The Niels Bohr International Academy

DARK

Neutrino Astronomy

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AstroDark-2021, December 8, 2021

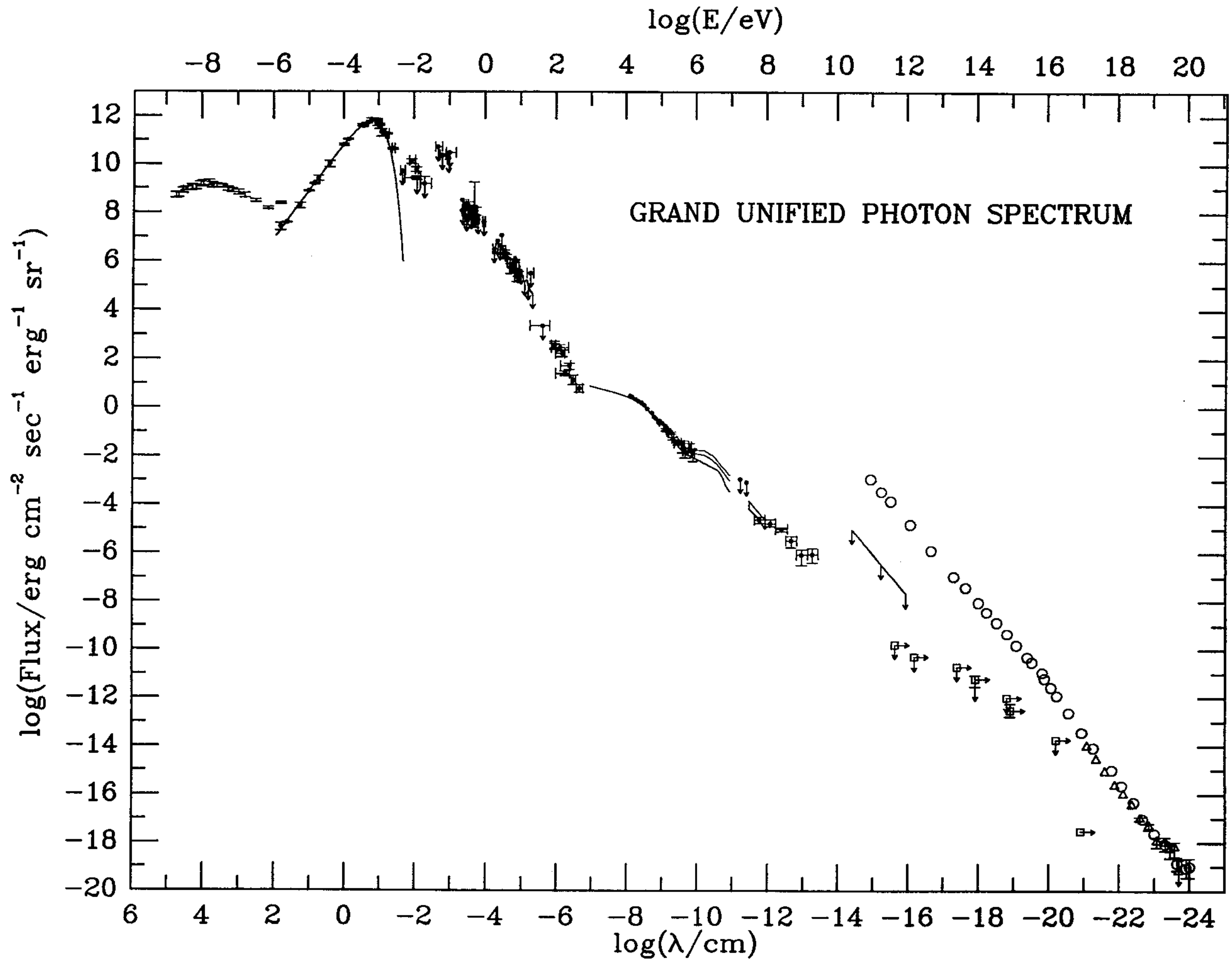
VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

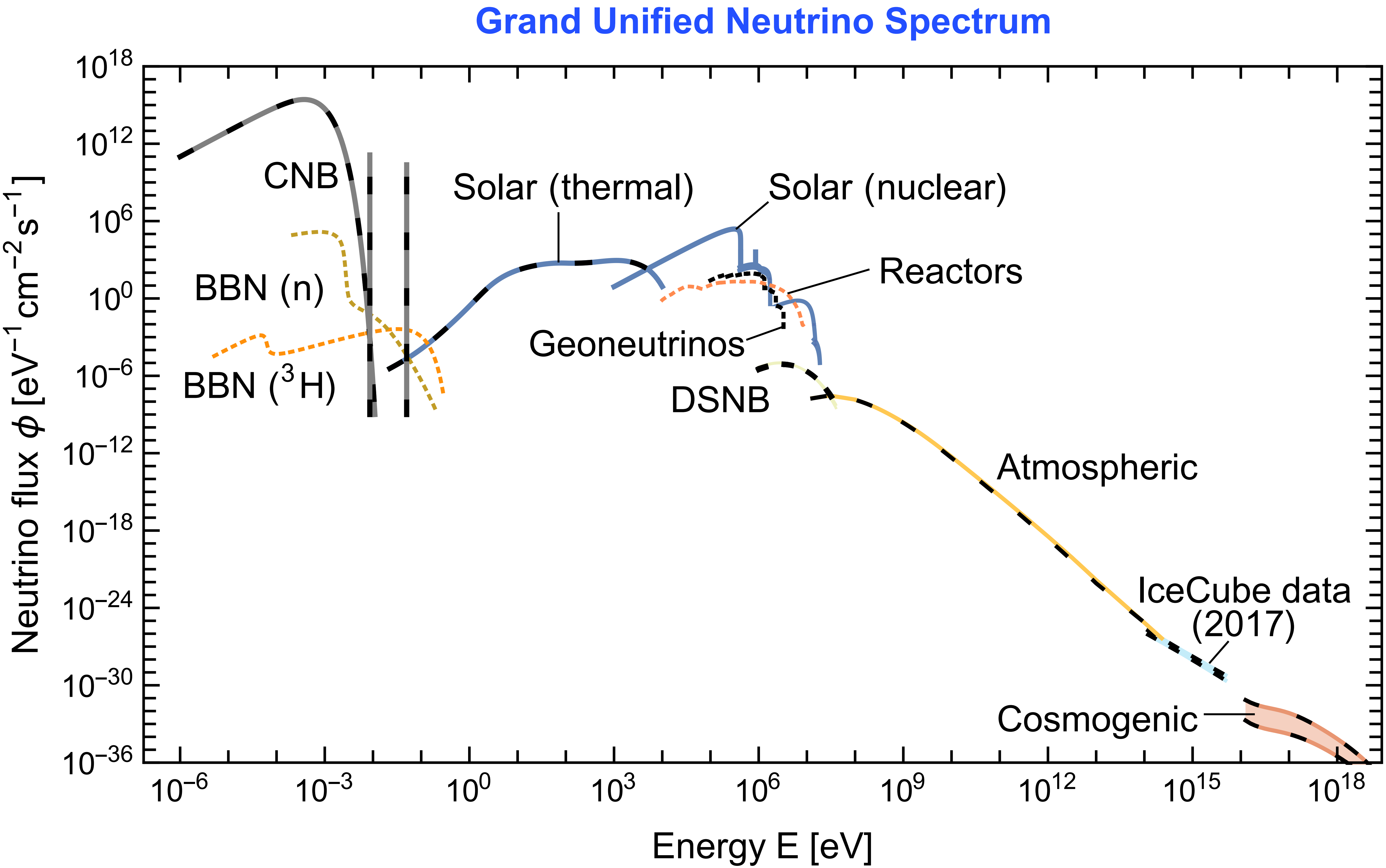
SFB 1258 Neutrinos Dark Matter Messengers

The Cosmos in Photons



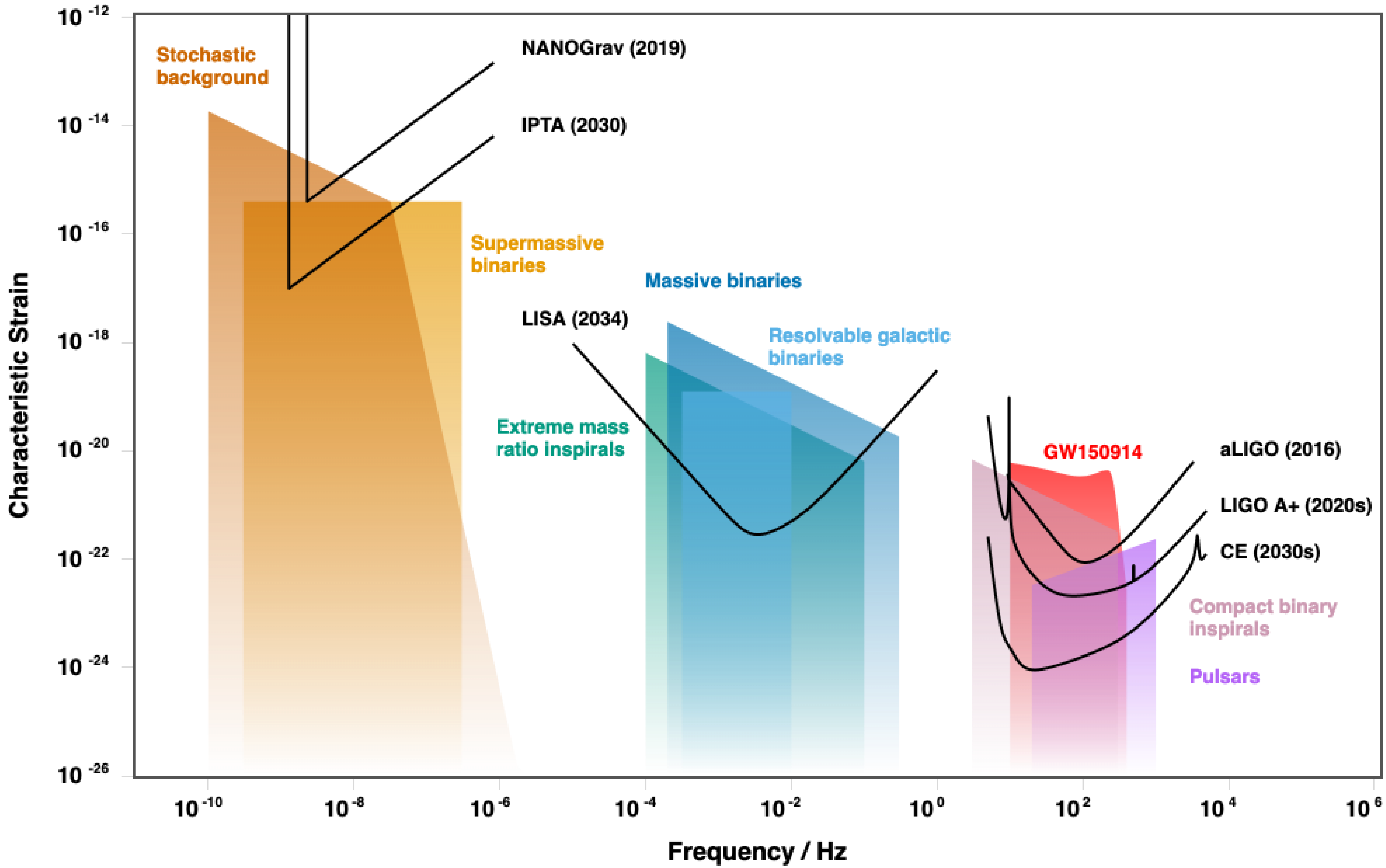
Ressel & Turner, Bull. Am. Astron. Soc. (1990). See also Hill, Masui, Scott, Appl. Spectrosc. (2018).

The Cosmos in Neutrinos



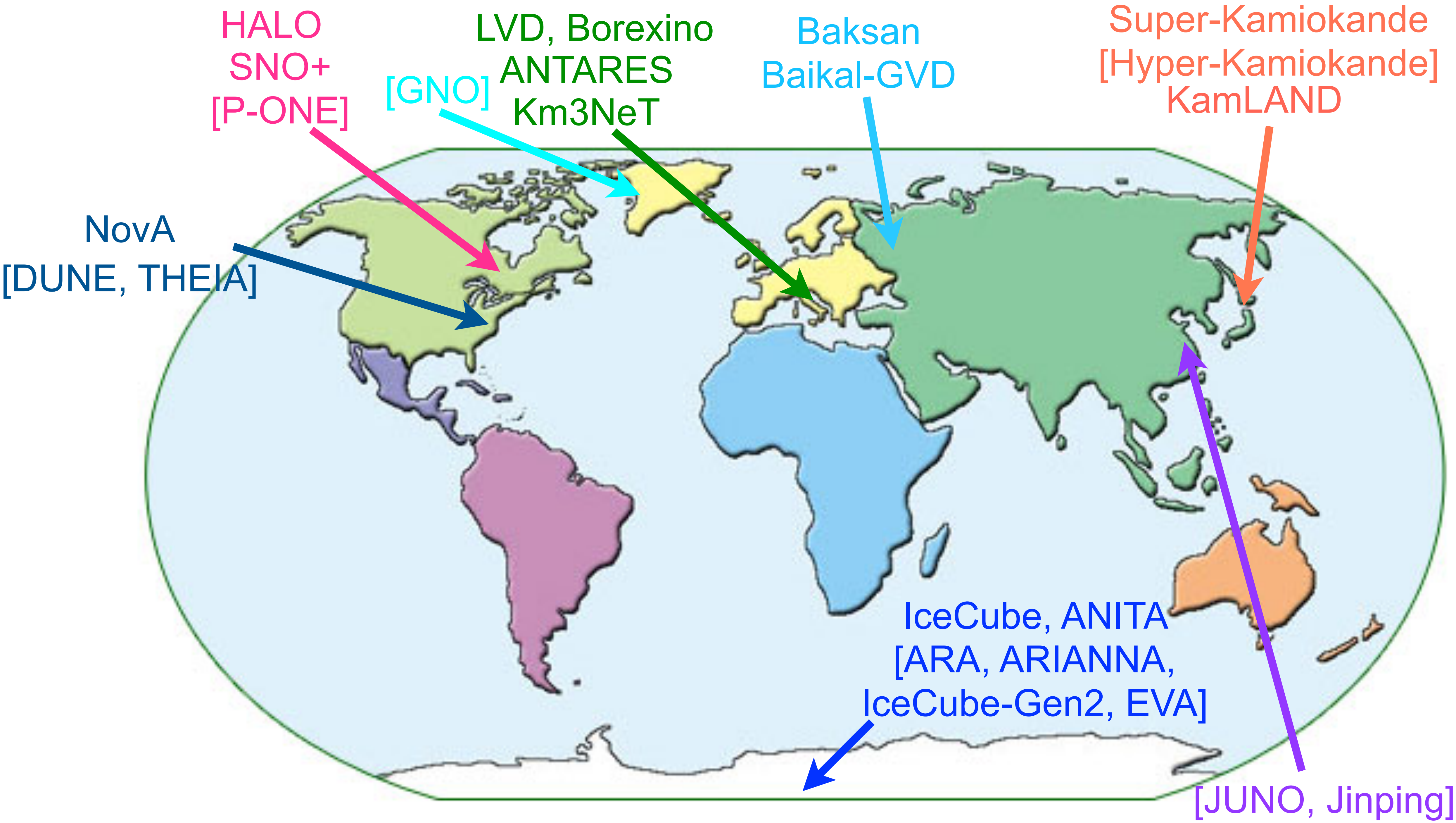
Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

The Cosmos in Gravitational Waves



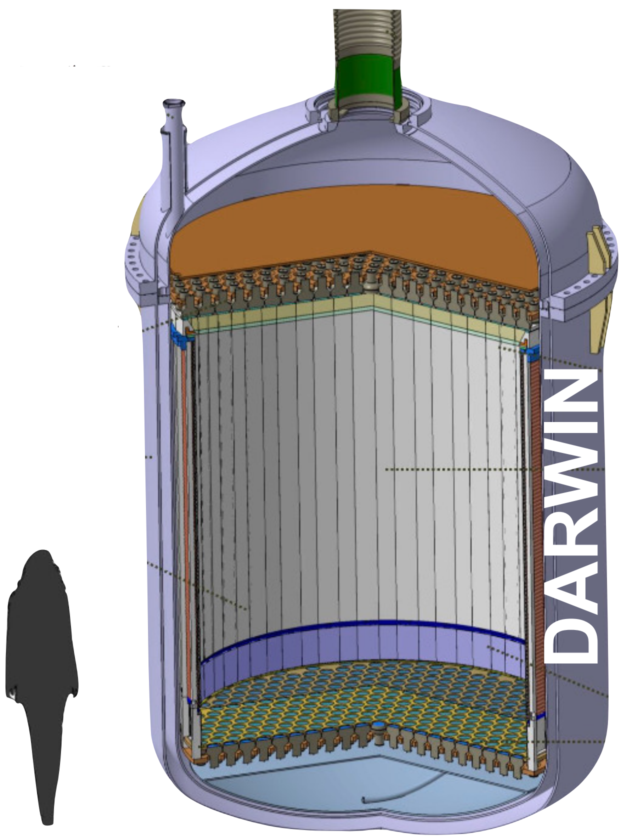
Shoemaker et al. (2019).

