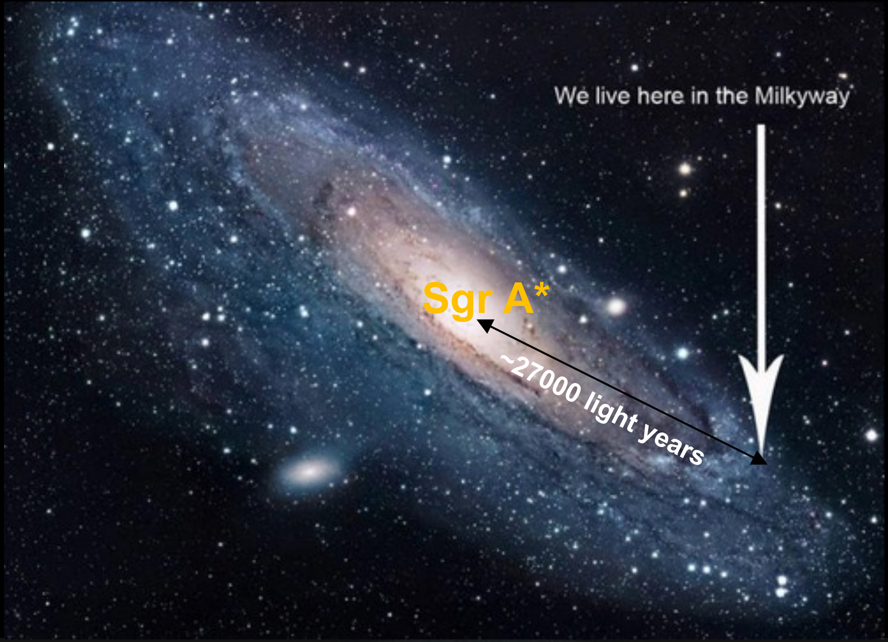
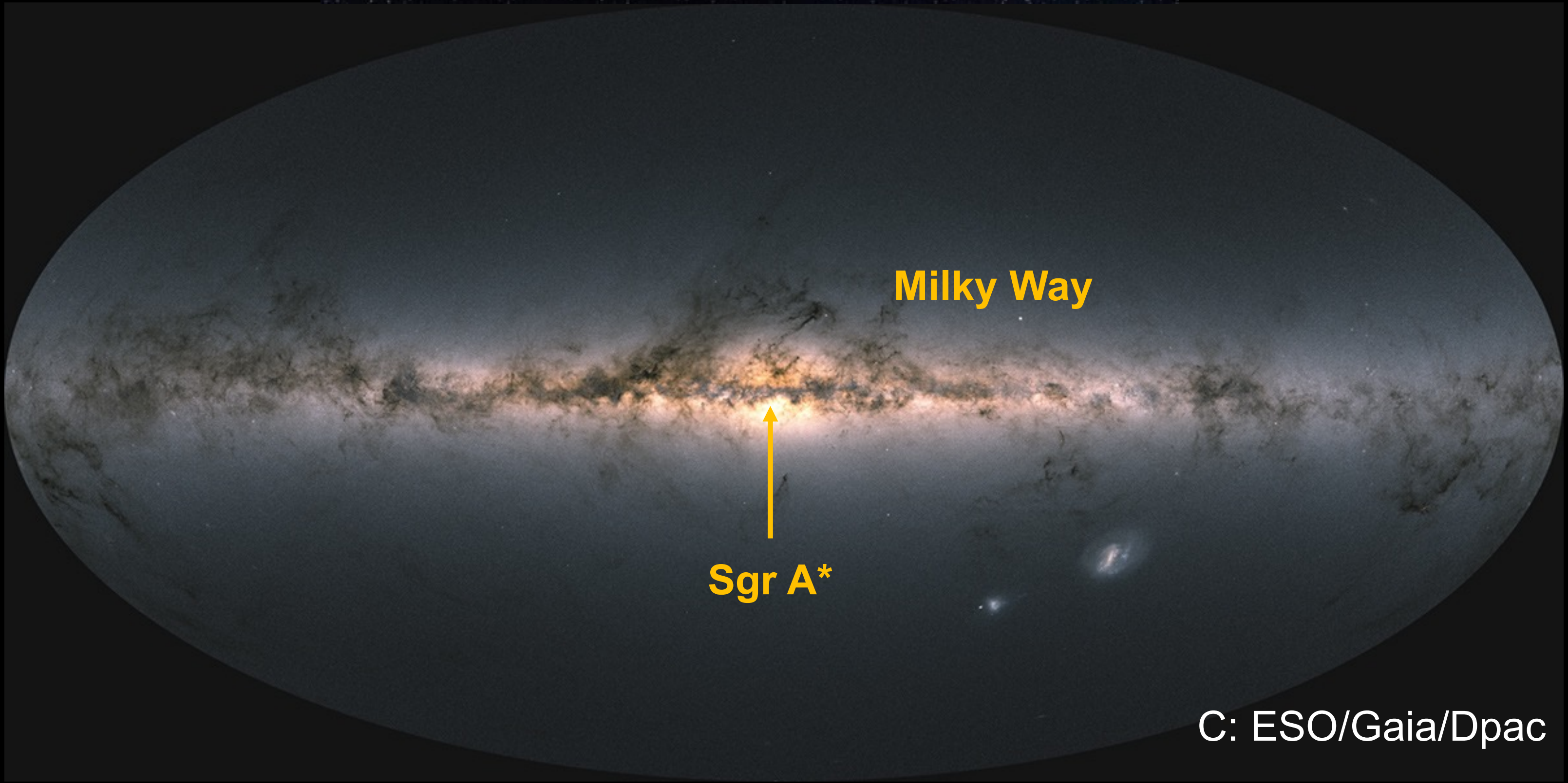
Multimessenger Perspectives on High-Energy Cosmic Neutrinos

Kohta Murase (Penn State/YITP)

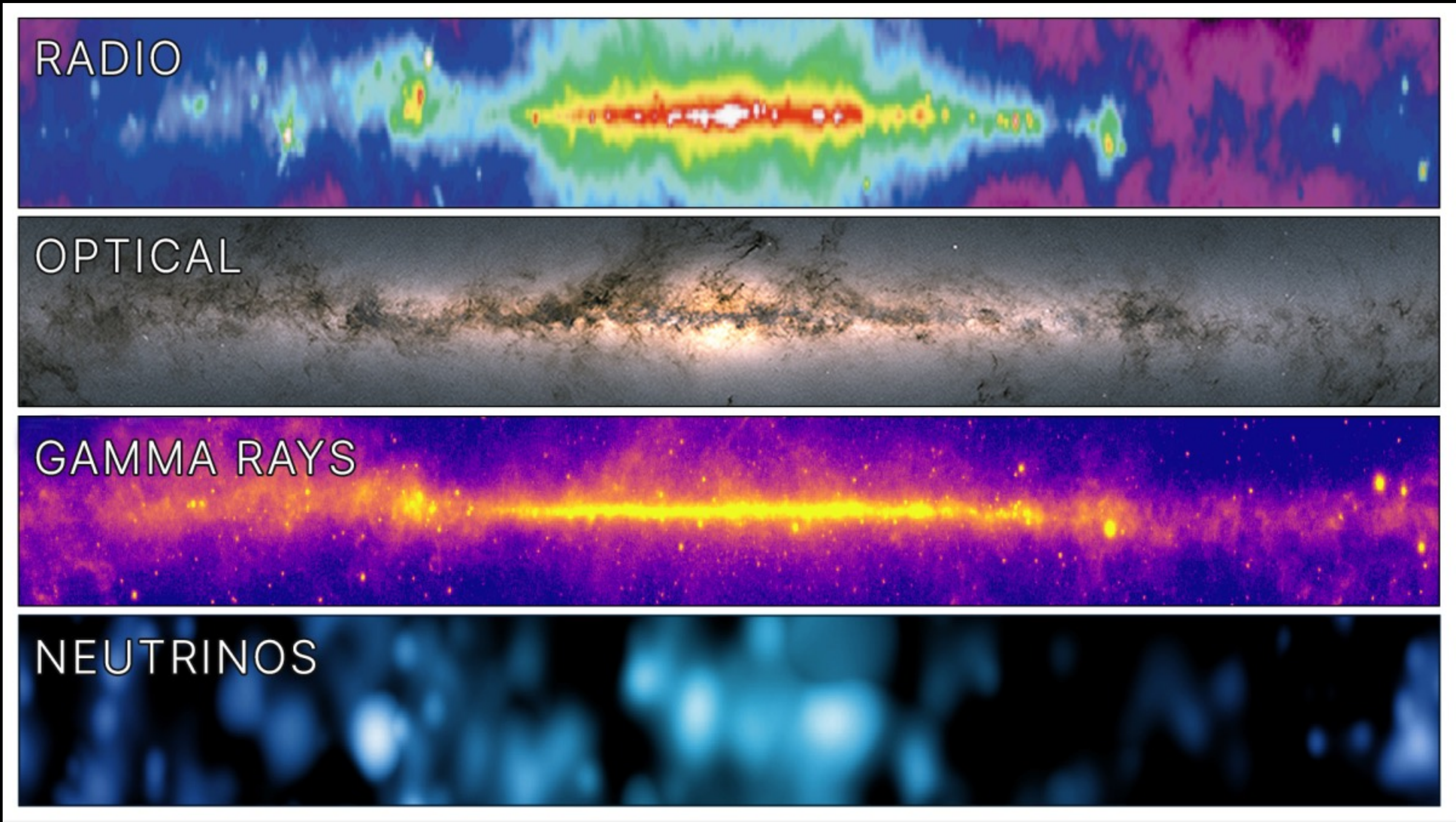
September 26

KIT Seminar


We live here in the Milkyway
Sgr A*
~27000 light years

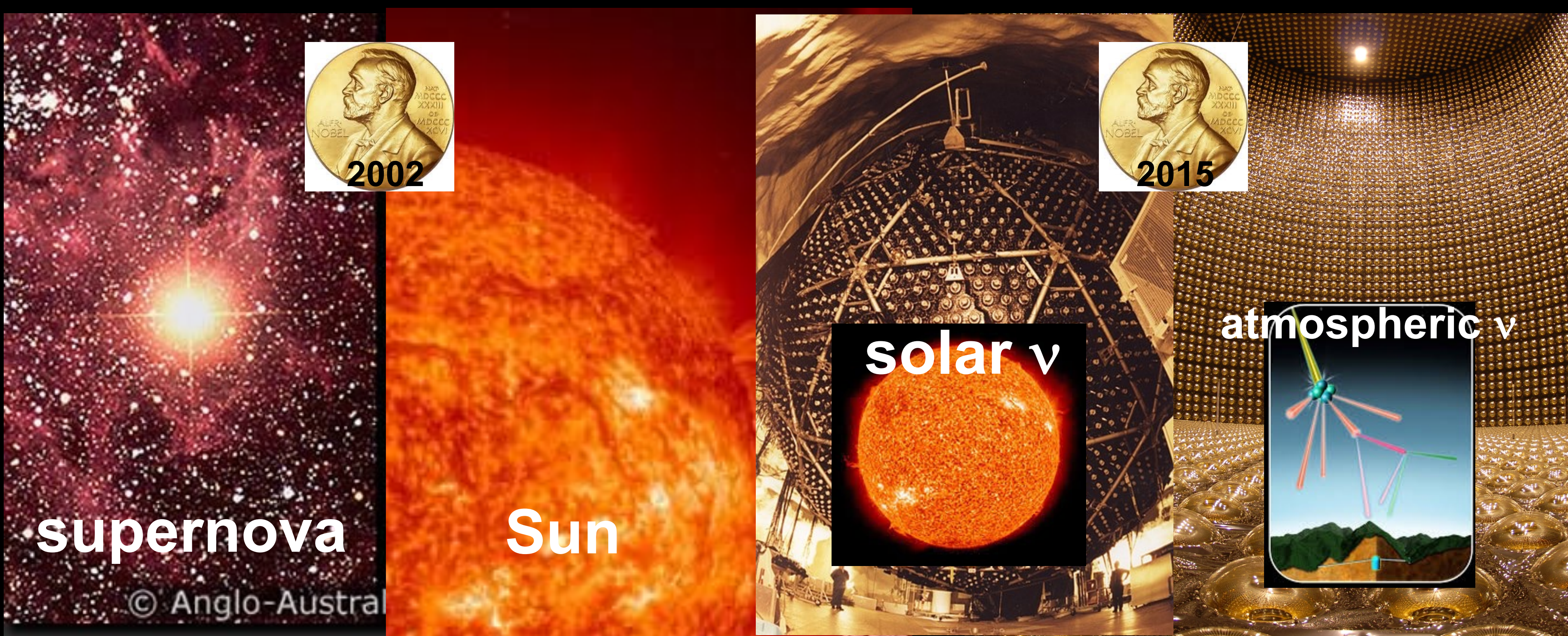

Milky Way
Sgr A*
C: ESO/Gaia/Dpac

2023: Milky Way Observed by Not Only Photons but also “Neutrinos”



Why Cosmic ν ?

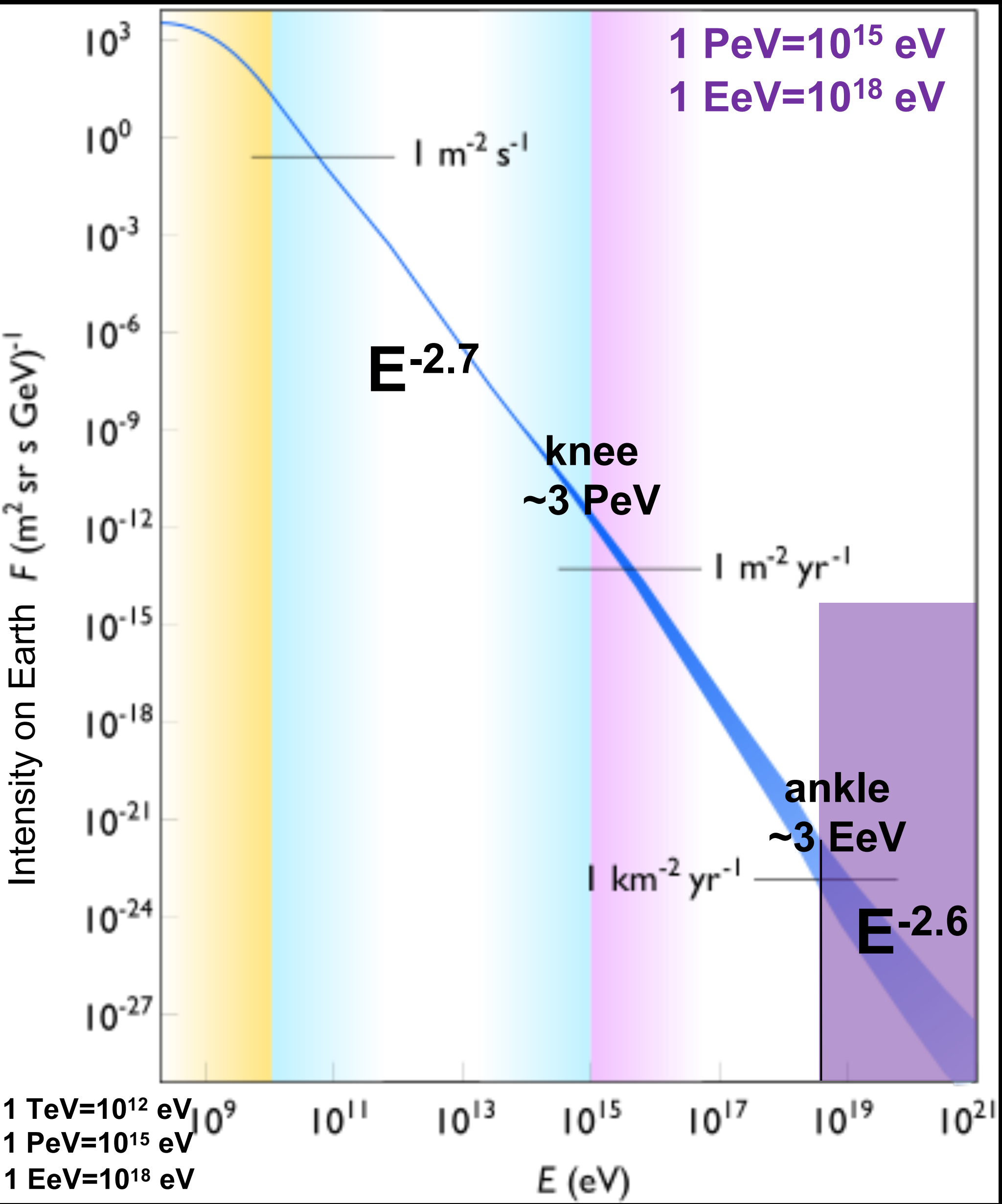
- Electrically neutral lepton
- Weak interaction: ghost particle
- Almost massless but tiny mass ($<1/10^6$ electron mass)



Astrophysics ***Particle Physics***

Prof. Kajita: “I want to thank the neutrinos, of course. And since neutrinos are created by cosmic rays, I want to thank them, too"

Cosmic-Ray Origin – A Century Old Puzzle



power-law spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

acceleration mechanisms?
propagation processes?

ultrahigh-energy cosmic rays "UHECRs"

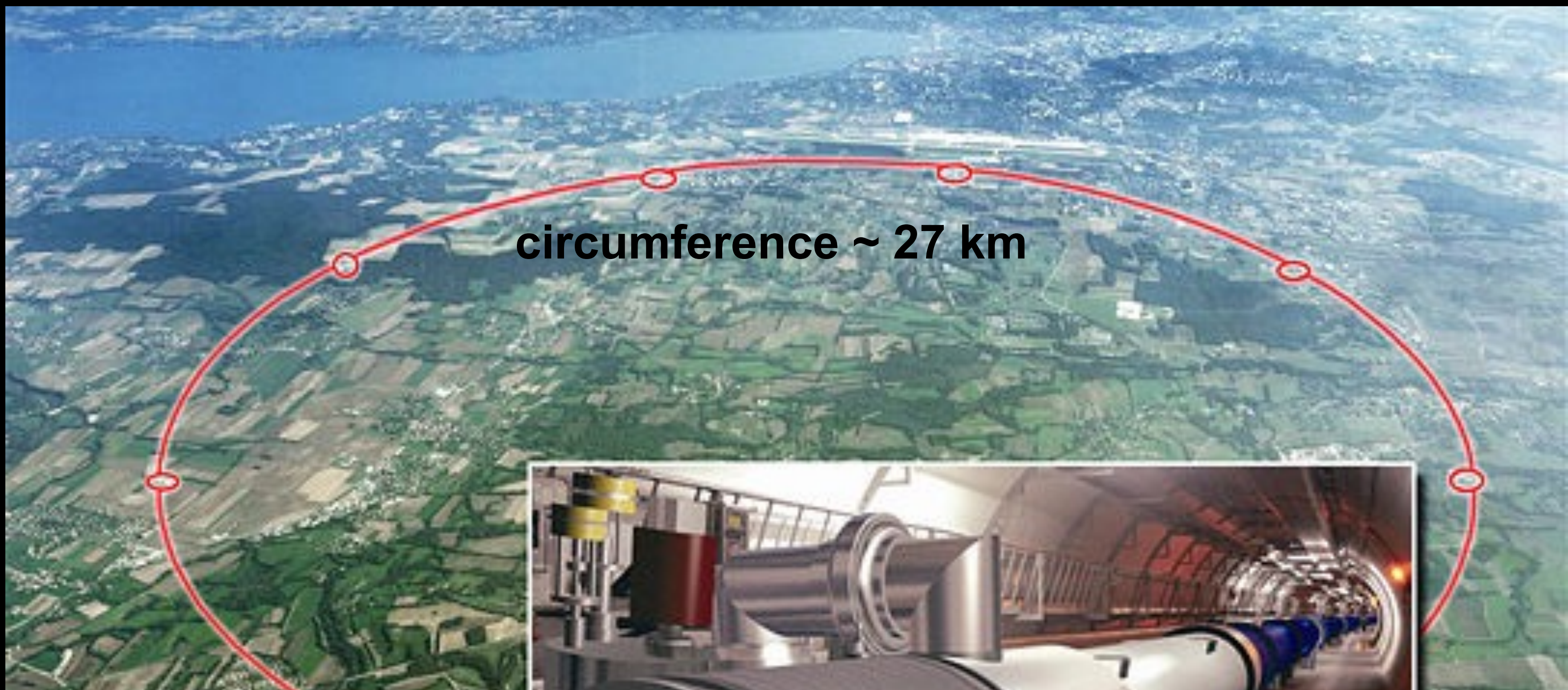
3×10^{20} eV ~ 50 J ~ kinetic energy of a tennis ball with 160km/h!

Amaterasu particle

$E \sim 2 \times 10^{20}$ eV

TA Collaboration 23 Science

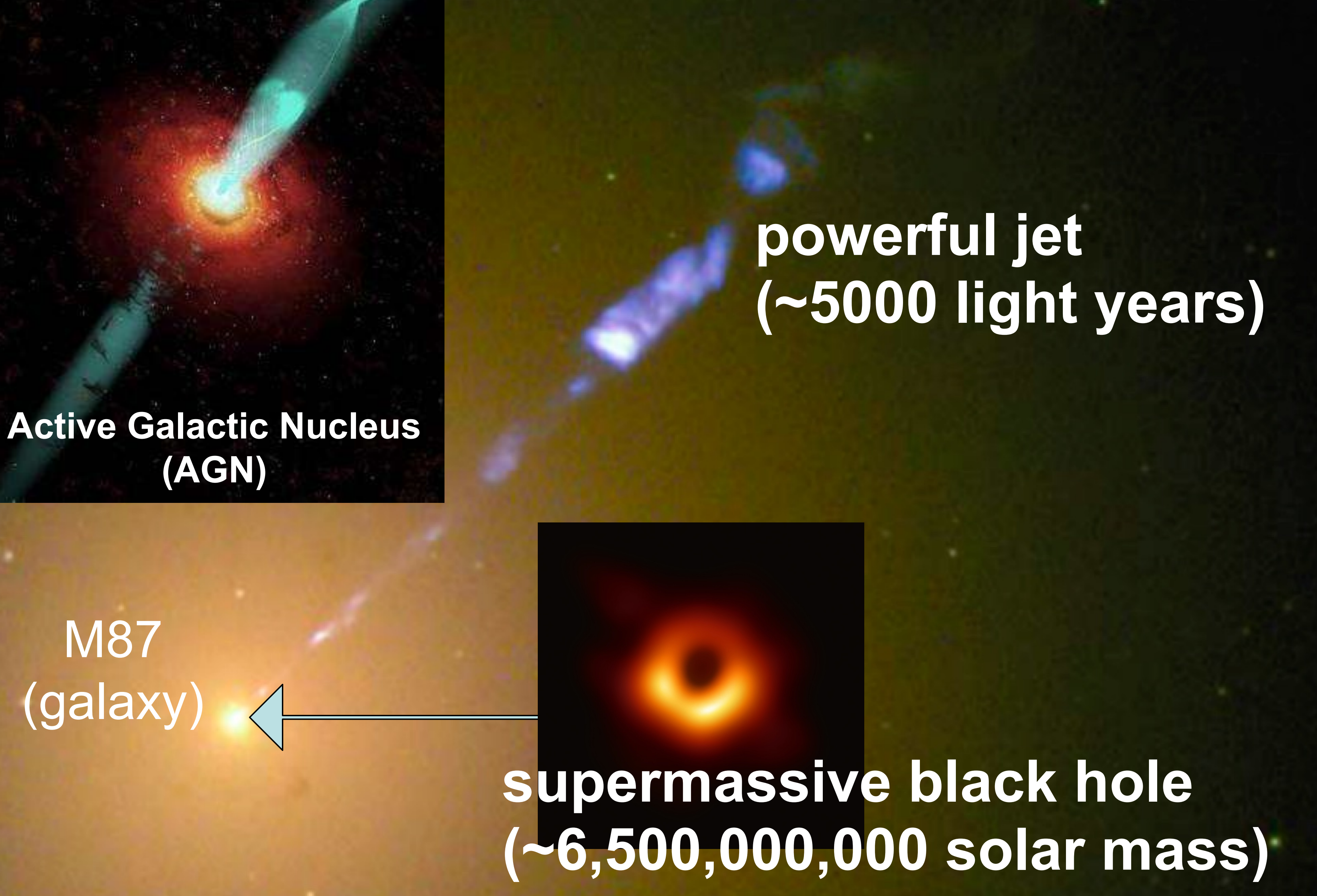
UHECR vs Large Hadron Collider (LHC)

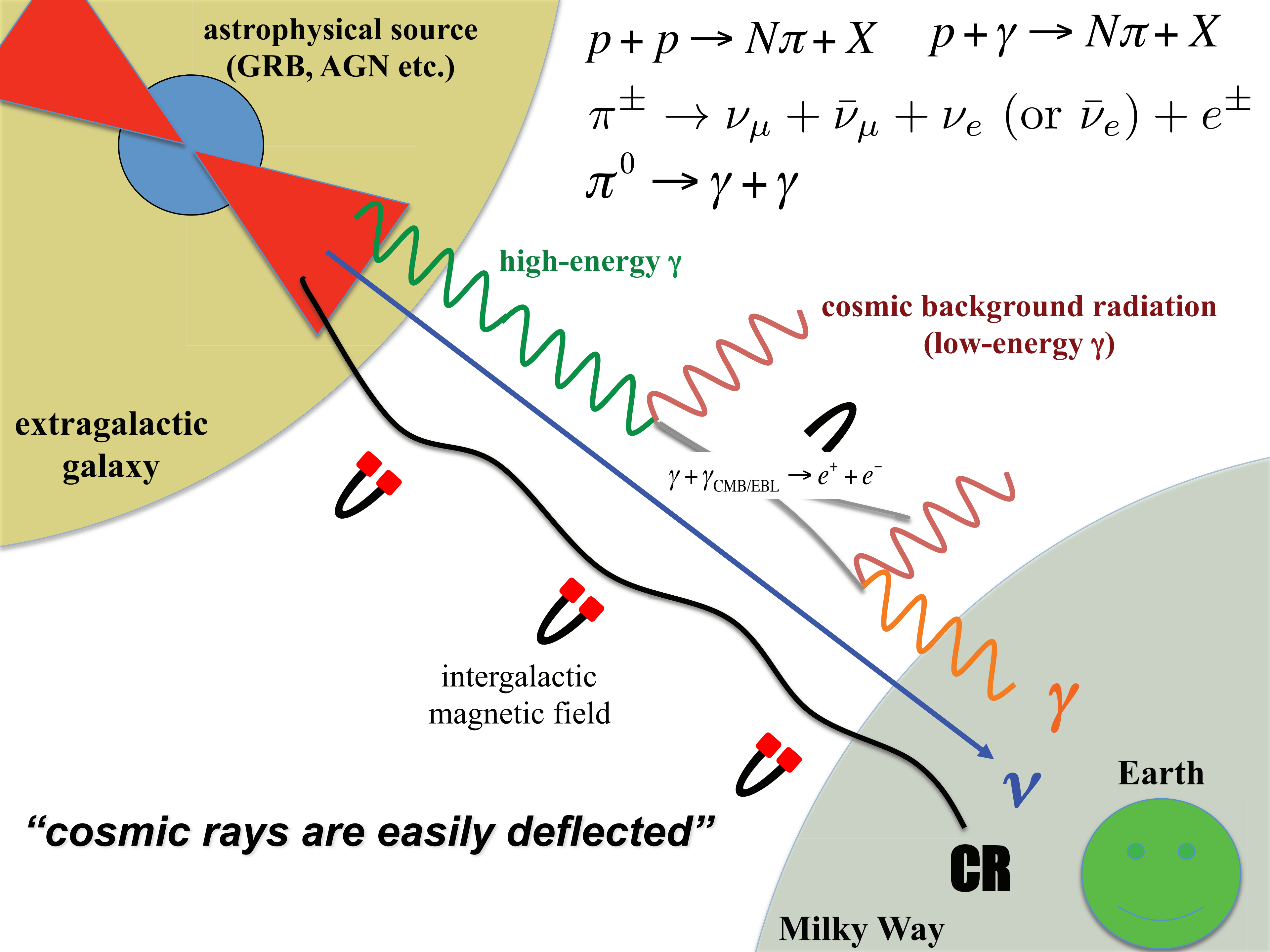


13.6 TeV=1.36x10^{13} eV
(center-of-mass frame)

UHECR energy (in the lab frame)
~ LHC w. a mercury orbit

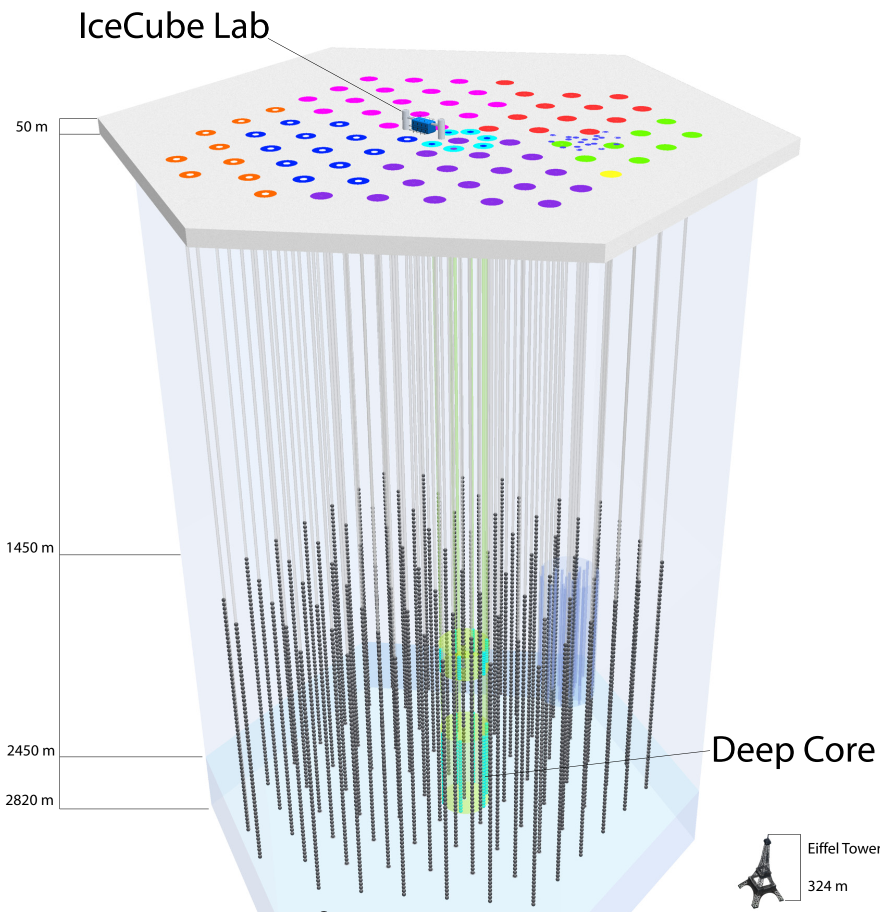
Cosmic Accelerators: Monster Black Holes?




astrophysical source
(GRB, AGN etc.)
$p + p \rightarrow N\pi + X$ $p + \gamma \rightarrow N\pi + X$
$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e$ (or $\bar{\nu}_e$) $+ e^{\pm}$
$\pi^0 \rightarrow \gamma + \gamma$
high-energy γ
cosmic background radiation
(low-energy γ)
extragalactic
galaxy
$\gamma + \gamma_{CMB/EBL} \rightarrow e^+ + e^-$
γ
intergalactic
magnetic field
ν
Earth
"cosmic rays are easily deflected"
CR
Milky Way

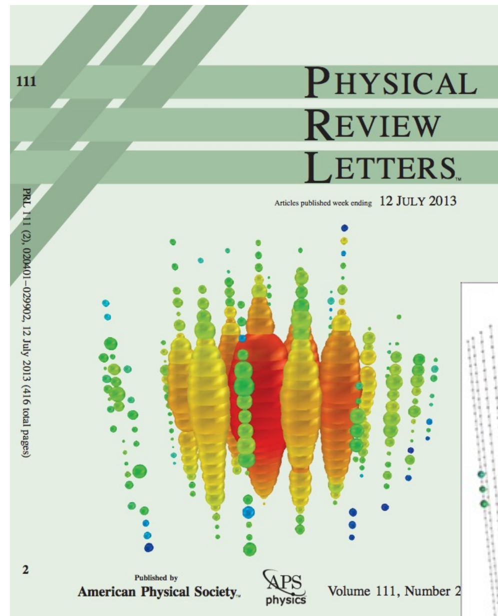
IceCube & Discovery of High-Energy Cosmic Neutrinos

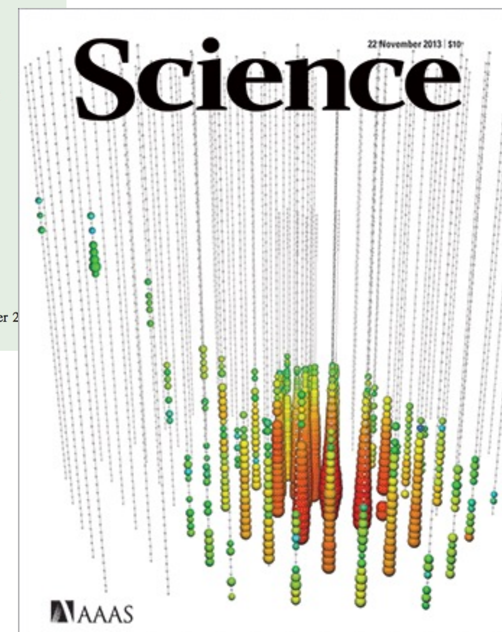
IceCube @ south pole completed in 2010



- volume~1 km^3, mass~Gton
- 86 strings (120 m spacing)
- 5160 PMTs (17 m spacing)

2012-2013: evidence of high-energy cosmic ν



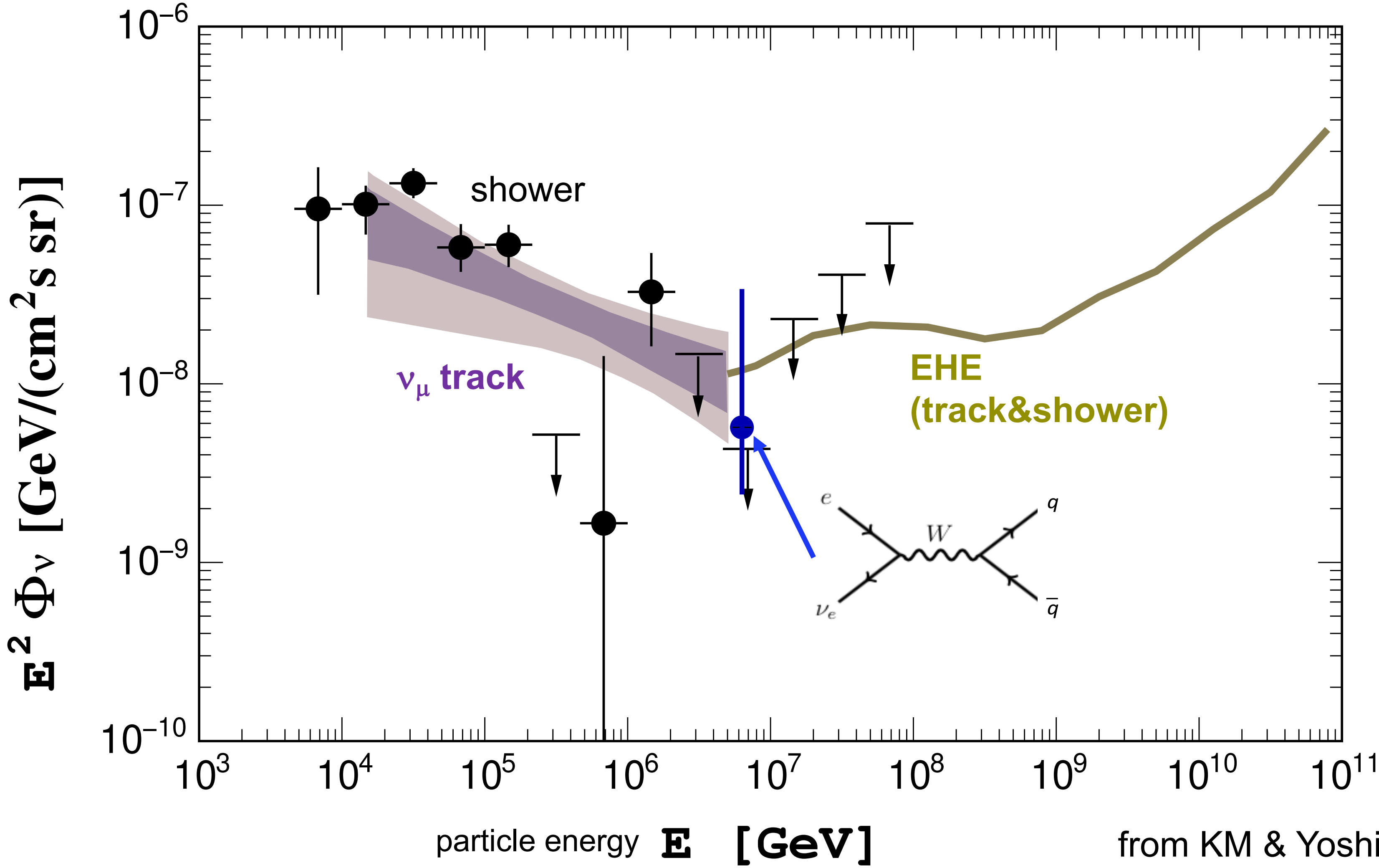


All-Sky Neutrino Flux & Spectrum

all-sky ν flux (intensity)

$E_\nu^2\Phi_\nu \sim 10^{-8}\text{-}10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

