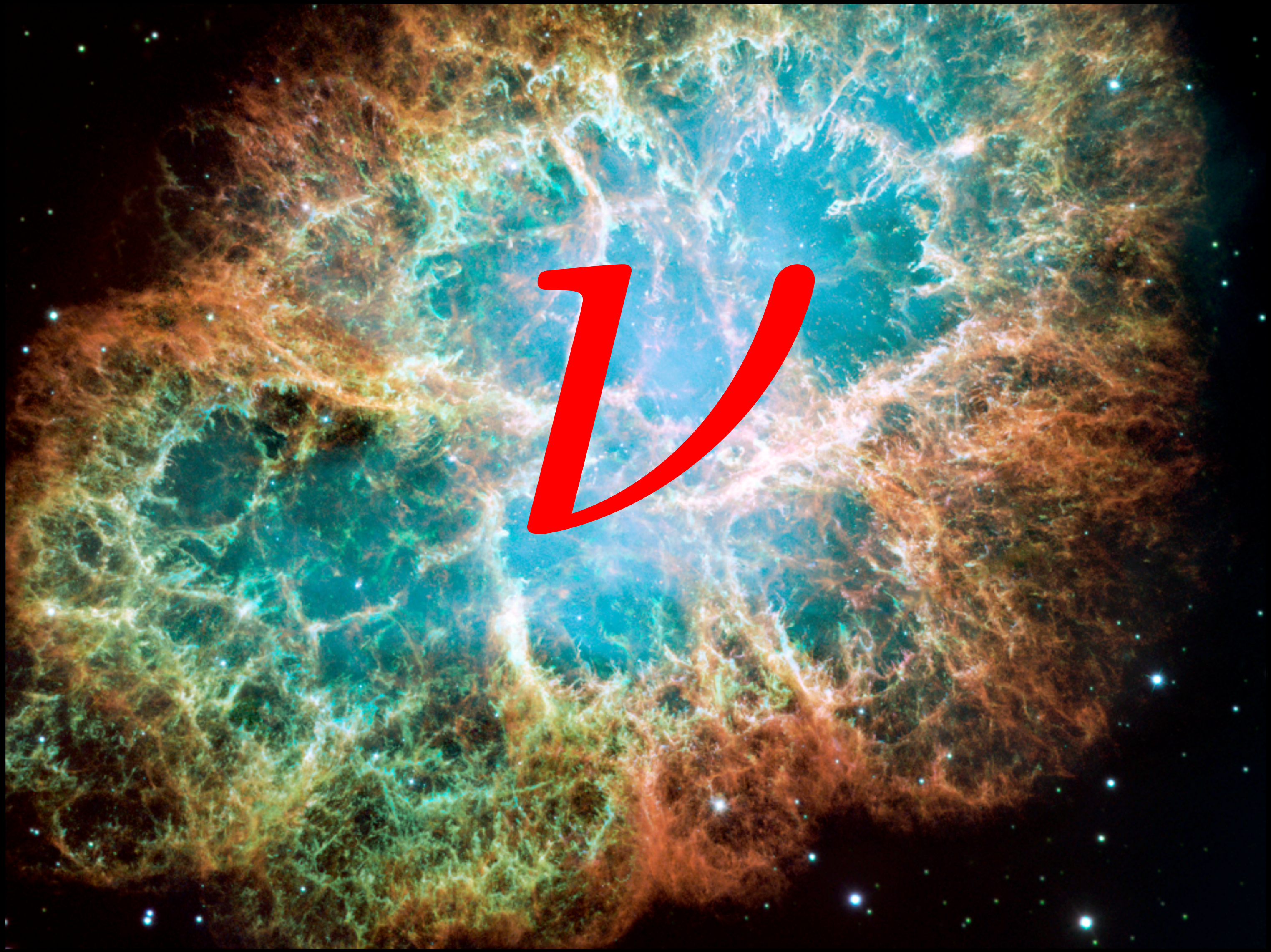
Ghostly Messengers of the Cosmos

Irene Tamborra (Niels Bohr Institute)

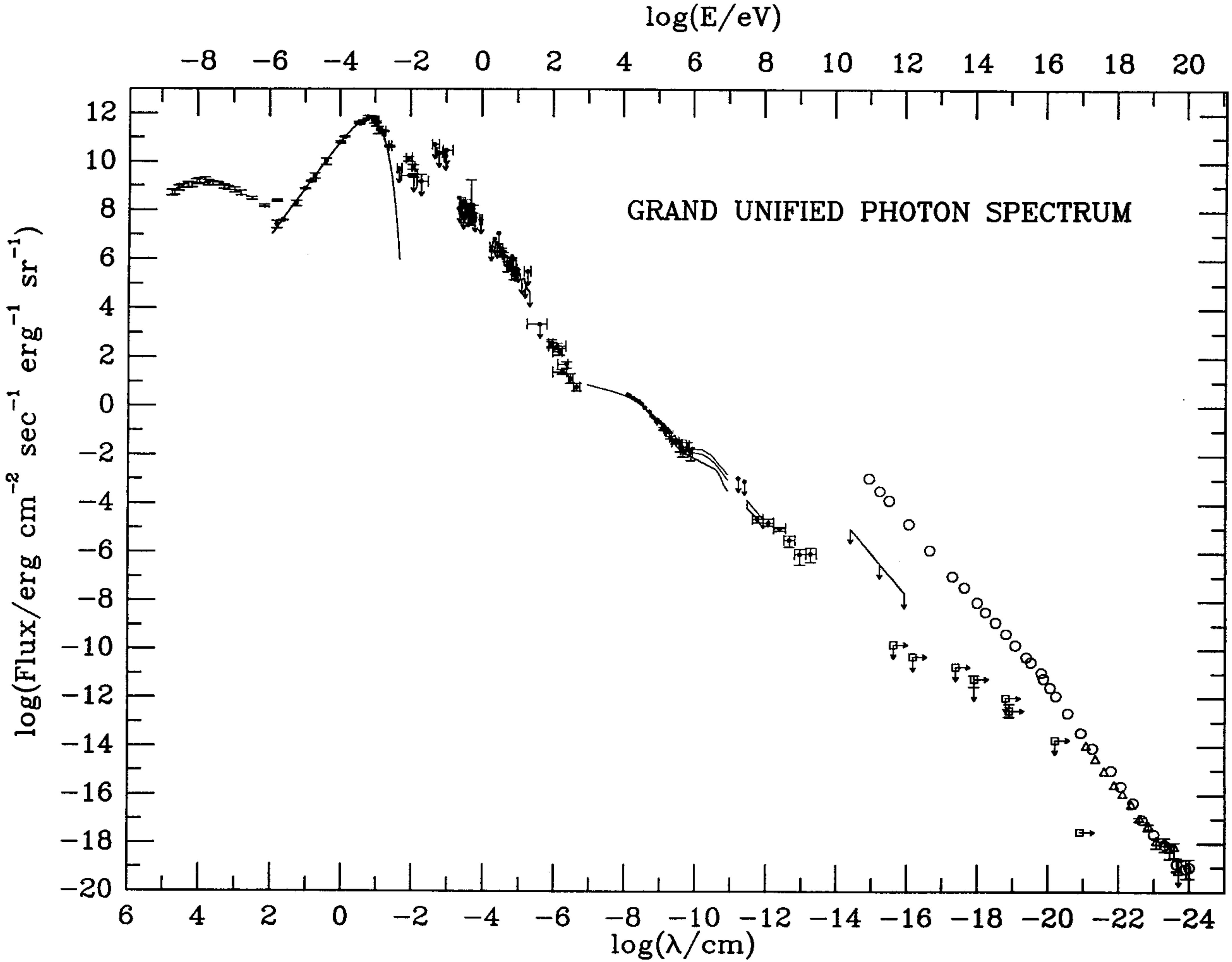


CERN, December 2, 2020

VILLUM FONDEN
Sapere Aude
CARLSBERG FOUNDATION
SFB 1258 Neutrinos Dark Matter Messengers

Exploring the Cosmos through our Senses

Sight: the Cosmos in Photons



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

The Cosmos through More Senses

Outline

- Neutrino astronomy: current status
- Neutrinos and compact astrophysical sources
- Neutrinos and cosmic accelerators
- Neutrinos and physics beyond the Standard Model
- Outlook

Neutrinos

ν_e

Ghostly

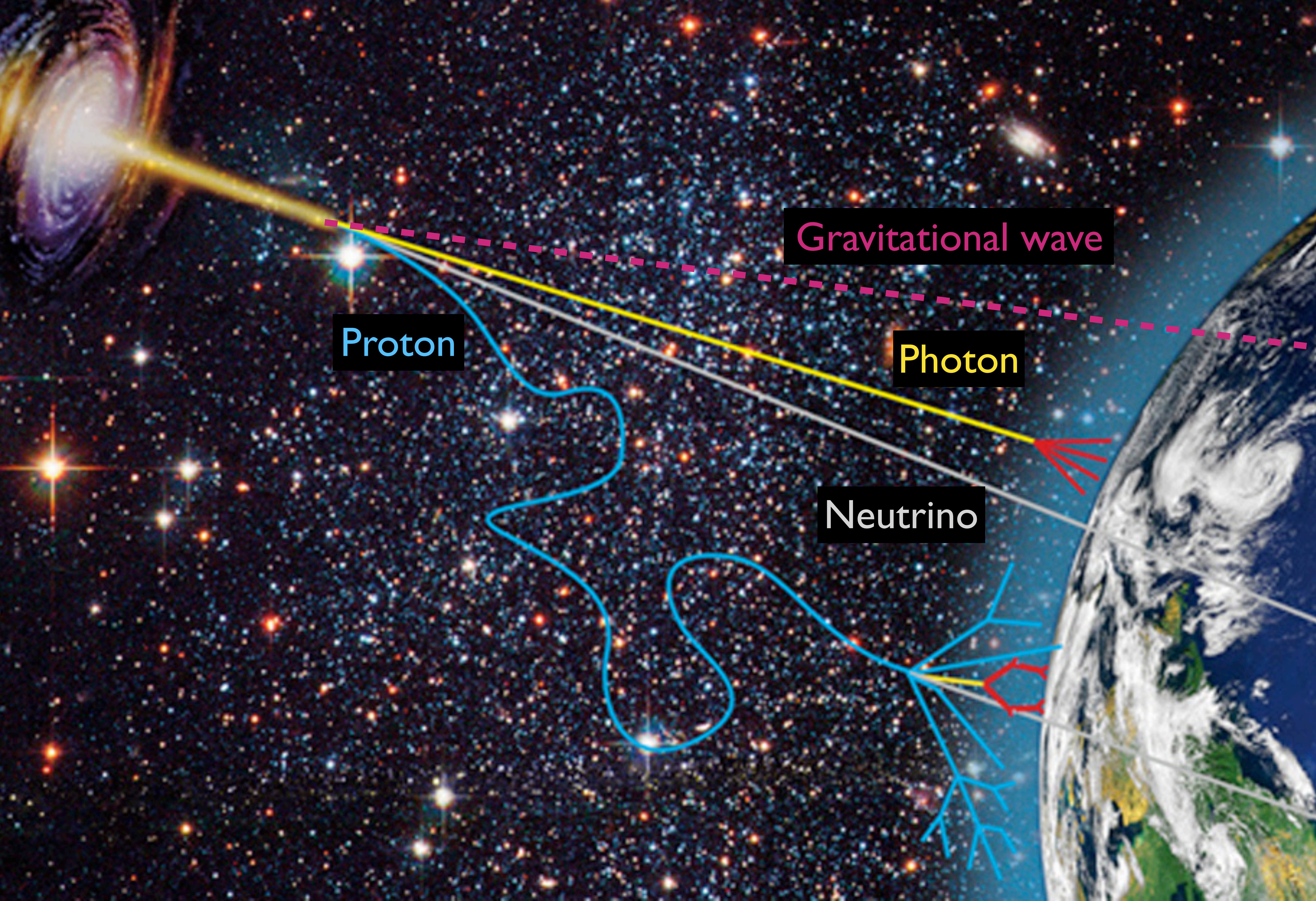
Abundant

ν_τ

Elusive

ν_μ

Ideal Messengers



Truly Novel Property of Neutrinos

Neutrinos **oscillate** into each other by flavor mixing, because of their tiny non-vanishing mass.

Flavor states

ν_e

ν_μ

ν_τ

= **Linear combination**

Mass states

ν_1

ν_2

ν_3

Flavor Oscillations

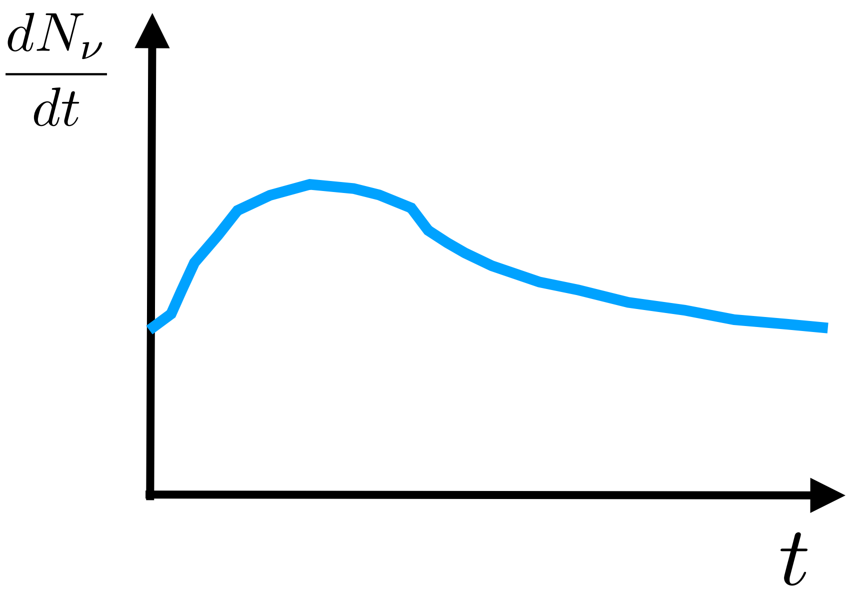
- Neutrino flavor ratio give us information about **neutrino properties**.
- Flavor conversions are affected by background fermion distribution.
- In turn, flavor conversions can affect source dynamics.
  ⇨ Study of flavor evolution allows to learn about **source properties**.

Powerful Probes in Astrophysics

Energy distribution

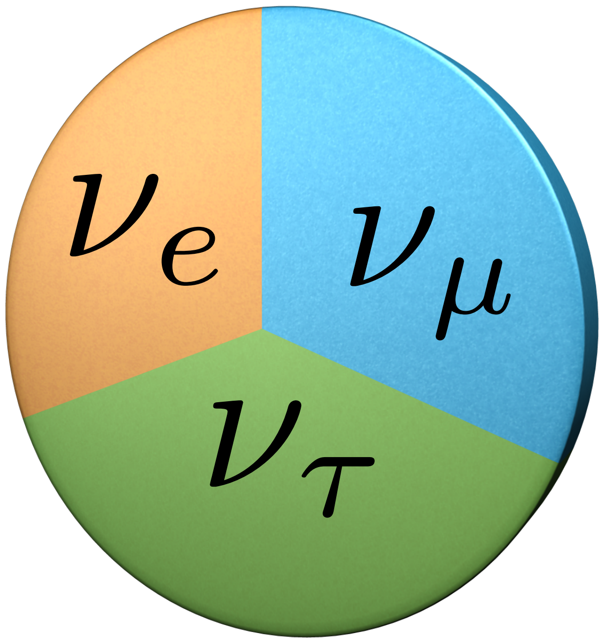
Similar to photons

Neutrino curve



Similar to photons

Flavor ratio



Neutrinos only!

The Dream of Neutrino Astronomy

If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino.

Bethe and Peierls (1934)

Only neutrinos, with their extremely small cross sections, can enable us to see into the interior of a star ...

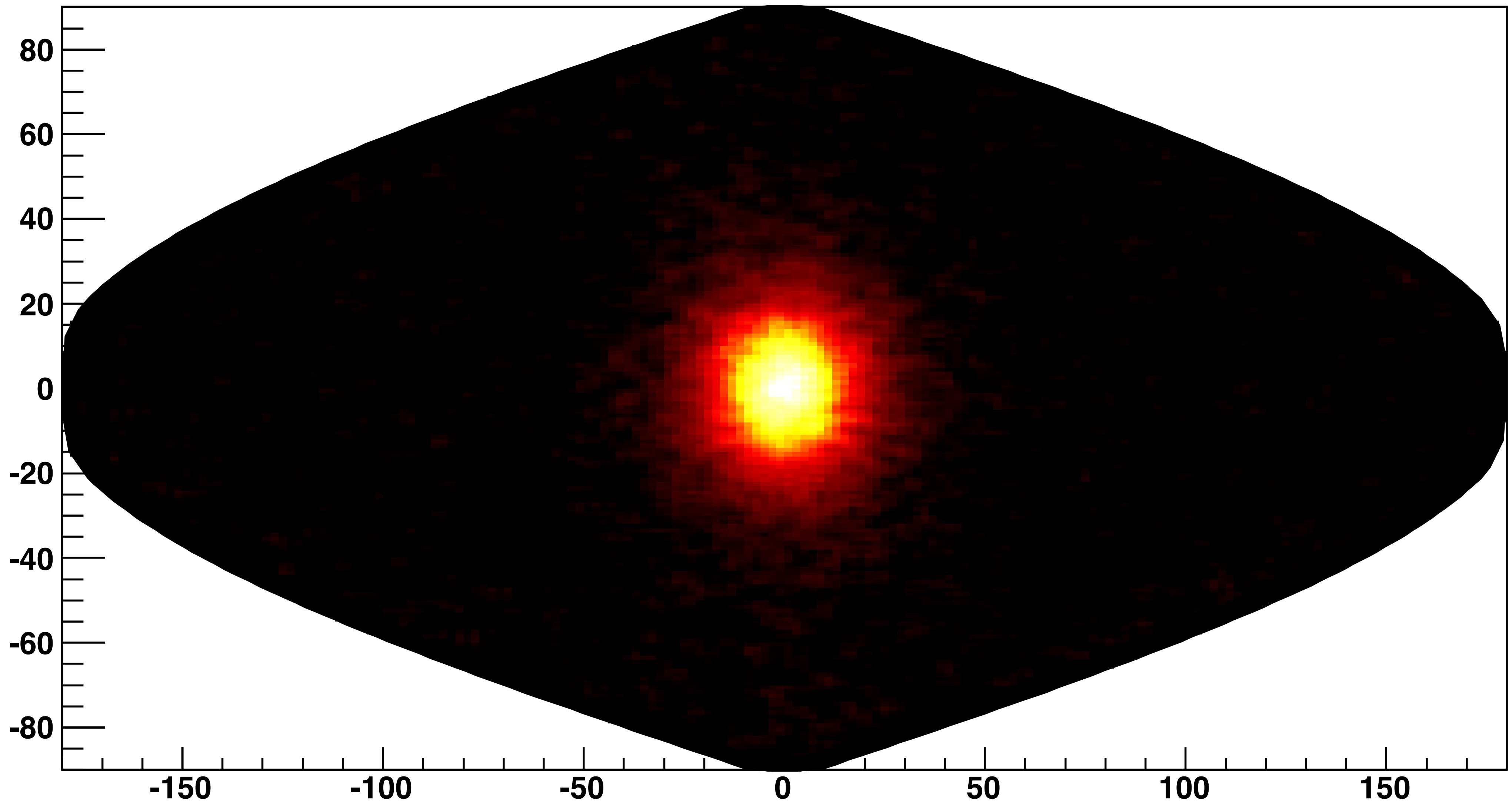
Bahcall (1964)

The title is more of an expression of hope than a description of the book's contents...the observational horizon of neutrino astrophysics may grow...perhaps in a time as short as one or two decades.

Bahcall, Neutrino Astrophysics (1989)

Sources of Neutrino Astronomy as of 2020: No. 1

How Did We Learn About the Sun? Neutrinos!



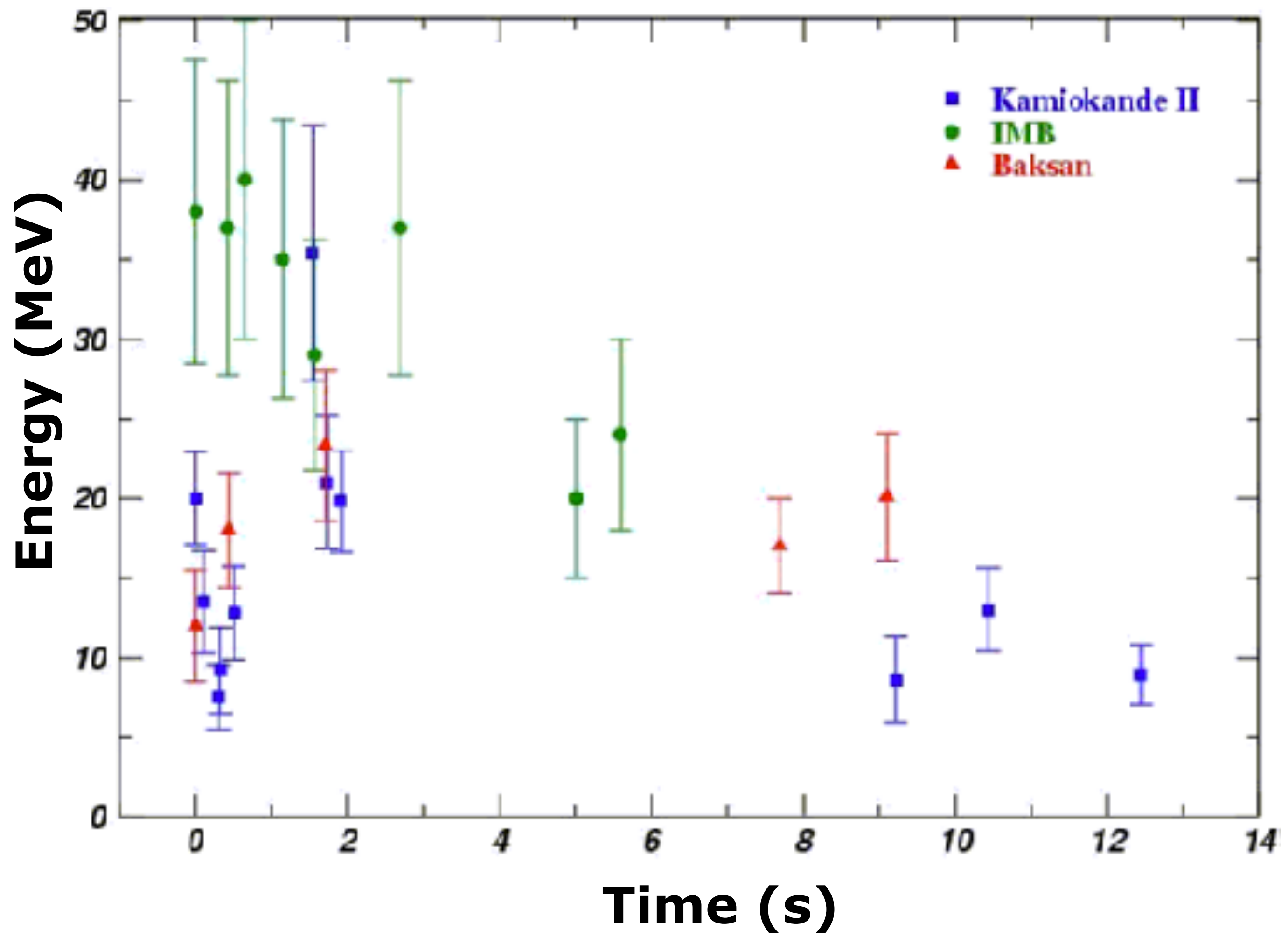
- Deficit of measured solar neutrino flux. ⇨ **Discovery of neutrino oscillations**.
- Neutrino flux strongly dependent from Sun solar interior. ⇨ **Standard Solar Model Test**.

