Neutrino Astrophysics II

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14th International Neutrino Summer School, August 7-18, 2023

The Cosmos in Neutrinos
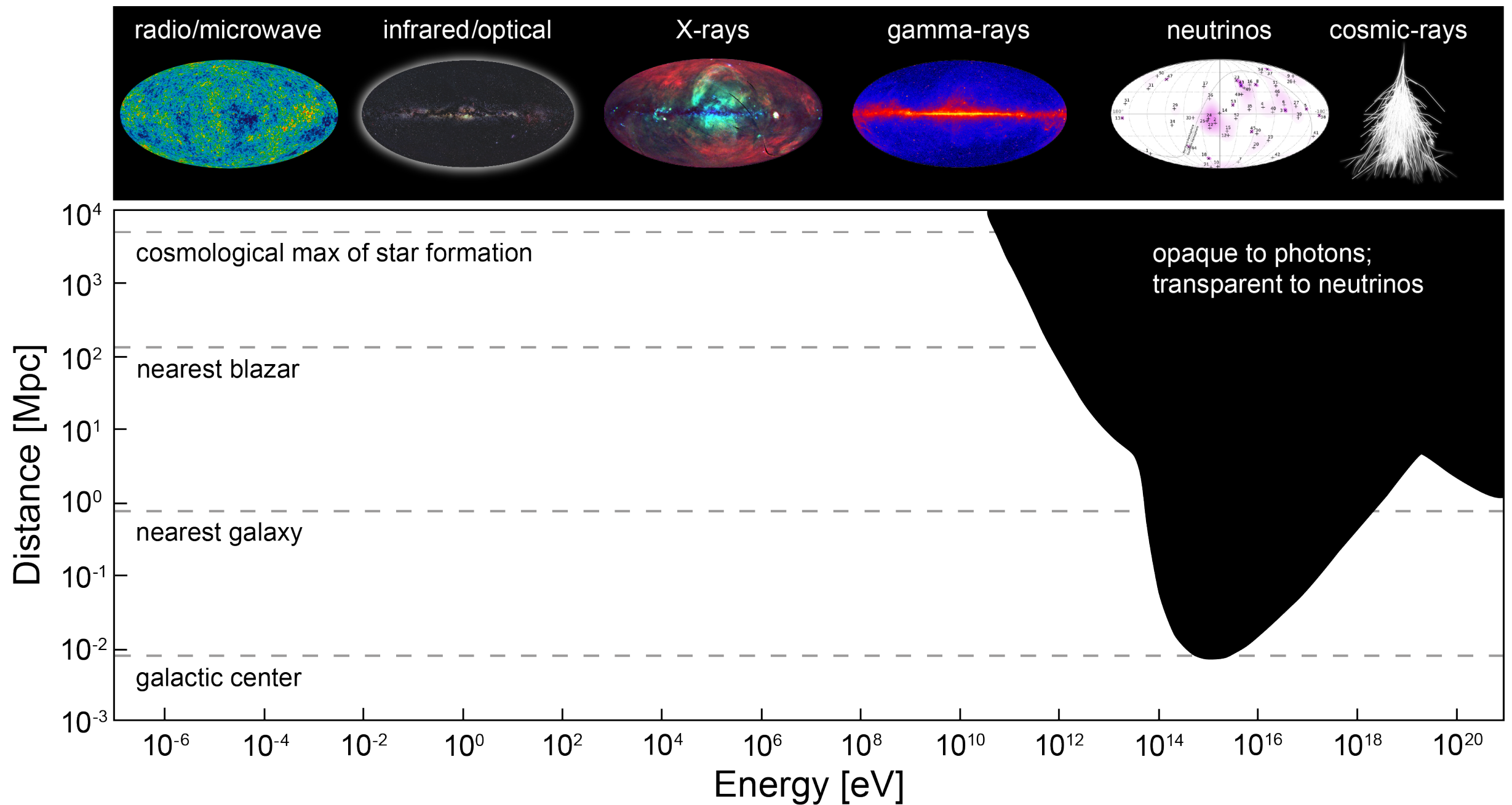
Grand Unified Neutrino Spectrum
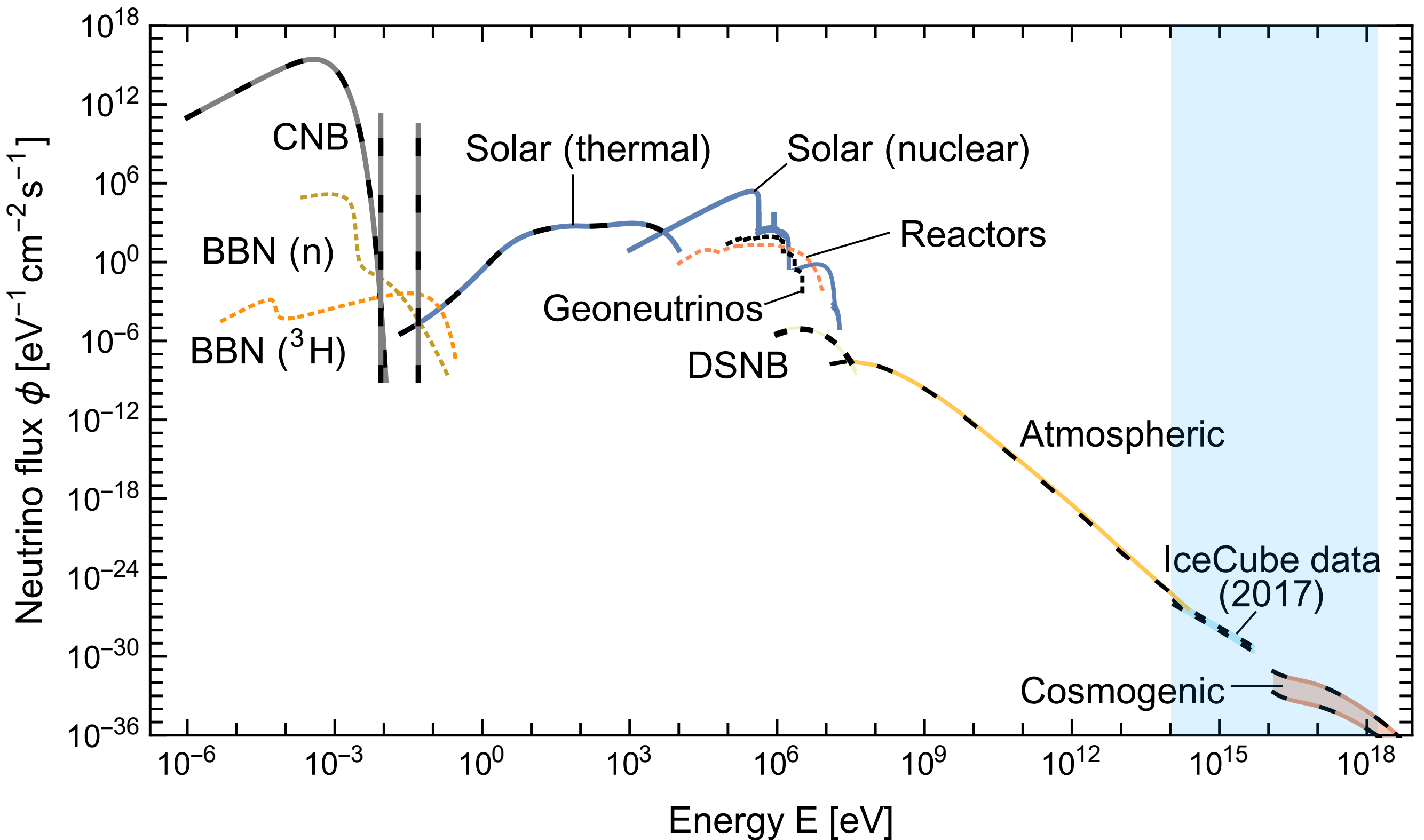
Lecture 2:
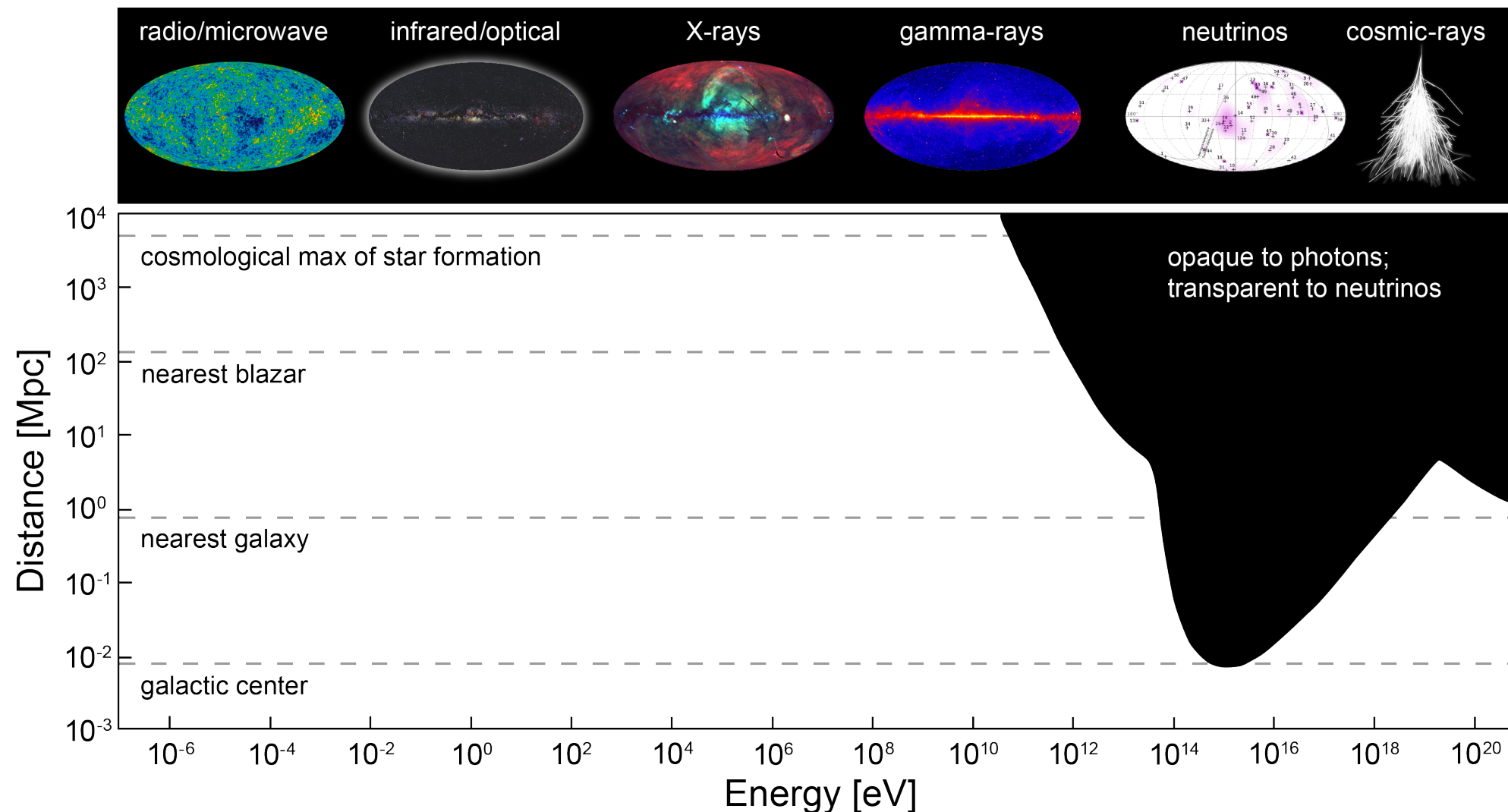# Neutrinos from Cosmic Accelerators

Intended Learning Objectives

- Particle production and acceleration in cosmic accelerators

- Cosmic ray, gamma-ray and neutrino connections

- Sources

High Energy Neutrino Astronomy

Neutrinos

Image labels (left to right): radio/microwave, infrared/optical, X-rays, gamma-rays, neutrinos, cosmic-rays

Plot — Distance [Mpc] vs Energy [eV]:
- cosmological max of star formation
- nearest blazar
- nearest galaxy
- galactic center
- opaque to photons; transparent to neutrinos

Neutrinos

- Neutrinos are neutral, point back to the source.
- Neutrinos come in three flavors.
- Neutrinos do not interact with medium particles; ideal messengers.
- Sensitive to distant (far away) sources.
- Probe electromagnetically opaque sources.
- Cross sections are very small. Neutrinos are hard to detect.
- Neutrinos cover spots of the very high-energy universe.

Cosmic Rays and Gamma-Rays

Cosmic rays

- Charged nuclei are deflected by magnetic fields.
- The directional information carried by cosmic rays is lost at low-medium energies.
- Cosmic rays preserve the directional information at the highest energies; bending radius is large against propagation distance ($R = \dfrac{pc}{Ze} = B \times r_L$).

Anchordoqui, Phys. Rep. 801 (2019) 1-93, arXiv: 1807.09645.
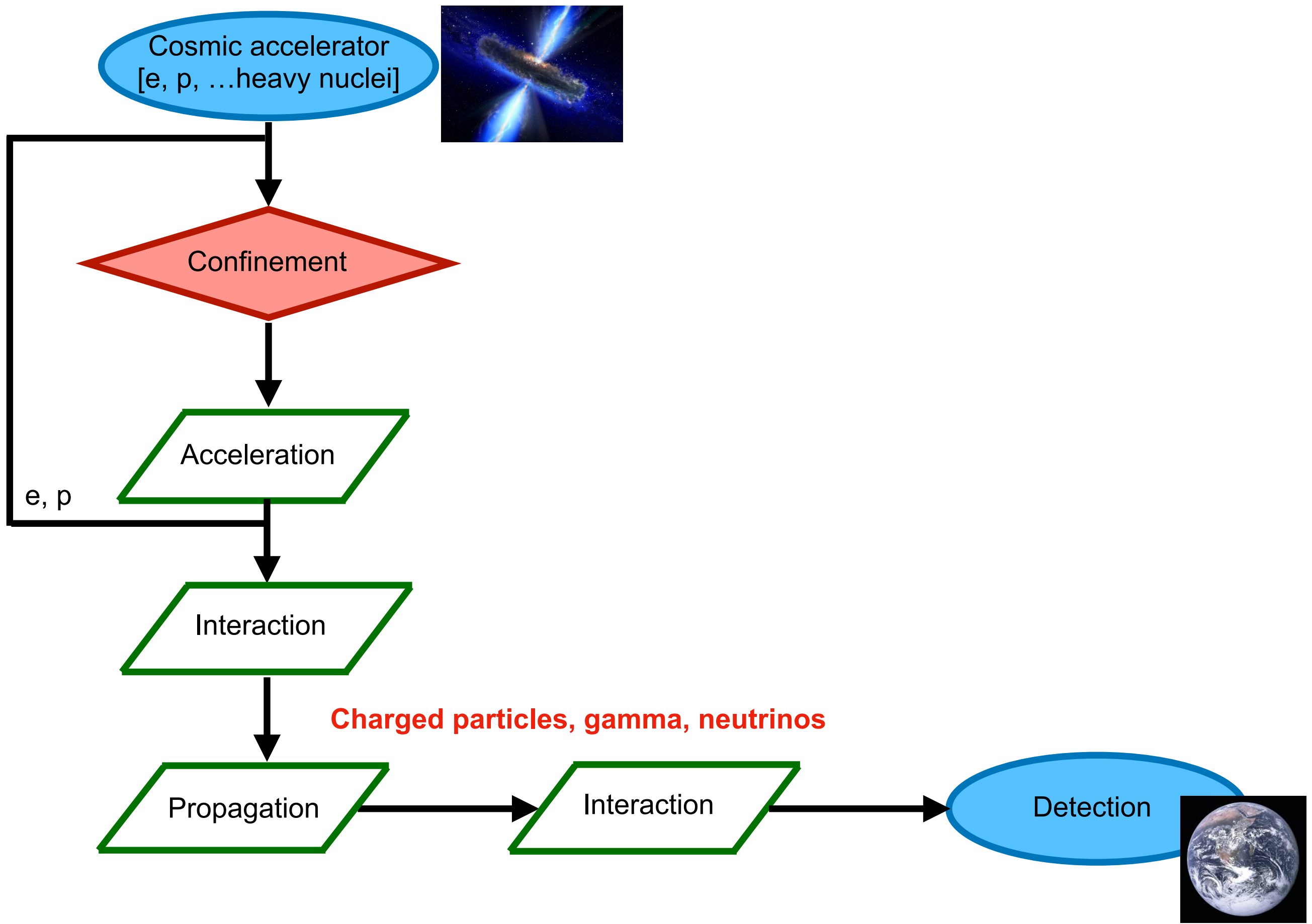
Photons

- Photons are neutral, point back to the source.
- Interact with charged particles via inverse Compton, annihilation to electron positron pairs.
- The observable distance in photons is limited.

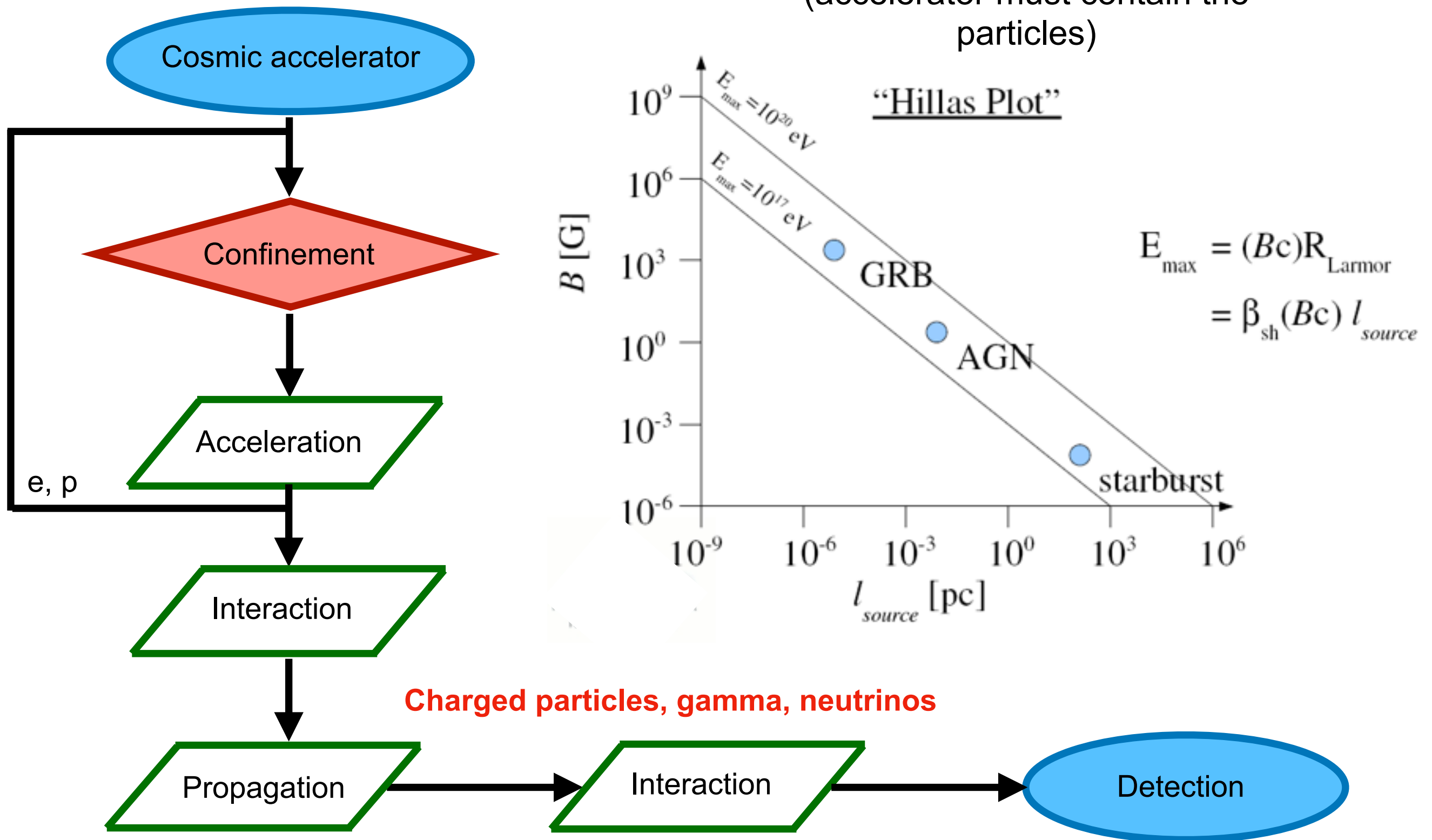Hinton and Hofmann, Ann. Rev. Astron. Astrophys. 47 (2009) 523-565, arXiv: 1006.5210.

Particle Production
in Cosmic Accelerators
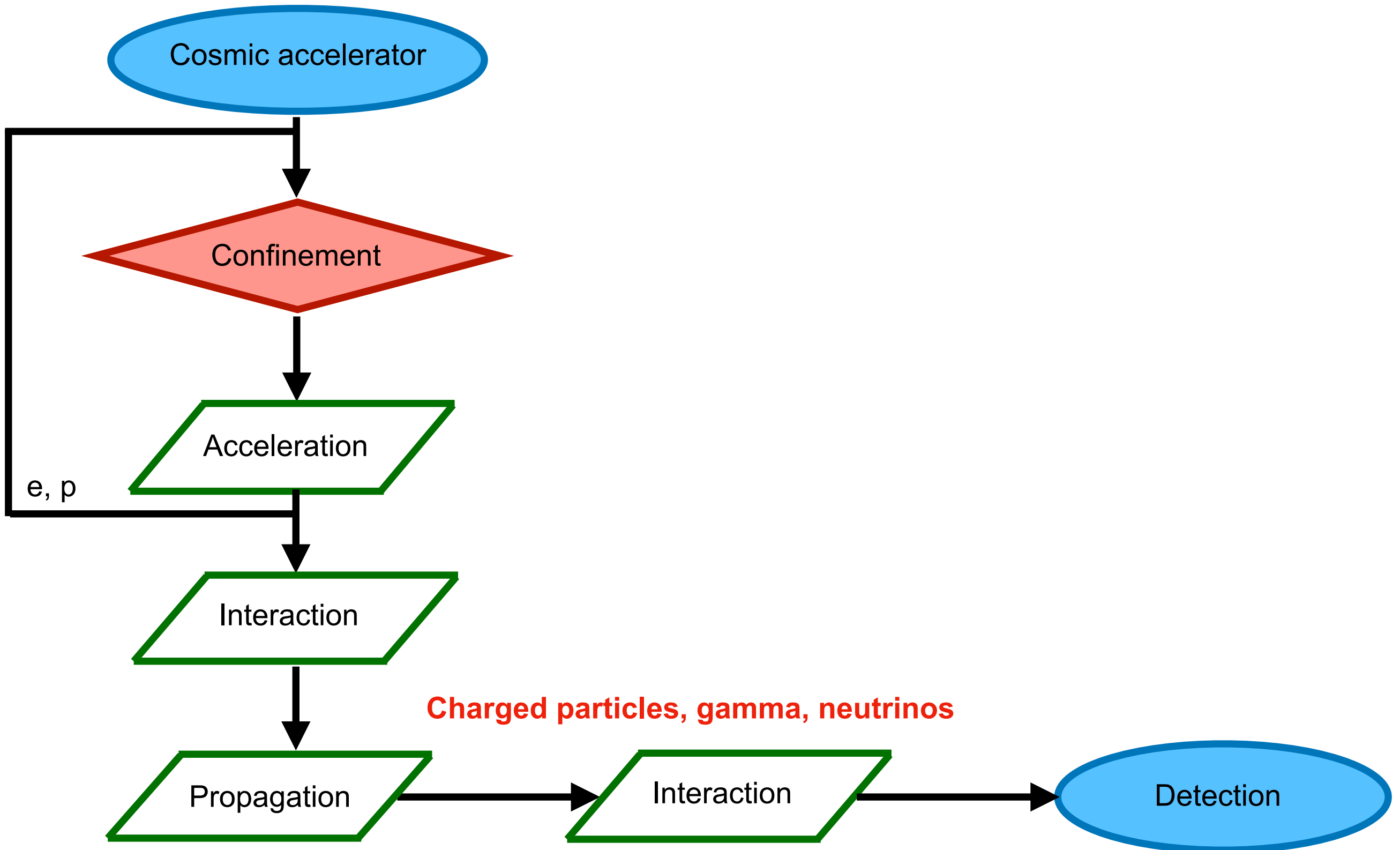
Particle Production and Acceleration

Confinement

Magnetic field vs. accelerator size
(accelerator must contain the particles)

Cosmic accelerator

Confinement

Acceleration

e, p

Interaction

Propagation

Charged particles, gamma, neutrinos

Interaction

Detection

"Hillas Plot"

$$E_{max} = (Bc)R_{Larmor}$$
$$= \beta_{sh}(Bc)\, l_{source}$$

GRB

AGN

starburst

$E_{max} = 10^{20}$ eV

$E_{max} = 10^{17}$ eV

B [G]

l_{source} [pc]

