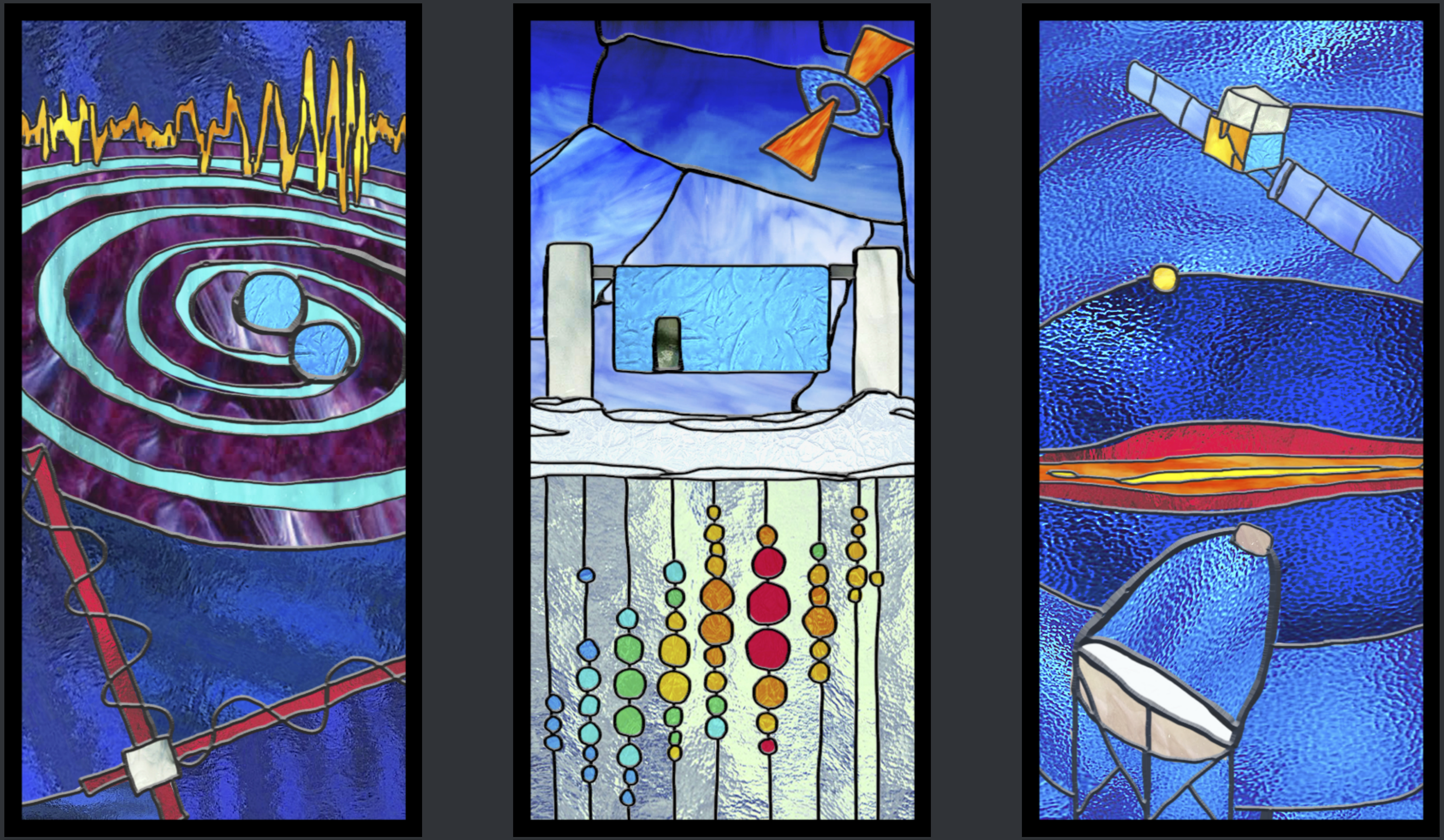

Neutrino Telescopes and Results

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Niels Bohr Institute

ISAPP School Paris Saclay

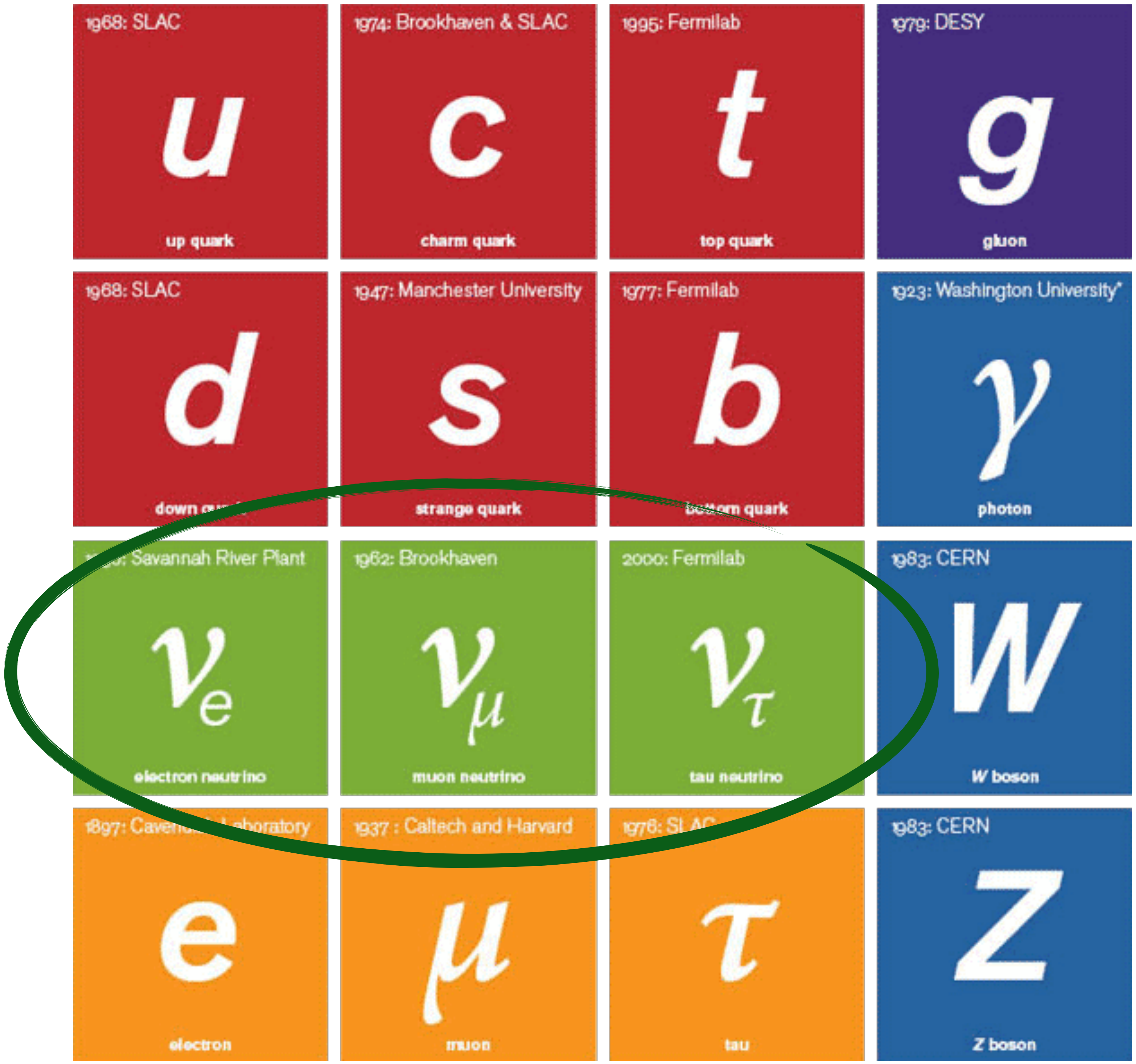
VILLUM FONDEN

KØBENHAVNS
UNIVERSITET

The Elusive Neutrino

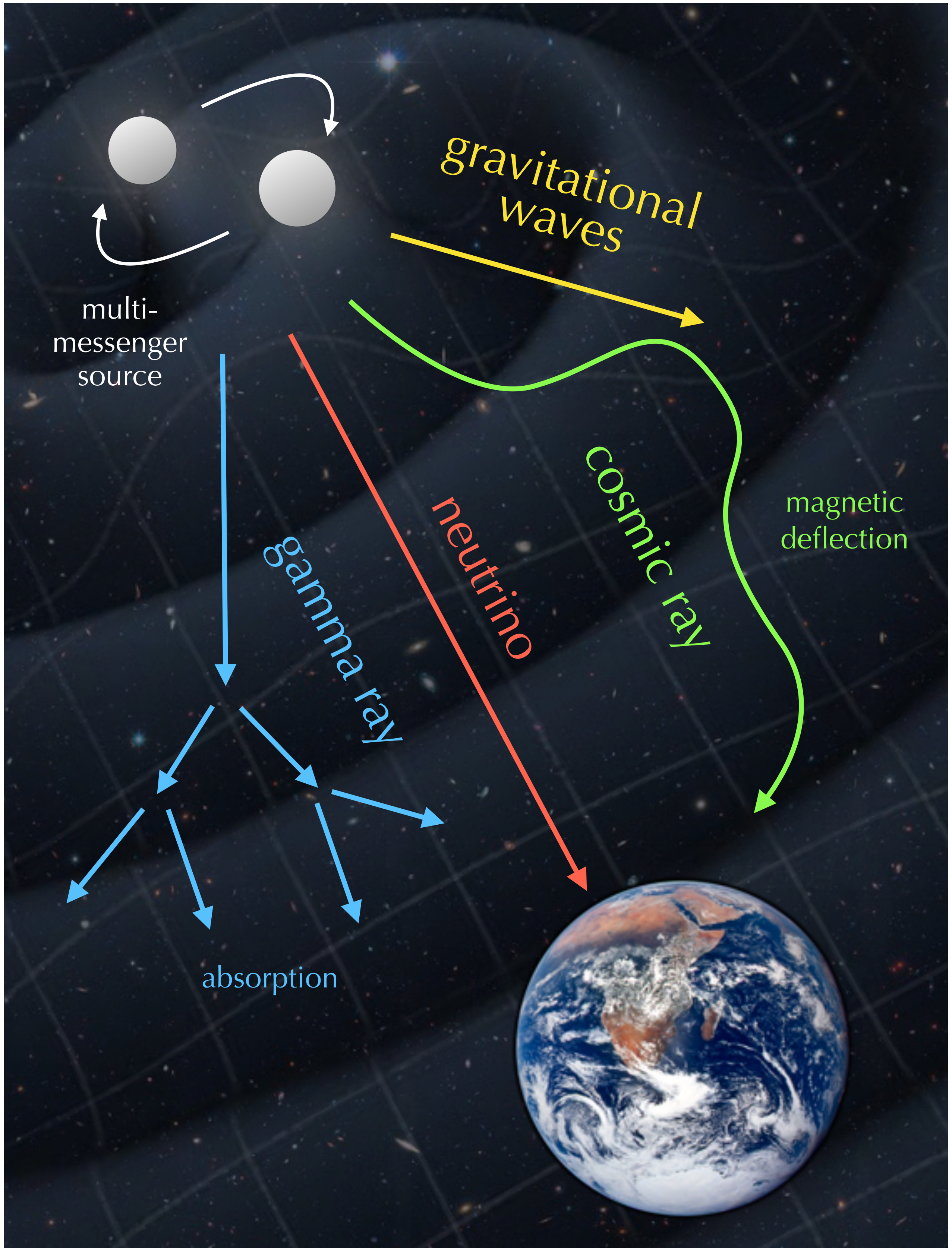
- **three neutrino flavours**
- very small masses *(unknown origin)*
- large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **unique probe of high-energy astrophysics**

Standard Model of Particle Physics

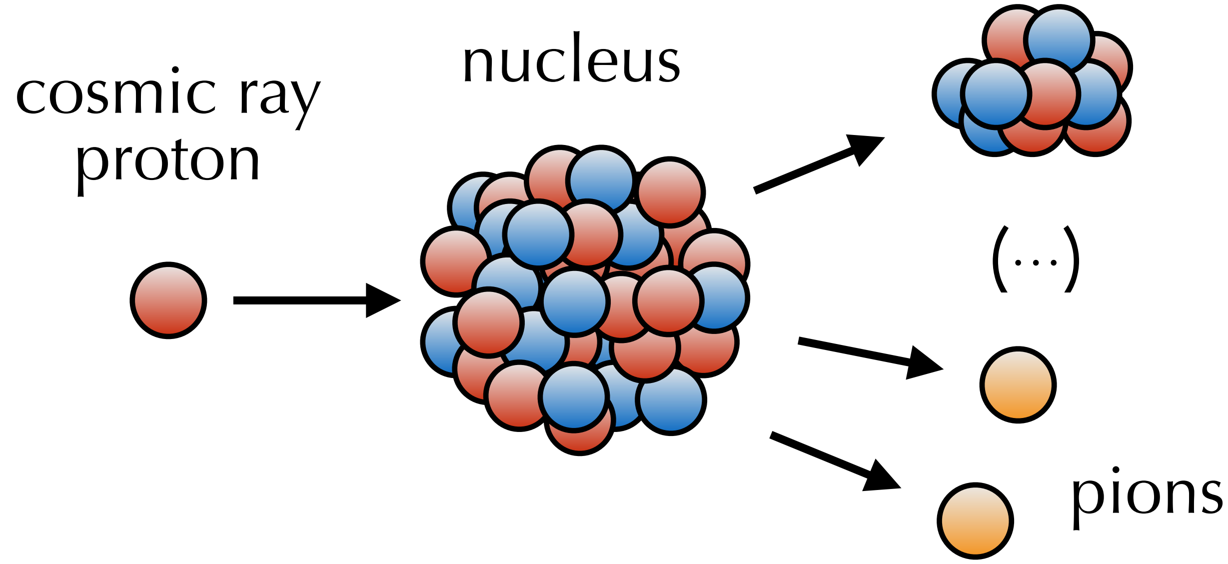


(+ Higgs boson)

Multi-Messenger Paradigm



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


cosmic ray proton

nucleus

(…)

pions

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

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

Neutrino Energies

- Average energy fraction of pions from CR nucleons:

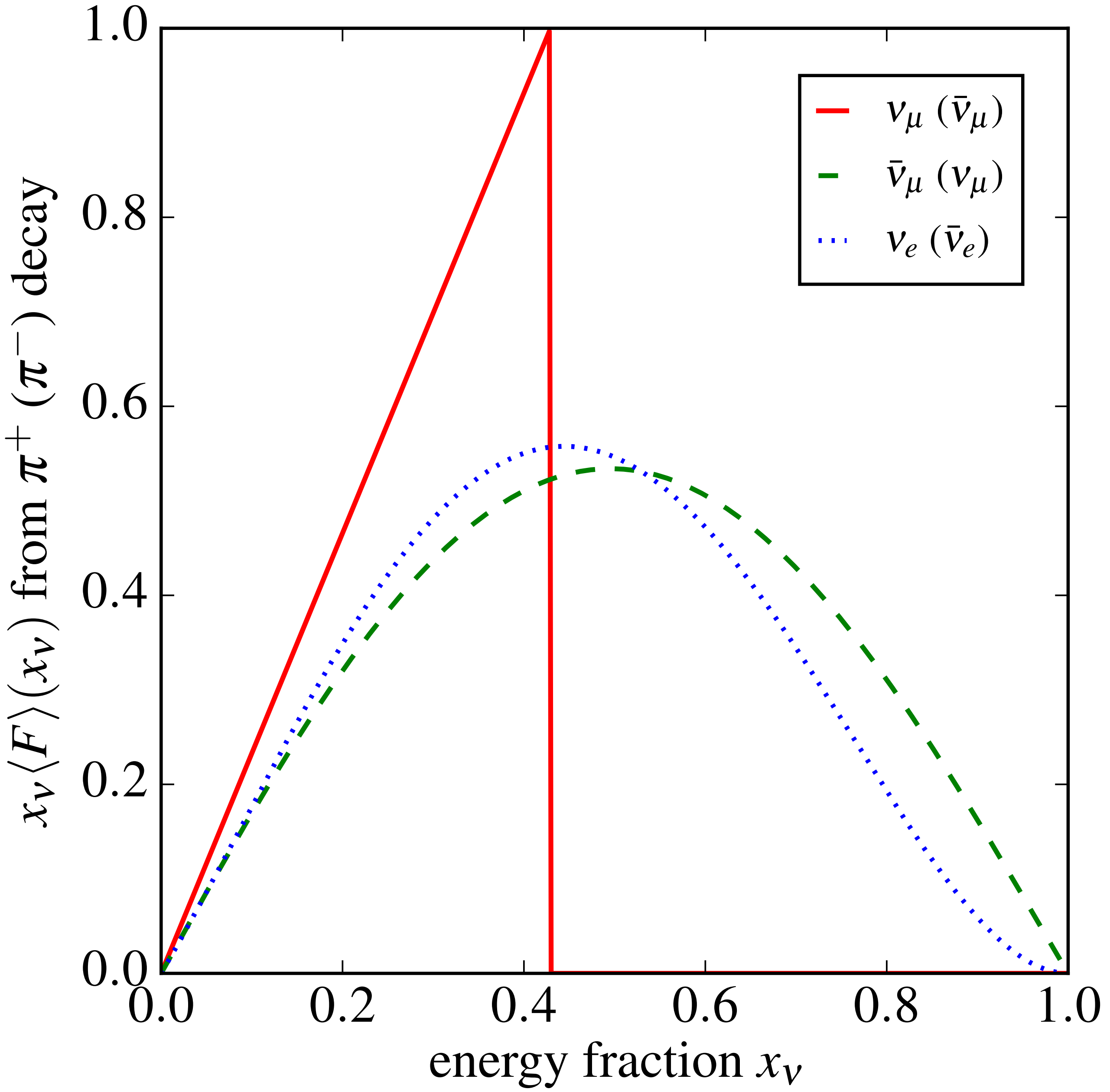
$$\langle x_\pi \rangle \simeq 20\,\%$$

- Average energy fraction from relativistic pions ($r_\pi = (m_\mu/m_\pi)^2$)

$$\langle x_{\nu_\mu} \rangle = \frac{1 - r_\pi}{2} \simeq 21\,\%$$

$$\langle x_{\bar\nu_\mu} \rangle = \frac{3 + 4r_\pi}{20} \simeq 26\,\%$$

$$\langle x_{\nu_e} \rangle = \frac{2 + r_\pi}{10} \simeq 26\,\%$$

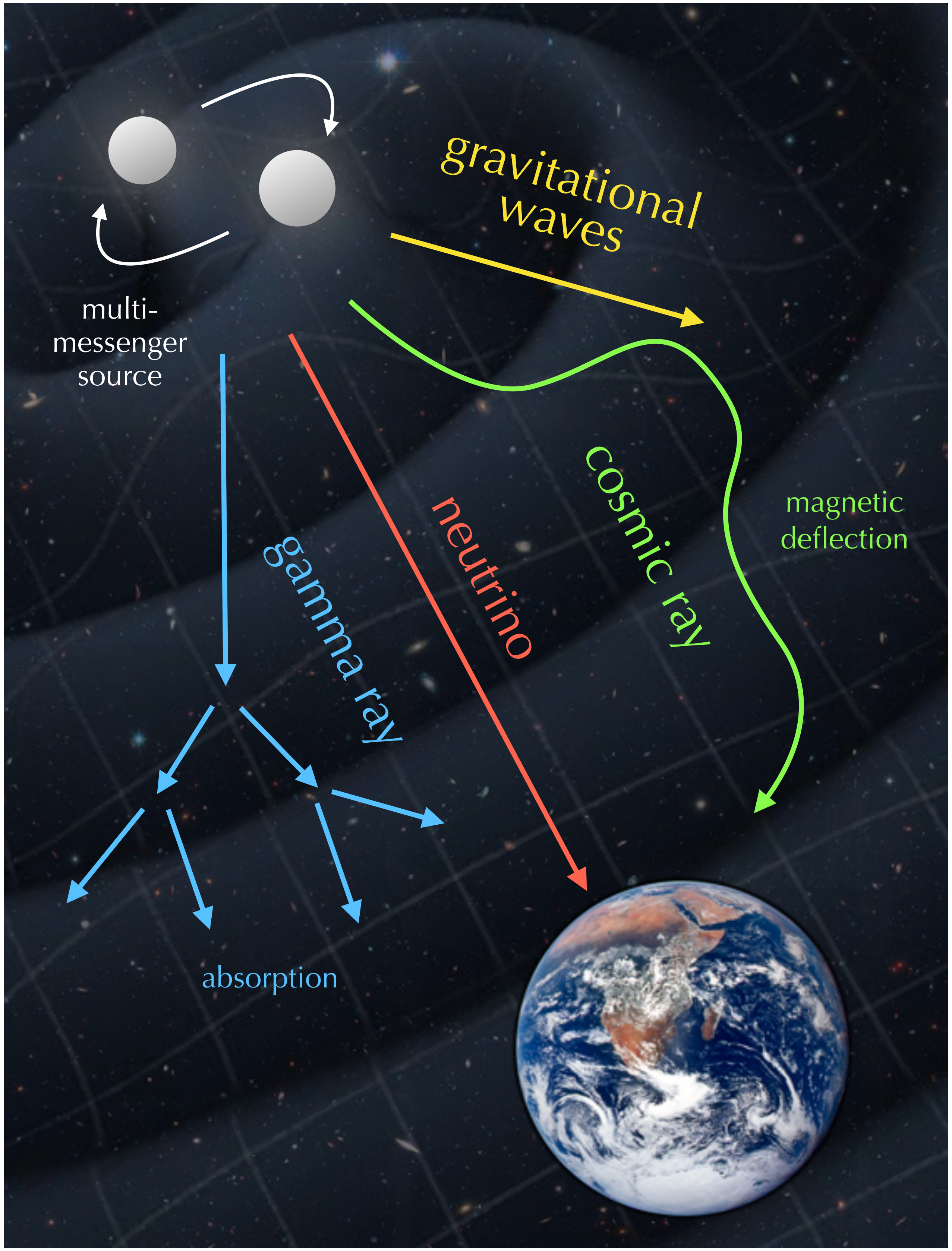


- Approximately:

$$\langle E_\nu \rangle \simeq \frac{1}{2}\langle E_\gamma \rangle \simeq \frac{1}{20}E_{\rm N}$$

[e.g. Lipari, Lusignoli & Meloni '07]

Neutrino 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

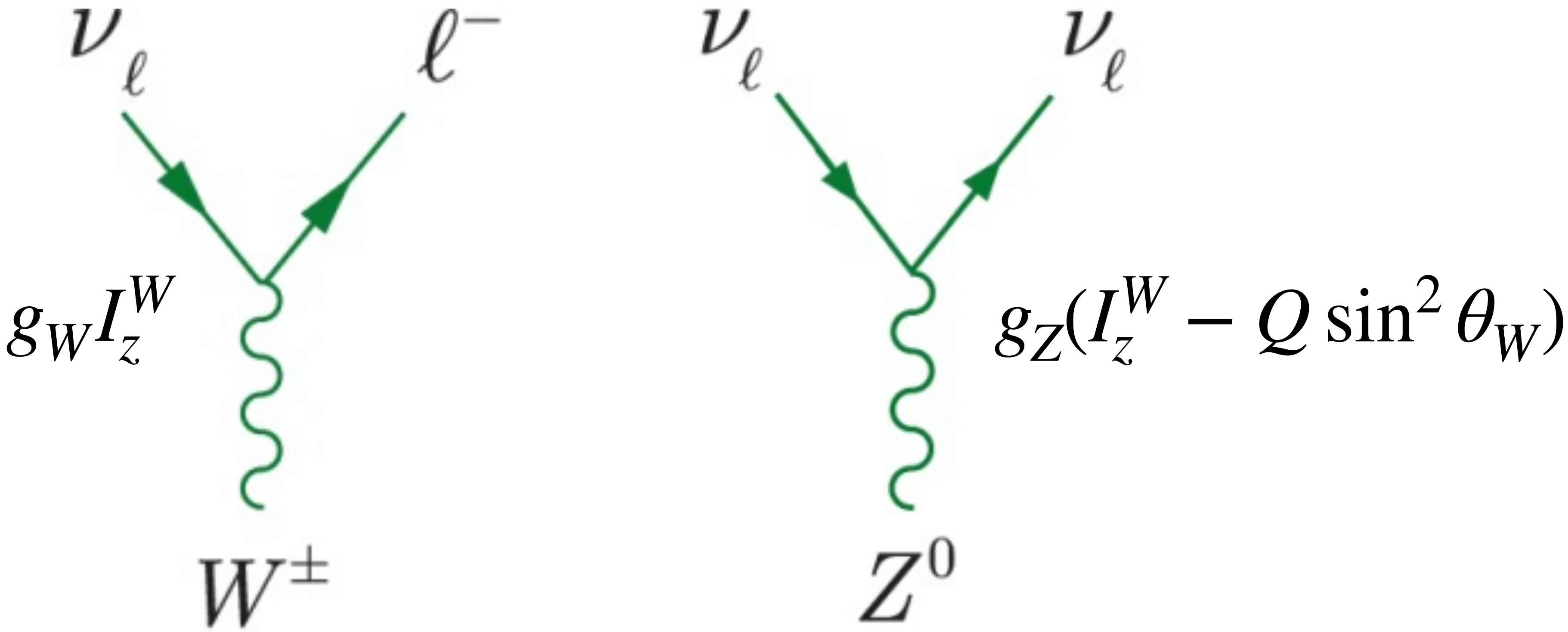
BUT, very difficult to detect!

Neutrinos in the Standard Model

Neutrinos are part of weak isospin doublets and anti-doublets:

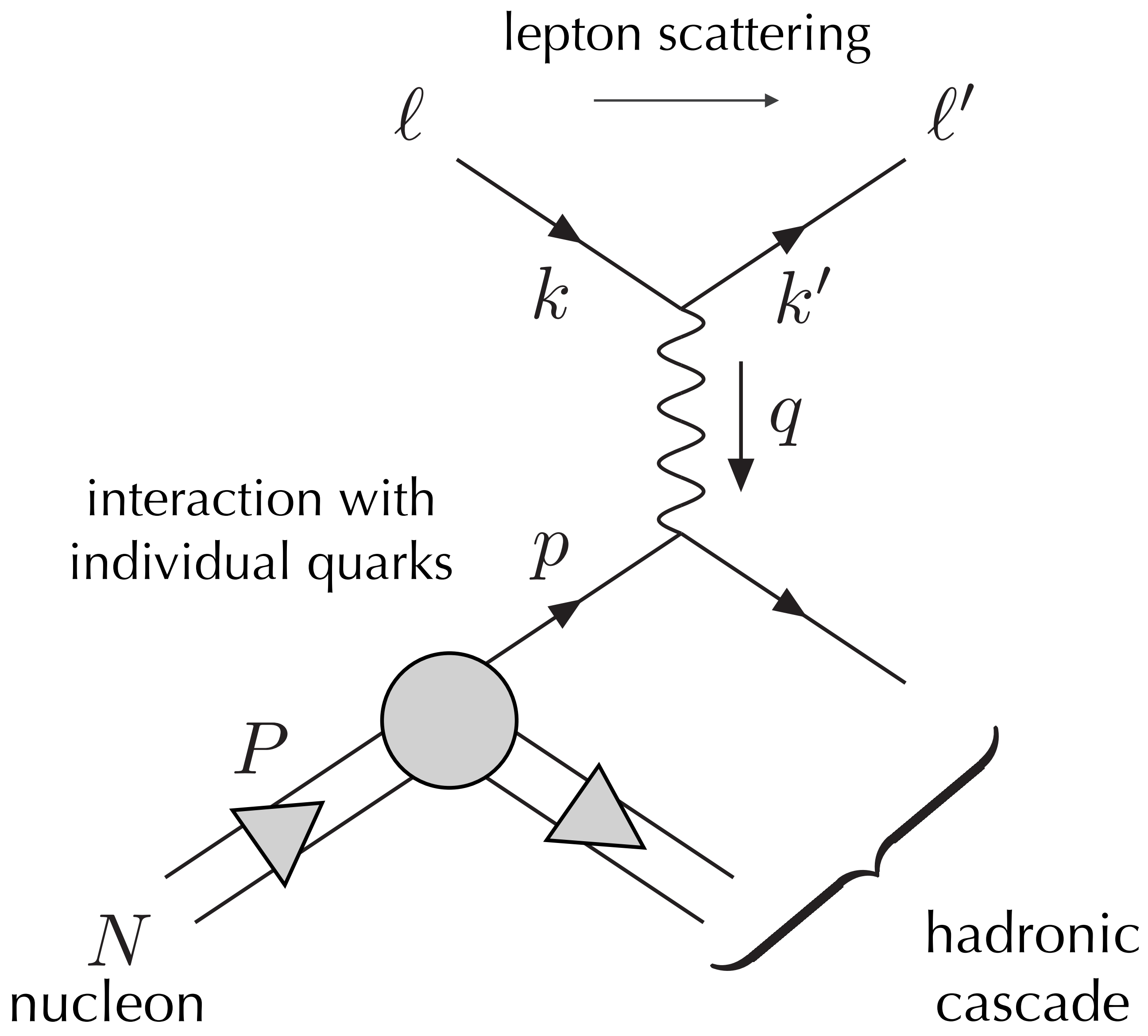
$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \quad \begin{pmatrix}e^+\\ \overline{\nu}_e\end{pmatrix}_R \quad \begin{pmatrix}\mu^+\\ \overline{\nu}_\mu\end{pmatrix}_R \quad \begin{pmatrix}\tau^+\\ \overline{\nu}_\tau\end{pmatrix}_R$$

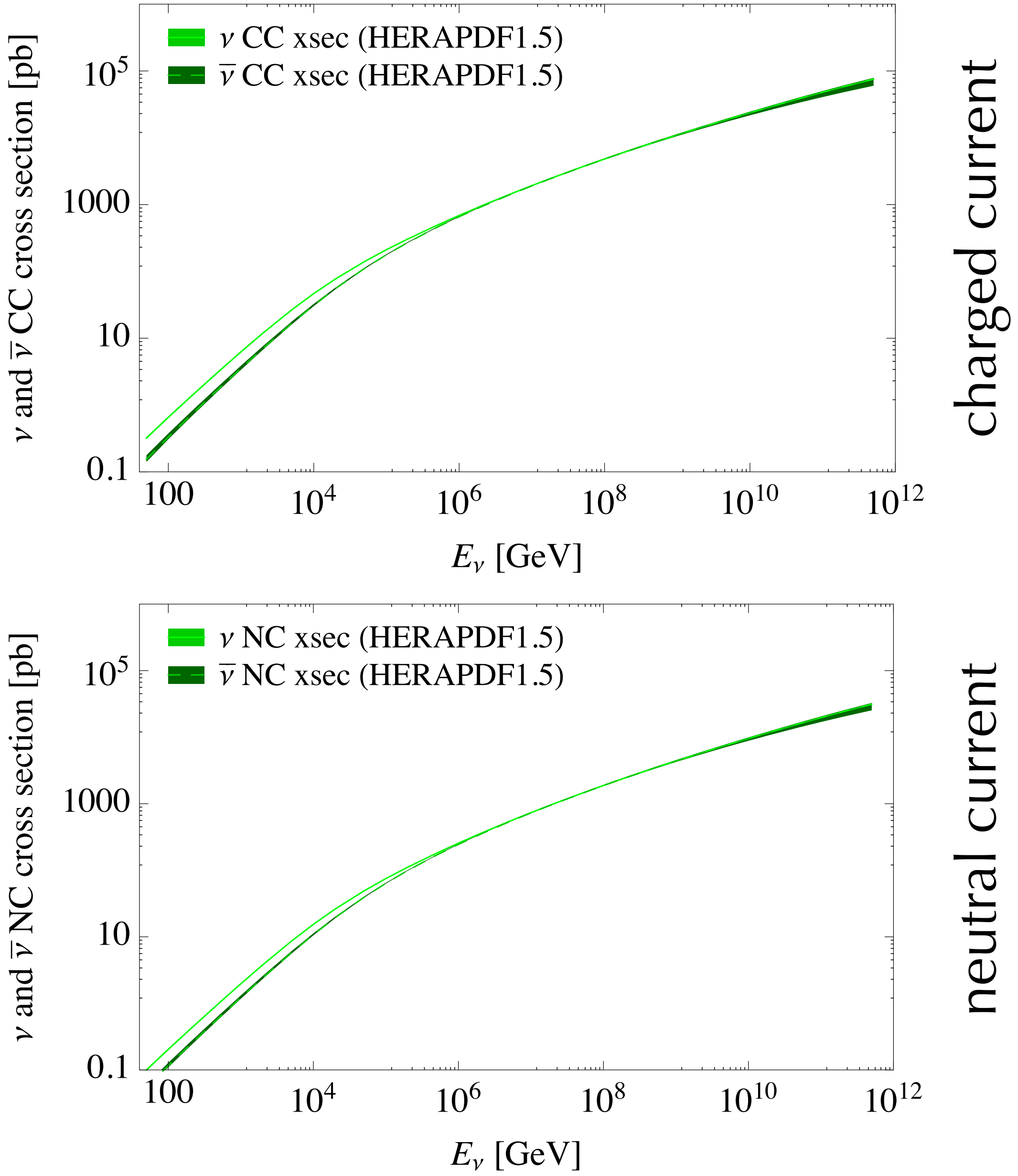
Participate in **charged** (W) **and neutral** (Z) **current** interactions:



Neutrino Interactions

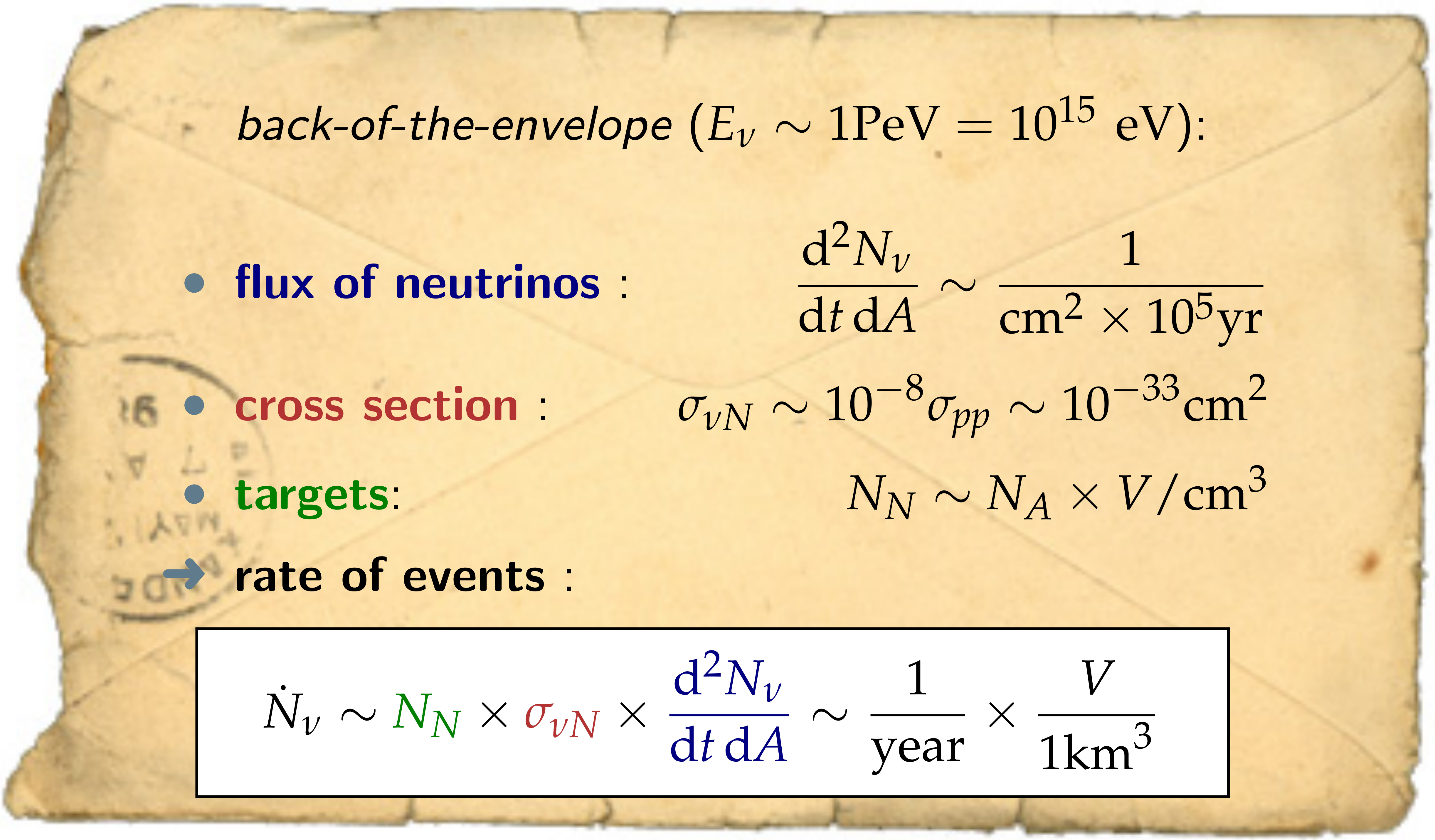
- Low-energy (<10GeV) neutrino interaction with matter in coherent, quasi-elastic or resonant interactions.
- High-energy neutrinos interact with nuclei via **deep inelastic scattering.**





[Cooper-Sarkar, Mertsch & Sarkar'11]

Detector Requirements



back-of-the-envelope $(E_\nu \sim 1\mathrm{PeV} = 10^{15}\ \mathrm{eV})$:

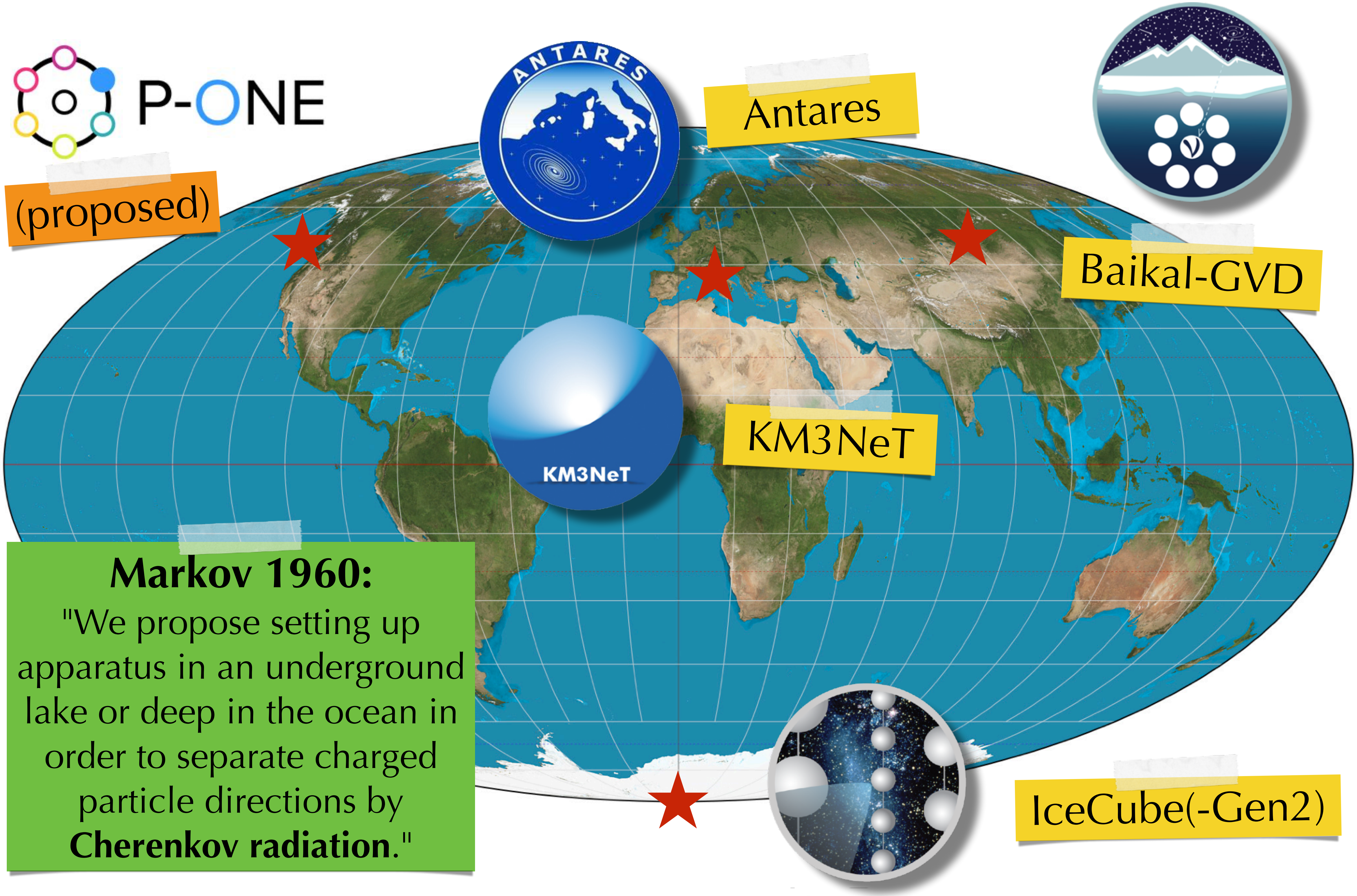
- **flux of neutrinos** : $$\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5\mathrm{yr}}$$
- **cross section** : $$\sigma_{\nu N} \sim 10^{-8}\sigma_{pp} \sim 10^{-33}\mathrm{cm}^2$$
- **targets**: $$N_N \sim N_A \times V/\mathrm{cm}^3$$

→ **rate of events** :

$$\boxed{\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}}$$

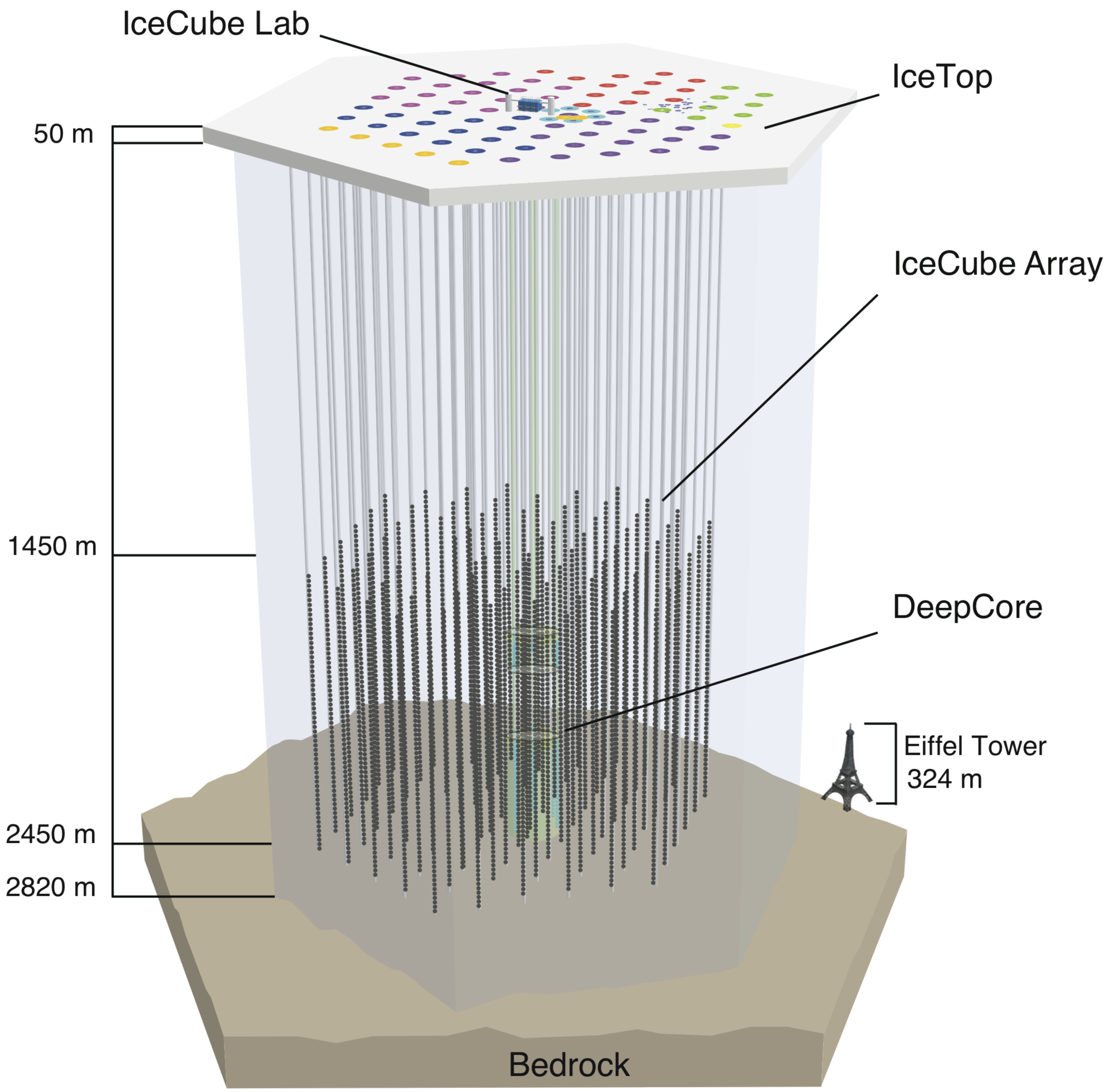
minimum detector size: 1km³

Optical Cherenkov Telescopes



Markov 1960:
"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by **Cherenkov radiation.**"

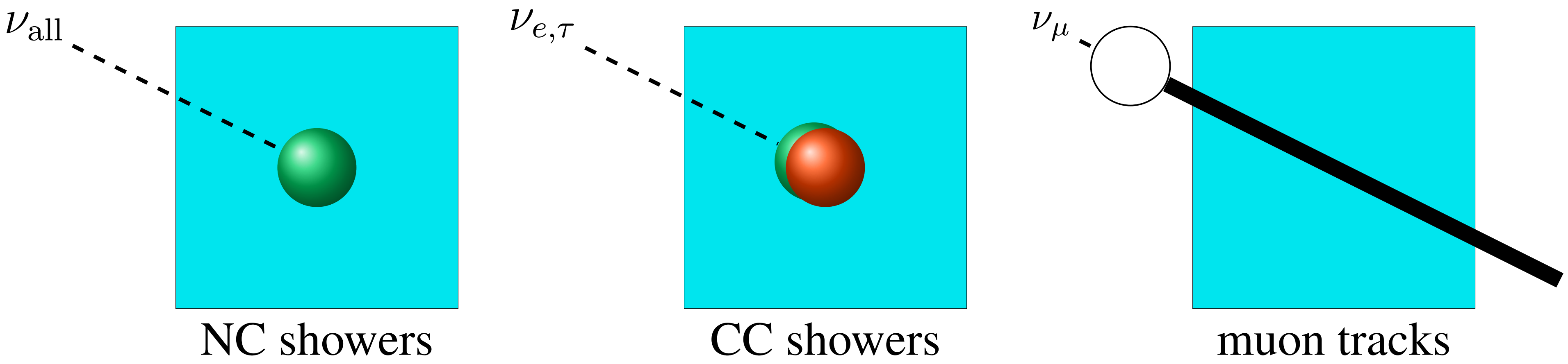
IceCube Observatory



- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 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

Optical Cherenkov Detection

“cascades”
&
“tracks”



