The Niels Bohr International Academy

DARK

Cosmic Messengers

Irene Tamborra

Niels Bohr Institute, University of Copenhagen

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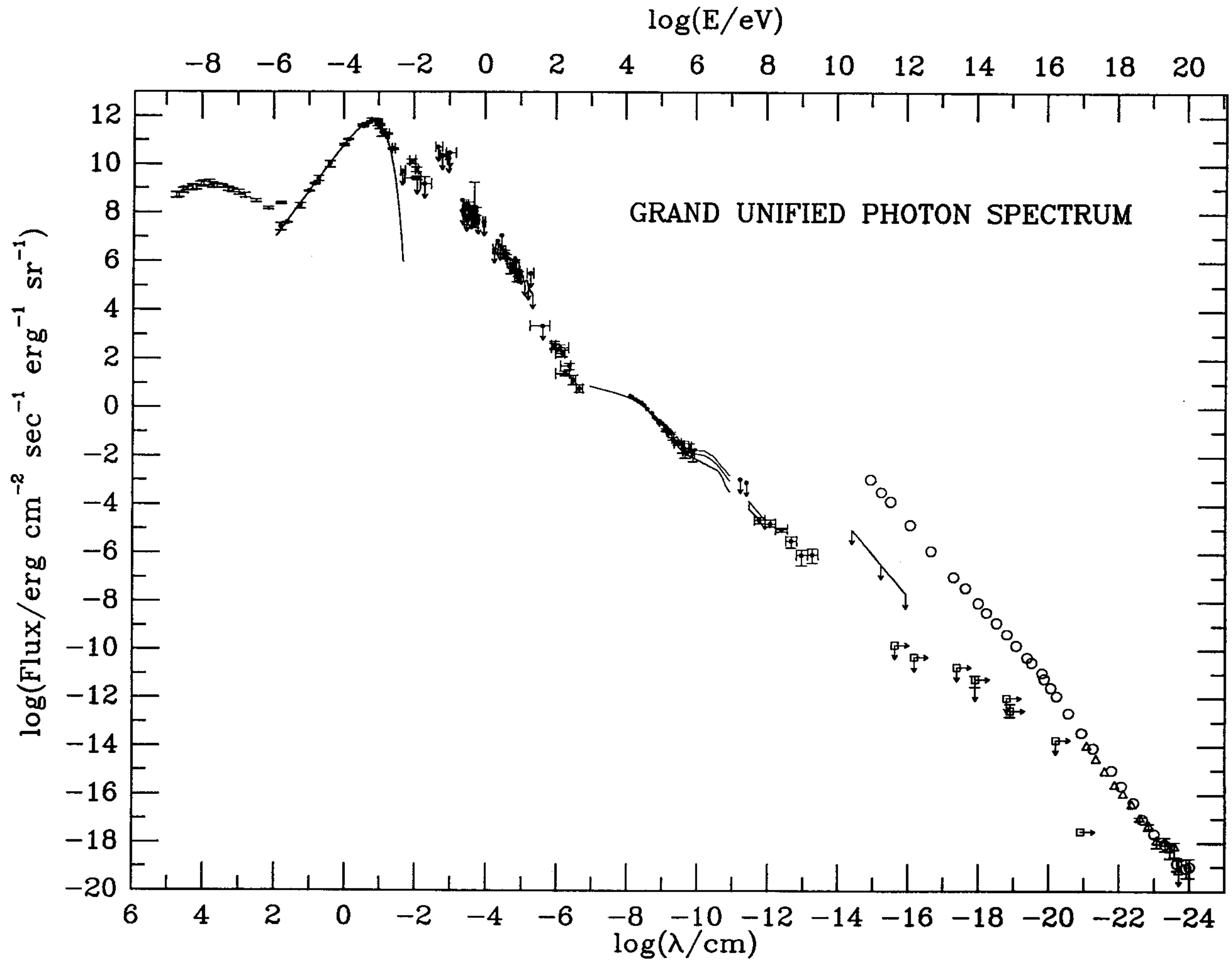
VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

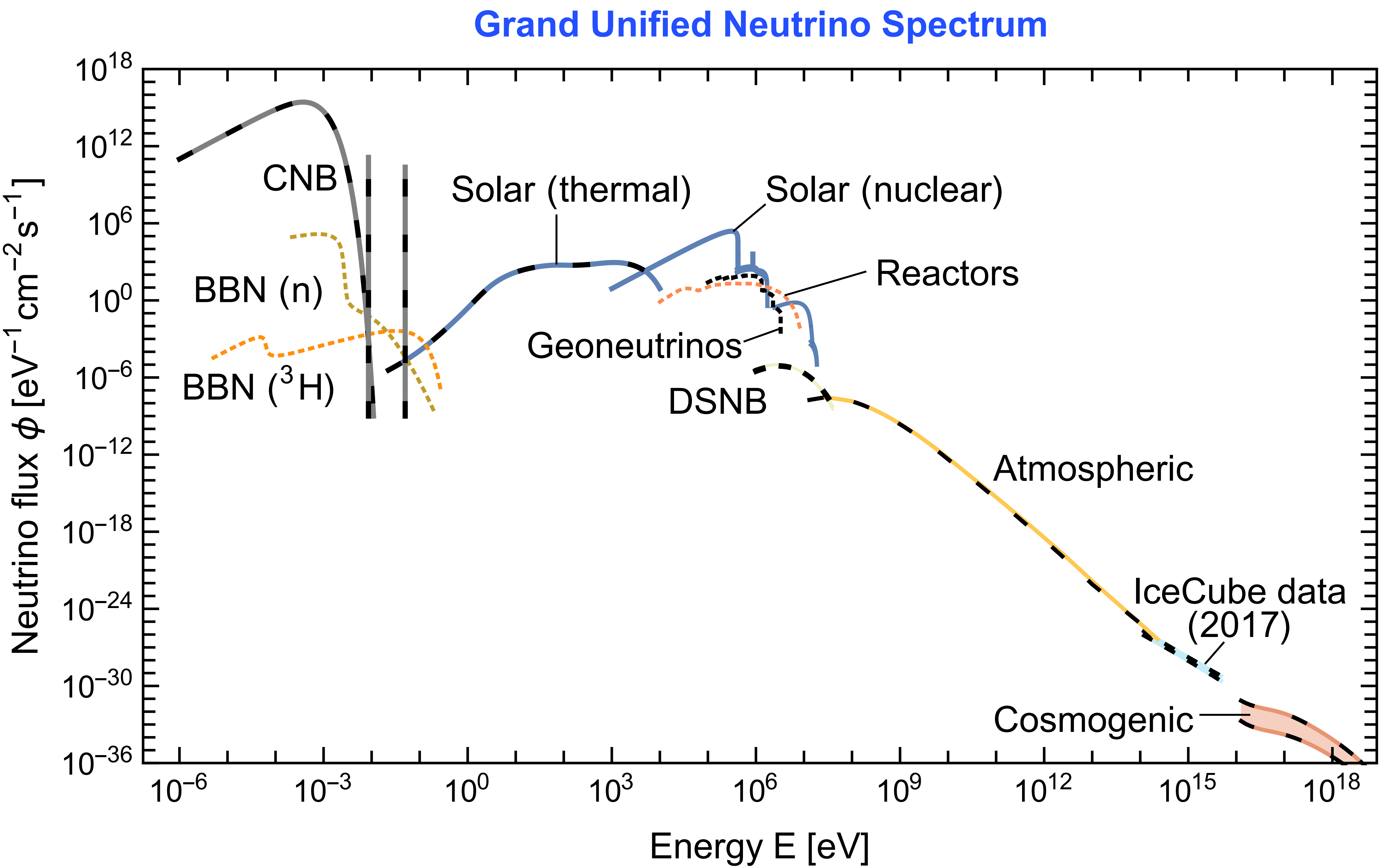
SFB 1258 Neutrinos Dark Matter Messengers

The Cosmos in Photons



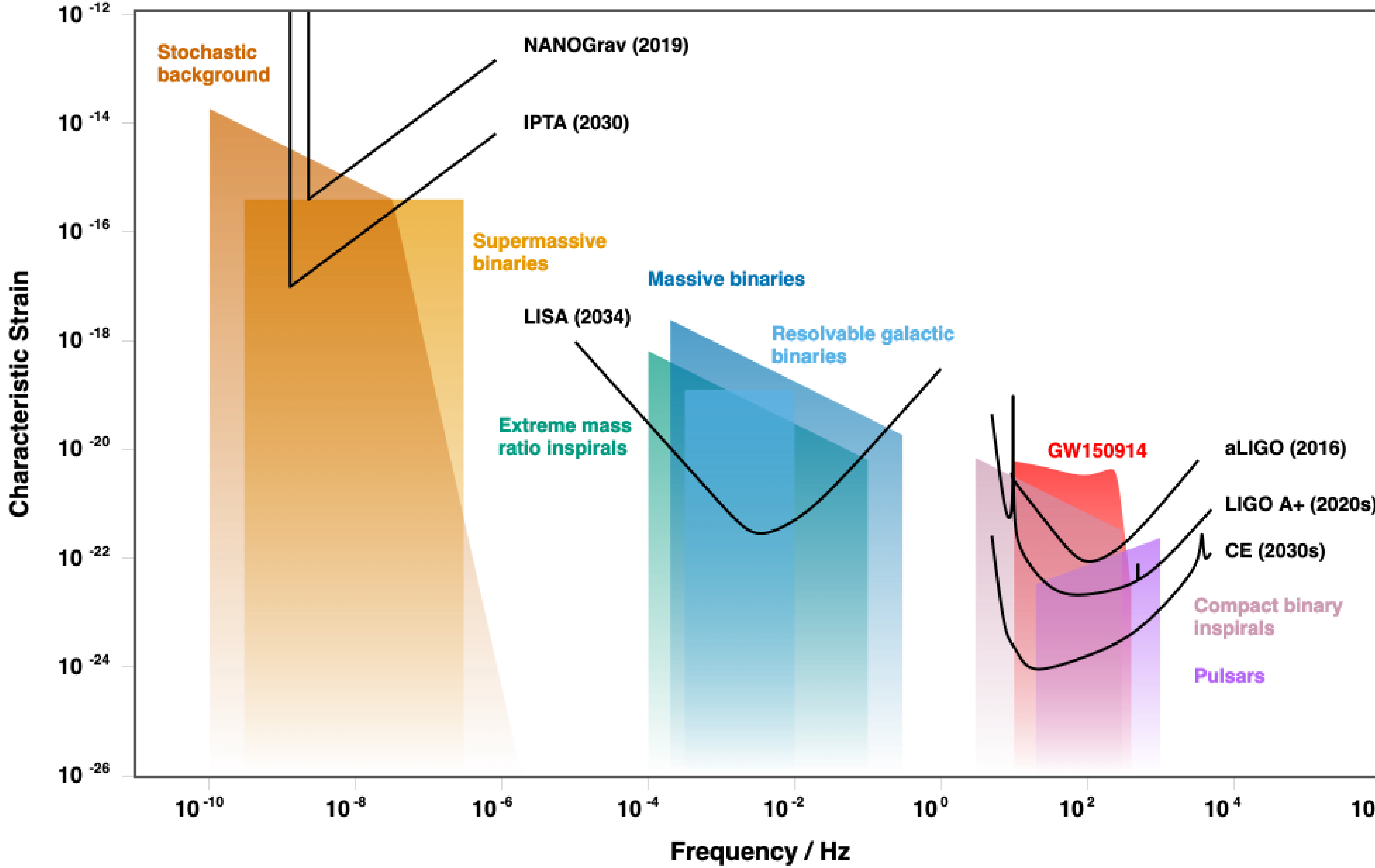
Ressel & Turner, Bull. Am. Astron. Soc. (1990). See also Hill, Masui, Scott, Appl. Spectrosc. (2018).

The Cosmos in Neutrinos



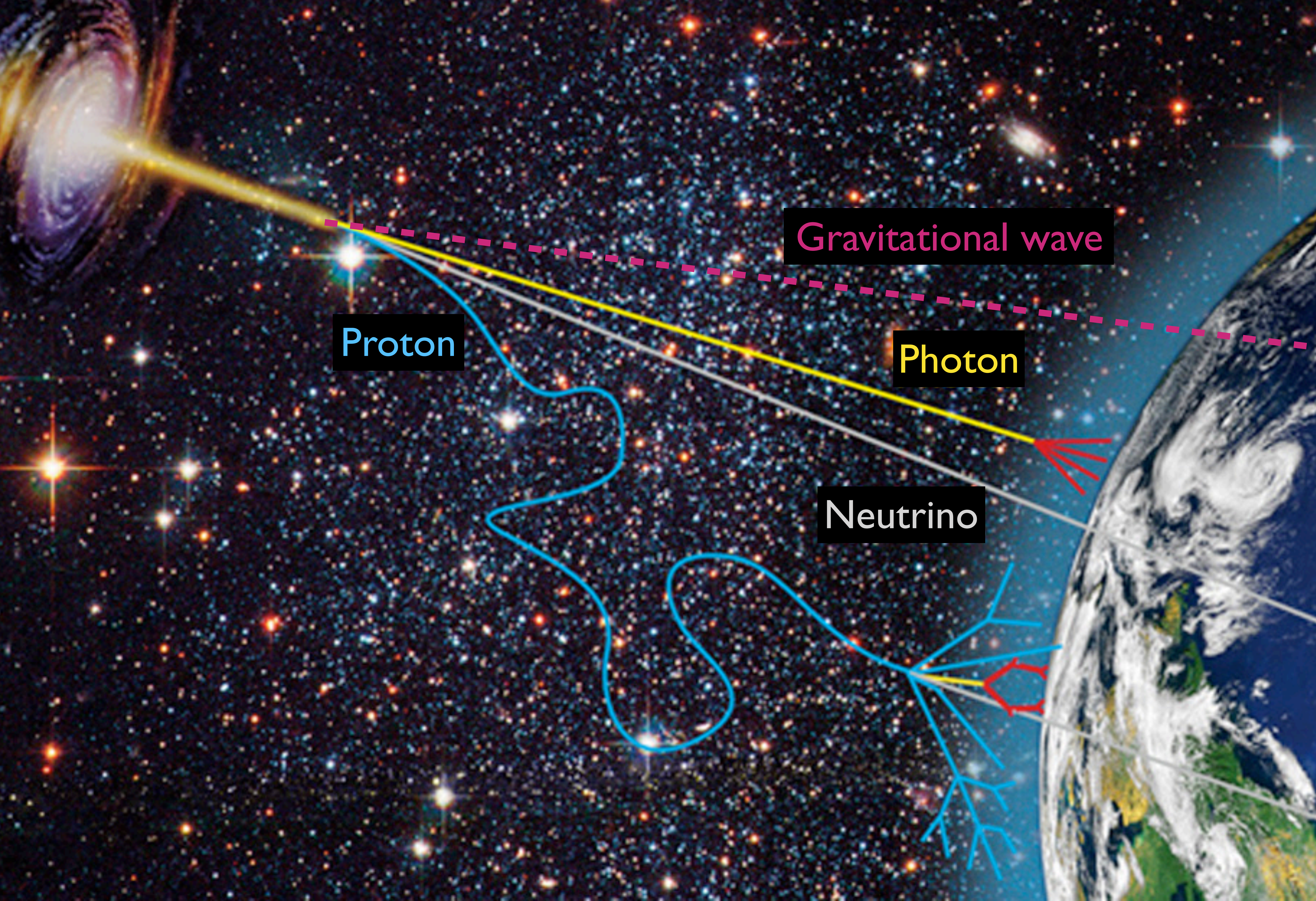
Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

