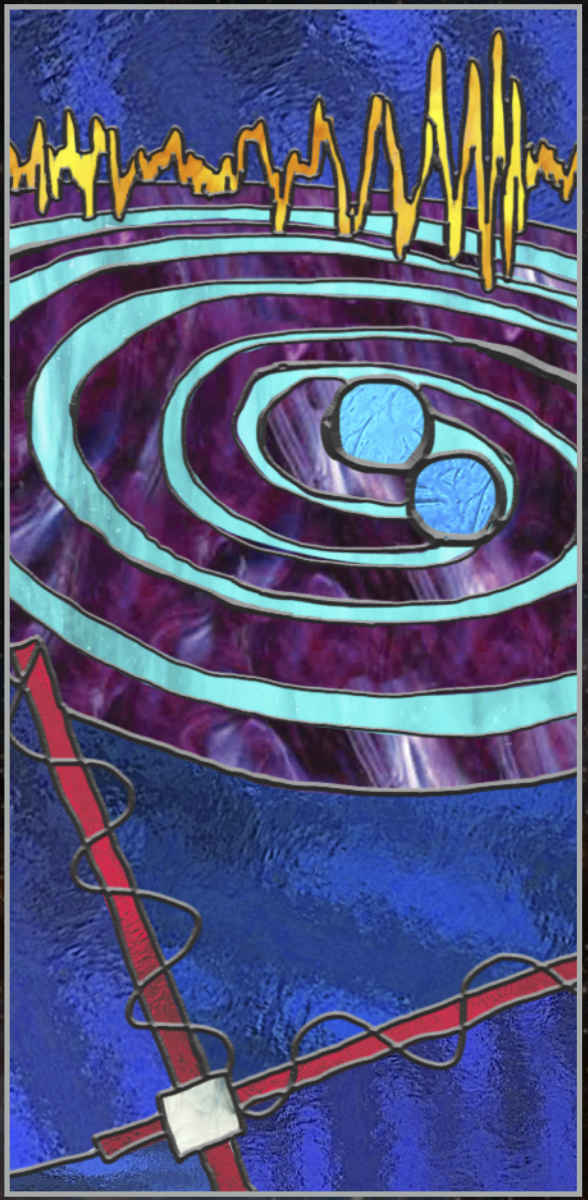
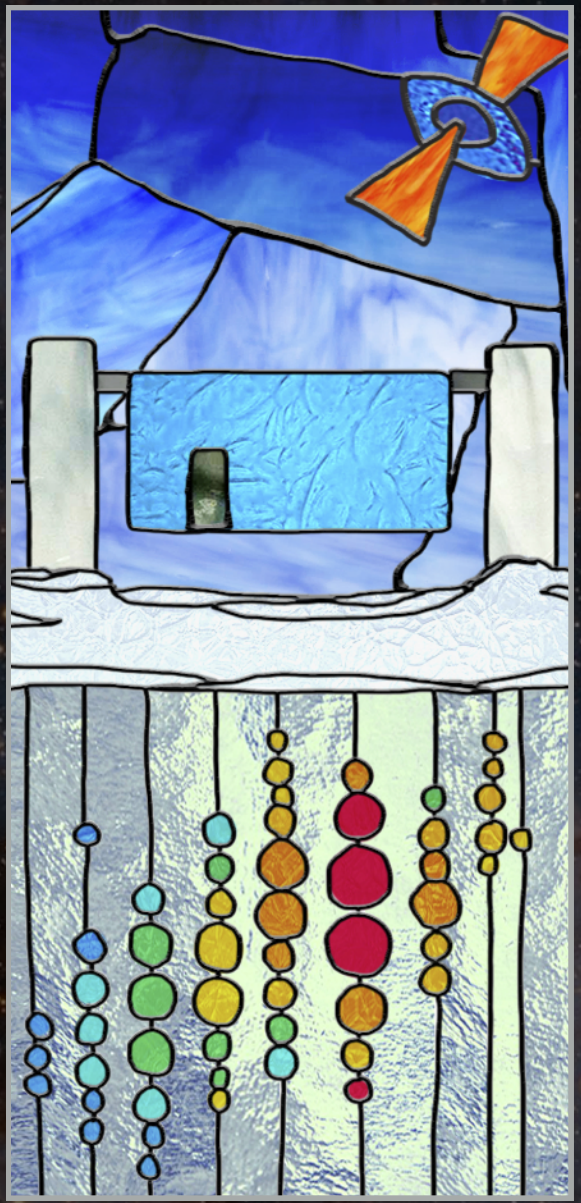
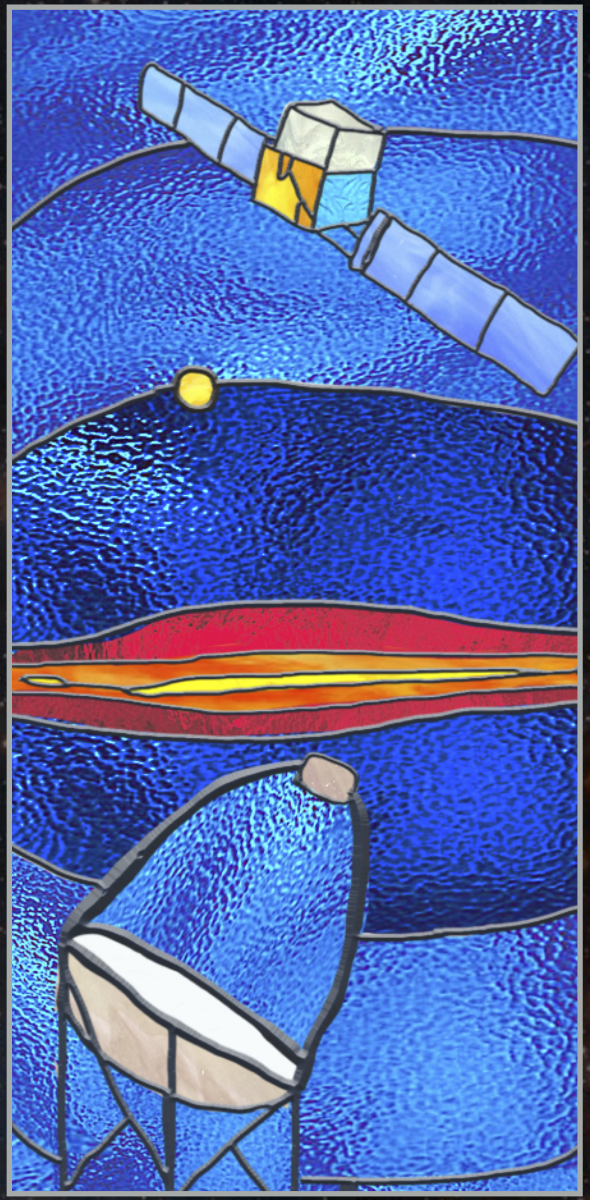
  

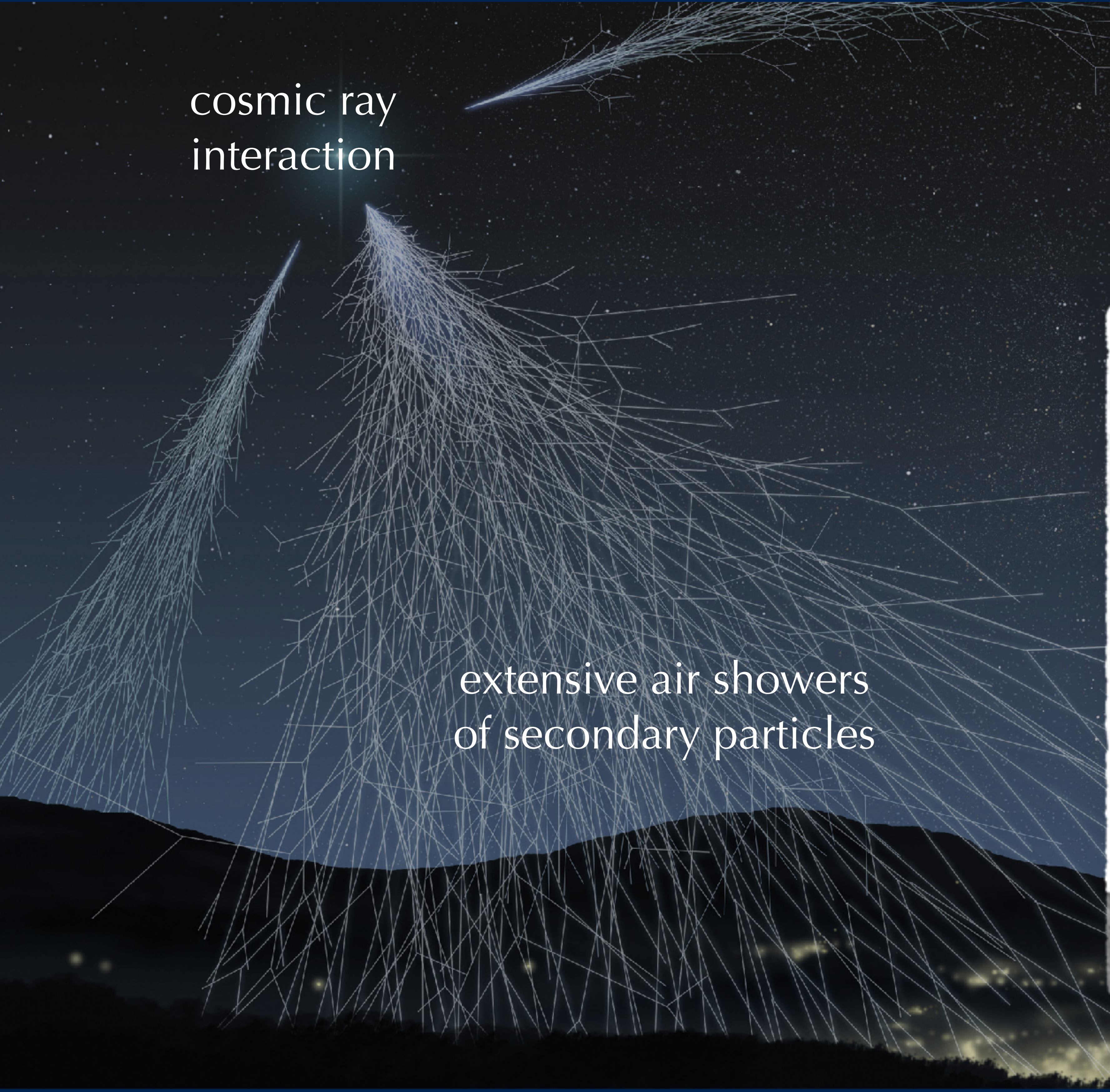
The Dawn of Multi-Messenger Astronomy

Markus Ahlers
Niels Bohr Institute
Georges Lemaître Chair 2023

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Cosmic Radiation

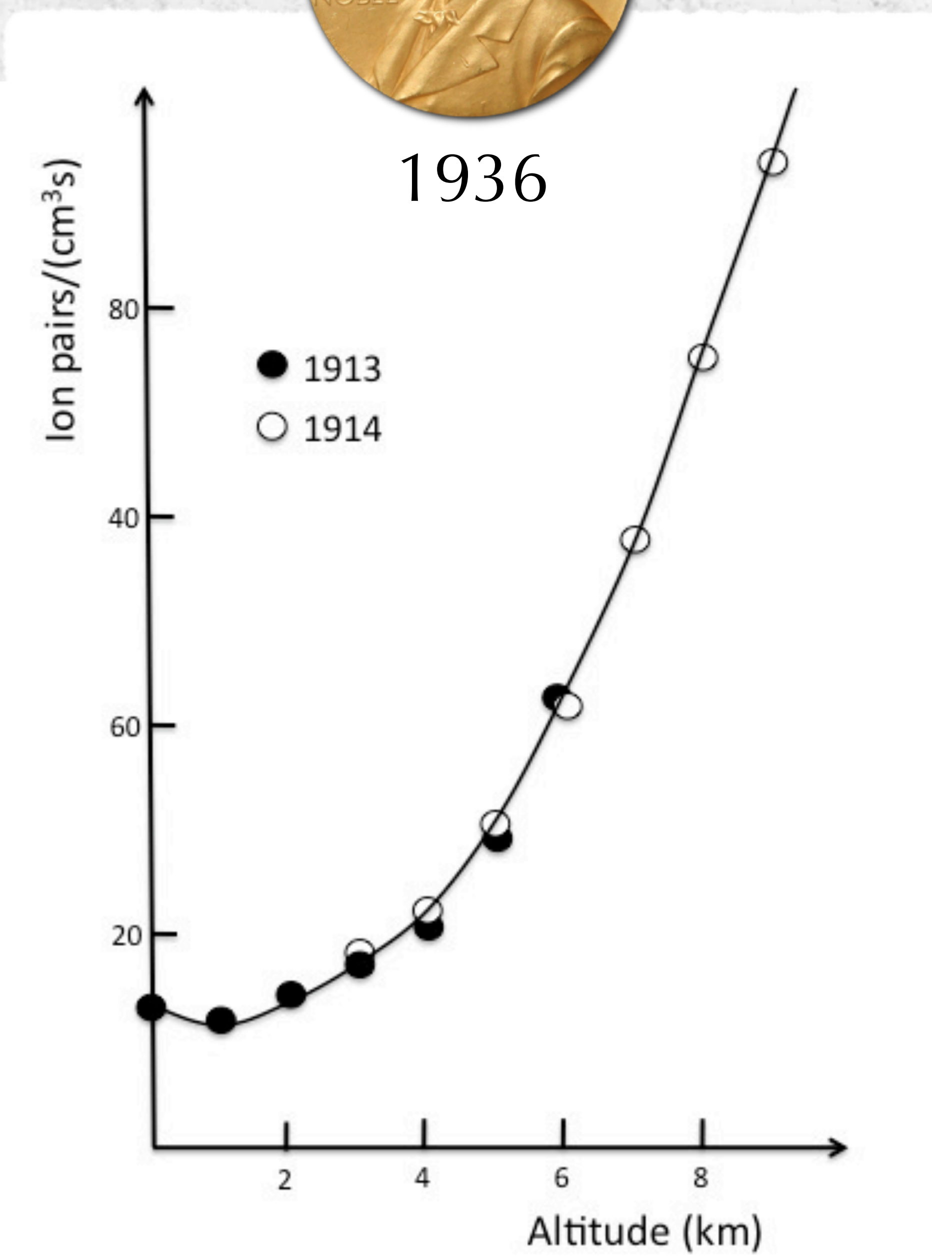


Cosmic rays cause the "mysterious" discharge of electroscope observed as early as 1785 by Coulomb.

gold-leaf electroscope (ca 1900)

Cosmic Radiation

1936



discharge rate increases with altitude

Cosmic Radiation

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

VOL. 43, NO. 2 | JANUARY 15, 1933 | SECOND SERIES

On Compton's Latitude Effect of Cosmic Radiation

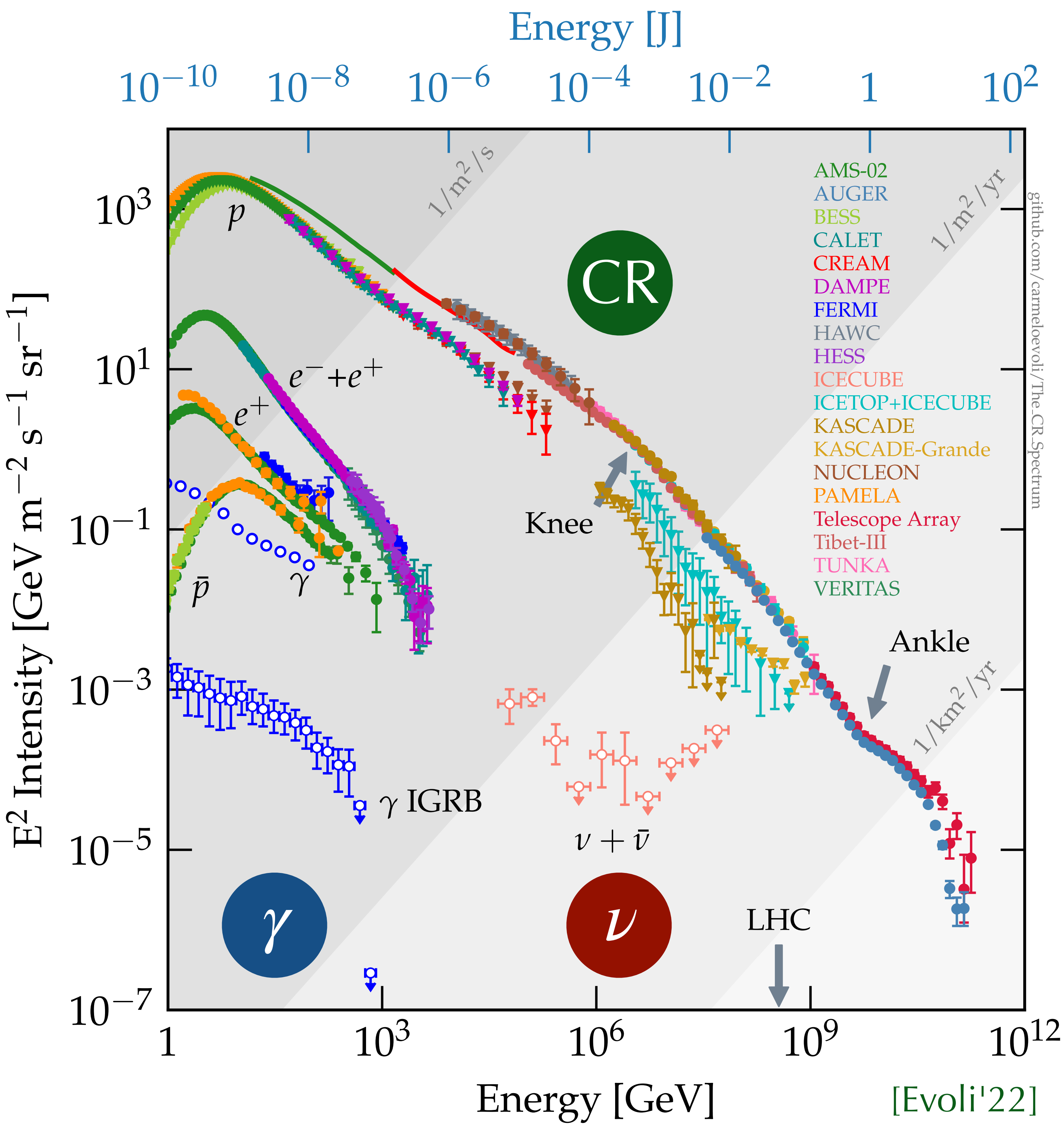
G. LEMAITRE AND M. S. VALLARTA, *University of Louvain and Massachusetts Institute of Technology*

(Received November 18, 1932)

By considering the influence of the earth's magnetic field on the motion of charged particles (electrons, protons, etc.) coming to the earth from all directions in space, it is shown that the experimental variation of cosmic-ray intensity with magnetic latitude, as found by Compton and his collaborators, is fully accounted for. The cosmic radiation must contain charged particles of energy between limits given in the paper. The experimental curve may be represented by a suitable mixture of rays of these energies, but it is not at all excluded that a part of the radiation may consist of photons or neutrons. For predominantly negative particles there must be in the region of rapidly varying intensity a predominant amount of rays coming from the east, and conversely for positive rays. Because of the fact that in regions near the magnetic equator there is a predominance of rays coming nearly horizontally, the absorption by the atmosphere may be increased. Finally the fact that Compton's result definitely shows that the cosmic rays contain charged particles gives some support to the theory of super-radioactive origin of these rays advanced by one of the present authors.

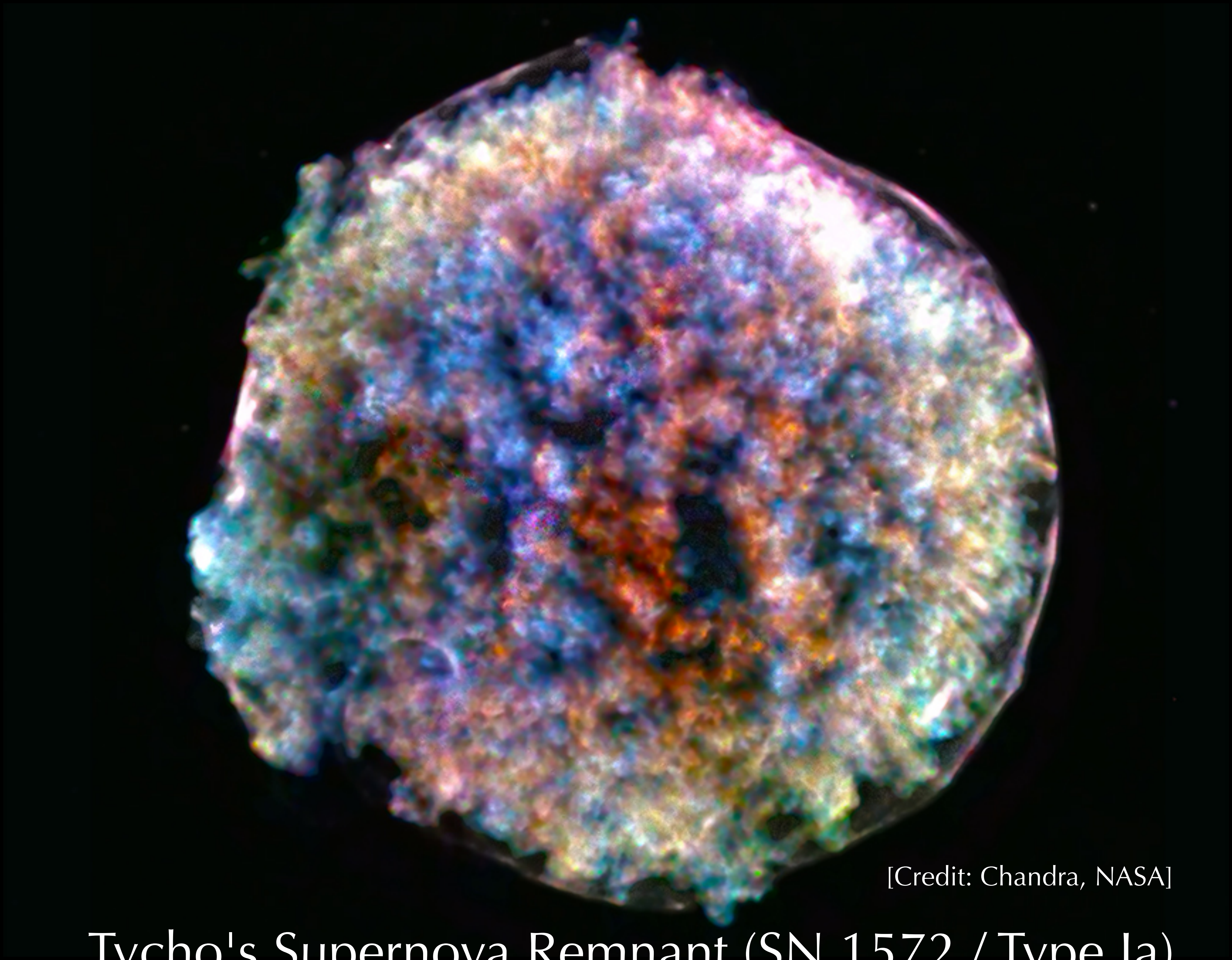
Status of Cosmic Rays

- Cosmic rays (CRs) are **energetic nuclei** and (at a lower level) leptons.
- Spectrum follows a **power-law** over many orders of magnitude, indicating a **non-thermal origin**.
- **direct observation** with satellite and balloon-borne experiments up to TeV
- **indirect observation** as air showers above 10 TeV



[Evoli'22]

Supernova Remnants



Tycho's Supernova Remnant (SN 1572 / Type Ia)

Galactic Cosmic Rays

- *Standard paradigm*: Galactic CRs accelerated in supernova remnants

  [Baade & Zwicky'34]
  [Ginzburg & Sirovatskii'64]

- diffusive shock acceleration:

$$n_{\rm CR} \propto E^{-\Gamma}$$

- rigidity-dependent escape from Galaxy:

$$n_{\rm CR} \propto E^{-\Gamma-\delta}$$

- Arrival directions of cosmic rays are scrambled by magnetic fields.

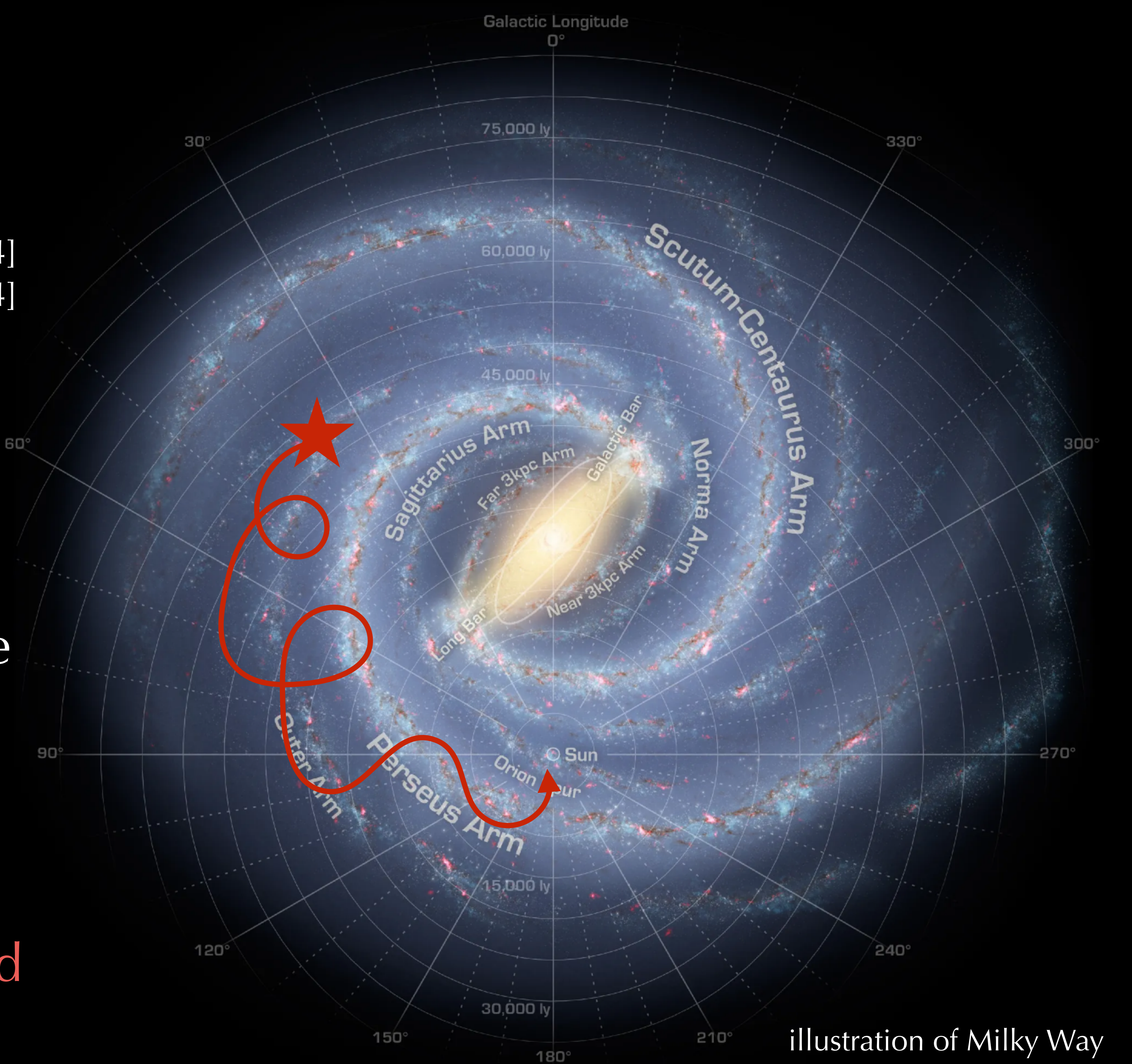
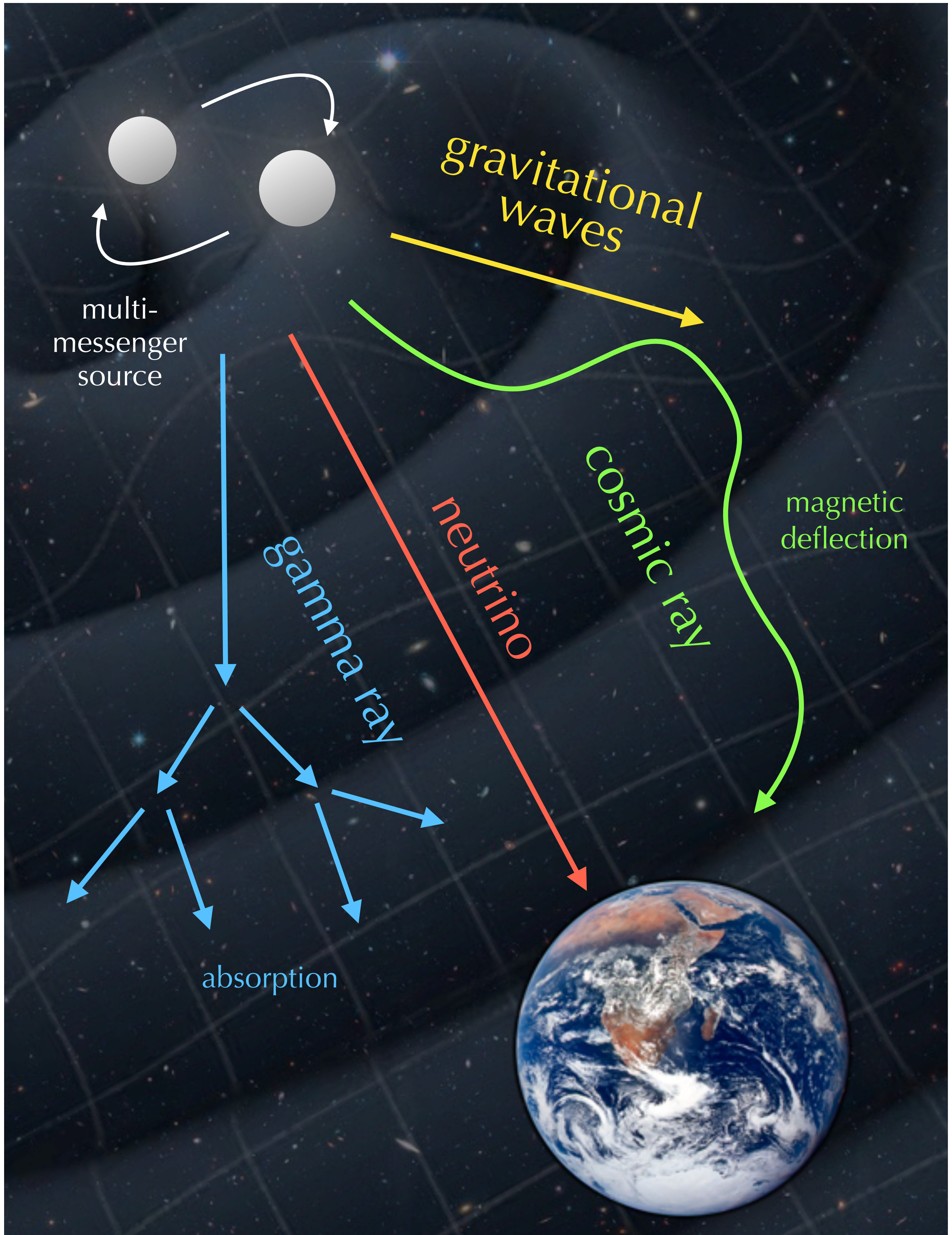
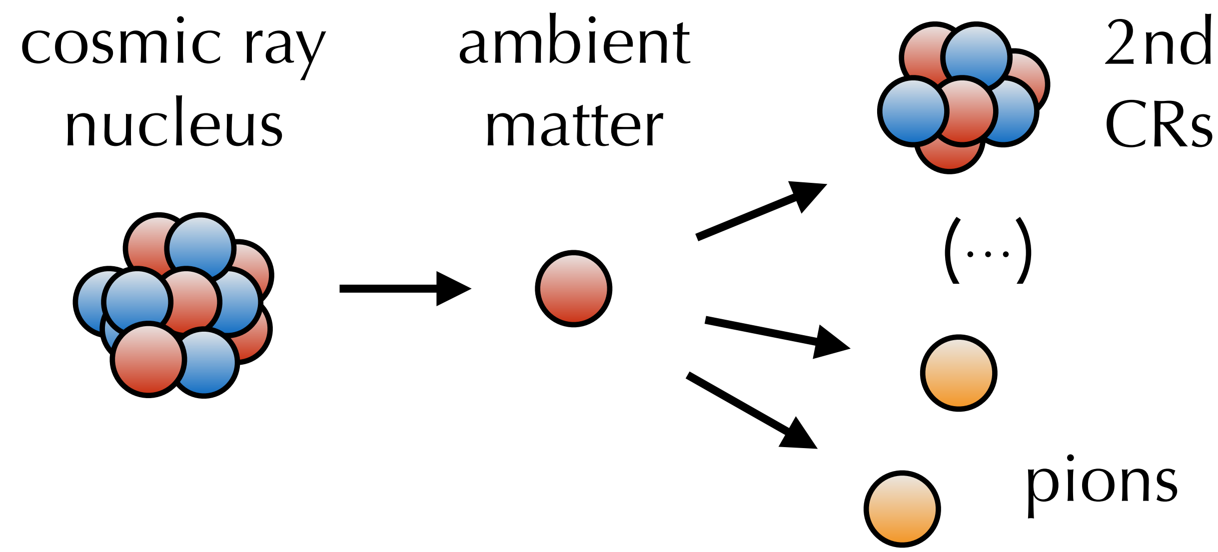


illustration of Milky Way
[Credit: NASA]

