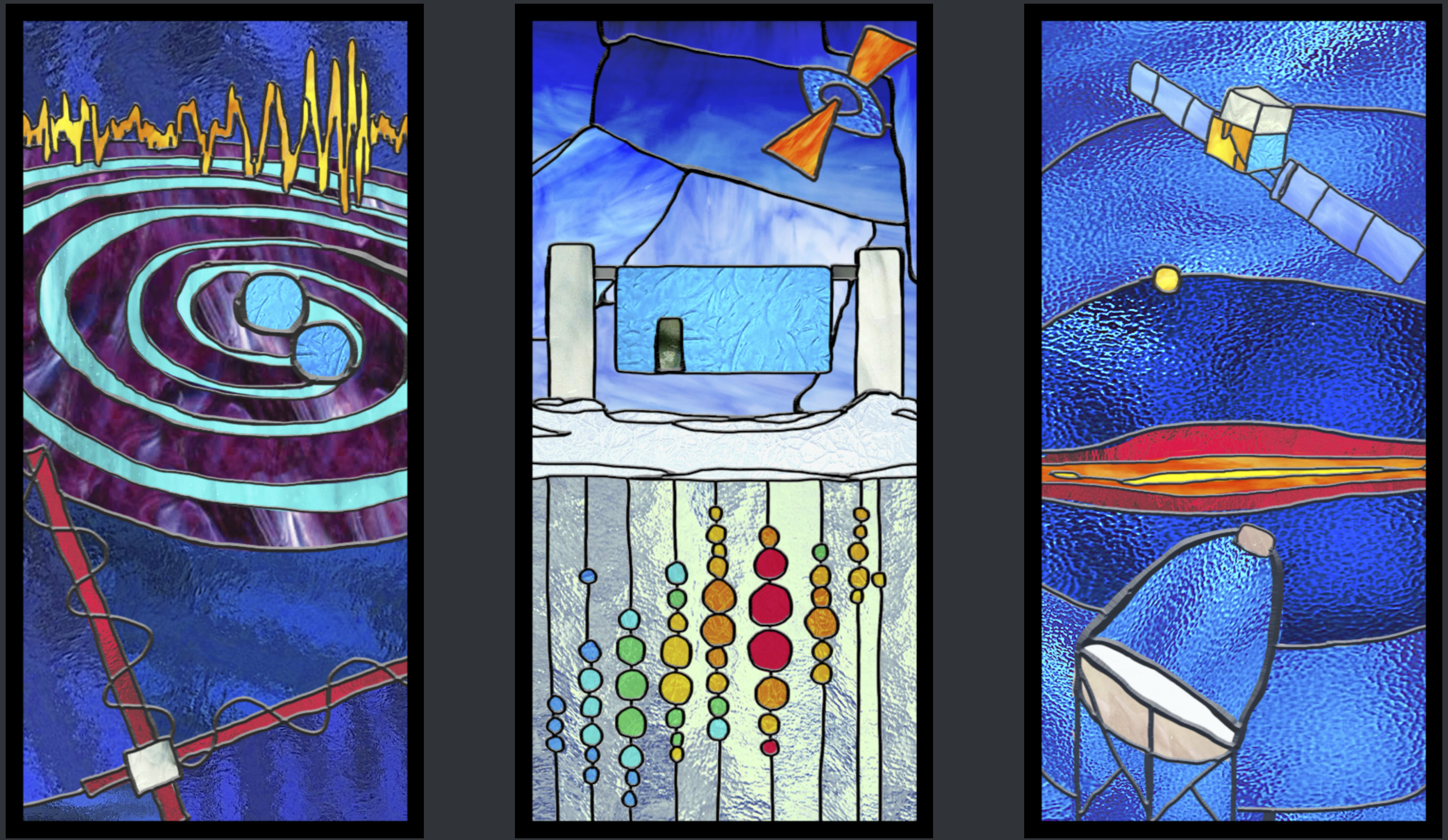


The UHE Universe in the Multimessenger Paradigm

- Lessons from Neutrinos -

Markus Ahlers

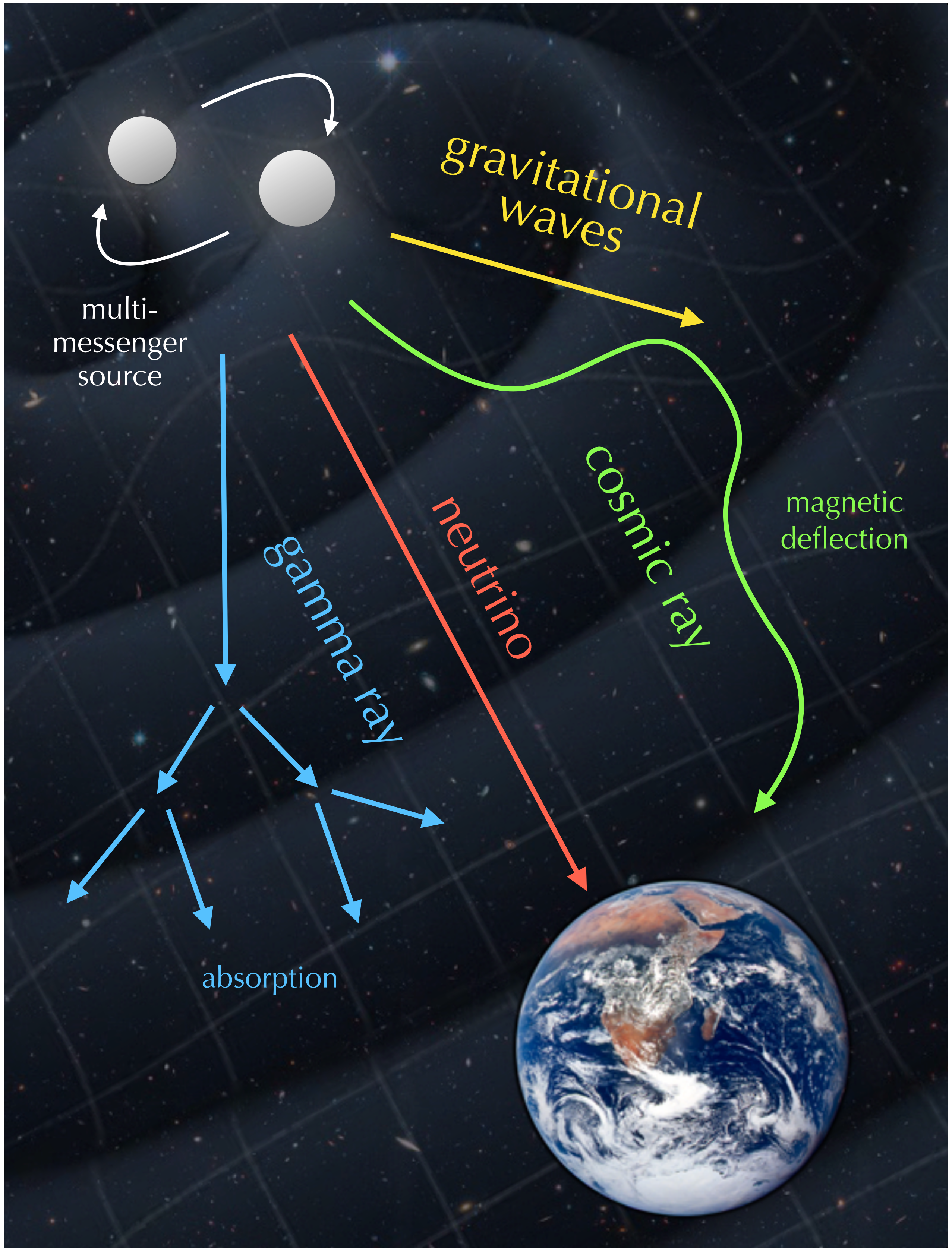
Niels Bohr Institute

GCOS Workshop, May 20, 2021

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields (unlike cosmic rays)

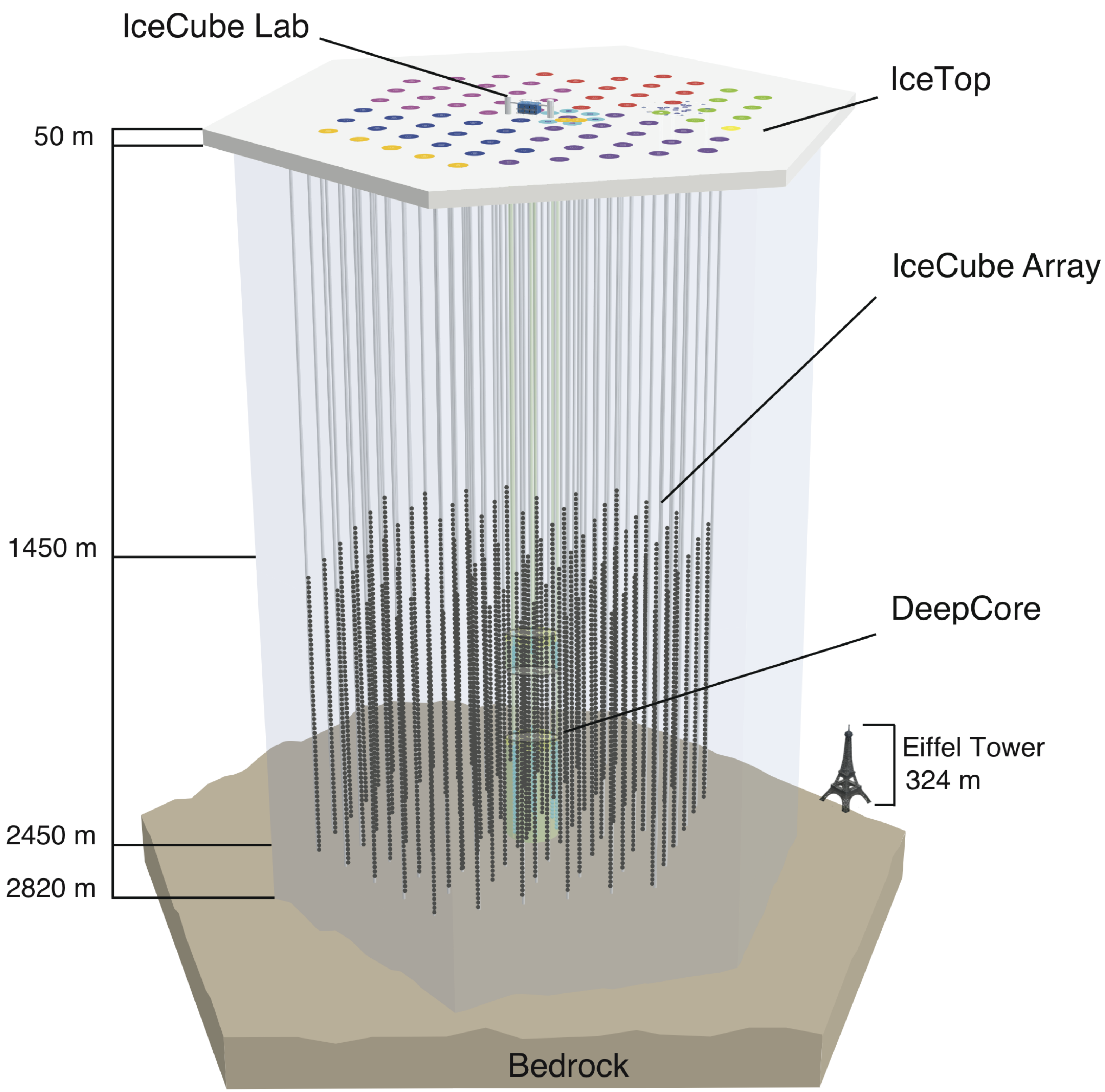
coincident with photons and gravitational waves

no absorption in cosmic backgrounds (unlike gamma-rays)

smoking-gun of unknown sources of cosmic rays

BUT, very difficult to detect!

IceCube Observatory

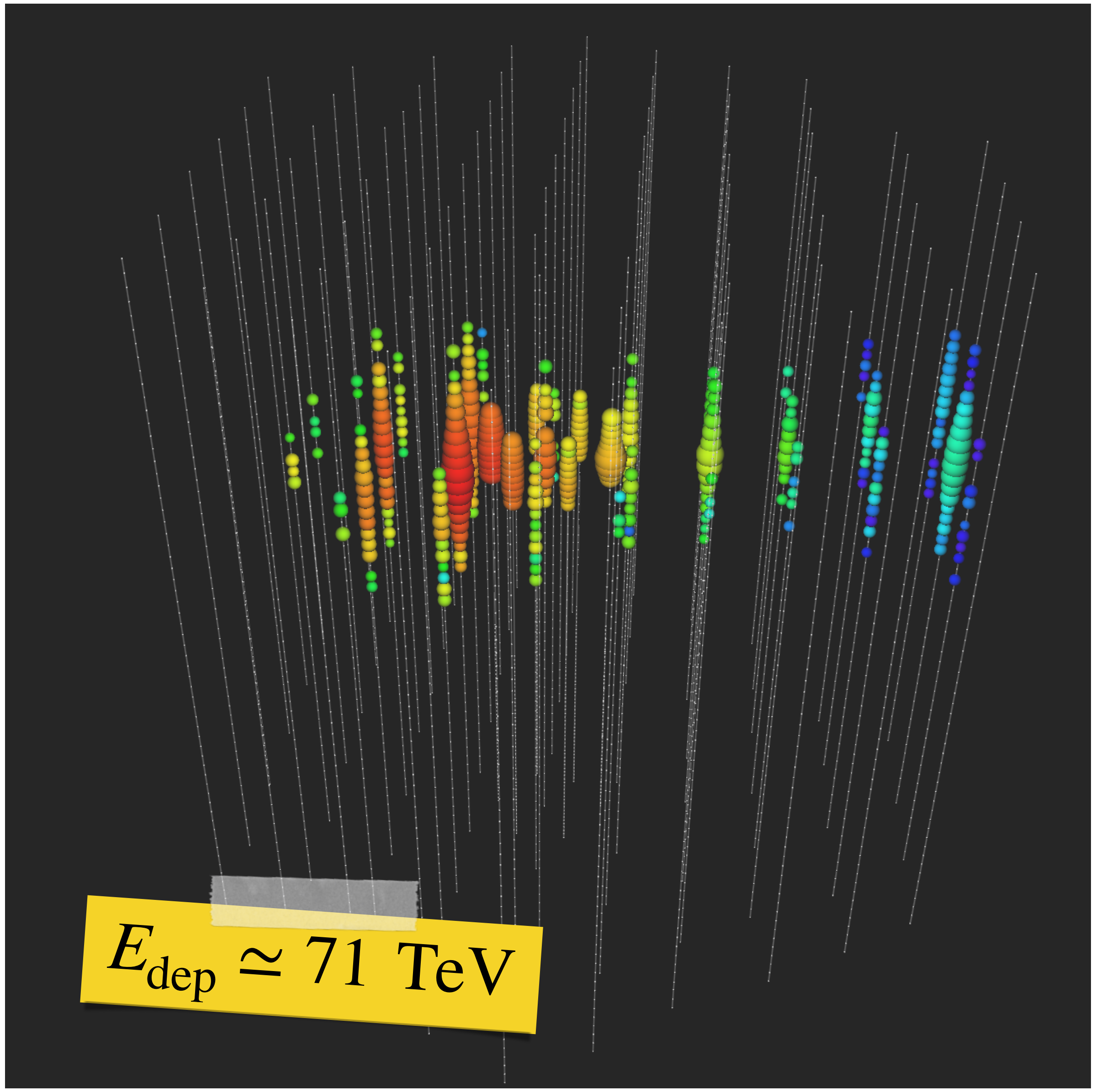


- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

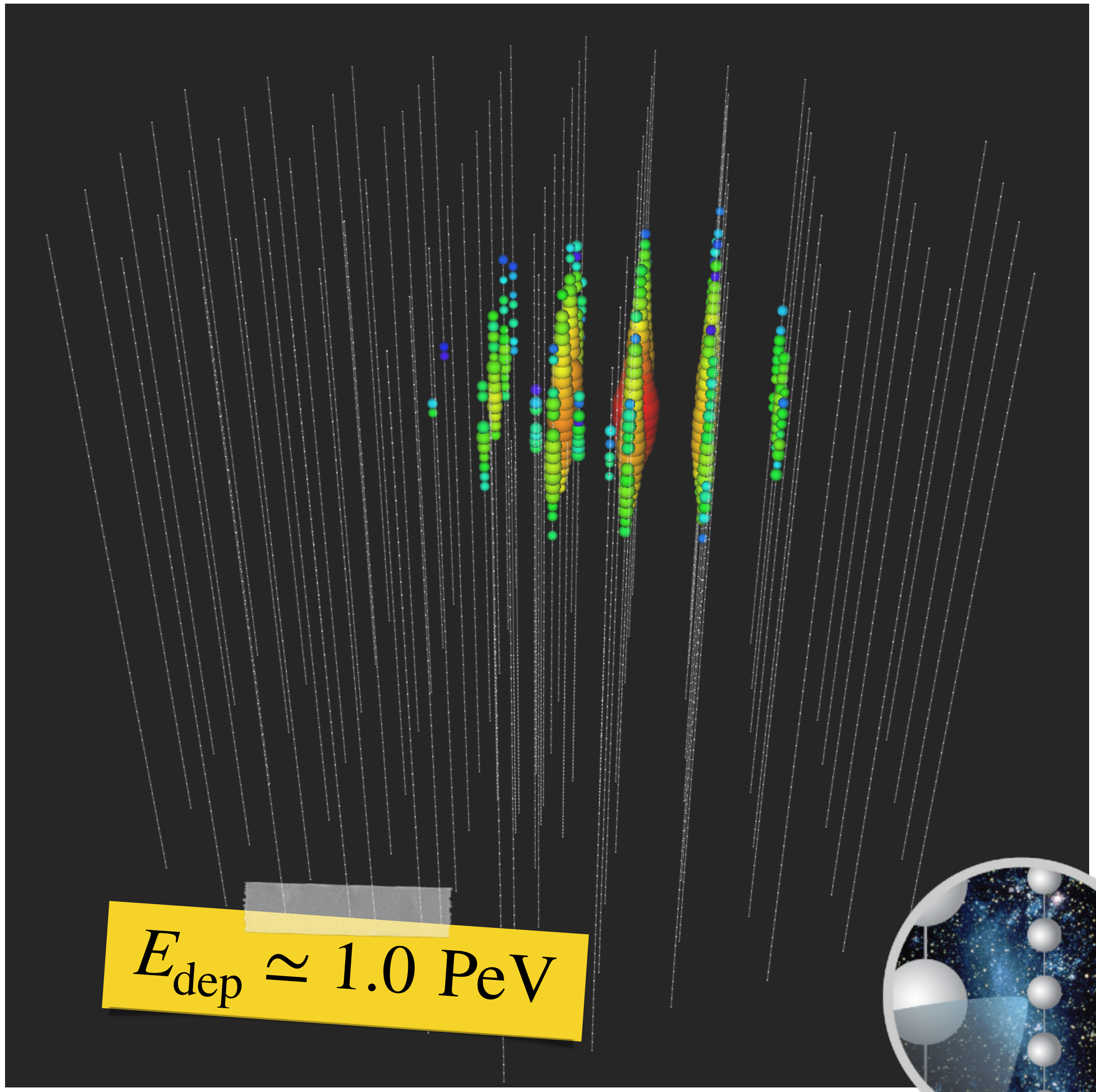
High-Energy Neutrinos

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

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



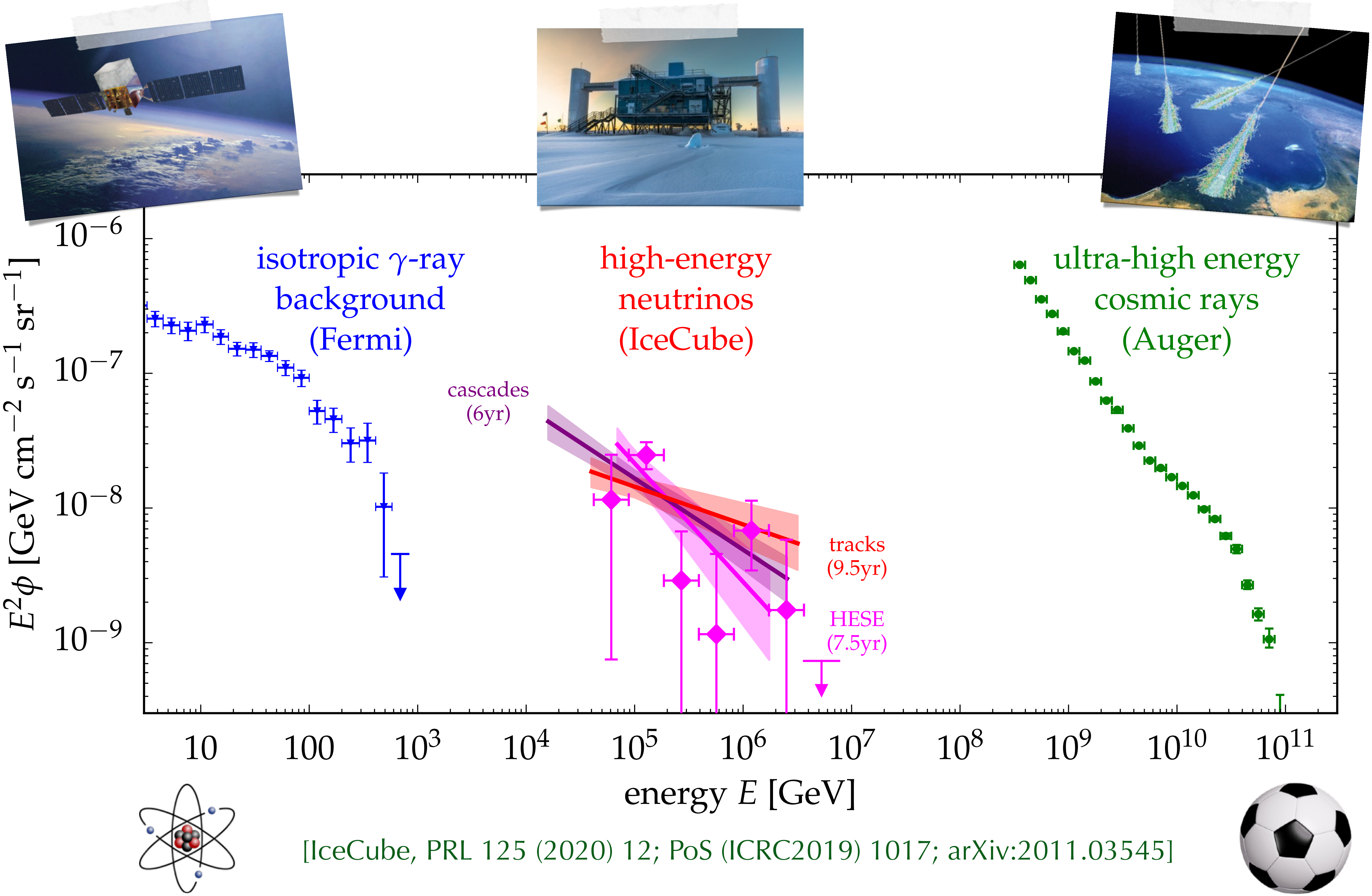
"cascade event" (e.g. NC interactions)



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

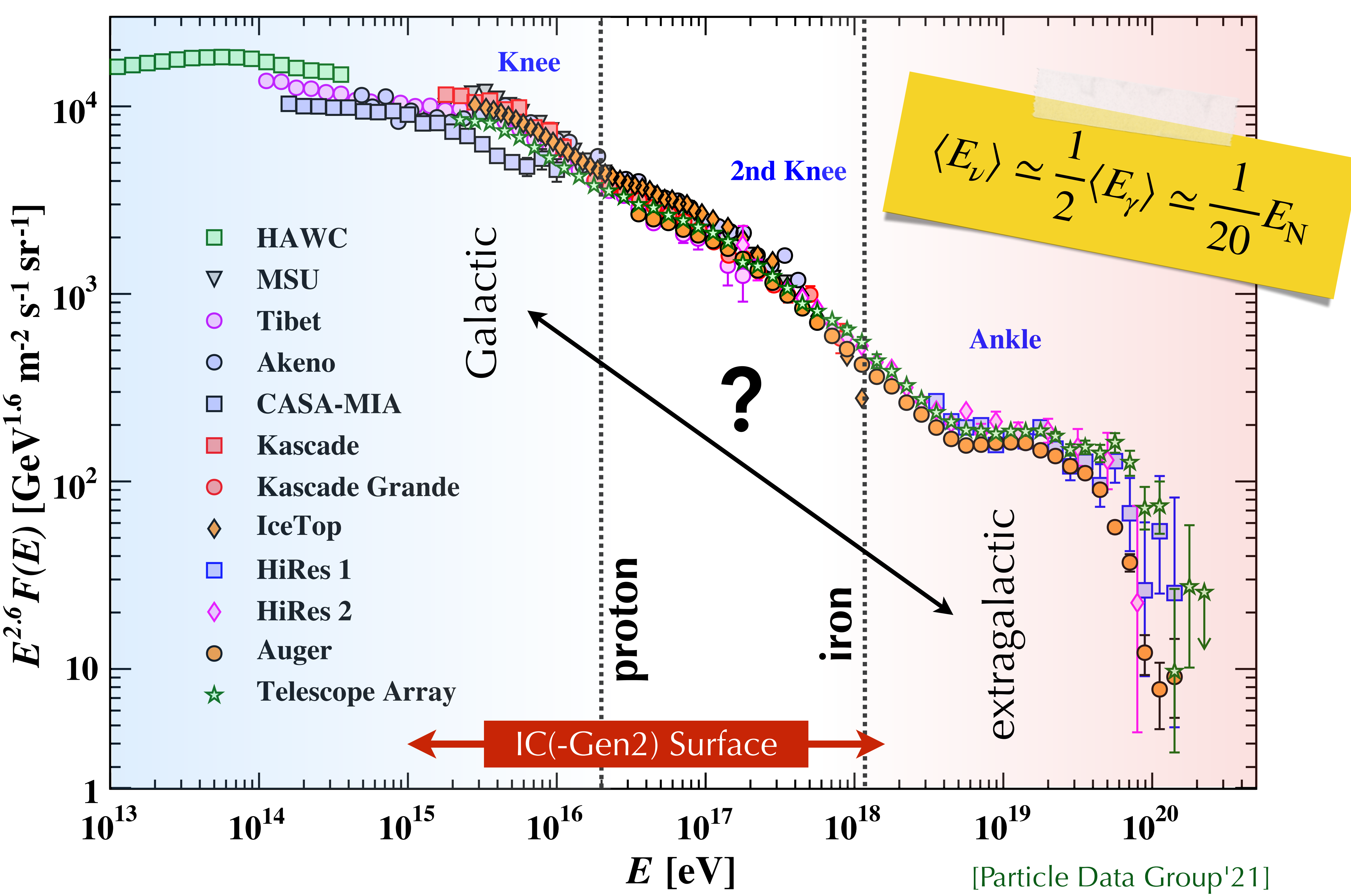
ICECUBE

Diffuse TeV-PeV Neutrinos

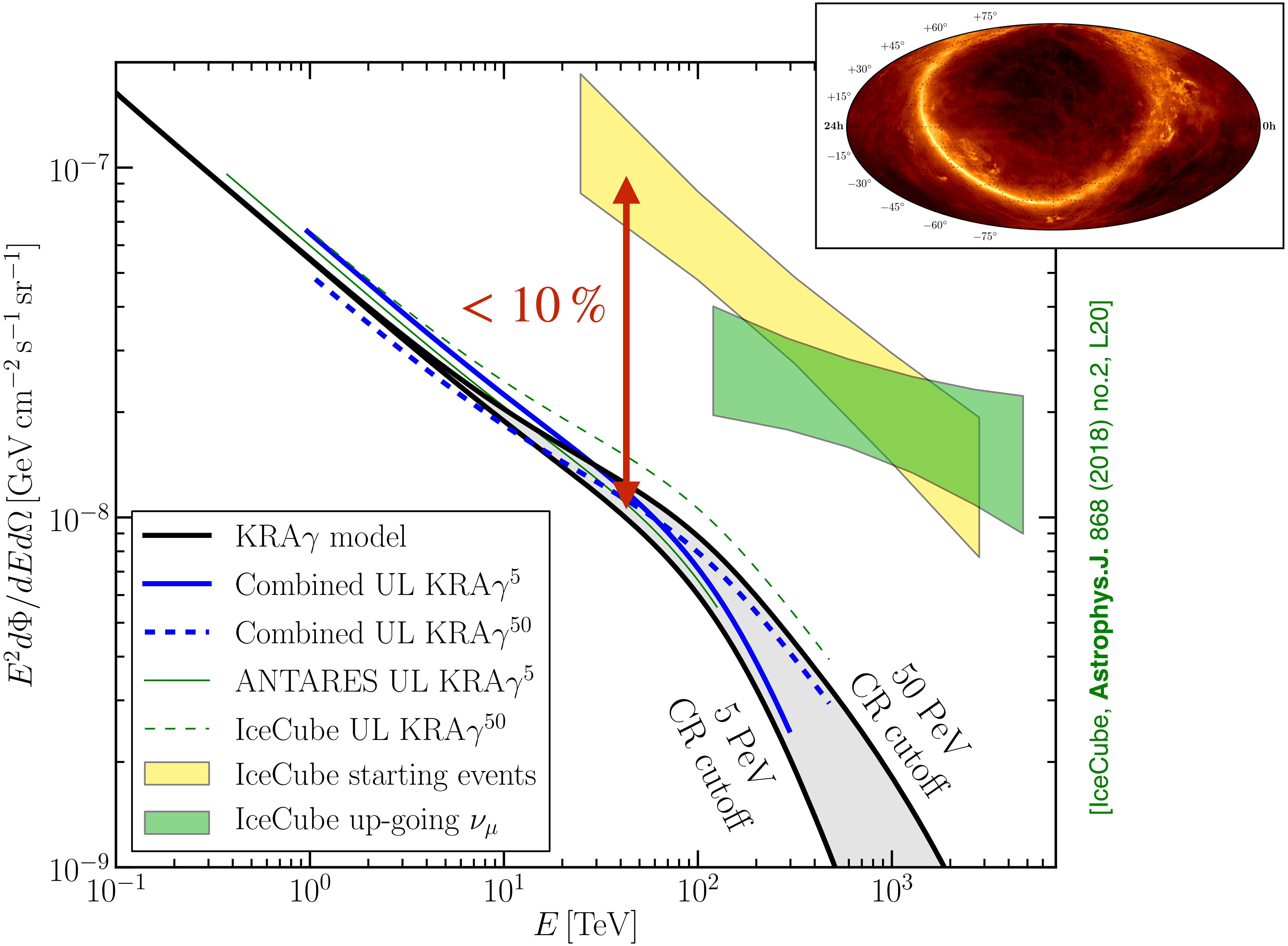


[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Very-High Energy Cosmic Rays



[Particle Data Group'21]

