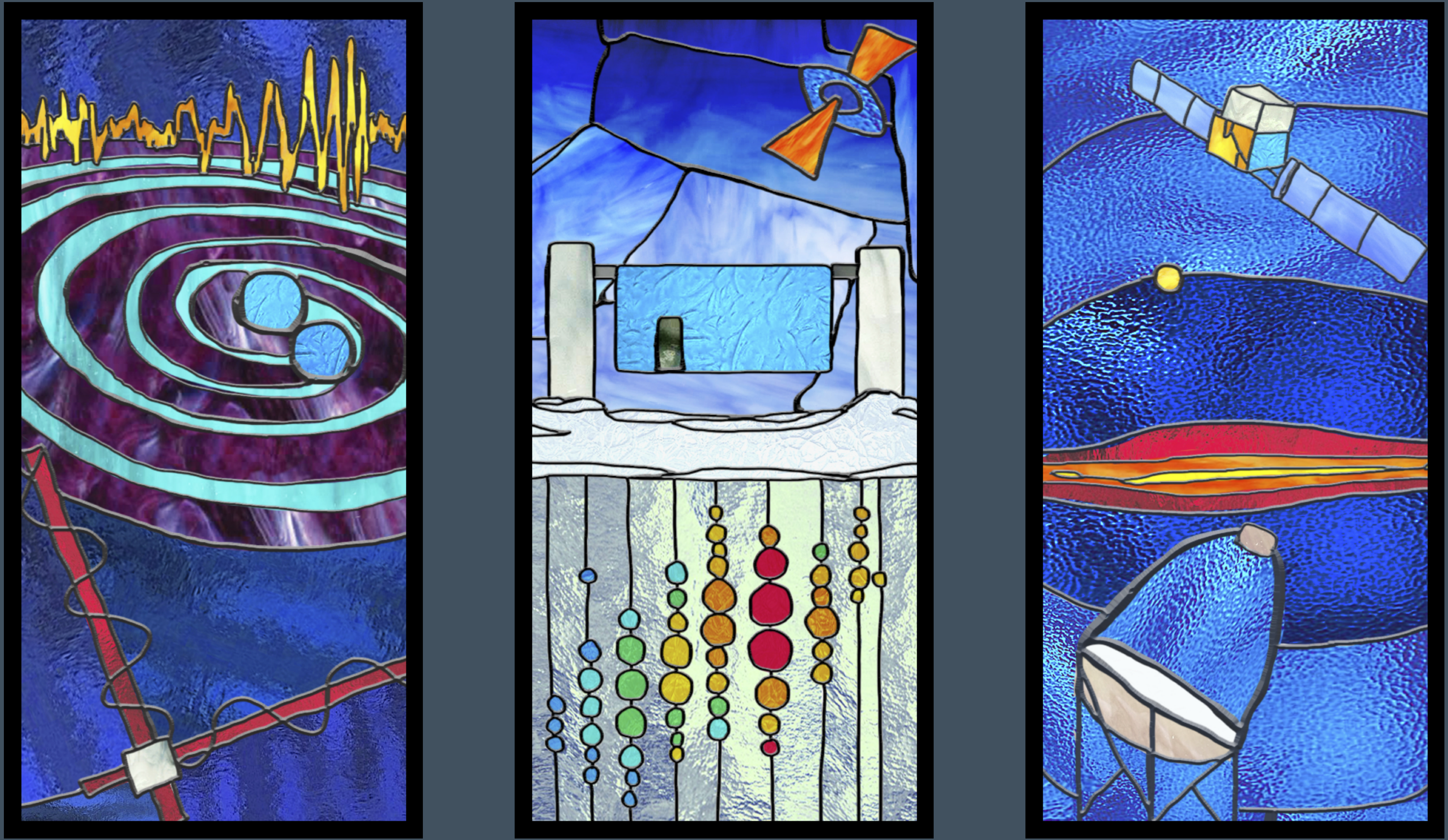


# Neutrinos and Multi-Messenger Astronomy

VILLUM FONDEN

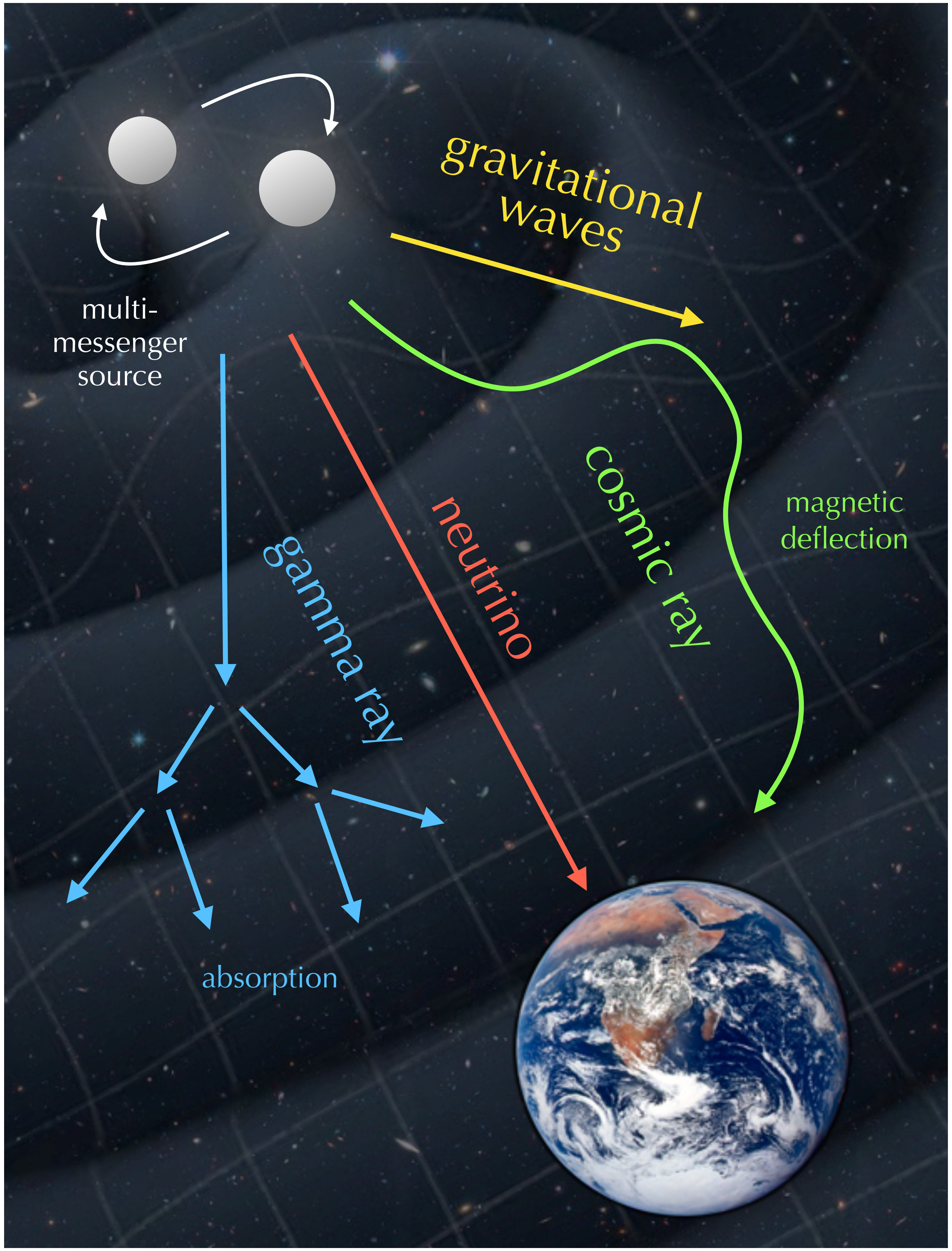
Markus Ahlers, NBI Copenhagen

*KSETA Workshop*

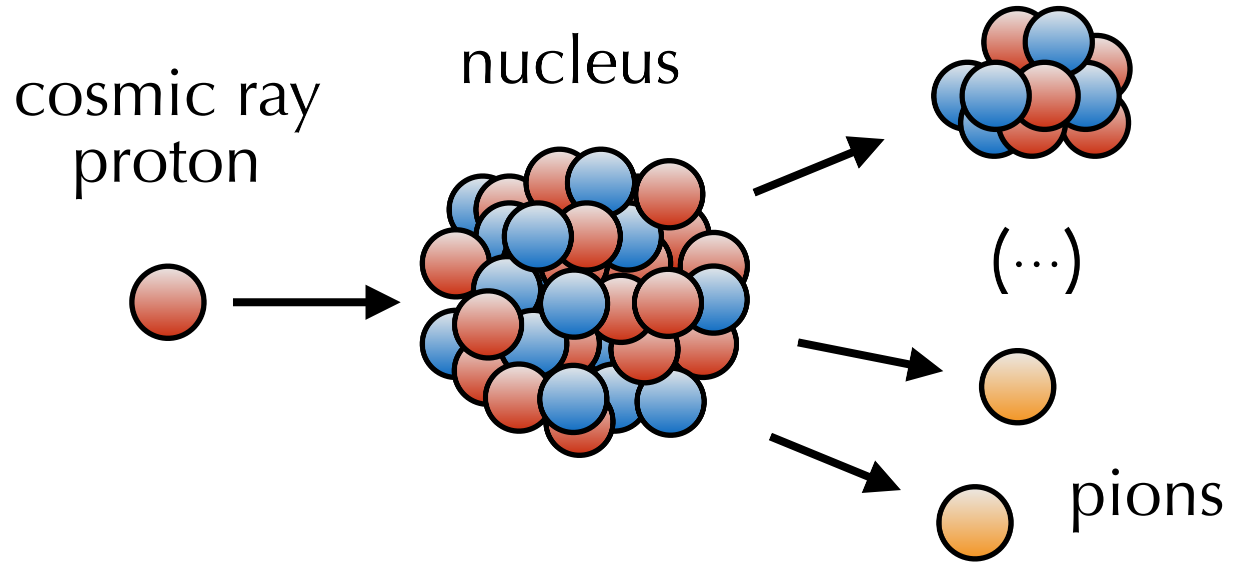
*February 17, 2020*

KØBENHAVNS UNIVERSITET

# Multi-Messenger Astronomy



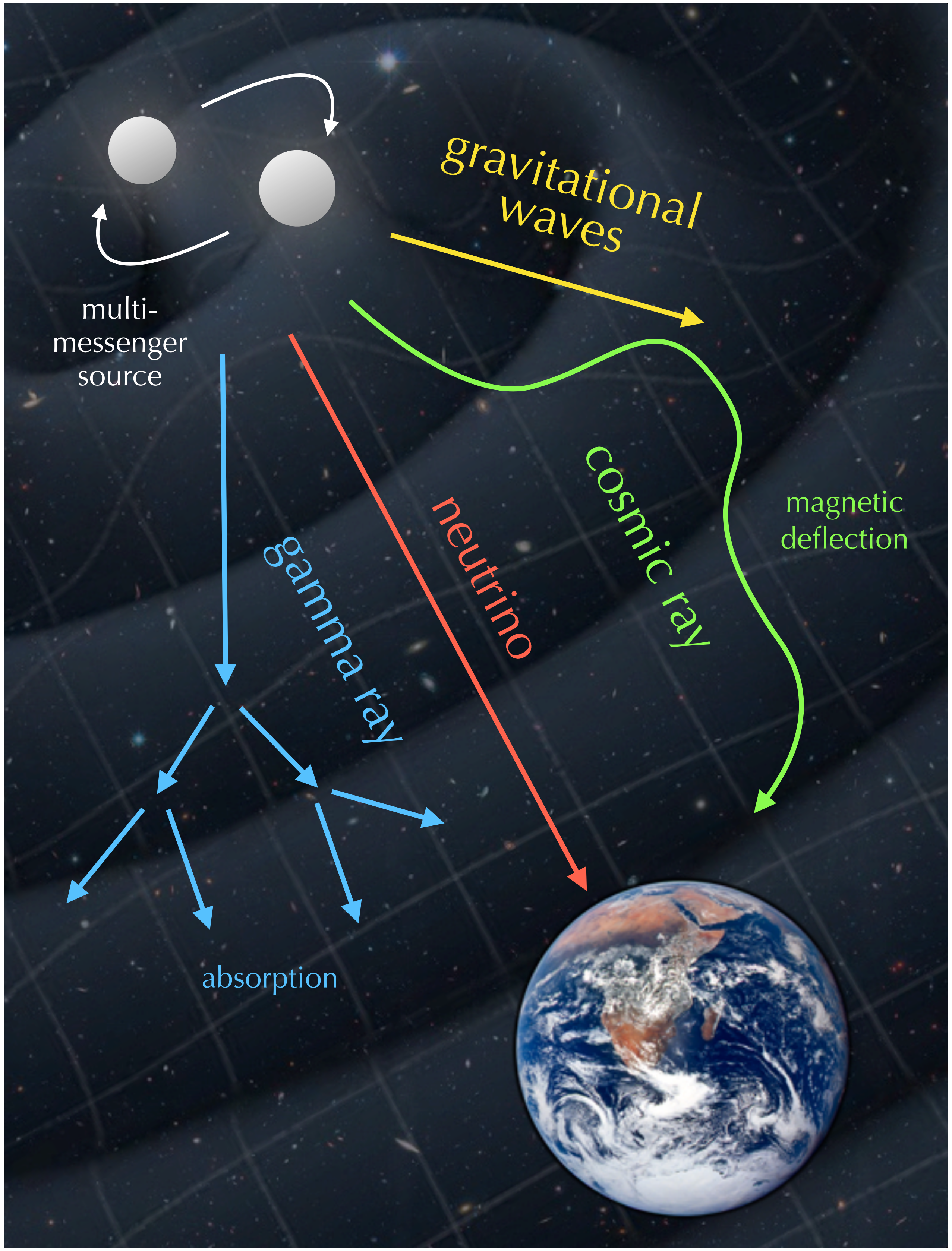

Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.




Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^0 \rightarrow \gamma + \gamma$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

# Multi-Messenger Astronomy




Unique abilities of **cosmic neutrinos**:

**no deflection** in magnetic fields (unlike cosmic rays)

**coincident** with photons and gravitational waves

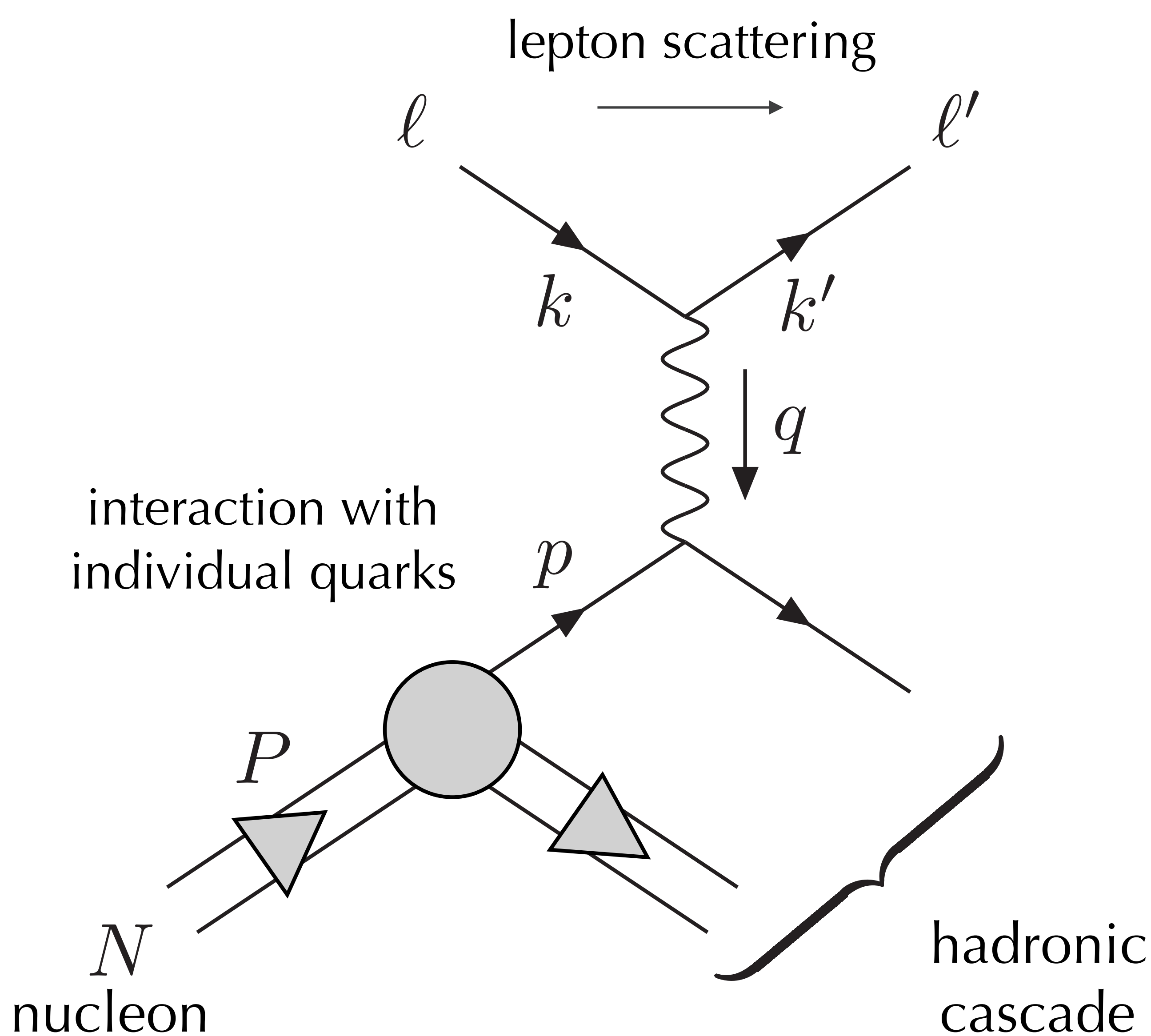
**no absorption** in cosmic backgrounds (unlike gamma-rays)

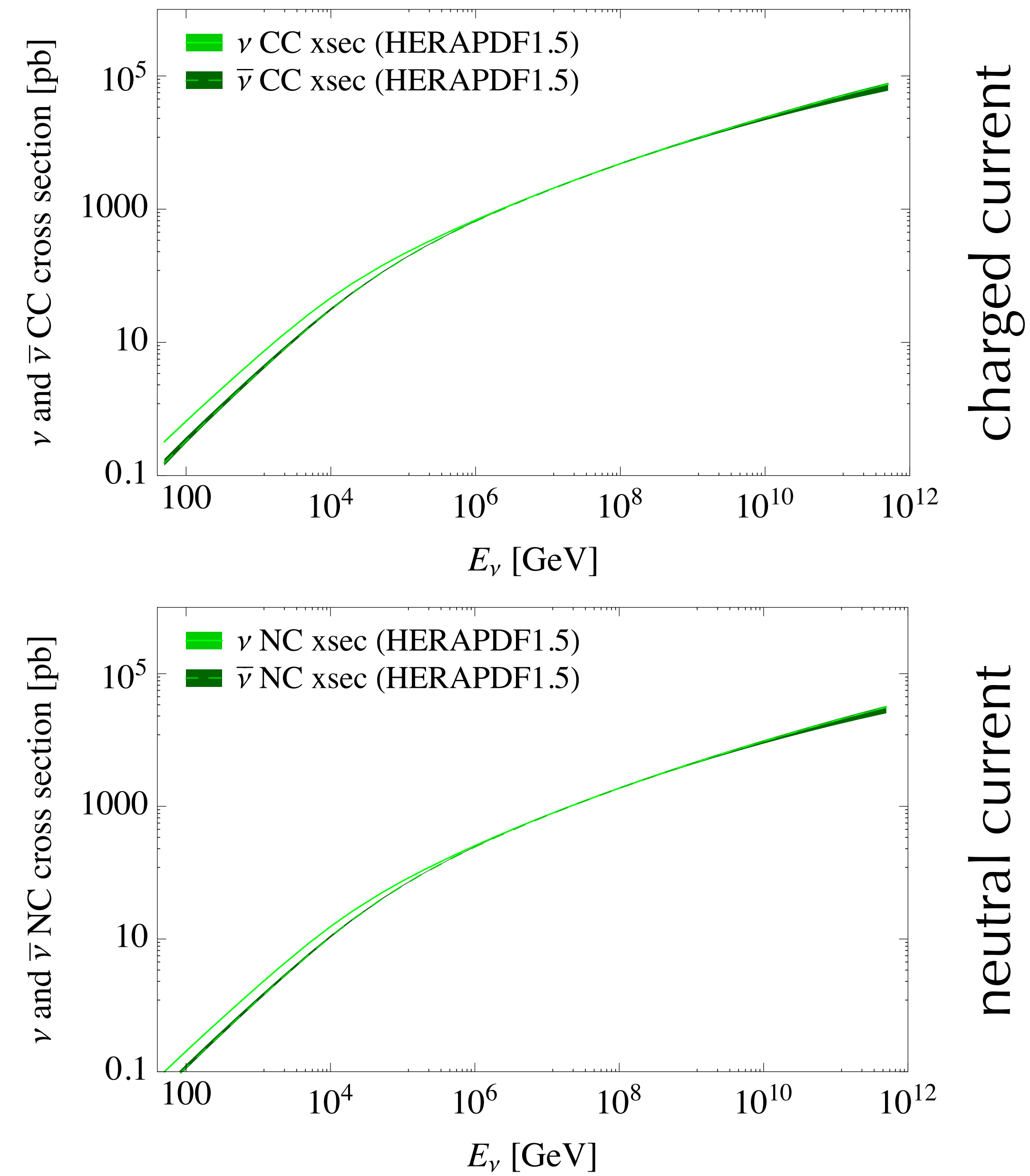
**smoking-gun** of unknown sources of cosmic rays

**BUT,** very difficult to detect!

# Neutrino Interactions

- Low-energy (<10GeV) neutrino interaction with matter in coherent, quasi-elastic or resonant interactions.
- High-energy neutrinos interact with nuclei via **deep inelastic scattering.**




[Cooper-Sarkar, Mertsch & Sarkar'11]

# Detector Requirements

Neutrino **charged and neutral current (CC & NC) interactions** are visible by Cherenkov emission of relativistic secondaries in transparent media.

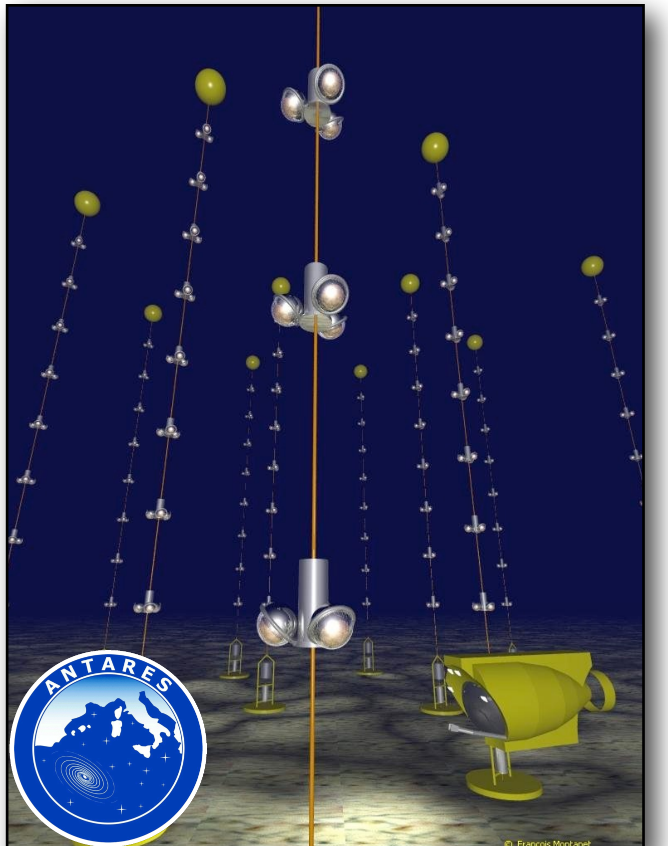
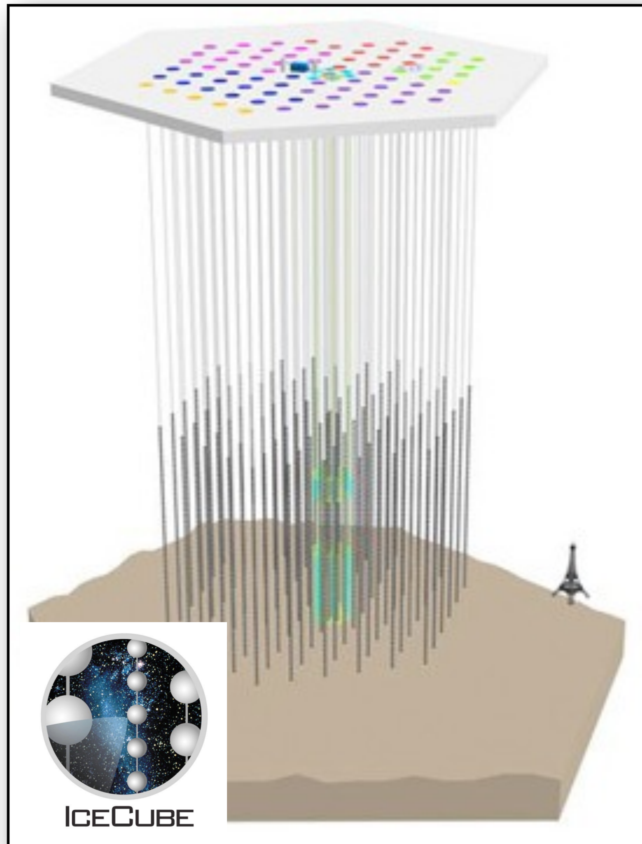
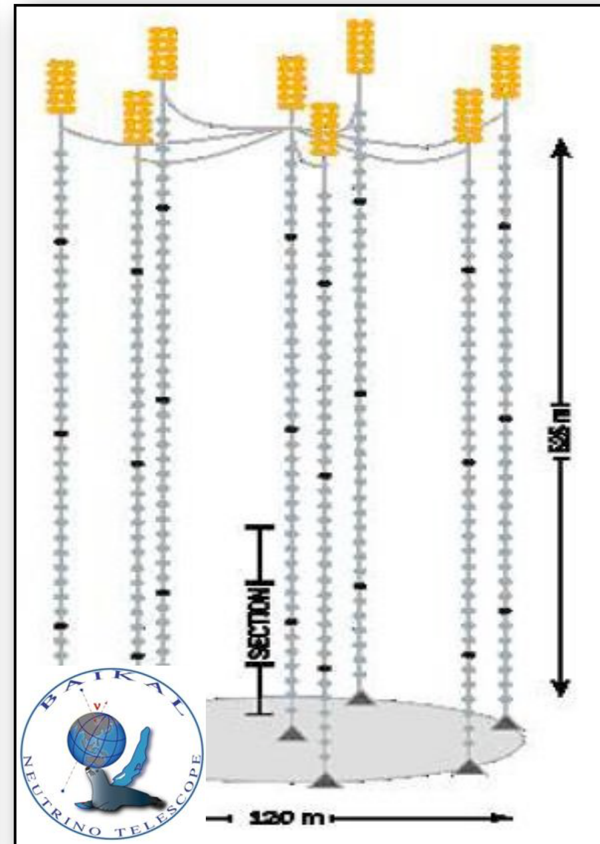
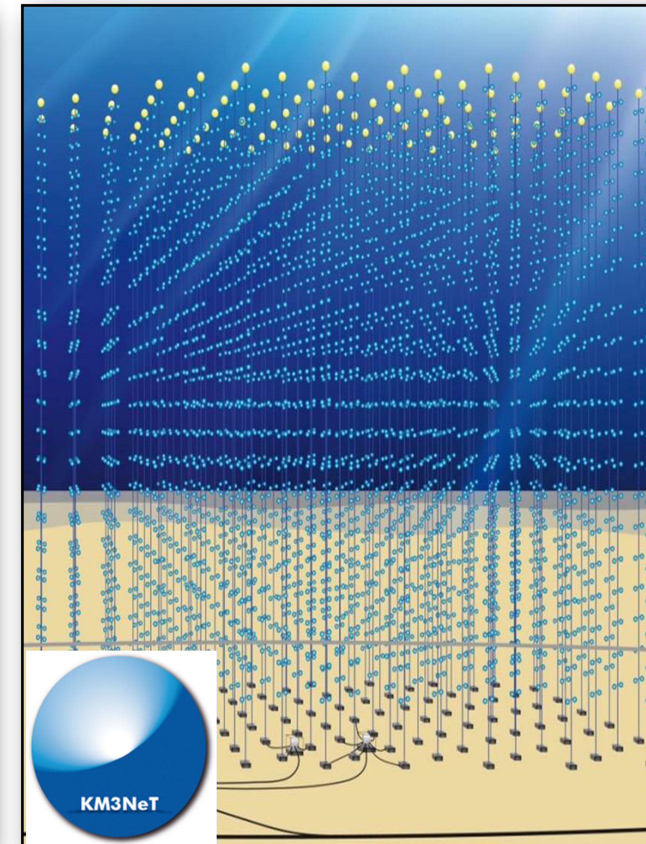
**PeV $\nu$-flux:** $$F \simeq \frac{1}{10\,\mathrm{yr}\,\mathrm{m}^2}$$

**cross section:** $$\sigma_{\nu\mathrm{N}} \sim 10^{-8}\sigma_{pp} \sim 10^{-33}\mathrm{cm}^2$$

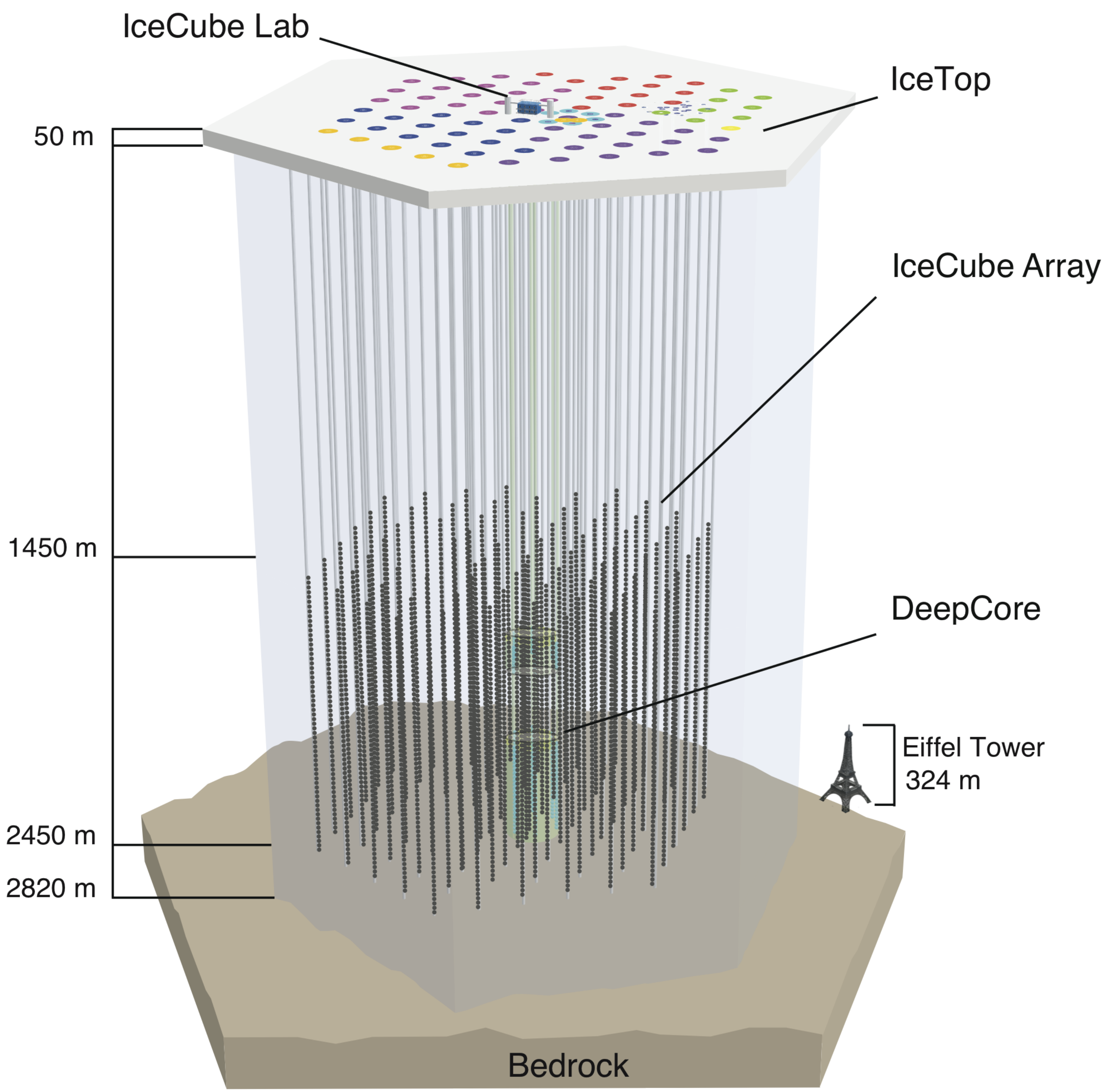
**event rate:** $$F \times \sigma_{\nu\mathrm{N}} \times \frac{N_A}{\mathrm{cm}^3} \sim \frac{\mathrm{few}}{\mathrm{yr}} \times \frac{V}{\mathrm{km}^3}$$

**minimum detector size: 1km$^3$**

# Cherenkov Observatories

| Antares | IceCube | Baikal-GVD | KM3NeT/ARCA |
|---|---|---|---|
|  |  |  |  |
| Mediterranean | South Pole | Lake Baikal | Mediterranean |
| since 2008 | fully instrumented since 2011 | under construction (5 out of 8 clusters) | under construction (3 out of 230 DUs) |
| ~0.01 km$^3$ | ~1 km$^3$ | ~0.4 km$^3$ (Phase 1)<br>~1km$^3$ | ~0.1 km$^3$ (Phase 1)<br>~1 km$^3$ |
| 885 OMs (10″) | 5160 OMs (10″) | 2304 OMs (10″) | 4140 OMs (31x3″) |

# IceCube Observatory

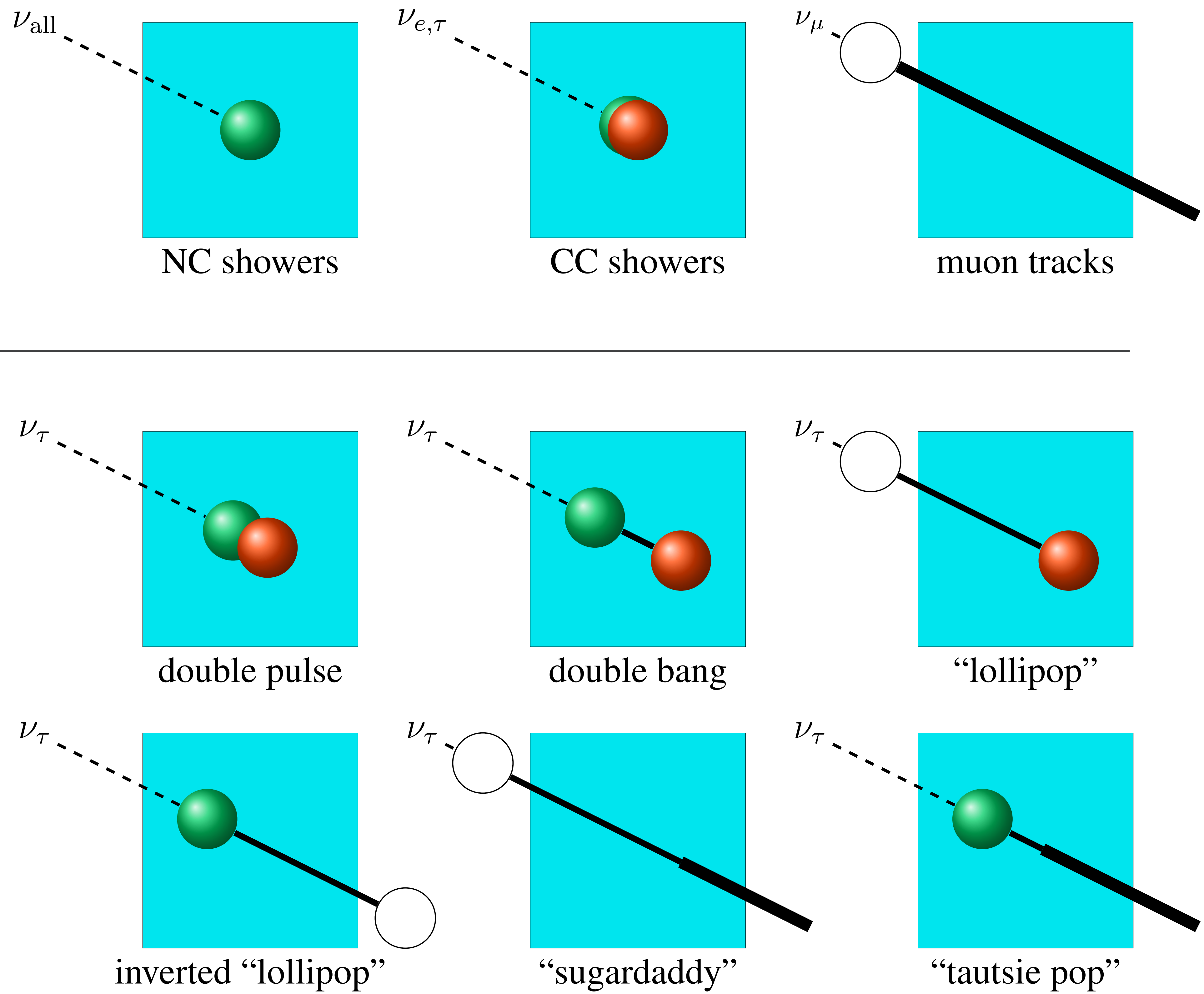



- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- price tag: **€0.3 per ton**

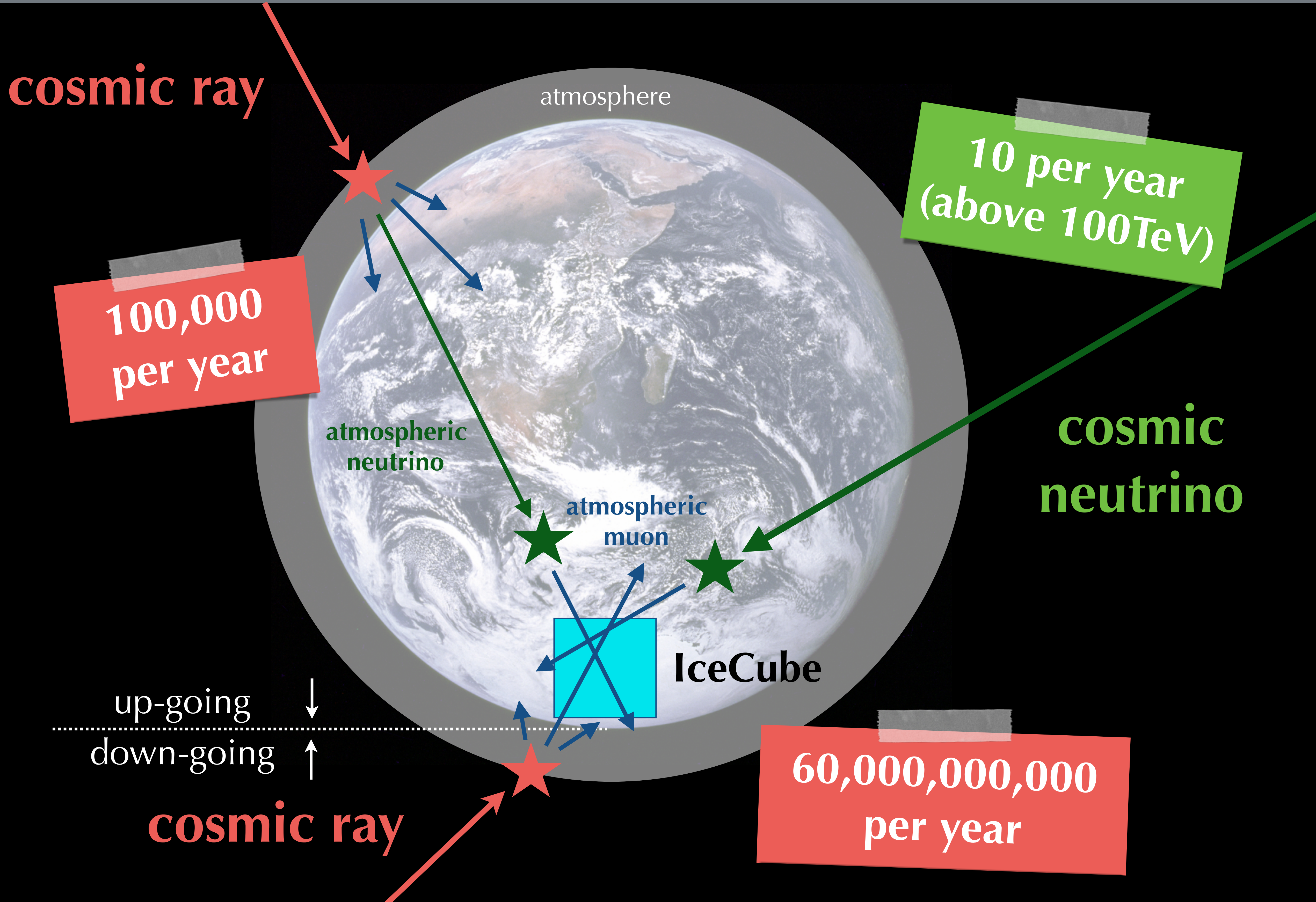
# Optical Cherenkov Detection

"cascades" & "tracks"