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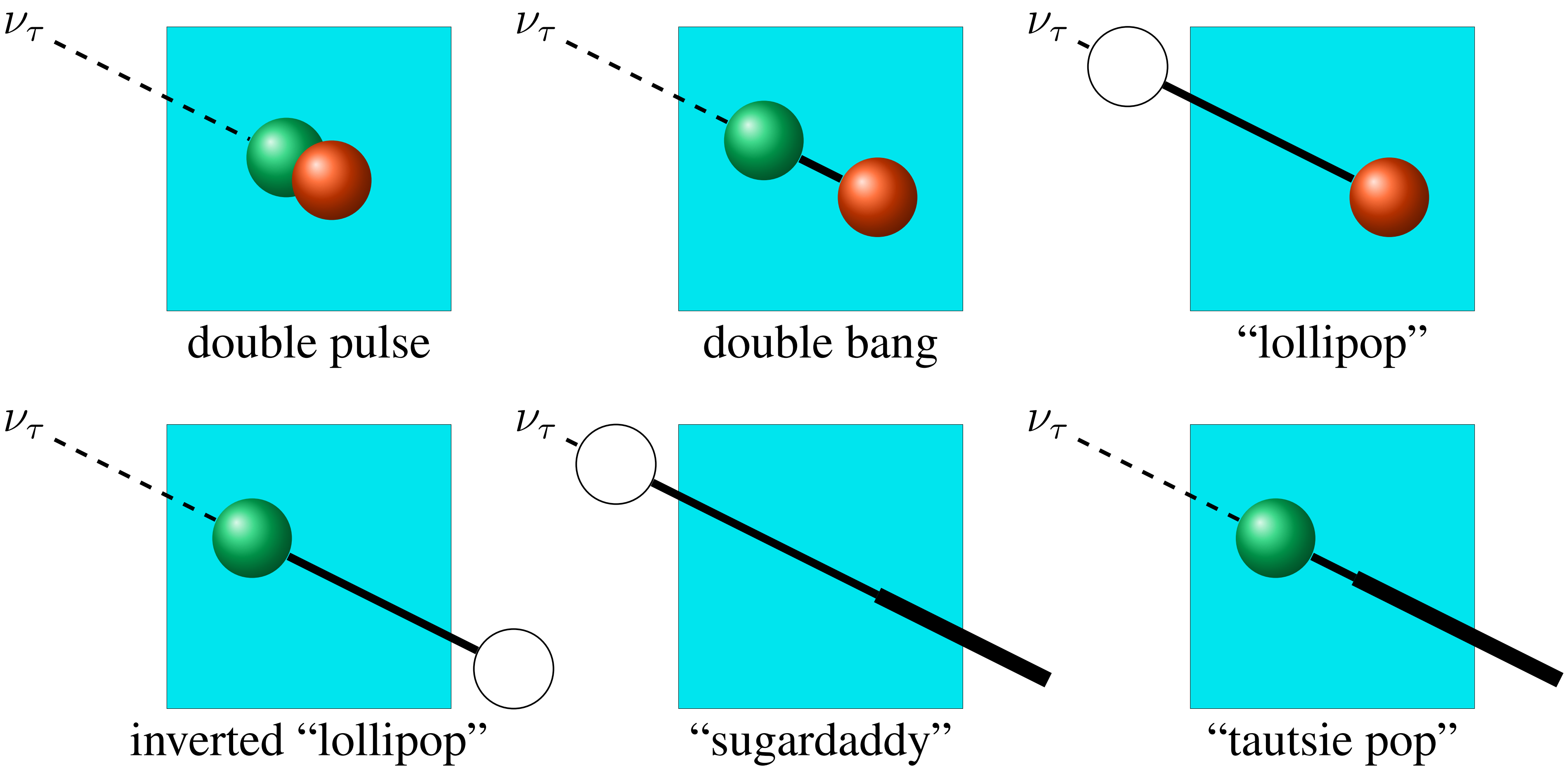
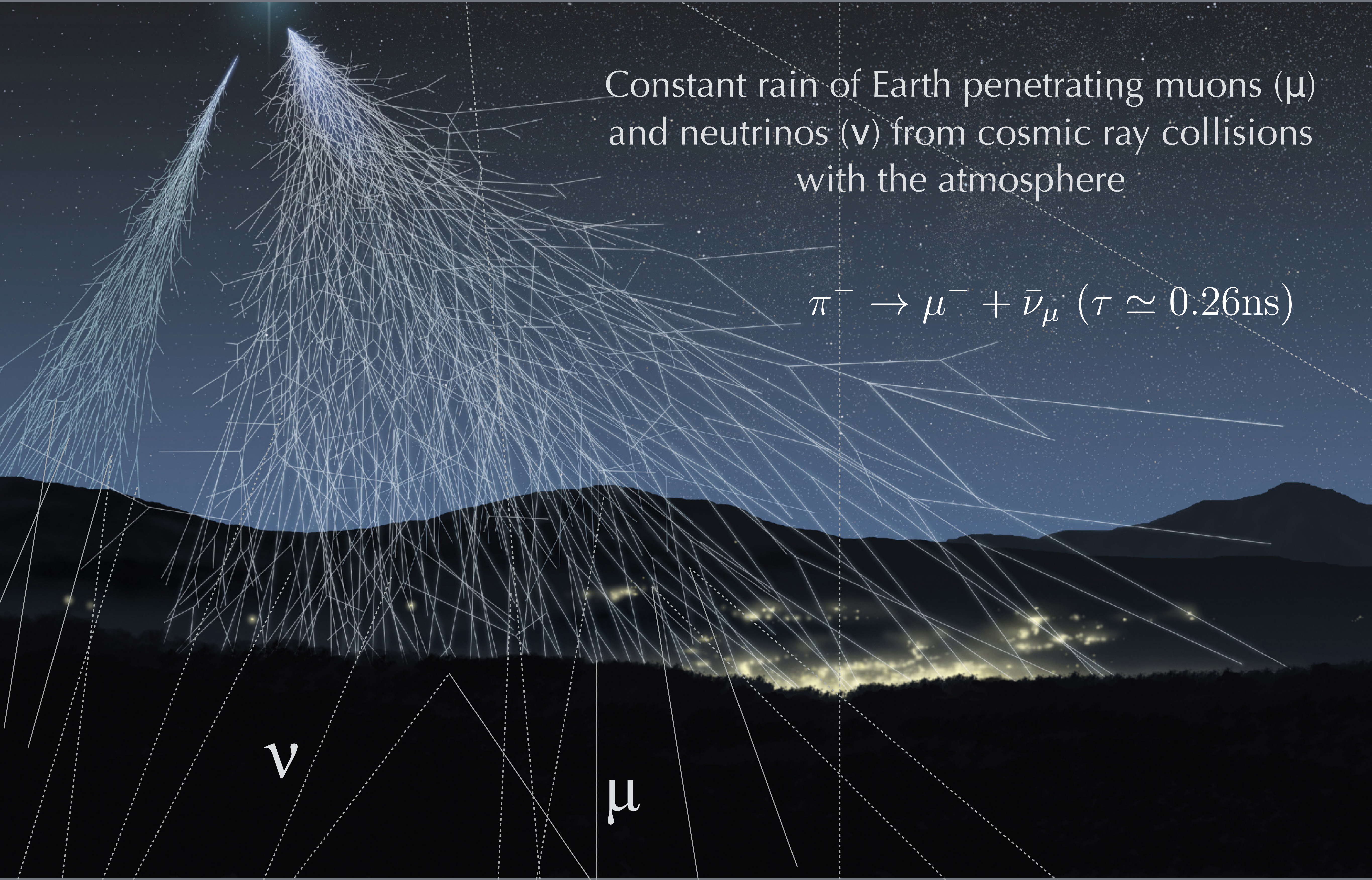
rare events
from CC ν_τ
interactions



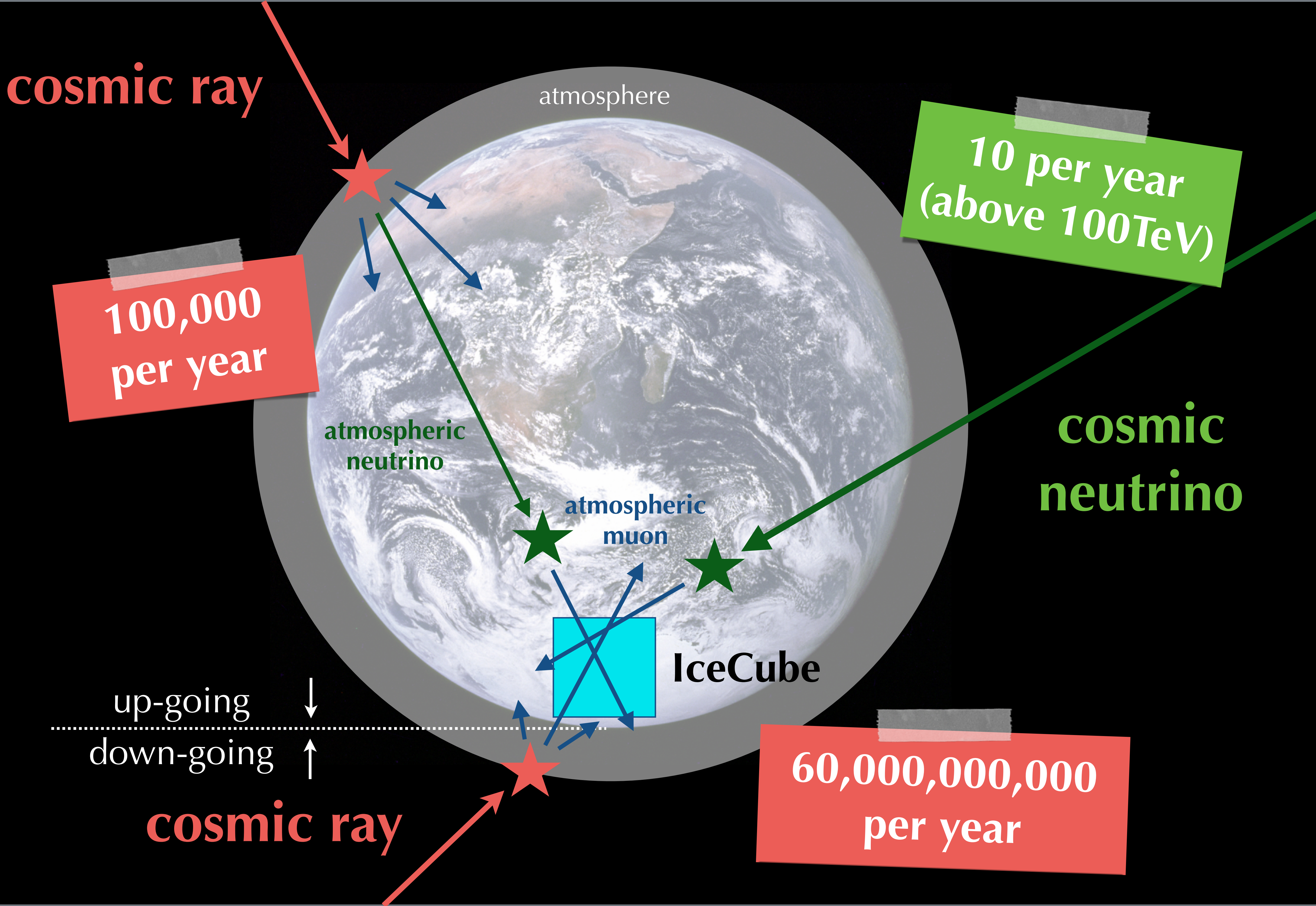
Atmospheric Neutrinos



Constant rain of Earth penetrating muons (μ) and neutrinos (ν) from cosmic ray collisions with the atmosphere

$$\pi^- \to \mu^- + \bar{\nu}_\mu \ (\tau \simeq 0.26\text{ns})$$

Neutrino Selection I



cosmic ray

atmosphere

10 per year
(above 100TeV)

100,000
per year

atmospheric
neutrino

atmospheric
muon

cosmic
neutrino

IceCube

up-going ↓

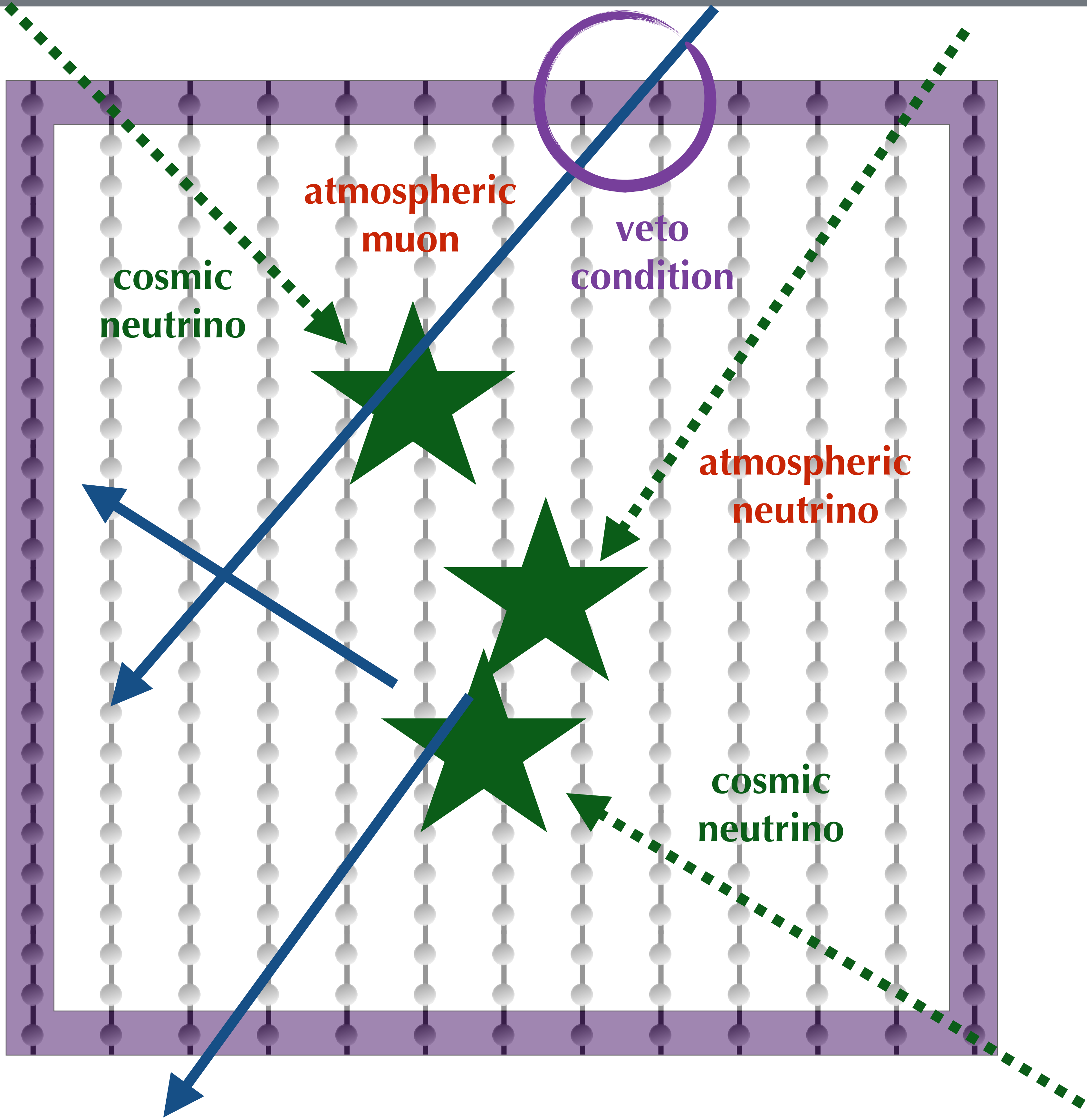
down-going ↑

cosmic ray

60,000,000,000
per year

Neutrino Selection II

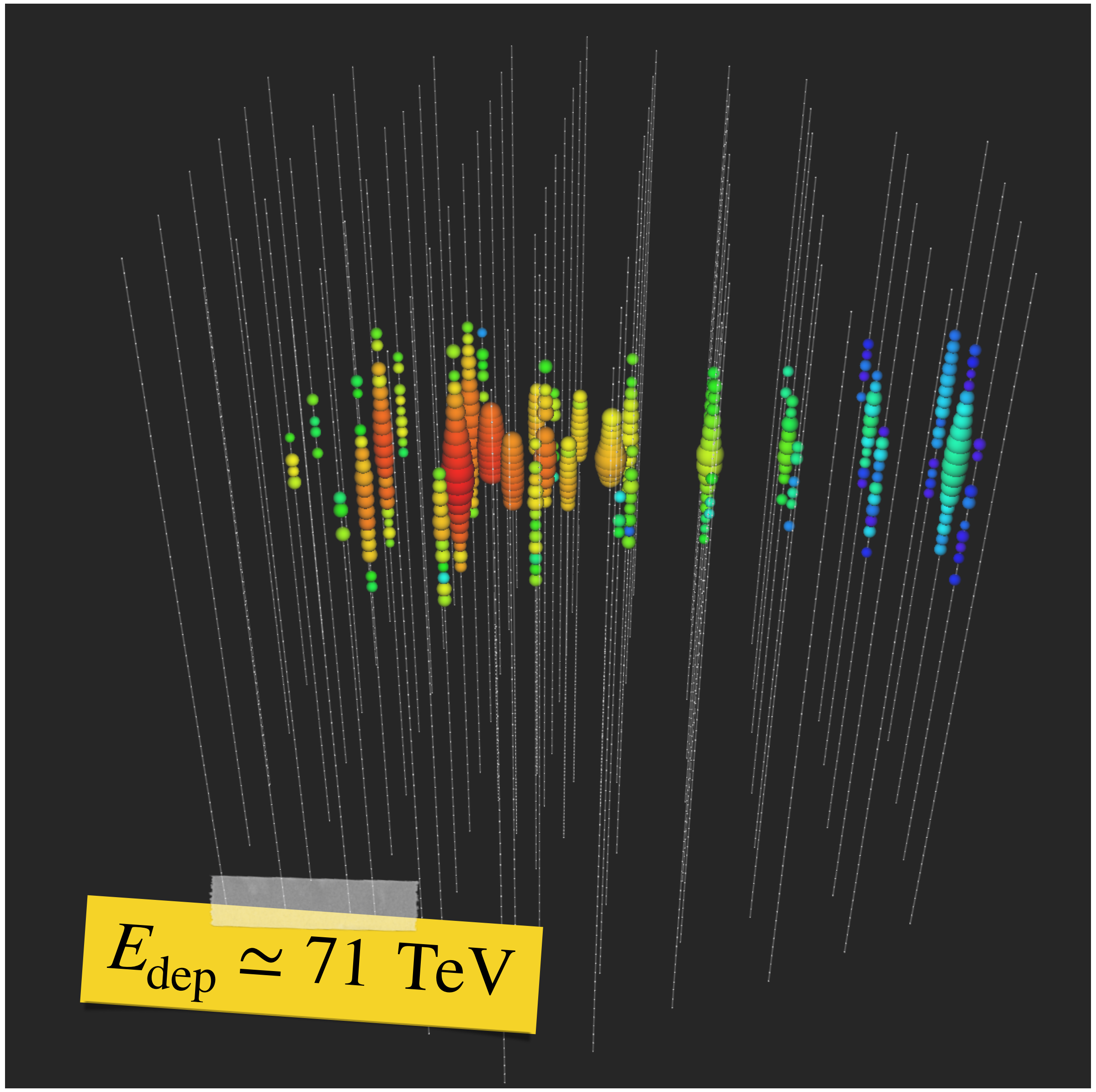
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis



High-Energy Neutrinos

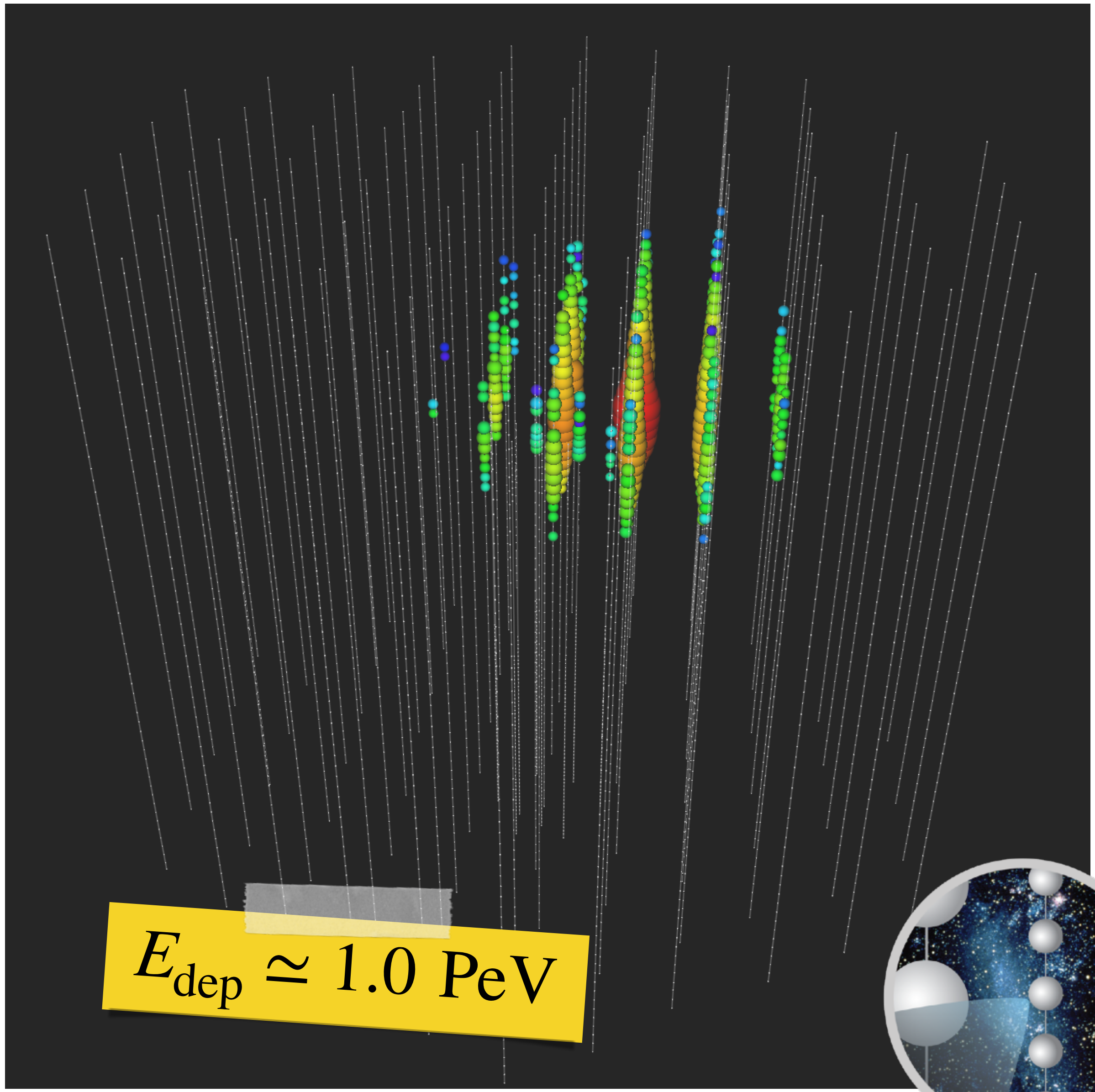
First observation of high-energy astrophysical neutrinos by IceCube in 2013.

"track event" (e.g. ν_μ CC interactions)



$E_{\rm dep} \simeq 71$ TeV

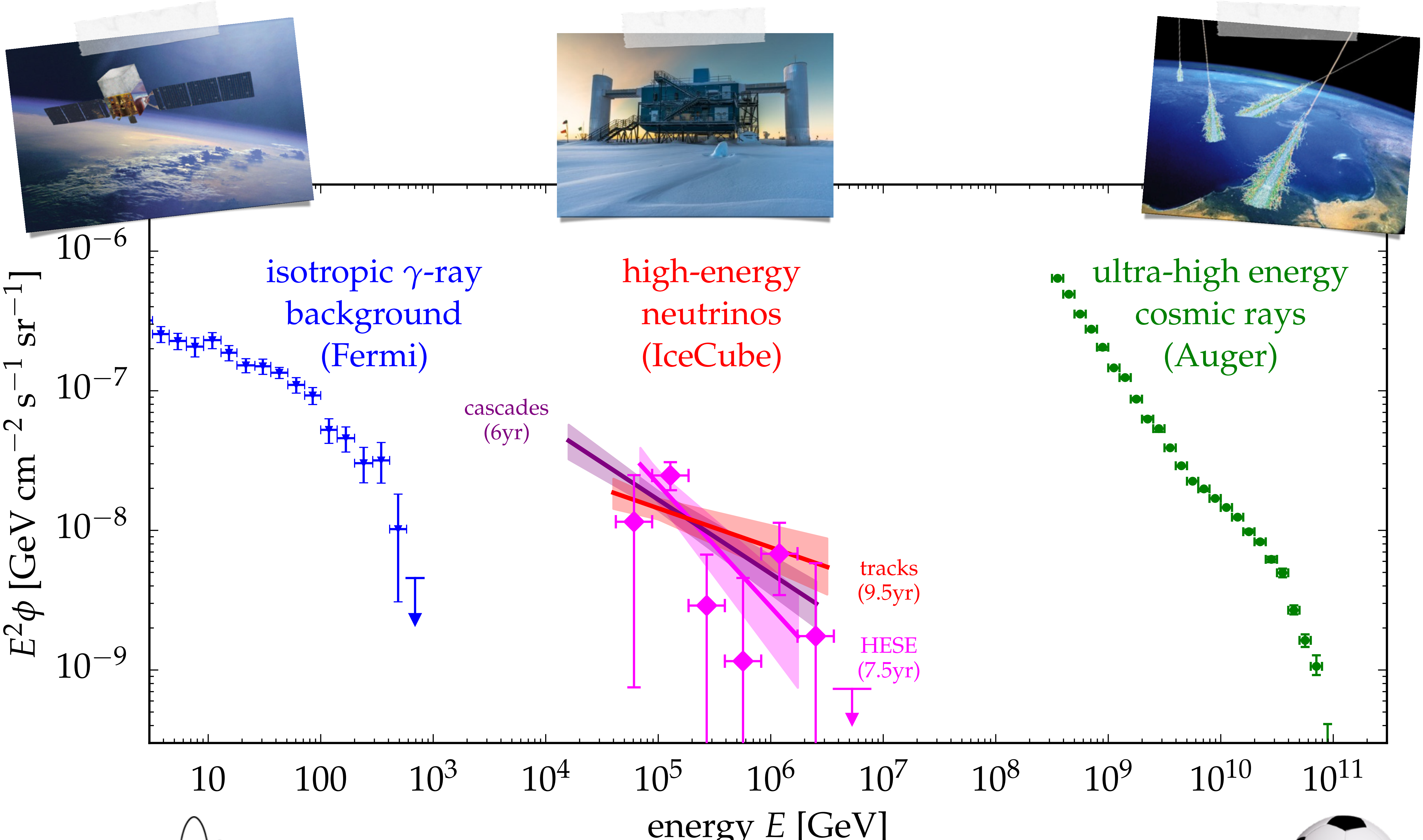
"cascade event" (e.g. NC interactions)

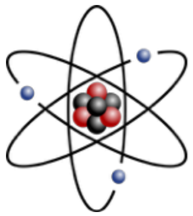


$E_{\rm dep} \simeq 1.0$ PeV

(colours indicate arrival time of Cherenkov photons from **early** to **late**)

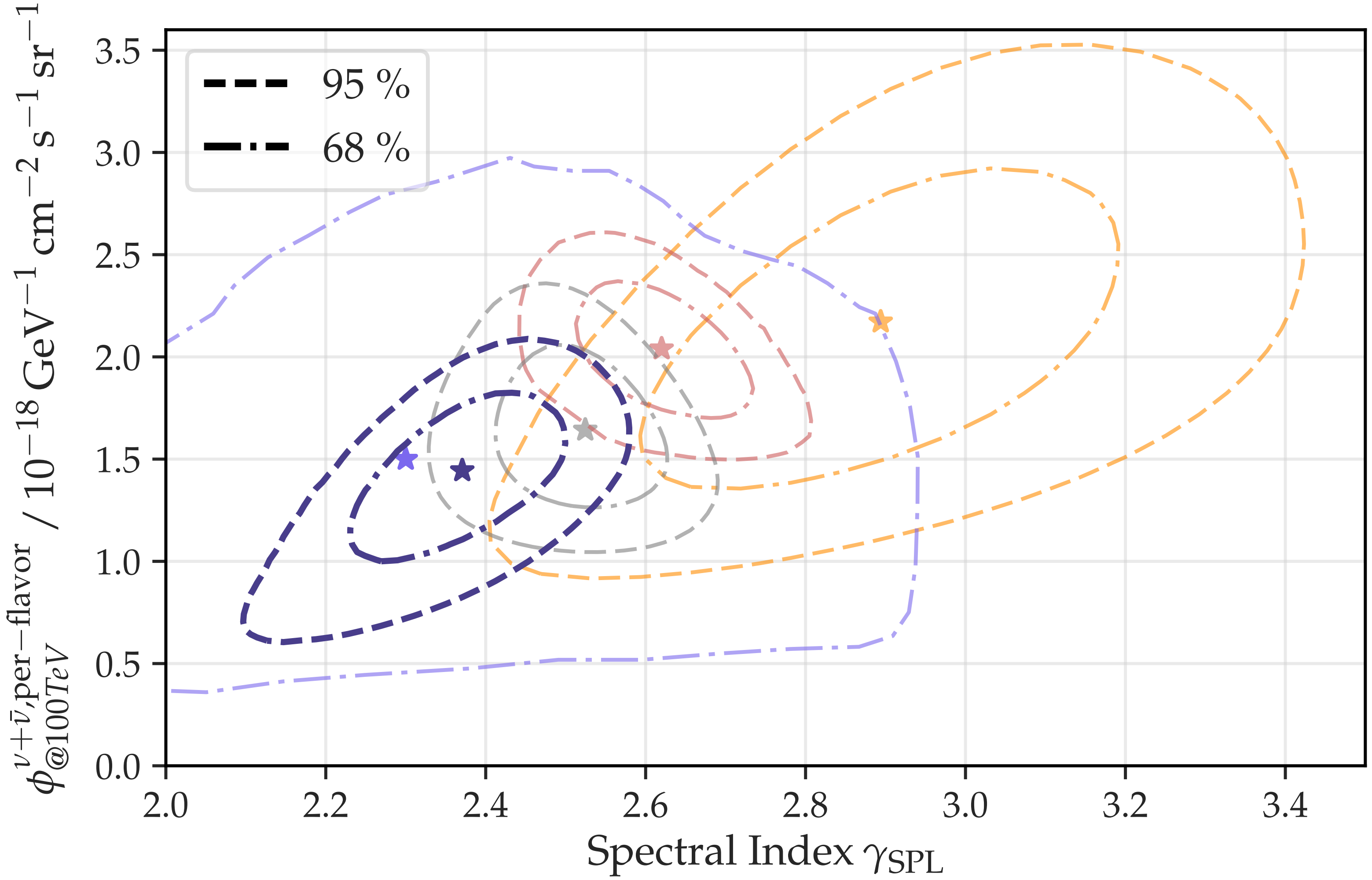
Diffuse TeV-PeV Neutrinos



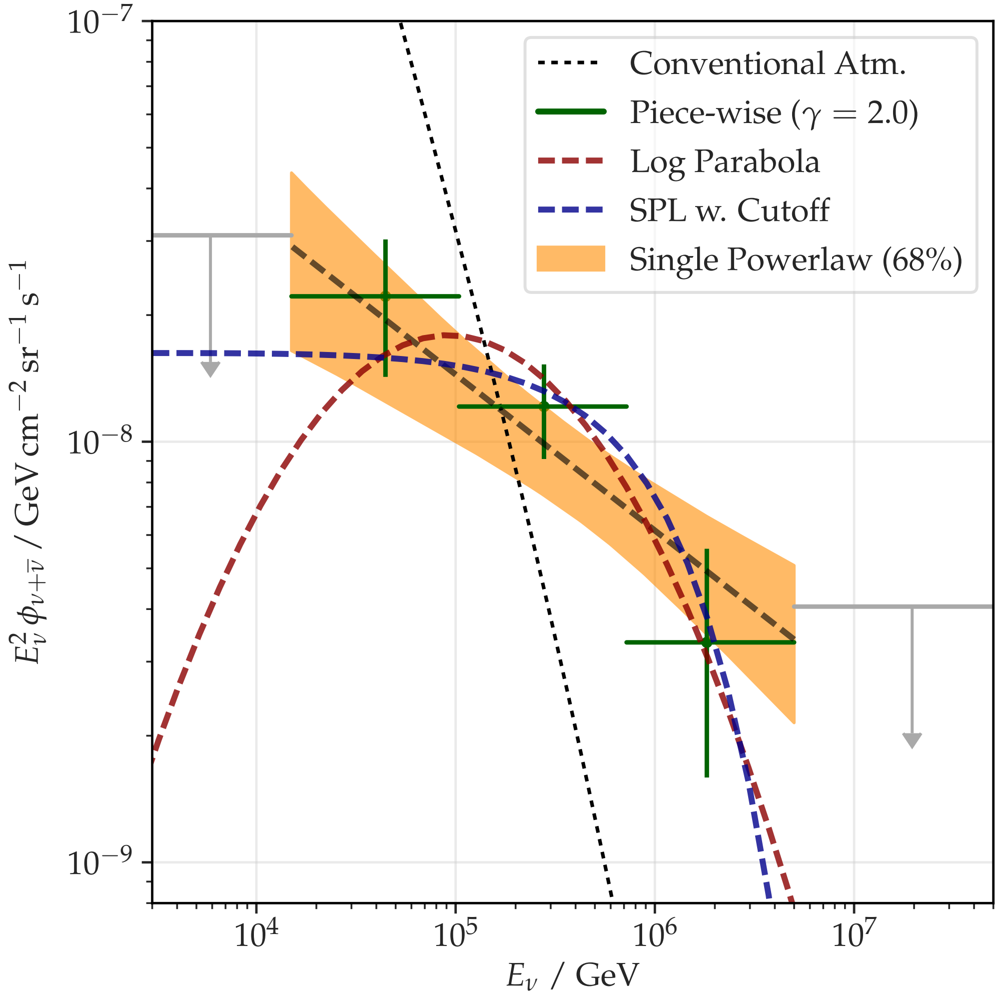


[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Isotropic Diffuse Flux

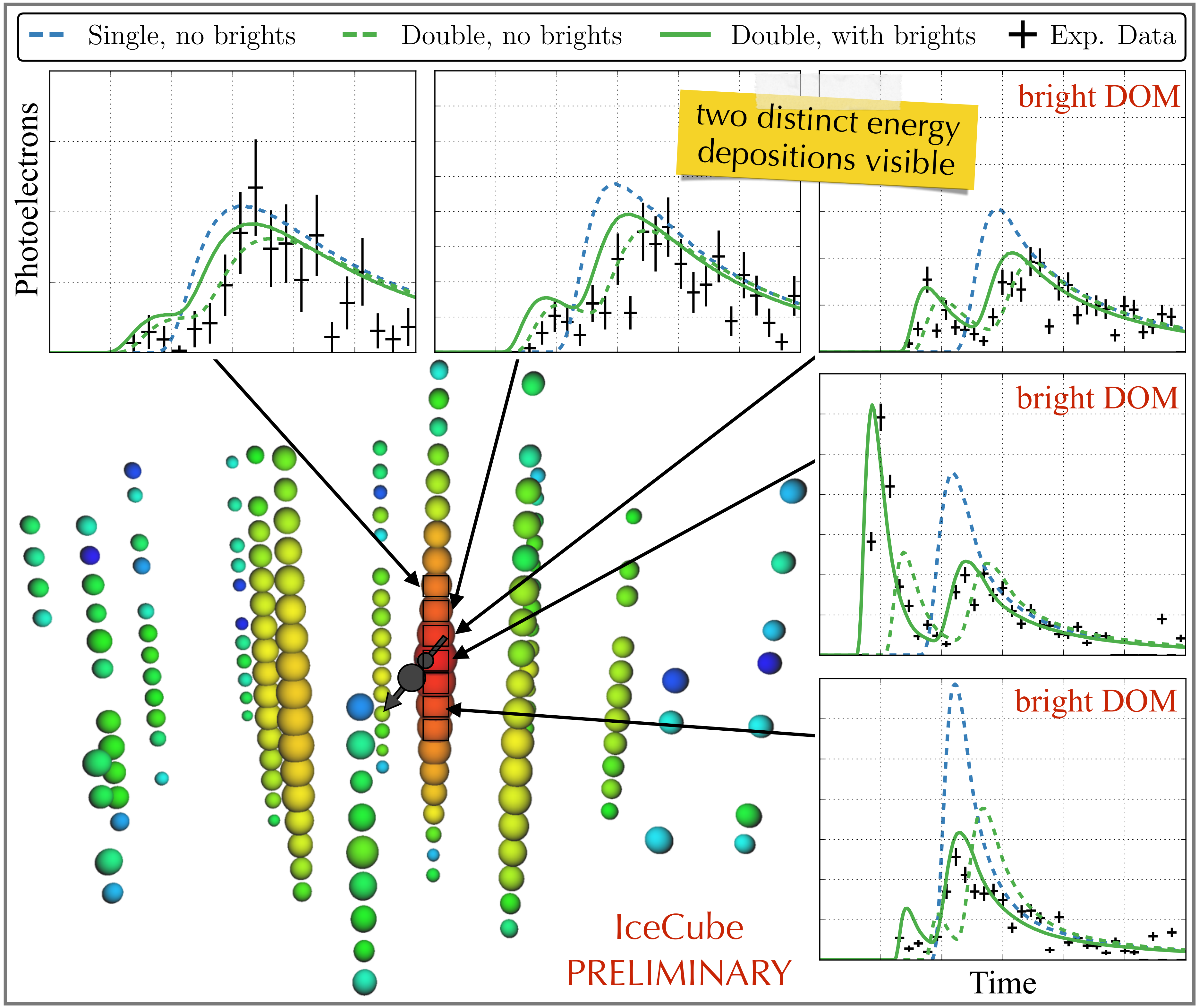


[IceCube, ApJ (2022) 928]



- Diffuse **flux level agrees** across analyses (*within their overlapping energy regions*).
- However, **mild tension between spectral index** for a "vanilla" single power-law flux.

Astrophysical Flavours



two distinct energy depositions visible

[IceCube, arXiv:2011.03561]

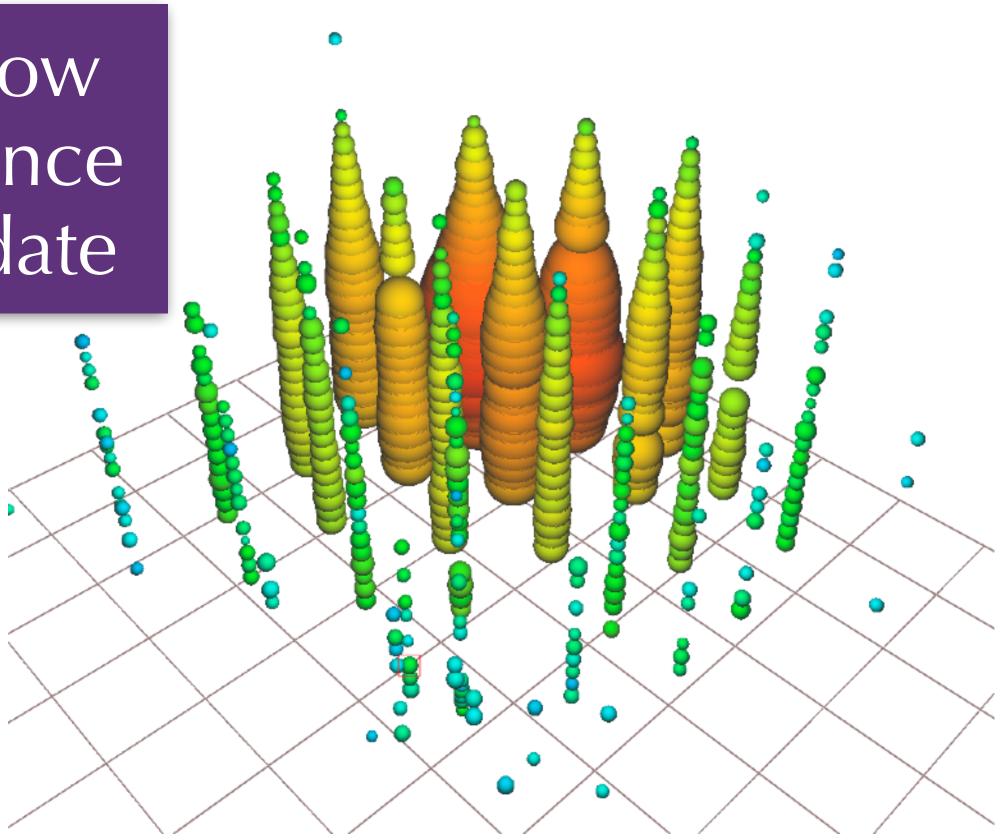
tau neutrino candidate

ICECUBE

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

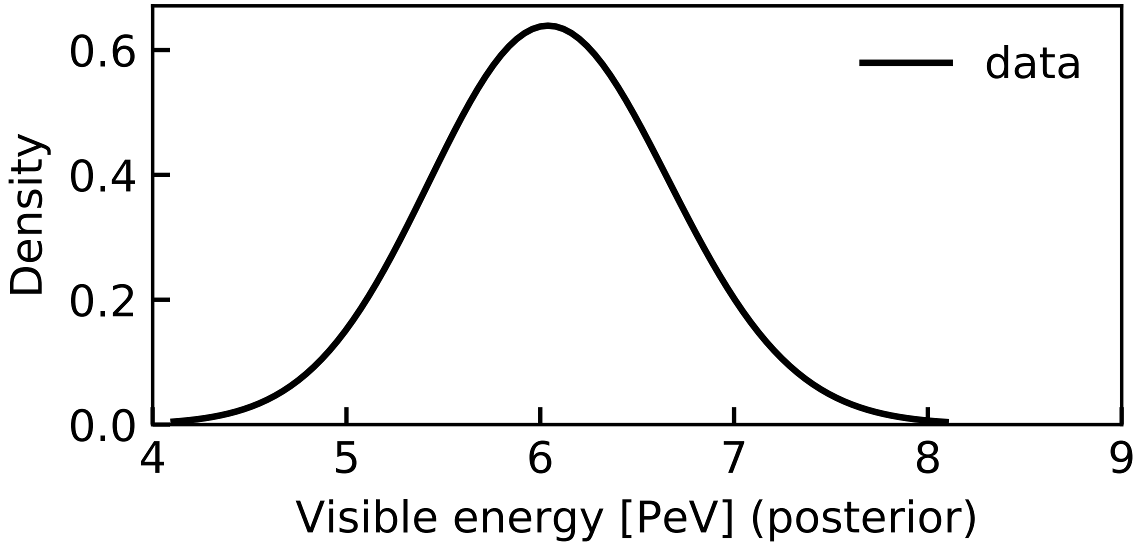
Astrophysical Flavours

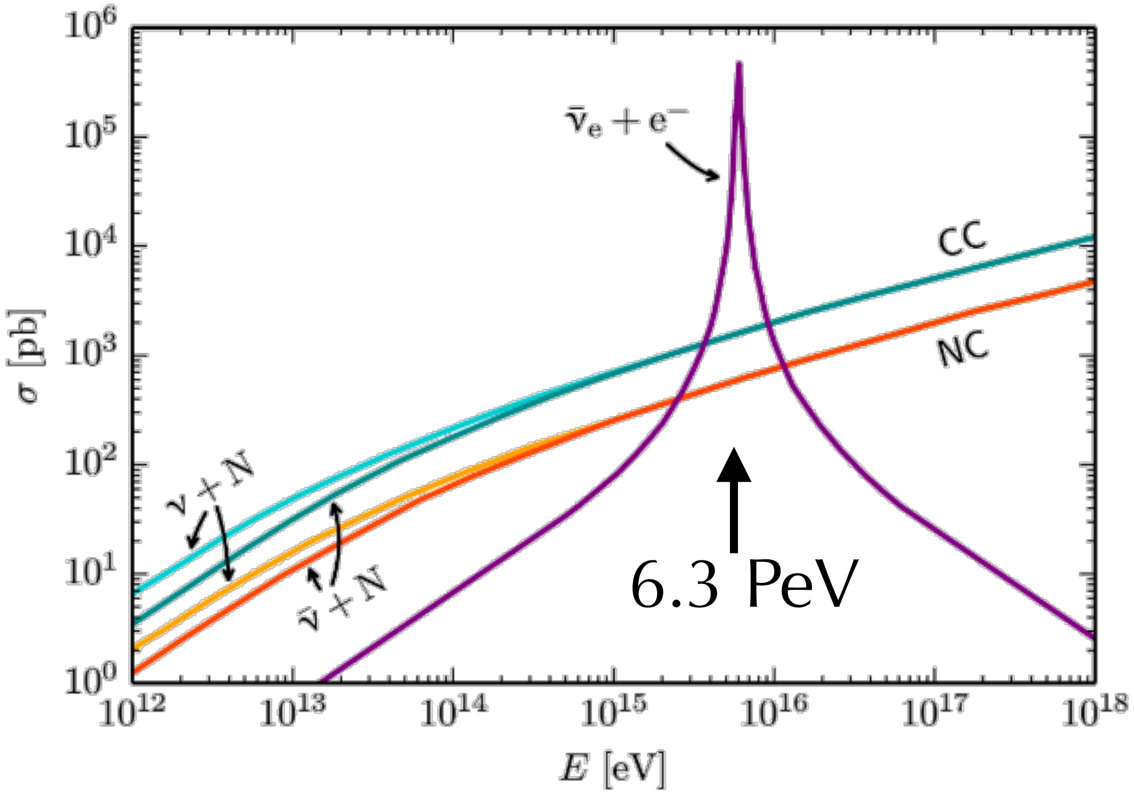
Glashow resonance candidate

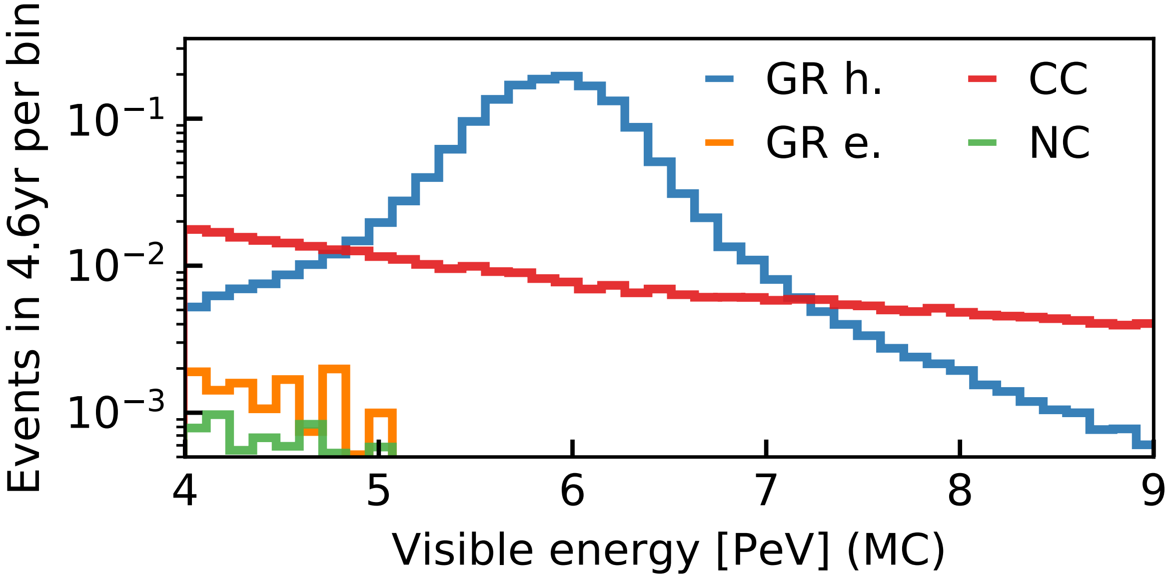


Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

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







[IceCube, Nature 591 (2021) 220-224]

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"atmospheric" mixing

~~CP~~ Dirac phase $\propto \sin\theta_{13}$

"solar" mixing

~~CP~~ Majorana phases

flavour transition probability (in vacuum):

$$P_{\nu_\alpha\to\nu_\beta}(\ell) = \sum_{i=1}^{3}\sum_{j=1}^{3} U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\exp\left(i\frac{\Delta m^2_{ij}\ell}{2E_\nu}\right)$$