Neutrino "Telescopes"

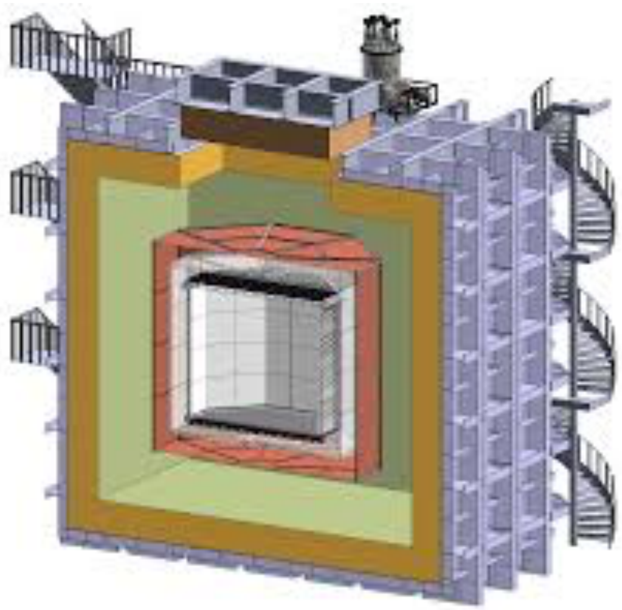


Neutrino “Telescopes”

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). Beacom, Farr, Vogel, PRD (2002). Agnes et al., JCAP (2021).

Core-Collapse Supernovae

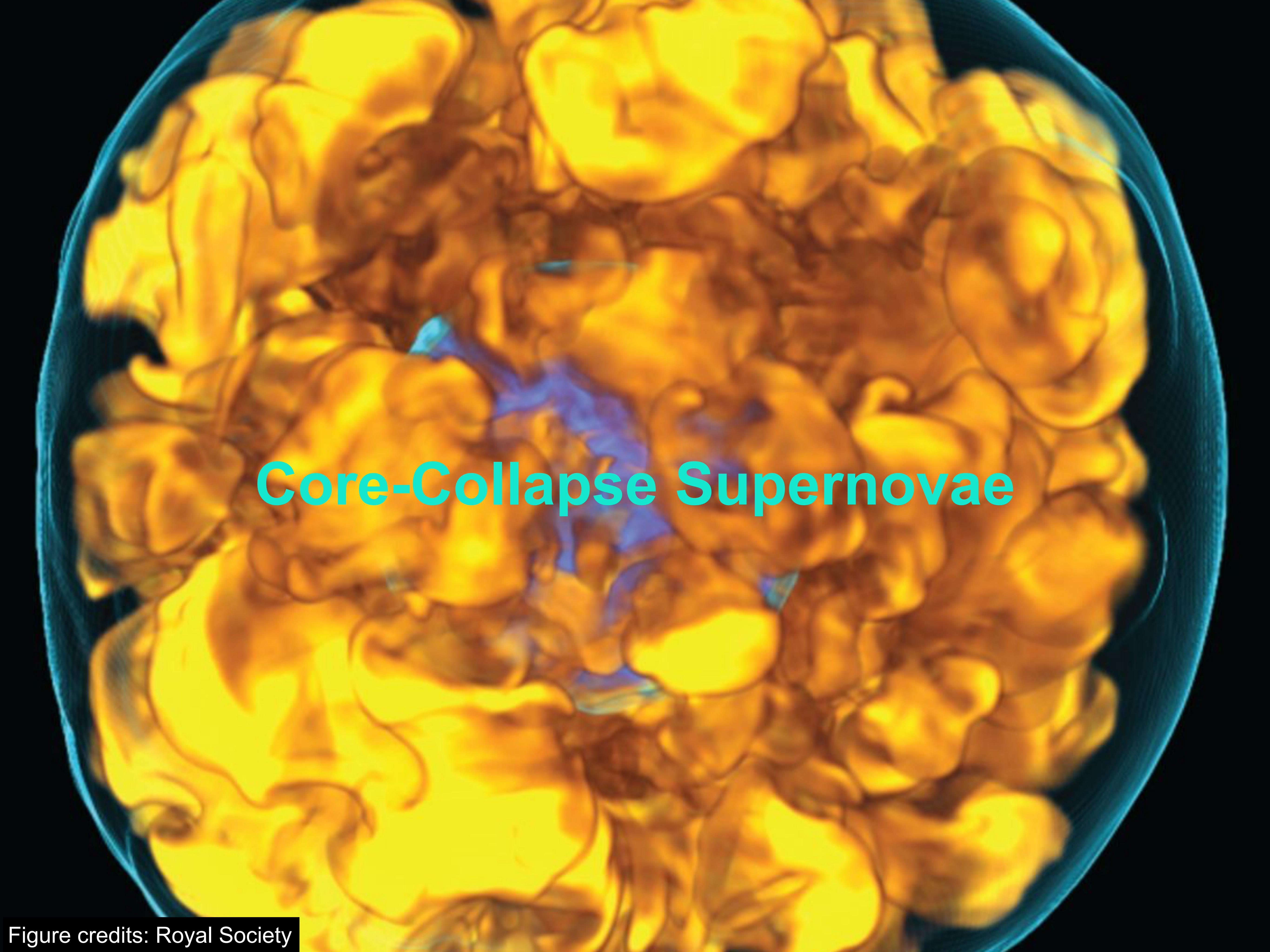
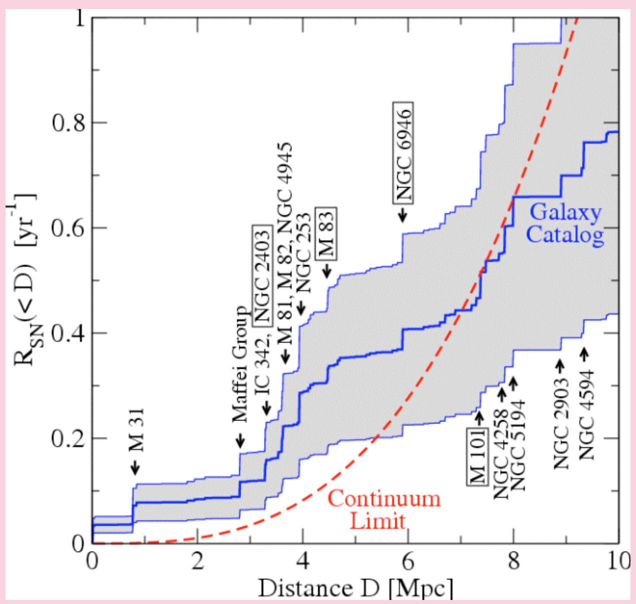


Figure credits: Royal Society

Detection Frontiers

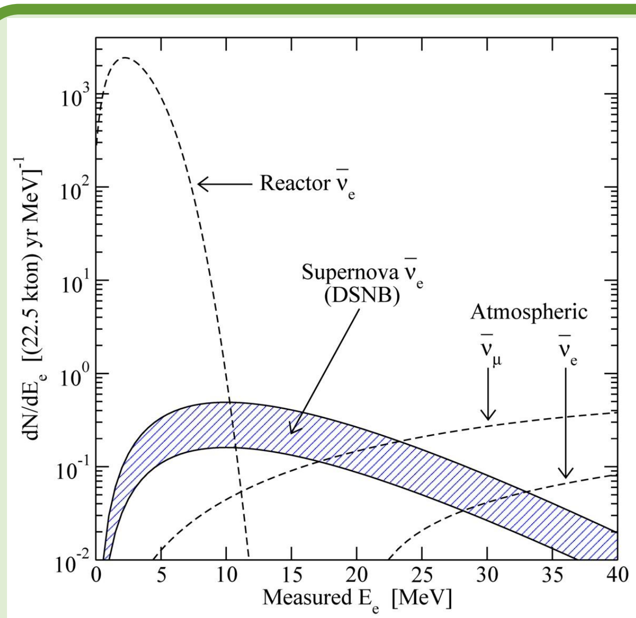
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

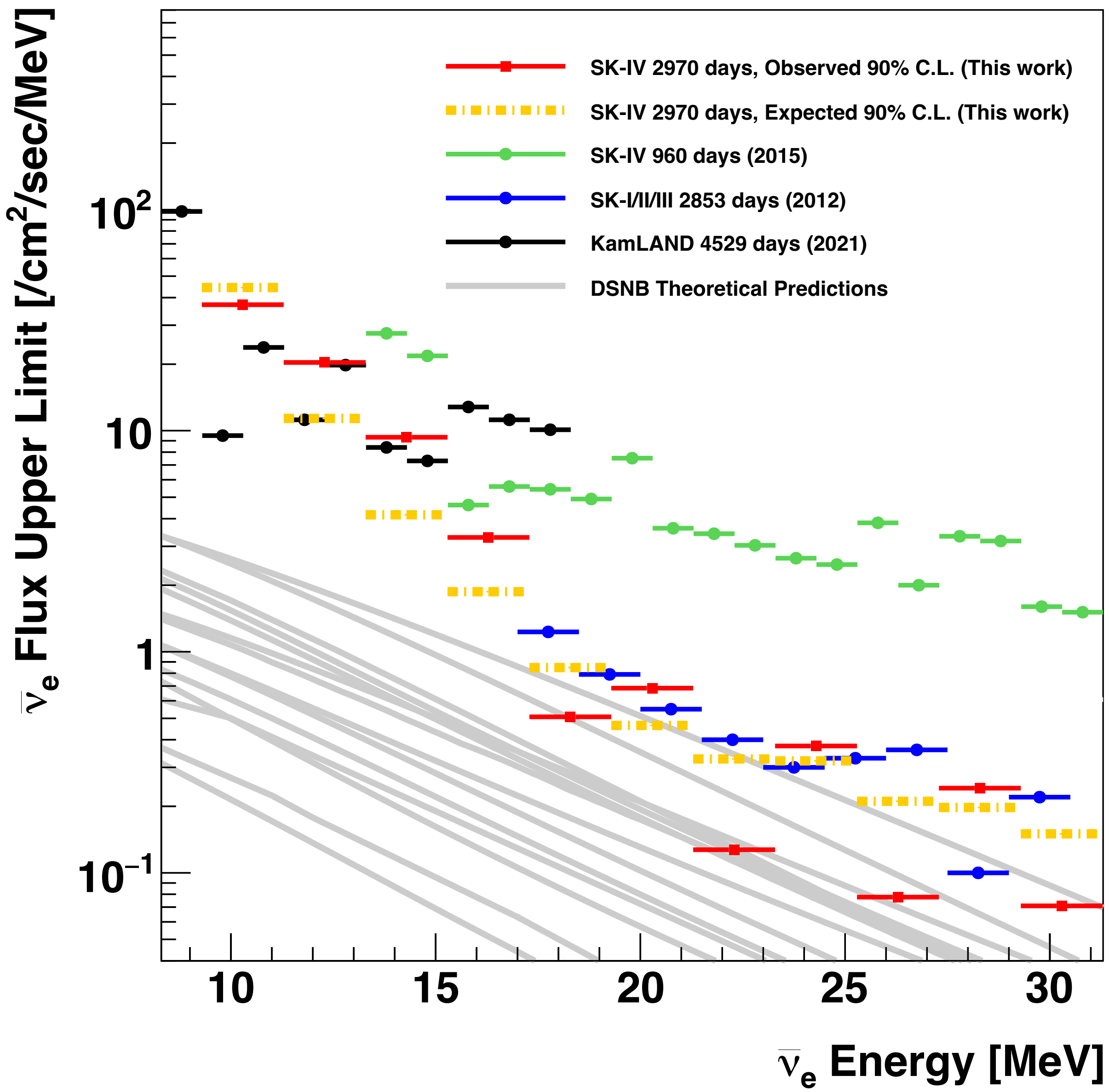
Sensitivity to general properties.



Diffuse Supernova Background
(one supernova per second).

Average supernova emission. Guaranteed signal.

Diffuse Supernova Neutrino Background

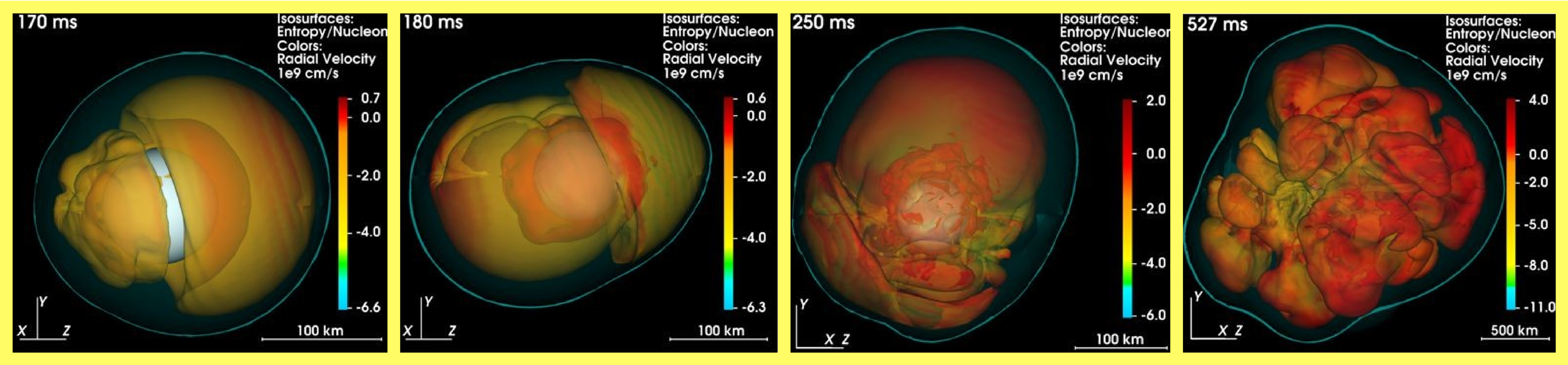


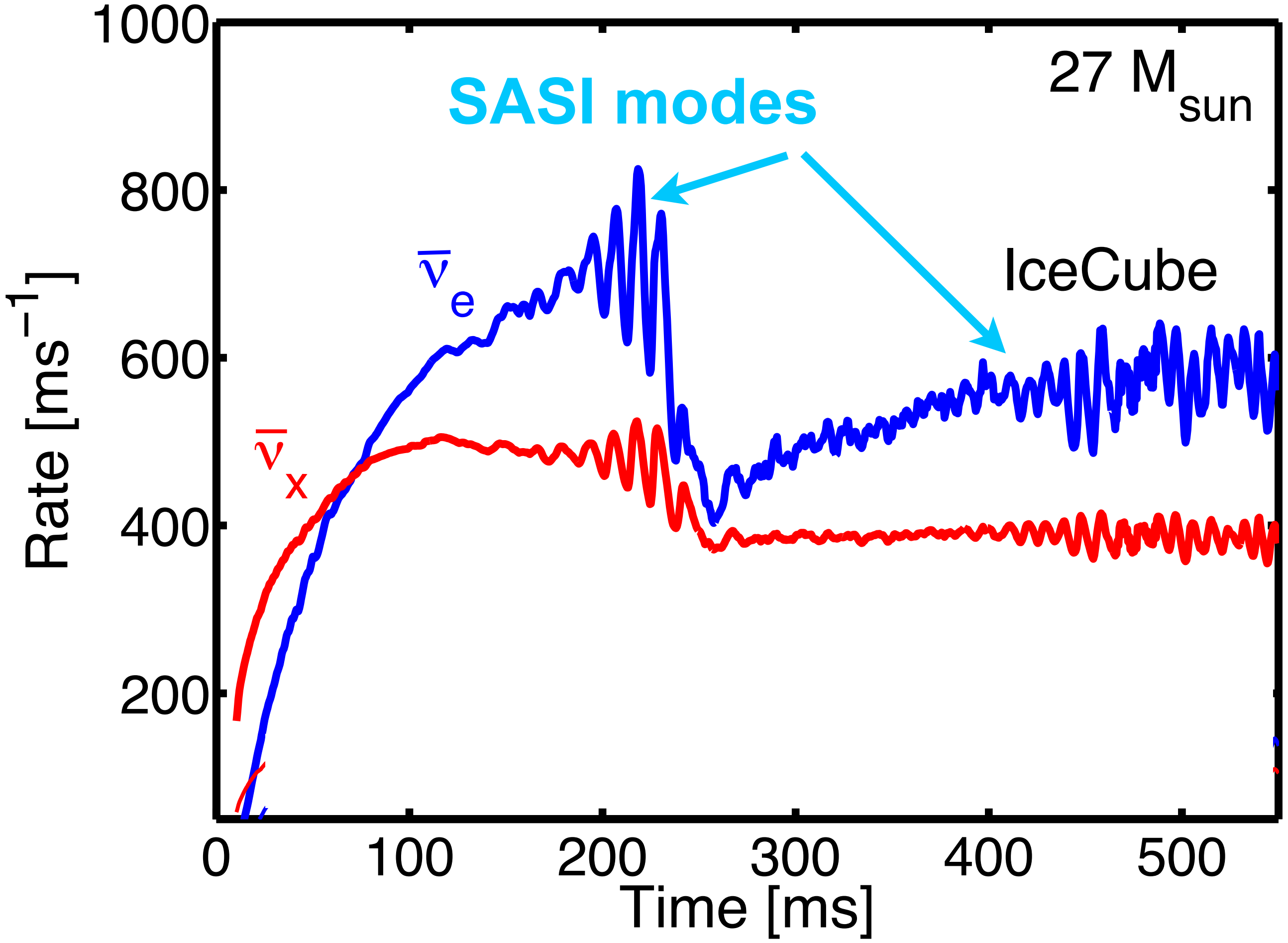
- Independent test of local supernova rate.
- Constraints on fraction of black hole forming collapses.
- Affected by binary interactions (mass transfer and mergers), uncertainties on stellar evolution.

