The Niels Bohr International Academy

Dark Cosmology Centre

VILLUM FONDEN

SFB 1258 Neutrinos Dark Matter Messengers

The High Energy Neutrino Sky

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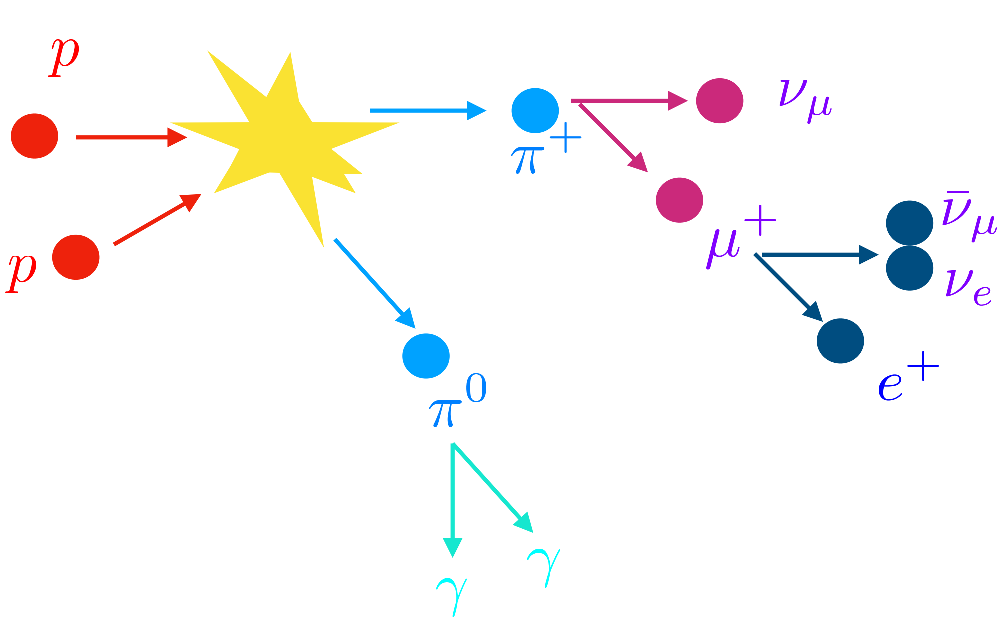
Invisibles18 Workshop

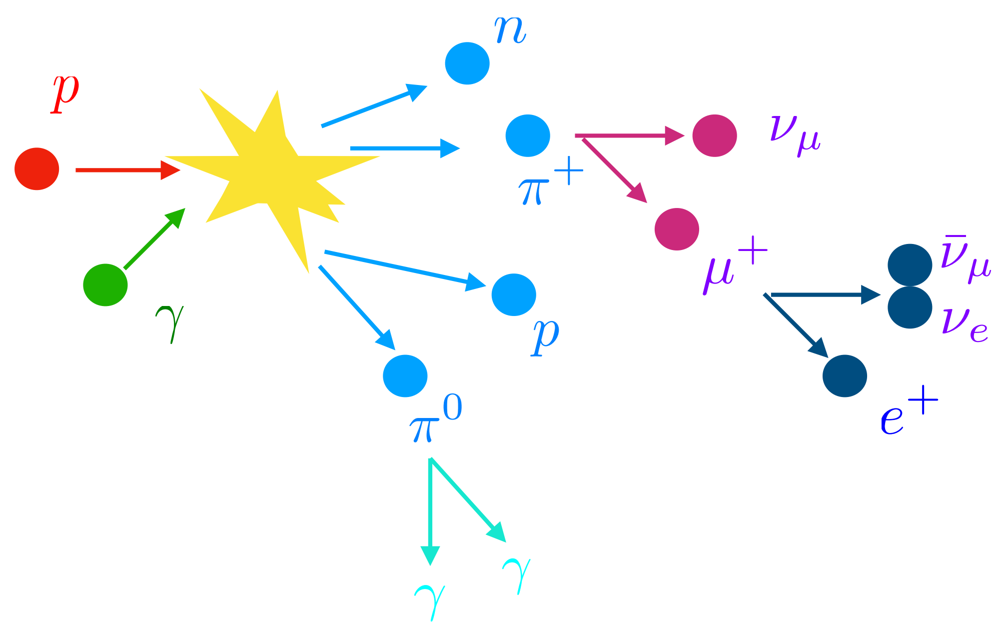
Karlsruhe, September 4, 2018

High Energy Neutrino Production

Proton-proton interactions



Proton-photon interactions

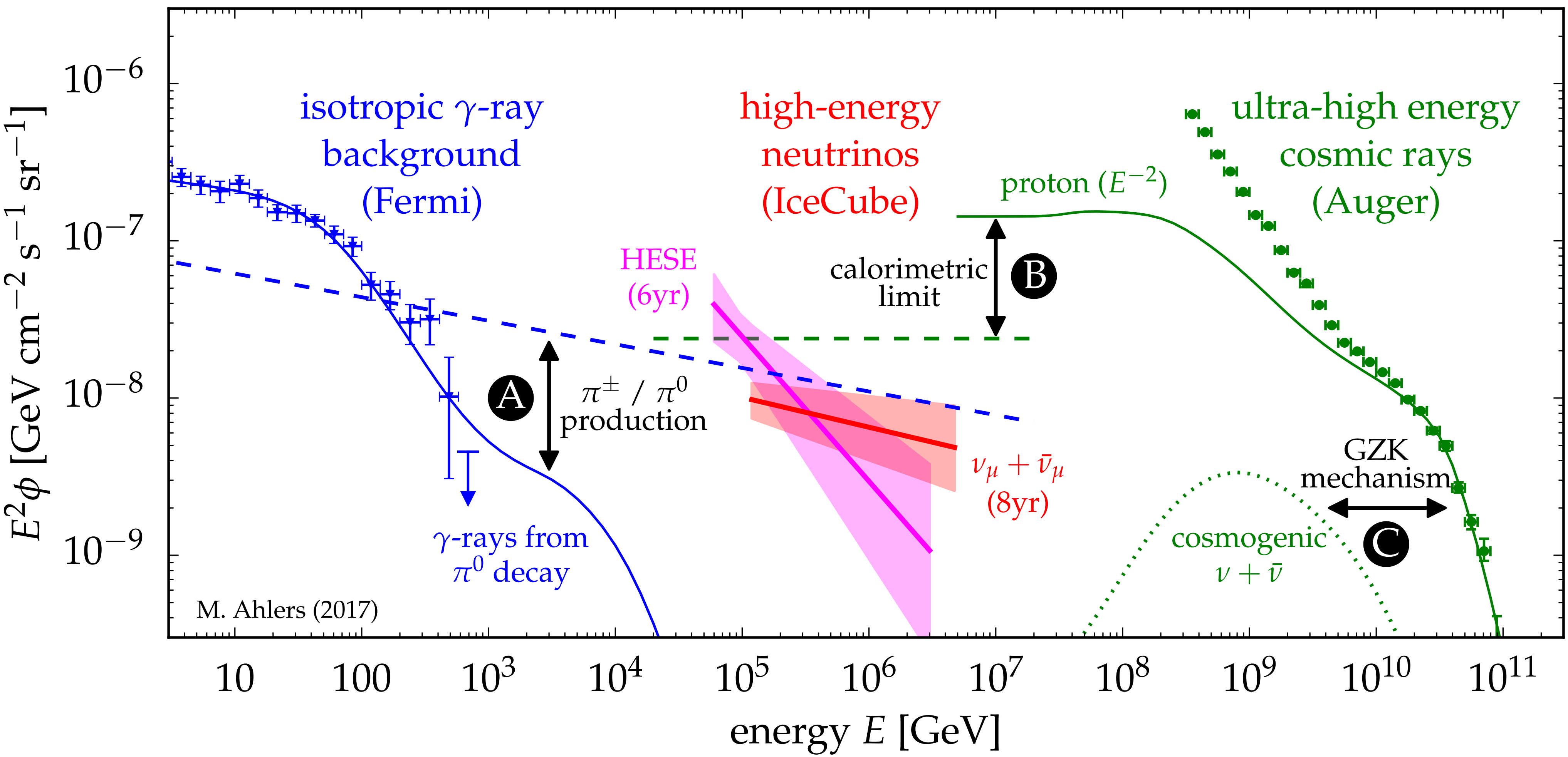


Electron and muon neutrinos are produced by charged pion decay.

Gamma-ray photons are produced by neutral pion decay.

Anchordoqui et al., PLB (2004). Kelner, Aharonian, Bugayov, PRD (2006). Kelner, Aharonian, PRD (2008).