**rare events** from high-energy $\nu_\tau$ CC interactions

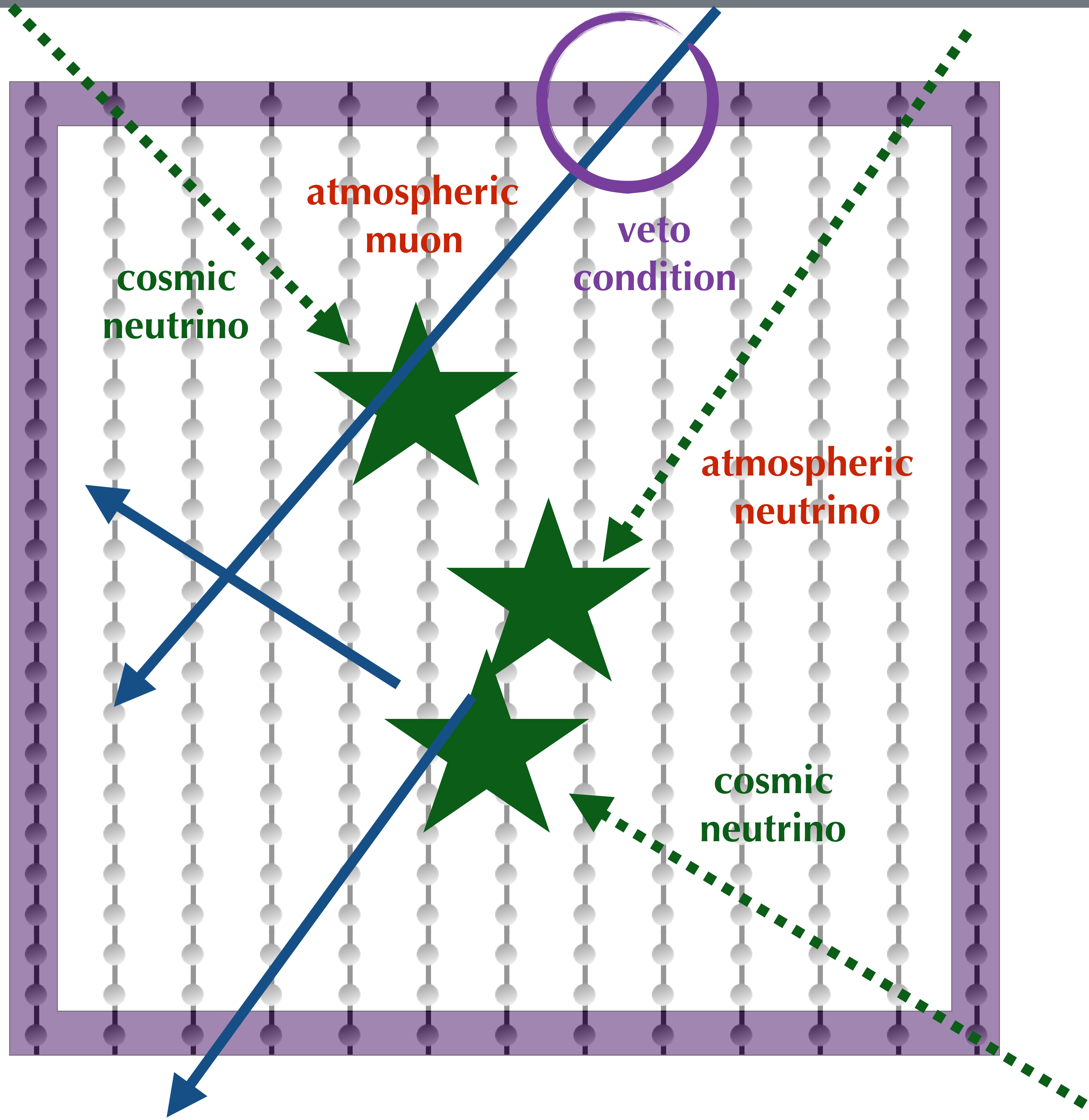


# Neutrino Selection I



# Neutrino Selection II

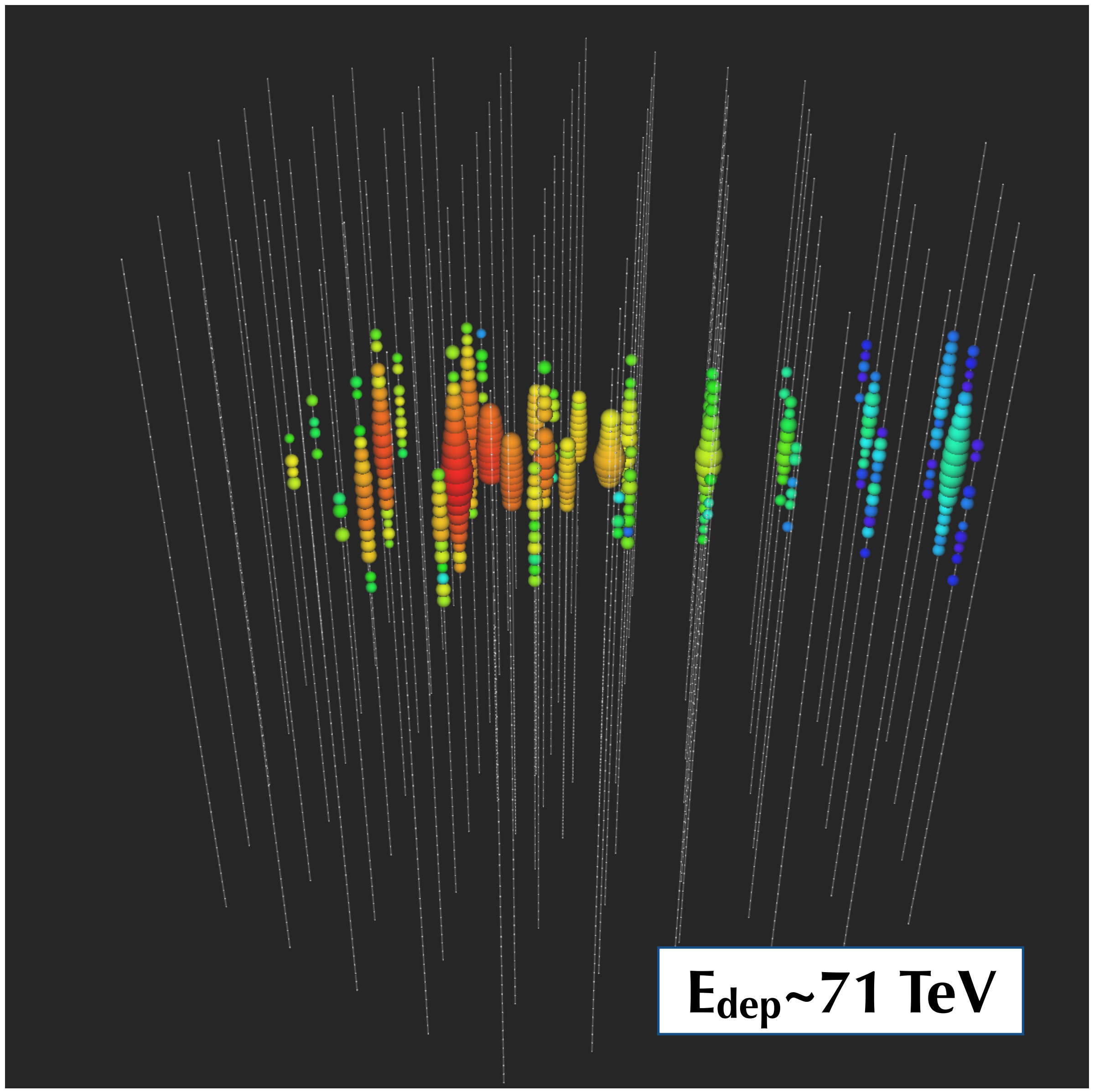
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis

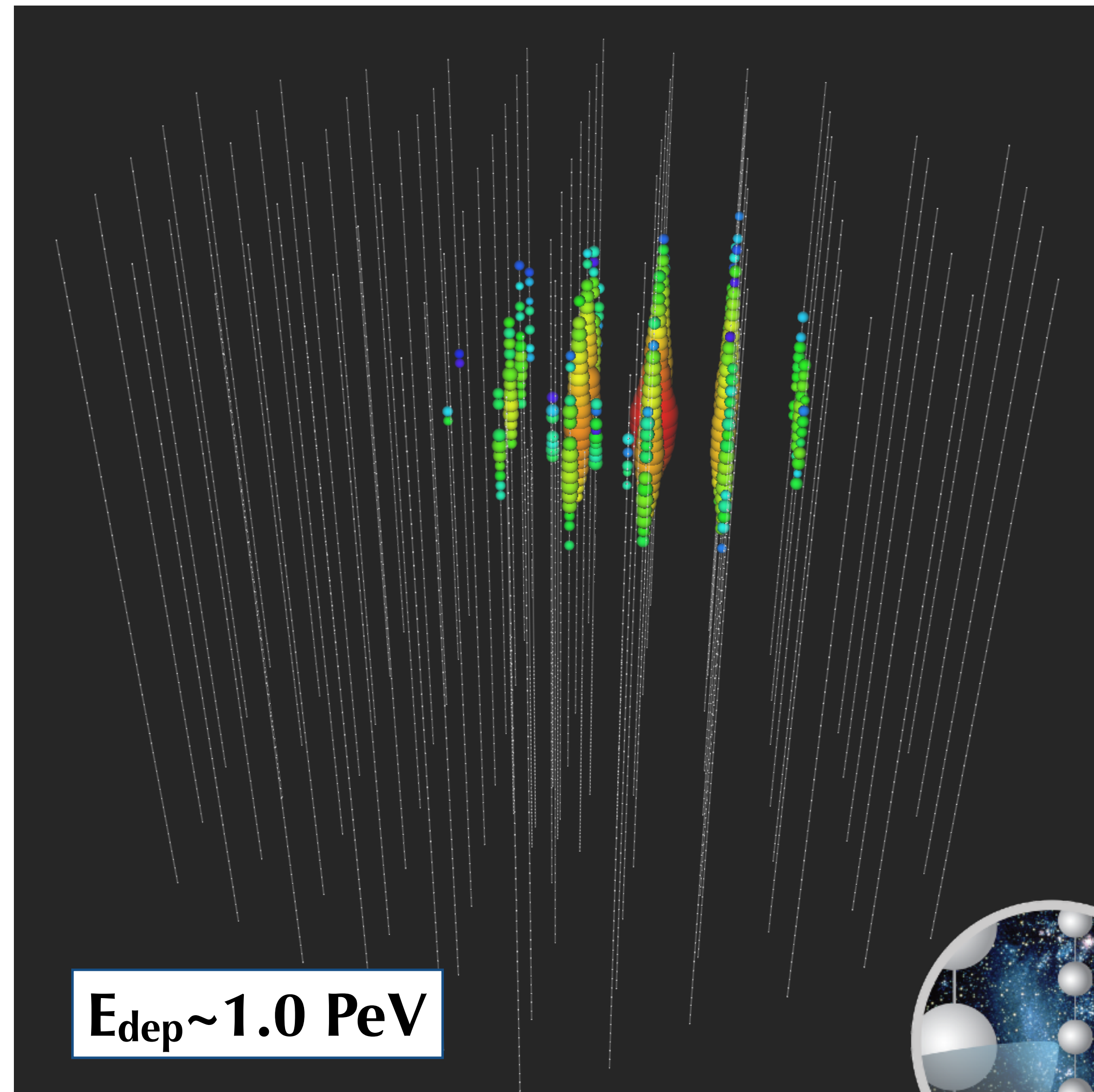


# Breakthrough in 2013

**First observation of high-energy astrophysical neutrinos by IceCube!**

**"track event"** (from $\nu_\mu$ scattering) **"cascade event"** (from all flavours)

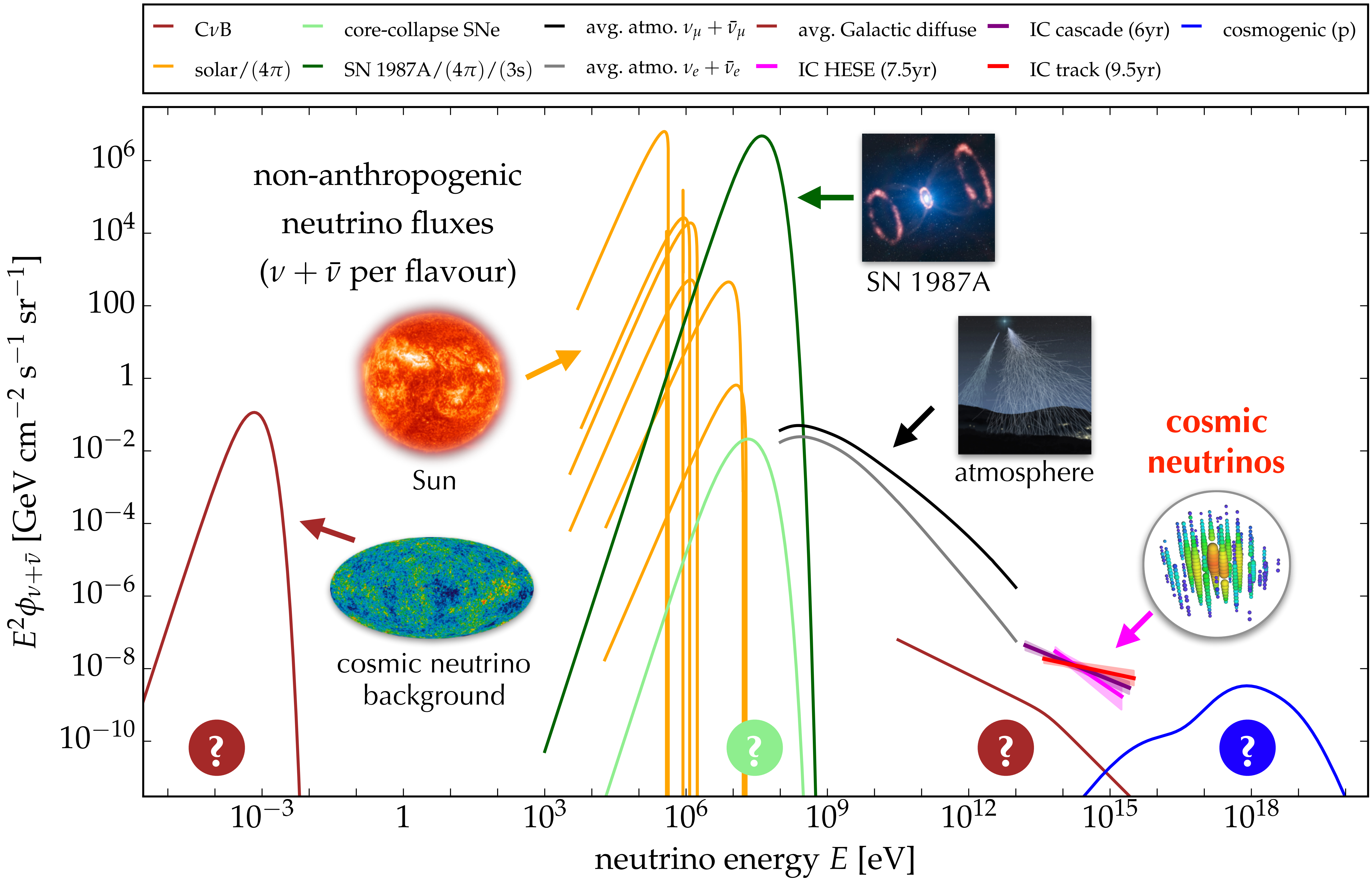


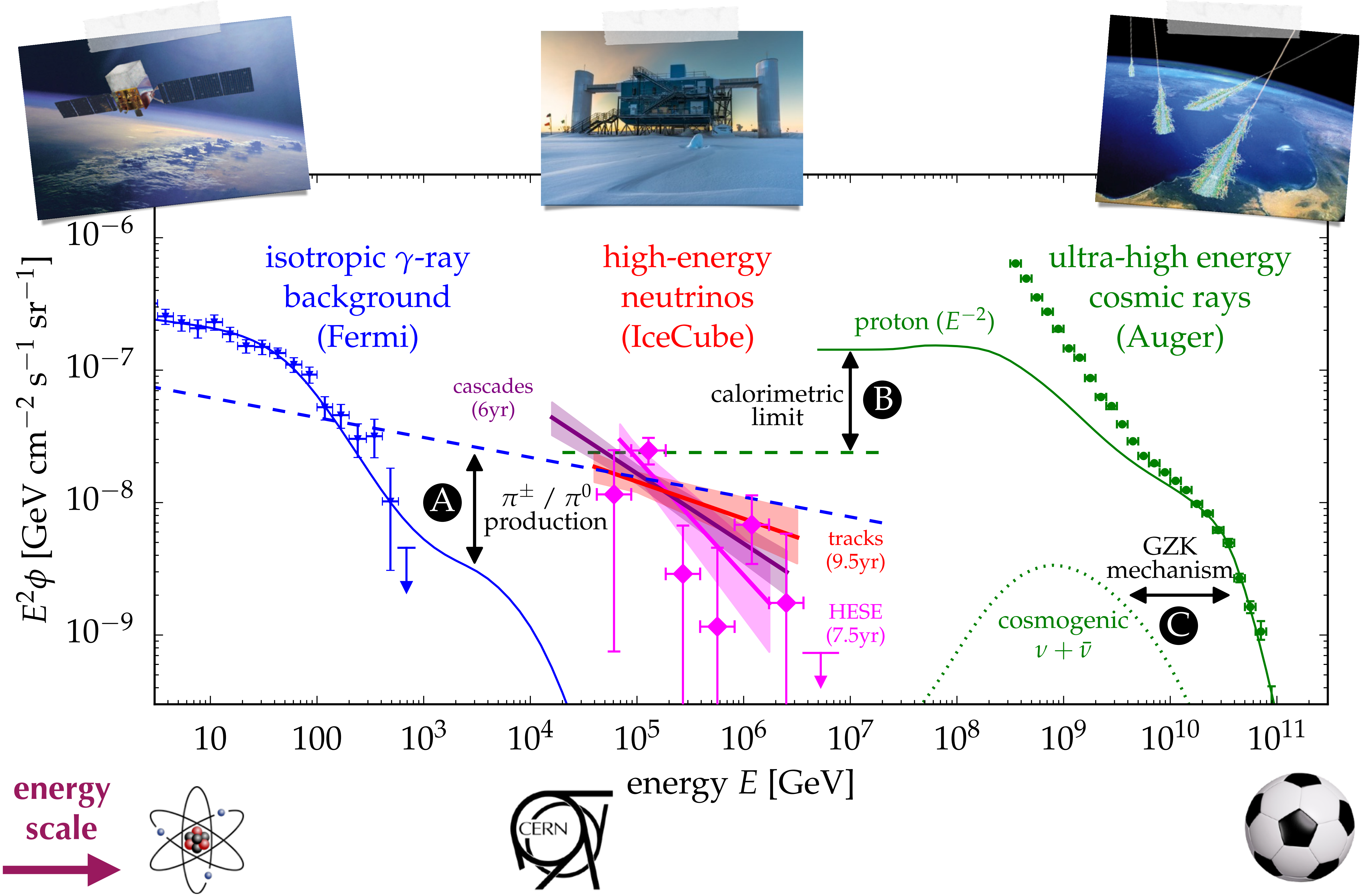

ICECUBE

["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

# Astrophysical Neutrino Fluxes

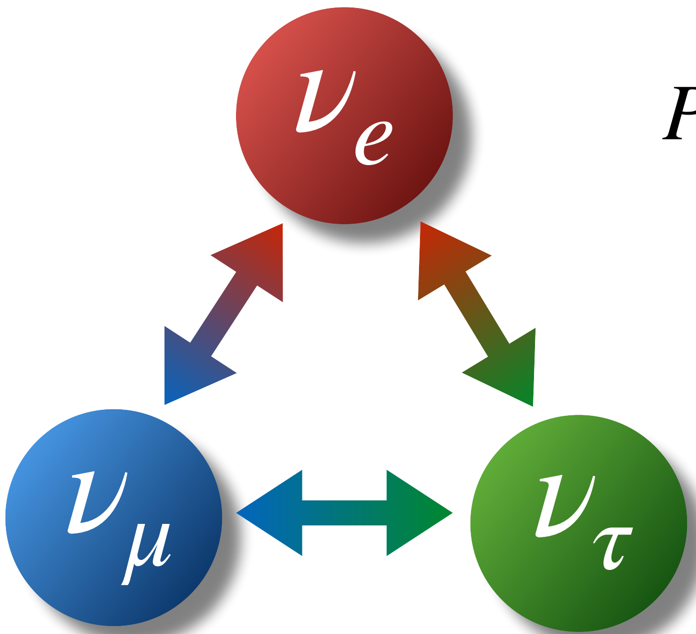


# Diffuse TeV-PeV Neutrinos

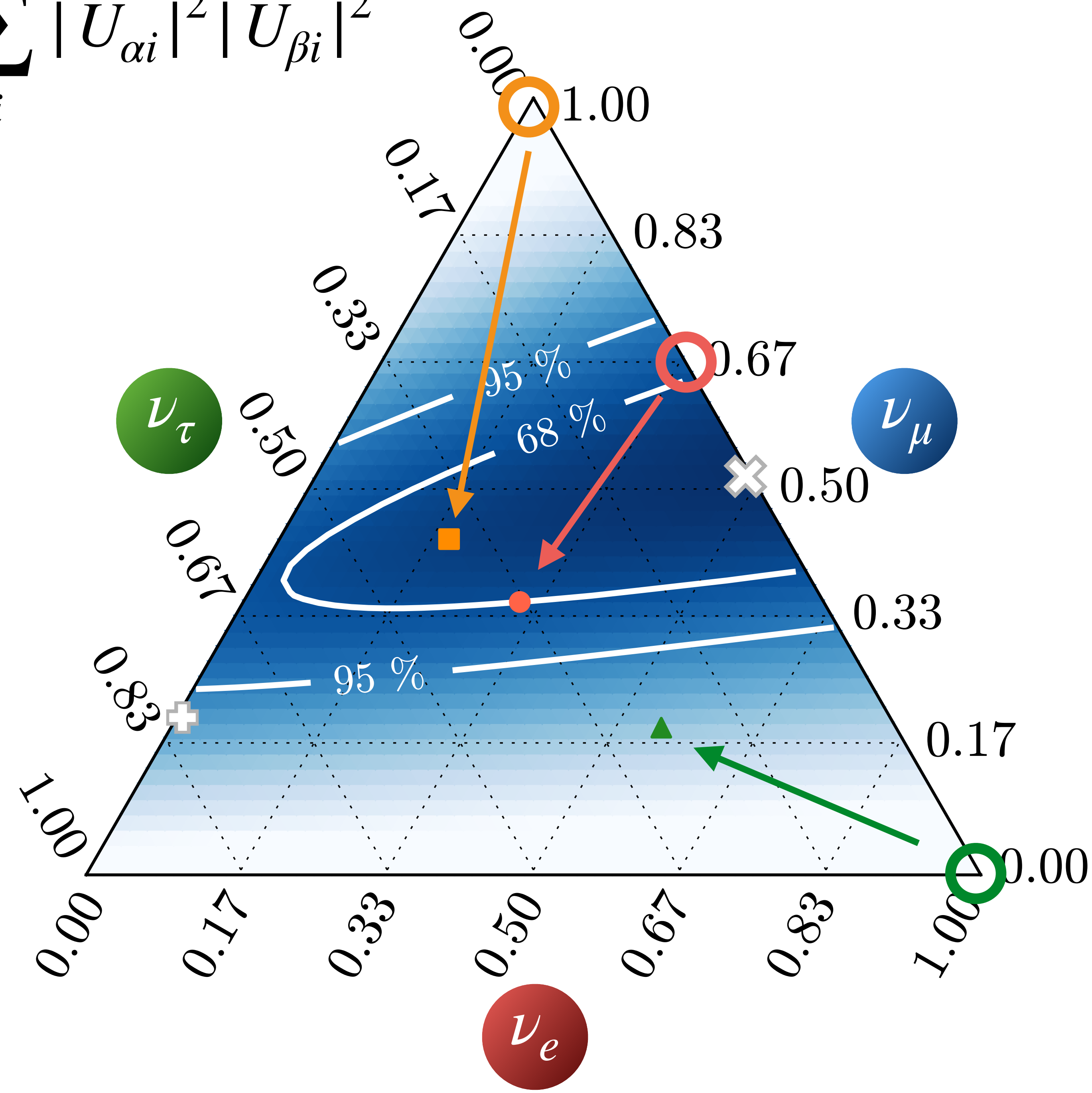


# Astrophysical Flavours

Oscillation of neutrino flavours between source and observatory.




$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

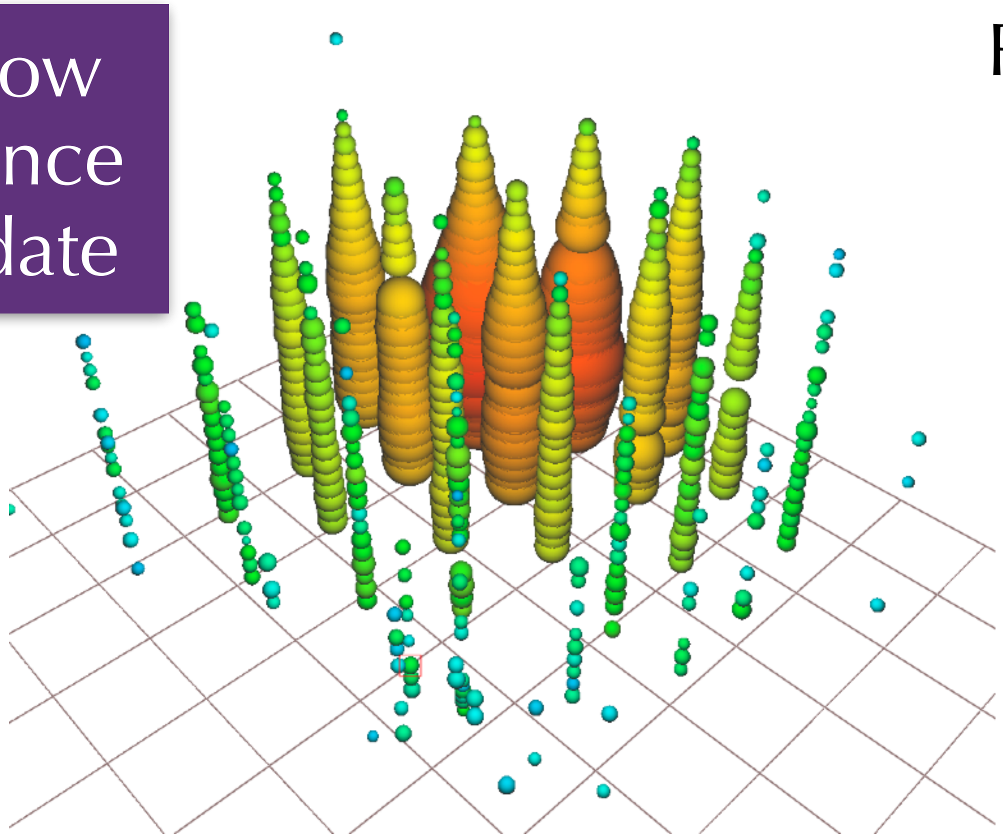



| initial composition: | $\nu_e : \nu_\mu : \nu_\tau$ |
|---|---|
| *pion & muon decay:* | $1 : 2 : 0$ |
| *muon-damped decay:* | $0 : 1 : 0$ |
| *neutron decay:* | $1 : 0 : 0$ |

Cosmic neutrinos visible via their **oscillation-averaged flavour.**

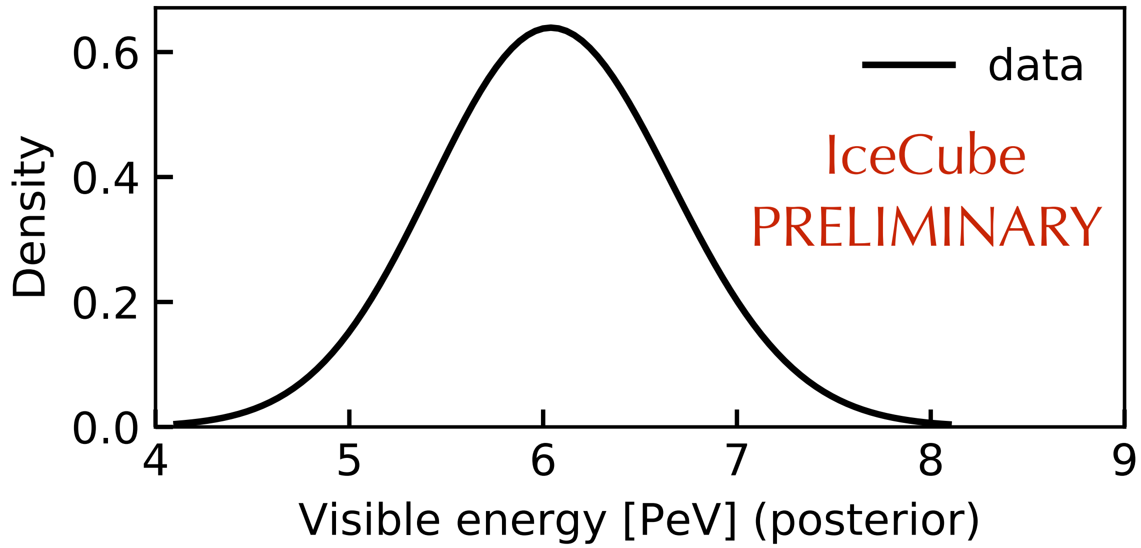
# Astrophysical Flavours

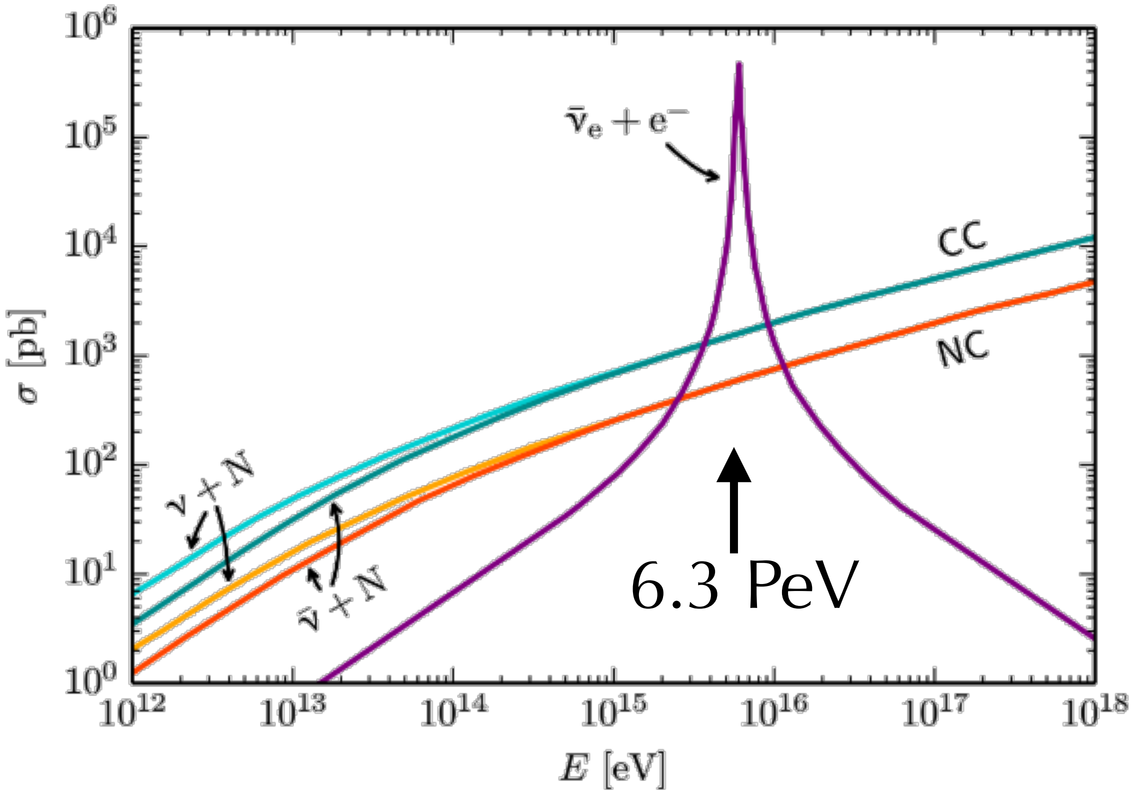
Glashow resonance candidate

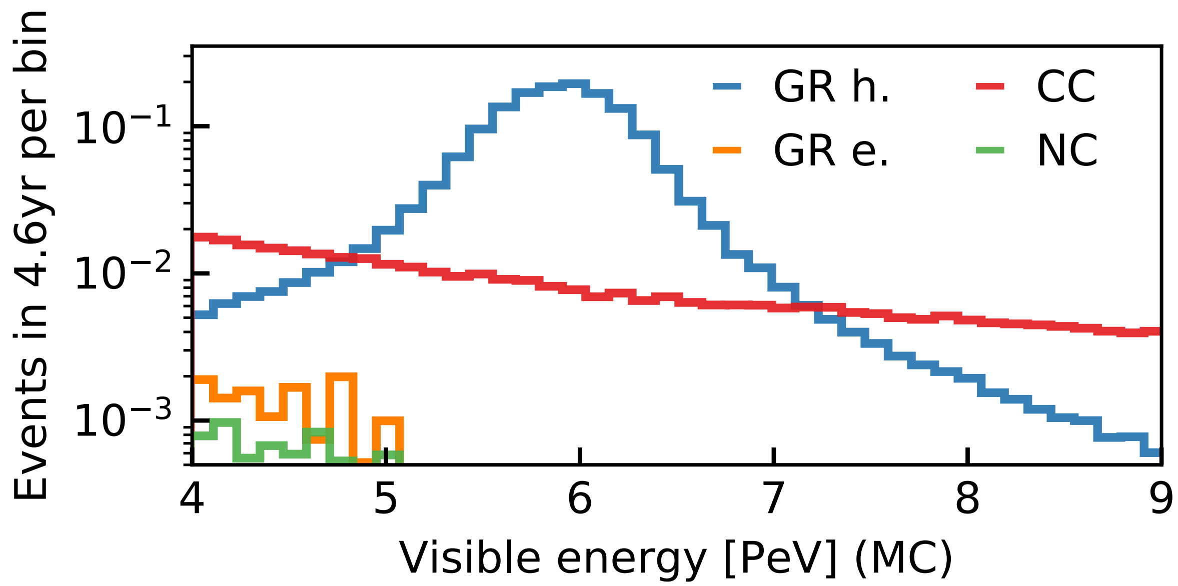


Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

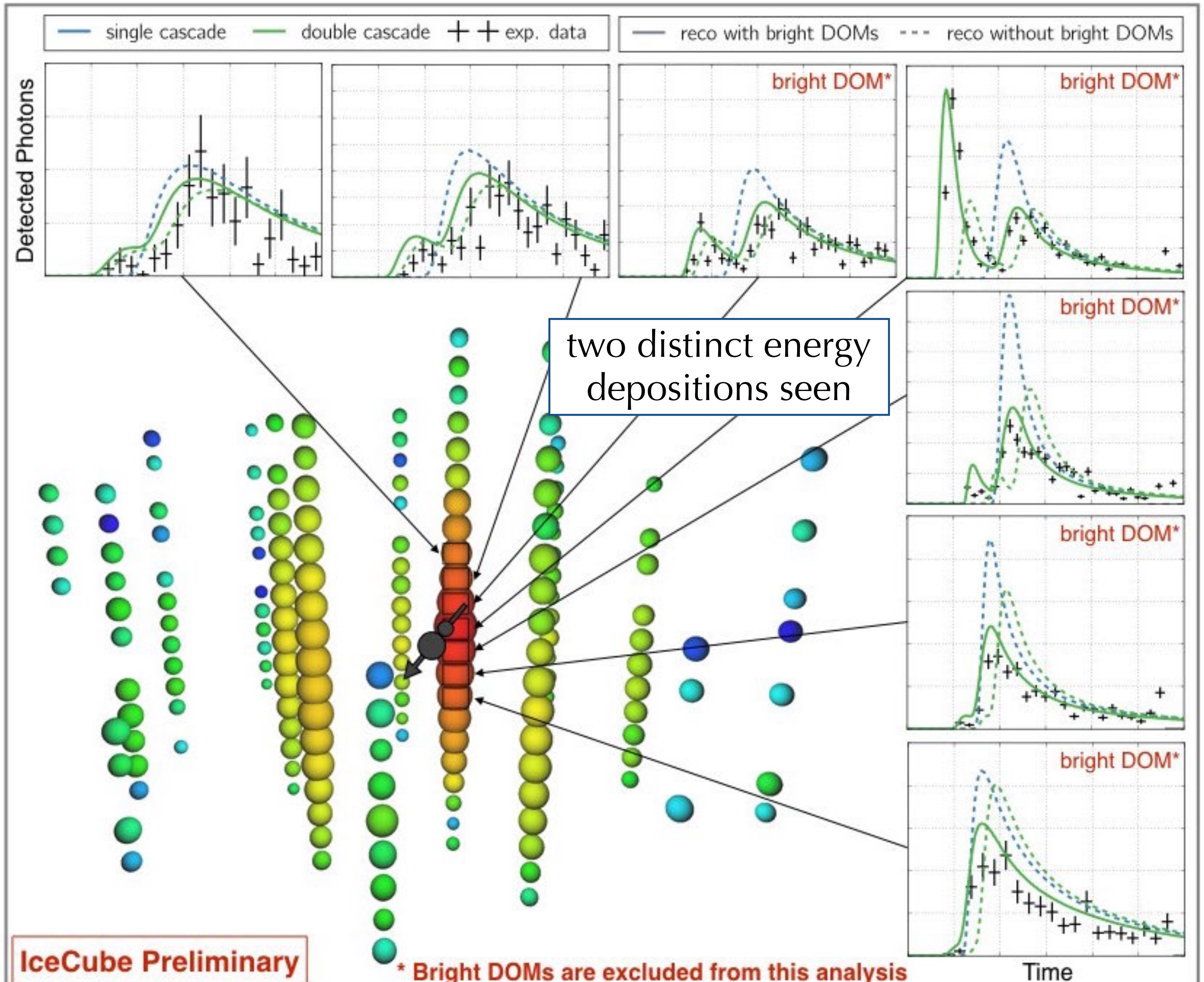


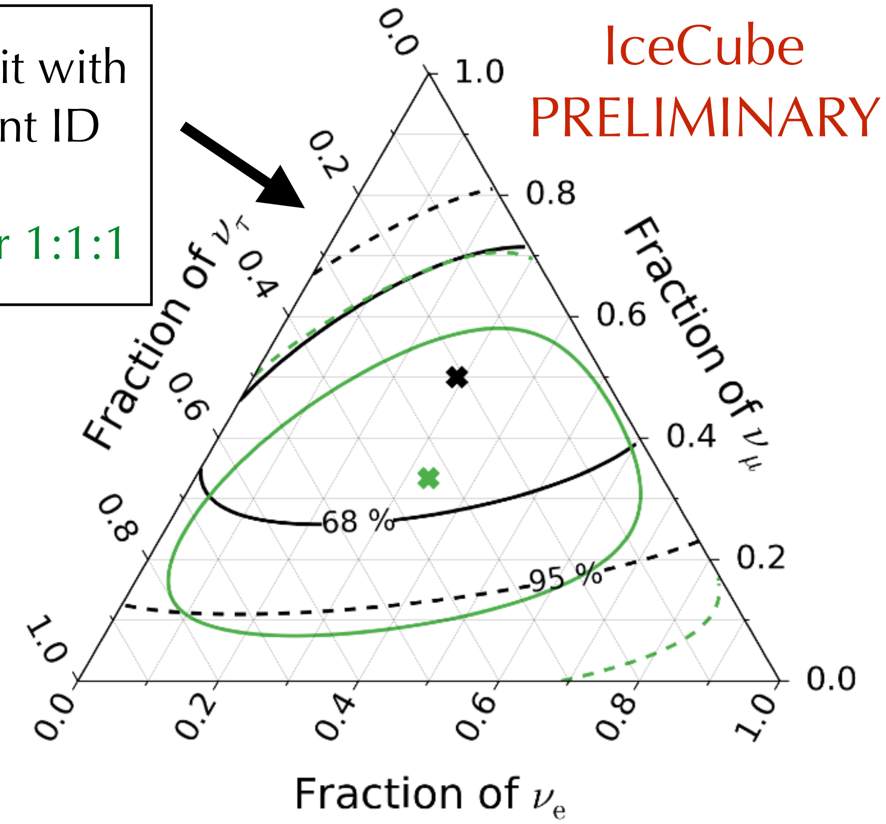



# Astrophysical Flavours

tau neutrino candidate



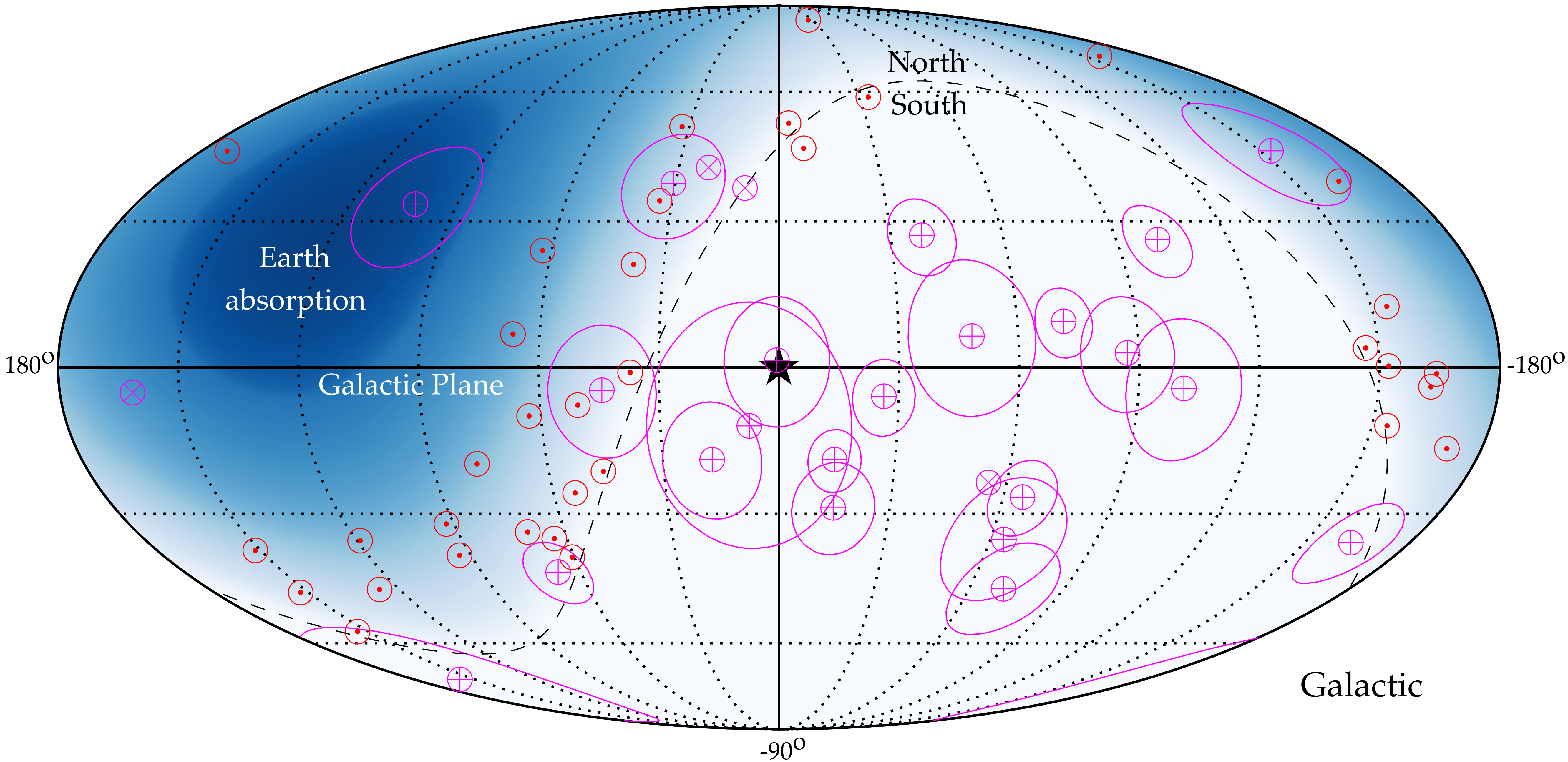

HESE 7.5yr fit with ternary event ID & sensitivity for 1:1:1




- **Tau neutrino** charged current interactions can produce delayed hadronic cascades from tau decays.
- Arrival time of Cherenkov photons is visible in individual DOMs.