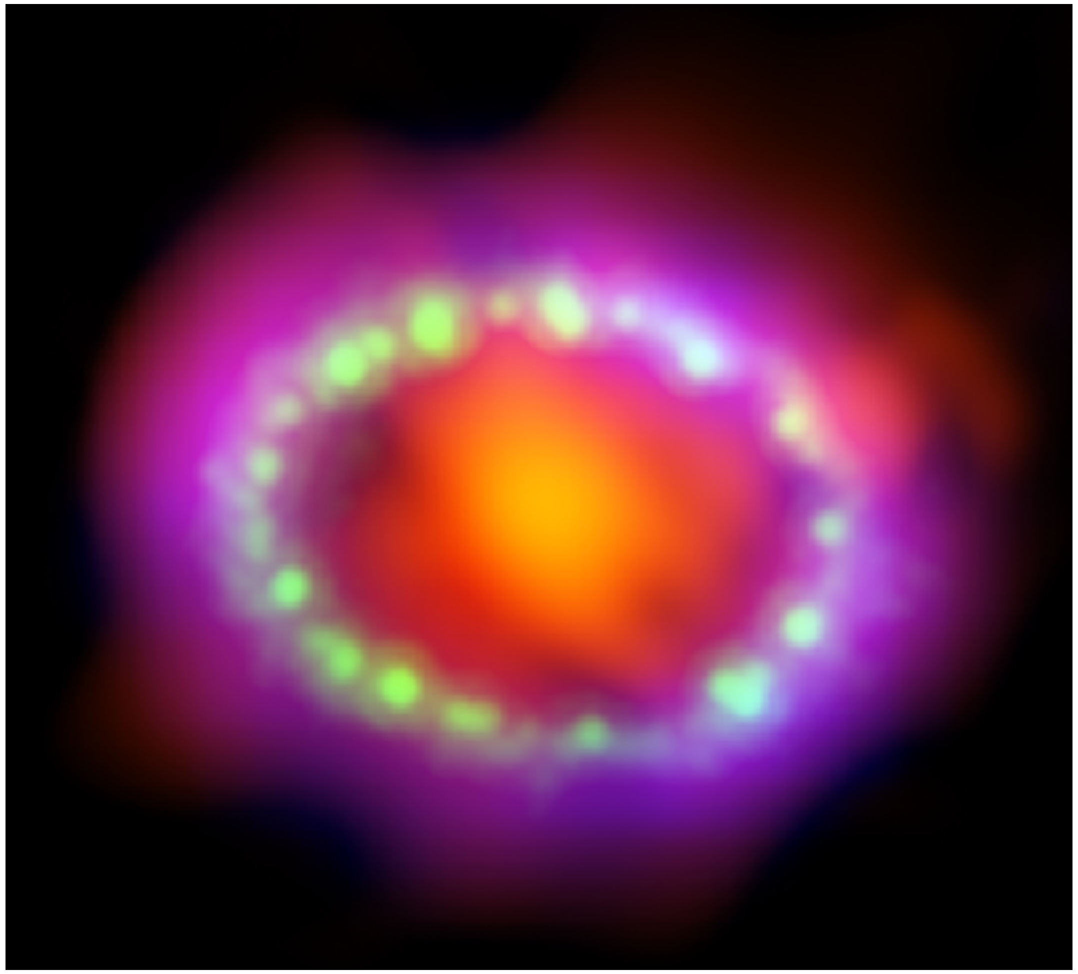
Image credits: Super-Kamiokande Collaboration.

Sources of Neutrino Astronomy as of 2020: No.2

The Local Supernova (SN 1987A)

Neutrinos: unique probes of stellar collapse





Feb. 24, 1987: “Did you hear what happened today? 10^{58} neutrinos! All in one go!”

From L. Pontecorvo’s memories (F. Close).

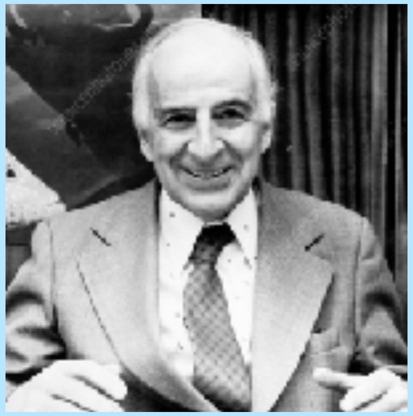
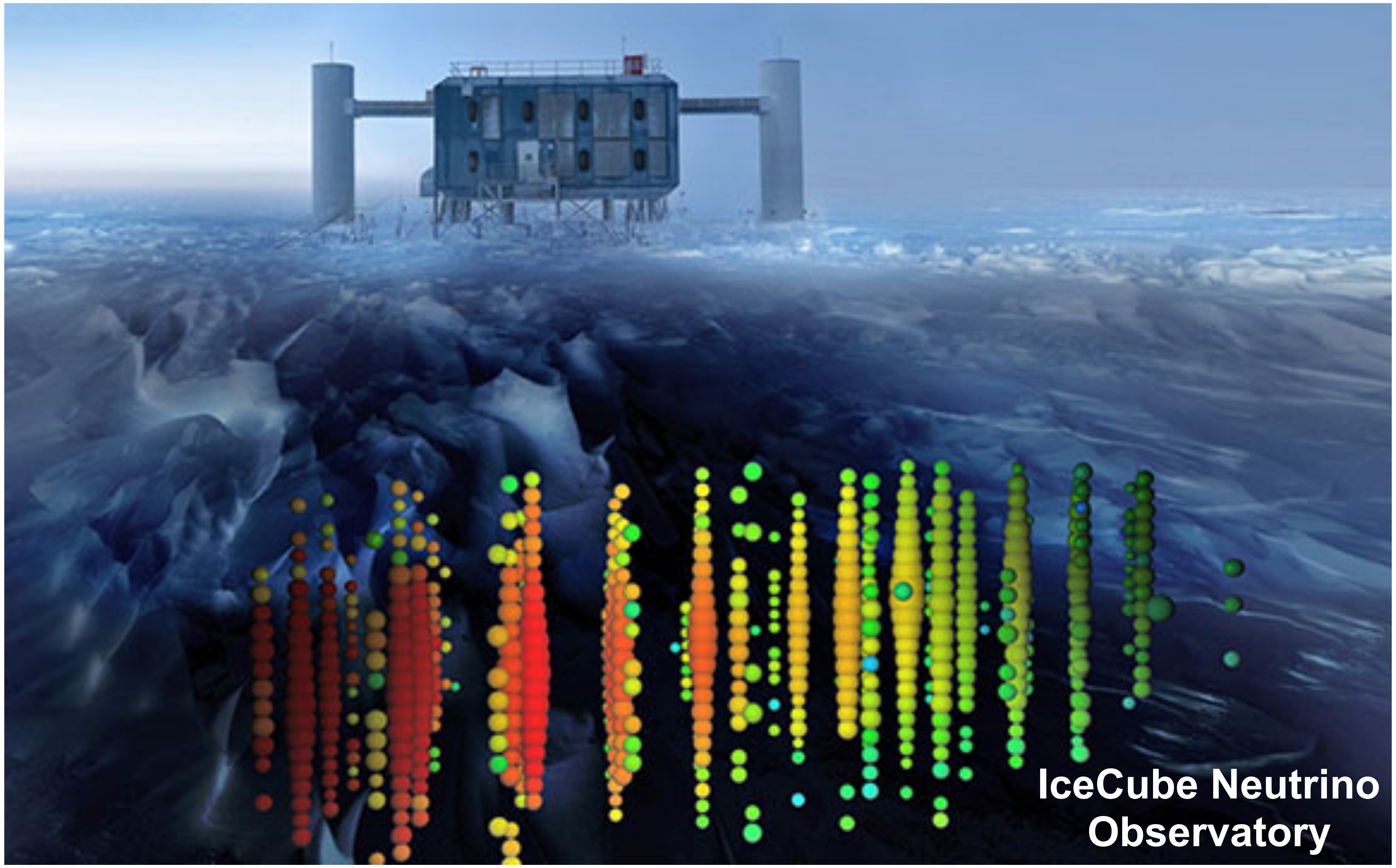


Image credits: NASA, CERNCOURIER.

Sources of Neutrino Astronomy as of 2020: No. 3

The High Energy Neutrino Astronomy Era Is Now!



- **2013:** Detection of two neutrinos with PeV energy, the highest energy ever observed.

⇩

- **2020:** Robust evidence of astrophysical flux with yet unknown origin!

IceCube Collaboration, Science (2013); PRL (2014); ApJ (2015); PRL (2015).

What's Next?

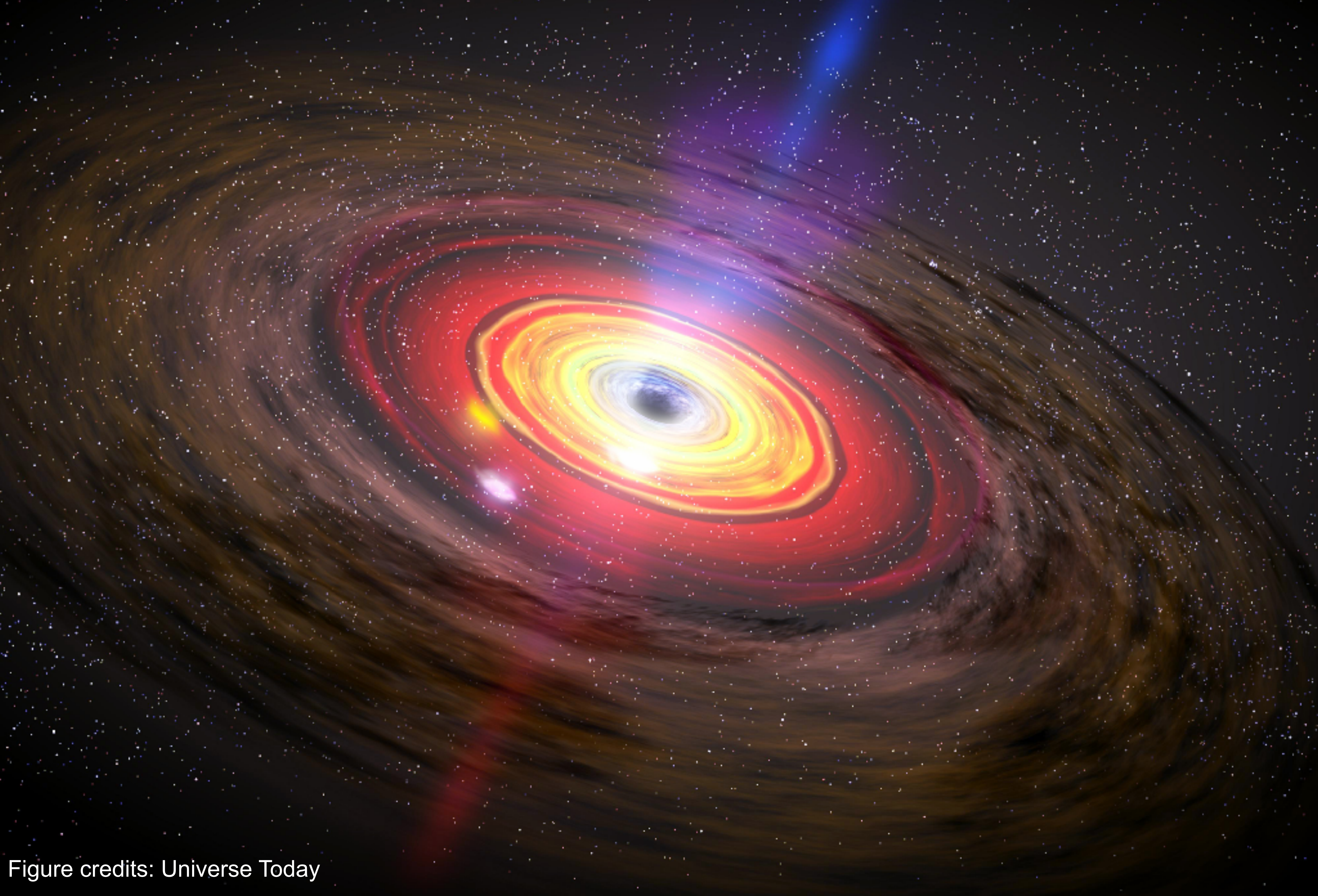
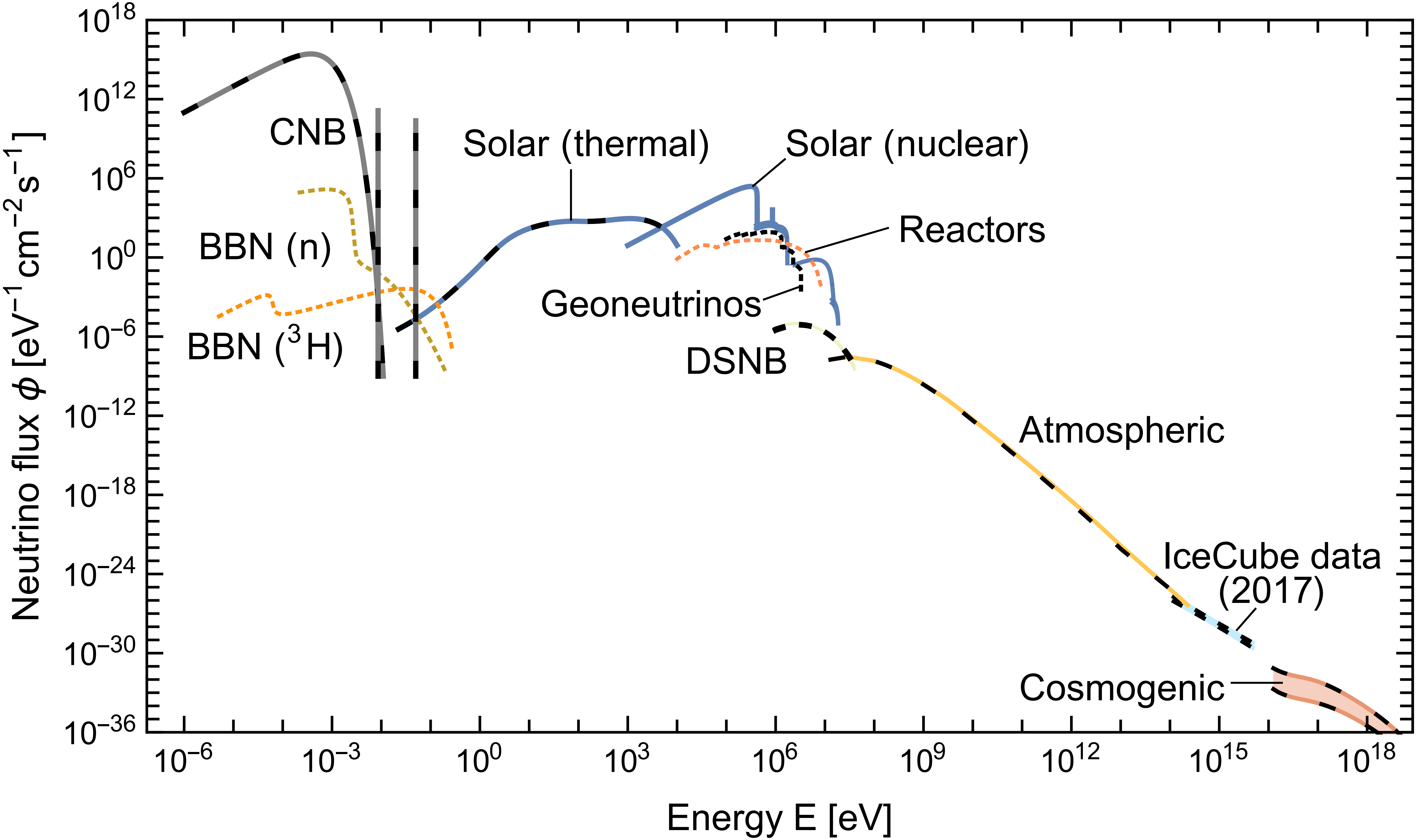


Figure credits: Universe Today

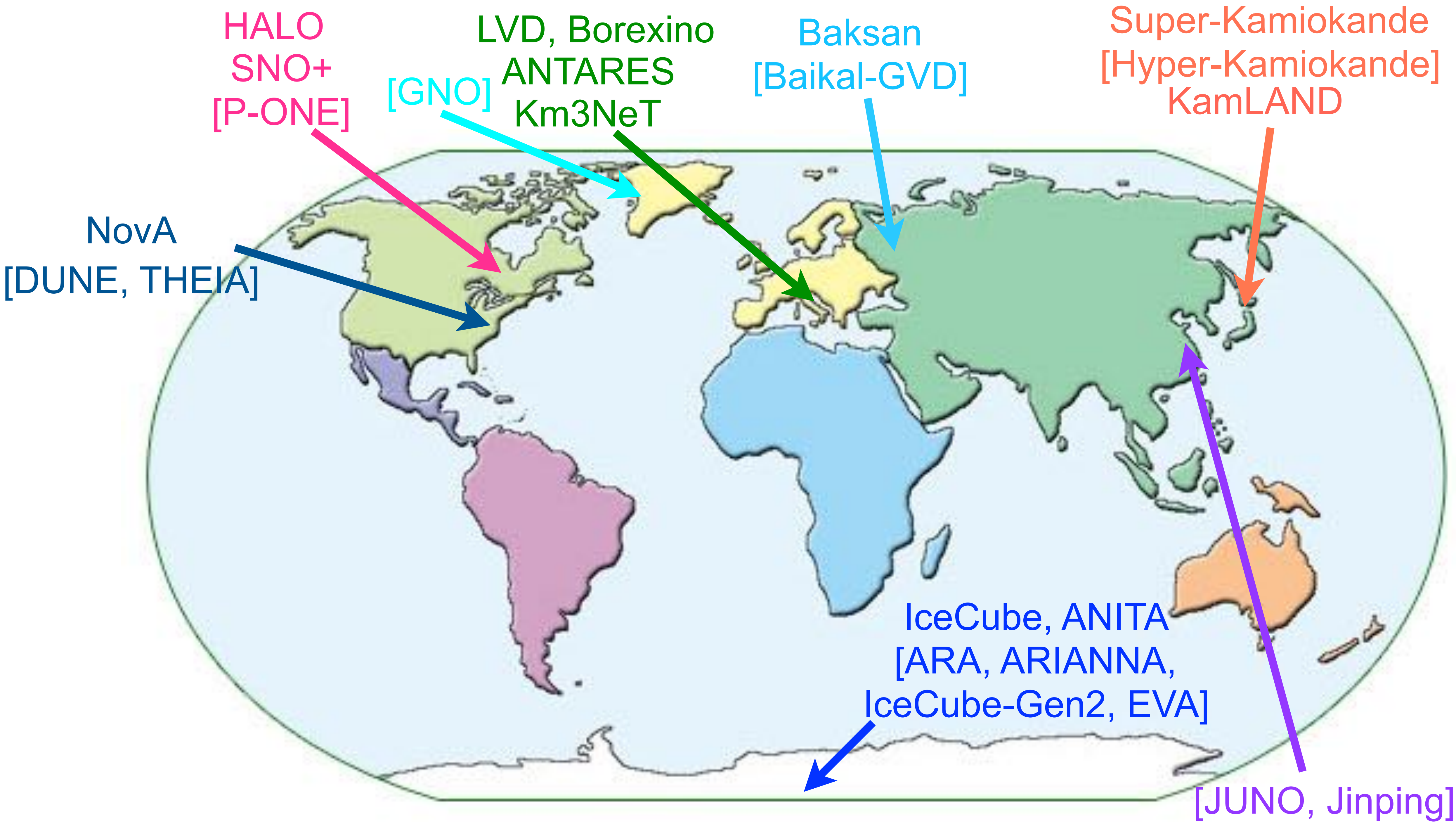
Touch: the Cosmos in Neutrinos

Grand Unified Neutrino Spectrum



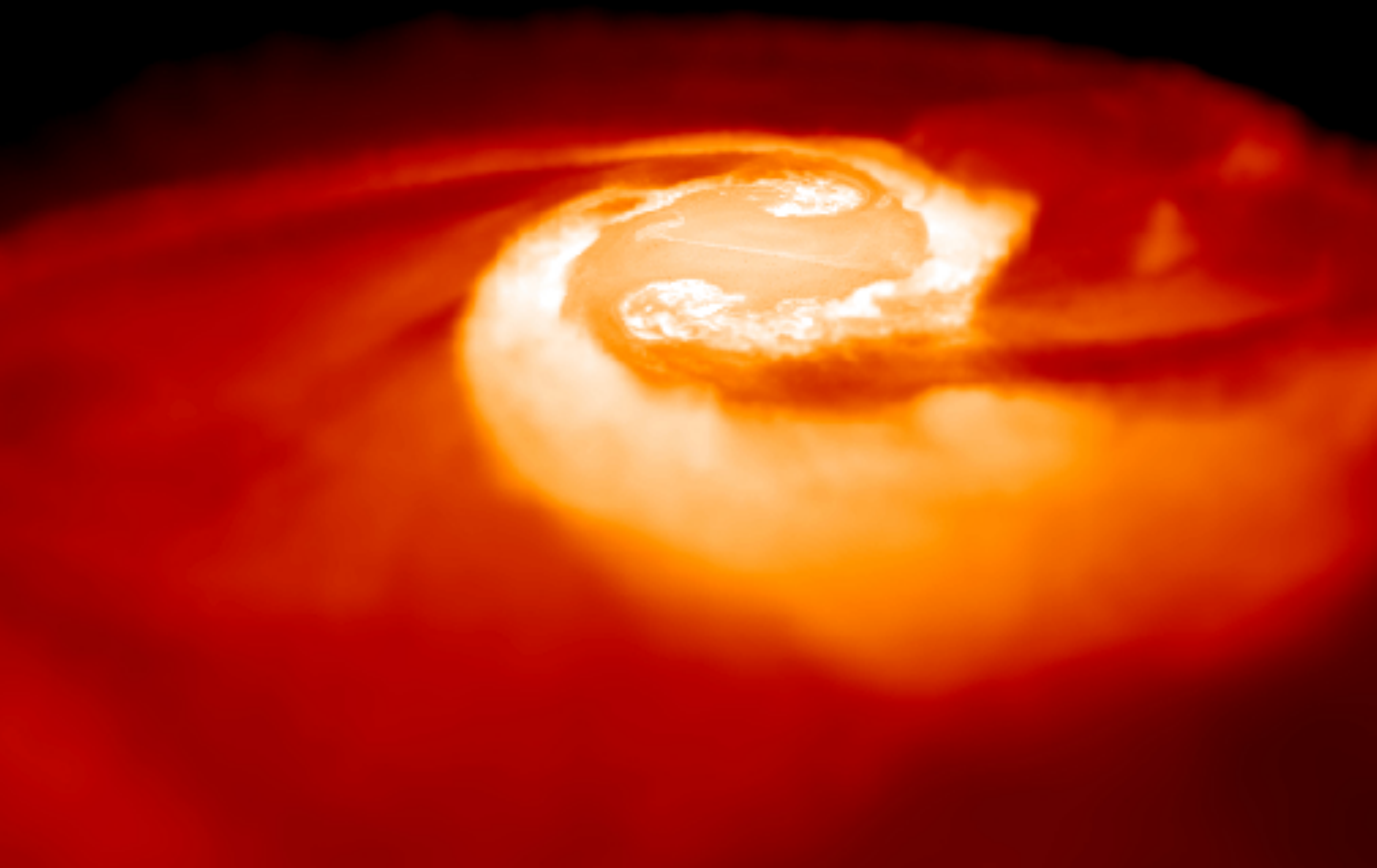
Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020, in press).