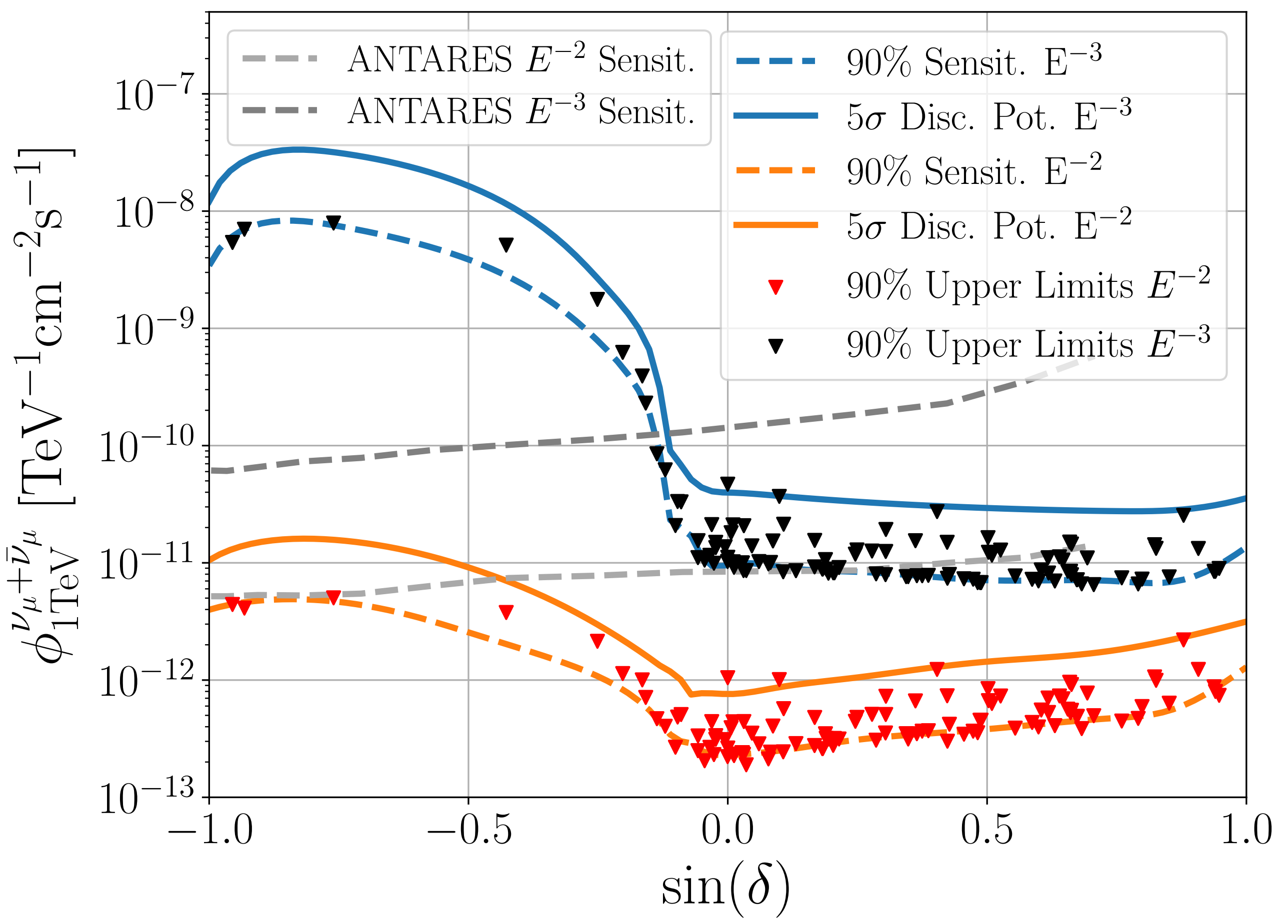


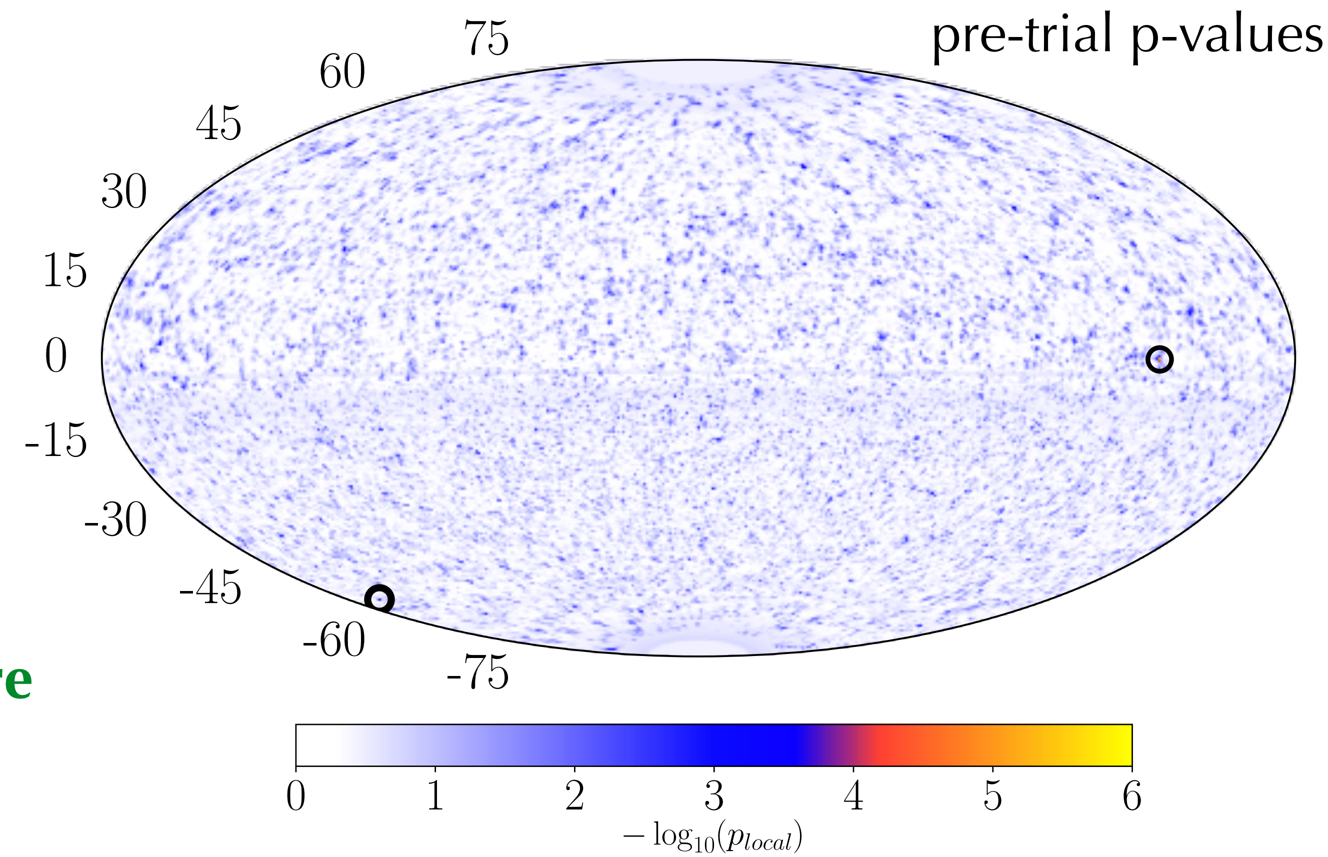
Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

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.

Point Source vs. Diffuse Flux

Populations of extragalactic neutrino sources can be visible

individual sources

or by the

combined isotropic emission.

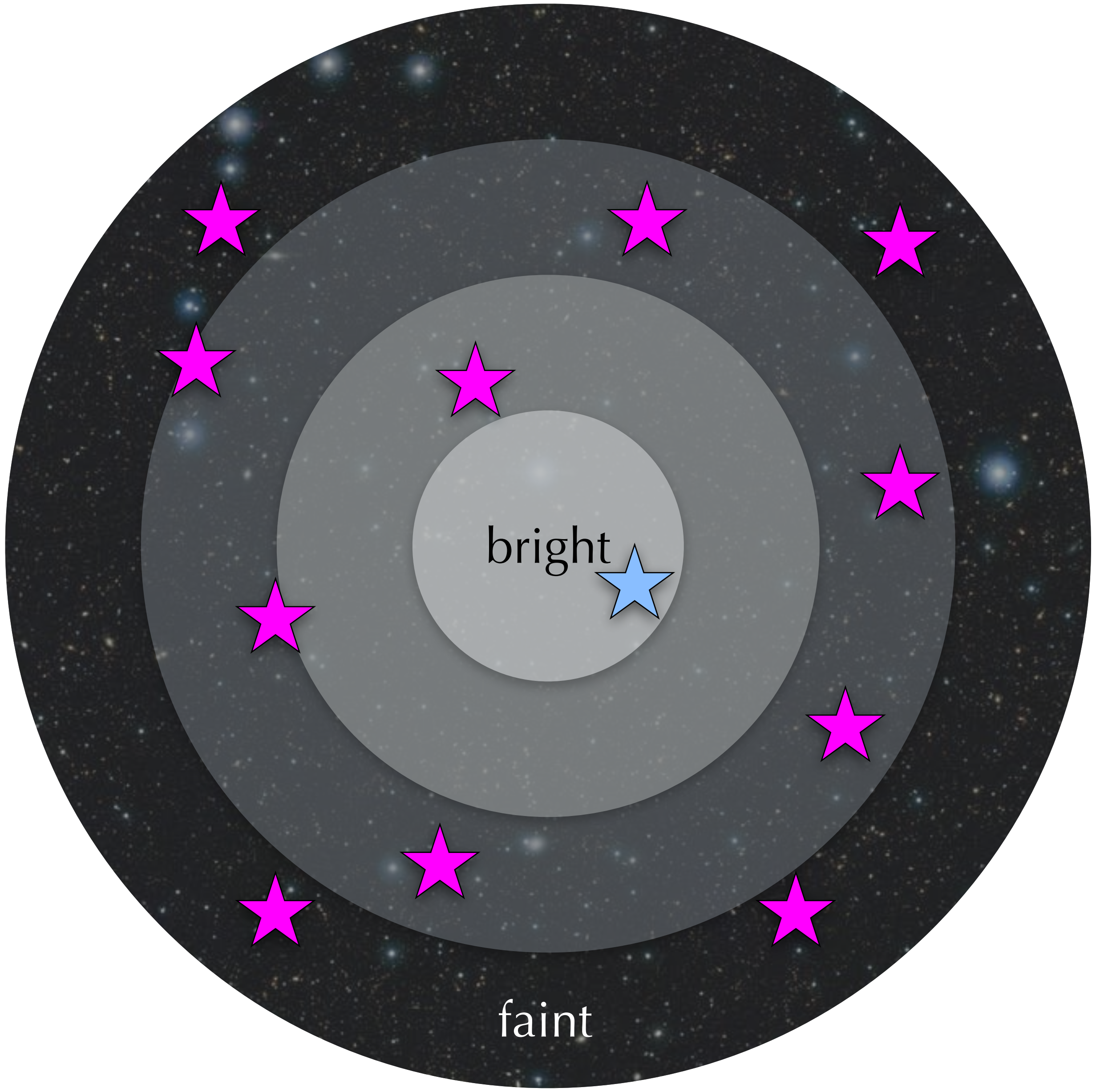
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

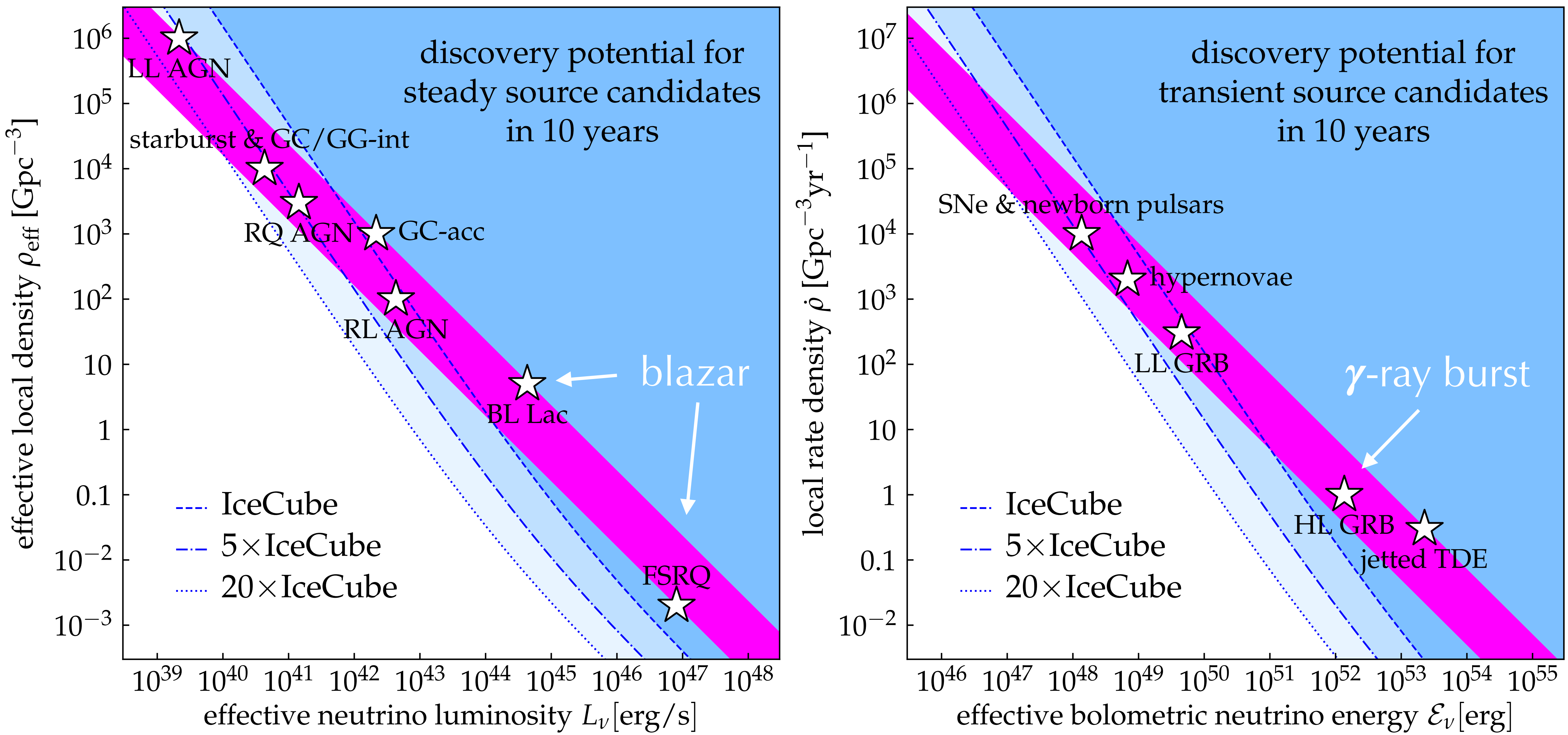
source luminosity.

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



Hubble horizon

Point Source vs. Diffuse Flux



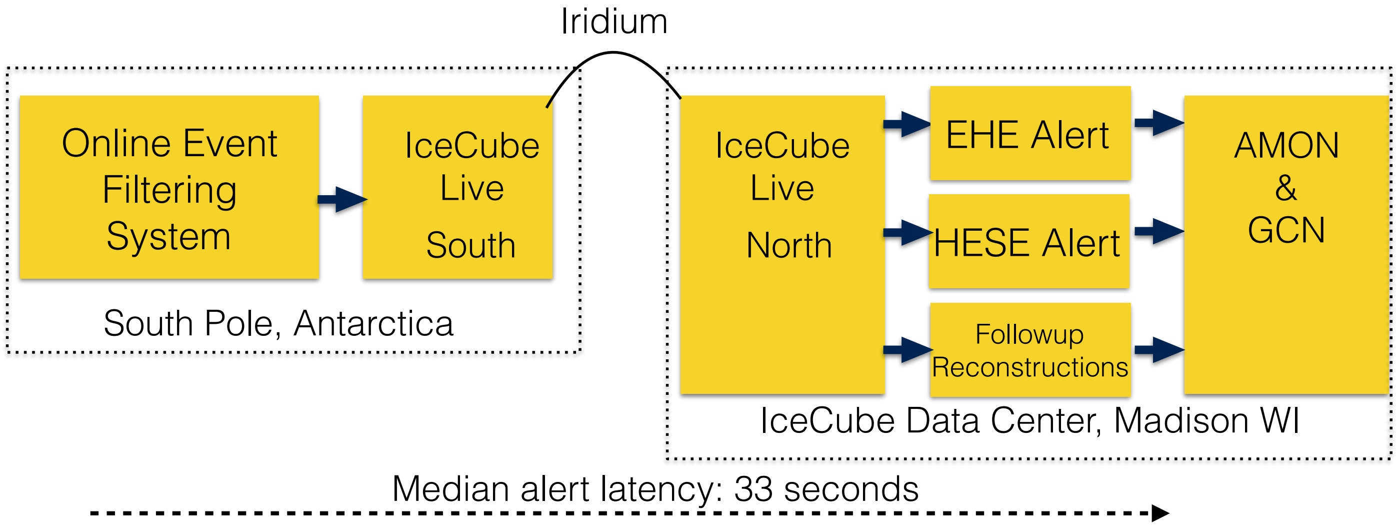
[Murase & Waxman'16; Ackermann *et al.*'19]

- Rare sources, like blazars or GRBs, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).
- Consistent with results of IceCube analyses of GRBs and Fermi-LAT blazars.

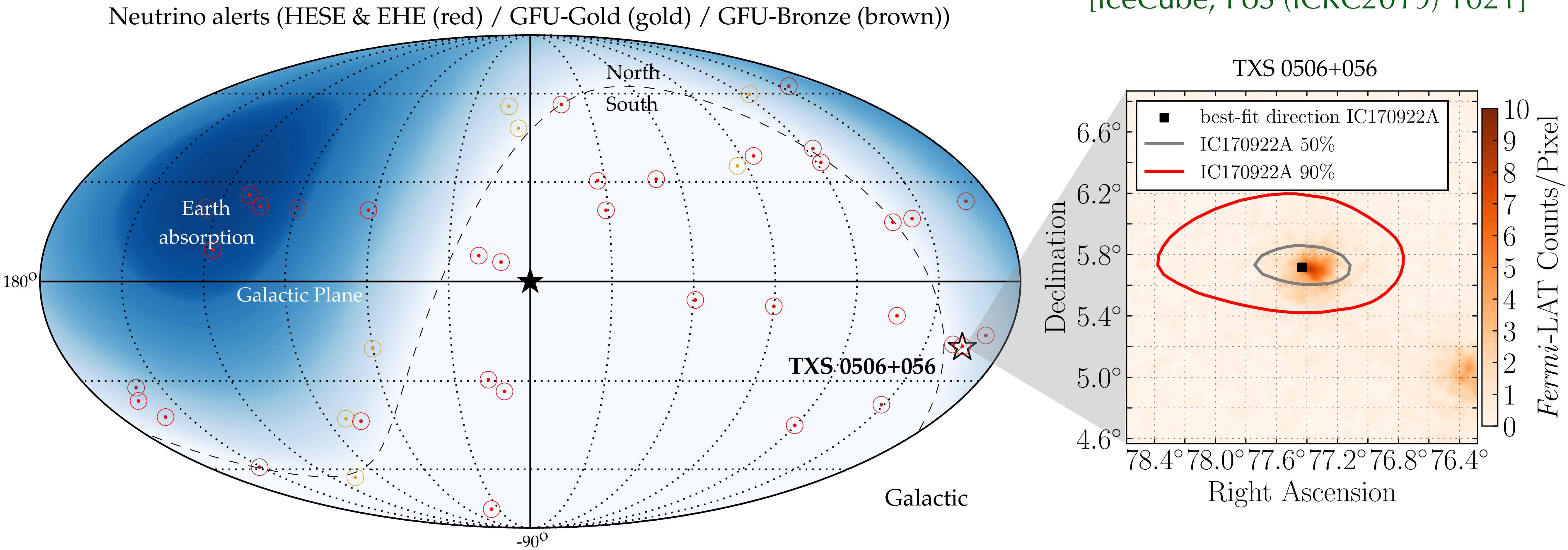
[IceCube, ApJ 835 (2017) 45; ApJ 843 (2017) 2]

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

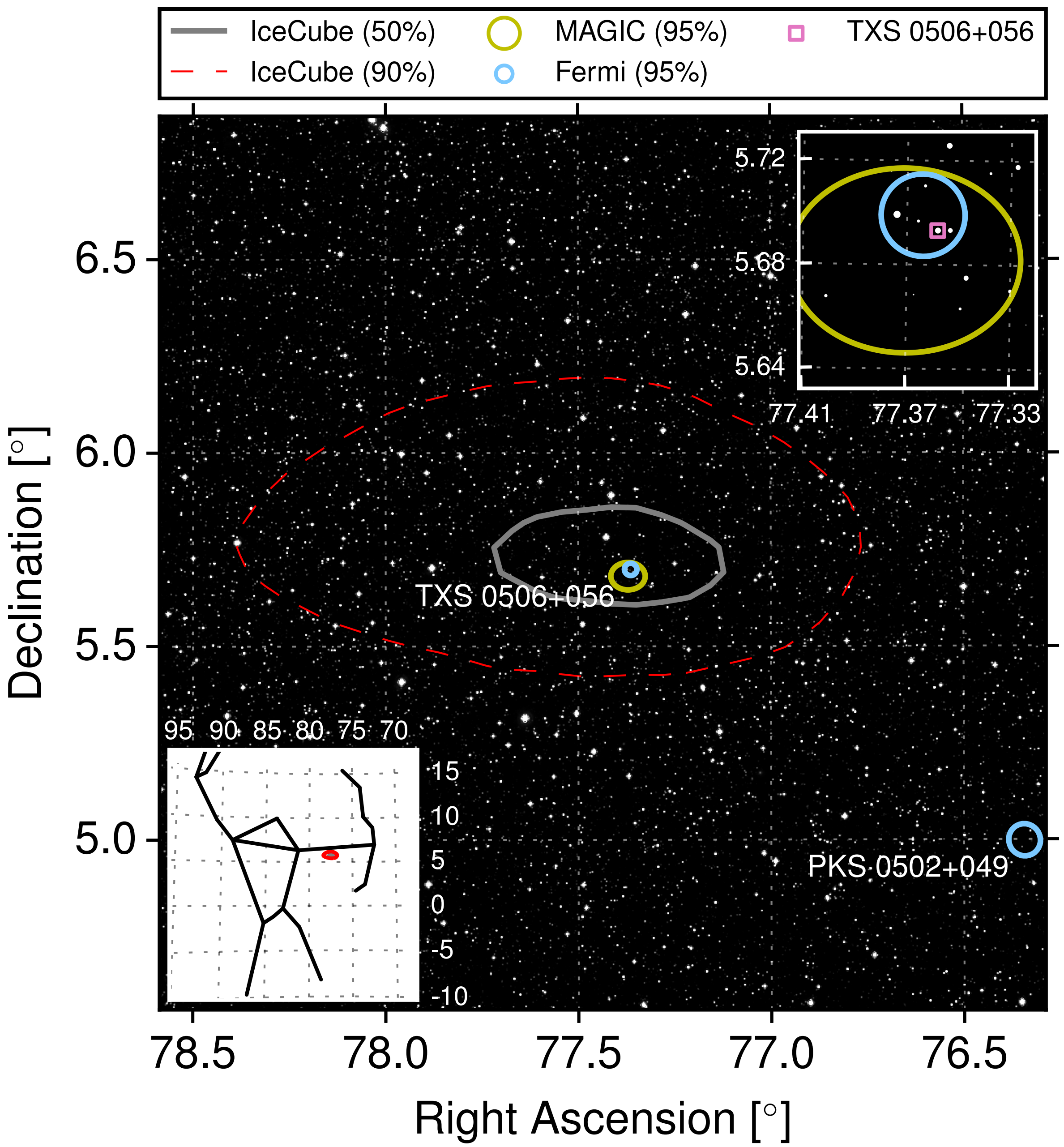
- **Gold alerts:** ~10 per year
  >50% signalness
- **Bronze alerts:** ~20 per year
  30-50% signalness



[IceCube, PoS (ICRC2019) 1021]



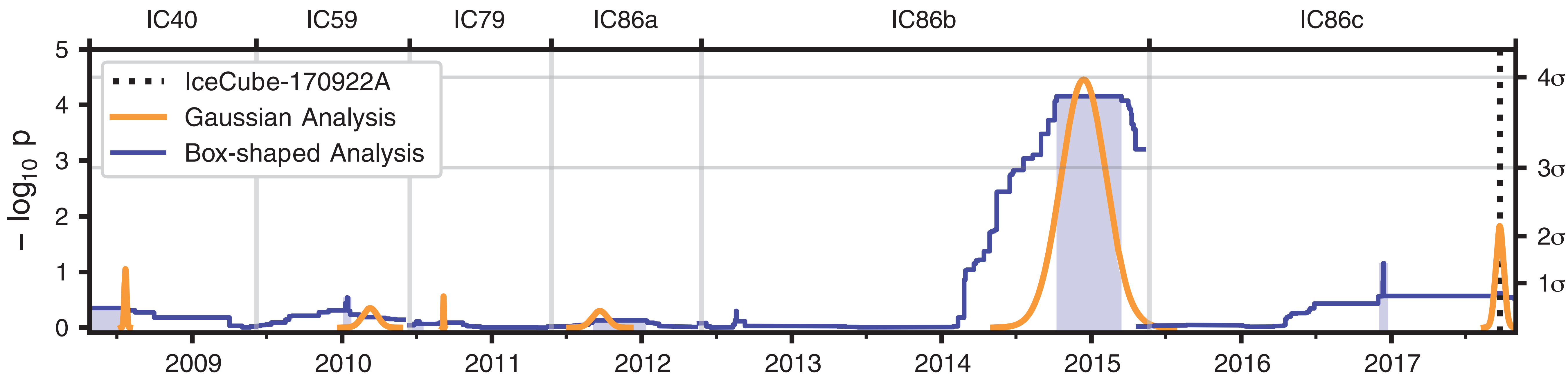
TXS 0506+056



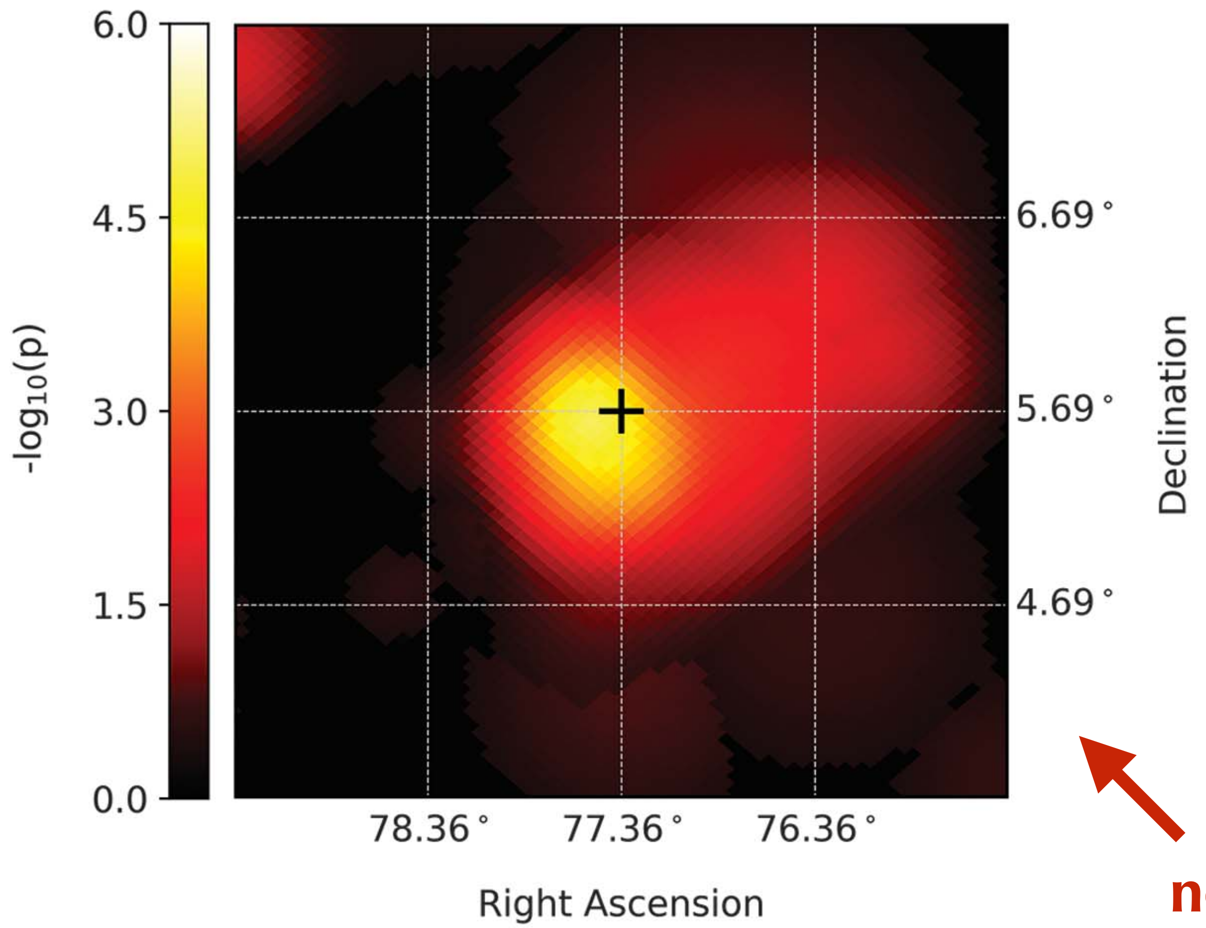
[IceCube++, Science 361 (2018) 6398]

- 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

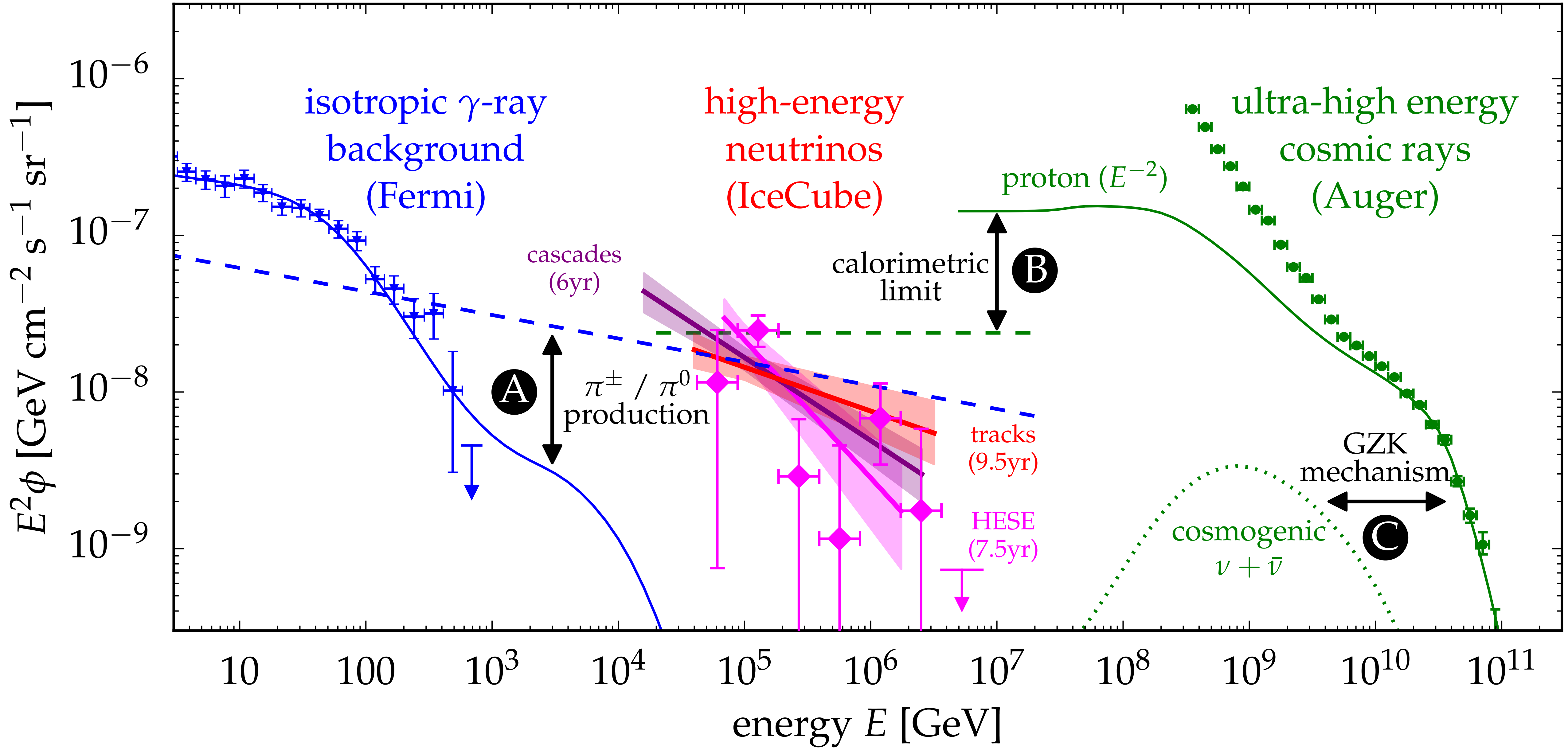


[IceCube, Science 361 (2018) 6398]