# Status of Neutrino Astronomy

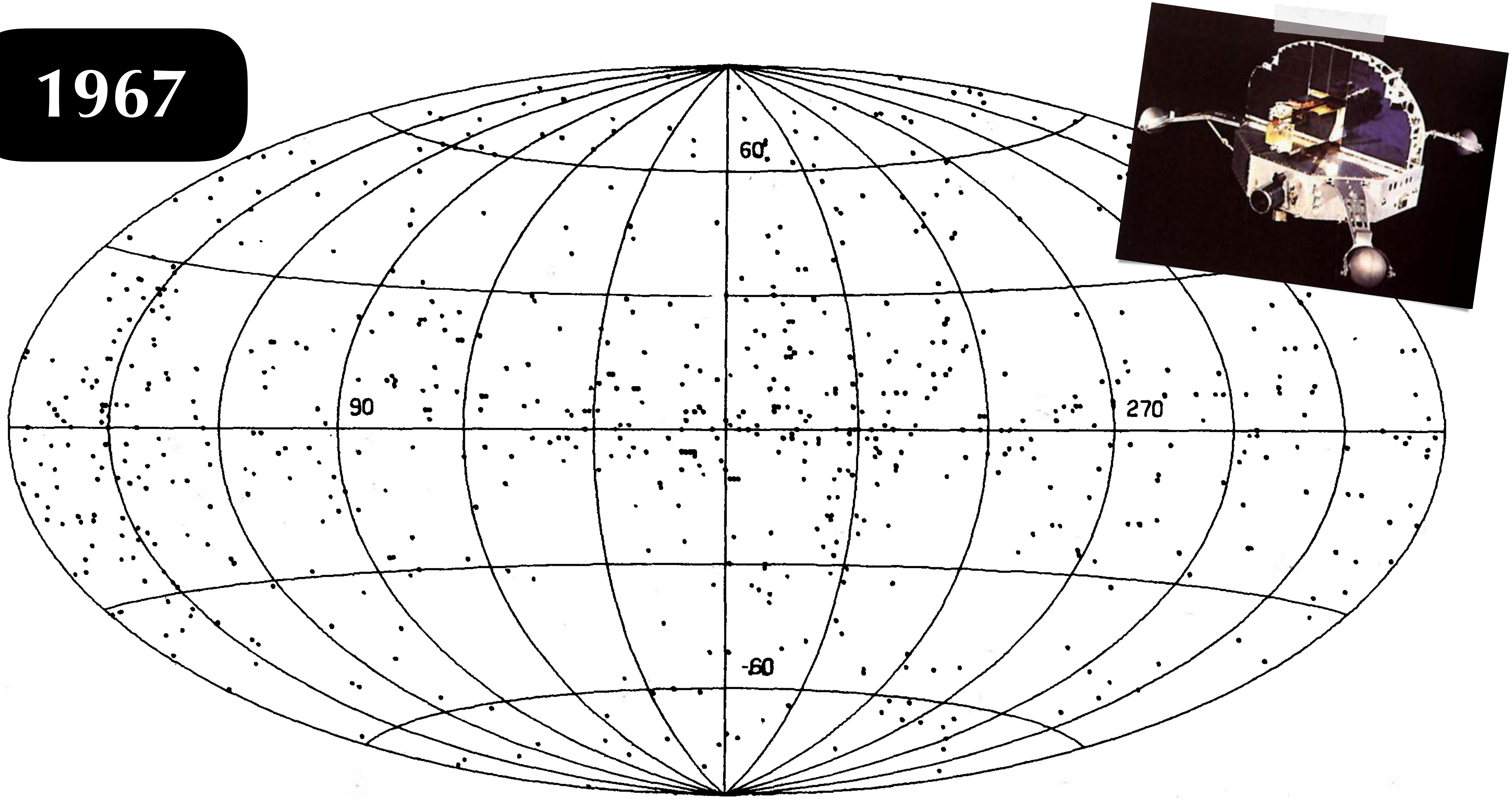
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))




**No significant** steady or transient emission from known Galactic and extragalactic high-energy sources (*except for one candidate*).

# Status of Neutrino Astronomy

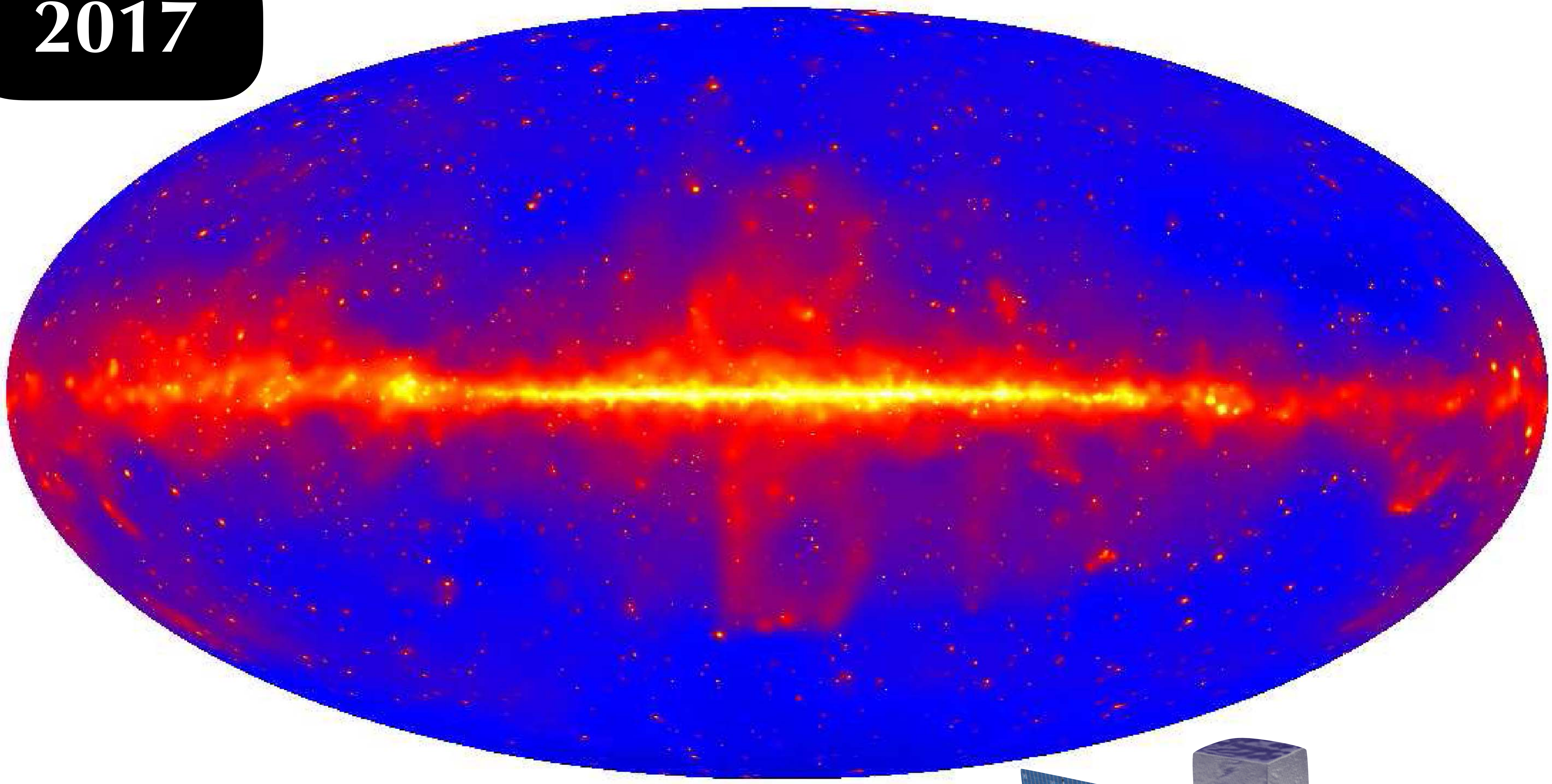
**1967**



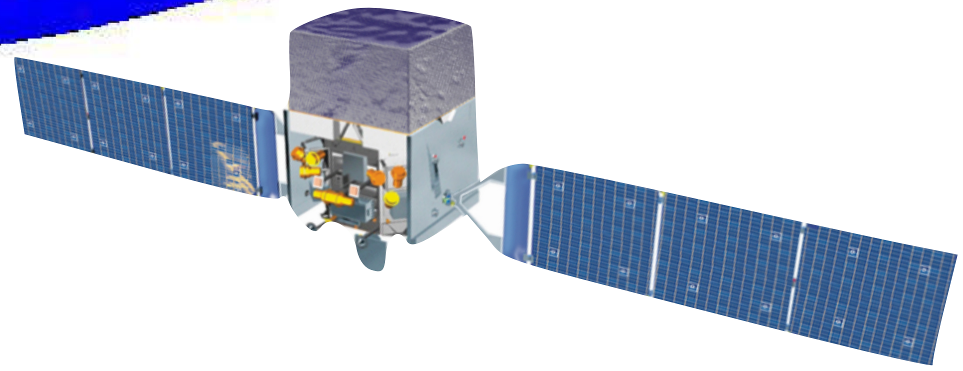

**Orbiting Solar Observatory** (OSO-3) (Clark & Kraushaar'67)

# Status of Neutrino Astronomy

**2017**



**Fermi-LAT** gamma-ray count map

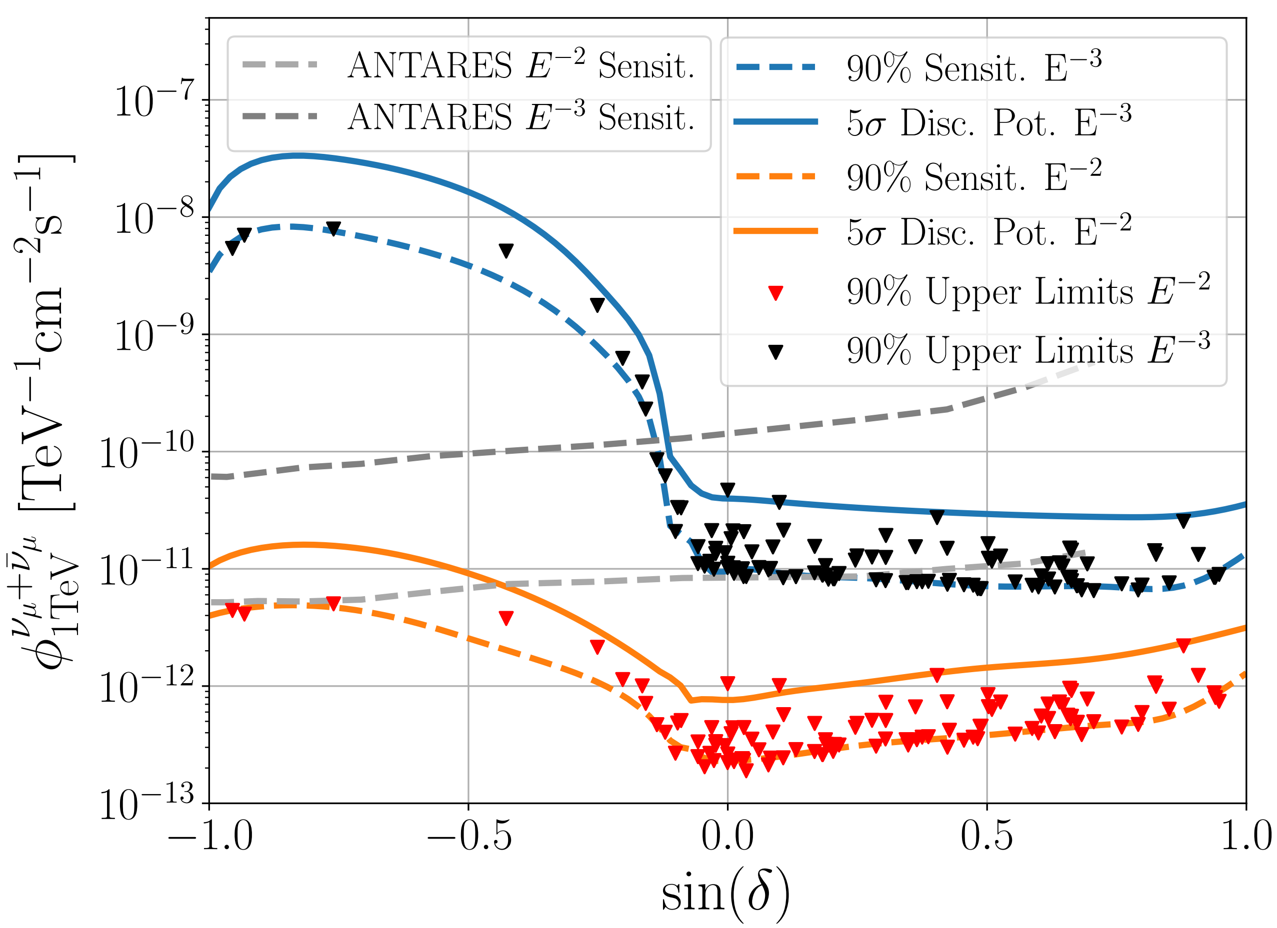


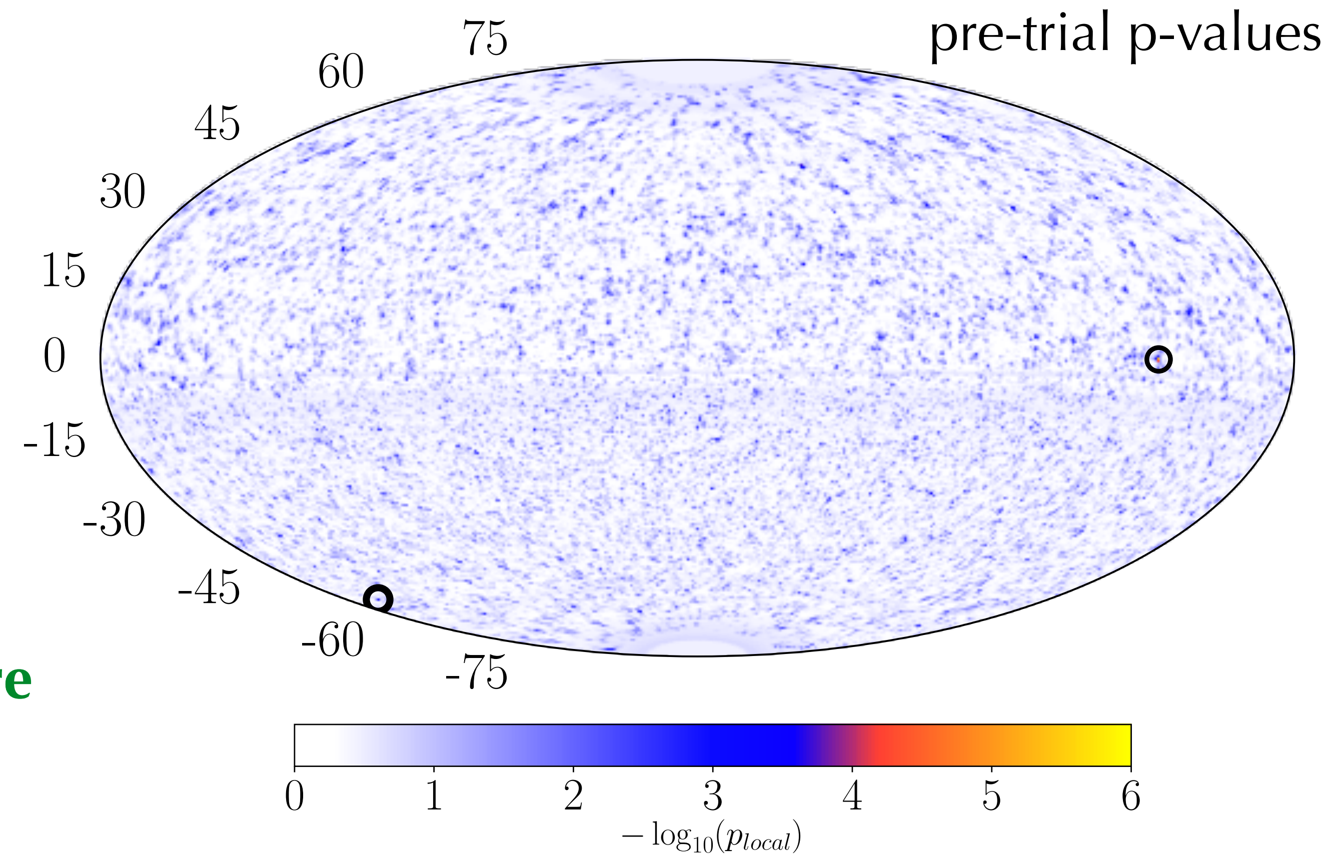
# Search for Neutrino Sources

**IceCube and ANTARES/KM3NeT with complementary field of views.**

ICECUBE

**Southern Hemisphere | Northern Hemisphere**



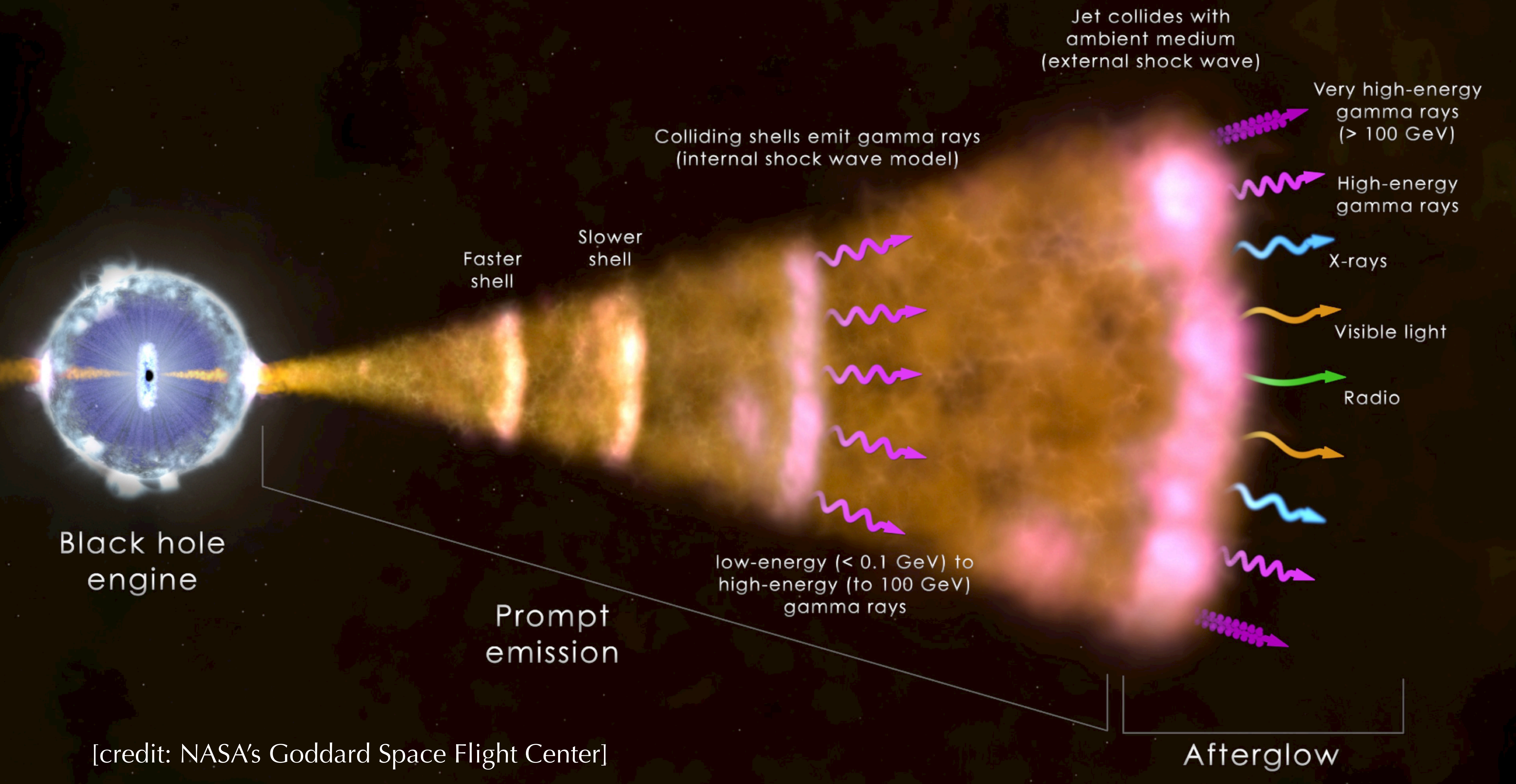




[IceCube, PRL 124 (2020) 051103]

- **No significant** time-integrated point sources emission in all-sky search.
- **No significant** time-integrated emission from known Galactic and extragalactic high-energy sources.

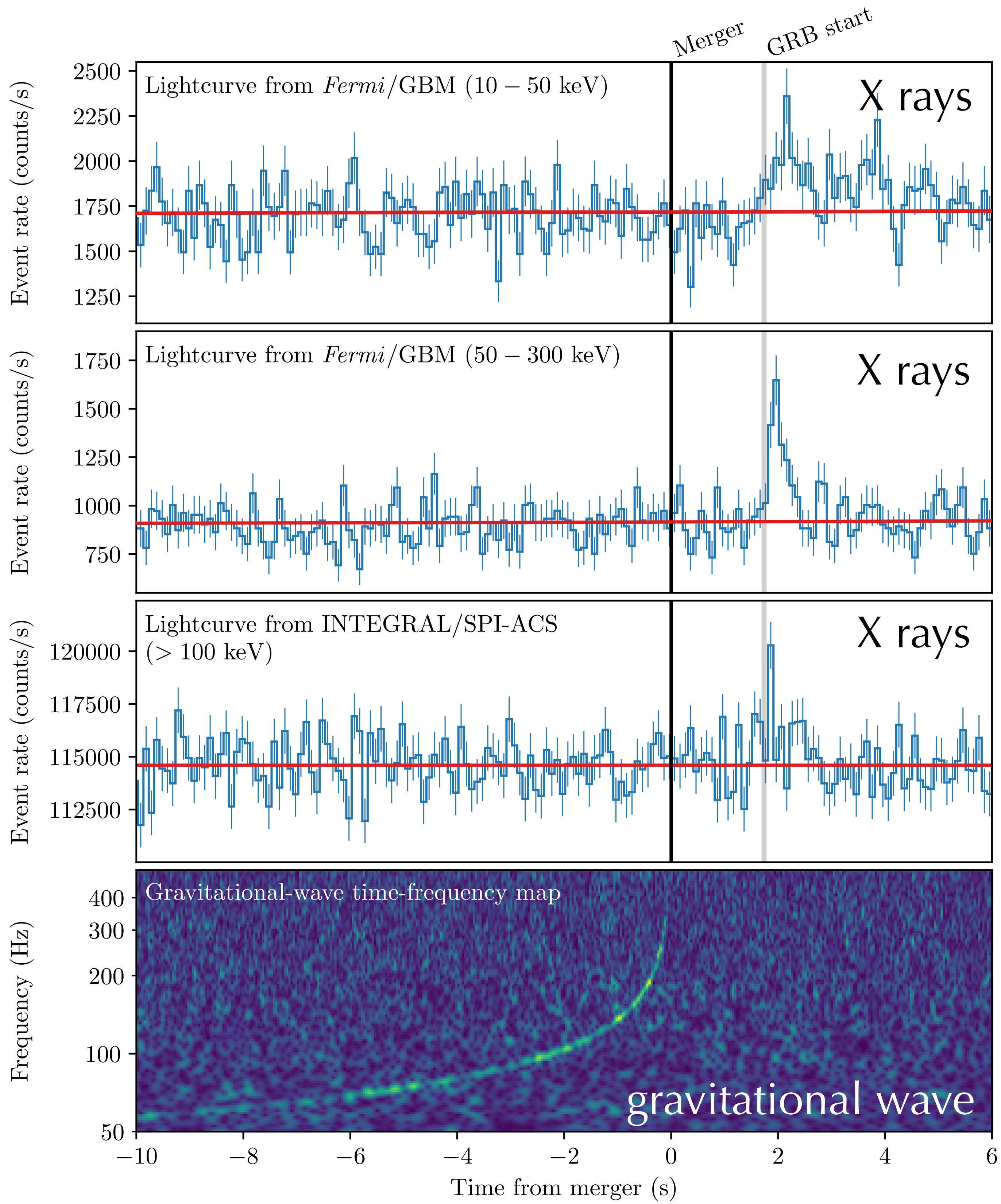
# Gamma-Ray Bursts

High-energy neutrino emission is predicted by cosmic ray interactions with radiation at various stages of the GRB evolution.

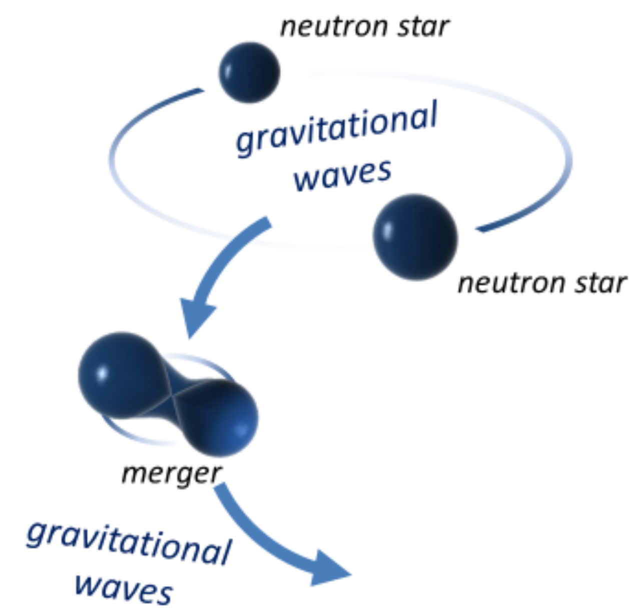



[credit: NASA's Goddard Space Flight Center]

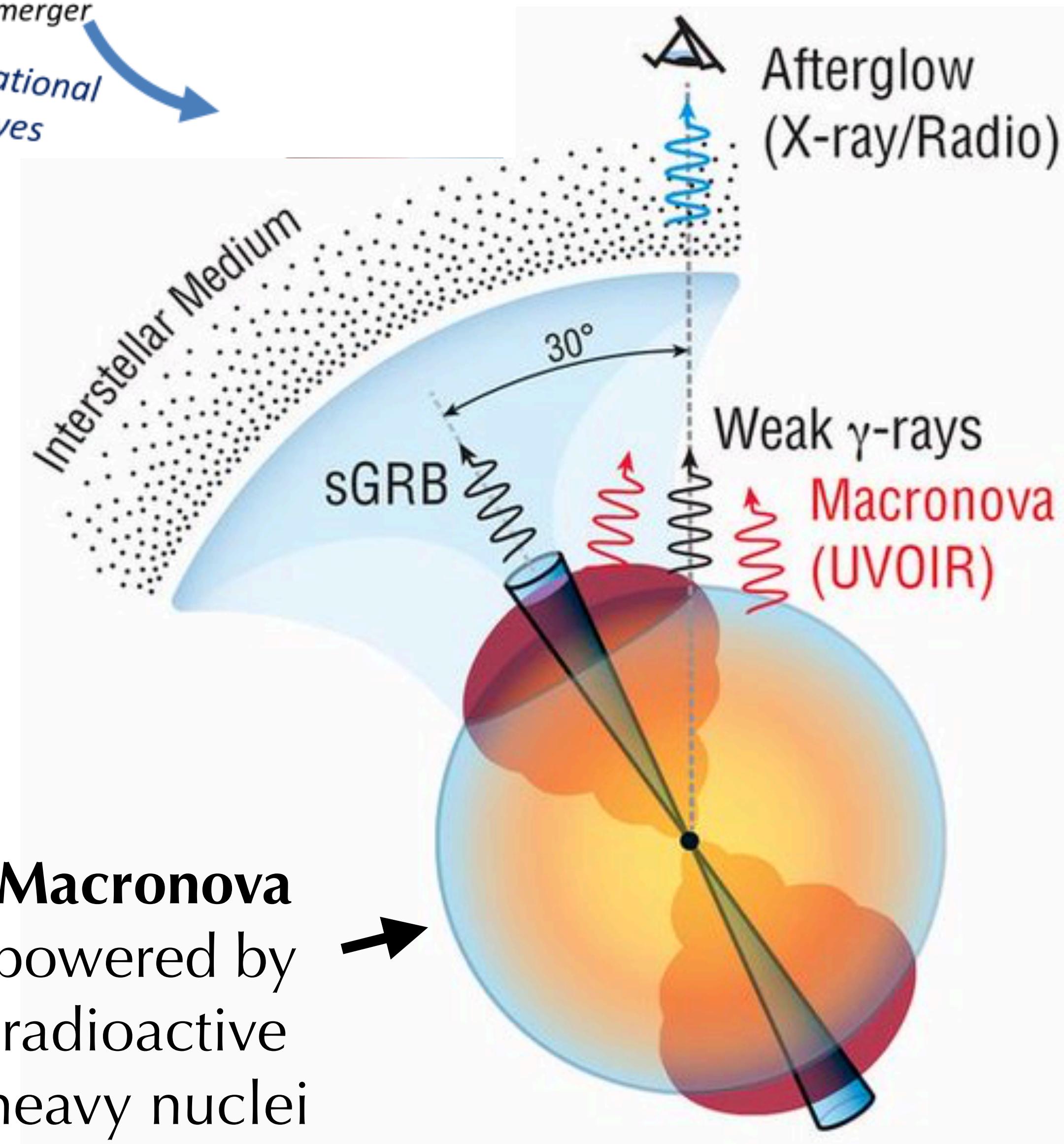
# GRBs and Gravitational Waves



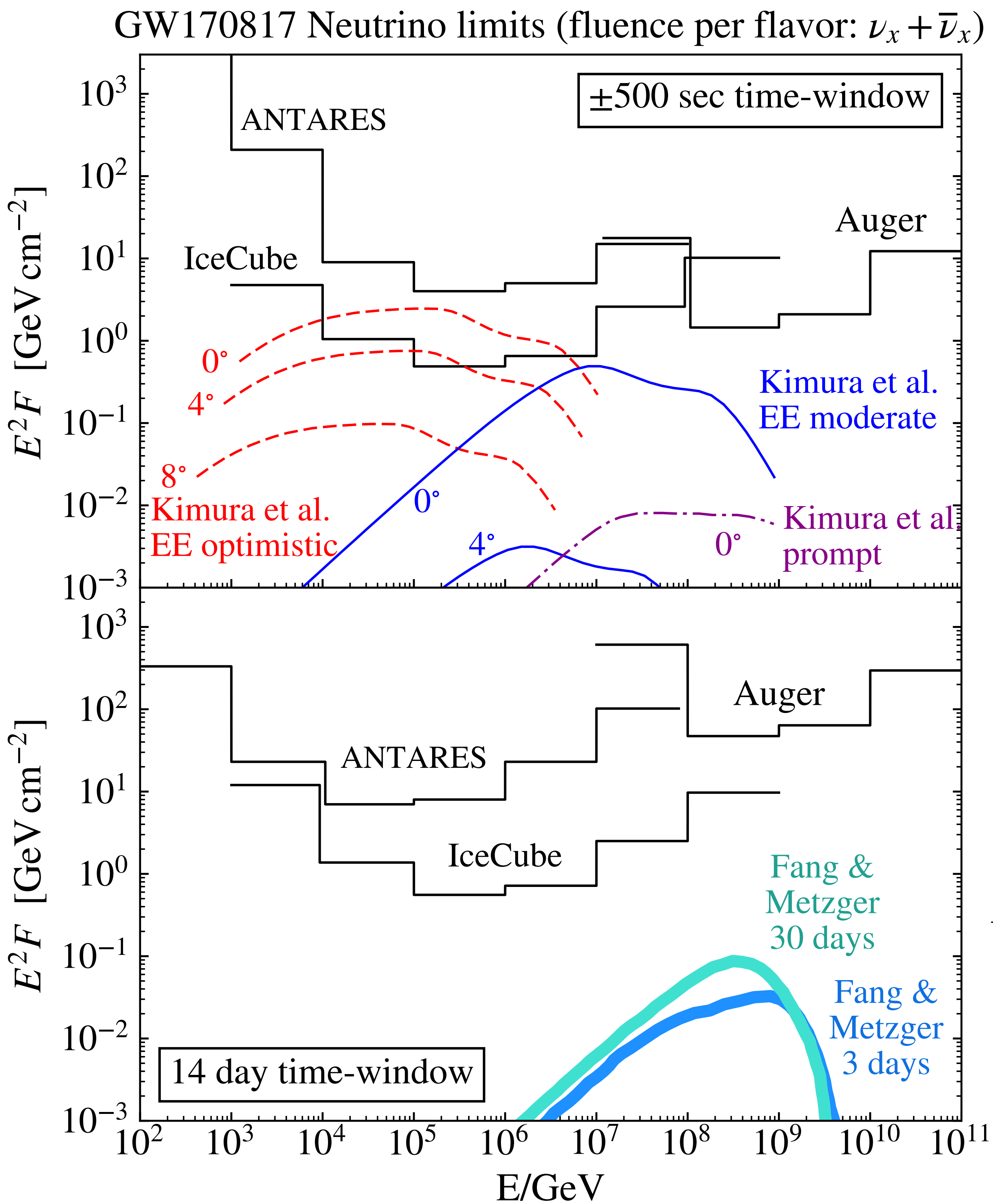

[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]



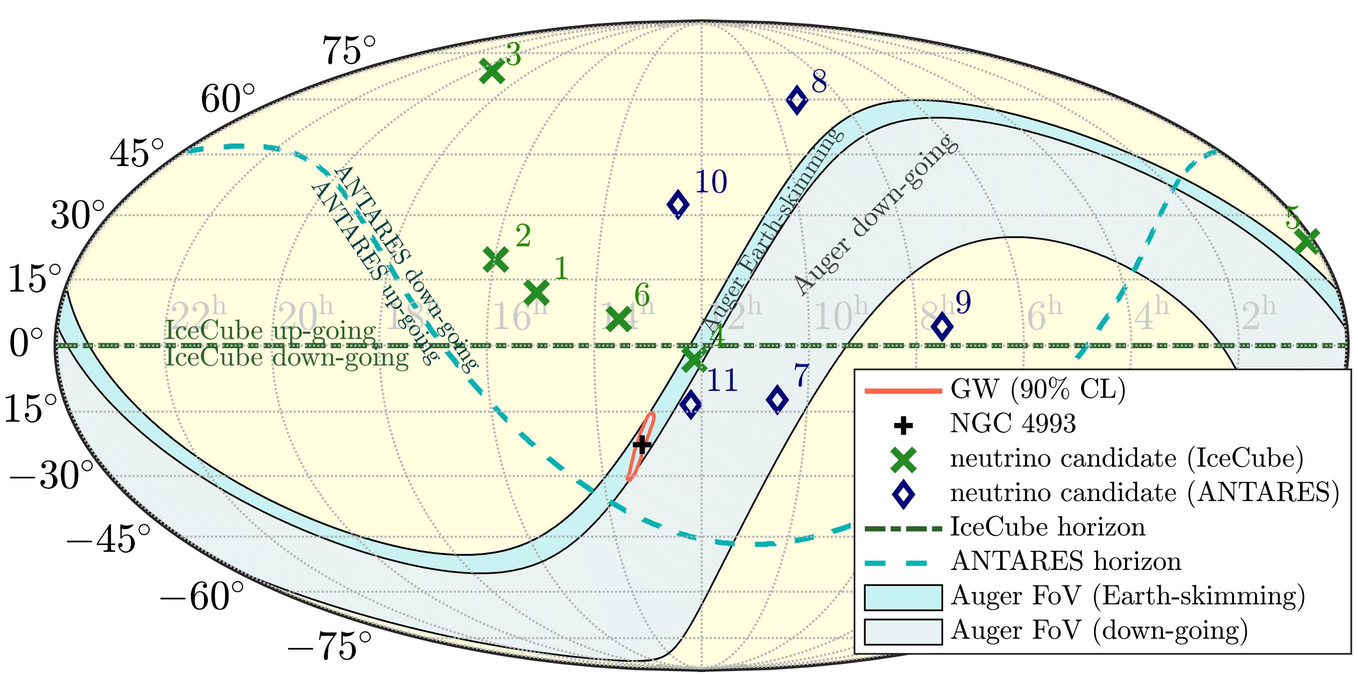

GW 170817
&
GRB 170817A



# GRB 170817A



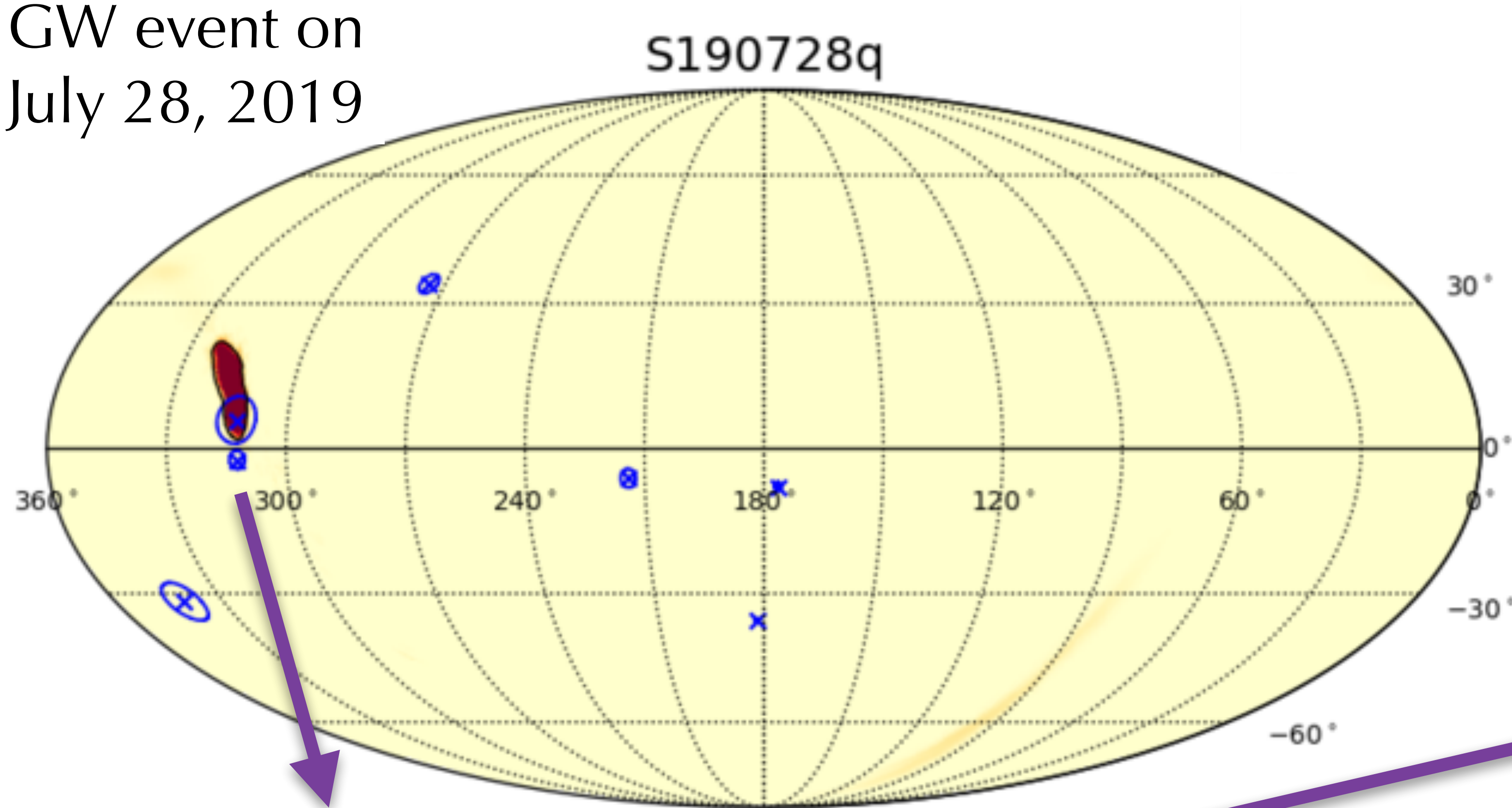

- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle.**



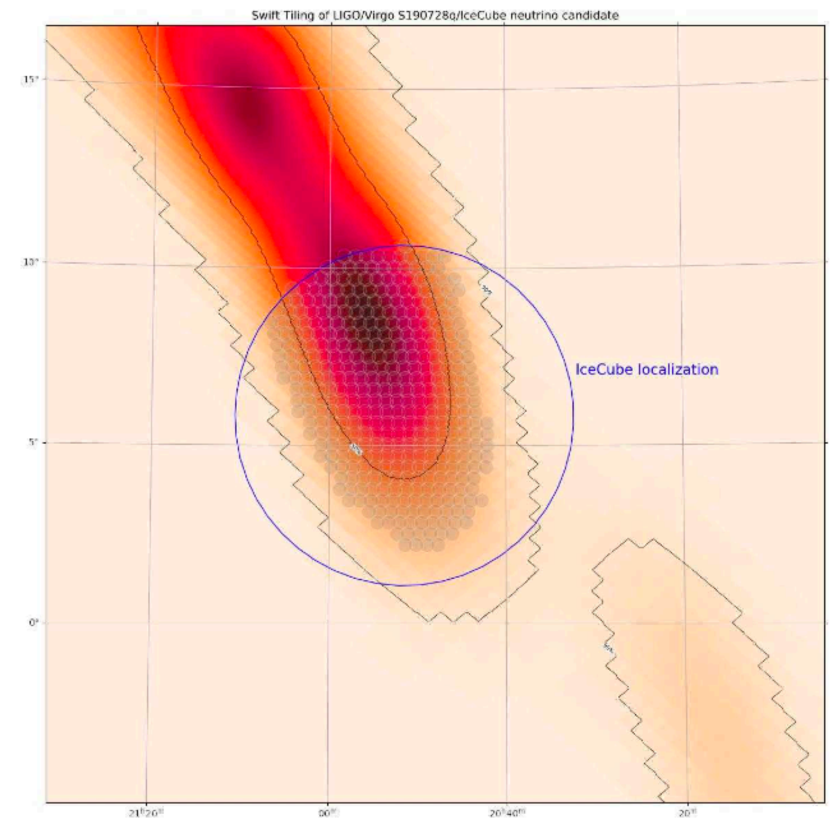

[ANTARES, IceCube, Auger & LVC, ApJ 850 (2017) 2]