Neutrino "Telescopes"



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

Compact Neutrino Sources



Core-Collapse Supernovae

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

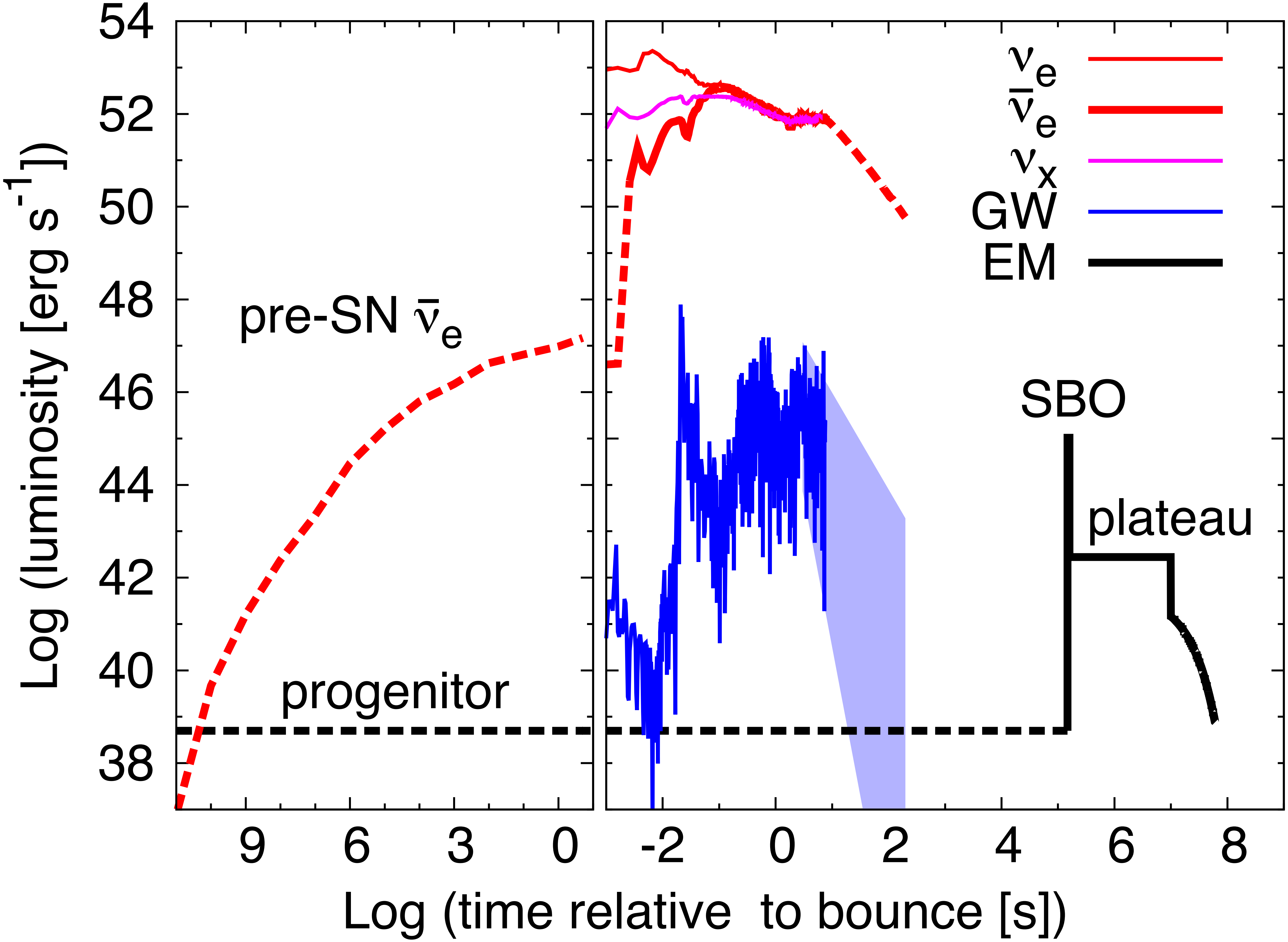
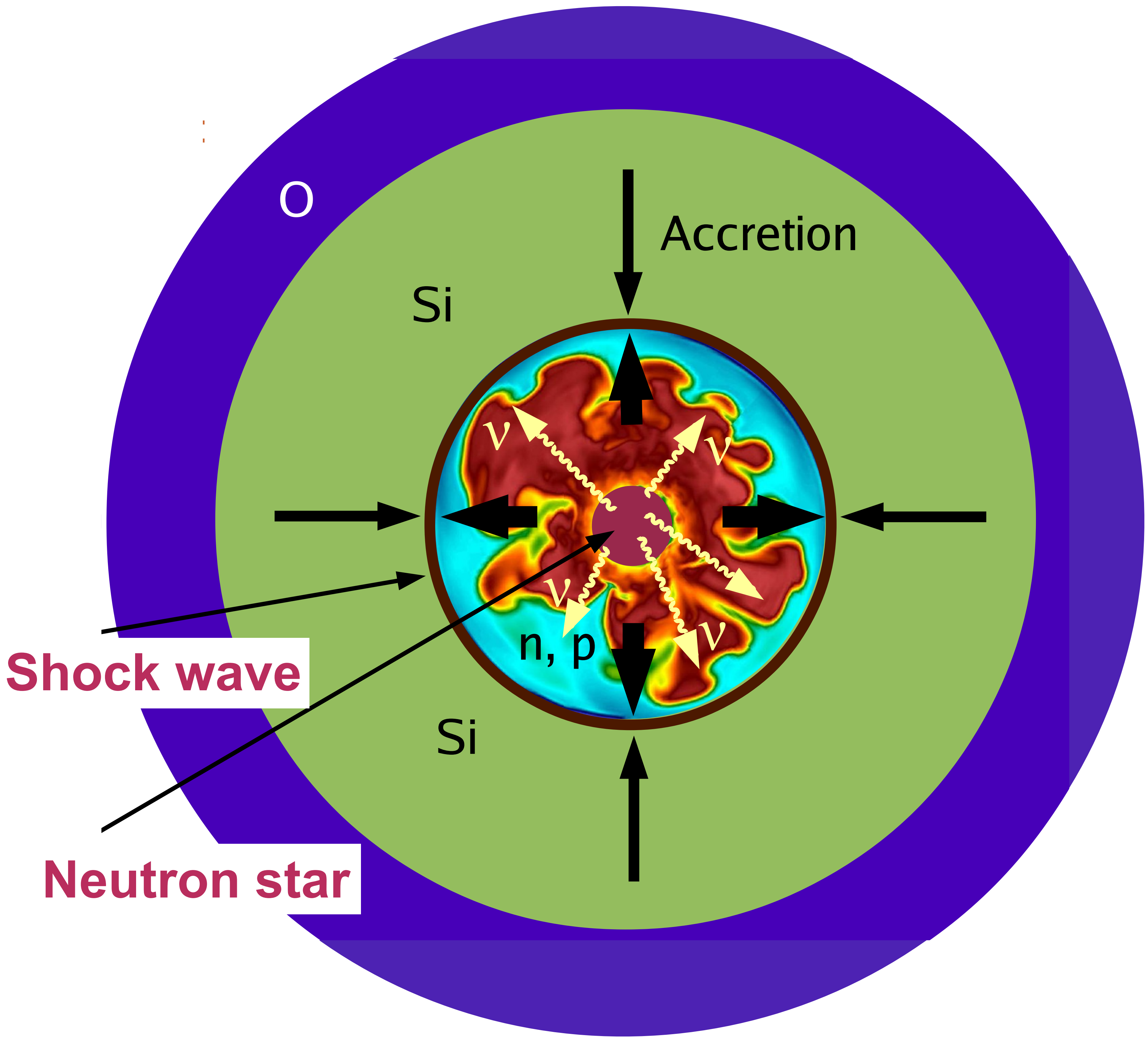


Figure from Nakamura et al., MNRAS (2016).

Supernova Explosion Mechanism

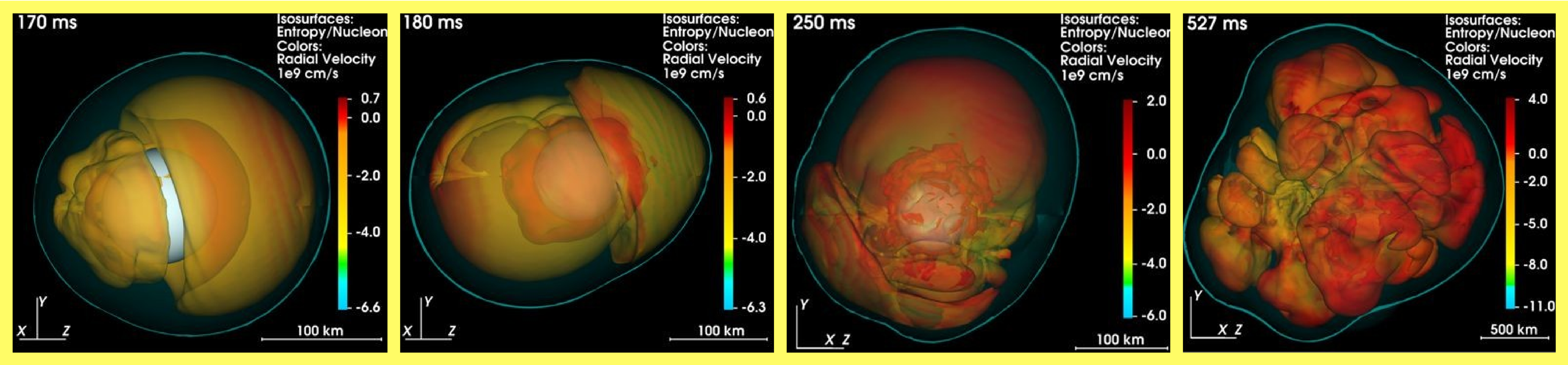
Shock wave forms within the iron core. It dissipates energy by dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.

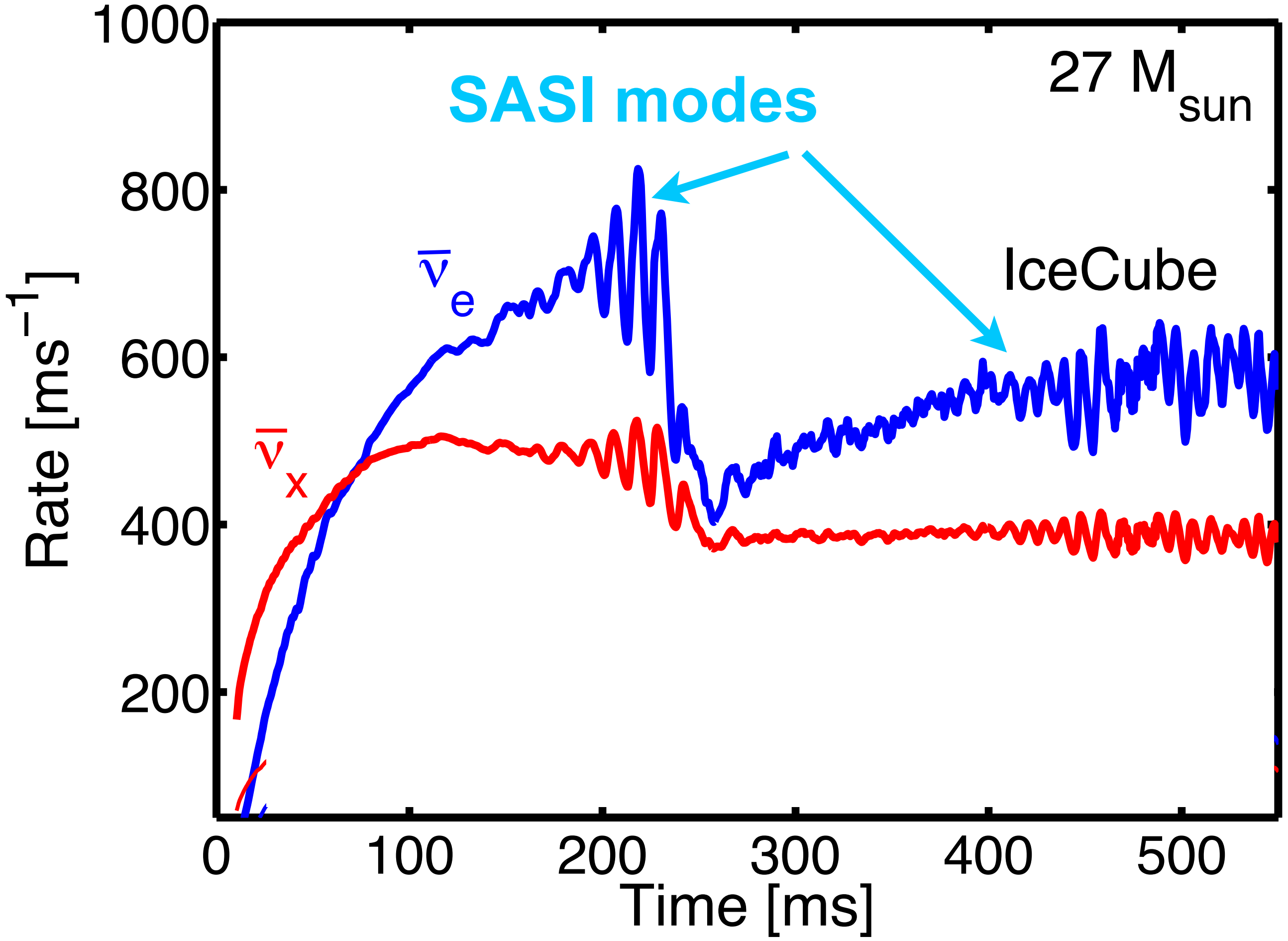


Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

Fingerprints of Explosion Mechanism

Standing Accretion Shock Instability (SASI)

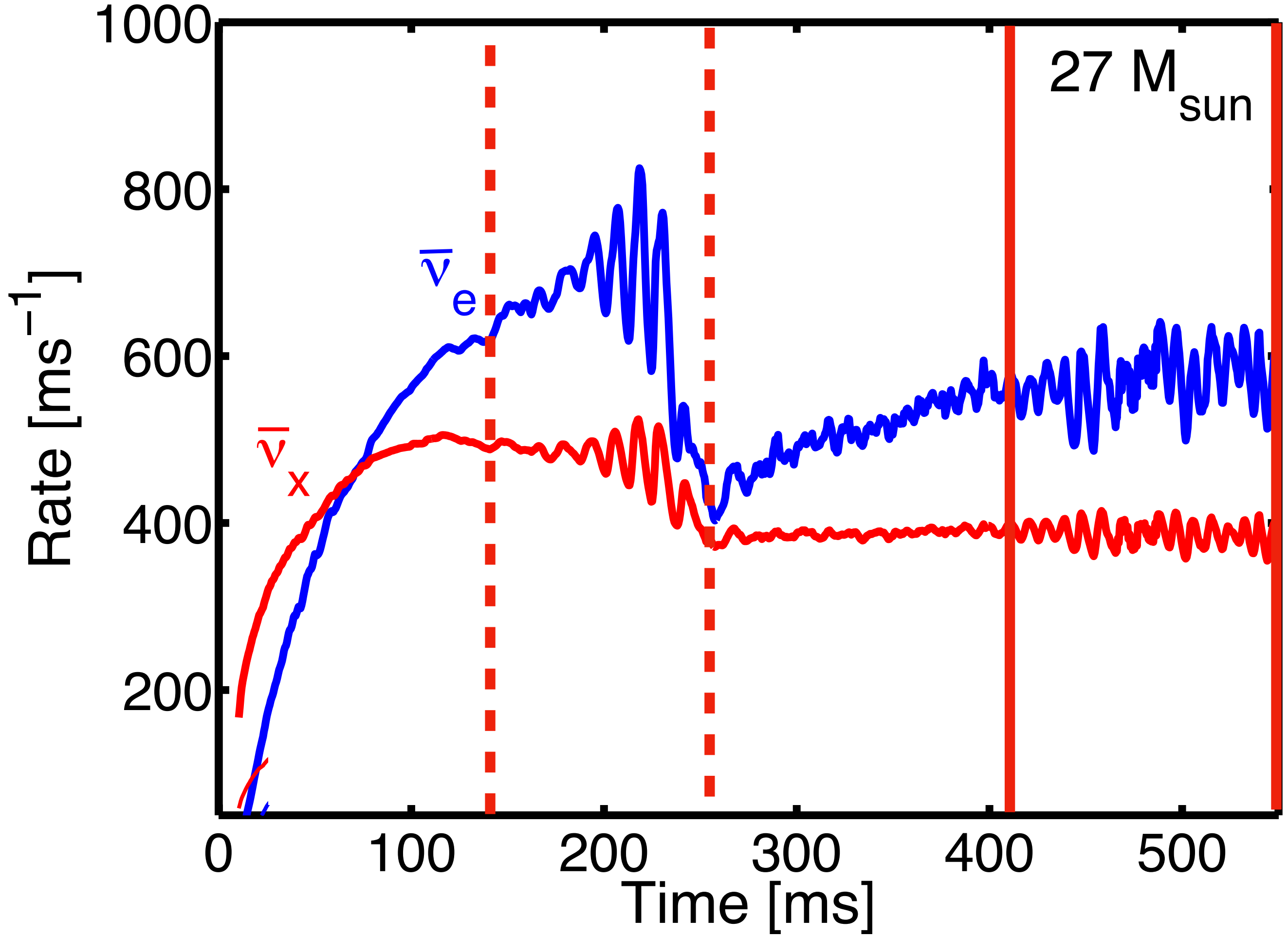




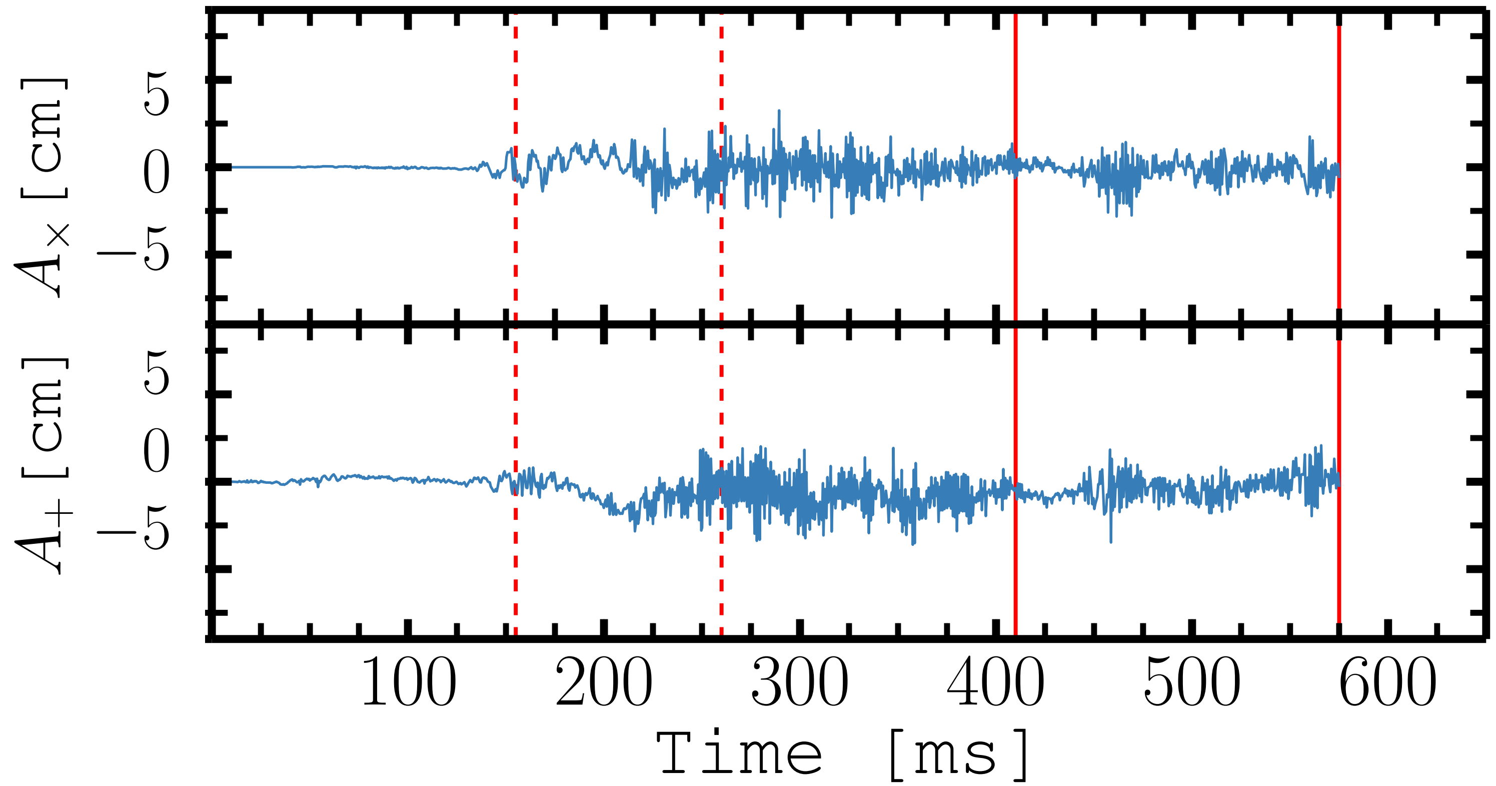
SASI frequency: O(85) Hz.