Messengers of the High Energy Heavens

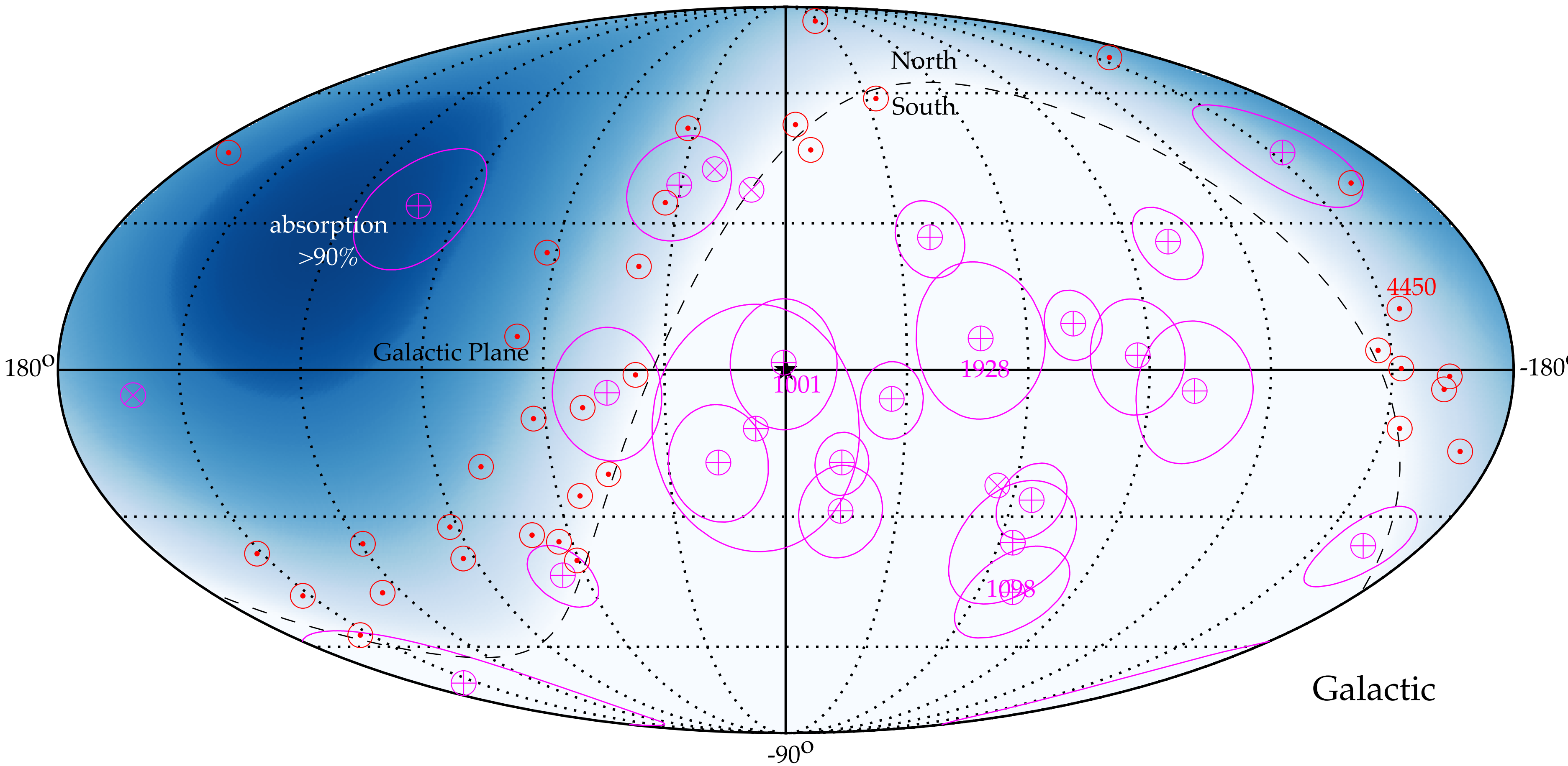


Neutrinos, gamma rays and cosmic rays have similar energies.

Figure taken from Ahlers & Halzen, arXiv: 1805.11112.

Neutrino Arrival Directions

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



No evidence of clustering in arrival directions of HE neutrinos ➡ Isotropic distribution

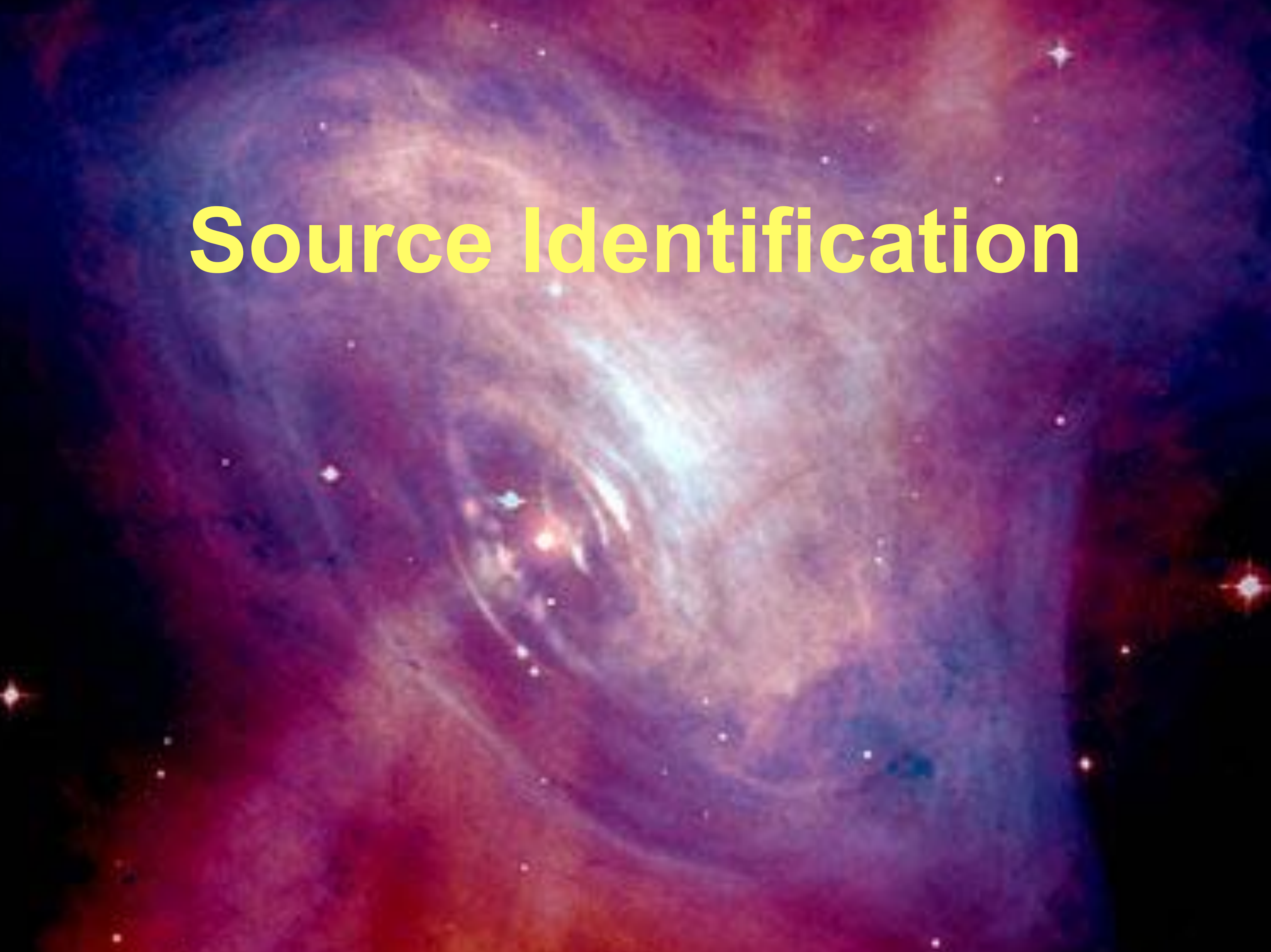
➡ **Neutrinos of extragalactic origin**.

Figure taken from Ahlers & Halzen, arXiv: 1805.11112.

Emerging Tasks

- Find the sources of IceCube's high energy neutrinos.
- Identify any connection with UHECR & electromagnetic emission.
- Understand production mechanisms of high energy cosmic particles.
- Use multi-messenger data to obtain a unique view on sources.
- Test physics beyond the Standard Model.

Source Identification



Where Are These Neutrinos Coming From?

★ New physics?

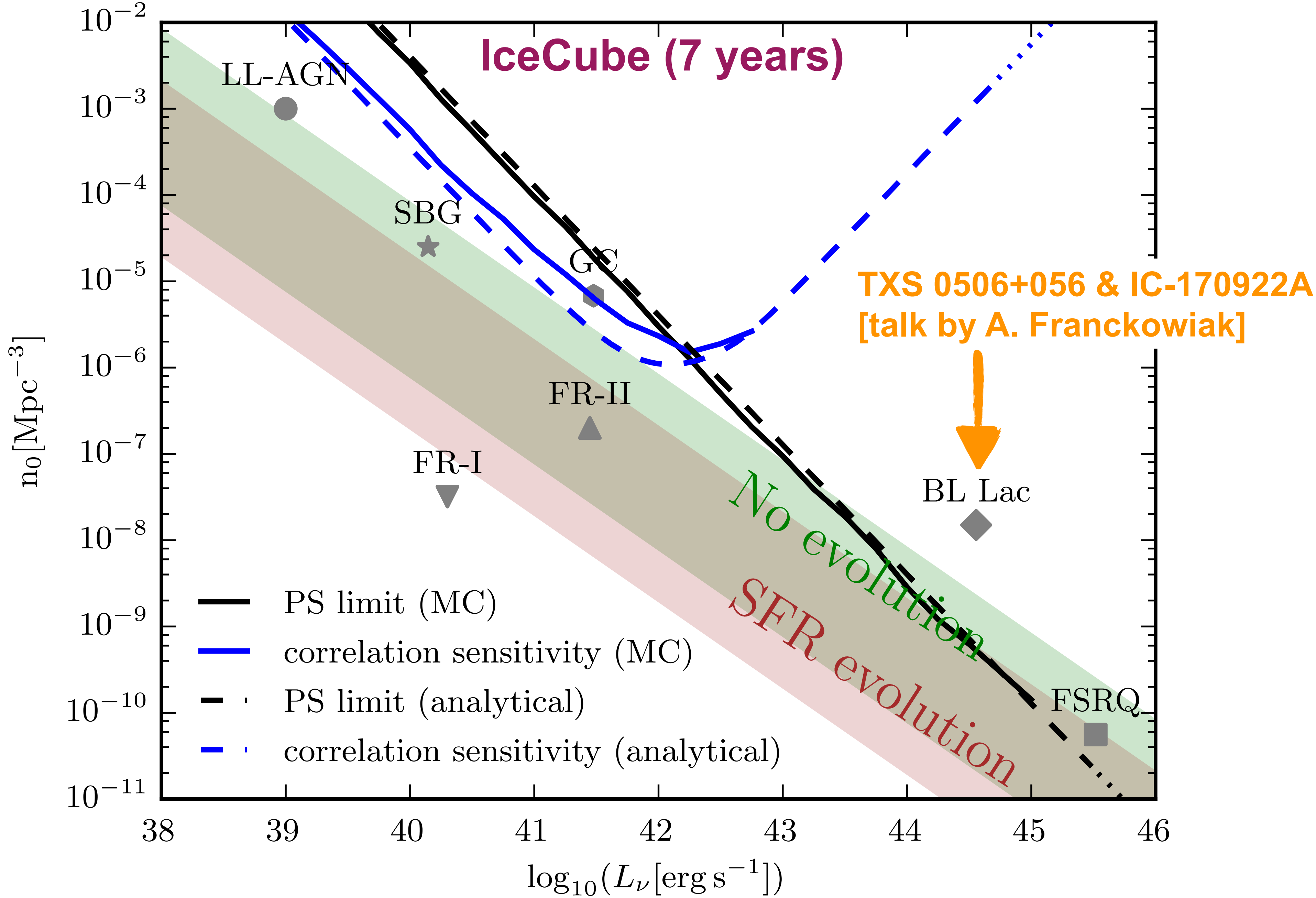
★ Galactic origin [sub-dominant contribution]

★ **Extragalactic origin**

- Star-forming galaxies
- Gamma-ray bursts
- Active galactic nuclei, blazars
- Cluster of galaxies
- Tidal disruption events
- Low-power or choked sources