Multi-Messenger Astronomy



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

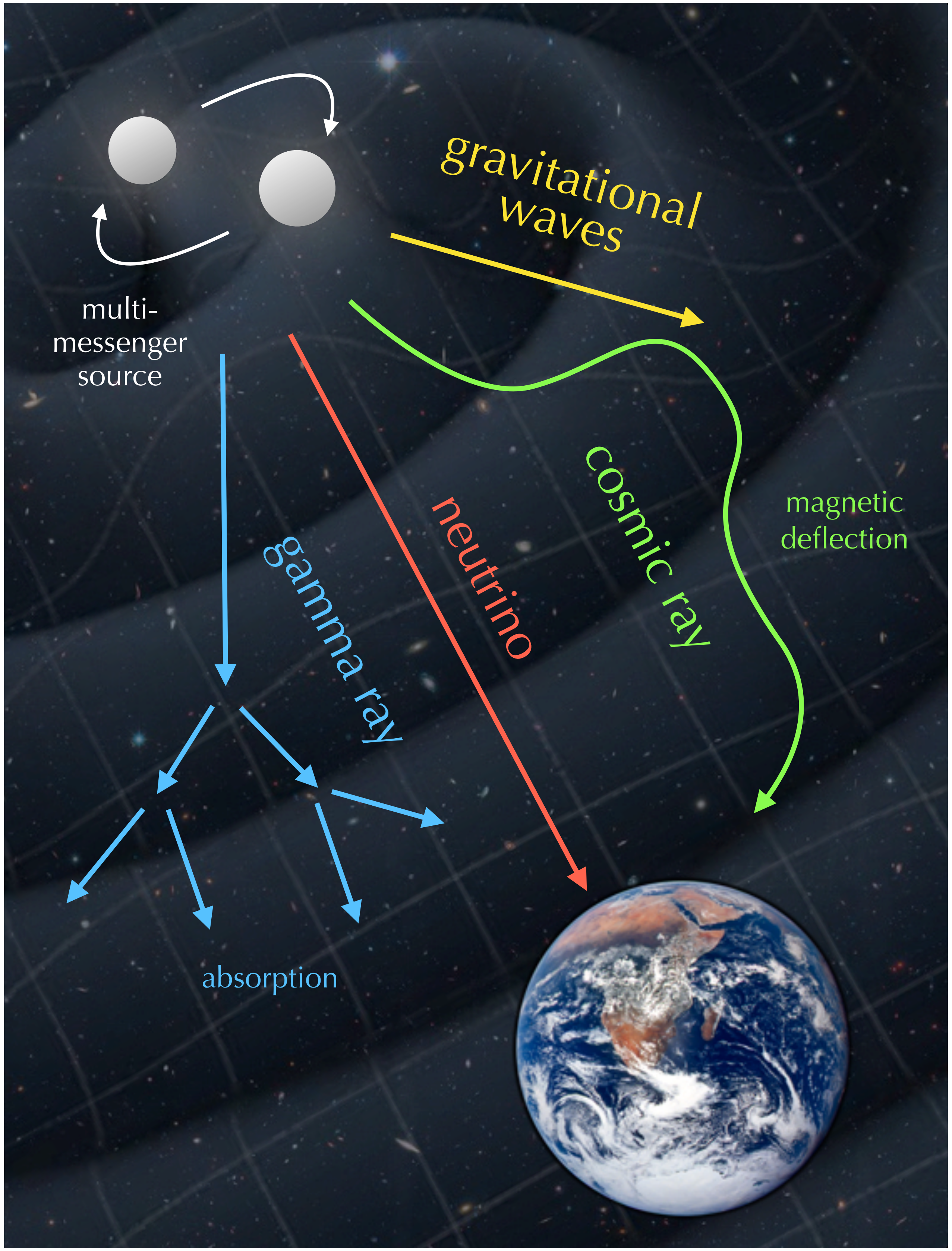


Secondary **neutrinos** and **gamma-rays** from pion decays:

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

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

Neutrino Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

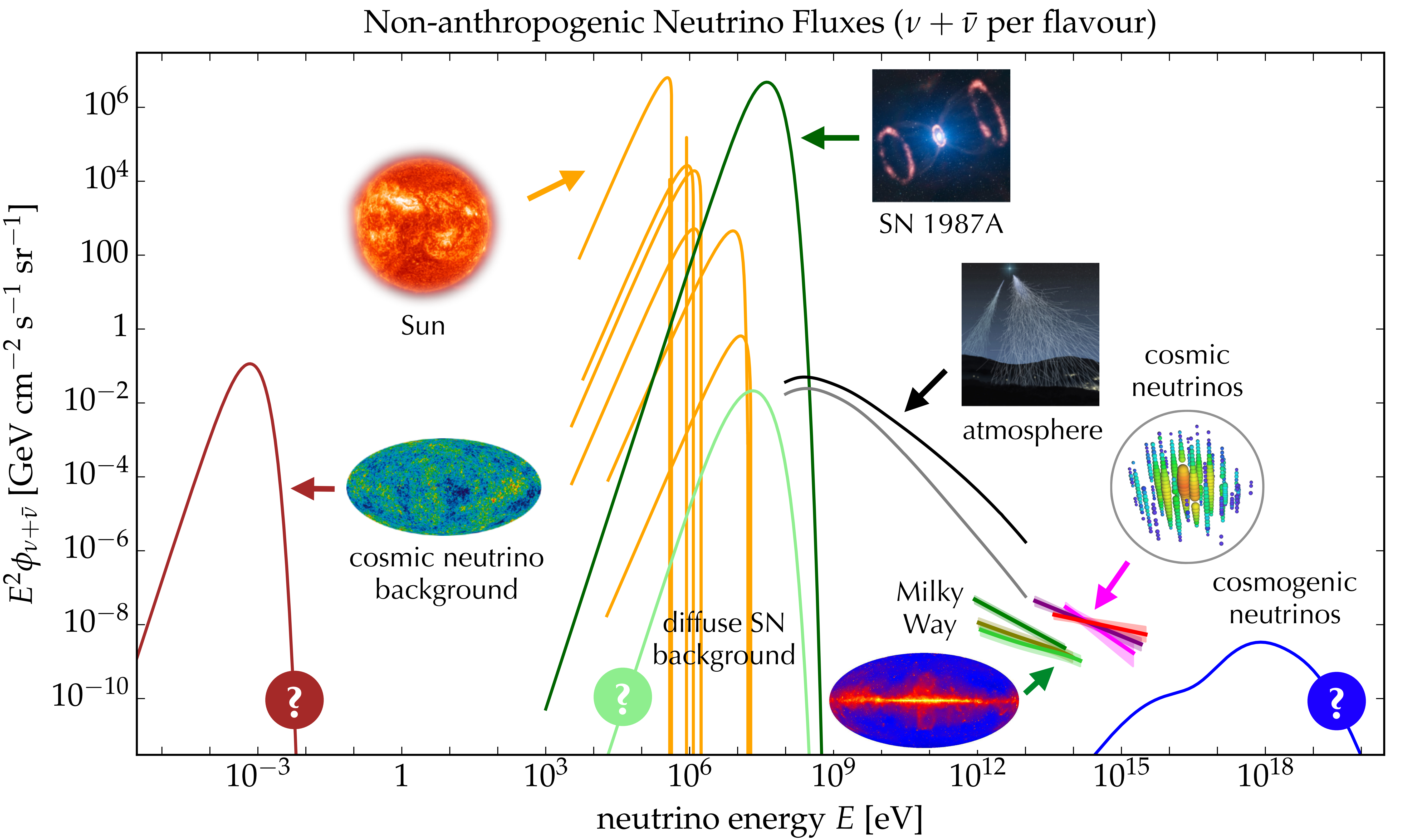
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

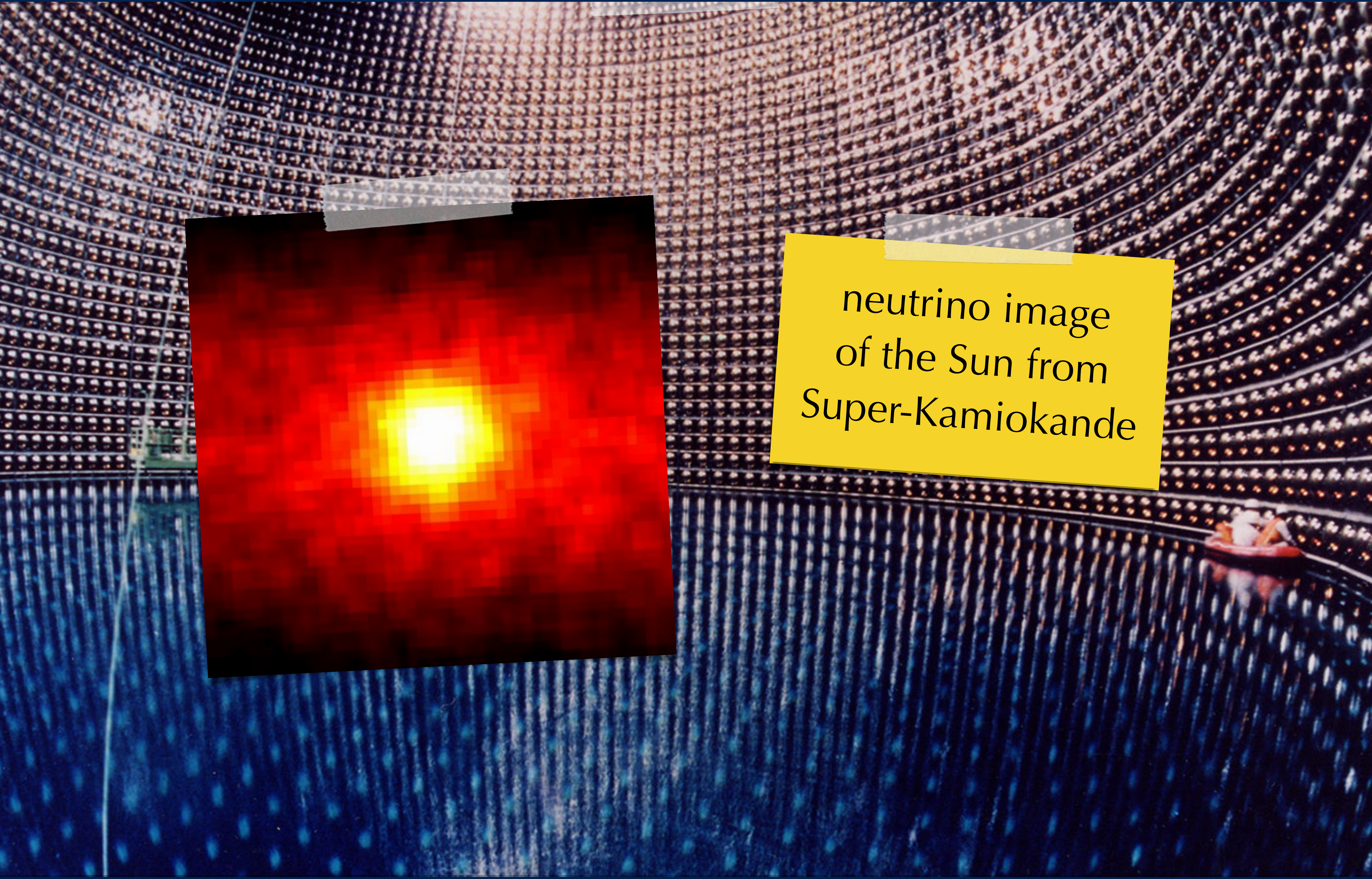
smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

Astrophysical Neutrinos

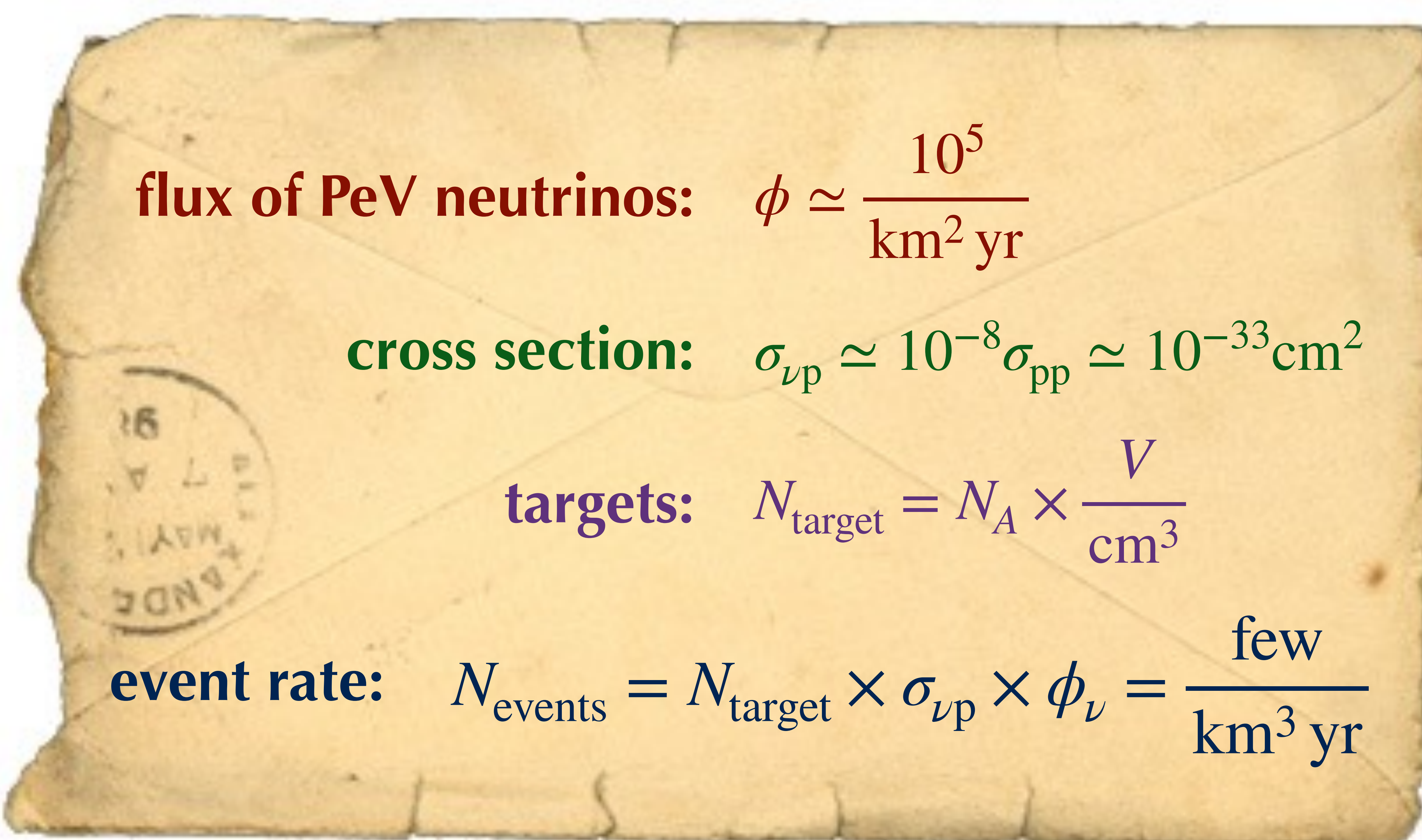


Solar Neutrinos



Neutrino Astronomy

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



flux of PeV neutrinos: $\phi \simeq \frac{10^5}{\mathrm{km}^2\,\mathrm{yr}}$

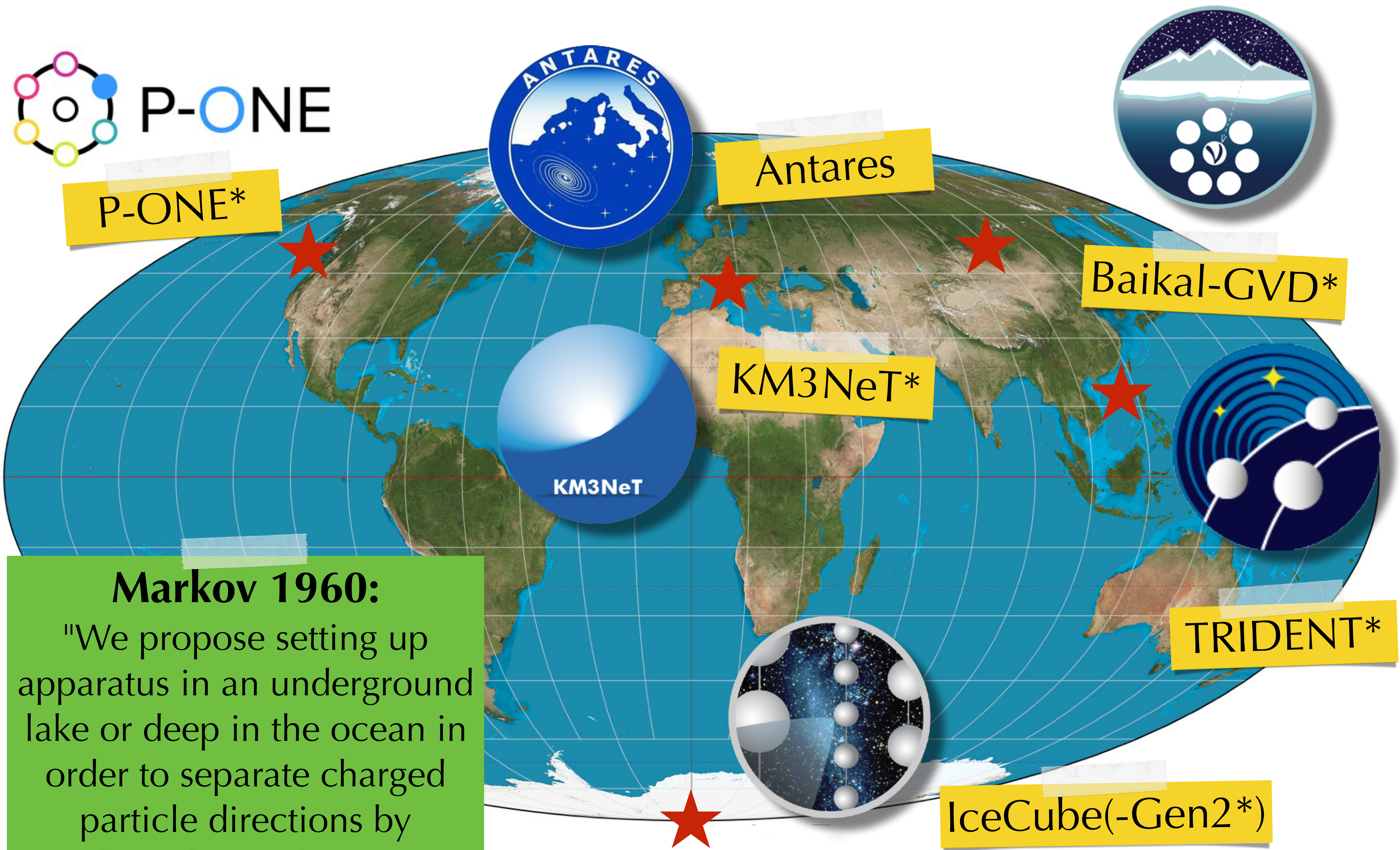
cross section: $\sigma_{\nu\mathrm{p}} \simeq 10^{-8}\sigma_{\mathrm{pp}} \simeq 10^{-33}\mathrm{cm}^2$

targets: $N_{\mathrm{target}} = N_A \times \frac{V}{\mathrm{cm}^3}$

event rate: $N_{\mathrm{events}} = N_{\mathrm{target}} \times \sigma_{\nu\mathrm{p}} \times \phi_\nu = \frac{\mathrm{few}}{\mathrm{km}^3\,\mathrm{yr}}$

minimum detector size: 1km³

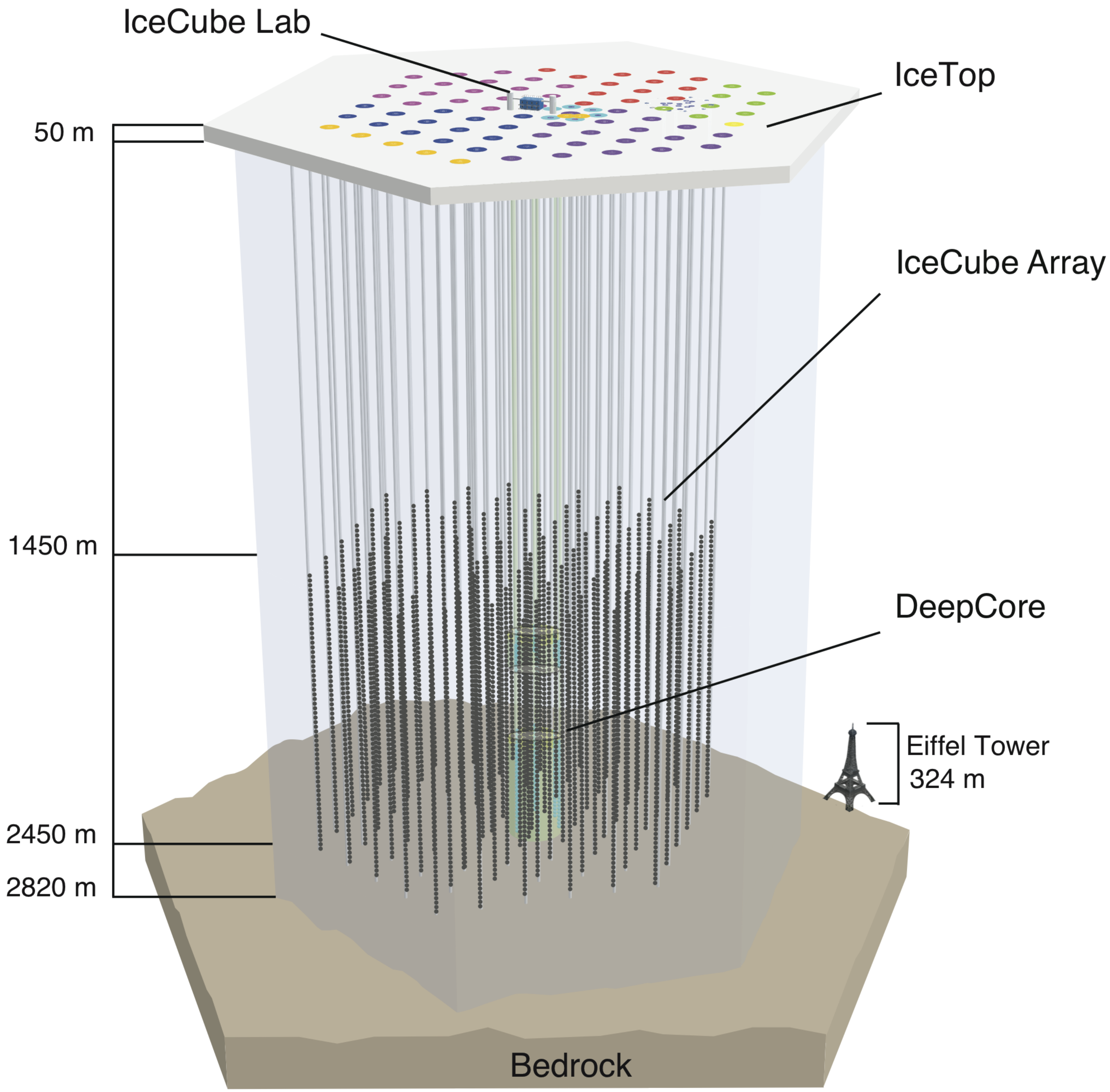
Optical Cherenkov Telescopes



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."