Tamborra et al., PRL (2013), PRD (2014). Kuroda et al., ApJ (2017). Walk, Tamborra et al., PRD (2018). Walk, Tamborra et al., PRD (2019). Melson et al., APpJL (2015).

Fingerprints of Explosion Mechanism



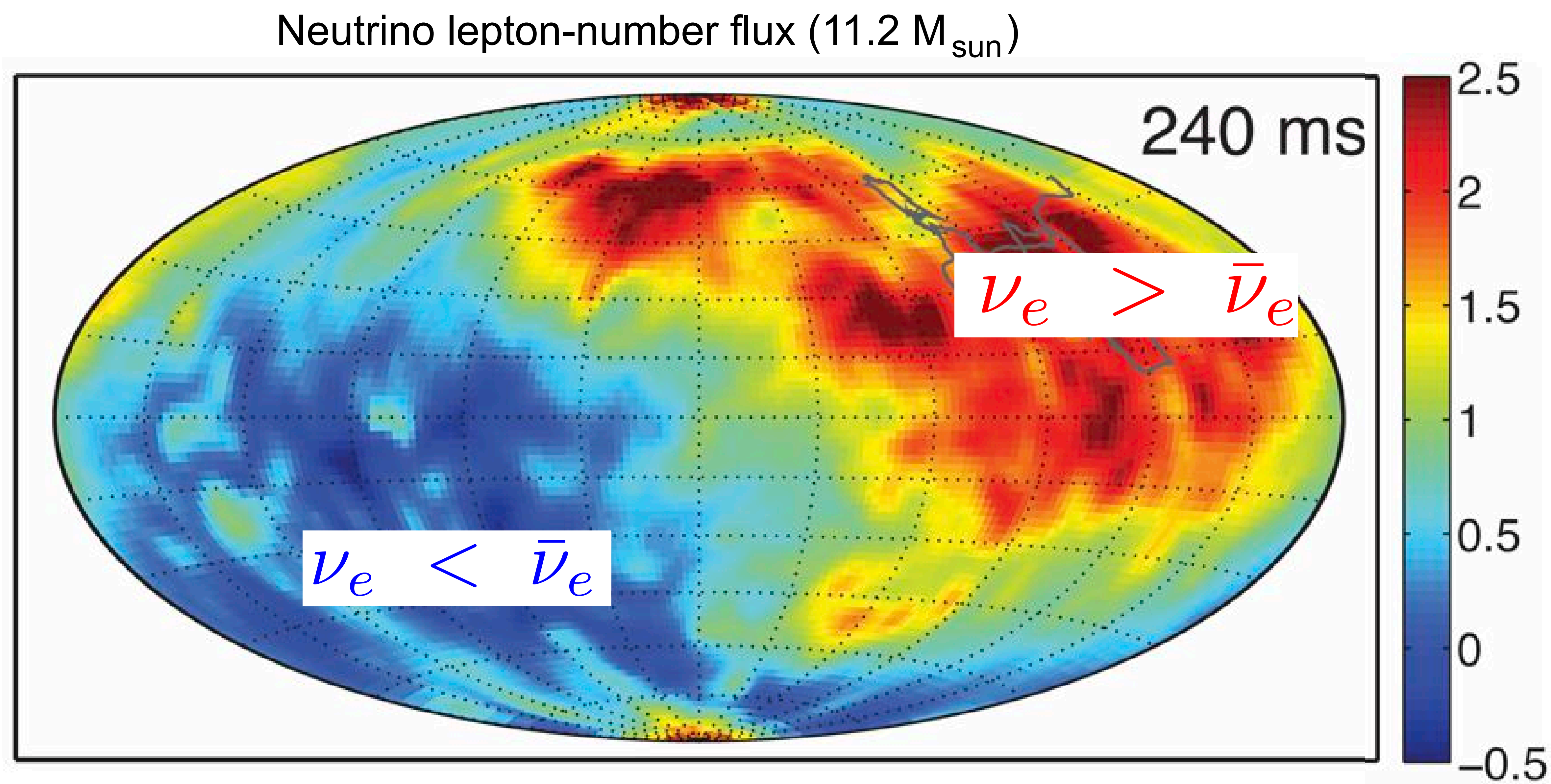
Neutrinos



Gravitational waves

Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017,2019). Walk, Tamborra et al., PRD (2018,2019).

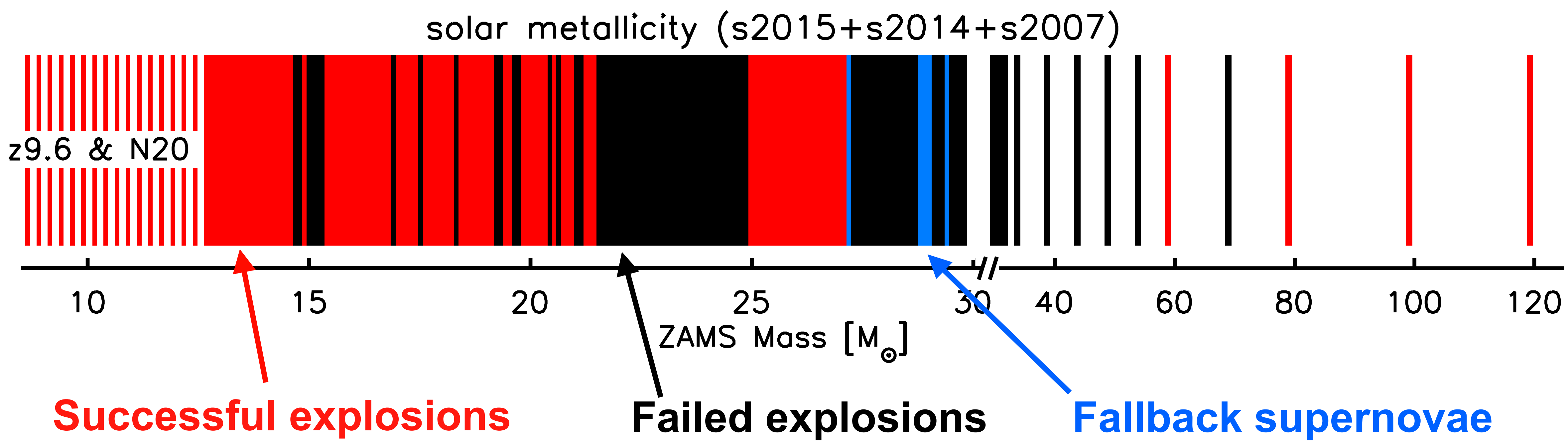
LESA: Neutrino-Driven Instability

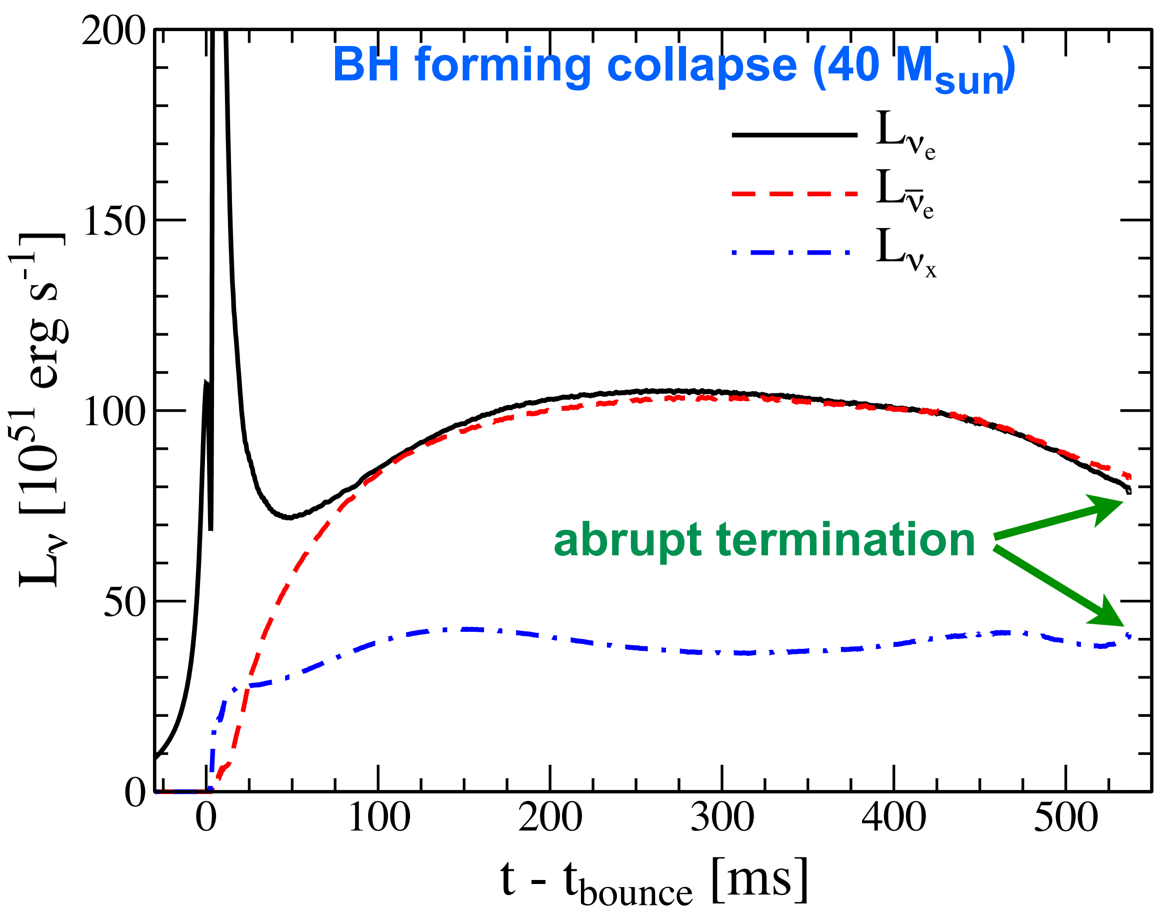


Lepton-number emission asymmetry (**LESA**): Large-scale feature with **dipole character**.

Tamborra et al., ApJ (2014). Janka et al., ARNPS (2016). Glas et al., (2018), Vartanyan et al., MNRAS (2019), O'Connor & Couch, ApJ (2018). Walk, Tamborra et al., PRD (2019). Walk, Tamborra et al., PRD (2020). …

Fingerprints of Black Hole Formation



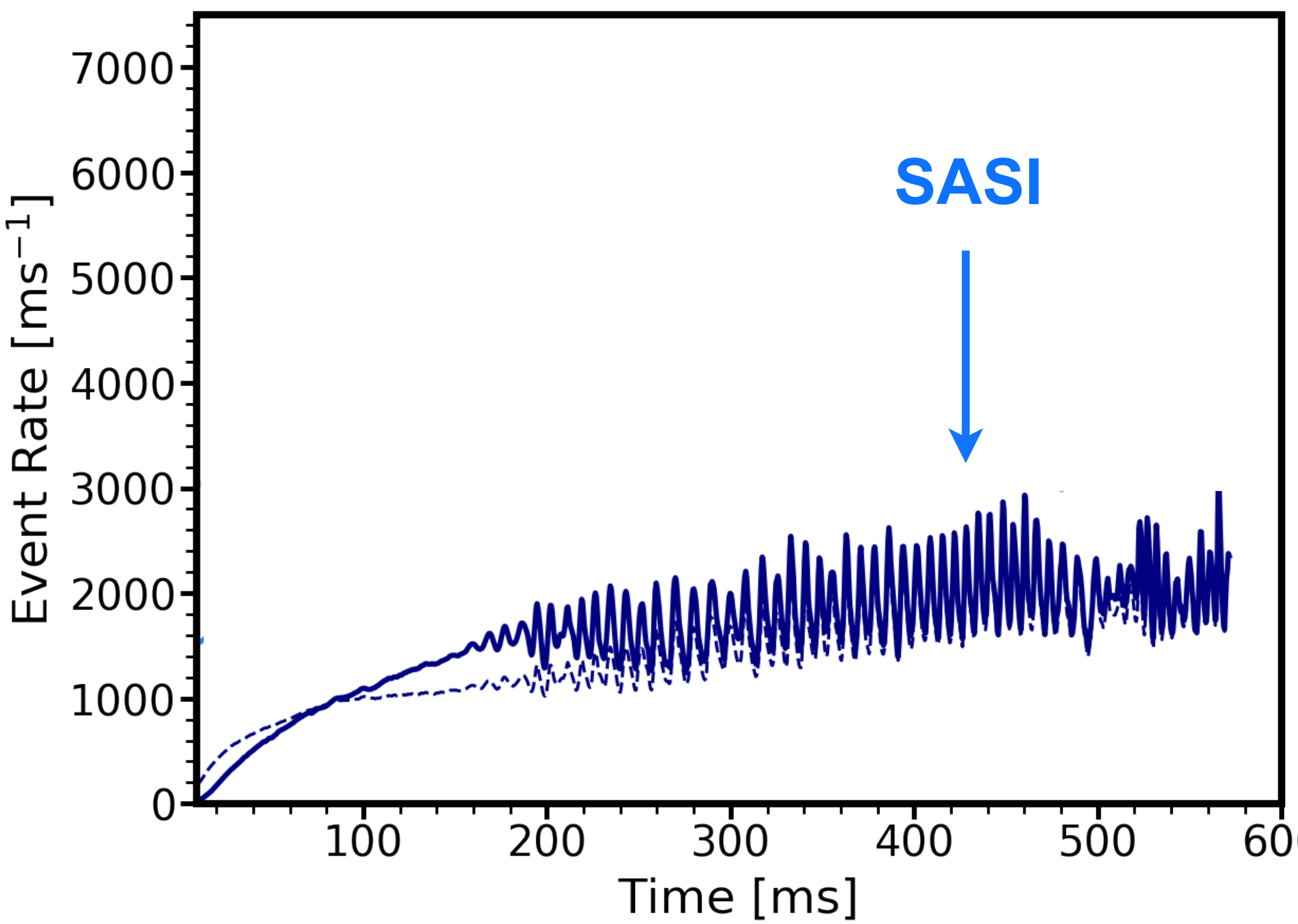


- Low mass supernovae can form black holes.
- Neutrinos reveal black hole formation.
- Black hole forming collapses up to 20-40% of total.

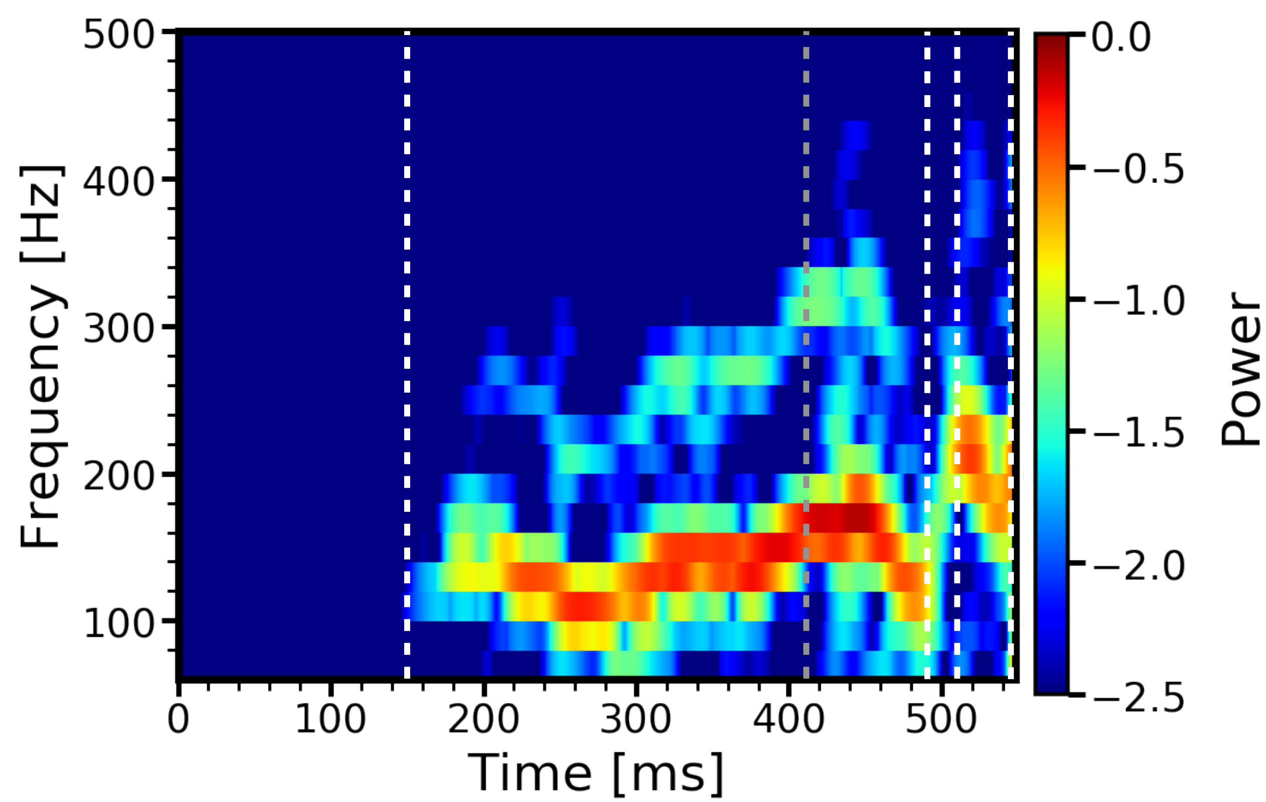
Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). Kuroda et al., MNRAS (2018). Adams et al., MNRAS (2017. Gerke, Kochanek & Stanek, MNRAS (2015). Basinger et al., arXiv: 2007.15658.

Fingerprints of Black Hole Formation

40 $M_\odot$ Model



Neutrinos (and gravitational waves) probe black hole formation.



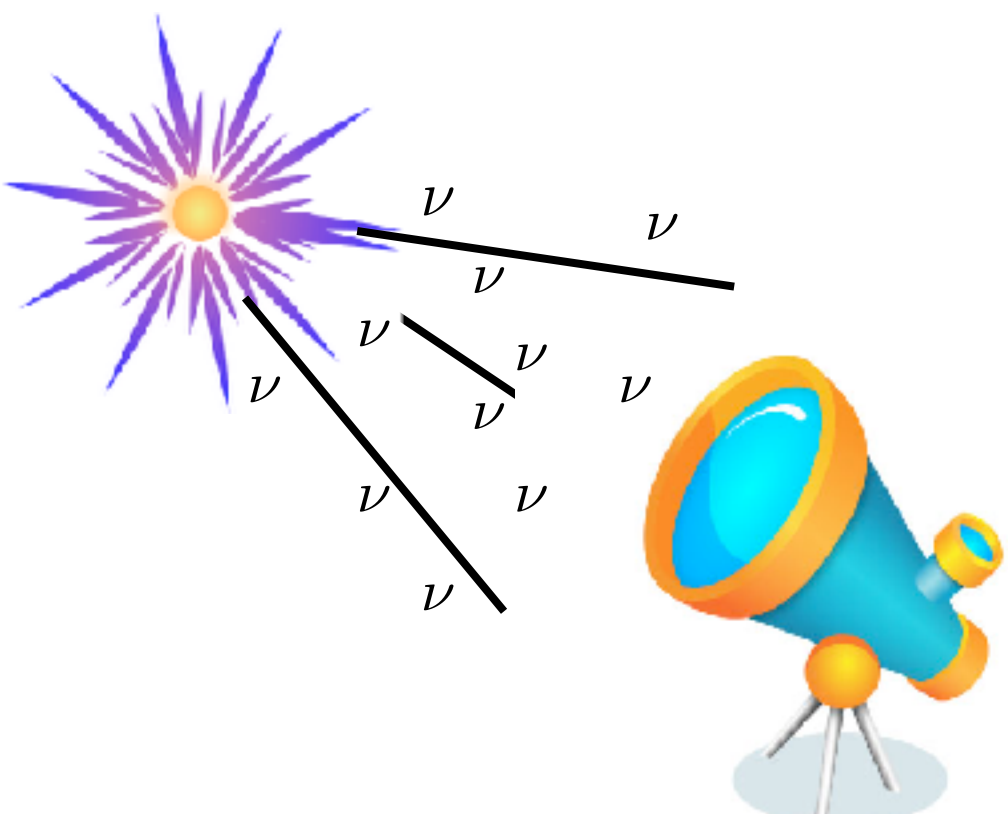
SASI frequency evolution
= Shock radius evolution

Walk, Tamborra, Janka, Summa, Kresse, PRD (2020).

Neutrino Alert

SuperNova Early Warning System (SNEWS 2.0).

