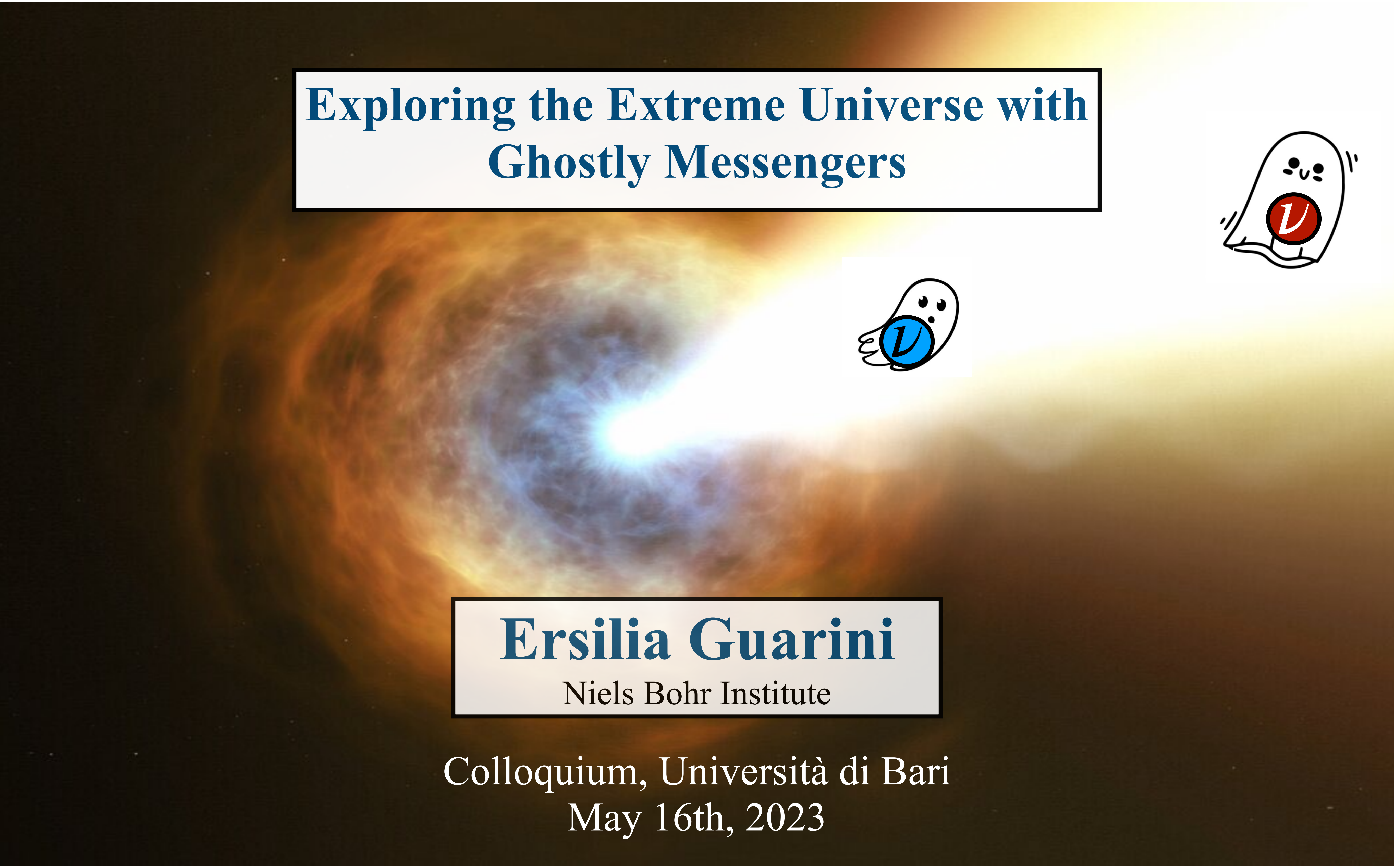
The Niels Bohr International Academy

DARK



Exploring the Extreme Universe with Ghostly Messengers

Ersilia Guarini

Niels Bohr Institute

Colloquium, Università di Bari

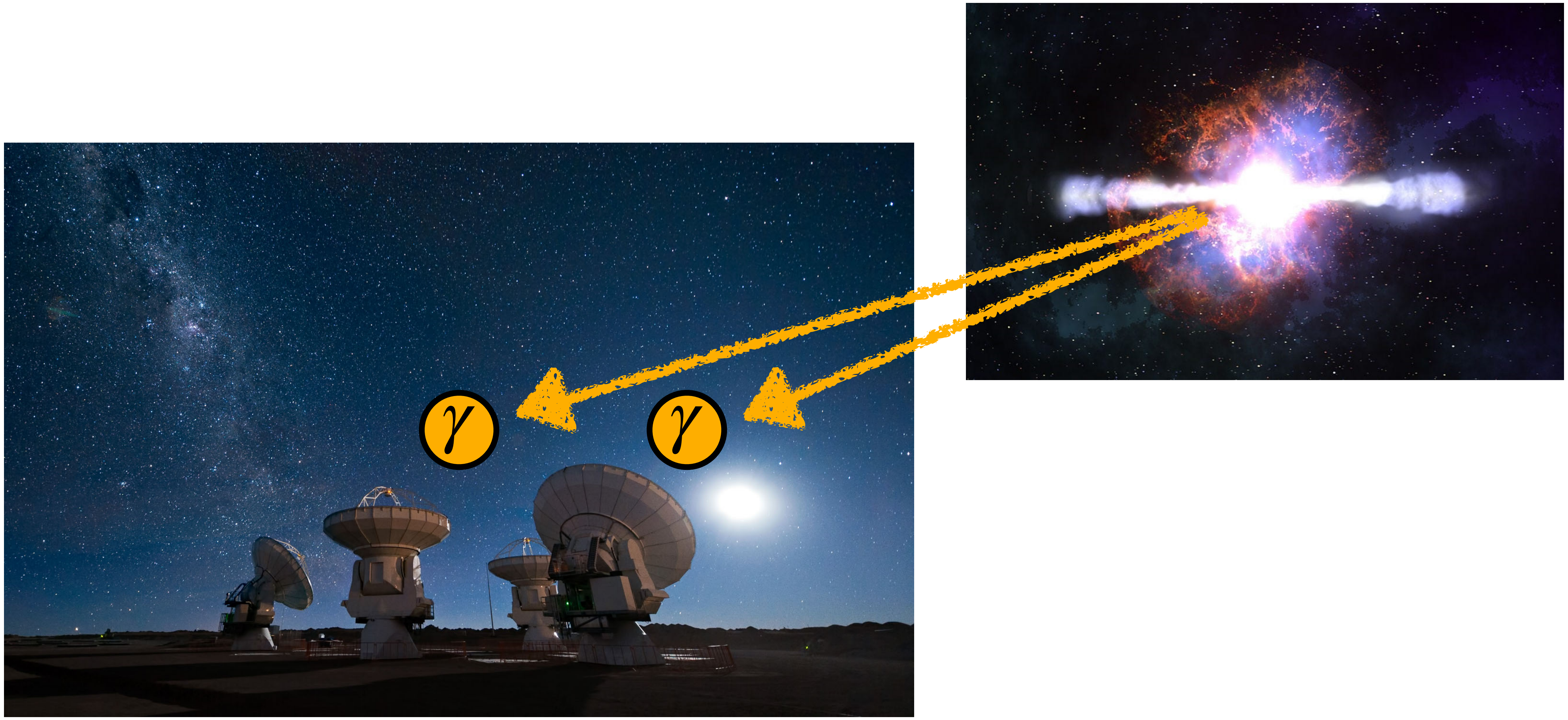
May 16th, 2023

CARLSBERGFONDET

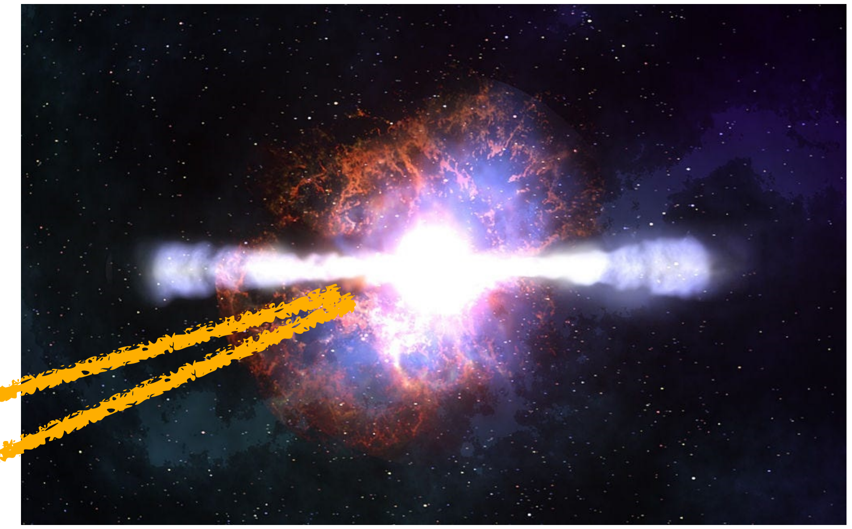
Outline

- The multi-messenger astrophysics era: current status.
- Supernovae.
- Neutron star mergers.
- Cosmic accelerators.
- Conclusions and outlook.

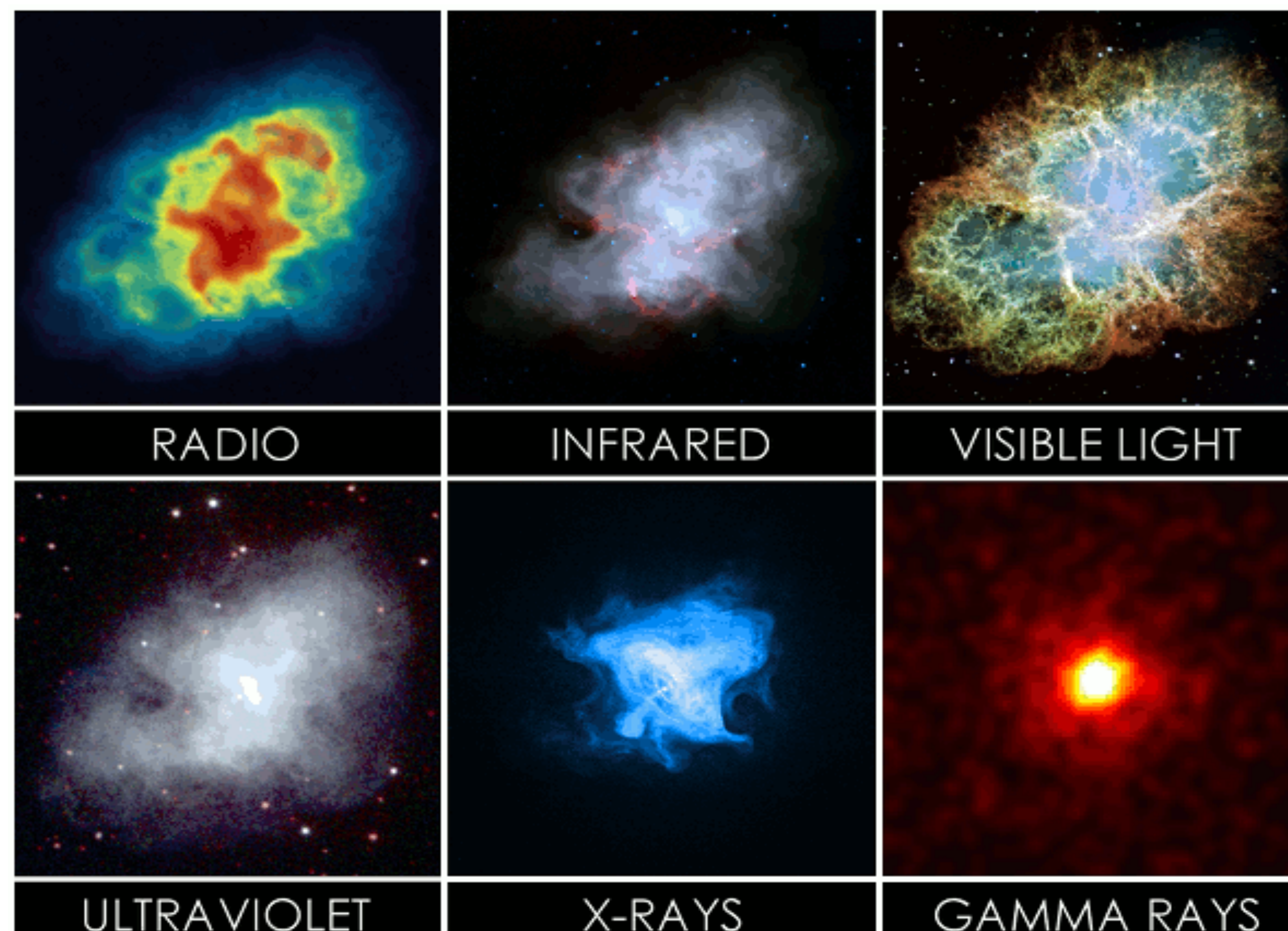
Looking at the Universe through Photon Lenses



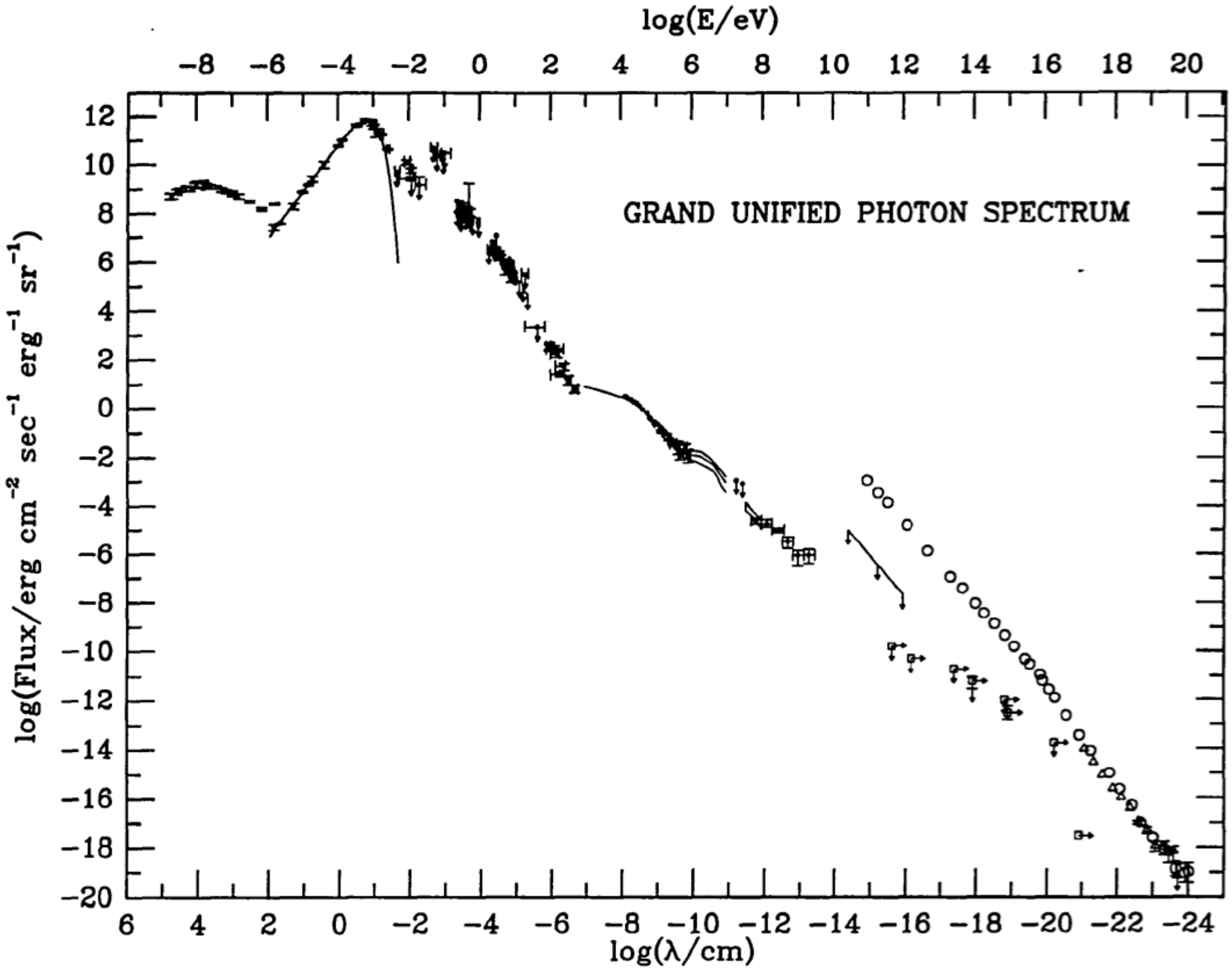
Looking at the Universe through Photon Lenses



We are great photon hunters!



The Grand Unified Photon Spectrum



Ressel and Turner, Comments Atrophys. , Bull. Am. Astron. Soc. 22 (1990)

Photon Astronomy

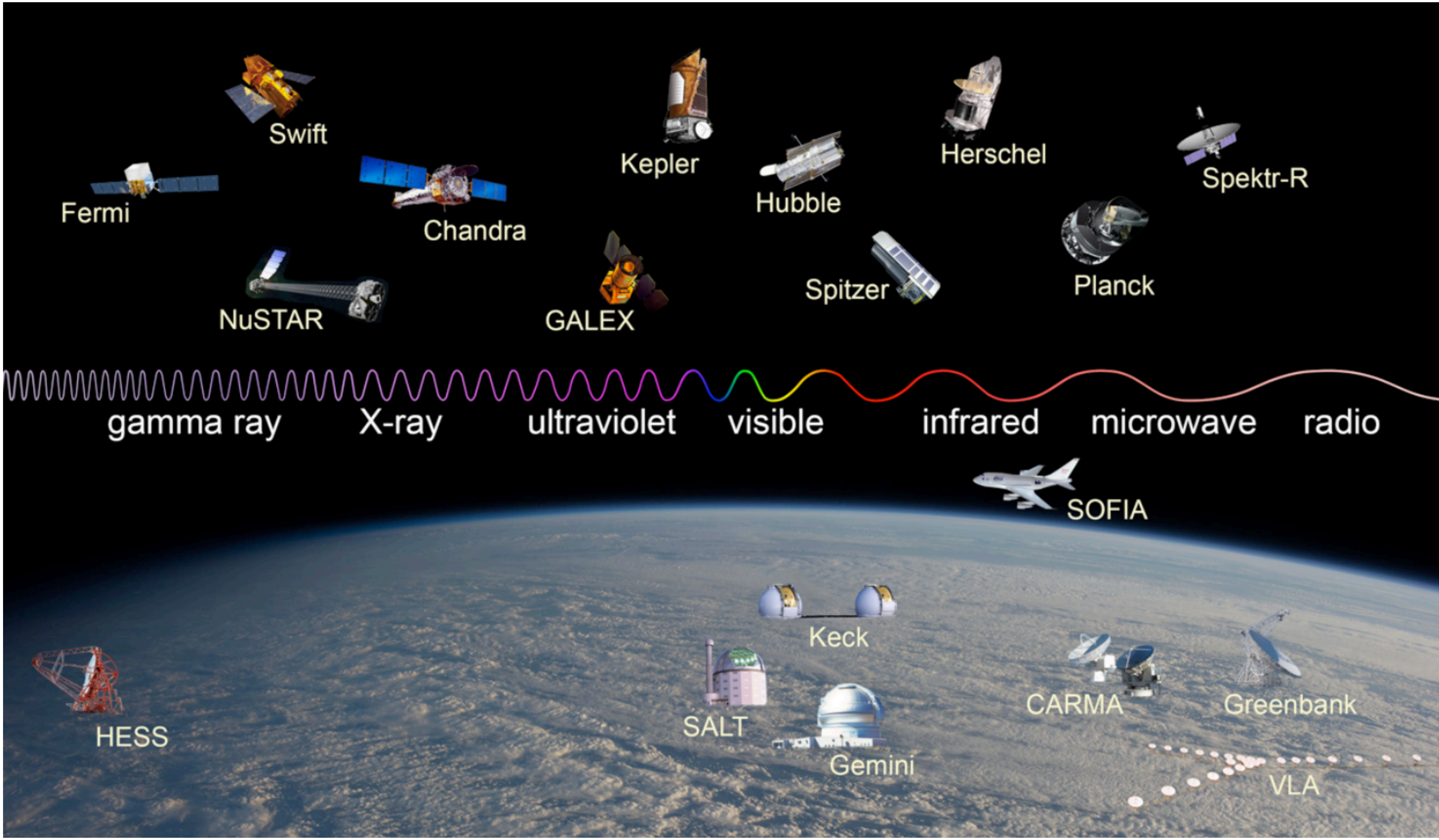


Image credit: Goddard Space Flight Center

Atmosphere Opacity

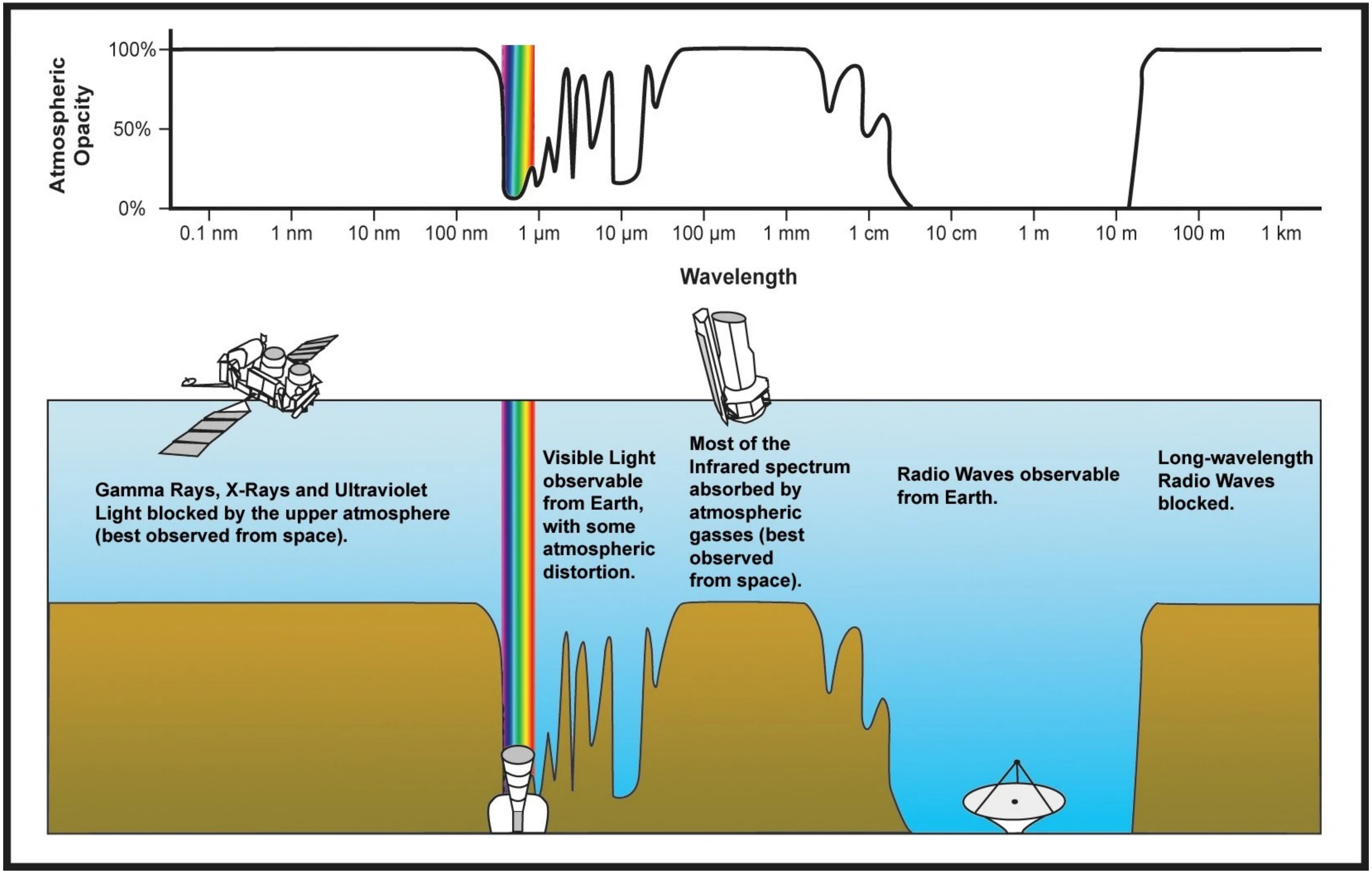
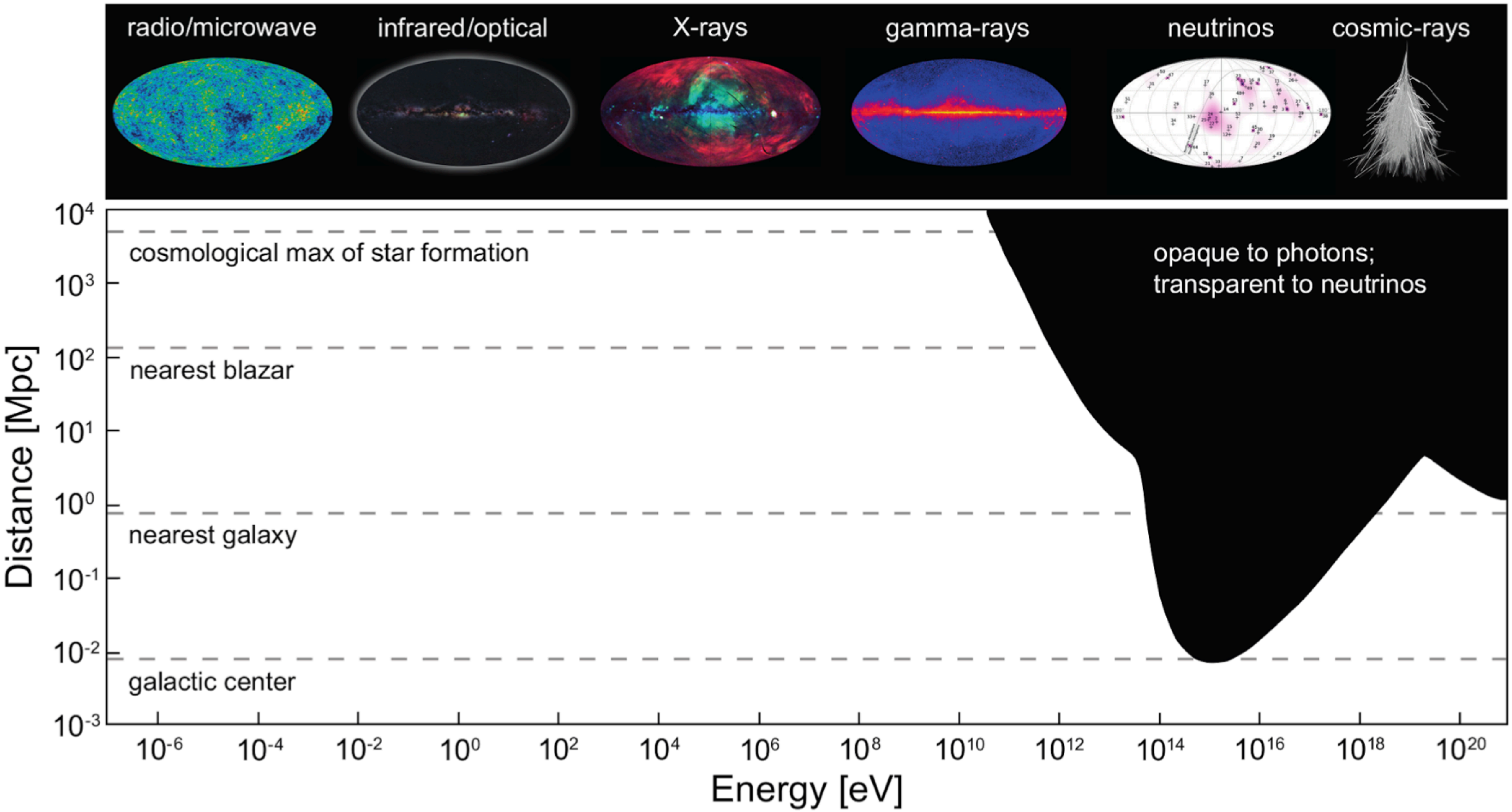