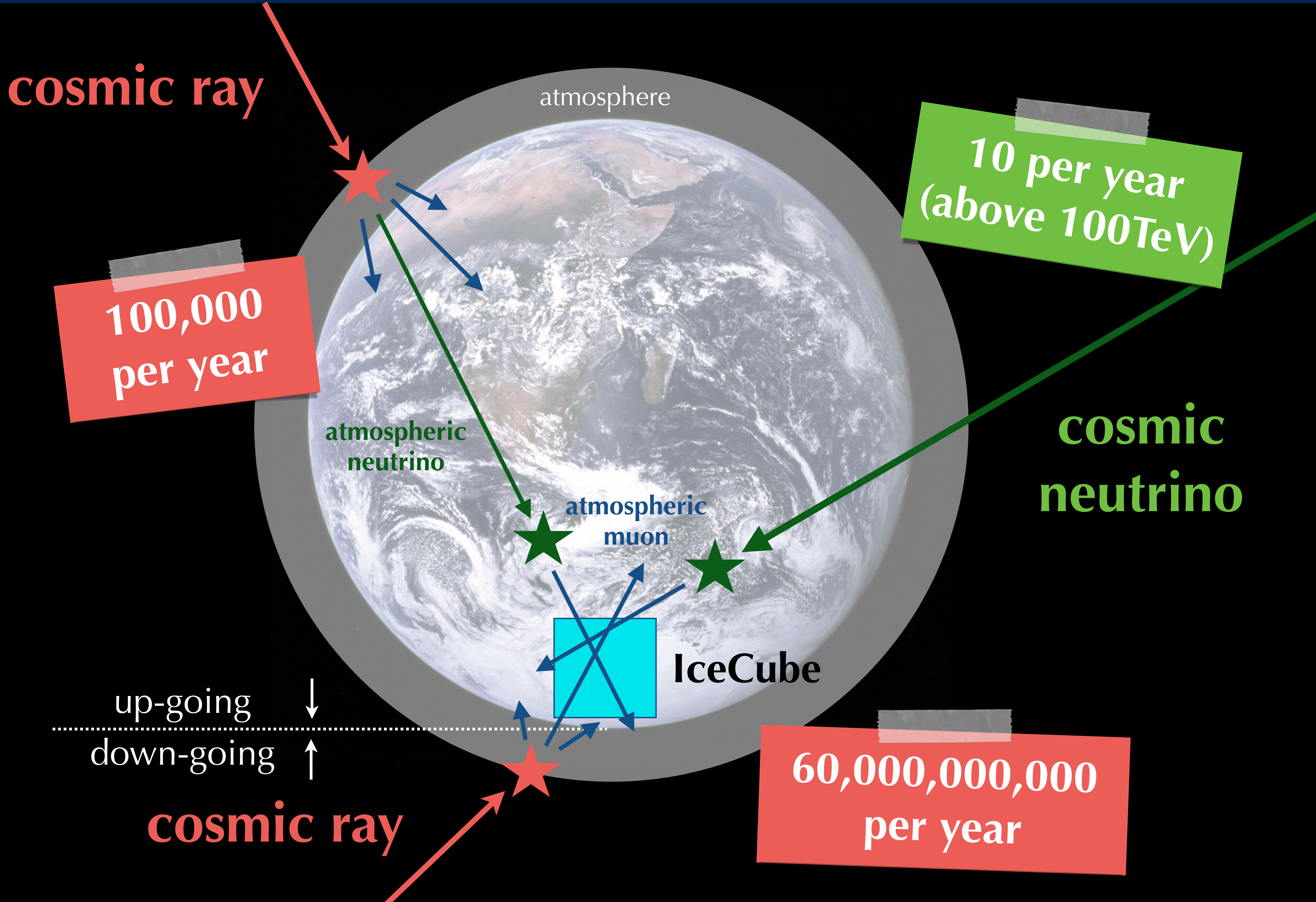
**planned or under construction*

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

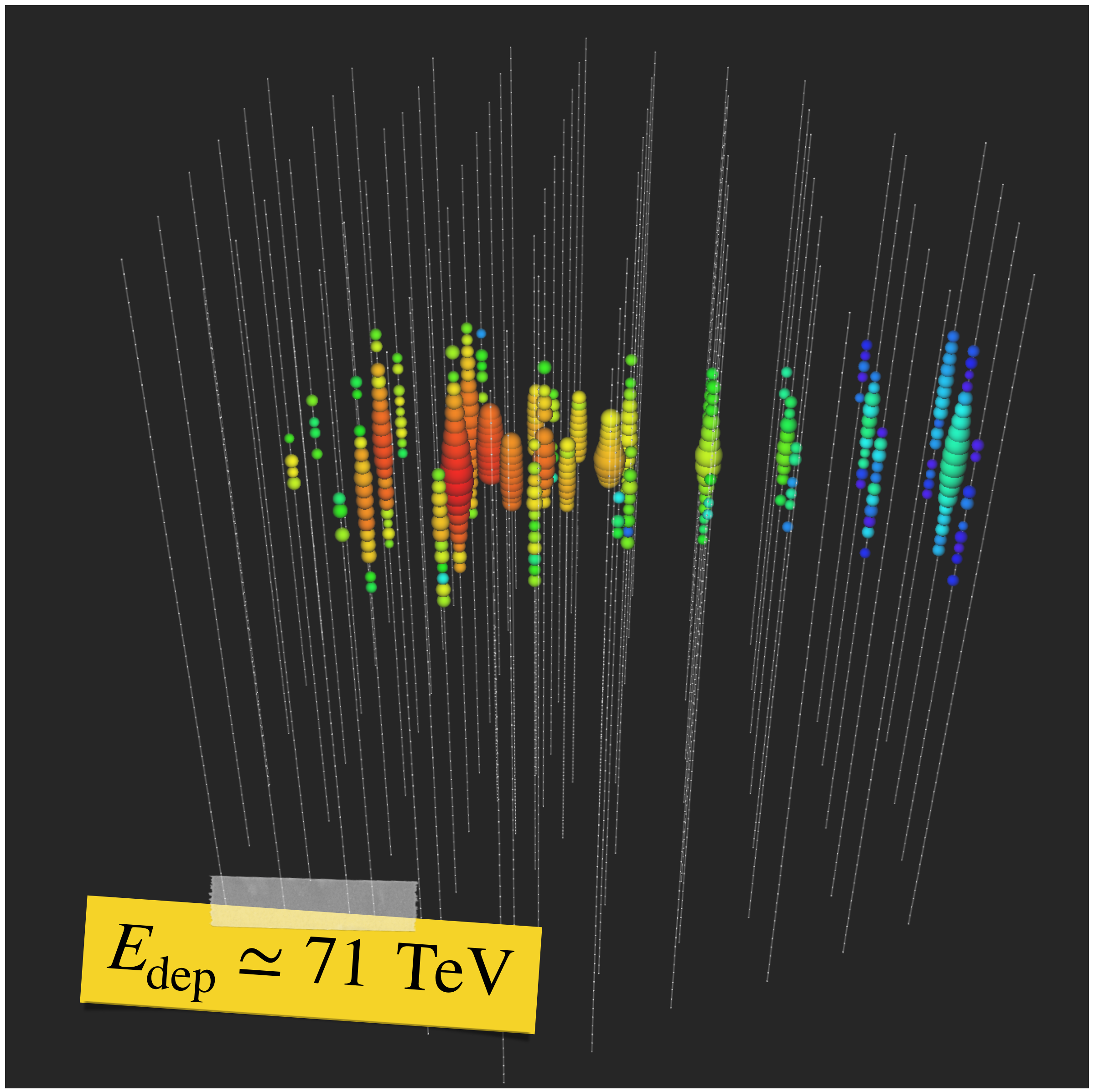
Neutrino Selection



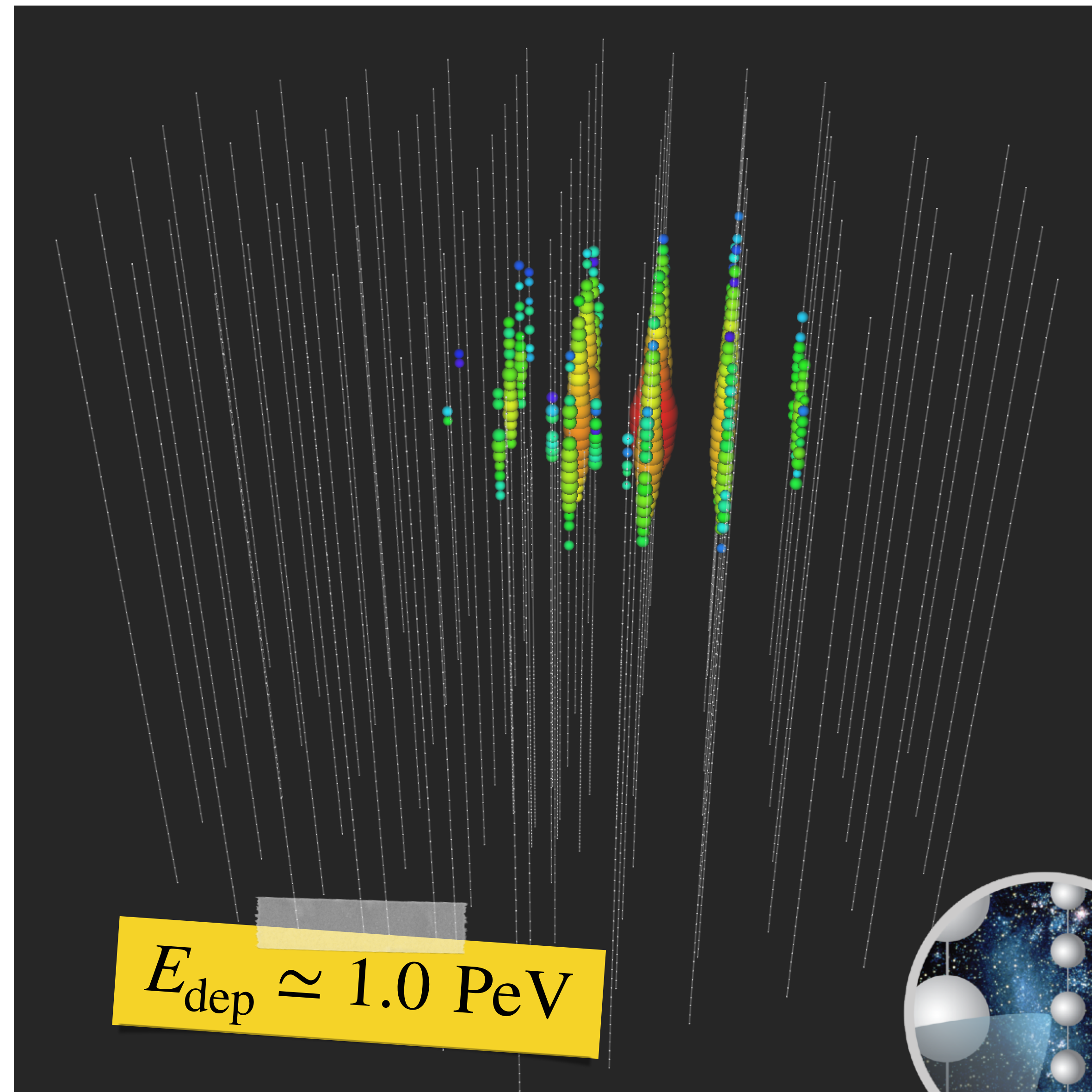
High-Energy Neutrinos

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

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



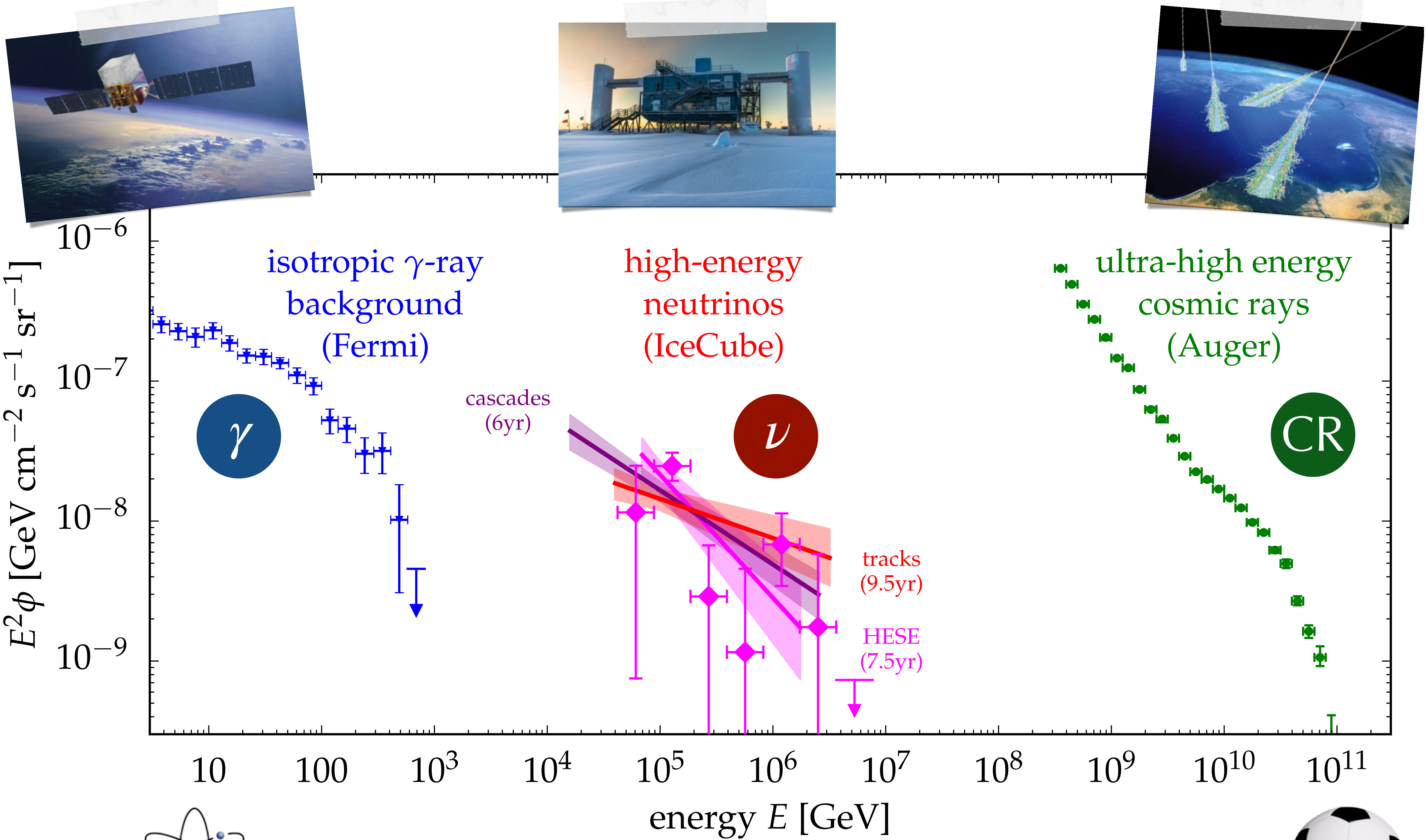
"cascade event" (e.g. NC interactions)

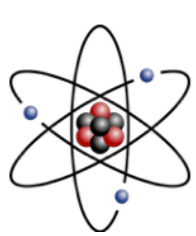


(colours indicate arrival time of Cherenkov photons from **early** to **late**)

ICECUBE

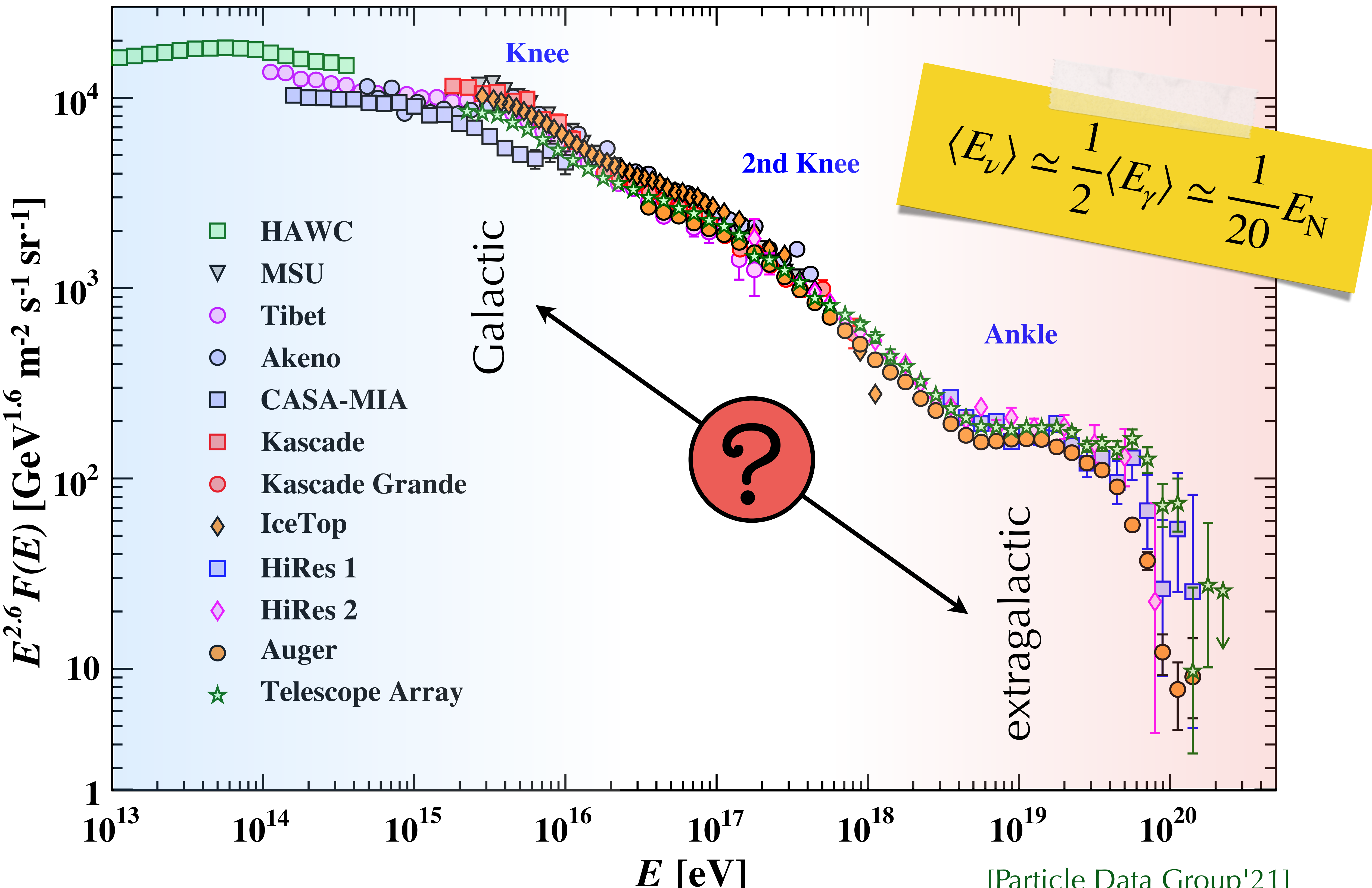
Diffuse TeV-PeV Neutrinos





[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; PRD 104 (2021) 022002]

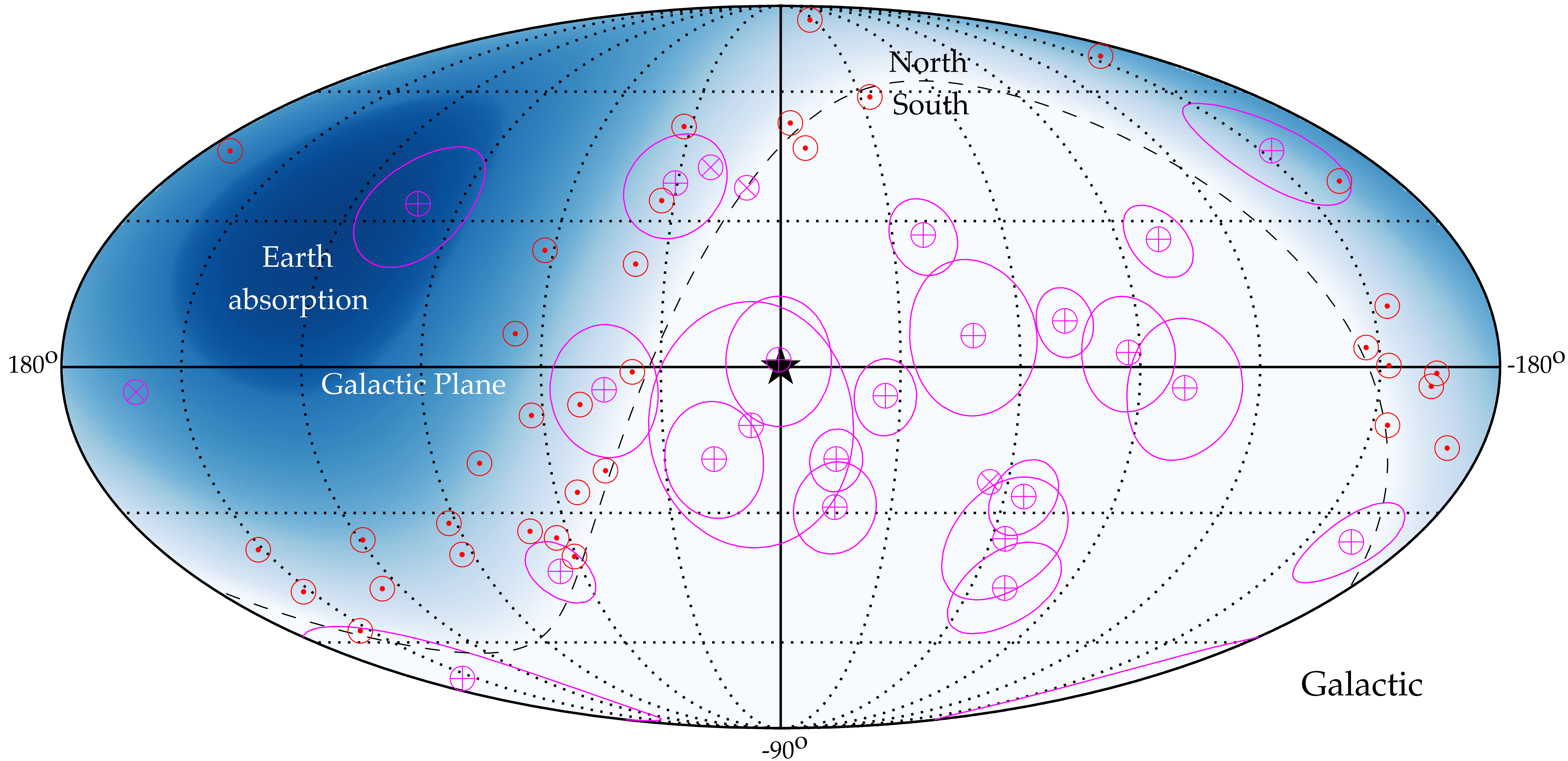
Very-High Energy Cosmic Rays



[Particle Data Group'21]

Status of Neutrino Astronomy

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



No (5σ) discovery of steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

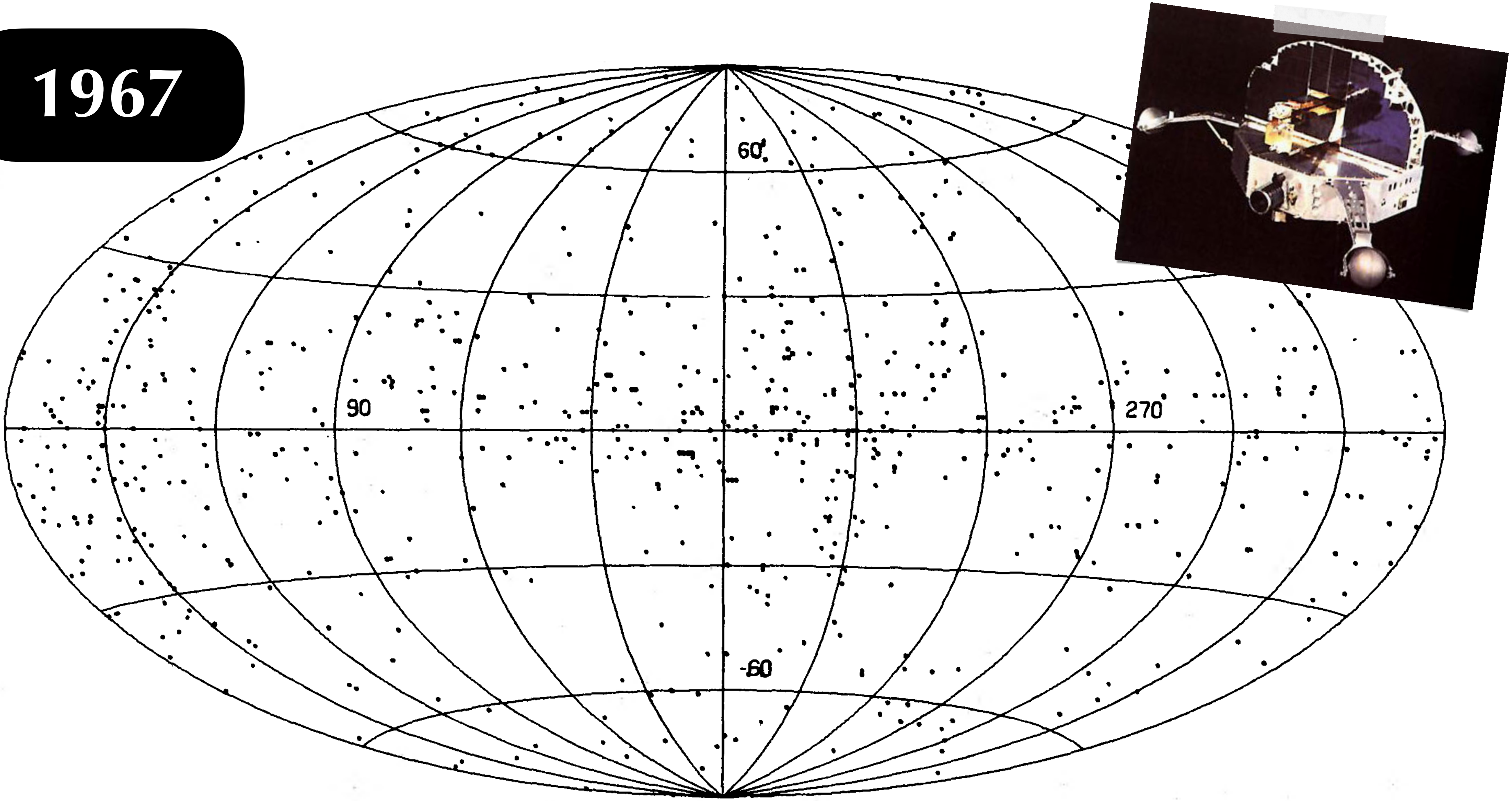
Status of Neutrino Astronomy

Neutrino sources are hiding in plain sight.

[Credit: John Beacom, CCAPP]

Status of Neutrino Astronomy

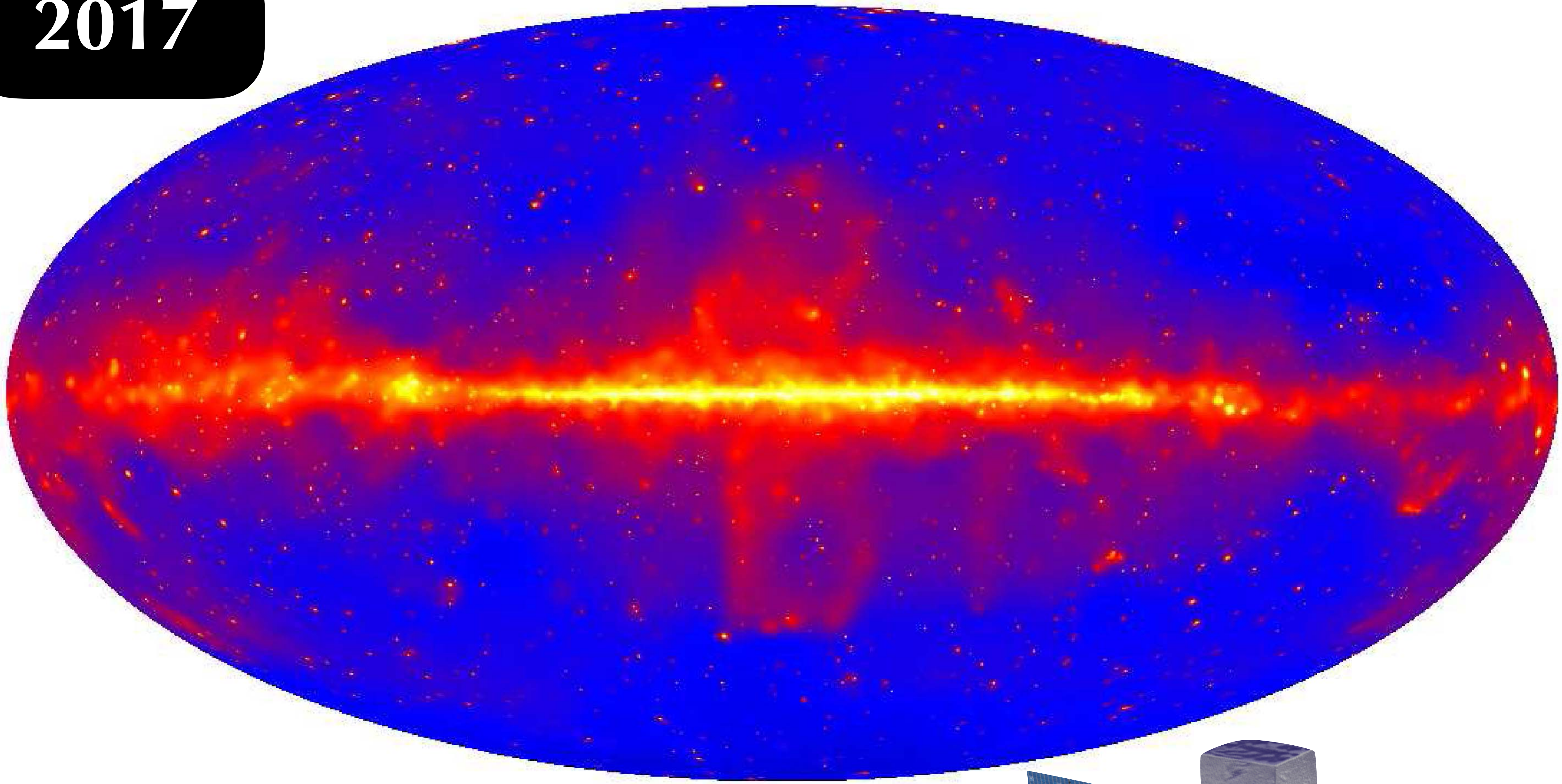
1967



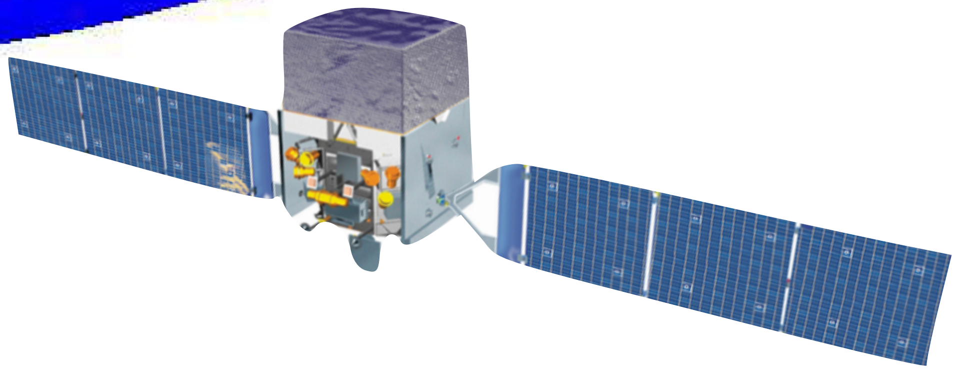
Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

2017



Fermi-LAT gamma-ray count map



Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

combined isotropic emission.

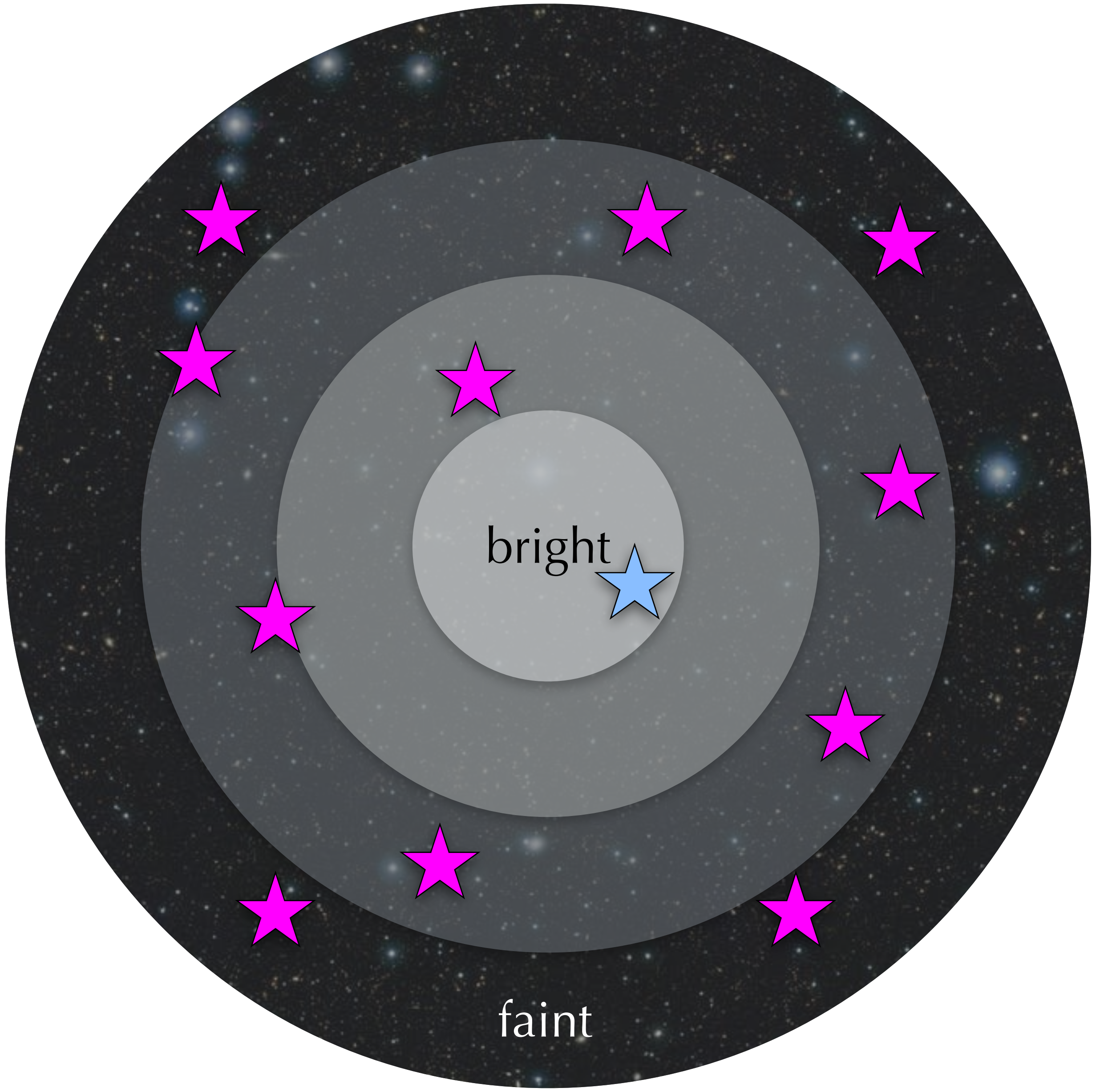
The relative contribution can be parametrized (*to first order*) by the average

local source density ρ_{eff}

and

source luminosity L_ν

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



Hubble-Lemaître horizon

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

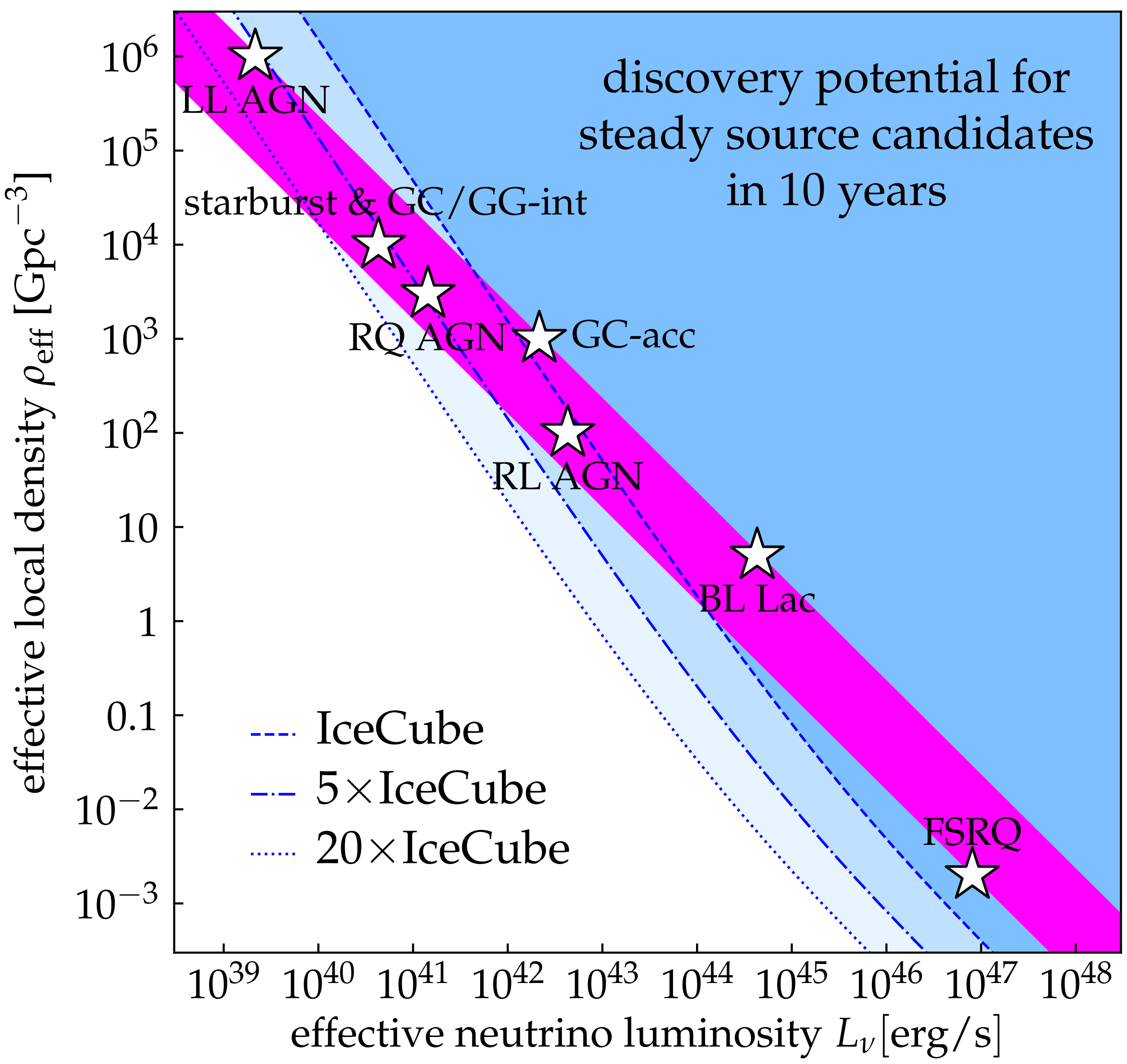
combined isotropic emission.