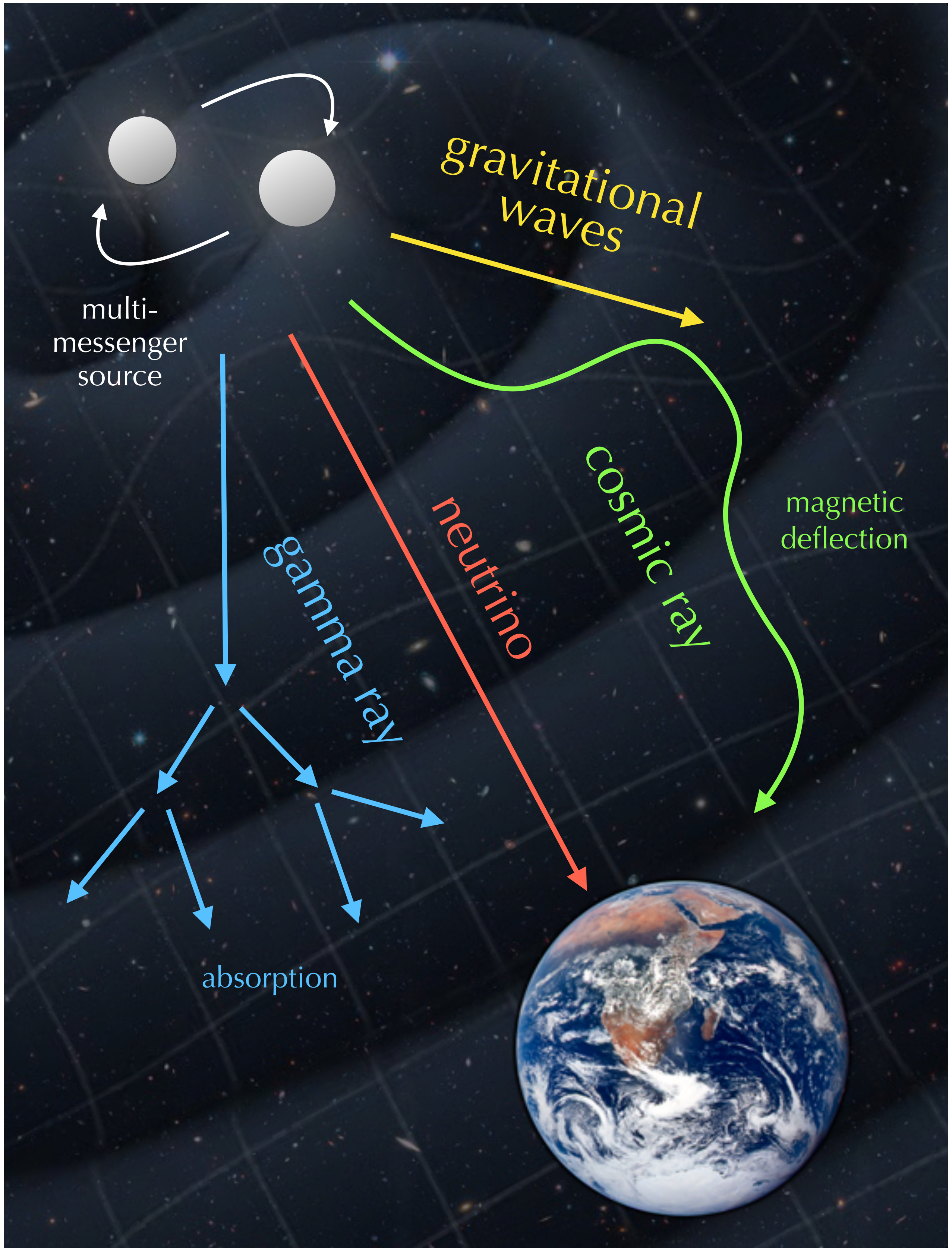
- Independent 3.5σ evidence for a **neutrino flare** (13±5 excess events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of Fermi-LAT γ-rays**.

neutrino "morphology" of 2014/15 flare



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

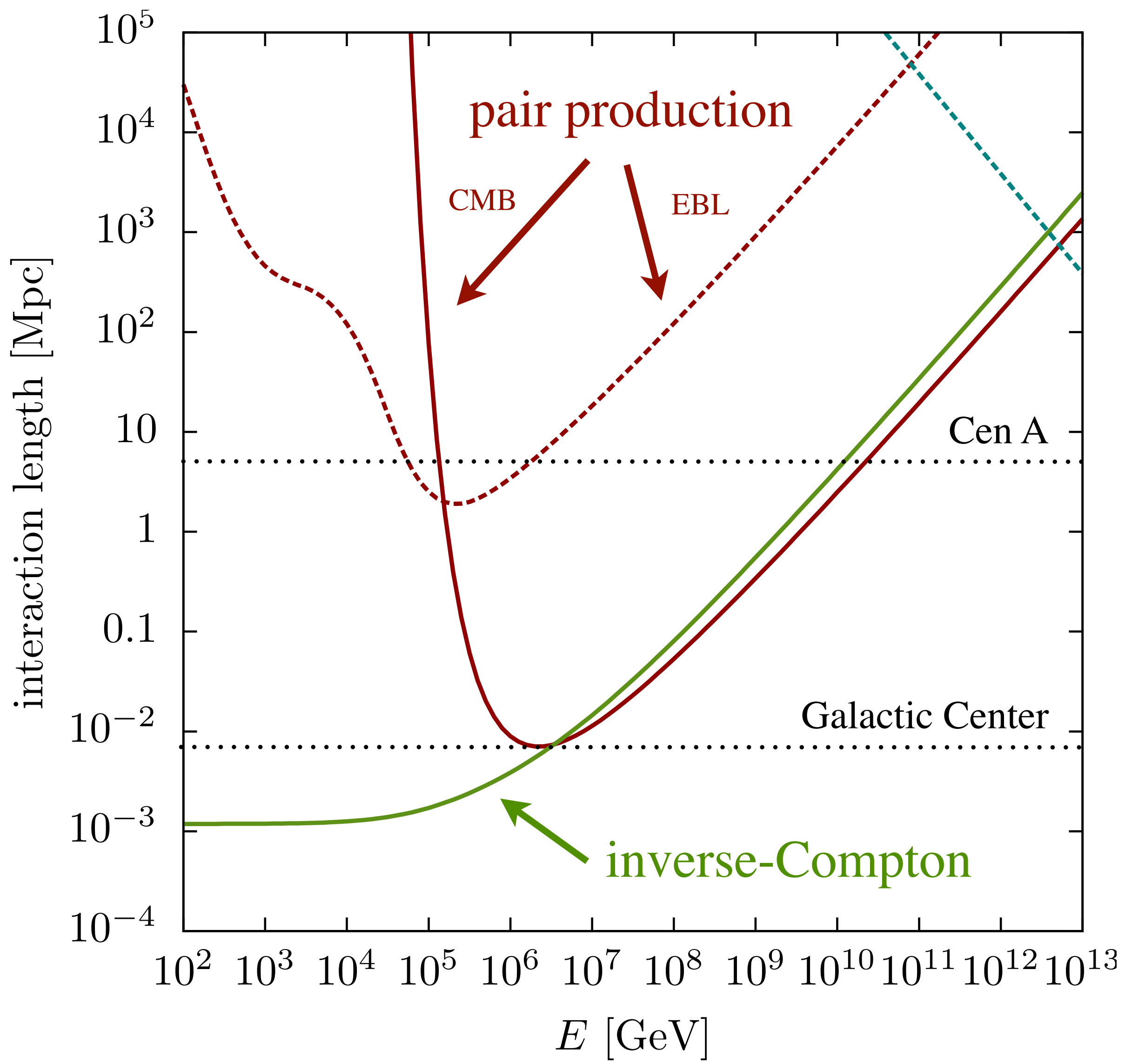
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

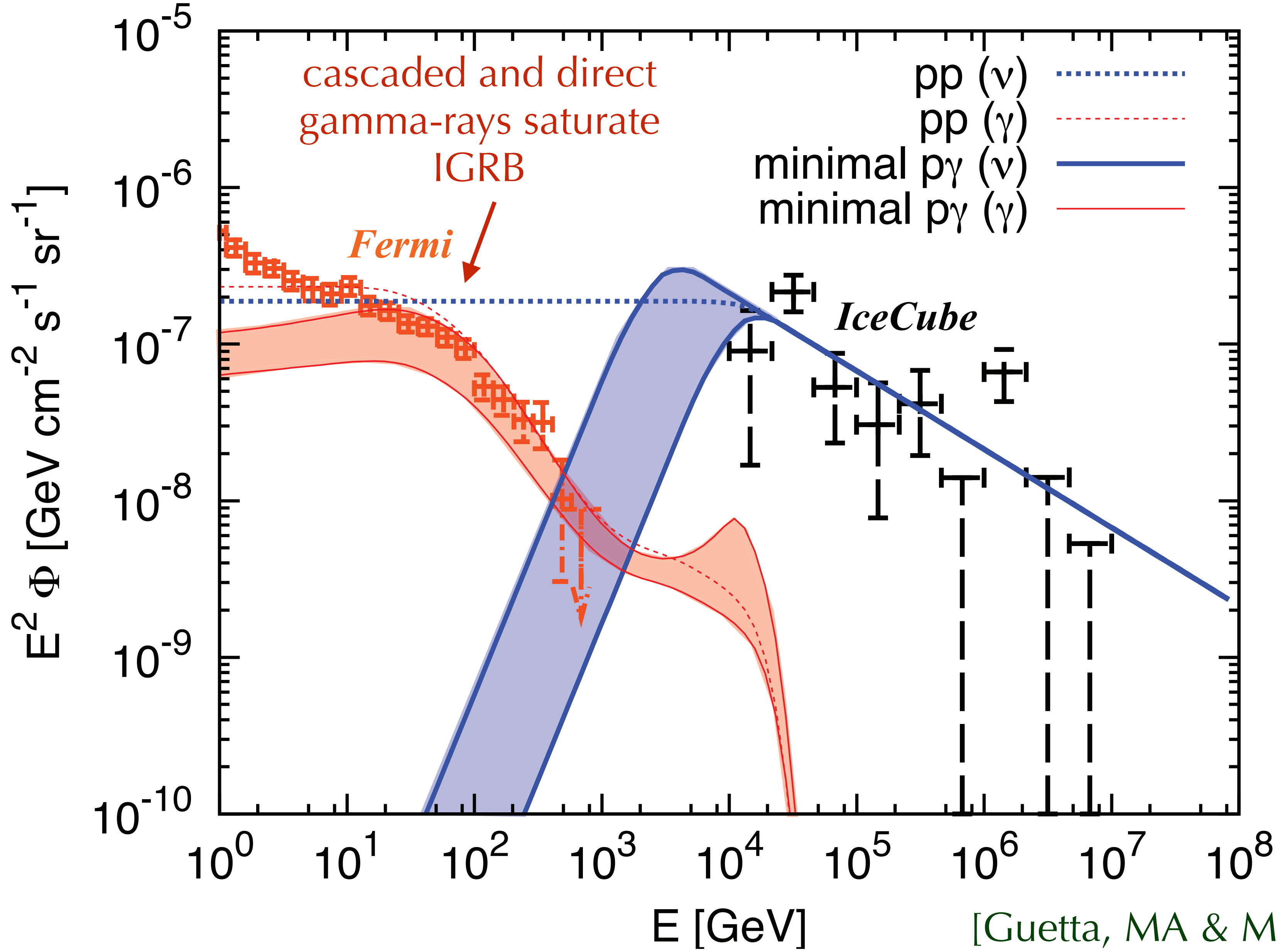
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

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



Hadronic Gamma-Rays

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



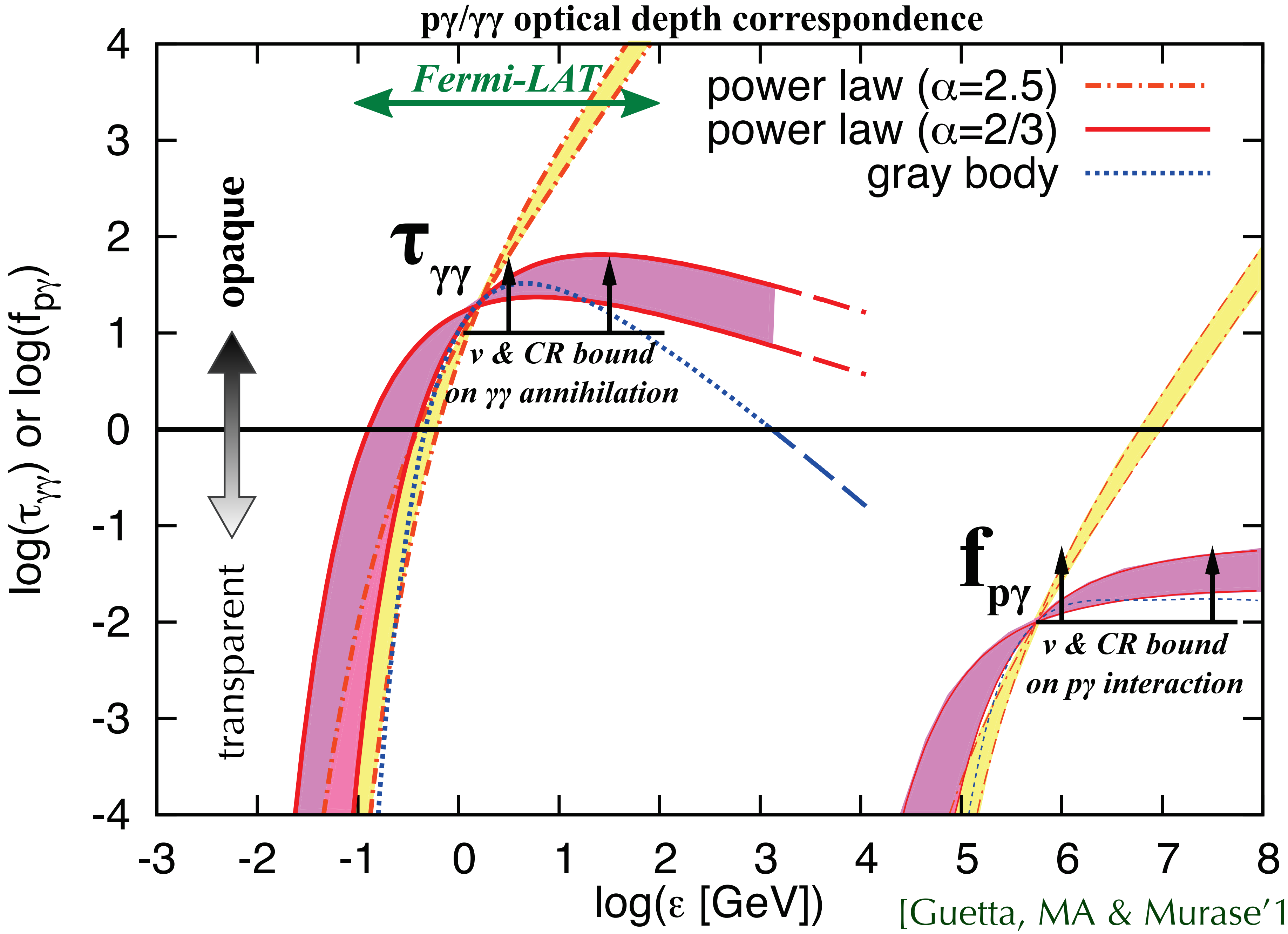
[Guetta, MA & Murase'16]

[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]

Hidden Sources?

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

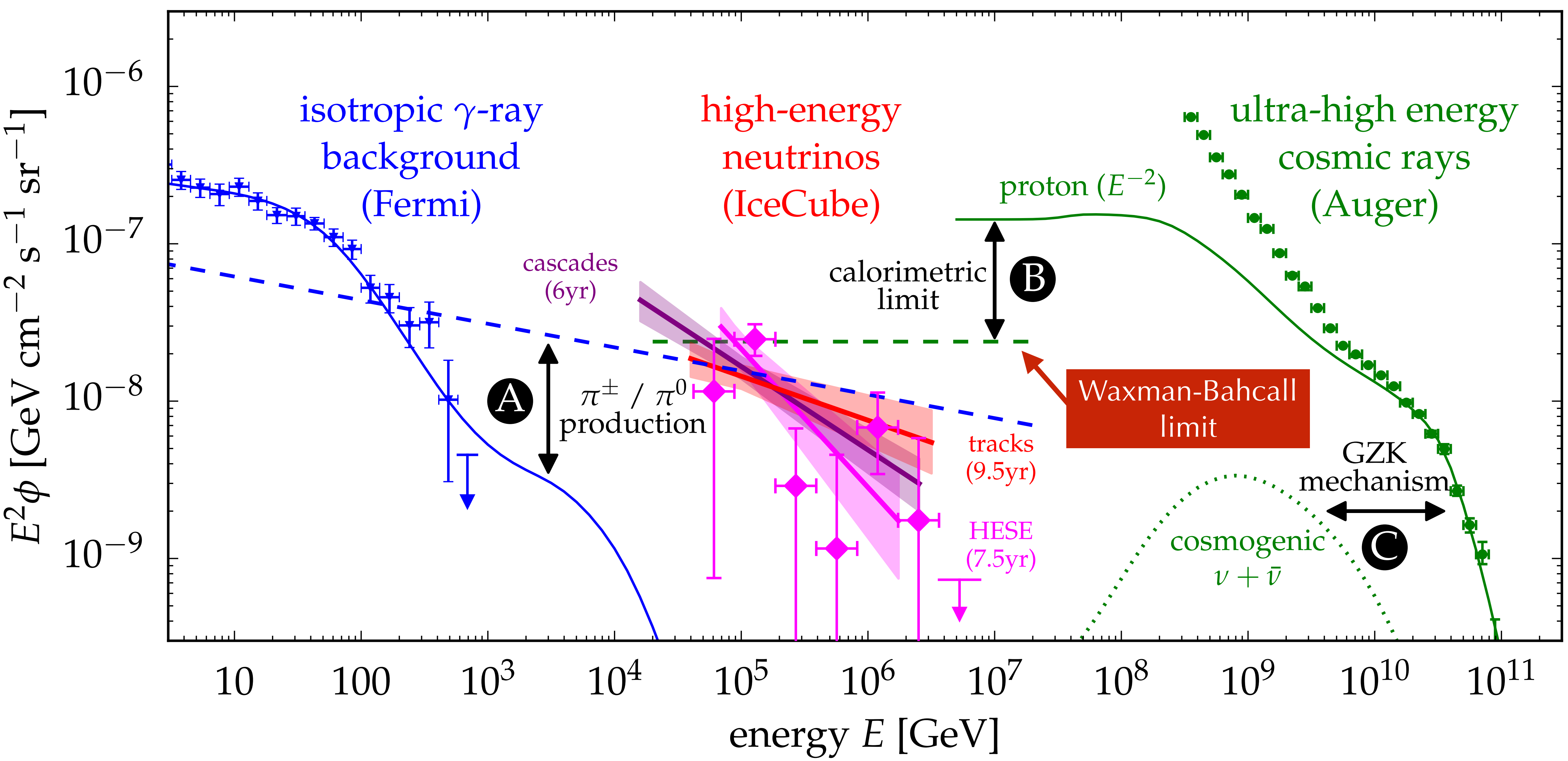


[Guetta, MA & Murase'16]

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

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

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 $\Gamma \simeq 2.04$) :

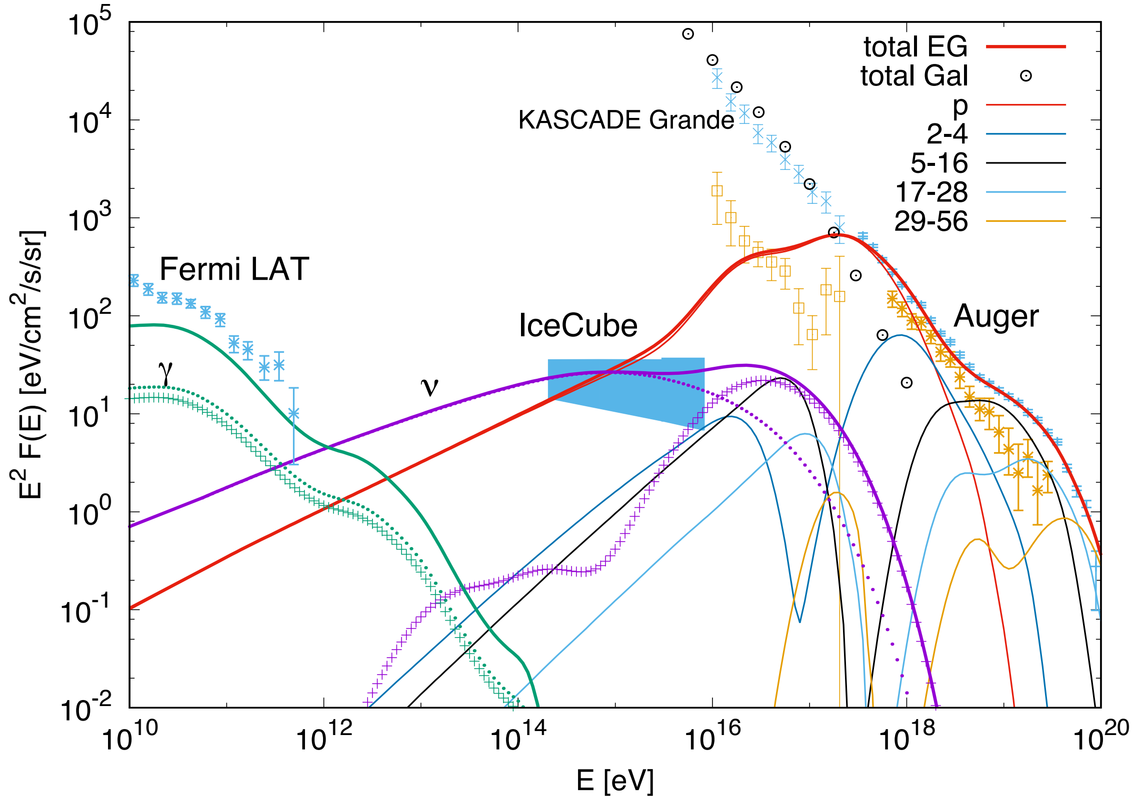
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43} \mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

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

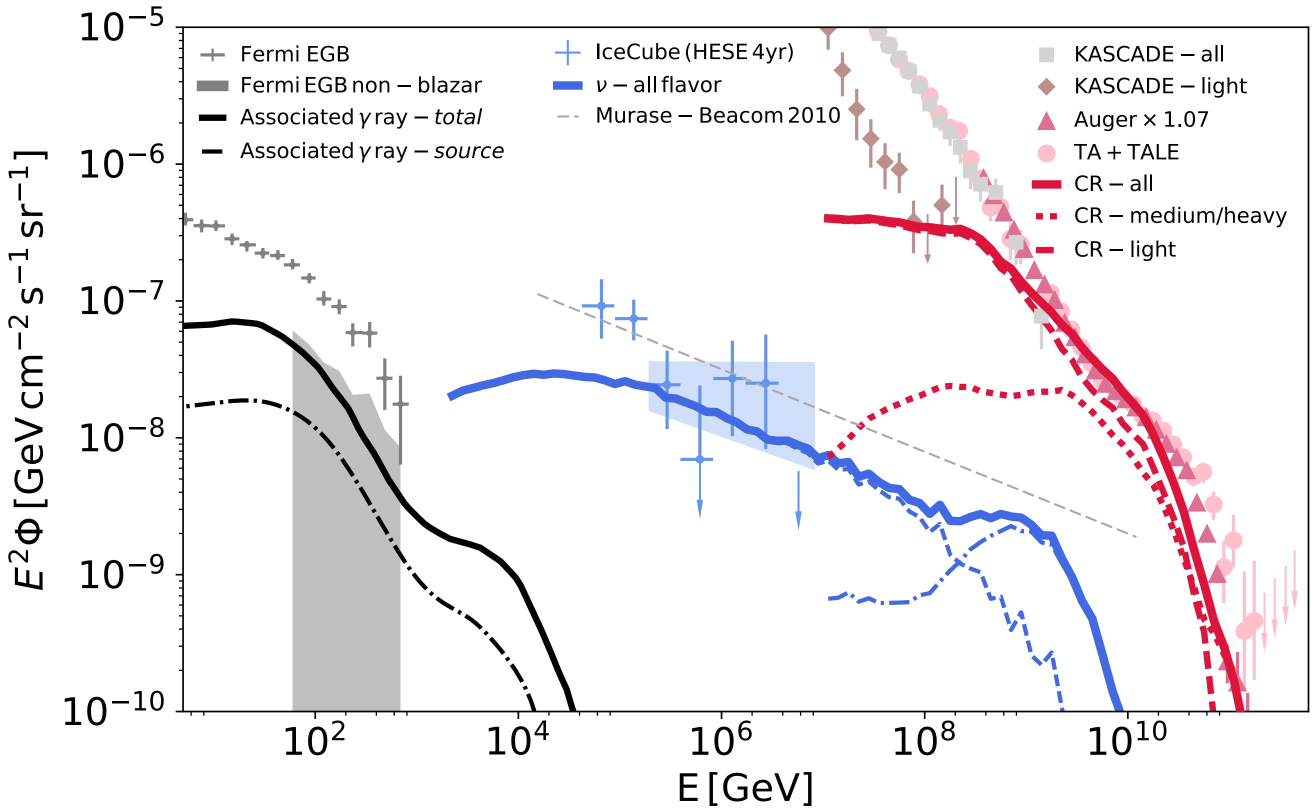
- **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).

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?



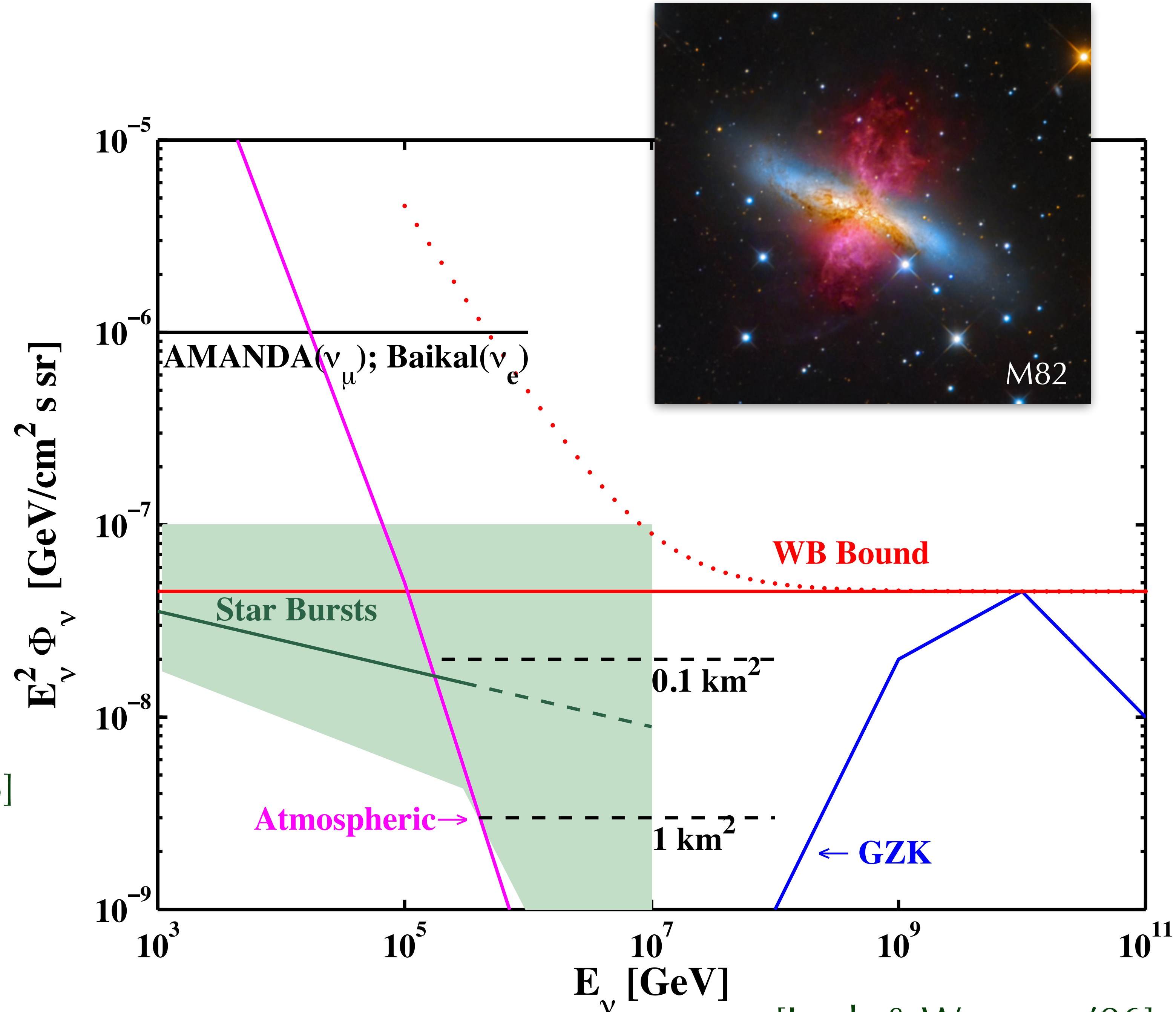
[Kachelriess, Kalashev, Ostapchenko & Semikoz'17]



[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.