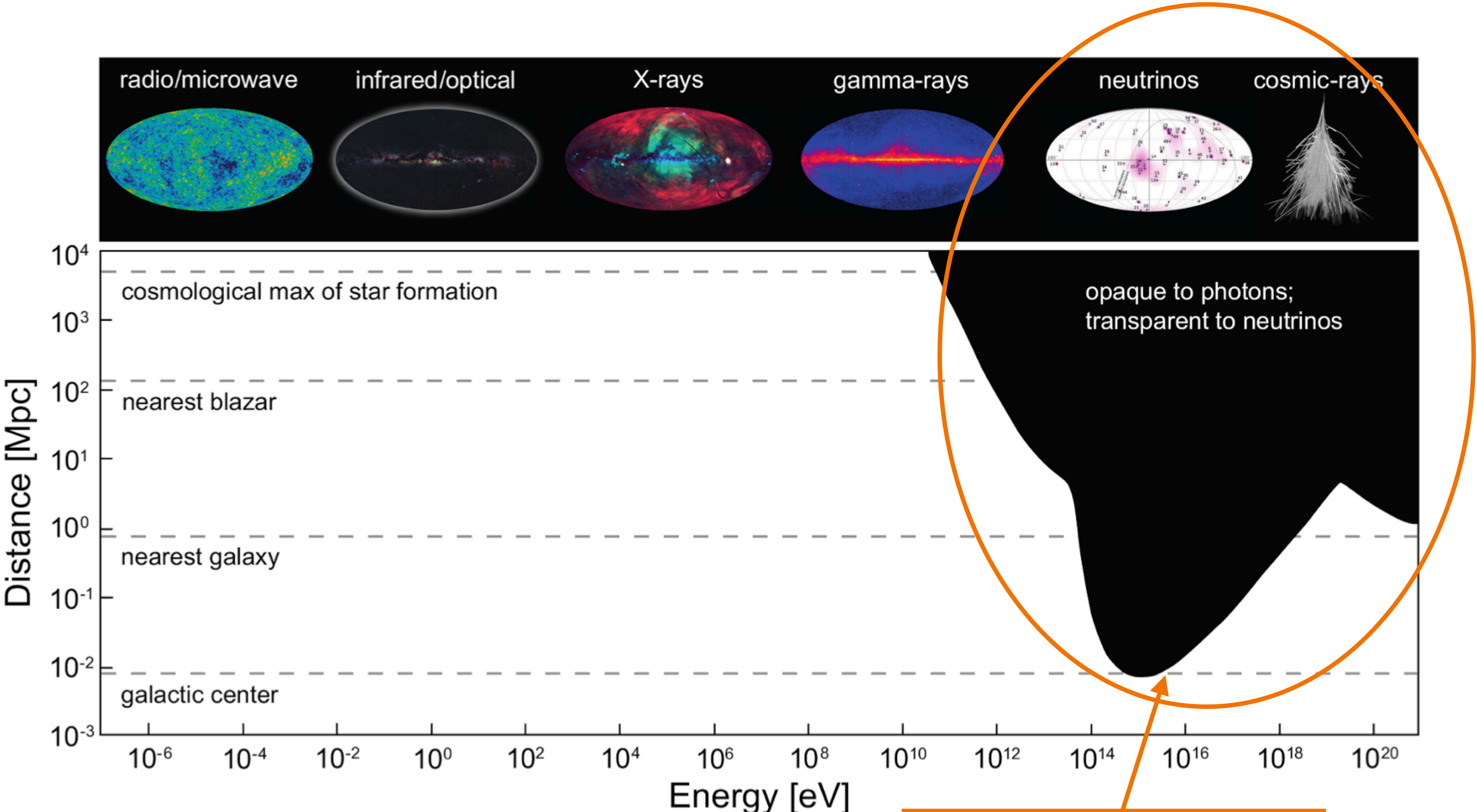
Image credit: ESA/Hubble

Universe Opacity to Electromagnetic Radiation



IceCube Collaboration, J. Phys. G. (2021)

Universe Opacity to Electromagnetic Radiation



IceCube Collaboration, J. Phys. G. (2021)

We need new messengers
to probe
the extreme Universe

What if we could change our glasses?

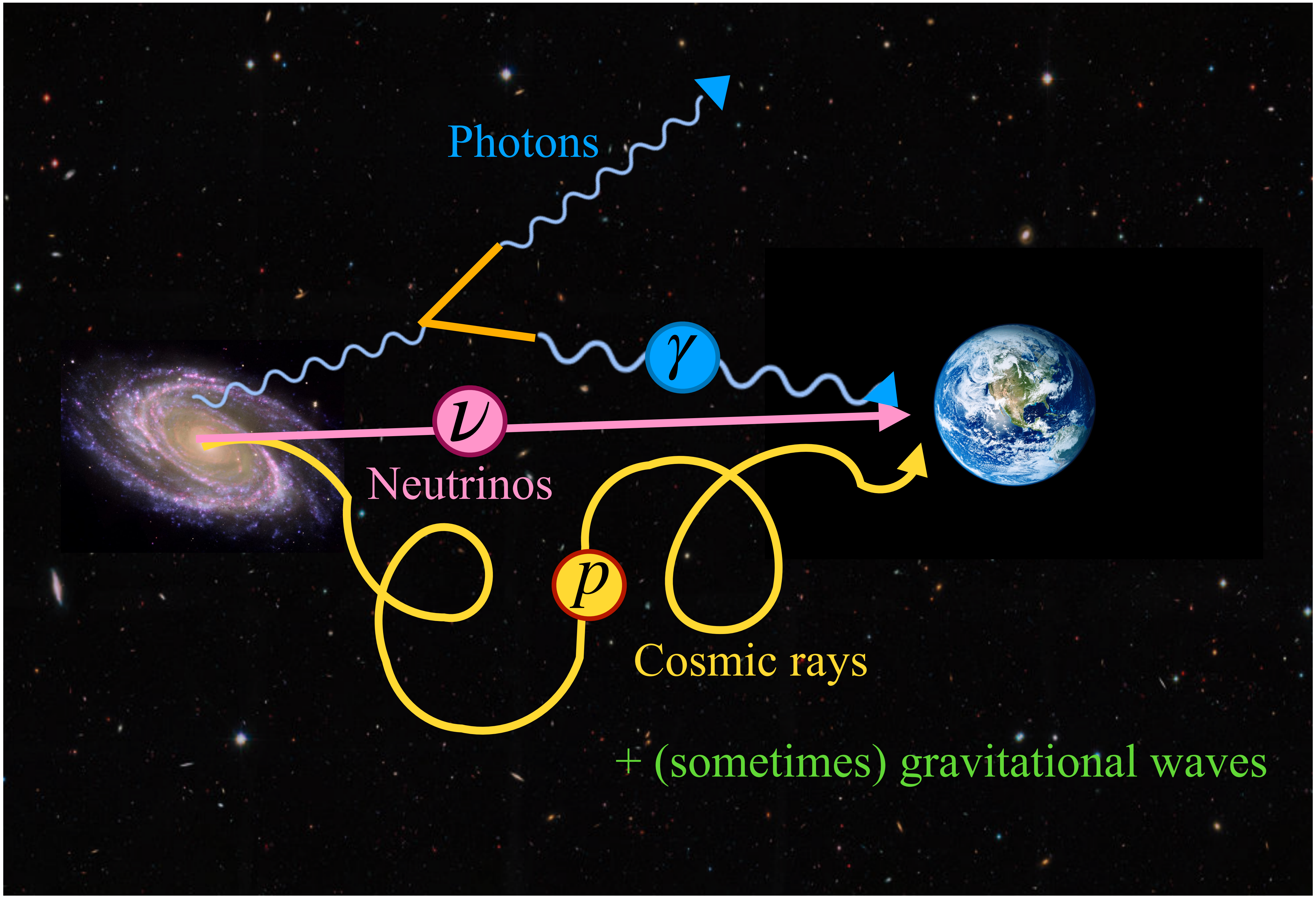
Ghostly Messengers from the Cosmos

Elusive

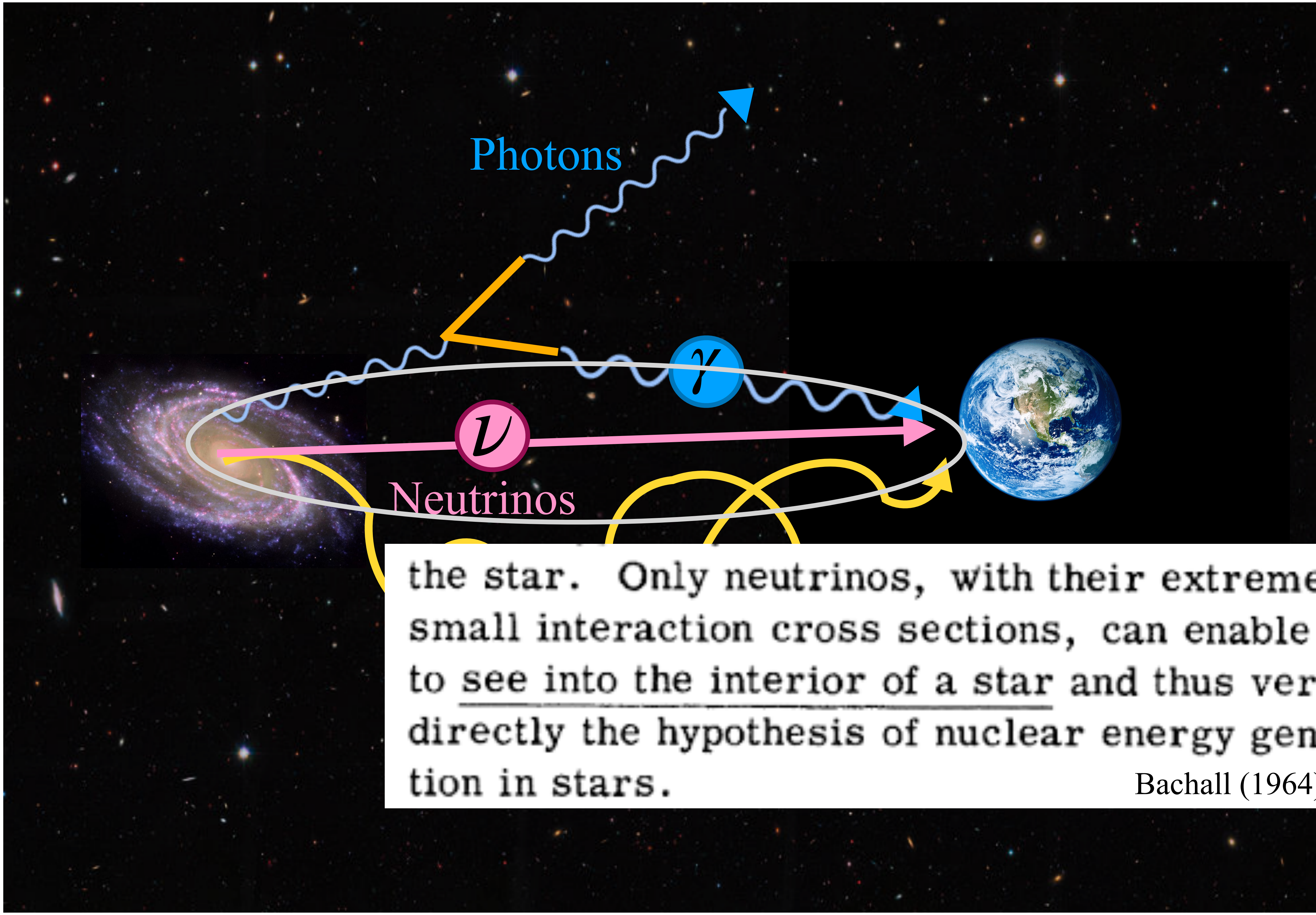
Abundant

3 flavors
oscillating

The Multi-Messenger Astronomy Era



Looking at the Universe through Neutrino Lenses

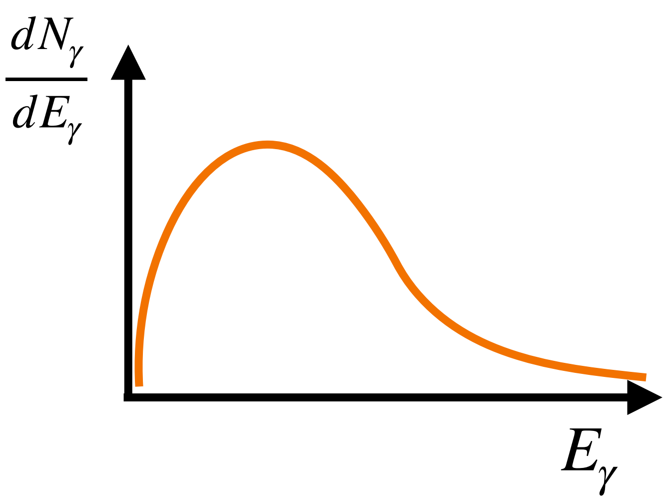


> the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

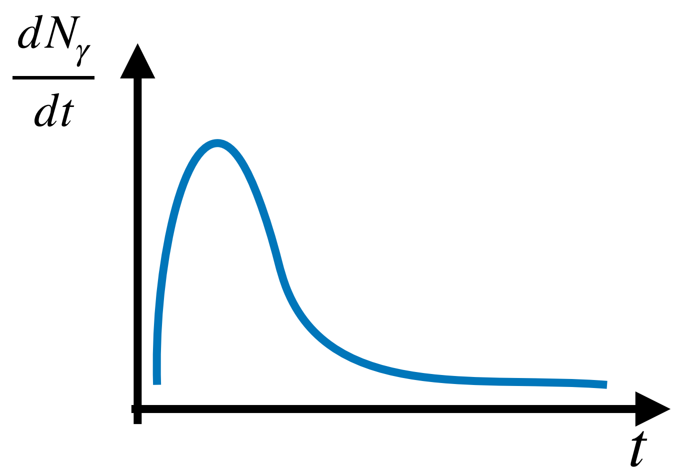
Bachall (1964)

Photons VS Neutrinos

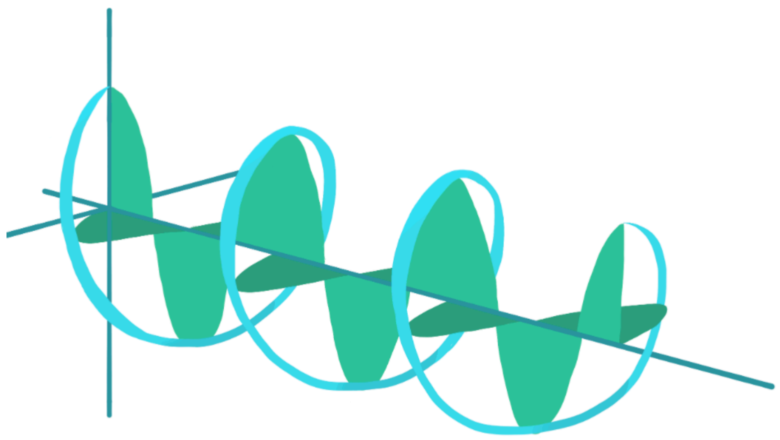
Photons



Photon energy distribution

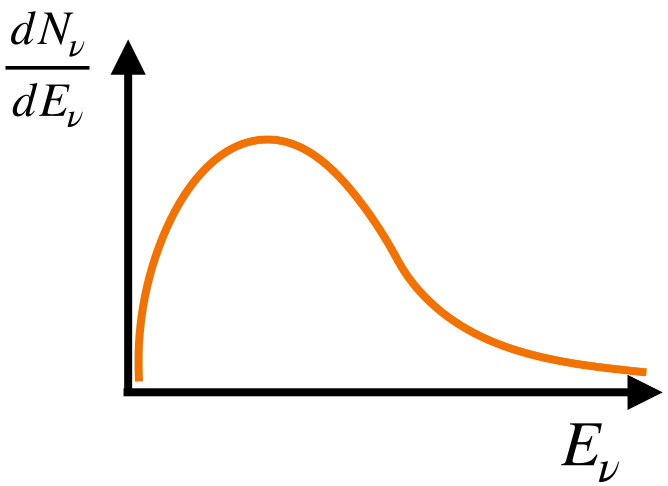


Lightcurve

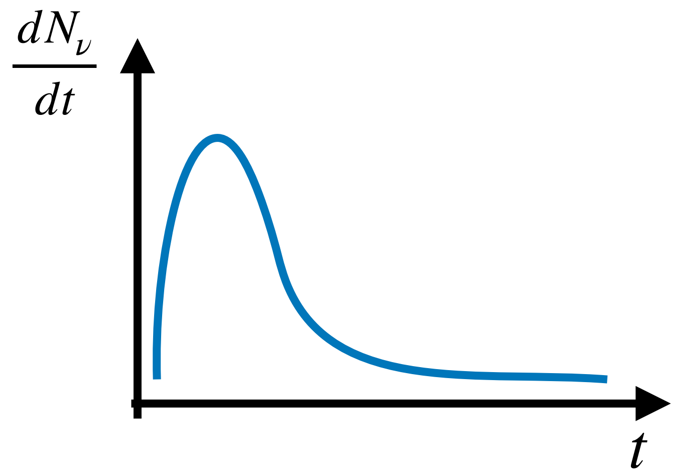


Polarization

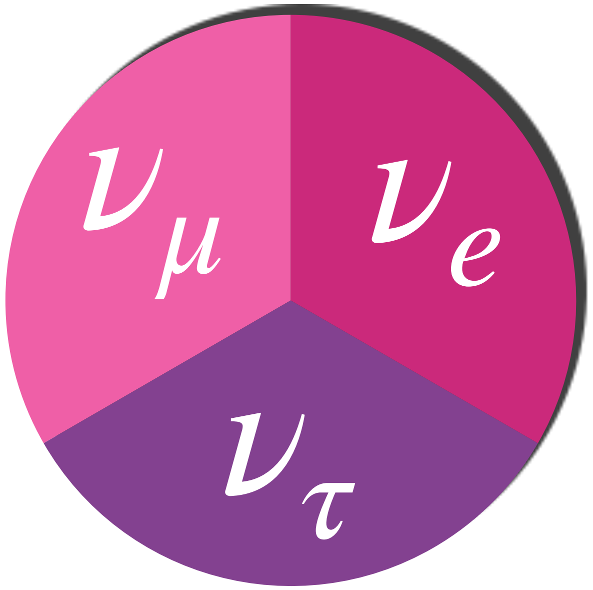
Neutrinos



Neutrino energy distribution

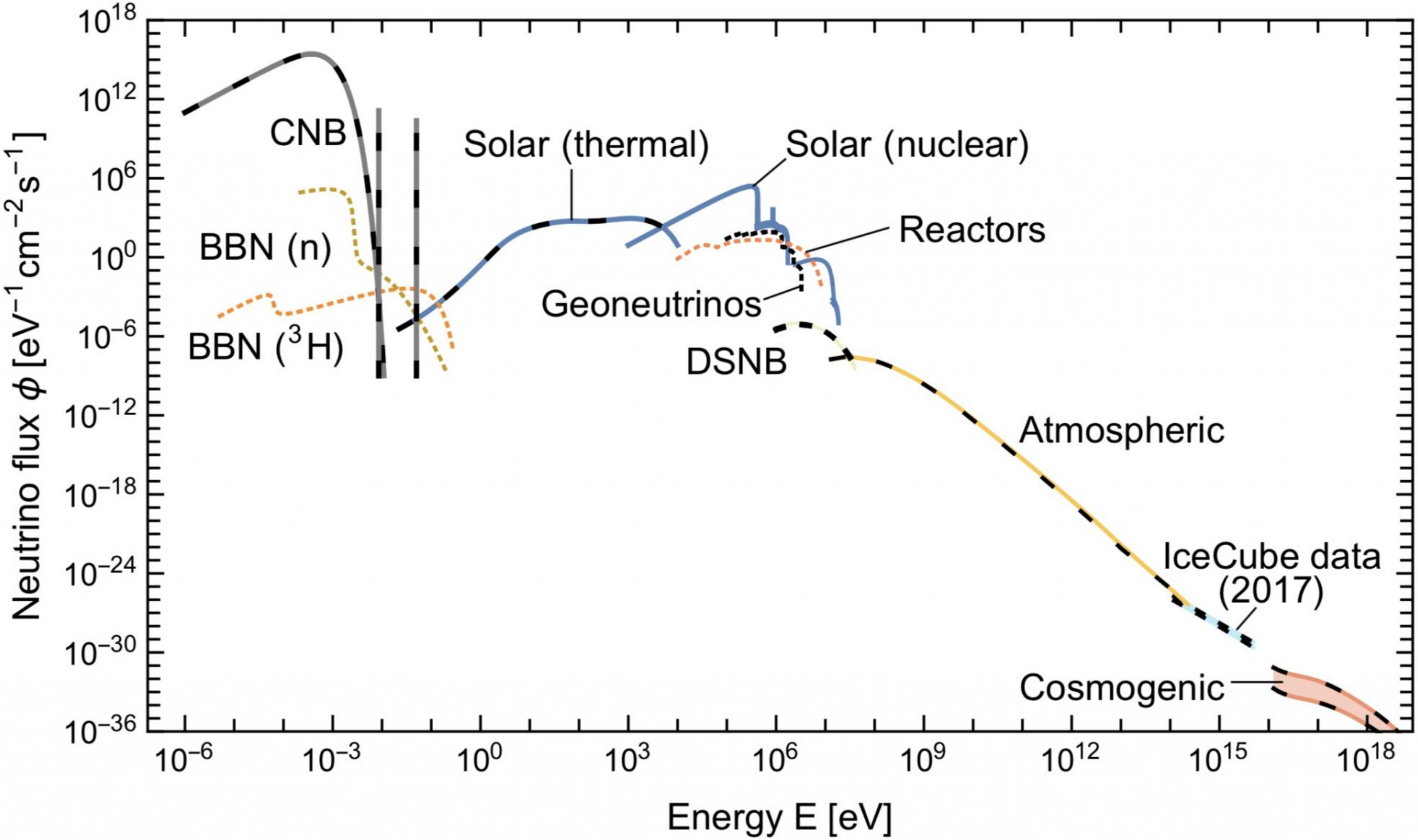


Neutrino curve



Flavor

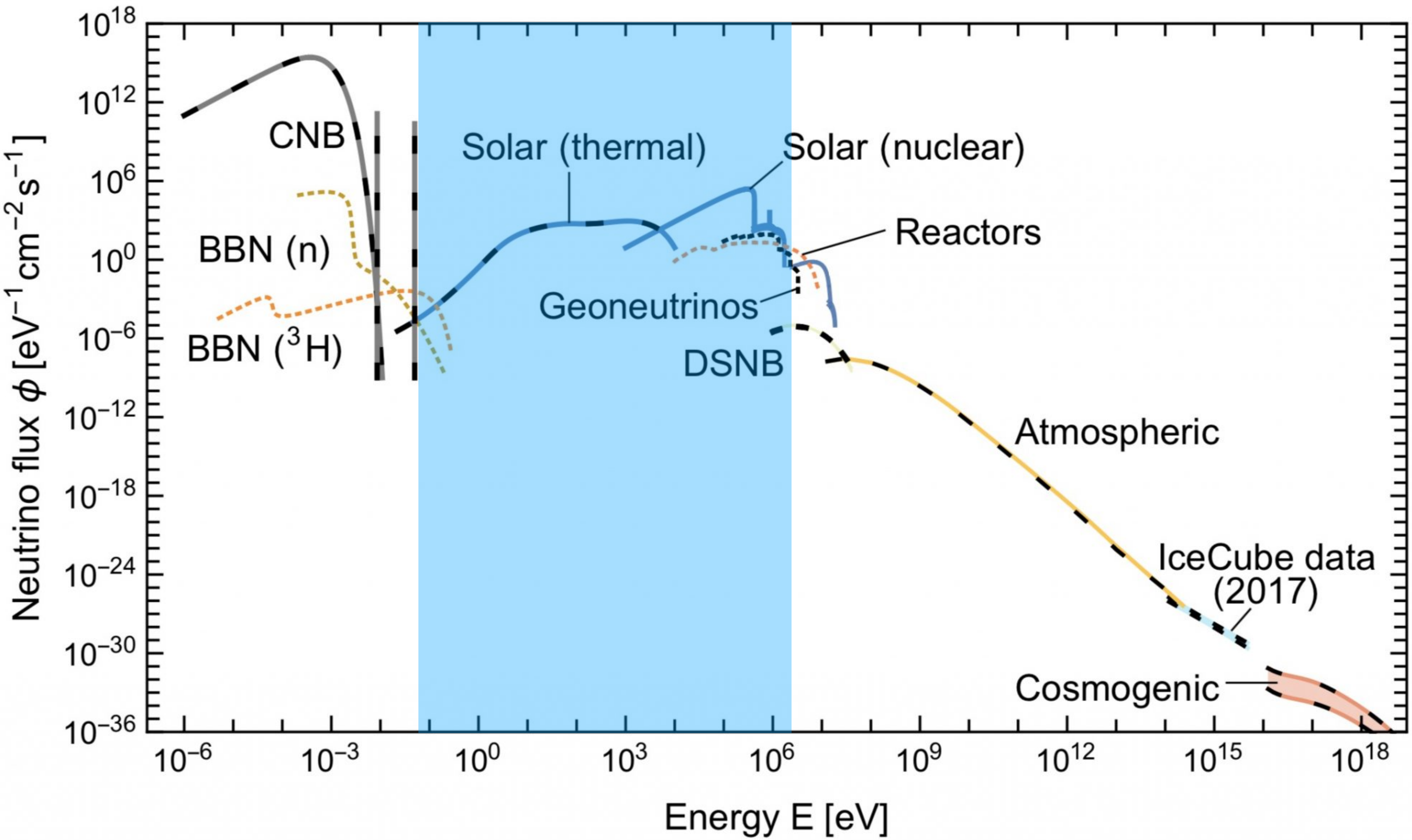
The Grand Unified Neutrino Spectrum



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

The Dream of Multi-Messenger Astrophysics is Coming to Life!