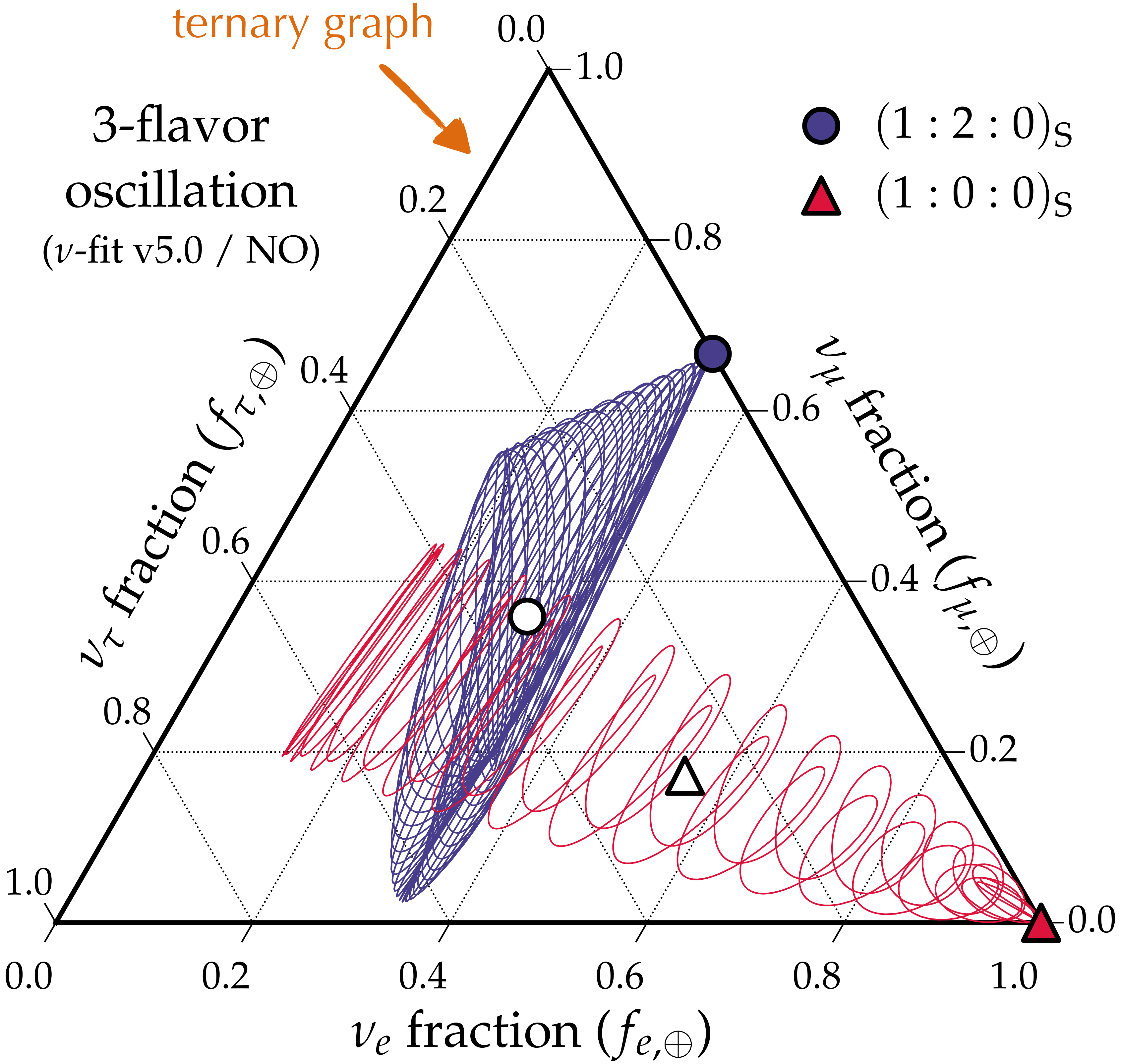
notation: $c_{ij} \equiv \cos\theta_{ij}$ & $s_{ij} \equiv \sin\theta_{ij}$ & $\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Astrophysical Flavours

ternary graph

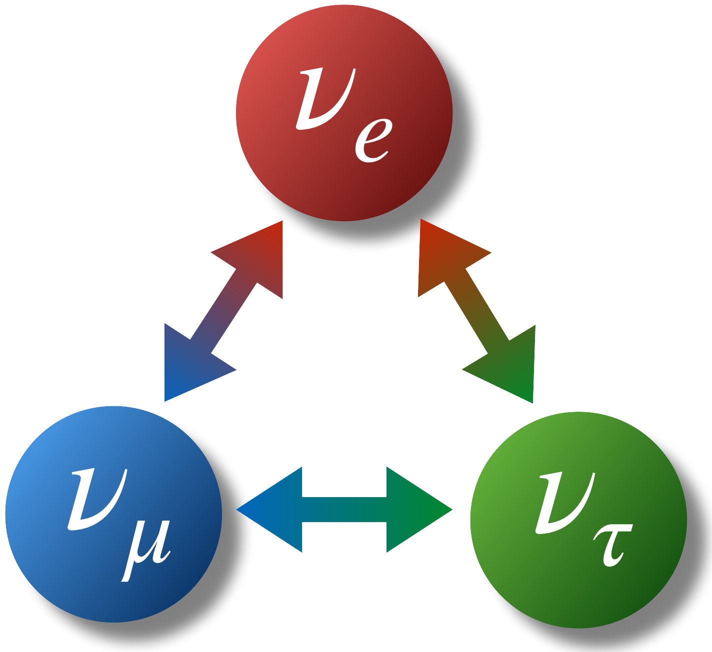
3-flavor oscillation

(ν-fit v5.0 / NO)



flavor ratios on production

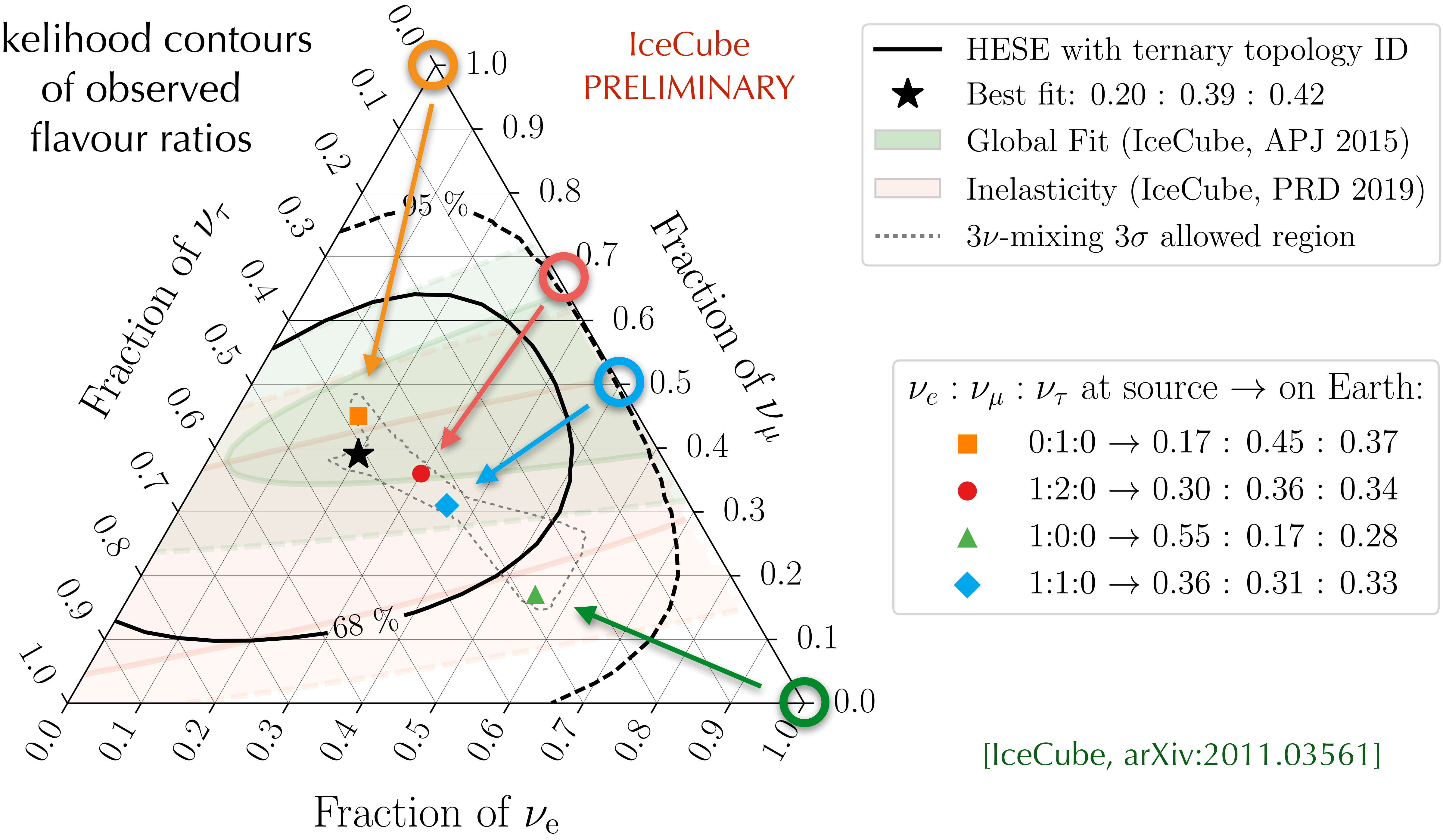
Superposition of flavor and mass states induce oscillations.



Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.

Likelihood contours of observed flavour ratios



$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:

🟧 0:1:0 → 0.17 : 0.45 : 0.37

● 1:2:0 → 0.30 : 0.36 : 0.34

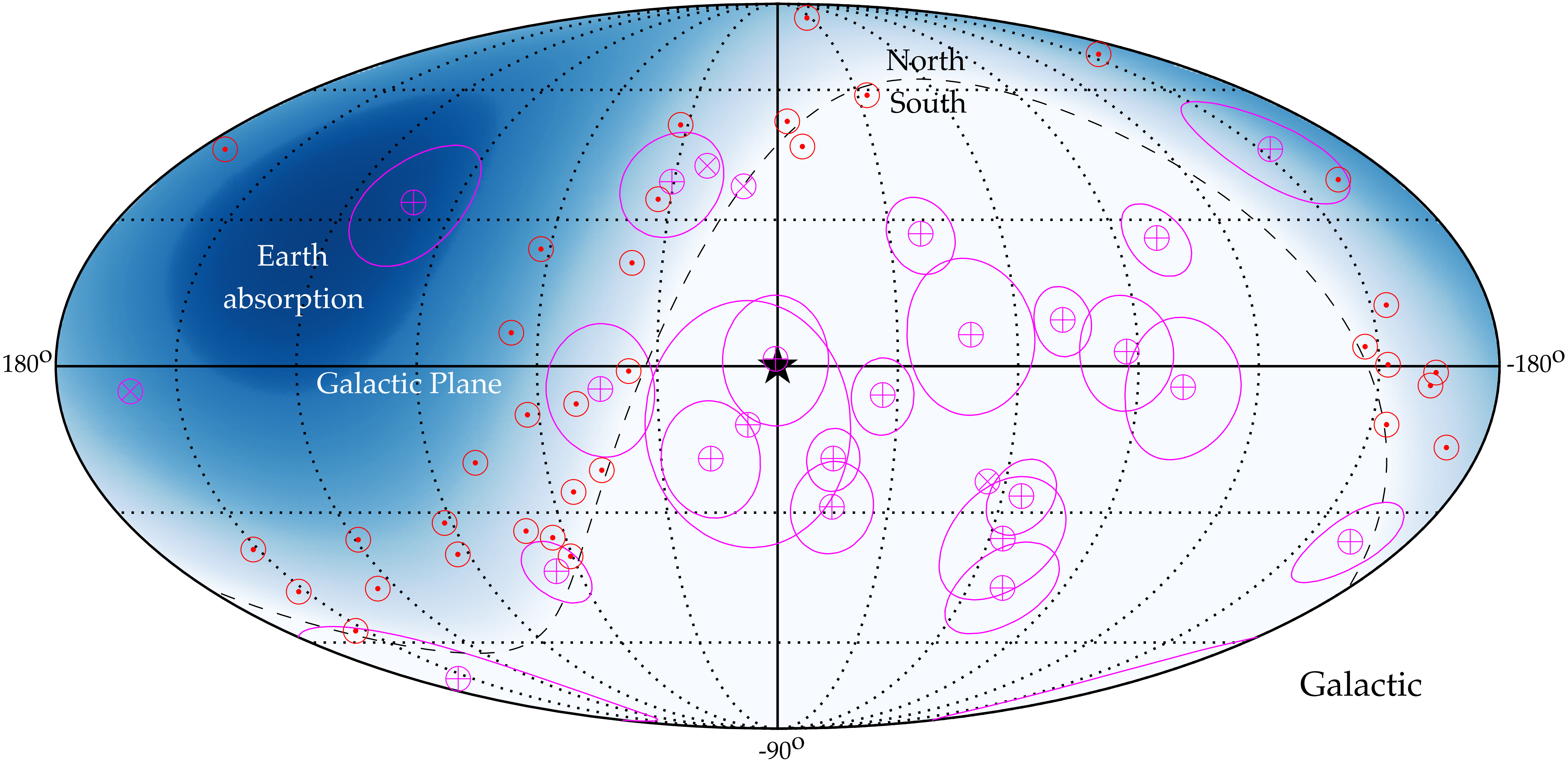
▲ 1:0:0 → 0.55 : 0.17 : 0.28

◆ 1:1:0 → 0.36 : 0.31 : 0.33

[IceCube, arXiv:2011.03561]

Status of Neutrino Astronomy

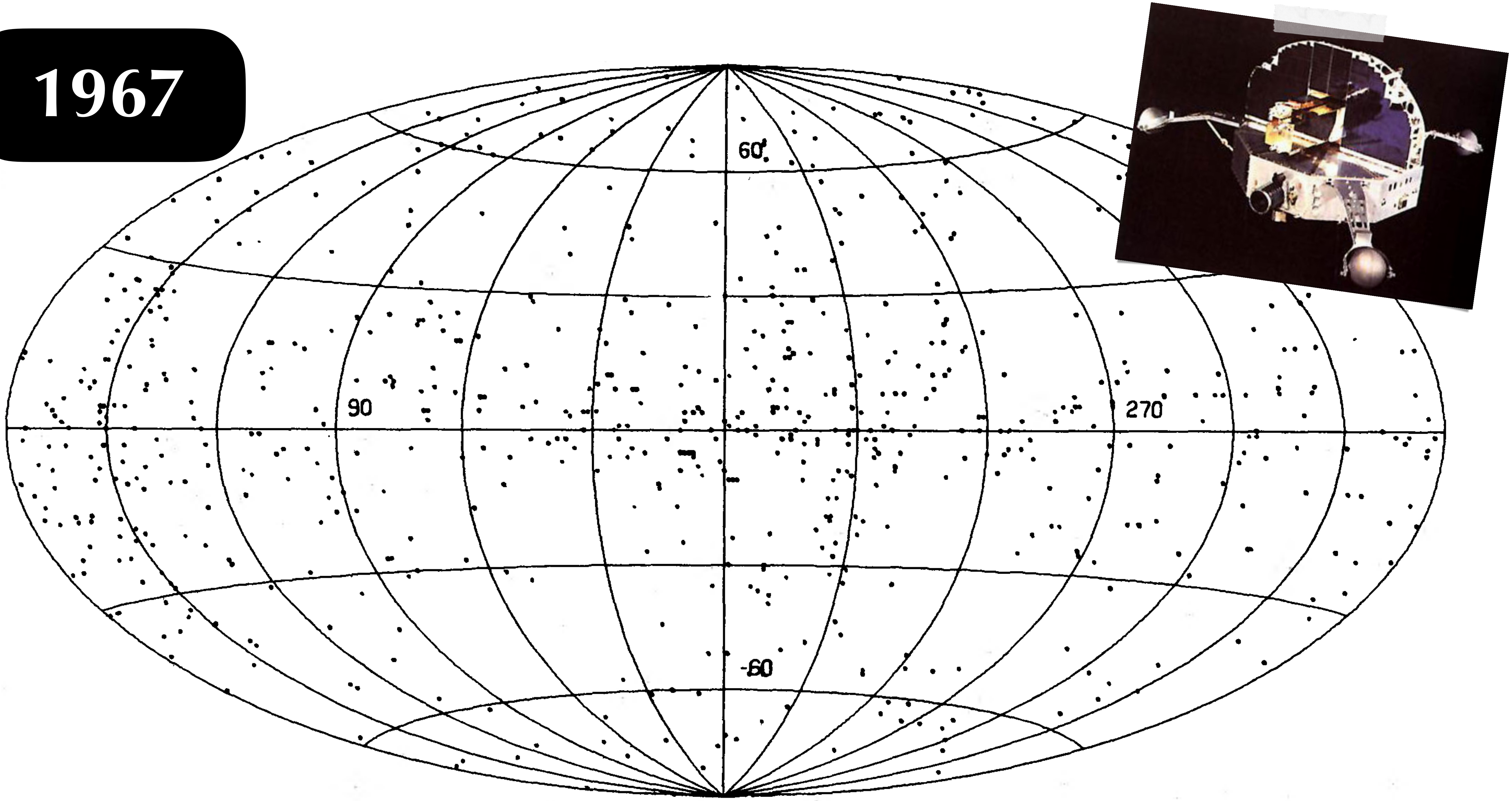
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Status of Neutrino Astronomy

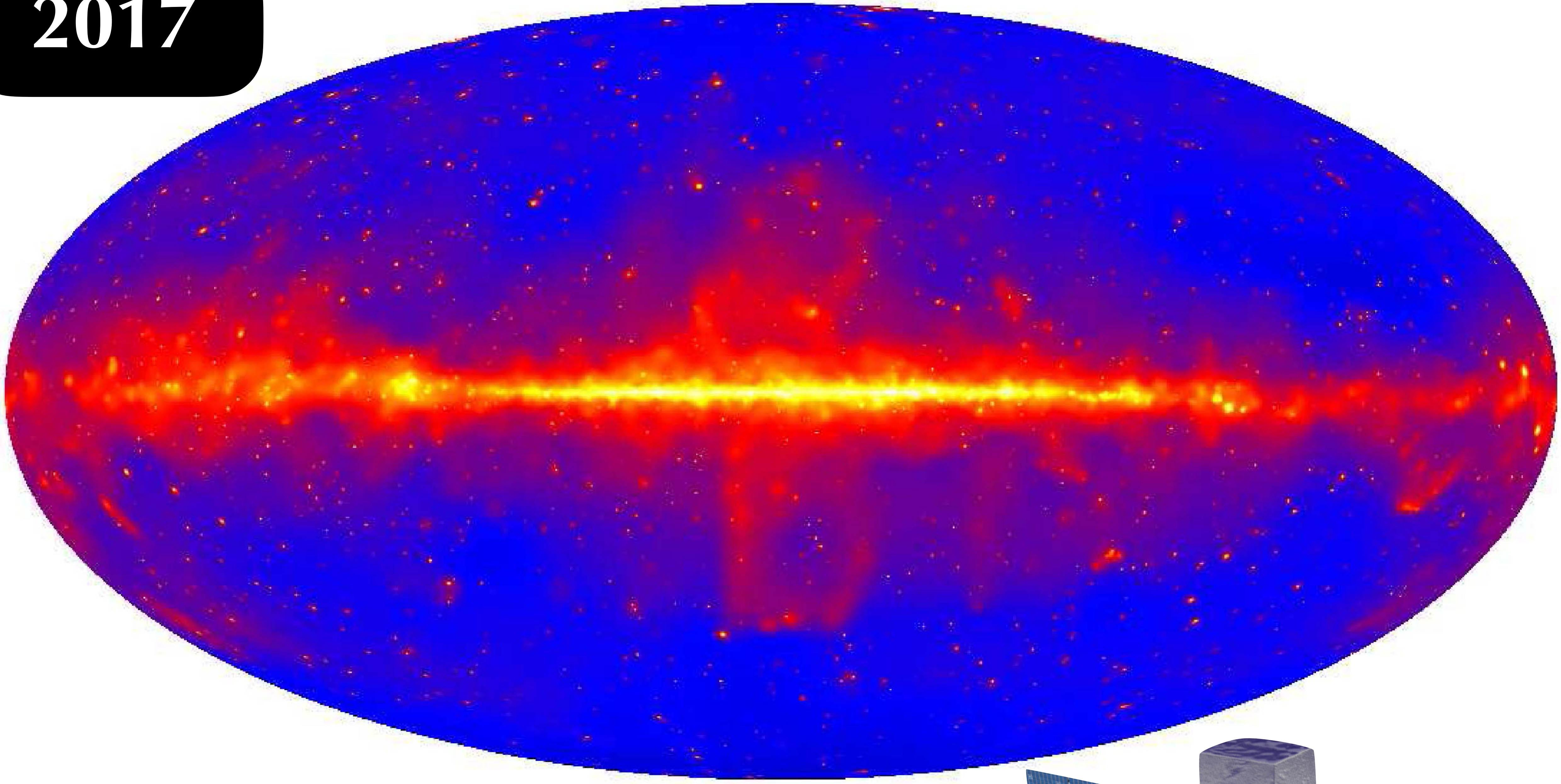
1967

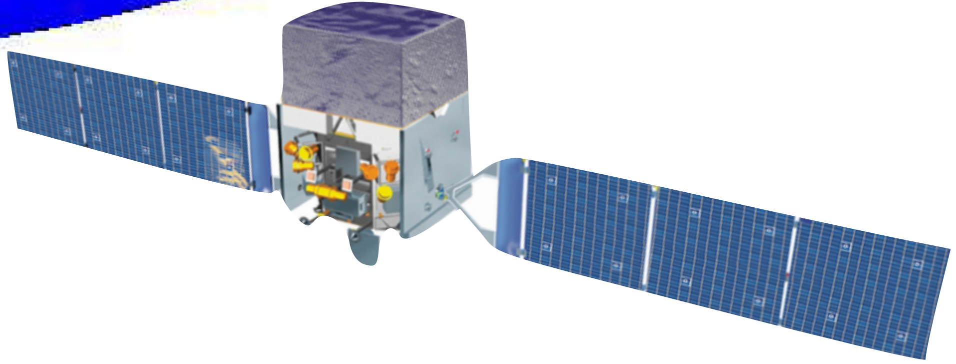


Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

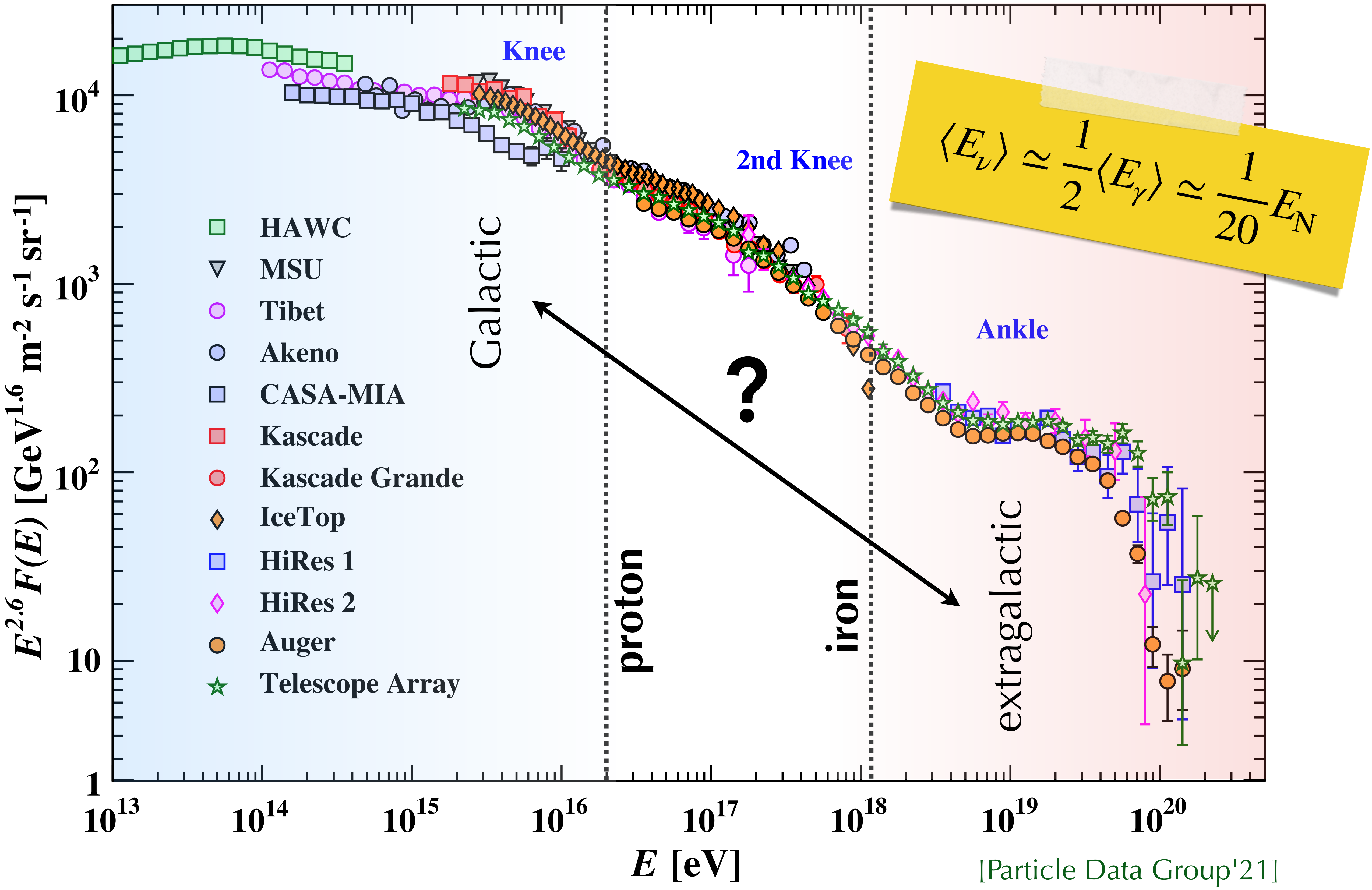
2017





Fermi-LAT gamma-ray count map

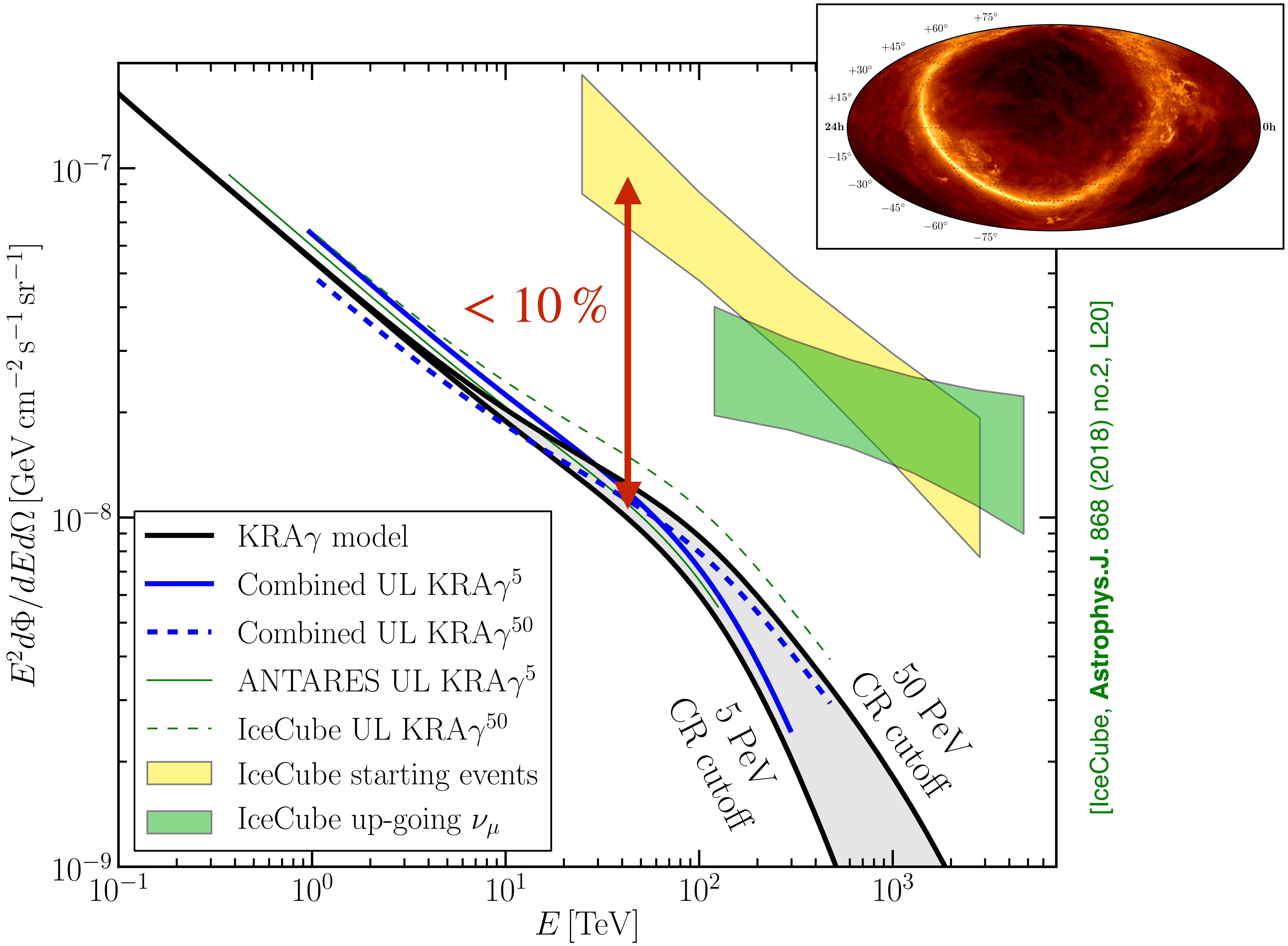
Very-High Energy Cosmic Rays



$$\langle E_\nu\rangle \simeq \frac{1}{2}\langle E_\gamma\rangle \simeq \frac{1}{20}E_N$$

[Particle Data Group'21]

Galactic Neutrino Emission



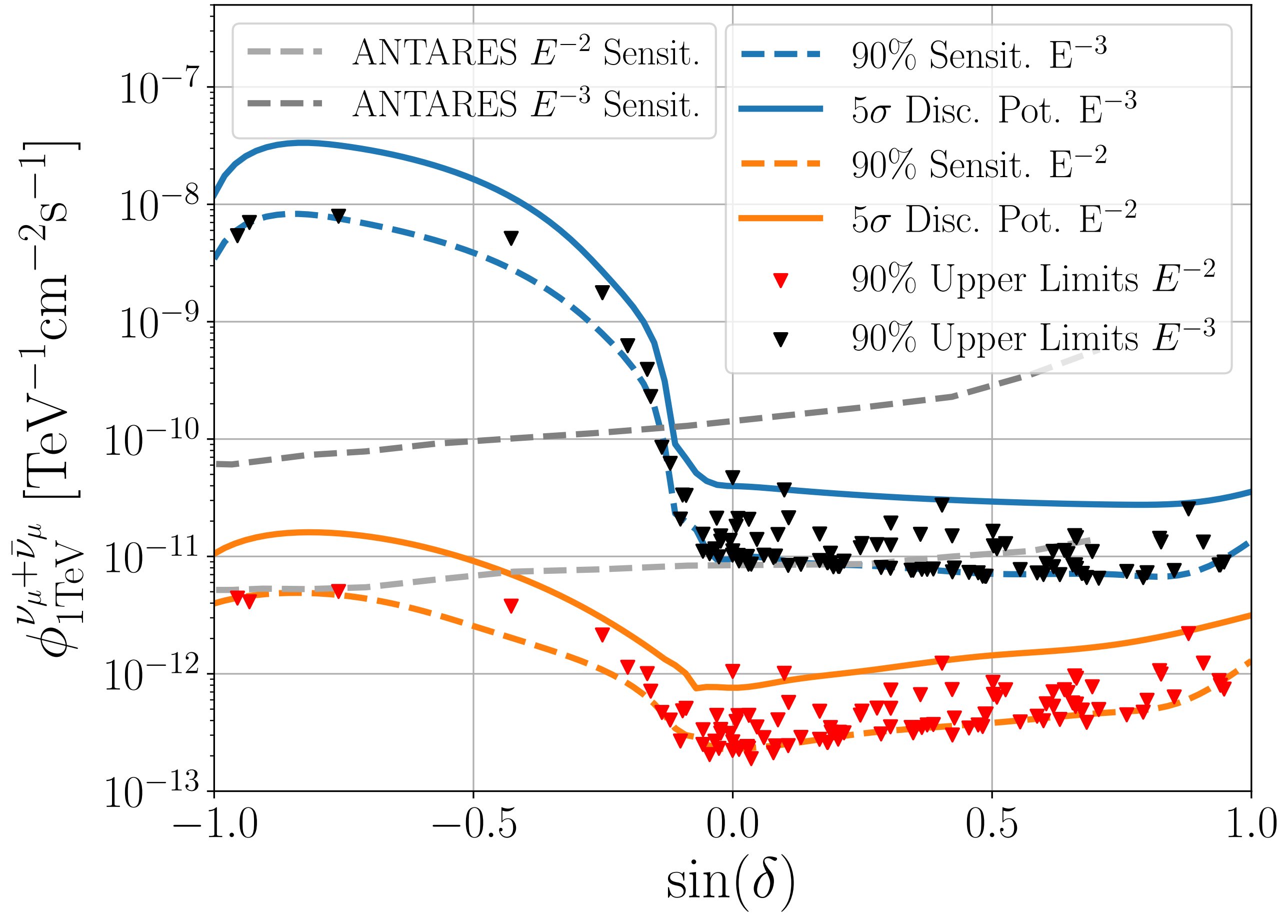
[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

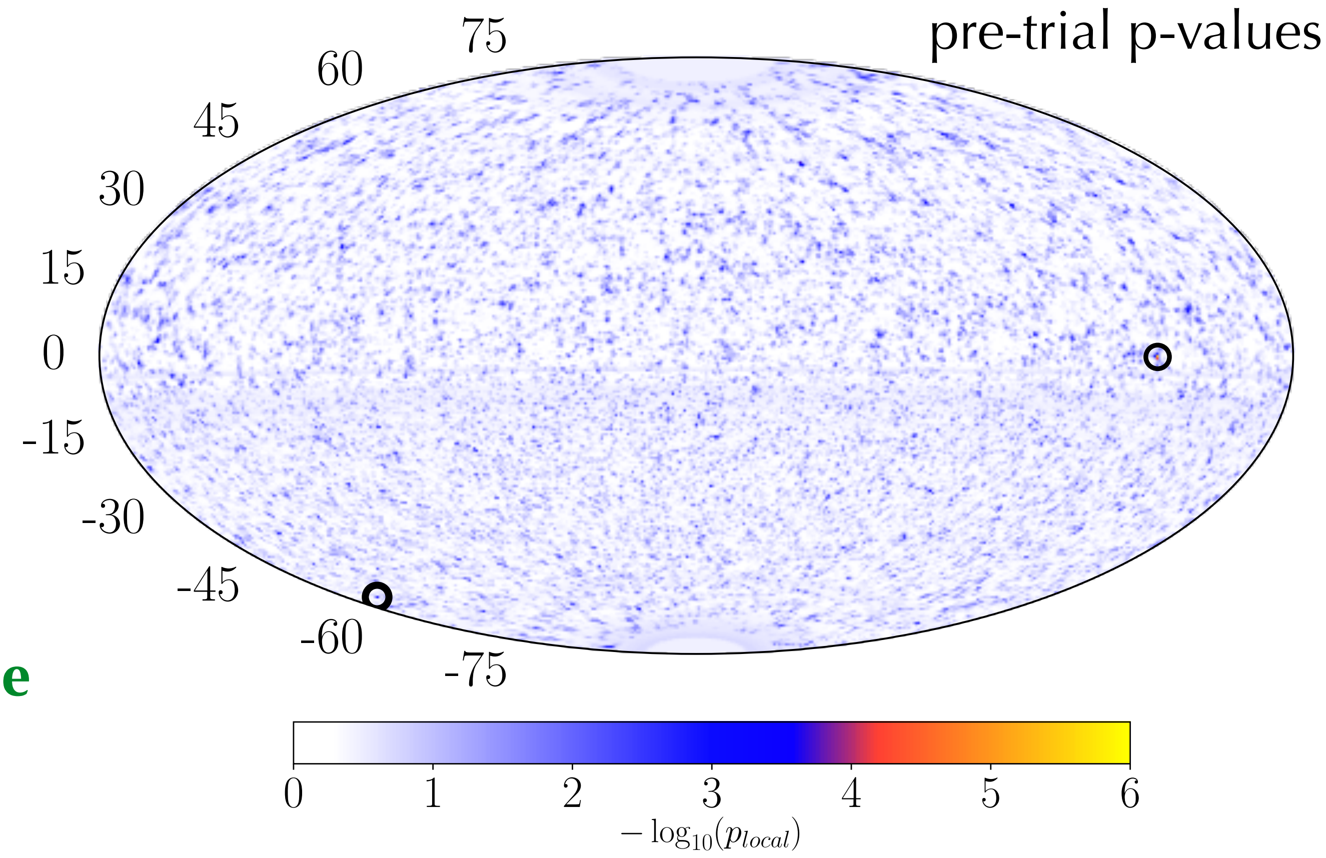
Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere

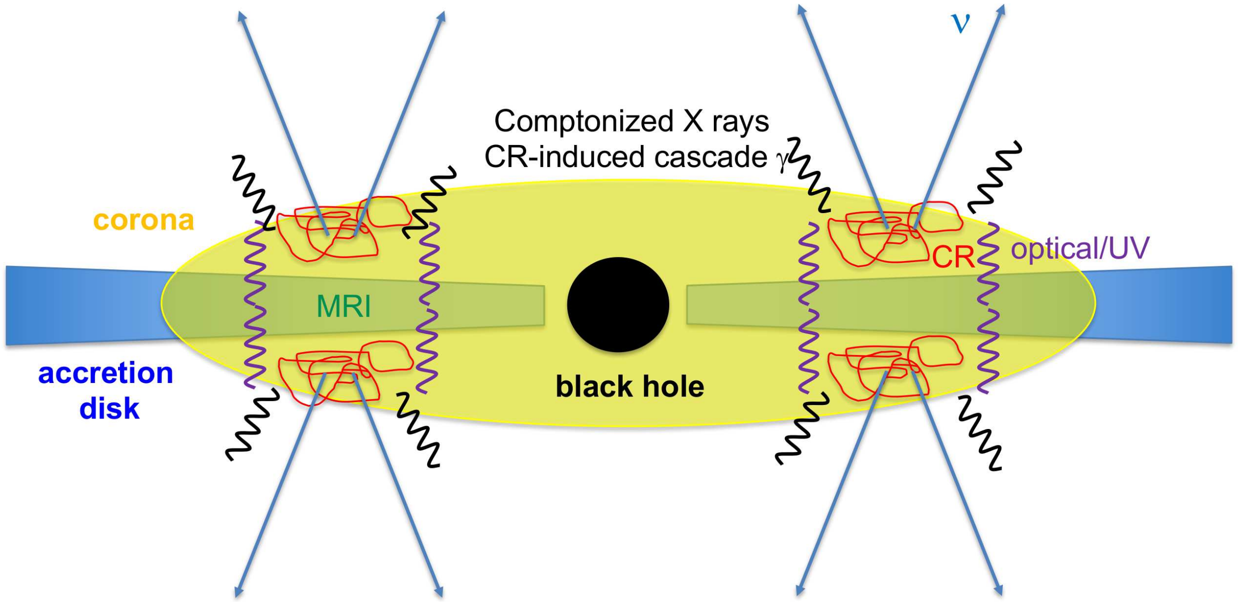




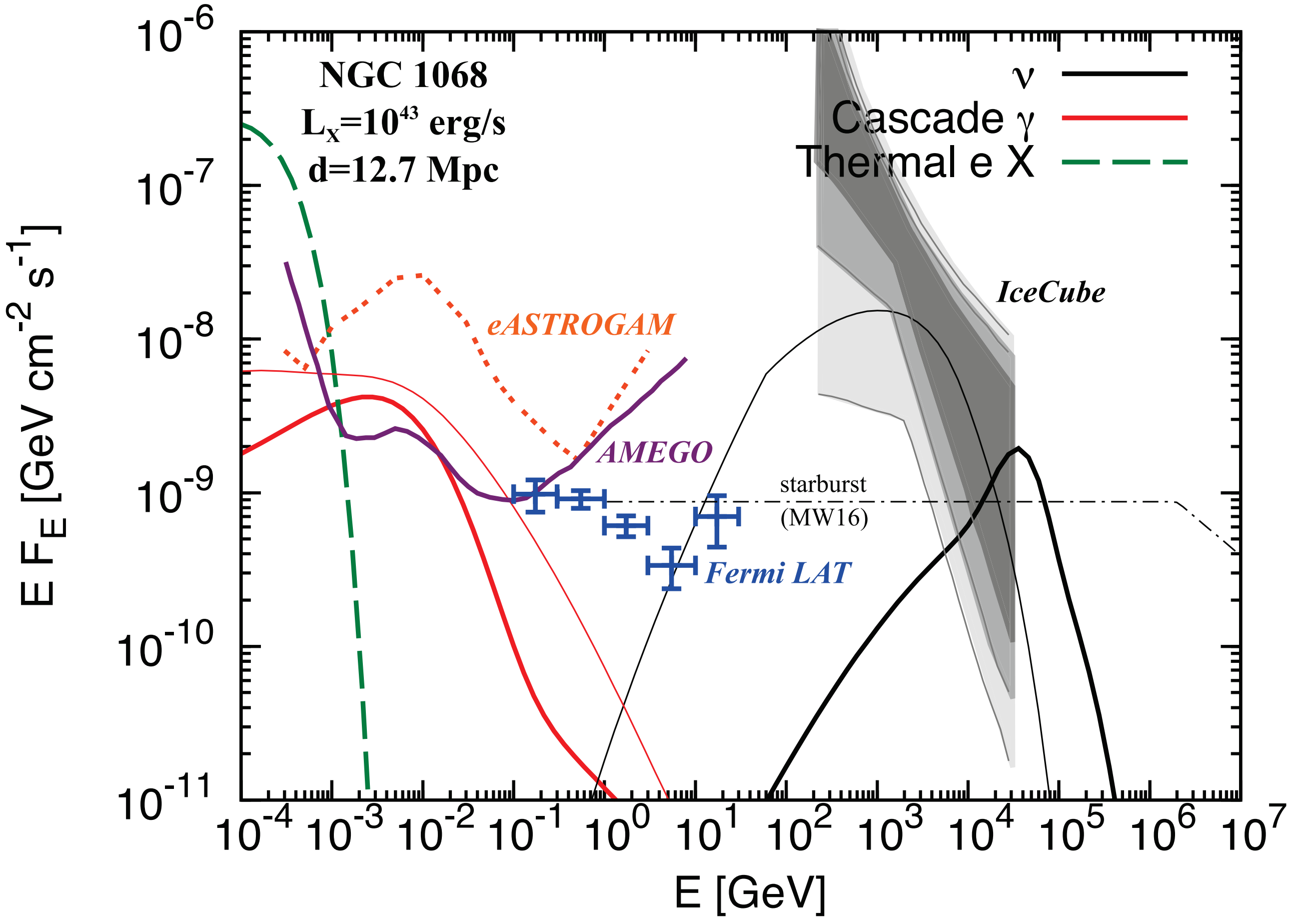
[IceCube, PRL 124 (2020) 5]

- **No significant** time-integrated point sources emission in all-sky search.
- **No significant** time-integrated emission from known Galactic and extragalactic high-energy sources, but interesting candidates, e.g. NGC 1068.

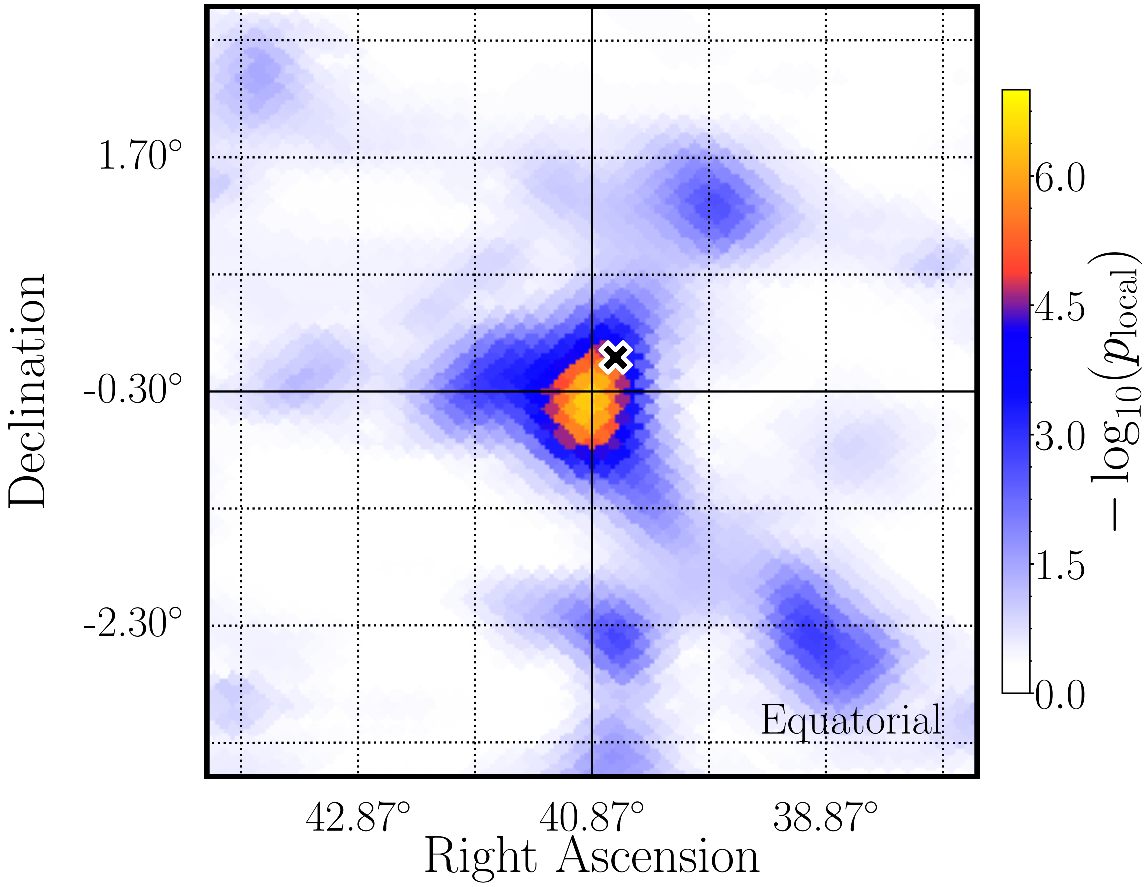
Northern Hot Spot



- Northern hot spot in the vicinity of the AGN **NGC 1068** has a **significance of 3.3σ**
- Emission can be modelled via stochastic **CR acceleration in AGN coronae.**



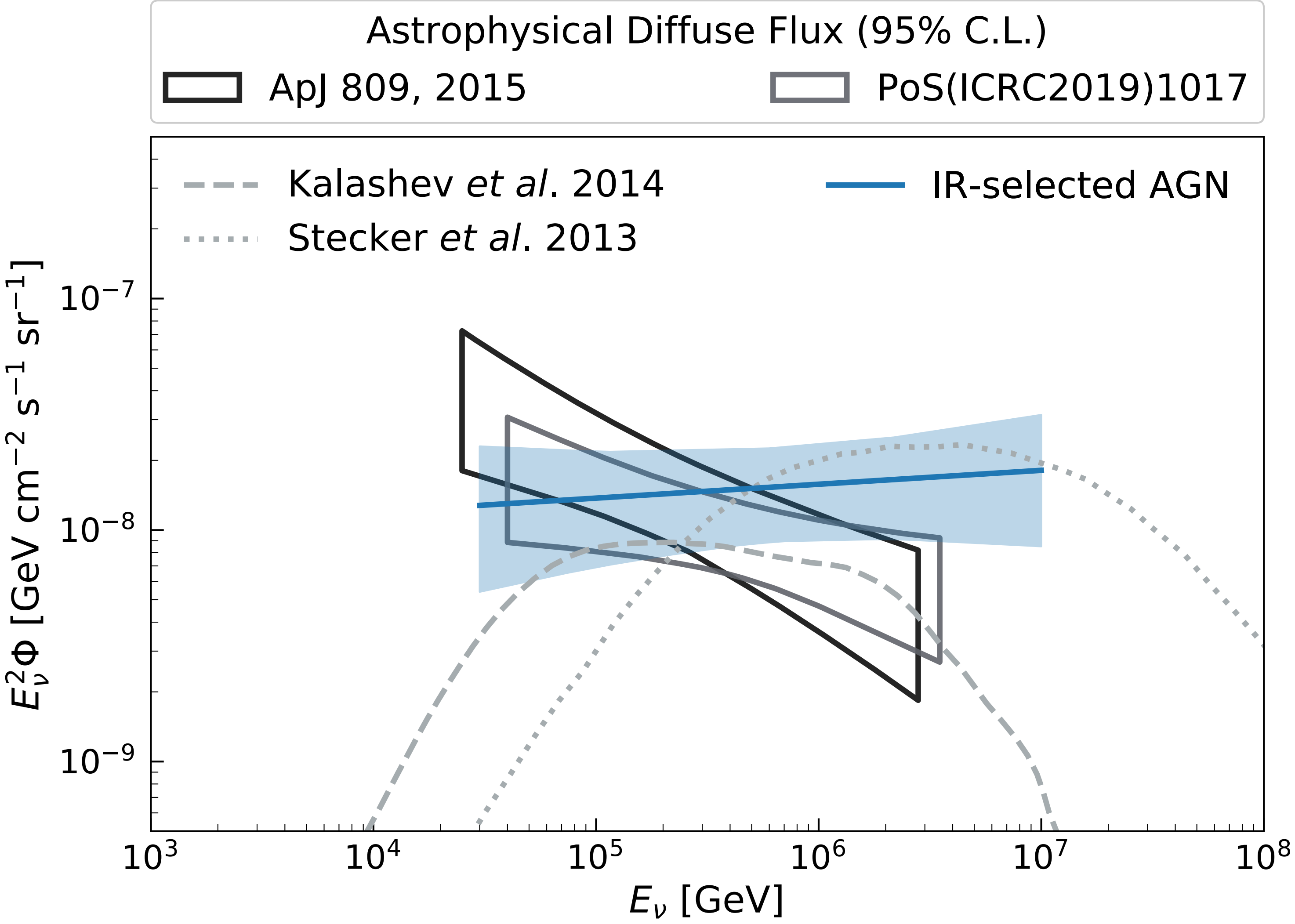
[Murase, Kimura & Meszaros, PRL 125 (2020)]



[IceCube, PRL 124 (2020) 5]

Active Galactic Nuclei

- IceCube finds a 2.6σ **excess** for AGN selected by their IR emission.
- Neutrino production is not directly visible via hadronic γ-ray emission due to $\gamma\gamma_{\rm bgr}$ scattering.