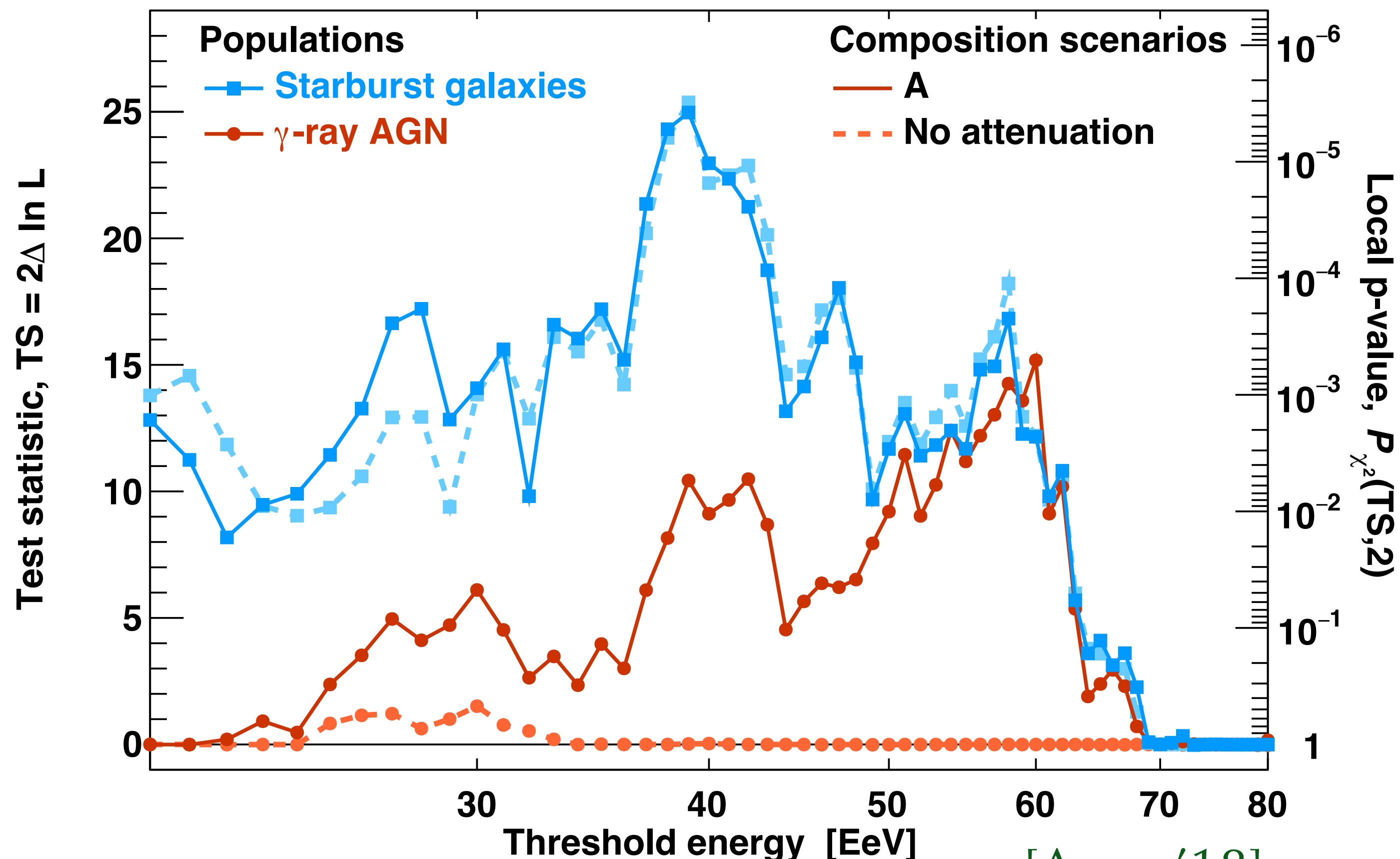


[Loeb & Waxman '06]

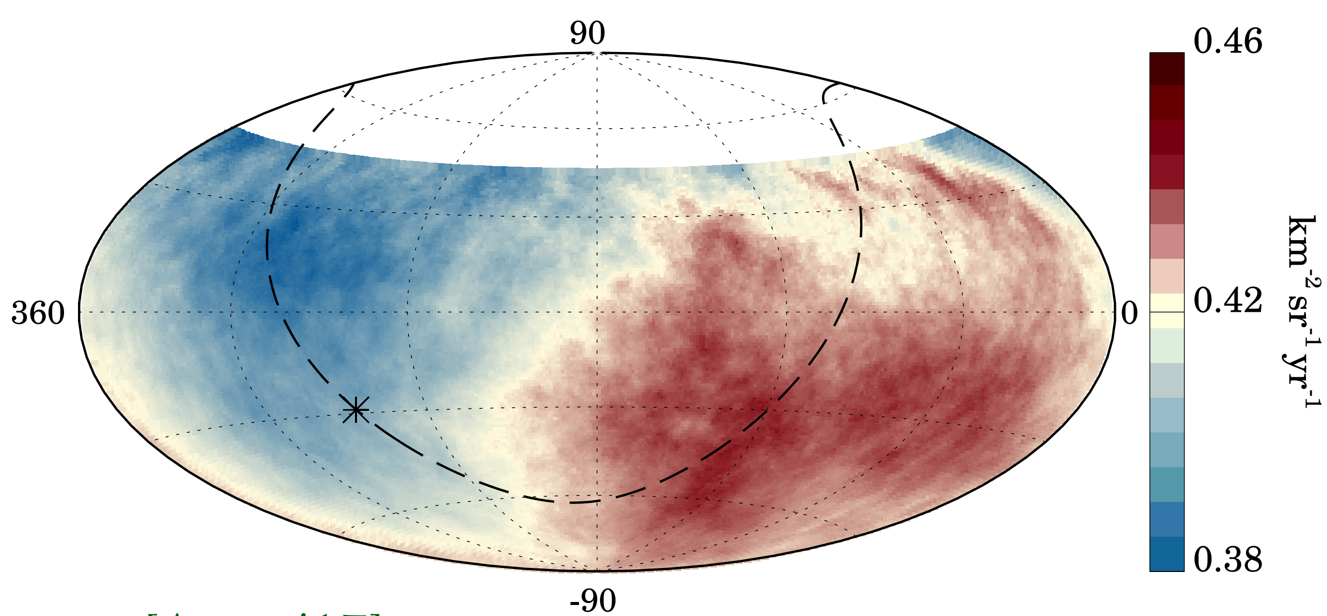
[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]
[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

UHE CR Anisotropy

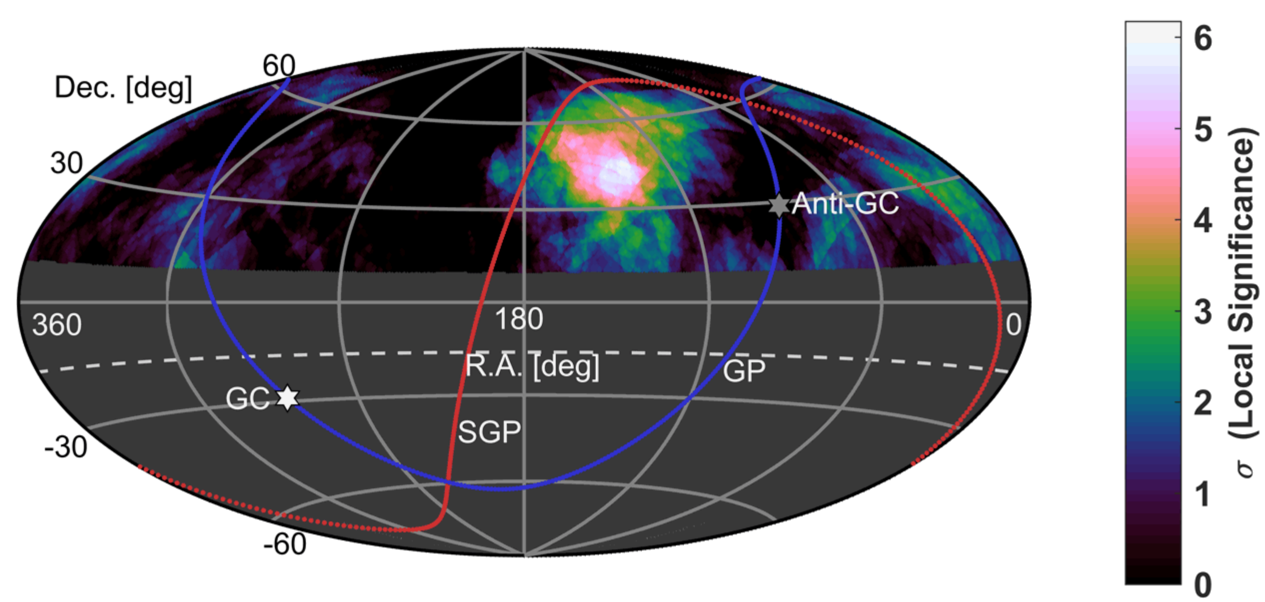
- UHE CR arrival direction above 8EeV show strong (6.5%) **dipole anisotropy** (5.2σ). [Auger'17]
- Arrival directions of UHE CRs above 40 EeV show **correlation with local starburst galaxies** (4σ).
- Indications for **medium-scale anisotropy** above 16 EeV in Northern Hemisphere (3.7σ) [TA'18]



[Auger'18]



[Auger'17]



[TA'18]

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.

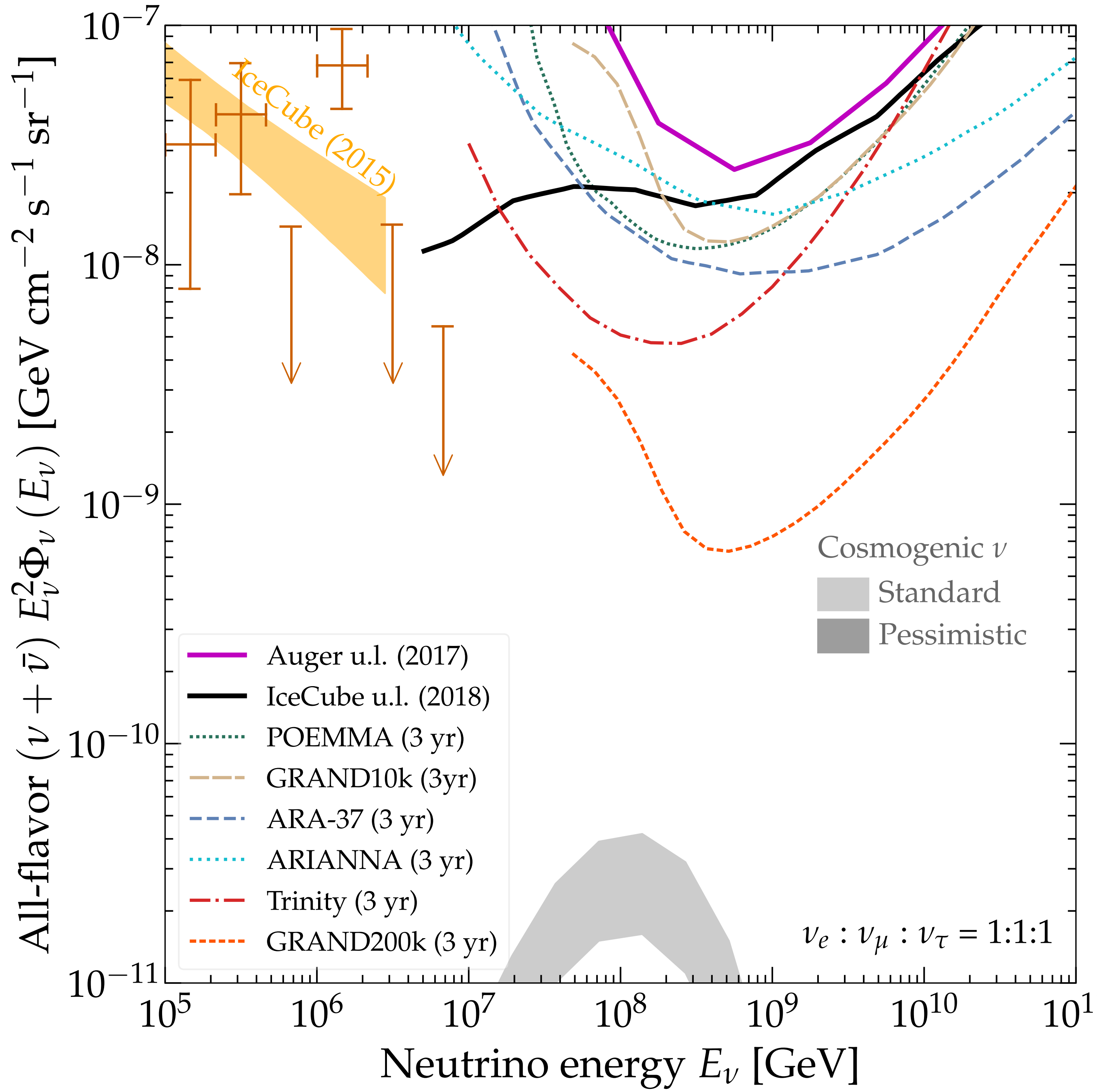
- ***Principal challenge:*** Only 5% of observed TeV-PeV neutrinos are expected to correlate with UHE CRs.

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

"Observable Universe"
in neutrinos and UHE CRs

Hubble horizon

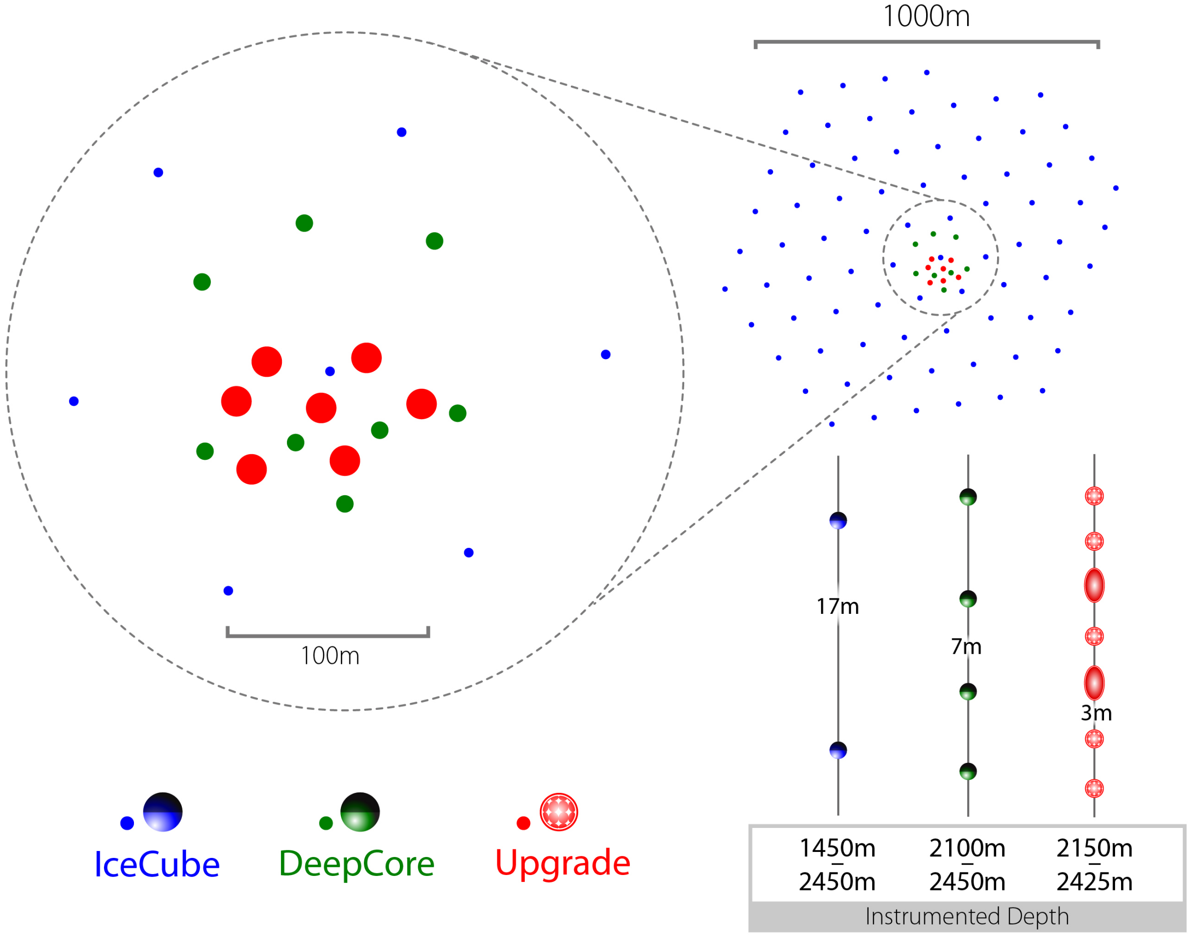
- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal energies.
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.

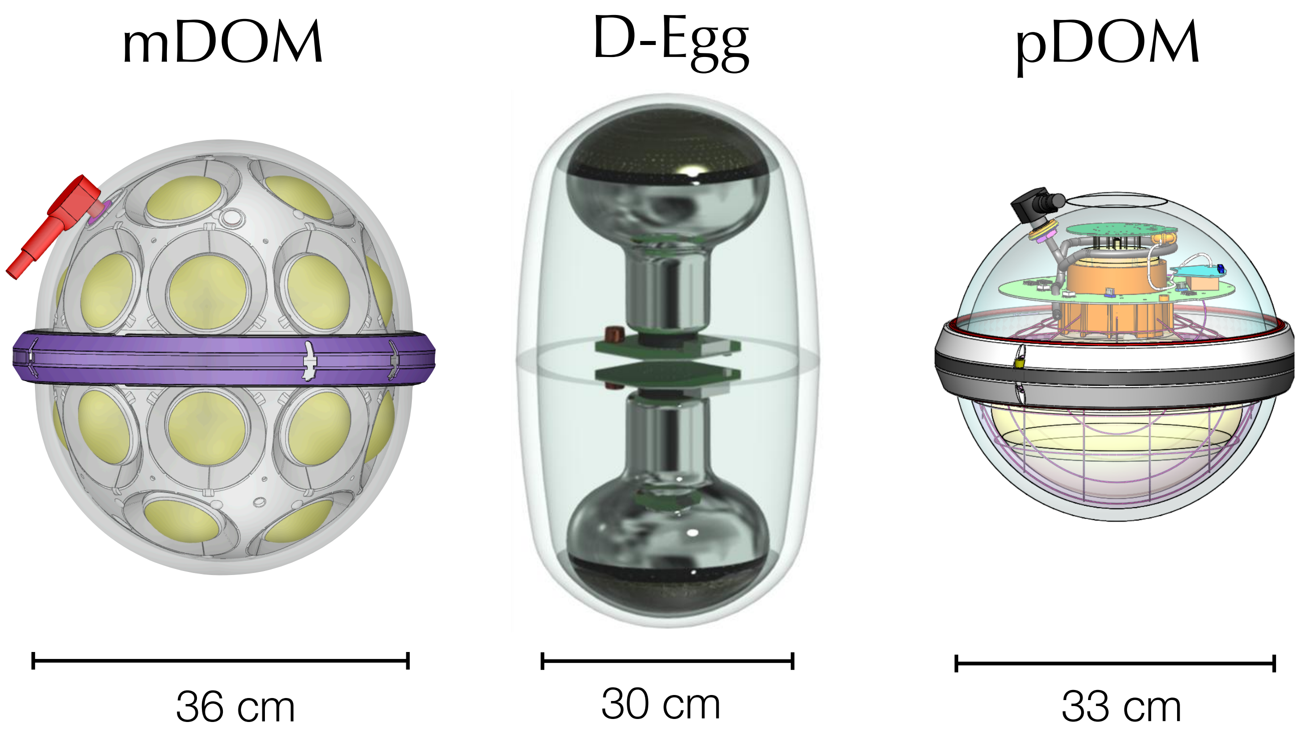


[Alves Batista *et al.*'19]

Outlook: 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**

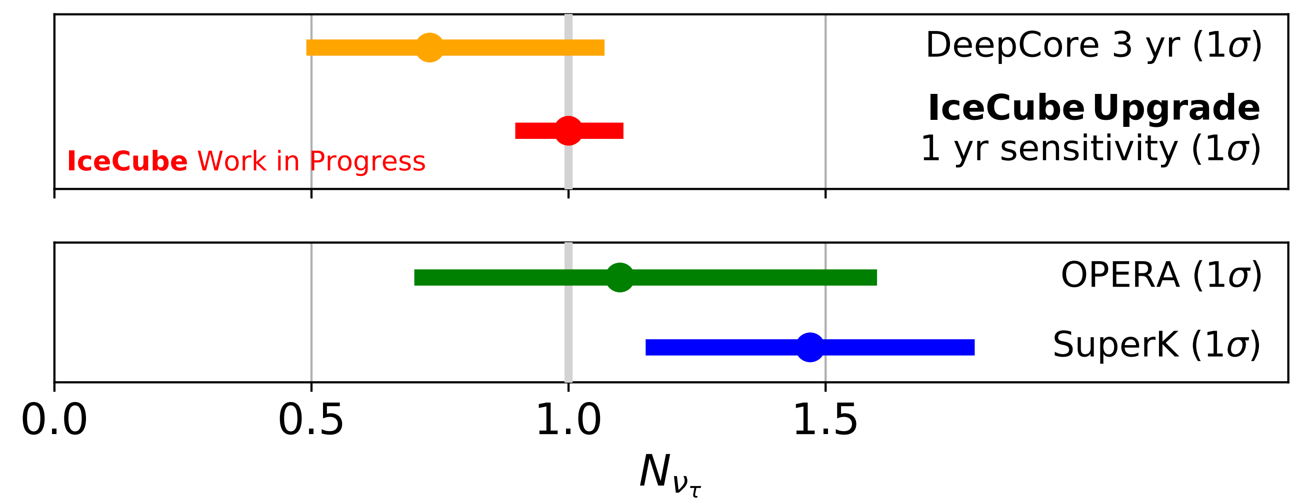


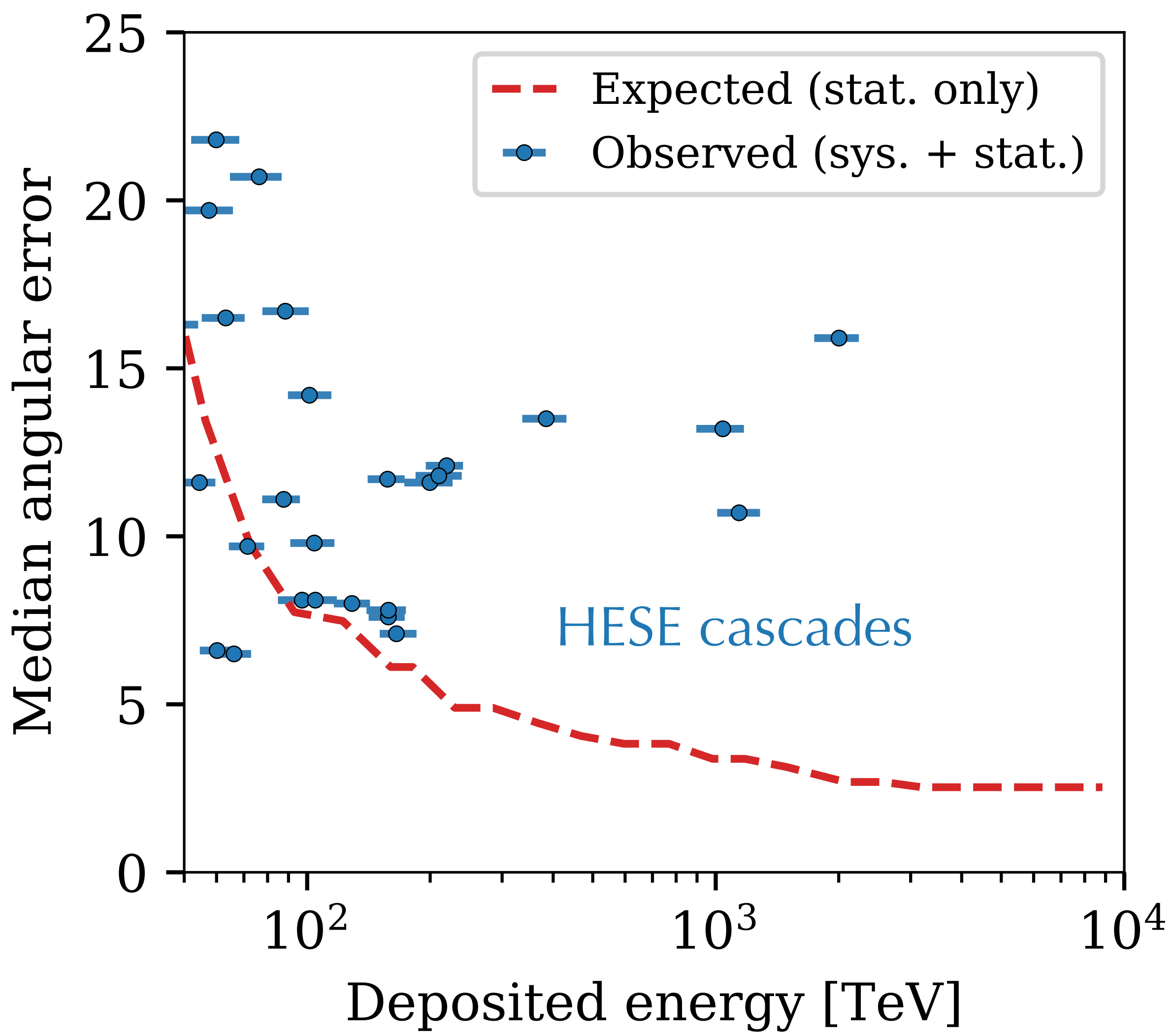


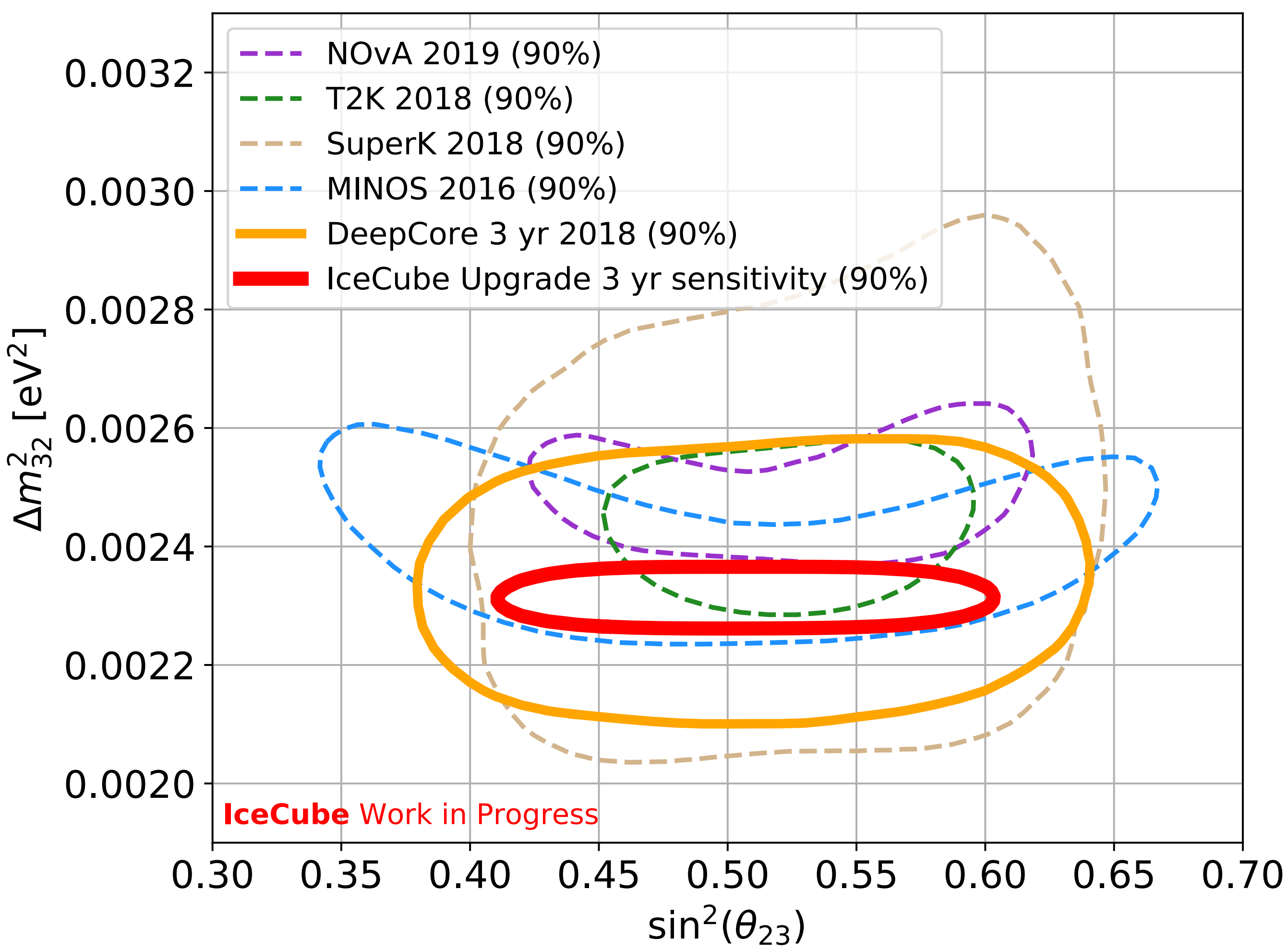
Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance

- **Improved energy and angular reconstructions** of IceCube data



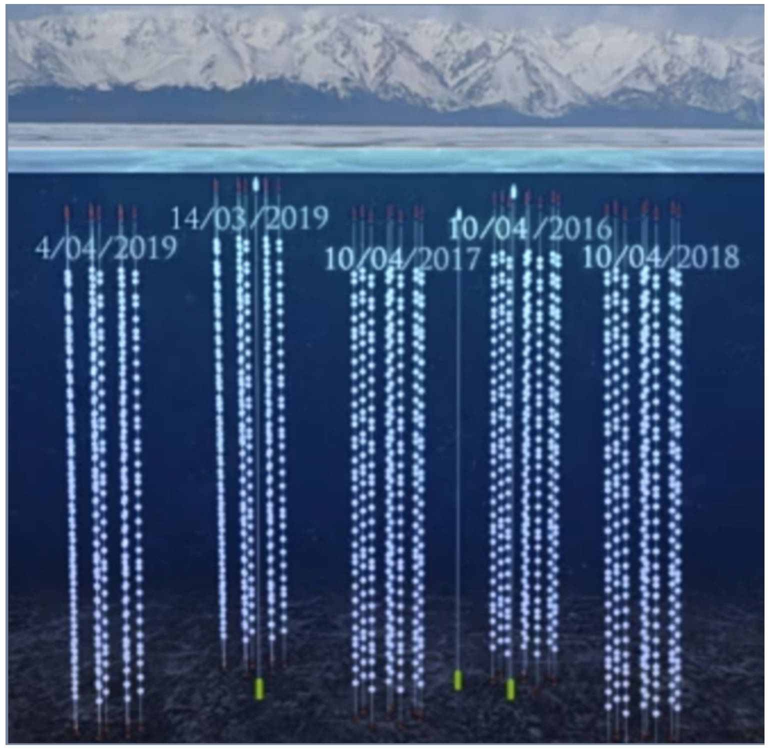




[IceCube, PoS (ICRC2019) 1031]

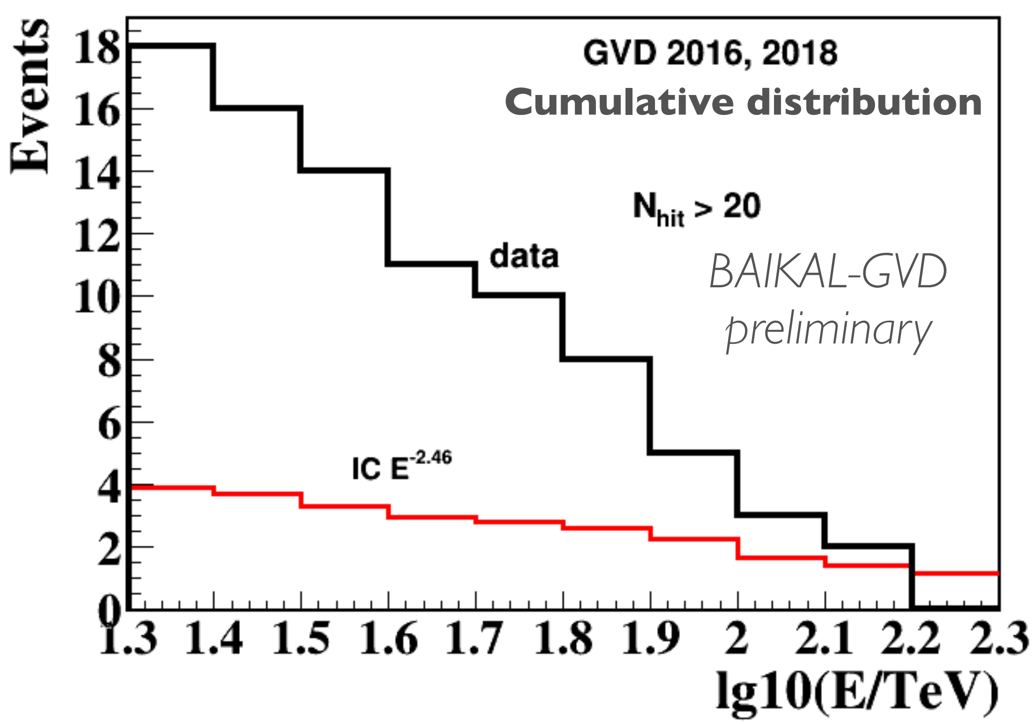
Outlook: Baikal-GVD

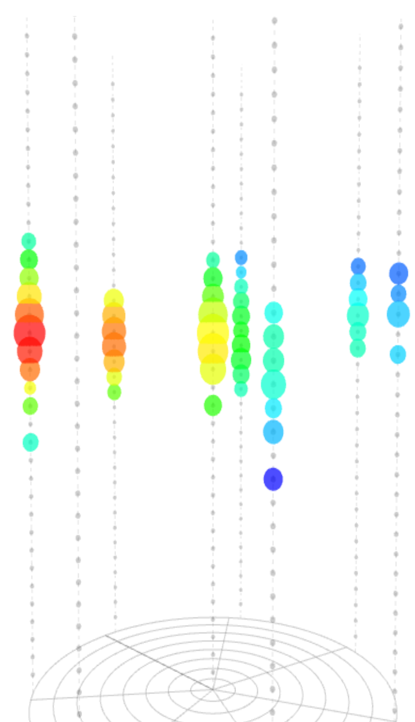
BAIKAL-GVD



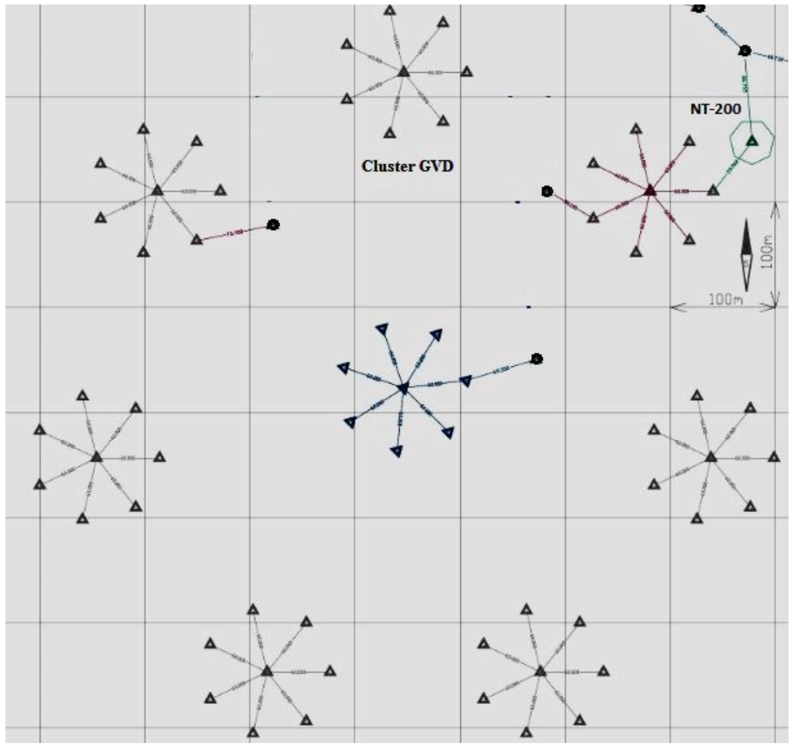
detector outline in 2019

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by end of 2021 (~0.4 km³)
- cluster depth: 735–1260 m
- **status March 2021: 7 clusters**
- **final goal**: 27 clusters (~1.4 km³)