Figure from Abe et al., arXiv: 2109.11174. Moller et al., 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).

Supernova Explosion Mechanism

Standing Accretion Shock Instability (SASI)

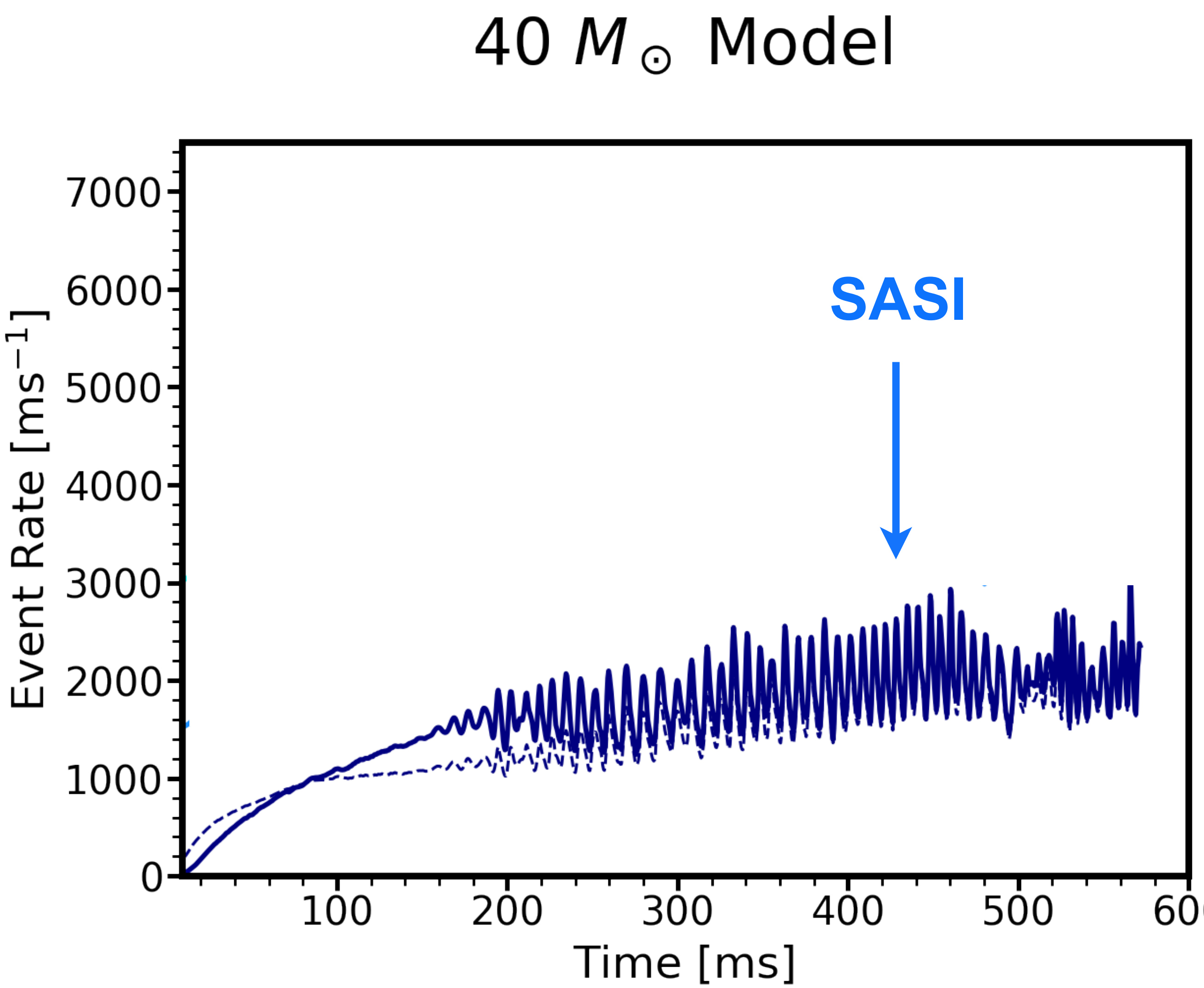




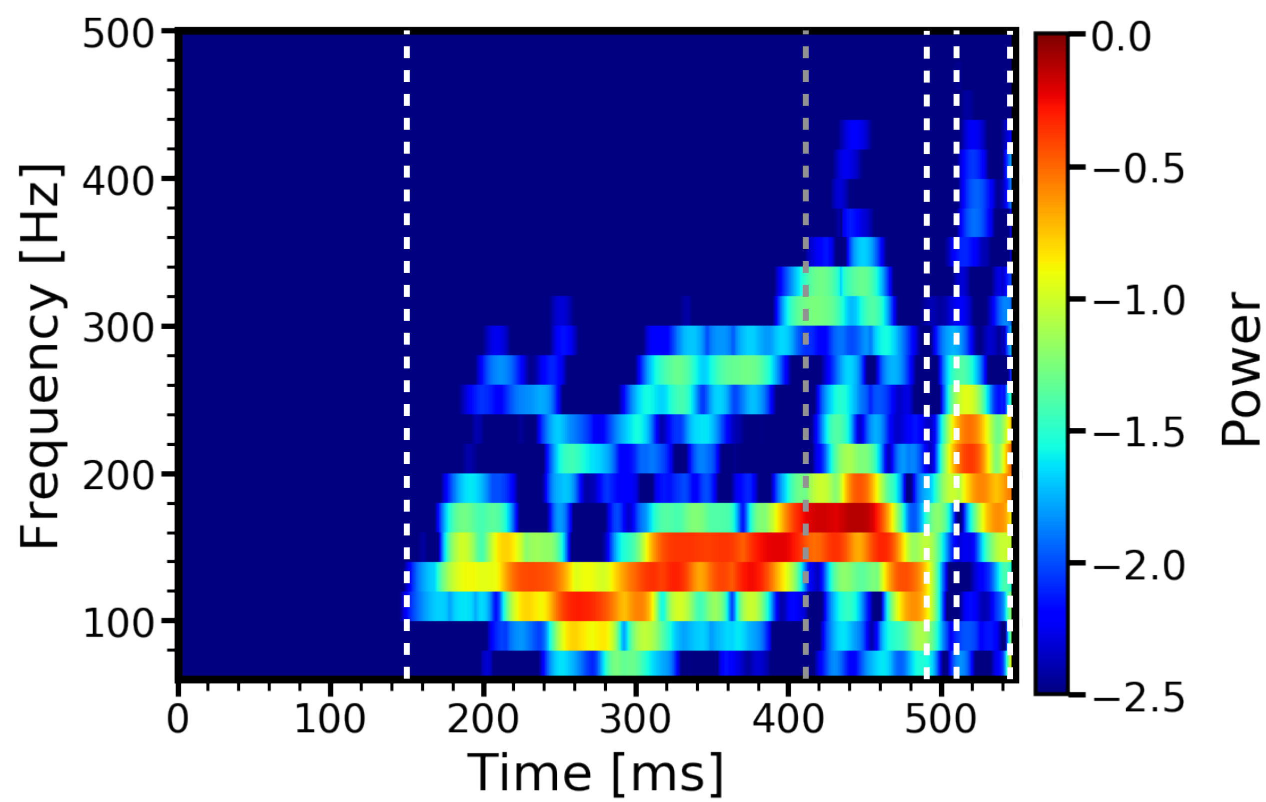
Neutrinos and gravitational waves carry imprints of the physics occurring before the explosion.

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).

Fingerprints of Black Hole Formation



Neutrinos (and gravitational waves) probe black hole formation.



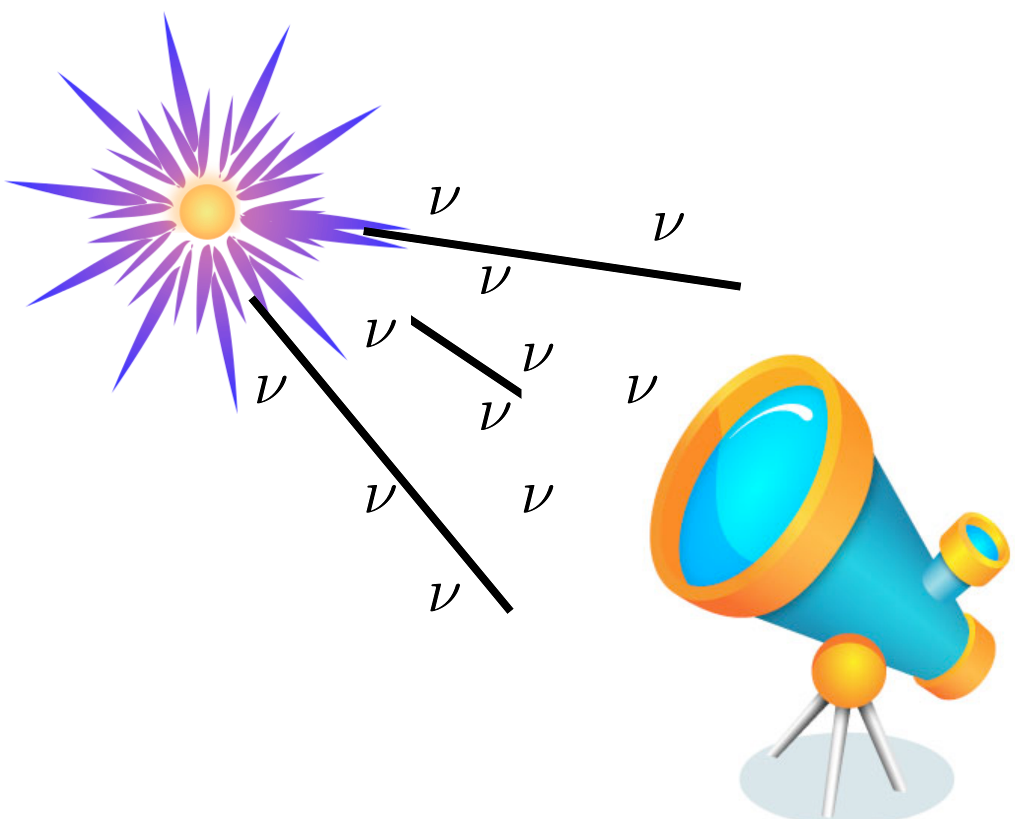
SASI frequency evolution
= Shock radius evolution

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

Neutrino Alert

SuperNova Early Warning System (SNEWS 2.0).

Network to alert astronomers of a burst.

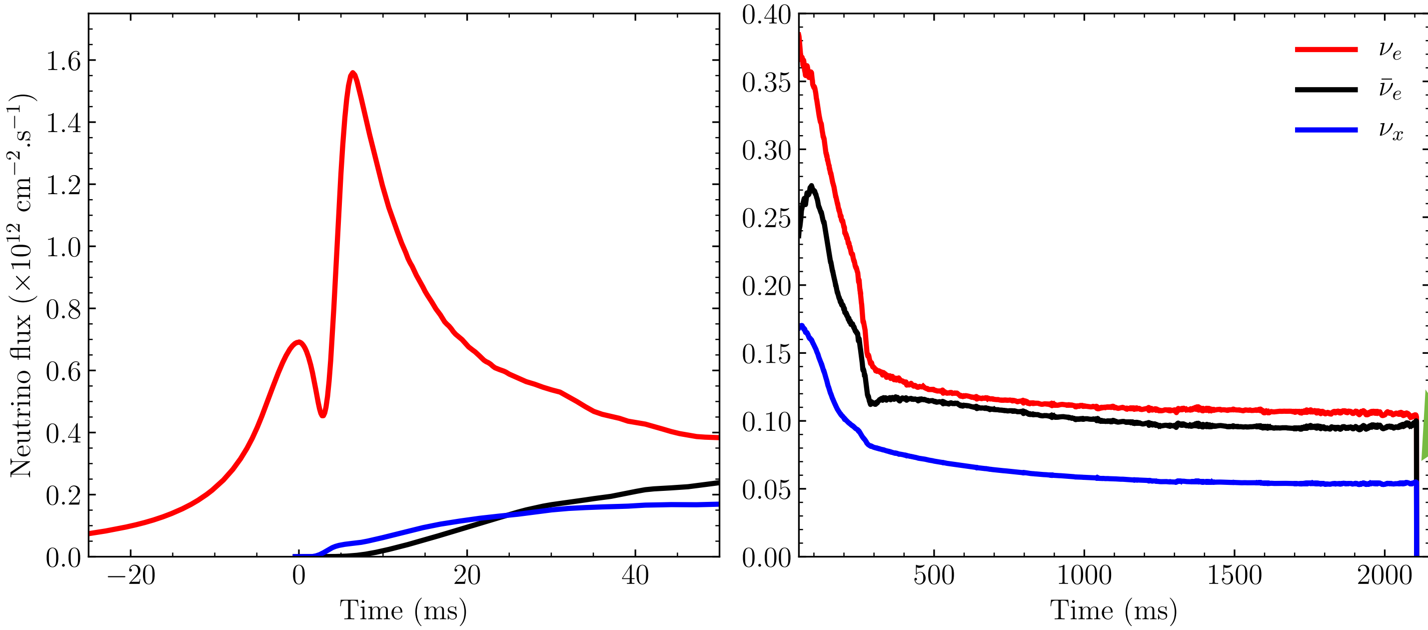


Determination of **supernova direction** with neutrinos.

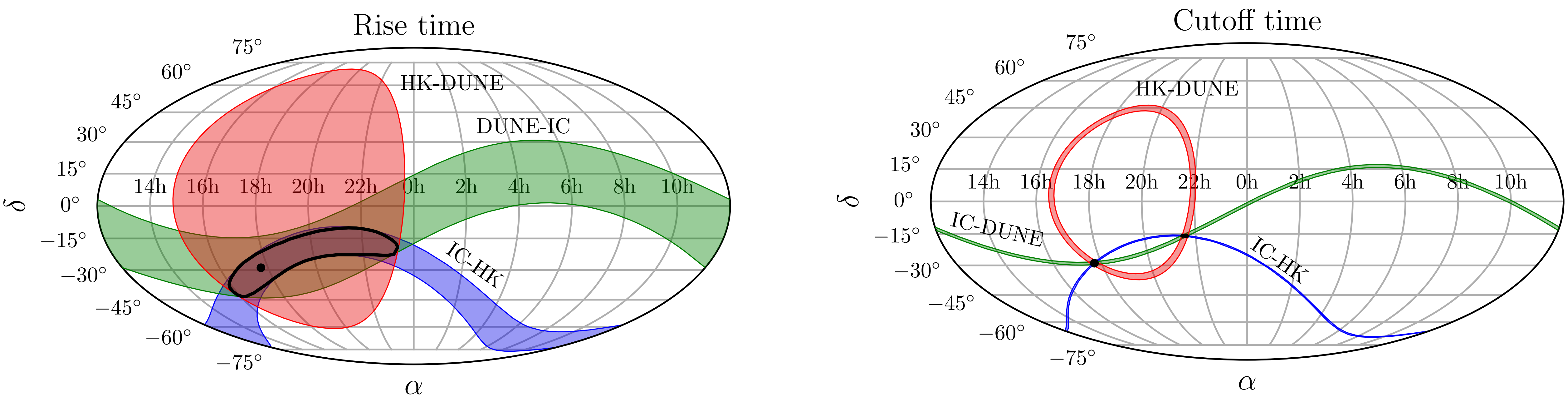
Crucial for electromagnetically dark or weak supernova.

