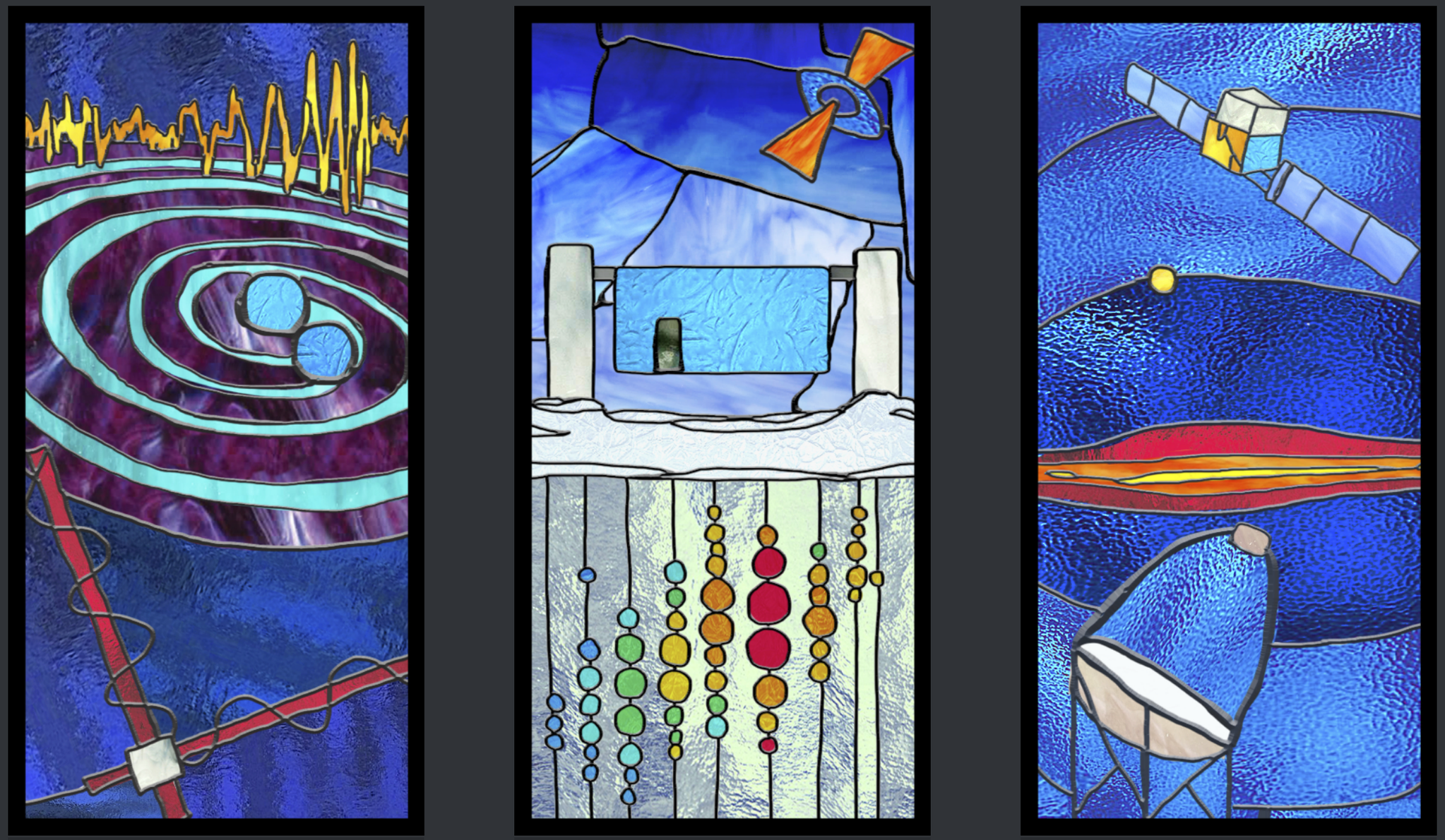


High-Energy Neutrino Observations by IceCube

Markus Ahlers

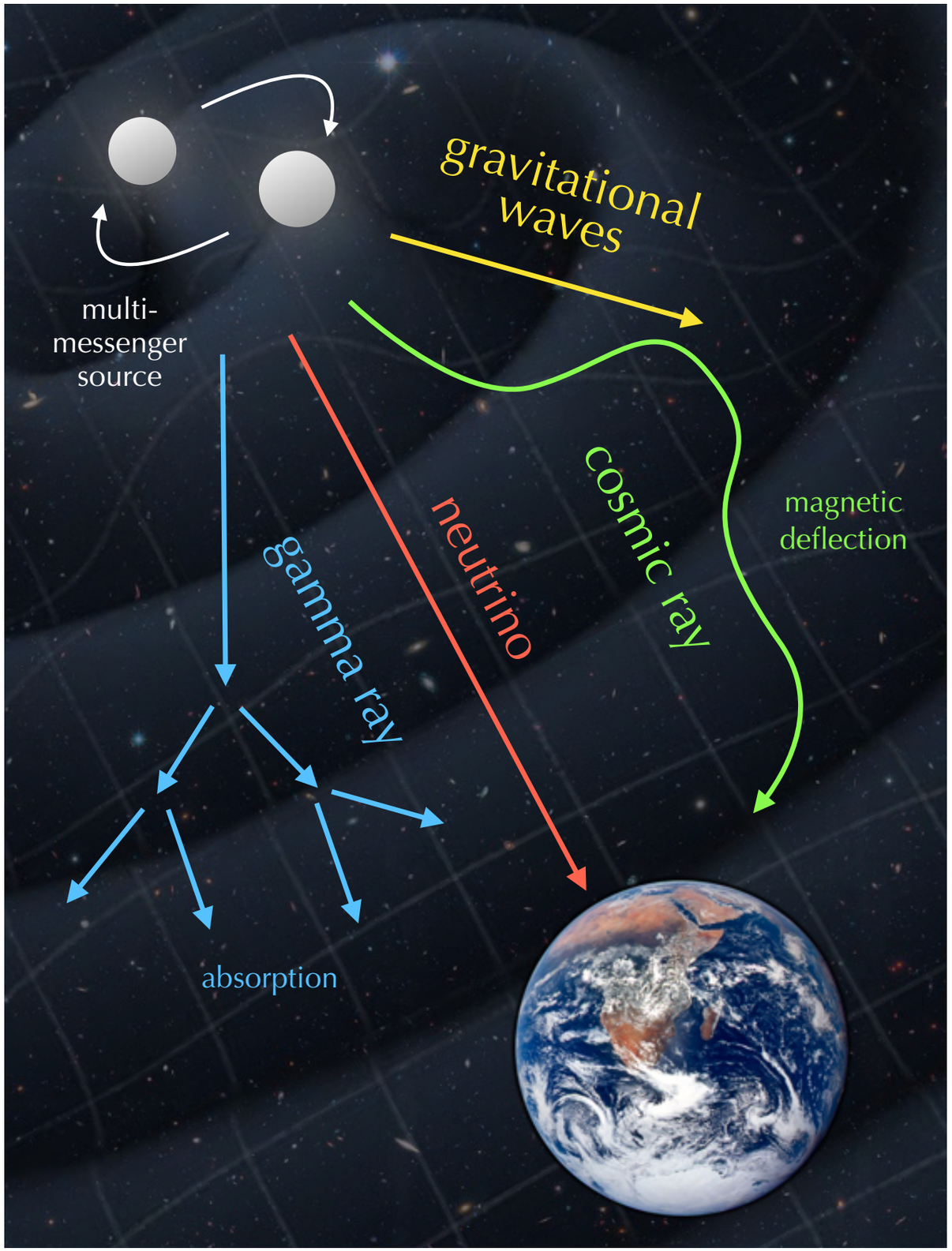
Niels Bohr Institute

Fermi Symposium, April 14, 2021

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

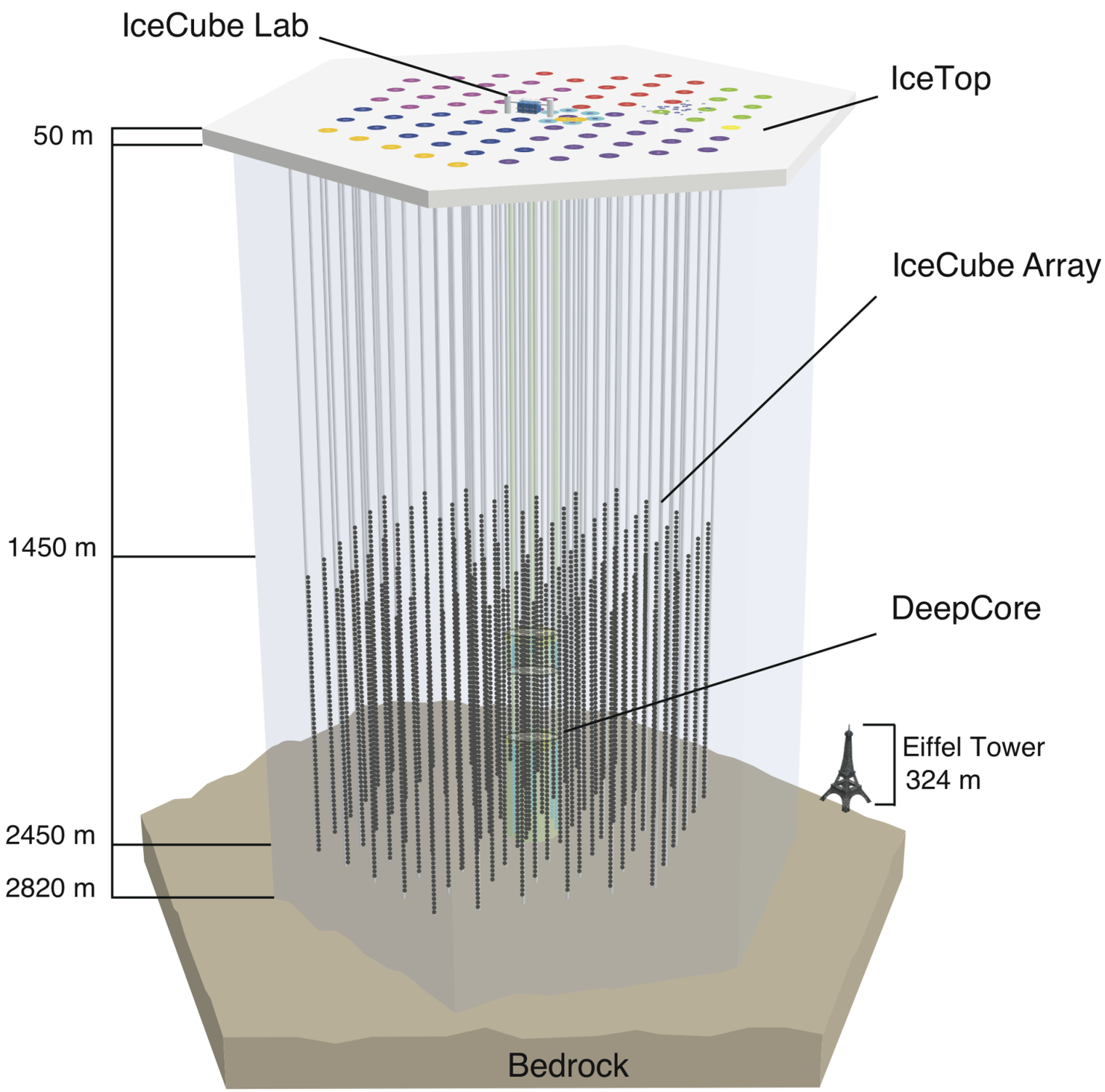
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

IceCube Observatory

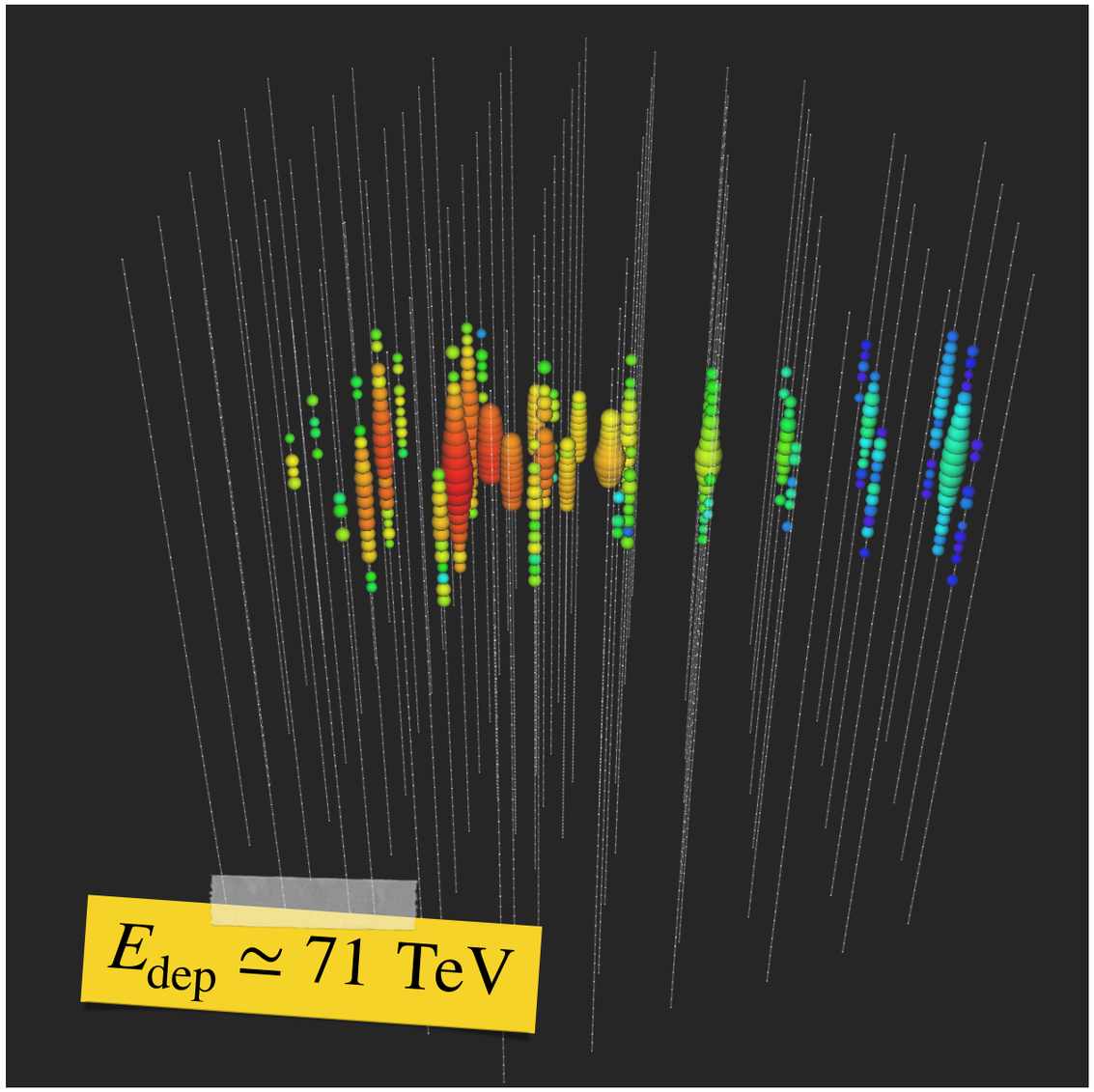


- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

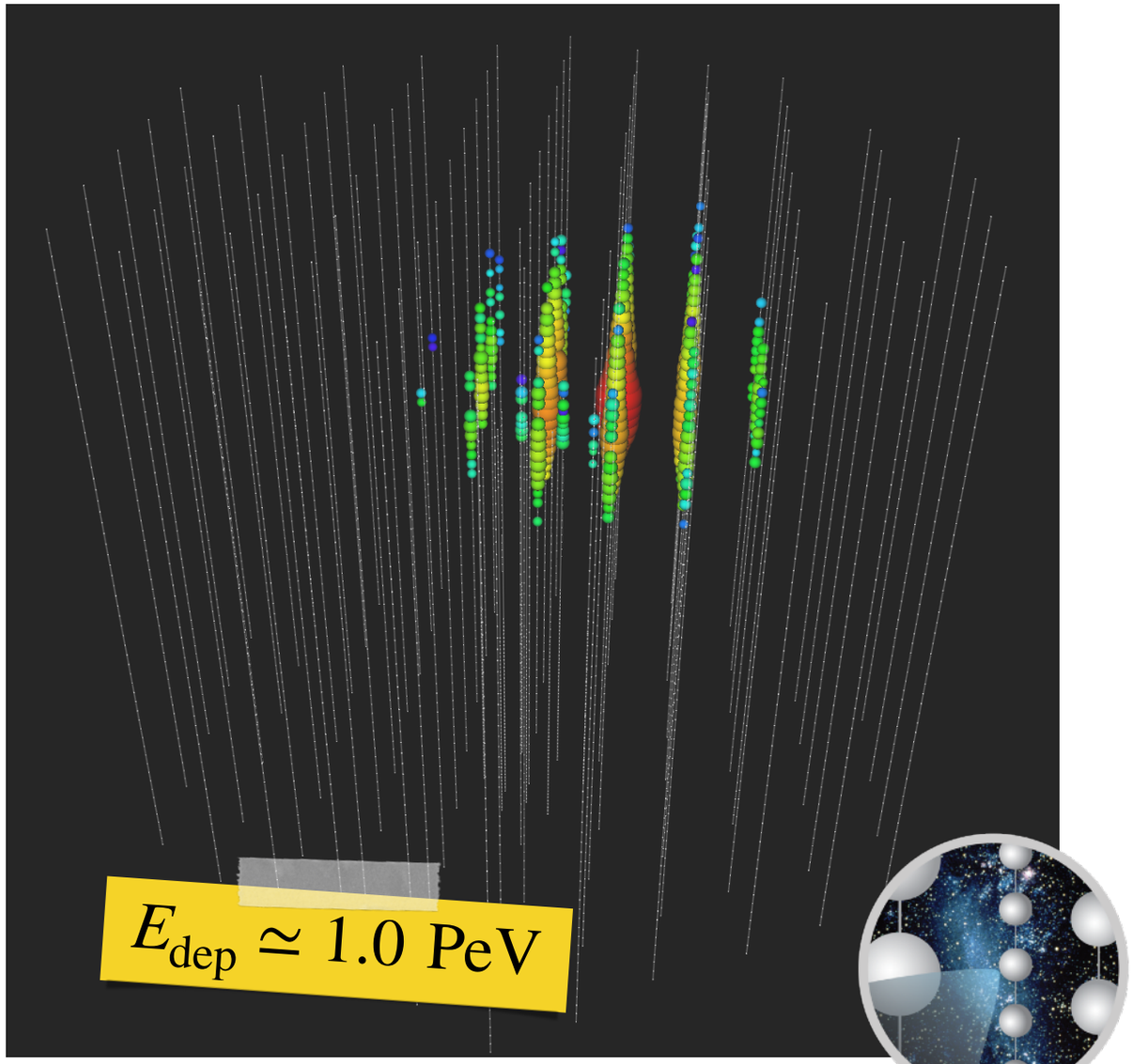
High-Energy Neutrinos

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

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



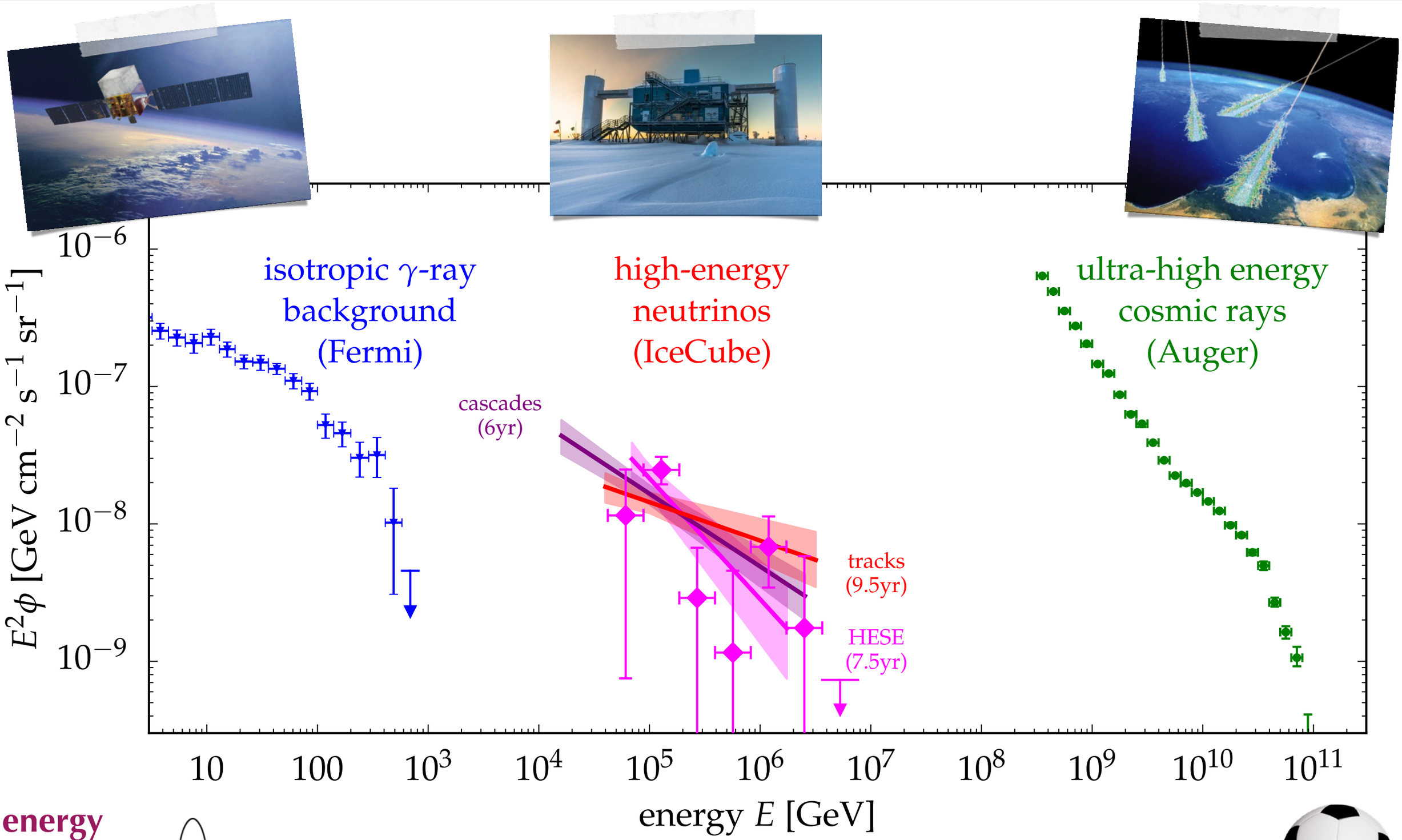
"cascade event" (e.g. NC interactions)



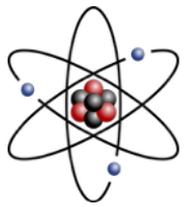
(colours indicate arrival time of Cherenkov photons from **early** to **late**)

ICECUBE

Diffuse TeV-PeV Neutrinos

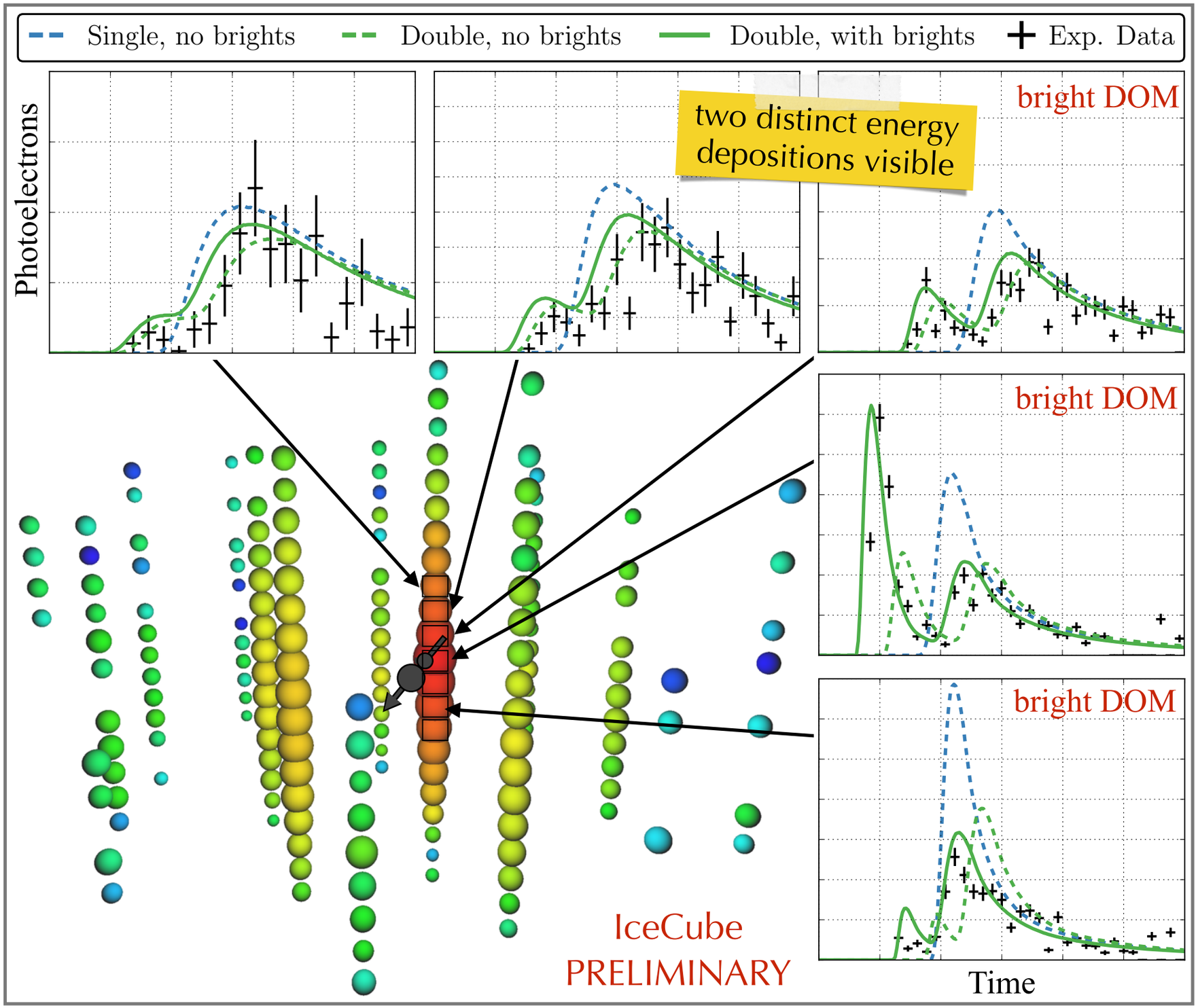


energy scale



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

Astrophysical Flavours



[IceCube, arXiv:2011.03561]

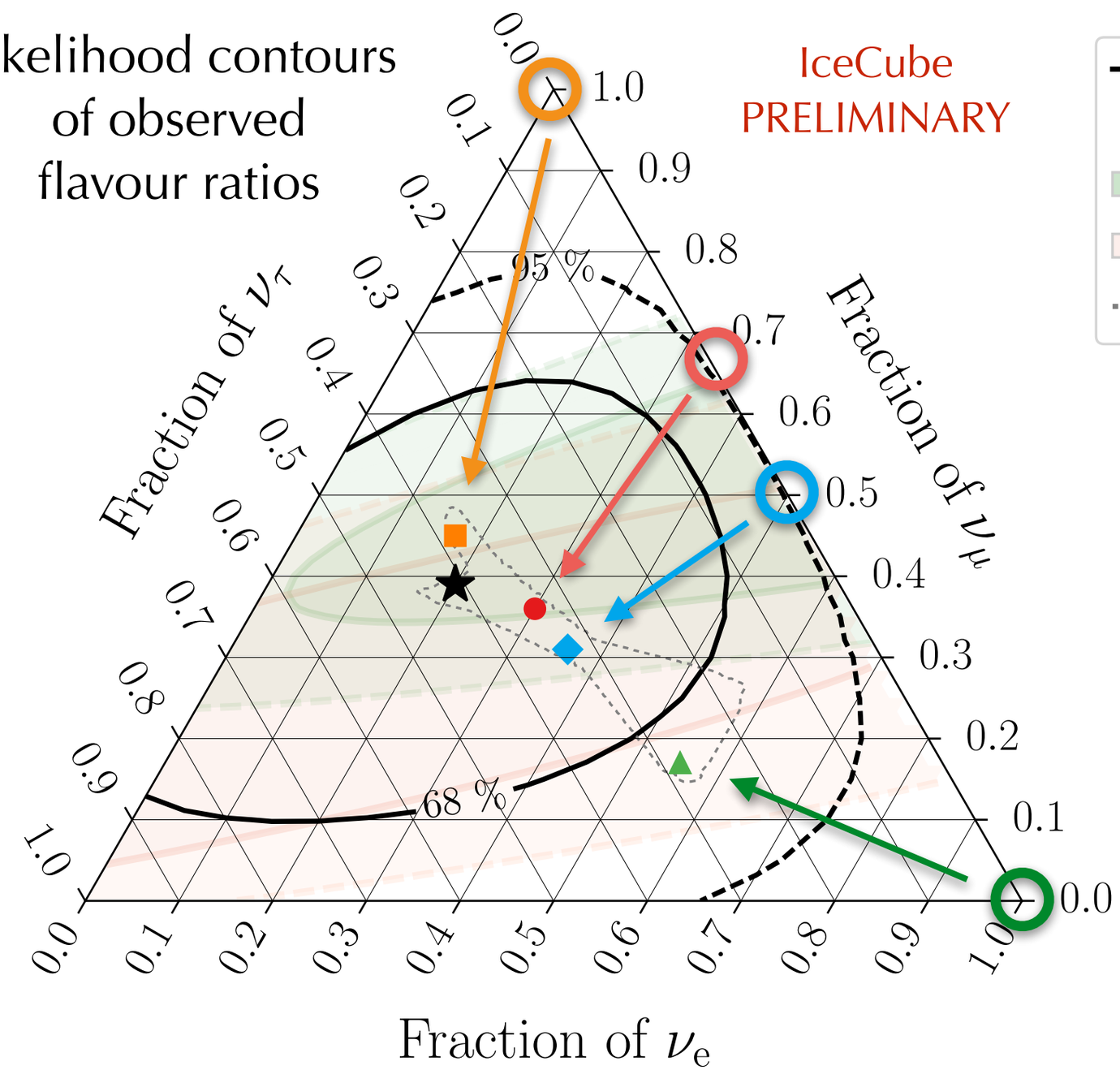
tau neutrino candidate

- **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



HESE with ternary topology ID
Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
Inelasticity (IceCube, PRD 2019)
3ν-mixing 3σ allowed region