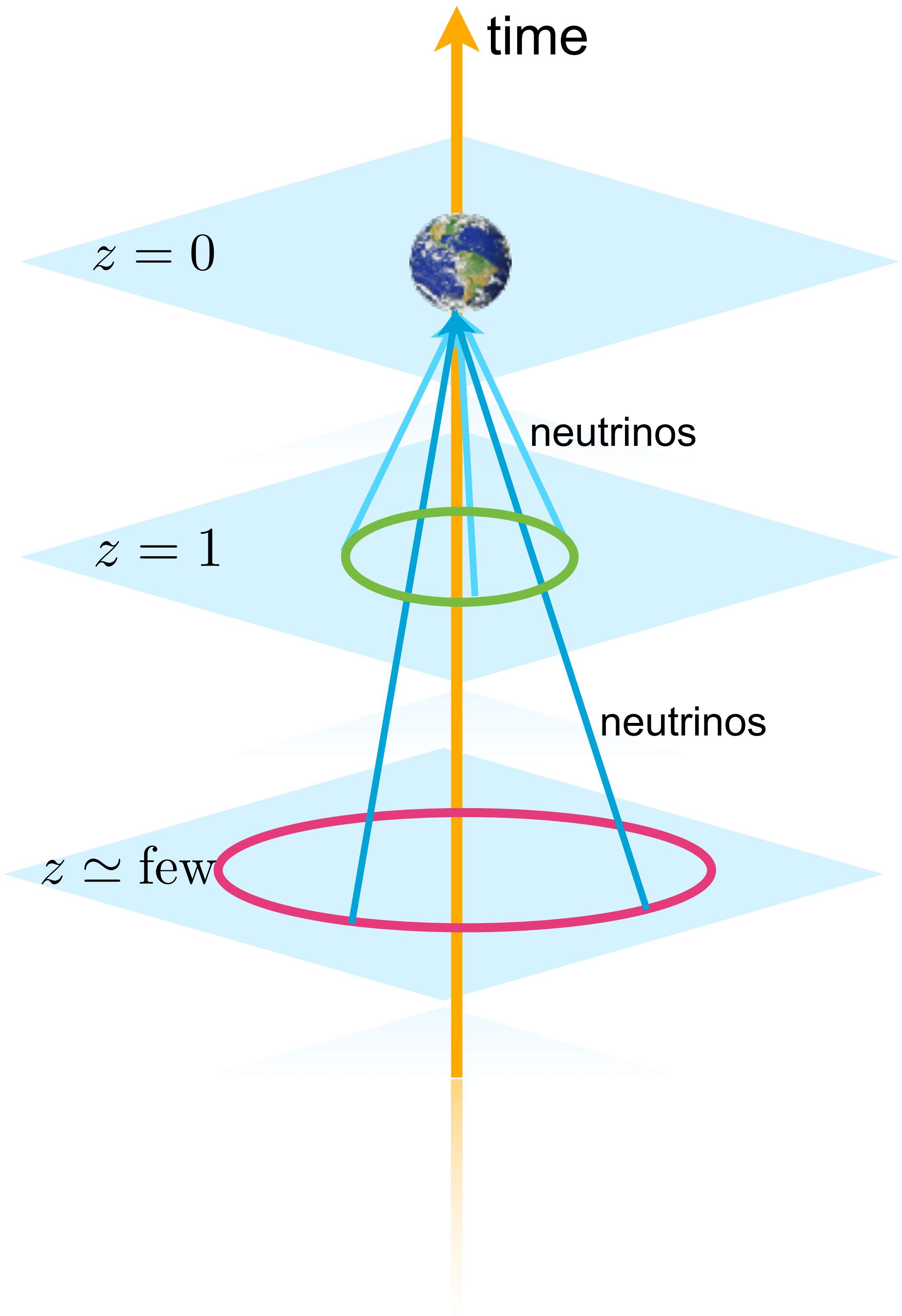
Network to alert astronomers of a burst.



Determination of **supernova direction** with neutrinos.

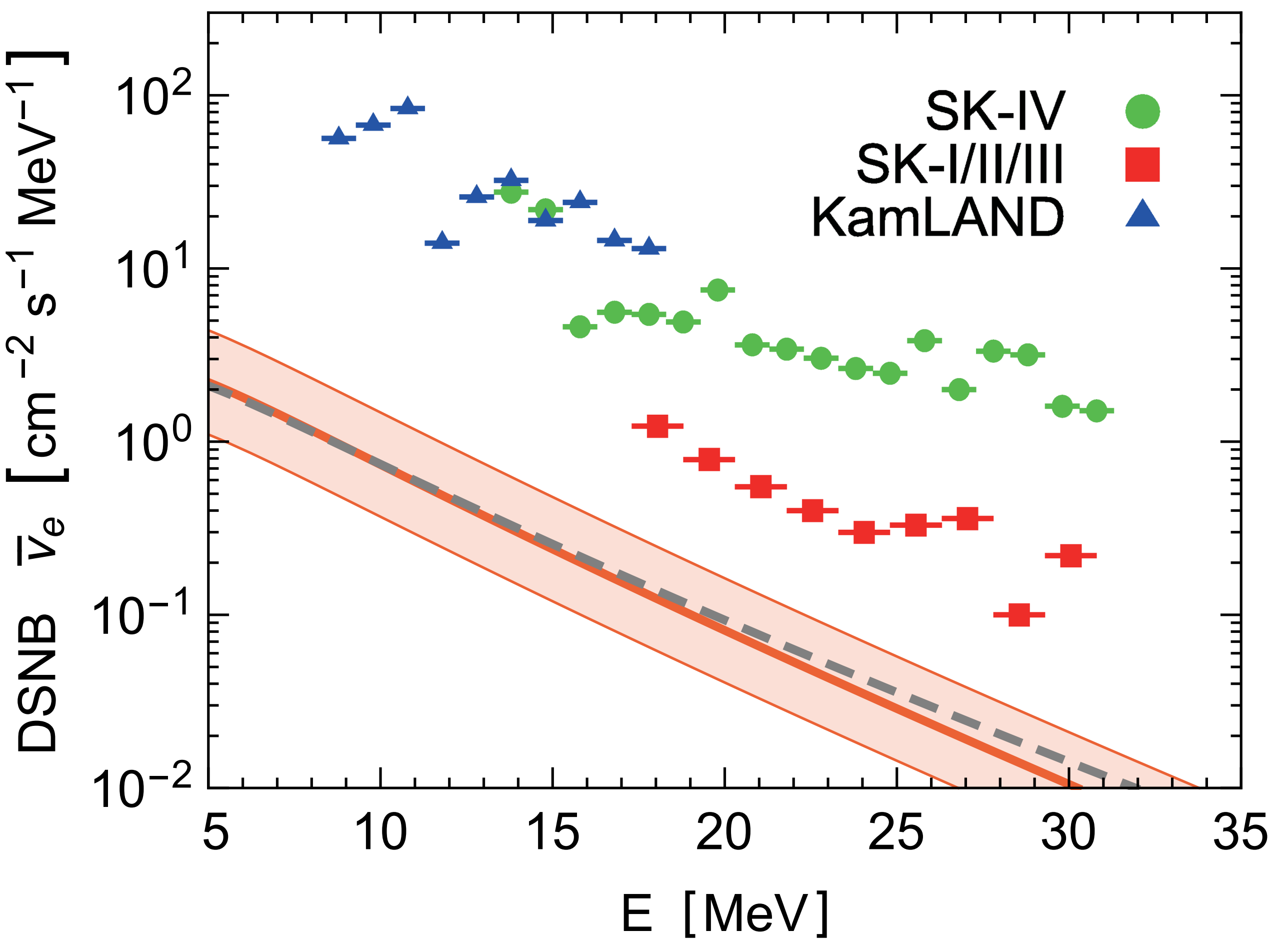
Crucial for electromagnetically dark or weak supernova.

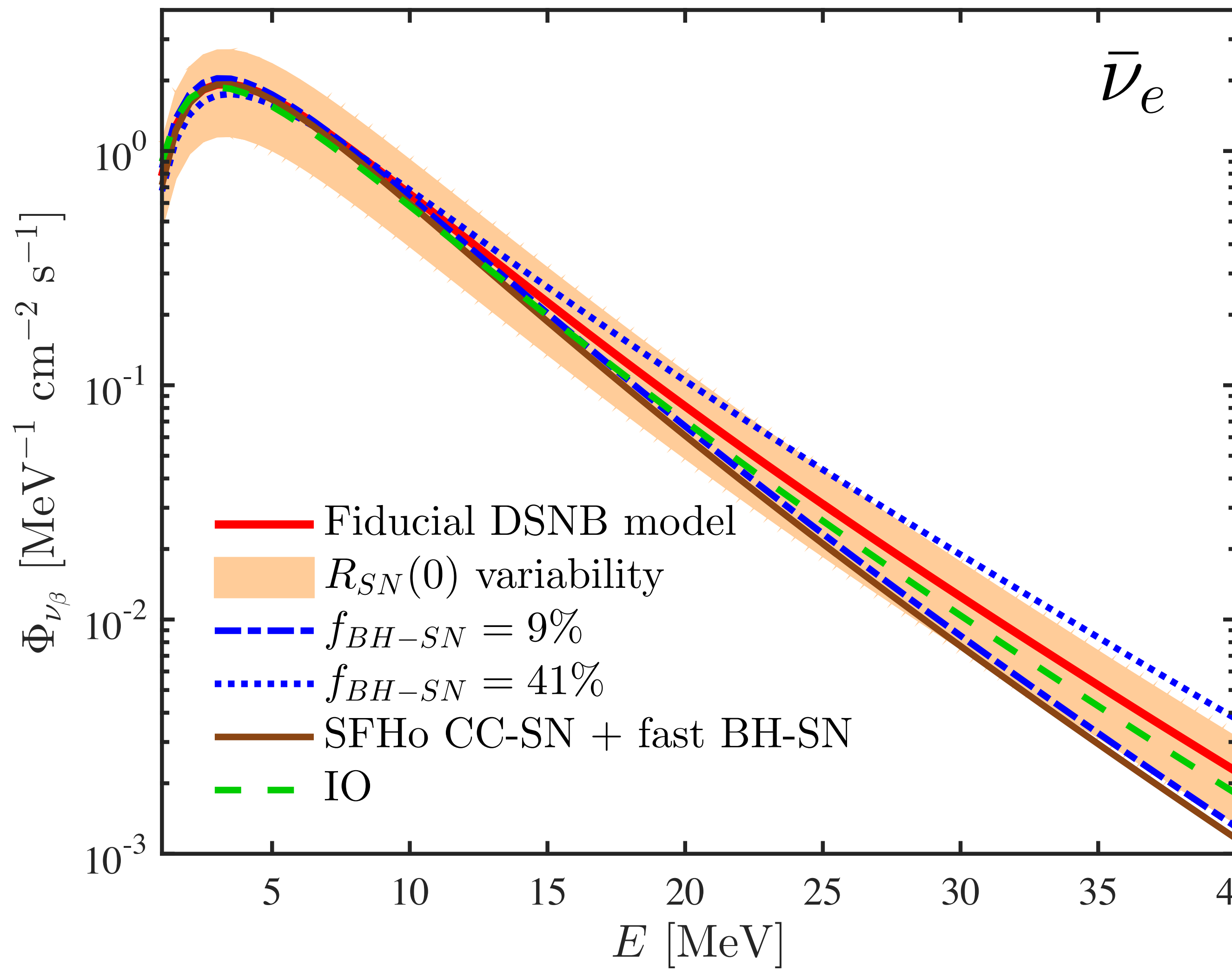
SNEWS 2.0, arXiv: 2011.00035. Beacom & Vogel (1999). Tomas et al. (2003). Fisher et al. (2015). Linzer & Scholberg, PRD (2019). Brdar, Lindner, Xu, JCAP (2018). Muehlbeier et al., PRD (2013).



Diffuse Supernova Neutrino Background

Fingerprints of Supernova Population



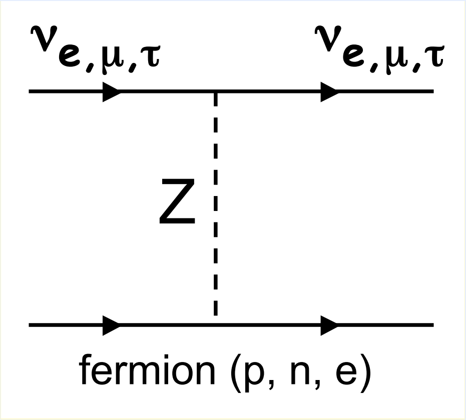


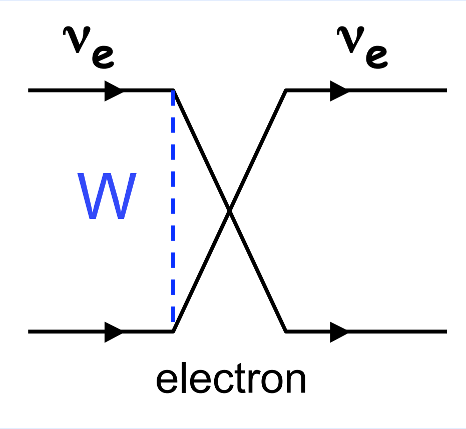
- This background is a **guaranteed** signal!
- DSNB detection will happen soon with, e.g., upcoming Super-K-Gd and JUNO.
- Independent test of the supernova rate (~30% precision).
- Constraints on fraction of black hole forming collapses.

Figures from Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020) & Moller, Suliga, Tamborra, Denton, JCAP (2018). Mirizzi, Tamborra et al. (2016). Lunardini (2010). Beacom (2010). Kresse, Ertl, Janka (2020). Nakazato et al., ApJ (2015). Horiouchi et al., MNRAS (2018). Lunardini & Tamborra, JCAP (2012).

Flavor Evolution

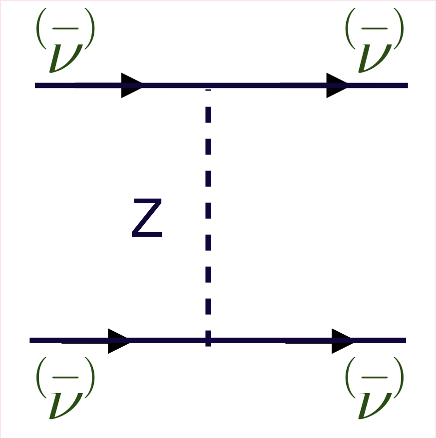
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

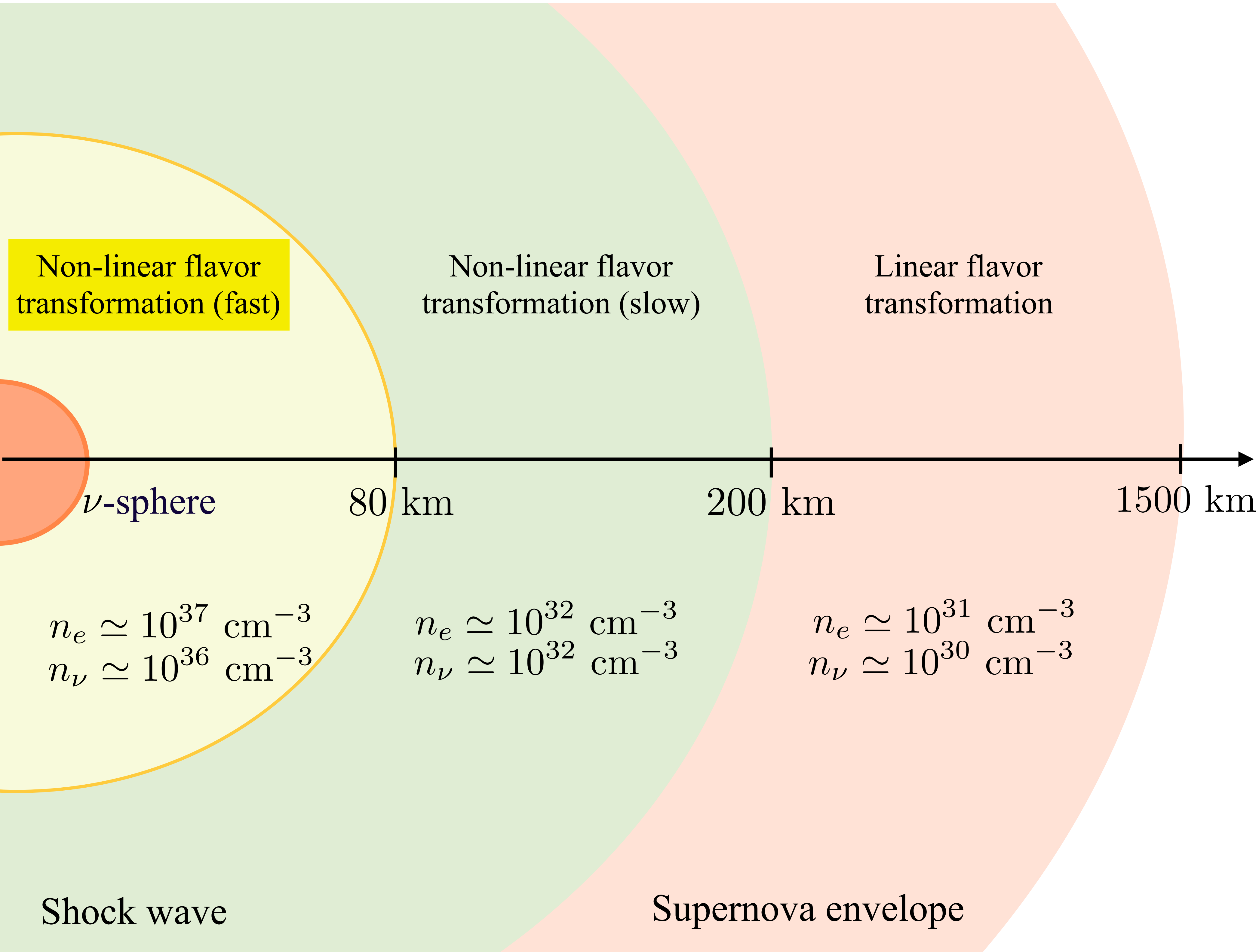


Neutrinos interact among themselves.

Non-linear phenomenon, trajectory is crucial!

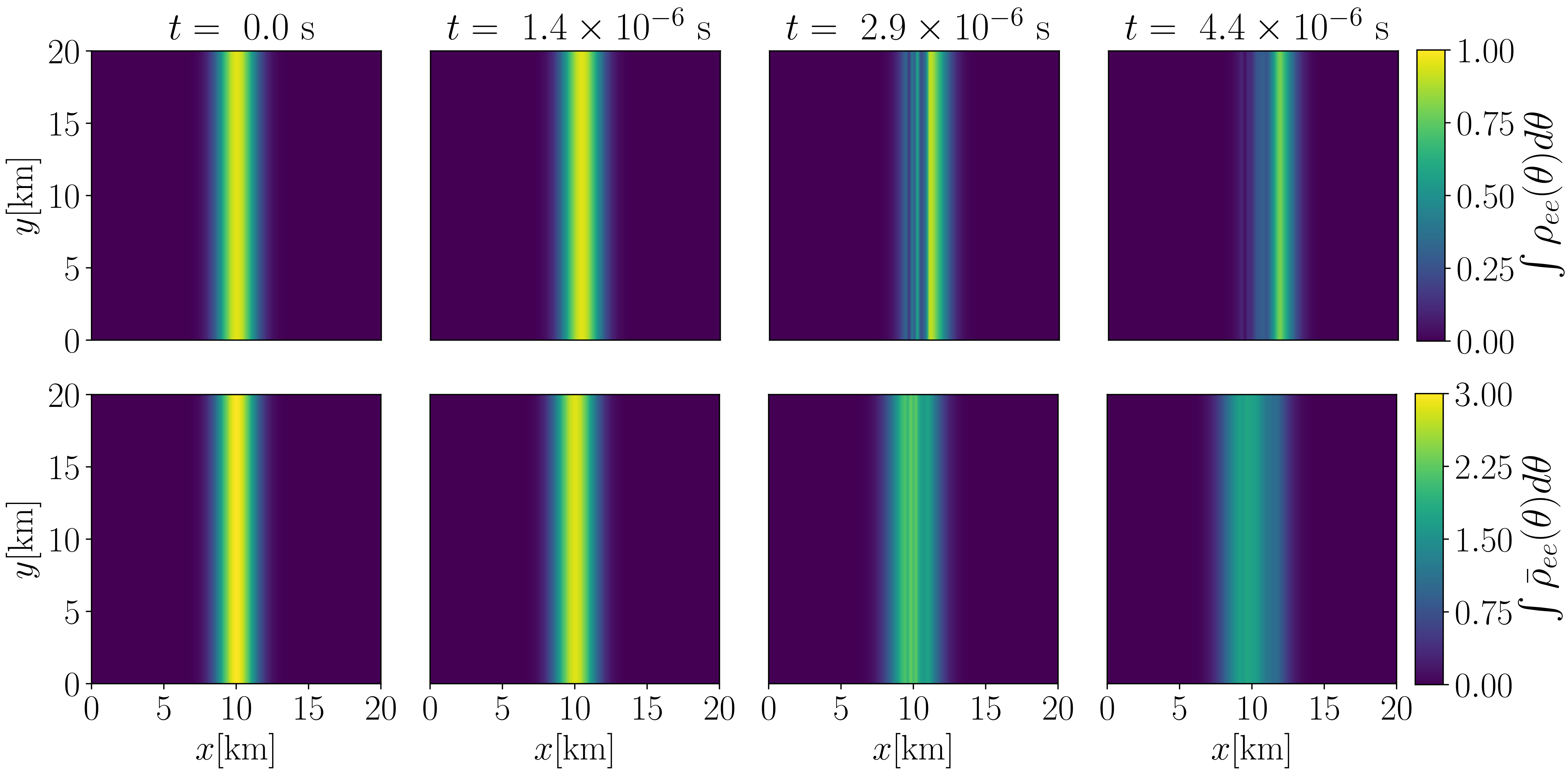
Recent review: Tamborra & Shalgar, Ann. Rev., arXiv: 2011.01948

Simplified Picture of Flavor Conversions



Recent review: Tamborra & Shalgar, Ann. Rev., arXiv: 2011.01948.

Flavor Conversions in Multi-D



- Flavor instabilities are damped by neutrino advection (not predicted by analytical methods!).
- **Further work needed!**

Shalgar, Padilla-Gay, Tamborra, JCAP (2020).