[IceCube, ArXiv:2111.10169]

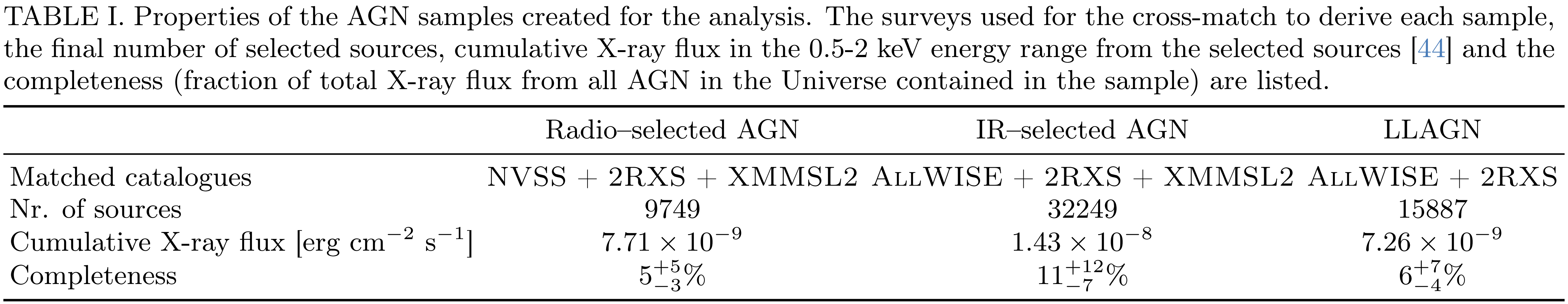


TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources [44] and the completeness (fraction of total X-ray flux from all AGN in the Universe contained in the sample) are listed.

	Radio–selected AGN	IR–selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	AllWISE + 2RXS + XMMSL2	AllWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [erg cm^{-2} s^{-1}]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	5^{+5}_{-3}%	11^{+12}_{-7}%	6^{+7}_{-4}%

Point Source vs. Diffuse Flux

Populations of extragalactic neutrino sources can be visible

individual sources

or by the

combined isotropic emission.

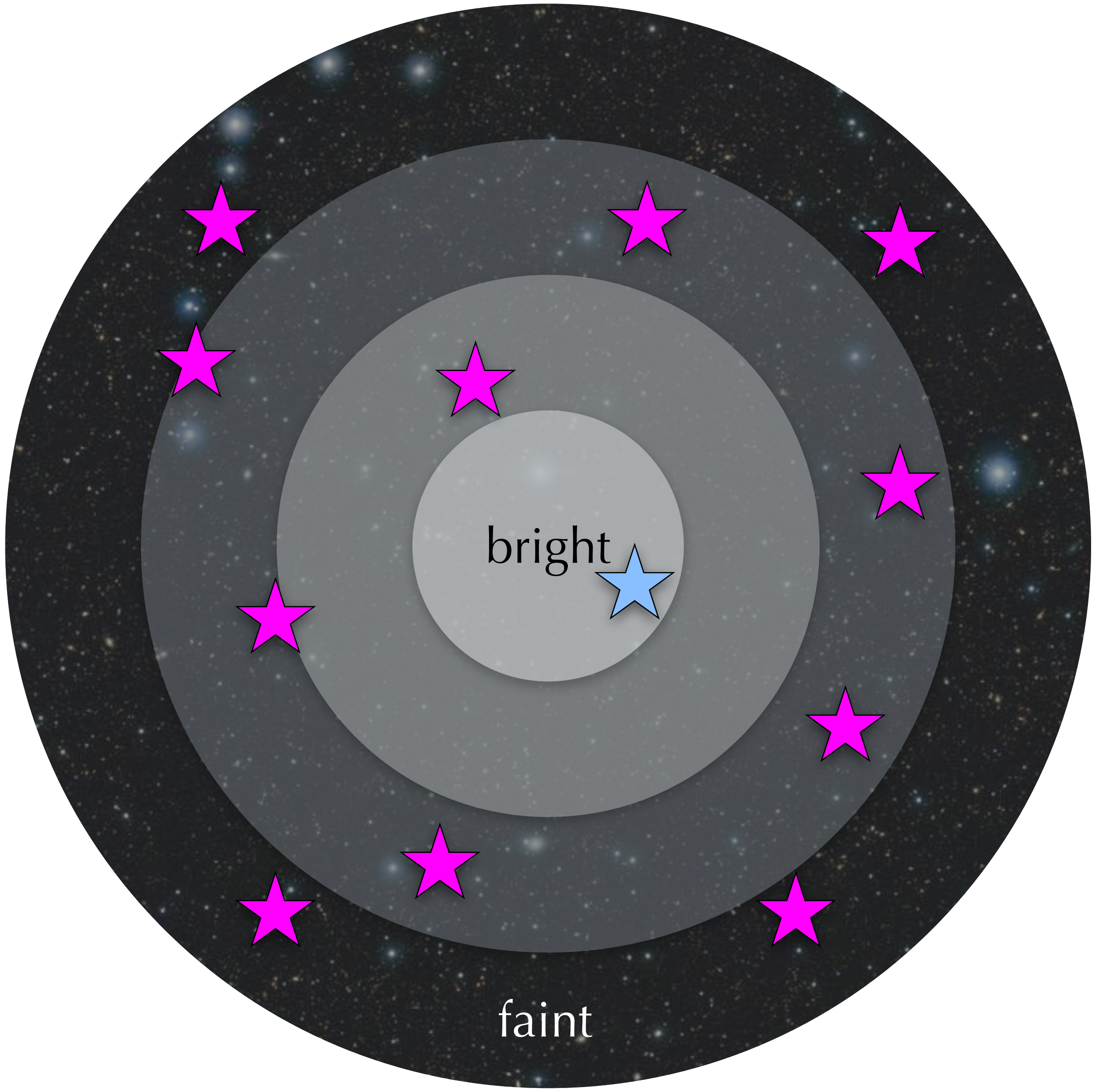
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

source luminosity.

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

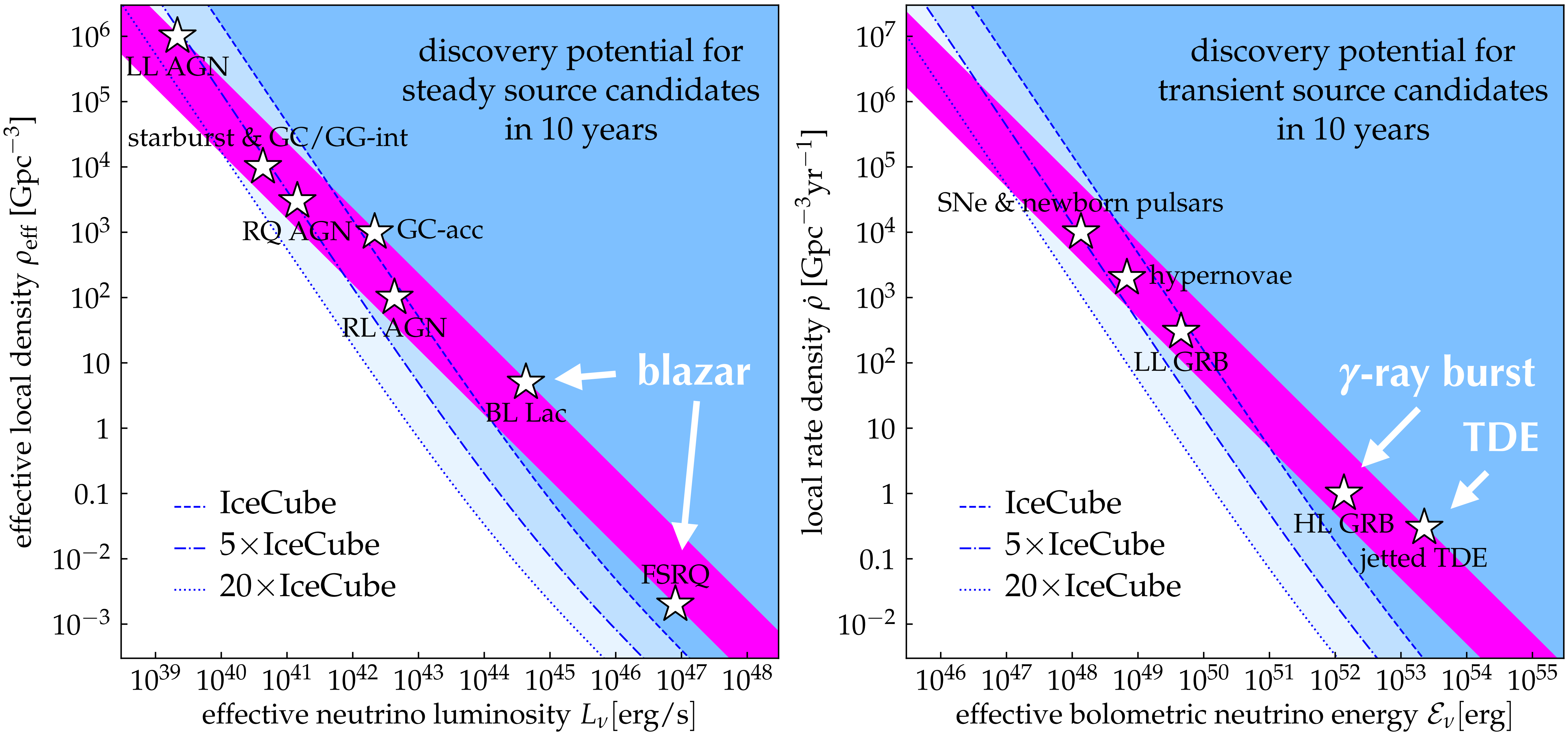


Hubble horizon

Point Source vs. Diffuse Flux

Neutrino sources are hiding in plain sight.

Point Source vs. Diffuse Flux

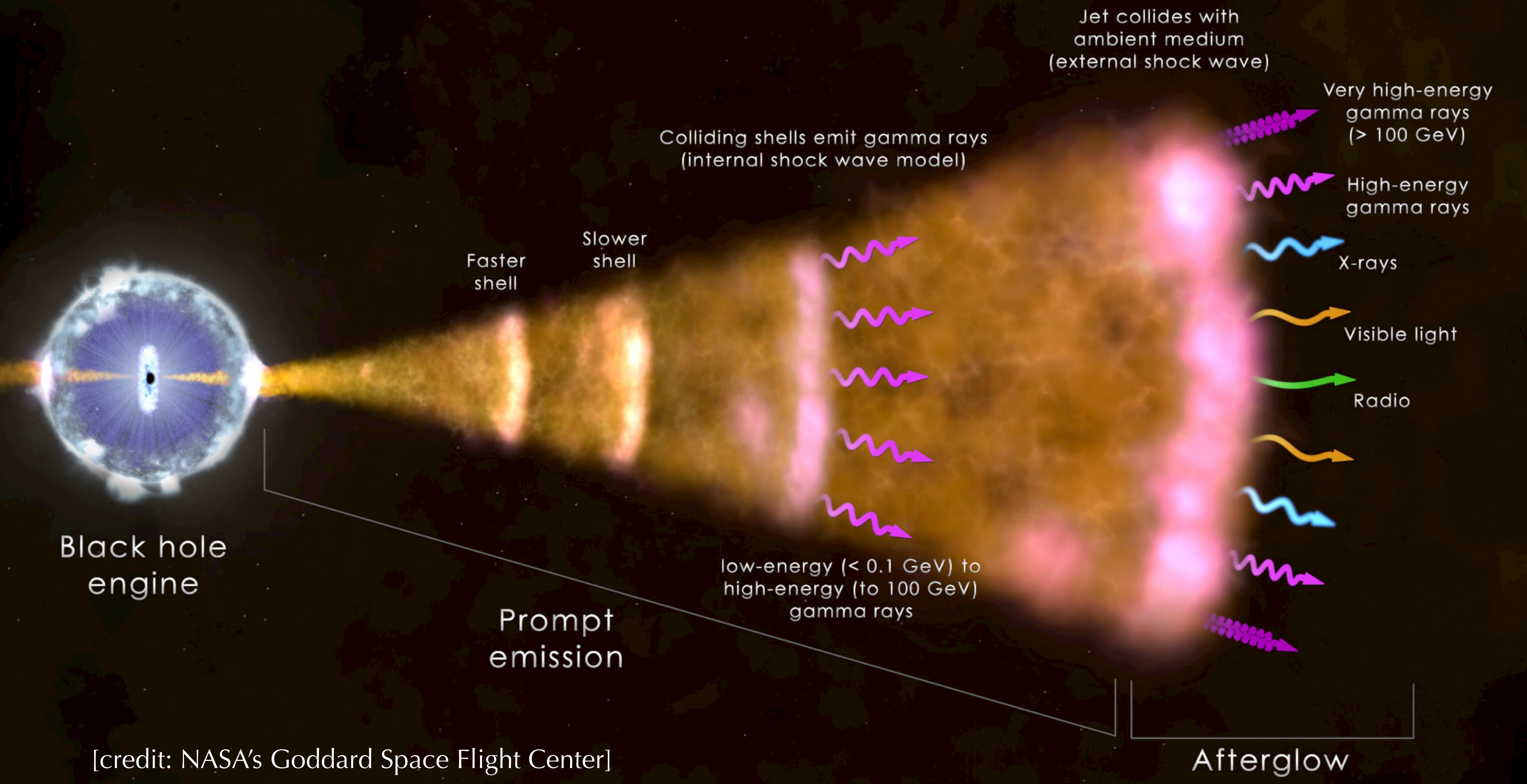


[Murase & Waxman'16; Ackermann *et al.*'19]

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

Gamma-Ray Bursts

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

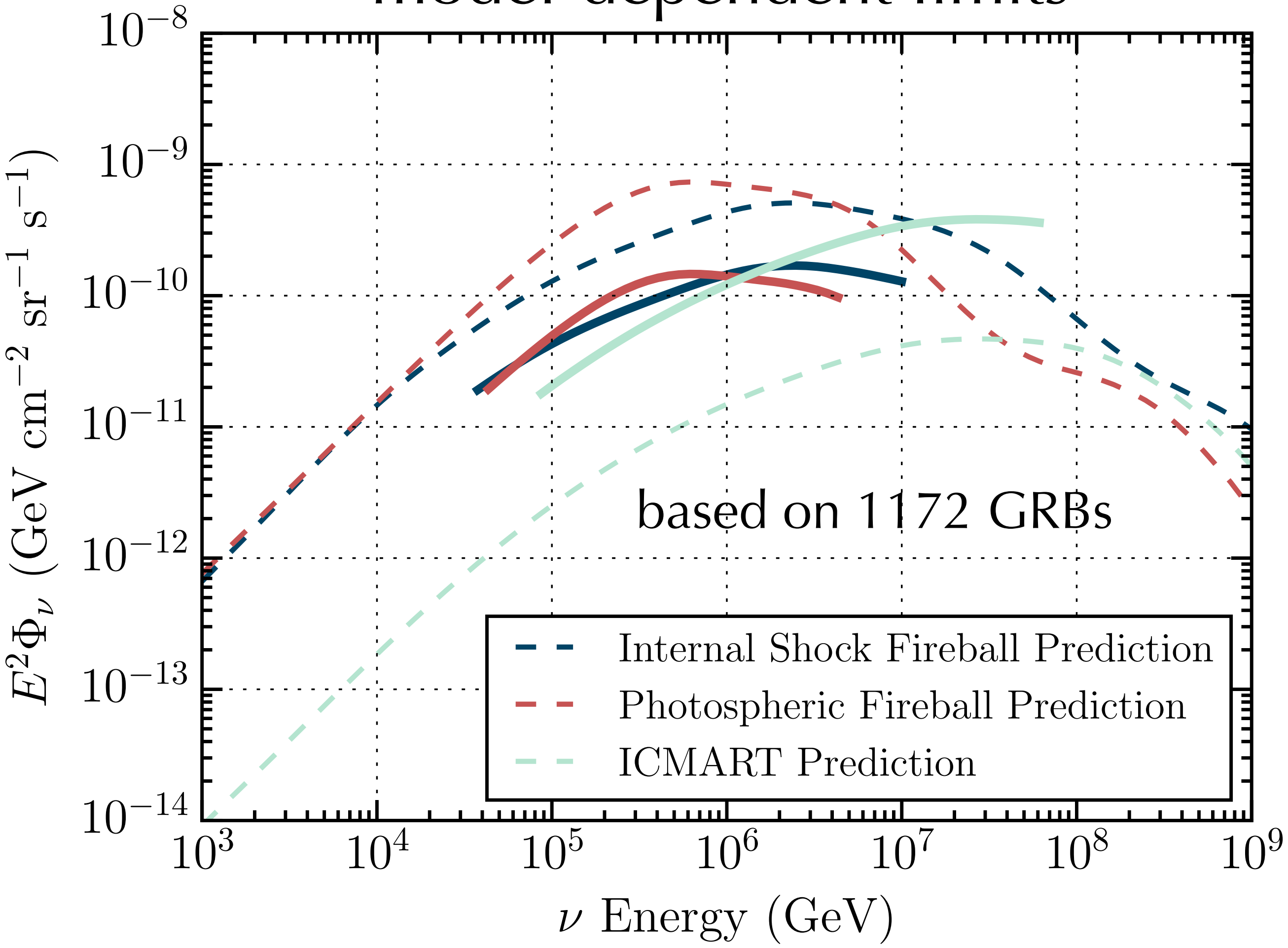


[credit: NASA's Goddard Space Flight Center]

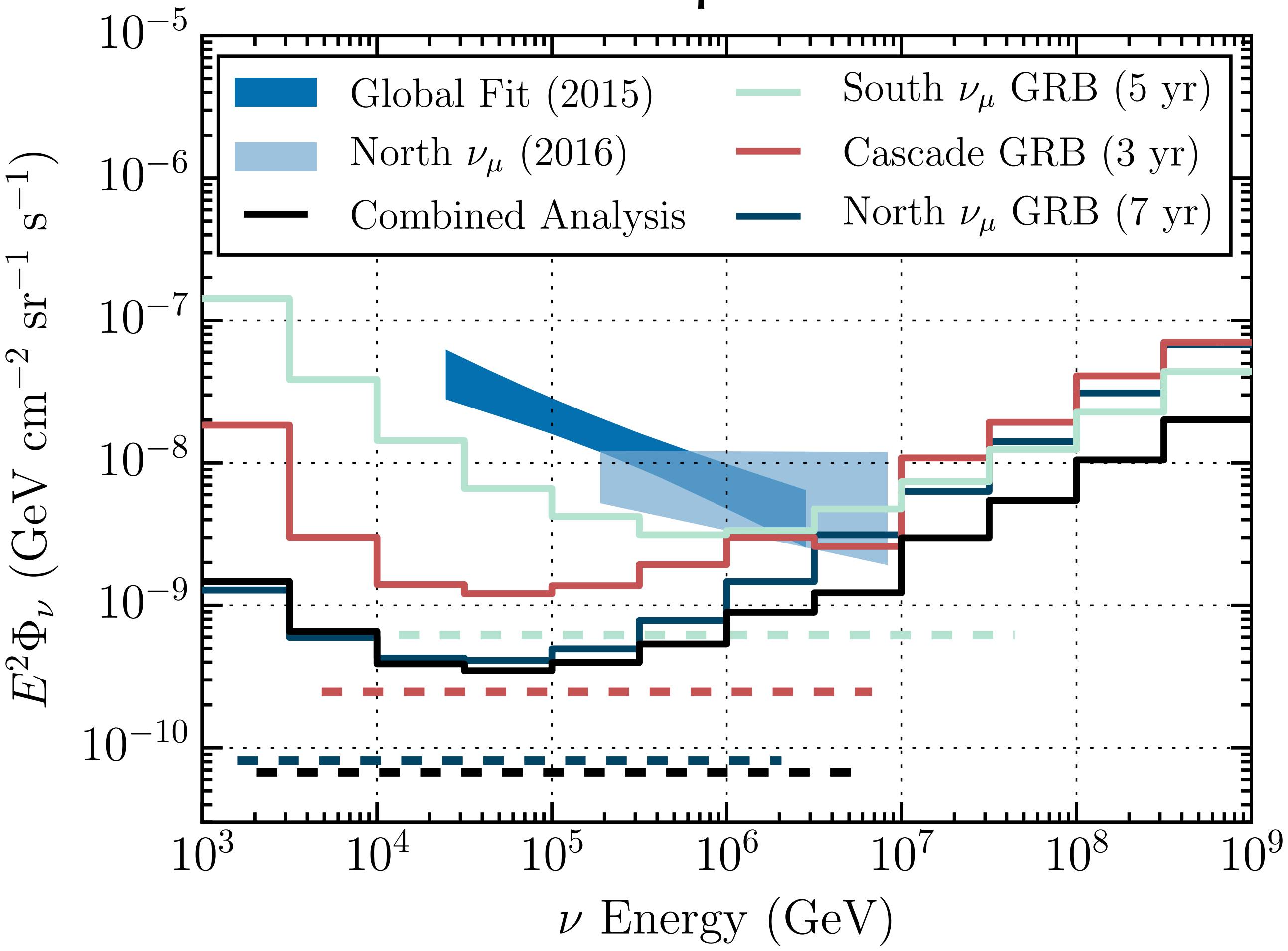
Gamma-Ray Burst Limits

- IceCube routinely follows up on γ-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]

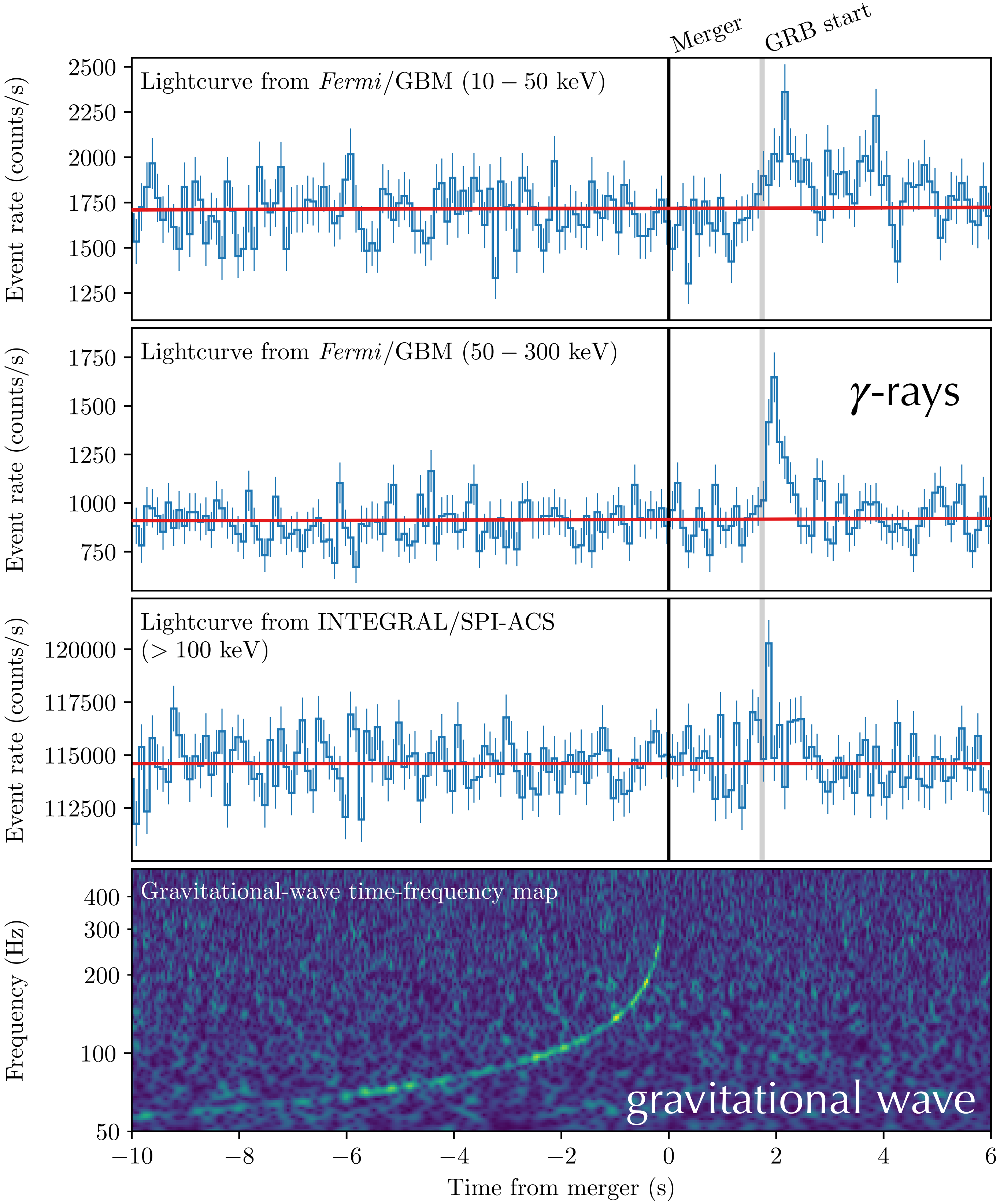
model-dependent limits



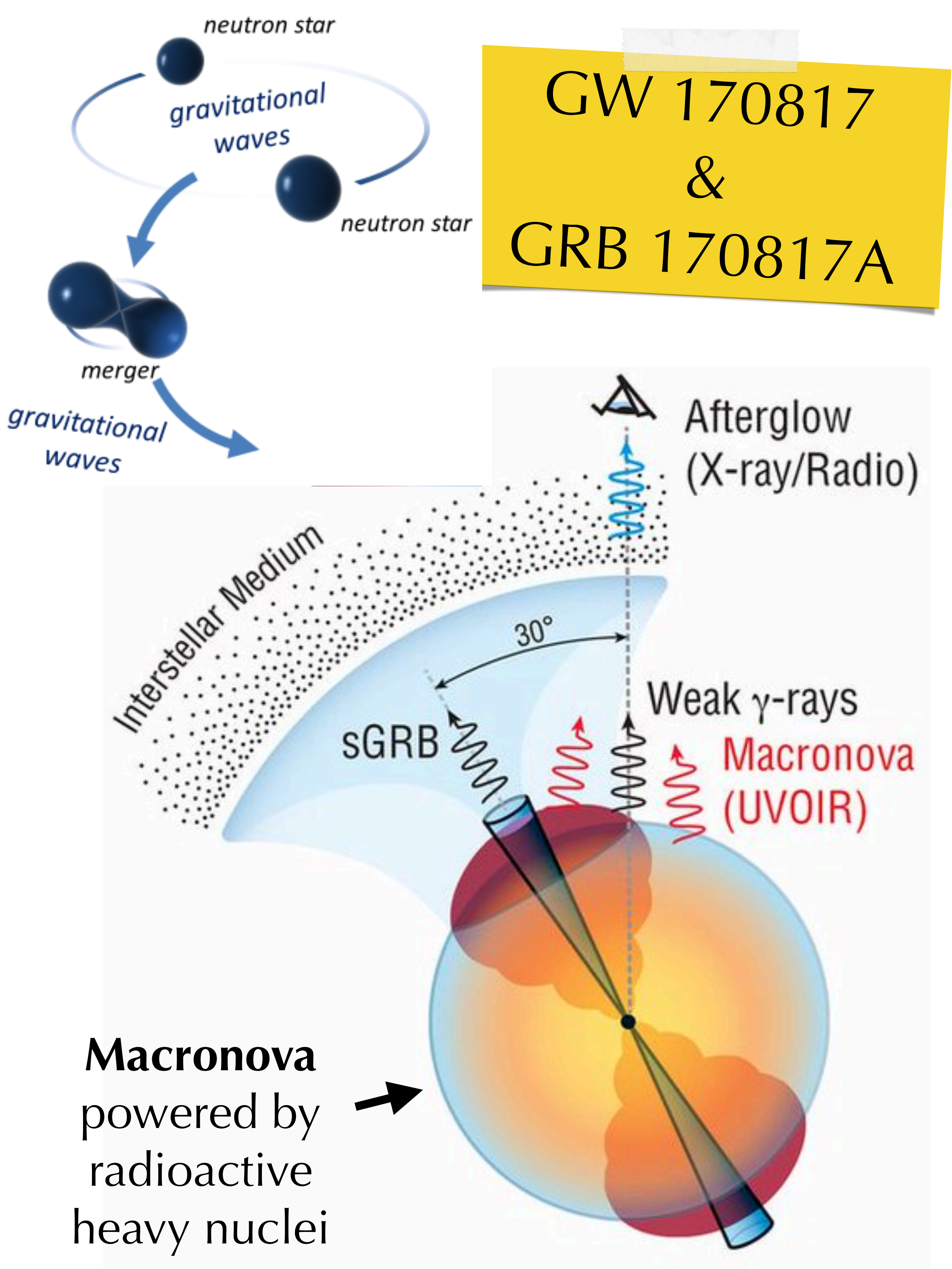
model-independent limits



GRBs and Gravitational Waves



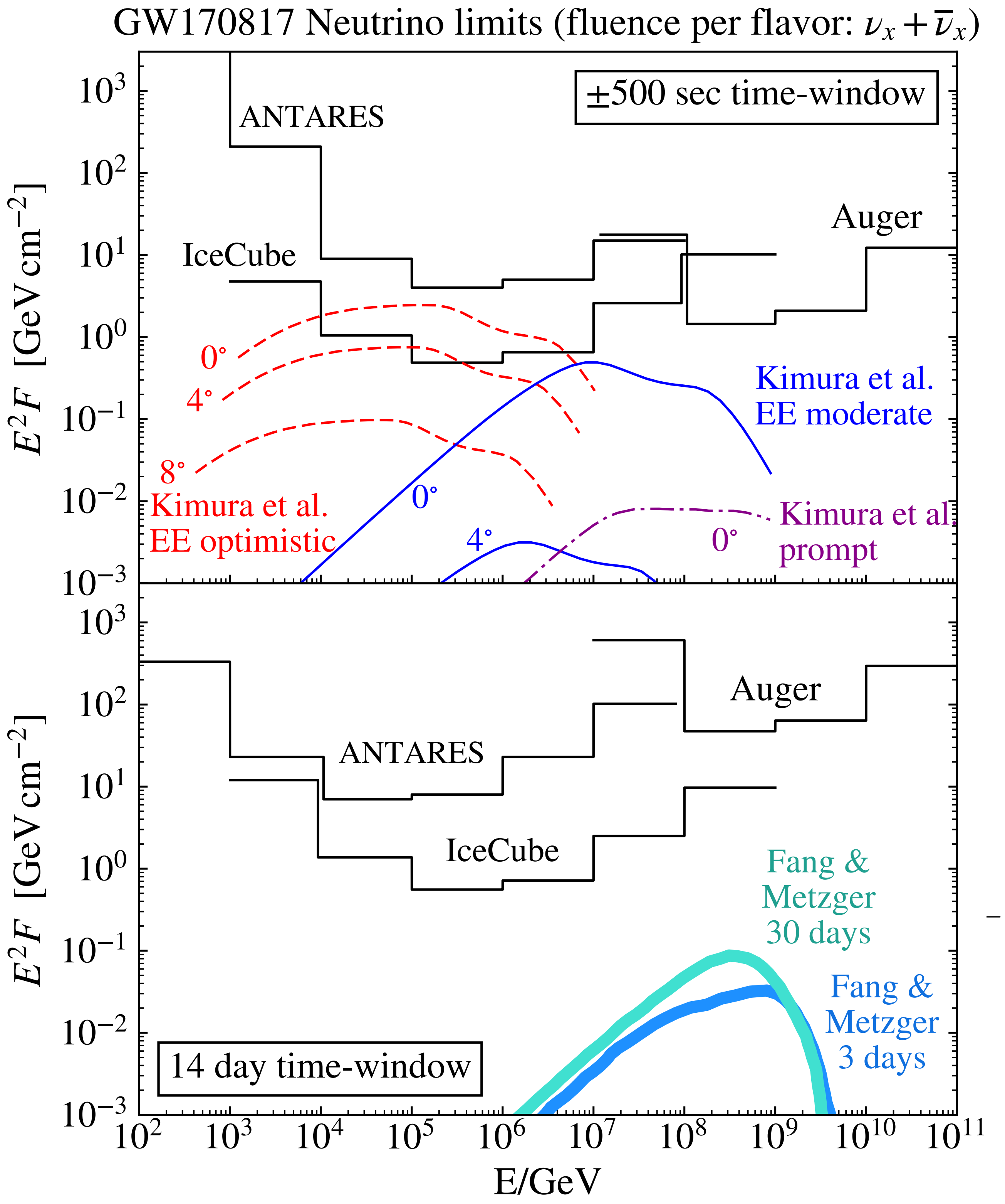
[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]



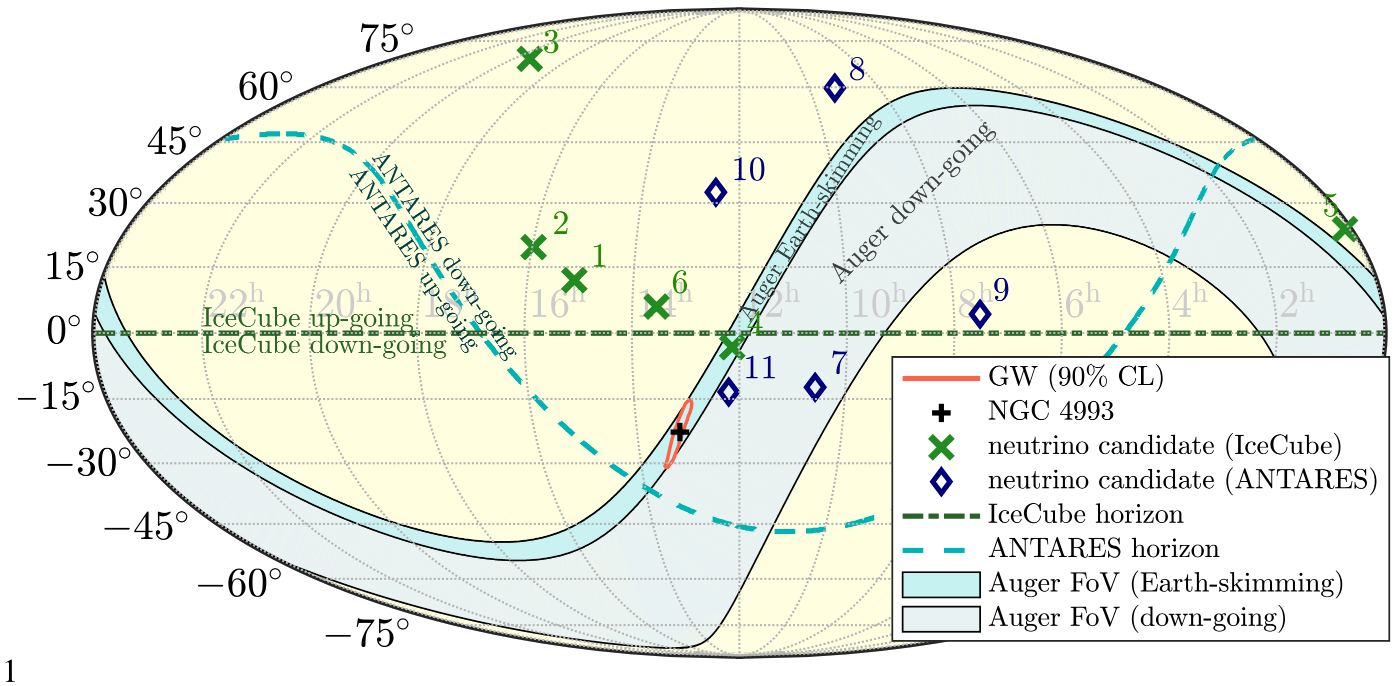
GW 170817
&
GRB 170817A

Macronova powered by radioactive heavy nuclei

GRB 170817A

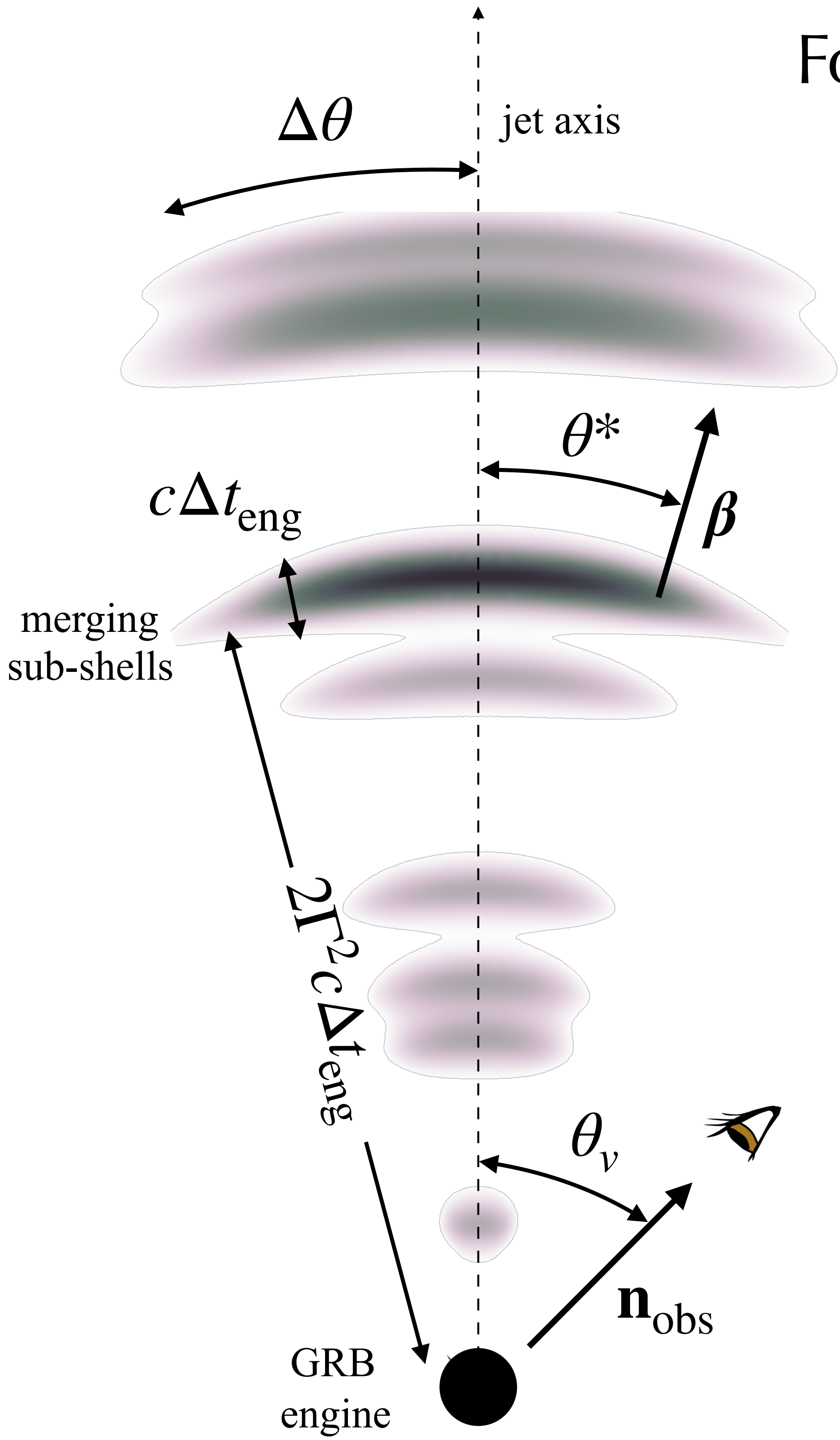


- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle.**

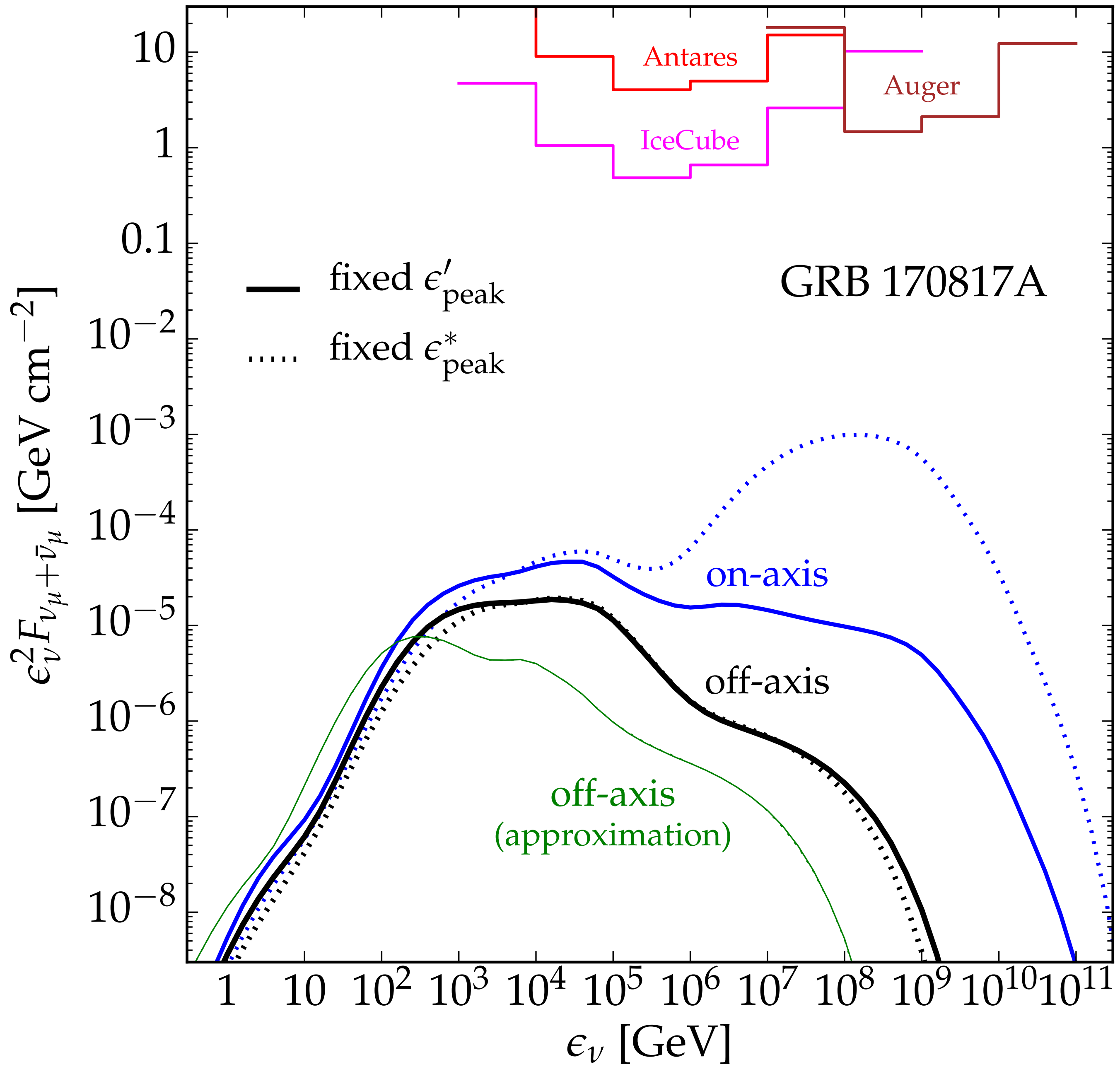


[ANTARES, IceCube, Auger & LVC, ApJ 850 (2017) 2]