The Cosmos in Gravitational Waves



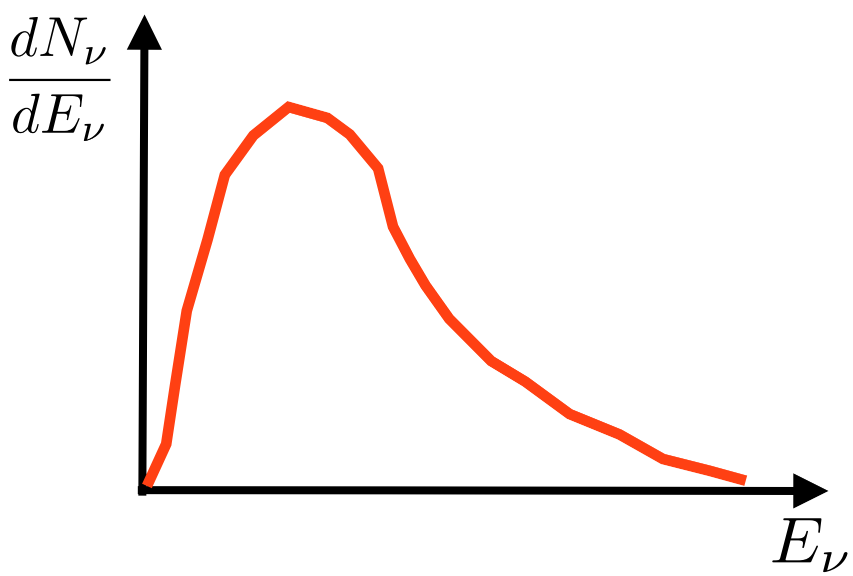
Shoemaker et al. (2019).

Neutrinos as Ideal Messengers



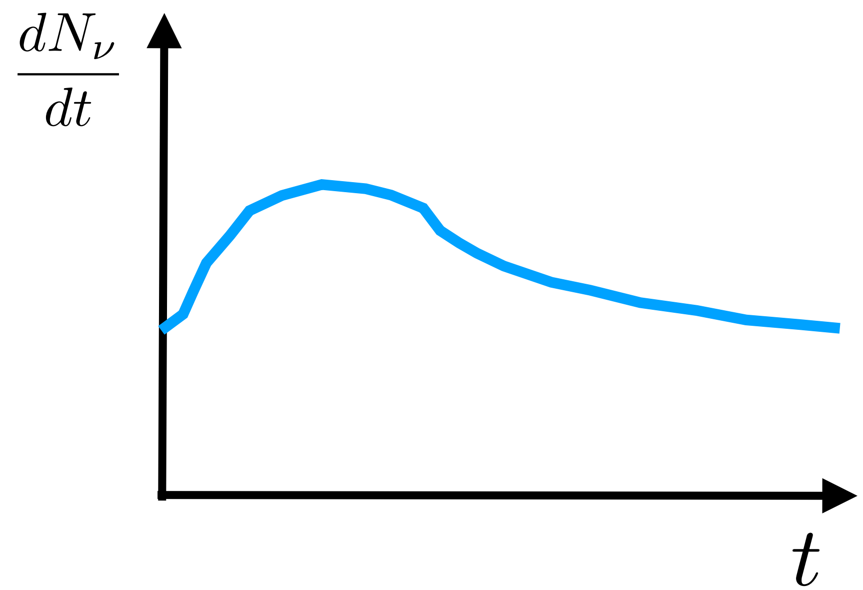
Powerful Probes in Astrophysics

Energy distribution



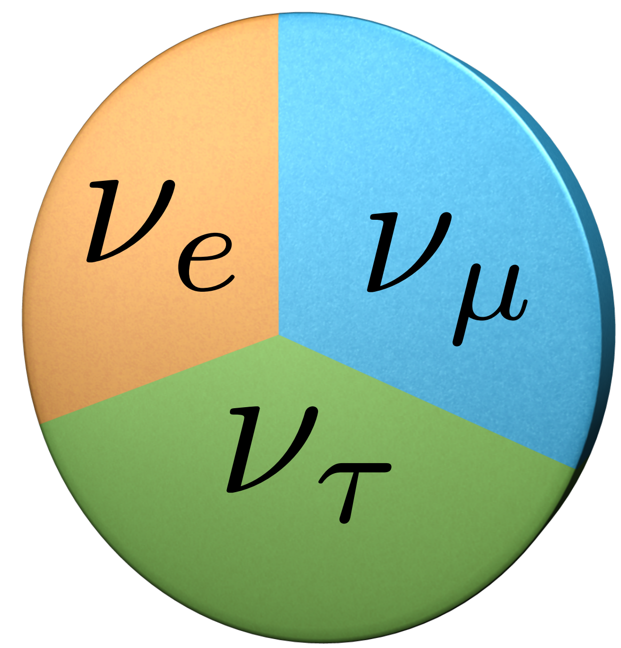
Similar to photons

Light curve



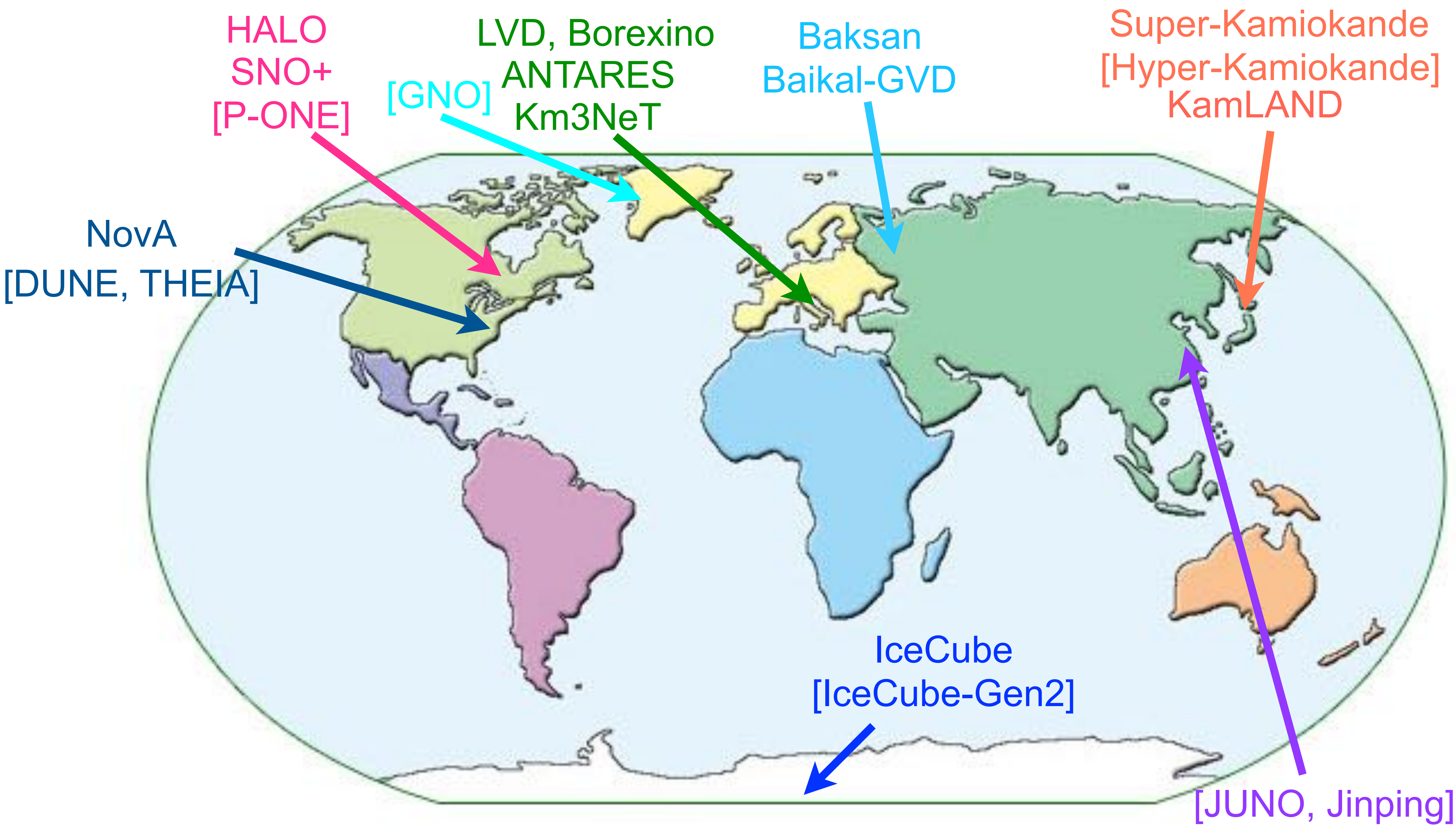
Similar to photons

Flavor ratio



Neutrinos only!

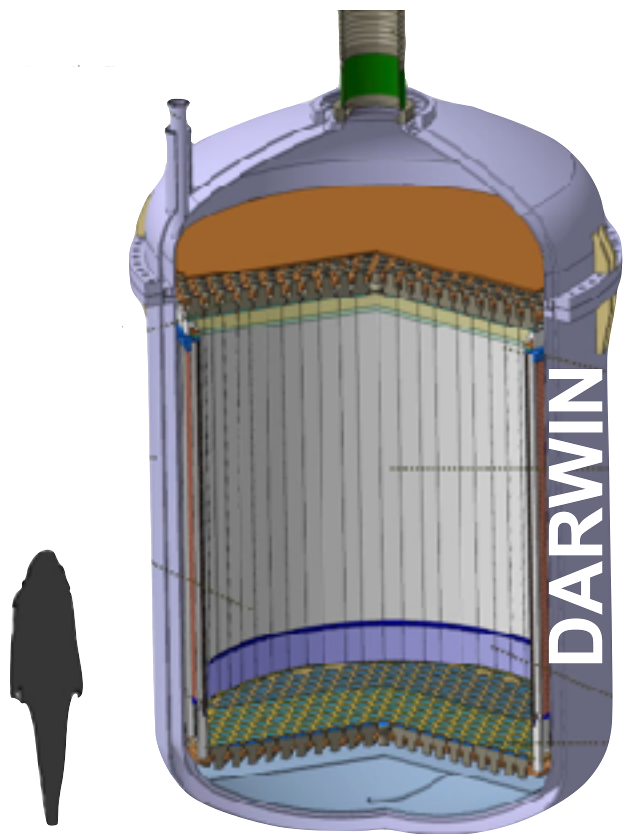
Neutrino "Telescopes"



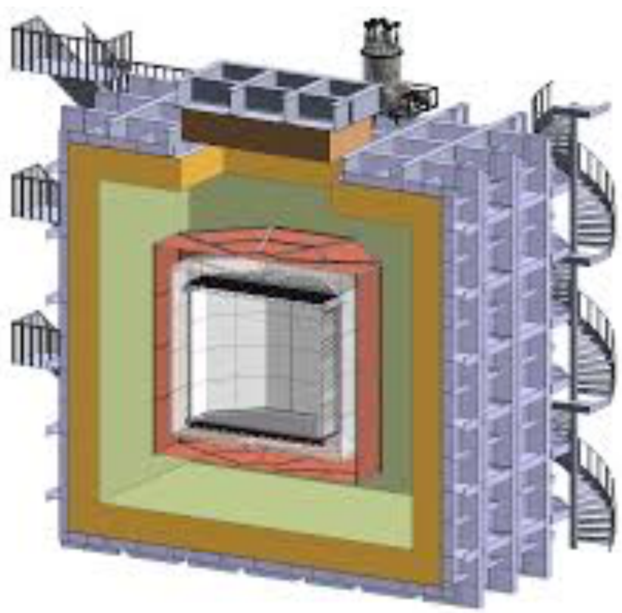
Fundamental to combine astrophysical signals from detectors employing different technologies (e.g., Cherenkov and liquid scintillator detectors).