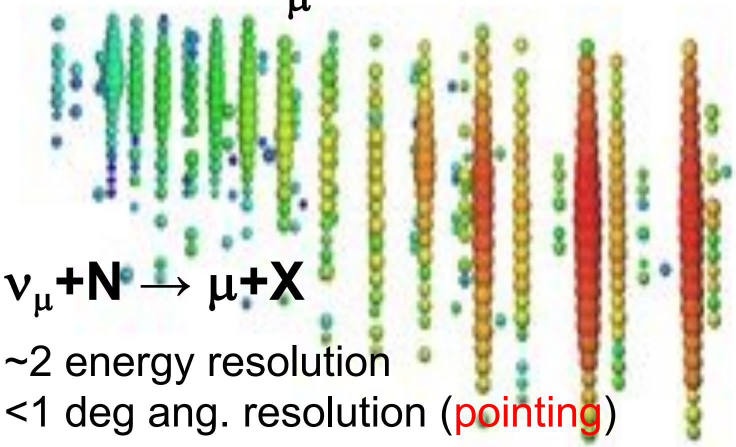
IceCube Collaboration 20 PRL
IceCube Collaboration 21 Nature



from KM & Yoshida

Detection of High-Energy Neutrinos

"ν_μ track"

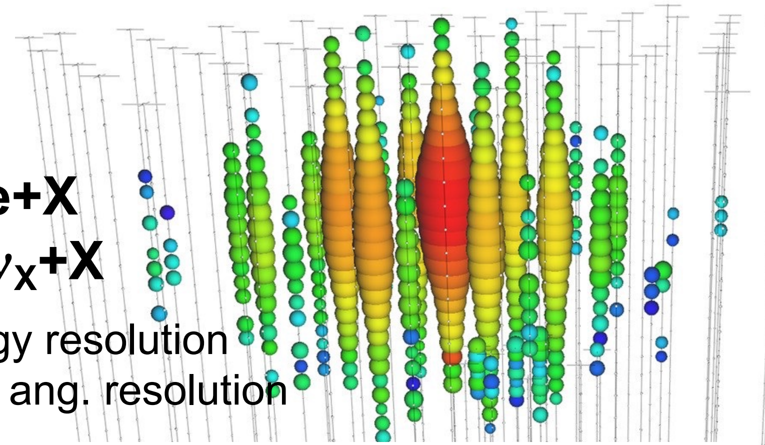


ν_μ+N → μ+X

~2 energy resolution

<1 deg ang. resolution (pointing)

"shower"

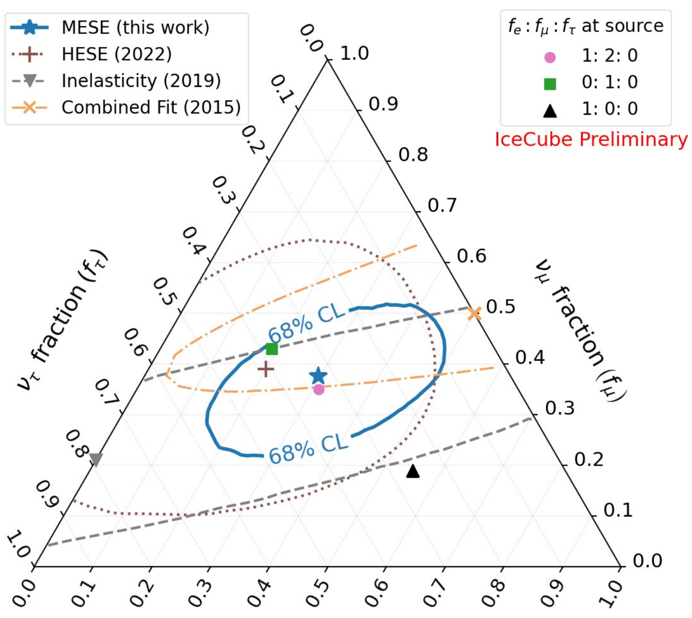


ν_e+N → e+X

ν_X+N → ν_X+X

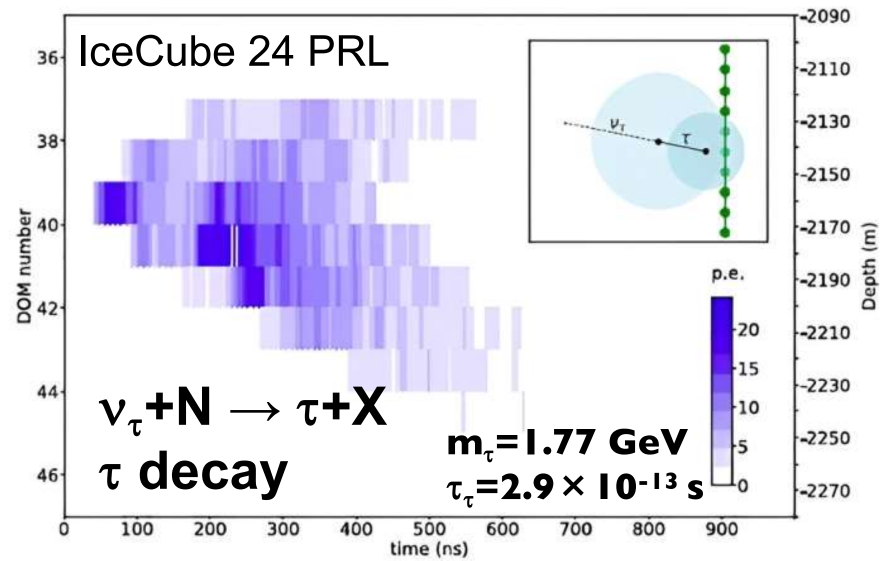
~15% energy resolution

~10-15 deg ang. resolution



IceCube 25 ICRC

"double cascades"



ν_τ+N → τ+X

τ decay

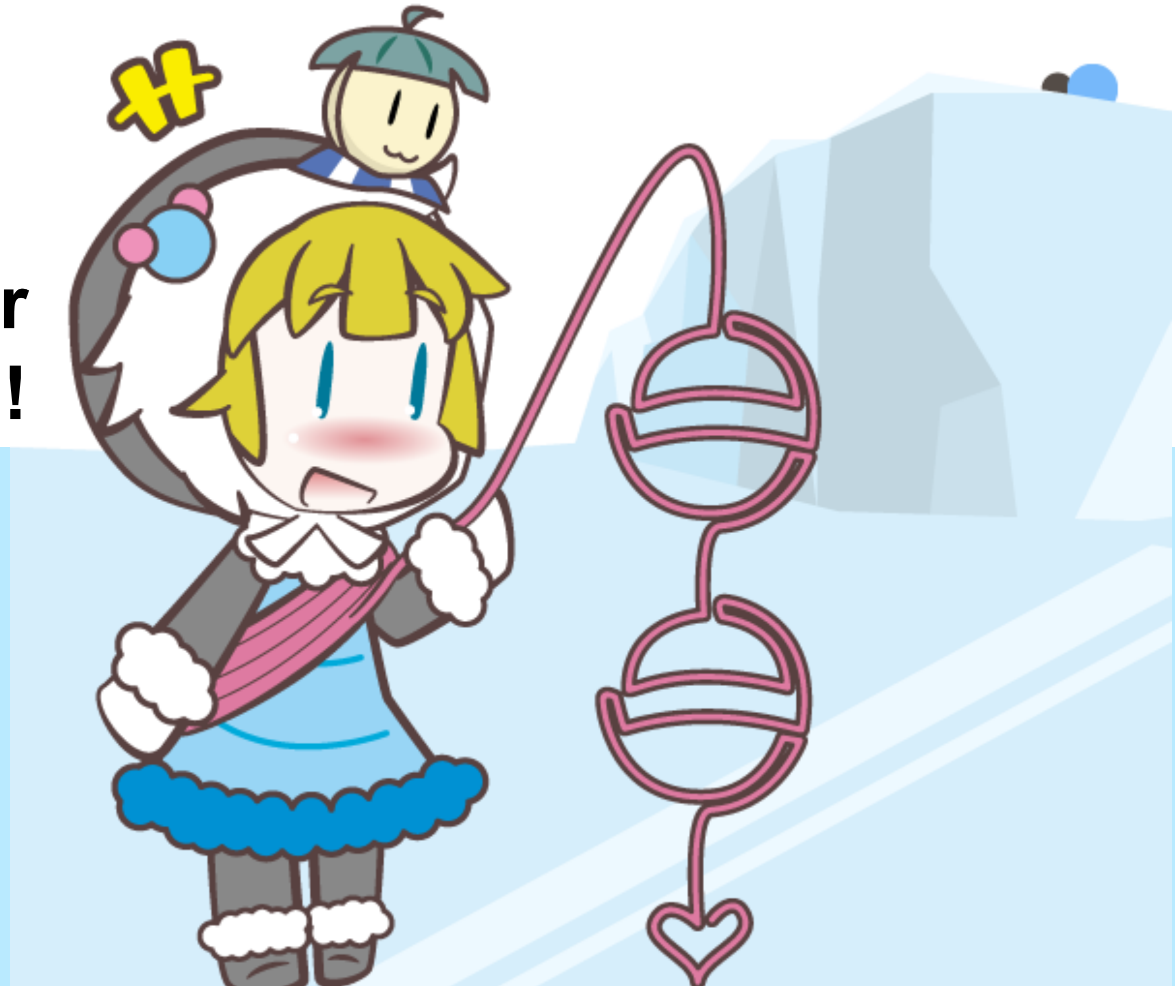
m_τ=1.77 GeV

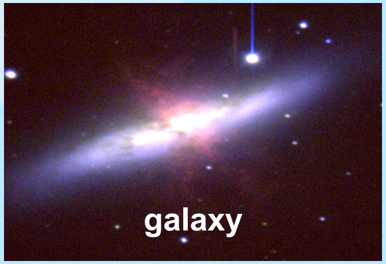
$\tau_\tau = 2.9 \times 10^{-13}$ s

7 candidates found though neutral network (>5σ)

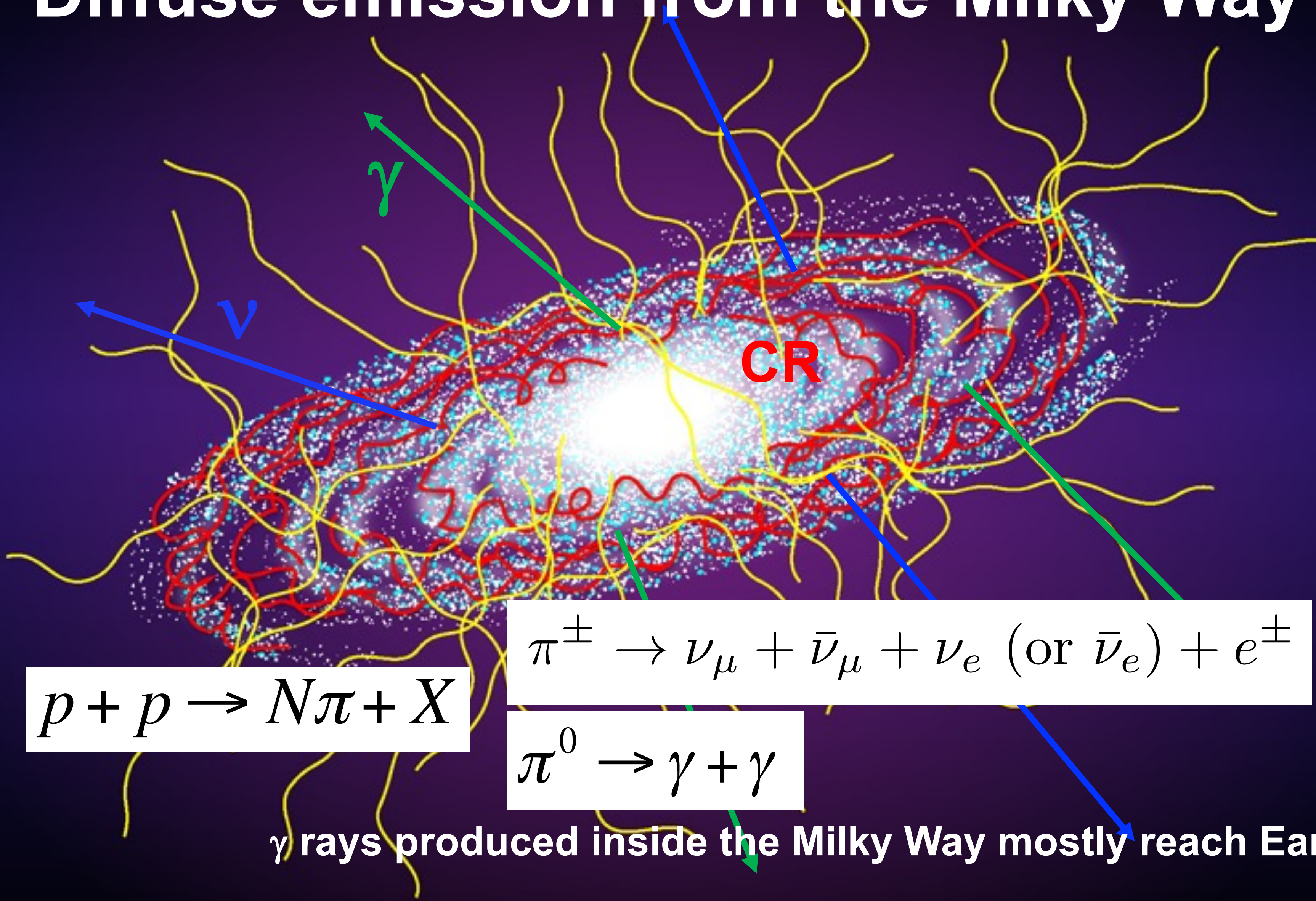
Where do neutrinos come from?

monster fishing!!





Diffuse emission from the Milky Way



$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}\ (\text{or}\ \bar{\nu}_{e}) + e^{\pm}$$

$$p + p \rightarrow N\pi + X$$

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

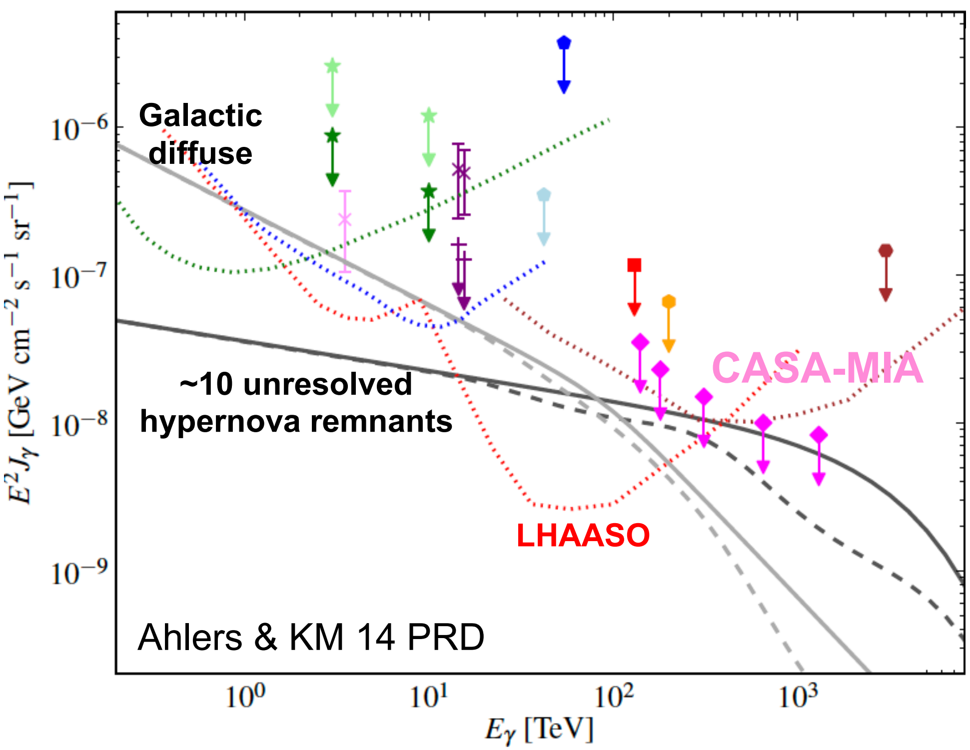
γ rays produced inside the Milky Way mostly reach Earth

Importance of Multimessenger Connection – Milky Way Case

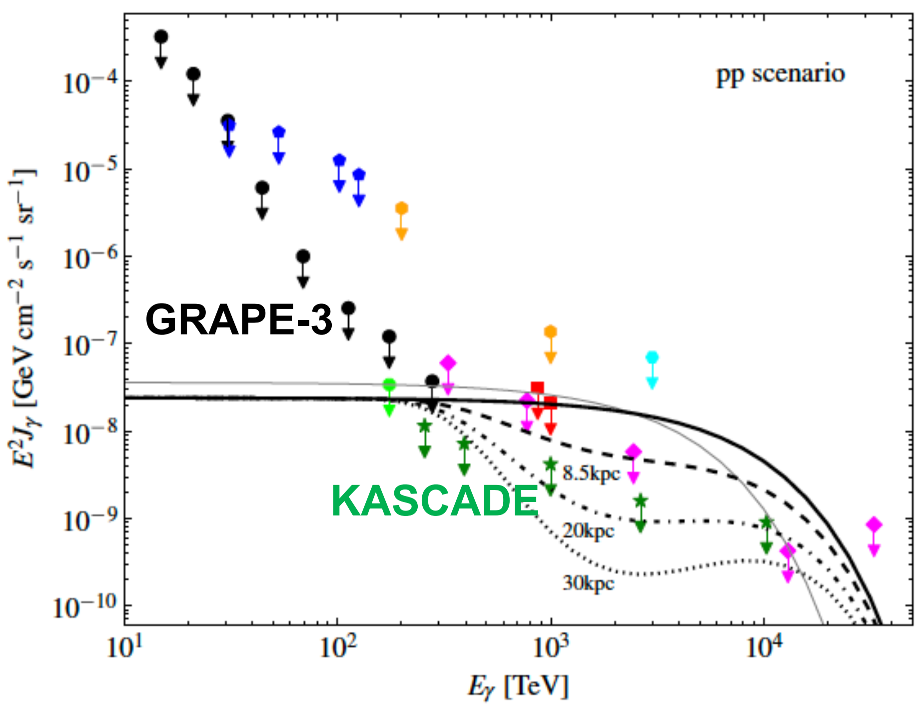
A decade ago, neither γ rays NOR νs were observed in the sub-PeV range.
(Note that most γ rays from Galactic sources reach Earth.)
But we already learned that Galactic contribution to IceCube νs is subdominant.

$p + p \to N\pi + X$ $\pi^0:\pi^{\pm} \sim 1:2 \to$ $\mathbf{E_\gamma^2\,\Phi_\gamma : E_\nu^2\,\Phi_\nu \sim 2:3}$ (comparable)

Galactic Plane $|b| < 2^\circ$

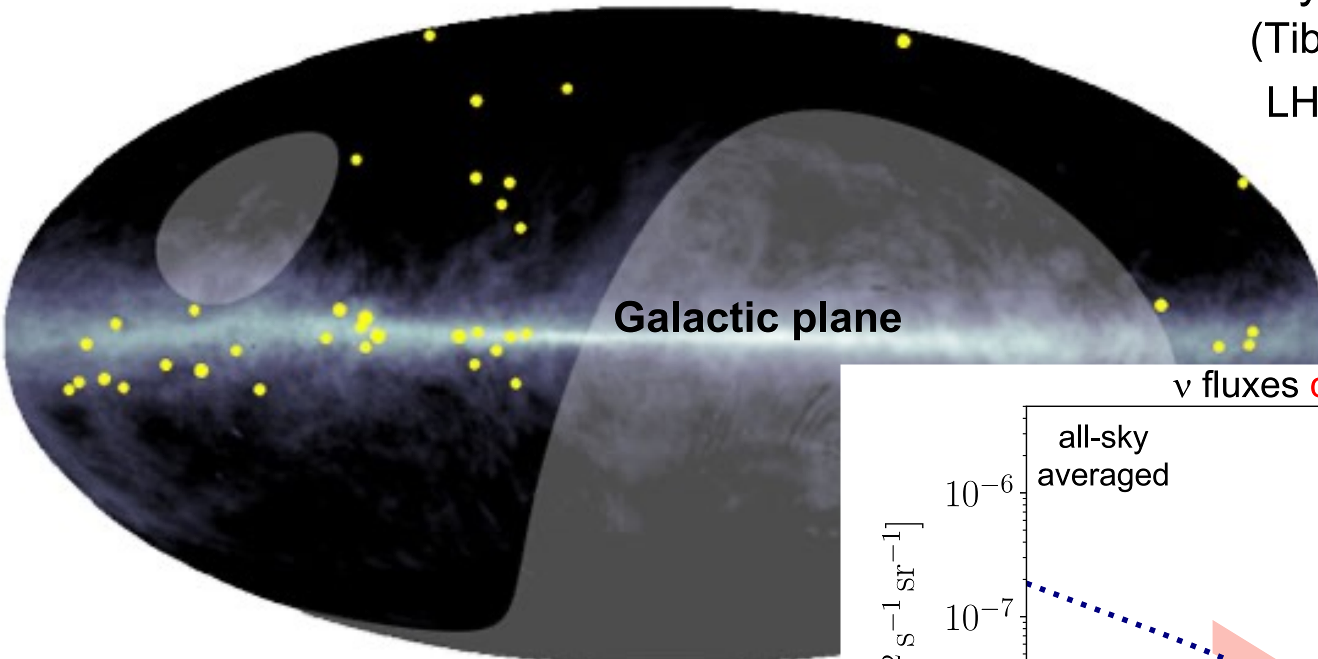


Galactic Halo (quasi-isotropic)

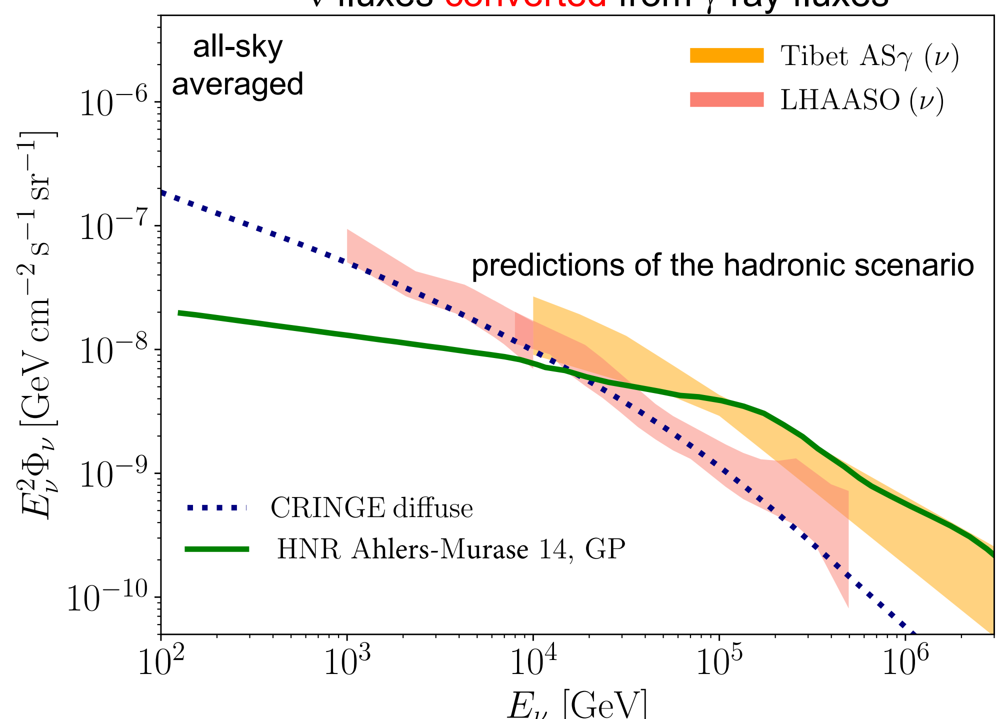


Galactic Diffuse Sub-PeV Gamma Rays Are NOW Measured

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)



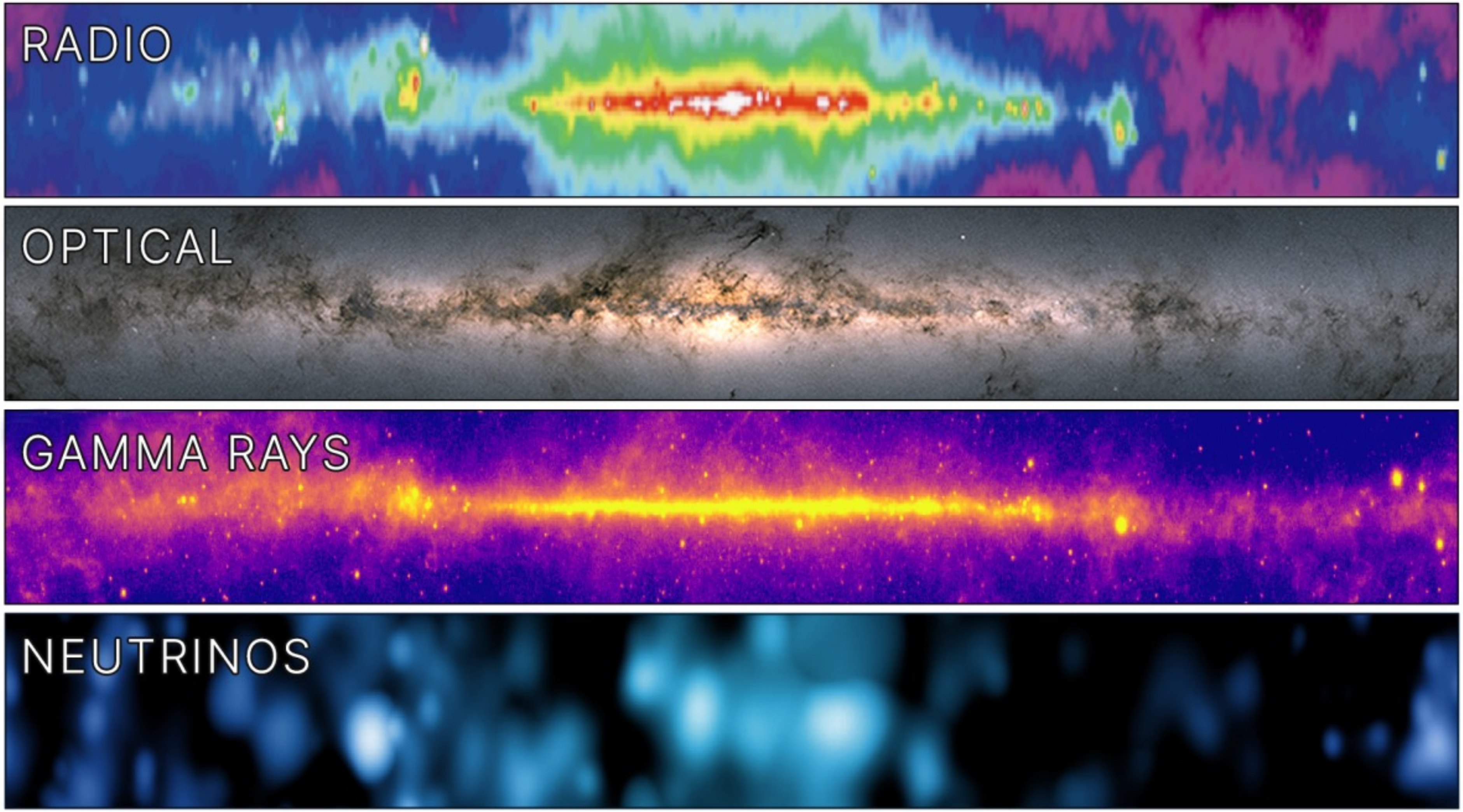
ν fluxes converted from γ-ray fluxes



Fang & KM 21 ApJ, 23 ApJL

2023: Evidence of Neutrinos from the Milky Way

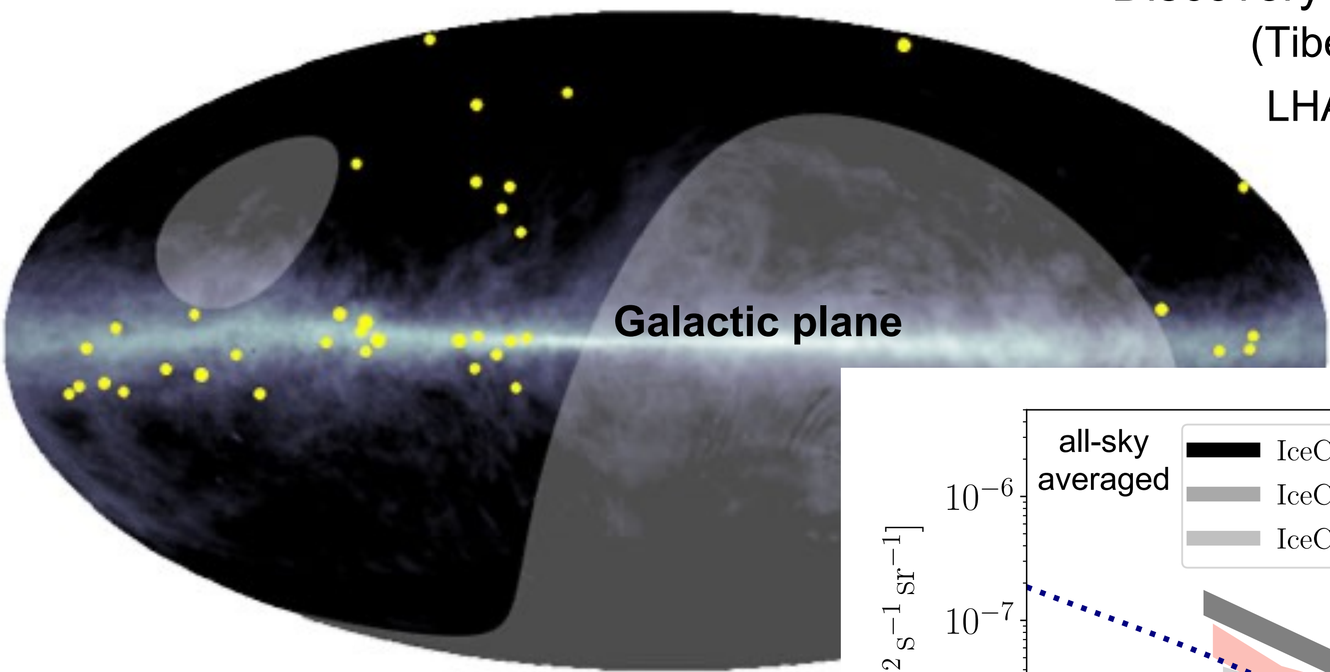
IceCube 23 Science

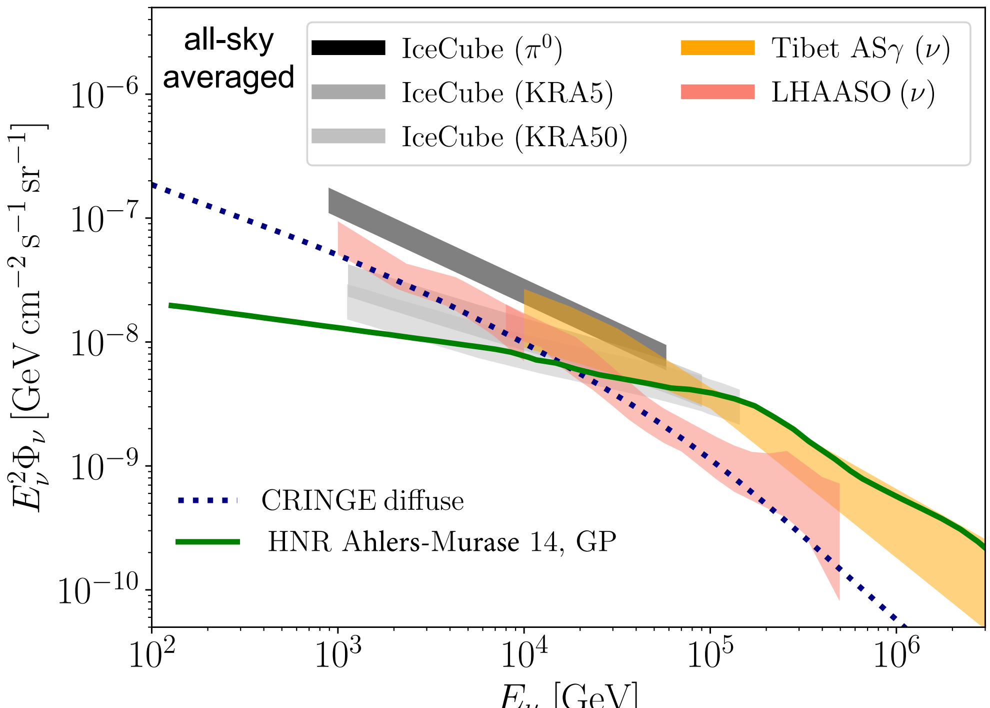


Neutrino emission from the Milky Way (~10% of total) has been observed w. 4.5σ

Galactic Multimessenger Connection: Current

Discovery of sub-PeV γ rays in 2021
(Tibet ASγ Collaboration 21 PRL
LHAASO Collaboration 23 PRL)





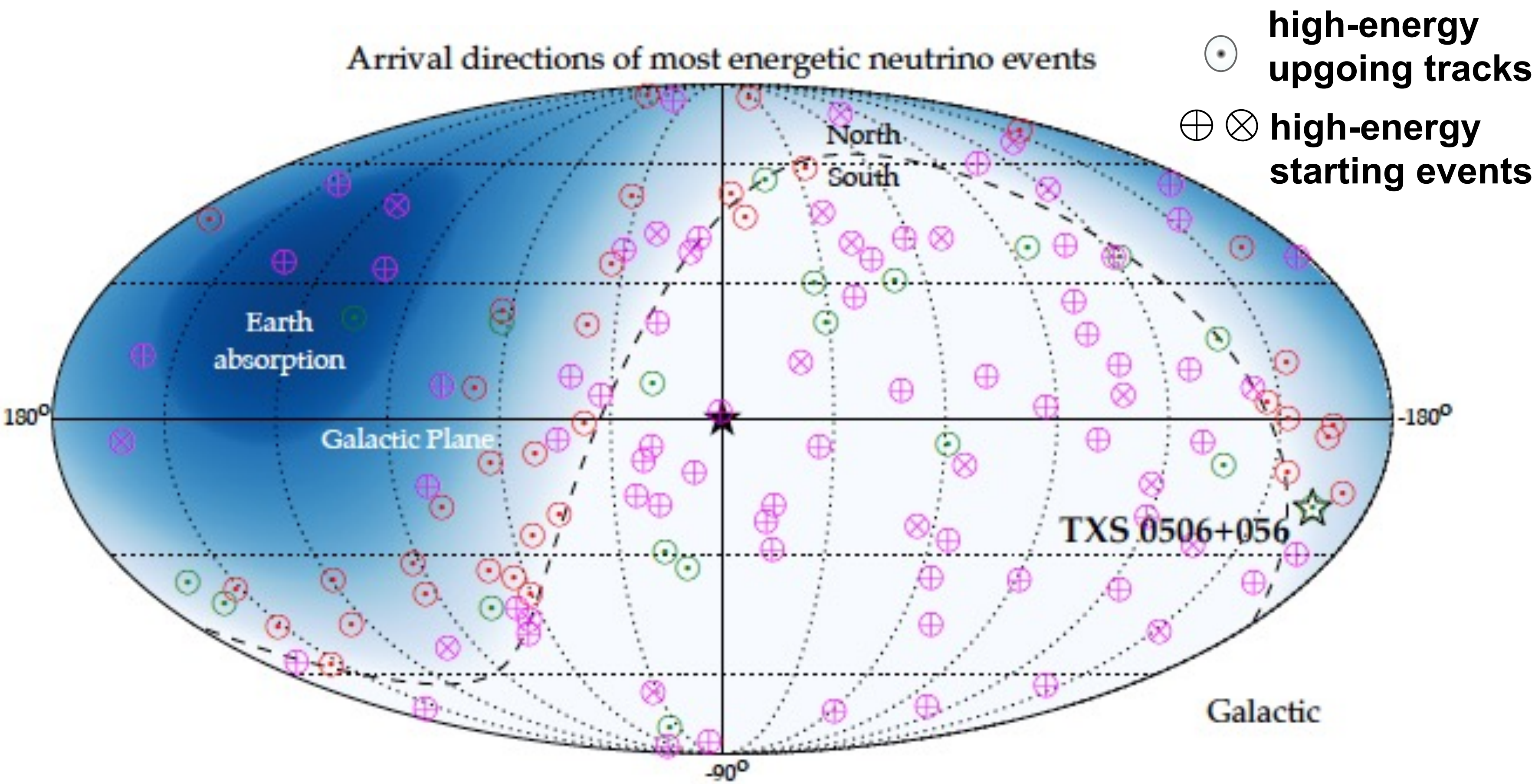
Fang & KM 21 ApJ, 23 ApJL

- **Supporting hadronic (pp) origin**
- **Truly diffuse emission**

vs

Unresolved (extended) sources

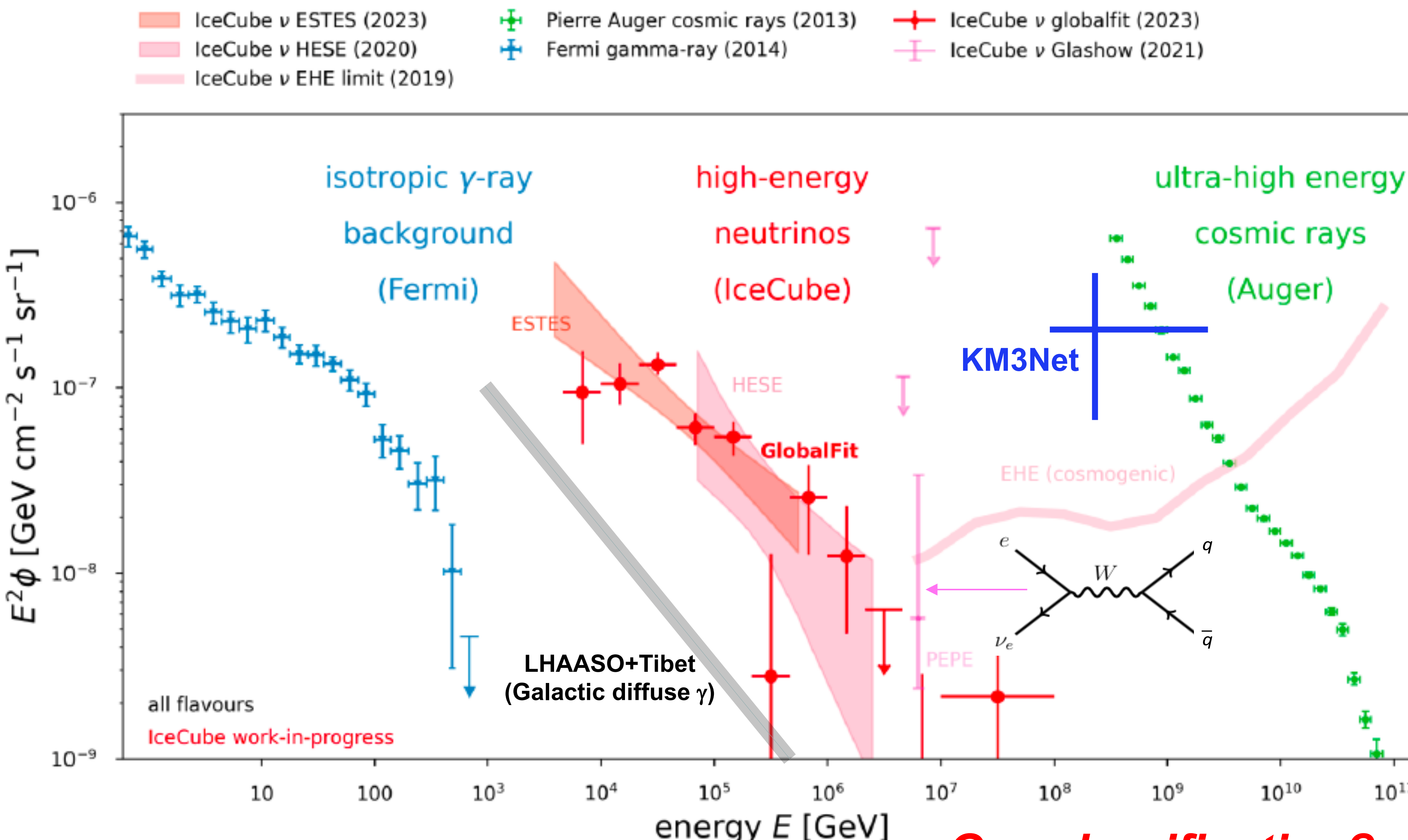
High-Energy Neutrino Sky



consistent w. isotropic distribution/extragalactic origins

#Galactic contribution: ~10% (IceCube 23 Science)

All-Sky Multimessenger Flux & Spectrum

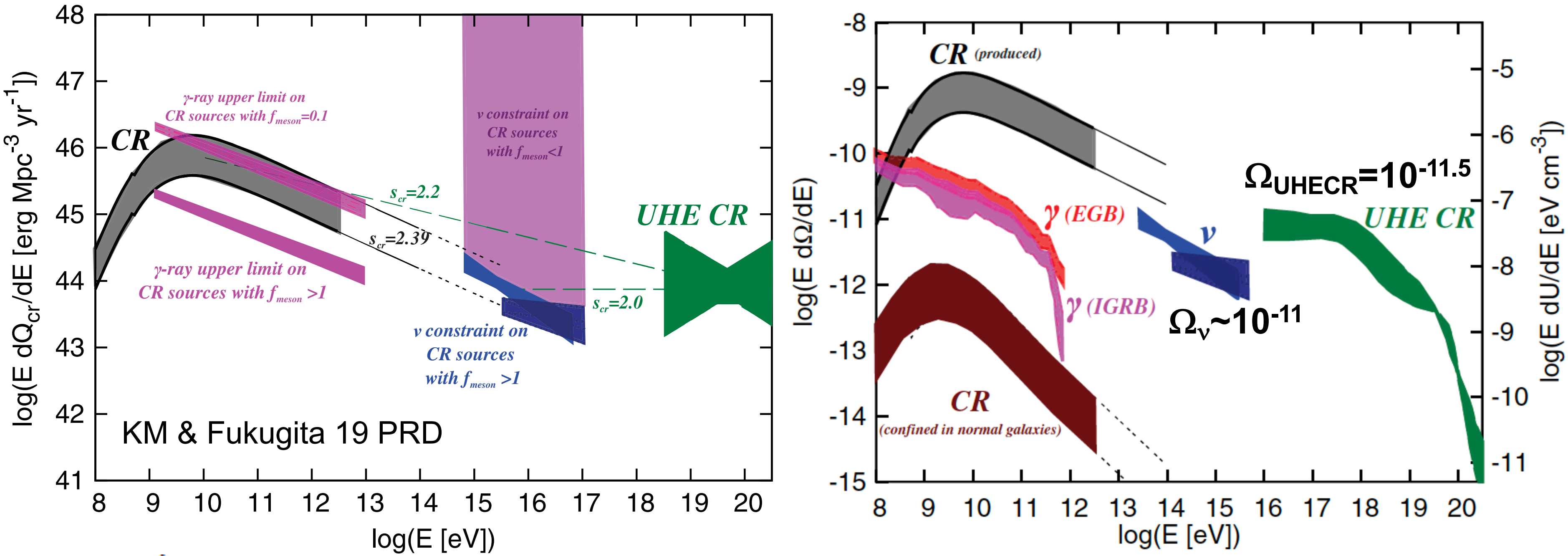


IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

Grand-unification?