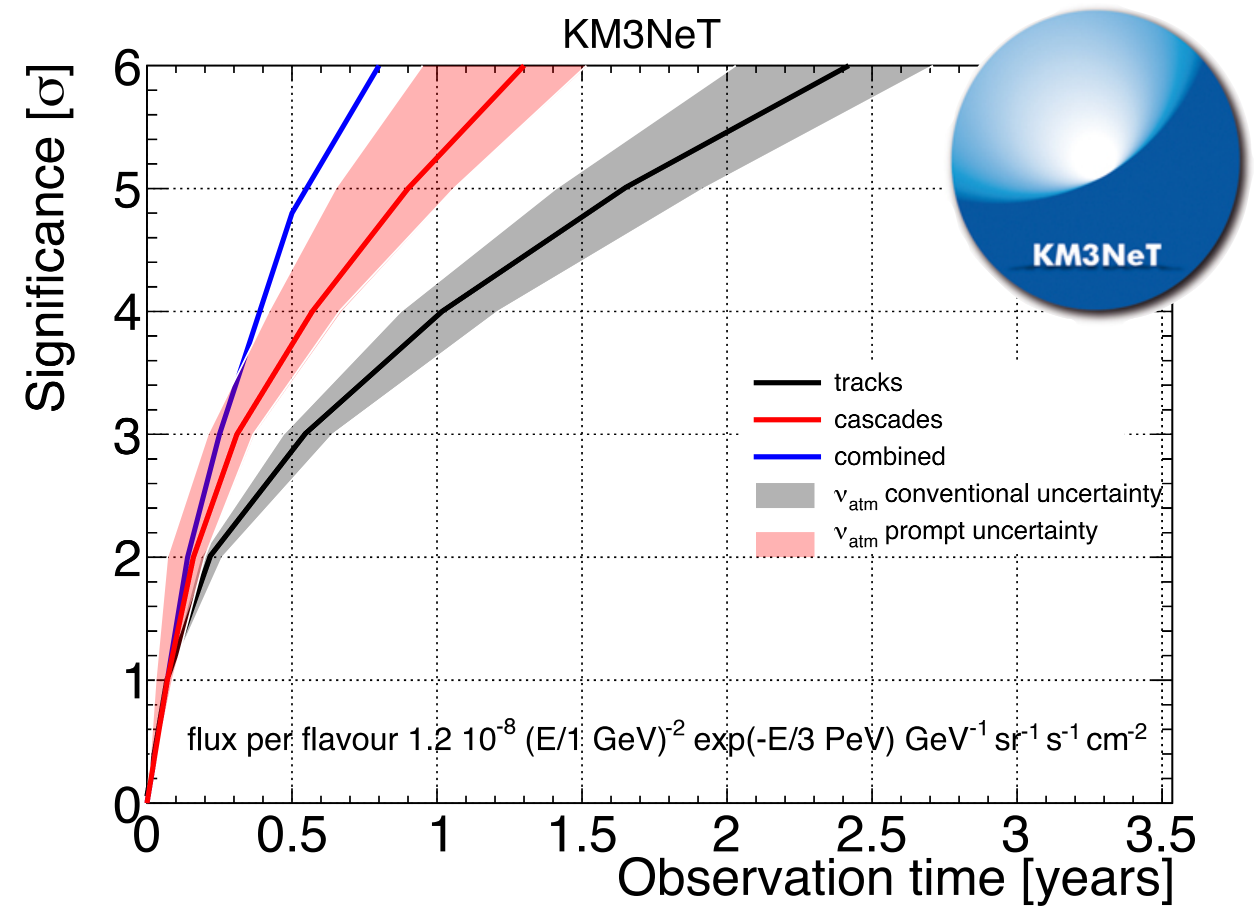
~157 TeV cascade event

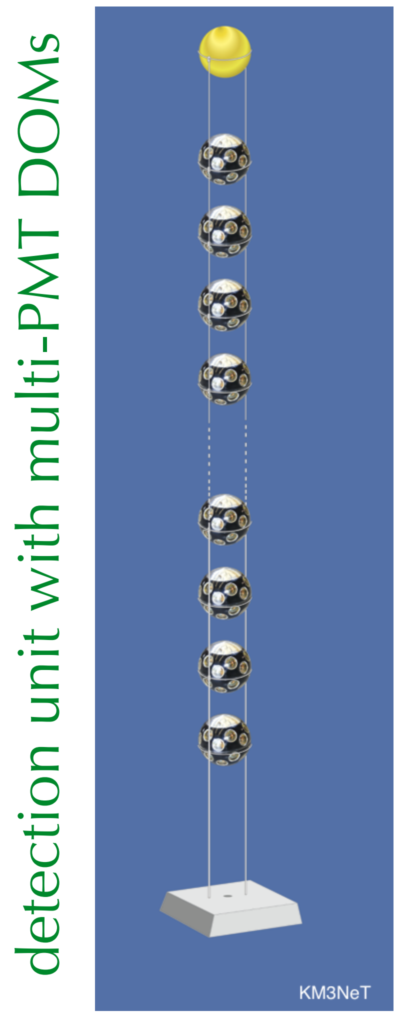


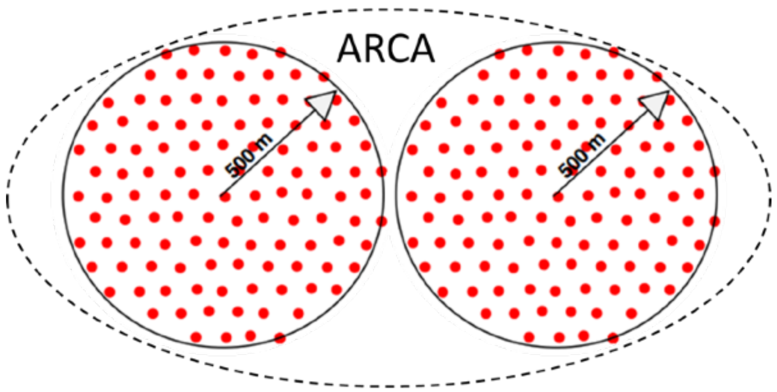
GVD-Phase 1

Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status April 2021: 6 DUs**
- September 2021: +12 DUs



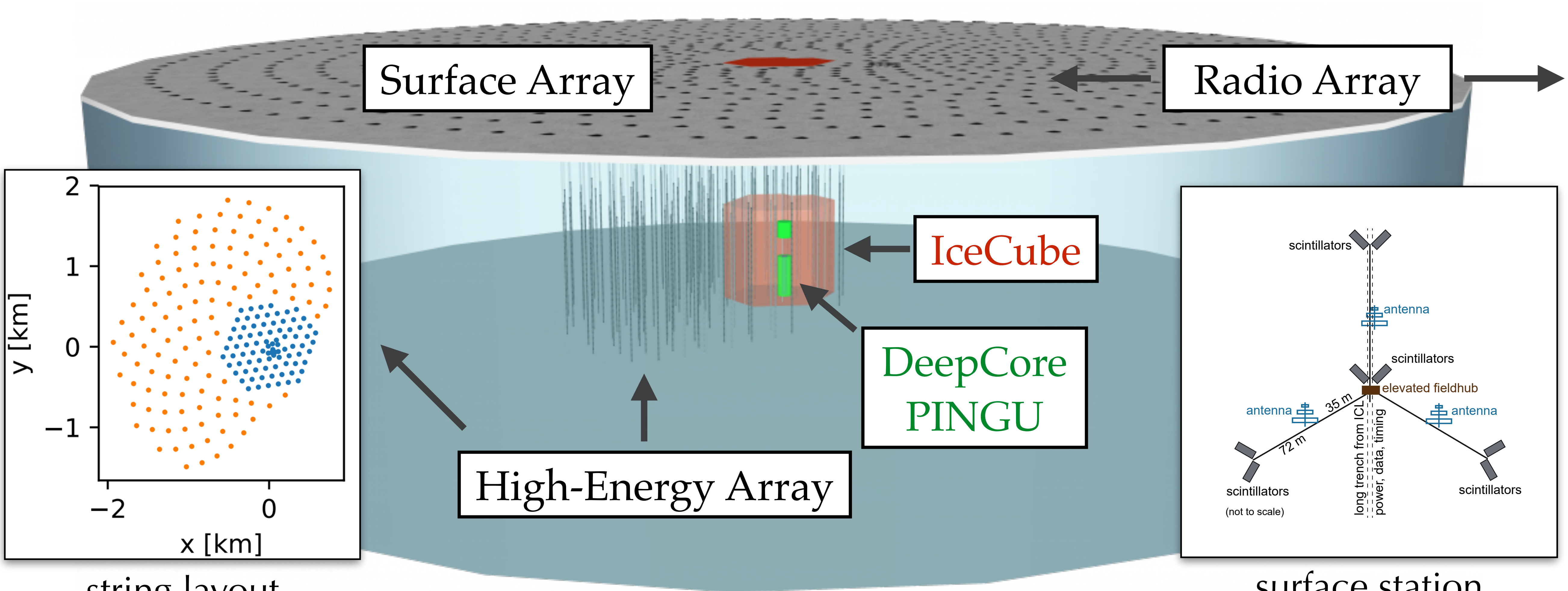




- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

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

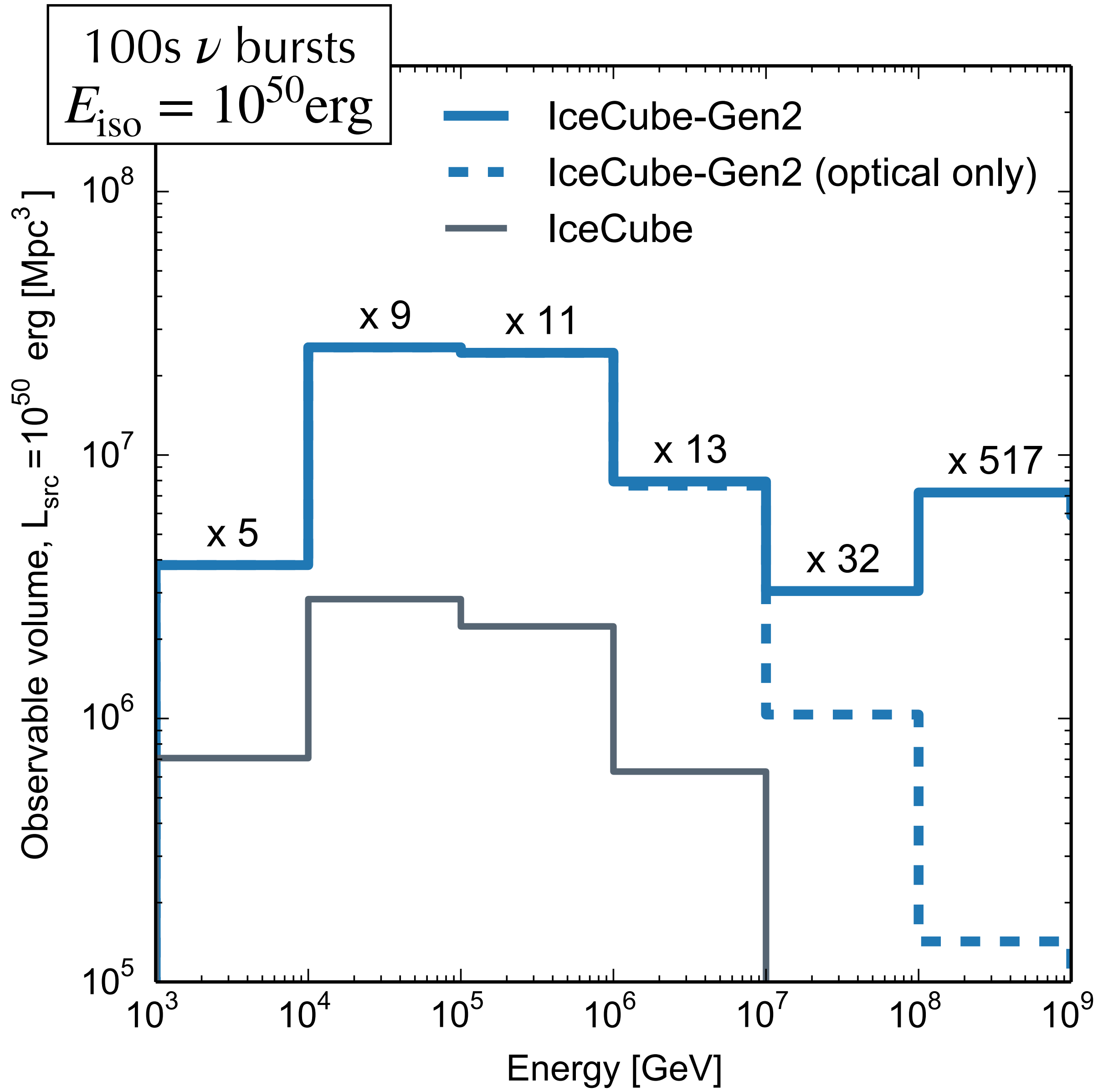


string layout

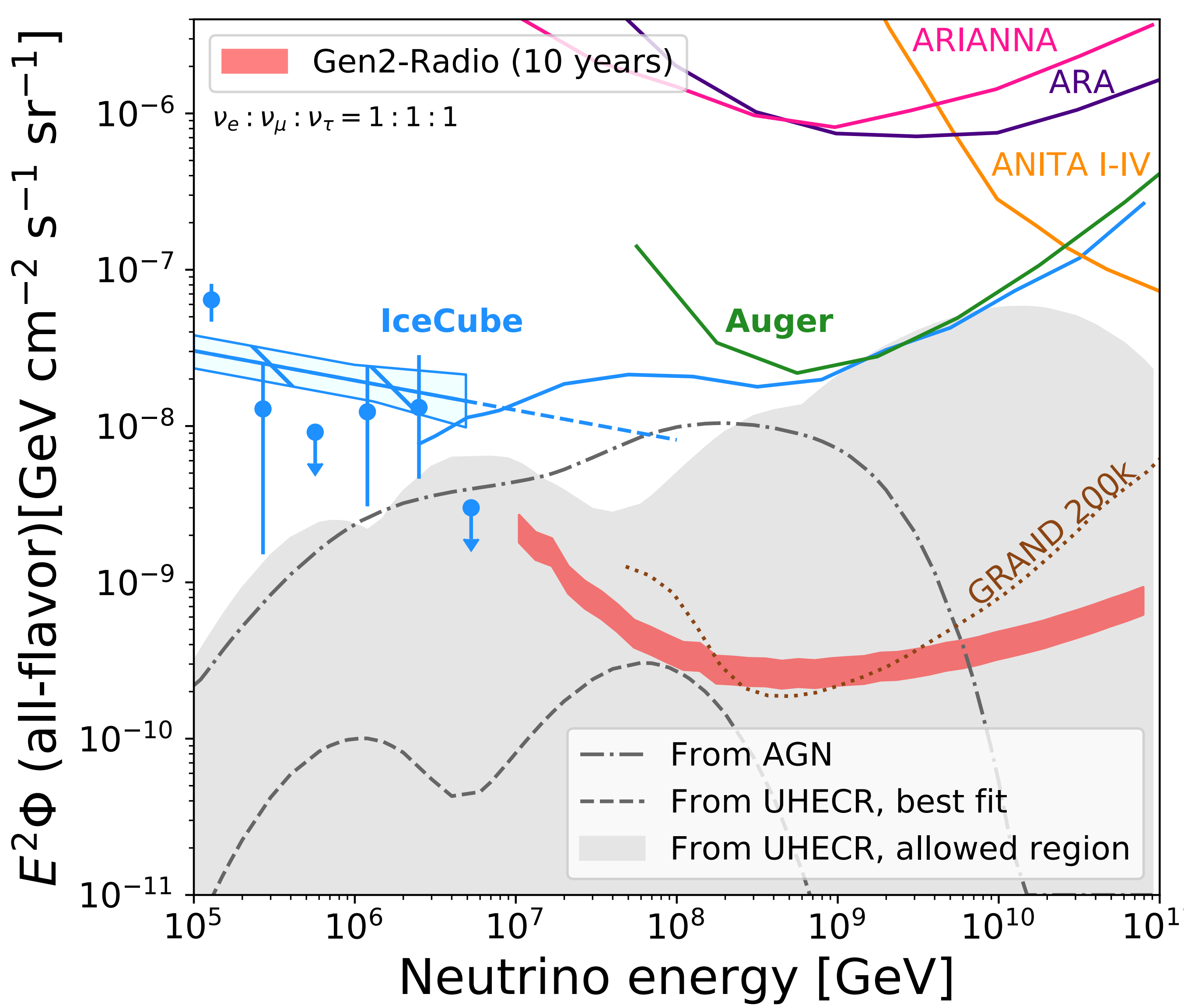
surface station

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

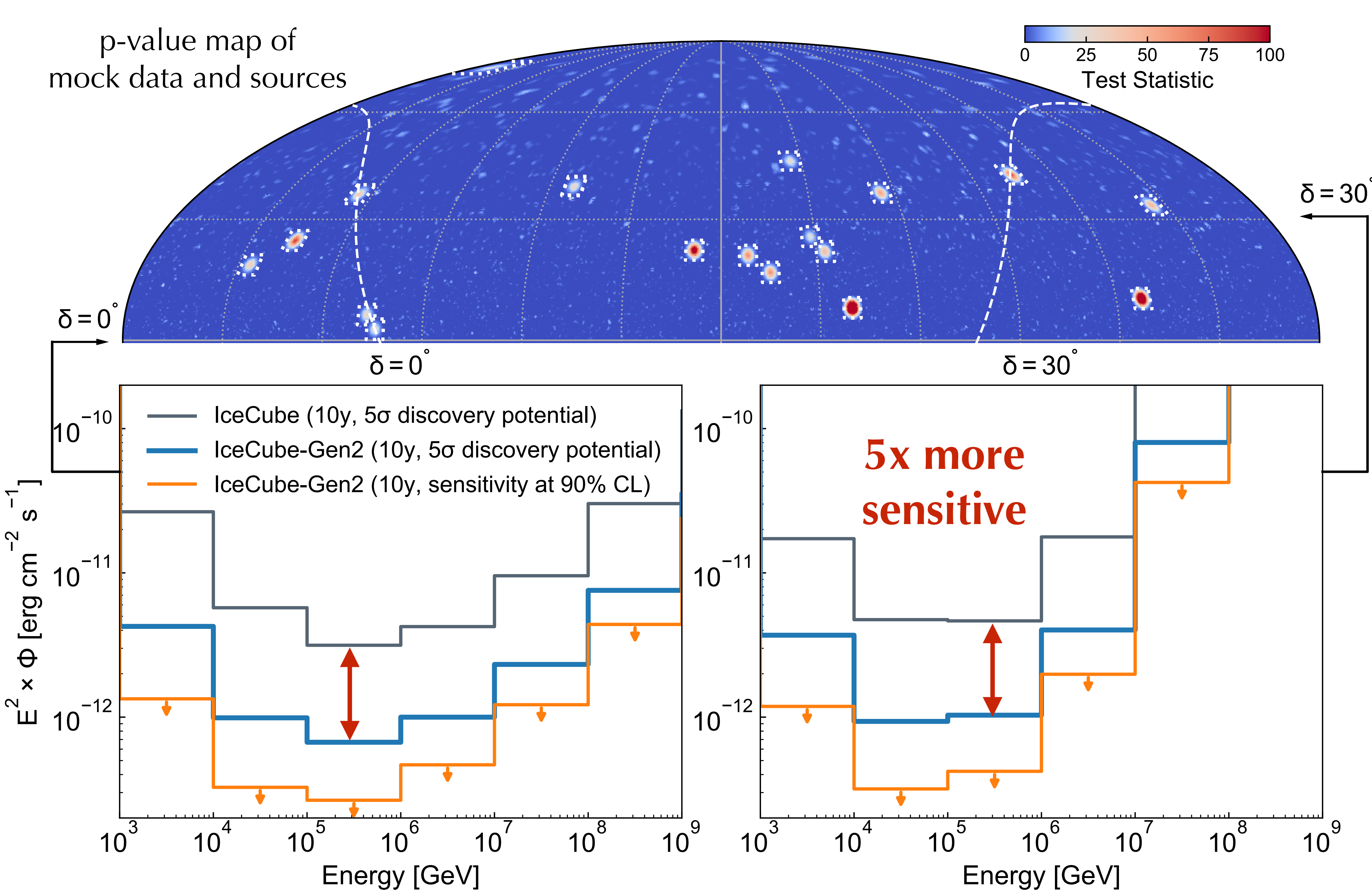
Improved sensitivity for neutrino sources to find the origin of the isotropic TeV-PeV flux



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



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



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

Summary

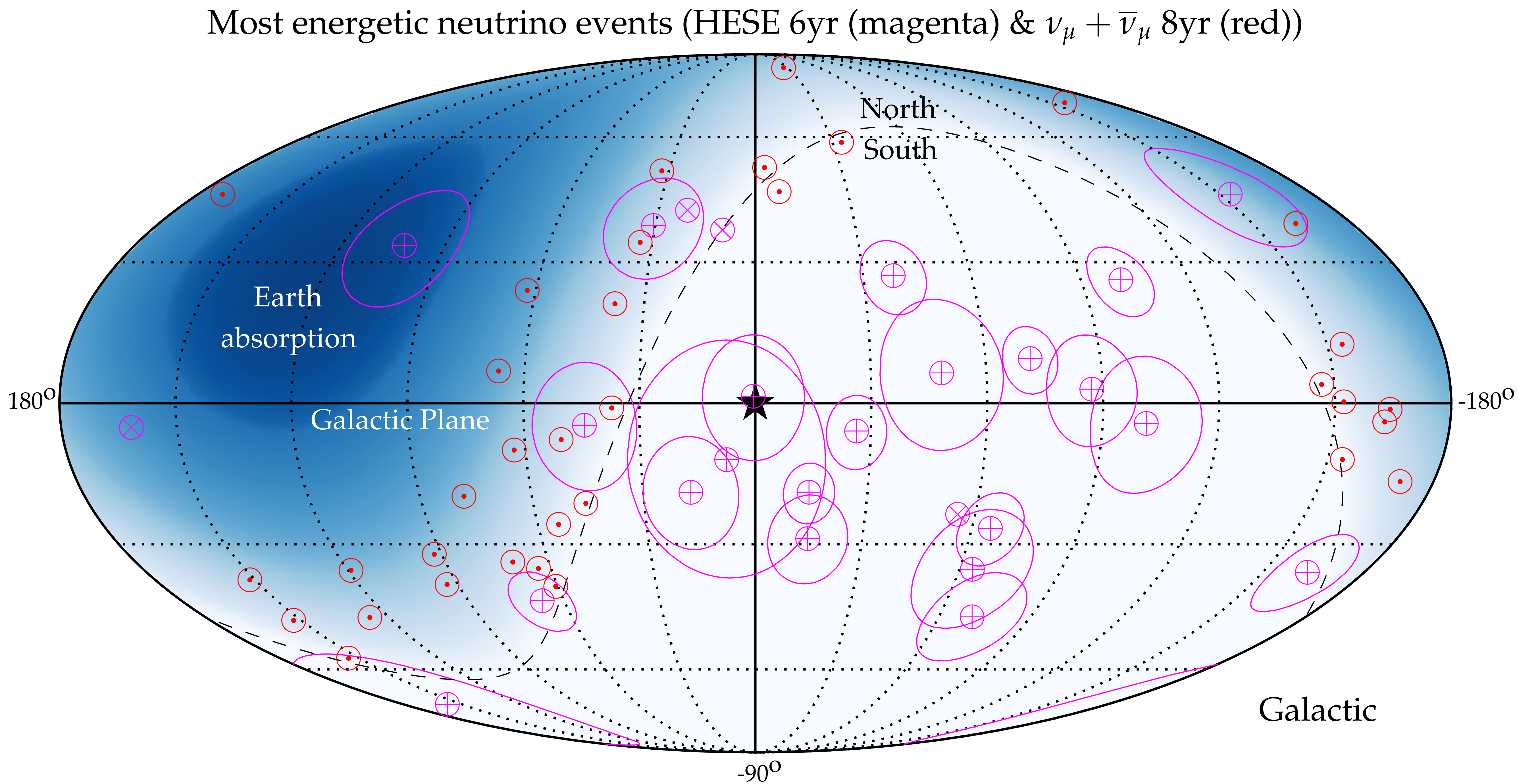
- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**
- So far, **no significant** point sources, but many **interesting candidates**.
- Intensity of cosmic neutrinos is comparable to that of ultra-high energy cosmic-rays (*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,...)
- More on IceCube-Gen2 "here" at GCOS on Thursday:

  Tianlu Yuan (optical extension) & **Alan Coleman** (radio extension)

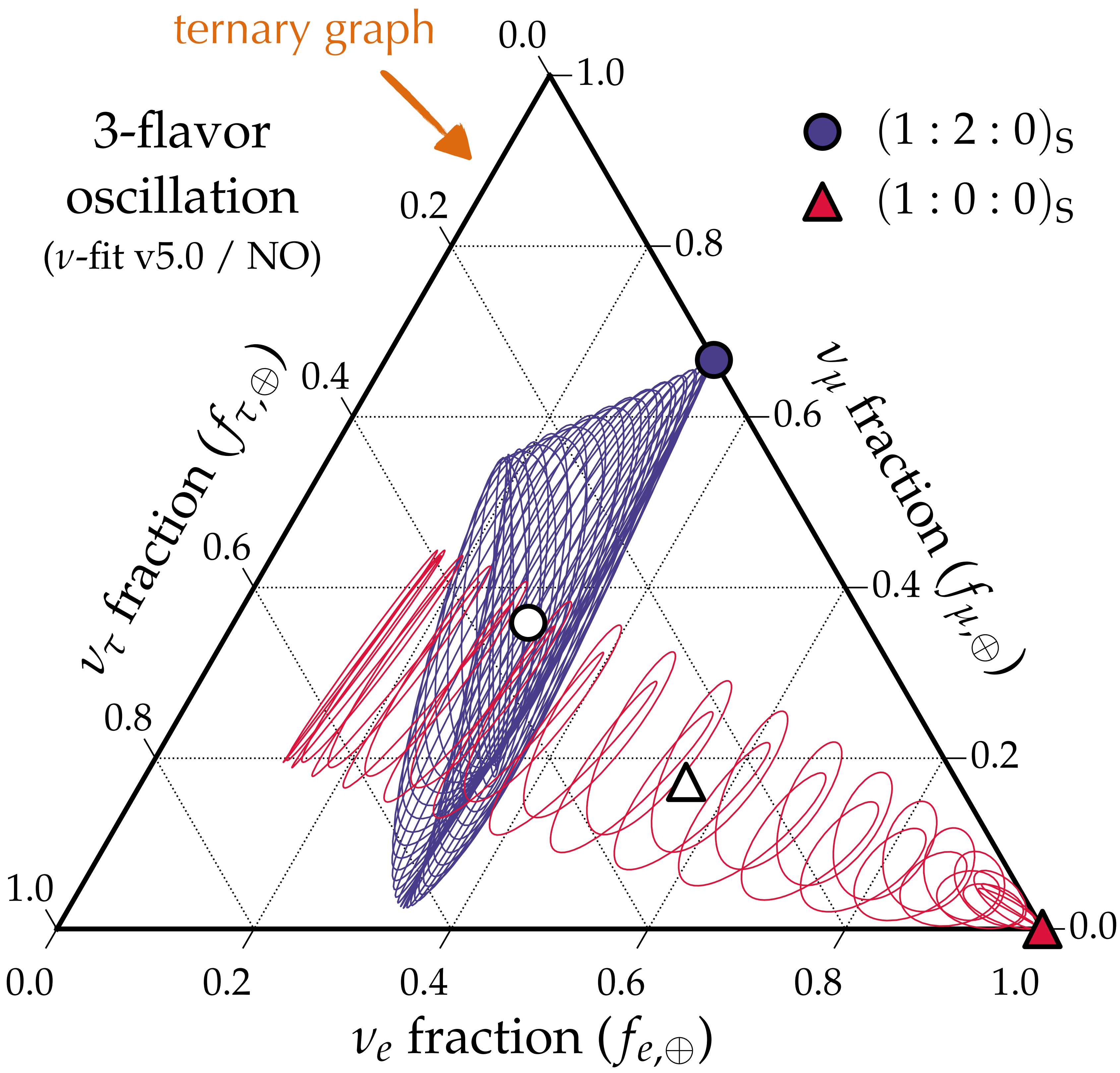
Backup Slides

Status of Neutrino Astronomy



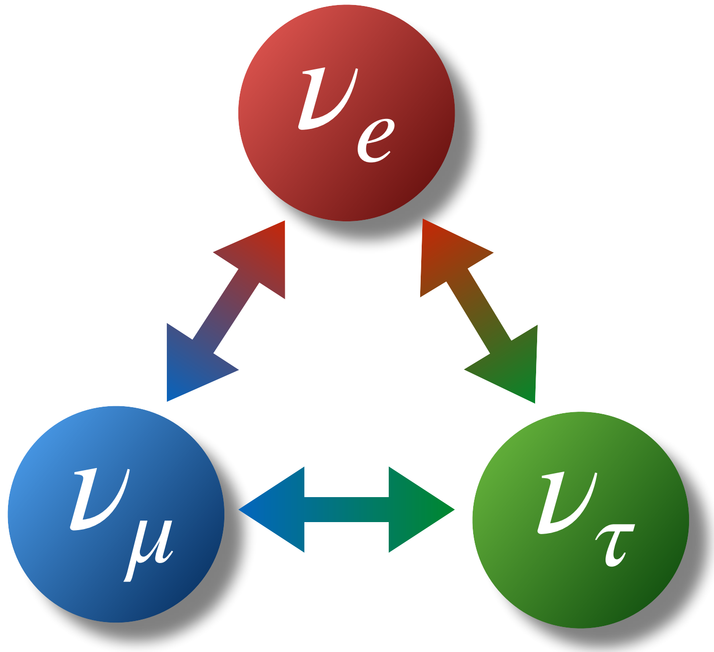
No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Astrophysical Flavours

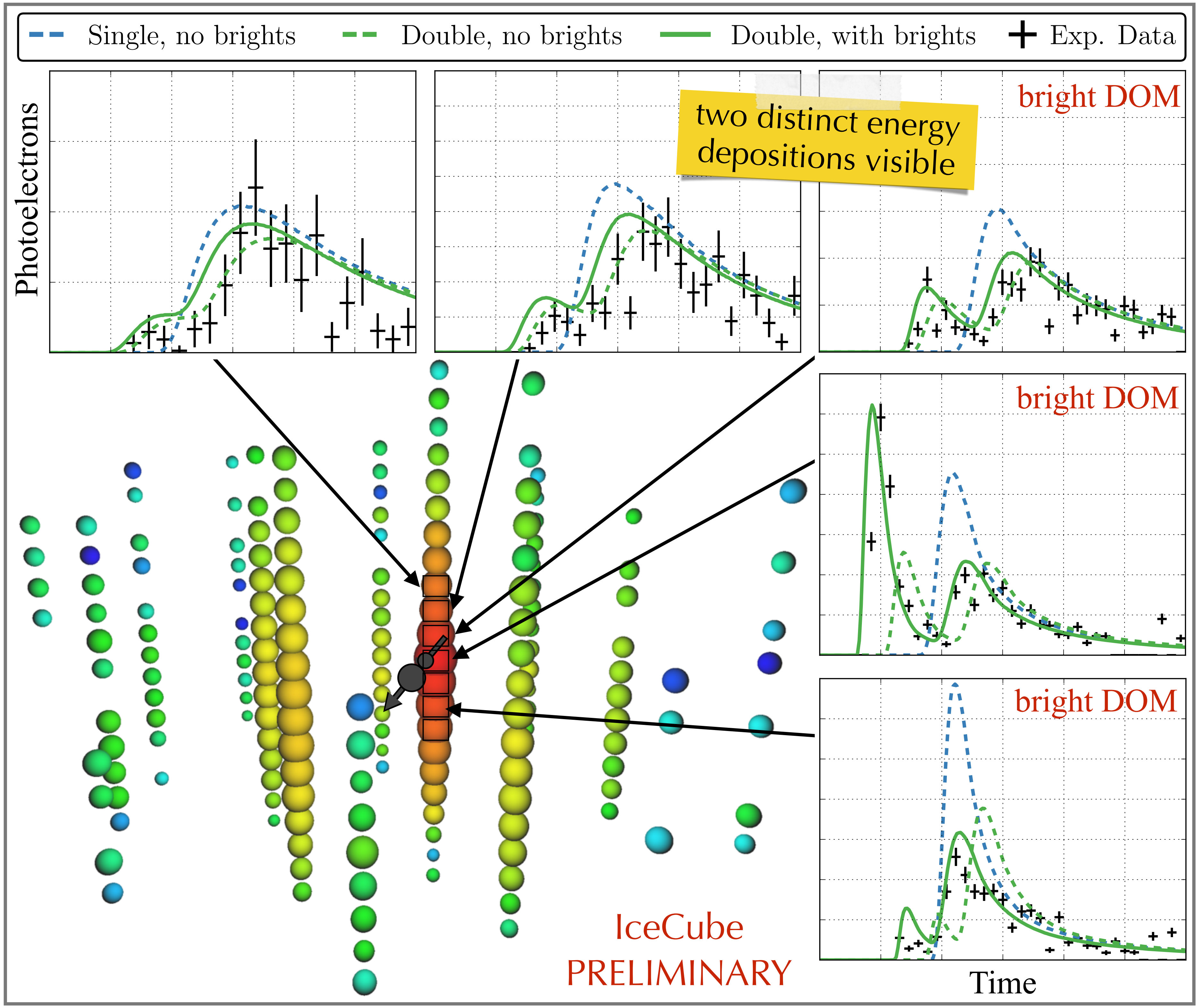


flavour ratios
on production

Superposition of flavour and mass states induces oscillations.