Neutrino “Telescopes”

Neutrino Telescopes Based on Coherent Scattering



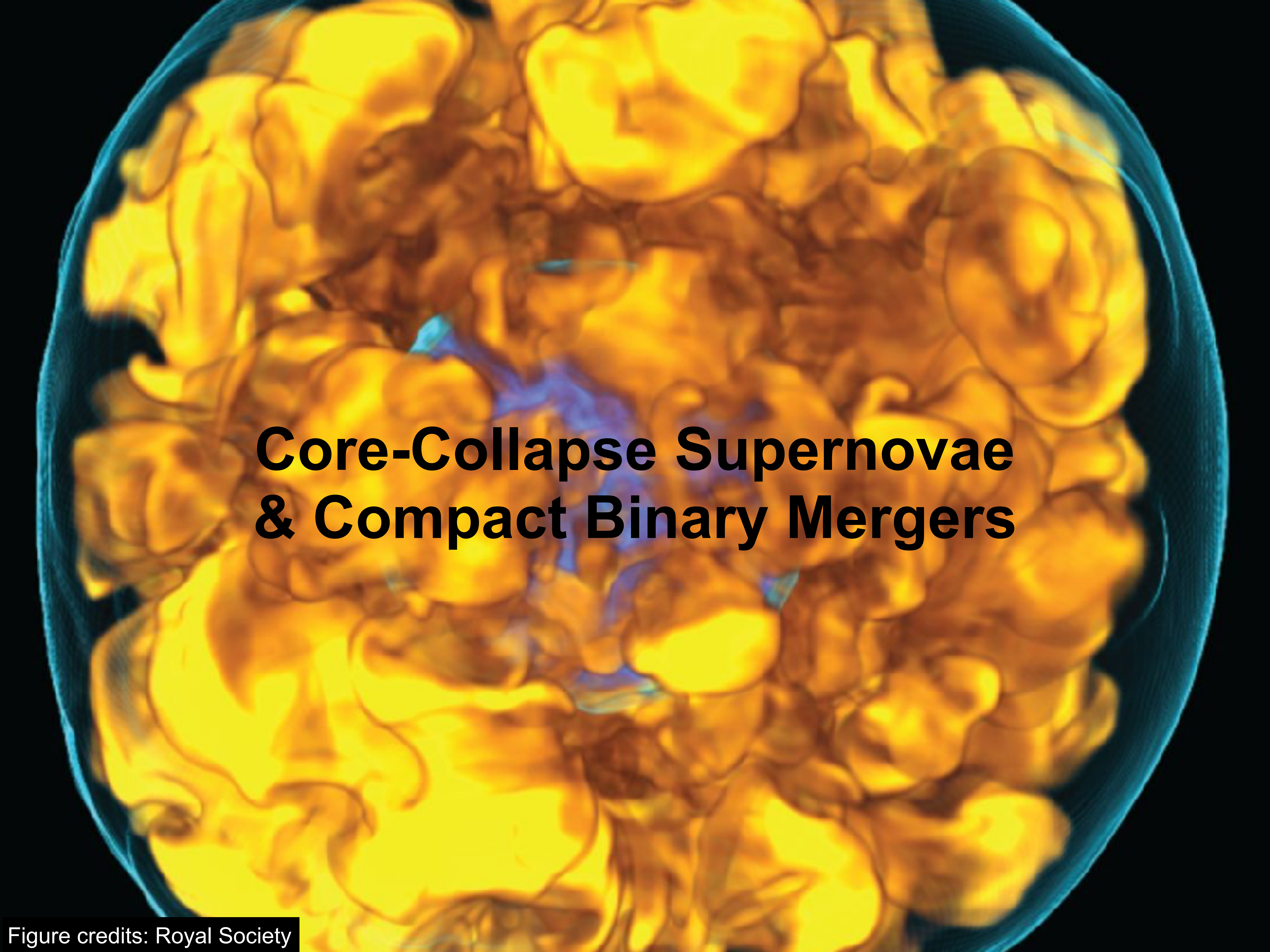
DarkSide-20k & ARGO



RES-NOVA

- Flavor insensitive (complementary to other neutrino telescopes).
- Compact size and excellent time resolution.

Pattavina, Ferreiro Iachellini, Tamborra, PRD (2020). Lang, McCabe, Reichard, Selvi, Tamborra, PRD (2016). Horowitz et al. PRD (2003). Drukier and Stodolsky, PRD (1984). Agnes et al., JCAP (2021).



Core-Collapse Supernovae & Compact Binary Mergers

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

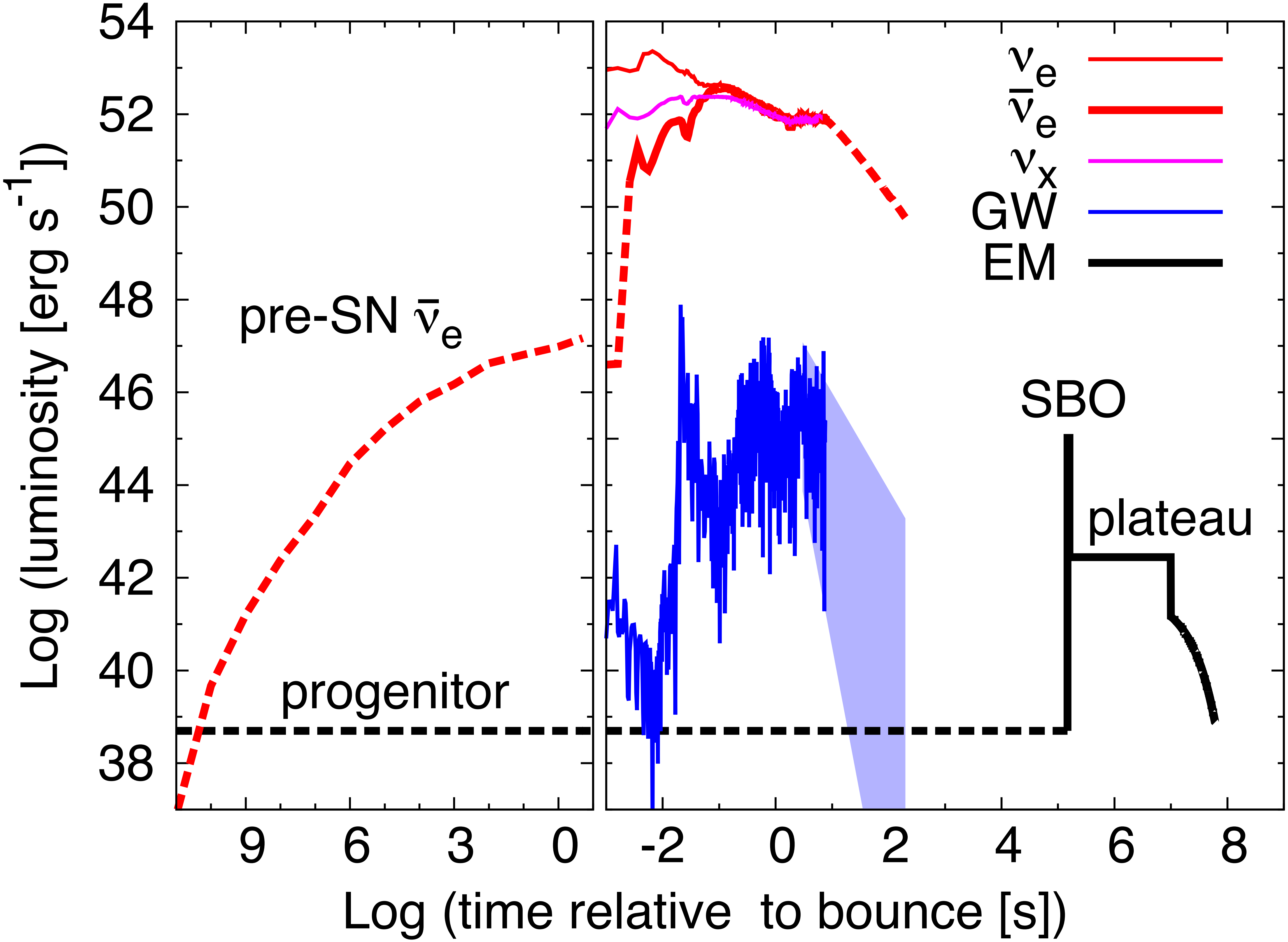
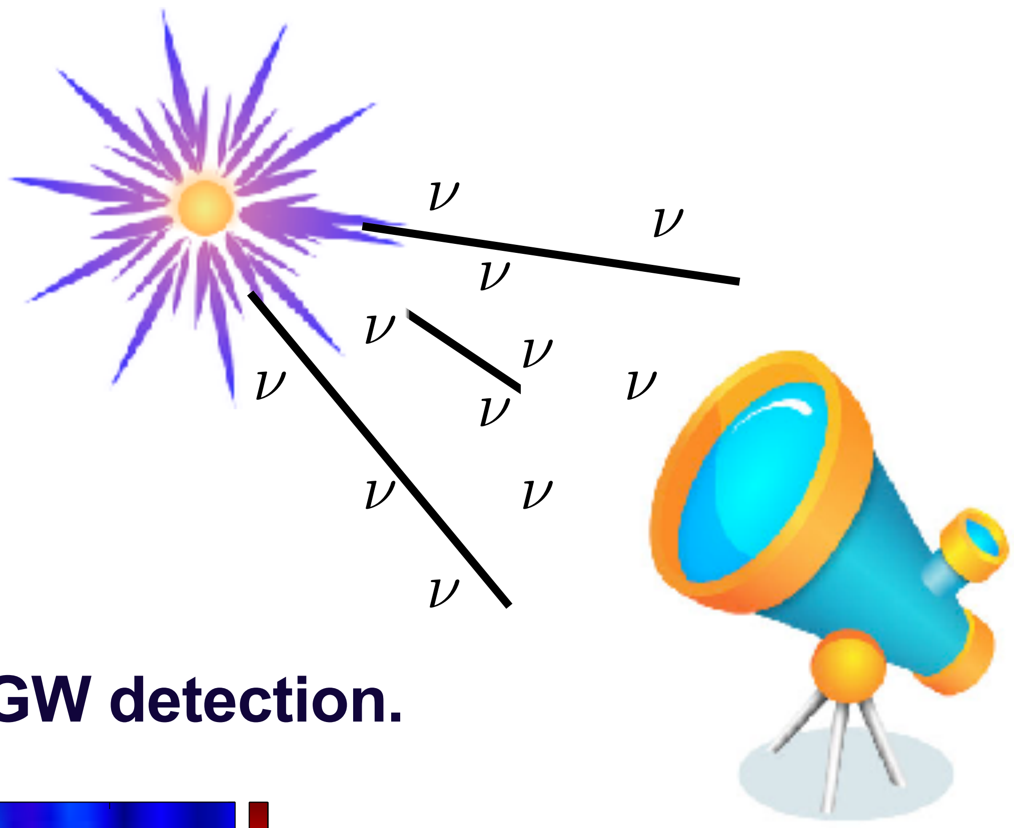


Figure from Nakamura et al., MNRAS (2016).

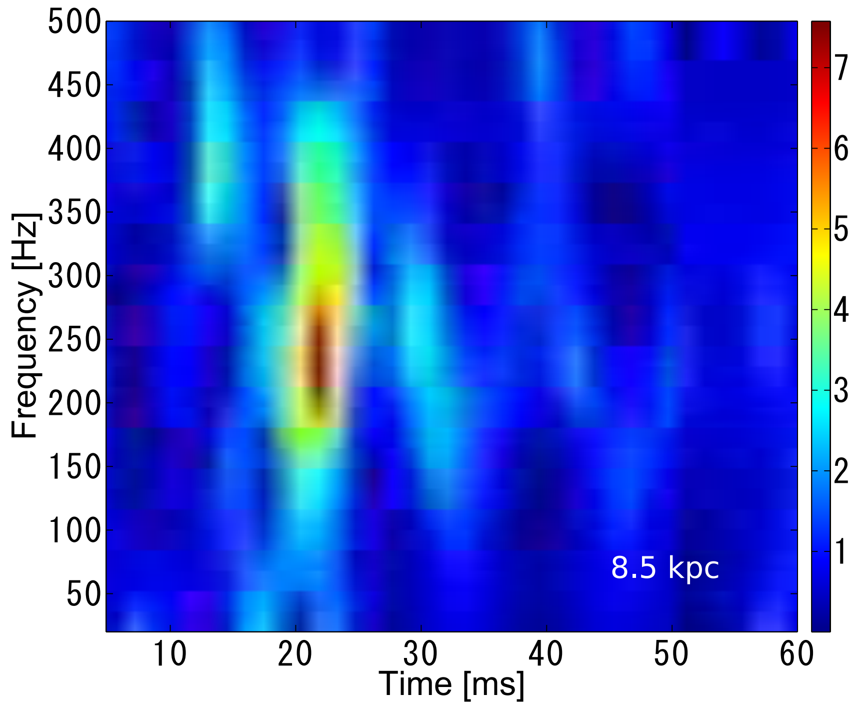
Neutrino Alert

SuperNova Early Warning System 2.0.

Supernova direction and distance.



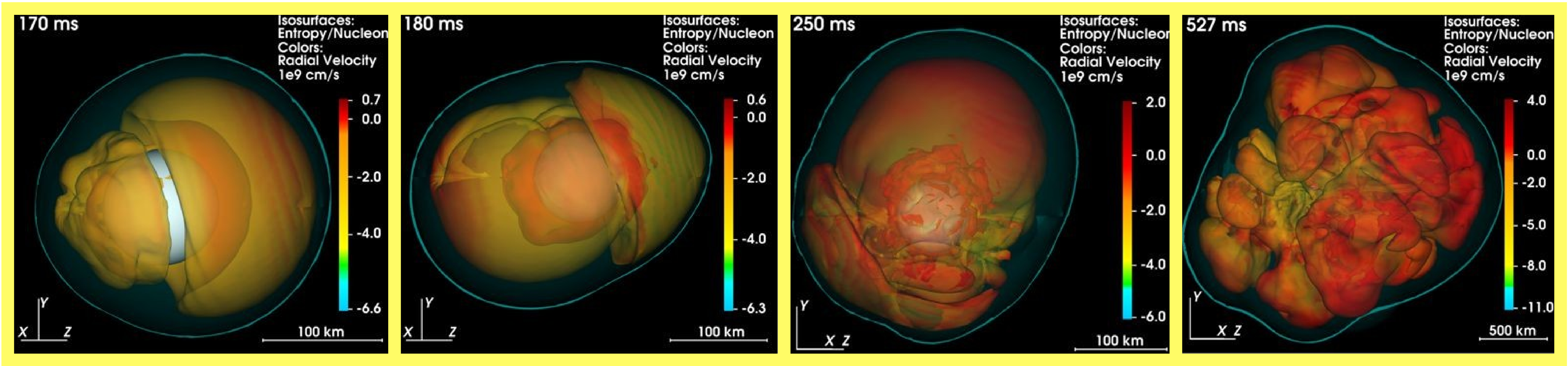
Neutrino timing for GW detection.