GRB 170817A - Revisited

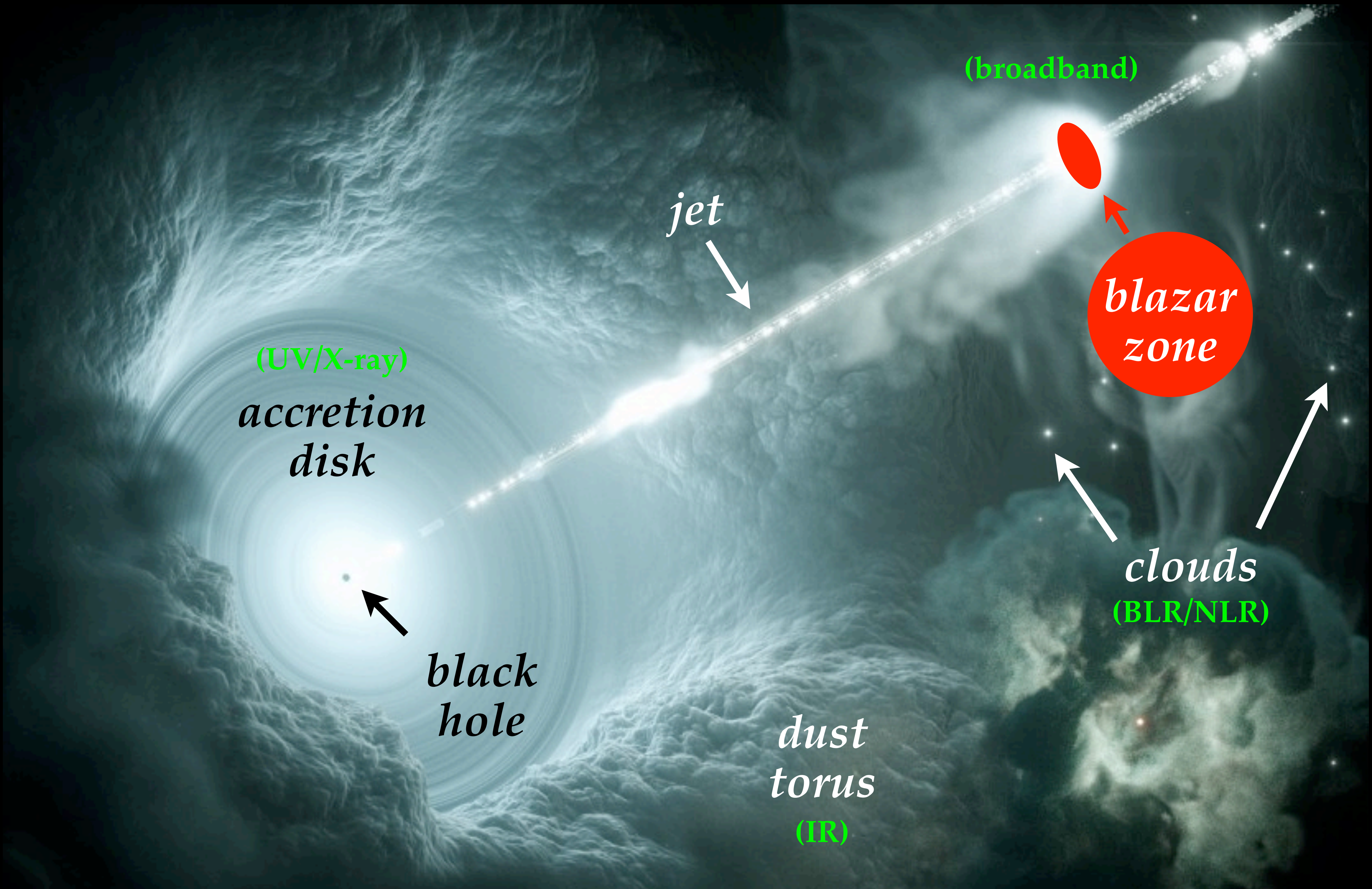


Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



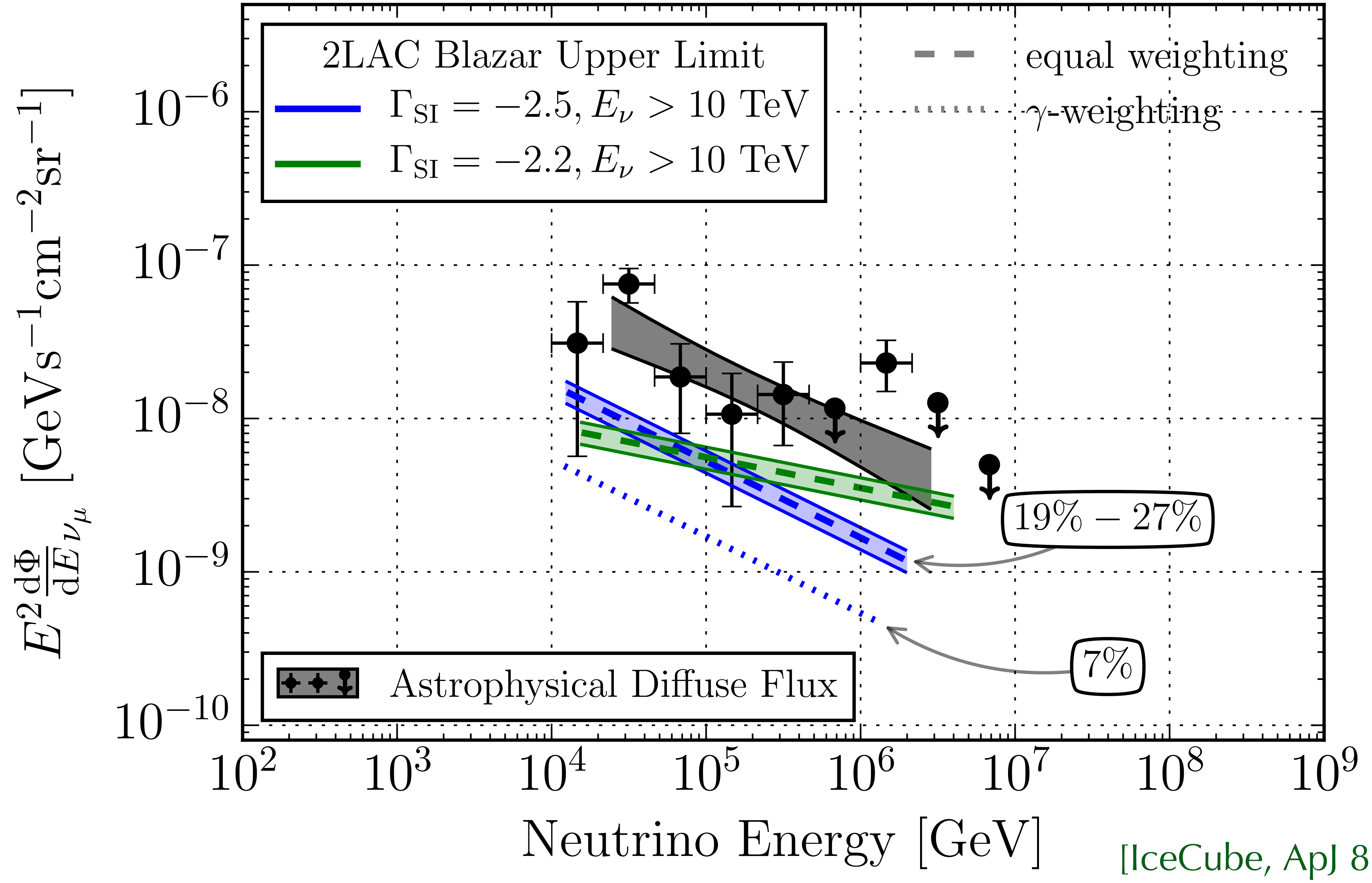
[MA & Halser MNRAS 490 (2019) 4]

Blazars



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

Fermi-LAT Blazar Limits



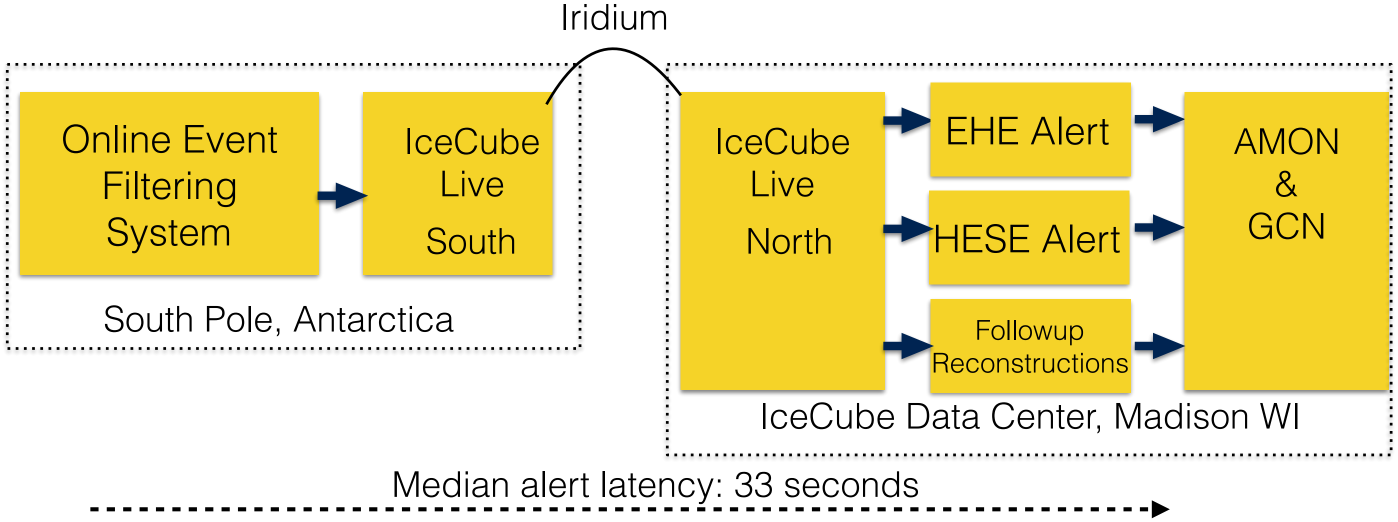
[IceCube, ApJ 835 (2017) 45]

Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation.

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



Iridium

Online Event Filtering System → IceCube Live South

South Pole, Antarctica

IceCube Live North → EHE Alert → AMON & GCN

IceCube Live North → HESE Alert → AMON & GCN

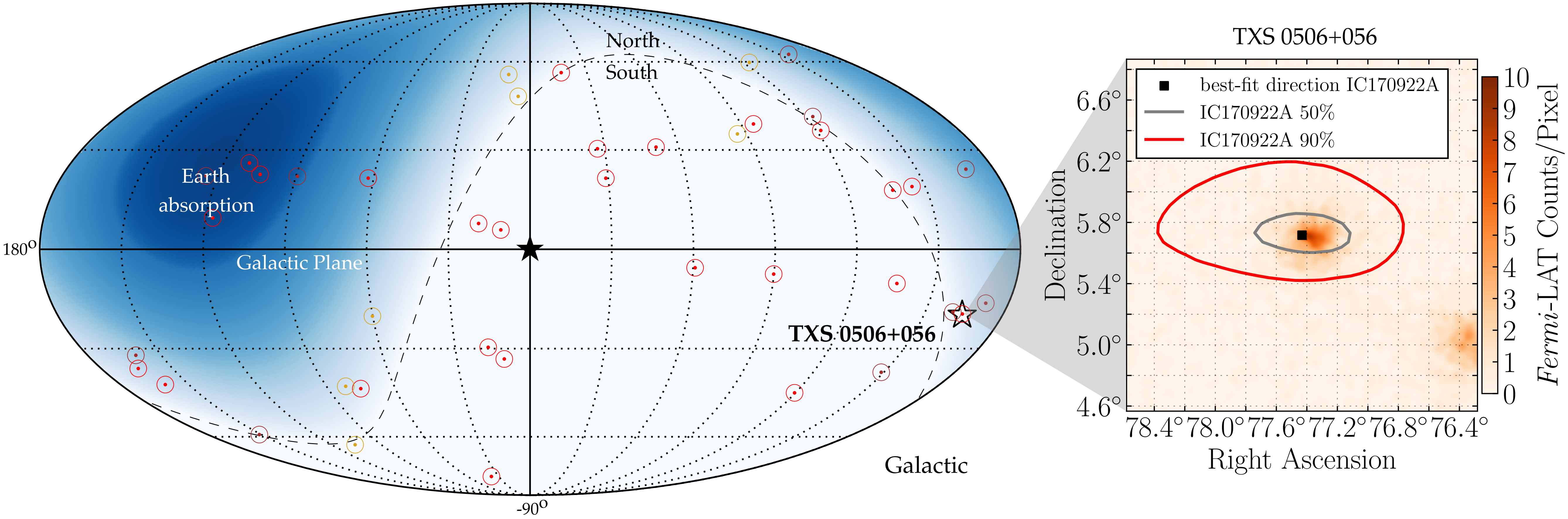
IceCube Live North → Followup Reconstructions → AMON & GCN

IceCube Data Center, Madison WI

Median alert latency: 33 seconds

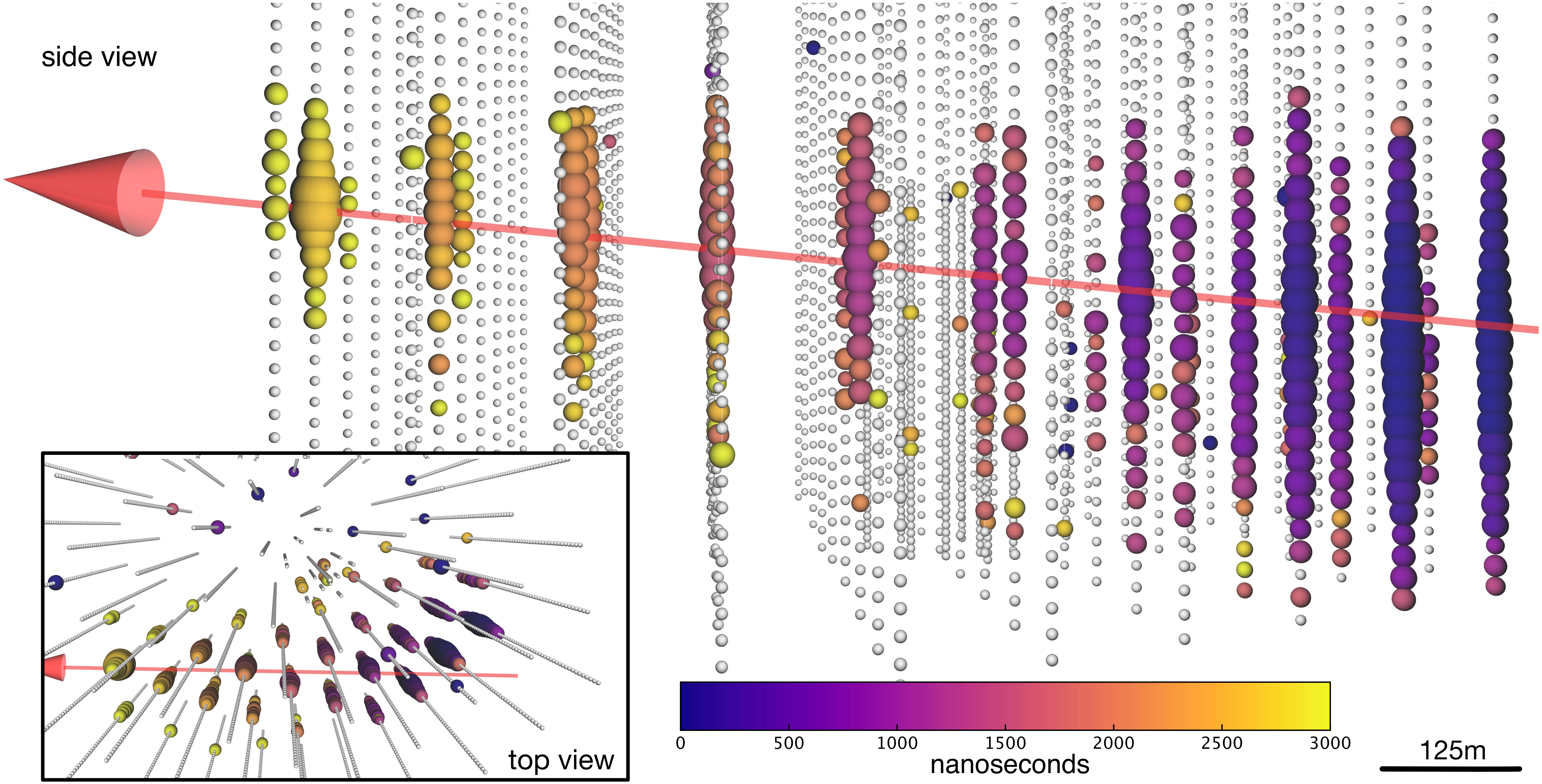
[IceCube, PoS (ICRC2019) 1021]

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



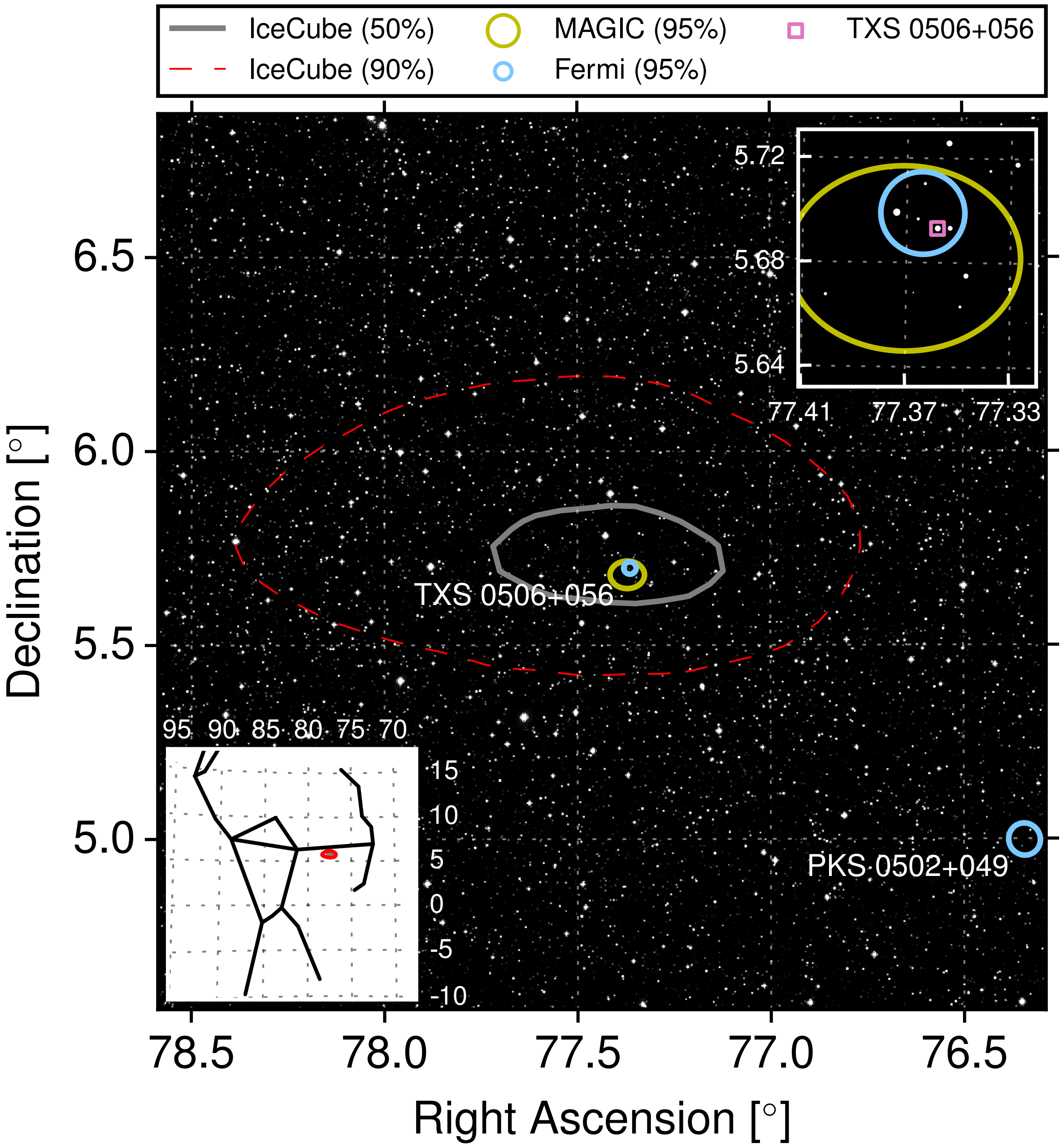
Realtime Neutrino Alerts

IC-170922A



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

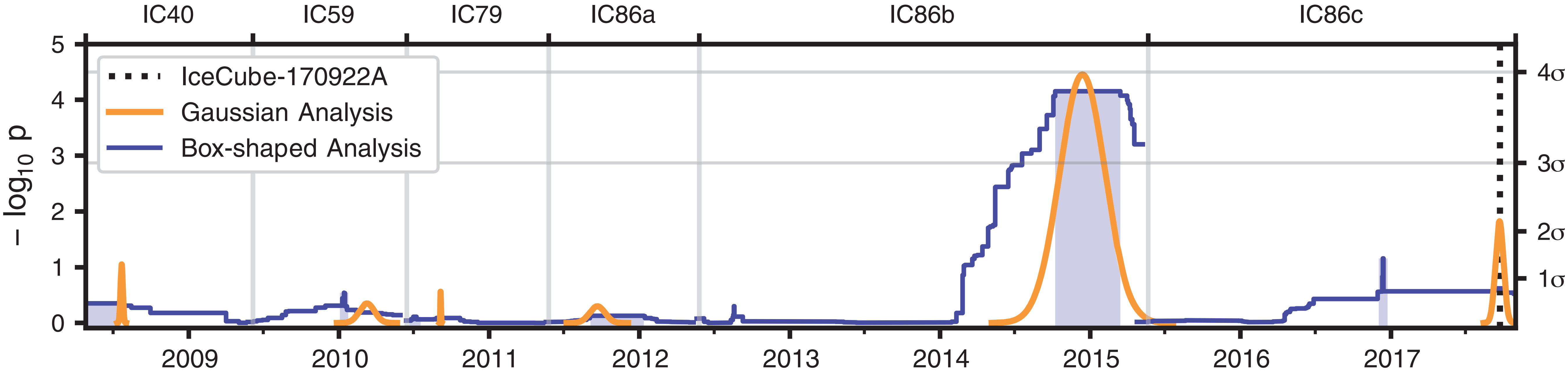
TXS 0506+056



[IceCube++, Science 361 (2018) 6398]

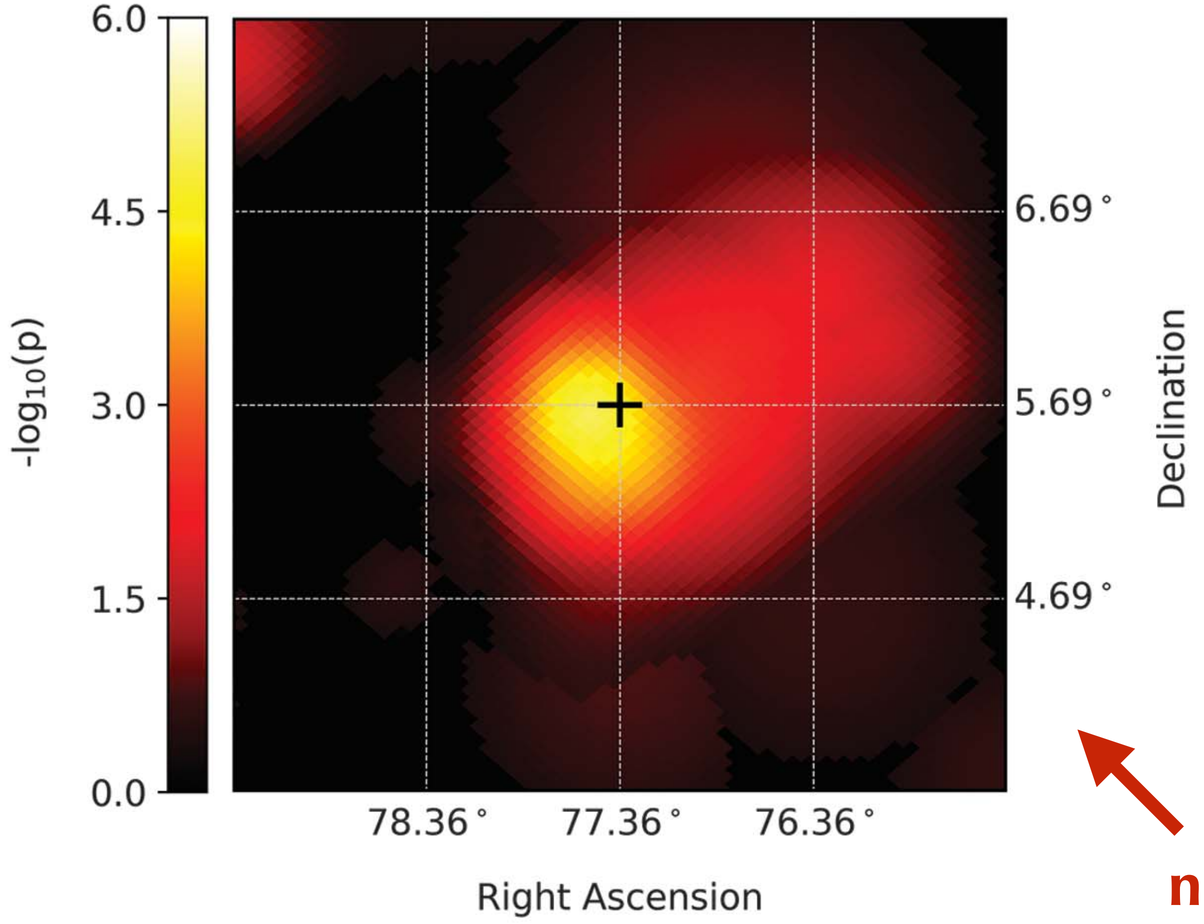
- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Neutrino Flare in 2014/15



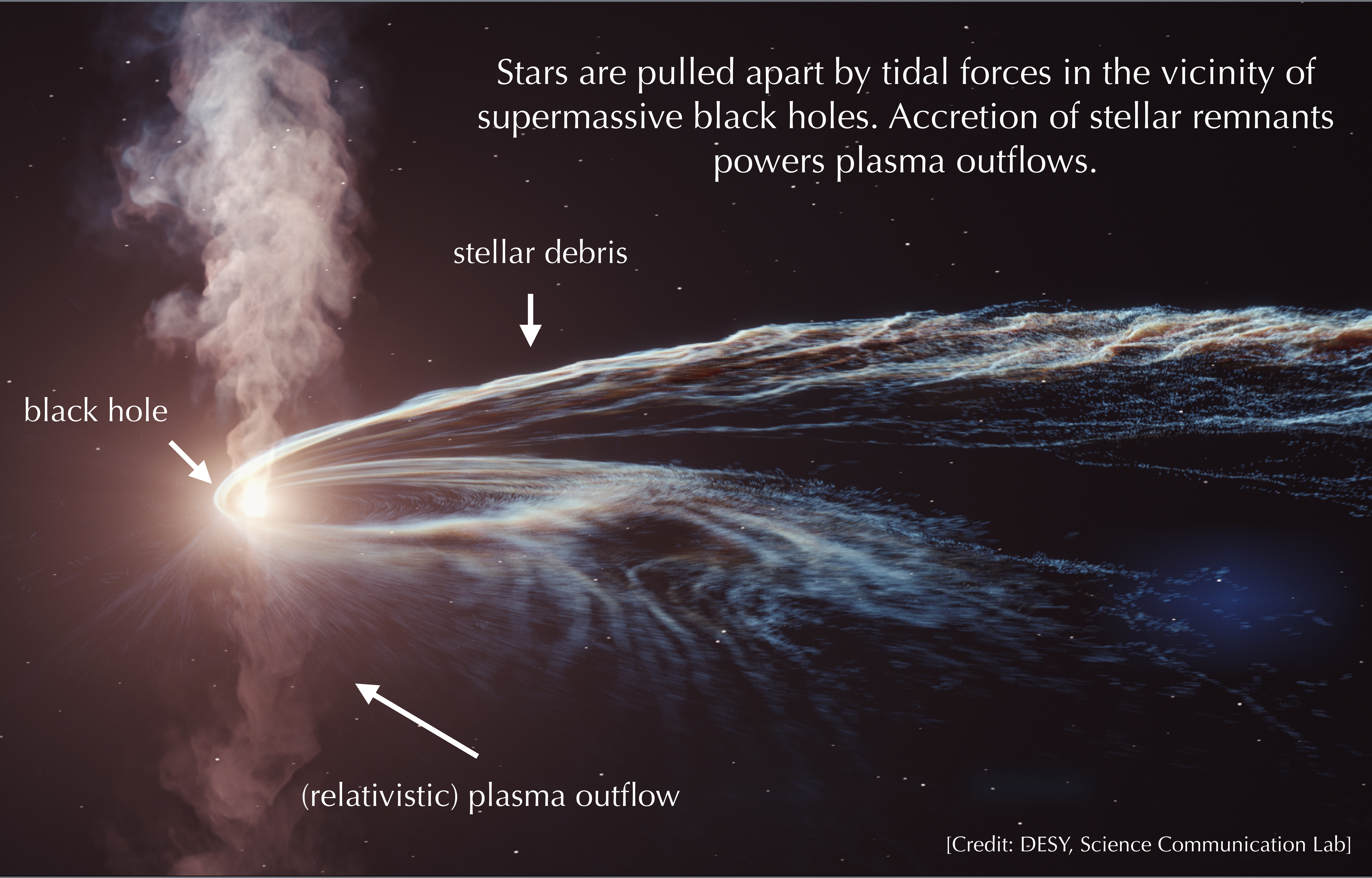
[IceCube, Science 361 (2018) 6398]

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



neutrino "morphology" of 2014/15 flare

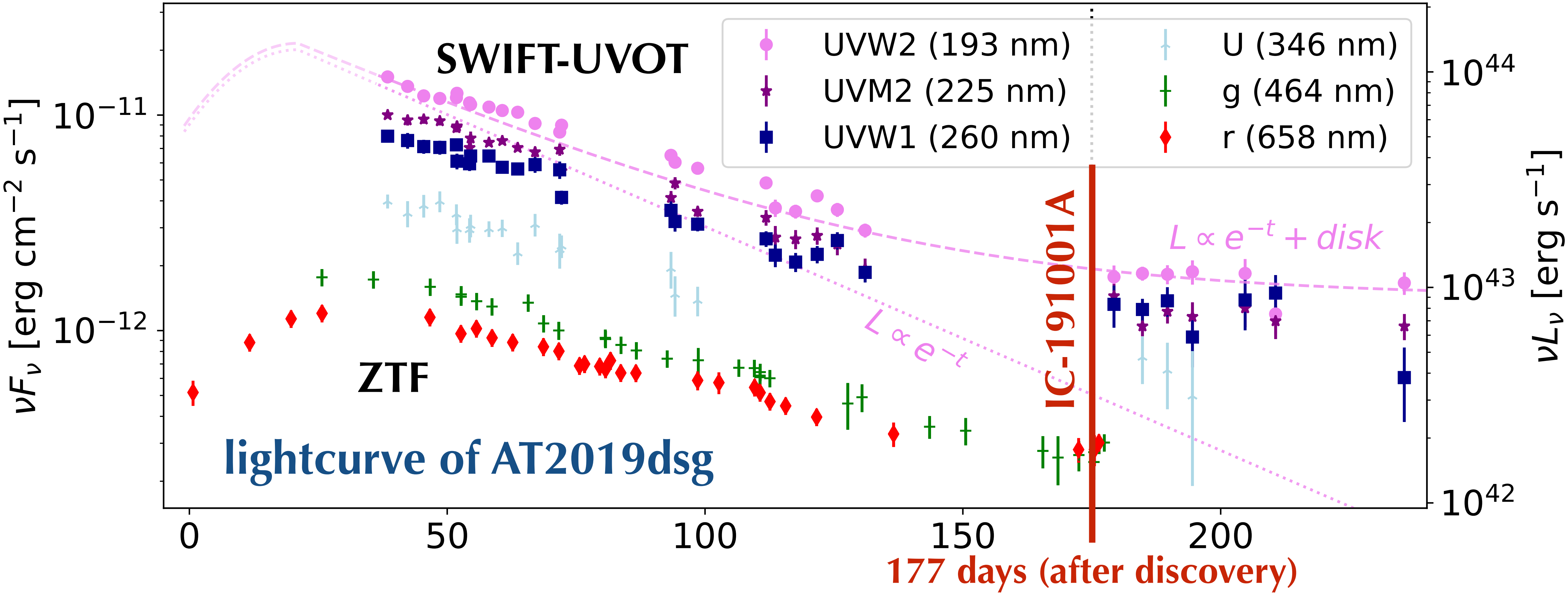
Tidal Disruption Events



Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants powers plasma outflows.

[Credit: DESY, Science Communication Lab]

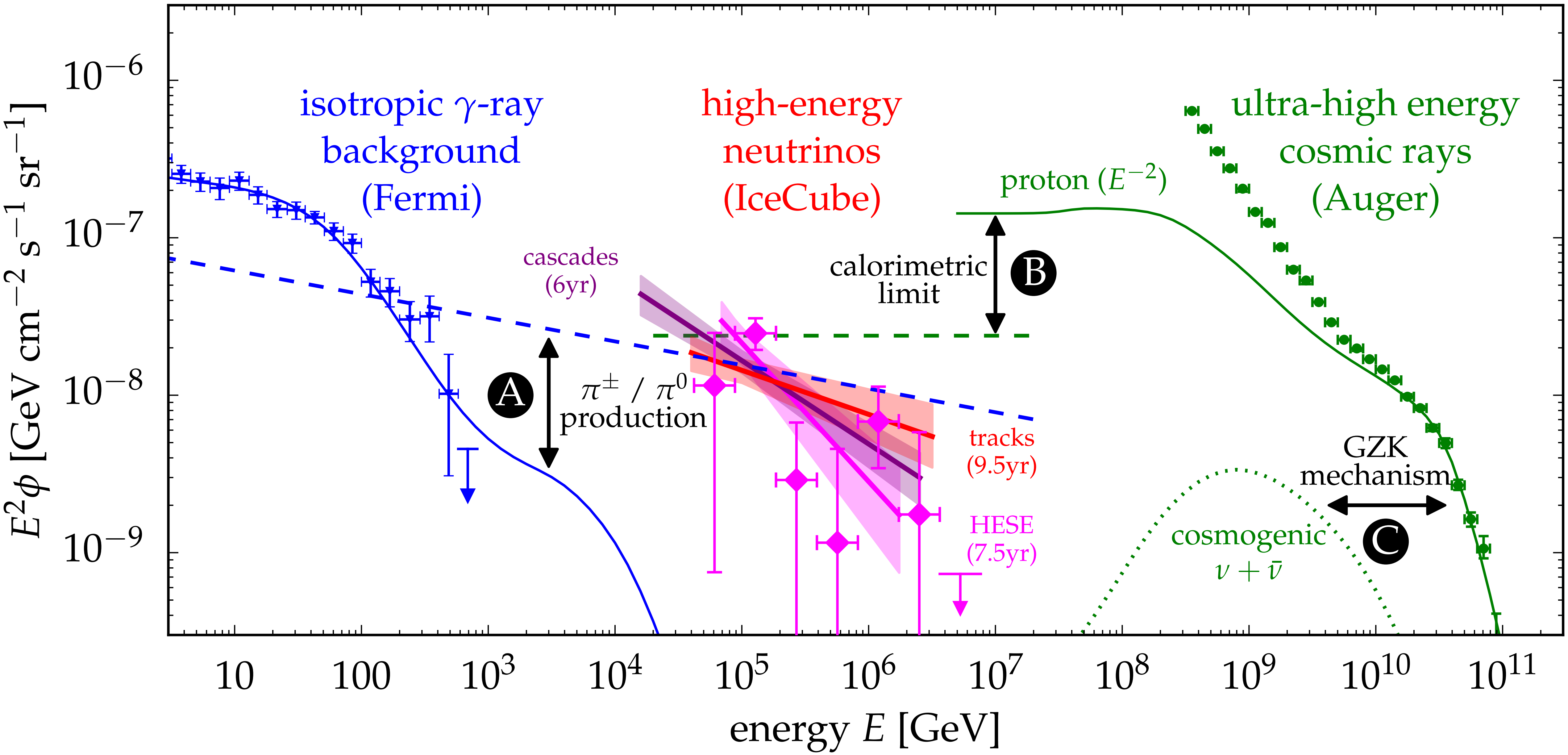
Tidal Disruption Events



- Association of IC-191001A with TDE AT2019dsg and IC-200530A with AT2019fdr.
- Plot shows optical/UV data from Zwicky-Transient Facility (ZTF) and SWIFT-UVOT for AT2019dsg
- Combined **chance for random correlation** of TDEs and IceCube alerts is **0.034%**.

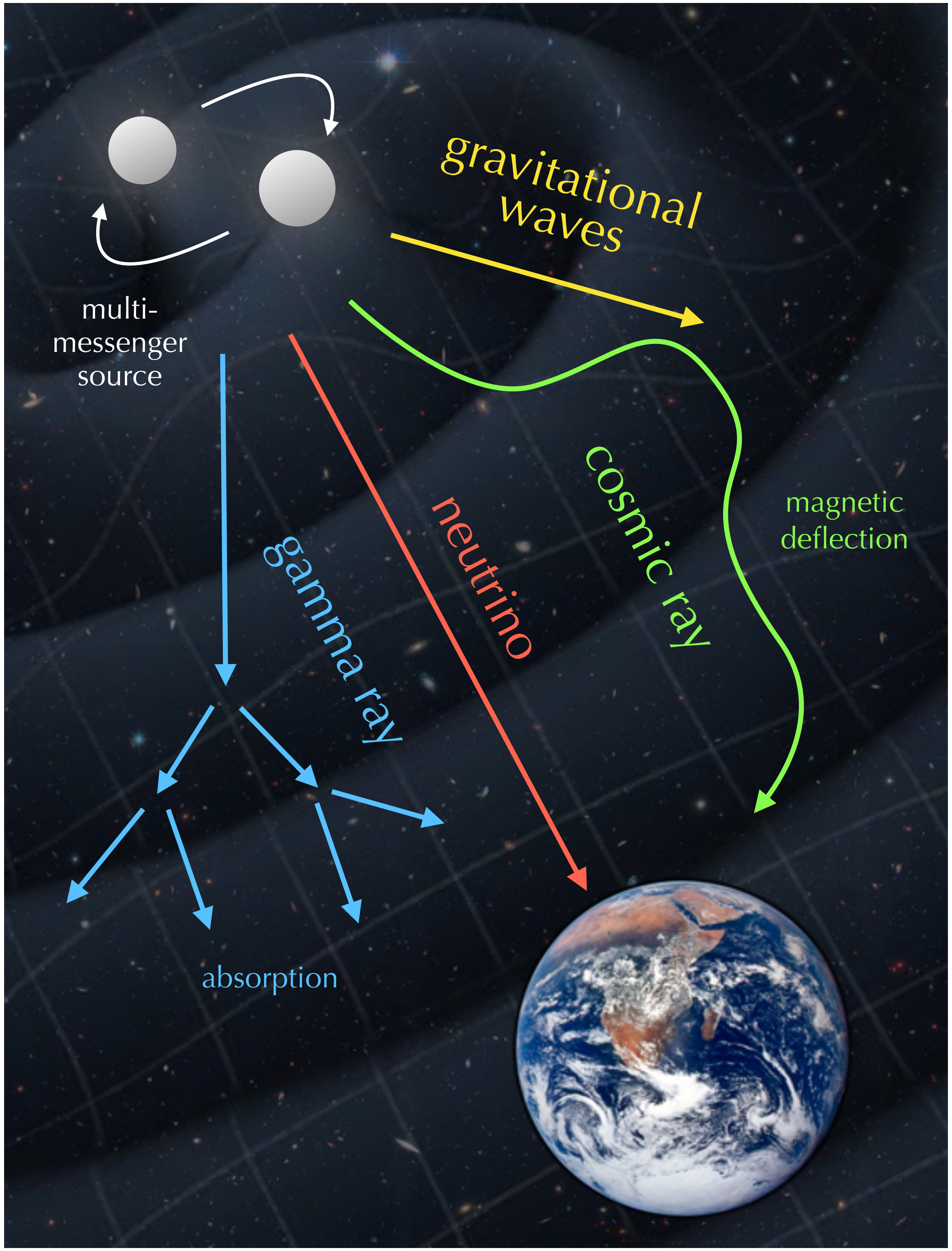
[Stein et al. Nature Astron. 5 (2021) 5; Reusch et al. arXiv:2111.09390]

Multi-Messenger Interfaces



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

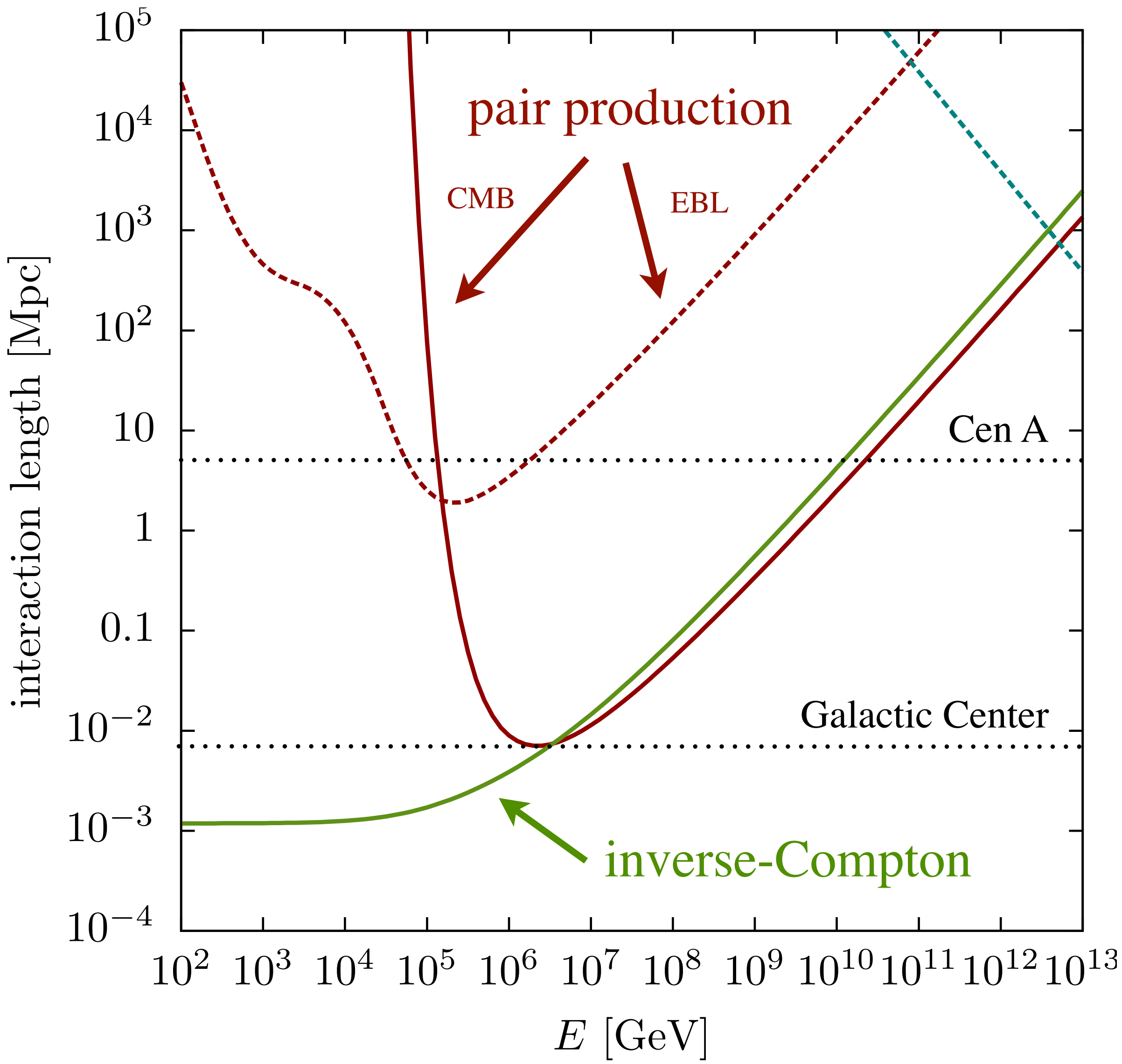
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

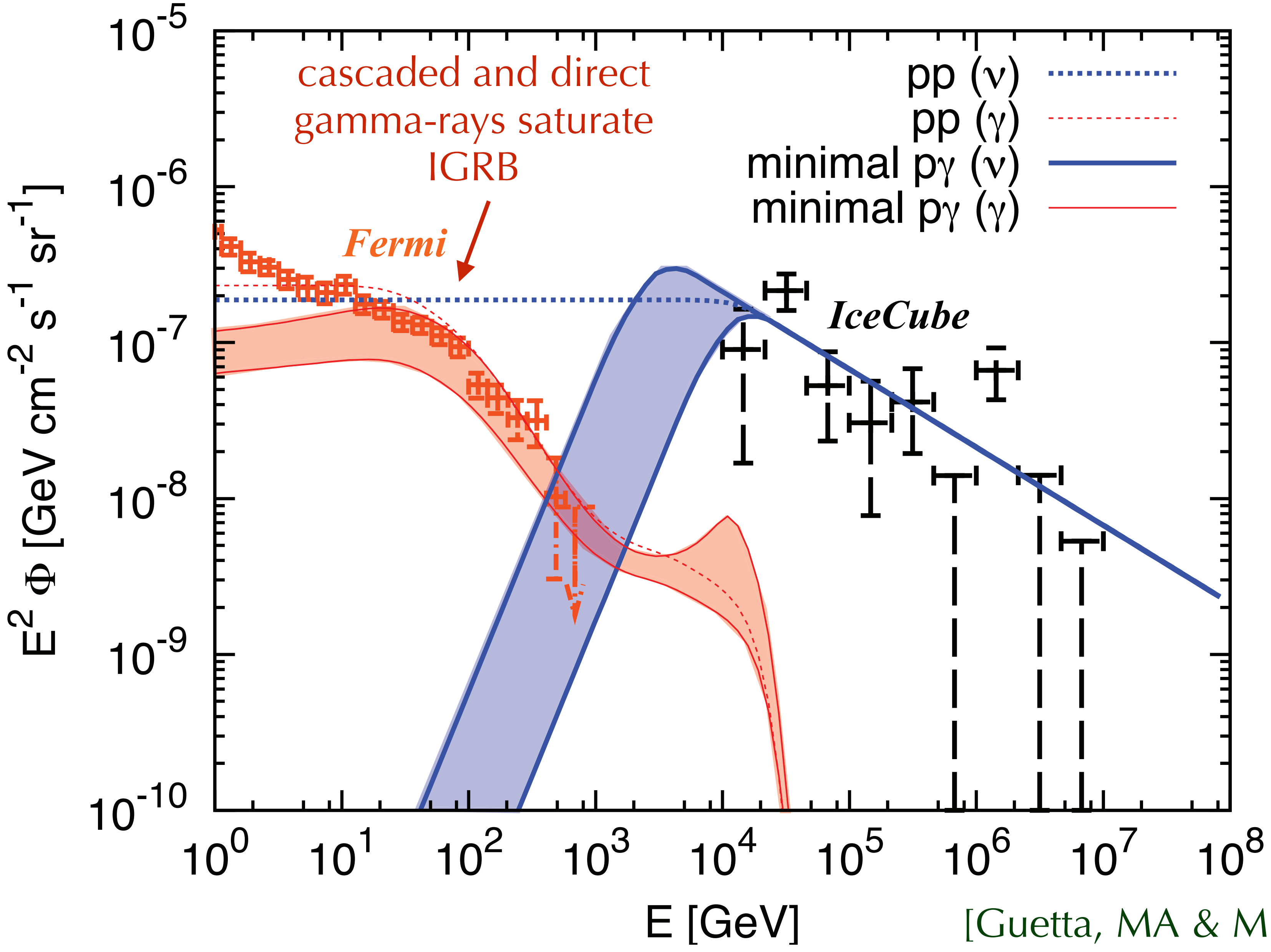
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

$$e^\pm + \gamma_{\rm bg} \to e^\pm + \gamma \quad \text{(ICS)}$$



Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) or radiation (pγ) 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]

Non-Blazar Limit

- Photon fluctuation analyses of Fermi-LAT data allow to constrain the source count distribution of blazars below the source detection threshold.