SNEWS 2.0, New J. Phys. (2021). 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). Sarfati, Hansen, Tamborra, arXiv: 2110.02347. Gullin et al., arXiv: 2109.13242.

Triangulating Black Hole Forming Collapses



Abrupt signal termination

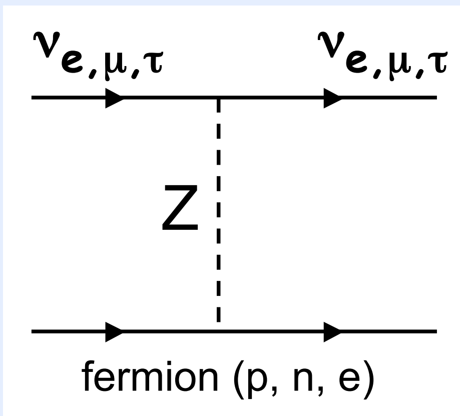


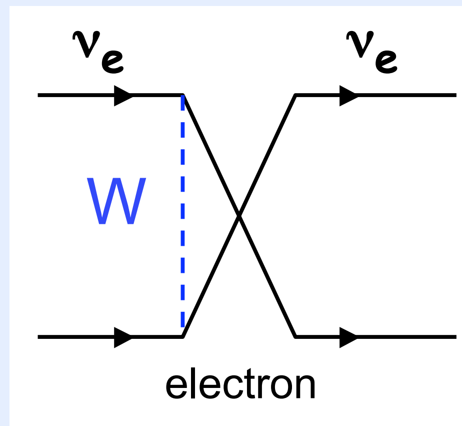
Triangulation through the end tail of the neutrino curve

- allows to achieve one order of magnitude improvement in the pointing precision
- is insensitive to neutrino mixing scenario.

Sarfati, Hansen, Tamborra, arXiv: 2110.02347. Gullin et al., arXiv: 2109.13242. Muehlbeier et al., PRD (2013). Brdar, Lindner, Xu, JCAP (2018). Hansen, Lindner, Scholer, PRD (2020).

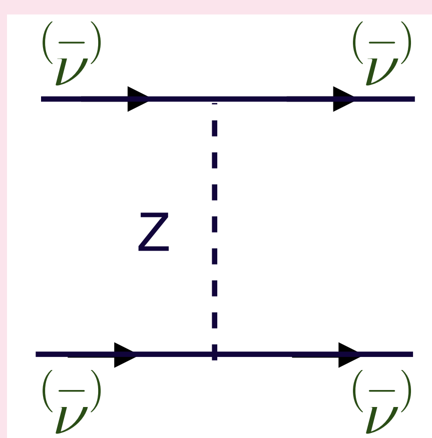
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.



Neutrinos interact among themselves.

Non-linear phenomenon!

Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021).

Fast Pairwise Neutrino Conversion

Flavor conversion (vacuum or MSW): $\nu_e(p) \to \nu_\mu(p)$.

Lepton flavor violation by mass and mixing.

Pairwise flavor exchange by $\nu - \nu$ scattering:
$$\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$$
$$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$$

No net lepton flavor change.

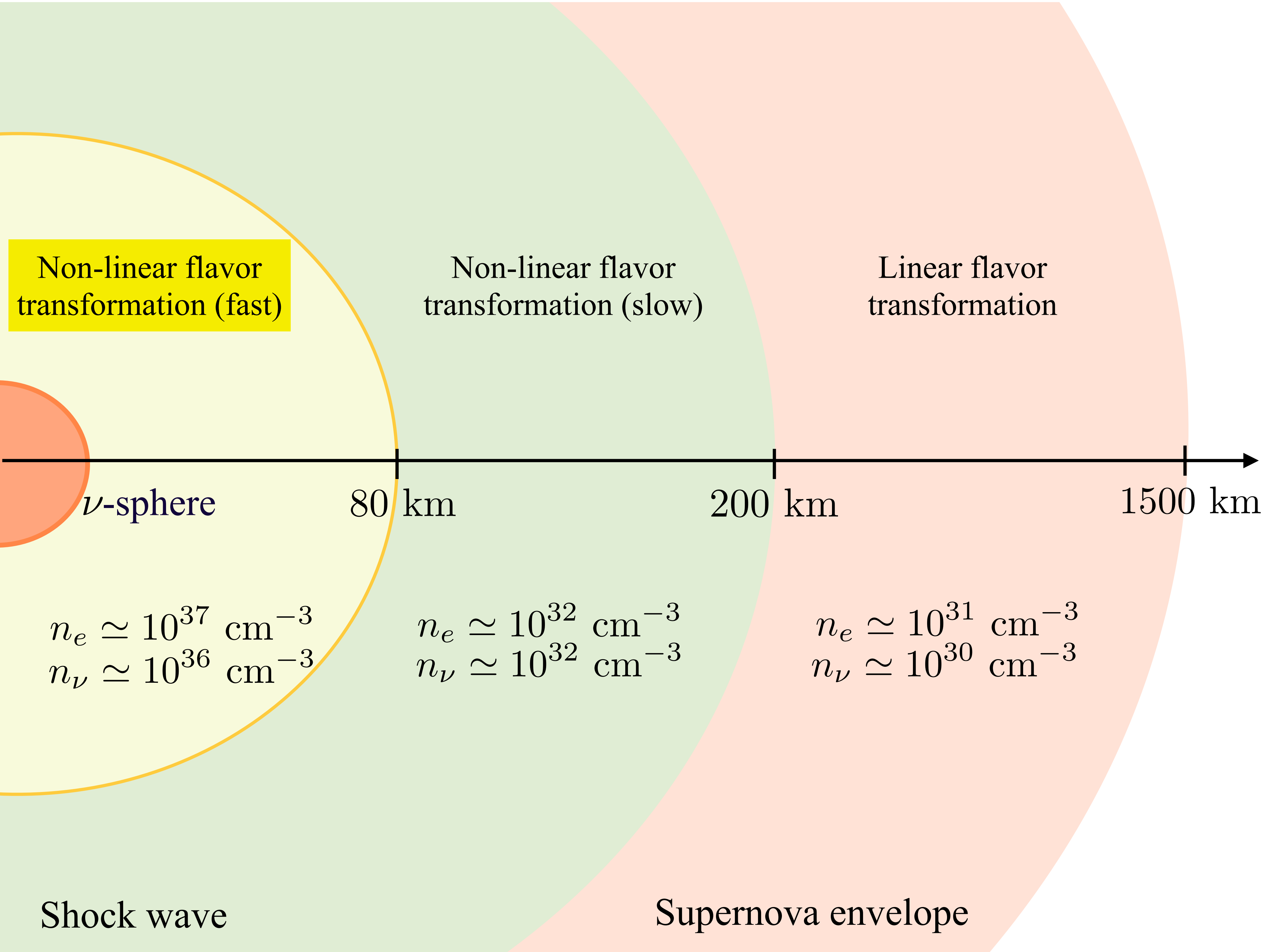
Growth rate: $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42\ \mathrm{m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5\ \mathrm{km}^{-1}$ ⇒ **“Fast” conversion**

⇑

Neutrino angular distributions **crucial**.

Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021).

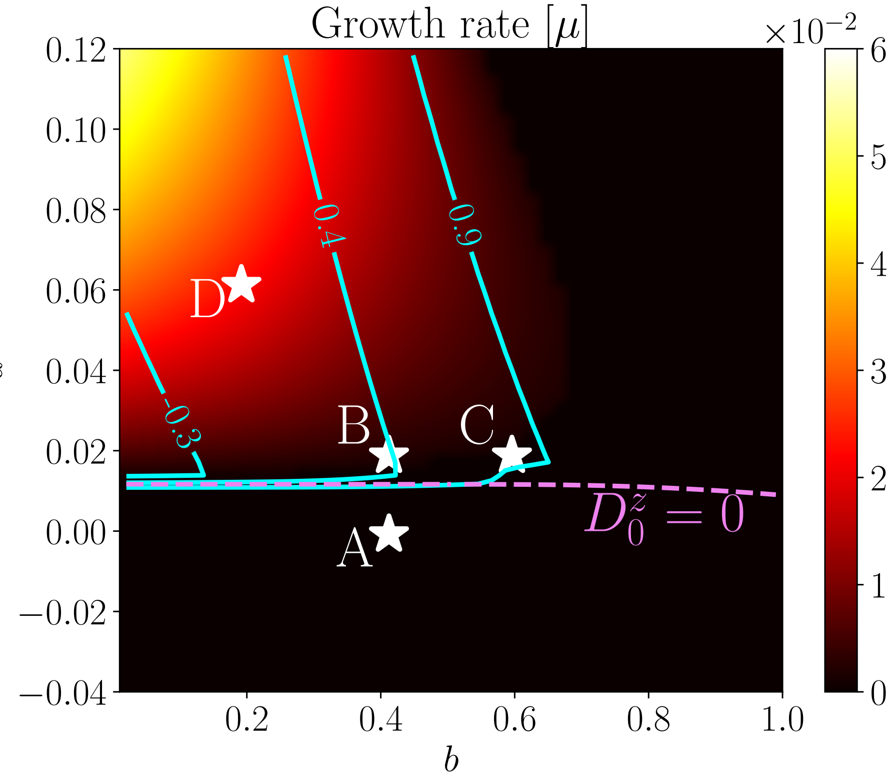
Simplified Picture of Flavor Conversions



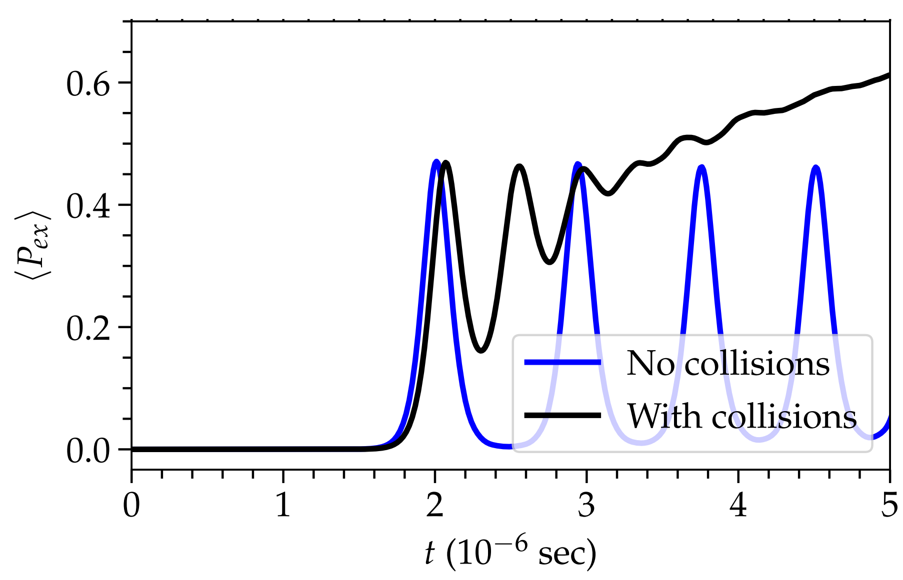
Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021).

Non-Linear Flavor Conversion

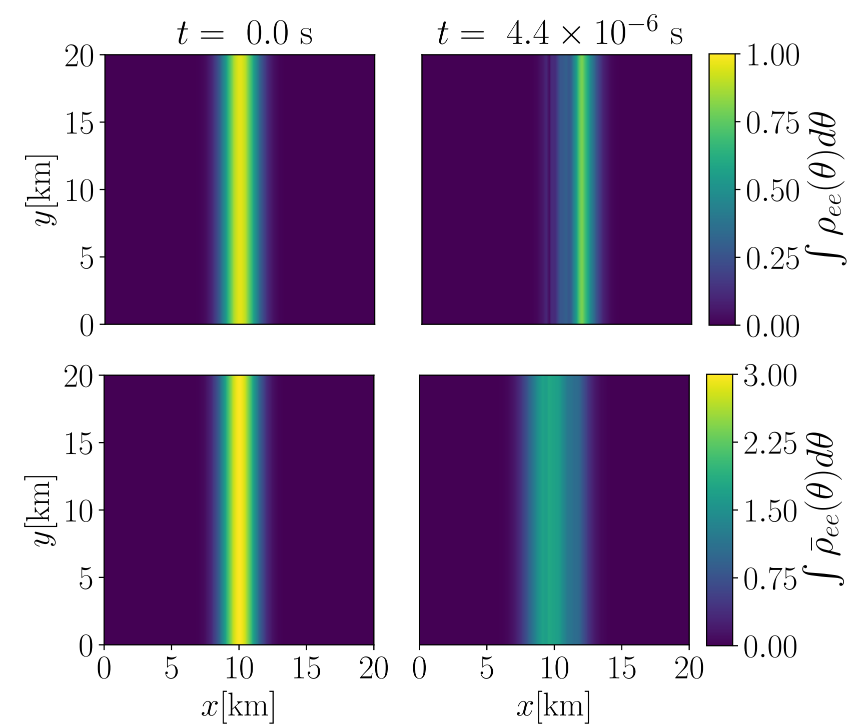
Growth rate vs. conversion probability



Collisions



Neutrino advection



- Growth rate of flavor instability is not predictive of the amount of flavor mixing.
- Neutrino conversion is strongly affected by direction-changing collisions.
- Flavor instabilities are damped by neutrino advection.
- Further work needed!

Padilla-Gay, Tamborra, Raffelt, arXiv: 2109.14627. Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalrgar, Tamborra, PRD (2020, 2021). Richers, Willcox, Ford, PRD (2021). Sigl, arXiv: 2109.00091. Wu et al., PRD (2021). Johns, arXiv: 2104.11369. Martin et al., PRD (2021). …

Compact Binary Mergers

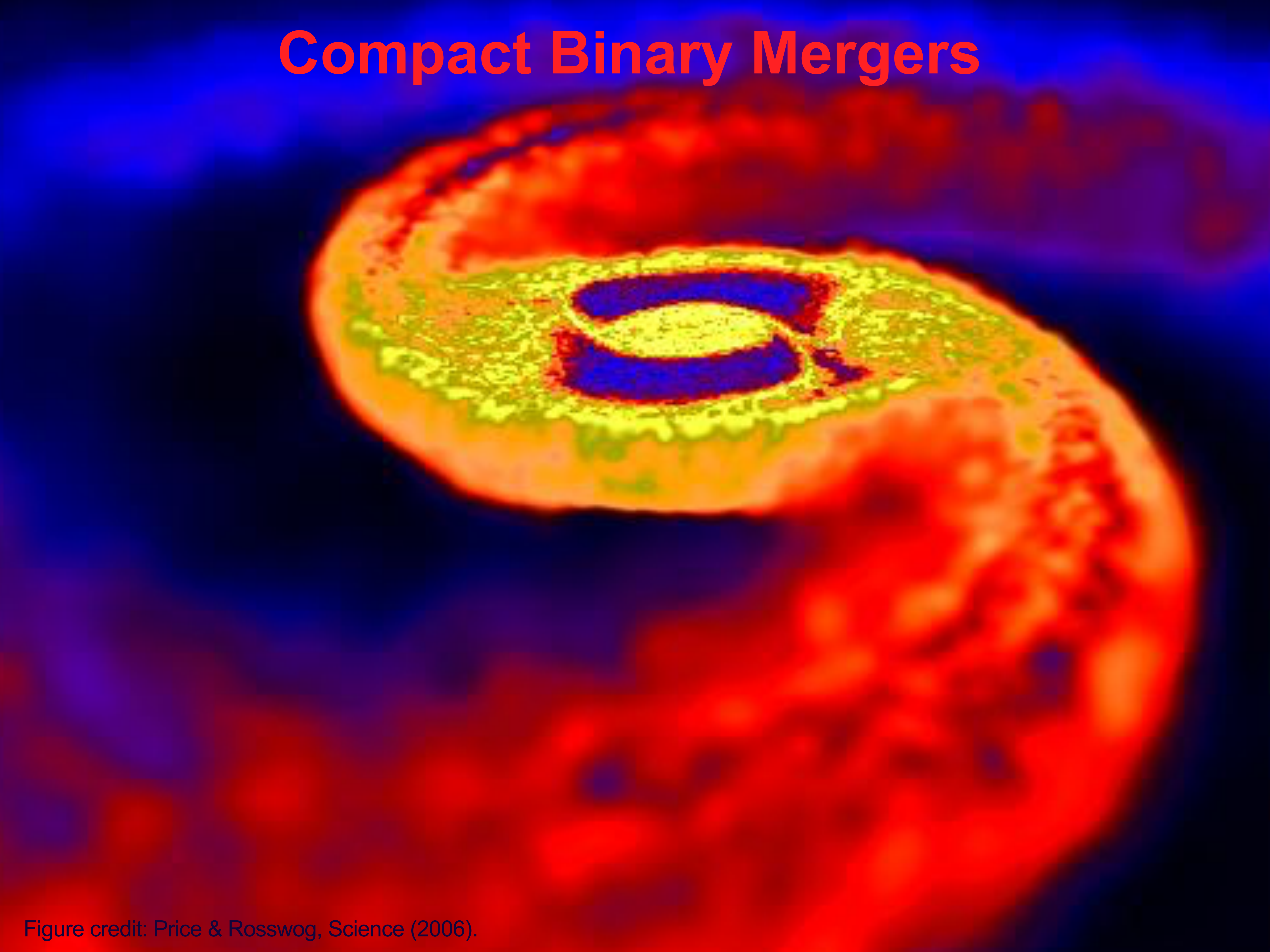


Figure credit: Price & Rosswog, Science (2006).