Hillas, Ann. Rev. Astron. Astrophys. 22 (1984) 425. Image credit: A. Taylor.
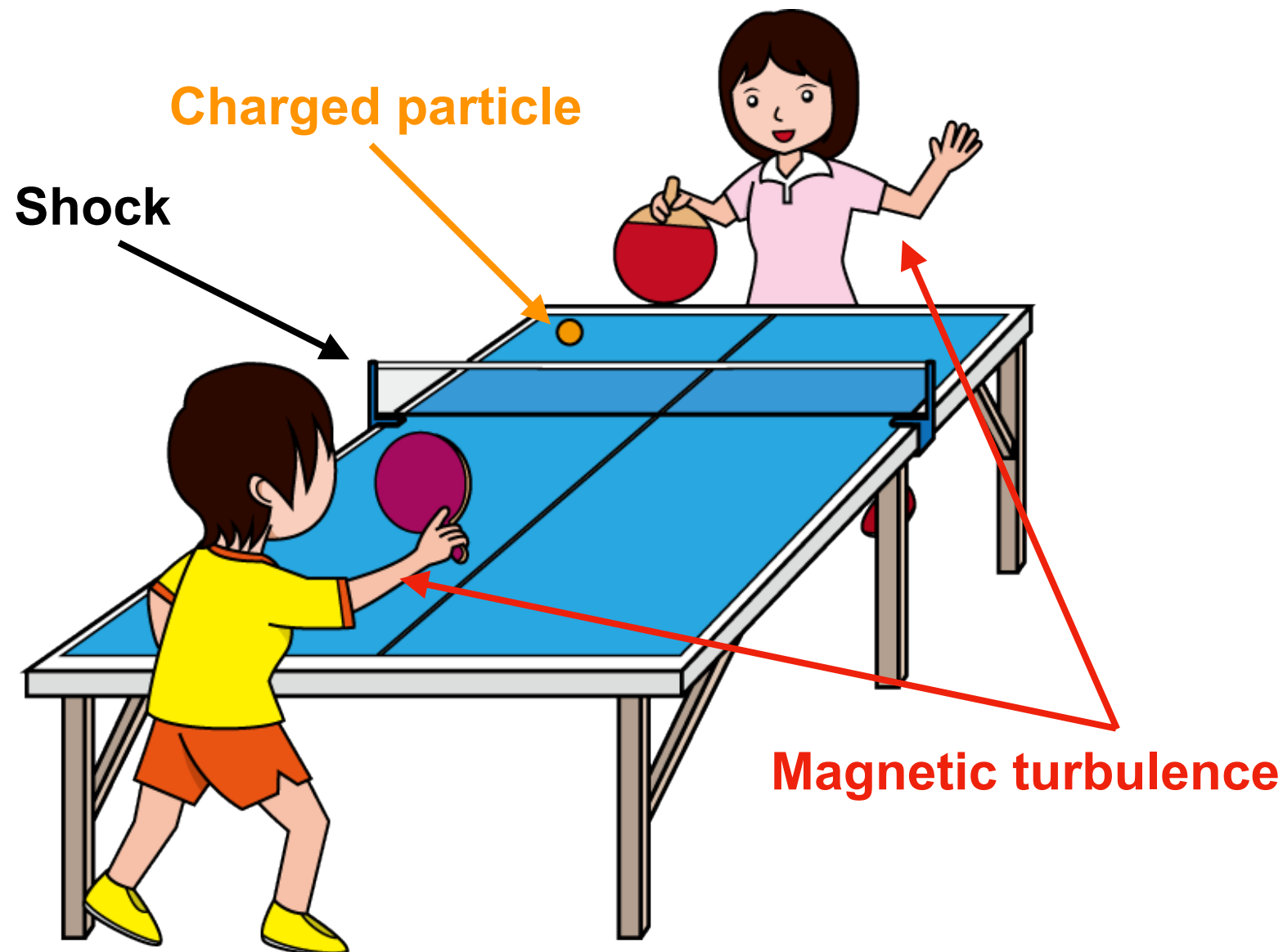
Acceleration

Diffusive Shock Acceleration

Diffusive shock acceleration (first order Fermi acceleration) leads to a power-law energy distribution.

Let us assume to have plasma on both sides of the shock and an isotropic distribution of charged particles (obtained via diffusion in the magnetic field).

Charged particles (or cosmic rays) cross the shock back and forth multiple times, each time gaining energy.
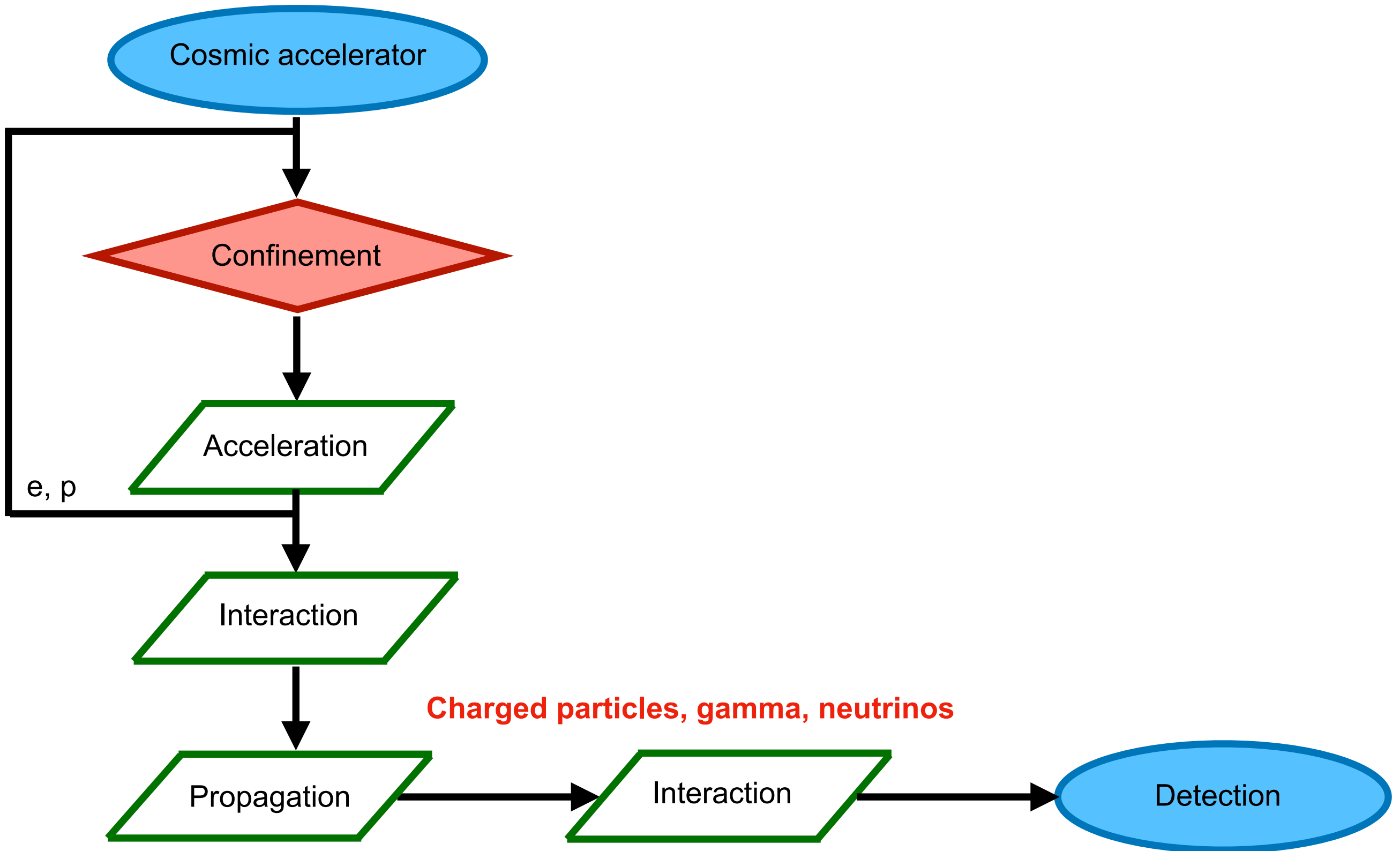
Power Law Energy Distribution

The energy distribution of particles in cosmic accelerators is a power-law
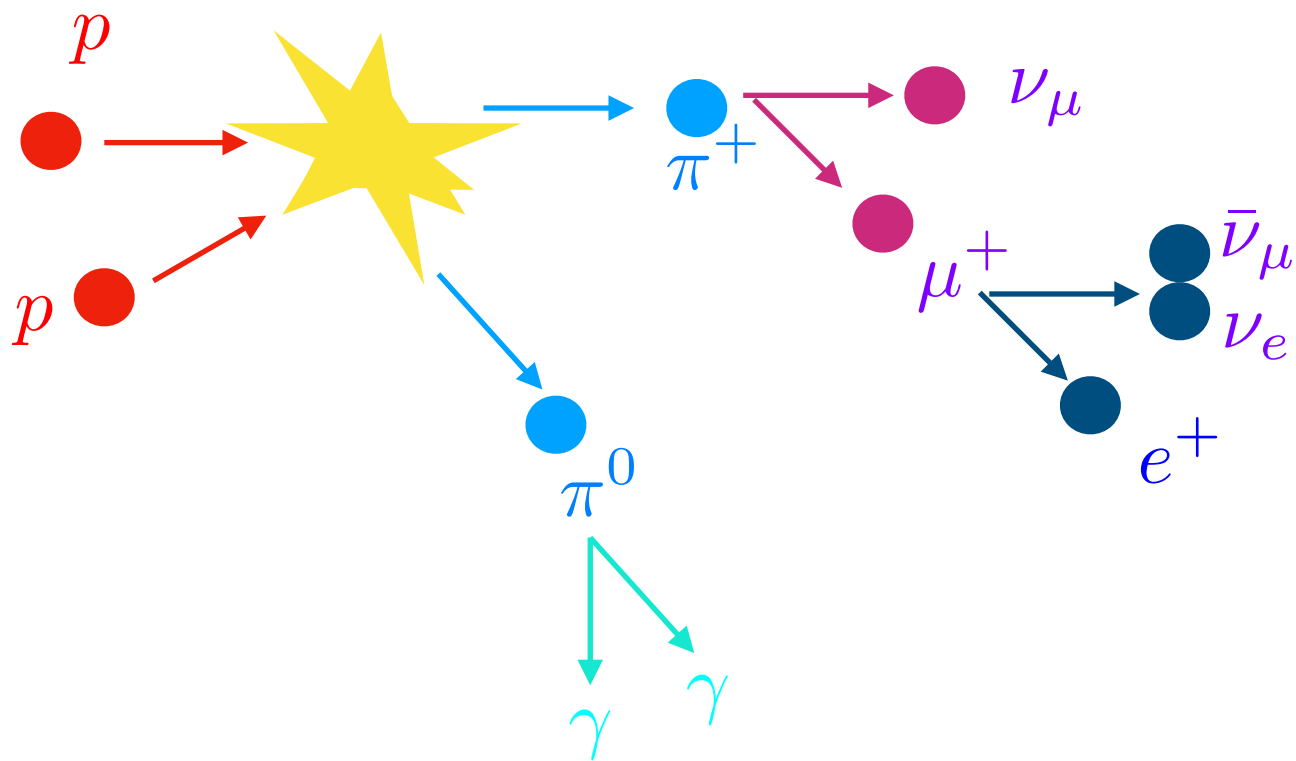
$$N(E) \propto E^{\alpha}$$

with α being a constant. This energy distribution is a non-thermal one and it differs from the Maxwellian distribution.
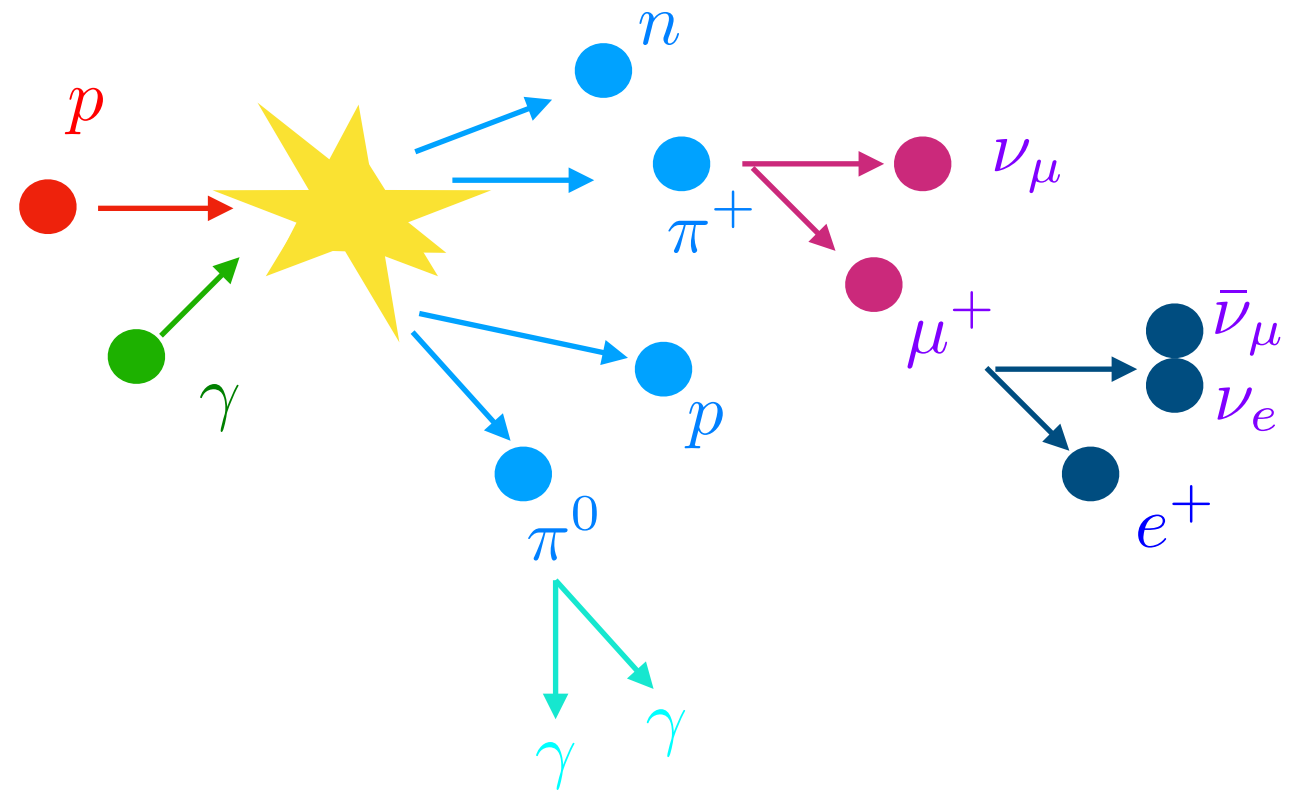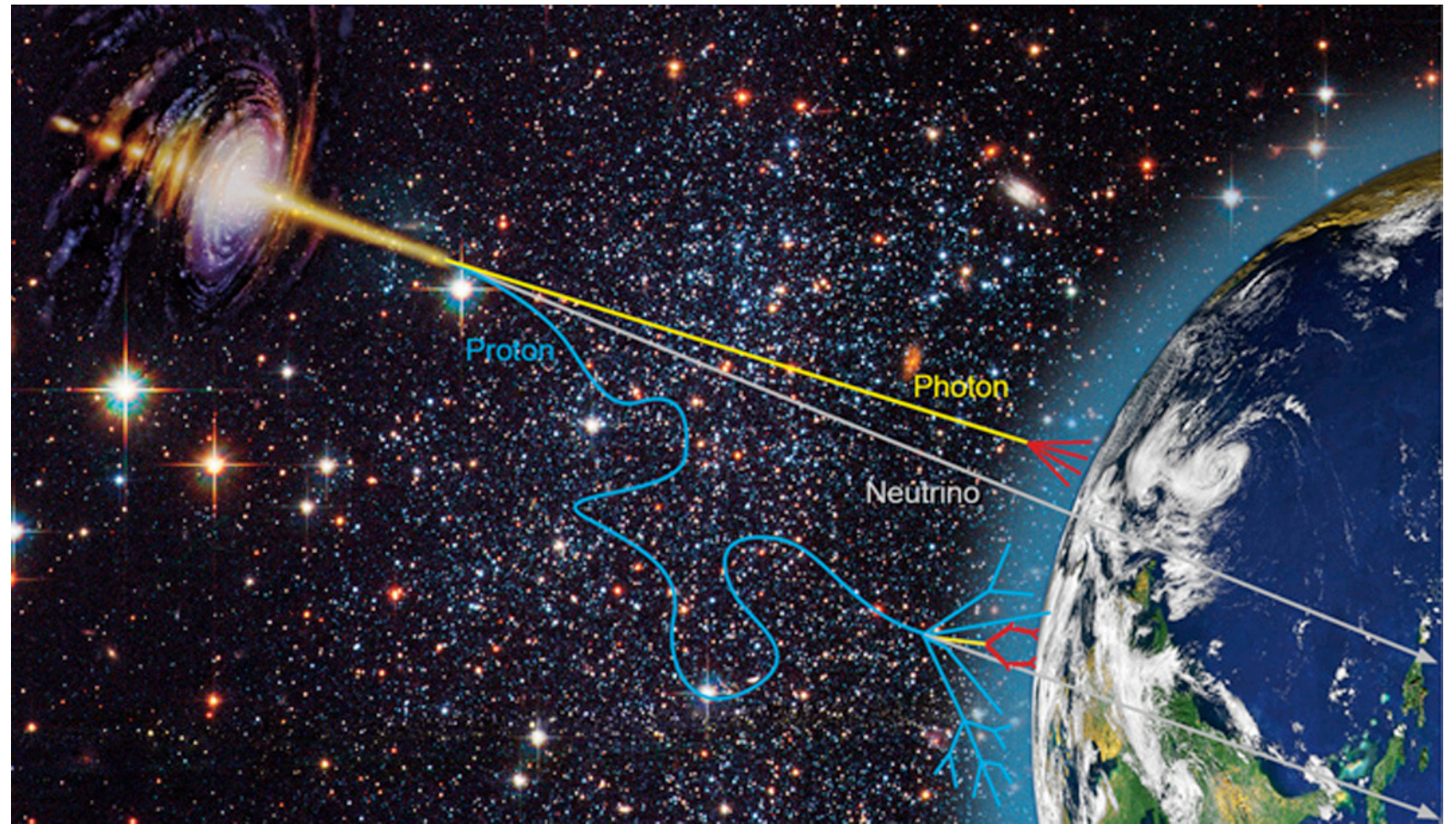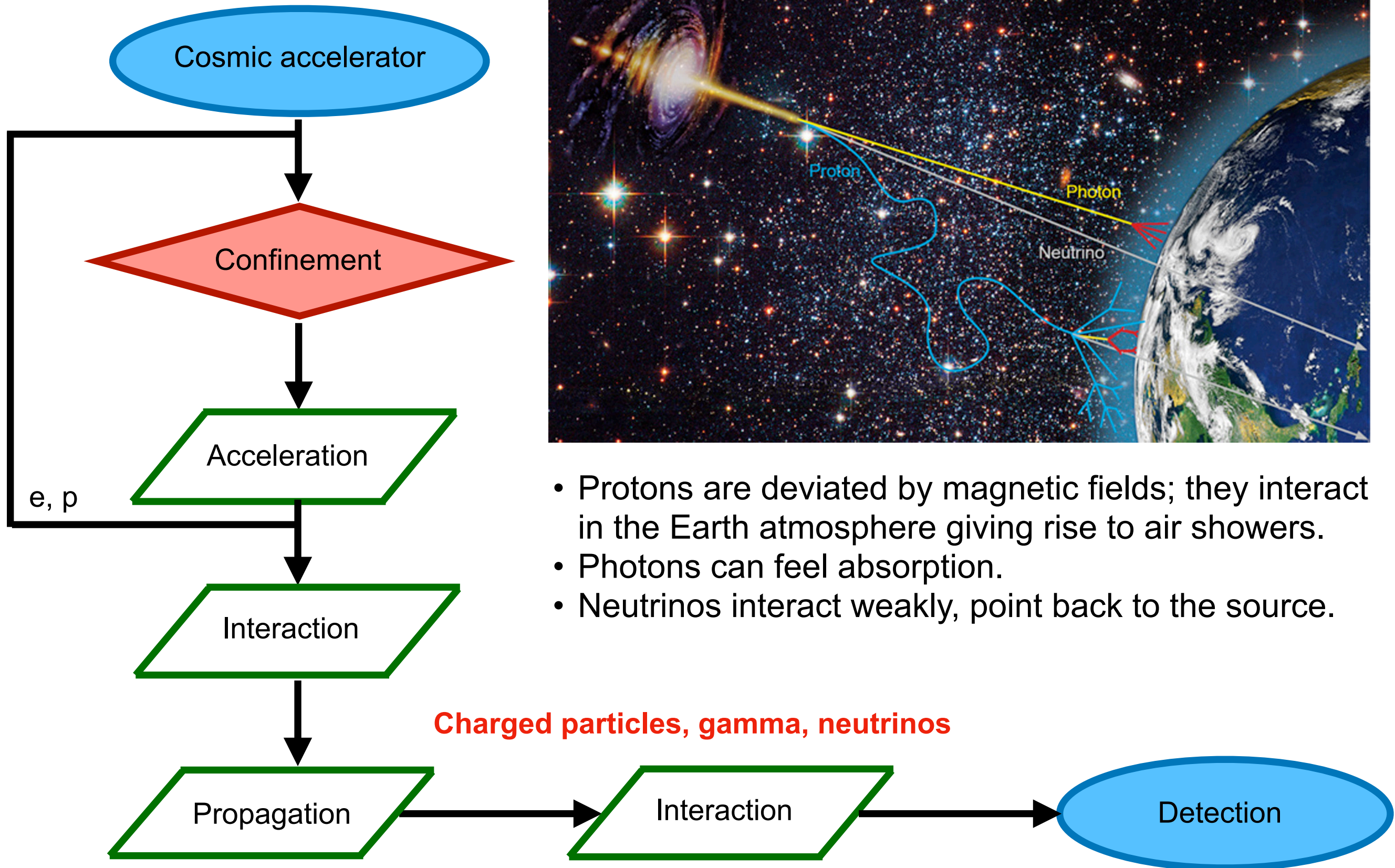
Interaction

Interaction

Electron and muon neutrinos are produced by charged pion decay.

Gamma-ray photons are produced by neutral pion decay.

Charged particles, gamma-rays, and neutrinos carry information about the source.

Propagation and Interaction


```
         ┌─────────────────────┐
         │  Cosmic accelerator │
         └─────────────────────┘
                    │
                    ▼
              ◇ Confinement ◇
                    │
                    ▼
           ╱ Acceleration ╱
  e, p              │
                    ▼
           ╱ Interaction ╱
                    │
                    ▼
        ╱ Propagation ╱ ──→ ╱ Interaction ╱ ──→ ( Detection )
```

- Protons are deviated by magnetic fields; they interact in the Earth atmosphere giving rise to air showers.
- Photons can feel absorption.
- Neutrinos interact weakly, point back to the source.