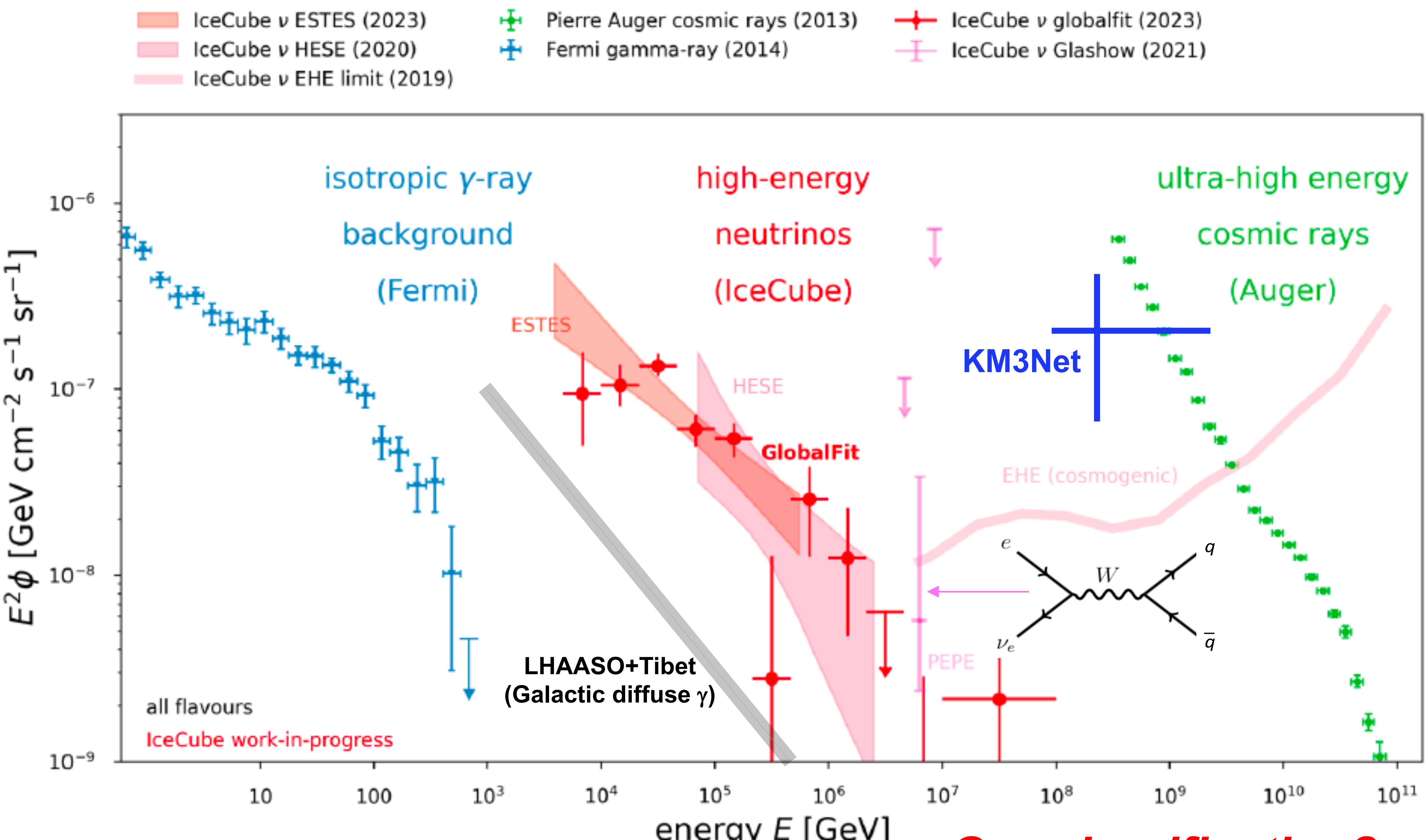
Energy Budgets of High-Energy Cosmic Particles

UHECR energy generation ~ sub-PeV ν energy generation ~ sub-TeV γ-ray energy generation



	ccSN (CR)	HN (CR)	DNS (CR)	GRB (γ)	LL GRB (γ)	TDE (γ)
Q [erg Mpc^{-3} yr^{-1}]	$10^{46.6}$	$10^{45.5}$	$10^{44.5}$	$10^{43.6}$	$10^{43.5}$	$10^{43.5}$
ρ [Mpc^{-3} yr^{-1}]	10^{-4}	$10^{-5.5}$	$10^{-5.8}$	10^{-9}	$10^{-6.5}$	$10^{-10.5}$
	SBG (γ)	AGN (X)	BL Lac (γ)	FSRQ (γ)	RG (γ)	Accr/Mger (CR)
Q [erg Mpc^{-3} yr^{-1}]	$10^{44.5}$	$10^{46.3}$	$10^{45.4}$	$10^{44.3}$	$10^{44.6}$	$10^{46.5}$
n [Mpc^{-3}]	10^{-4}	$10^{-4}-10^{-3}$	$10^{-7}-10^{-6.5}$	$10^{-9}-10^{-8}$	$10^{-5}-10^{-4}$	$10^{-6}-10^{-5}$

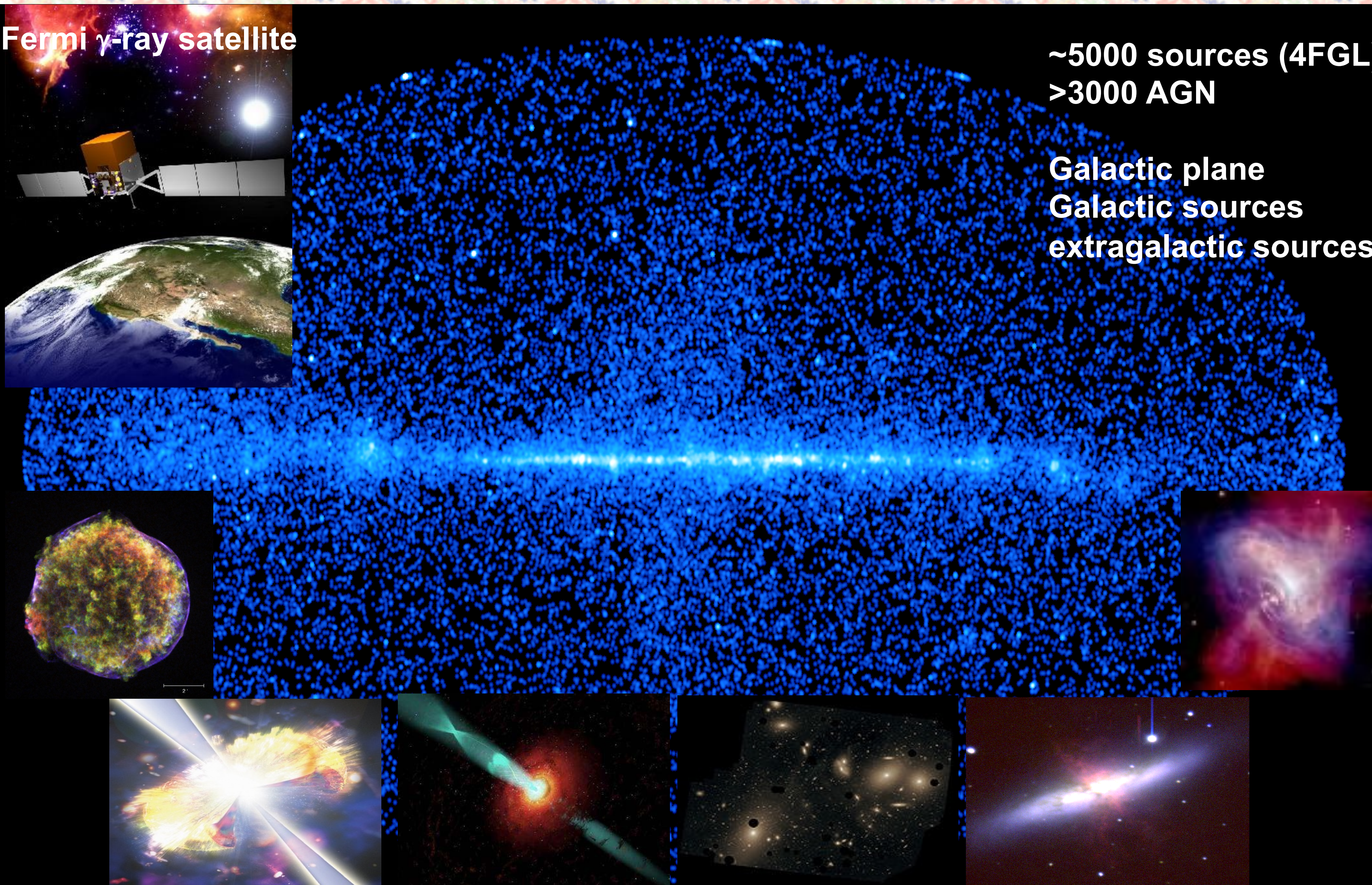
All-Sky Multimessenger Flux & Spectrum



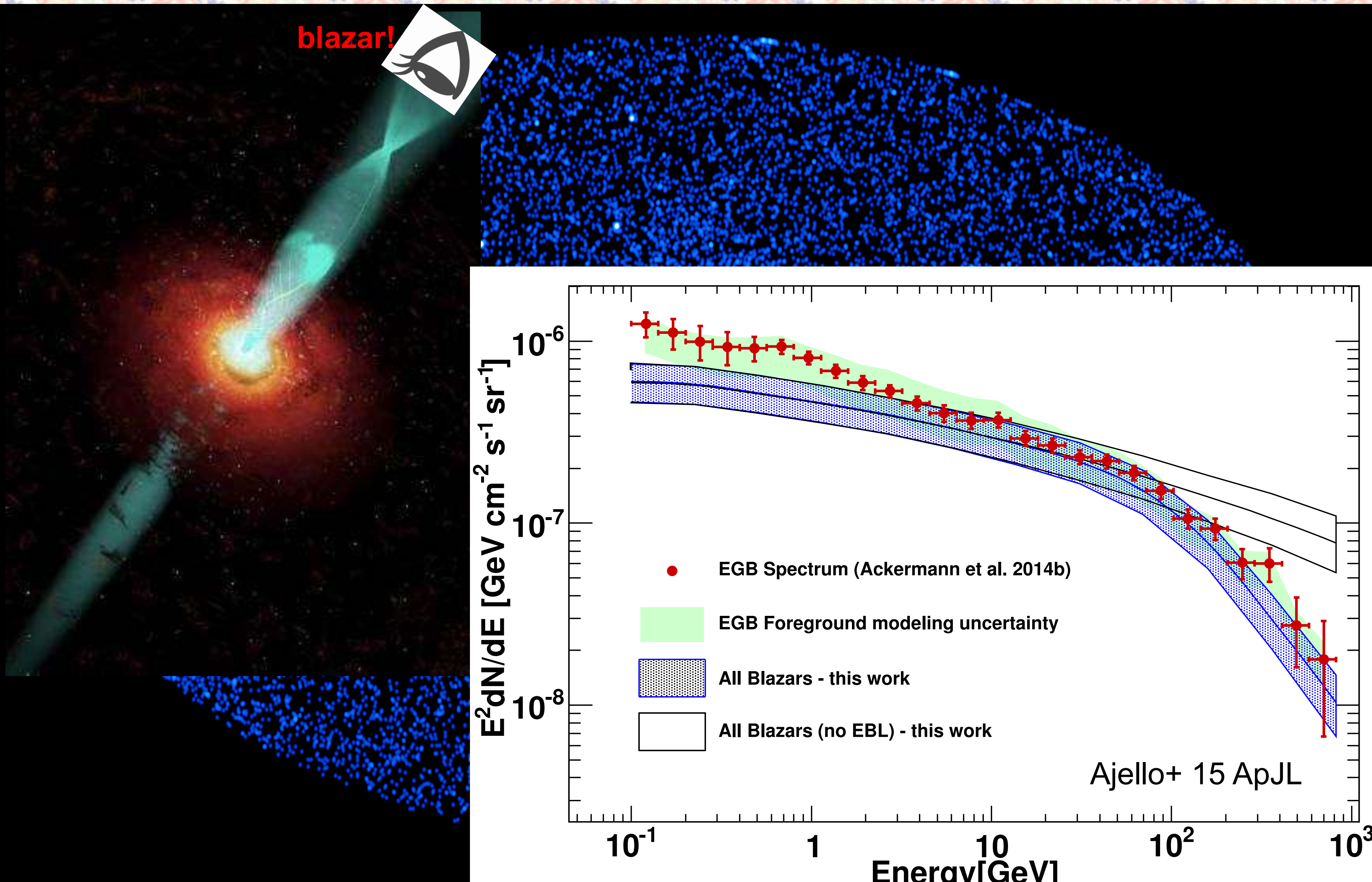
IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ

Grand-unification?

High-Energy Gamma-Ray Sky



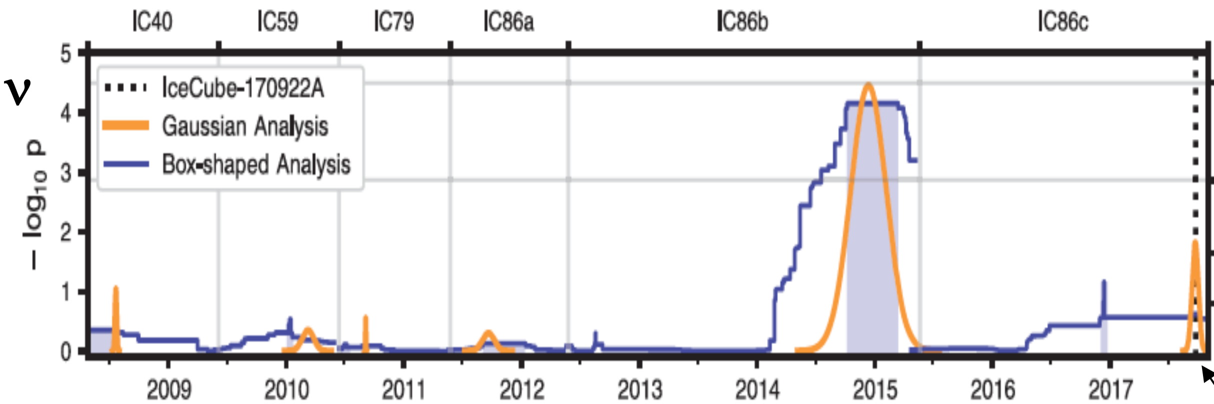
Extragalactic γ-Ray Sky: Dominated by On-Axis Jetted AGN



2017: Hints of Neutrinos from On-Axis Jetted AGN

IceCube 2018 Science

ν



TXS 0506+056

"blazar"

2017 multimessenger flare

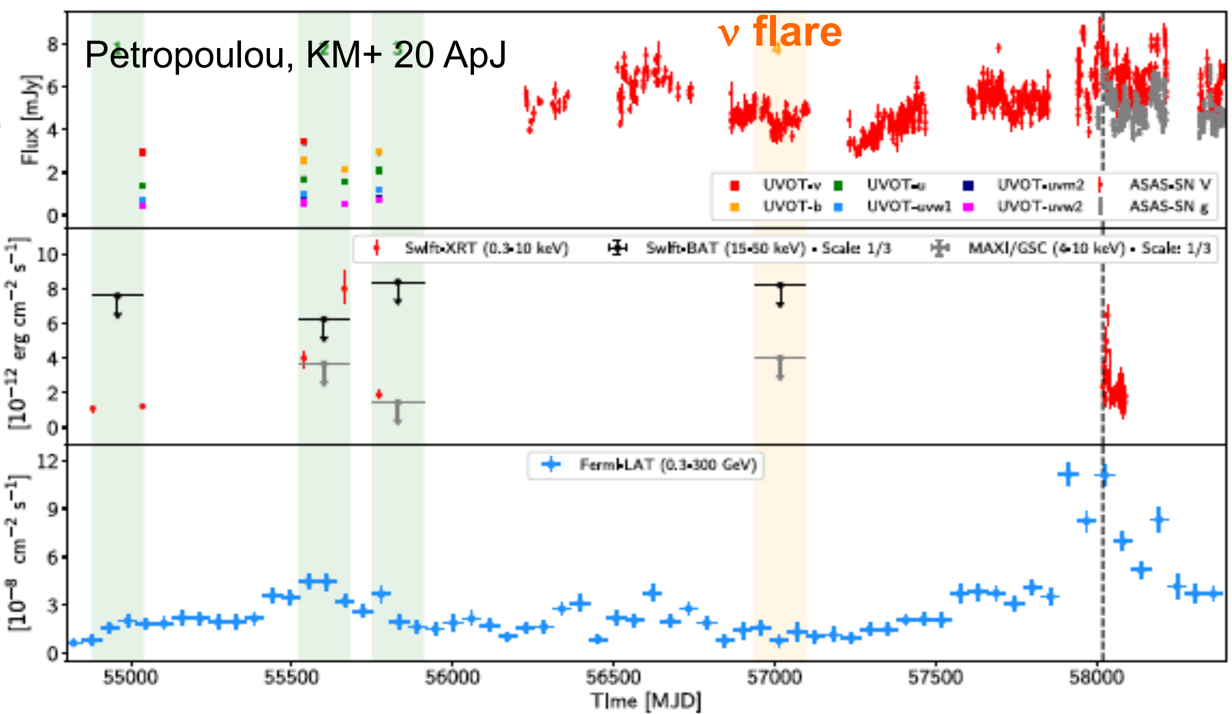
2014-2015

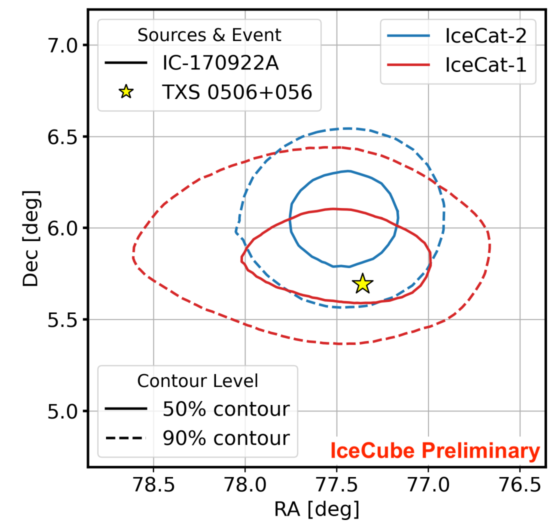
ν flare

radio

X

γ

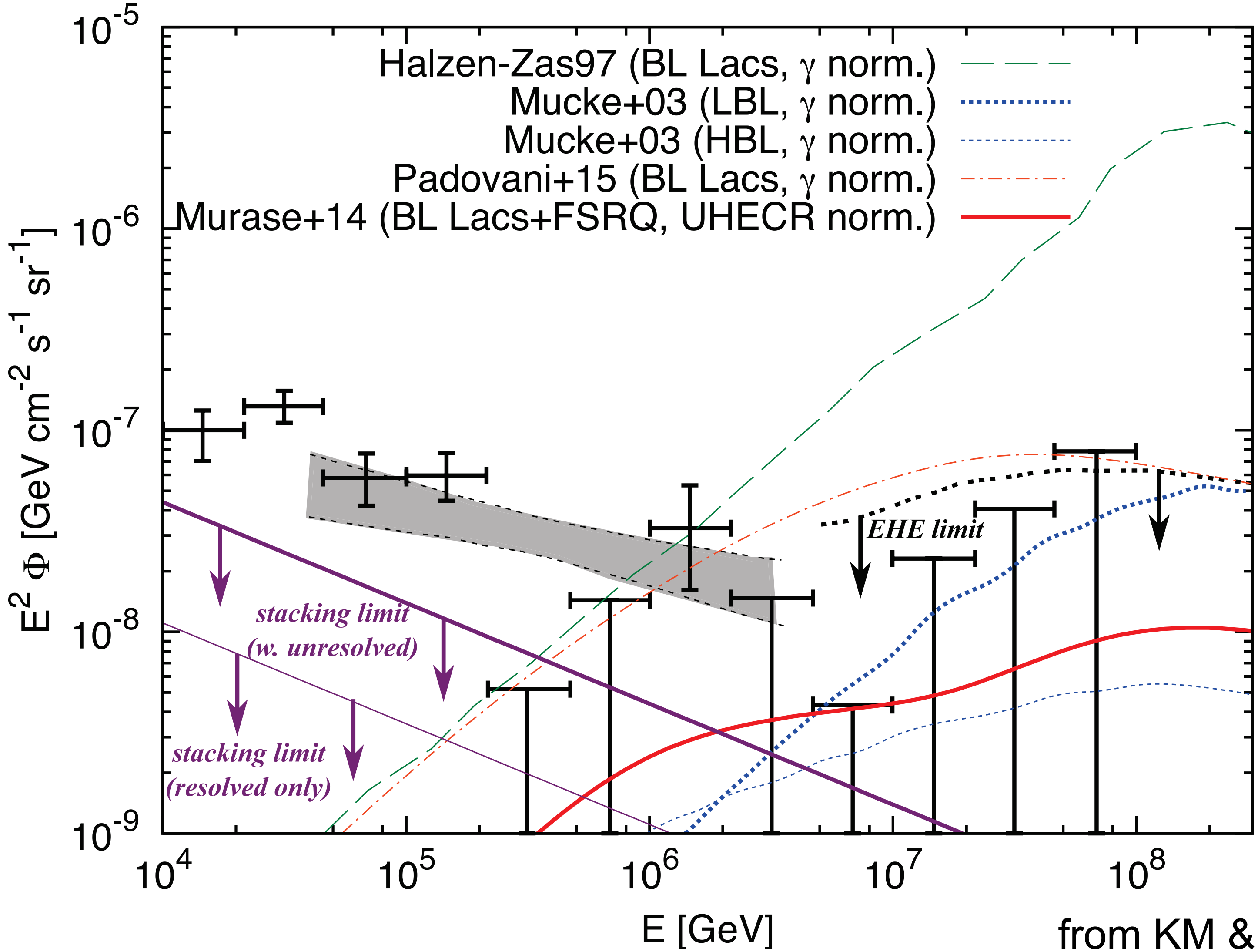




IceCube 25 ICRC

Extragalactic ν Sky: NOT Dominated by On-Axis Jetted AGN

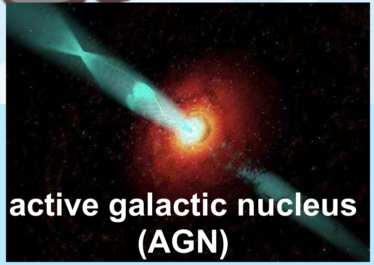
Stacking searches are powerful to constrain νs from on-axis jetted AGN

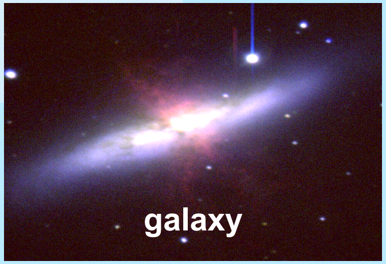


from KM & Stecker 23

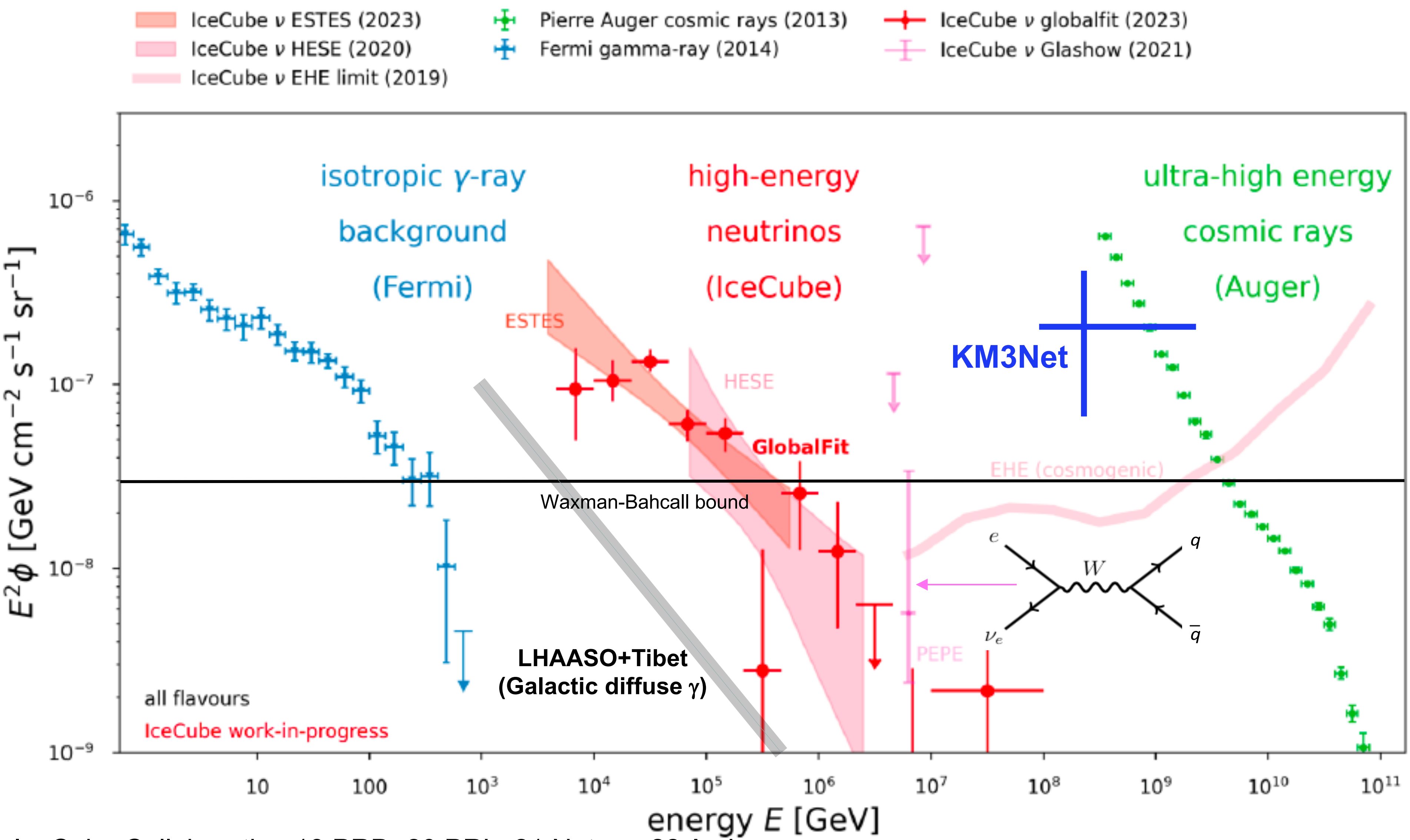
Where do neutrinos come from?

Multi-messenger analyses disfavor on-axis jetted AGN (and classical γ-ray bursts) as the "dominant" ν origin

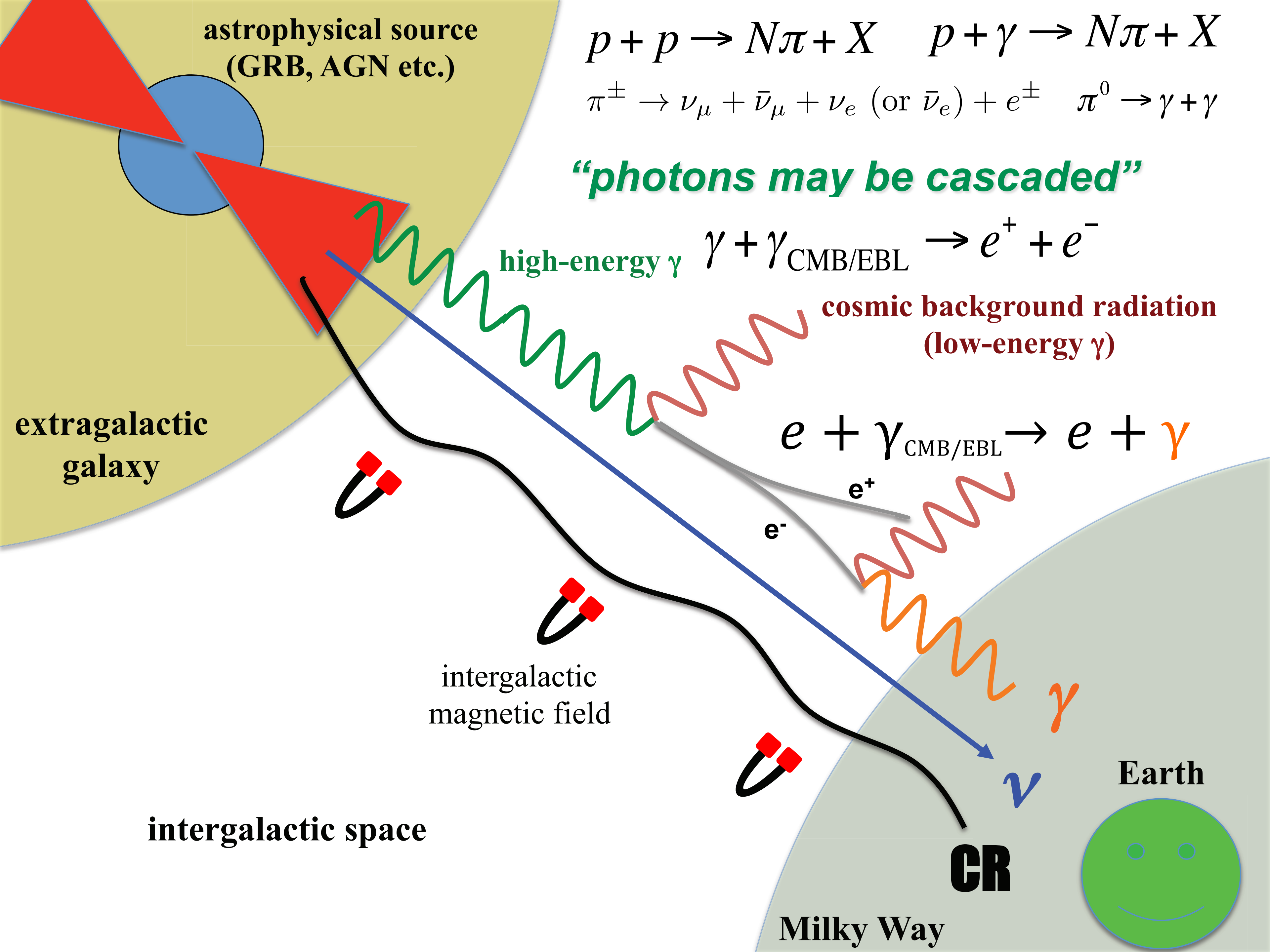




All-Sky Multimessenger Flux & Spectrum



IceCube Collaboration 18 PRD, 20 PRL, 21 Nature, 22 ApJ


astrophysical source
(GRB, AGN etc.)
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$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e$ (or $\bar{\nu}_e$) $+ e^{\pm}$
$\pi^0 \rightarrow \gamma + \gamma$
"photons may be cascaded"
high-energy γ
$\gamma + \gamma_{CMB/EBL} \rightarrow e^+ + e^-$
cosmic background radiation
(low-energy γ)
$e + \gamma_{CMB/EBL} \rightarrow e + \gamma$
e^+
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extragalactic
galaxy
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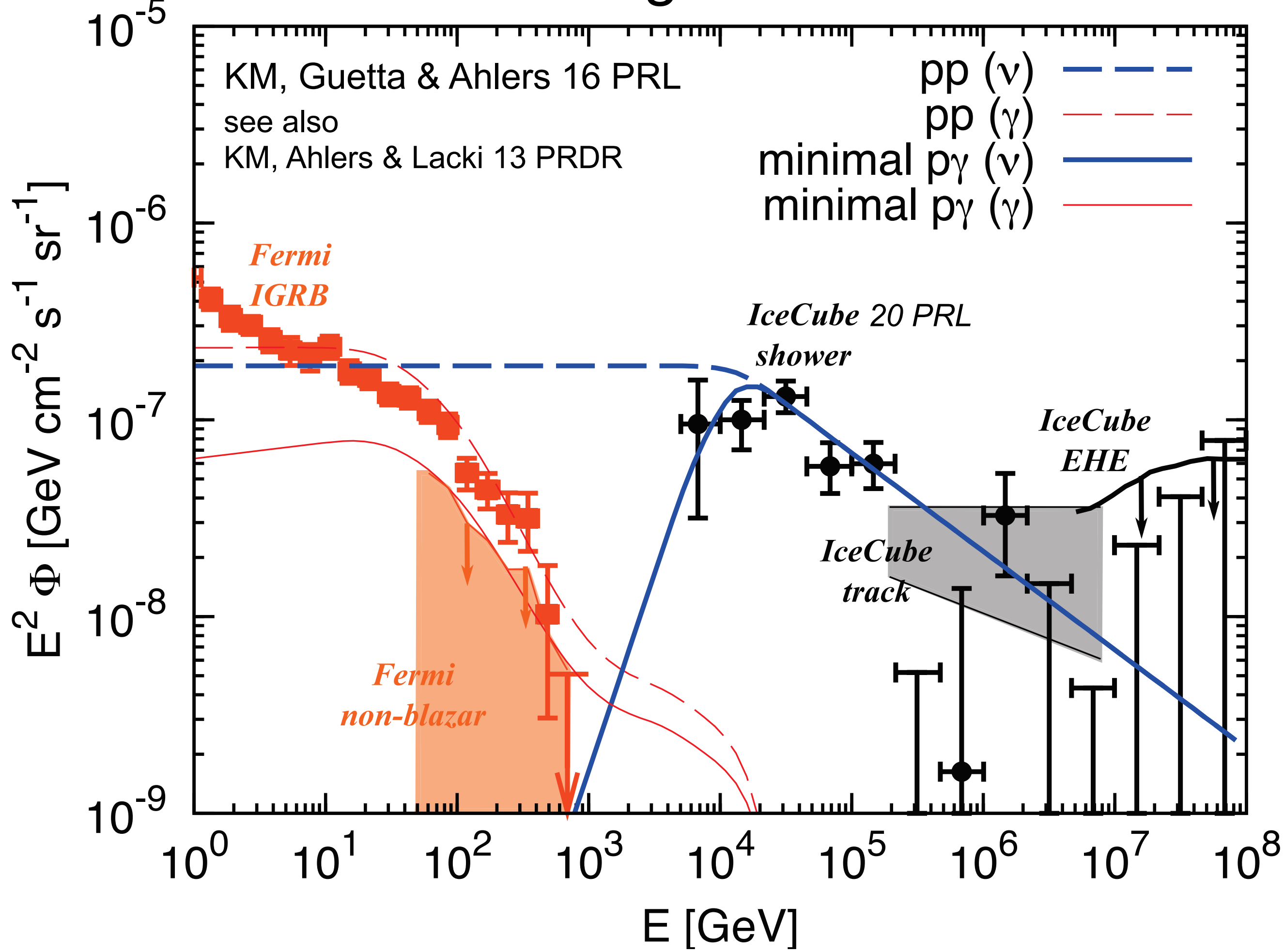
intergalactic space
CR
Milky Way