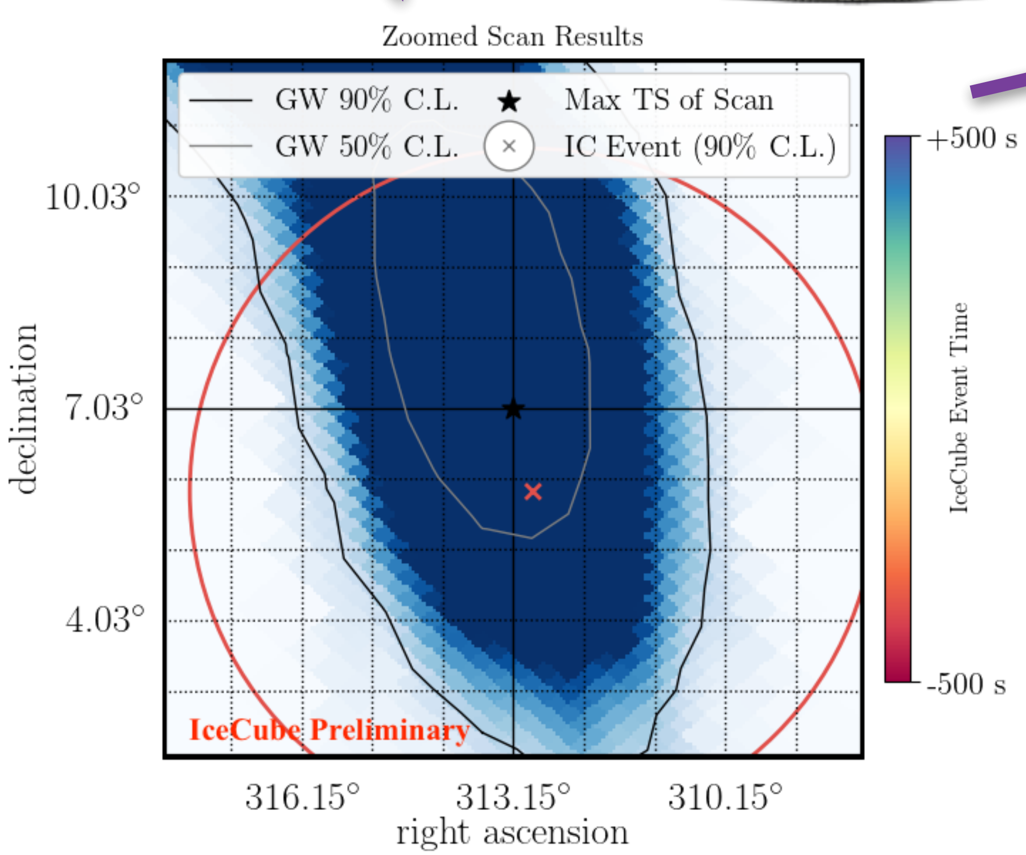
# Gravitational Wave Follow-Up

GW event on
July 28, 2019




Swift-XRT search tiling



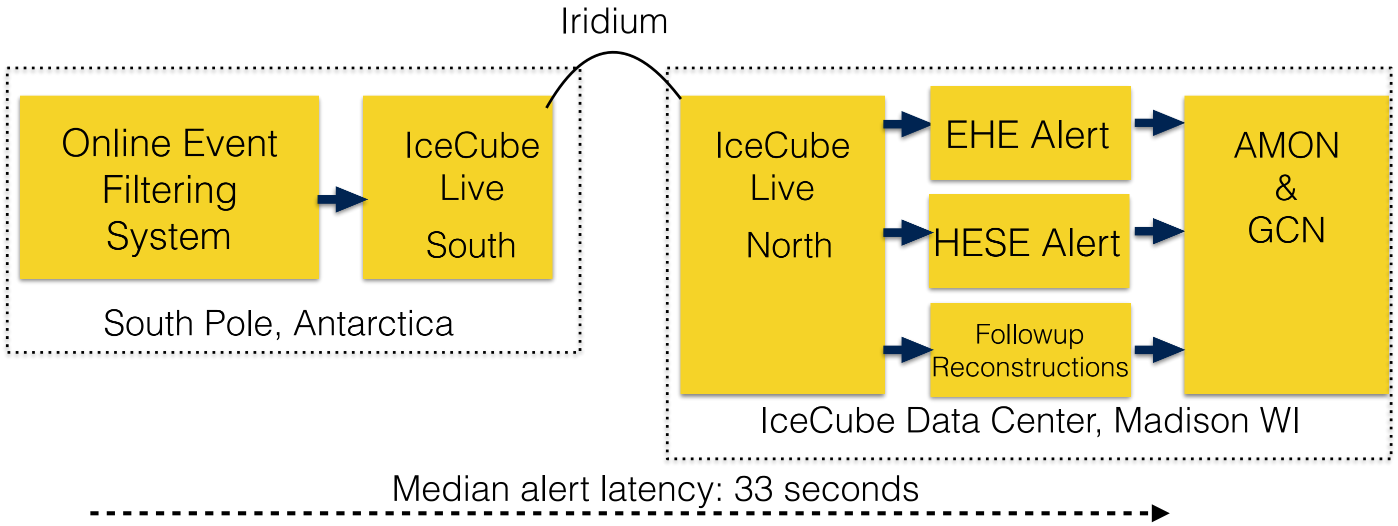




- IceCube responds to public LIGO/Virgo alerts with low latency.
- Astrophysical neutrino candidates released if background probability <1%.
- Neutrino information allows to tailor EM follow-up of pointing observatories.

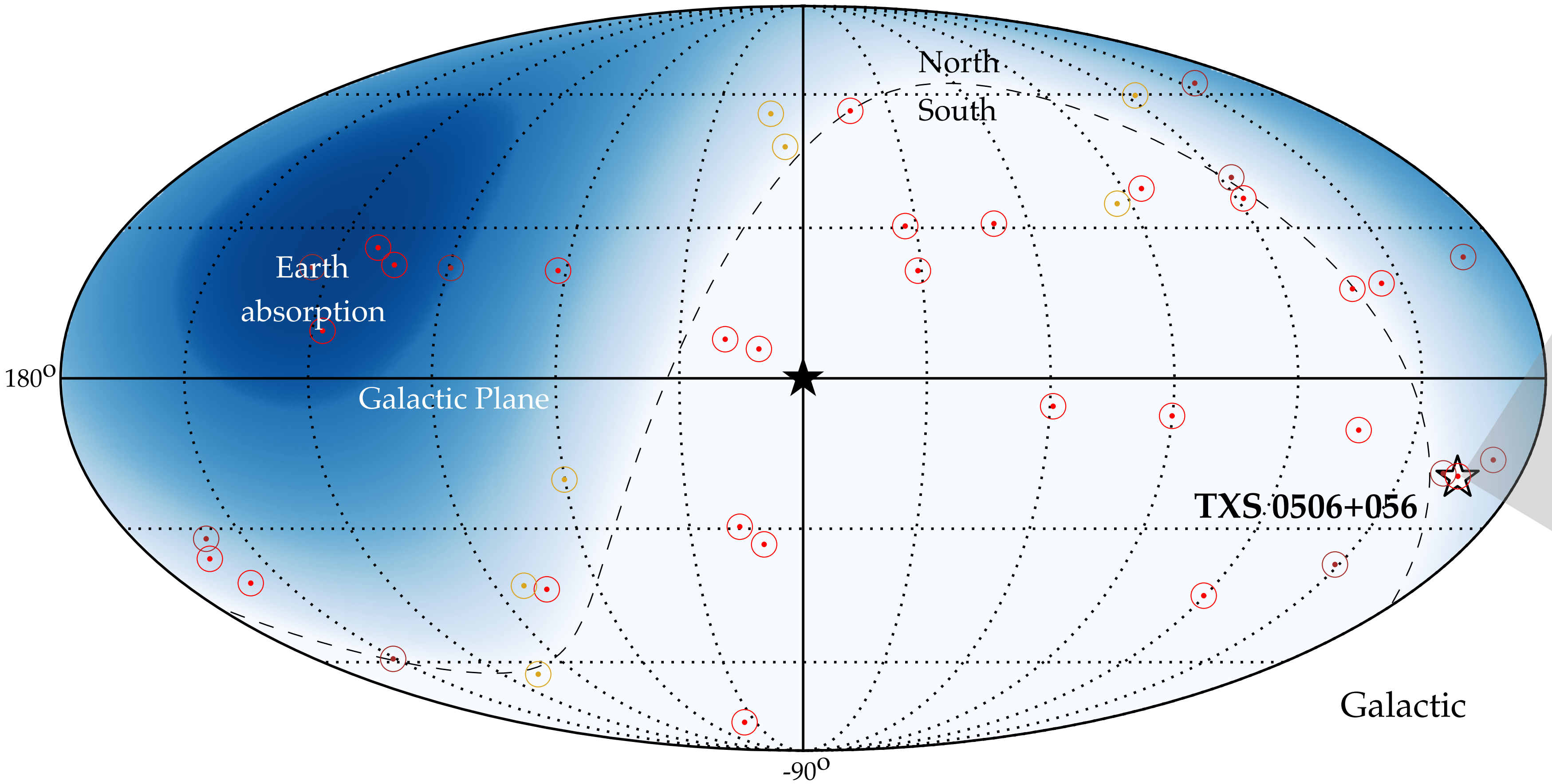
# Realtime Neutrino Alerts

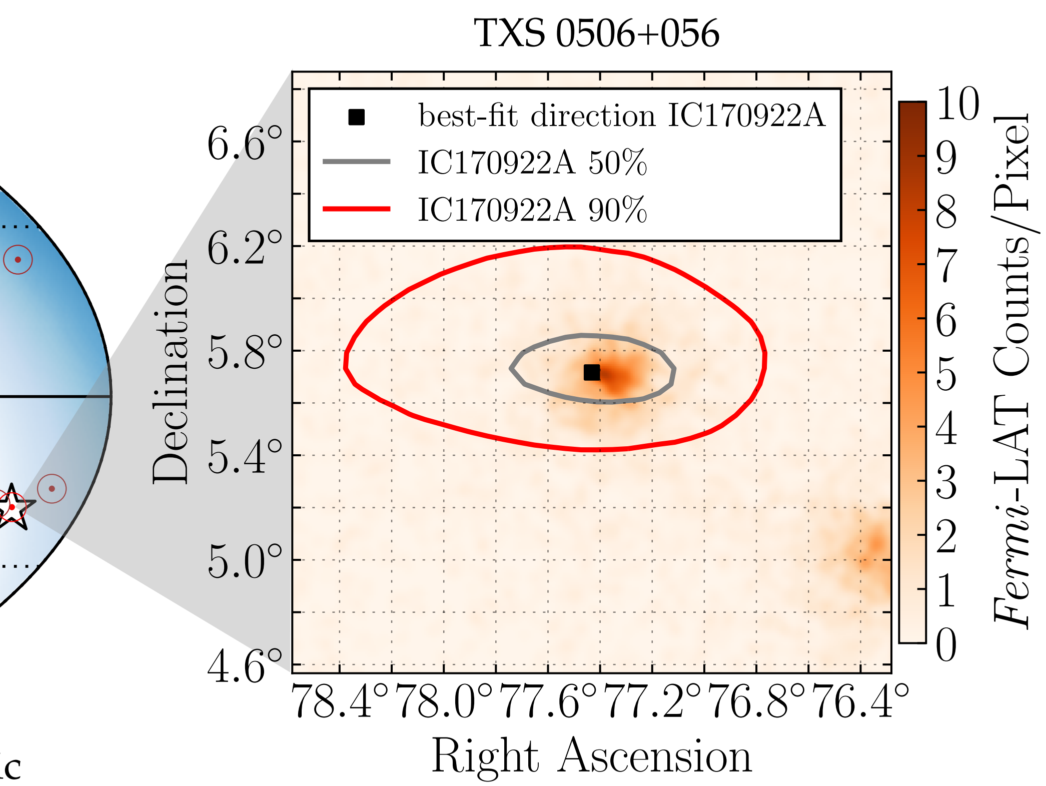
**Low-latency** (<1min) **public neutrino alert system** established in April 2016.

- ✦ **Gold alerts:** ~10 per year
  >50% signalness
- ✦ **Bronze alerts:** ~20 per year
  30-50% signalness



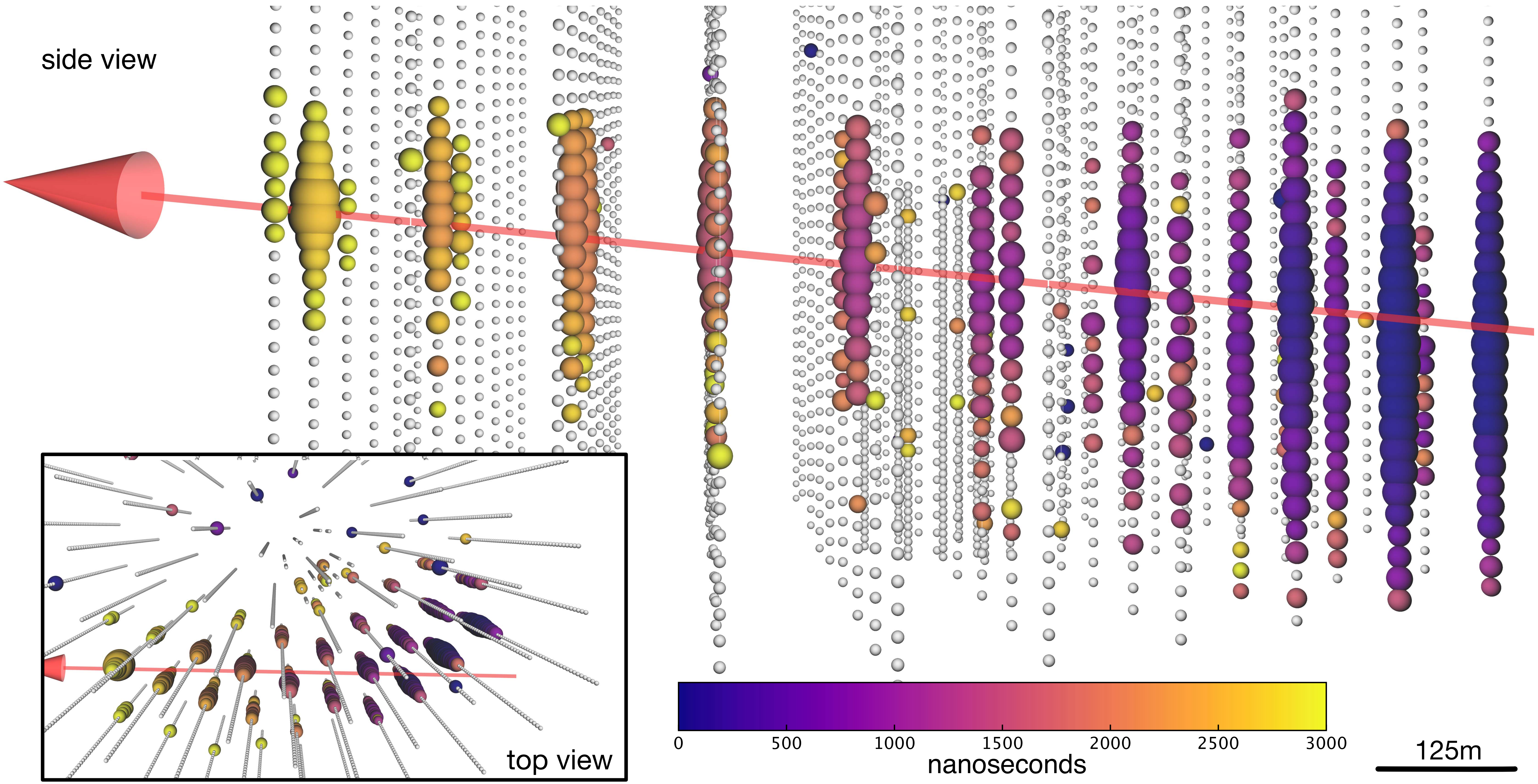

Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))



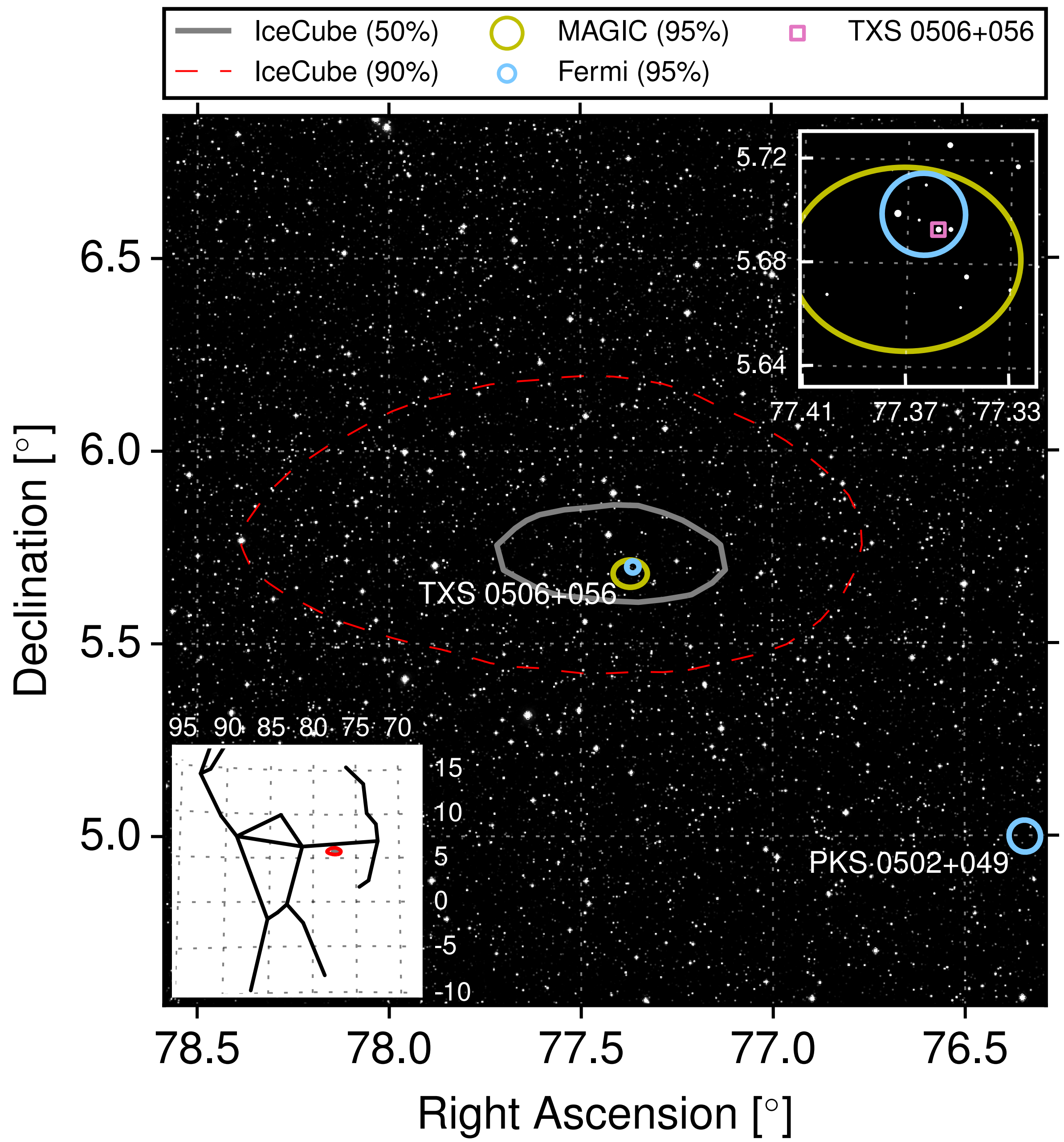
# Realtime Neutrino Alerts

## IC-170922A




up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

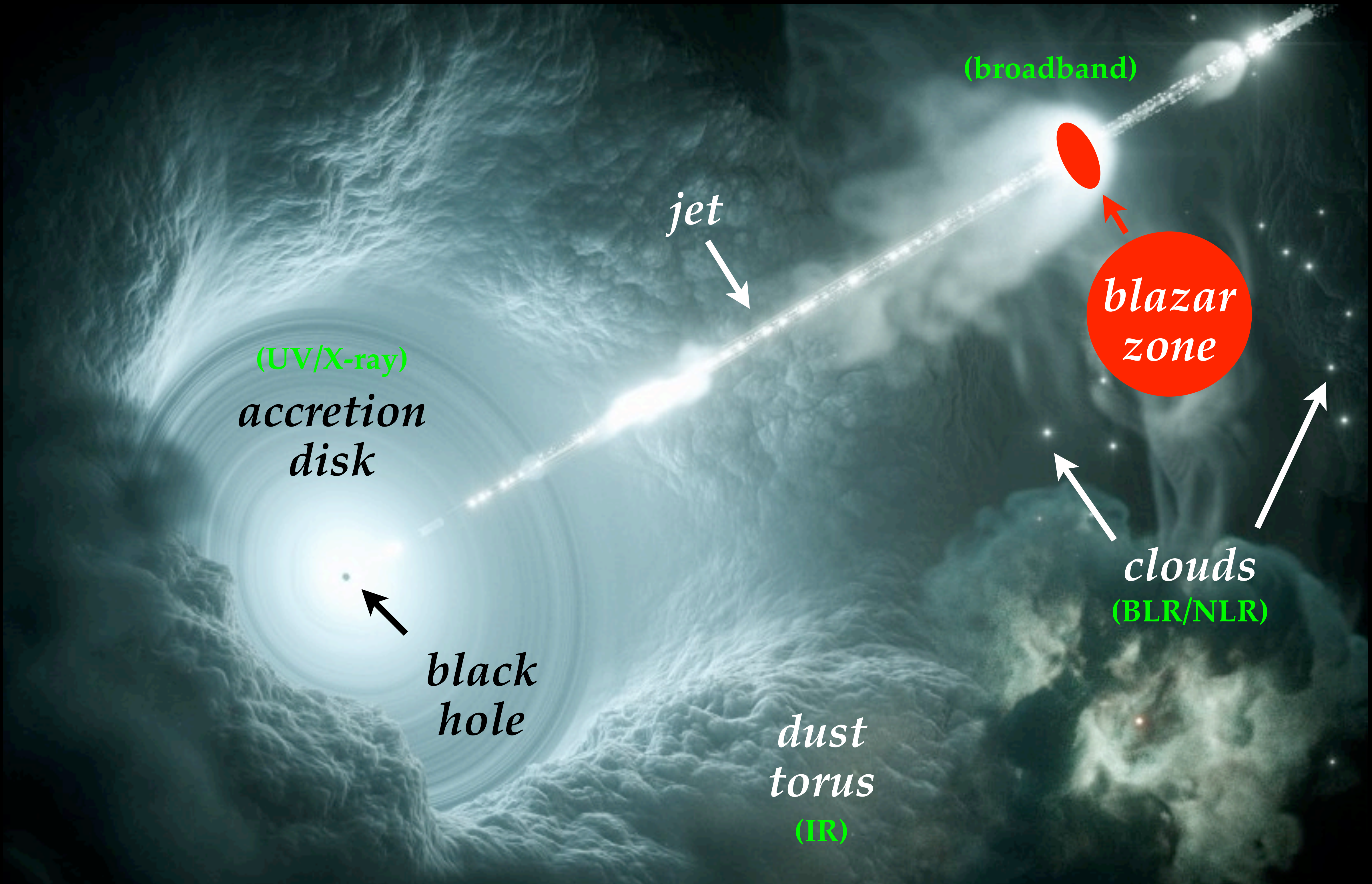
# TXS 0506+056





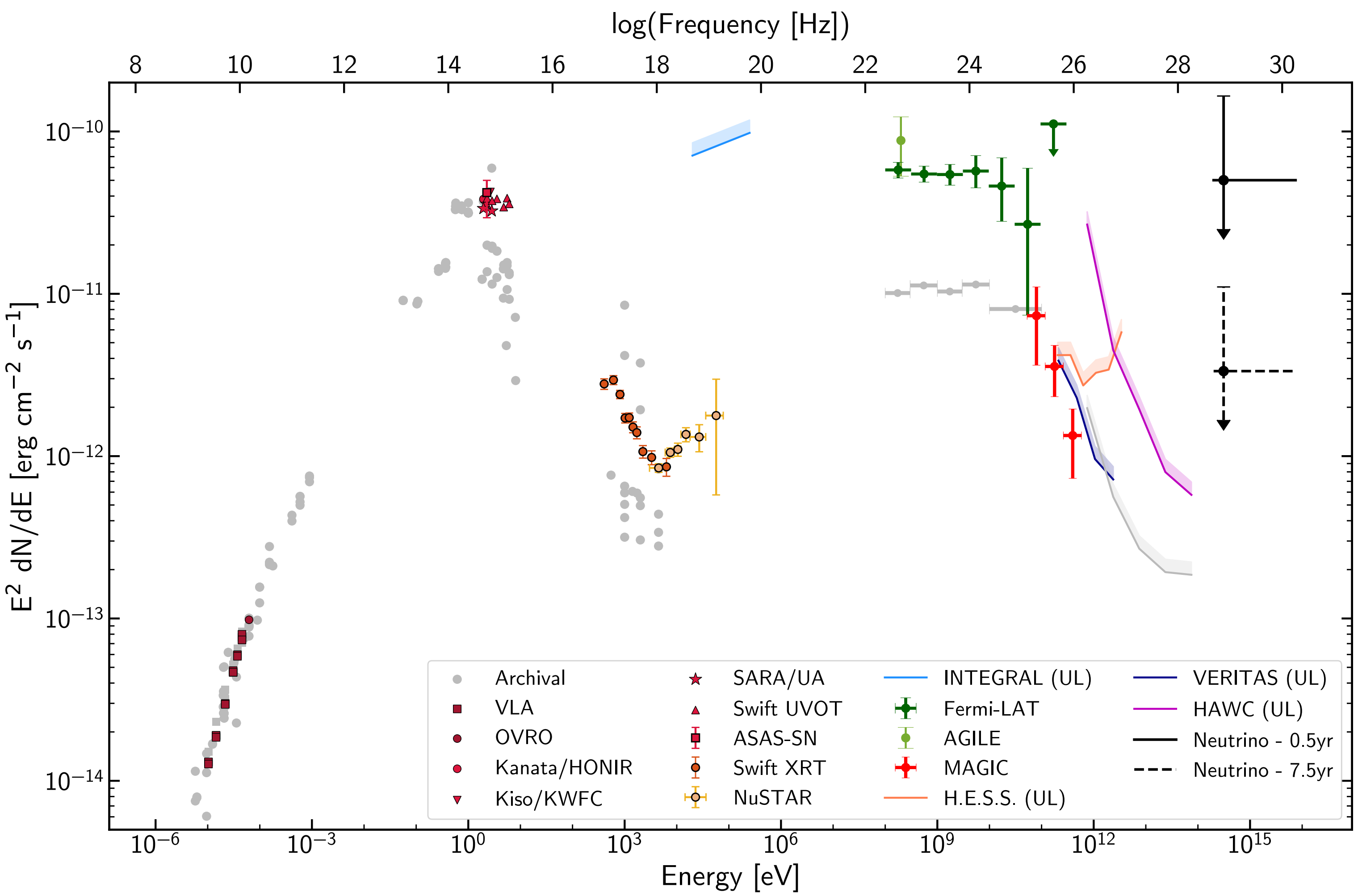
- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3$\sigma$-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

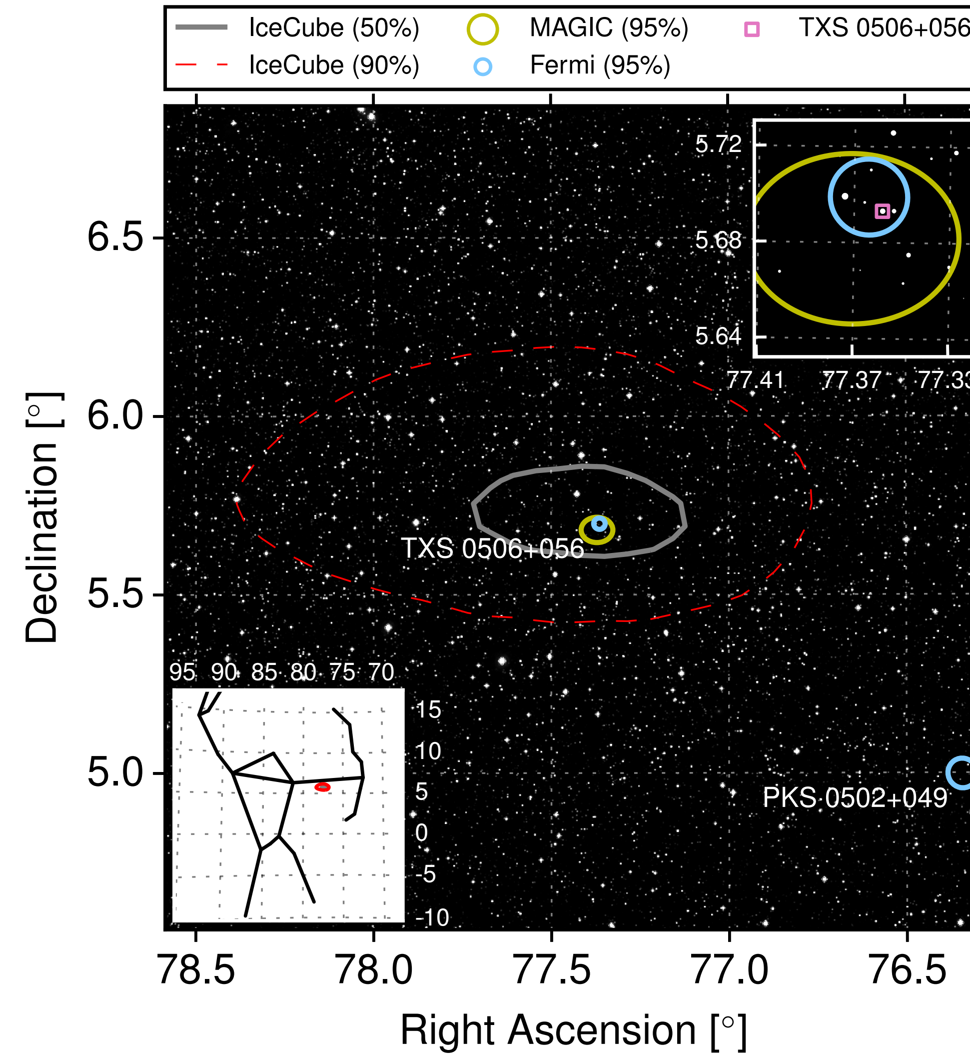
# Blazars as Neutrino Factories




Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

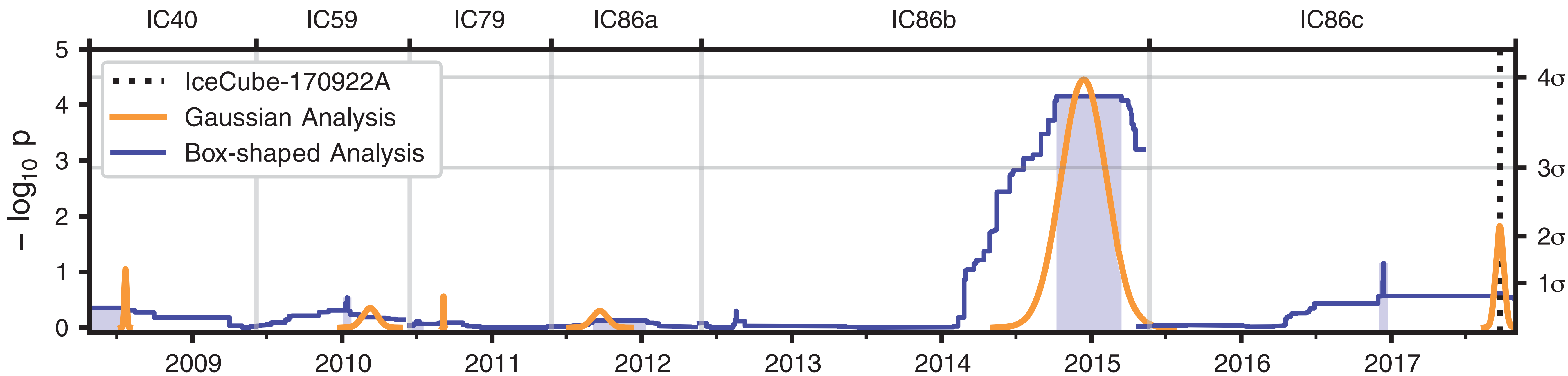
# Neutrino Flare in 2017



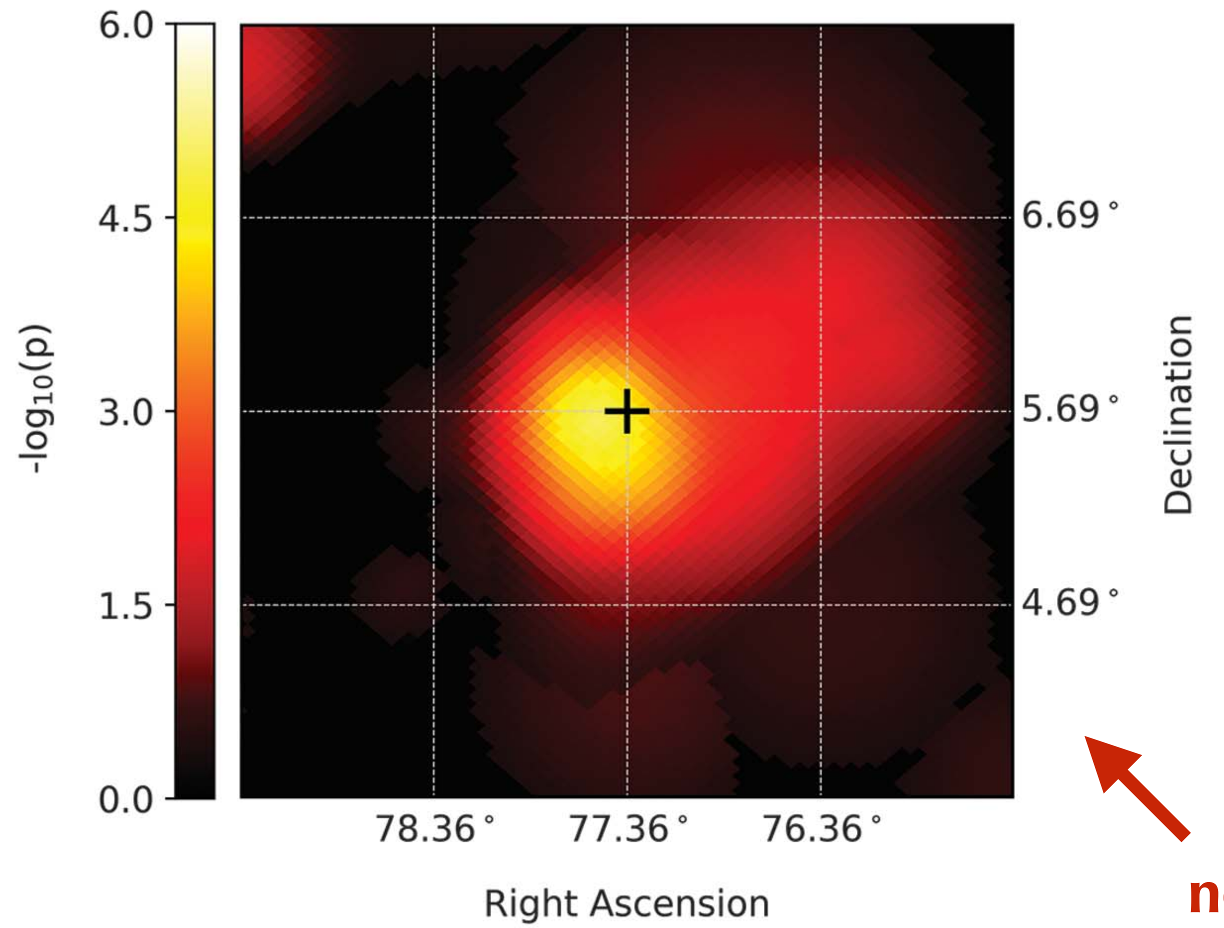




- Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.
  [Keivani *et al.*'18.; Gao *et al.*'18; Cerruti *et al.*'18; Zhang, Fang & Li'18; Gokus *et al.*'18; Sahakyan'18]
- Neutrino flux limited to **less than one event** by theoretically feasible cosmic ray luminosity and X-ray data. [Murase, Oikonomo & Petropoulou'18]
- **Eddington bias**: expected number of events expected from BL Lacs observed by one event in the range **0.006 - 0.03** [Strotjohann, Kowalski & Franckowiak'18]

# Neutrino Flare in 2014/15



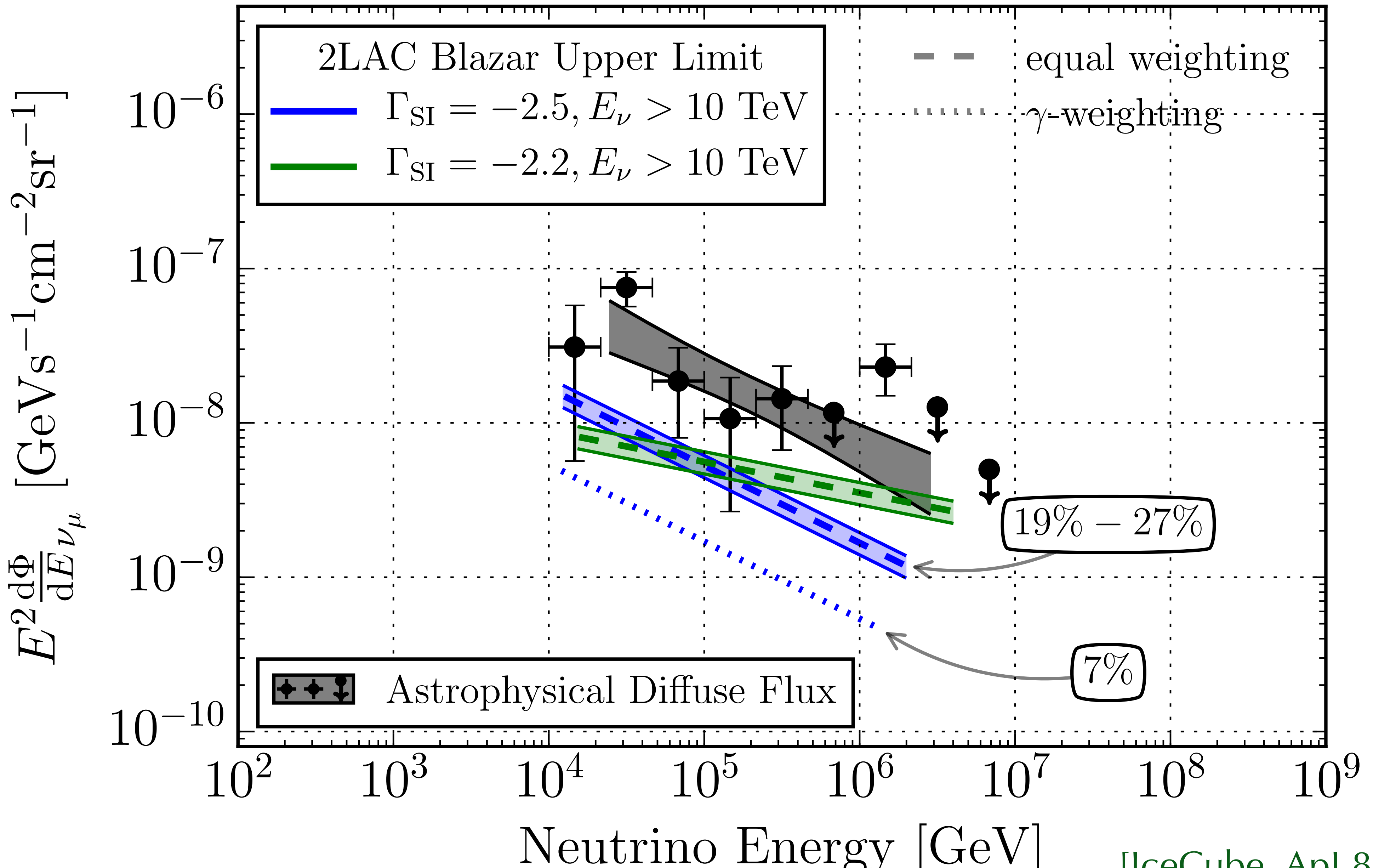

[IceCube, Science 361 (2018) no.6398, 147-151]




**neutrino "morphology" of flare**

- Independent 3.5$\sigma$ evidence for a **neutrino flare** (13±5 events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of gamma-rays** (Fermi-LAT).