Charged particles, gamma, neutrinos

Propagation at Earth

The ratio of flavors at the source is expected to be $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Neutrinos **convert** into each other by flavor mixing. One can proof that

$$P(\nu_\mu \to \nu_\mu) = P(\nu_\tau \to \nu_\tau) = P(\nu_\mu \leftrightarrow \nu_\tau) = \frac{1}{8}\left[4 - \sin^2(2\theta_\odot)\right]$$

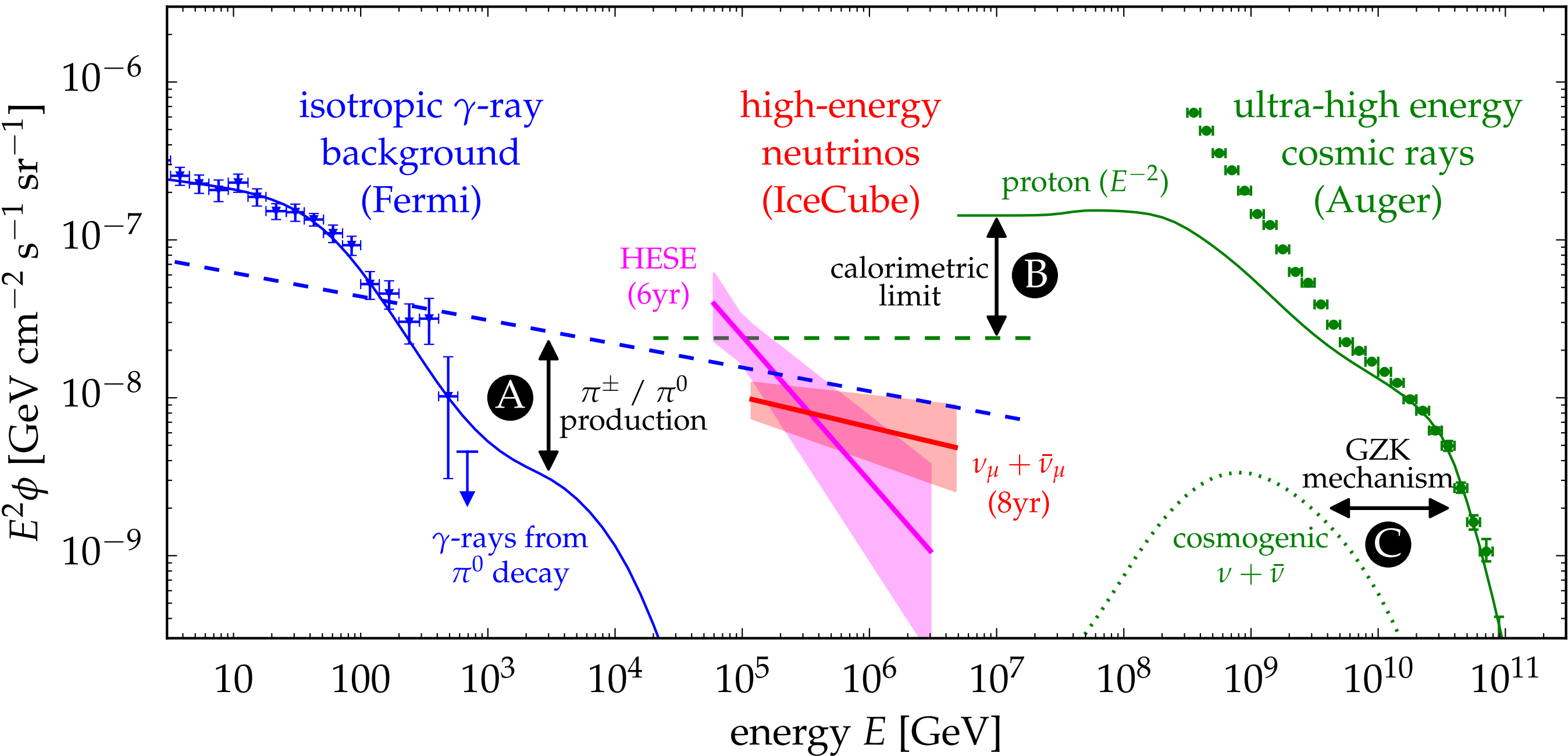$$P(\nu_\mu \leftrightarrow \nu_e) = P(\nu_e \leftrightarrow \nu_\tau) = \frac{1}{4}\sin^2(2\theta_\odot) \ ,$$

and

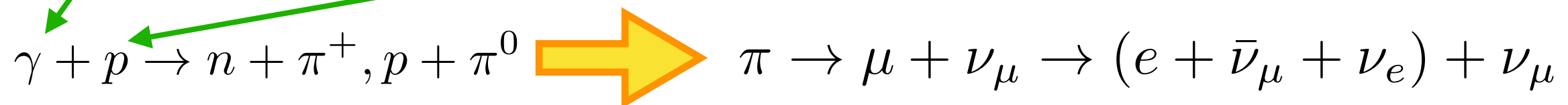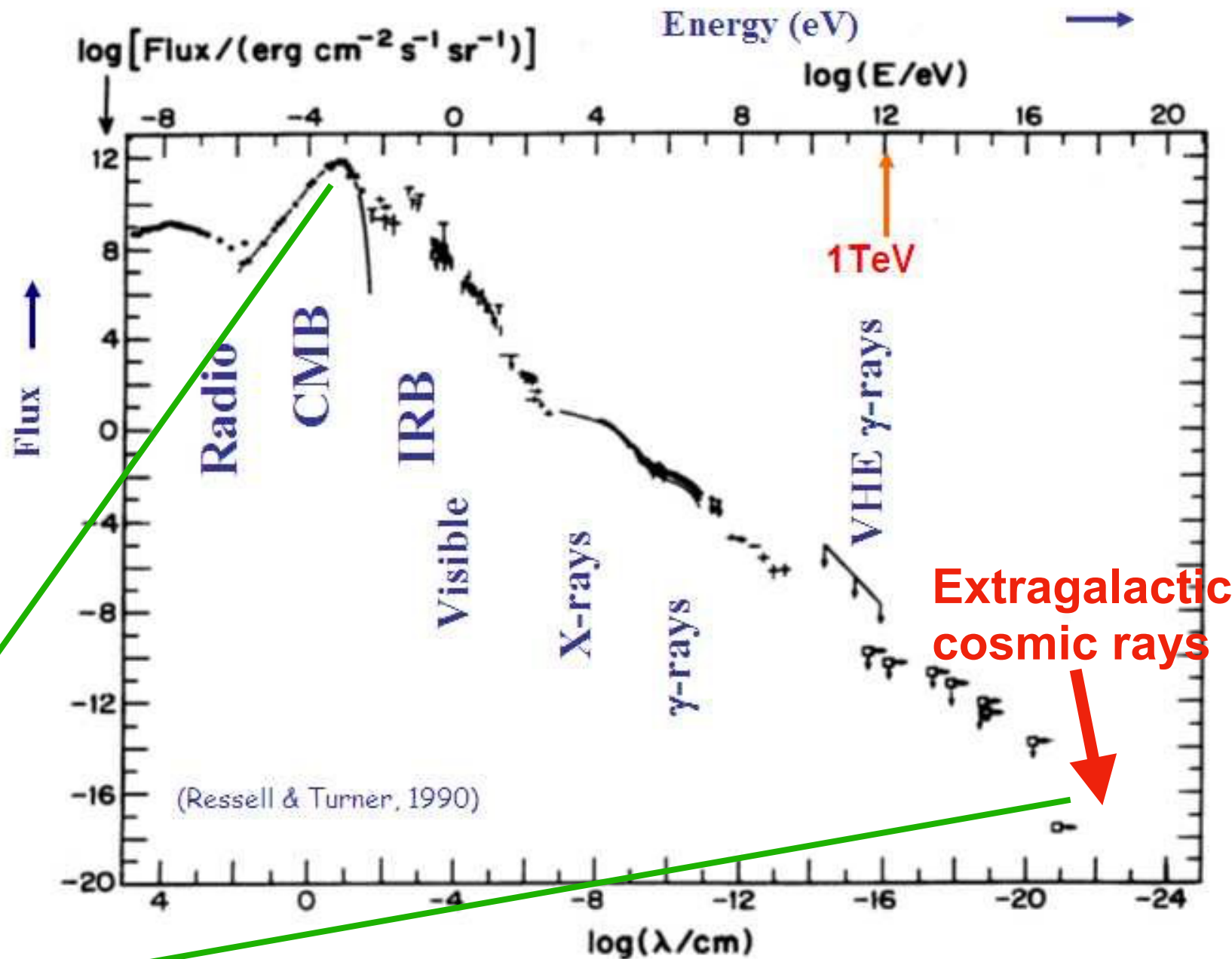$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2(2\theta_\odot) \ ,$$

with $\sin^2(2\theta_\odot) \sim 8/9$.

The distance to the source is much larger than the oscillation length. When arriving at Earth, the original flavor admixture mixes up to $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

See e.g. Anchordoqui et al., JHEAp (2014).

Messengers of the High Energy Sky

Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).

How Big Should the Detector Be?

$$\gamma + p \rightarrow n + \pi^+, p + \pi^0 \implies \pi \rightarrow \mu + \nu_\mu \rightarrow (e + \bar{\nu}_\mu + \nu_e) + \nu_\mu$$
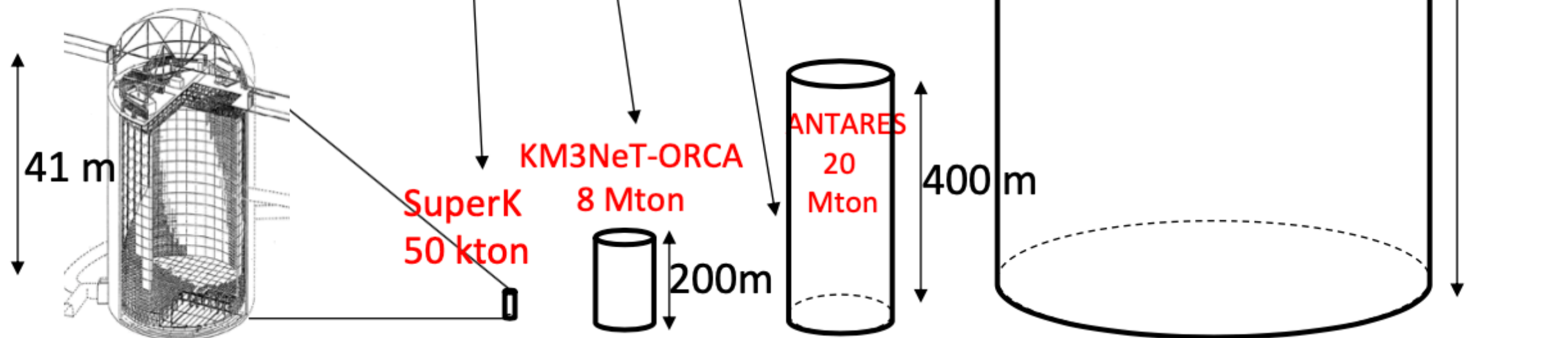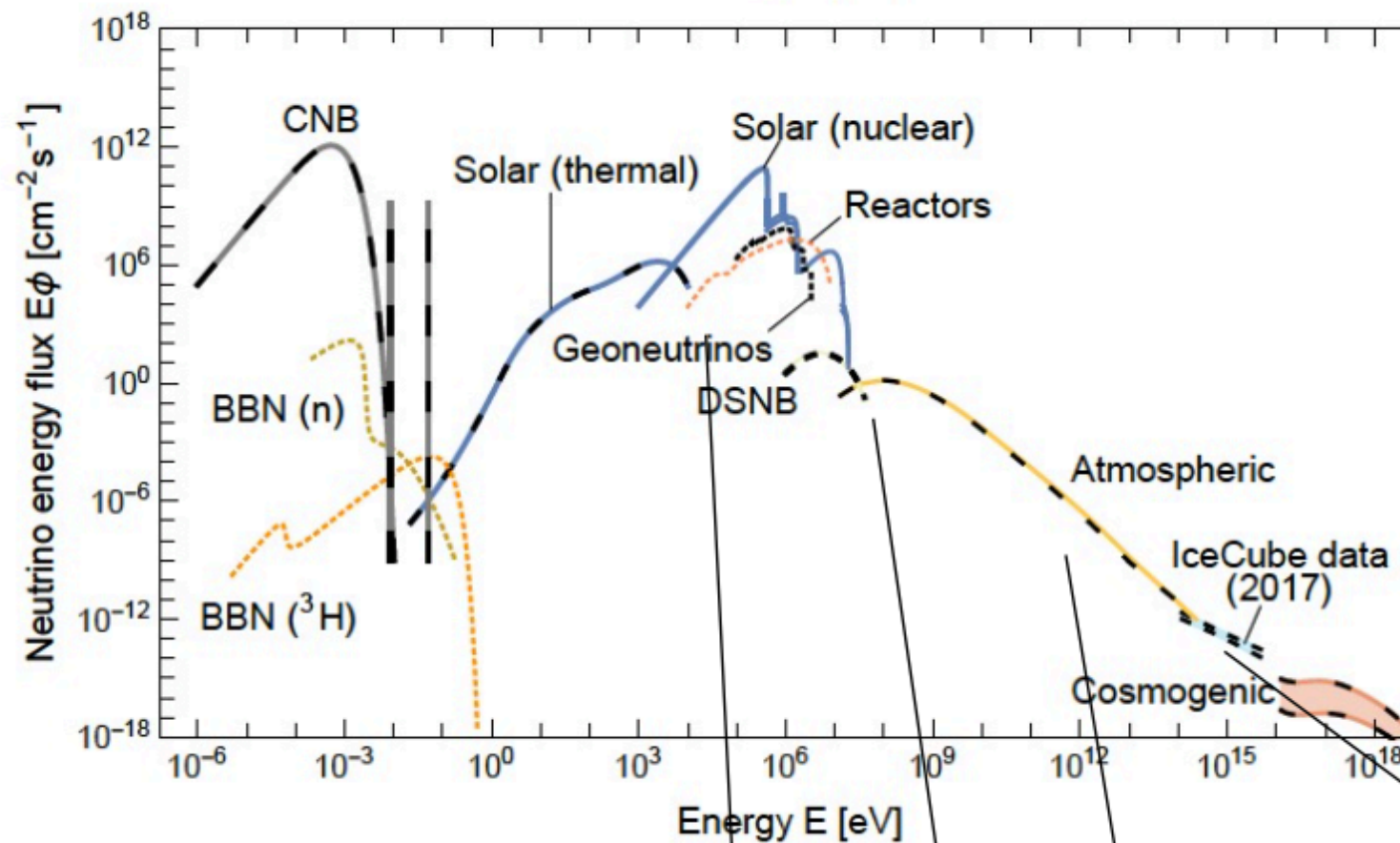
If cosmic rays interact with the CMB, neutrinos with energy of 10^6 TeV (EeV) are produced. **One event per cubic kilometer per year.** Neutrinos point back at their source!

Neutrino "Telescopes"
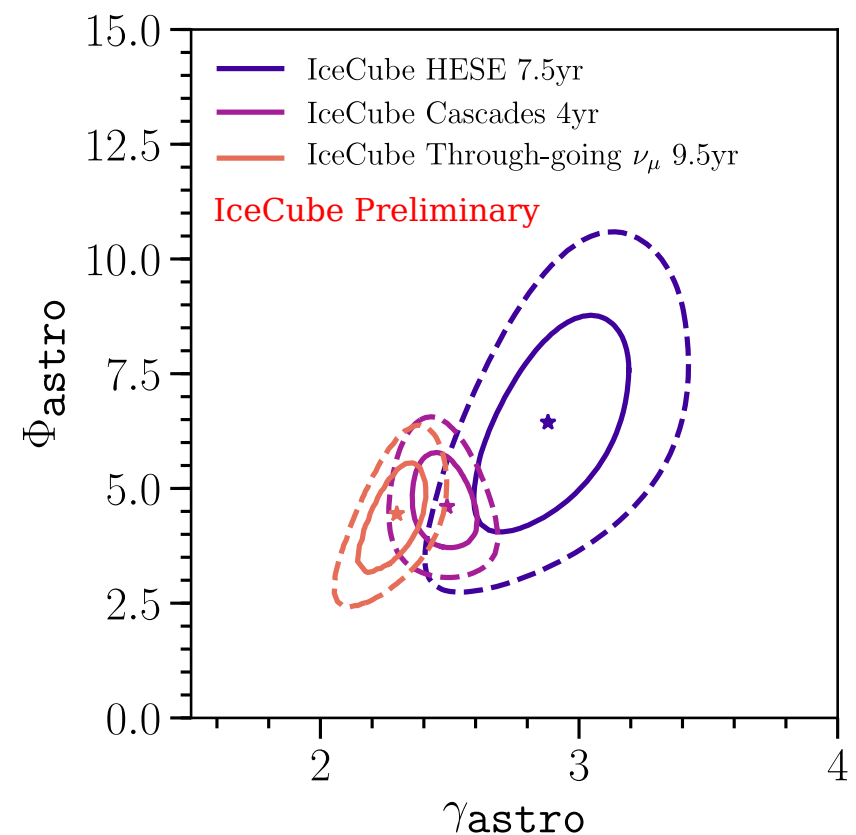
$\sigma(\nu p)/\sigma(\gamma p)= 10^{-7}$ at 1 TeV

Need very large detectors

IceCube
GVD
KM3NeT-ARCA
1 Gton

1000m

41 m

SuperK
50 kton

KM3NeT-ORCA
8 Mton

ANTARES
20
Mton

400 m

200m

Image credit: P. Coyle.
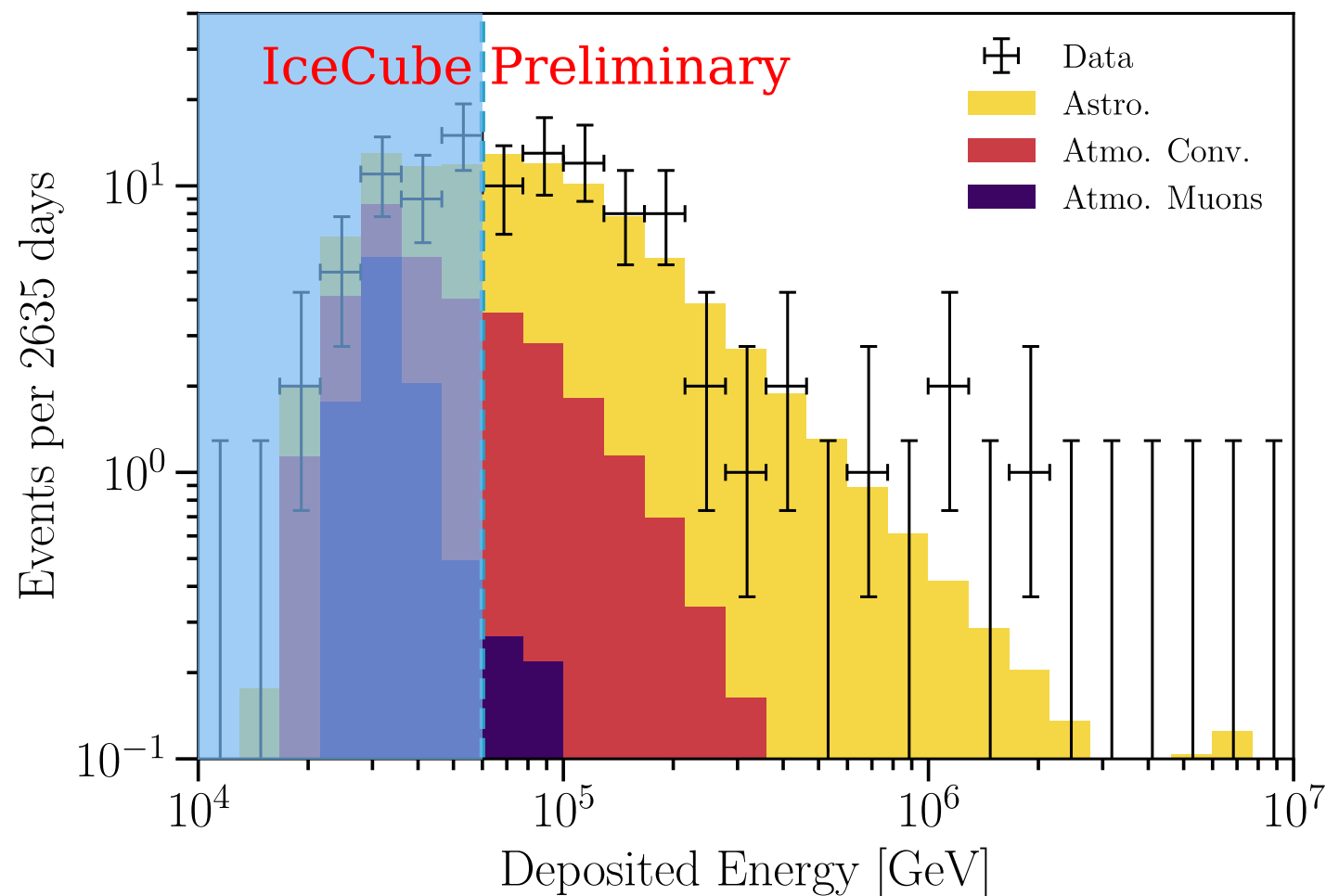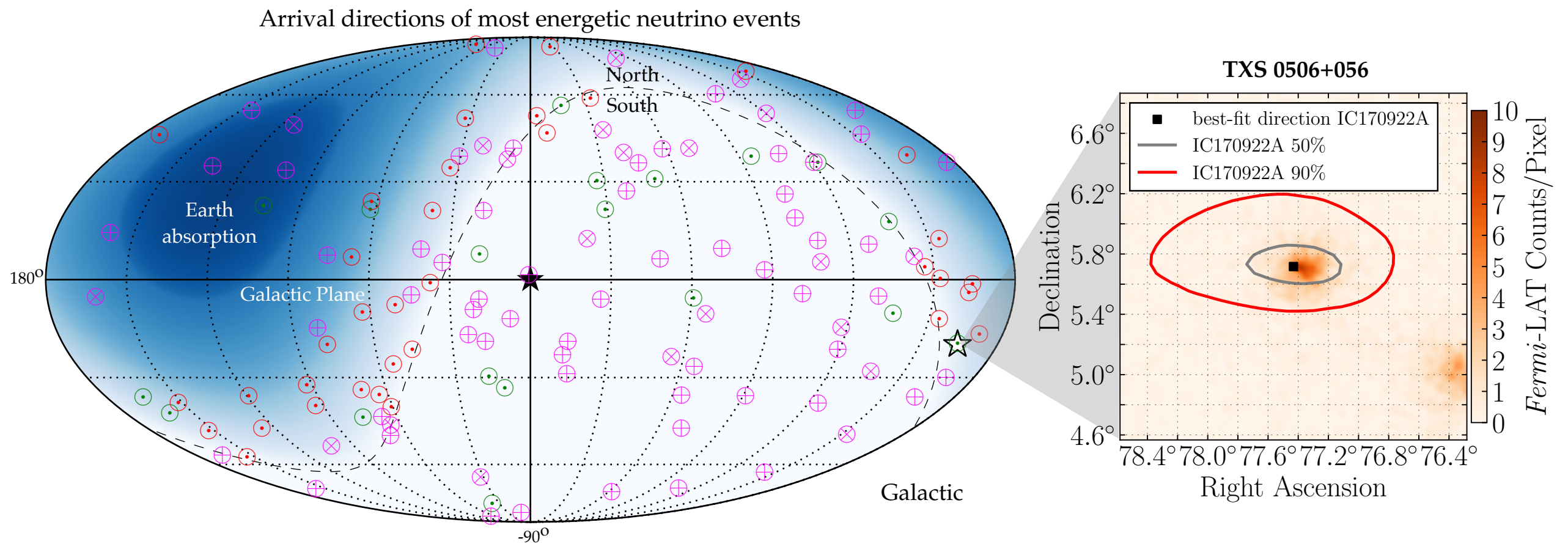
Detection of High Energy Neutrinos

IceCube has detected hundreds of neutrinos with energies over 100 TeV (10 times larger than the highest energies achieved by any particle at LHC).
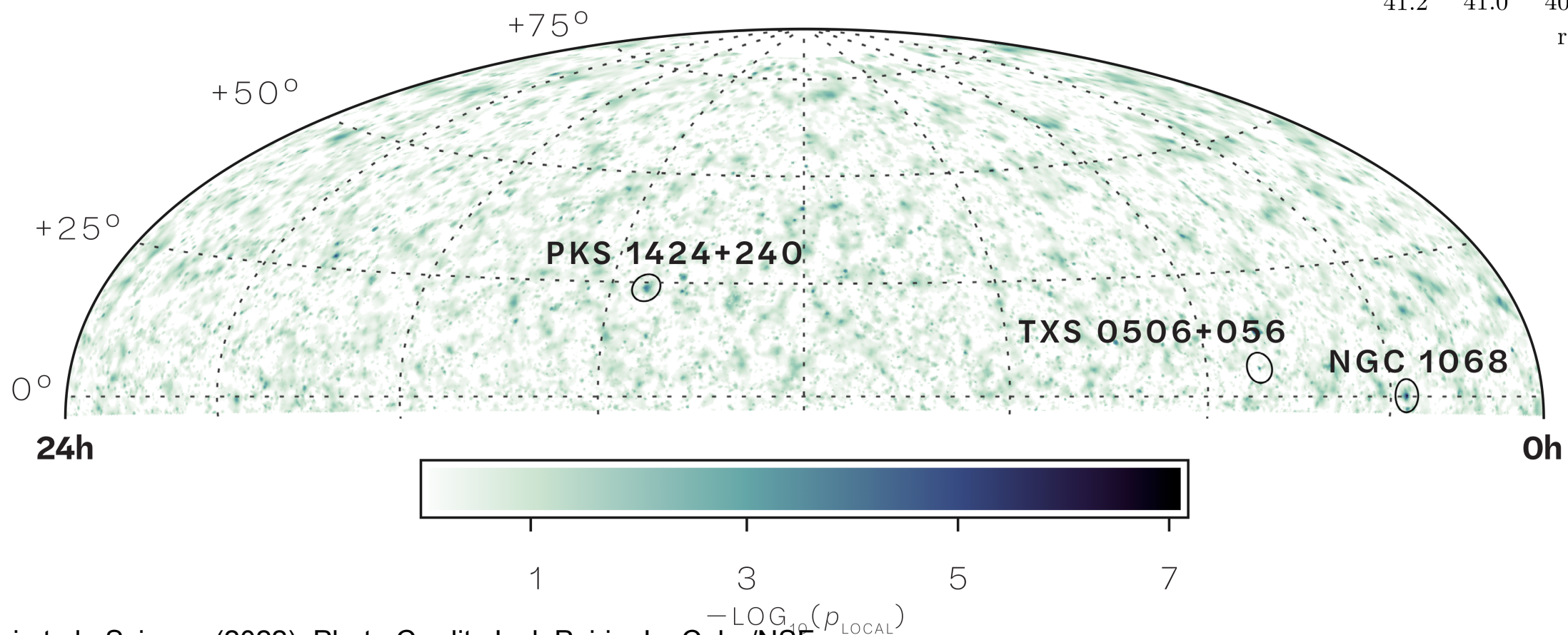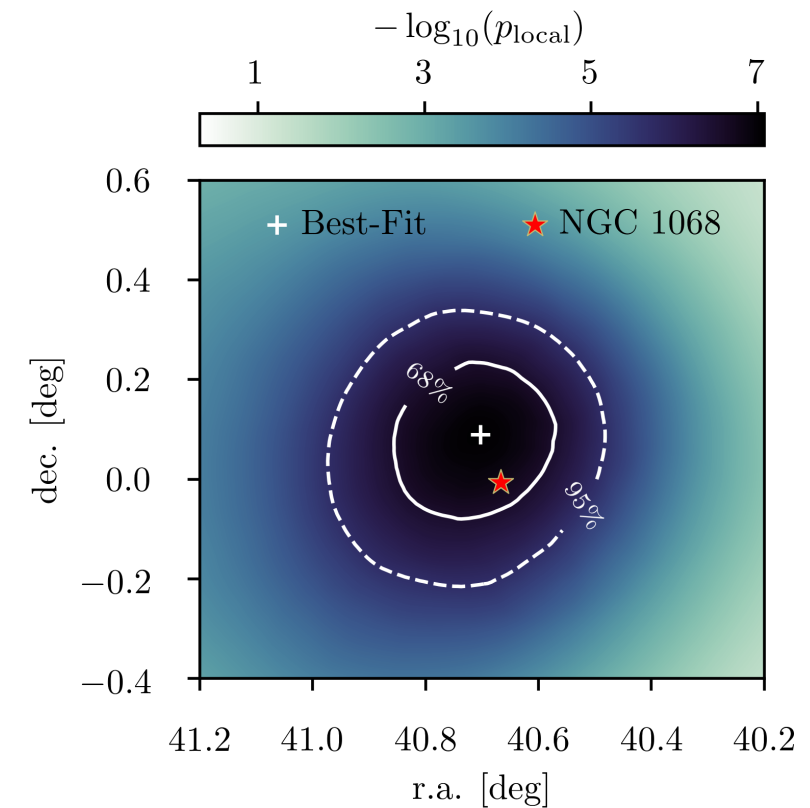
Some of these neutrinos have PeV energies, i.e. energies thousands of times greater than what's needed to create the heaviest of the known fundamental particles.