Extragalactic Multimessenger Connection

10-100 TeV ν IceCube data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



Fermi γ-ray data are violated (>3σ) if ν sources are γ-ray transparent

→ IceCube ν sources: hidden (i.e., γ-ray opaque) cosmic-ray accelerators

Extragalactic Multimessenger Connection

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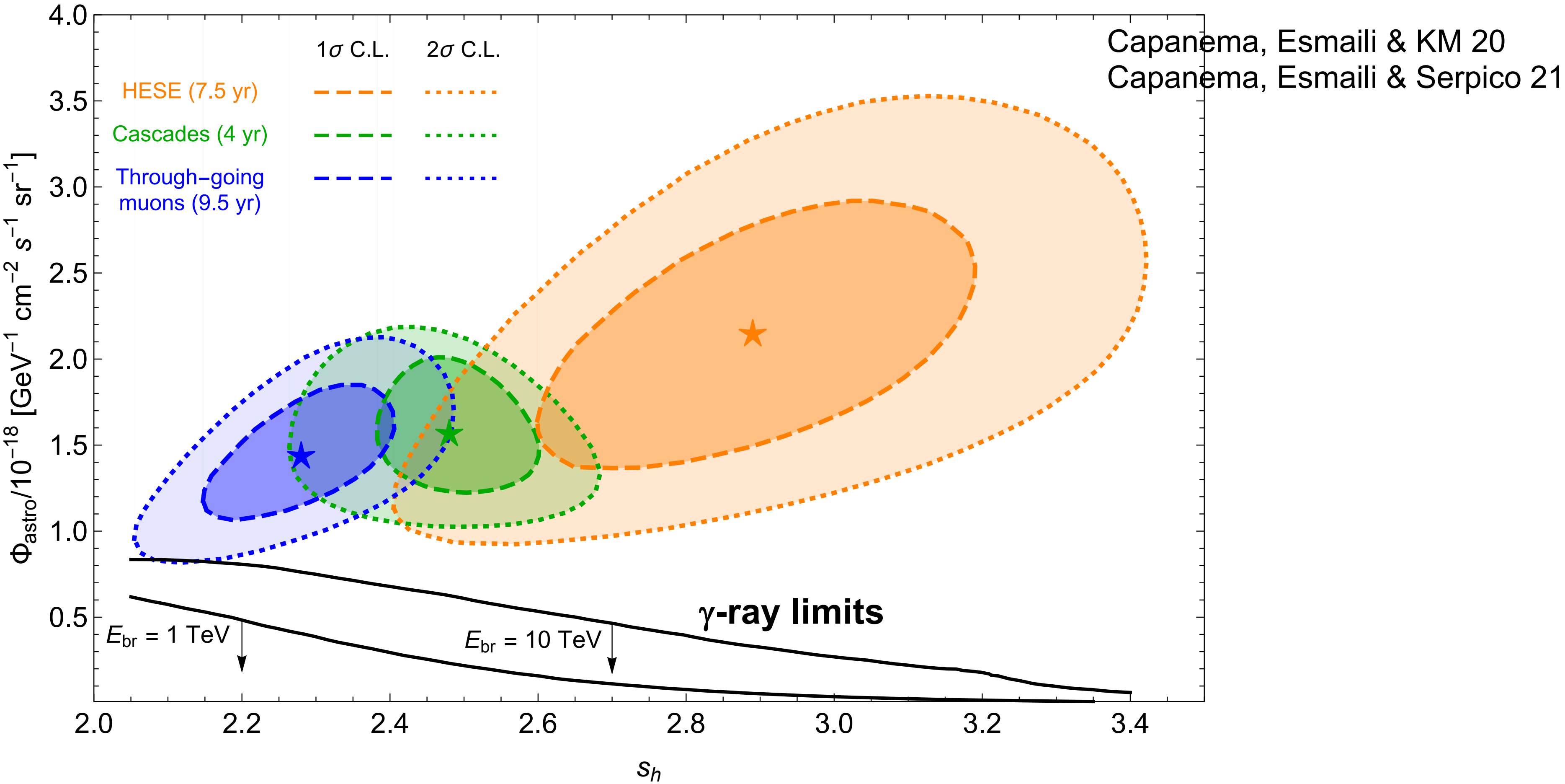

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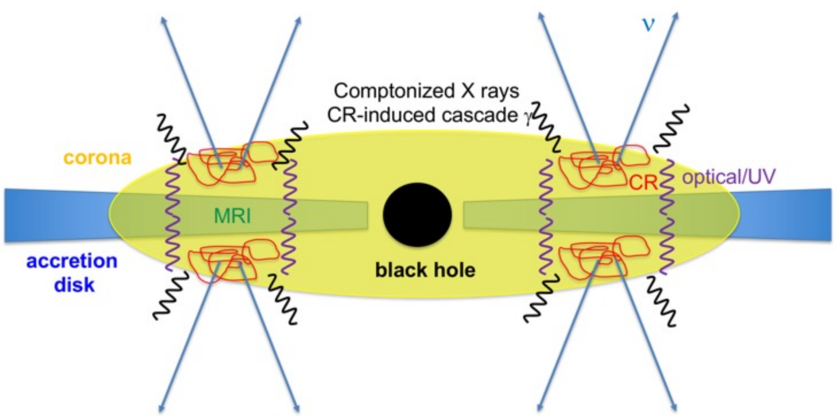
Prediction of Hidden Neutrino Sources

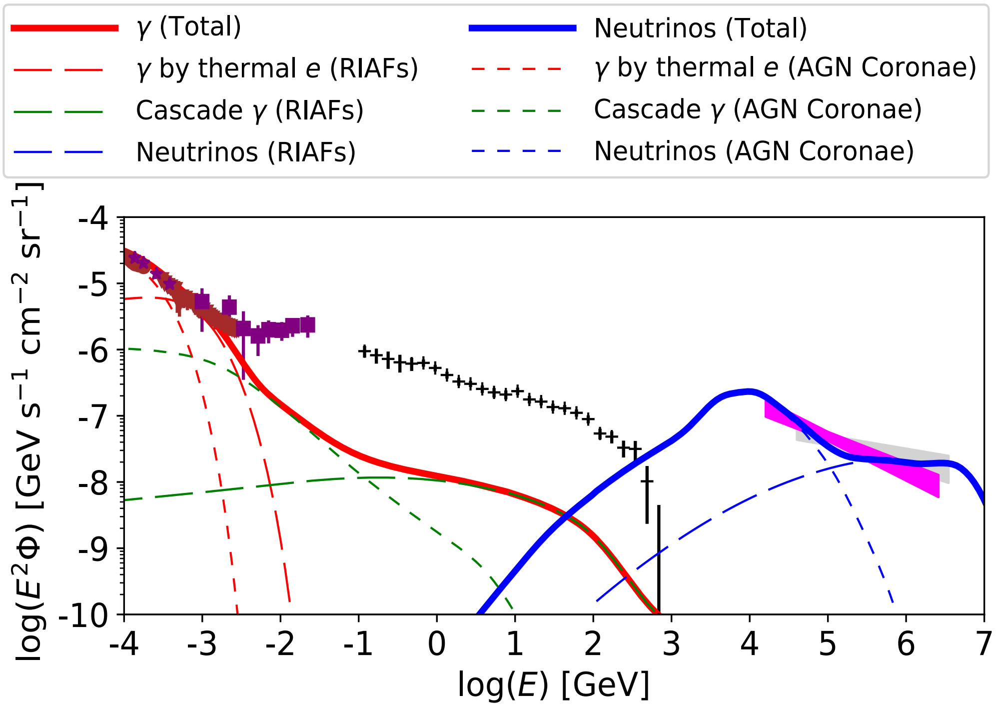
Hidden (i.e., γ-ray opaque) ν sources are actually "natural" in pγ scenarios

γγ→e⁺e⁻ optical depth $\tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}^{\rm eff}}{\sigma_{p\gamma}^{\rm eff}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$

KM, Kimura & Meszaros 20 PRL
Kimura, KM & Meszaros 21 Nature Comm.



accretion disk + "corona"
opt/UV=multi-temperature blackbody
X-ray=Compton by thermal electrons



All-sky 10-100 TeV *neutrino flux can be explained by AGN*

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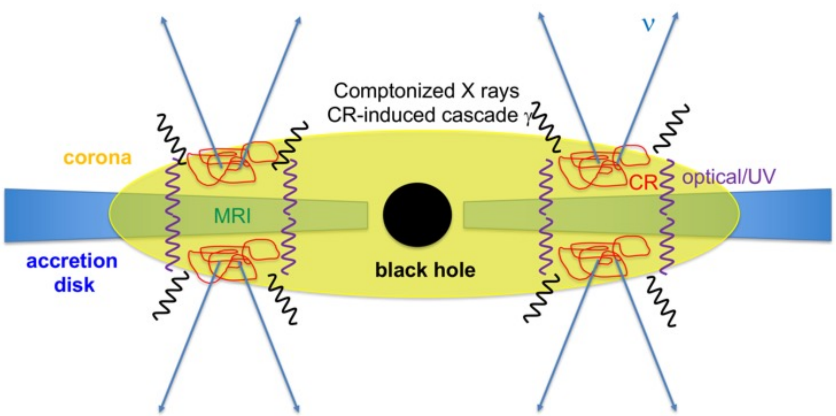

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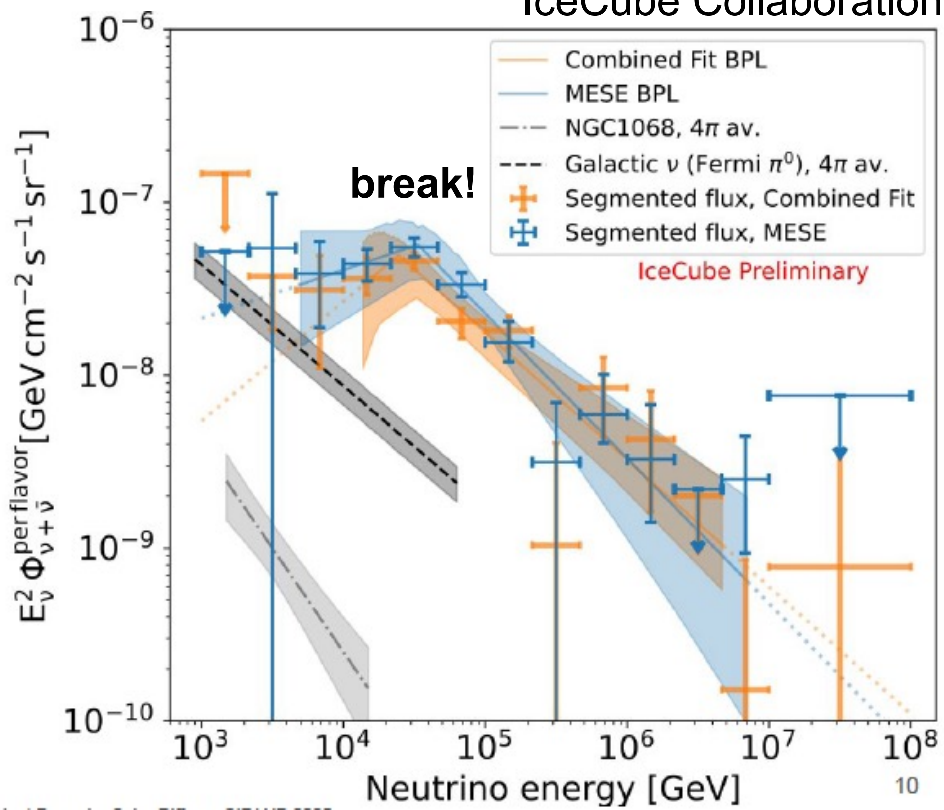
IceCube Collaboration 25



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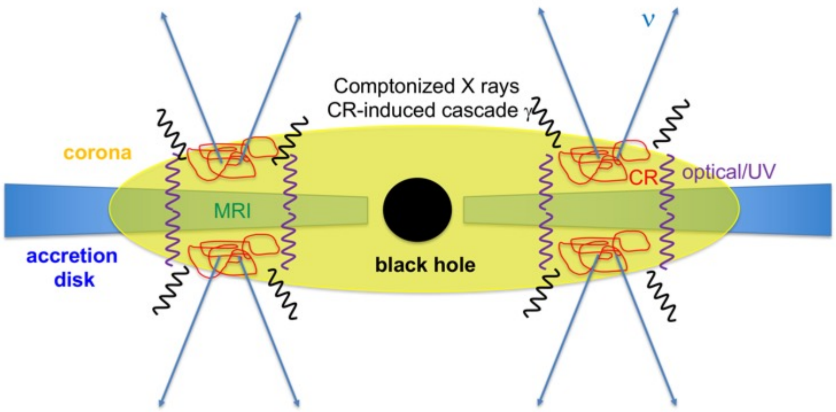

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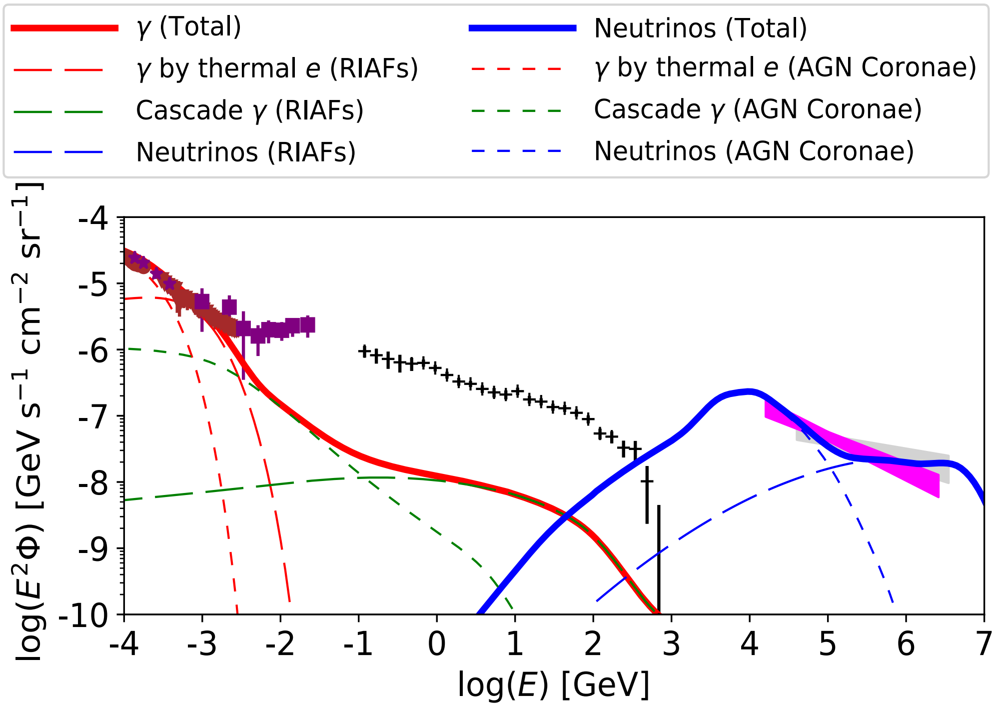


All-sky 10-100 TeV *neutrino flux can be explained by AGN*

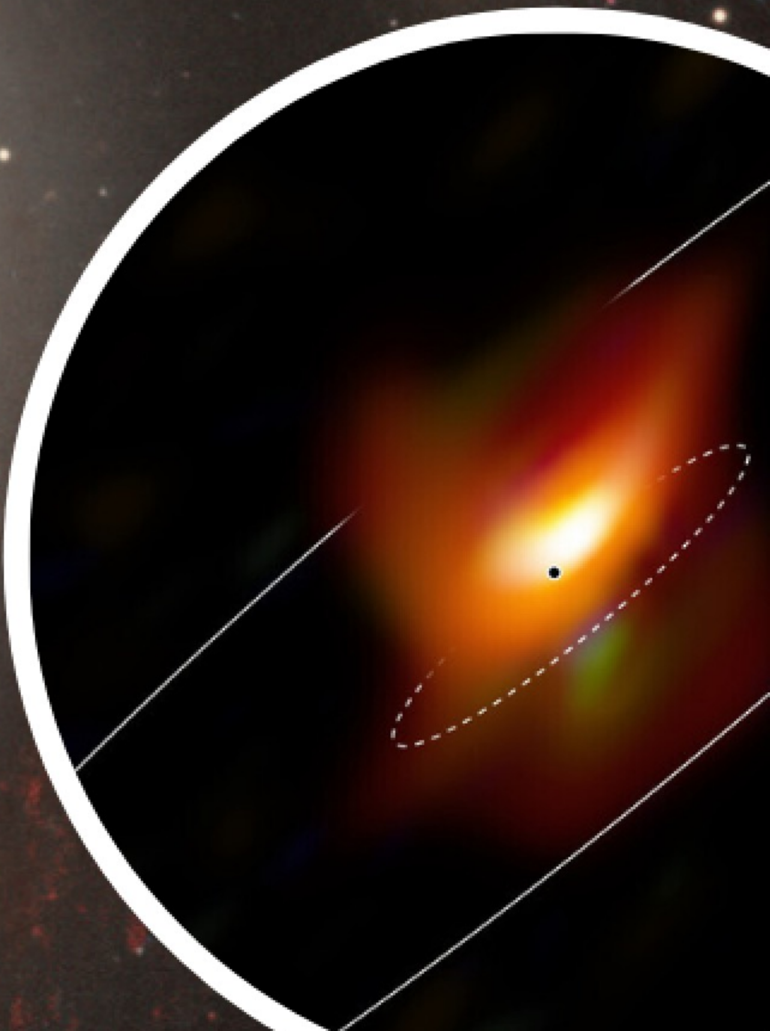
But do such hidden ν source (candidates) exist??

NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

Science JOURNALS AAAS

IceCube Collaboration*†



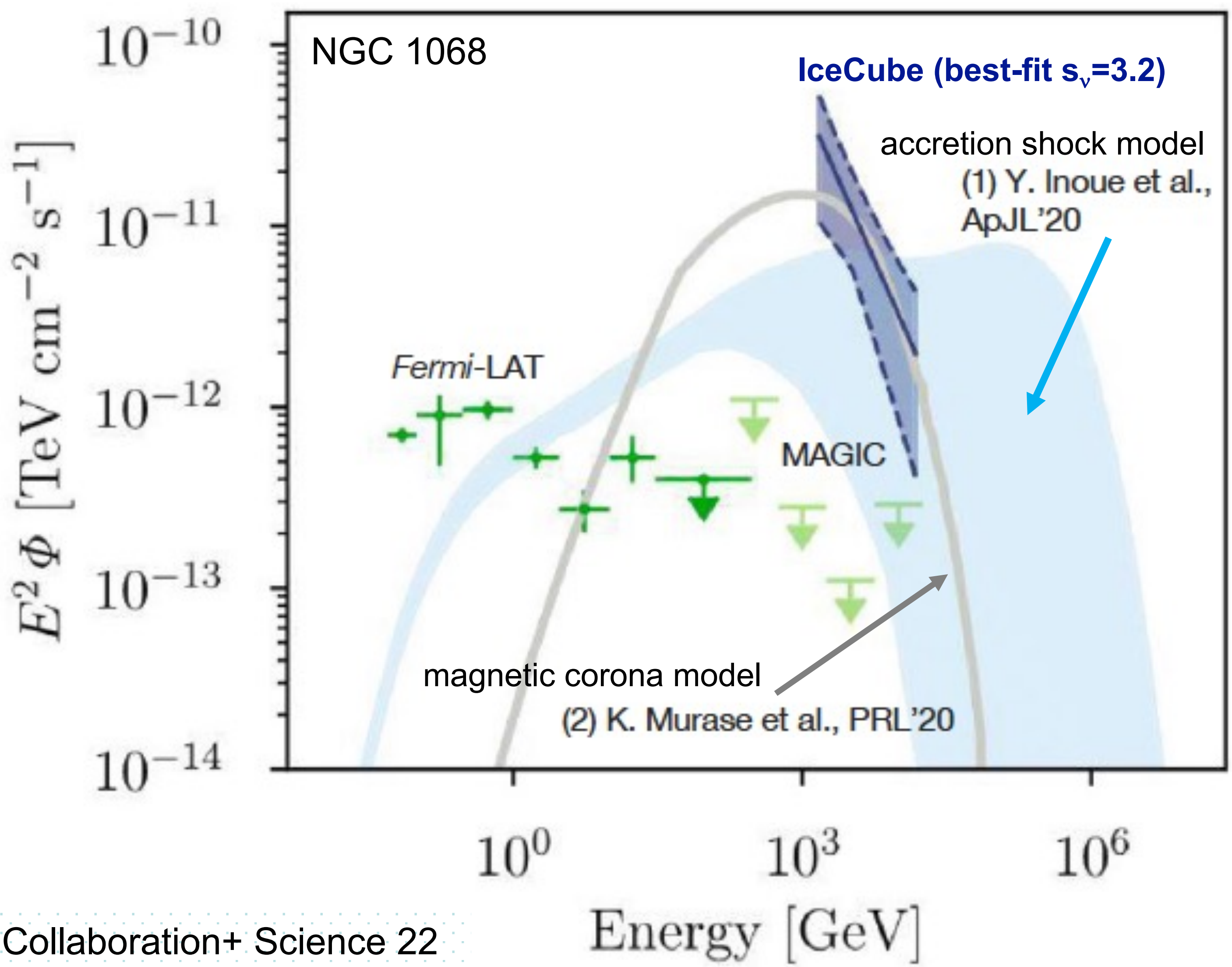
ASTRONOMY

Neutrinos unveil hidden galactic activities

By Kohta Murase[1,2,3]

An obscured supermassive black hole may be producing high-energy cosmic neutrinos

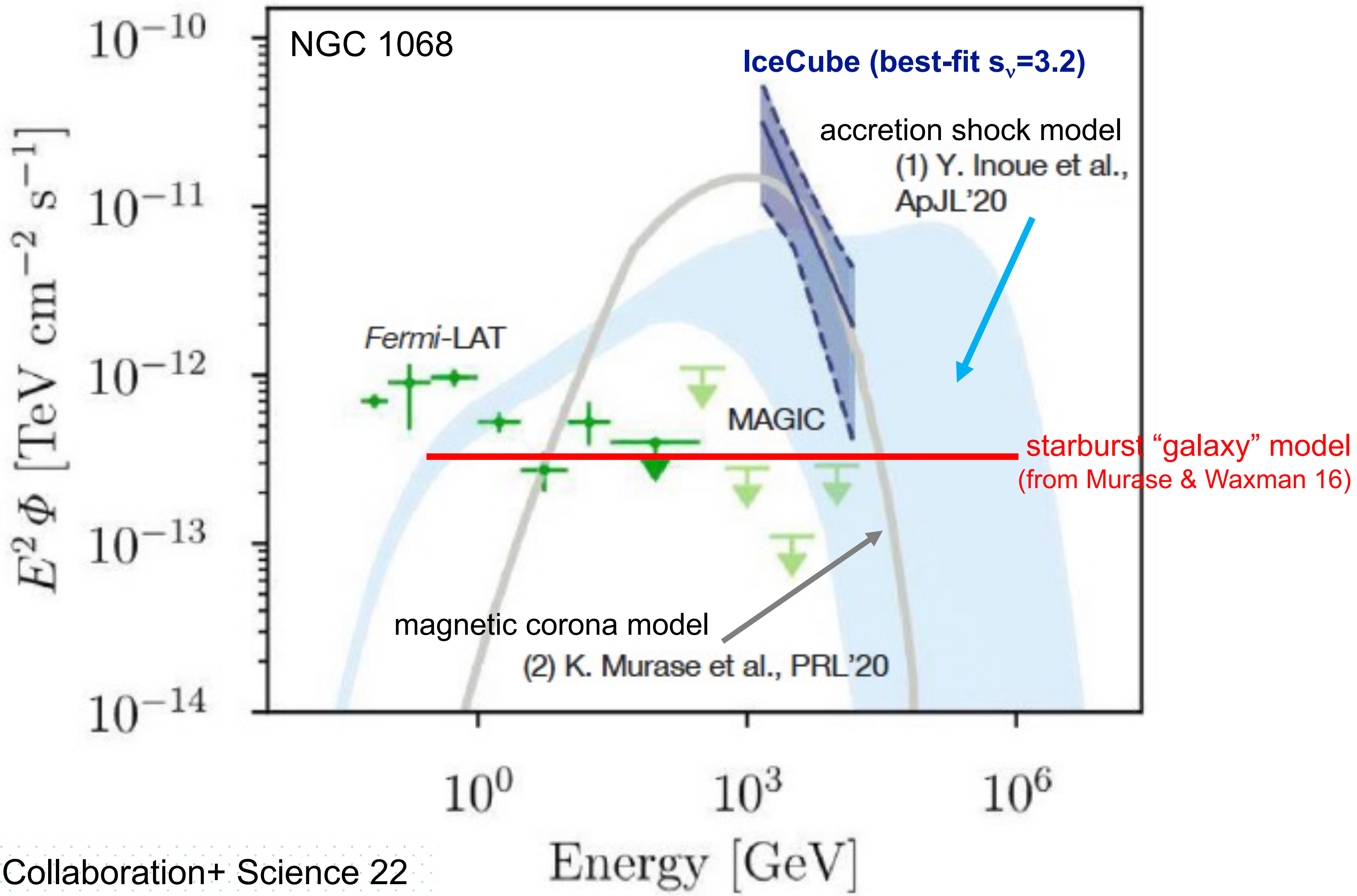
Obscured AGN as a Hidden Neutrino Source



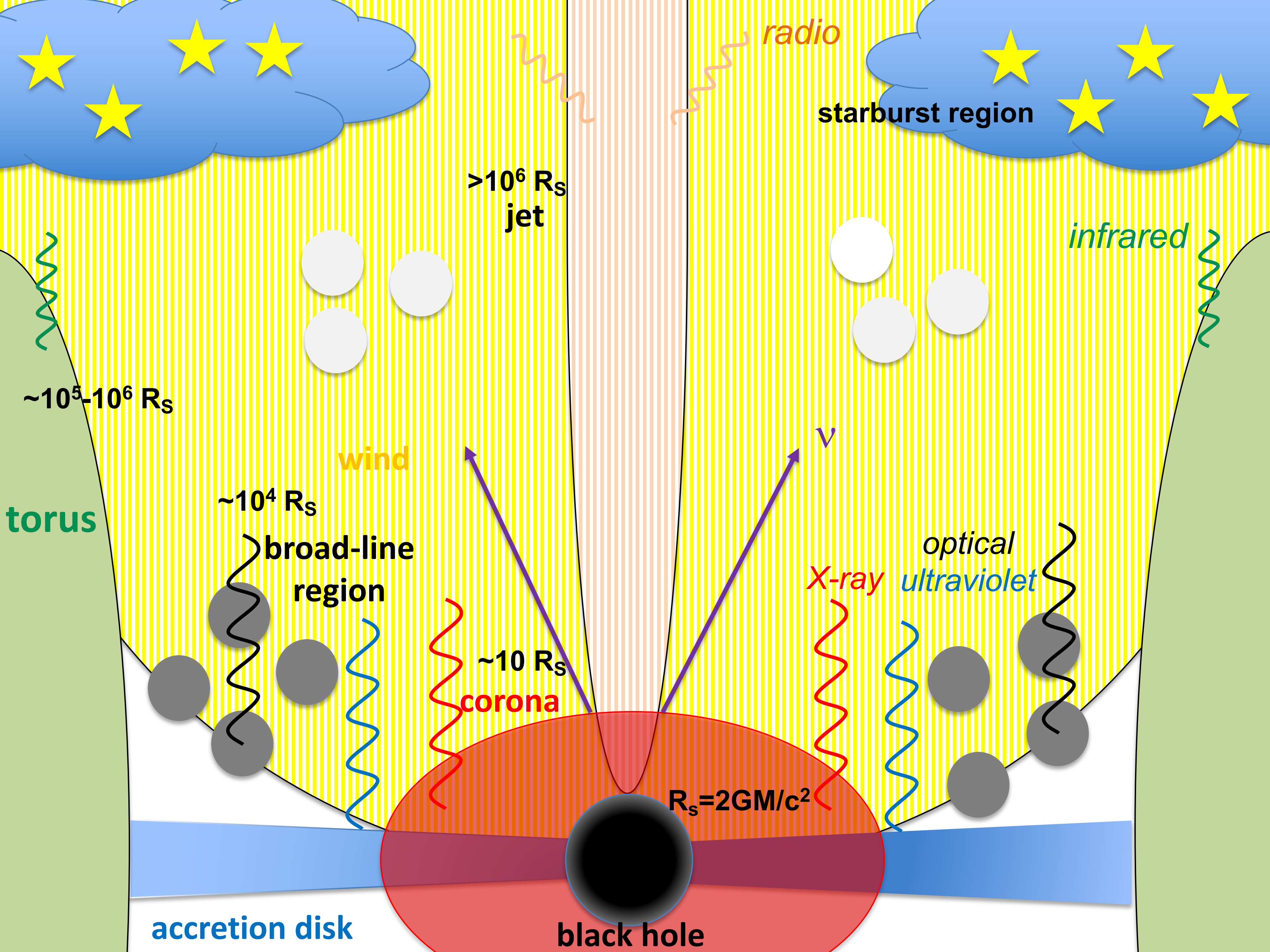
IceCube Collaboration+ Science 22

Obscured AGN as a Hidden Neutrino Source

L_ν~3x10^{42} erg/s << L_{bol} ~ 10^{45} erg/s < L_{Edd} ~ 3x10^{45} erg/s: reasonable energetics



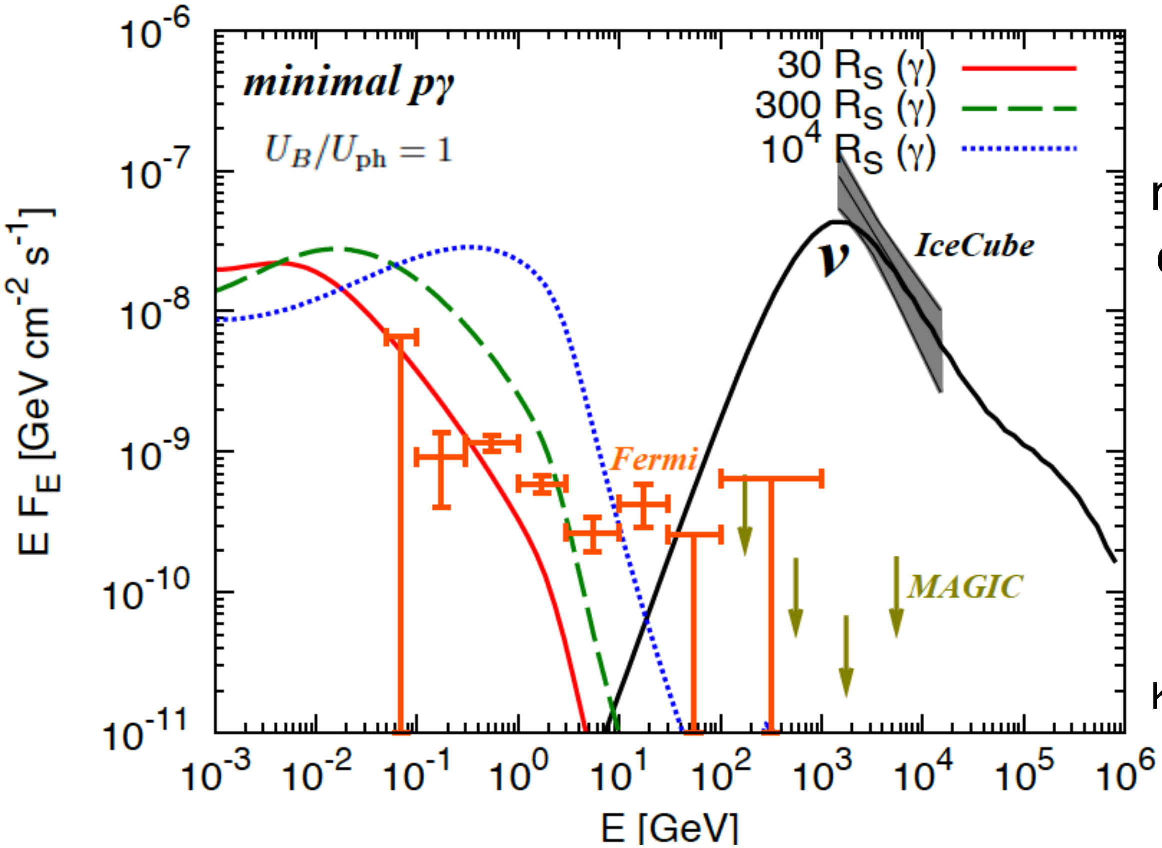
IceCube Collaboration+ Science 22


radio
starburst region
>10⁶ Rs
jet
infrared
~10⁵-10⁶ Rs
wind
ν
~10⁴ Rs
torus
broad-line
region
optical
X-ray
ultraviolet
~10 Rs
corona
Rs=2GM/c²
accretion disk
black hole

Where Do Neutrinos Come from?