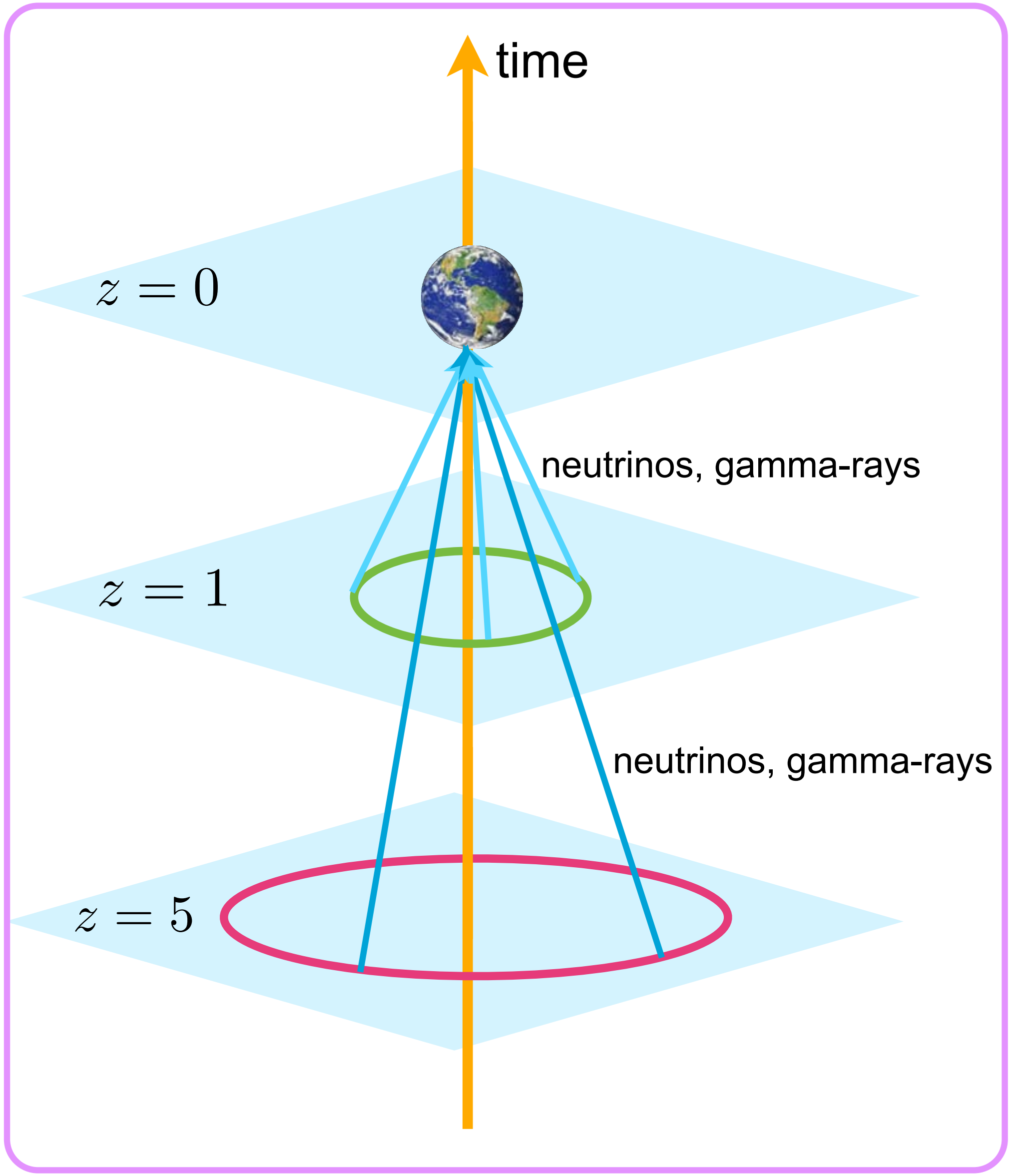
Anchordoqui et al., JHEAp (2014). Meszaros, arXiv: 1511.01396. Waxman, arXiv: 1511.00815. Murase, arXiv: 1511.01590.

Neutrino Point Sources



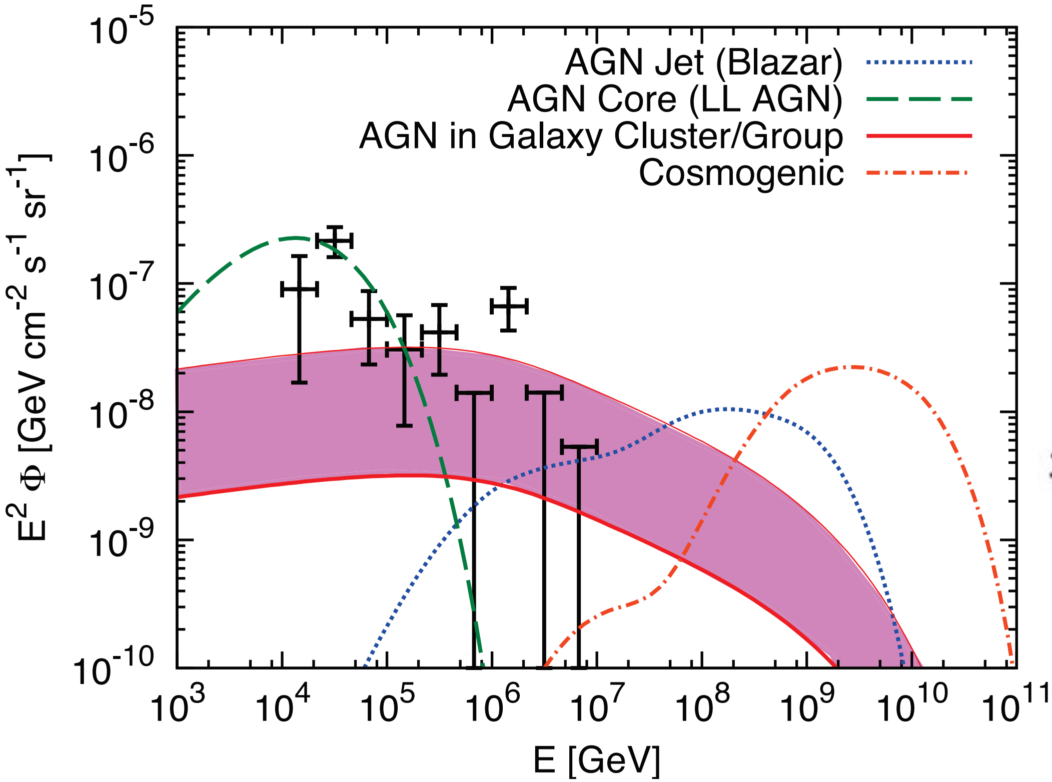
Mertsch, Rameez, Tamborra, JCAP (2017). Murase & Waxman PRD (2016). Feyereisen,Tamborra, Ando, JCAP (2017).

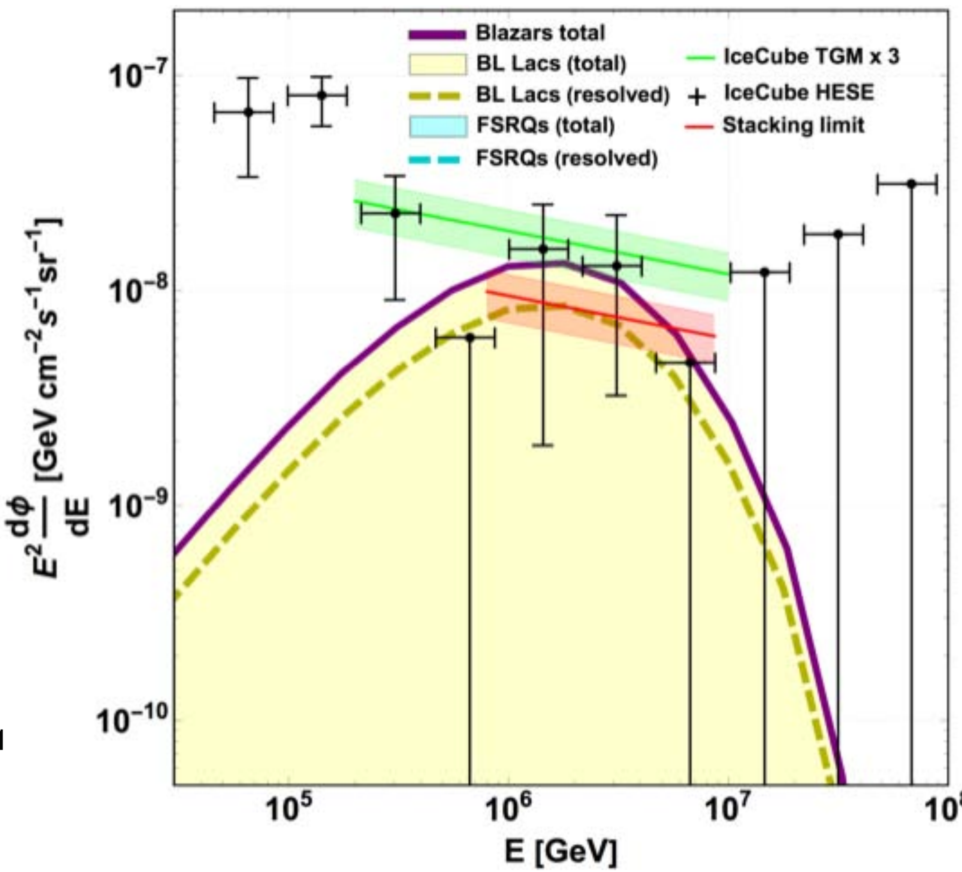
Diffuse Neutrino Backgrounds



- Spectral energy distribution
- Distribution of sources with redshift
- Distribution of sources with luminosity
- Comoving volume (cosmology)

Active Galactic Nuclei (Blazars)