IceCube Coll., Science 342 (2013); IceCube Coll., Astrophys. J. 833 (2016). IceCube Coll., arXiv: 1907.11266

Neutrino-Source Association: Transient Source (2017)

Arrival directions of most energetic neutrino events

TXS 0506+056

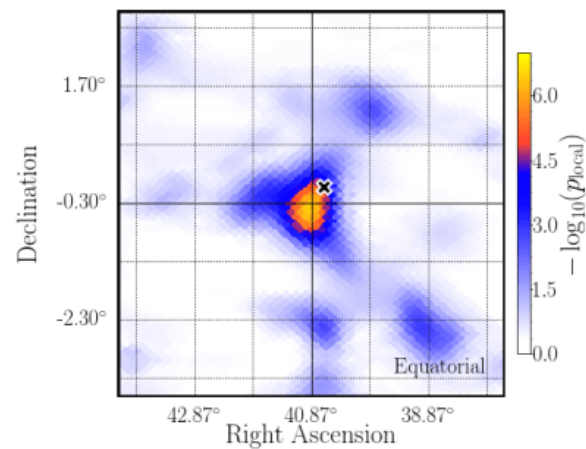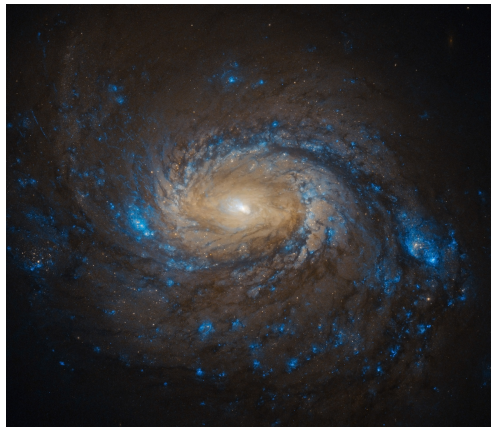Figure taken from Aartsen et al.,J. Phys. G (2021).

Neutrino-Source Association: Steady Source (2022)

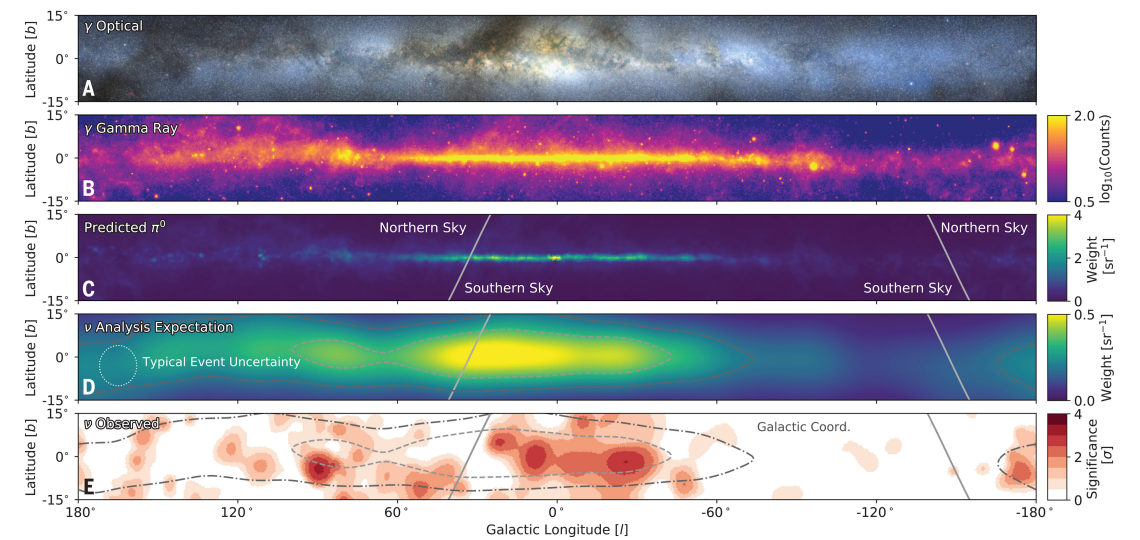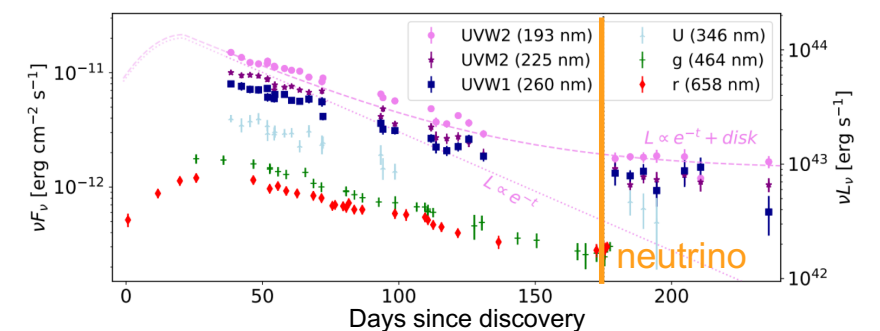# Many More Neutrino-Source Associations
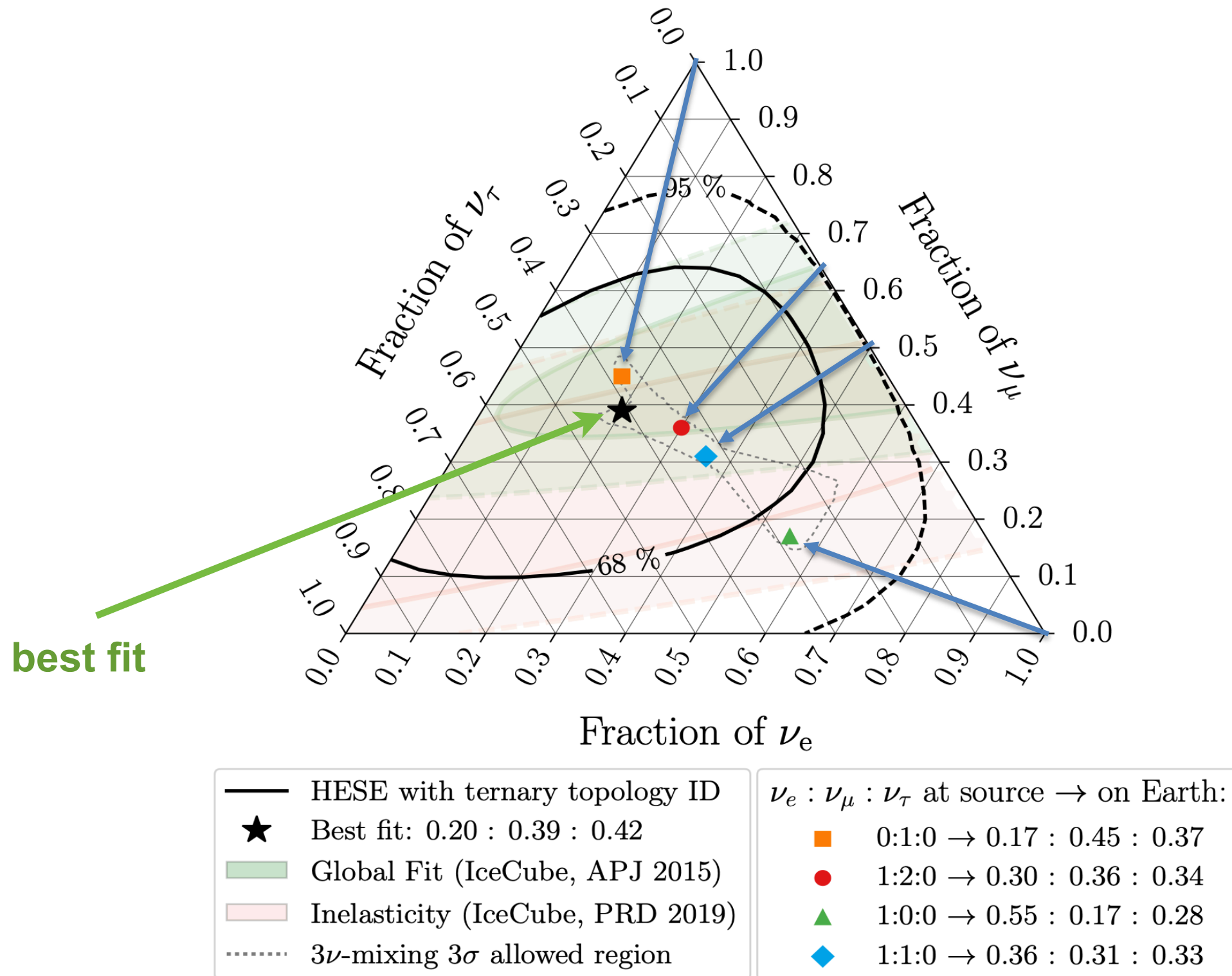
Starburst Galaxies

Our Galaxy

Blazars
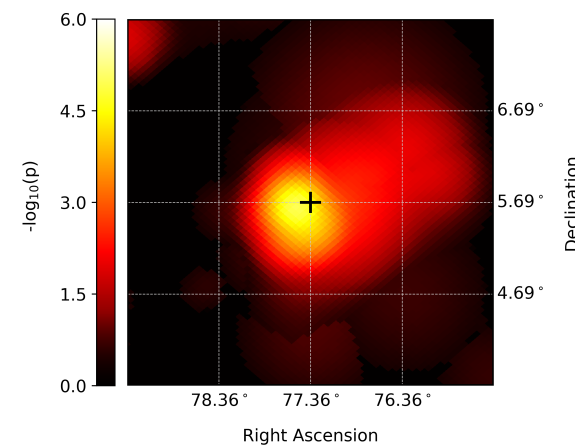
Tidal Disruption Events or Superluminous Supernovae?

Image credits: IceCube Collaboration.

Neutrino Flavor Ratio

Flavor composition at Earth

best fit

Legend:

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

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

■ (orange)	0:1:0 → 0.17 : 0.45 : 0.37
● (red)	1:2:0 → 0.30 : 0.36 : 0.34
▲ (green)	1:0:0 → 0.55 : 0.17 : 0.28
◆ (blue)	1:1:0 → 0.36 : 0.31 : 0.33

Not yet possible to pinpoint the production mechanism.

Sources

Neutrino Sources

We need a large detector volume to overcome the small cross-section of neutrinos. This implies that the observed extragalactic neutrino events may come from a large number of weak sources.

Which sources may be detectable?

Let us suppose that there is a class of sources with typical luminosity in neutrinos L_ν and density ρ in space. The total rate of neutrinos per unit area will be

$$F_\nu = \int L_\nu \rho \frac{d^3 r}{4\pi r^2} = \frac{1}{4\pi} \int L_\nu \rho \, d\Omega \, dr$$

The flux per unit of solid angle is

$$\frac{dF_\nu}{d\Omega} = \xi \frac{L_\nu \rho R_H}{4\pi}$$

where the Hubble radius is $R_H = c/H_0 \simeq 4000 \text{ Mpc}$

The factor $\xi \sim 2 - 3$ accounts for the cosmological evolution of the sources.

Neutrino Sources

If we compare this to the flux observed by IceCube, we have

$$\xi \frac{L_\nu \rho R_H}{4\pi} = \frac{E_\nu dN_\nu}{d\Omega d\ln(E_\nu)} = 2.8 \times 10^{-8} \frac{\text{GeV}}{\text{cm}^2 \text{ s sr}} = 1.3 \times 10^{46} \frac{\text{erg}}{\text{Mpc}^2 \text{ yr sr}}$$

where the flux is normalized to the IceCube measurement for the sum of all three neutrino flavors and E^{-2} spectrum.

Inverting the equation above, one obtains the minimum power-density needed to produce the observed neutrino flux as

$$\rho L_\nu = \frac{4 \times 10^{43}}{\xi} \frac{\text{erg}}{\text{Mpc}^3 \text{ yr}} \sim 10^{43} \frac{\text{erg}}{\text{Mpc}^3 \text{ yr}}$$

Viable sources must be above a line in luminosity-density space, otherwise they are not sufficiently luminous to produce the observed flux.

Neutrino Sources
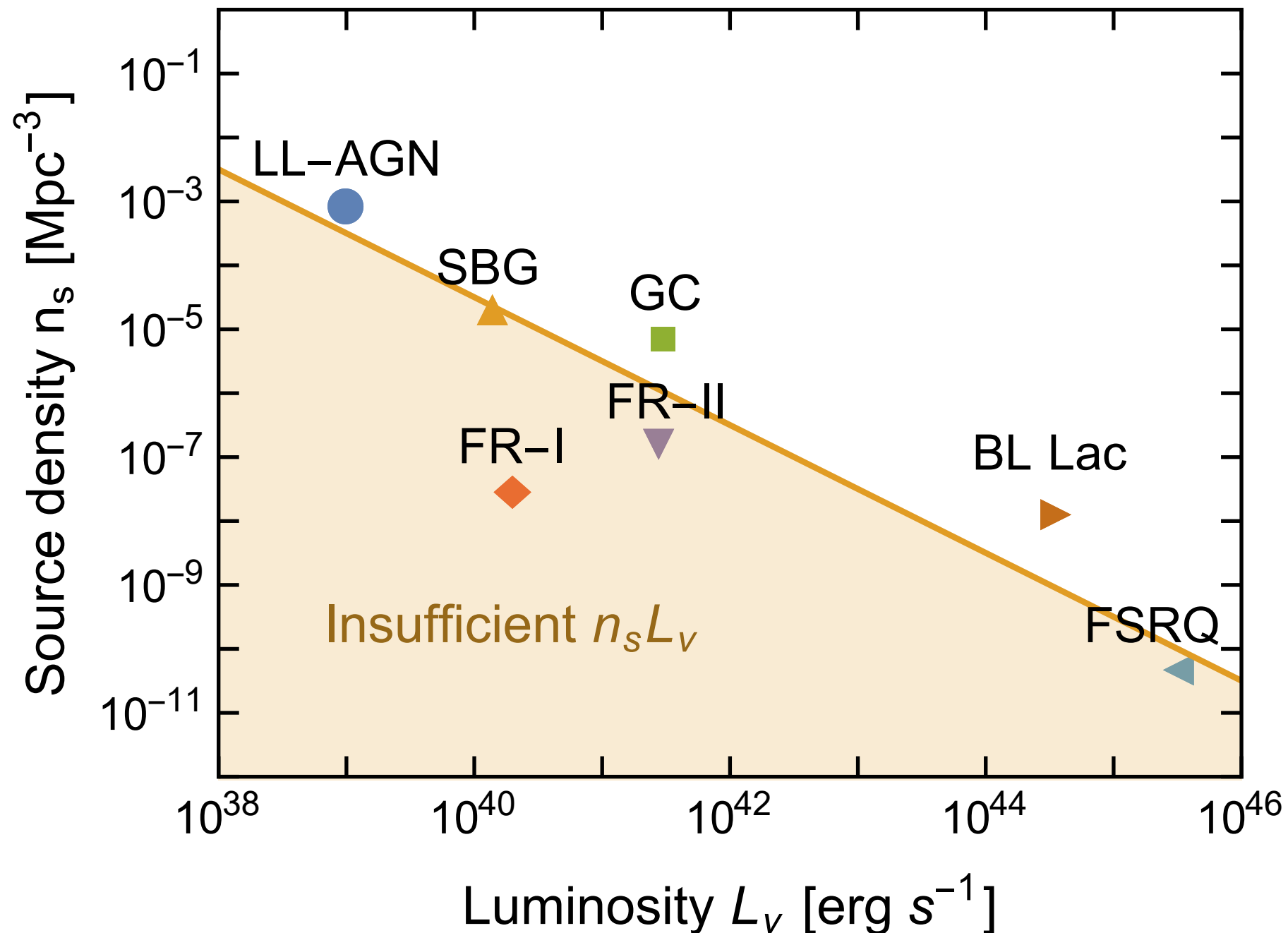
The solid line shows the minimum total neutrino luminosity needed to provide the flux per flavor. The broken lines show the minimum luminosity if the efficiency for neutrino production is 0.1-10% of the total.

Figure from Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

Where Are These Neutrinos Coming From?

★ Galactic origin

★ **Extragalactic origin**

- Star-forming galaxies

- Gamma-ray bursts

- Active galactic nuclei, blazars

- Cluster of galaxies

- Tidal disruption events

- Low-power or choked sources

Neutrinos from the Galactic Plane ᴛᴜᴍ

IceCube Coll., Science (2023).