$\gamma + \gamma \rightarrow e^+ + e^-$
for 0.1-300 GeV γ rays

$$\tau_{\gamma\gamma} \sim \left(\frac{1}{4\pi}\right)\left(\frac{\sigma_{\gamma\gamma}}{R}\right)\left(\frac{L_X}{m_e c^3}\right)\left(\frac{\varepsilon_\gamma}{m_e c^2}\right) \gtrsim 10$$



model-independent constraint considering elemag. cascade

$R < (10\text{-}30)\ R_S$

(BSM applications (e.g., Herrera & KM 24)
→ constraints on $\sigma_{DM\text{-}p}$ at sub-GeV)

KM 22 ApJL, Das, Zhang & KM 24 ApJ

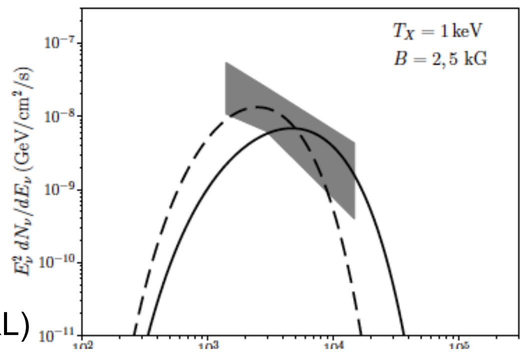
compatible w. pγ calorimetry ($f_{p\gamma}$>1) condition: **$R < 30\text{-}100\ R_S$**

Massive black hole: sub-PeV proton accelerator & ideal beam dump

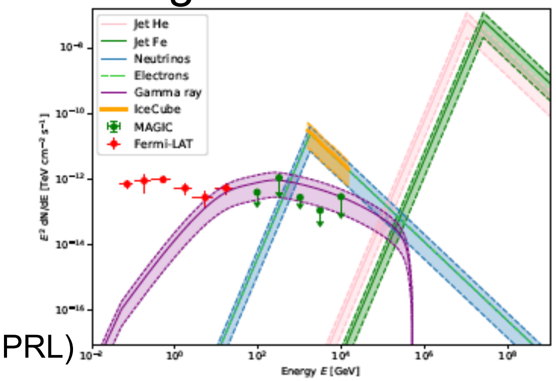
Multimessenger Implications for Neutrino Production Mechanisms

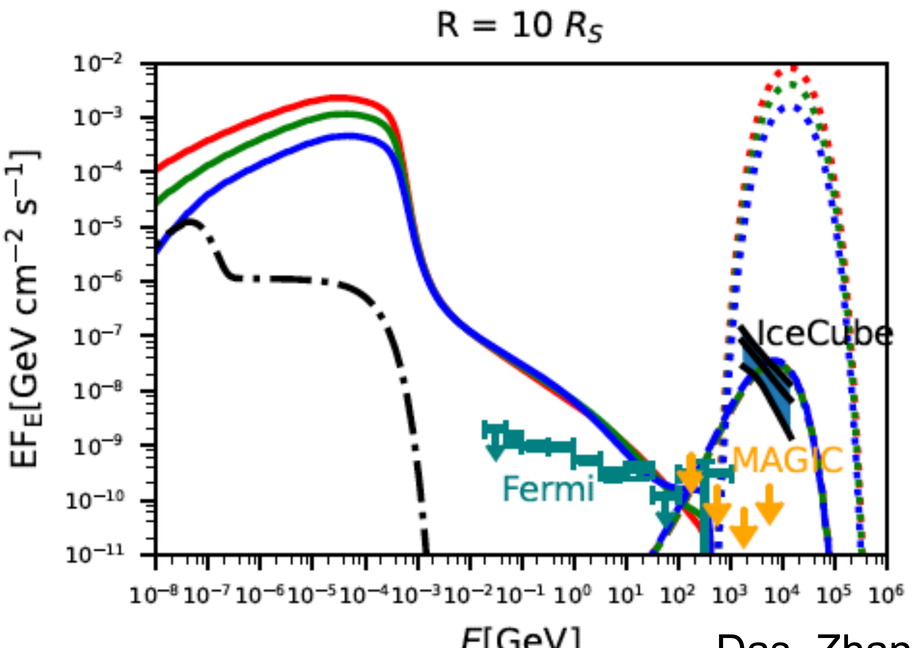
- Multimessenger connection is robust and must be considered
- Exotic models are excluded if relevant processes are consistently included
- Also unlikely by the energetics requirement: $L_{CR} < L_{bol} \sim L_{Edd} \sim 10^{45}$ erg/s

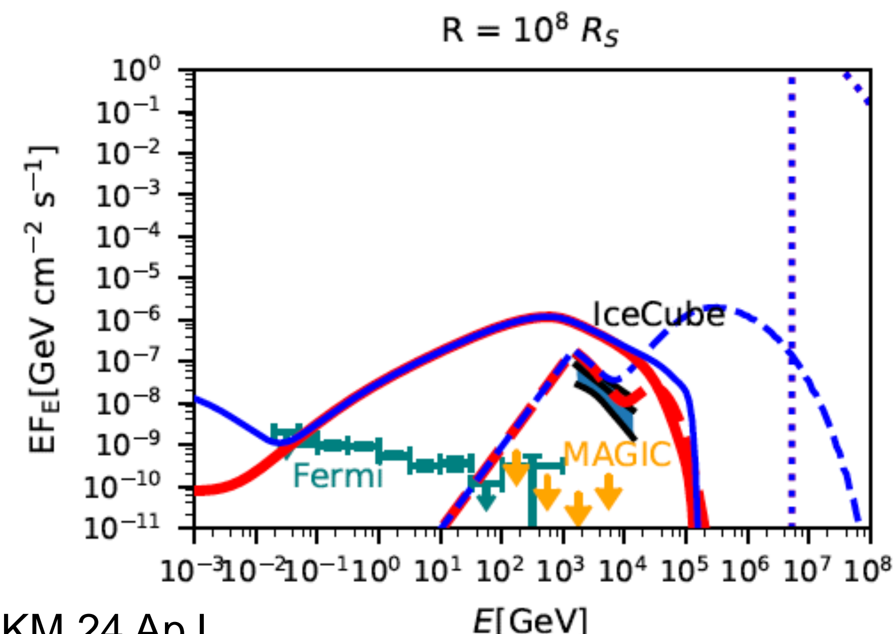
Neutrinos from $\gamma\gamma \to \mu^+\mu^-$
(Hooper & Plant 23 PRL)



Neutrons from photodisintegration
(Yasuda, Inoue & Kusenko 25 PRL)

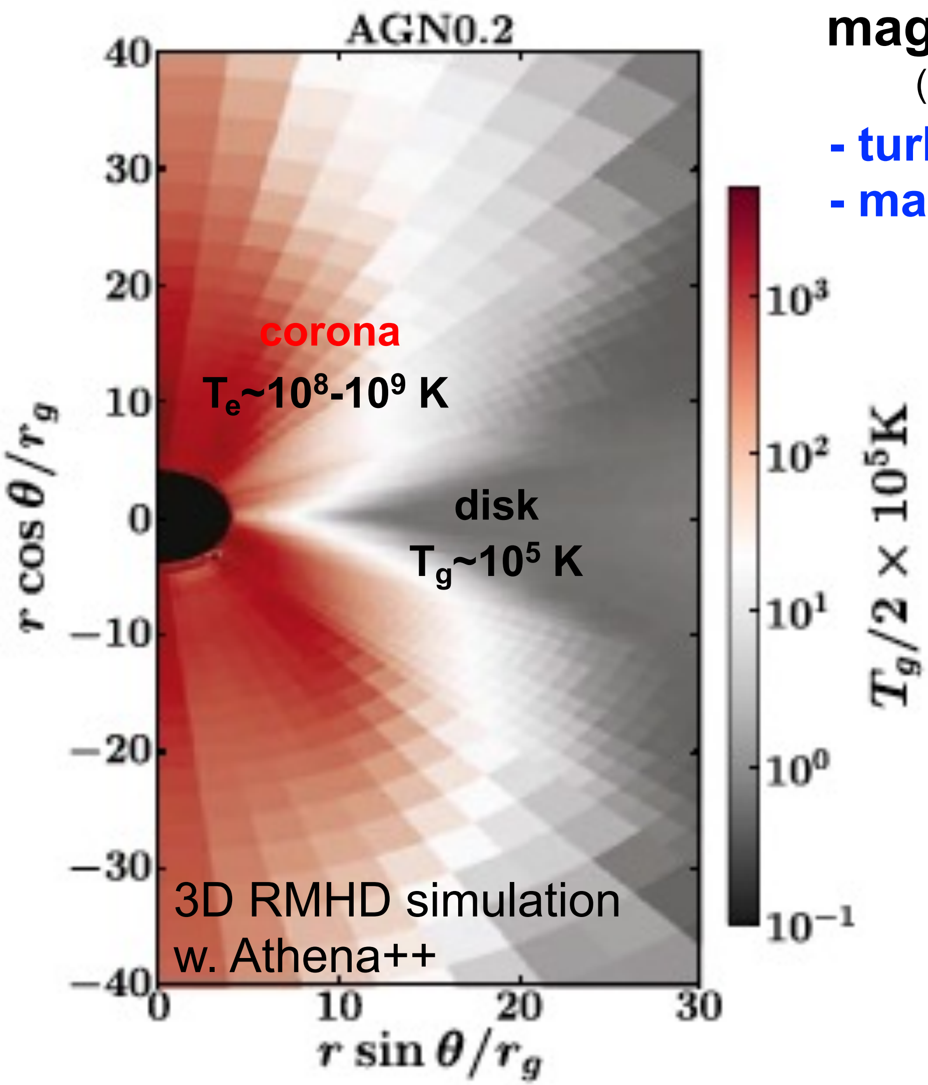






Das, Zhang & KM 24 ApJ

Details of Particle Acceleration Sites? - Unknown



Jiang, Blaes, Stone & Davis 19
see also Miller & Stone 00, Liska+ 22

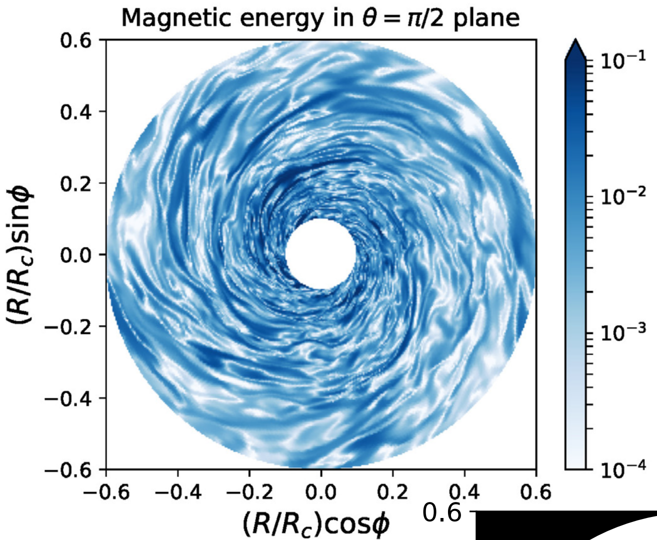
magnetically-powered corona

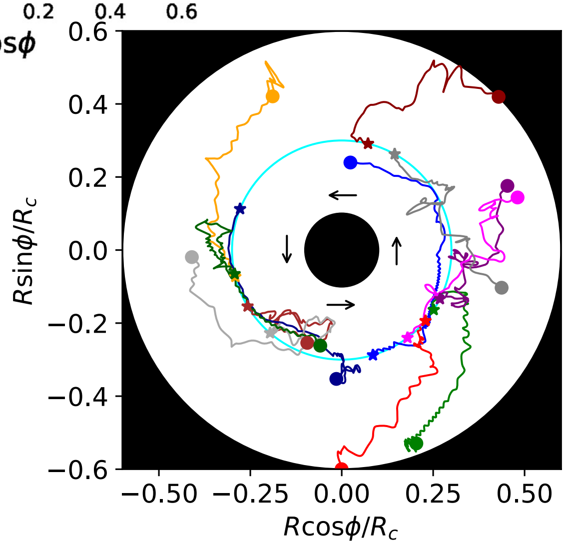
(KM+ 20, Kheirandish, KM & Kimura 21)

- **turbulence/shear**
- **magnetic reconnection**

Particle Acceleration Mechanism in Coronae (Extra)?

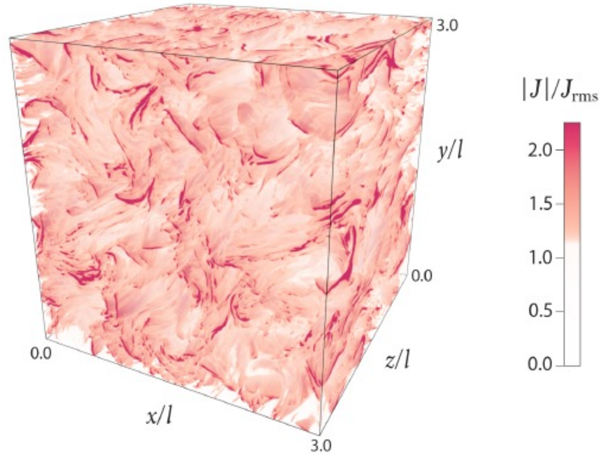
stochastic acc. in 3D global MHD simulations

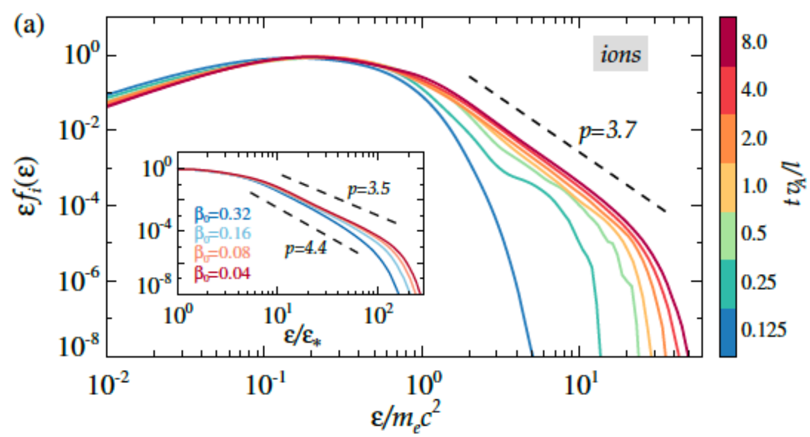




Kimura, Tomida & KM 19 MNRAS
Sun & Bai 21 MNRAS

stochastic acc. in 3D PIC simulations



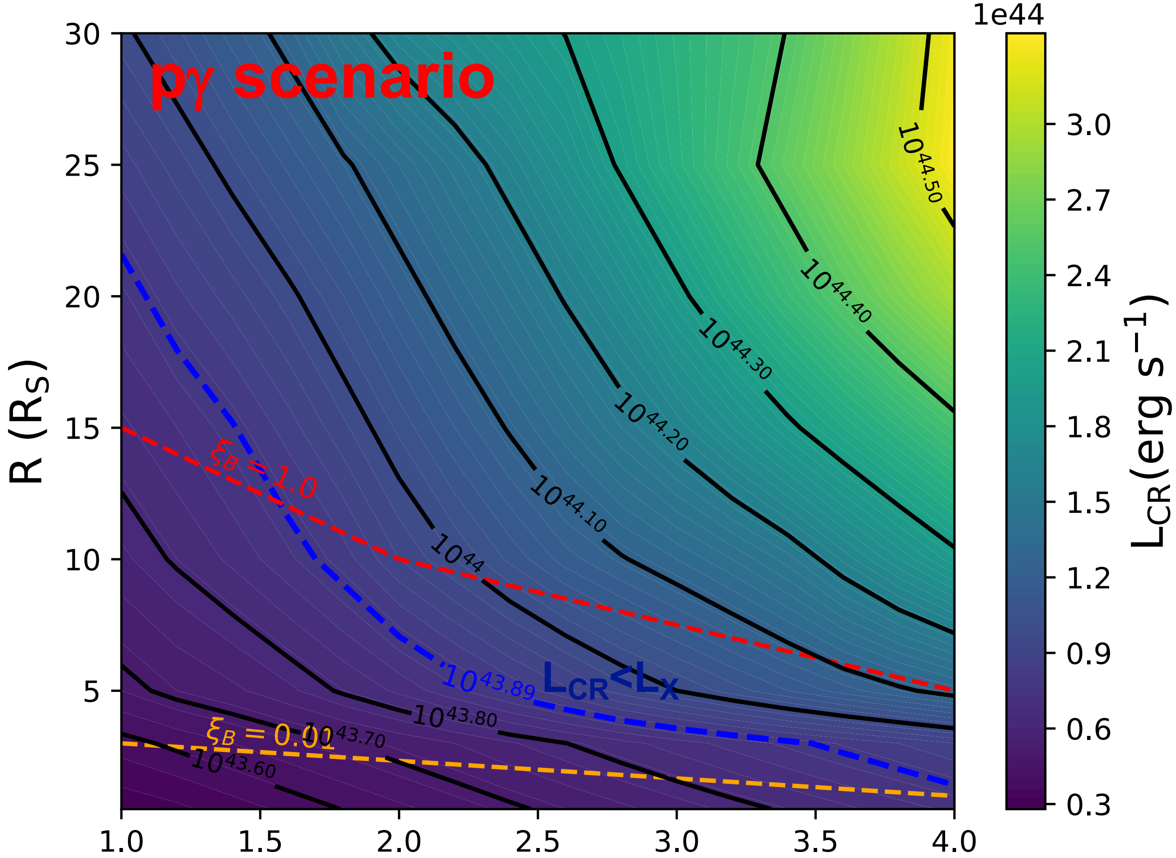


see also Hoshino 15 PRL, Zhdankin+ 17 PRL
Comisso & Sironi 22

High-energy neutrinos now meet the frontier of astroplasma physics

Multimessenger Implications for Coronae as ν Production Sites

Multimessenger constraints are improved by updated Fermi-LAT analyses (Ajello, KM & McDaniel 23 ApJL)



Das, Zhang & KM 24 ApJ

CR energetics constraint

$L_{CR} < L_X$

→ **R <~ (1-20) R_S**

γ-ray constraint

$\xi_B = U_B/U_{ph}$ >~0.1

synchrotron cascade

→ **R <~ (5-15) R_S**

$\xi_B = U_B/U_{ph}$ <~0.1

inverse-Compton cascade

→ **R < R_{ISCO} unlikely**

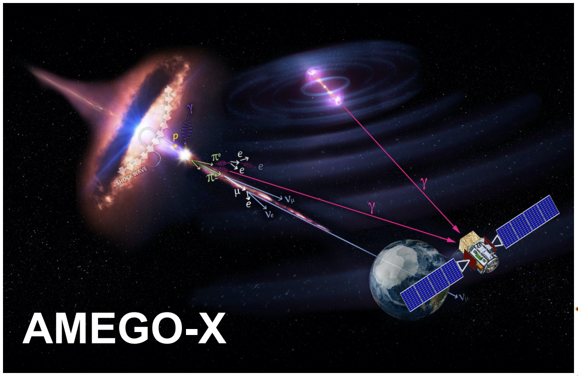
If ν emission comes from X-ray coronae, plasma should be magnetically dominated

$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\rm BH} m_p}{\sqrt{3}\zeta_e \sigma_T R^2 U_\gamma}\xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3}\zeta_e \lambda_{\rm Edd}}\right)\xi_B^{-1}$$

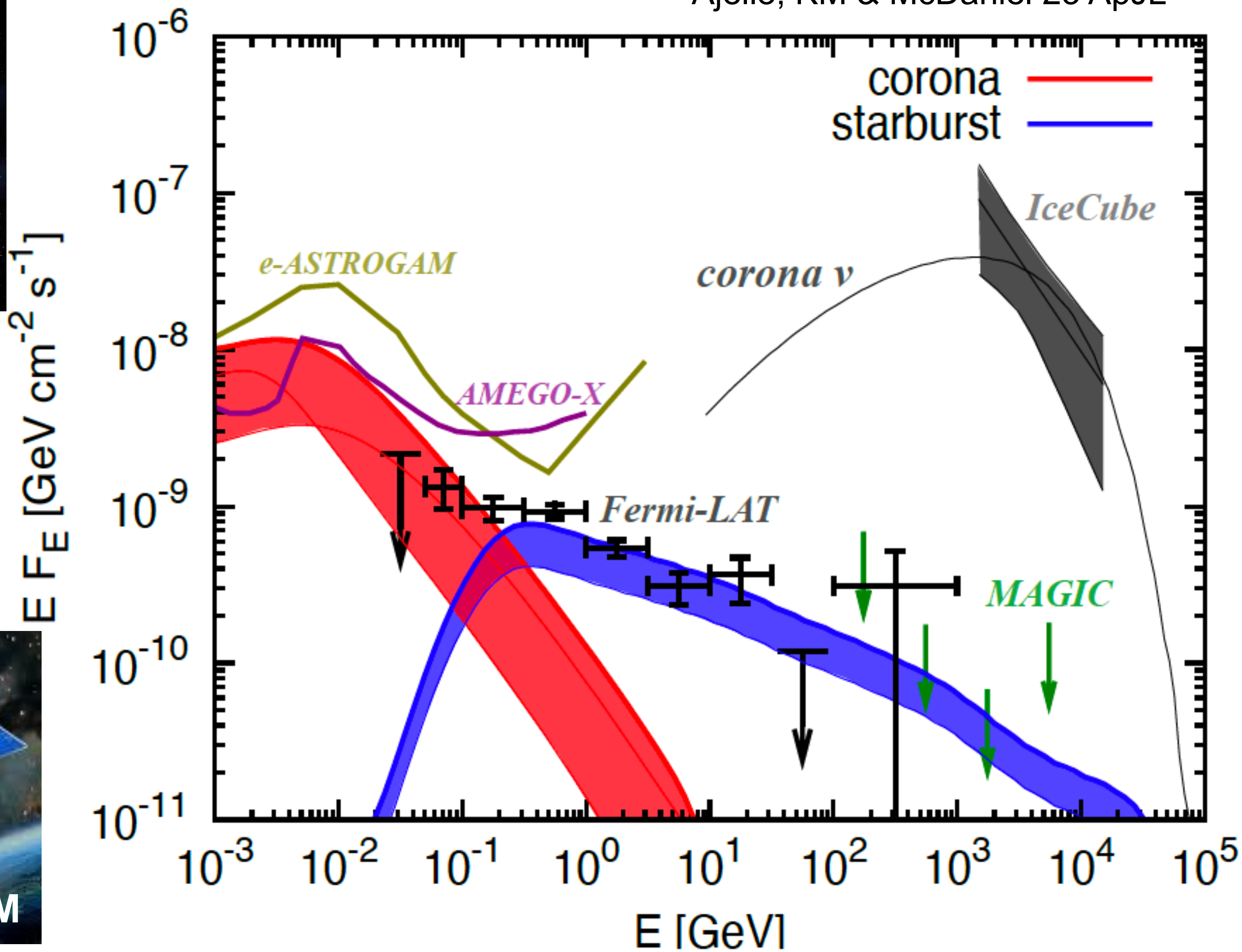
τ_T~0.1-1 for X-ray corona, λ_{Edd}~0.5

ξ_B >~ 0.1 leads to **β <~ 1**

γ Rays Must Not Be Gone: Hints & Future MeV γ-Ray Tests



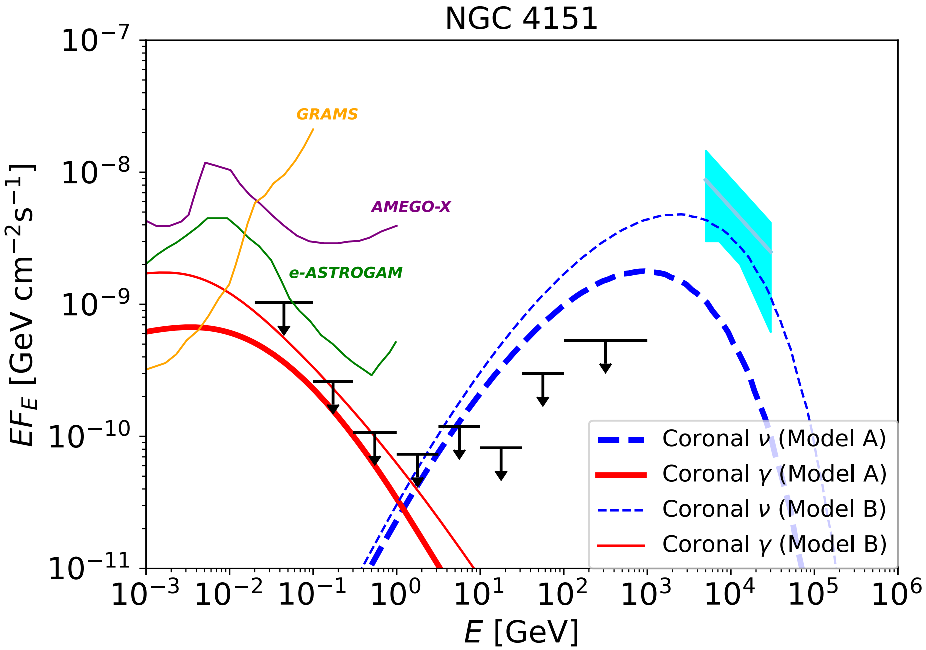
Ajello, KM & McDaniel 23 ApJL

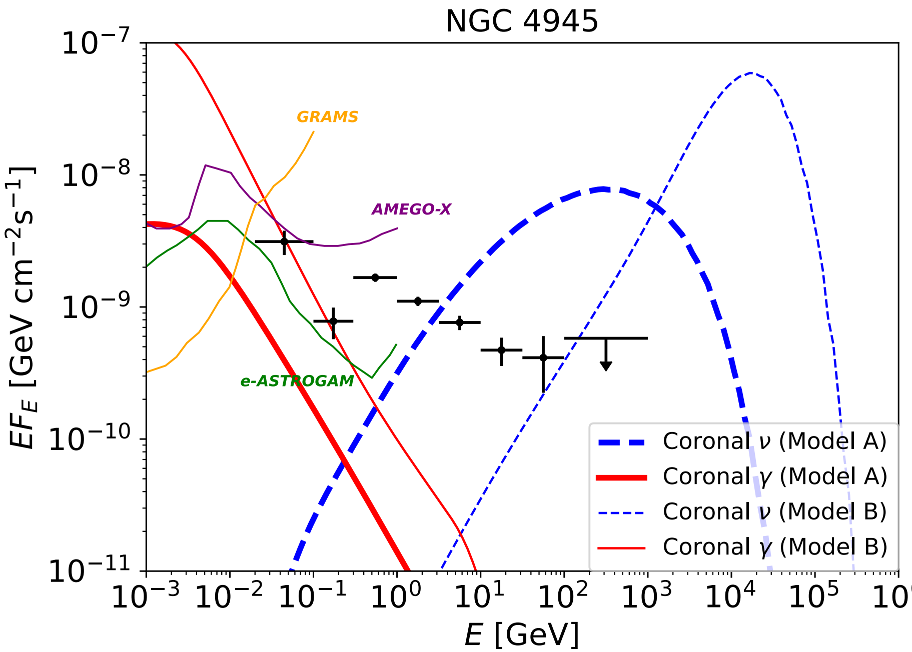


- Corona model prediction: cascade γ rays should appear in the MeV range
- Fermi γ-ray observation: sub-GeV “excess” over the starburst component

Other AGNs?

- \- Corona model prediction: ν luminosity ~ intrinsic X-ray luminosity
  brightest in north: NGC 1068, NGC 4151 (KM+ 20 PRL, KM+ 24 ApJL)
  brightest in south: NGC 4945, Circinus
  \- IceCube ν TeV excess: (IceCube Collaboration 24a, 24b, 24c)
  NGC 1068 (~4σ), NGC 4151 (~3σ), Circinus (~3σ for AGNs in south)
  \- Fermi γ-ray sub-GeV excess:
  NGC 1068, NGC 4945



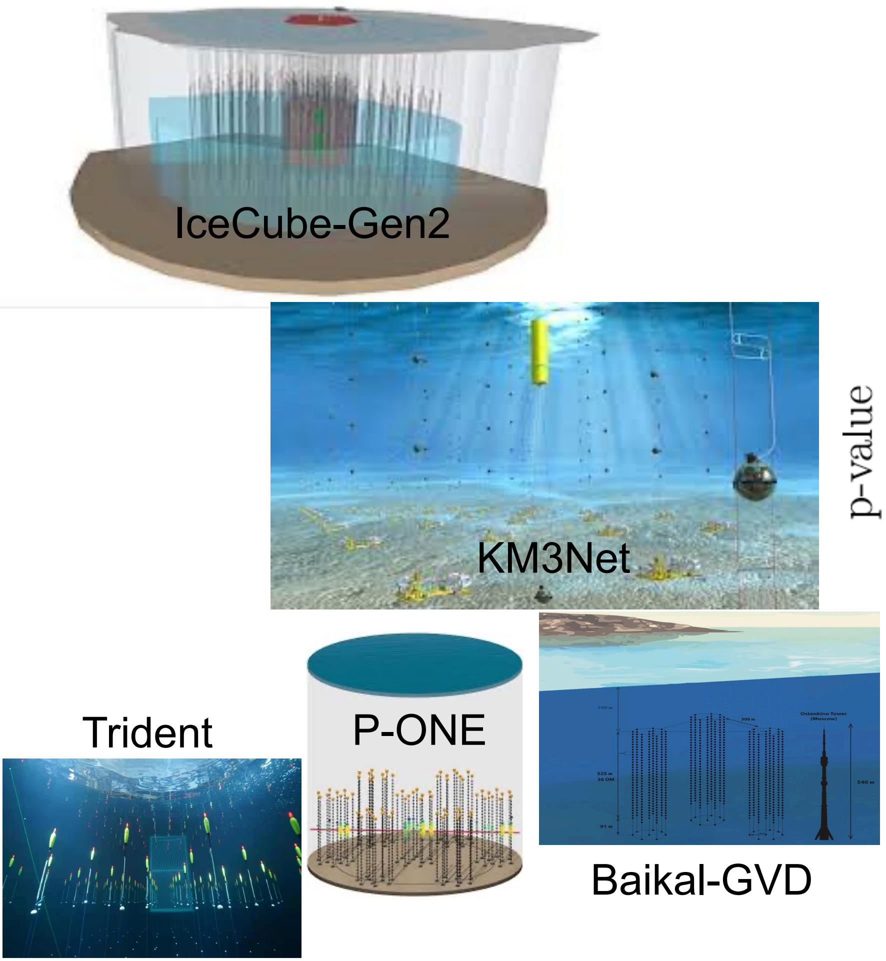


Model A: same as NGC 1068
Model B: P_{CR}/P_{vir}=8%

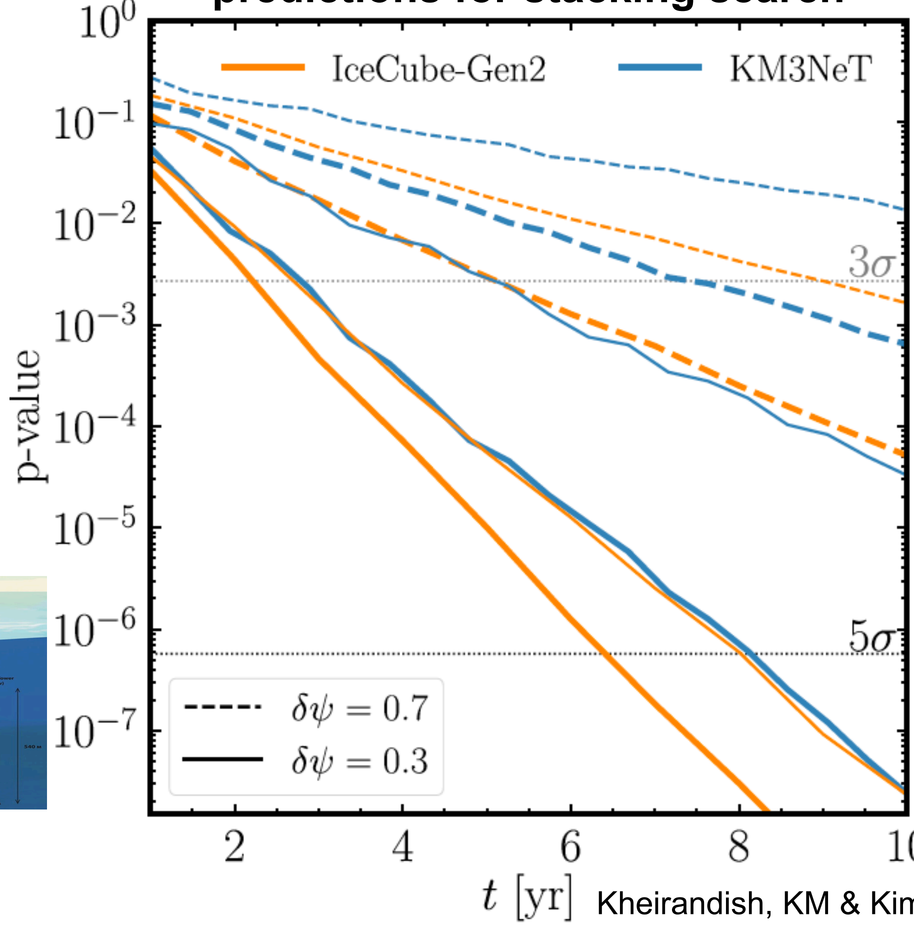
KM, Karwin, Kimura, Ajello & Buson 24 ApJL

Further Tests with Neutrinos

- 2.6σ with 8 yr upgoing ν_μ events and IR-selected AGN (IceCube 22 PRD)
- Good news for KM3Net/Baikal-GVD/P-ONE: many bright AGN in south



predictions for stacking search

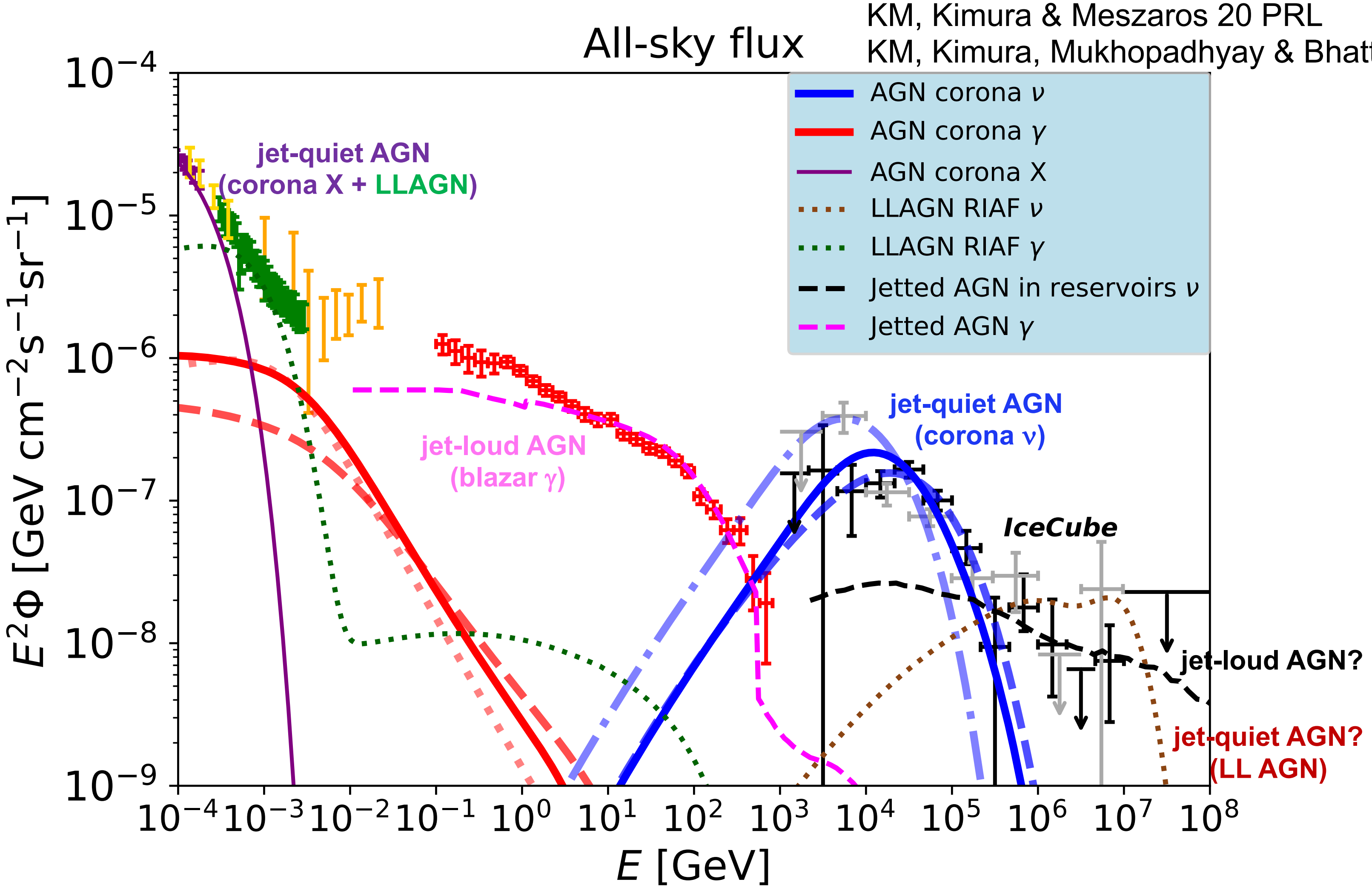


Kheirandish, KM & Kimura 21 ApJ

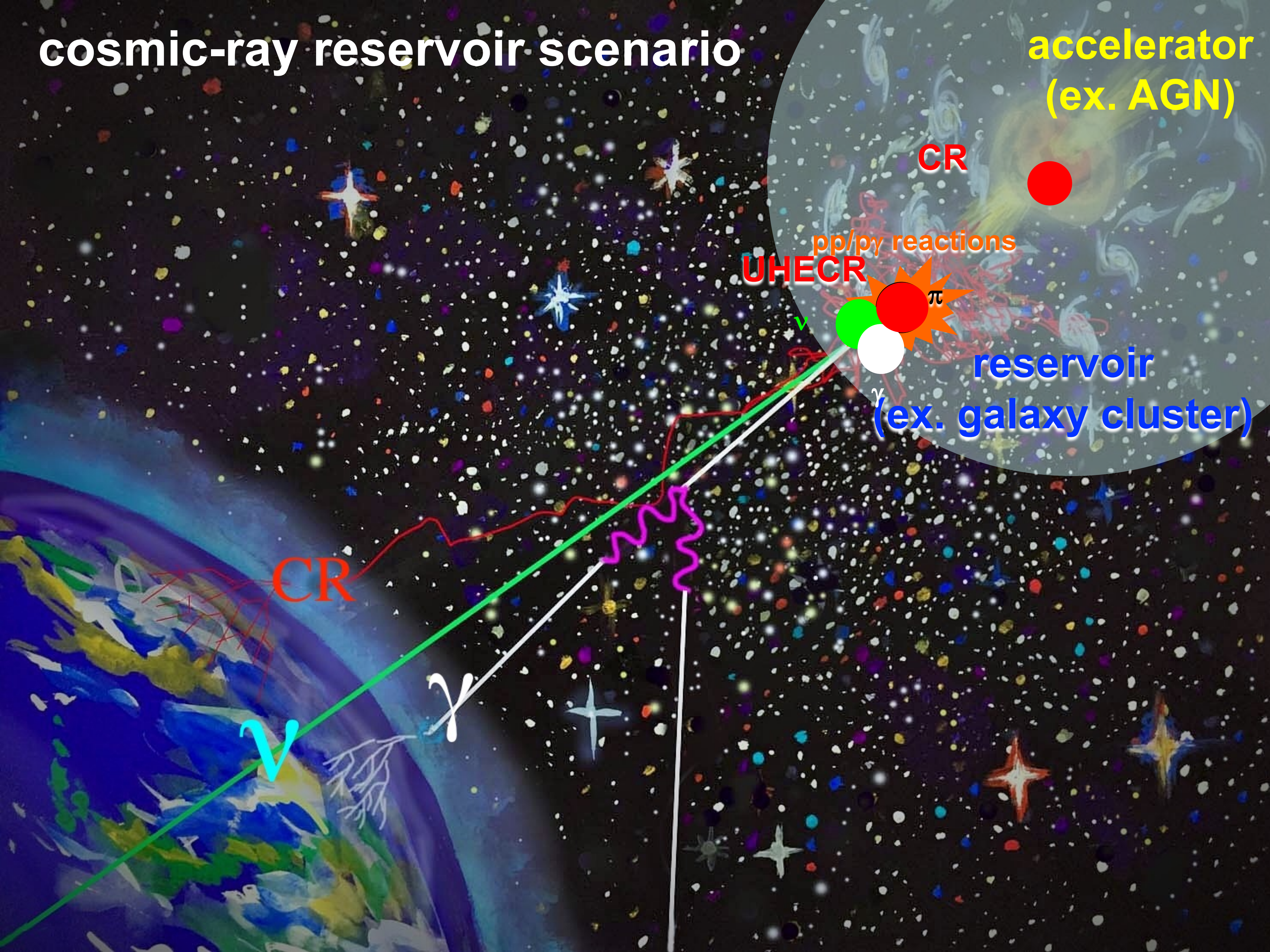
testable w. near-future data or by next-generation neutrino detectors