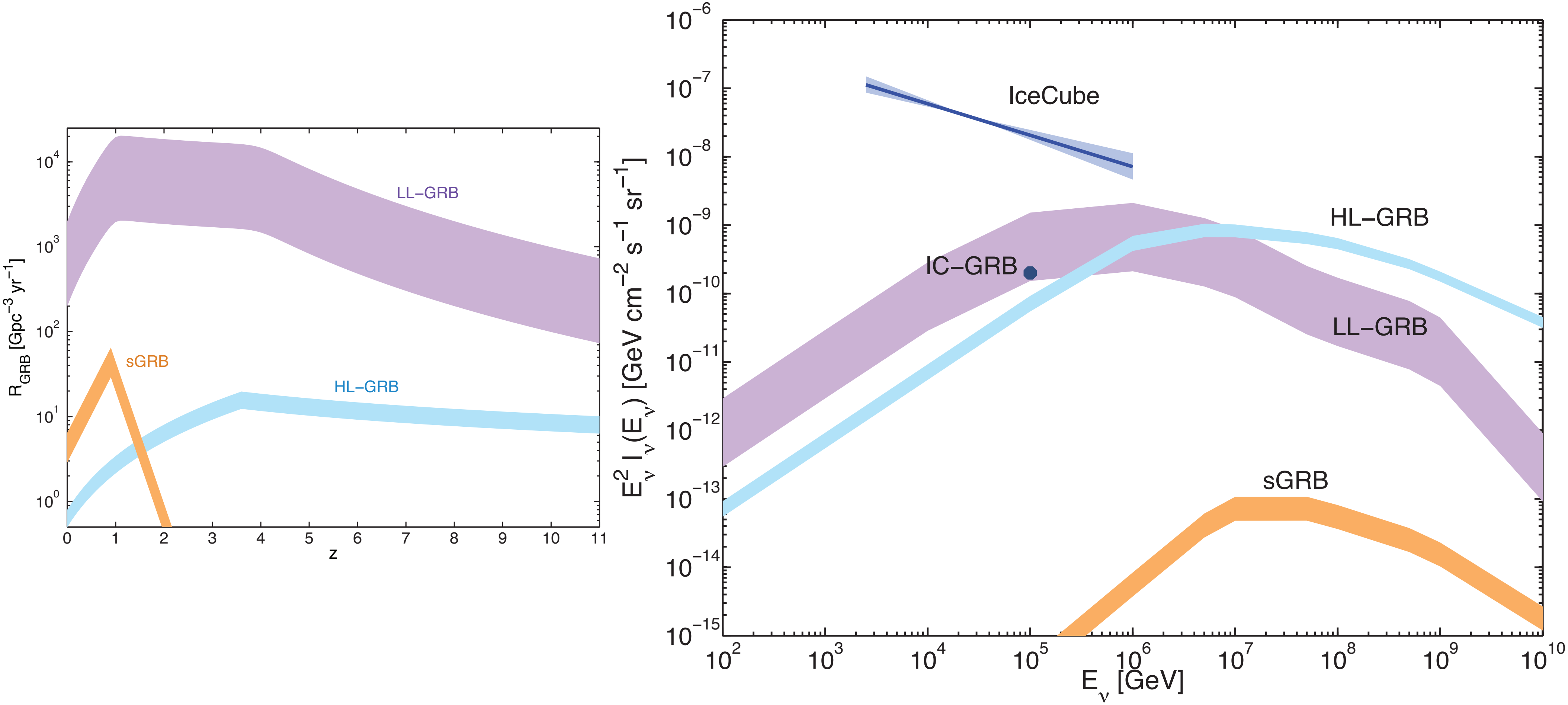




- AGN among suspected cosmic ray sources and as such natural candidate neutrino sources.
- Contribution from AGN is strongly model-dependent, but might be sizable.
- Resolved and unresolved blazars can partly explain the IceCube flux (w/o violating stacking bounds).

Palladino et al., arXiv: 1806.04769. Padovani et al., MNRAS (2015). Murase, arXiv: 1511.01590.

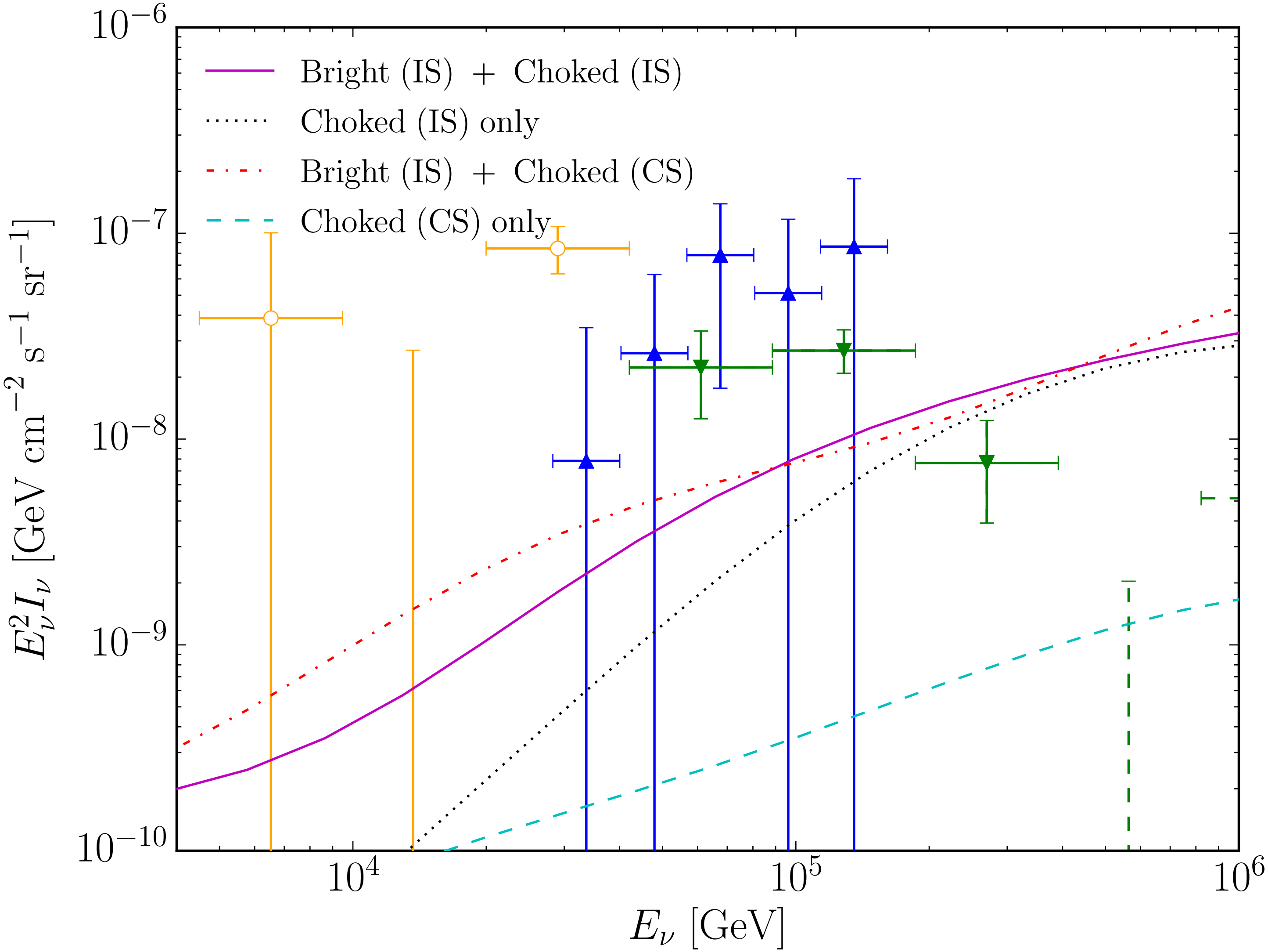
Gamma-Ray Bursts



- Dedicated stacking searches on GRBs unsuccessful up to now.
- Bright GRBs can make up to few % of the high-energy IceCube flux.
- Low luminosity GRBs can emit sizeable neutrino flux!

Tamborra & Ando, JCAP (2015), Liu&Wang (2013), Murase&Ioka (2013), Liang et al. (2006), Boncioli, Biehl, Winter (2018).

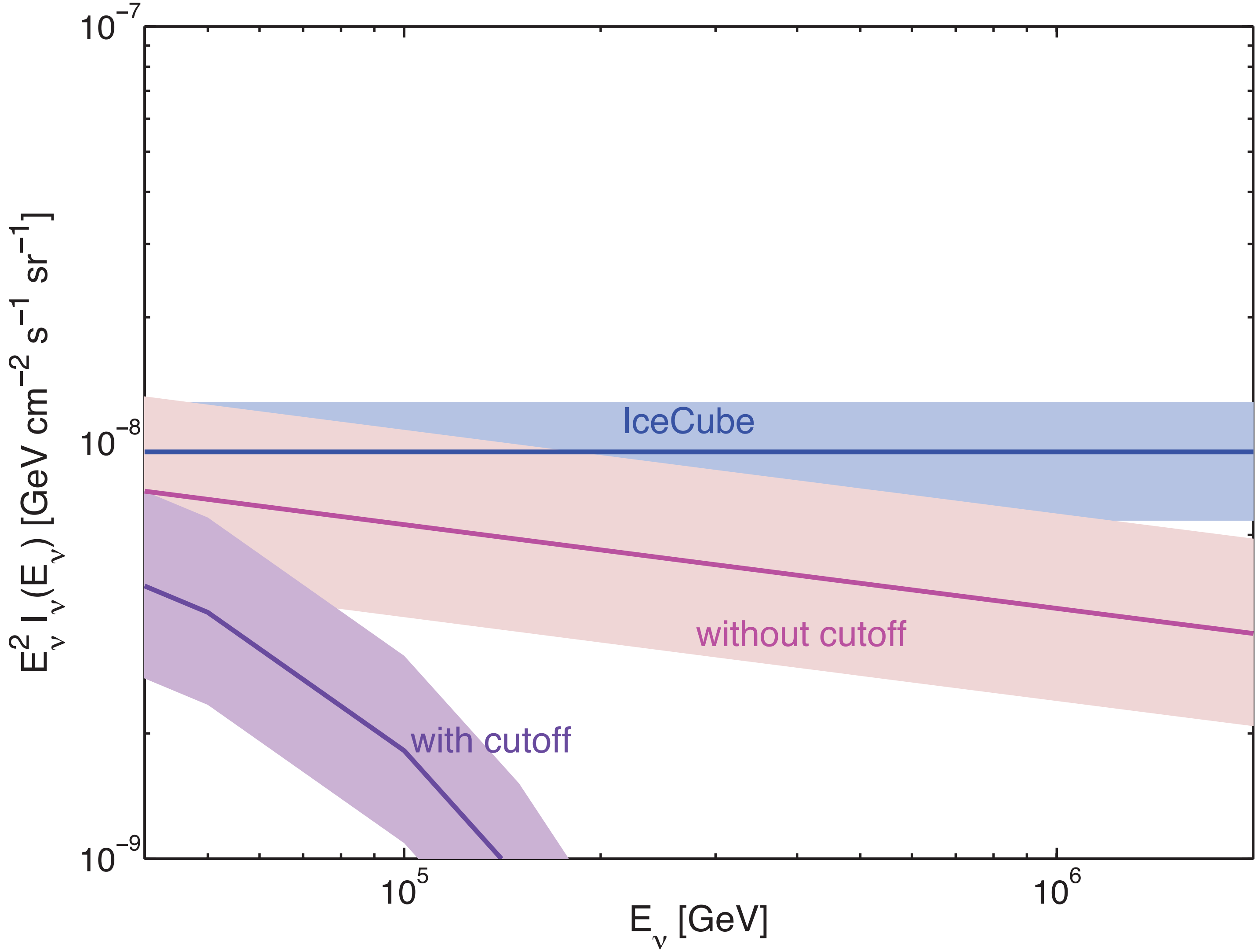
The Low-Energy Excess (30-400 TeV)



- Electromagnetically hidden sources invoked to interpret the low-energy excess.
- Although hidden GRBs can produce a copious amount of neutrinos, they cannot be the sources of excess of neutrino events at low energies.