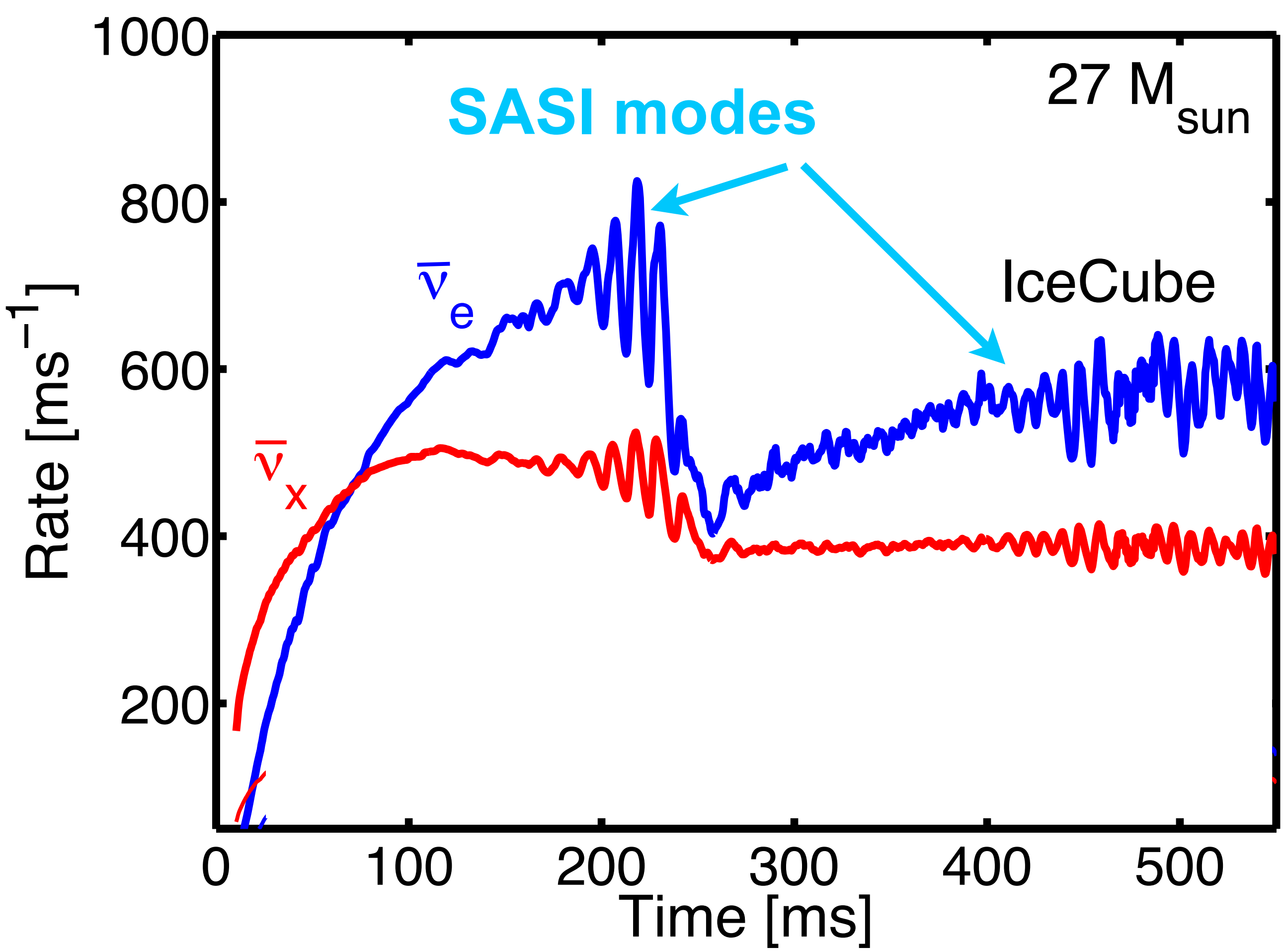


SNEWS 2.0, arXiv: 2011.00035. Tomas et al. (2003). Fisher et al. (2015). Linzer & Scholberg, PRD (2019). Brdar et al., JCAP (2018). Muehlbeier et al., PRD (2013). Segerlund et al. (2021). Mukhopadhayay et al., ApJ (2020). Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016).

Supernova Explosion Mechanism

Standing Accretion Shock Instability (SASI)

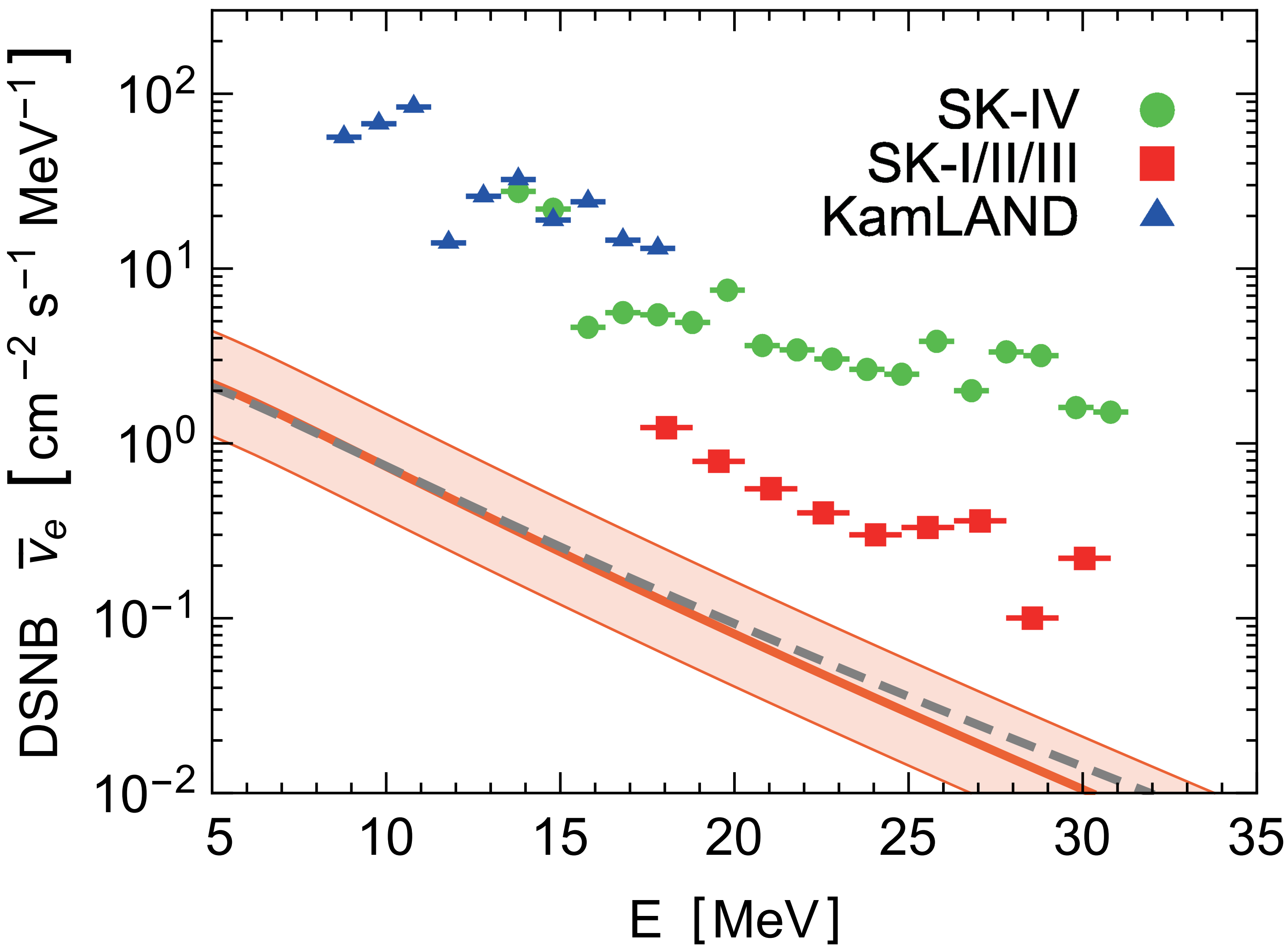




Neutrinos and gravitational waves carry imprints of the physics occurring before the explosion.

Tamborra et al., PRL (2013), PRD (2014). Kuroda et al., ApJ (2017). Walk, Tamborra et al., PRD (2018), PRD (2019). Melson et al., APpJL (2015). Andresen et al., MNRAS (2017,2019). Recent reviews: Burrows & Vartanyan (2021). Janka (2017). Mirizzi, Tamborra et al. (2016).

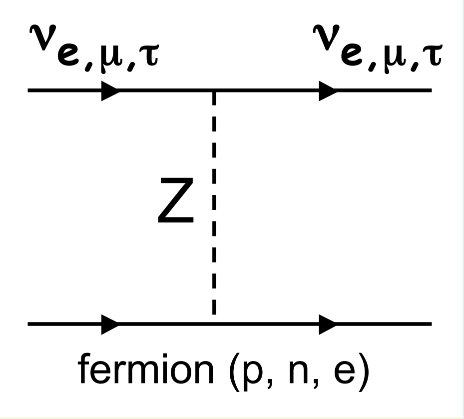
Diffuse Supernova Neutrino Background

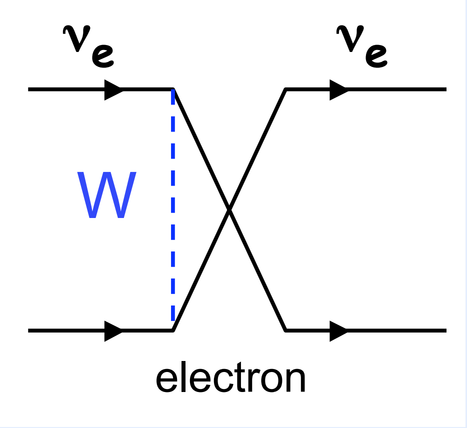


- The diffuse supernova neutrino background is a **guaranteed** signal!
- Independent test of supernova rate.
- Constraints on fraction of black hole forming collapses.
- Affected by binary interactions (mass transfer and mergers).

Figure from Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020). Moller, Suliga, Tamborra, Denton, JCAP (2018). Kresse, Ertl, Janka, ApJ (2020). Nakazato et al., ApJ (2015). Horiouchi et al., MNRAS (2018). Lunardini & Tamborra, JCAP (2012). Horiuchi et al., PRD (2021).

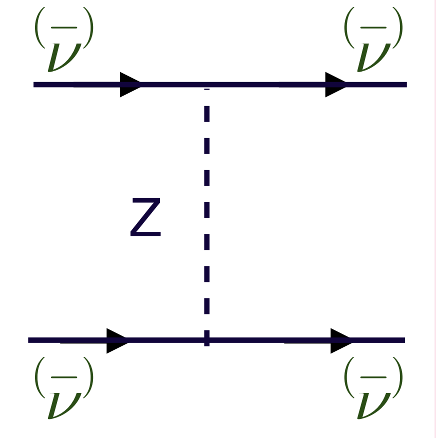
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

