High-energy cosmic neutrinos:

Where do we stand, where do we go, And how do we get there

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

HIRSAP Workshop
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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

1962: First cosmic rays with $>10^{20}$ eV


1962: First cosmic rays with $>10^{20}$ eV
2019: We are getting close to finding what is making them!

Using UHECRs to find their sources is tough

- The Universe is opaque to UHECRs
  - CRs lose energy by scattering on the cosmic microwave background (CMB):

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$$

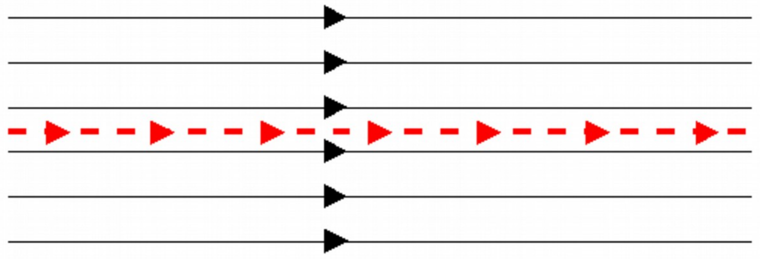
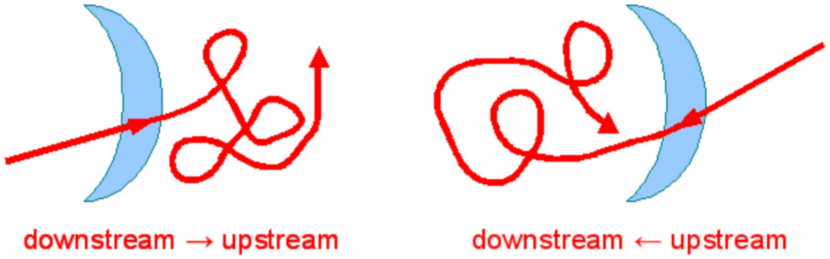
  - Protons above $4 \cdot 10^{9}$ GeV do not survive more than ~100 Mpc

- Cosmic rays do not point back at their sources
  - Magnetic fields: μG (Milky Way) – nG (extragalactic)
  - Deflections of up to tens of degrees

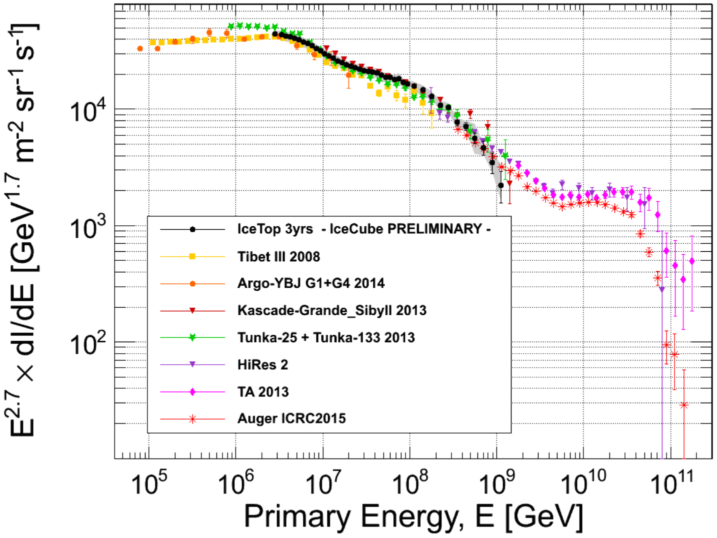
- Uncertainties about how high-energy particle showers work

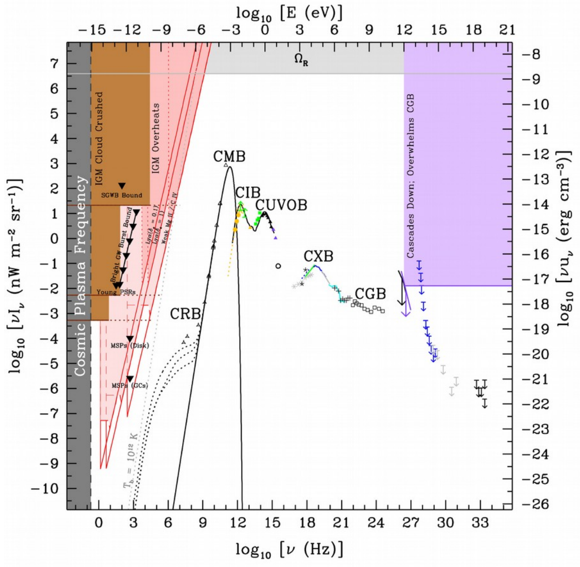
Jellyfish Nebula , NASA

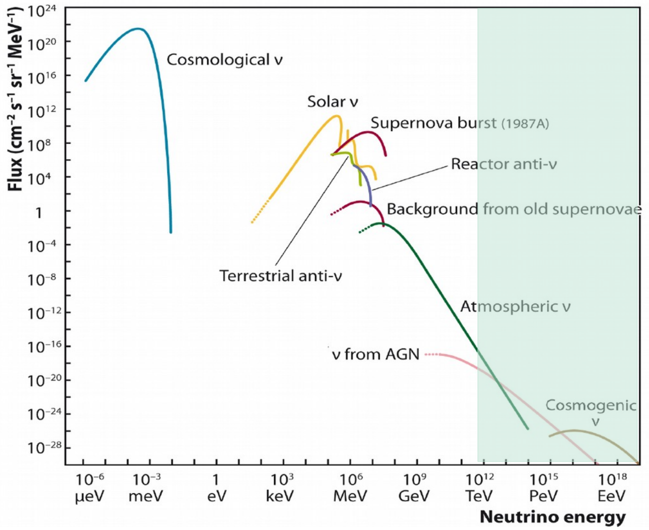
Luckily, UHECR sources should be wasteful…

	Man-made accelerators	Astrophysical accelerators
		
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

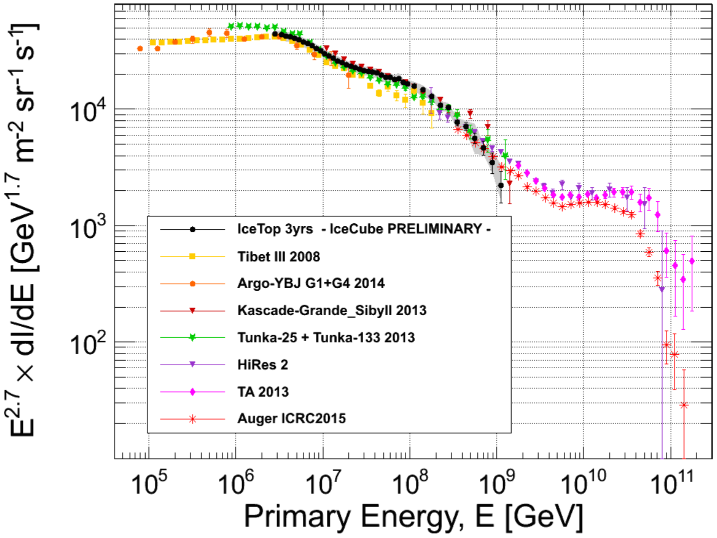
Astrophysical accelerators *inevitably* make high-energy secondaries

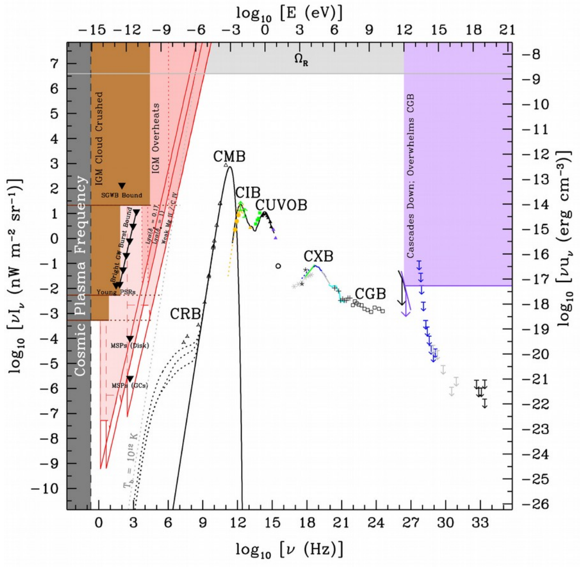


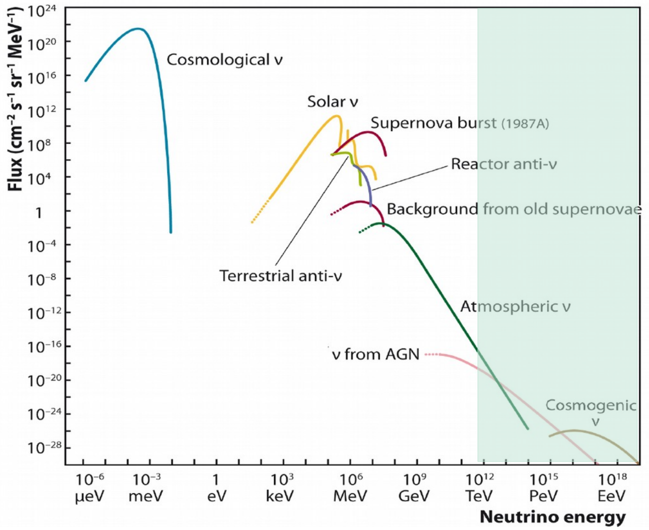




UHE cosmic rays + Photons → Neutrinos



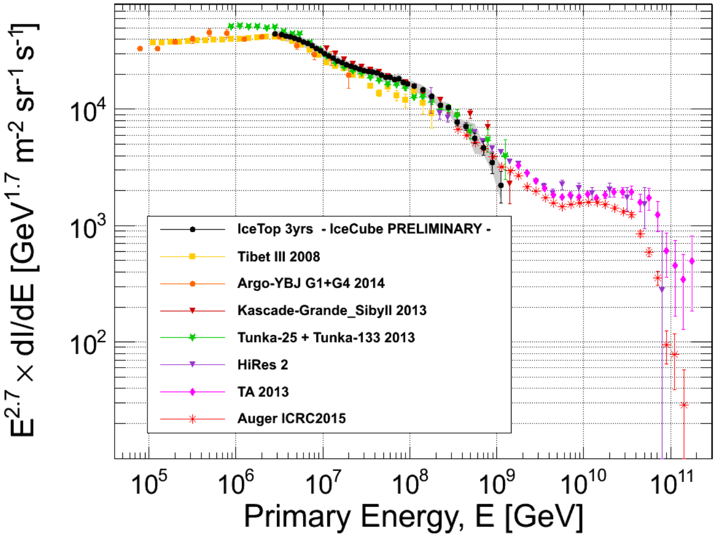


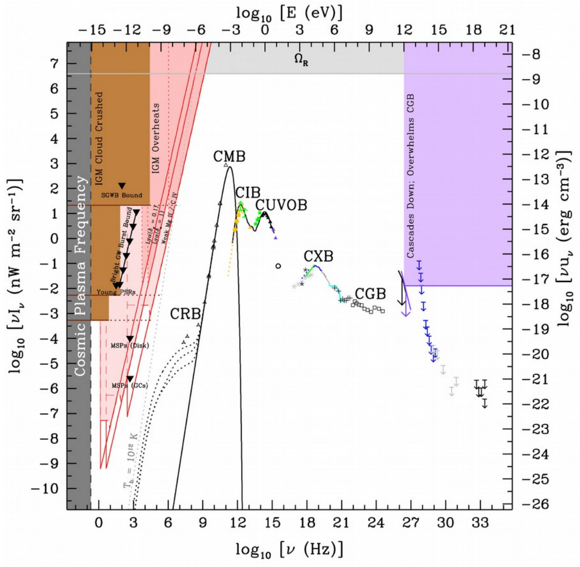


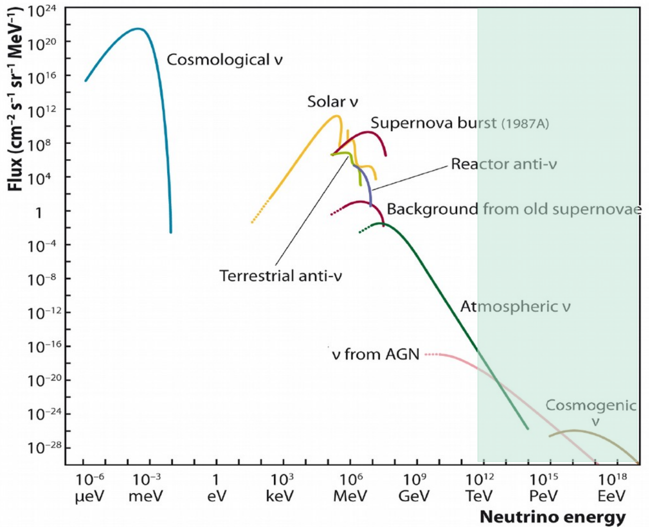
UHE cosmic rays + Photons → Neutrinos

0.1–100 PeV .... MeV .... TeV–PeV

EeV–ZeV .... meV .... 1–100 EeV







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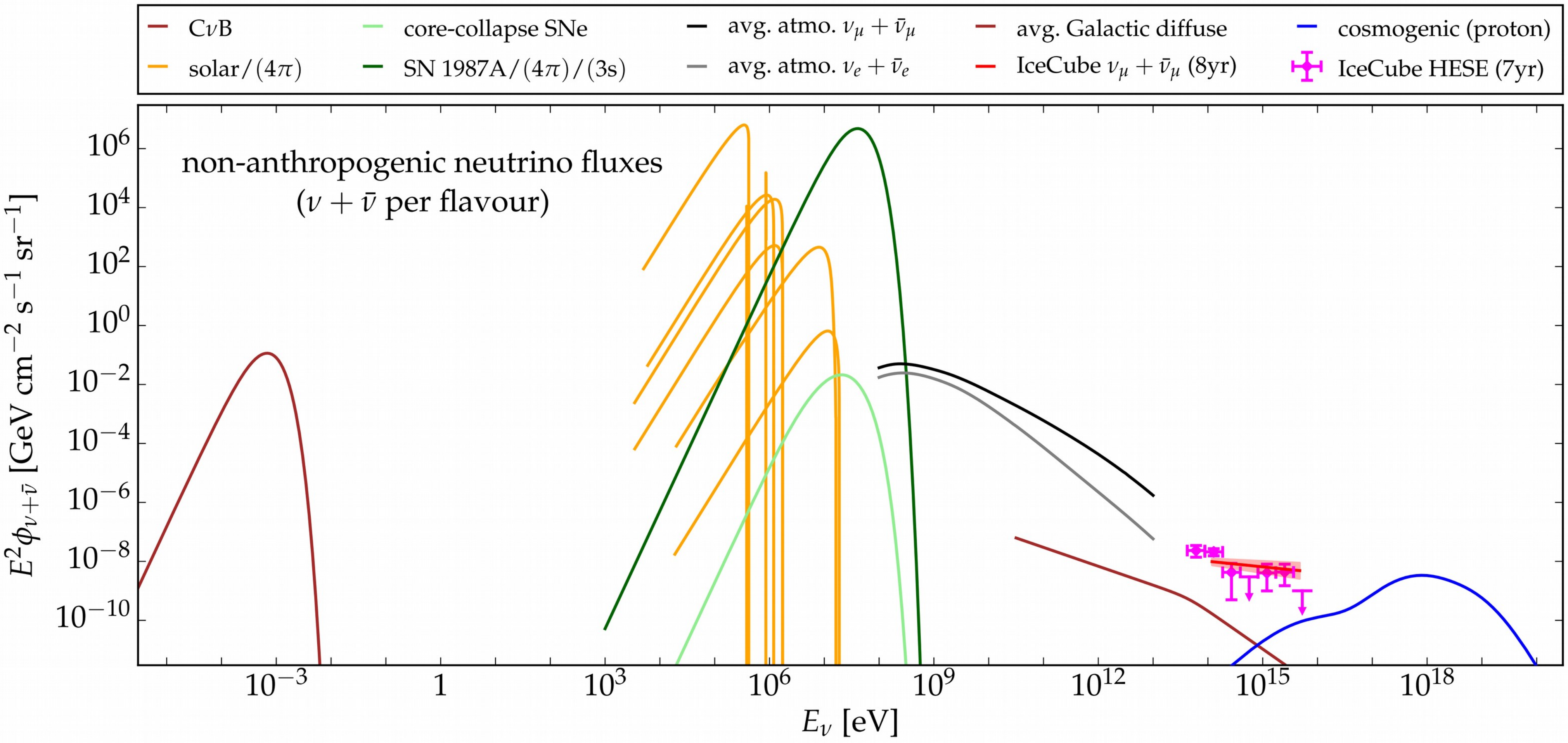
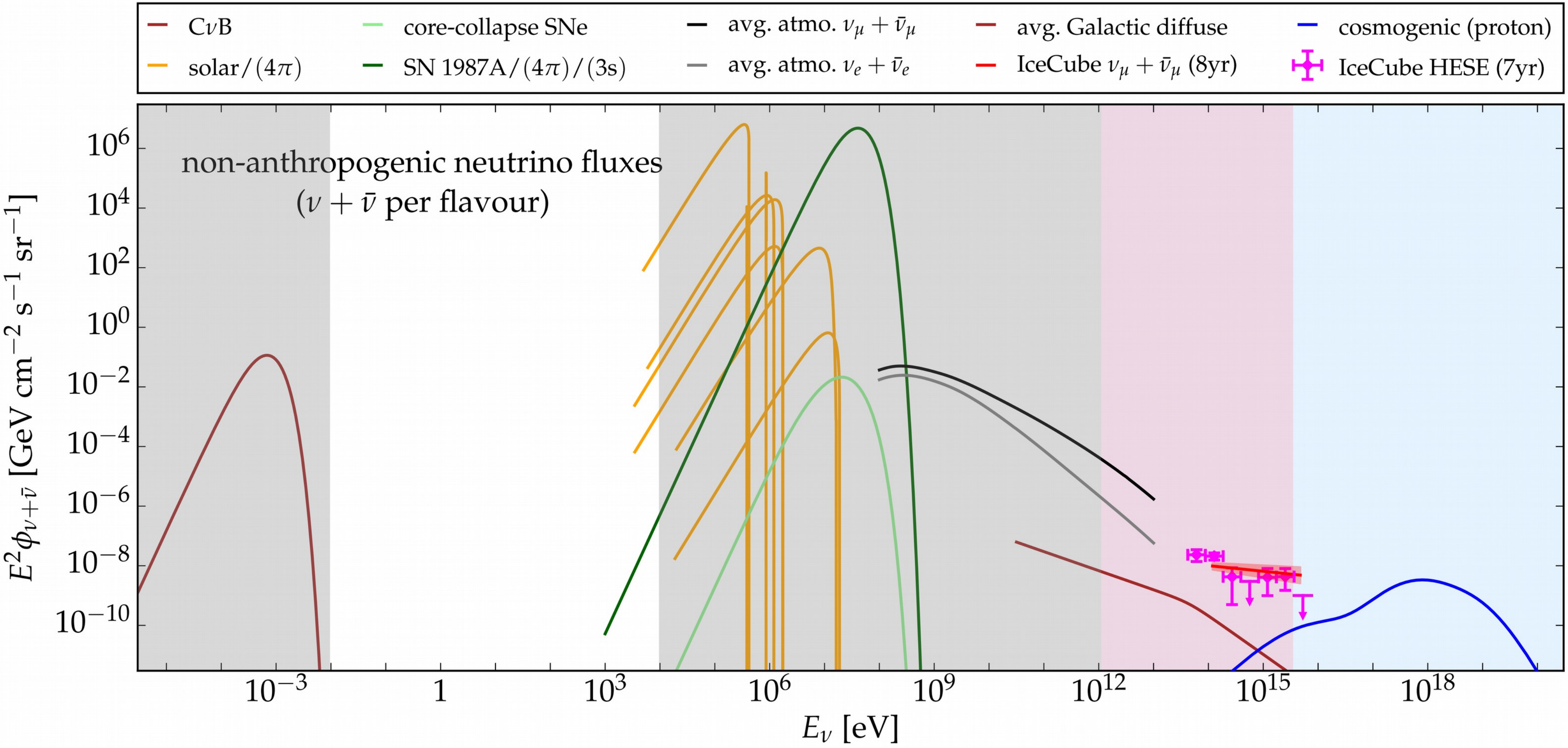


Figure courtesy of Markus Ahlers
Also in: Van Elewyck, **MB** *et al.*, PoS(ICRC2019), 1023



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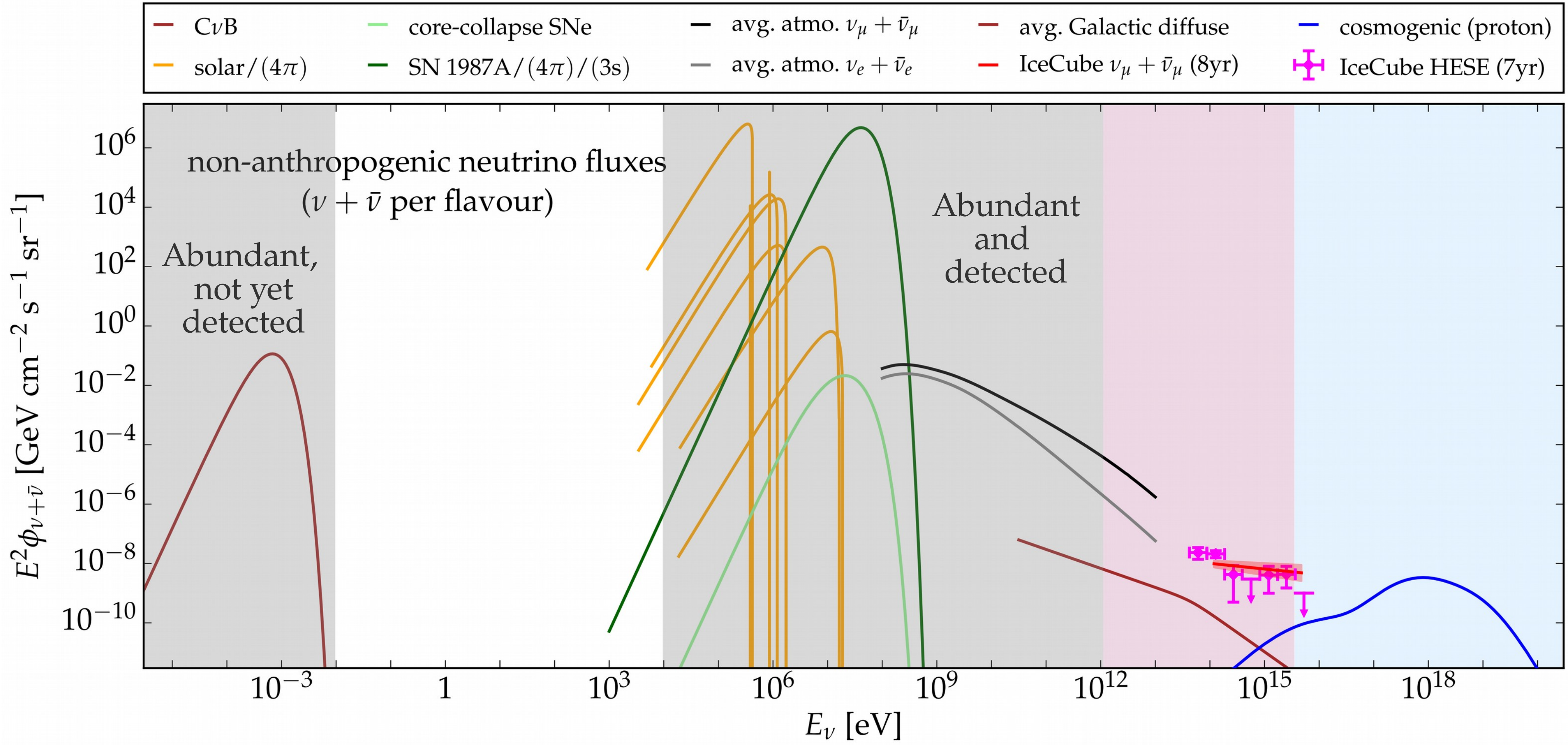

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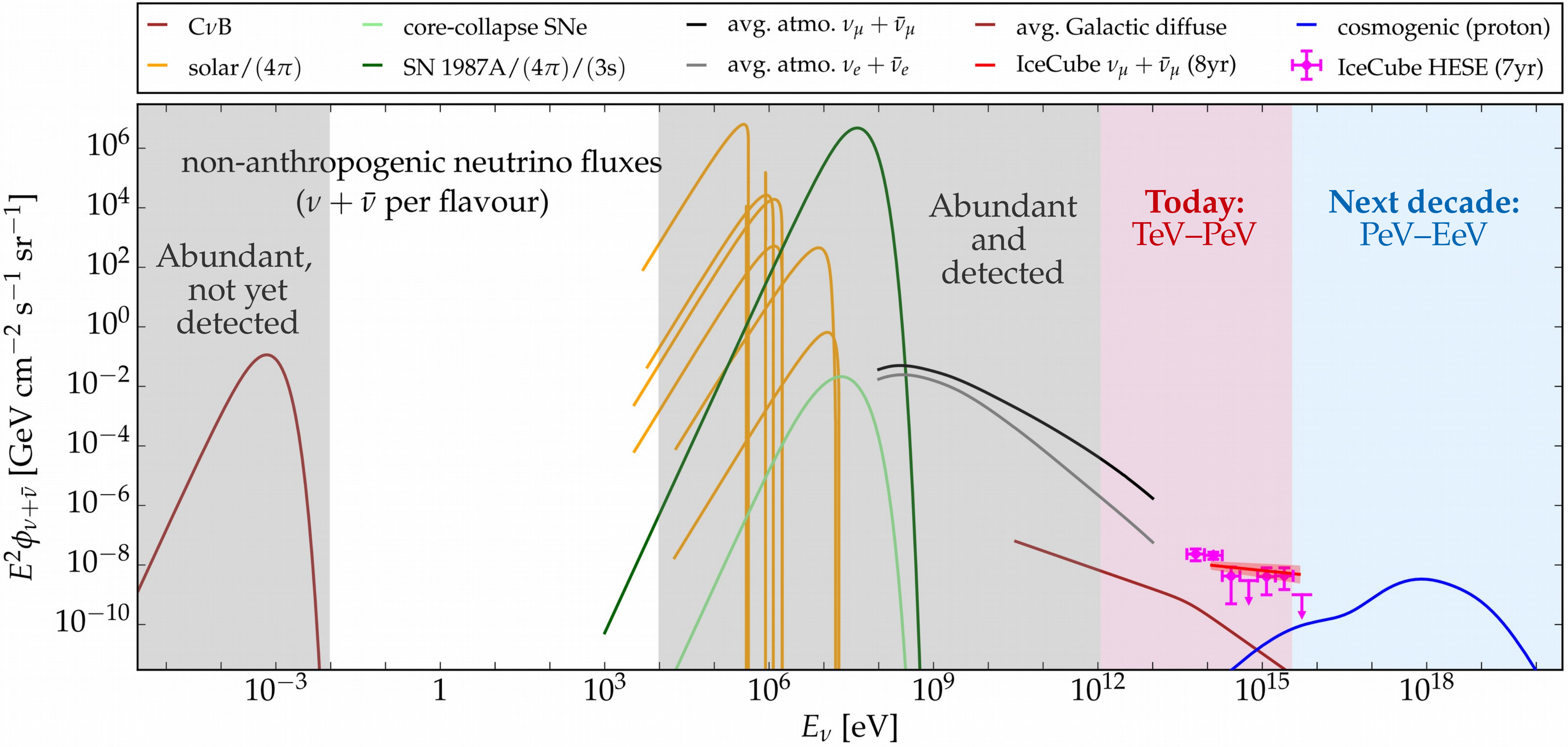

Figure courtesy of Markus Ahlers
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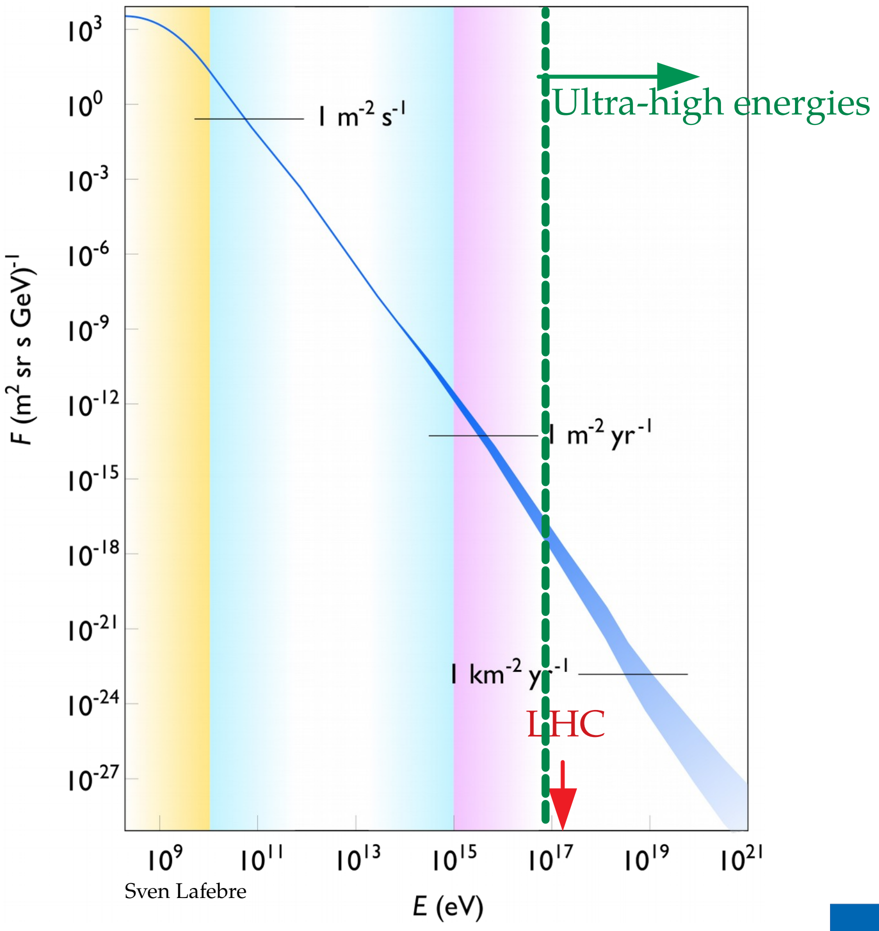
Why study high-energy astrophysical neutrinos?

They are key to answering two major questions –

1. What makes the most energetic particles we detect?
2. How does particle physics look at these energies?

Flux of cosmic rays at Earth



Sven Lafebre

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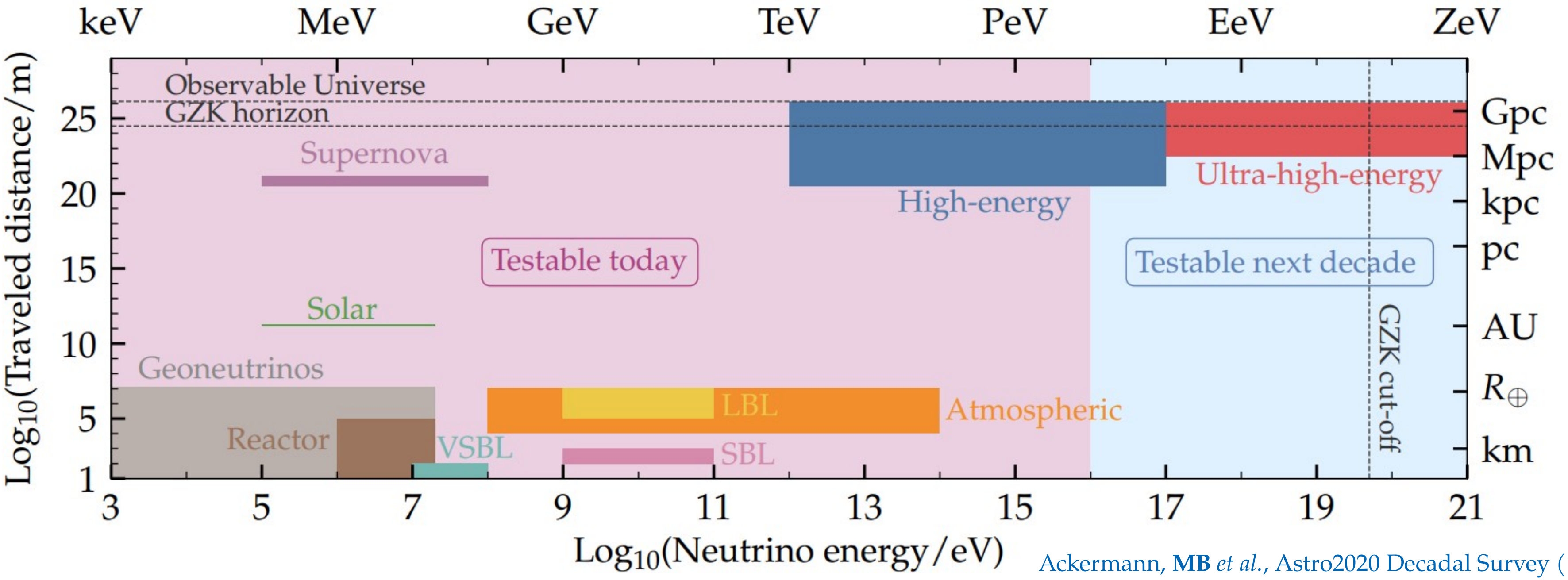

Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04333)

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   ↦ But they are also difficult to detect

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3 Neutrinos are weakly interacting
$\mapsto$ They bring untainted information across cosmological scales
$\mapsto$ But they are also difficult to detect

4 Neutrinos have a unique quantum number: flavor
$\mapsto$ Powerful probe of astrophysics and neutrino physics
$\mapsto$ But flavor is hard to reconstruct

Prediction and discovery

The multi-messenger connection: a simple picture

$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0}, \;\; \mathrm{Br} = 2/3 \\ n + \pi^{+}, \;\; \mathrm{Br} = 1/3 \end{cases}$$

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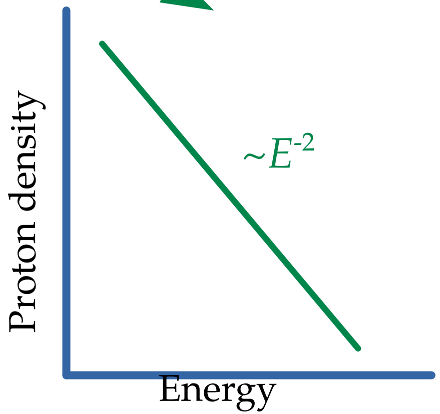

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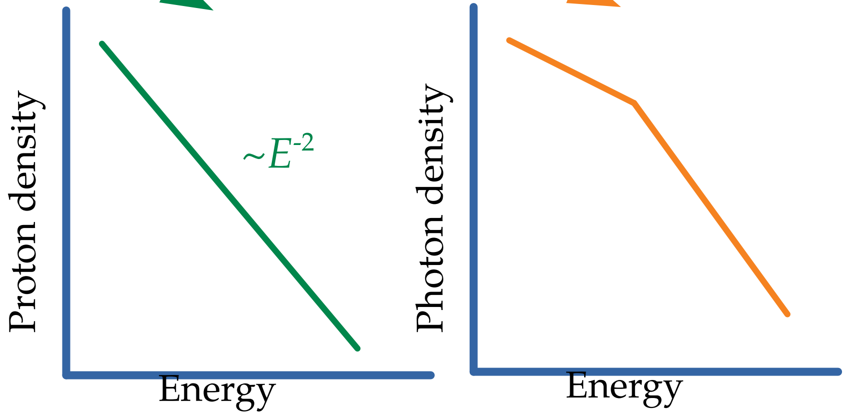

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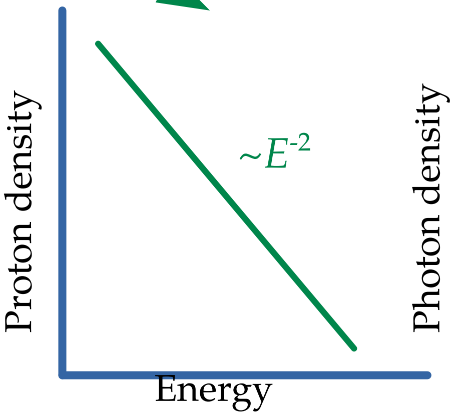
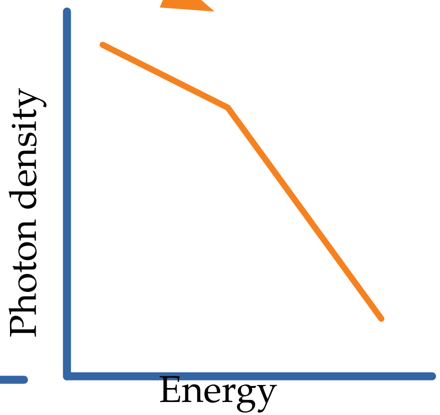
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n\ (\text{escapes}) \rightarrow p + e^- + \bar{\nu}_e$$





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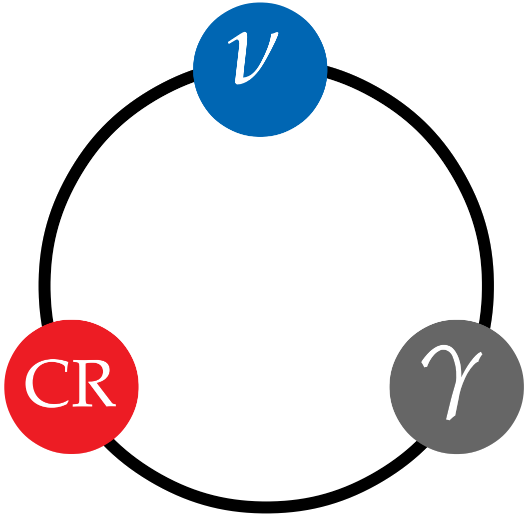

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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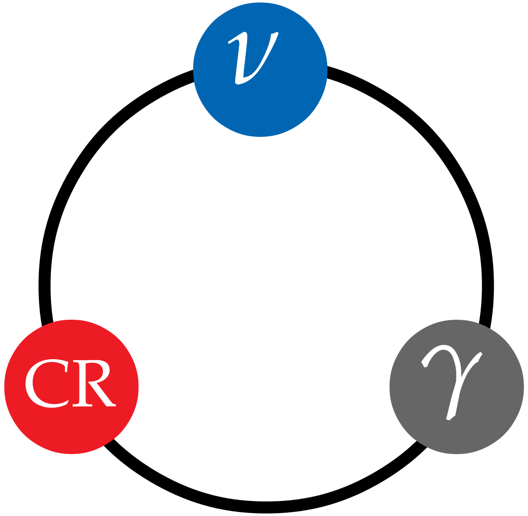

1 PeV　　　　　20 PeV

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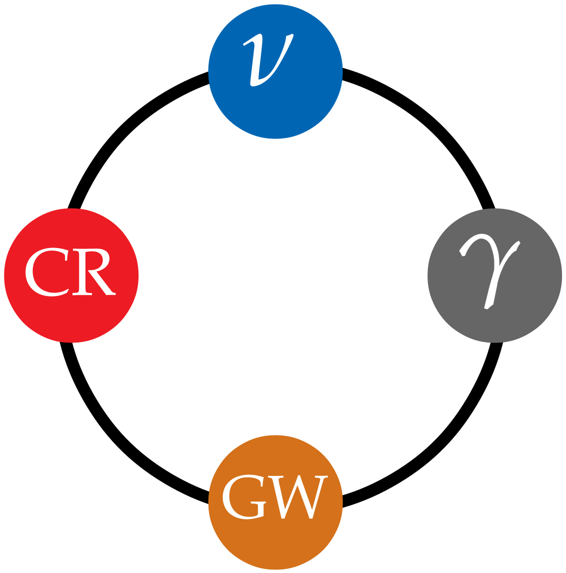

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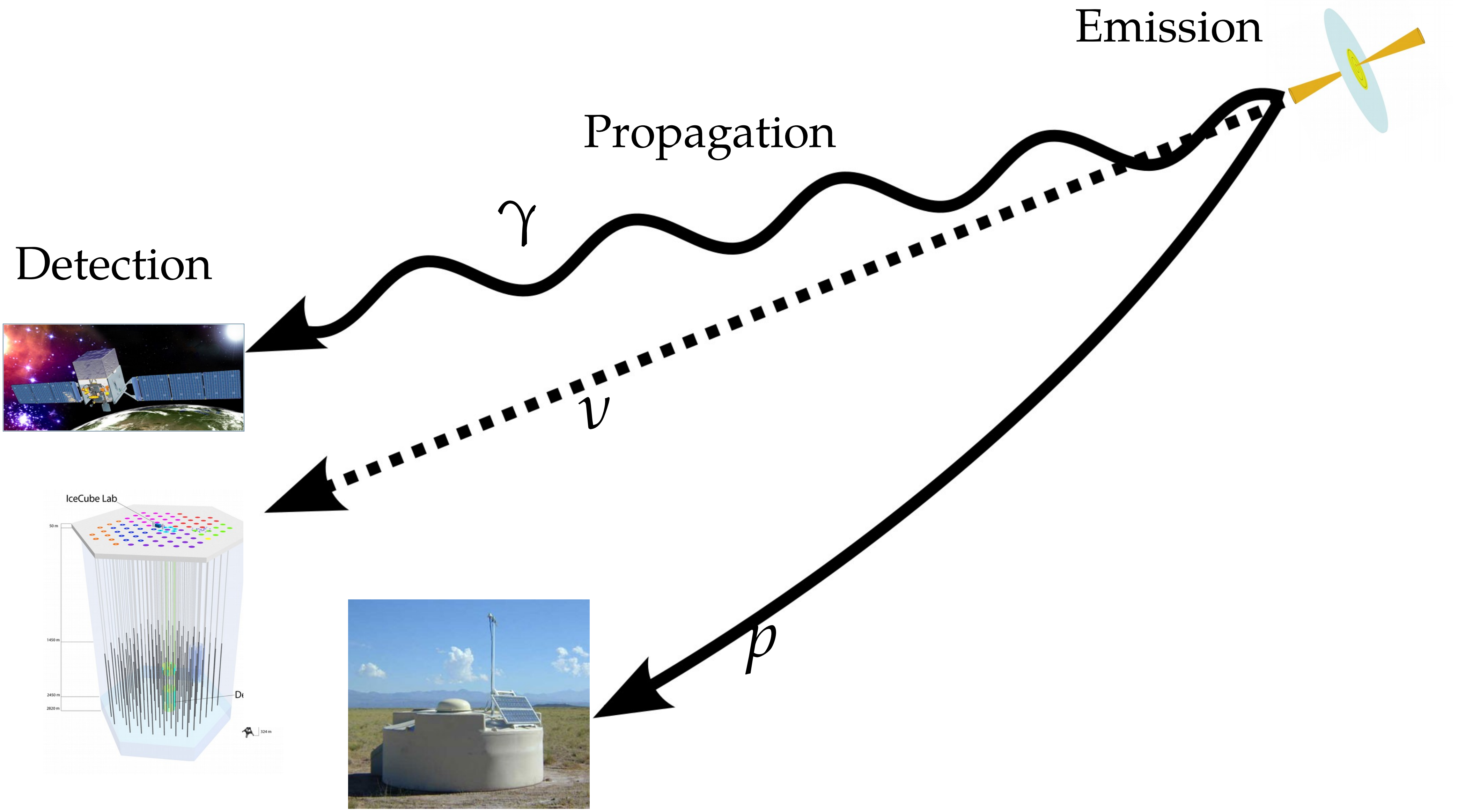
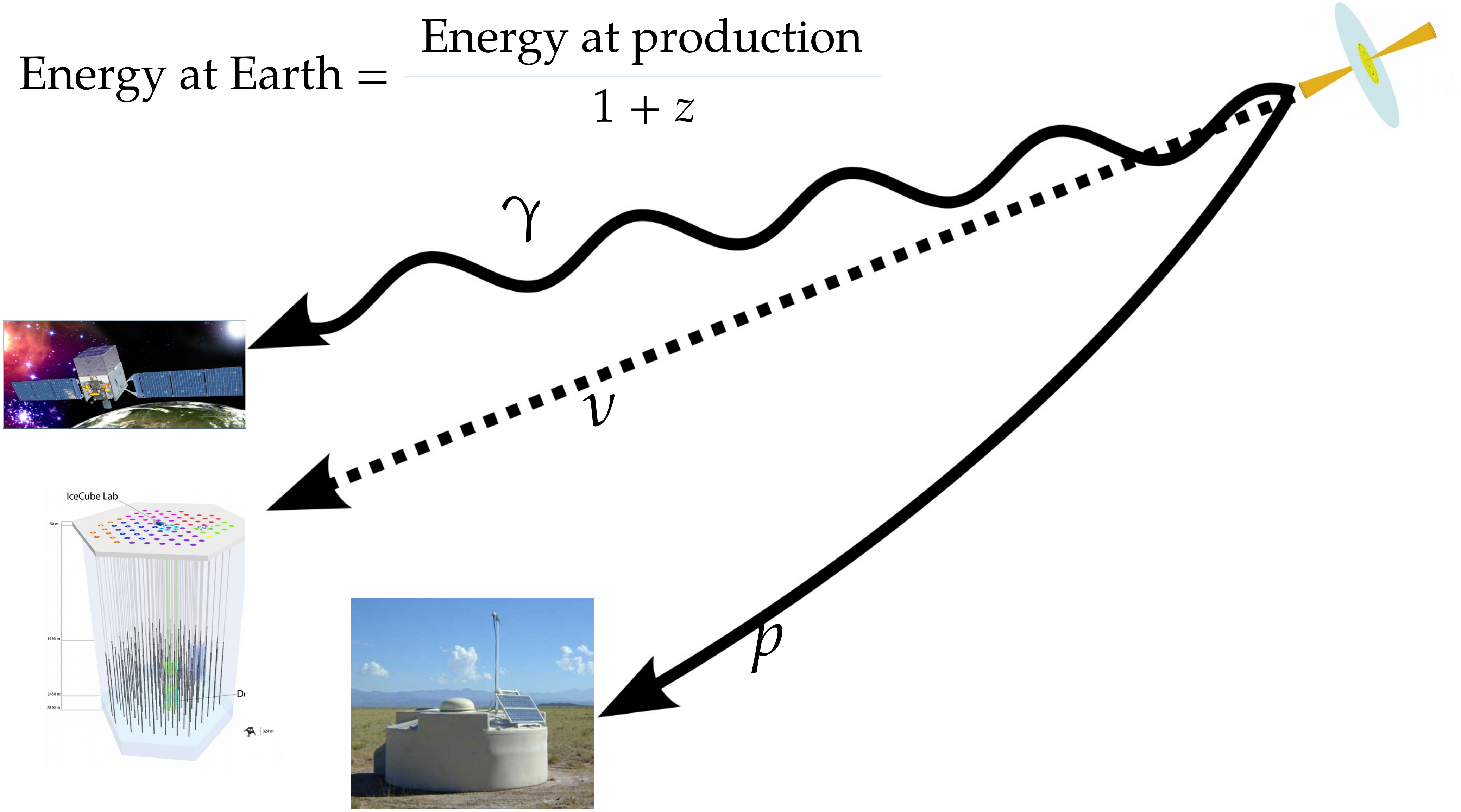

Emission
Propagation
Detection
γ
ν
p
IceCube Lab
50 m
1450 m
2450 m
2820 m
324 m

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$



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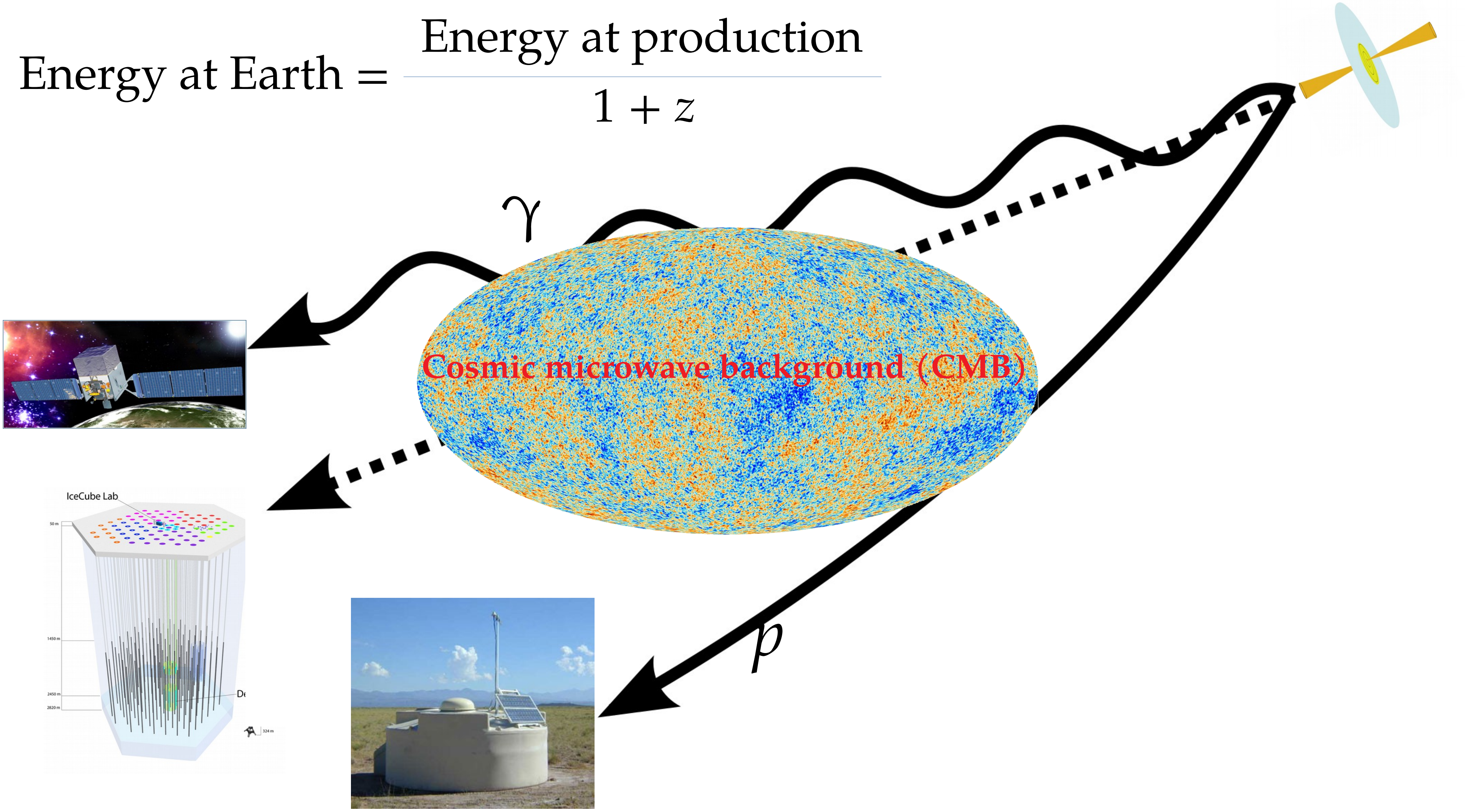

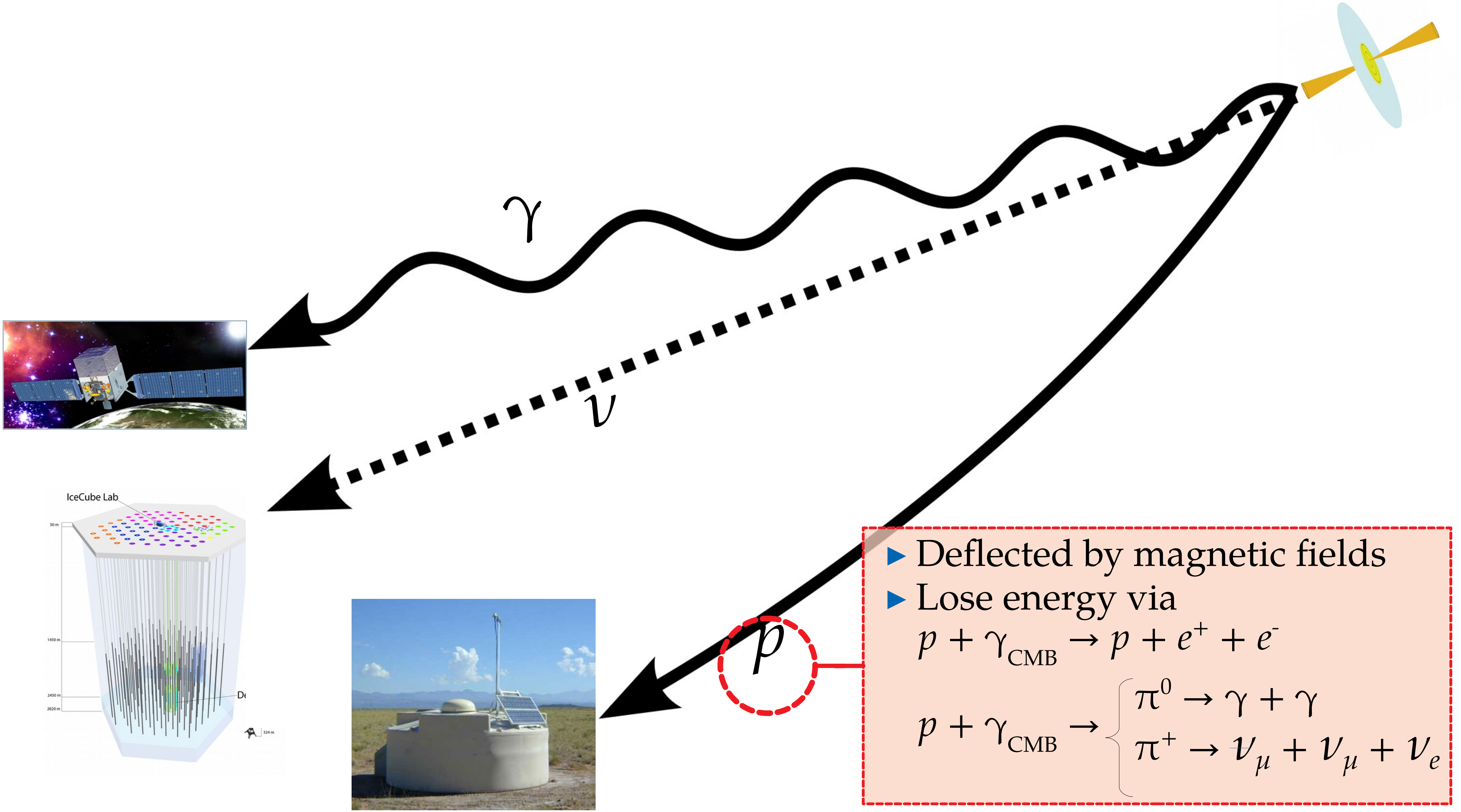

γ
ν
p
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$
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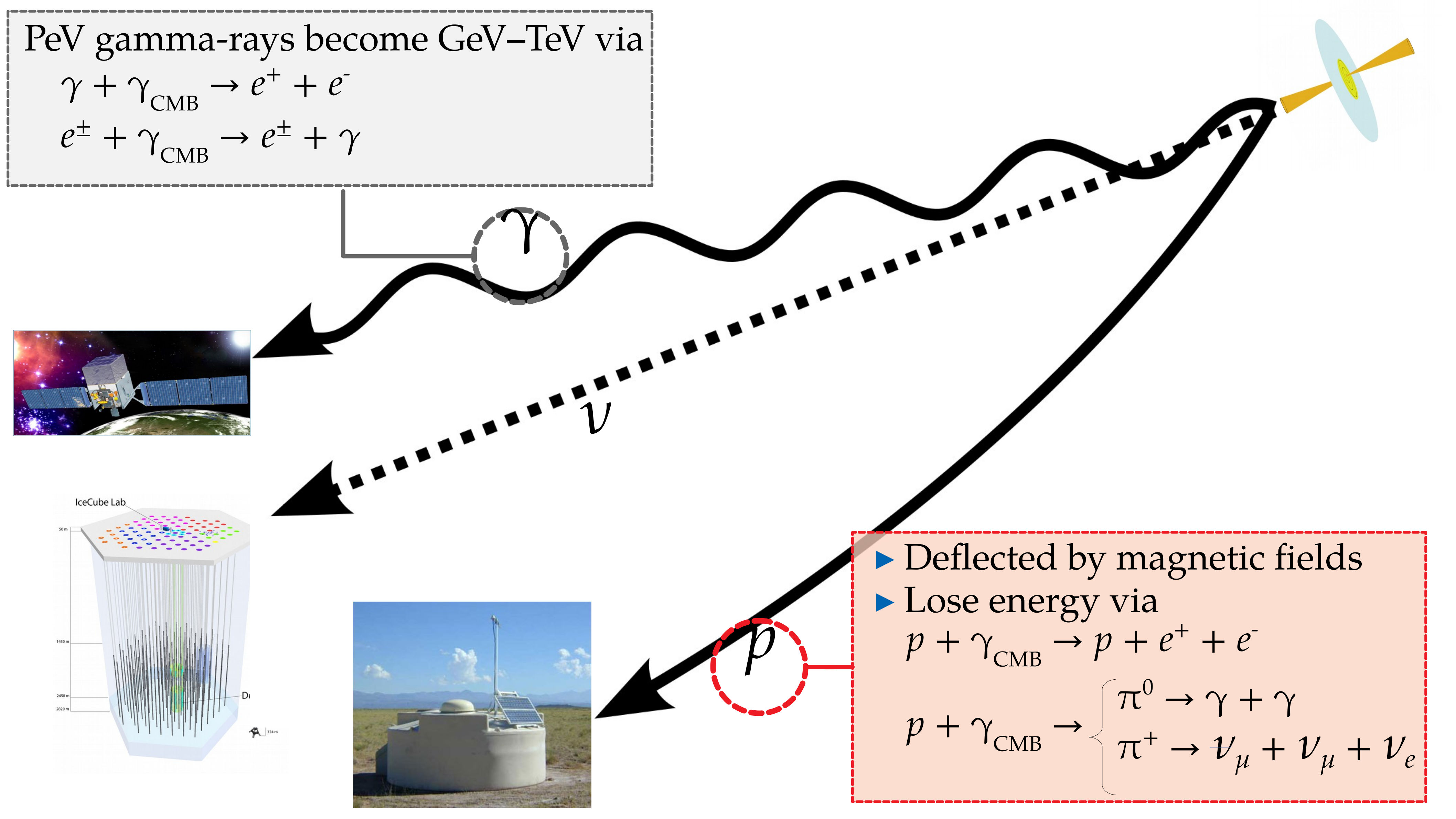
PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{\mathrm{CMB}} \rightarrow e^{+} + e^{-}$
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γ
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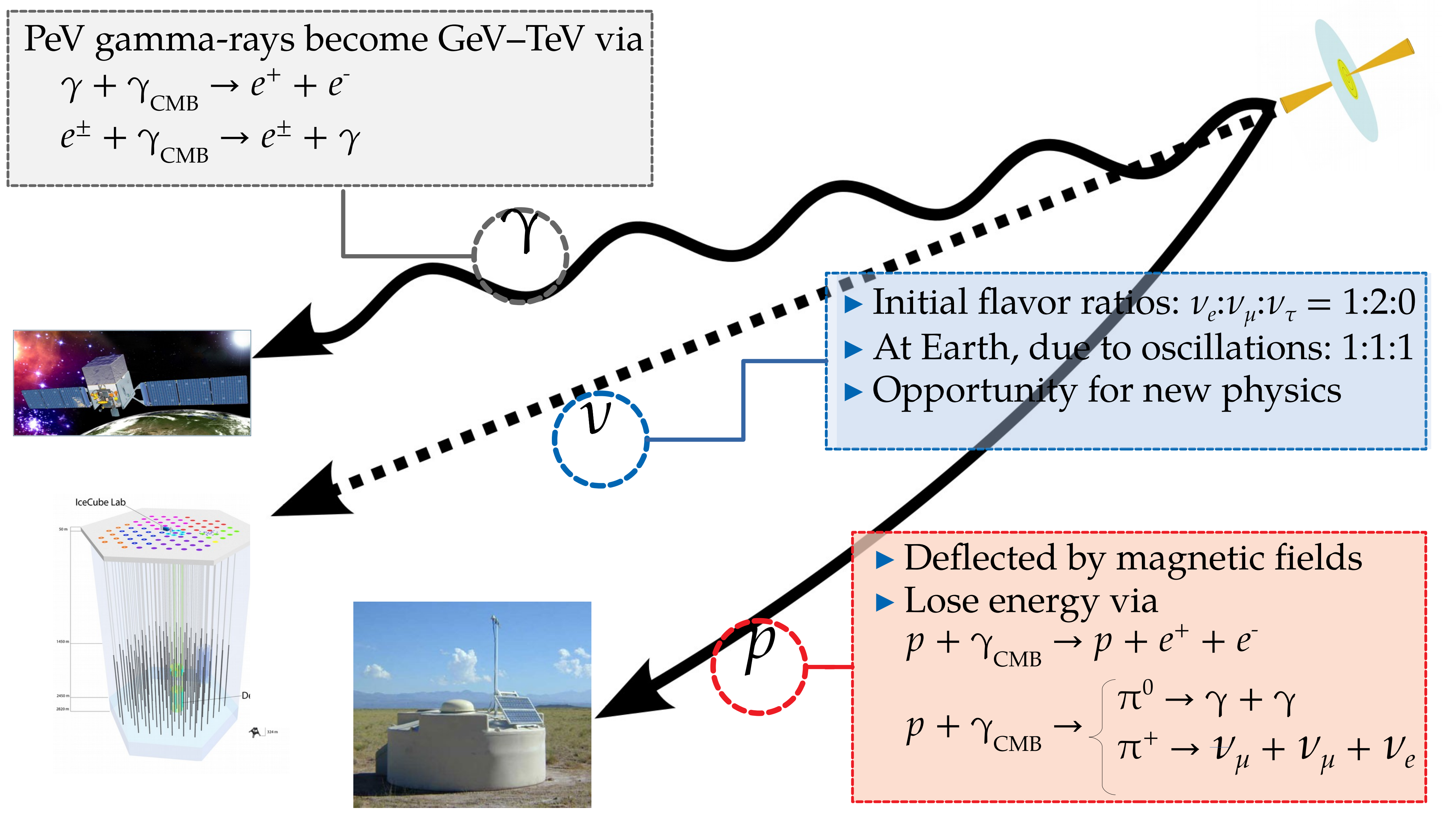
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γ
ν
p
▸ Initial flavor ratios: $\nu_e{:}\nu_\mu{:}\nu_\tau = 1{:}2{:}0$
▸ At Earth, due to oscillations: 1:1:1
▸ Opportunity for new physics
▸ Deflected by magnetic fields
▸ Lose energy via
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IceCube Lab

How many neutrinos? The Waxman-Bahcall bound

- Energy production rate of extragalactic cosmic-ray protons in the energy range 10^{19}–10^{20} eV:

$$\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]} \sim 5 \cdot 10^{44}~{\rm erg~Mpc^{-3}~yr^{-1}}$$

- So, the energy-dependent generation rate of cosmic rays is $E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} = \frac{\dot{\varepsilon}_{\rm CR}^{[10^{19},10^{21}]}}{\ln(10^{21}/10^{19})} \approx 10^{44}~{\rm erg~Mpc^{-3}~yr^{-1}}$

- Protons lose a fraction $\epsilon < 1$ in photohadronic production of pions in the sources

- Present-day energy density of $\nu_\mu + \bar{\nu}_\mu$: $E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx \frac{1}{4} \epsilon ~ t_{\rm H} ~ E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$

$\mathrm{Br}(p+\gamma \to \pi^+) = 0.5$ × Fraction of π energy going to $\nu_\mu + \bar{\nu}_\mu$

Hubble time: $t_{\rm H} \sim 10^{10}$ yr

- Maximum neutrino intensity is for $\epsilon = 1$: $I_{\rm max} \approx \frac{1}{4} \xi_z ~ t_{\rm H} \frac{c}{4\pi} E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} \approx 1.5 \cdot 10^{-8} \xi_z~{\rm GeV~cm^{-2}~s^{-1}~sr^{-1}}$

- So the expected neutrino flux is $E_\nu^2 \Phi_{\nu_\mu} \equiv \frac{c}{4\pi} E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{2} \epsilon I_{\rm max}$

Waxman & Bahcall, *PRD* 1999

Waxman-Bahcall bound: $E_\nu^2 \Phi_{\nu_\mu} \approx 0.75 \cdot 10^{-8} \xi_z ~ \epsilon~{\rm GeV~cm^{-2}~s^{-1}~sr^{-1}}$

The need for km-scale detectors

Predicted by Waxman-Bahcall 1998

- Neutrino flux at TeV–PeV: $E^2 \cdot \Phi \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

- Neutrino-nucleon cross section: $\sigma_{\nu p} \sim 10^{-35}\ \mathrm{cm}^2\ (E/\mathrm{GeV})^{0.36}$

At center-of-mass energy of 1 GeV:
$\sigma_{pp} \sim 10^{-28}\ \mathrm{cm}^2$
$\sigma_{\gamma p} \sim 10^{-29}\ \mathrm{cm}^2$

- Number of detected neutrinos from half the sky in 1 yr:

$$N = (n_{\mathrm{nucl}} \cdot V_{\mathrm{det}}) \cdot (2\pi) \cdot (1\ \mathrm{yr}) \cdot \int_{100\ \mathrm{TeV}} \Phi(E) \cdot \sigma_{\nu p}(E)\, \mathrm{d}E$$

- To detect $N > 10$ neutrino, we needed

$$V_{\mathrm{det}} > 1\ \mathrm{km}^3$$

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Number density of nucleons: $\sim N_{\mathrm{Av}}$ cm^{3}

Detector volume

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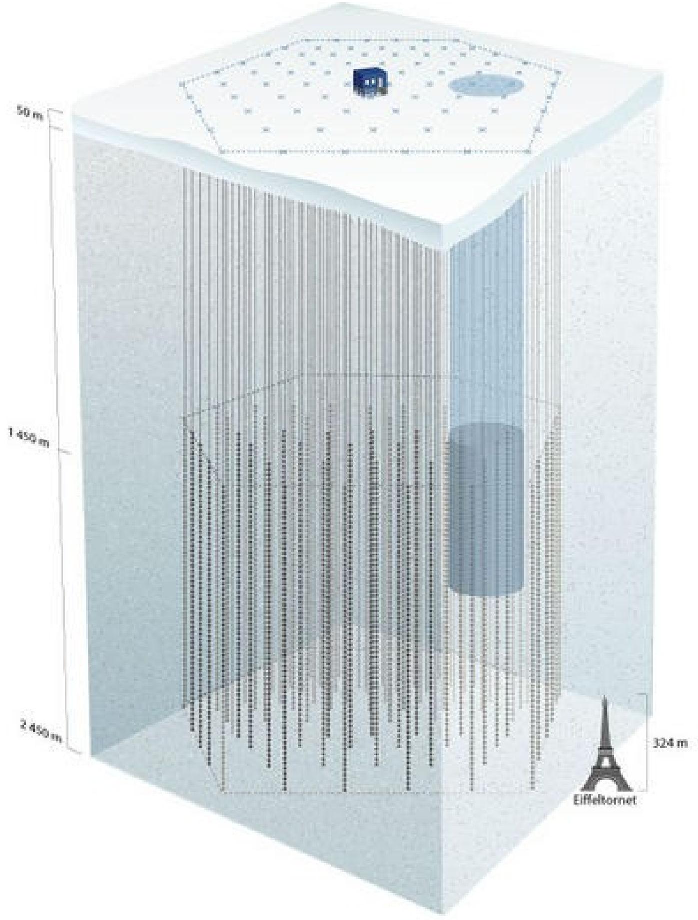
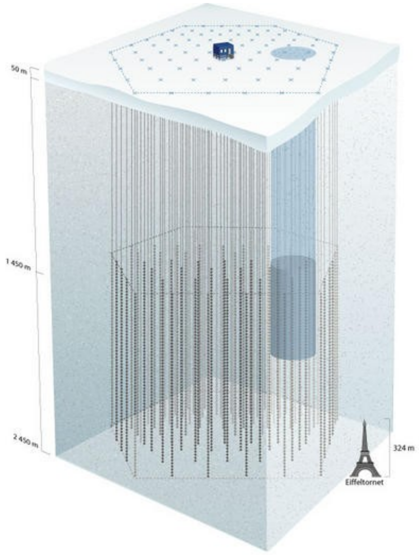
IceCube – What is it?



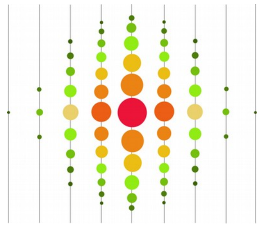
- Km^3 in-ice Cherenkov detector in Antarctica
- >5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

IceCube (8 years)

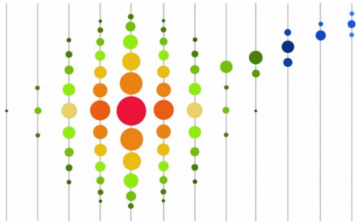
km³ in-ice
Cherenkov detector



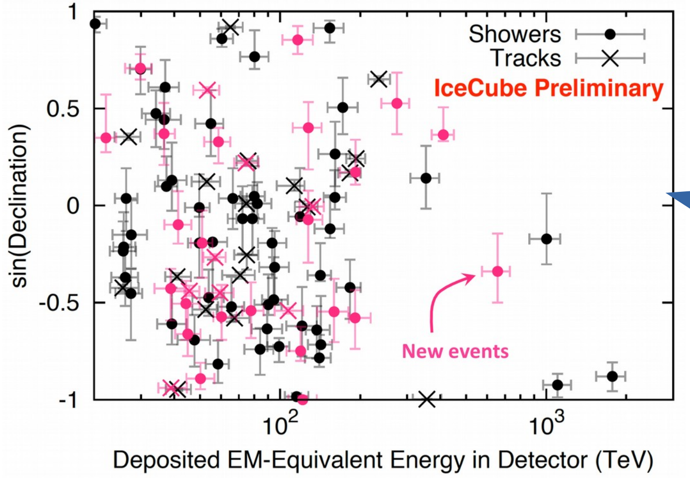
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)

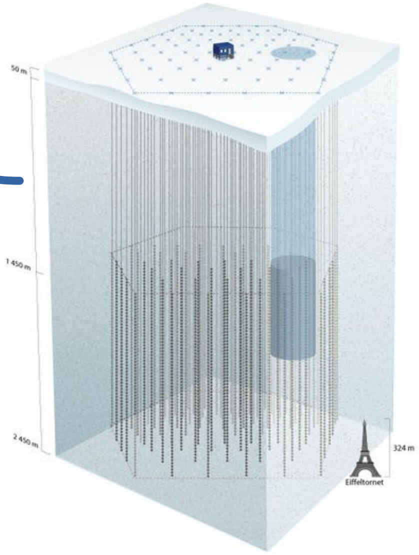


103 contained events, 15 TeV–2 PeV



IceCube (8 years)

km³ in-ice
Cherenkov detector



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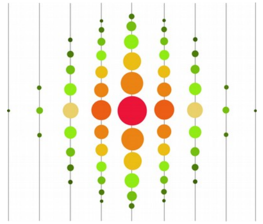

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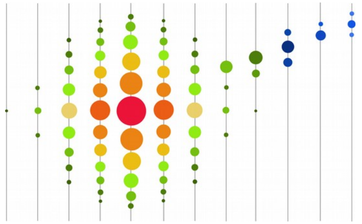

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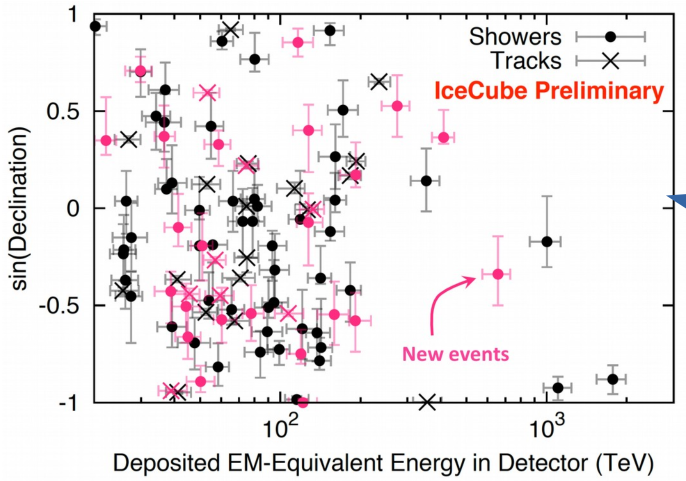
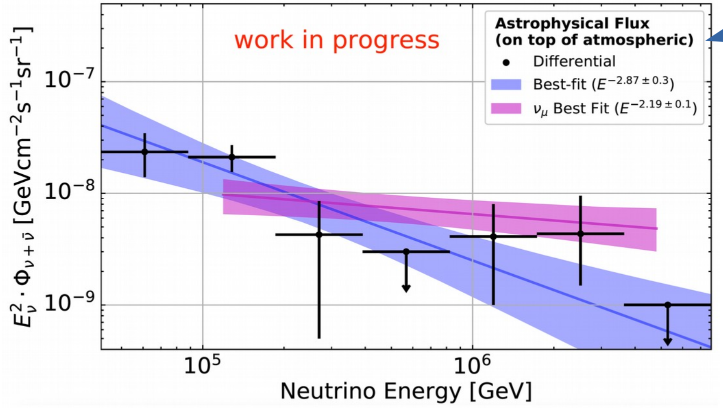


Astrophysical ν flux detected at $> 7\sigma$



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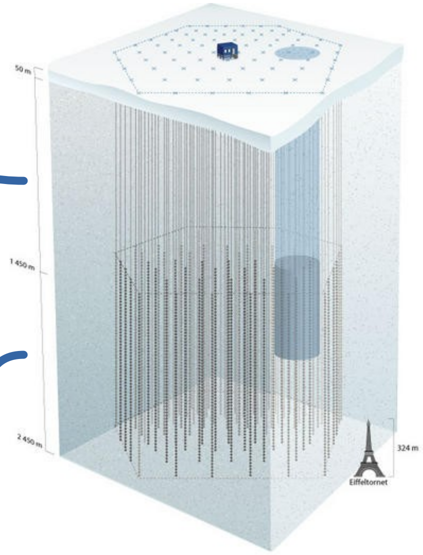
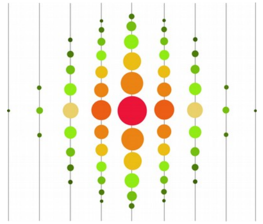
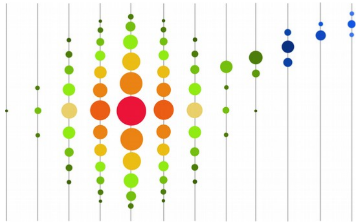
km³ in-ice
Cherenkov detector



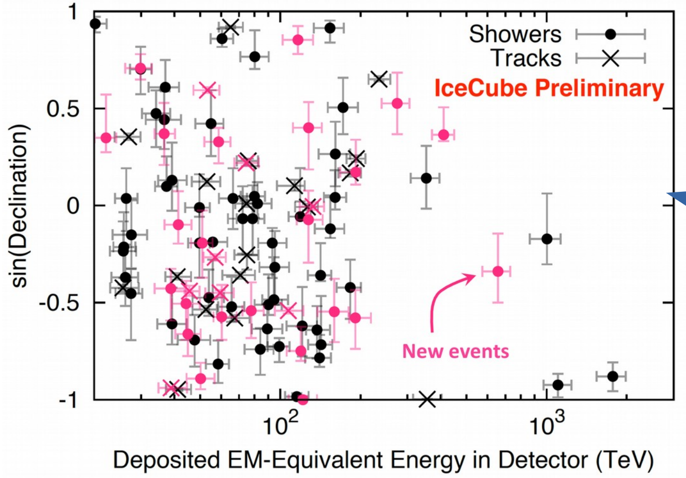
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)

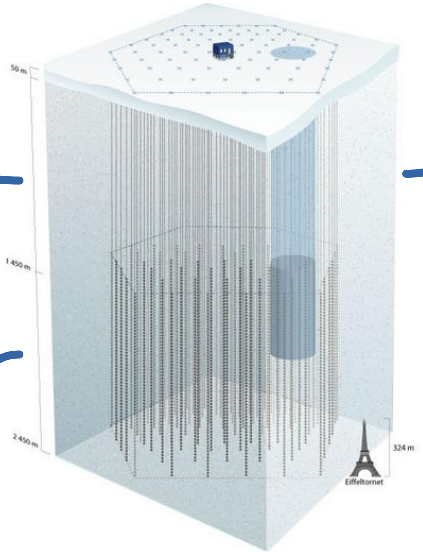


103 contained events, 15 TeV–2 PeV

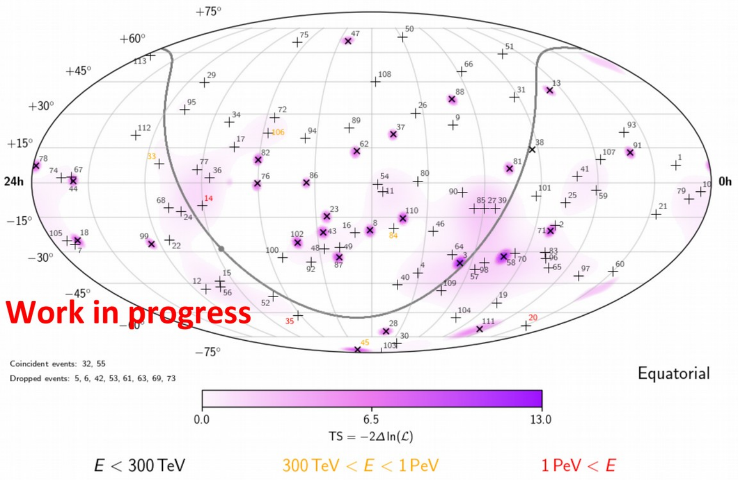


IceCube (8 years)

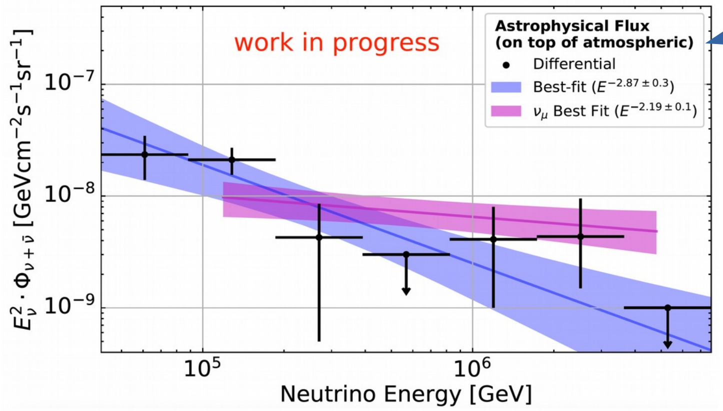
km³ in-ice
Cherenkov detector



Arrival directions compatible with isotropy



Astrophysical ν flux detected at $> 7\sigma$



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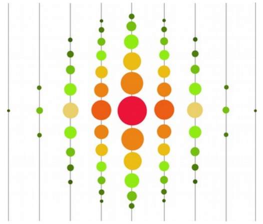

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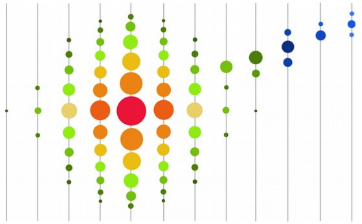

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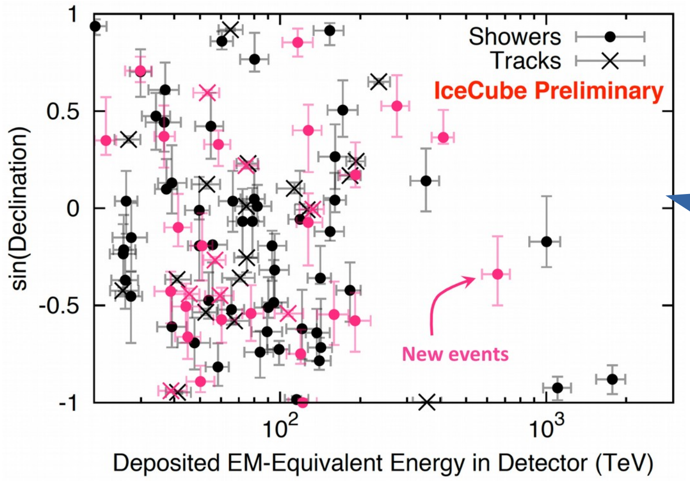

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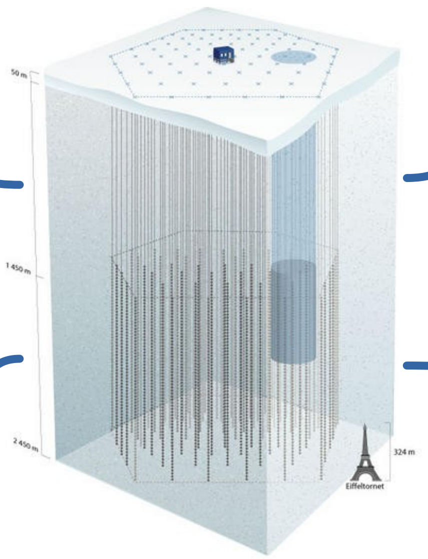

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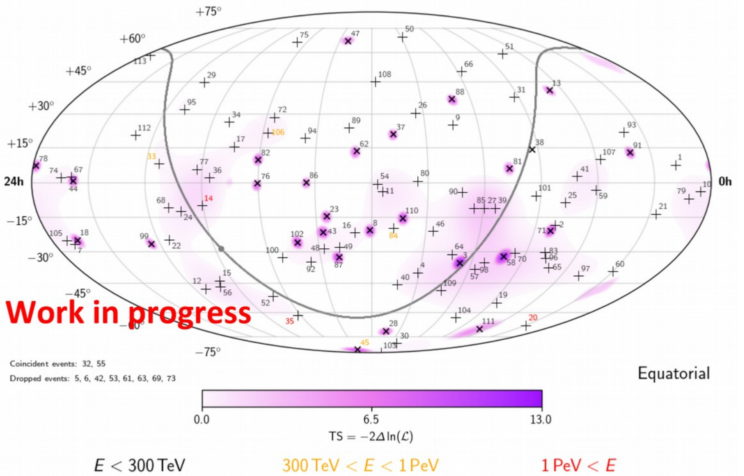

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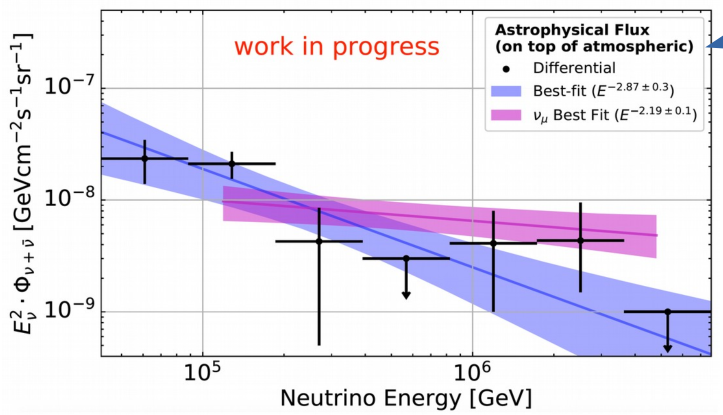

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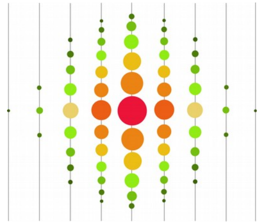

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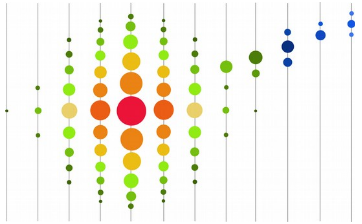
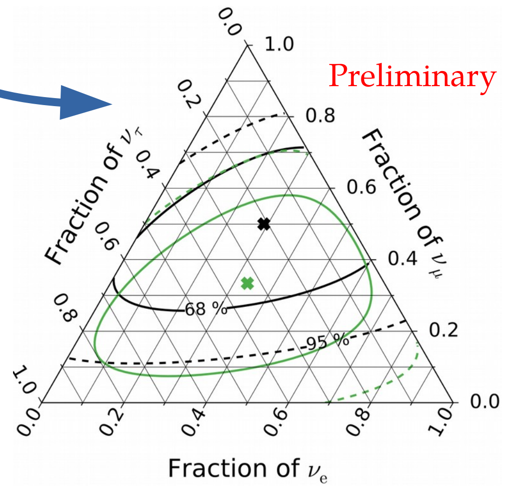


Flavor composition



Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

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Neutrino production

The Hillas criterion

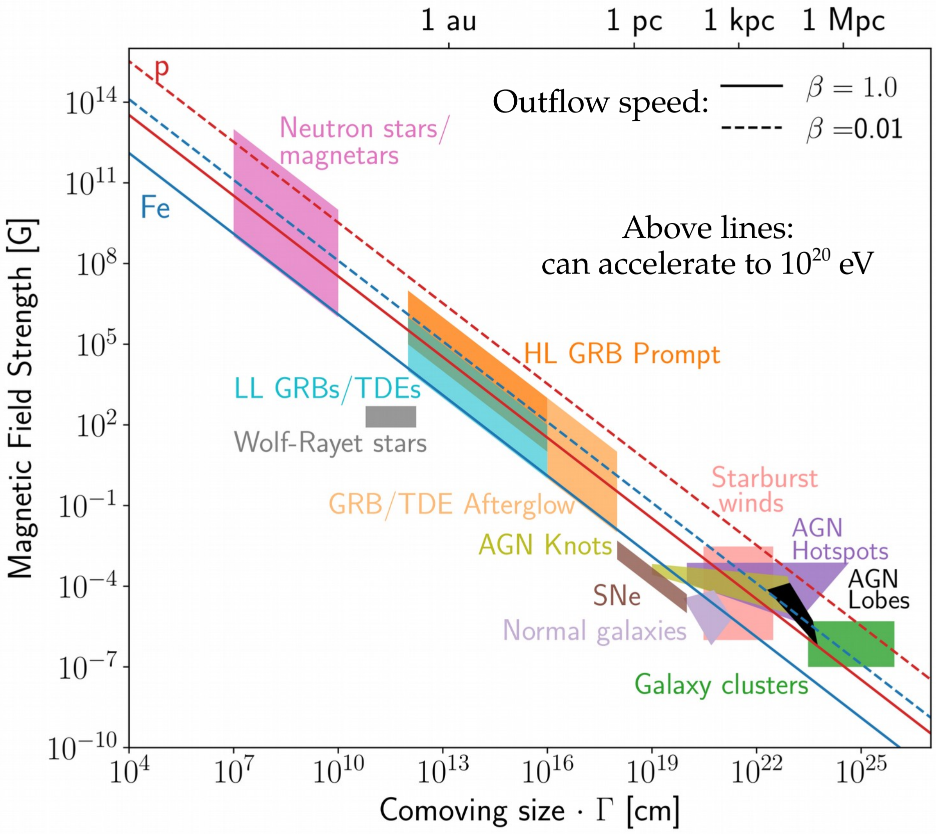
- Necessary condition for a source to accelerate cosmic rays

- Particles must stay confined:

Larmor radius < Size of acceleration region

$$R_{\mathrm{L}} = E/(Z\,e\,B) < (R\,\Gamma)$$

- Maximum energy:



$$E_{\mathrm{max}} \approx \left(3\cdot 10^{20}\ \mathrm{eV}\right)\eta^{-1}\beta_{\mathrm{sh}}Z\left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right)\left(\frac{B}{100\ \mathrm{G}}\right)$$

Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

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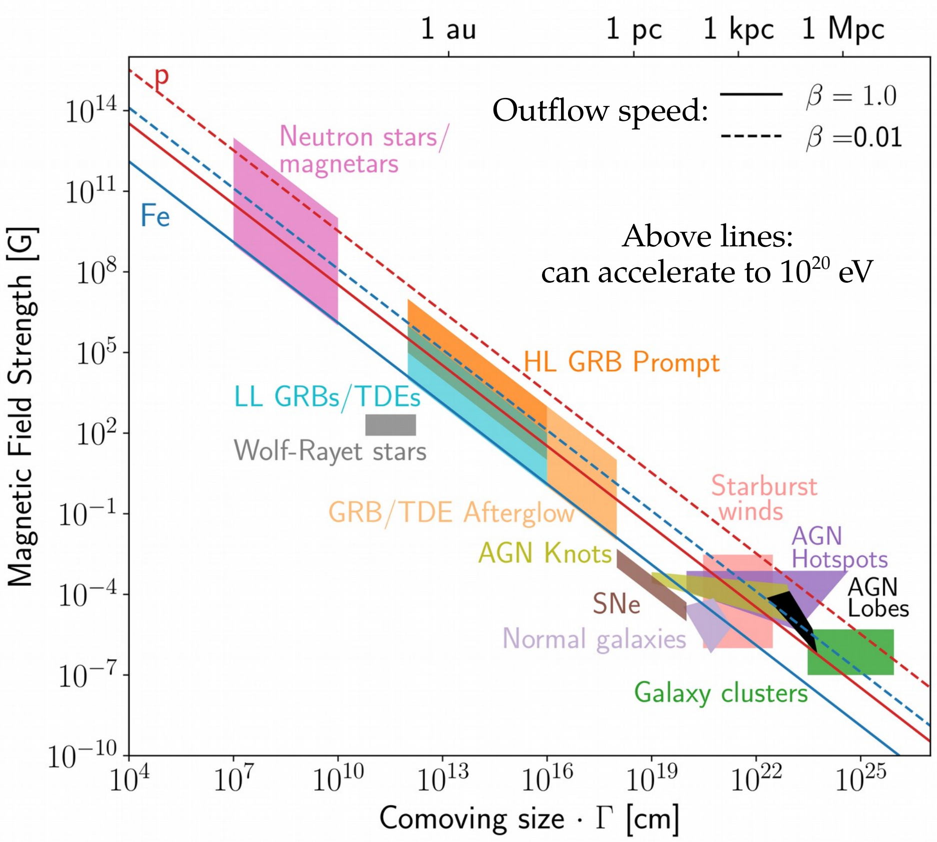

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Electric charge of the particle

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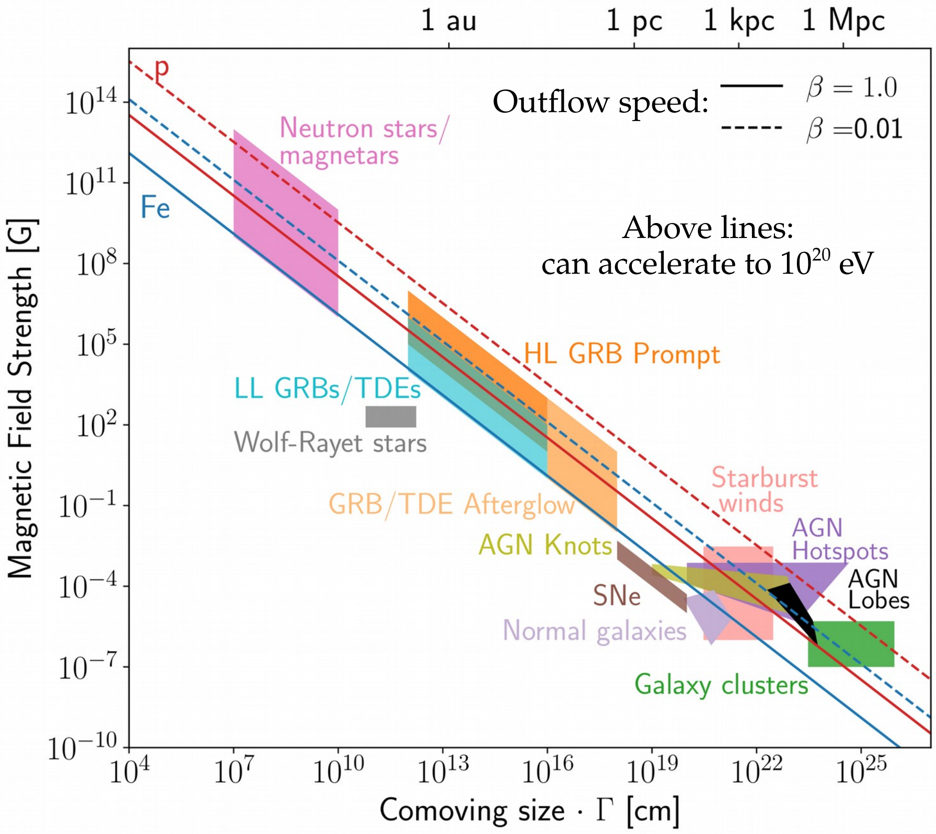
Bulk Lorentz factor of accelerating region

- Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\mathrm{sh}} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$

Speed v_{sh}/c of the outflow



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

Kinematics of high-energy neutrino production (1/2)

- What are the proton and photon energies needed for $p + \gamma \to \Delta$?

Four-vectors

$$(p_p + p_\gamma)^2 = p_\Delta^2 \Rightarrow p_p^2 + p_\gamma^2 + 2p_p \cdot p_\gamma = p_\Delta^2$$

But $p^2 = m^2$ for massive particles, so $m_p^2 + 2p_p \cdot p_\gamma = m_\Delta^2$.

Now, $p_p \cdot p_\gamma = E_p E_\gamma - \bar{p}_p \cdot \bar{p}_\gamma = E_p E_\gamma - |\bar{p}_p| \cdot |\bar{p}_\gamma| \cos\theta_{p\gamma}$.

For the photon, $|\bar{p}_\gamma| = E_\gamma$. For the high-energy proton, $|\bar{p}_p| = \sqrt{E_p^2 - m_p^2} \approx E_p$.

So, $p_p \cdot p_\gamma = E_p E_\gamma \left(1 - \cos\theta_{p\gamma}\right)$. Plugging this back yields $E_p E_\gamma = \dfrac{m_\Delta^2 - m_p^2}{2\left(1 - \cos\theta_{p\gamma}\right)}$.

- For a head-on collision ($\cos\theta_{p\gamma} = -1$):

$$\boxed{E_p E_\gamma = \frac{(1.232\ \text{GeV})^2 - (0.938\ \text{GeV})^2}{4} \approx 0.16\ \text{GeV}^2}$$

Kinematics of high-energy neutrino production (2/2)

- What are the energies of the neutrinos produced?

- In a $p + \gamma \rightarrow \pi^+$ interaction, the average pion energy is $E_\pi = E_p/5$

- In each decay $\pi^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+$, the average $\nu_\mu + \bar{\nu}_\mu$ energy is $E_\nu = E_\pi/4$

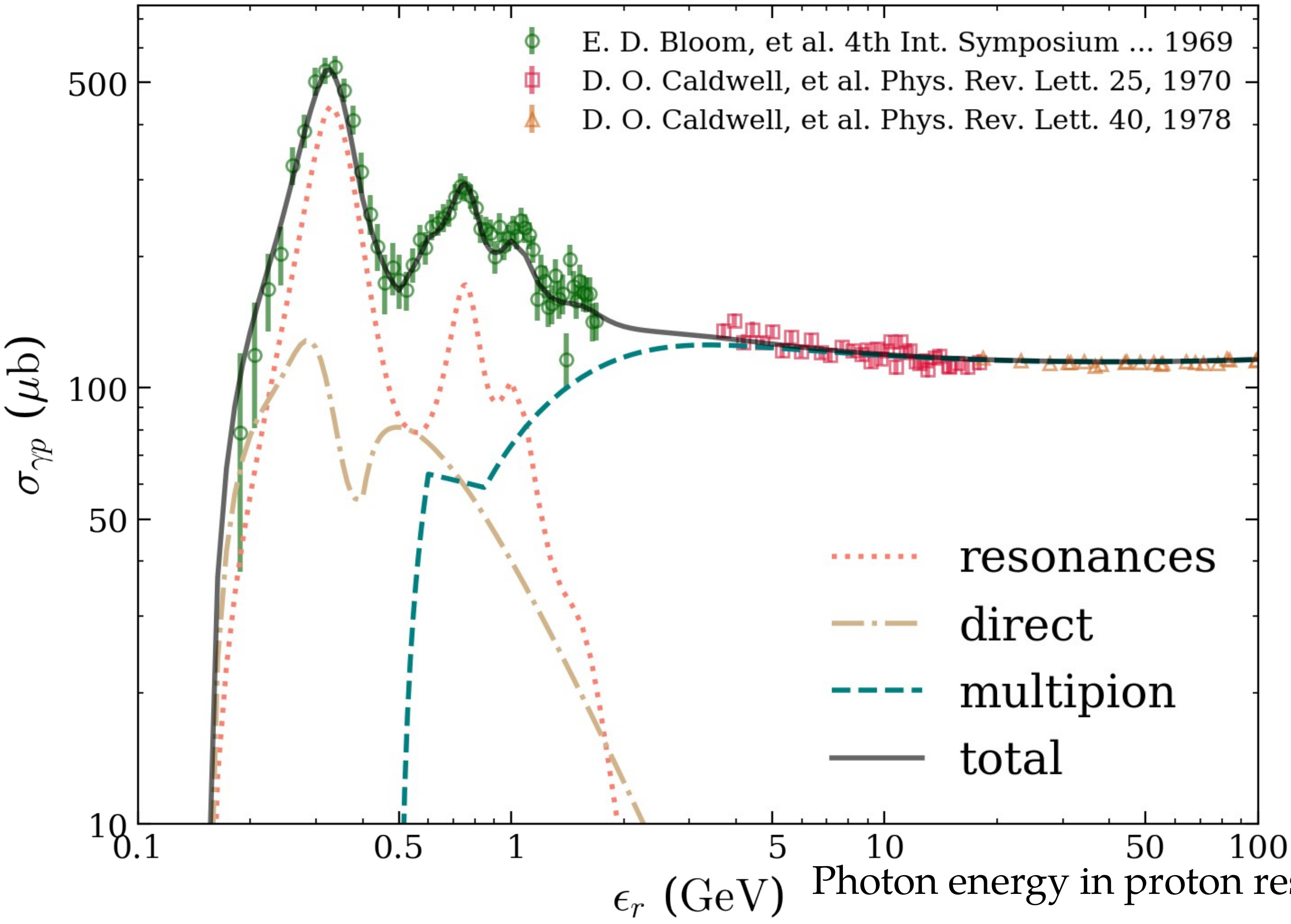
- Therefore, each neutrino takes an average fraction of proton energy

$$\boxed{E_\nu/E_p = 1/20 = 5\%}$$

- So:

If we see ν with energy…	**… they were made by p with energy**
PeV ($\equiv 10^{15}$ eV)	20 PeV (these reach Earth)
10 EeV ($\equiv 10^{19}$ eV)	200 EeV (these do not!)