Denton & Tamborra, JCAP (2018). Murase, Guetta, Ahlers, PRL (2016).

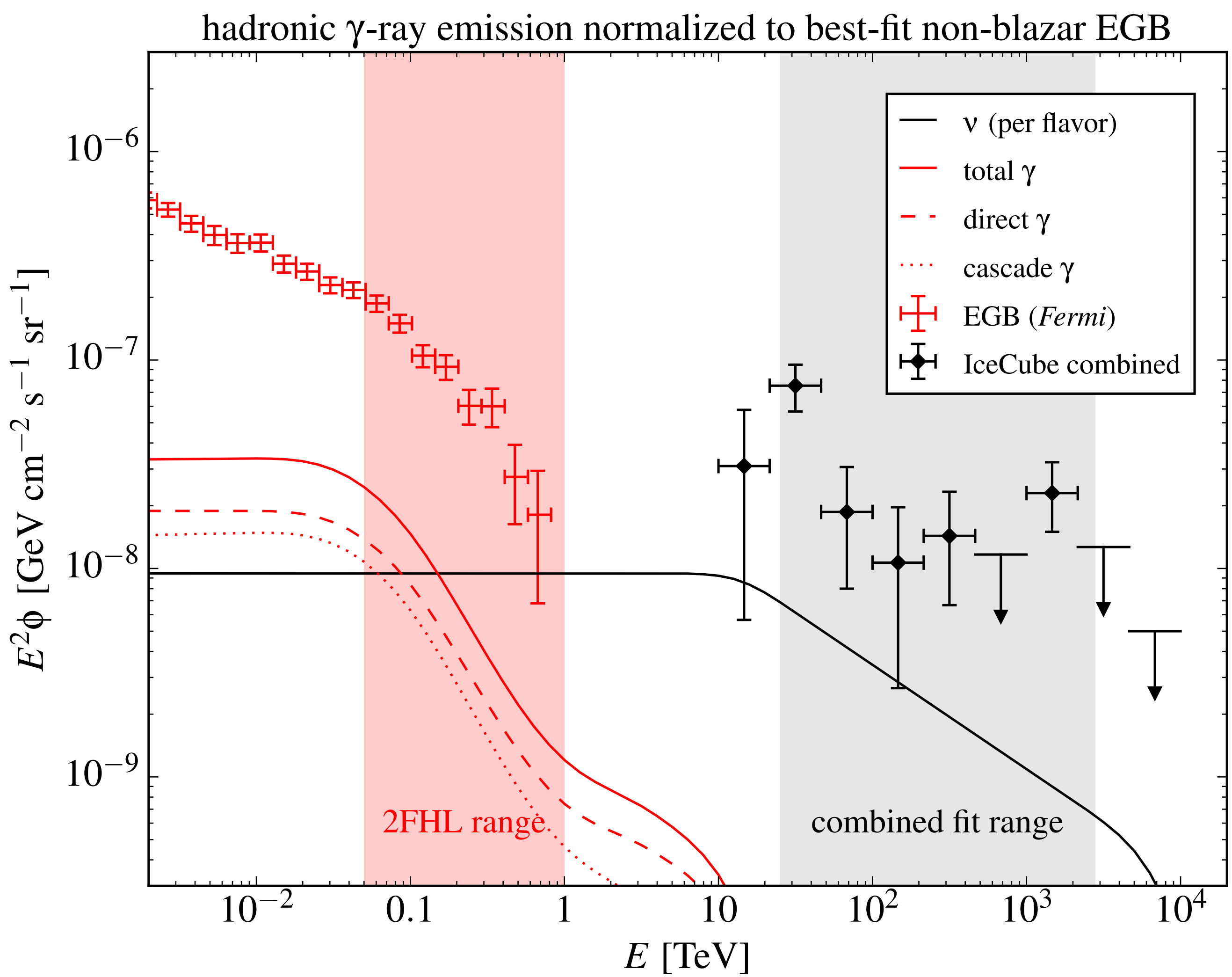
Star-Forming Galaxies



Under calorimetric conditions, star-forming galaxies efficiently produce neutrinos!

Tamborra, Ando, Murase, JCAP (2014). Thompson et al. (2006), Fields et al. (2010), Makiya et al. (2011), Stecker&Venters(2011). Loeb&Waxman (2006), Lacki et al. (2011), Murase et al. (2013).

Star-Forming Galaxies

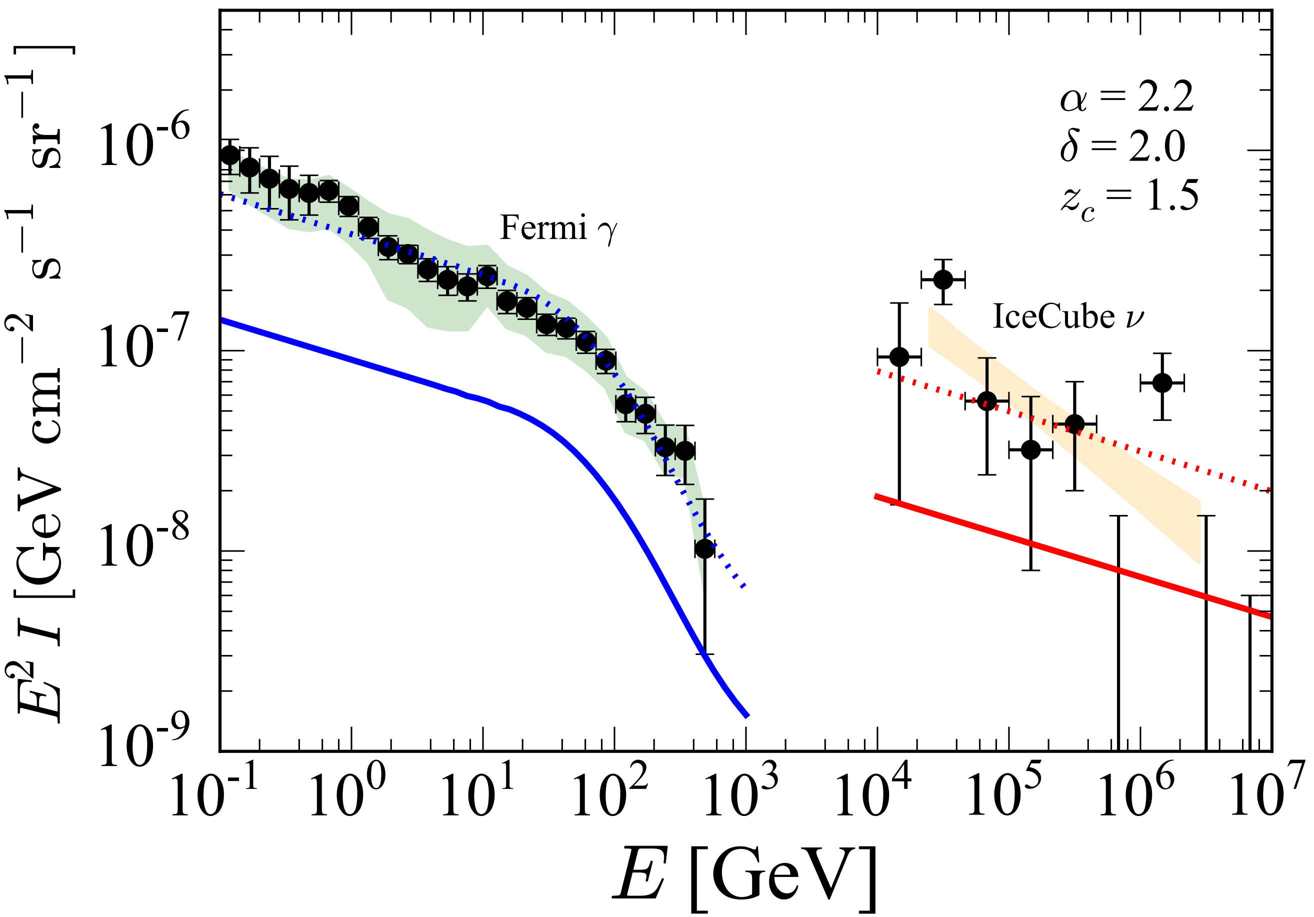


Fermi finds that blazars make 86% of the total extra-galactic gamma-ray background.

Results in possible tension with star-forming galaxies as dominant source of the diffuse neutrino background.

Bechtol et al., ApJ (2017). Fermi Collaboration, PRL (2016).