Astrophysical Flavours



[IceCube, arXiv:2011.03561]

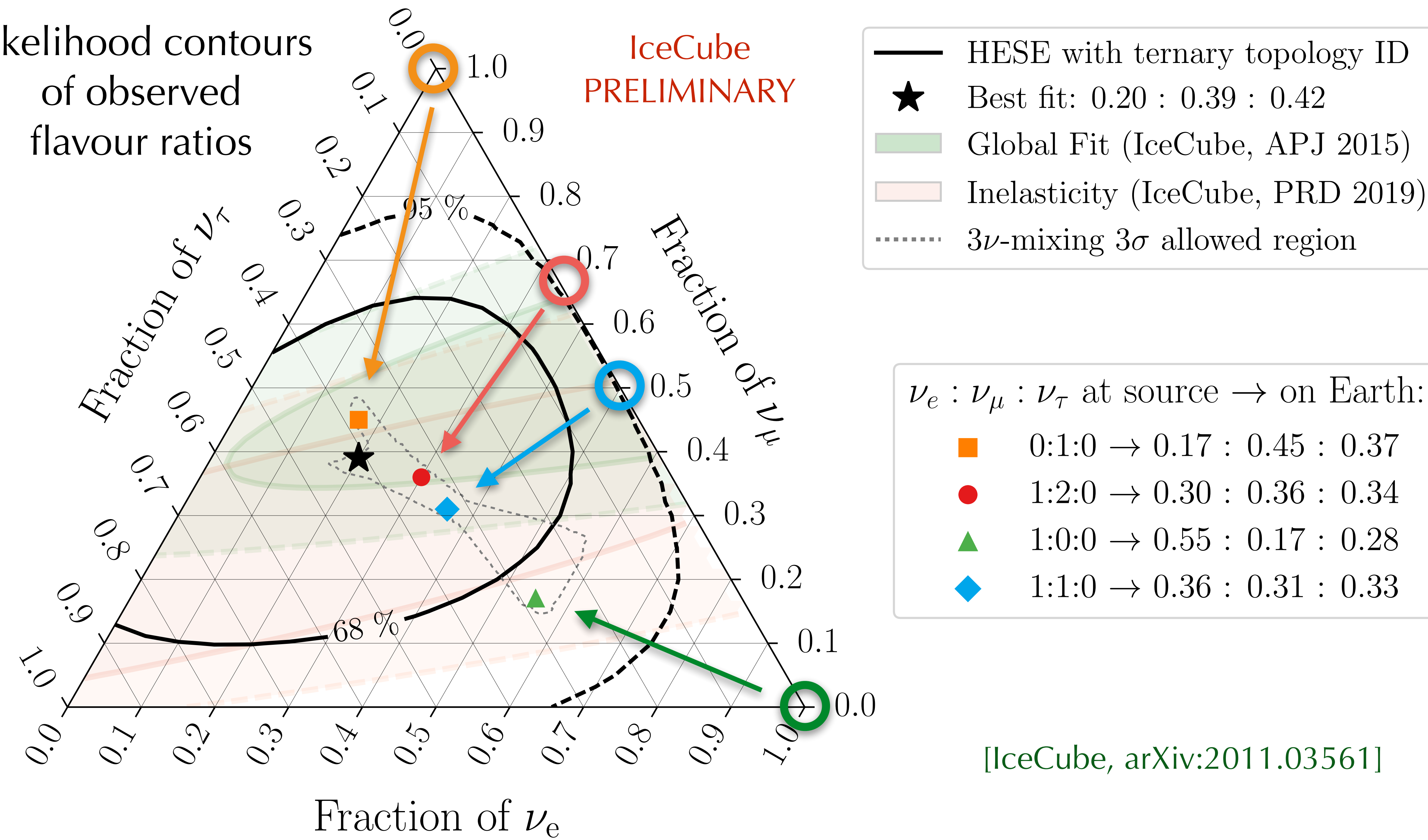
tau neutrino candidate

- **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

Cosmic neutrinos visible via their oscillation-averaged flavour.

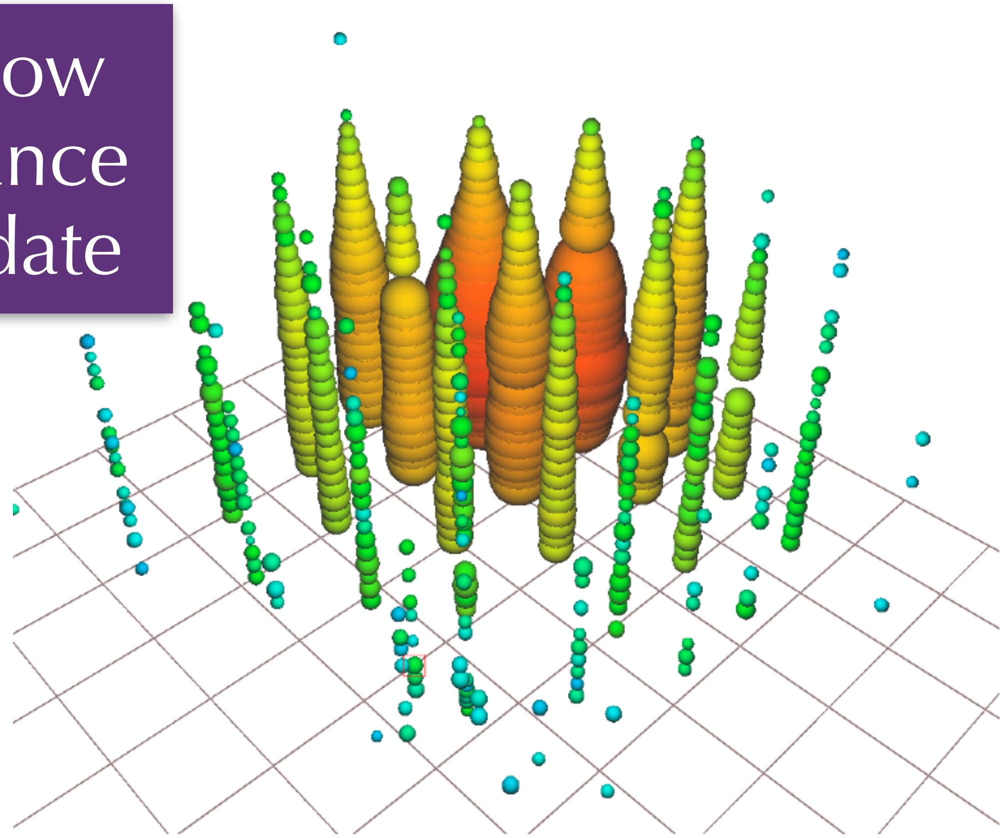
Likelihood contours of observed flavour ratios



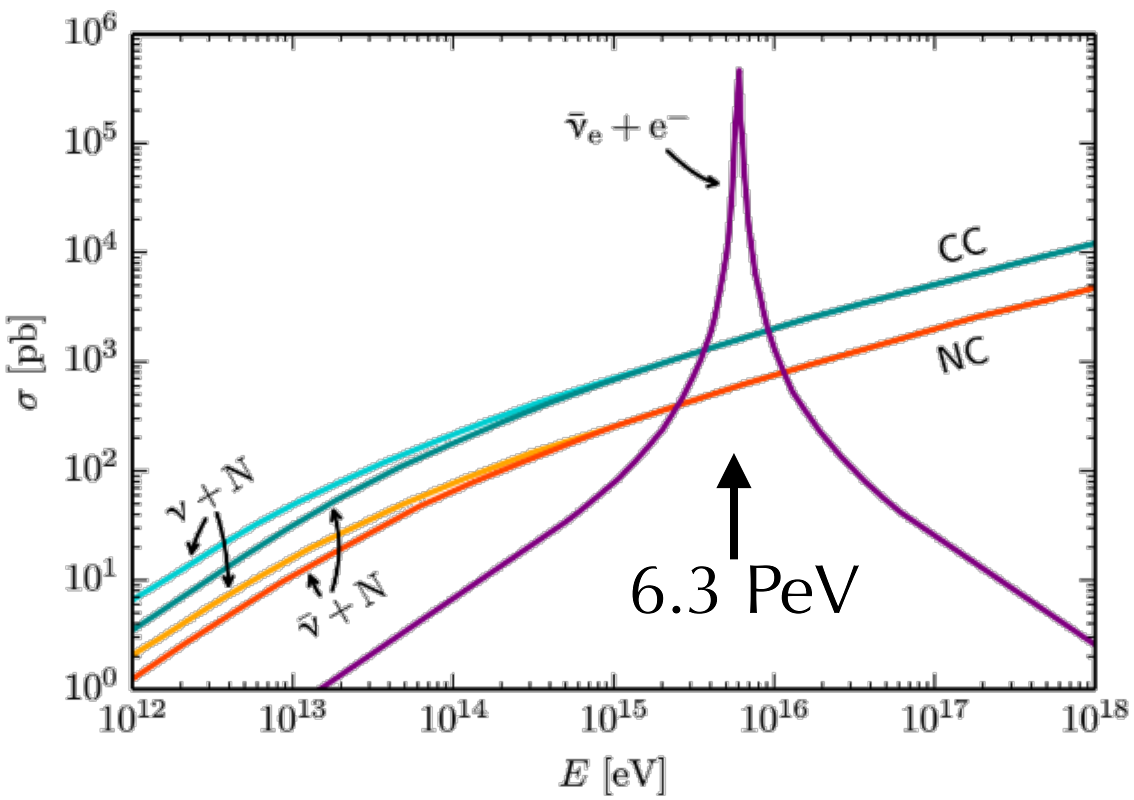
[IceCube, arXiv:2011.03561]

Astrophysical Flavours

Glashow resonance candidate

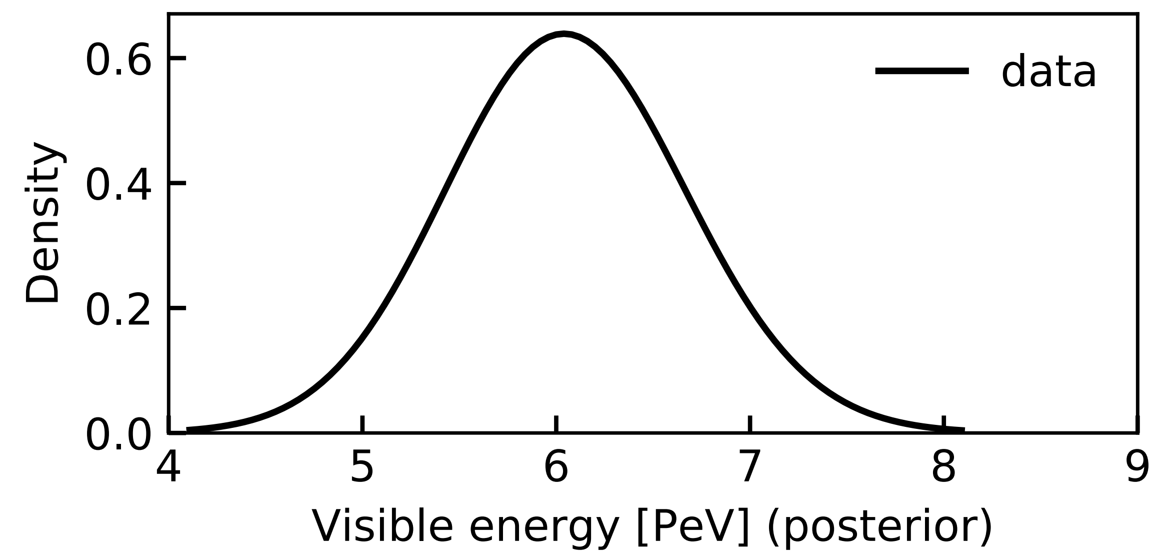


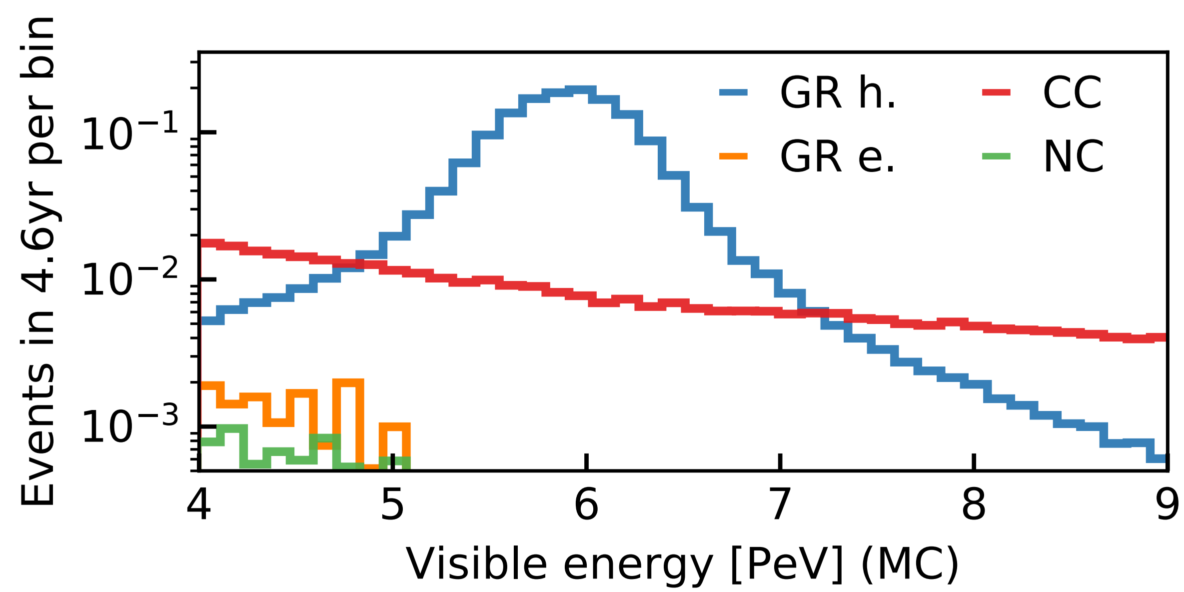
ICECUBE



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

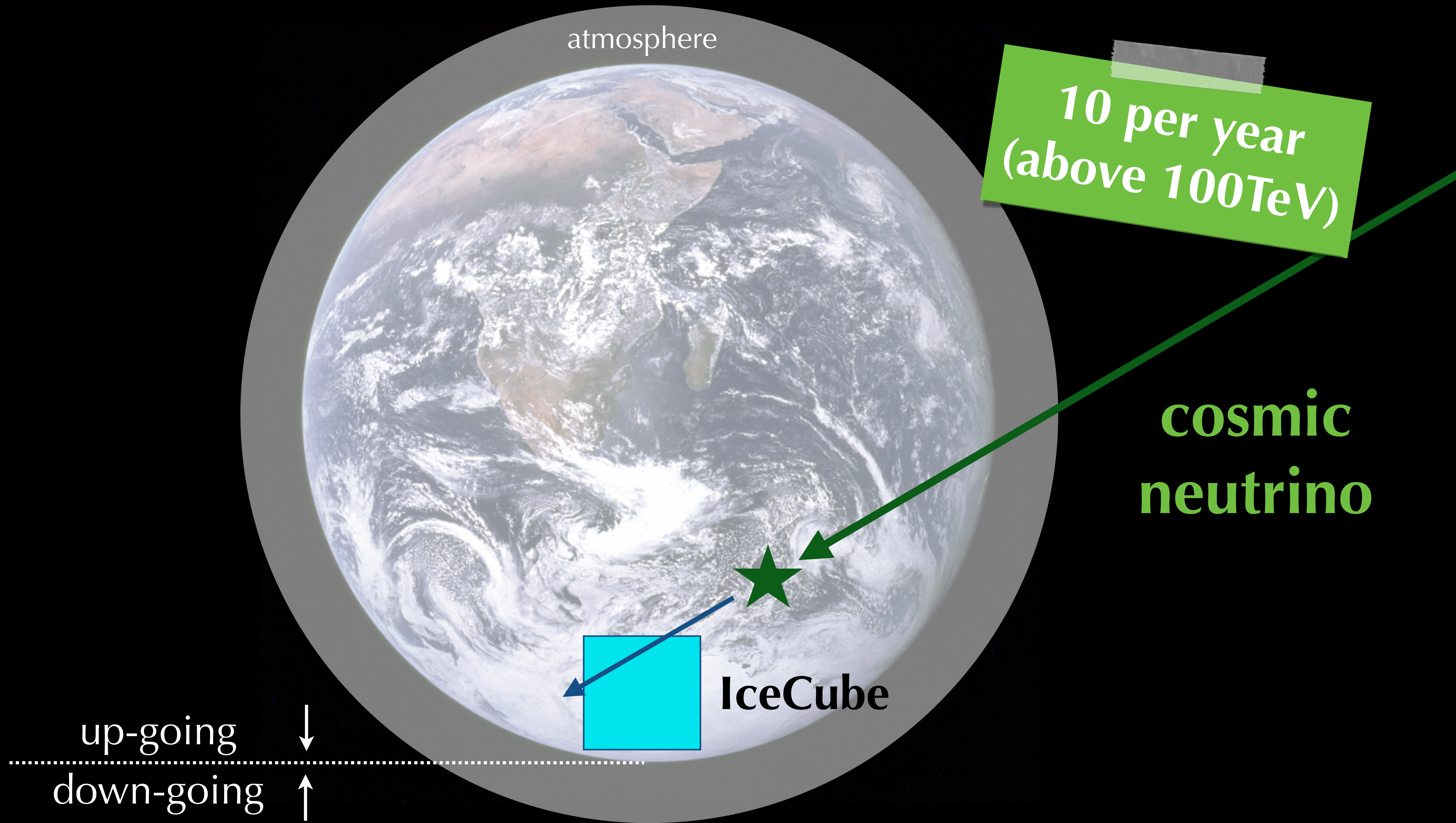
$$\bar{\nu}_e + e^- \to W^- \to X$$



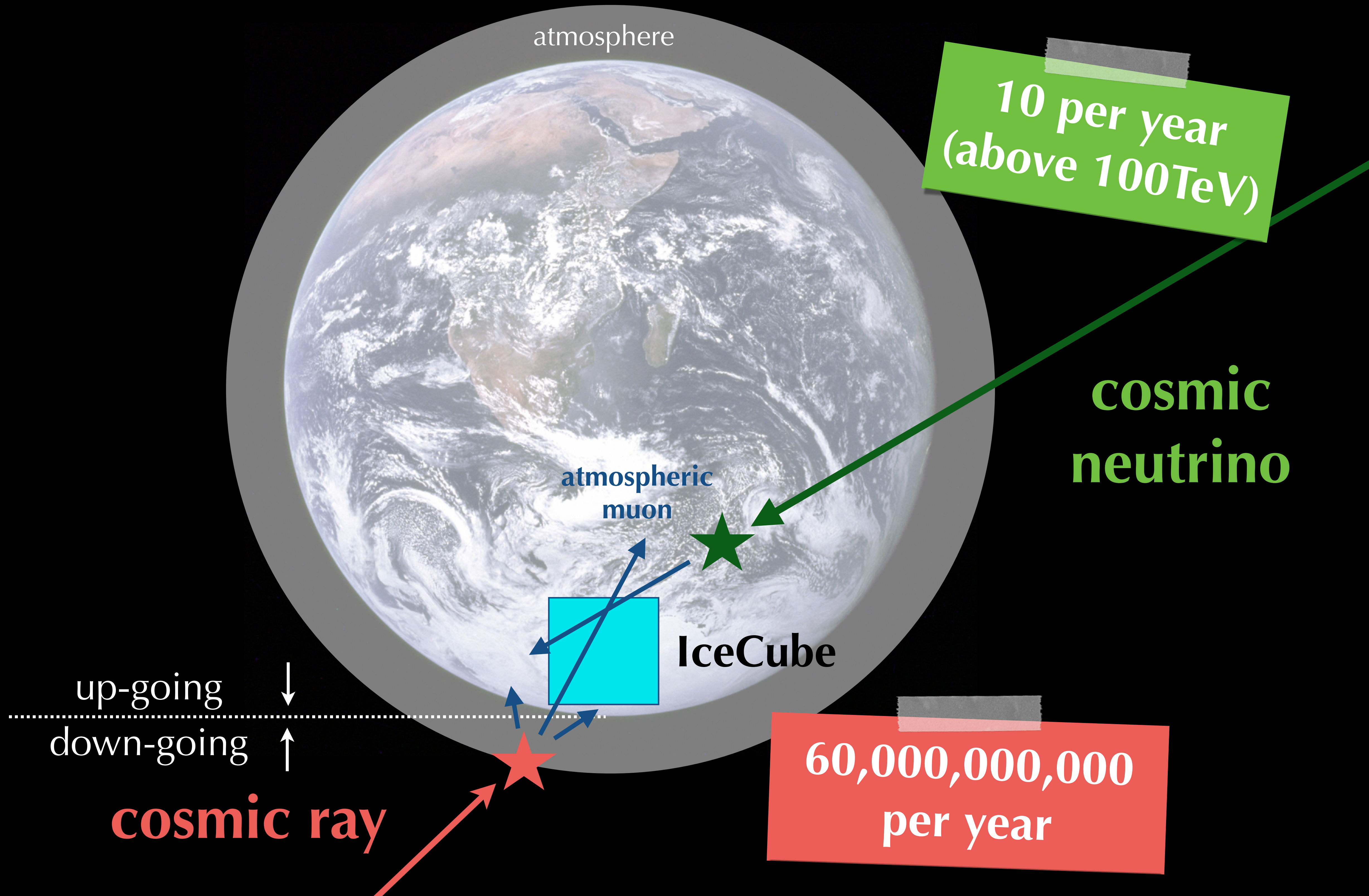


[IceCube, Nature 591 (2021) 220-224]

Neutrino Selection I



Neutrino Selection I



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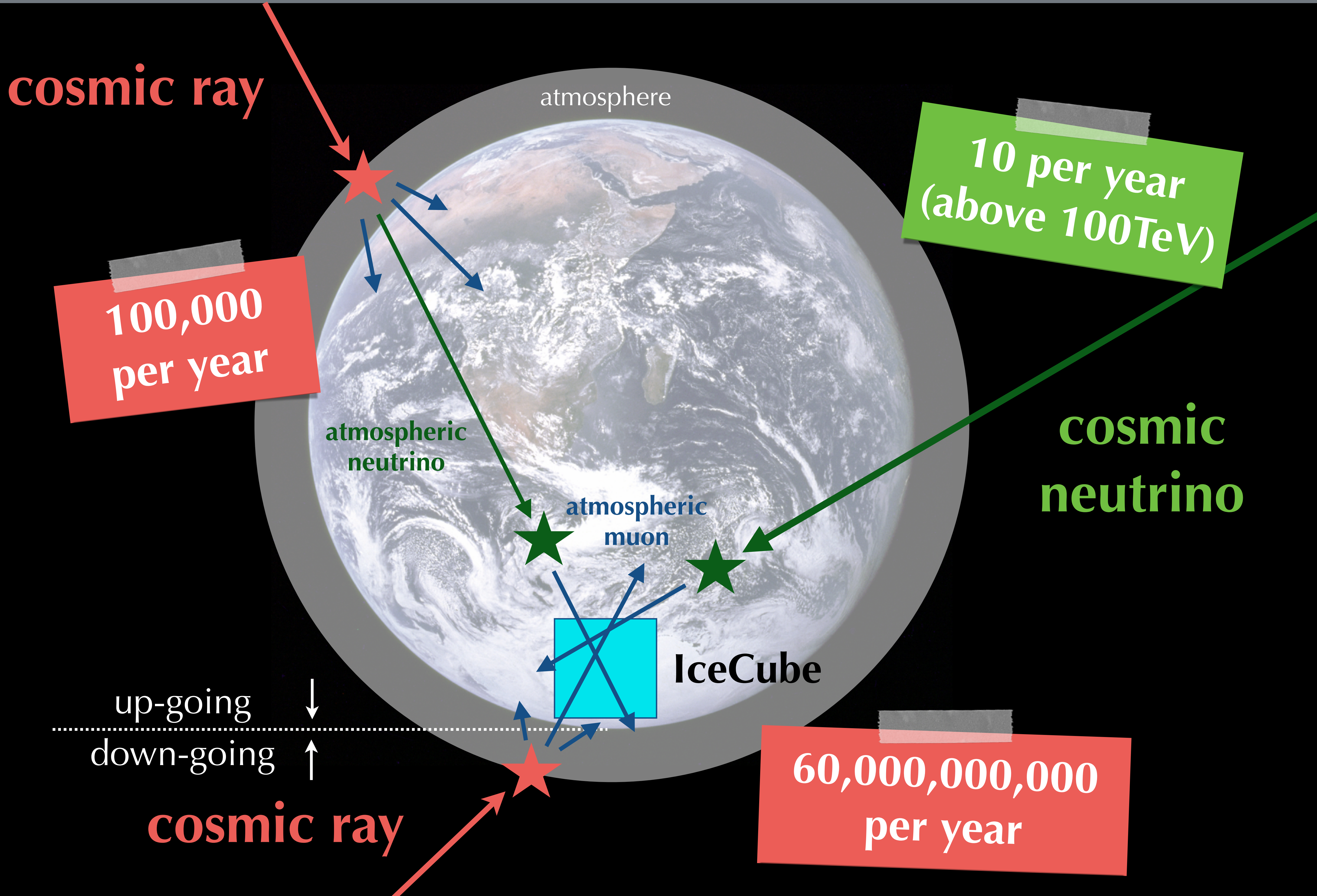
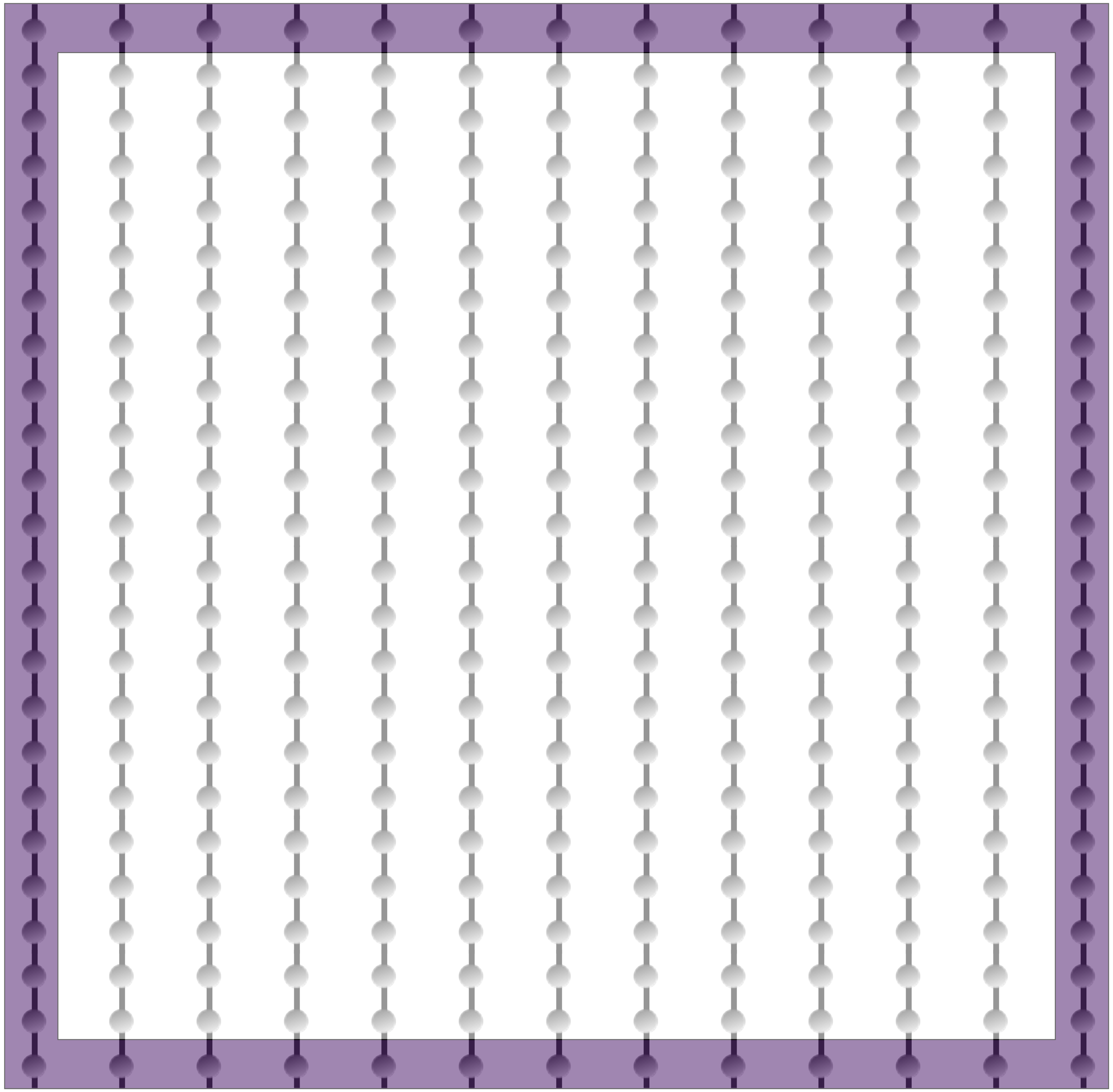