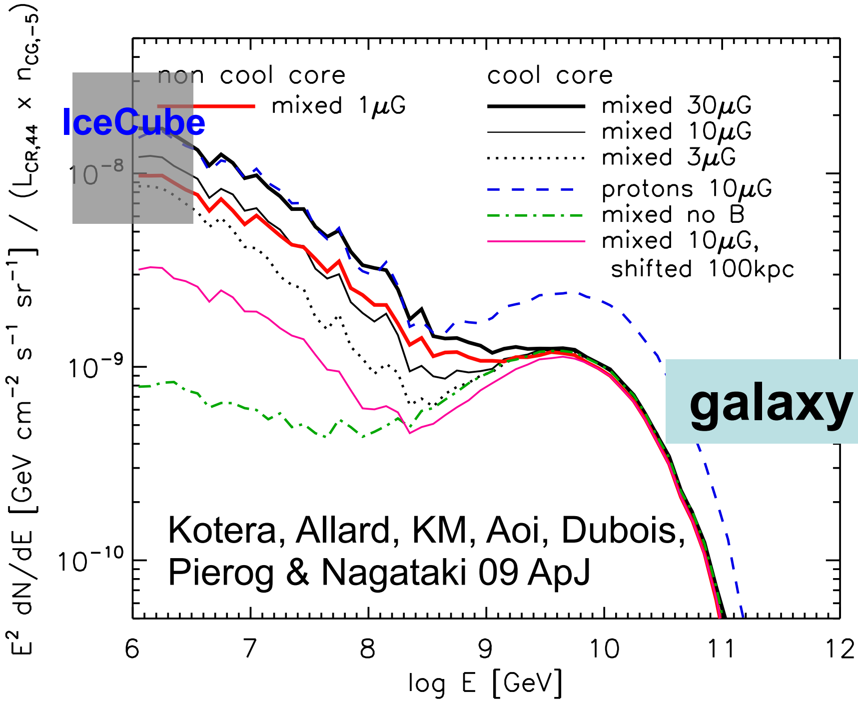
AGN Can Dominate the All-Sky ν and X-/γ-Ray Fluxes

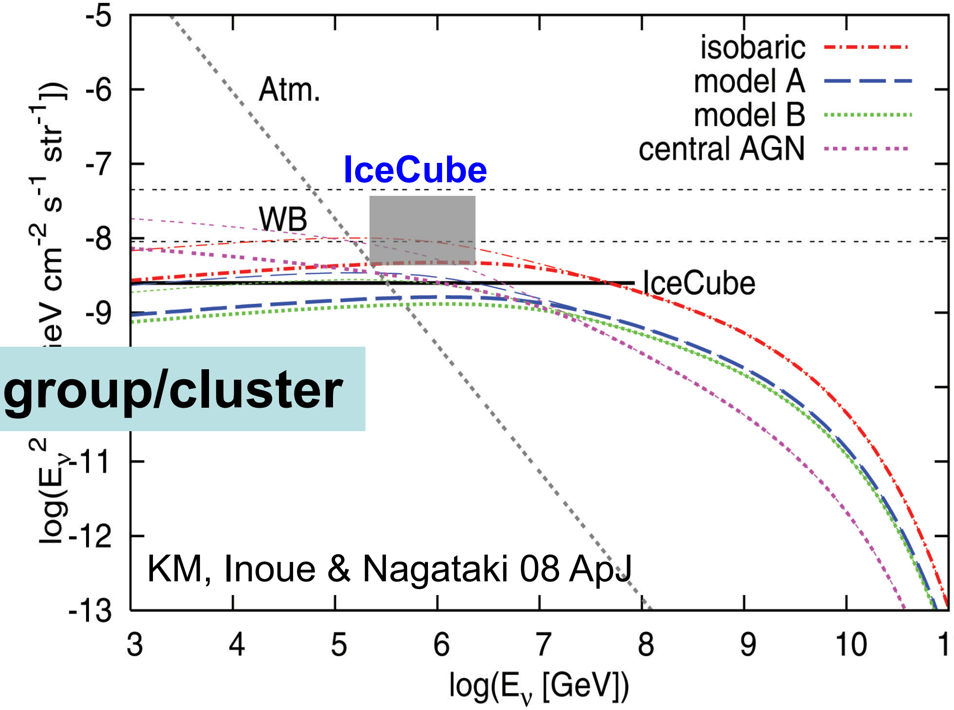
KM, Kimura & Meszaros 20 PRL
KM, Kimura, Mukhopadhyay & Bhattacharya 25

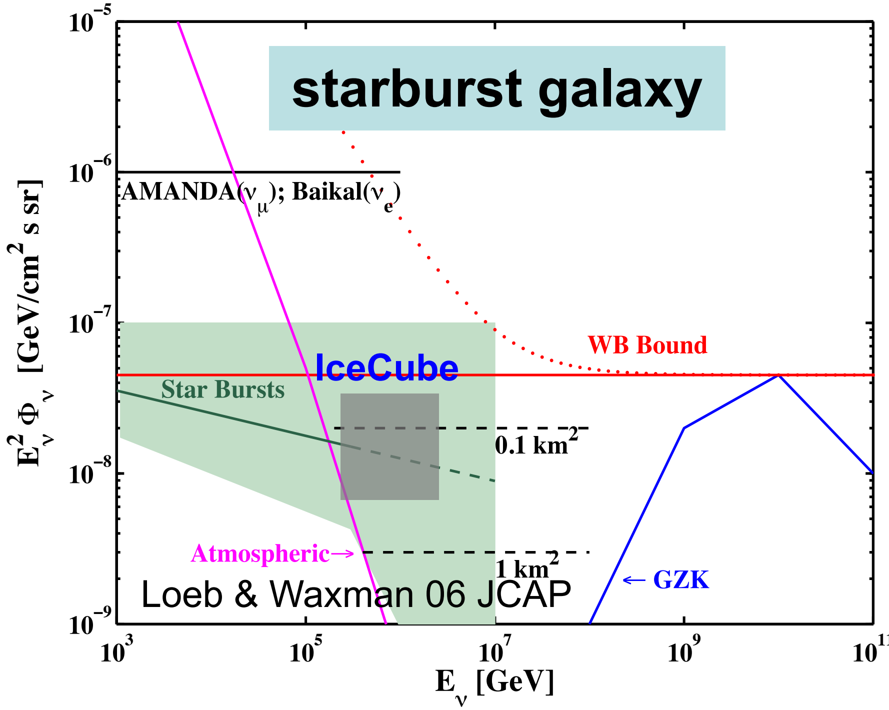


- Jet-quiet AGN (coronae) can explain the all-sky neutrino intensity self-consistently.
- But >100 TeV neutrinos may originate from different source classes – "more open"


cosmic-ray reservoir scenario
accelerator
(ex. AGN)
CR
pp/pγ reactions
UHECR
π
ν
γ
reservoir
(ex. galaxy cluster)
CR
γ
ν



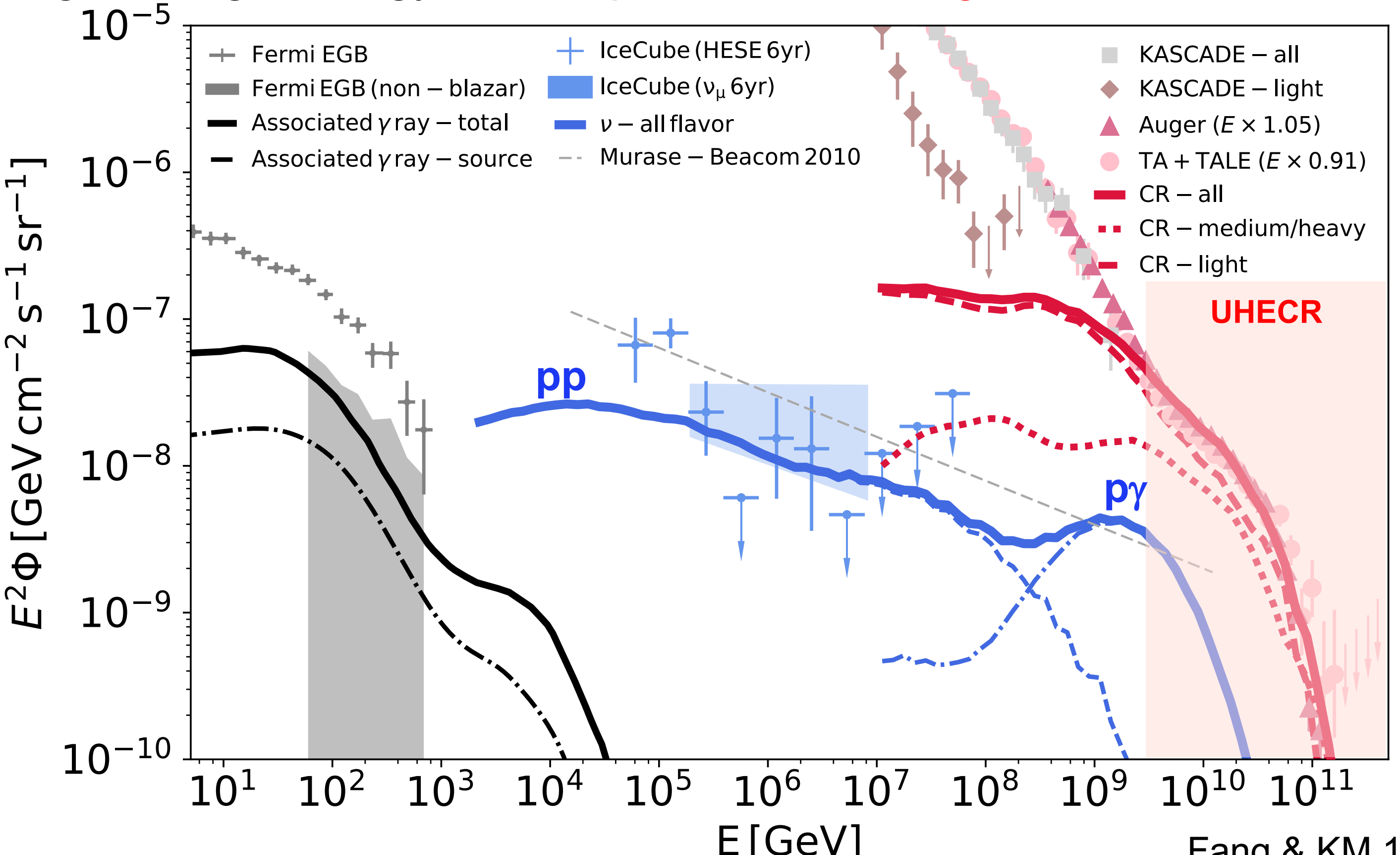




>0.1 PeV IceCube data: consistent w. earlier theoretical predictions

High-Energy Astro-Particle Grand-Unification?

> PeV νs may be physically related to UHECRs and isotropic diffuse γ rays (unification)
Exploring ultrahigh-energy νs is important for testing the ν-UHECR connection



Fang & KM 18 Nature Phys.
(cf. Unger, Farrar & Anchordoqui 15)

- Jetted AGN as "UHECR" accelerators
- Neutrinos from confined CRs & UHECRs from escaping CRs
- Smooth transition from PeV (source ν) to EeV (cosmogenic ν)

Supermassive black holes as multimessenger sources?
Need more statistics for "discoveries"

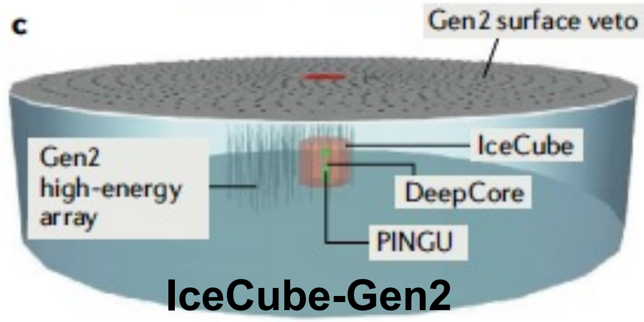
Jet-quiet AGN
Hidden ν sources (NGC 1068…)

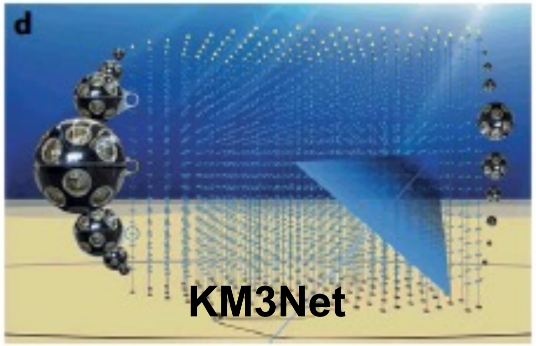
Jetted AGN
Unification, flares (TXS 0506+056…)

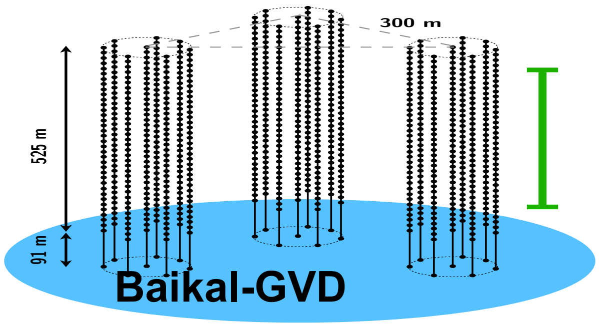
Tidal disruption event

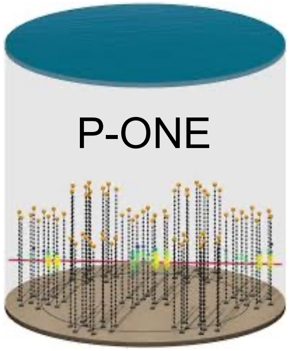
Bright Future (w. Some Patience)

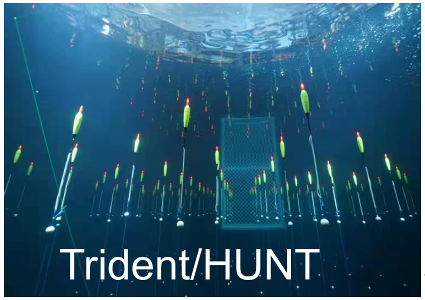
AMEGO-X

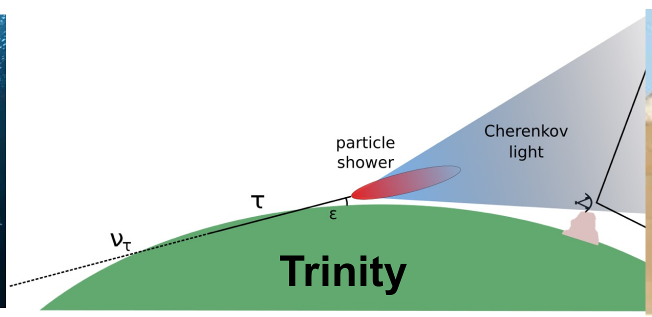


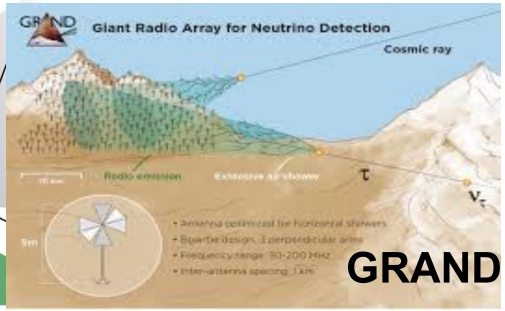


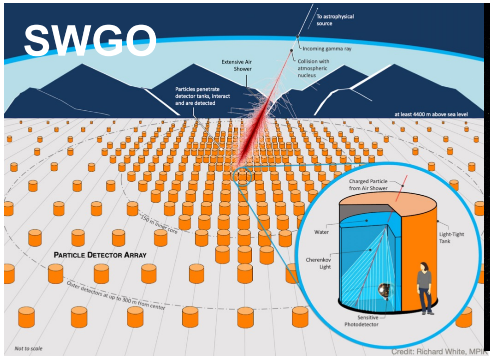


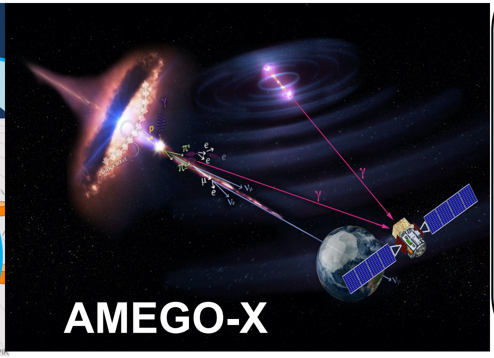












More multimessenger data in the next decade will enable us to test the proposed models

Summary

Success of multimessenger approaches to high-energy ν sources

all-sky sub-TeV γ flux ~ all-sky sub-PeV ν-ray flux ~ all-sky UHECR flux

Multimessenger quests for the origin of high-energy cosmic neutrinos

- Galactic: multimessenger connection is now observed
  supporting the hadronic origin of the Galactic diffuse γ-ray flux
- Extragalactic: multimessenger connection requires γ-ray hidden ν sources
  AGN (jet-quiet): could be the dominant sources of the all-sky neutrino flux
  NGC 1068: evidence of a hidden ν source **(need more statistics!)**
  → νs should be produced within 10-30 Schwarzschild radii
  "unique" probe of non-thermal phenomena powered by black holes
  testable w. planned MeV γ-ray and ν detectors

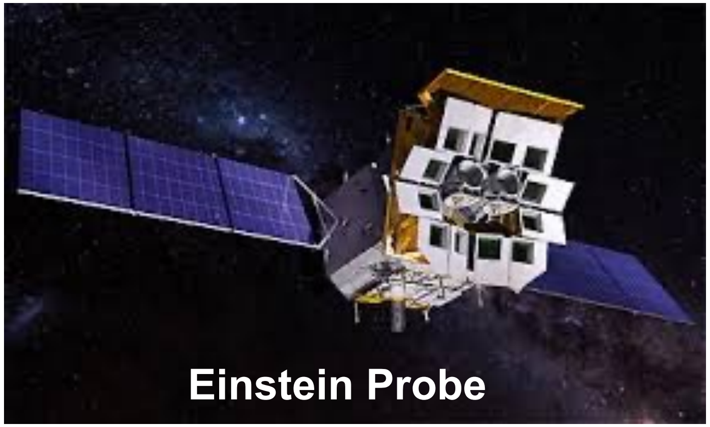
High-energy multimessenger transients

- Strategic multimessenger searches in the Rubin era

Multimessenger quests for particle physics (bonus)

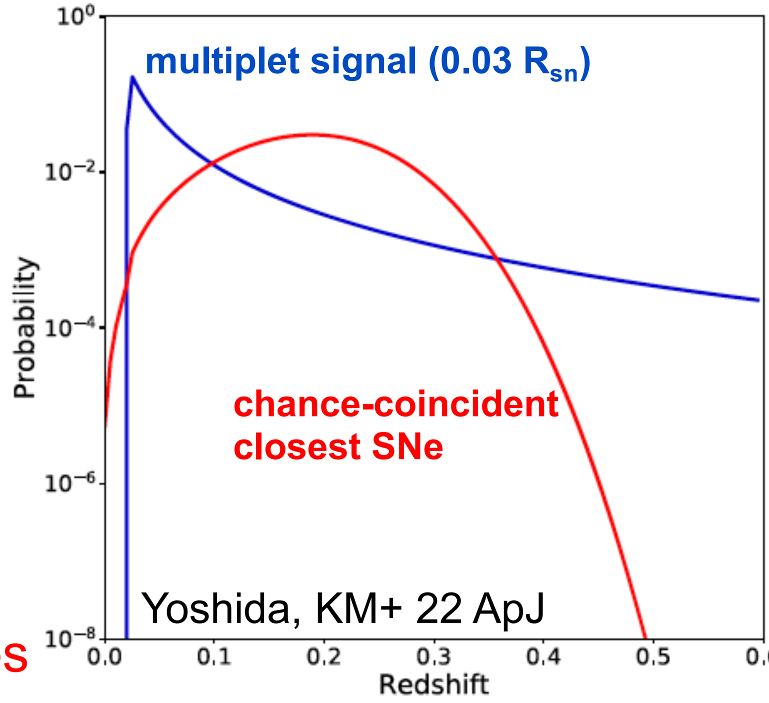
- Example: unique probe of very heavy dark matter up to the GUT scale

No Patience? Game Changing in ν Transient Searches



- Supernovae, tidal disruption events, low-luminosity gamma-ray bursts…
  (e.g., Stein+ 21 Nature Astronomy, Reusch+ KM 21 PRL)
- Testability of models have been limited by the number of detected transients

- Neutrino singlet followups would need spectroscopic information
- Neutrino multiplet followups
- Multimessenger alert (e.g., AMON) followups

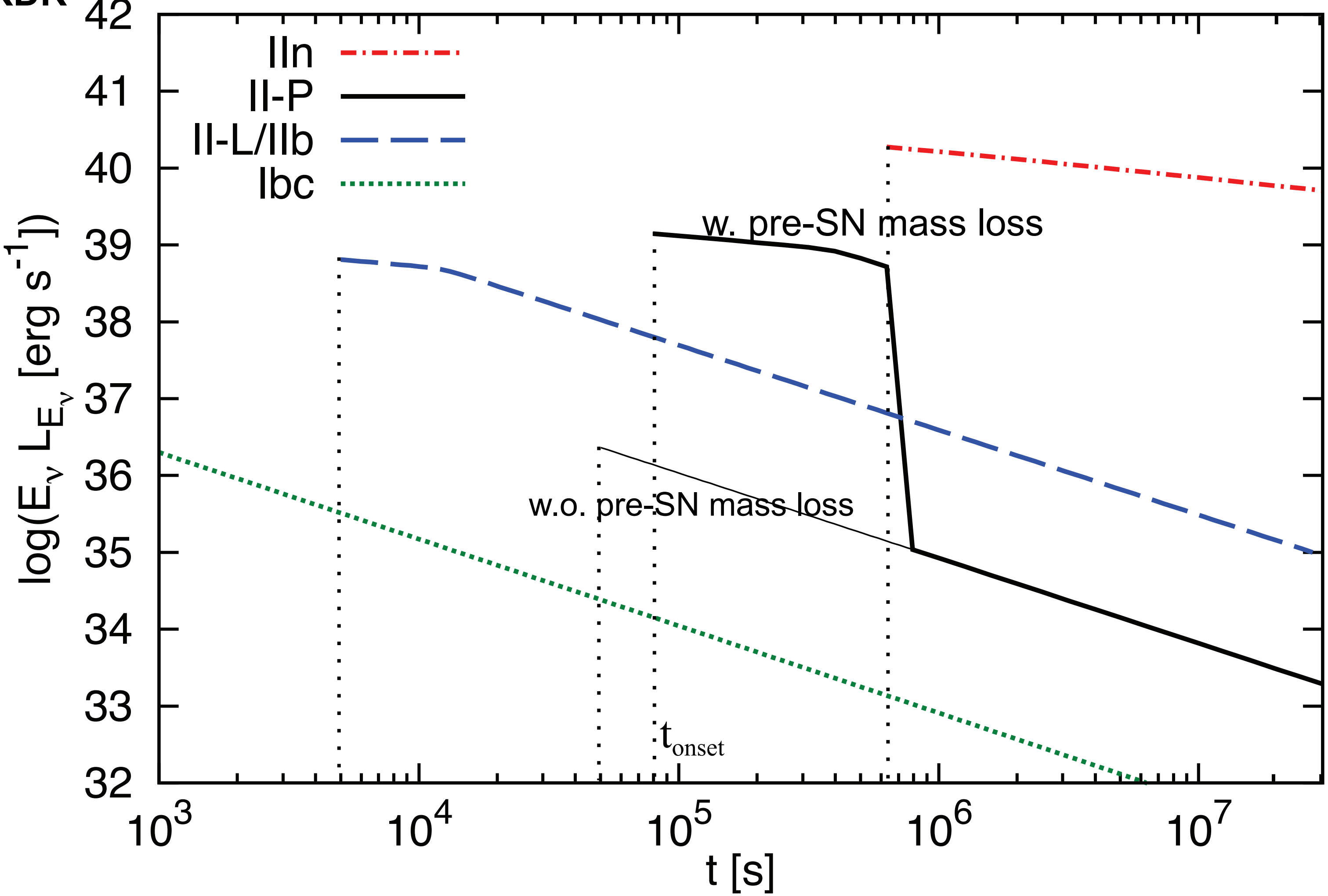


Interacting Supernovae as Multimessenger Transients

- Confined CSM (R_{cs} <~ 10^{15} cm): mass ejection or extended envelope
- May be common even for Type II-P SNe
  $dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)
- Shock accelerated cosmic rays produce cosmic rays, νs and γs
  (KM+ 11 PRD, KM 18 PRDR, KM 24 PRD)

Neutrino Light Curve

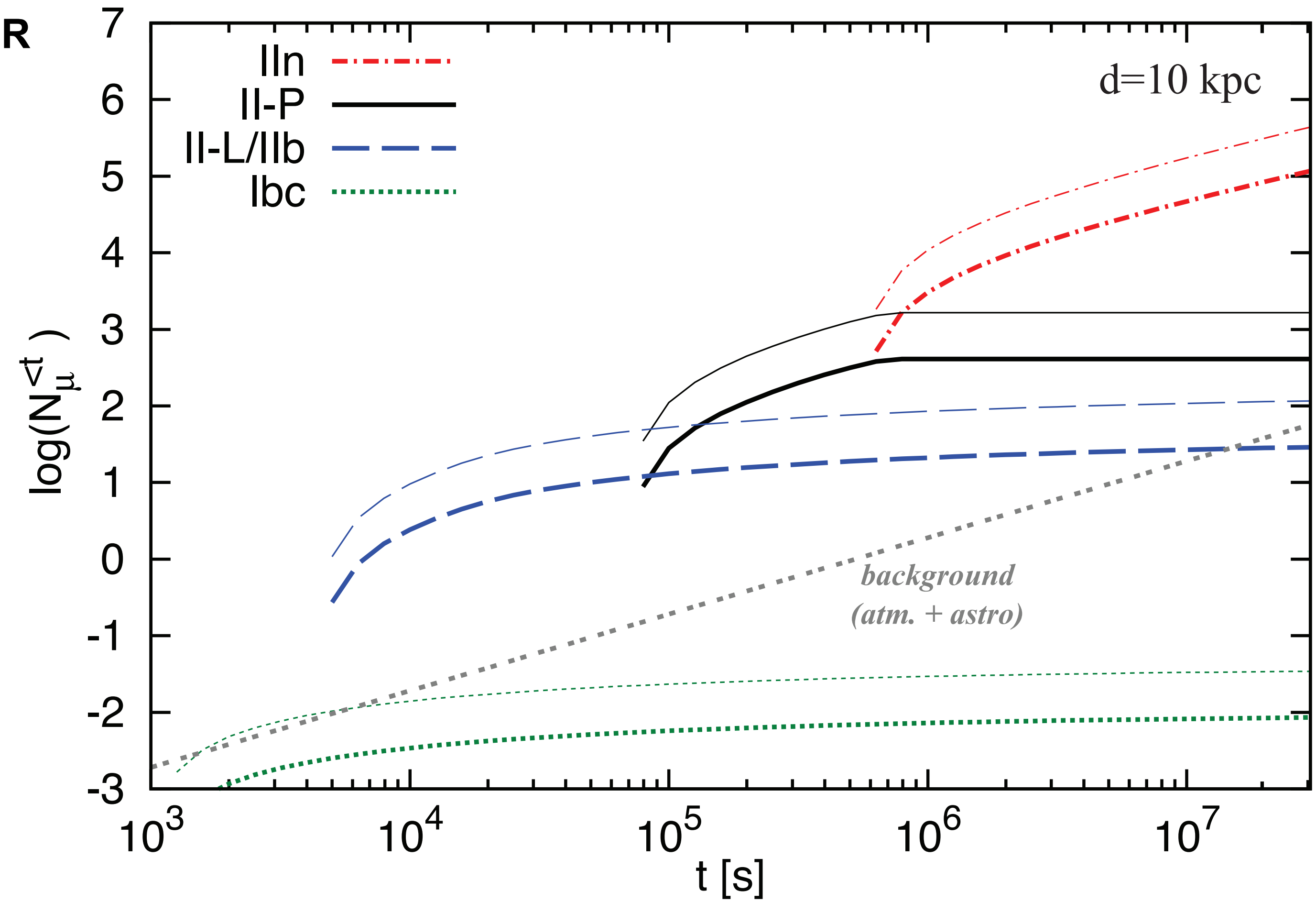
KM 18 PRDR



slowly declining light curves while pion production efficiency ~ 1

Next Galactic Supernova?

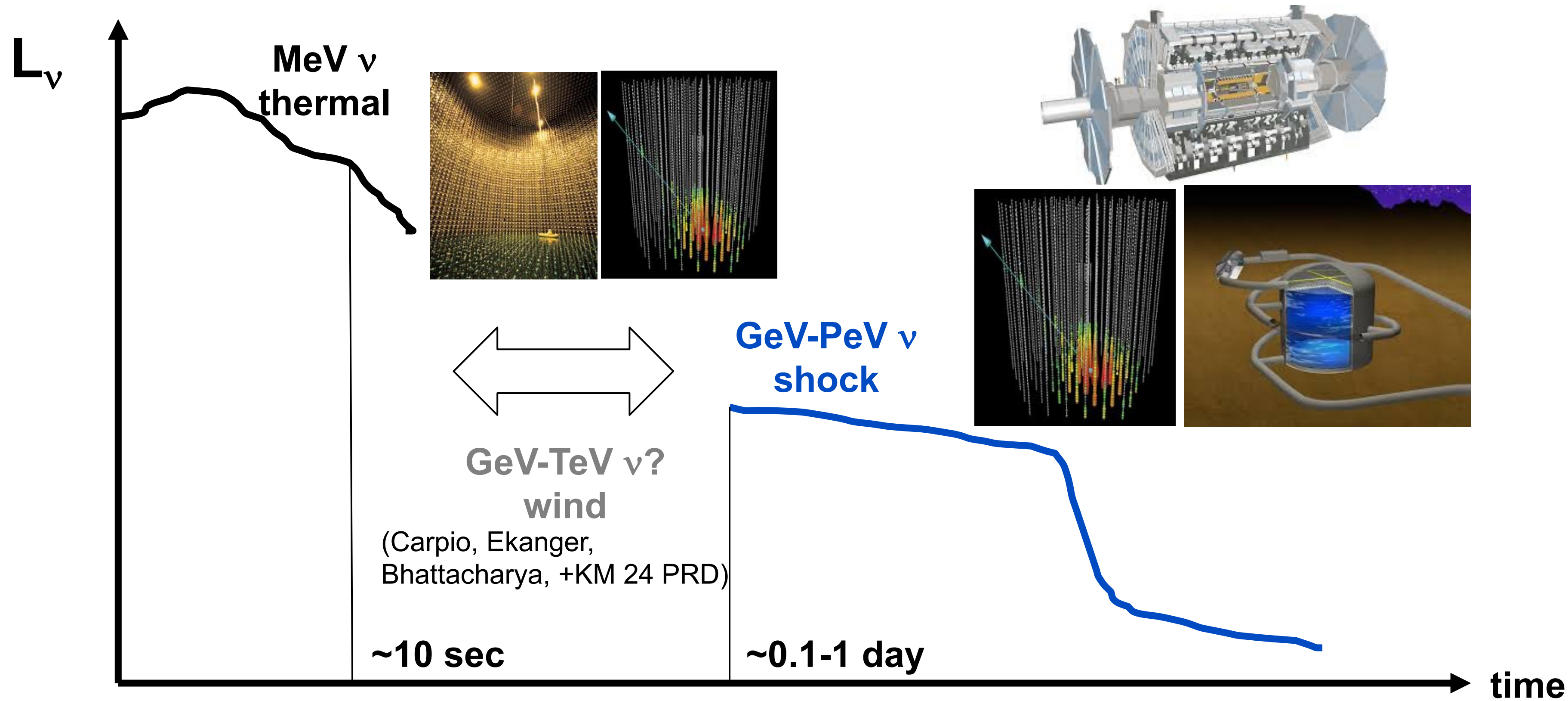
KM 18 PRDR



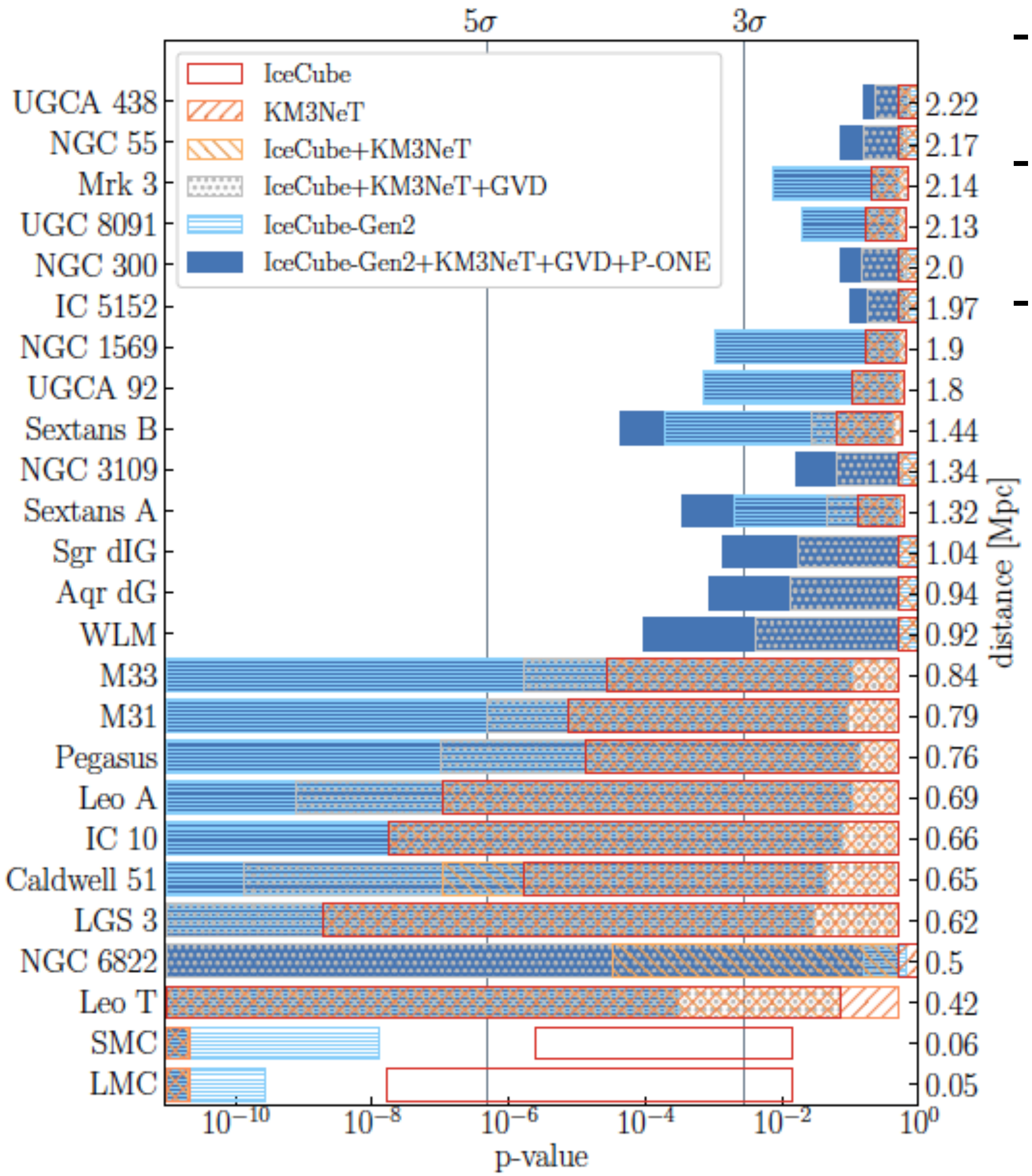
- Type II: ~100-1000 events of TeV ν from the next Galactic SN
  ex. Betelgeuse: ~10^3-3×10^6 events, Eta Carinae: ~10^5-3×10^6 events
- SNe as "multi-messenger" & "multi-energy" neutrino source
- "Real-time" detection of CR acceleration, testing Pevatrons, neutrino physics