Gamma-Ray Bursts

Image credit: Gomboc, Contemp. Phys. (2012).
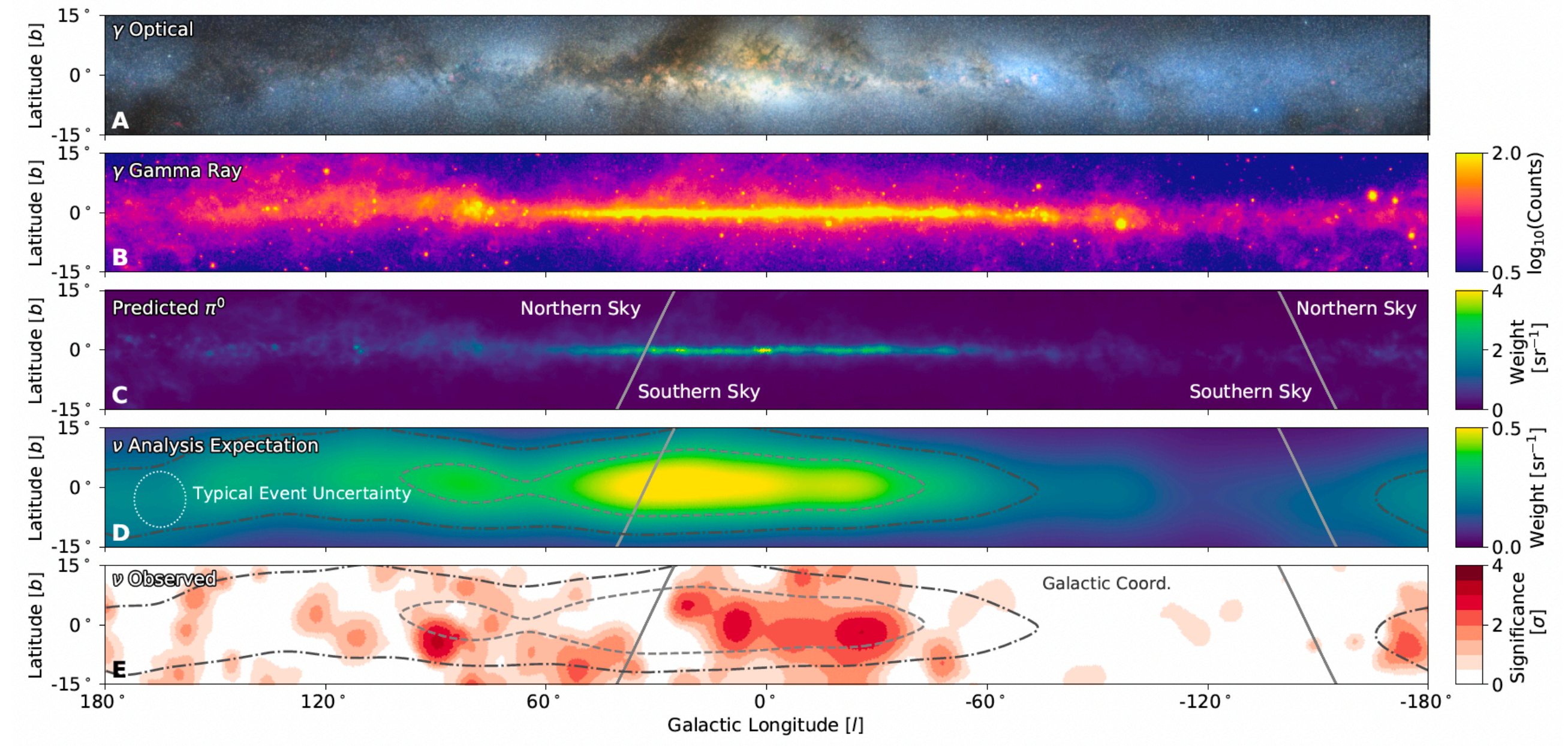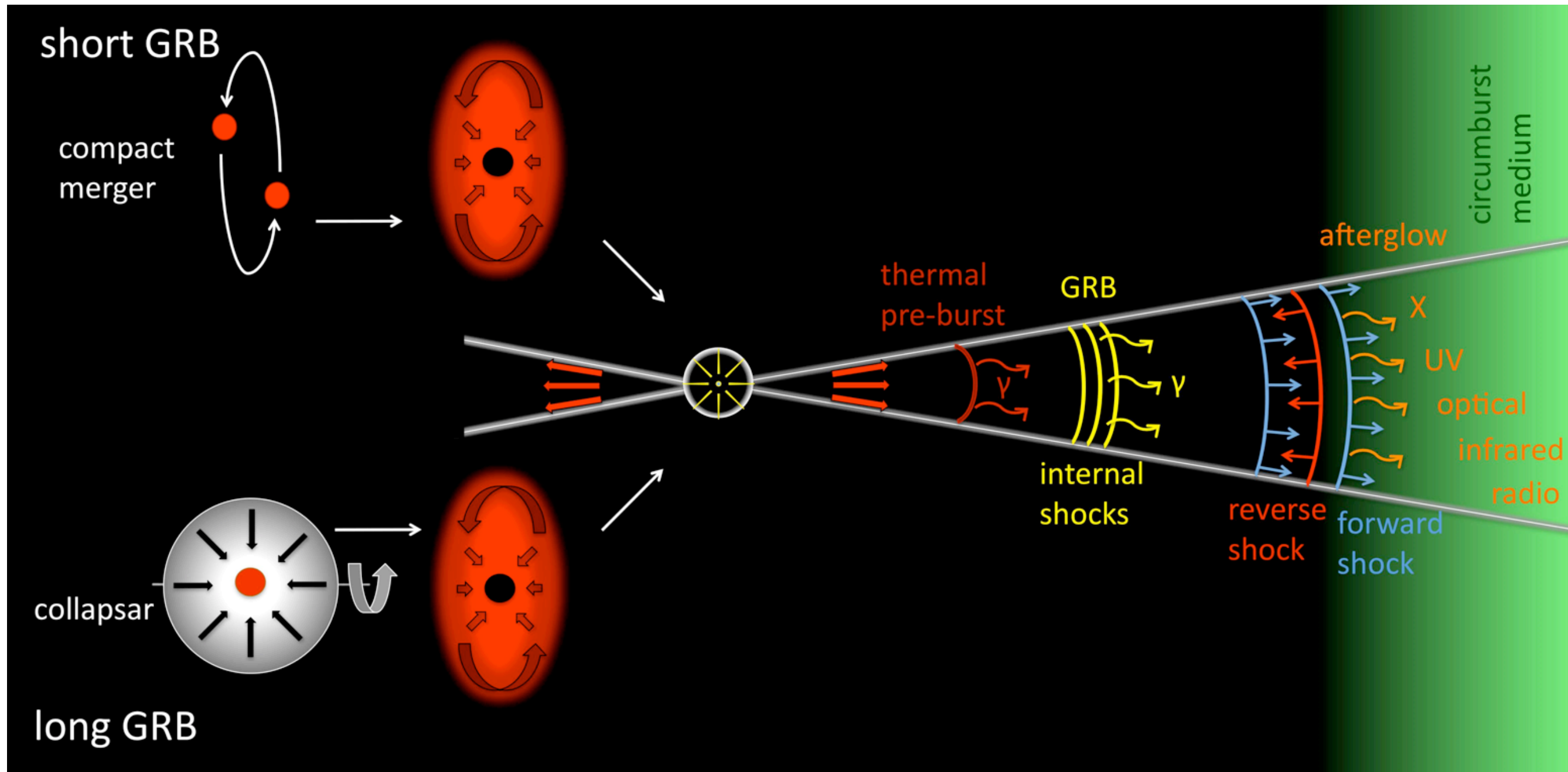
High Energy Neutrinos from Long GRBs
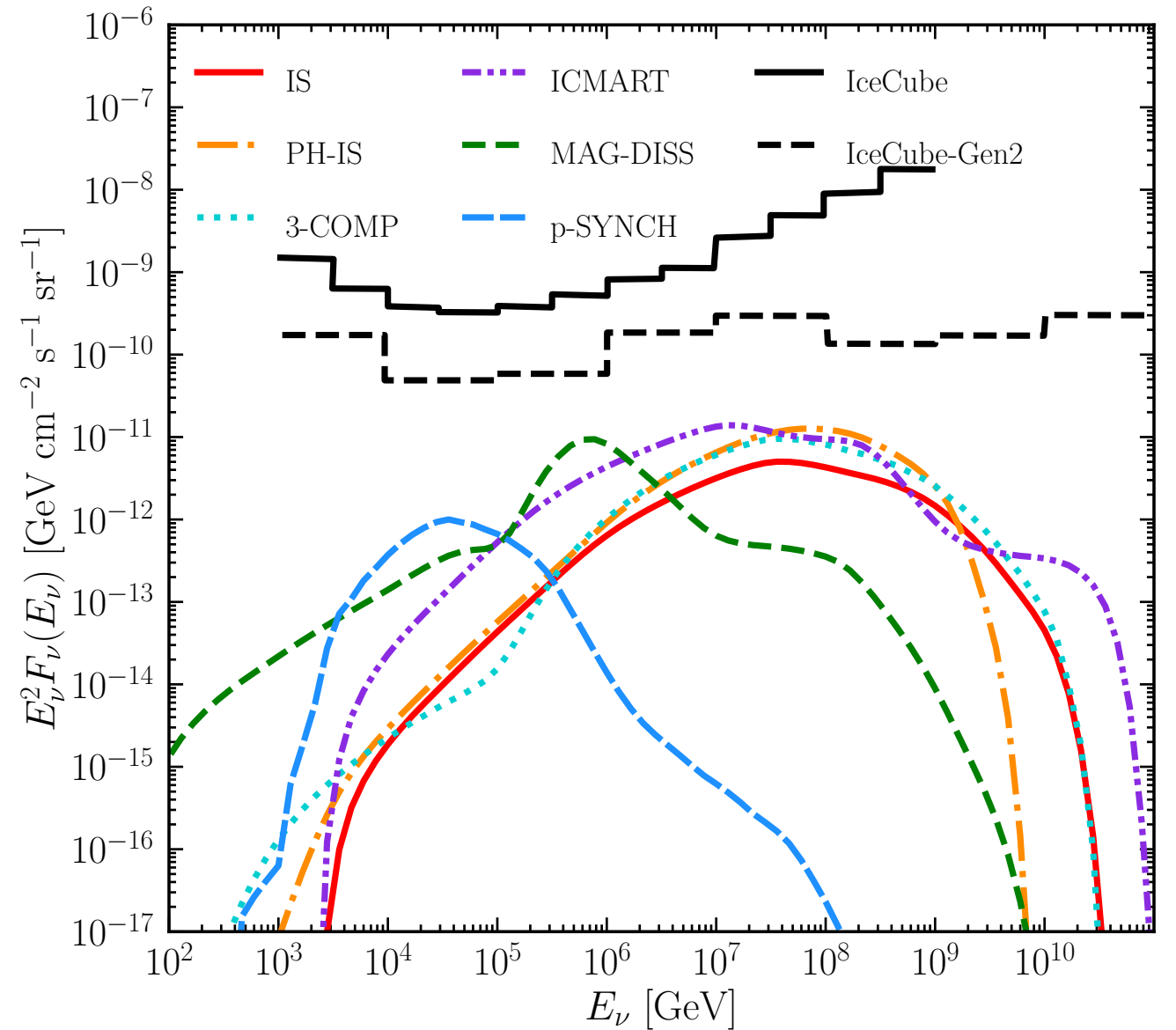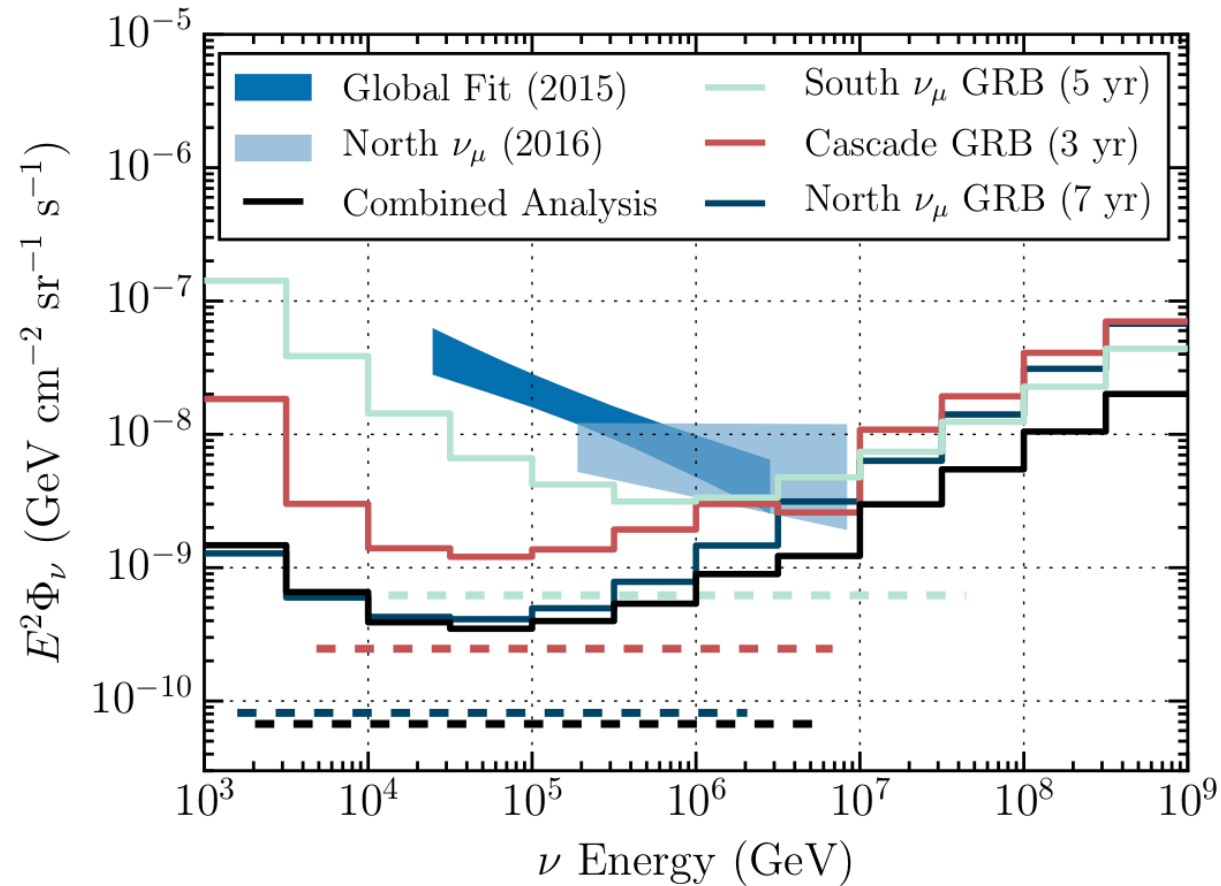
- No successful detection of high energy neutrinos from long GRBs (<1% to diffuse emission).

- Neutrino emission is strongly dependent on GRB emission mechanism.

- Neutrino emission from low-power GRBs can be copious.
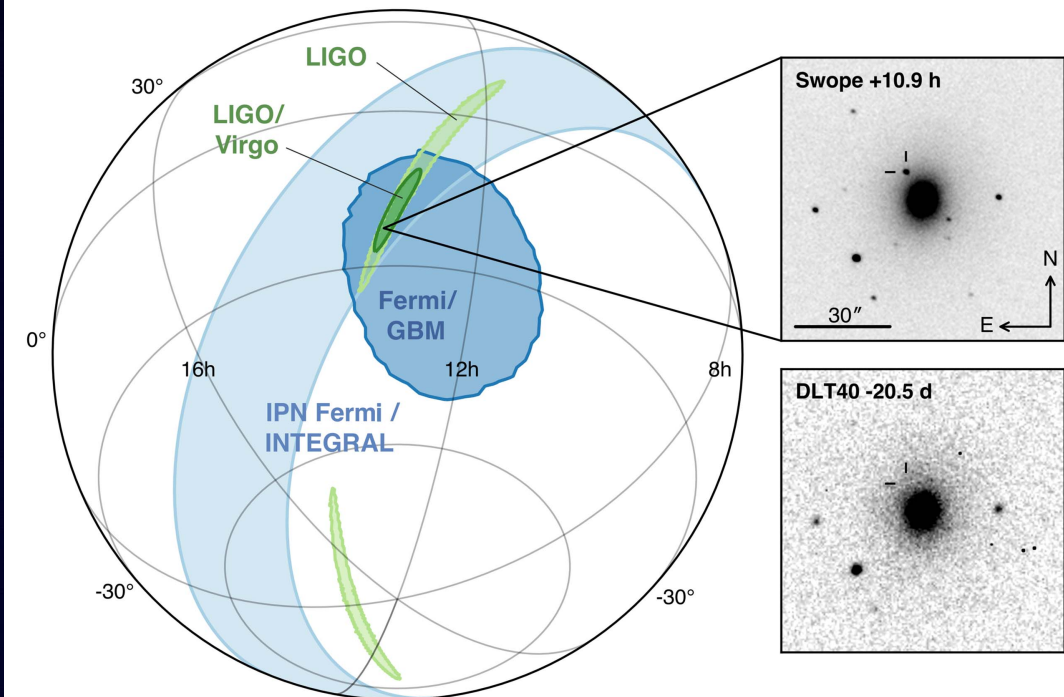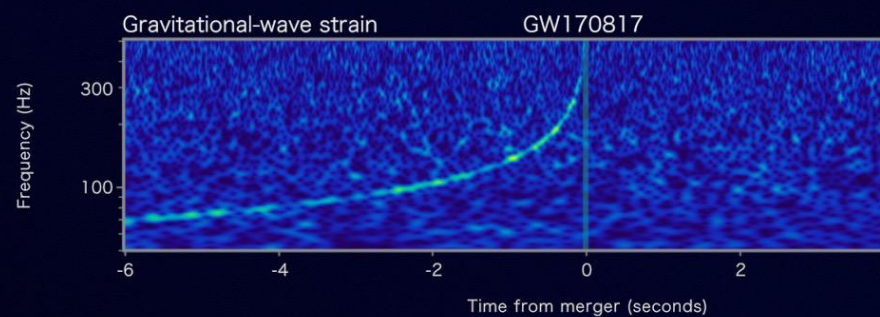
GW 170817
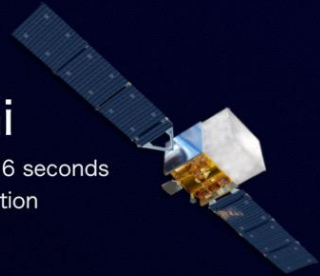
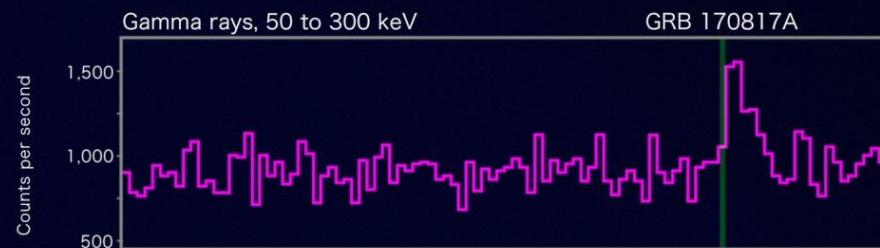First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

Figure credits: Abbott et al., ApJ (2017), ESA.

Optical (t ~ 1 day)

Merger Ejecta
Tidal Tail & Disk Wind

$v \sim 0.1$–0.3 c

erger   2012

Kimura et al.
EE optimistic

Kimura et al.
prompt

E (GeV)

b 14 day time window

ANTARES

Baikal

Auger

IceCube

Fang & Metzger
30 days

Fang &
Metzger
3 days

E (GeV)
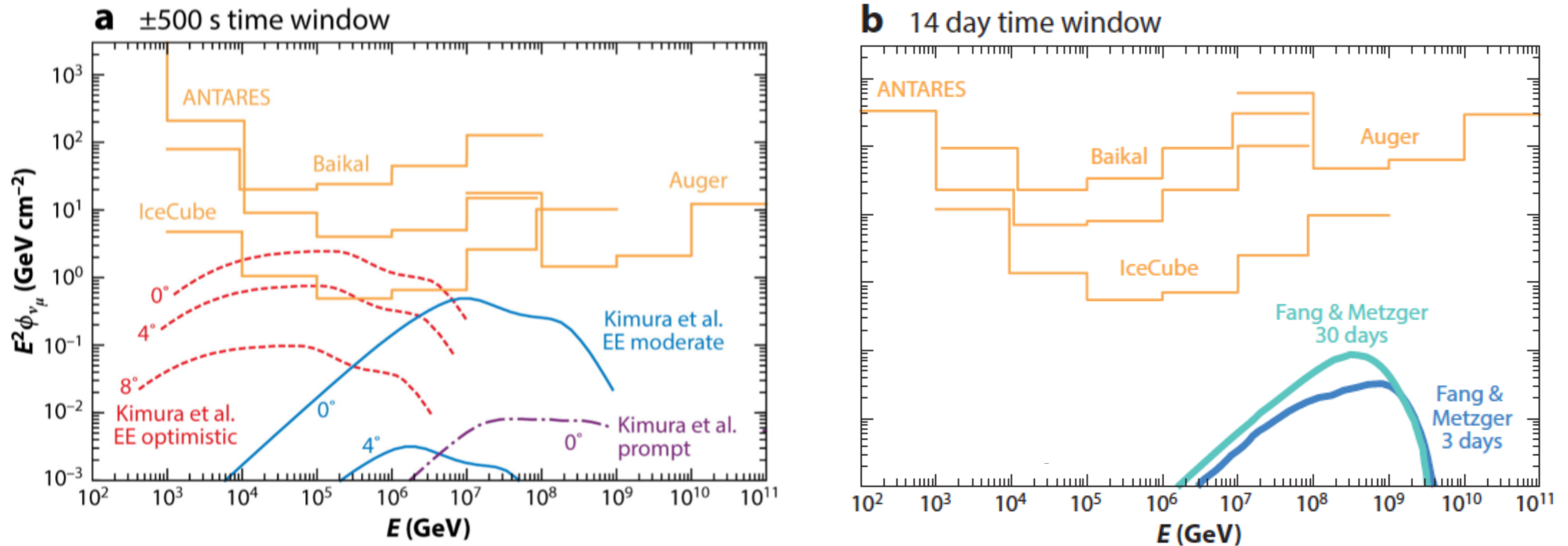
- No neutrinos detected from prompt short GRB phase.

- Neutrinos from long-lived ms magnetar following the merger.

- Neutrinos from internal shock propagating in kilonova ejecta.

- Favorable detection opportunities with multi-messenger triggers.

Figure credits: C. Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku & Kashiyama, PRD (2018). Ahlers & Halser, MNRAS (2019). Tamborra & Ando, JCAP (2015). Kimura et al., ApJ (2017).
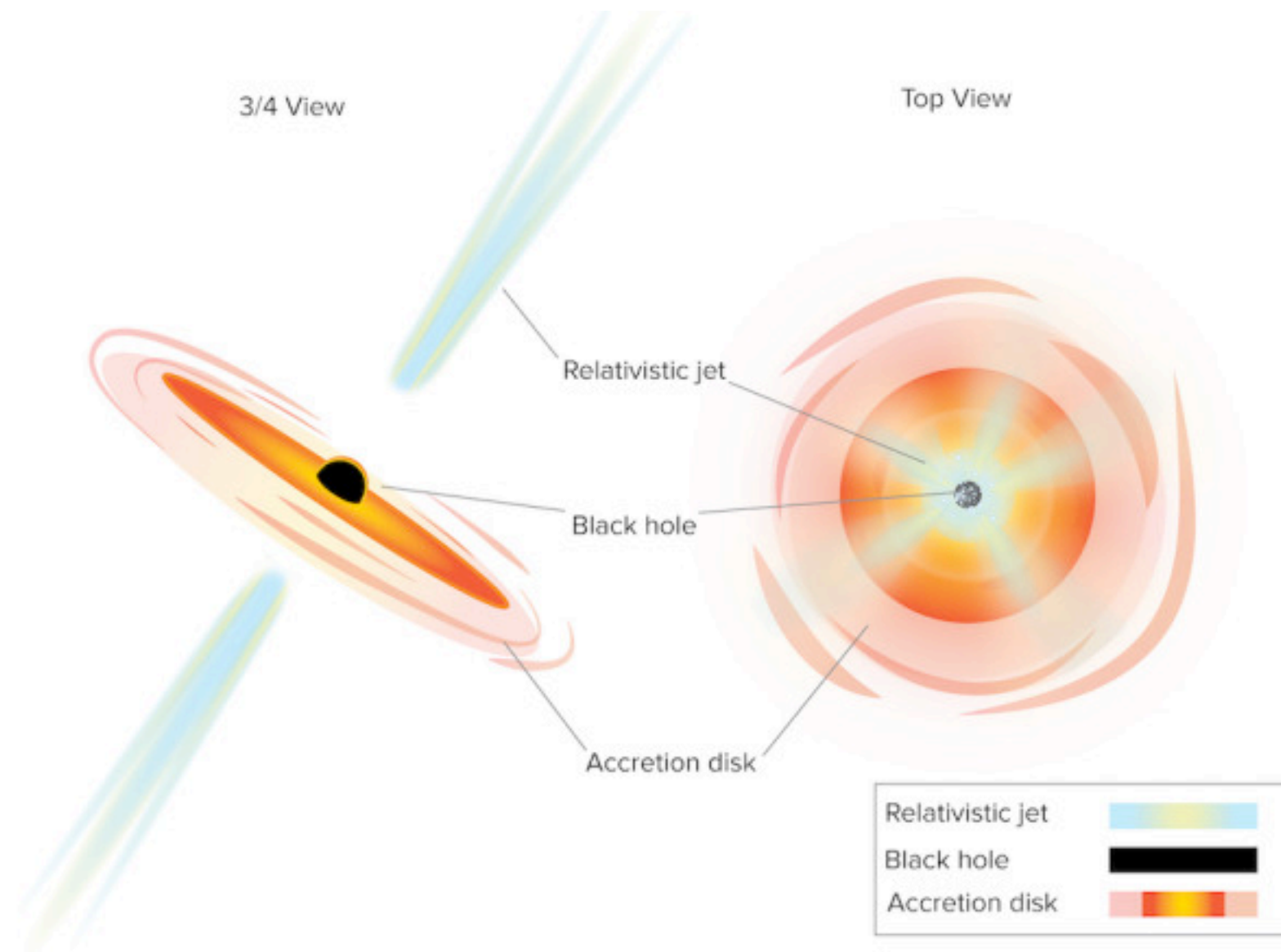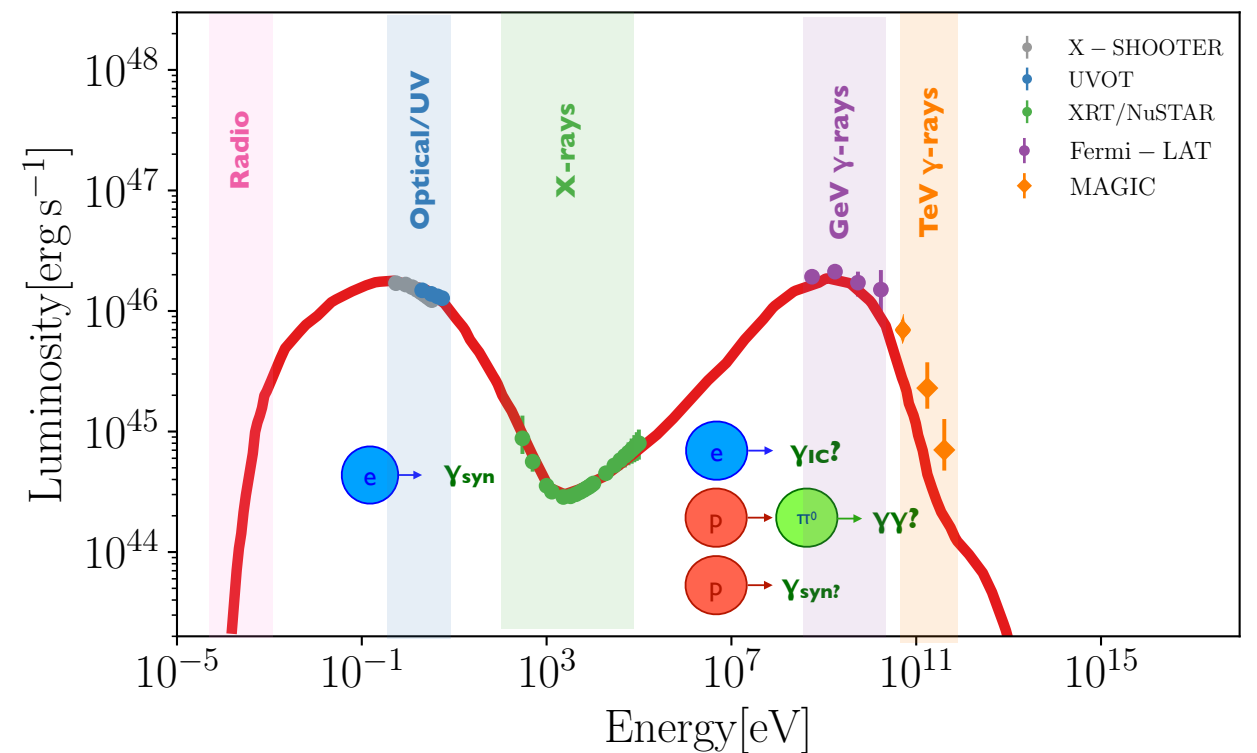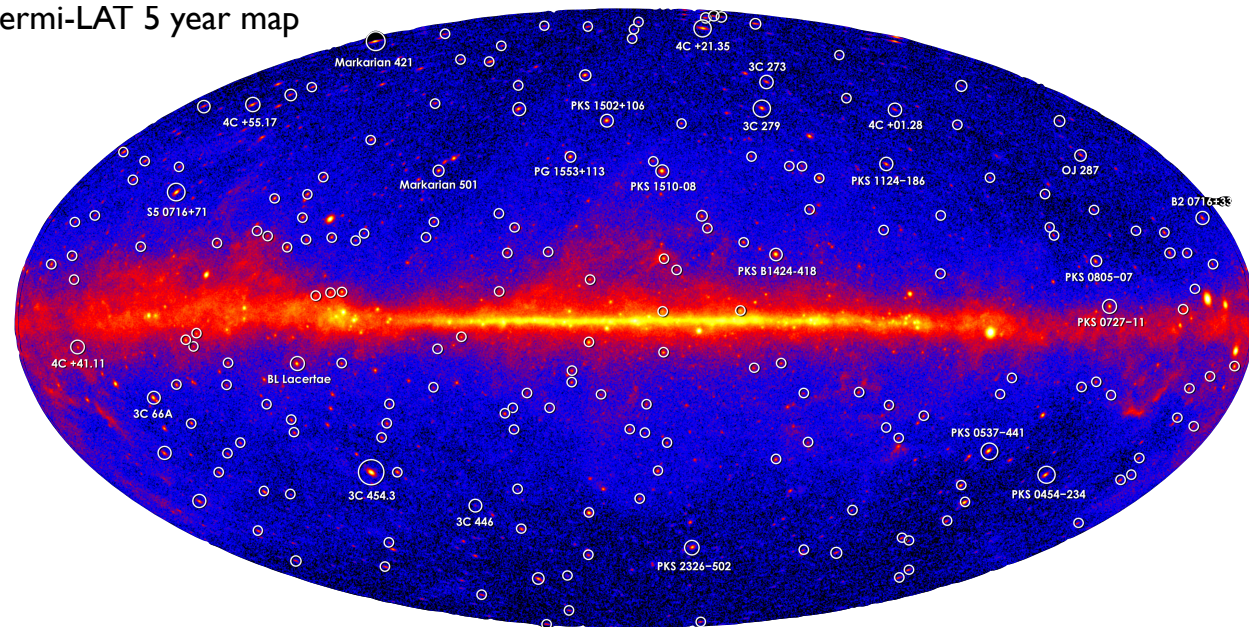
Blazars

Blazars (FSRQs & BL Lacs) constitute the most extreme subclass of AGNs with a relativistic jet closely aligned to the observer line of sight. A large sample of the Fermi sources are blazars.