The Grand Unified Neutrino Spectrum



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

1. The Sun Seen in Neutrinos

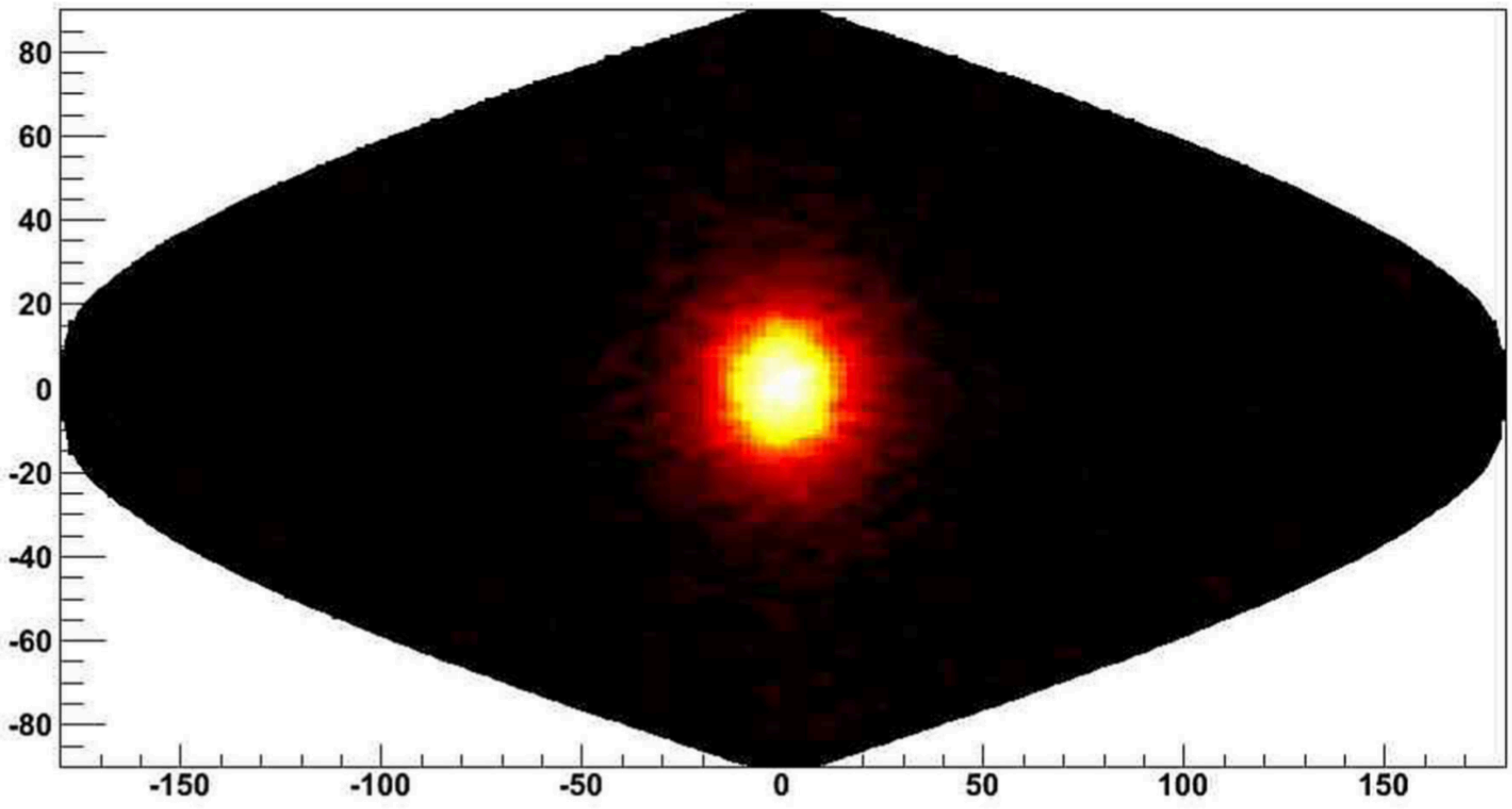
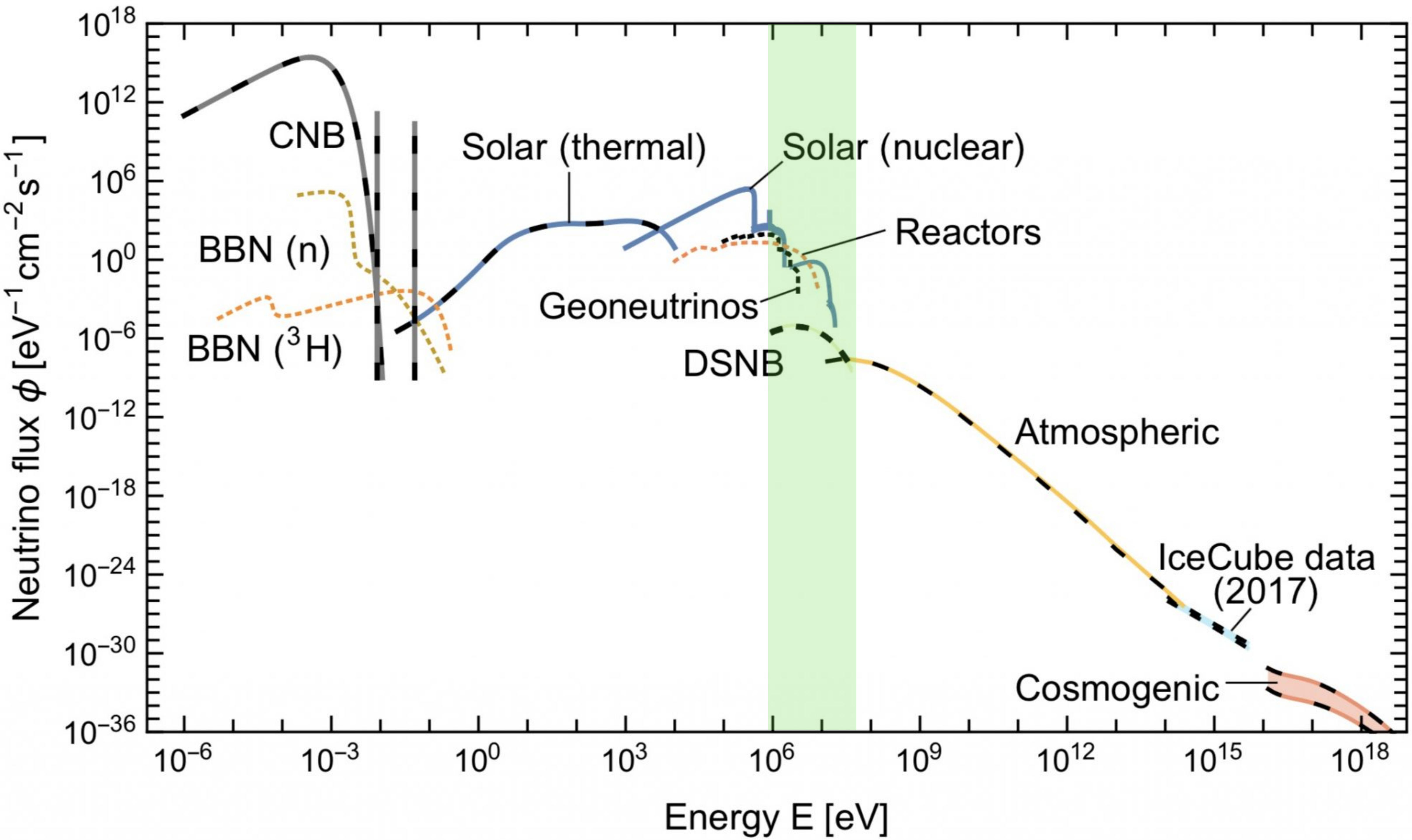


Image credit: SuperKamiokande collaboration

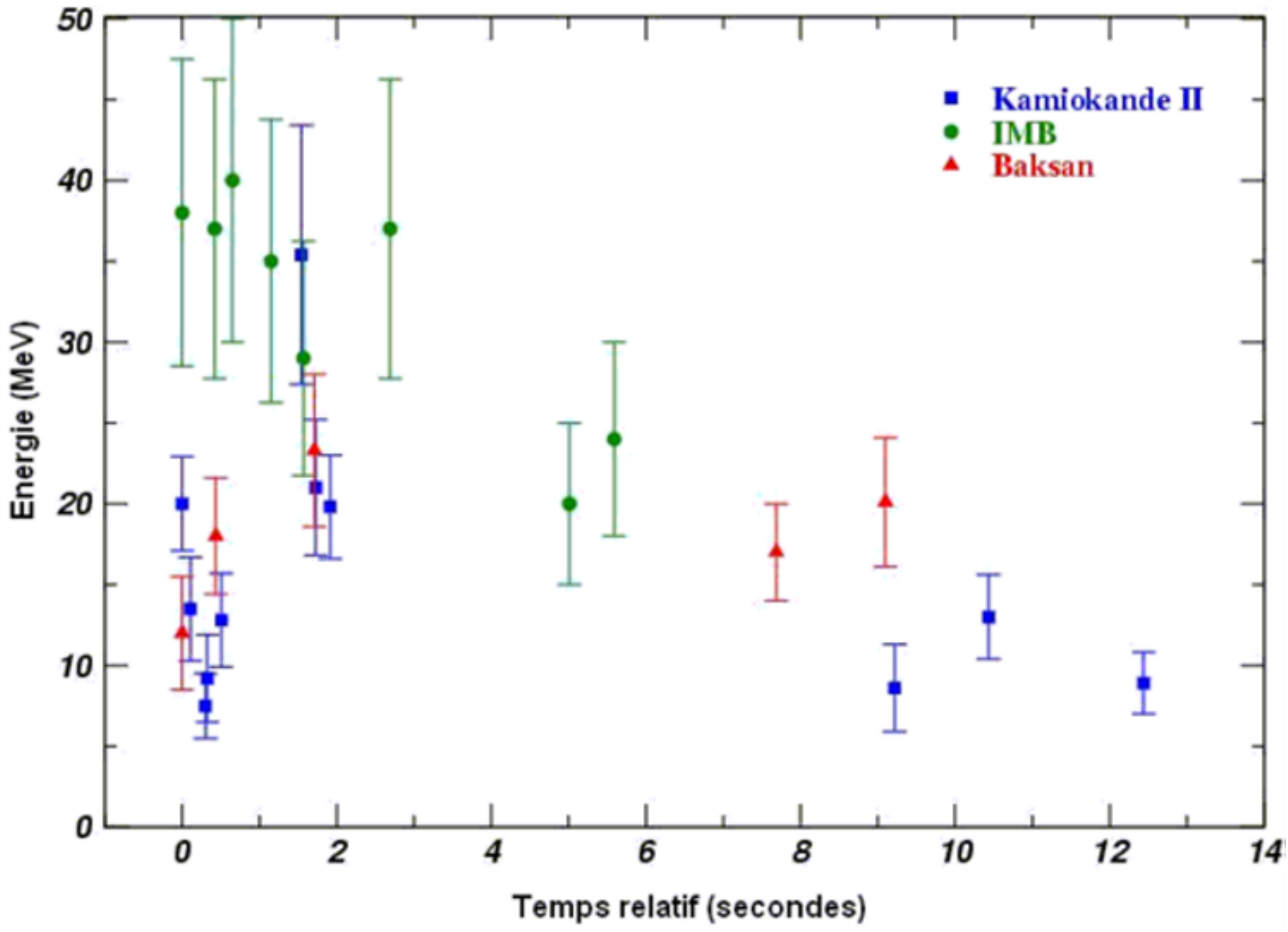
- Deficit of electron neutrinos from the Sun ⟶ **Discovery of neutrino oscillations**
- Neutrino flux depends on the solar interior and chemical composition ⟶ **Test of the Standard Solar Model**

The Grand Unified Neutrino Spectrum



Vitagliano, Tamborra and Raffelt, Rev. Mod. Phys. 92 (2020) 45006

2. Neutrinos from Supernovae



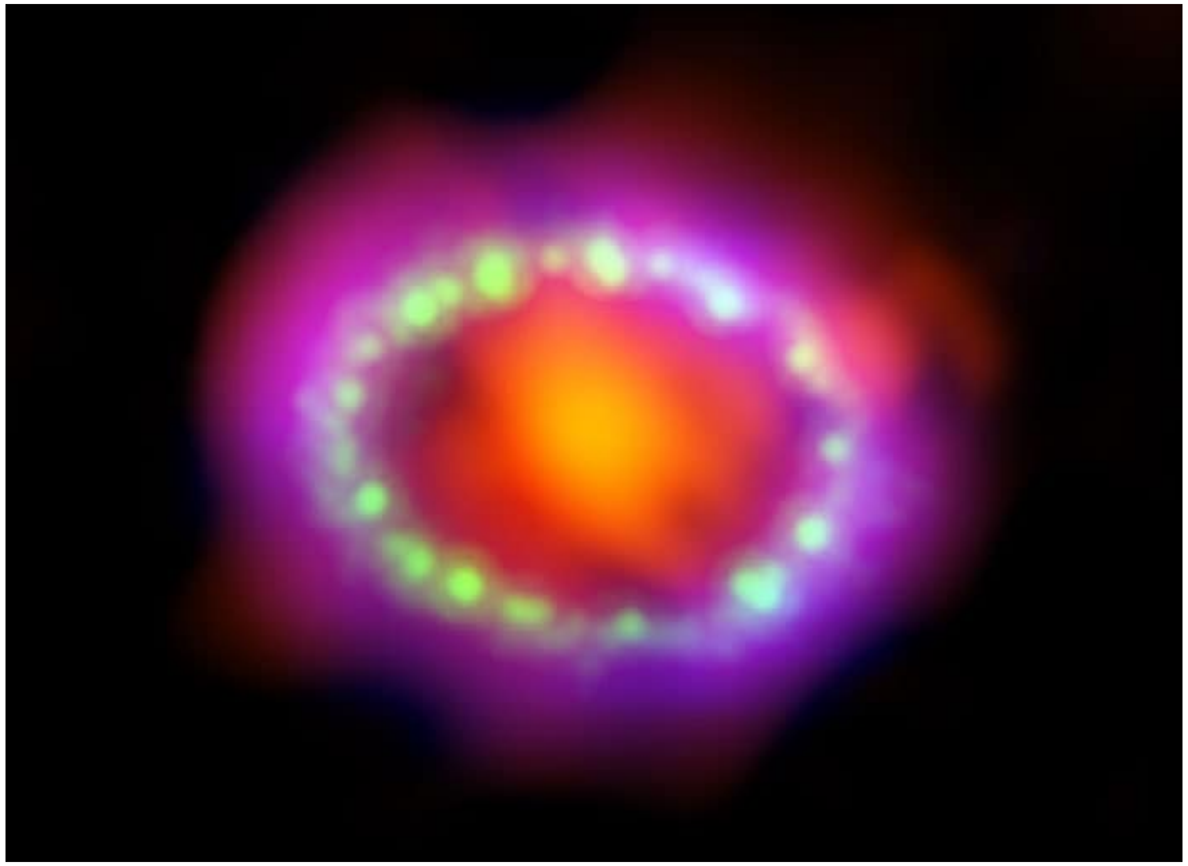
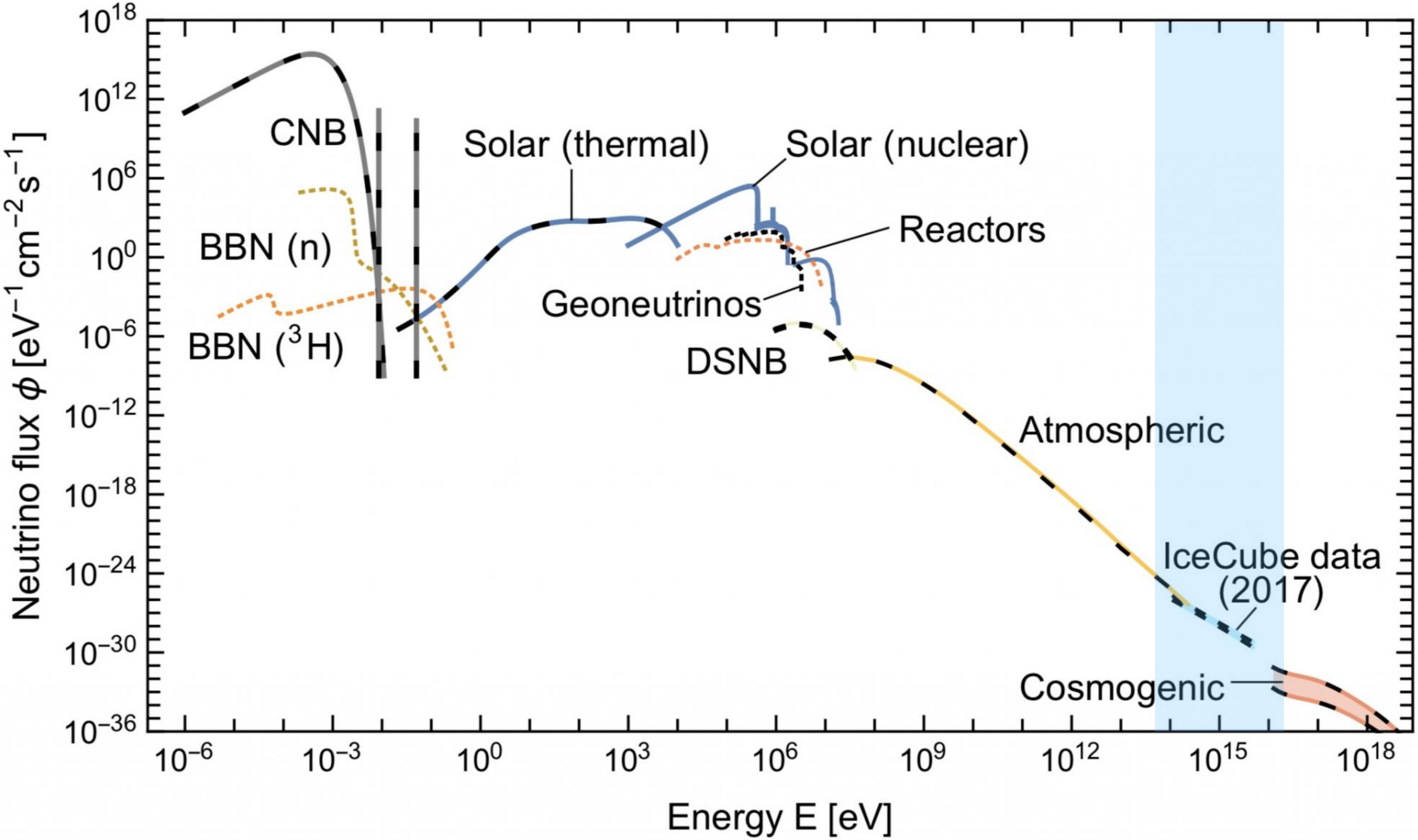


Image credit: NASA, Cerncourier

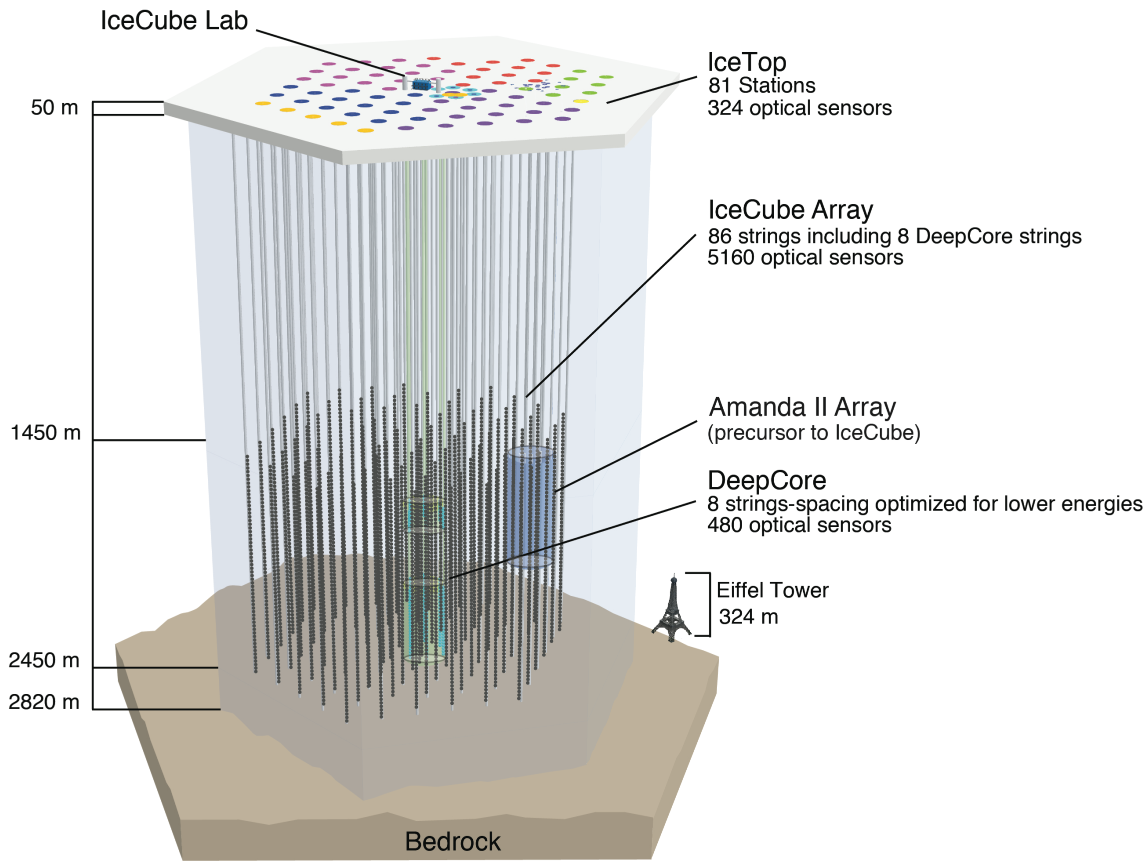
- Neutrinos as probes of the collapse of massive stars.
- *"Did you hear what happened today?* 10^{58} *neutrinos, all in one go!"* (L. Pontecorvo's memories)