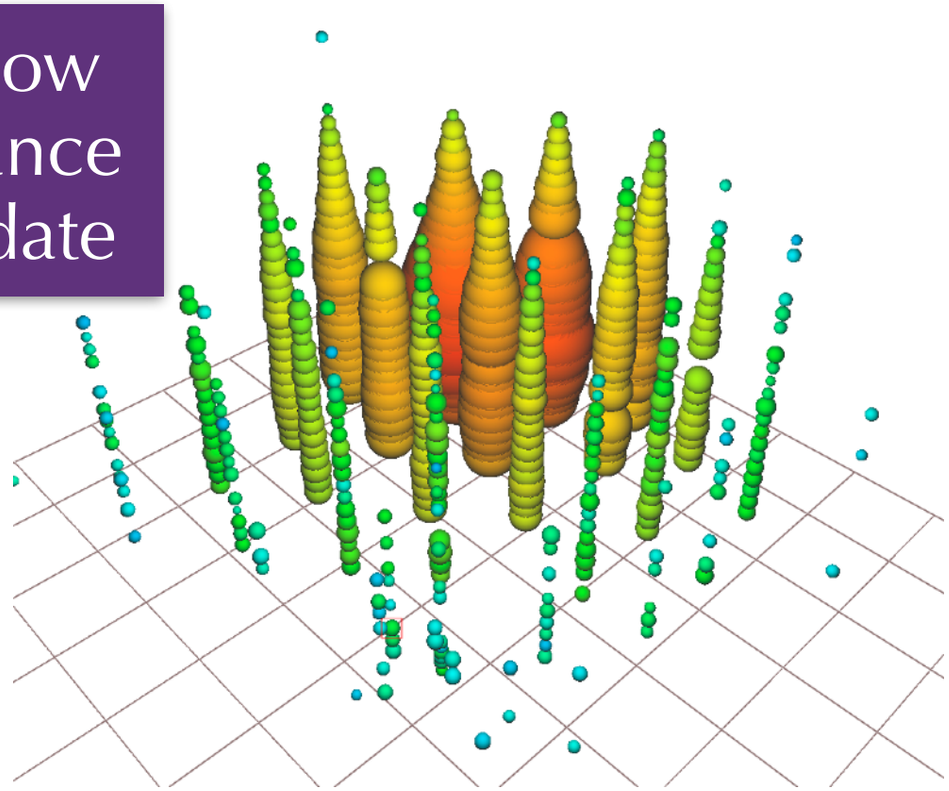
$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:

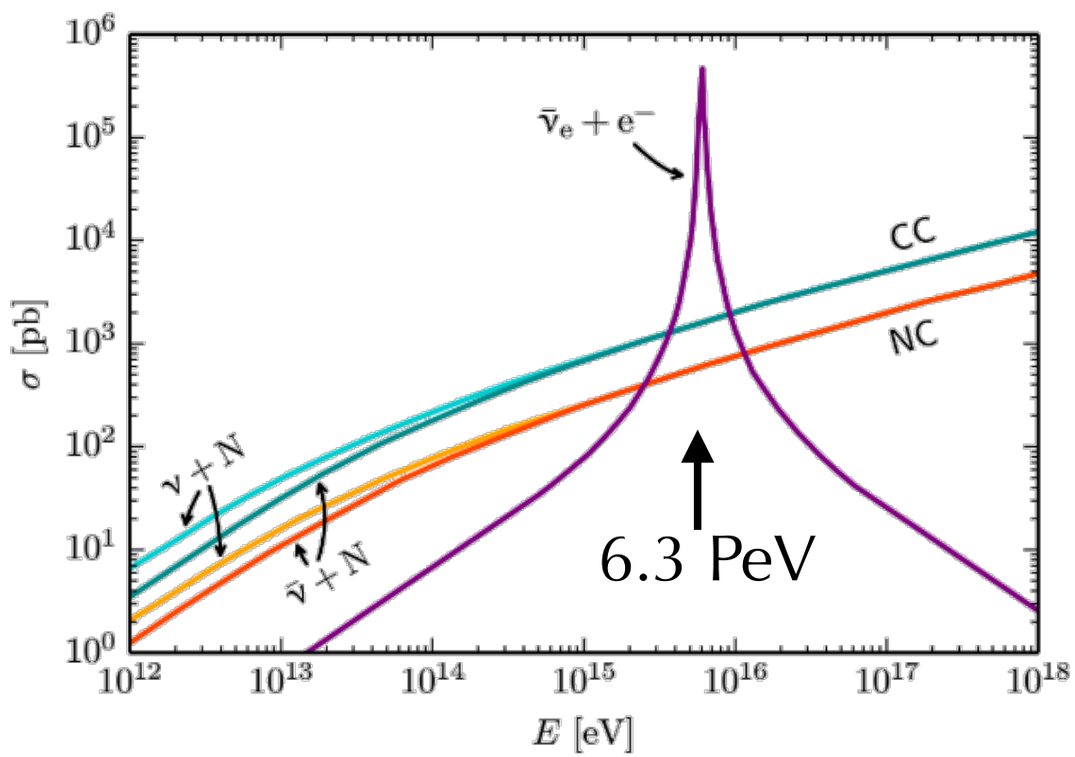
- 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
- 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
- 1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
- 1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

[IceCube, arXiv:2011.03561]

Astrophysical Flavours

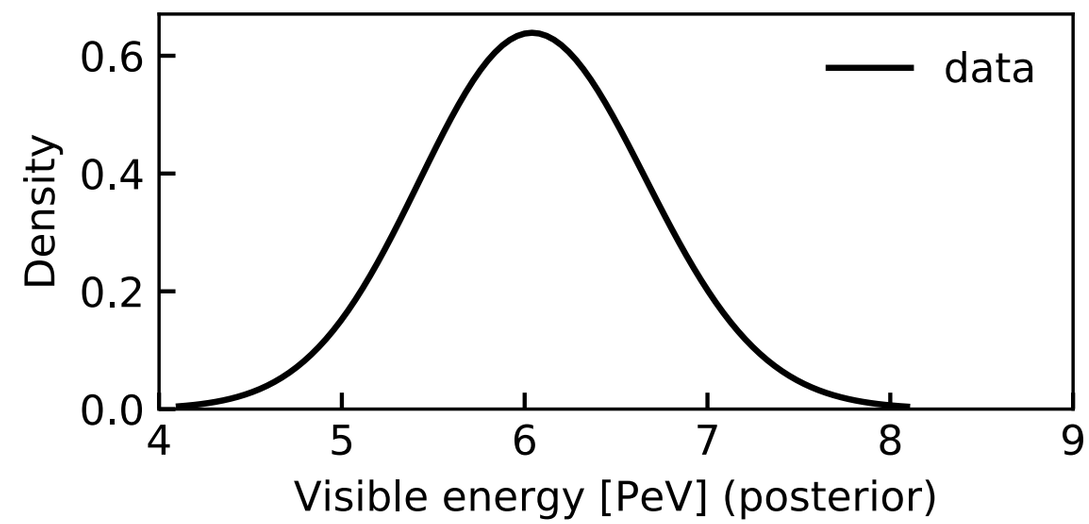
Glashow resonance candidate

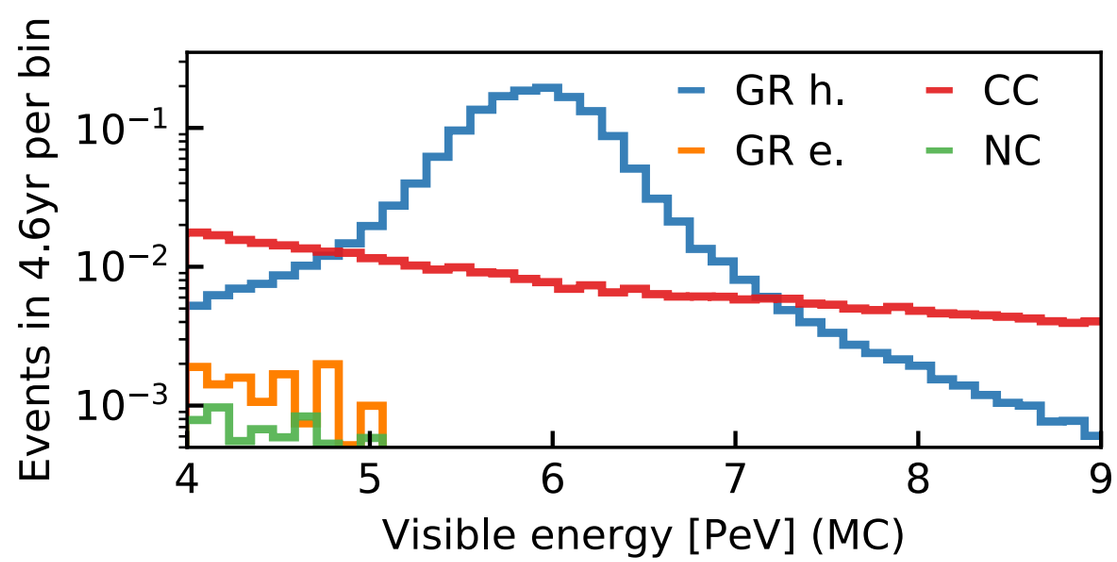




Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

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



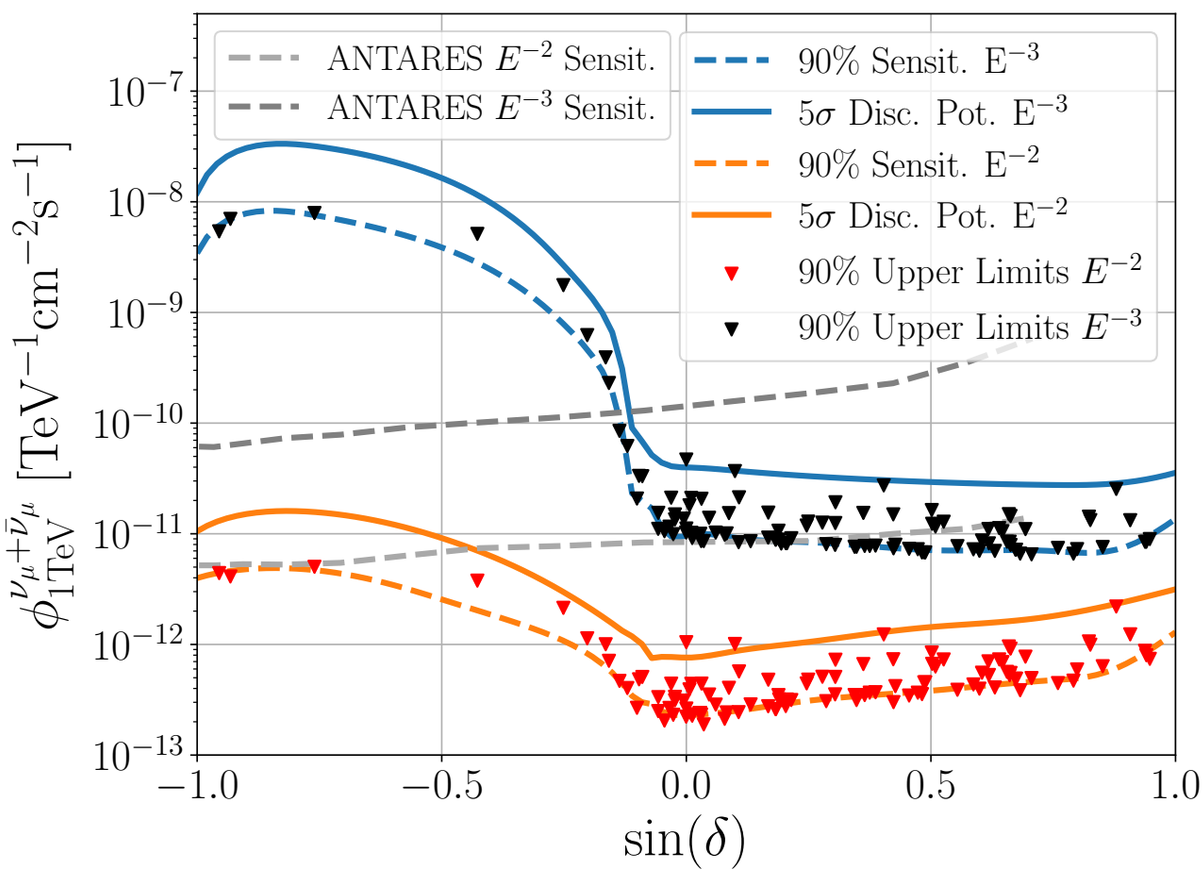


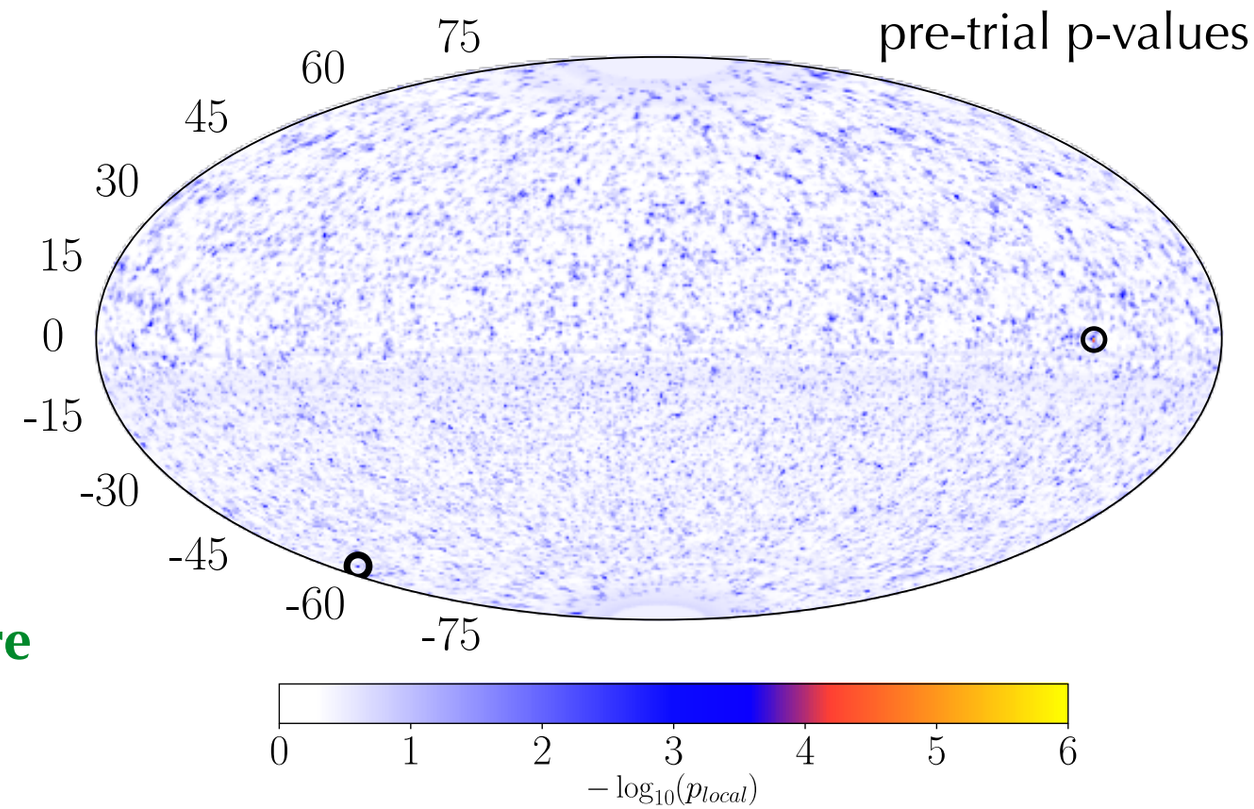
[IceCube, Nature 591 (2021) 220-224]

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.

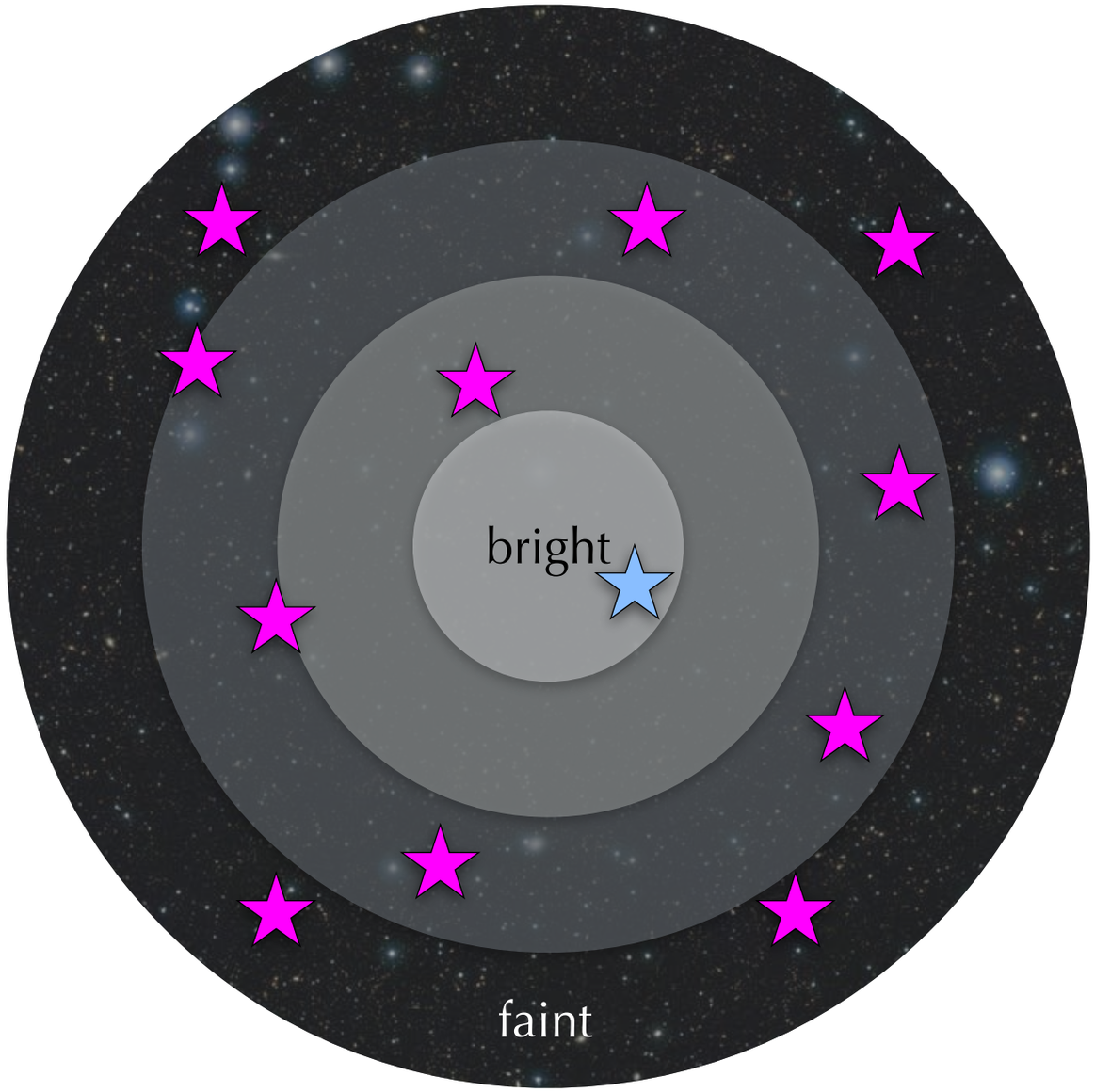
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

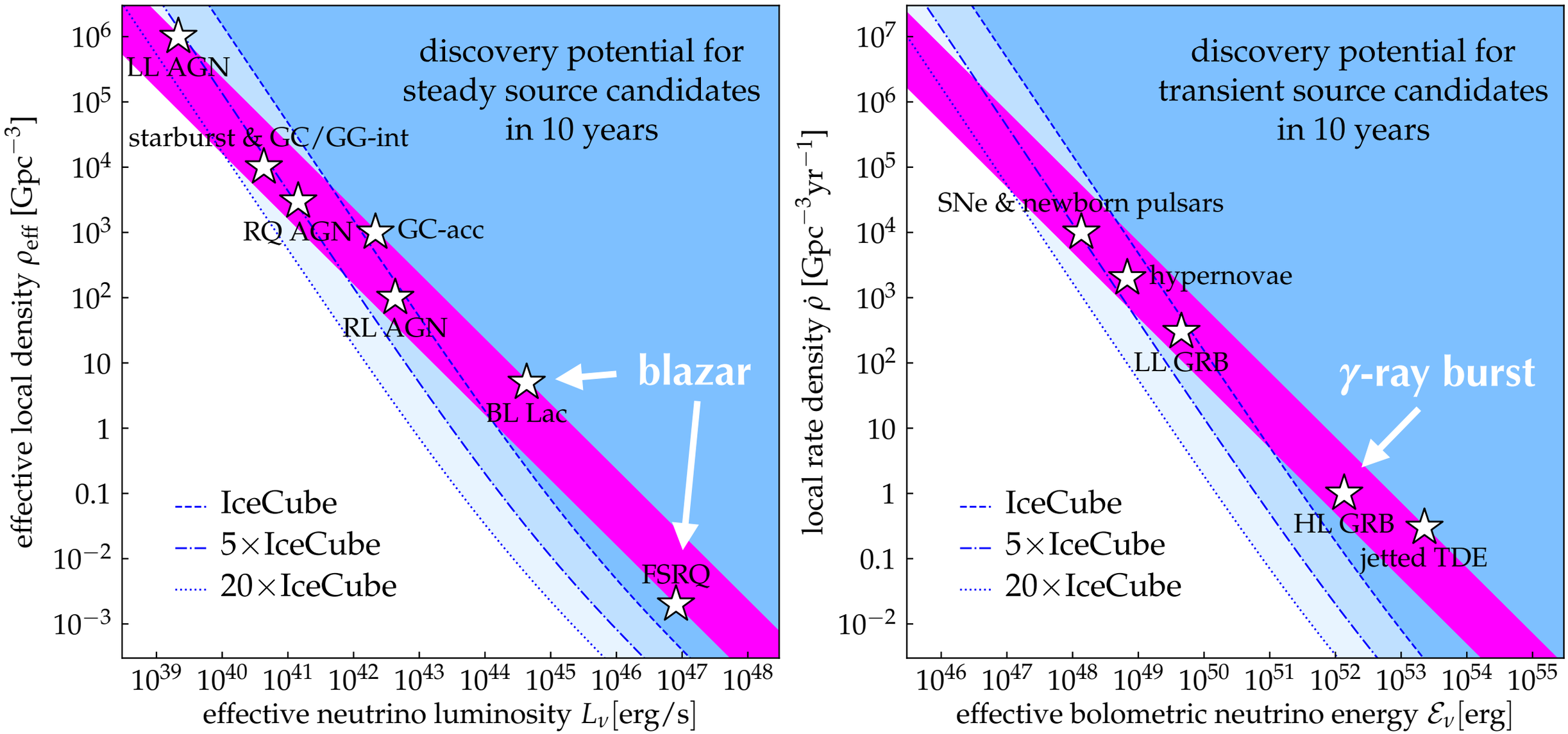
source luminosity.

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



Hubble horizon

Point Source vs. Diffuse Flux

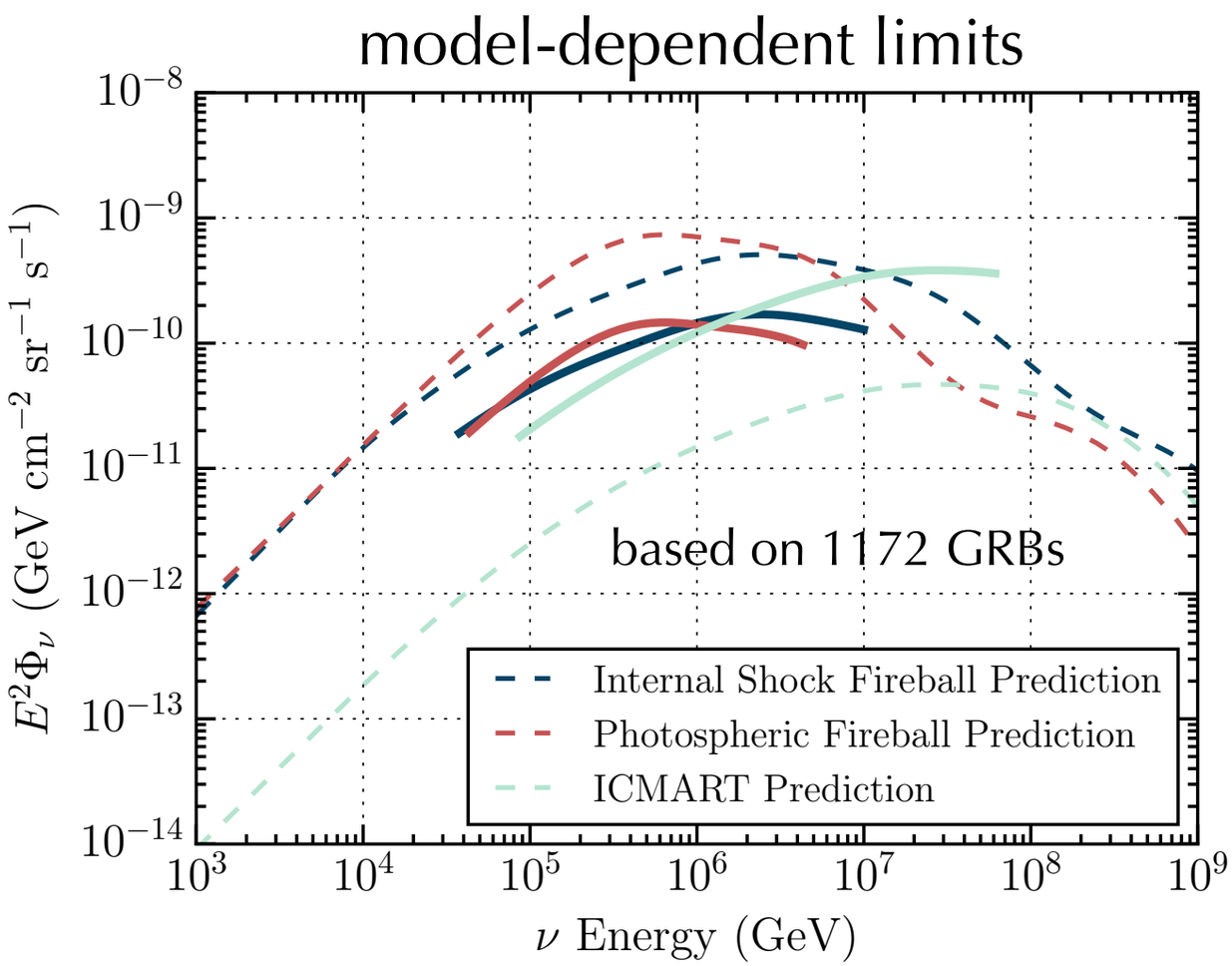


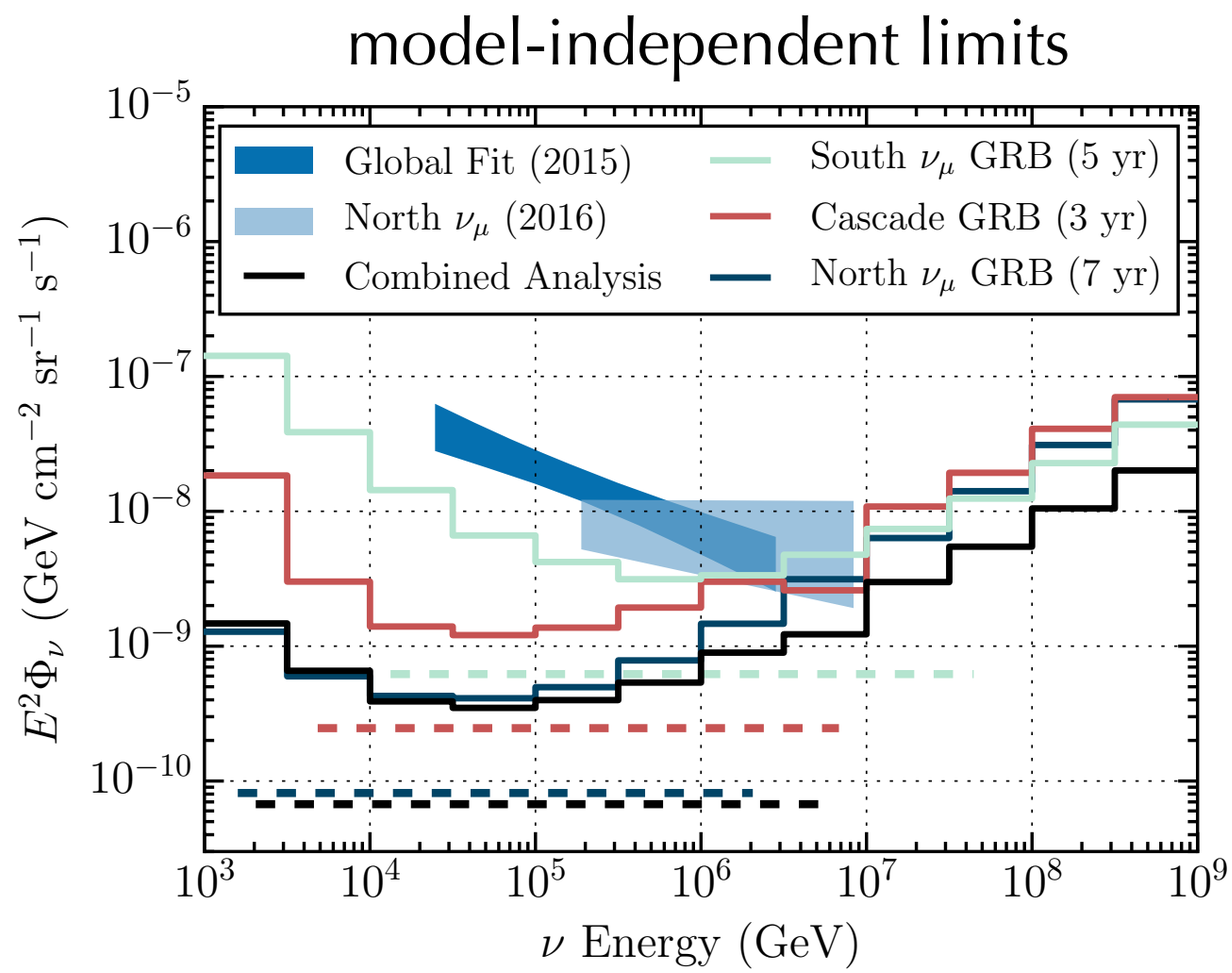
[Murase & Waxman'16; Ackermann *et al.'19*]