# Blazar Origin of the Isotropic Flux?




[IceCube, ApJ 835 (2017) 45]

Combined contribution of Fermi-LAT blazars **below 30%** of the isotropic TeV-PeV neutrino observation.

# Point Source vs. Diffuse Flux

Populations of extragalactic neutrino sources can be visible

**individual sources**

or by the

**combined isotropic emission.**

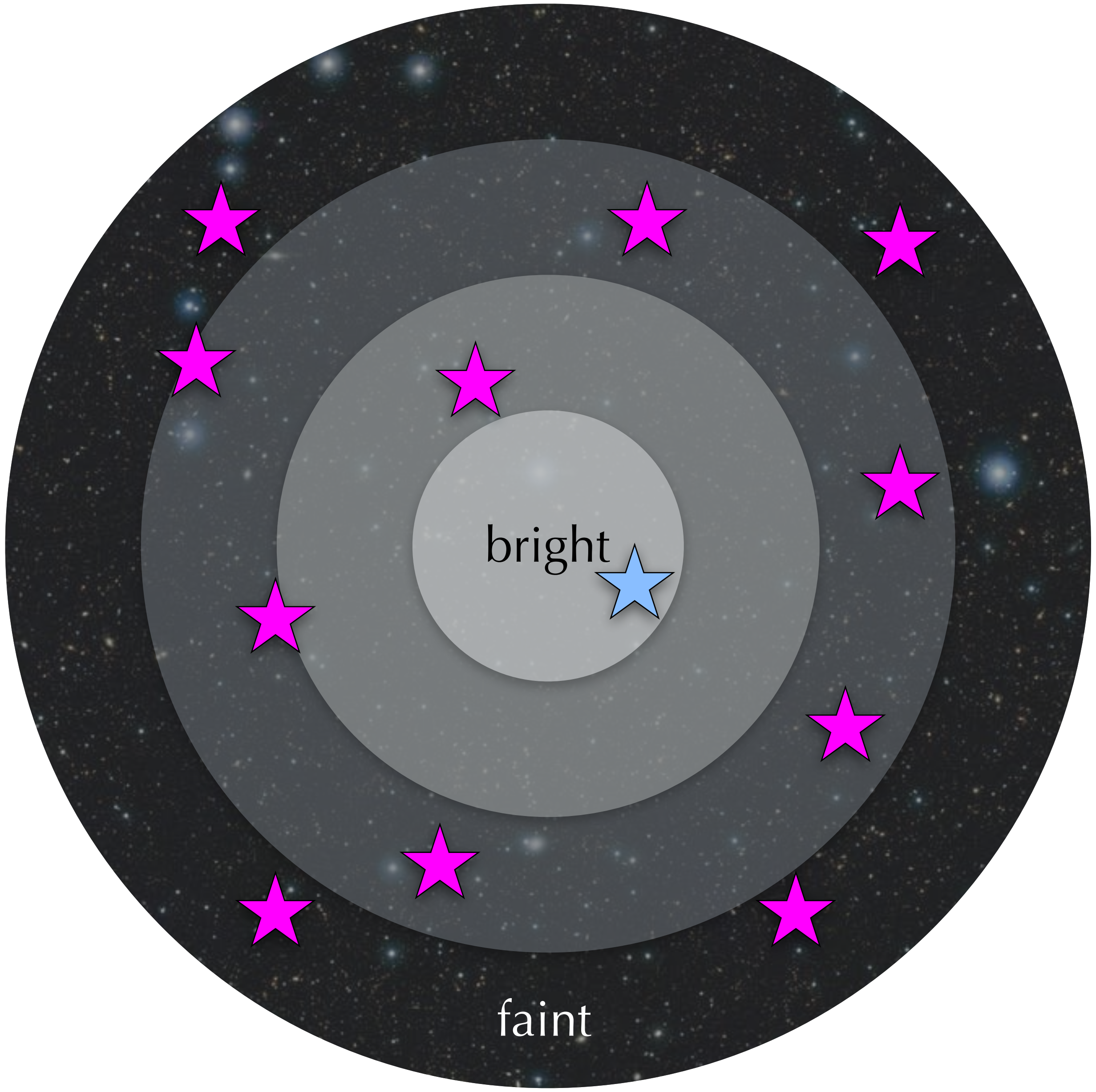
The relative contribution can be parametrized (*to first order*) by the average

**local source density**

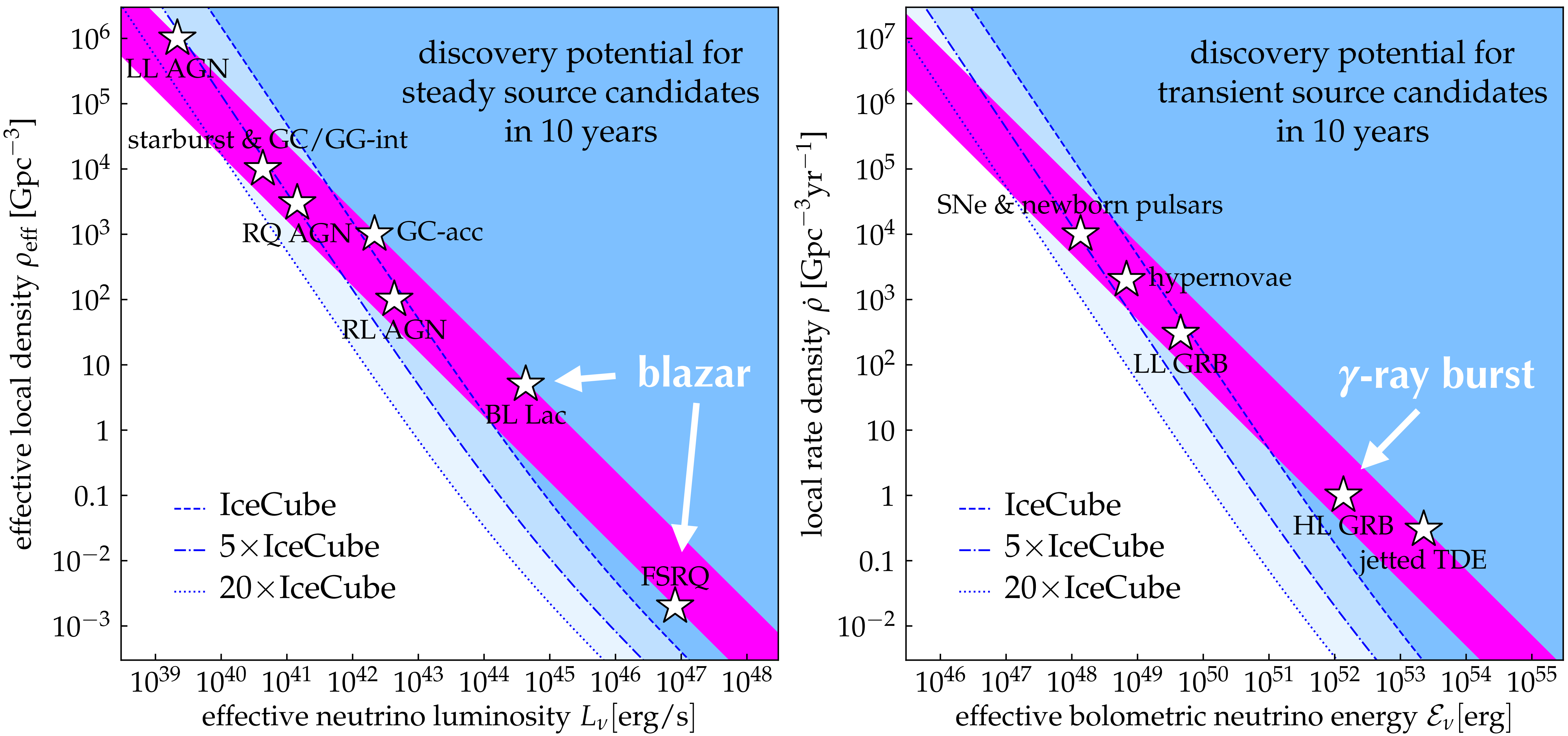
and

**source luminosity.**

"Observable Universe"
with far (faint) and near (bright) sources.




Hubble horizon




[Ackermann, MA, Anchordoqui, Bustamante *et al., Astro2020* arXiv:1903.04334]

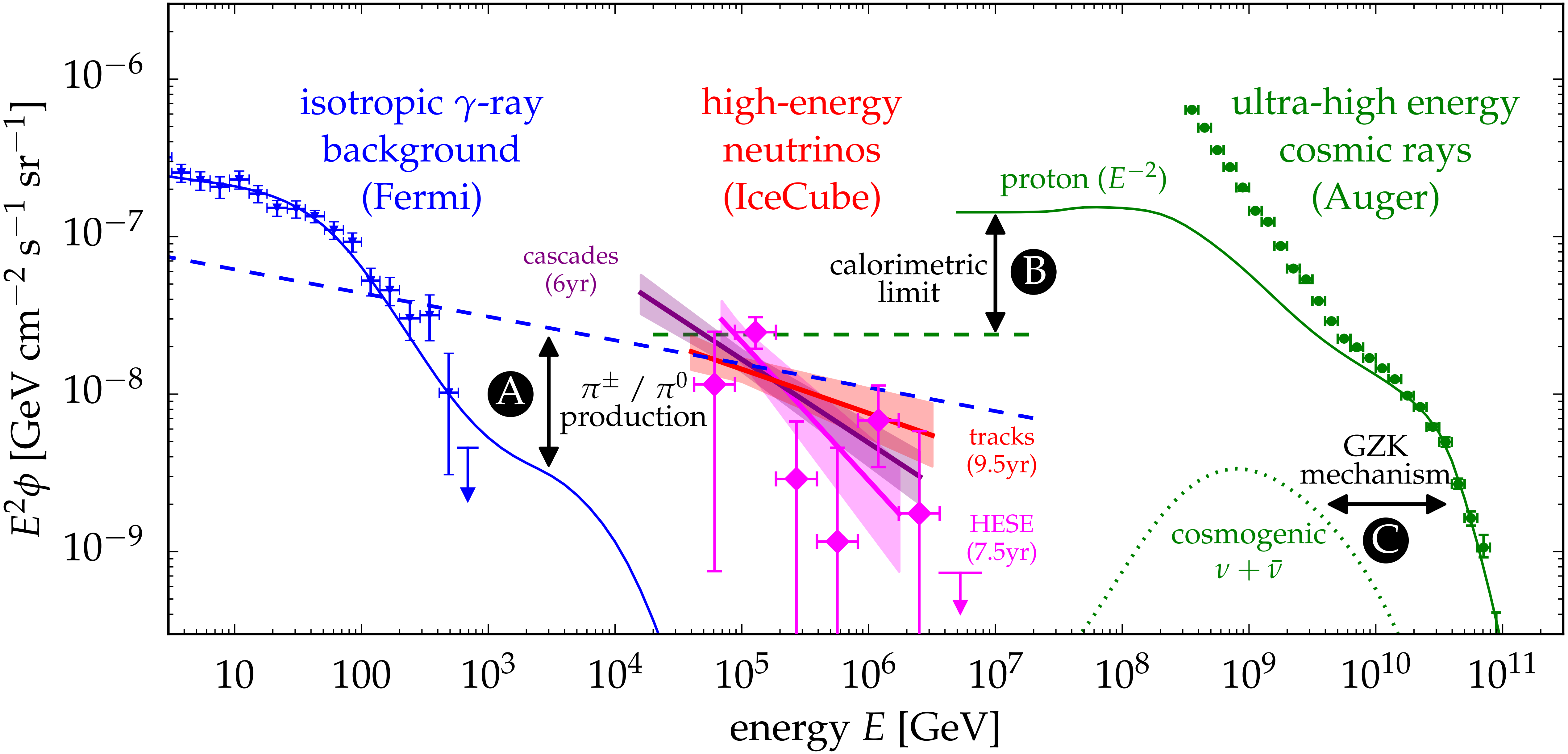
Rare sources, like blazars or $\gamma$-ray bursts, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).

# Point Source vs. Diffuse Flux

Neutrino sources are hiding in plain sight.

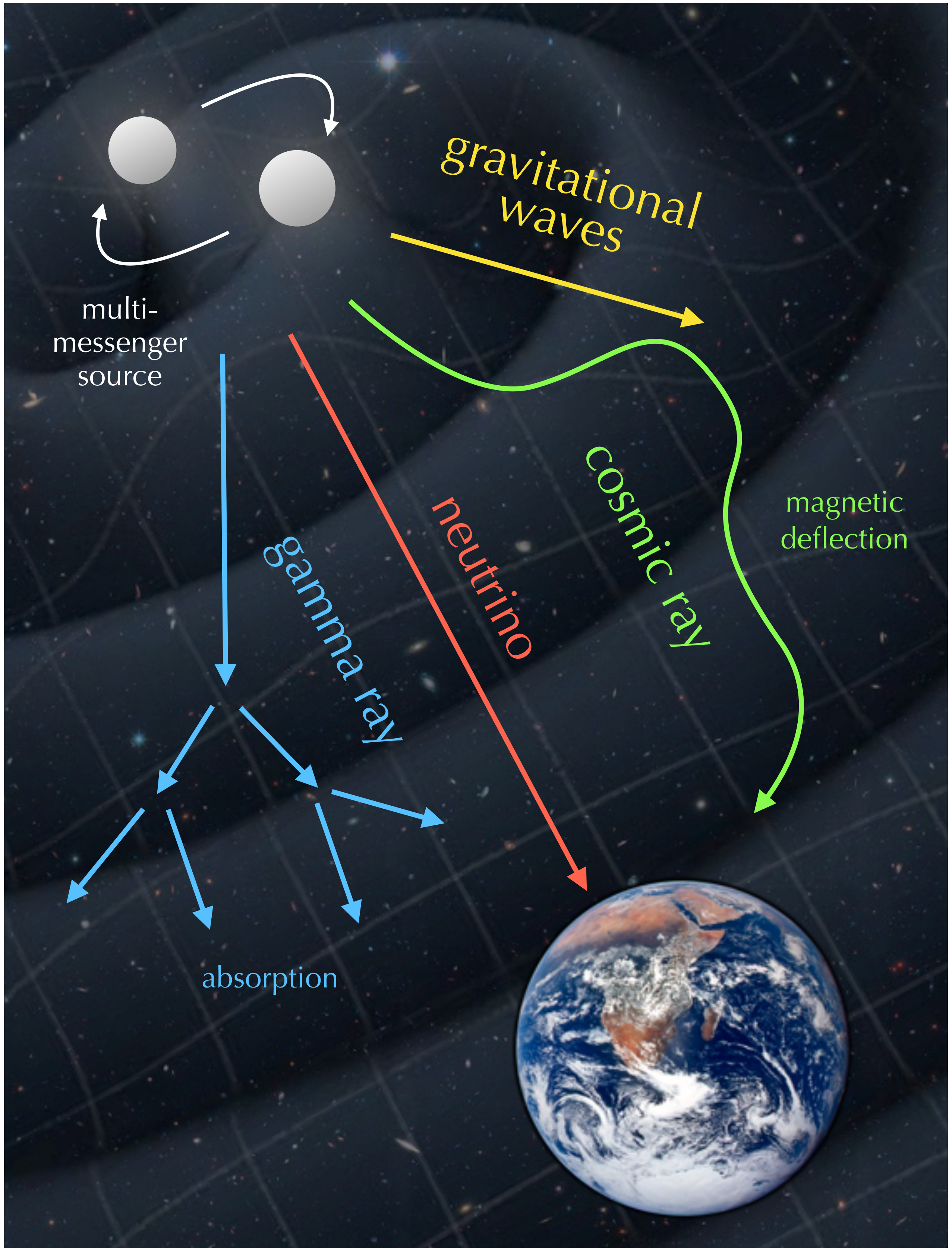
**We need to know what to look for!**

# Multi-Messenger Interfaces



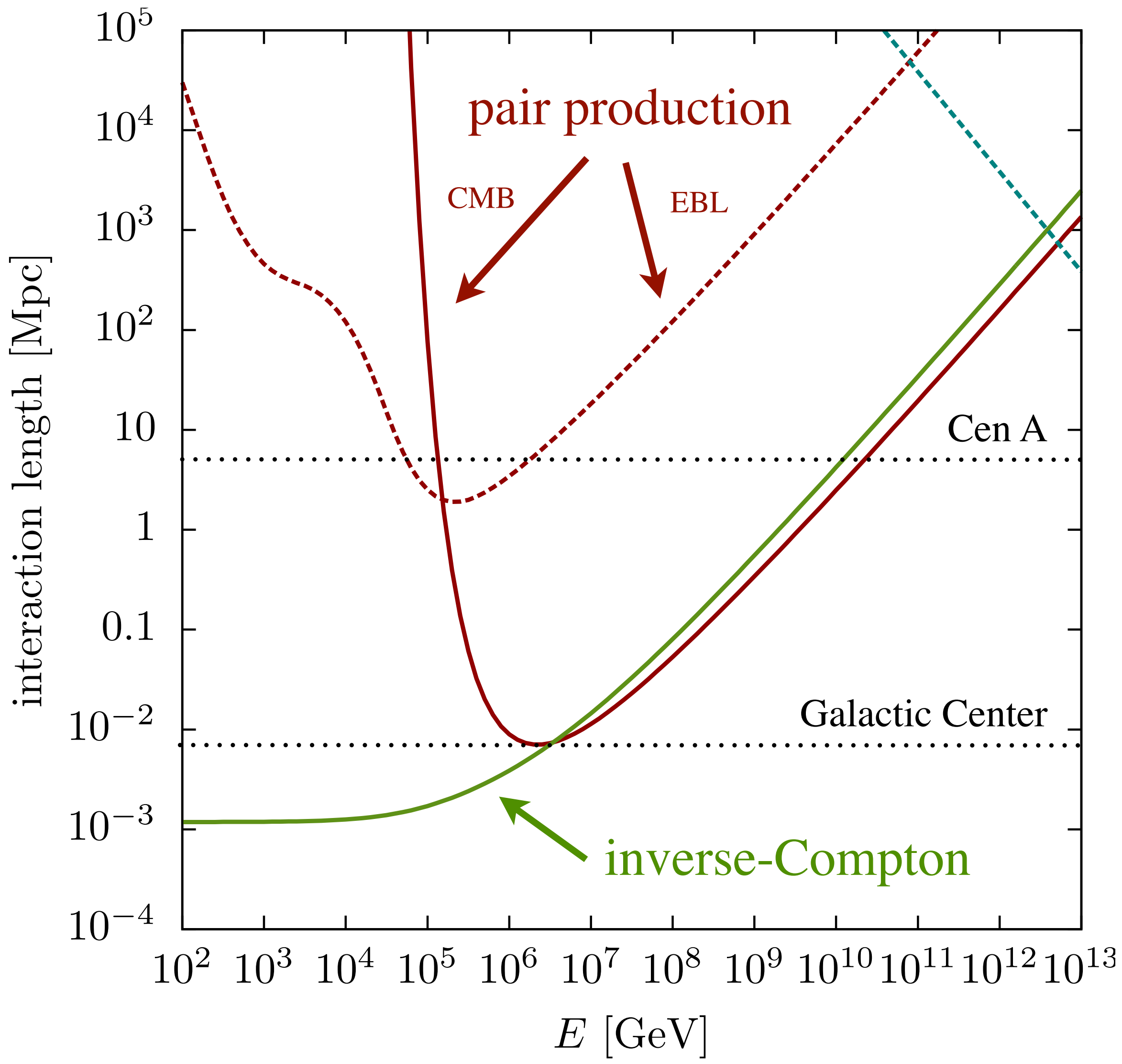

The high intensity of the neutrino flux compared to that of $\gamma$-rays and cosmic rays offers many interesting multi-messenger interfaces.

# Hadronic Gamma-Rays



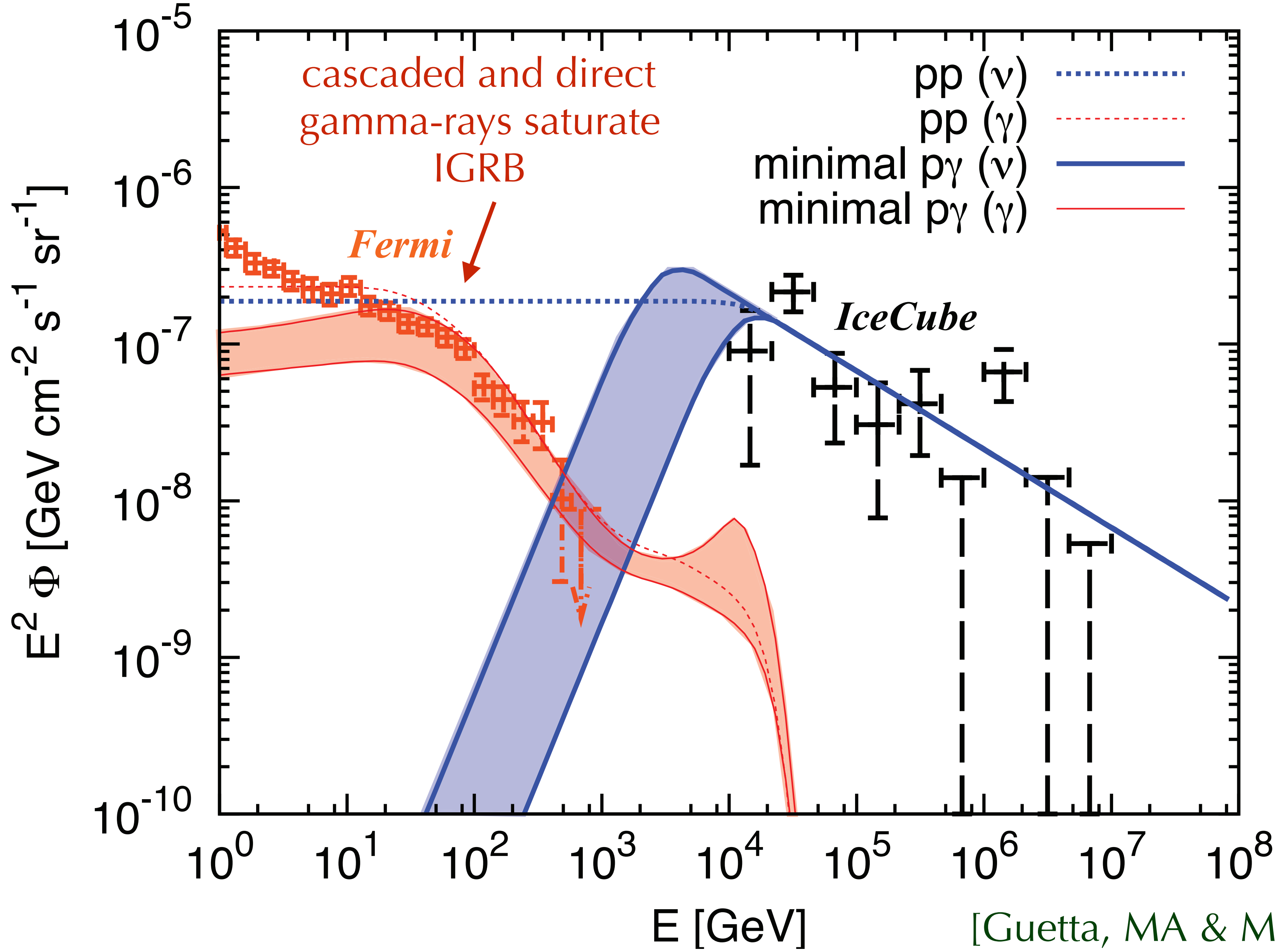

Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^0 \rightarrow \gamma + \gamma$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$



# Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) or radiation (p$\gamma$) saturate the isotropic diffuse gamma-ray background.



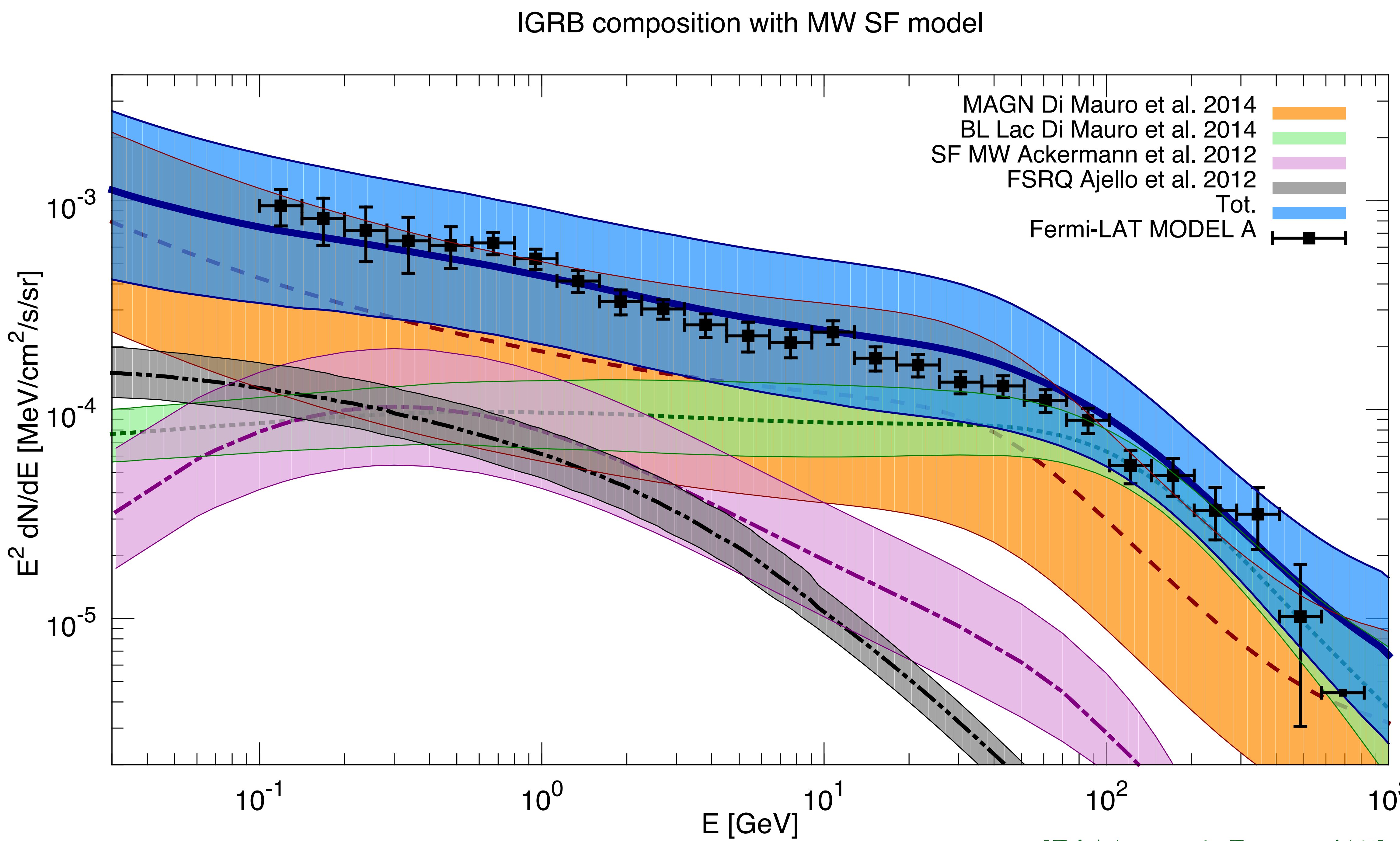

[Guetta, MA & Murase'16]

[see also Murase, MA & Lacki'13; Tamborra, Ando & Murase'14; Ando, Tamborra & Zandanel'15]

[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15; Palladino, Fedynitch, Rasmussen & Taylor'19]

# Isotropic Diffuse Gamma-Ray BGR

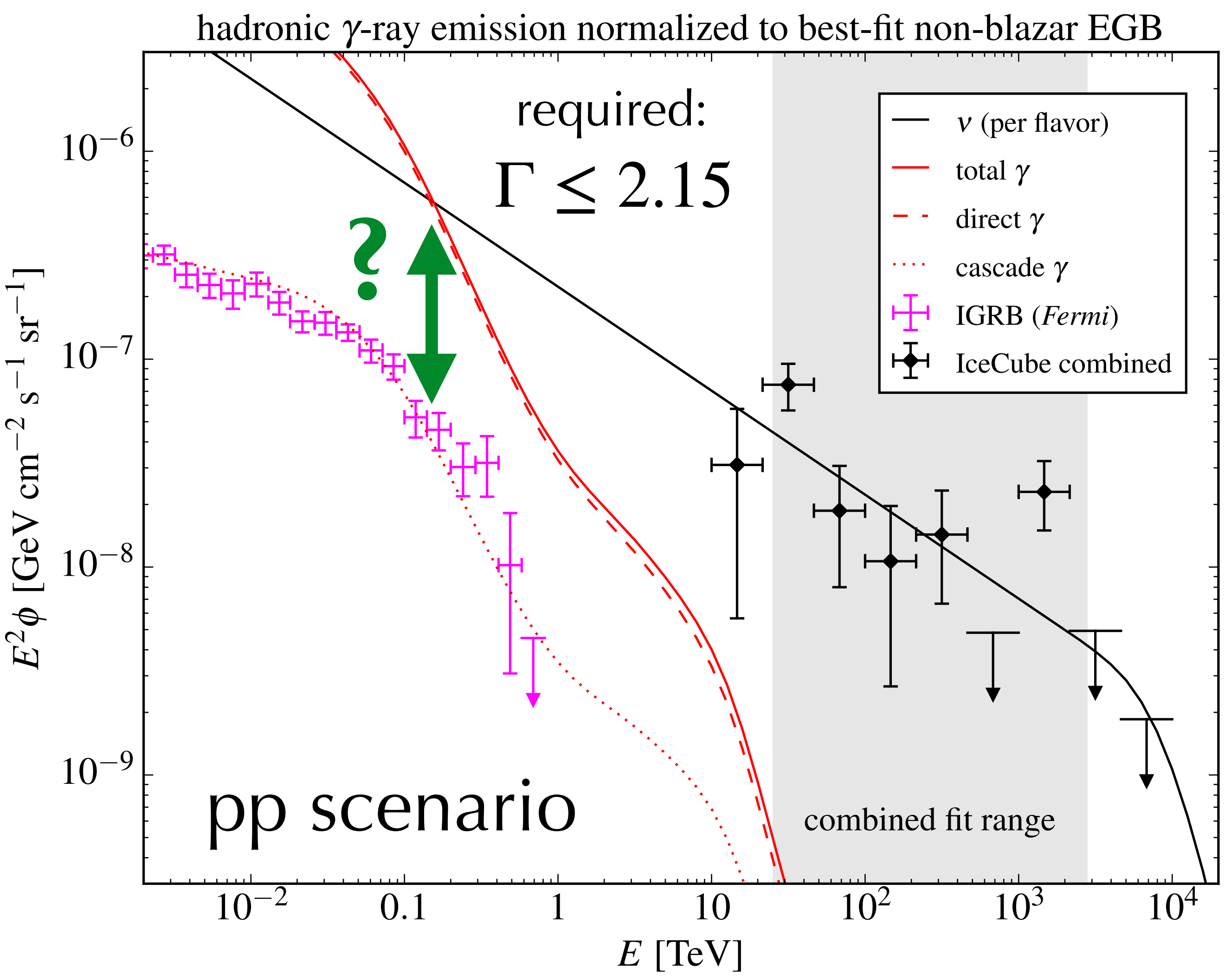
There is little room in the **isotropic diffuse $\gamma$-ray background** (IGRB) for “extra” $\gamma$-ray contributions.

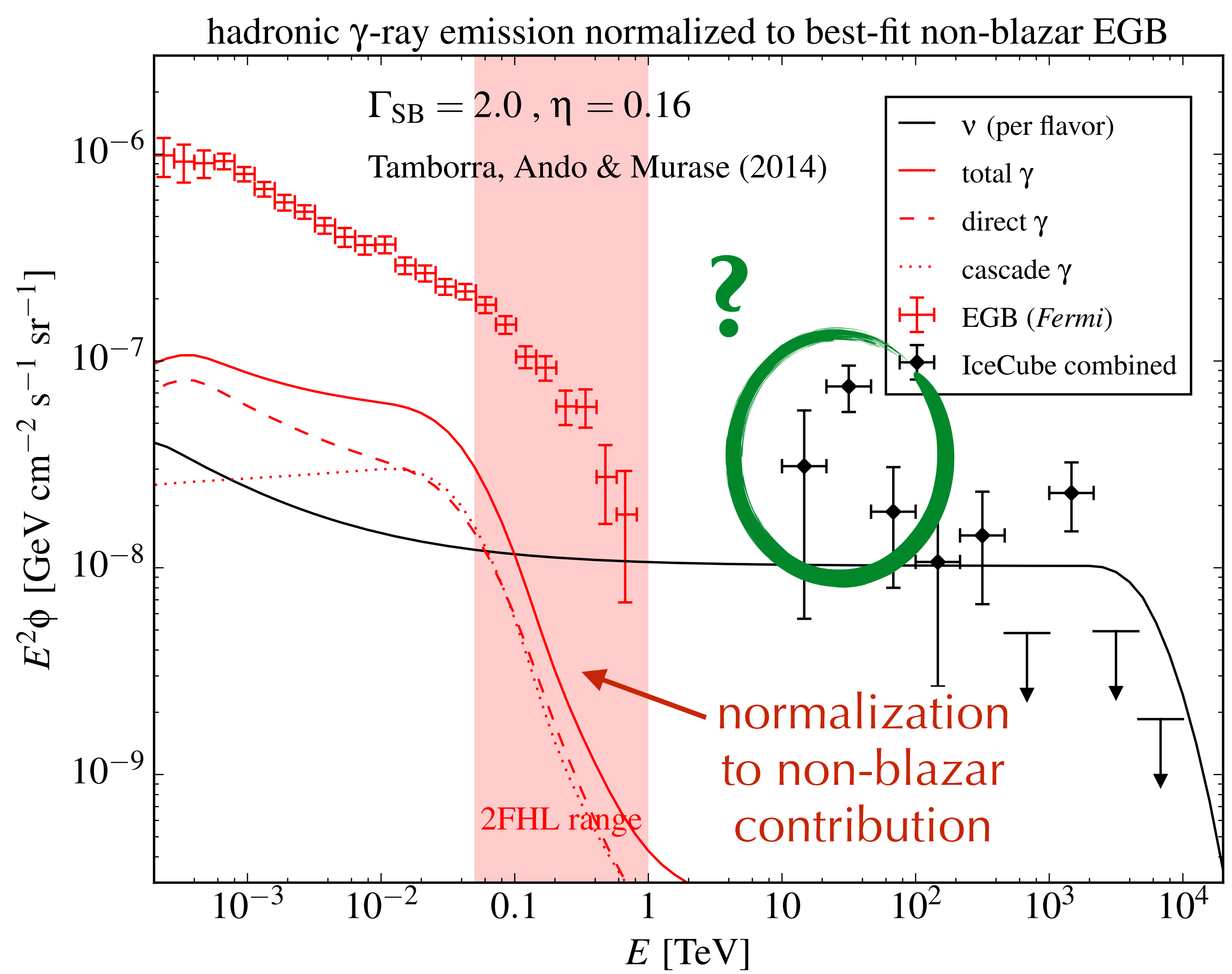



[Di Mauro & Donato’15]

# Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) in general overproduce $\gamma$-rays in the Fermi-LAT range.



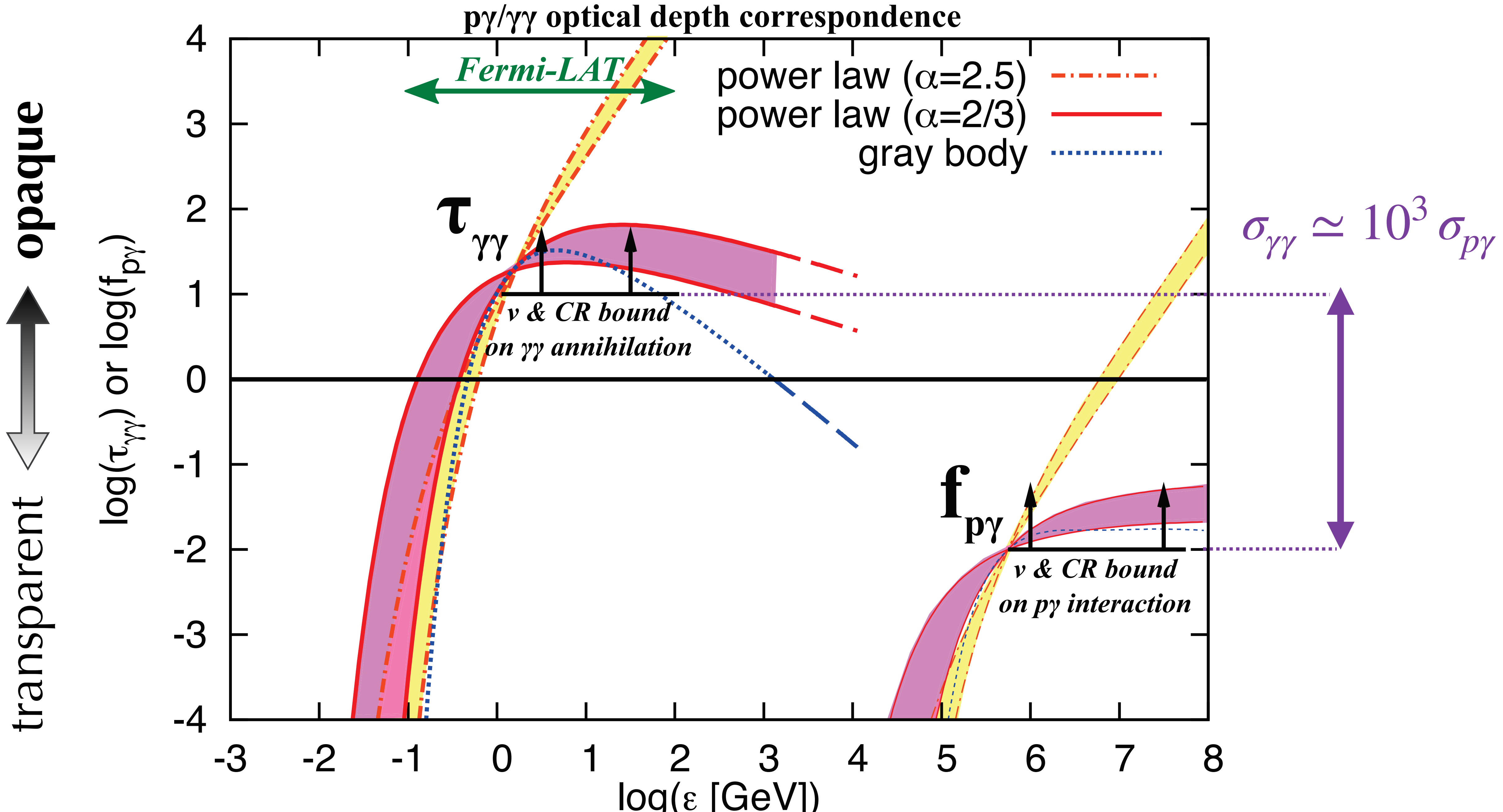




[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15]

[see also Murase, MA & Lacki'13; Tamborra, Ando & Murase'14; Ando, Tamborra & Zandanel'15]

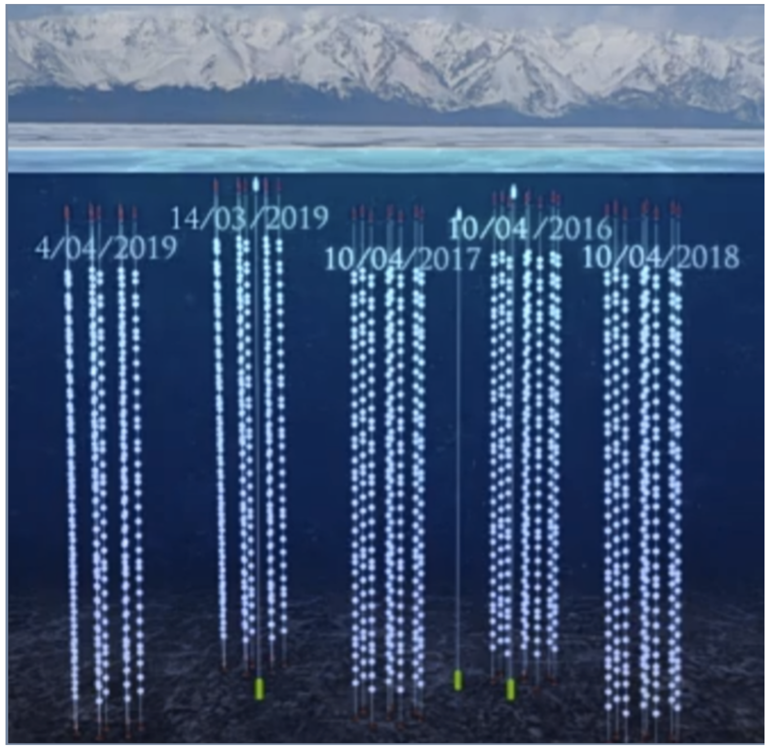
[Guetta, MA & Murase'16; Palladino, Fedynitch, Rasmussen & Taylor'19]

Efficient production of 10 TeV neutrinos in $p\gamma$ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN cores or chocked GRBs).