Beyond the Δ resonance (1/2)

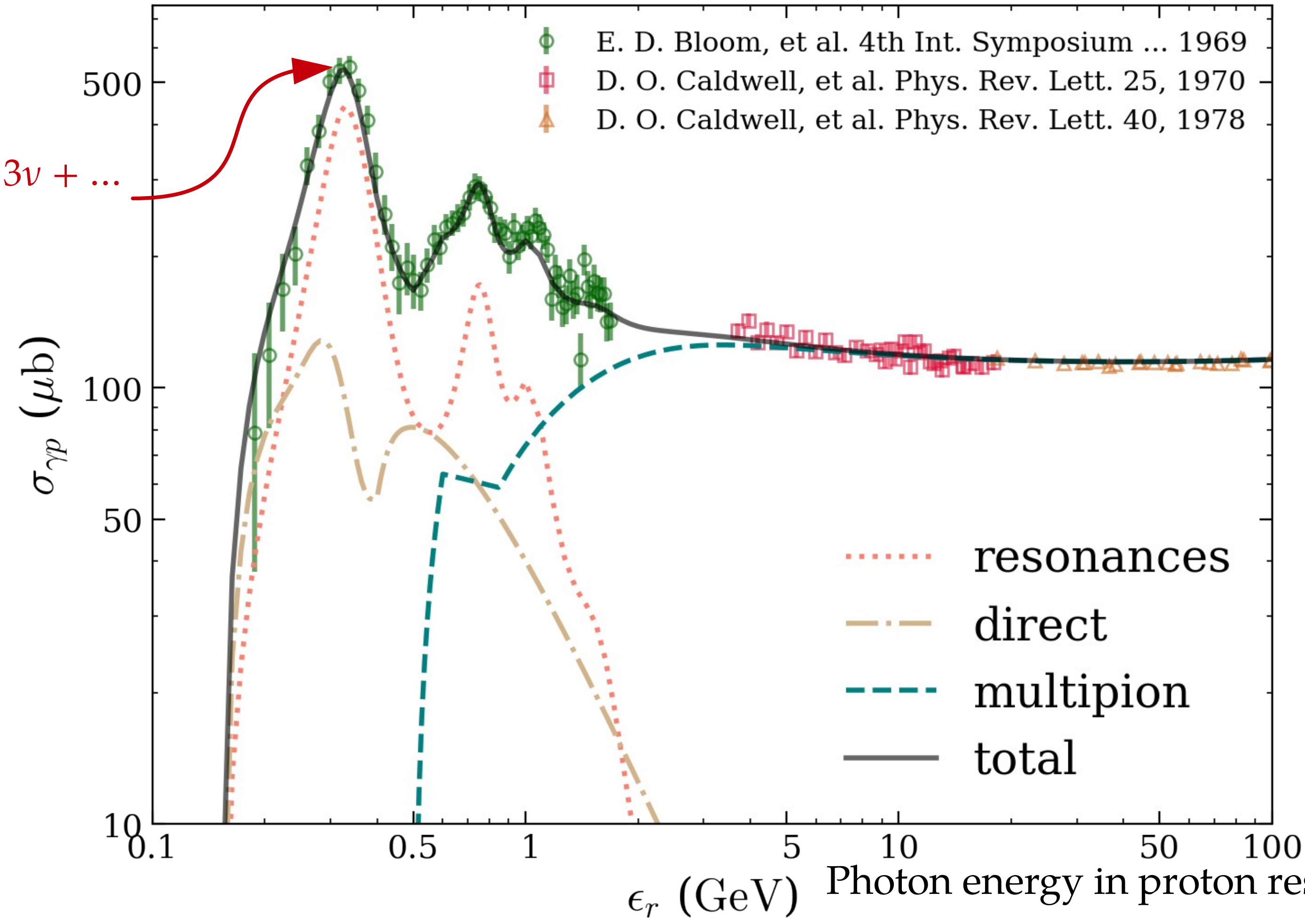


Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^{+} \rightarrow 3\nu + \ldots$



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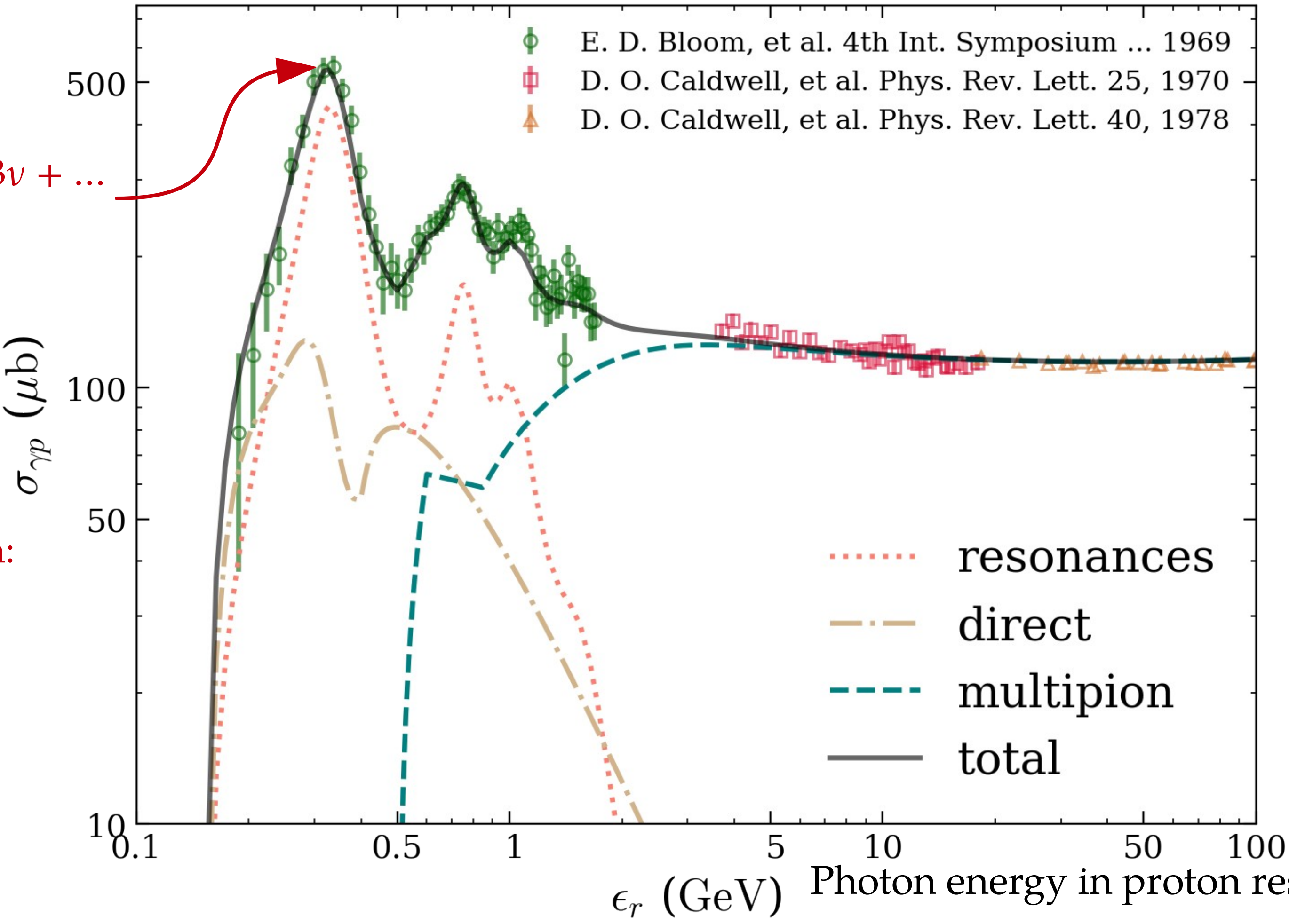
Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \to \Delta \to \pi^+ \to 3\nu + \ldots$

Resonance condition:
$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (2/2)

(1) Δ-resonance region

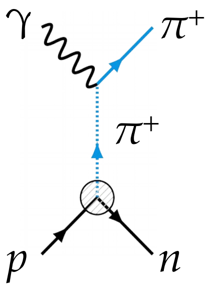
$$p + \gamma \xrightarrow{\Delta(1232)} p' + \pi$$

(2) Higher resonances

$$p + \gamma \xrightarrow{\Delta, N} \Delta' + \pi \ , \quad \Delta' \to p' + \pi$$

(3) Direct production (t channel)

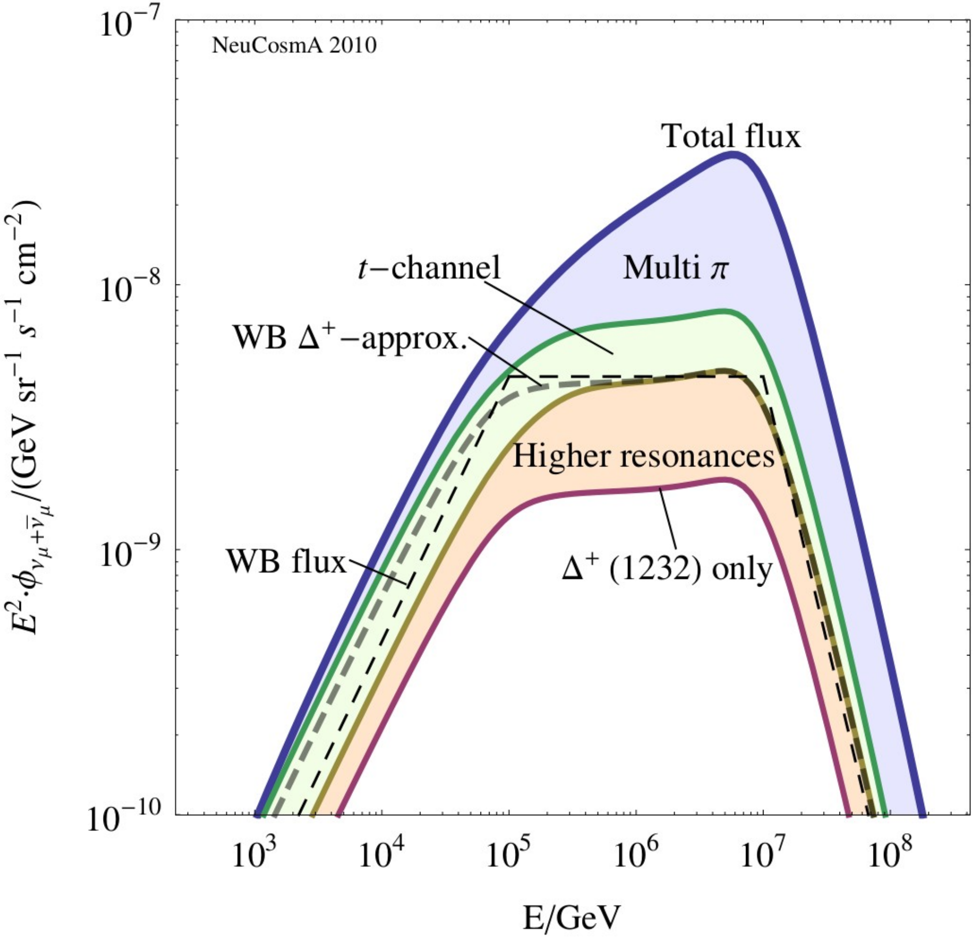
Same as (1) and (2), but in the t channel, *i.e.*, with a virtual pion



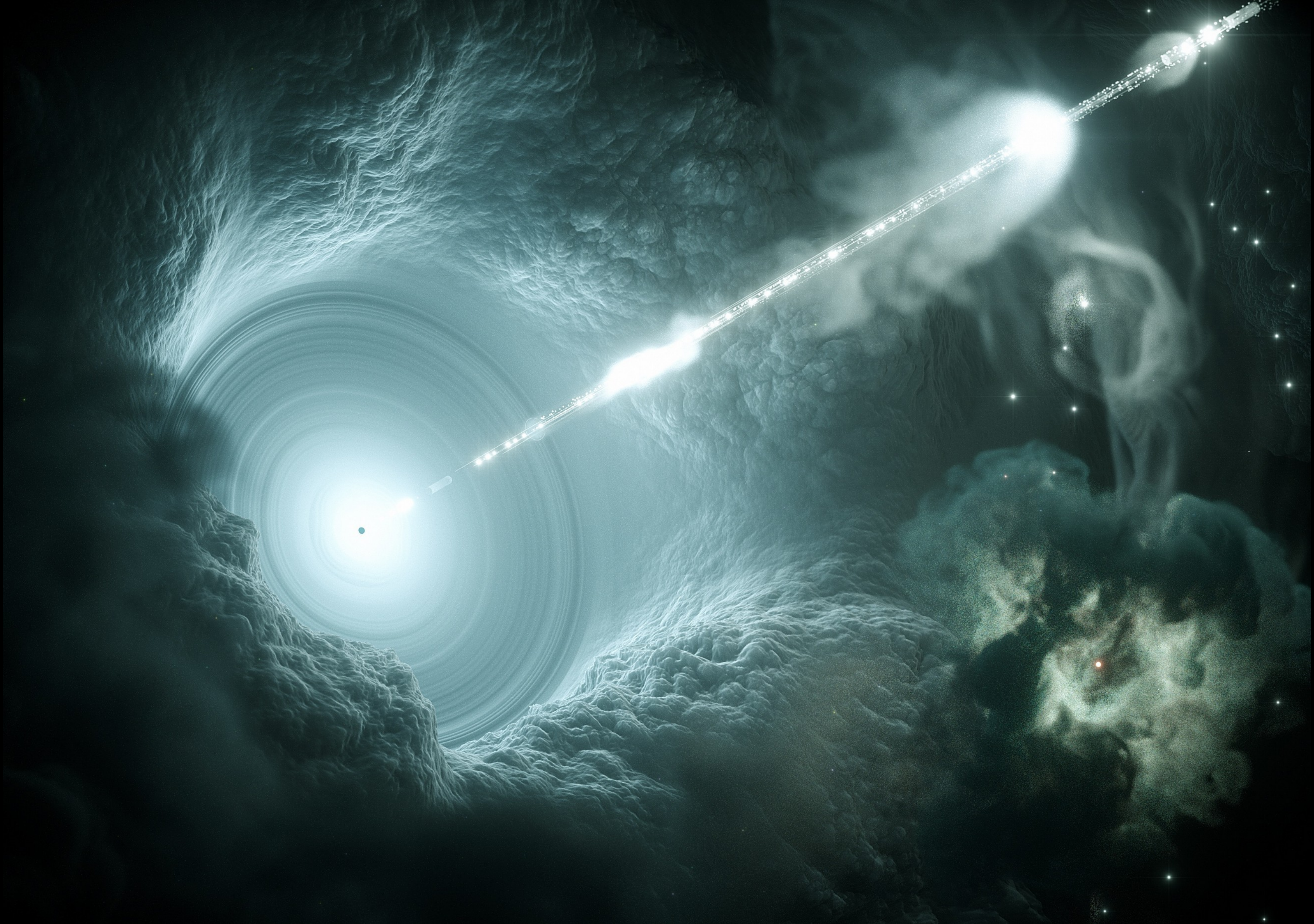
(4) Multi-pion production

Statistical production of two or more pions

E.g., neutrinos from a gamma-ray burst:



Mücke *et al.*, *Comput. Phys. Comm.* 2000
Hümmer *et al.*, *ApJ* 2010; Baerwald, Hümmer, Winter, *PRD* 2011

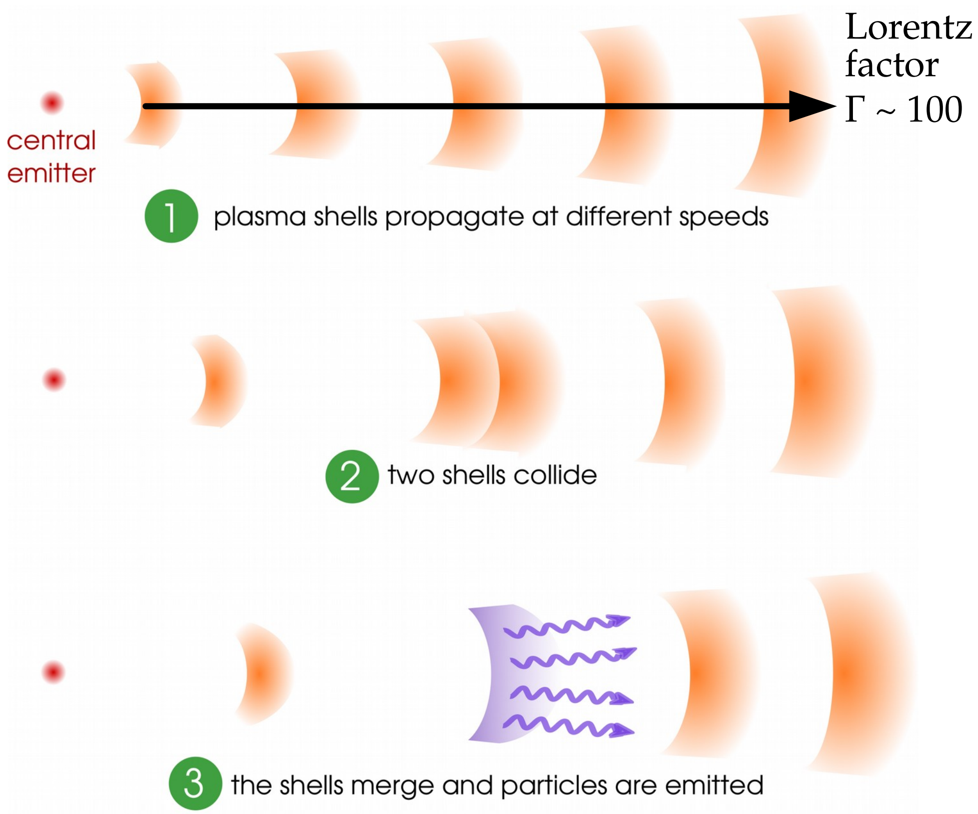


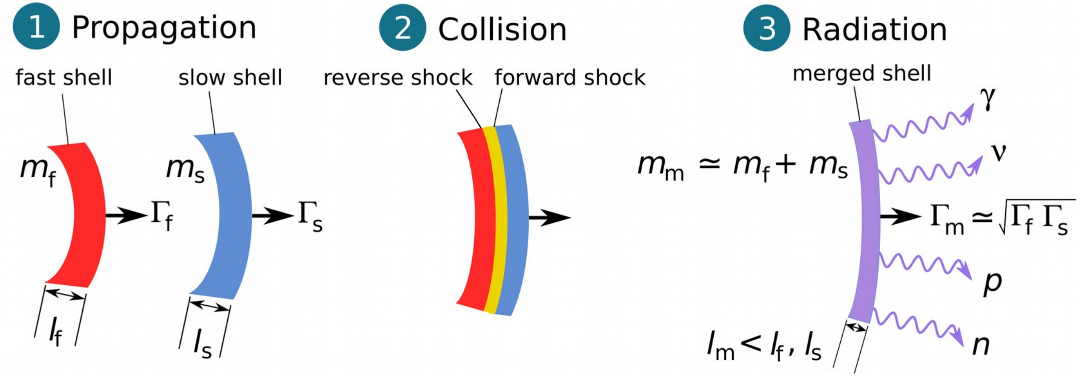
DESY

DESY

General anatomy of particle emission from a relativistic jet

Fireball model, internal collisions:





Part of the initial kinetic energy is radiated as γ, ν, and cosmic rays:

f_e : Fraction of energy in photons
f_p : Fraction of energy in protons
f_B : Fraction of energy in magnetic field

Uncertainly known

Kobayashi & Piran, *ApJ* 1997; Murase & Nagataki, *PRD* 2006; Guetta *et al.*, *ApJ* 2011
Baerwald, Hümmer, Winter, *PRD* 2011; **MB** *et al.*, *Nature Commun.* 2015

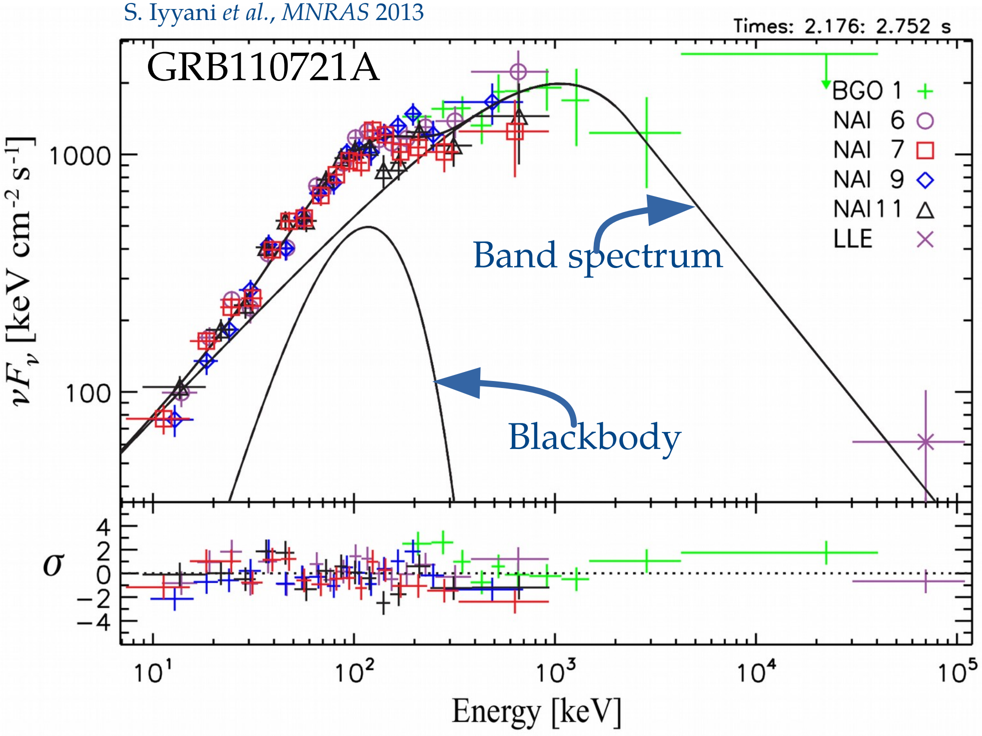
Gamma rays – spectrum basics

- Gamma-ray spectrum peaks at ~MeV
- Typically fitted by the Band function,

$$\nu F_\nu(E_\gamma) \propto \begin{cases} \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\alpha} \exp(-E_\gamma/E_0) & , E_\gamma < (\alpha-\beta)E_0 \\ \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\beta} & , E_\gamma \geq (\alpha-\beta)E_0 \end{cases}$$

- The spectrum evolves in time
- Some bursts are better fitted by a broken power law
- There might be multiple components

S. Iyyani *et al.*, *MNRAS* 2013



D. Band *et al.*, *ApJL* 1993

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⟨α⟩ = -1

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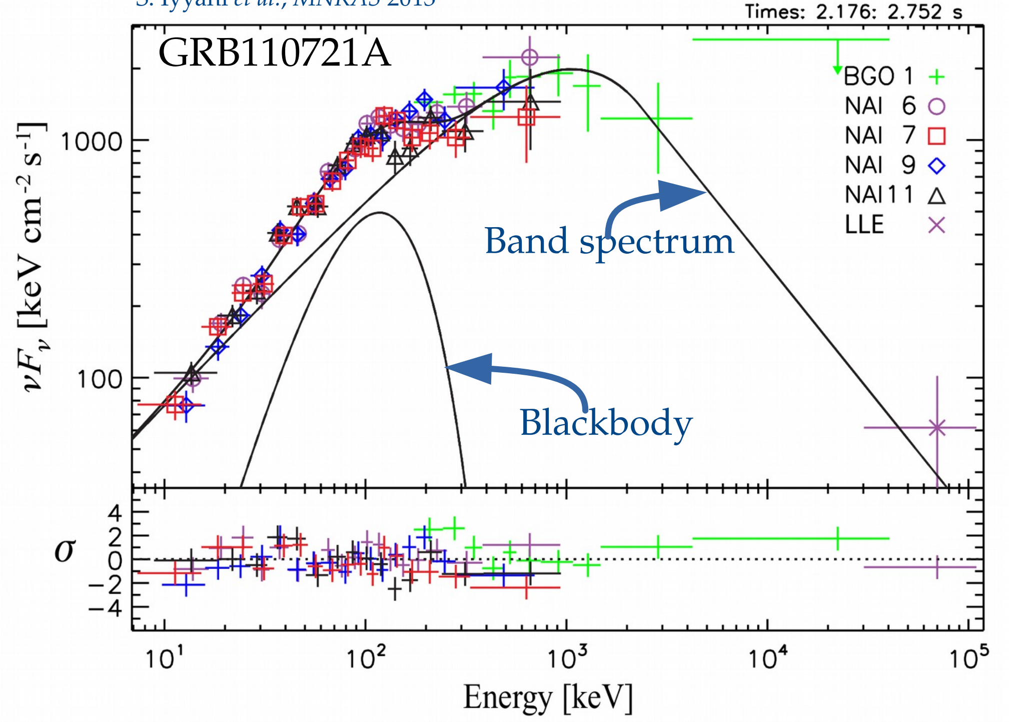
⟨β⟩ = -2

S. Iyyani *et al.*, *MNRAS* 2013



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D. Band *et al.*, *ApJL* 1993

Cooking up neutrinos from a flaring gamma-ray source

Energy in neutrinos $\propto$ energy in gamma rays

All the details are in the proportionality constant

Ingredients:

▸ Gamma-ray luminosity (erg s^{-1})	Measured
▸ Variability time scale (s)	Measured
▸ Shape of photon spectrum	Measured
▸ Redshift	Measured (sometimes)
▸ Bulk Lorentz factor of jet	Estimated
▸ Energy partition into e, p, magnetic field	Estimated (if not guessed)

The fine print

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^{\infty} \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

The fine print

$$\underbrace{\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu)}_{\text{Energy in neutrinos } \propto \text{ energy in gamma rays}} = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

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E. Waxman & J. Bahcall, *PRL* 1997
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The fine print

Energy in neutrinos $\propto$ energy in gamma rays

Fraction of p energy given to π
in one interaction (~20%)

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Baryonic loading

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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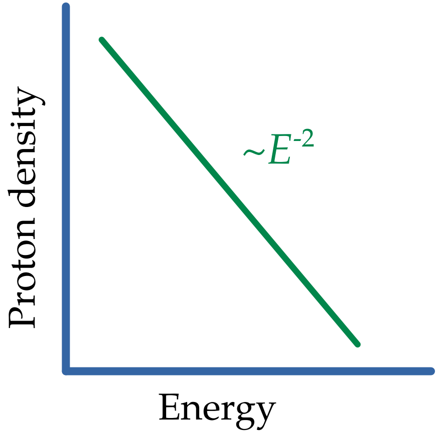
Baryonic loading

Optical depth to $p\gamma$: $$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg s}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

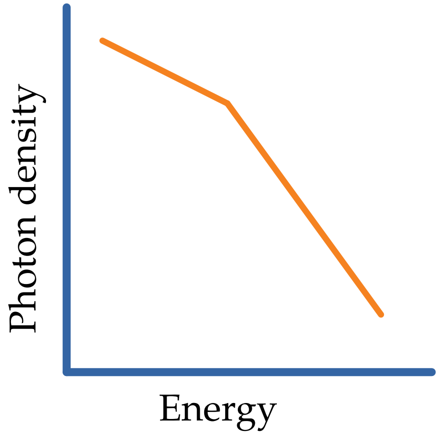
E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

The prompt neutrino fluence from one GRB

Protons



Photons



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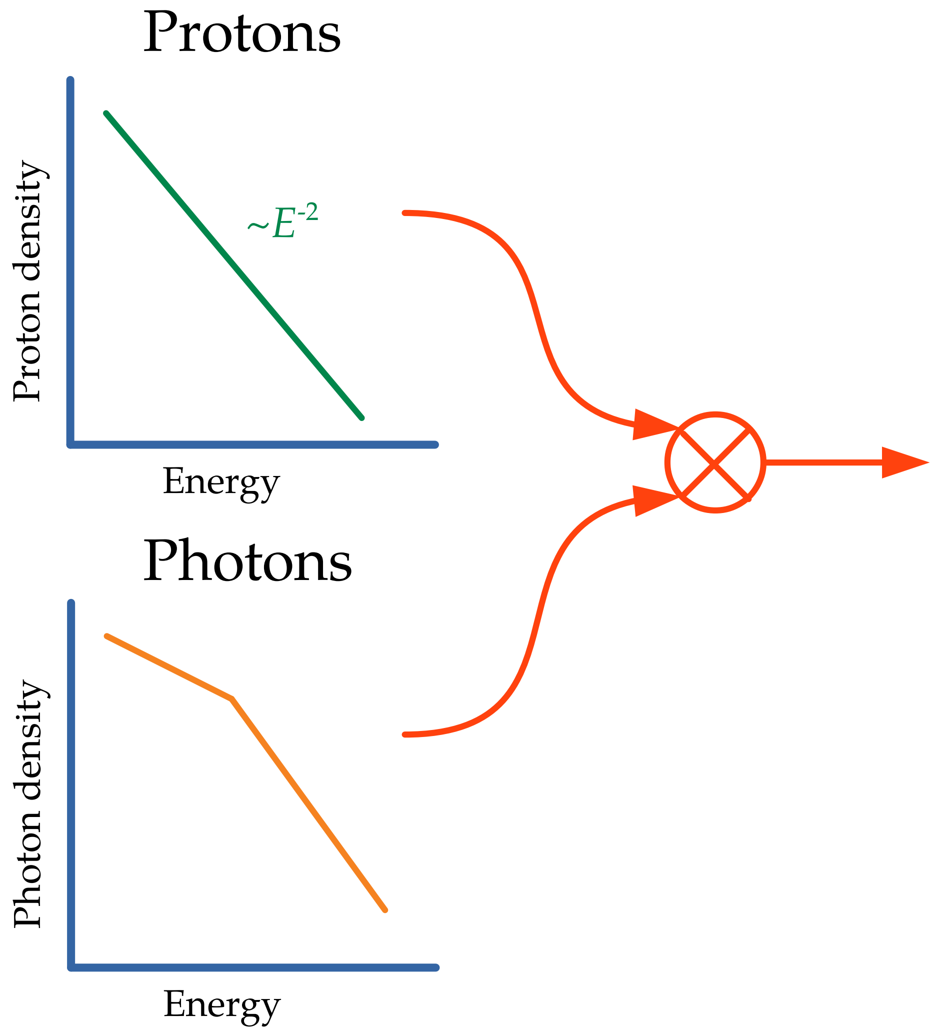

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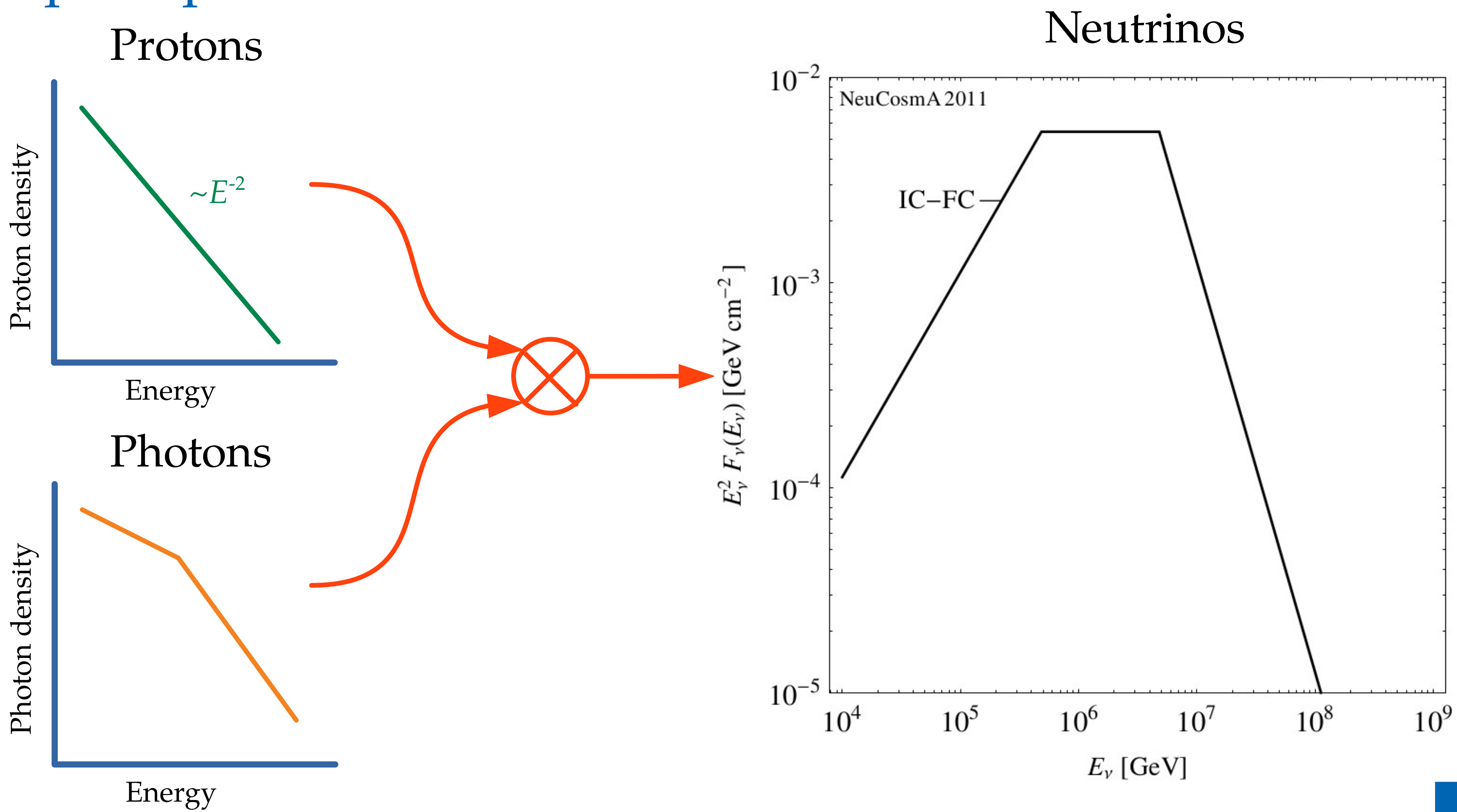

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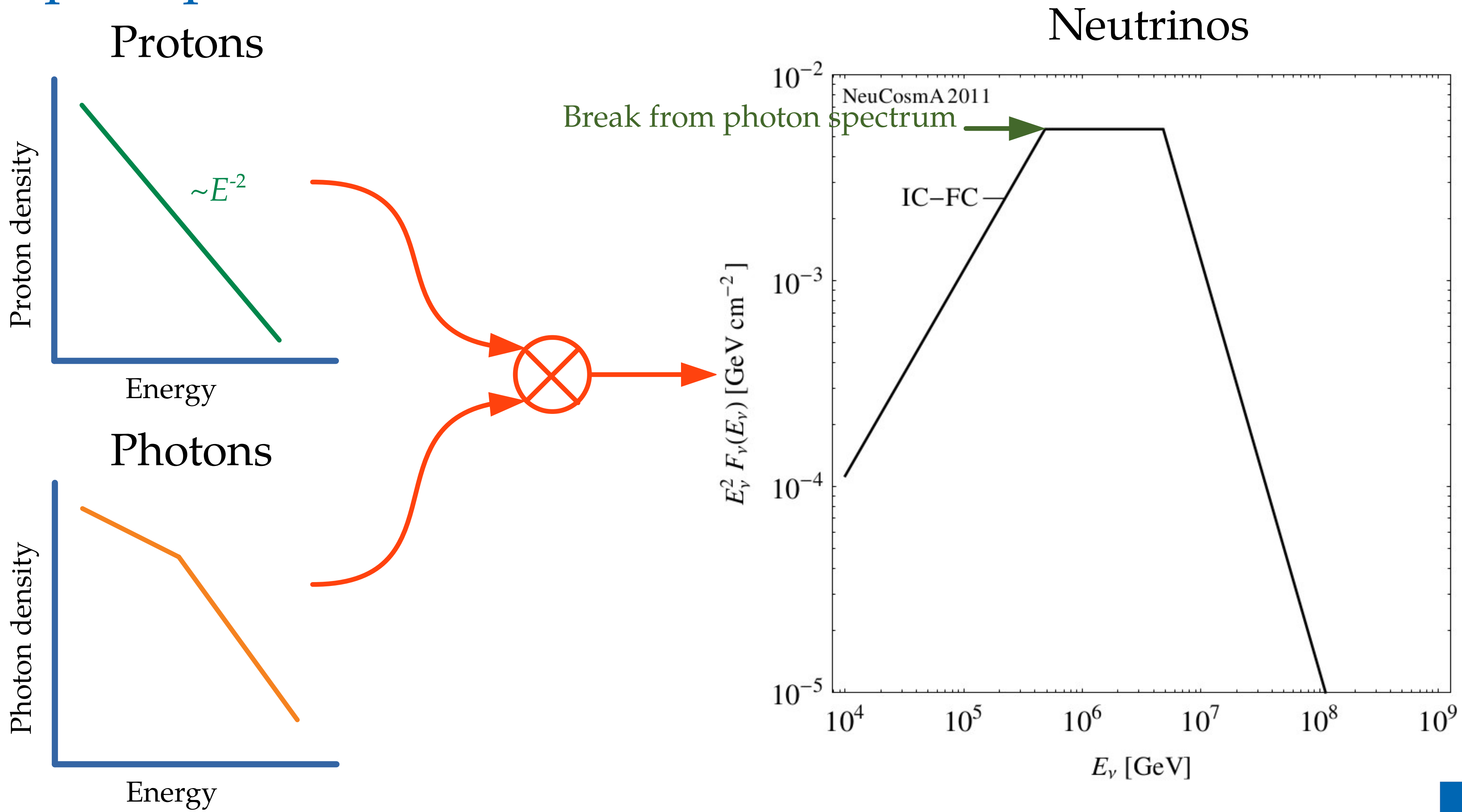

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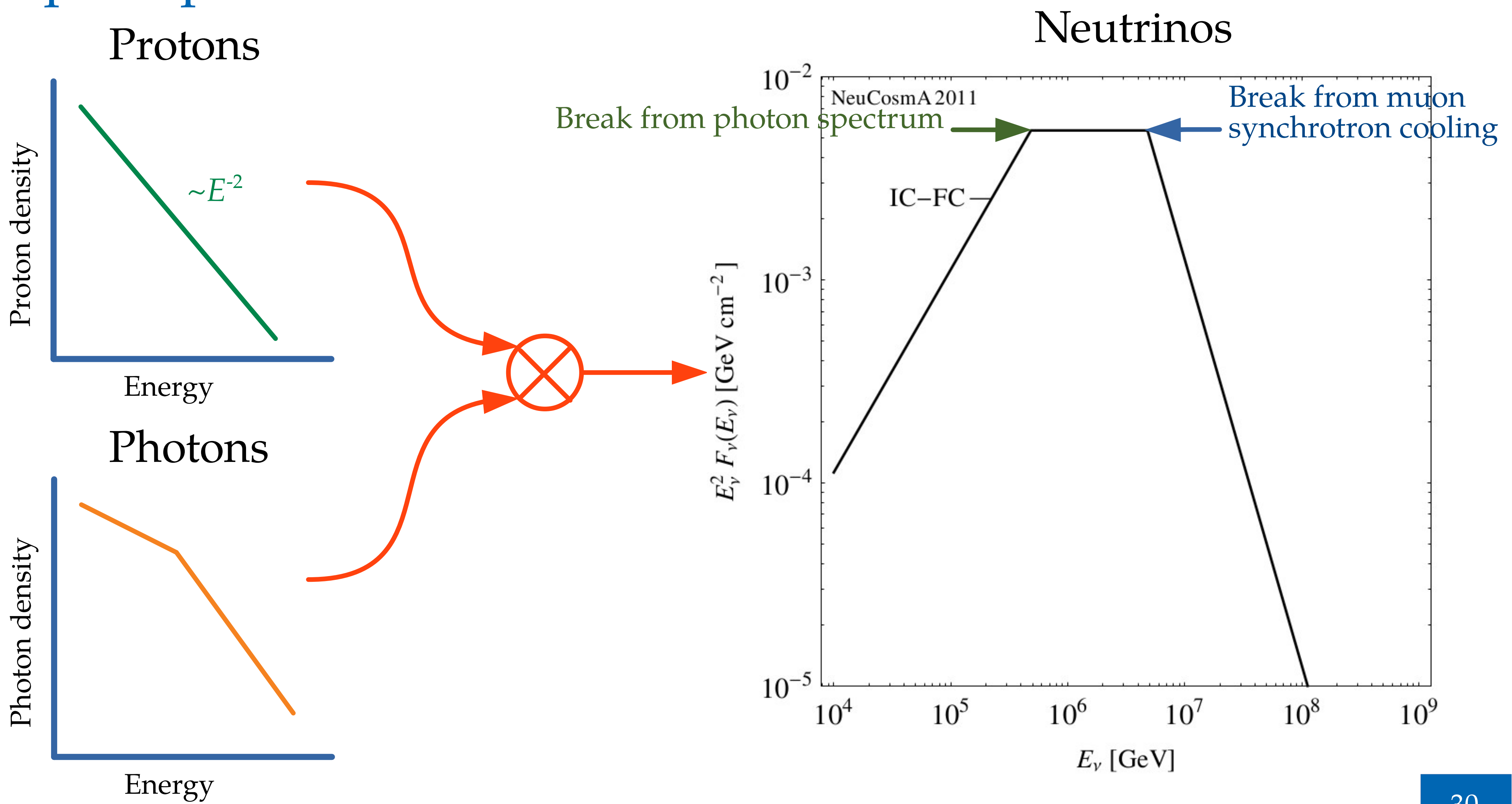


Neutrino propagation

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 & \hookrightarrow \gamma + \gamma \\ n + \pi^+ & \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16 \text{ GeV}}{0.66 \text{ meV}} \approx 2 \cdot 10^{11} \text{ GeV}$$

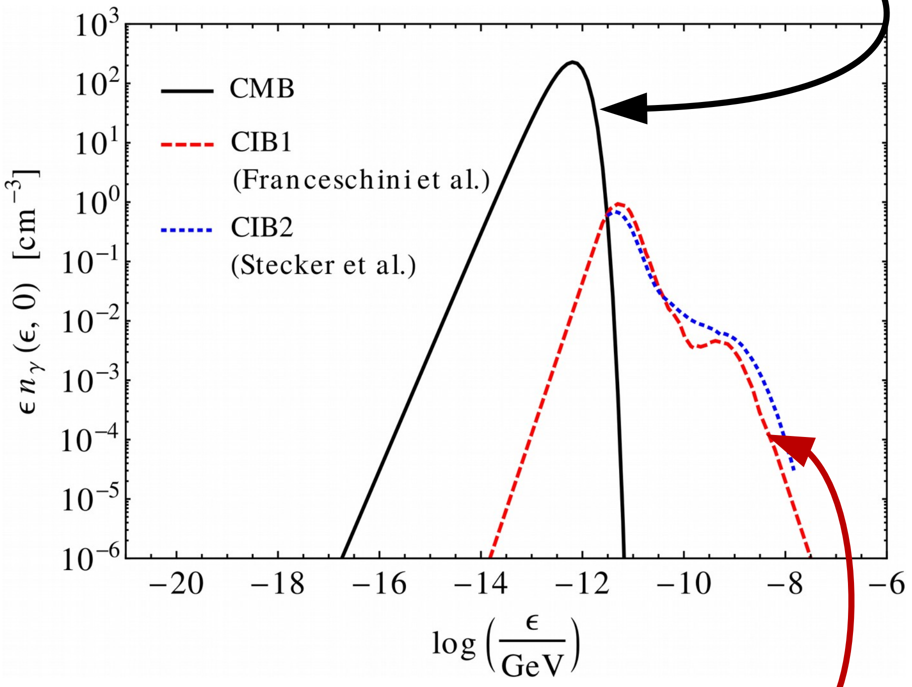
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10} \text{ GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, $\langle\epsilon\rangle \sim 0.66$ meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \to \Delta \to \begin{cases} p + \pi^0 \quad \text{↱} \; \gamma + \gamma \\ n + \pi^+ \quad \text{↳} \; \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

$$p + \gamma \to p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

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Accounting also for pair production and CMB width:

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Mean free path:

$$\begin{aligned}(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} &= (413\ \mathrm{cm}^{-3} \times 200\ \mu\mathrm{barn})^{-1} \\ &\approx 10^{25}\ \mathrm{cm} \\ &\approx 4\ \mathrm{Mpc}\end{aligned}$$

Energy-loss scale:

$$\begin{aligned}L &= (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} \\ &\approx (1/0.2) \times 4\ \mathrm{Mpc} \\ &\approx 20\ \mathrm{Mpc}\end{aligned}$$

A more detailed calculation yields

$$L_{\mathrm{GZK}} = 50\ \mathrm{Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \to \Delta \to \begin{cases} p + \pi^0 & \hookrightarrow \gamma + \gamma \\ n + \pi^+ & \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

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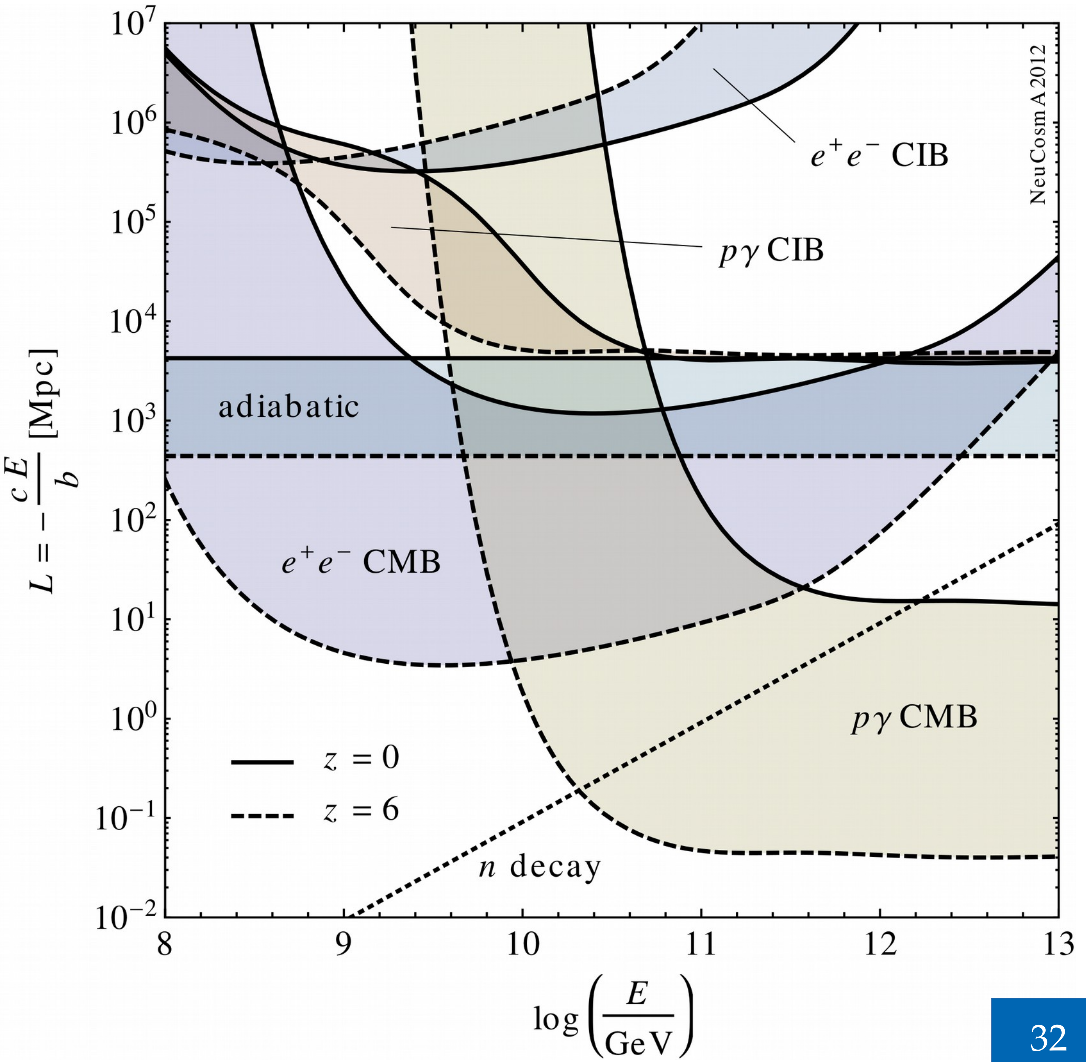


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

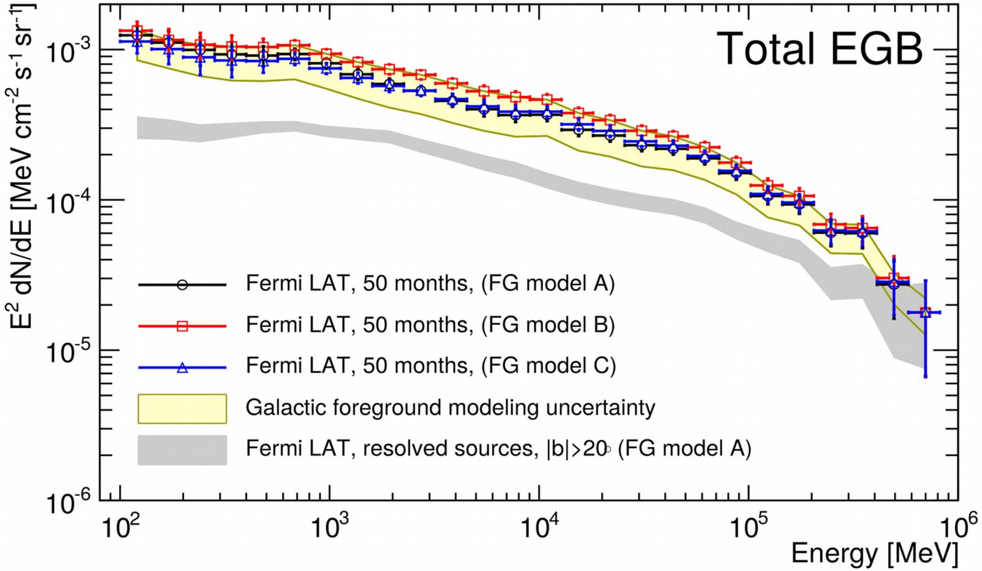
Pair production:

$$\gamma_{astro} + \gamma_{cosmo} \rightarrow e^- + e^+$$

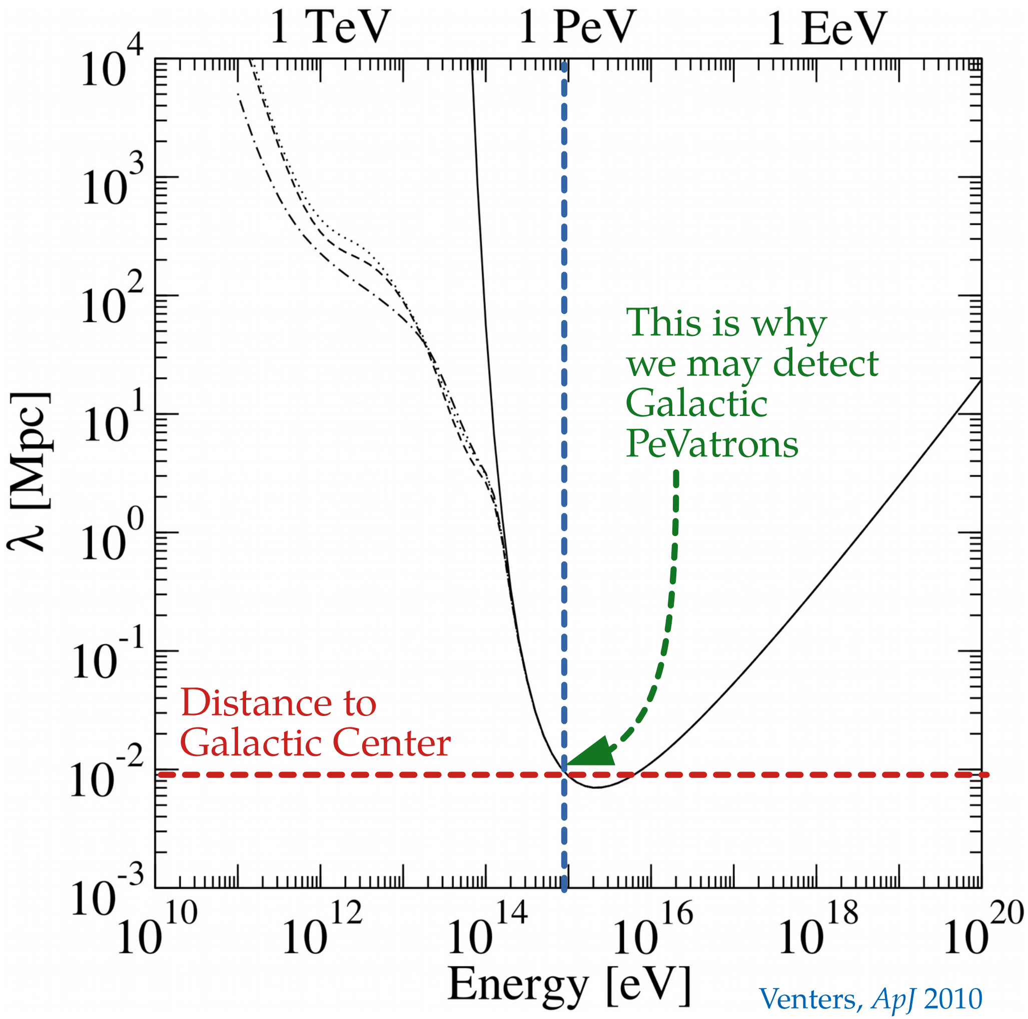
Inverse Compton scattering:

$$e^{\pm} + \gamma_{cosmo} \rightarrow e^{\pm} + \gamma$$

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc ($>$ 40 EeV)
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect	Easy	Hard	Easy

Note: This is a simplified view

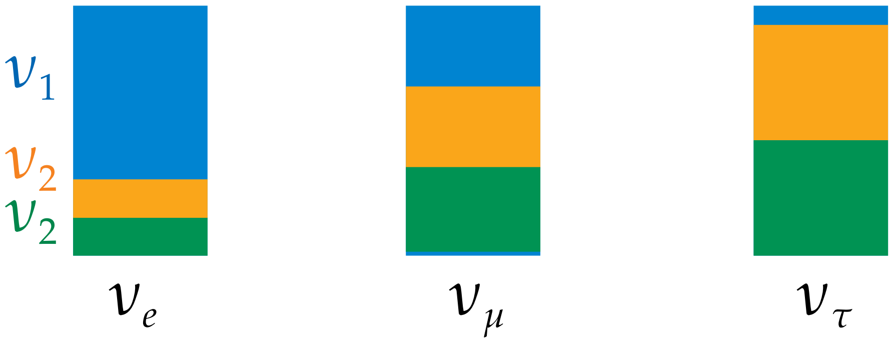
Neutrinos – The ultimate smoking gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect	Easy	Hard	Easy

Note: This is a simplified view

Neutrinos: Quintessential quantum particles

Neutrinos are created and detected as weak interaction states –



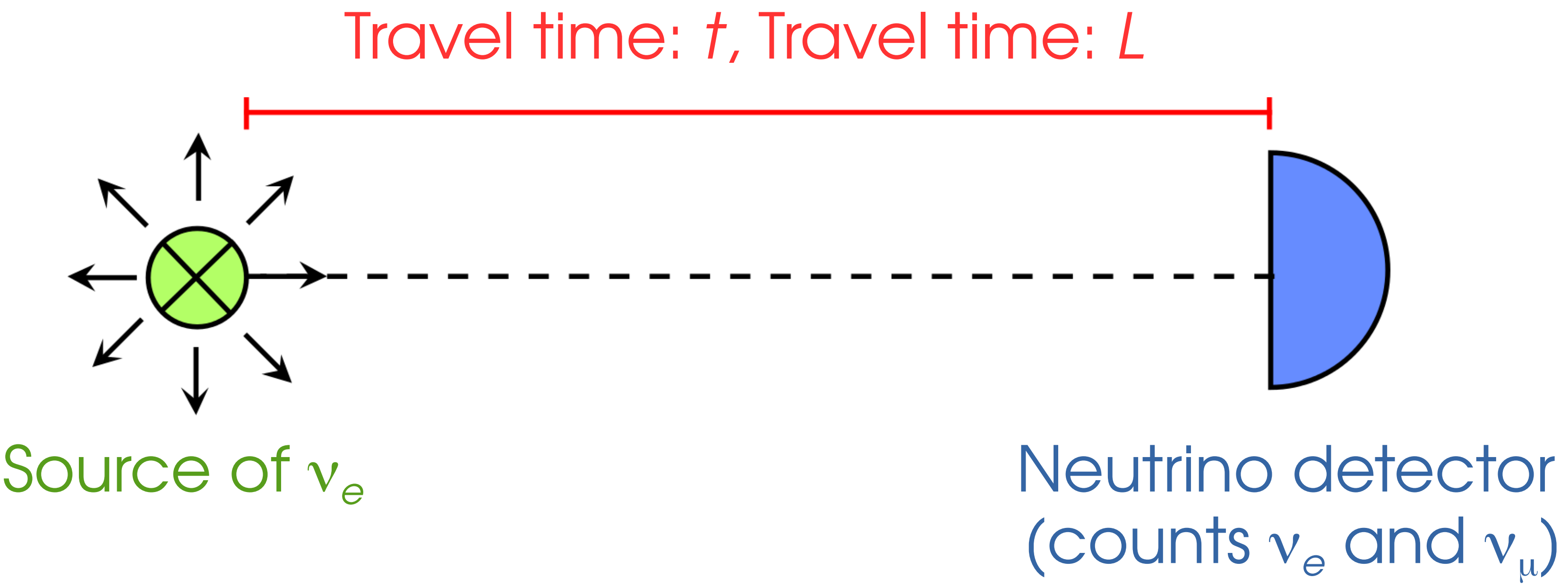
Coefficients of a mixing matrix (fixed by Nature)

$$\nu_\alpha = \sum_{j=1}^{3} U^*_{\alpha i} \nu_j \quad \text{for} \quad \alpha = e, \mu, \tau$$

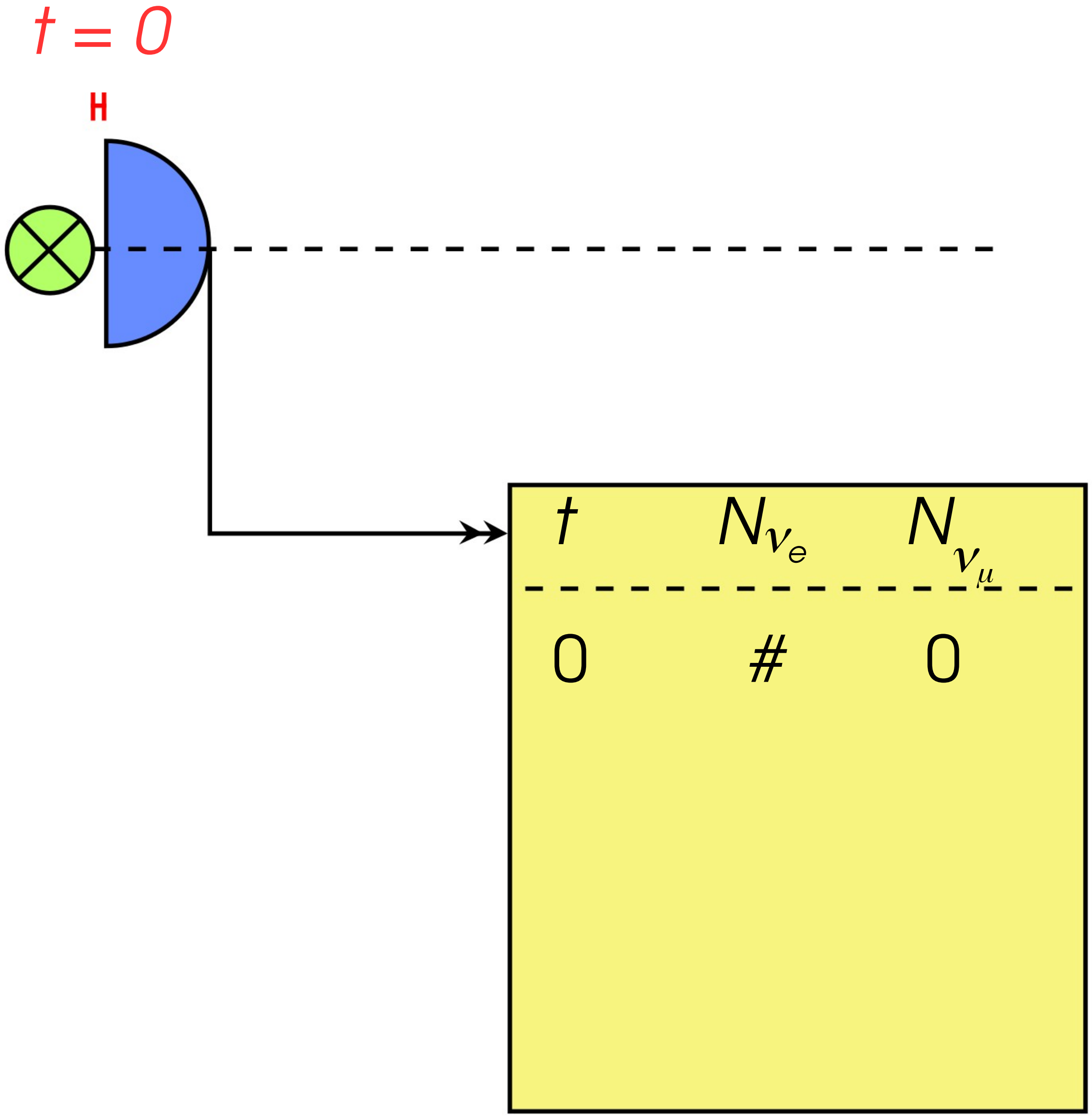
ν_1, ν_2, ν_3 have different masses, so they travel at different speeds

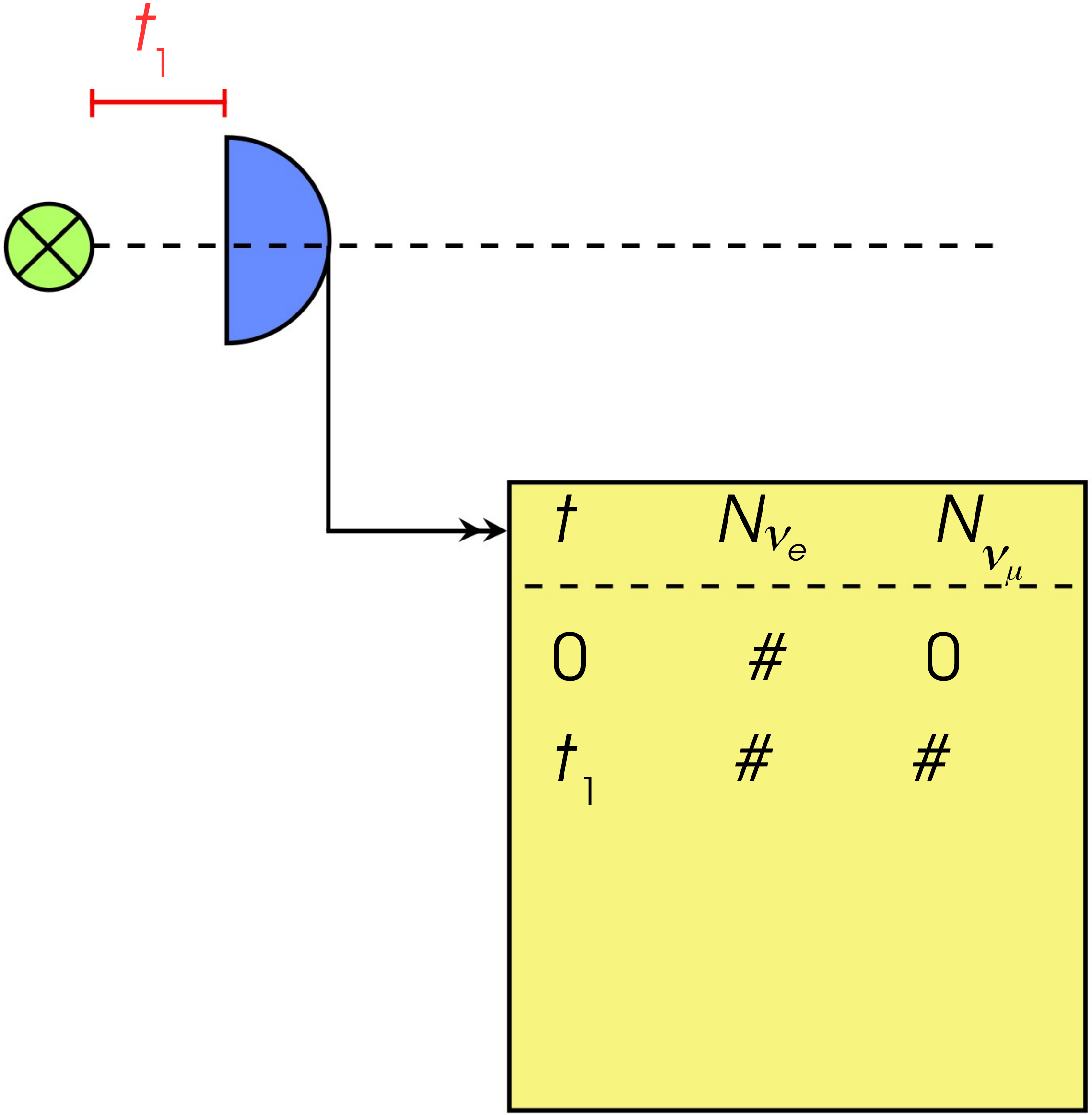
Their superposition changes with time –

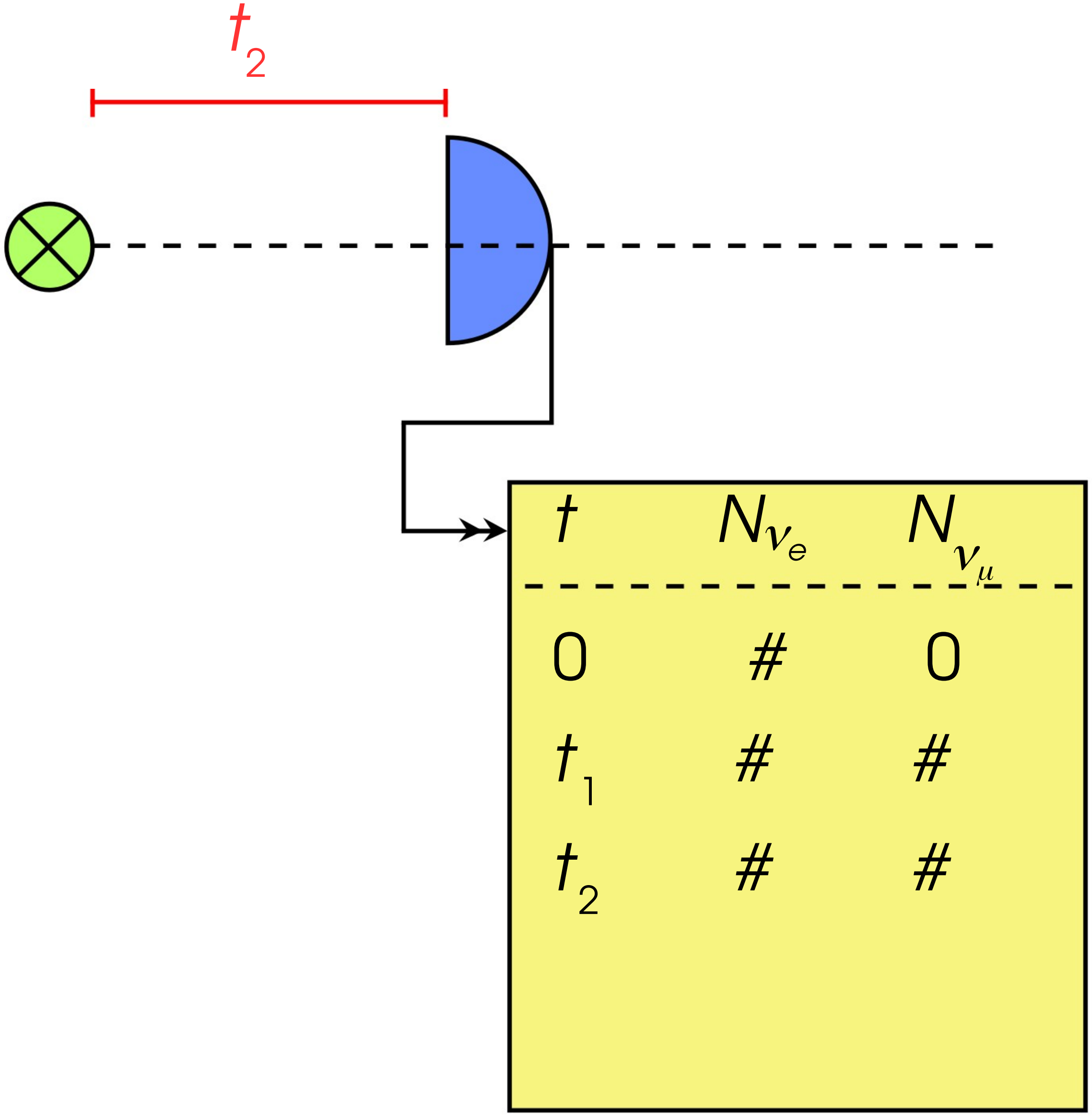
$$\nu_\alpha(L) = \sum_{j=1}^{3} U^*_{\alpha i} e^{-i m_j L/E} \nu_j$$



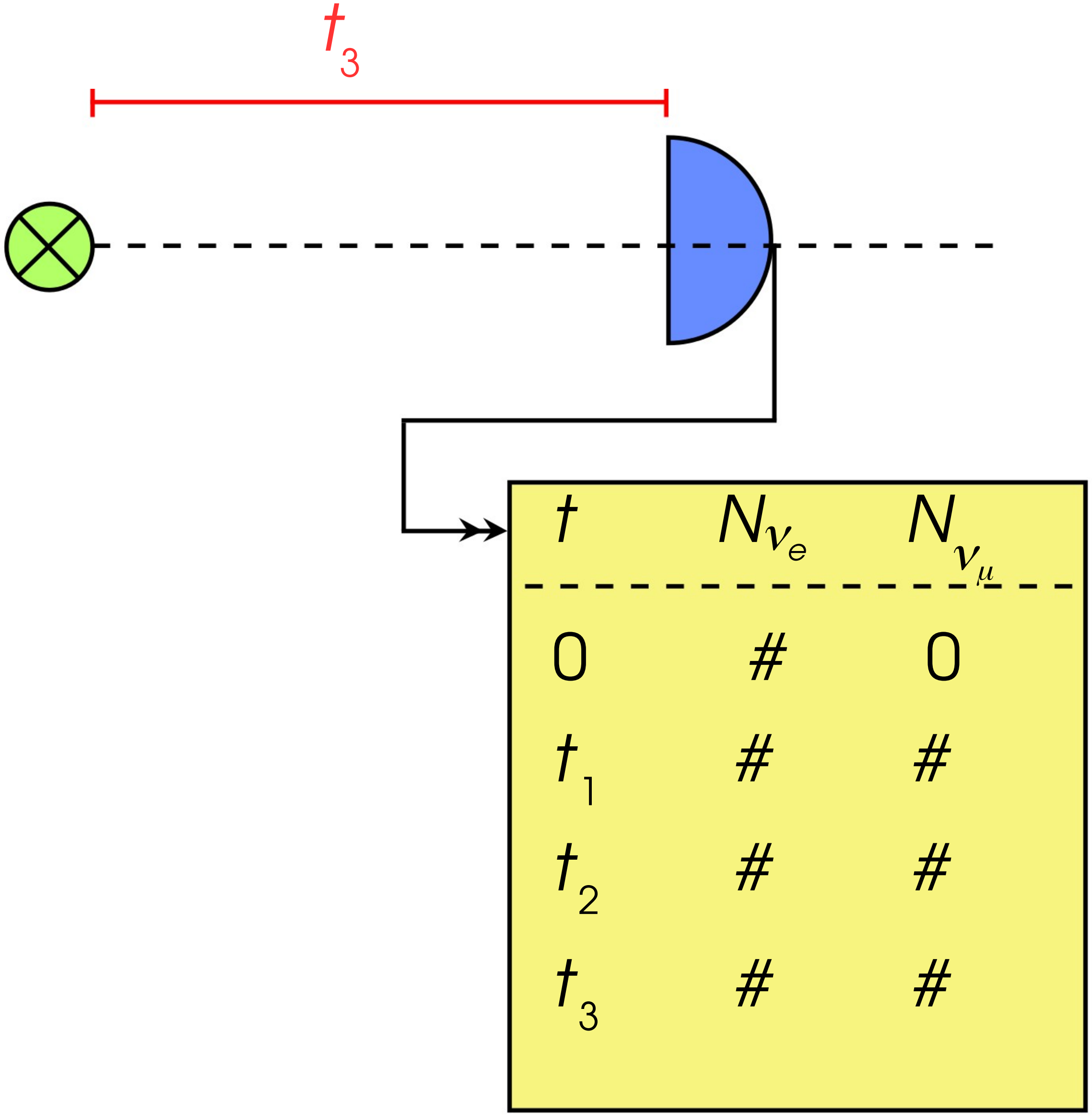
Travel time: t, Travel time: L
Source of ν_e
Neutrino detector
(counts ν_e and ν_μ)


$t = 0$
H
t
N_{ν_e}
N_{ν_μ}
0
#
0


t_1
t
N_{ν_e}
N_{ν_μ}
0
#
0
t_1
#
#

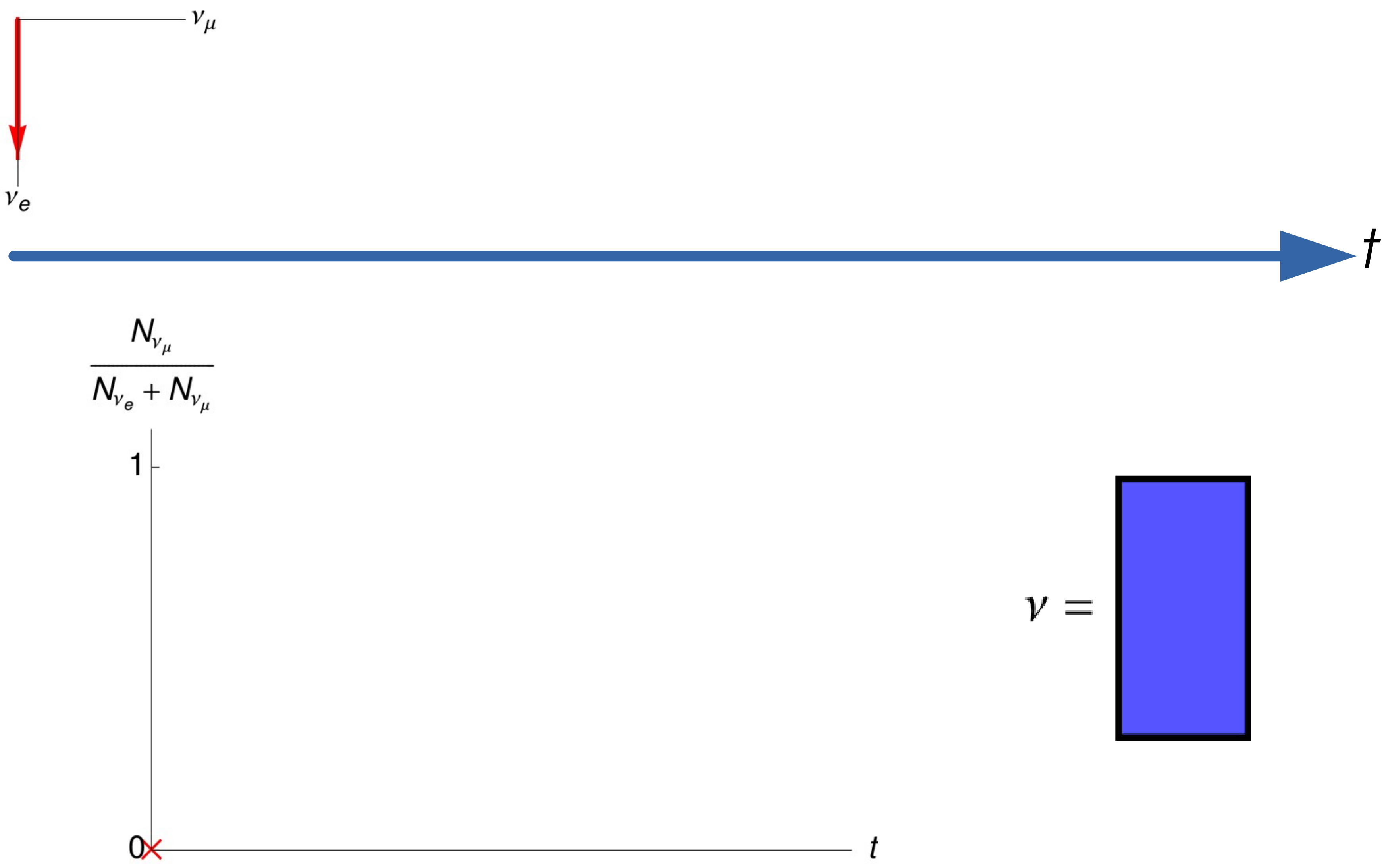


t_2
t N_{ν_e} N_{ν_μ}
0 # 0
t_1 # #
t_2 # #

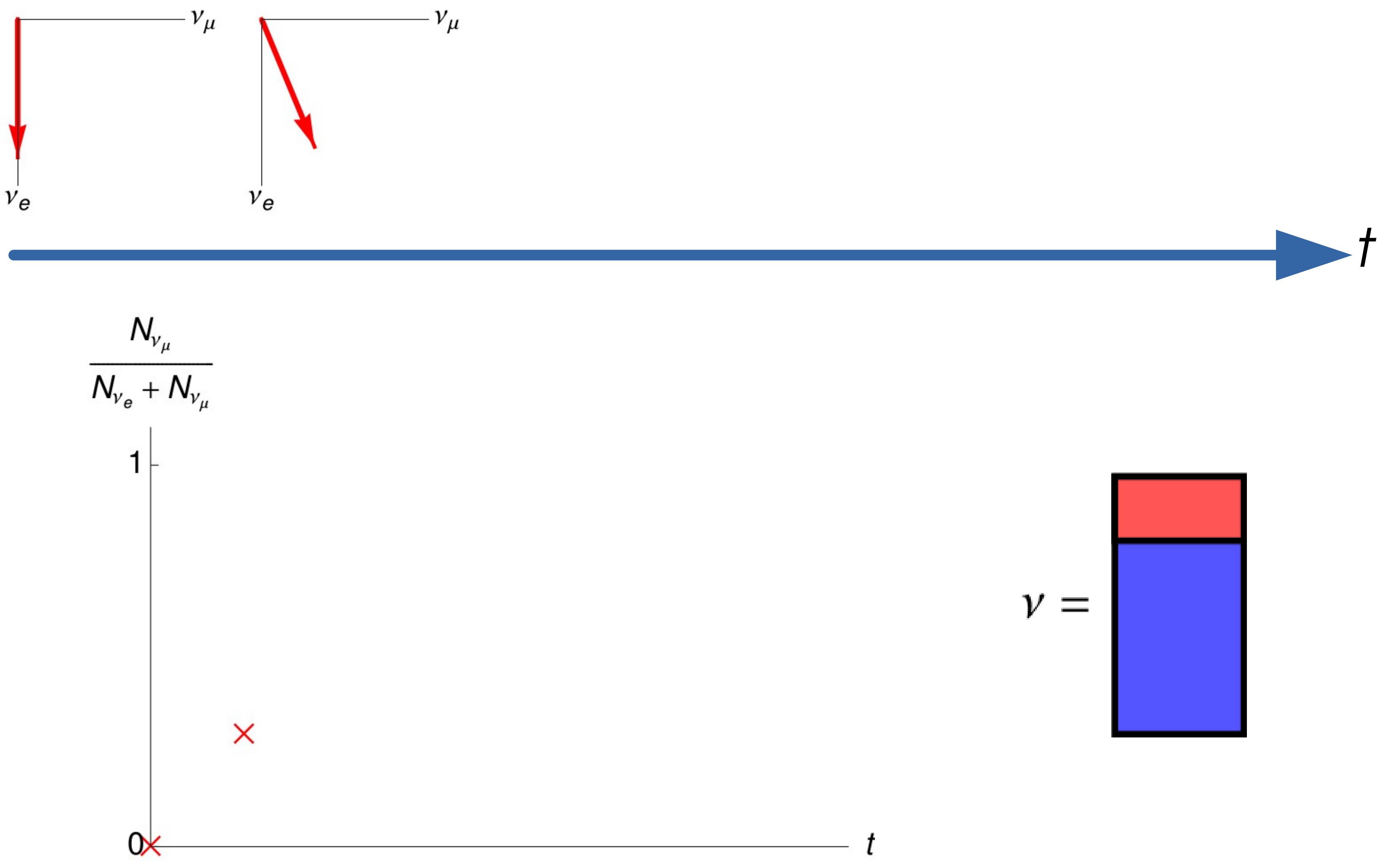


t_3
t
N_{ν_e}
N_{ν_μ}
0
#
0
t_1
#
#
t_2
#
#
t_3
#
#

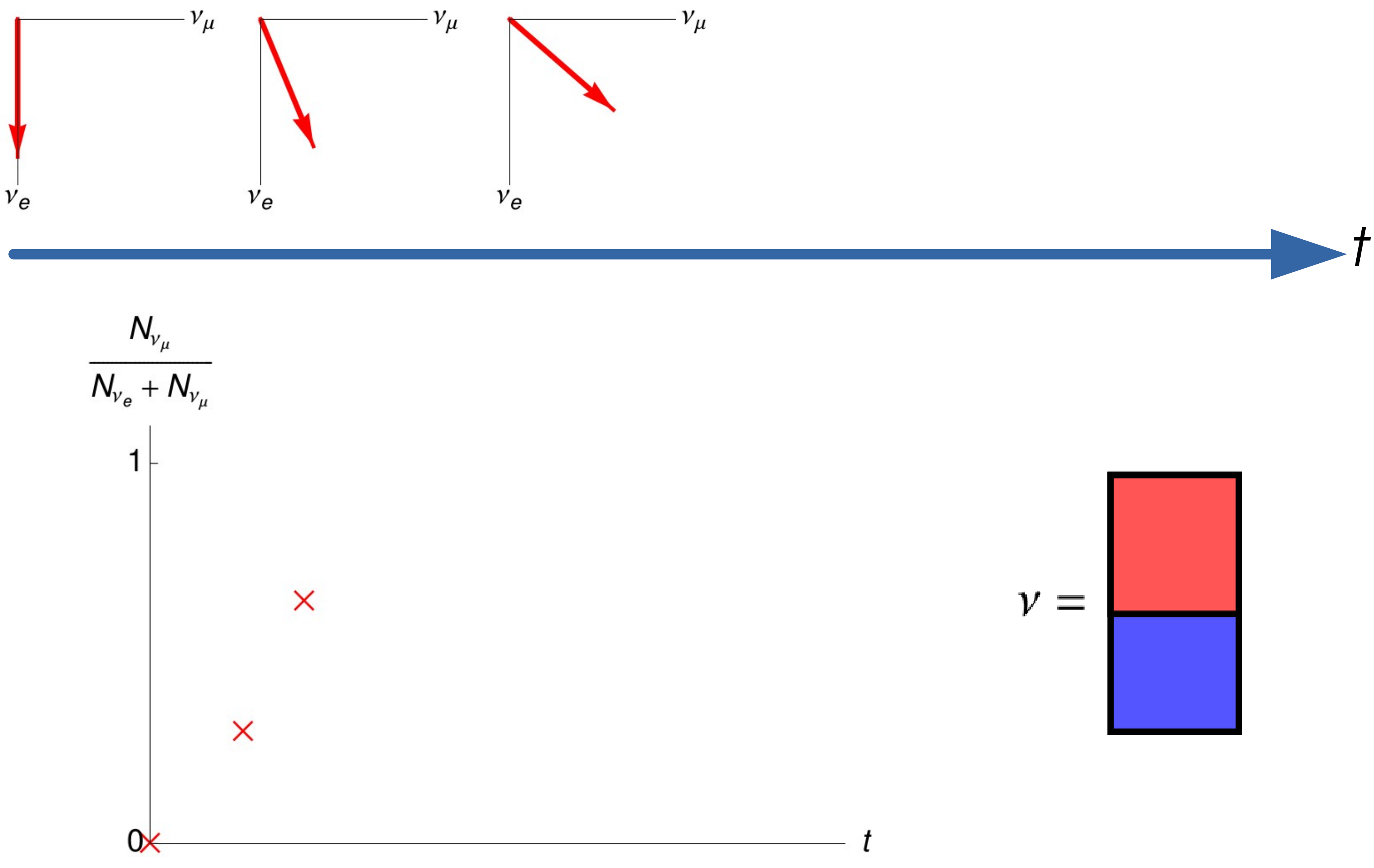

t

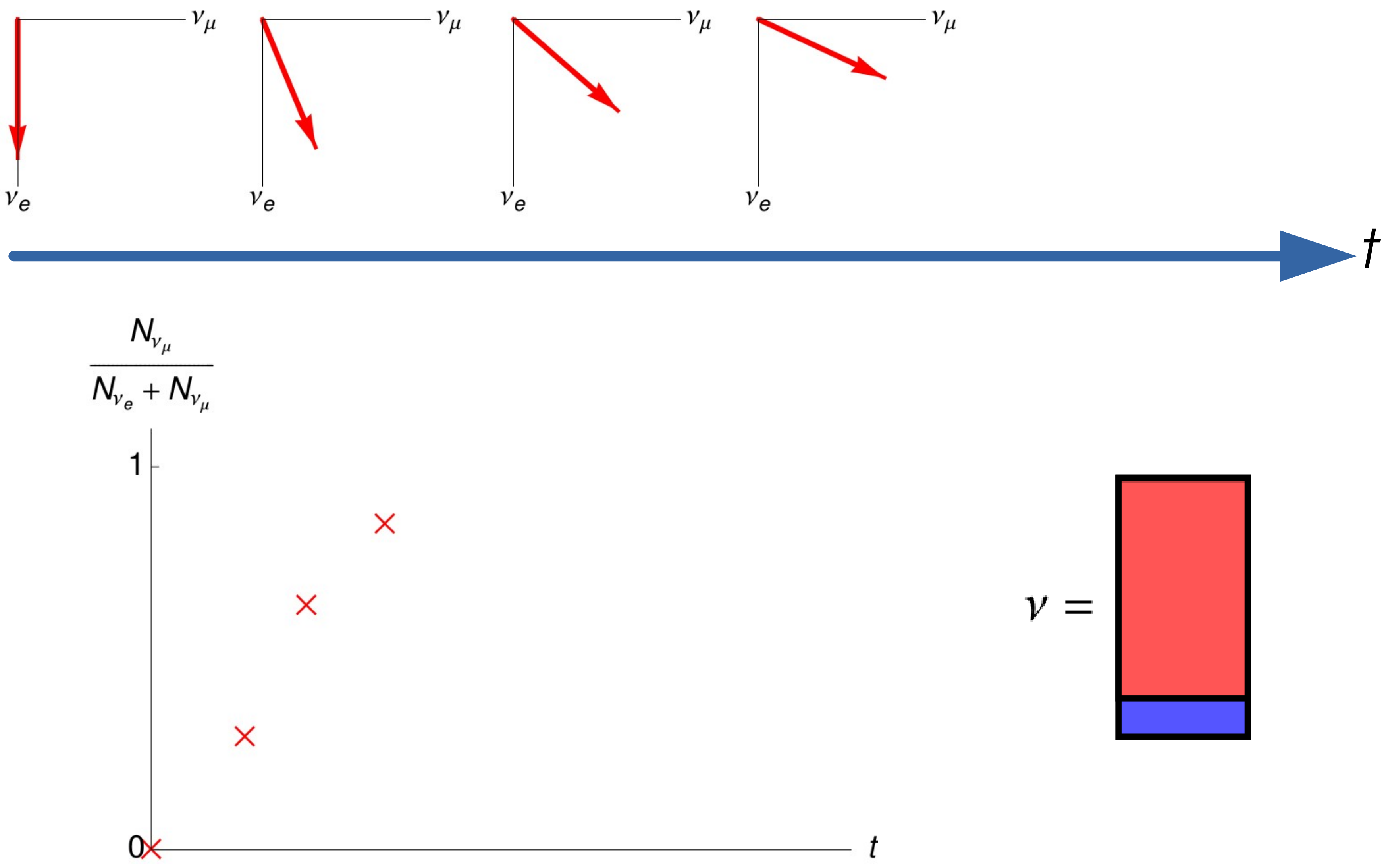


ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

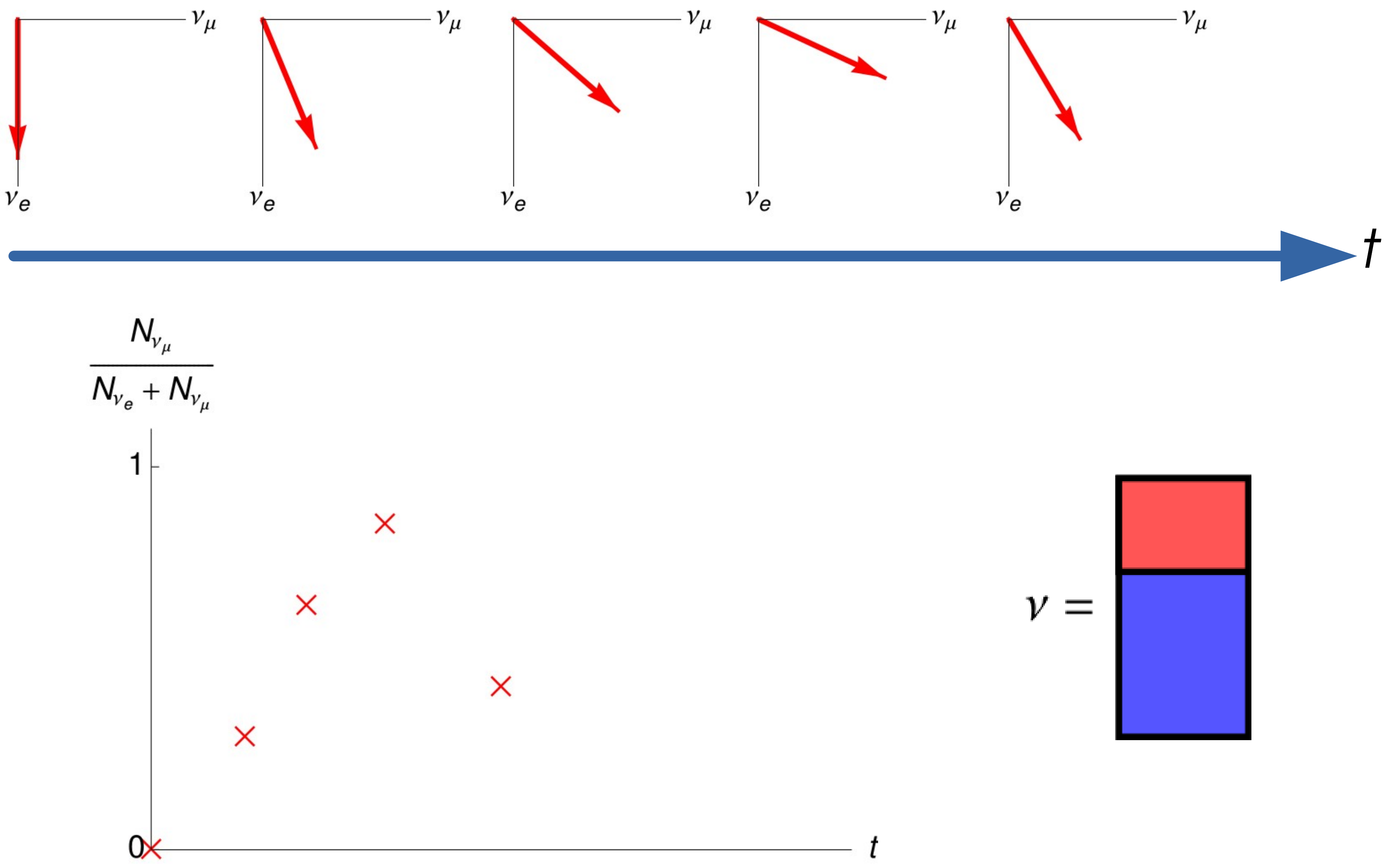


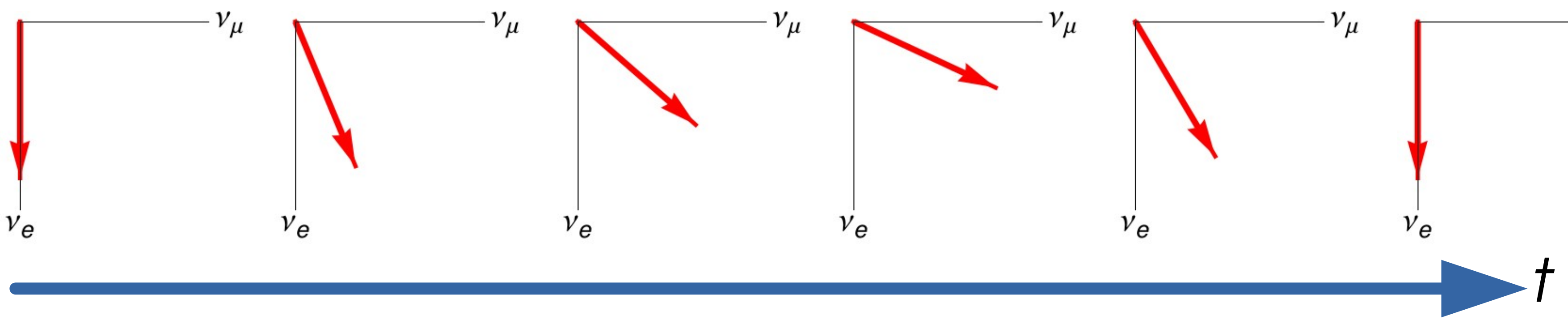
ν_μ
ν_e
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

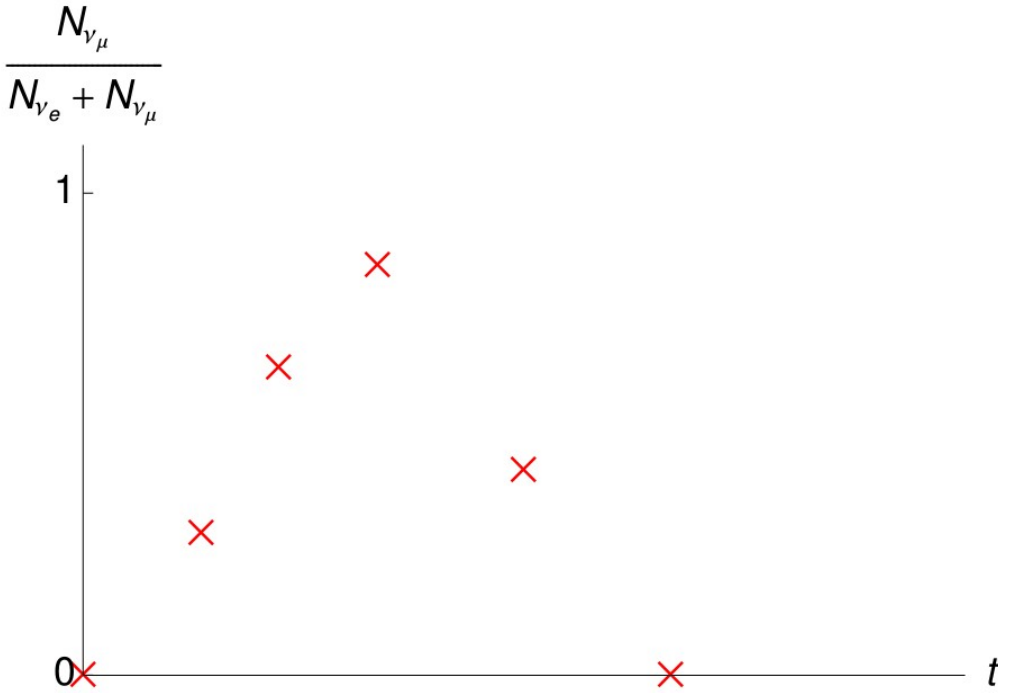

ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

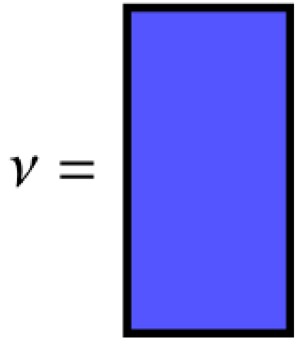


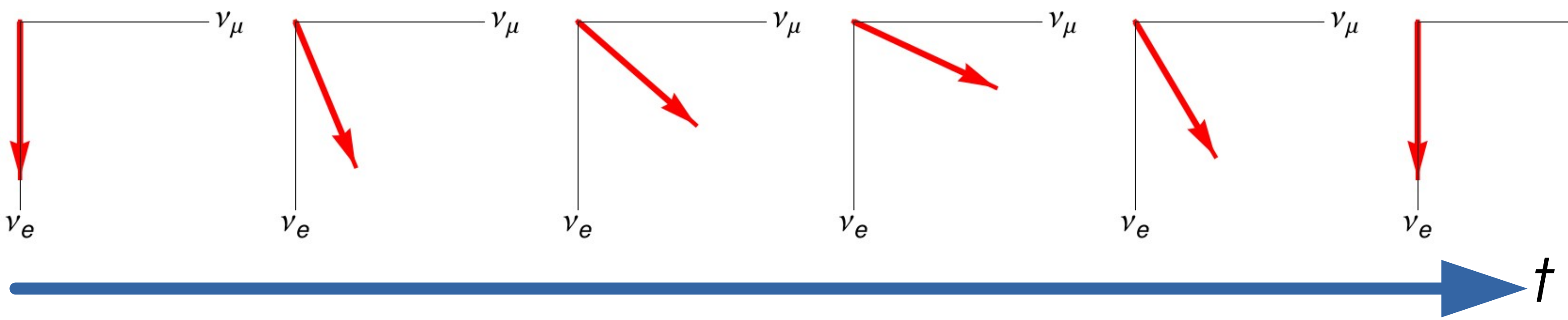
ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$


ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e}+N_{\nu_\mu}}$
1
0
t
$\nu =$

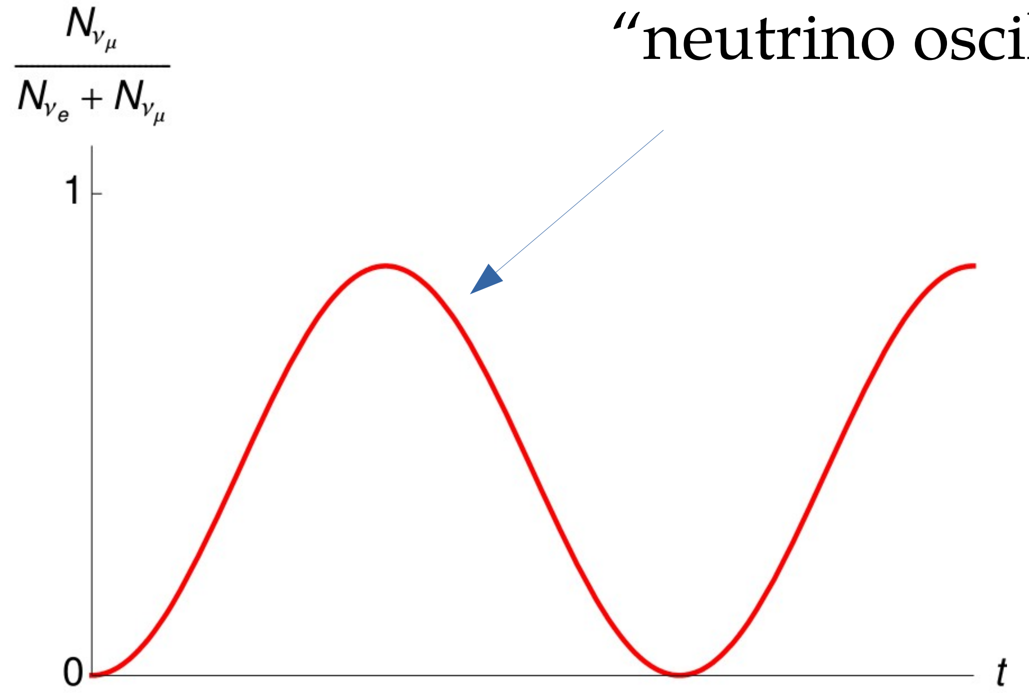

ν_μ
ν_e
t

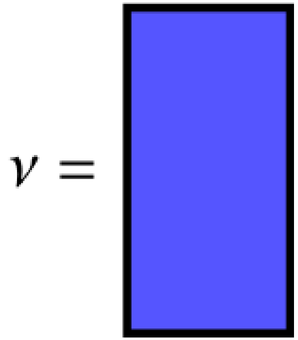

$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t


$\nu =$



“neutrino oscillations”





Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu1} & U^*_{\mu2} & U^*_{\mu3}\\ U^*_{\tau1} & U^*_{\tau2} & U^*_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \to \nu_\beta$: $$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

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$\theta_{23} \approx 48°$
$\theta_{13} \approx 9°$
$\theta_{12} \approx 34°$
$\delta \approx 222°$

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… But high-energy neutrinos oscillate *fast*

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$
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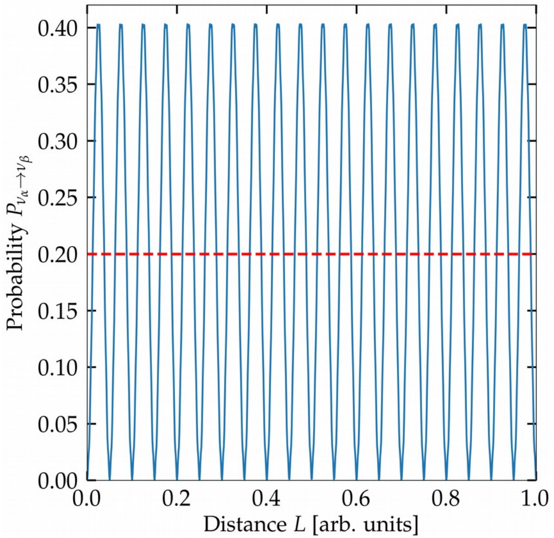

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2$ ~ 0.1 pc

~ 8% of the way to Proxima Centauri
$\ll$ Distance to Galactic Center (8 kpc)
$\ll$ Distance to Andromeda (1 Mpc)
$\ll$ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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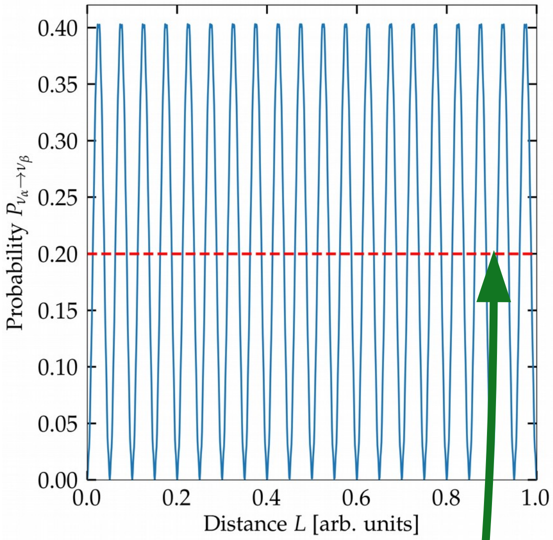
$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$



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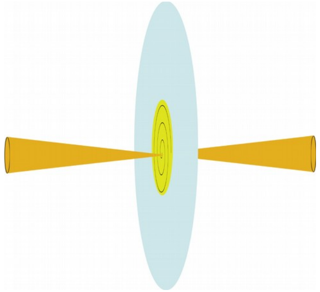
Flavor composition

Astrophysical neutrino sources

Earth

Up to a few Gpc



ν_e

ν_μ

ν_τ

Flavor mixing changes the number

of ν of each flavor, N_e, N_μ, N_τ

ν_e

ν_μ

ν_τ

- Different processes yield different ratios of neutrinos of each flavor:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

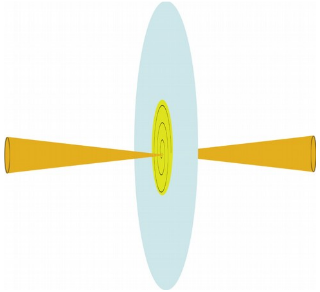
- Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Flavor composition

Astrophysical neutrino sources   Earth

Up to a few Gpc



ν_e

ν_μ

ν_τ

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ν_e

ν_μ

ν_τ

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$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,\mathrm{S}}$$

Standard oscillations
or
new physics

Why are flavor ratios useful?