Figure credit: Sophia Dagnello, NRAO/AUI/NSF.

Blazars

- Blazar flares have been observed at different energy bands and with different durations from several years to a few minutes.

- A few dozens of high energy neutrinos found along the same direction of blazars, some also in temporal association with a flare.
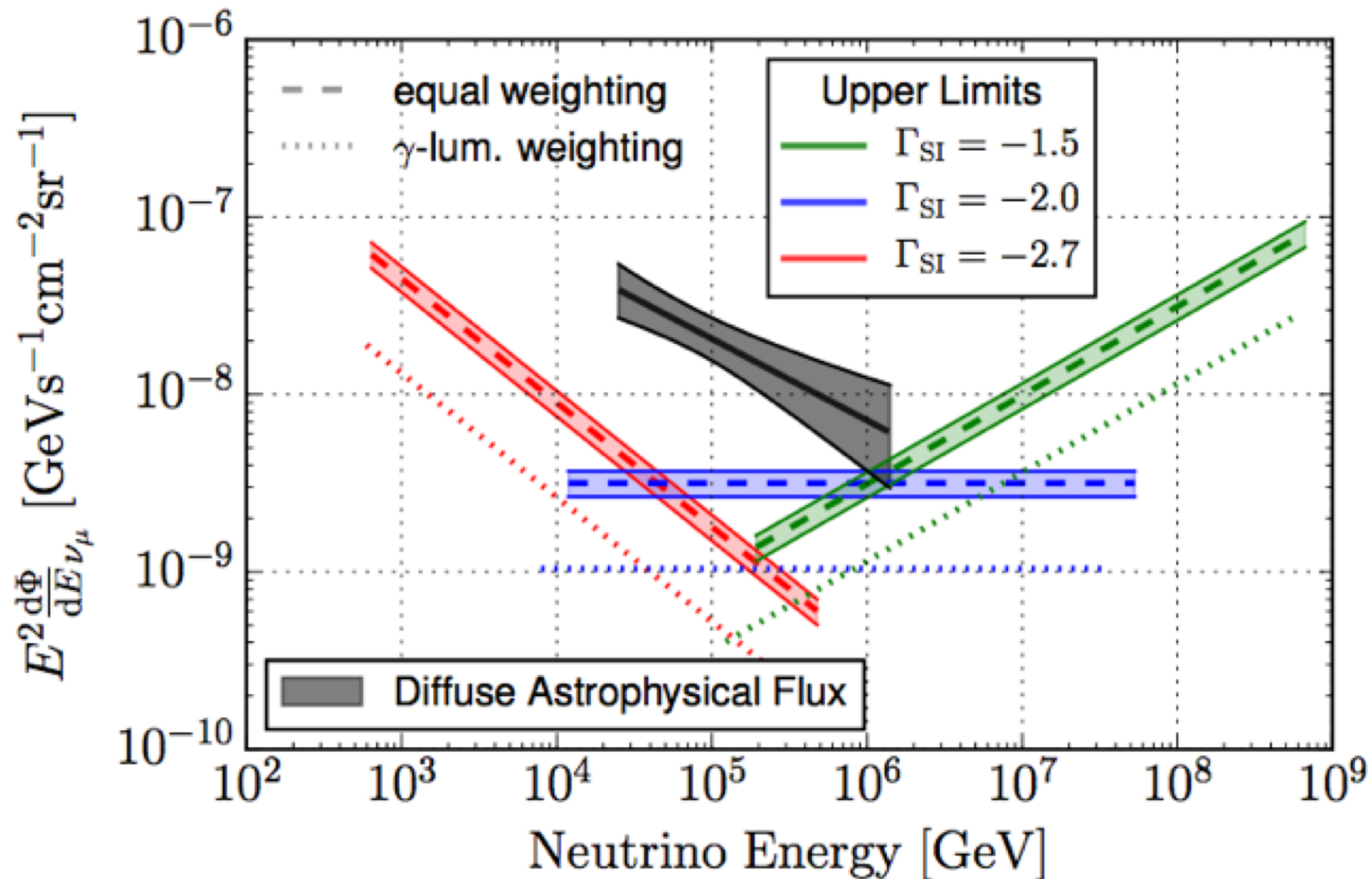

Figure credit: Foteini Oikonomou.

IceCube Neutrinos and Blazars

Blazars cannot explain the observed diffuse neutrino flux, but several IceCube neutrino events are likely in coincidence with blazars.
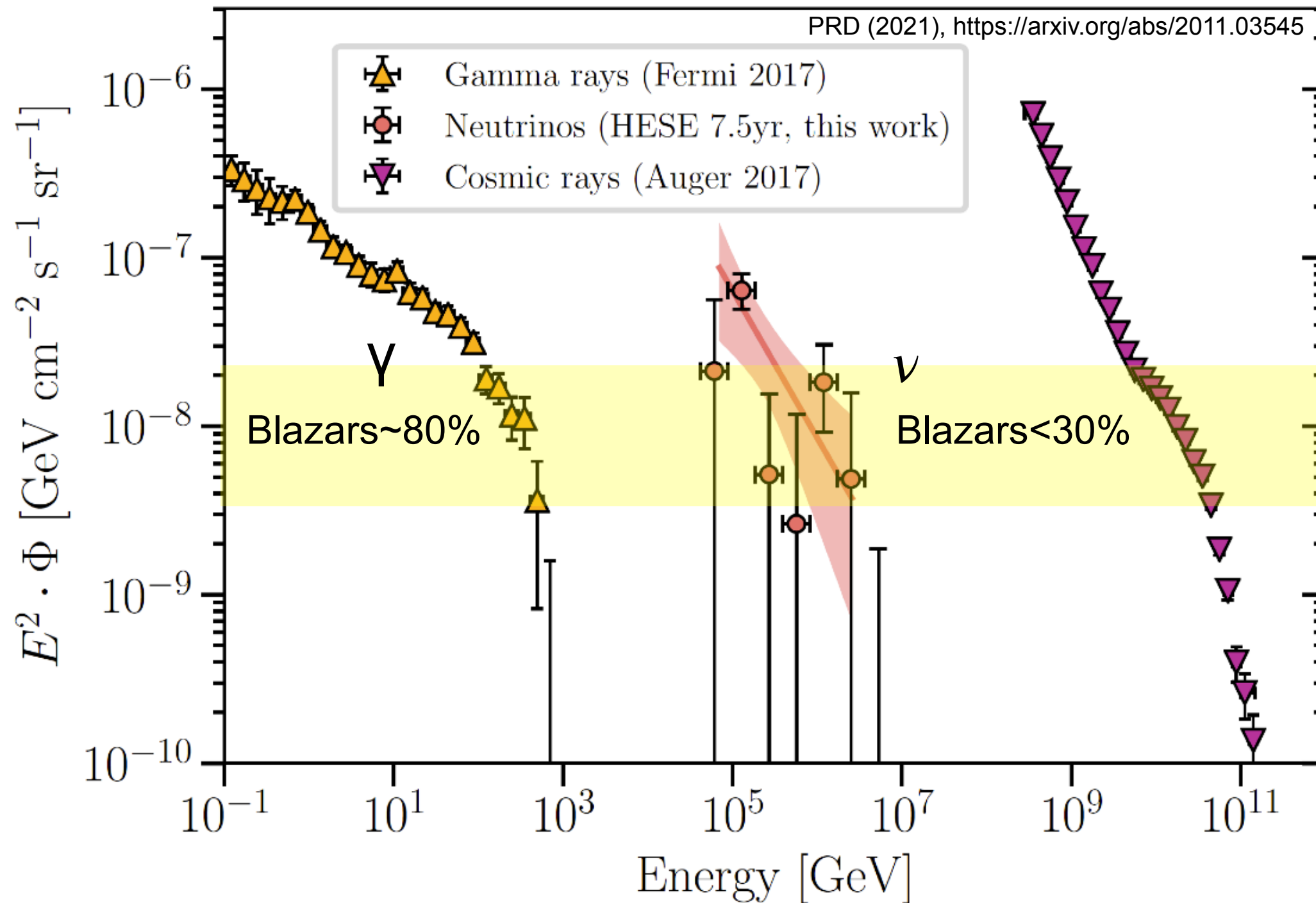

Figure credit: Foteini Oikonomou.
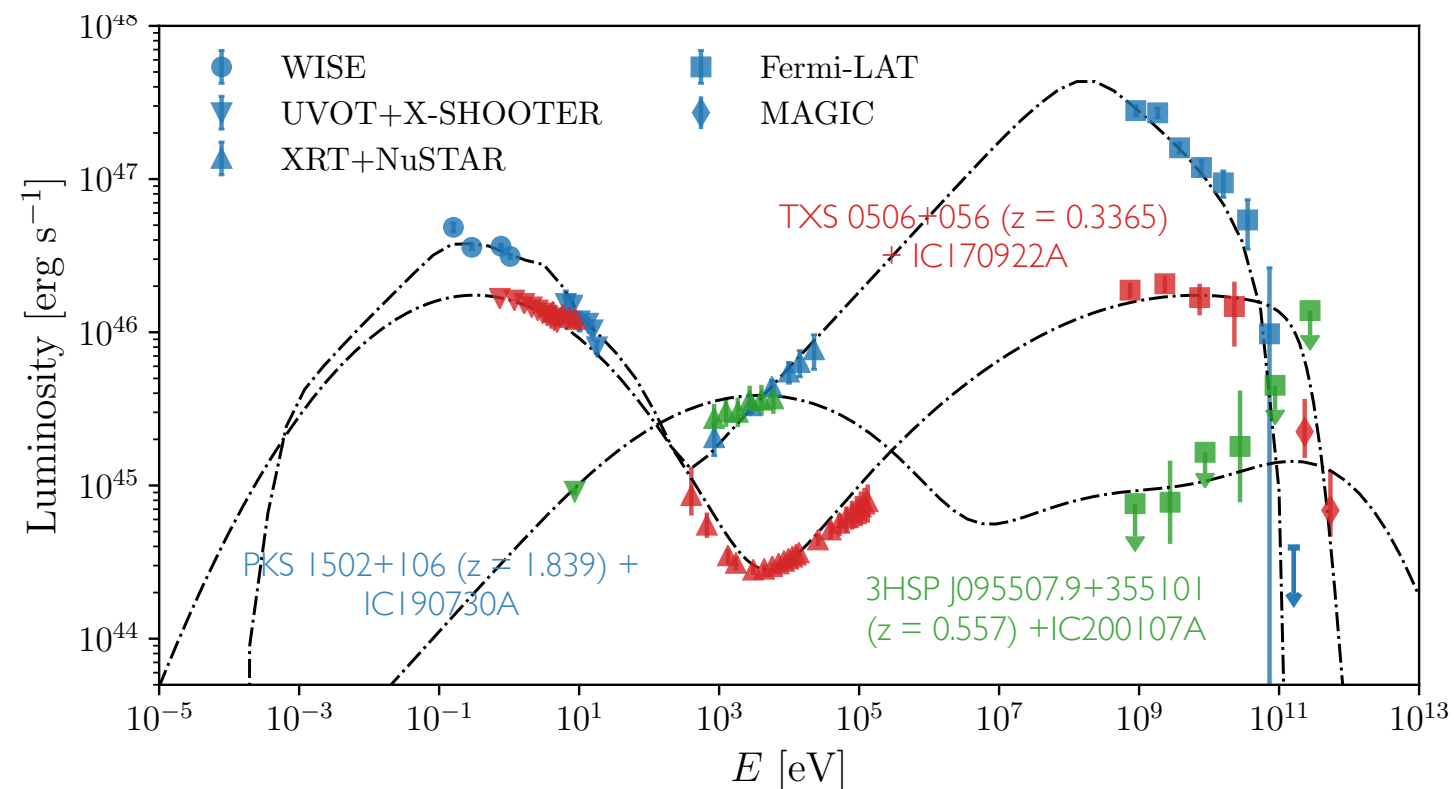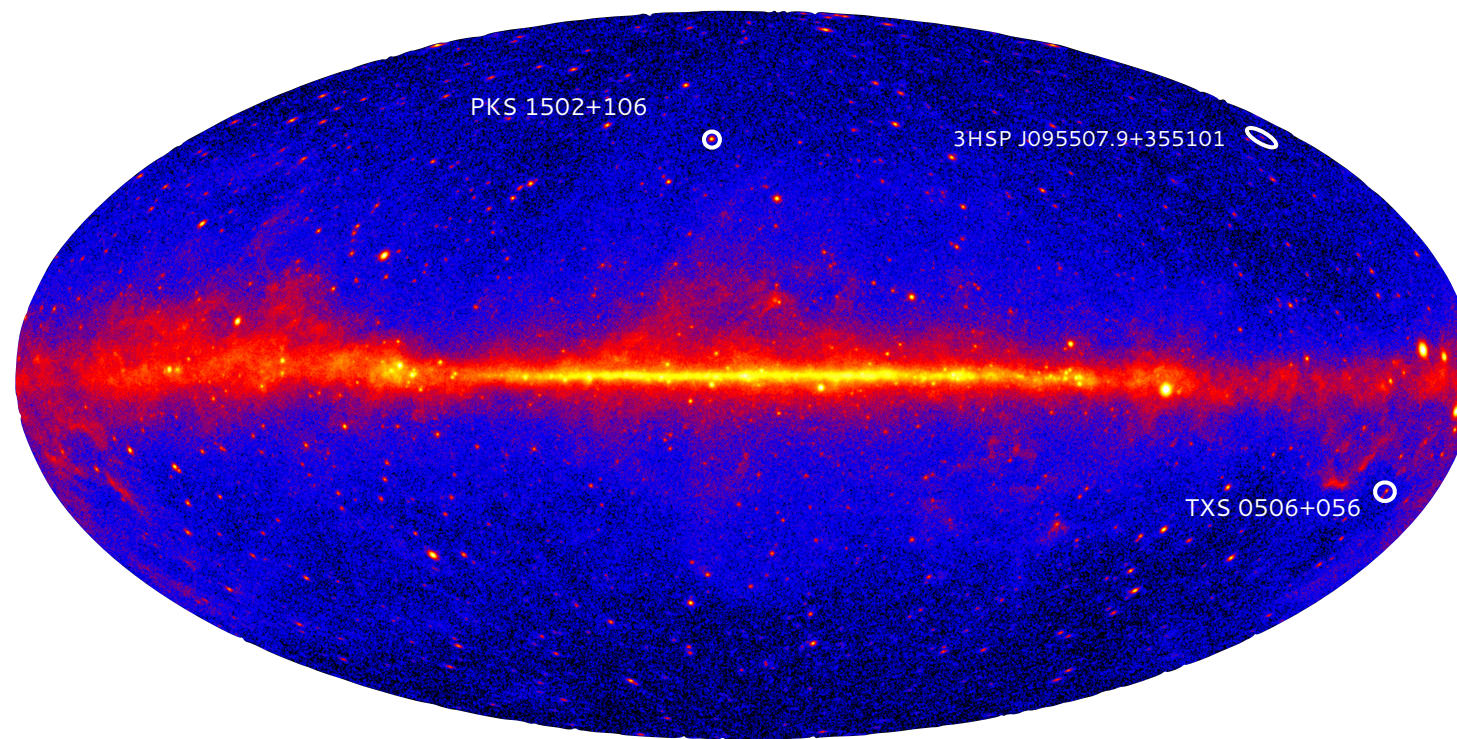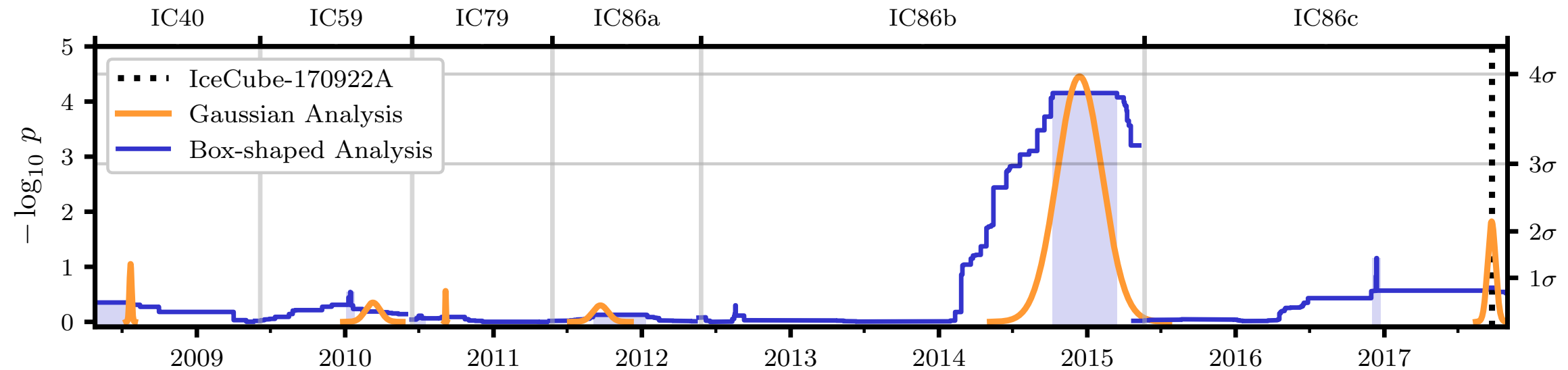
Blazar Contribution to Diffuse Emission

Fermi LAT blazars could explain a small fraction of the observed neutrinos, despite blazars being dominant sources in the diffuse gamma-ray background above 10 GeV.
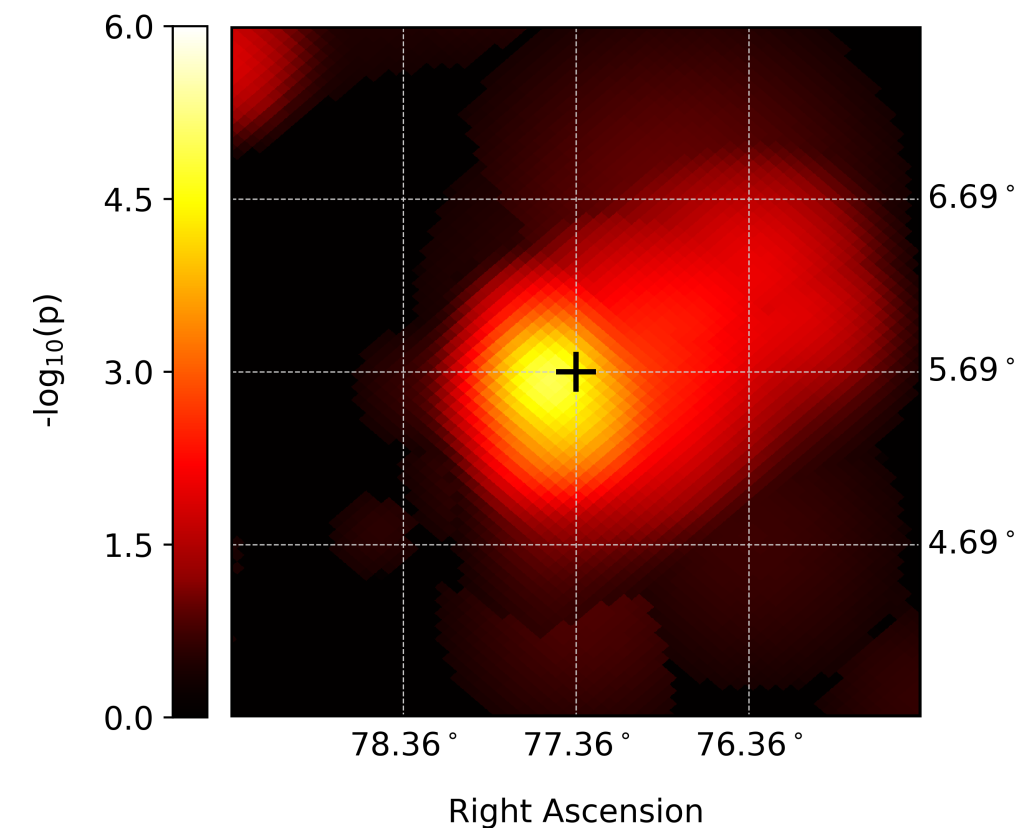
Figure credit: IceCube, ApJ (2017).

Blazar Contribution to Diffuse Emission
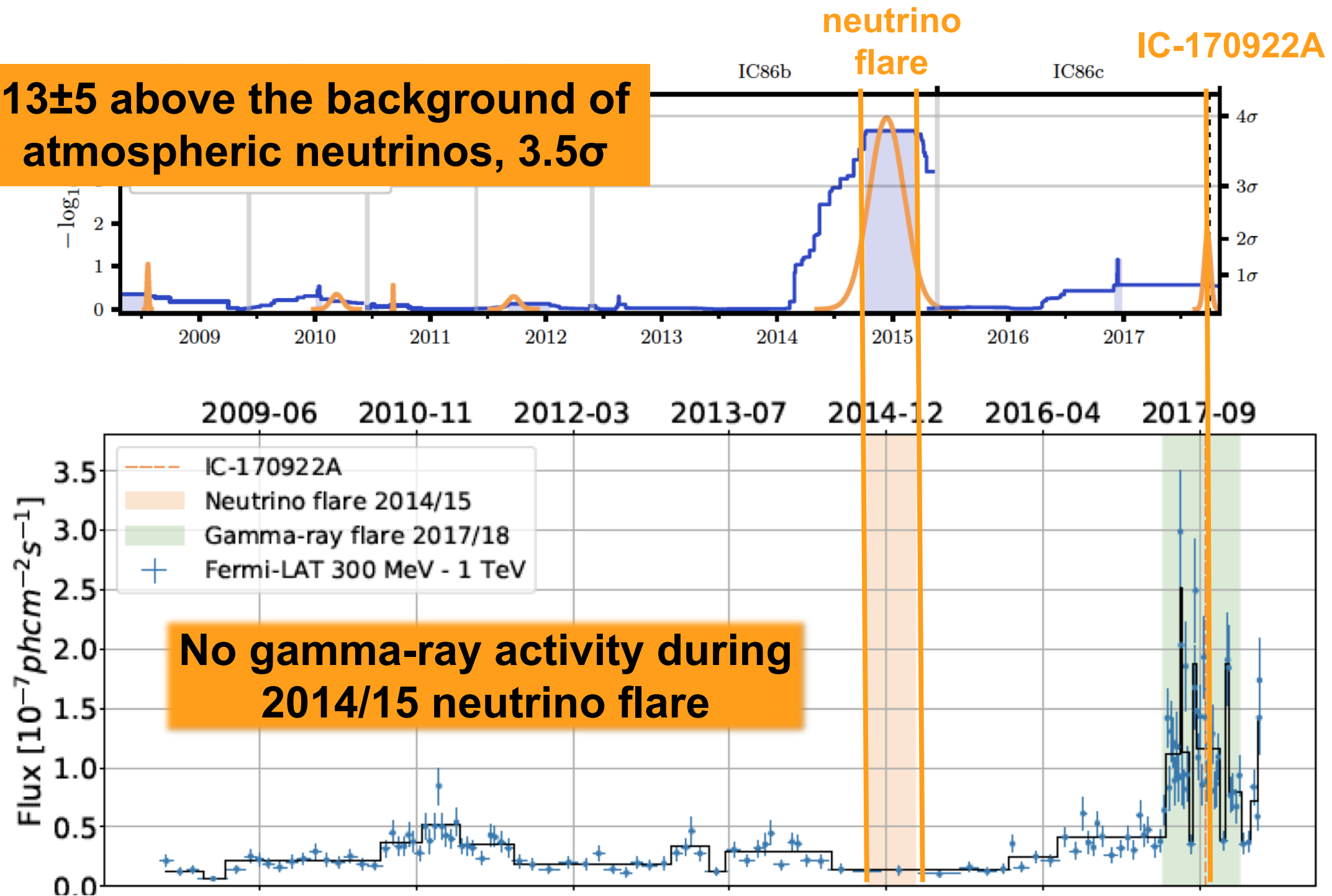
TXS 0506+056 & IC 170922A

- First high-energy neutrino traced back to its birthplace?