- Inferred blazar contribution to EGB above 50 GeV:
  - Fermi Collaboration'15:

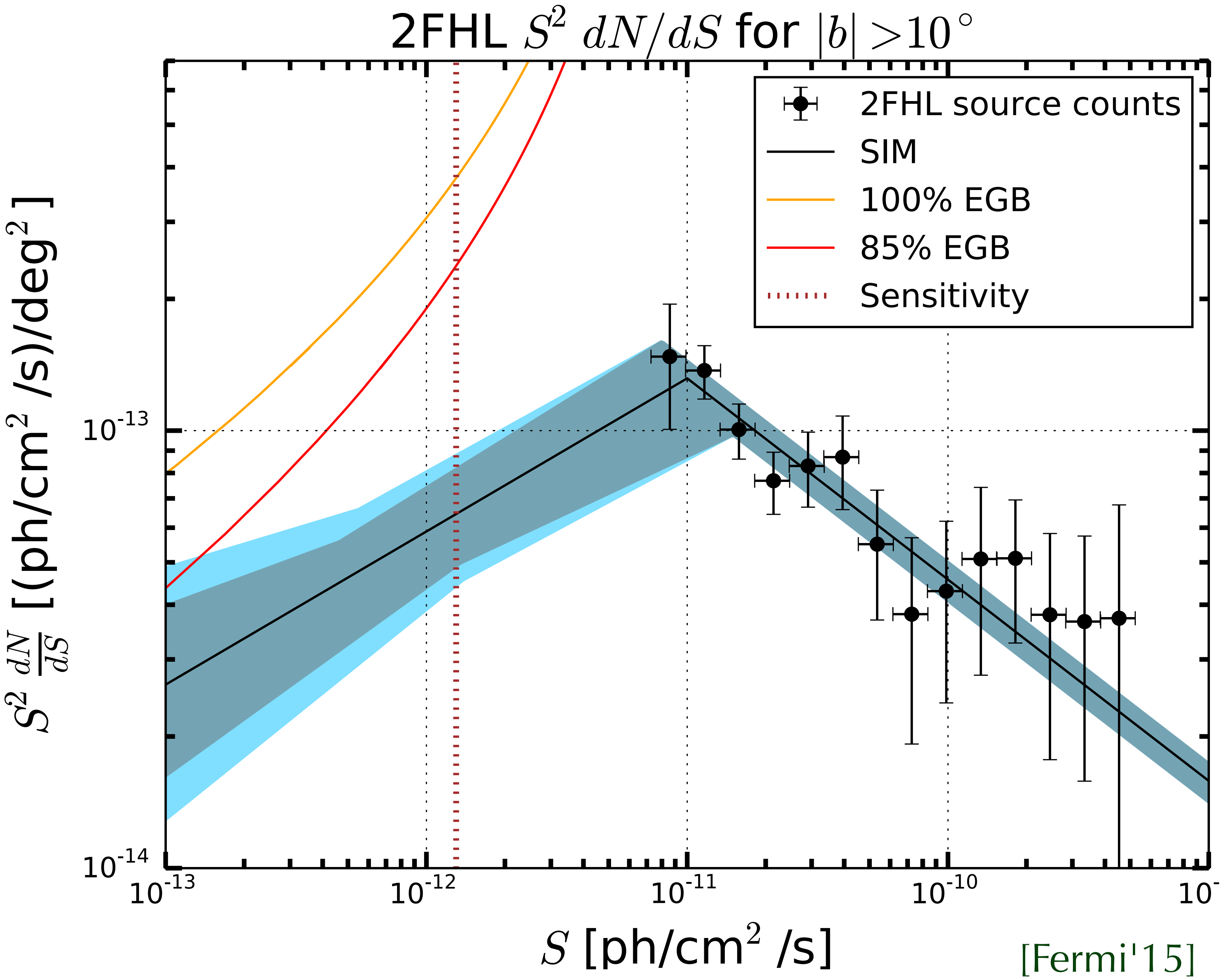
    $$86^{+16}_{-14}\,\%$$

  - Lisanti *et al.*'16:

    $$68^{+9}_{-8}(\pm 10)_{\rm sys}\,\%$$

  - Zechlin *et al.*'16

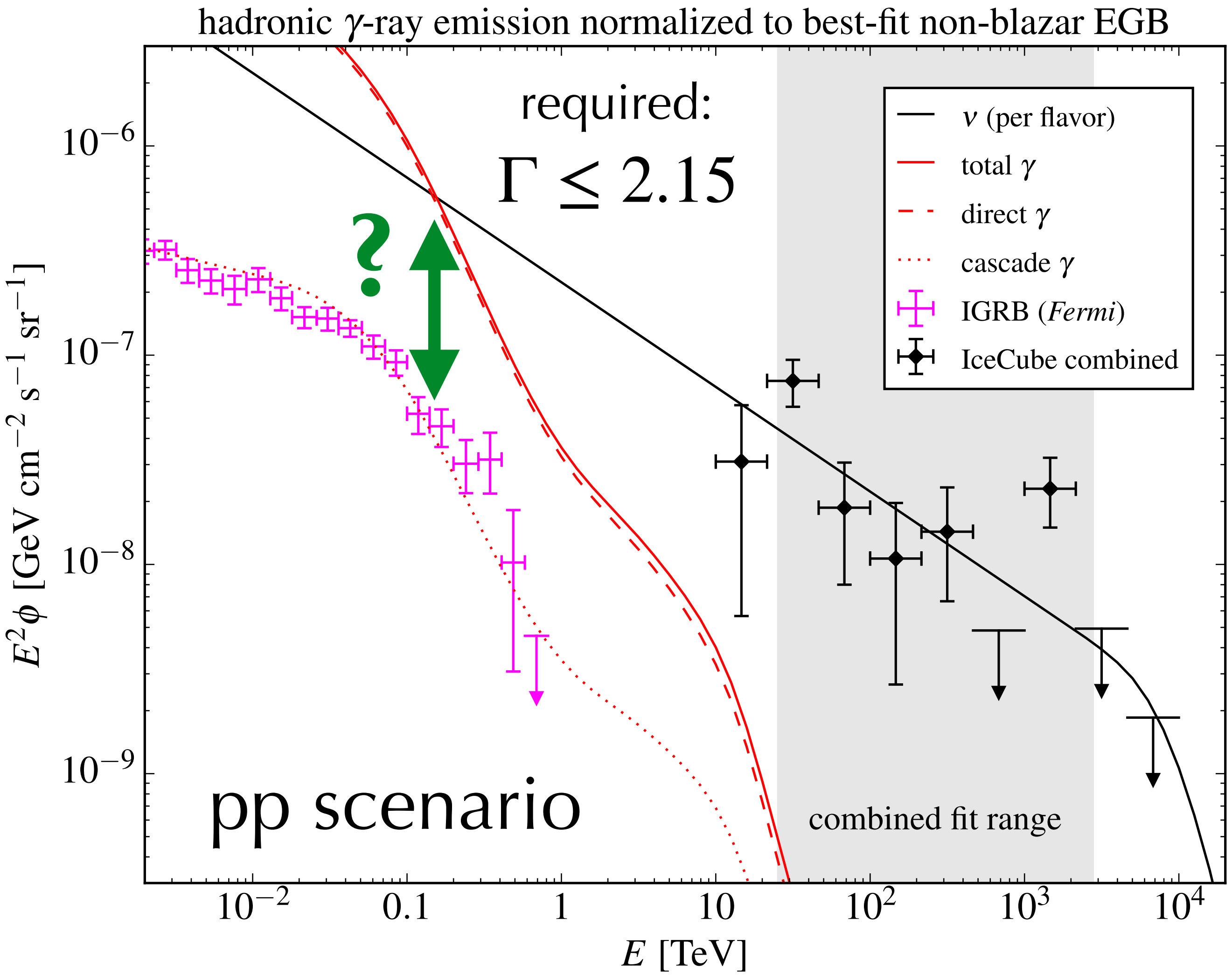
    $$81^{+52}_{-19}\,\%$$

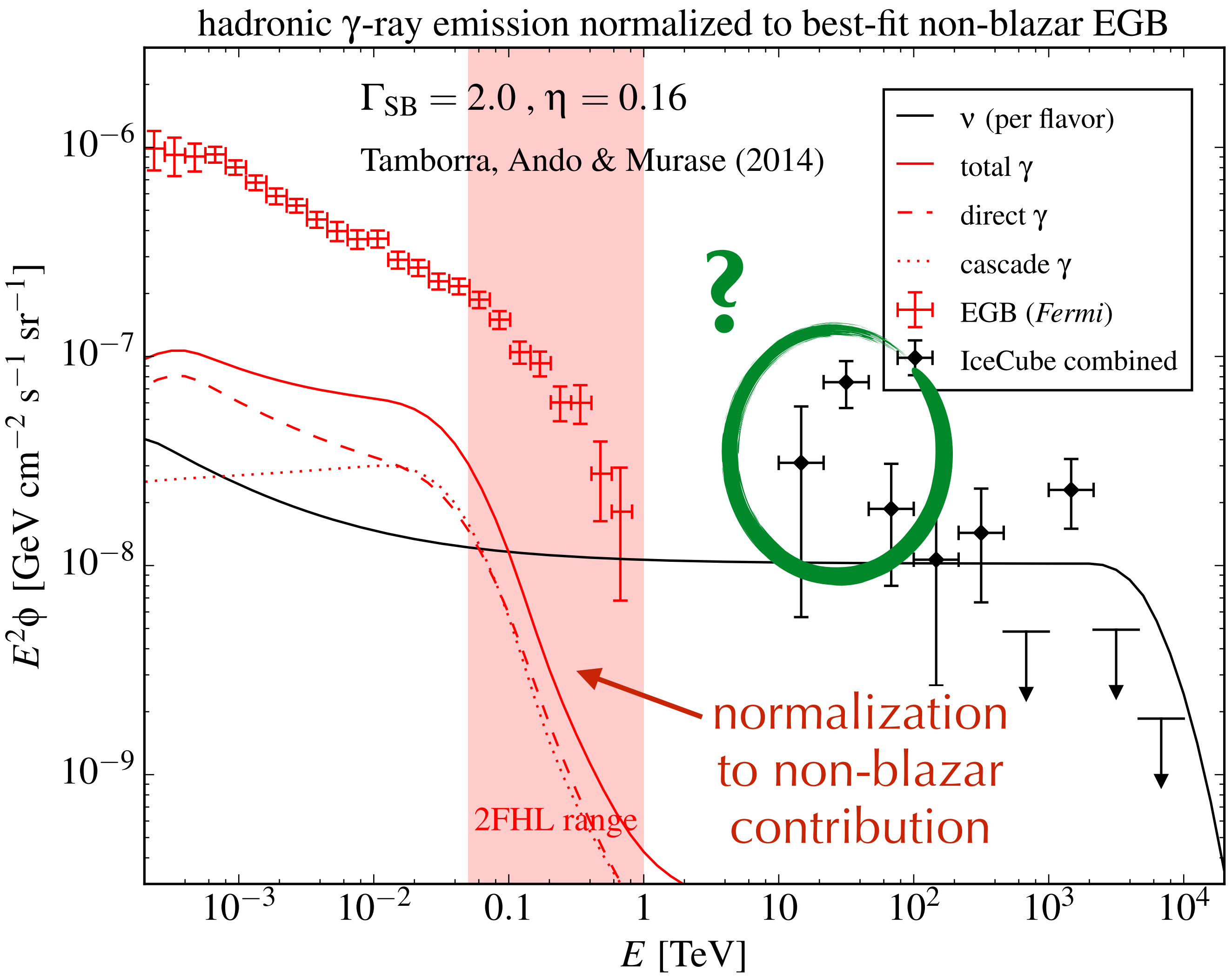


[Fermi'15]

Hadronic Gamma-Rays

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





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

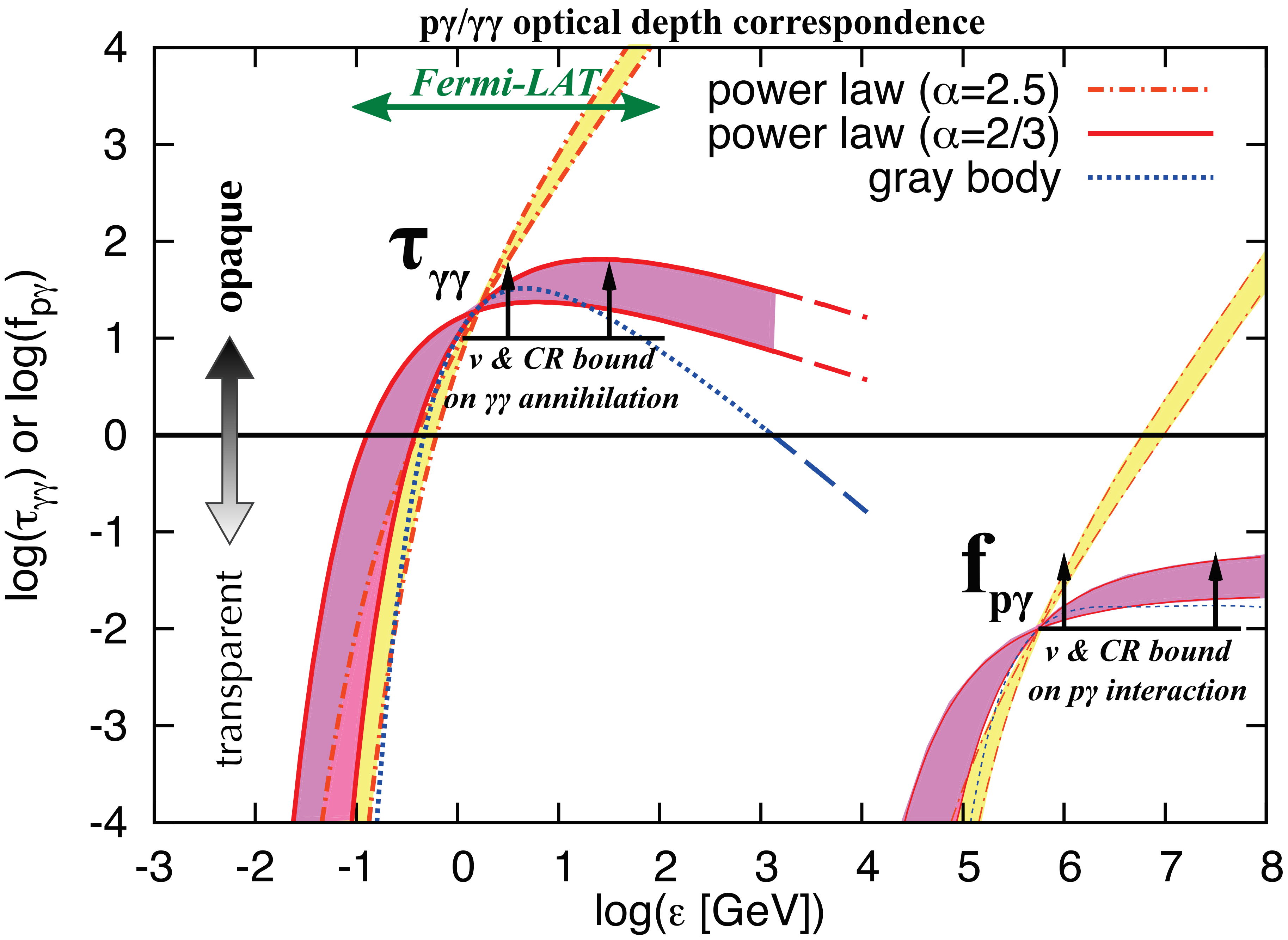
[see also Murase, MA & Lacki'13; Tamborra, Ando & Murase'14; Ando, Tamborra & Zandanel'15]

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

[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

Hidden Sources?

Efficient production of 10 TeV neutrinos in pγ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).

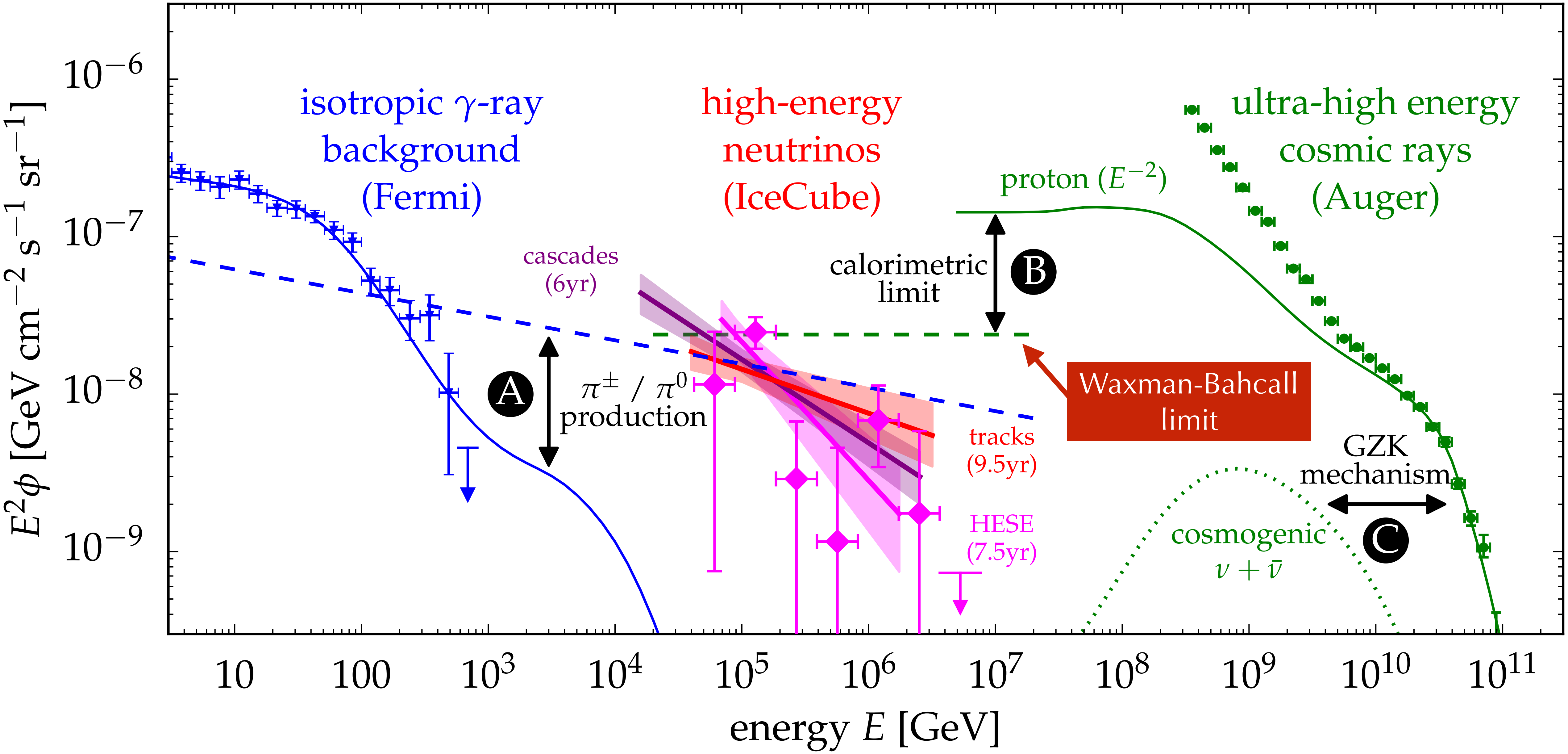


High pion production efficiency implies strong internal ***γ*-ray absorption in Fermi-LAT energy range:**

$$\tau_{\gamma\gamma} \simeq 1000 f_{p\gamma}$$

[Guetta, MA & Murase'16]

Multi-Messenger Interfaces



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

Waxman-Bahcall Limit

- 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 (ξ_z : redshift evolution factor) :

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

- Limited by **pion production efficiency**: $f_\pi \lesssim 1$ [Waxman & Bahcall'98]

- Similar UHE **nucleon emission rate** density (local minimum at $\Gamma \simeq 2.04$) :

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

[Auger'16; see also Jiang, Zhang & Murase'20]

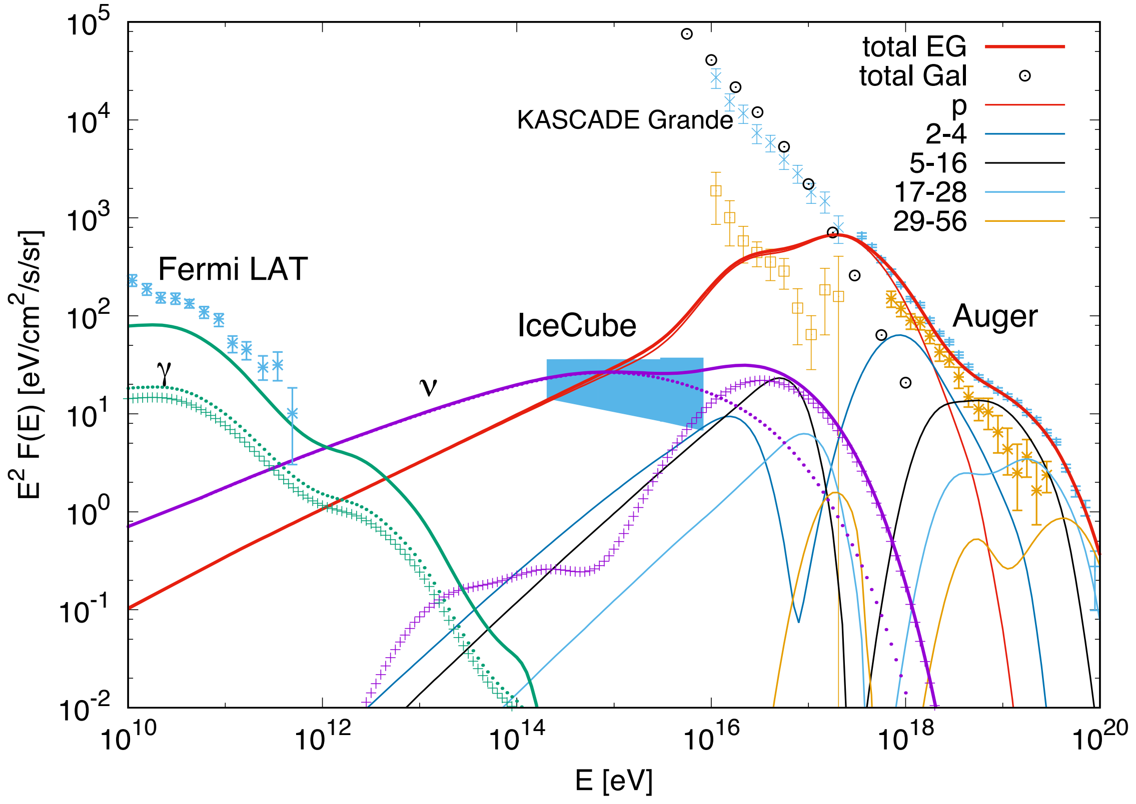
- **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).

Cosmic Ray Calorimeters

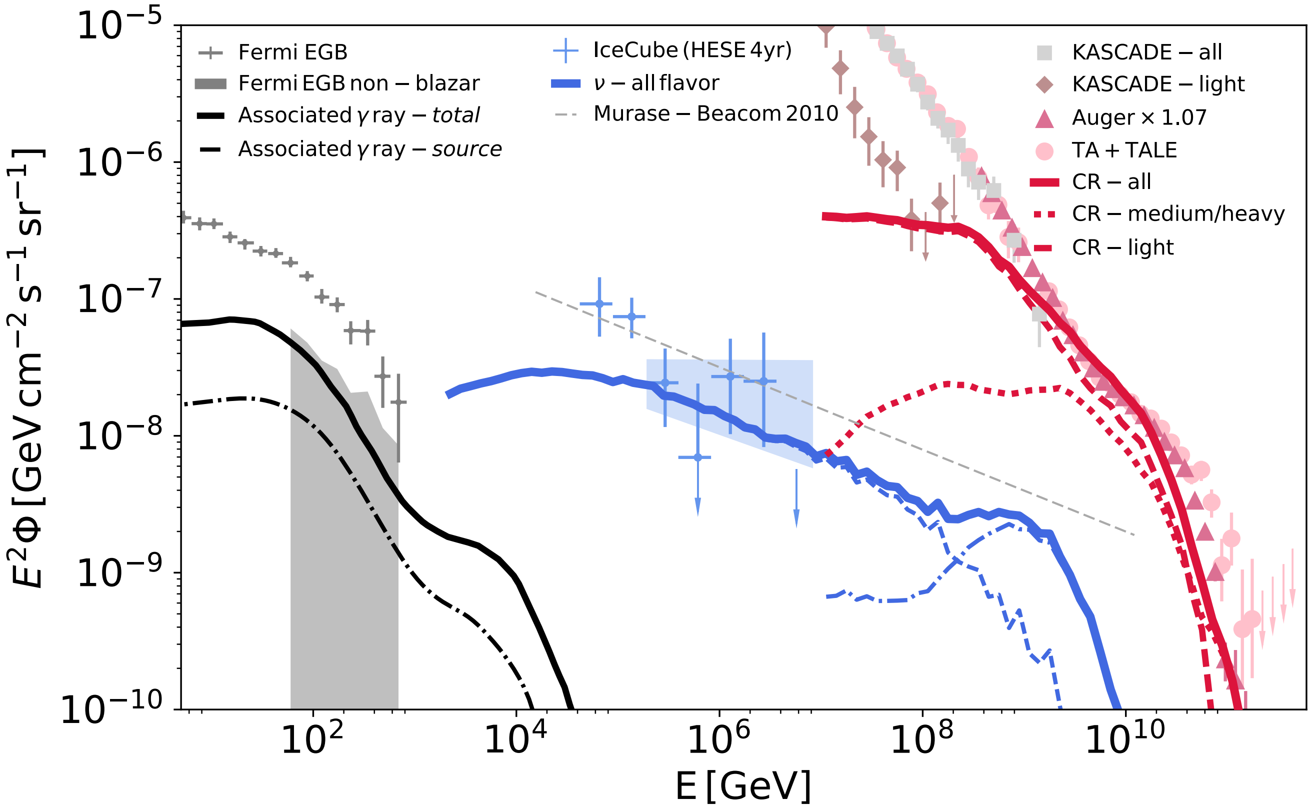
- Competing requirements for efficient CR acceleration and subsequent interaction can be accommodated in **multi-zone models**.
- Magnetic confinement in CR calorimeters, such as **starburst galaxies**, could provide a unified origin of UHE CRs and TeV–PeV neutrinos.

[Loeb & Waxman '06]

- "*Grand Unification*" of UHE CRs, γ-rays and neutrinos?



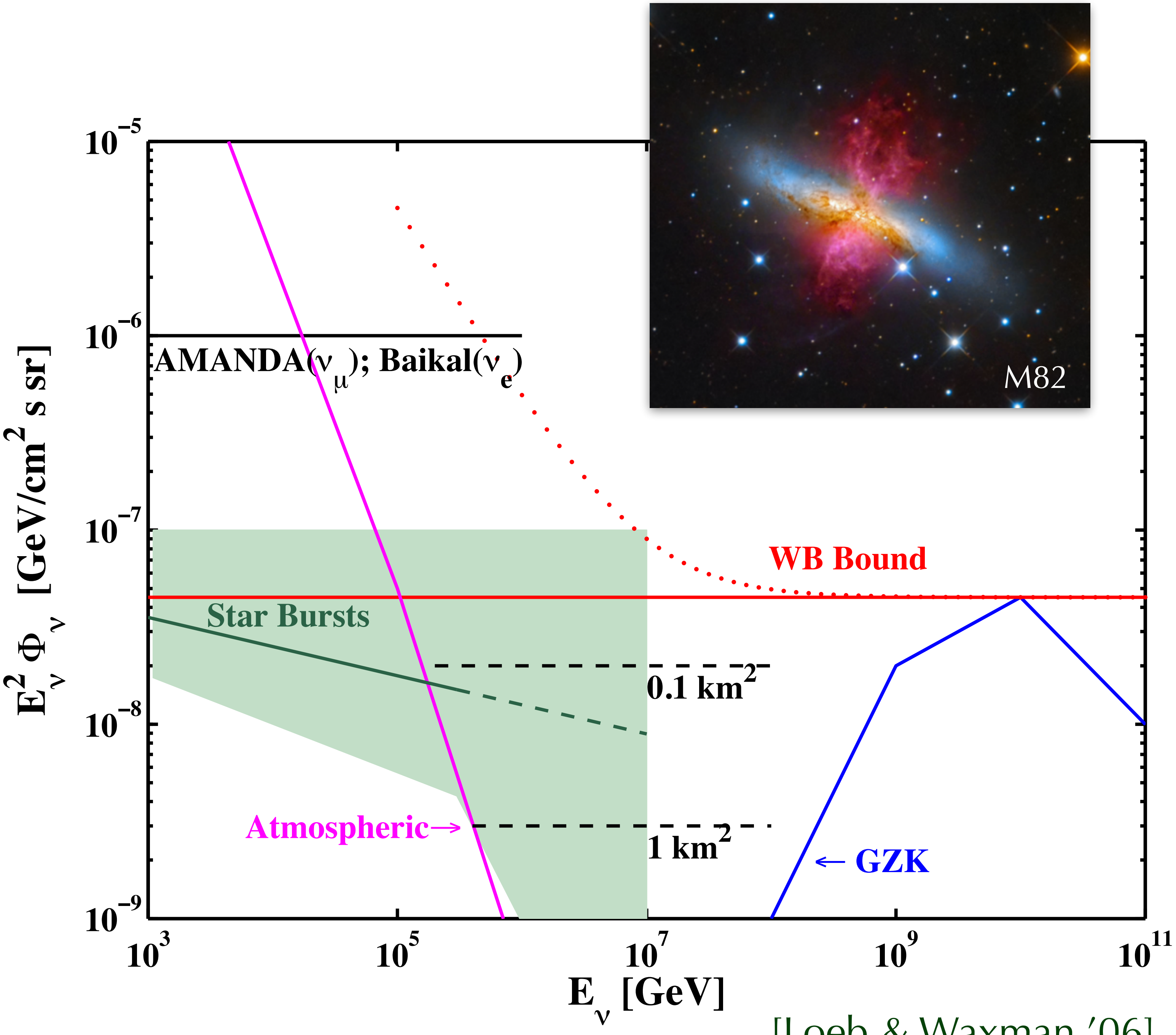
[Kachelriess, Kalashev, Ostapchenko & Semikoz'17]



[Fang & Murase'17]

Starburst Galaxies

- High rate of **star formation** and SN explosions enhances (UHE) CR production.
- Low-energy cosmic rays remain magnetically confined and eventually collide in **dense environment**.
- In time, efficient **conversion of CR energy density into γ-rays and neutrinos**. [Loeb & Waxman '06]
- Power-law neutrino spectra with high-energy softening from CR leakage and/or acceleration.



[Loeb & Waxman '06]

[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]
[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

UHE CR-Neutrino Correlations?

- Unified source models are tested by joint neutrino & CR analyses by **ANTARES, Auger, IceCube & TA**.
  [PoS (ICRC2019) 842]
- So far, no significant correlations have been identified.
- ***Principal challenge:*** Only 5% of observed TeV-PeV neutrinos are expected to correlate with UHE CRs.

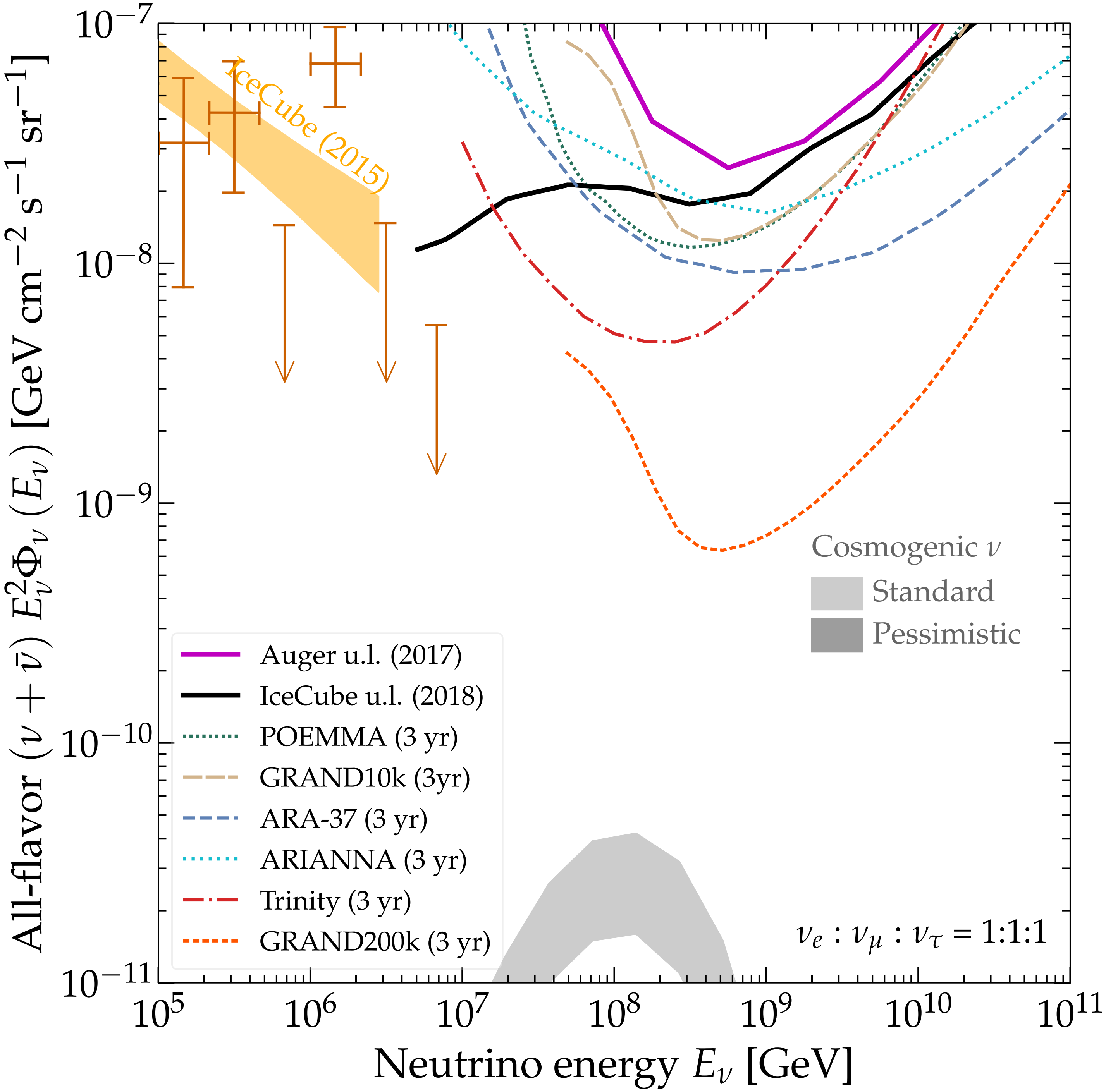
$$\frac{\lambda_{\rm GZK}}{\lambda_{\rm Hubble}} \sim 5\,\%$$

"Observable Universe"
in neutrinos and UHE CRs

Hubble horizon

Cosmogenic Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- 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.
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.

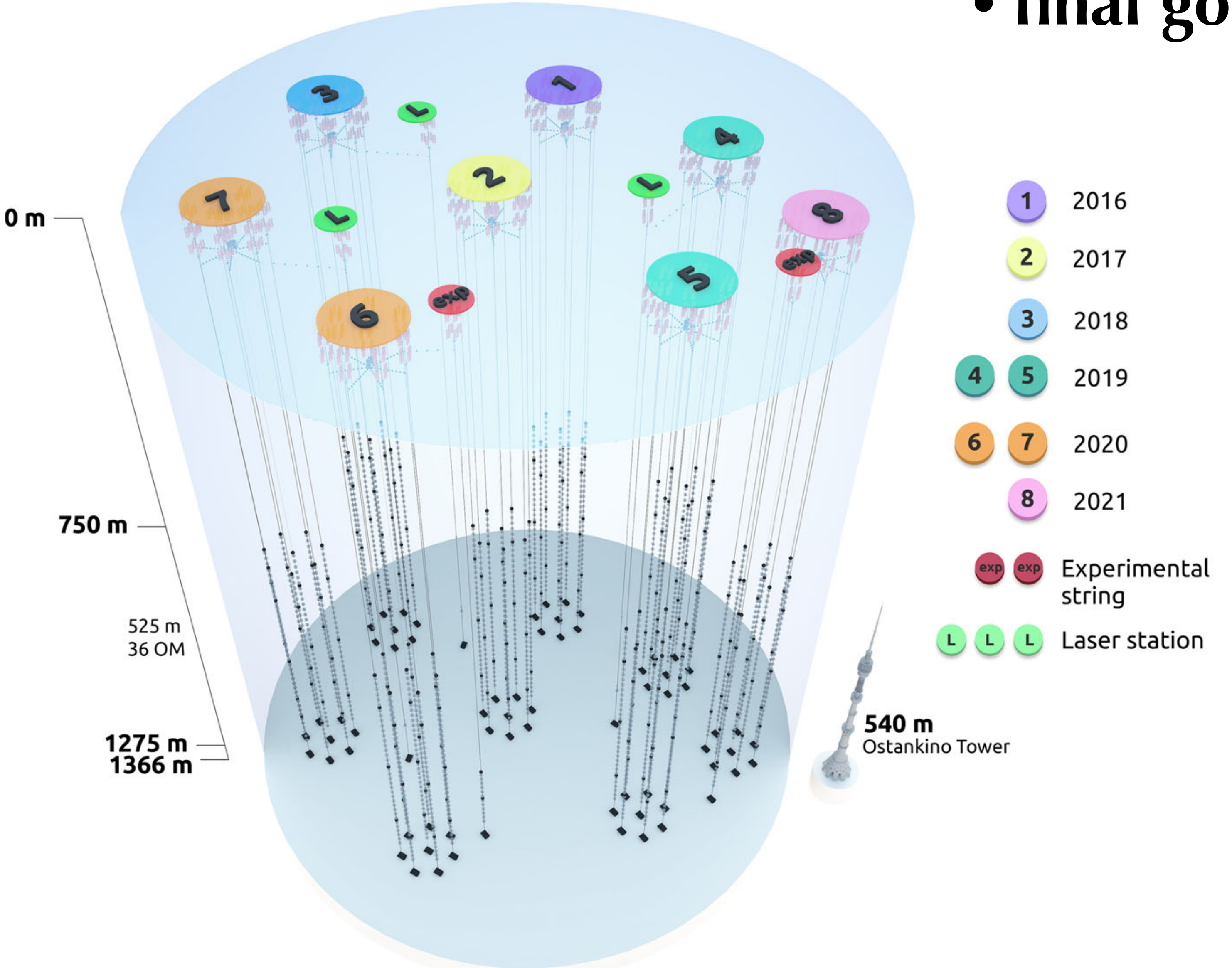


[Alves Batista *et al.*'19]

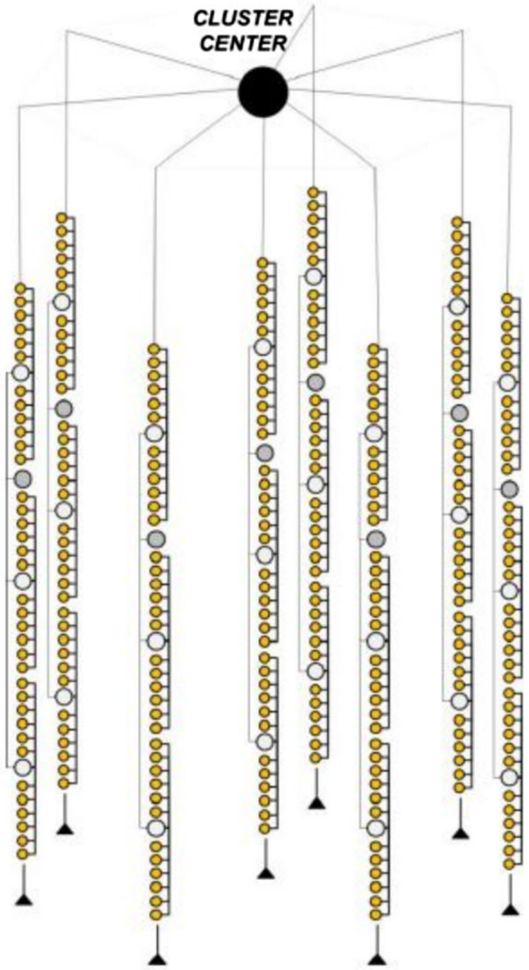
Outlook: Baikal-GVD

BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status April 2022: 9(+1) clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

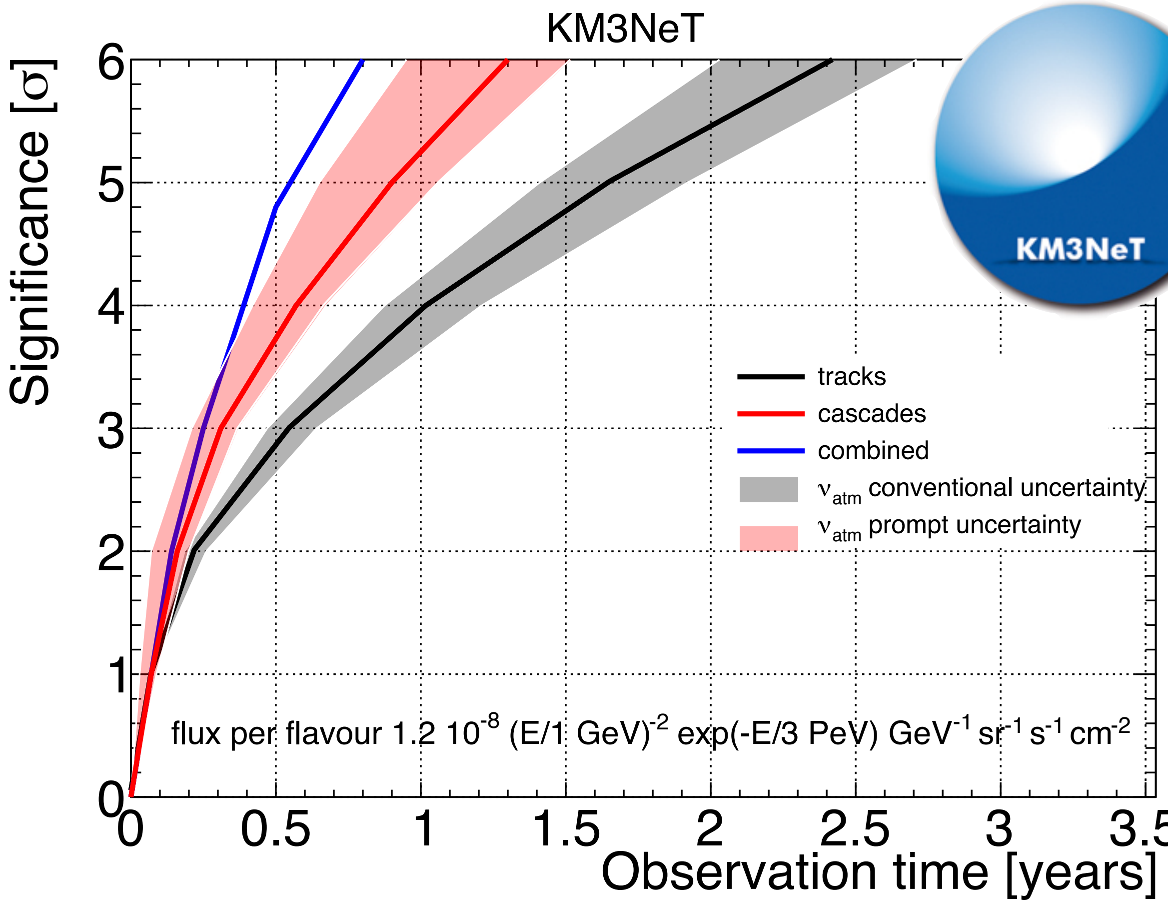


1	2016
2	2017
3	2018
4 5	2019
6 7	2020
8	2021
exp exp	Experimental string
L L L	Laser station

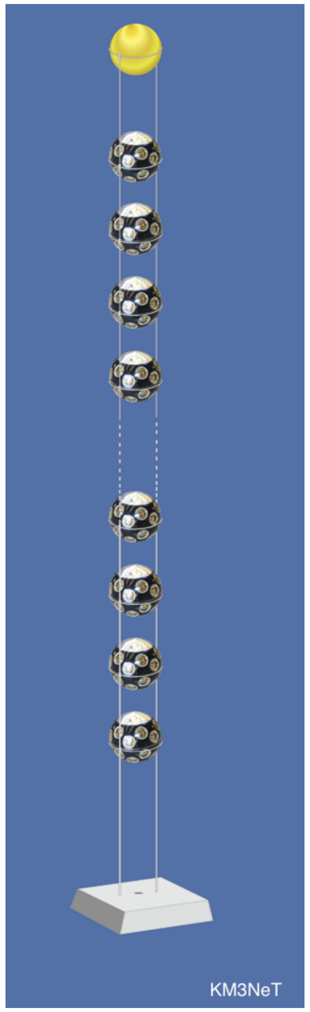


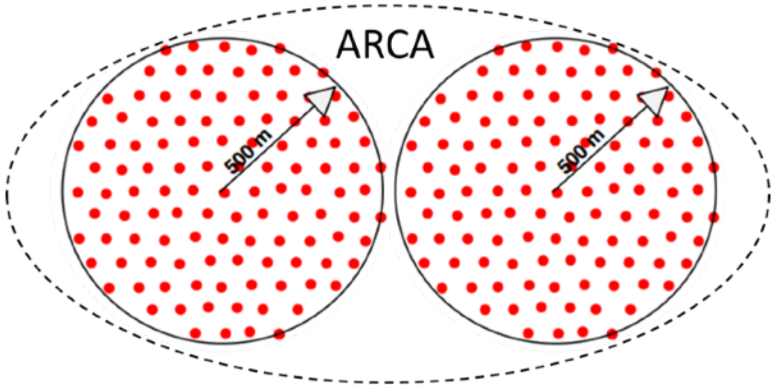
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status April 2022: 8 (ARCA) DUs**
- **ORCA** : optimized for low-energy (GeV) and oscillation analyses



detection unit with multi-PMT DOMs



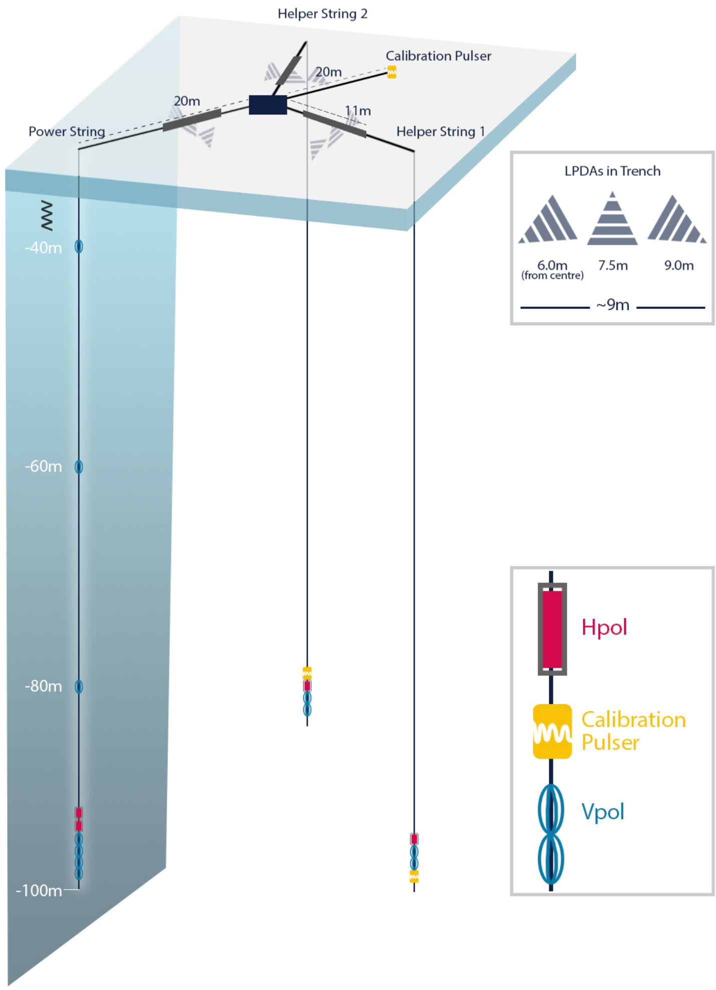


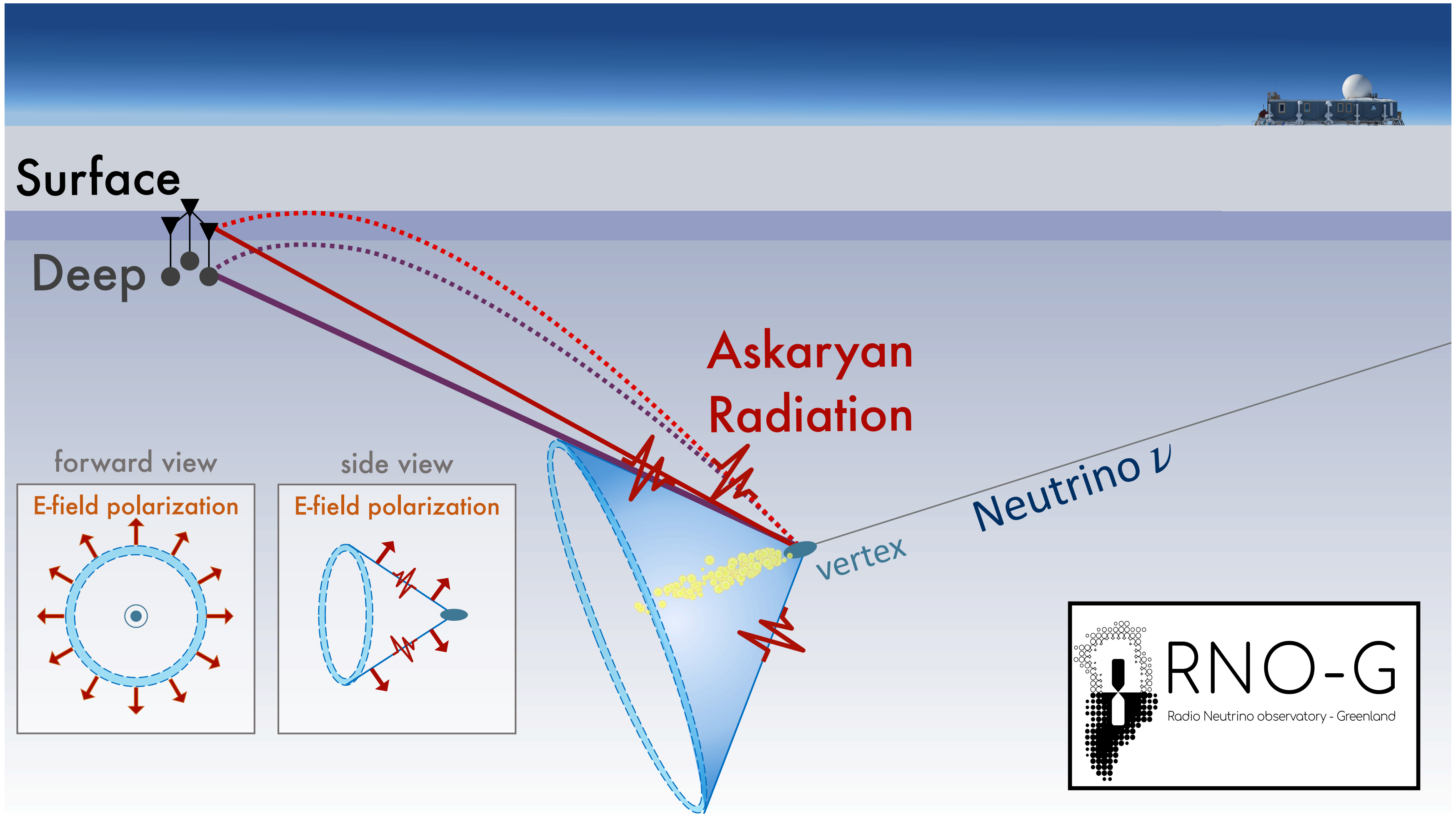
- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Outlook: RNO-G

- Detection principle of **ANITA, ARA & ARIANNA** (Antarctica)
- **Under construction:** Radio Neutrino Observatory-Greenland (**RNO-G**)

Askaryan effect:
Neutrino emission above 10 PeV can be observed via **coherent radio emission of showers** in radio-transparent media.