Tomographic Constraints



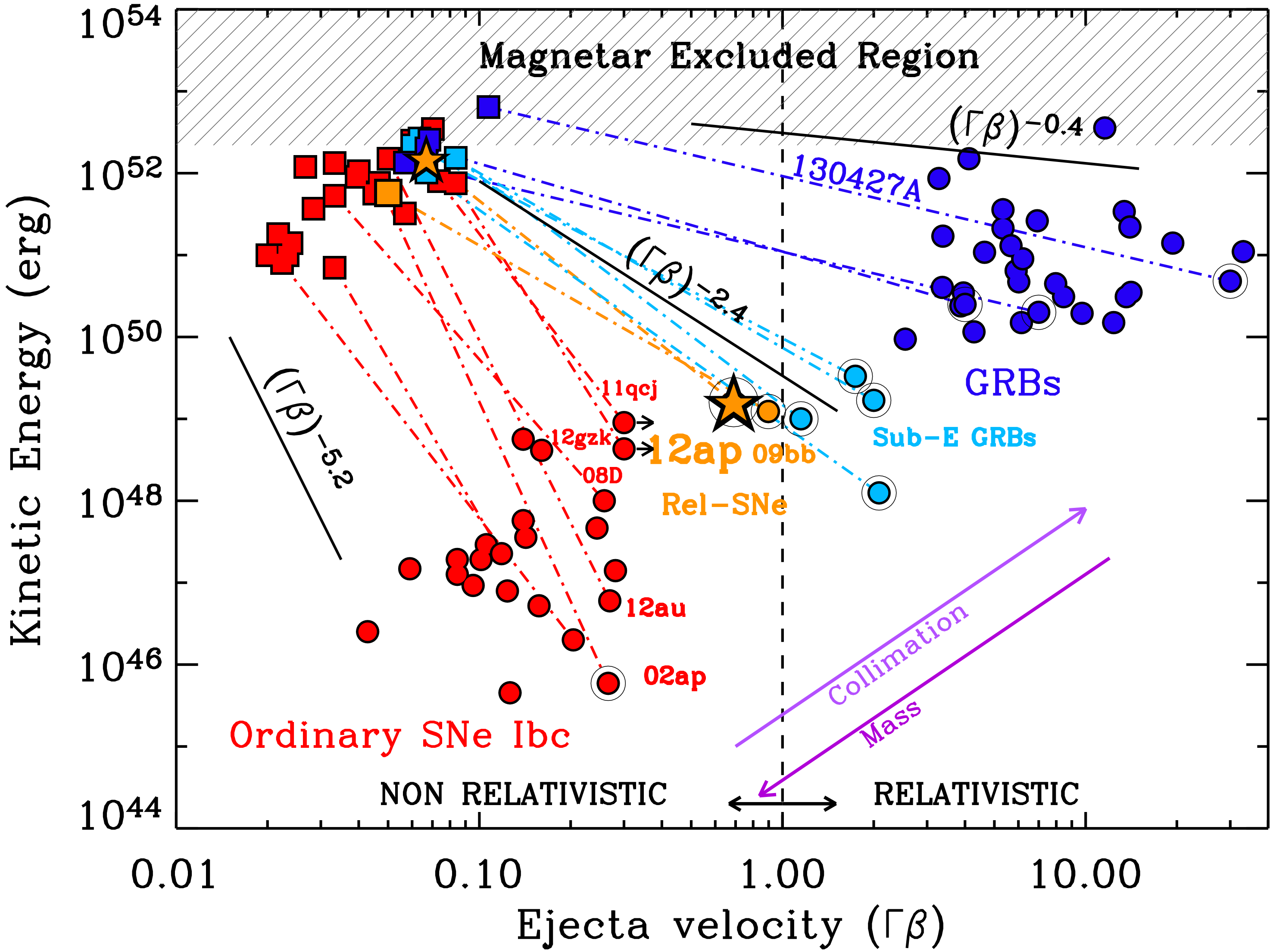
Cross-correlation between gamma rays and galaxy catalogs provides **tighter** bounds on neutrino sources.

Any p-p source with a spectrum softer than $E^{-2.1}$ and evolution slower than $(1+z)^3$ is excluded.

Ando, Tamborra, Zandanel, PRL (2015).

Probing the Source Physics

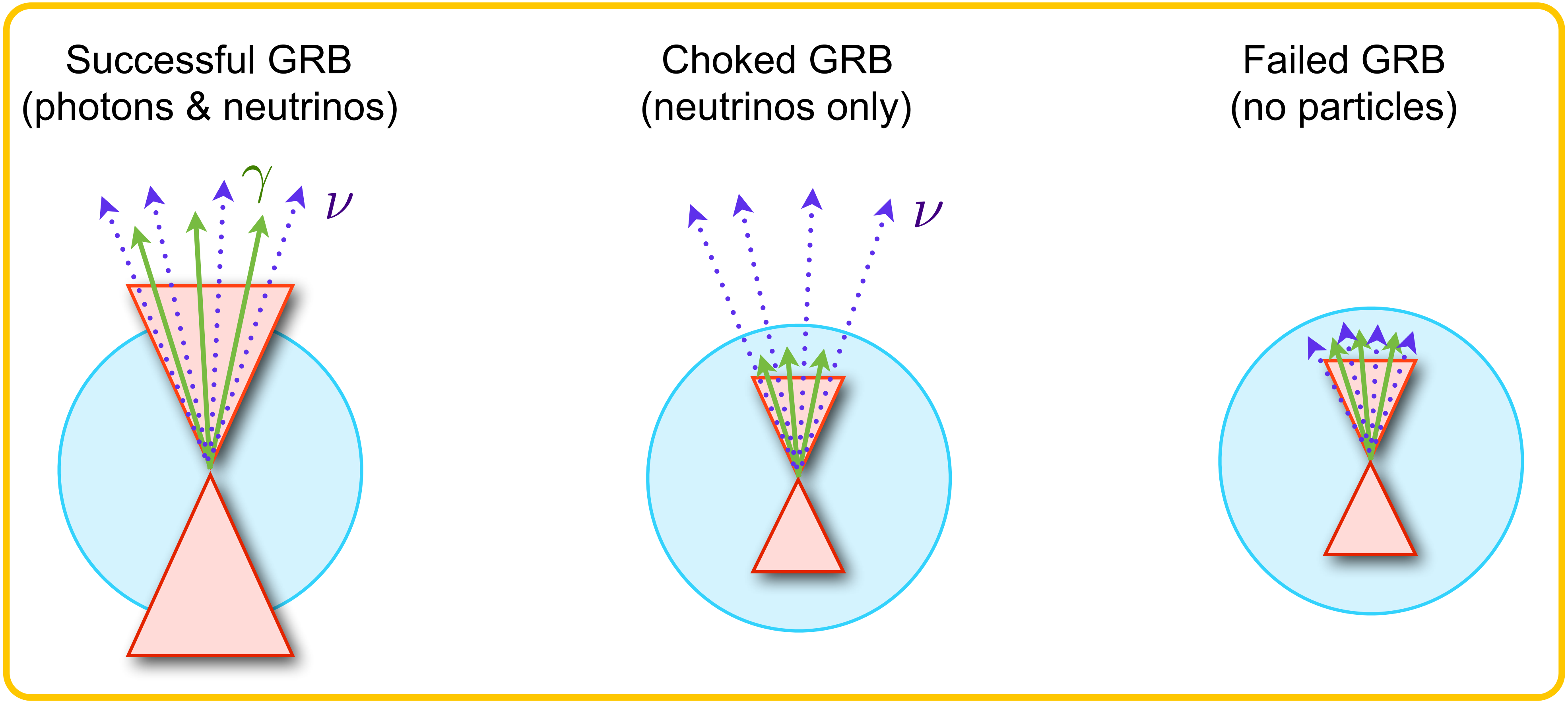
Supernova-GRB Connection



Continuum of stellar explosions originating from hydrogen-stripped envelopes.

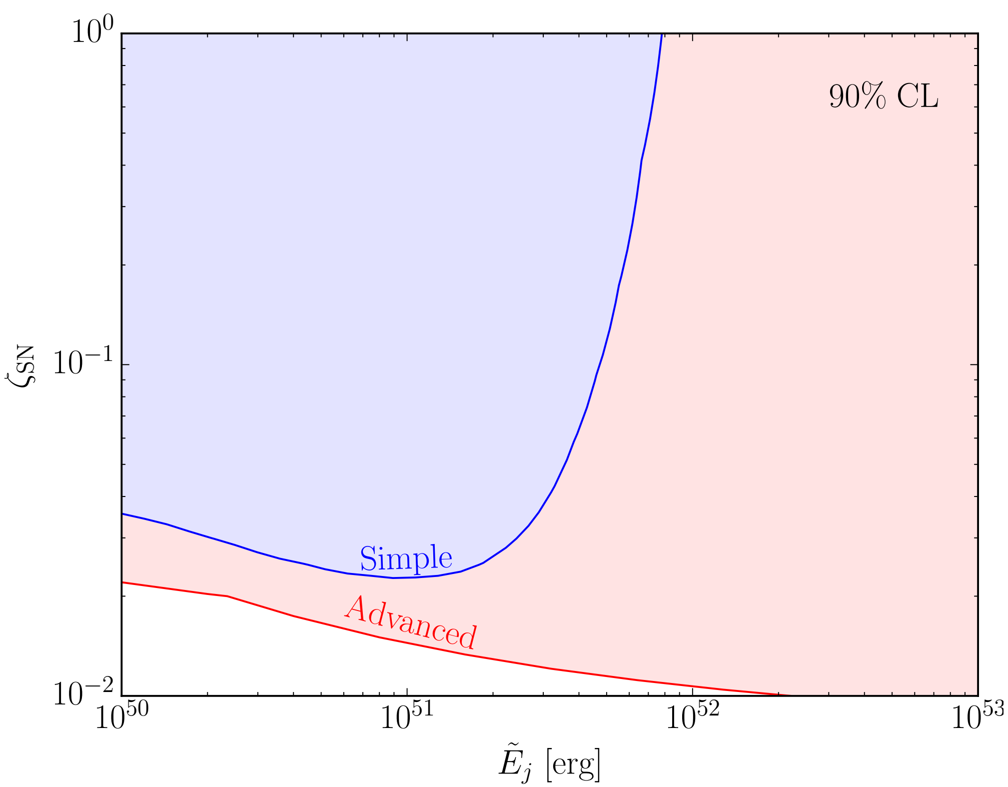
Margutti et al., ApJ (2014). Woosley & Bloom (2006). Bloom & Hjorth (2011). Lazzati et al. (2012). Piran et al. (2017). Sobacchi et al., MNRAS (2017).