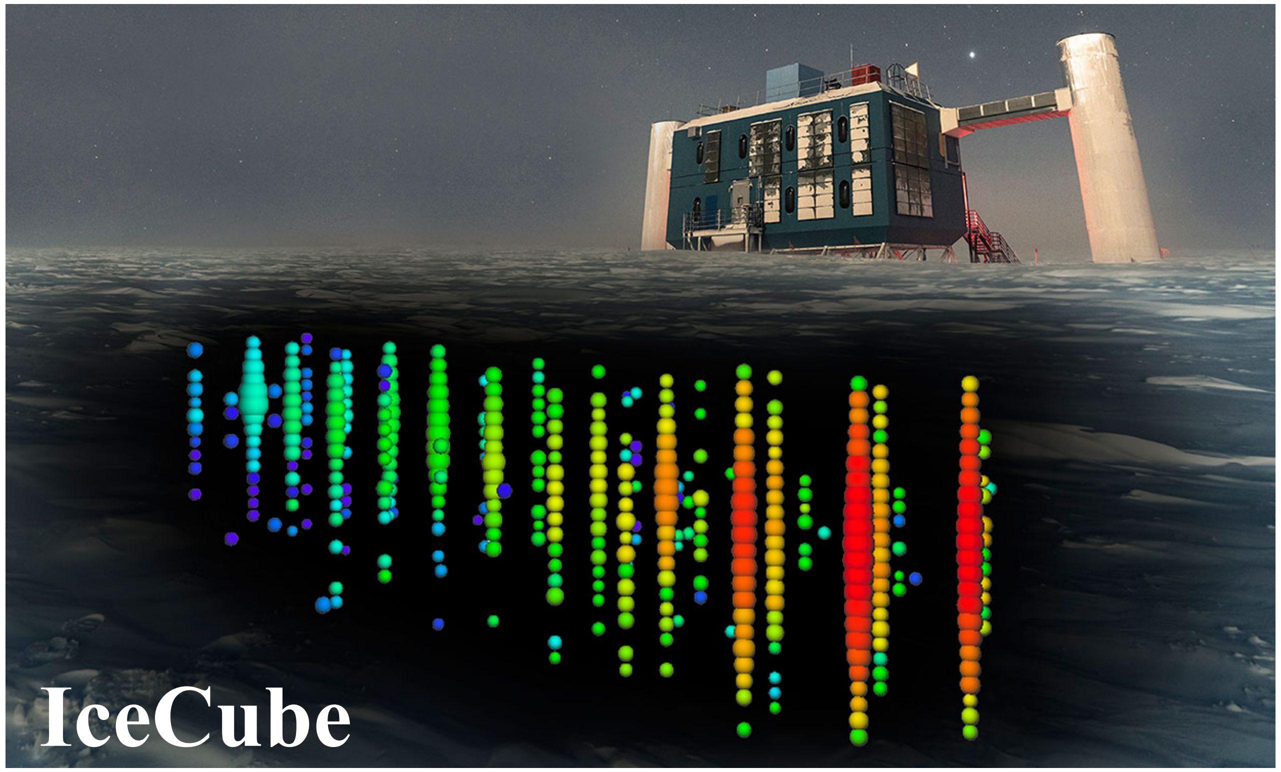
The Grand Unified Neutrino Spectrum



Vitagliano, Tamborra and Raffelt, Rev. Mod. Phys. 92 (2020) 45006

3. High Energy Neutrinos from the Universe





2013:
Two neutrinos with PeV energies are detected at IceCube

2017:
Discovery of a diffuse astrophysical flux of yet unknown origin

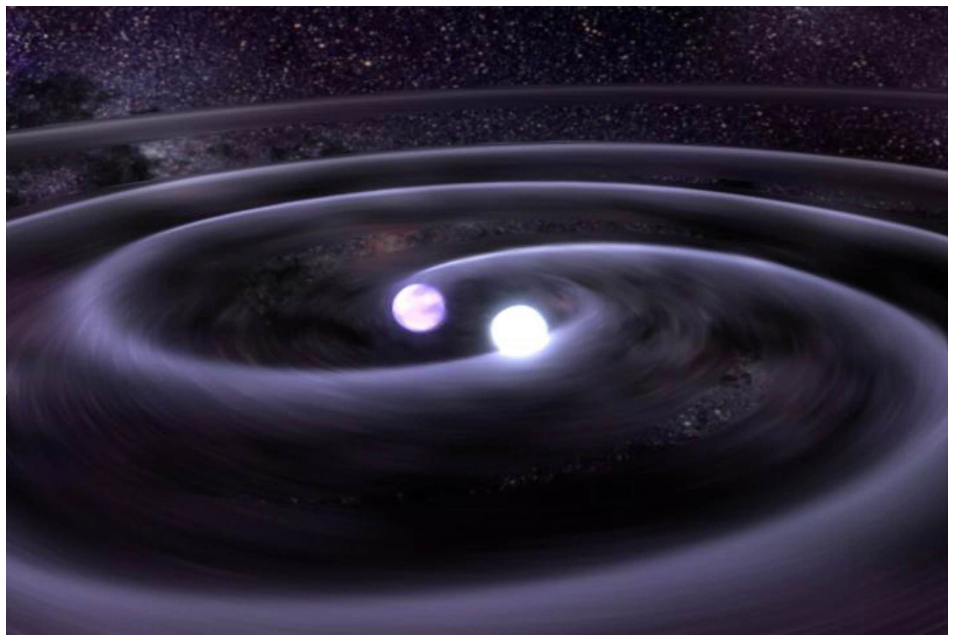
2018:
Observation of a neutrino in association with the blazar TXS0506+056

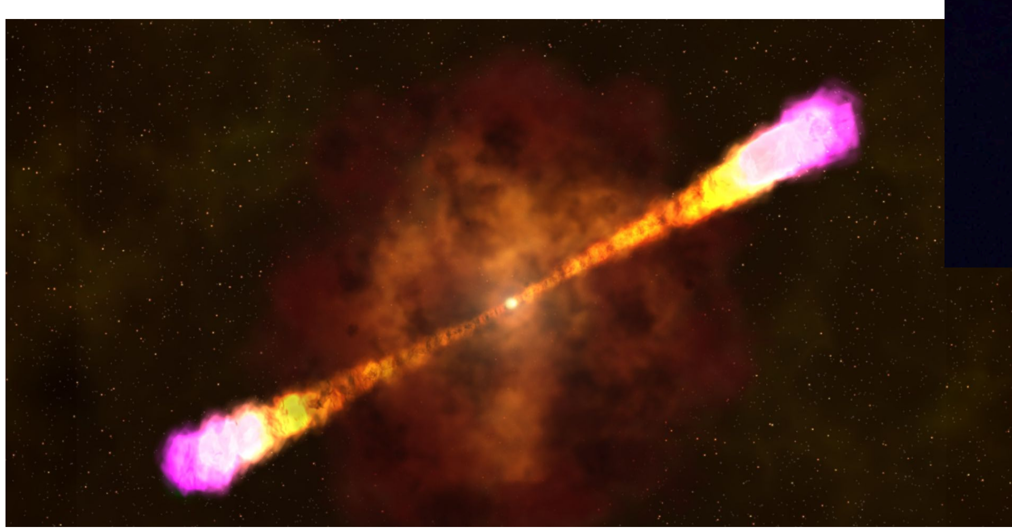
2022:
Observation of 79 neutrinos associated with NGC 1068!

4. Neutron Star Mergers

August 17, 2017

- GW170817 observed by Advanced LIGO and Virgo detectors
- GRB 170817A observed the *Fermi* Gamma-ray Burst Monitor and at the *International Gamma-Ray Astrophysics Laboratory*





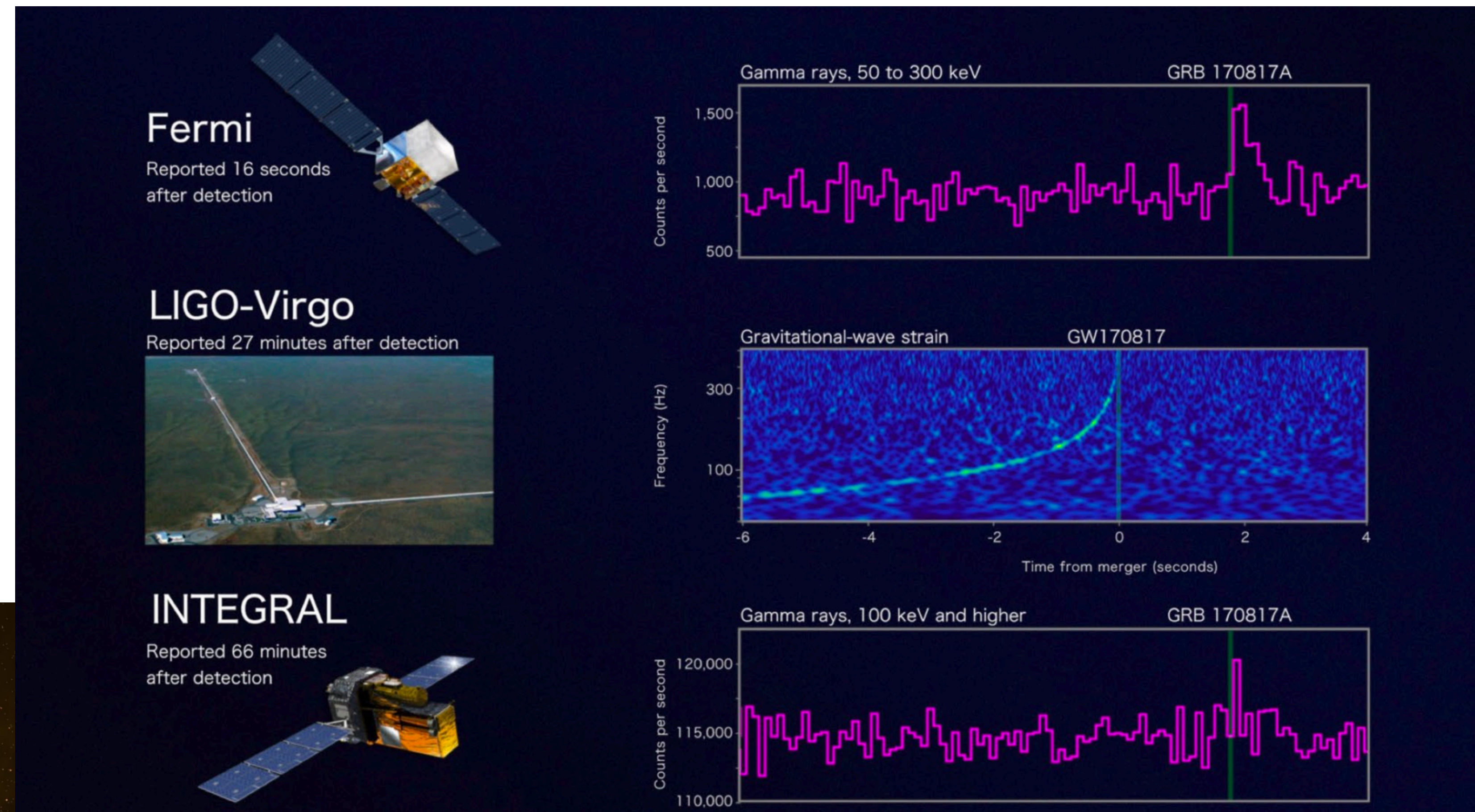
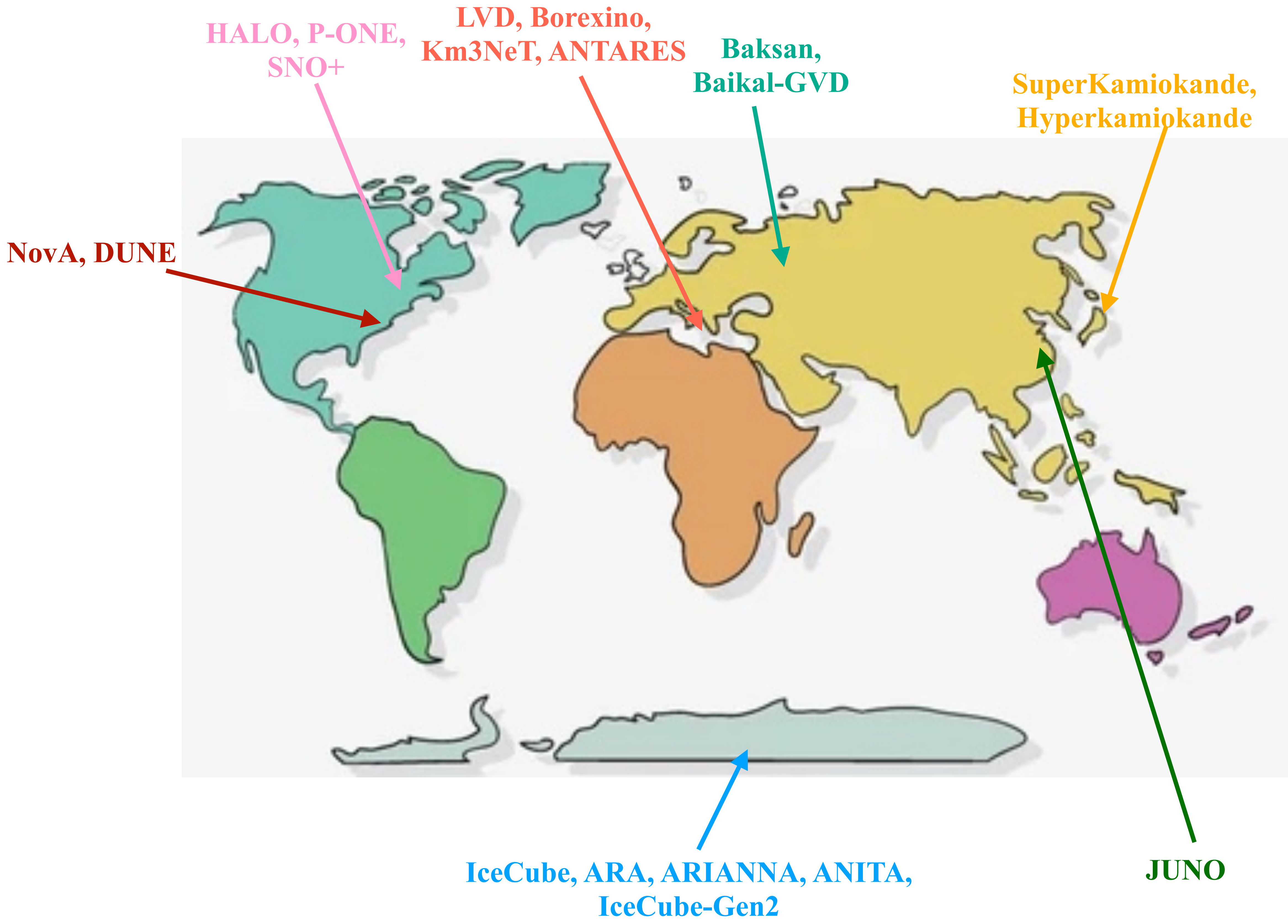
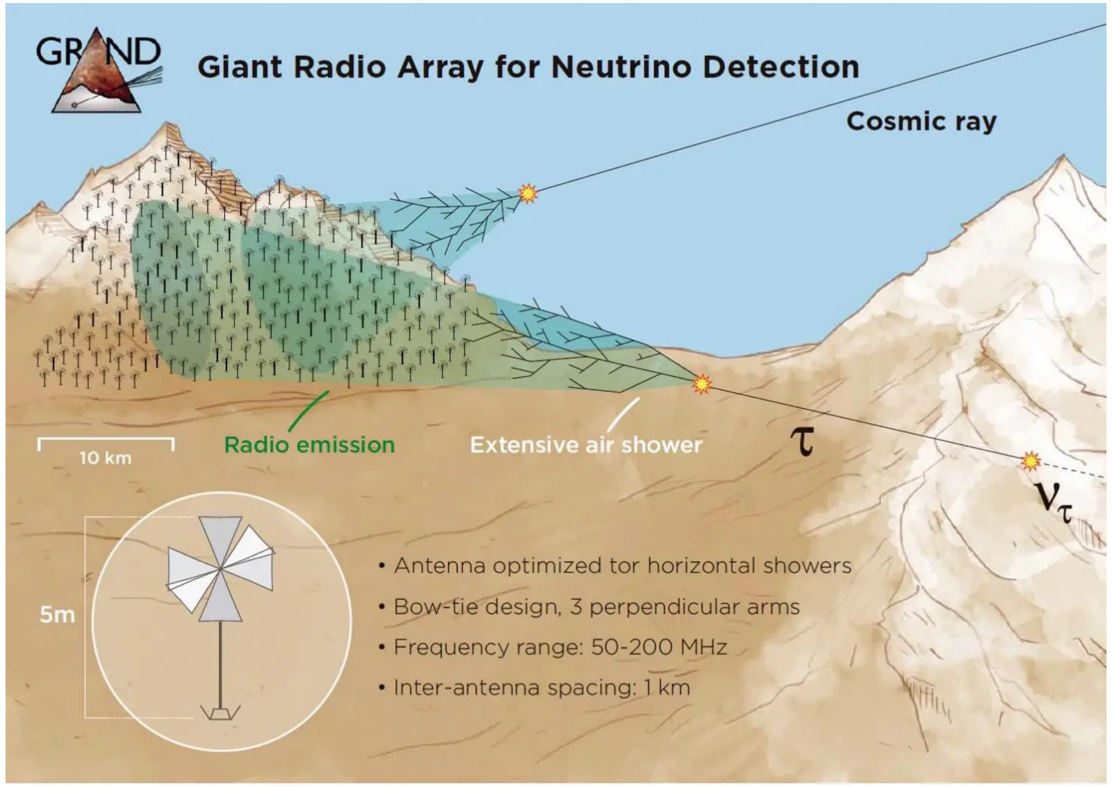


Image Credit: NASA, ESA, LVC

Neutrino Hunters' Map

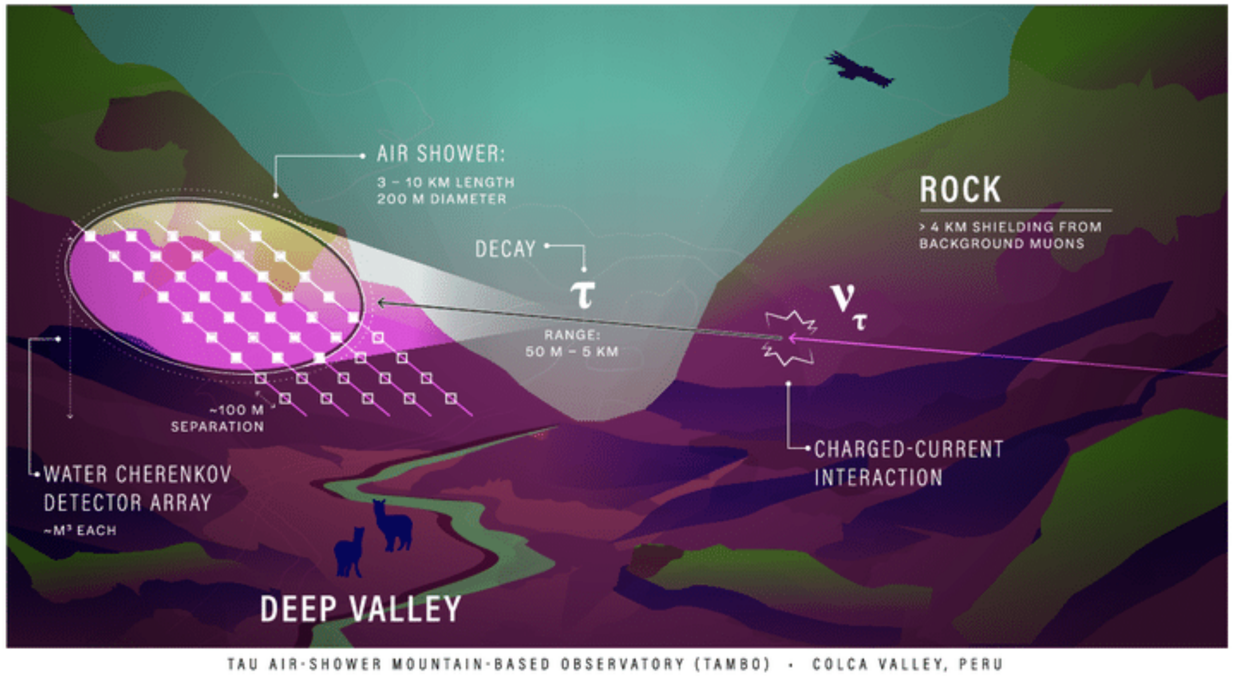


Upcoming Ultra-High-Energy Neutrino Telescopes



GRAND

POEMMA



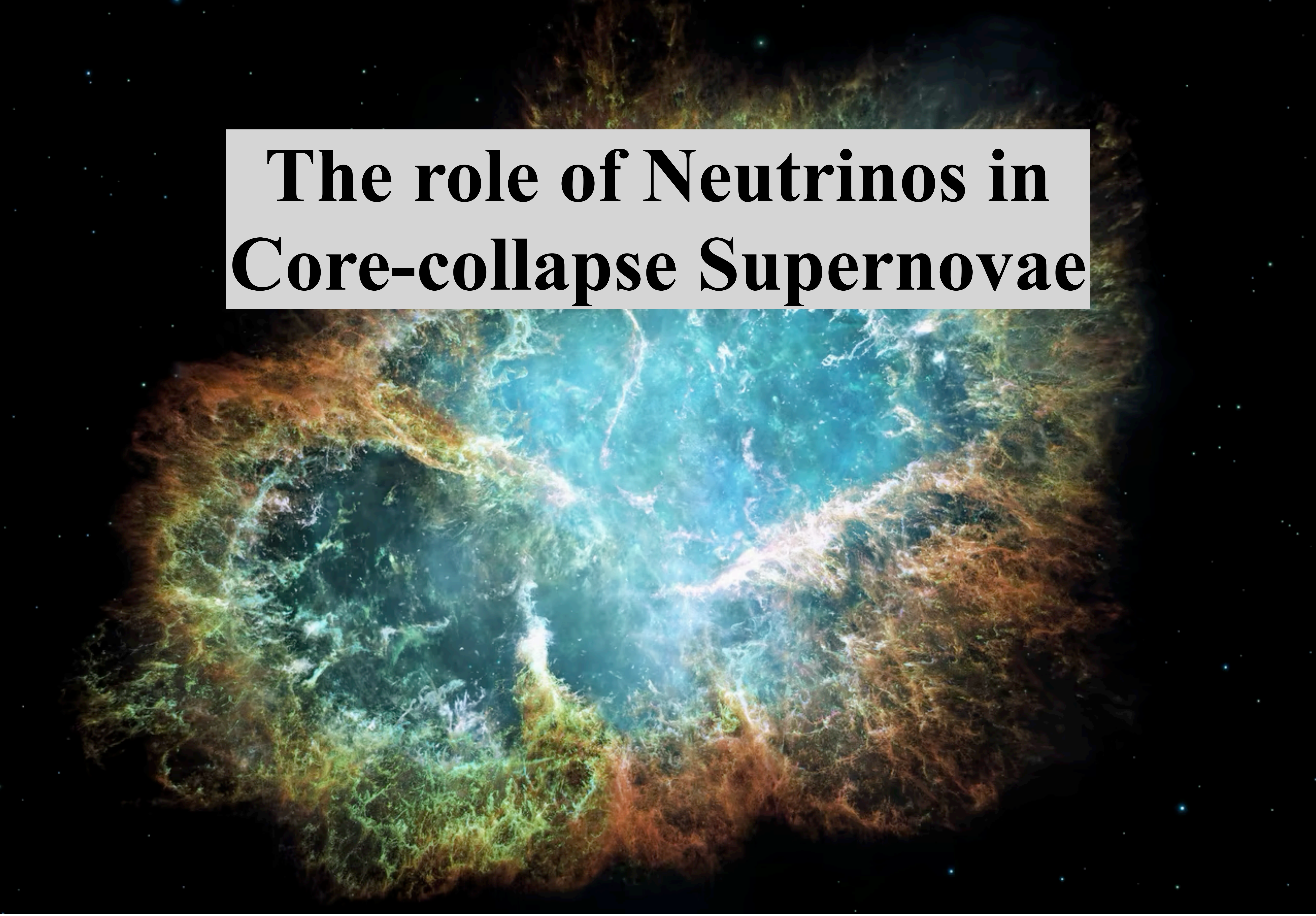
TAMBO

Upcoming neutrinos telescopes will allow us to collect many high-energy neutrino data!

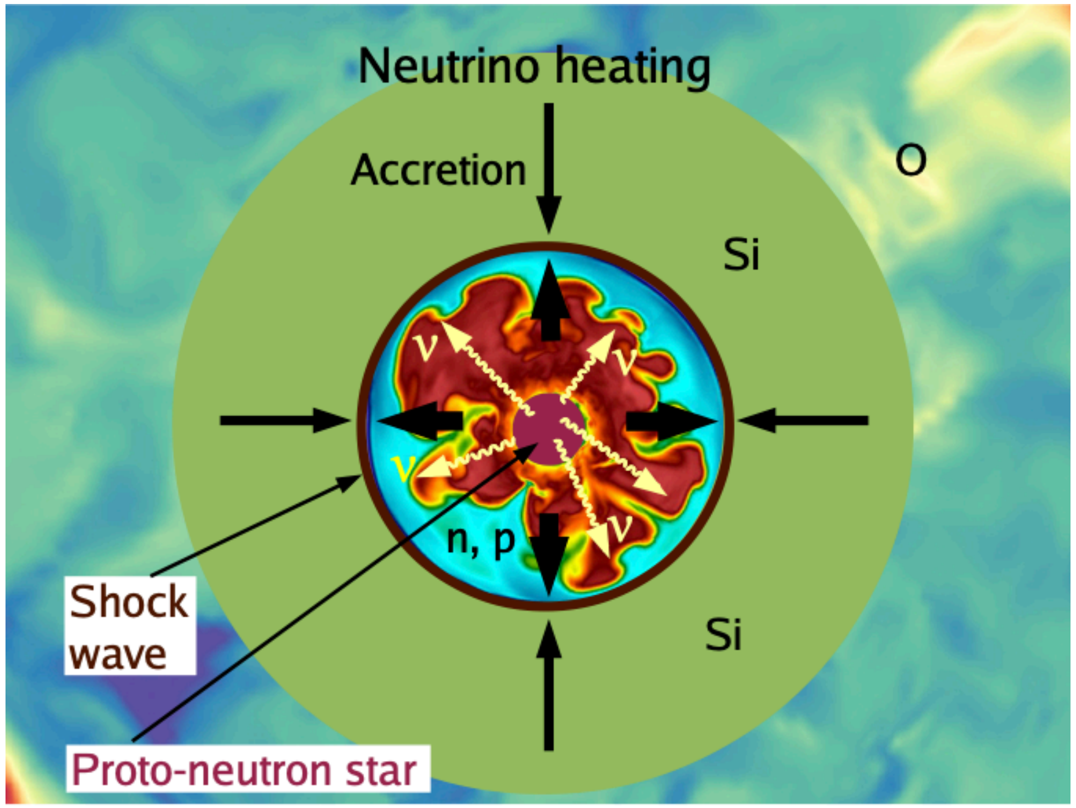
GRAND, arXiv:1810.09994; POEMMA, arXiv:1907.06217; TAMBO, arXiv:2002.06475

How can we use neutrinos?