Compact Binary Mergers

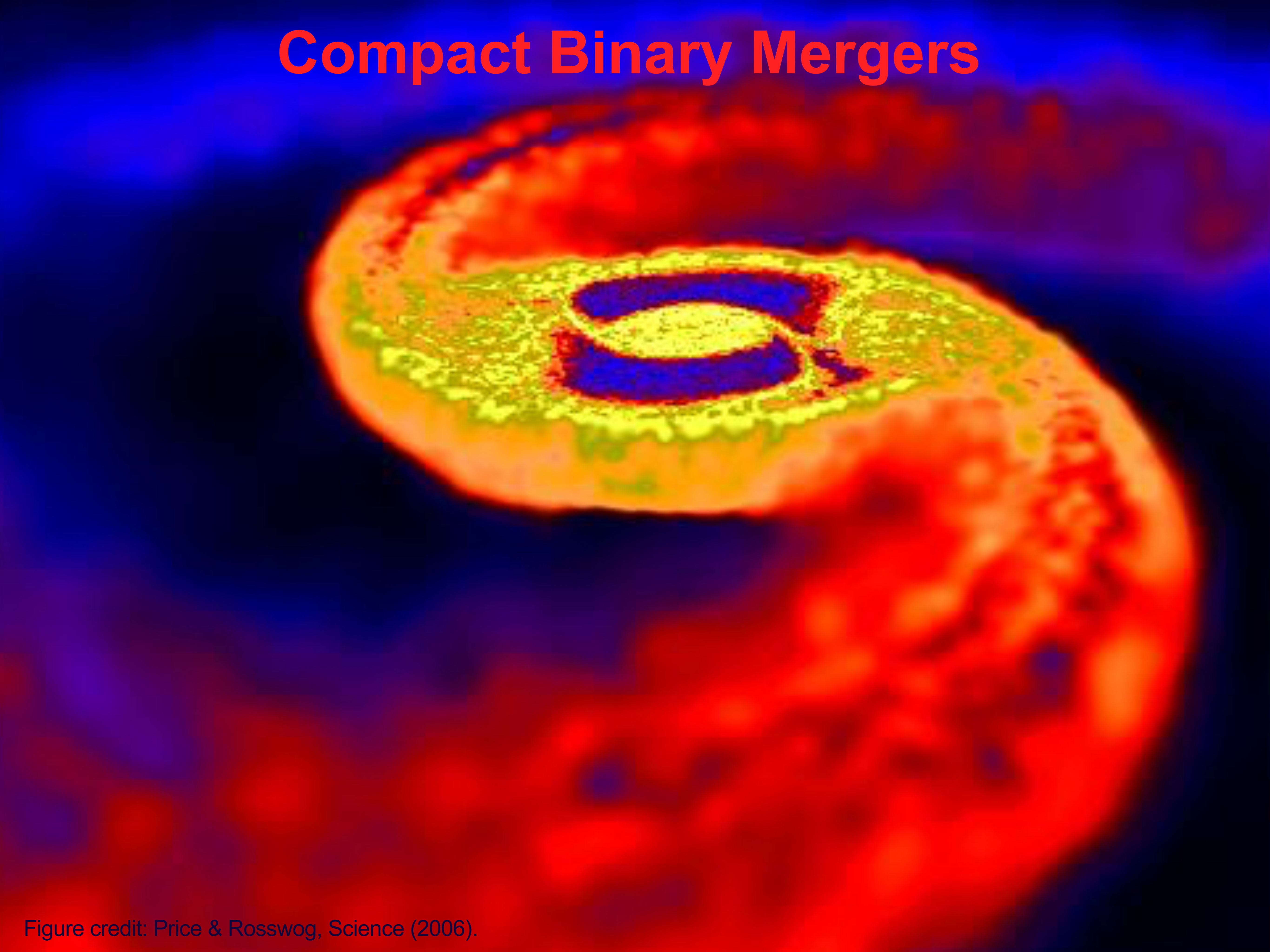
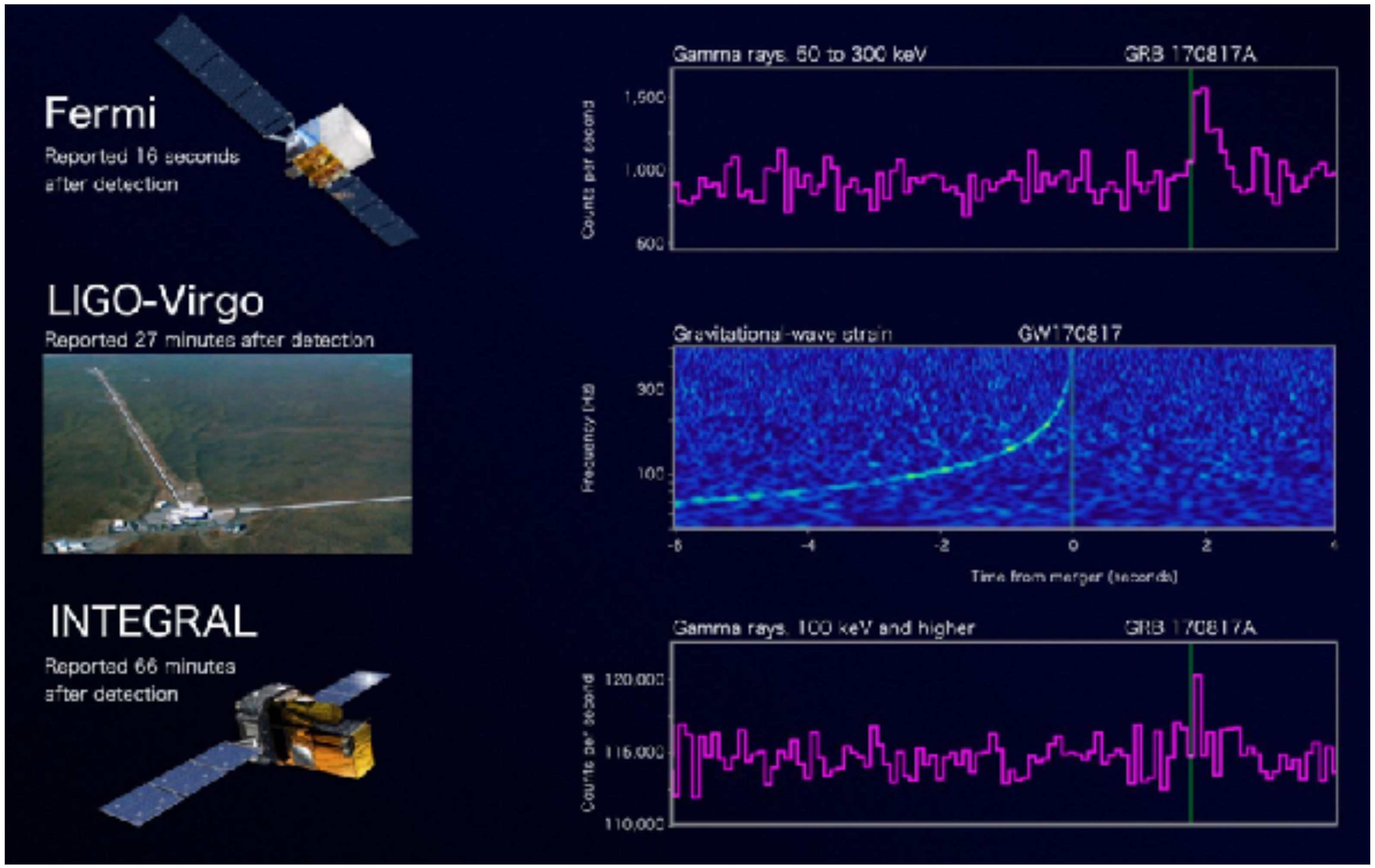
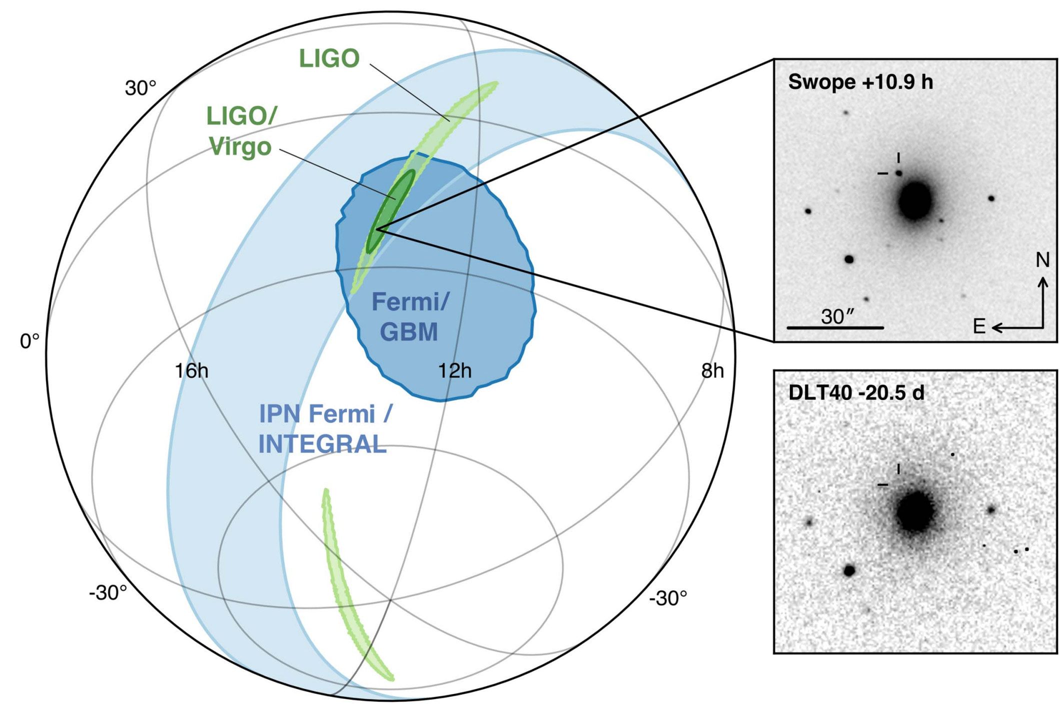


Figure credit: Price & Rosswog, Science (2006).

Fingerprints of Compact Binary Mergers

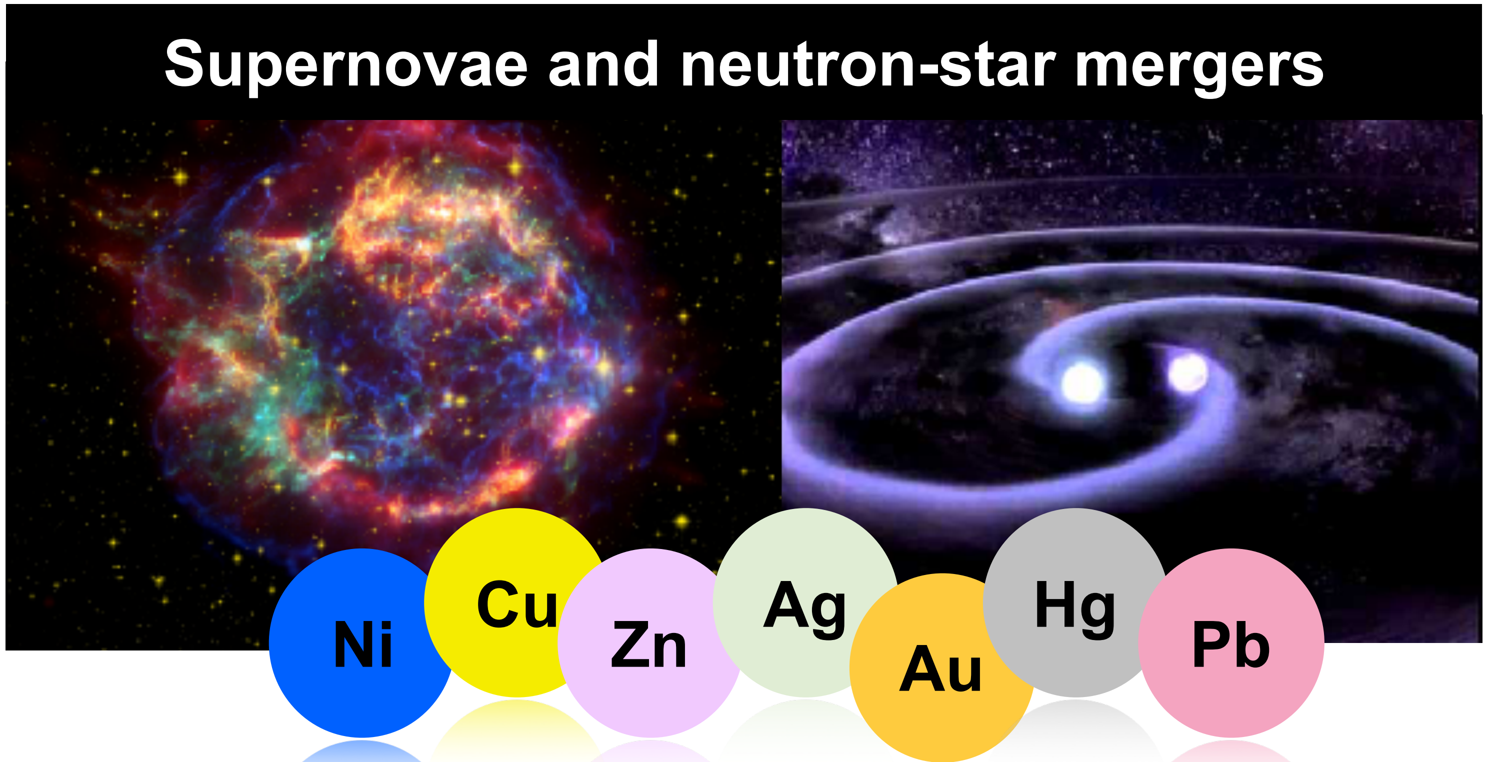




First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

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

Neutrino Fingerprints in Compact Mergers

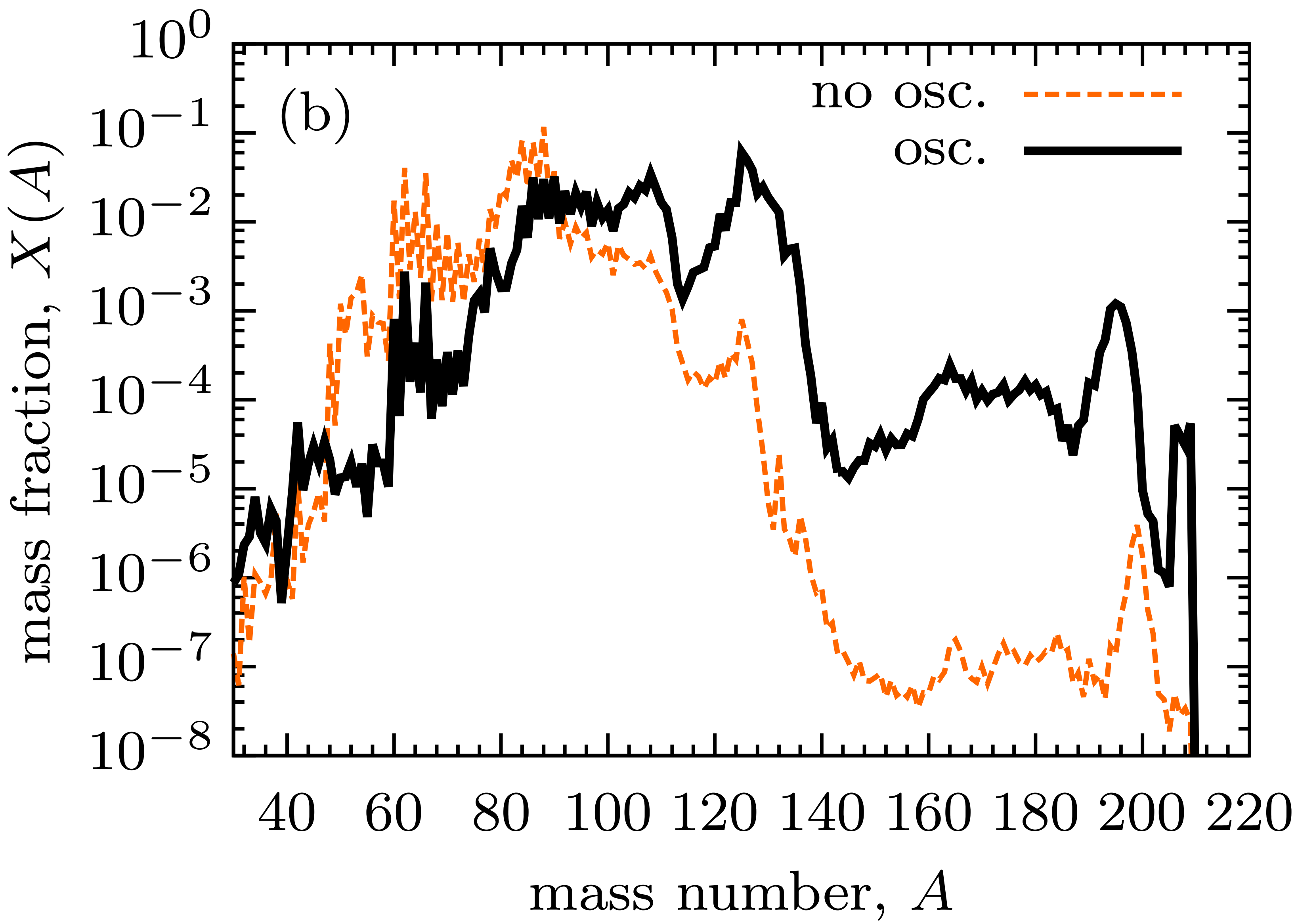


Synthesis of new elements could not happen without neutrinos.

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

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

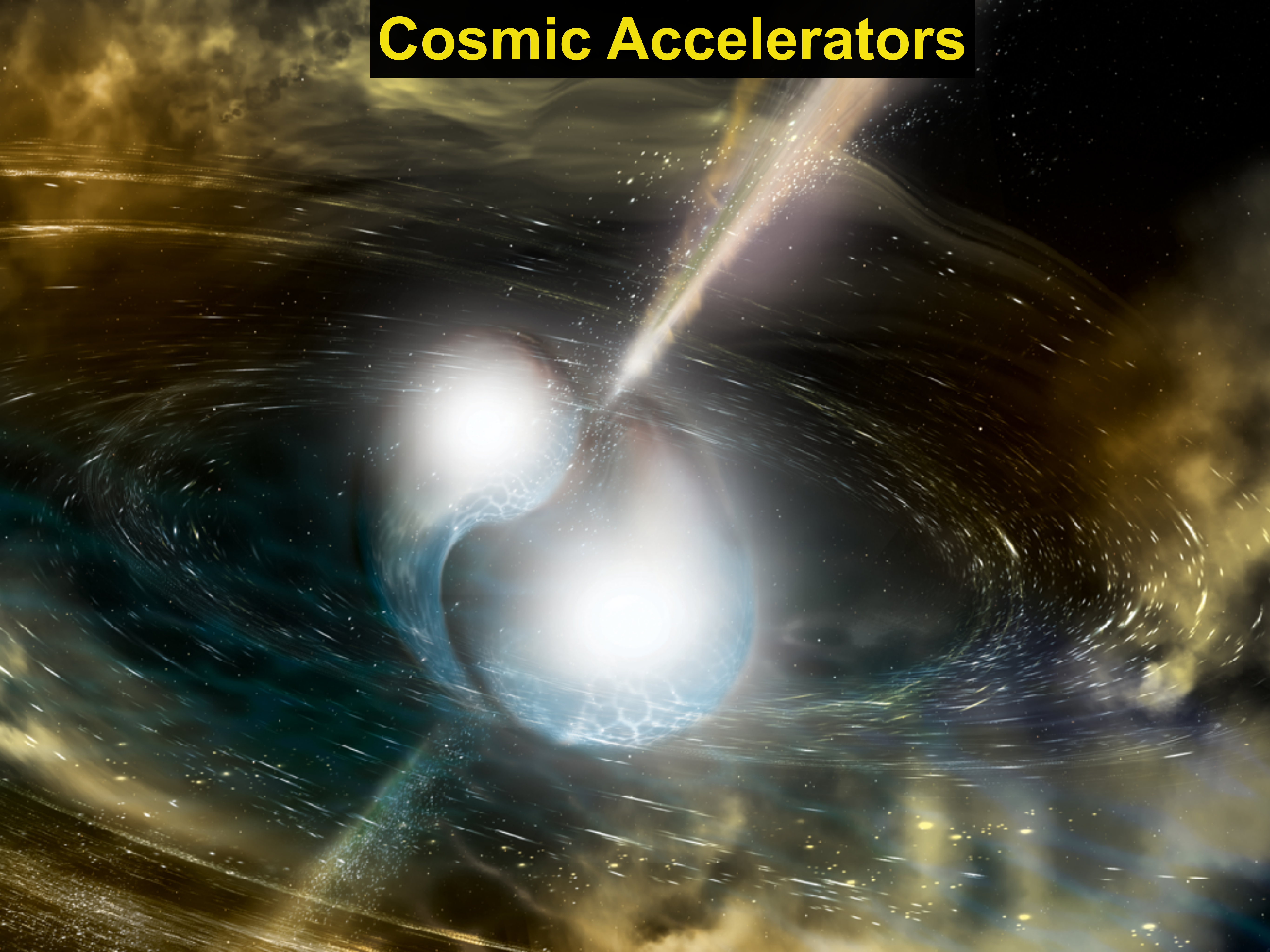
Neutrino Fingerprints in Compact Mergers



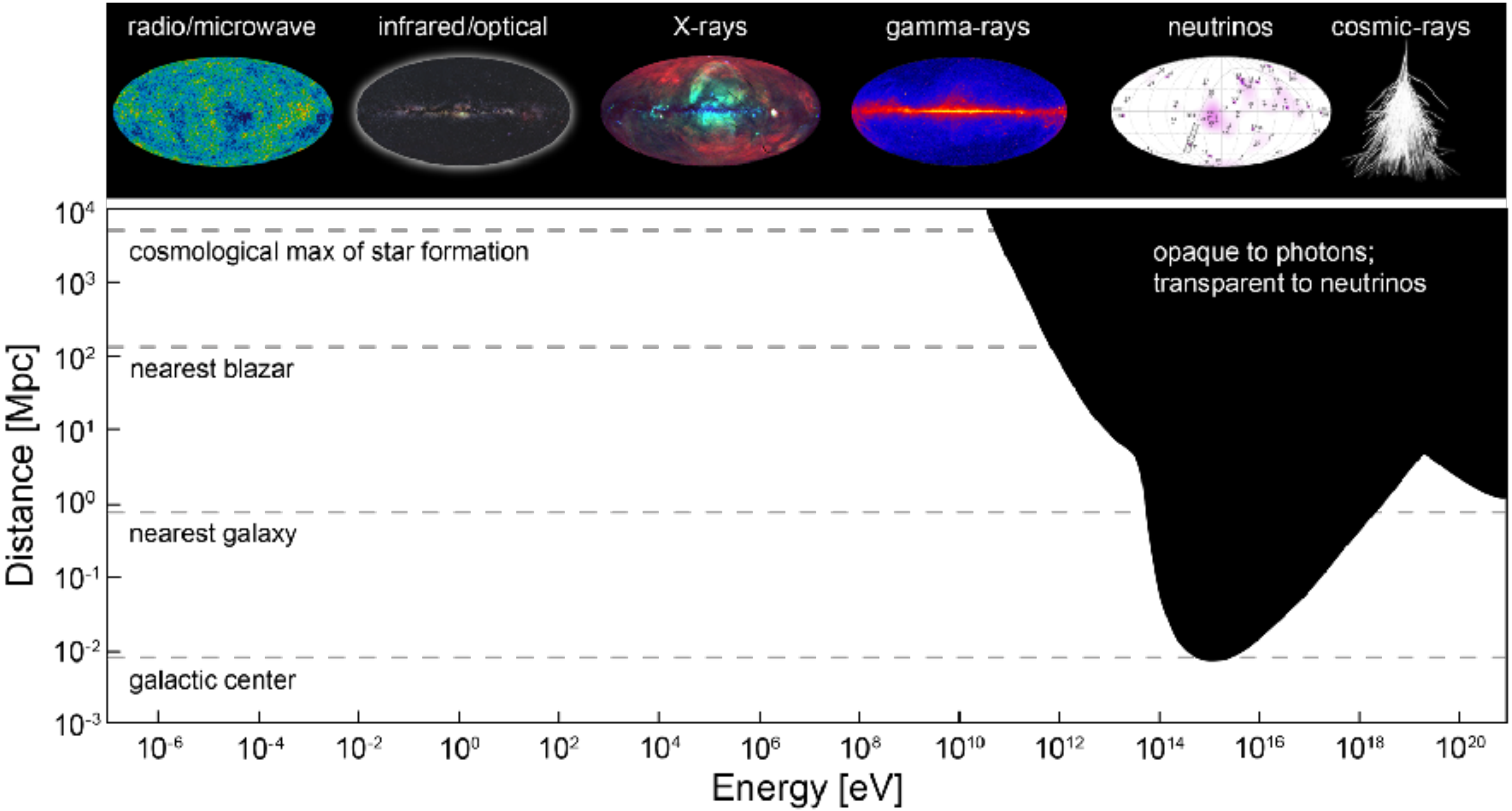
- Flavor conversions may lead to an enhancement of nuclei with A>130 (kilonova implications).
- More work needed to grasp how neutrinos affect electromagnetic emission.

Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). Padilla-Gay, Shalgar, Tamborra, JCAP (2020, in press). George, Wu, Tamborra, Ardevol-Pulpillo, Janka, PRD (2020).

Cosmic Accelerators



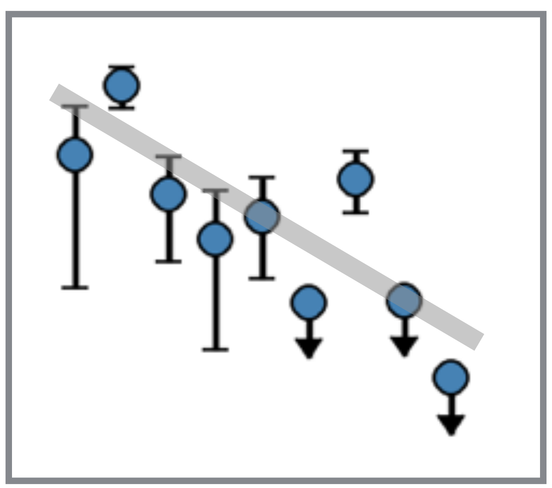
High Energy Neutrino Astronomy

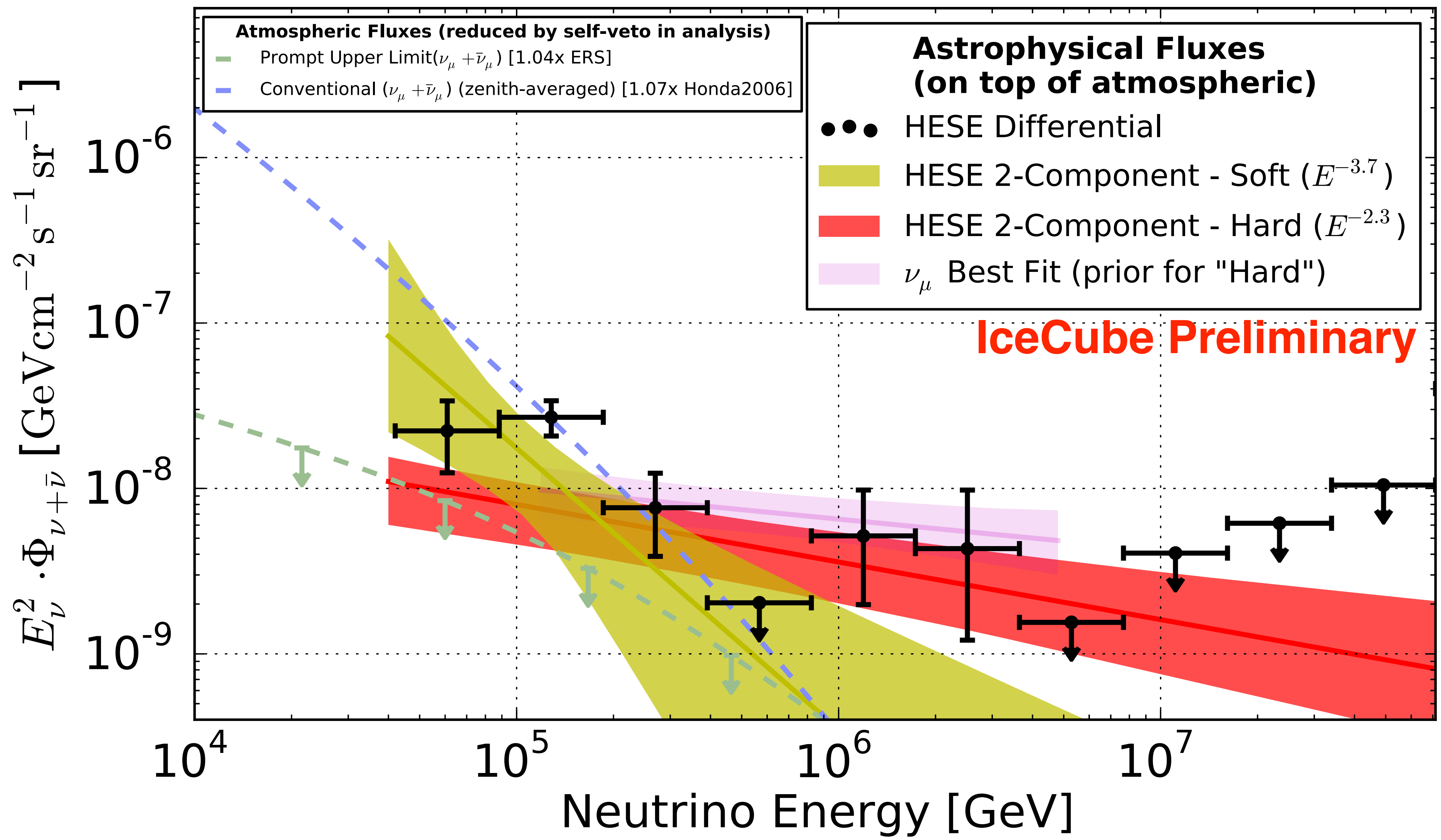


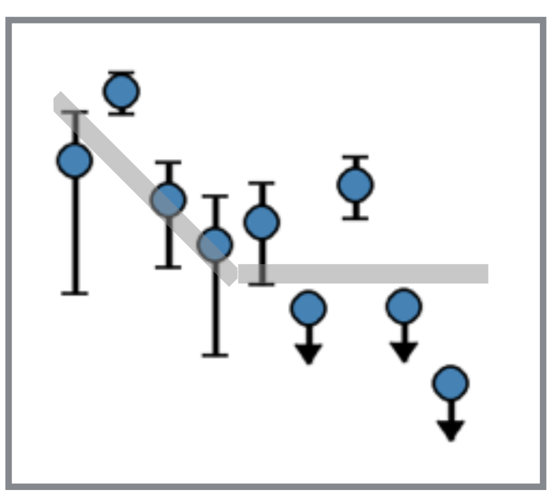
- 20% of the Universe is opaque to electromagnetic radiation.
- Non-thermal Universe powered by cosmic accelerators.

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

Measured Astrophysical Neutrino Flux



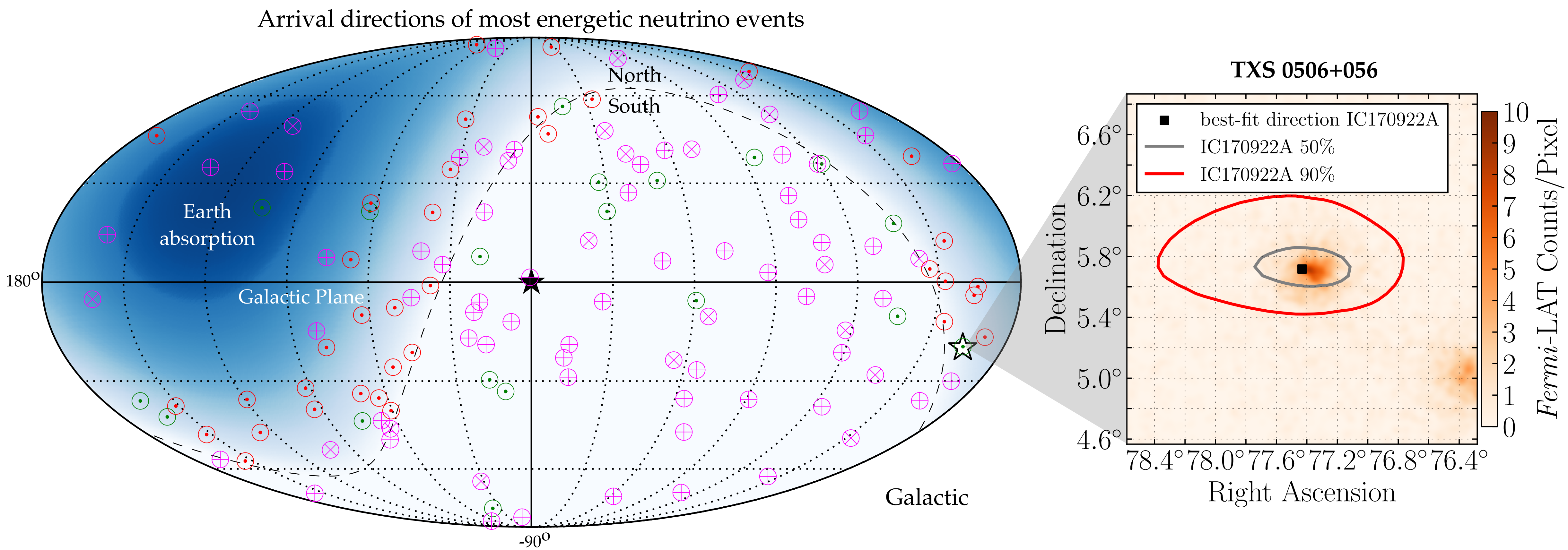




Are we seeing a spectral flattening of energy spectrum?

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

Measured Astrophysical Neutrino Flux



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

Neutrinos of extragalactic origin.

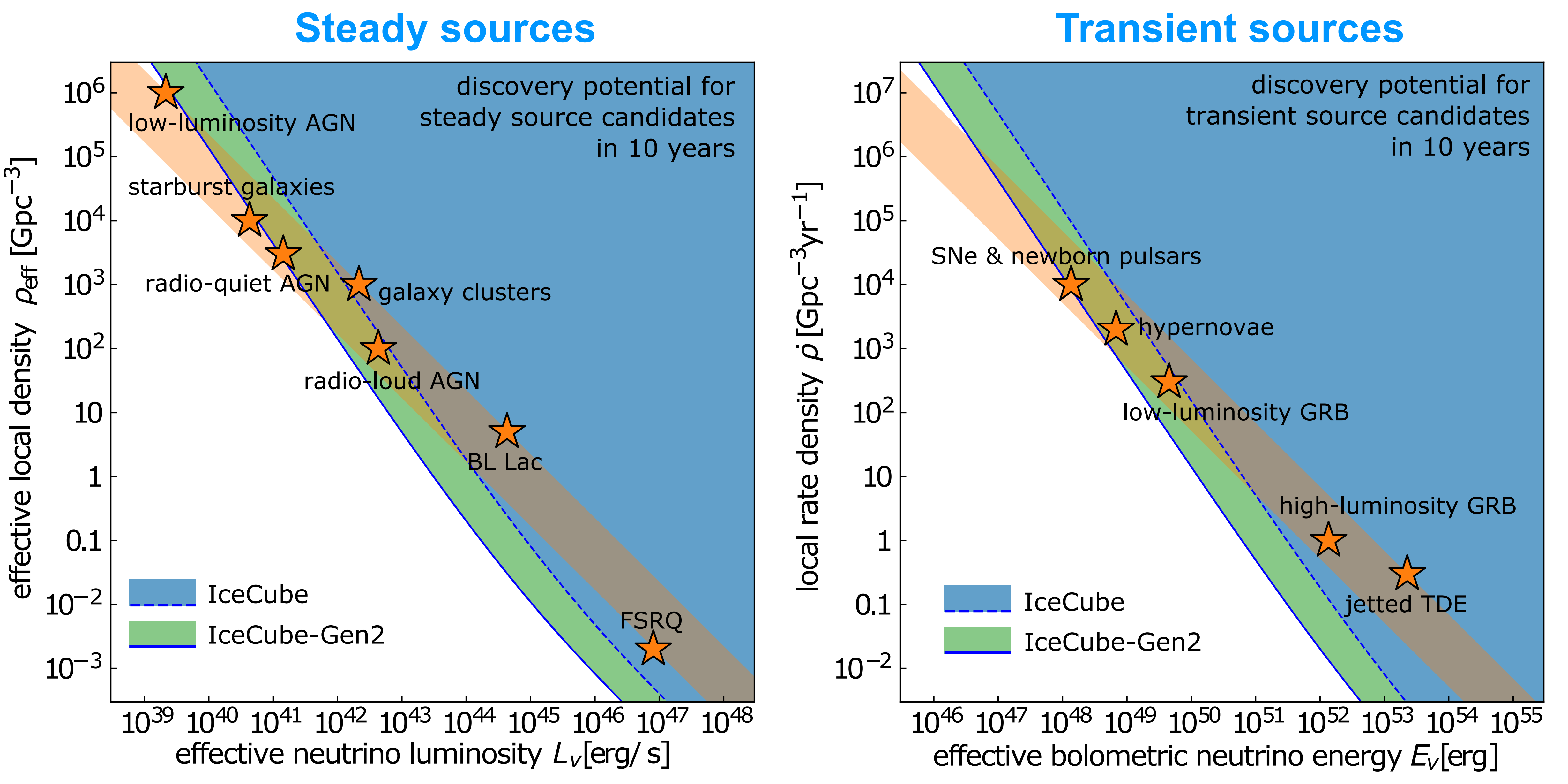
Figure taken from Aartsen et al., arXiv: 2008.04323.

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.

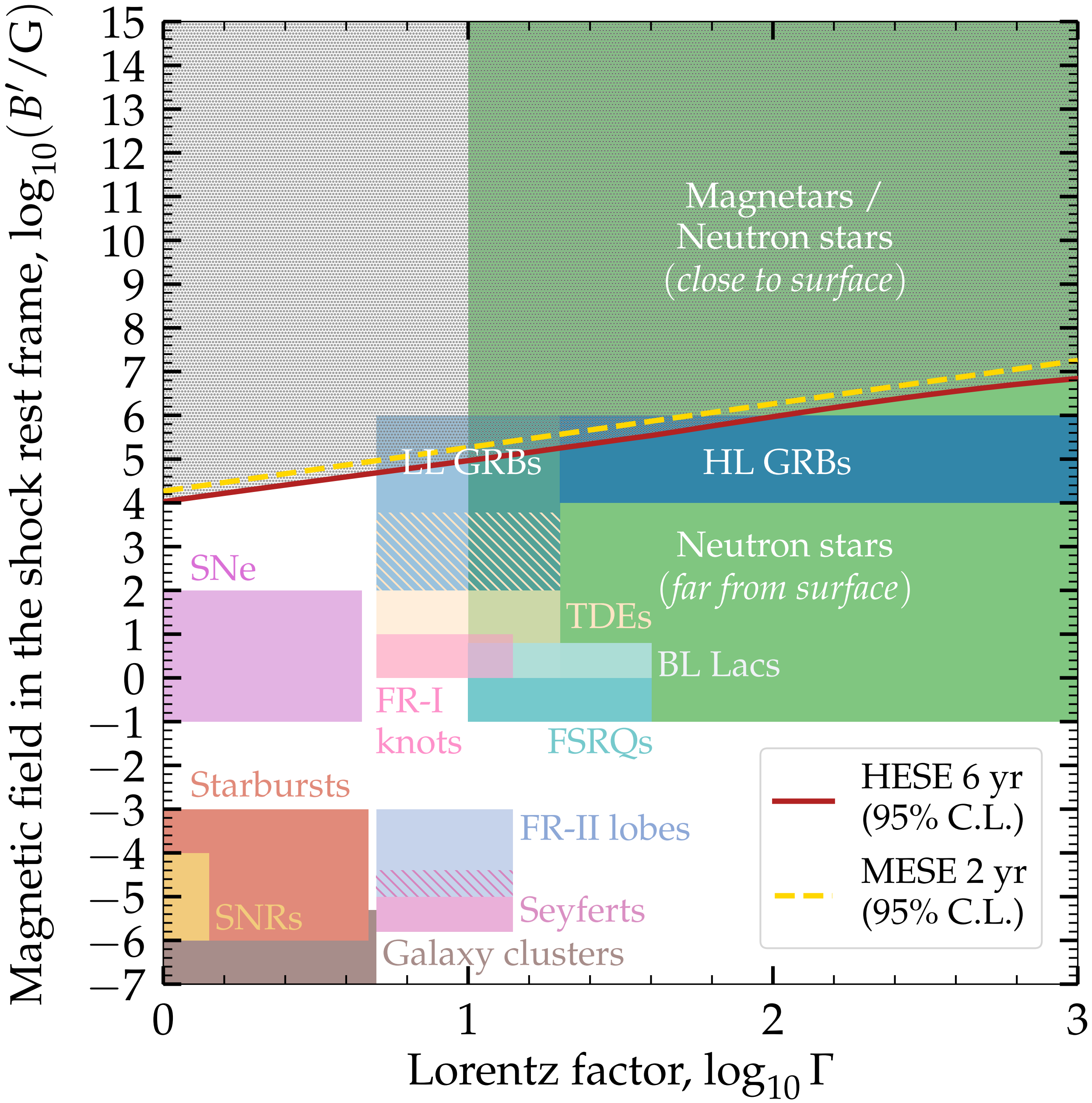
Anchordoqui et al., JHEAp (2014). Meszaros, arXiv: 1511.01396. Waxman, arXiv: 1511.00815. Murase, arXiv: 1511.01590.

Where Are These Neutrinos Coming From?



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

Fingerprints of Source Properties



IceCube data can already constrain:

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

Bustamante & Tamborra, PRD (2020). Denton & Tamborra, ApJ (2018). Denton & Tamborra, JCAP (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).