[Guetta, MA & Murase'16]

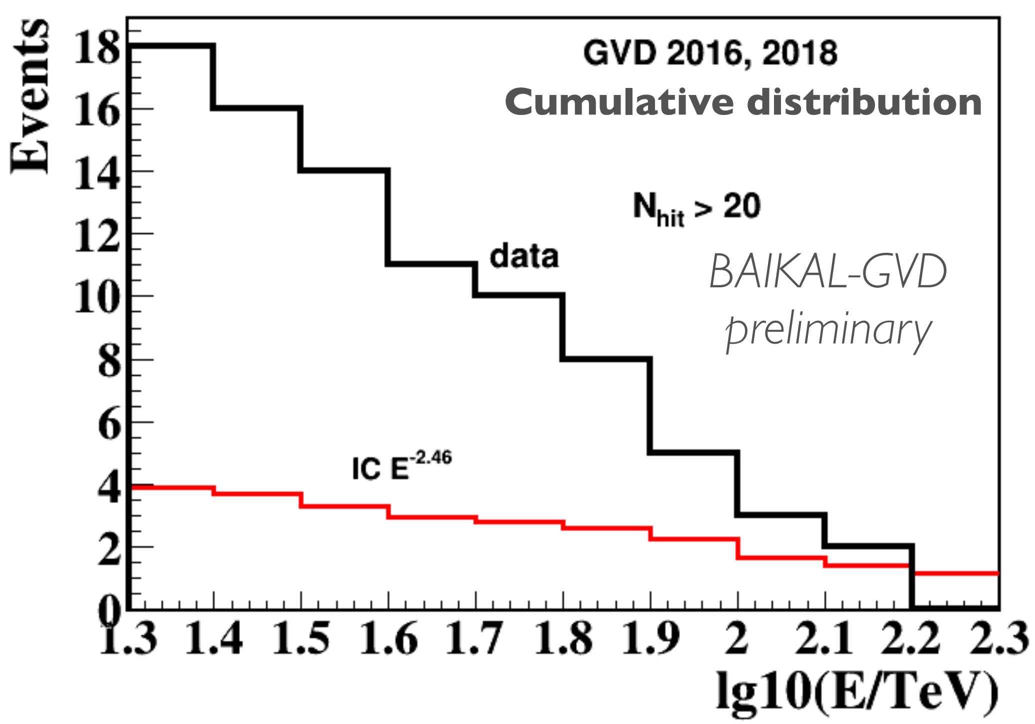
# Outlook: Baikal-GVD

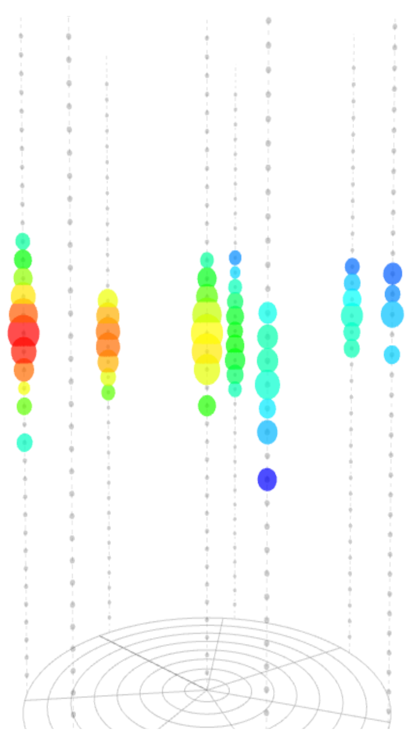




present detector outline (2019)

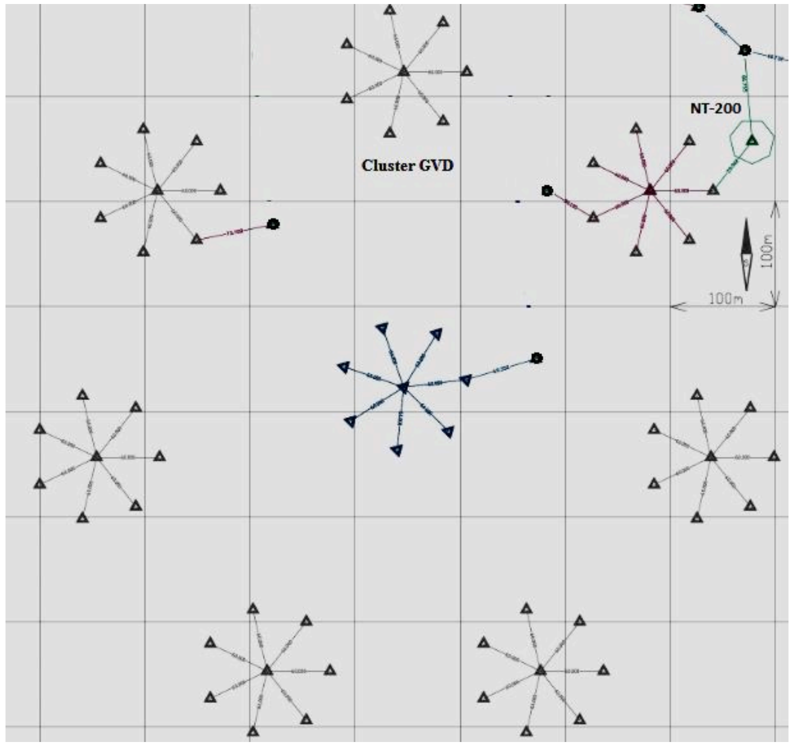
- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- since April 2019: 5 clusters
- **final goal**: 27 clusters (~1.4 km³)

BAIKAL-GVD



~157 TeV cascade event

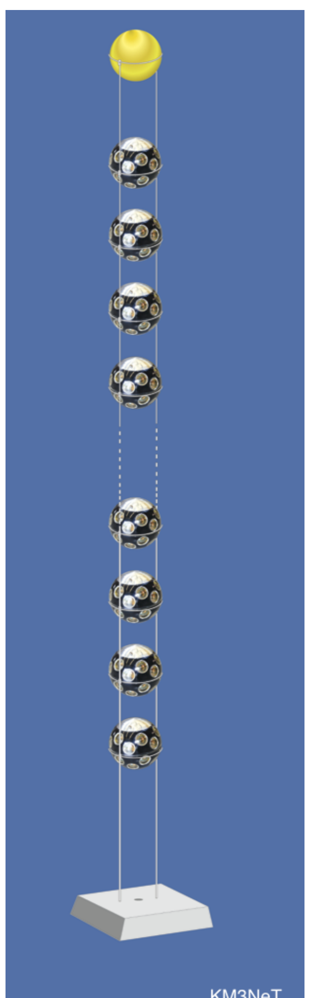


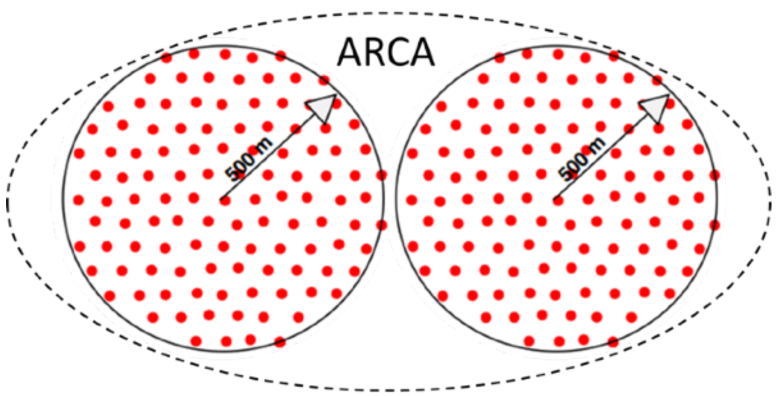

GVD-Phase 1

# Outlook: KM3NeT/ARCA

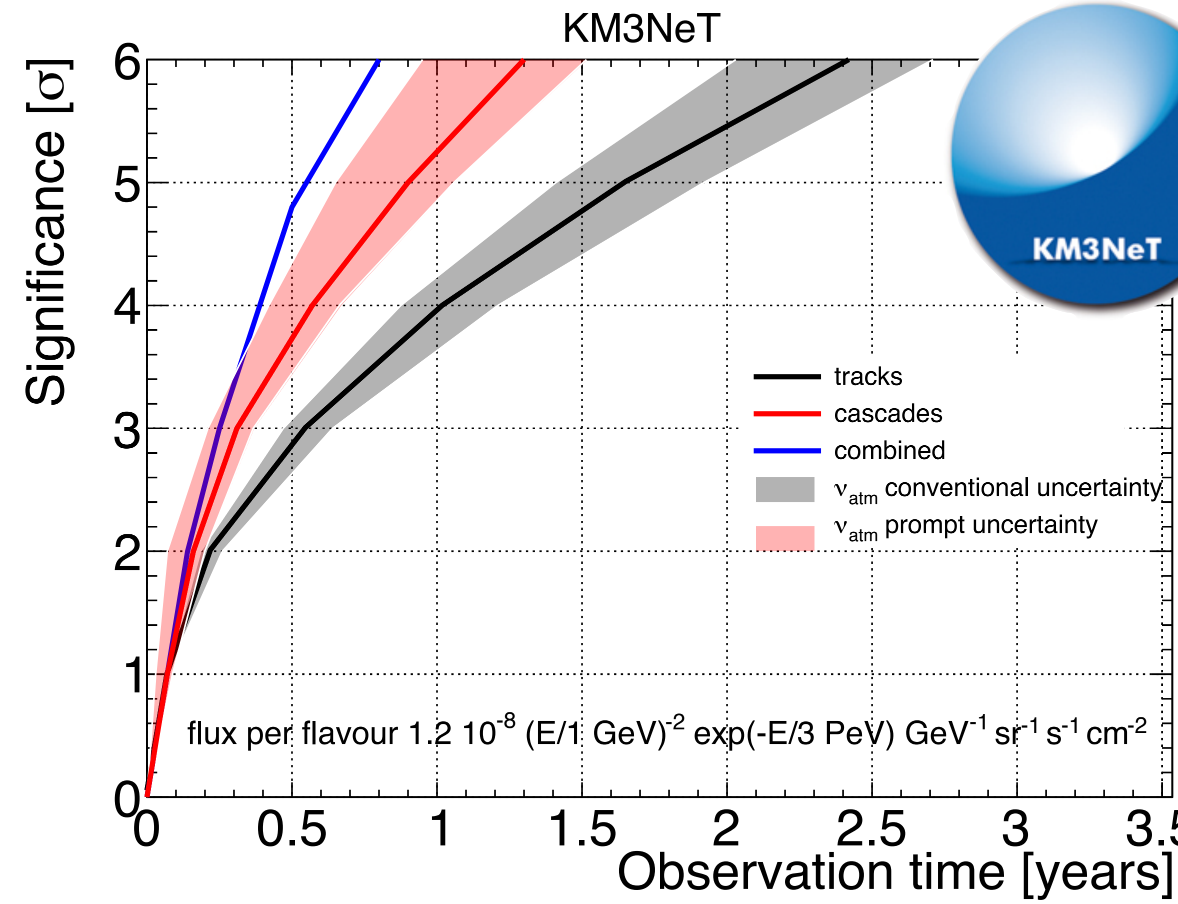
- **ARCA :** 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km³)
- 3 DU deployed off the coast of Italy (1 DU recovered after shortage)
- 2 DUs operated until March 2017

detection unit with multi-PMT DOMs



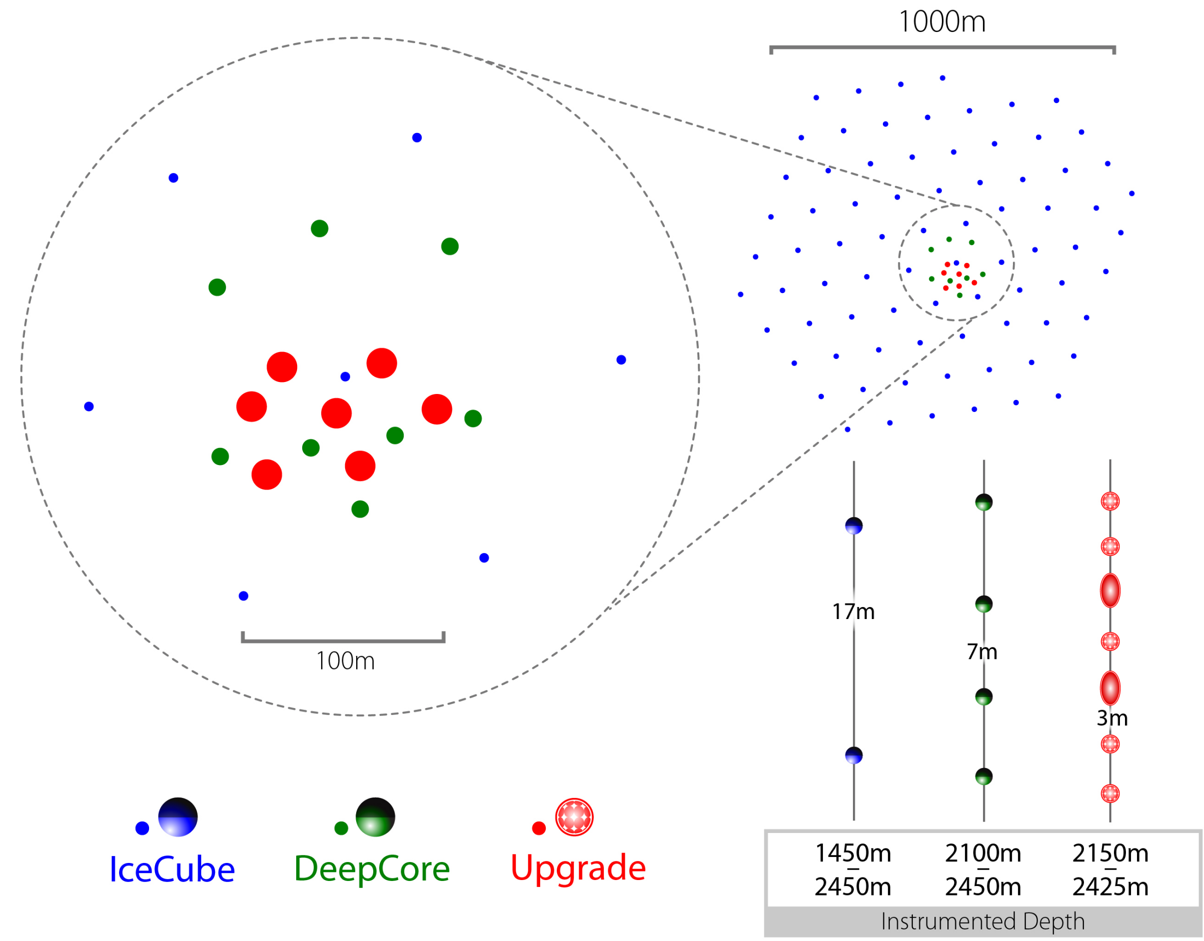


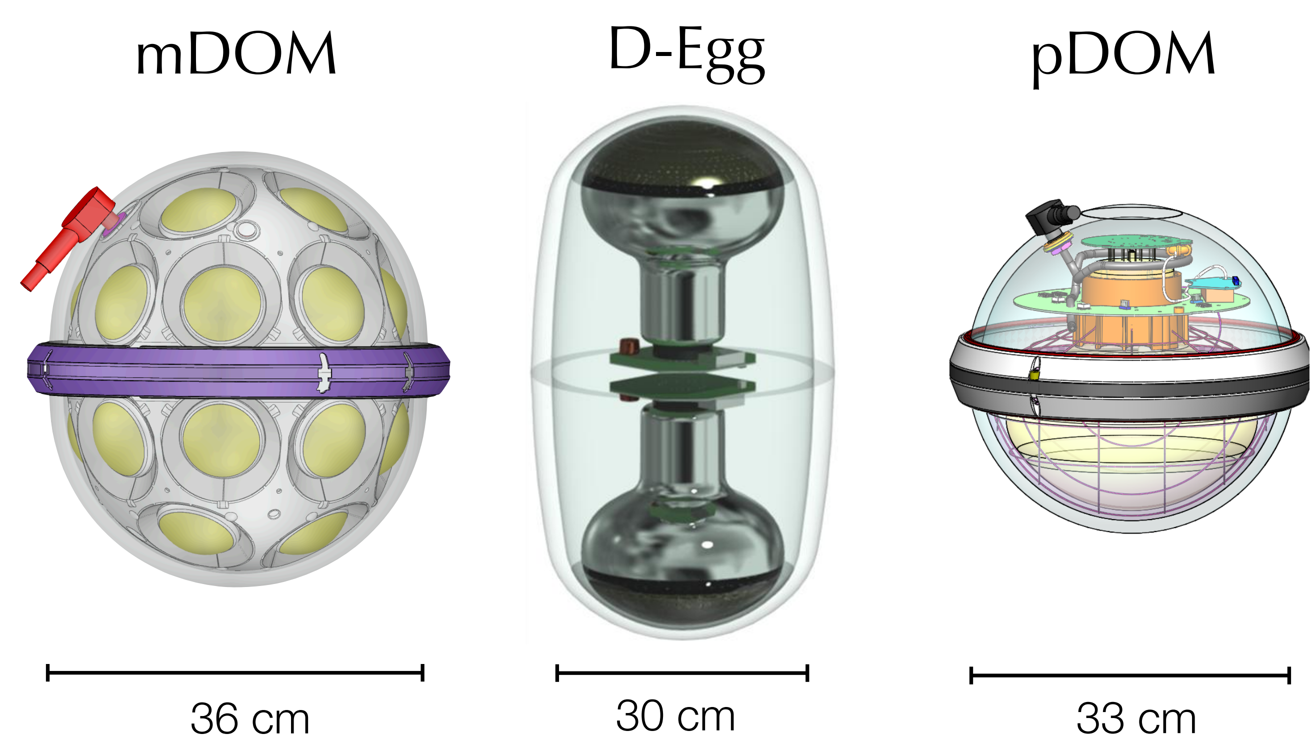



- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

# Outlook: IceCube Upgrade

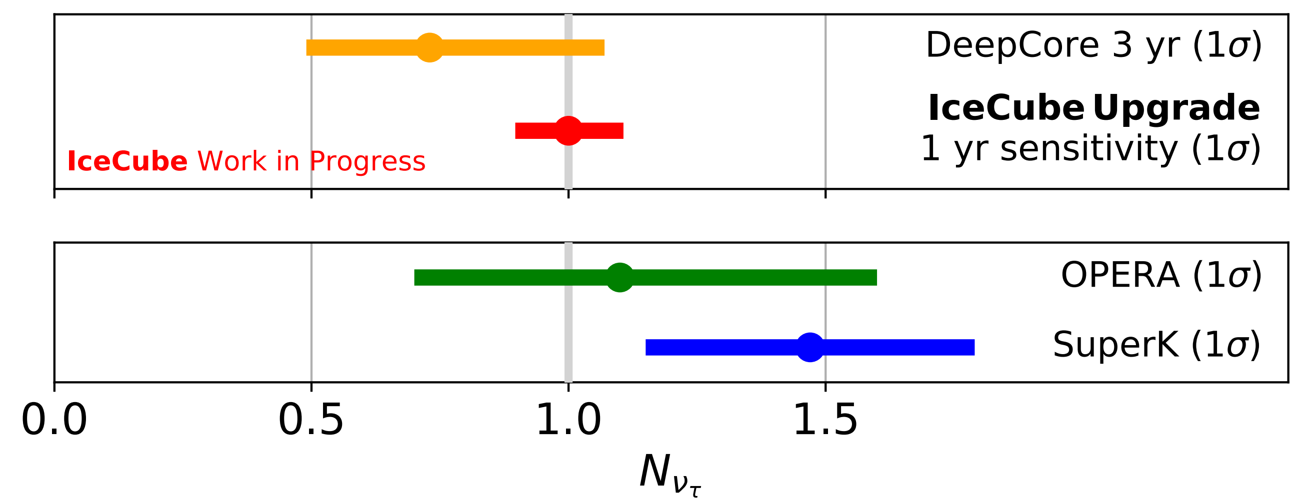
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- Midscale NSF project with an estimated total cost of $23M
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2022/23**

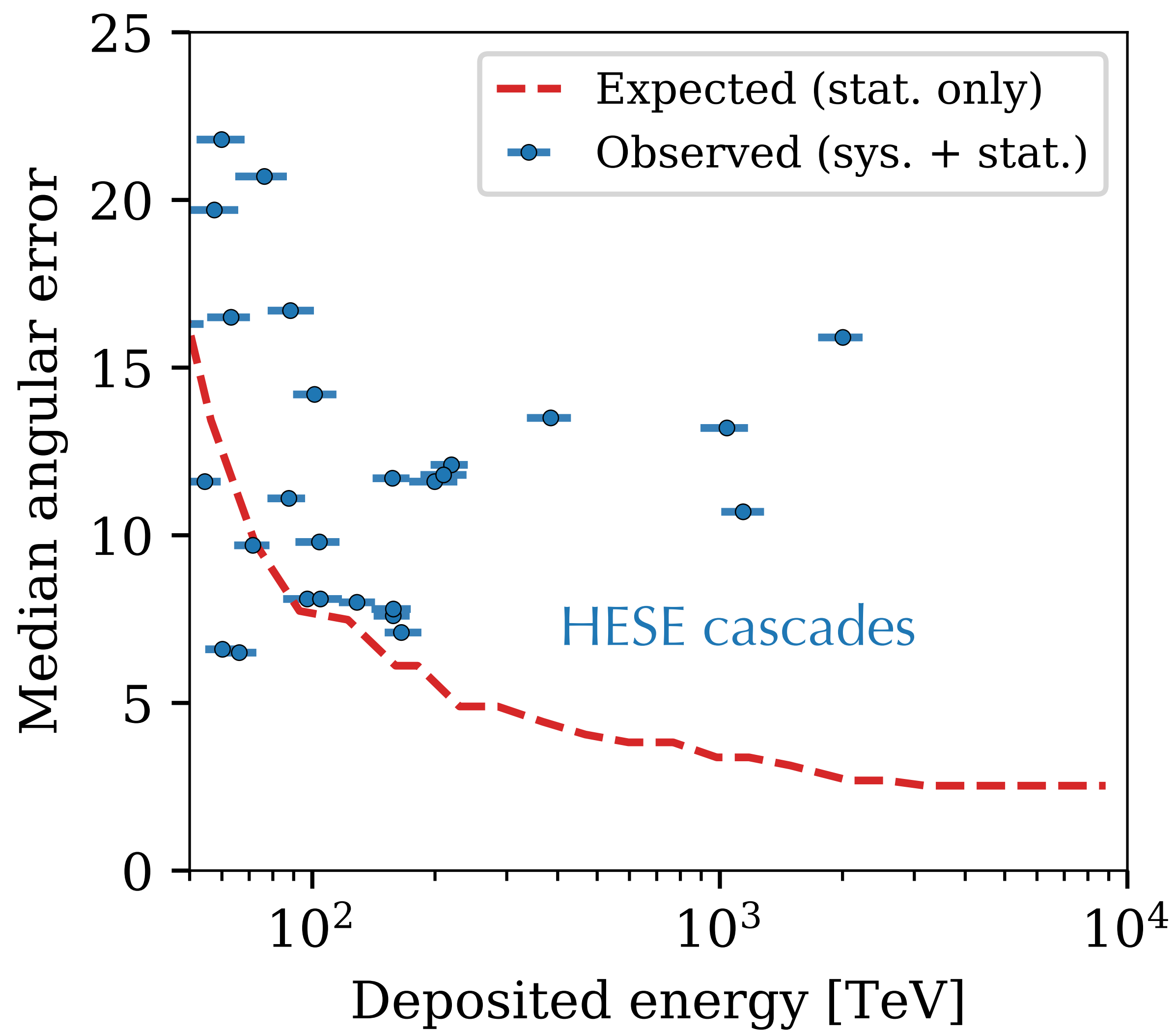


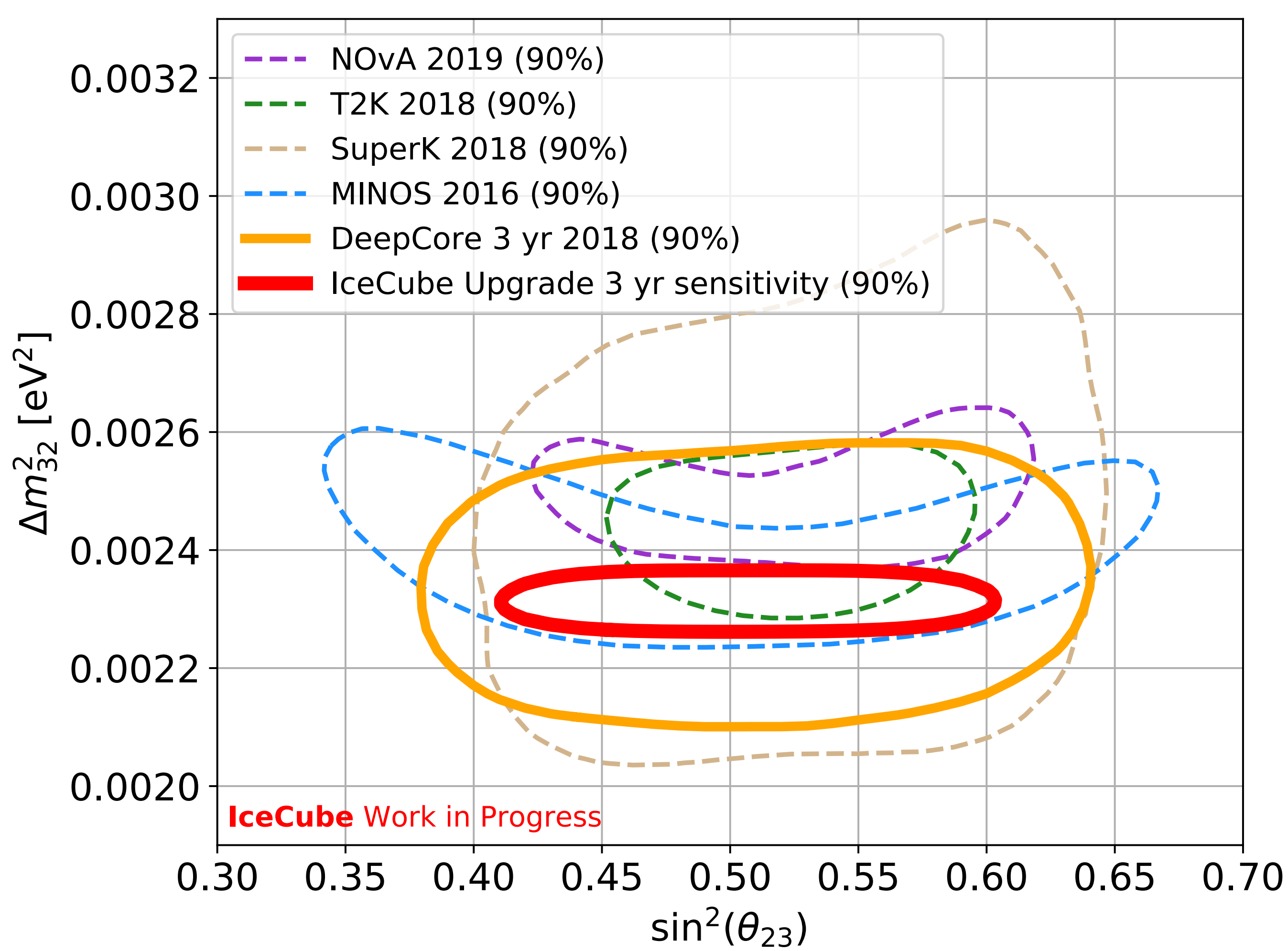



# Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance
- **Improved energy and angular reconstructions** of IceCube data




[IceCube, PoS(ICRC2019) 1177]

# Astro2020 Decadal Survey

Astro2020 Science White Paper

## Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos

**Thematic Area:** Multi-Messenger Astronomy and Astrophysics

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**Mauricio Bustamante**, *Niels Bohr Institute, University of Copenhagen*
**Amy Connolly**, *The Ohio State University*
**Cosmin Deaconu**, *University of Chicago*
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**Peter Gorham**, *University of Hawaii, Manoa*
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March 2019

Astro2020 Science White Paper

## Fundamental Physics with High-Energy Cosmic Neutrinos

**Thematic Area:** Cosmology and Fundamental Physics

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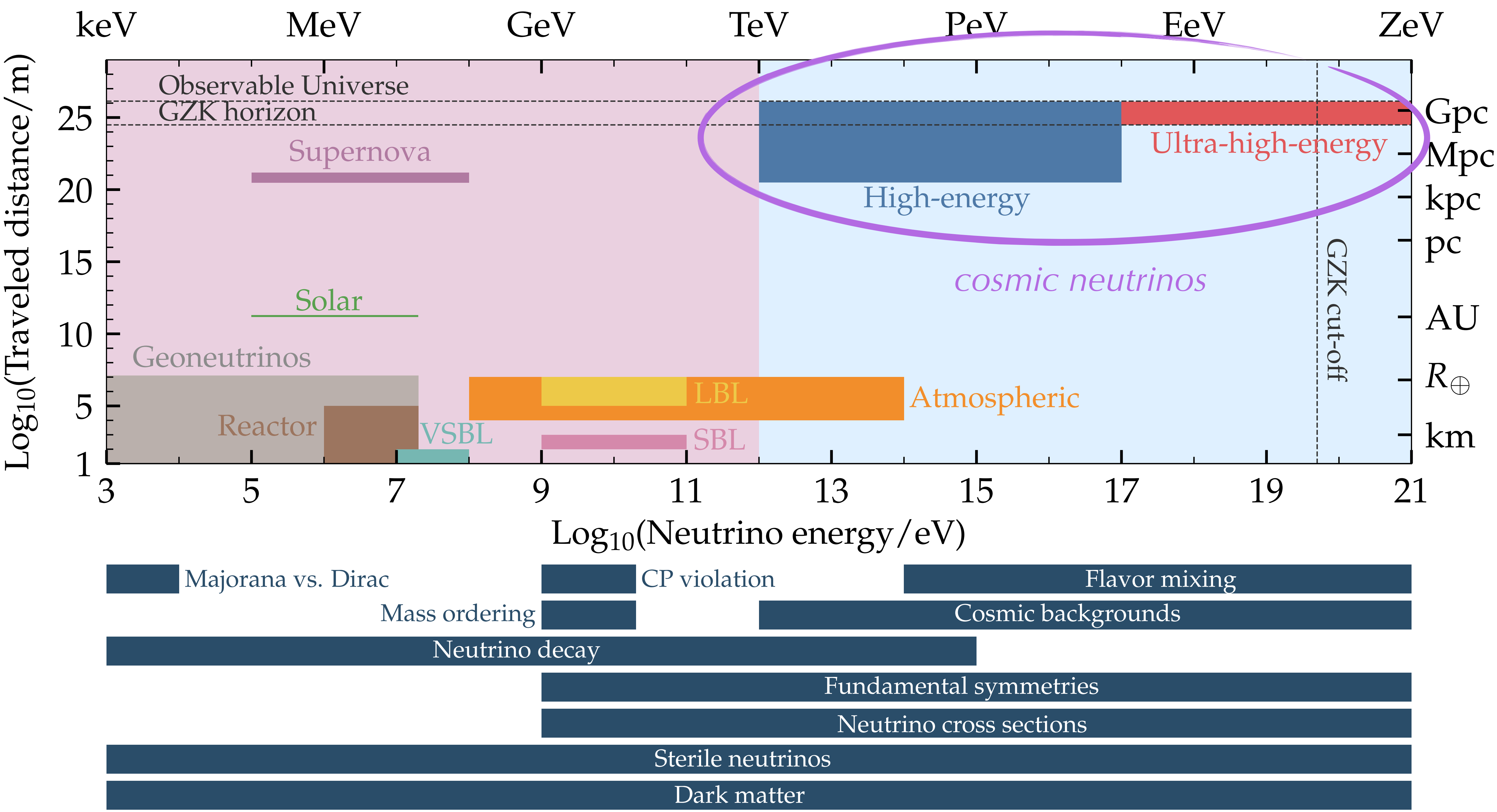
March 2019

[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04333 & arXiv:1903.04334]

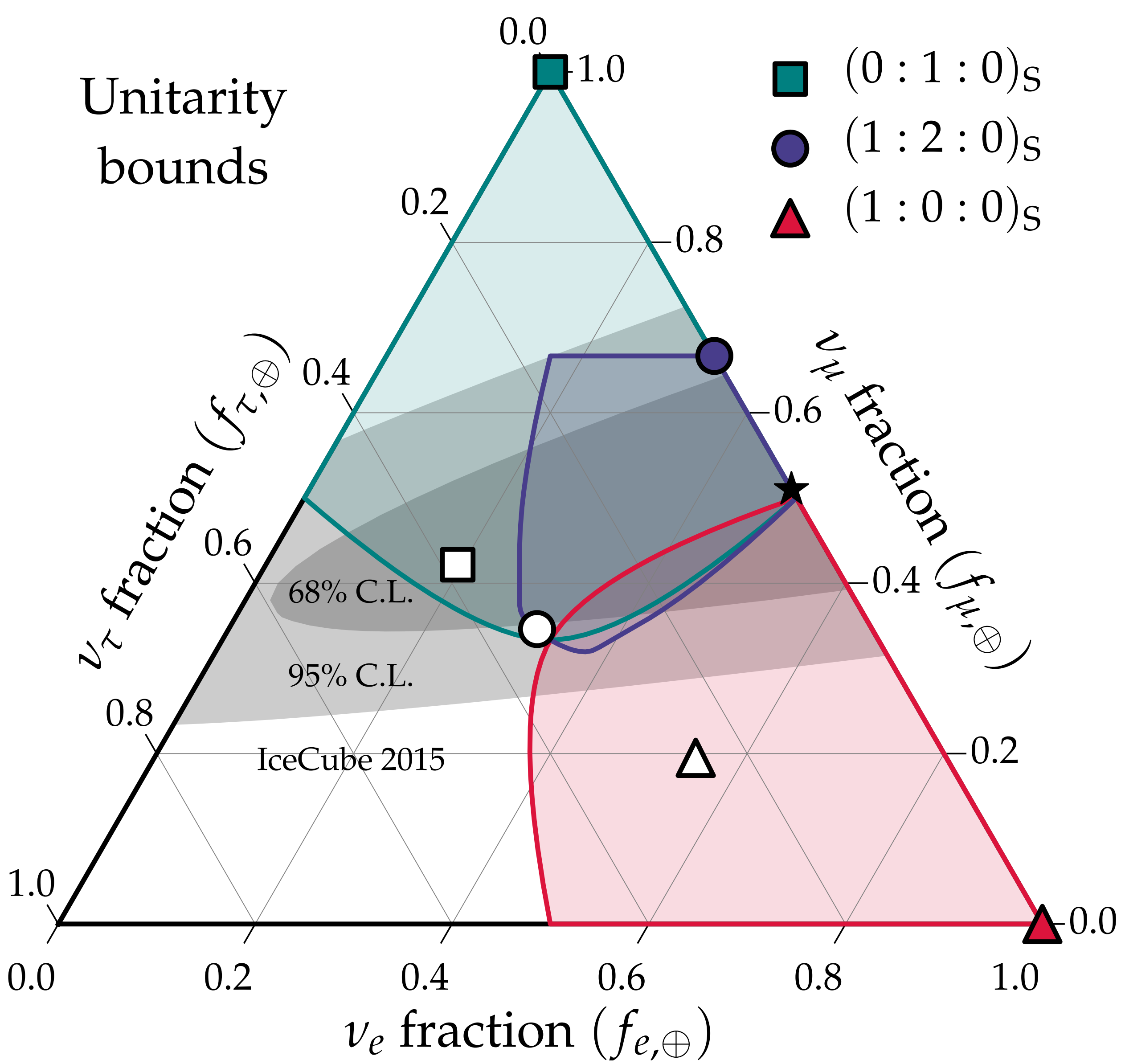
# Probe of Fundamental Physics



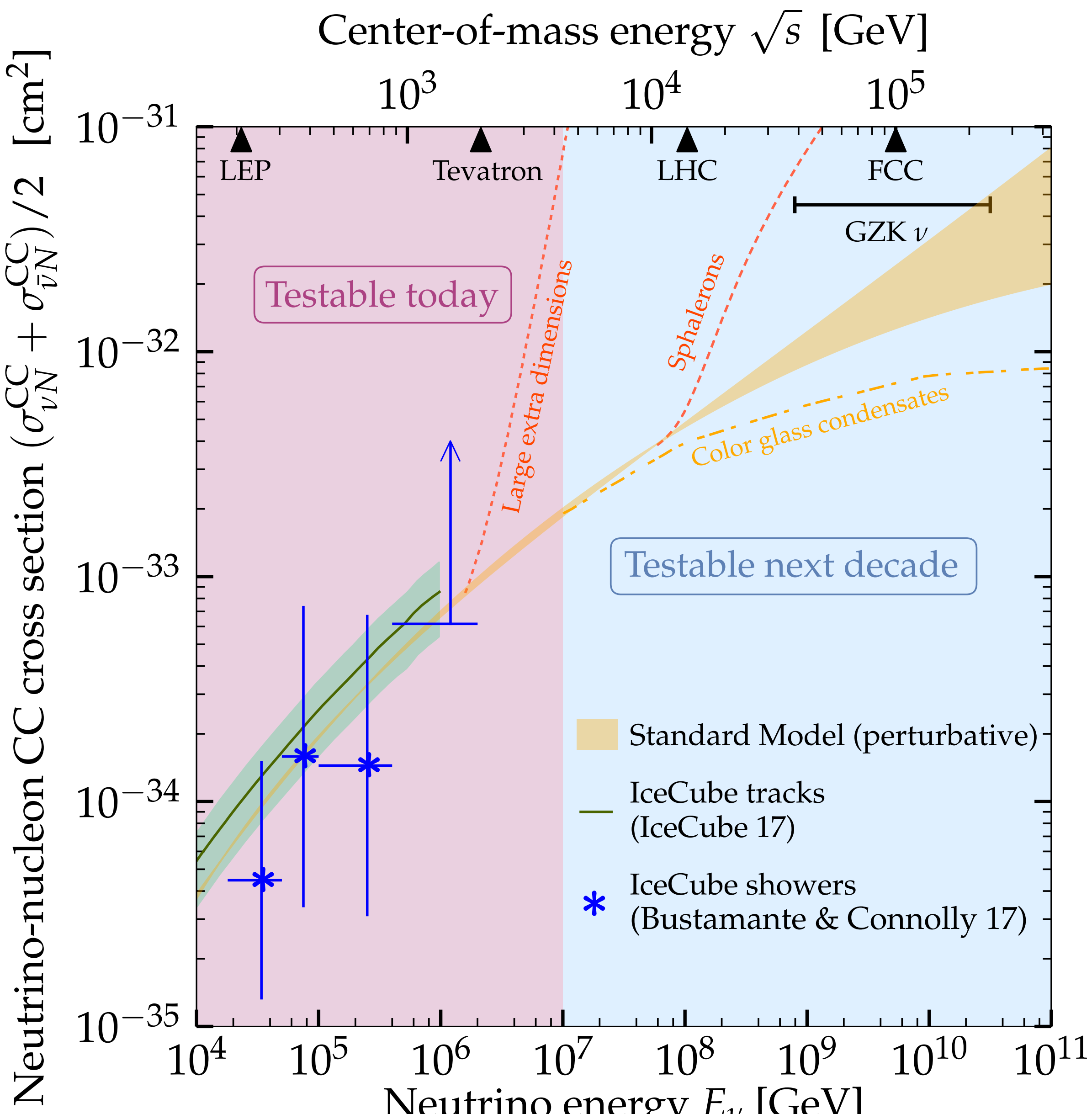

[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04334]

# Probe of Fundamental Physics

Probe of exotic neutrino mixing, e.g. in **Lorentz-invariance violating** extensions of the neutrino Standard Model.