Compact Binary Mergers

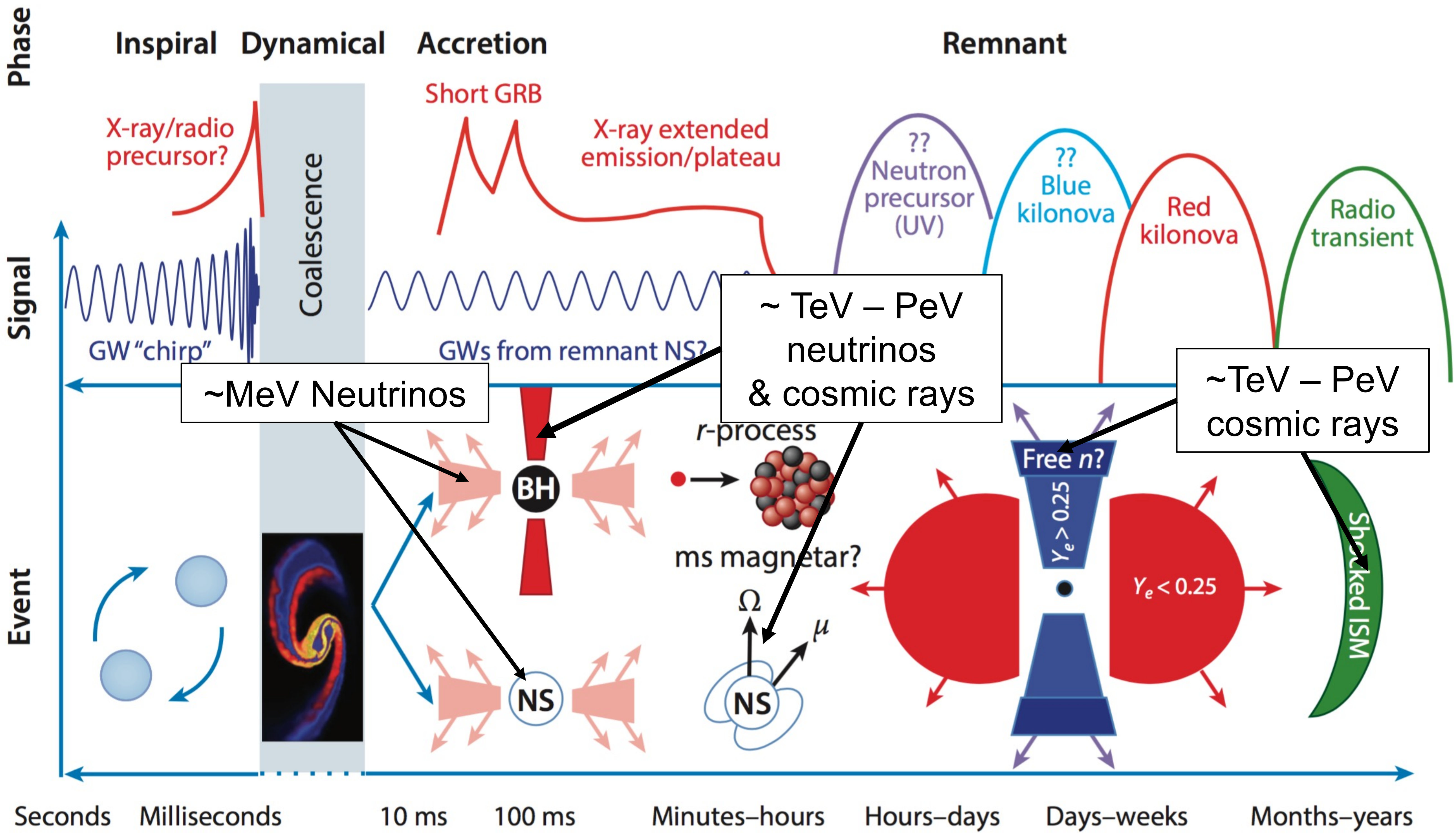
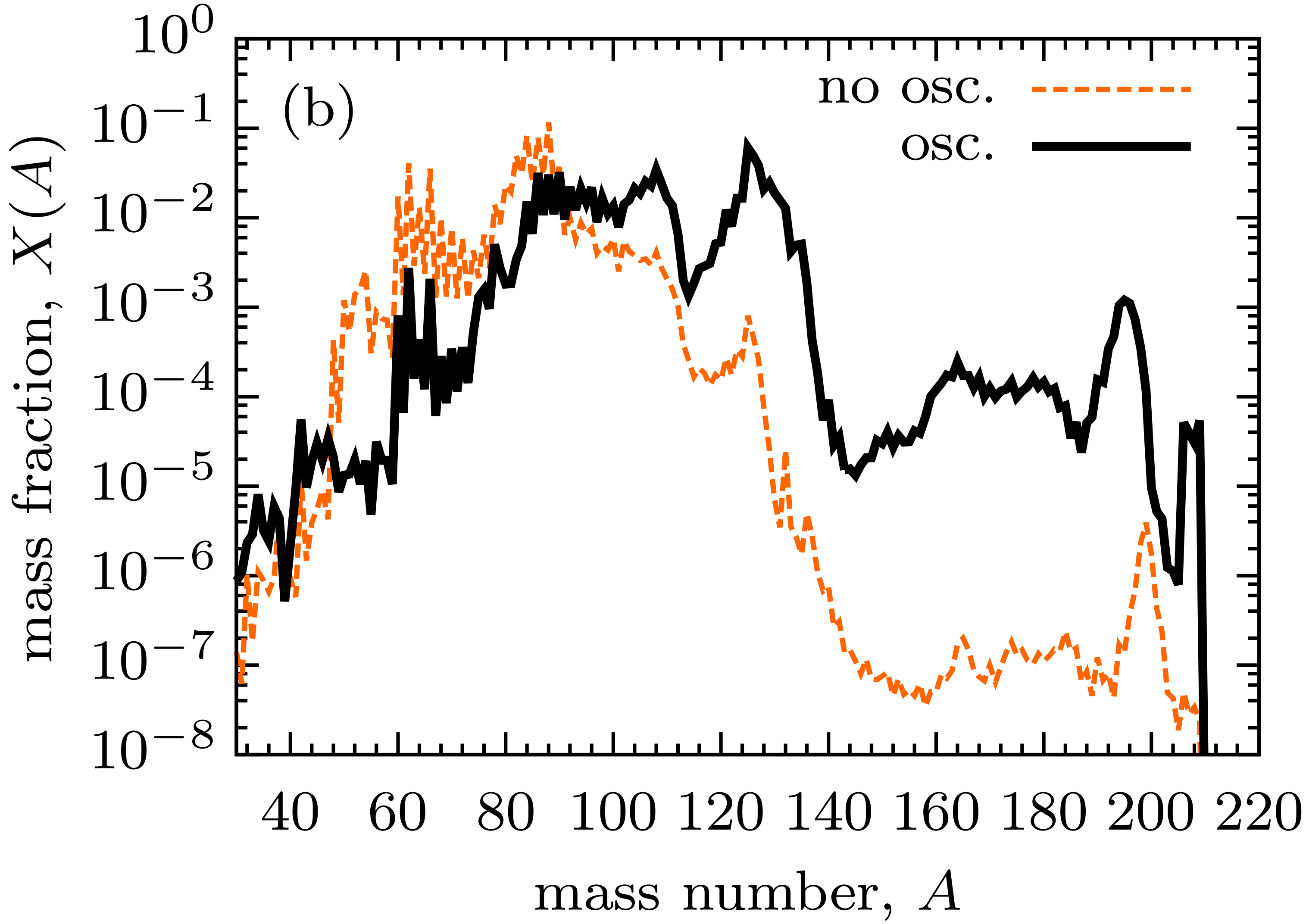
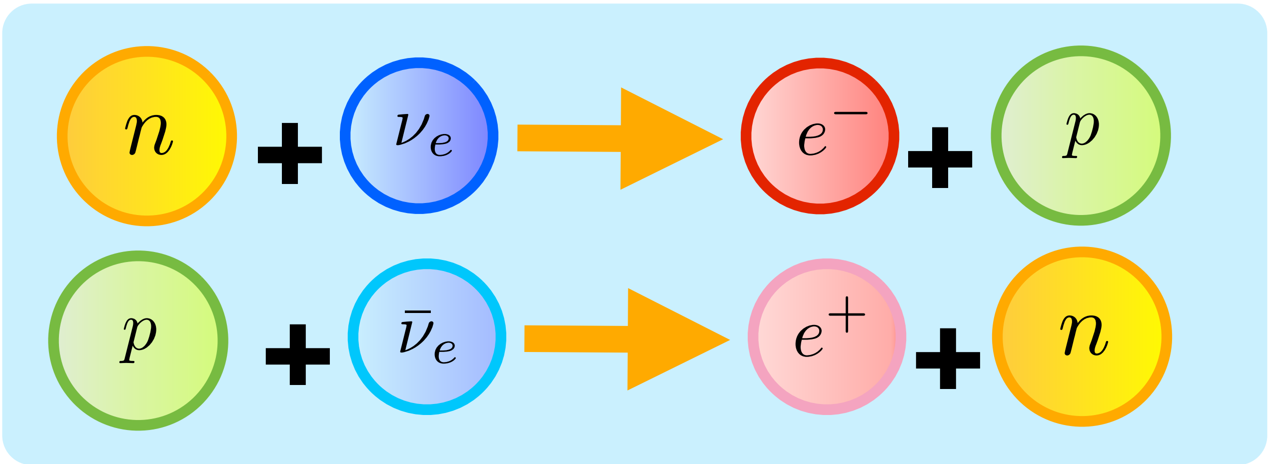


Figure credit: Brian Metzger.

Do Neutrinos Affect Element Production?

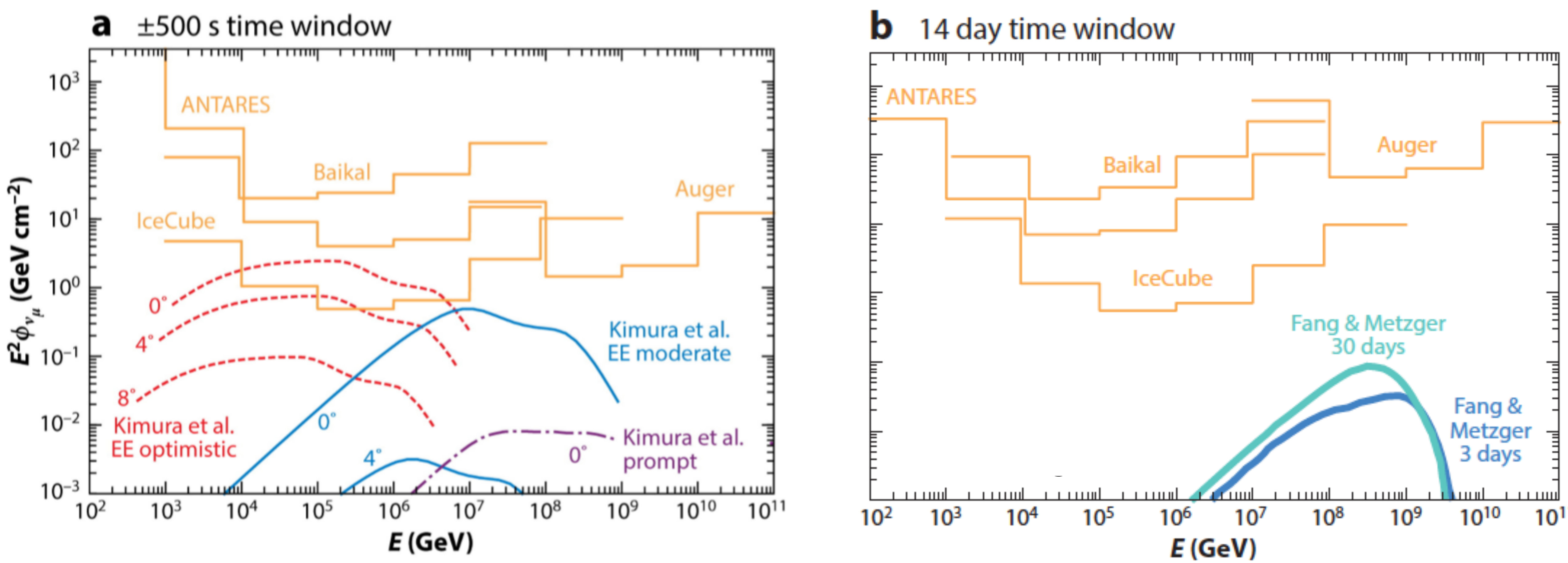




Flavor conversion may lead to an enhancement of nuclei with A>130 (kilonova implications).
More work needed!

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).

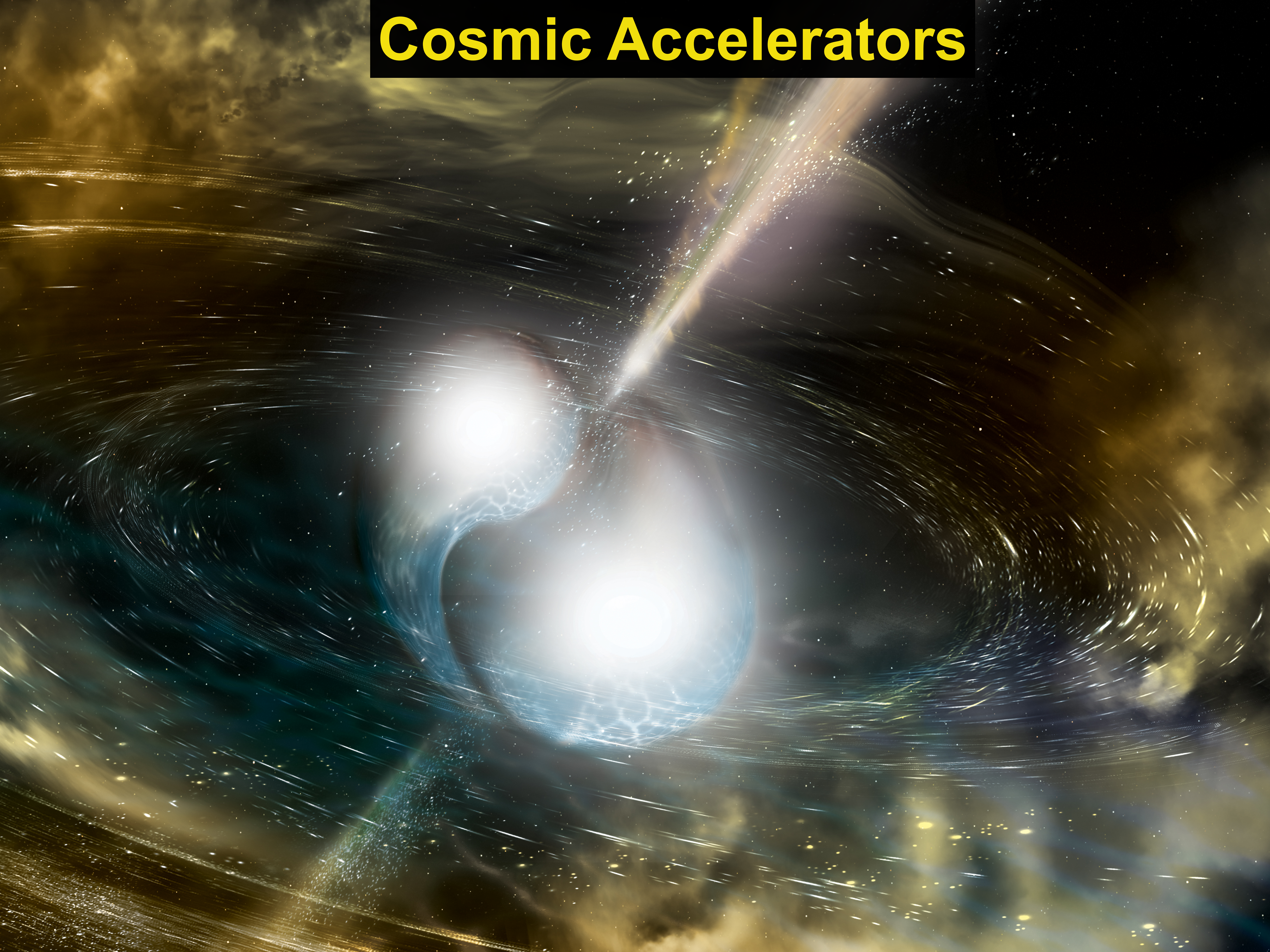
High Energy Neutrinos from GRB 170817A?