Be Best Prepared for Nearby Cosmic Explosions

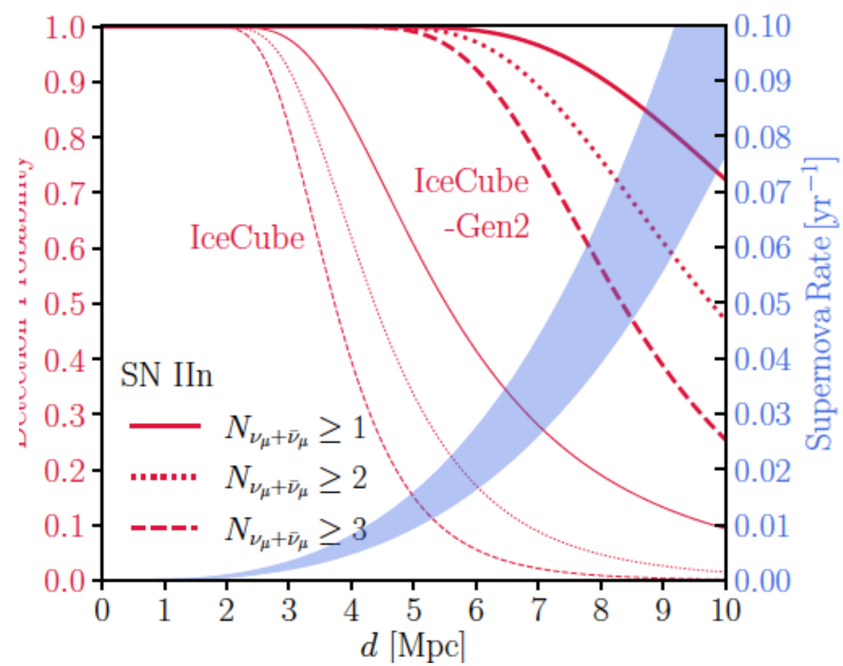
- Supernovae (SNe): “multimessenger” & “multi-energy” ν sources
- ~1000 events of TeV ν from the next Galactic SNe (KM 18 PRDR, 24 PRD)
- LHC ATLAS/CMS as cosmic ν detectors (Wen, Arguelles, Kheirandish & KM 24 PRL)
- Monitoring with ”global ν detector network” (Kheirandish & KM 23 ApJL)



Detectability of “Minibursts”



- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II (CCSM): detectable to ~3-4 Mpc
  IIn: detectable to ~10 Mpc



Kheirandish & KM 23 ApJL

Detection w. Large Hadron Collider

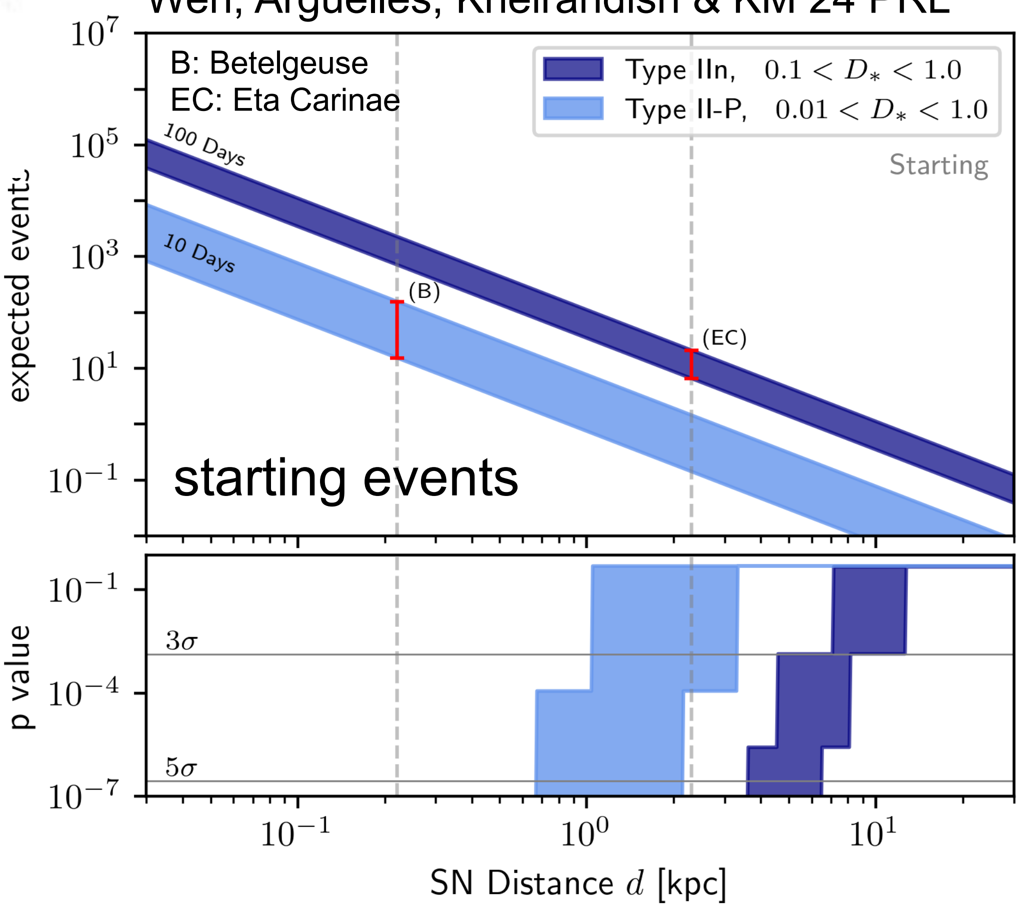
diameter 22m

length 40m

LHC ATLAS

calorimeter ρV=4 kt

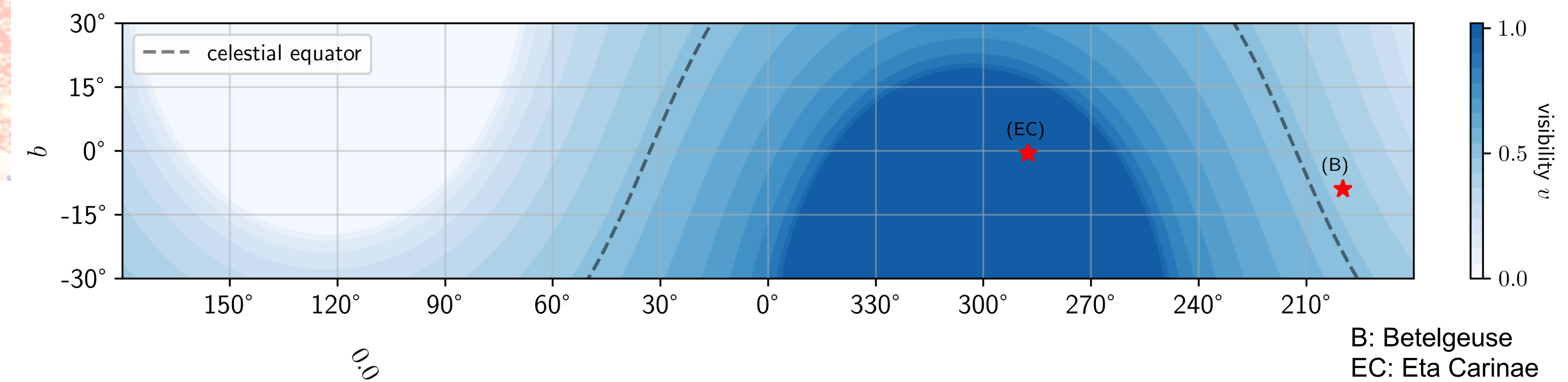
Wen, Arguelles, Kheirandish & KM 24 PRL



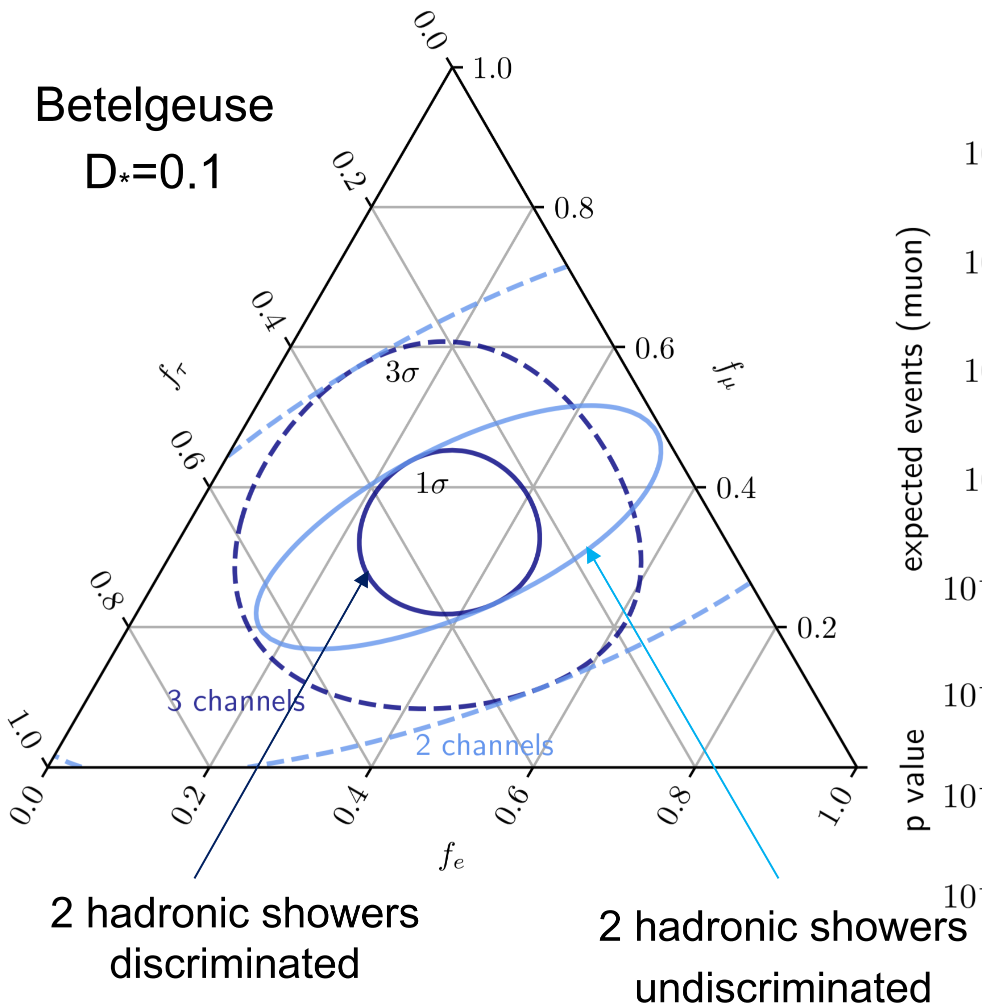
$N \sim \rho V N_A \sigma_{\nu N} E_\nu \Phi_\nu$

$\sim 3\text{x}10^{-3} E_\nu \Phi_\nu$

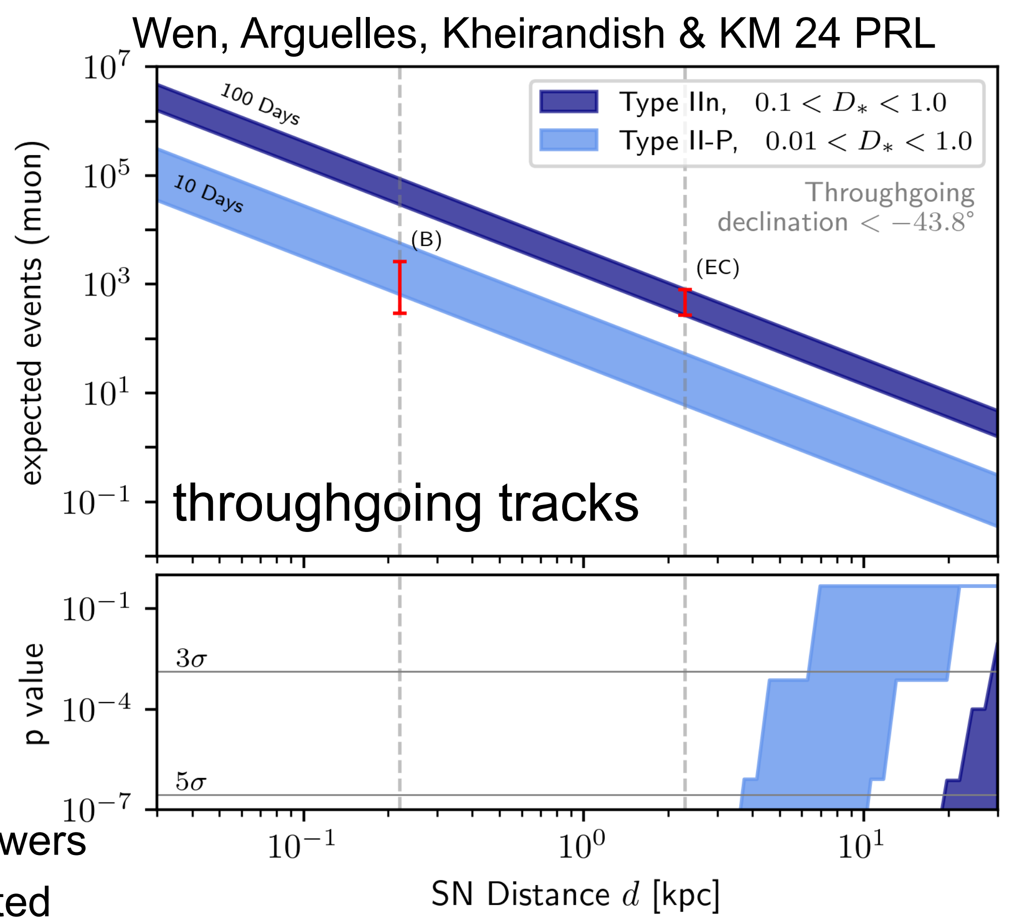
$\sim 1\ (E_\nu \Phi_\nu / 300\ \text{cm}^{-2})$



celestial equator
b
30°
15°
0°
-15°
-30°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
(EC)
(B)
visibility v
1.0
0.5
0.0
B: Betelgeuse
EC: Eta Carinae

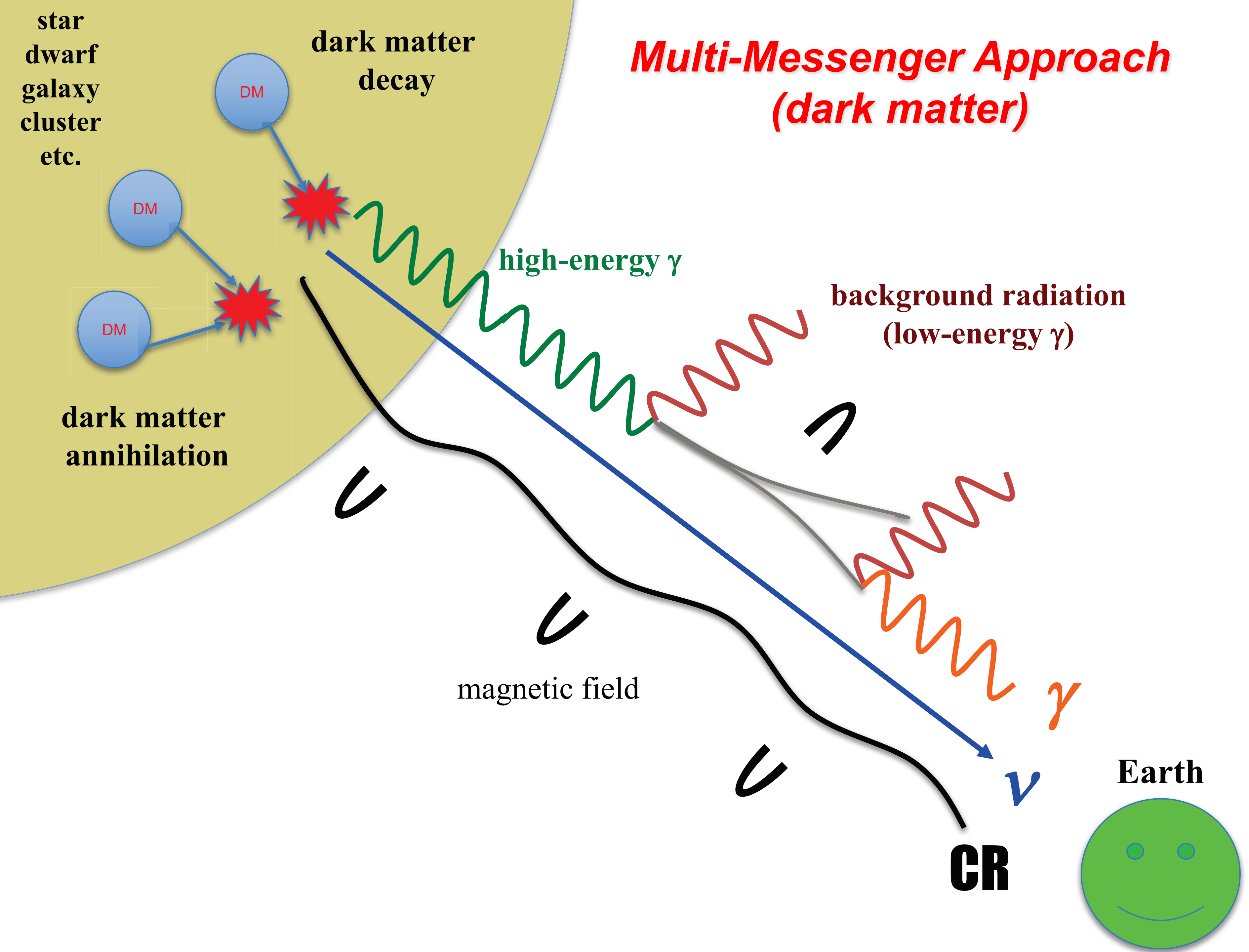


Betelgeuse
D*=0.1
f_τ
f_μ
f_e
3σ
1σ
3 channels
2 channels
0.0
0.2
0.4
0.6
0.8
1.0
2 hadronic showers discriminated
2 hadronic showers undiscriminated



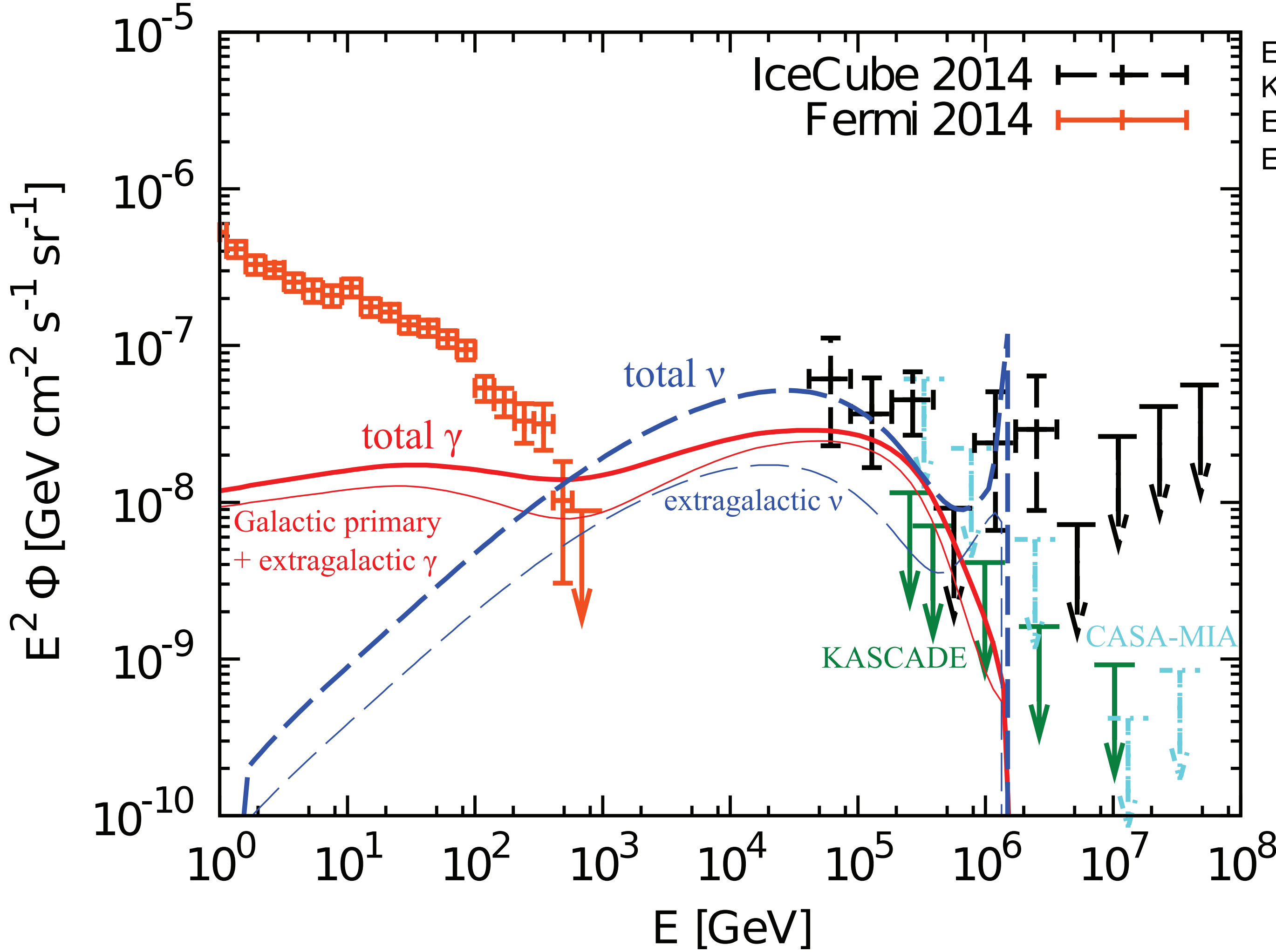
Wen, Arguelles, Kheirandish & KM 24 PRL
Type IIn, $0.1 < D_* < 1.0$
Type II-P, $0.01 < D_* < 1.0$
100 Days
10 Days
Throughgoing
declination $< -43.8°$
(B)
(EC)
expected events (muon)
throughgoing tracks
p value
3σ
5σ
SN Distance d [kpc]

Multi-Messenger Approach (dark matter)



Multimessenger Emission of Decaying Dark Matter

Heavy dark matter remain largely unexplored by direct/collider experiments



Ellis+ 92, Gondolo 92, Gondolo+ 93
KM & Beacom 12
Esmaili & Serpico 13
Esmaili & Serpico 15

DM → $\nu_e+\nu_e$ (12%)
DM → b+bbar (88%)

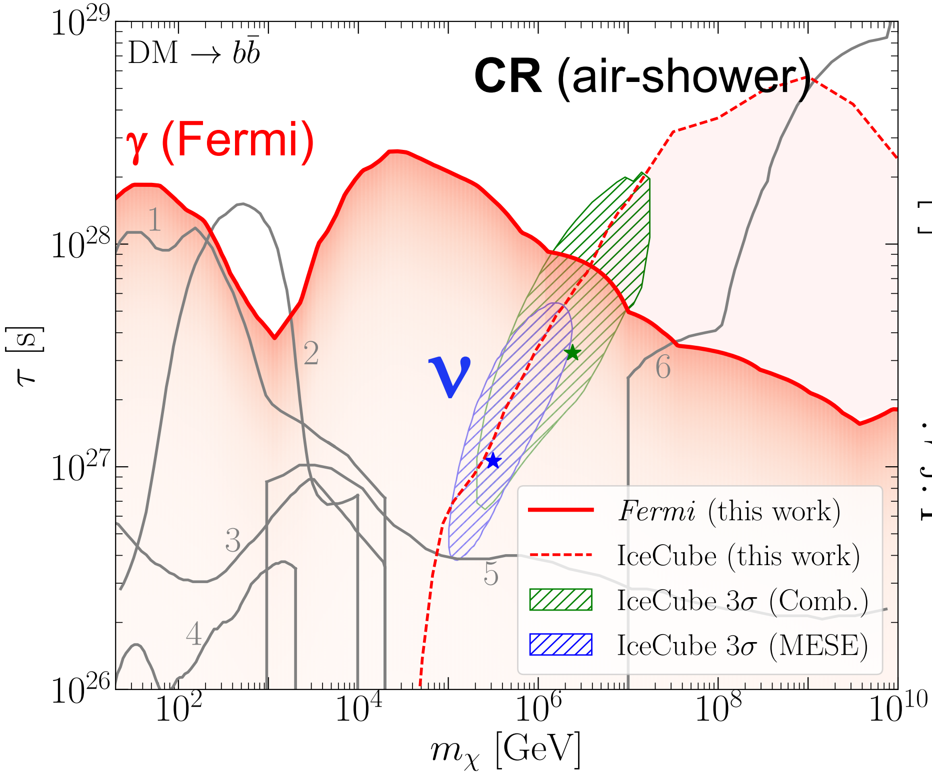
(similar results in other models that are proposed)

Largely constrained by Fermi (sub-TeV γ) and air-shower (sub-PeV γ) data

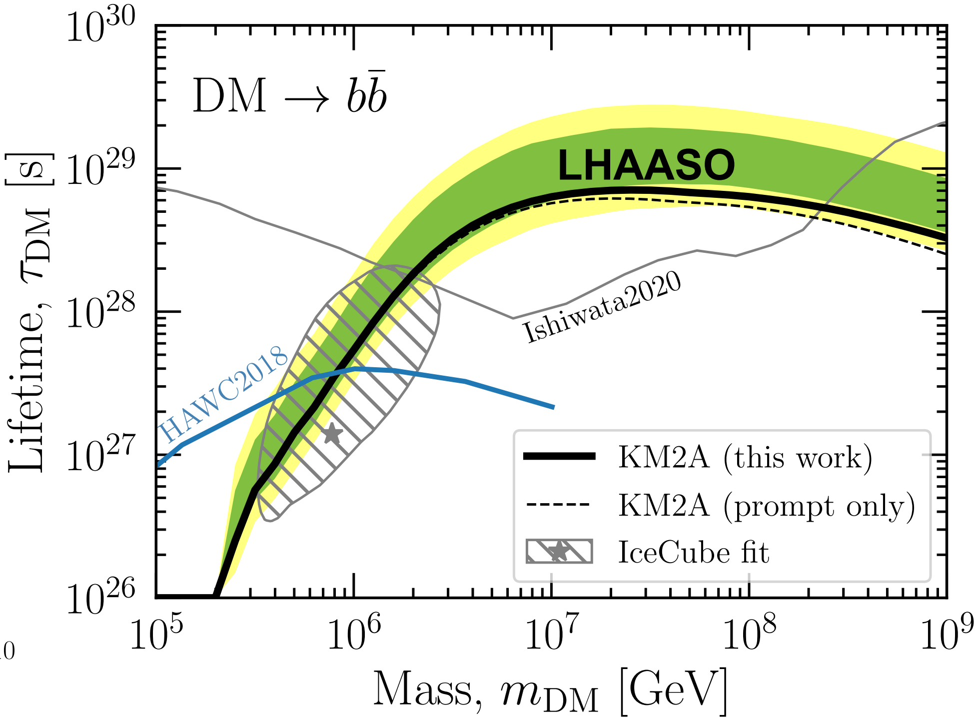
KM, Laha, Ando & Ahlers 15 PRL

Multimessenger Search for Superheavy Dark Matter

Cohen, KM, Rodd, Safdi, and Soreq 17 PRL

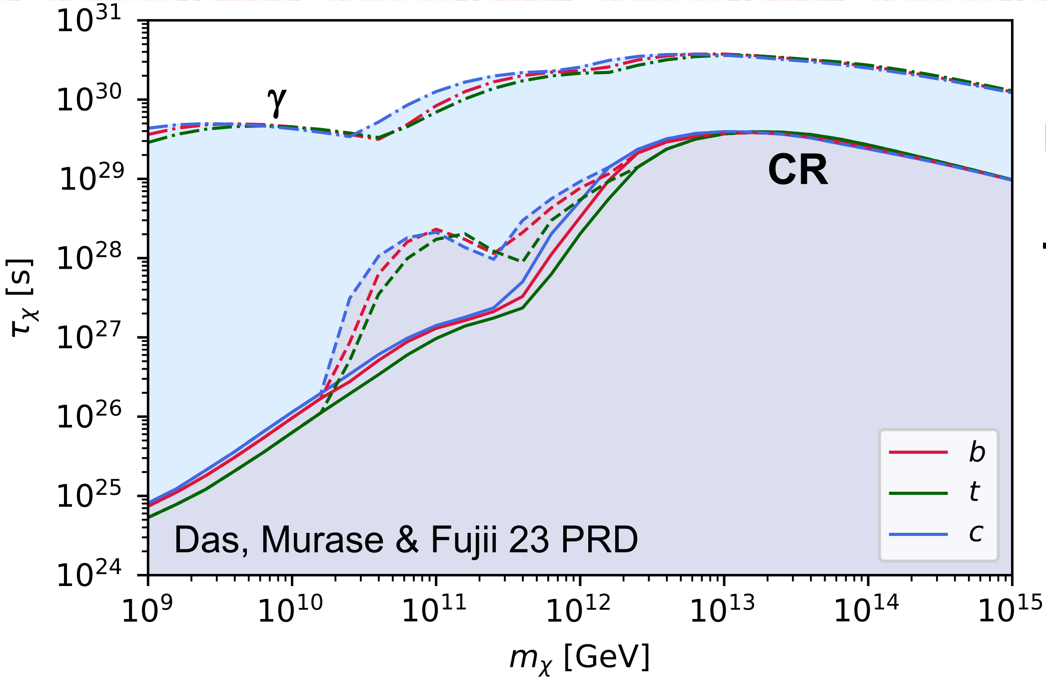


LHAASO Collaboration 22 PRL



- LHAASO and Fermi limits are complementary and comparable around PeV
- Nearly excluding dark matter scenarios to explain the all-sky IceCube ν data
- Unique probes of superheavy dark matter that is difficult to directly test

Multimessenger Search for Superheavy Dark Matter

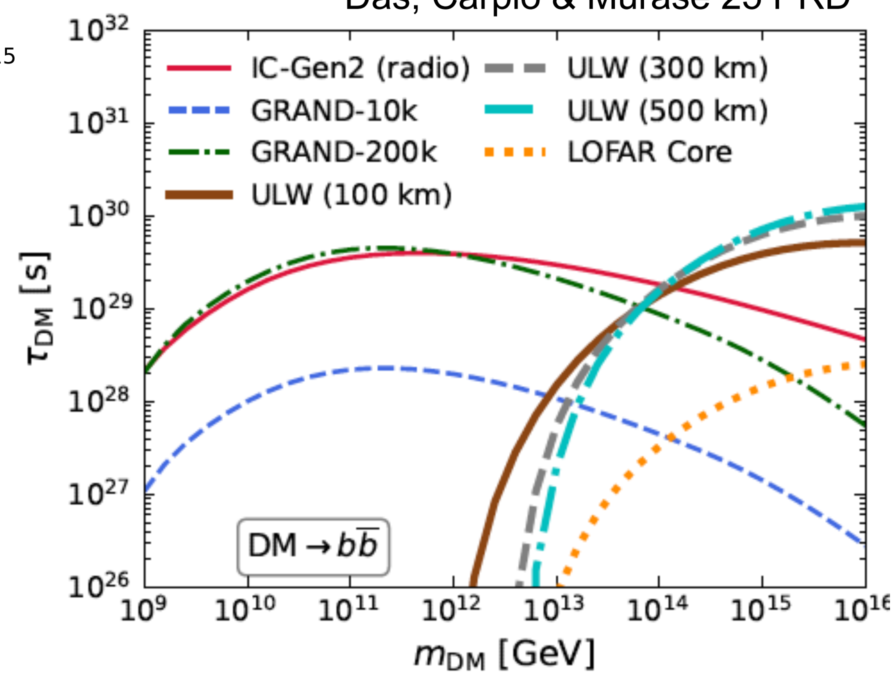


UHECR detectors (Auger)

- Upper limits on UHEγ
  $\tau_{DM} > 10^{30}$ s up to GUT scale

UHE ν detectors

- Gen2-radio & GRAND
  subject to unknown astro bkg.
- lunar radio detection
  $\tau_{DM} >\sim 10^{30}$ s up to GUT
  no astro bkg. at such UHE



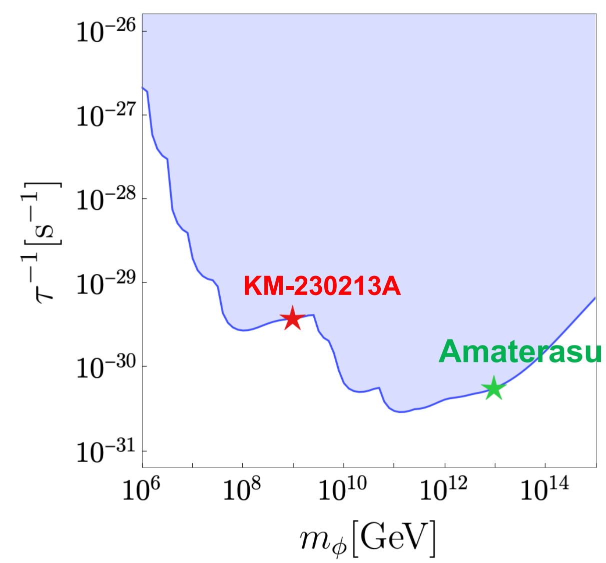
Example: Inflaton Dark Matter

- Inflaton dark matter models in (modified) natural inflation (entropy dilution necessary)
- Scalar dark matter

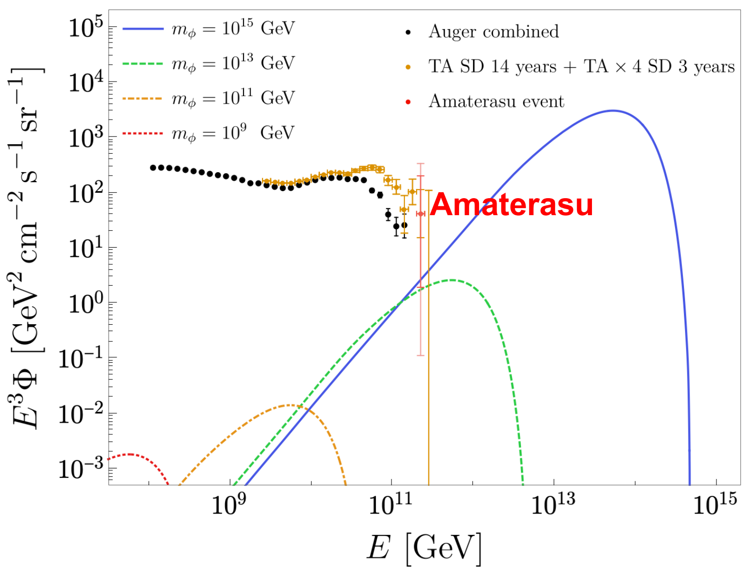
$$\phi \to H\bar{q}q,\ \bar{H}\bar{l}l,\ \bar{H}H,\ gg,\ AA,\ BB,$$

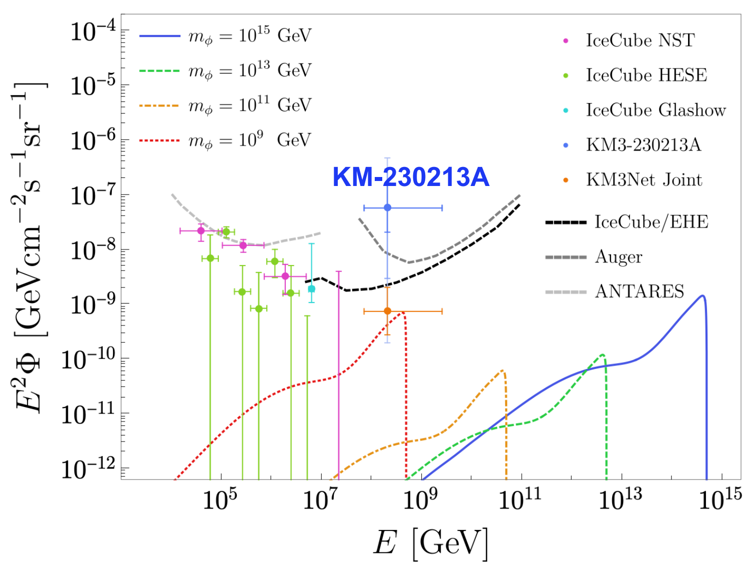
- UHE neutrons can also be used as good probes of superheavy DM

KM, Narita & Yin JCAP 25



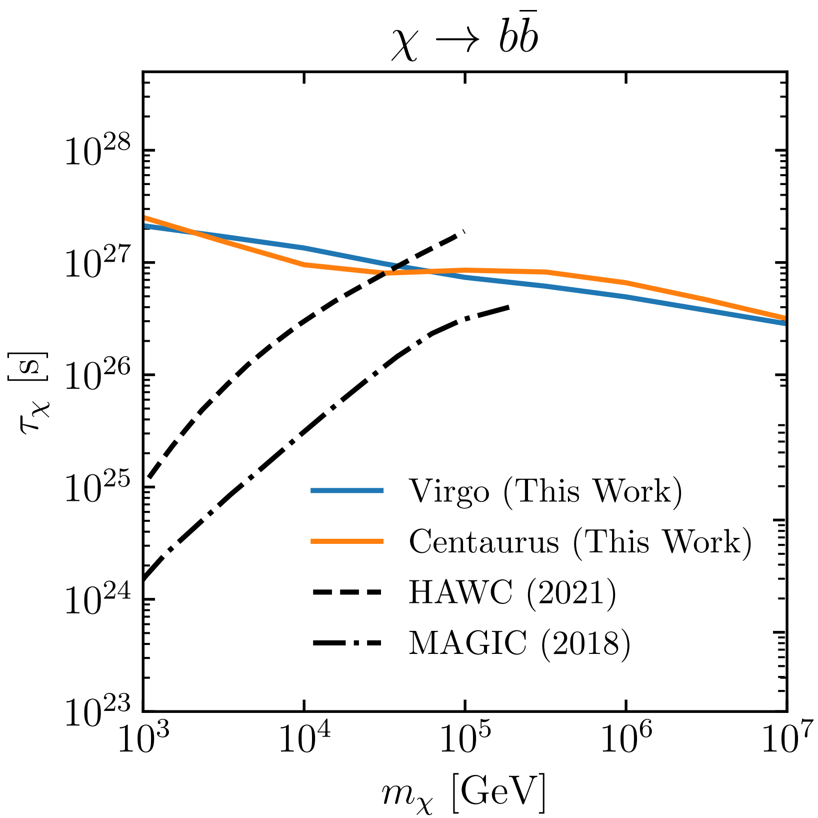
E [GeV]



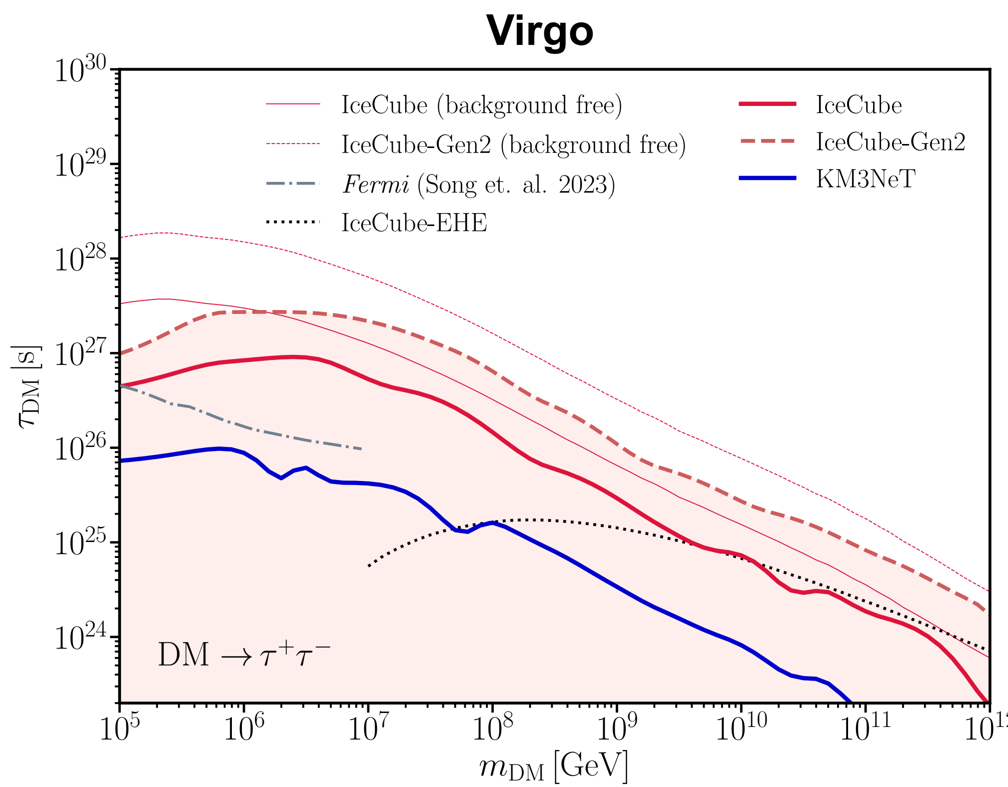


Search for Heavy Dark Matter in Galaxy Clusters

Song, KM & Kheirandish 24 JCAP



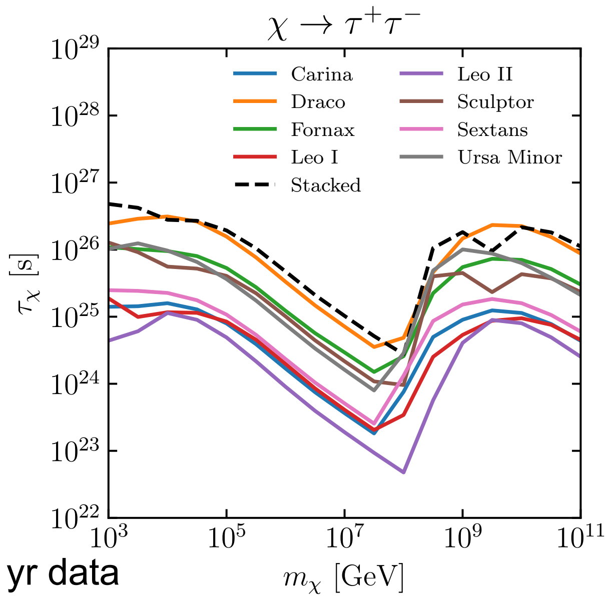
Chianese, Kheirandish & KM 25 in prep.