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

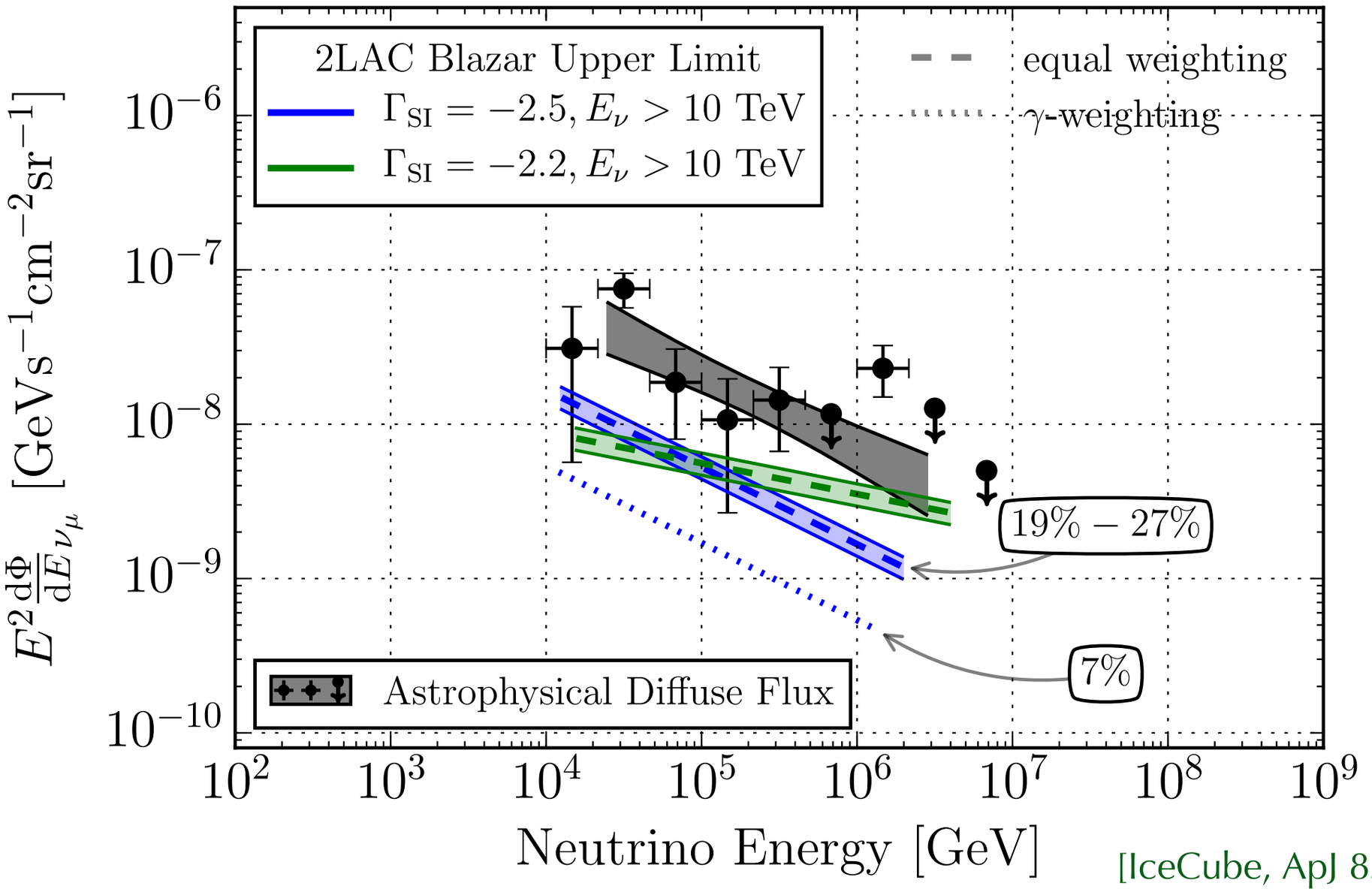
Gamma-Ray Burst Limits

- 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]





Fermi-LAT Blazar Limits



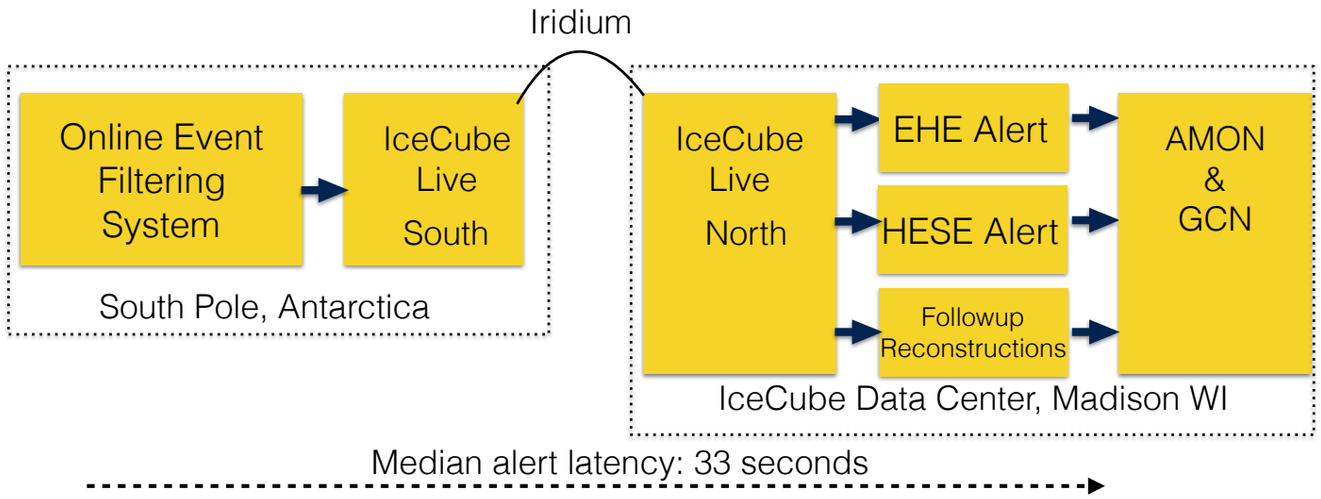
[IceCube, ApJ 835 (2017) 45]

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

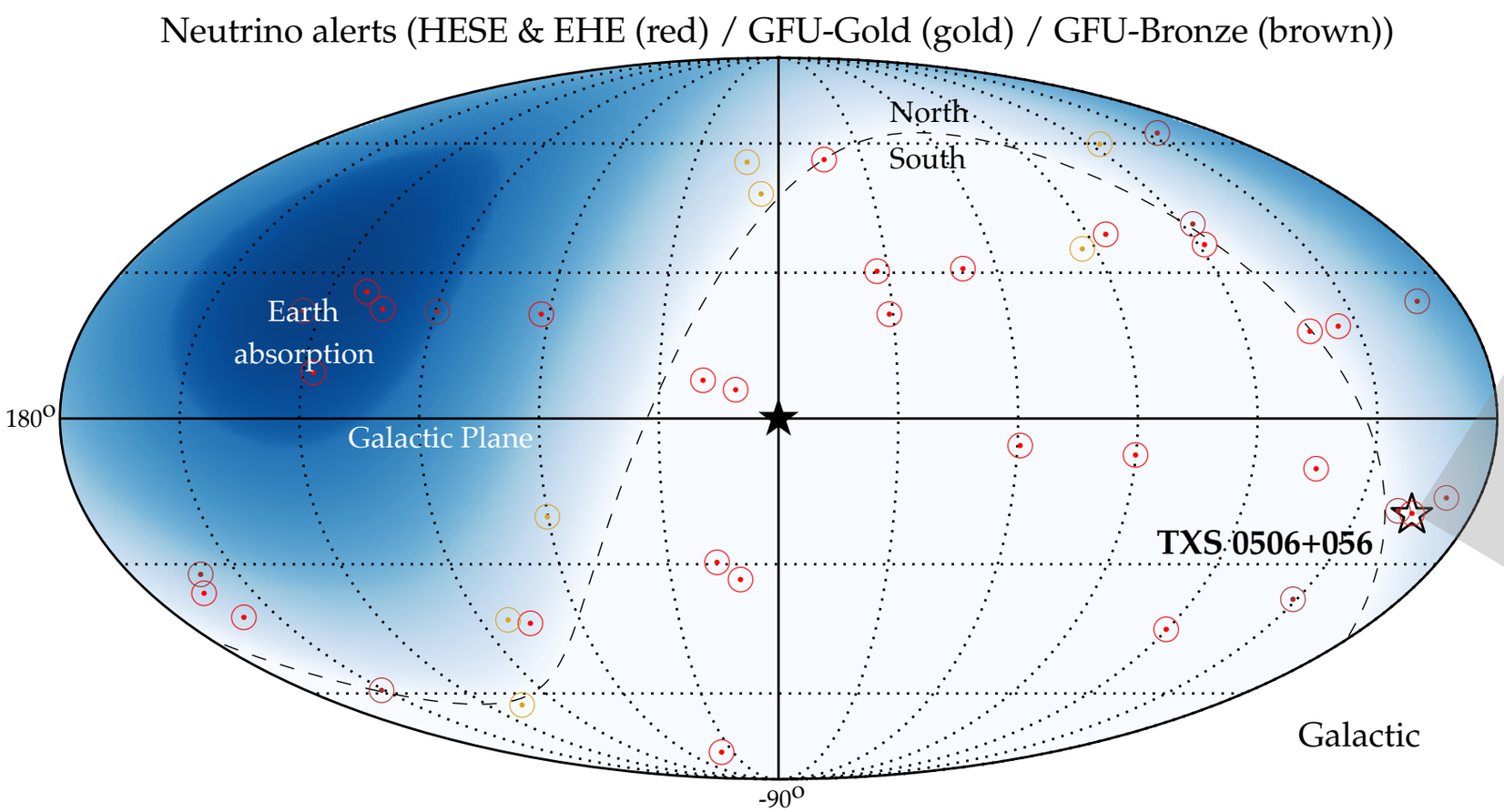
Realtime Neutrino Alerts

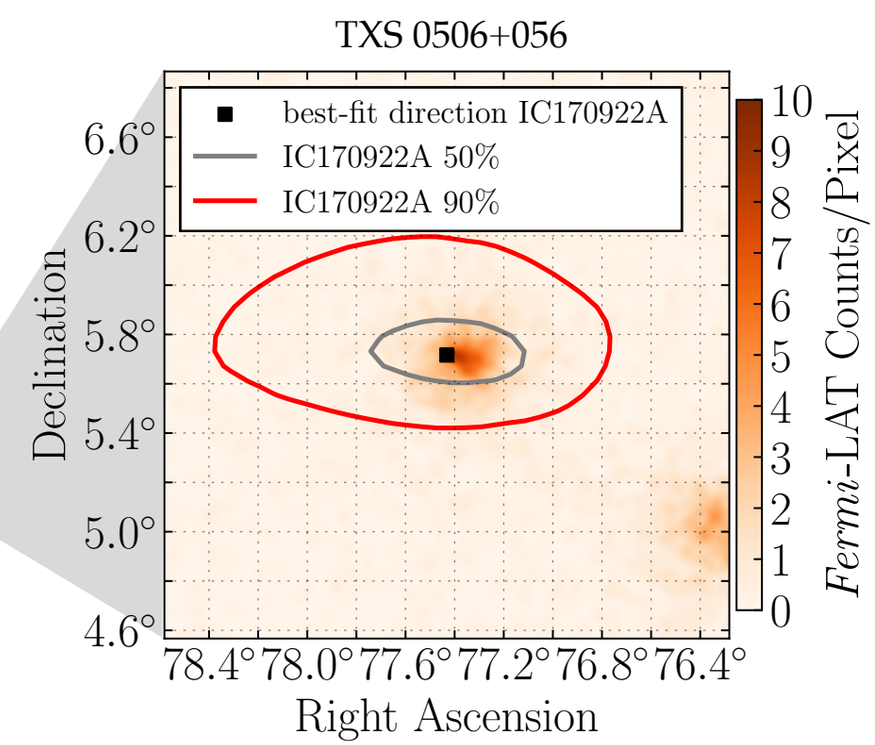
Low-latency (<1min) **public neutrino alert system** established in April 2016.

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

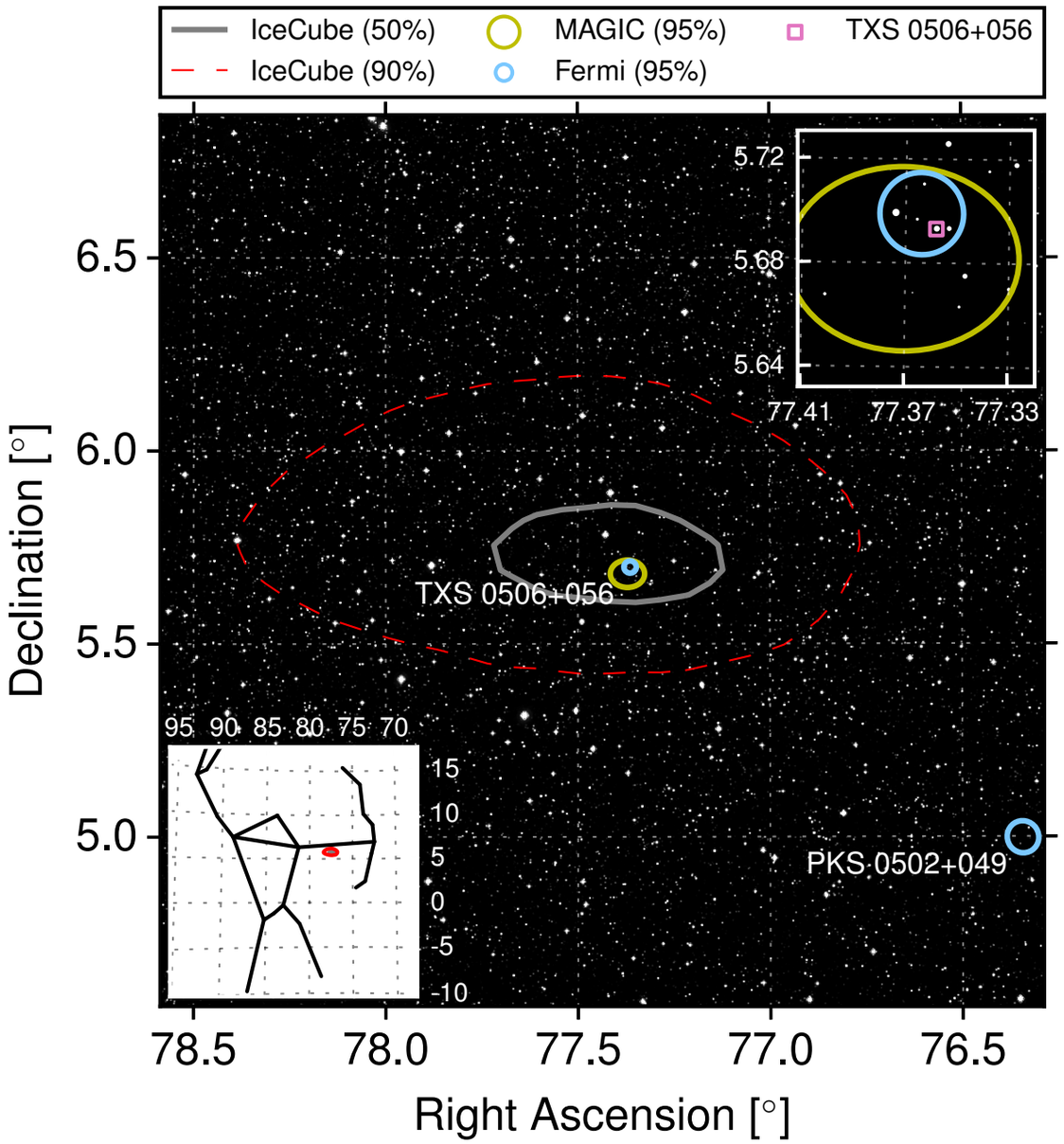


[IceCube, PoS (ICRC2019) 1021]





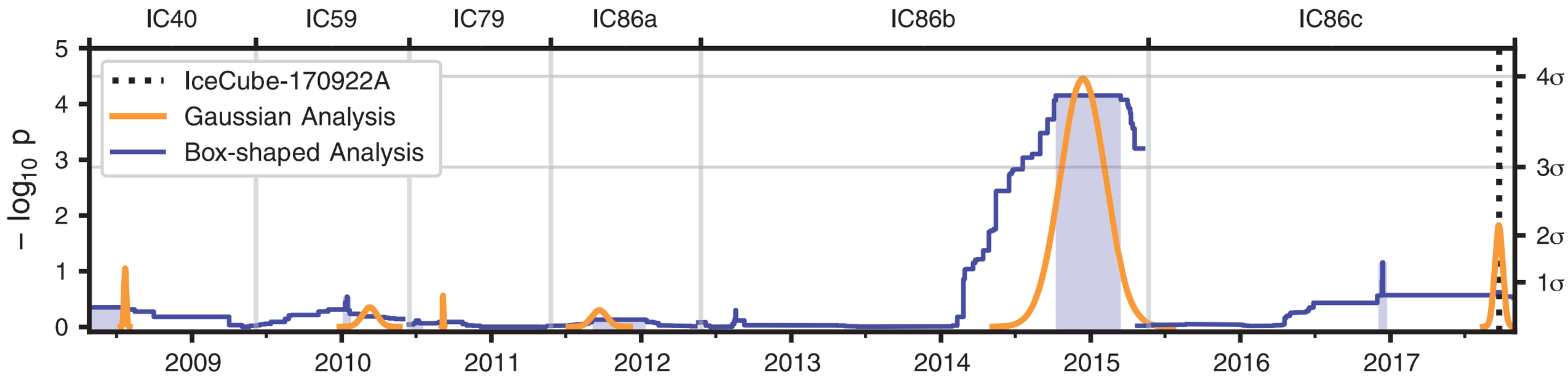
TXS 0506+056



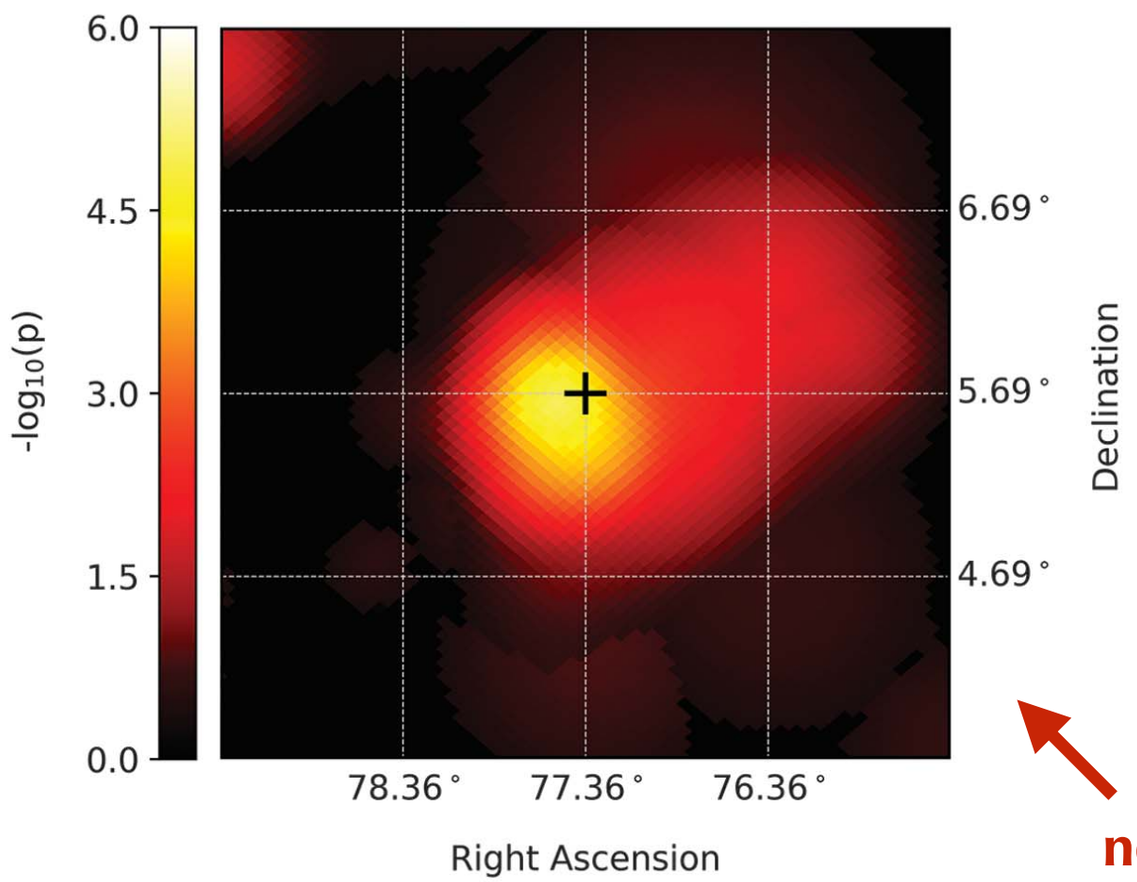
[IceCube++, Science 361 (2018) 6398]

- 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



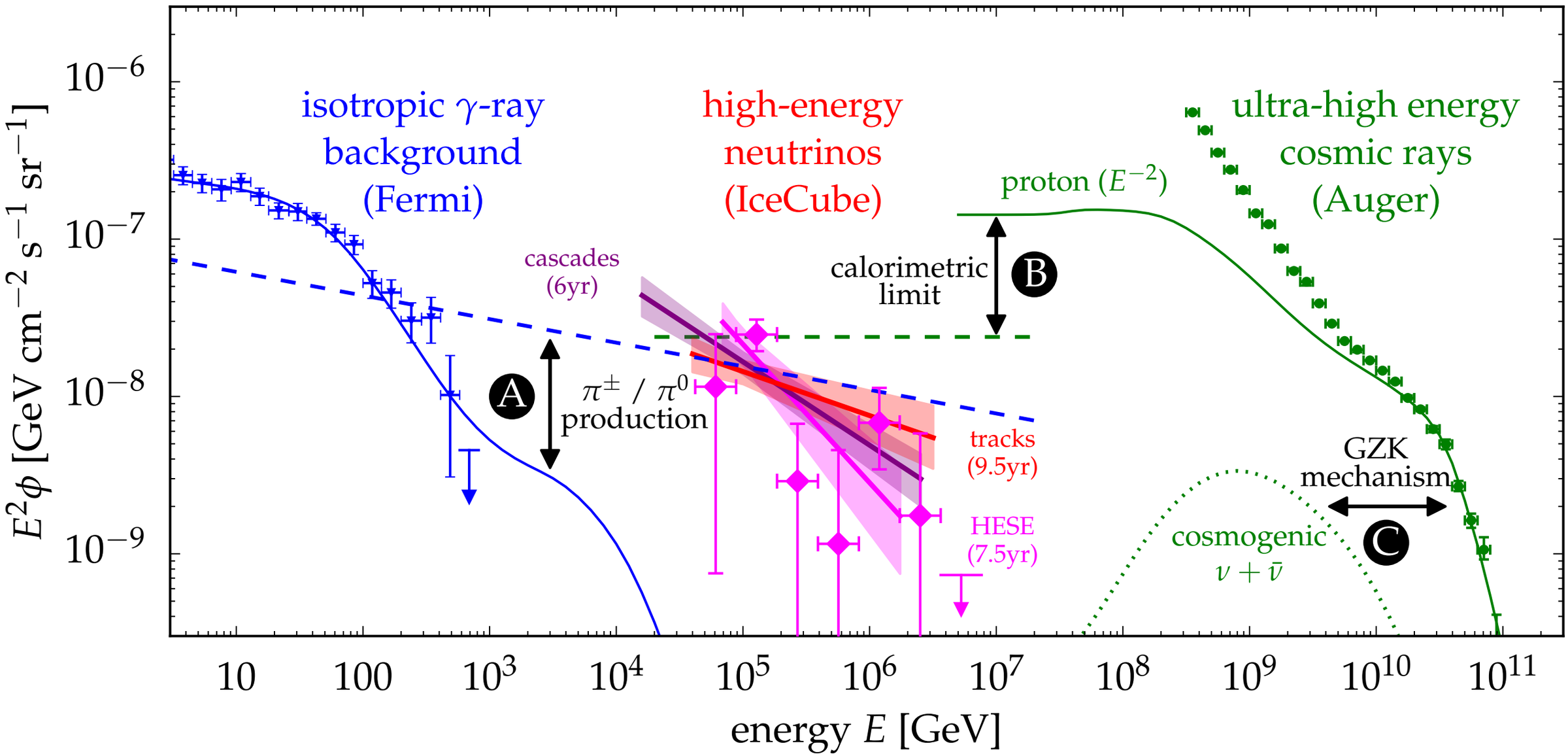
[IceCube, Science 361 (2018) 6398]



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

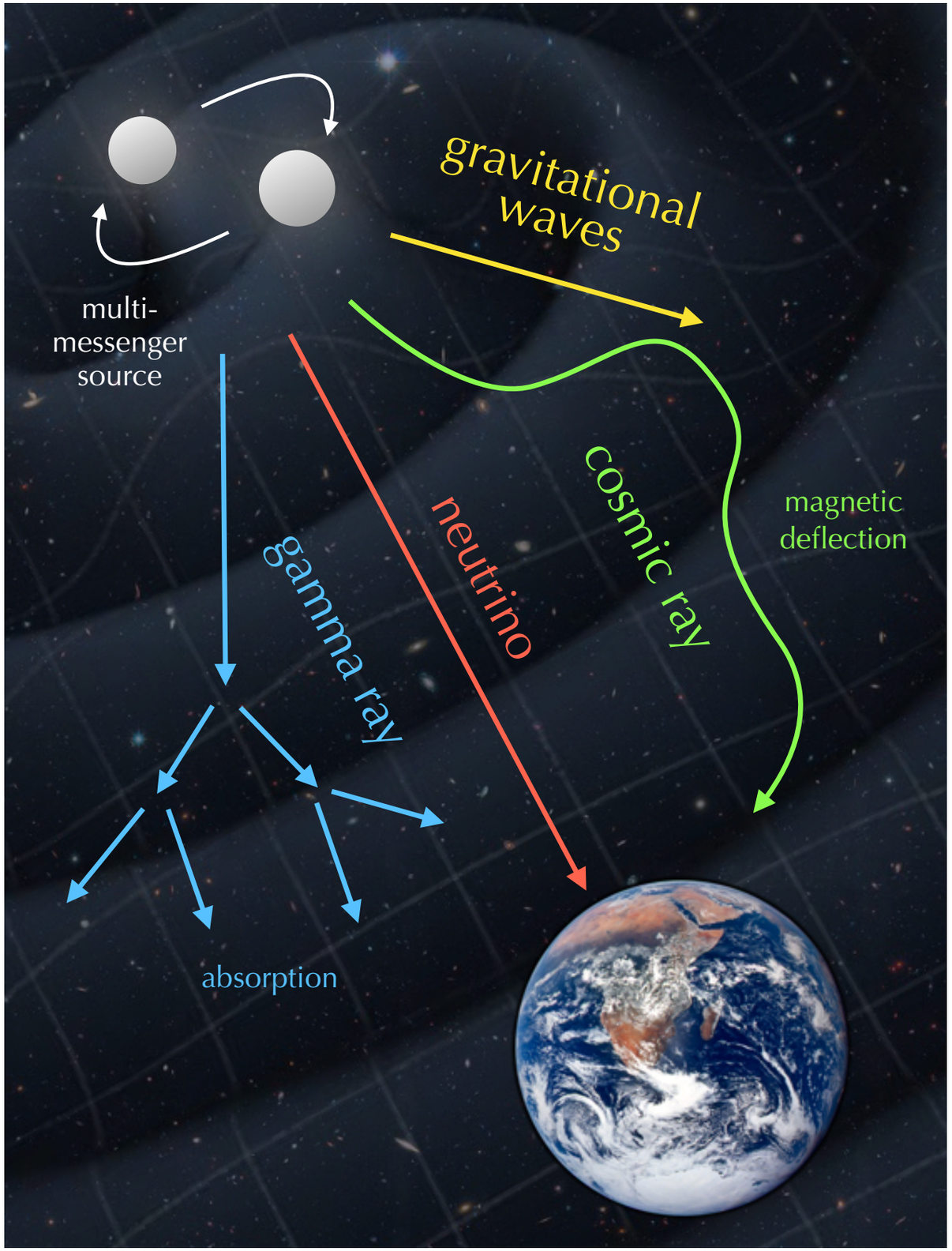
neutrino "morphology" of 2014/15 flare

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.