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

local source density $\rho_{\rm eff}$

and

source luminosity L_ν



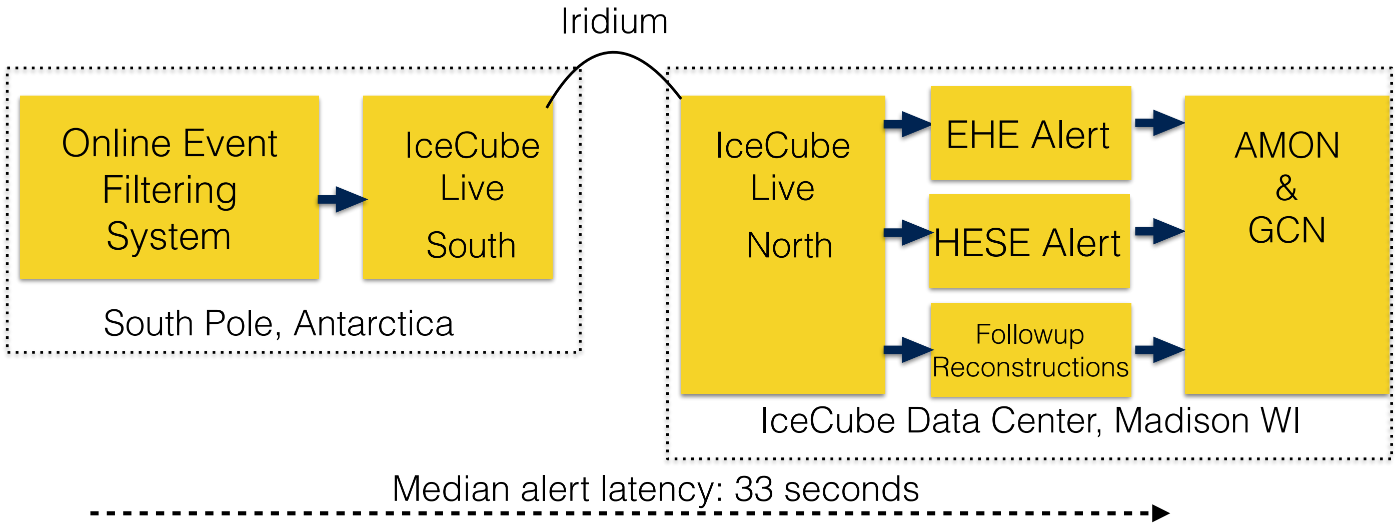
[Ackermann, MA, Anchordoqui, Bustamante *et al.*'19]
[see also Murase & Waxman'16]

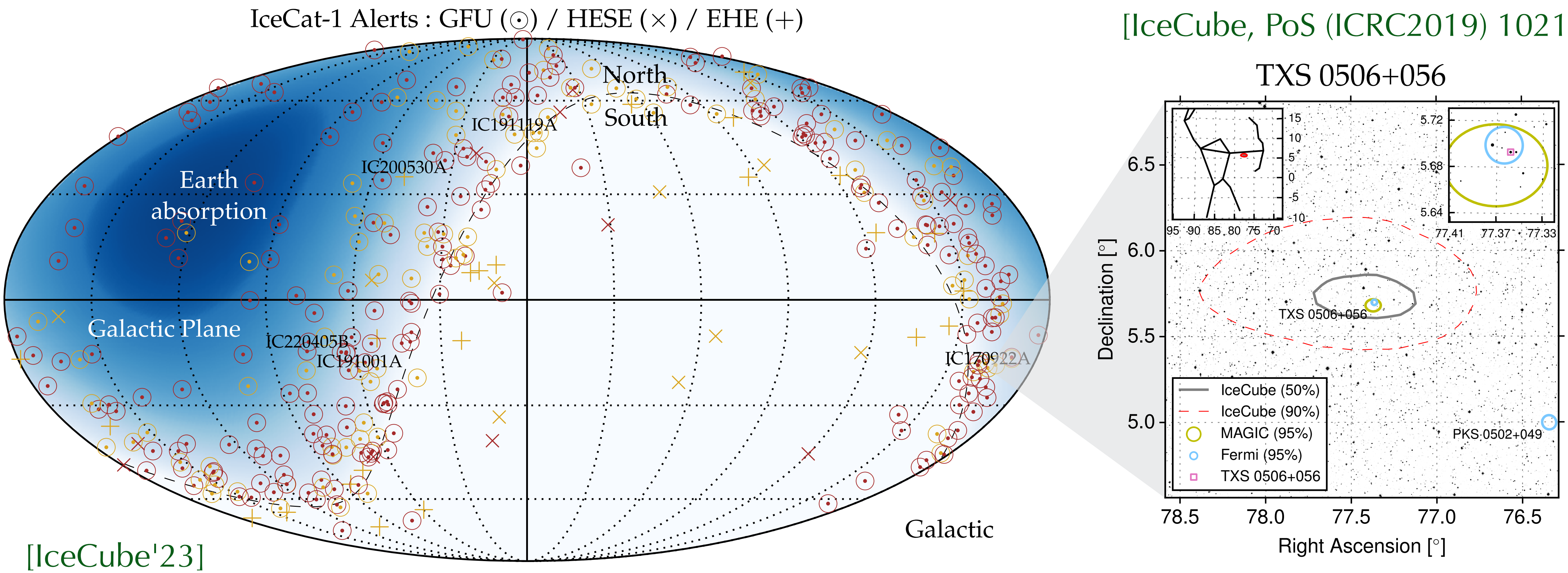
Realtime Neutrino Alerts

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

- **Gold alerts:** about **10 per year**
  50% signalness (on average)

- **Bronze alerts:** about **20 per year**
  30% signalness (on average)



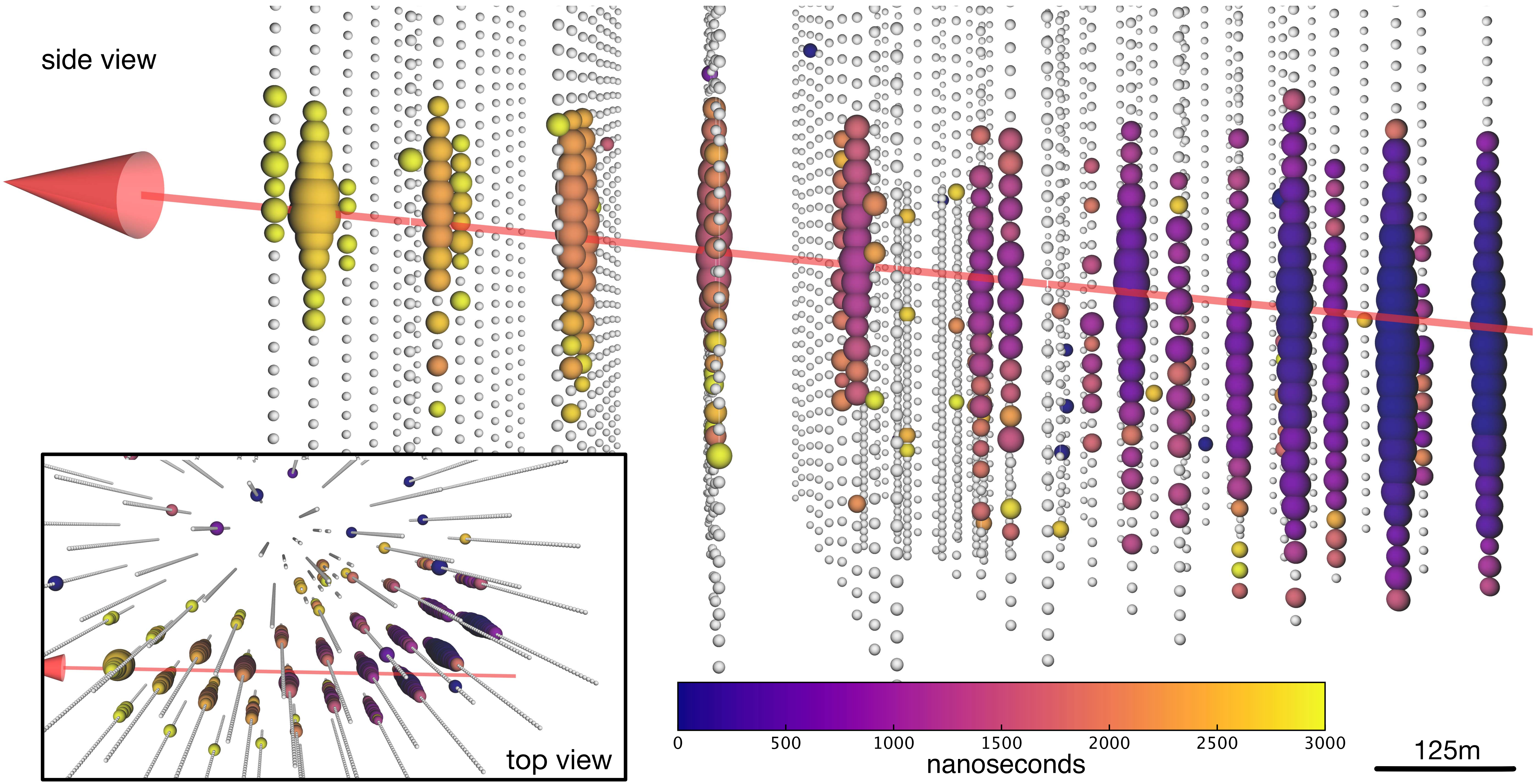


[IceCube'23]

[IceCube, PoS (ICRC2019) 1021]

Realtime Neutrino Alerts

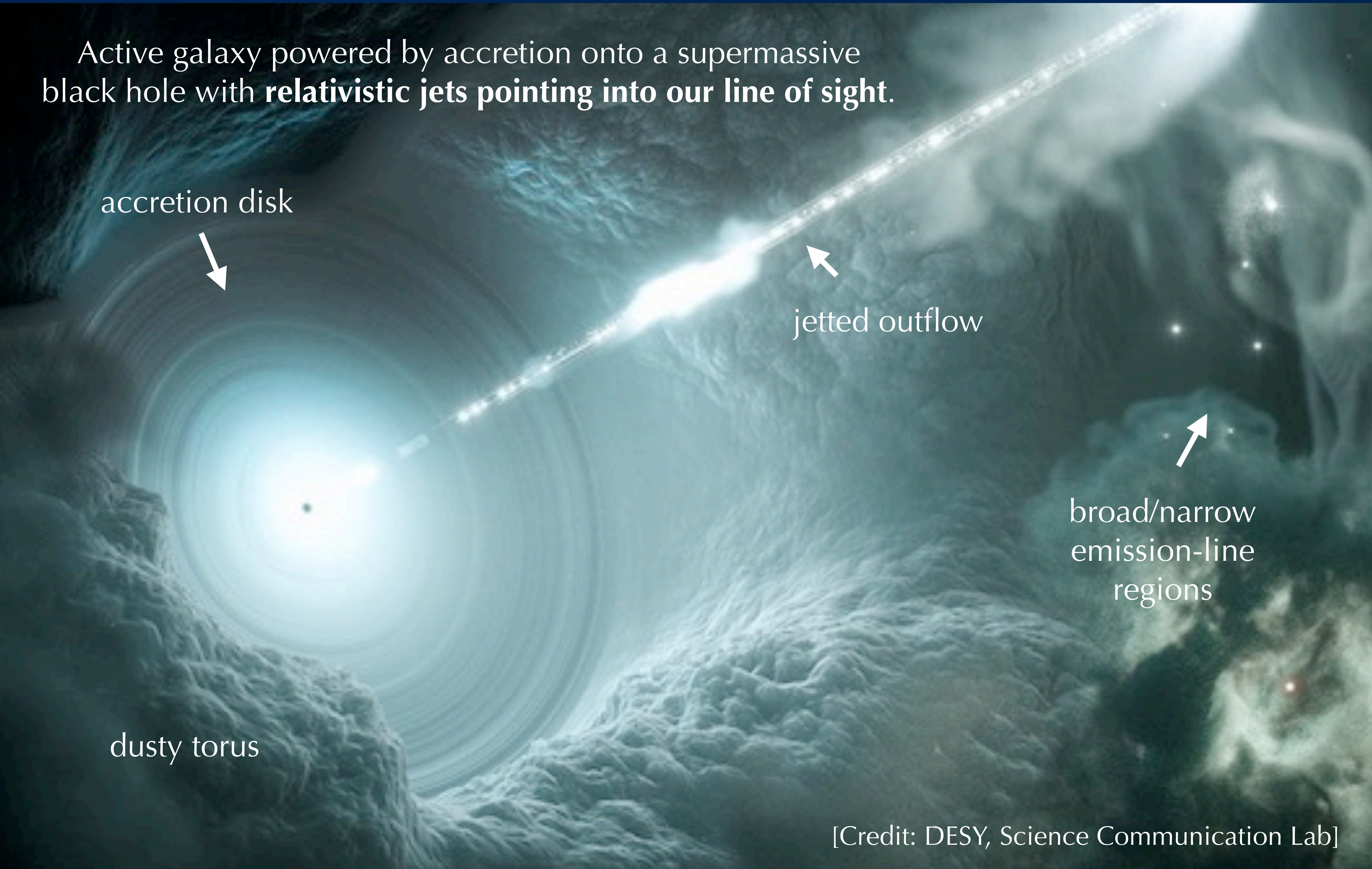
IC170922A



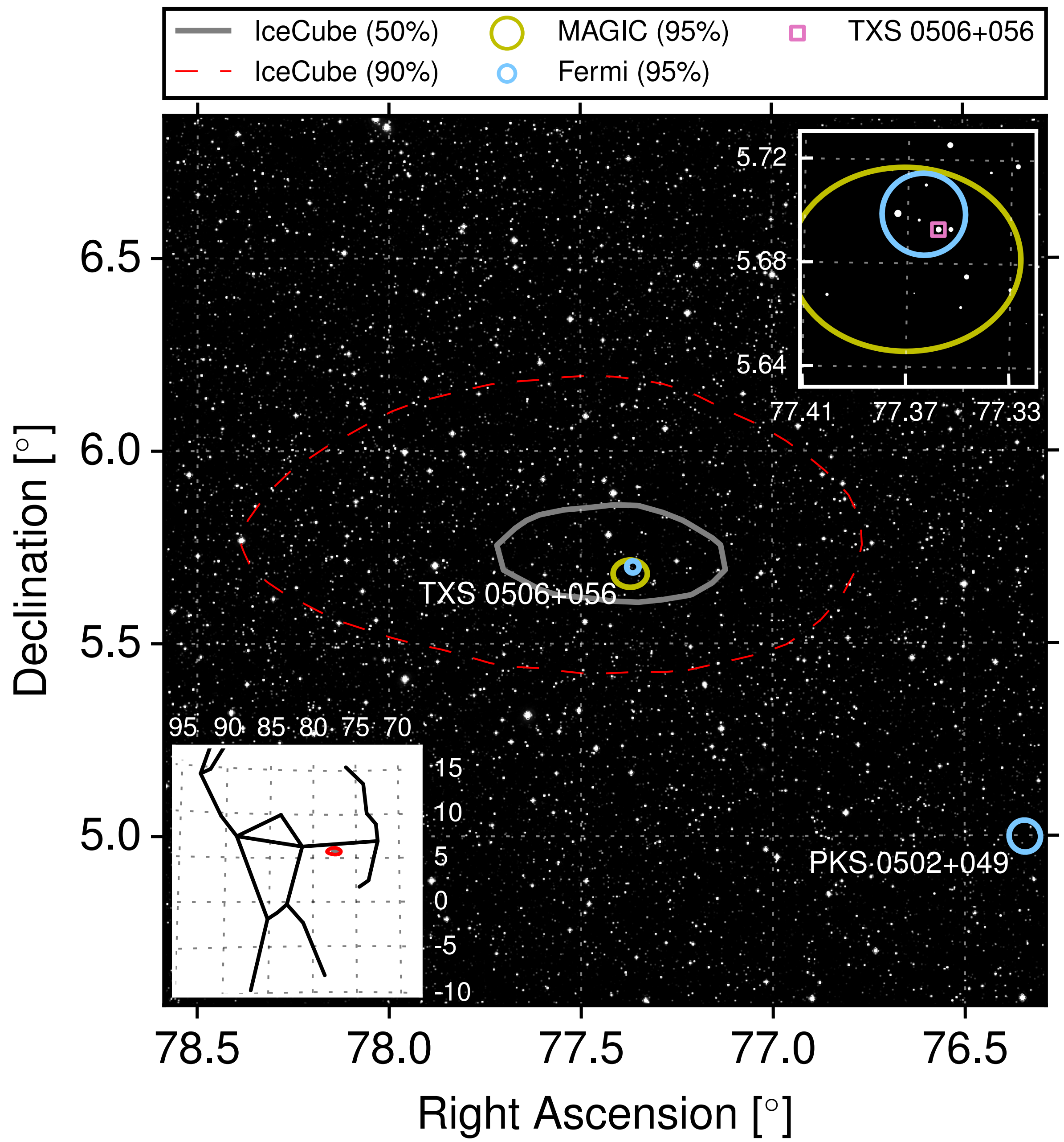
up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

Blazars

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



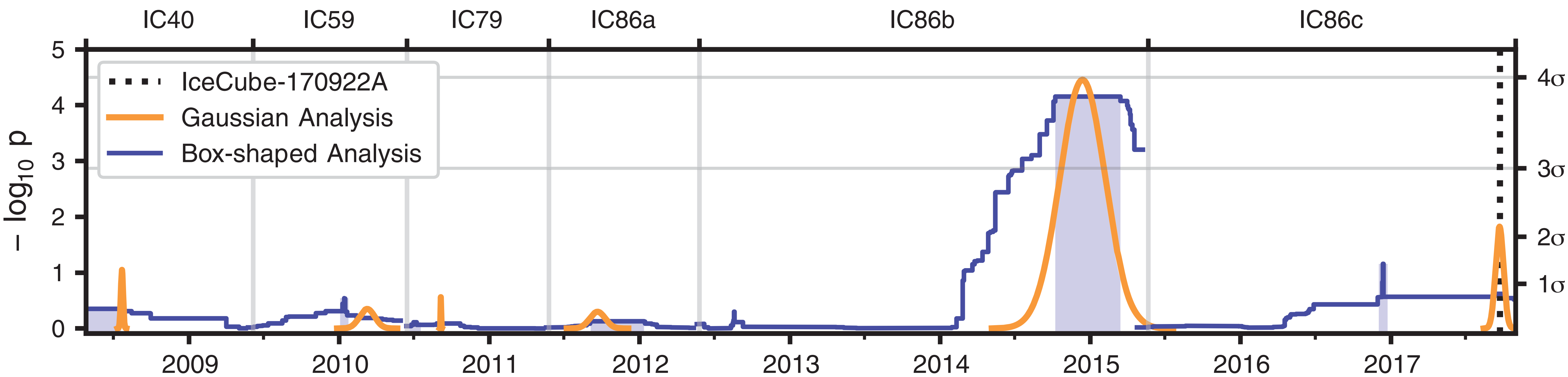
TXS 0506+056



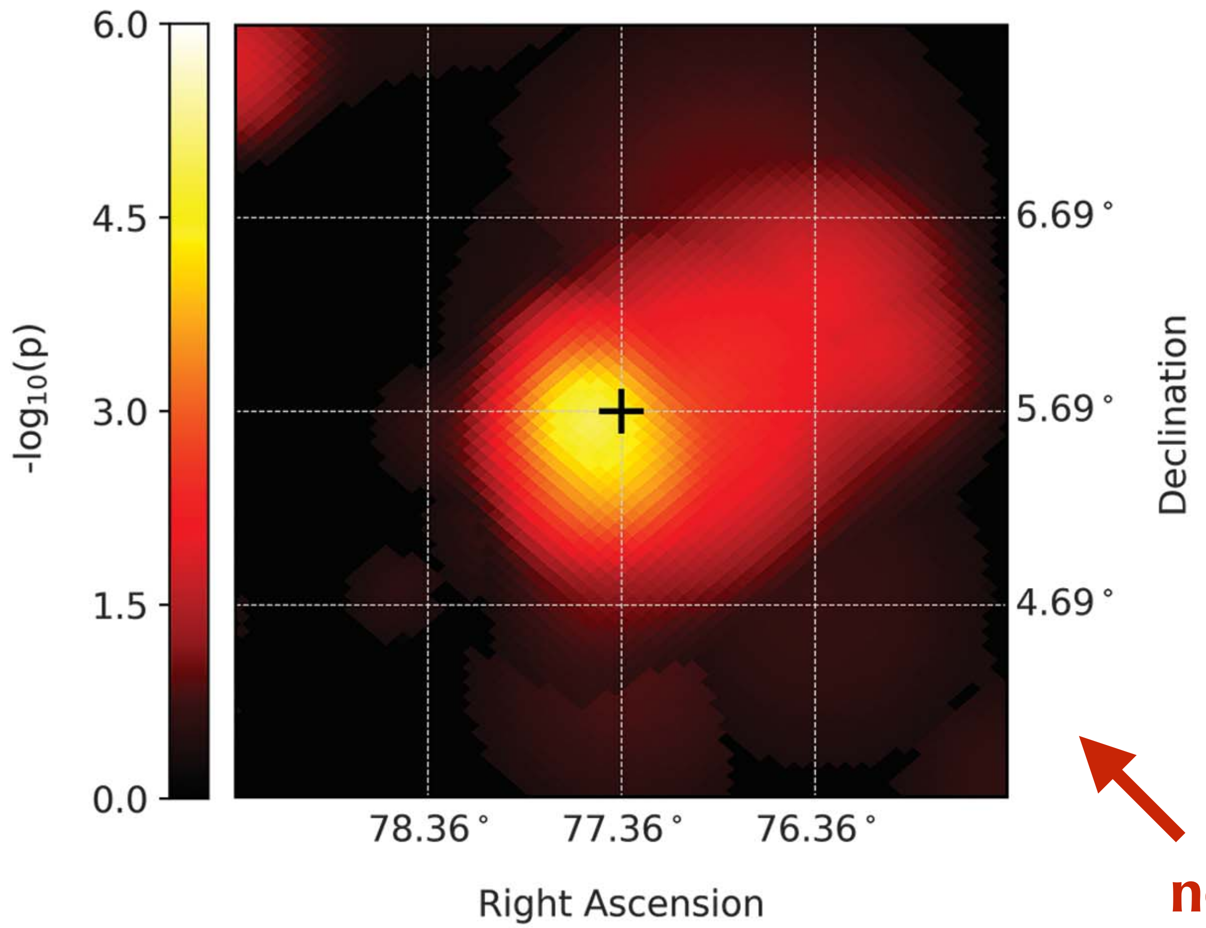
[IceCube++, Science 361 (2018) 6398]

- IC170922A 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



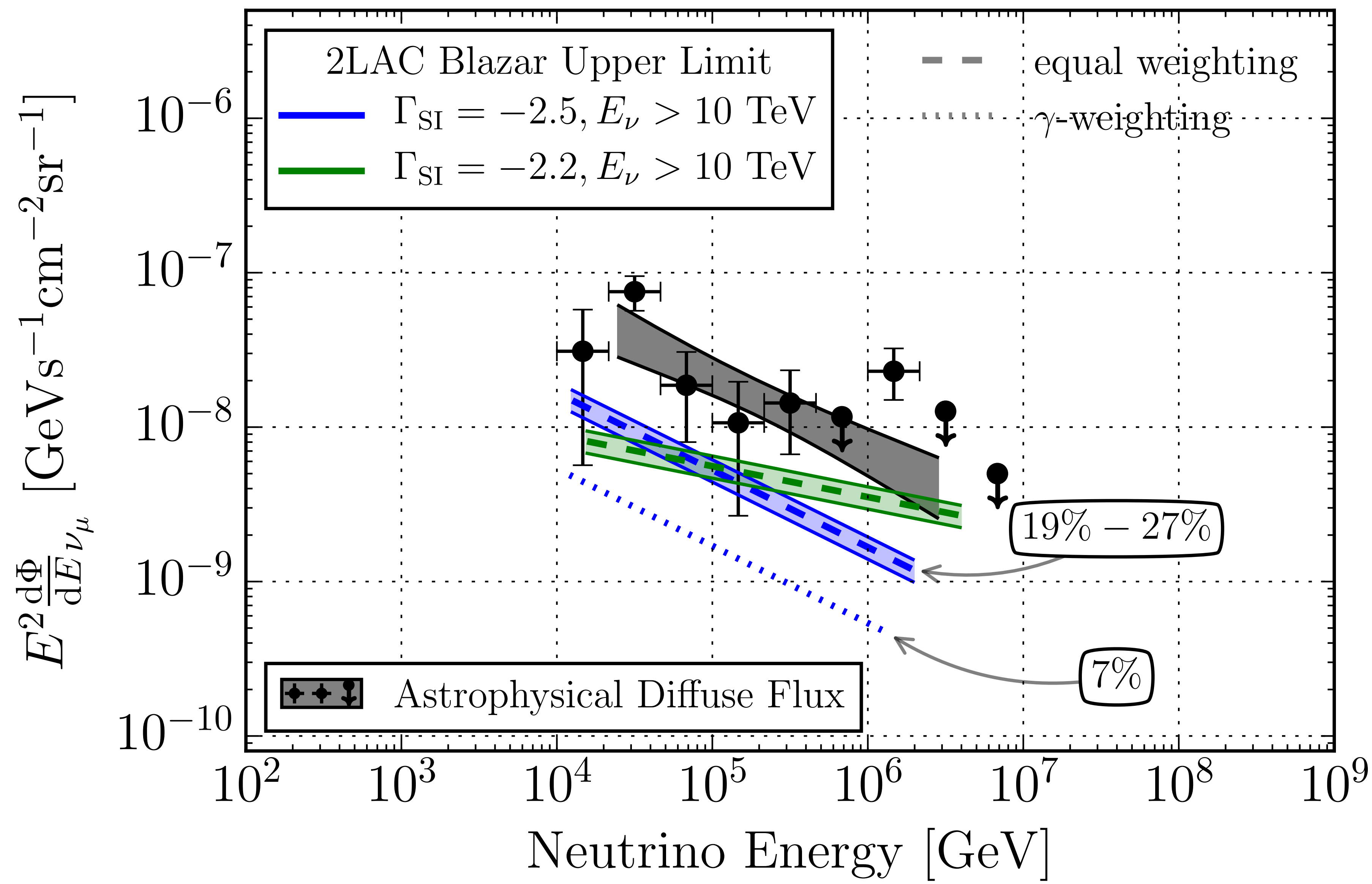
[IceCube, Science 361 (2018) 6398]



- 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

Fermi-LAT Blazar Stacking

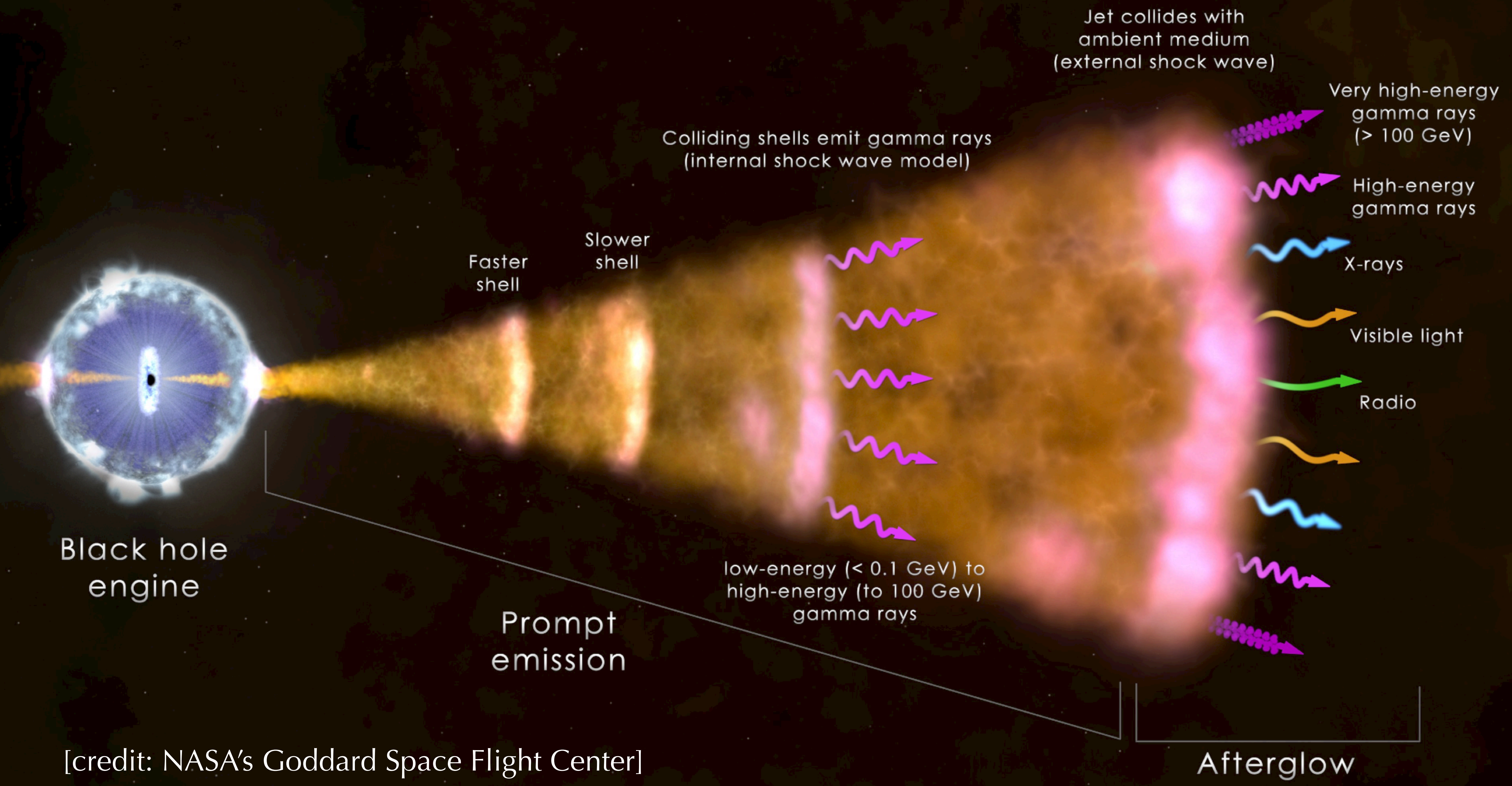


[IceCube, ApJ 835 (2017) 45]

- Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation. [IceCube, ApJ 835 (2017) 45]
- MeV-detected (1FLE) **below 1%**; "hard" emitters (3FHL) **below 17%** [IceCube, ApJ 938 (2022) 1; PoS ICRC2019 (2020) 916]

Gamma-Ray Bursts

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

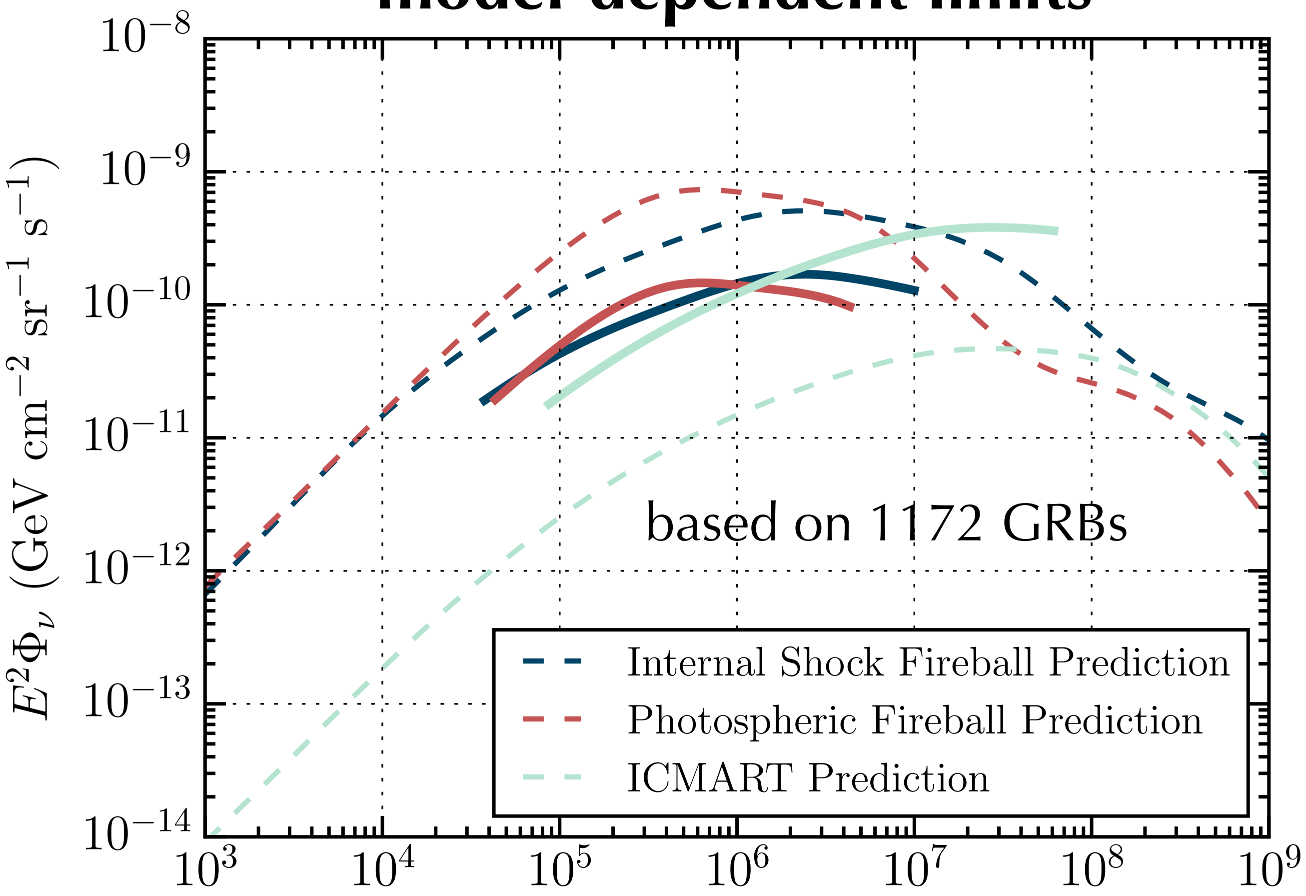


[credit: NASA's Goddard Space Flight Center]