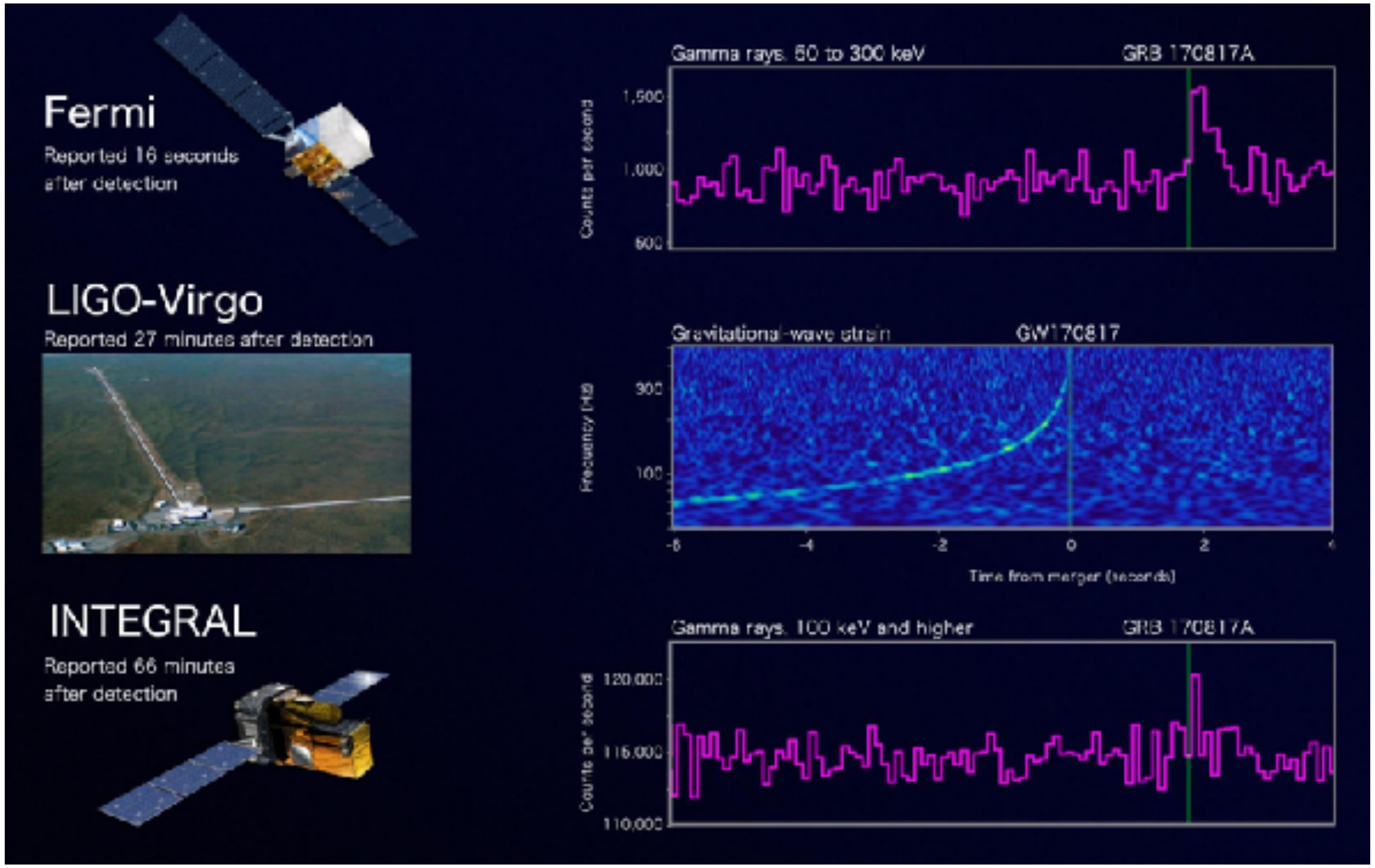


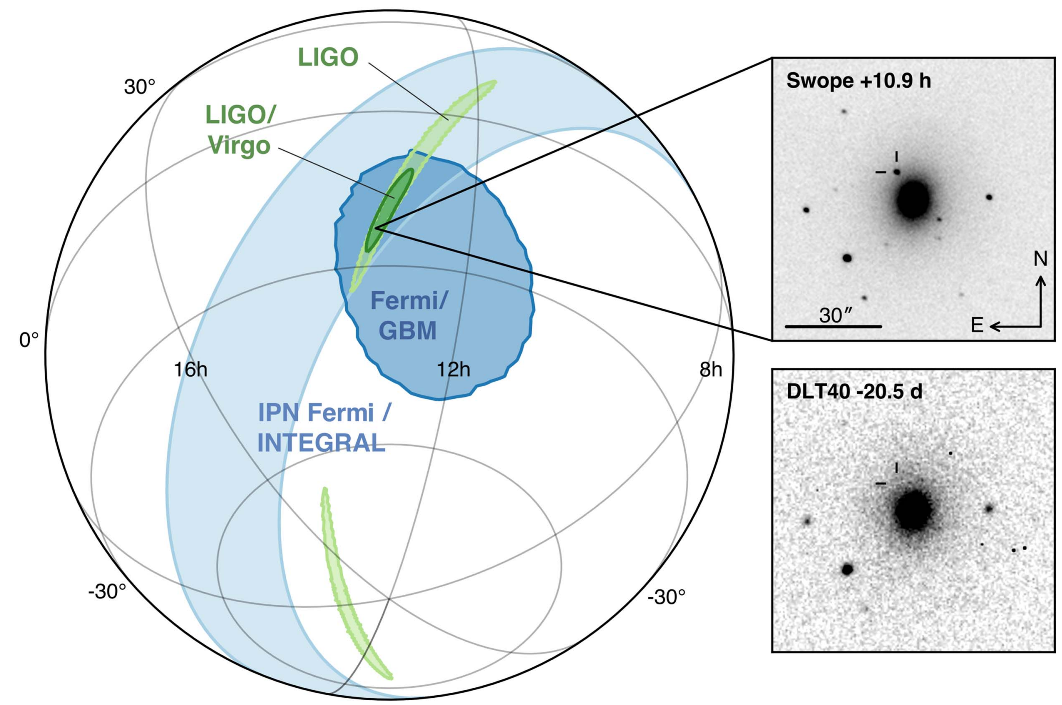
Neutrinos interact among themselves.

Non-linear phenomenon!

Recent review: Tamborra & Shalgar, Ann. Rev. (2021, in press).

GW 170817

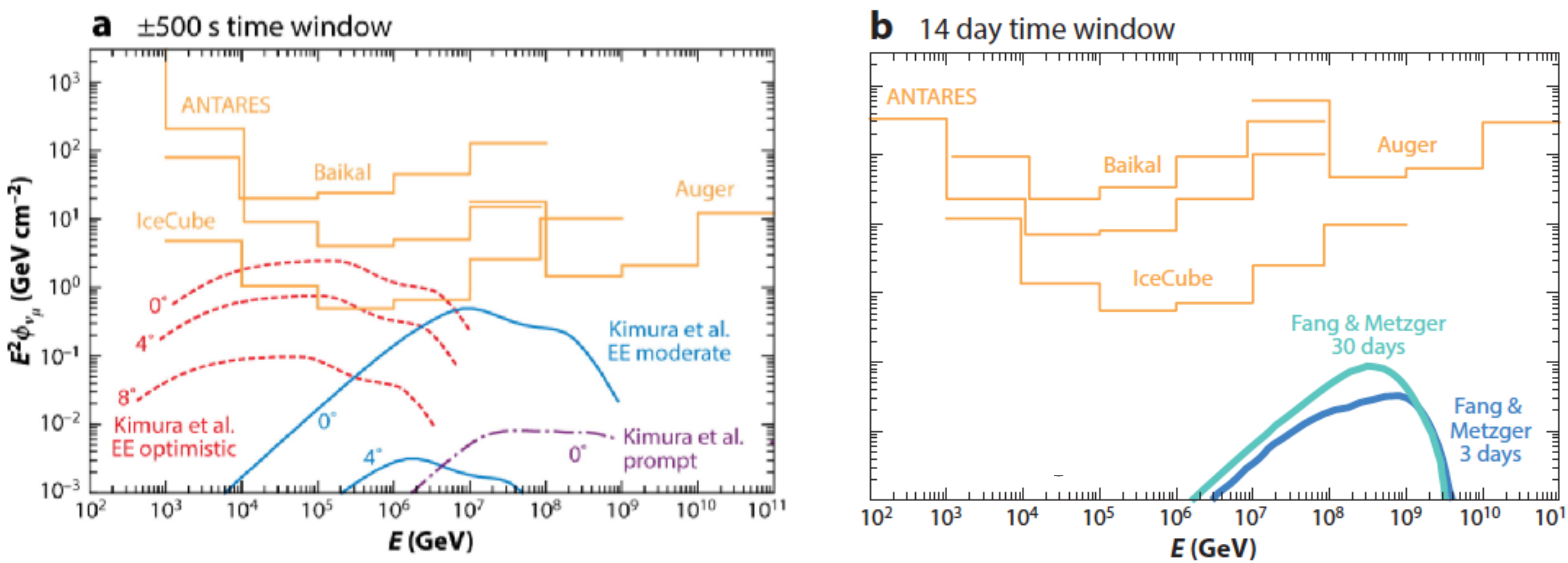




First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

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

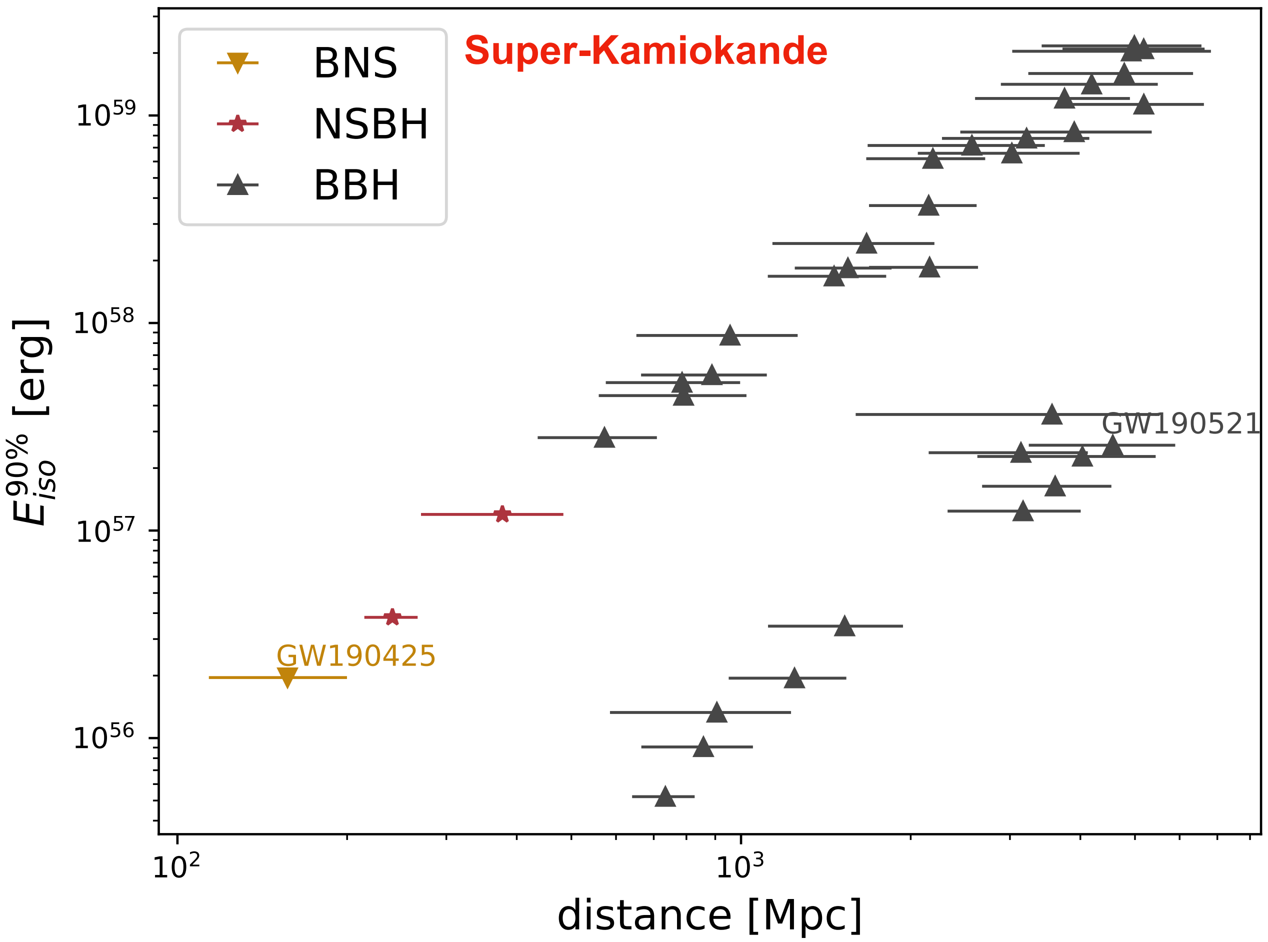
High Energy Neutrinos from GRB 170817A?



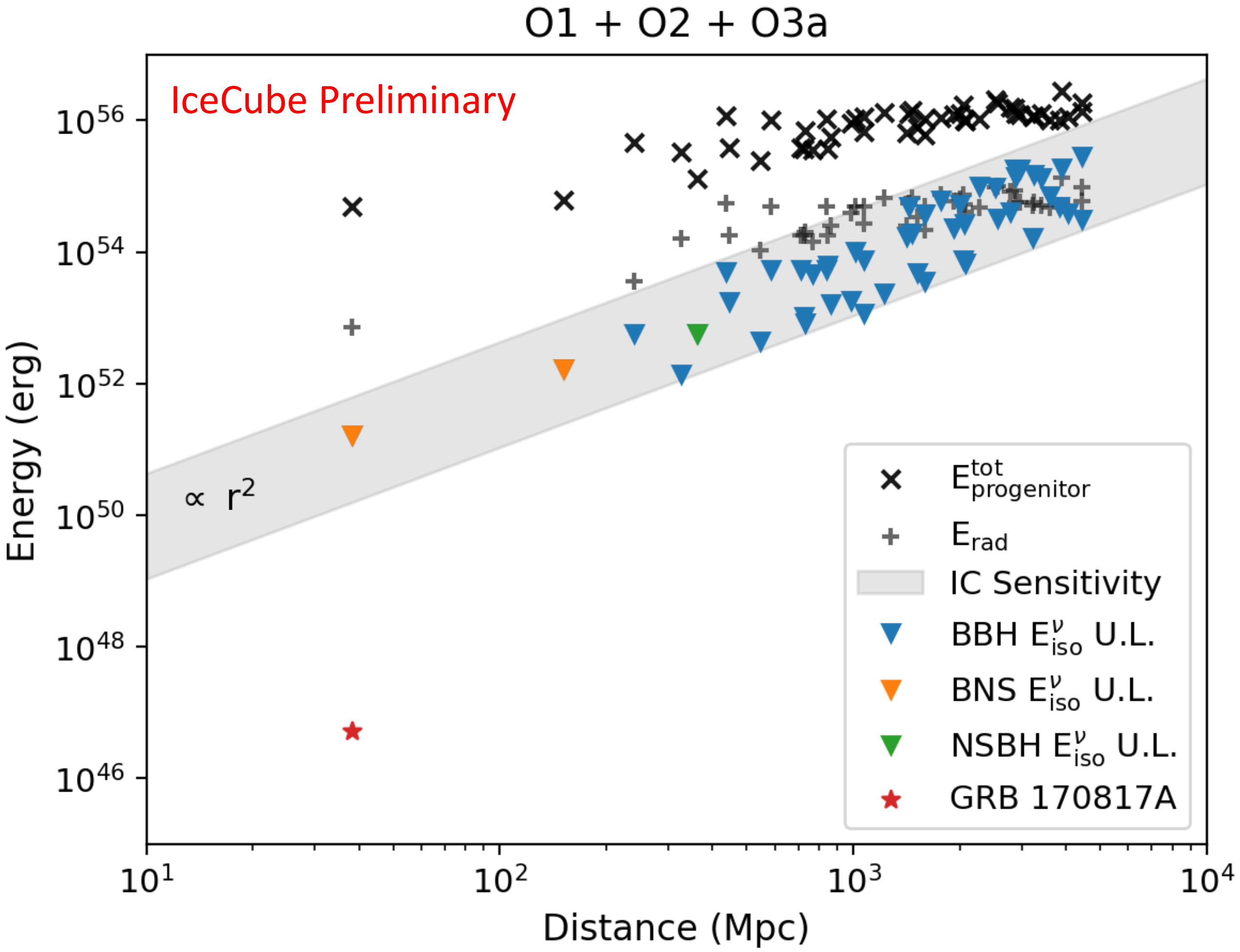
- No neutrinos detected from prompt short GRB phase.
- Neutrinos from long-lived ms magnetar following the merger.
- Neutrinos from internal shock propagating in kilonova ejecta.
- Favorable detection opportunities with multi-messenger triggers.

Figure credit: Christian 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).