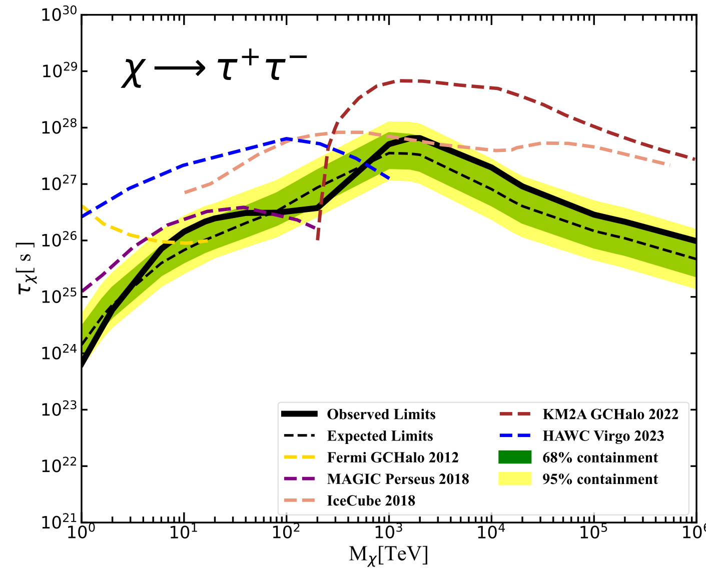


- Fermi limits overwhelm MAGIC/HAWC limits thanks to γ-ray cascades.
- LHAASO and updated IceCube analyses will be useful.

Search for Heavy Dark Matter in Dwarf Galaxies

decaying dark matter

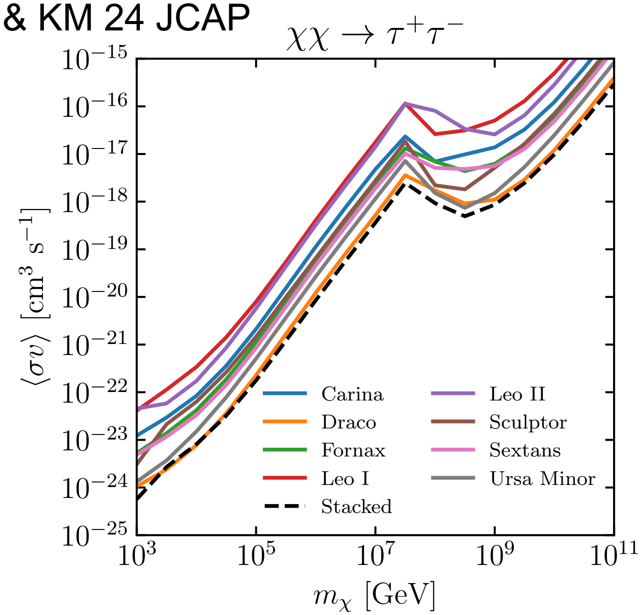


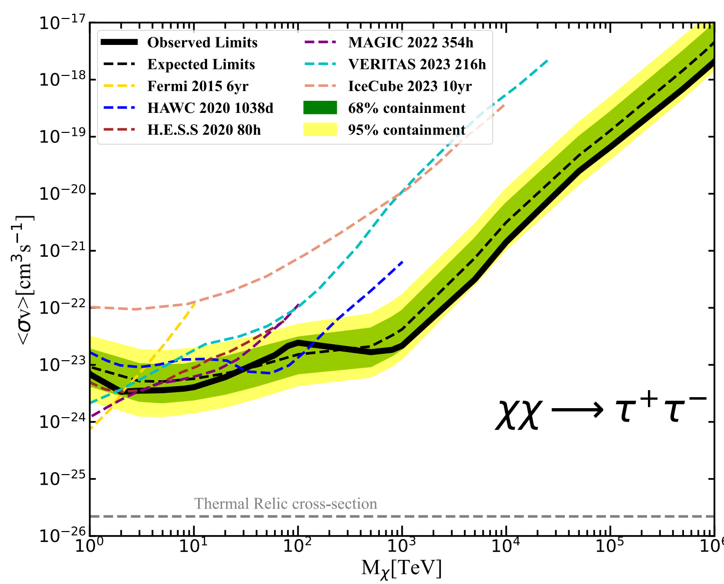


Fermi-LAT 14 yr data
Song, Hiroshima & KM 24 JCAP

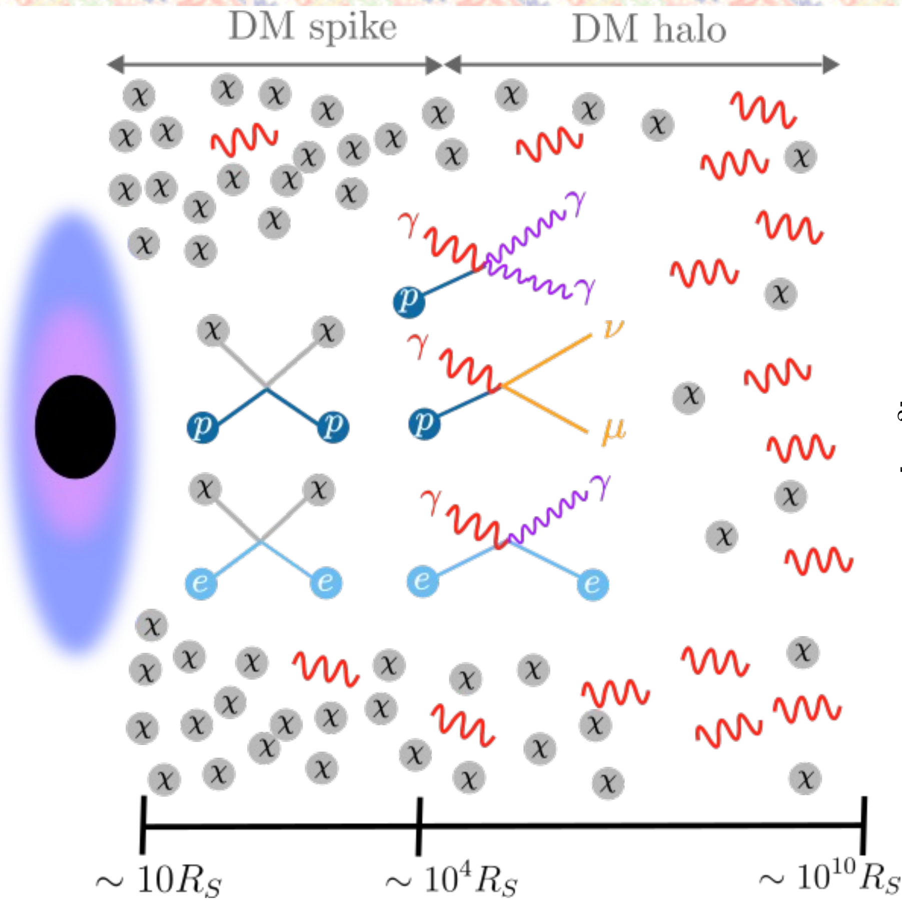
LHAASO Collaboration 24 PRL

annihilating dark matter

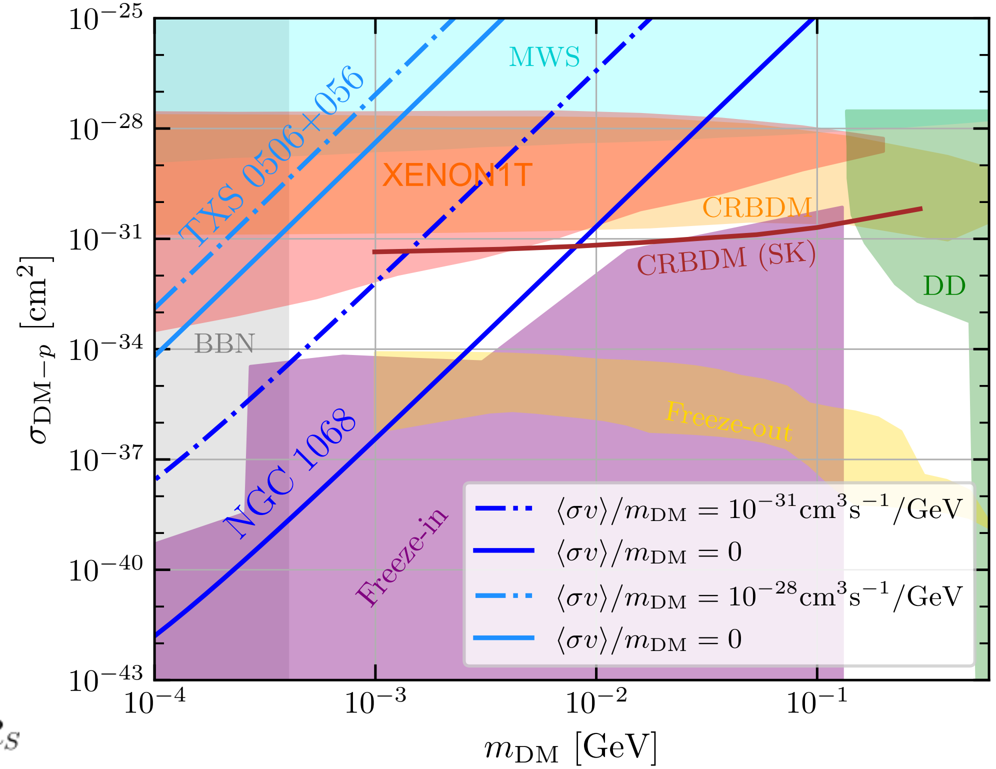




Supermassive Black Hole Neutrinos as a Probe of Dark Matter



Herrera & KM 24 PRDL
Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker 2408.08947

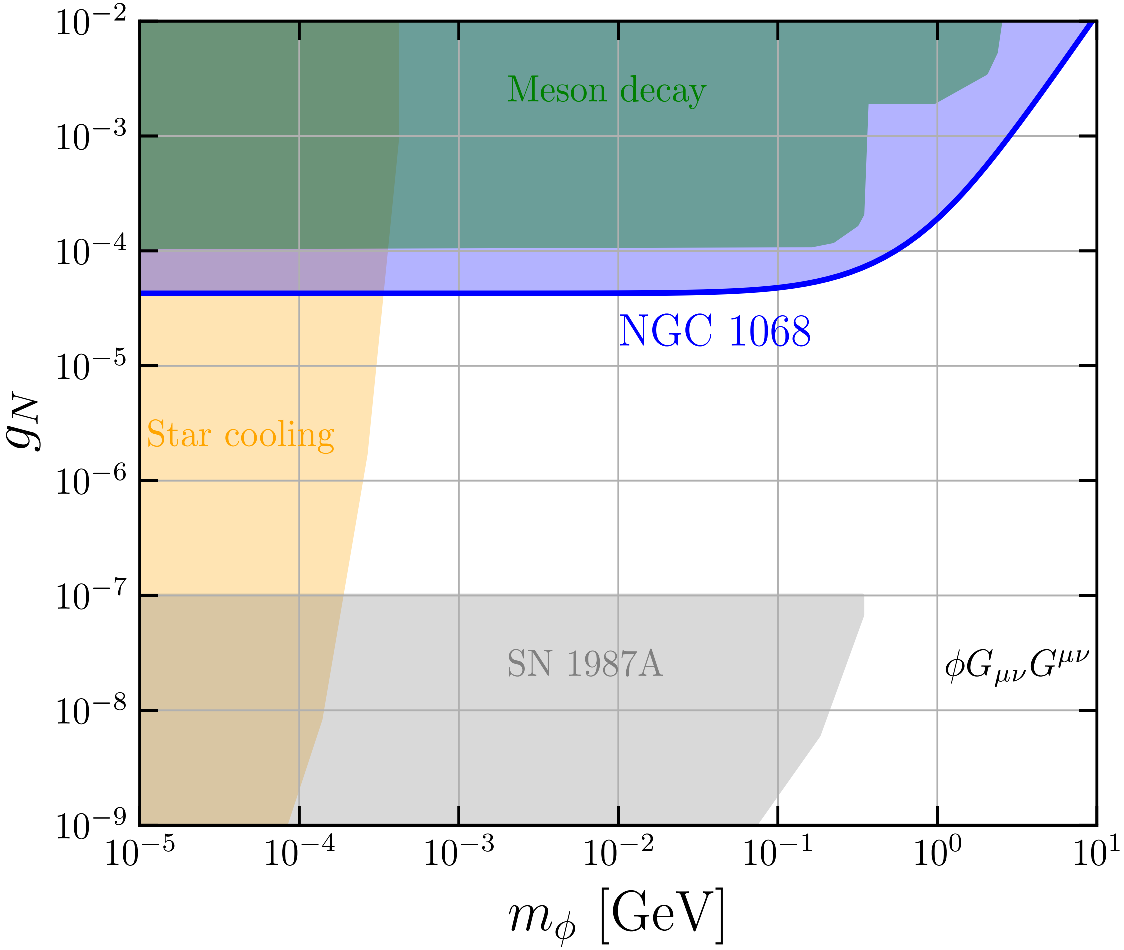


- AGN νs originate from CRs within 10-30 Schwarzschild radii
- High DM density at the center of AGN ("DM spike")
- CR cooling due to DM-SM scattering

Most stringent constraints on DM-p scattering for DM in the MeV range

Example of Scalar-Mediated DM-Nucleon Interactions

Herrera & KM 24 PRDL



$$\mathcal{L} \supset -m_\chi \bar{\chi}\chi - g_N \phi \bar{N} N - g_\chi \phi \bar{\chi}\chi$$

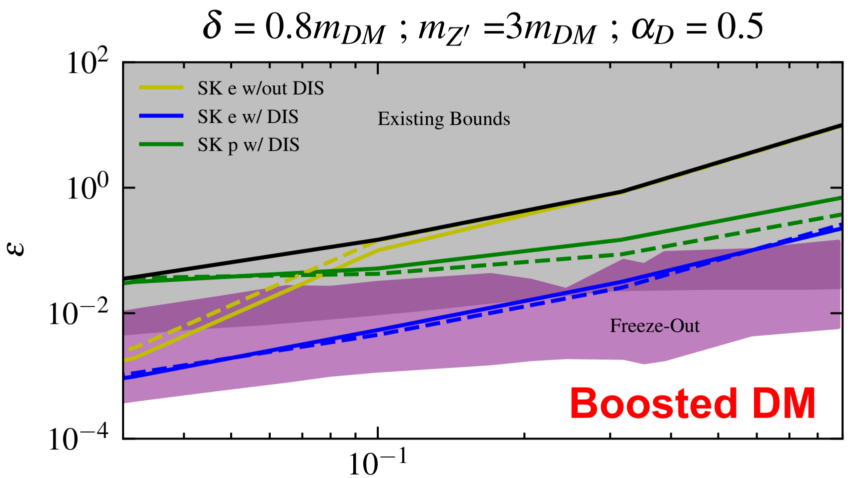
$$\frac{d\sigma^{\phi}_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}} = \frac{m_\phi^4}{\left(q^2 + m_\phi^2\right)^2} \frac{d\sigma_{\mathrm{DM-CR}i}}{dT_{\mathrm{DM}}}$$

non-relativistic DM cross section

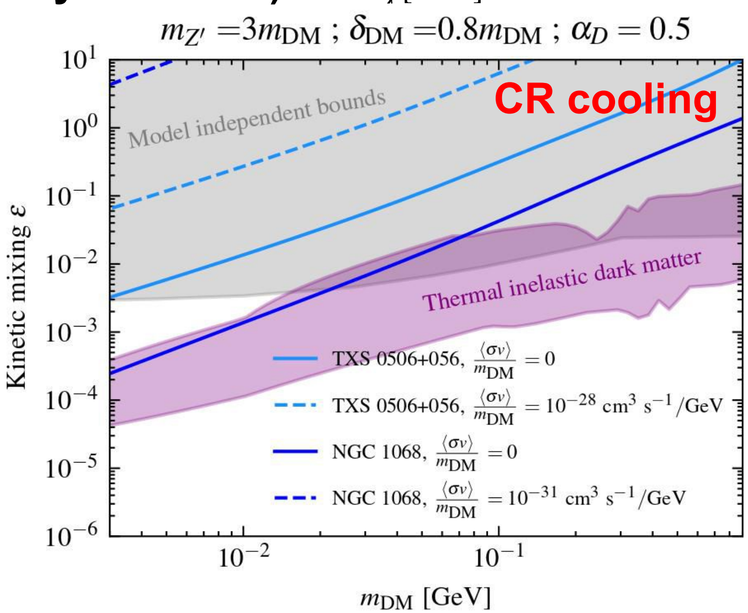
$$\sigma_{\mathrm{DM}-N} = \frac{g_\chi^2 g_N^2 \mu_{\chi-N}^2}{\pi m_\phi^4}$$

- NGC 1068 observations enable us to probe new parameter space

Application to Inelastic Dark Matter

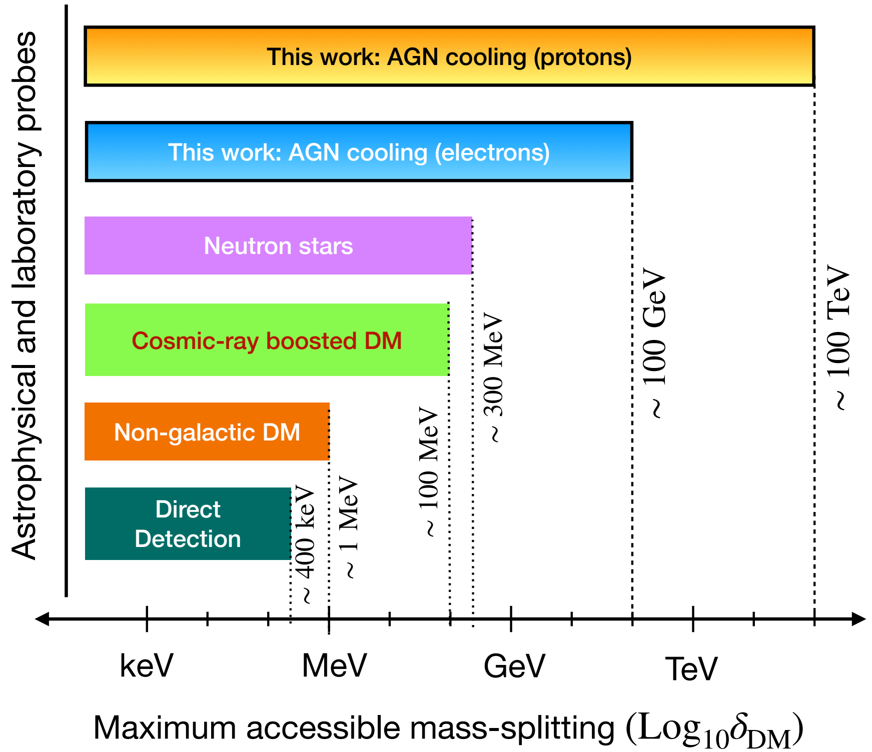


(heavy mediator)



$$\chi_1 + i \to \chi_2 + i'$$

- DM may be inelastic (ex. pseudo-Dirac)
- DIS can be important!
- CR cooling limits (IceCube)
- Boosted DM limits (Super-K)



Gustafson, Herrera, Mukhopadhyay, KM & Shoemaker 2408.08947

Secret Neutrino Interactions

$$\mathcal{L} \supset G\nu\nu\phi \qquad \mathcal{L} \supset G\bar{\nu}\not{Z}'\nu$$

Bardin, Bilenky & Pontecorvo 70

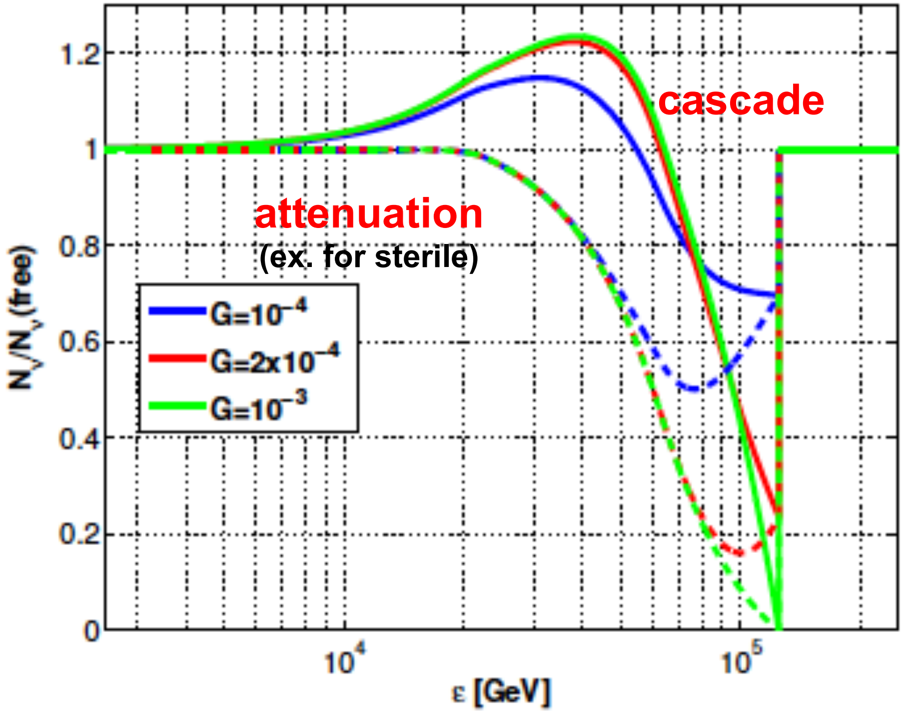
Applications to IceCube
Ioka & KM 14 PTEP
Ng & Beacom 14 PRD

ex. Majorana ν self-interactions via a scalar (Blum, Hook & KM 14)

$$\mathcal{L} = -\frac{g}{\Lambda^2}\Phi(HL)^2 + cc.$$

SSB
lepton # violation

$$\mathcal{L} = -\frac{1}{2}\sum_i (m_{\nu_i} + \mathcal{G}_i\phi)\,\nu_i\nu_i + cc + \ldots, \quad m_{\nu_i} = \frac{g_i \mu v^2}{\Lambda^2}$$



BSM ν–ν and ν-DM interactions via MeV mediators:

1. small-scale structure problems
2. Hubble tension

HE neutrinos interact w. cosmic neutrino background or dark matter

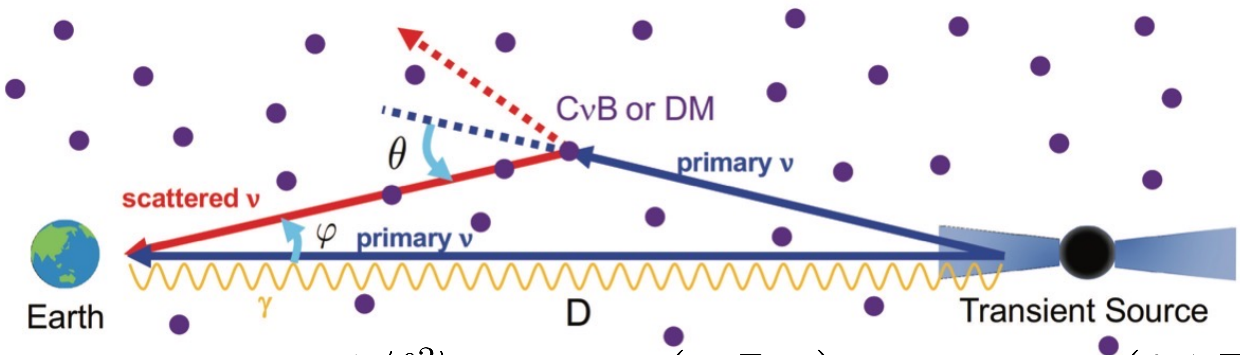
$$\epsilon_{\rm res} = \frac{m_\phi^2}{2m_\nu} = 1\ {\rm PeV}\left(\frac{m_\phi}{10\ {\rm MeV}}\right)^2\left(\frac{m_\nu}{0.05\ {\rm eV}}\right)^{-1}$$

→ **modulation in neutrino spectra**

ex. Blum. Hook & KM 14, Araki+ 14 PRD, Shoemaker & KM 16 PRD…

BSM Tests with Multi-Messenger Transients

BSM ν-ν/ν-DM interactions could alleviate H_0 tension & small-scale issues

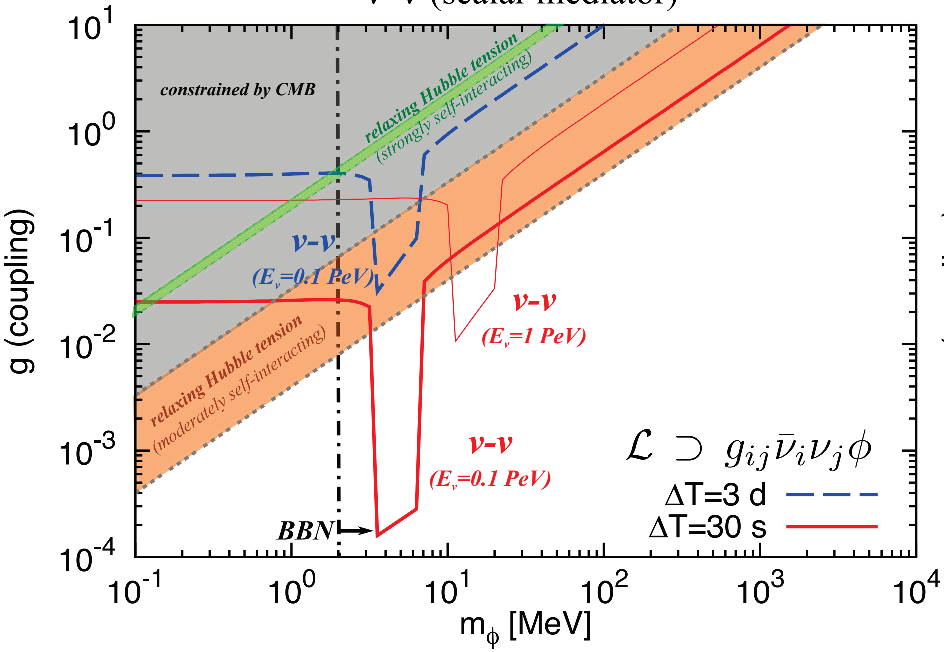


"time delay" signatures
(**neutrino echoes**)

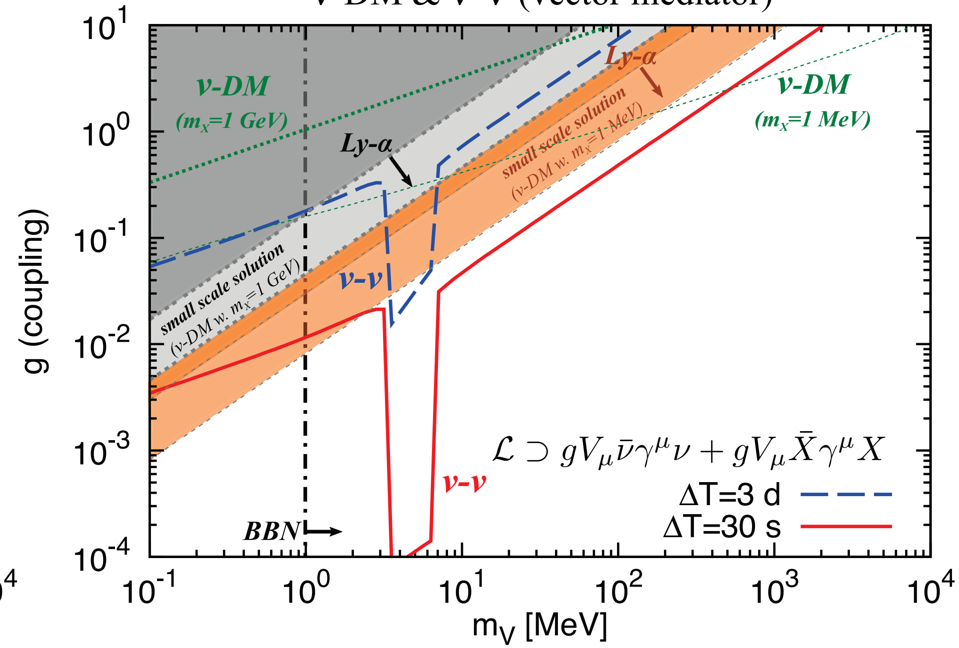
$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4}D \simeq 77\ \mathrm{s}\left(\frac{D}{3\ \mathrm{Gpc}}\right)C^2\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

KM & Shoemaker 19 PRL

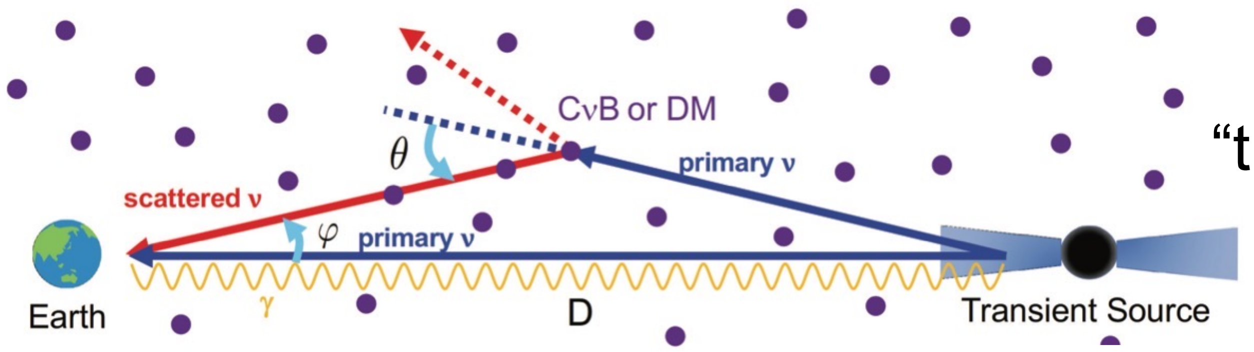
ν-ν (scalar mediator)



ν-DM & ν-ν (vector mediator)

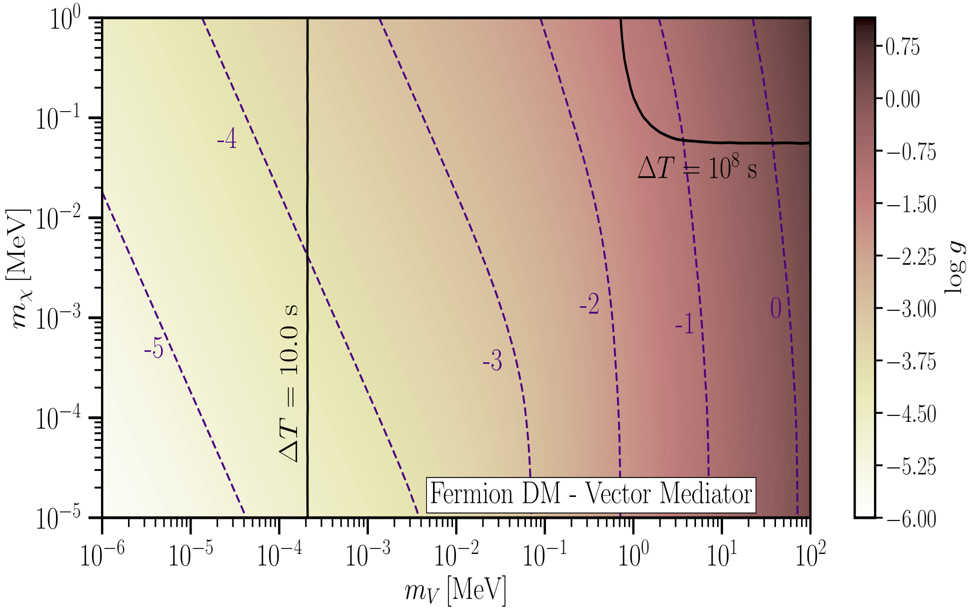


BSM & Time-Domain Multi-Messenger Astrophysics

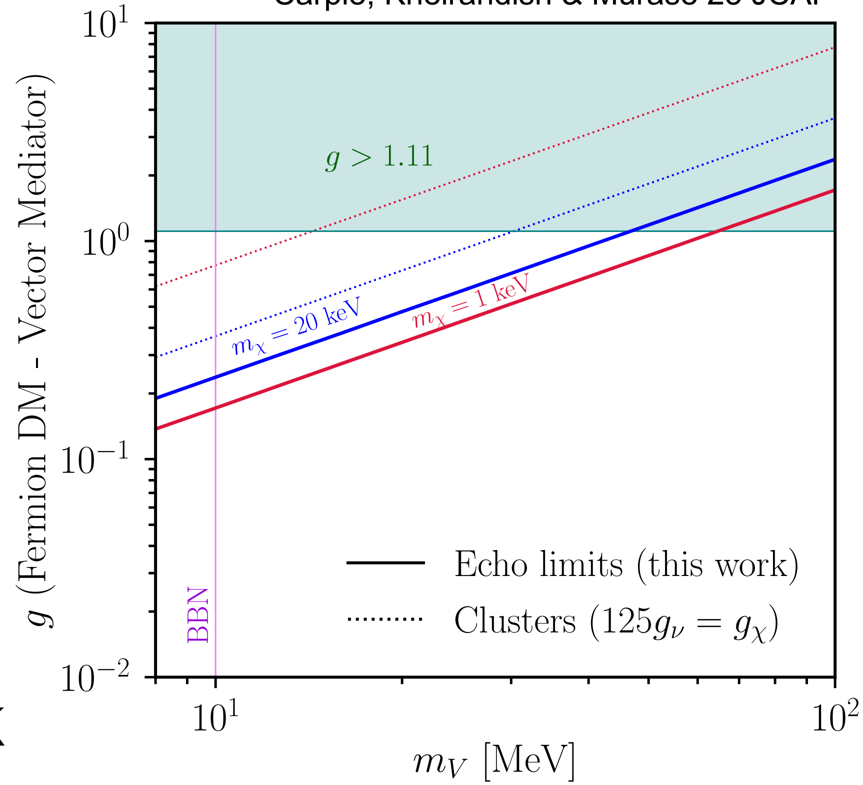


KM & Shoemaker 19 PRL

"time delay" signatures
(**neutrino echoes**)



Carpio, Kheirandish & Murase 23 JCAP



Next Galactic supernova at 10 kpc
-> ~20000 events within 0.5 s @ Hyper-K