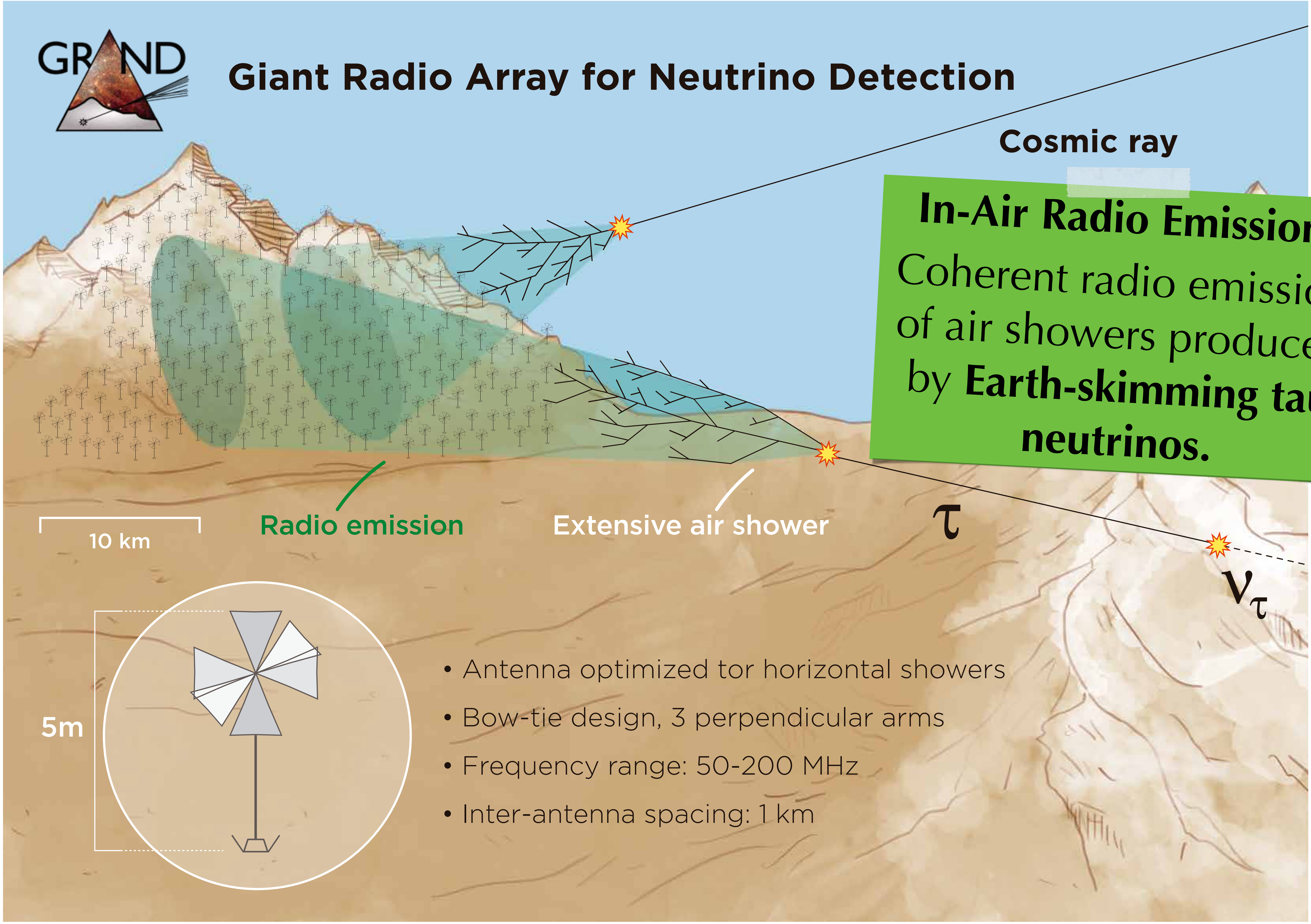




[RNO-G JINST 16 (2021) 3]

Vision: GRAND

[GRAND SCPMA 63 (2020) 1]



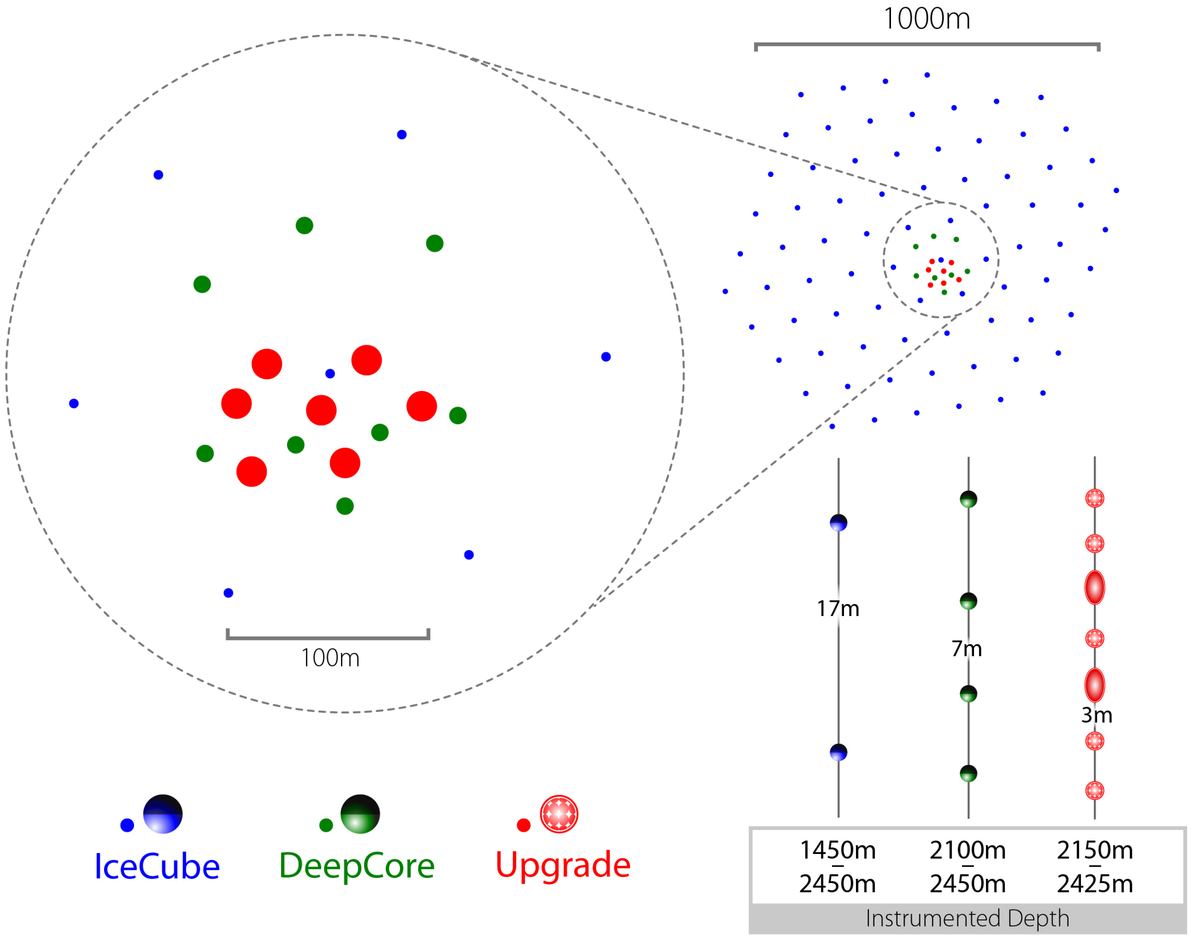
In-Air Radio Emission:

Coherent radio emission of air showers produced by **Earth-skimming tau neutrinos.**

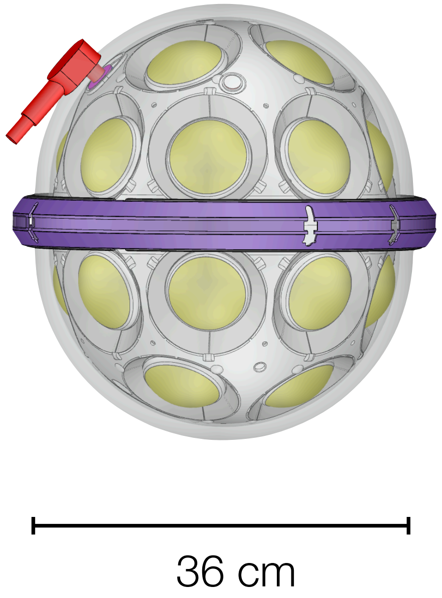
- Antenna optimized tor horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km

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
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Aim: deployment in 2023/24**

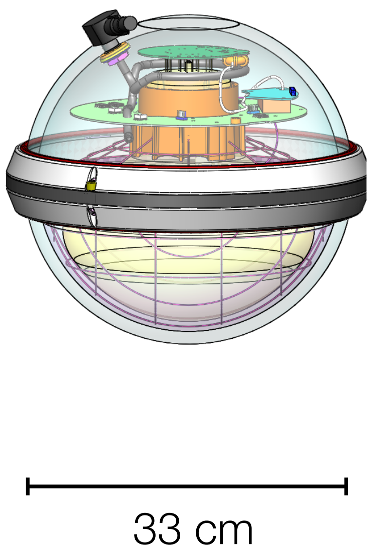


mDOM



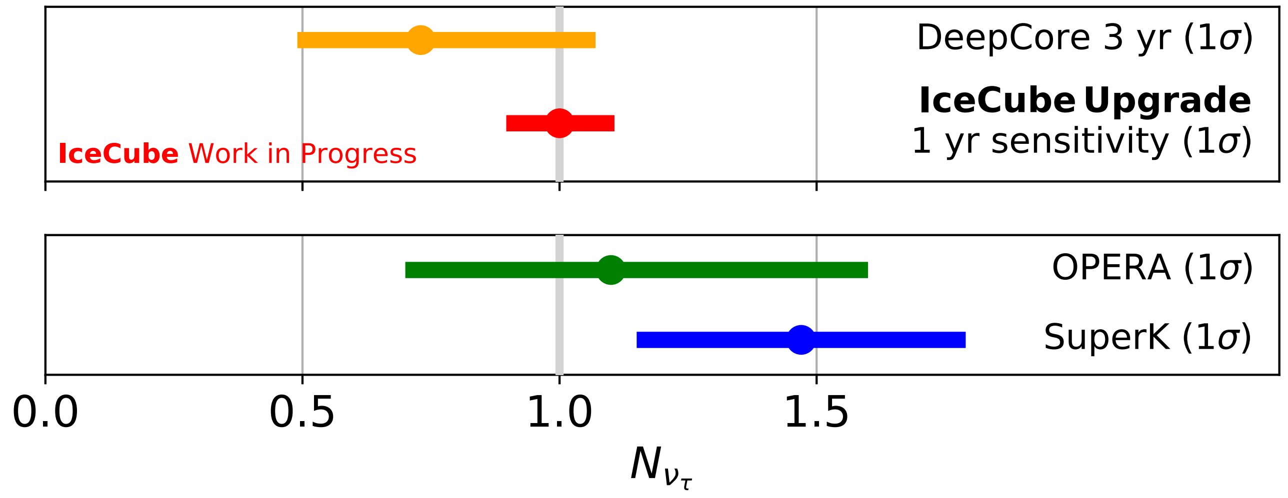
D-Egg

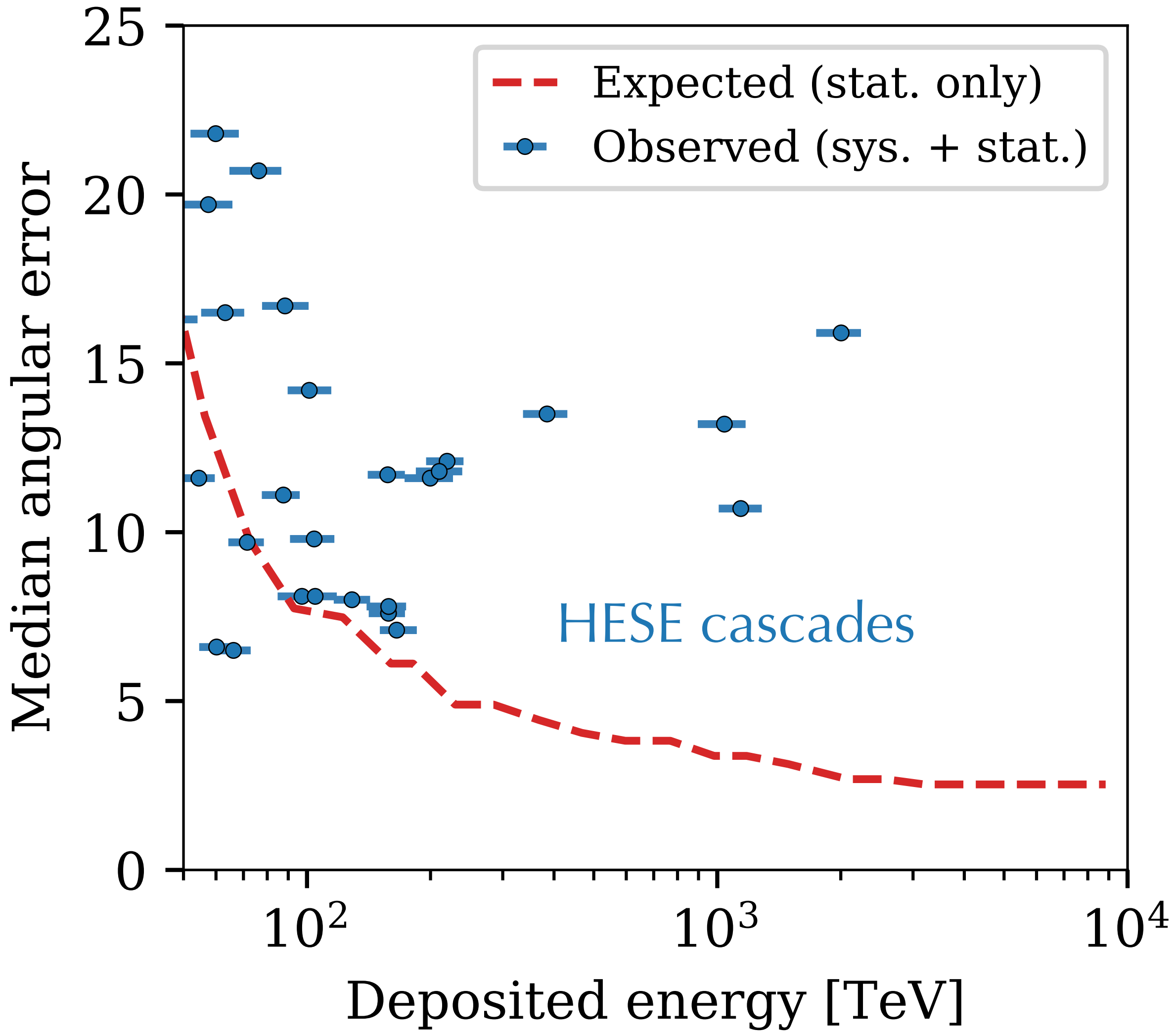
pDOM

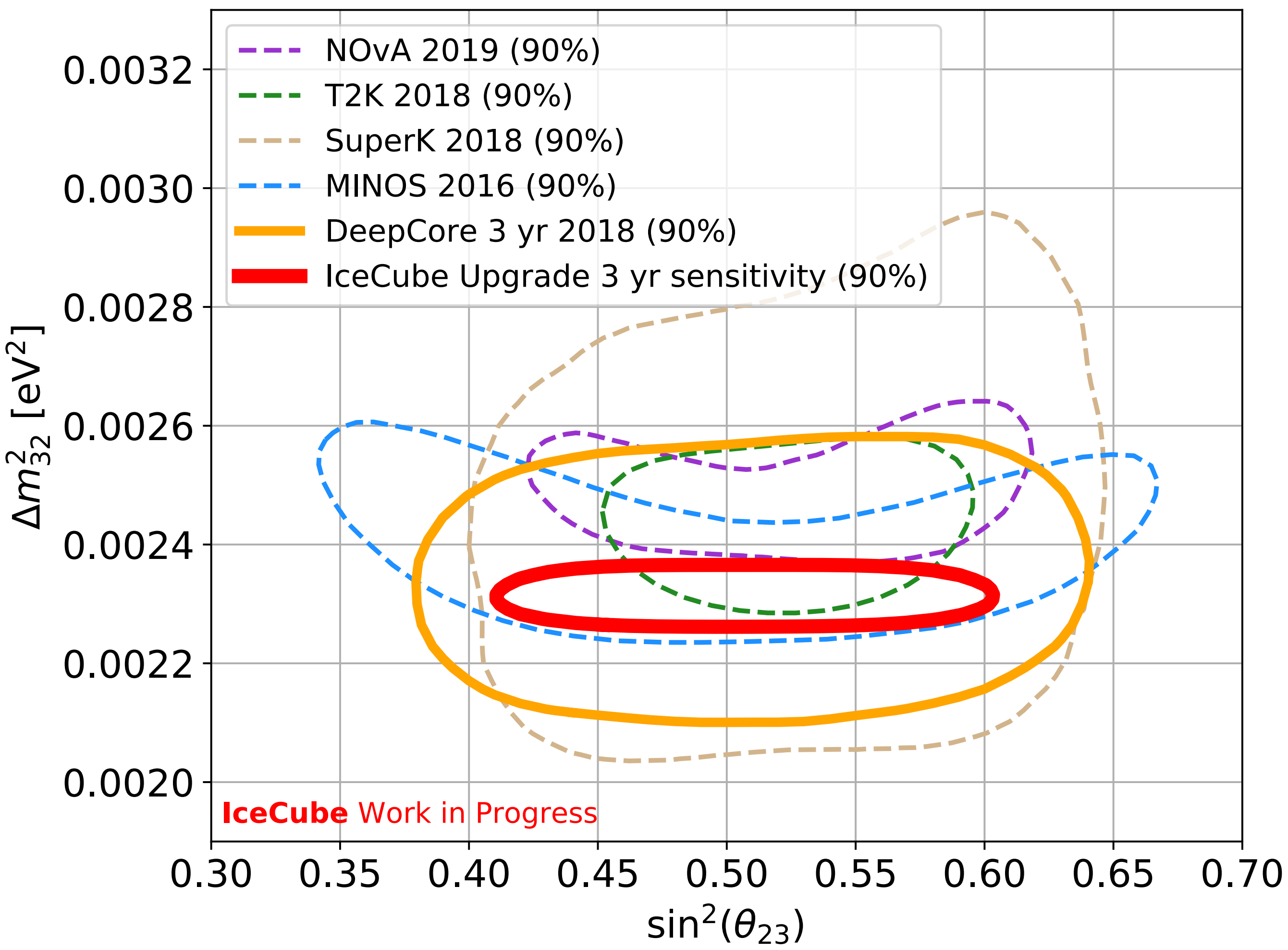


Outlook: IceCube Upgrade

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



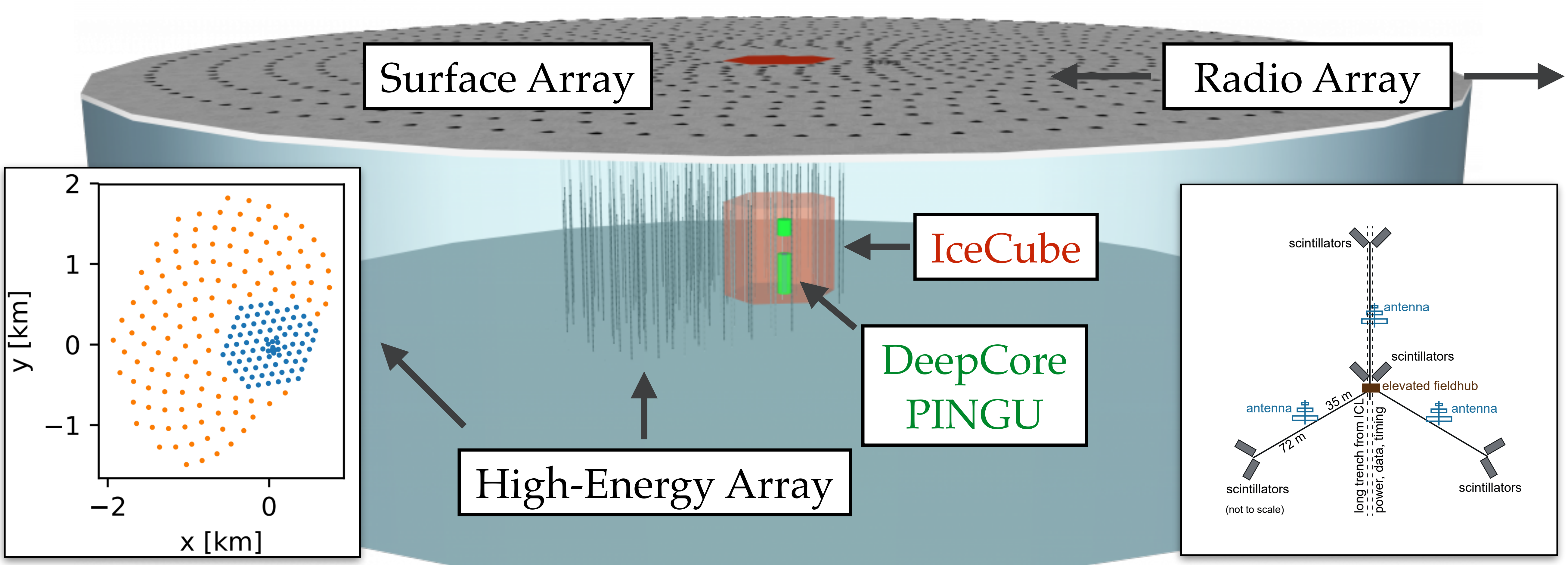




[IceCube, PoS (ICRC2019) 1031]

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** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10PeV neutrino detection



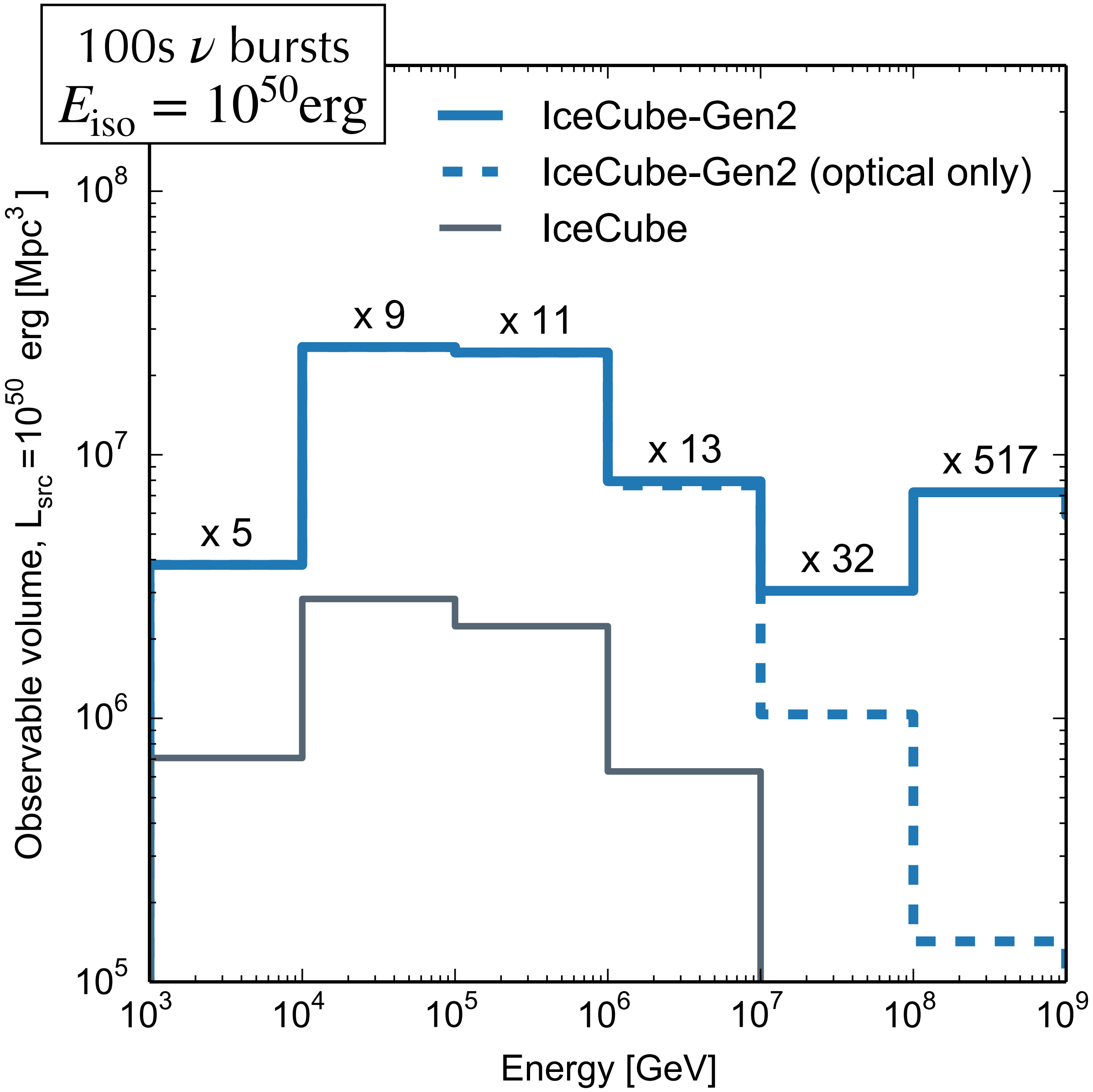
string layout

surface station

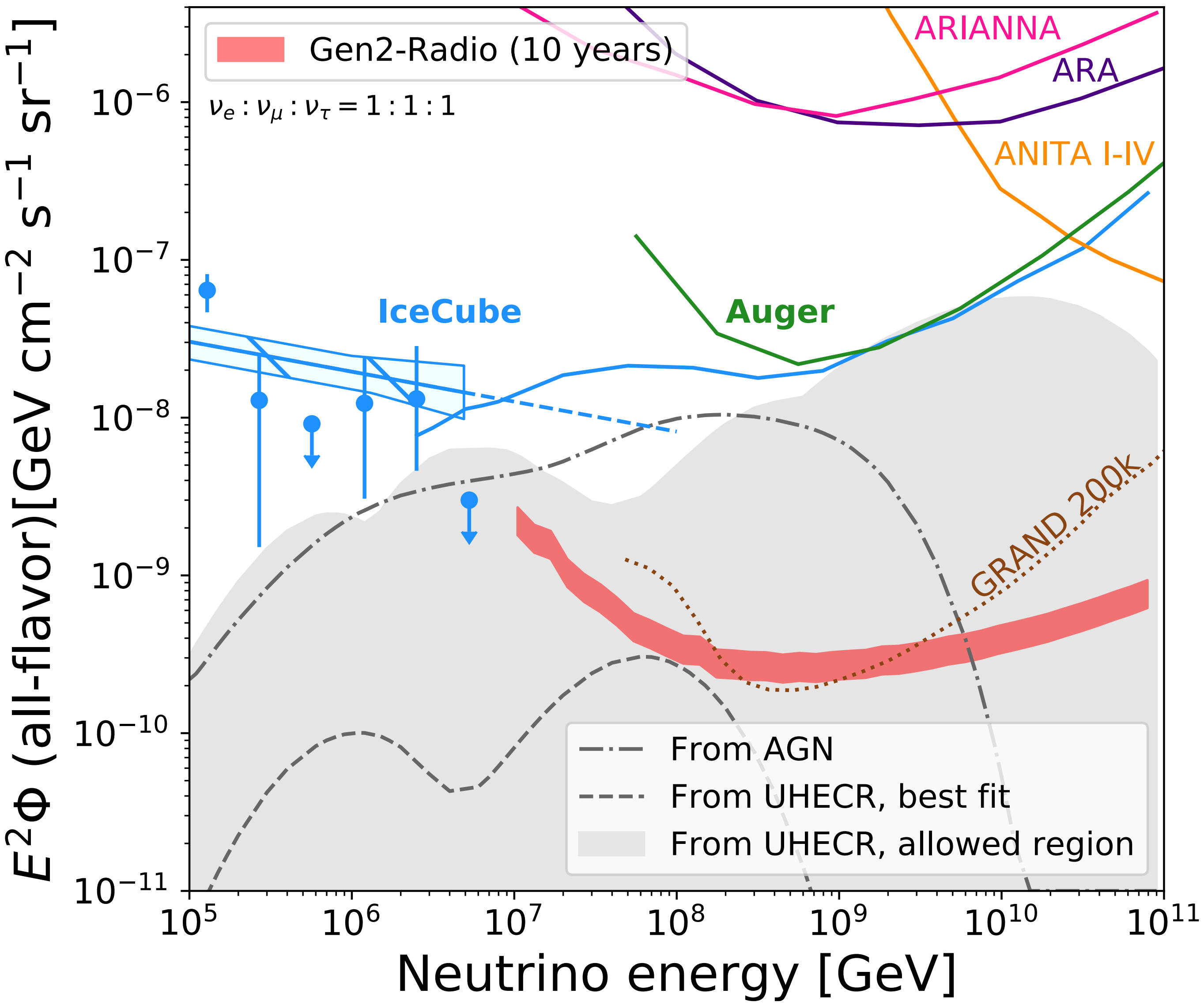
[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Vision: IceCube-Gen2

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



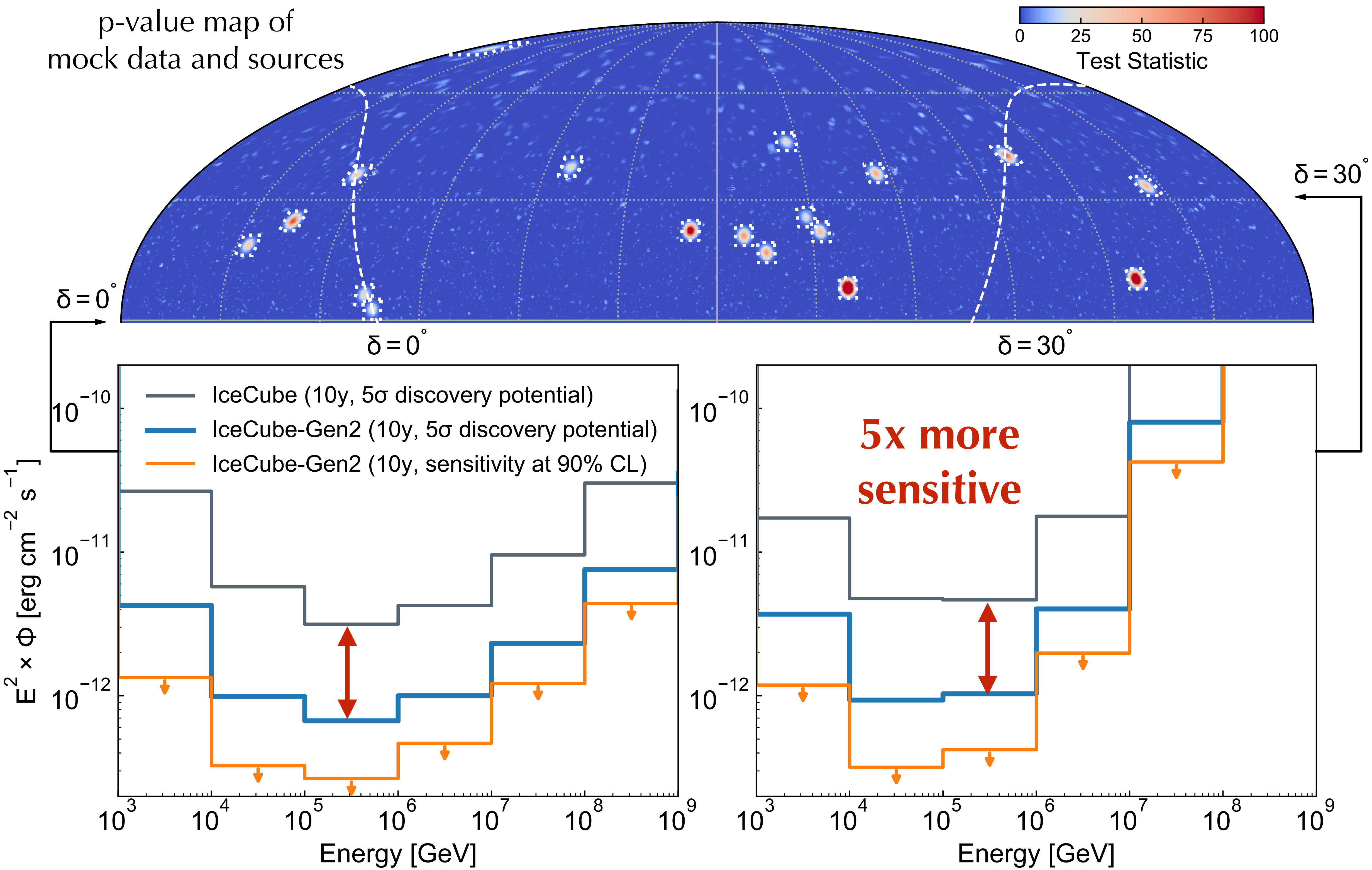
Precision measurement of **PeV-EeV neutrino fluxes** with extended in-ice optical and surface radio array



[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Vision: IceCube-Gen2

p-value map of
mock data and sources



5x more sensitive

[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Summary

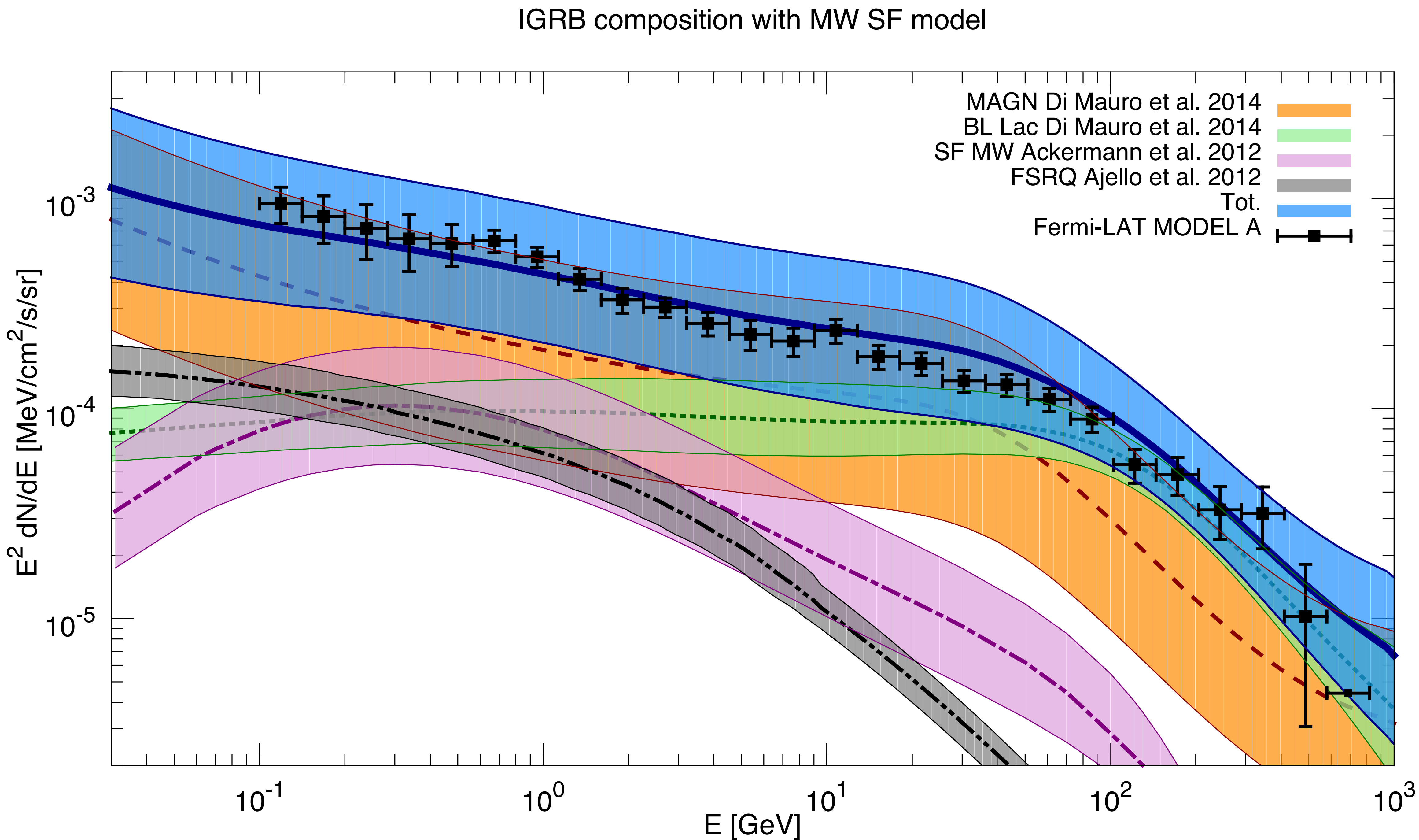
- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**
- So far, **no significant** point sources, but many **interesting candidates**.
- Intensity of cosmic neutrinos is comparable to that of ultra-high energy cosmic-rays (*Auger/TA*) and γ-rays (*Fermi-LAT*).
- Many interesting options for joint **multi-messenger studies**.
- Essential for future discoveries are **multi-messenger partners** facilitating low-latency studies.
- In parallel, development of **neutrino telescopes for the next decade** with complementary FoV and/or increased sensitivity and energy coverage.