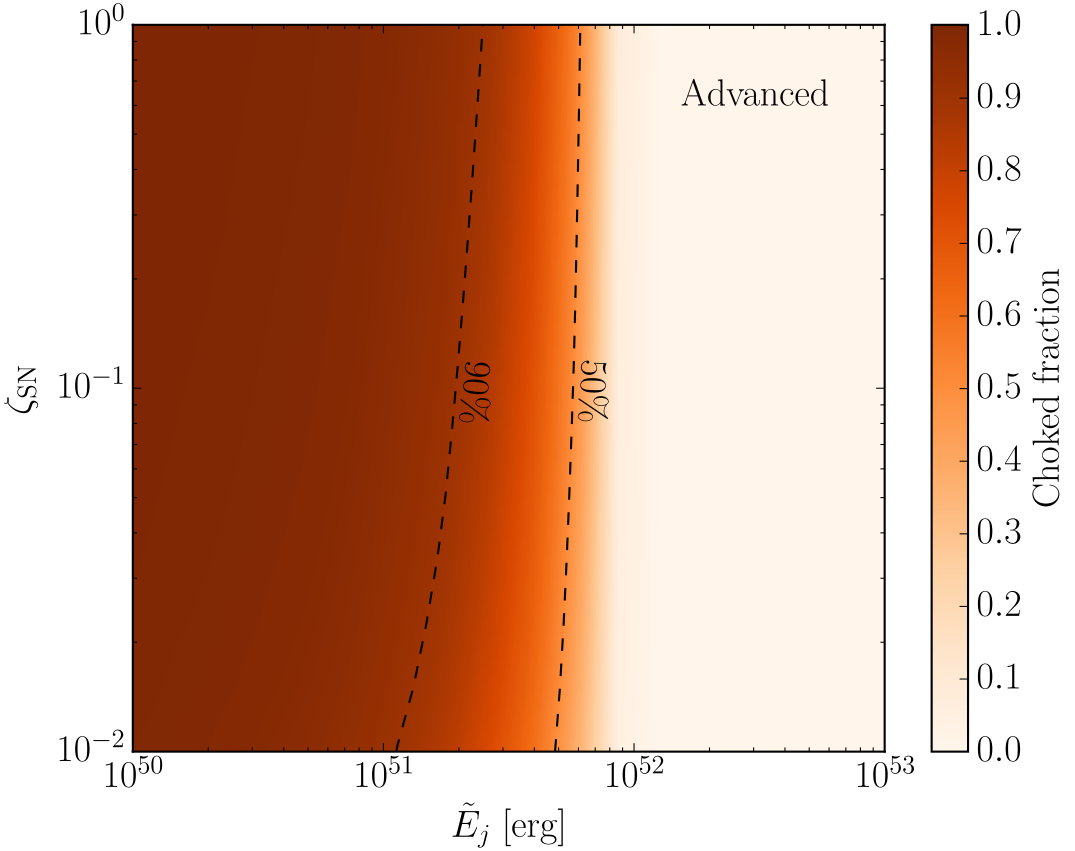
Supernova-GRB Connection



Neutrinos may be the only particles successfully escaping the stellar envelope.

Supernova-GRB Connection

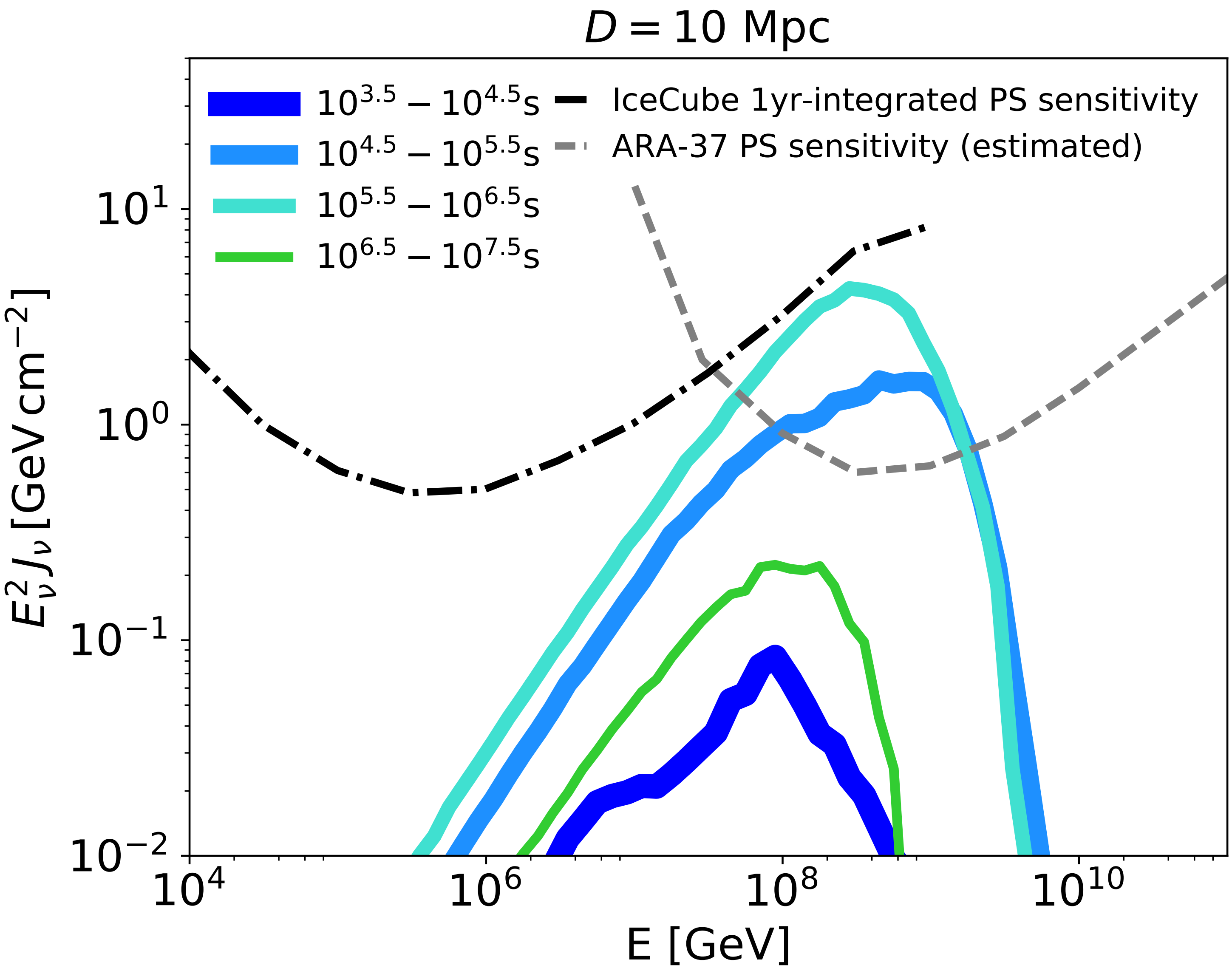




IceCube data constrain the fraction of SNe harboring jets and the fraction of choked jets (compatible with electromagnetic observations of bright jets).

Denton & Tamborra, ApJ (2018). Denton & Tamborra, JCAP (2018).
Tamborra & Ando, PRD (2016). Senno et al., PRD (2015). Meszaros & Waxman, PRL (2001).

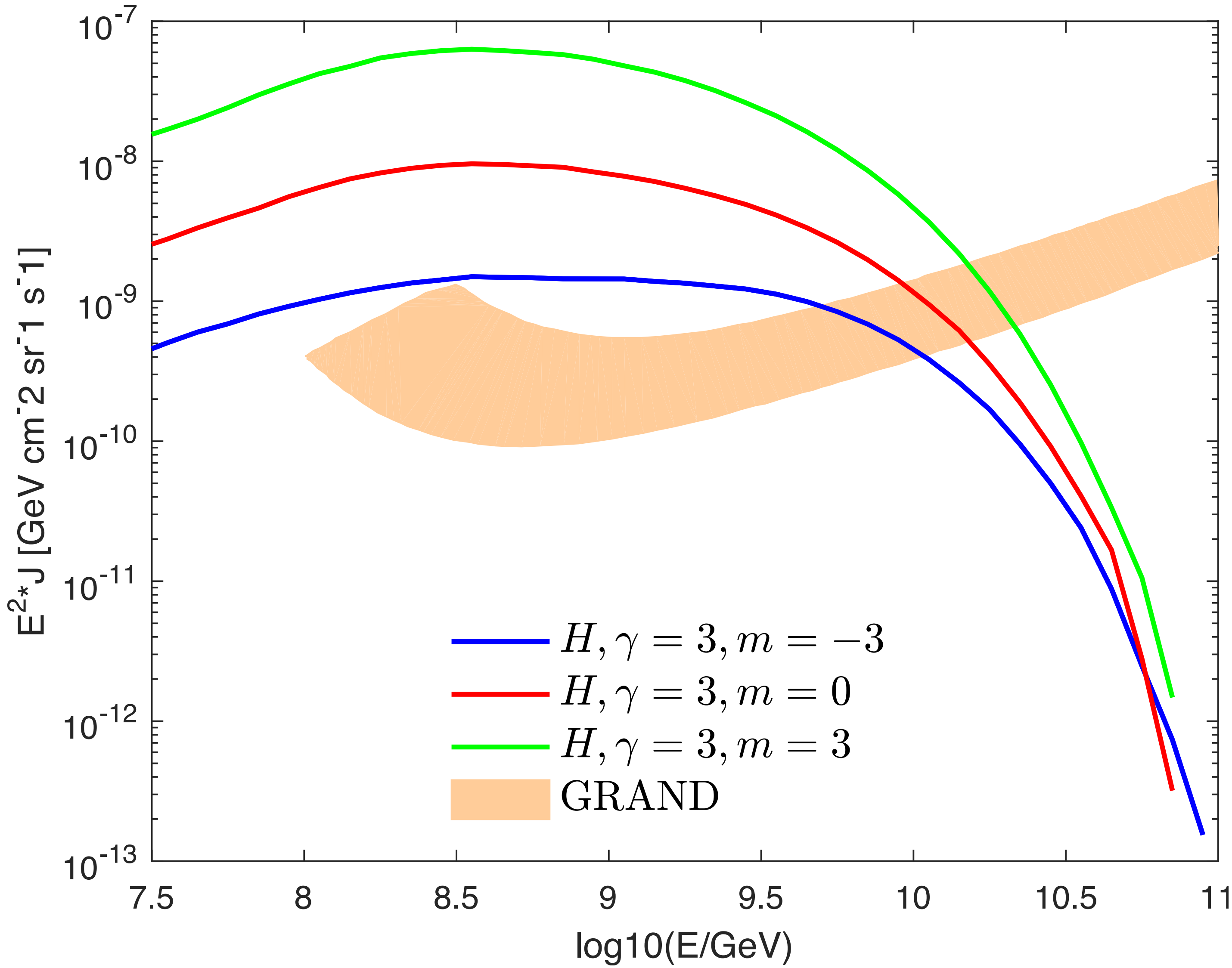
Millisecond Magnetars



Long-lived ms magnetar following NS merger may produce neutrinos up to 1 year.
Neutrinos (in coincidence with GWs) would be smoking gun signal for long-lived magnetar.

Fang & Metzger, ApJ (2017).