- The normalization of the flux is uncertain – but it cancels out in flavor ratios:

$$\alpha\text{-flavor ratio at Earth } (f_{\alpha,\oplus}) = \frac{\text{Flux at Earth of } \nu_\alpha \ (\alpha = e, \mu, \tau)}{\text{Sum of fluxes of all flavors}}$$

- Ratios remove systematic uncertainties common to all flavors

- Flavor ratios are useful in astrophysics and particle physics

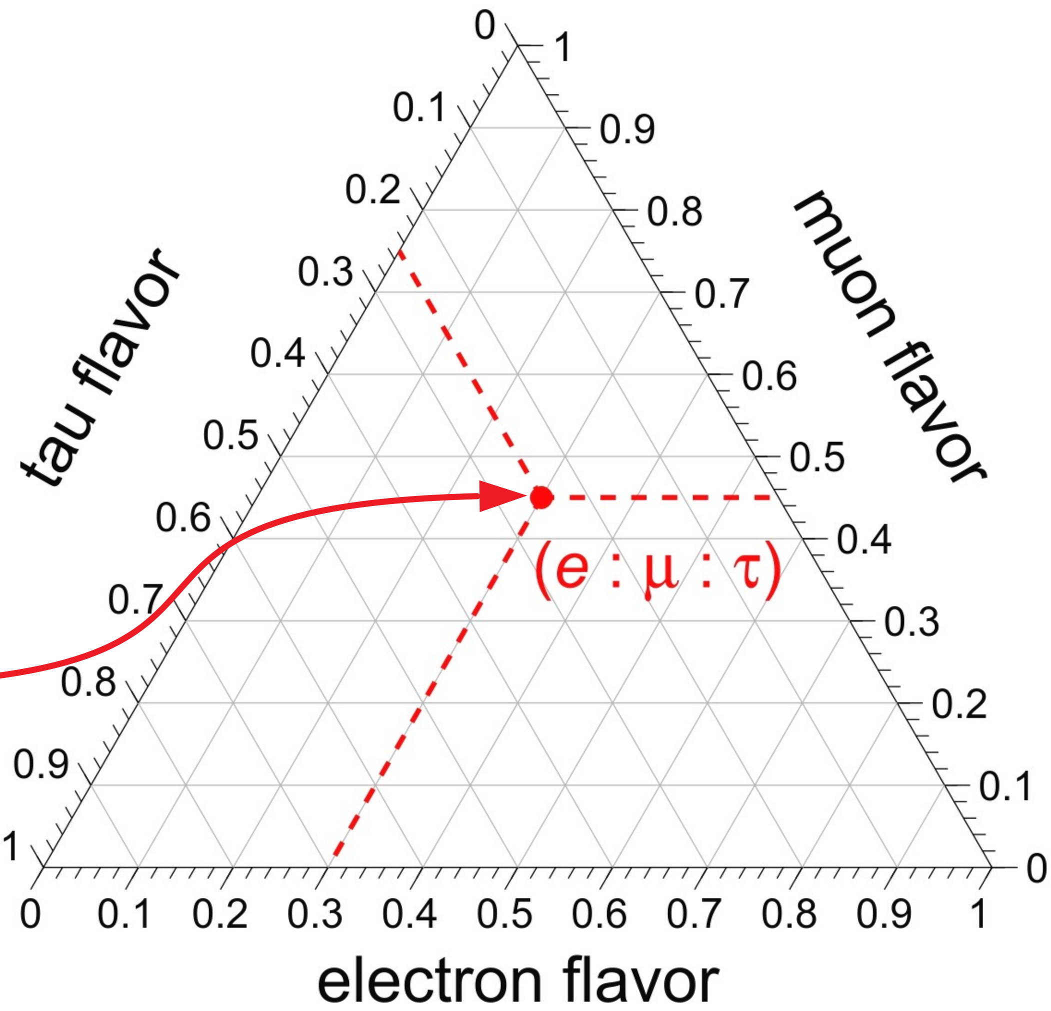
Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

Reading a ternary plot

Assumes underlying unitarity – sum of projections on each axis is 1

How to read it: Follow the tilt of the tick marks, *e.g.*,

$(e{:}\mu{:}\tau) = (0.30{:}0.45{:}0.25)$



One likely TeV–PeV ν production scenario:

$p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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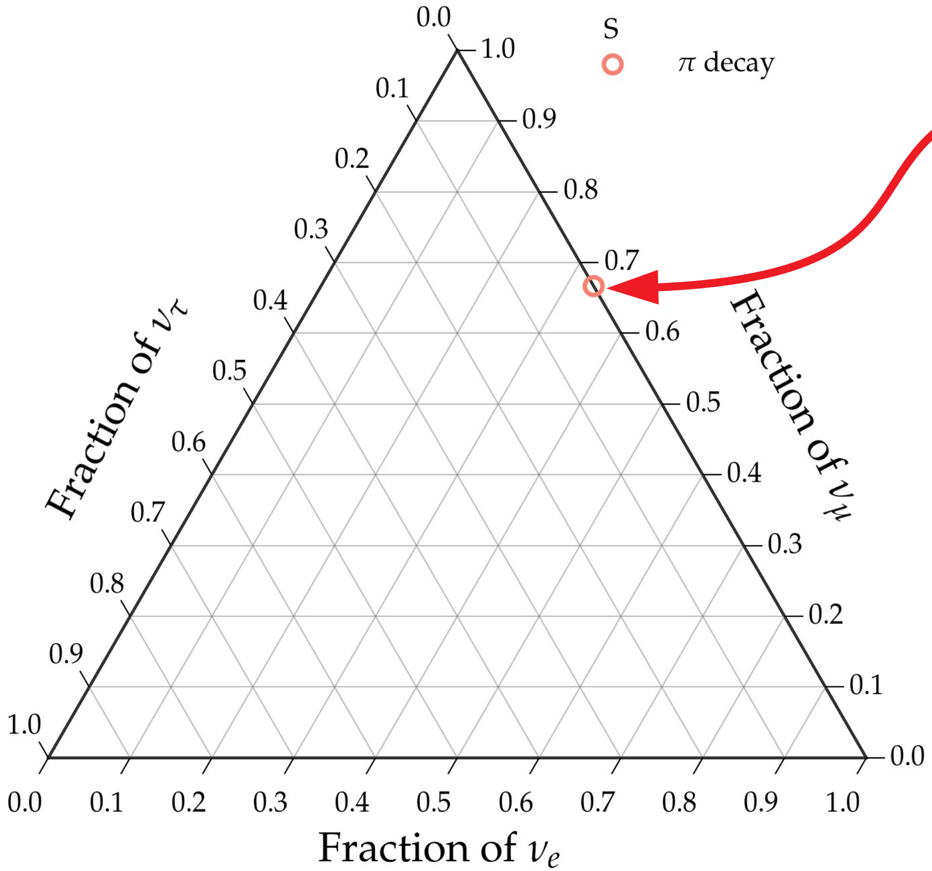

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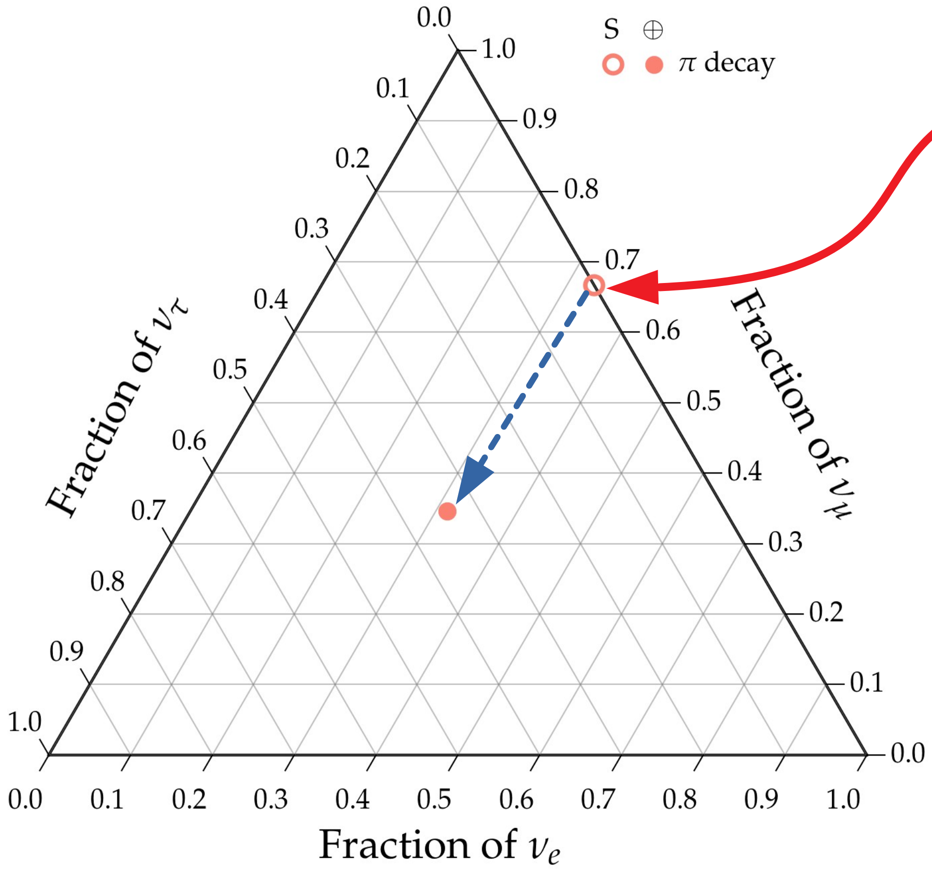

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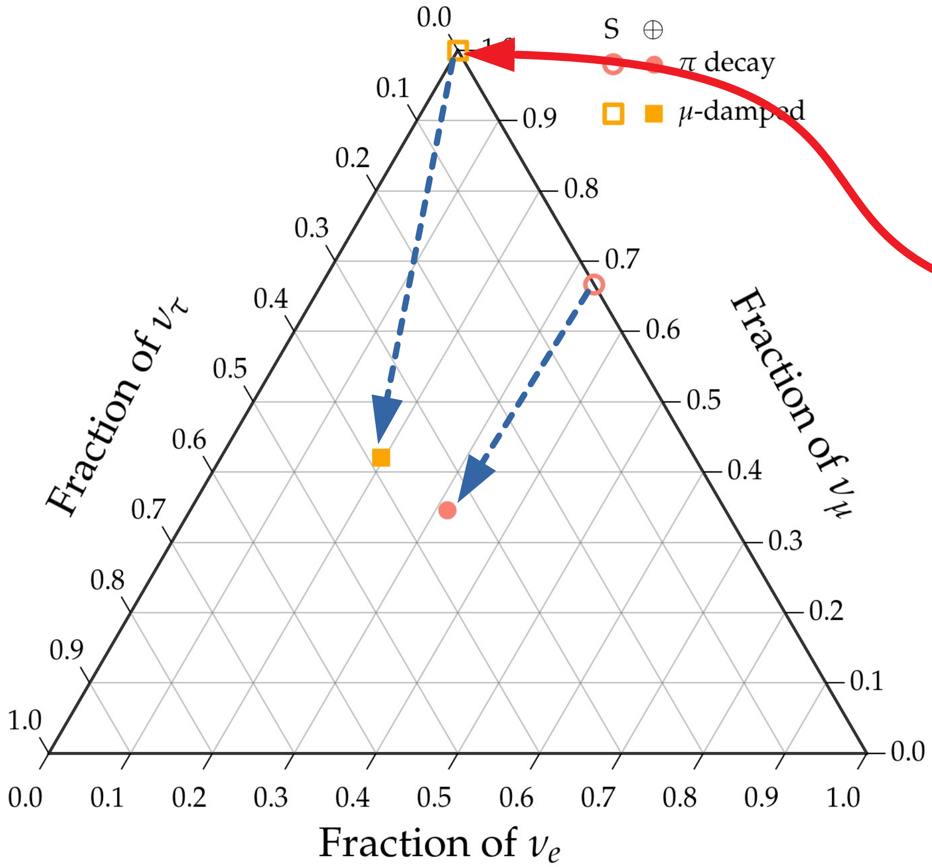


Full π decay chain

$(1/3:2/3:0)_S$

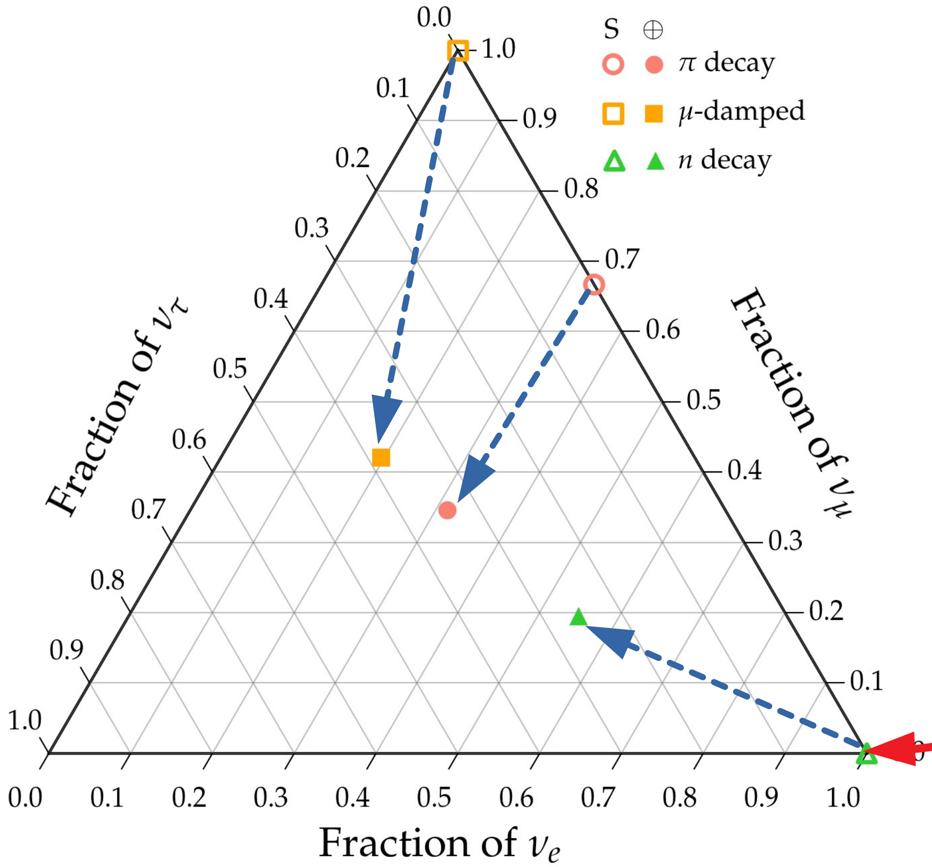
Muon damped

$(0:1:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:

$$p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu \quad \text{followed by} \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



Full π decay chain

$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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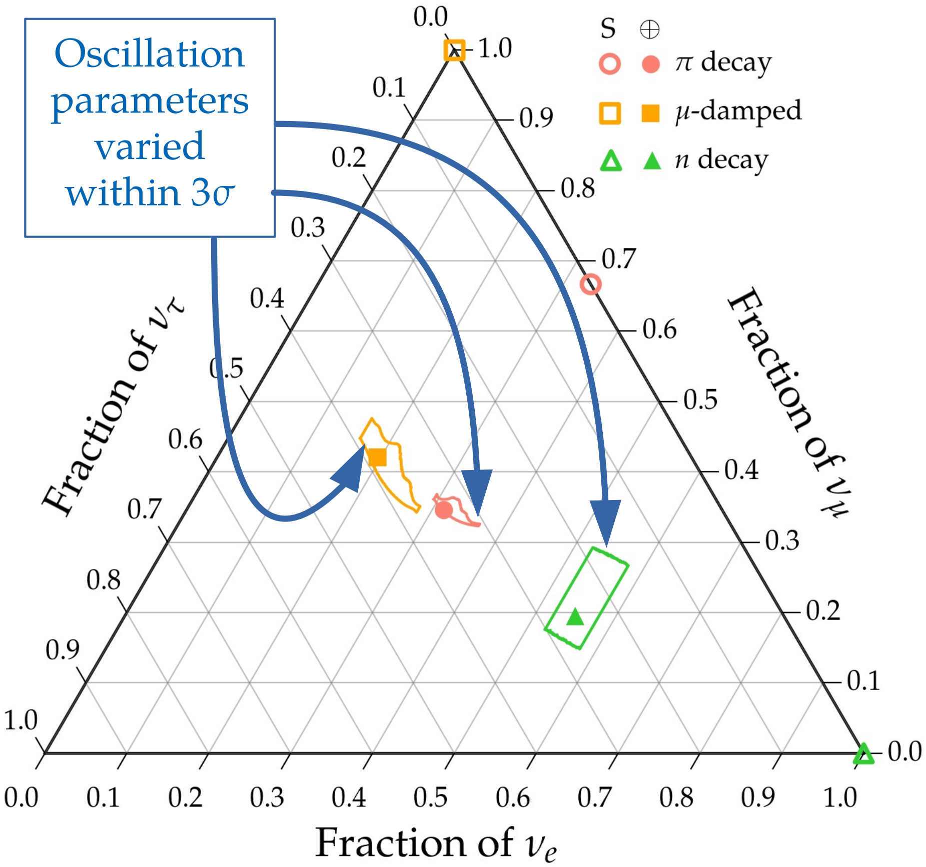

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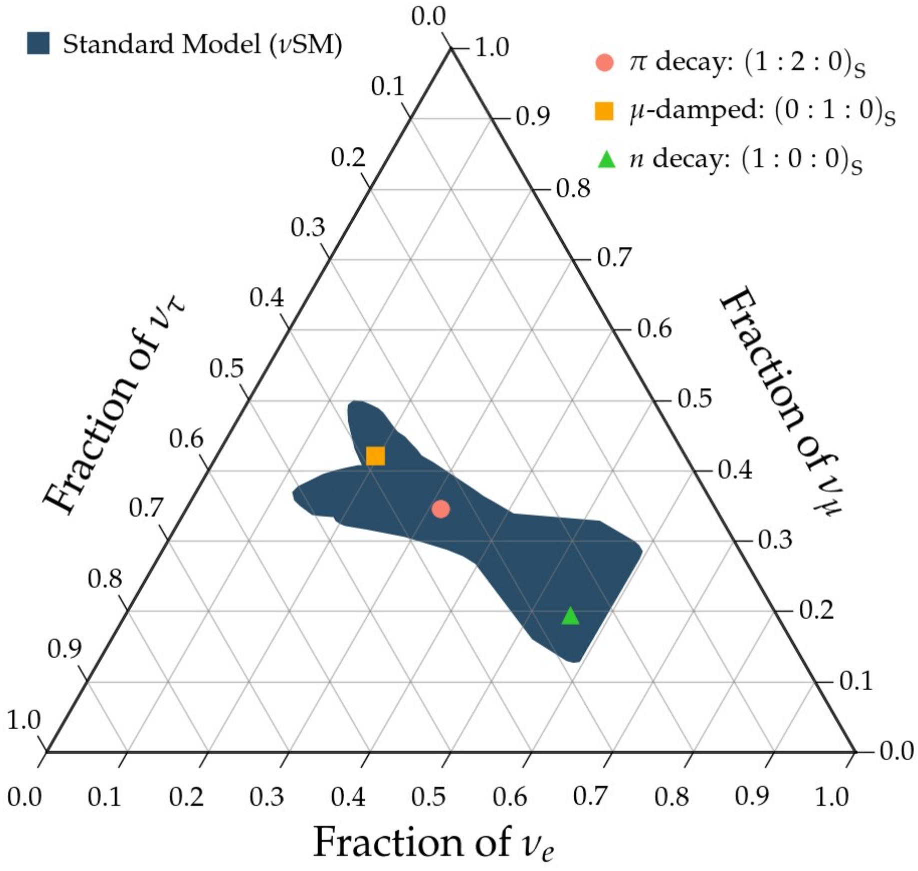
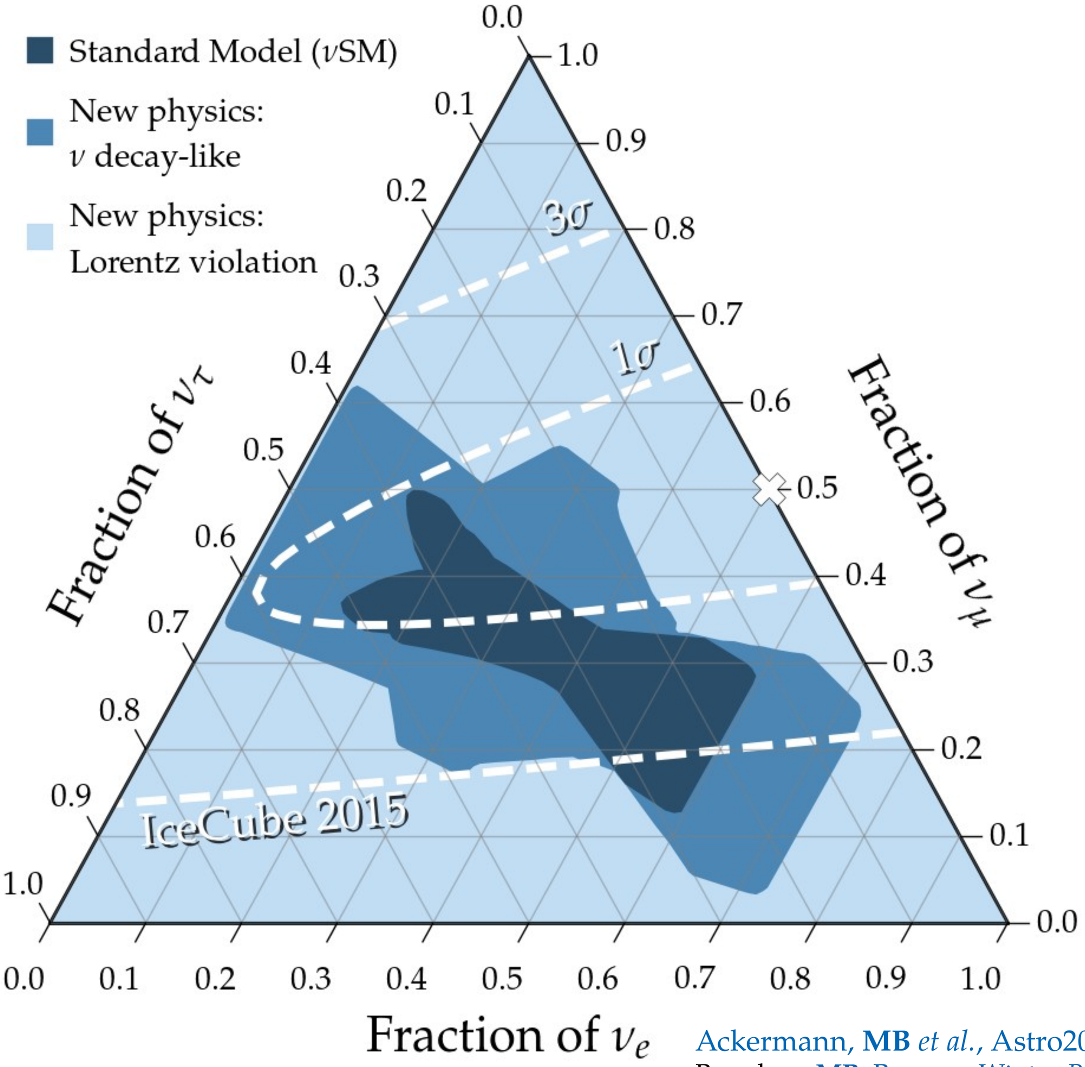


All possible flavor ratios at the sources

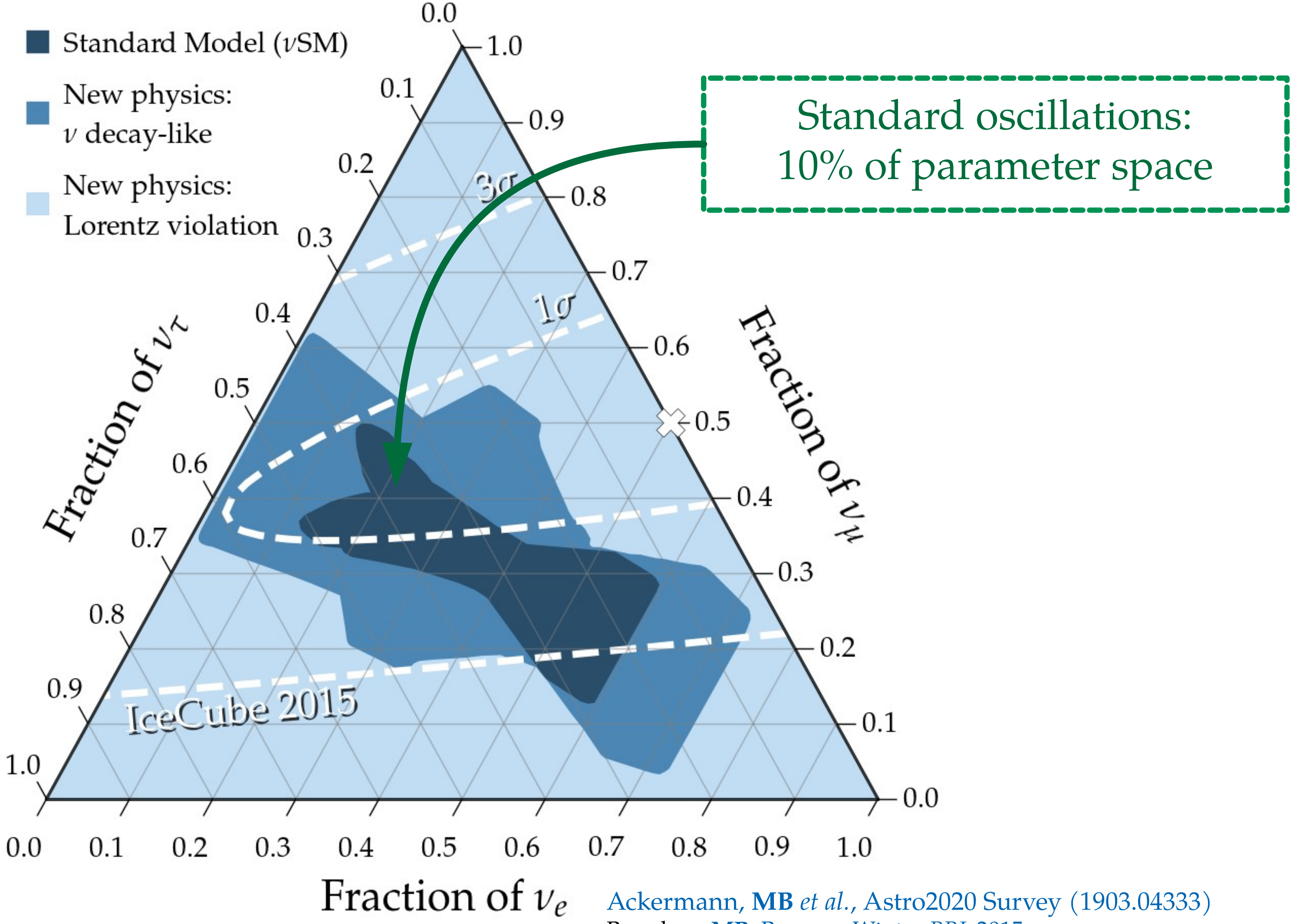
+

Vary oscillation parameters within 3σ

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes



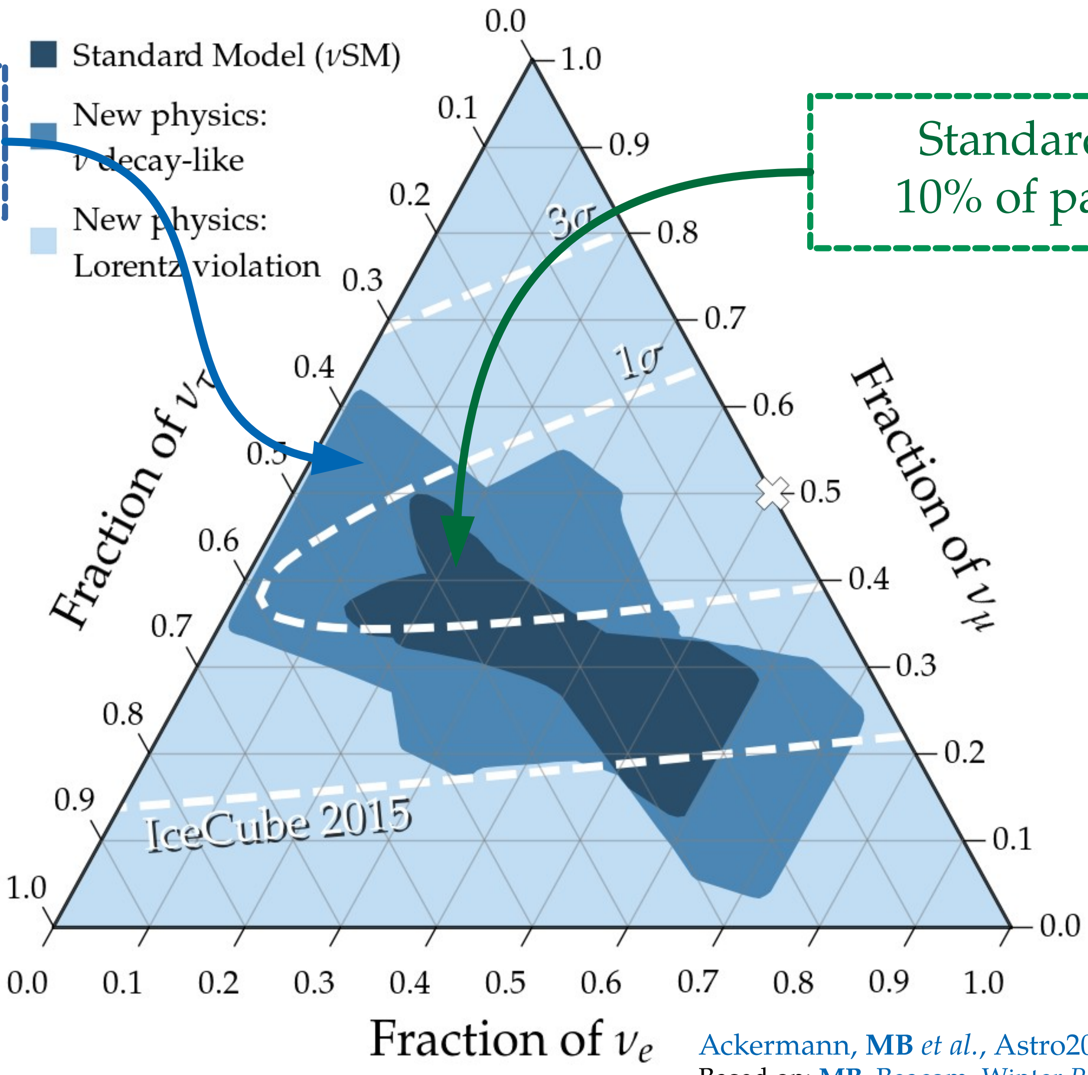
Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

Neutrino decay
30% of parameter space

Standard oscillations:
10% of parameter space



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333)
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Neutrino decay
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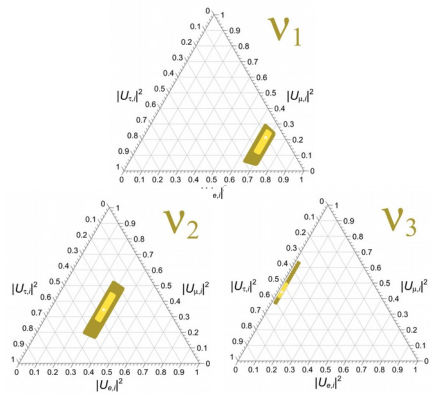
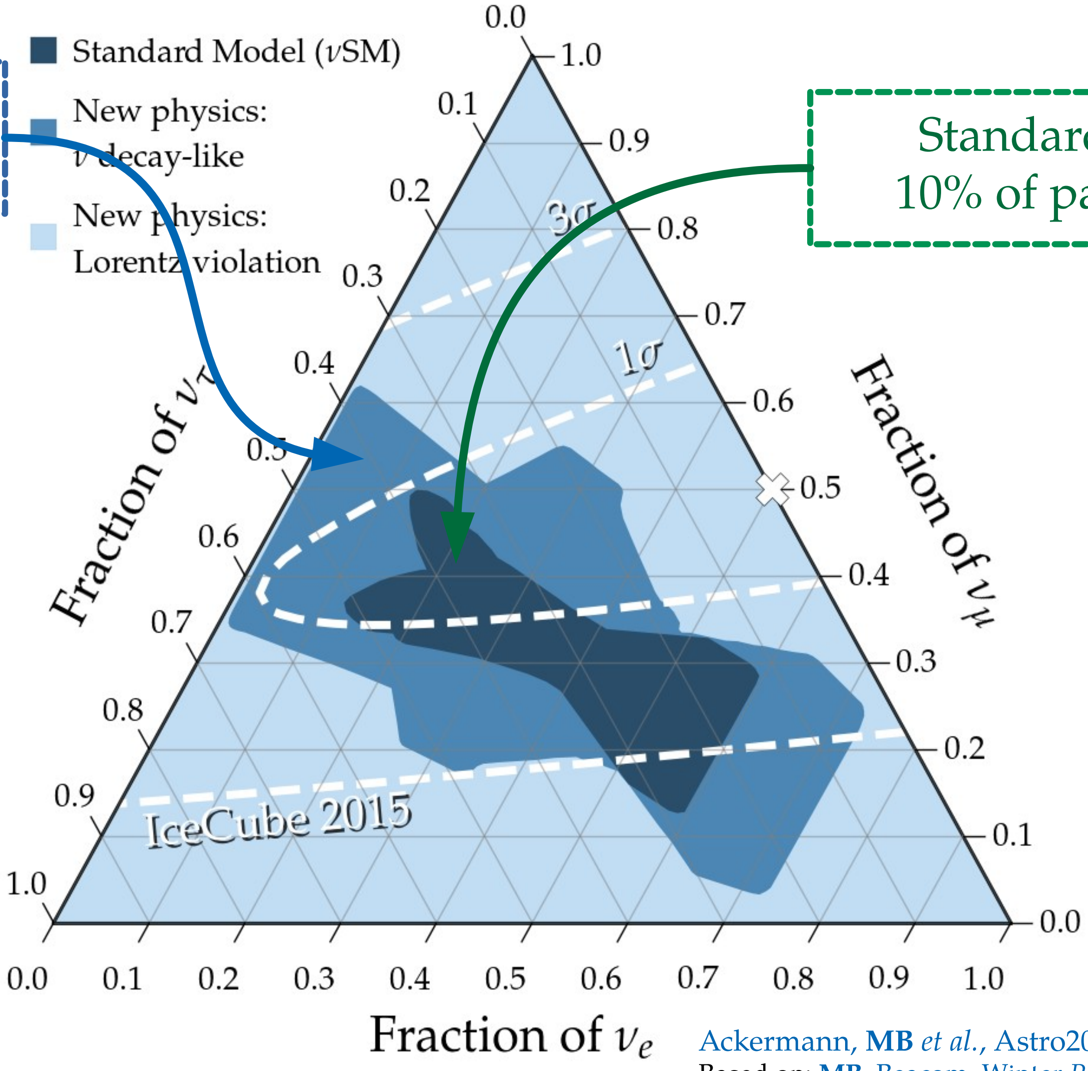
$\nu_2, \nu_3 \rightarrow \nu_1$ or $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10$ s eV^{-1}

MB, Beacom, Murase *PRD* 2017
Baerwald, **MB**, Winter *JCAP* 2012



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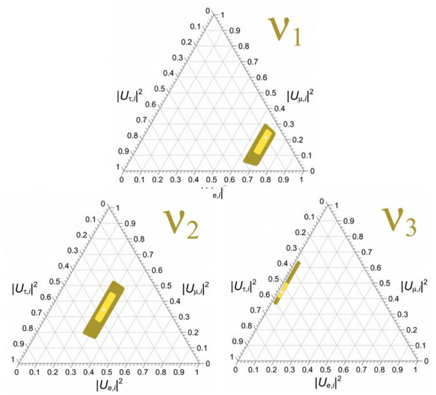

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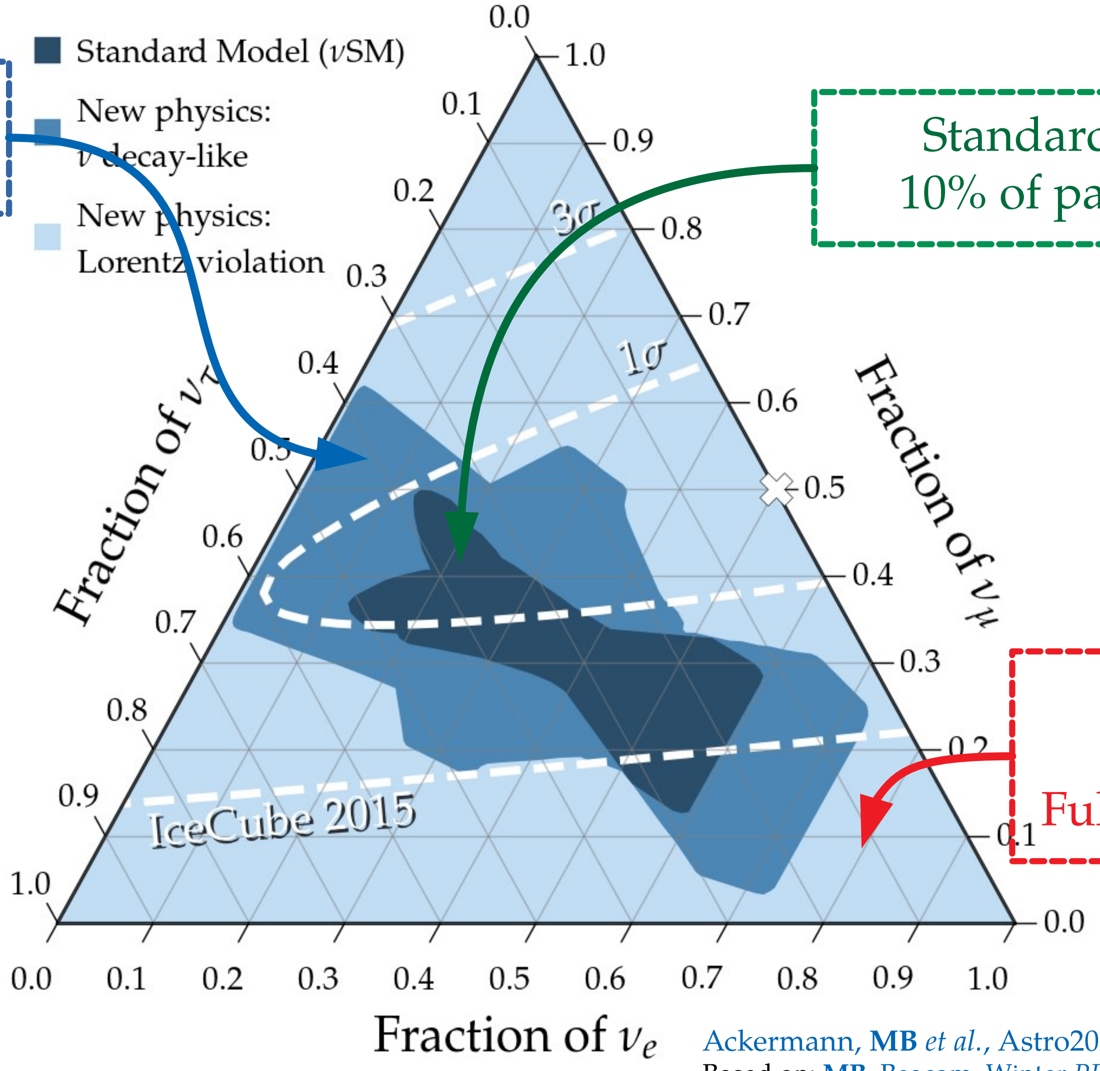

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Lorentz, CPT violation, etc:
Full parameter space

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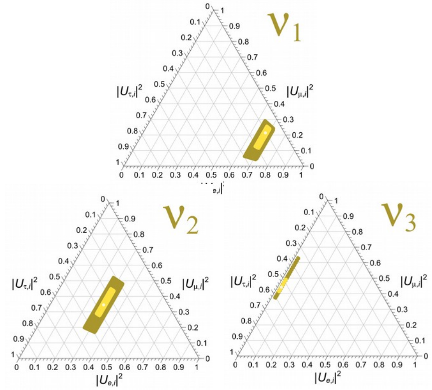

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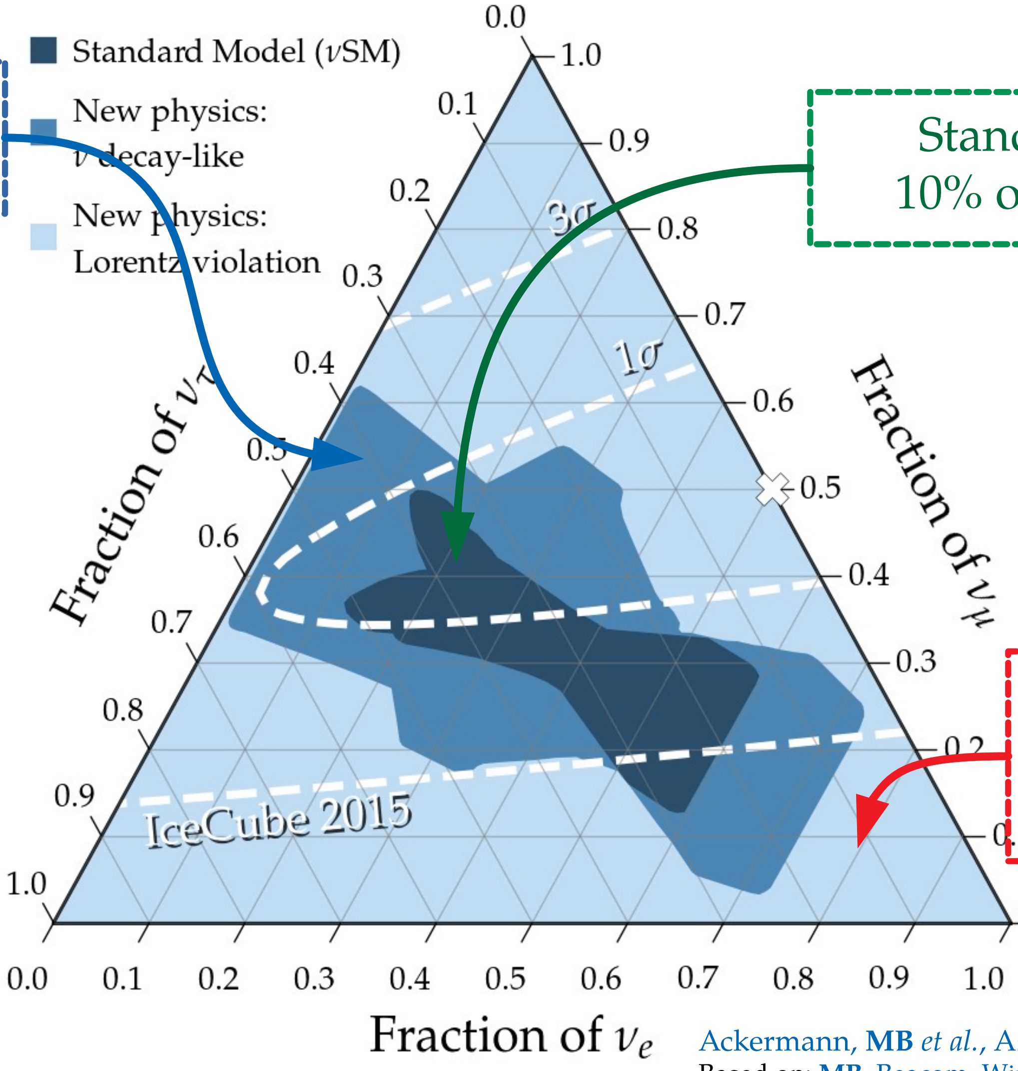

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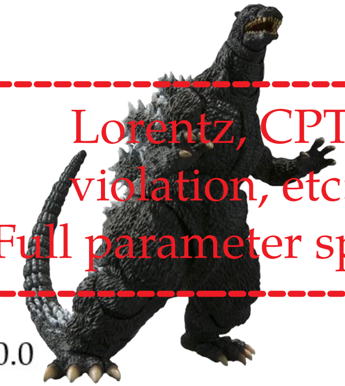
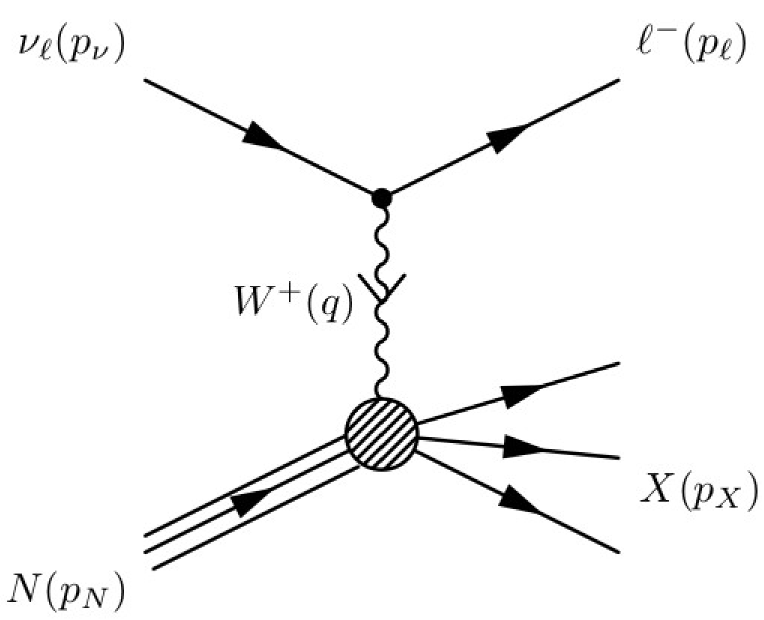


Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

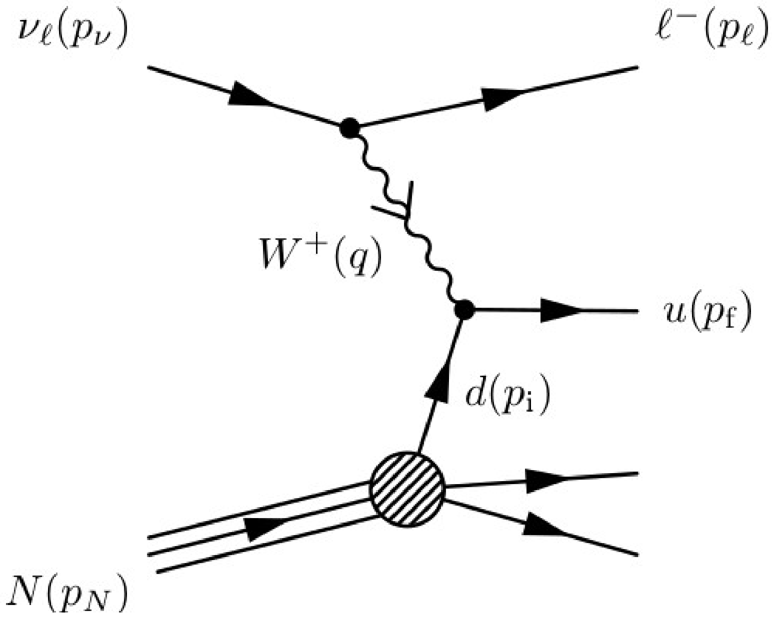
Neutrino detection

Neutrino-nucleon deep inelastic scattering

What you see



Beneath the hood

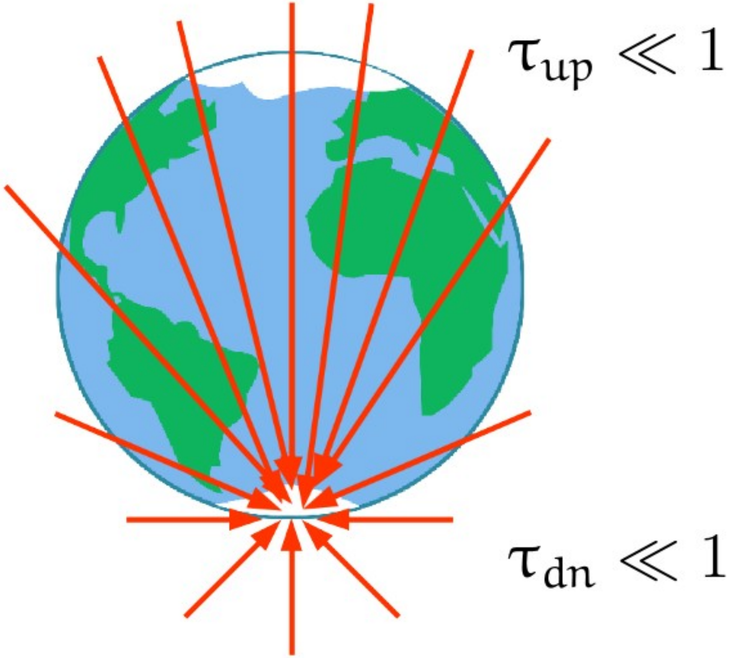


(Plus the equivalent neutral-current process (Z-exchange))

High-energy neutrinos are attenuated inside Earth

$$\text{Optical depth to } \nu\text{N int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



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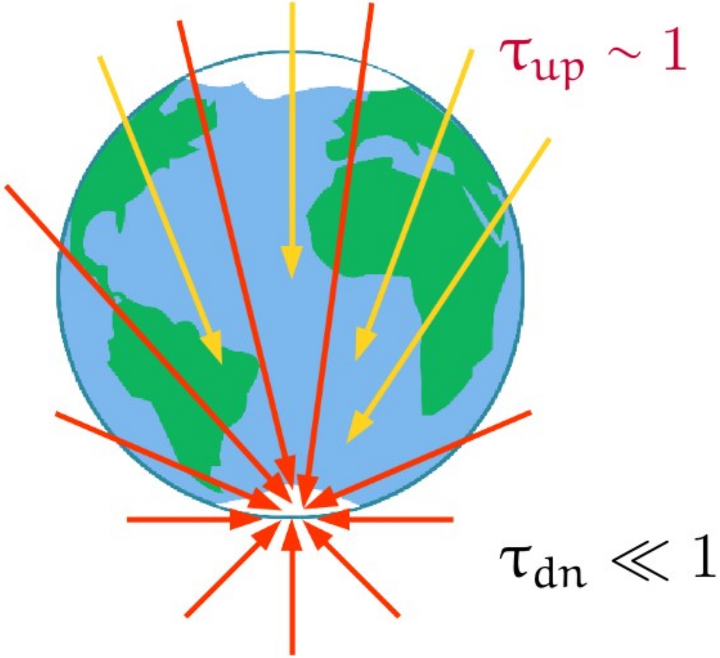

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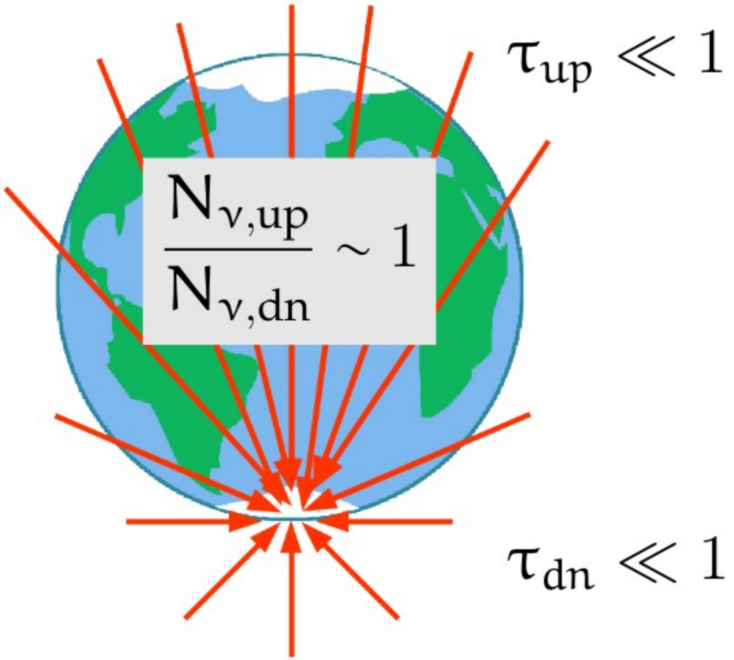

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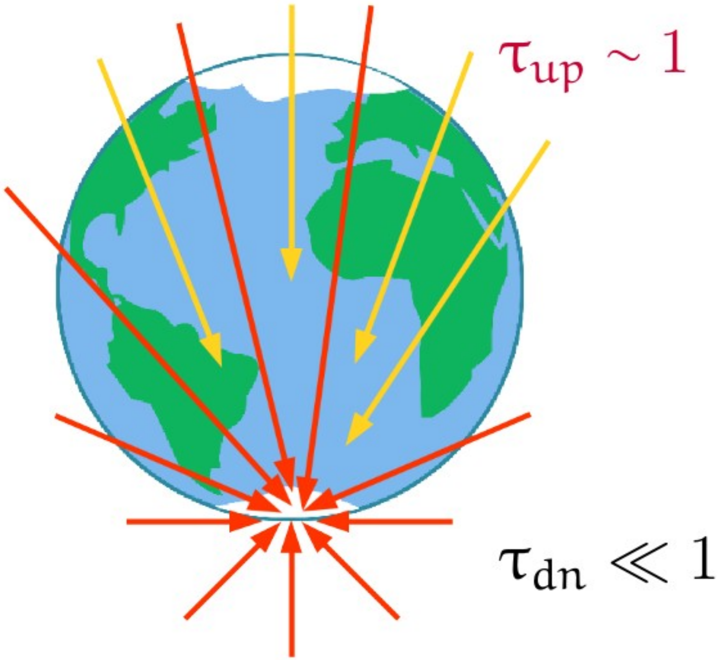

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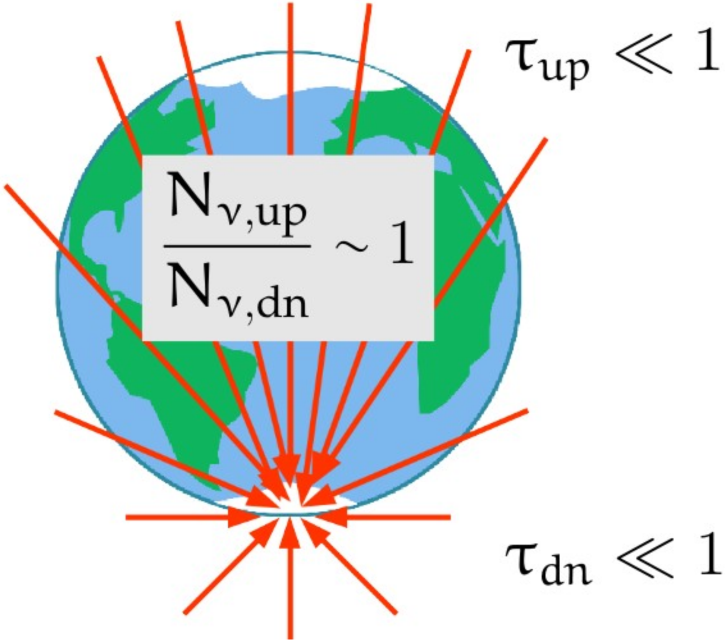

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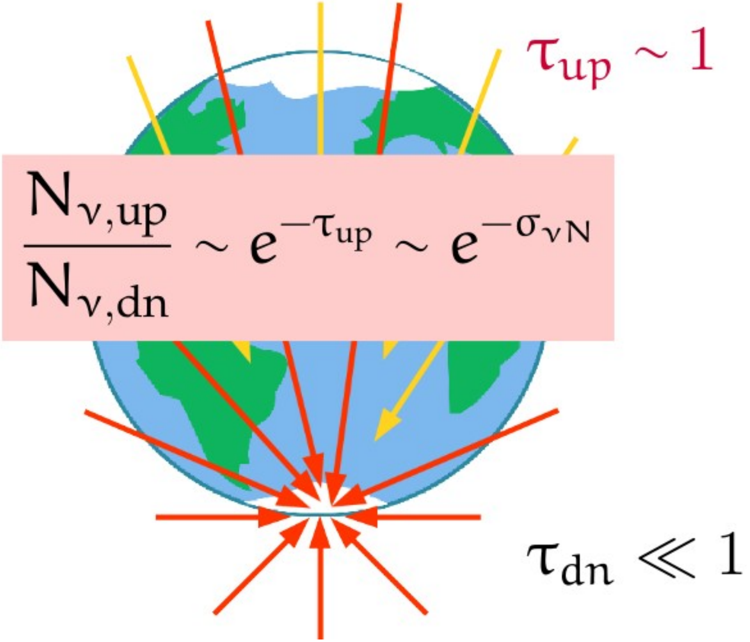
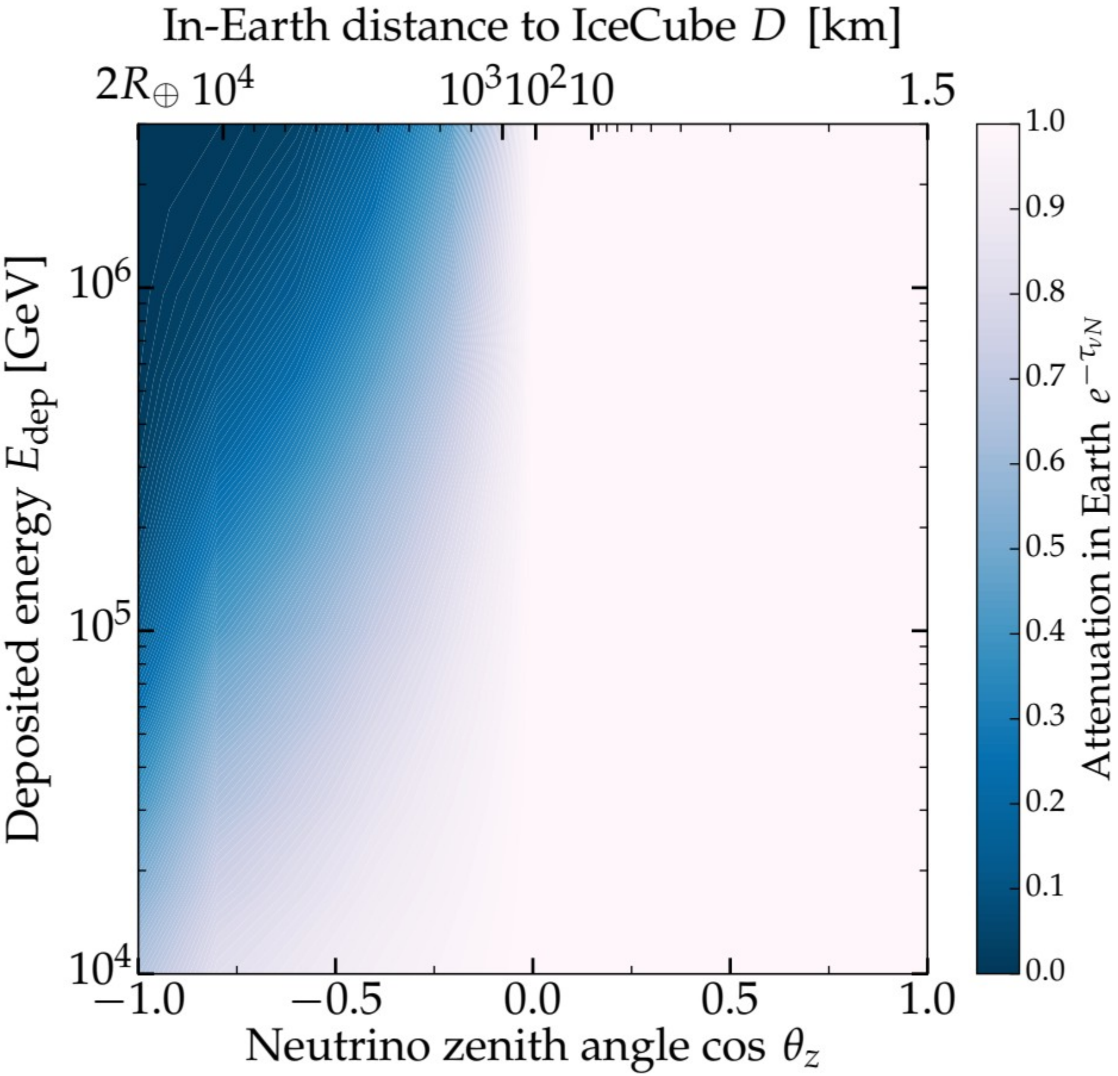
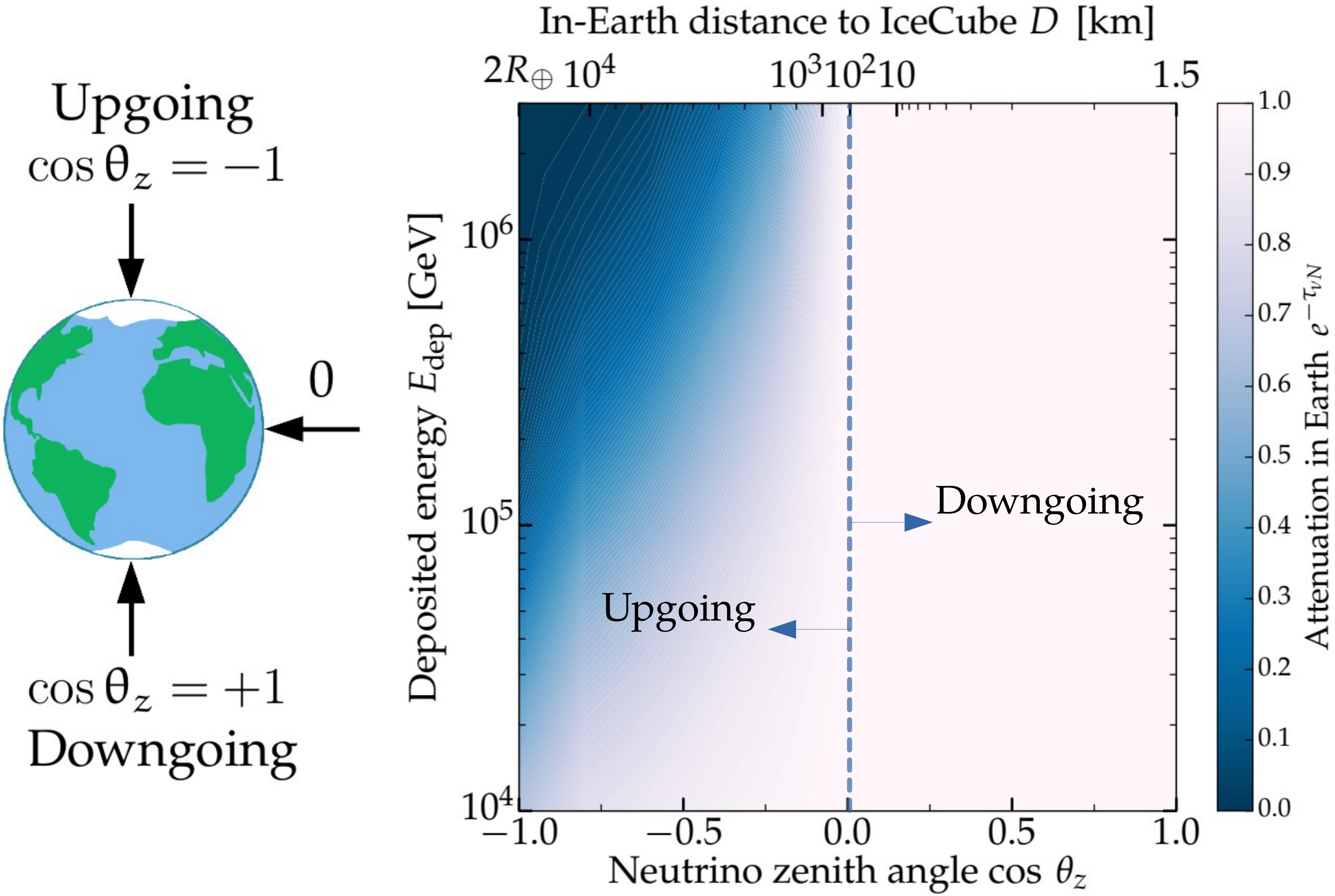



In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^4
10^5
10^6
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\,\theta_z$
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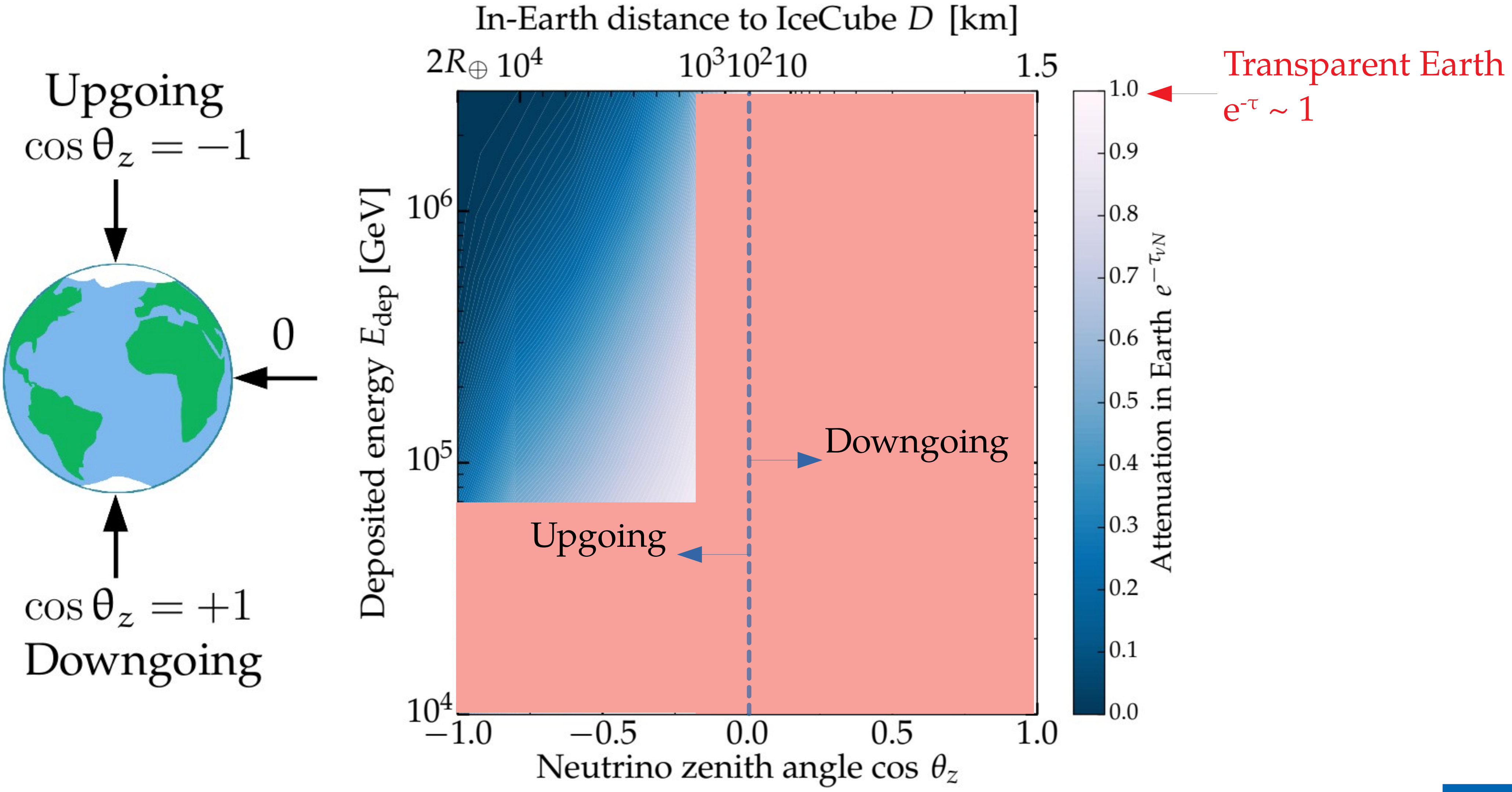
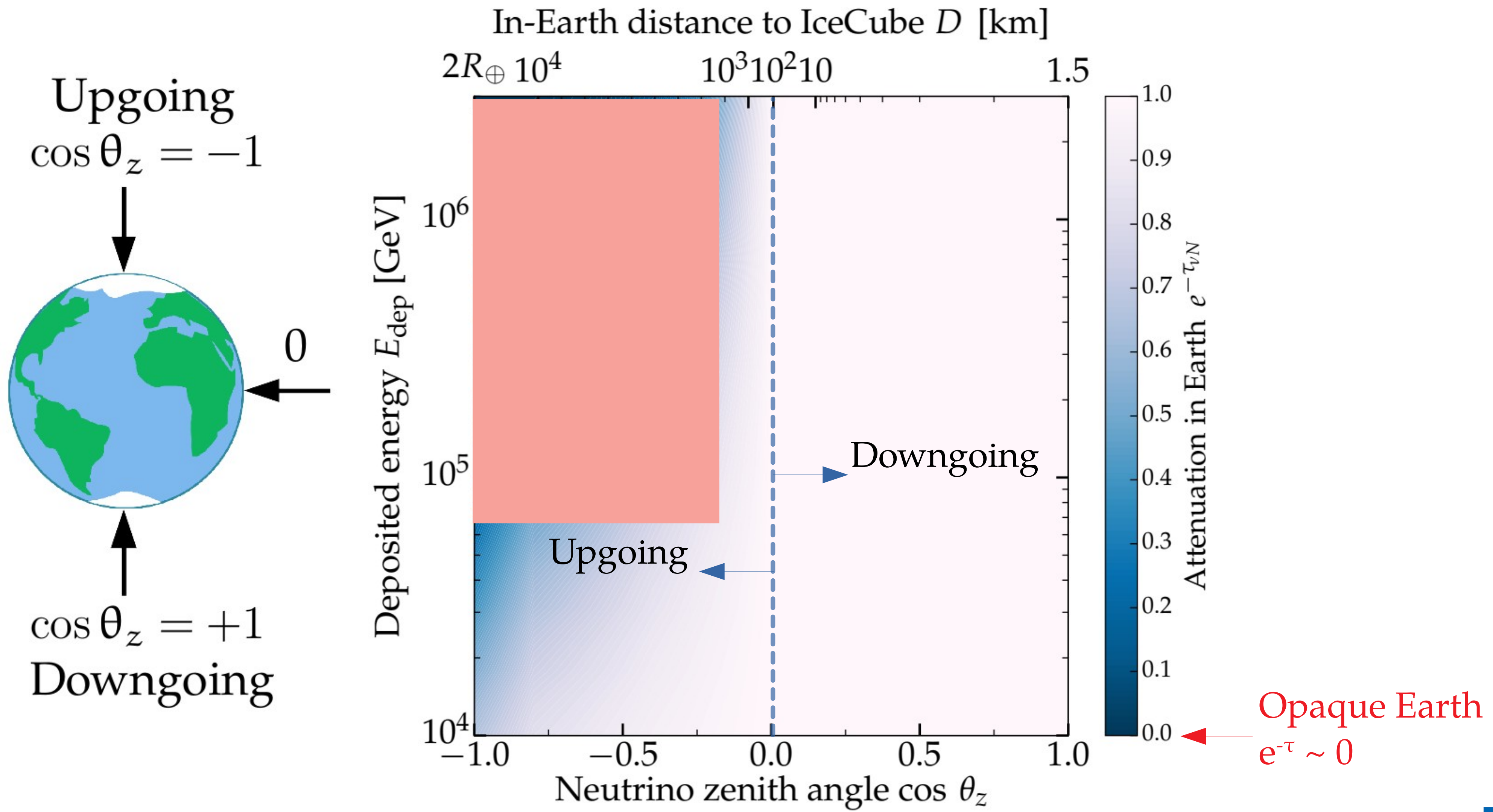
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0


Upgoing
cos θz = −1
0
cos θz = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θz
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^{−τνN}
Transparent Earth
e^{-τ} ~ 1



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$\cos\theta_z = -1$
0
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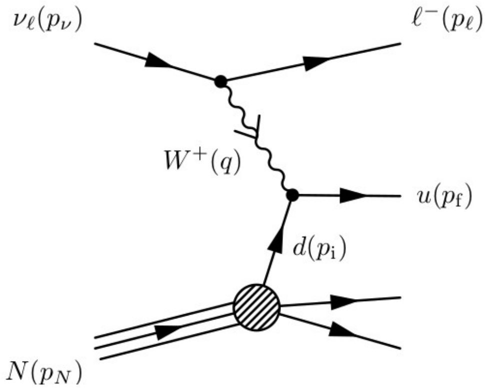
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4
10^5
10^6
Downgoing
Upgoing
-1.0 -0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Opaque Earth
$e^{-\tau} \sim 0$

Computing & measuring the cross section

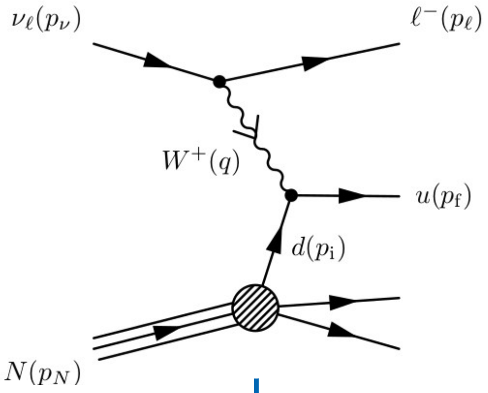
Computing & measuring the cross section

SM



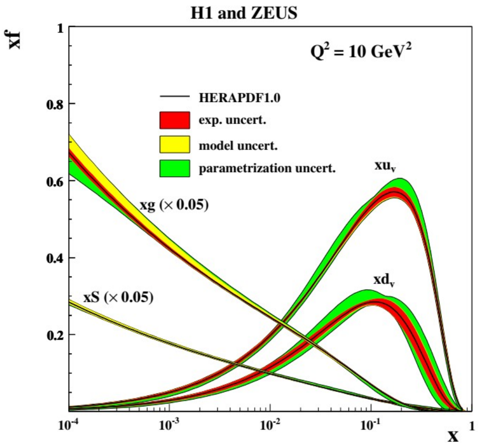
Computing & measuring the cross section

SM



+

PDFs



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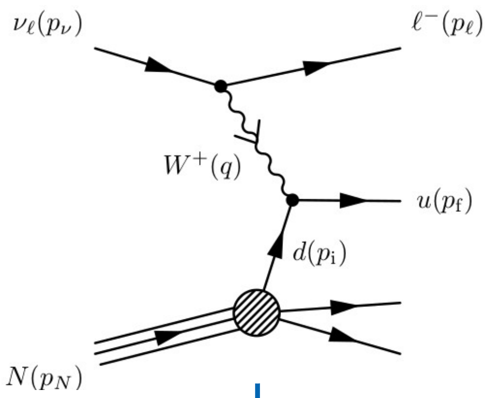
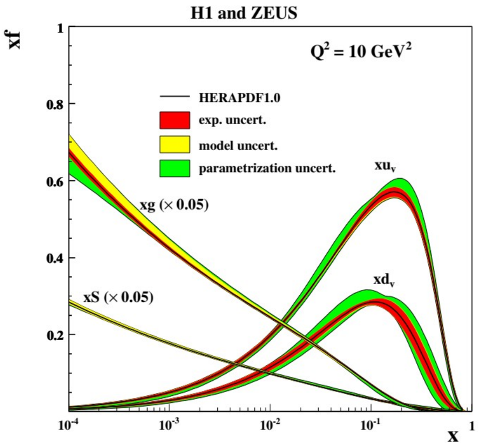
SM



+

PDFs



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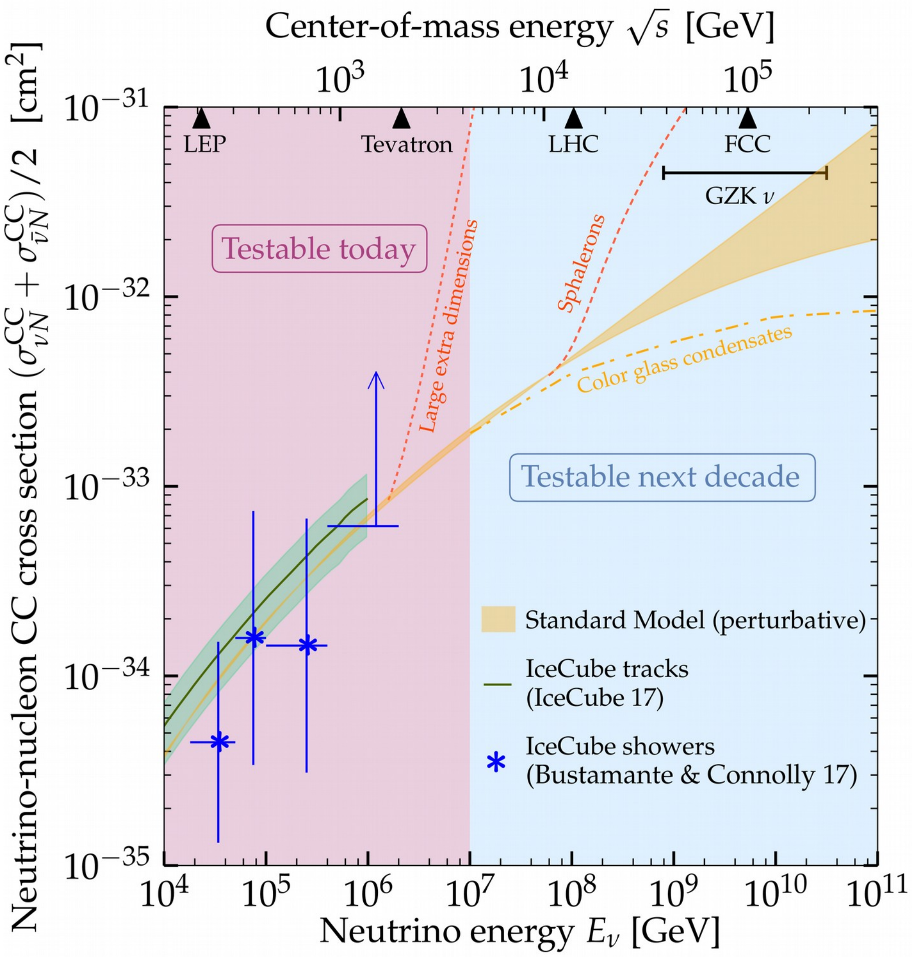


Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04333)

How does IceCube see neutrinos?