Gravitational Wave Follow-up



(a) Limits on $E_{\mathrm{iso}}^{\nu_\mu}$

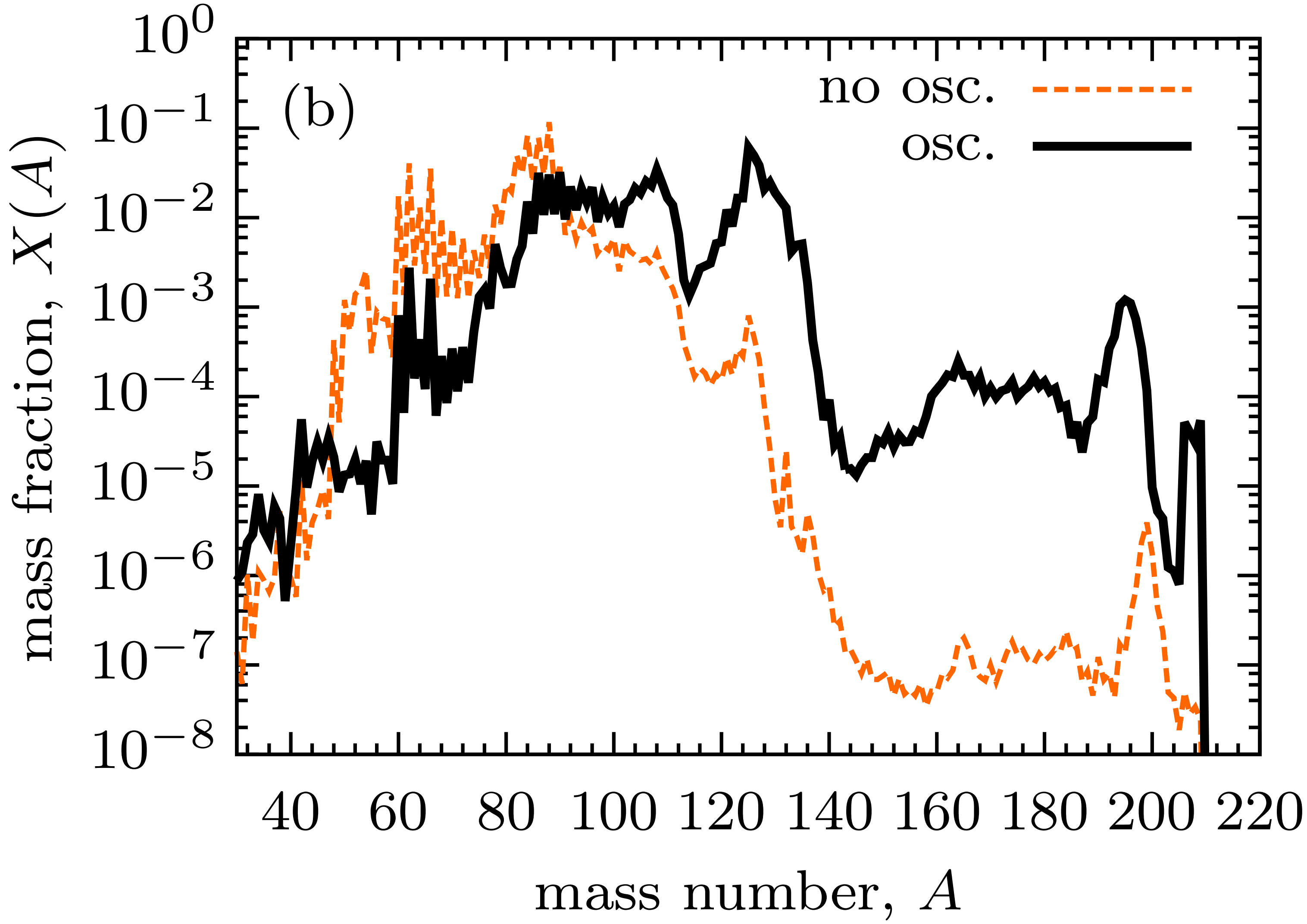


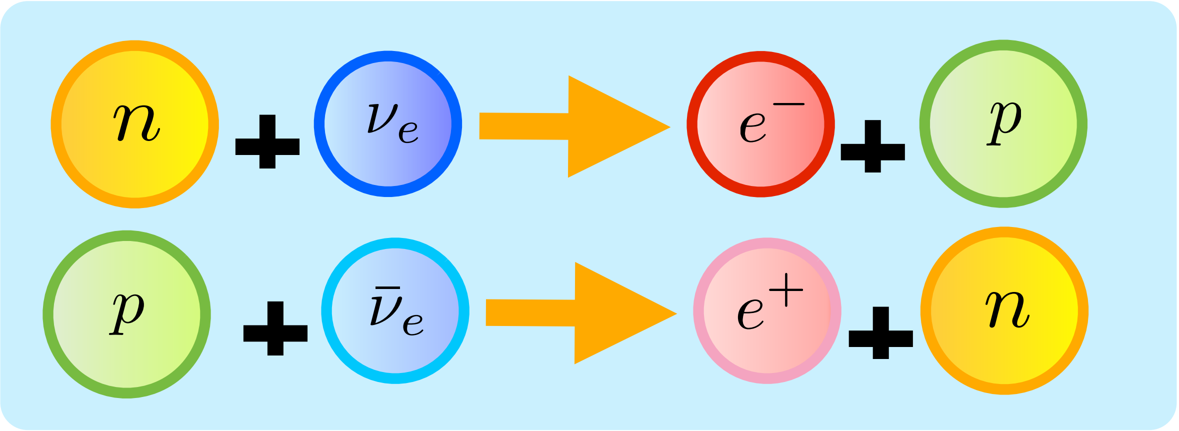
No significant neutrino counterpart found.

Upper limits on the neutrino emission can be placed based on their non-observation.

Abe et al., arXiv: 2104.09196. Doga Veske, ICRC 2021, PoS 950.

Do Neutrinos Affect Element Production?

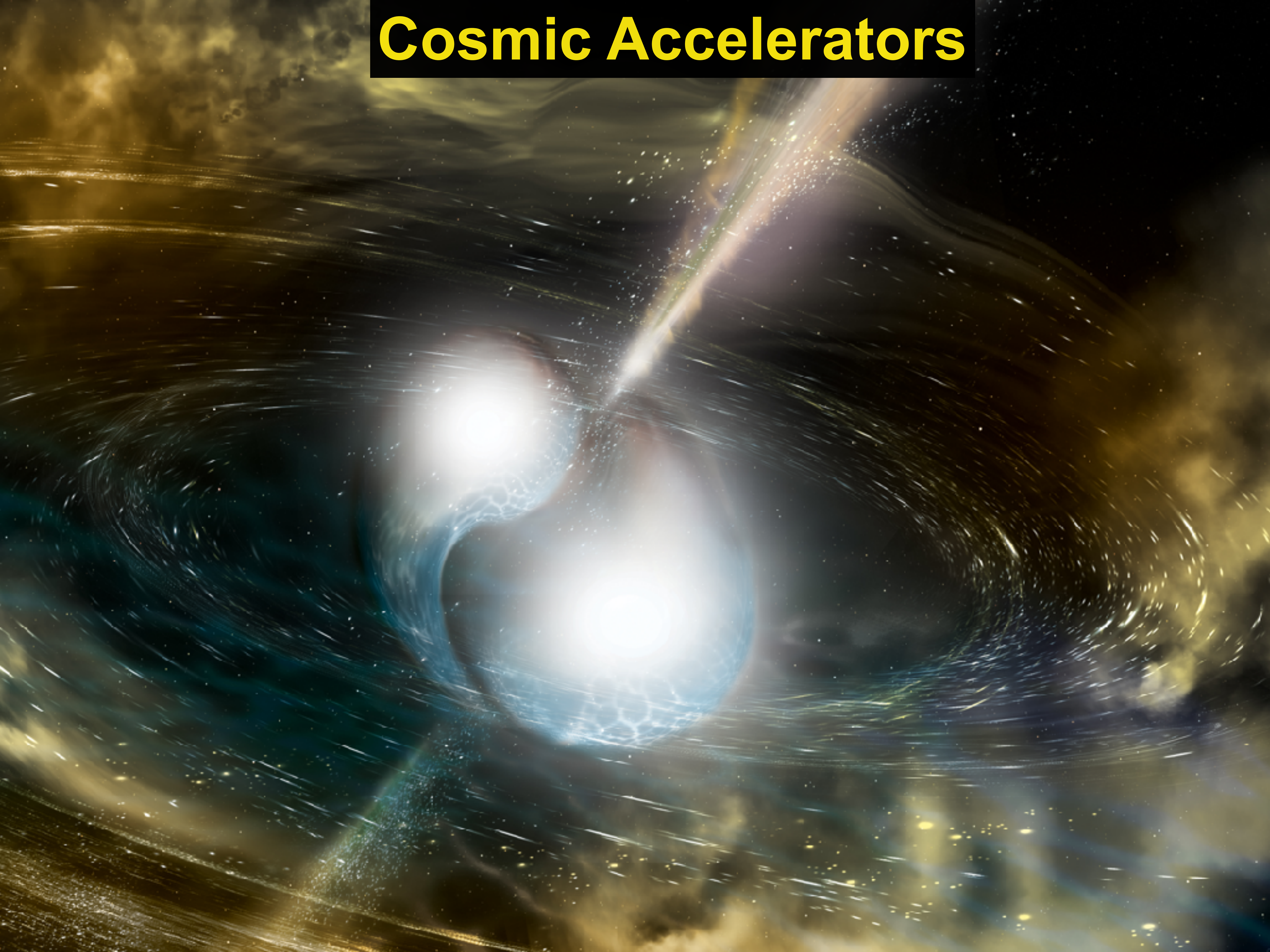




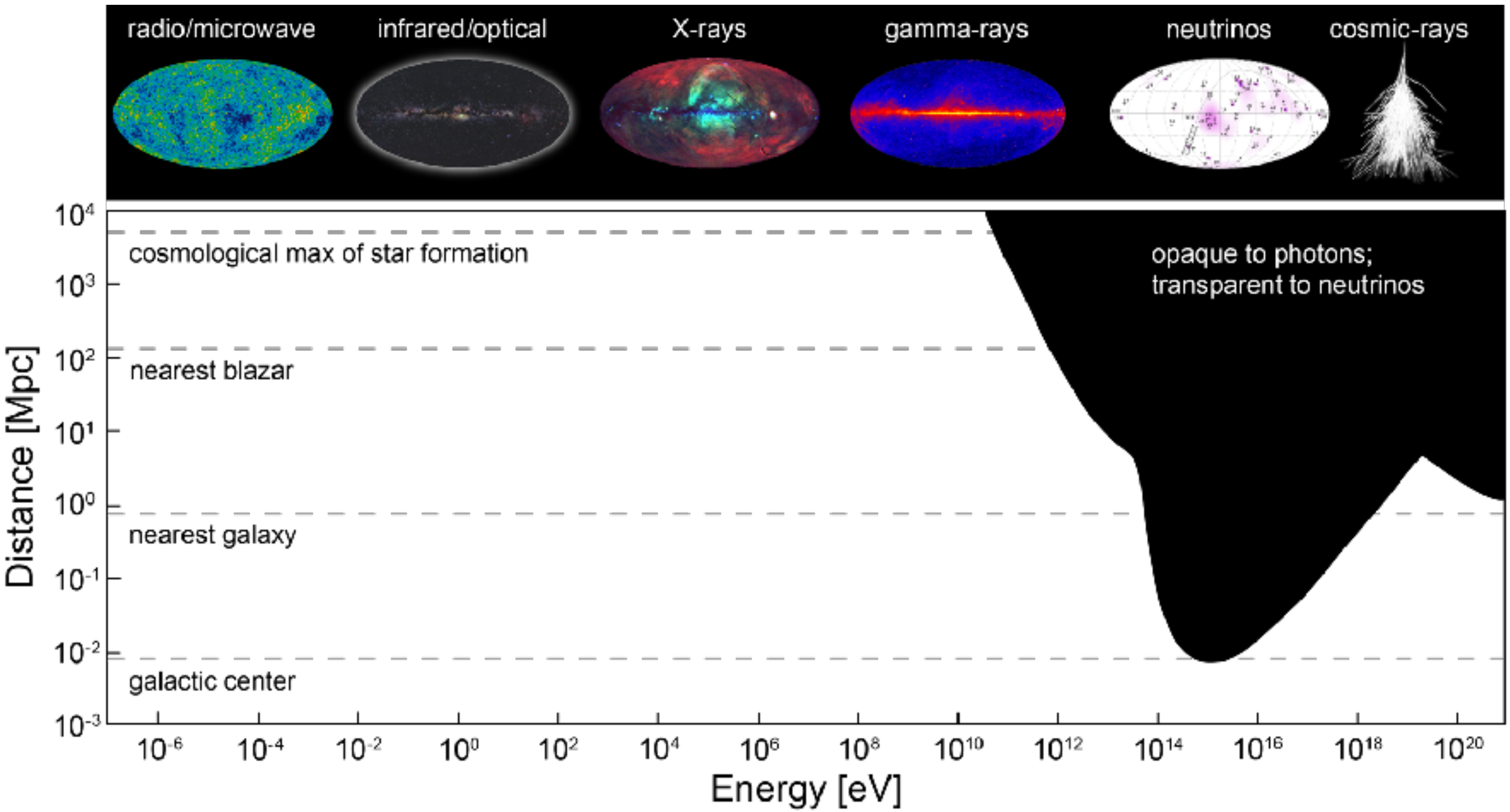
Flavor conversion may lead to an enhancement of nuclei with A>130 (kilonova implications).
More work needed!

Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). George et al., PRD (2020). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). Li & Siegel, PRL (2021).