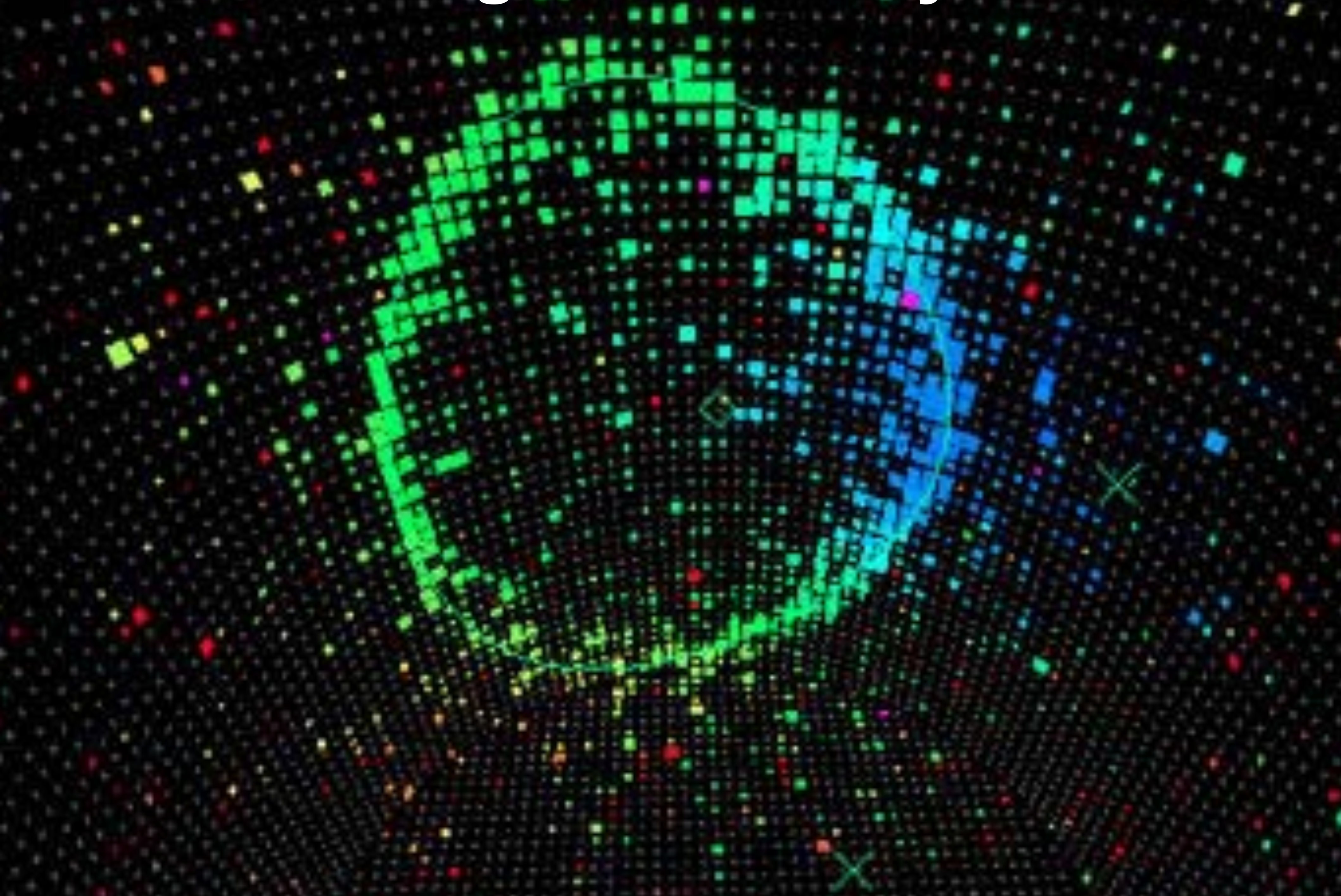
Cosmogenic Neutrinos



Neutrinos can hint towards redshift evolution and nuclear composition of cosmic ray sources.

Moller, Denton & Tamborra, to appear. Alves Batista et al., arXiv: 1806.10879.

Probing Particle Physics



Why?

- Neutrinos with highest energies (PeV) ➡ Probes of Physics at new energy scales.
- Neutrinos with the longest baseline (Gpc) ➡ Efficiently enhancing small effects.
- We have data!

High energy neutrinos can tell us about

- Dark matter annihilation and decay
- New interactions and neutrino secret interactions
- Neutrino decay
- Sterile neutrinos
- Lorentz invariance violation
- Anomalous neutrino magnetic moment
- Non-standard neutrino interactions
- Matter effects
- ….

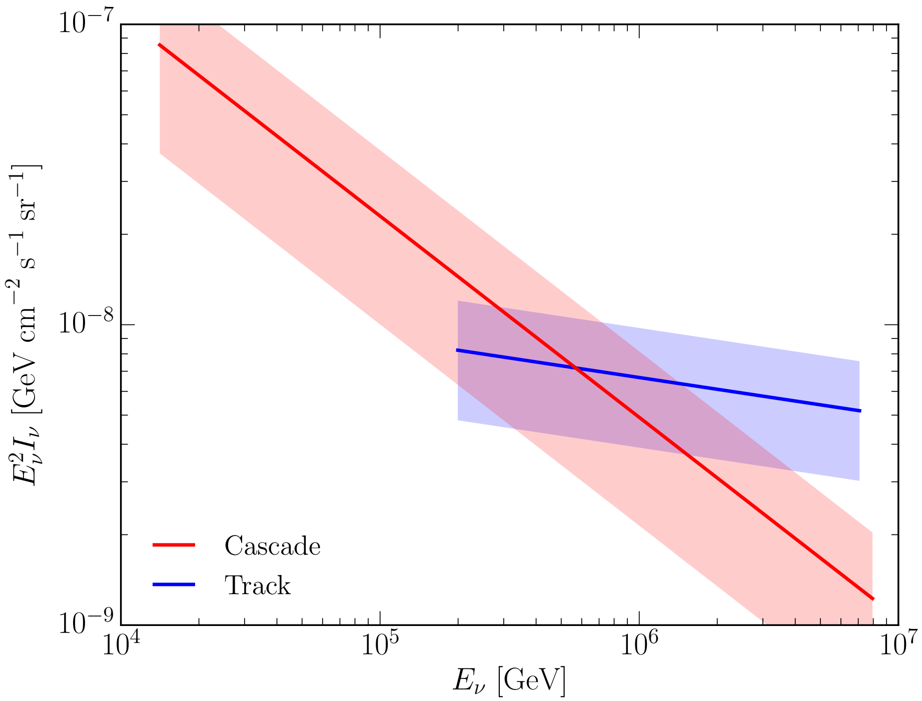
Physics Beyond the Standard Model

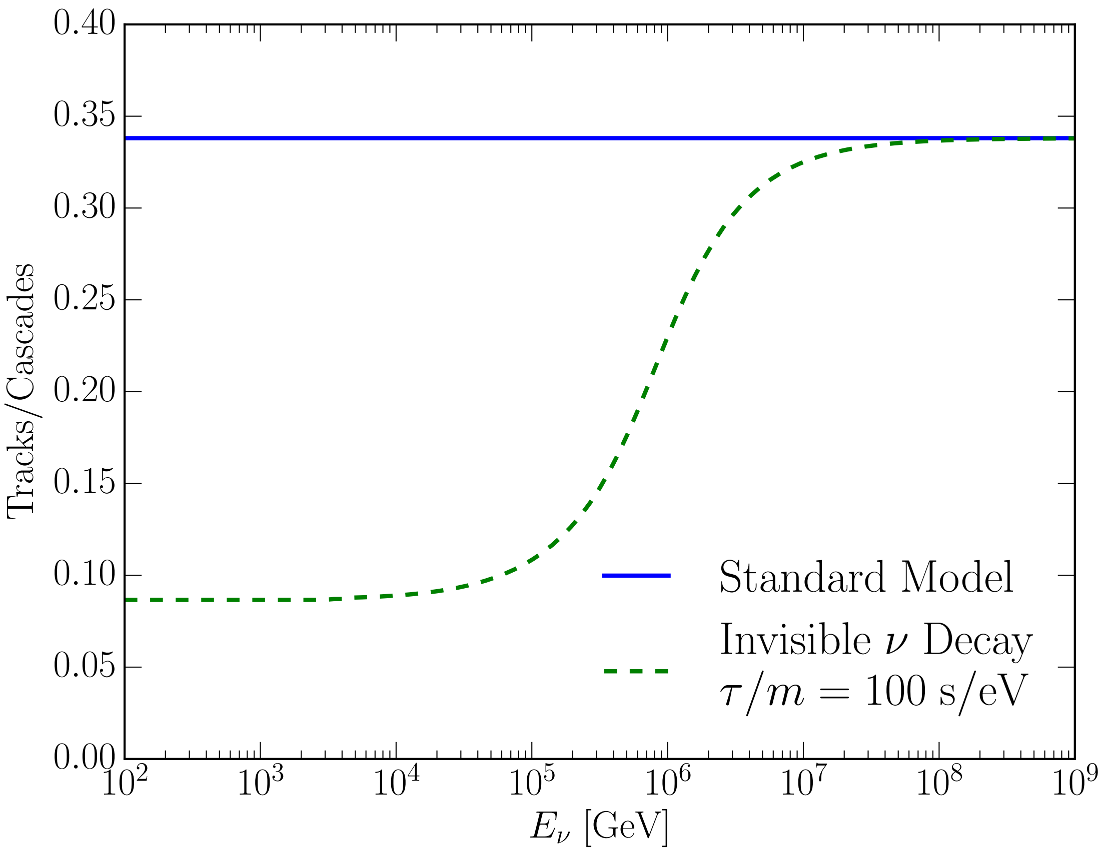
Fraction of parameter space excludable by IceCube and IceCube-Gen2.

Scenario	Exclusion by IceCube	Exclusion by IceCube-Gen2
Complete flavor triangle	42%	96%
Standard mixing	2%	73%
Non-standard neutrino production	17%	93%
NSI at production	5%	84%
Matter effetcs	0%	71%
Pseudo-Dirac neutrino	14%	85%
Decay	14%	85%
Quantum decoherence	2%	73%
Sterile neutrino	10%	86%
Effective operator	36%	94%
Interaction with DM	42%	96%
Shortcut through extra dimension	11%	80%
NSI in Earth matter	30%	92%
NSI at detection	11%	89%

Rasmussen et al., PRD (2017). Ahlers, Helbing, Ios Heros, arXiv: 1806.05696.

An Example: Invisible Neutrino Decay





Invisible neutrino decay with $\tau/m = 10^2 \mathrm{s/eV}$ solves tension between track and cascade data.

Denton & Tamborra, PRL (2018, in press). See also arXiv: 1808.07629.

Conclusions

- Observation of extragalactic neutrinos opens a new window on high-energy Universe.
- Sources not yet resolved, multi-messenger methods powerful.
- Composition of IceCube energy spectrum seems complex.
- High energy neutrinos are already useful as probes of source physics.
- High energy neutrinos are unique probes of particle physics at new scales.

Thank you for your attention!