Two types of fundamental interactions …

Charged-current (CC)

$\nu_l + N \to \boxed{l} + \boxed{\text{hadrons}}$

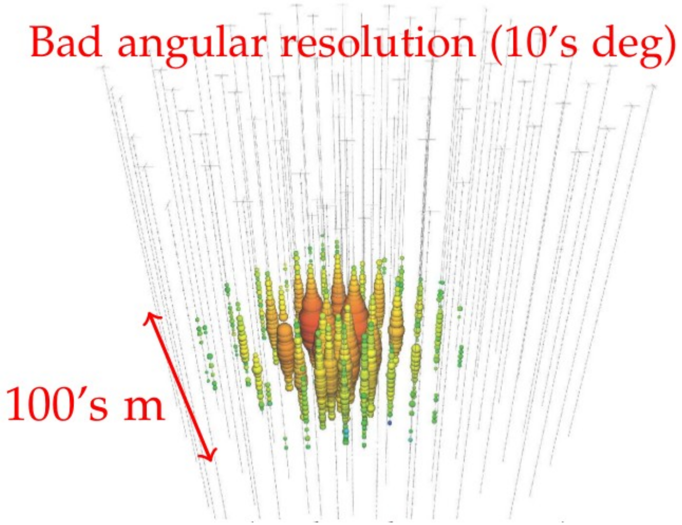
Neutral-current (NC)

$\nu_l + N \to \nu_l + \boxed{\text{hadrons}}$

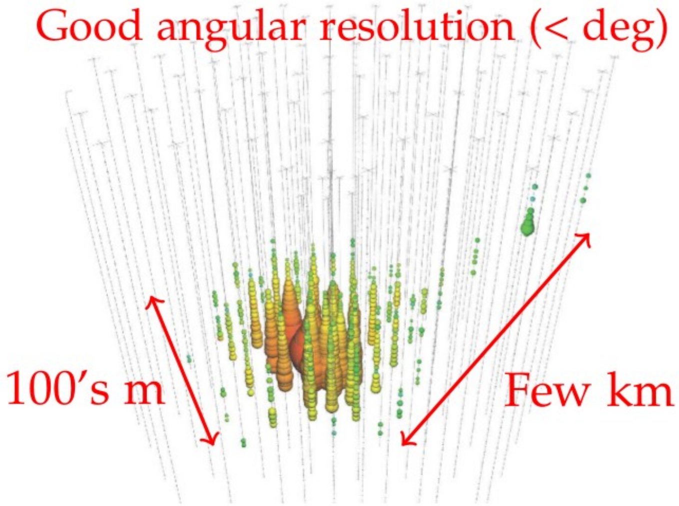
These shower and make light

…create two event topologies …

Showers — From CC ν_e or ν_τ, or NC ν_x

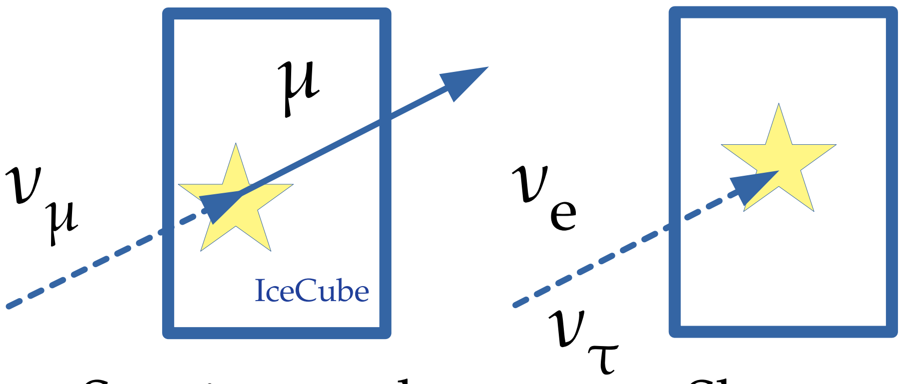


Tracks — From CC ν_μ mainly



Contained *vs.* uncontained events

Contained events



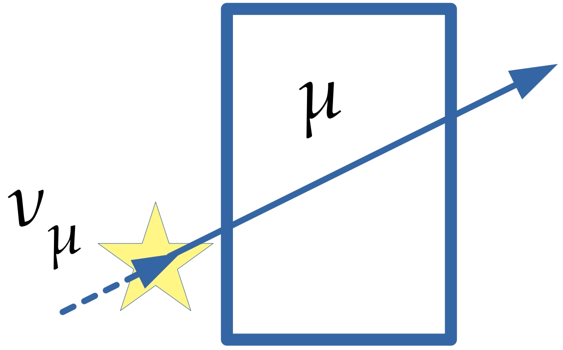
Starting track

Shower

Pro: Clean determination of E_ν

Con: Few events (~100)

Uncontained events



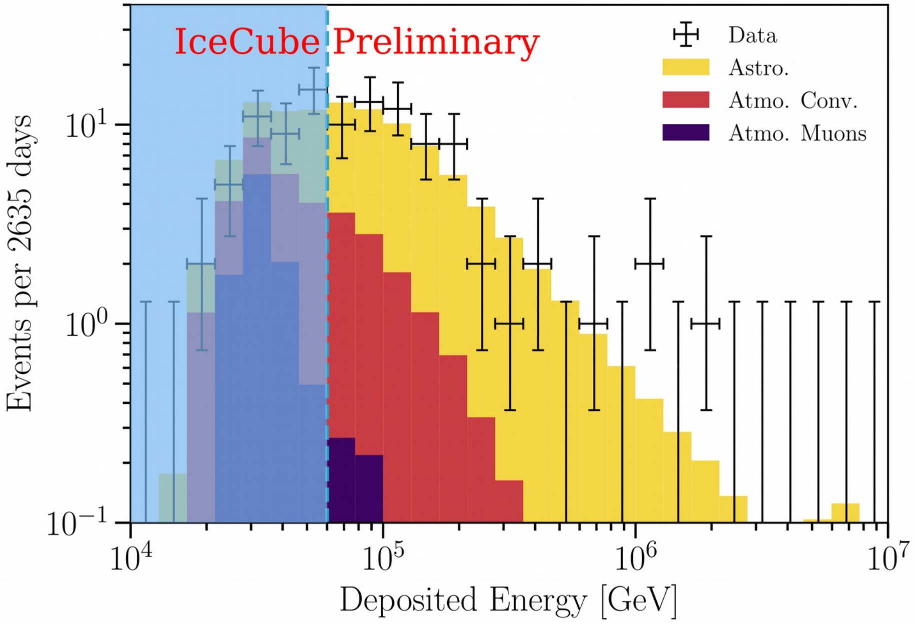
Through-going muon

Pro: Lots of events (few 10k)

Con: Uncertain estimates of E_ν

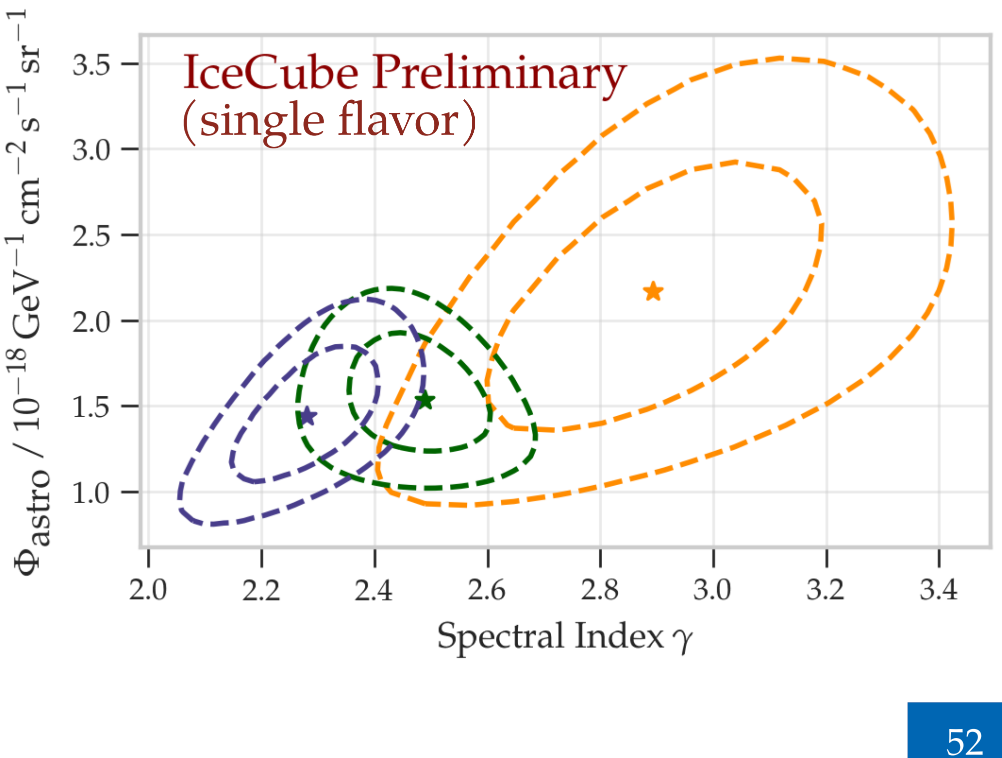
IceCube results: Energy spectrum

100+ contained events above 60 TeV (8 yr):



Data is fit well by a single power law:

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = \Phi \left(\frac{E}{100\ \mathrm{TeV}} \right)^{-\gamma} 10^{-18}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$



IceCube Collab., ICRC 2019
Schneider, ICRC 2019

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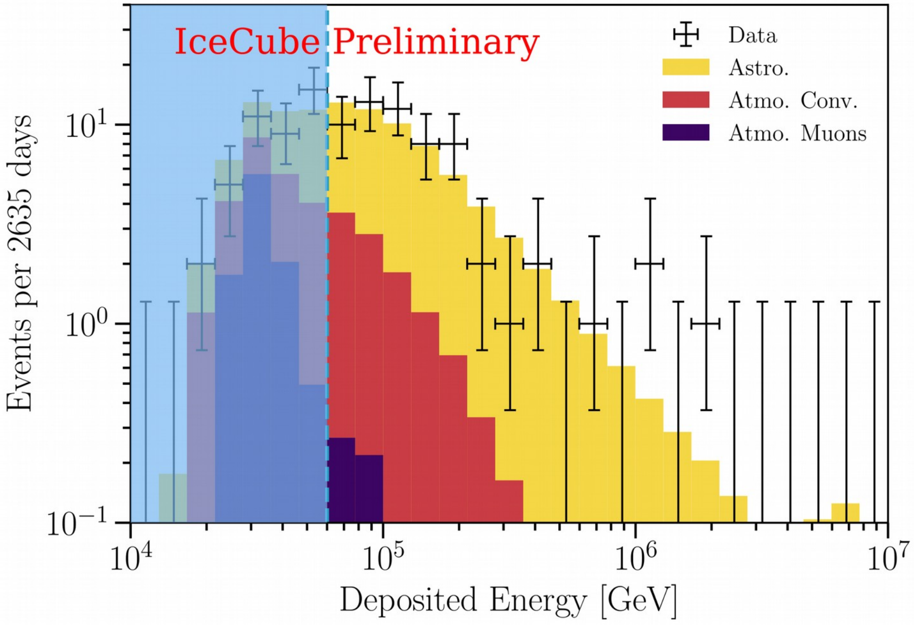

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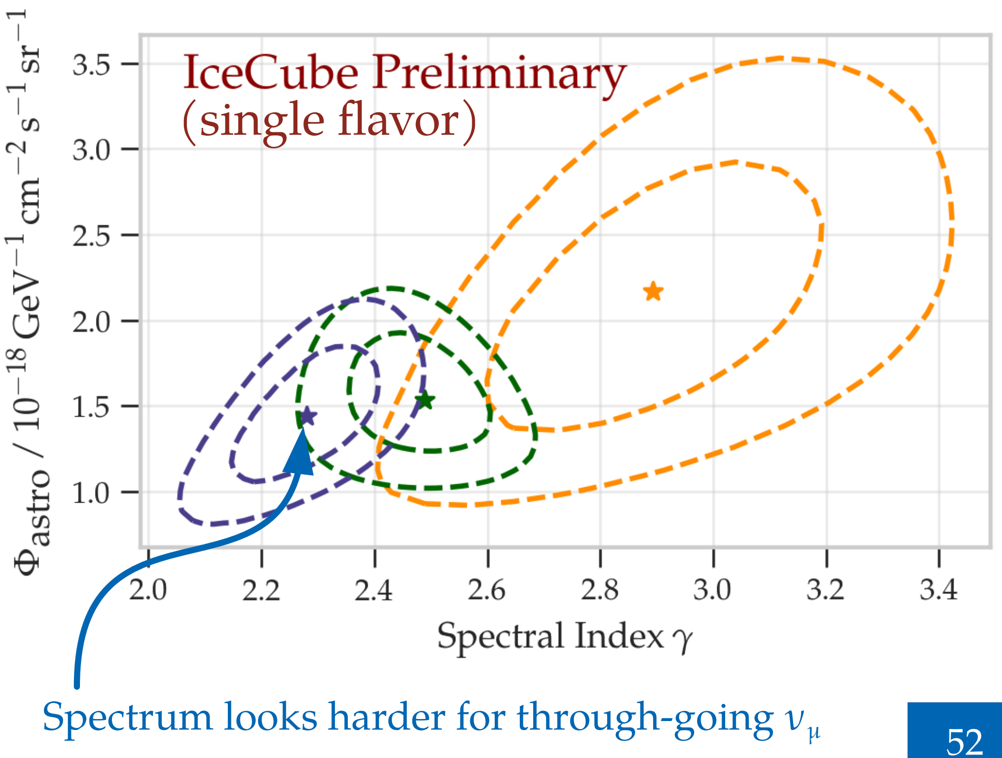
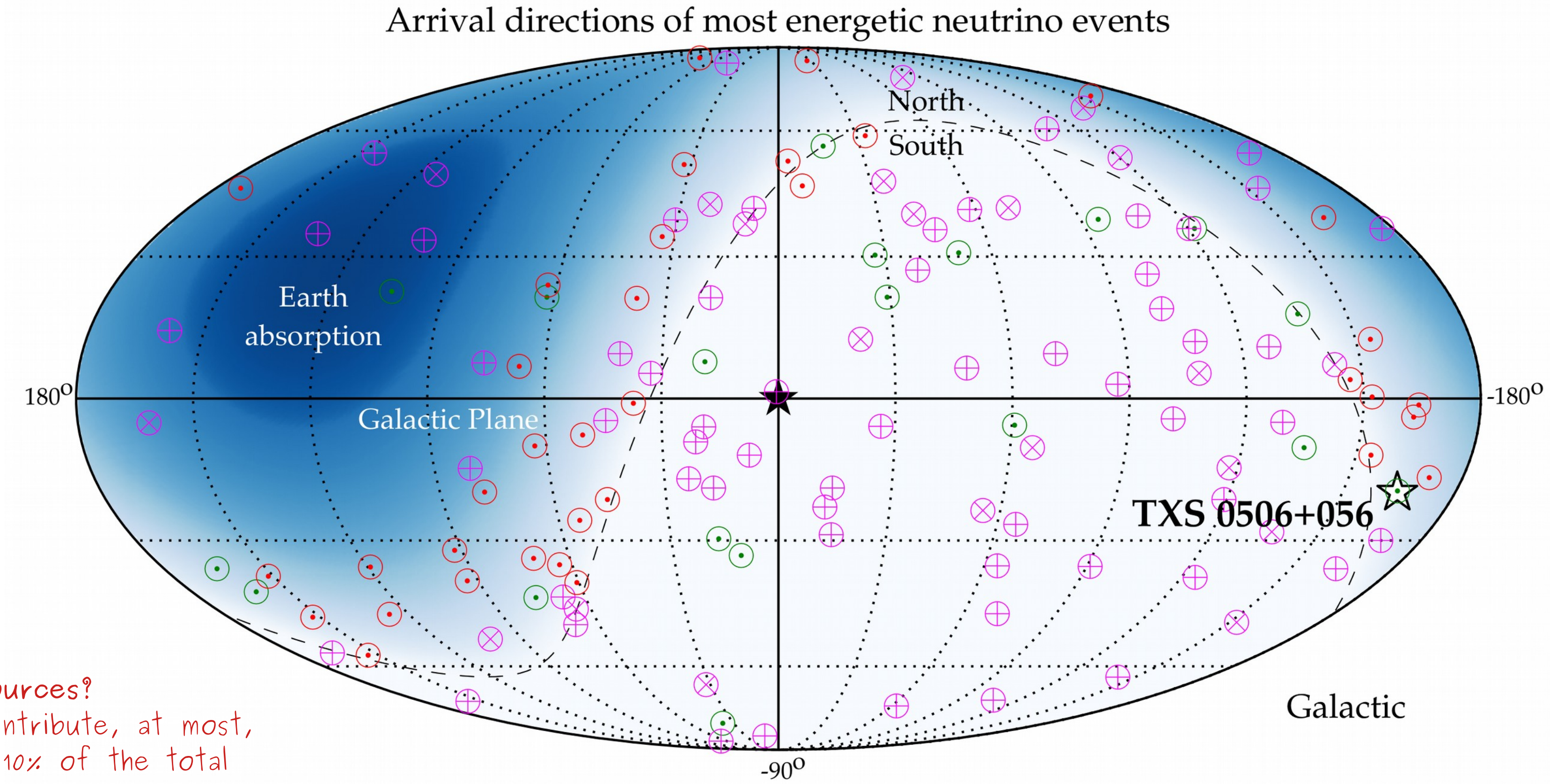


Spectrum looks harder for through-going ν_μ

IceCube Collab., ICRC 2019
Schneider, ICRC 2019

IceCube results: Arrival directions

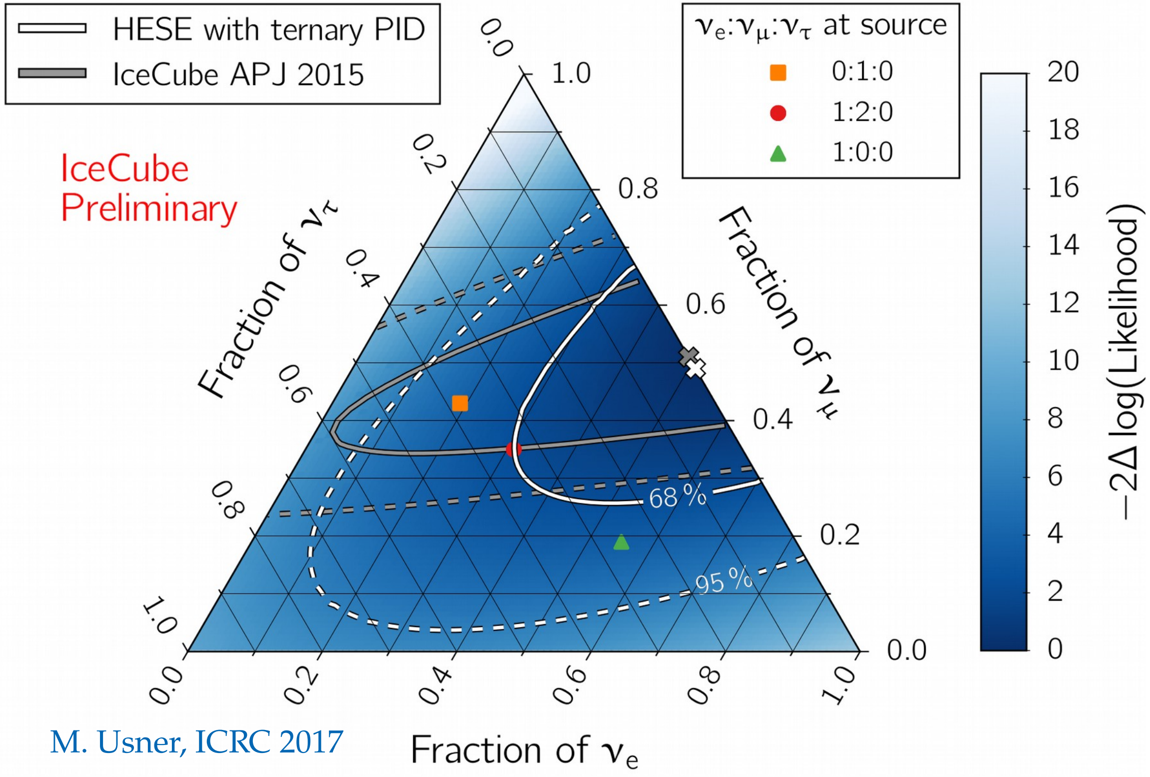
Distribution of arrival directions (8 yr) is compatible with an isotropic distribution of sources:



Milky Way sources?
They only contribute, at most, a few times 10% of the total diffuse flux

Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04334)

IceCube results: Flavor composition



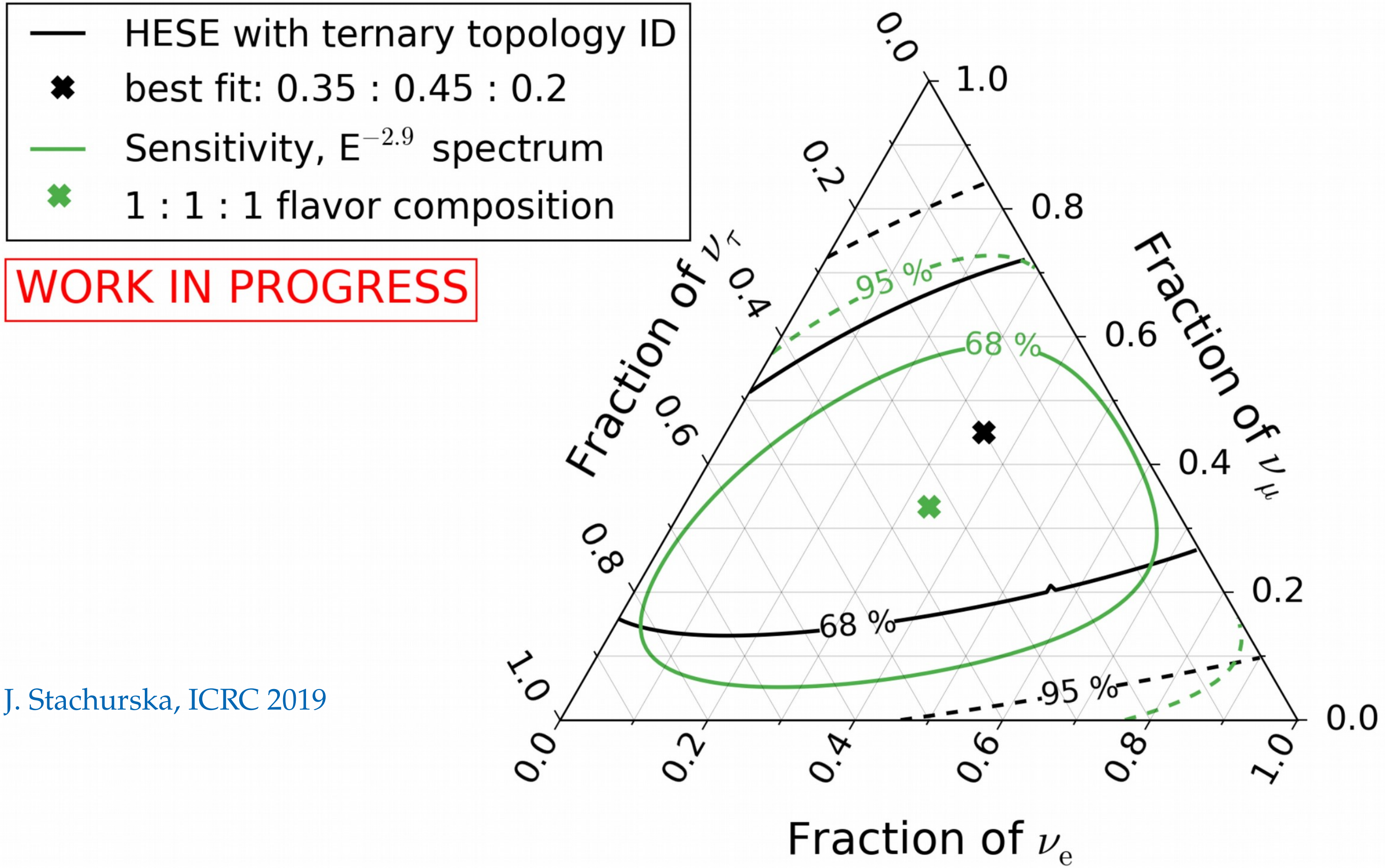
M. Usner, ICRC 2017

- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

Li, **MB**, Beacom *PRL* 2019

IceCube results: Flavor composition

There are 2 ν_τ candidate events which change the flavor composition:



J. Stachurska, ICRC 2019

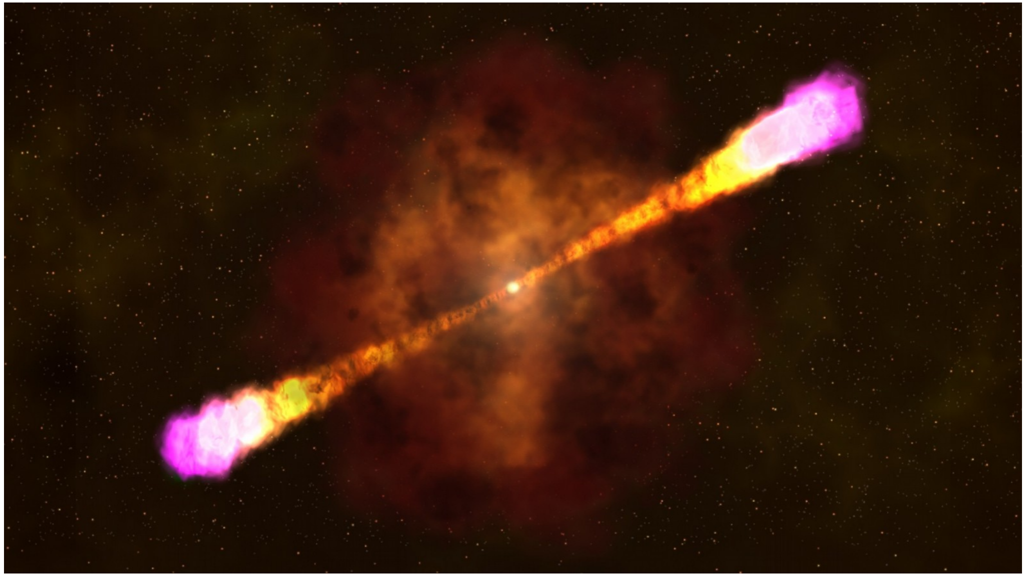
Looking for the sources

Three Strategies to Reveal Sources Using TeV–PeV ν

- **Look at bright e.m. point sources**
  - **Examine single sources** → No evident single steady source, *one* transient source
  - **Stack several similar sources** → Ruled out gamma-ray bursts, blazars as dominant
- **Look for neutrino multiplets**
  - **Clustered in direction** → Placed generic limits on source number density and luminosity
  - **Clustered in direction *and* time** → Used to trigger follow-ups by other detectors
- **Use the diffuse neutrino flux** → Any population of candidate sources must account for all or part of it

Gamma-ray bursts and blazars – *not* dominant

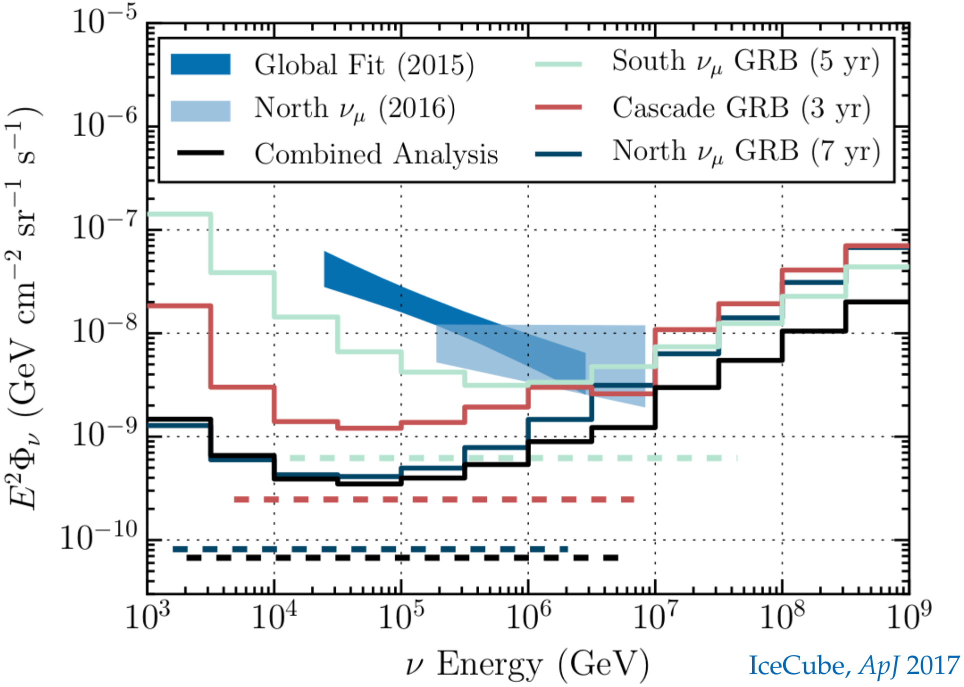
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

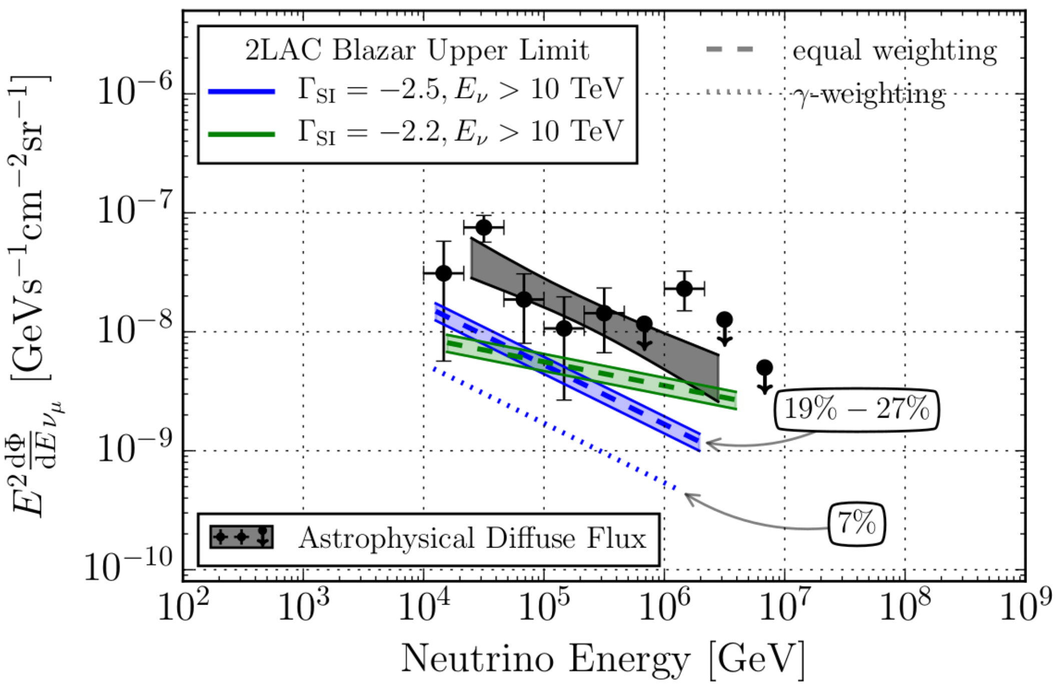


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



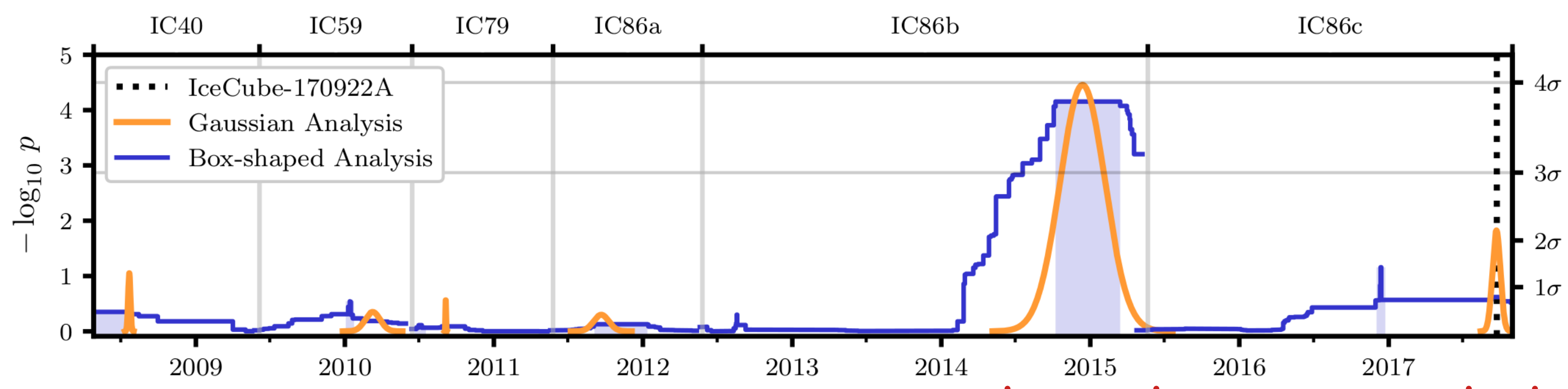
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

… but we have seen *one* blazar neutrino flare!

Recent news:
The starburst Seyfert galaxy NGC 1068 is also a potential neutrino source candidate (1908.05993)

Blazar TXS 0506+056:



Important:
If every blazar produced neutrinos as TXS 0506+056, the diffuse neutrino flux would be 20x higher than observed!

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

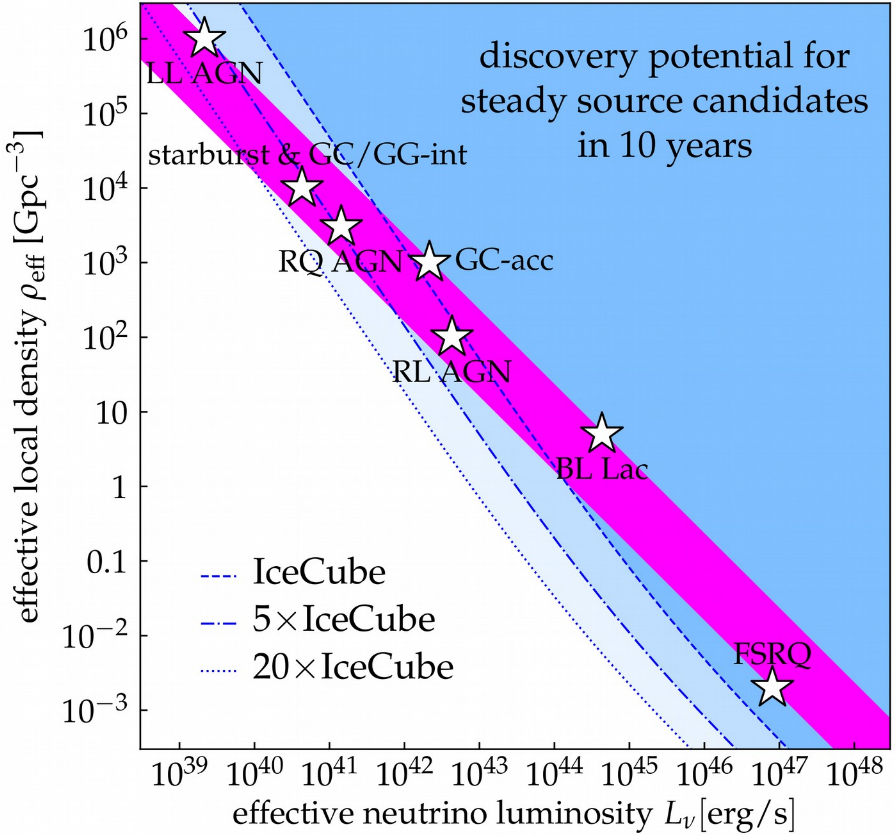
Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \text{TeV}}\right)^{-2.1\pm0.2}\ \text{TeV cm}^{-2}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

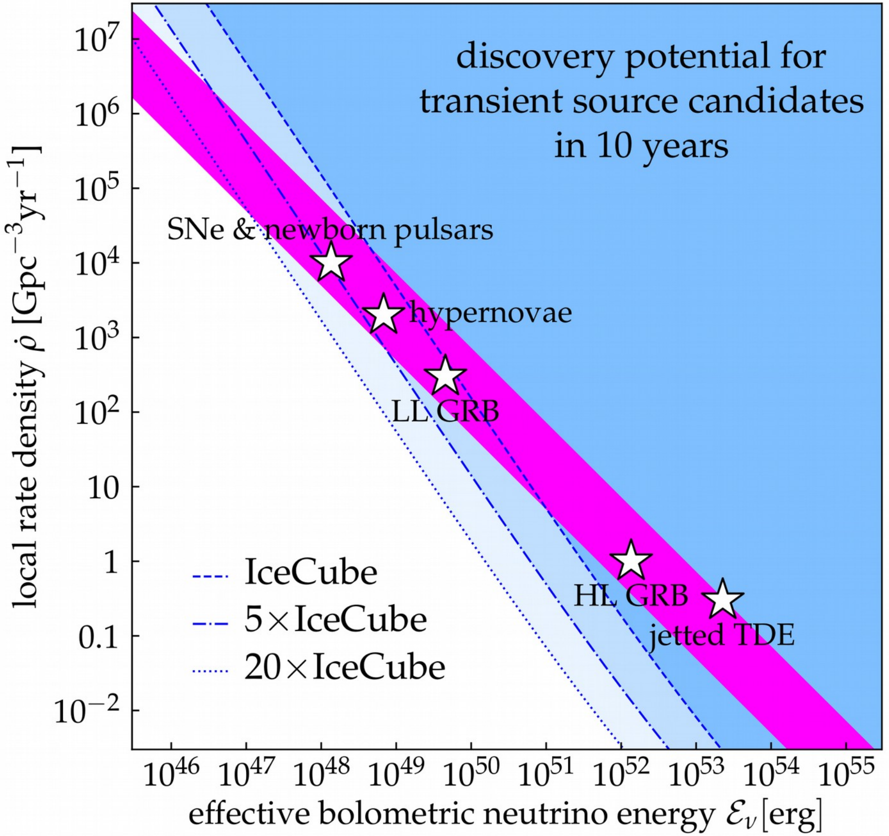
Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\Phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-12}$ TeV cm^{-2} s^{-1}



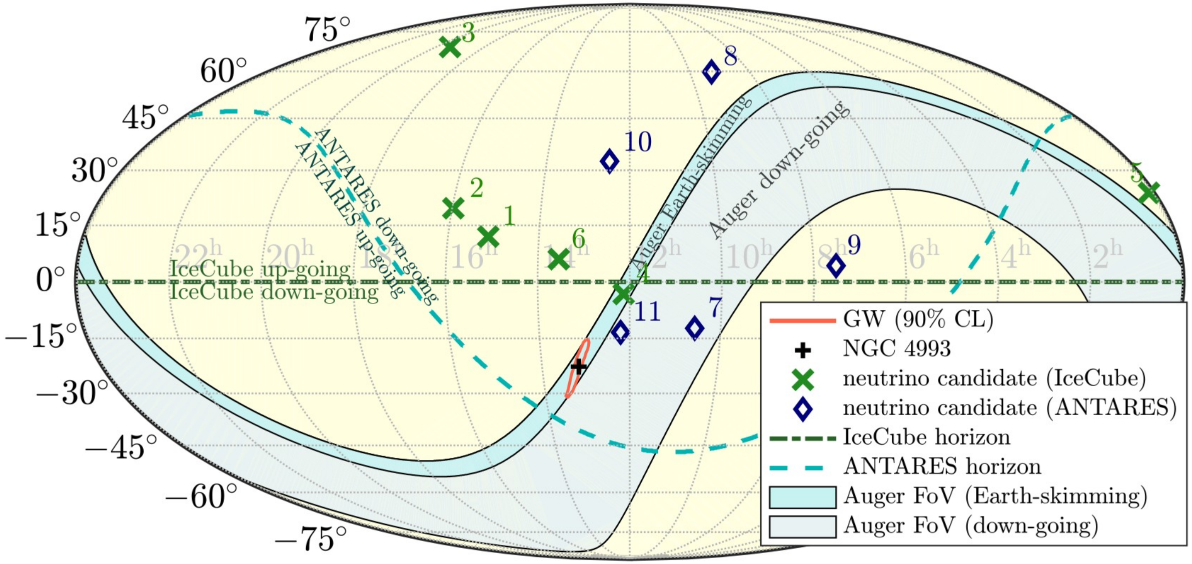
Closest source with $E^2F_{\nu_\mu+\bar{\nu}_\mu} = 0.1$ GeV cm^{-2}

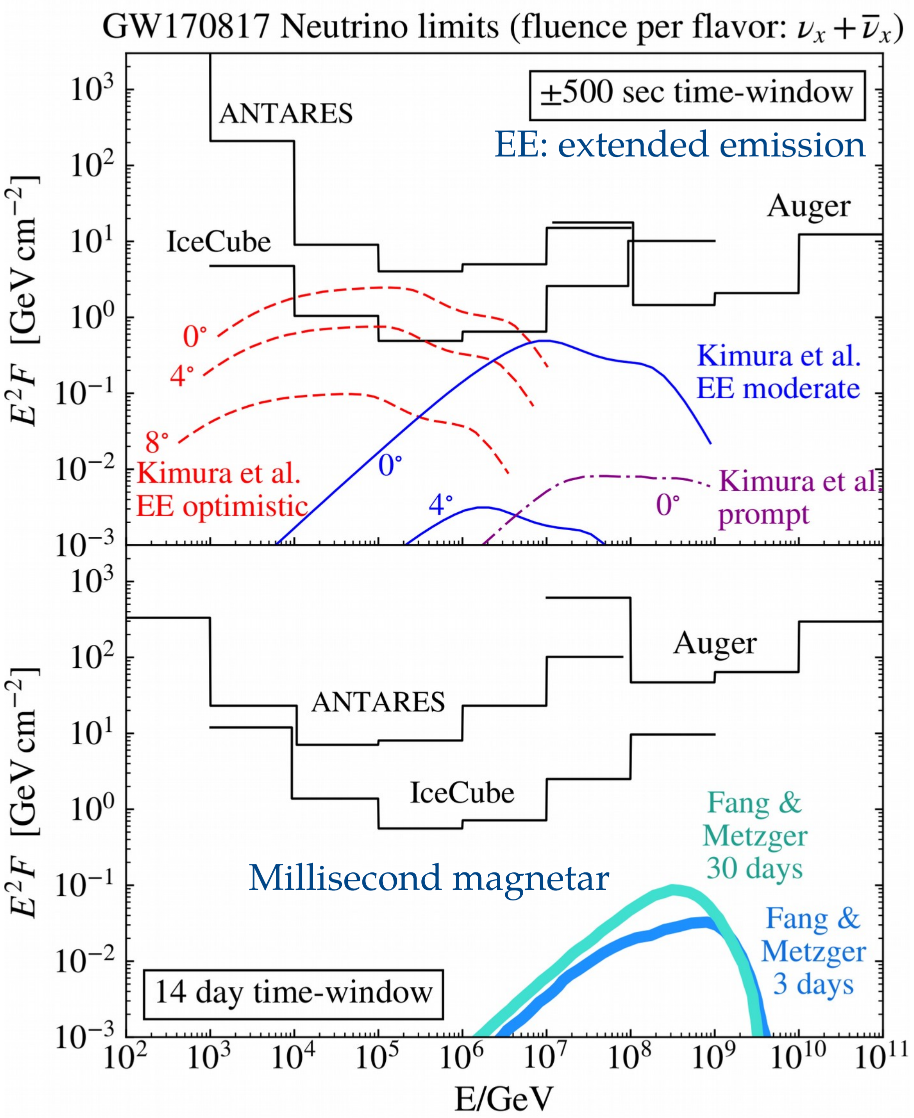


Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

The next frontier: UHE neutrinos

Quo vadis?

Recall the threshold condition for $p\gamma \to \pi\ (\to \nu)$:

$$E_p \cdot E_{\gamma_{\rm target}} = 0.2\ \mathrm{GeV}^2$$

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$E_\nu = E_p/20$

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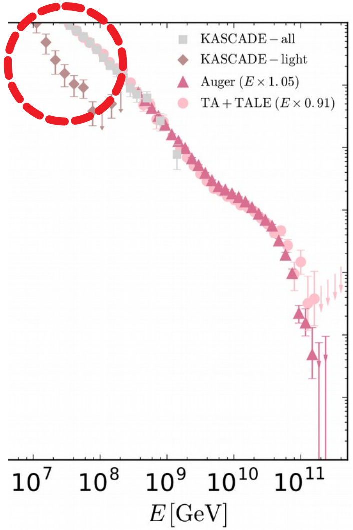

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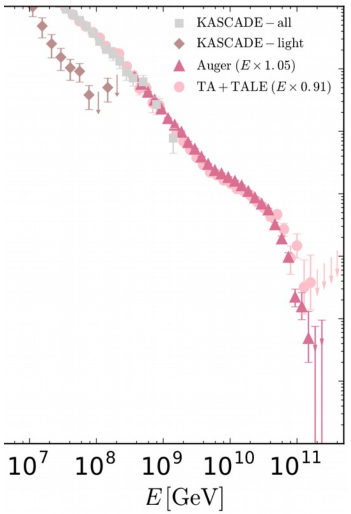

- Inside sources: Protons: $20 \cdot 10^6$ GeV; Photons: 10^{-8} GeV → Neutrinos: 10^6 GeV
- CR propagation: Protons: 10^{11} GeV; Photons: 10^{-12} GeV → Neutrinos: $\sim 10^{10}$ GeV

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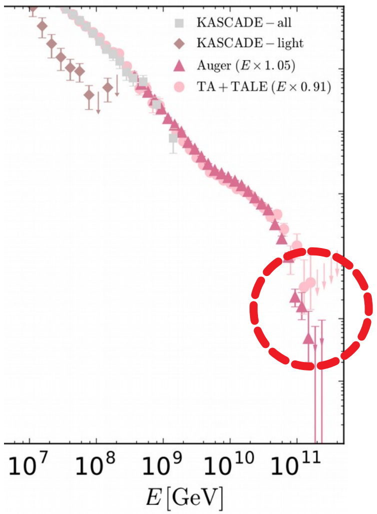

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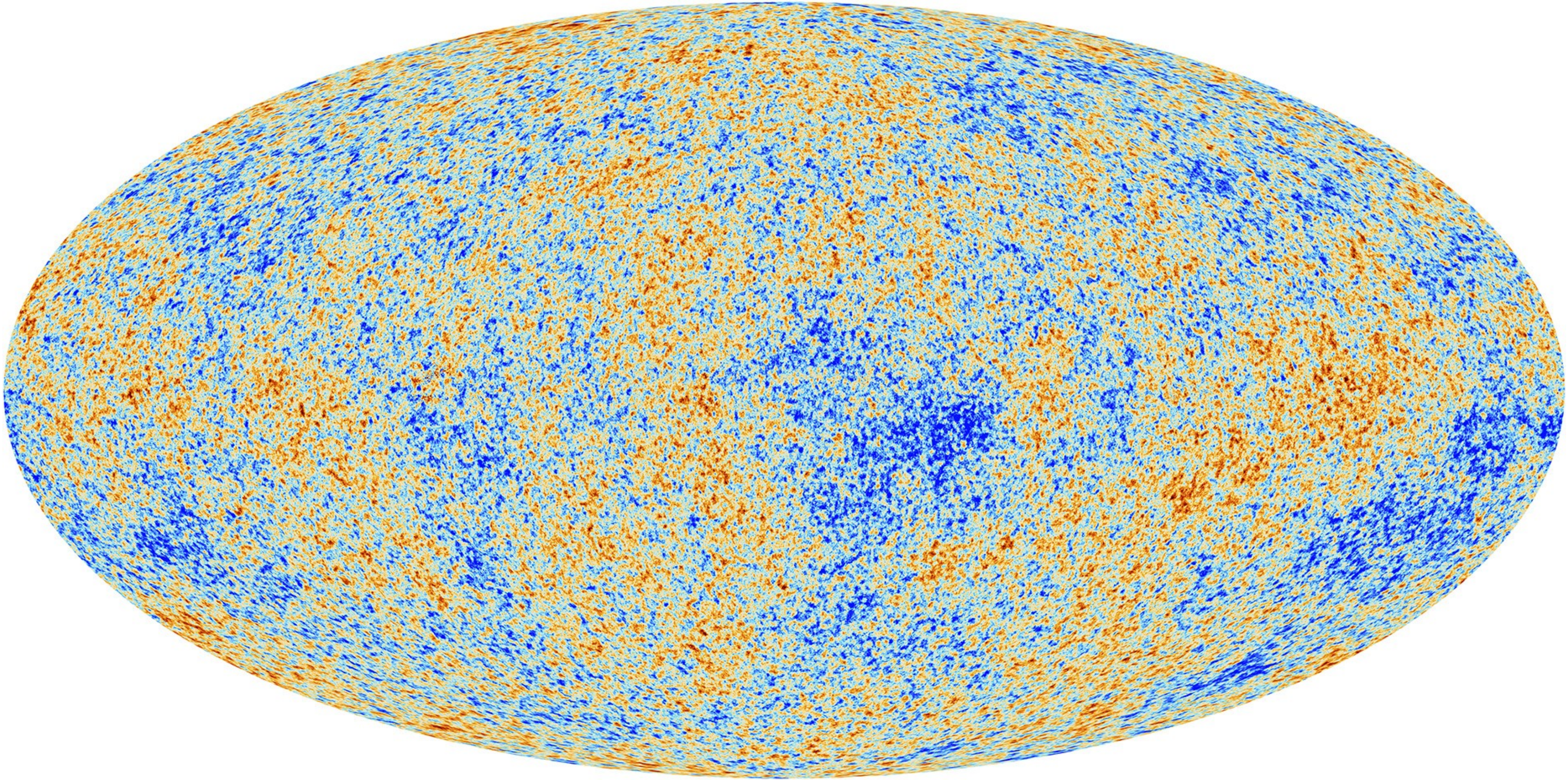

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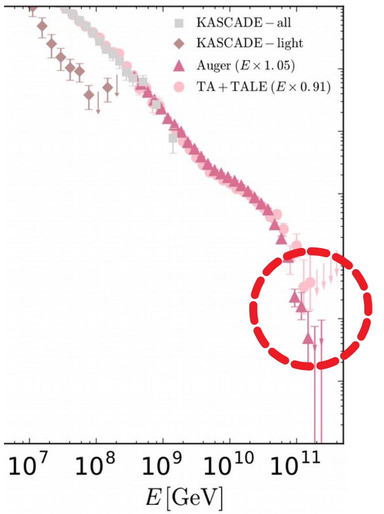

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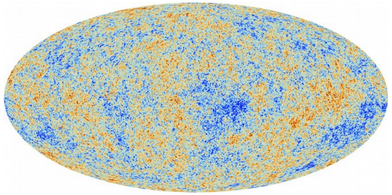
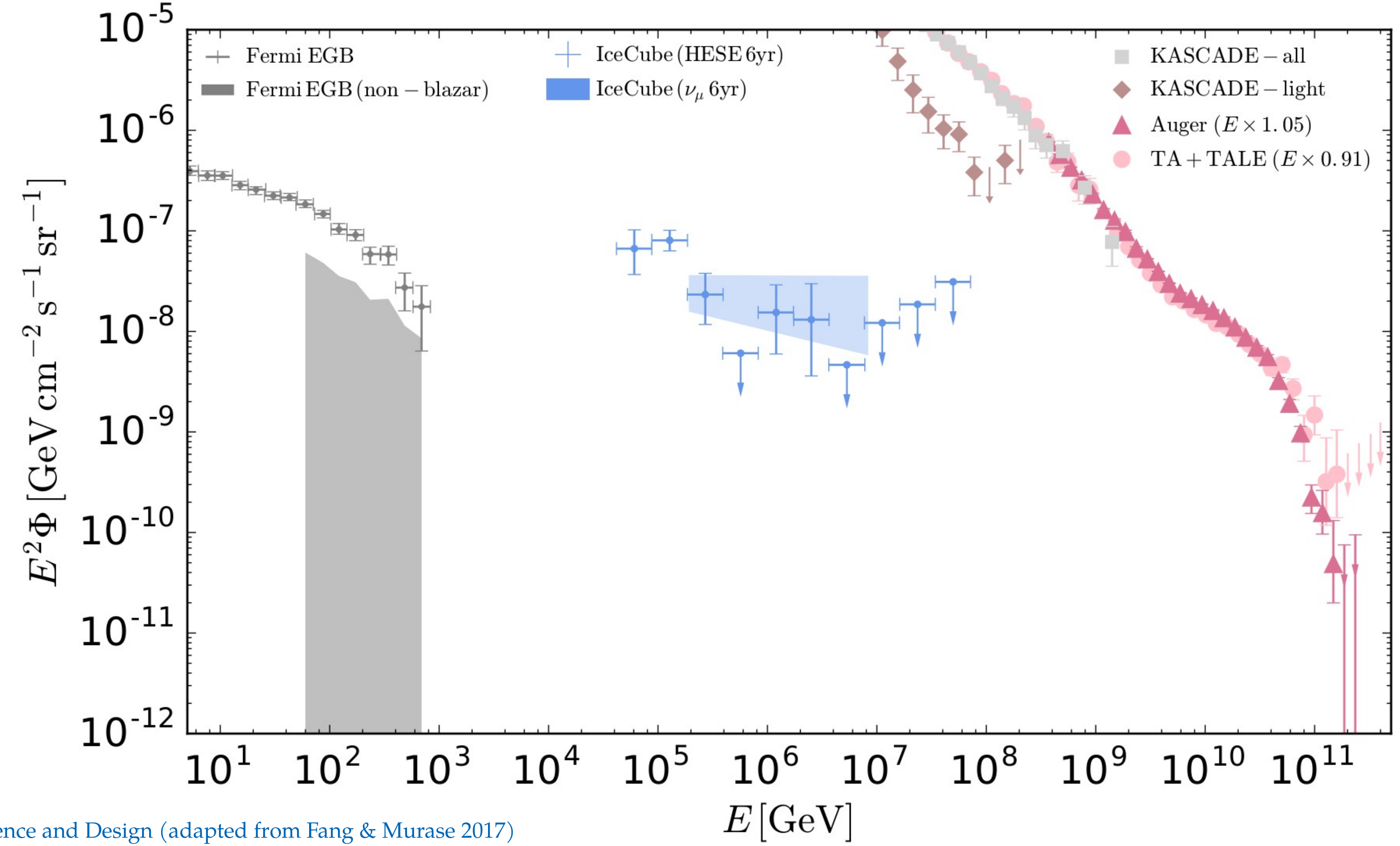
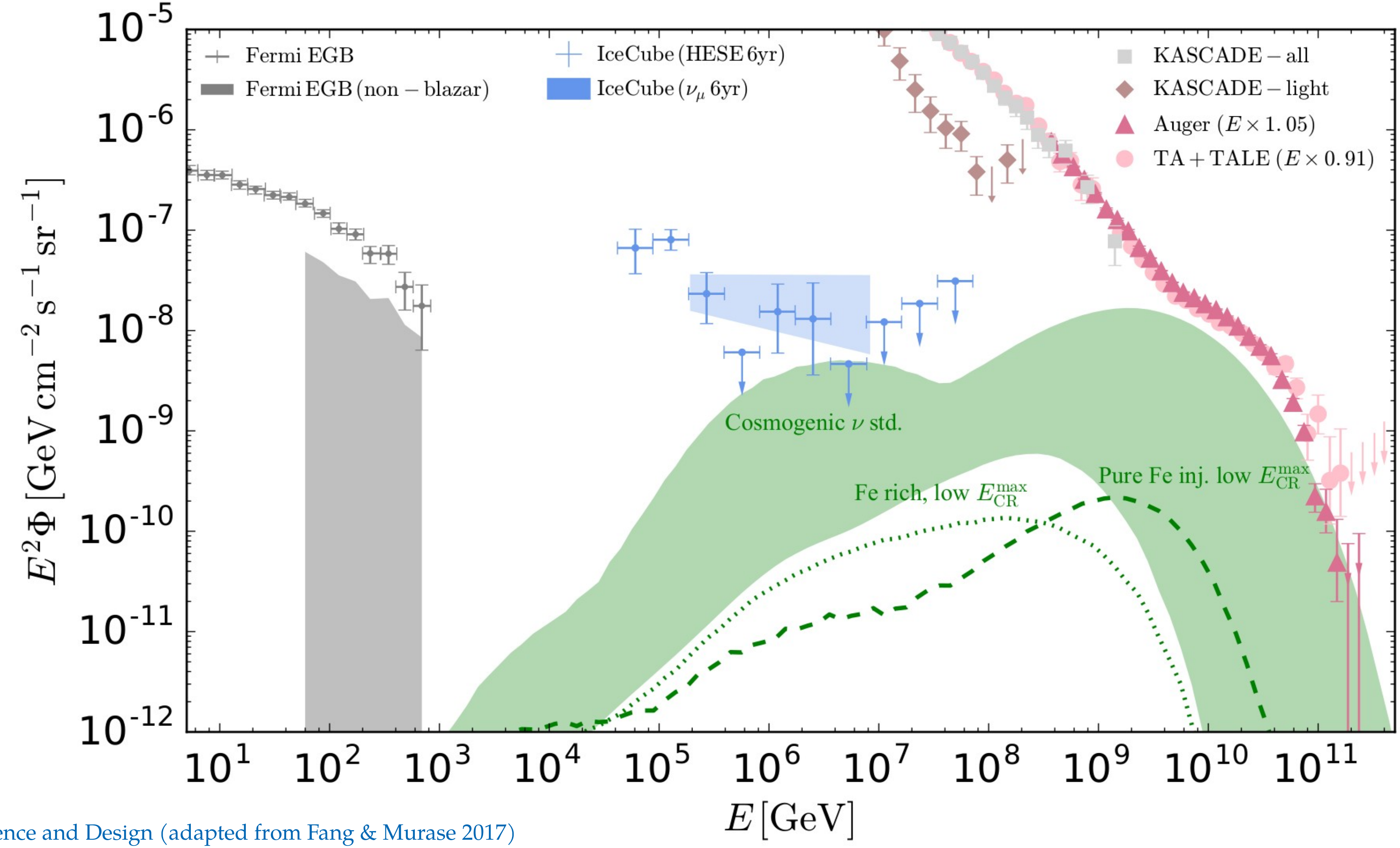




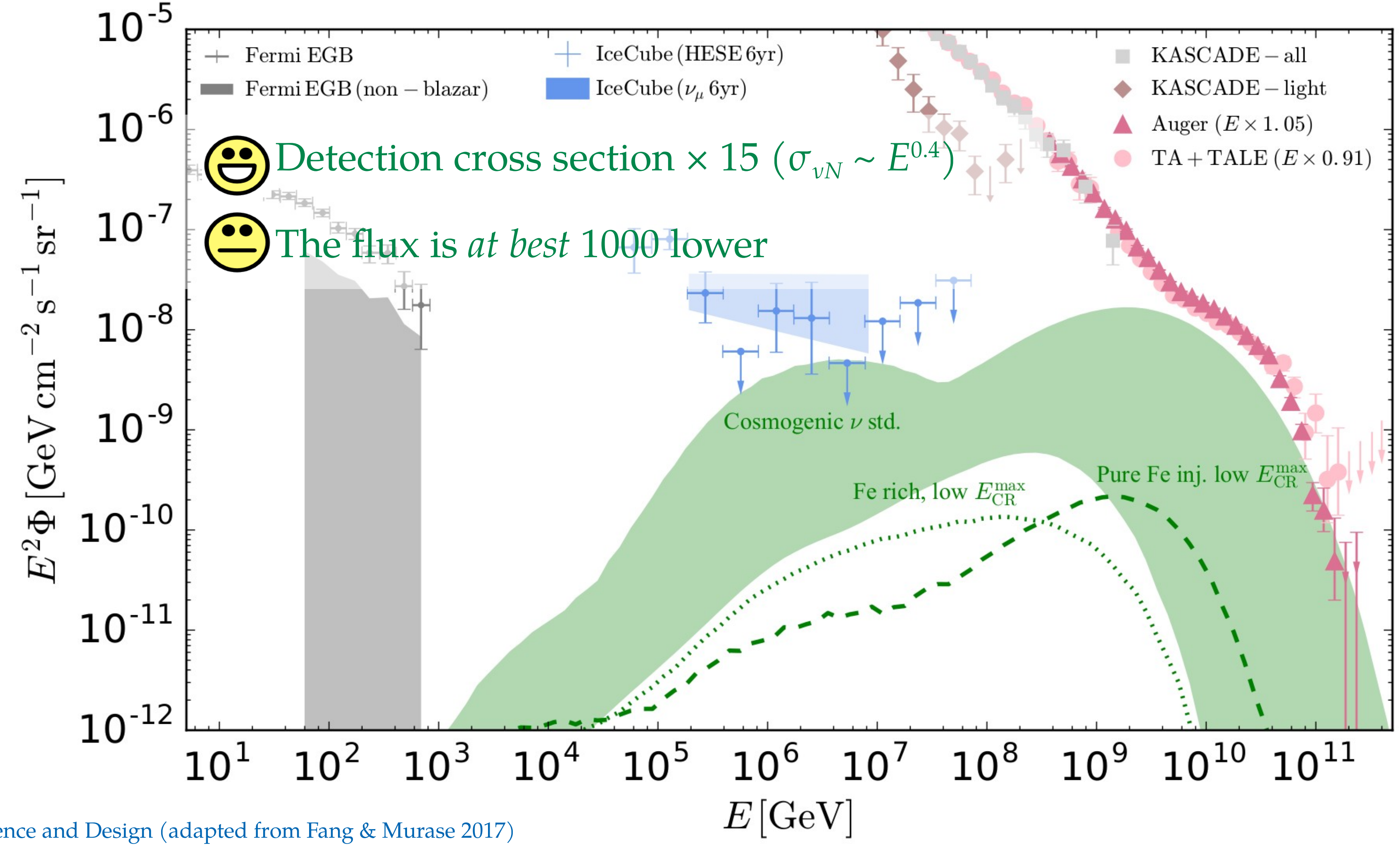
GRAND: Science and Design (adapted from Fang & Murase 2017)



GRAND: Science and Design (adapted from Fang & Murase 2017)

Detection cross section × 15 ($\sigma_{\nu N} \sim E^{0.4}$)

The flux is *at best* 1000 lower



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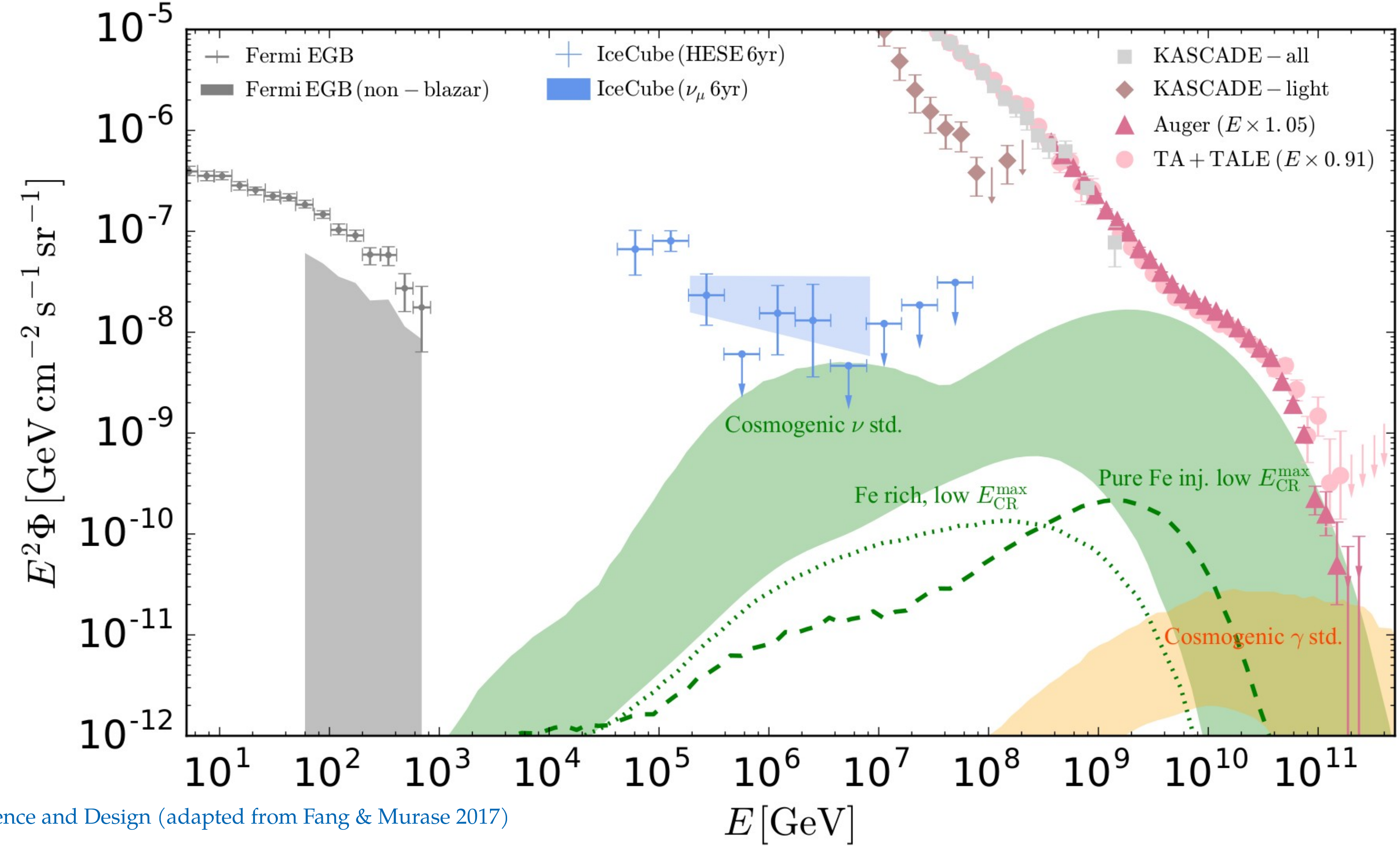

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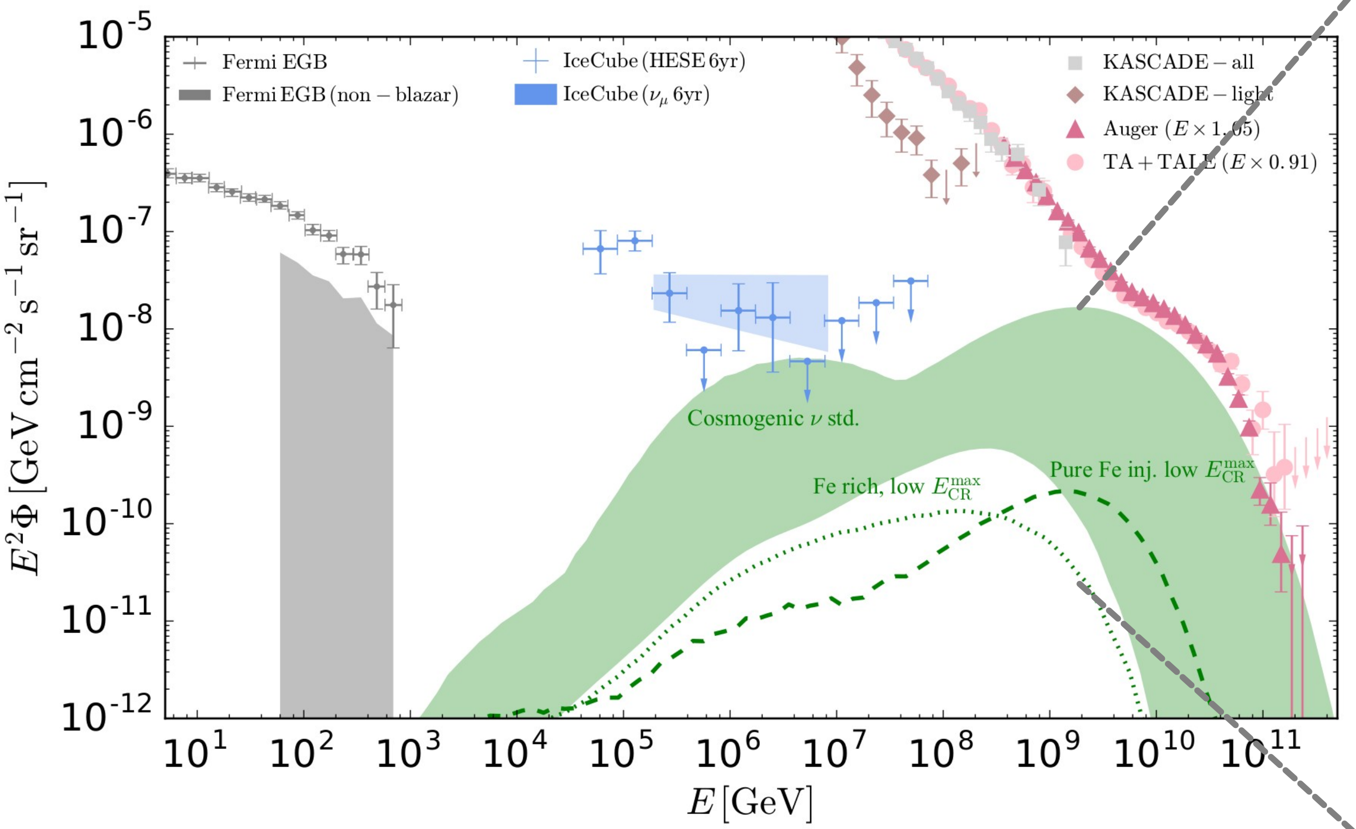
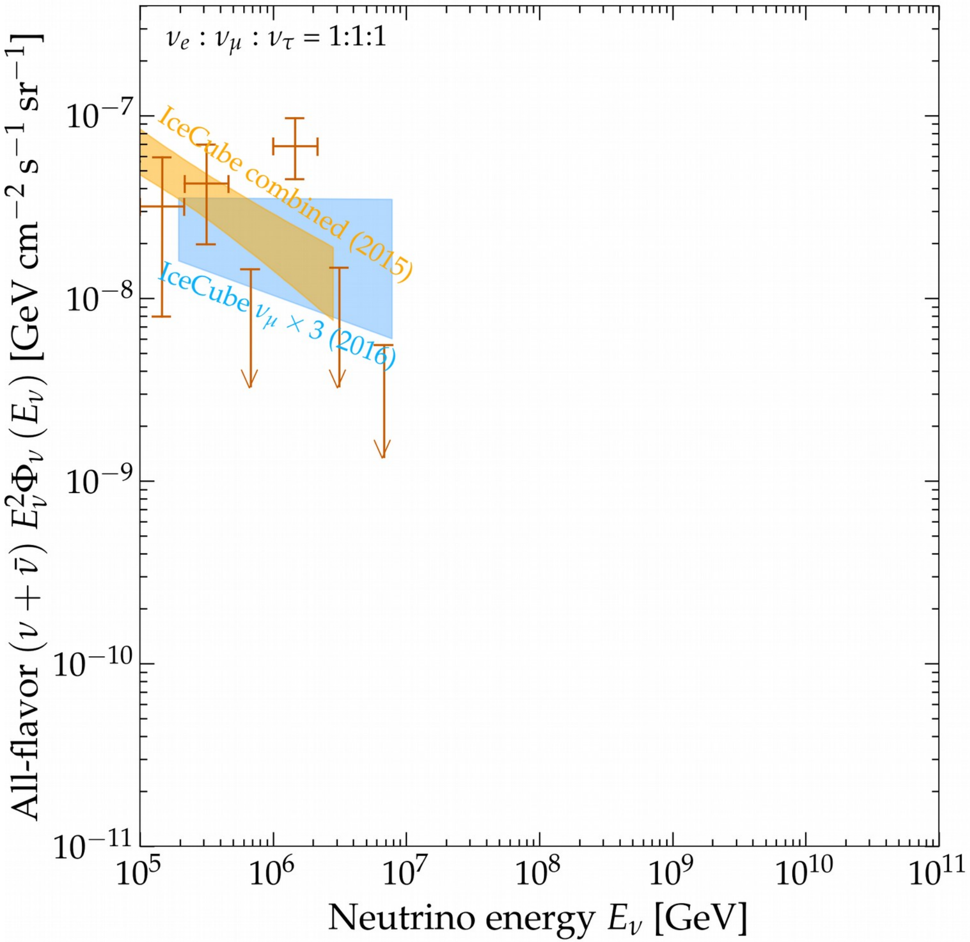
UHE ν flux – how low?

Higher cosmogenic ν flux



Lower cosmogenic ν flux

UHE neutrinos – where do we stand?



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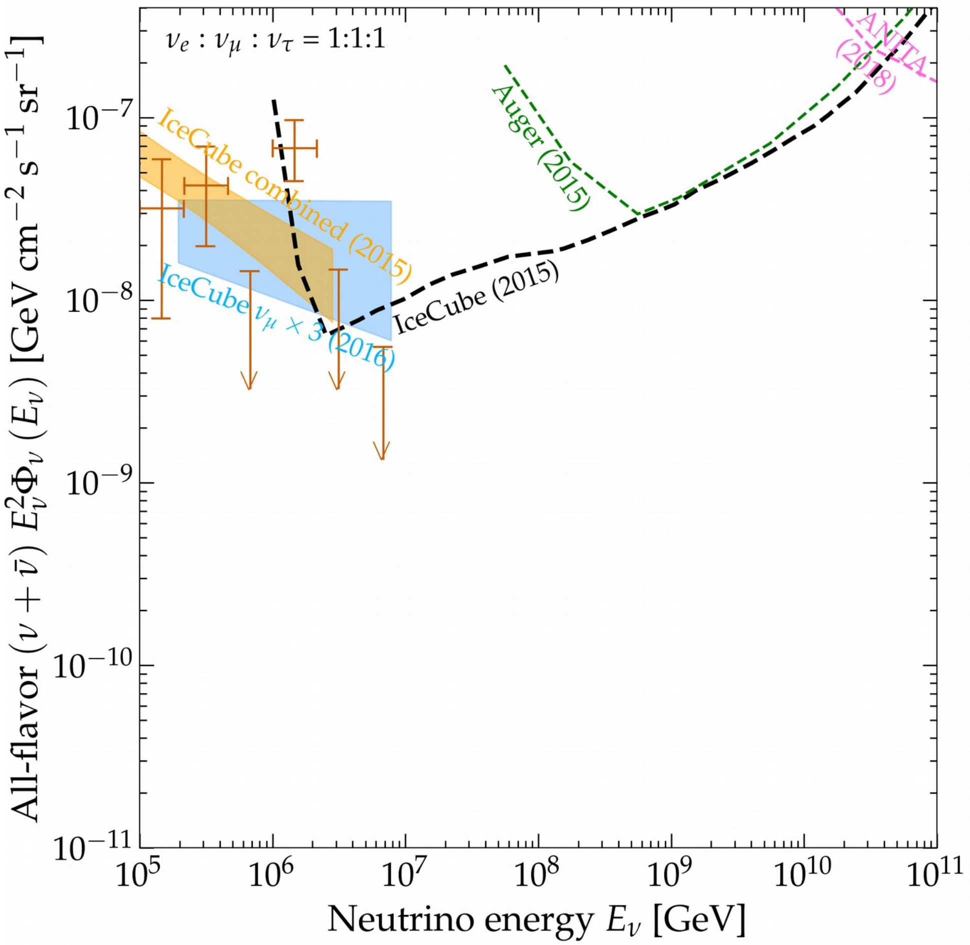
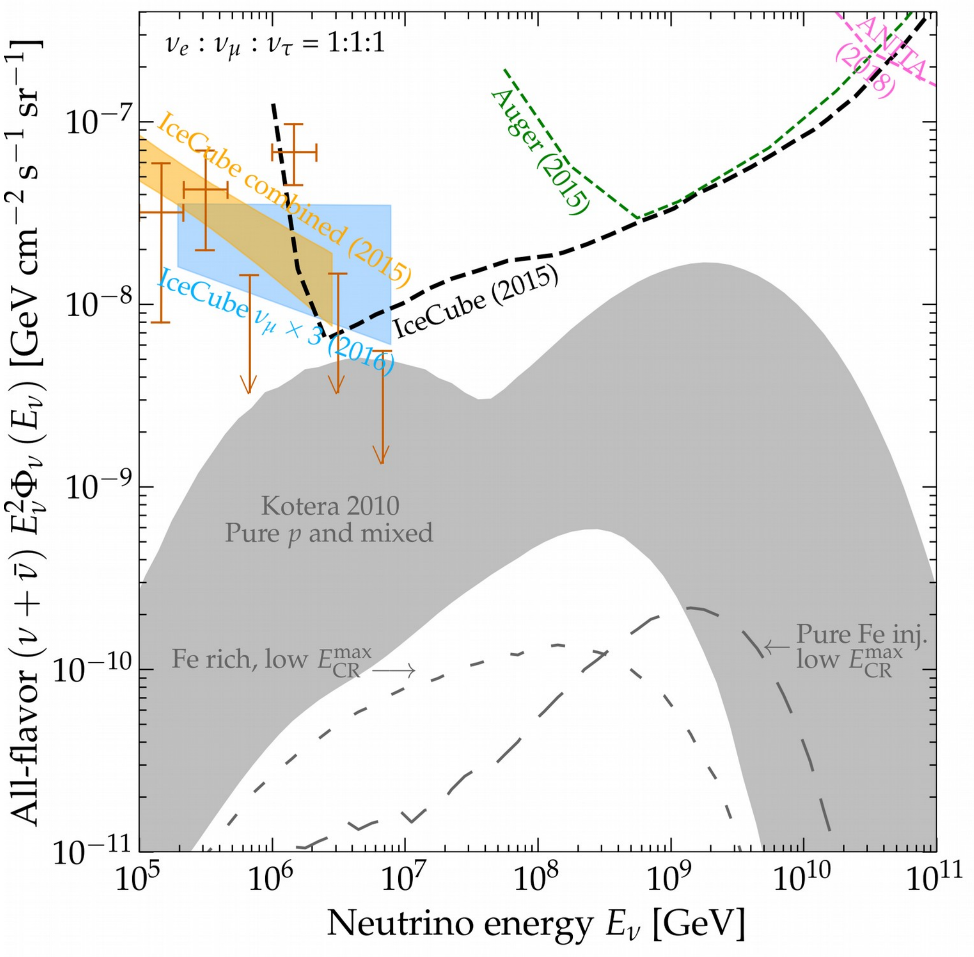


Existing upper limits

UHE neutrinos – where do we stand?

Flux predictions (Kotera 2010)



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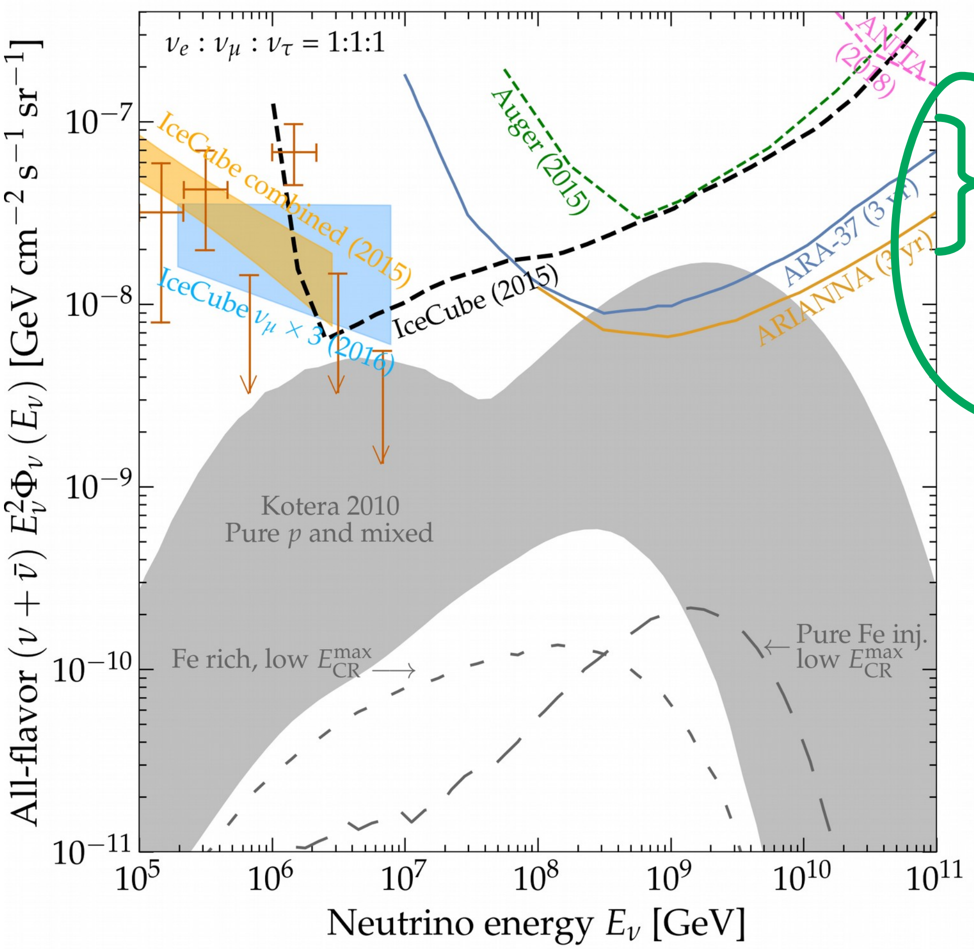


Flux predictions (Kotera 2010)

Existing upper limits

Future reach of existing in-ice radio detectors

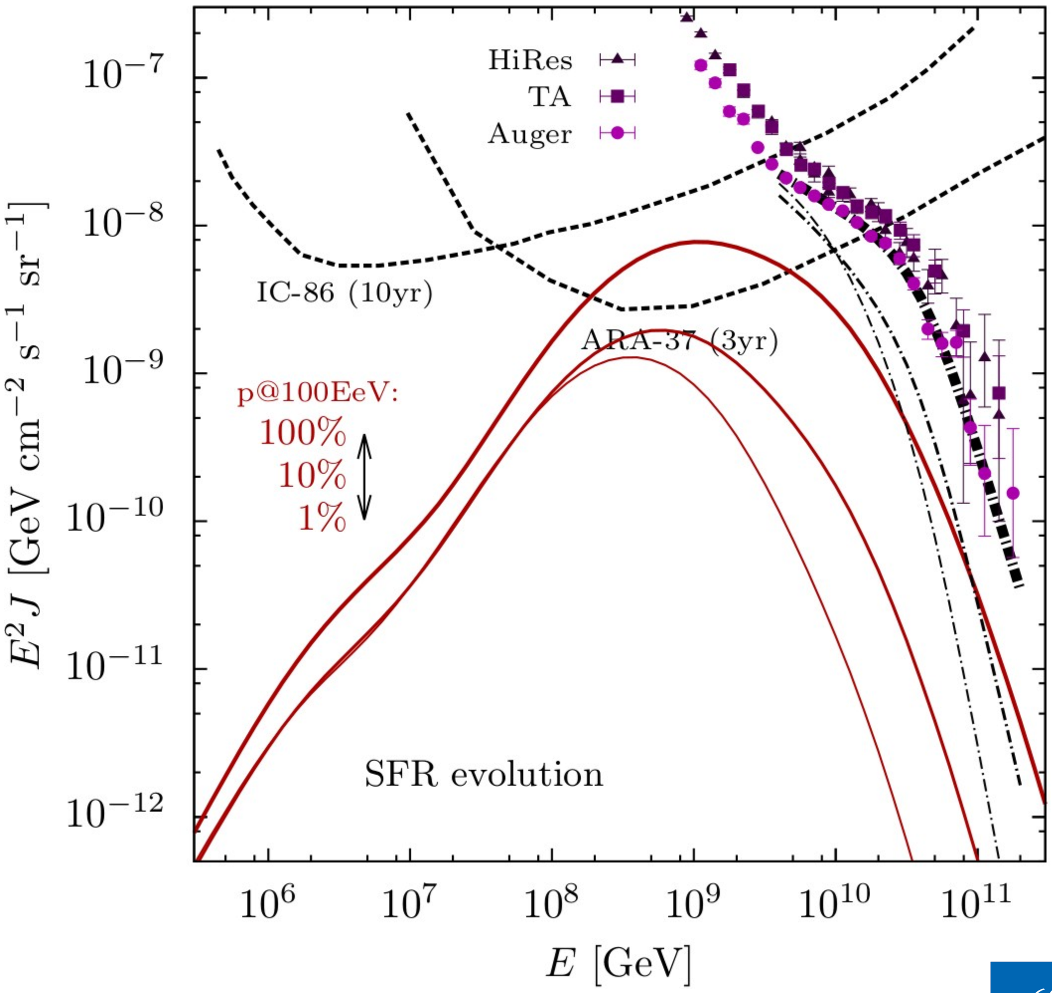
The proton fraction is the driver

Ahlers & Halzen, *PRD* 2012

- Cosmogenic ν production is mainly due to UHECR protons
- Consider a mixed mass composition
- Proton fraction:

$$f_p = 1 - \left(1 + \left(\frac{E}{10^{19}\ \mathrm{eV}}\right)^{-\alpha}\right)^{-1}$$

- Nuclei fraction: $f_A = 1 - f_p$



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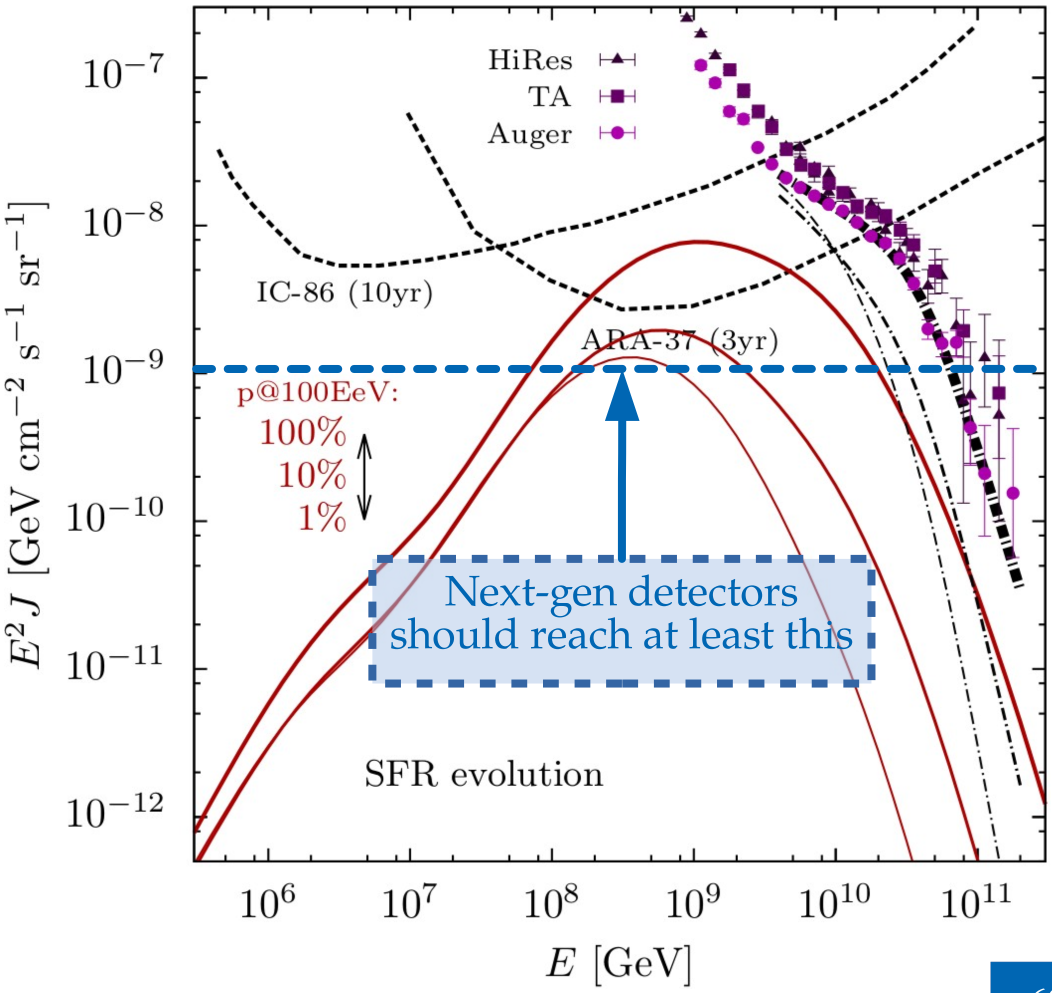


Updated cosmogenic ν fluxes

- Predictions from fits to 2017 Auger UHECR spectrum & composition

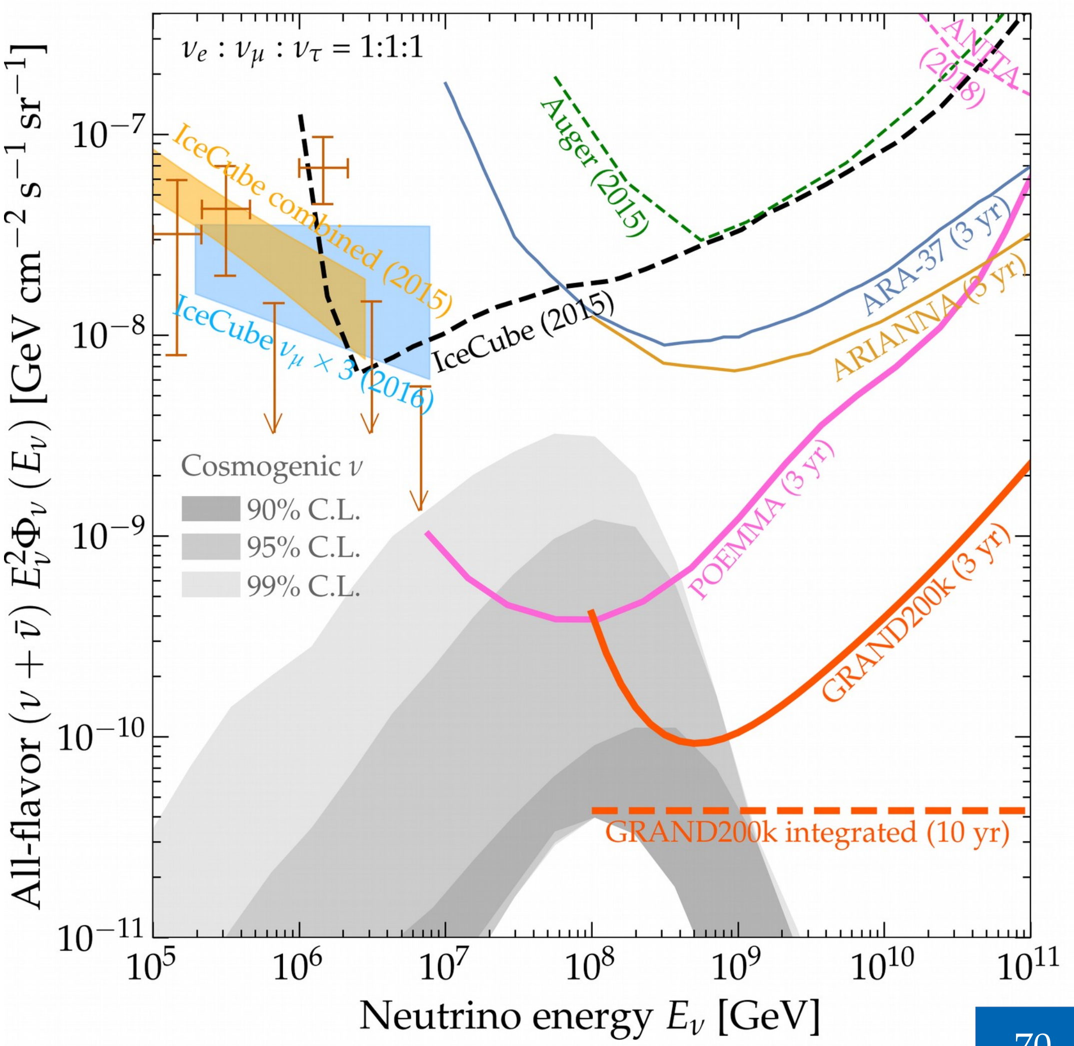
  [Pierre Auger Collab., *JCAP* 2017]

- Simultaneously vary (CRPropa):
  - Spectral index γ (*i.e.*, $E^{-\gamma}$)
  - Source evolution m (*i.e.*, $(1+z)^m$)
  - Maximum rigidity $R_{\rm cut}$ (*i.e.*, $e^{-R/R_{\rm cut}}$)

- Best-fit values:
  $\gamma = 1$, $m = -1.5$, $\log_{10}(R_{\rm cut}/{\rm V}) = 18.69$

- The ν fluxes are ~10 × lower, mainly due to low $R_{\rm cut}$ and negative m

Plot from GRAND Collab., *Sci. China Phys. Mech. Astron.* 2020



Alves Batista *et al.*, *JCAP* 2019
See also: Heinze *et al.*, *ApJ* 2019

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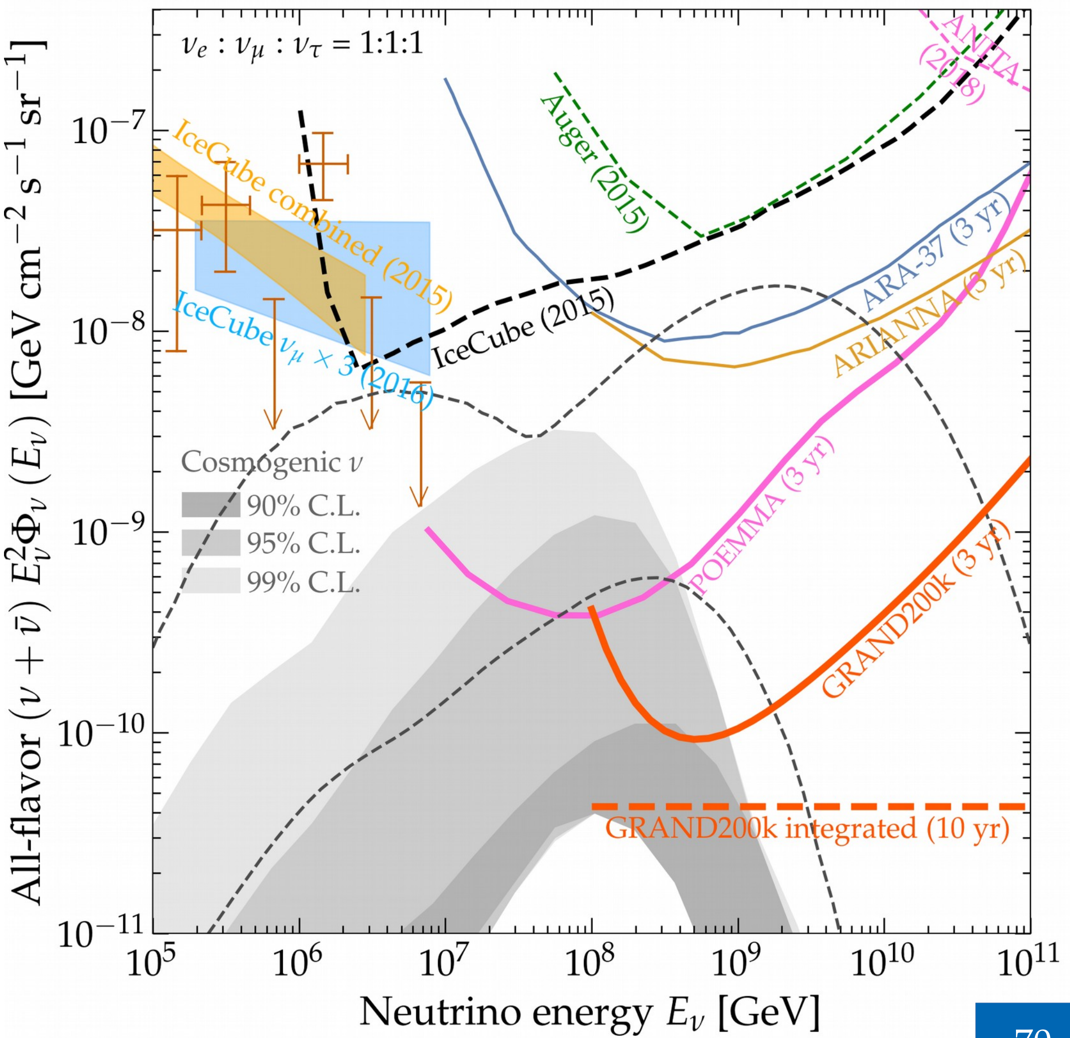

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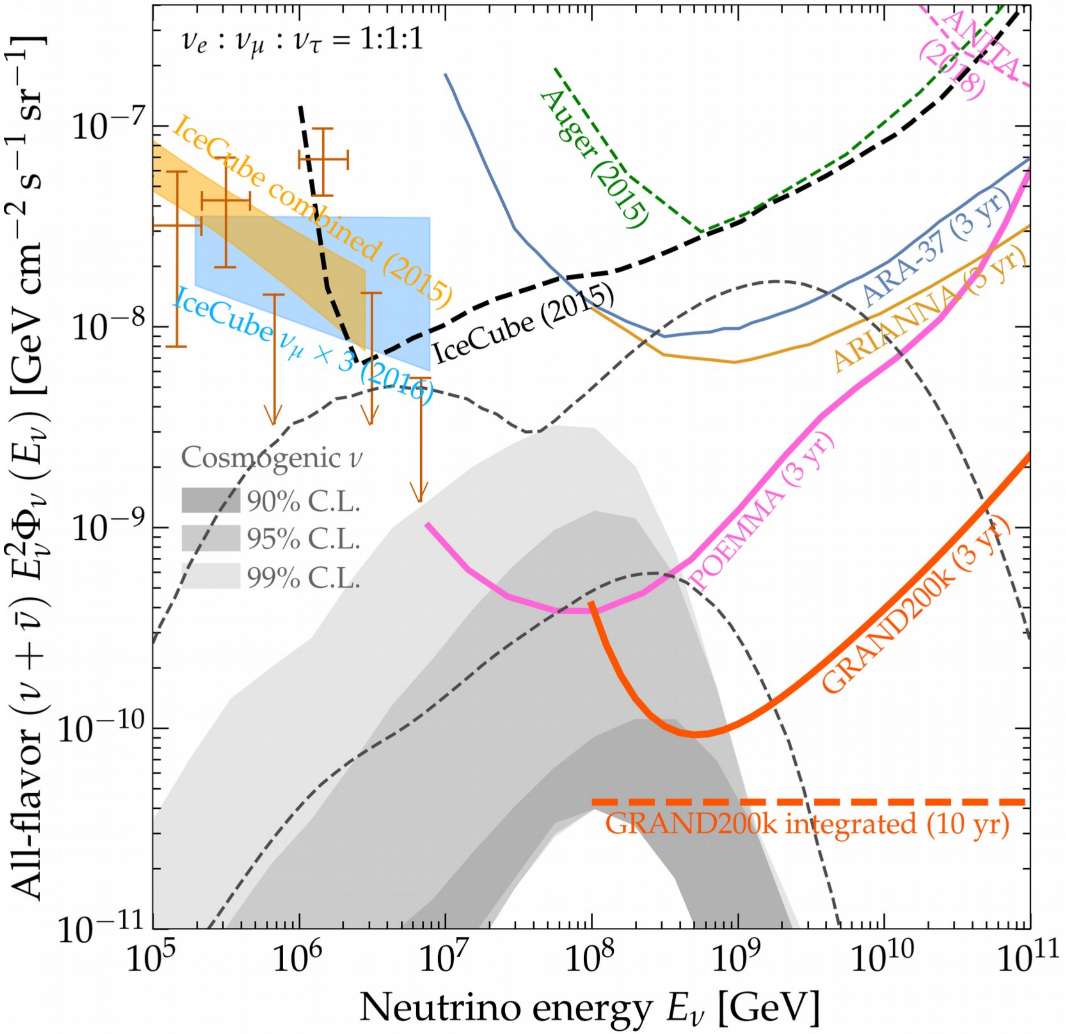
How to detect UHE neutrinos

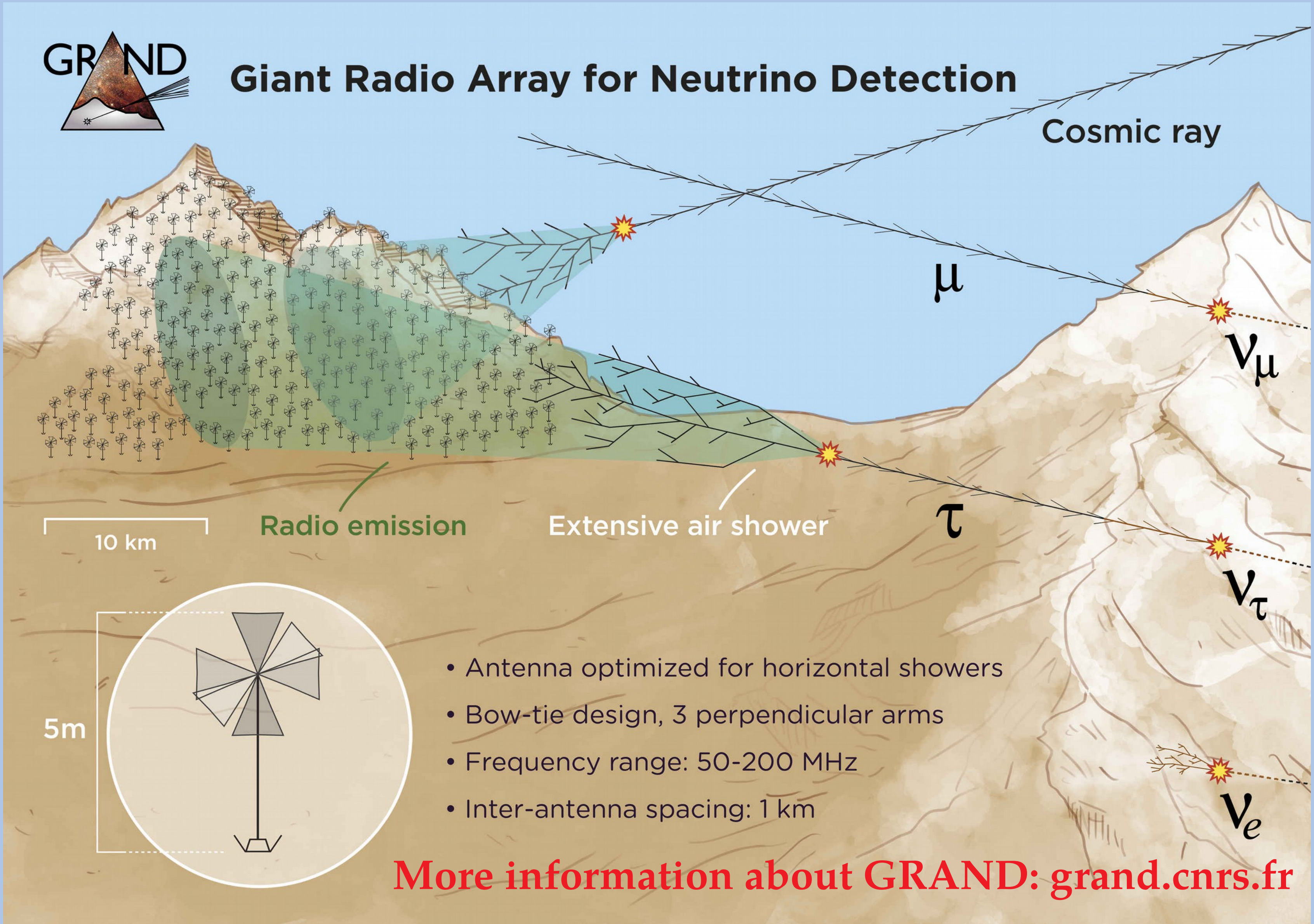
Today

- In-ice Cherenkov: IceCube
- Horizontal showers: Auger
- In-ice radio: ARA, ARIANNA
- Ice & air radio: ANITA
- Fluorescence: MAGIC, Ashra

Next decade

- In-ice Cherenkov: IceCube-Gen2
- In-water Cherenkov: KM3NeT, Baikal-GVD
- Horizontal showers: AugerPrime
- Fluorescence: POEMMA?, Trinity?
- In-ice radio: RNO?
- Atmospheric radio: TAROGE?, BEACON?, GRAND?




GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
More information about GRAND: grand.cnrs.fr

What are you taking home?

- Cosmic TeV–PeV neutrinos are firmly detected:
  Powerful probes of the non-thermal Universe and high-energy particle physics

- We have detected *one* source — but it is challenging to explain it

- Still unknown, but getting there:
  - Where do most neutrinos come from?
  - What are, precisely, their spectrum, arrival directions, flavor composition?