Cosmic Accelerators



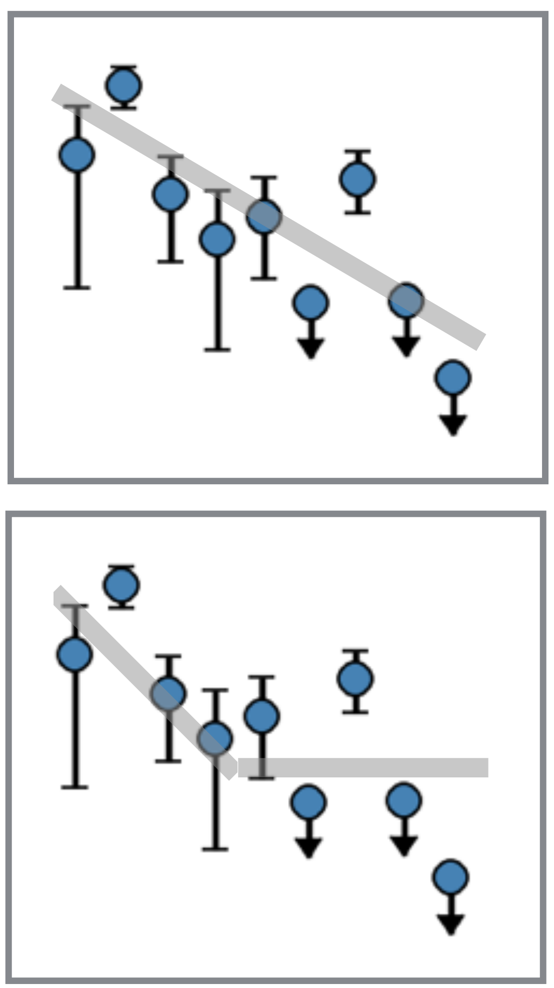
High Energy Neutrino Astronomy

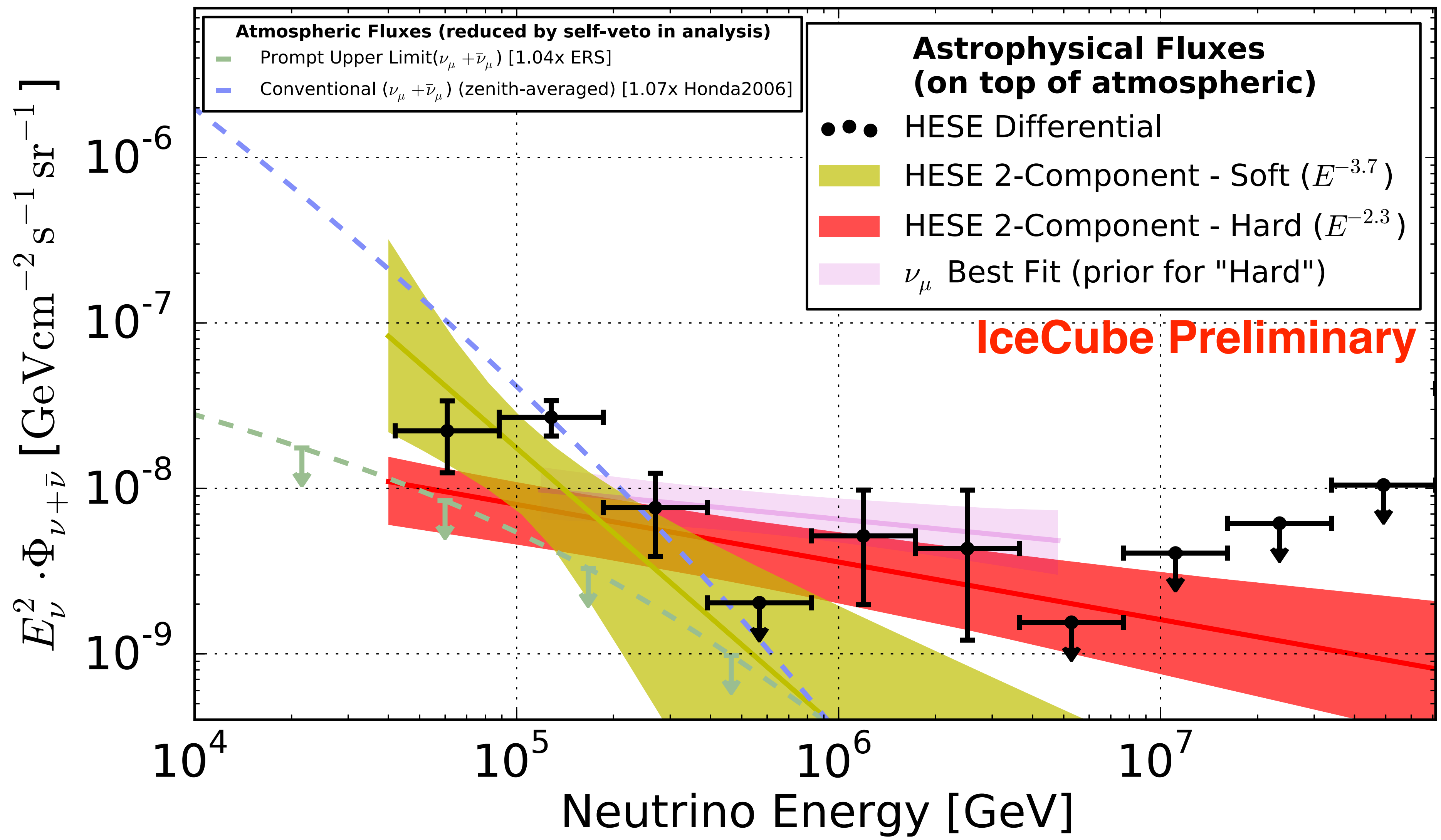


- 20% of the Universe is opaque to electromagnetic radiation.
- Non-thermal Universe powered by cosmic accelerators.

Image credits: https://icecube.wisc.edu/science/highlights/neutrino_astronomy

Measured Astrophysical Neutrino Flux

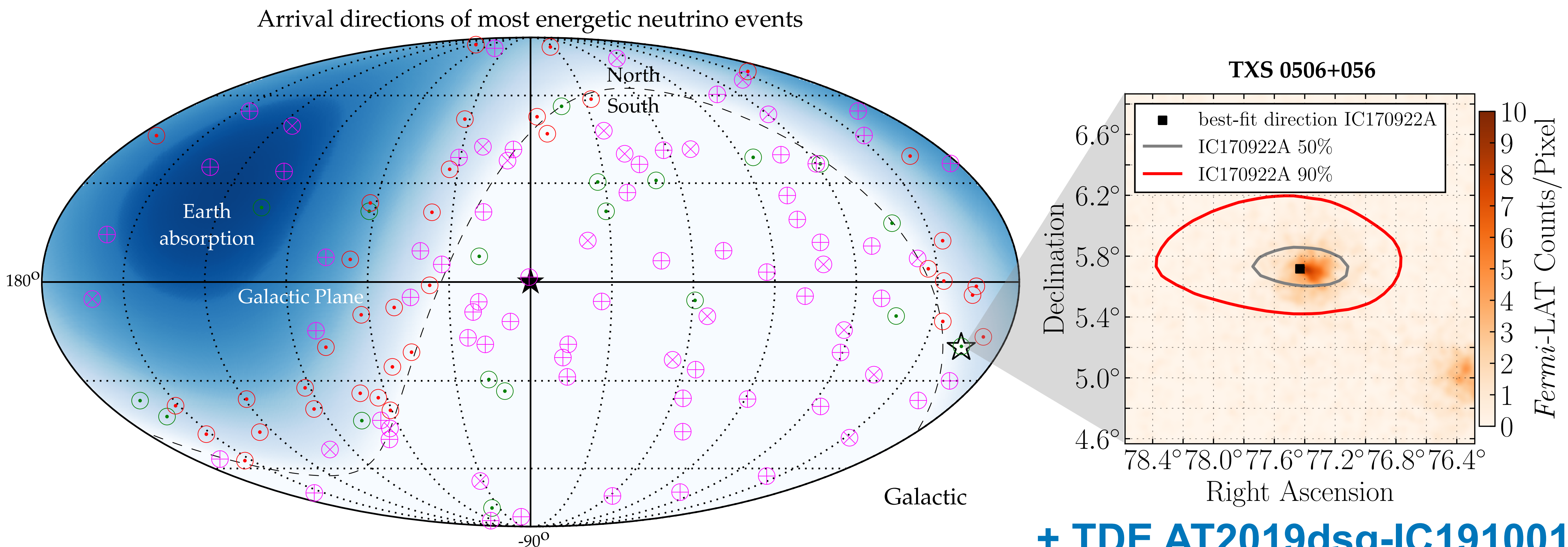




Are we seeing a spectral flattening of energy spectrum?

Figures taken from Ahlers & Halzen, Prog. Part. Phys. (2018). See also arXiv: 2011.03545.

Measured Astrophysical Neutrino Flux



+ TDE AT2019dsg-IC191001A coincidence & a dozen more likely associations?

No evidence of clustering in arrival directions of high-energy neutrinos.

Neutrinos of extragalactic origin.

Figure taken from Aartsen et al., arXiv: 2008.04323. Stein et al., Nature Astronomy (2021). 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.

Where Are These Neutrinos Coming From?

Do we really see a connection among all messengers?

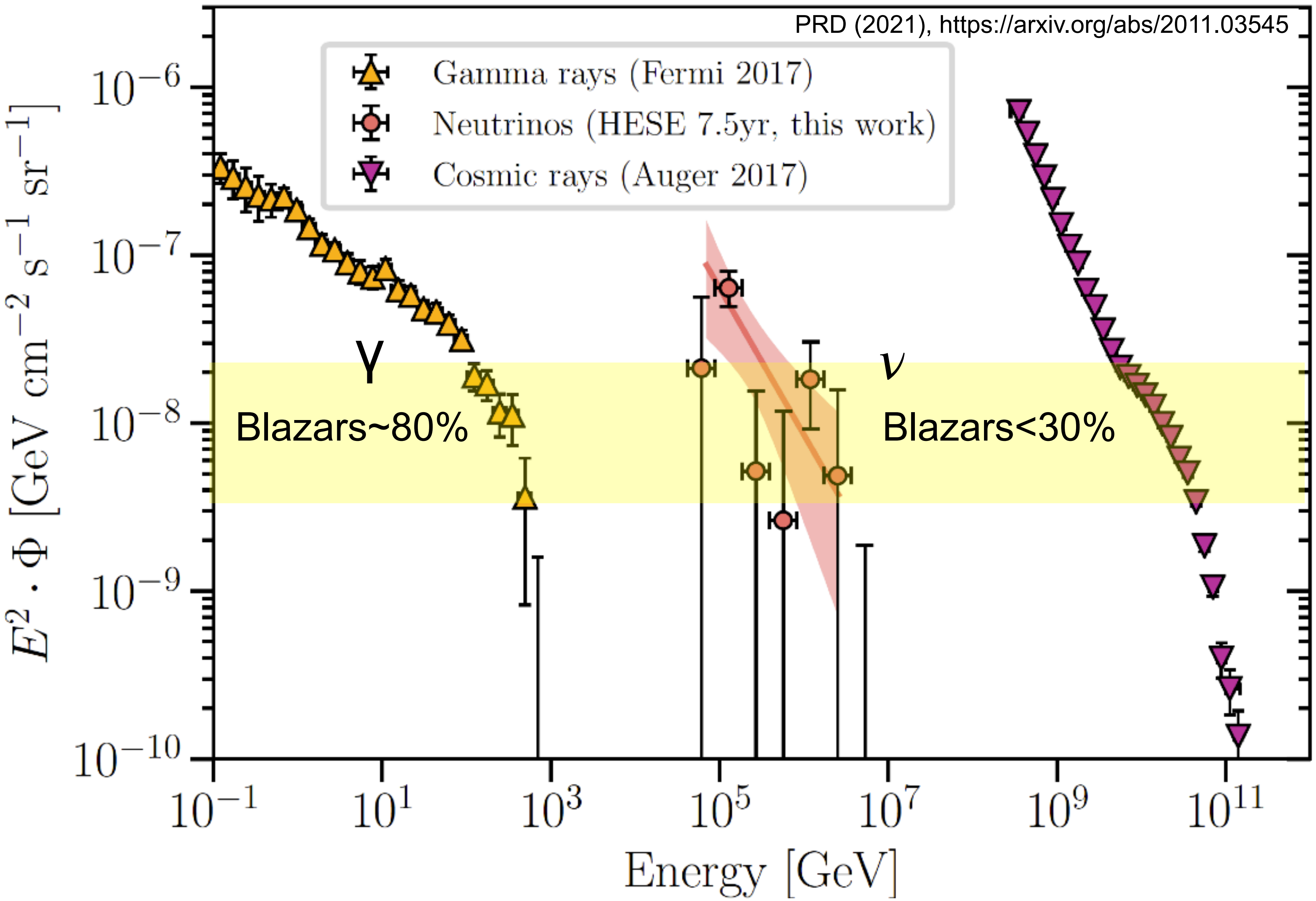
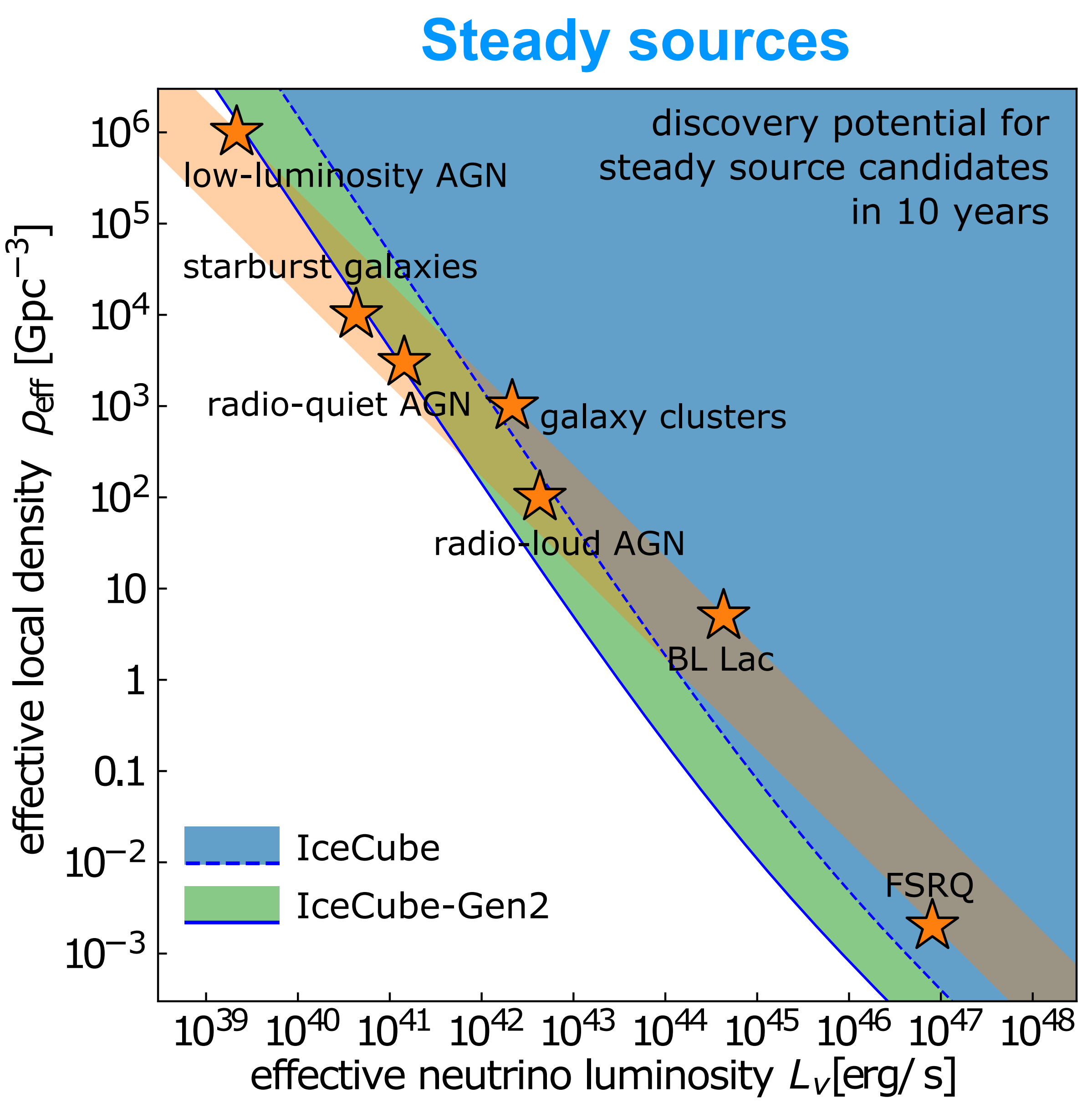