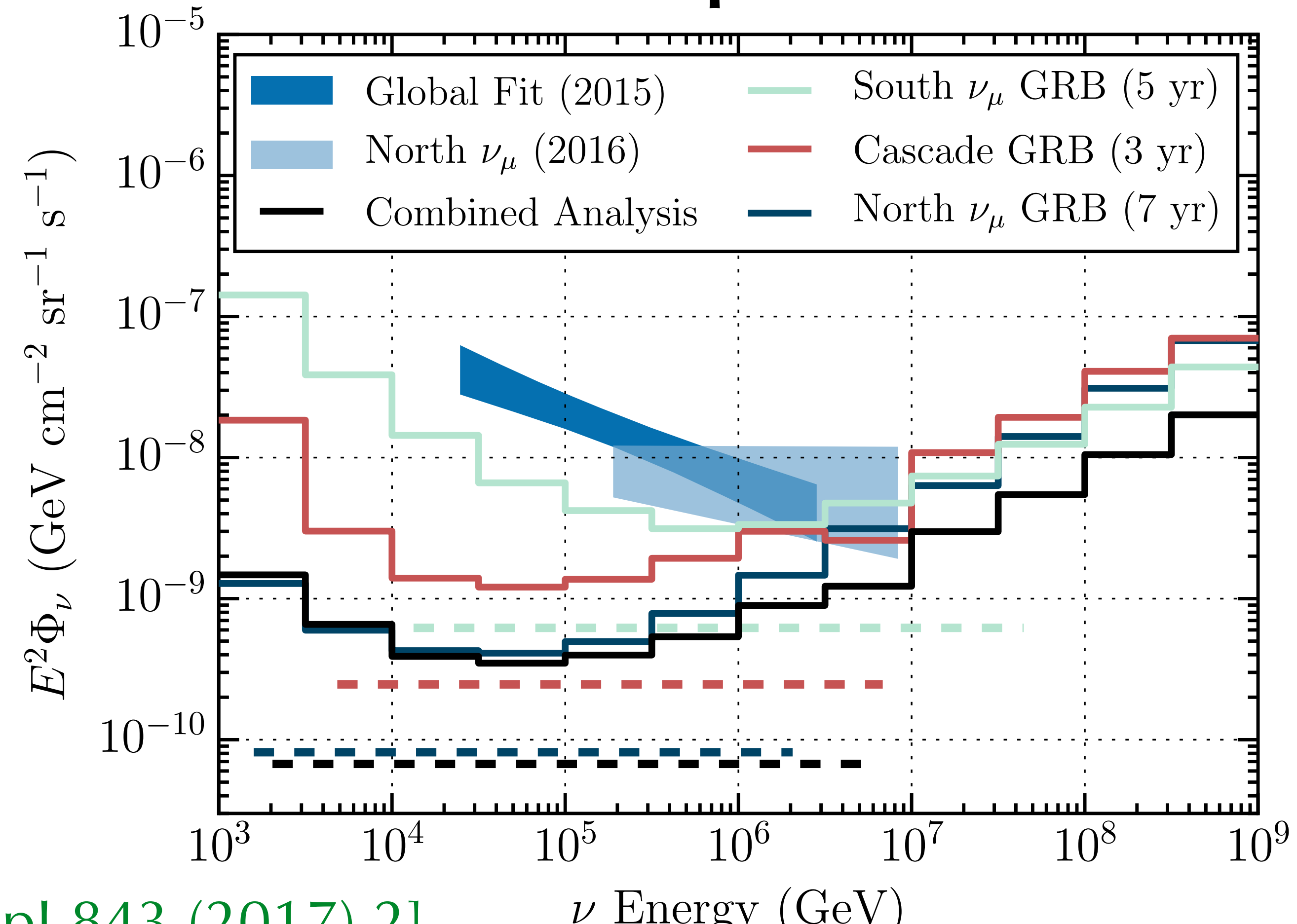
GRB Neutrino Limits

- IceCube routinely follows up on γ-ray bursts. [IceCube, ApJ 843 (2017) 2]
- Search is most sensitive to "prompt" (<100s) neutrino emission. [Waxman & Bahcall '97]
- Contribution to diffuse flux **below 1%** for "prompt" phase and **below 27%** for neutrino emission within 3h. [IceCube, ApJ 939 (2022) 2]

model-dependent limits

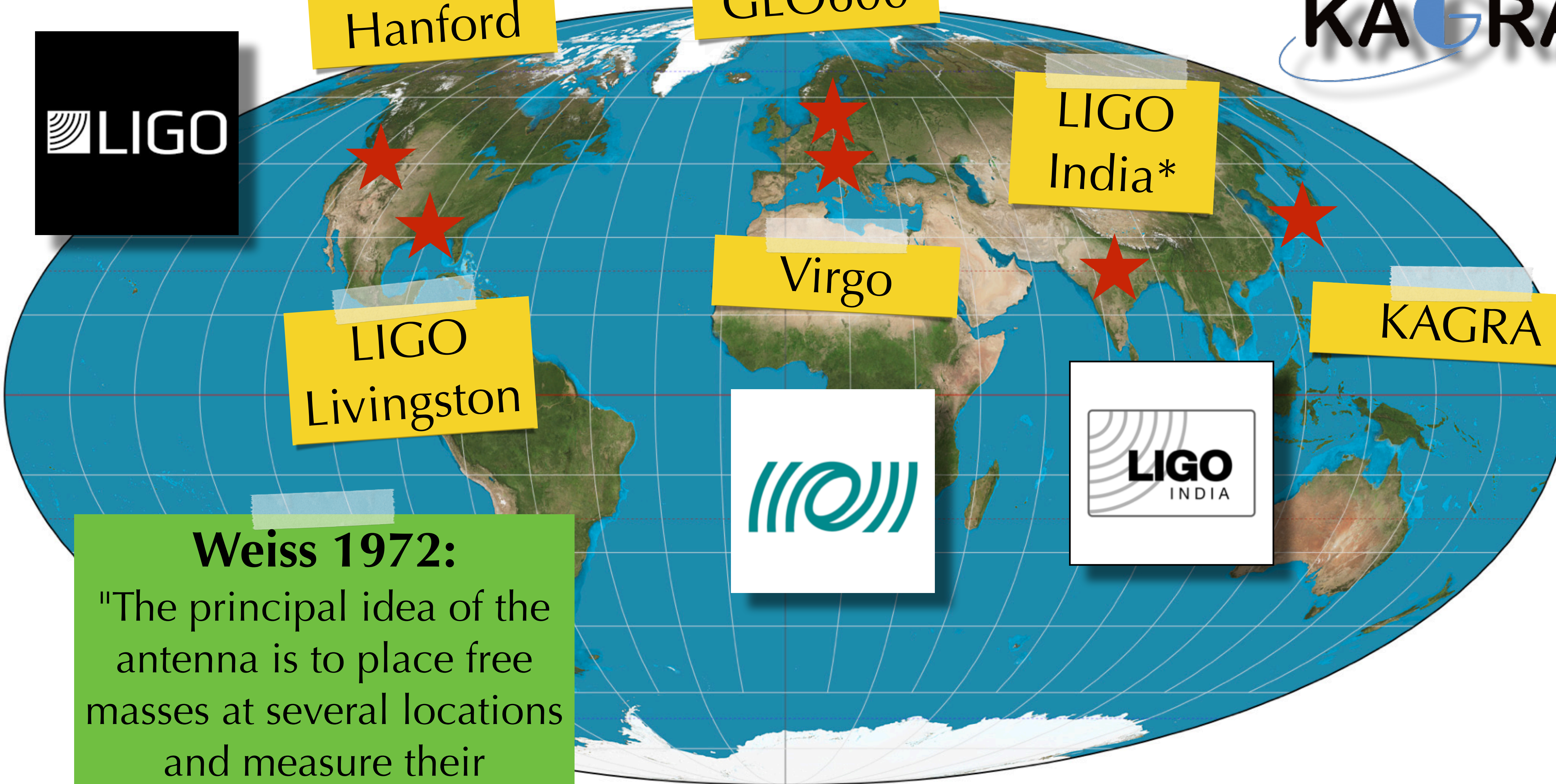


model-independent limits



[IceCube, ApJ 843 (2017) 2]

Gravitational Wave Interferometers



Weiss 1972:

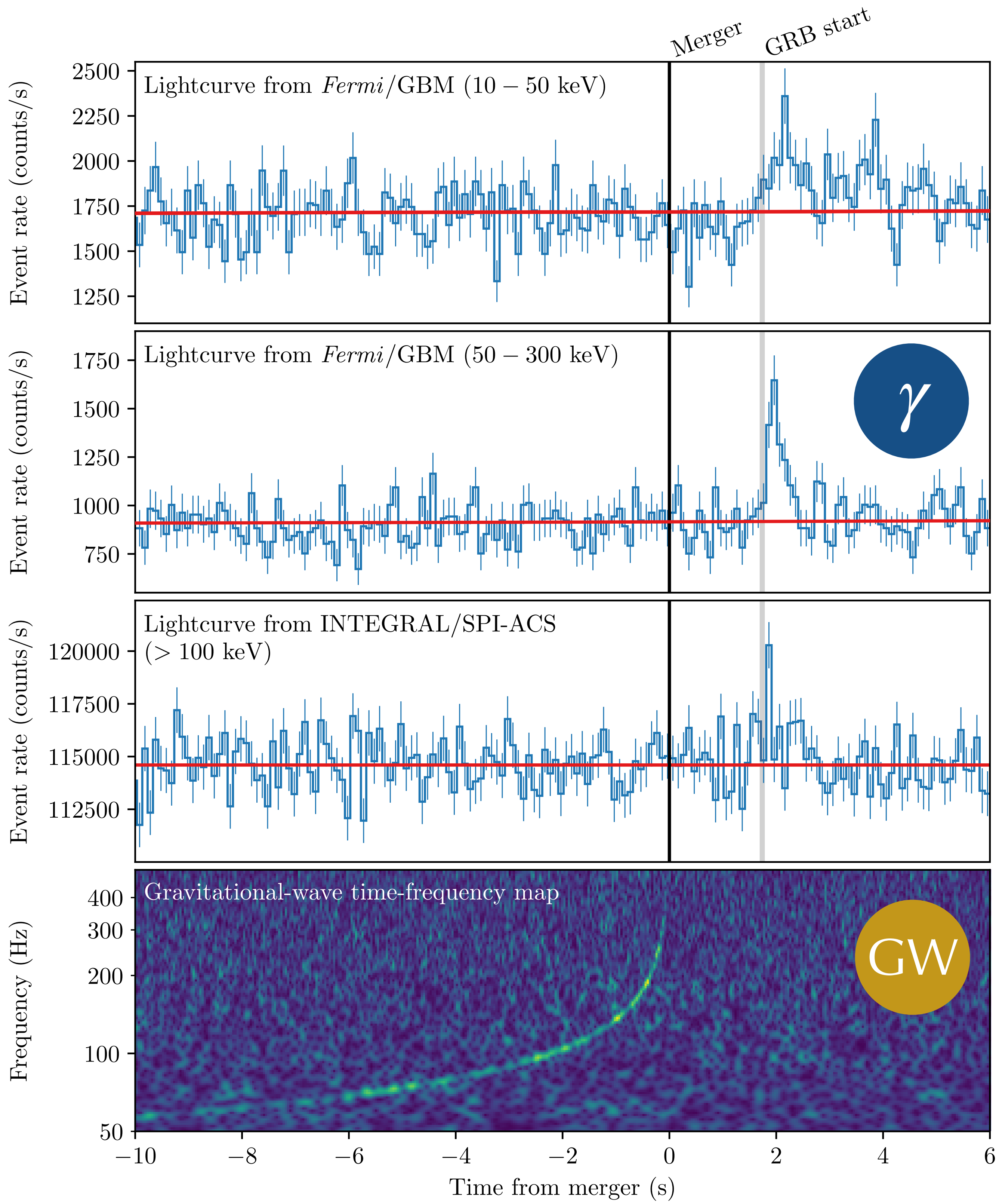
"The principal idea of the antenna is to place free masses at several locations and measure their separations interferometrically."

**under construction*

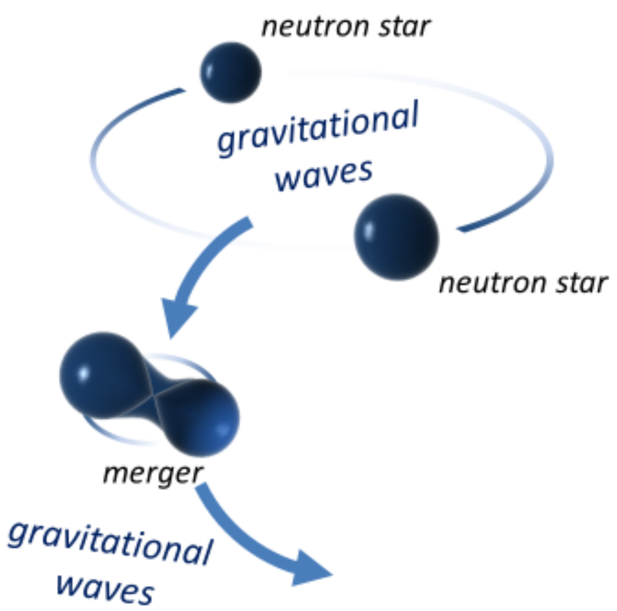
+ Pulsar Timing Arrays

(stochastic GW background)

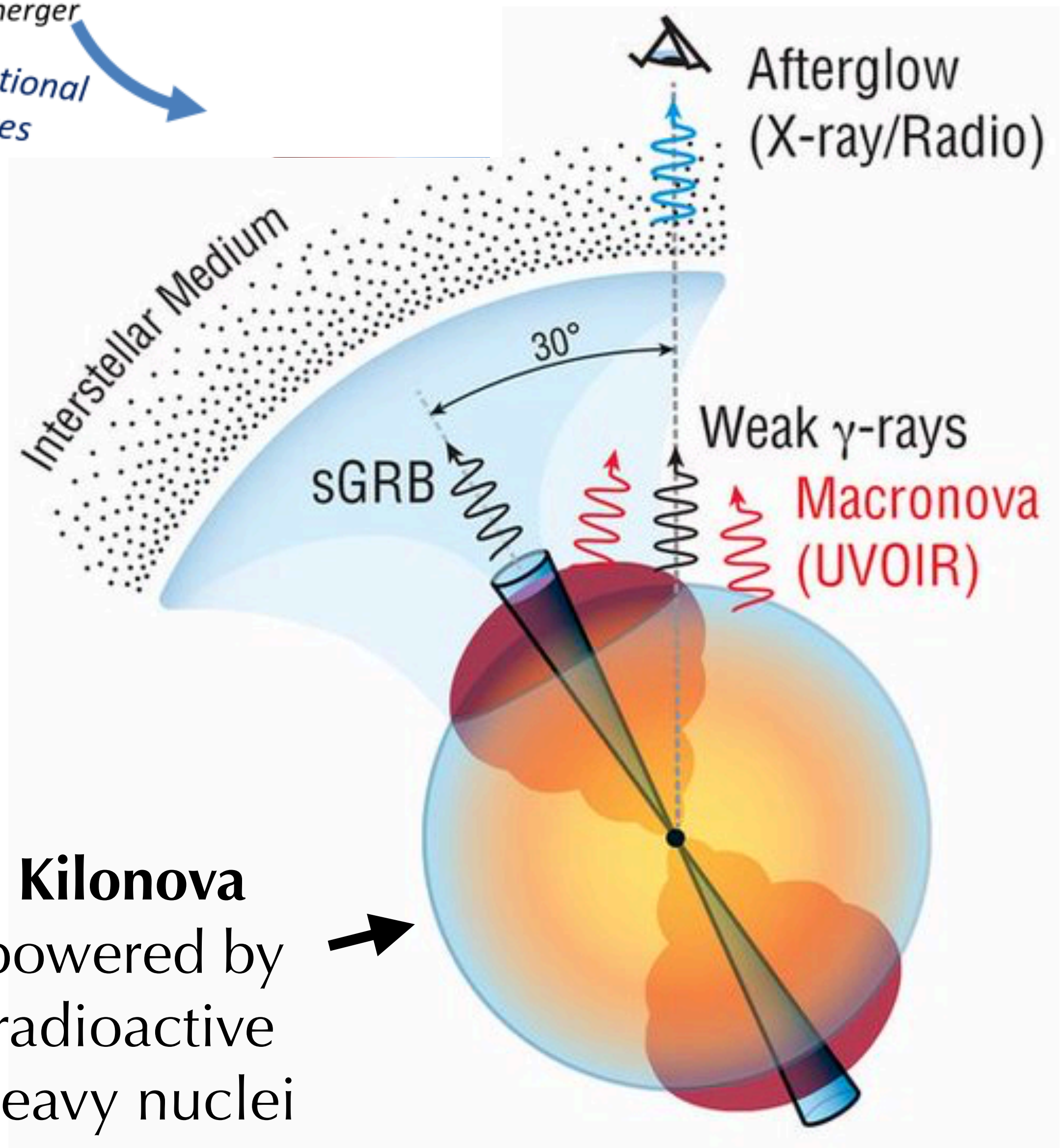
GRBs and Gravitational Waves



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

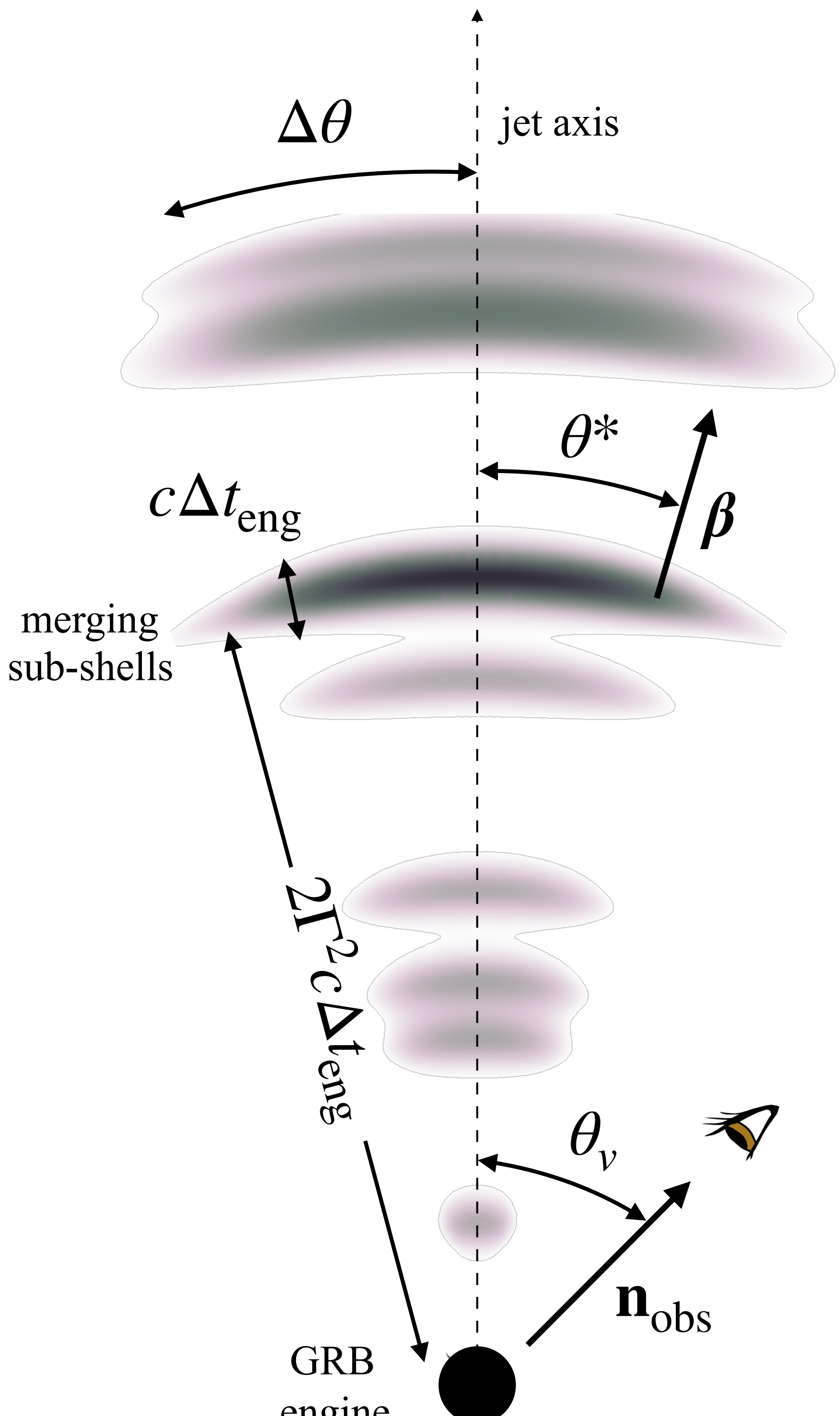


GW 170817
&
GRB 170817A

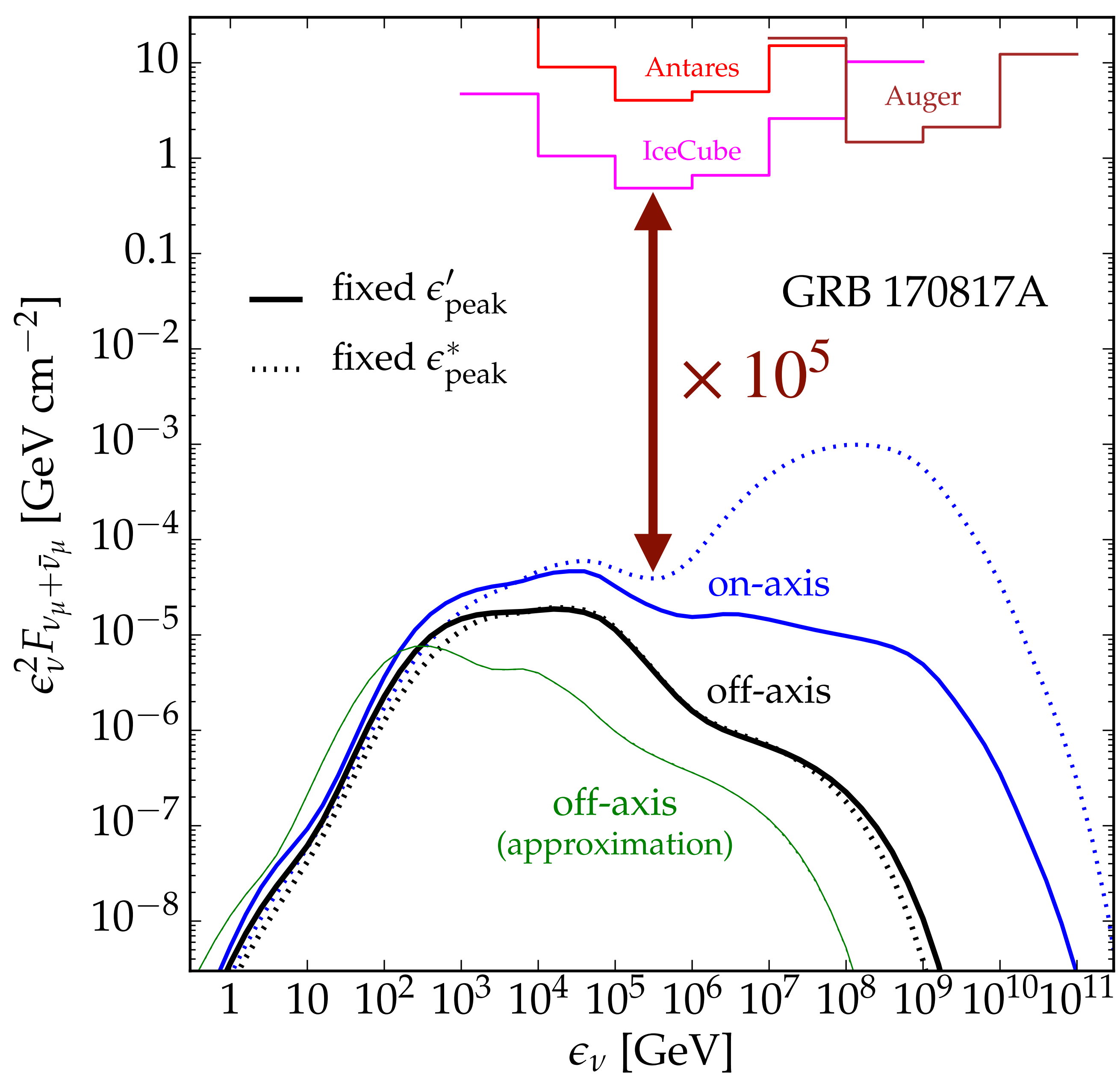


Kilonova powered by radioactive heavy nuclei

GRB 170817A - Neutrino Limits

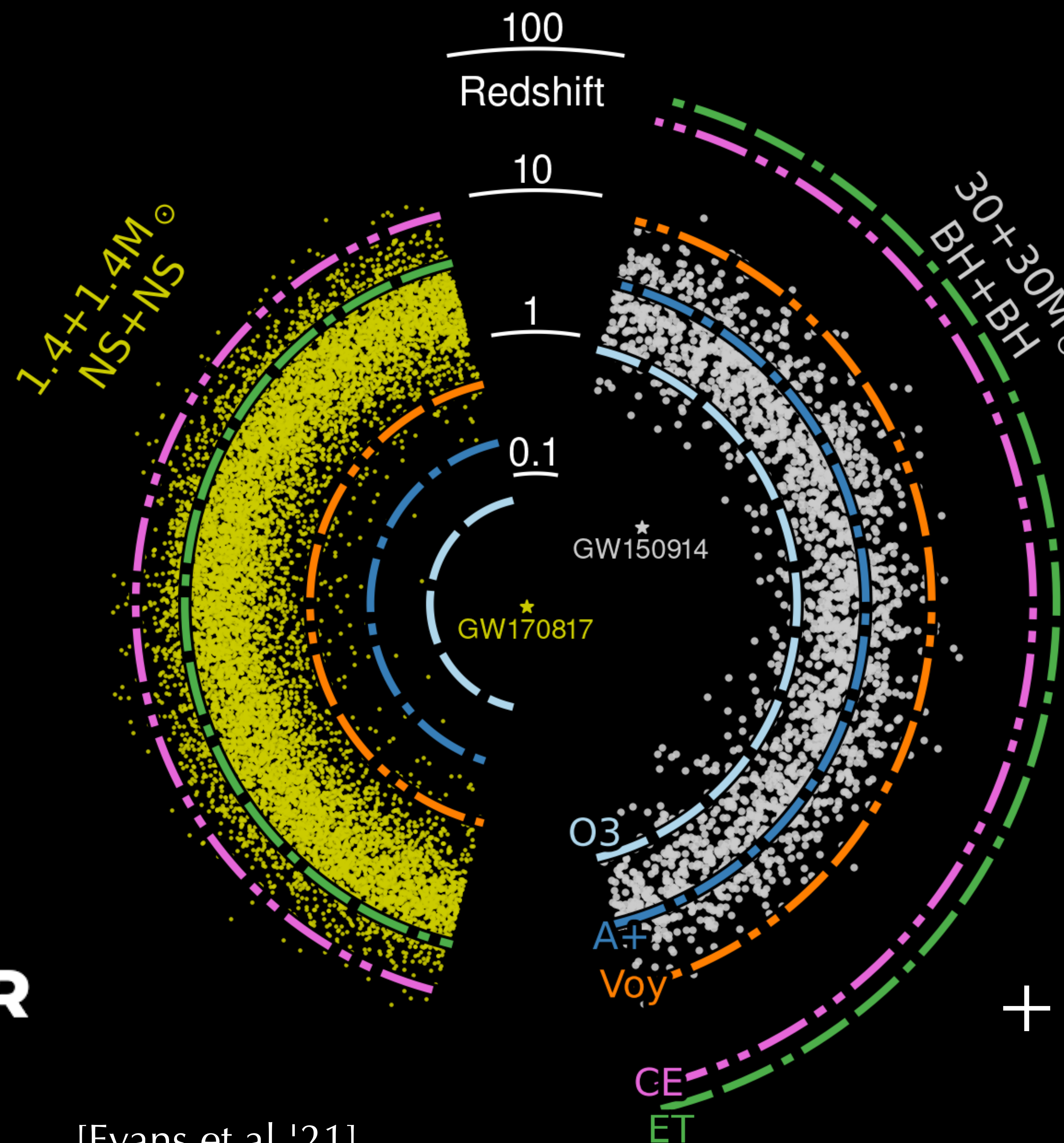


No detection of neutrinos in prompt phase consistent with **off-axis emission.**



[MA & Halser'19]

Next-Generation GW Detectors



[Evans et al.'21]

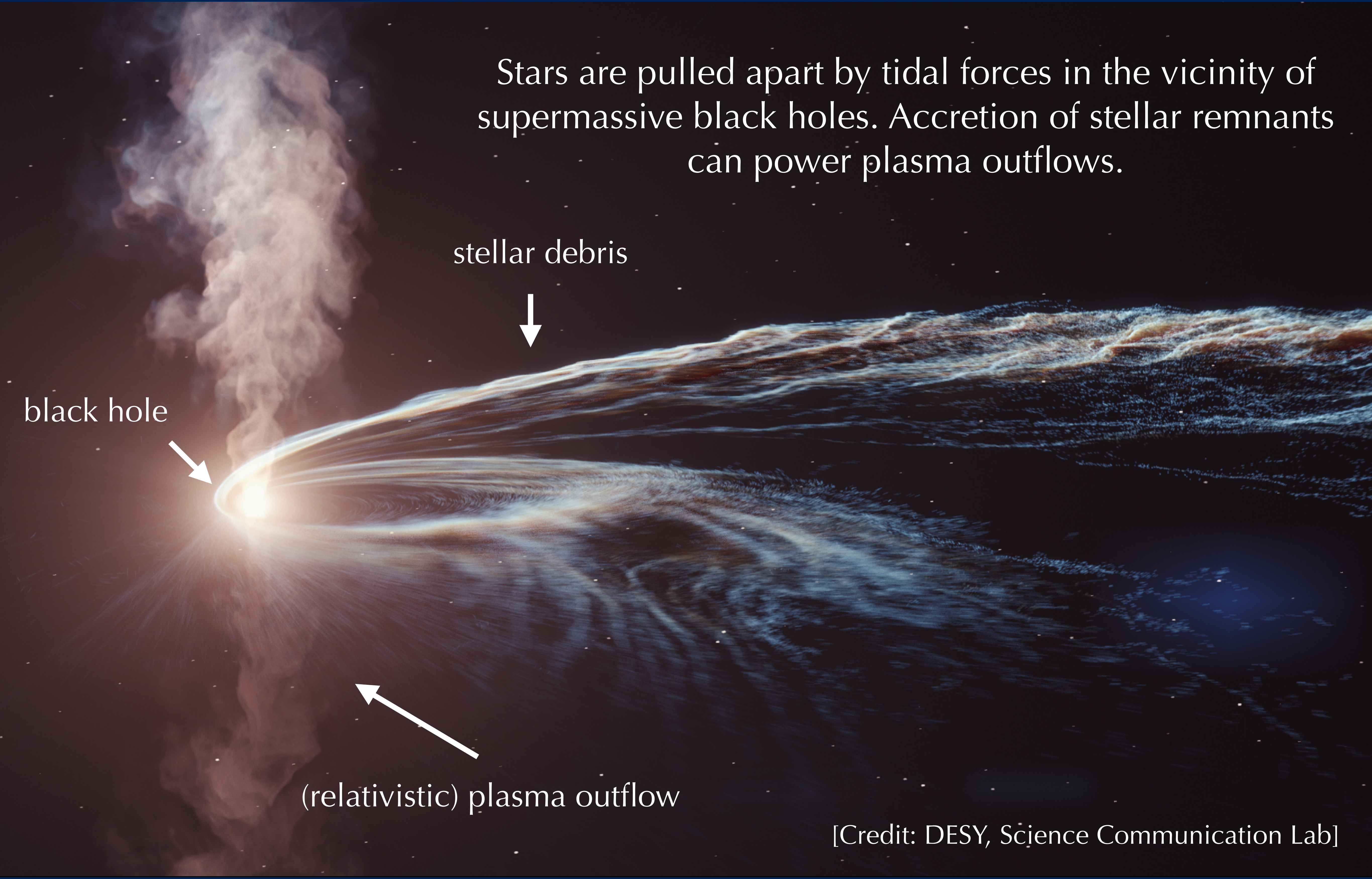
Runs O4/O5
A+ / Voyager

+ LISA

(low frequency)