- Exciting prospects: larger statistics, better reconstruction, higher energies

More?
- *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

Backup slides

Particle physics with high-energy cosmic ν

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} \, (E/\mathrm{PeV})^{-n} \, (L/\mathrm{Gpc})^{-1} \, \mathrm{PeV}^{1-n}$

- Improvement over current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
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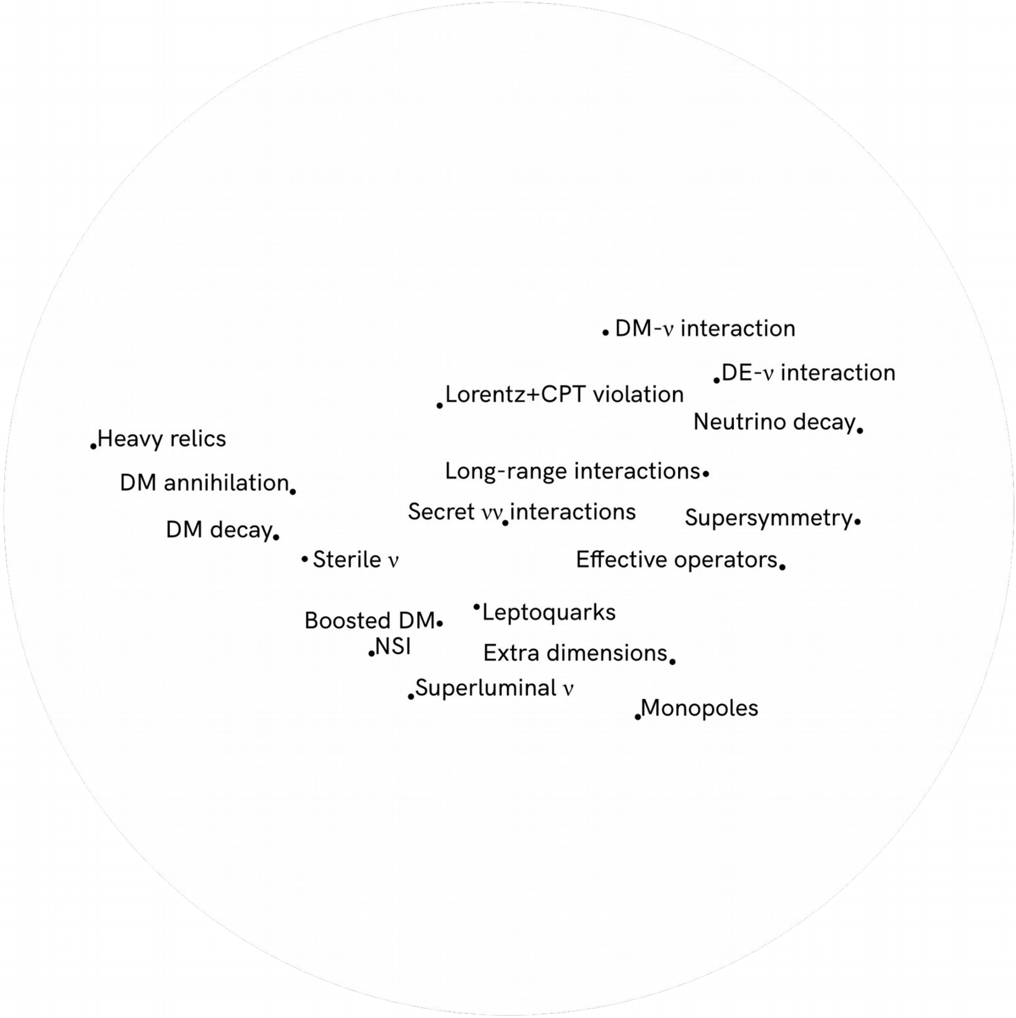
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns



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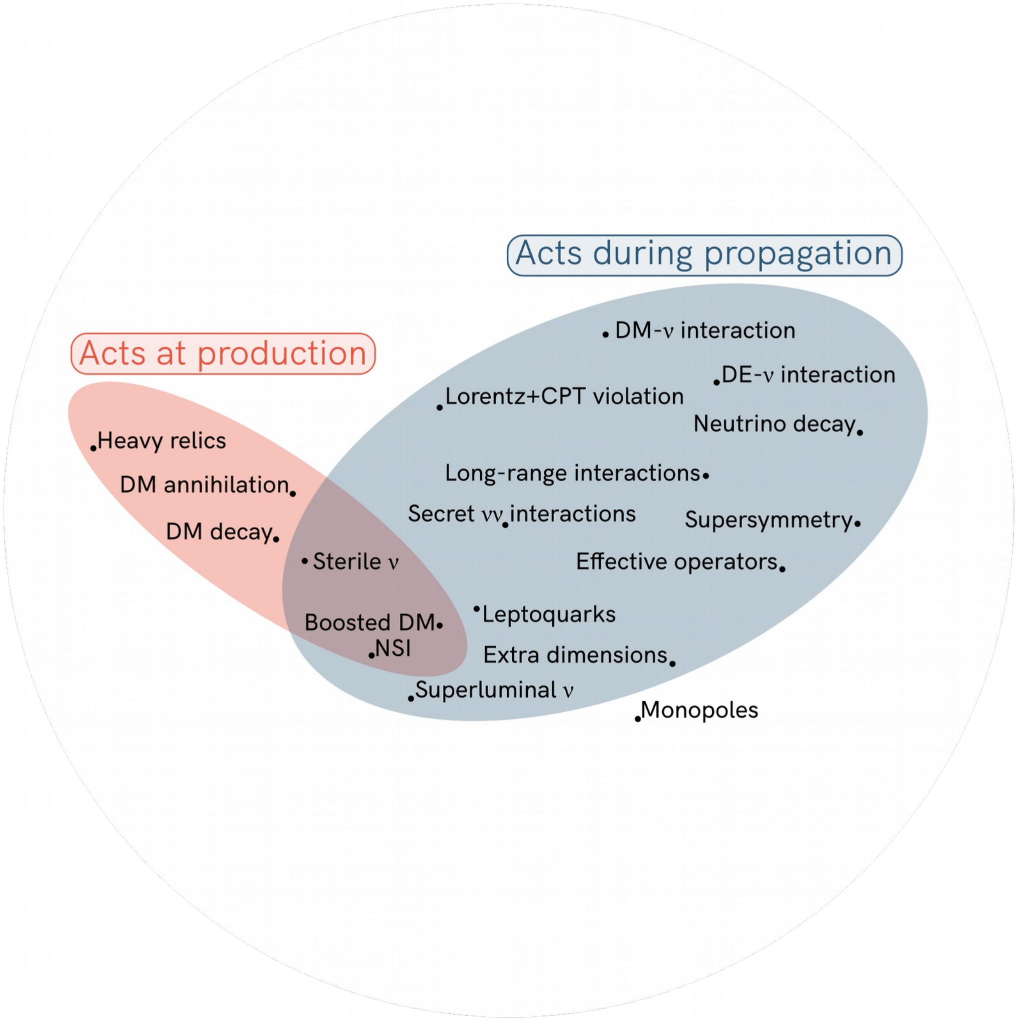

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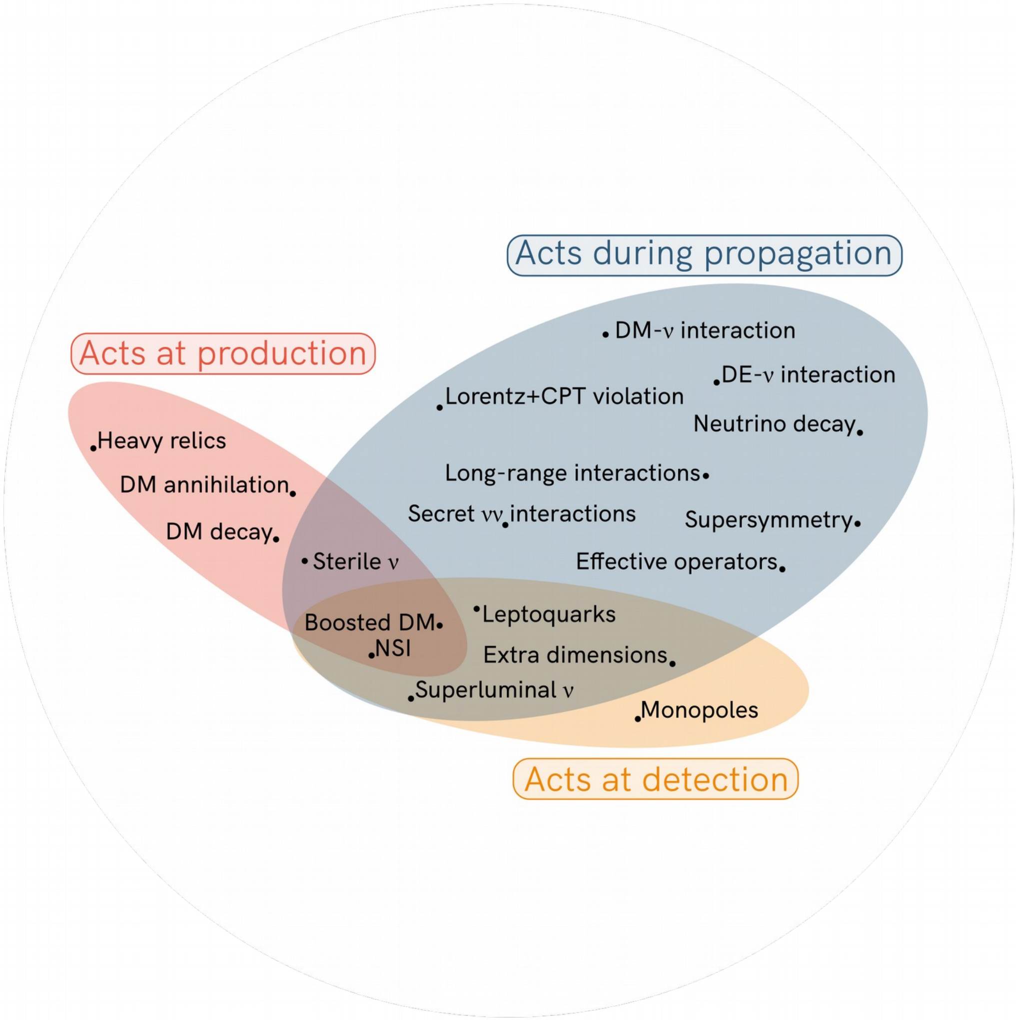

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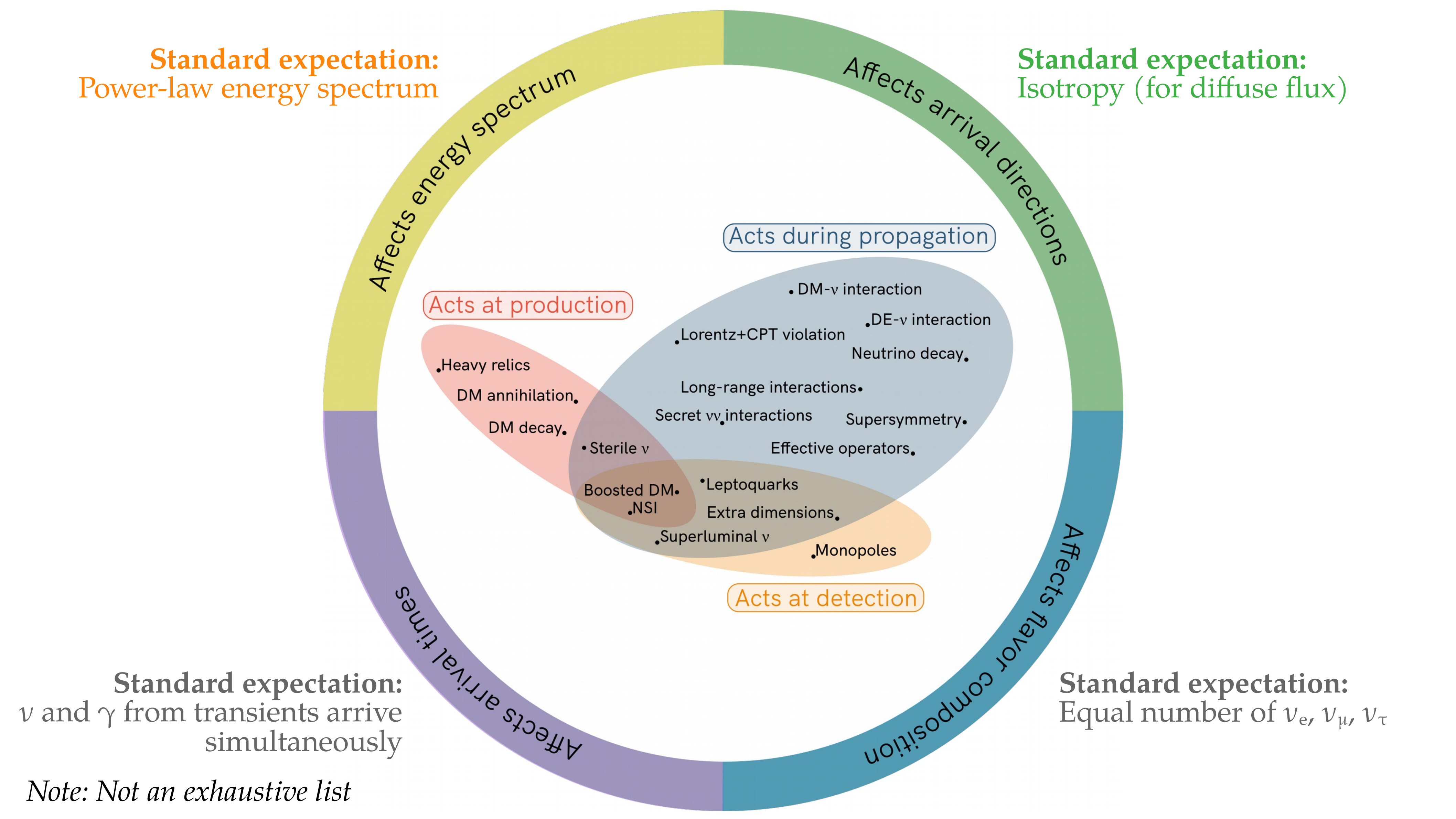

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
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Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
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Equal number of ν_e, ν_μ, ν_τ
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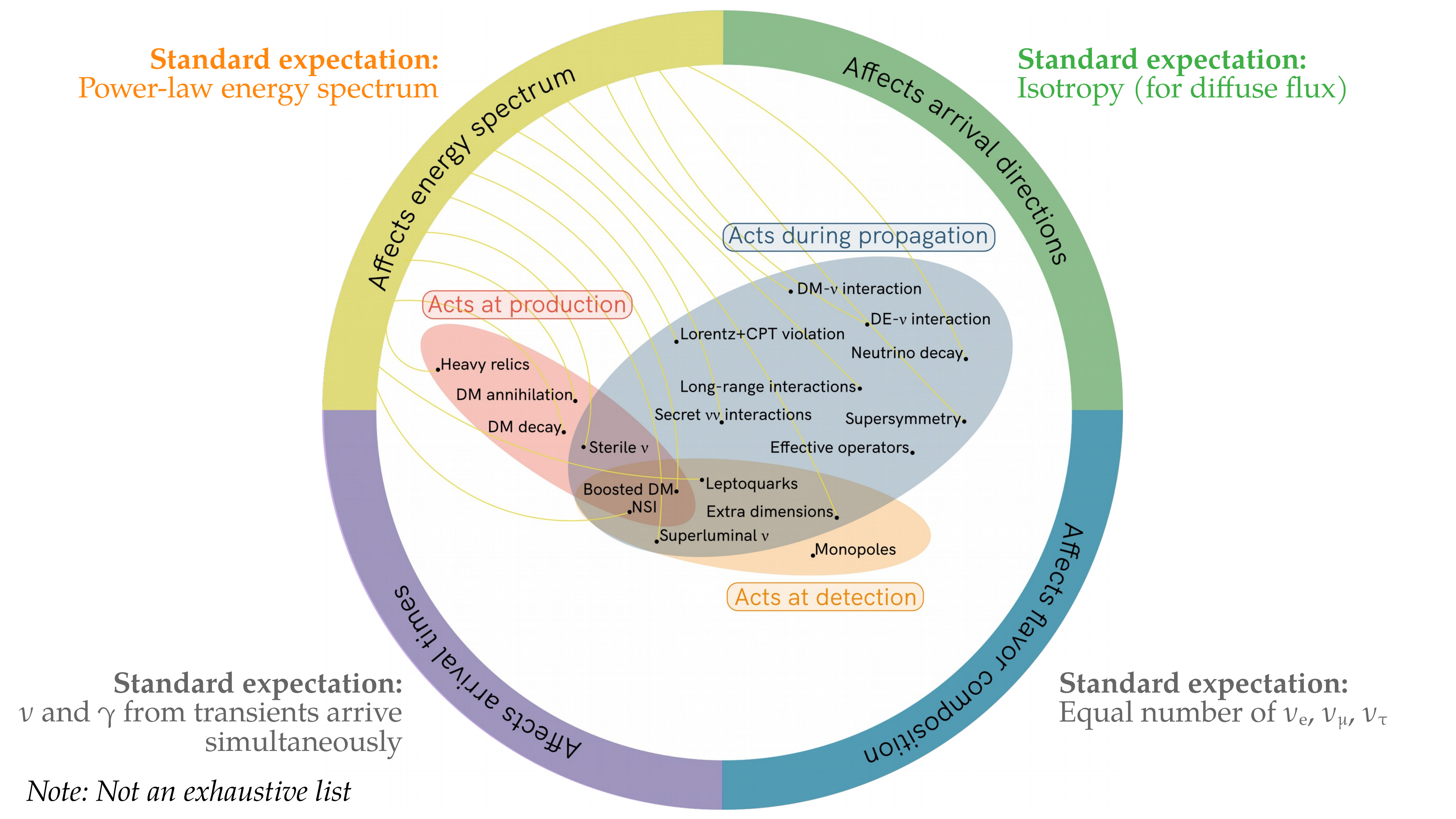

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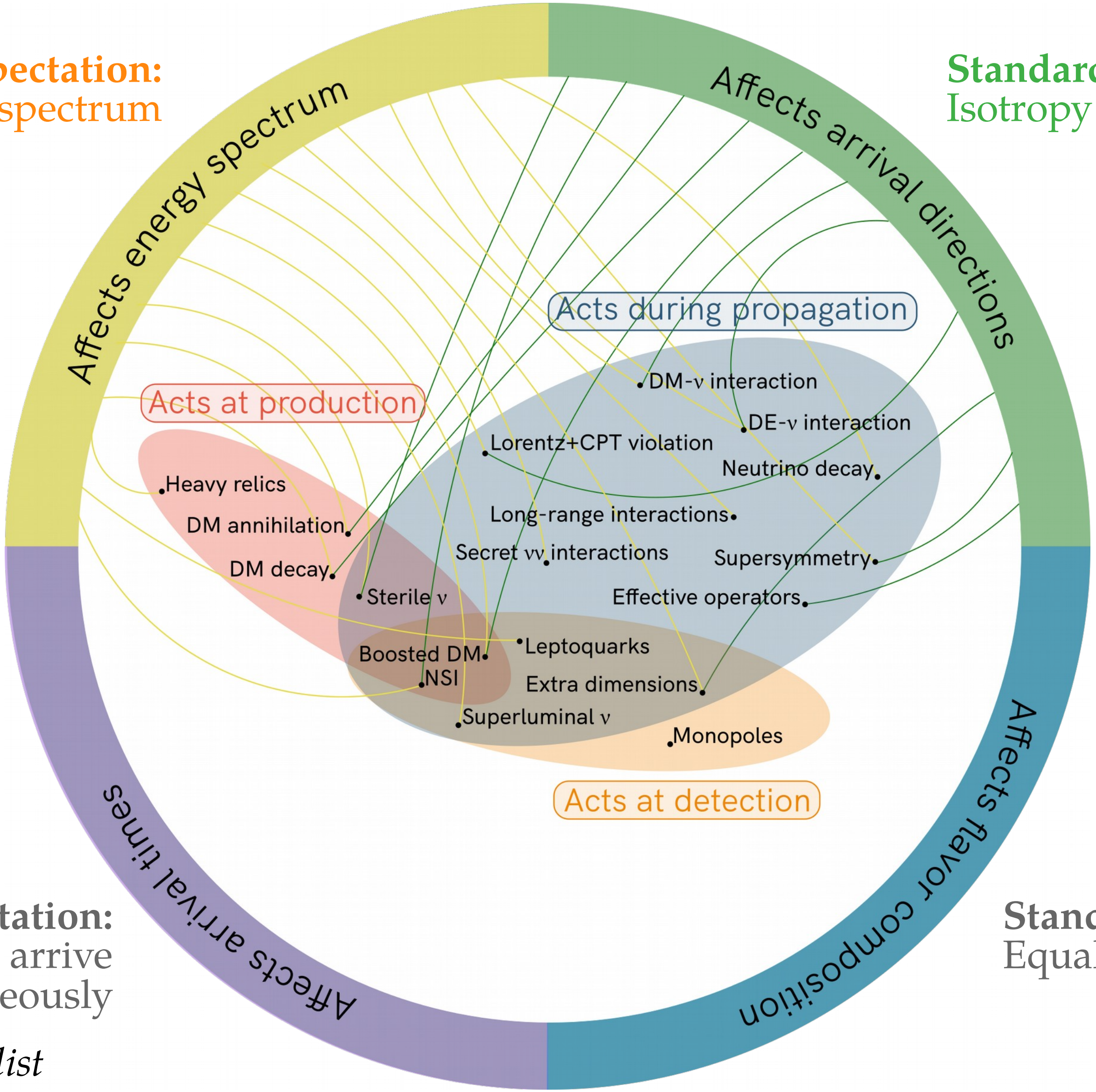

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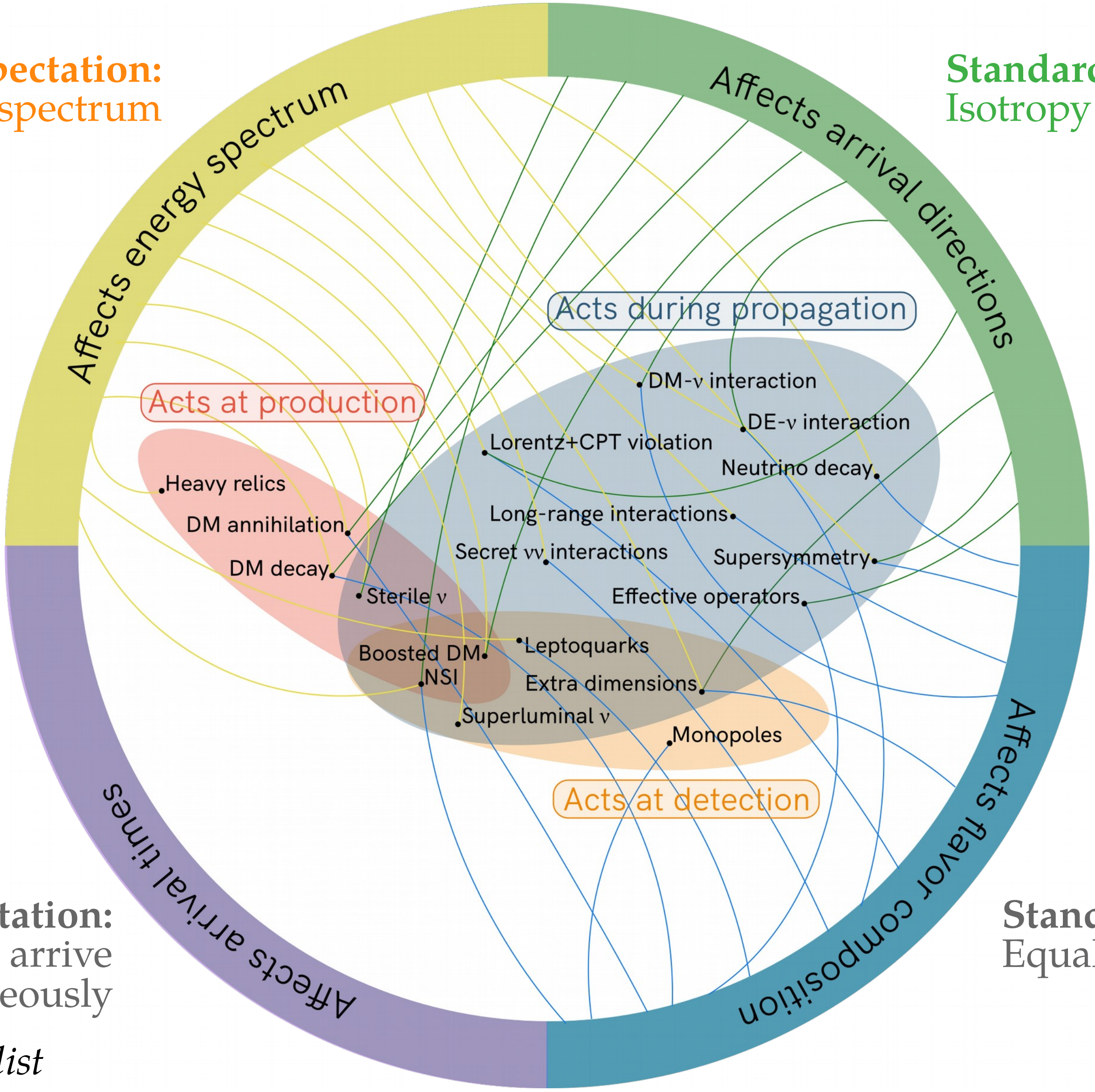

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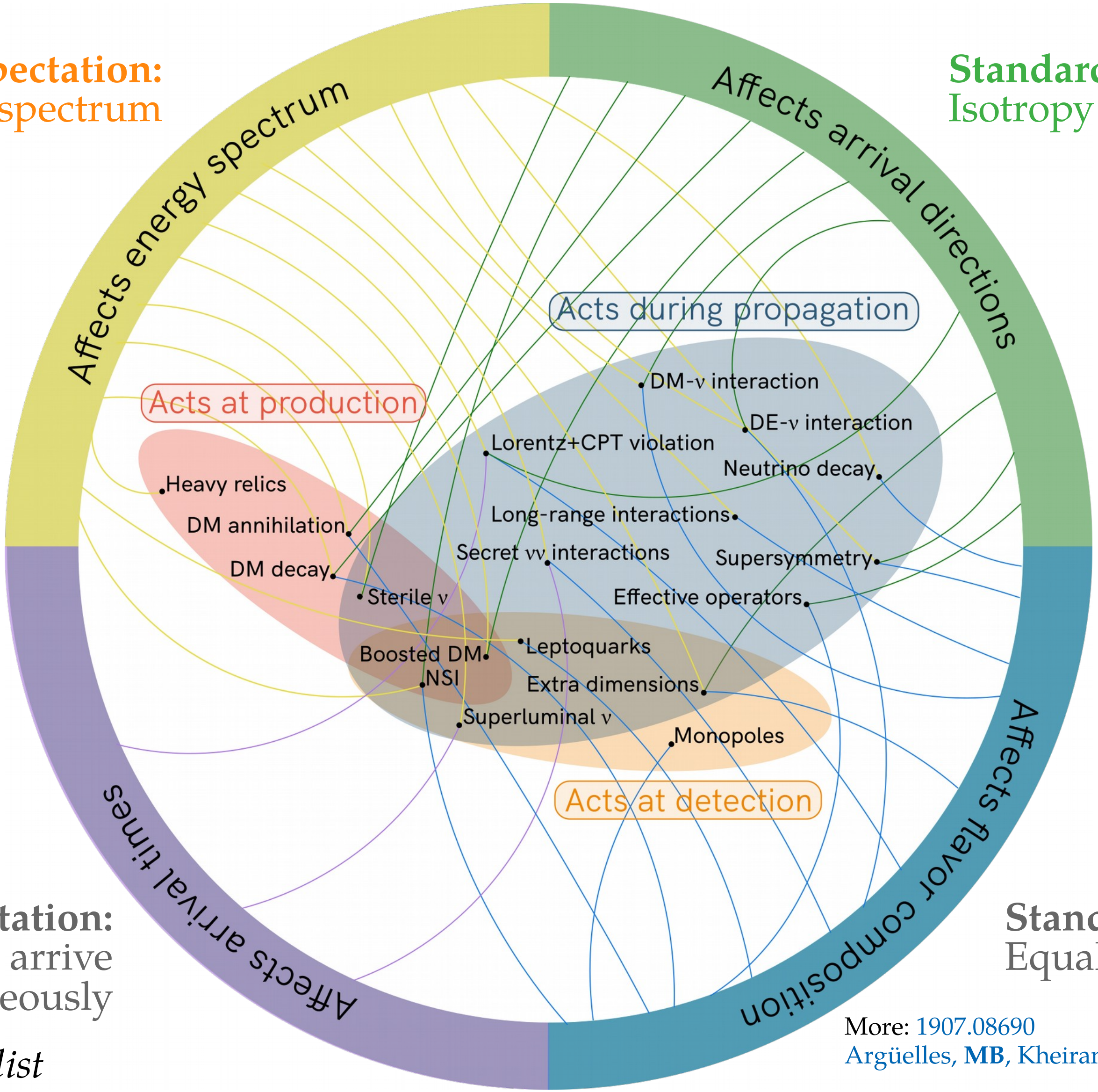

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More: 1907.08690
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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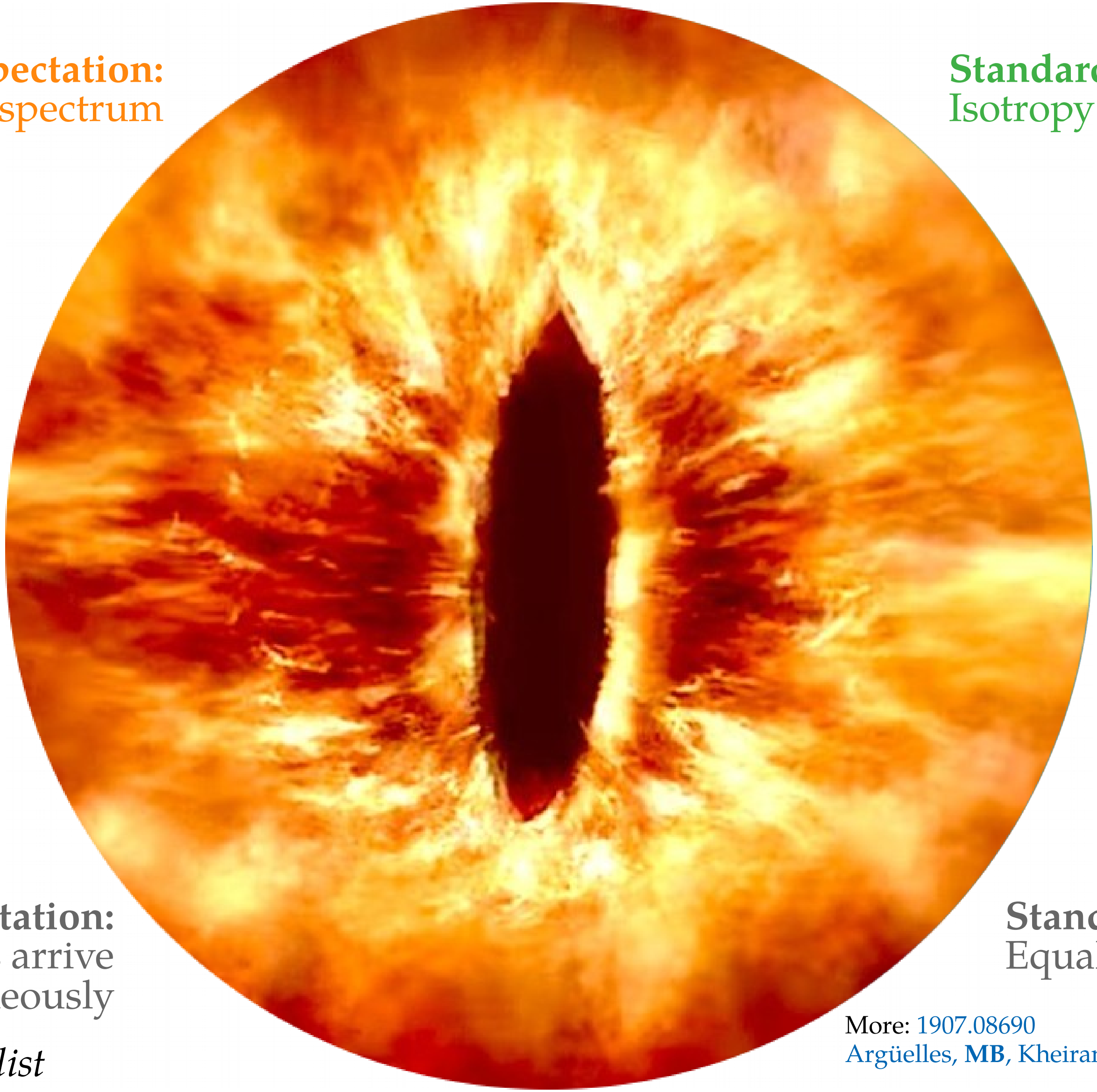

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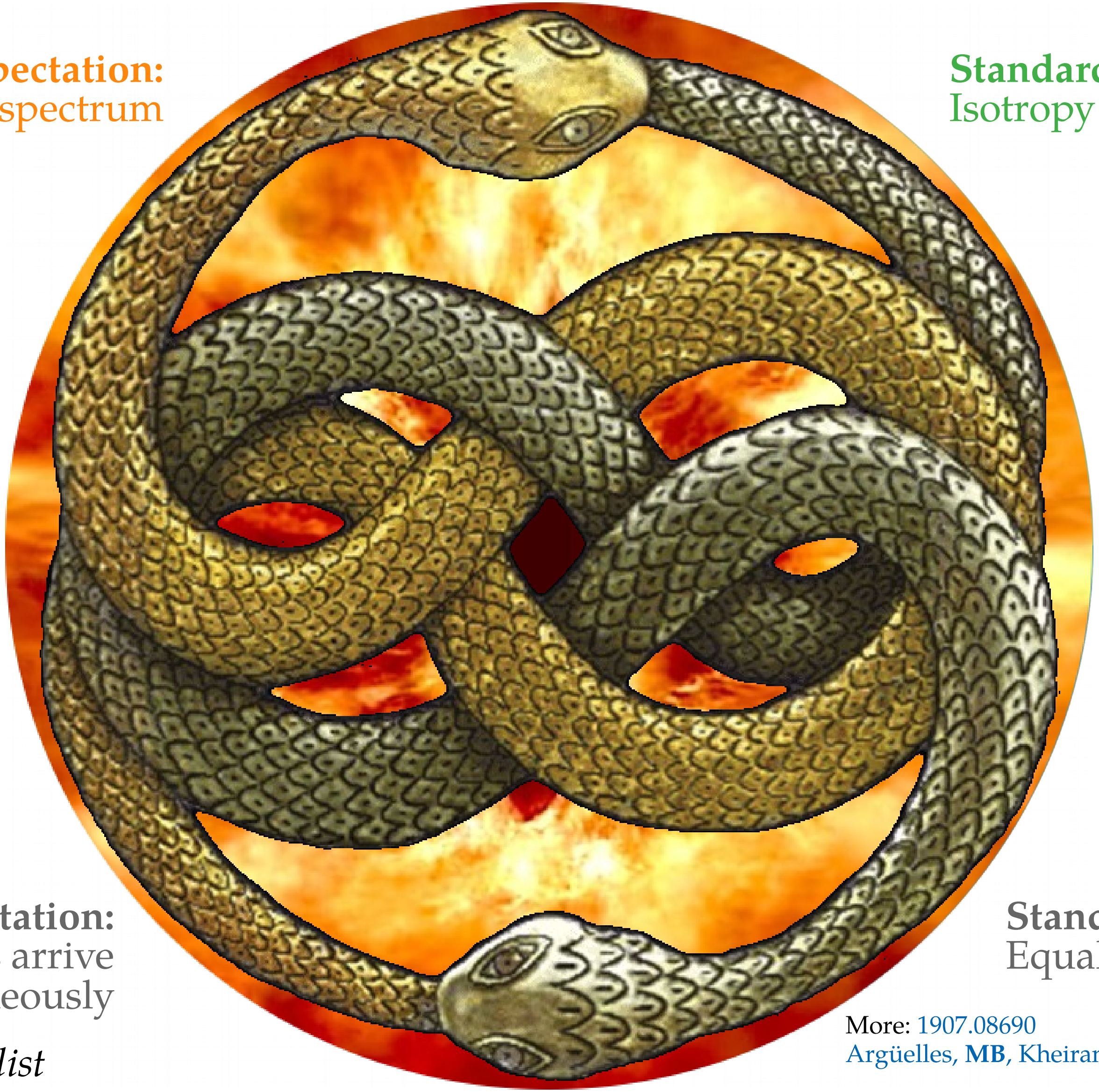

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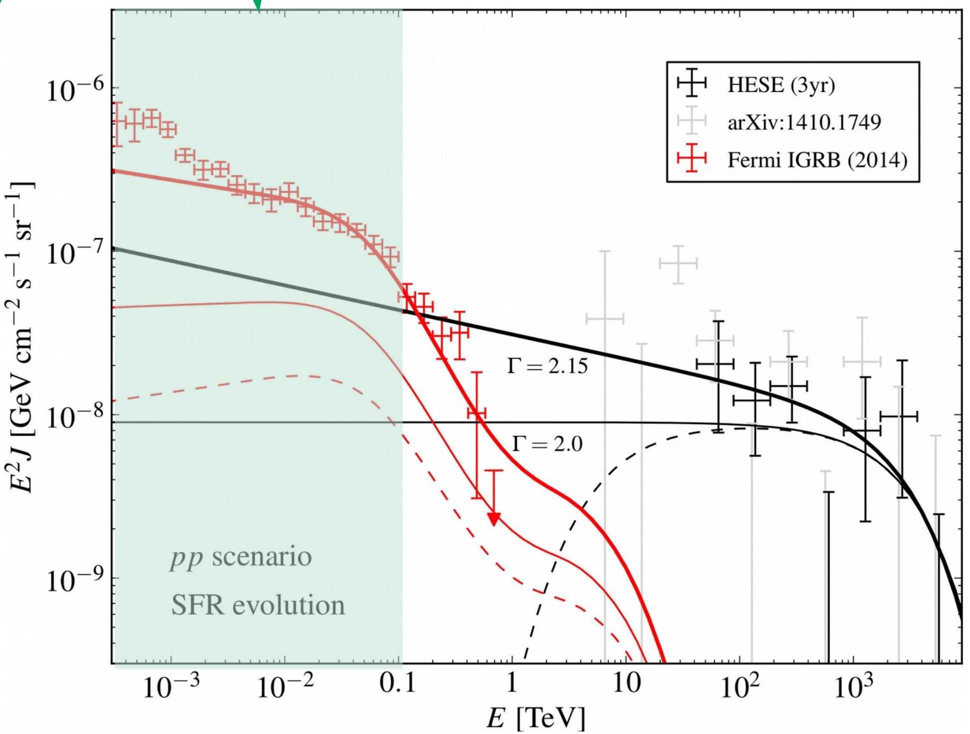
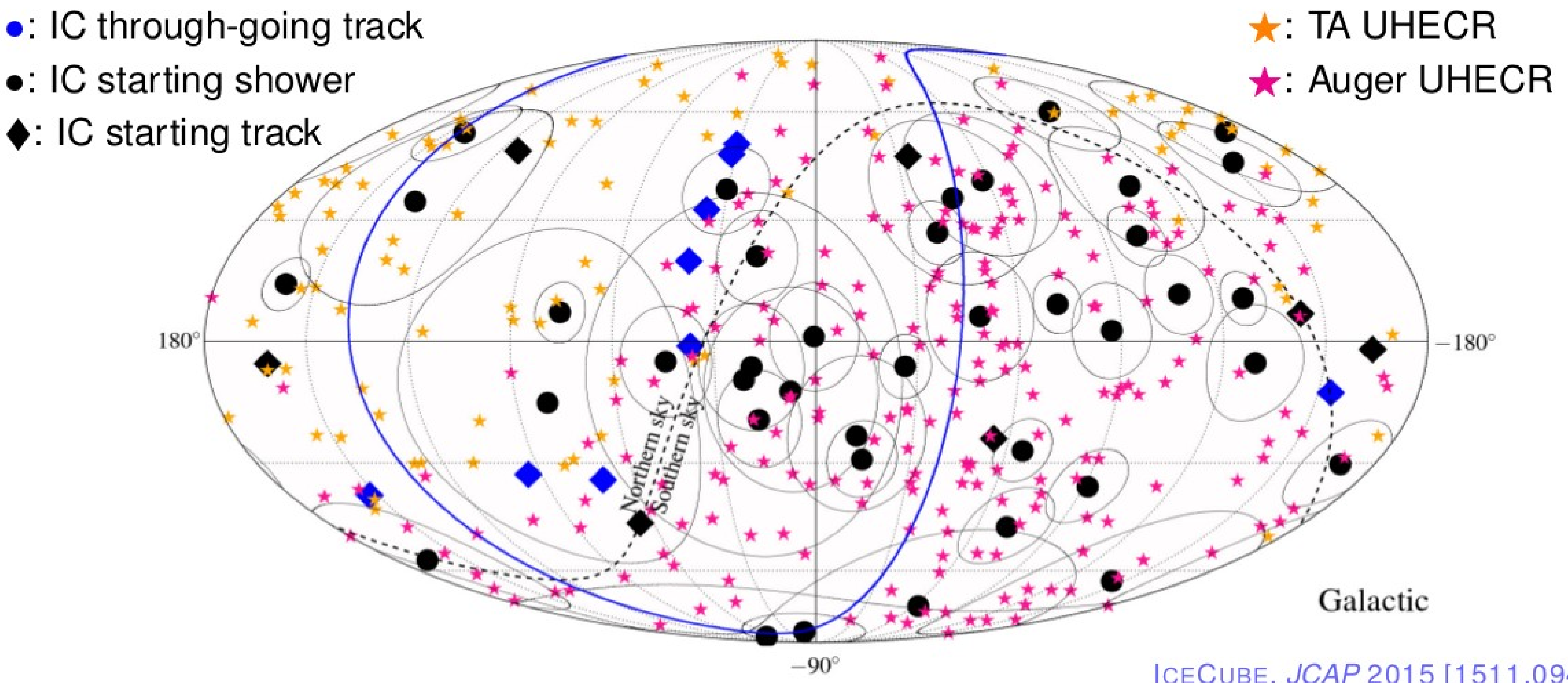
Constraints from the gamma-ray background

- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum $E^{-\Gamma}$
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- But IceCube found $\Gamma = 2.5$–2.7
- Therefore, production via *pp* is disfavored between 10–100 TeV

Murase, Ahlers, Lacki, *PRD* 2013



Neutrino–UHECR angular correlation?



IceCube, *JCAP* 2015 [1511.09408]

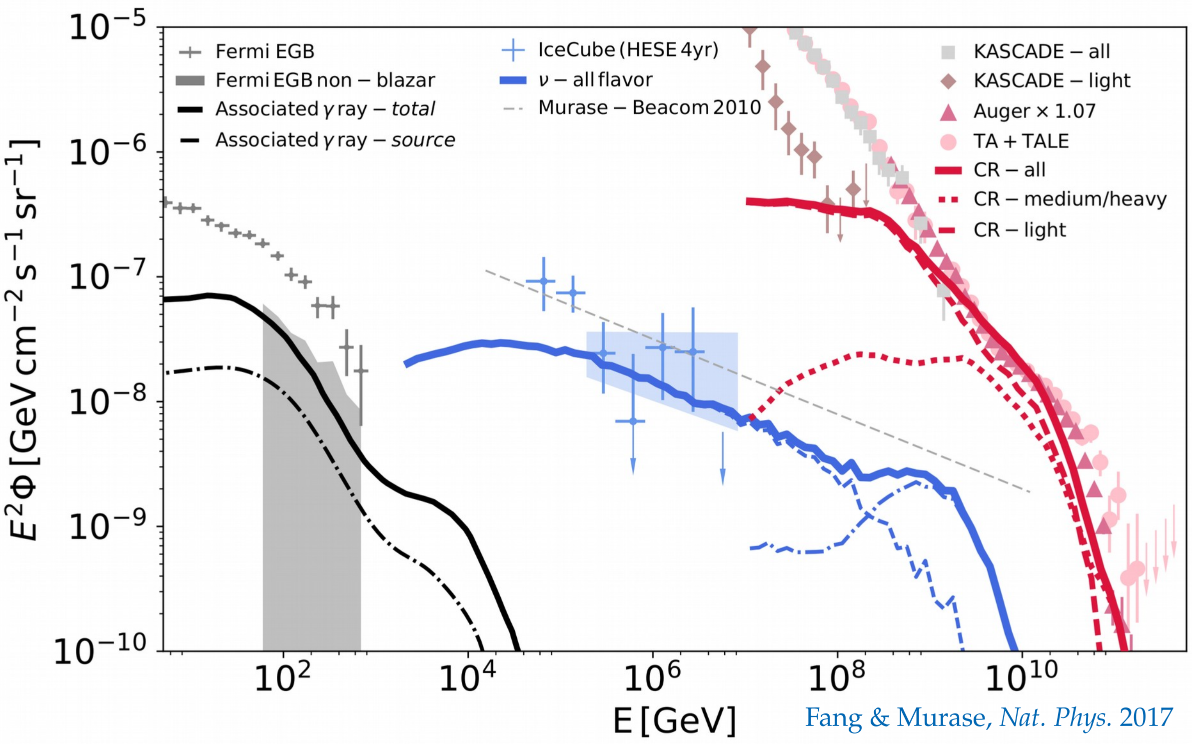
No significant correlation with UHECRs (<3.3σ)

A null neutrino-UHECR correlation *makes sense*

- UHECRs trace sources within $\lambda_{\rm GZK} \approx 100$ Mpc
- Neutrinos come from anywhere inside the Hubble horizon $D_{\rm H} \approx 4$ Gpc
- So the maximum possible correlation is $\dfrac{\lambda_{\rm GZK}}{D_{\rm H}} \approx 2.5\%$
- Current number of IceCube high-energy starting tracks (HESE): ~25
- ∴ Expected UHECR correlation with only ~1 neutrino
- Signal weakened by magnetic deflection, angular resolution, *etc.*

Grand-unified ν–UHECR–gamma-ray model

- Black-hole jets in galaxy clusters accelerate cosmic rays
- UHECRs make ν and γ in the magnetized cluster medium
- UHECRs above 0.1 EeV escape
- Consistent w/ observed UHECR spectrum, composition, isotropy
- Explains IceCube neutrinos
- Explains non-blazar *Fermi* EGB

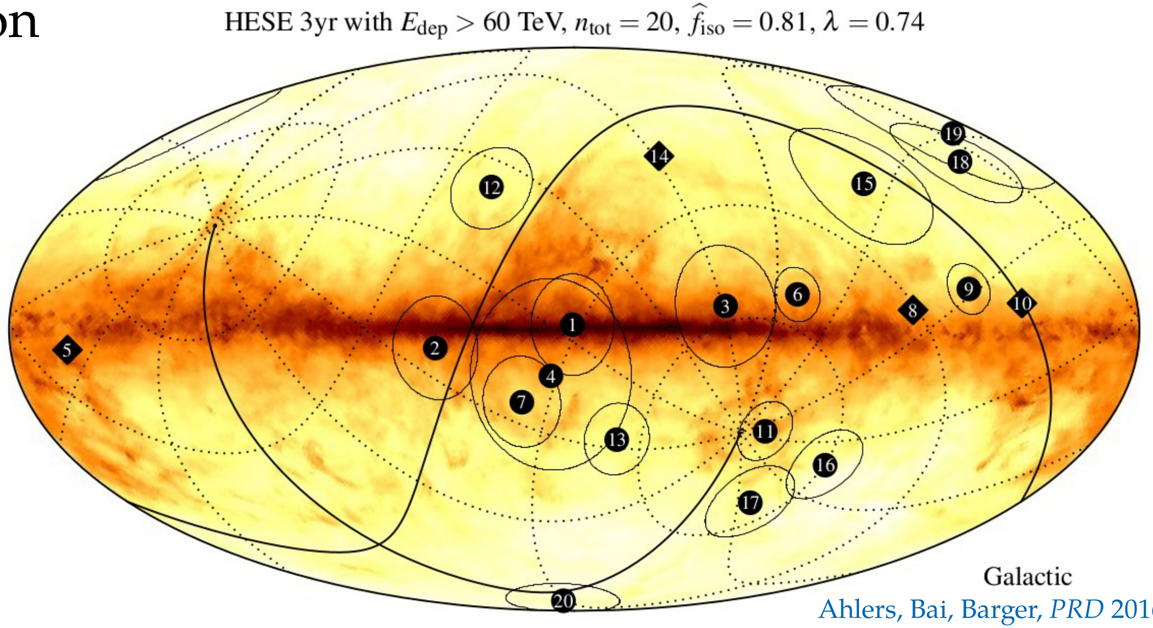


Fang & Murase, *Nat. Phys.* 2017

PeV neutrino sources in the Milky Way?

Candidates for full or partial contribution:

- ▸ Diffuse Galactic gamma-ray emission
- ▸ Unidentified gamma-ray sources
- ▸ Fermi bubbles
- ▸ Supernova remnants
- ▸ Pulsars
- ▸ Microquasars
- ▸ Sagitarius A*
- ▸ Galactic halo
- ▸ Heavy dark matter decay



Ahlers, Bai, Barger, *PRD* 2016

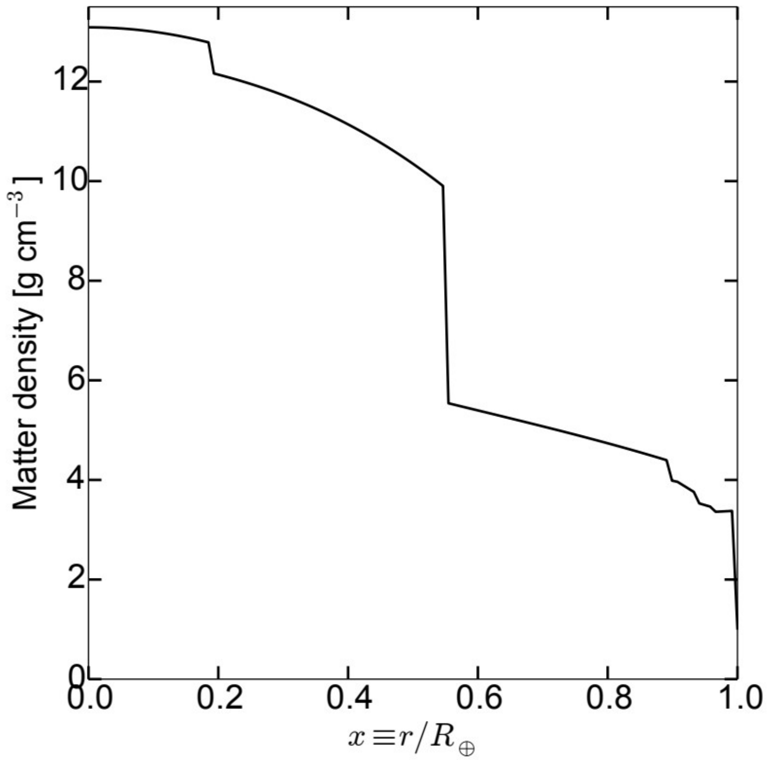
Contribution from Galactic sources: $< 14\%$

IceCube, *ApJ* 2017

A feel for the in-Earth attenuation

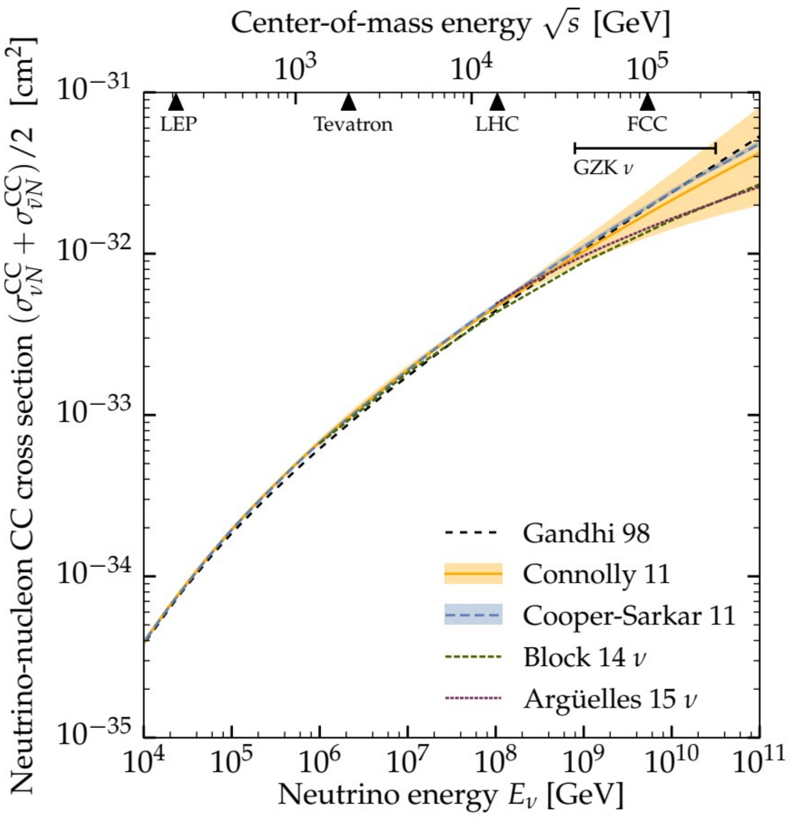
Earth matter density

(Preliminary Reference Earth Model)



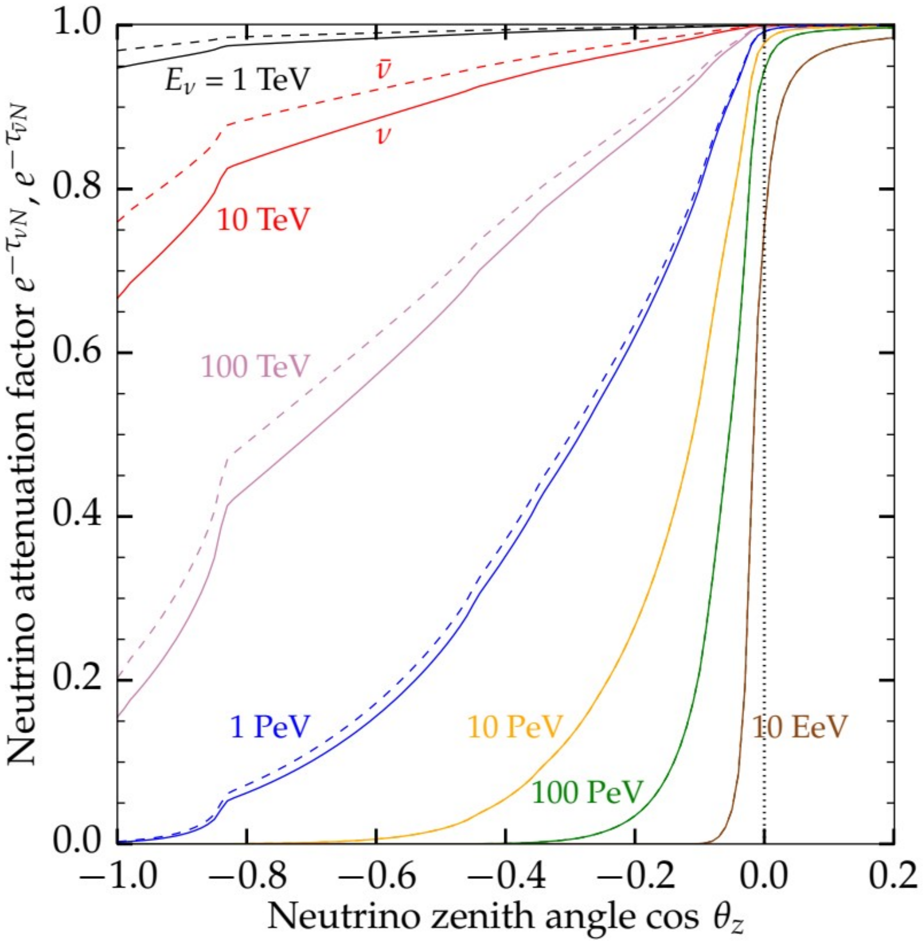
+

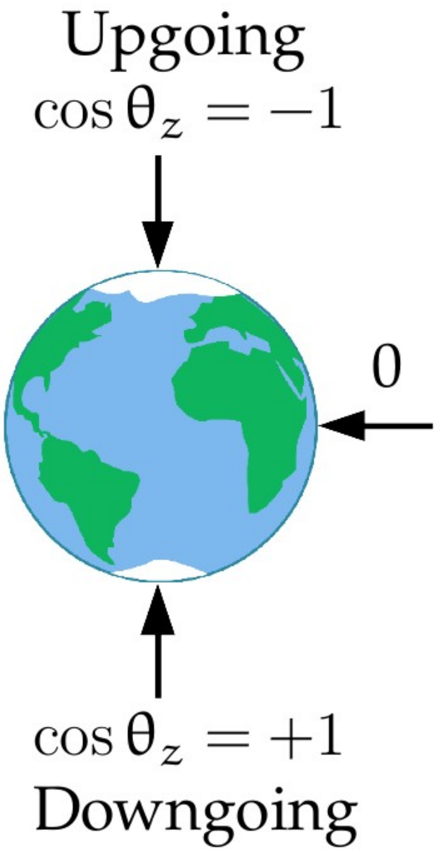
Neutrino-nucleon cross section

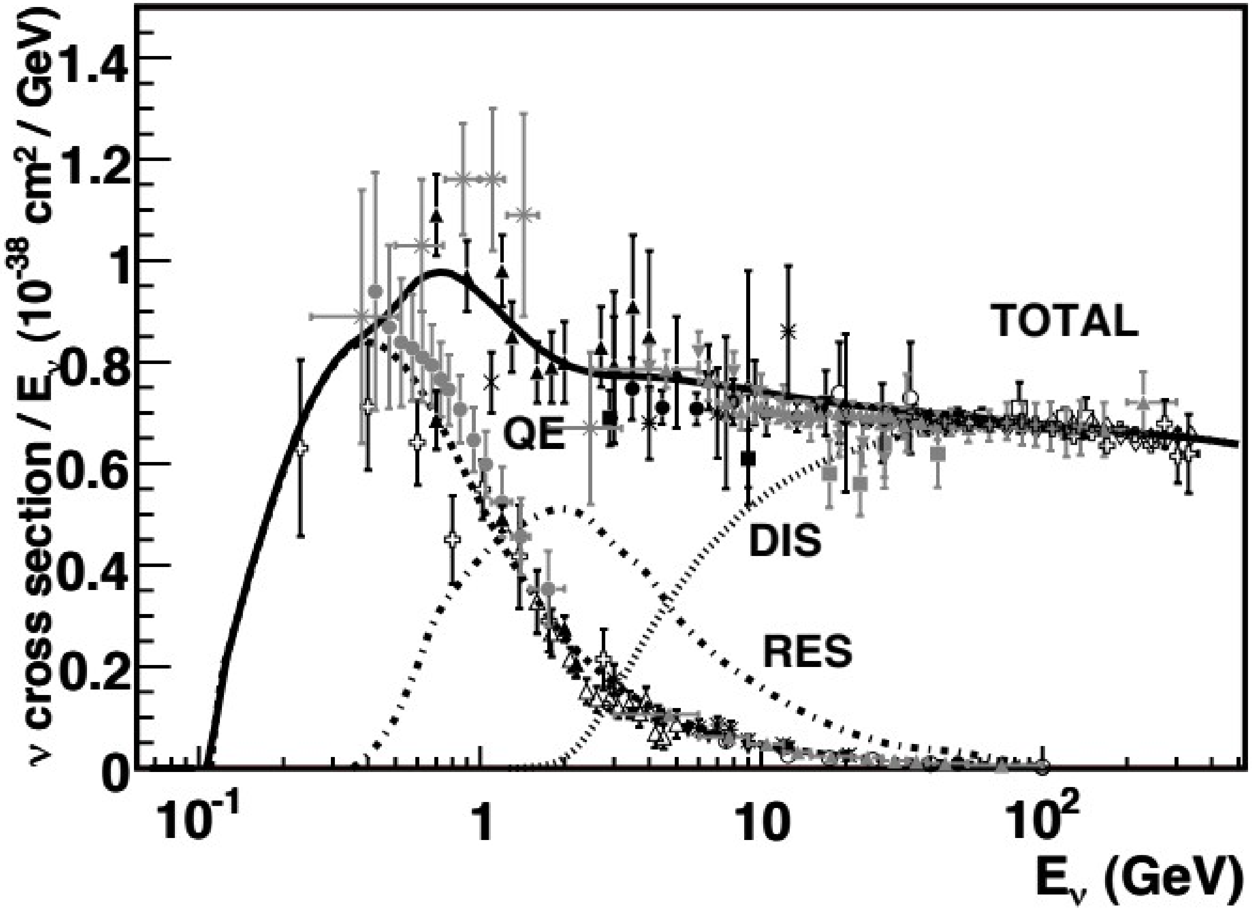


A feel for the in-Earth attenuation

=

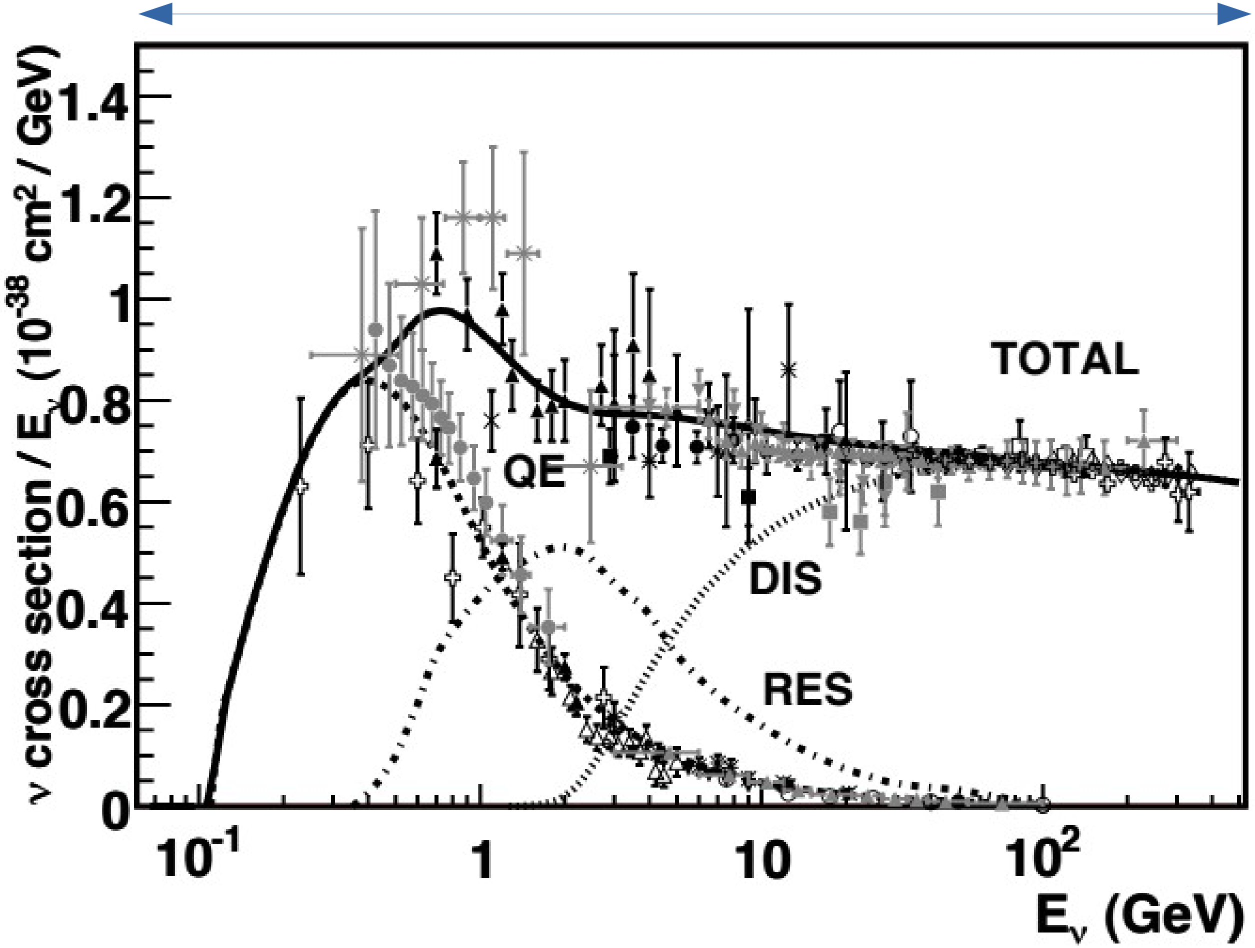






Particle Data Group

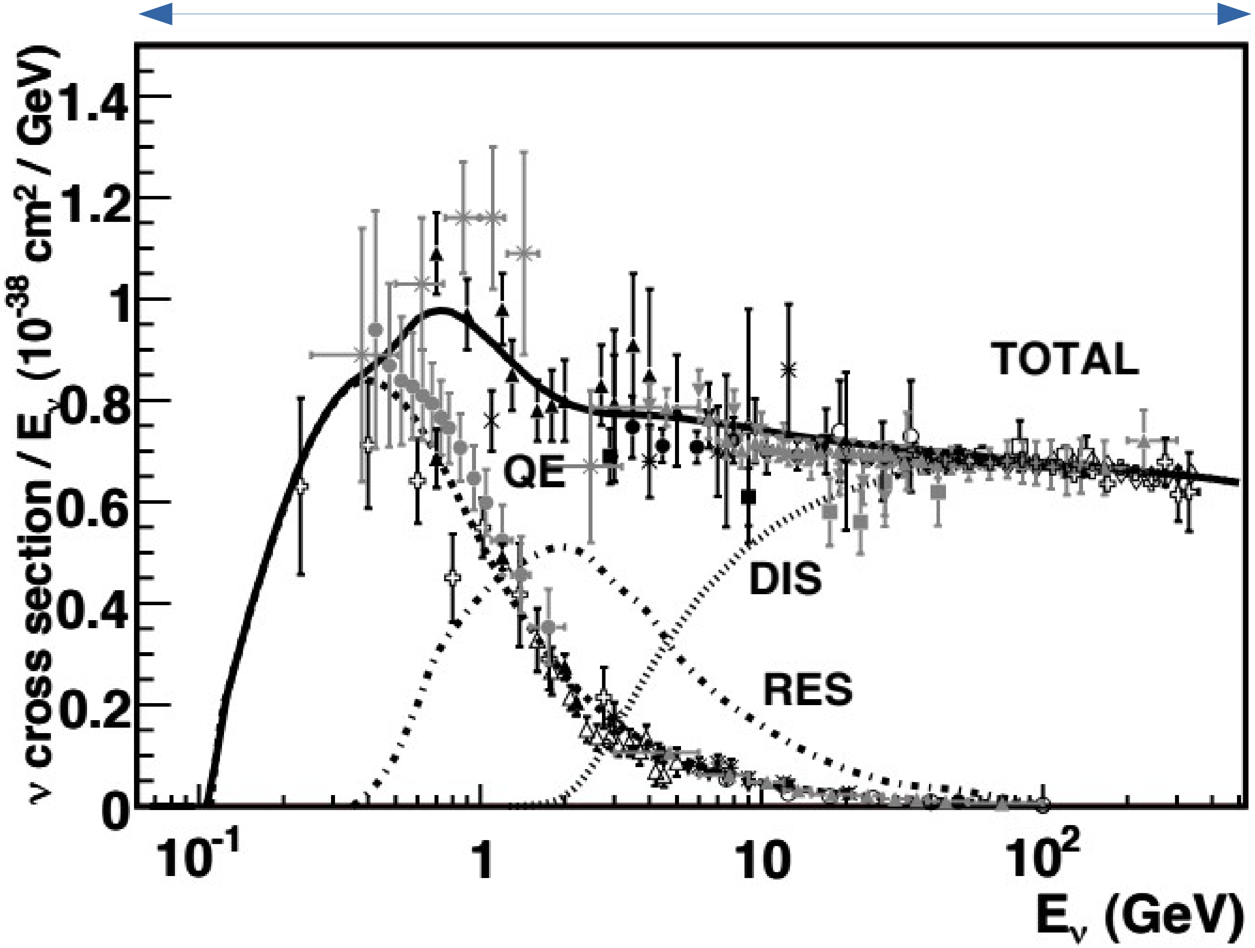
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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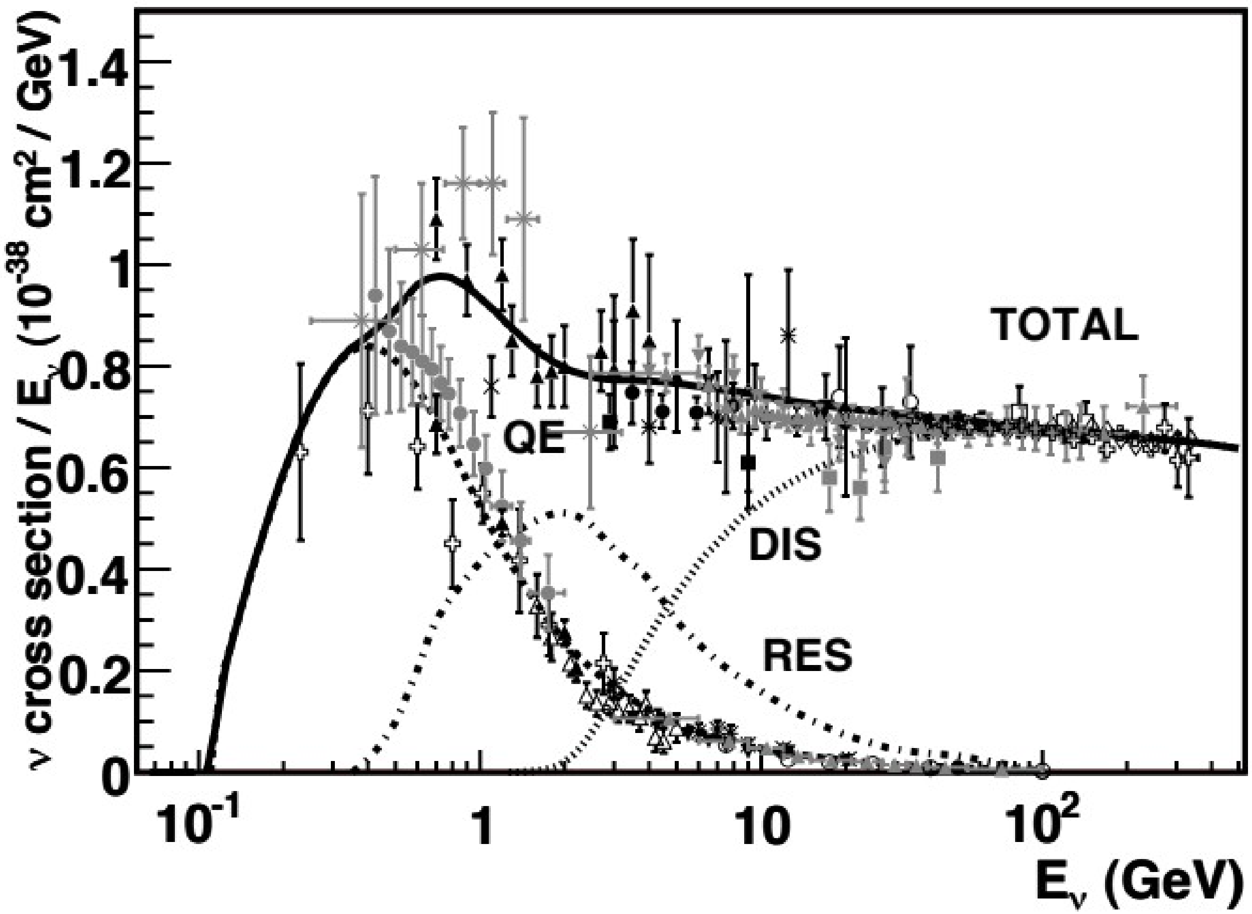
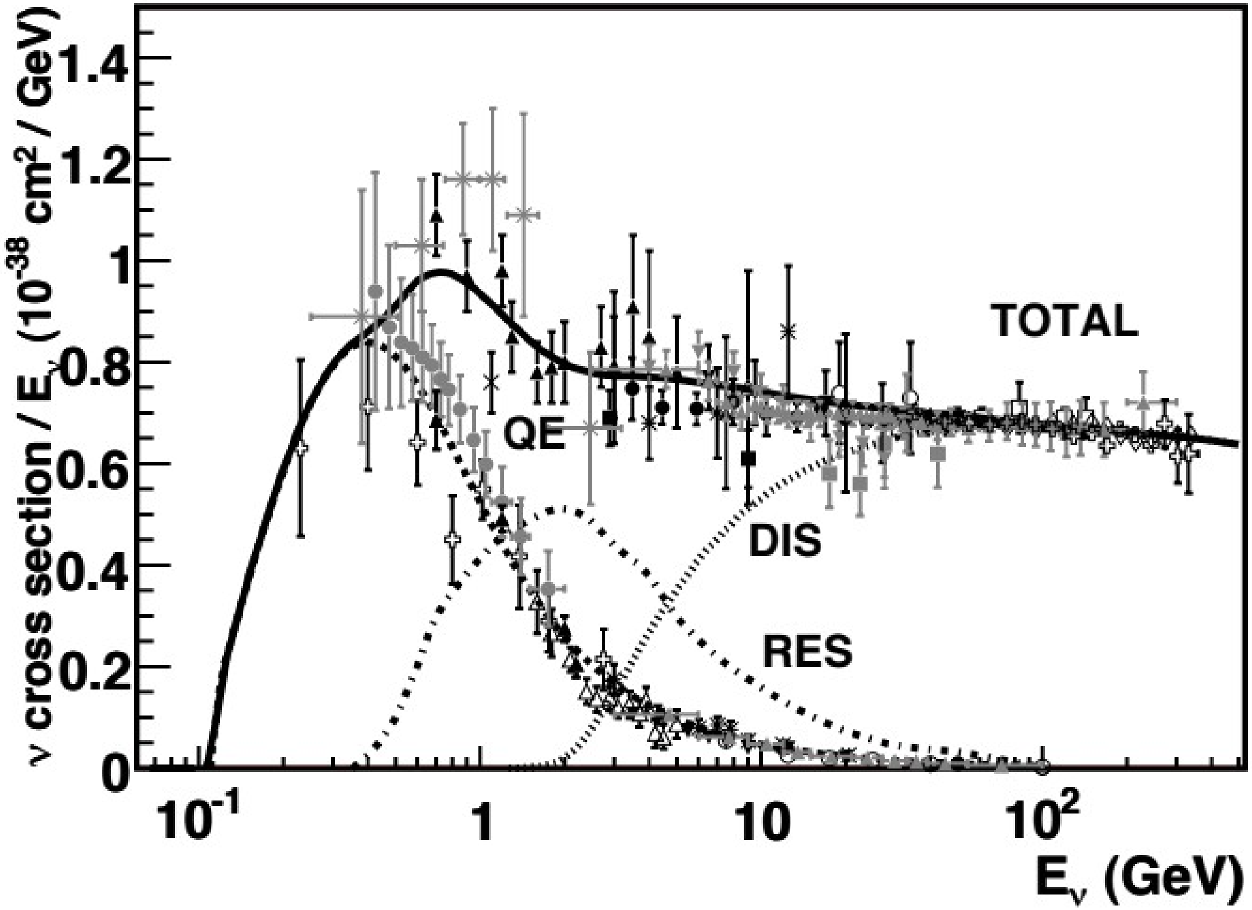


Particle Data Group

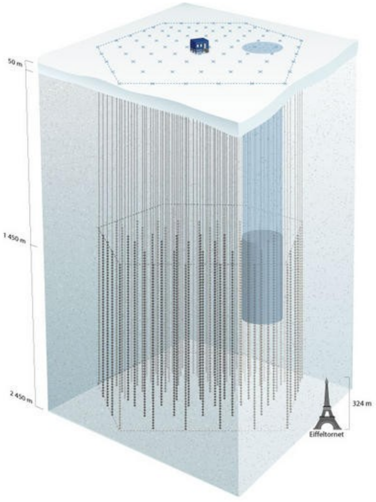
No measurements … until recently!

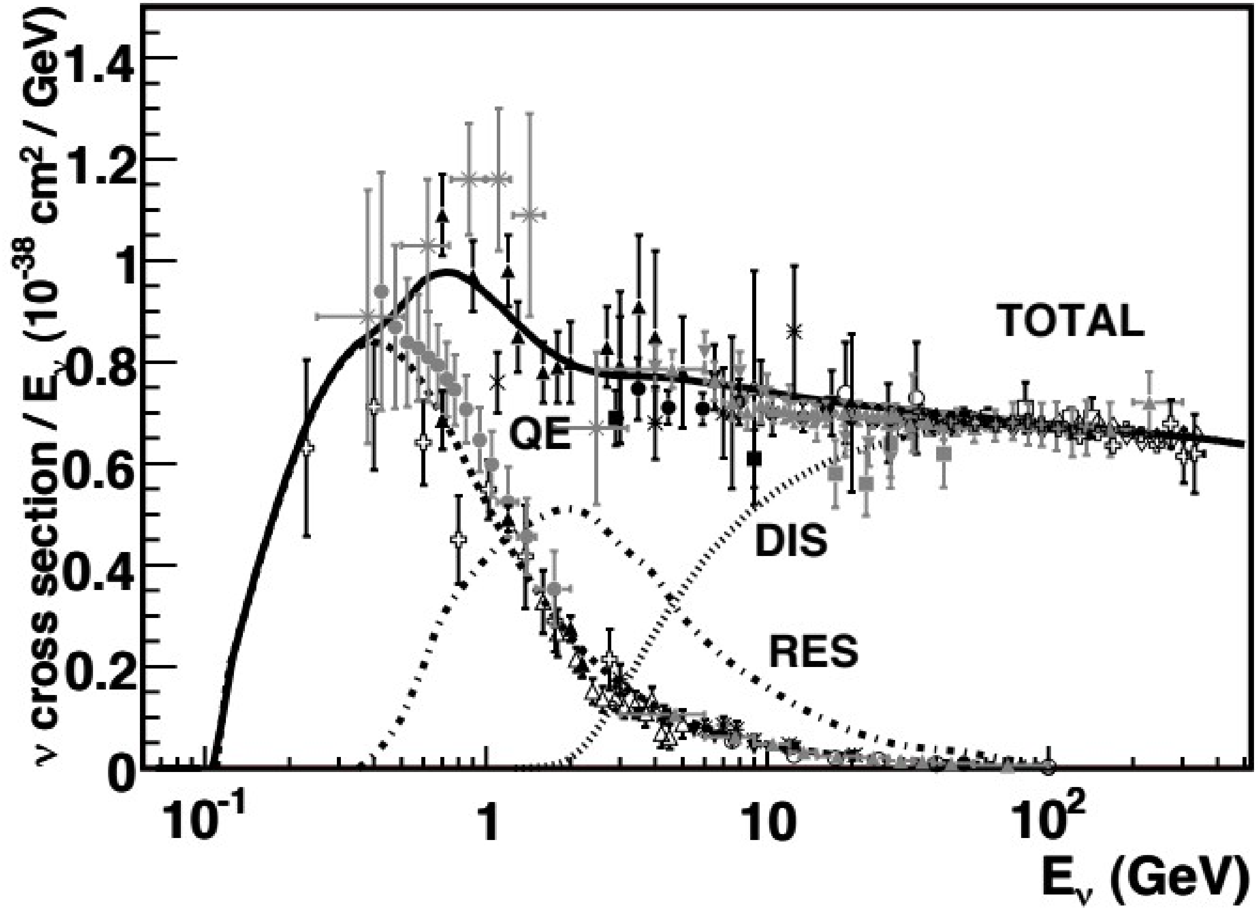
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



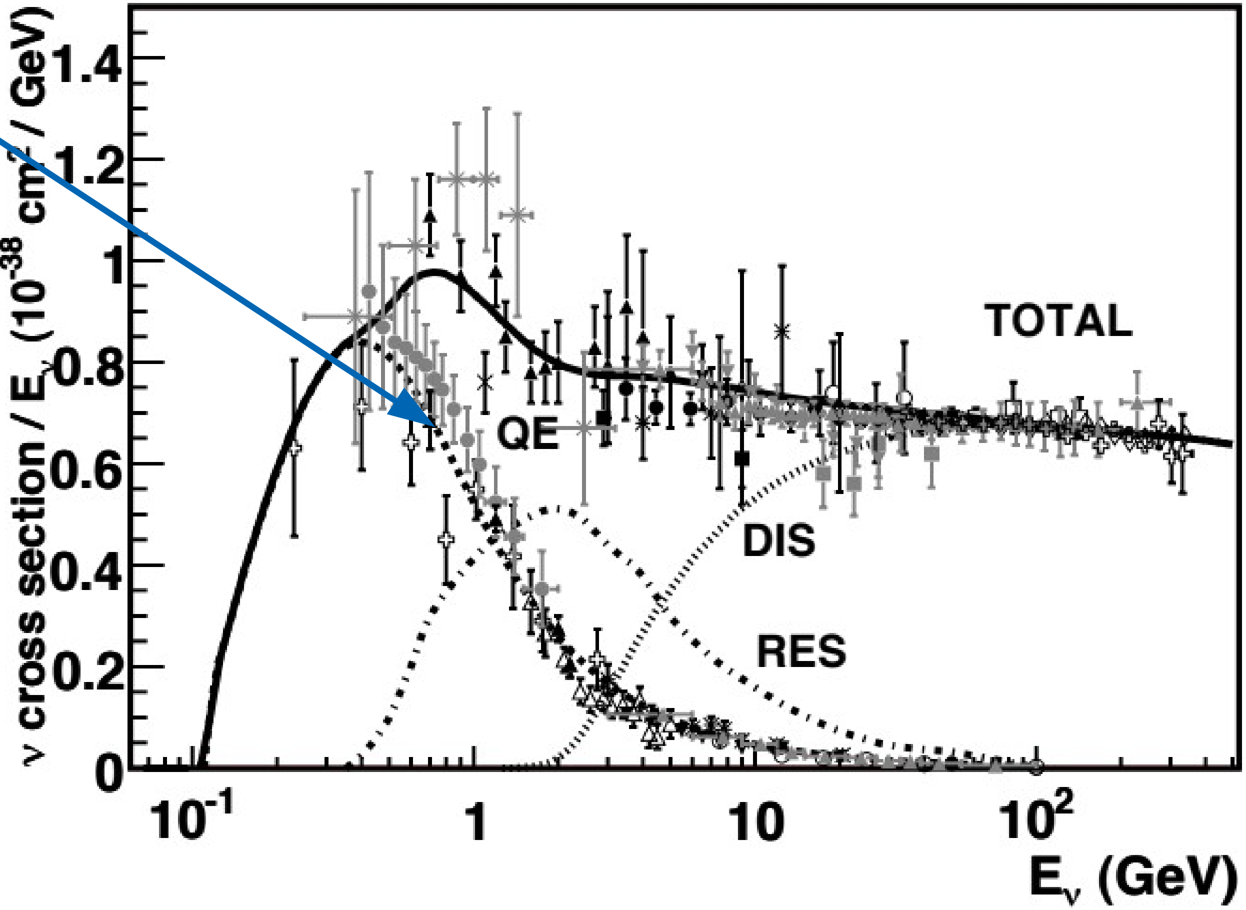


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



Particle Data Group

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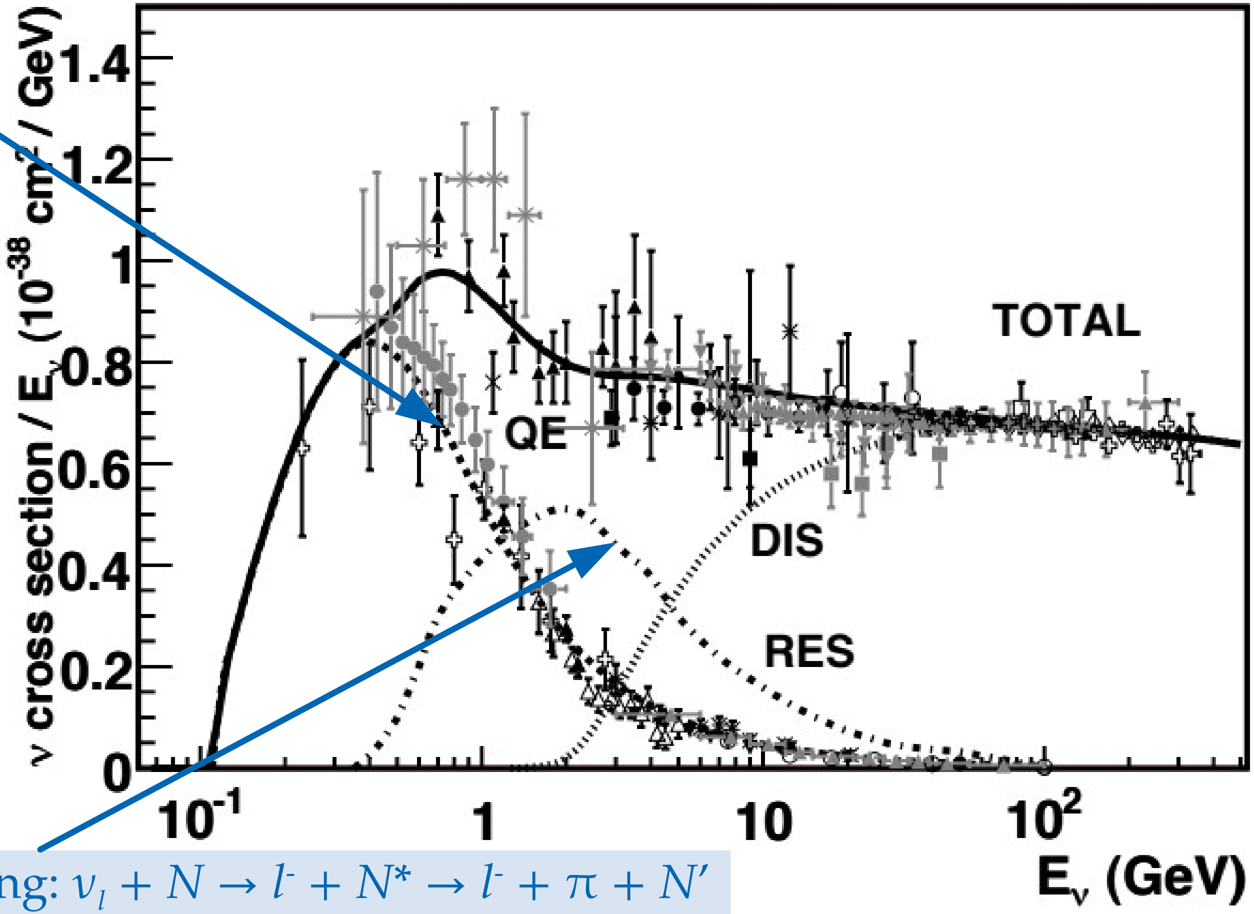
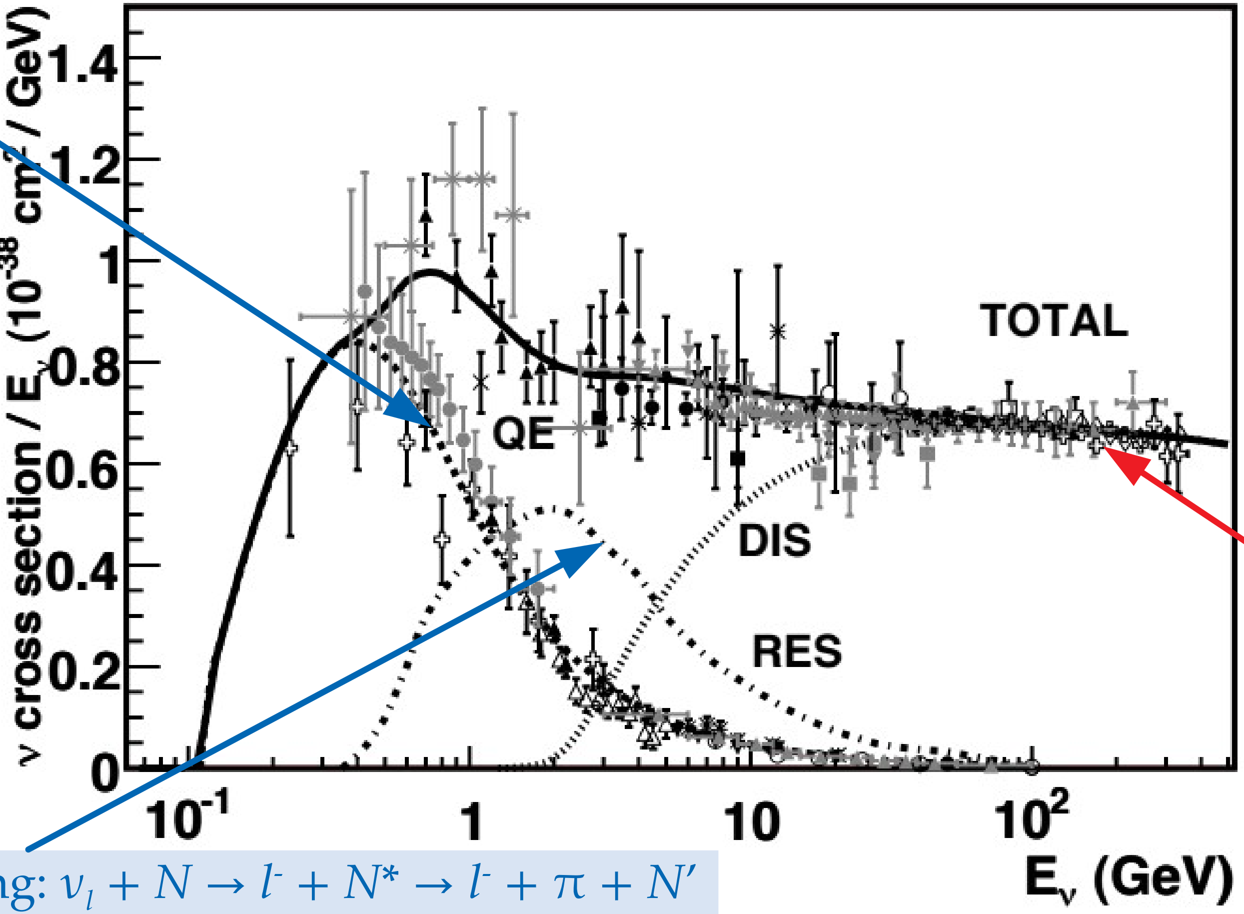


Resonant scattering: $\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

Particle Data Group

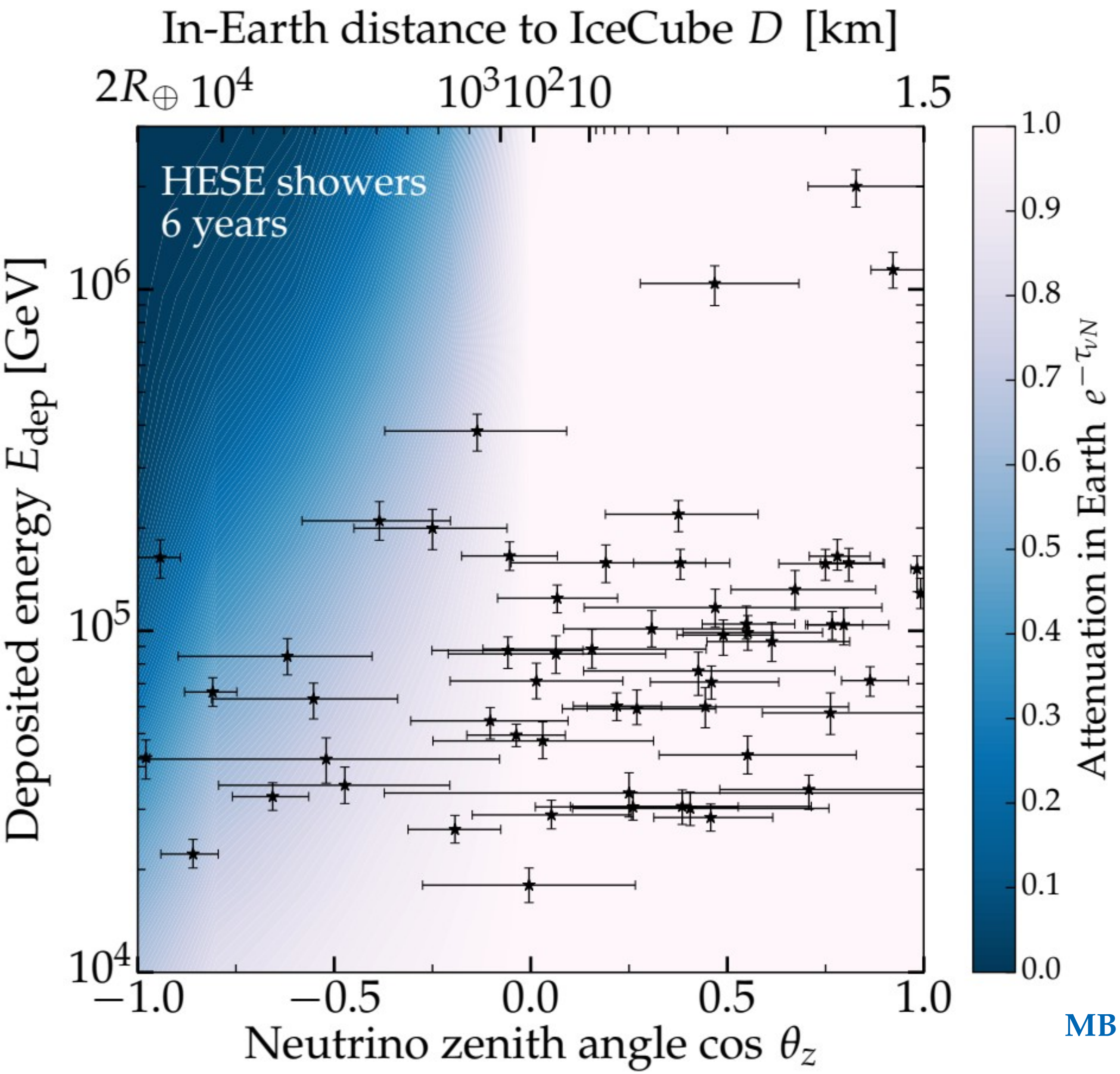
Quasi-elastic scattering:
$\nu_l + n \to l^- + p$
$\overline{\nu}_l + p \to l^+ + n$



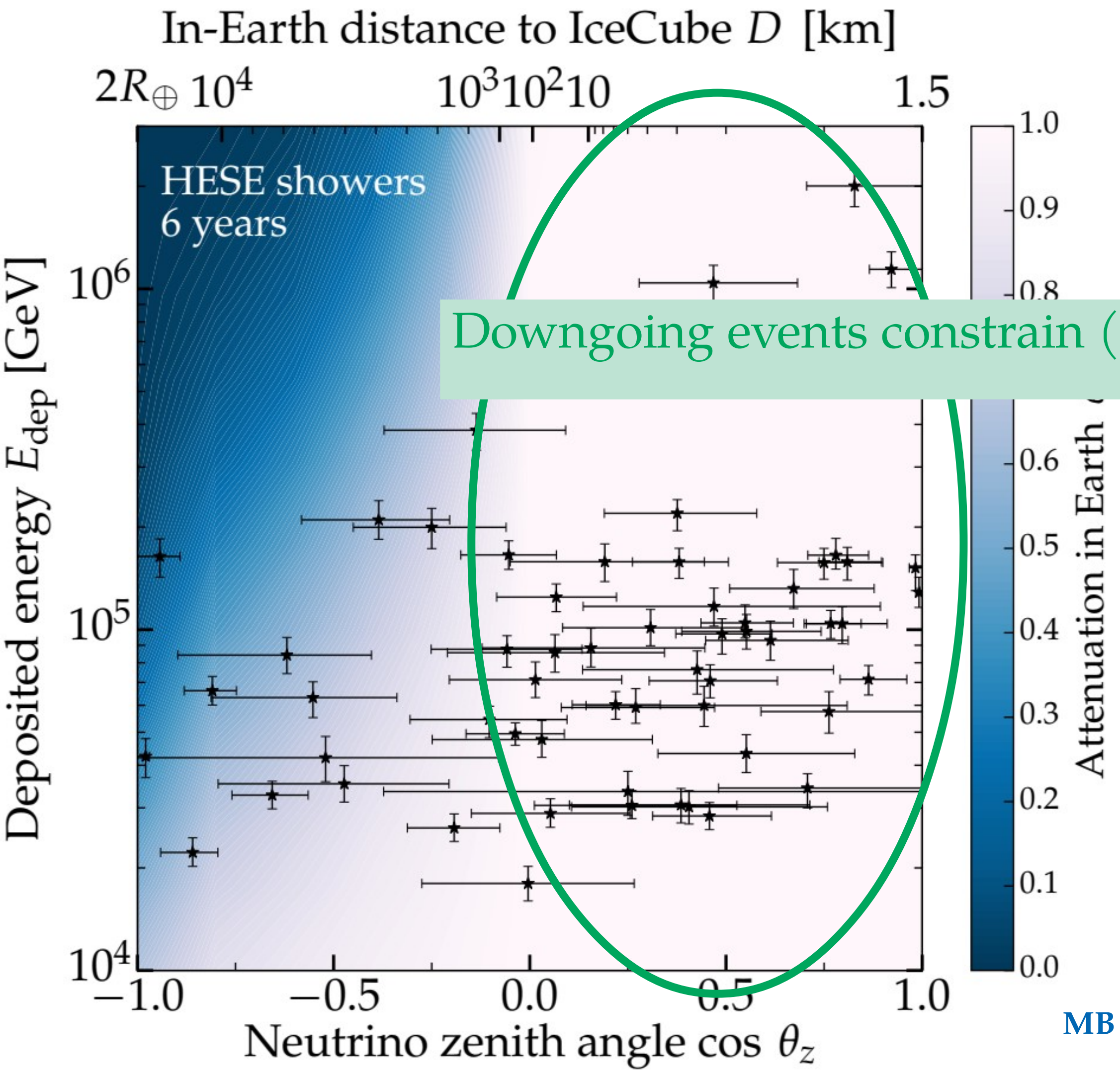
Deep inelastic scattering:
$\nu_l + N \to l^- + X$
$\overline{\nu}_l + N \to l^+ + X$

Resonant scattering: $\nu_l + N \to l^- + N^* \to l^- + \pi + N'$

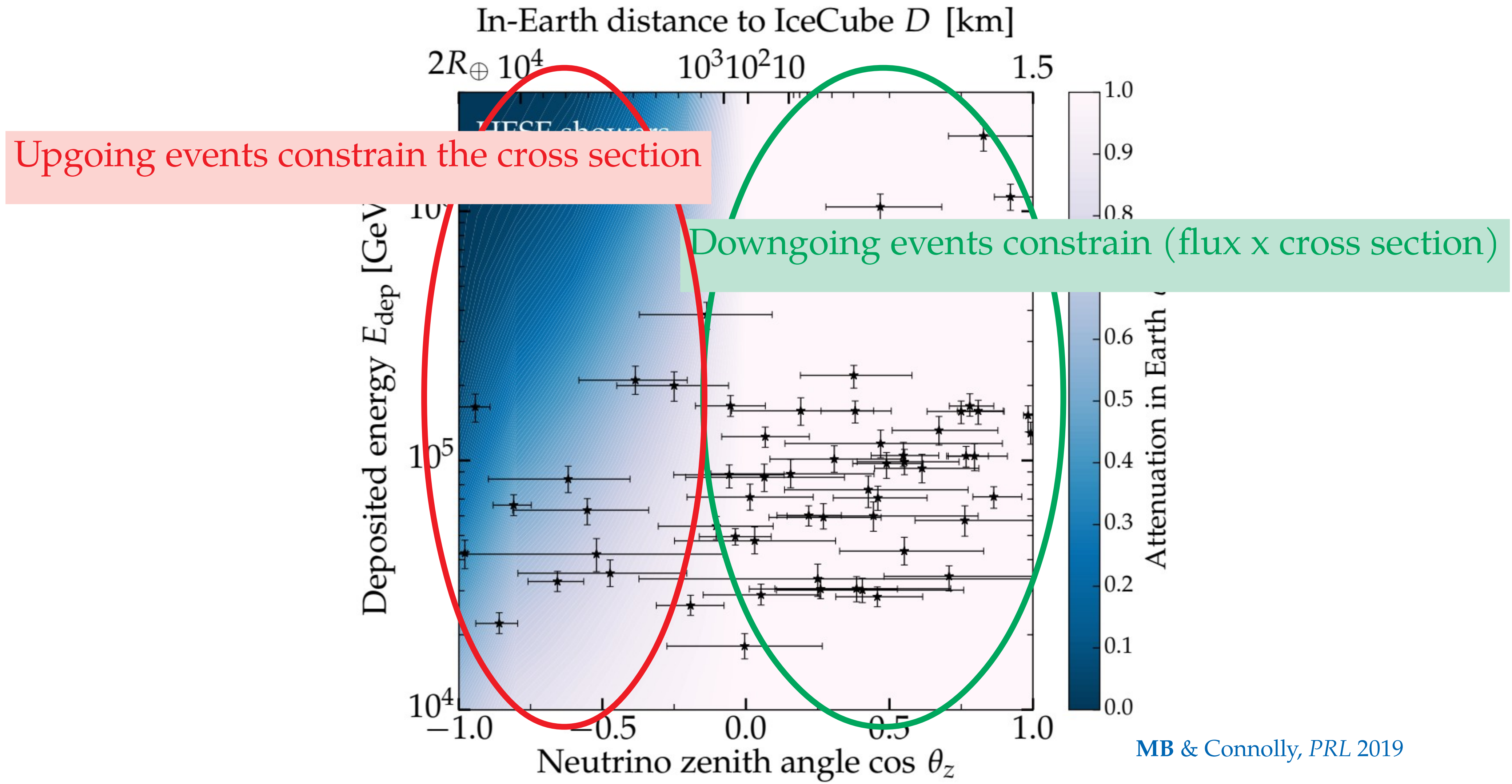
Particle Data Group



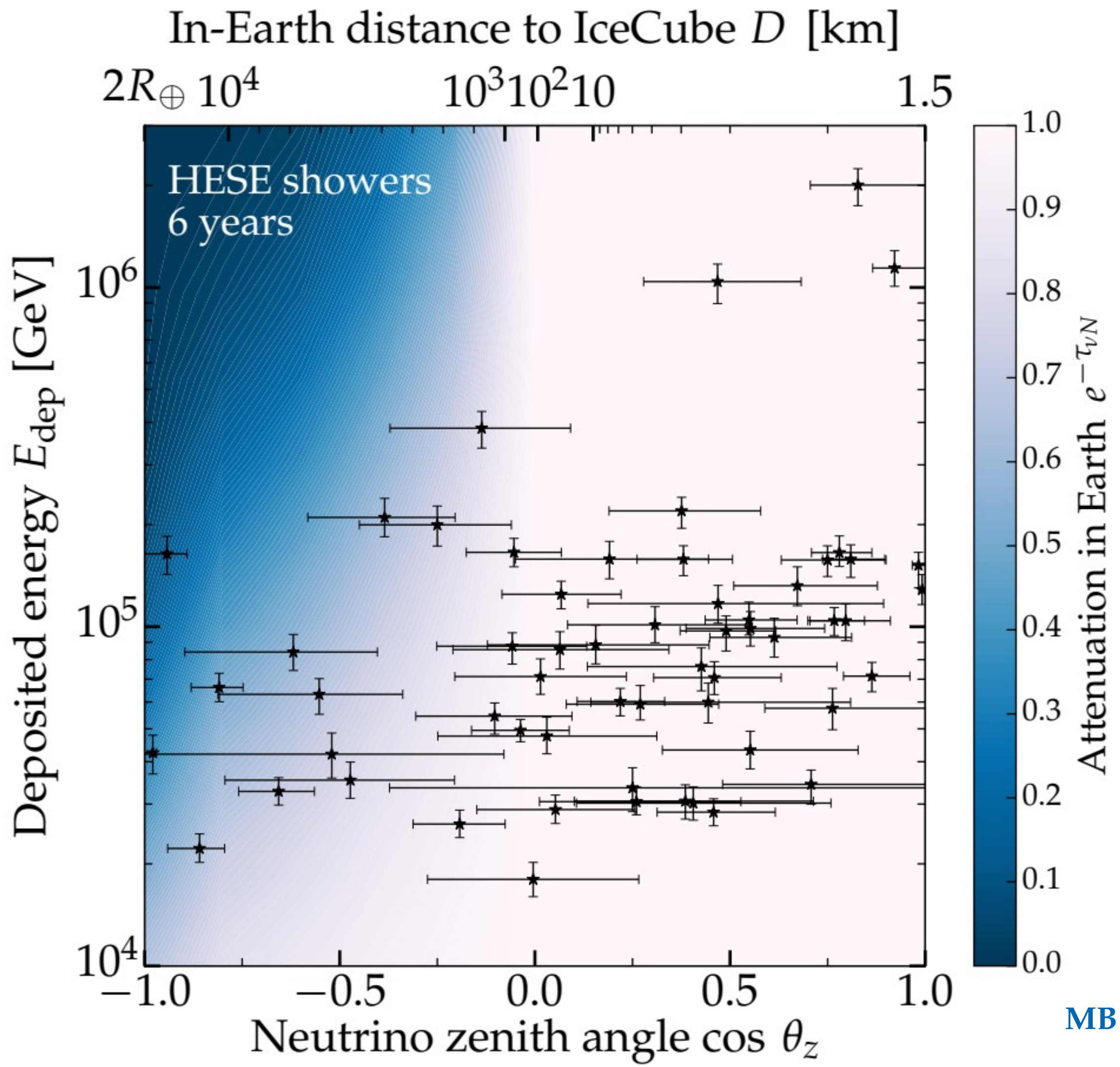
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