- Among 50 brightest blazars in 3LAC.

- Located ~4billion light years away.

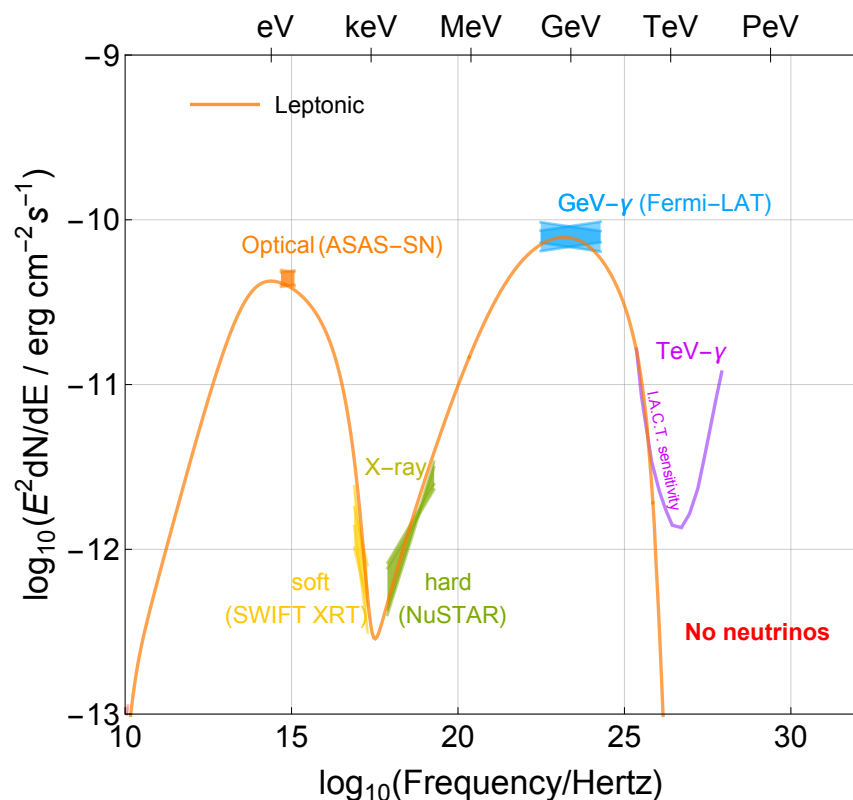- No clear correlation with events in time.

IceCube Coll., Science 2018. Blaufuss (IceCube), GCN Circular 21916, Tanaka et al. (Fermi-LAT), AT 10791, Fox et al. (Swift and NuSTAR), AT 10845, Mirzoyan et al. (MAGIC), AT 10817, de Naurois et al. (HESS), AT 10787, Mukherjee et al. (VERITAS), AT 10833.

TXS 0506+056: What about Gamma-Rays?
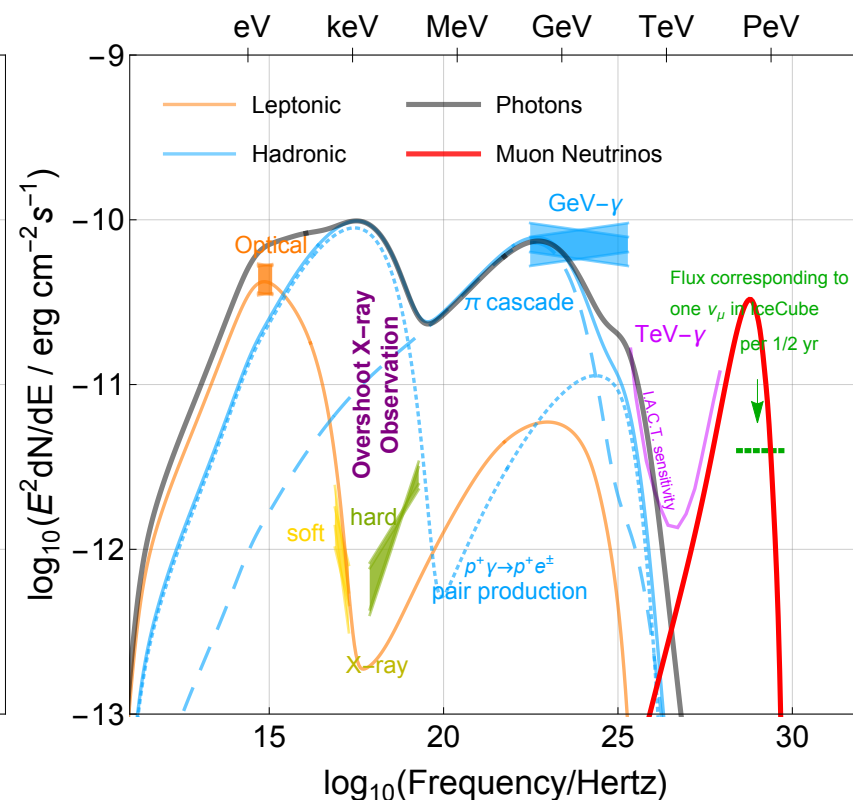

Figure credit: A. Franckowiak.
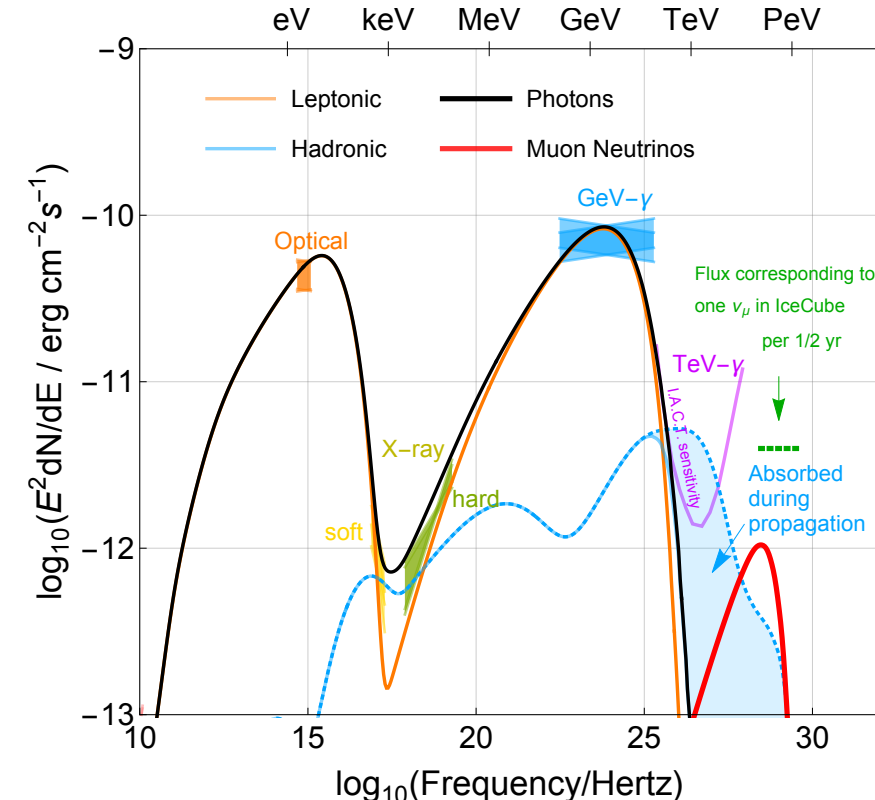
TXS 0506+056

Leptonic Model

No neutrino production

Hadronic Model

Observed x-ray flux overshot

## Hybrid Model

All spectra well reproduced

TXS 0506+056 is likely a "masquerading BL-Lac" (i.e., flat-spectrum radio quasar with hidden broad lines and a standard accretion disk).

Multi-zone models seem to work better. Clear picture of neutrino production under debate.

Gao et al., Nat. Astron. (2019). Padovani et al., MNRAS (2019).

Neutrinos from the Active Galaxy NGC 1068
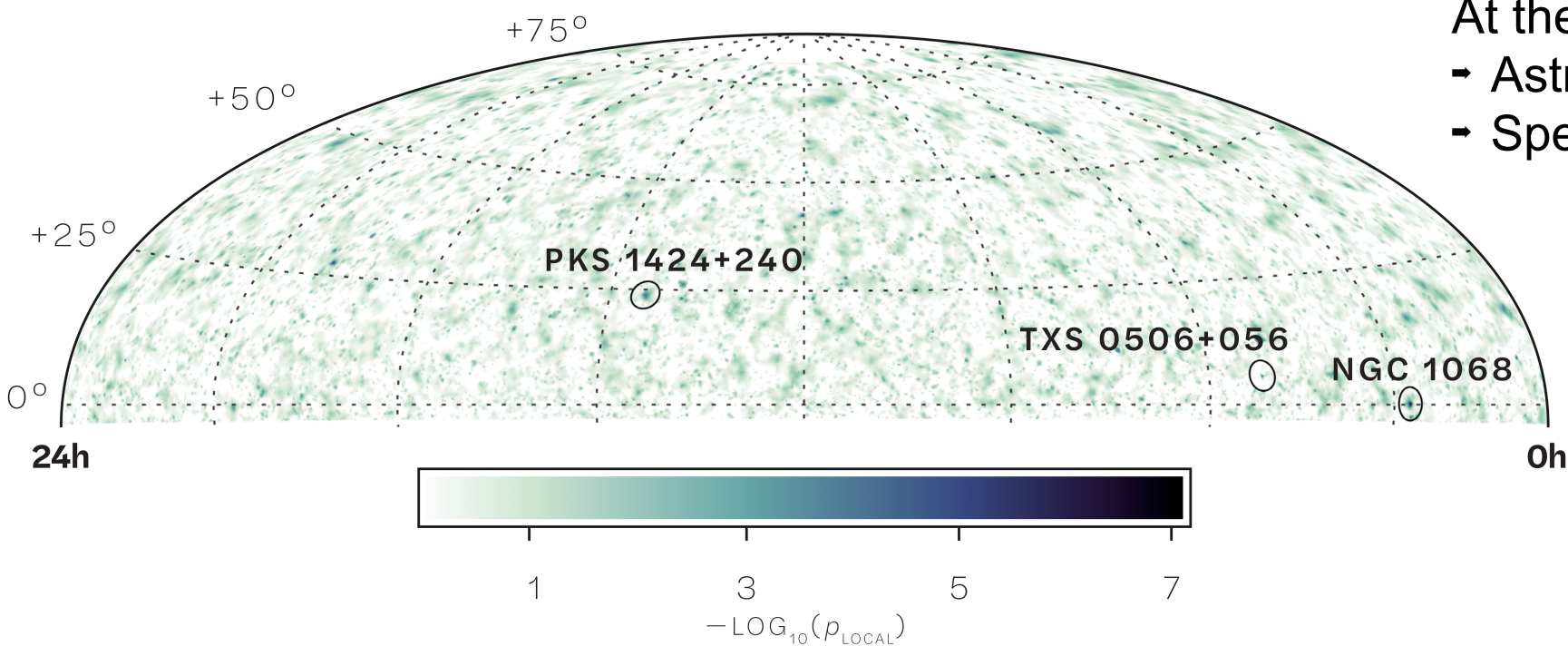
At the NGC1068 location:

➥ Astrophysical neutrino events = 79^{+22}_{-20}
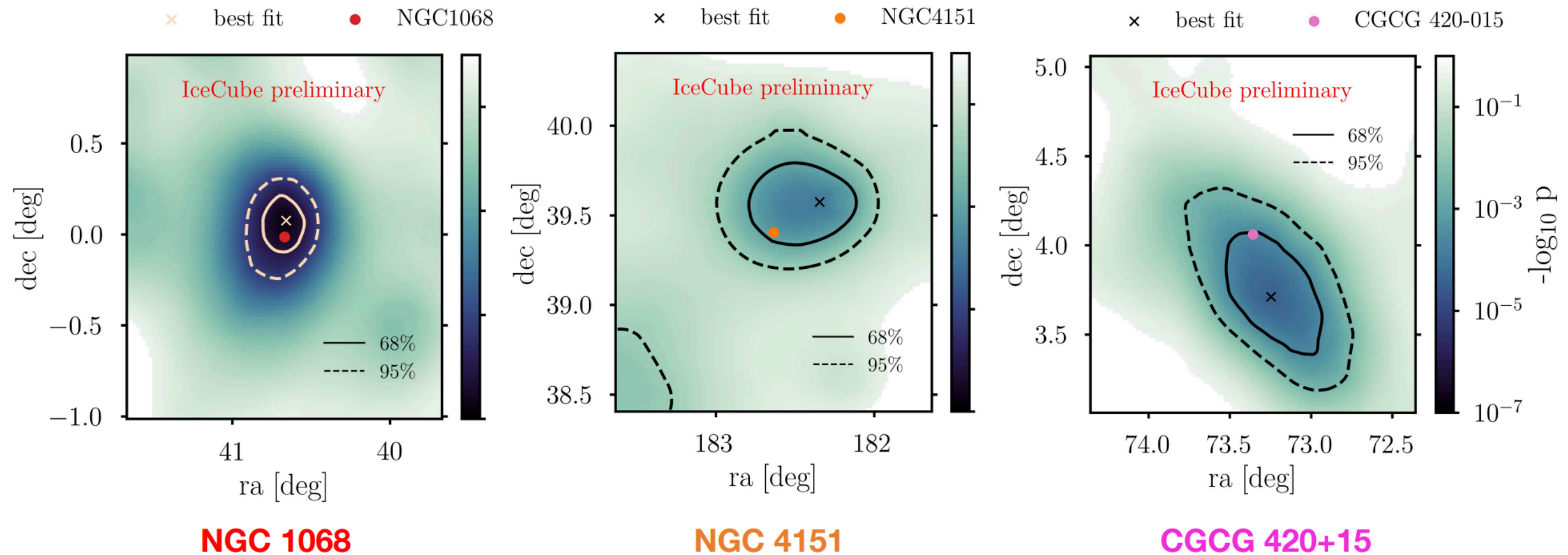
➥ Spectral index = 3.2 ± 0.2

Abbasi et al., Science (2022).
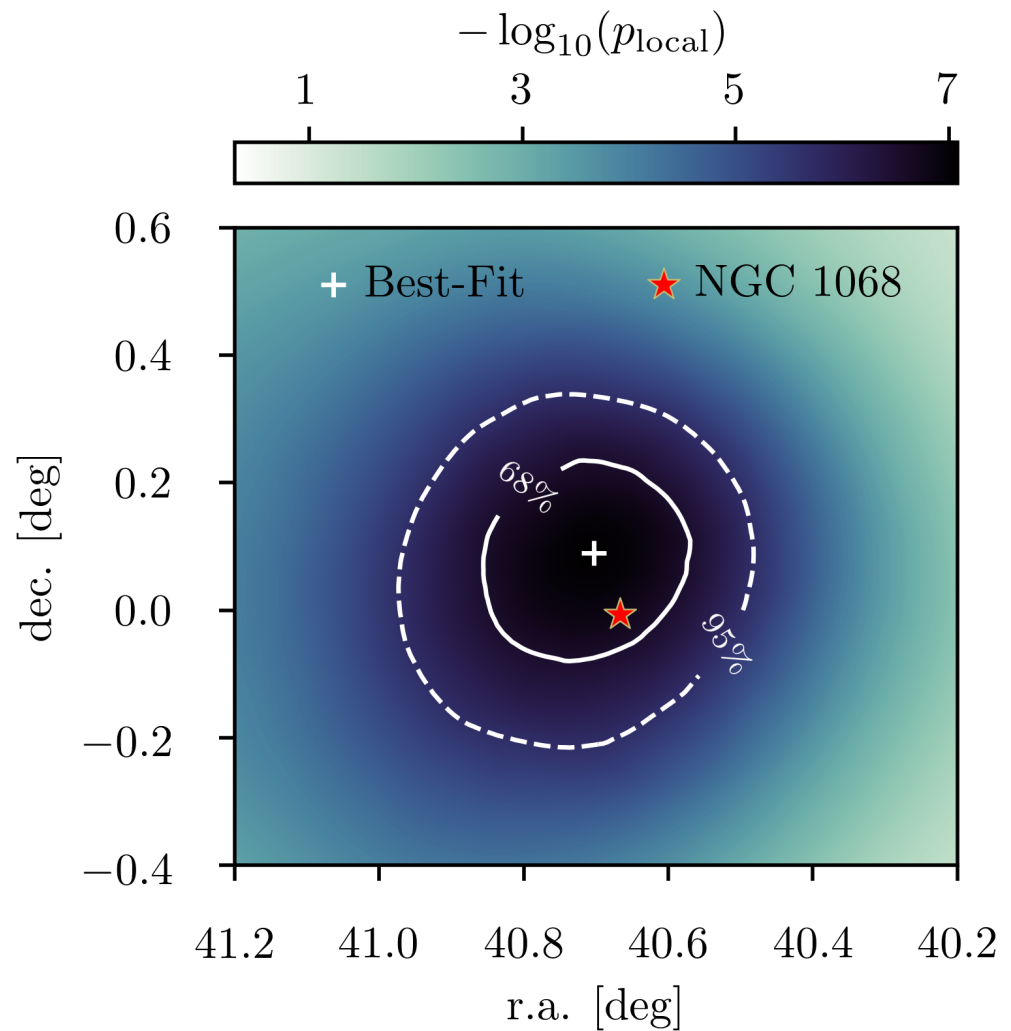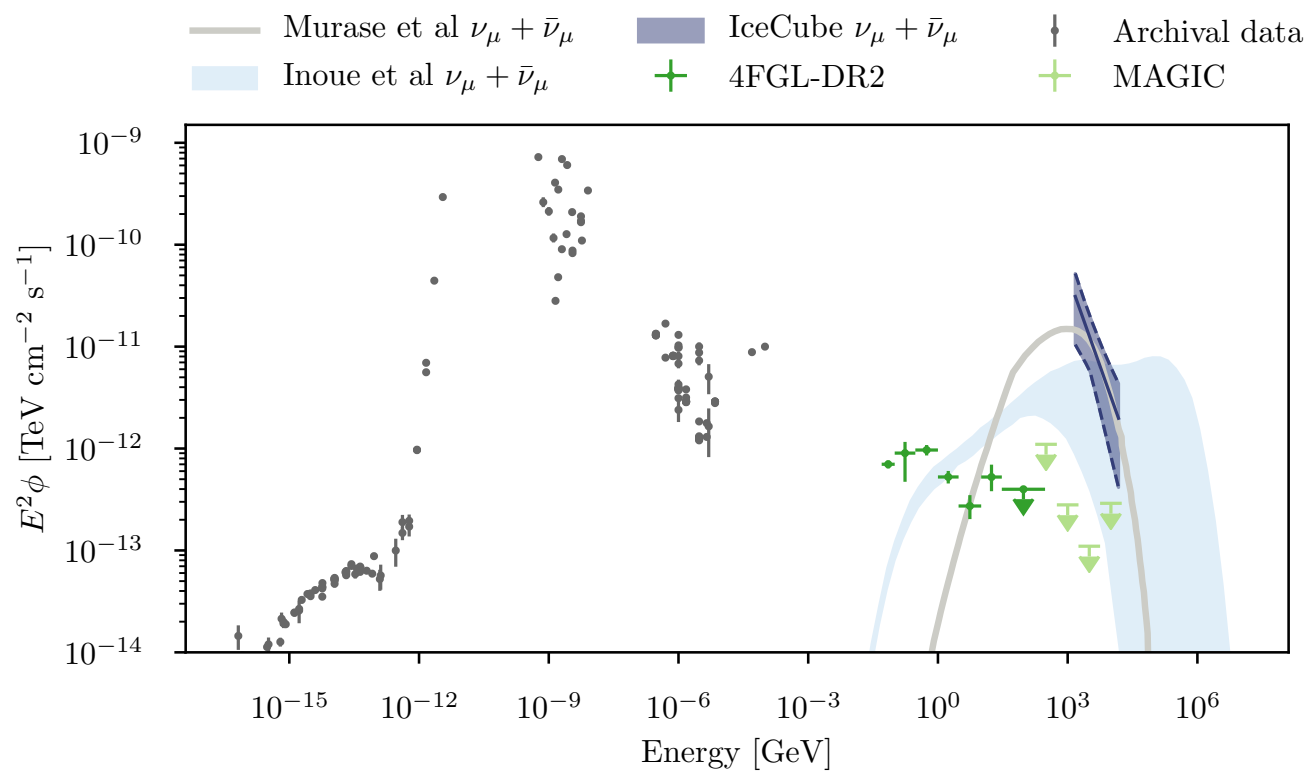
NGC 1068:
Neutrinos as a new lens to explore the galaxy core.
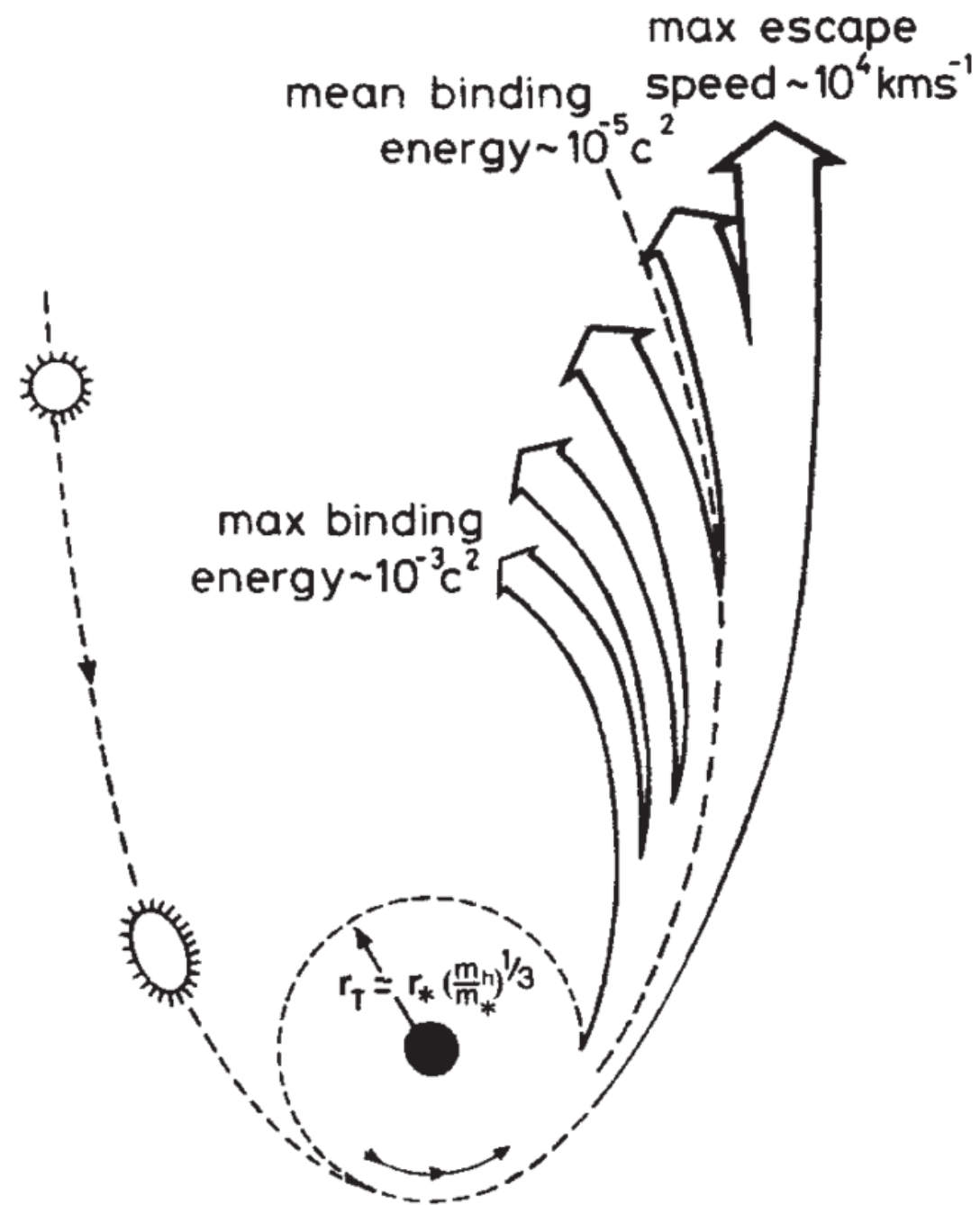Neutrinos carry information about the obscured supermassive black hole

Credit: NASA/JPL-Caltech

Do We See More Seyfert Galaxies?