The role of Neutrinos in Core-collapse Supernovae



The Role of Neutrinos in the Explosion



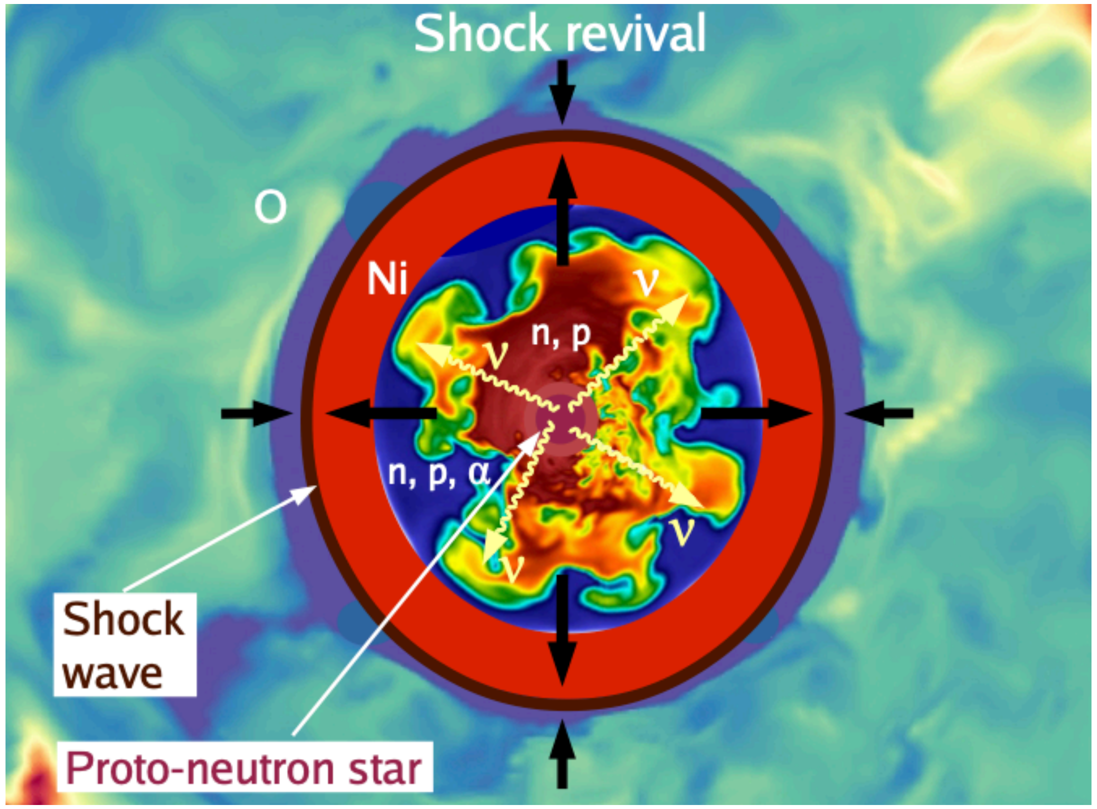


Image from: Janka, arXiv:1702.08825

- Shock wave dissipates energy by dissociating the Iron layer.
- **Neutrinos** provide energy and revival the stalled shock wave.

See also: Mirizzi et al. 2016 for a Review. Melson et al., Atrophys. J. L. (2015); Tamborra et al., PRD (2014).
See also: Tamborra et al., PRL (2013), Kuroda et al., ApJ (2017).Walk et al., PRD (2018, 2019, 2020). Andresen et al. , MNRAS (2017, 2019). Takiwaiki et al., MNRAS (2021). Lin et al., PRD (2020). Mezzacappa et al., Phys. Rev. D (2023)

Diffuse Supernova Neutrino Background

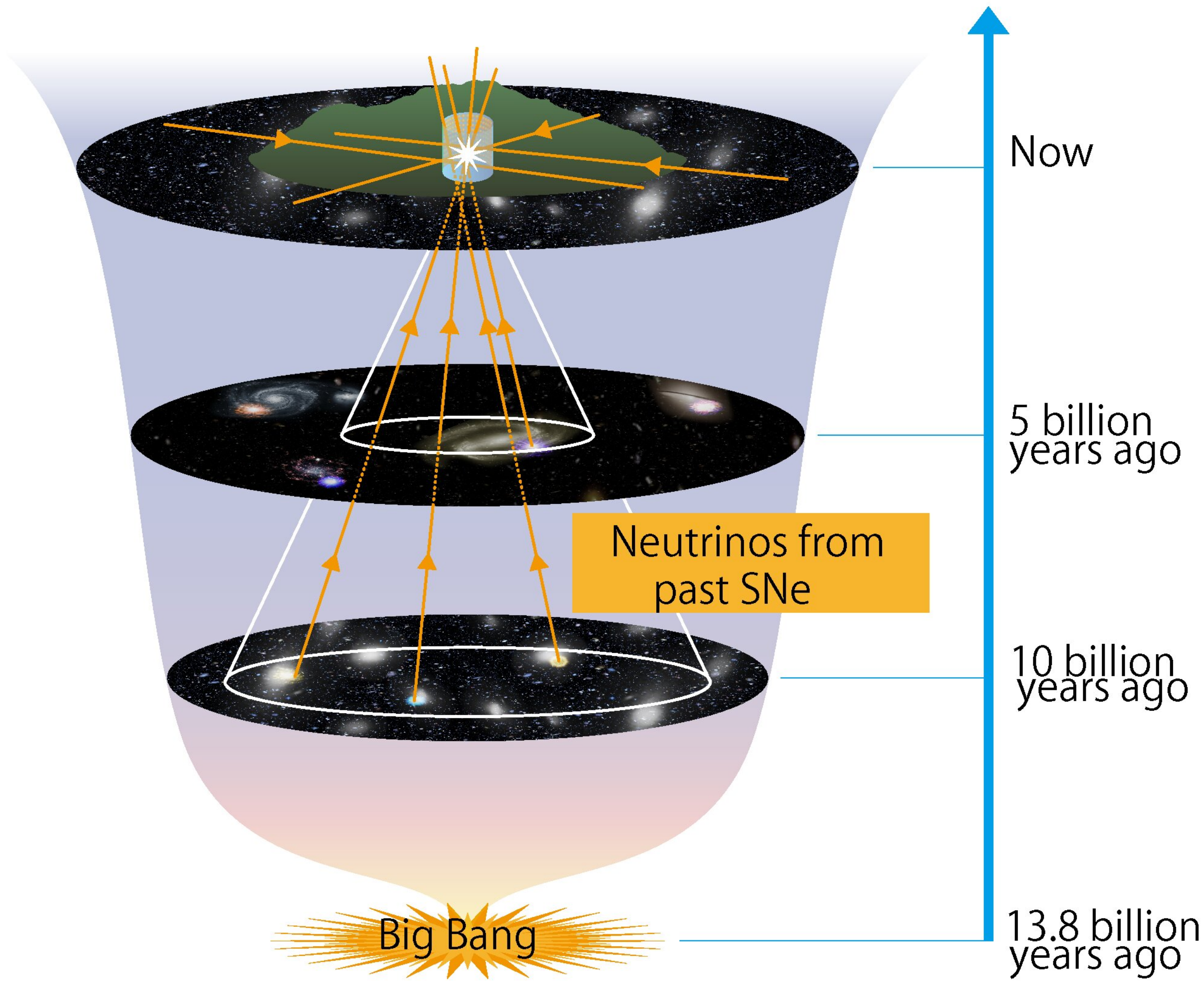
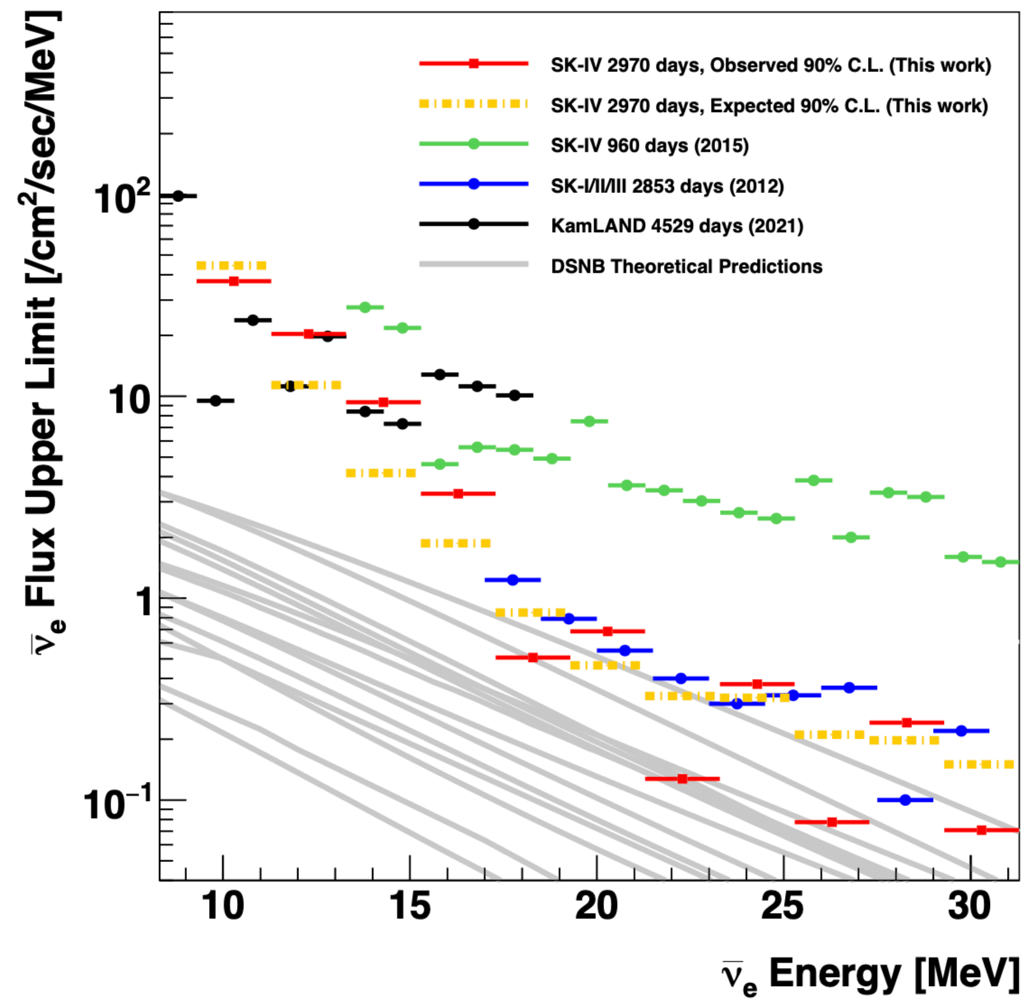


Image Credit: SuperKamiokande Collaboration

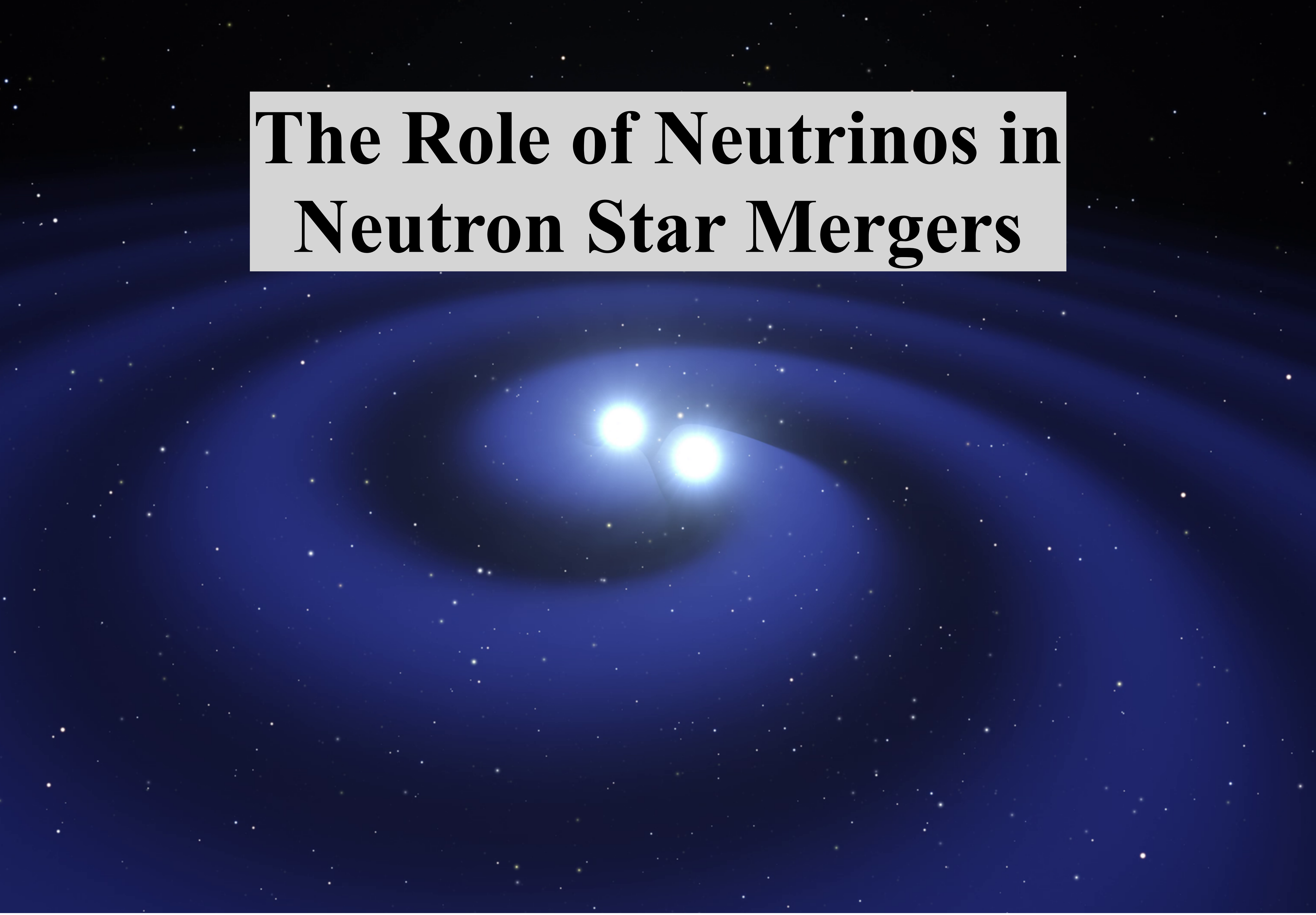


Abe et al., PRD (2021)

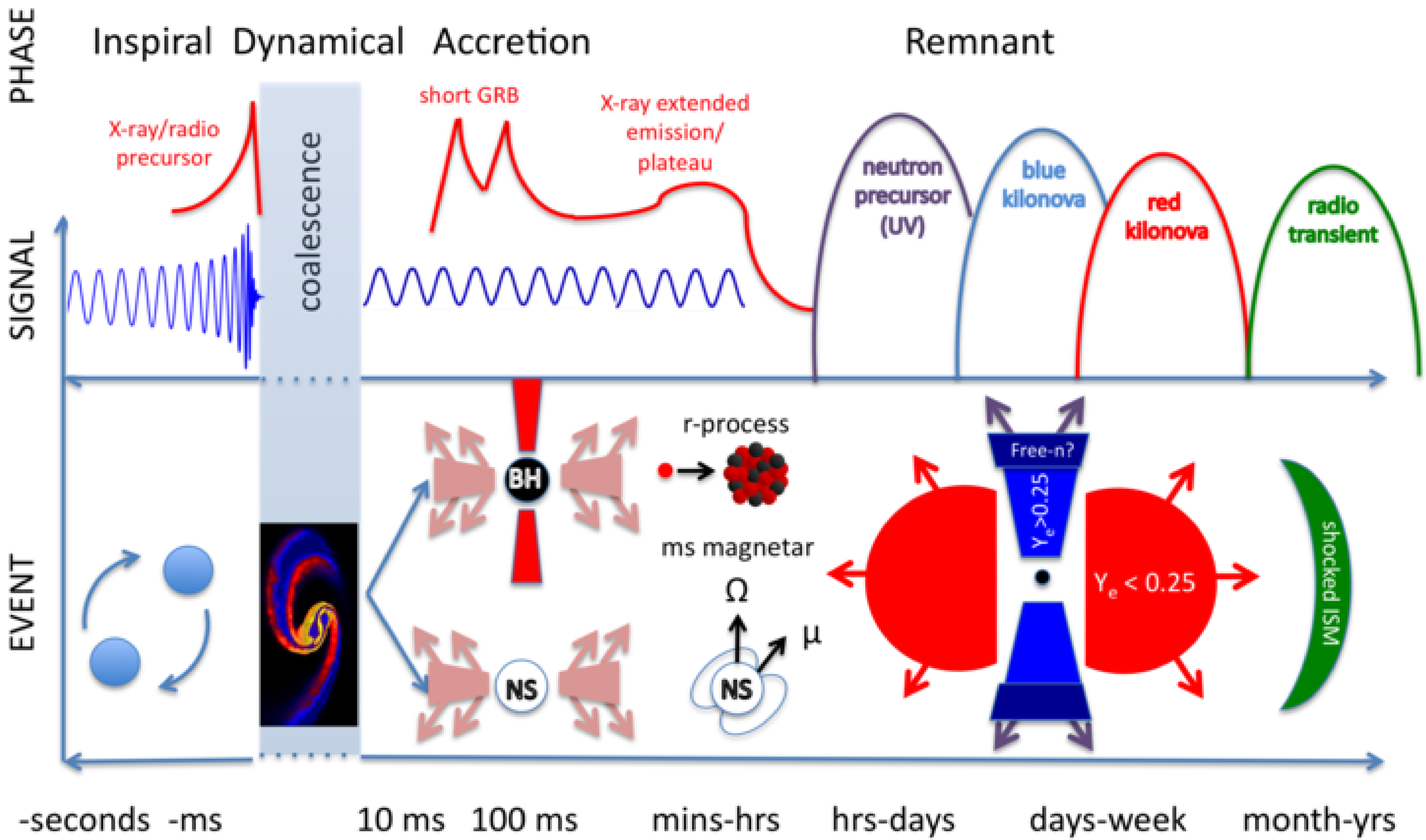
- DSNB detection will be possible with the upcoming Super-K-Gd, Hyper-Kamiokande, JUNO.
- It will provide us with test of the supernova rate.

See also: Moller et al., JCAP (2018). Kresse et al., ApJ (2021). Lunardini&Tamborra, JCAP (2012). Horiuchi et al., PRD (2021).

The Role of Neutrinos in Neutron Star Mergers



Binary Merger: a Cookbook



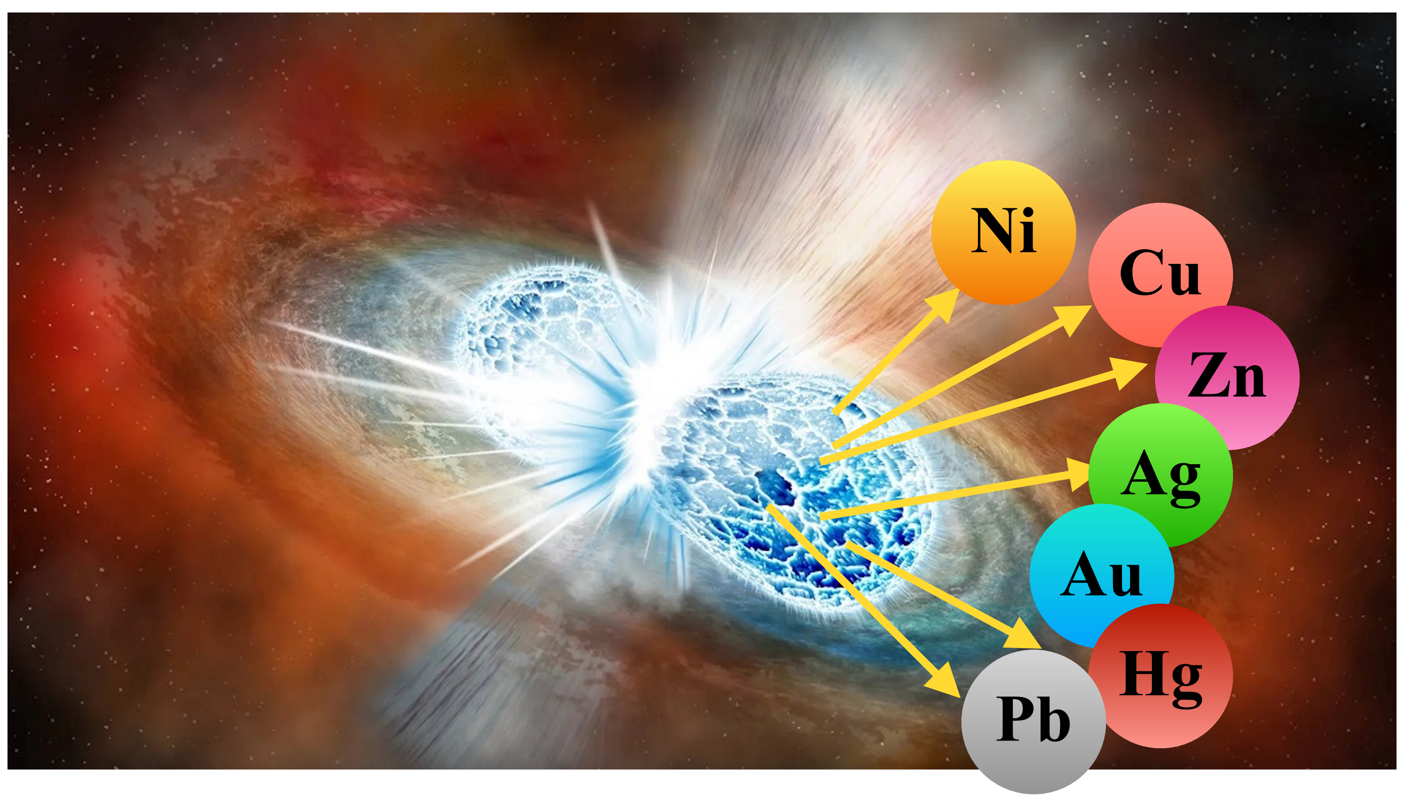
Fernández and Metzger., Ann. Rev. Nucl. Part. Sci (2016)

Nucleosynthesis of Heavy Elements

$$n \quad \nu_e \rightarrow p \quad e^-$$

$$p \quad \bar{\nu}_e \rightarrow n \quad e^+$$

- Nucleosynthesis of heavy elements strictly depends on **neutrino flavor.**
- Neutrinos enhances the production of heavy elements.