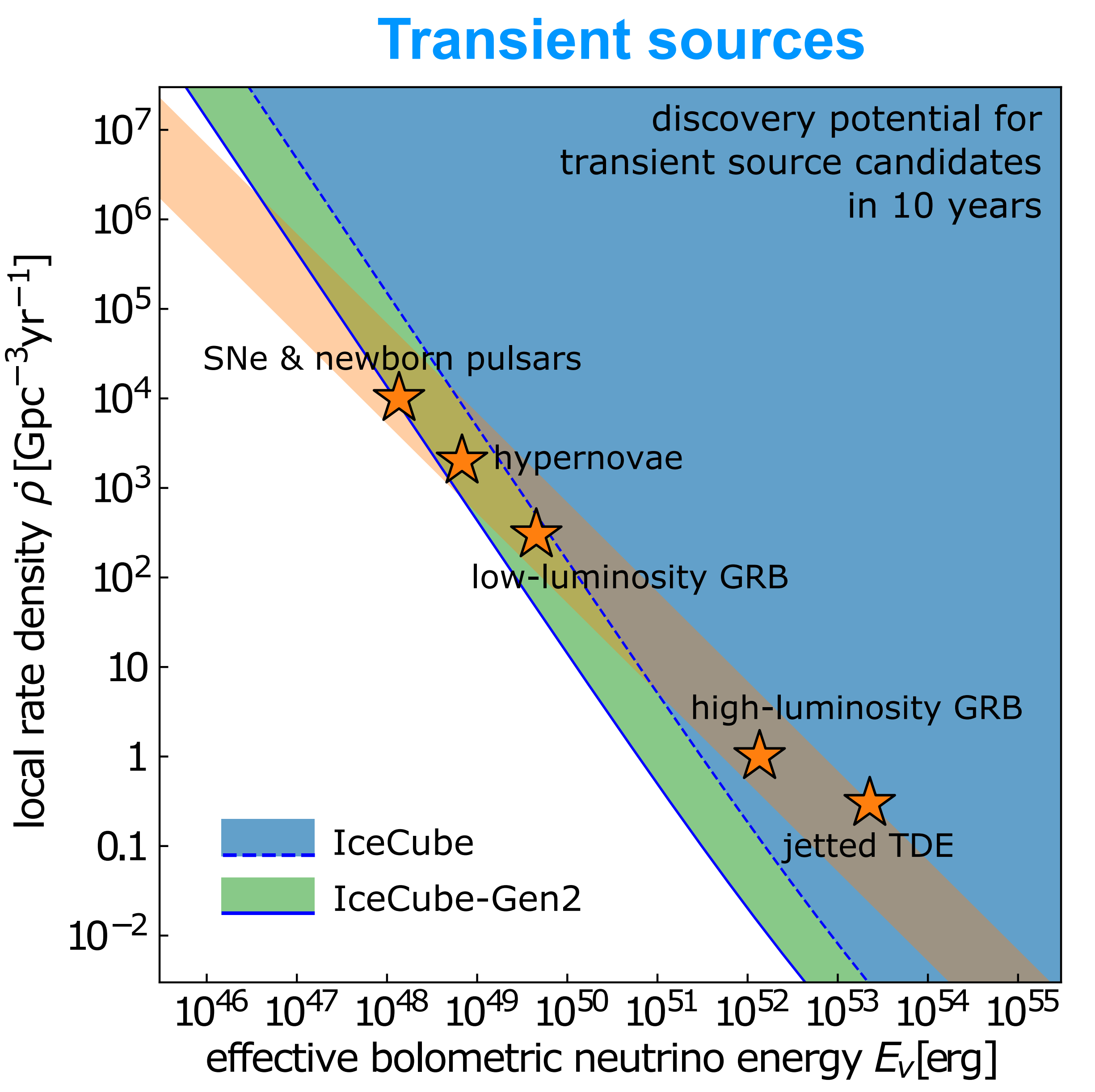
Figure credit: Marek Kowalski, ICRC 2021, PoS 022.

Emerging Tasks

- Find the sources of IceCube's high energy neutrinos.
- Identify any connection with UHECR, electromagnetic emission, and gravitational waves.
- 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.

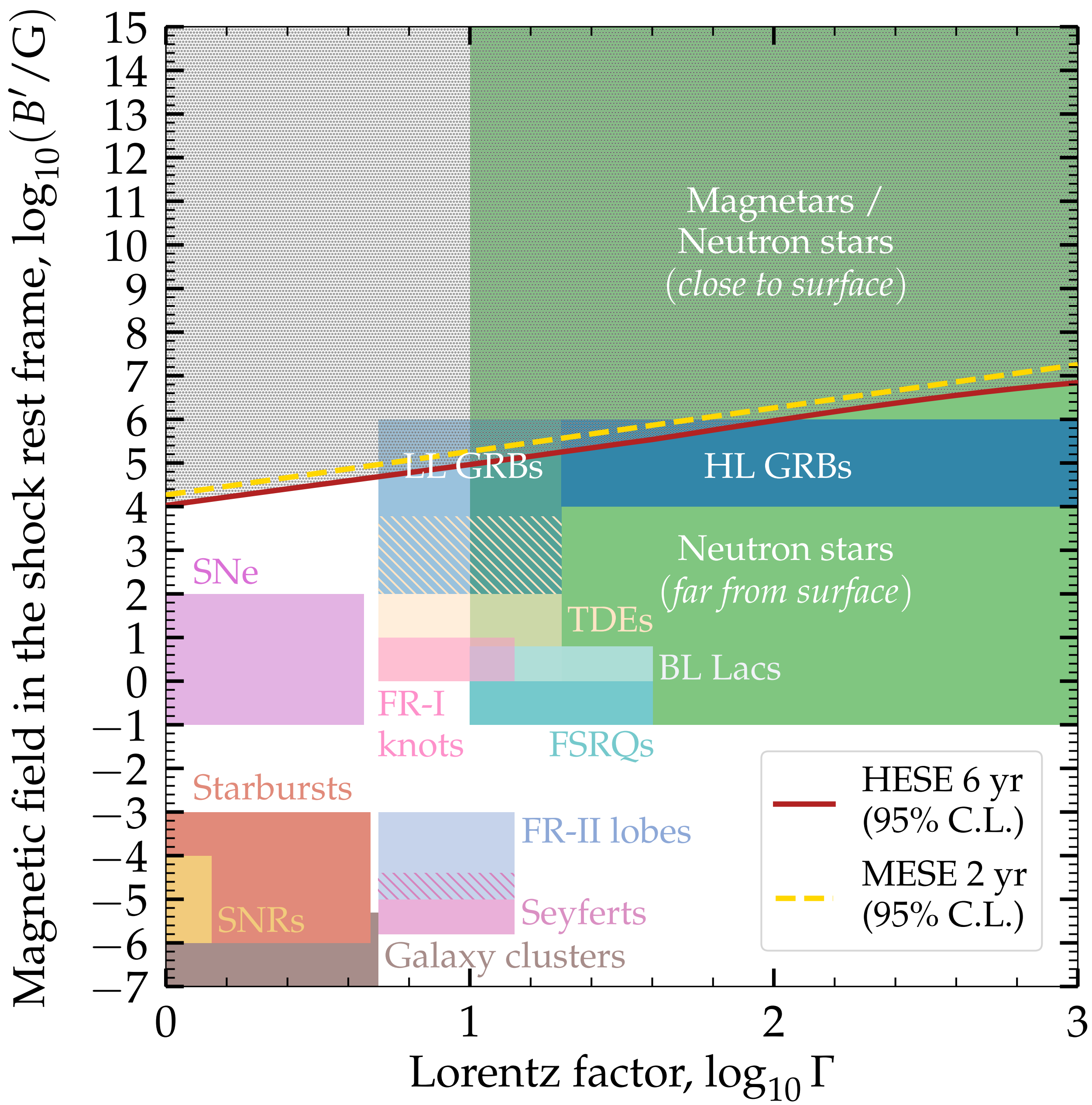
Where Are These Neutrinos Coming From?





Figures taken from Aartsen et al., arXiv: 2008.04323. Mertsch, Rameez, Tamborra, JCAP (2017). Musase & Waxman, PRD (2016). Ando, Tamborra, Zandanel, PRL (2015). Feyereisen, Tamborra, Ando, JCAP (2017).

Fingerprints of Source Properties



IceCube data can already constrain, e.g.:

- Fraction of supernovae harboring (choked) jets.
- Magnetic field of the sources.
- Source redshift evolution.

Bustamante & Tamborra, PRD (2020). Denton & Tamborra, ApJ (2018). Esmaili & Murase, JCAP (2018). Tamborra & Ando, PRD (2016). Senno et al., PRD (2015). Meszaros & Waxman, PRL (2001). Levan et al., ApJ (2014). Winter, PRD (2013). Ando, Tamborra, Zandanel, PRL (2015).

A Laboratory for New Physics

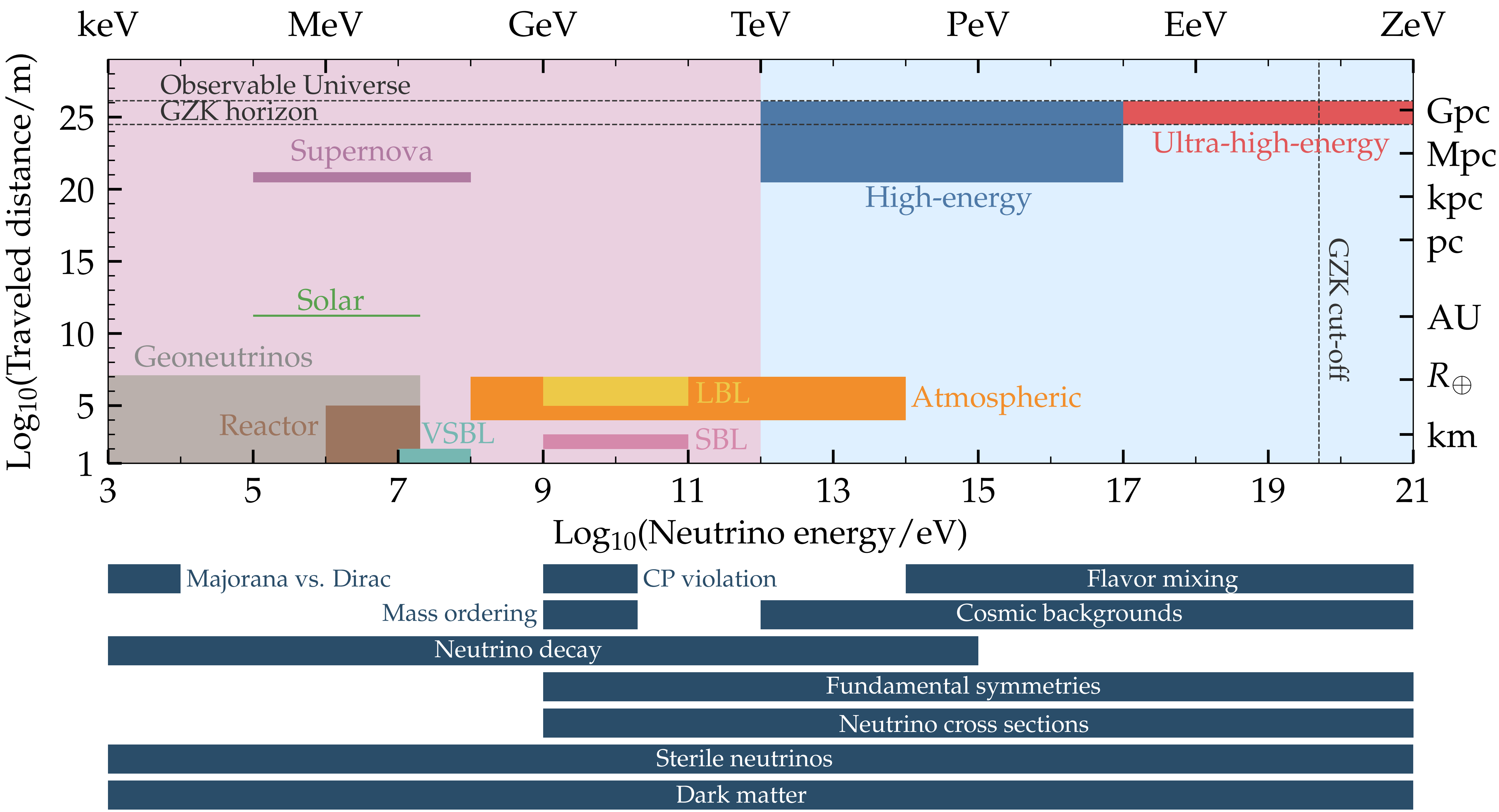


Figure taken from Ackermann et al., arXiv: 1903.04333. Suliga, Tamborra, PRD (2021). Suliga, Tamborra, Wu JCAP (2019, 2020). Tamborra et al., JCAP (2012). Bustamante, Rosenstrom, Shalgar, Tamborra, PRD (2020). Shalgar, Tamborra, Bustamante, PRD (2021). Denton & Tamborra, PRL (2018).

Conclusions

- Neutrinos are fundamental cosmic messengers.
- Low energy neutrinos carry imprints of the source engine and affect the synthesis of the heavy elements.
- Neutrino mixing relevant, not yet complete understanding.
- High energy neutrinos carry information on source aftermath. Sources unknown. Growing number of likely associations.
- Astrophysical neutrinos are probes of new physics.

Thanks!