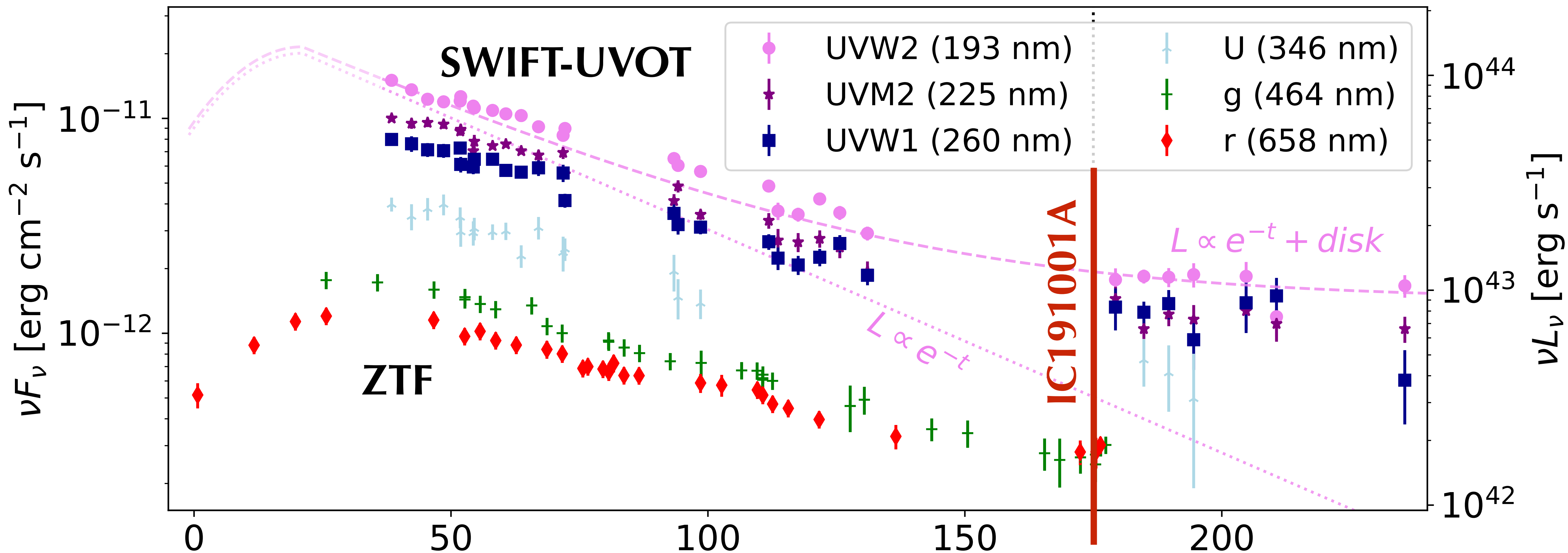
Tidal Disruption Events (TDEs)

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



[Credit: DESY, Science Communication Lab]

Tidal Disruption Events (TDEs)



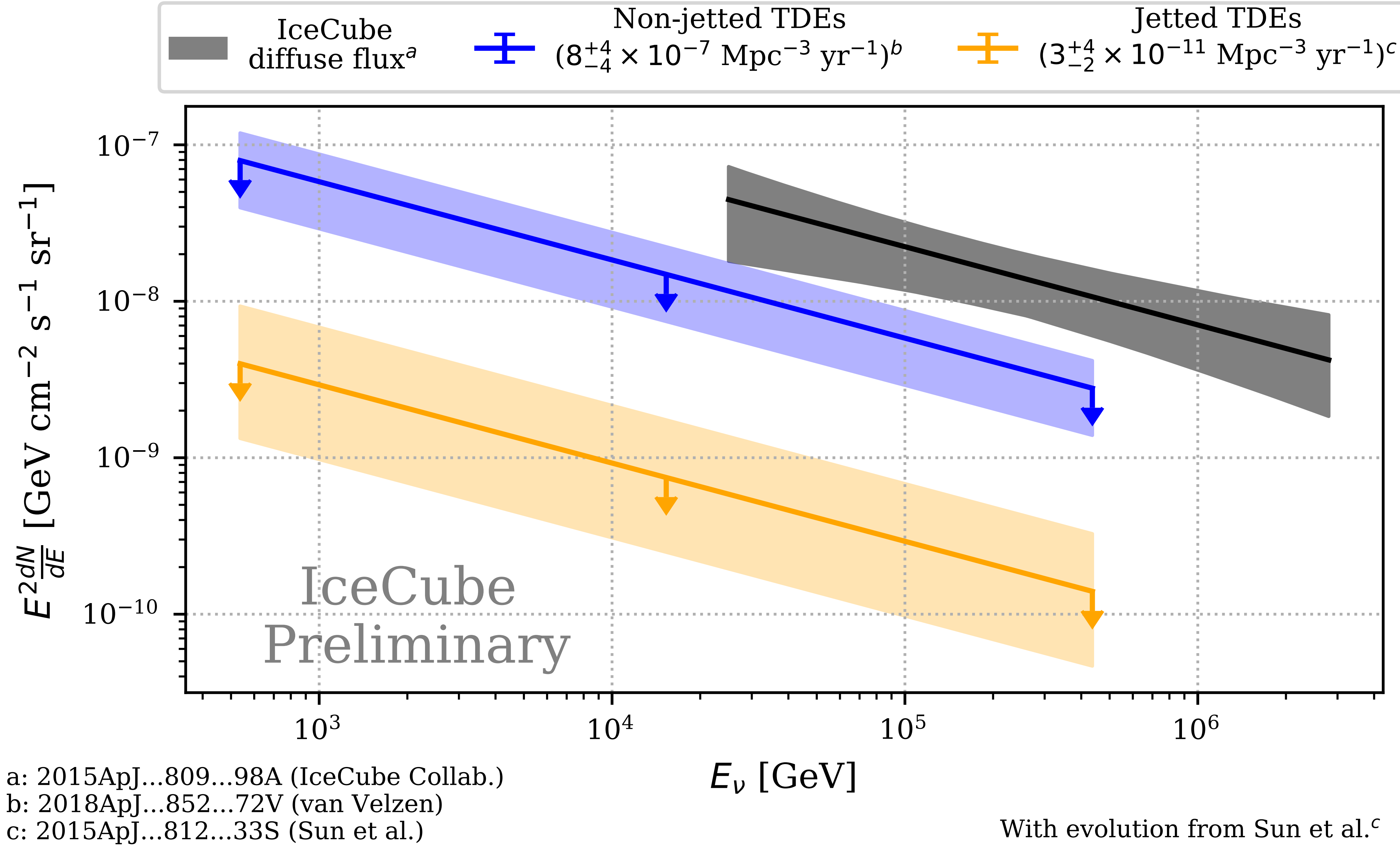
[Stein et al. Nature Astronomy 5 (2021) 5]

177 days (after discovery)

- Association of alert IC191001A with radio-load TDE AT2019dsg
- Chance for random correlation of TDEs and IceCube alerts is 0.5%.
- Other associations with TDE candidates, *e.g.* IC200530A & AT2019fdr.

[Reusch et al. PRL 128 (2022) 221101; Walter & Lunardini ApJ 948 (2023) 1]

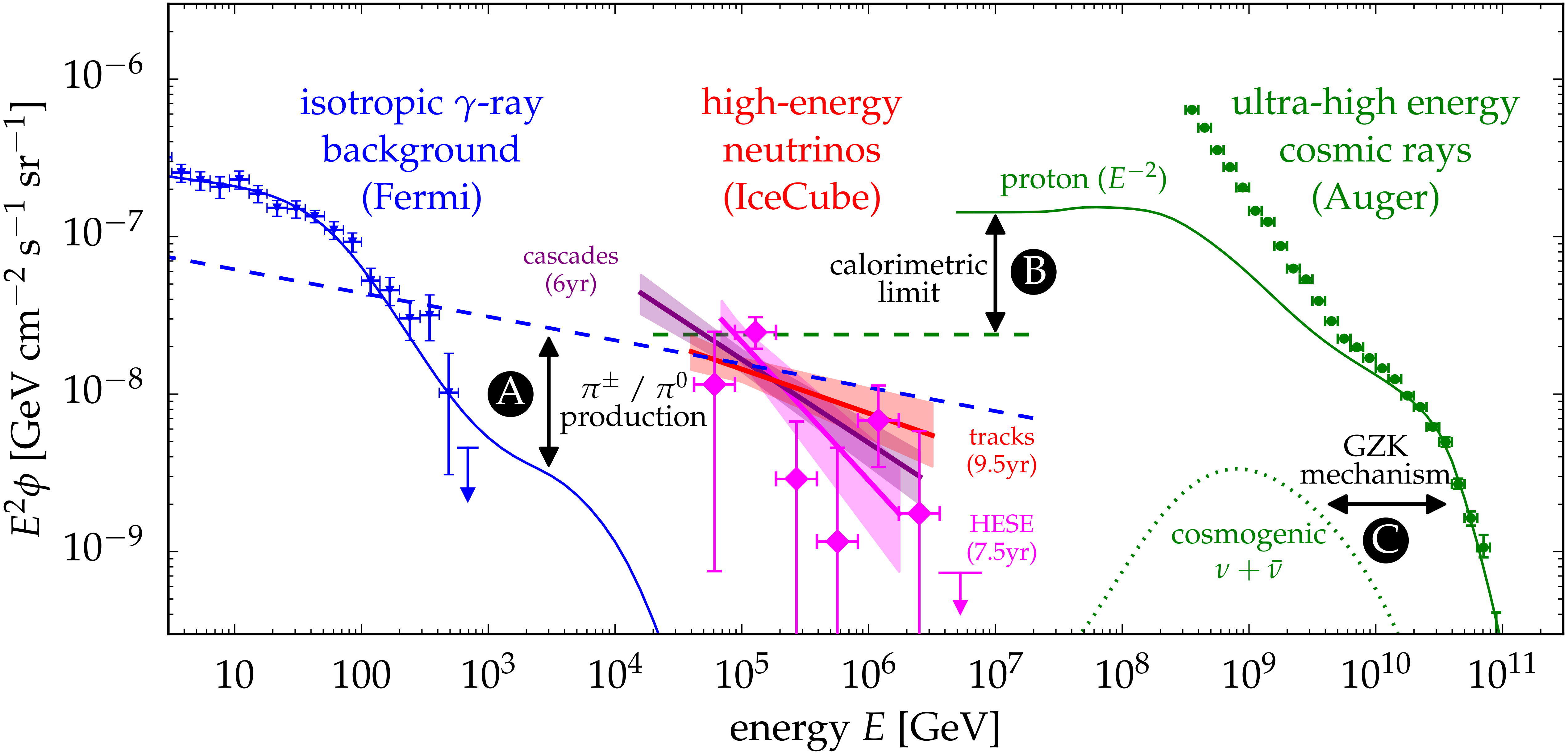
TDE Neutrino Limits



[IceCube, PoS (ICRC2019) 1016]

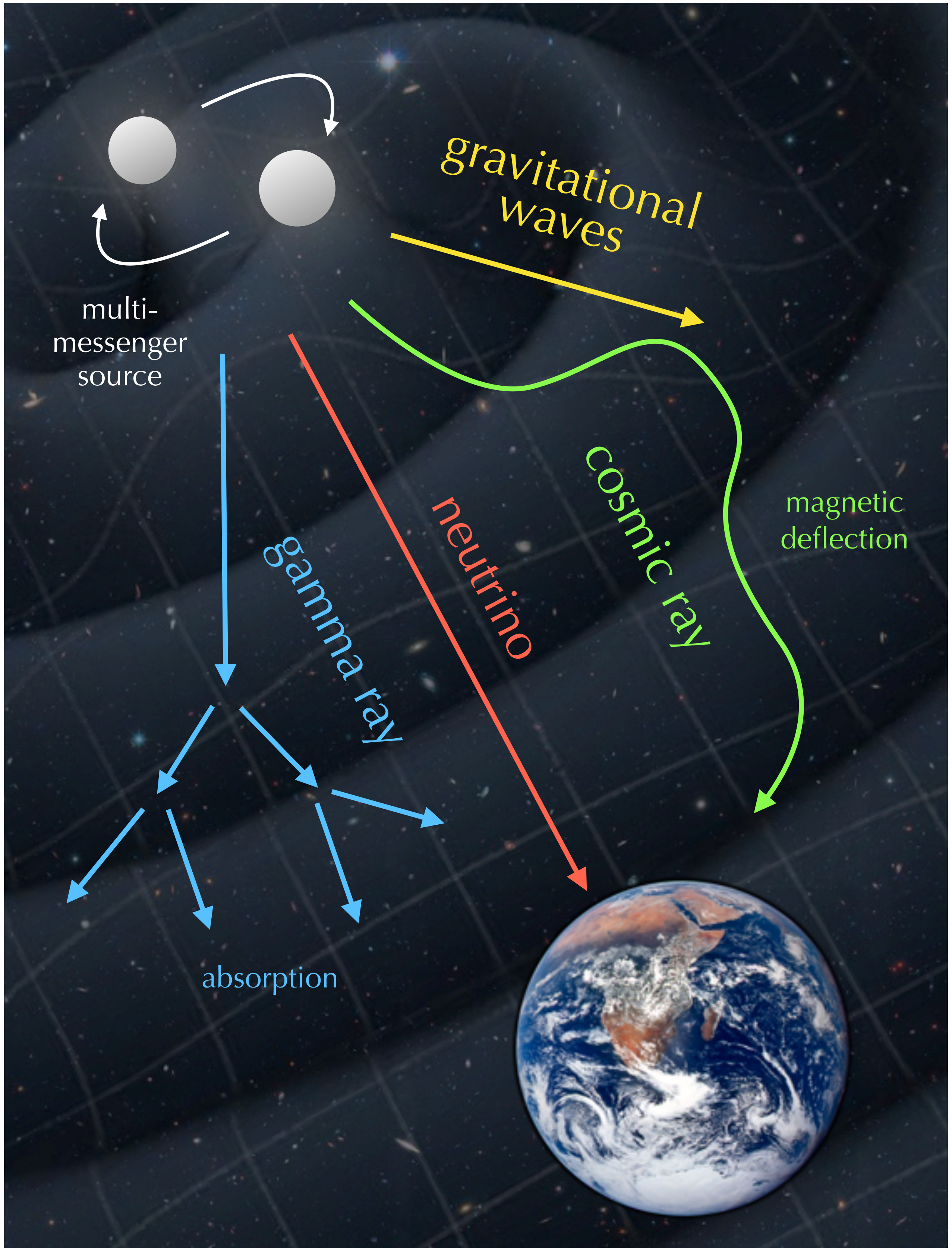
Limits derived based on stacking of 3 jetted and 13 non-jetted TDEs.
Contribution to diffuse flux **below 2%** and **below 26%**, respectively.

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.

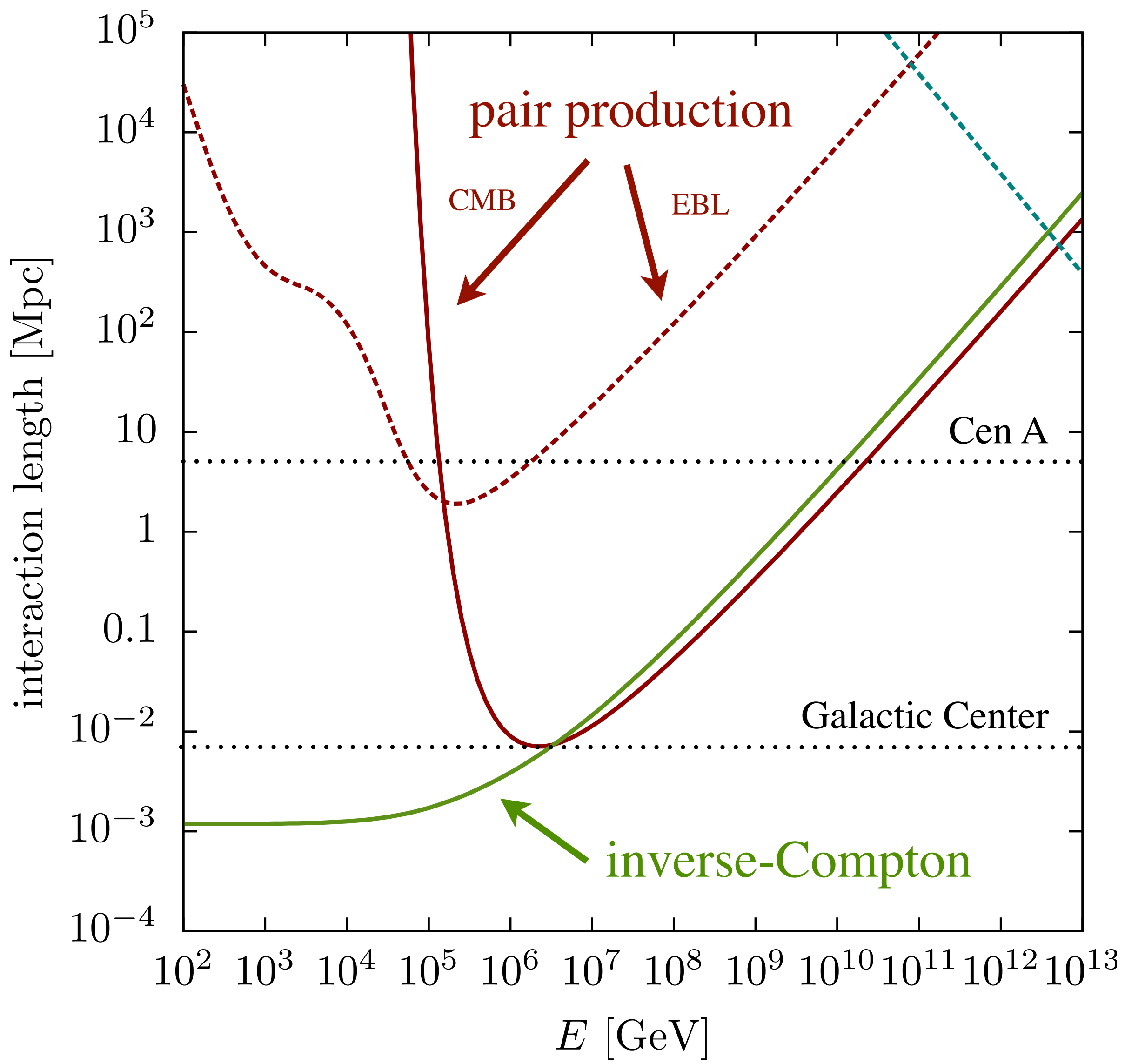
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

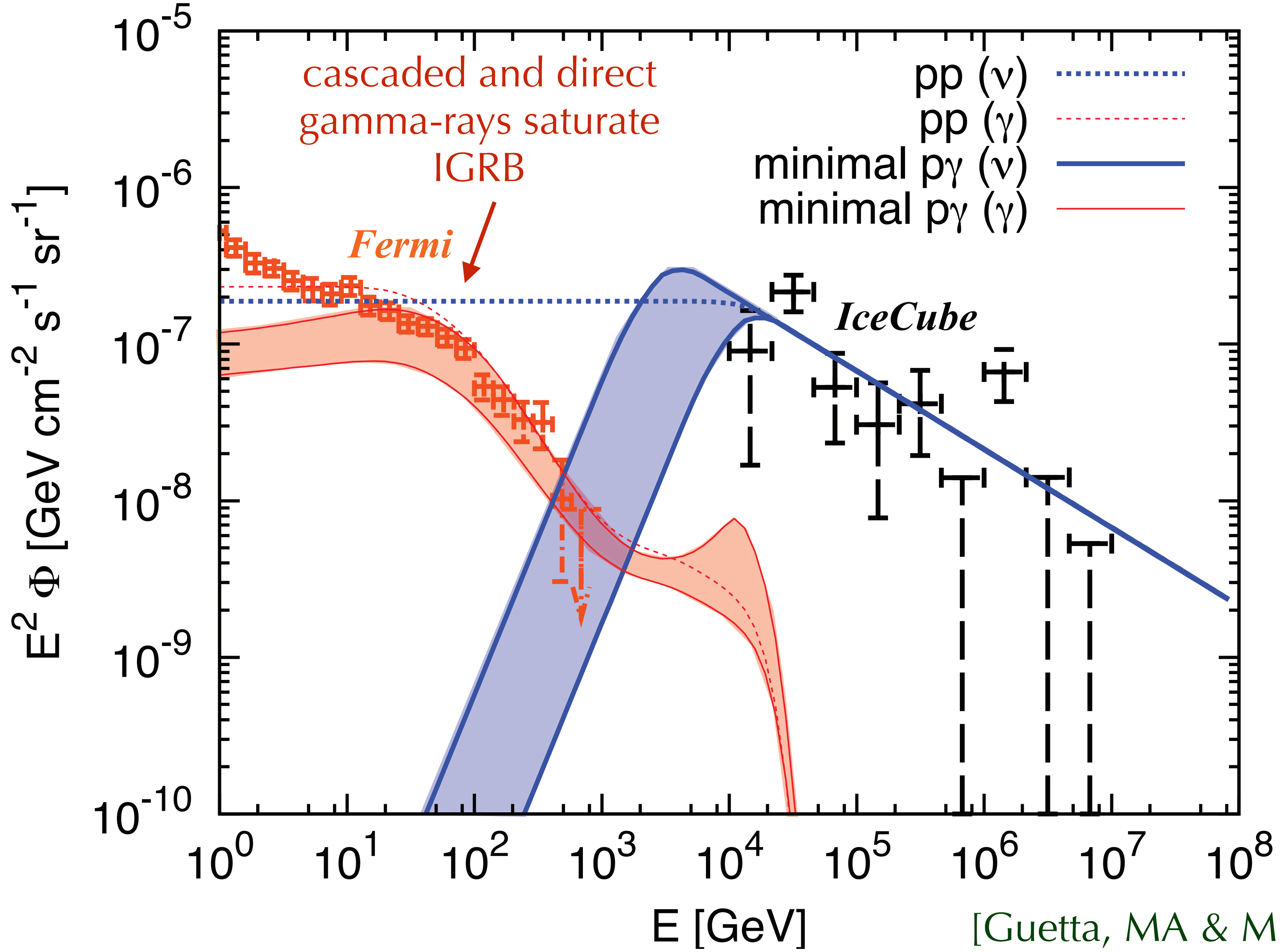
$$\gamma + \gamma_{\rm bg} \rightarrow e^+ + e^- \quad \text{(PP)}$$

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



Hadronic Gamma-Rays

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



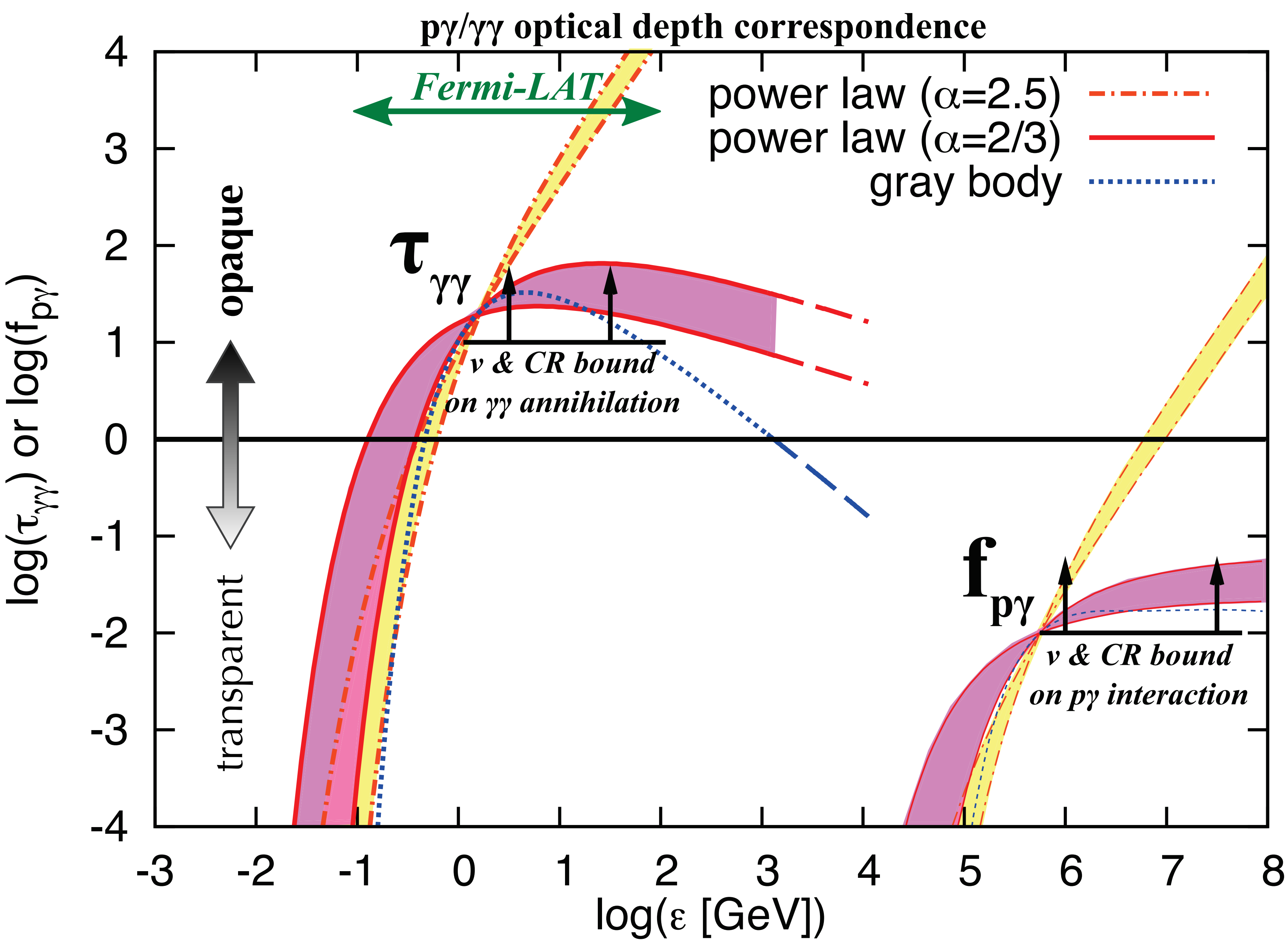
[Guetta, MA & Murase'16]

[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 $p\gamma$ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).



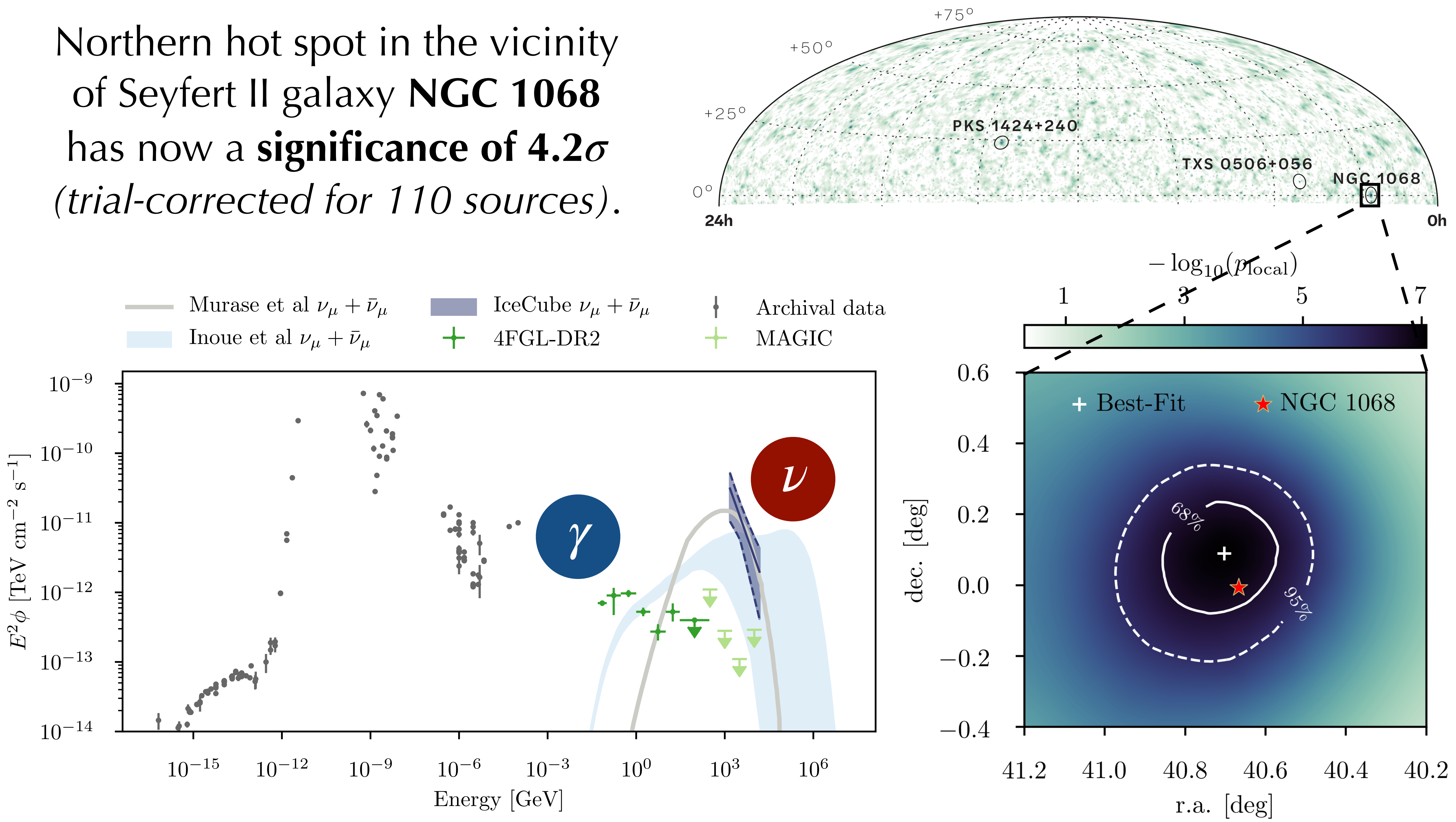
High pion production efficiency implies strong internal **γ-ray absorption in Fermi-LAT energy range:**

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

[Guetta, MA & Murase'16]

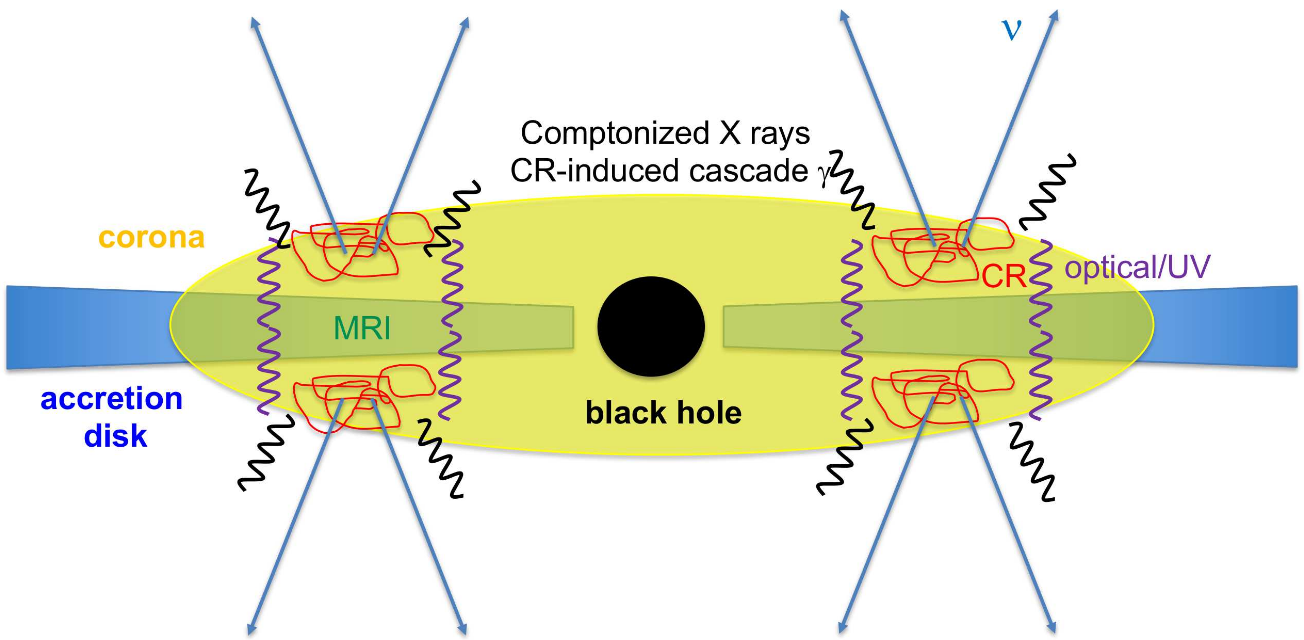
Excess from NGC 1068

Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** has now a **significance of 4.2σ** *(trial-corrected for 110 sources)*.