(Baikal-GVD, KM3NeT, P-ONE, RNO-G, IceCube-Gen2, ARA, ARIANNA, GRAND,…)

Backup Slides

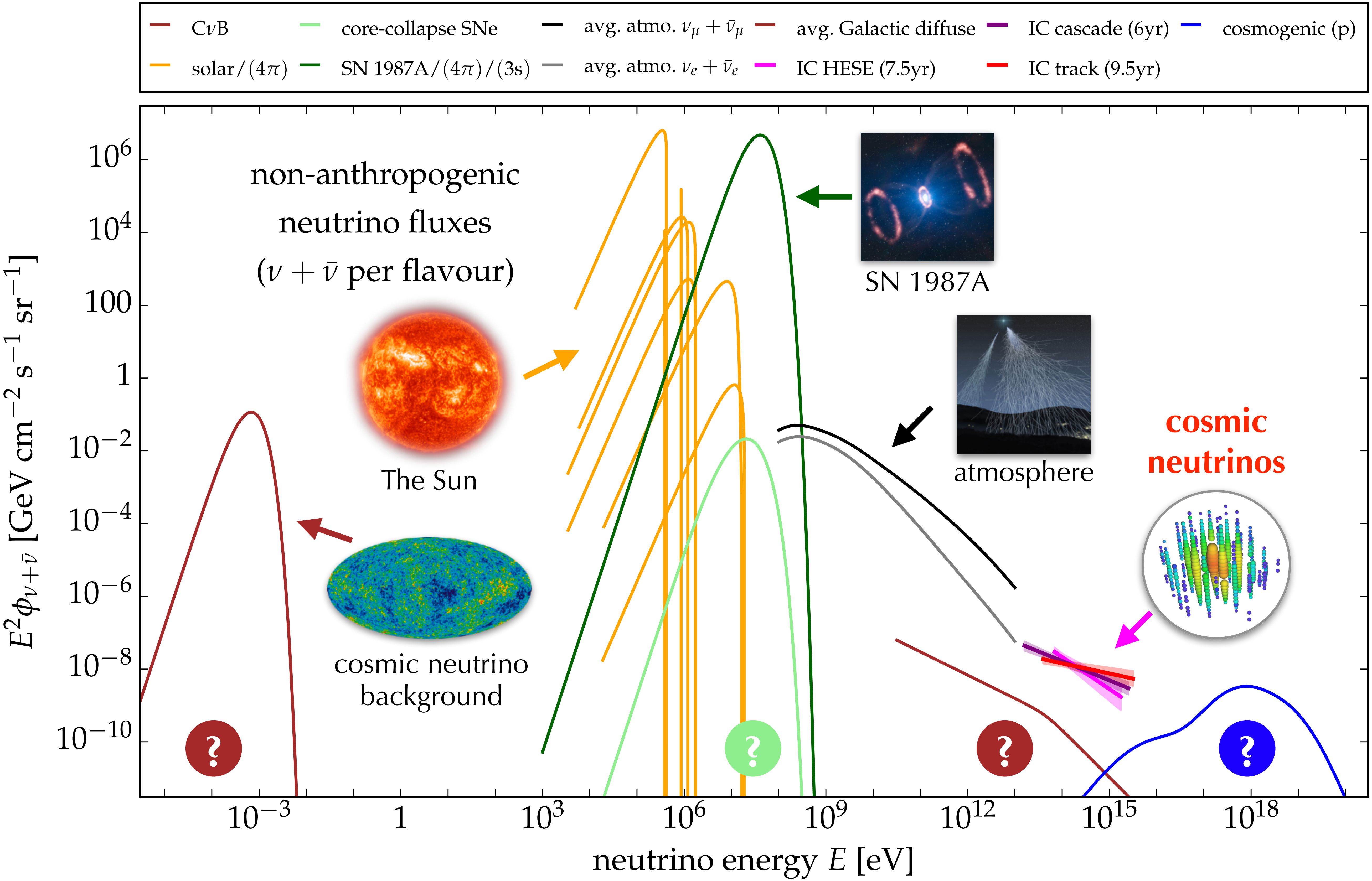
Isotropic Diffuse Gamma-Ray BGR

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



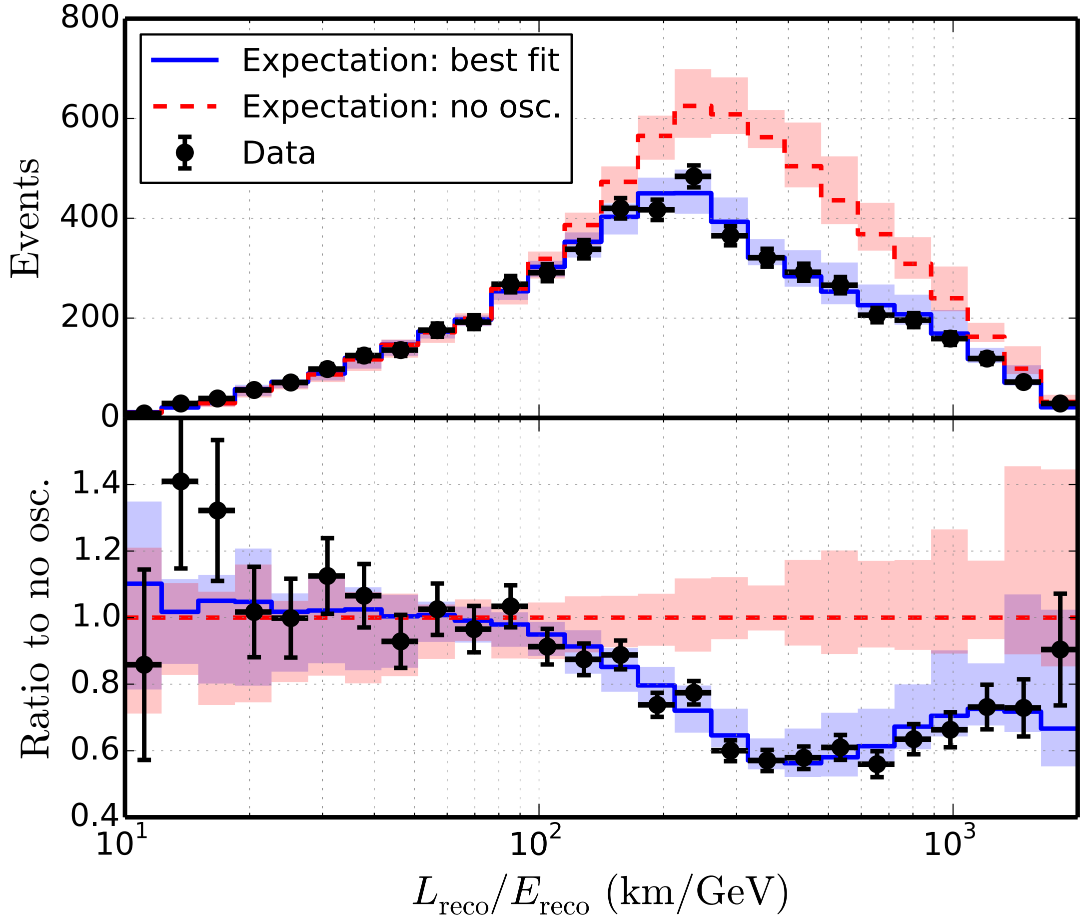
[Di Mauro & Donato’15]

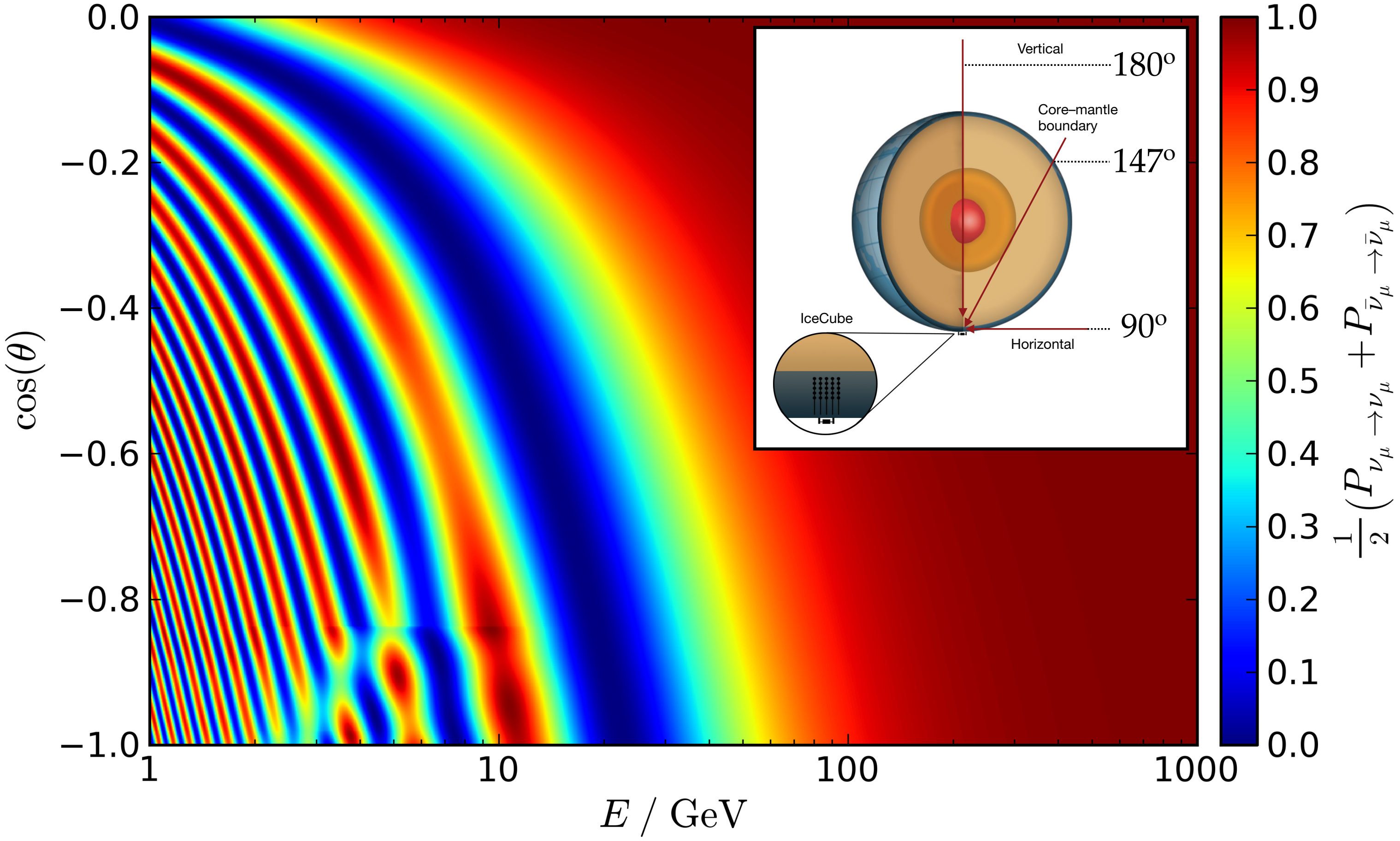
Astrophysical Neutrino Fluxes



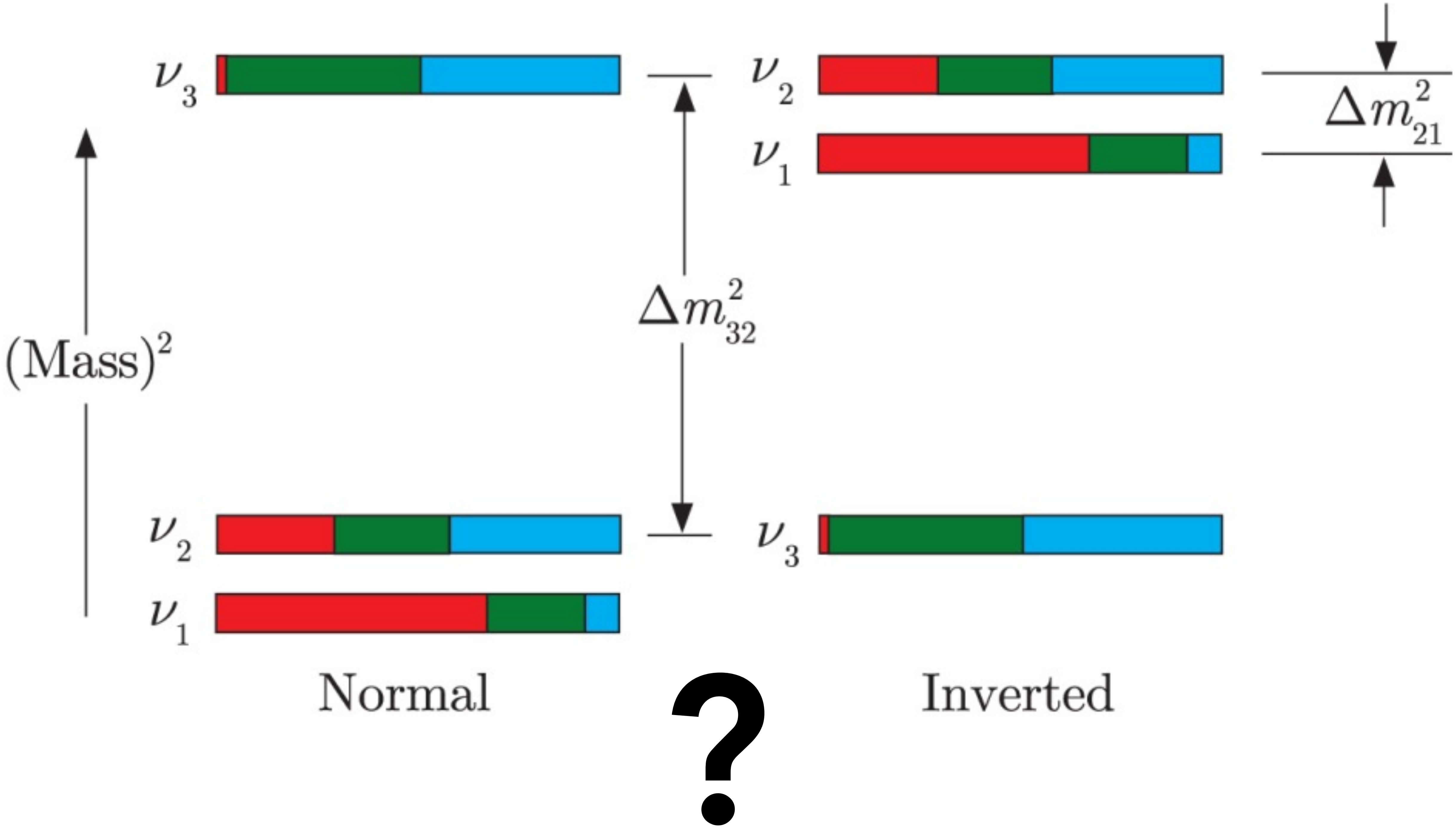
Atmospheric Neutrino Oscillations

- 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*).
- Together with measurements of tau neutrino **appearance** (OPERA, Super-K & IceCube), the data is consistent with **oscillations between tau and muon neutrinos**.





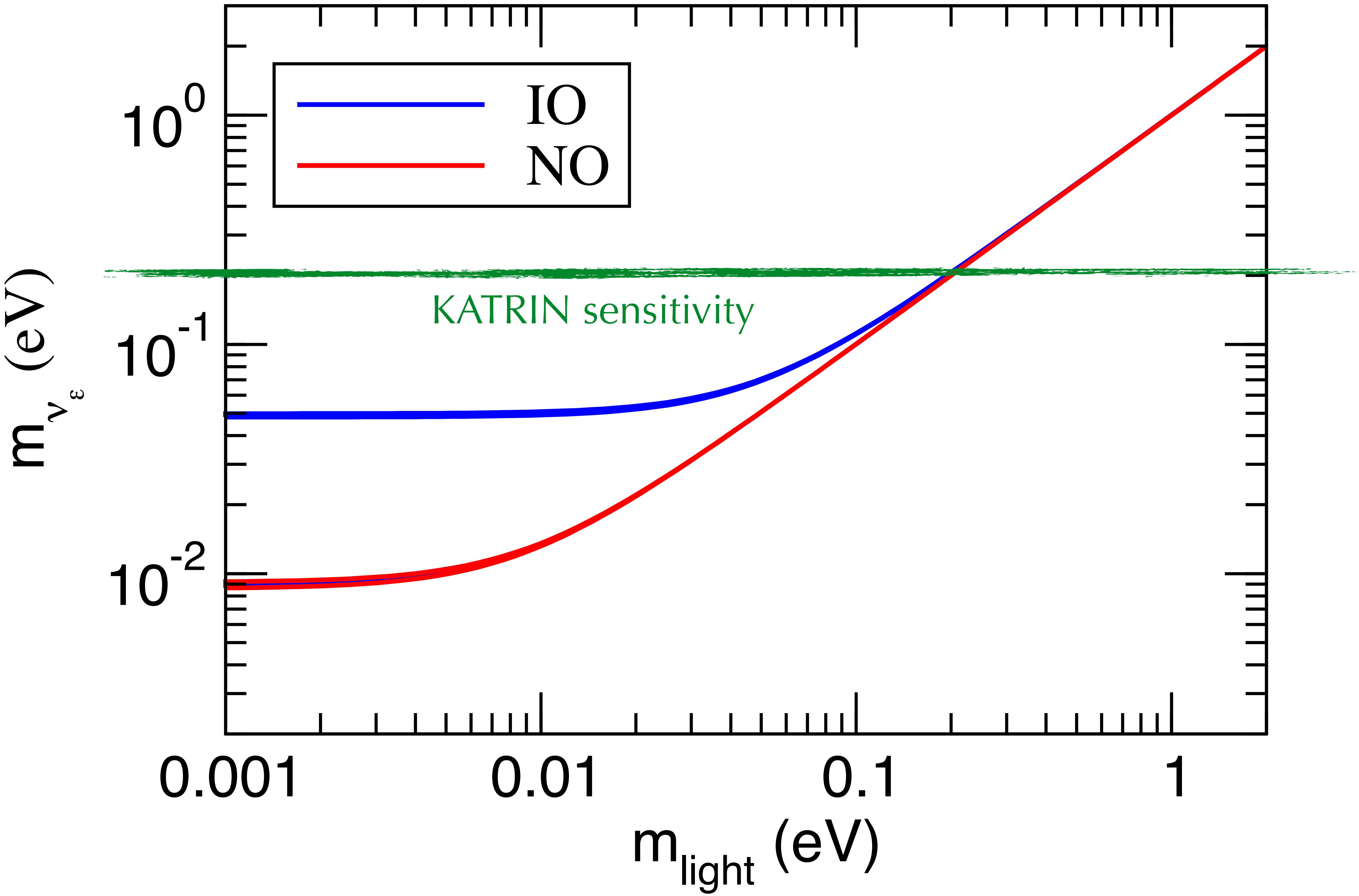
Neutrino Mass Ordering



colours show relative contribution of ν_e, ν_μ and ν_τ

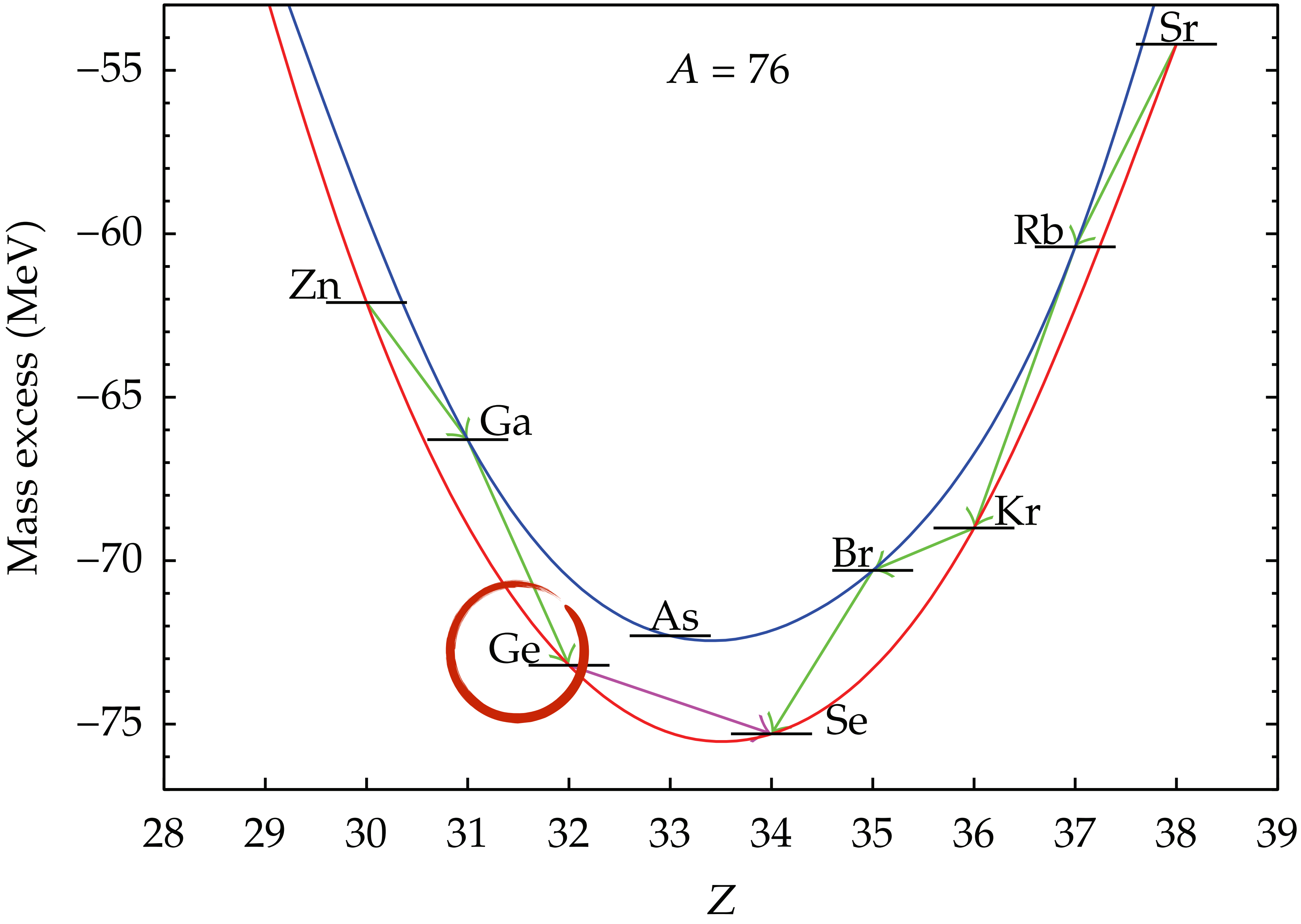
Direct Neutrino Mass Measurement

Effective electron neutrino mass term : $(m_{\nu_e}^{\mathrm{eff}})^2 \equiv \sum |U_{ei}|^2 m_i^2$



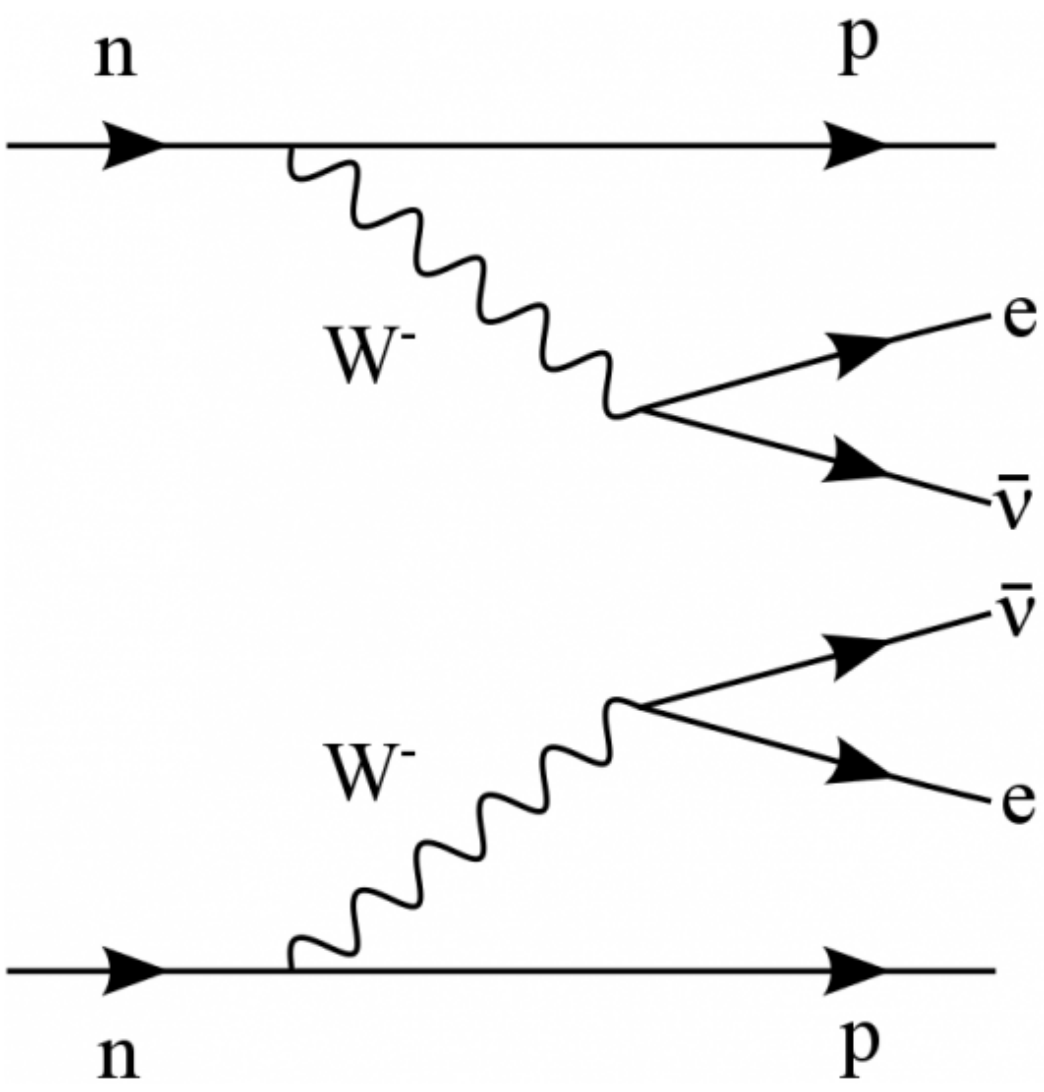
Neutrino-Less Double-Beta Decay

If neutrinos are their own anti-particles **(Majorana fermions)**, they can be detected by double-beta decay experiments.

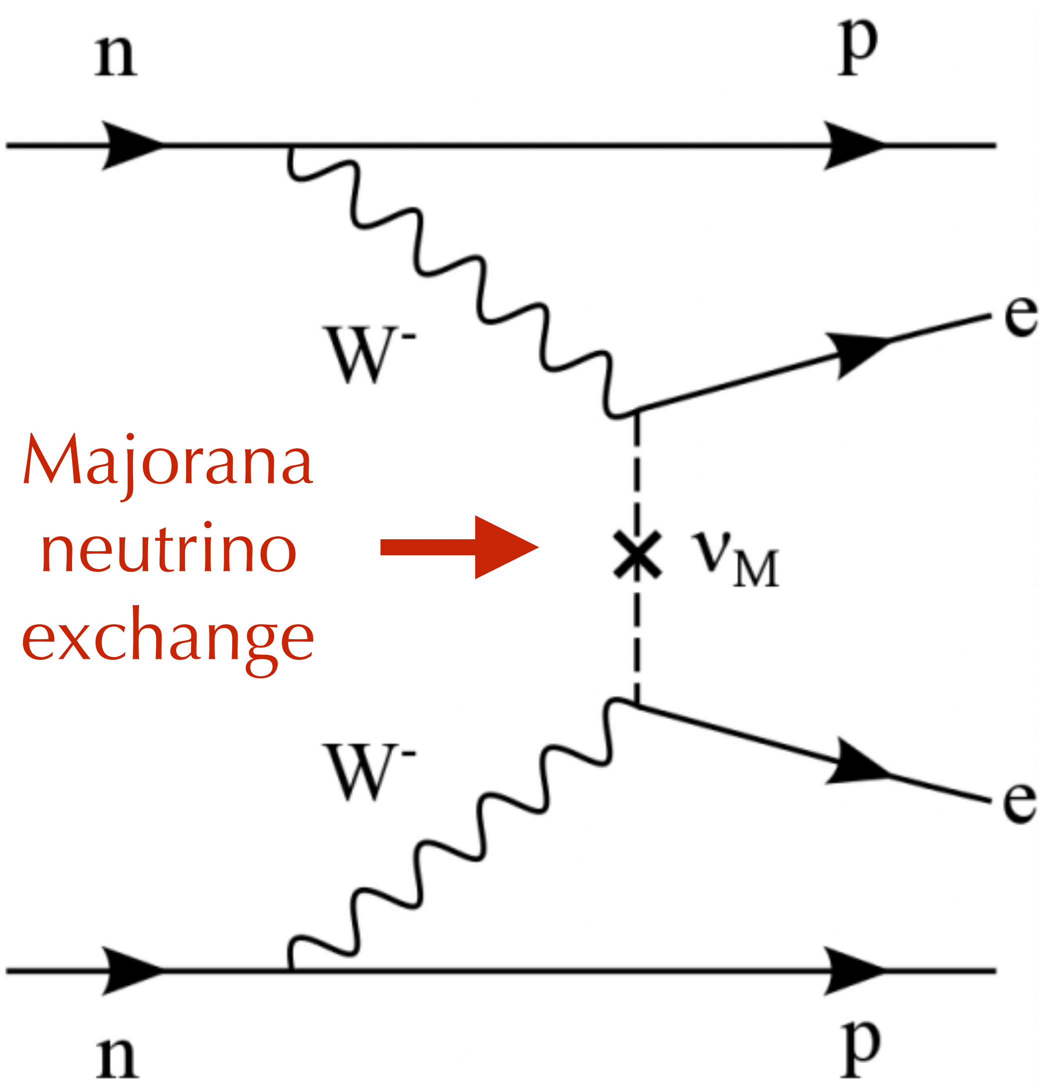


Neutrino-Less Double-Beta Decay

$2\nu\beta\beta$



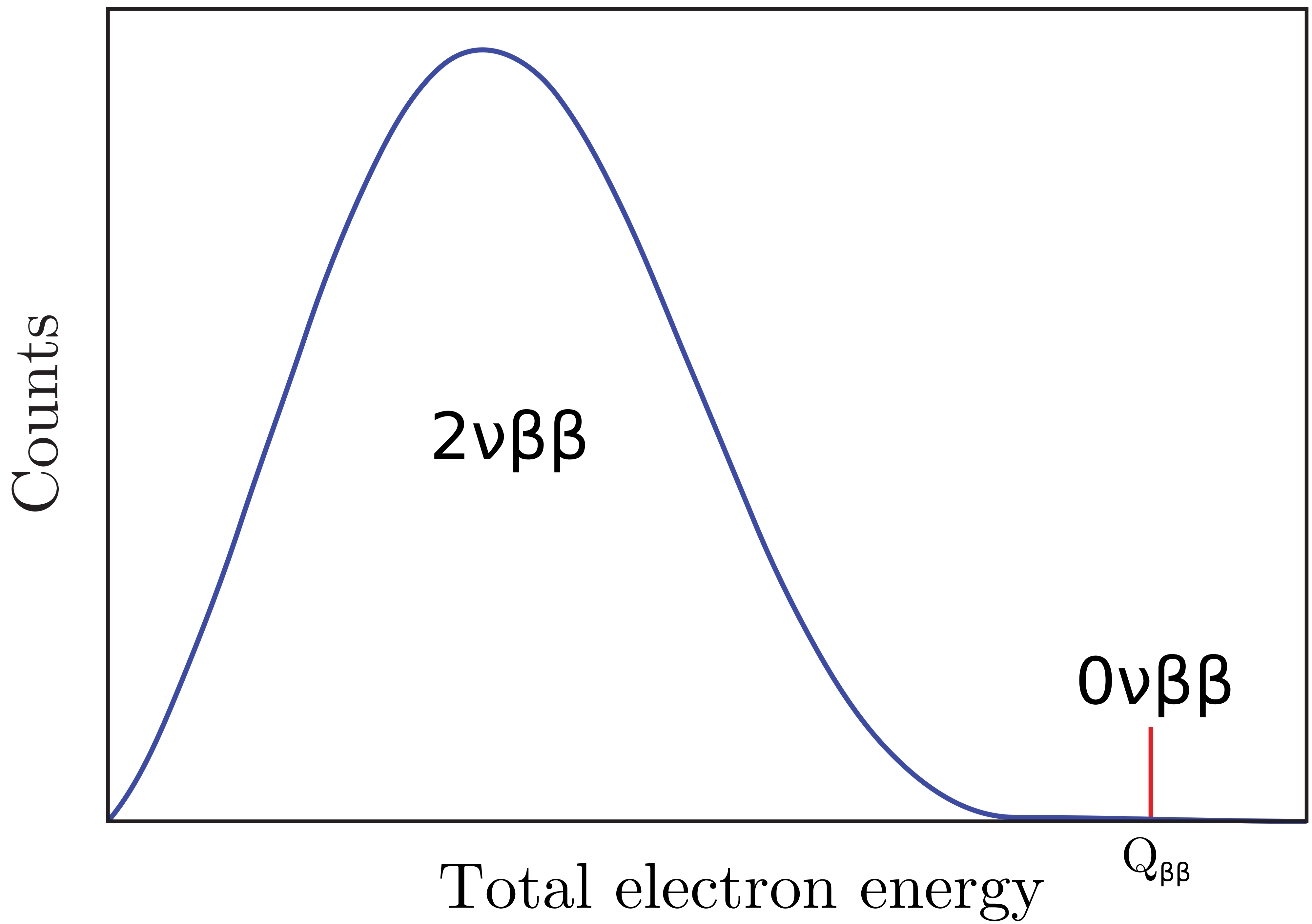
$0\nu\beta\beta$



Majorana neutrino exchange

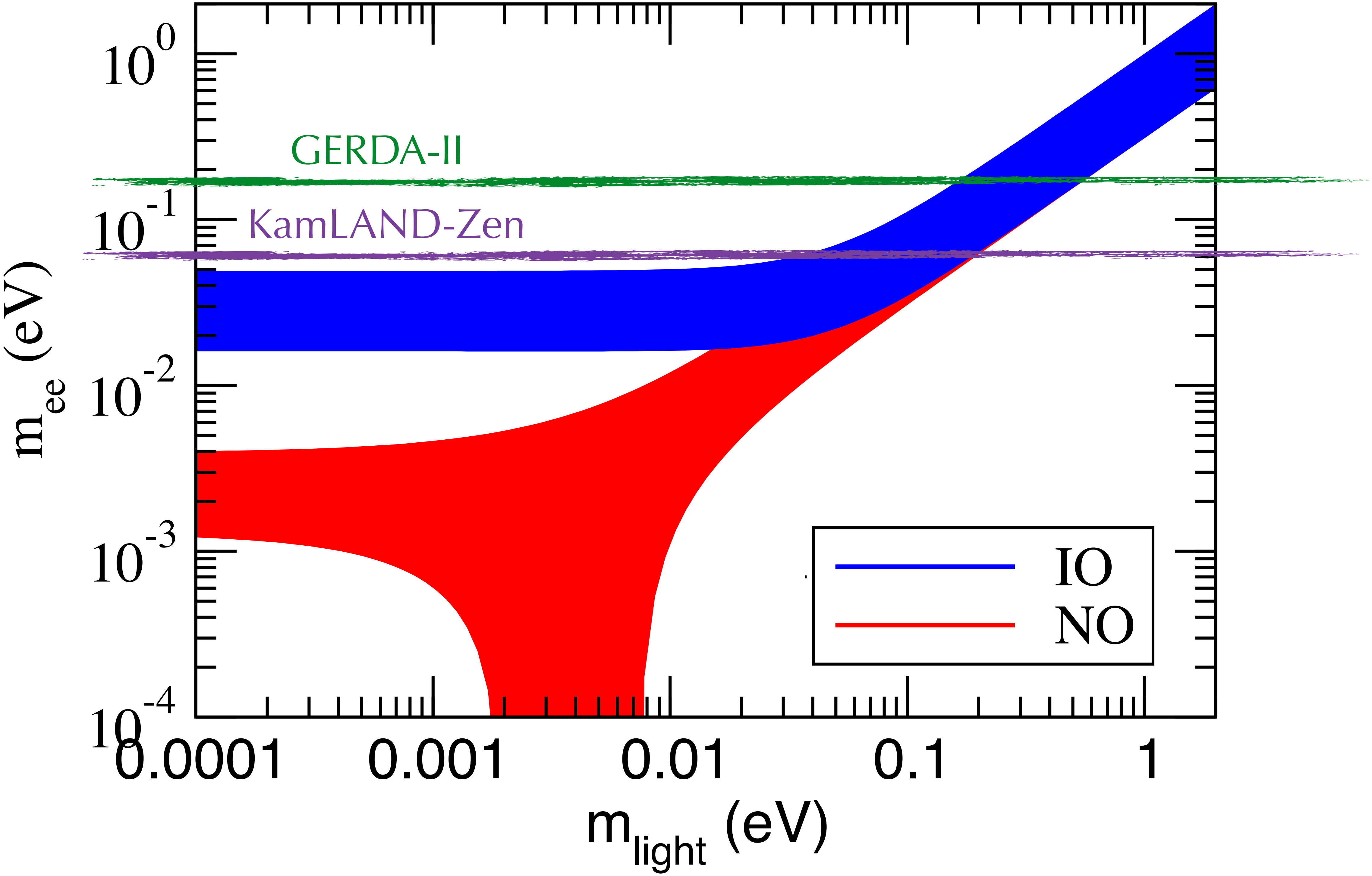
Neutrino-Less Double-Beta Decay

expected electron spectrum with no backgrounds

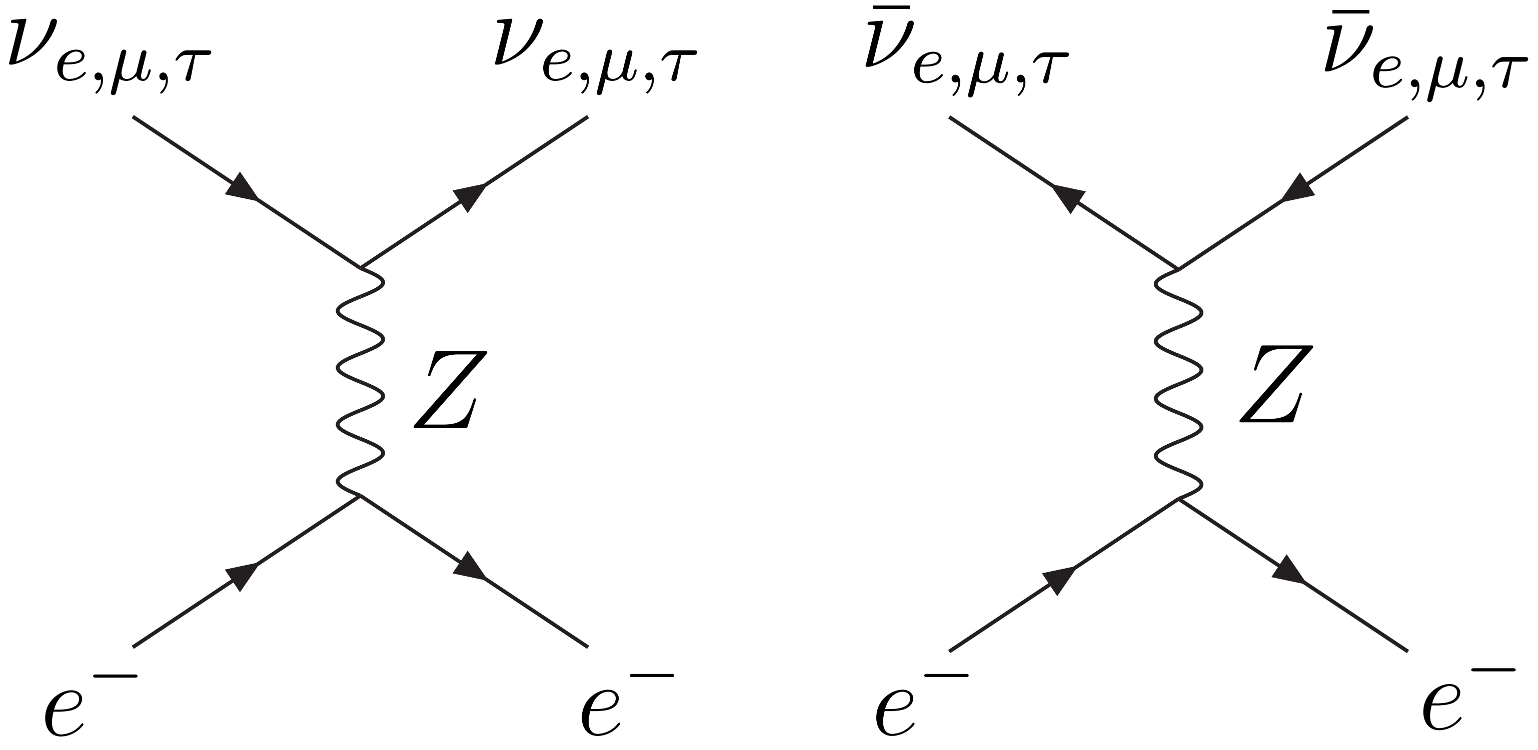


Neutrino-Less Double-Beta Decay

Effective Majorana neutrino mass : $m_{ee} = \left| \sum U_{ei}^2 m_i \right|$

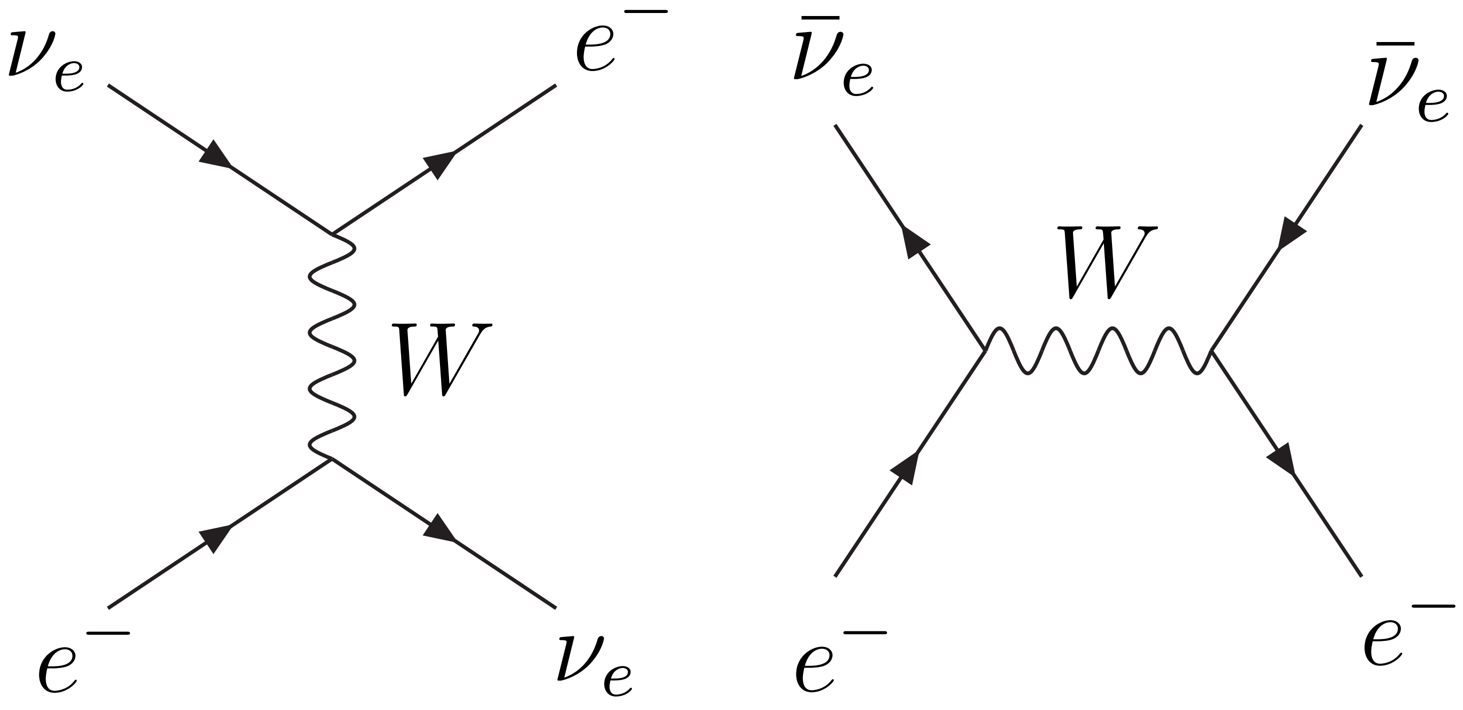


Matter Effects



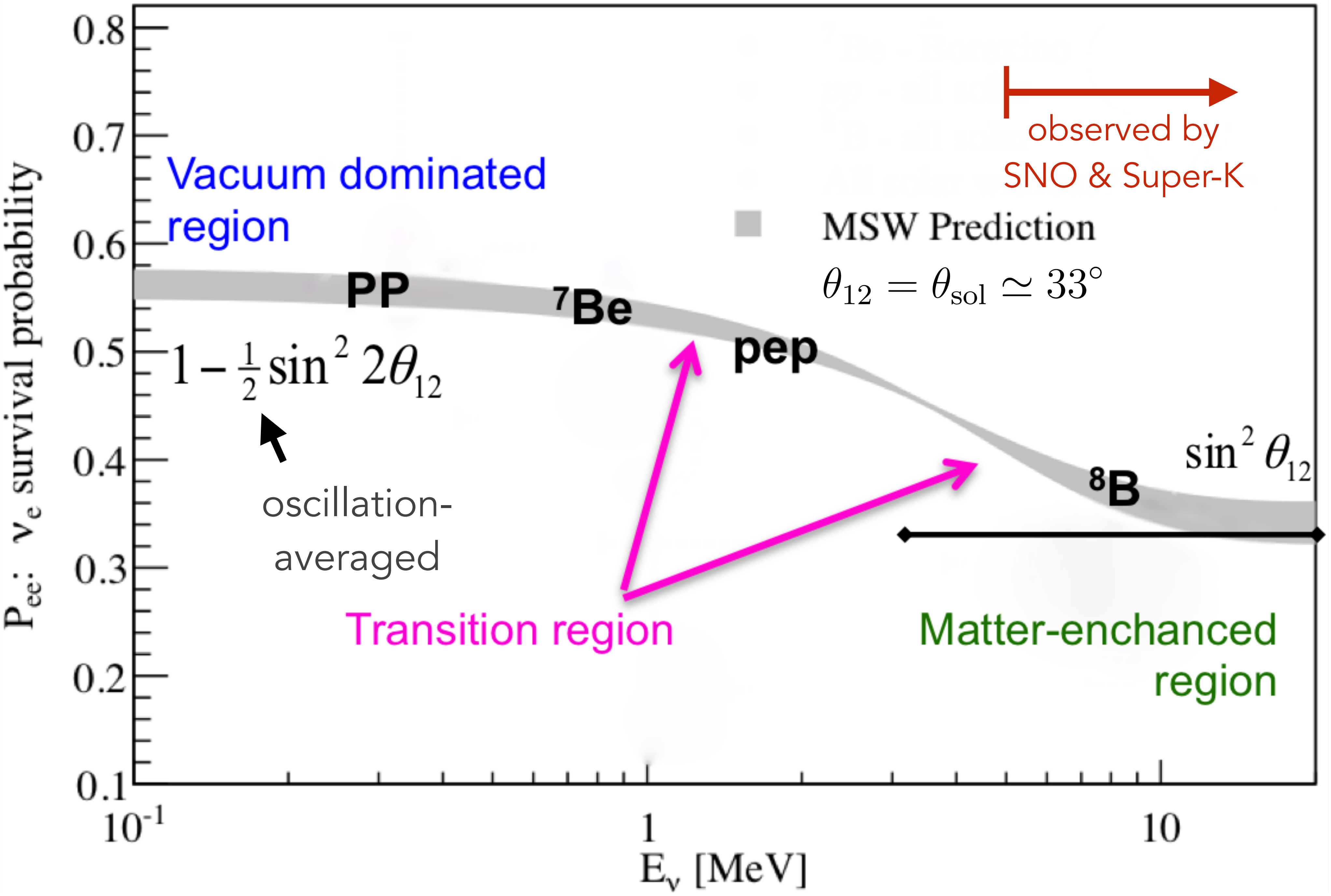
all neutrinos

only electron (anti-)neutrinos

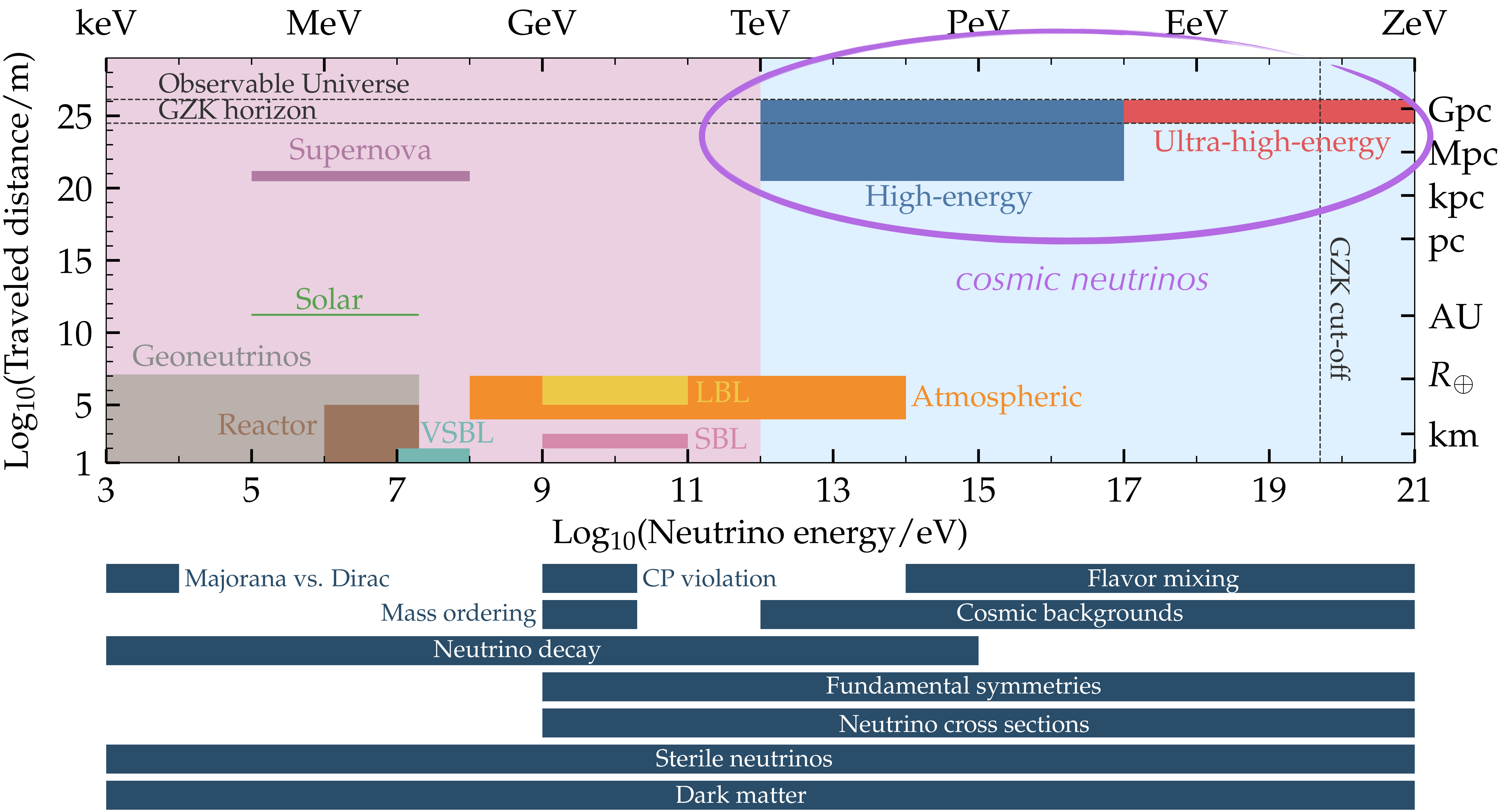


Matter Effects

Matter effects can introduce a strong **energy** and **time/length dependence** in the neutrino flavour transition.



Probe of Fundamental Physics



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

Pion Production Efficiency

- pion production depend on target opacity $\tau = \ell\sigma n$
- "bolometric" pion production efficiency (inelasticity κ):

$$f_\pi = 1 - \exp(-\kappa\tau)$$

- inelasticity per pion : $\kappa_\pi = \kappa / \langle N_{\text{all }\pi}\rangle \simeq 0.17 - 0.2$
- "bolometric" relation of the production rates Q:

$$E_\pi^2 Q_{\pi^\pm}(E_\pi) \simeq \frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle + \langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle} \left[f_\pi E_N^2 Q_N(E_N)\right]_{E_N = E_\pi/\kappa_\pi}$$

- charged-to-neutral pion ratio:

$$K_\pi \equiv \frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle} \simeq \begin{cases} 2 & pp \quad \text{(CR-gas collision)} \\ 1 & p\gamma \quad \text{(CR-photon collision)} \end{cases}$$

- or in more compact form with K_π:

$$E_\pi^2 Q_{\pi^\pm}(E_\pi) \simeq f_\pi \frac{K_\pi}{1 + K_\pi} \left[E_N^2 Q_N(E_N)\right]_{E_N = E_\pi/\kappa_\pi}$$

Neutrino and Gamma-Ray Emission

- neutrino emission from charged pion decay

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

$$\frac{1}{3}\sum_\alpha E_\nu Q_{\nu_\alpha}(E_\nu) \simeq \left[E_\pi Q_{\pi^\pm}(E_\pi)\right]_{E_\pi \simeq 4E_\nu}$$

- γ-ray emission from neutral pion decay

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

$$\frac{1}{2}E_\gamma Q_\gamma(E_\nu) \simeq \left[E_\pi Q_{\pi^0}(E_\pi)\right]_{E_\pi \simeq 2E_\gamma}$$

- neutrino and γ-ray emission are related as

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{4}\underbrace{\frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle}}_{K_\pi \simeq 1-2}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

- γ-ray emission is attenuated in sources and, in particular, in the extragalactic radiation background