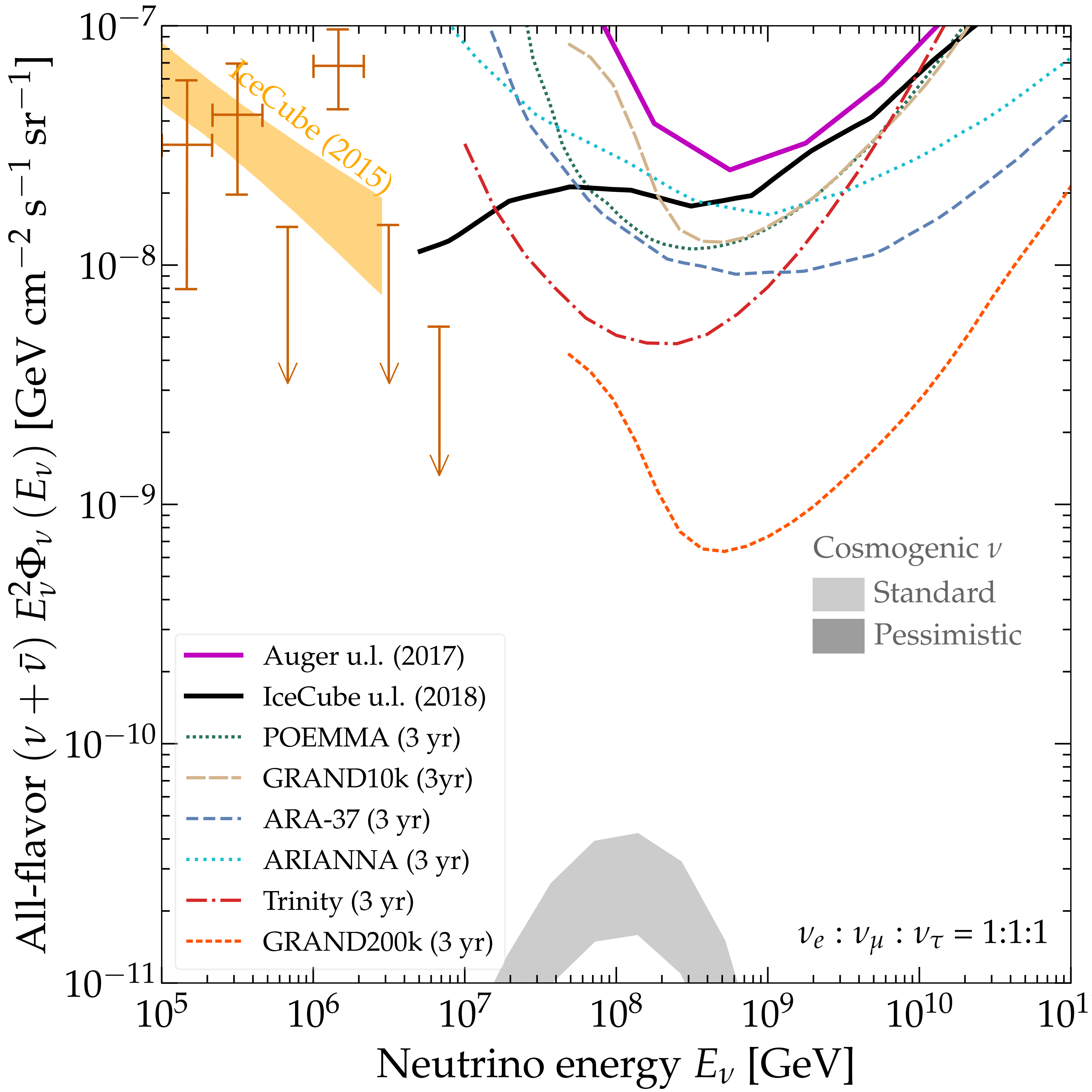



Probe of **neutrino-nucleon cross sections** at very-high energies.




[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04333 & arXiv:1903.04334]

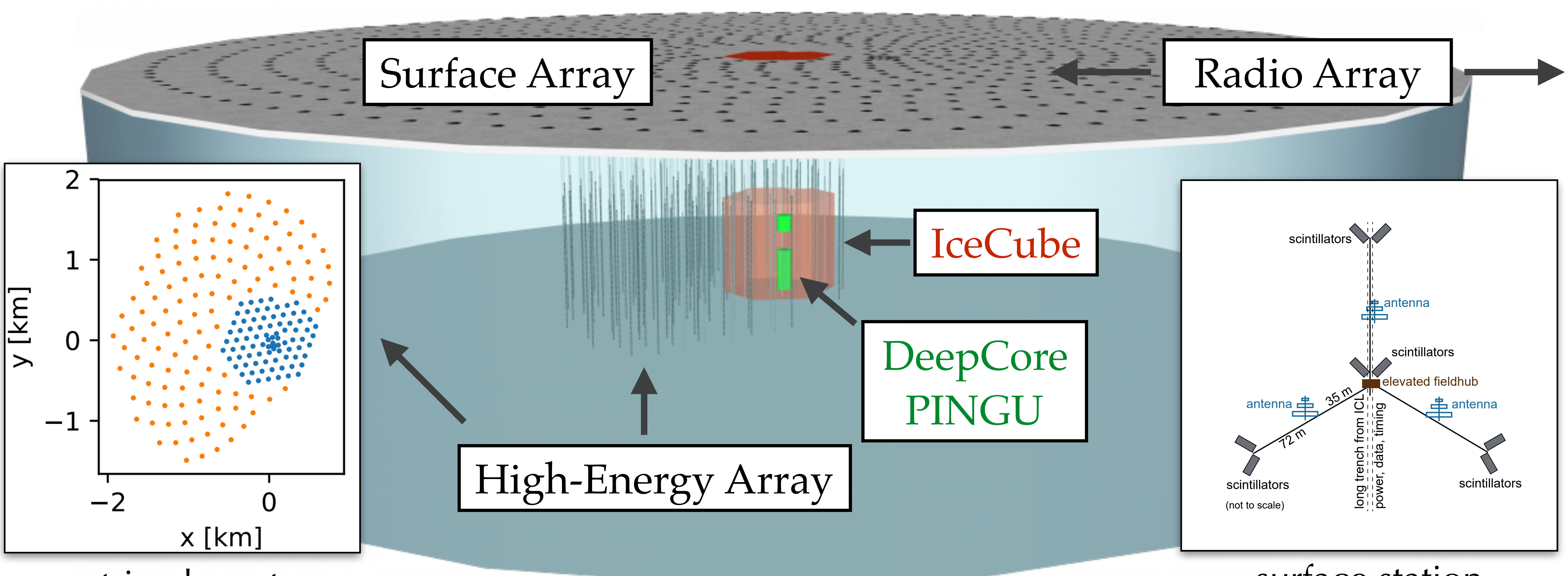
- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
  [Berezinsky&Zatsepin'70]
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal energies.
  [e.g. MA *et al.*'10; MA & Halzen'12]
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.




[Alves Batista *et al.*'19]

# Vision: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillator panels & radio antennas) for cosmic ray veto
- **Askaryan radio array** for >10PeV neutrino detection

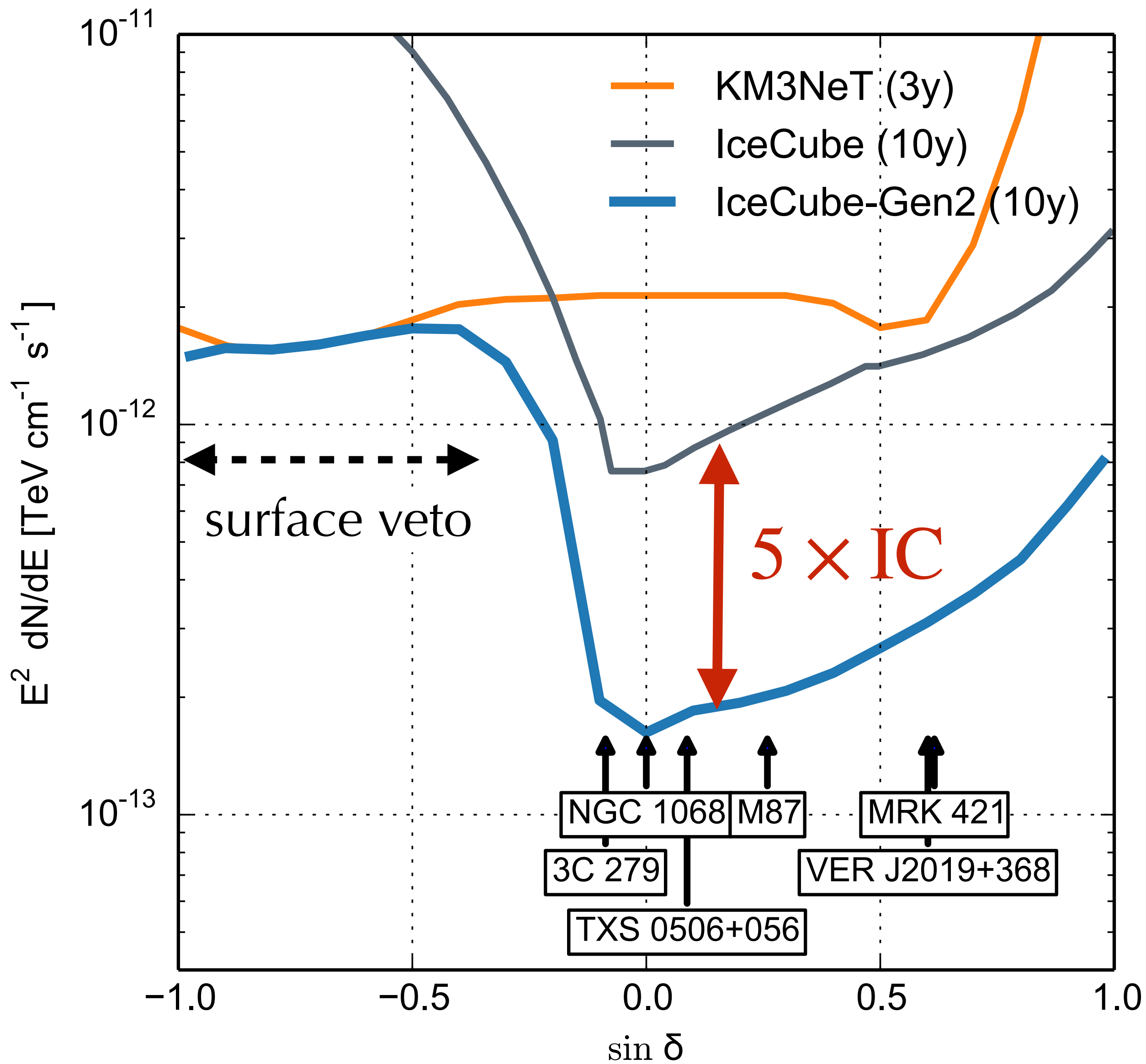



string layout

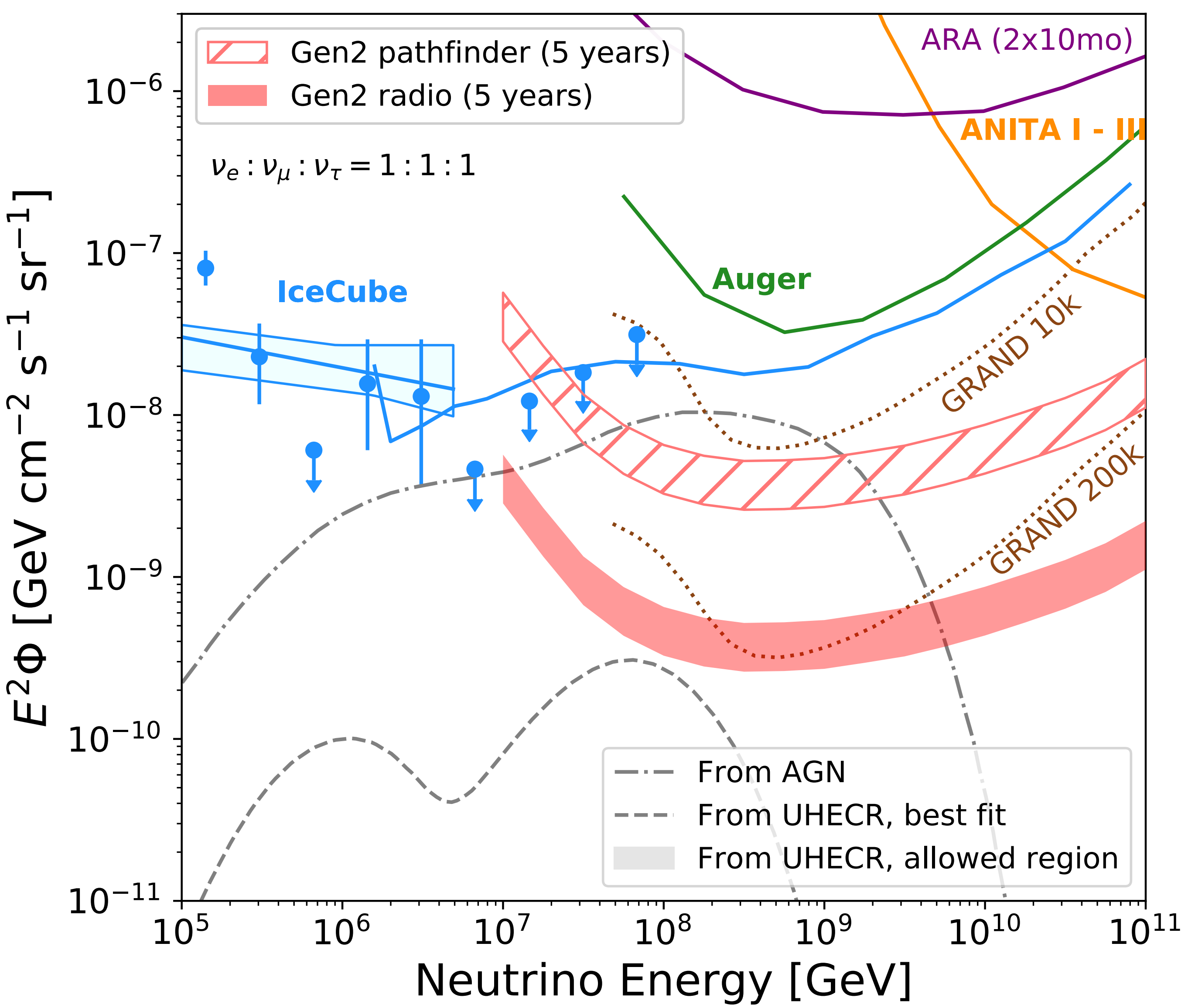
surface station

# Vision: IceCube-Gen2

**Improved sensitivity** for neutrino point sources to find the origin of the isotropic TeV-PeV flux




Precision measurement of **PeV-EeV neutrino fluxes** with extended in-ice optical and surface radio array



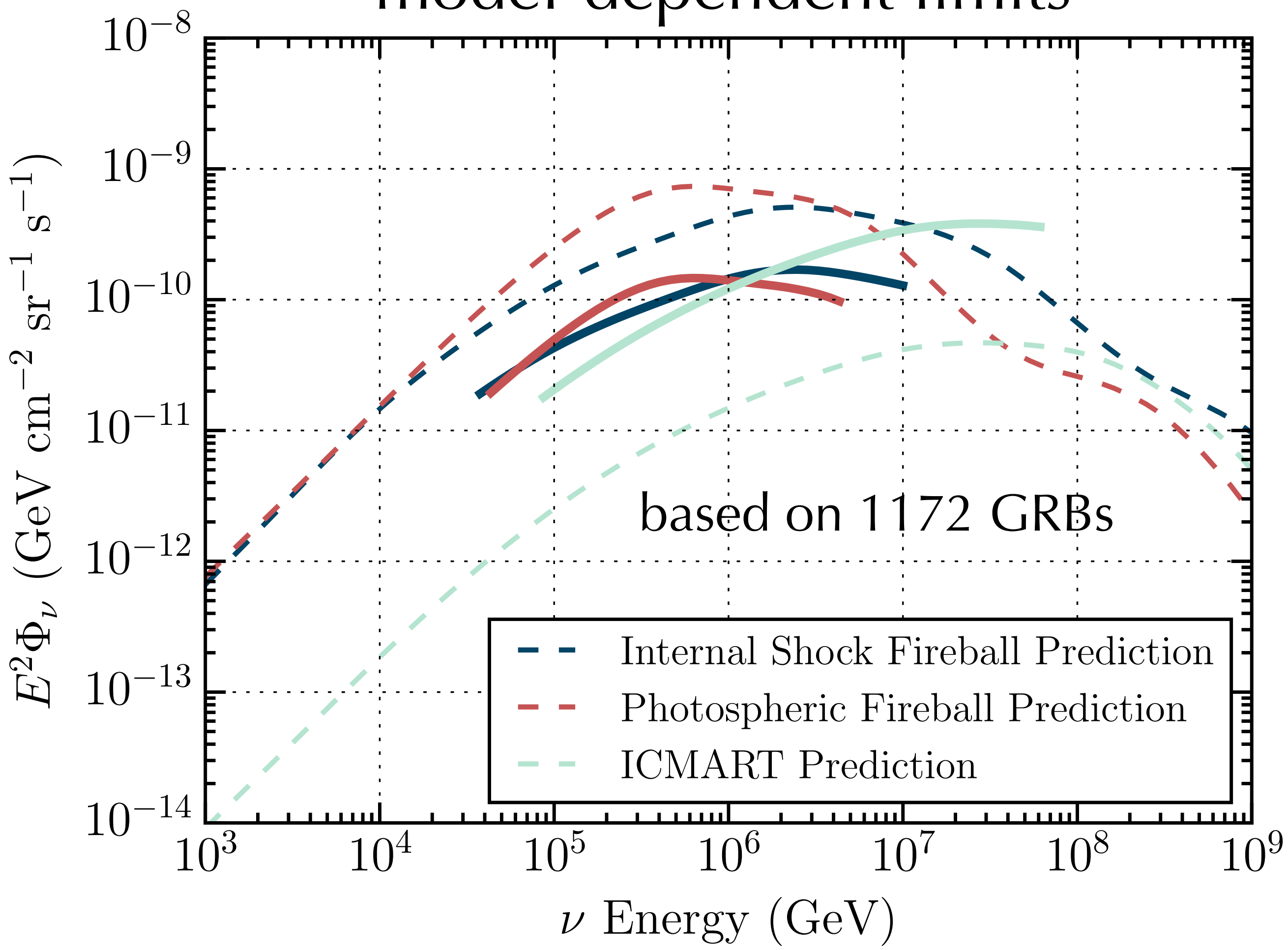
# Summary

- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**
  - *Consistent with point-source limits?*
  - *Consistent multi-messenger picture?*
- So far, **no significant point sources**, except blazar TXS 0506+056.
  - *Are there more sources like TXS?*
  - *How do we find them?*
- Essential for future discoveries are **multi-messenger partners** facilitating low-latency studies.
  - *Fermi-LAT, Magic, H.E.S.S., HAWC, Swift-XRT, VERITAS, LIGO/Virgo,…*
- In parallel, development of **next-generation neutrino telescopes** with increased sensitivity and energy coverage.

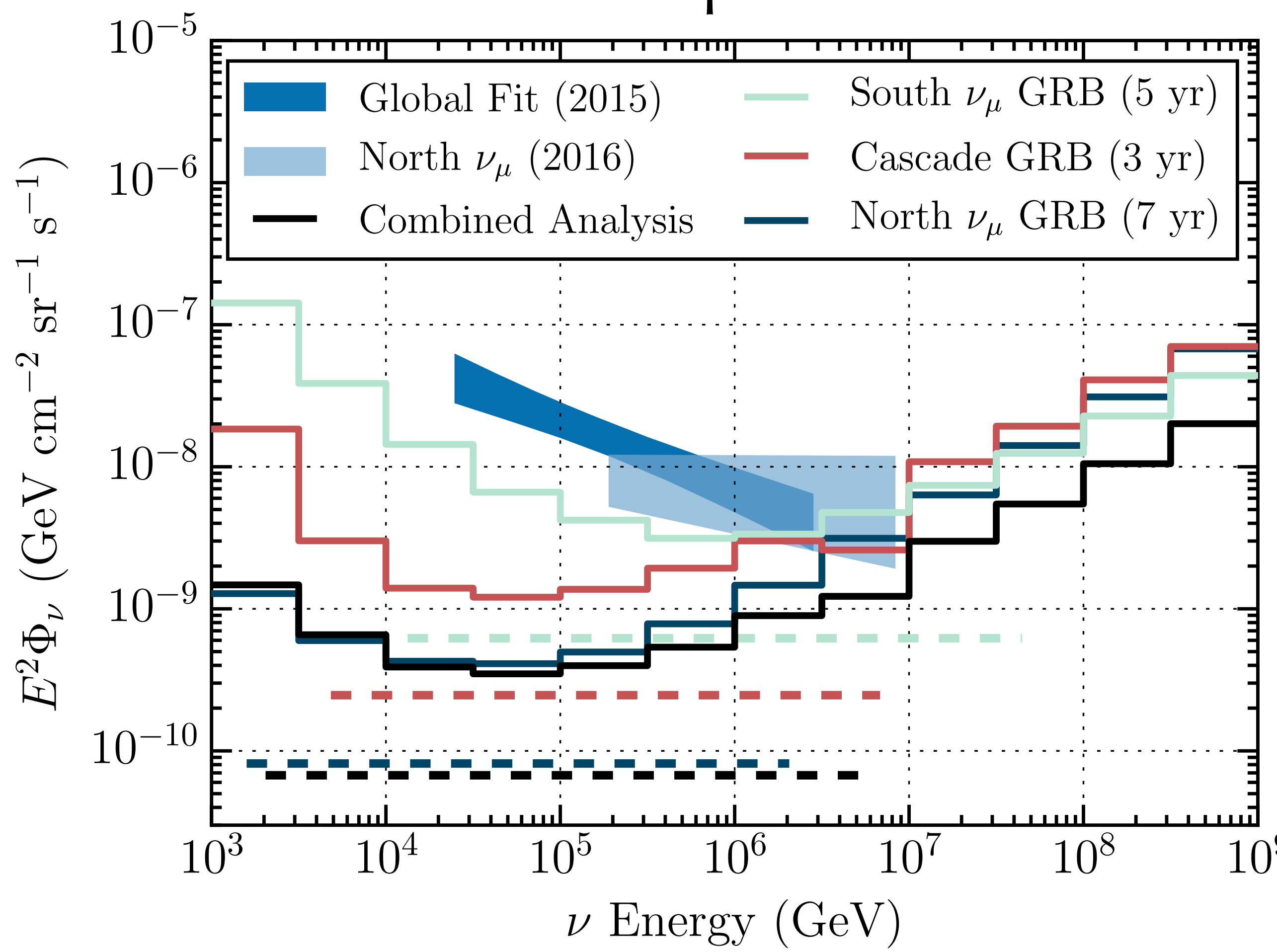
# Backup Slides

- IceCube routinely follows up on $\gamma$-ray bursts. [IceCube, ApJ 843 (2017) 2]
- Search is most sensitive to "prompt" (<100s) neutrino emission.
- Neutrino predictions based on the assumption of **cosmic ray acceleration in internal shocks**. [Waxman & Bahcall '97]

model-dependent limits




model-independent limits

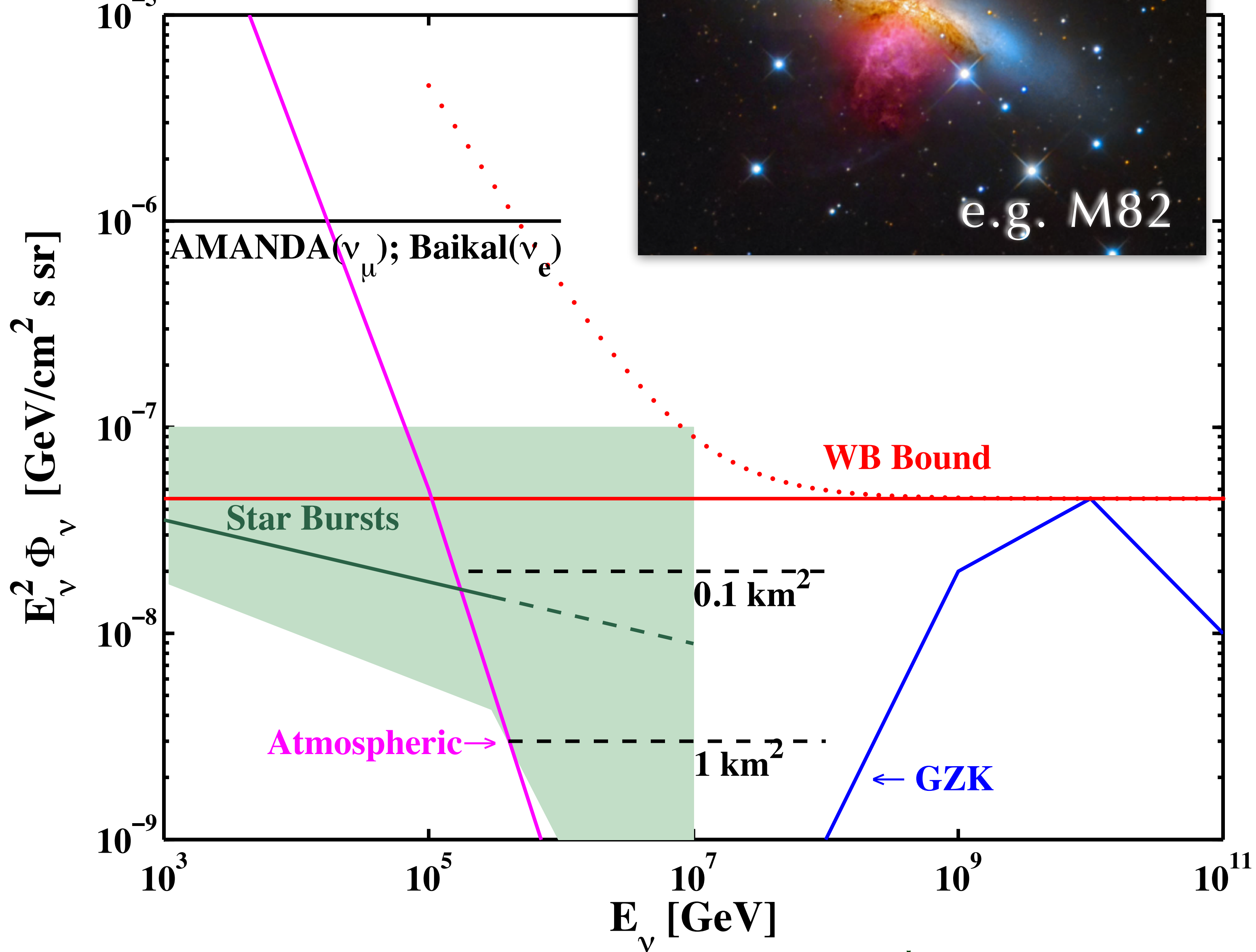


# Starburst Galaxies

- **Intense star formation enhances UHE CR production**, e.g. by gamma-ray bursts.
- Low-energy cosmic rays remain magnetically confined and eventually **collide in dense environment**.
- In time, efficient **conversion of CR energy density into gamma-rays and neutrinos**.

[Loeb & Waxman '06]

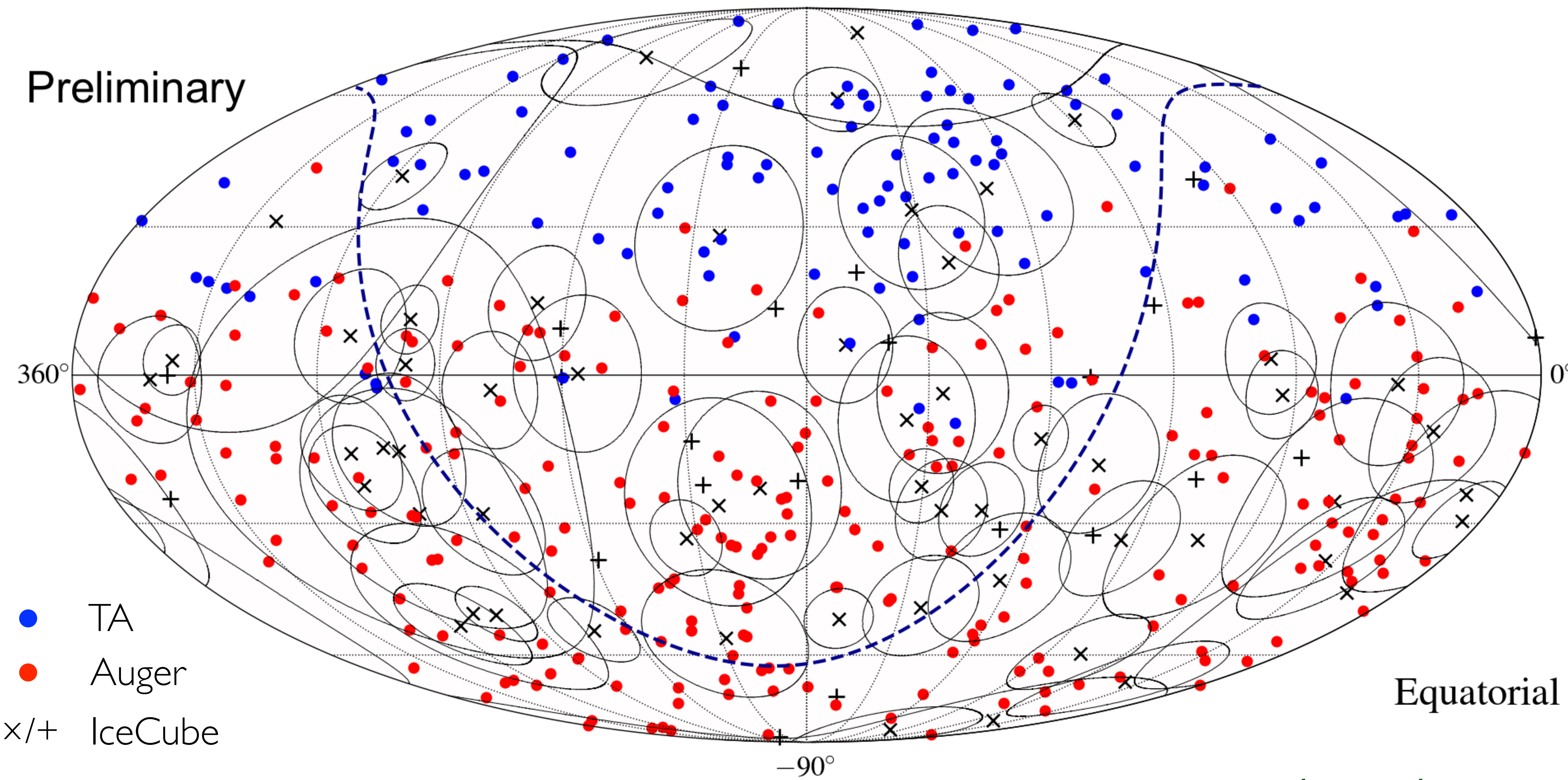
- Expect power-law neutrino spectra with high-energy break from CR leakage.


[Loeb & Waxman '06]

# UHE CR Composition

- **No significant cross-correlation** found between UHE CRs and HE neutrinos.
- Galactic and extragalactic magnetic fields can introduce **significant angular deflections and time delays:** $\Delta t \simeq d(\Delta\psi)^2$
- Maximal cross-correlation **limited by GZK horizon** : $\lambda_{\rm GZK}/\lambda_{\rm Hubble} \simeq 5\,\%$




[Auger, IceCube & Telescope Array'17]

# Cosmic Ray Calorimeters

- UHE CR proton emission rate density: [e.g. MA & Halzen'12]

$$[E_p^2 Q_p(E_p)]_{10^{19.5}\mathrm{eV}} \simeq 8 \times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- neutrino flux can be estimated as ($\xi_z$ : factor accounting for redshift evolution) :

$$E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}}_{\sim \text{ IceCube diffuse}}$$

➜ limited by pion production efficiency: $f_\pi \leq 1$ [Waxman & Bahcall'98]

- **similar** UHE nucleon emission rate density (local minimum at $\Gamma \simeq 2.04$) [Auger'16]

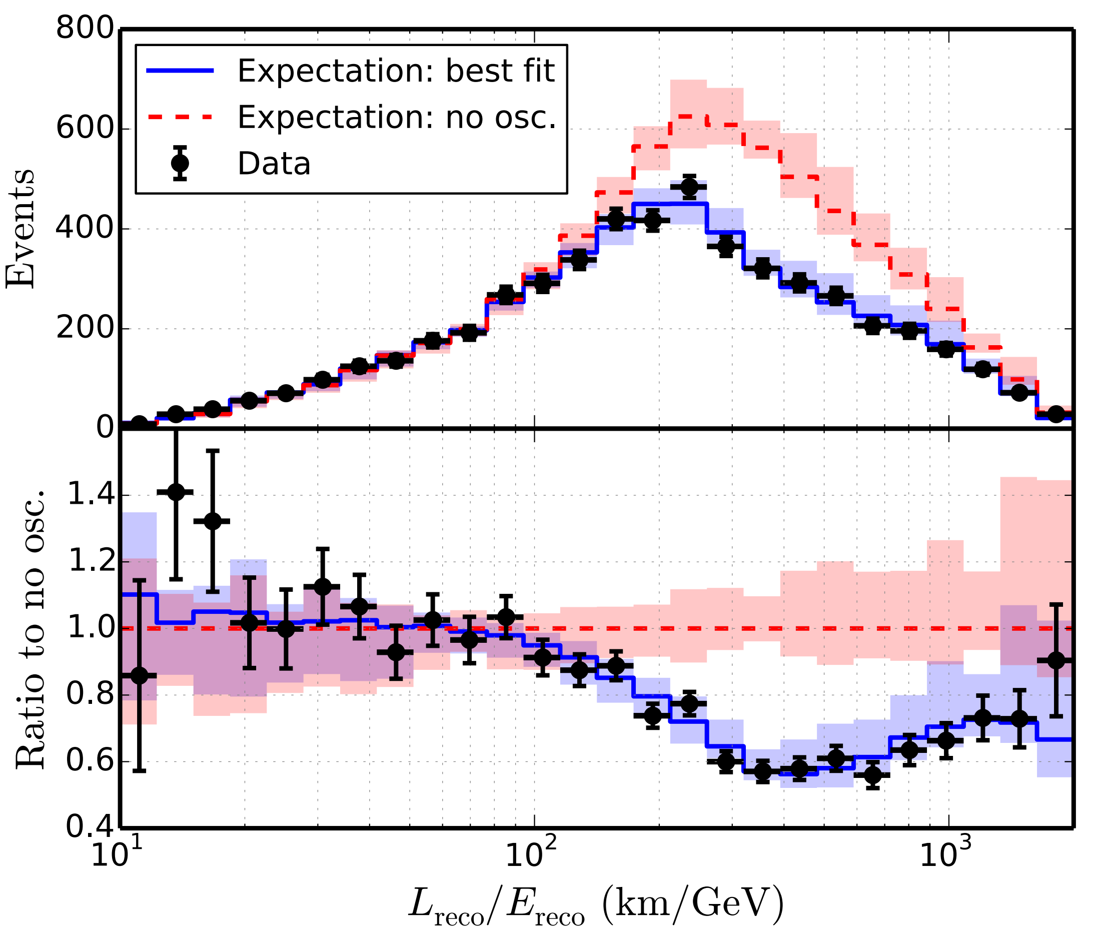
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

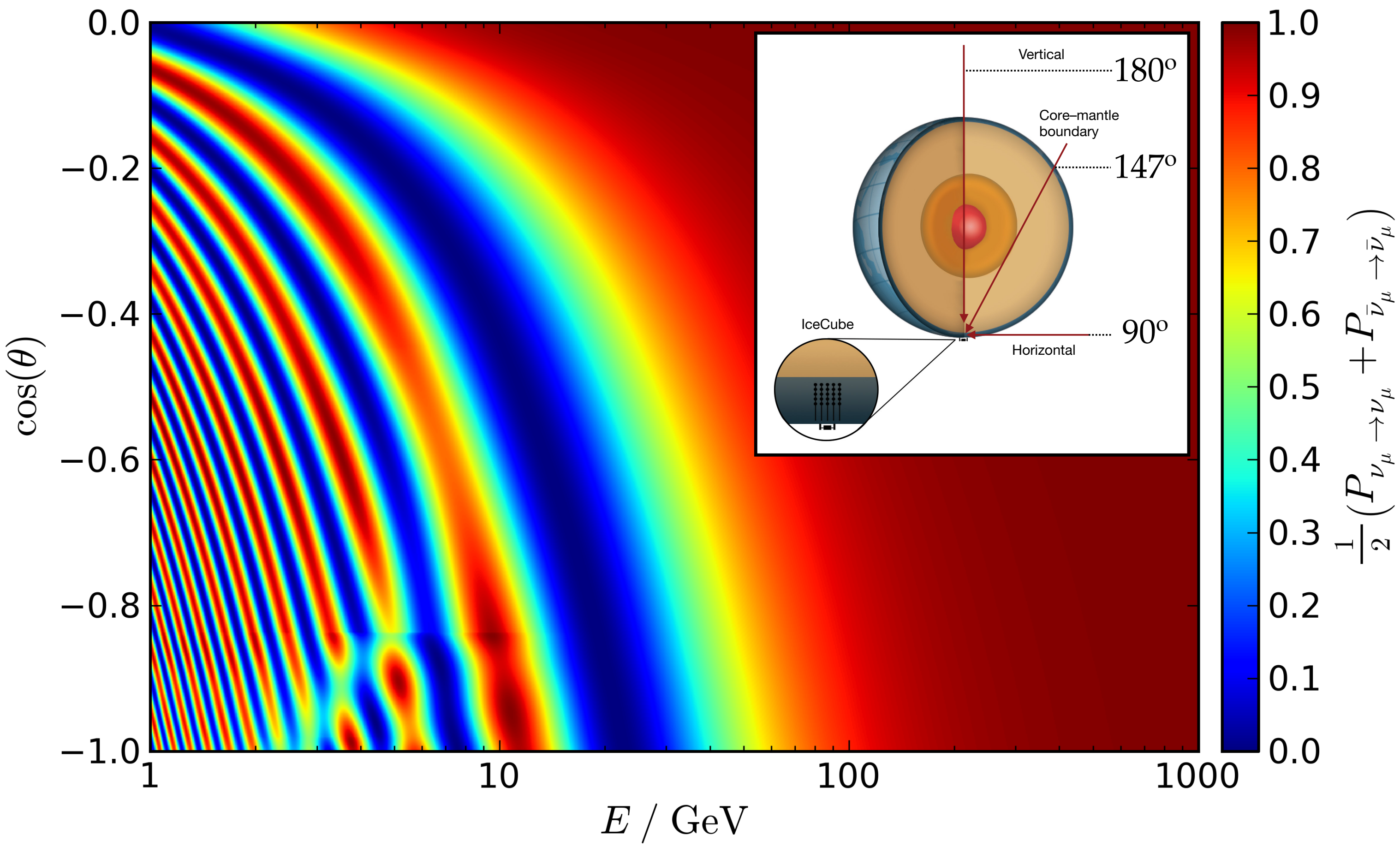
- Sources of UHECRs could be embedded in "calorimetric" environments ($f_\pi = 1$), producing a large flux of neutrinos, *e.g.*, **starburst galaxies** or **galaxy clusters**.