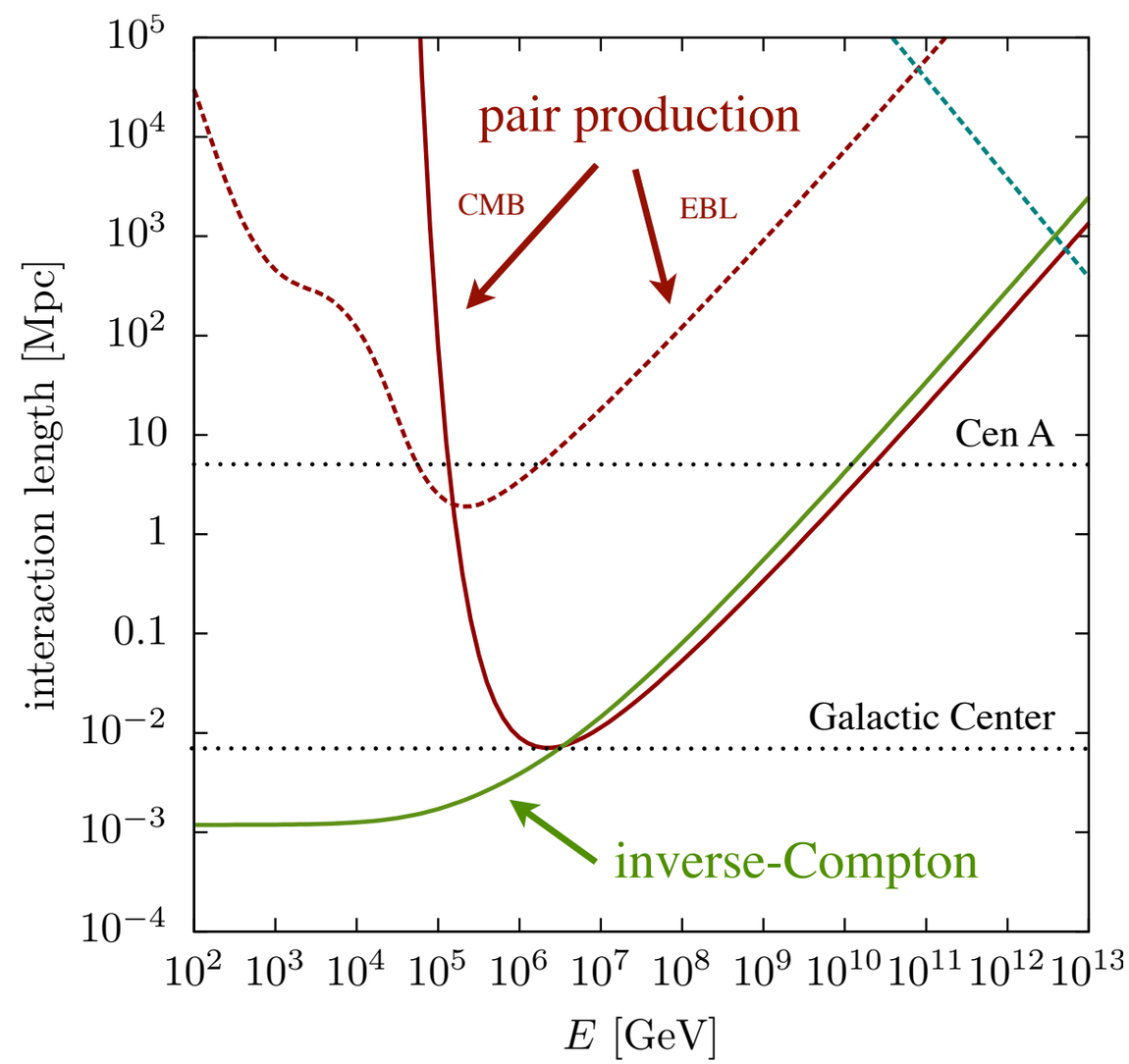
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

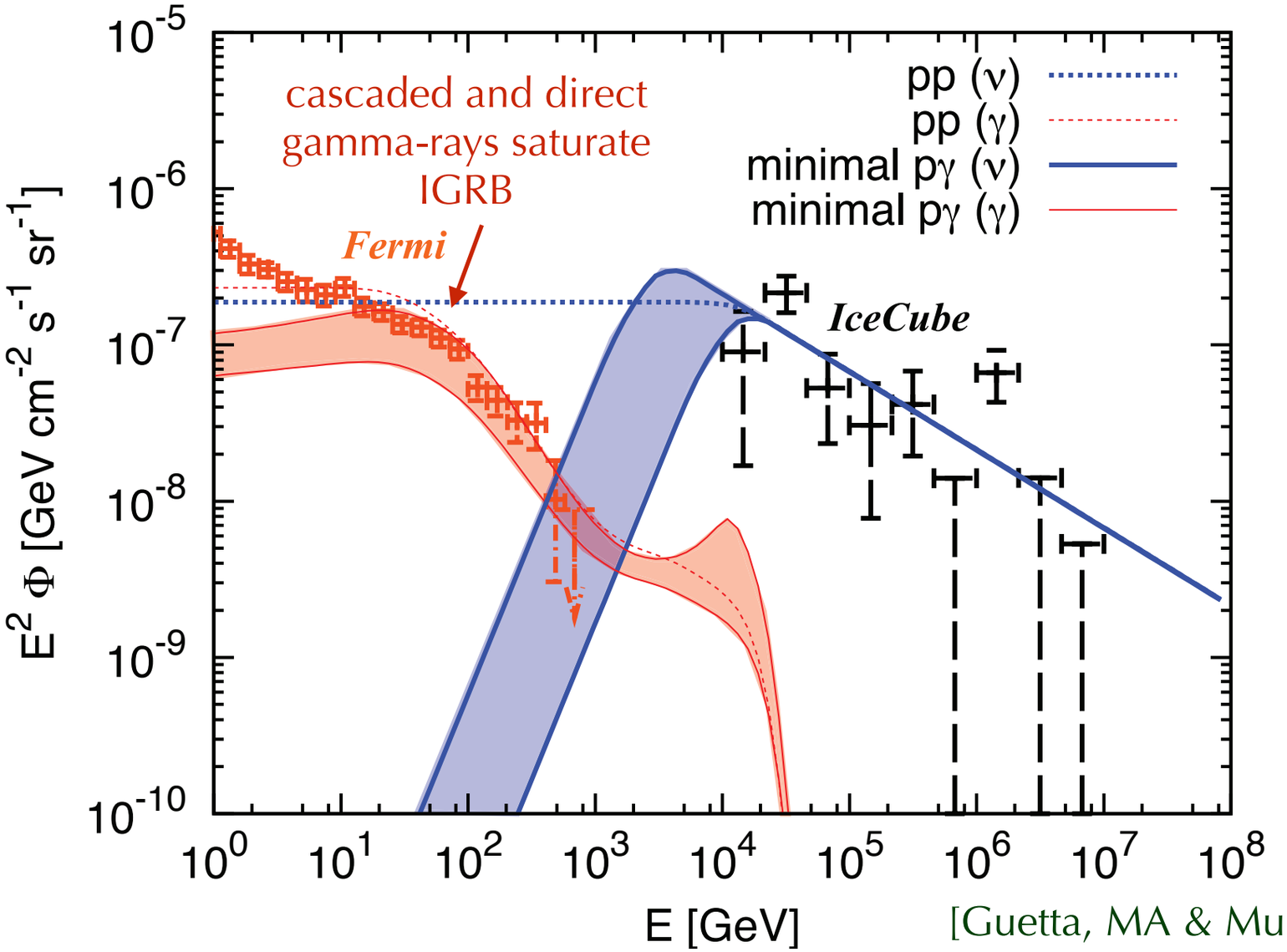
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

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



Hadronic Gamma-Rays

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

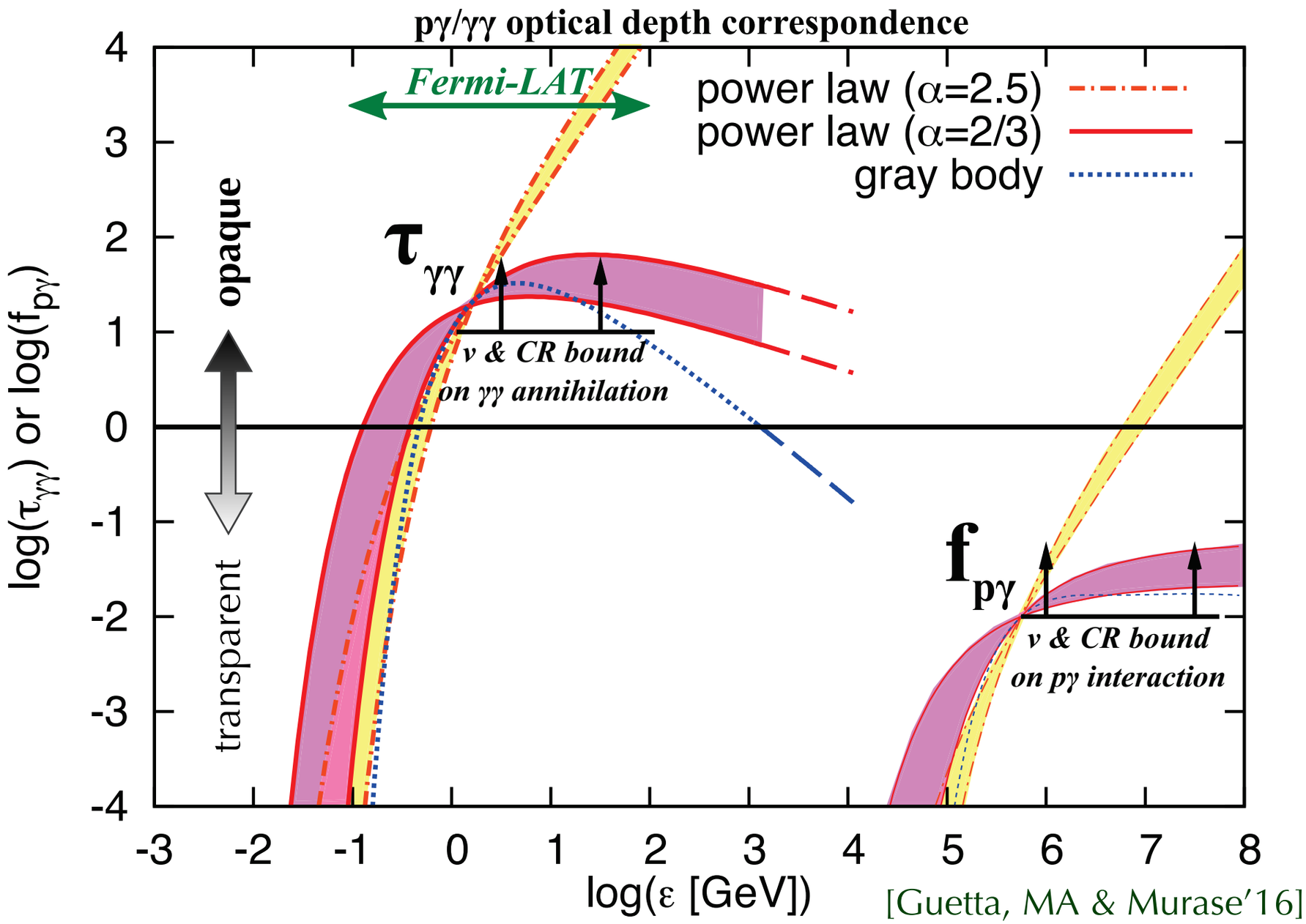


[Guetta, MA & Murase'16]

[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]
[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).



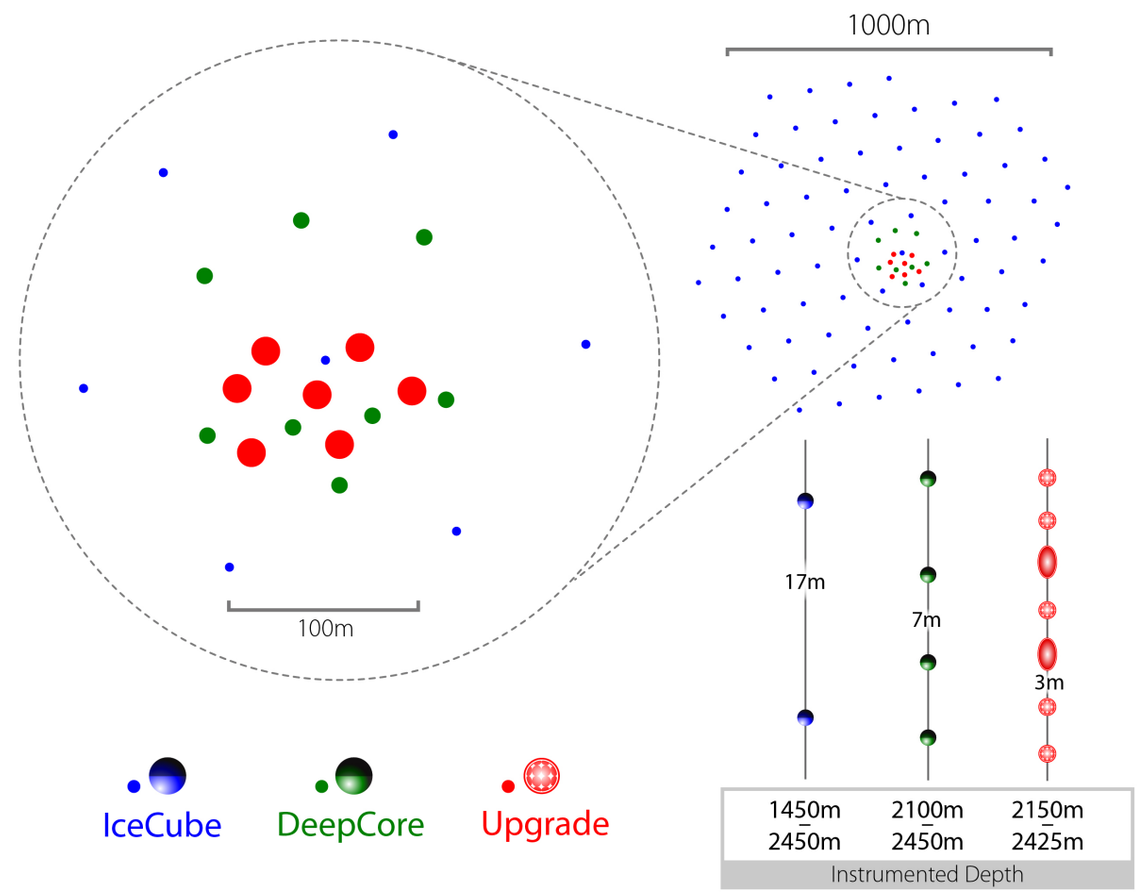
[Guetta, MA & Murase'16]

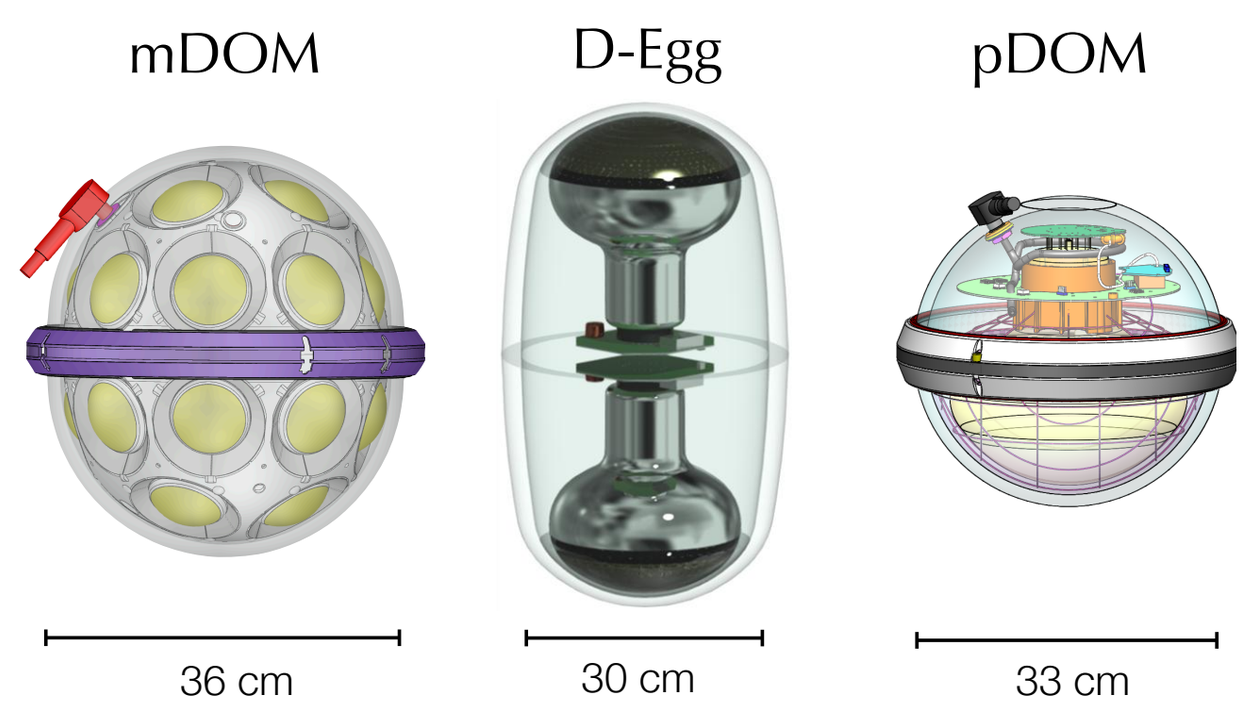
High pγ pion production efficiency implies strong internal **γ-ray absorption in Fermi-LAT energy range:**

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

Outlook: IceCube Upgrade

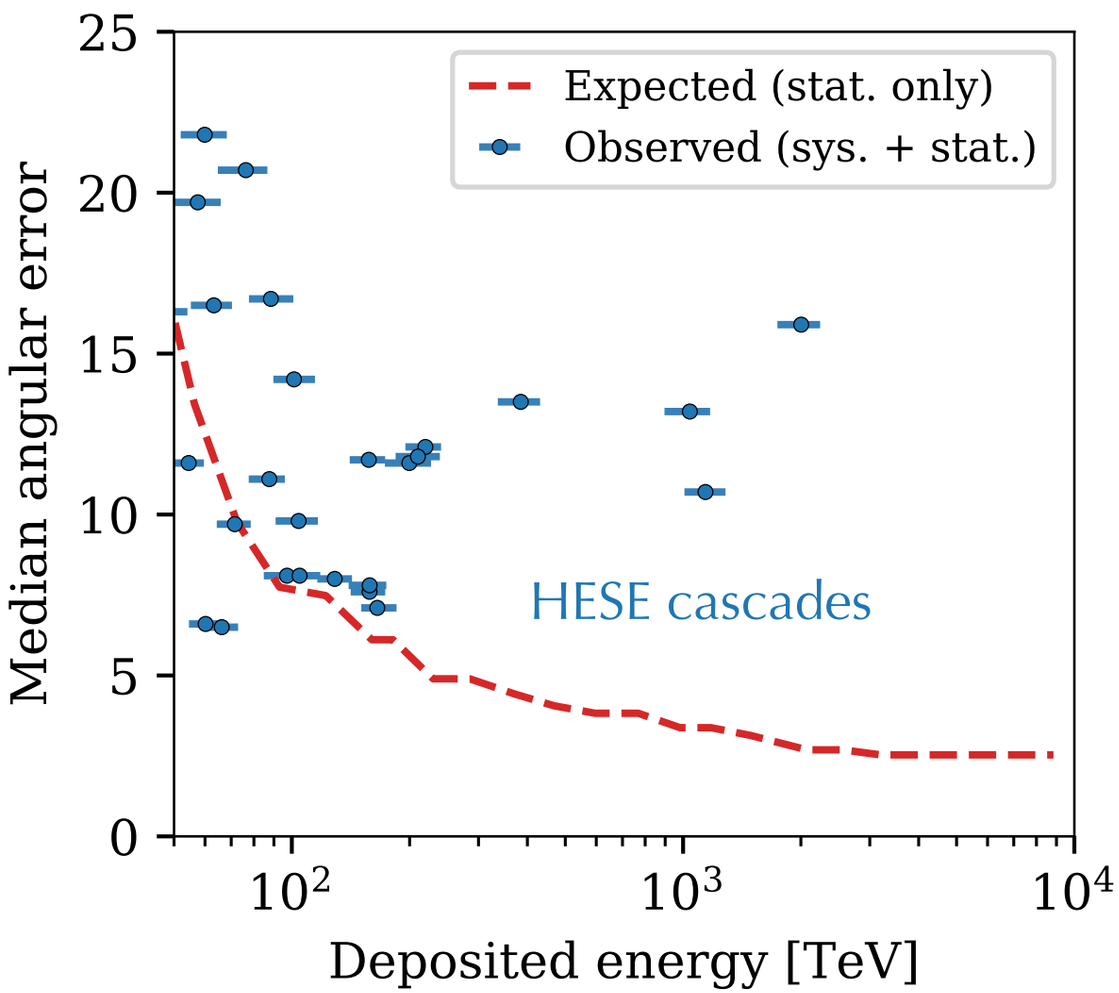
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- Midscale NSF project with an estimated total cost of $23M
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2023/24**

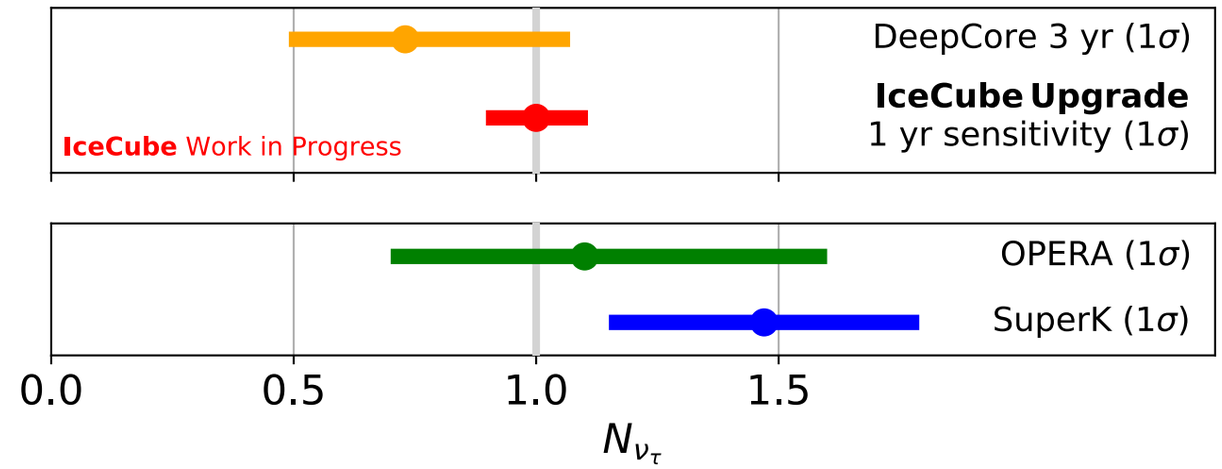


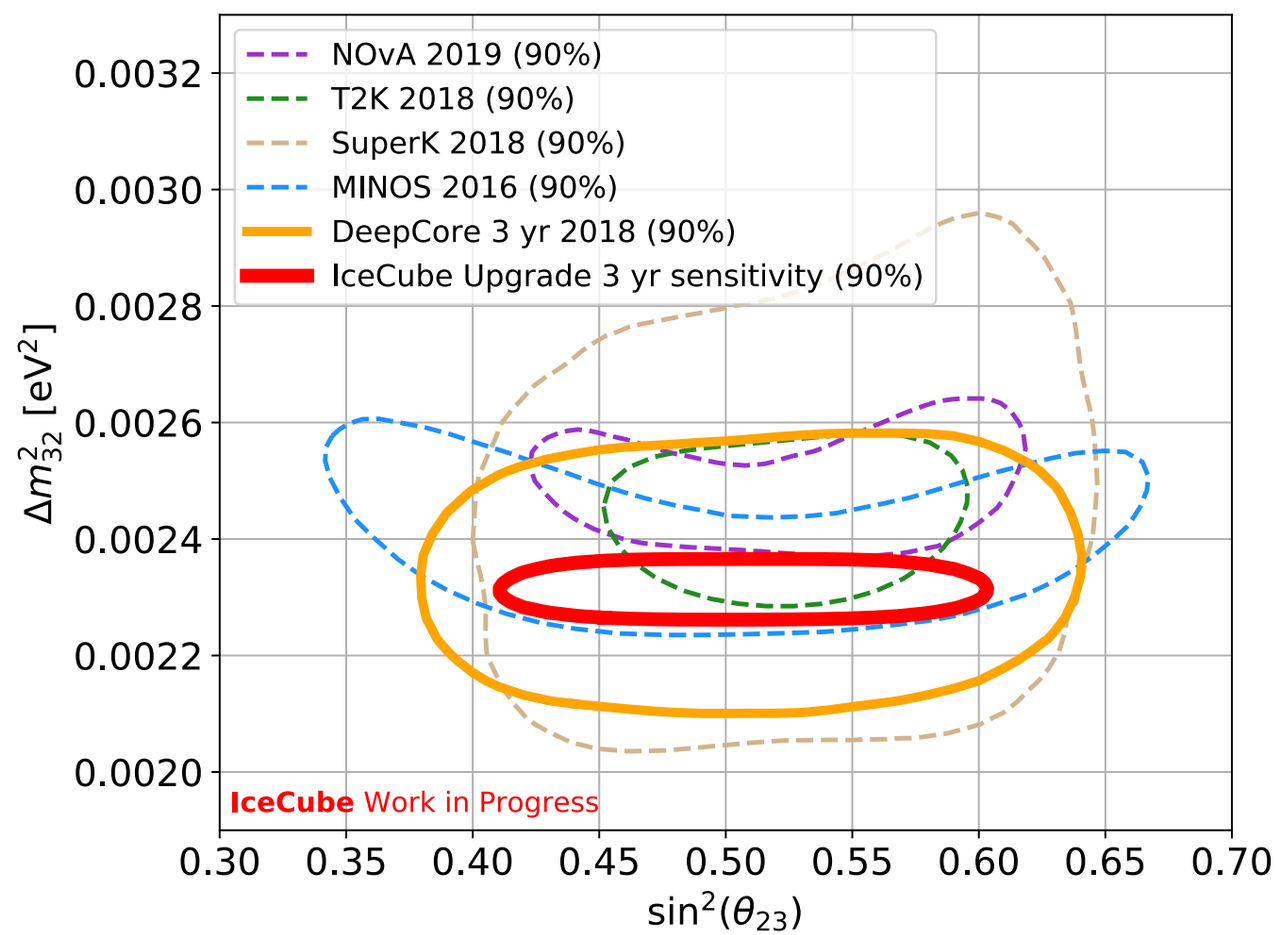


Outlook: IceCube Upgrade

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



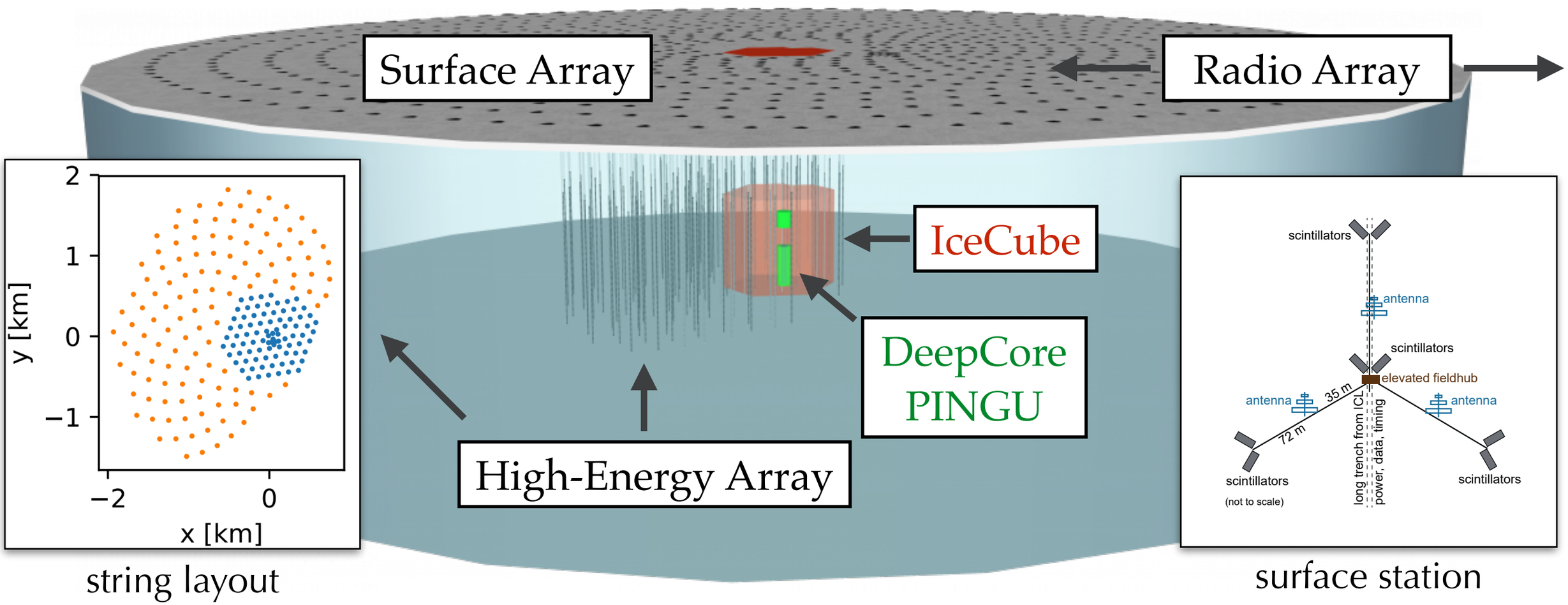




[IceCube, PoS (ICRC2019) 1031]

Vision: IceCube-Gen2

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



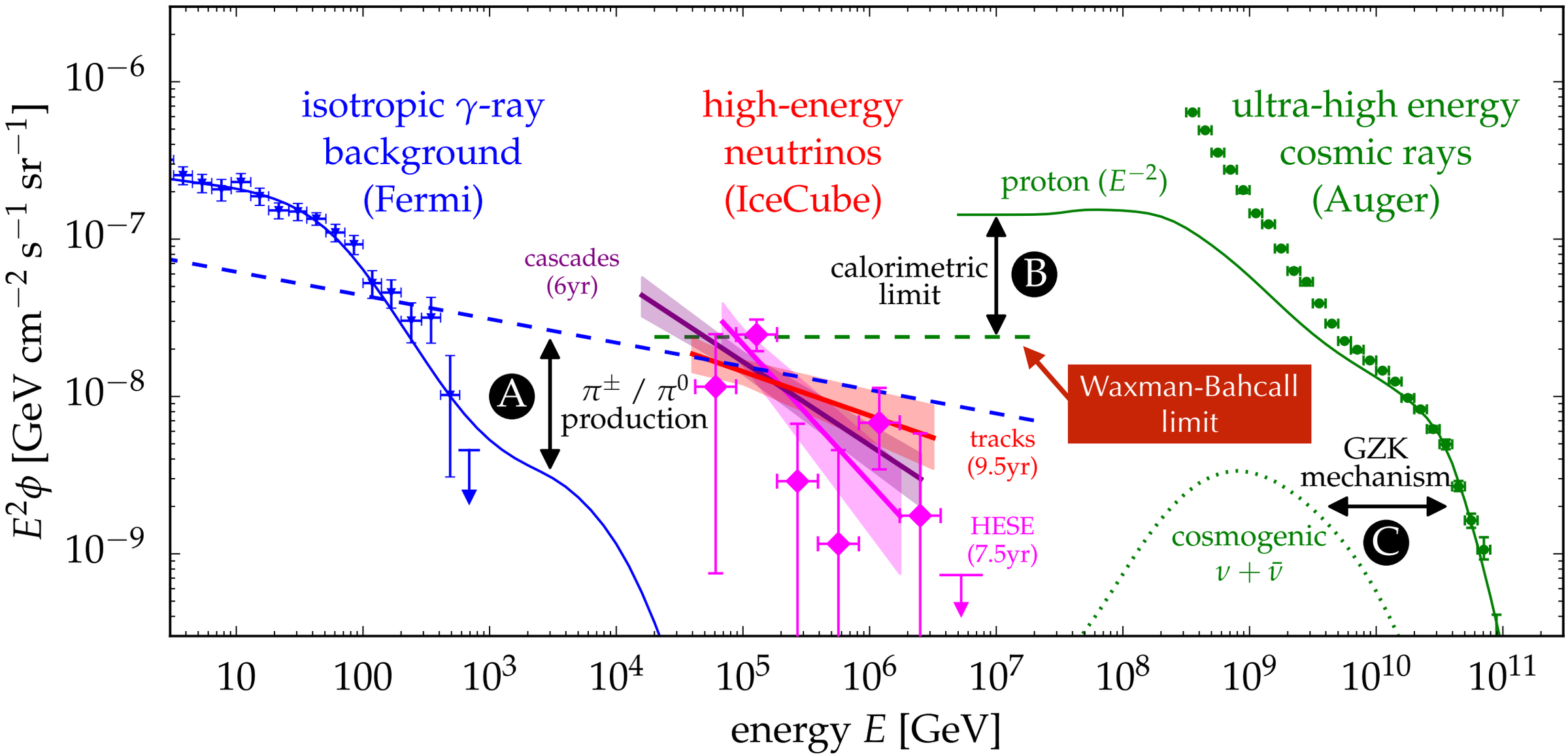
[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