Neutrino Selection II

- 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



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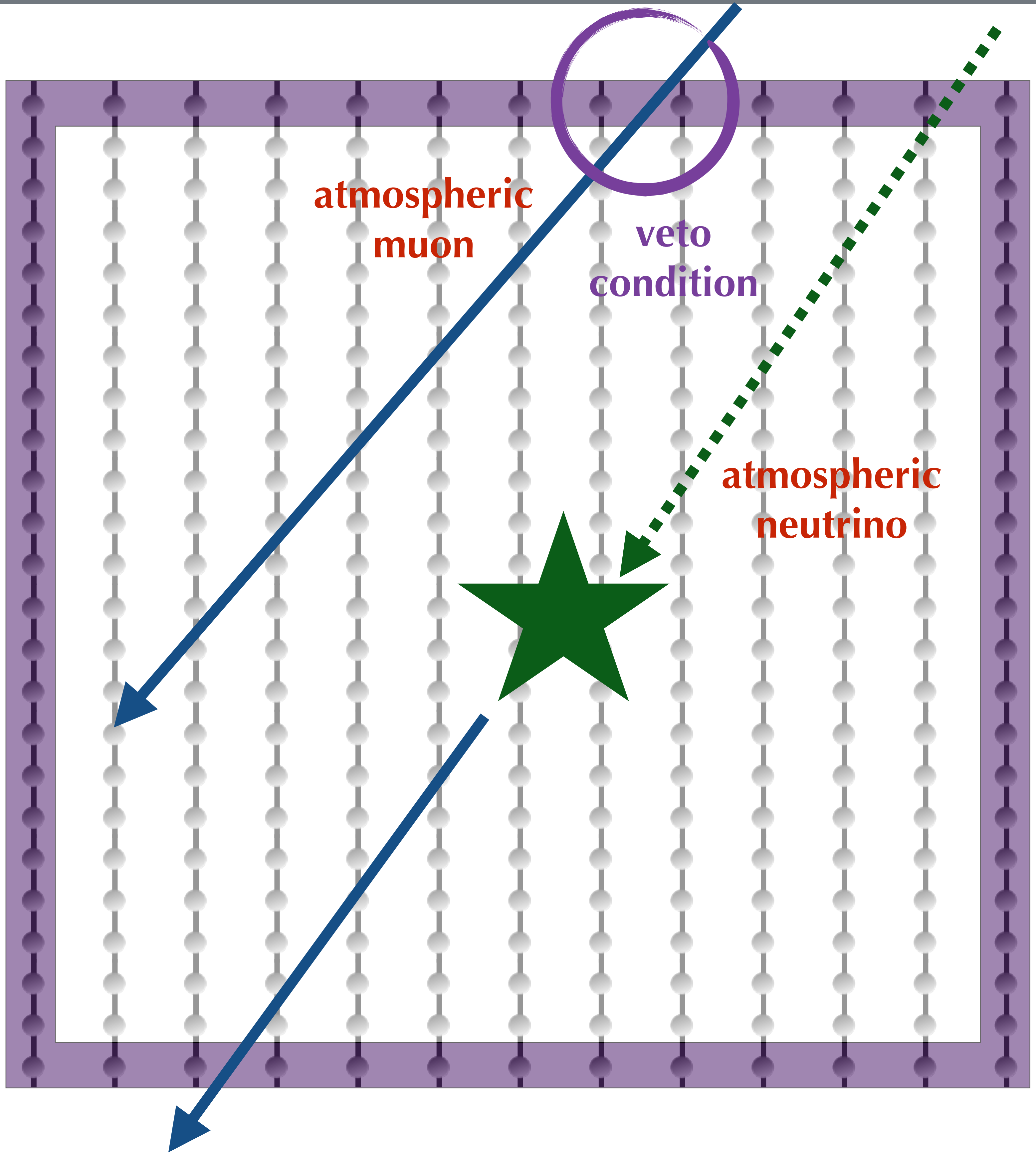

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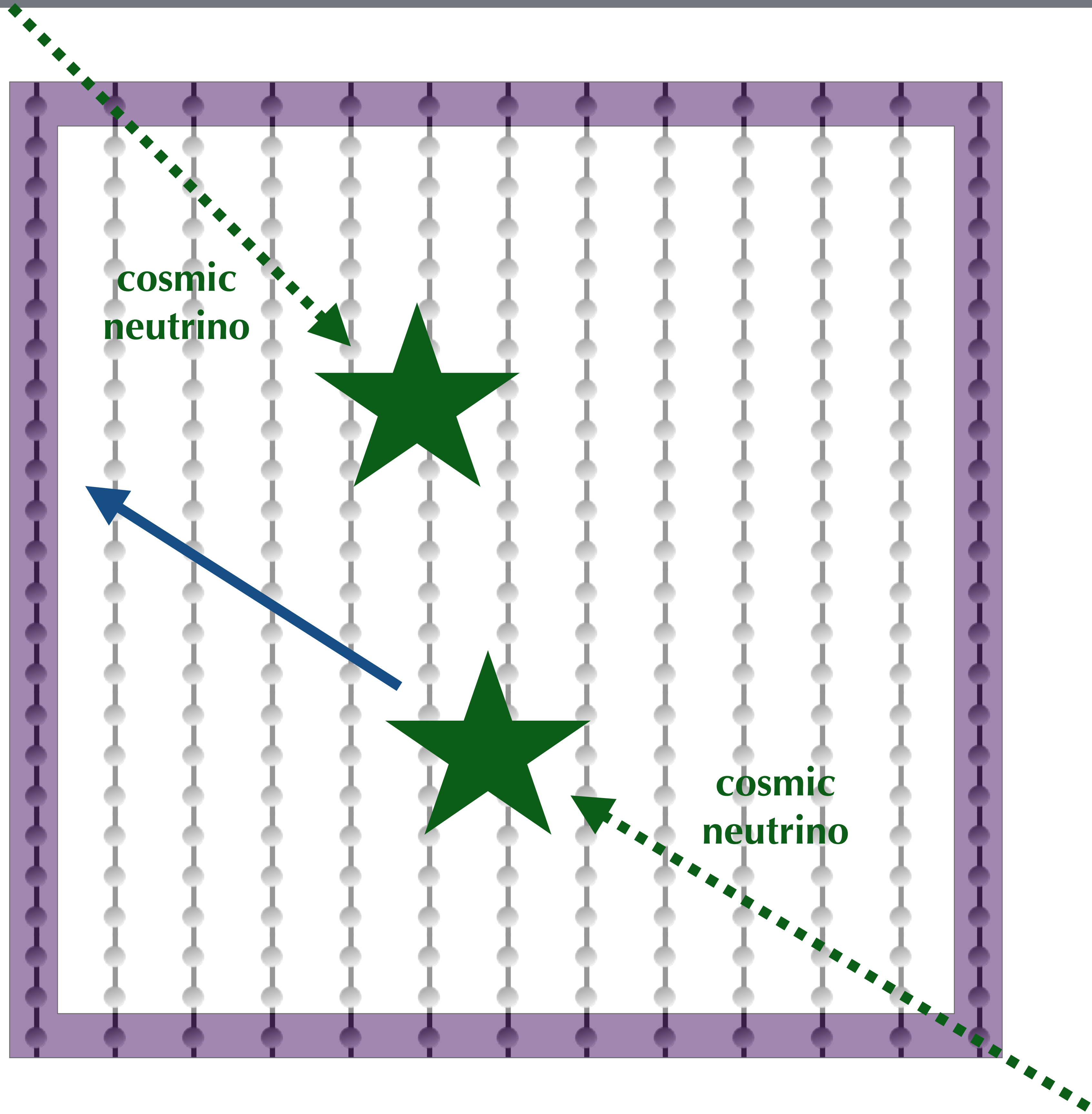
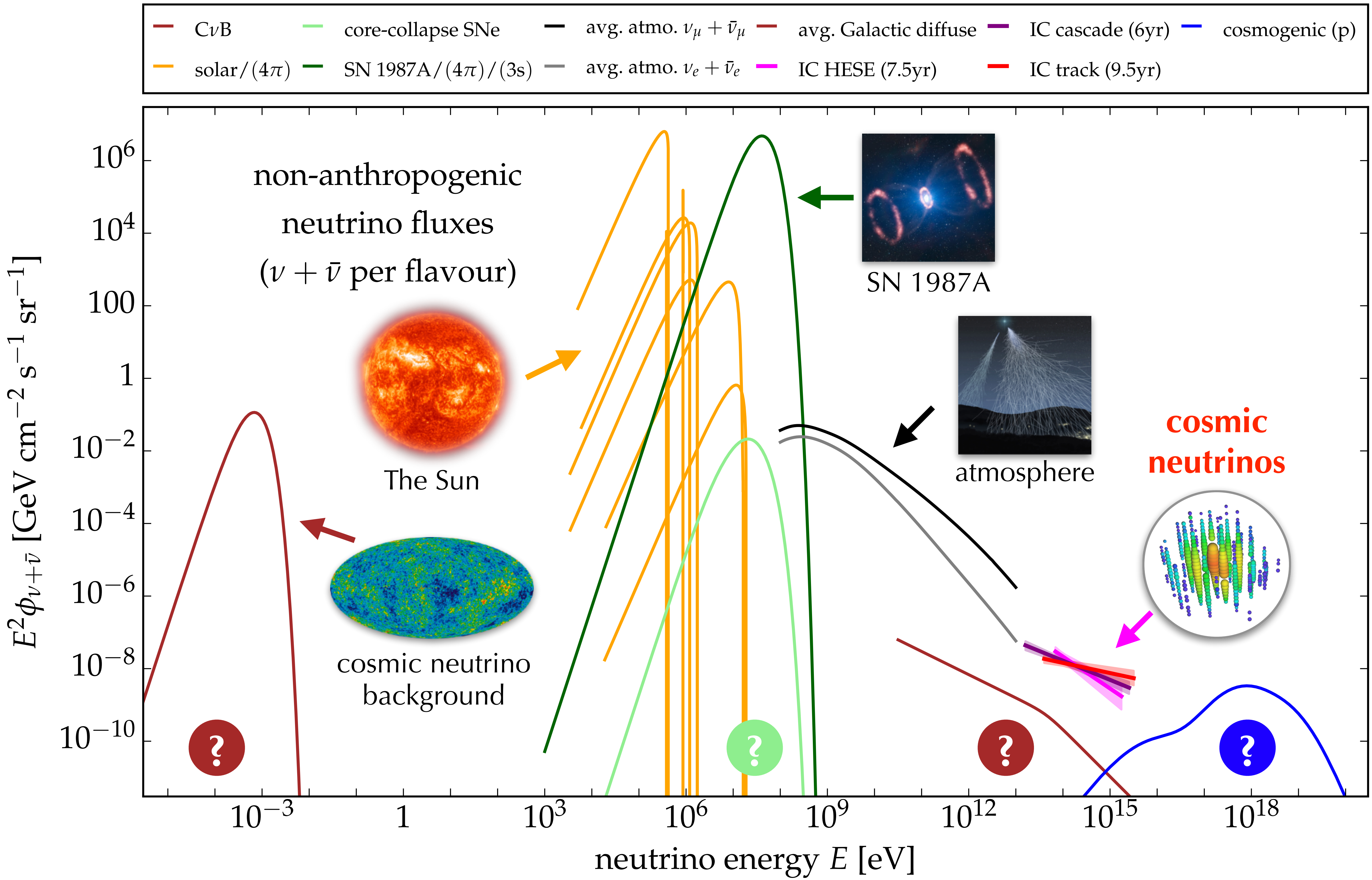
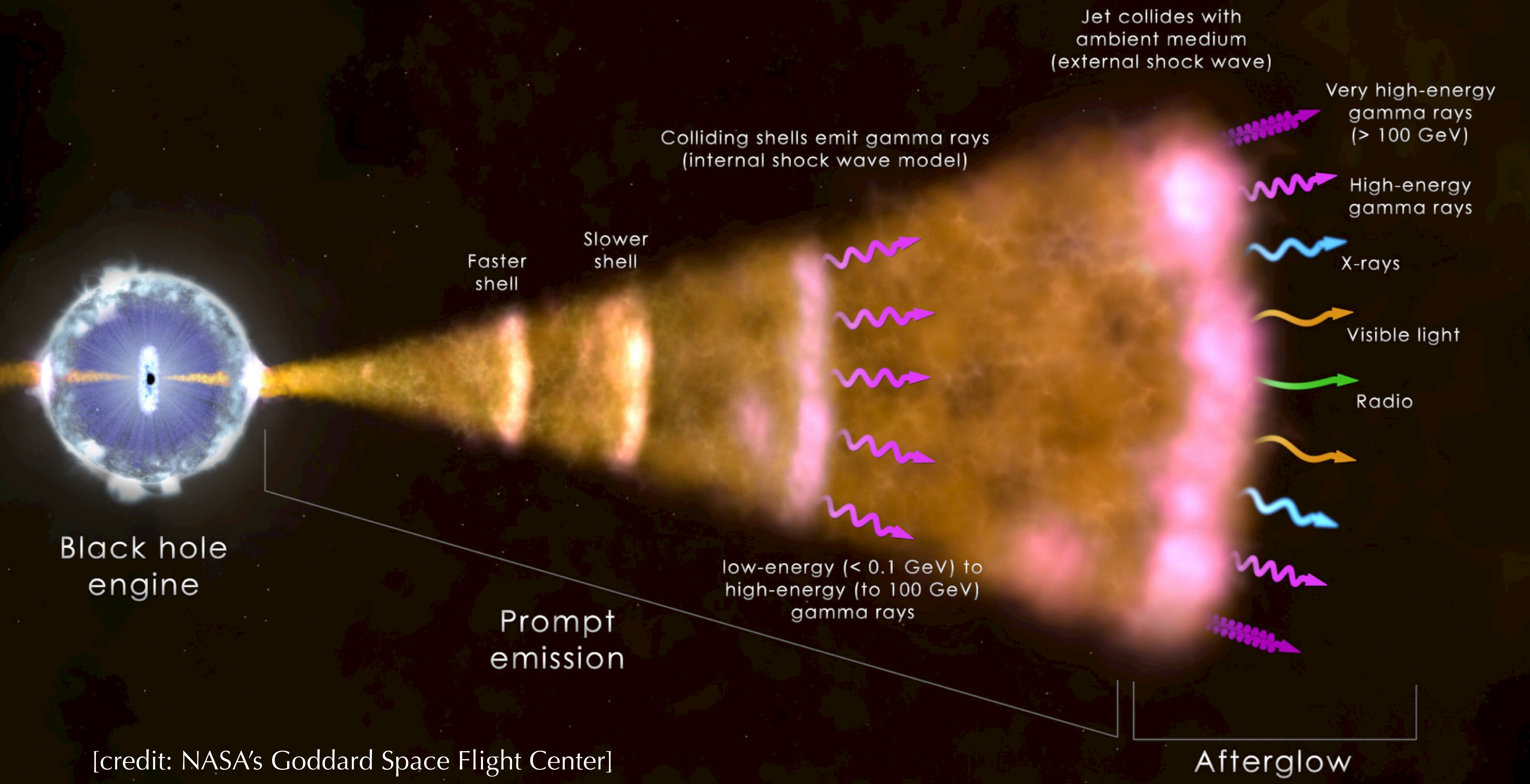


Astrophysical Neutrino Fluxes



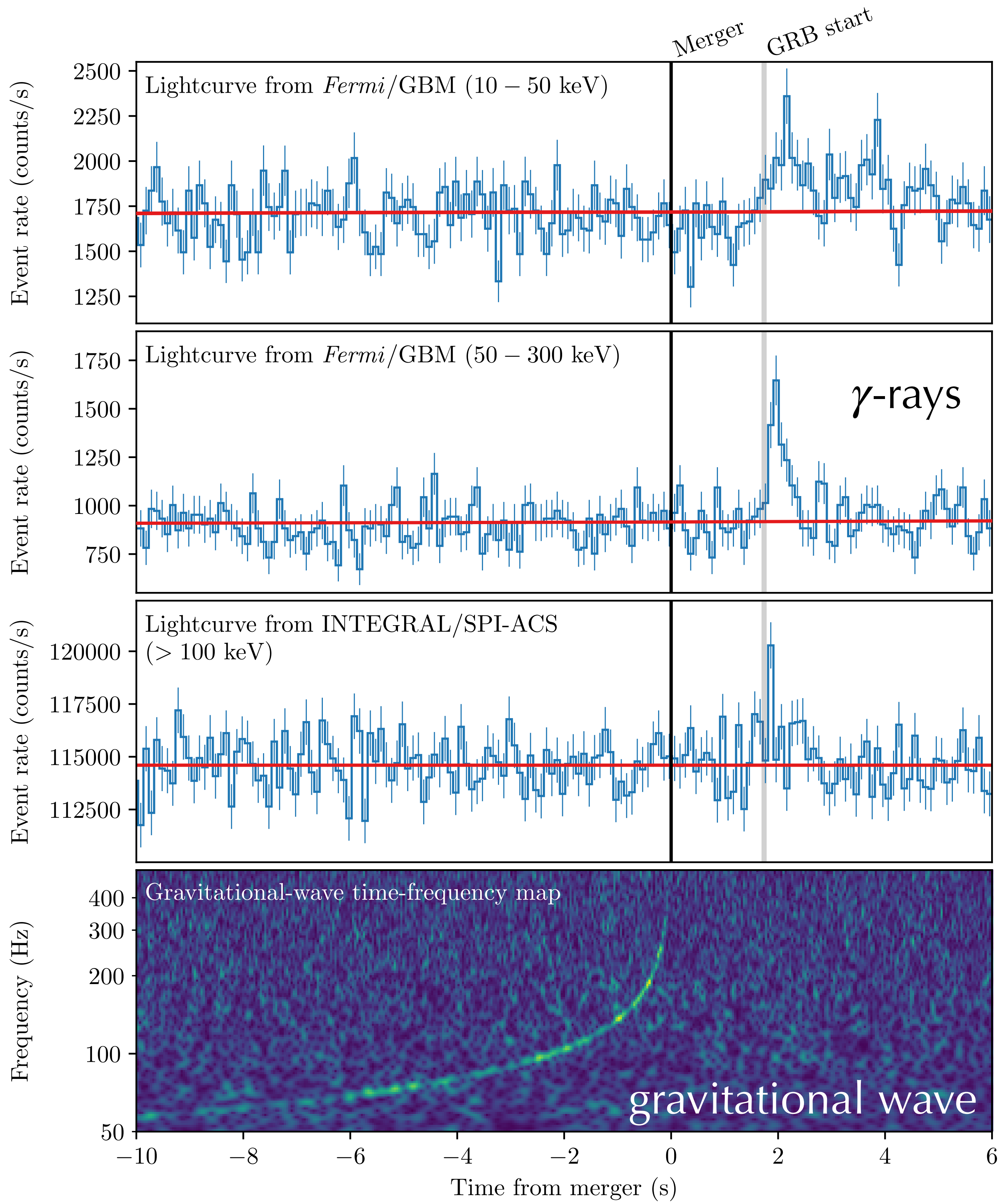
Gamma-Ray Bursts

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



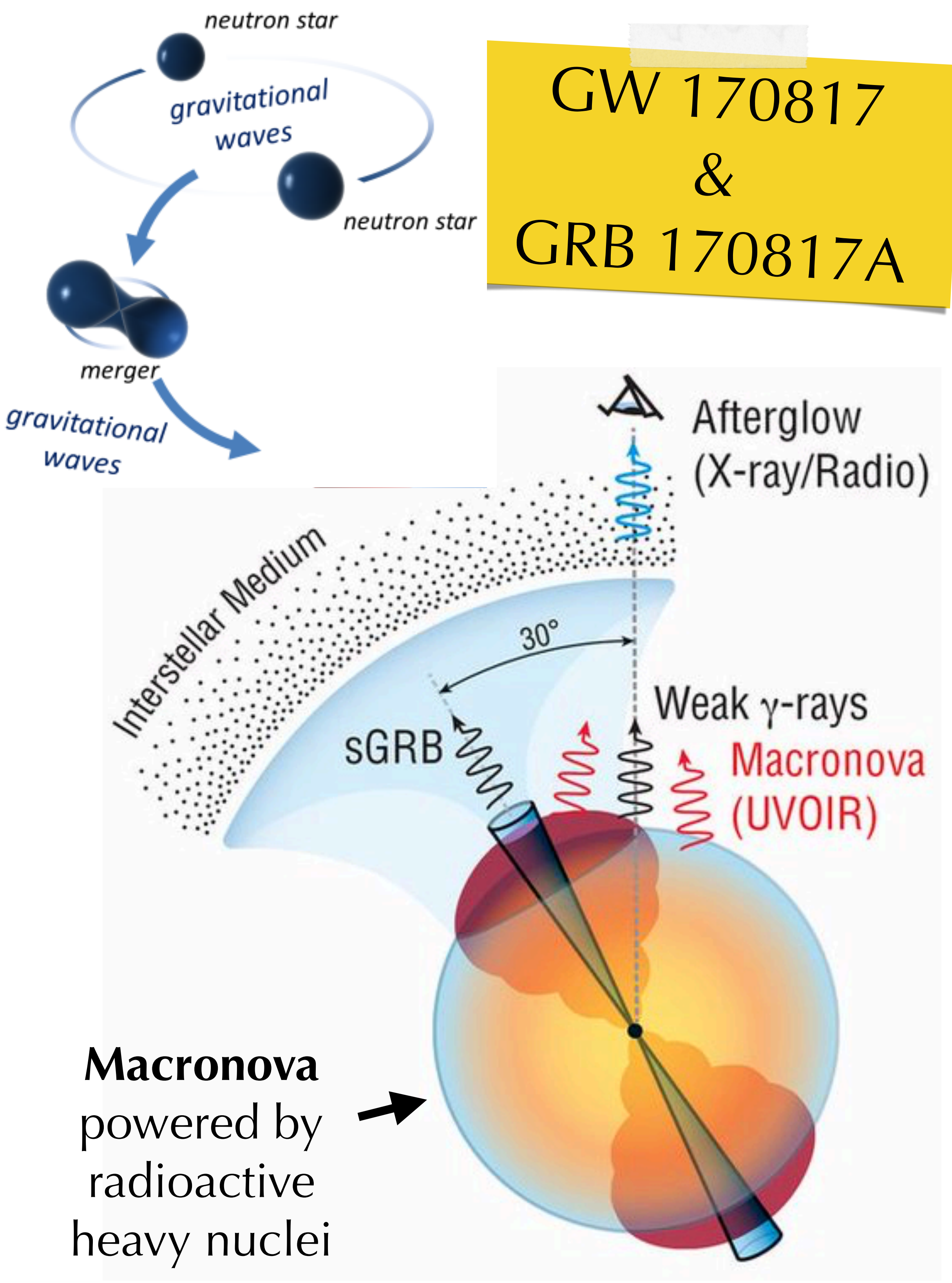
[credit: NASA's Goddard Space Flight Center]

GRBs and Gravitational Waves



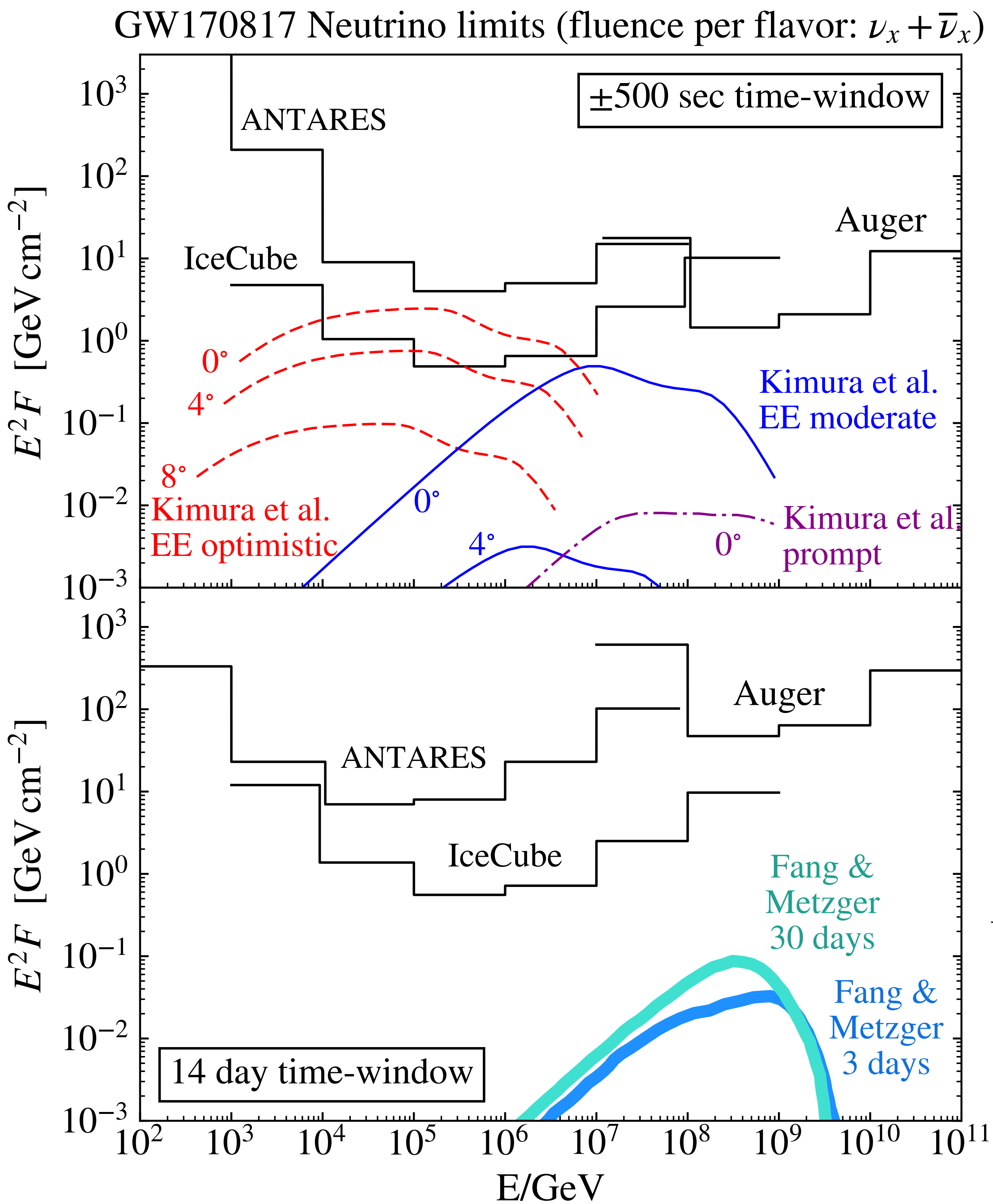
[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]