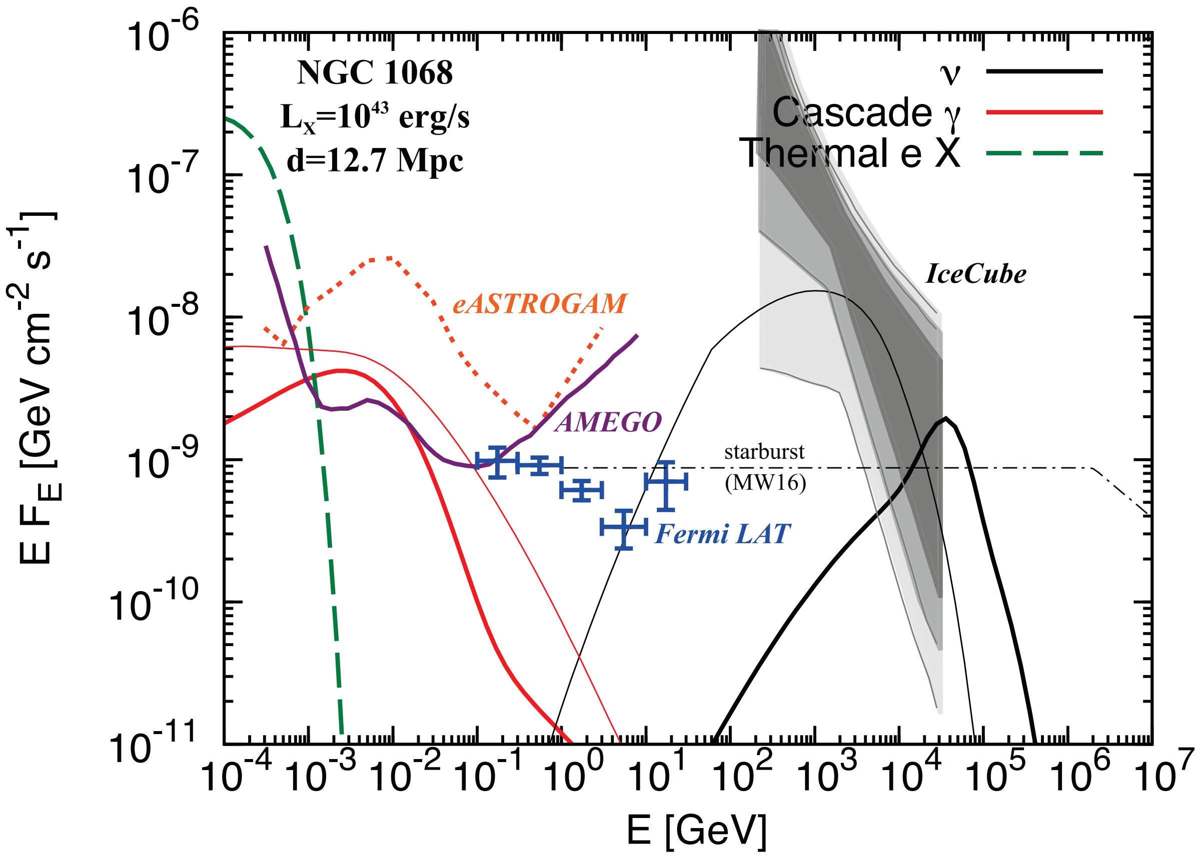


[IceCube, PRL 124 (2020) 5 **(2.9σ post-trial)**; Science 378 (2022) 6619 **(4.2σ post-trial)**]

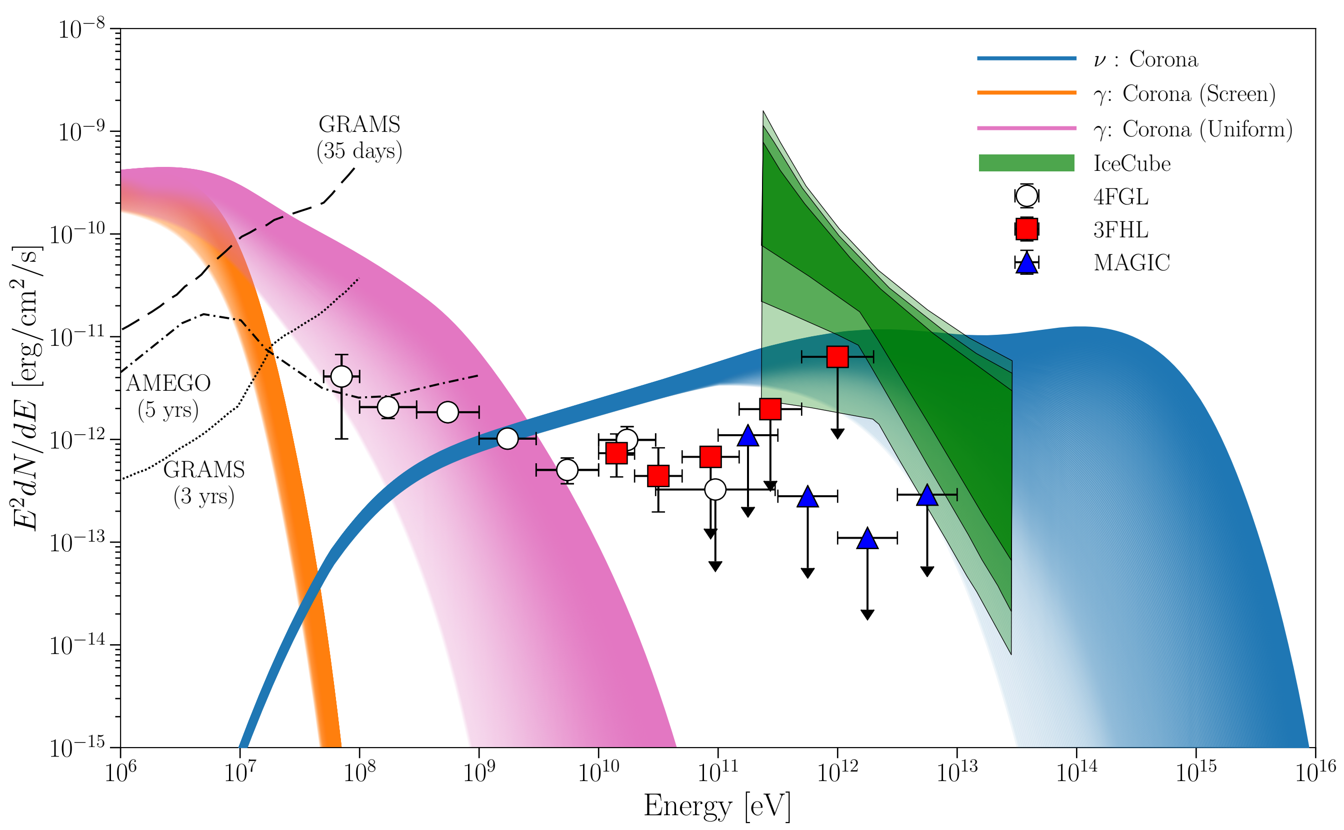
Excess from NGC 1068



- **Soft spectrum** ($\gamma = 3.2 \pm 0.2$) within 1.5-15 TeV indicates peak or cutoff in ν emission.
- Effective **absorption** of accompanying γ-rays in X-ray photons of **AGN corona.**



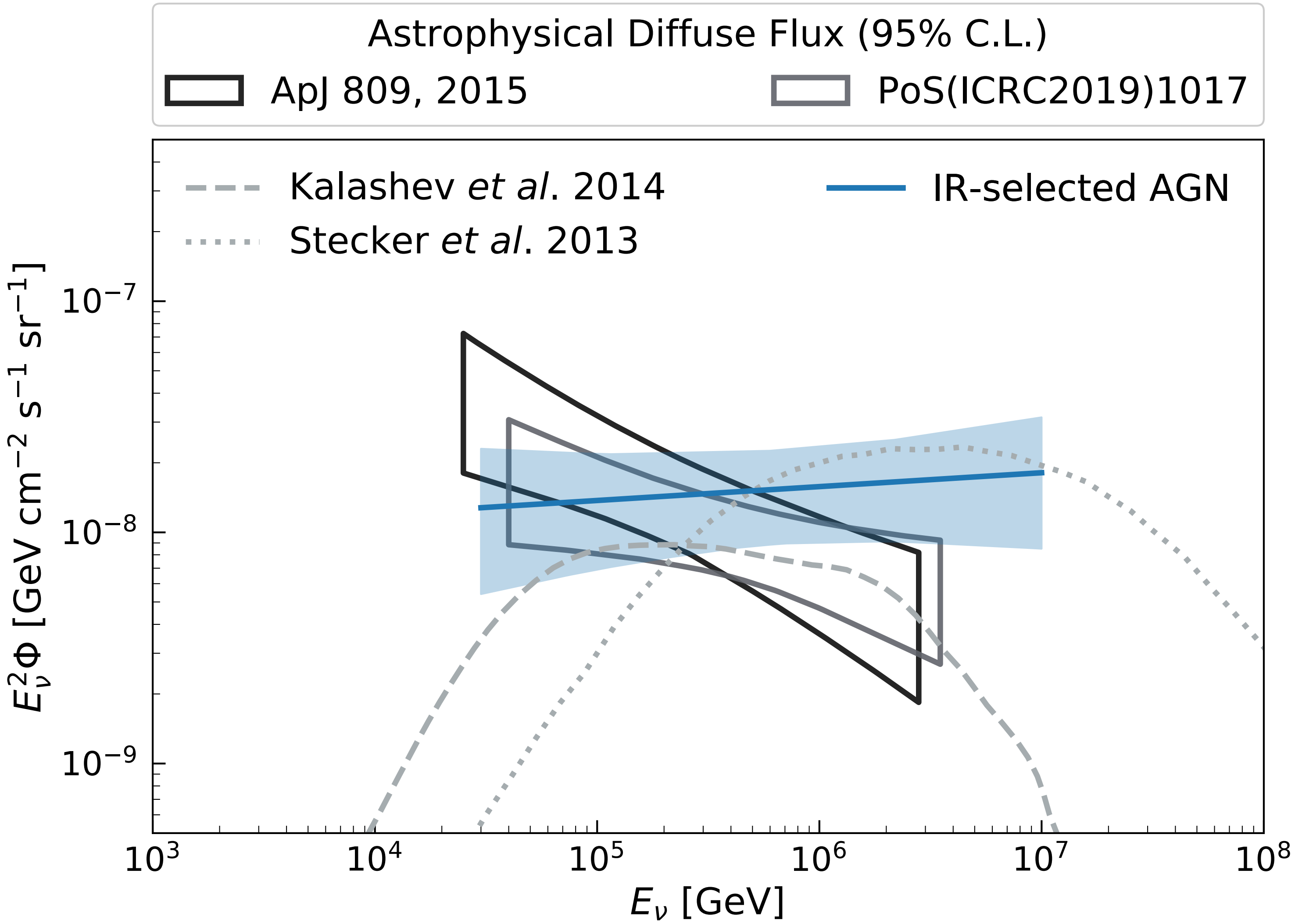
[Murase, Kimura & Meszaros '20]



[Inoue, Khangulyan & Doi '20]

AGN Core Stacking

- Hadronic γ-rays in **cores of AGNs** are suppressed due to pair production in X-ray background.
- IceCube finds a **2.6σ excess** for 32,249 AGN selected by their IR emission.



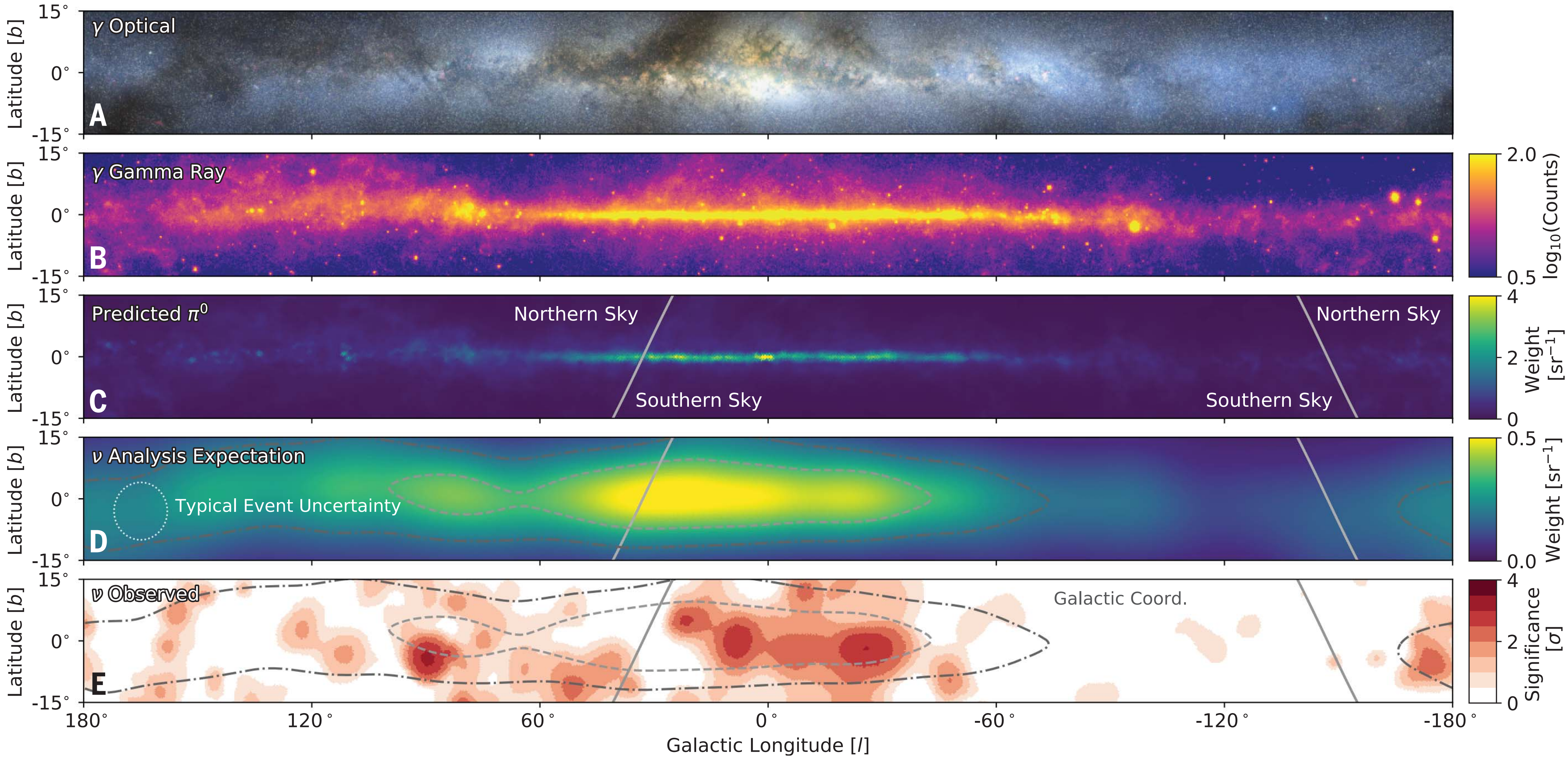
[IceCube, PRD 106 (2022) 2]

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	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

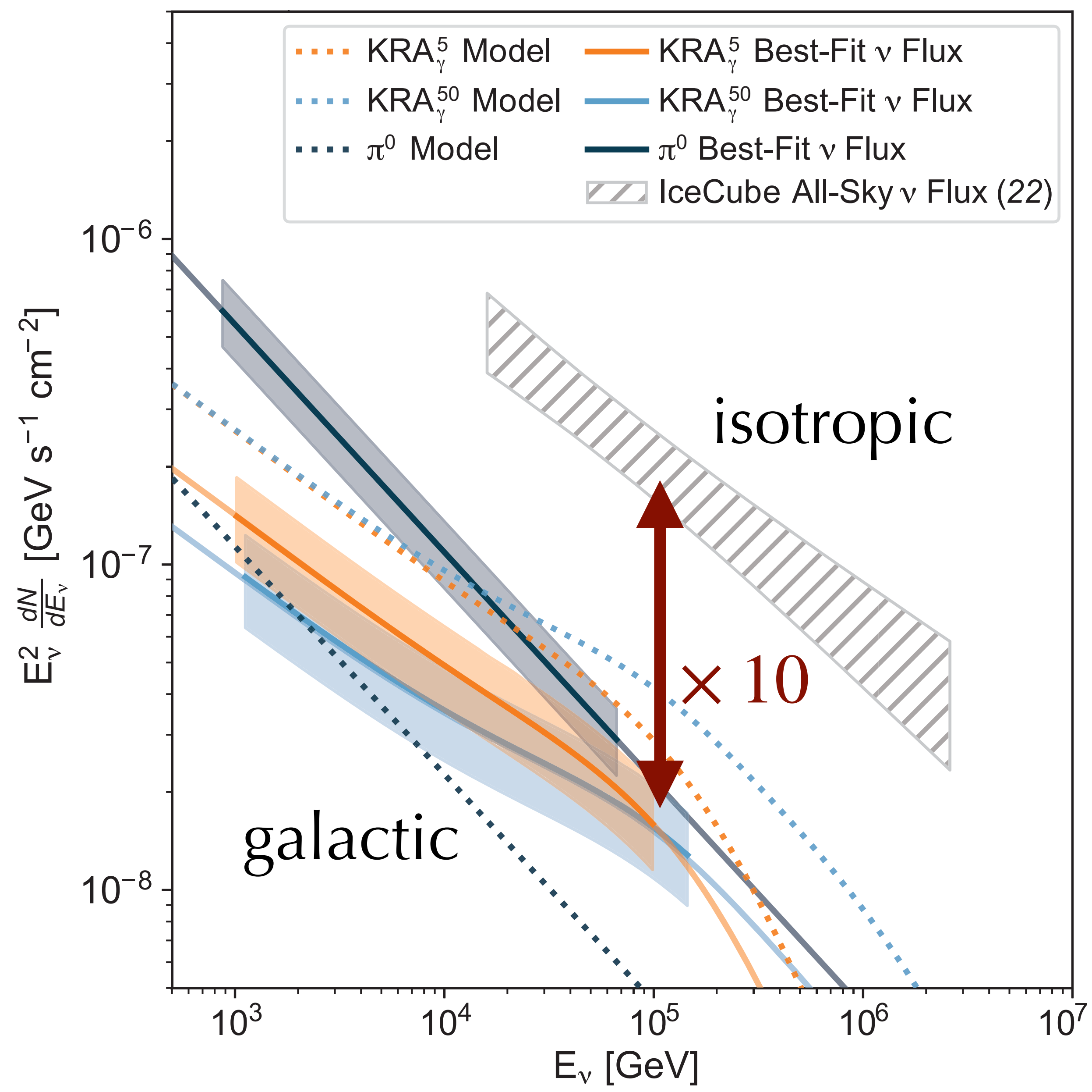
Galactic Neutrino Emission

Galactic diffuse ν emission at 4.5σ based on template analysis.

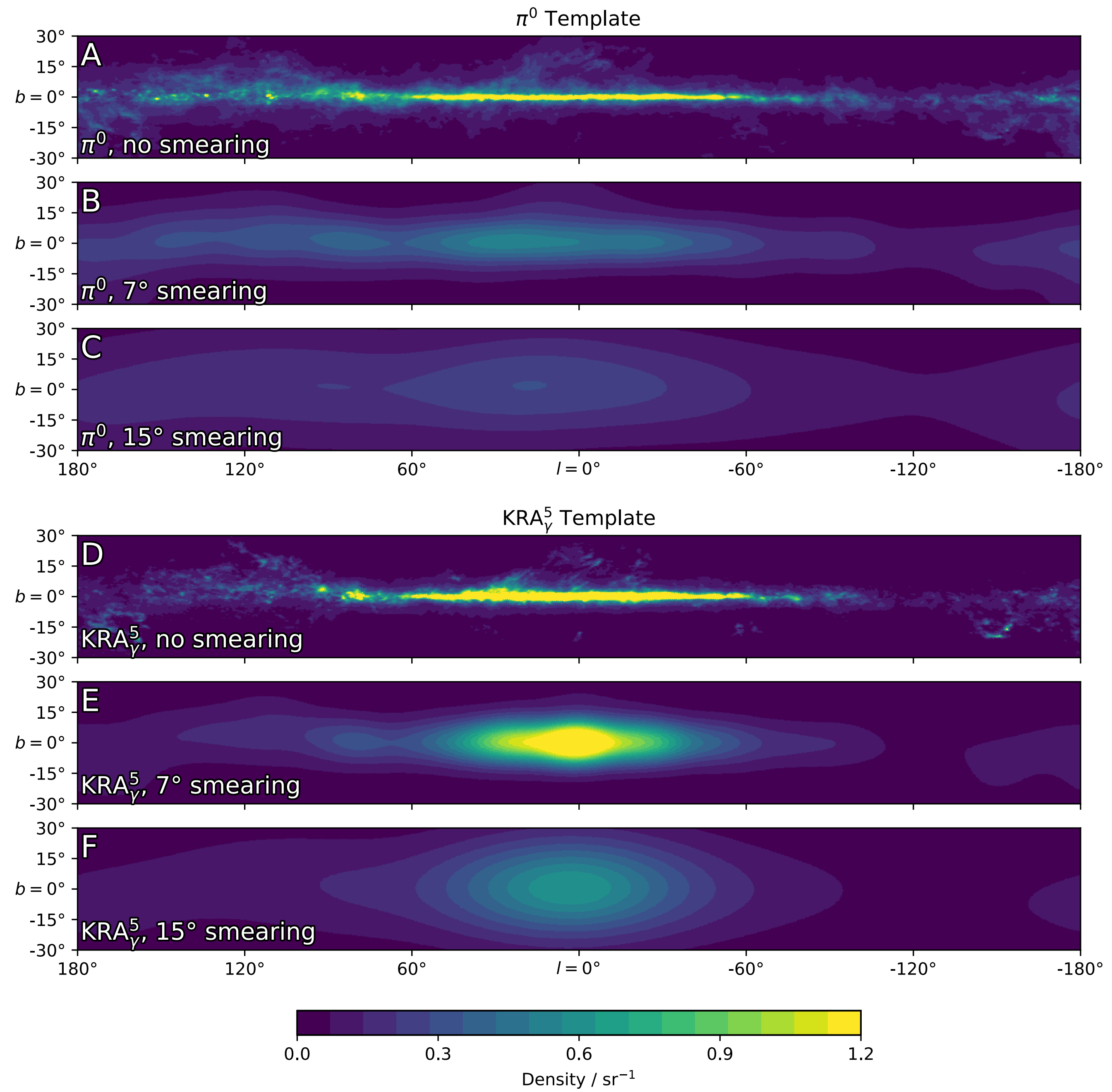


[IceCube **Science** 380 (2023)]

Best-fit normalization of spectra



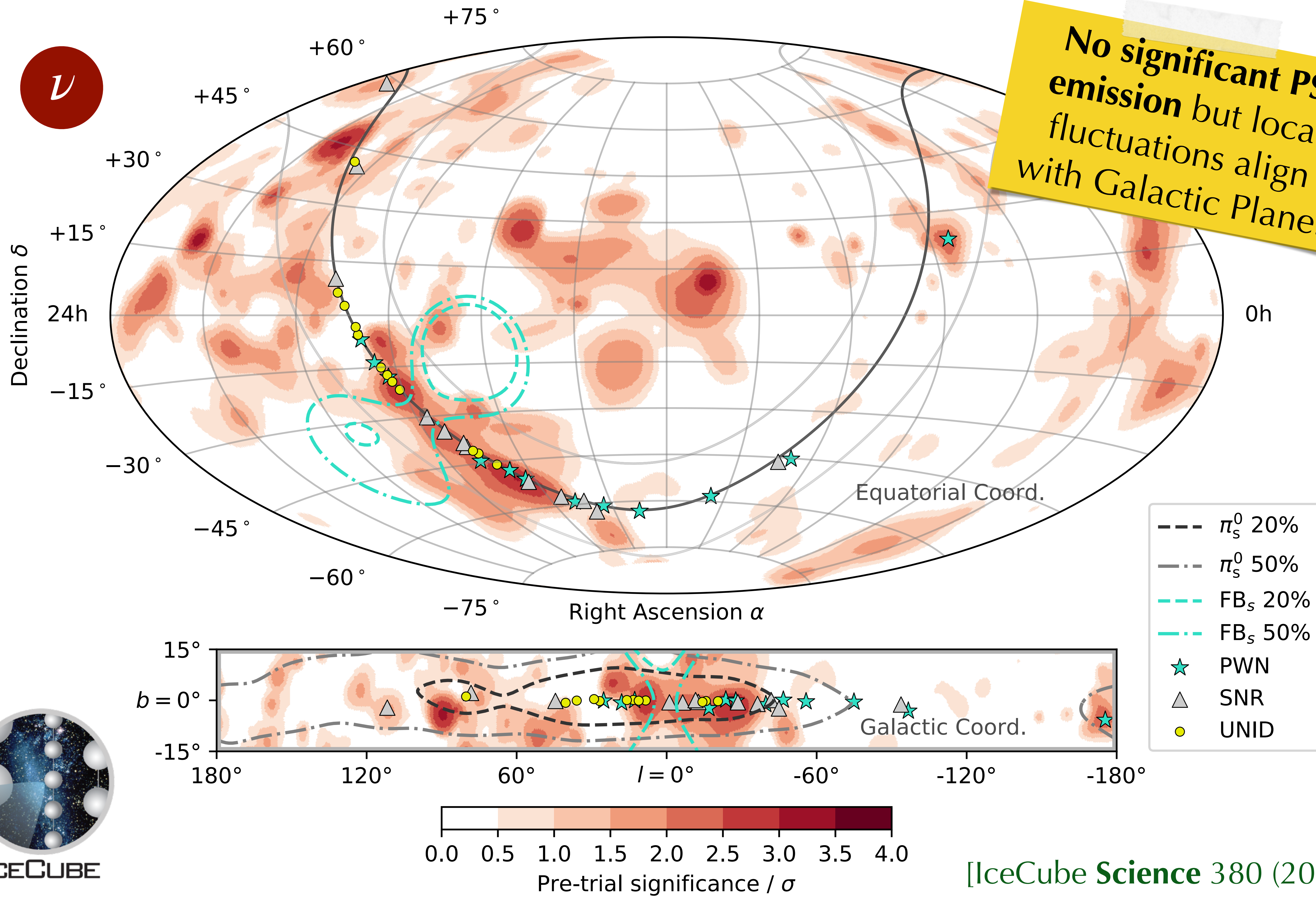
Templates with different resolution



[IceCube **Science** 380 (2023)] [**templates**: Fermi'12; Gaggero, Grasso, Marinelli, Urbano & Valli '15]

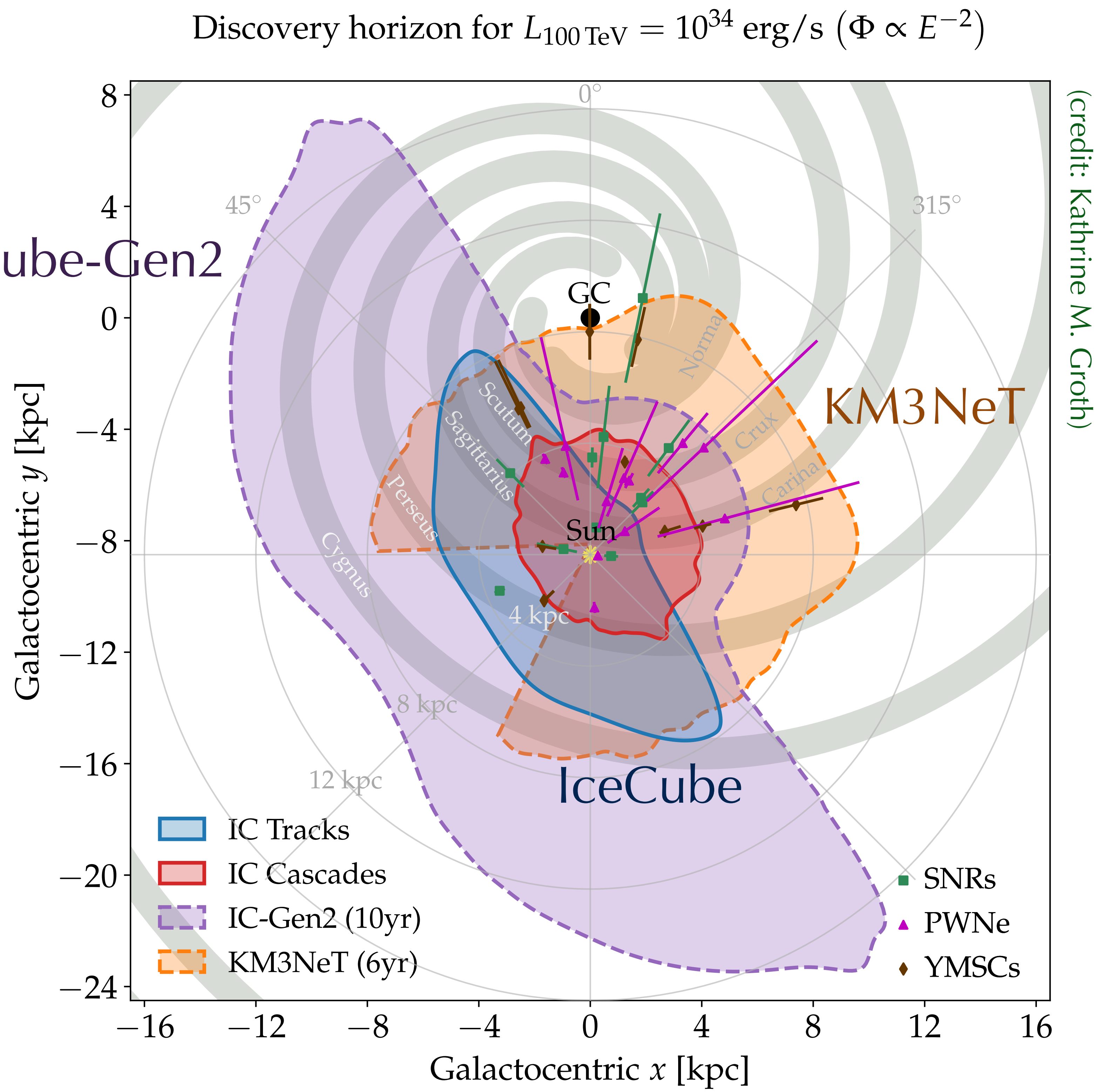
Point-Source Significance Map

No significant PS emission but local fluctuations align with Galactic Plane.