NGC 1068   **NGC 4151**   **CGCG 420+15**

catalog search **"hottest source"** (after accounting for trials) p = 0.01 (2.3σ)

Tidal Disruption Events

max escape speed $\sim 10^4 \, \mathrm{kms}^{-1}$

mean binding energy $\sim 10^{-5} c^2$

max binding energy $\sim 10^{-3} c^2$

$$r_T \simeq r_* \left(\frac{m_h}{m_*}\right)^{1/3}$$

M. Rees, Nature (1988).

Neutrino Emission
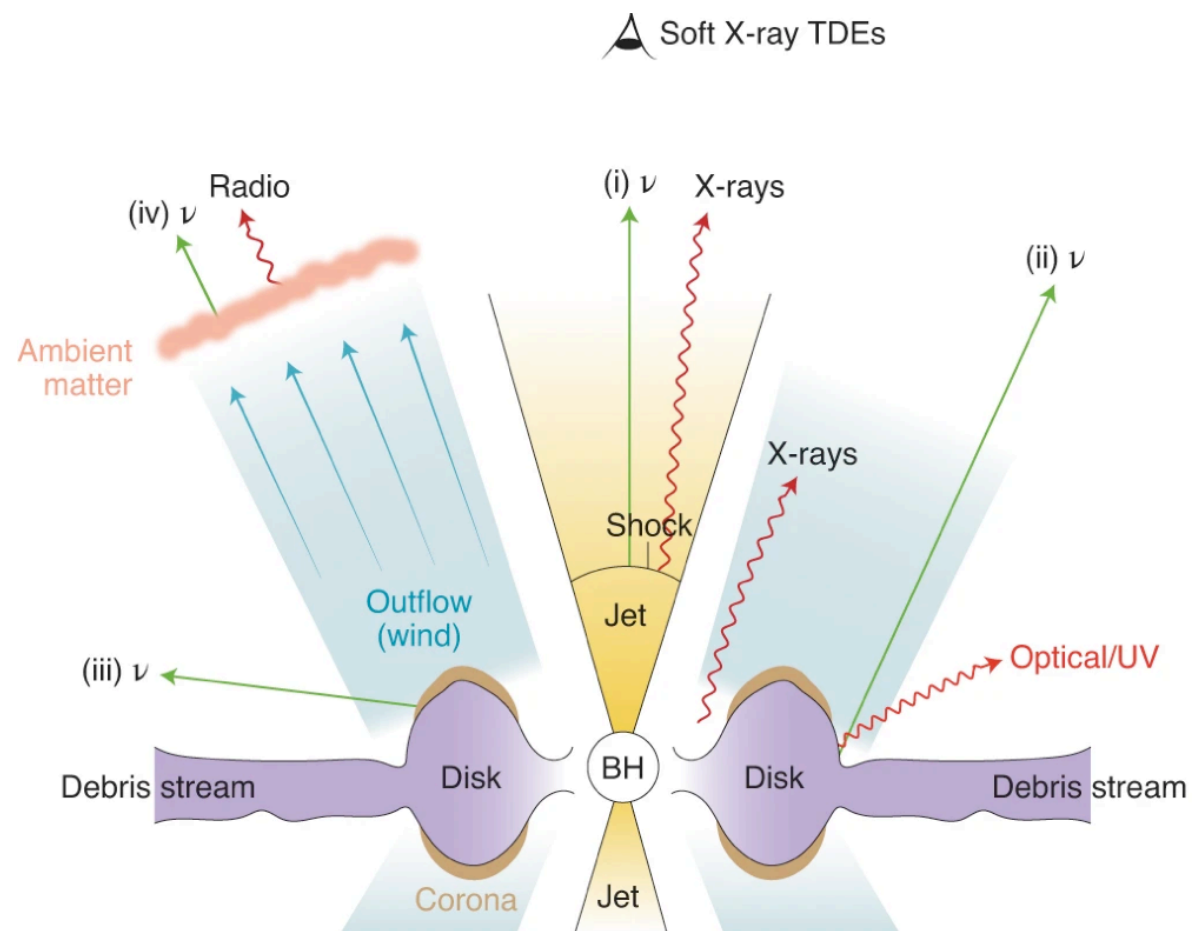
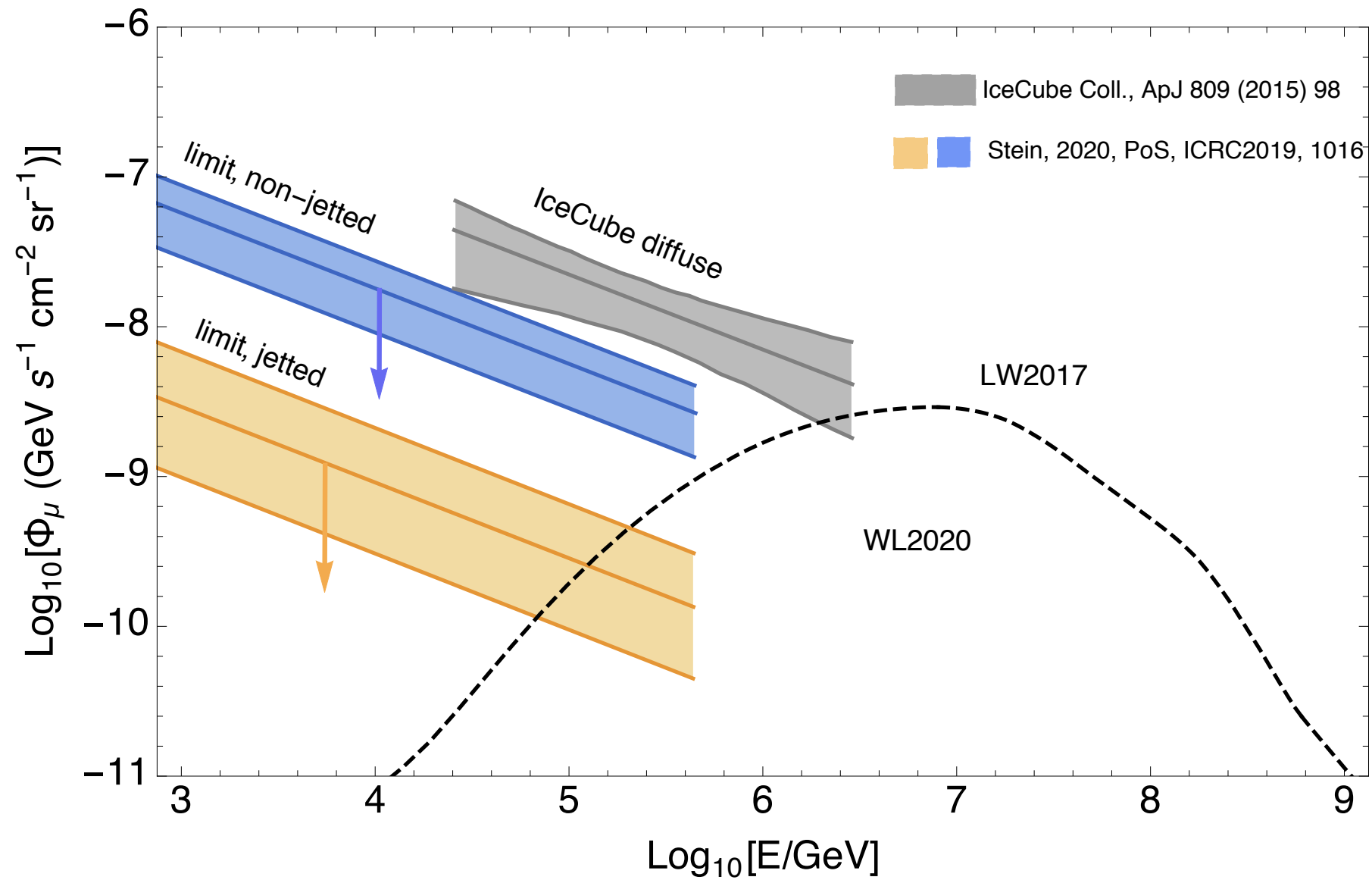

Neutrino production sites include:

- Relativistic jet
- Accretion disk/corona
- Wind/outflow

DESY.

- Conditions appear consistent with the production/detection of one PeV neutrino.

- Various theoretical scenarios currently under debate.

K. Hayasaki, Nat. Astr. (2021).

Contribution of TDEs to Diffuse Emission

TDEs could contribute up to 26% of the IceCube diffuse astrophysical flux.

Figure credit: Stein, PoS ICRC2019 (2020). Lunardini & Winter, PRD (2017).

# A TDE-Neutrino Association?
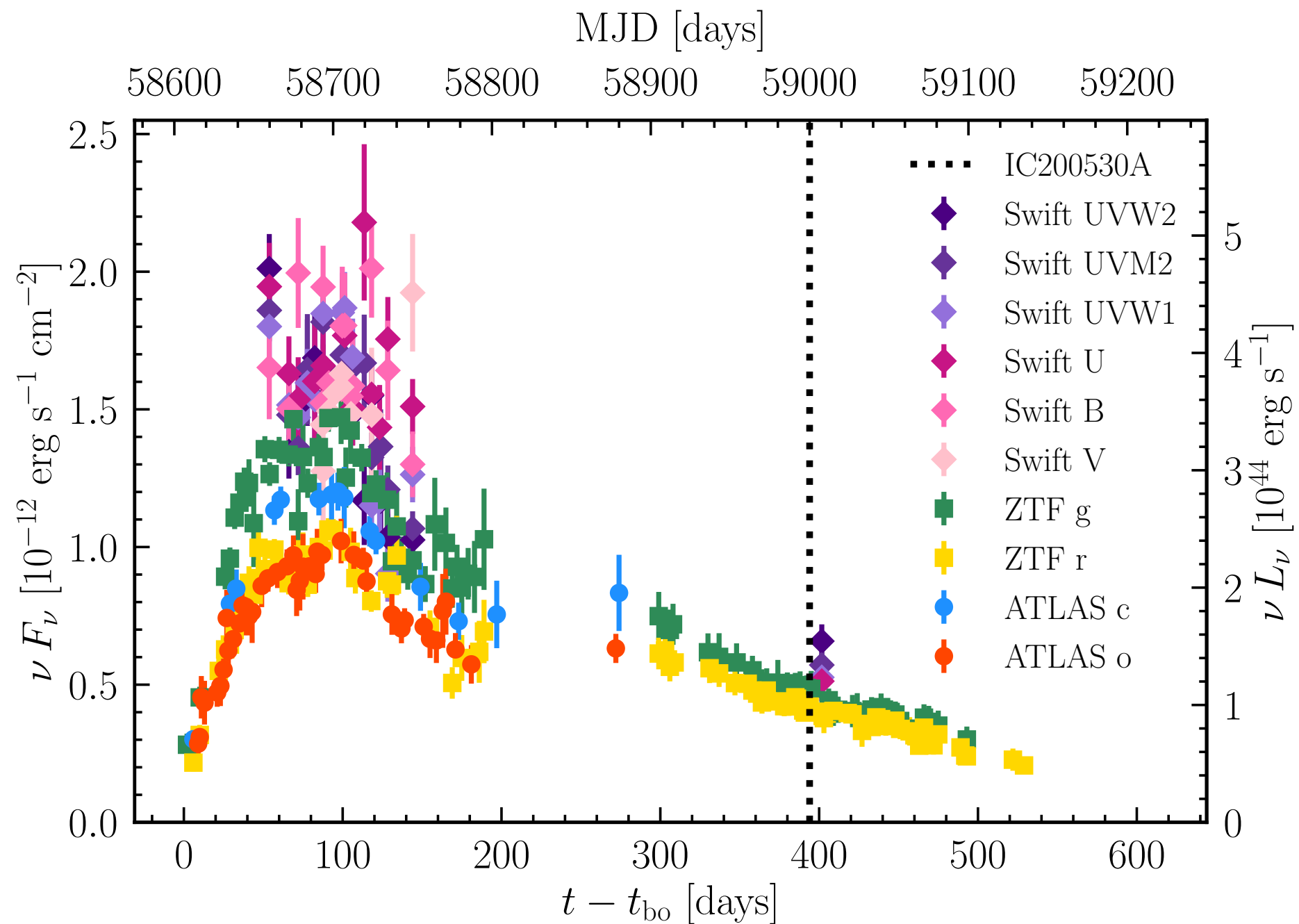
- Is AT2019fdr a TDE in a narrow-line Seyfert Galaxy? Neutrino event (IC200530A, 80 TeV) observed in coincidence with AT2019fdr.

- Classified as probably TDE, but AGN flare/SN origin cannot excluded.

Reusch et al., PRL (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022).

Superluminous Supernovae
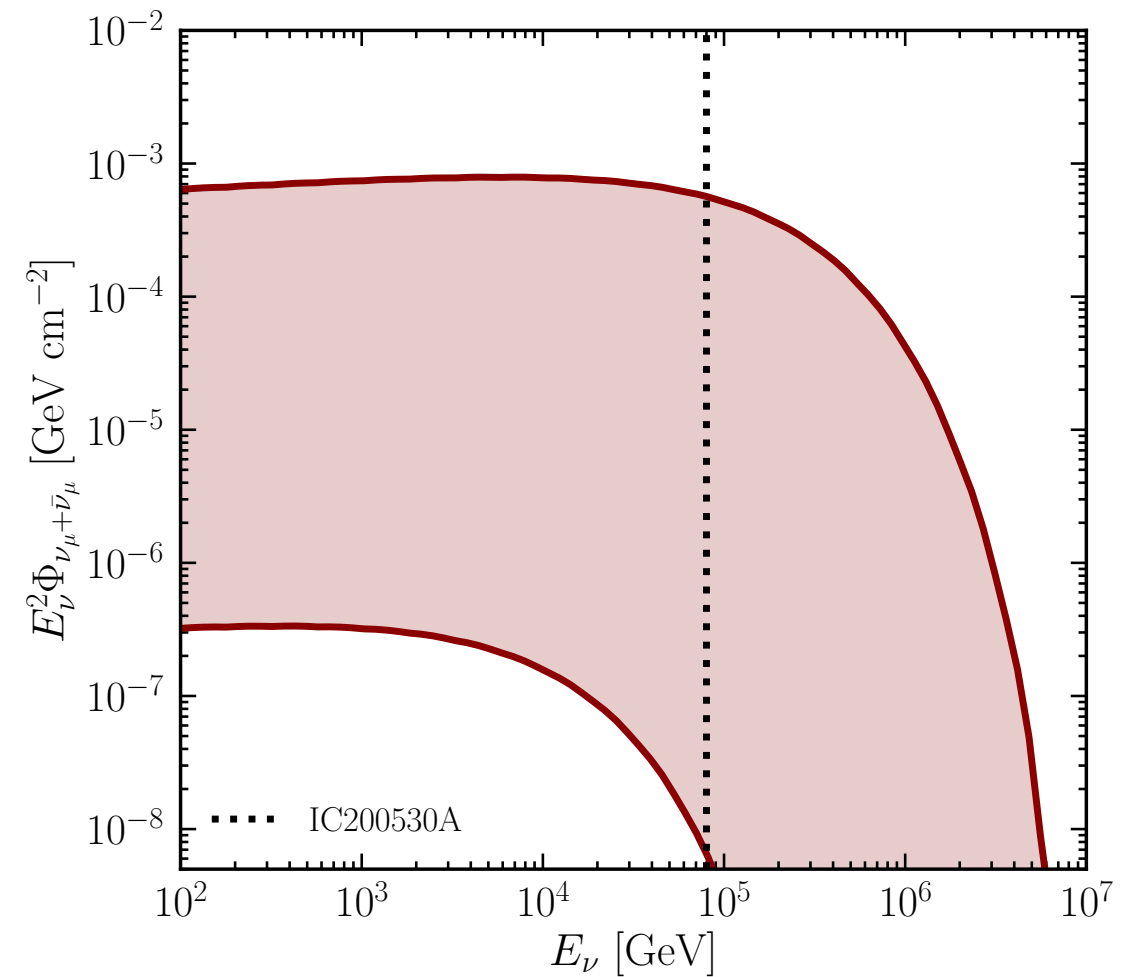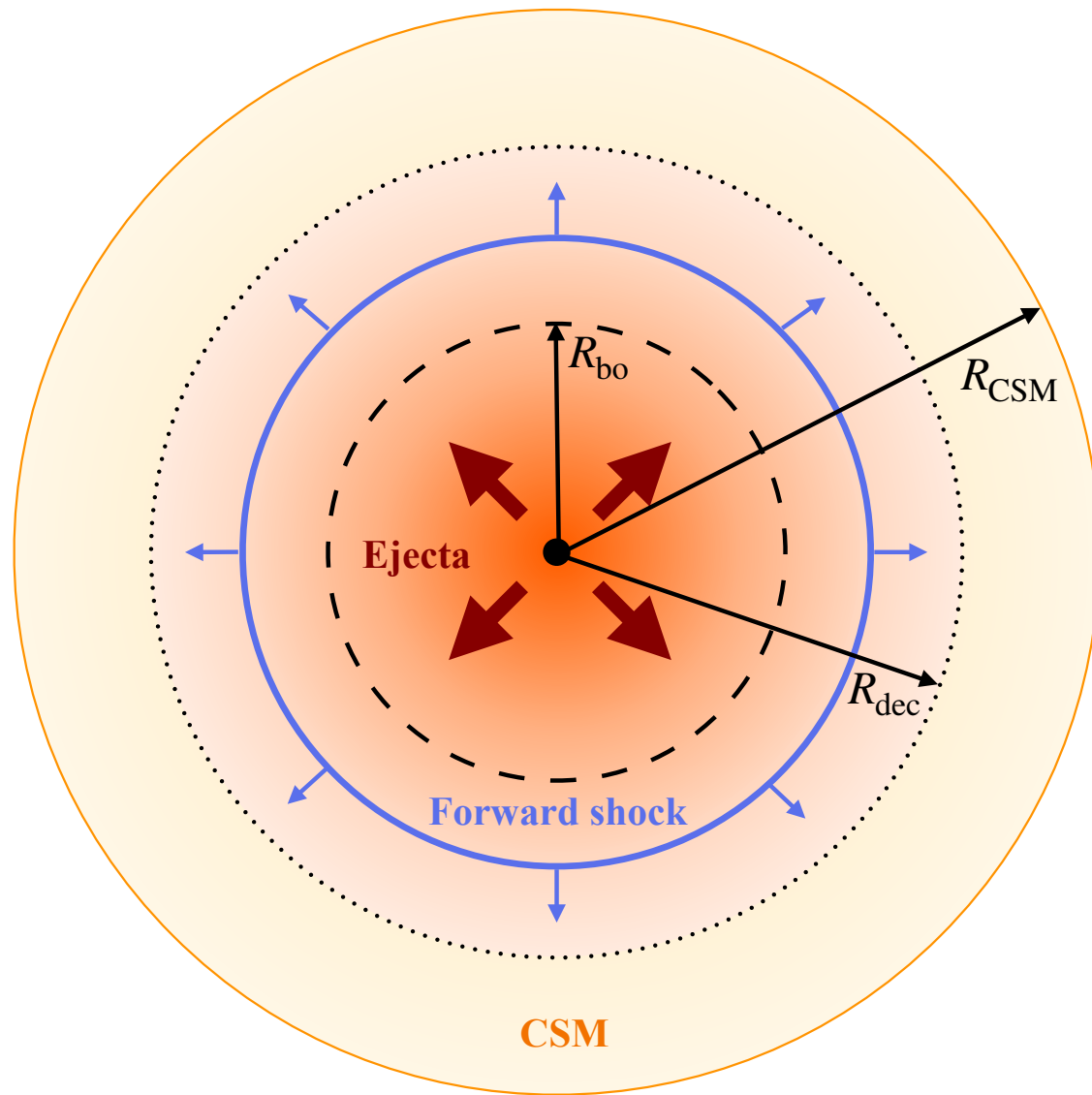
Thermal neutrinos are produced in the supernova core. High-energy (non thermal neutrinos) can be produced via pp collisions between the relativistic protons accelerated at the forward shock and the cold protons of the circumstellar medium.

Pitik, Tamborra, Angus, Auchettl, ApJ (2022).

Neutrinos from Supernovae
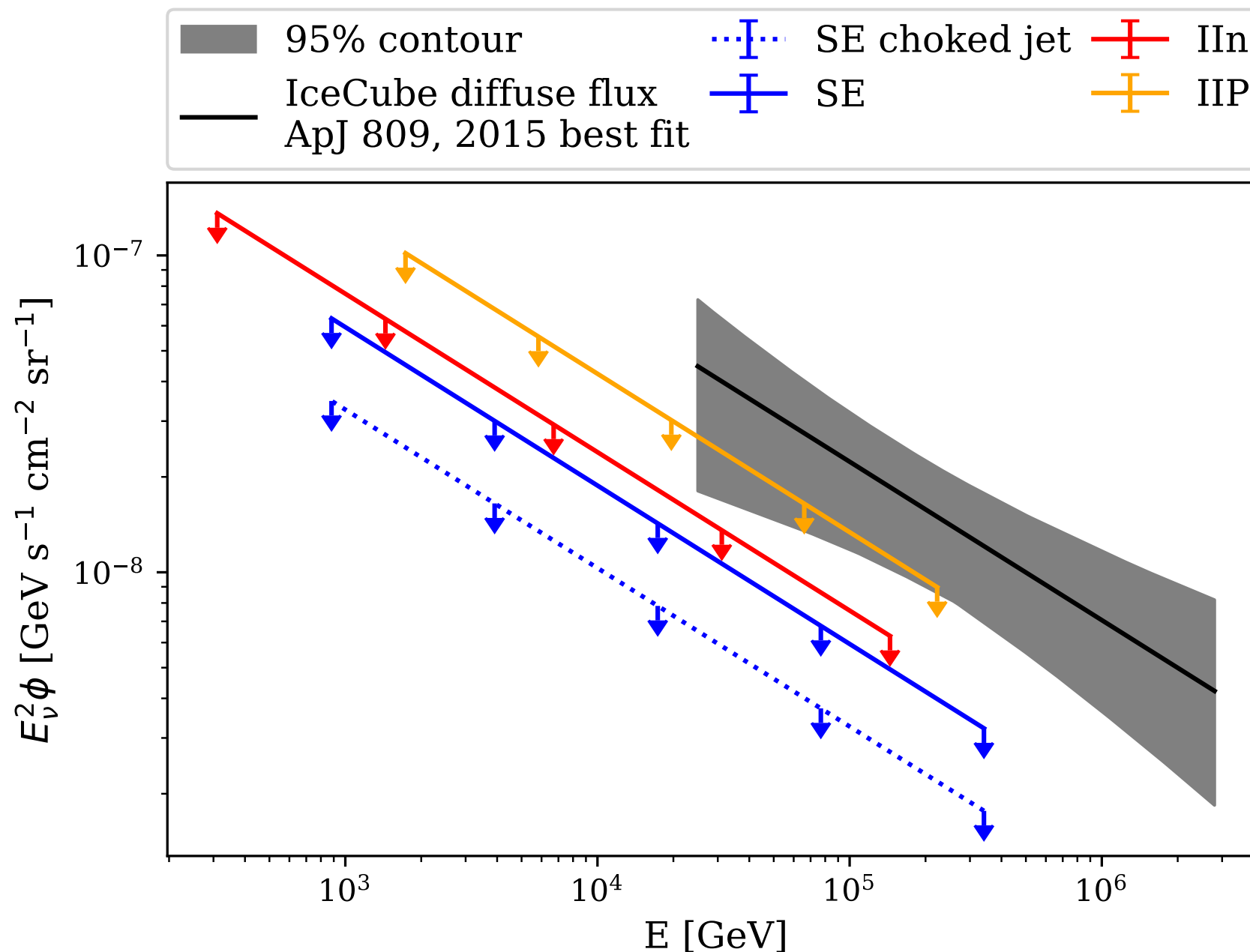
- No significant spatial or temporal correlation of high-energy neutrinos with supernovae found yet (upper limit on total energy emitted in neutrinos: 1.3×10^{49} erg for SNe IIn).

- SNe IIn (SNe IIP) do not contribute more than 33.9.6% (59.9%) to the diffuse neutrino flux observed by IceCube.

Take Home Messages

- High energy neutrinos of astrophysical origin: a new lens to learn about the (dark) universe.

- Growing number of neutrino observations in coincidence with EM emission.

- Acceleration sites and mechanisms of production of neutrinos and EM radiation to be better understood.

Additional references:

➡ Gaisser, Engel, Resconi, Cosmic Rays and Particle Physics, 2nd edition, Cambridge University Press

➡ Vitagliano, Tamborra, Raffelt, https://arxiv.org/abs/1910.11878 (Section XI)

➡ C. Guepin, K. Kotera, F. Oikonomou, https://arxiv.org/abs/2207.12205

➡ K. Murase, I. Bartos, https://arxiv.org/abs/1907.12506