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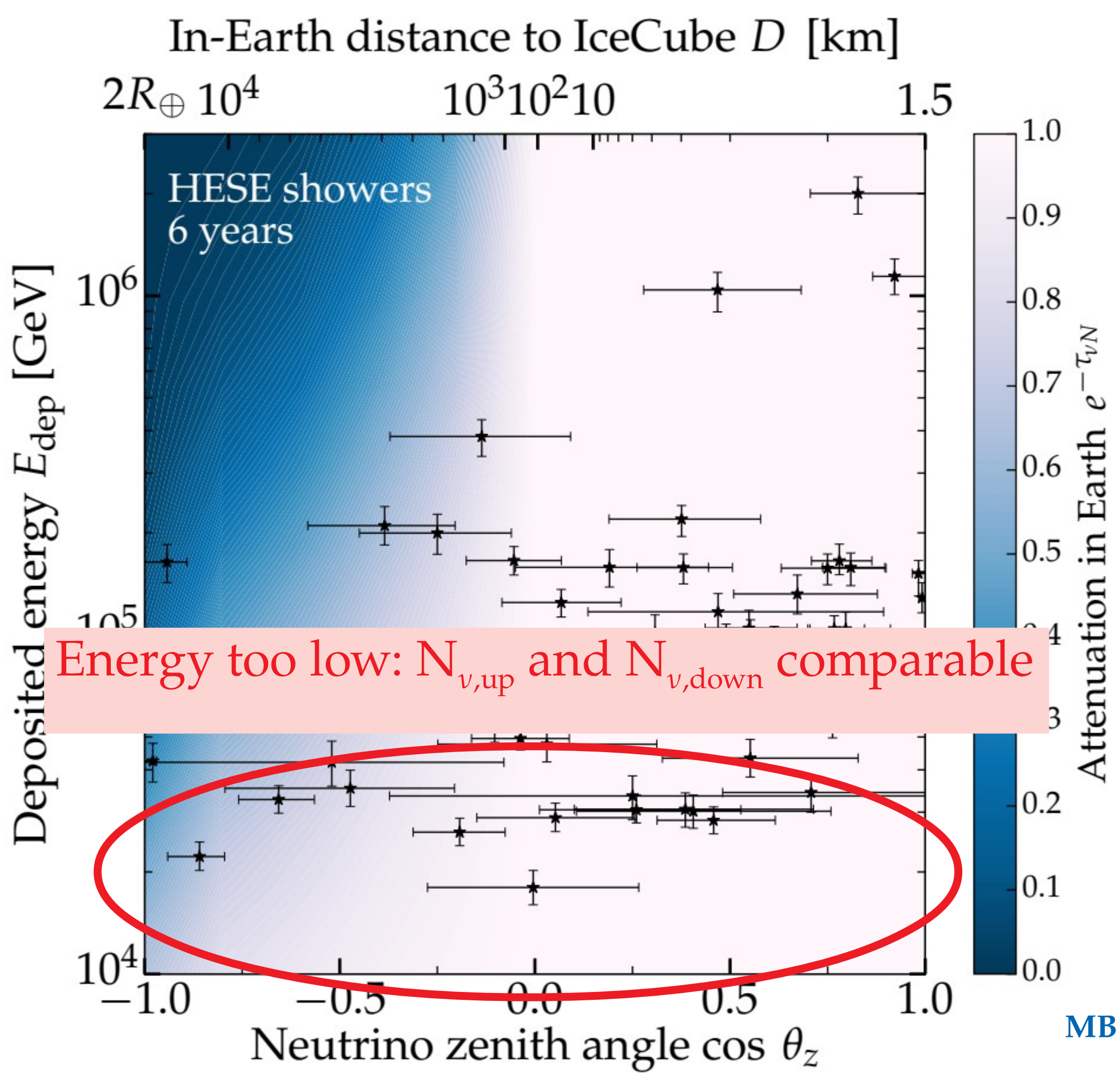

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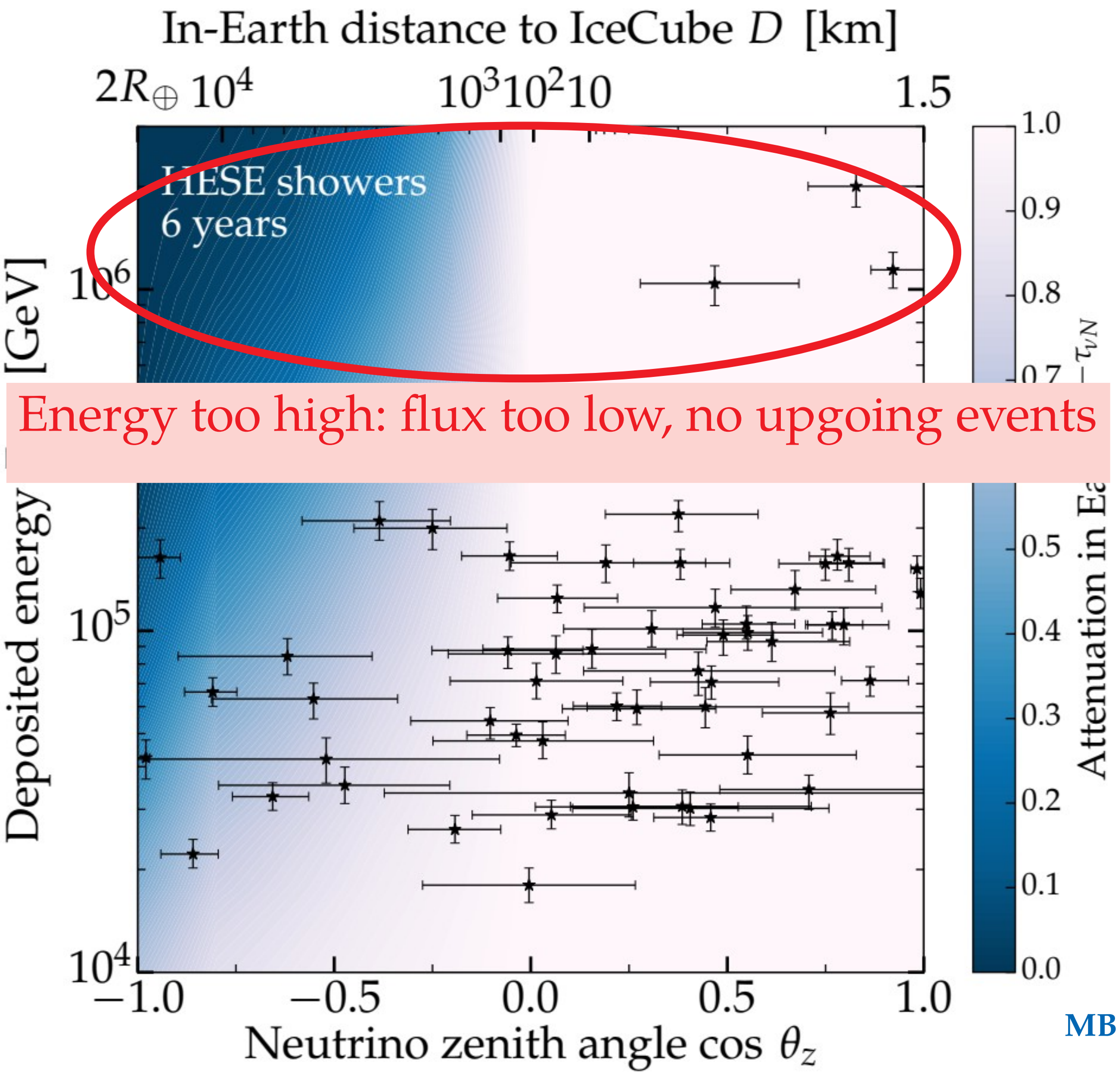
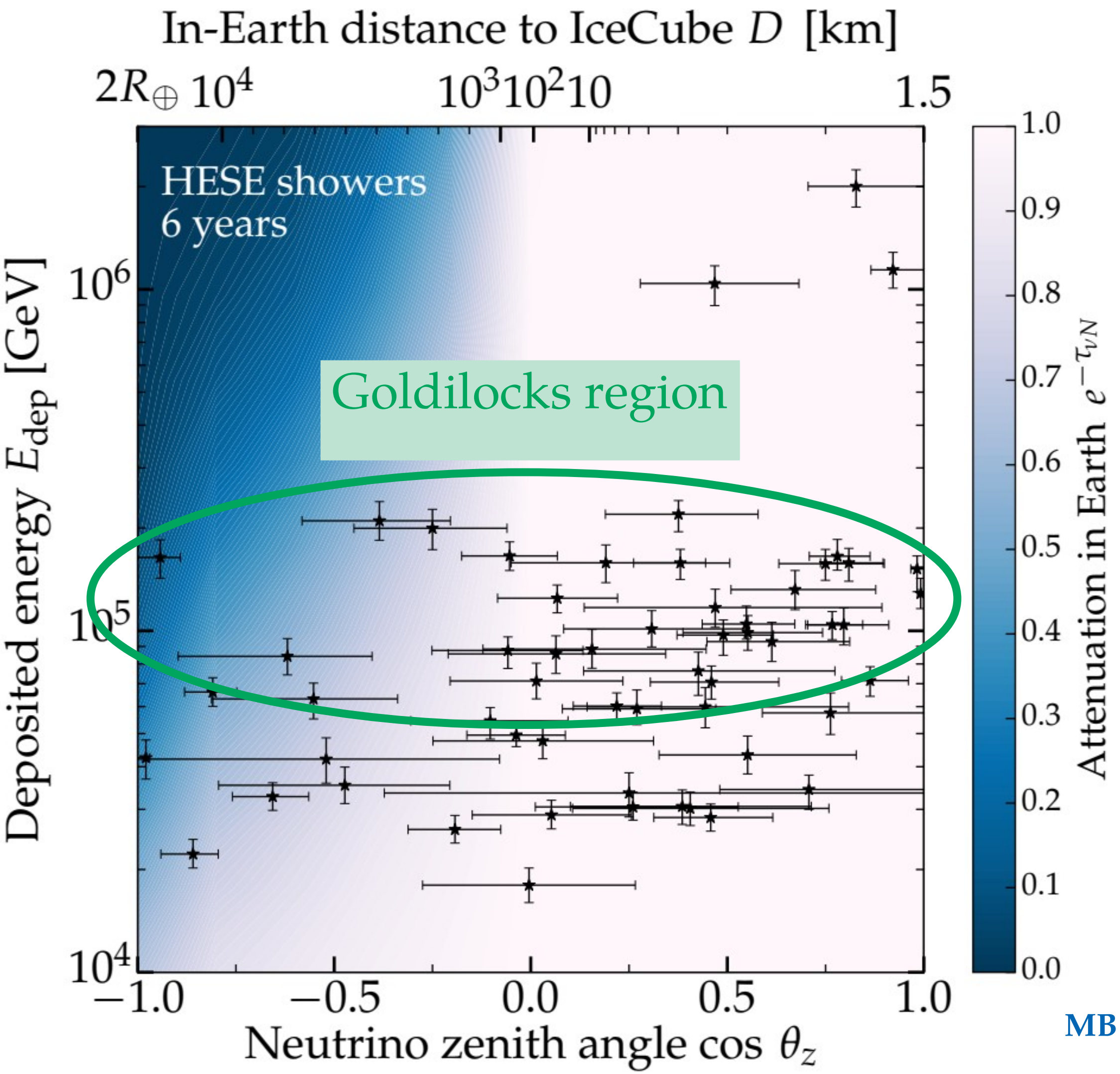
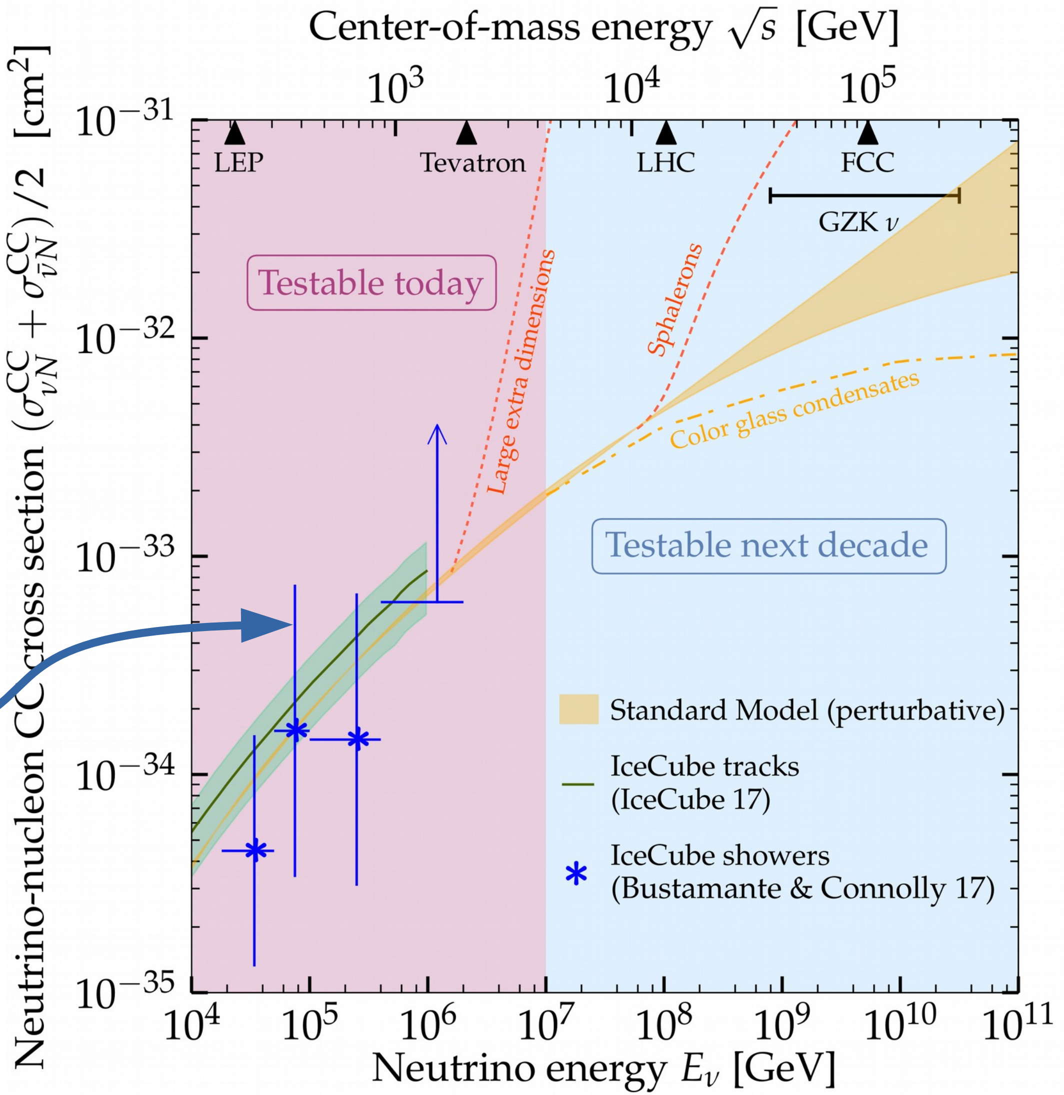


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - $\times$ 5 volume $\Rightarrow$ 300 showers in 6 yr
  - Reduce statistical error by 40%



Ackermann *et al.*, Astro2020 Decadal Survey (1903.04333)

Cross sections from:
MB & Connolly *PRL* 2019
IceCube, *Nature* 2017

UHE uncertainties can be smaller:
Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

- Fold in astrophysical unknowns (spectral index, normalization)
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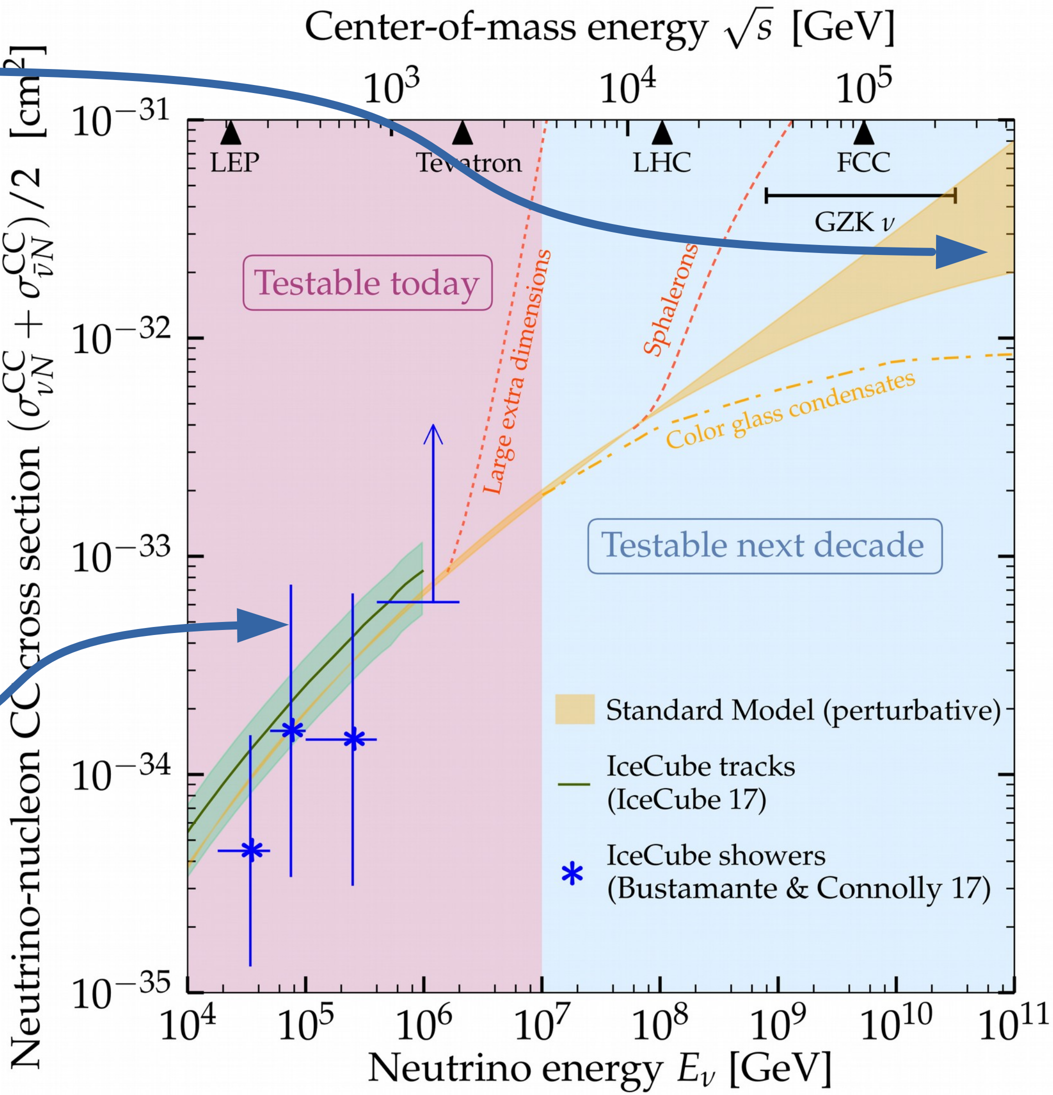

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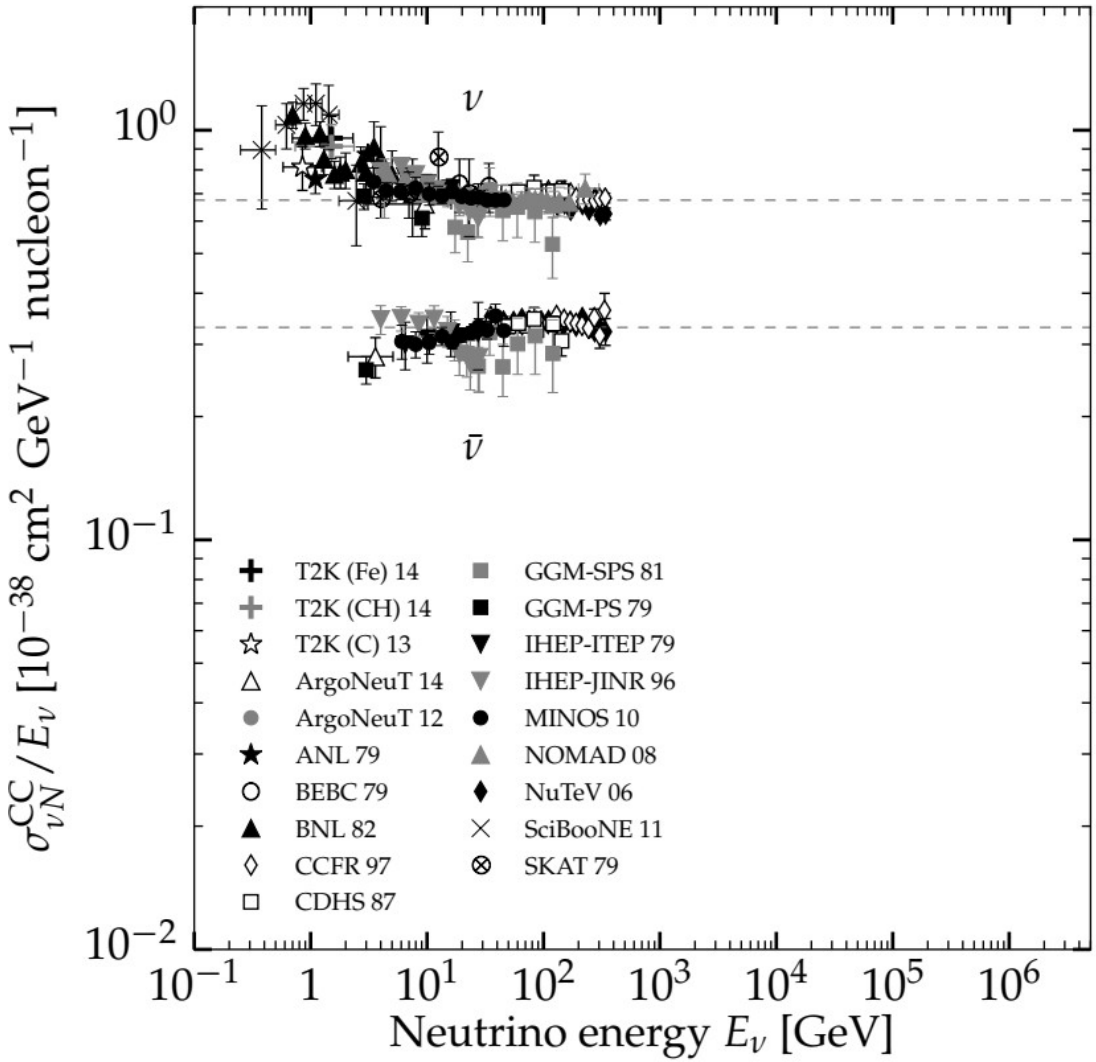

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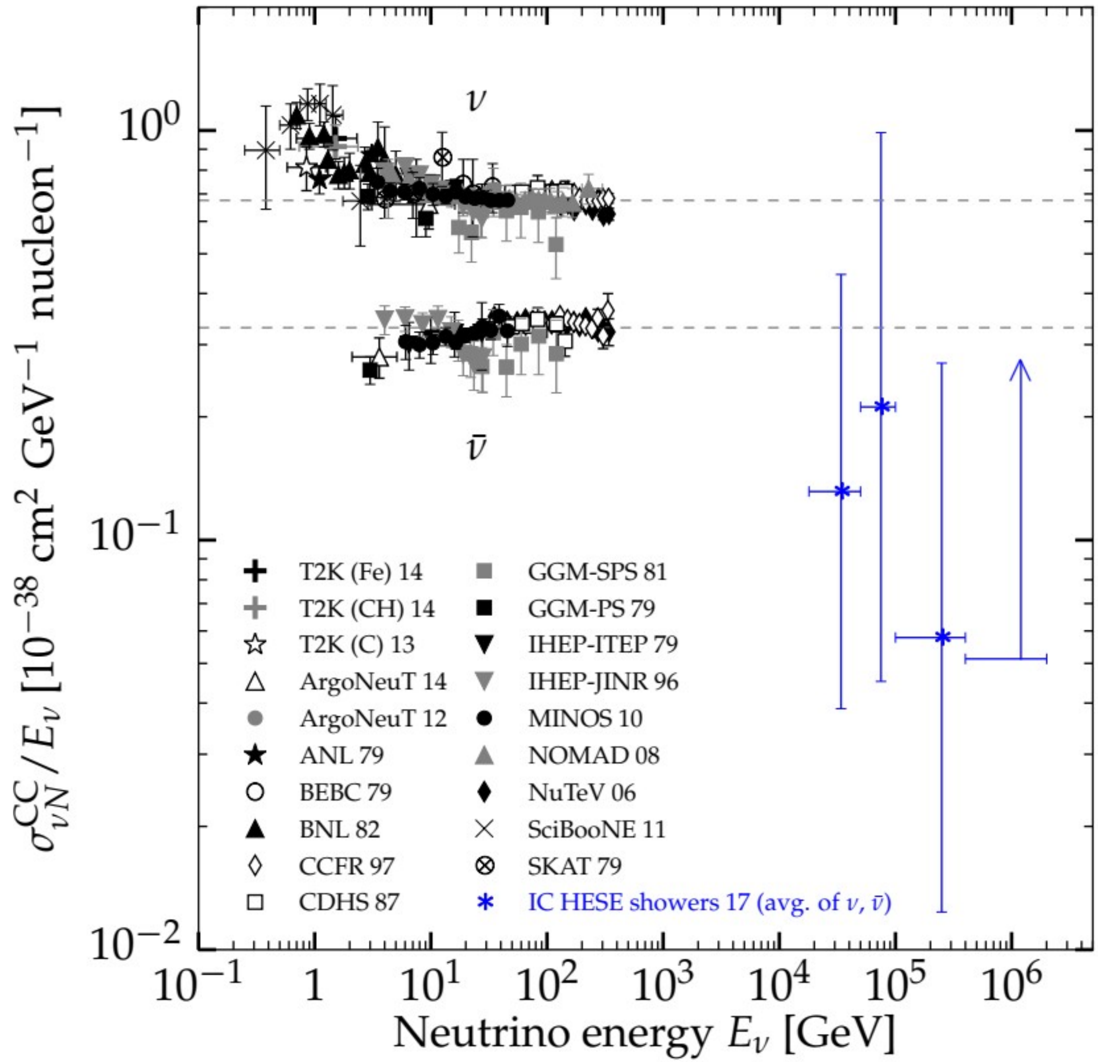

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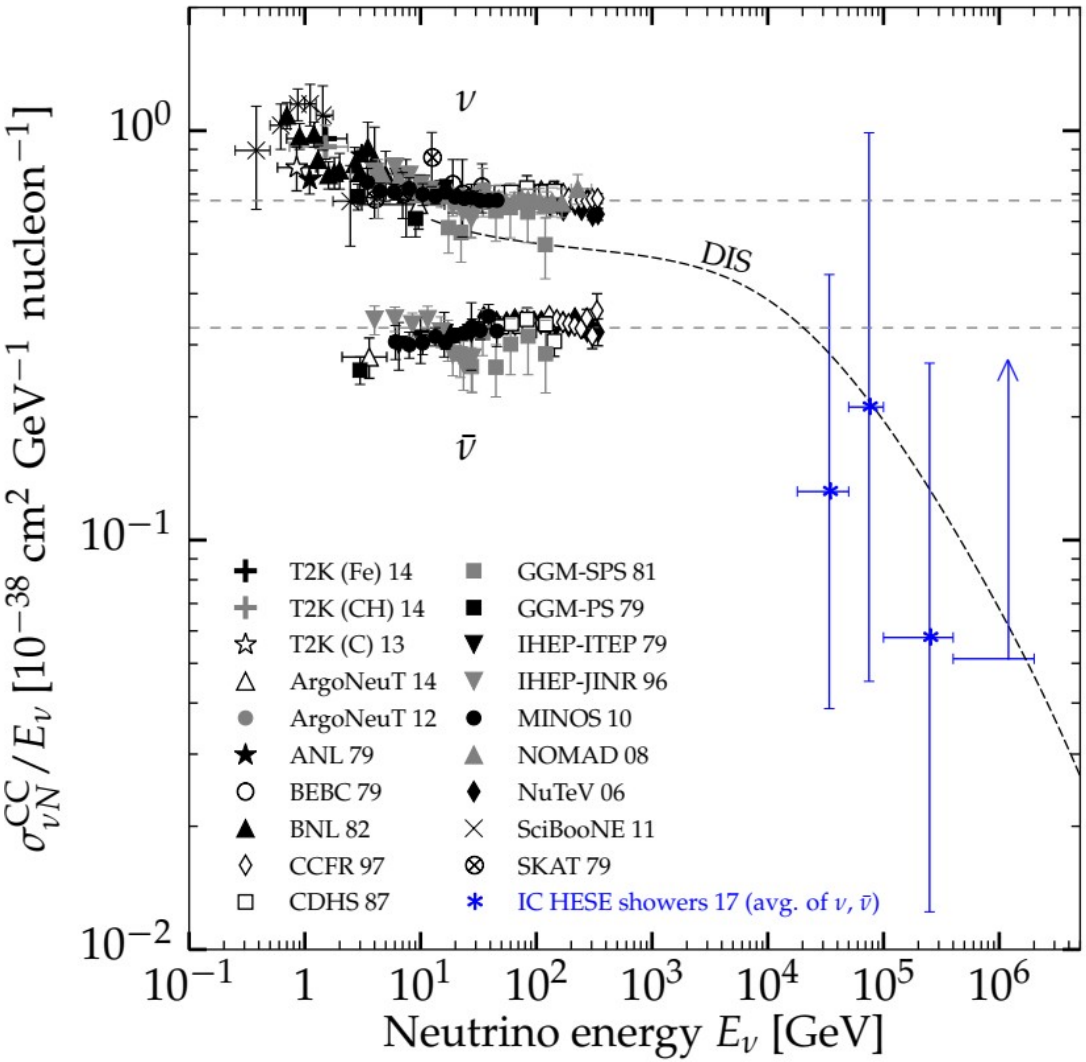
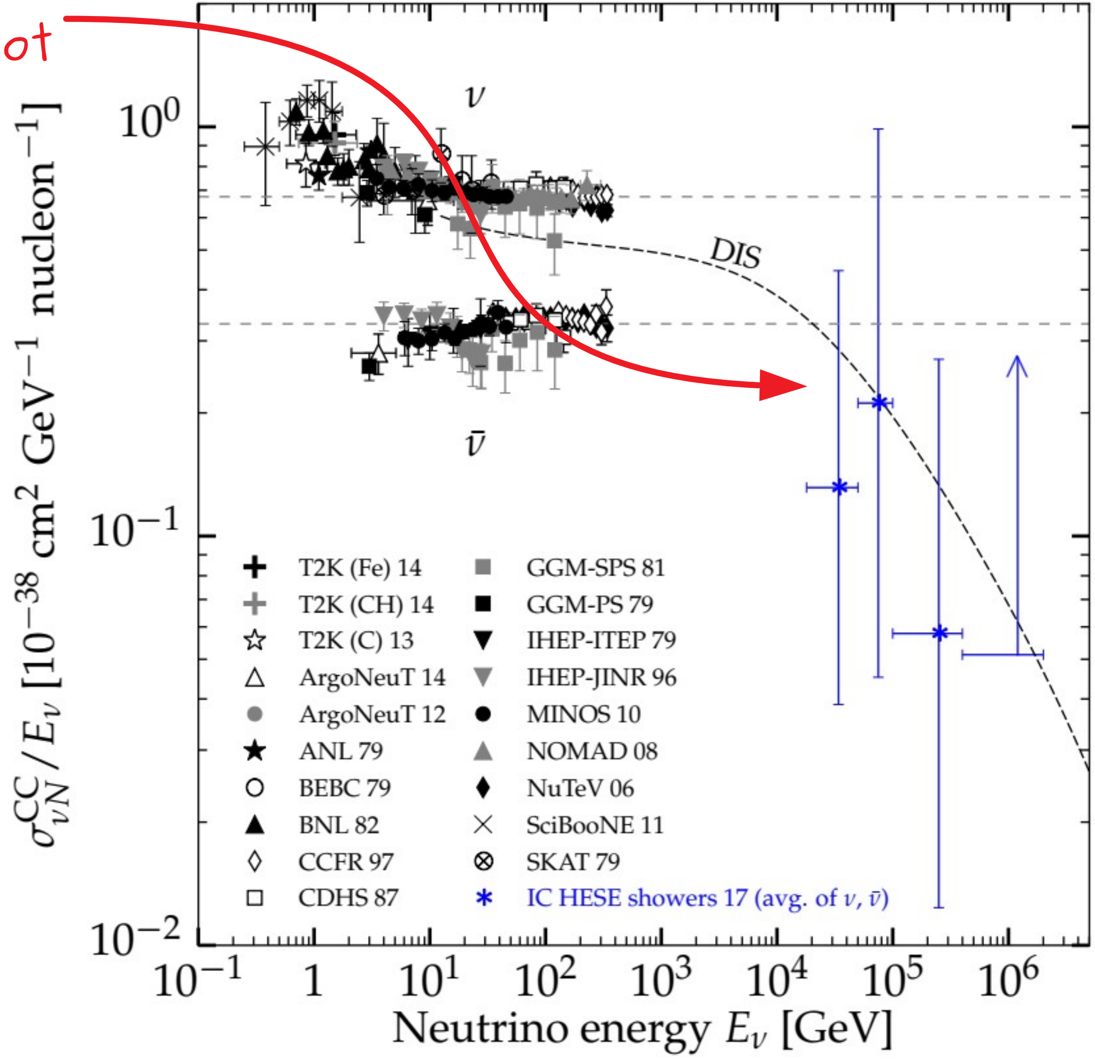


Extending the PDG cross-section plot

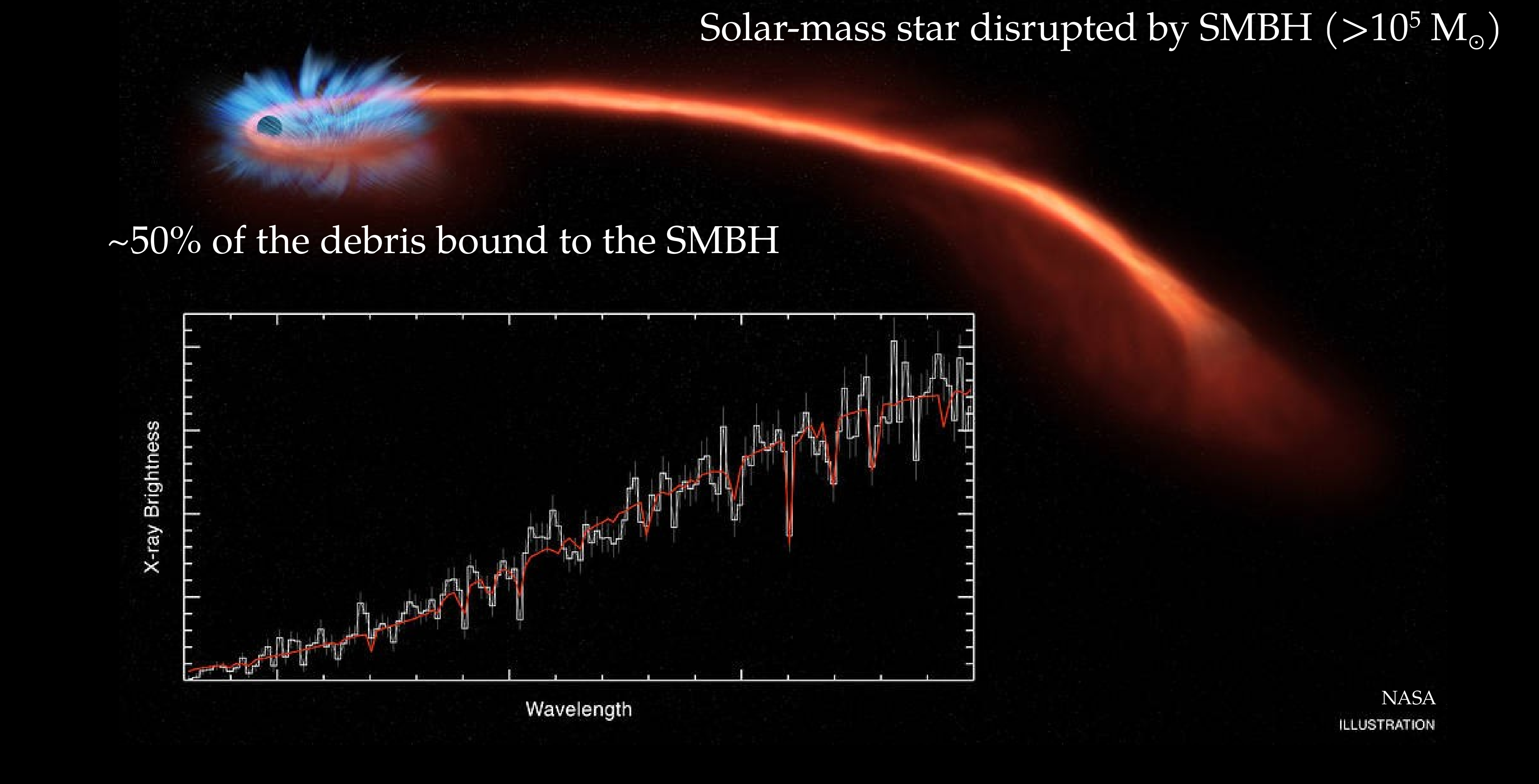


MB & A. Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  $\mapsto$ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  $\mapsto$ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  $\mapsto$ Following Standard-Model predictions, we take $\sigma_{\rm NC} = \sigma_{\rm CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  $\mapsto$ We assume equal fluxes, expected from production via pp collisions
  $\mapsto$ We assume the avg. ratio $<\sigma_{\nu \rm N}/\bar{\sigma}_{\nu \rm N}>$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  $\mapsto$ We assume equal flux of each flavor, compatible with theory and observations

Tidal disruption events



Tidal disruption events

- Mid-to-heavy star chemical composition might explain Auger composition
- Particles produced in internal collisions in jet (only 2 jetted TDEs seen so far)
- Inject ^{14}N and model nuclear cascades in jet
- TDEs follow the redshift evolution of SMBHs
- Fit to Auger UHECR spectrum + composition

$\sim(1+z)^{-3}$

See also: Lunardini & Winter, *PRD* 2017; Dai & Fang, *MNRAS* 2017; Guépin *et al.*, 1711.11274; Zhang, Murase, Oikonomou, Li, *PRD* 2017; Senno, Murase, Meszaros, *ApJ* 2017

Biehl, Boncioli, Lunardini, Winter, 1711.03555

Tidal disruption events

Baryonic loading

Local rate of jetted TDEs

$$G \equiv \xi_A \cdot \frac{\tilde{R}(0)}{0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}}$$

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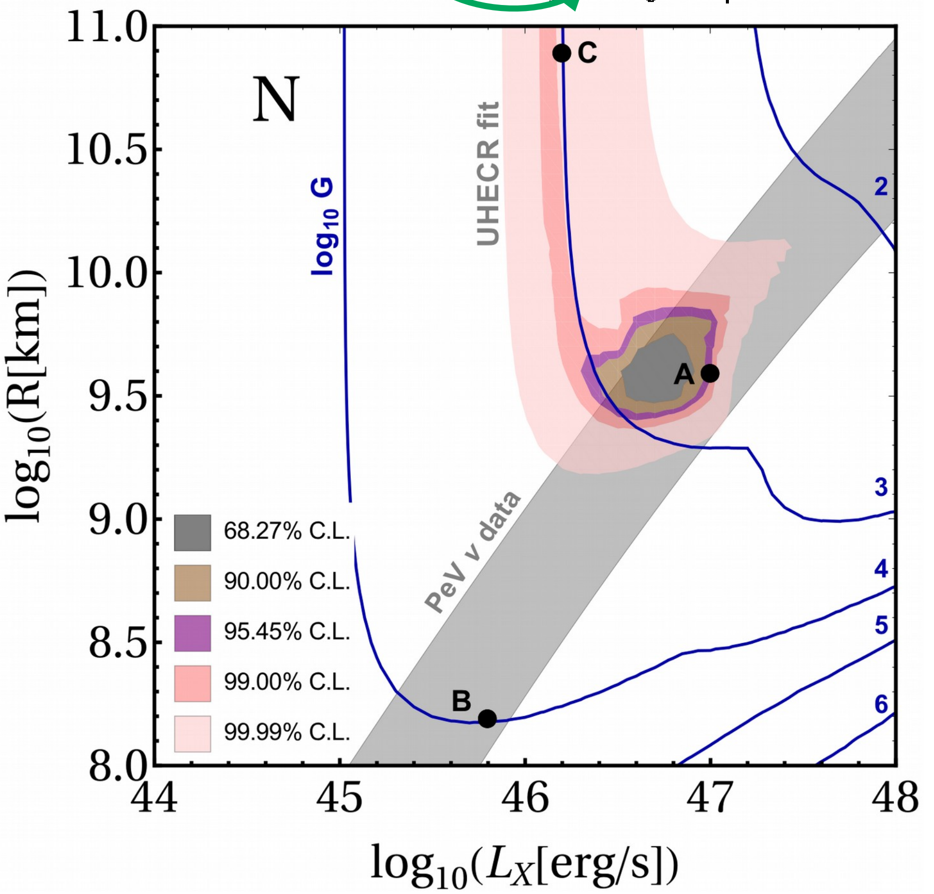

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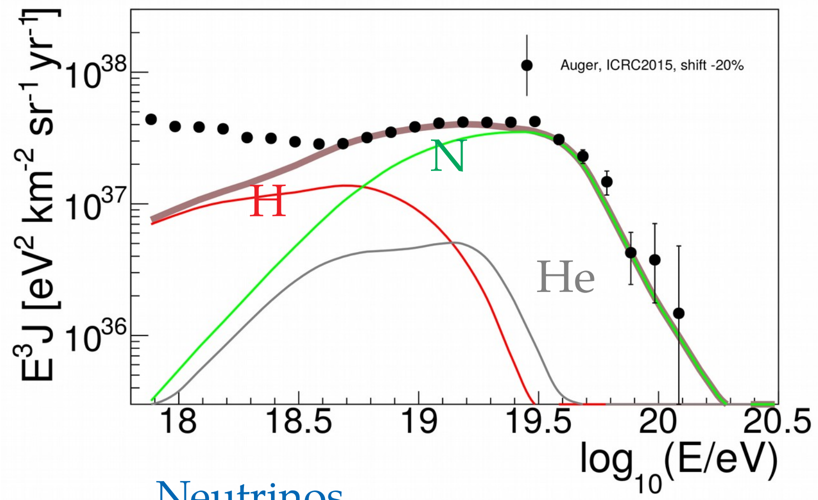
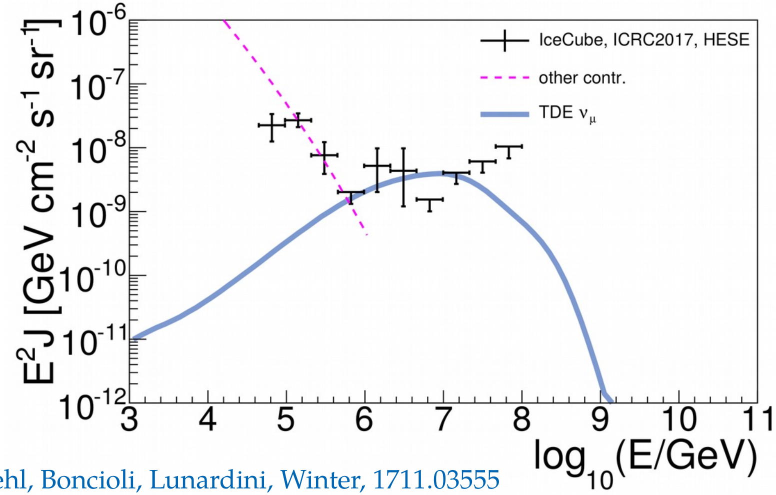
Cosmic rays



Neutrinos



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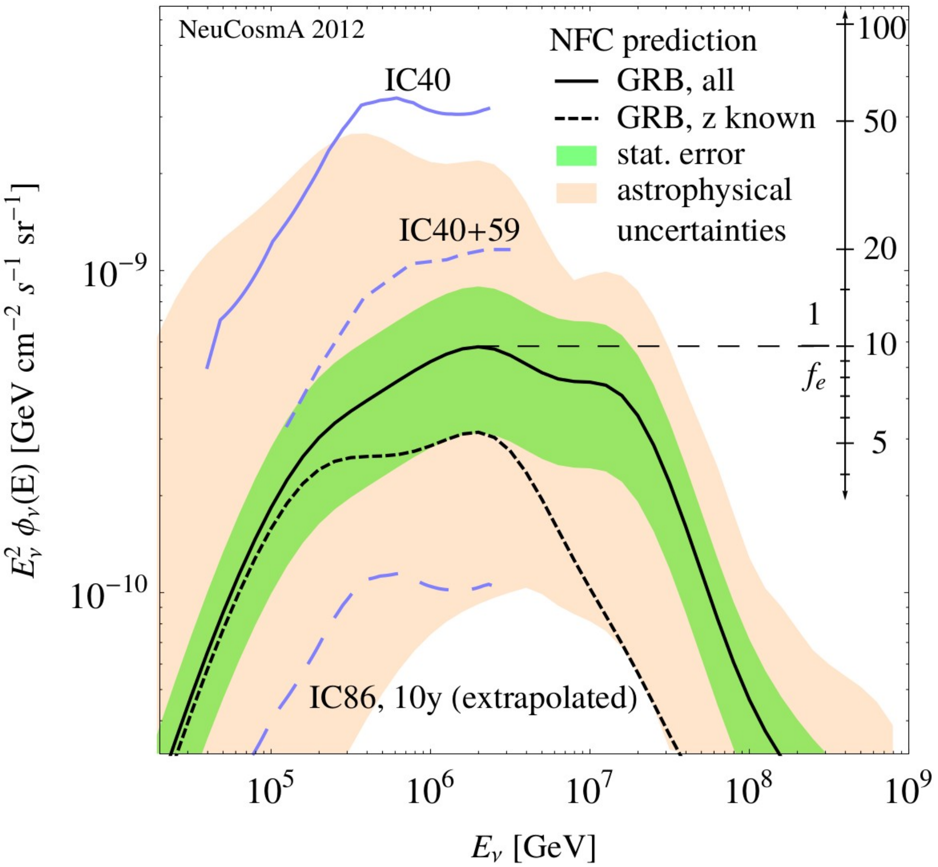
Diffuse flux of neutrinos from GRBs

- How do we estimate it?
- Compute the expected ν fluence from a sample of $N_{\rm obs}$ observed GRBs
- Stack the fluences to obtain the total F_ν
- Quasi diffuse flux:

$$\phi_\nu(E_\nu) = F_\nu(E_\nu)\,\frac{1}{4\pi}\,\frac{1}{N_{\rm obs}}\,\frac{667\ \text{bursts}}{\text{yr}}$$

($N_{\rm obs} = 117$ in the plot)

S. Hümmer, P. Baerwald, & W. Winter, *PRL* 2012



Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

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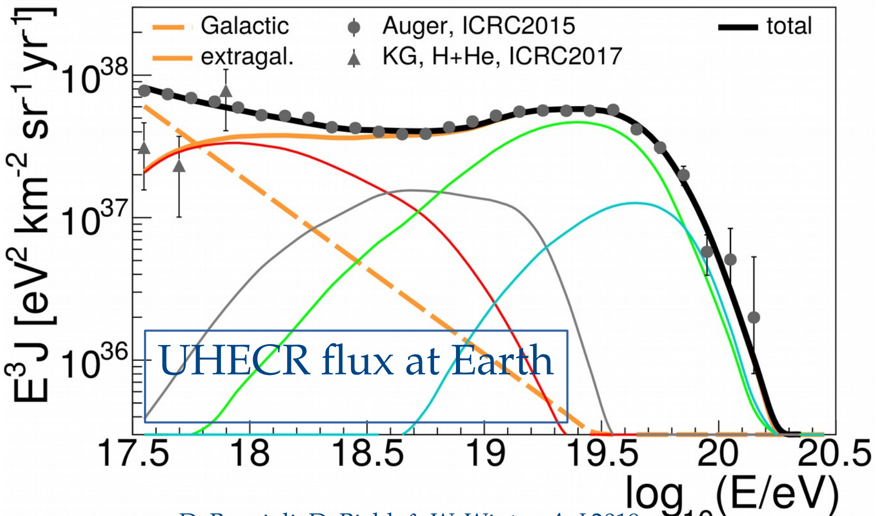

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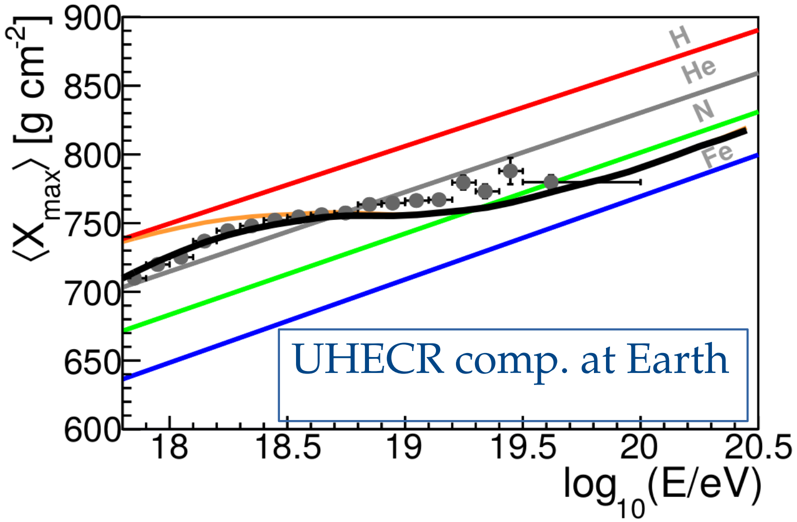

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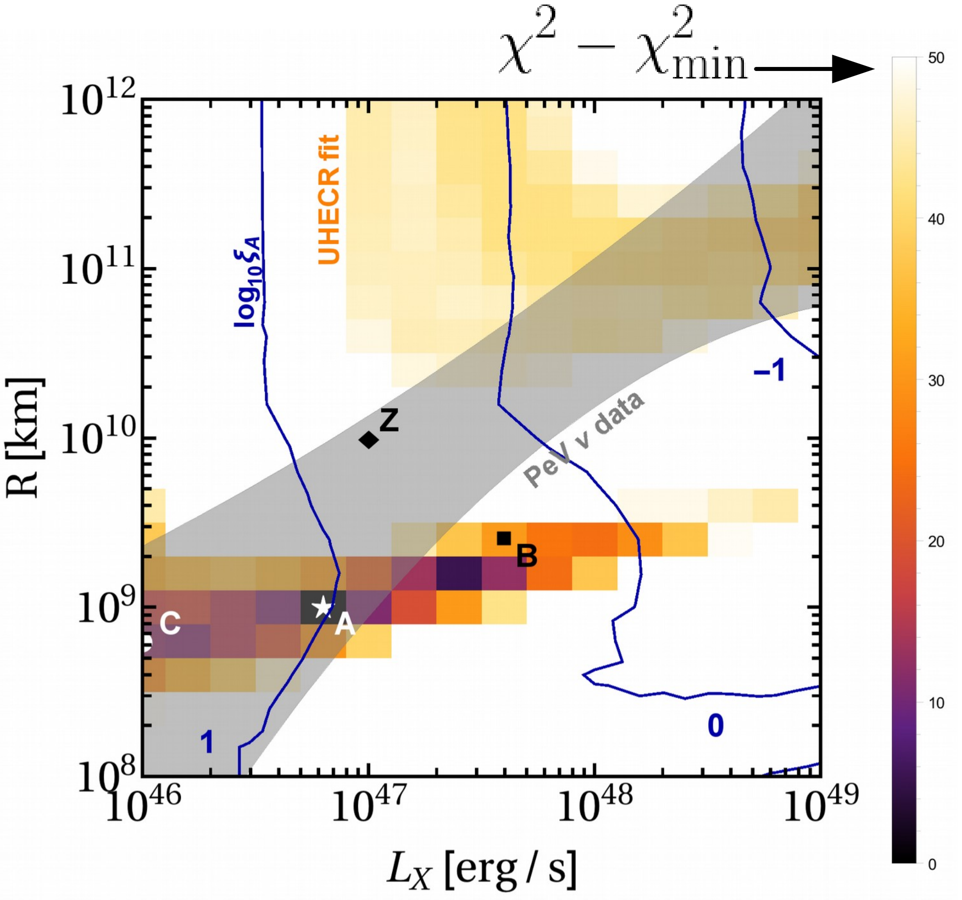


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

Neutrino zenith angle distribution

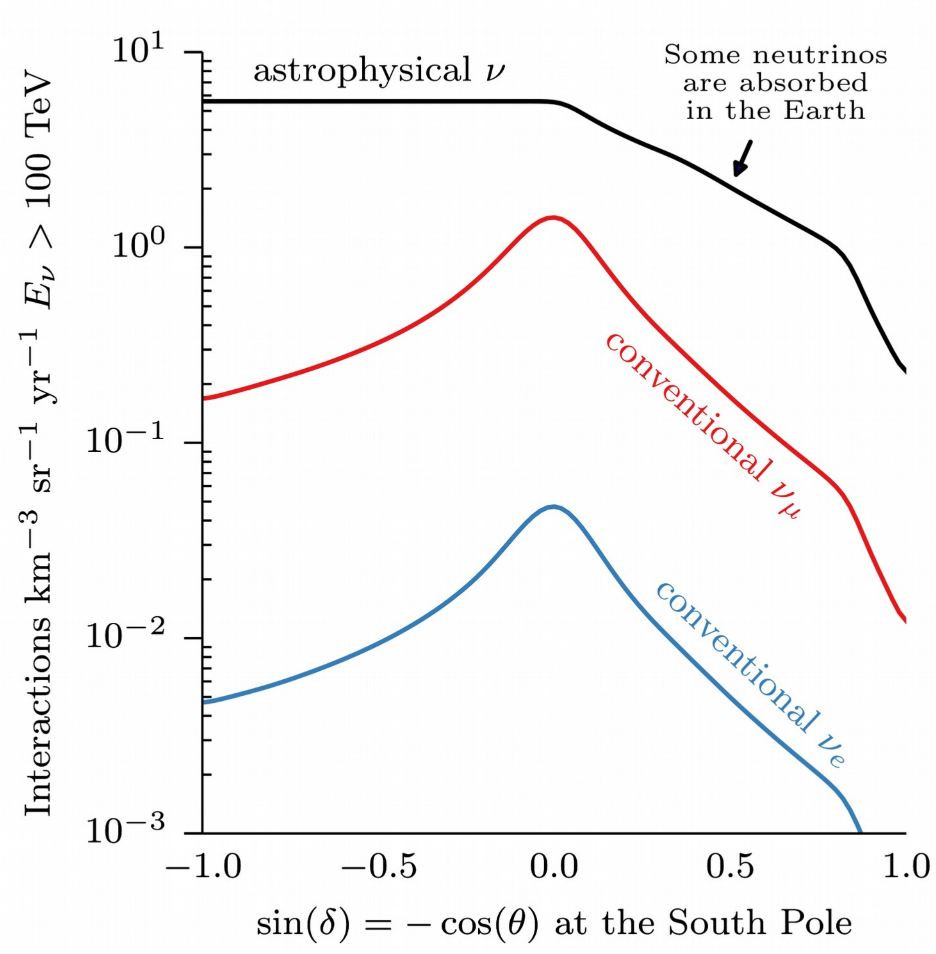
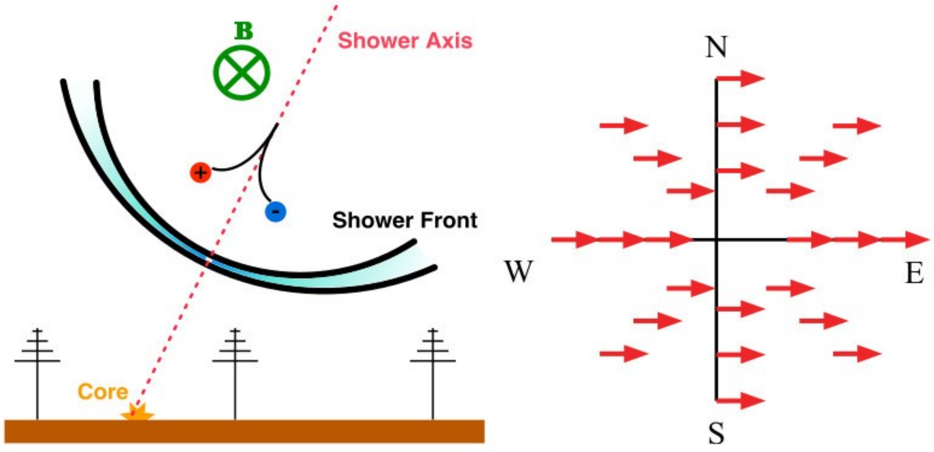


Figure by
Jakob Van Santen
ICRC 2017

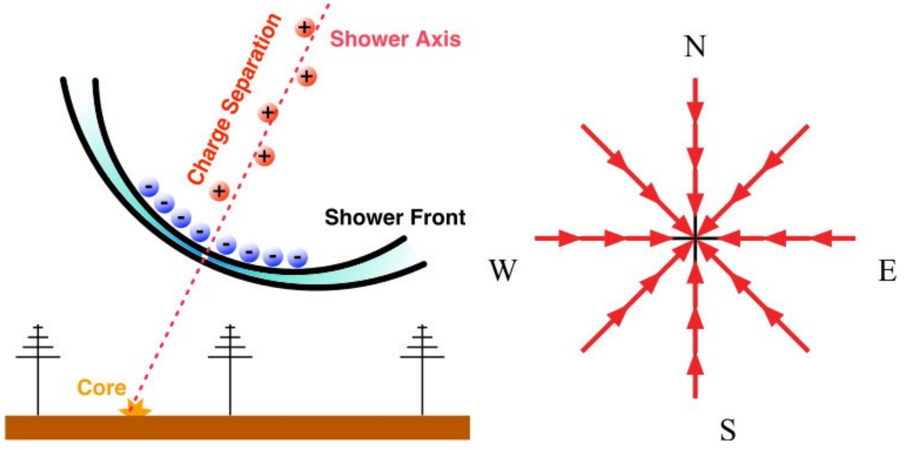
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

Askaryan



- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

Figures by H. Schoorlemmer and K. D. de Vries

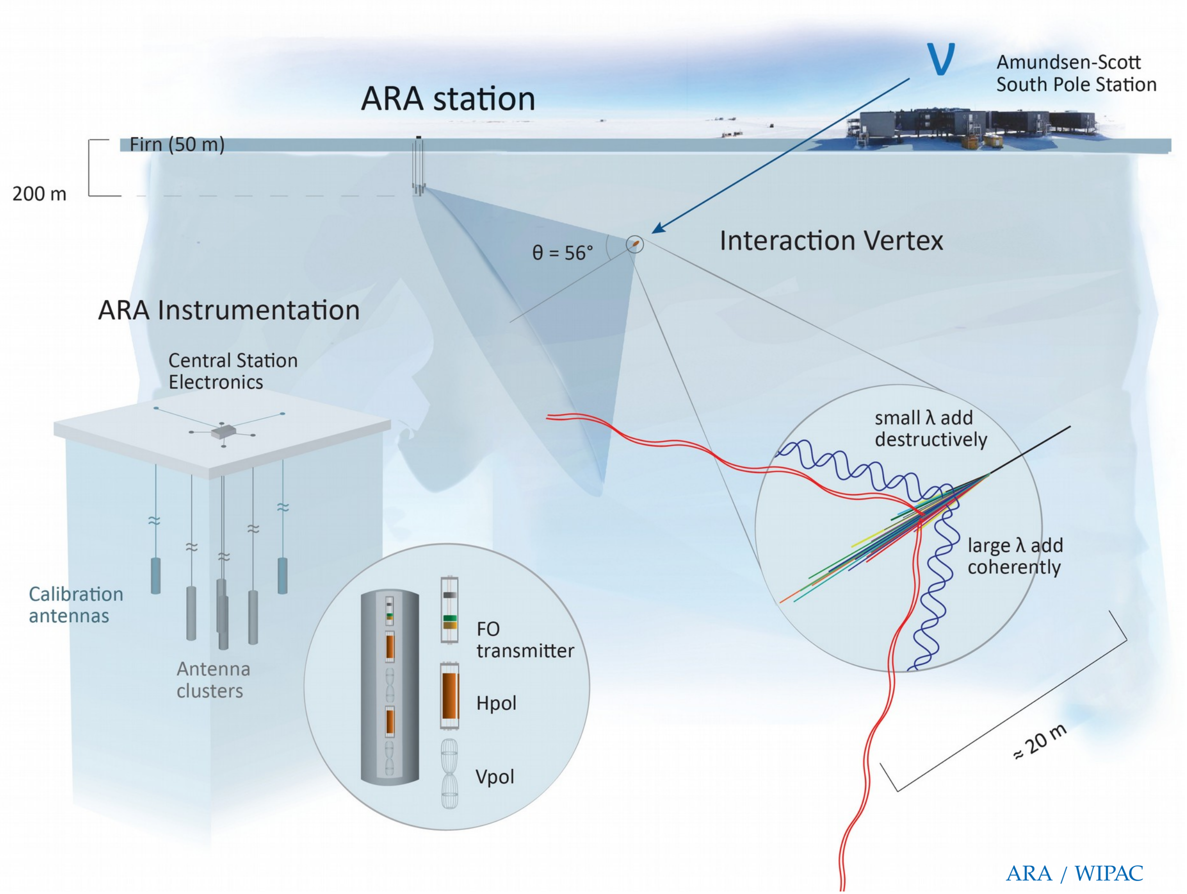
Radio emission: geomagnetic and Askaryan

Radio-detection of UHE neutrinos in ice

- Radio attenuation length in ice: few km ($vs.$ 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

No ν detected yet

(But UHECRs detected regularly!)

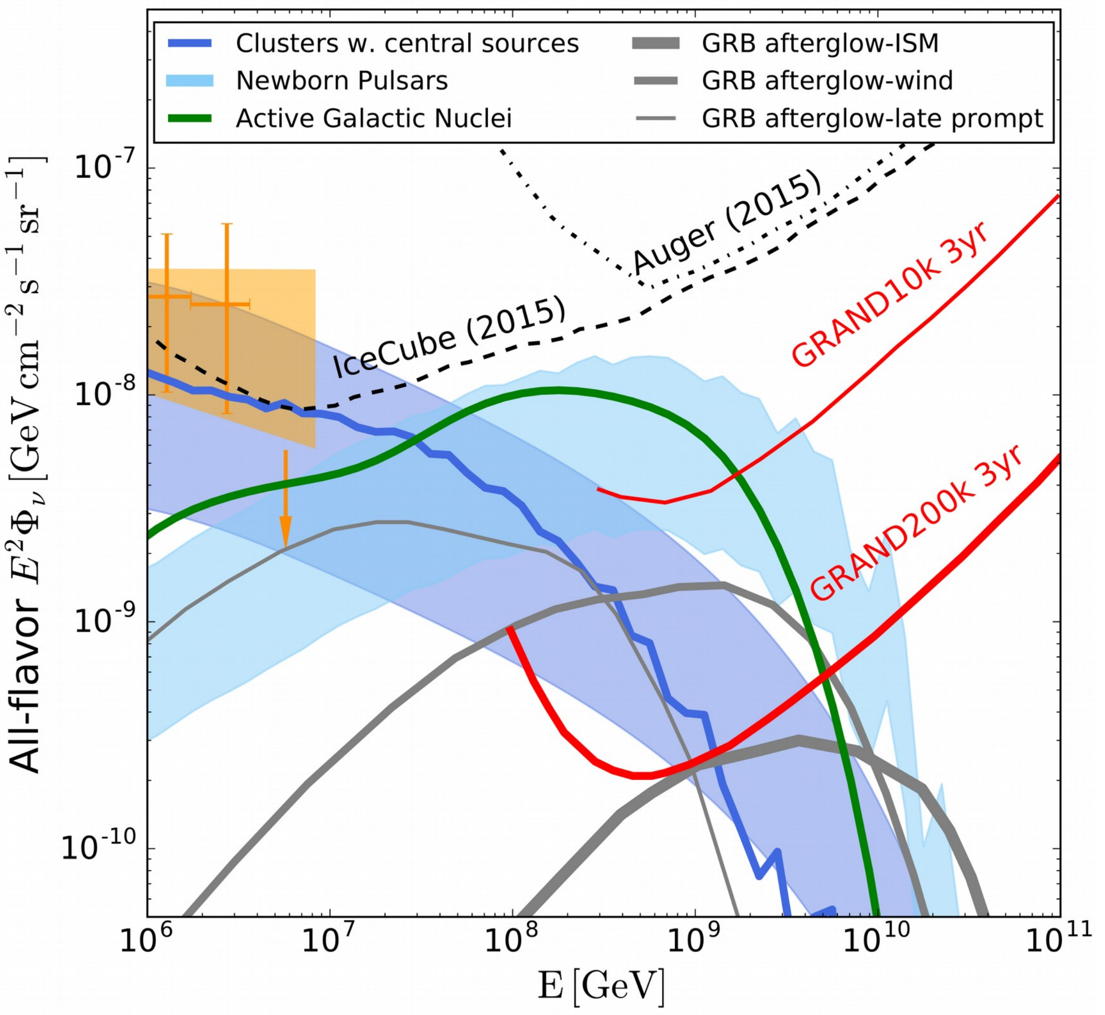


ARA / WIPAC

Astrophysical UHE neutrinos

- Diffuse flux of astrophysical UHE ν may exceed the cosmogenic flux
- First UHE ν seen may be astrophysical
- A few possibilities:
  - Galaxy clusters with central sources
    Murase, Inoue, Nagataki, *ApJ* 2008
    Fang & Murase, *Nat. Phys.* 2017
  - Fast-spinning newborn pulsars
    Fang, Kotera, Murase, Olinto, *PRD* 2014
  - Active galactic nuclei
    Murase, *Neutrino astronomy*, 1511.01590
  - GRB afterglows
    Murase, *PRD* 2007

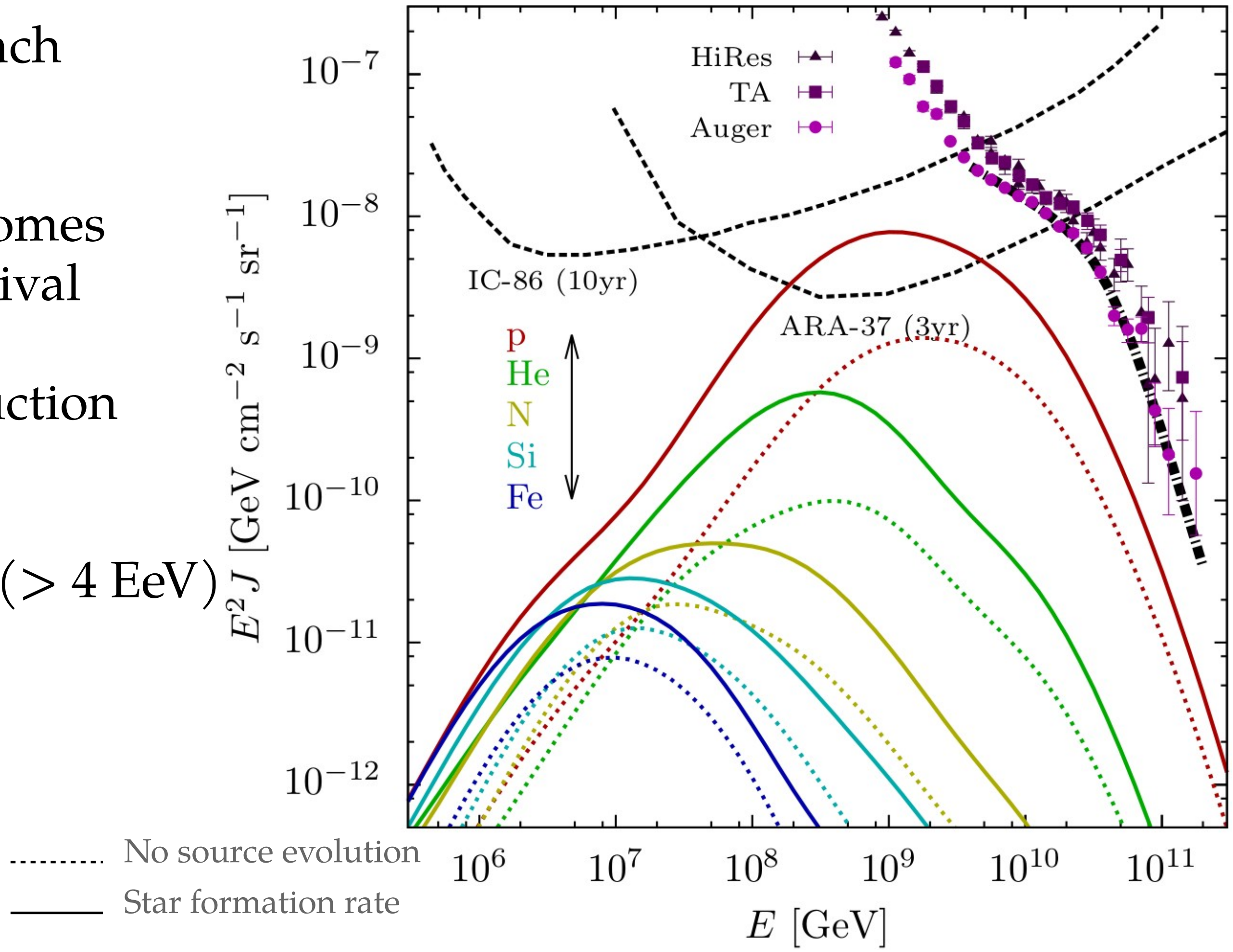
Plot by Ke Fang from GRAND: Science and Design



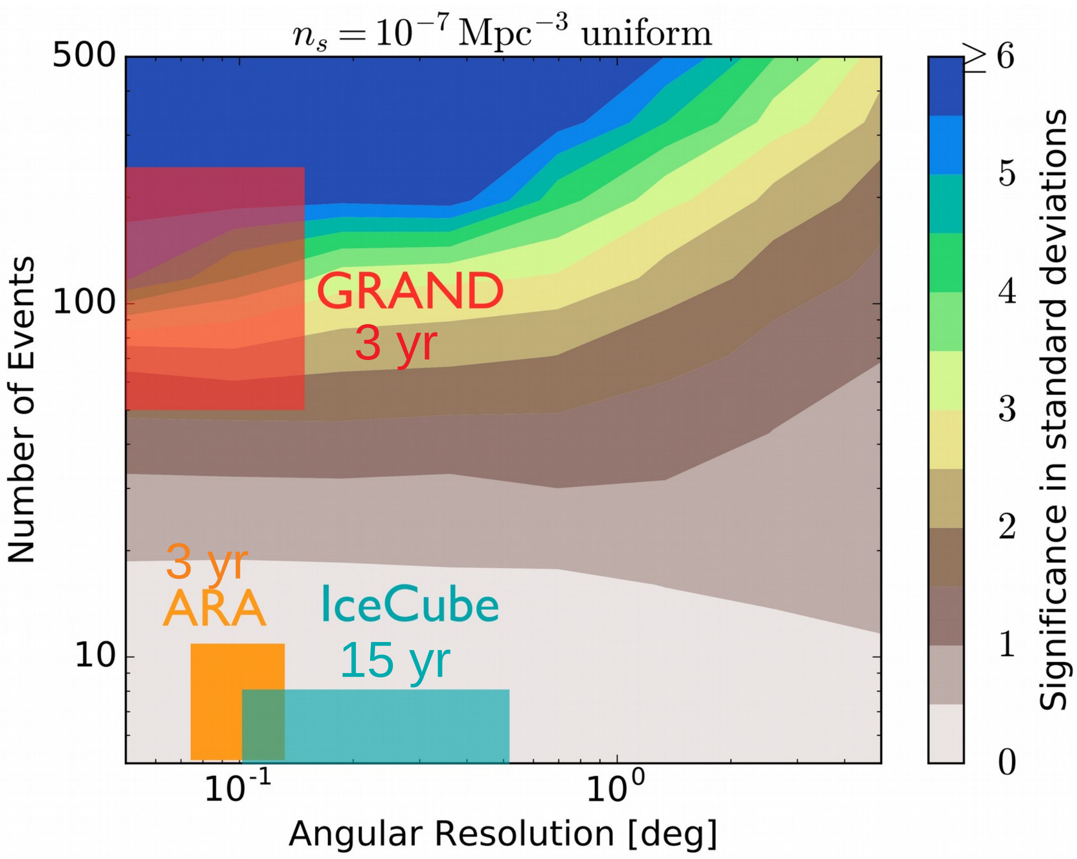
The Cosmogenic Neutrino Floor

Ahlers & Halzen, *PRD* 2012

- In a nucleus A of energy E, each nucleon has energy E/A
- Minimal cosmogenic ν flux comes from maximizing nuclei survival
- *I.e.*, from minimizing p production from photo-disintegration
- ν fluxes from UHECR nuclei (> 4 EeV) are presently beyond reach



Identifying UHE ν Point Sources



GRAND: Science and Design

- Look for event-count excesses within the point-spread-function
  [Fang *et al.*, *JCAP* 2016]
- Density n_s of equal-luminosity sources with uniform distribution (til 2 Gpc)
- E^{-2} point-source ν spectrum at EeV
- All-sky EeV point-source flux normalized to ~10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- Event rate between 1–10 EeV

Magnetic fields in GRBs

- Assuming gamma rays come from electron synchrotron:

$$B \approx \begin{cases} 10^5 \text{ G} & \text{in internal shocks } (10^8\text{–}10^{10} \text{ km}) \\ 1 \text{ G} & \text{in afterglow } (10^{11}\text{–}10^{13} \text{ km}) \end{cases}$$

A.M. Hillas, *Ann. Rev. Astron. Astrophys.* 1984; S. Hümmer *et al.*, *Astropart. Phys.* 2010
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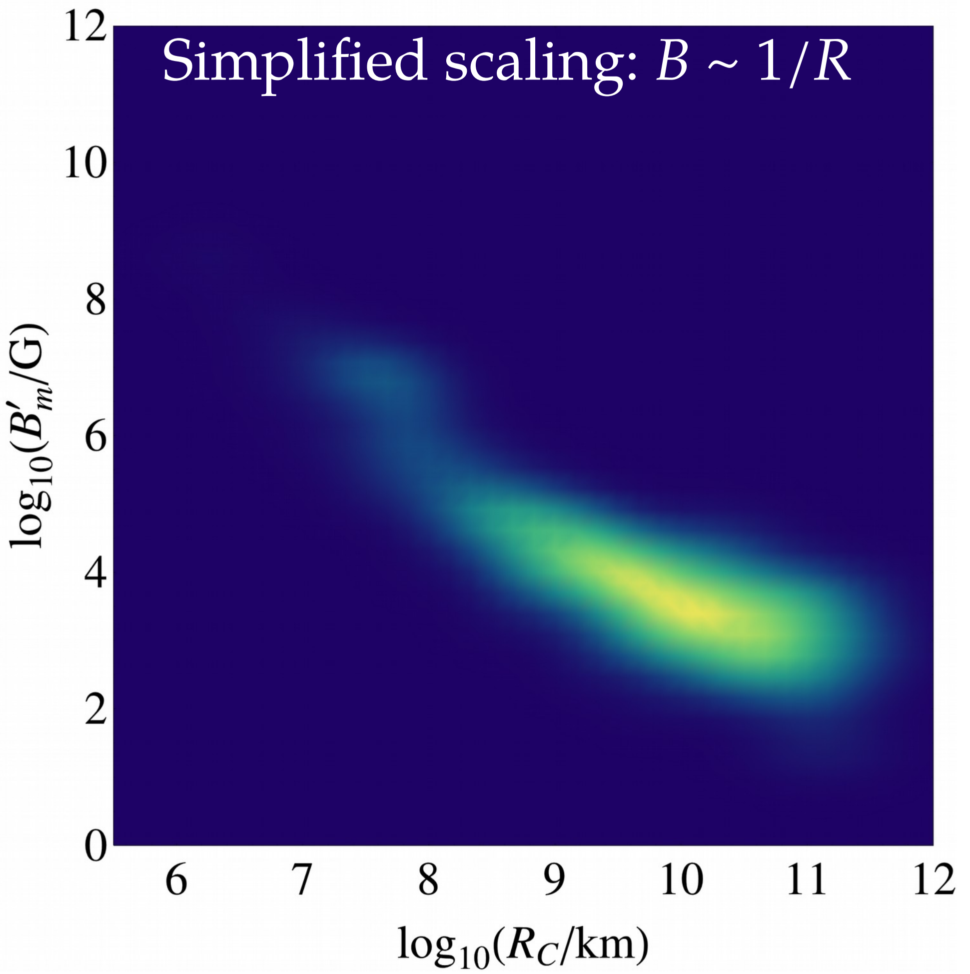

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- Hillas criterion:

  Larmor radius < Acceleration region

- To accelerate protons to 10^{11} GeV:

$$B \gtrsim 3 \cdot 10^{12} \left(\frac{\mathrm{km}}{R}\right)\ \mathrm{G}$$

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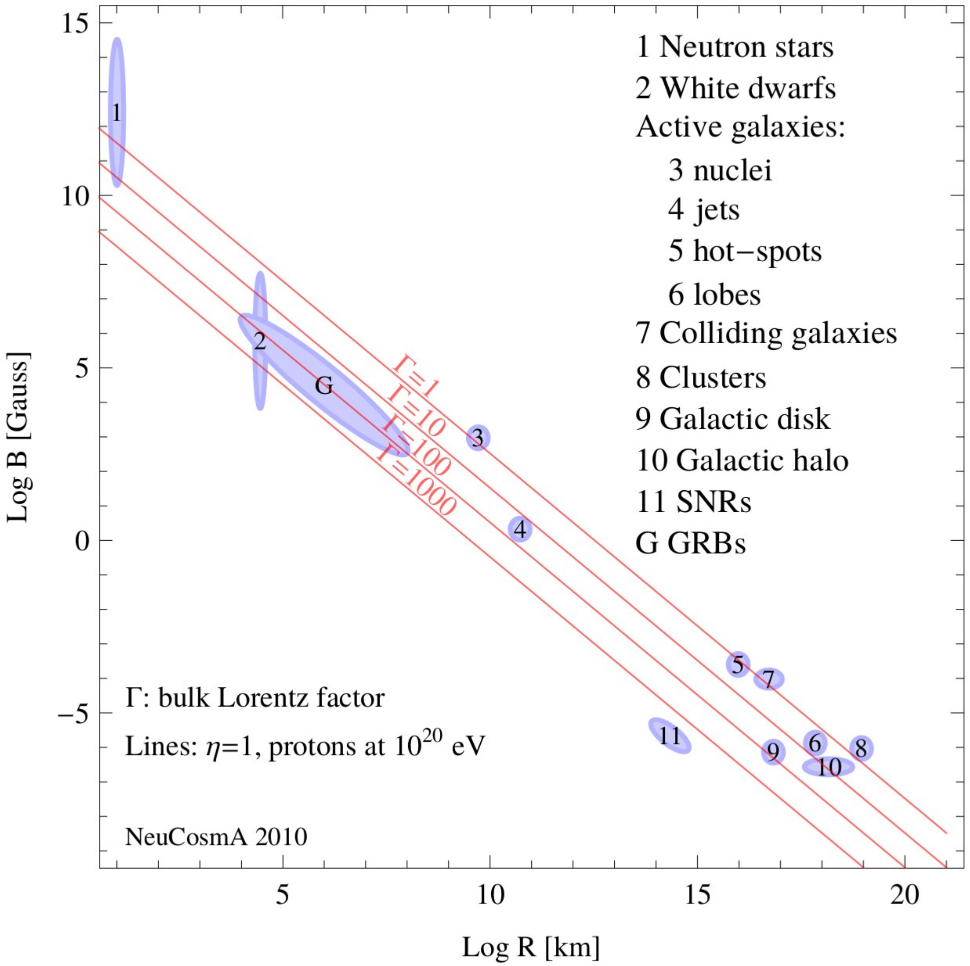

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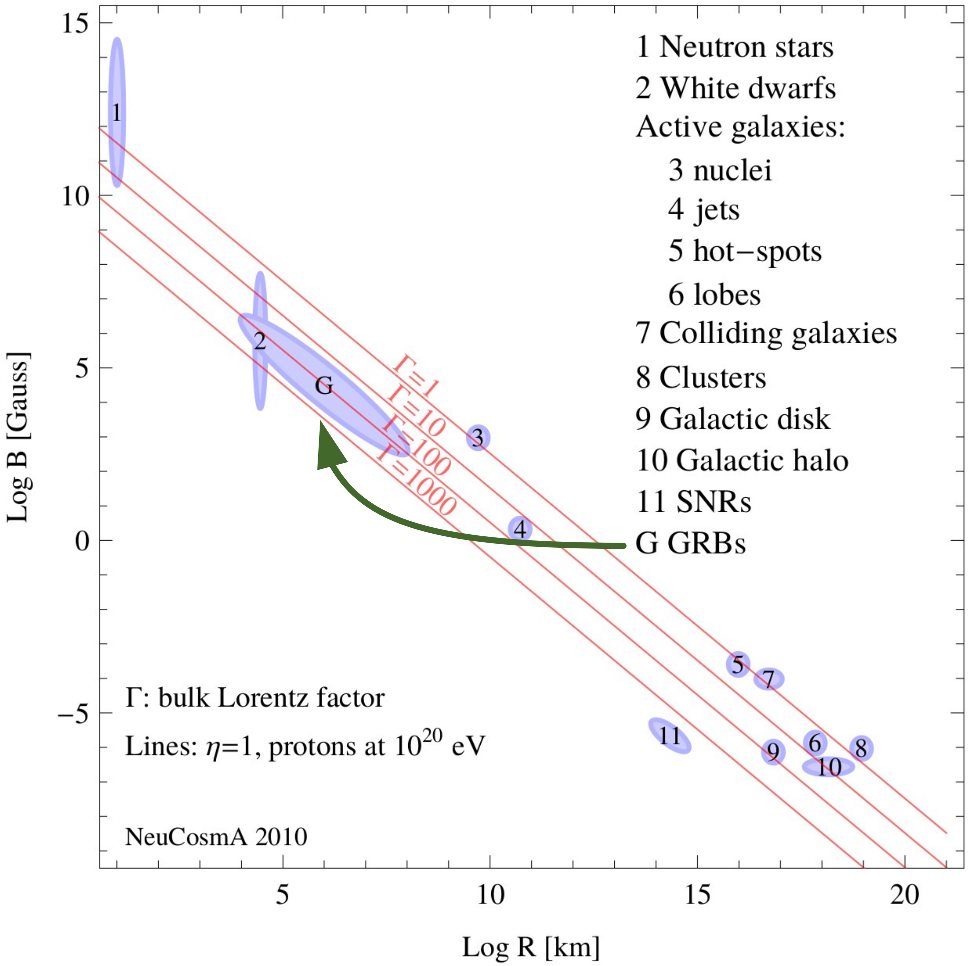

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What are the engines of GRBs?