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.
  - *Fermi-LAT, Magic, H.E.S.S., HAWC, Swift-XRT, VERITAS, LIGO/Virgo,…*
- In parallel, development of **future neutrino telescopes** with complementary FoV and/or increased sensitivity and energy coverage.
  - *Baikal-GVD, KM3NeT, P-ONE, RNO-G, IceCube-Gen2, ARA, ARIANNA, GRAND,…*

Backup Slides

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 $\Gamma \simeq 2.04$) :

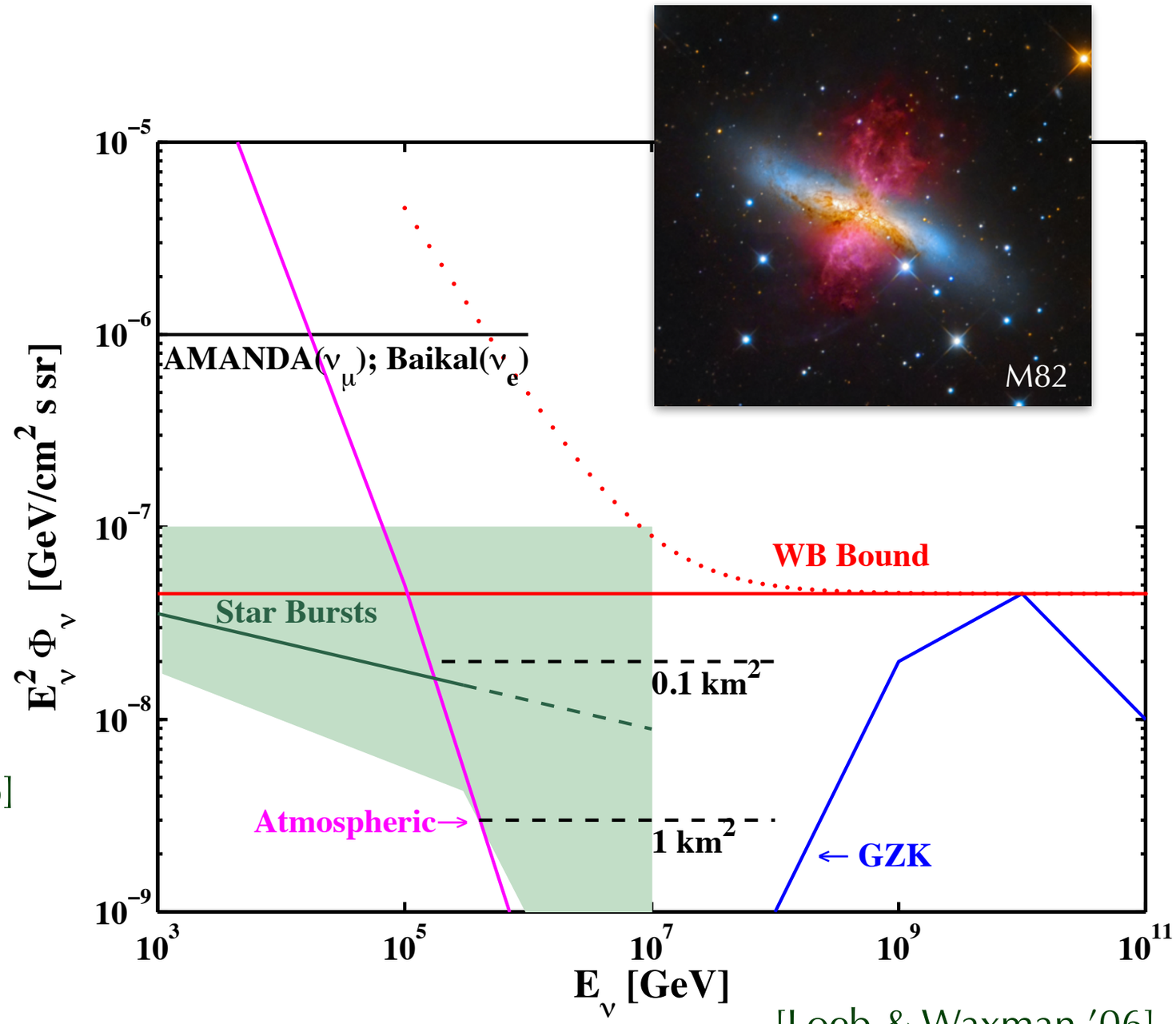
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43} \mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

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

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

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.

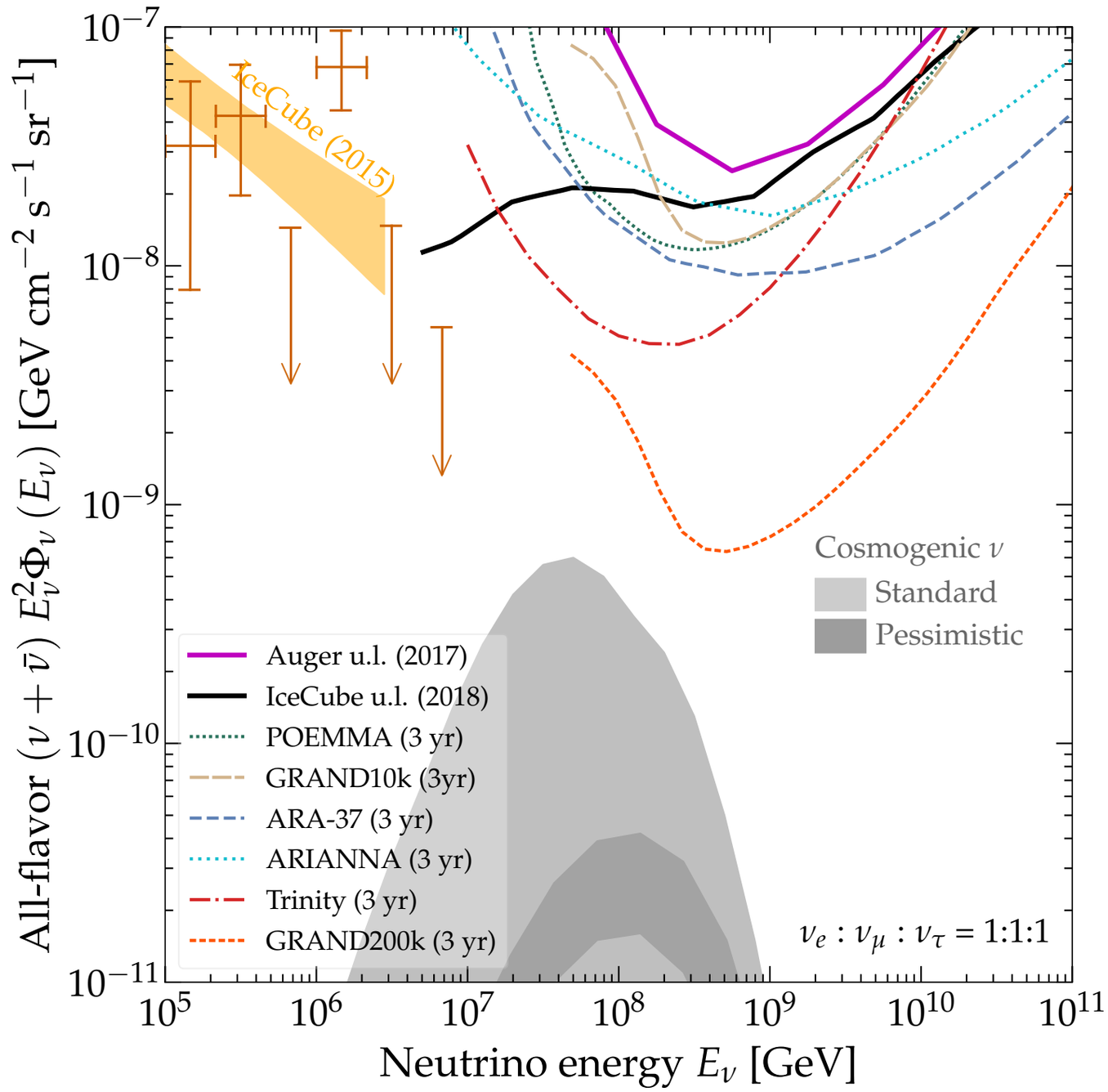


[Loeb & Waxman '06]

[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]

Cosmogenic Neutrinos

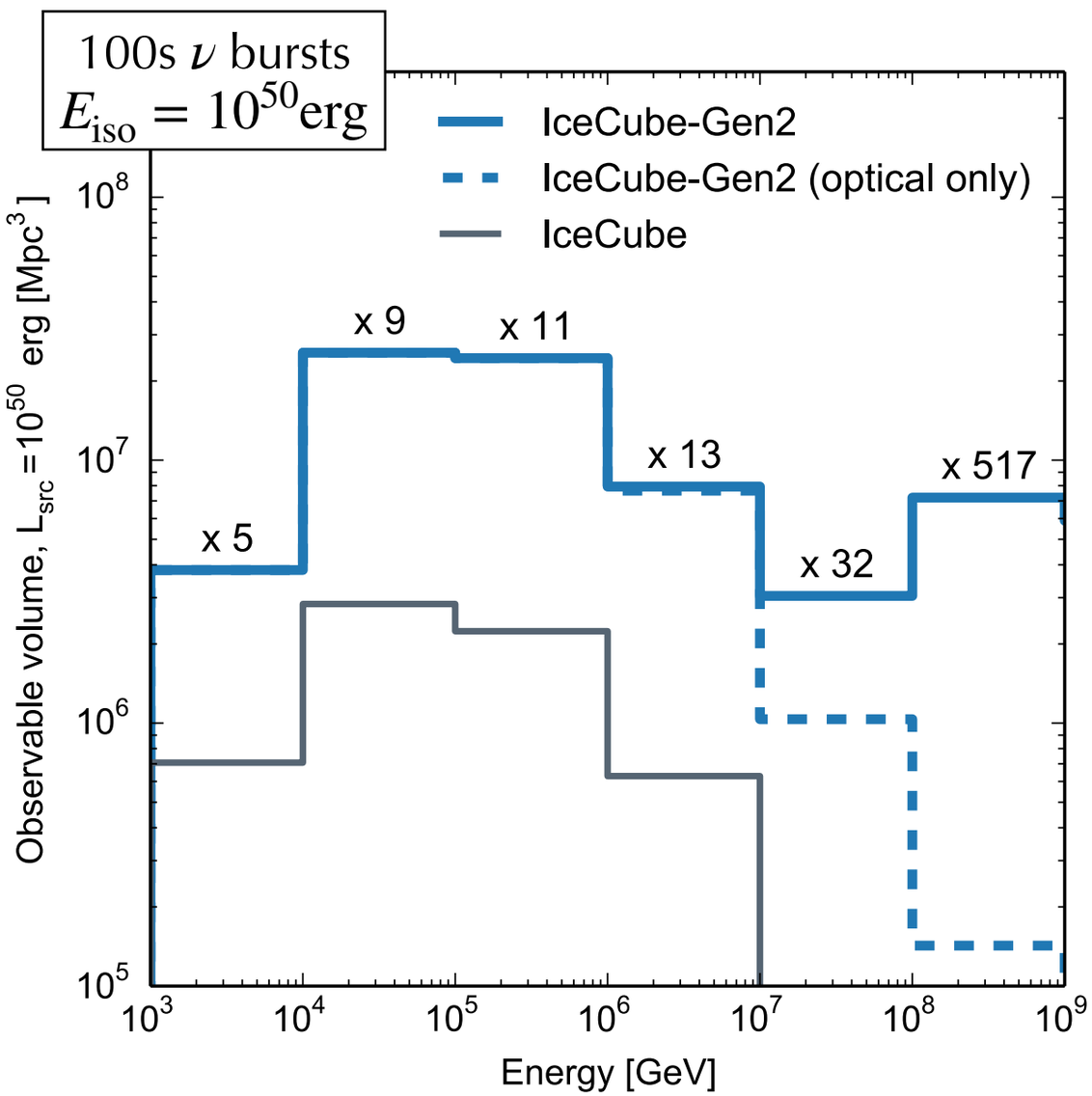
- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal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



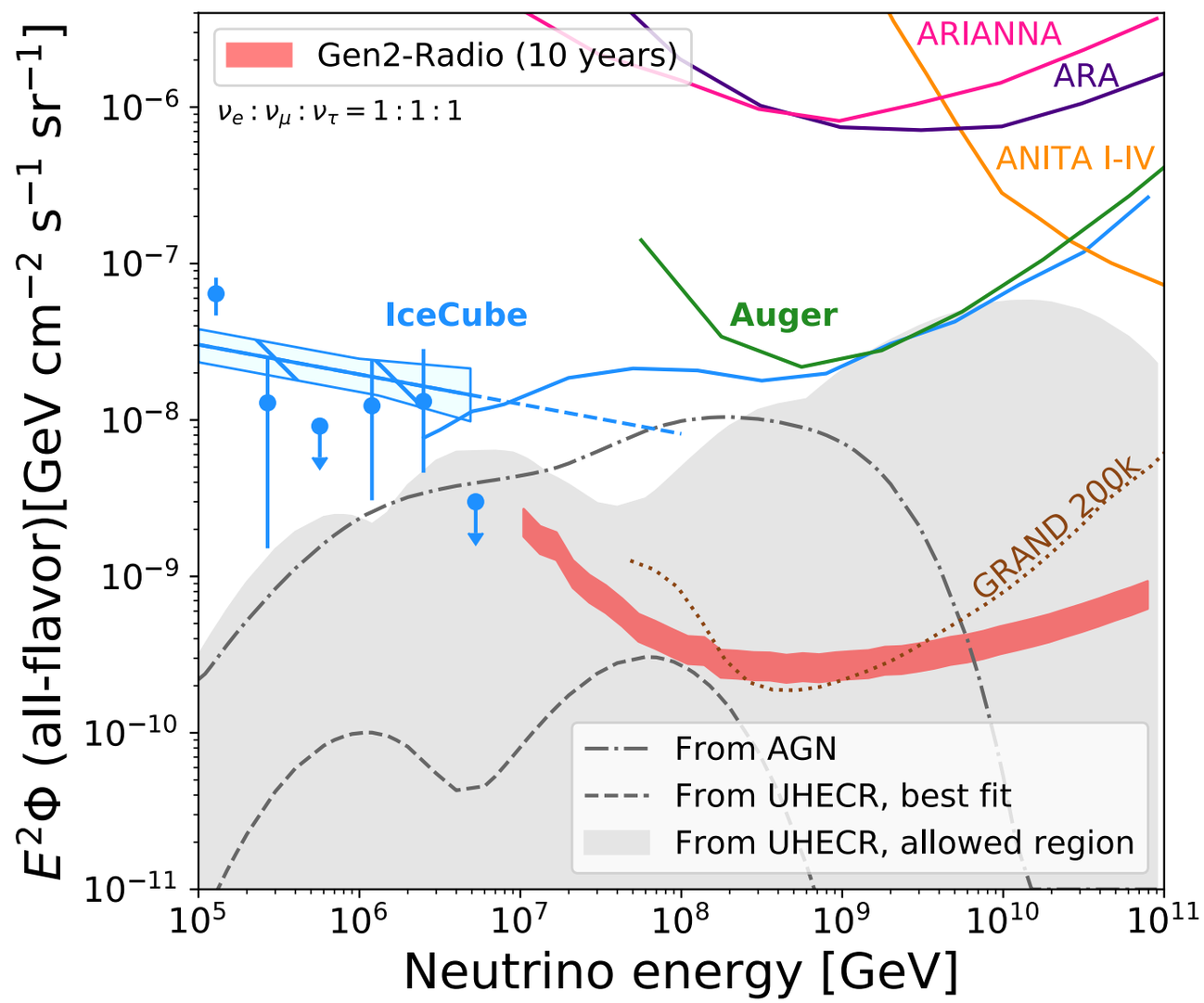
[Alves Batista *et al.*'19]

Vision: IceCube-Gen2

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

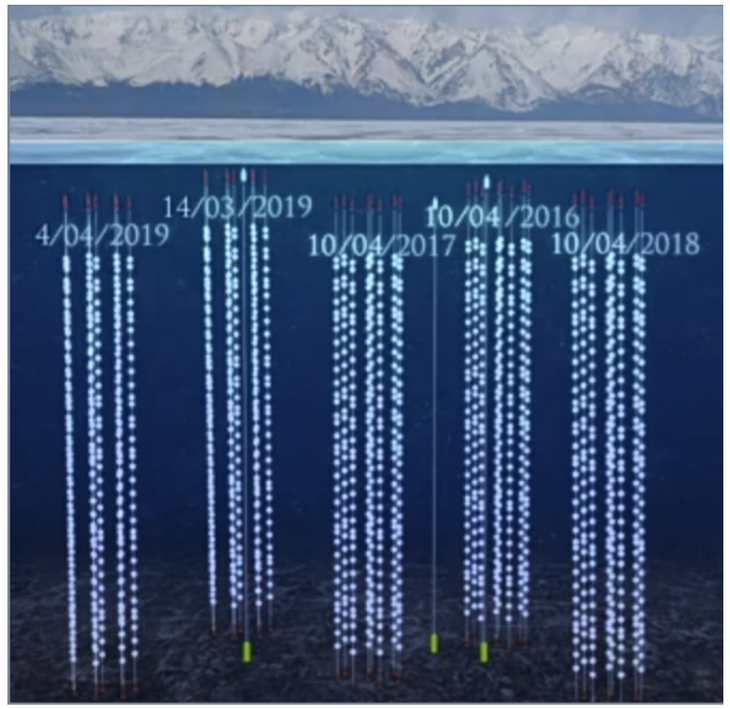


Precision measurement of **PeV-EeV neutrino fluxes** with extended in-ice optical and surface radio array



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

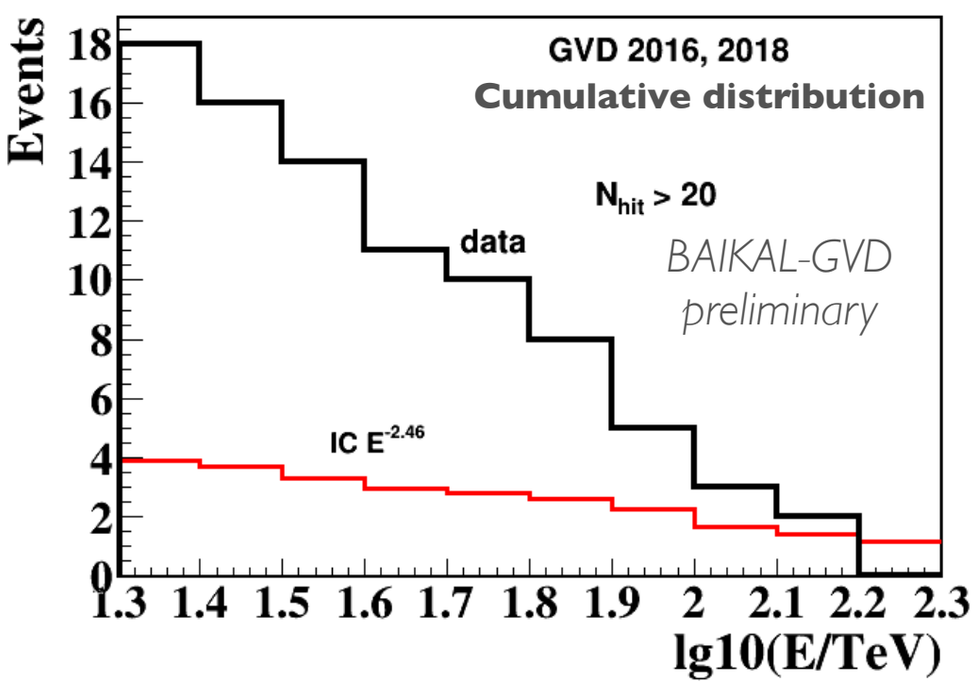
Outlook: Baikal-GVD

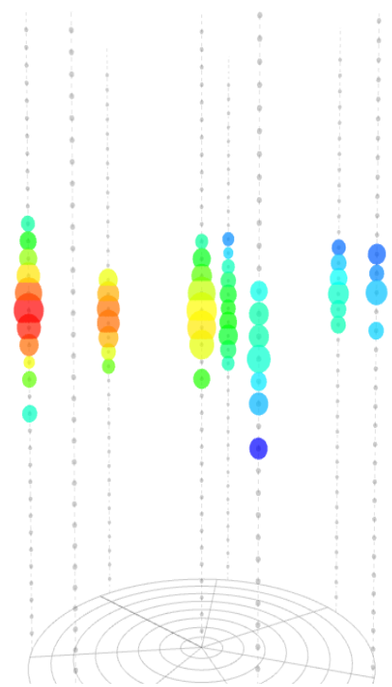


detector outline in 2019

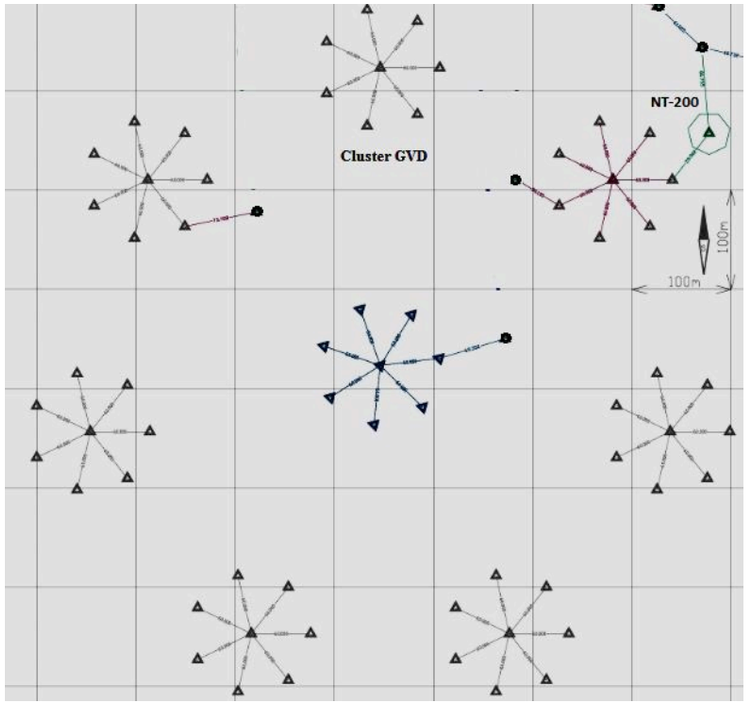
- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by end of 2021 (~0.4 km^3)
- cluster depth: 735–1260 m
- **status March 2021: 7 clusters**
- **final goal**: 27 clusters (~1.4 km^3)

BAIKAL-GVD





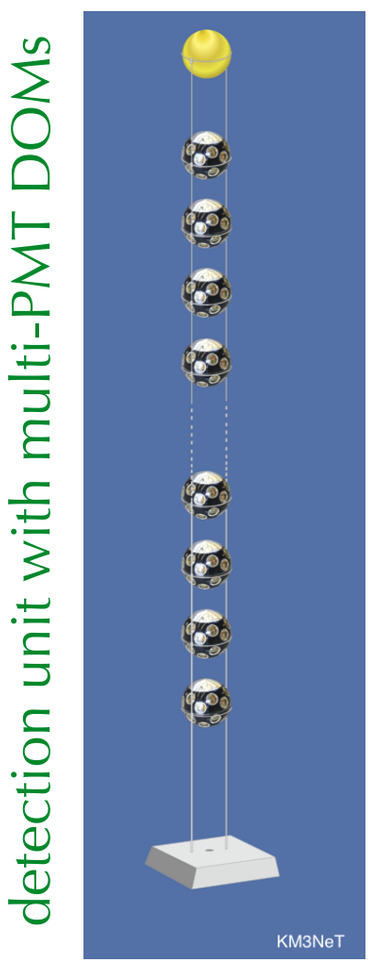
~157 TeV cascade event

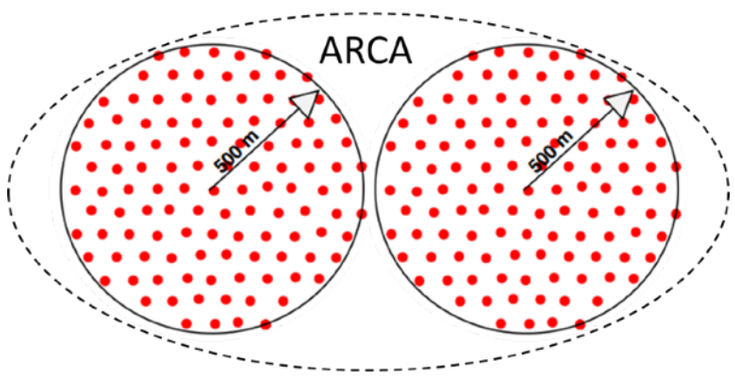


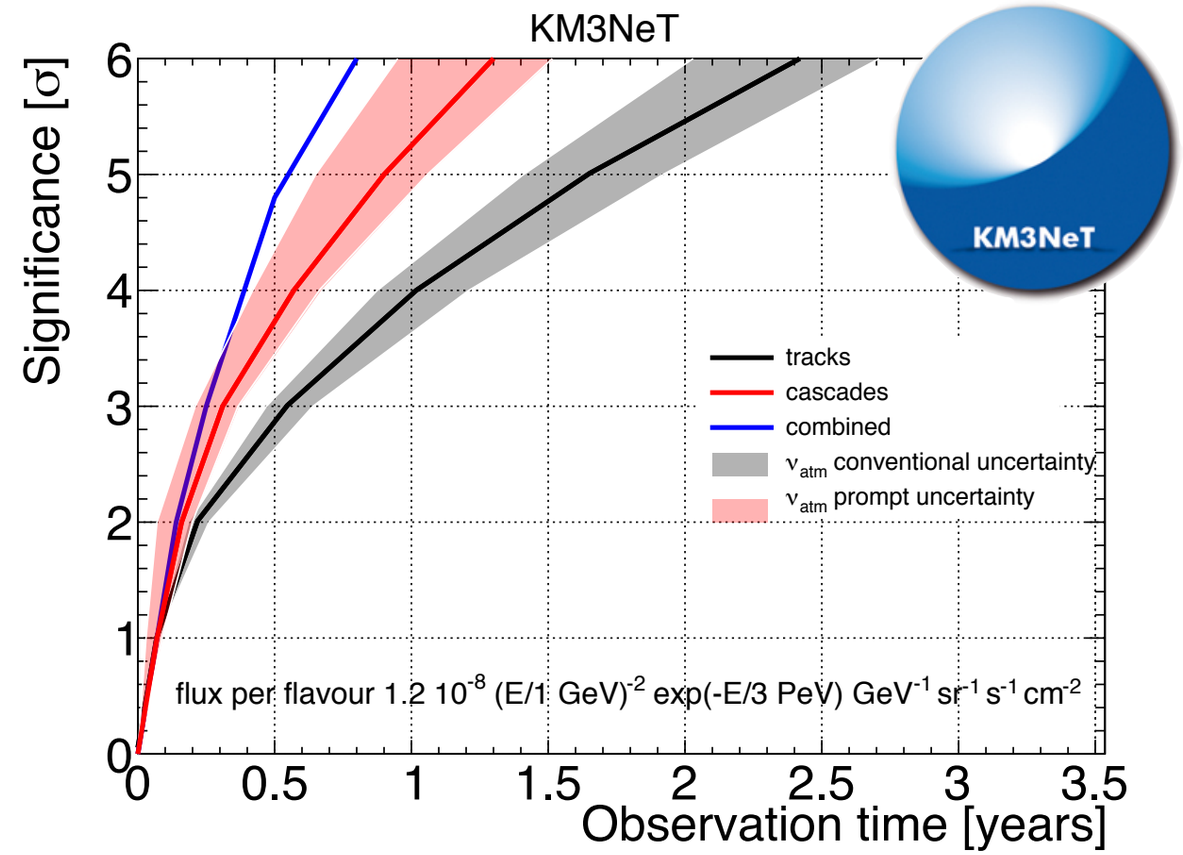
GVD-Phase 1

Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status March 2021: 1 DU**
- April 2021: +5 DUs
- September 2021: +12 DUs