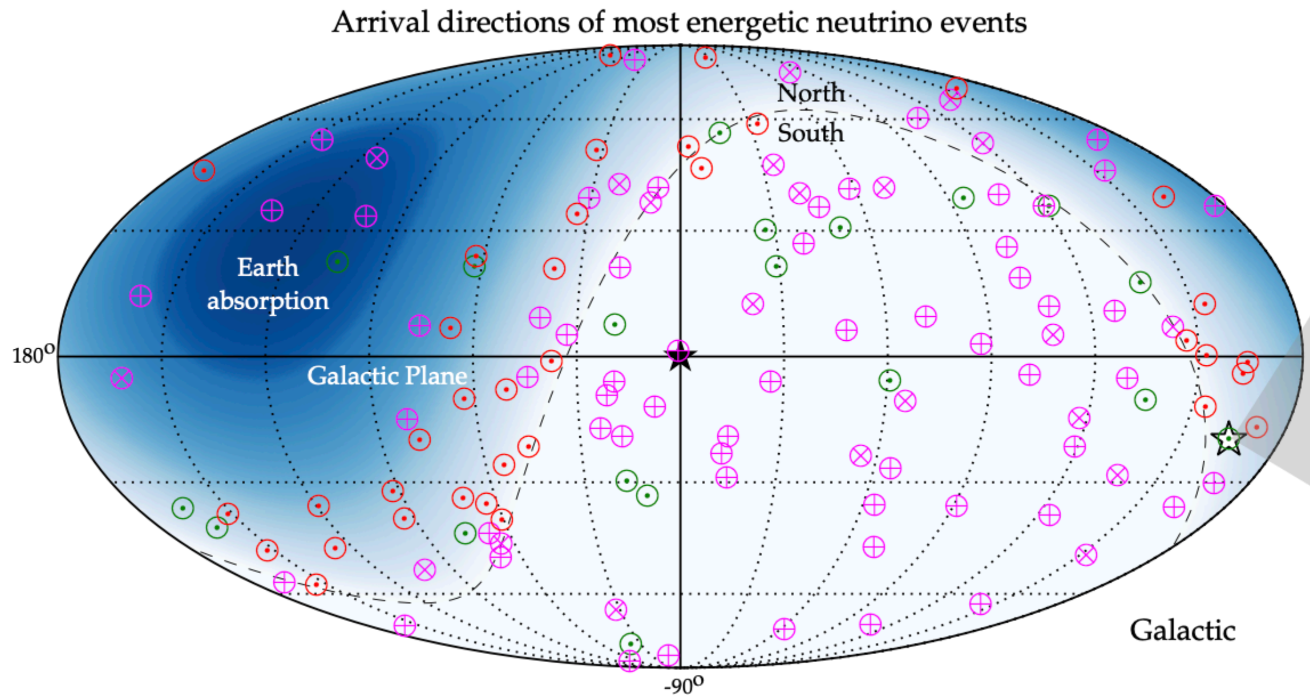


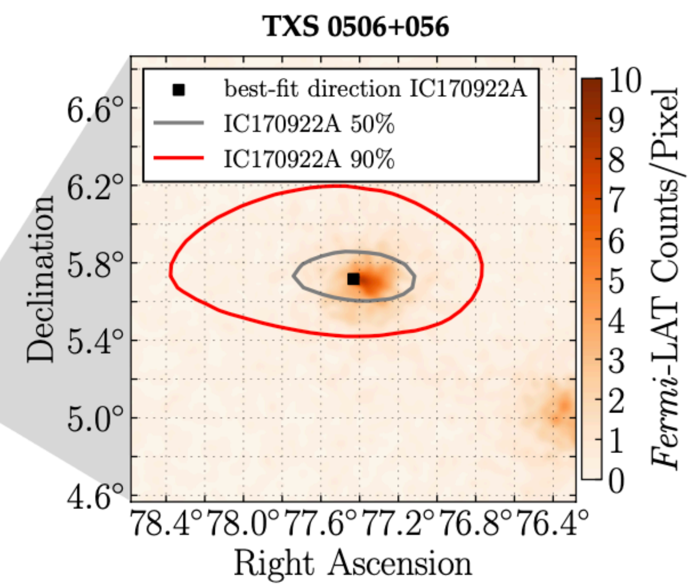
See Just et al., PRD (2022)

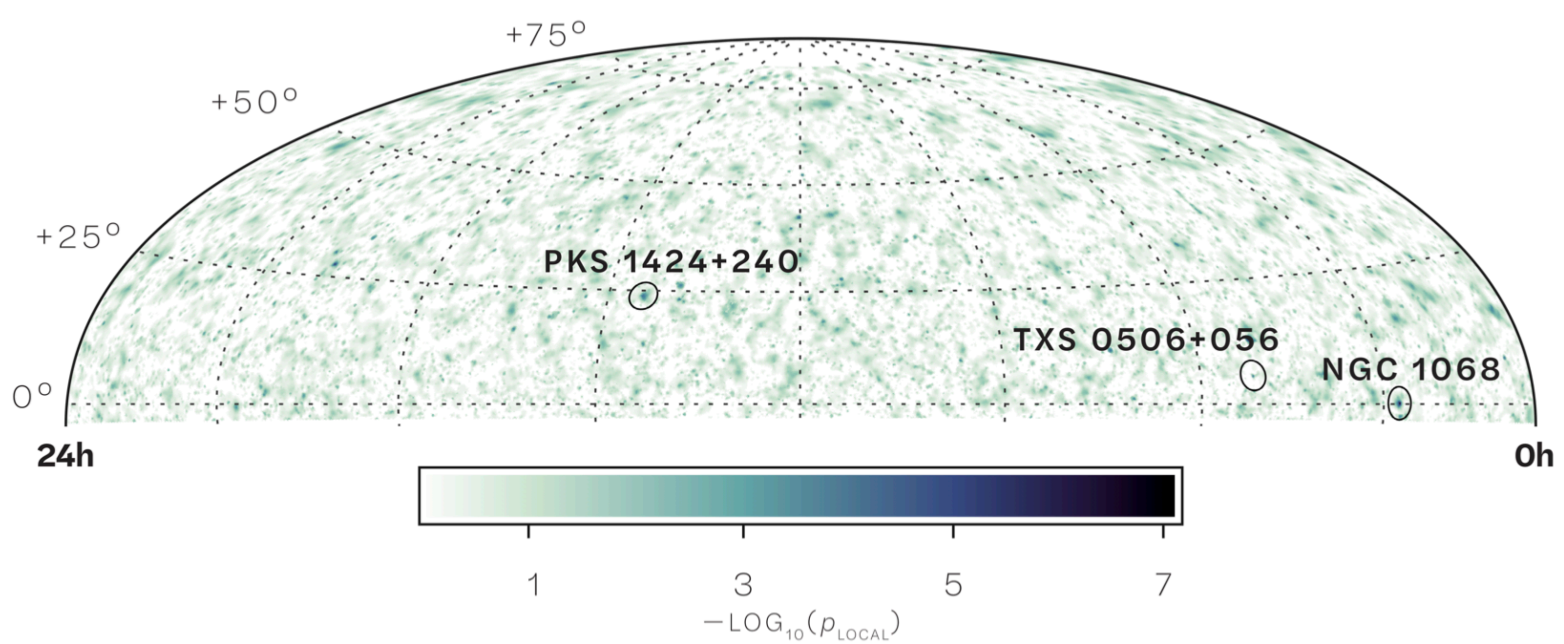
Cosmic Accelerators: A Window on The Extreme Universe

Astrophysical Neutrino Flux

High energy neutrinos are mostly of extragalactic origin.







IceCube Collaboration, J. Phys. G. (2019); IceCube Collaboration, arXiv:2211.09972 (2022)

High-Energy Neutrino Production

- Shocks are very common in astrophysics
- Particle can be accelerated at shocks as they bounce back and forth due to magnetic turbulences that act as mirrors… Like in a **ping pong table!**
- Electrons cool emitting photons, while protons mainly cool through photo-hadronic and hadronic interactions.

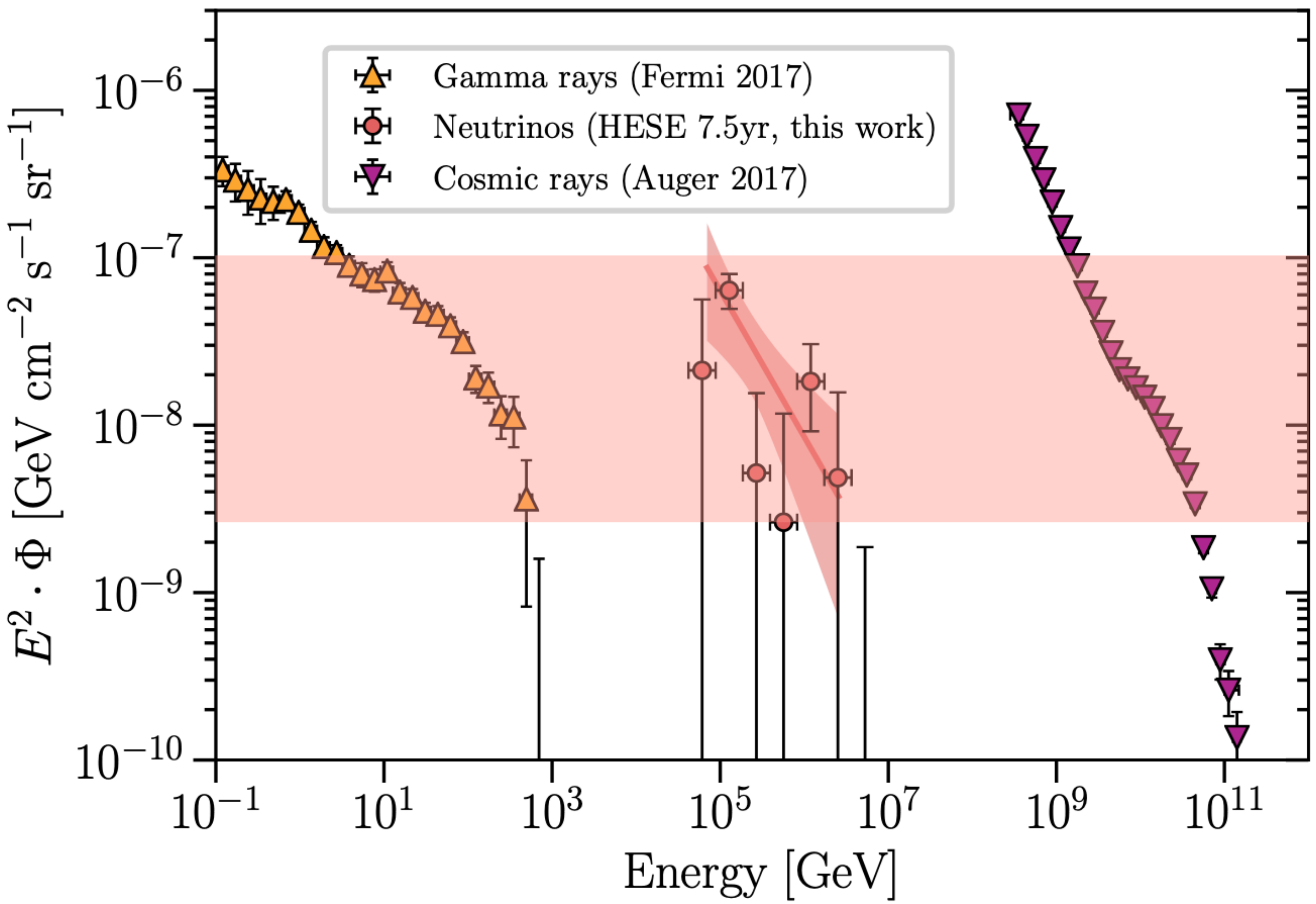
$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

$$p + p \rightarrow \pi^+ : \pi^- : \pi^0$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$$

$$\pi^0 \longrightarrow 2\gamma$$

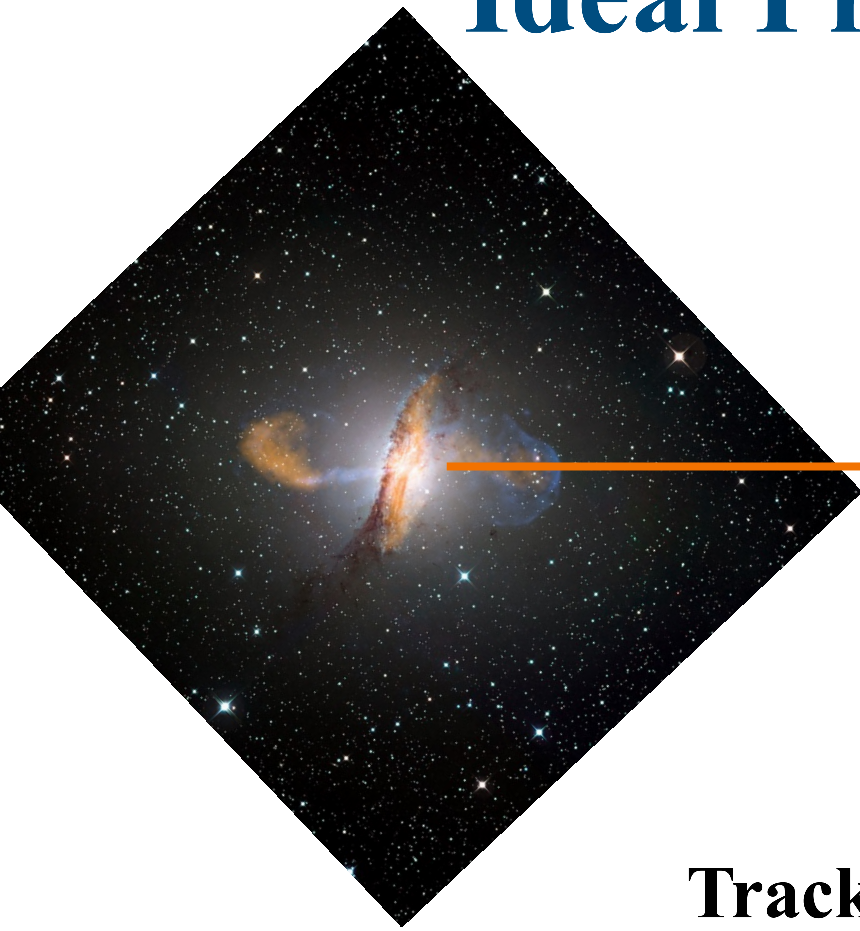
The High-Energy Multi-Messenger Spectrum

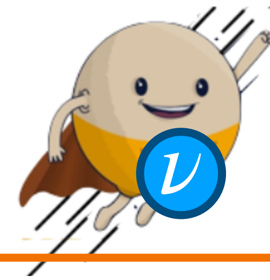


IceCube Collaboration, Abassi et al., Phys. Rev. D (2021)

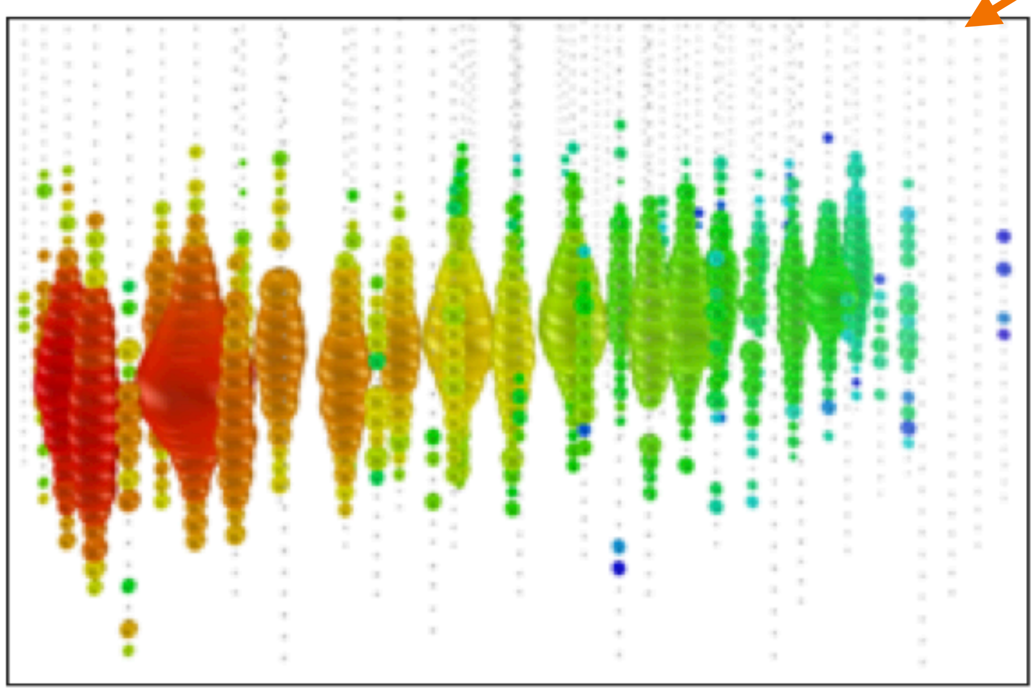
- Common origin for all the messengers?
- Excess of neutrinos with respect to gamma-rays → Sources opaque to gamma-rays?

Ideal Probes of the Extreme Universe

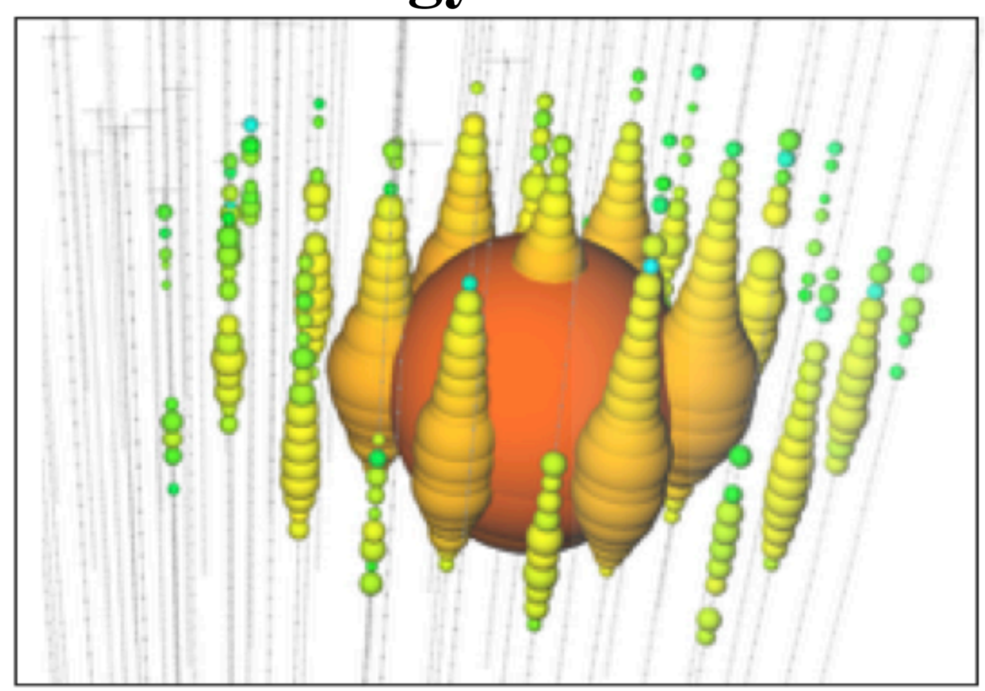




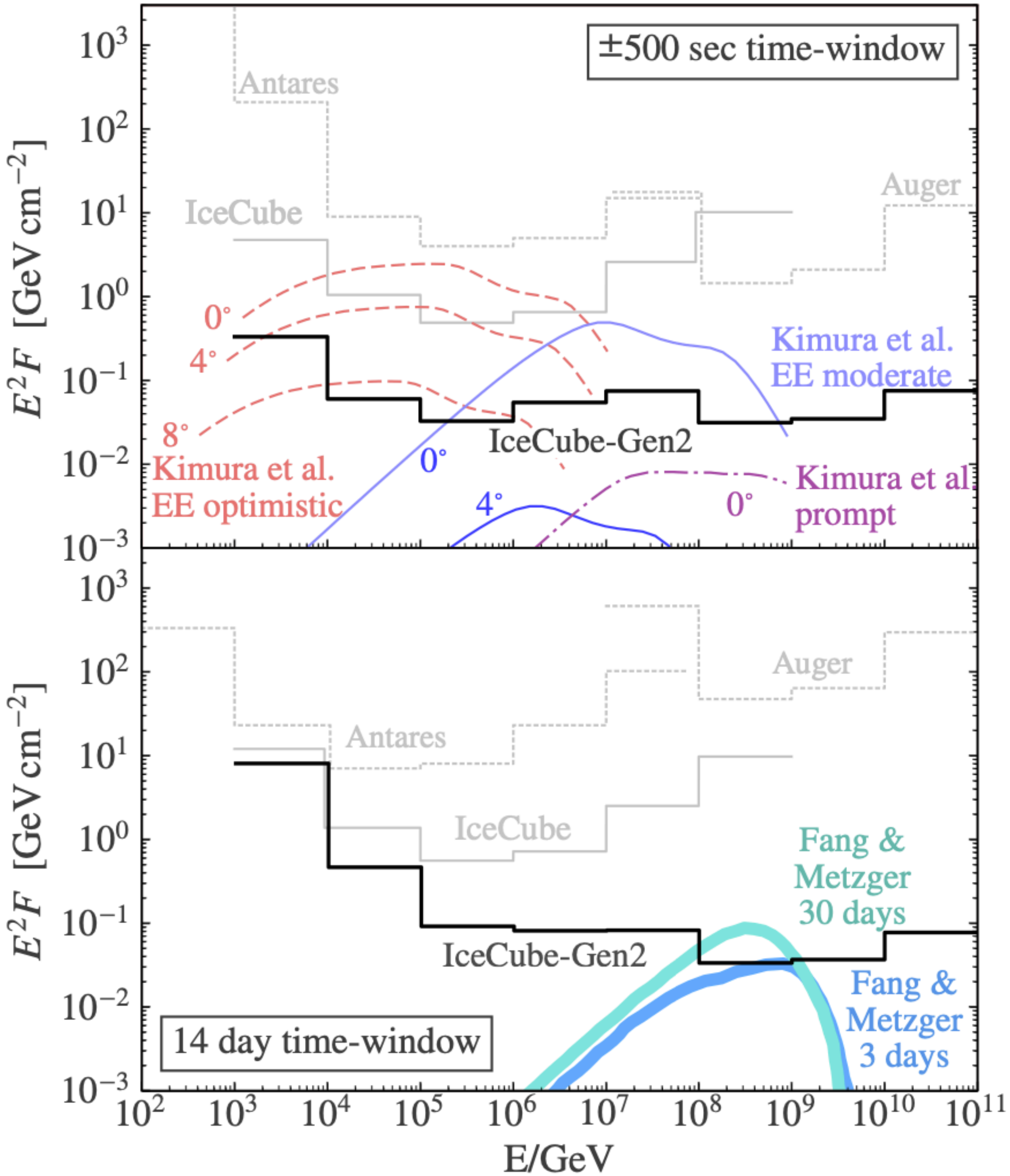
Track events:
Direction information

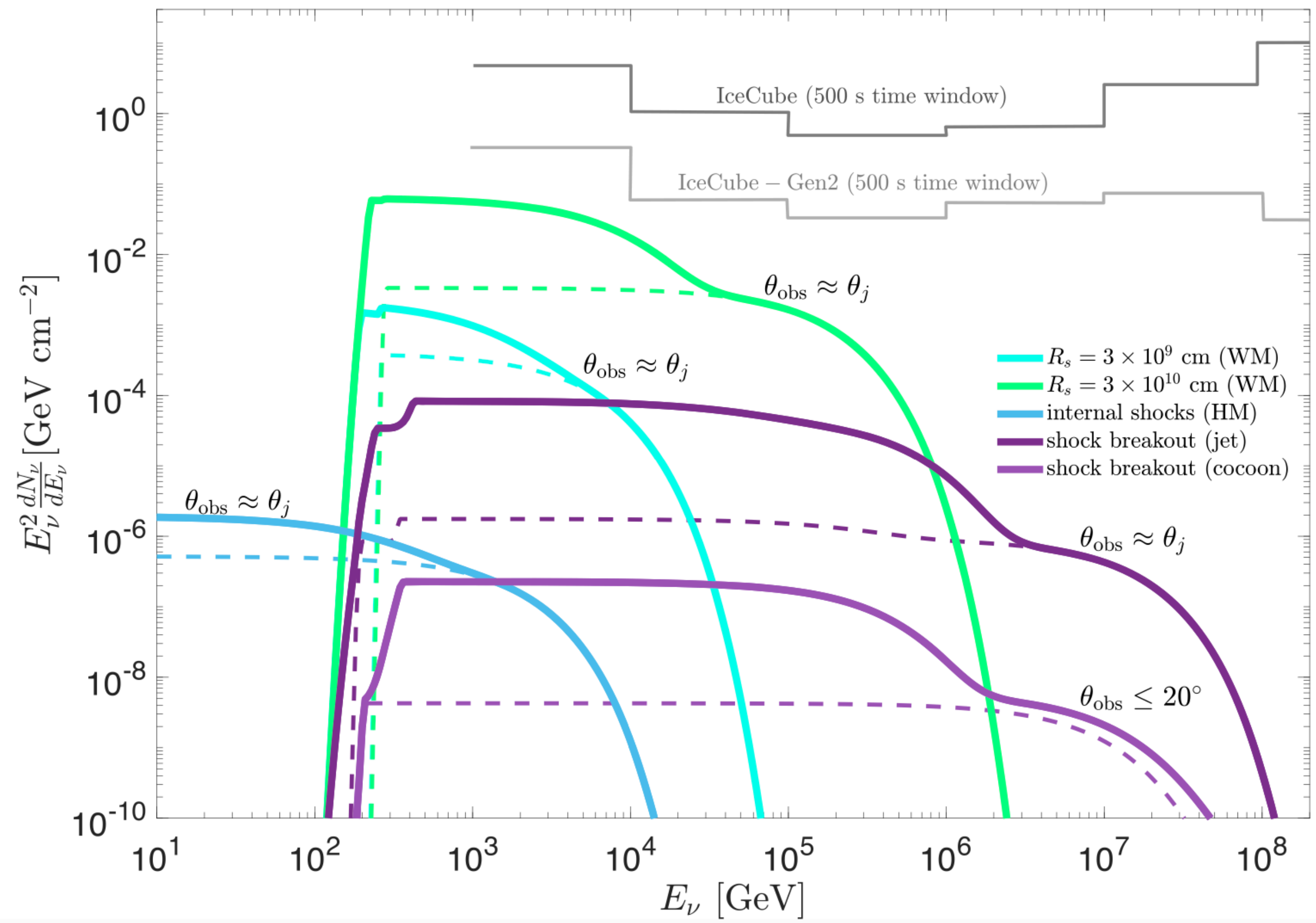


Cascade events:
Energy Information



Neutrinos from Neutron Star Mergers?