# Atmospheric Neutrino Oscillations

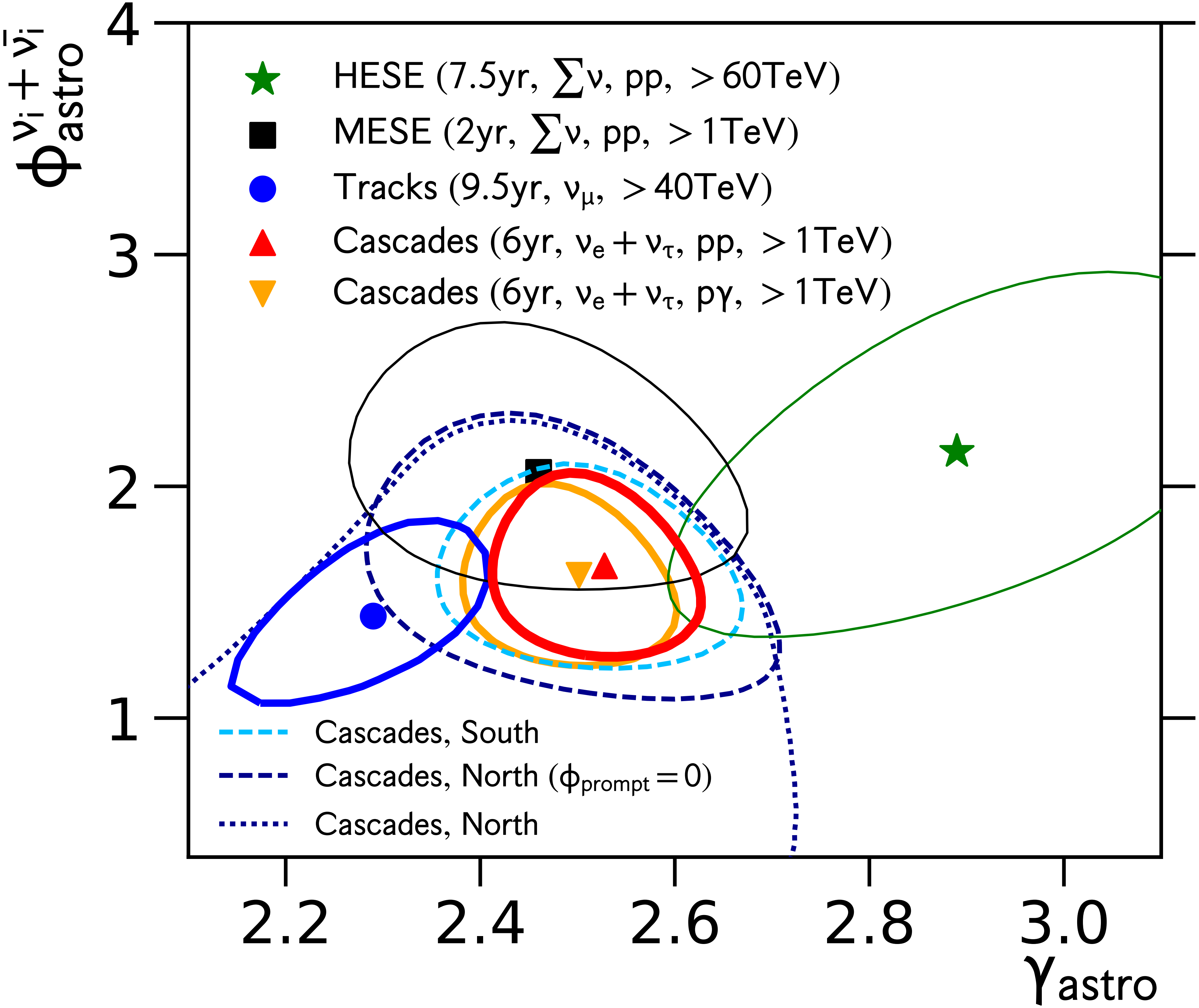
- Atmospheric neutrinos with energy E are observed with different zenith angles that correspond to different oscillation baselines L (*lower right plot*).
- Arranging the data into bins of L/E one can study the **disappearance** of atmospheric neutrinos (*lower left plot*):

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



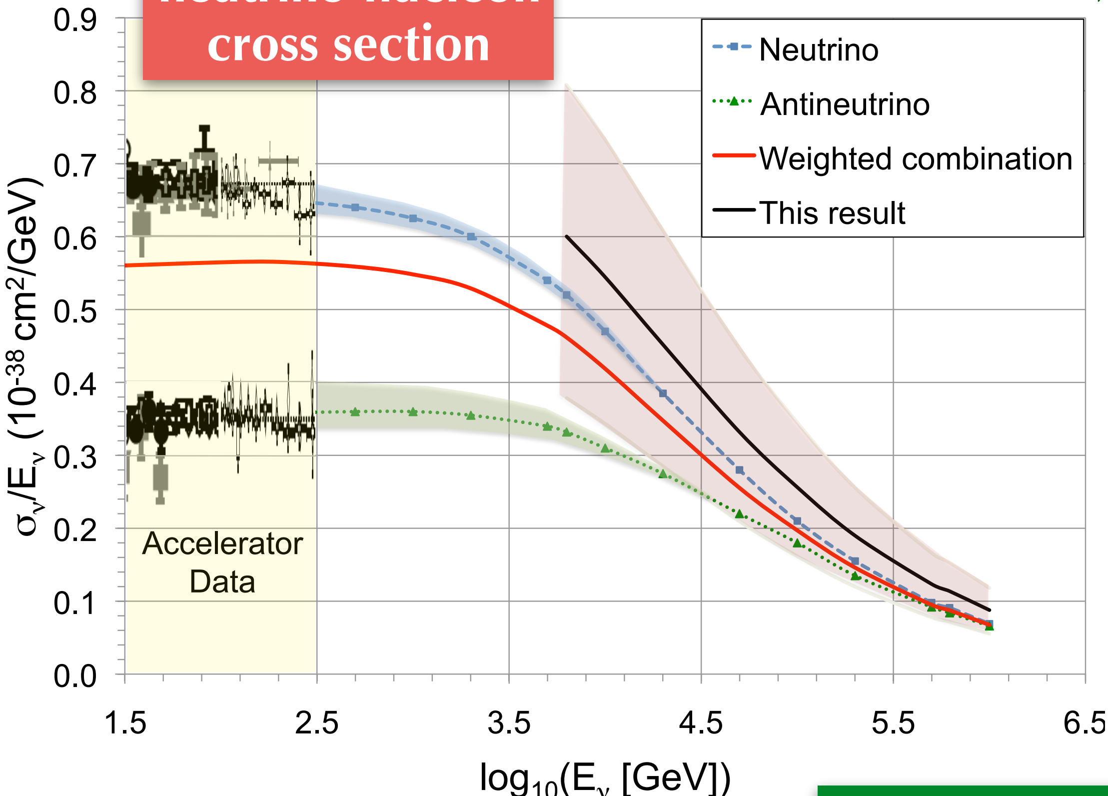
# Power-Law Fits

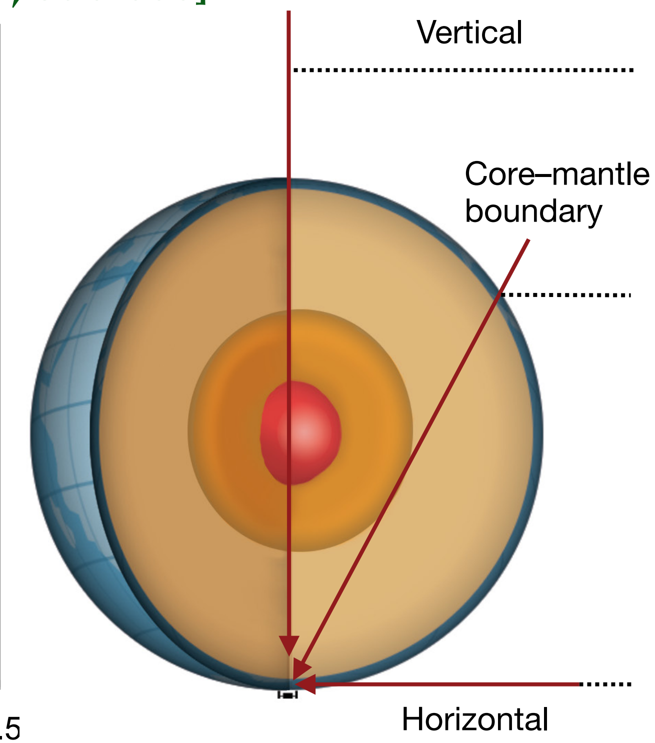


# Neutrino Physics

**neutrino-nucleon cross section**

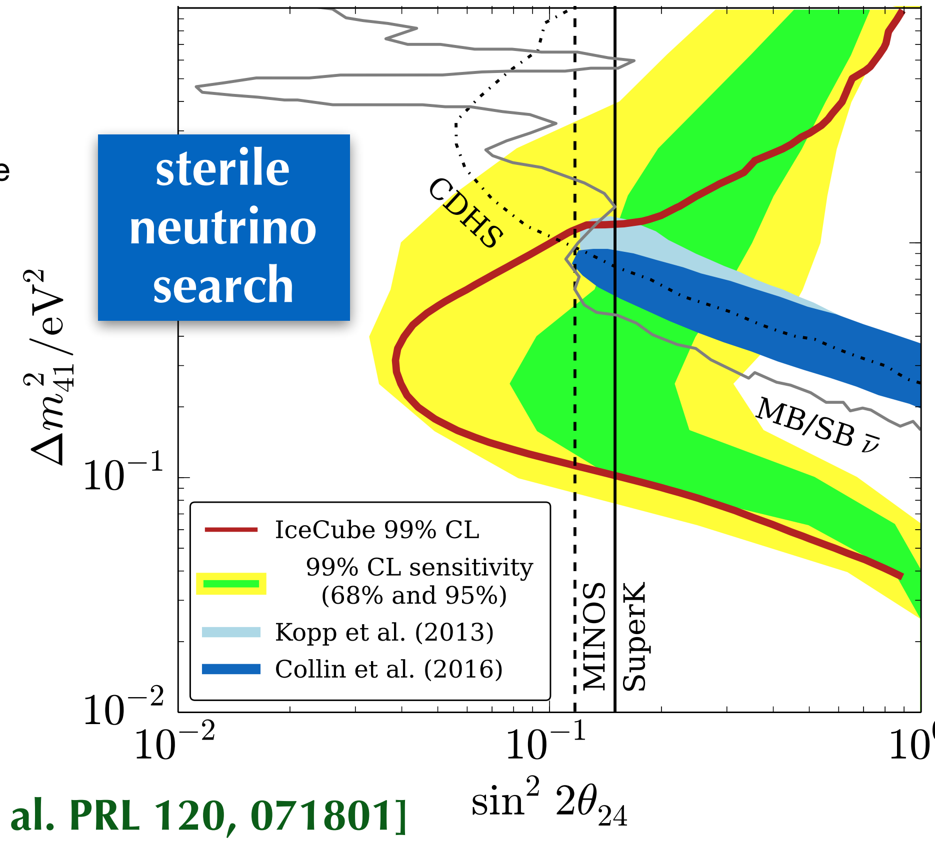
[Aartsen et al. Nature 551, 596-600]



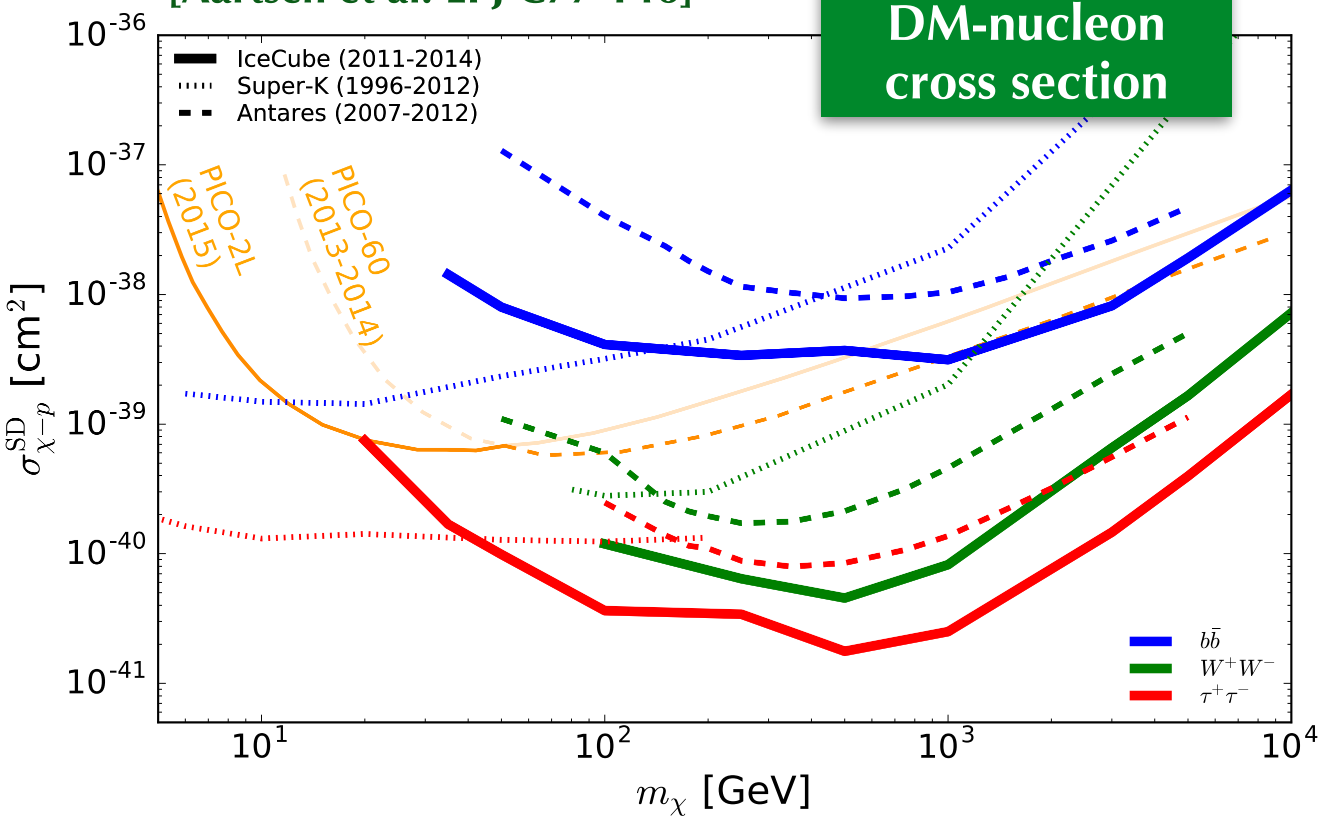

**sterile neutrino search**

[Aartsen et al. PRL 117, 071801]



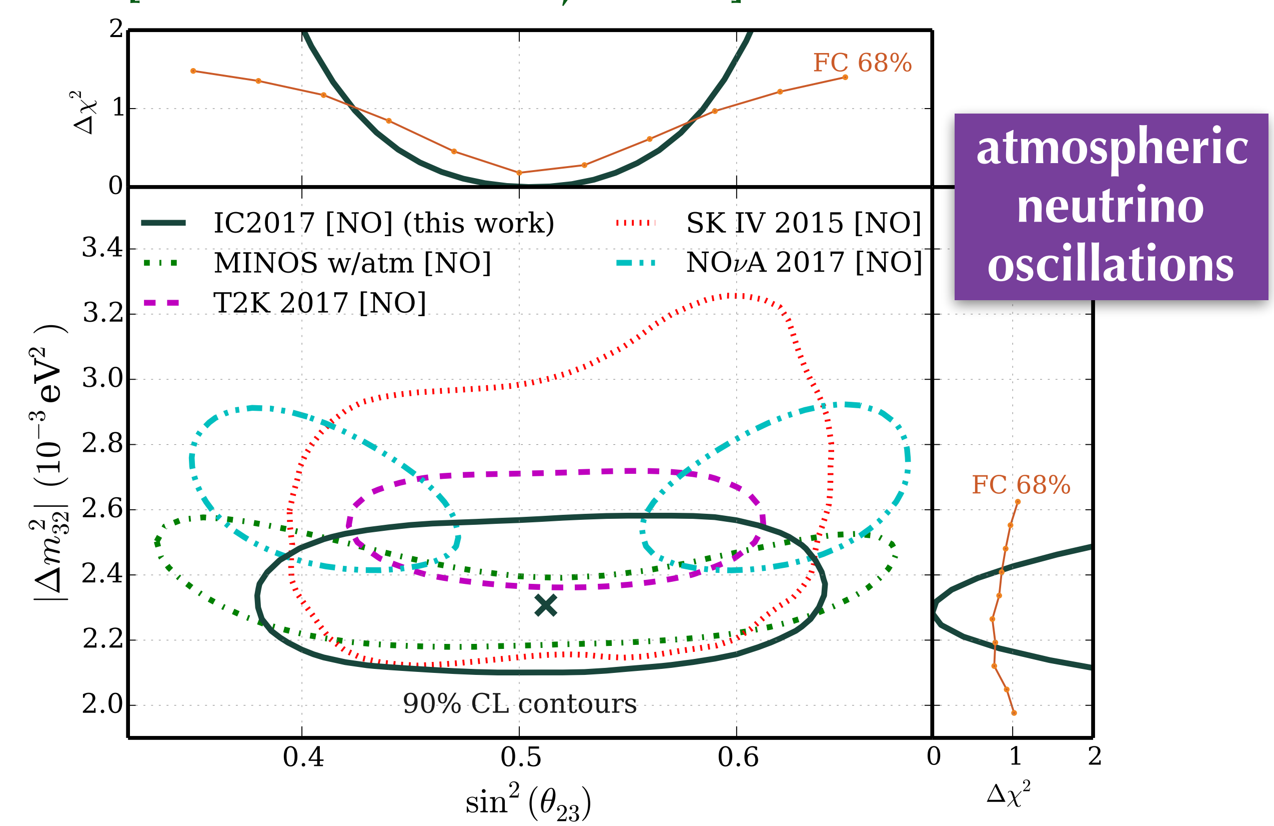

**spin-dependent DM-nucleon cross section**

[Aartsen et al. EPJ C77 146]

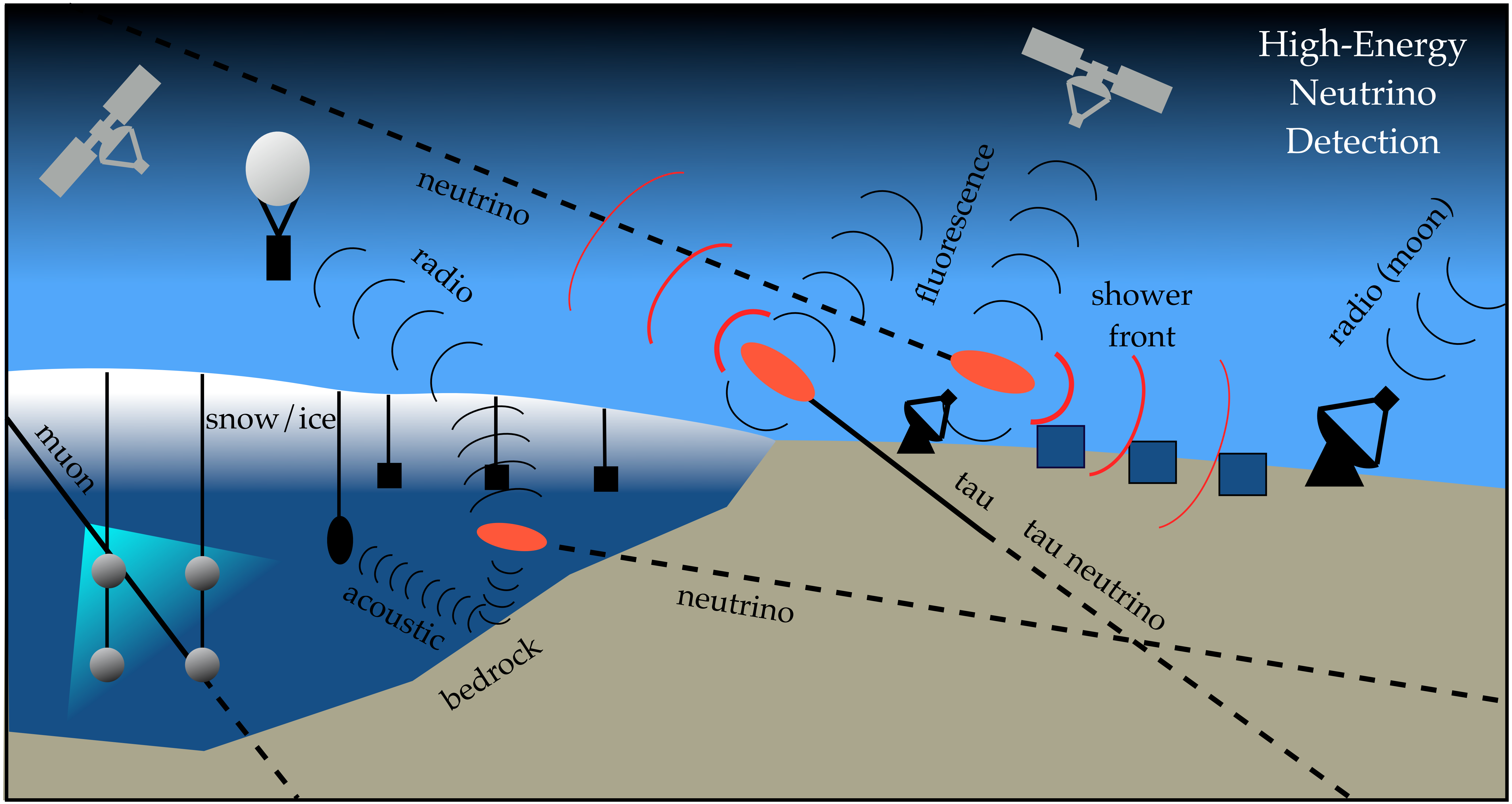



**atmospheric neutrino oscillations**

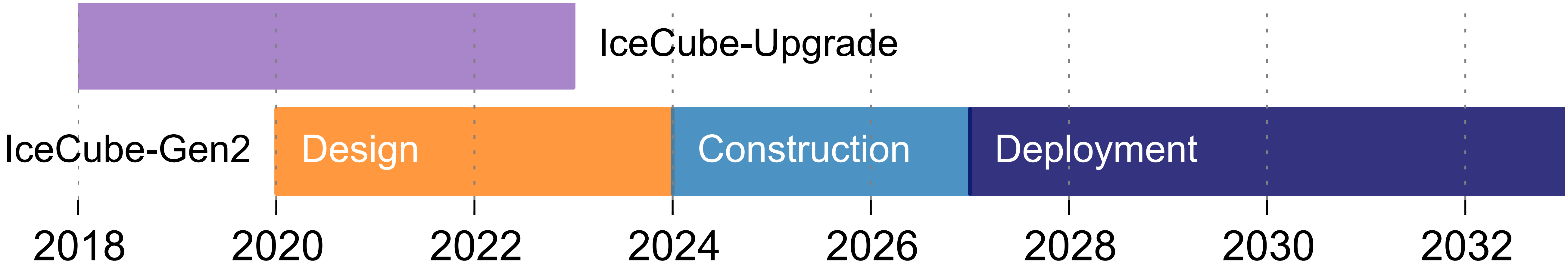
[Aartsen et al. PRL 120, 071801]

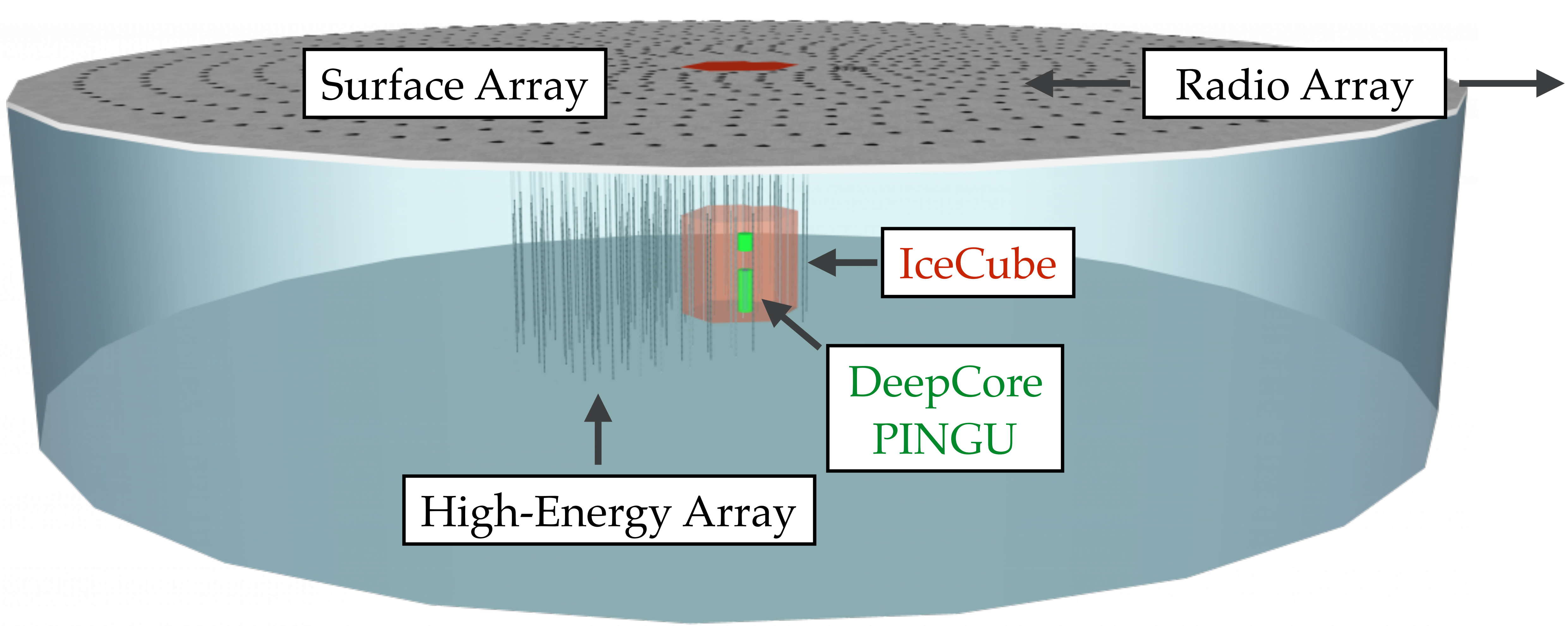


# Detection Principles



# IceCube-Gen2 Timeline



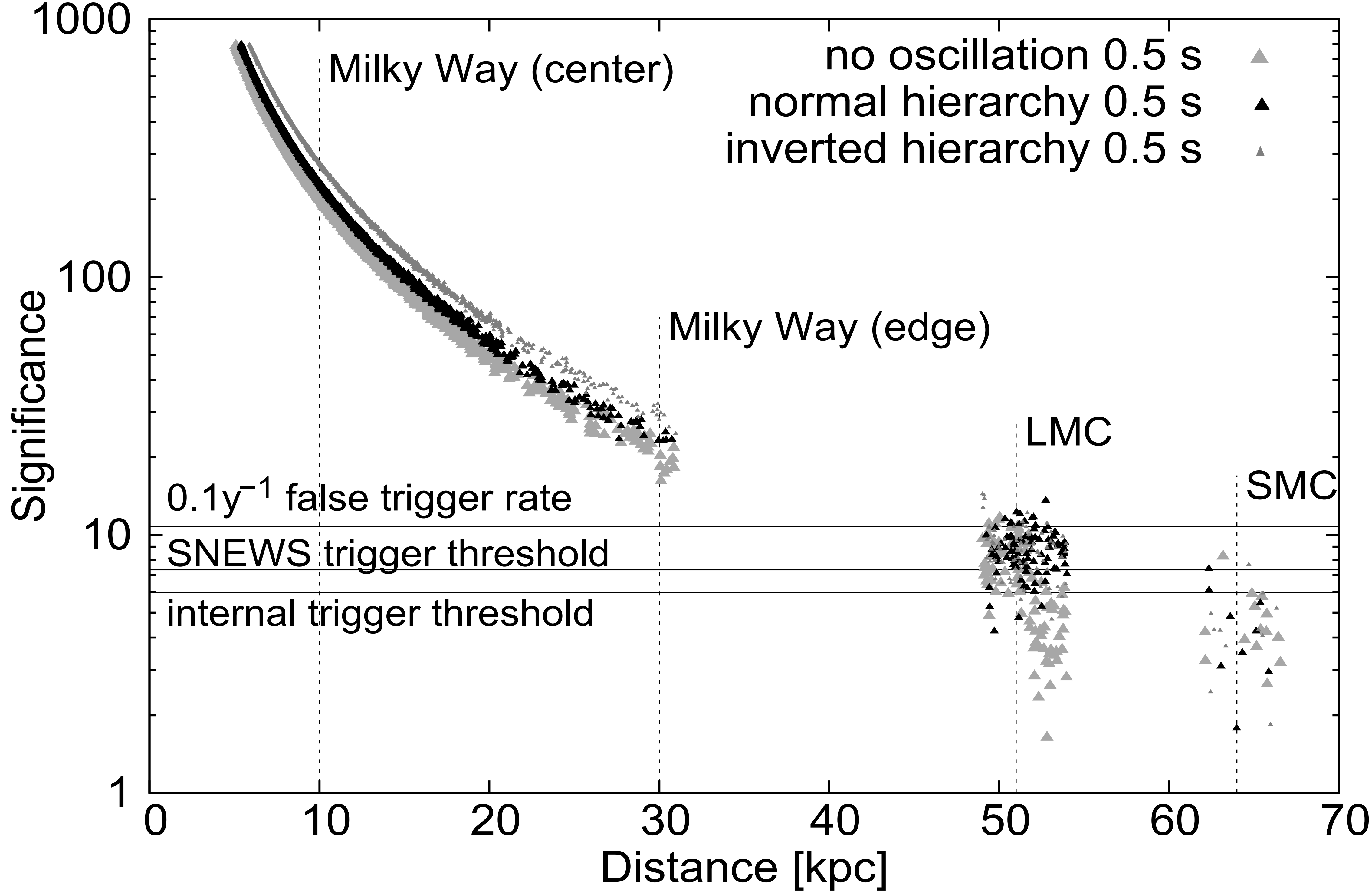



# Supernova Forecast

From K. Scholberg, J. Phys G 45:2017

| Detector | Type | Mass (kt) | Location | Events [10 kpc] |
|---|---|---|---|---|
| **IceCube** | **long string** | **600** | **South Pole** | **1,000,000** |
| *Hyper-K** | $H_2O$ | *374* | *Japan* | *75,000* |
| *DUNE** | *Ar* | *40* | *USA* | *3,000* |
| Super-K | $H_2O$ | 32 | Japan | 7,000 |
| *JUNO** | $C_nH_{2n}$ | *20* | *China* | *6,000* |
| NOvA | $C_nH_{2n}$ | 15 | USA | 4,000 |
| LVD | $C_nH_{2n}$ | 1 | Italy | 300 |
| KamLAND | $C_nH_{2n}$ | 1 | Japan | 300 |
| SNO+ | $C_nH_{2n}$ | 0.8 | Canada | 300 |
| Baksan | $C_nH_{2n}$ | 0.33 | Russia | 50 |
| Daya Bay | $C_nH_{2n}$ | 0.33 | China | 100 |
| Borexino | $C_nH_{2n}$ | 0.3 | Italy | 100 |
| MicroBooNE | Ar | 0.17 | USA | 17 |
| HALO | Pb | 0.08 | Canada | 30 |

# Supernova Neutrino Detection



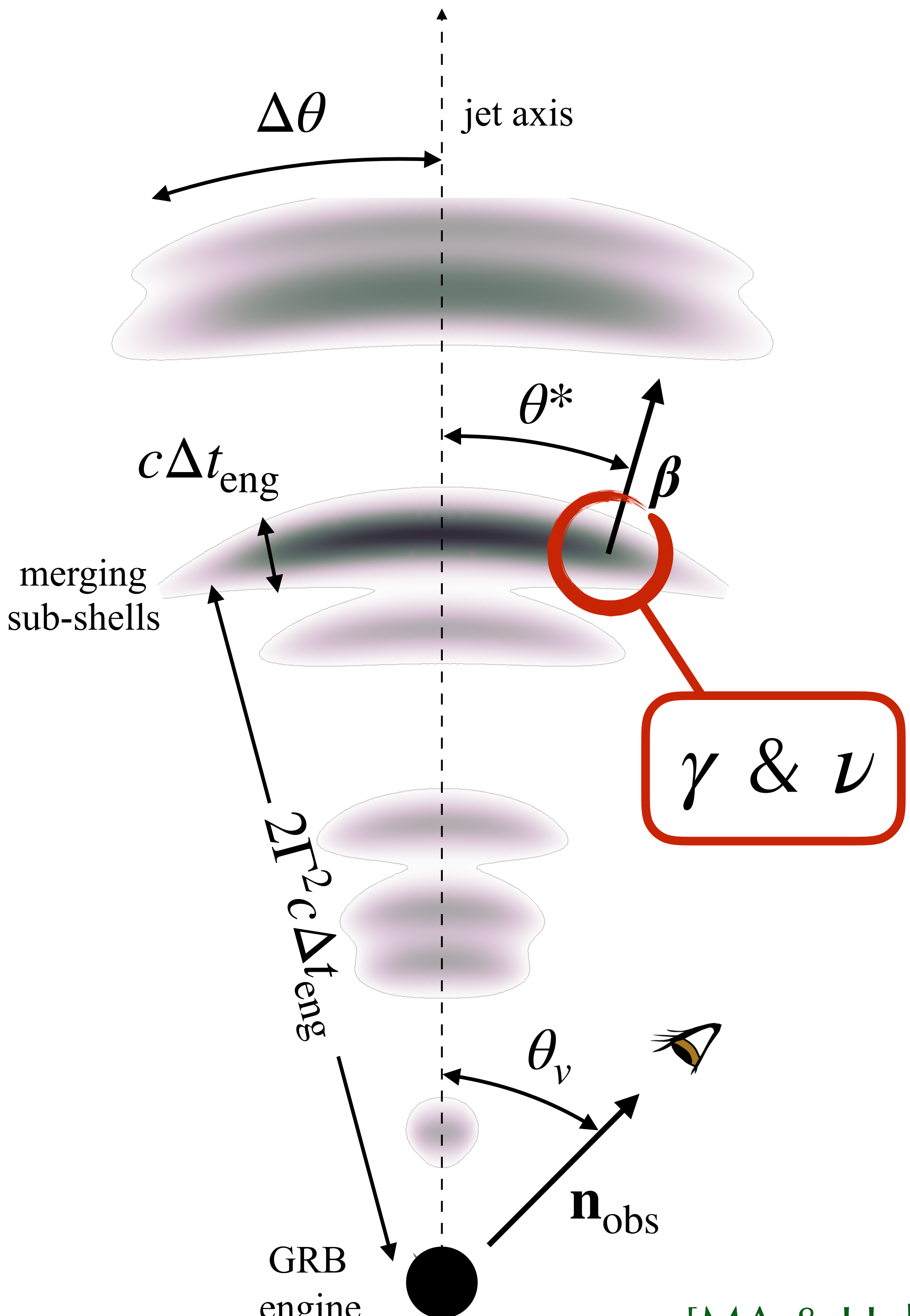
# Supernova Neutrino Detection

| Reaction | # Targets | # Signal Hits | Signal Fraction | Reference |
|---|---|---|---|---|
| $\bar{\nu}_e + p \rightarrow e^+ + n$ | $6 \cdot 10^{37}$ | 134 k (157 k) | 93.8 % (94.4 %) | Strumia & Vissani (2003) |
| $\nu_e + e^- \rightarrow \nu_e + e^-$ | $3 \cdot 10^{38}$ | 2.35 k (2.25 k) | 1.7 % (1.4 %) | Marciano & Parsa (2003) |
| $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ | $3 \cdot 10^{38}$ | 660 (720) | 0.5 % (0.4 %) | Marciano & Parsa (2003) |
| $\nu_{\mu+\tau} + e^- \rightarrow \nu_{\mu+\tau} + e^-$ | $3 \cdot 10^{38}$ | 700 (720) | 0.5 % (0.4 %) | Marciano & Parsa (2003) |
| $\bar{\nu}_{\mu+\tau} + e^- \rightarrow \bar{\nu}_{\nu+\tau} + e^-$ | $3 \cdot 10^{38}$ | 600 (570) | 0.4 % (0.4 %) | Marciano & Parsa (2003) |
| $\nu_e + {}^{16}O \rightarrow e^- + X$ | $3 \cdot 10^{37}$ | 2.15 k (1.50 k) | 1.5 % (0.9 %) | Kolbe et al. (2002) |
| $\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$ | $3 \cdot 10^{37}$ | 1.90 k (2.80 k) | 1.3 % (1.7 %) | Kolbe et al. (2002) |
| $\nu_{all} + {}^{16}O \rightarrow \nu_{all} + X$ | $3 \cdot 10^{37}$ | 430 (410) | 0.3 % (0.3 %) | Kolbe et al. (2002) |
| $\nu_e + {}^{17/18}O/{}^2_1H \rightarrow e^- + X$ | $6 \cdot 10^{34}$ | 270 (245) | 0.2 % (0.2 %) | Haxton (1999) |

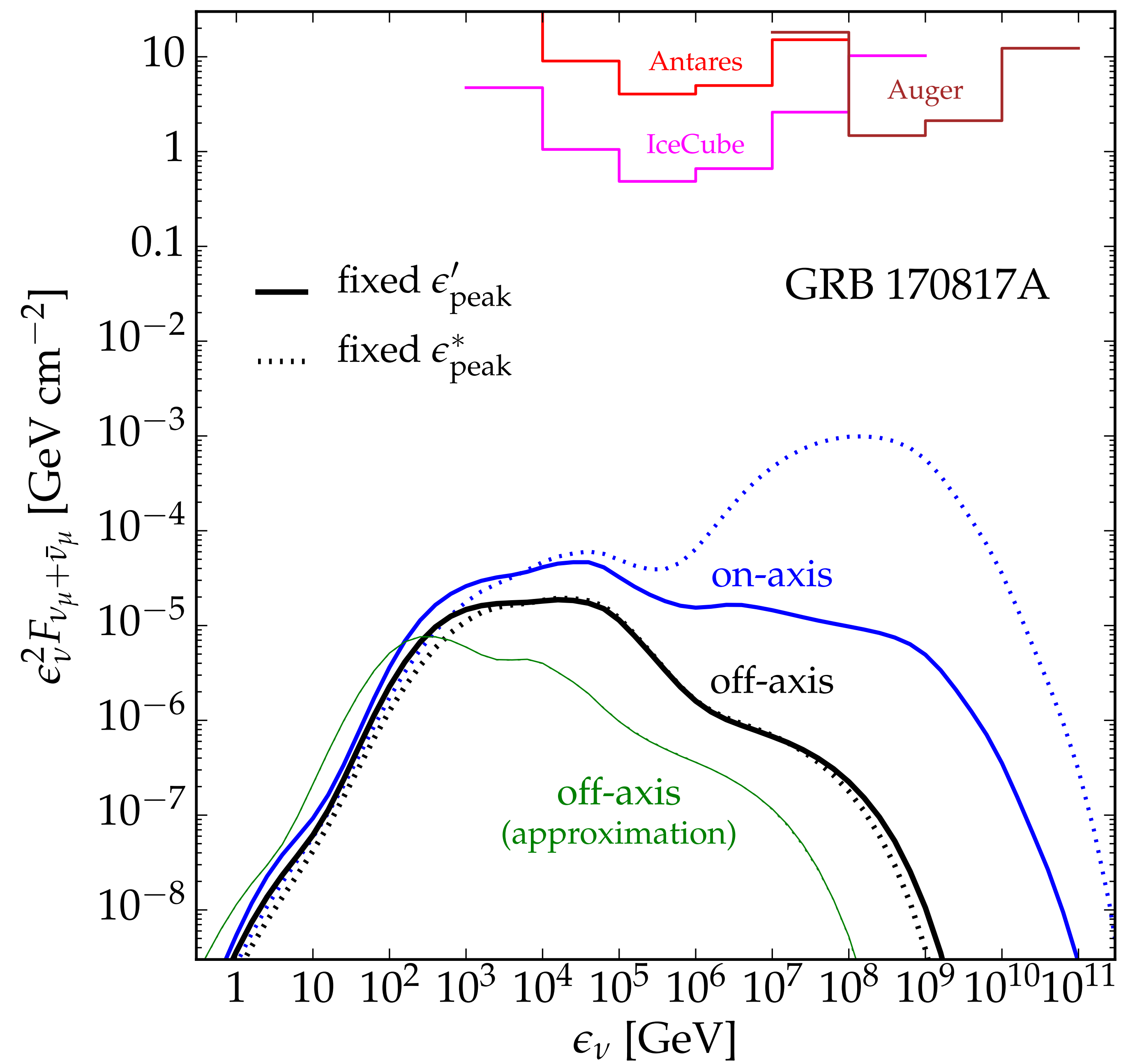
**Notes.** The approximate number of targets in a 1 $km^3$ ice detector, the detected number of hits at 10 kpc distance and their fraction in stars are given in the second, third and fourth column, respectively. In order to indicate the effect of neutrino oscillations in the star, signal hits and fractions are presented both assuming a normal neutrino hierarchy (Scenario A) and - in brackets - assuming an inverted hierarchy (Scenario B). The numbers are taken from the Garching model using the equation of state by Lattimer & Swesty (1991) and averaging over 0.8 s.

| Model | Reference | Progenitor mass ($M_\odot$) | $\#\nu$'s $t < 380$ ms | $\#\nu$'s all times |
|---|---|---|---|---|
| "Livermore" | (Totani et al., 1997) | 20 | $0.174 \times 10^6$ | $0.79 \times 10^6$ |
| "Garching LS-EOS 1d" | (Kitaura et al., 2006) | 8 – 10 | $0.069 \times 10^6$ | - |
| "Garching WH-EOS 1d" | (Kitaura et al., 2006) | 8 – 10 | $0.078 \times 10^6$ | - |
| "Garching SASI 2d" | (Marek et al., 2009) | 15 | $0.106 \times 10^6$ | - |
| "1987A at 10 kpc" | (Pagliaroli et al., 2009b) | 15 – 20 | | $(0.57 \pm 0.18) \times 10^6$ |
| "O-Ne-Mg 1d" | (Hüdepohl et al., 2010) | 8.8 | $0.054 \times 10^6$ | $0.17 \times 10^6$ |
| "Quark Star (full opacities)" | (Dasgupta et al., 2010) | 10 | $0.067 \times 10^6$ | - |
| "Black Hole LS-EOS" | (Sumiyoshi et al., 2007) | 40 | $0.395 \times 10^6$ | $1.03 \times 10^6$ |
| "Black Hole SH-EOS" | (Sumiyoshi et al., 2007) | 40 | $0.335 \times 10^6$ | $3.40 \times 10^6$ |

**Notes.** Number of recorded DOM hits in IceCube ($\approx \#\nu$'s) for various models of the supernova collapse and progenitor masses assuming a distance of 10 kpc, approximately corresponding to the center of our Galaxy. A normal neutrino hierarchy is assumed.




Revised neutrino emission in the from **off-axis emission of structured jets.**

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# Very-High Energy Cosmic Rays