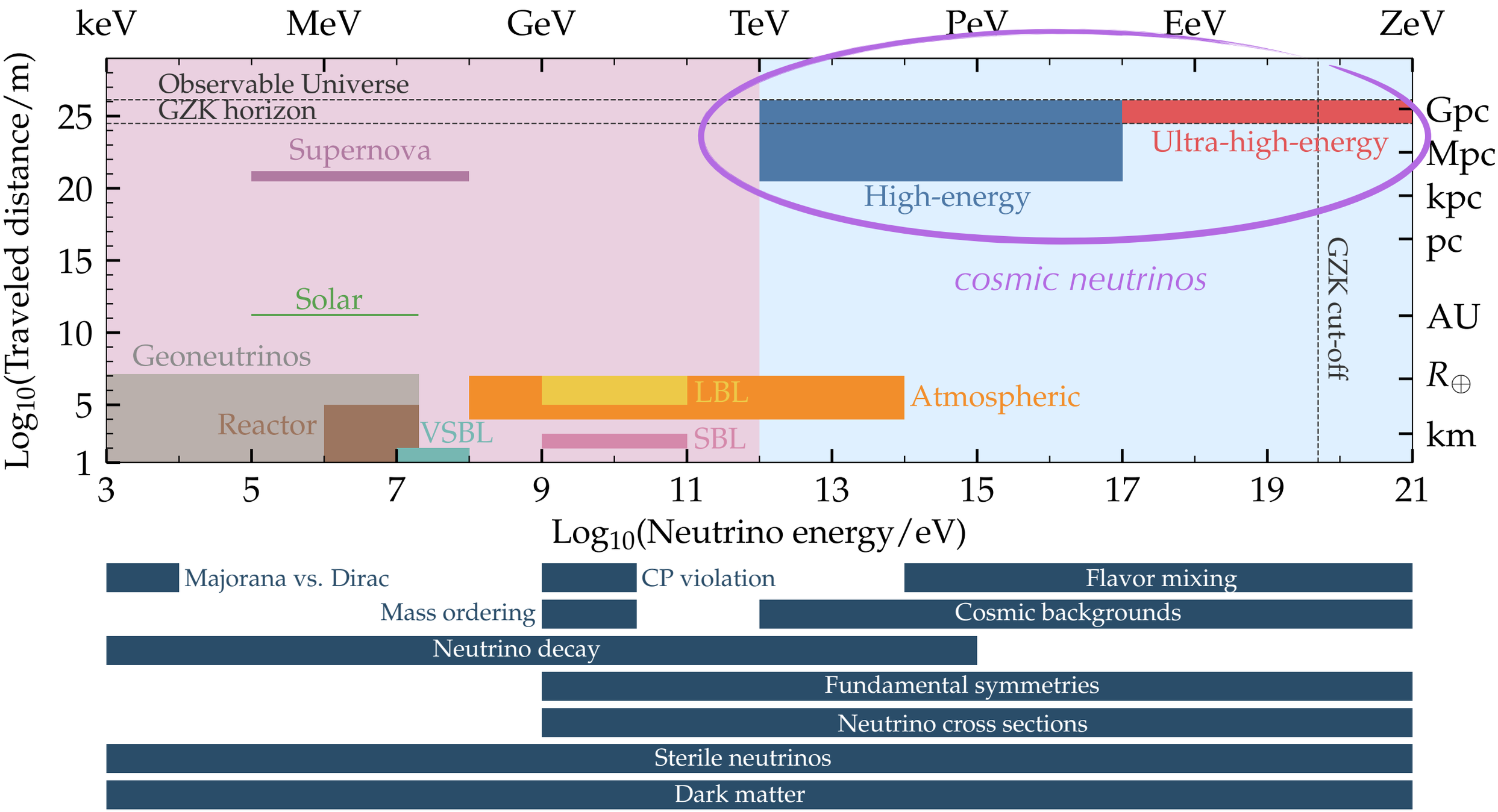






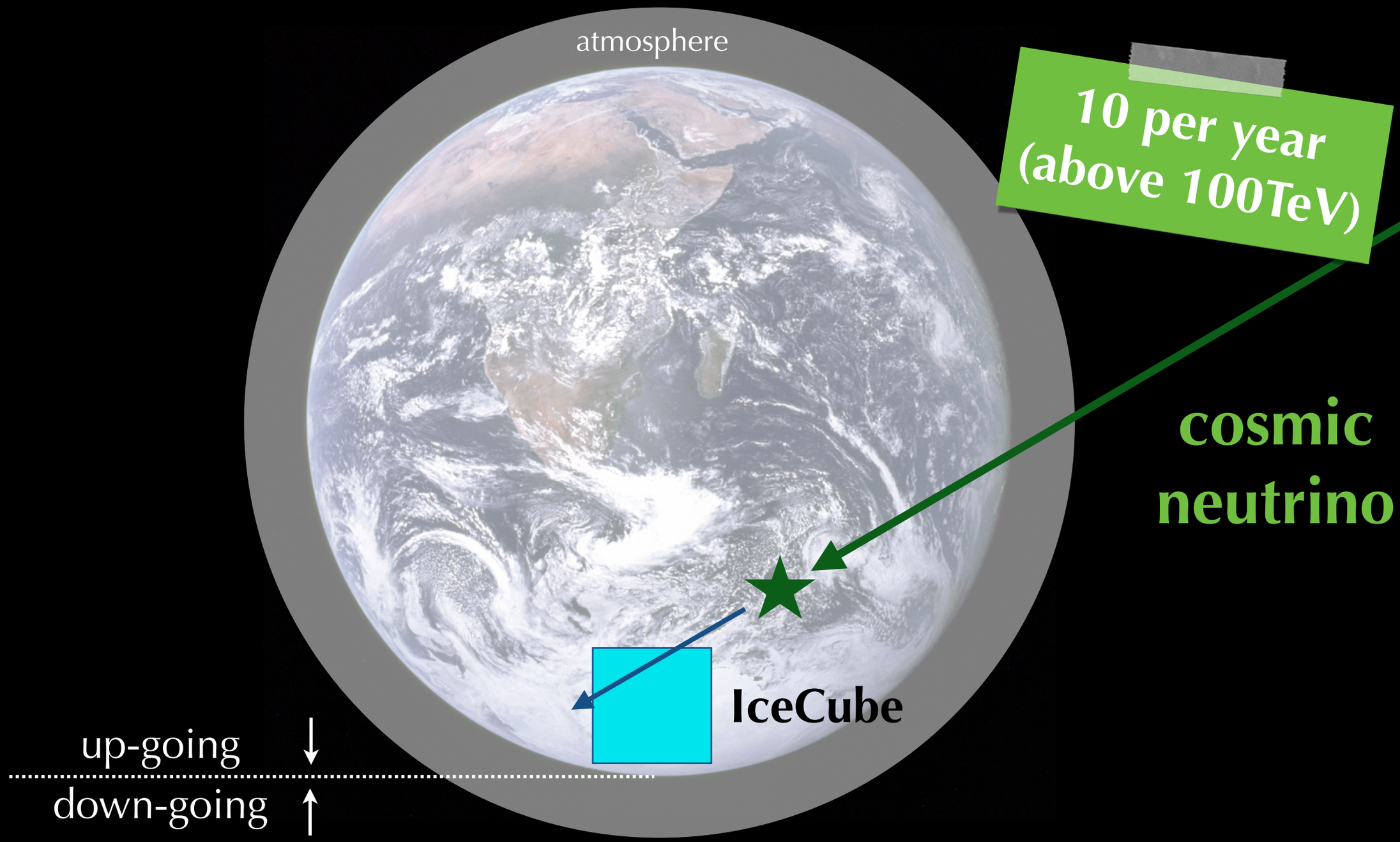
- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Probe of Fundamental Physics

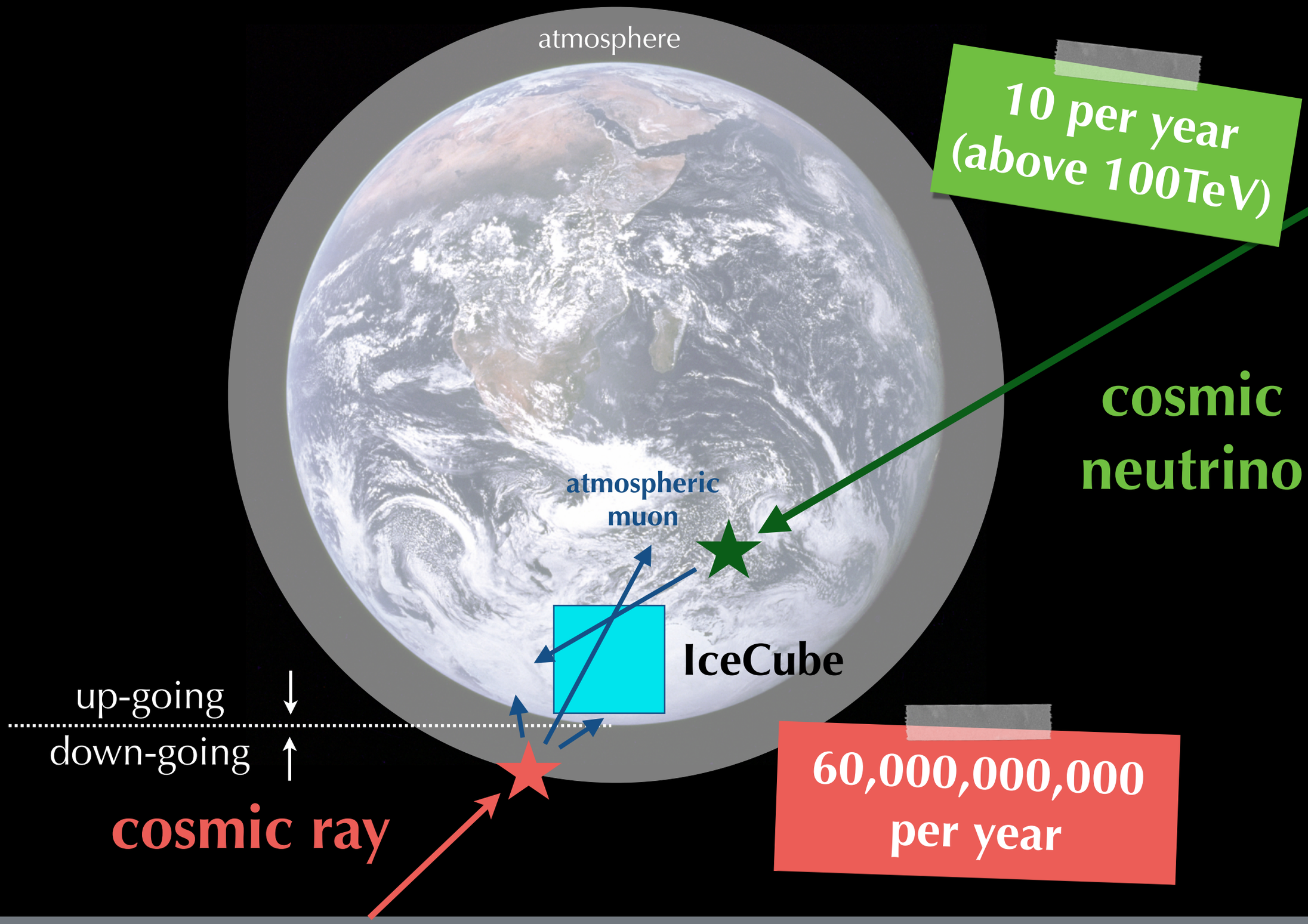


[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04334]

Neutrino Selection I



Neutrino Selection I



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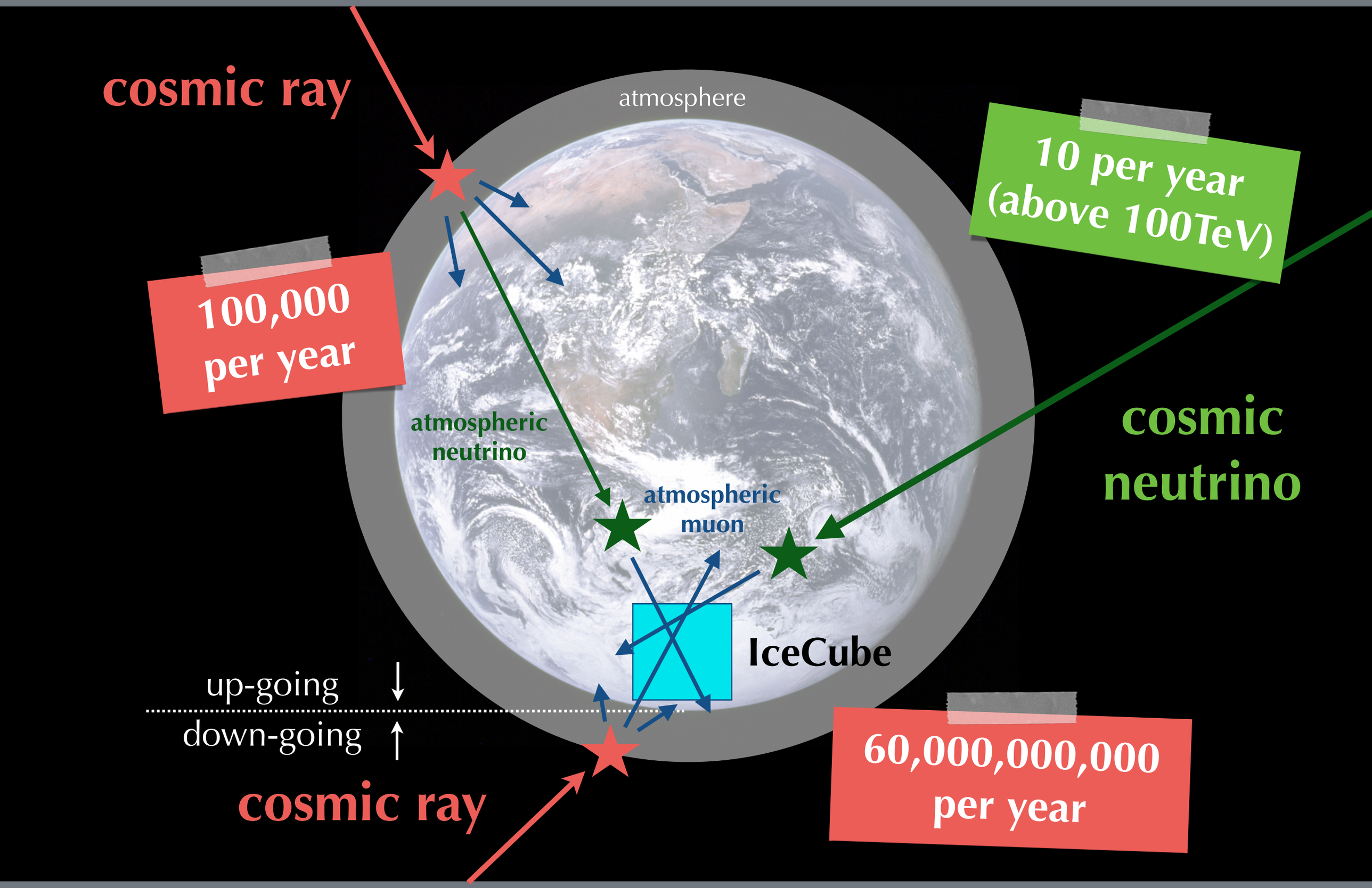
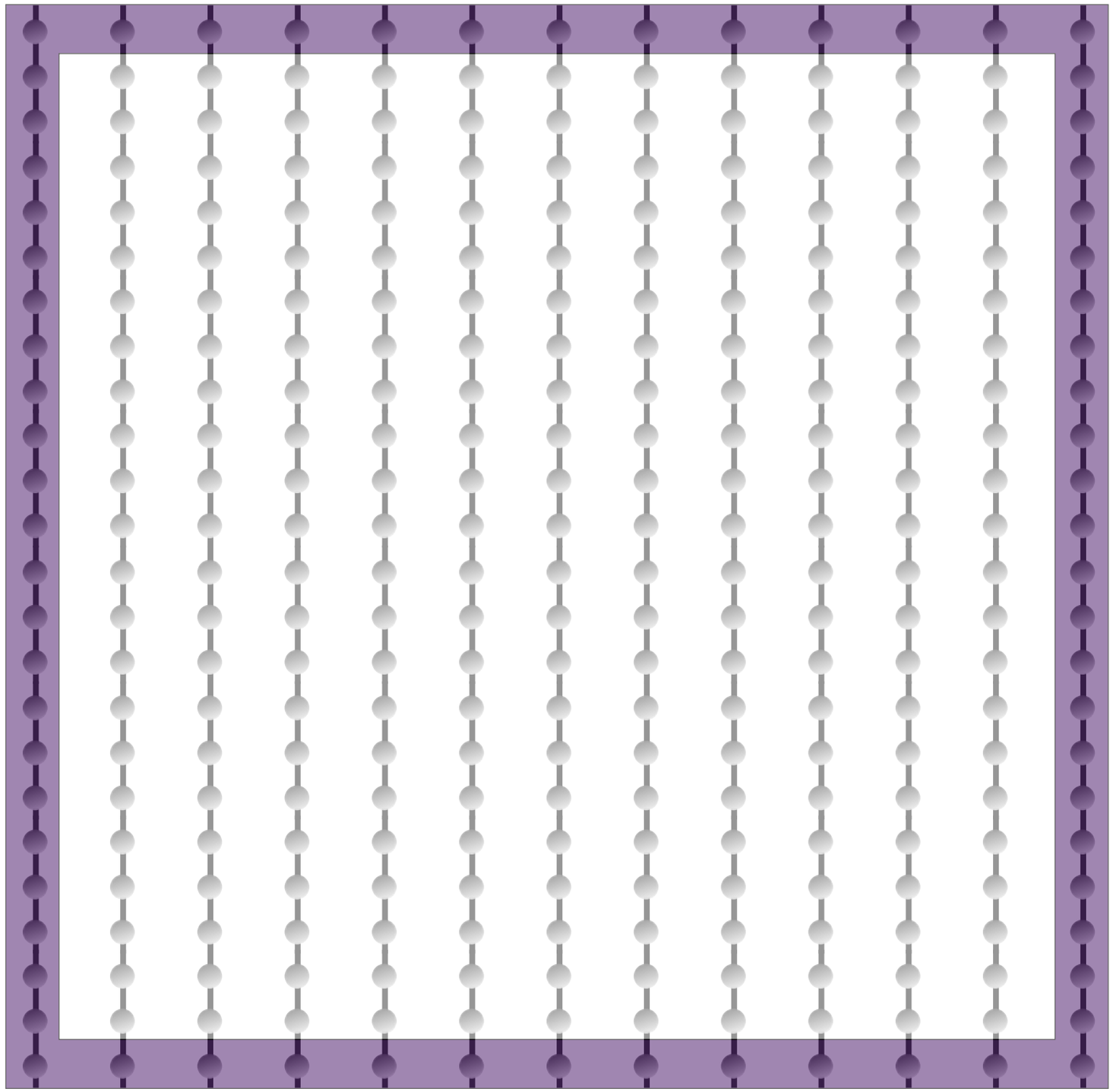


Neutrino Selection II

- 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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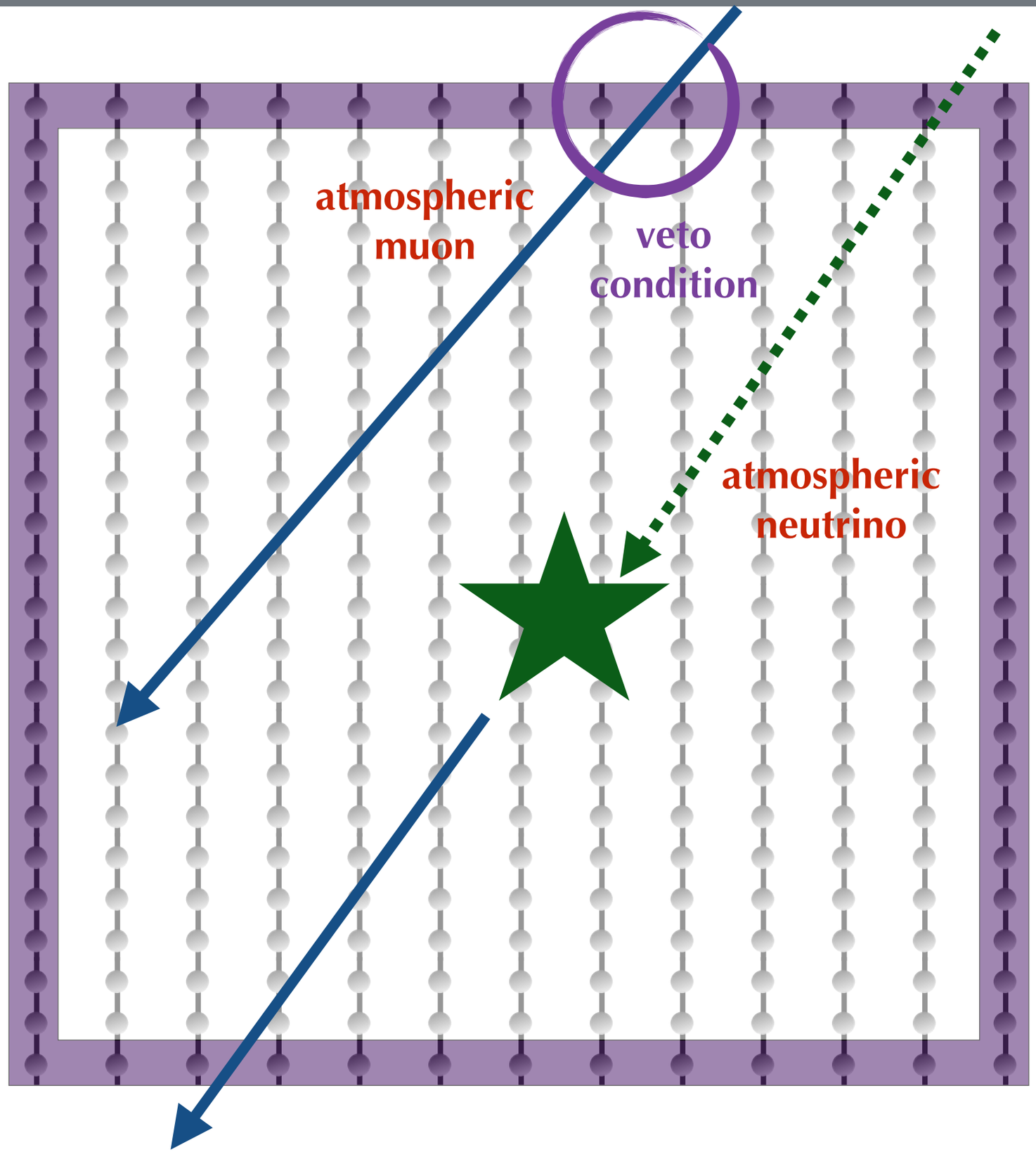

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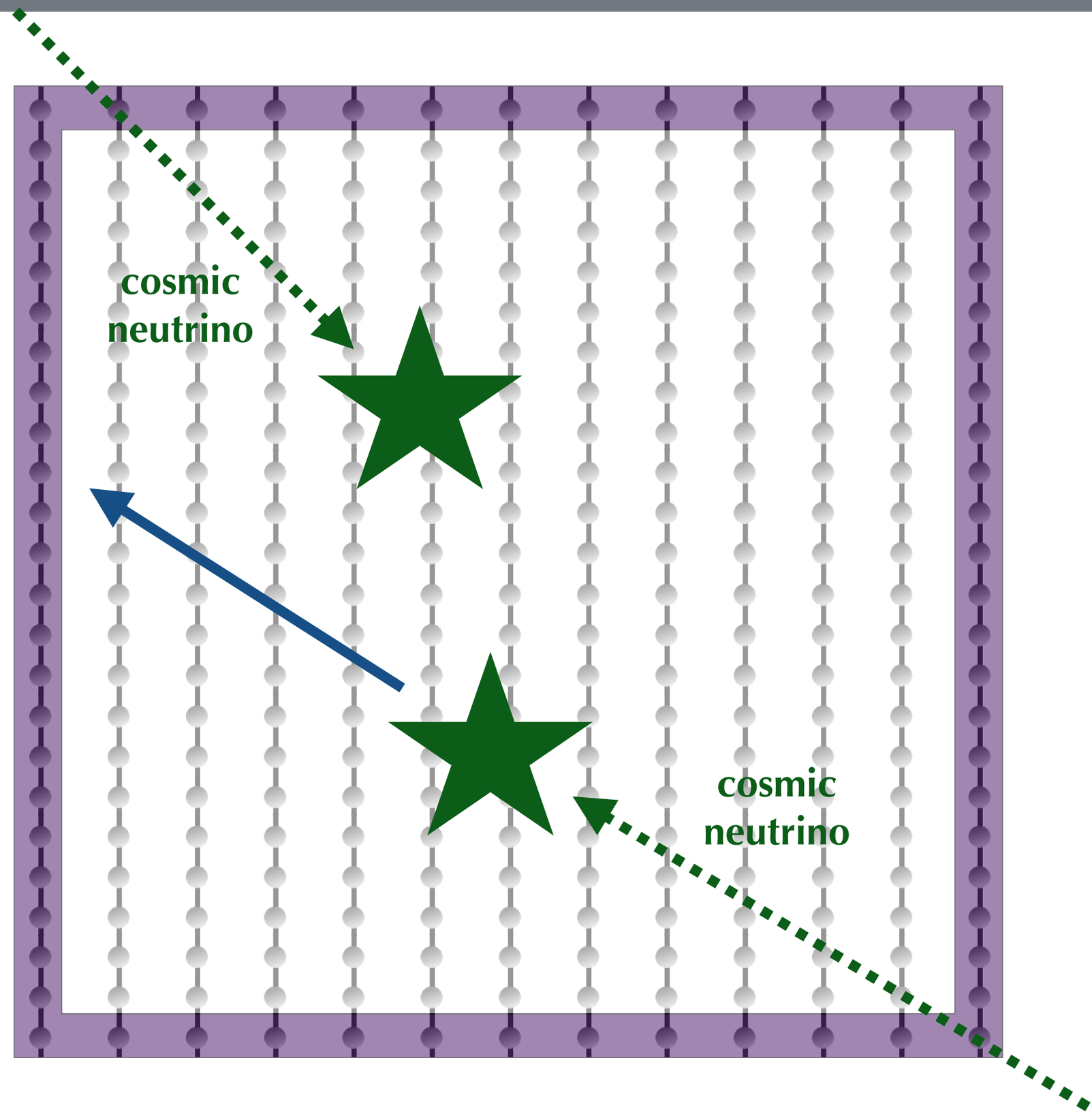
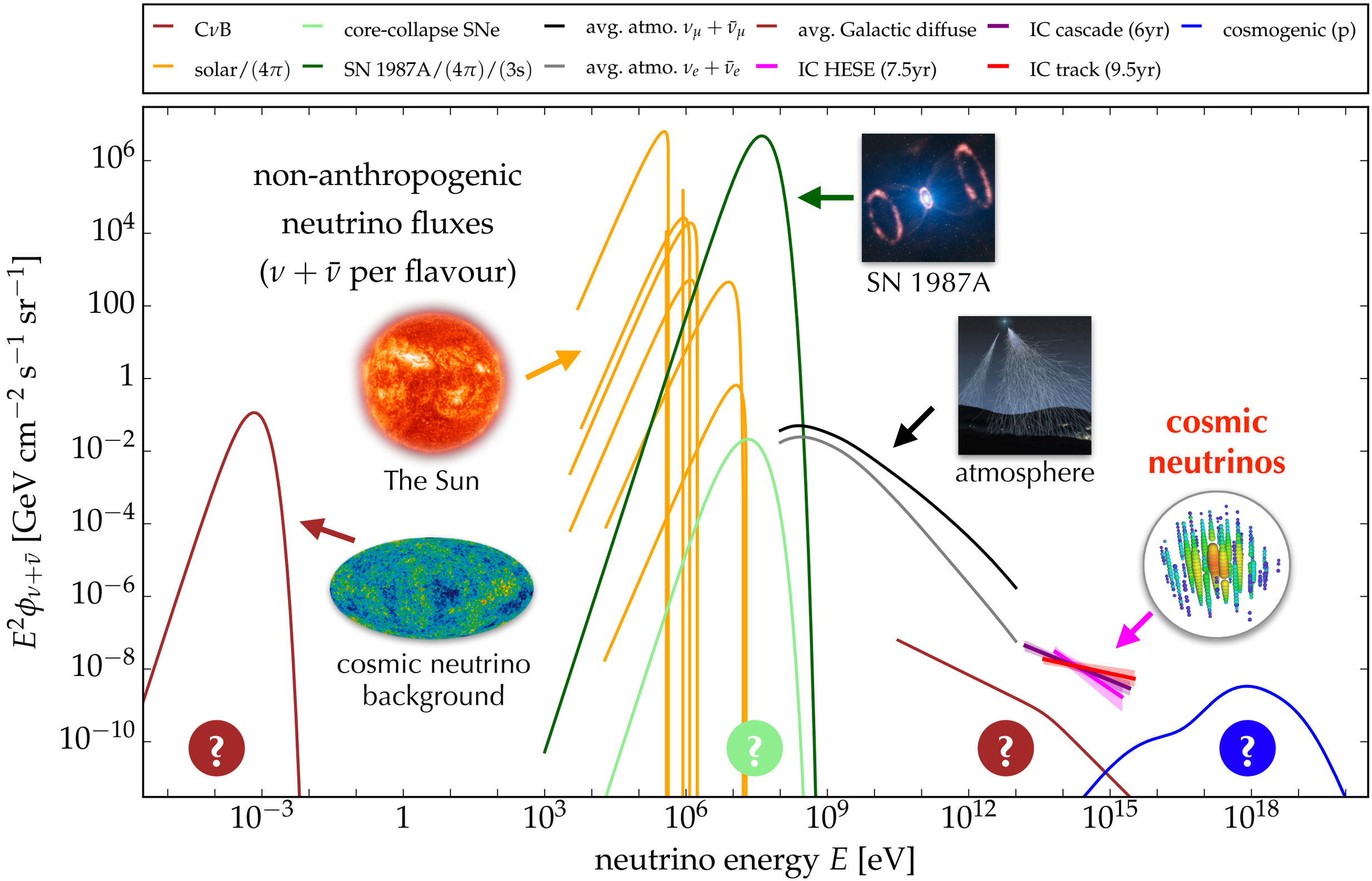
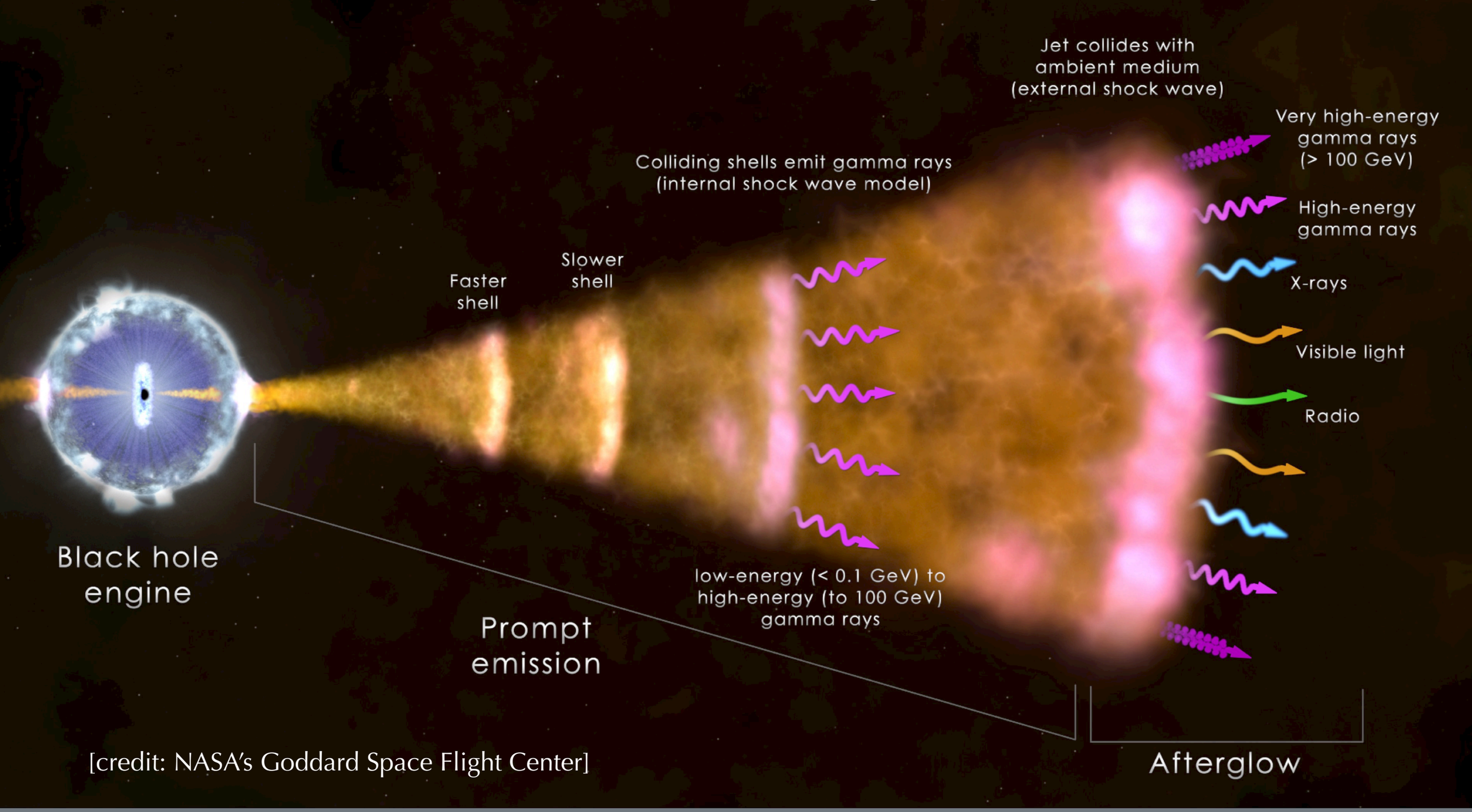