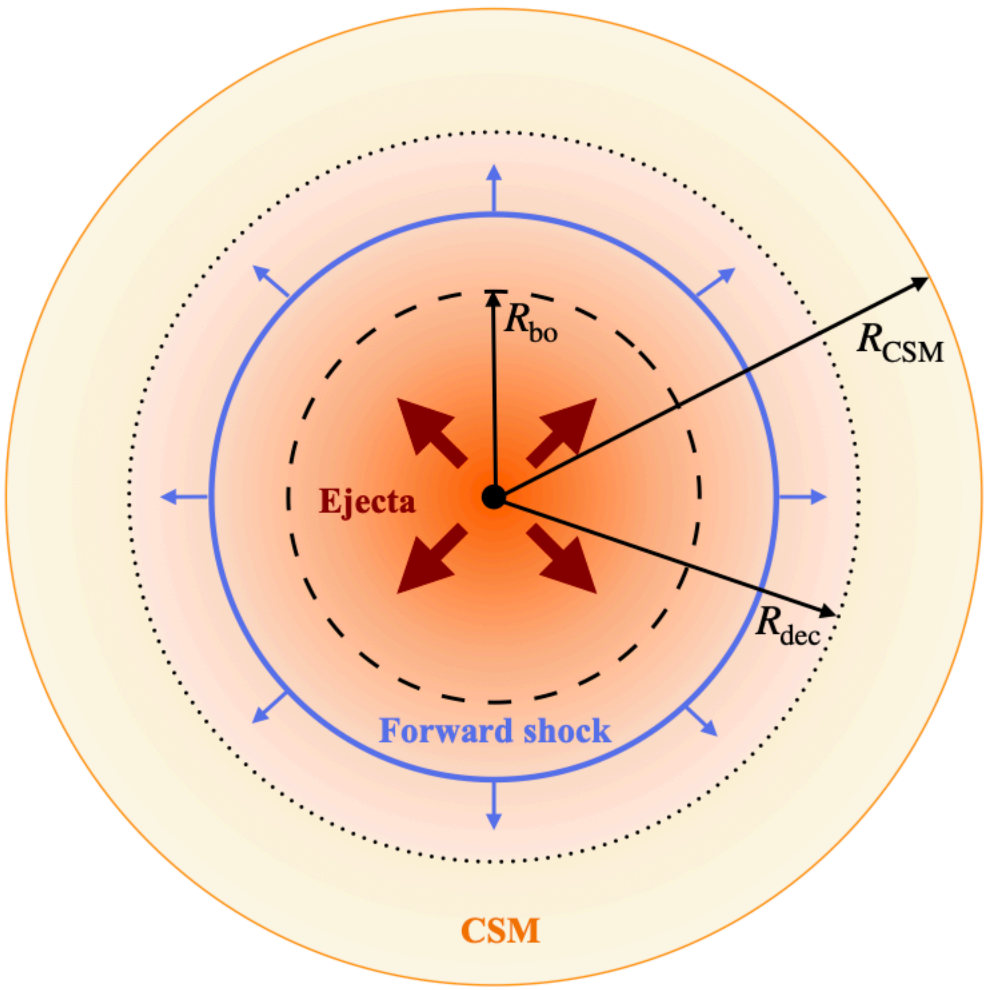


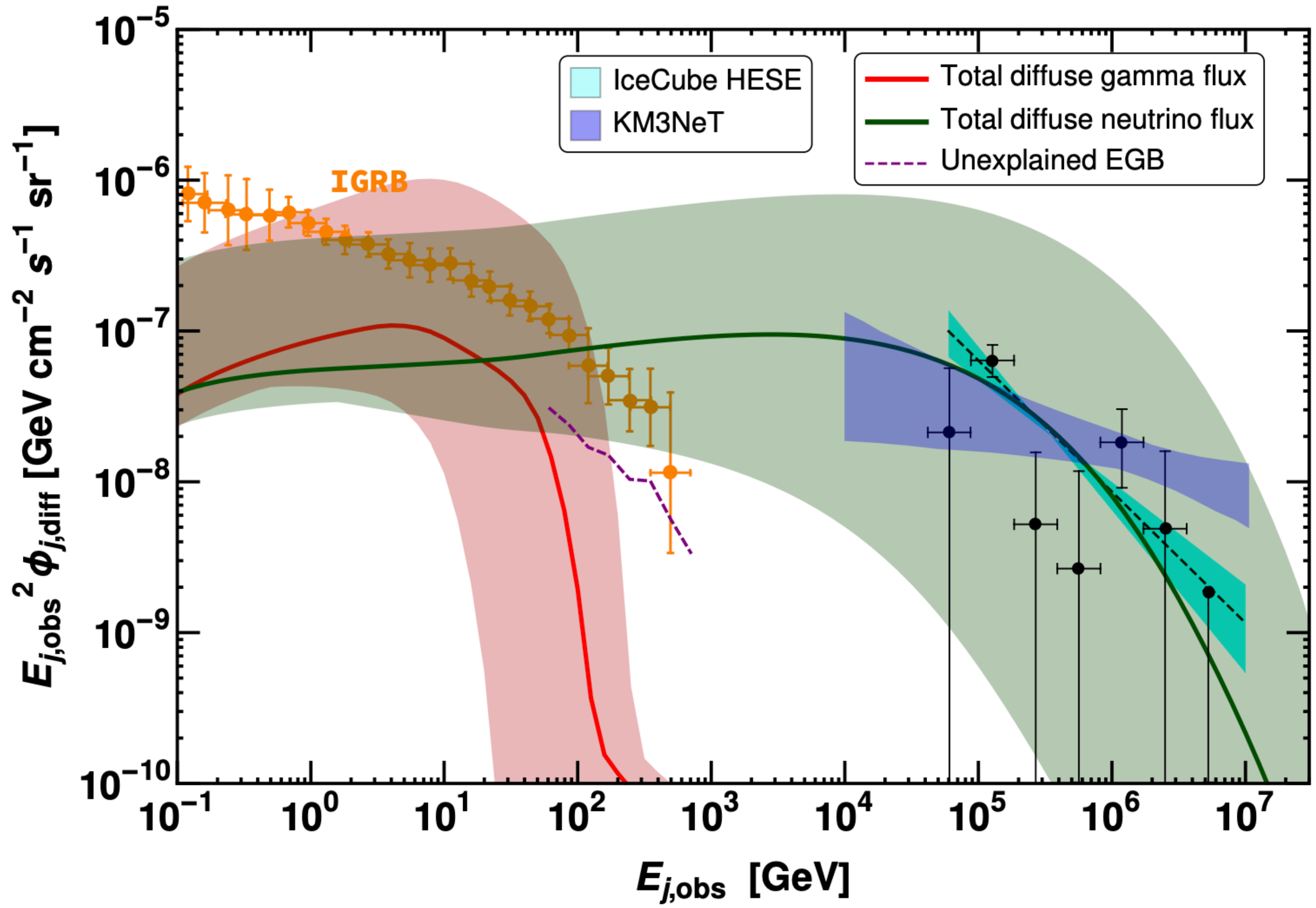


- No high-energy neutrino event associated with GRB 170817A expected at IceCube.
- Future neutrino telescopes will be sensitive to NS mergers.

Image credit: Kimura et al., PRD (2018). Fang & Metzger, ApJ (2017). Gottlieb & Globus, ApJ (2021).
See also: Murase & Bartos, Ann. Rev. (2019). Biehl et al., MNRAS (2018). Kyutoku & Kashiyama, PRD (2018)

Neutrinos from Supernovae?





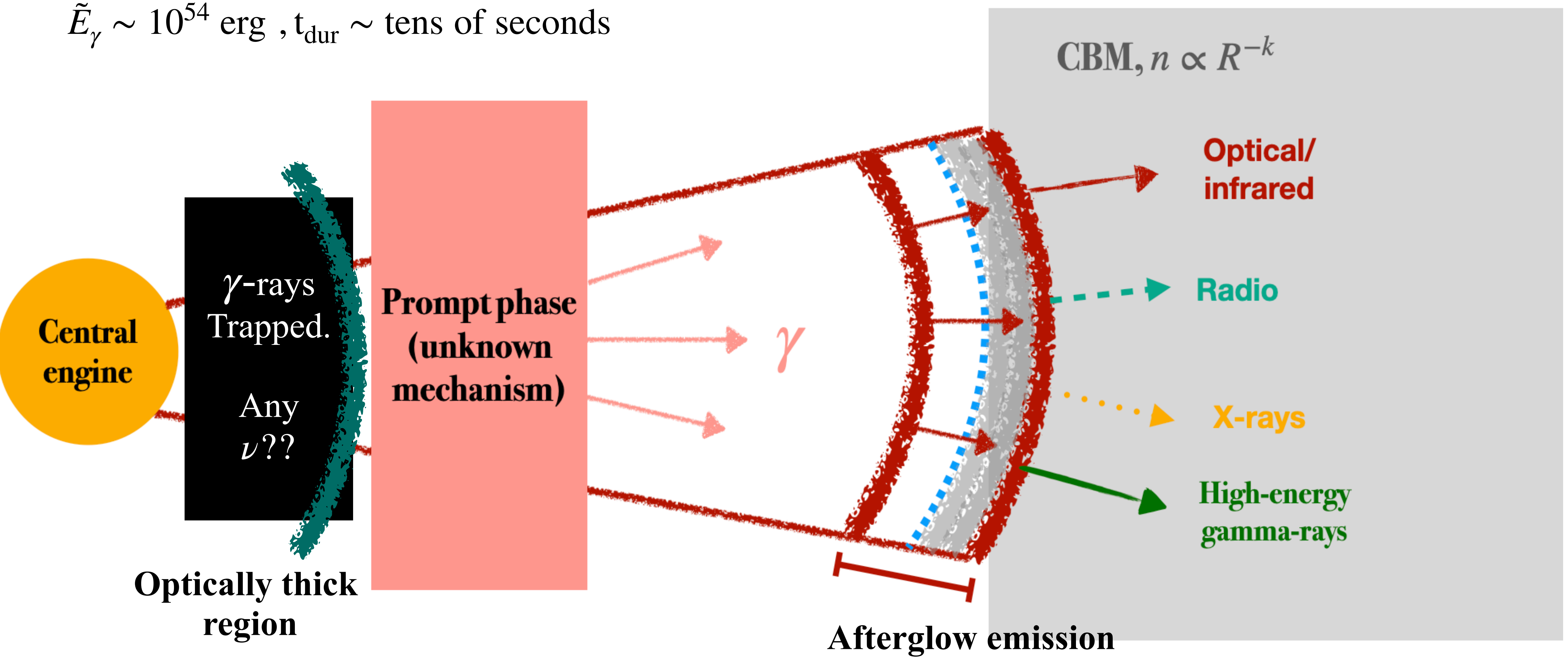
- Supernova interactions with the circumstellar medium could explain the high-energy neutrino diffuse flux.

Pitik et al., ApJ (2022). Sarah et al., JCAP (2022).
See also: Brose et al., MNRAS (2022). Murase et al., PRL (2016).

Probing Astrophysical Transients With Neutrinos

Long Gamma-Ray Bursts (GRBs)

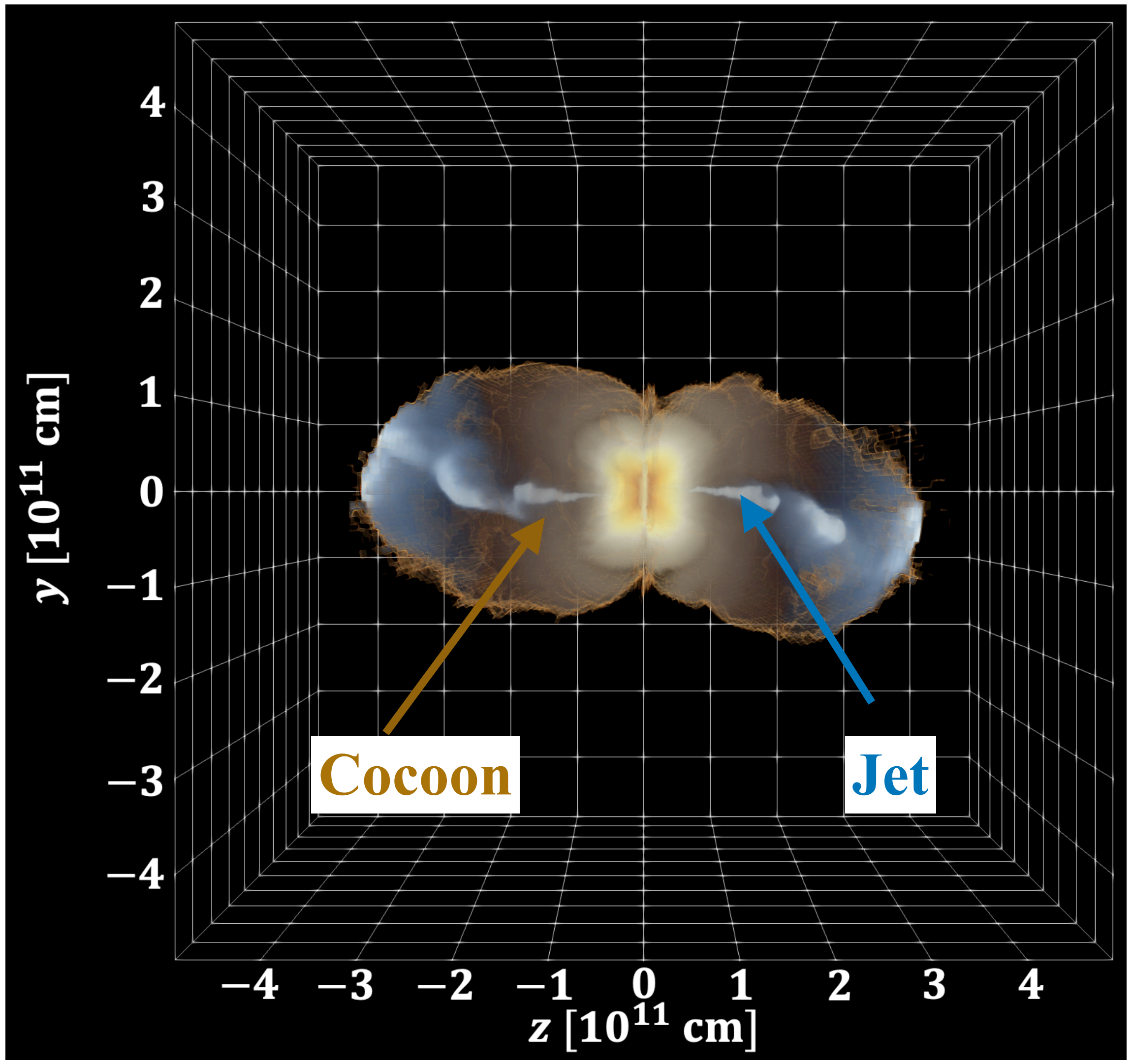
$\tilde{E}_\gamma \sim 10^{54}$ erg , $t_{dur} \sim$ tens of seconds



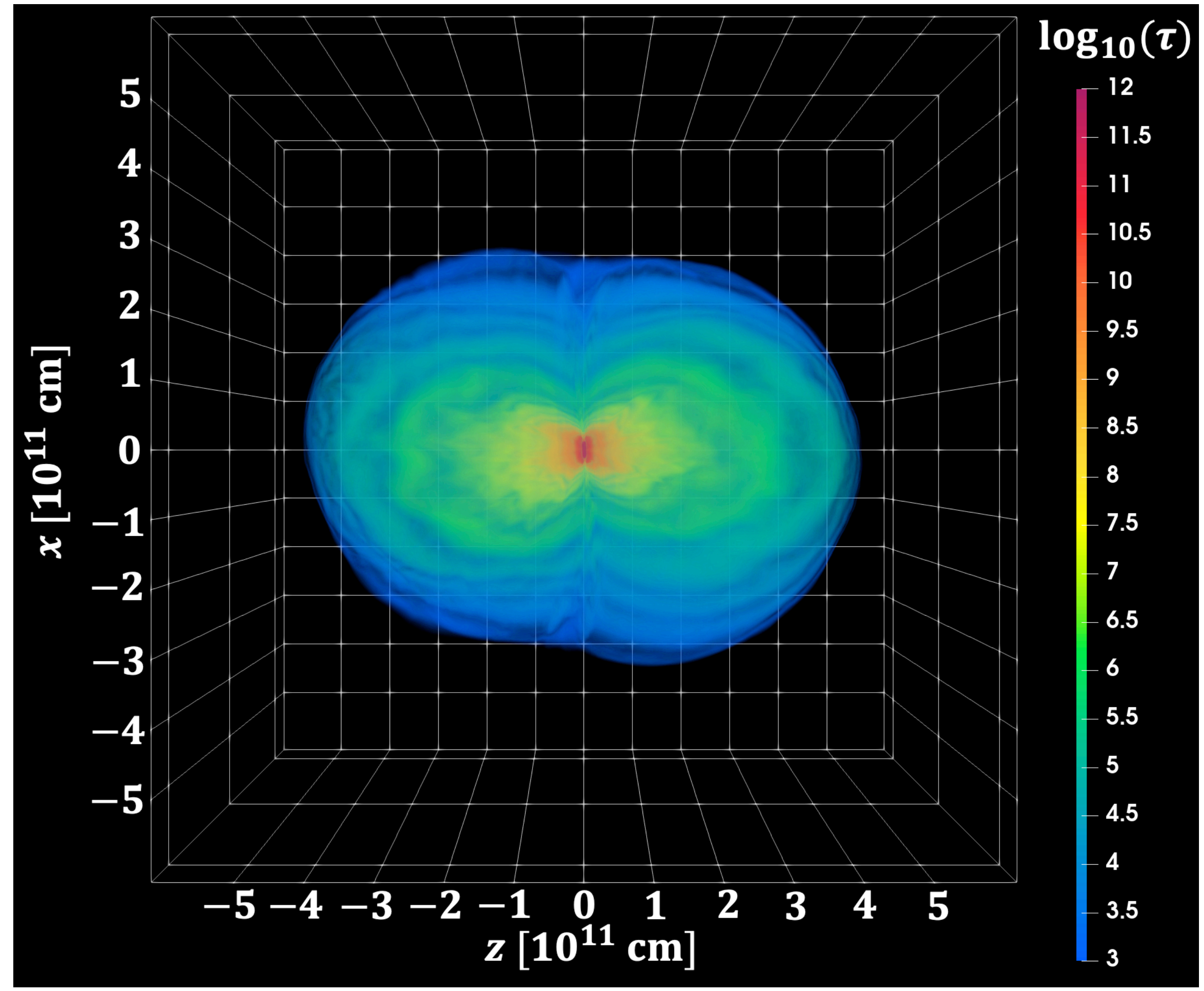
- Dissipation of energy starts deep in the outflow, where $\gamma-$rays are trapped$\longrightarrow$ Neutrinos?
- After the photosphere we observe the burst, produced during the **prompt phase**.
- The delayed emission lasting up to some weeks after the burst is called **afterglow**, observed across all the wavebands.

Optically Thick Collapsar Jets

Jet simulation



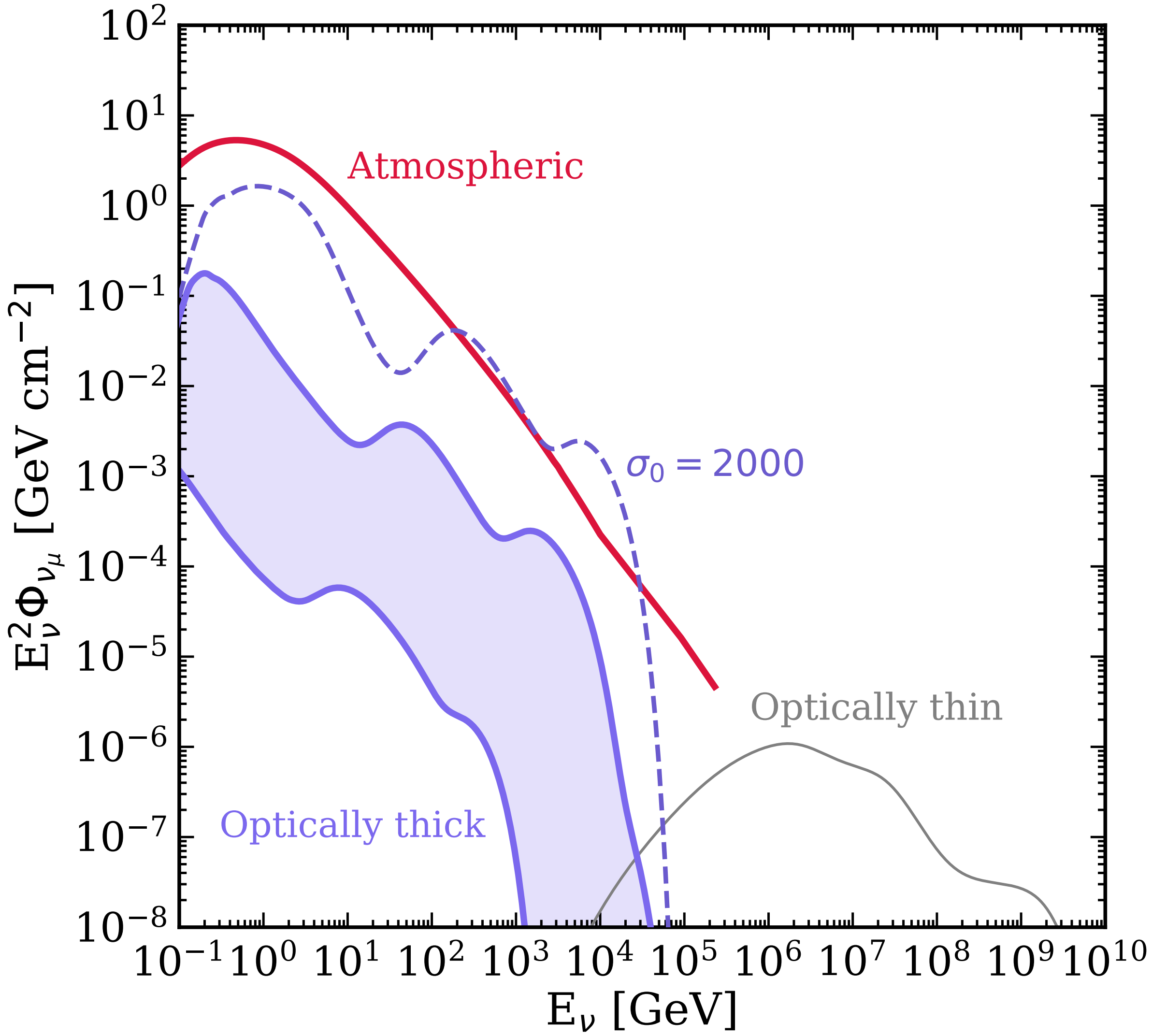
Optical depth

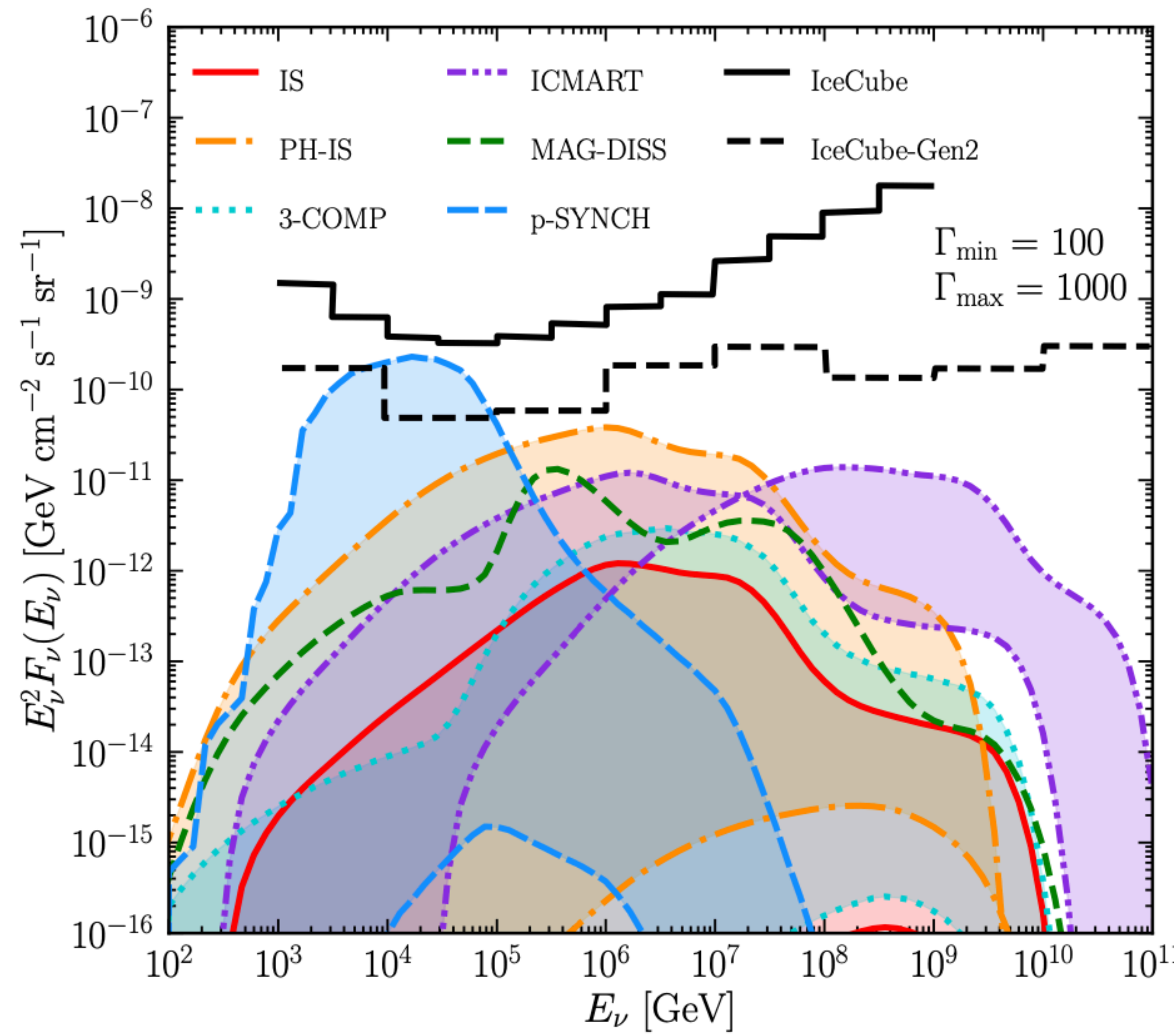


- The optical depth of the jet is extremely large at $R \simeq 10^{12}$ cm.
- Shock acceleration is inefficient at large optical depth.

Guarini, Tamborra and Gottlieb, PRD (2023) . Gottlieb et al., ApJ (2022).