[IceCube **Science** 380 (2023)]

Point-Source Discovery Horizon



[Ambrosone, Groth, Peretti & MA'23]

Point Source vs. Quasi-Diffuse Flux

Populations of galactic neutrino sources visible as

individual sources

and by the

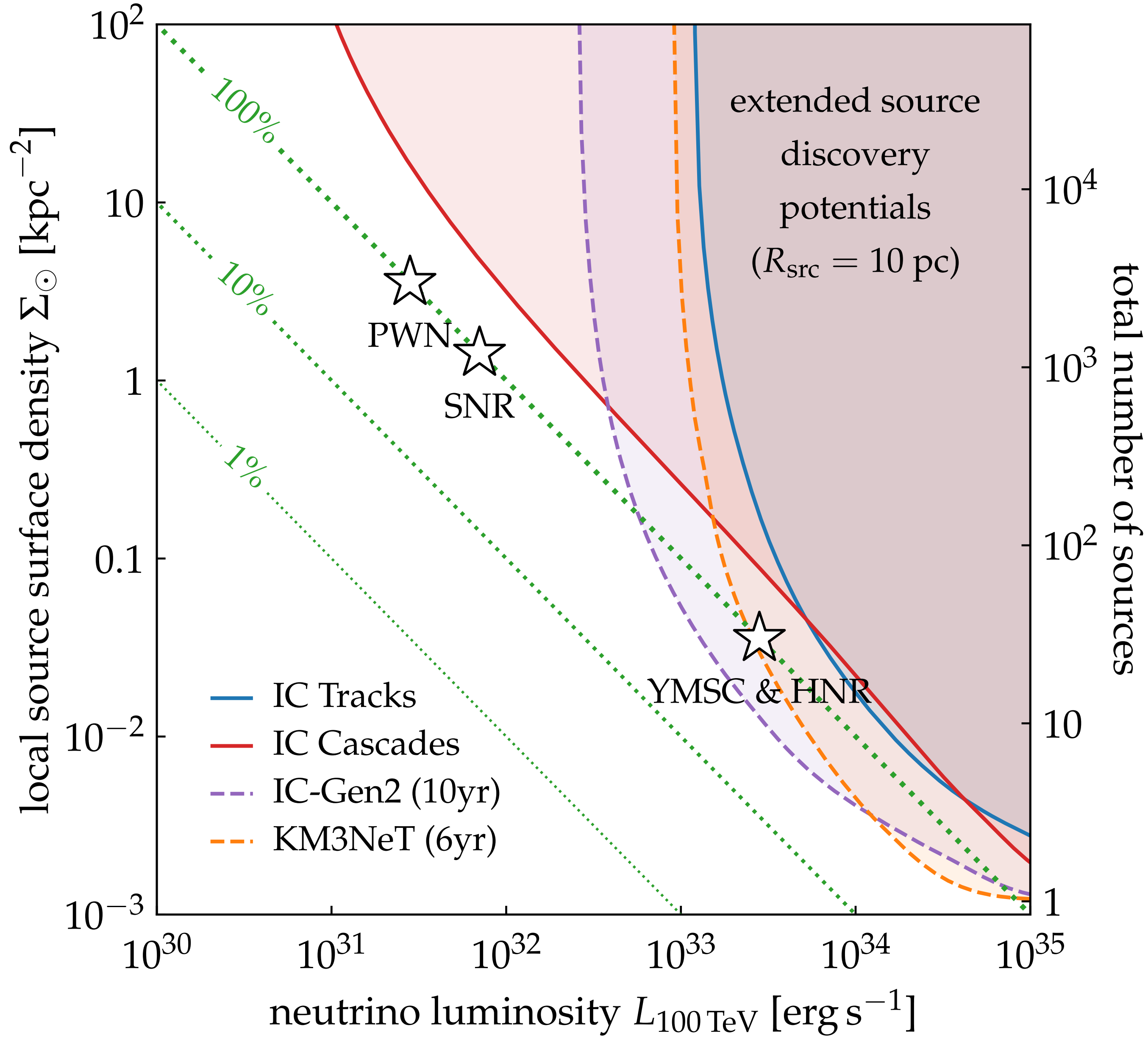
combined isotropic emission.

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

source surface density $\Sigma_\odot$

and

source luminosity $L_{100\mathrm{TeV}}$

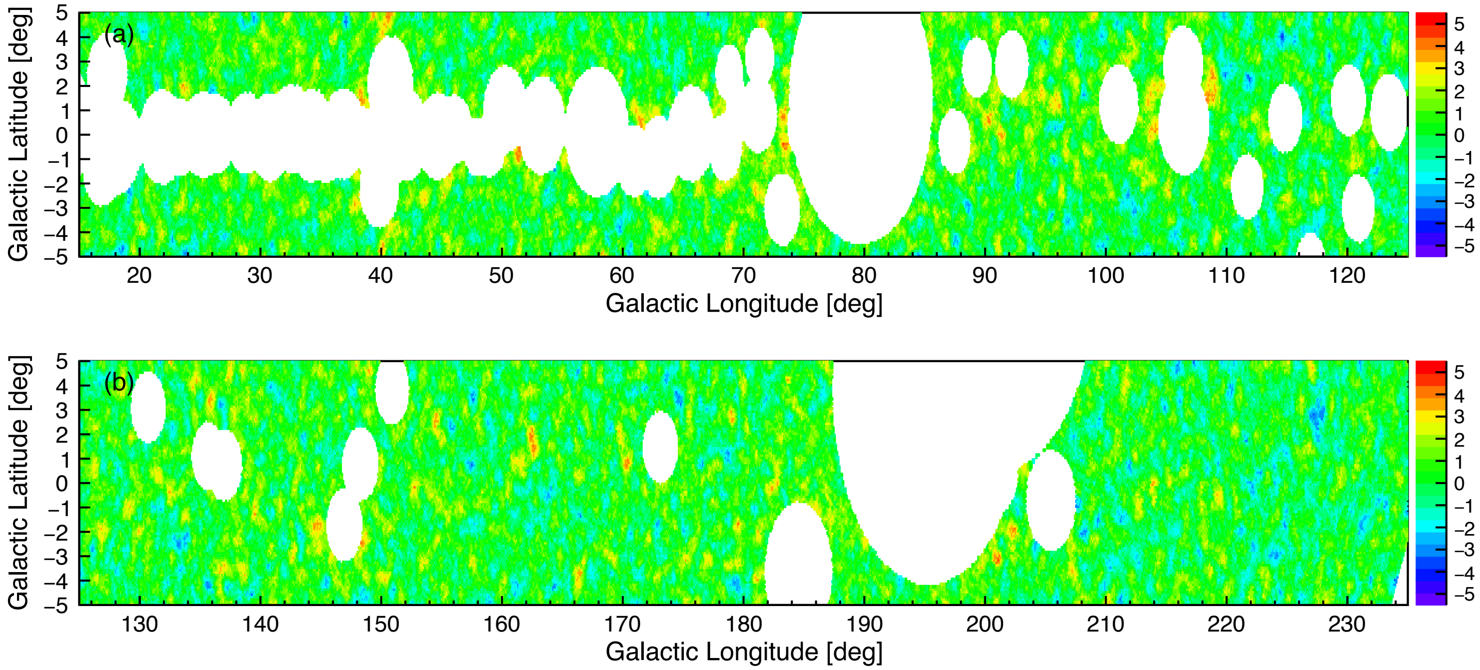


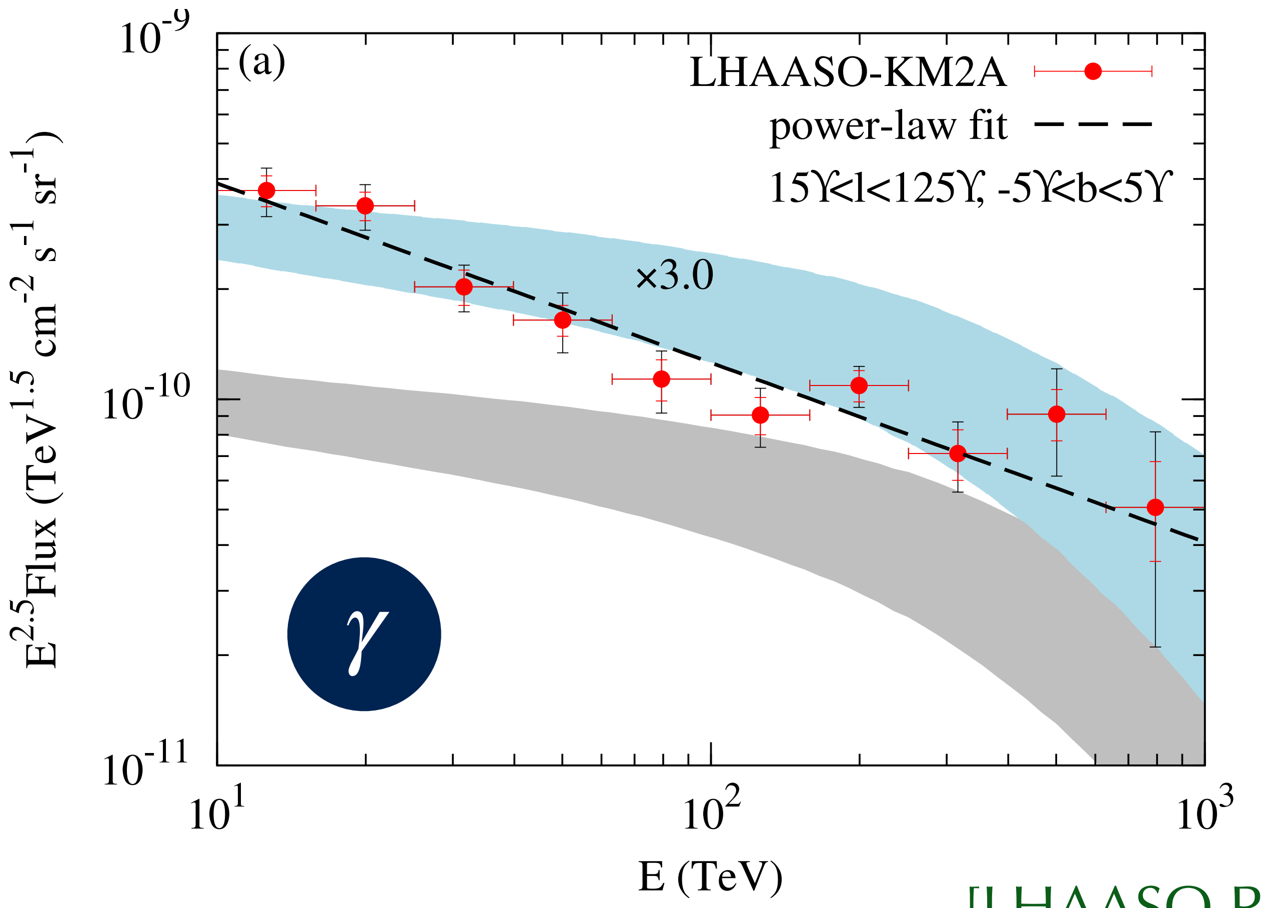
[Ambrosone, Groth, Peretti & MA'23]

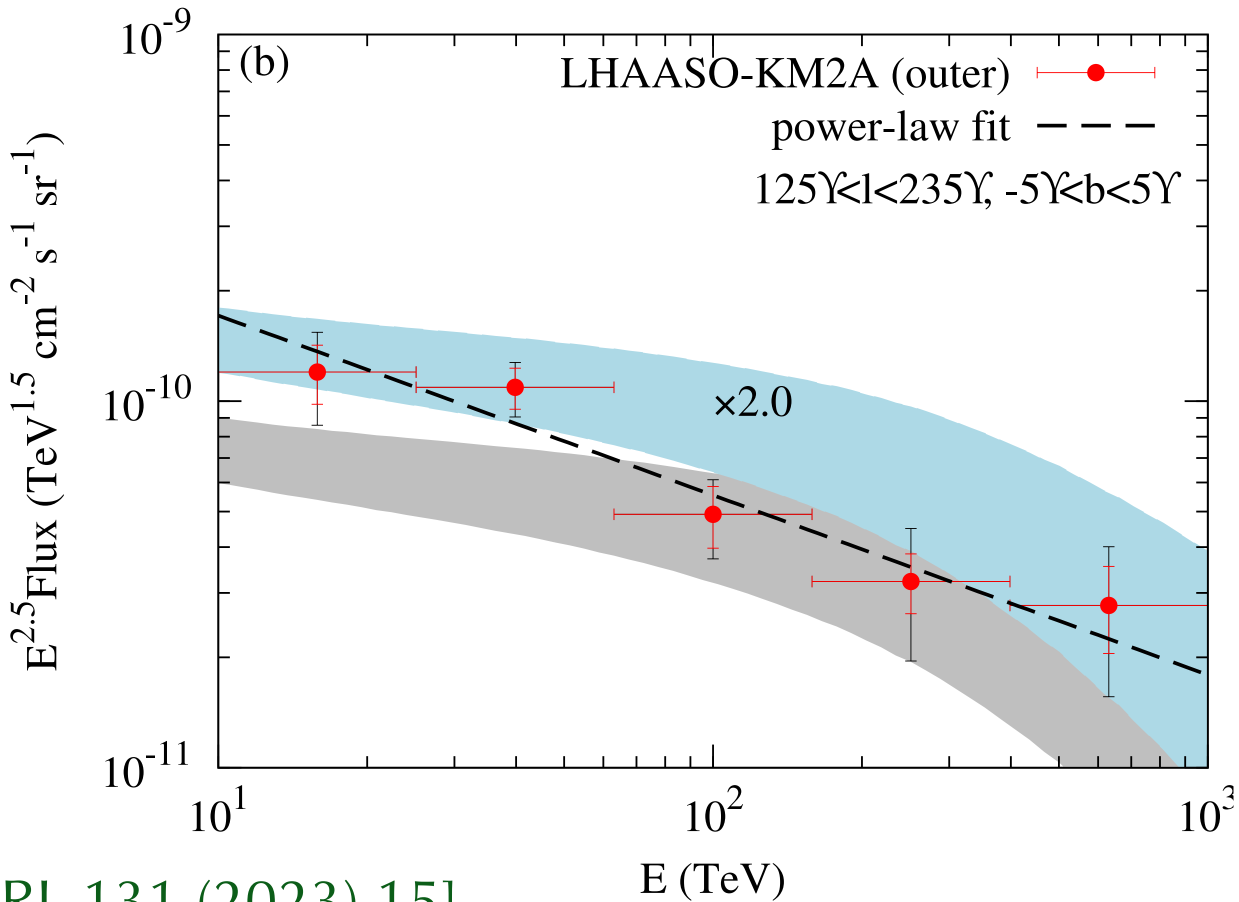
LHAASO Diffuse Emission

LHAASO observes **enhanced 0.1-1 PeV diffuse γ-ray emission** along Galactic Plane.

[LHAASO PRL 131 (2023) 15]



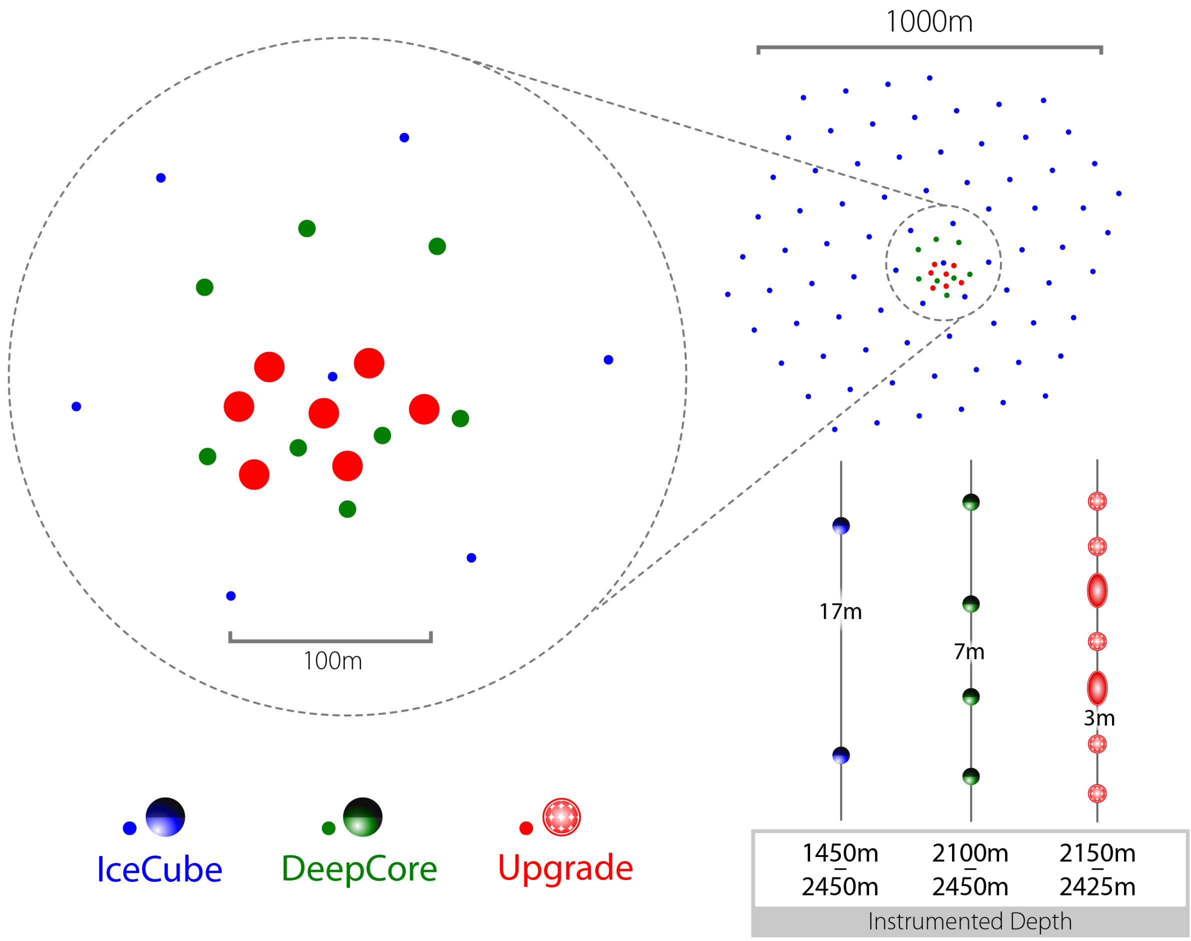


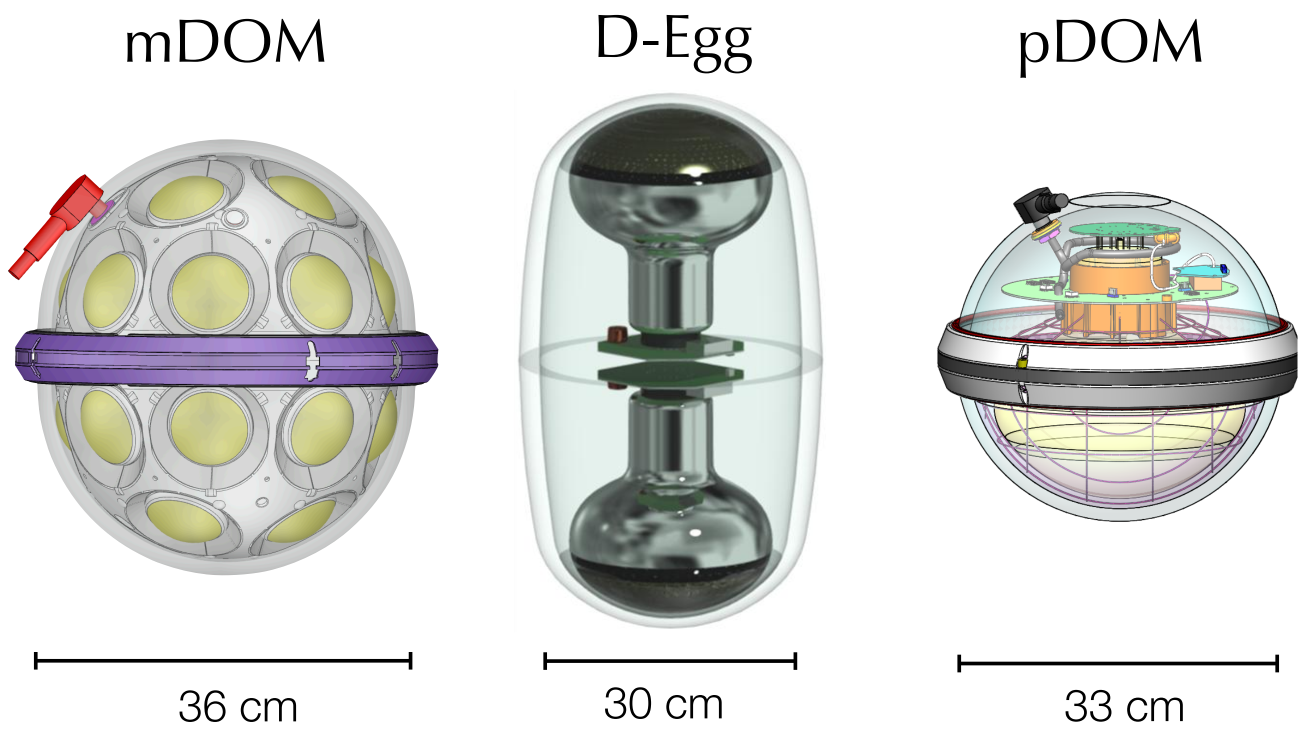


[LHAASO PRL 131 (2023) 15]

Outlook: IceCube Upgrade

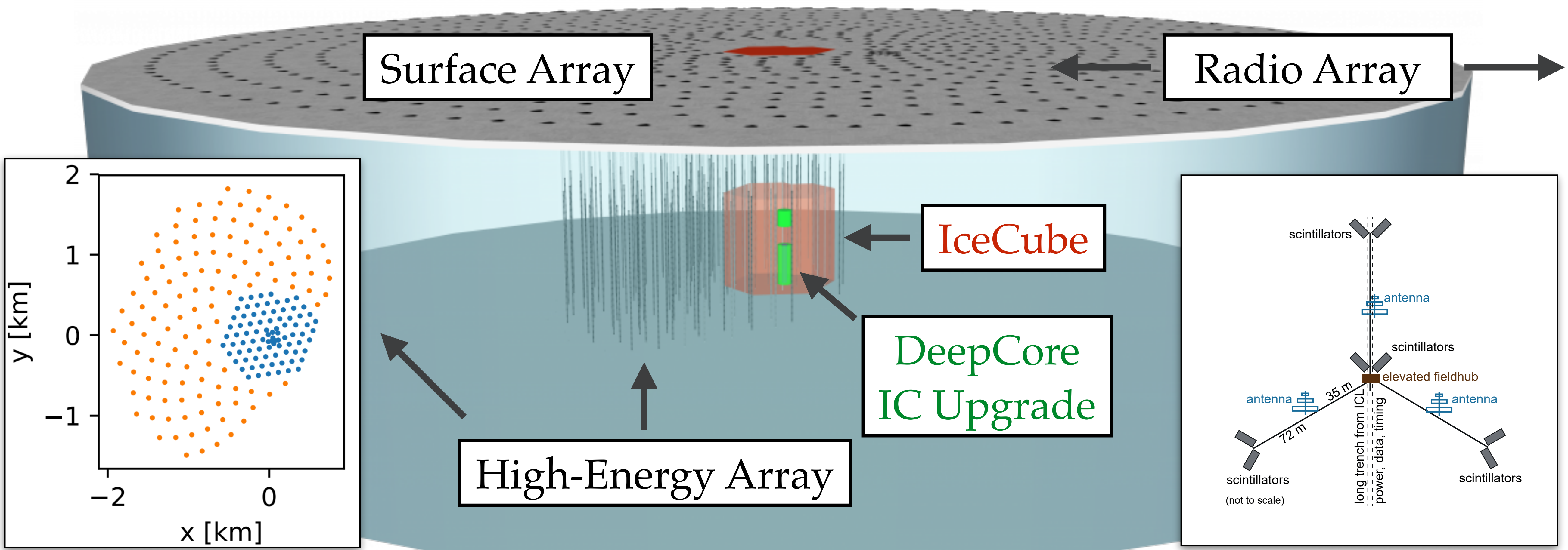
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Aim: deployment in 2025/26**





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

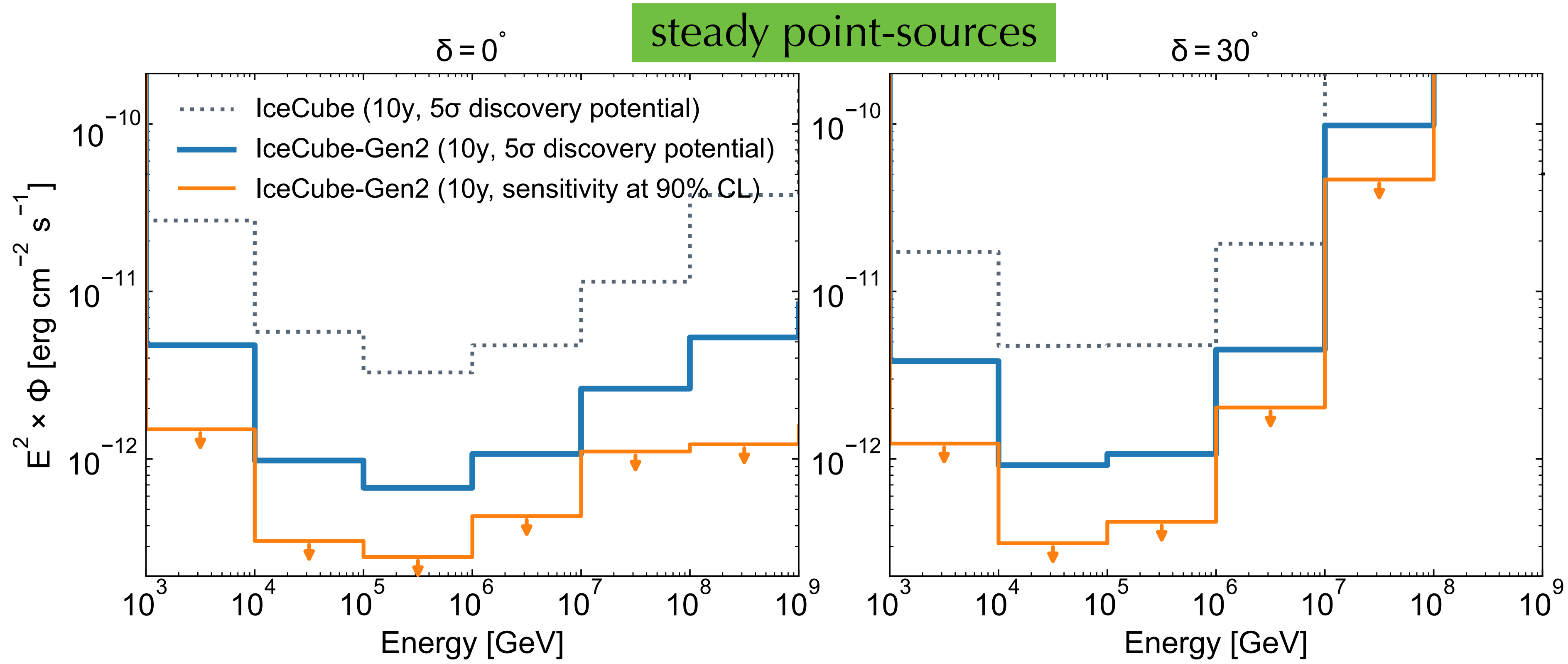
[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Vision: IceCube-Gen2

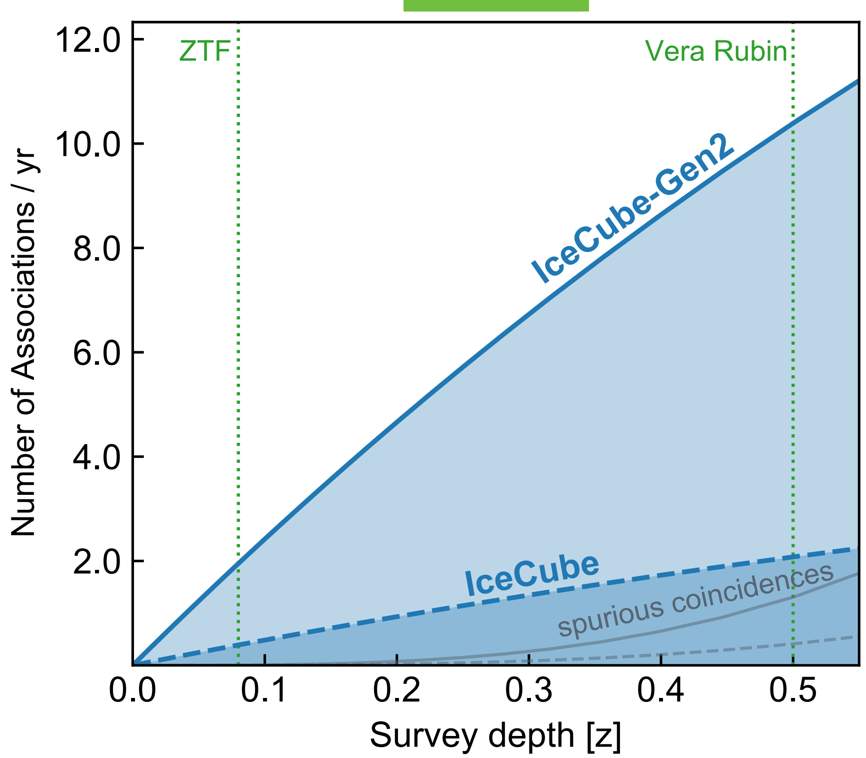
Discovery potentials of IceCube vs. IceCube-Gen2

[IceCube-Gen2 TDR]

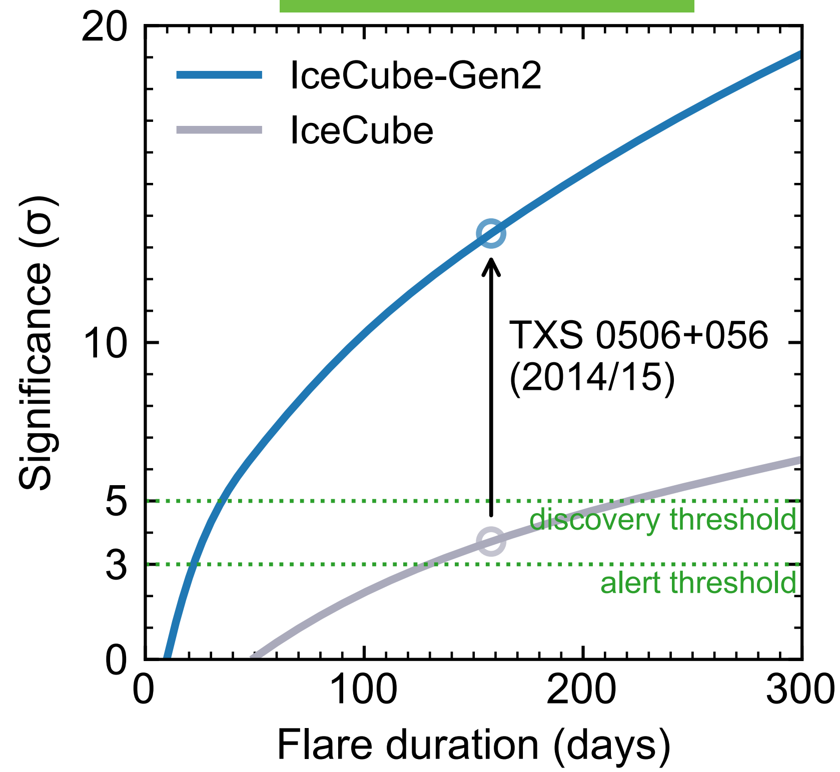
steady point-sources



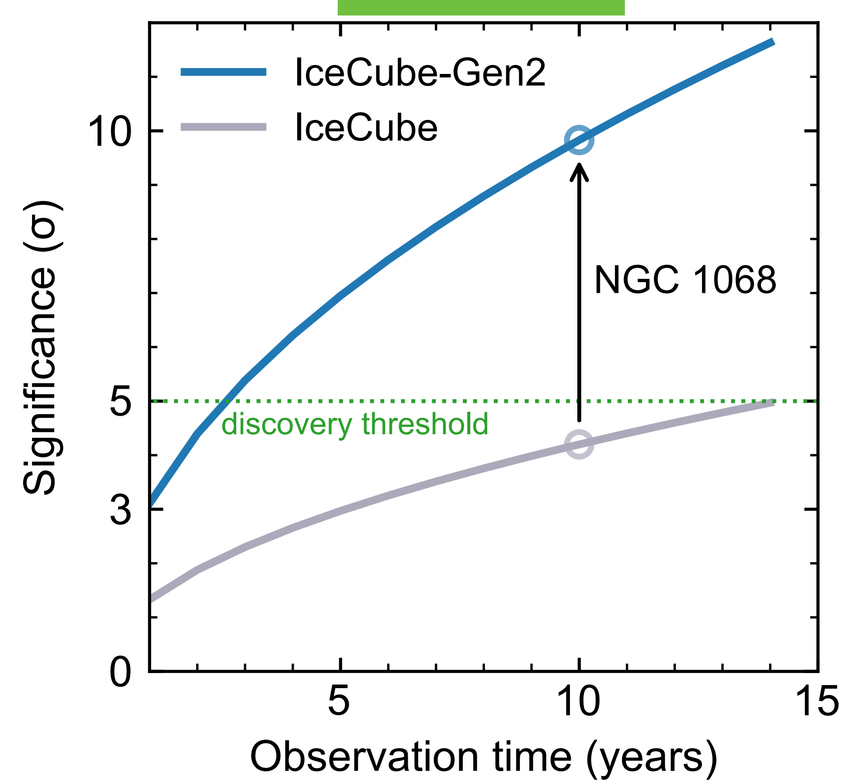
TDEs



TXS 0506+056



NGC 1068



Summary

- **Multi-messenger astronomy** offers a fresh look onto the Universe.
- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy neutrinos** in 2013.
- So far, **no (5σ) discovery** of point sources, but some **strong candidates**, in particular, **TXS 0506+056** (2017) and **NGC 1068** (2022).
- First **γ-ray burst GRB 170817A** (2017) observed in **gravitational waves**.
- Recent observation (4.5σ significance) of neutrino emission of the **Galactic Plane** (2023), consistent with models of **Galactic diffuse emission** from cosmic ray interactions in the interstellar medium.
- The **new/next generation of neutrino** (KM3NeT, Baikal-GVD, IceCube-Gen2), **γ-ray** (LHAASO, CTA, SWGO) and **GW observatories** (ET, CE, LISA) will usher in the area of high-energy multi-messenger astronomy.