Two requirements:

- High variability (~ms)
- Abundant available energy ($> 10^{51}$ erg)

C. Fryer *et al.*, 1904.10008

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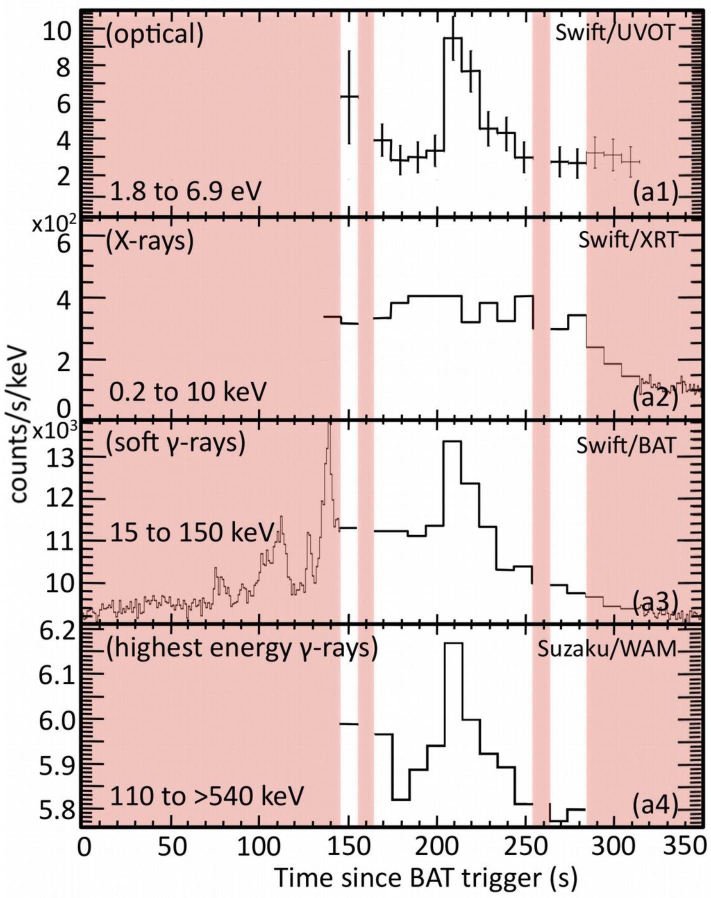
C. Fryer *et al.*, 1904.10008

Multi-wavelength emission

Unified model from optical to gamma-ray emission —



S. Guiriec *et al.*, *ApJL* 2016

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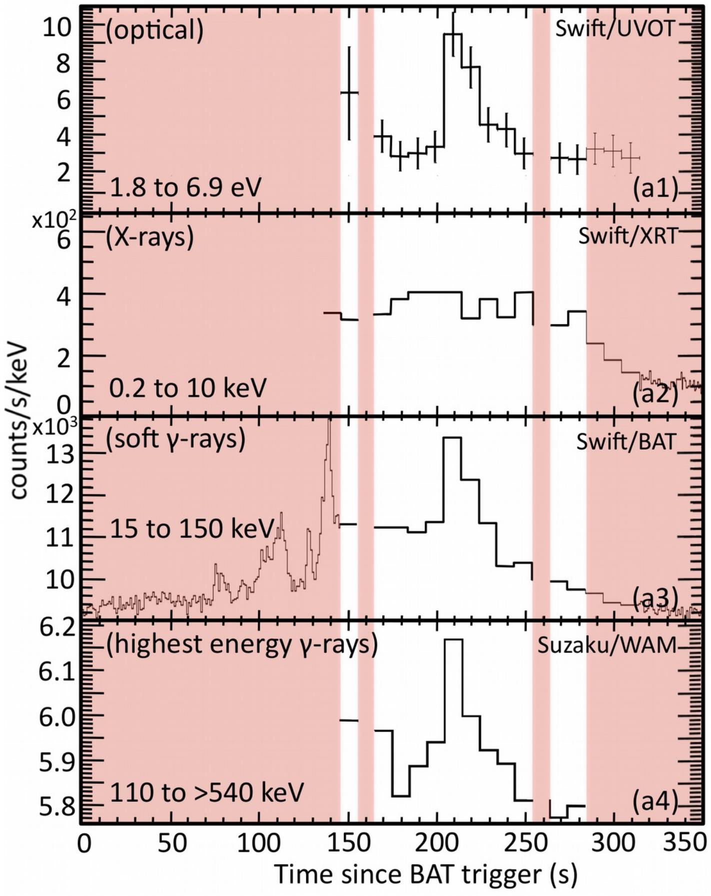

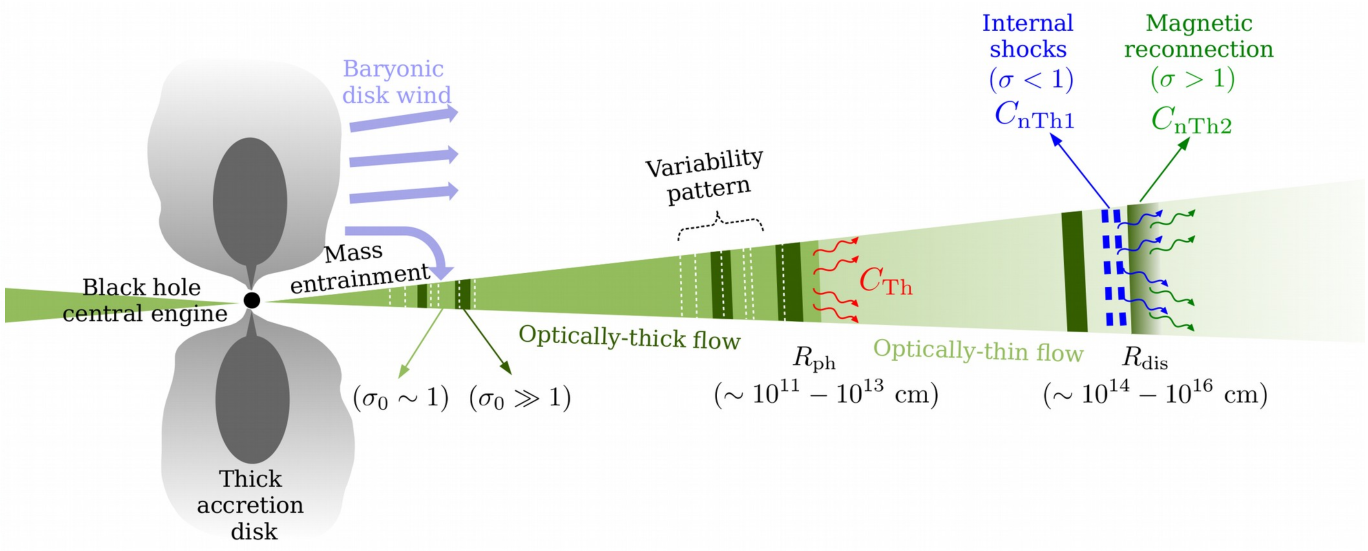

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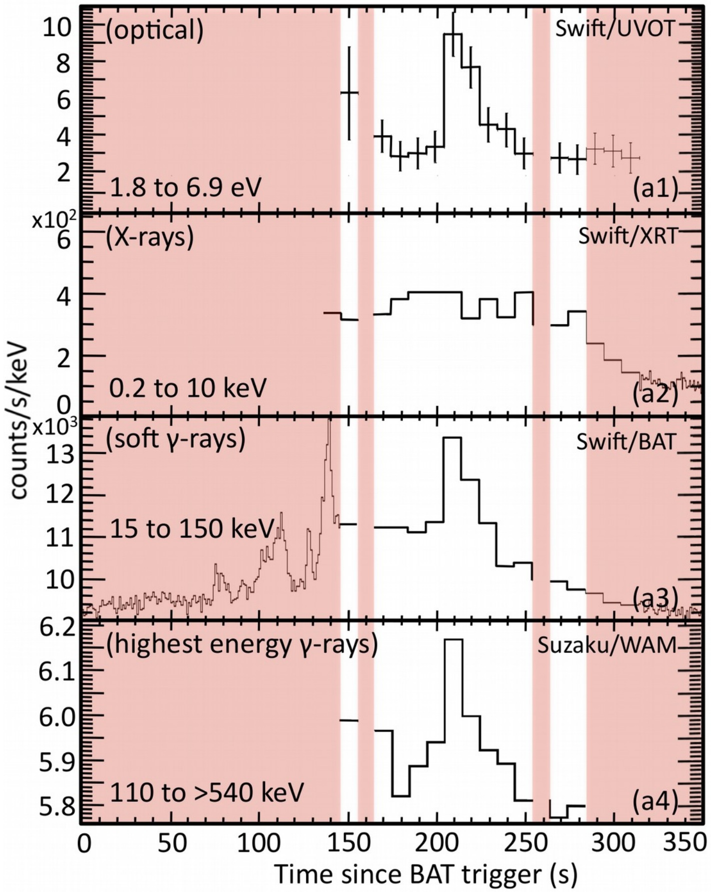

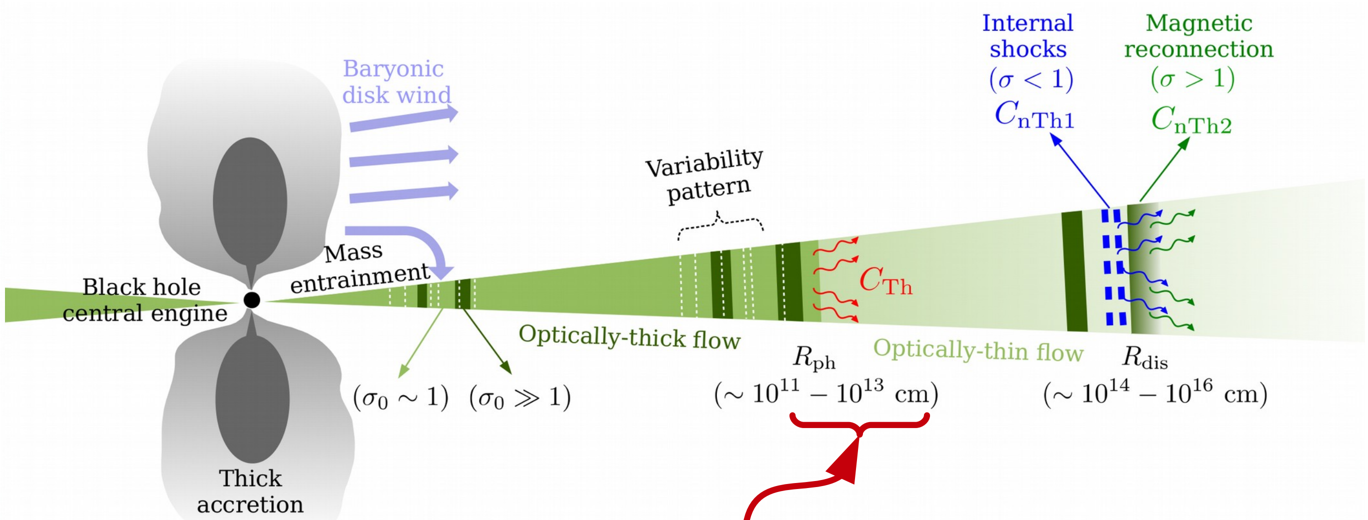

One early, photospheric thermal component

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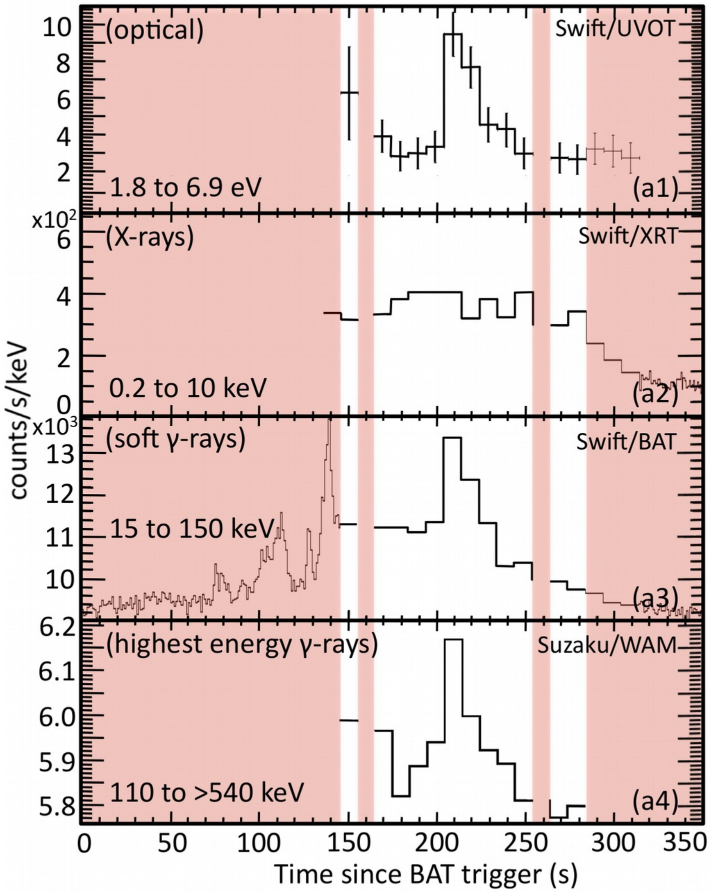
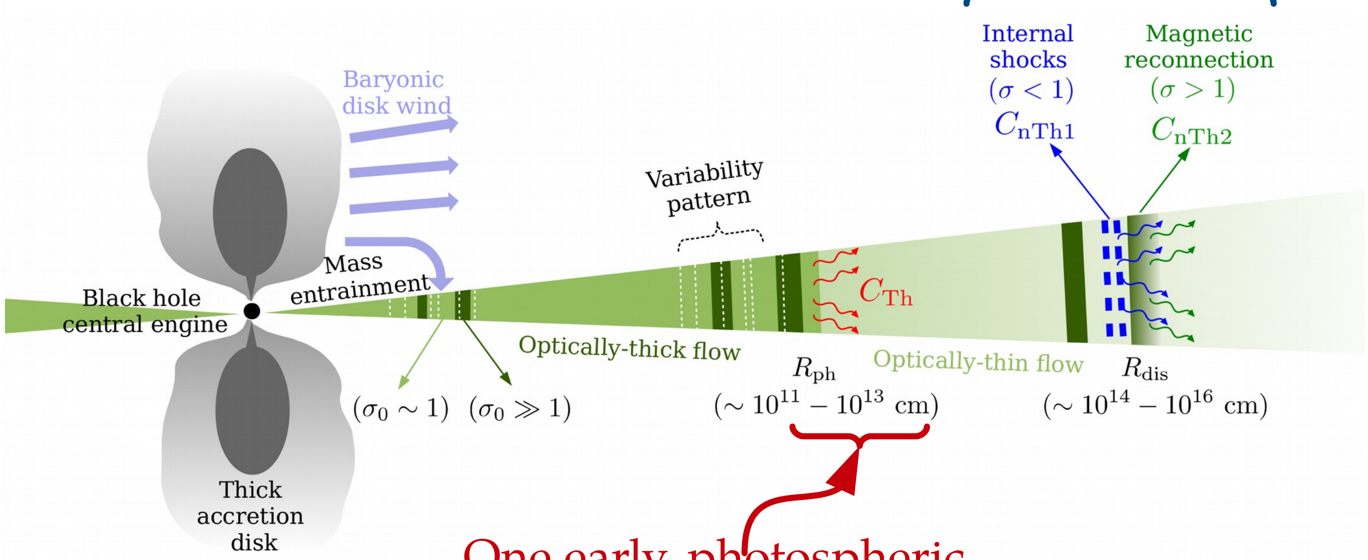


Two late non-thermal components



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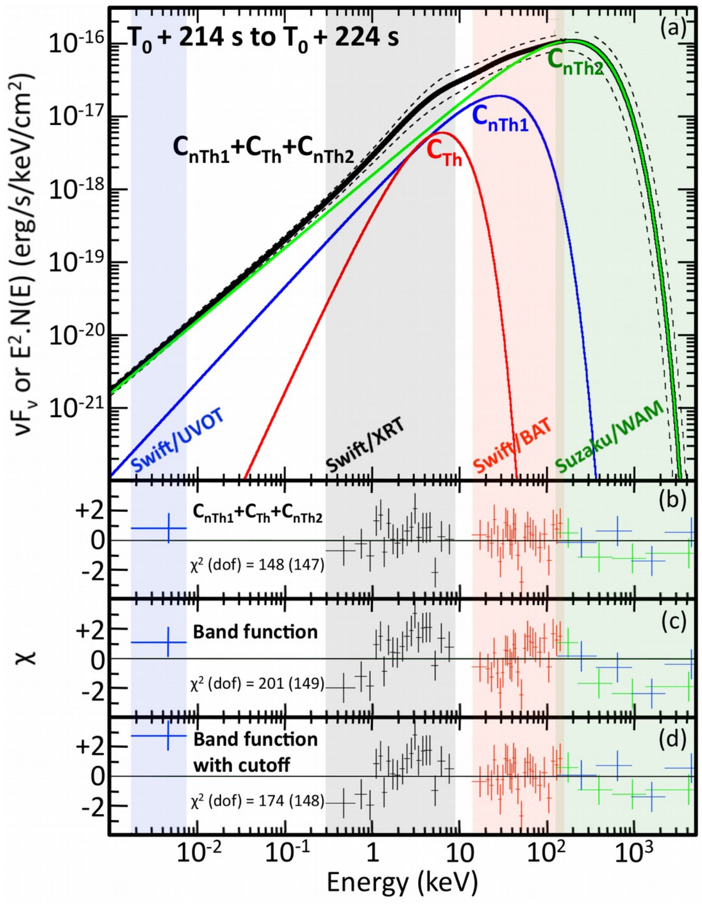

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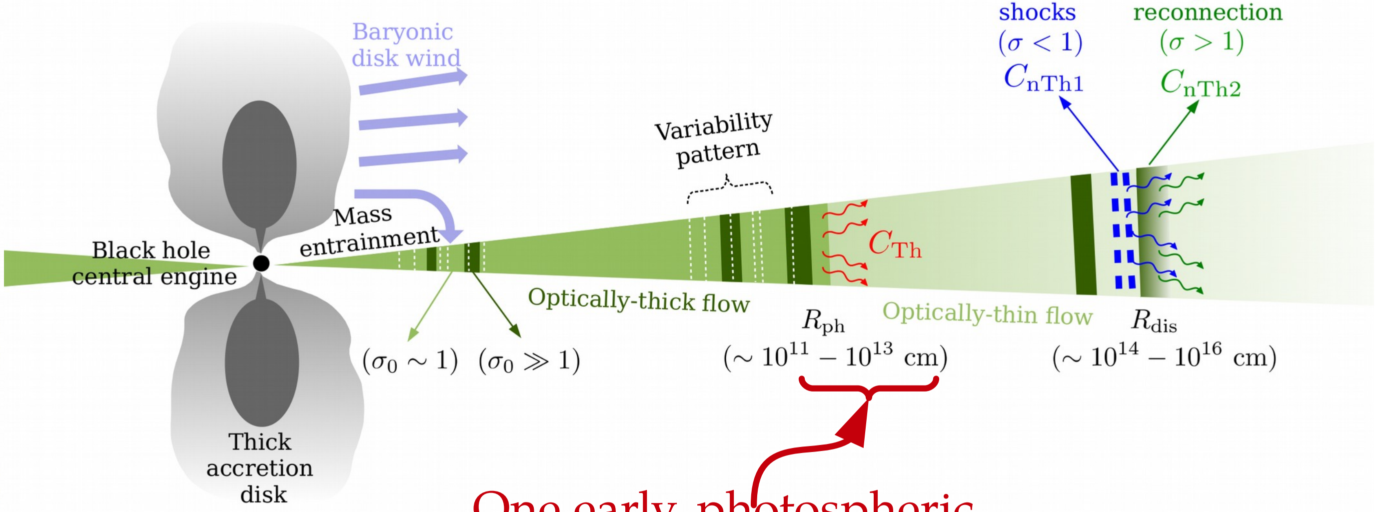

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Multi-component model of astrophysical neutrinos

- Four diffuse components:
  - Residual atmospheric (0.2–0.5 PeV):
    Conv. ($E^{-3.7}$) & prompt ($E^{-2.7}$) ν + muons
  - Galactic ν ($\lesssim$ PeV): *pp* with disc gas ($E^{-2.6}$), confined to $|b| < 5°$, $|l| < 45°$
  - Extragalactic ν from *pp*, *Ap*:
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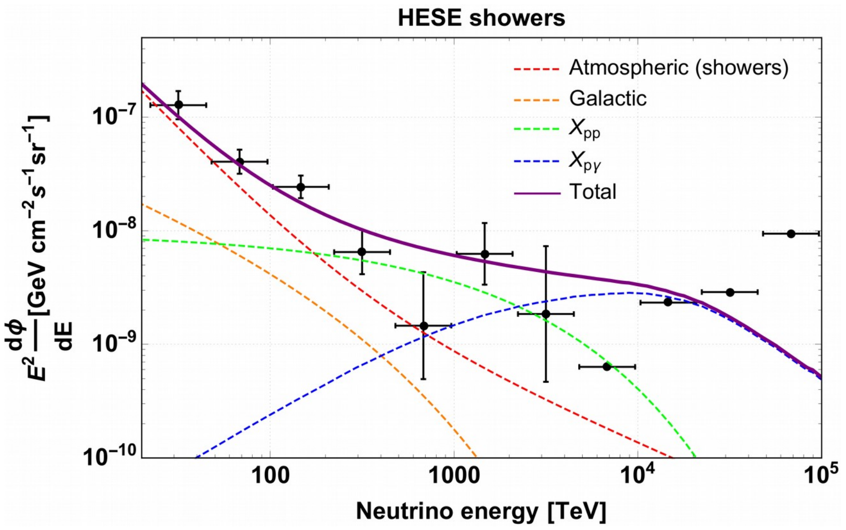

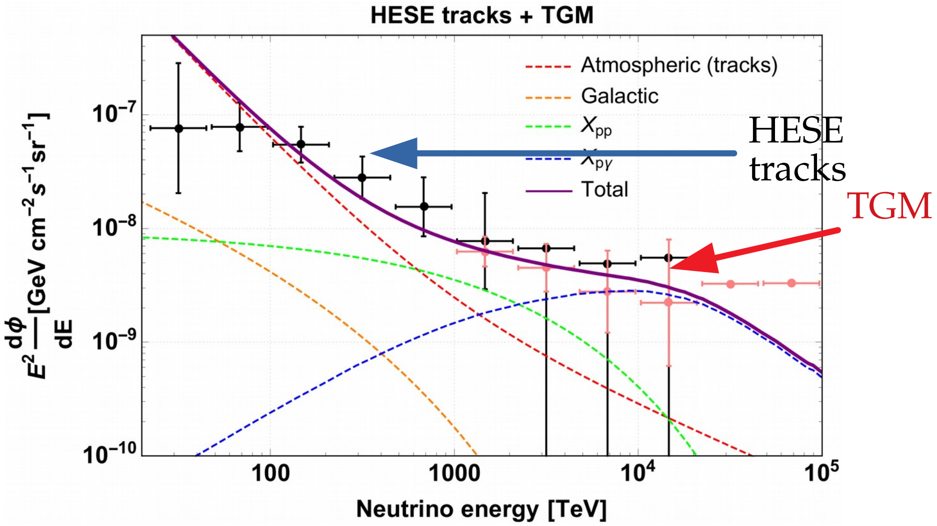

Palladino & Winter, 1801.07277

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Describes astrophysical ν better at low energies

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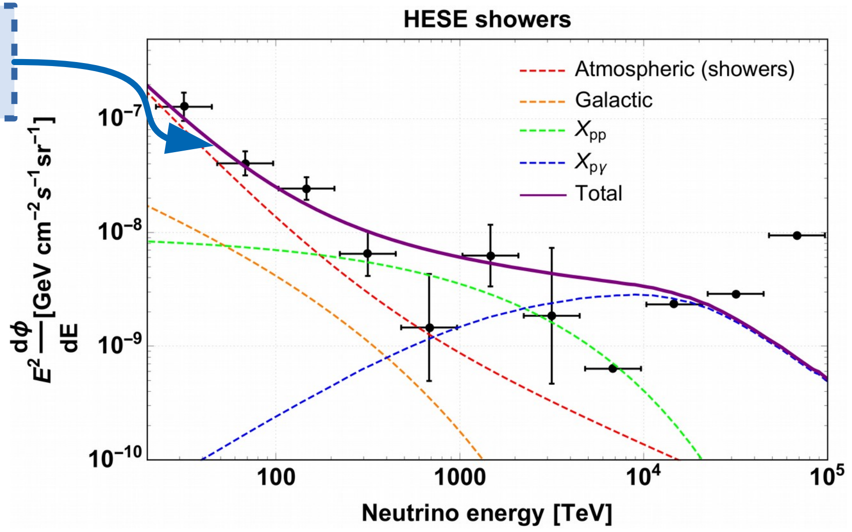

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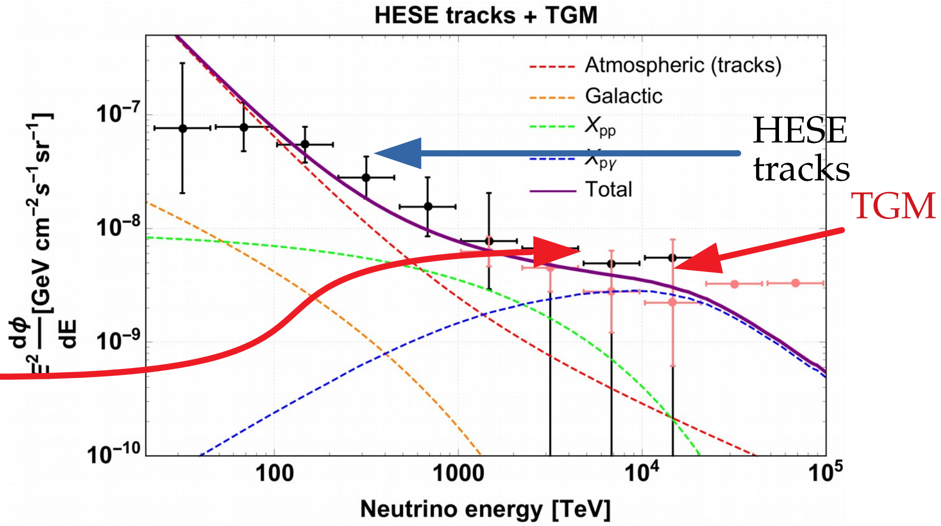

Describes astrophysical ν better at high energies

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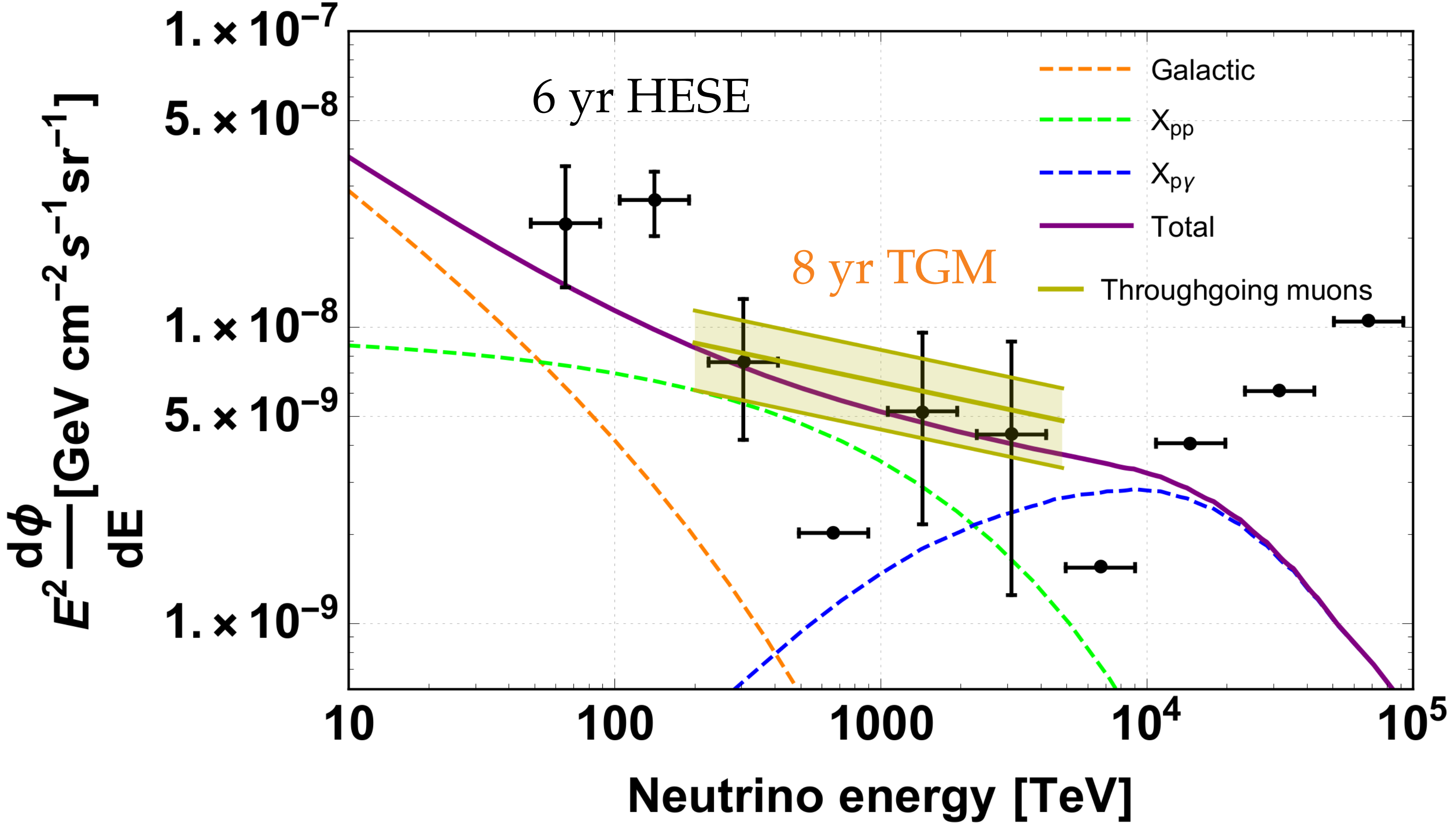


Palladino & Winter, 1801.07277

What lies beyond? *Take your pick*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]
  - General non-unitary propagation
    [Ahlers, **MB**, Mu, *PRD* 2018]

- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017]

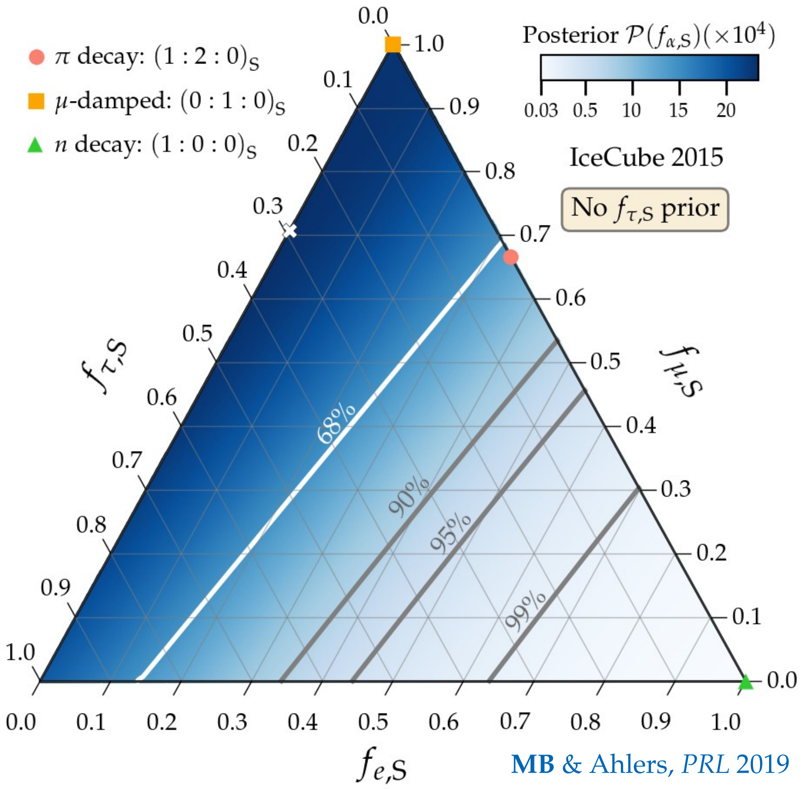
- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

Flavor – What is it good for?

Trusting particle physics
and learning about astrophysics



MB & Ahlers, *PRL* 2019

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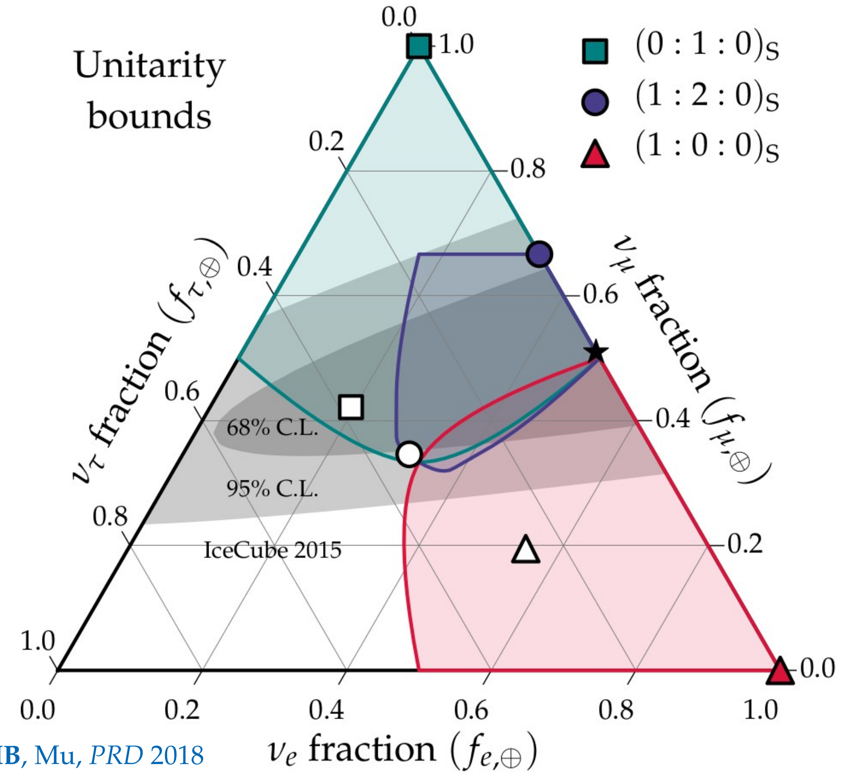
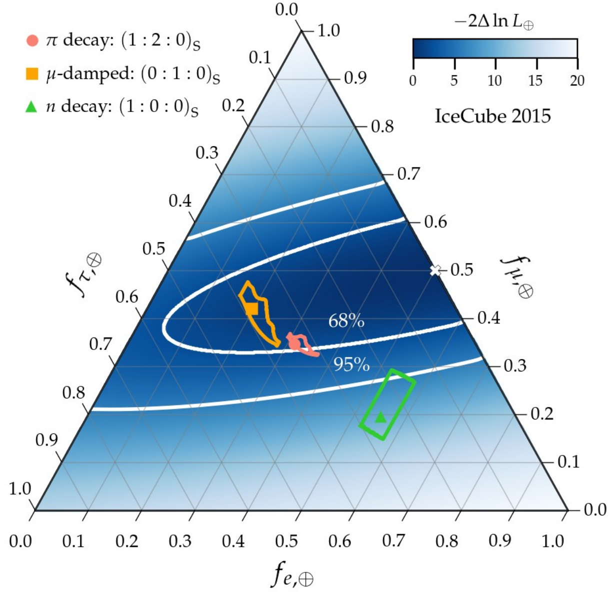


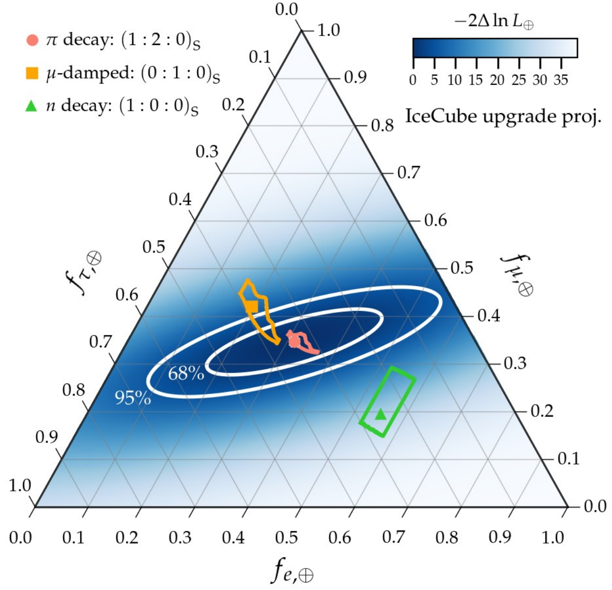
Ahlers, **MB**, Mu, *PRD* 2018

IceCube flavor composition

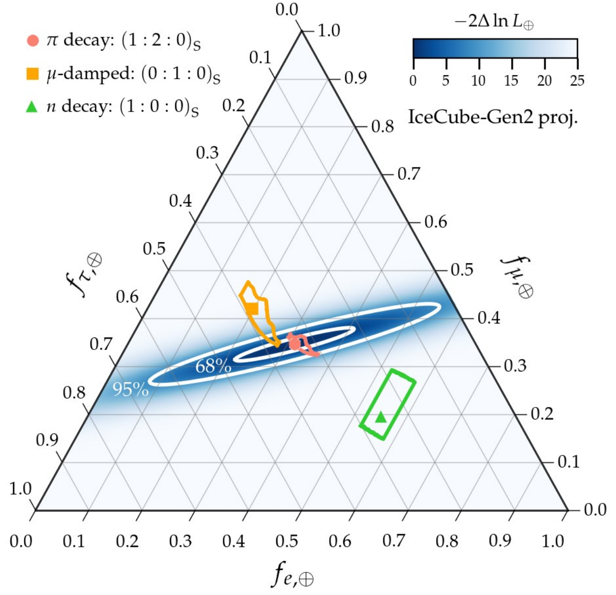
Today
IceCube



Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Hints of one ν_τ (not shown)

Assuming production by the full pion decay chain

Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes

[Li, **MB**, Beacom *PRL* 2019]

New physics – High-energy effects

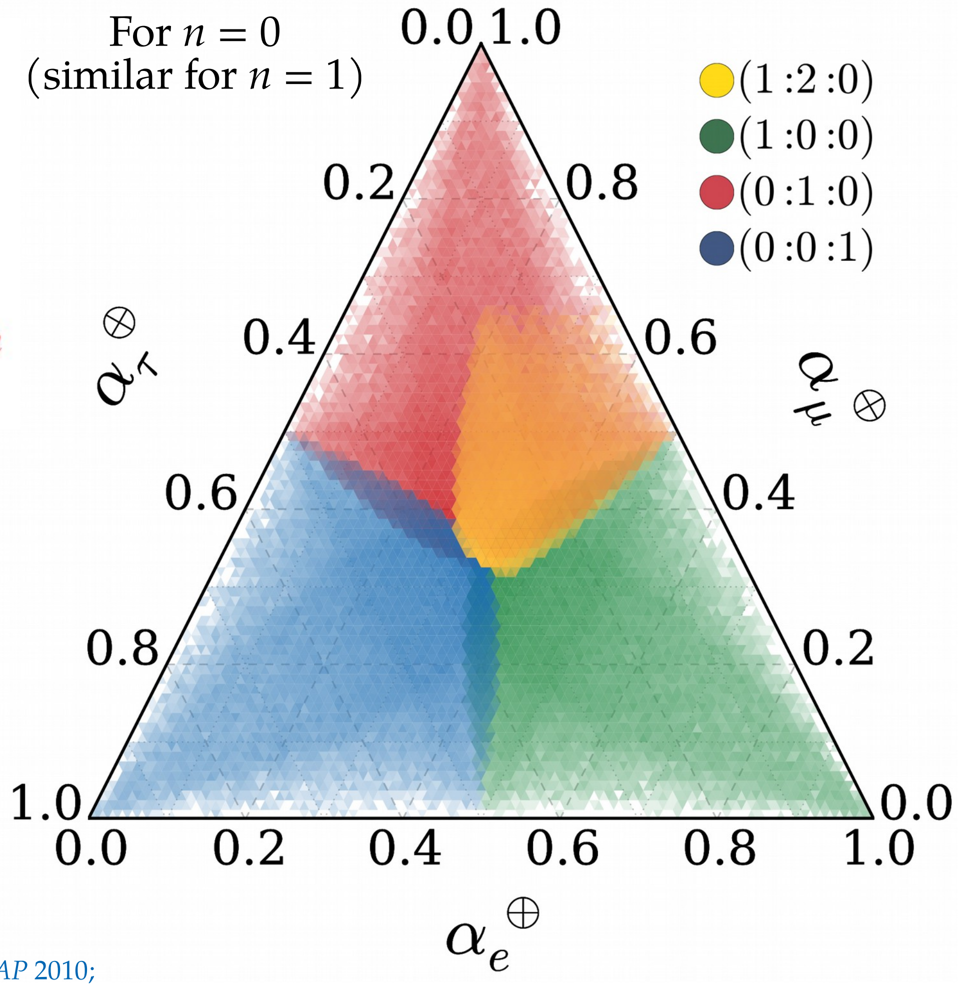
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

$$H_{\text{std}} = \frac{1}{2E} U^{\dagger}_{\text{PMNS}} \, \text{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\text{PMNS}}$$

$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U^{\dagger}_n \, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

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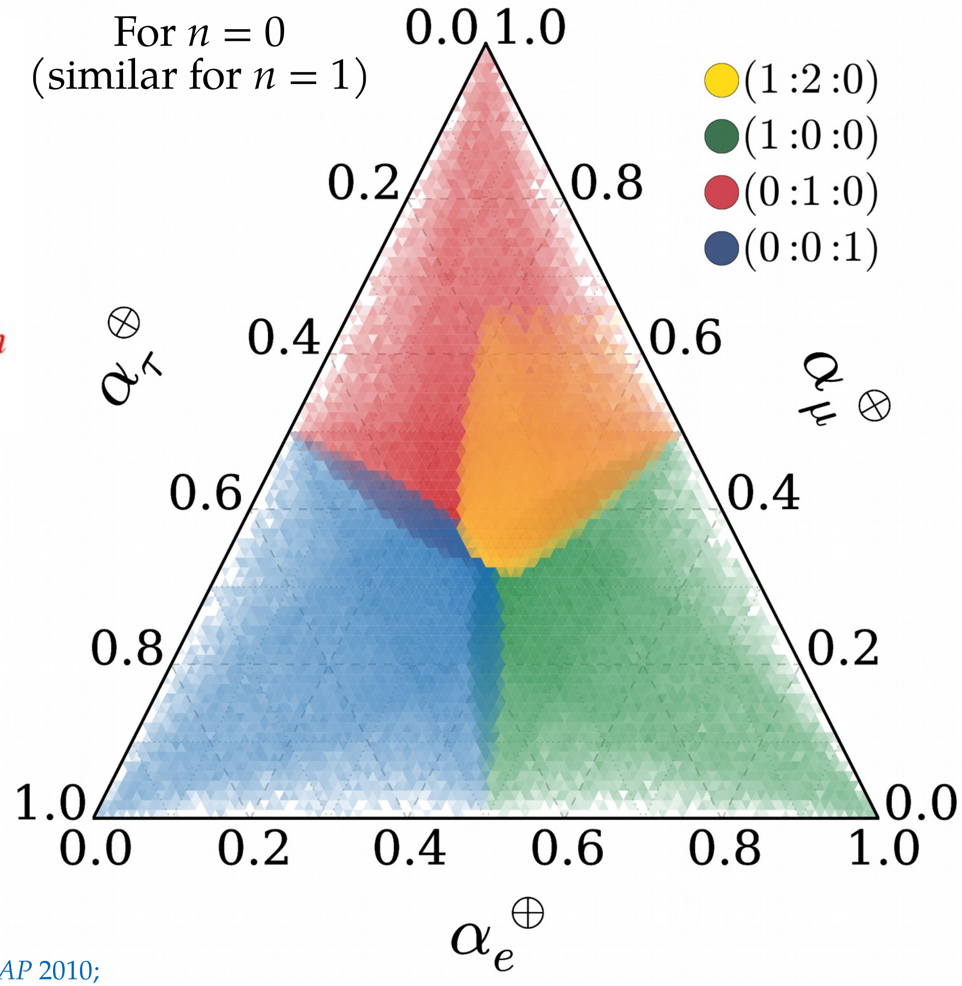

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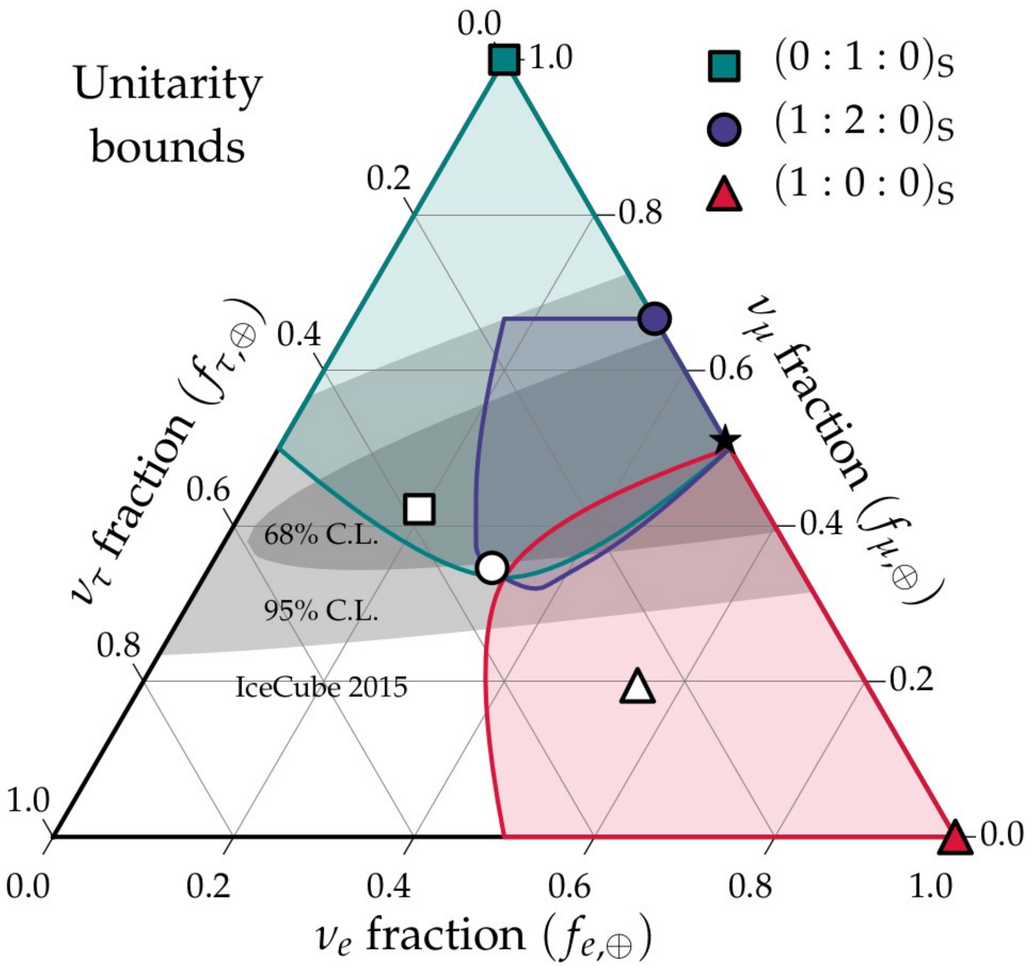
Using unitarity to constrain new physics

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{std}} + \mathrm{H}_{\mathrm{NP}}$$

- New mixing angles unconstrained
- Use unitarity ($\mathrm{U}_{\mathrm{NP}}\mathrm{U}_{\mathrm{NP}}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:

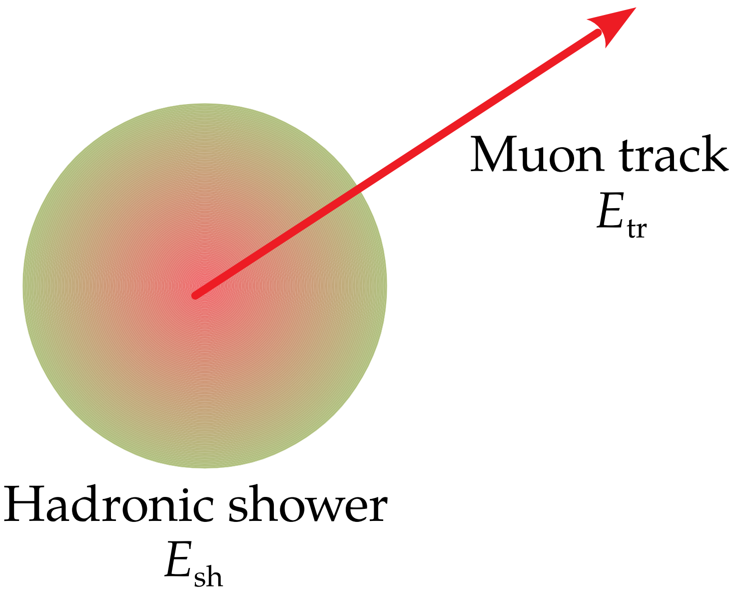
  $E_X = y\,E_\nu$ and $E_\mu = (1\text{-}y)\,E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\} y = (1 + E_{tr}/E_{sh})^{-1}$$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$



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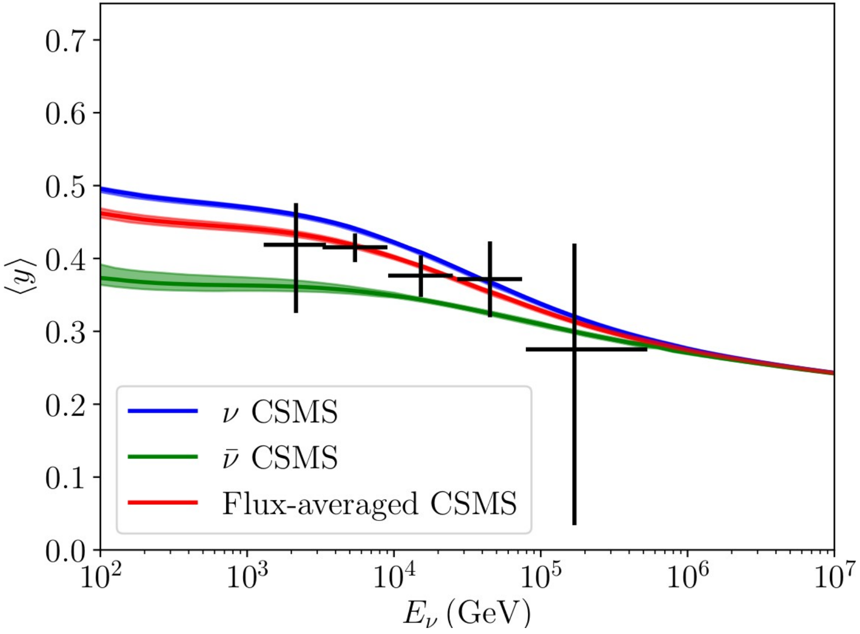
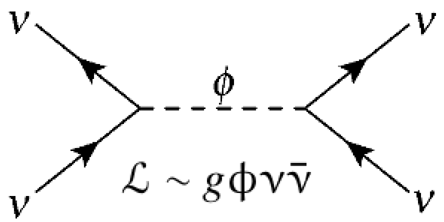


IceCube, *PRD* 2019

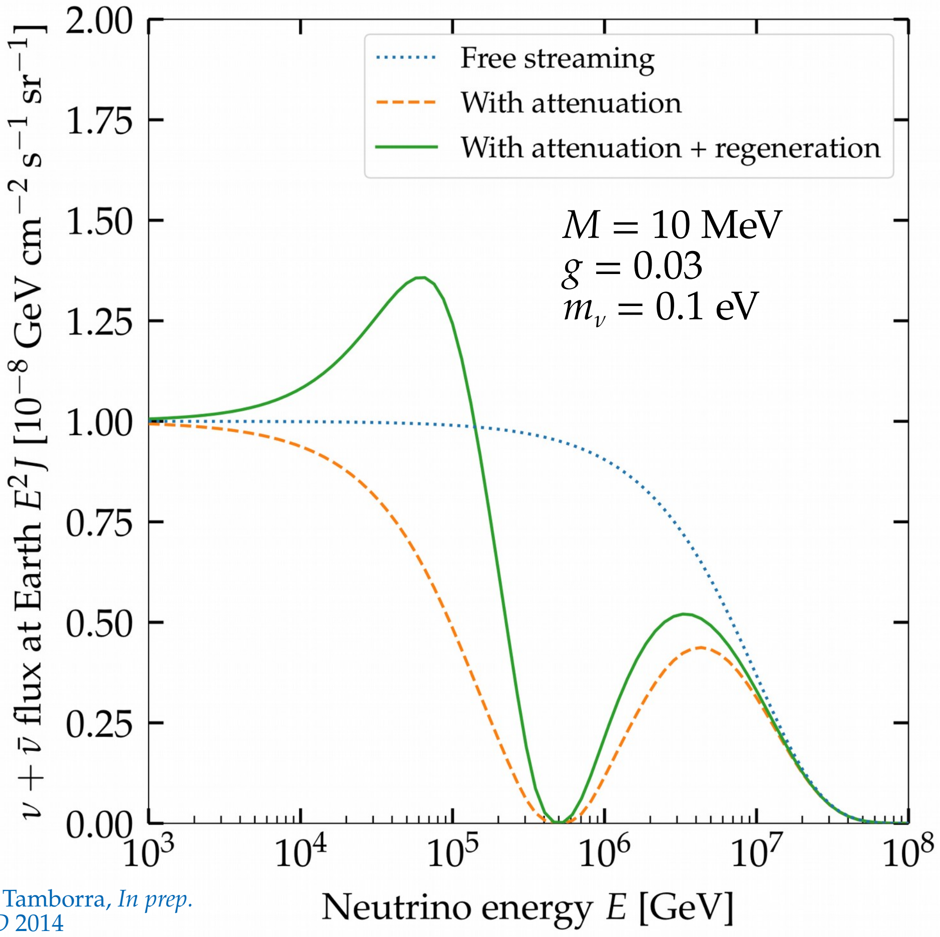
New physics in the spectral shape: $\nu\nu$ interactions

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Tamborra, *In prep.*
Ng & Beacom, *PRD* 2014
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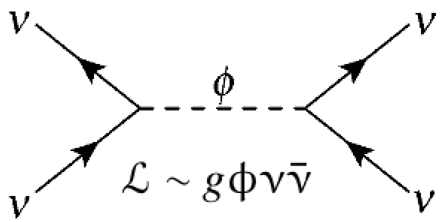

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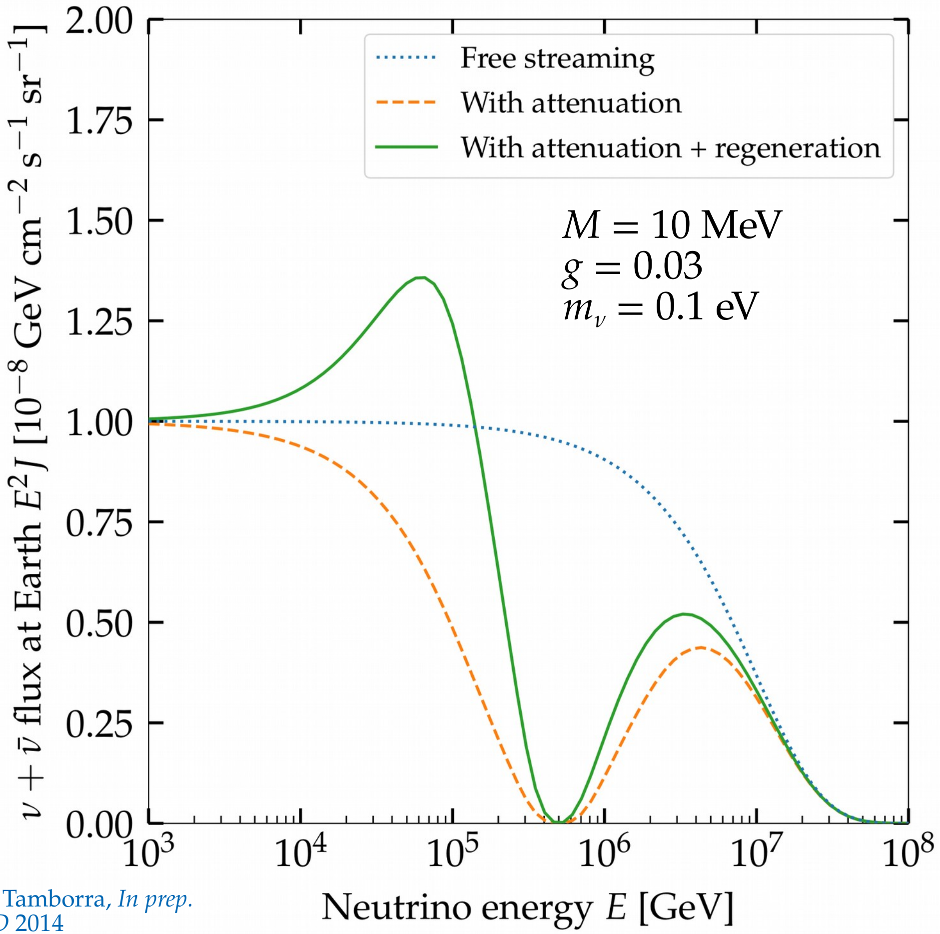

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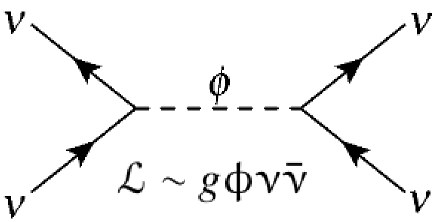

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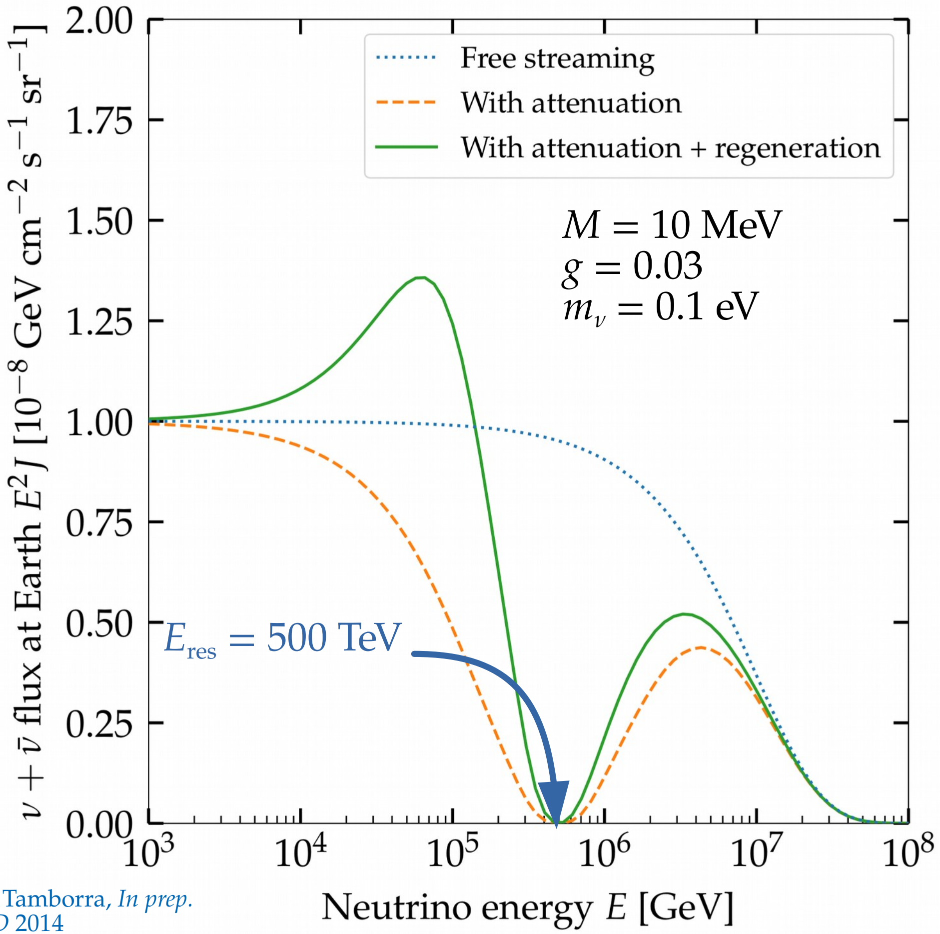

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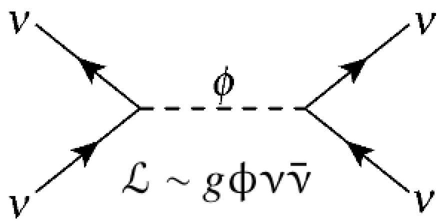
Blum, Hook, Murase, 1408.3799

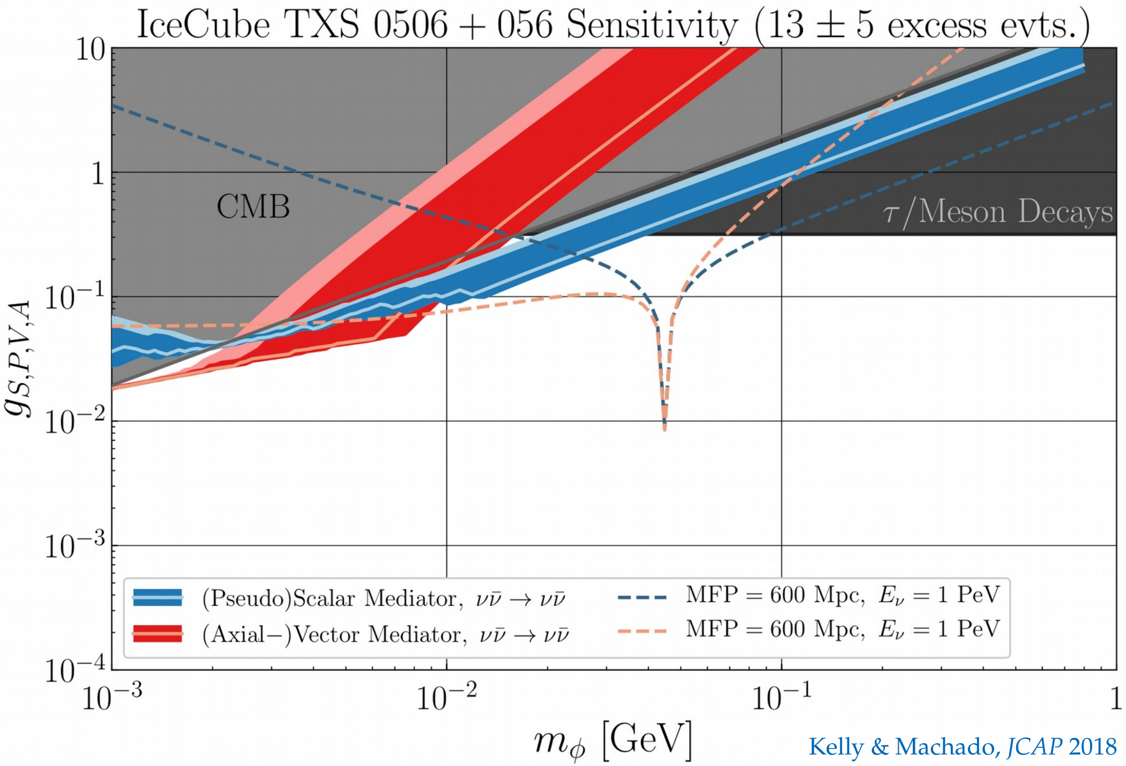
New physics in the spectral shape: $\nu\nu$ interactions

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $$\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}$$

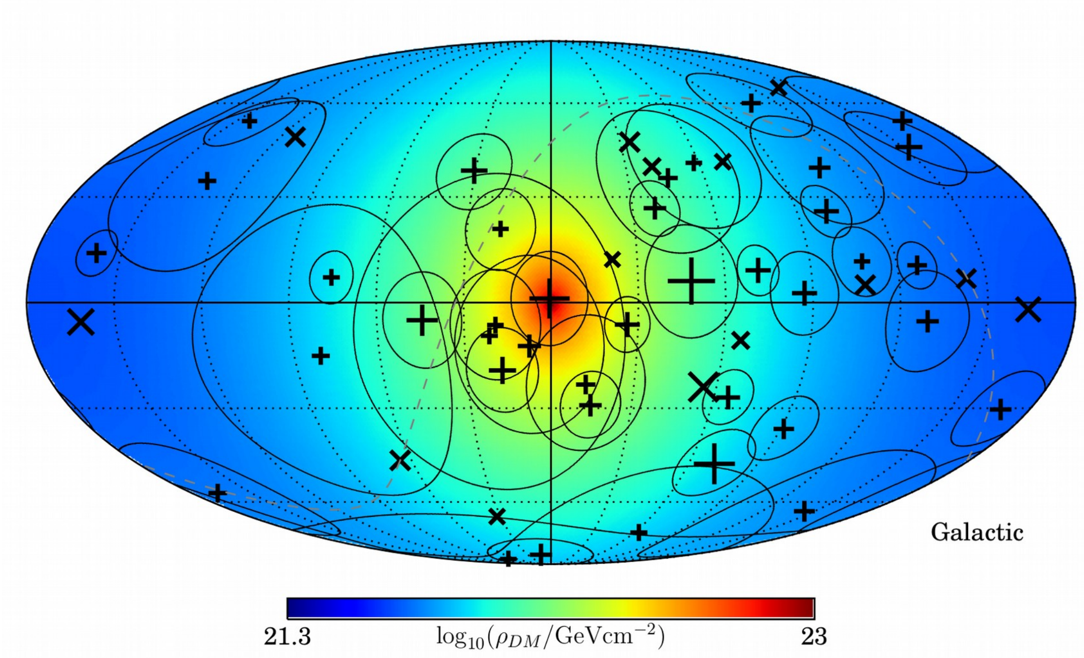
Resonance energy: $$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

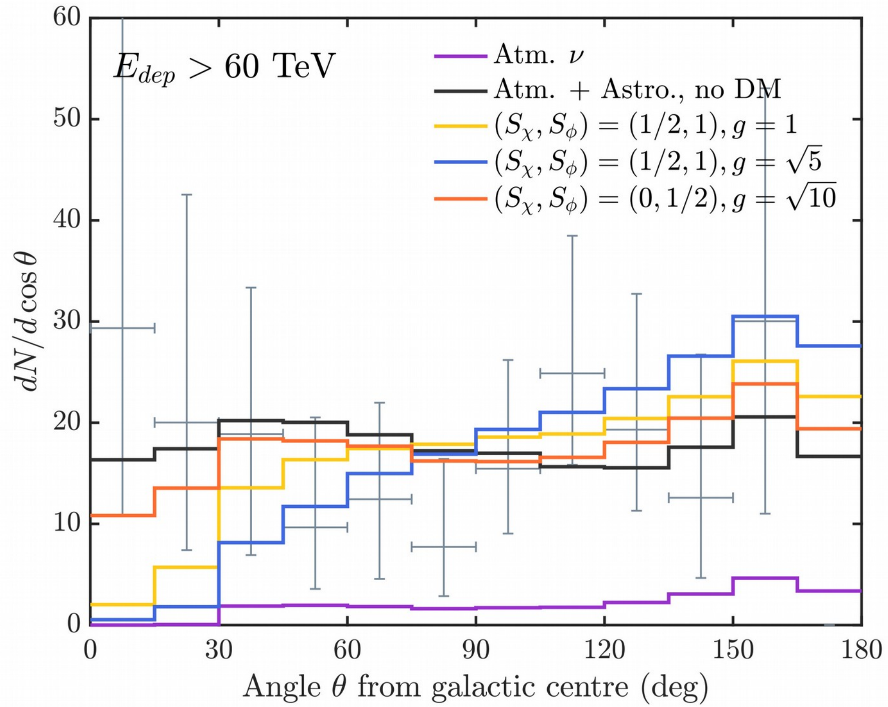


Kelly & Machado, *JCAP* 2018

New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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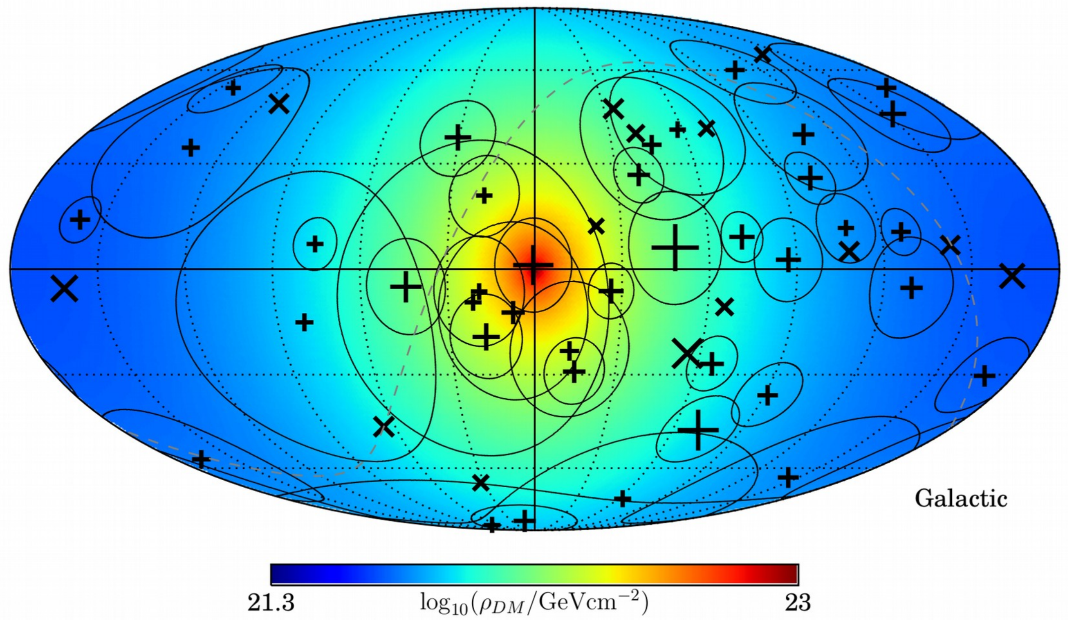

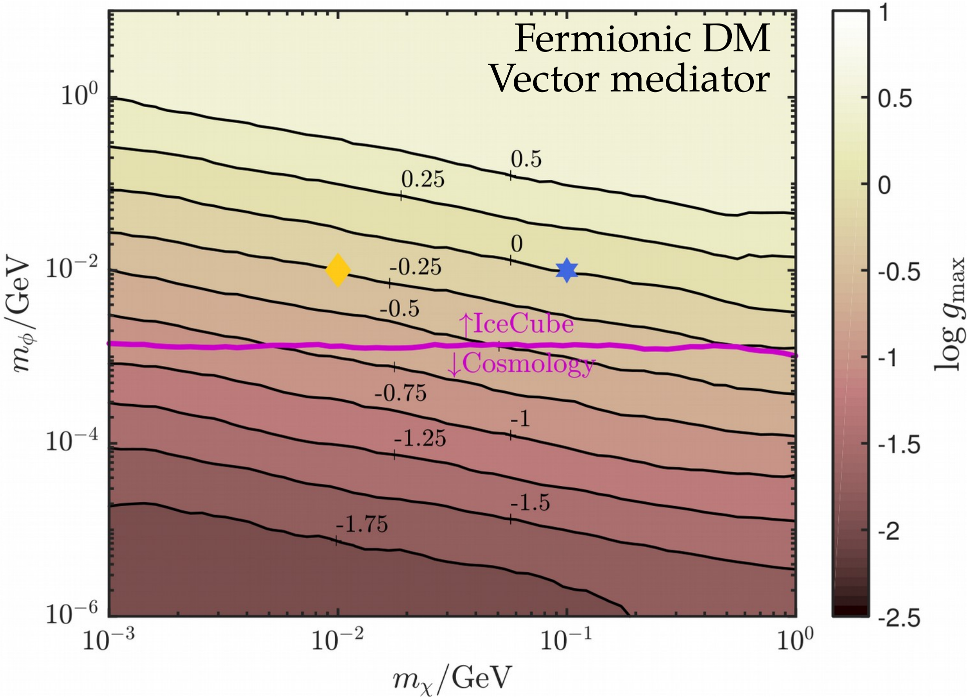

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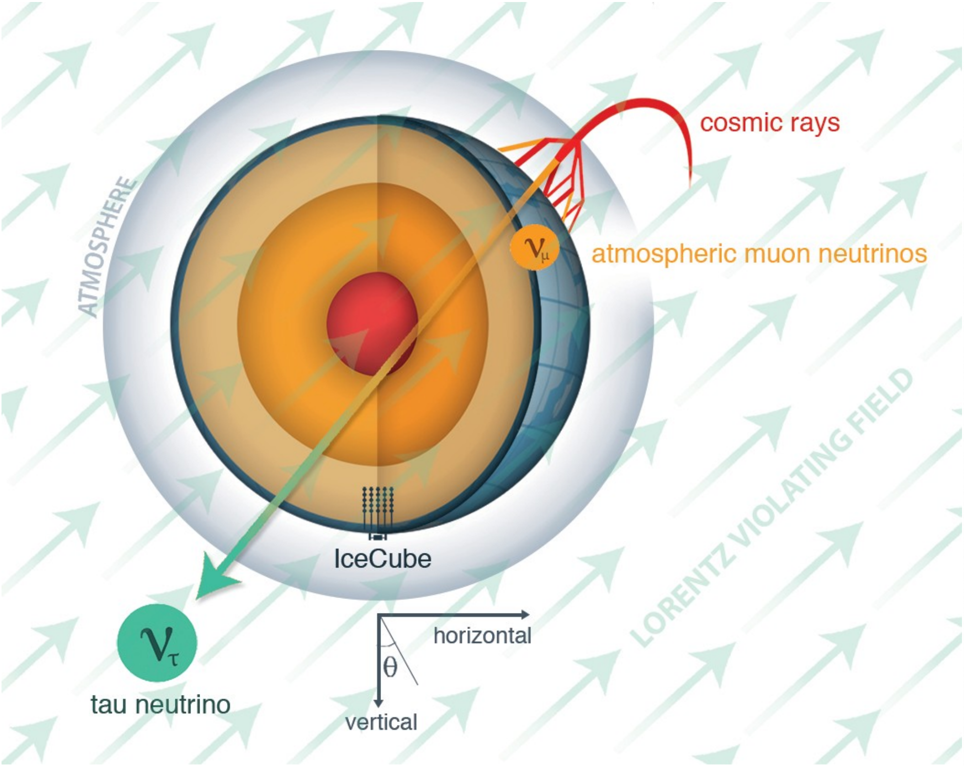
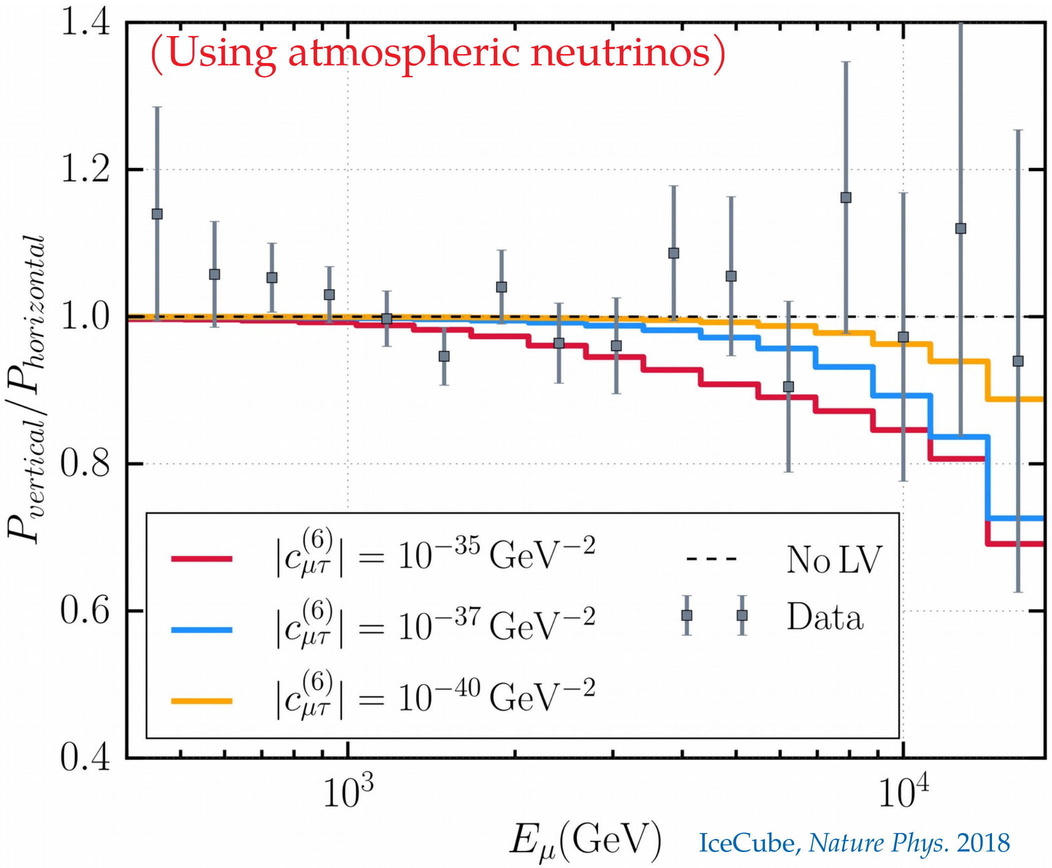
Argüelles, Kheirandish, Vincent, *PRL* 2017

New physics in the energy & angular distribution

Lorentz invariance violation – Hamiltonian: $H \sim m^2/(2E) + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)}$





IceCube, *Nature Phys.* 2018

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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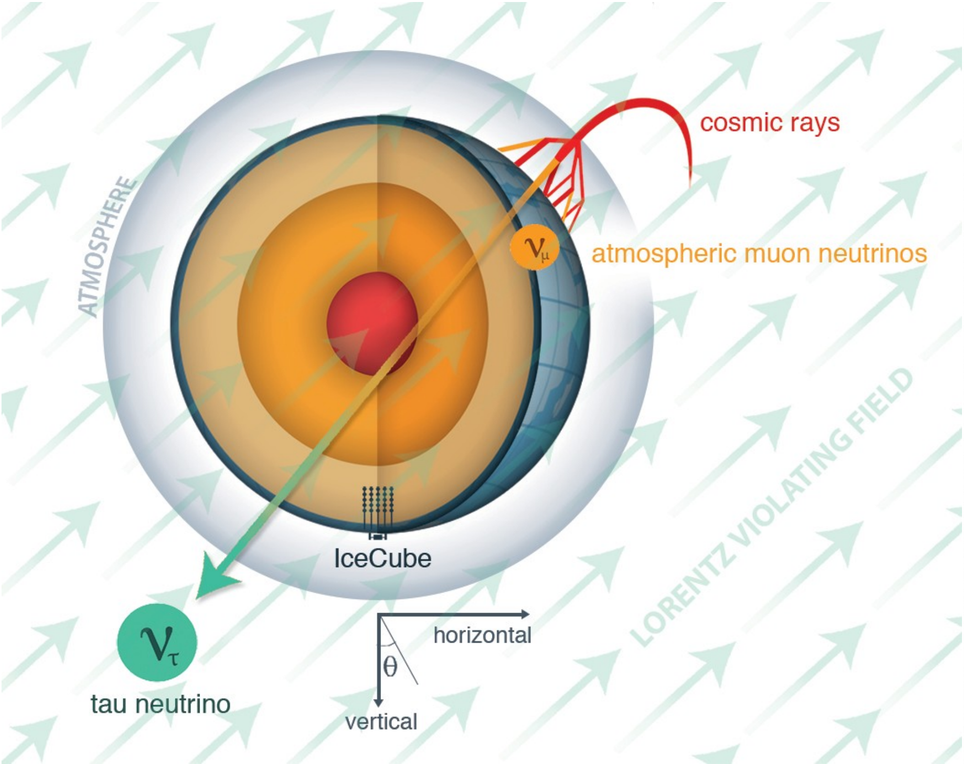

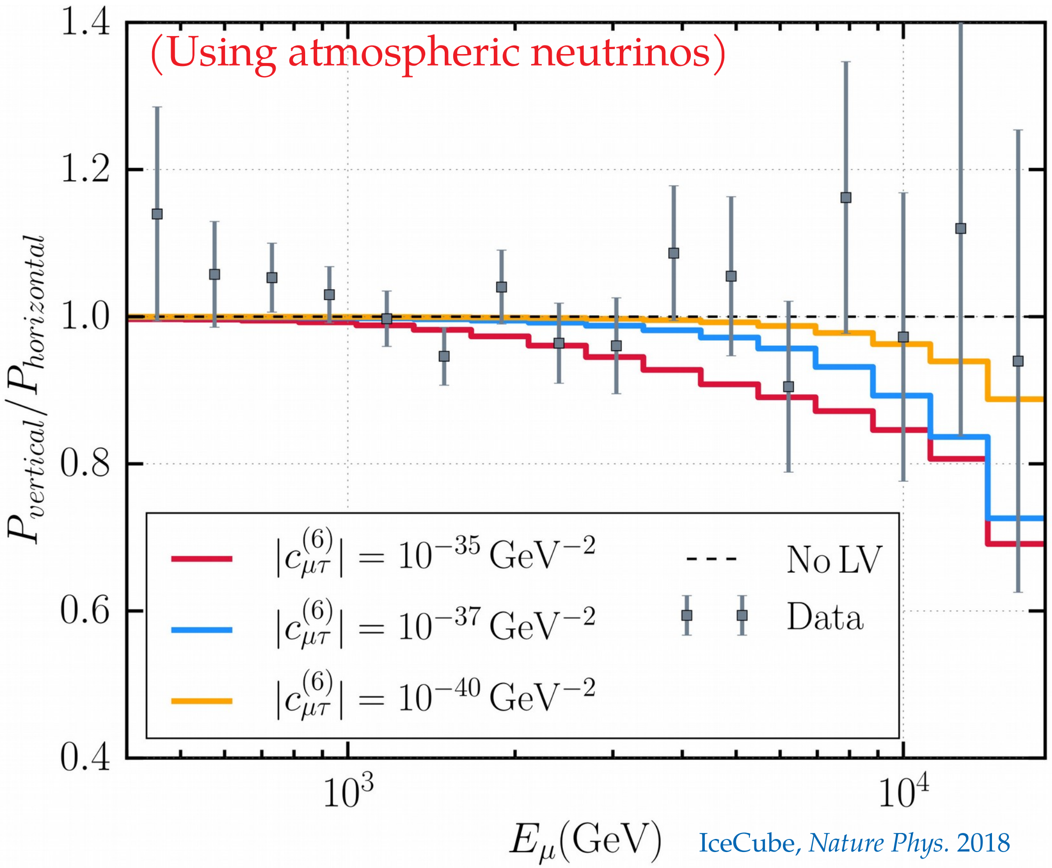

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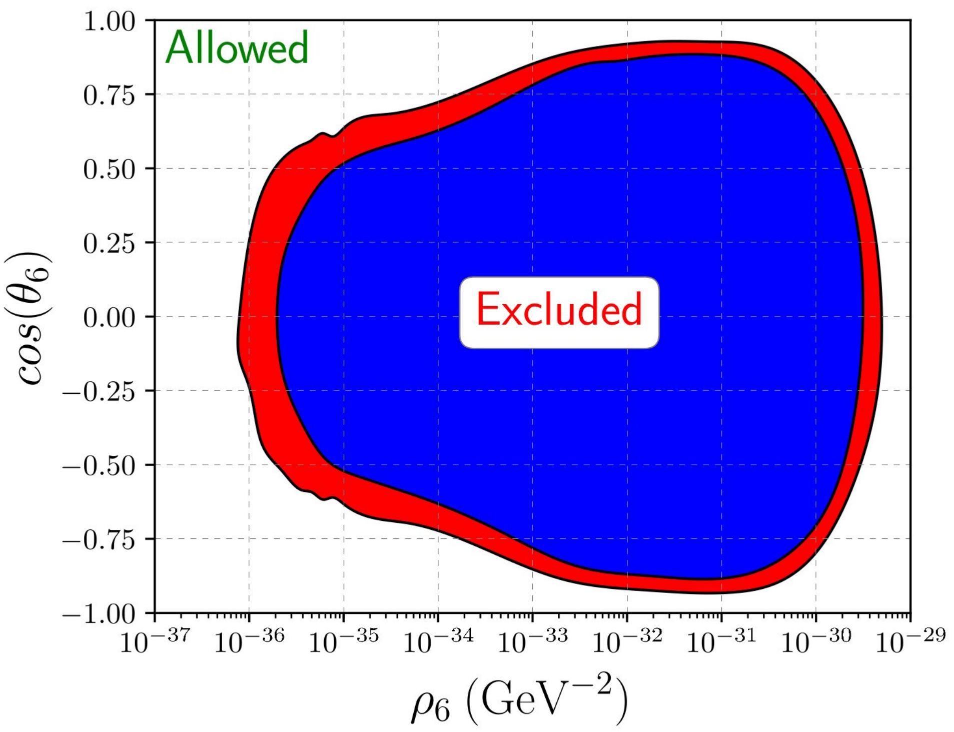
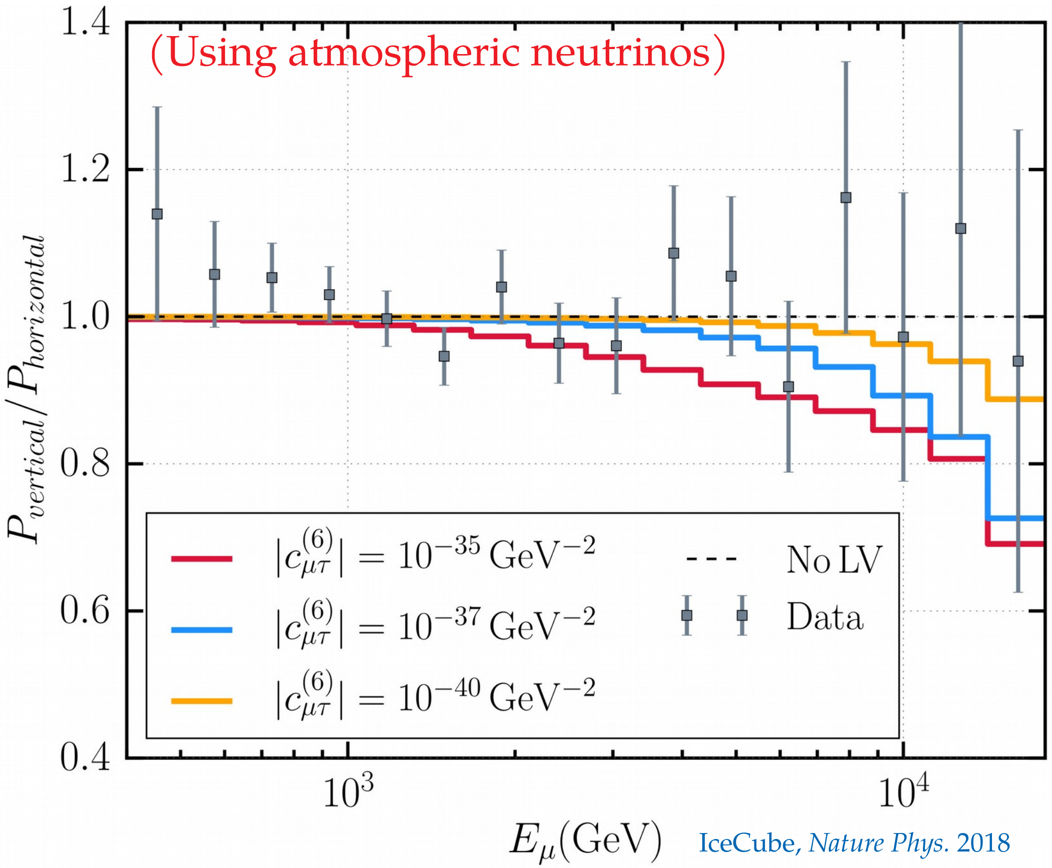
Best bounds come from IceCube

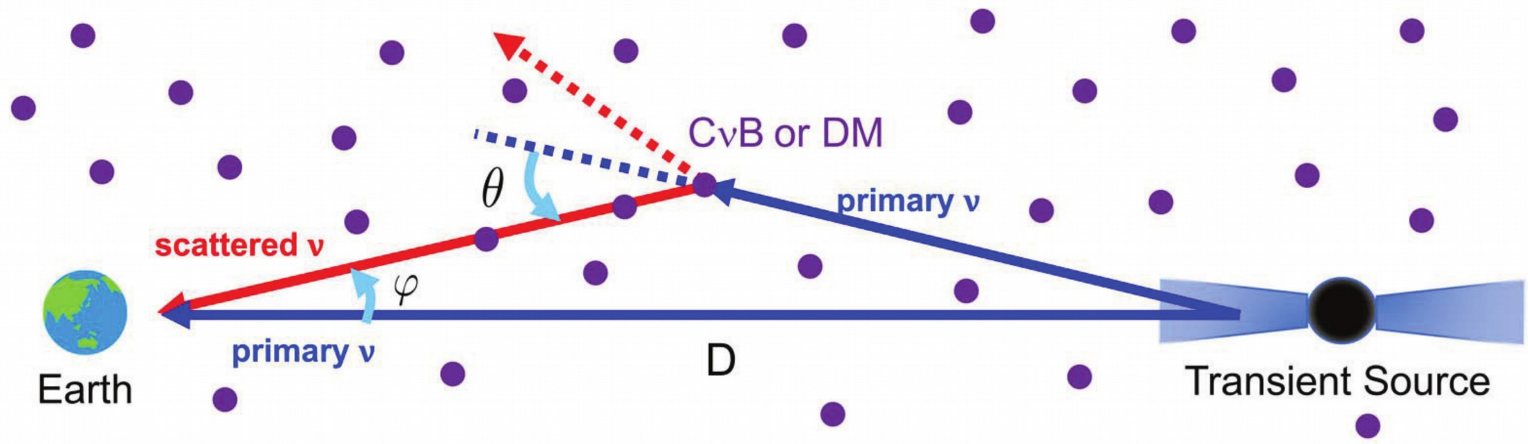




IceCube, *Nature Phys.* 2018

New physics in timing — TeV–PeV

Multiple secret $\nu\nu$ scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, 1903.08607

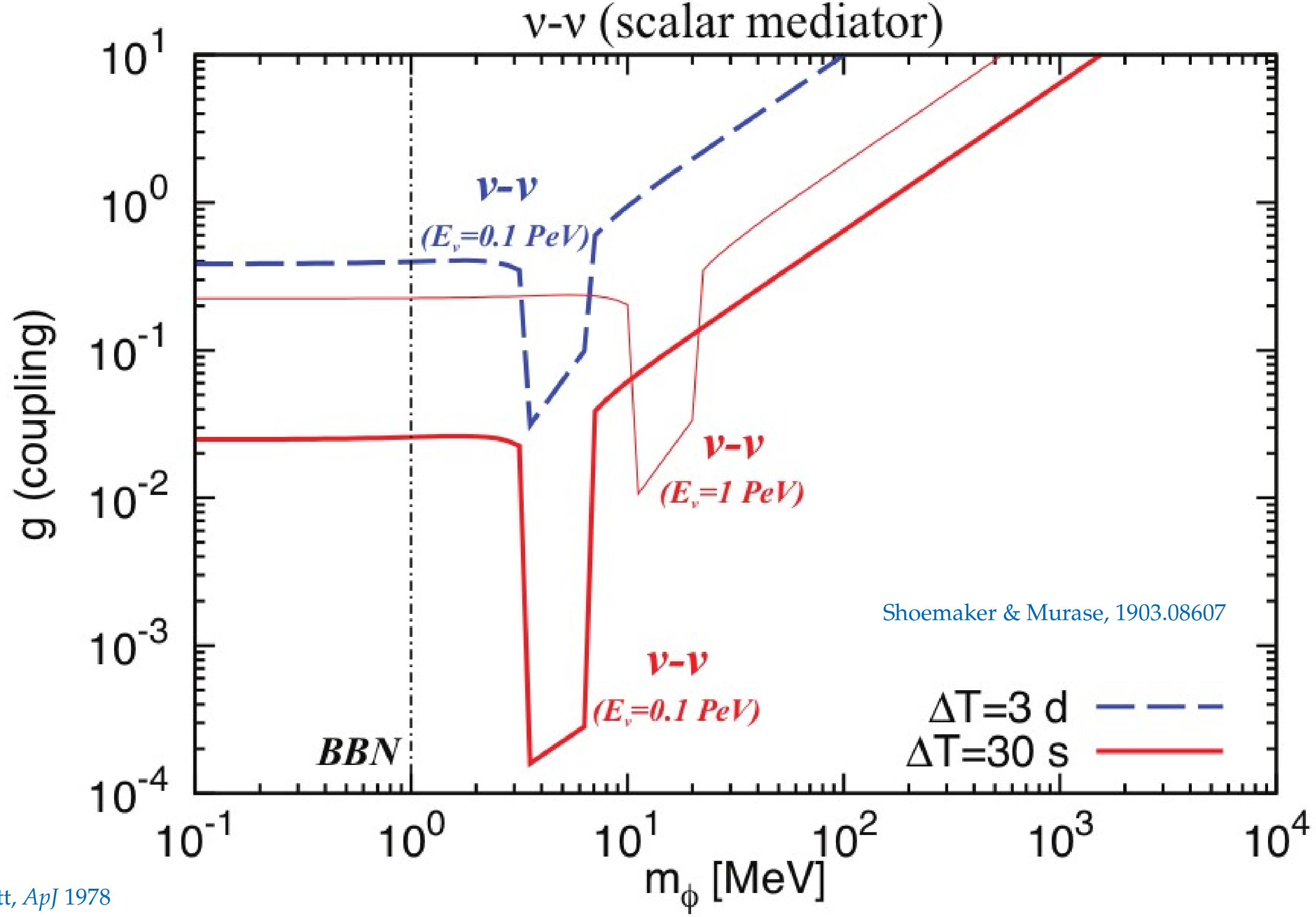
Characteristic time delay —

Optical depth to $\nu\nu$: $\tau_{\nu\nu} = n_\nu \, \sigma_{\nu\nu} \, D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — TeV–PeV



See also: Alcock & Hatchett, *ApJ* 1978

Neutrino zenith angle distribution

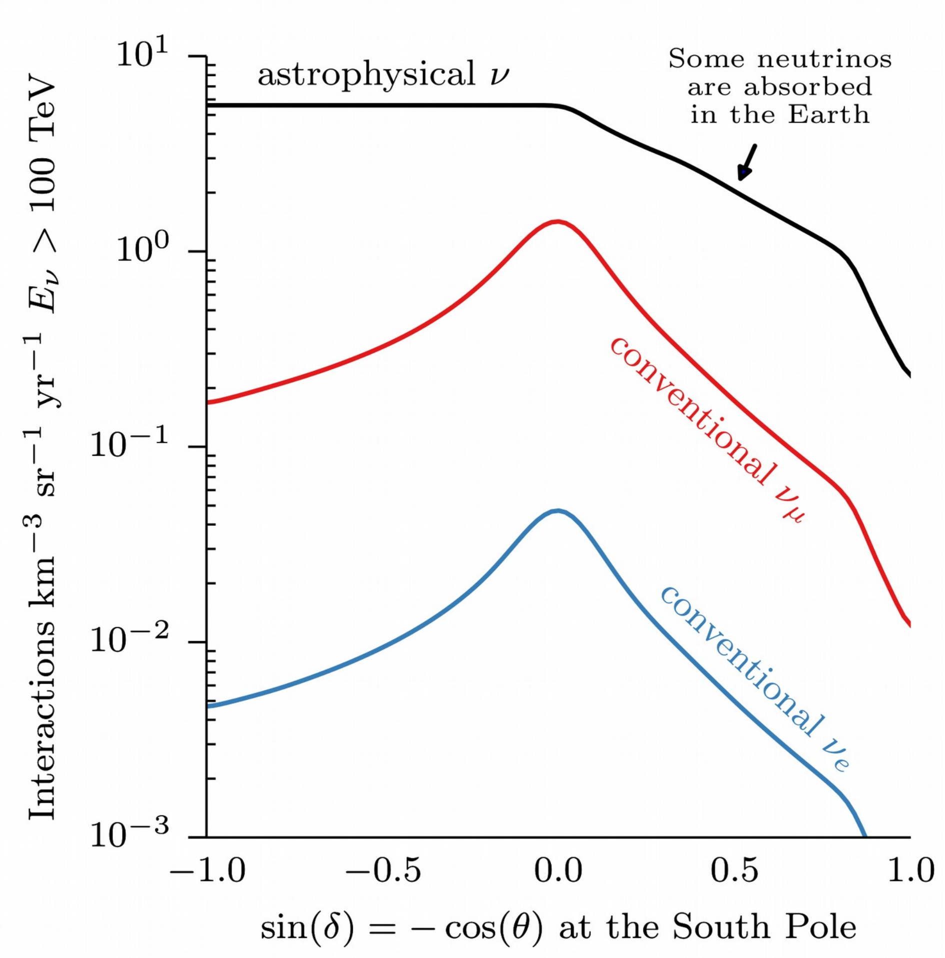
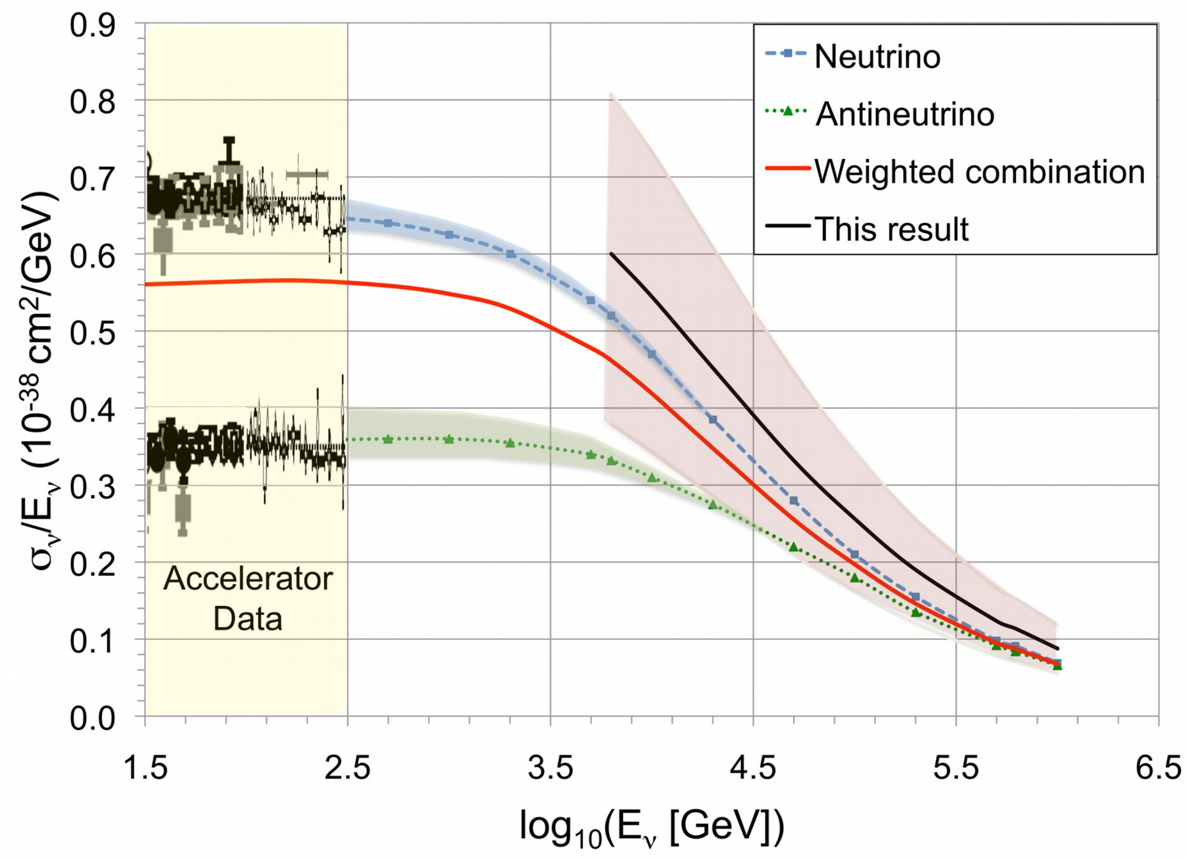


Figure by
Jakob Van Santen
ICRC 2017

Using through-going muons instead

- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio $\sigma_{\mathrm{obs}}/\sigma_{\mathrm{SM}}$
  $1.30\,^{+0.21}_{-0.19}(\mathrm{stat.})^{+0.39}_{-0.43}(\mathrm{syst.})$
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Flavor composition – a few source choices

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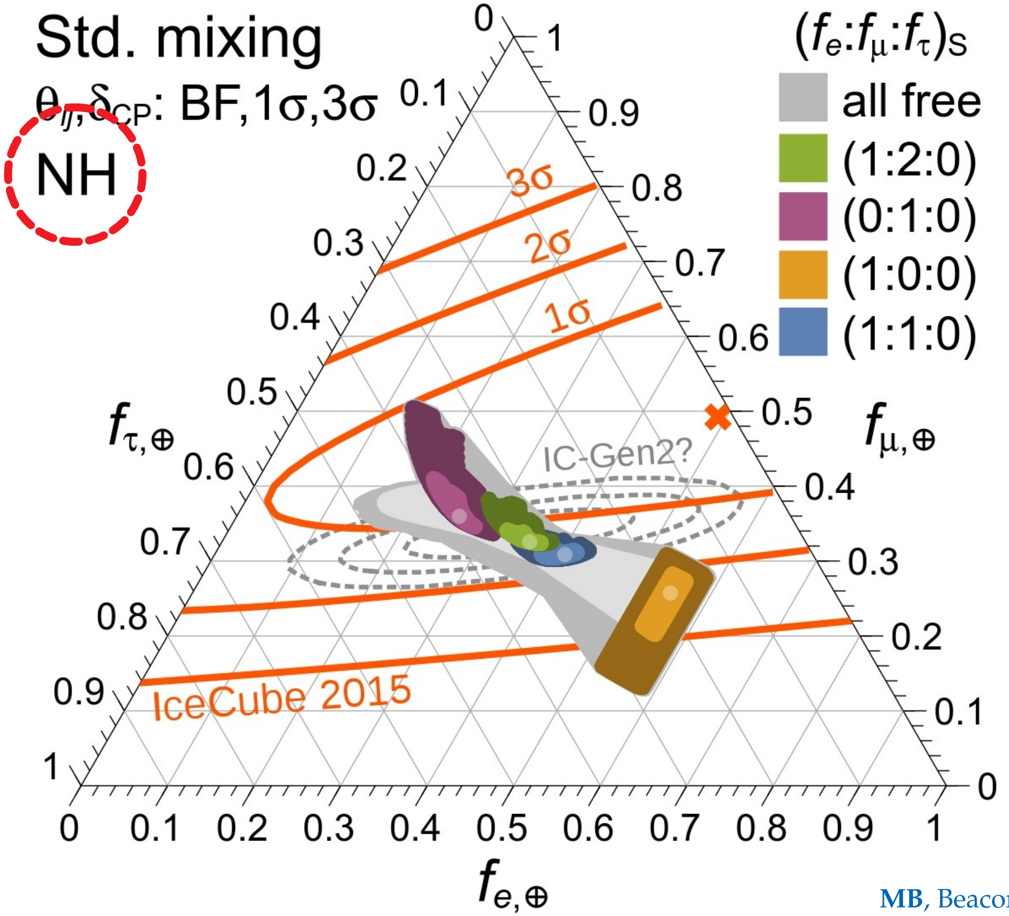
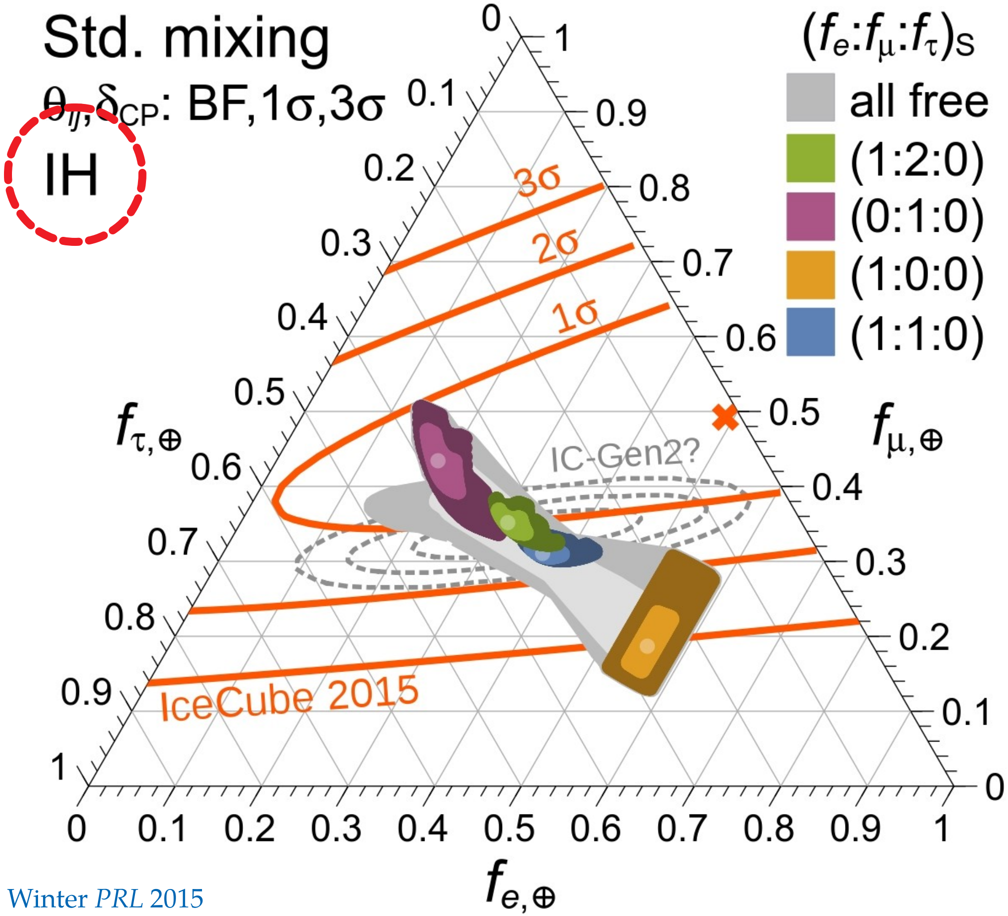
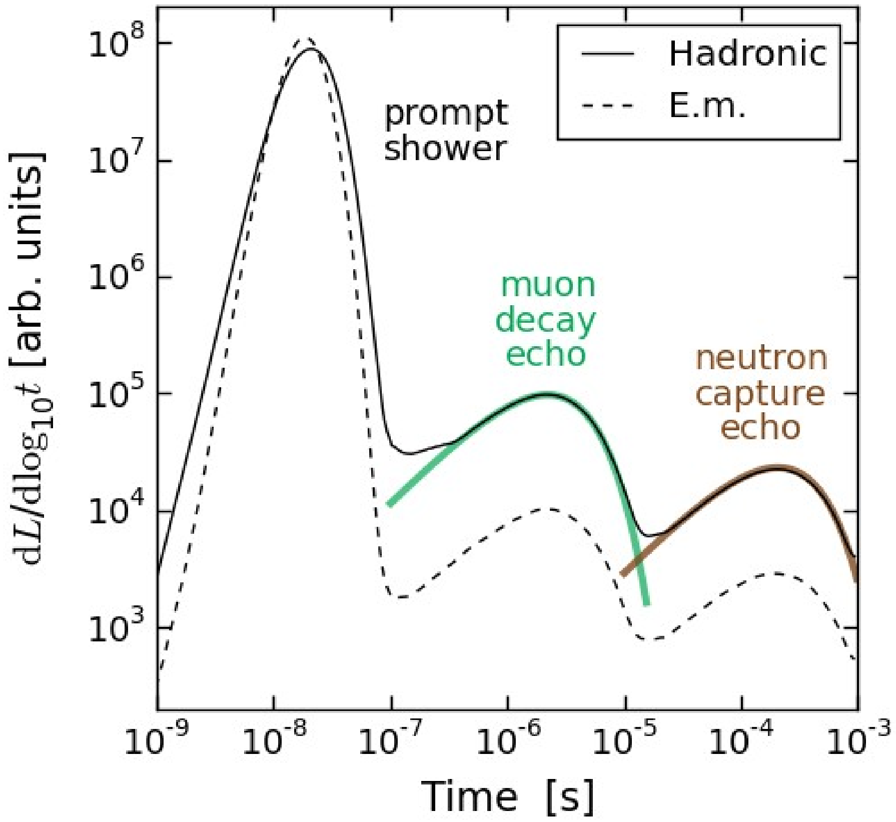


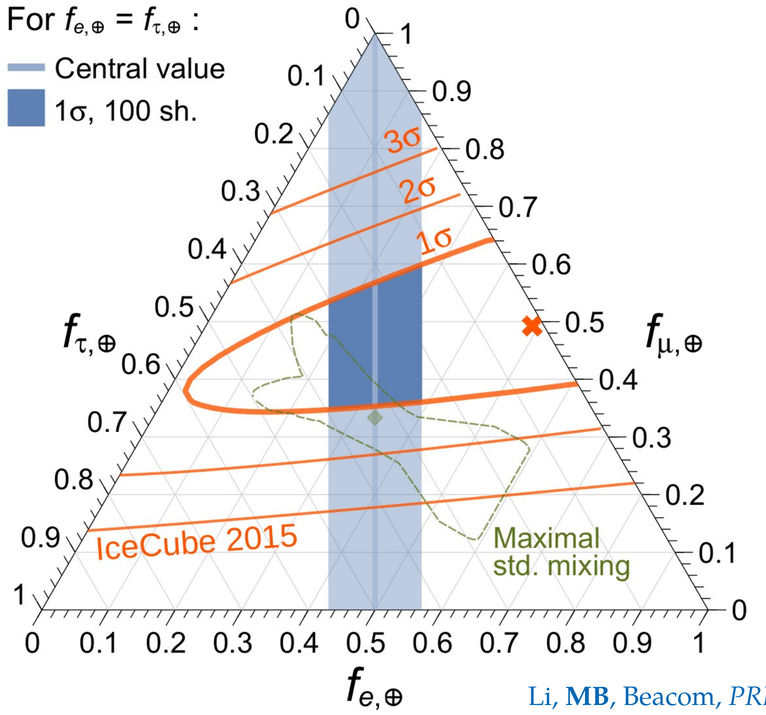


MB, Beacom, Winter *PRL* 2015

Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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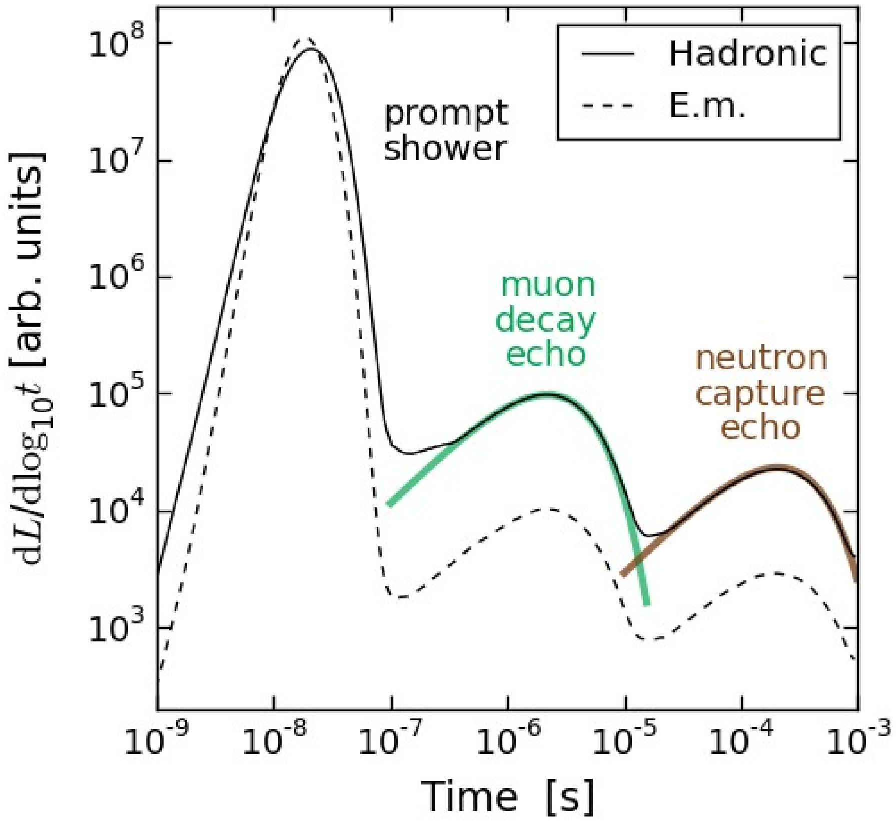
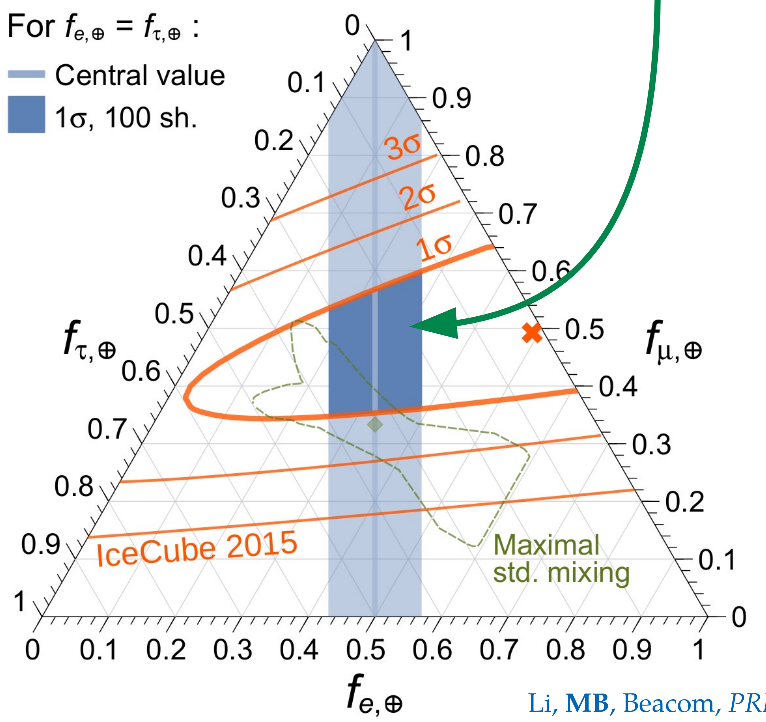