- 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.

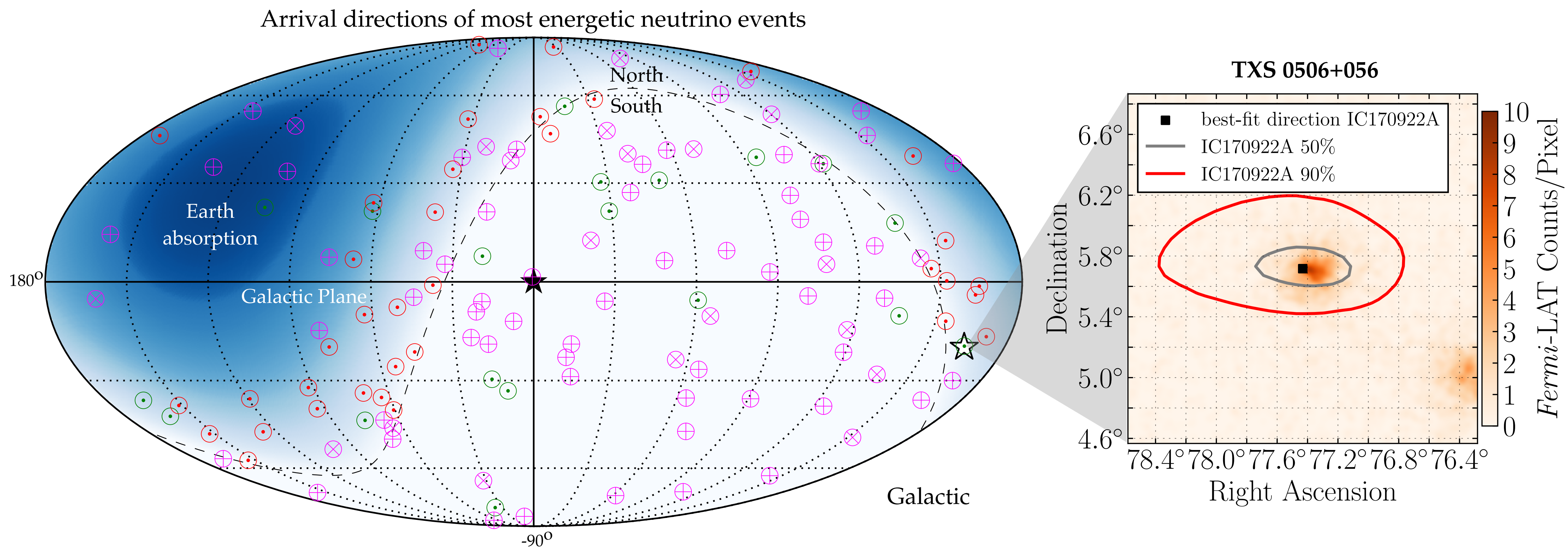
Figure credit: Christian Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku & Kashiyama, PRD (2018). Ahlers & Halser, MNRAS (2019). Tamborra & Ando, JCAP (2015). Kimura et al., ApJ (2017). Gottlieb & Globus, ApJL (2021).

Cosmic Accelerators



Measured Astrophysical Neutrino Flux

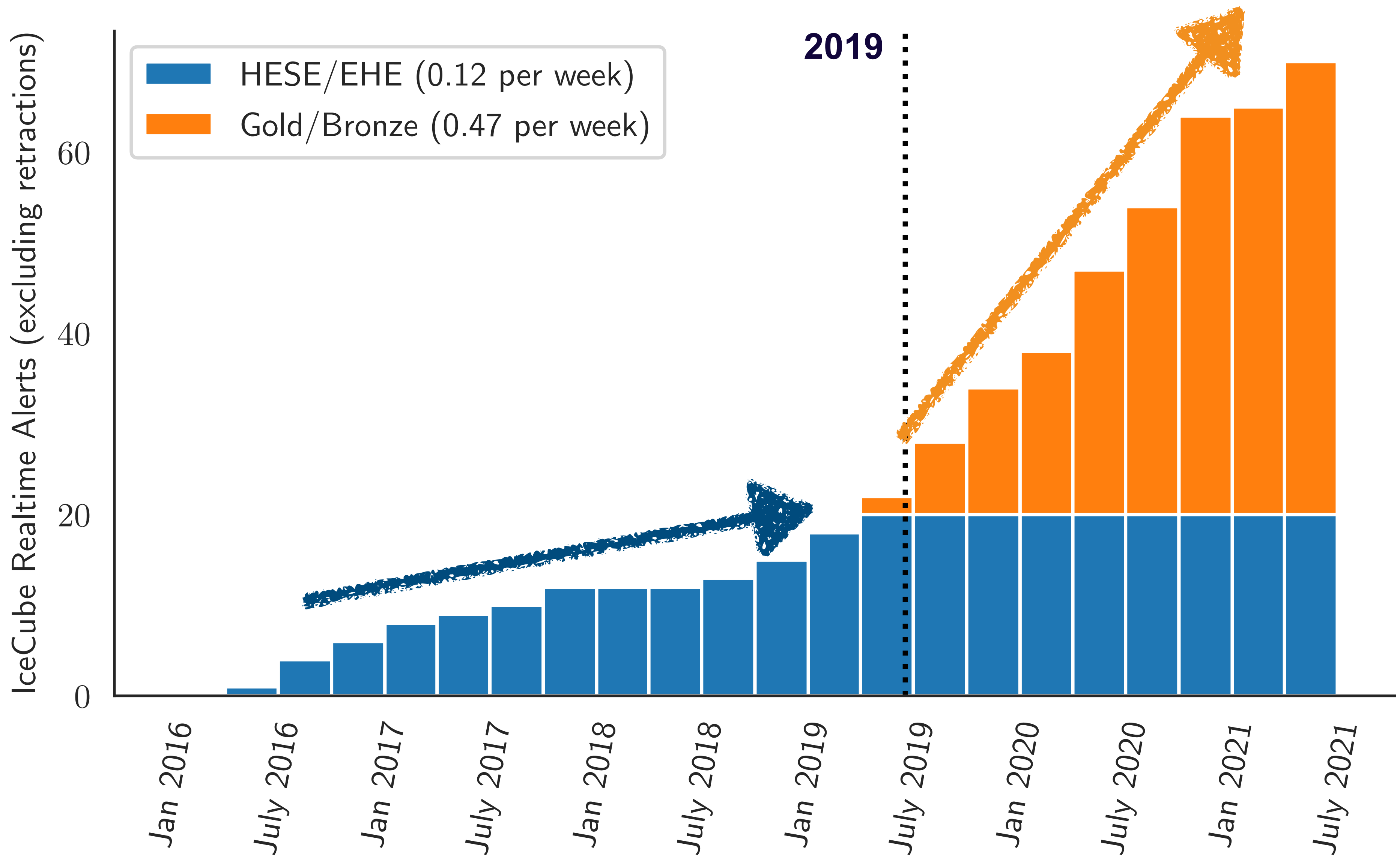
Neutrinos mostly of extragalactic origin.



+ TDE AT2019dsg, TDE/SLSN AT2019fdr & a dozen of likely associations?

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. Reusch et al., arXiv: 2111.09390. Abbasi et al., arXiv: 2111.10299. Pitik, Tamborra, Angus, Auchettl, arXiv: 2110.06944.

IceCube Alerts & Real Time Follow-Up

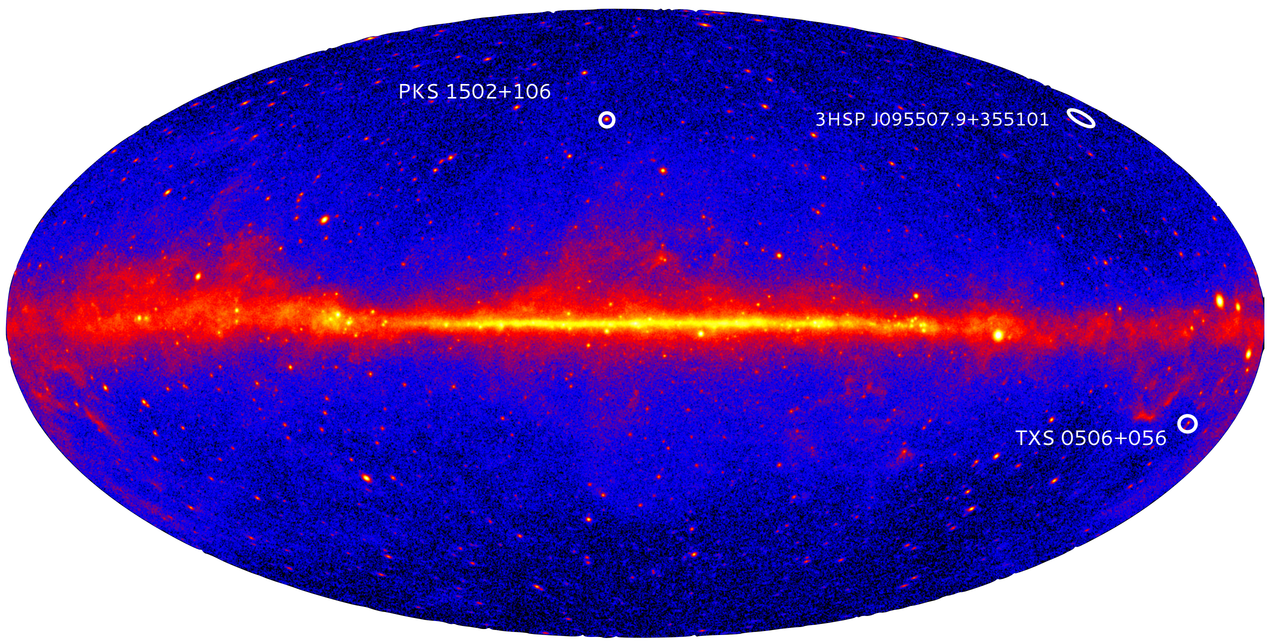


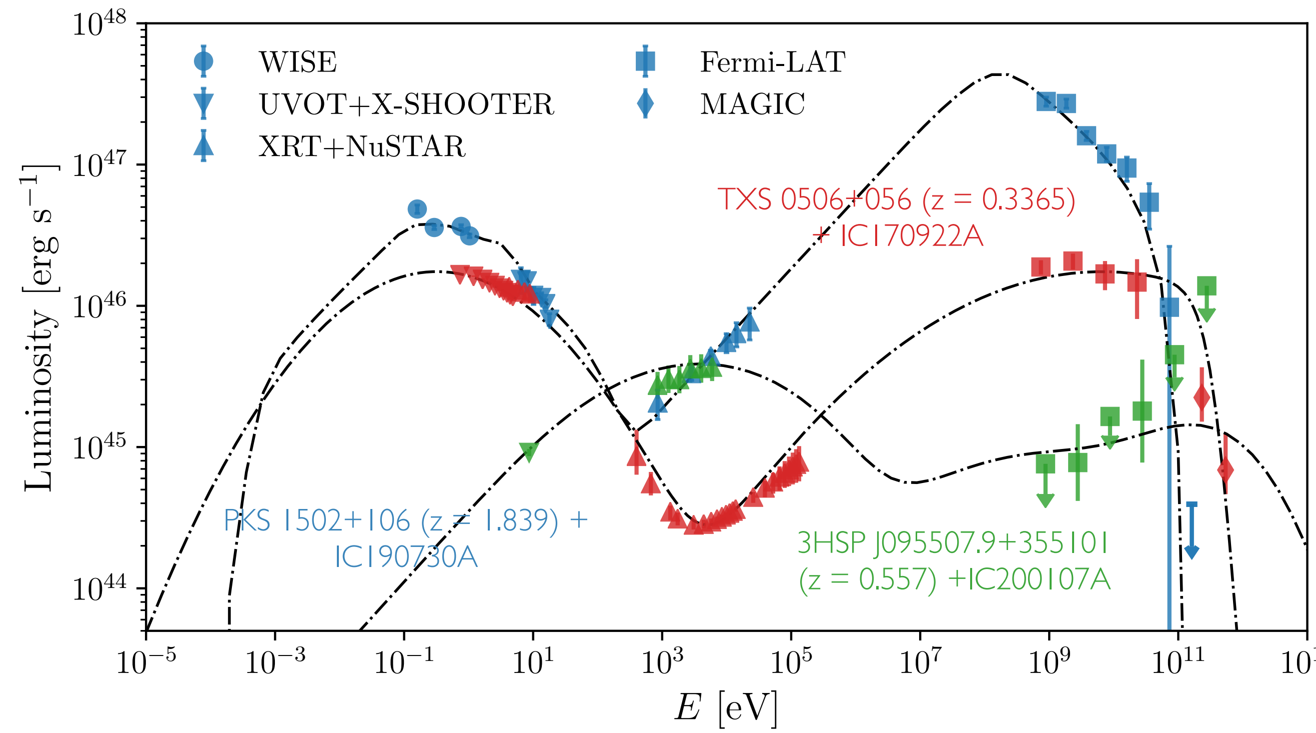
- IceCube releases alerts & responds to transient searches in real time.
- Used over 50 times (GRBs, FRBs, blazar flares, …); no significant detection.
- Current limits constrain nearby bright transients; future ones aim to constrain populations of sources.

Marek Kowalski, ICRC 2021, PoS 022.

High-Energy Neutrinos from Blazars?

Several IceCube neutrino events may be in coincidence with blazars.



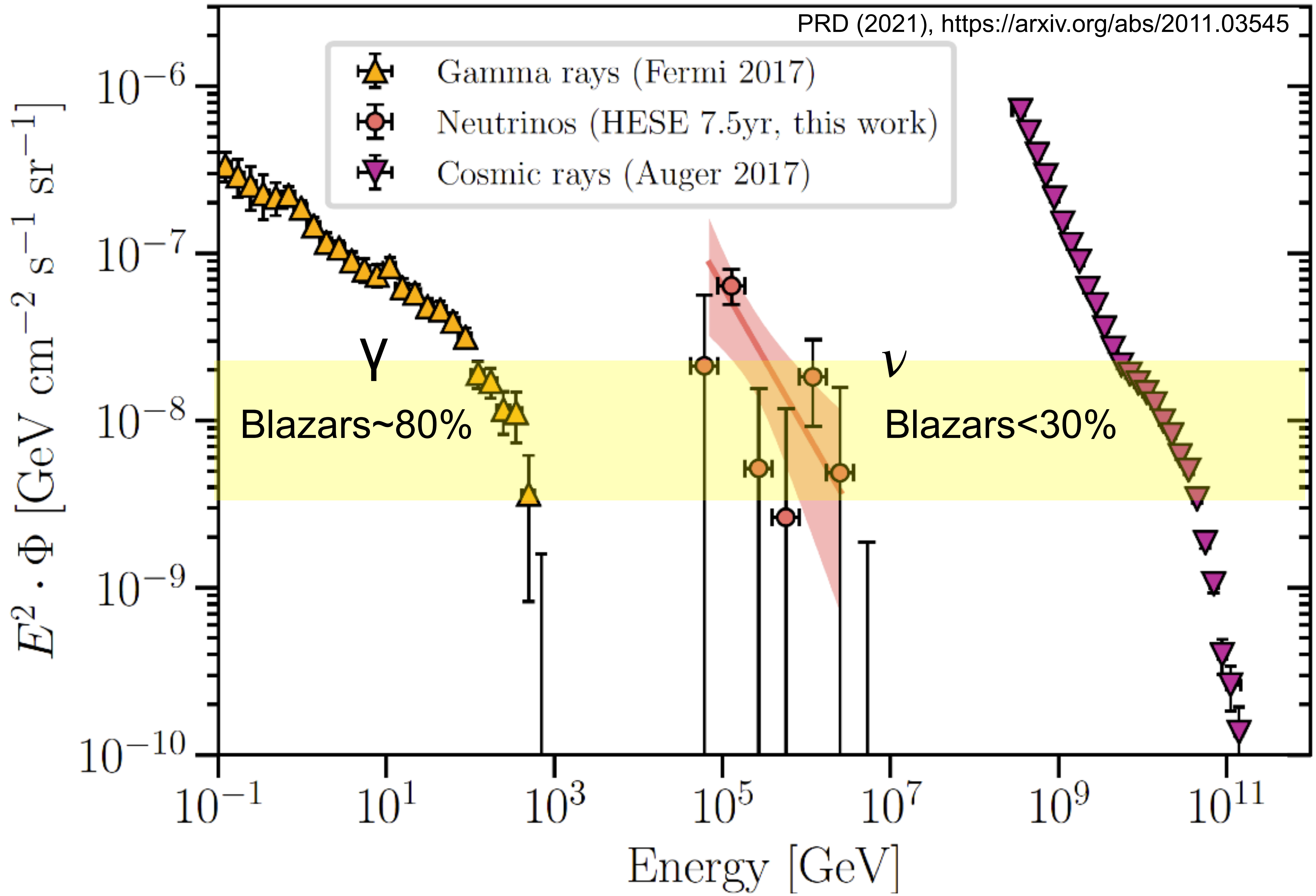


- Models statistically consistent with the detection of neutrinos but require extreme parameters, atypical of the blazar population.
- Need to move beyond one-zone model as well as investigate time variability.
- Where are neutrinos and photons produced?
- Multi-wavelength long-term evolution needs to be explored.
- Emerging trend of possible correlation between neutrino and radio/X-ray data to be understood.