Non-Standard Physics

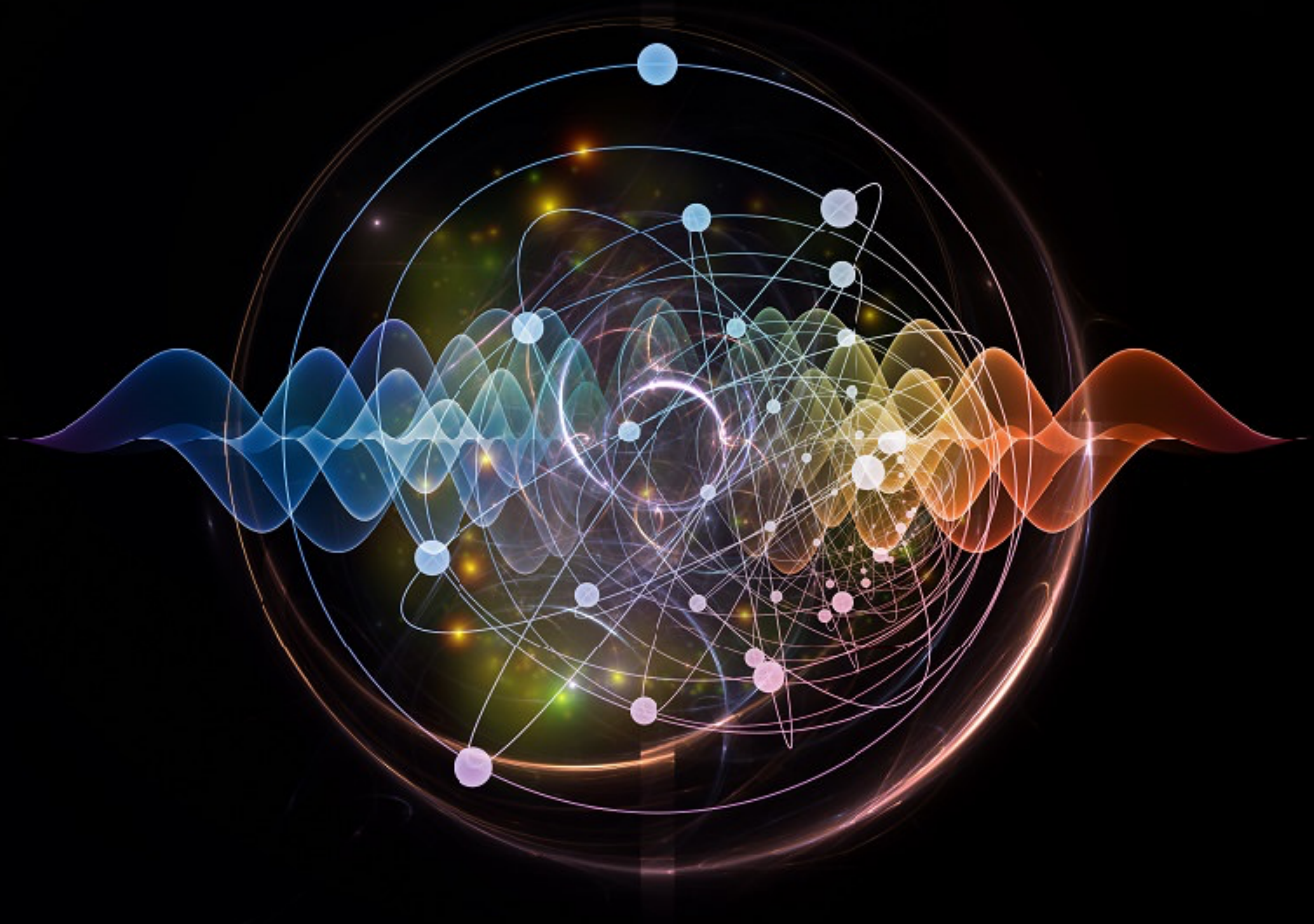


Figure credits: Tech Explorist

A Laboratory for Particle Physics

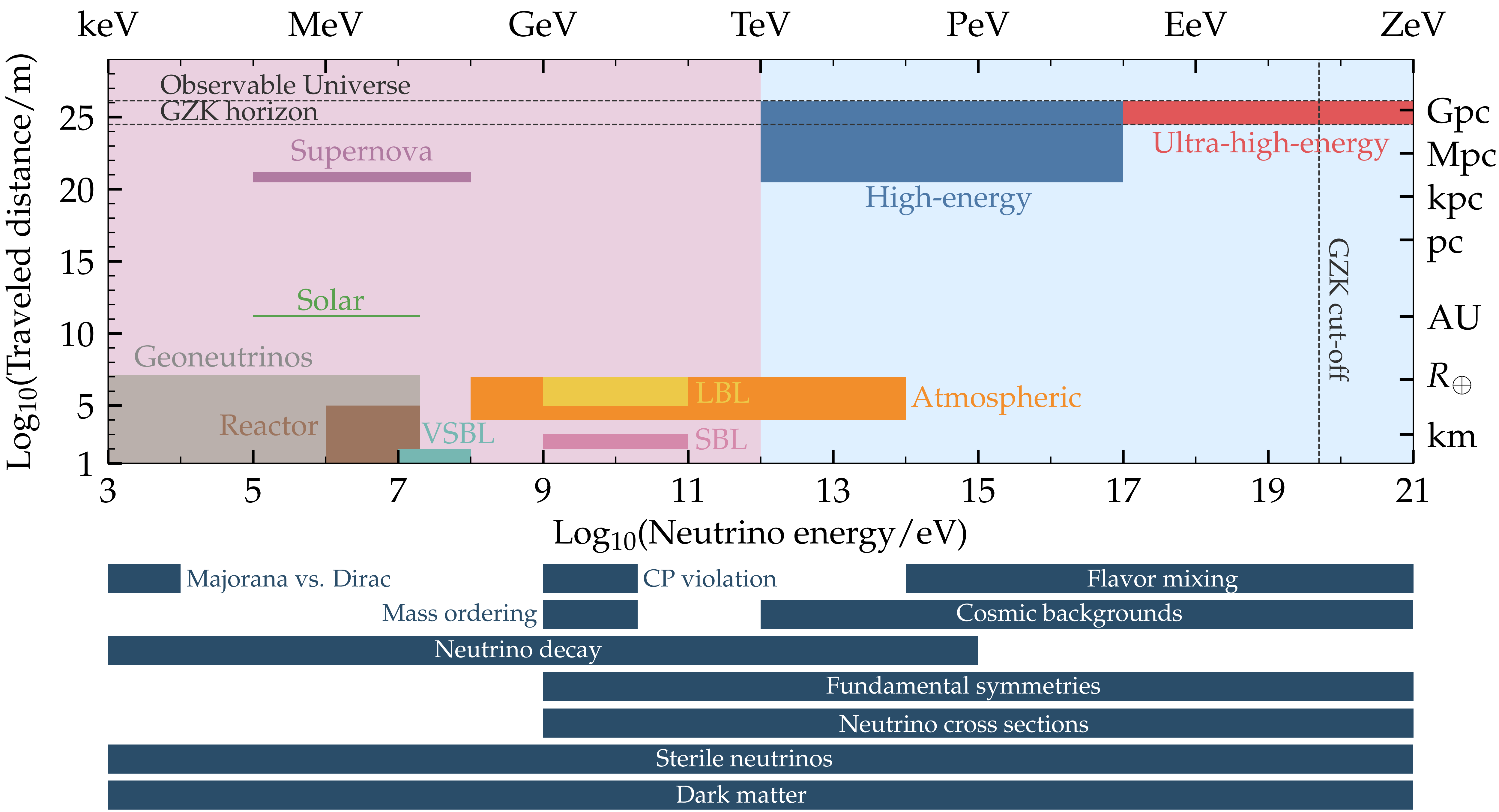
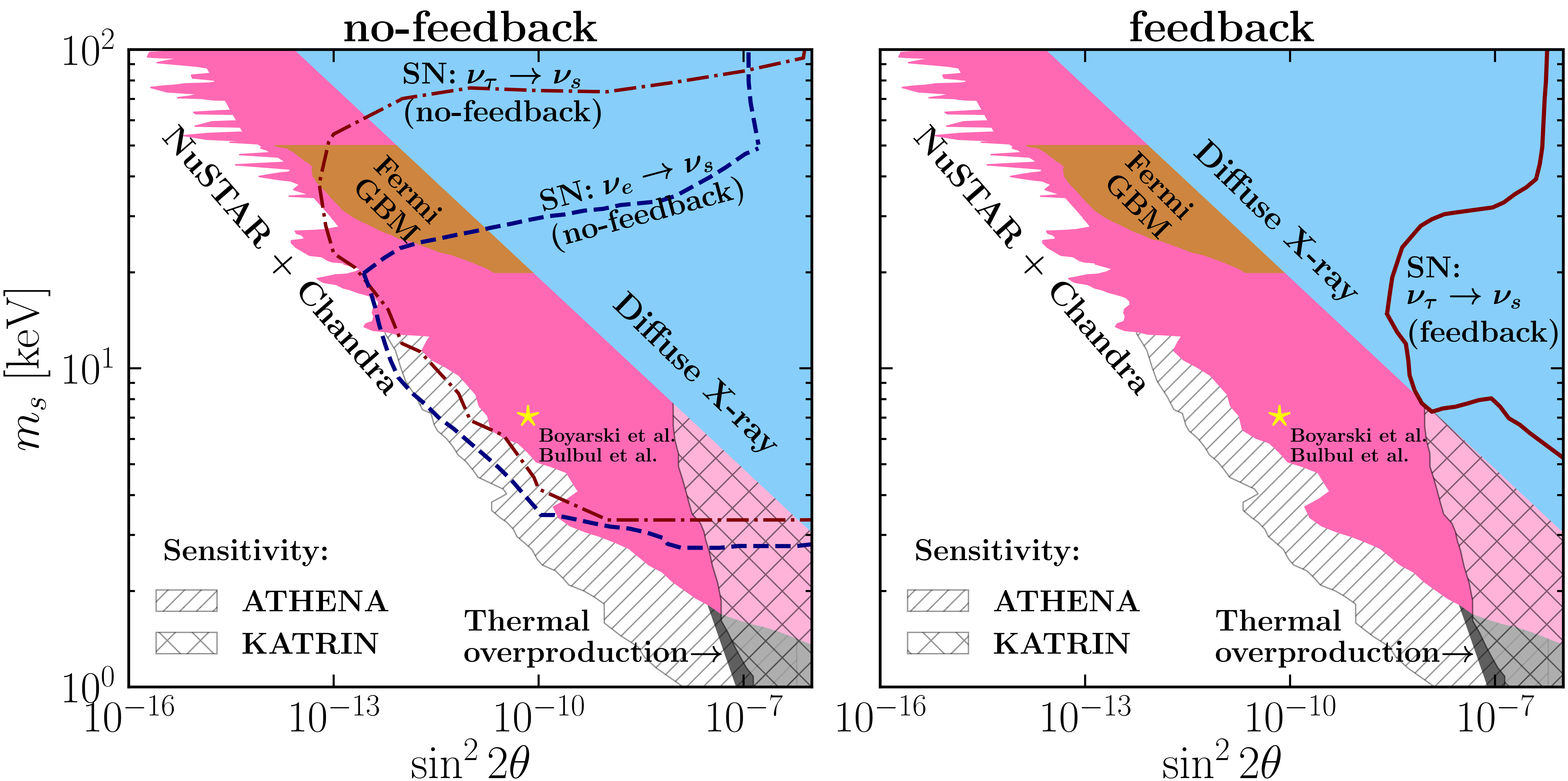


Figure taken from Ackermann et al., arXiv: 1903.04333.

KeV Mass Sterile Neutrinos



Robust bounds on the sterile neutrinos must be derived through a self-consistent and time-dependent estimation of the particle production and propagation.

Suliga, Tamborra, Wu, JCAP (2019). Suliga, Tamborra, Wu JCAP (2020).

New Kinds of Neutrino “Telescopes”

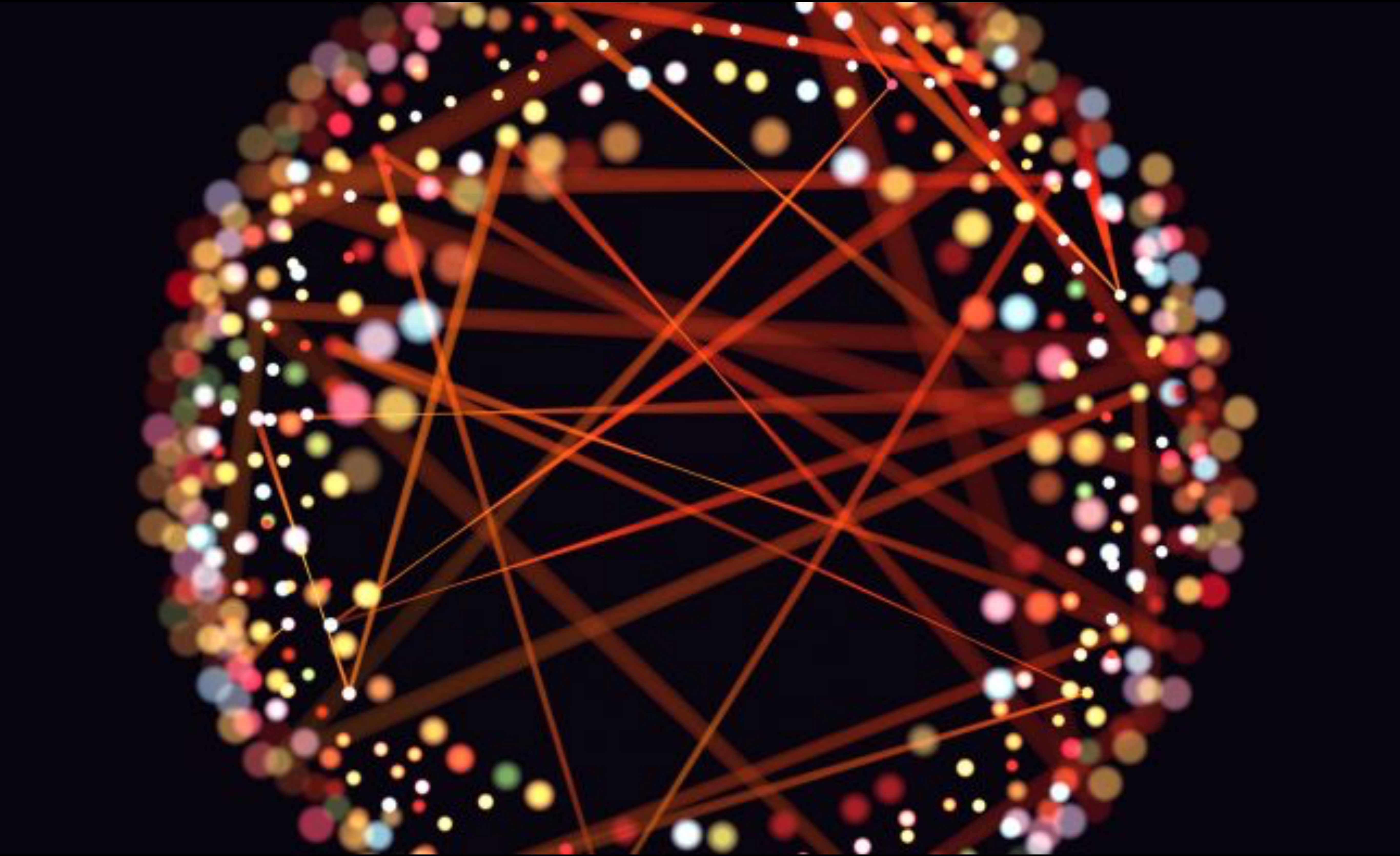
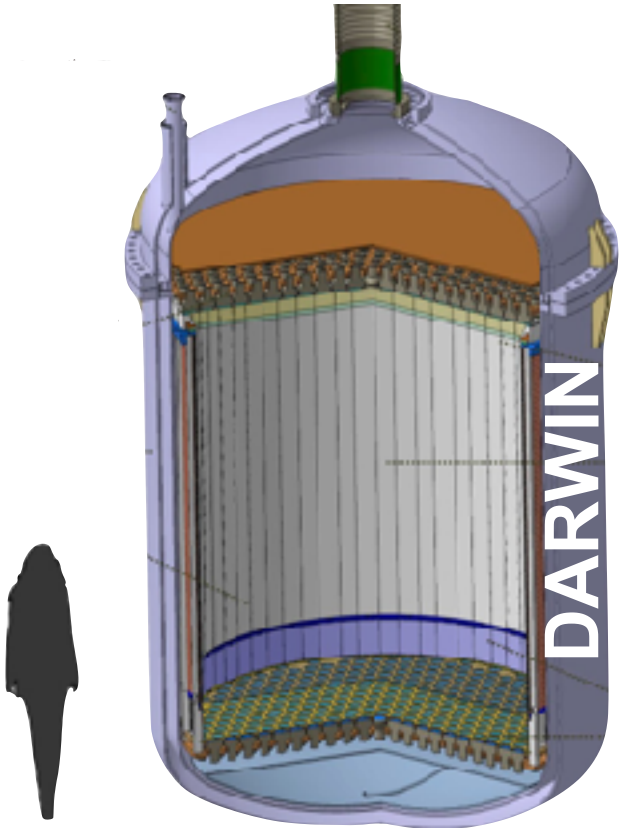


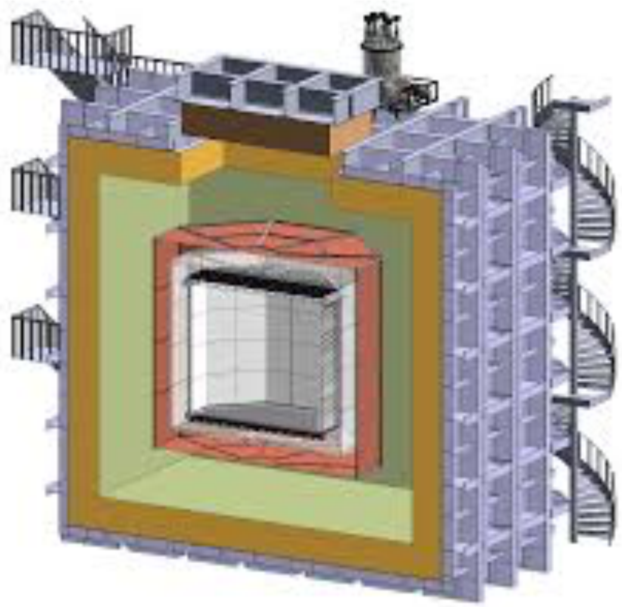
Figure credits: Matjaz Slanic

Low Energy Neutrino Frontier

Neutrino Telescopes Based on Coherent Scattering



DarkSide-20k & ARGO



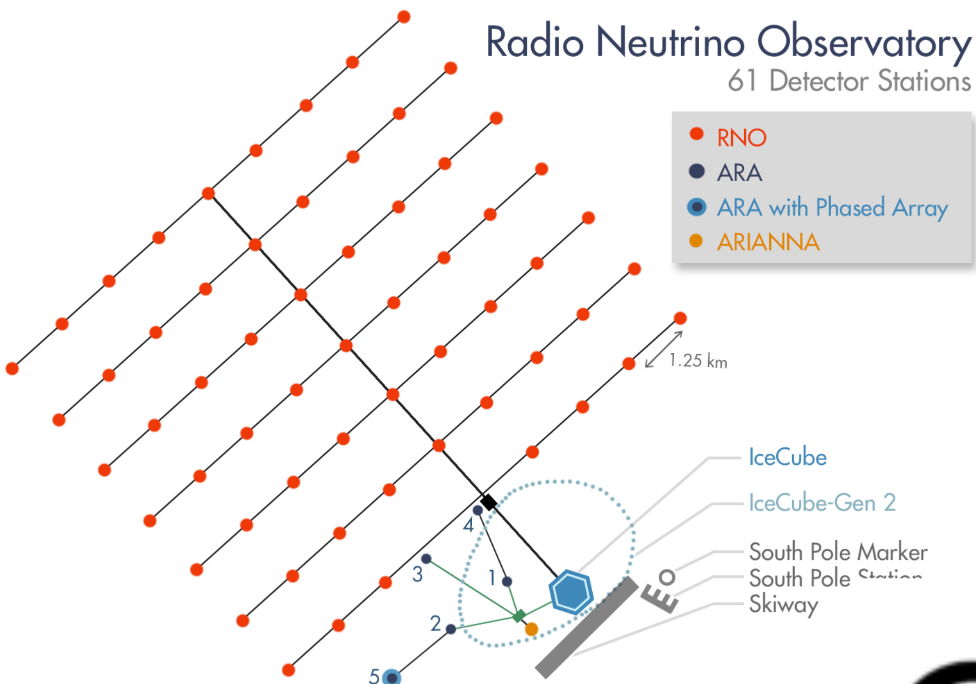
RES-NOVA

- 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., arXiv: 2011.07819.

Ultra High Energy Neutrino Frontier

Radio Neutrino Telescopes



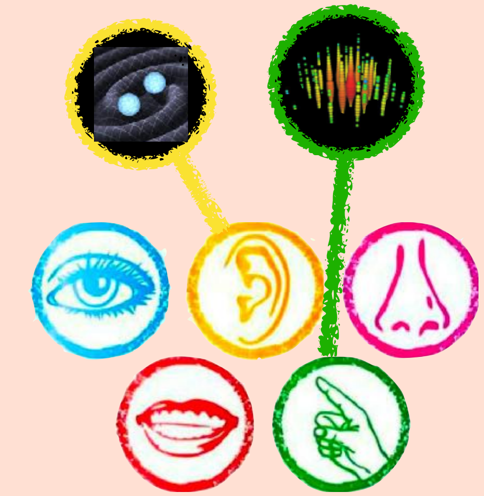
Credit: Cosmin Deaconu

GRAND

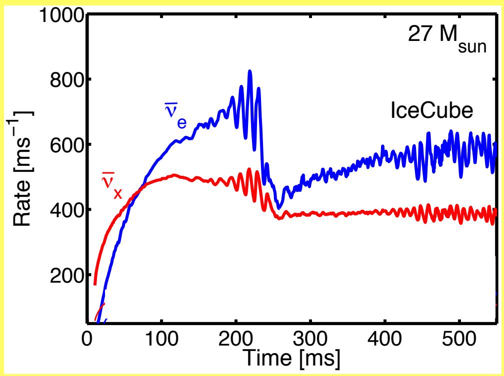
- Follow-up on pilot arrays (ARA, ARIANNA) and ANITA balloon.
- Explore continuation of PeV IceCube flux and UHE neutrinos.

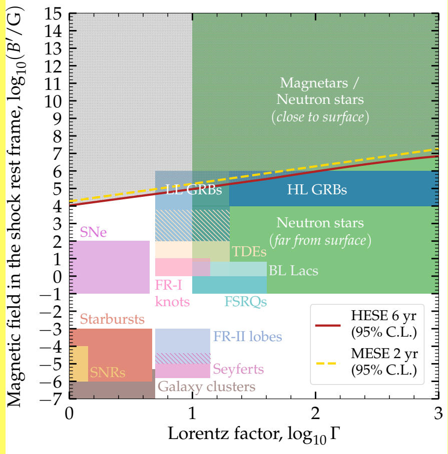
GRAND, arXiv: 1810.09994. RNO, arXiv: 1907.12526. RNO-G, arXiv: 2010.12279. PUEO, arXiv: 2010.02892.

Ideal messengers

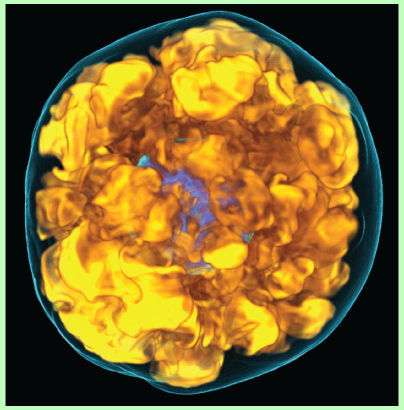


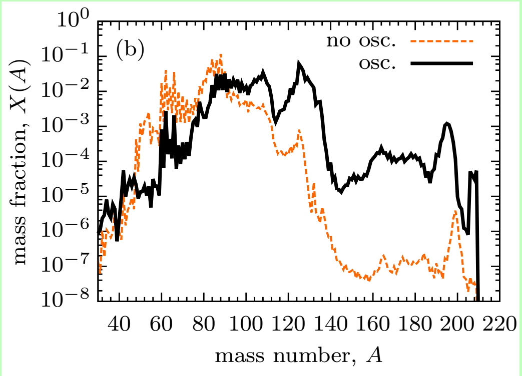
Unique probes of source physics



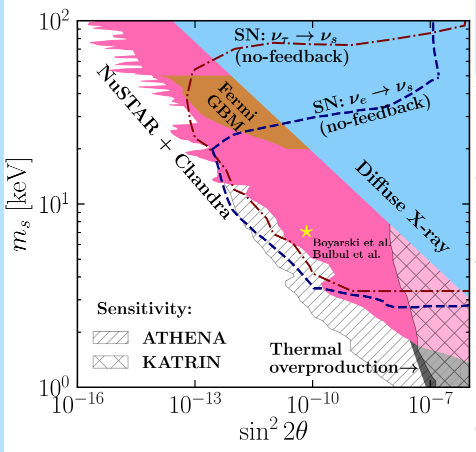


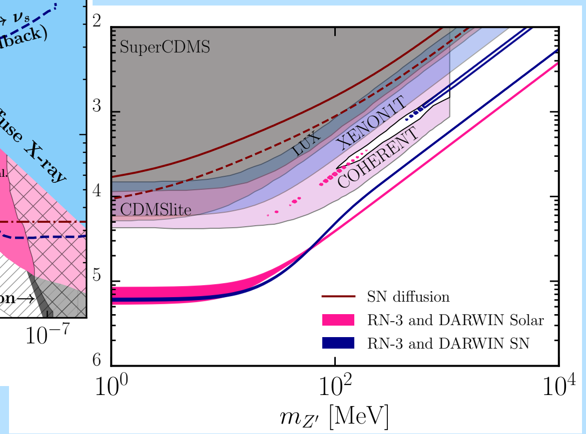
Key particles in compact sources



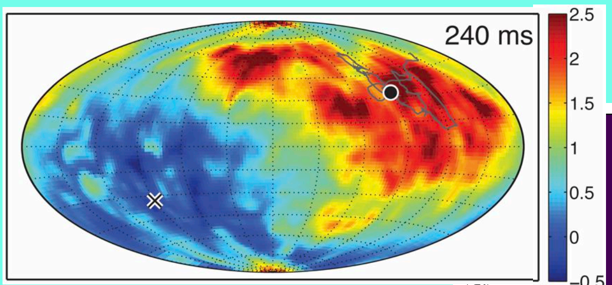


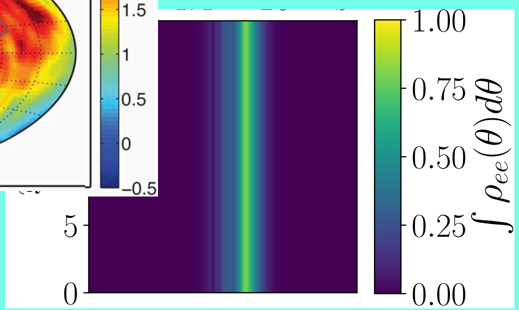
Gateway to Non-Standard Physics





Nu & source modeling just begun





Ready for new discoveries

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Thanks!