Astrophysical Neutrino Fluxes



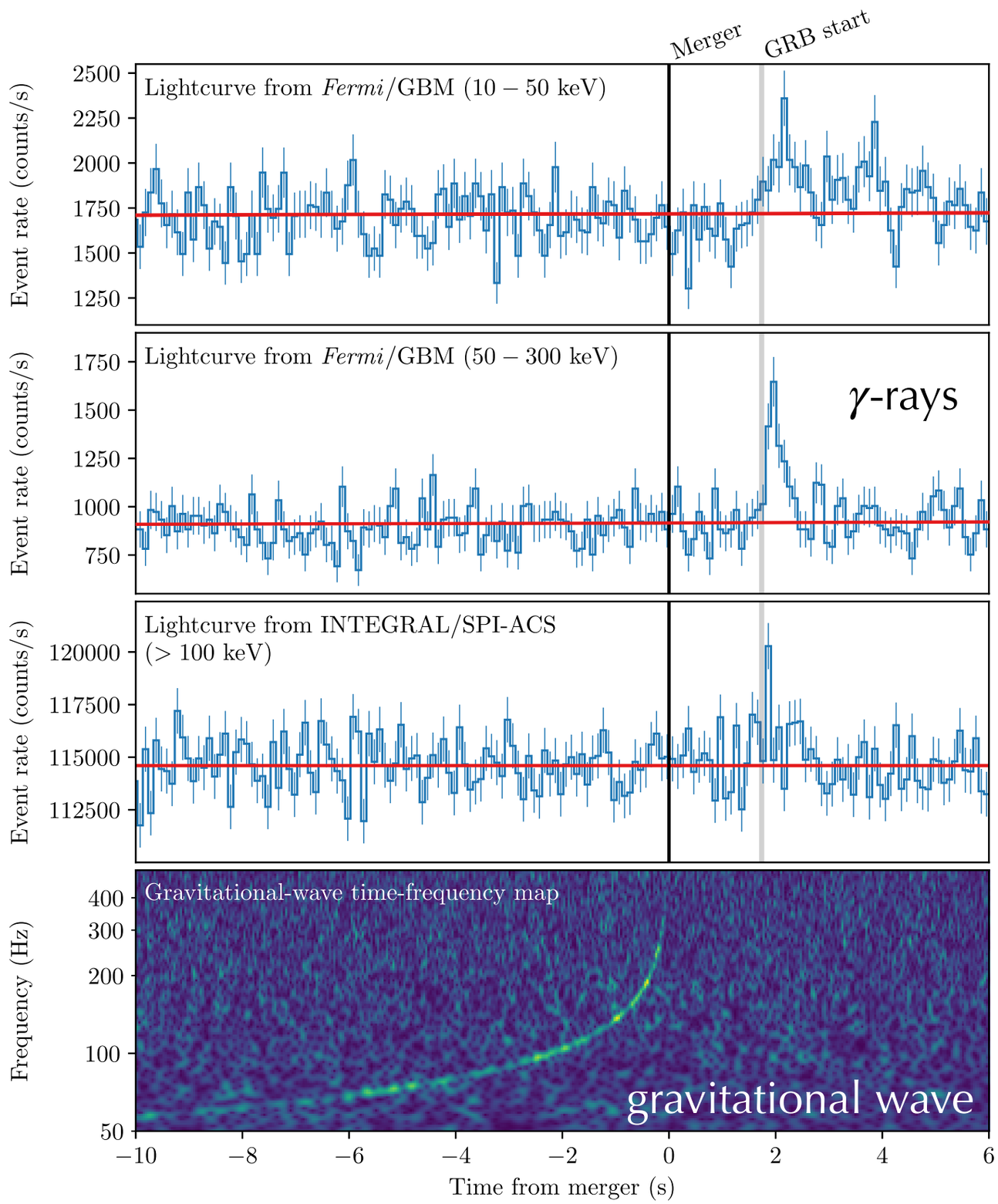
Gamma-Ray Bursts

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

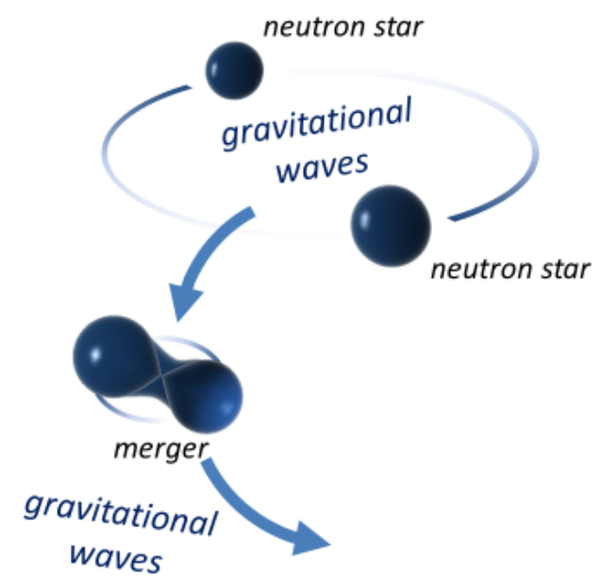


[credit: NASA's Goddard Space Flight Center]

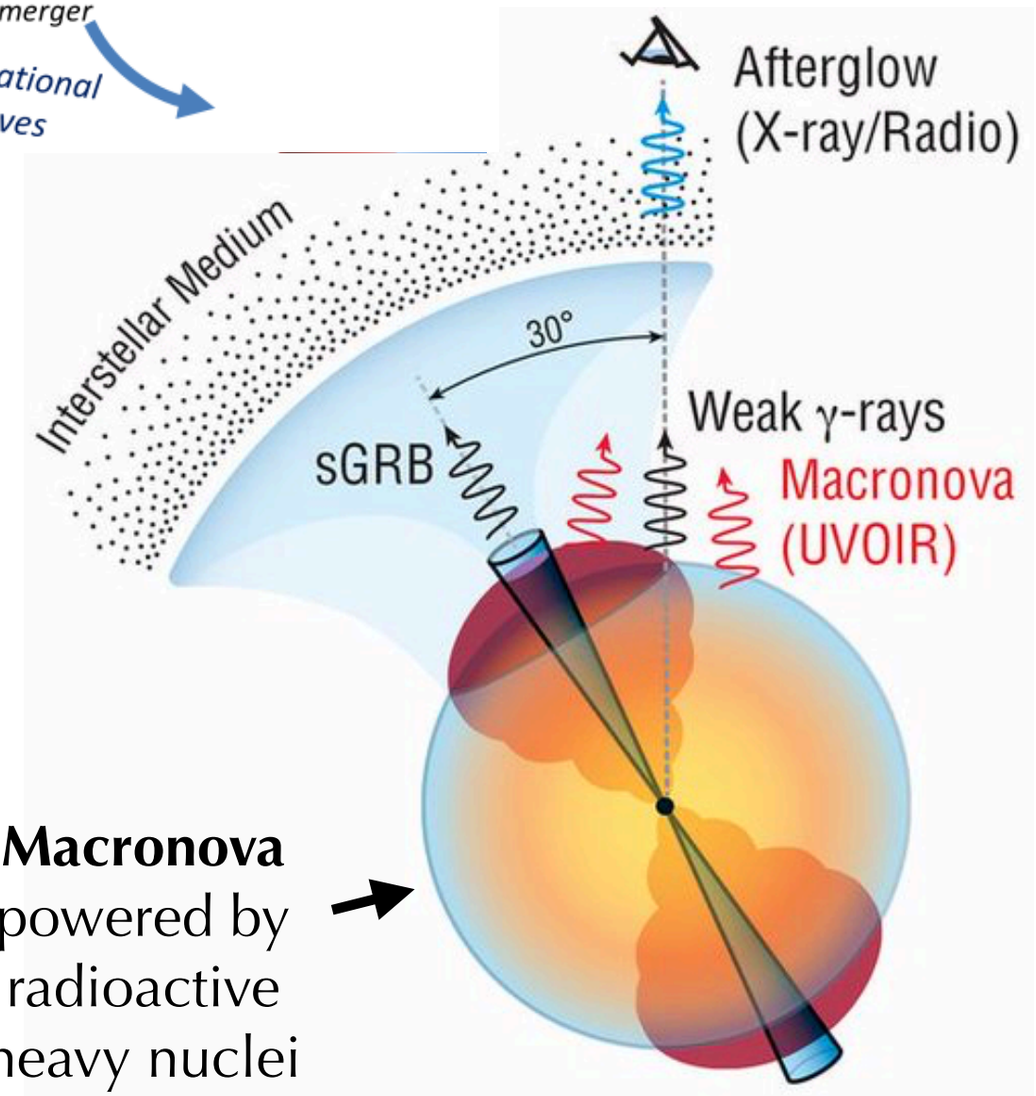
GRBs and Gravitational Waves



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

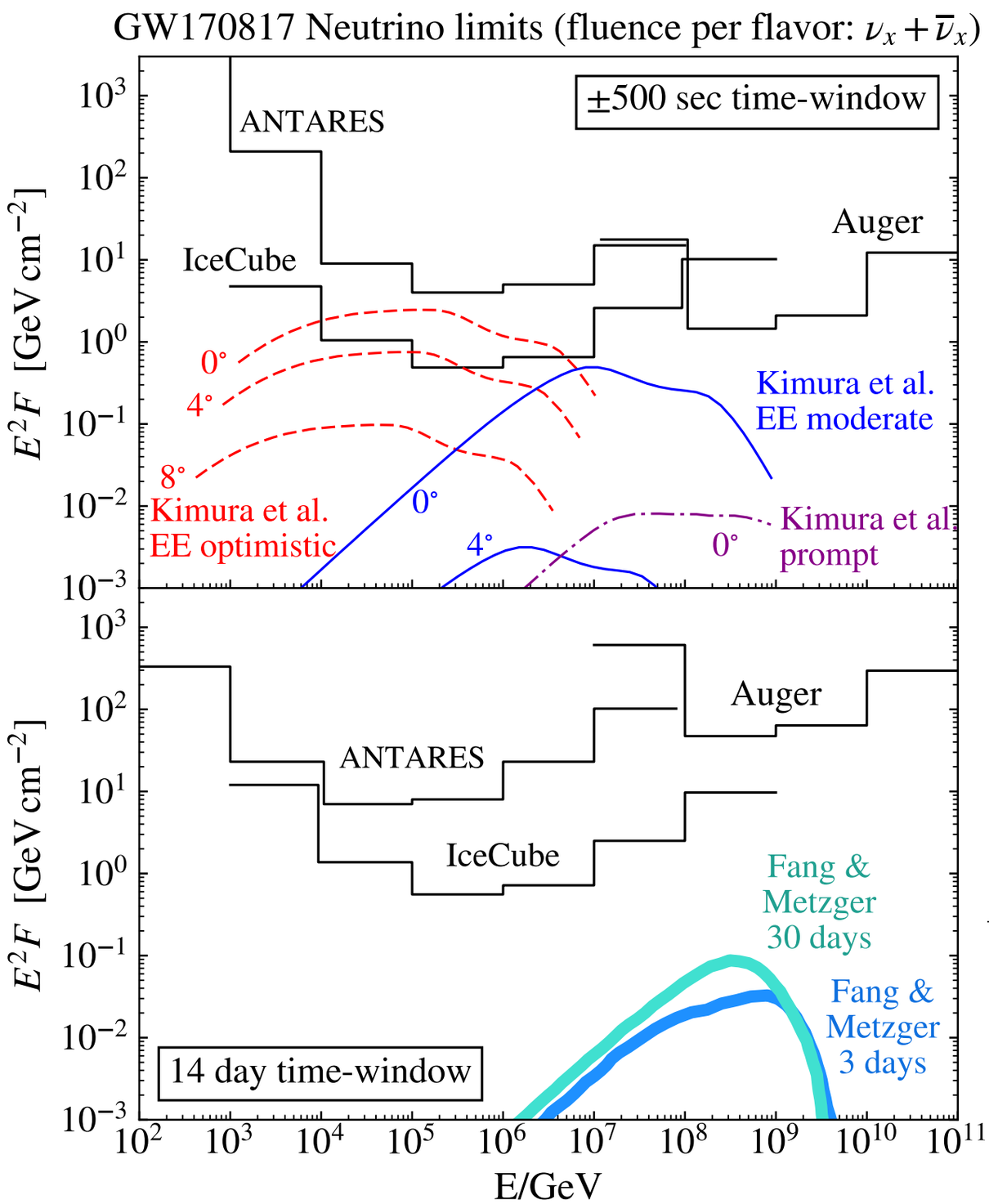


GW 170817
&
GRB 170817A

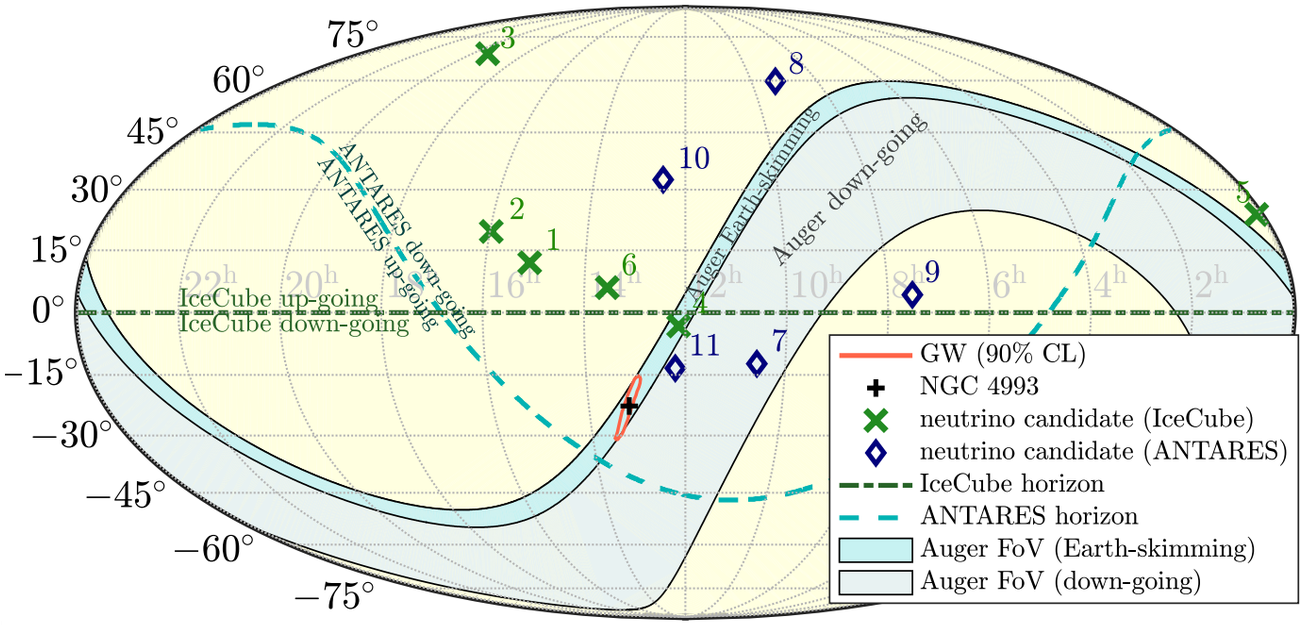


Macronova powered by radioactive heavy nuclei

GRB 170817A

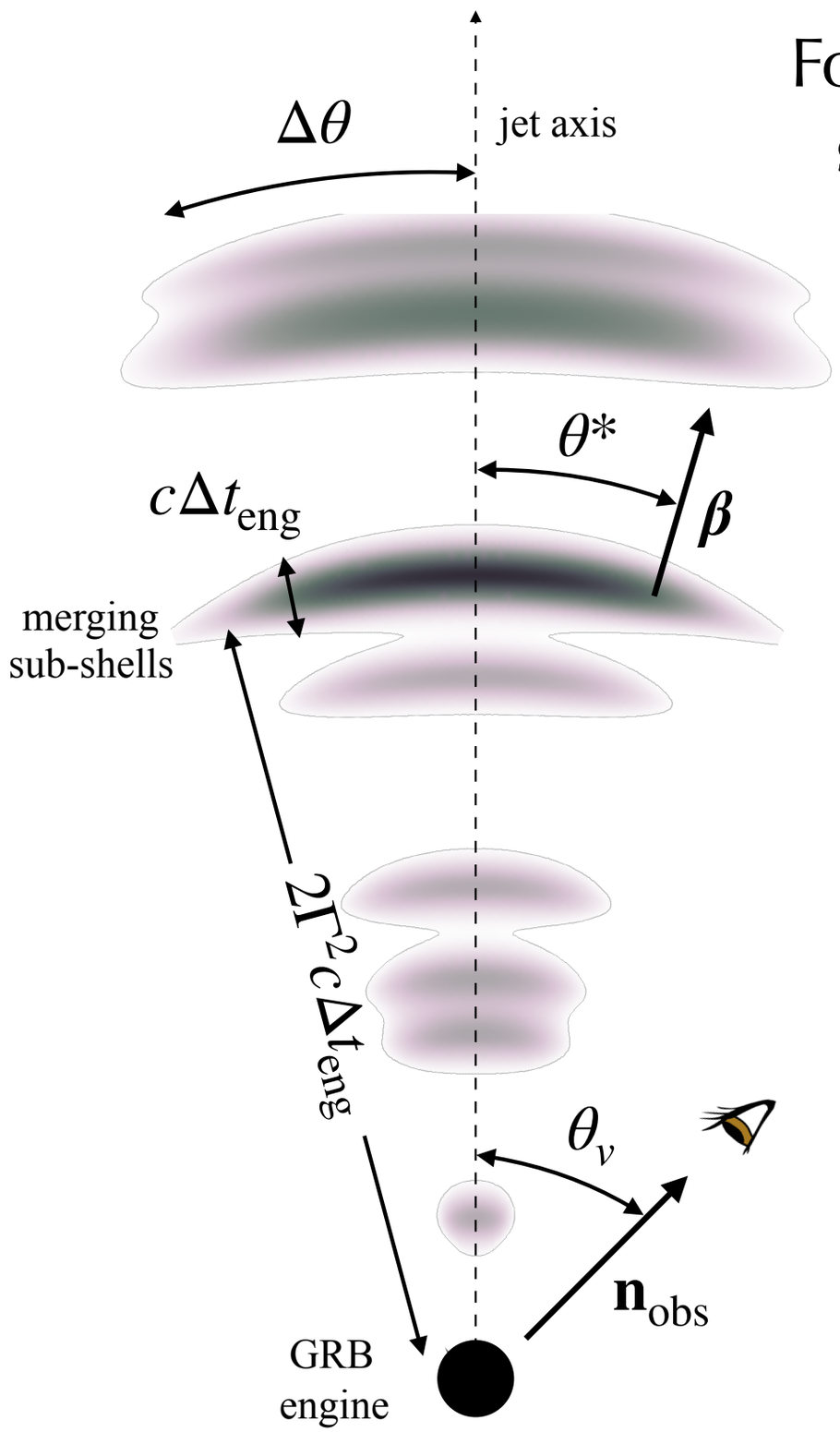


- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle.**

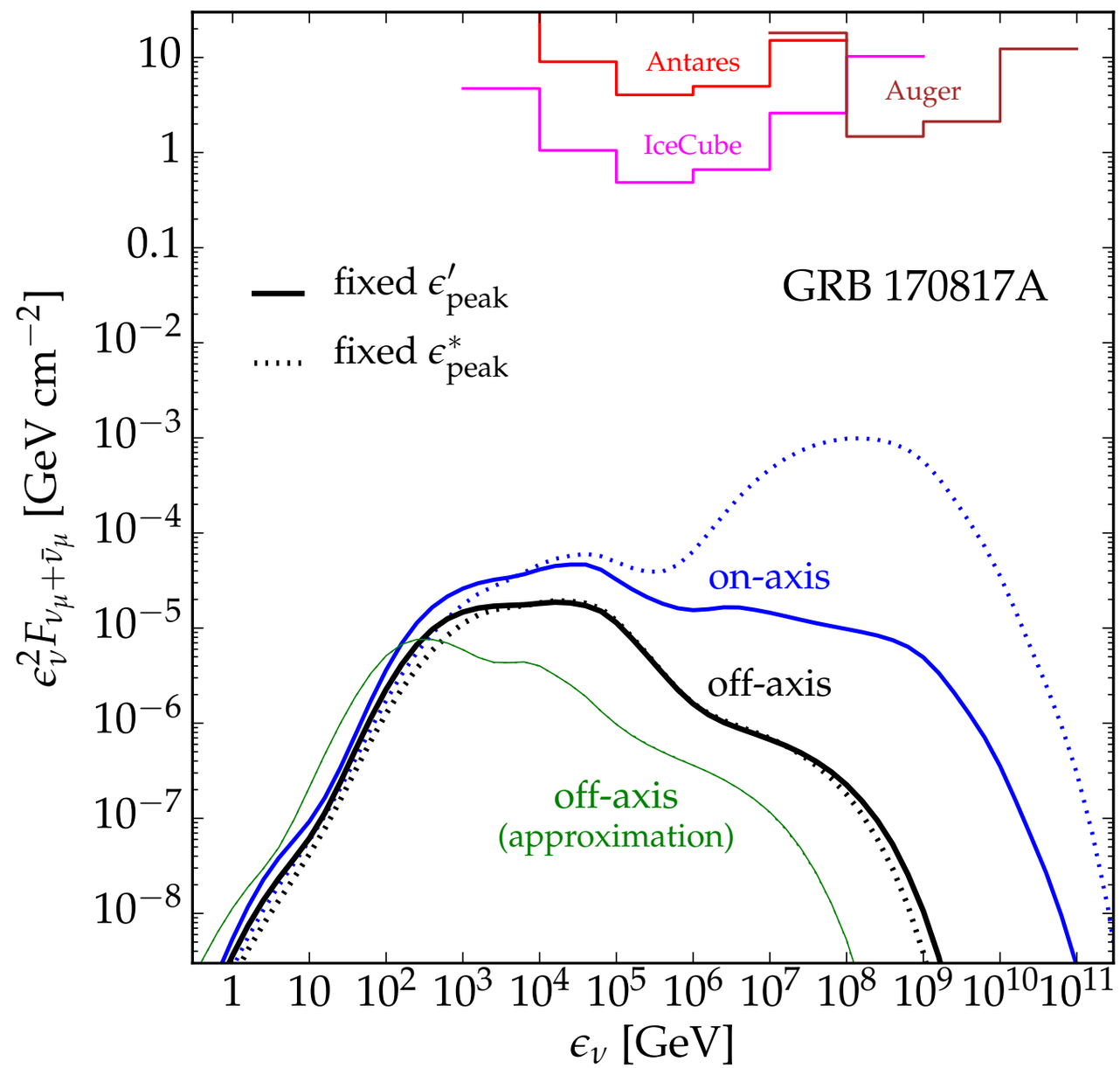


[ANTARES, IceCube, Auger & LVC, ApJ 850 (2017) 2]

GRB 170817A - Revisited

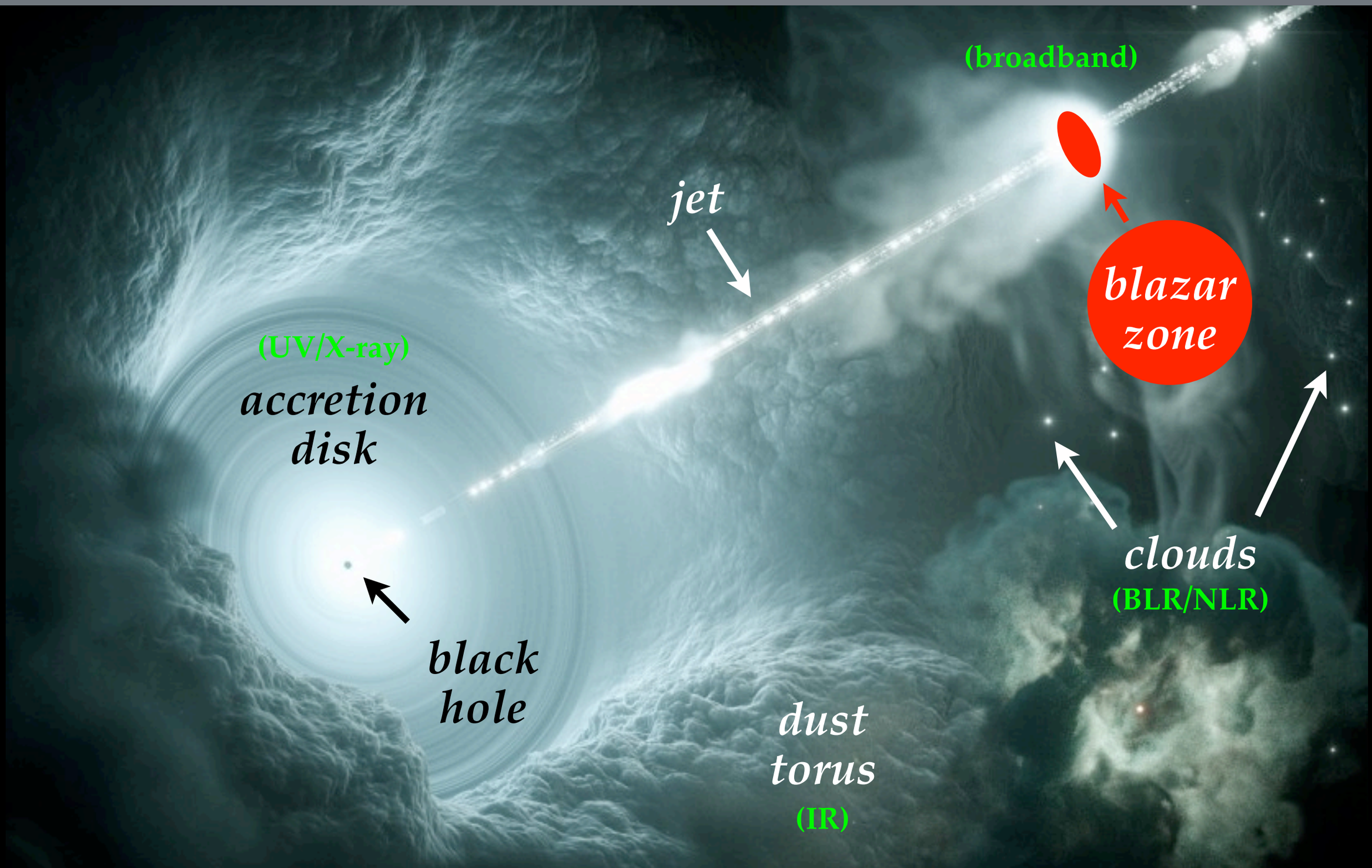


Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



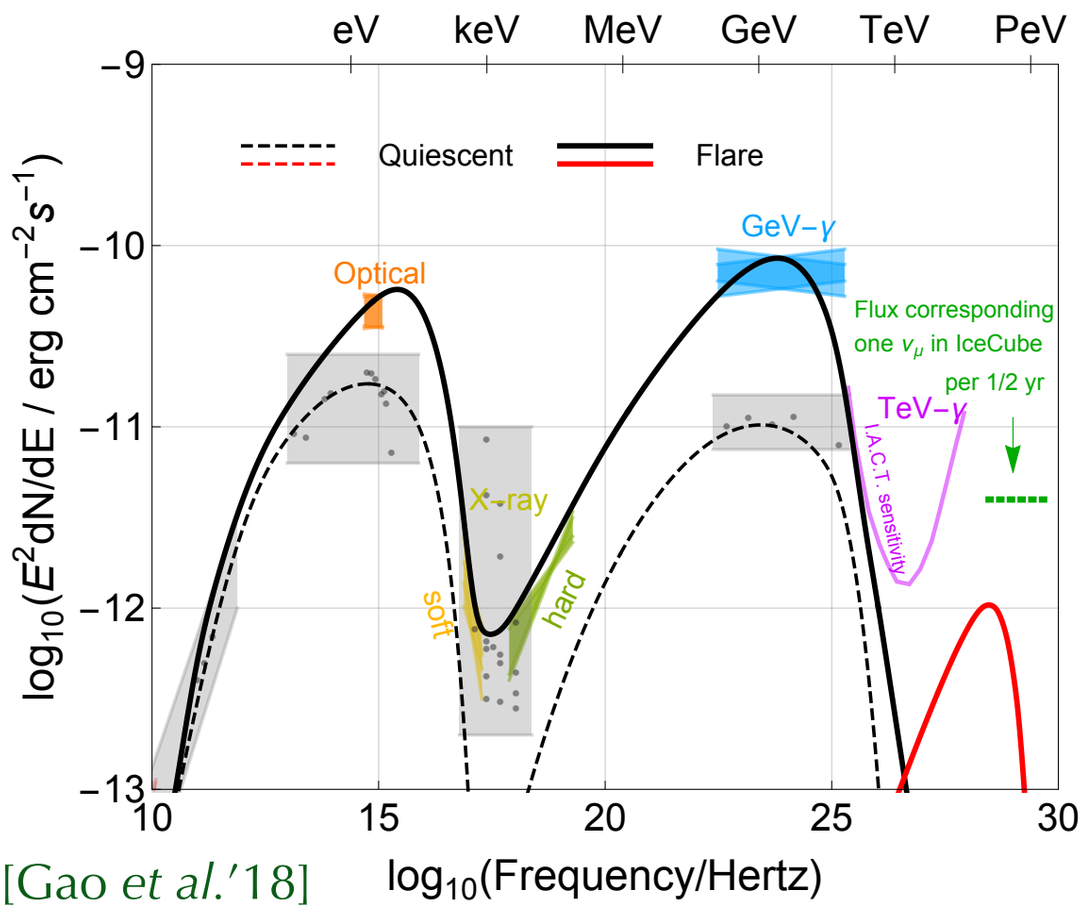
[MA & Halser MNRAS 490 (2019) 4]