Neutrinos as Probes of the Jet Nature

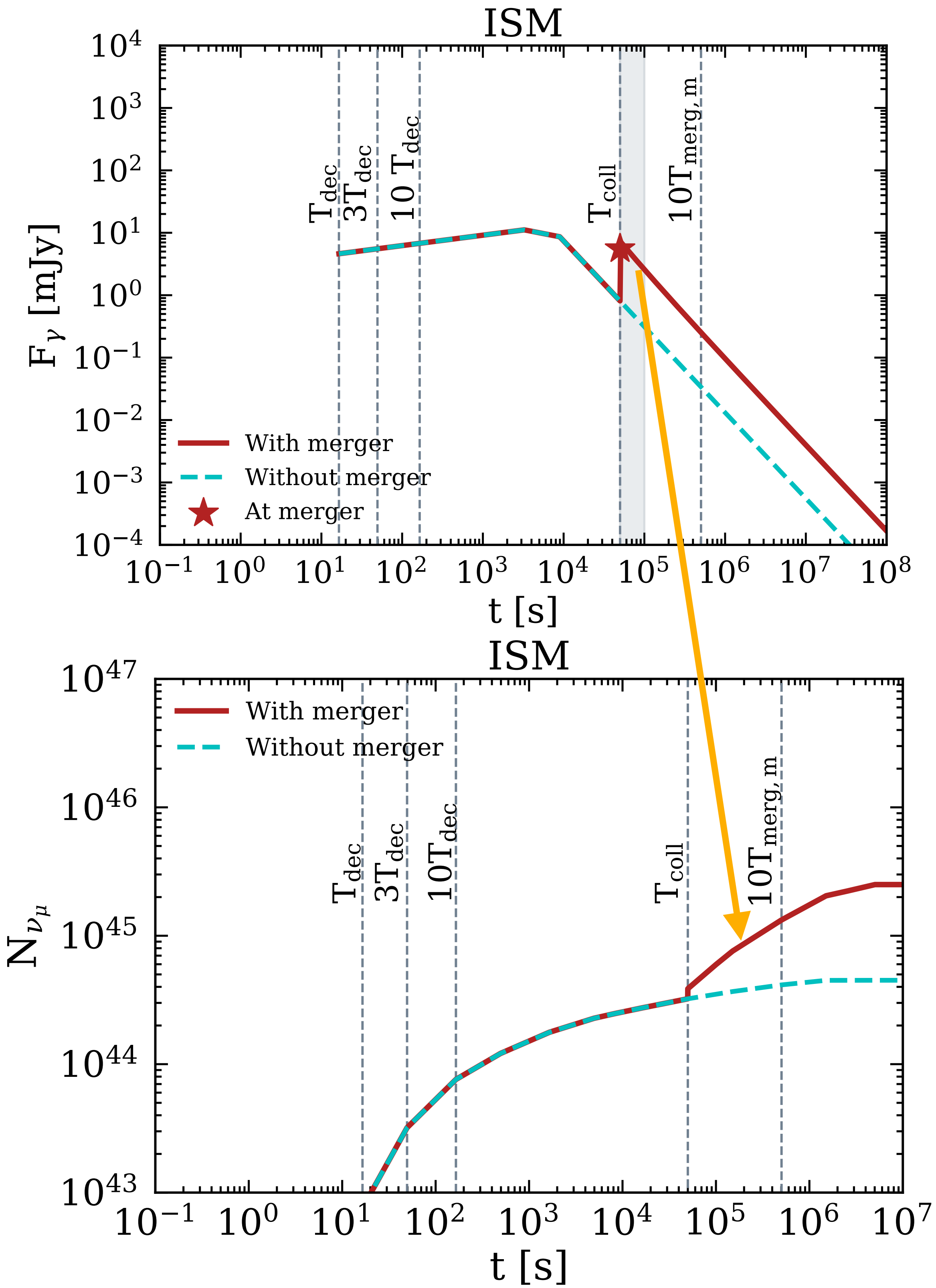




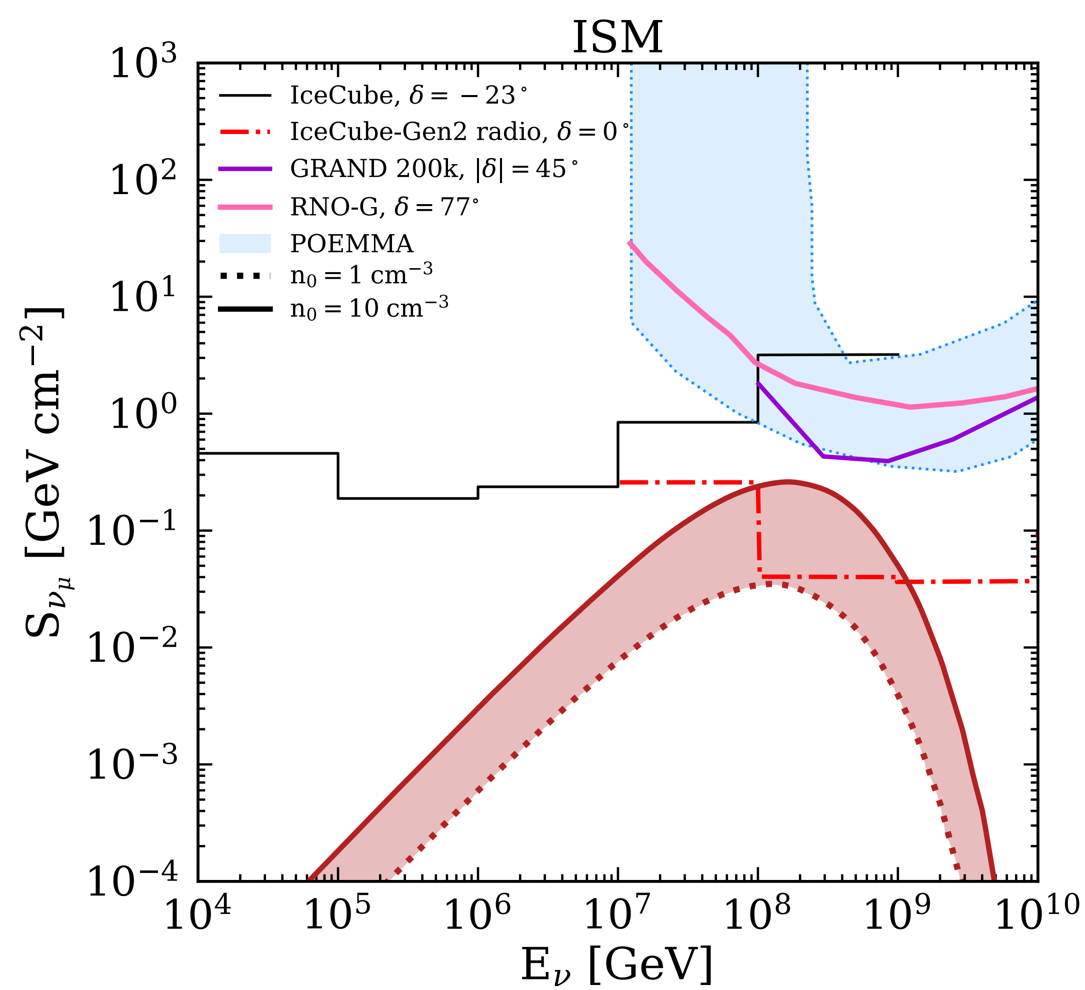
- Neutrinos can be produced below the photosphere only if the jet is **magnetized**.
- Well below the sensitivity range of IceCube ⟶ Optically thick jets cannot contribute to the high-energy diffuse flux!
- Prompt neutrinos very sensitive to the mechanism powering the jet.

Guarini, Tamborra and Gottlieb, PRD (2023); Pitik et al., JCAP (2022)

Neutrinos from GRB Afterglows



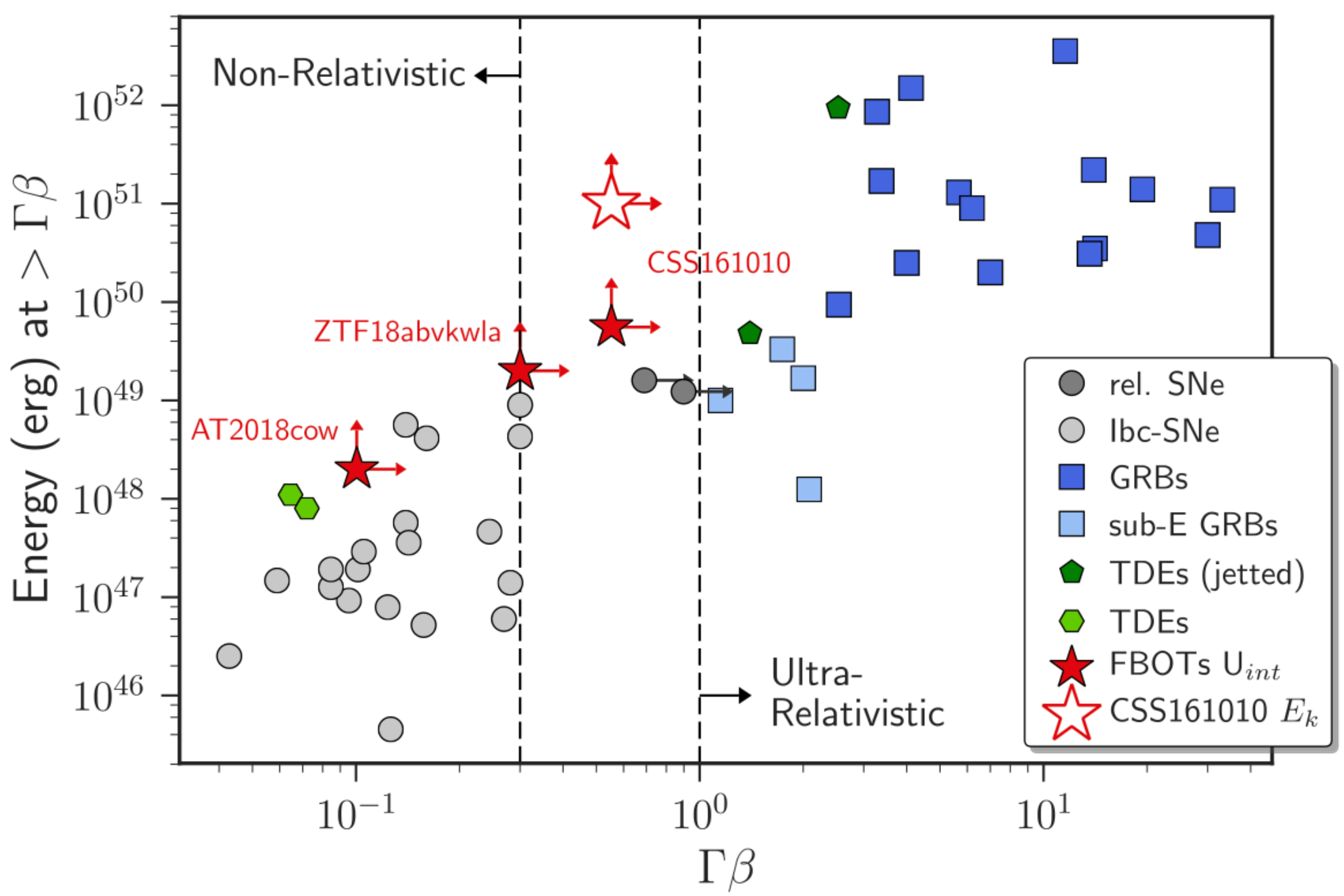
- The neutrino signal is expected to increase up to one order of magnitude.
- Neutrinos can disentangle the mechanism powering the jump and probe the medium around the burst.



Guarini et al., JCAP (2022), **Guarini** et al., MNRAS (in press)

Fast Blue Optical Transients (FBOTs)

- Supernova-like transients.
- Fast optical rise time.
- Optical peak luminosities: $L_{\text{peak}} \gtrsim 10^{44}$ erg s^{-1}.
- Theoretical models for the electromagnetic radiation are plugged with degeneracies.



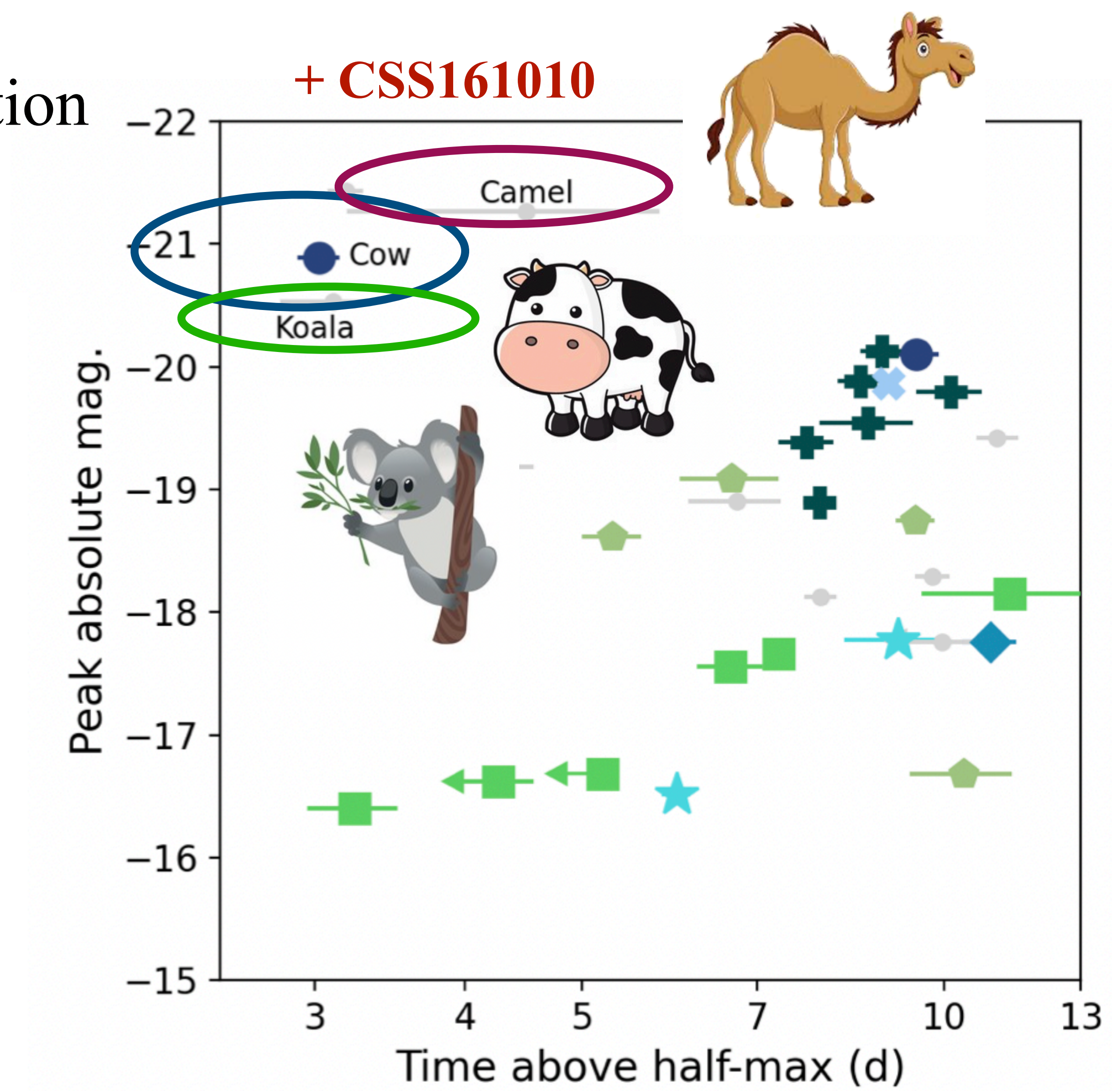
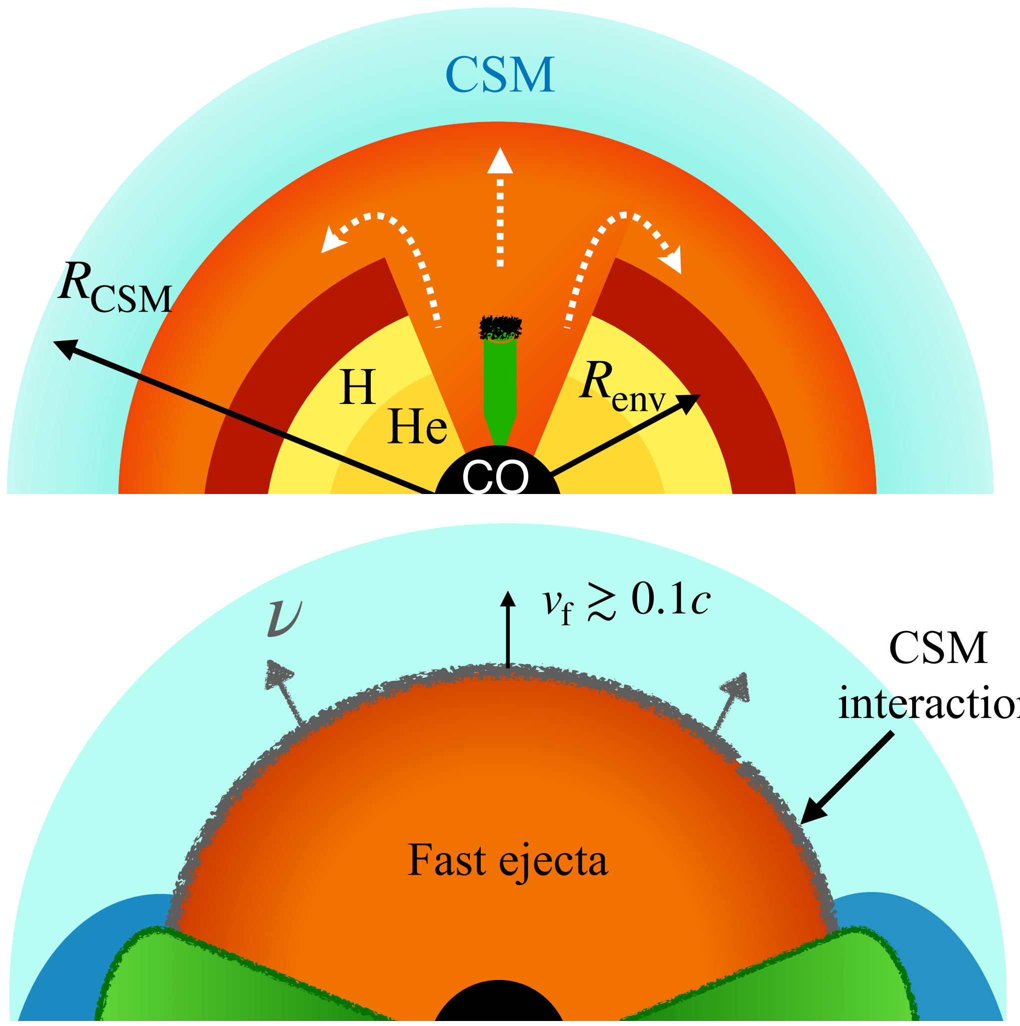
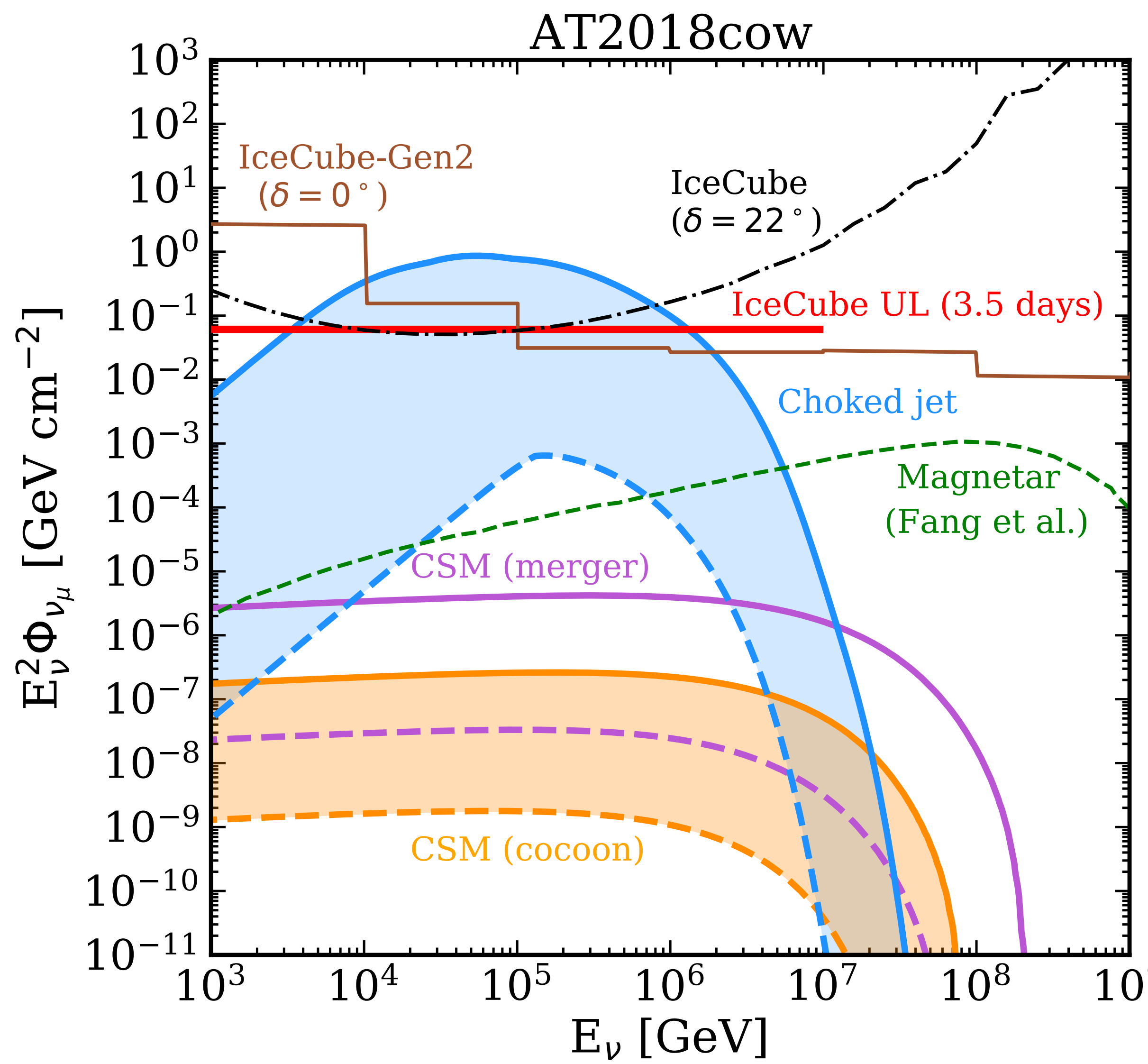


Image credit: Coppejans et al., ApJL (2020. Ho et al., arXiv:2105.08811 (2021).
See also: Perley et al., MNRAS (2019). Drout et al., ApJ (2014). Margutti et al., ApJ (2018)

Neutrino Signal from FBOTs





- The flux from a choked jet is direction dependent.
- The flux from CSM interaction is isotropic.
- Existing neutrino data already constrain the mechanism powering FBOTs.

Guarini, Tamborra and Margutti, ApJ (2022)

Conclusions and Outlook

- Multi-messenger observations can help to probe the source engine and allow us to study the origin of heavy elements.
- Neutrinos can help to disentangle the mechanism powering high-energy astrophysical sources.
- Future detectors will allow us to collect many neutrino data and unlock the unique possibility to look inside the most extreme environments of the Universe.

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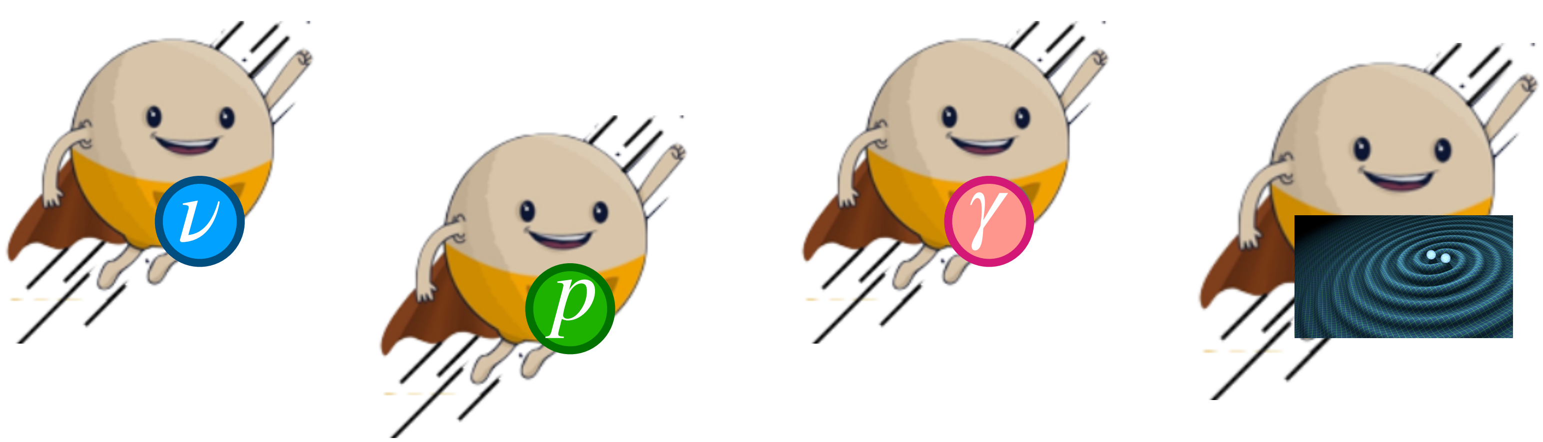
- Future detectors will allow us to collect many neutrino data and unlock the unique possibility to look inside the most extreme environments of the Universe.

Neutrinos are unique probes of the high-energy sky.

The dream of multi-messenger astronomy is here!



Thanks for your attention!

Questions?