Figure credit: Foteini Oikonomou.

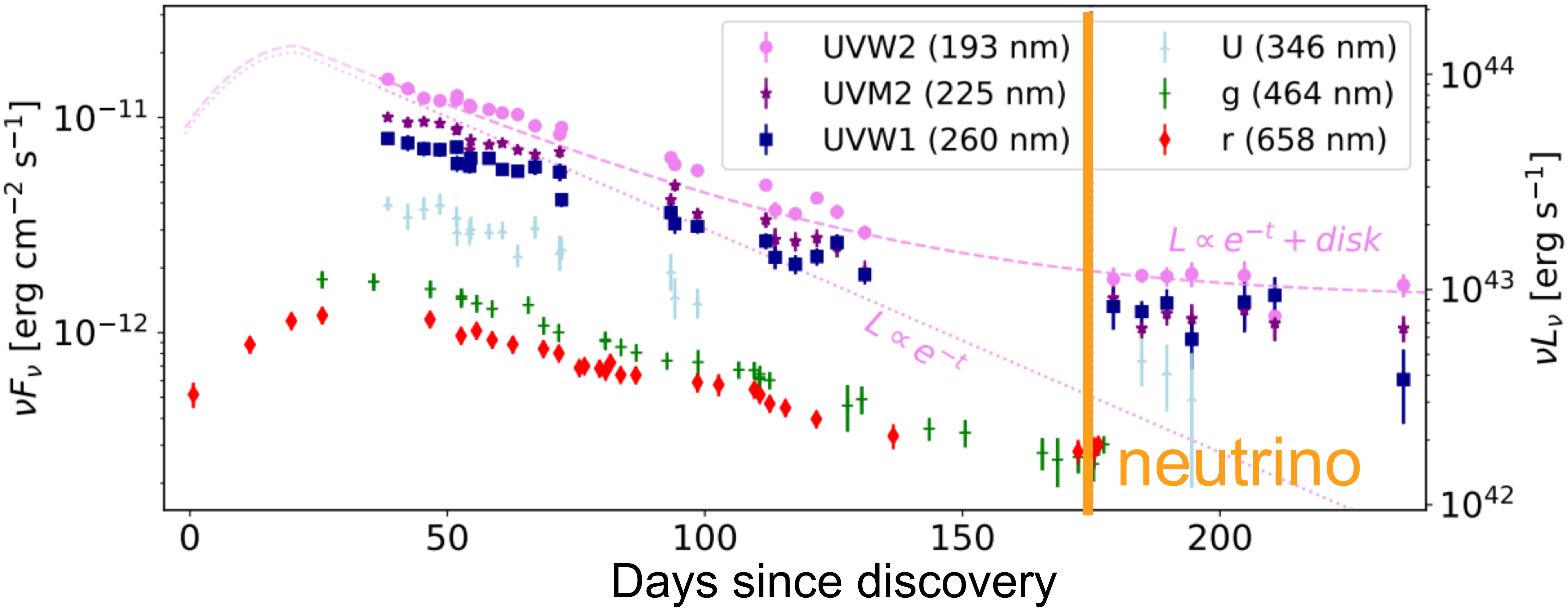
Where Are Neutrinos Coming From?

Do we really see a connection among all messengers?



Marek Kowalski, ICRC 2021, PoS 022.

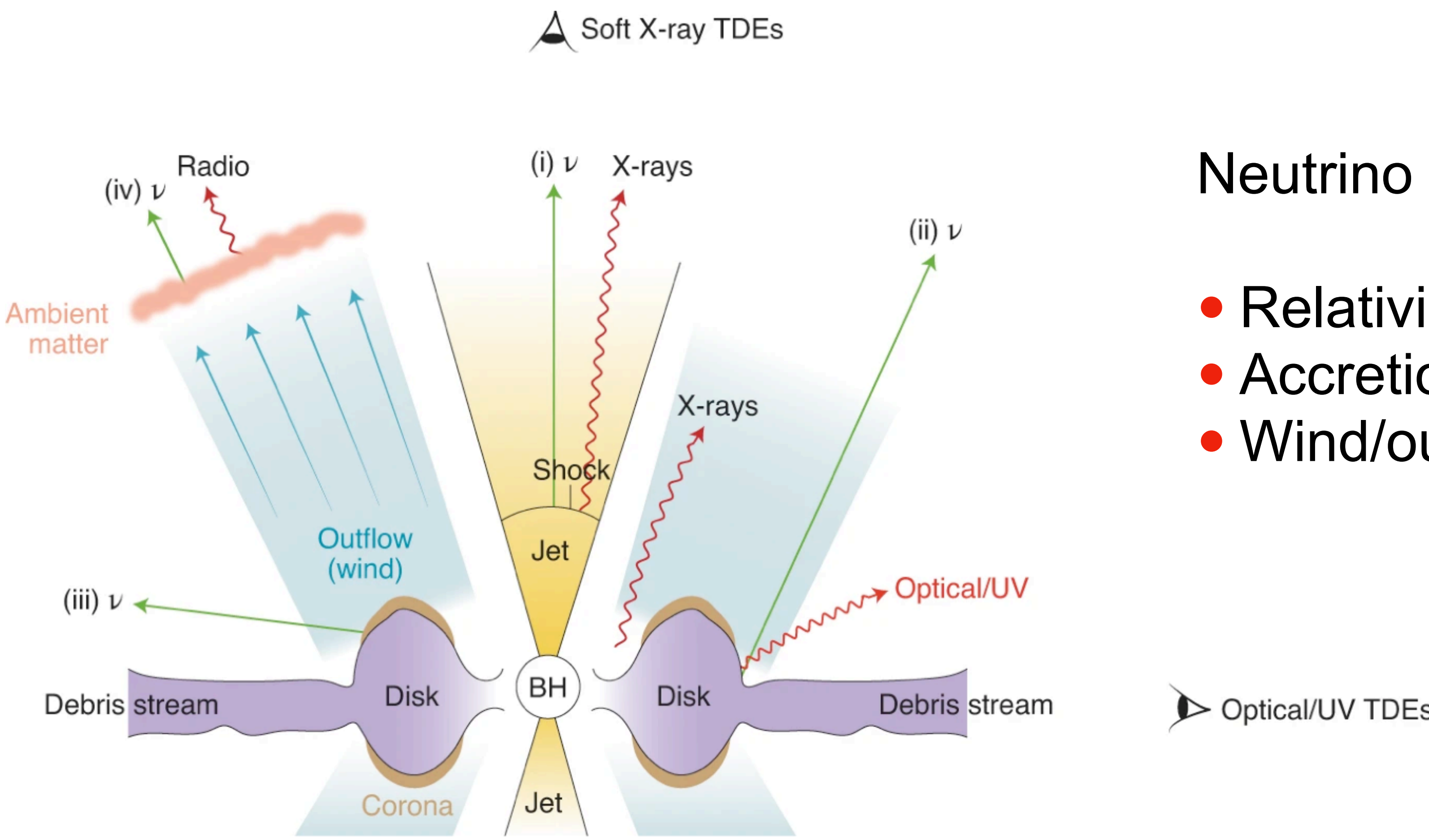
TDE AT2019dsg-IC191001A coincidence?



- Discovered by ZTF in April 2019. Second brightest ZTF TDE.
- Copious UV emission, rapid decay in X-rays, very large bolometric flux.
- Extended synchrotron emitting outflow emerging from radio analysis.
- Neutrino detected 175 days after discovery (0.2 PeV).

Stein et al., Nature Astronomy (2021).

TDE AT2019dsg-IC191001A coincidence?



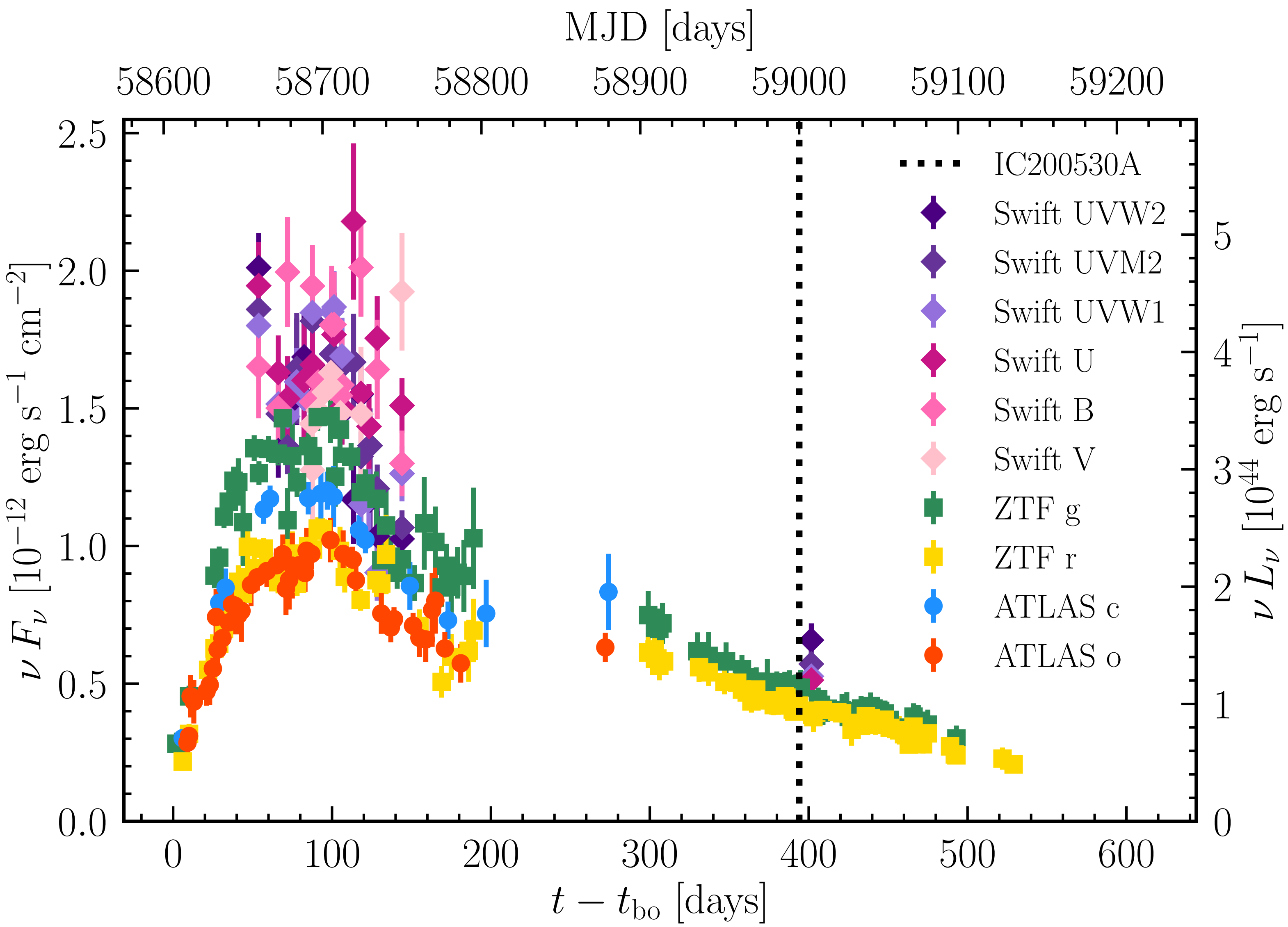
Neutrino production sites include:

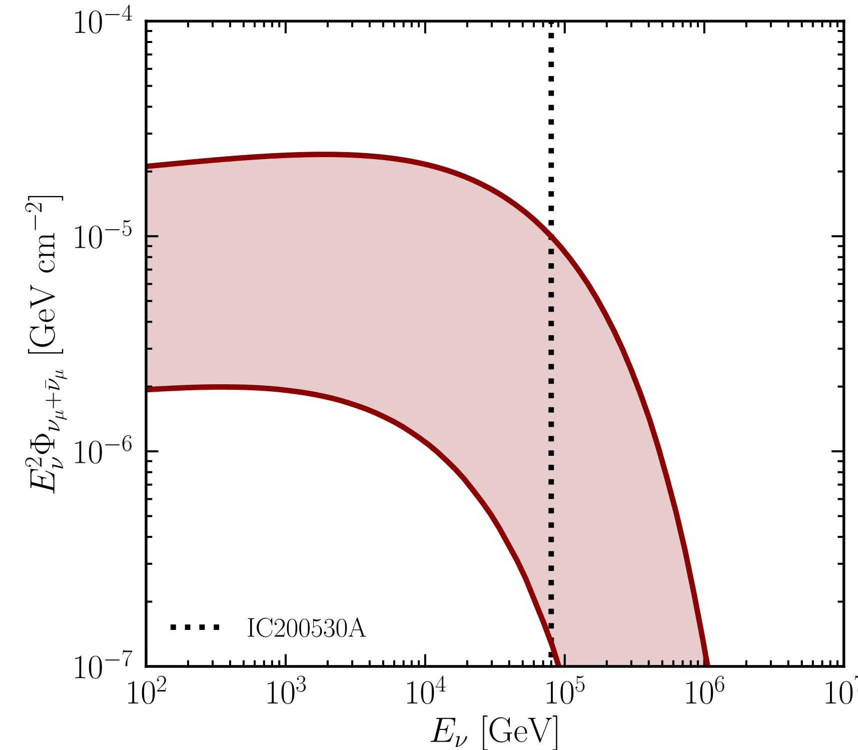
- Relativistic jet
- Accretion disk/corona
- Wind/outflow

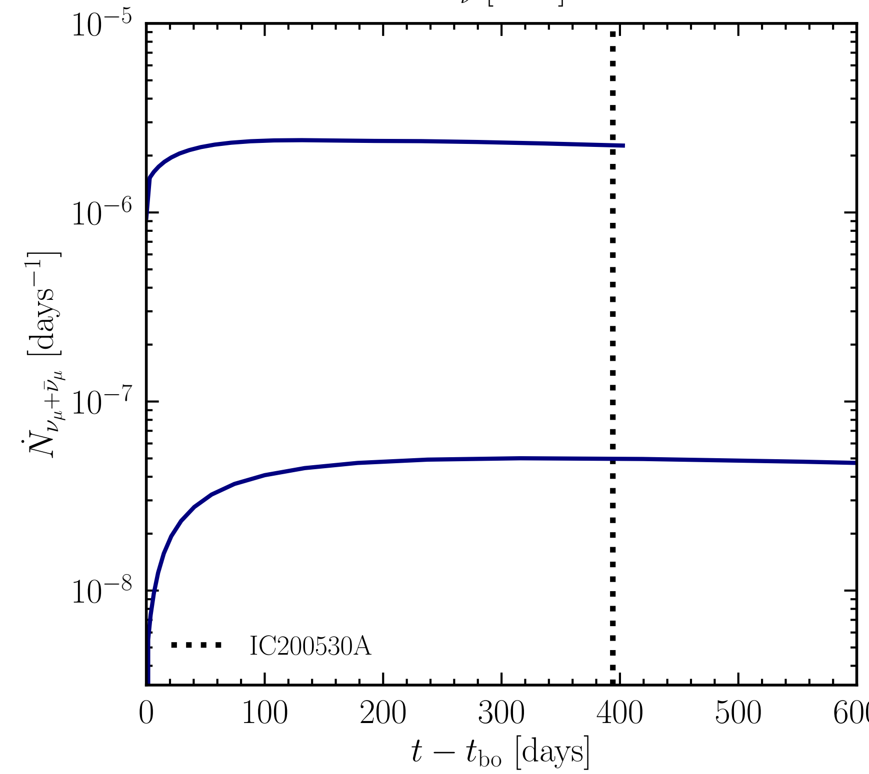
- Conditions appear consistent with the production/detection of one PeV neutrino.
- Various theoretical scenarios currently under debate.