Blazars

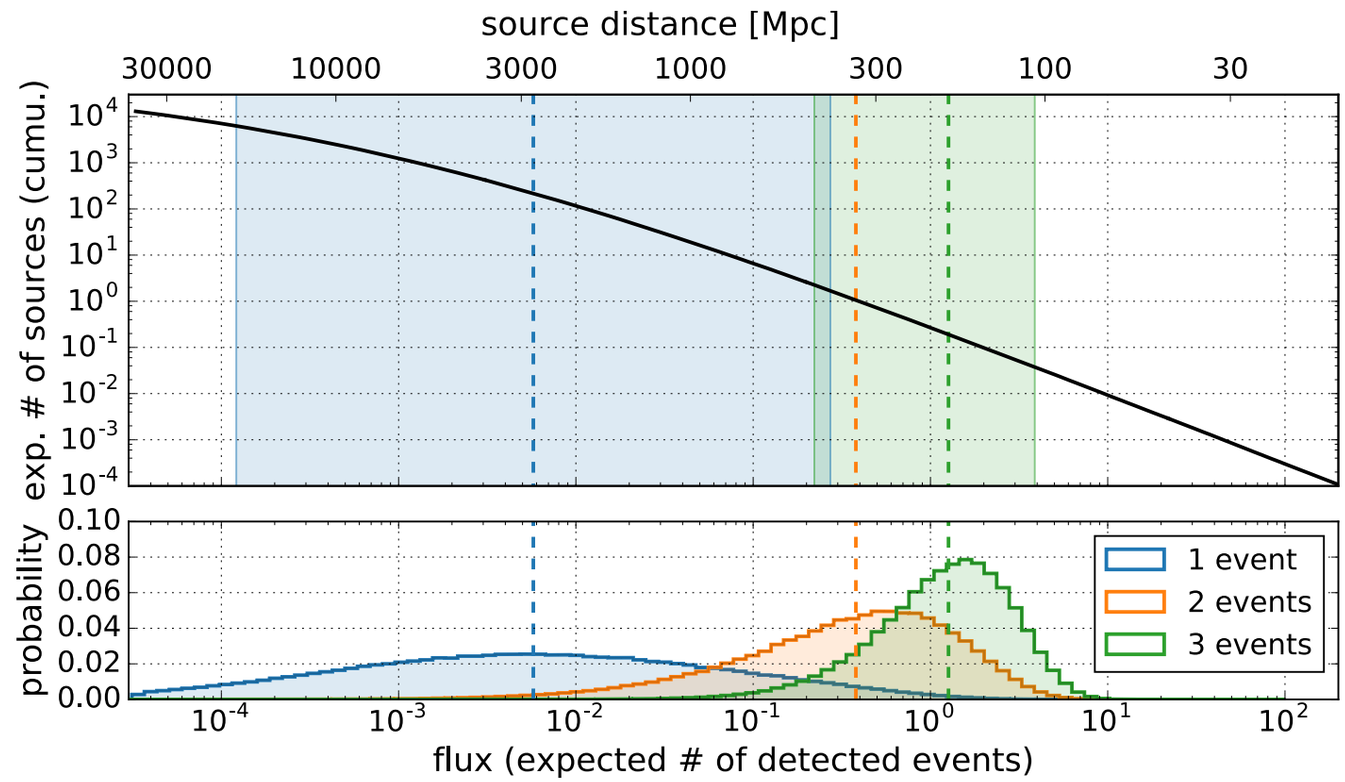


Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

Neutrino Flare in 2017



[Gao *et al.*'18]



[Strotjohann, Kowalski & Franckowiak'18]

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

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:

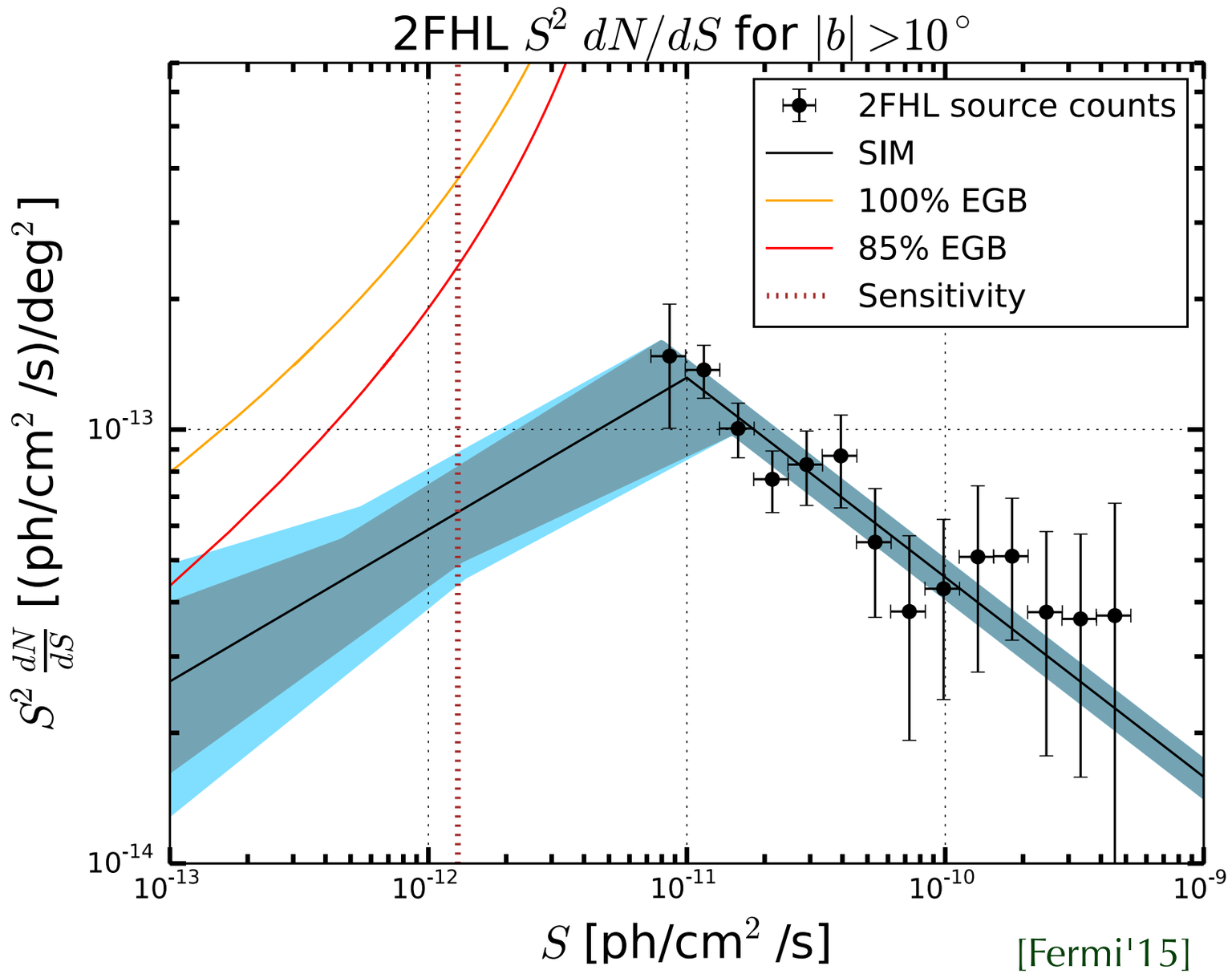
    $$86^{+16}_{-14}\,\%$$

  - Lisanti *et al.*'16:

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

  - Zechlin *et al.*'16

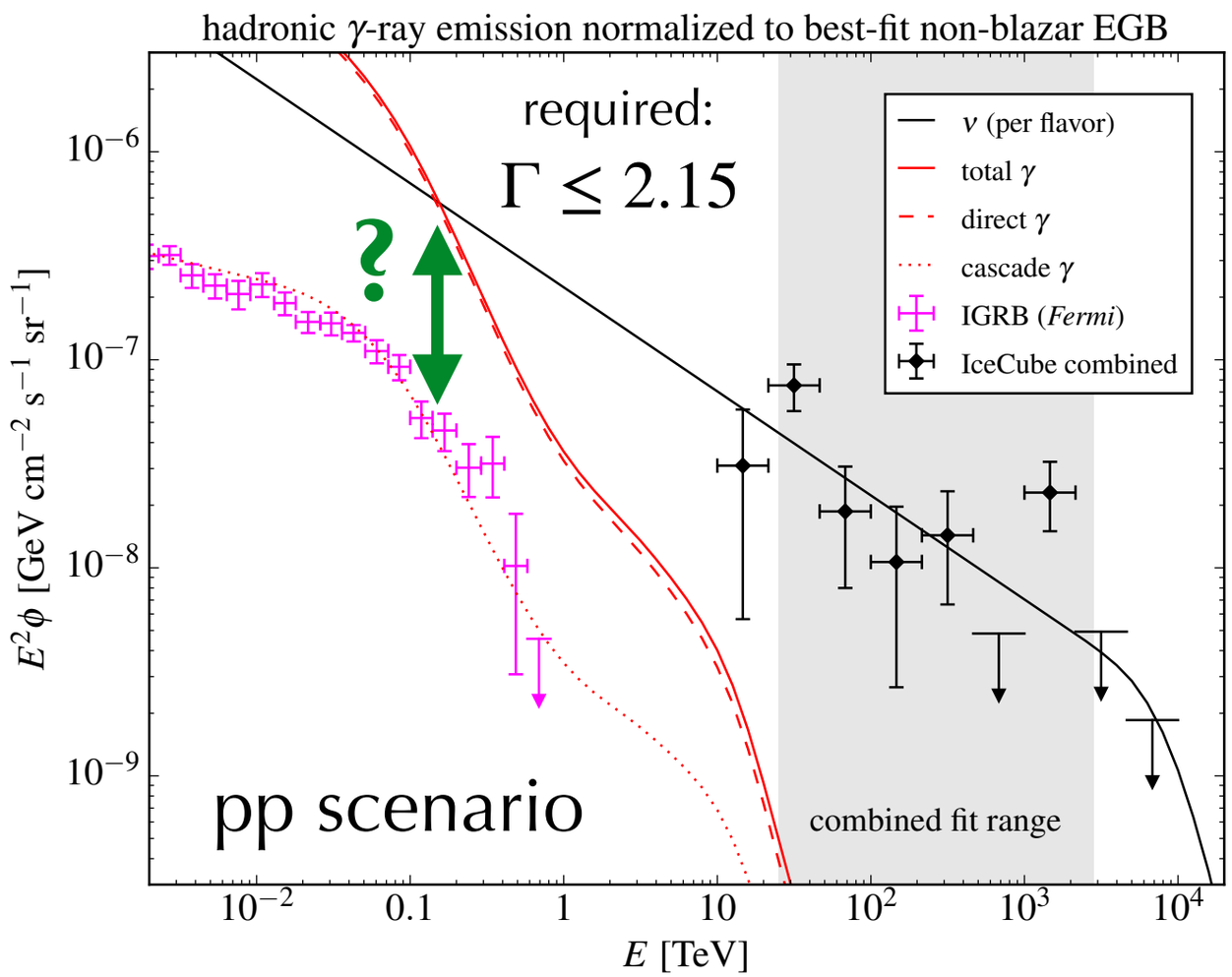
    $$81^{+52}_{-19}\,\%$$

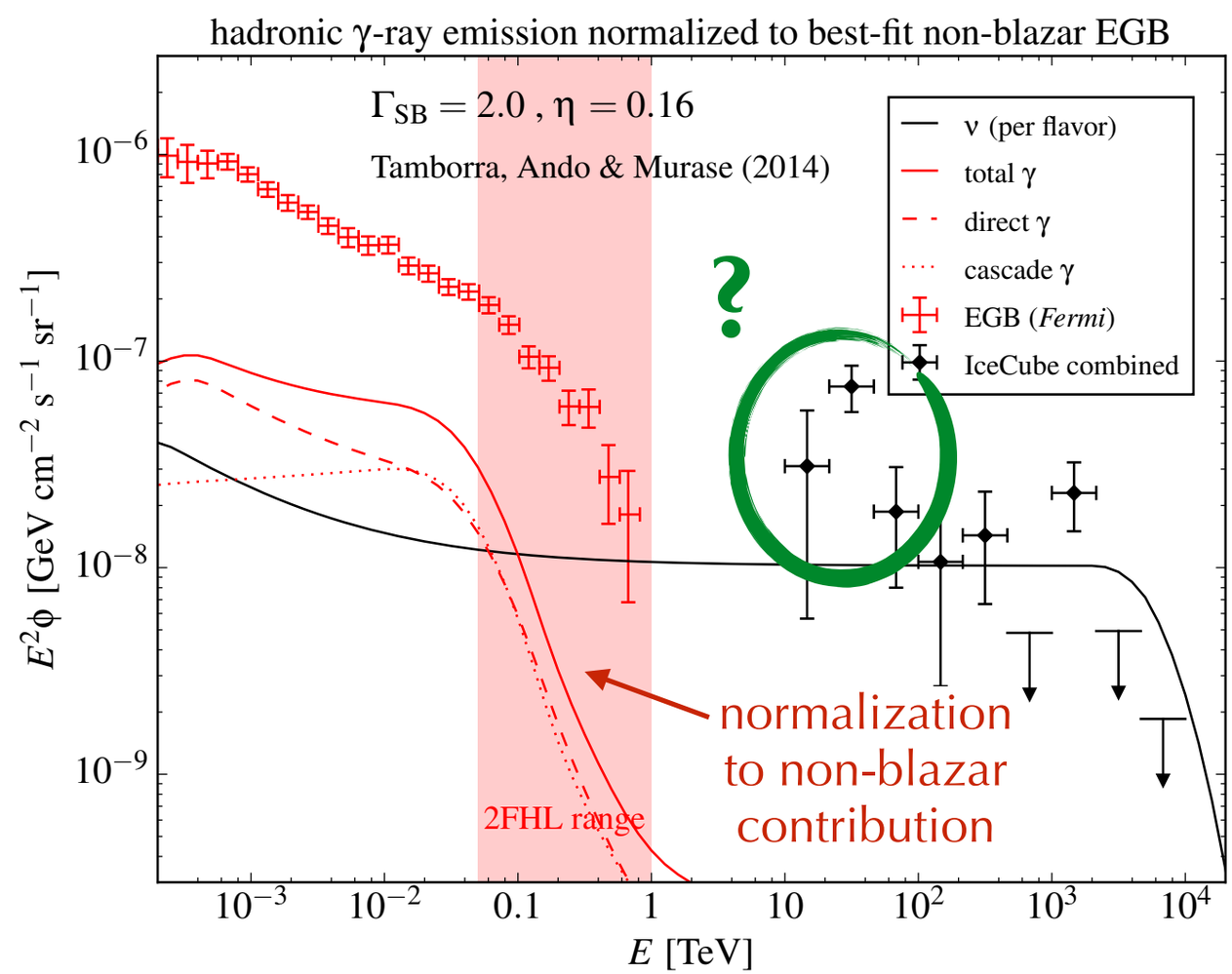


[Fermi'15]

Hadronic Gamma-Rays

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





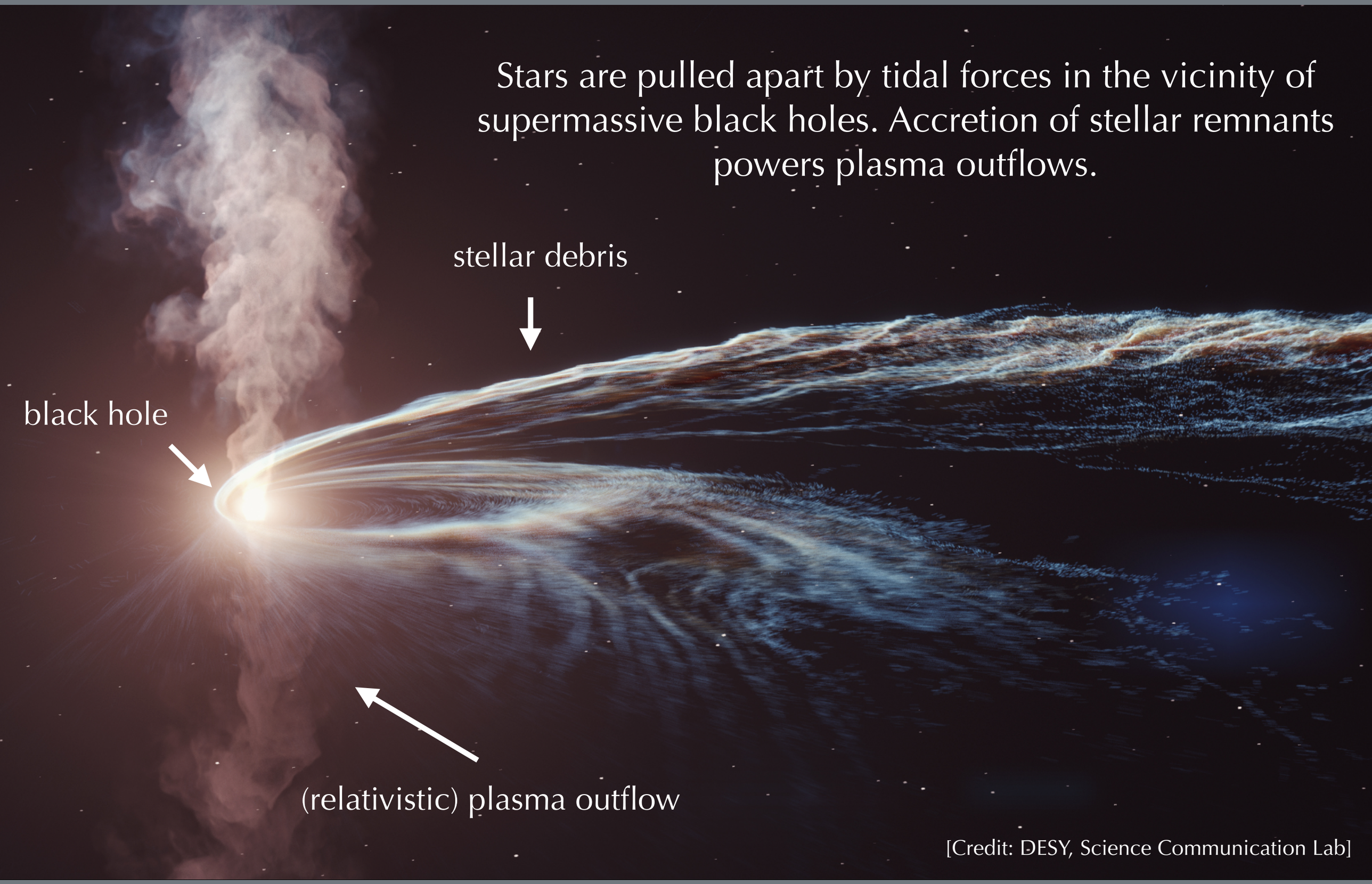
[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15]

[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



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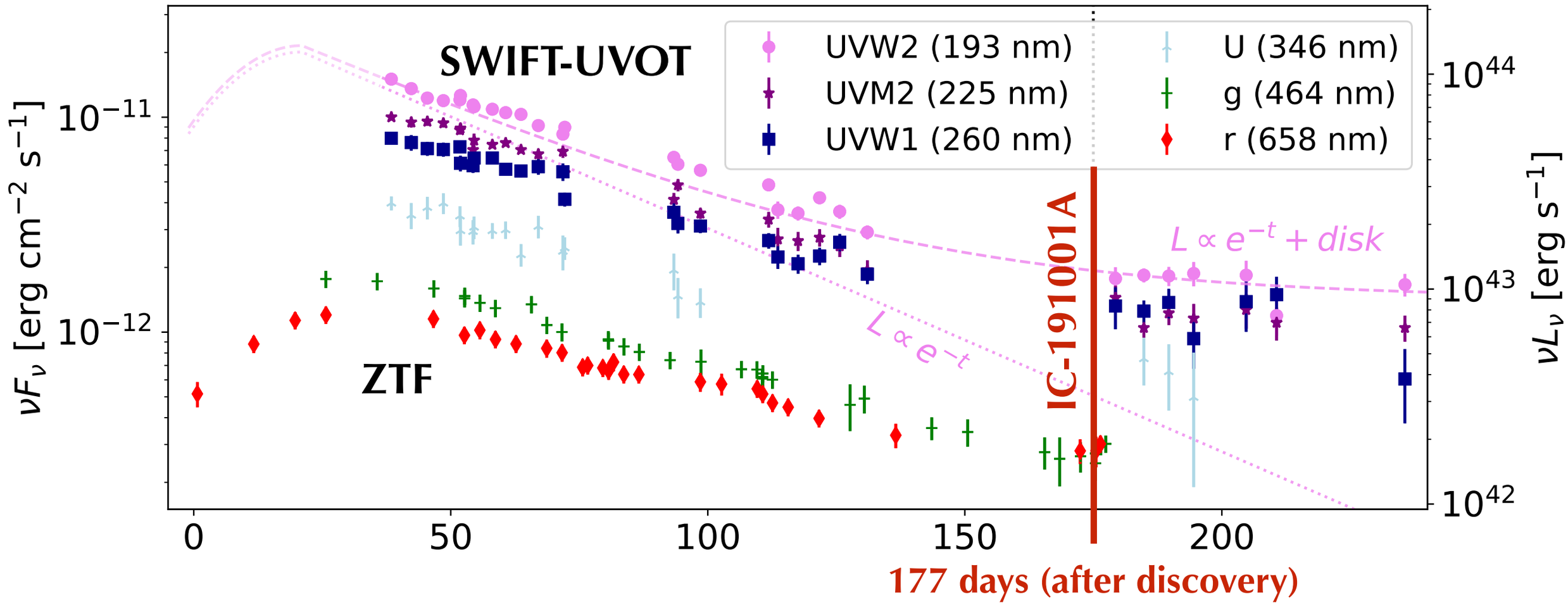


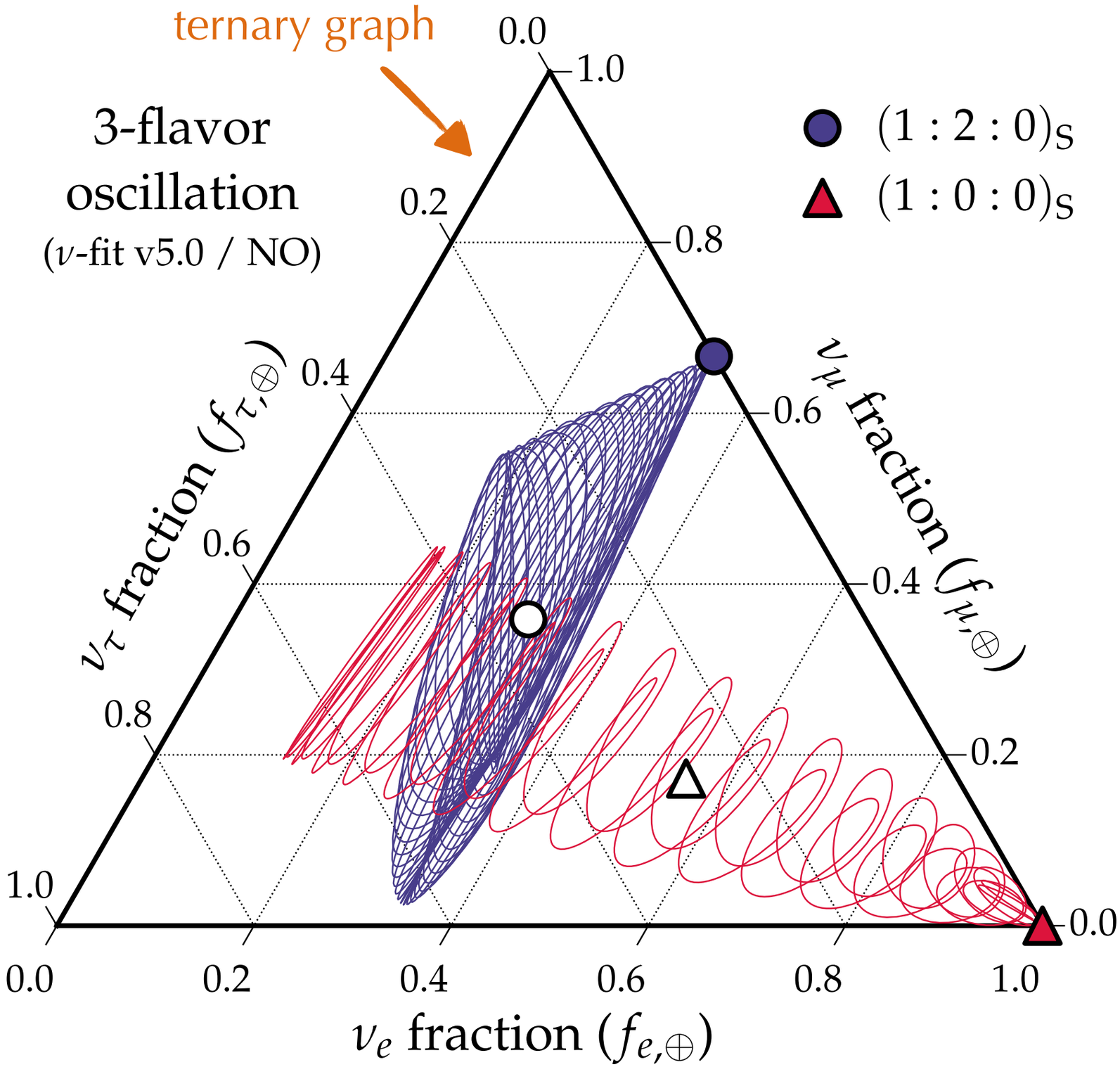
[Stein, R., Velzen, S.v., Kowalski, M. et al., Nature Astronomy (2021)]

- 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%.

Astrophysical Flavours

ternary graph

3-flavor oscillation
(ν-fit v5.0 / NO)

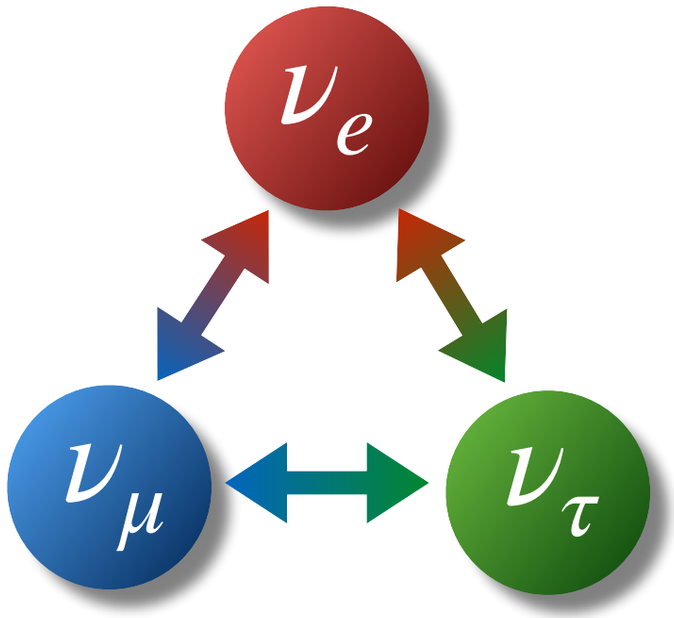


$(1:2:0)_S$

$(1:0:0)_S$

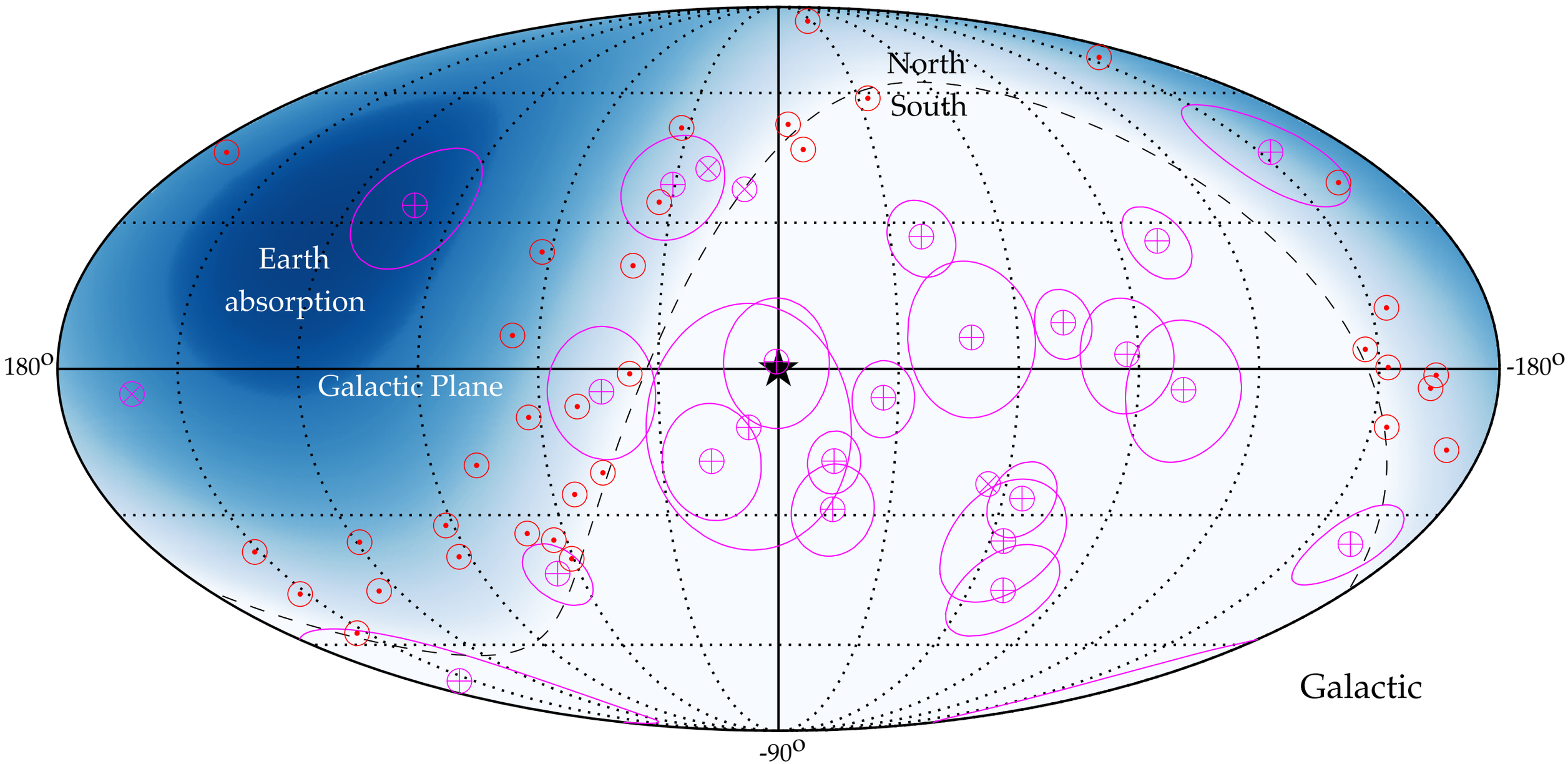
flavour ratios on production

Superposition of flavour and mass states induces oscillations.



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.**