GW 170817
&
GRB 170817A

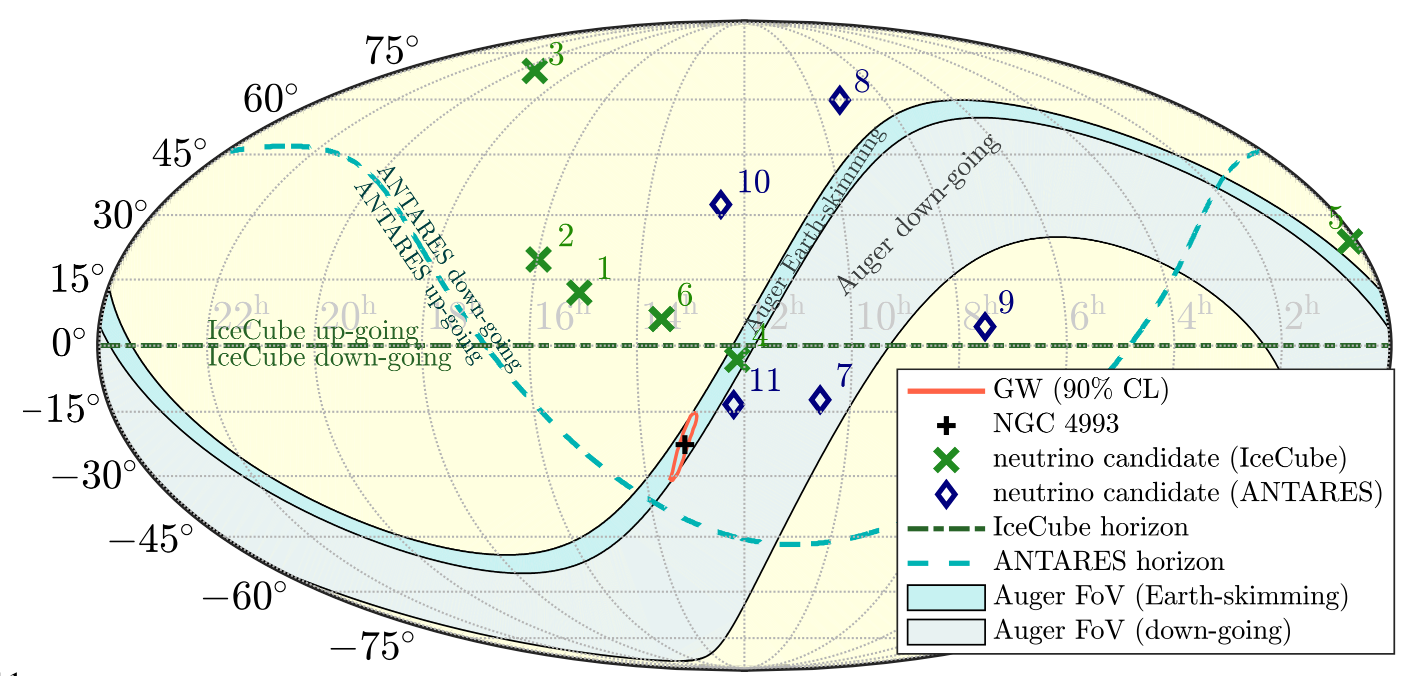


Macronova powered by radioactive heavy nuclei

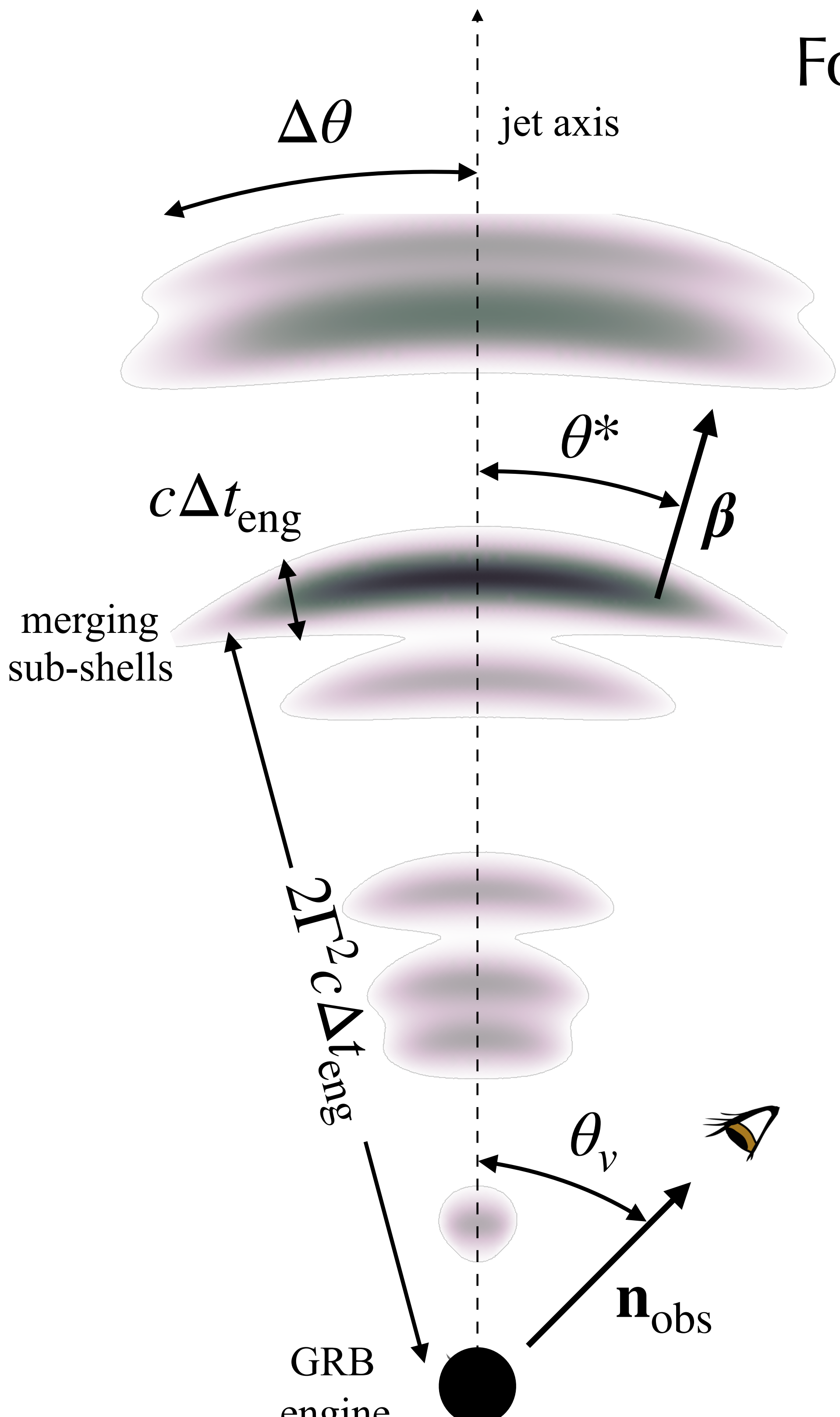
GRB 170817A



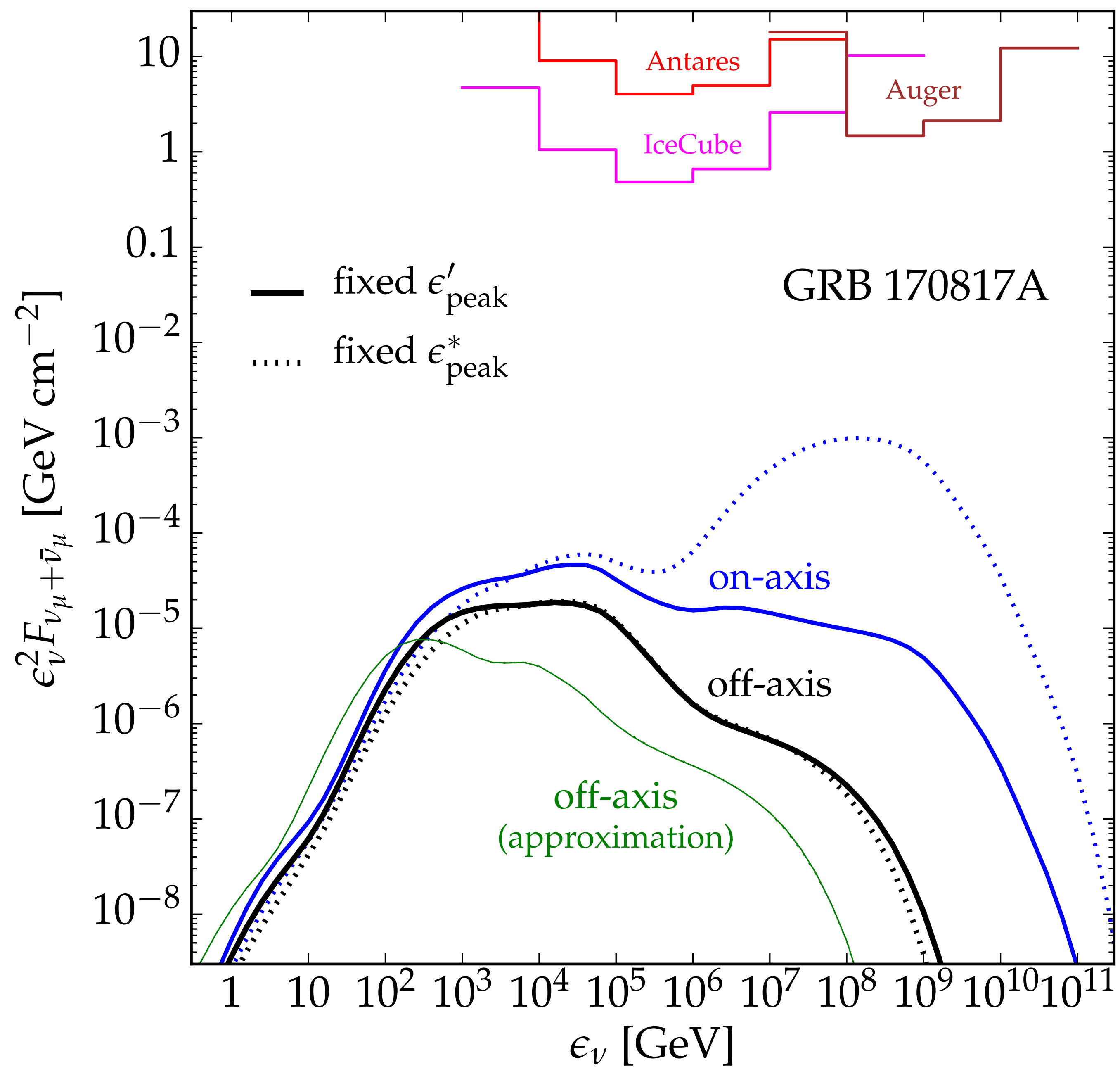
- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle.**



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

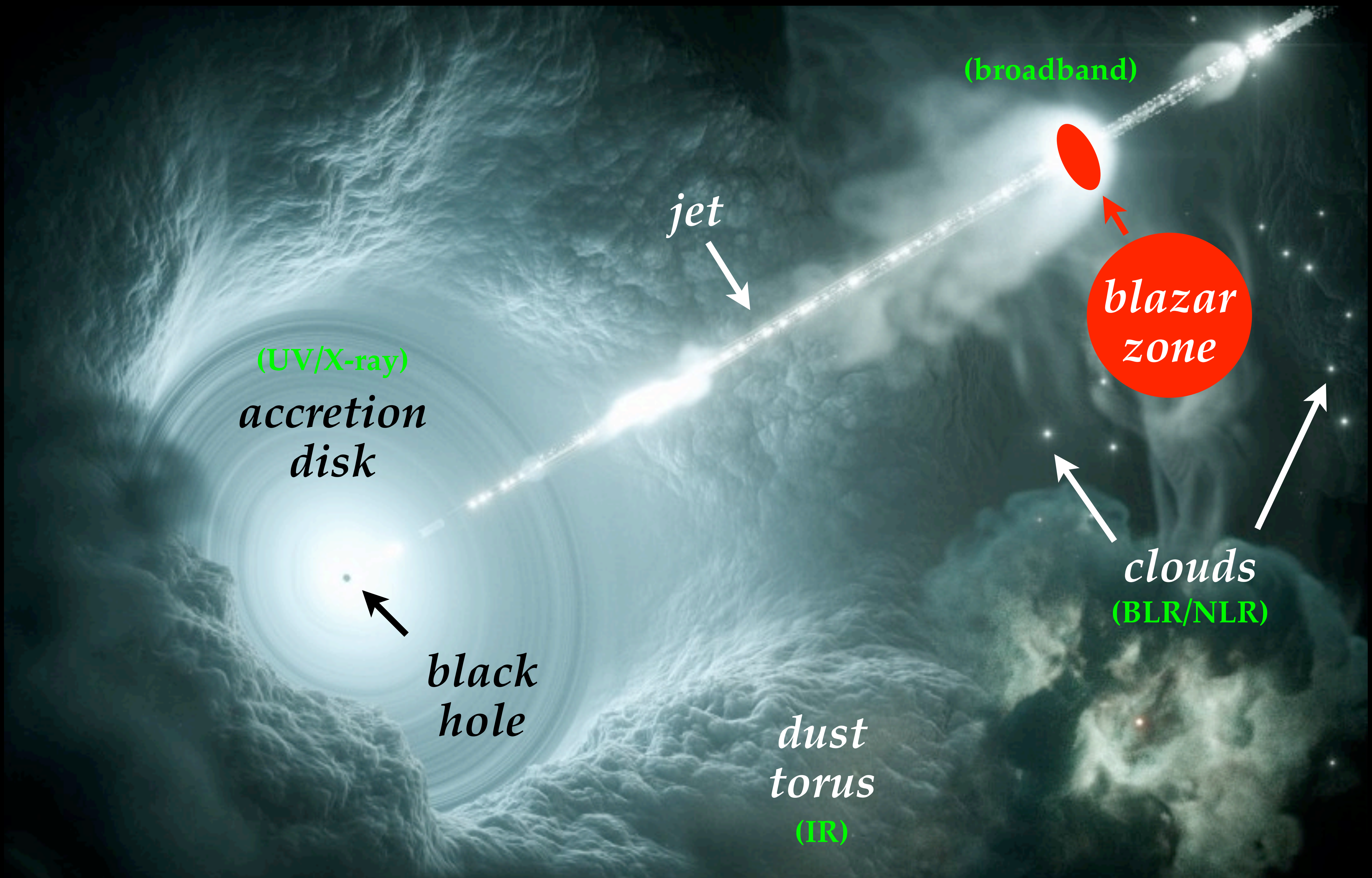


Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



[MA & Halser MNRAS 490 (2019) 4]

Blazars as Neutrino Factories



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

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:

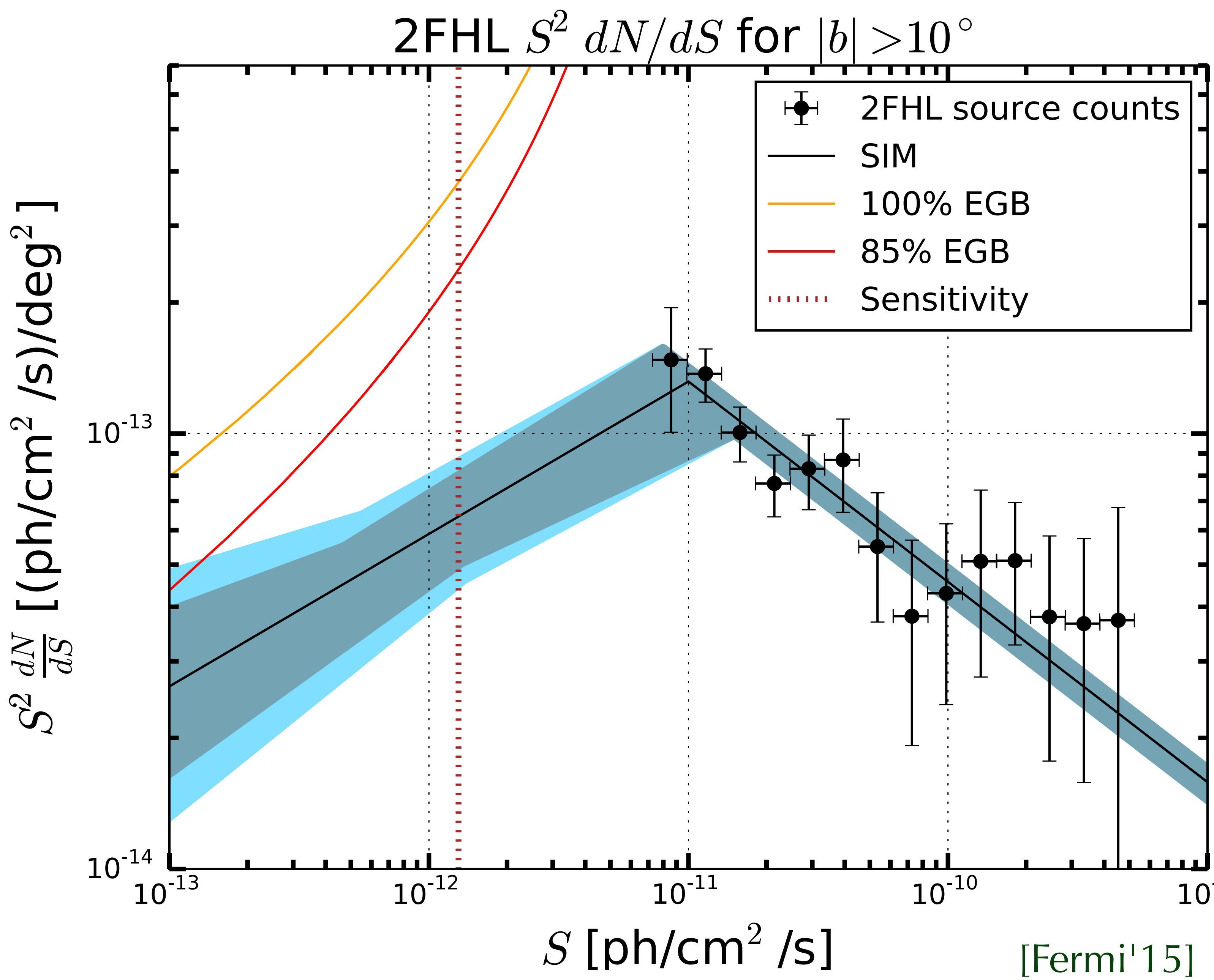
$$86^{+16}_{-14}\,\%$$

  - Lisanti *et al.*'16:

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

  - Zechlin *et al.*'16

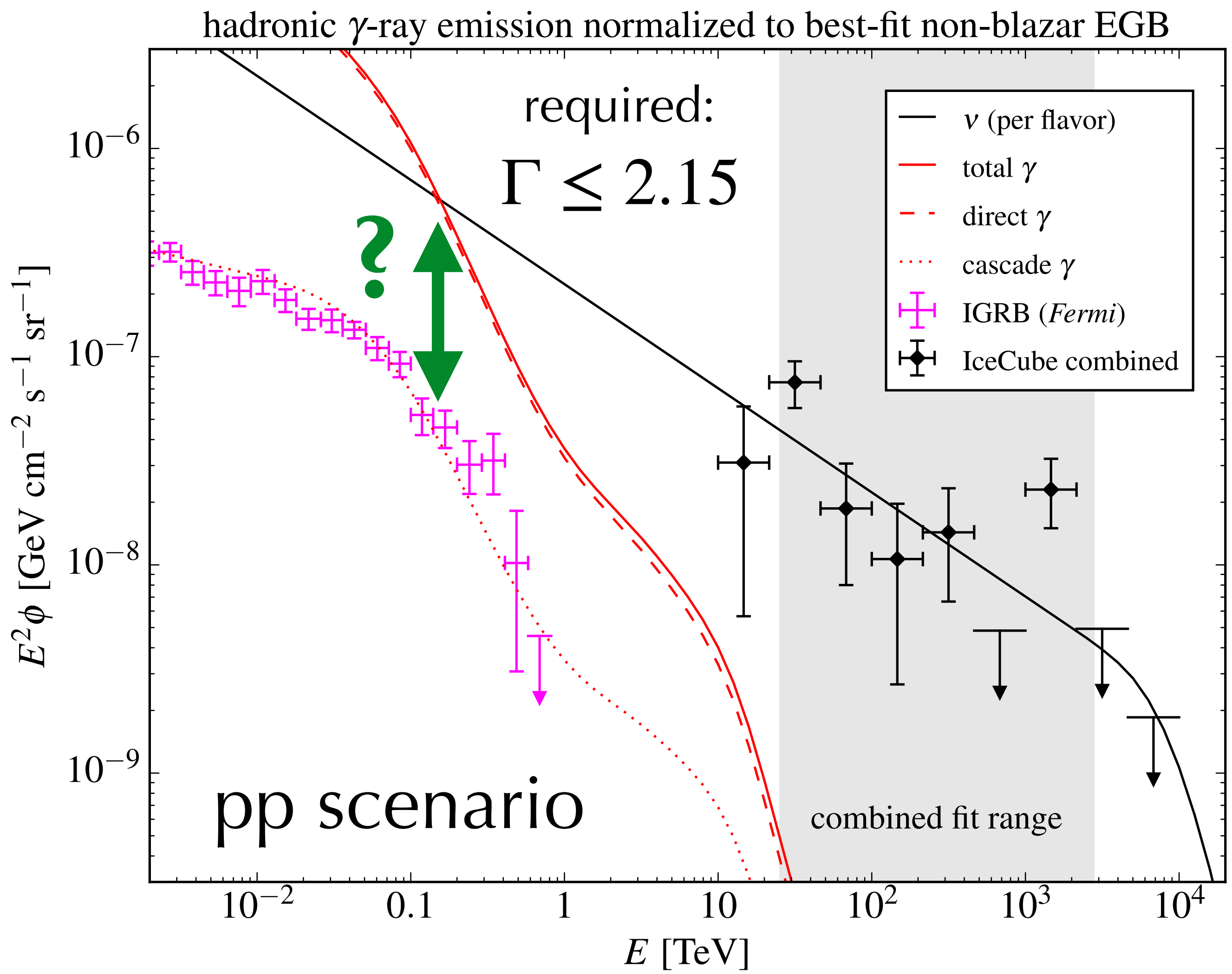
$$81^{+52}_{-19}\,\%$$

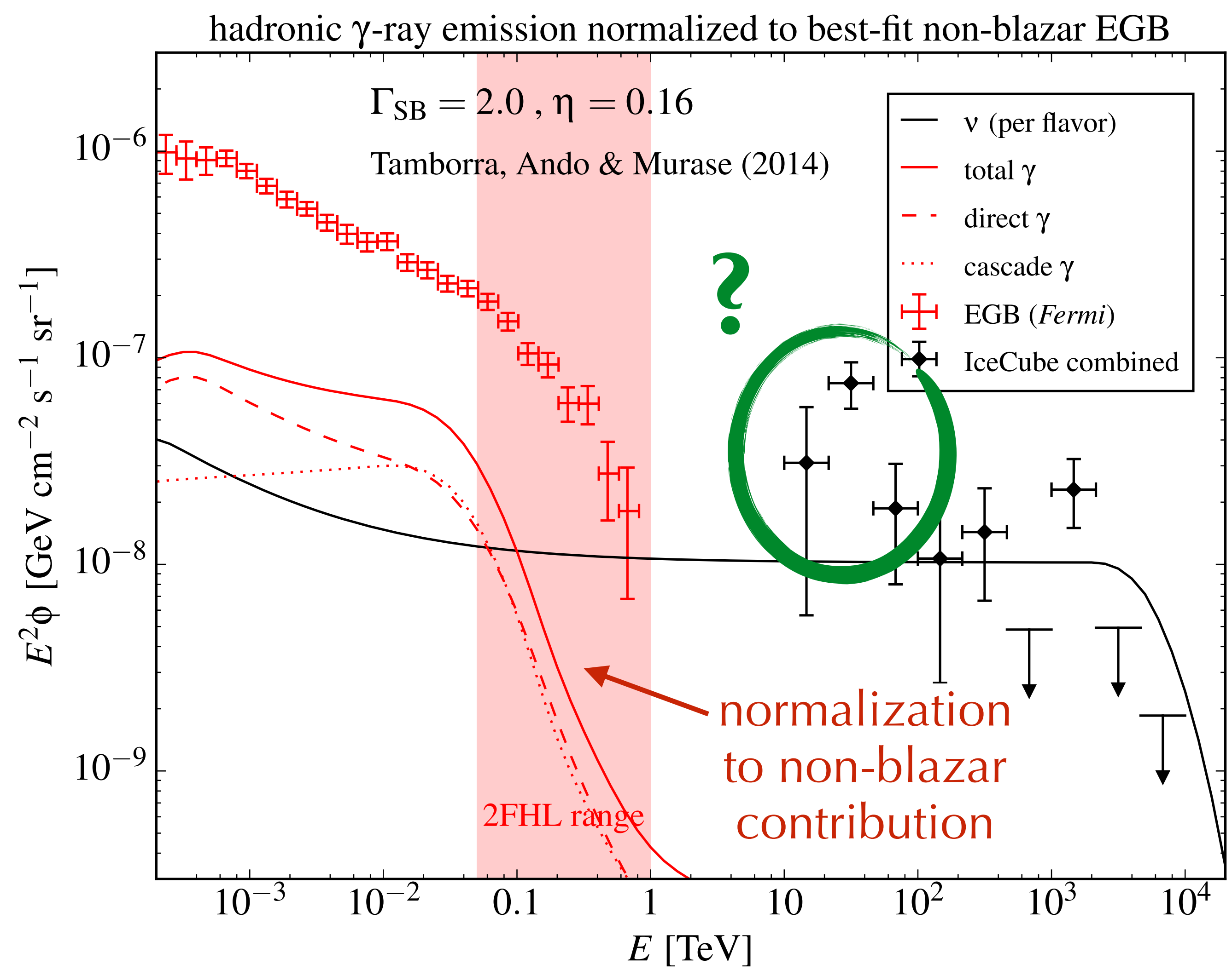


[Fermi'15]

Hadronic Gamma-Rays

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



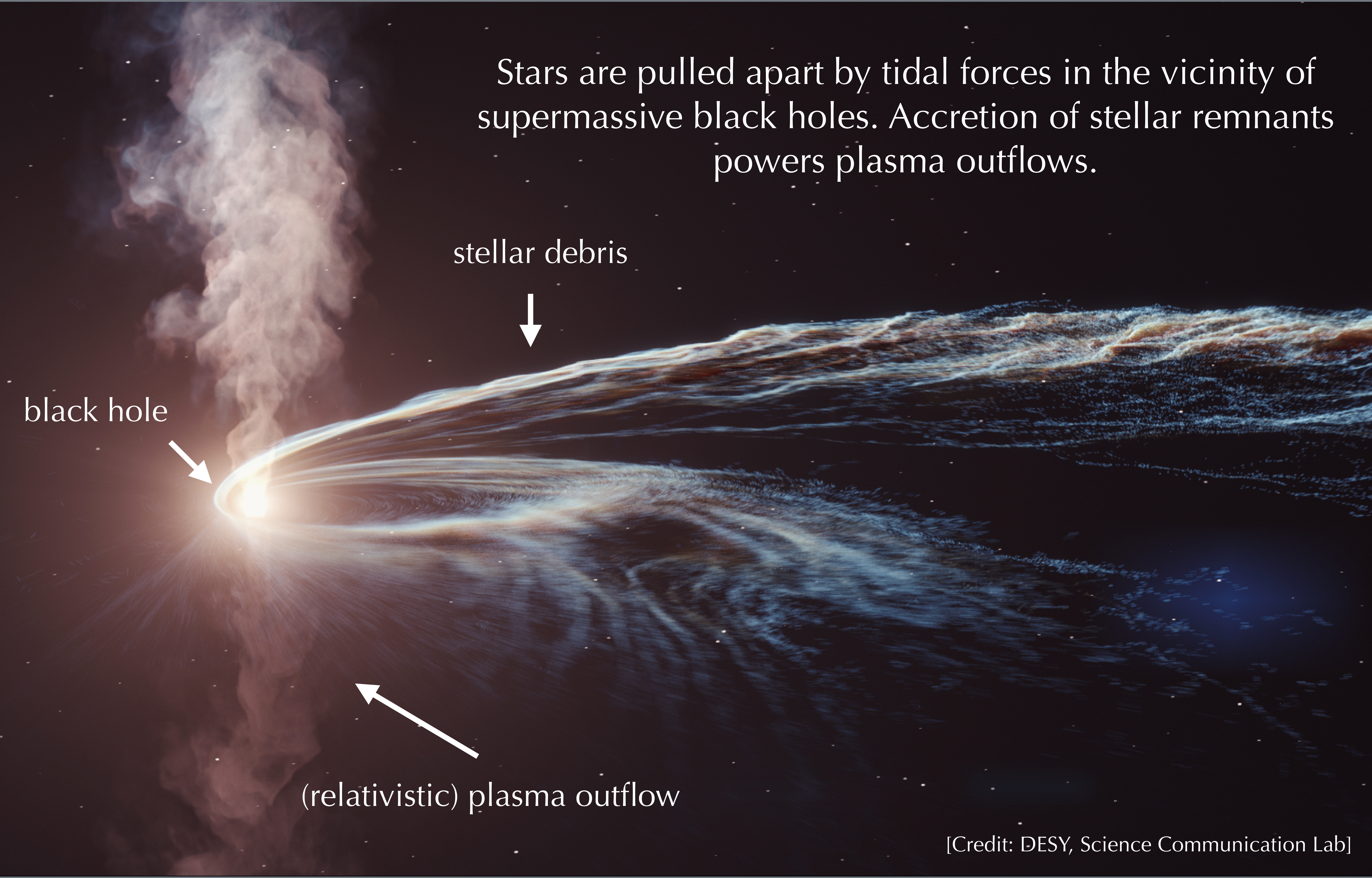


[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15]

[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]

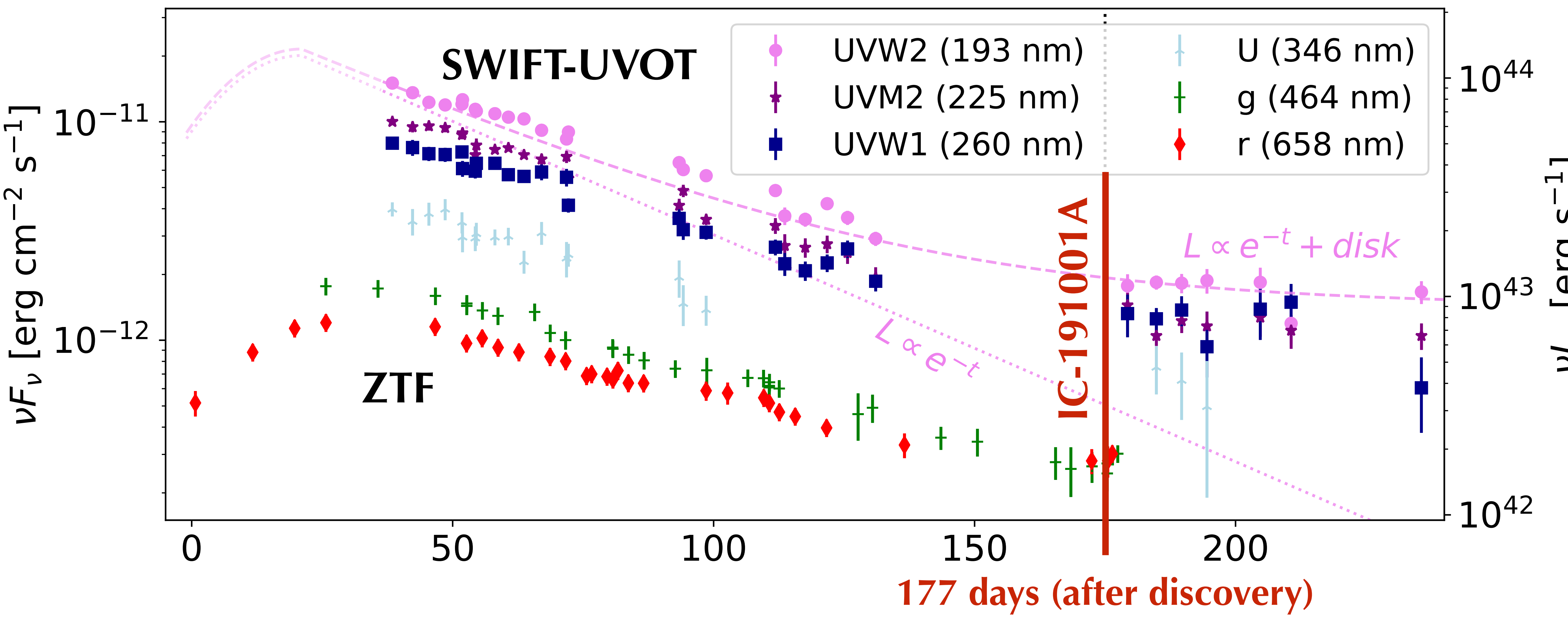
Tidal Disruption Events

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]

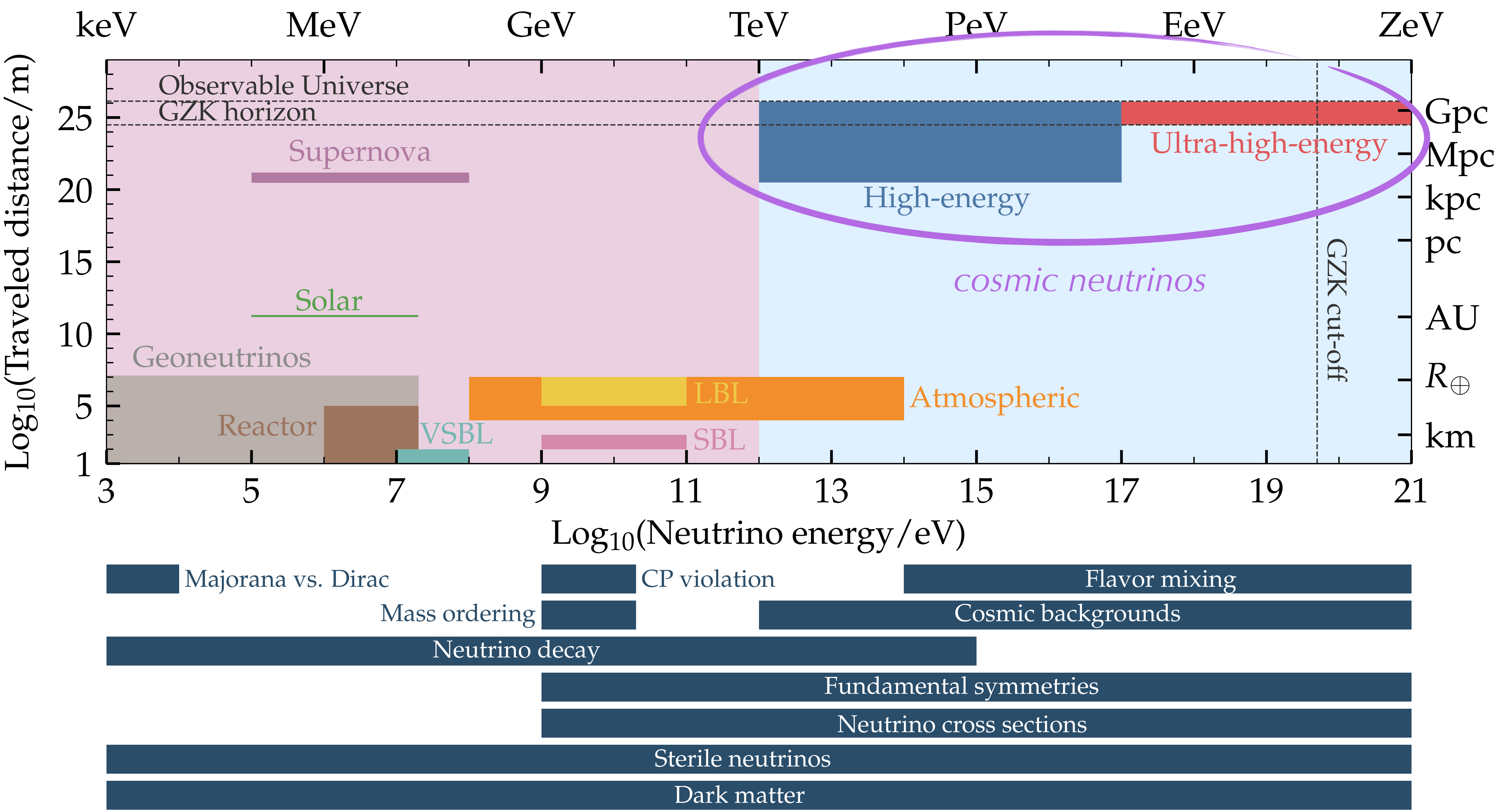
Tidal Disruption Events



[Stein, R., Velzen, S.v., Kowalski, M. et al., Nature Astronomy (2021)]

- Association of alert IC-191001A with radio-emitting TDE AT2019dsg
- Plot shows data from Zwicky-Transient Facility and SWIFT-UVOT.
- Chance for random correlation of TDEs and IceCube alerts is 0.5%.

Probe of Fundamental Physics



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