~10 × improvement over current measurement



Li, **MB**, Beacom, *PRL* 2019

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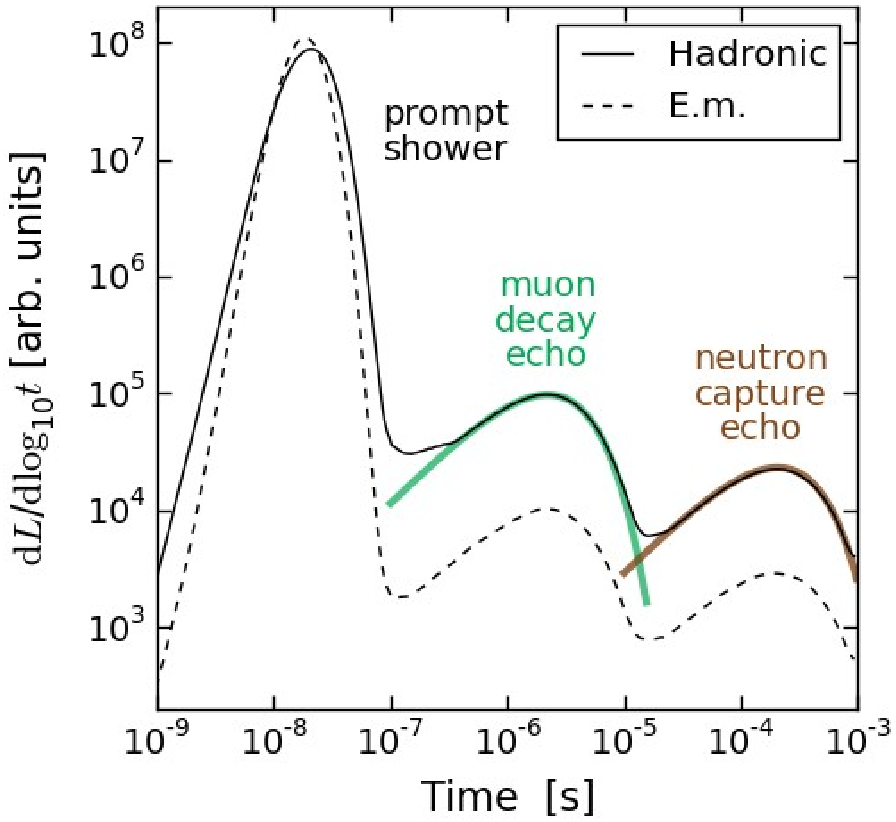

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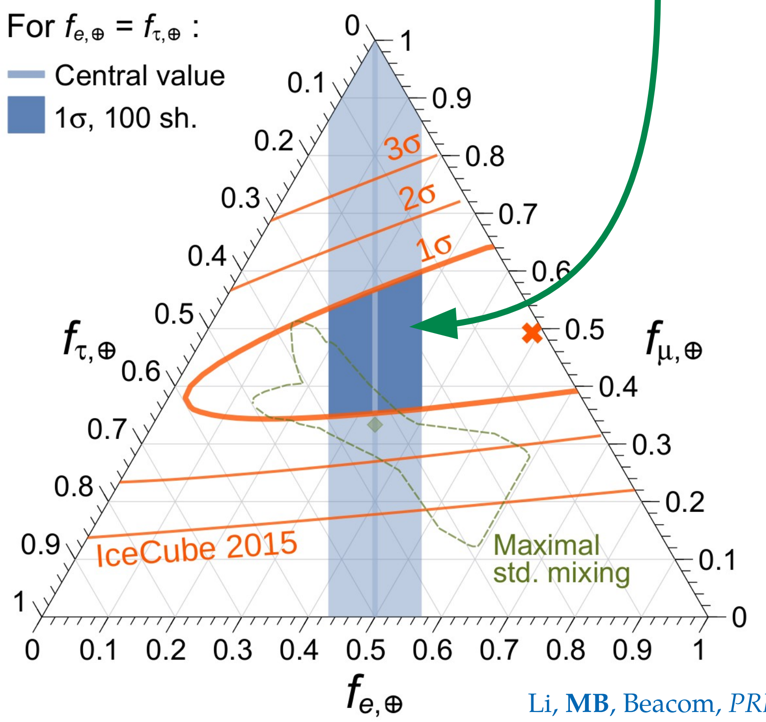
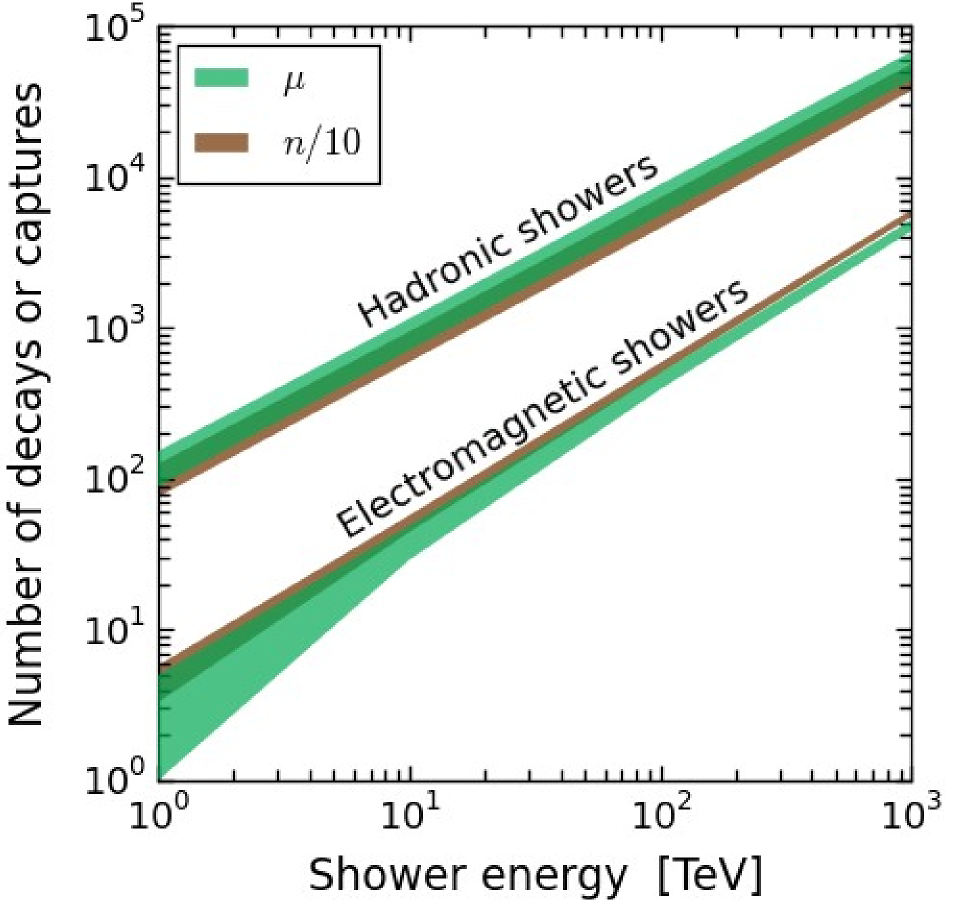
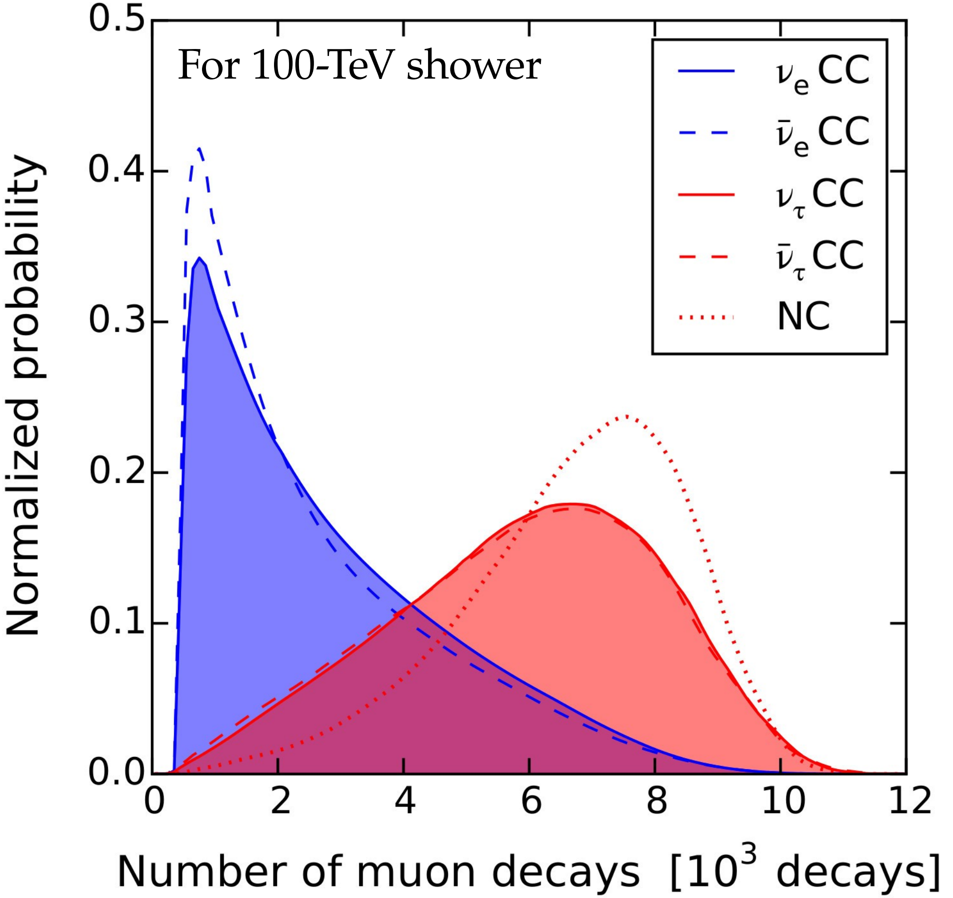


Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers

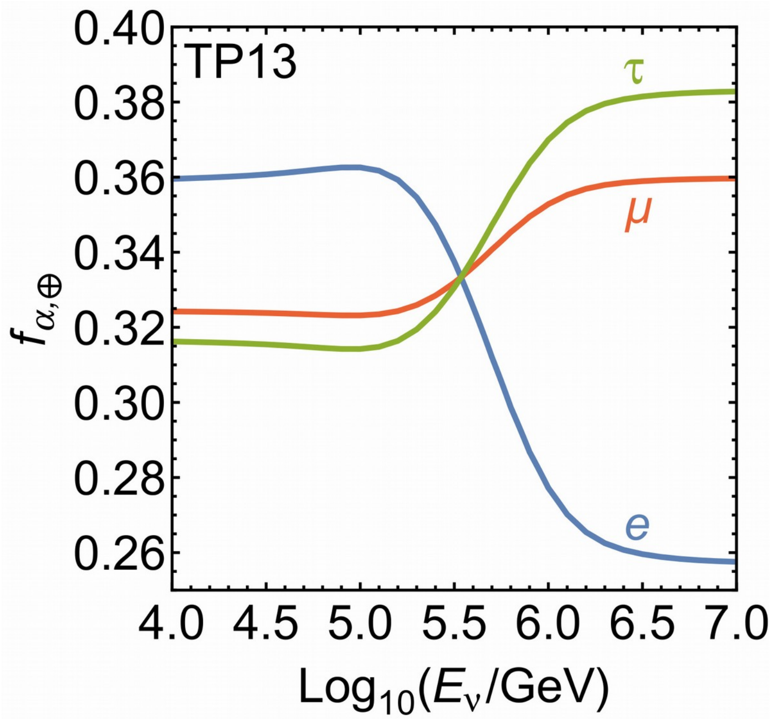


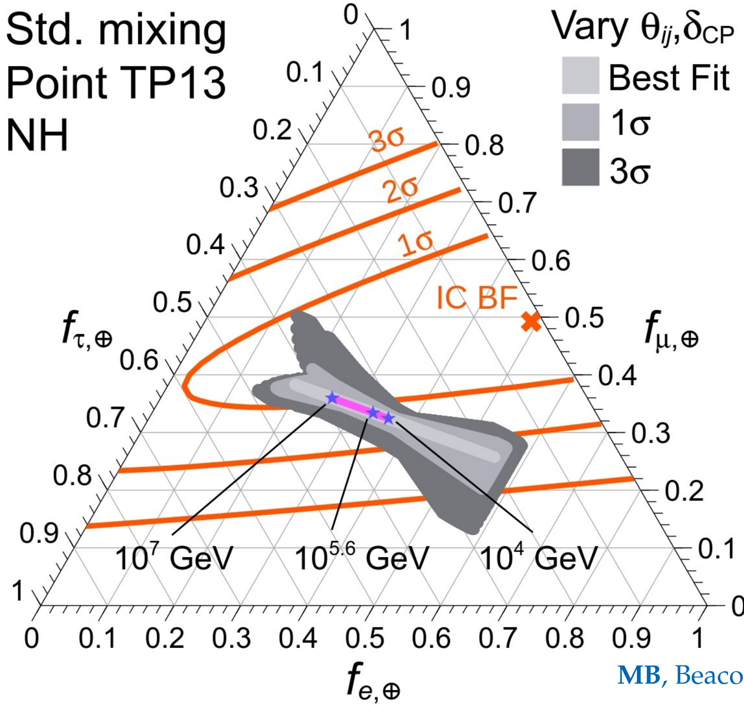


Li, **MB**, Beacom, *PRL* 2019

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –

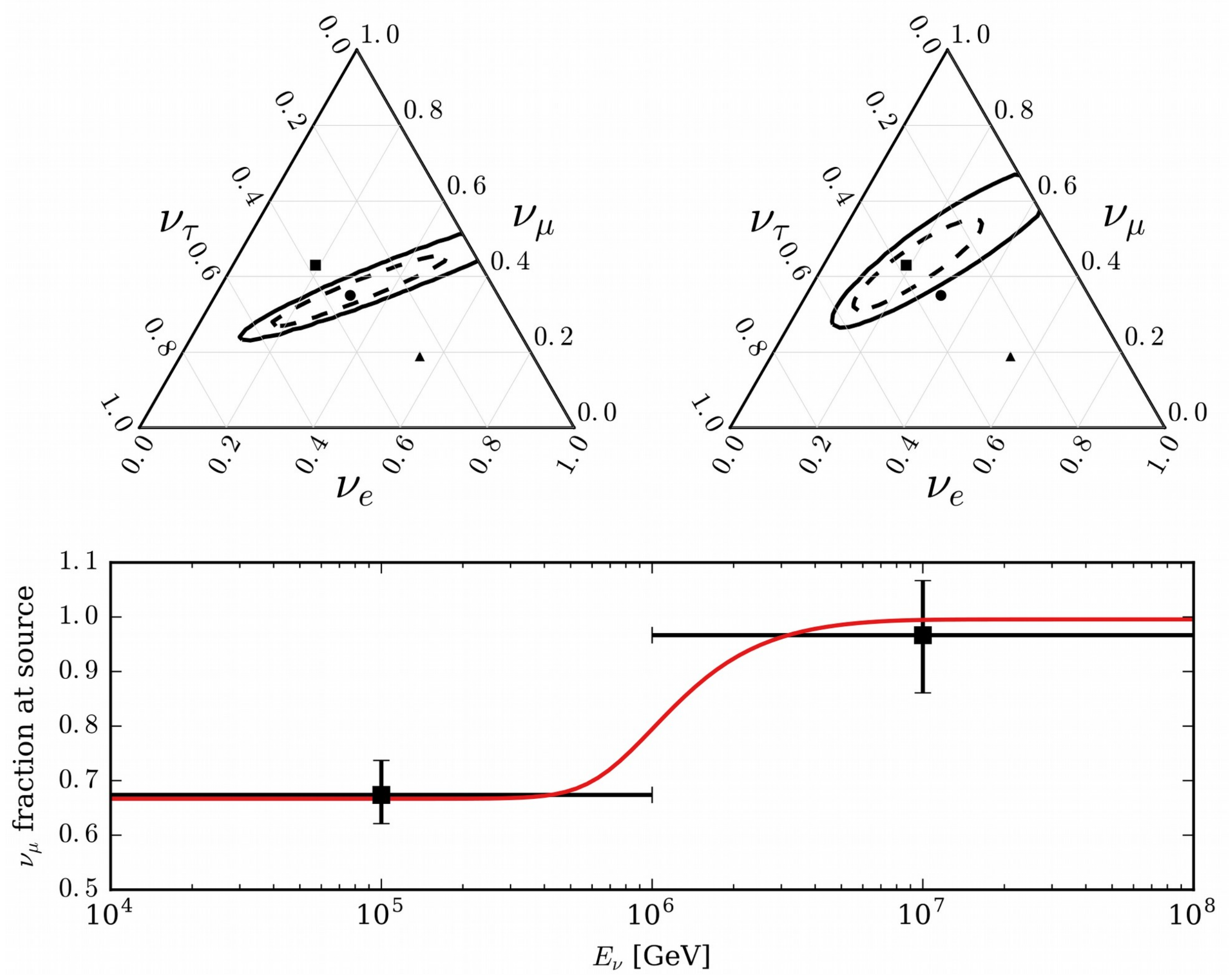




MB, Beacom, Winter *PRL* 2015

- ▶ TP13: $p\gamma$ model, target photons from electron-positron annihilation [Hümmer+, *Astropart. Phys.* 2010]
- ▶ Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

… Observable in IceCube-Gen2?



Borrowed from M. Kowalski

Flavor content of neutrino mass eigenstates

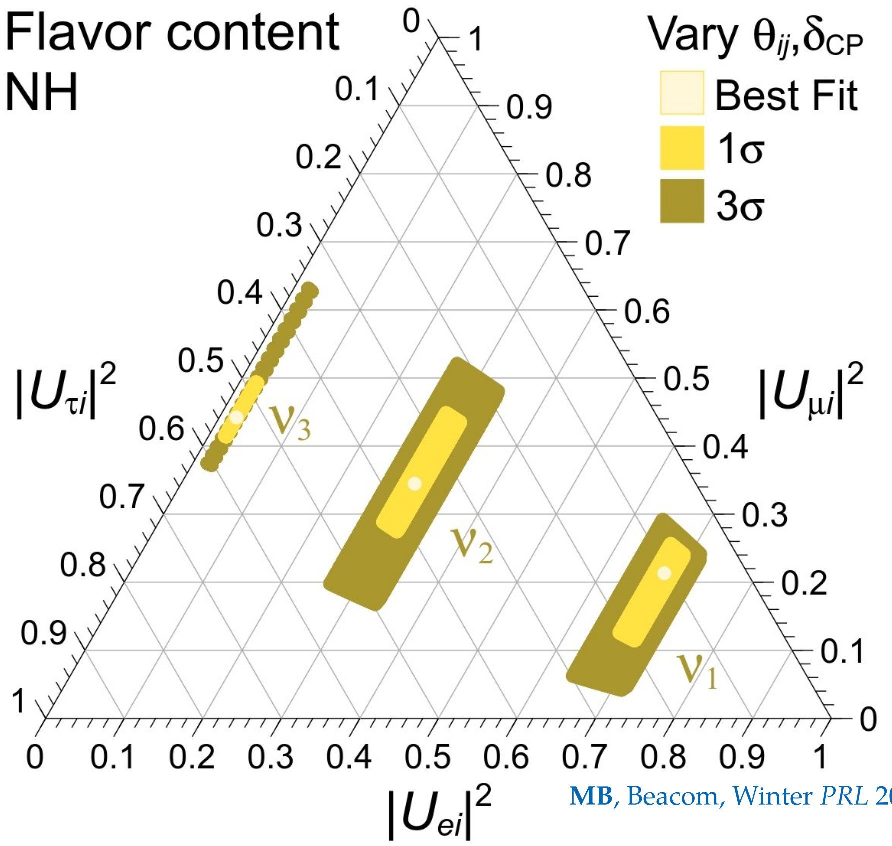
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

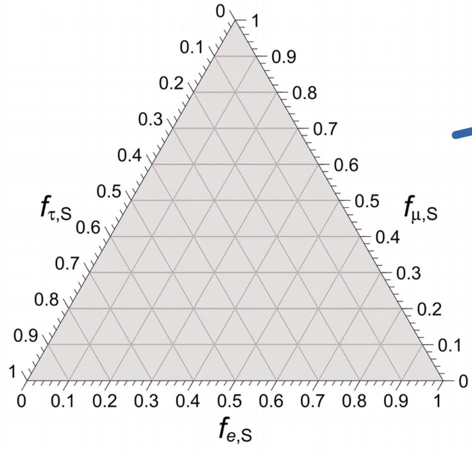
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources

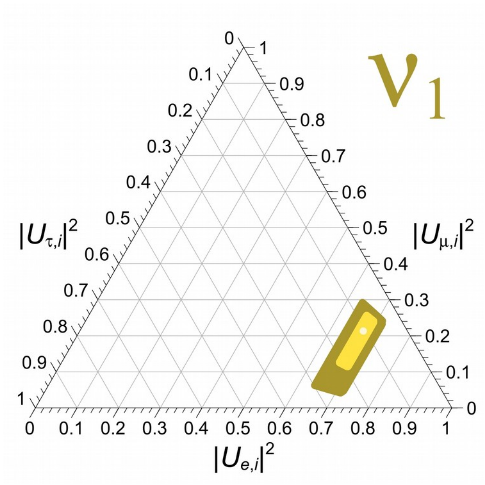


$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\nu_1 \text{ lightest and stable}}$

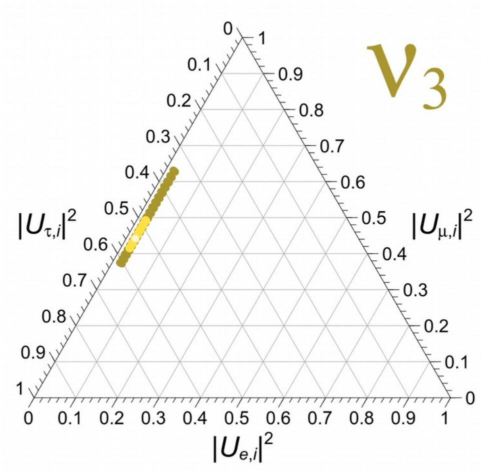
If all unstable neutrinos decay

$\underbrace{\nu_1, \nu_2 \to \nu_3}_{\nu_3 \text{ lightest and stable}}$

Earth



$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Measuring the neutrino lifetime

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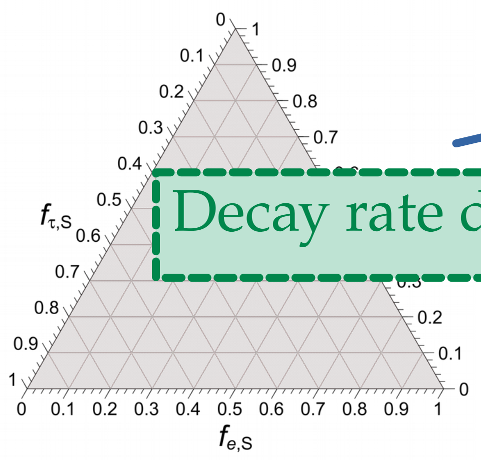


$$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\nu_1 \text{ lightest and stable}}$$

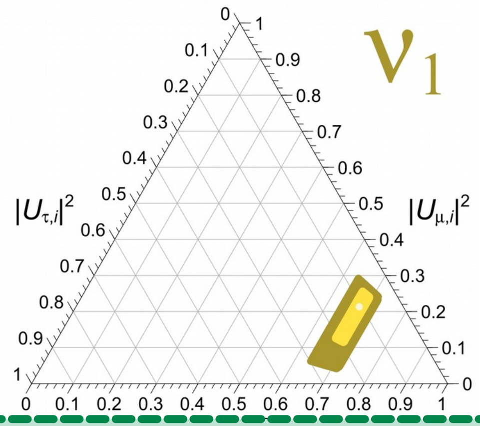
If all unstable

Decay rate depends on $\exp[- t \,/\, (\gamma\tau_i)] = \exp[- (L/E) \cdot (m_i/\tau_i)]$

$$\underbrace{\nu_1, \nu_2 \to \nu_3}_{\nu_3 \text{ lightest and stable}}$$

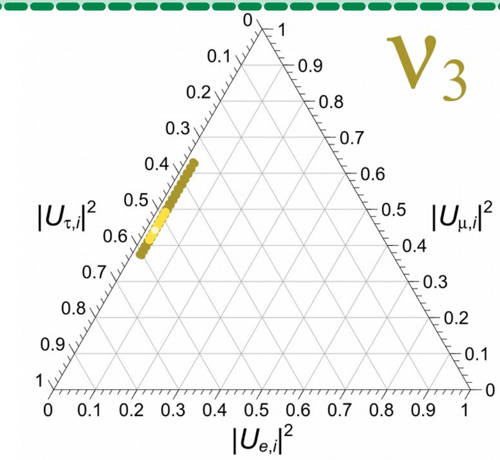
Earth

ν_1



$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

ν_3



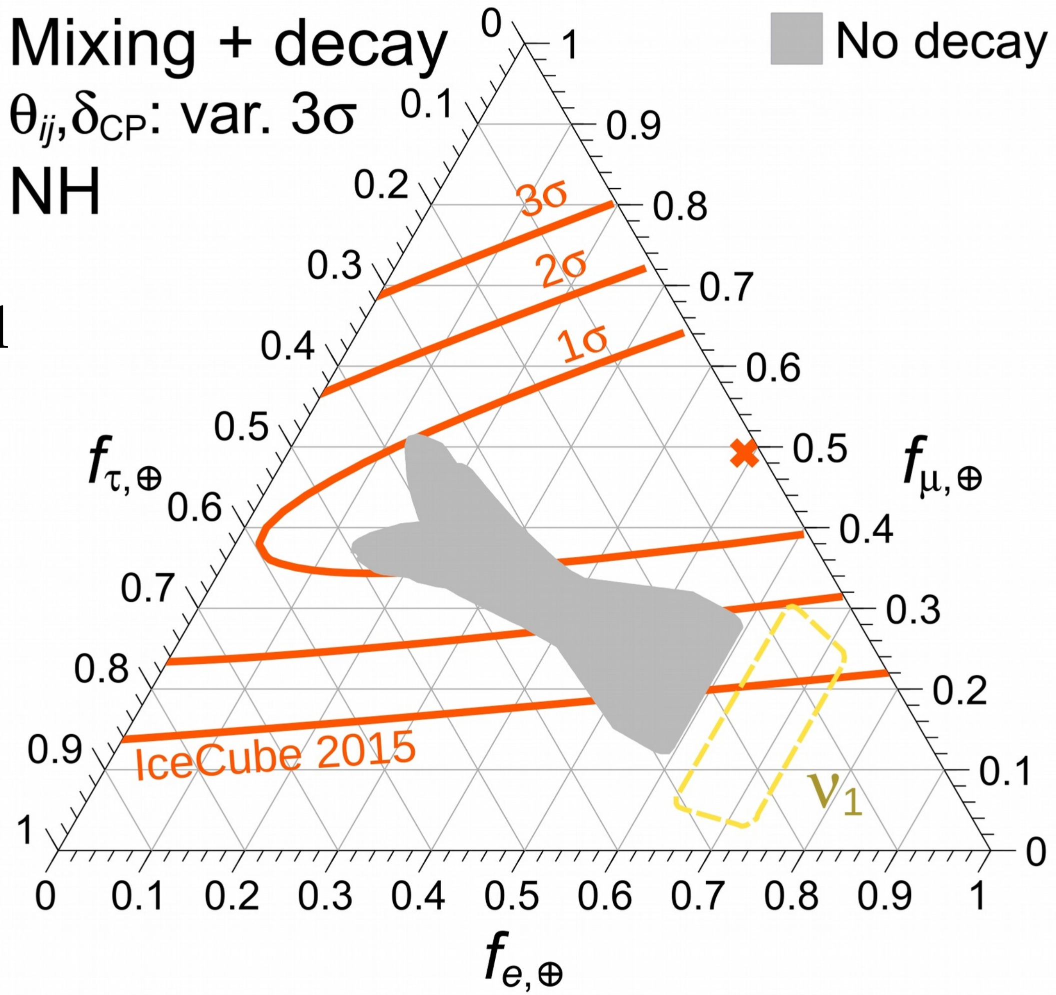
$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

Measuring the neutrino lifetime

Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- Any value of mixing parameters; and
- Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)



MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

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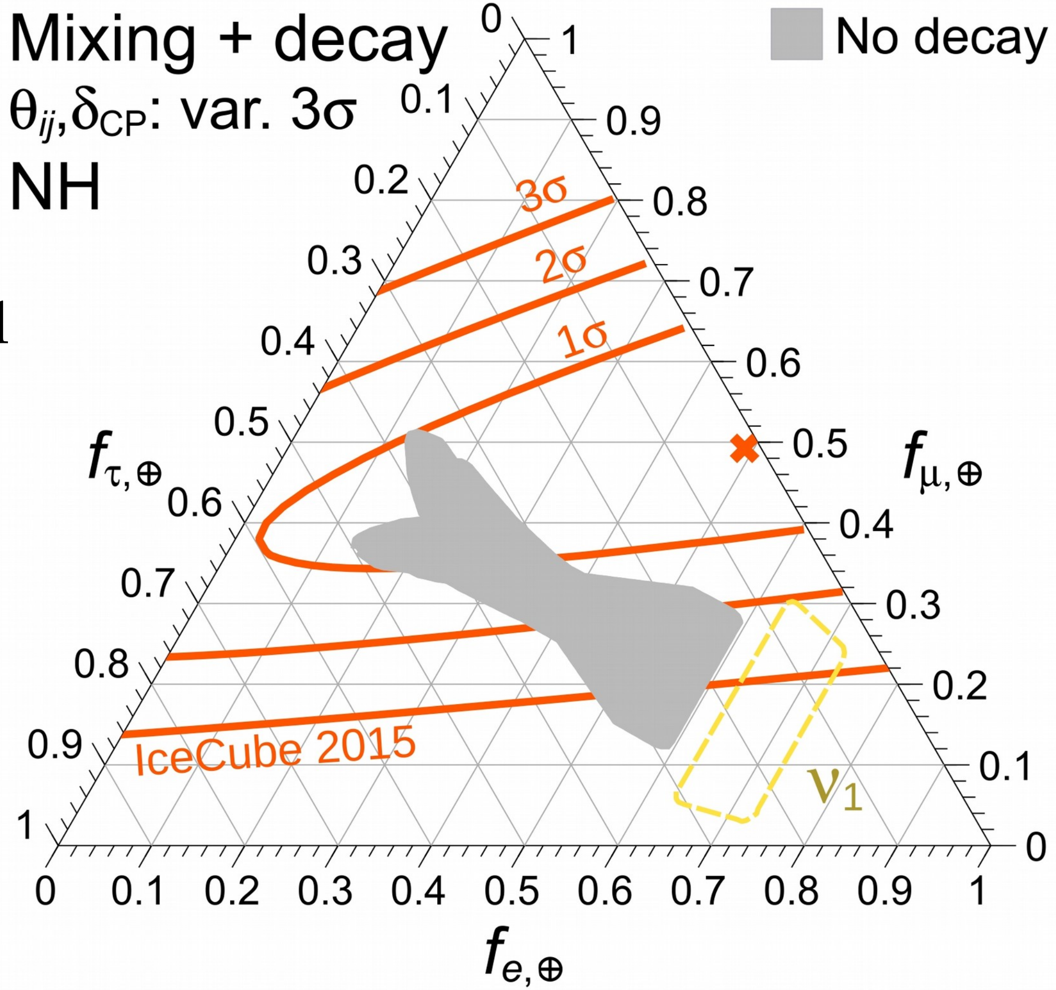

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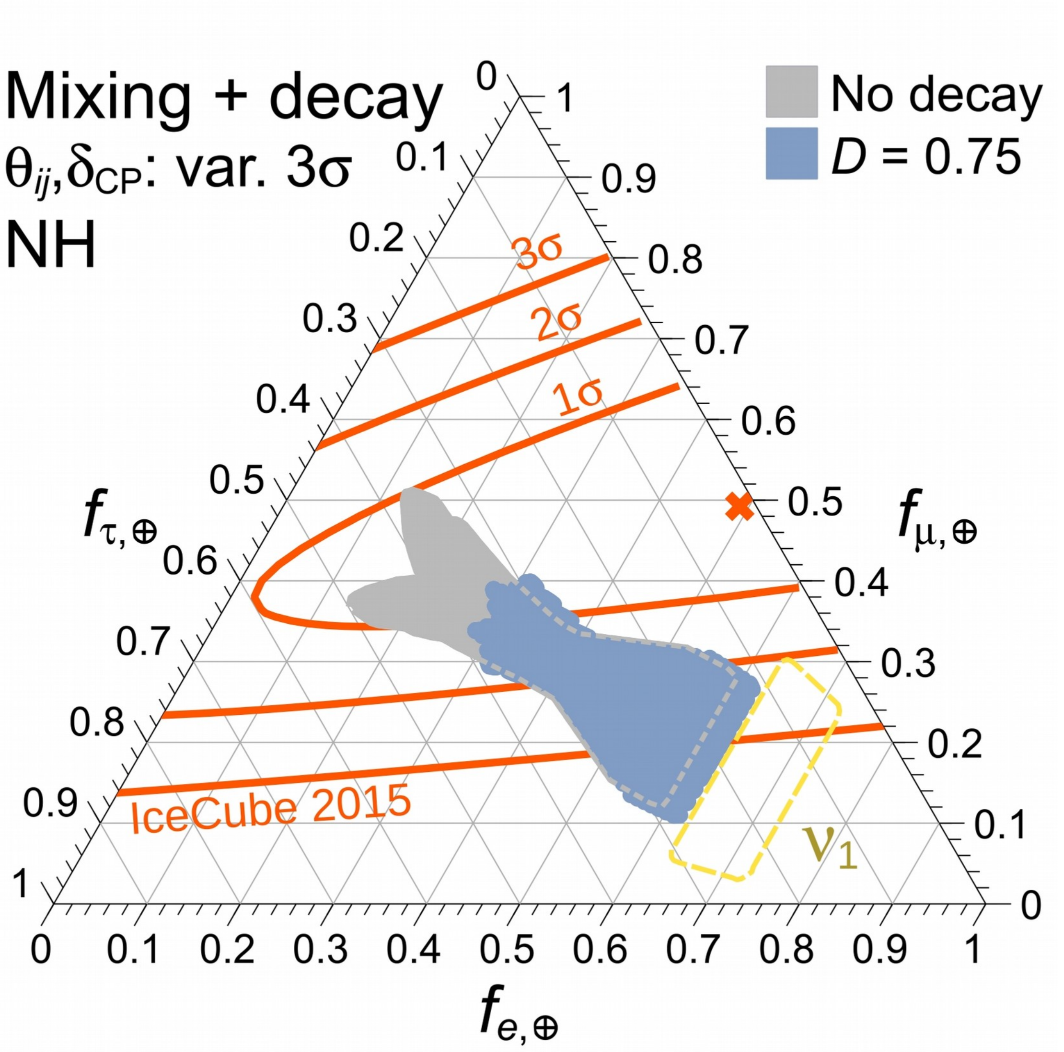

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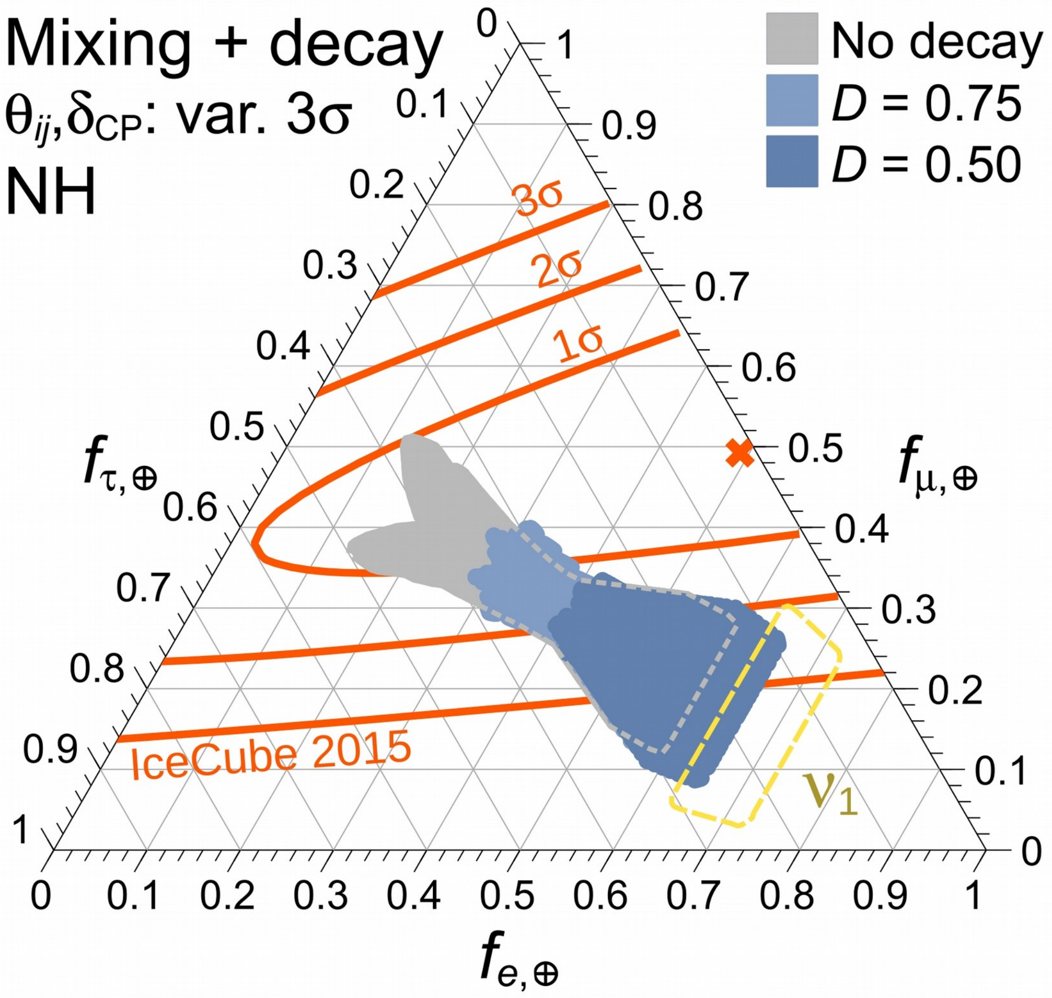

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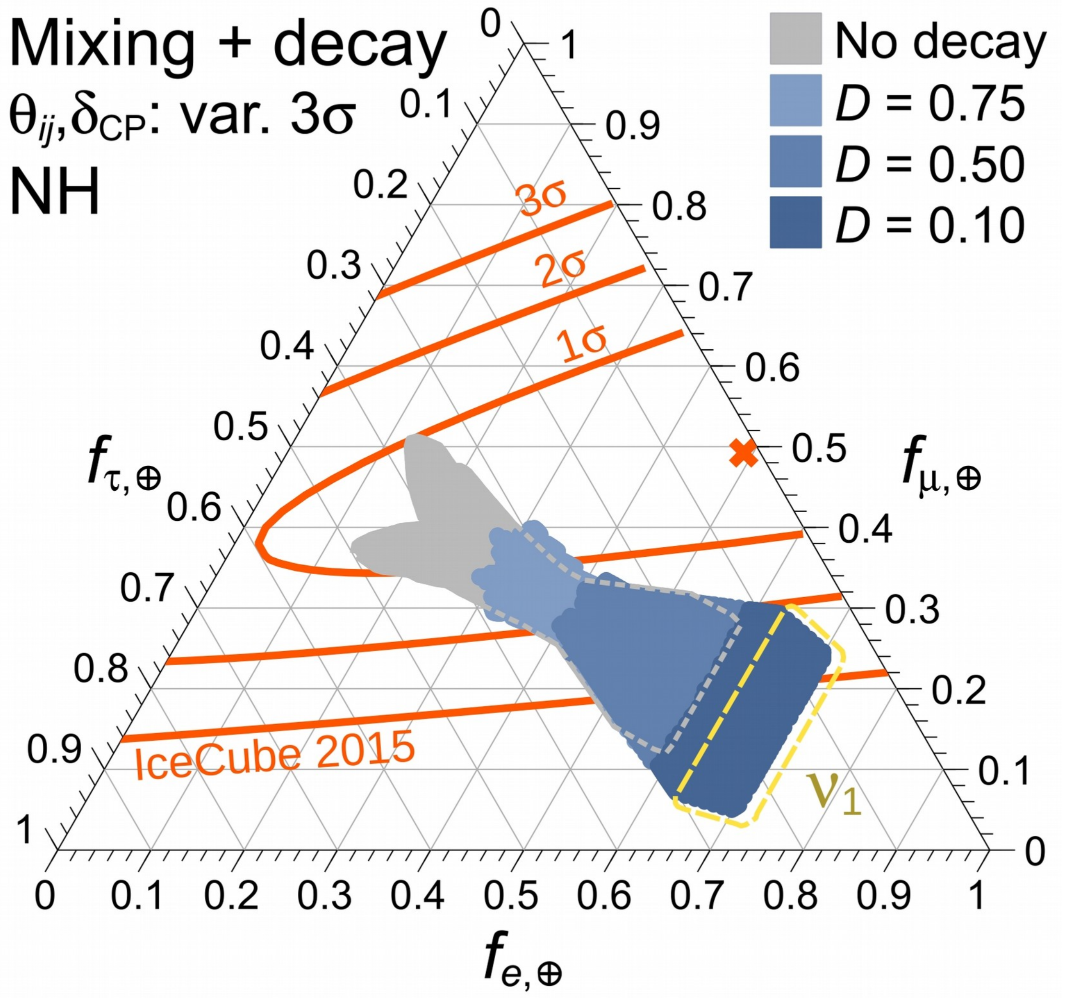

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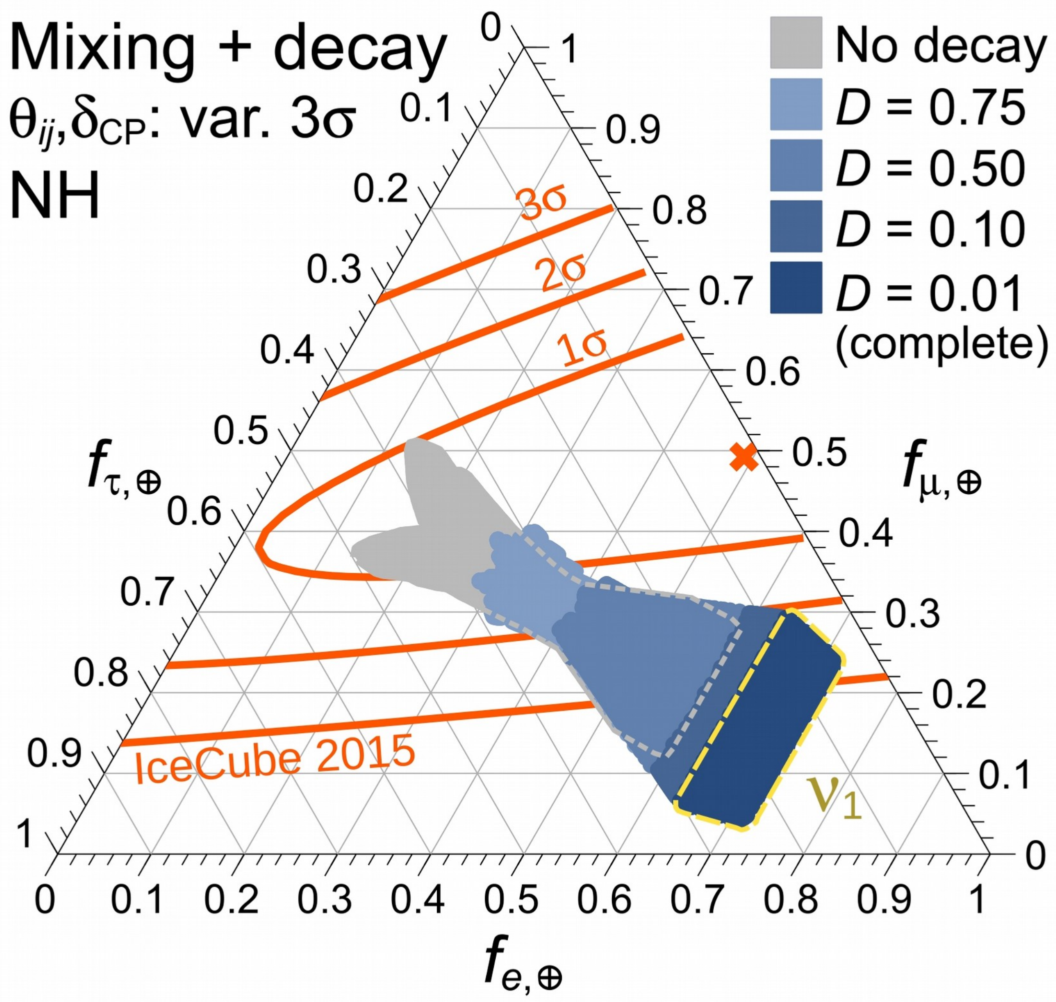

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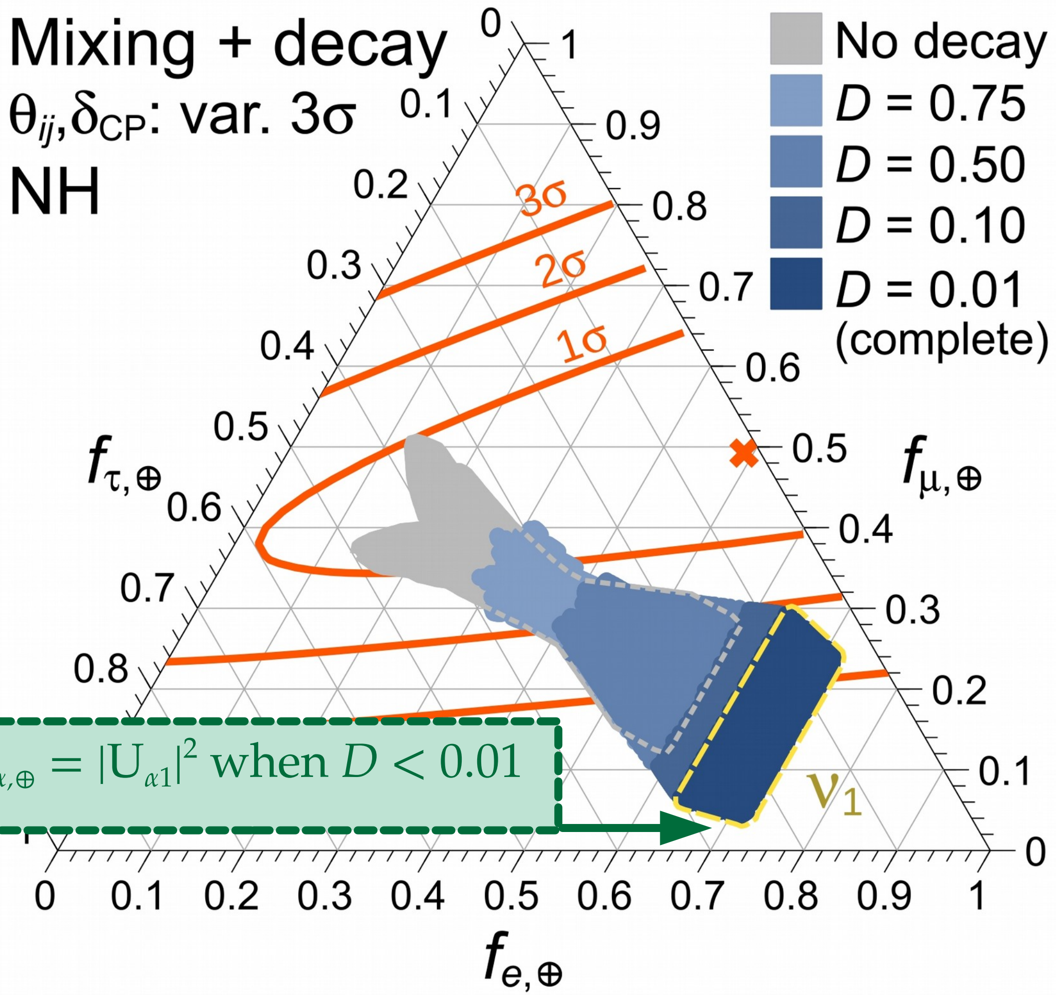
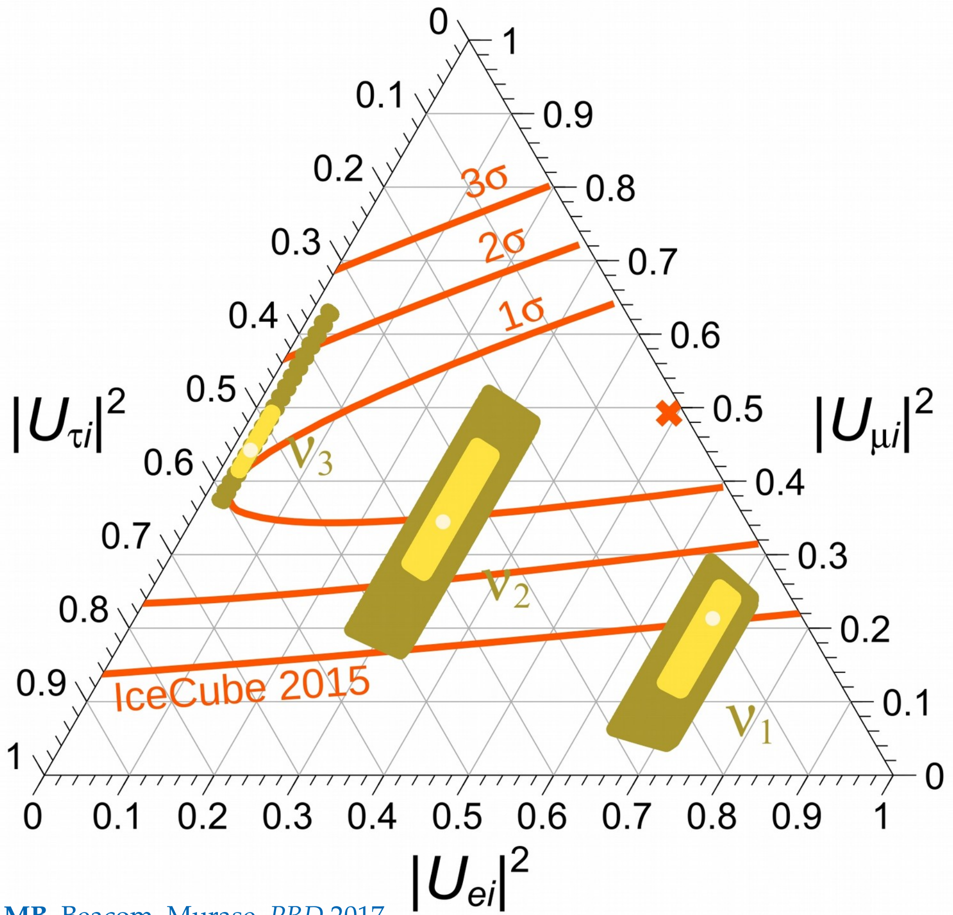
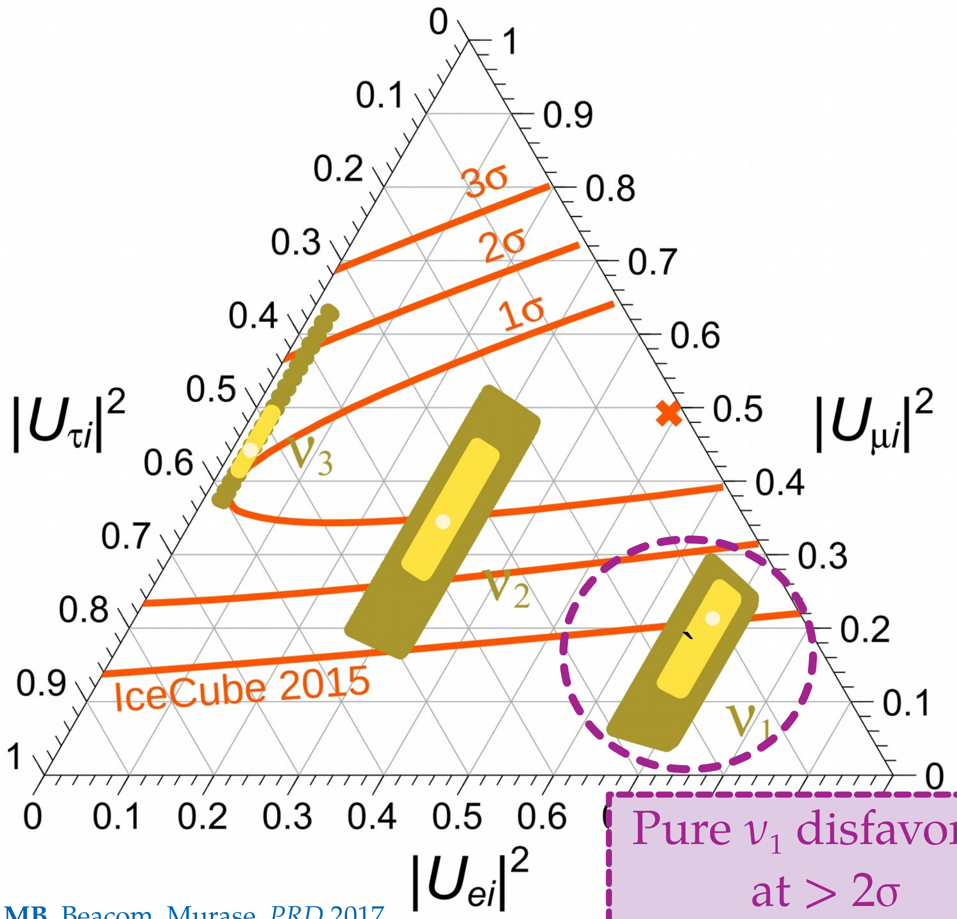


$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012



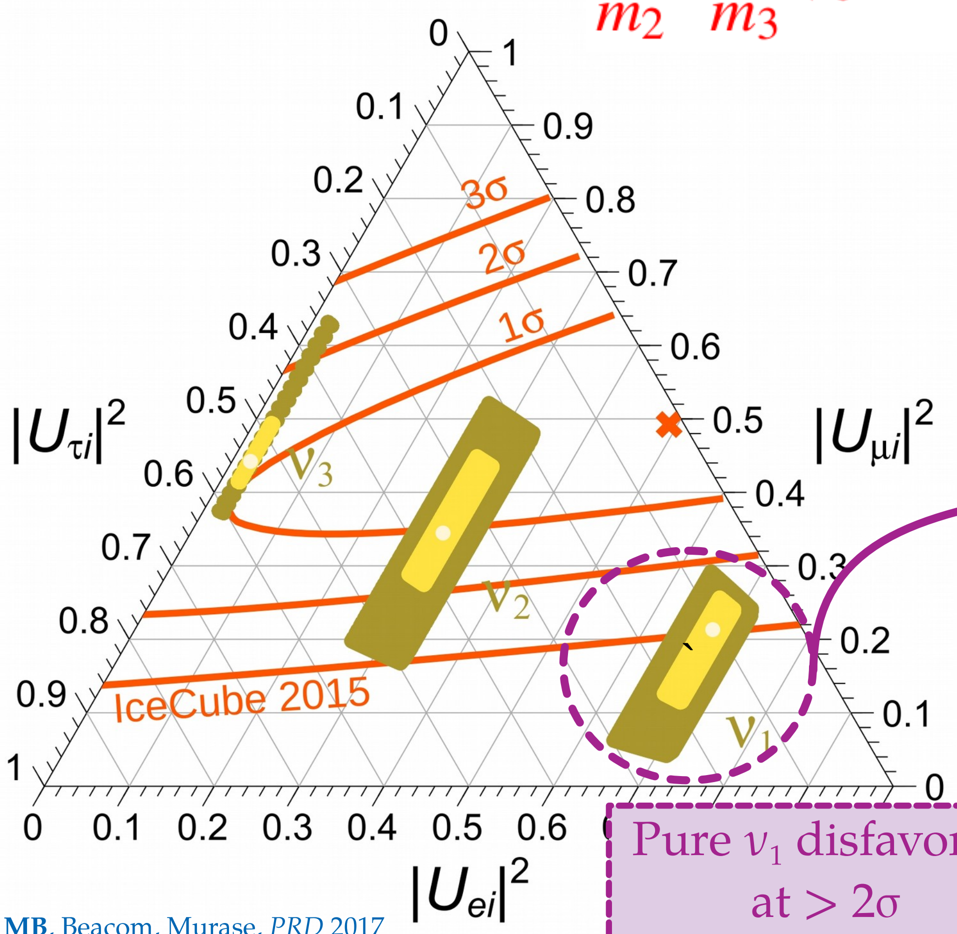
MB, Beacom, Murase, *PRD* 2017

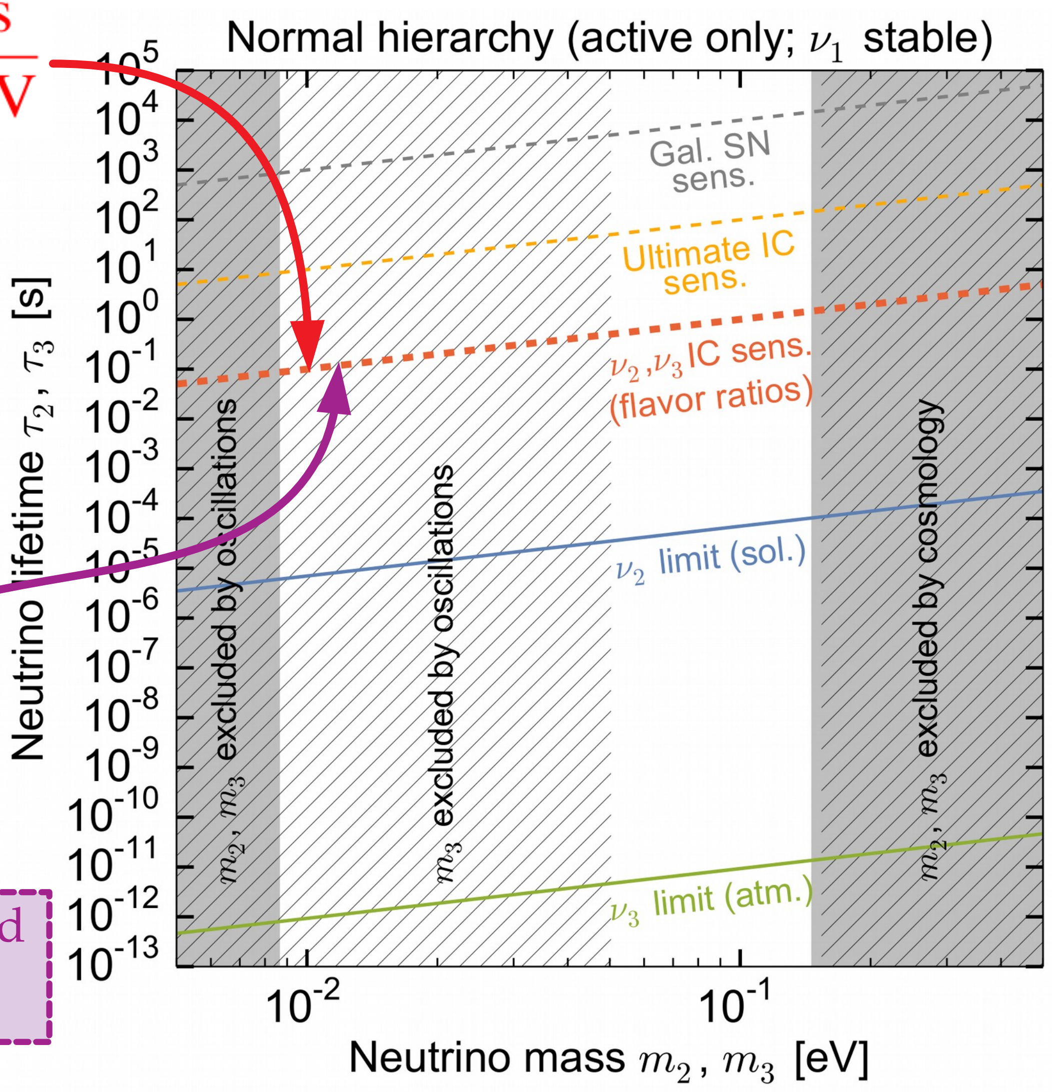


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \ \frac{\mathrm{s}}{\mathrm{eV}}$$



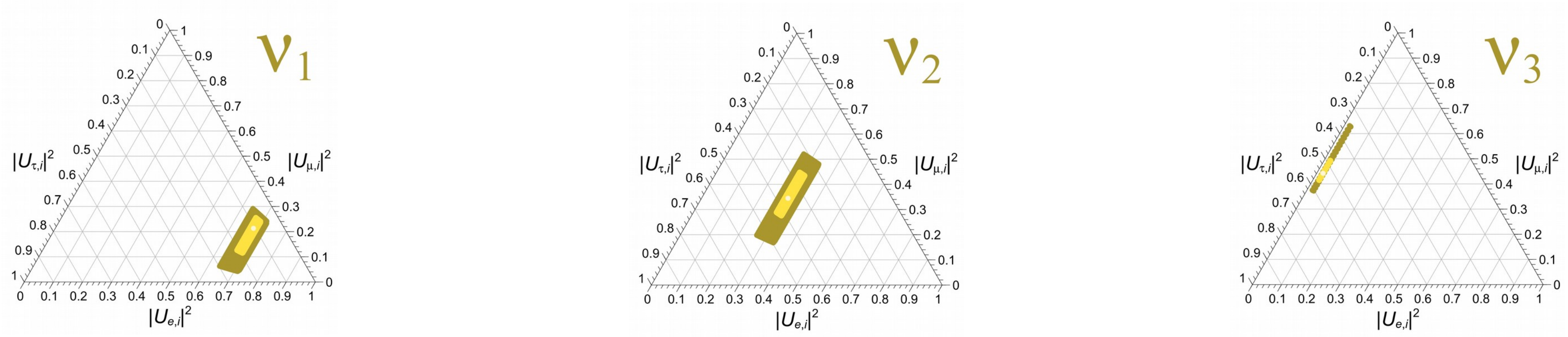


Pure ν_1 disfavored at $> 2\sigma$

MB, Beacom, Murase, *PRD* 2017

Two classes of new physics

- Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- Each one has a different flavor content:



- Flavor ratios at Earth are the result of their combination
- New physics may:
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

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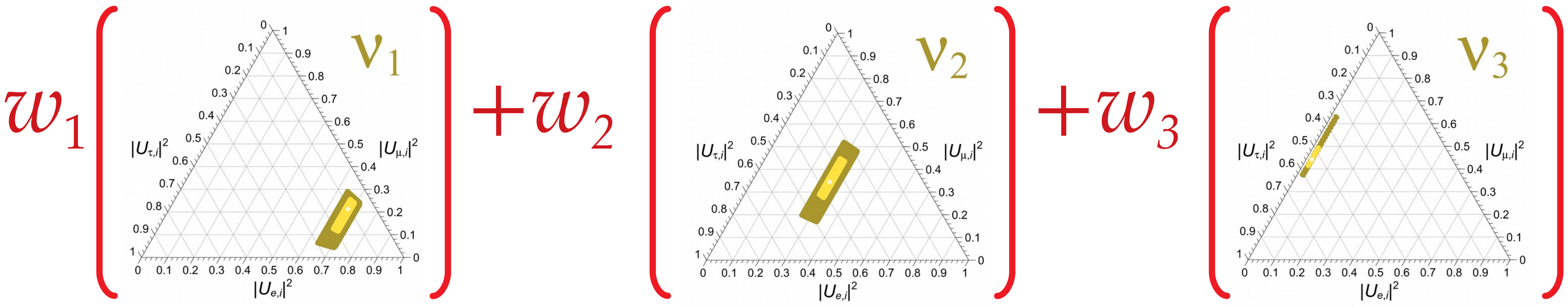

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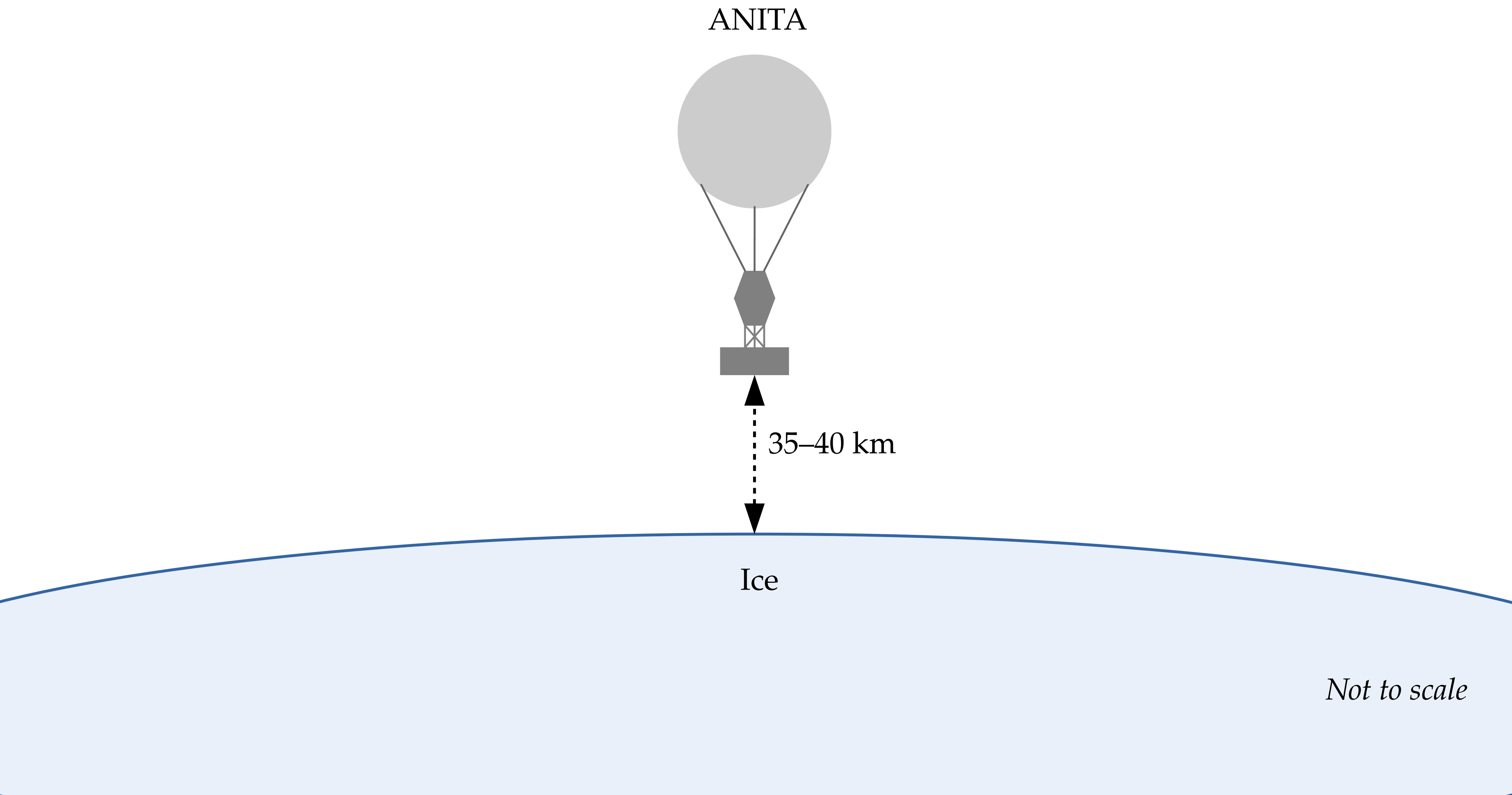
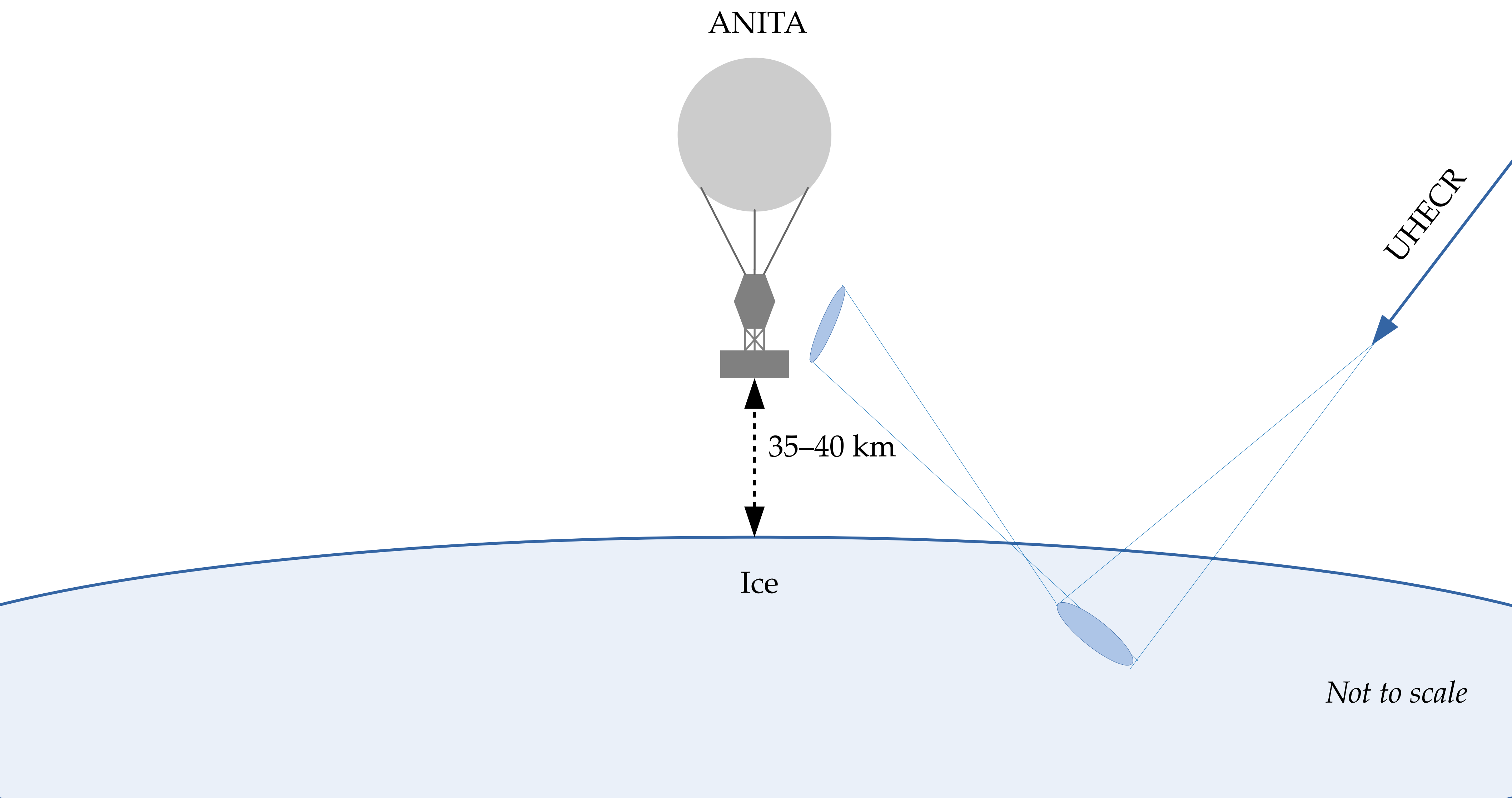
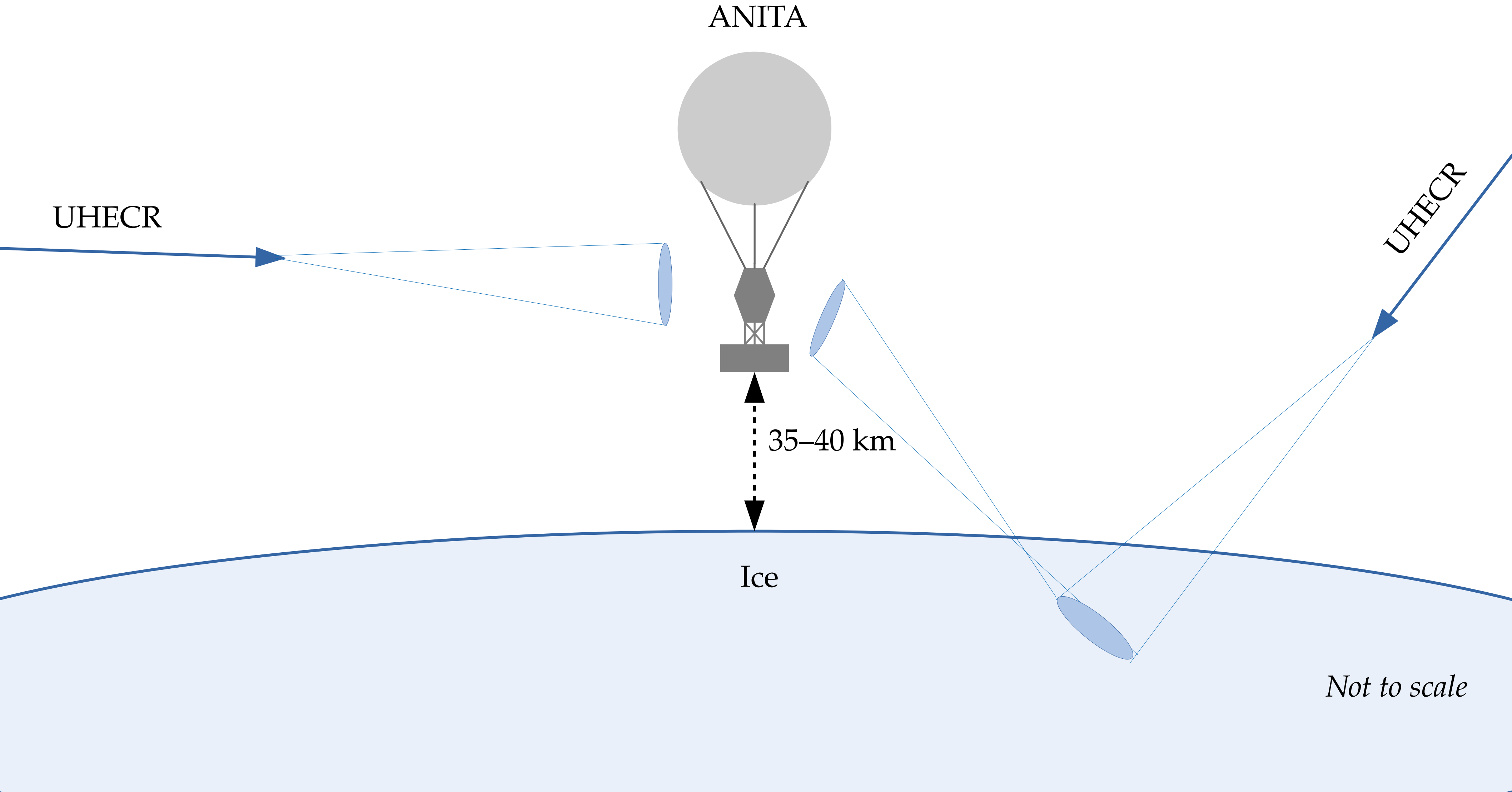
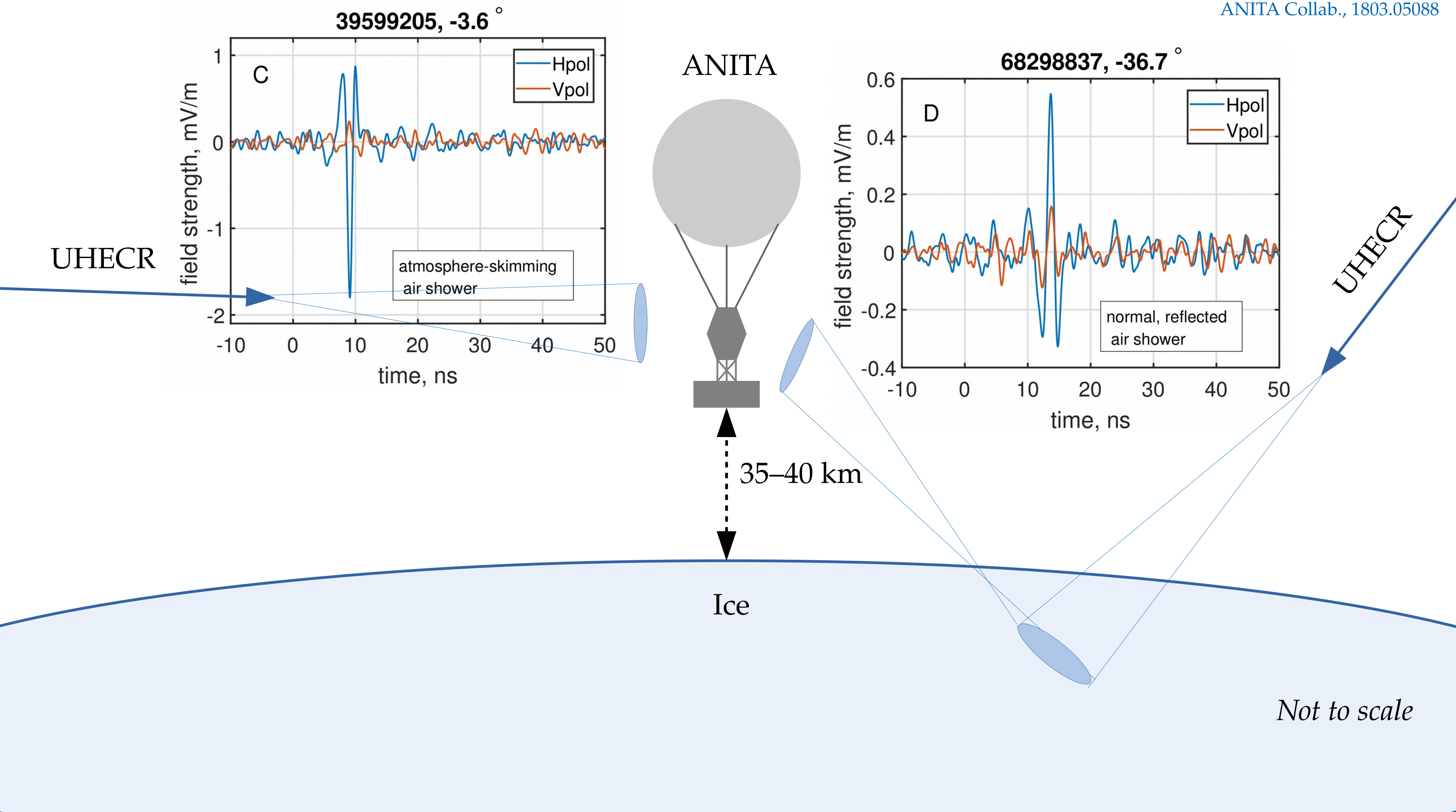
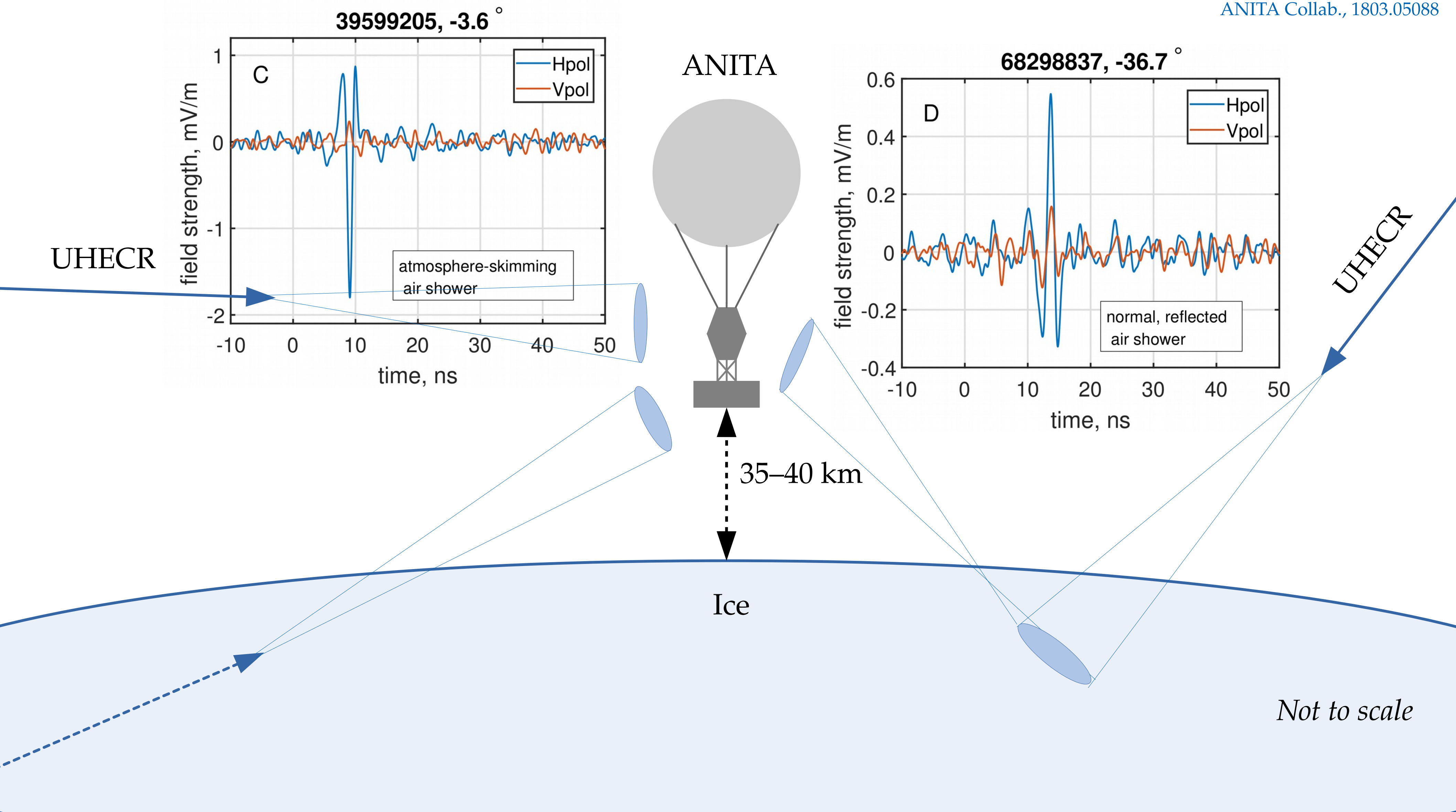

ANITA
35–40 km
Ice
Not to scale

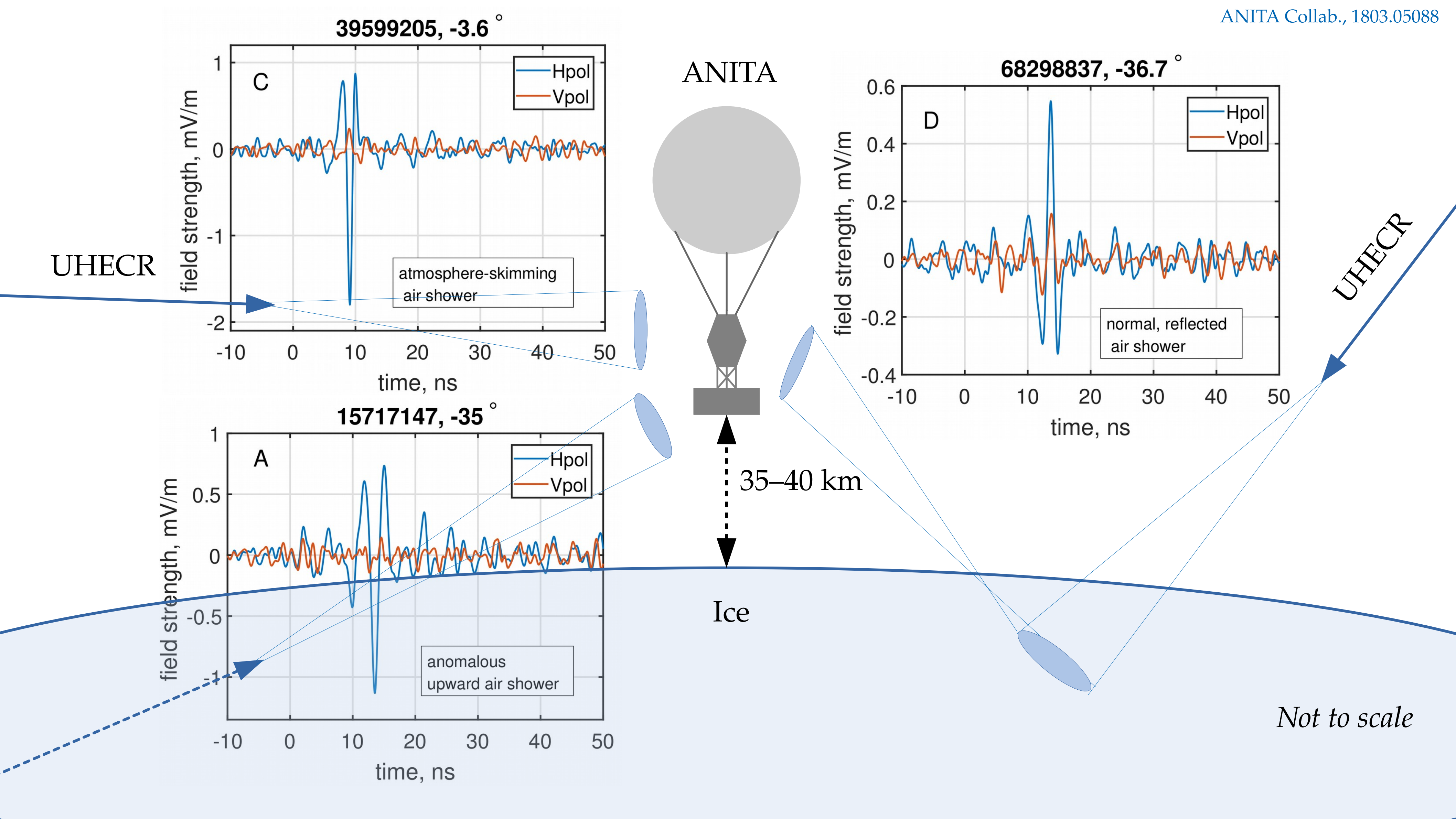

ANITA
UHECR
35–40 km
Ice
Not to scale


ANITA
UHECR
UHECR
35–40 km
Ice
Not to scale


39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
atmosphere-skimming air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected air shower
35–40 km
Ice
Not to scale

ANITA Collab., 1803.05088




ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
time, ns
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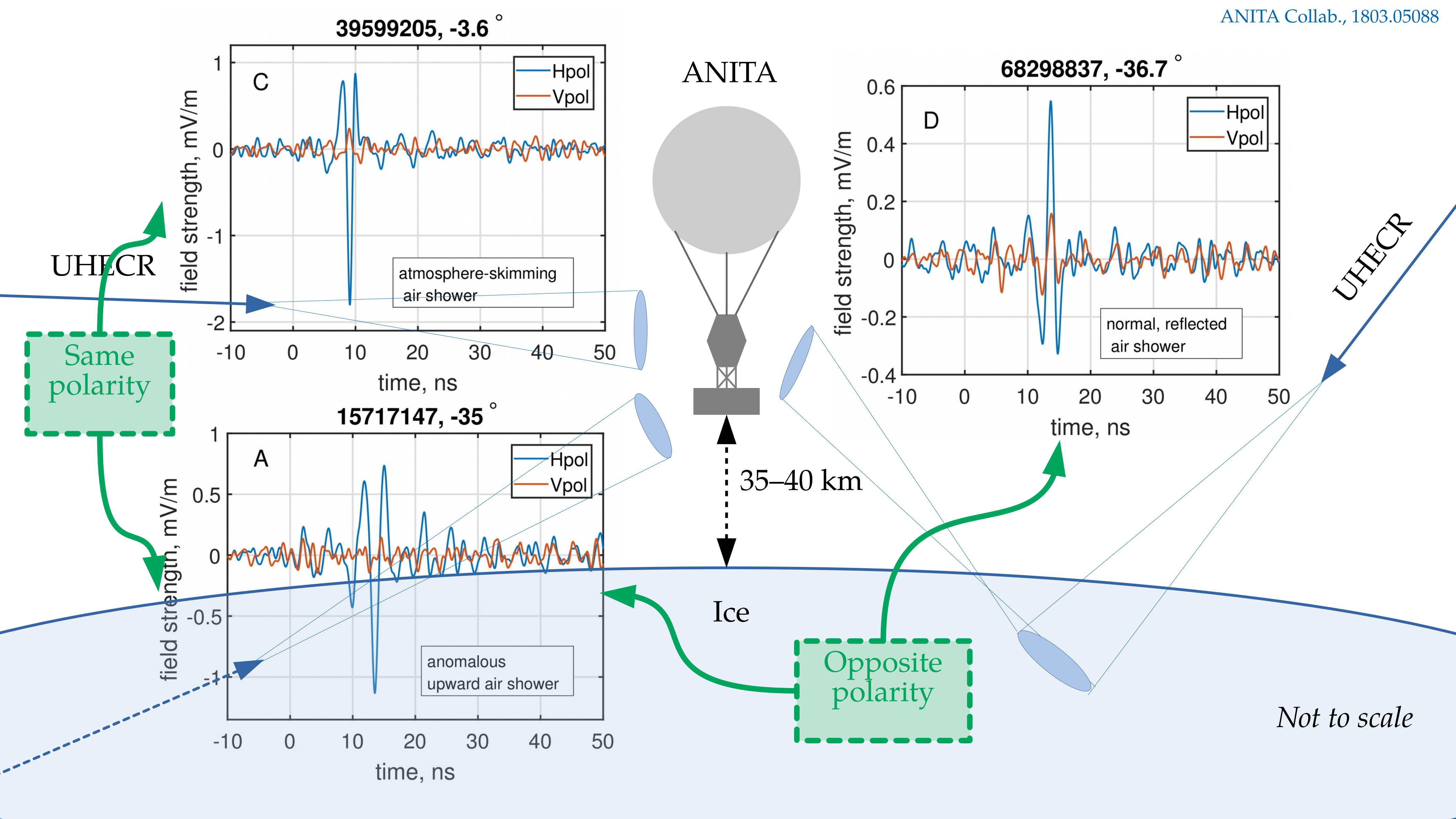
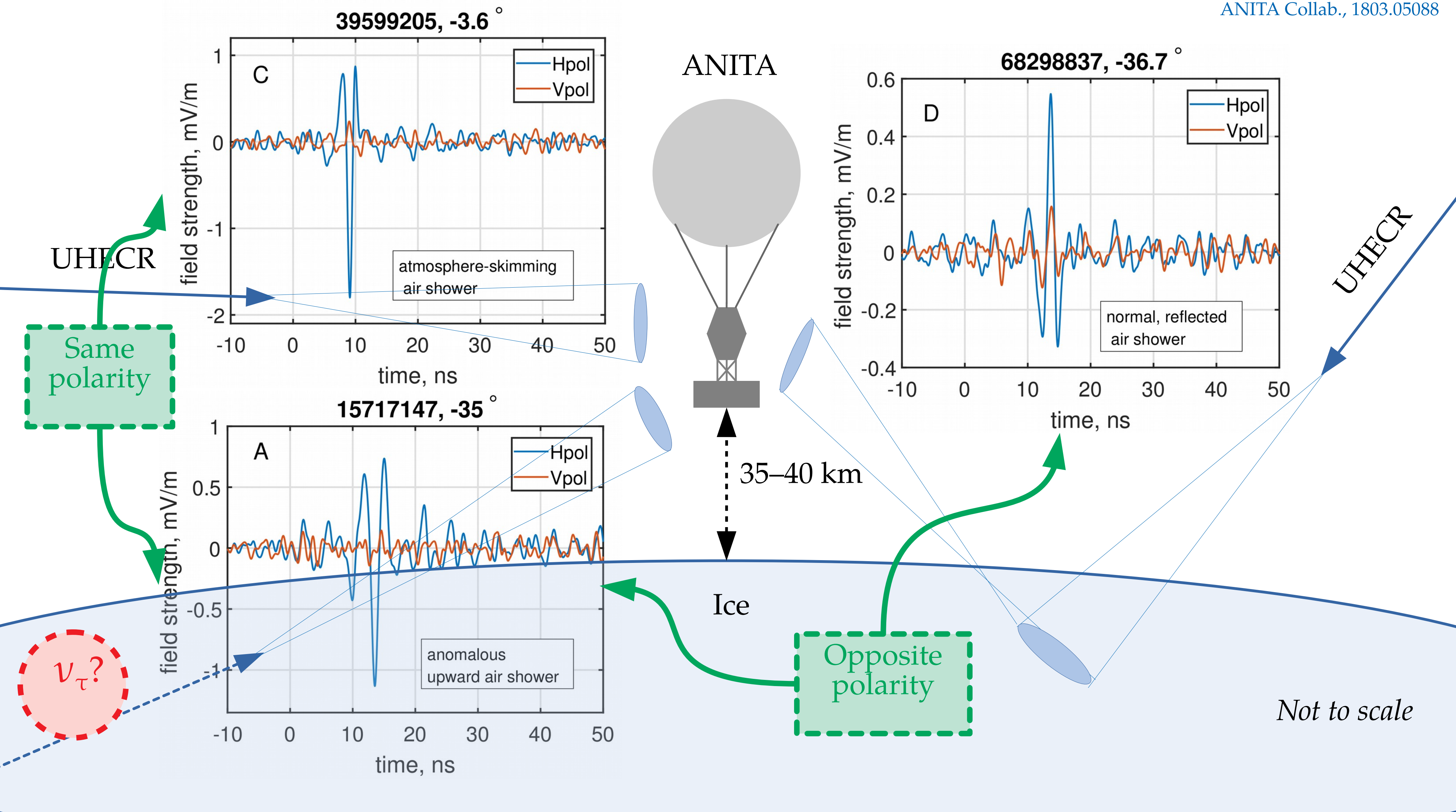
air shower
UHECR
ANITA
68298837, -36.7 °
D
normal, reflected
air shower
15717147, -35 °
A
anomalous
upward air shower
35–40 km
Ice
UHECR
Not to scale



ANITA Collab., 1803.05088
39599205, -3.6 °
C
Hpol
Vpol
atmosphere-skimming air shower
field strength, mV/m
time, ns
ANITA
68298837, -36.7 °
D
normal, reflected air shower
UHECR
UHECR
Same polarity
15717147, -35 °
A
anomalous upward air shower
35–40 km
Ice
Opposite polarity
Not to scale

ANITA Collab., 1803.05088



Mystery ANITA events – First UHE ν detected?

- Two upgoing, unflipped-polarity showers:
  - ANITA-1 (2006): 20°±0.3° dec., 0.60±0.4 EeV
  - ANITA-3 (2014): 38°±0.3° dec., 0.56±0.2 EeV
- Estimated background rate: $< 10^{-2}$ events
- Were these showers due to ν_τ? *Unlikely*
- Optical depth to νN interactions at EeV:

$$\frac{\text{Chord inside Earth}}{\text{Interaction length in Earth}} = \frac{7000 \text{ km}}{390 \text{ km}} = 18$$

- Flux is suppressed by $e^{-18} = 10^{-8}$

ANITA Collab., *PRL* 2016 + 1803.05088

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Transient astrophysical event?

- **ANITA-1 event:** none associated
- **ANITA-3 event:**
  - Type-Ia SN2014dz ($z = 0.017$)
  - Within 1.9°, 5 hours before event
  - Probability of chance SN: 3×10^{-3}
  - ν luminosity must exceed bolometric luminosity of 4×10^{42} erg s^{-1}

ANITA Collab., *PRL* 2016 + 1803.05088