K. Hayasaki, arXiv: 2102.11879. Winter & Lunardini, Nat. Astr. (2021). Liu et al., PRD (2020). Murase et al., ApJ (2020).

Another TDE-Neutrino Association?



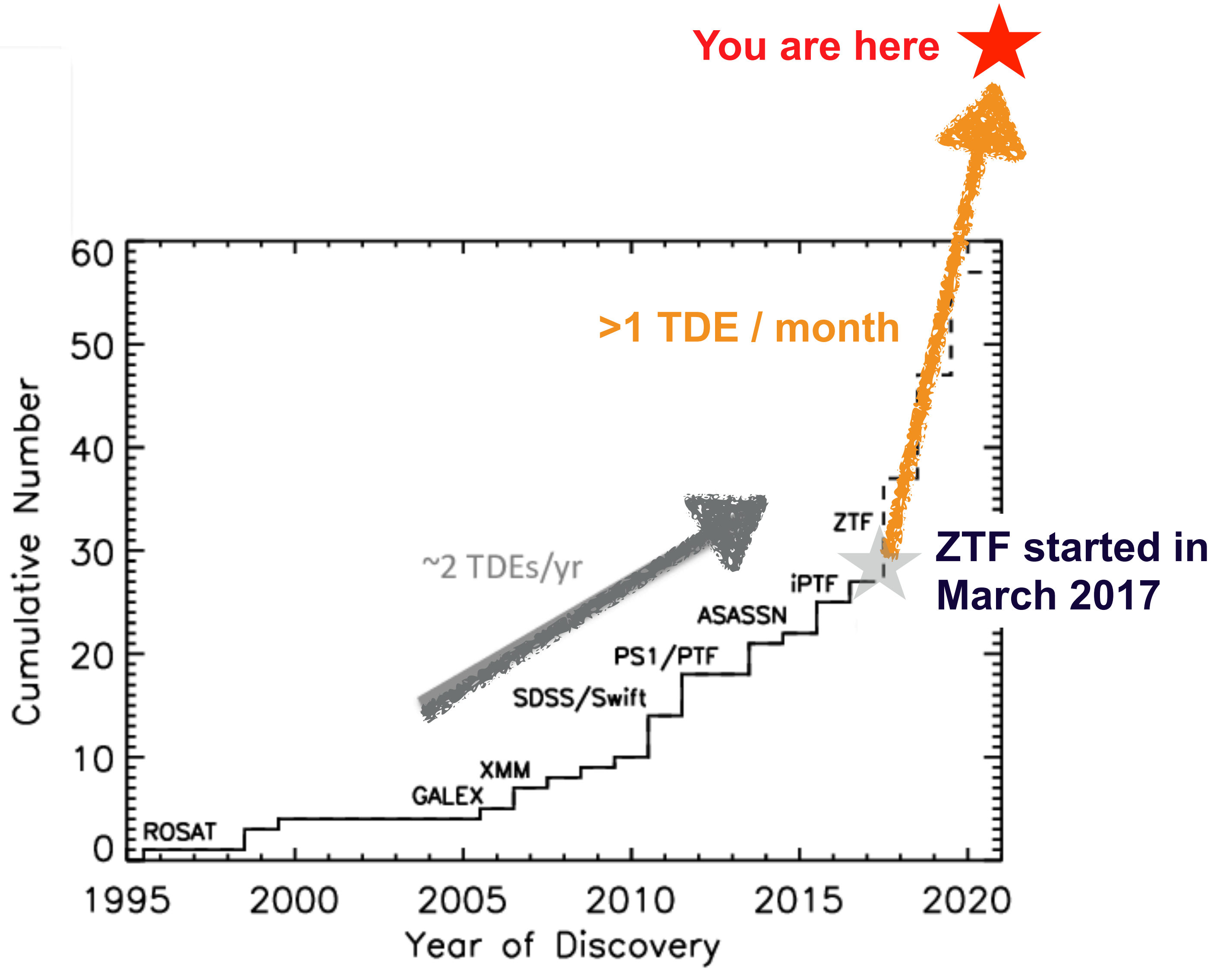




- Second event, AT 2019fdr, coincident with another neutrino event (IC200530A, 80 TeV).
- Is AT2019fdr a TDE in a narrow-line Seyfert Galaxy or a superluminous supernova?

Reusch et al., arXiv: 2111.09390. Pitik, Tamborra, Angus, Auchettl, arXiv: 2110.06944.

TDE-Neutrino Associations

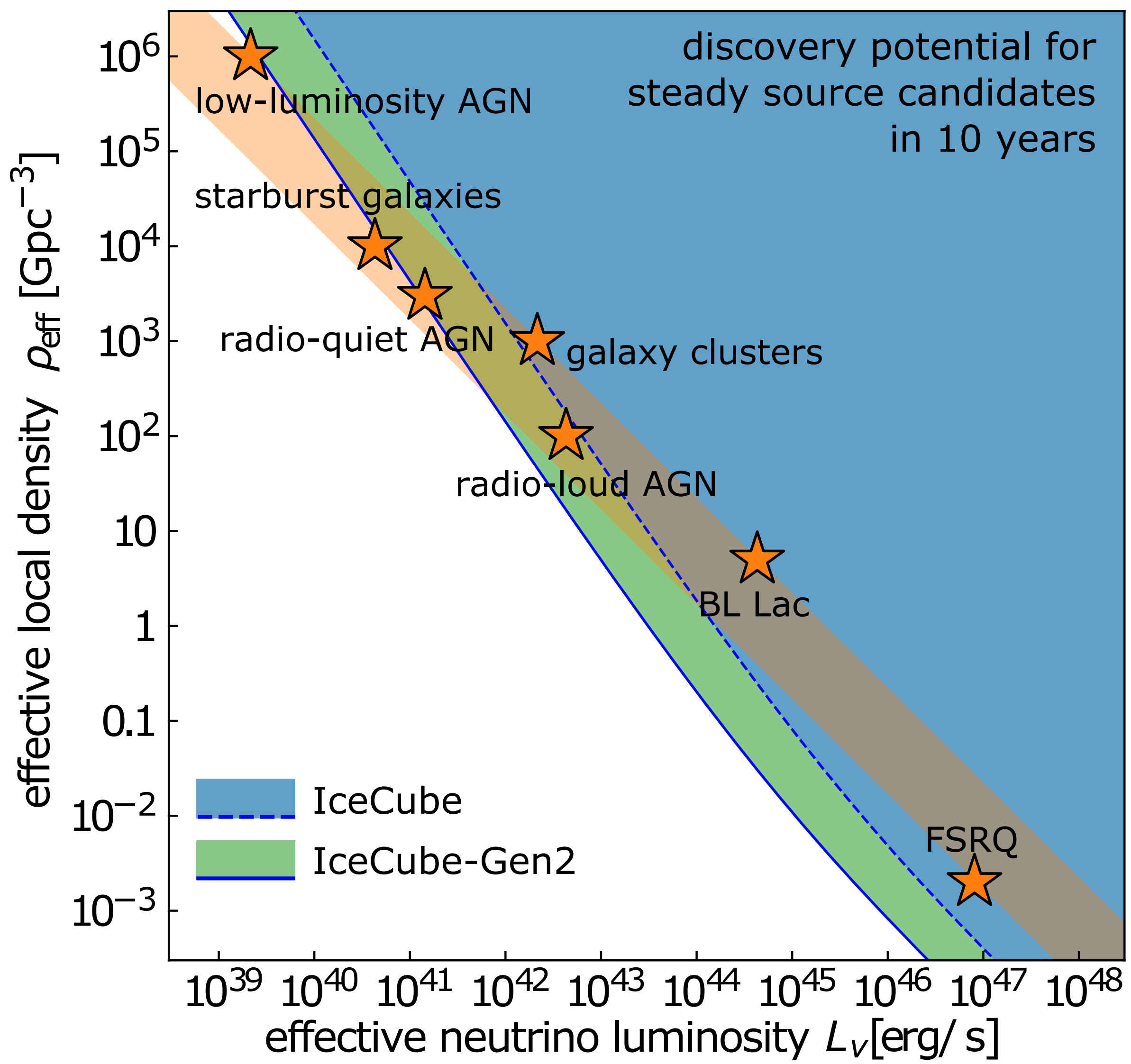


- We are entering a new era for the detection of TDEs, does this have implications on neutrino detection?
- Where are the neutrinos produced?
- Need to improve on our understanding of the TDE population.

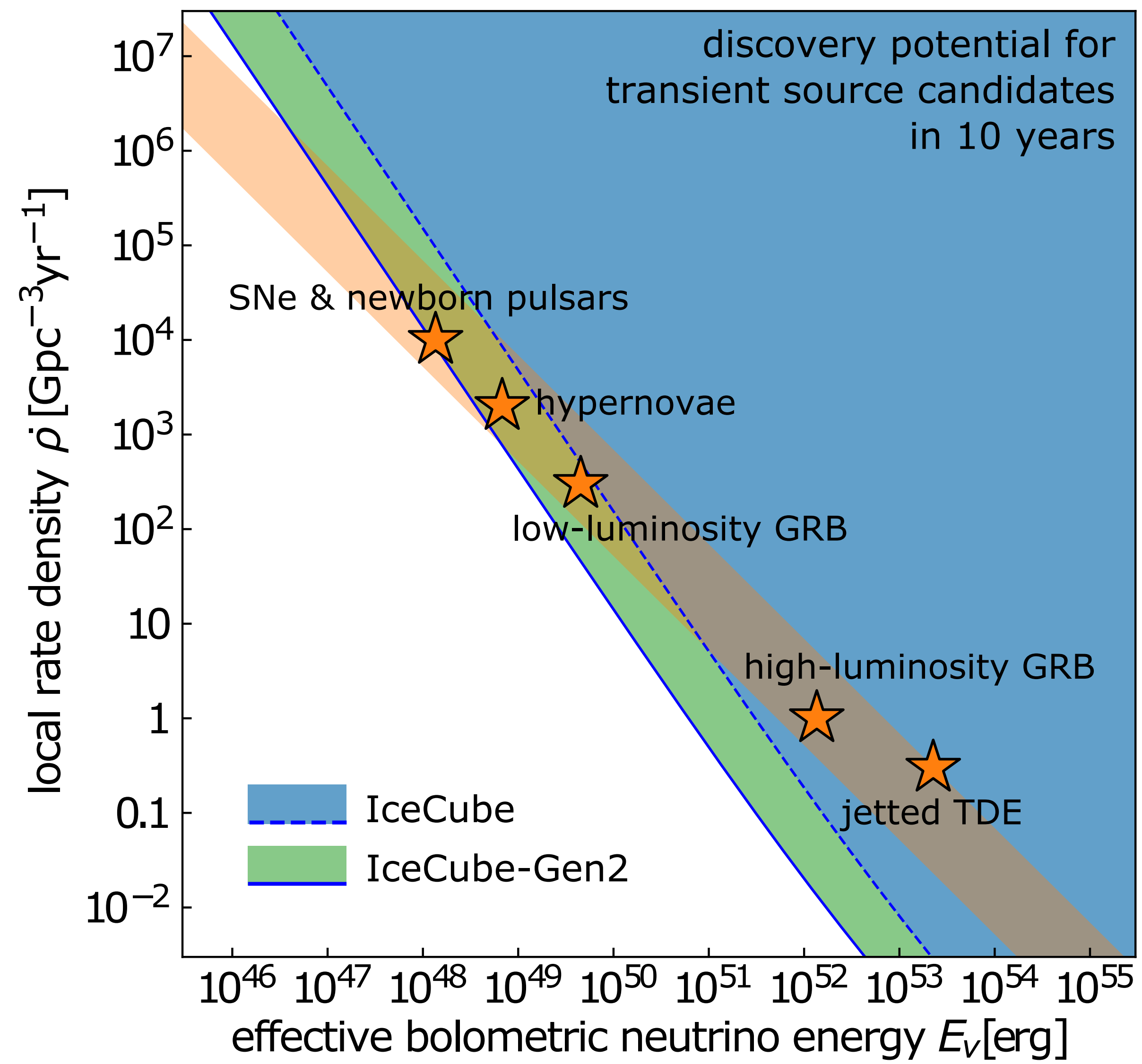
Figure credit: Robert Stein.

Neutrino Sources

Steady sources



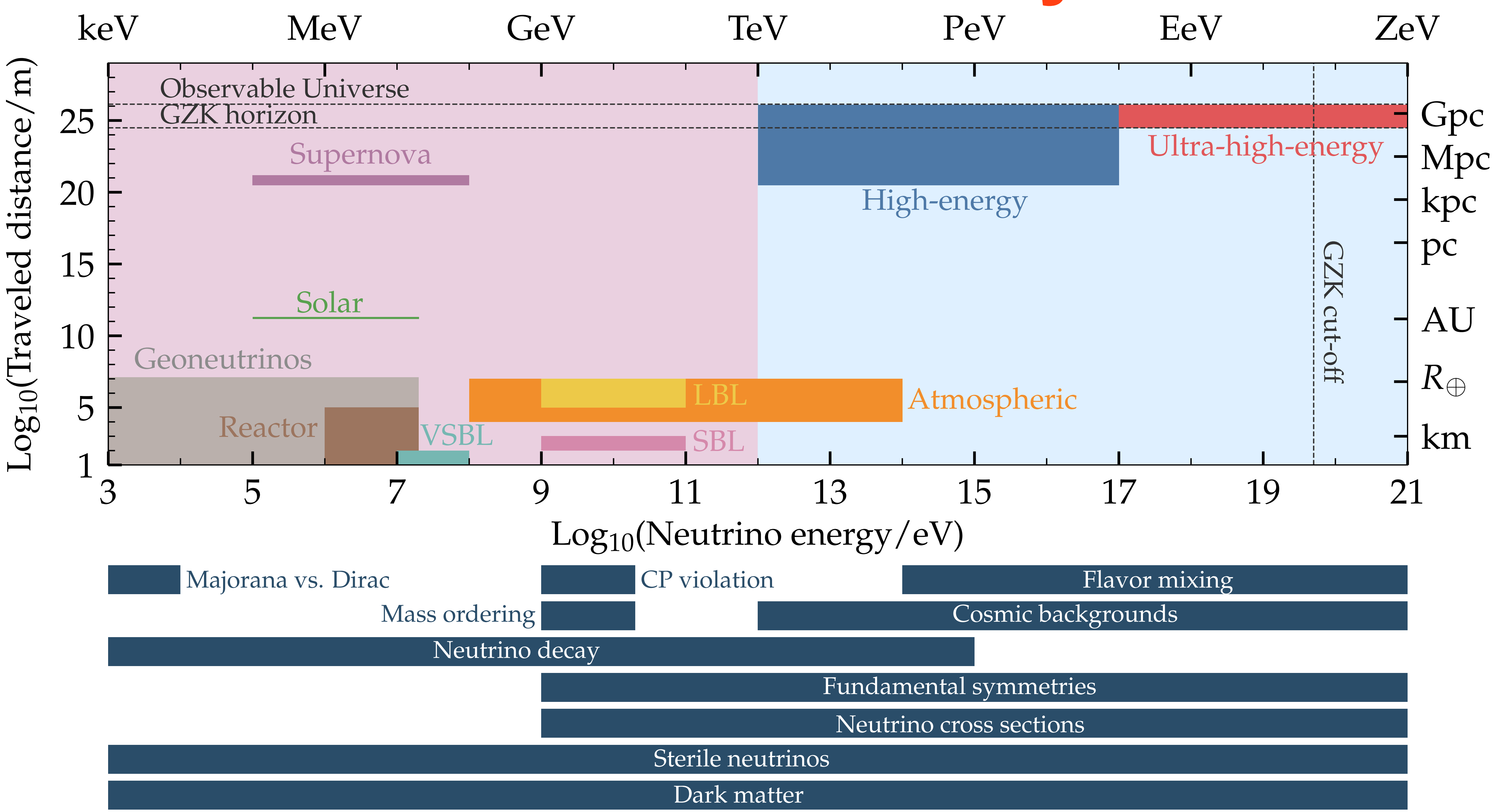
Transient sources



IceCube data can already constrain, e.g. magnetic field, redshift evolution of the sources, effective local density.

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). Bustamante & Tamborra, PRD (2020). Winter, PRD (2013).

What About New Physics?



- Non-standard physics may impact the neutrino emission properties and the duration of the neutrino burst.
- Non-standard physics may have an effect on the source physics.

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

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 physics. Sources unknown. Growing number of likely associations.**

Thank you!