The Niels Bohr International Academy

DARK

Neutrino Counterparts of Gravitational Wave Sources

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XIX International Workshop on Neutrino Telescopes
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VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

SFB 1258 Neutrinos Dark Matter Messengers

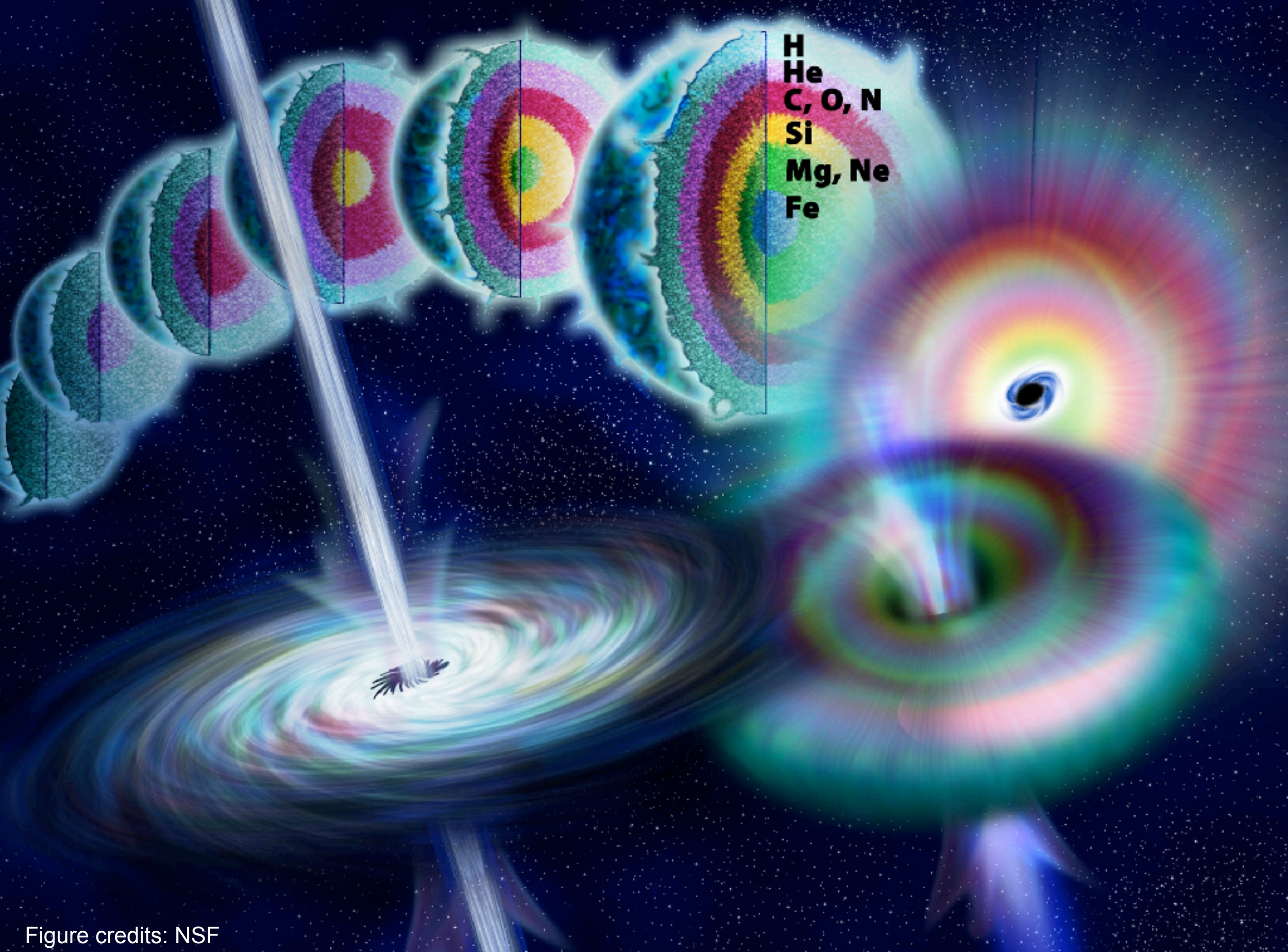


Figure credits: NSF

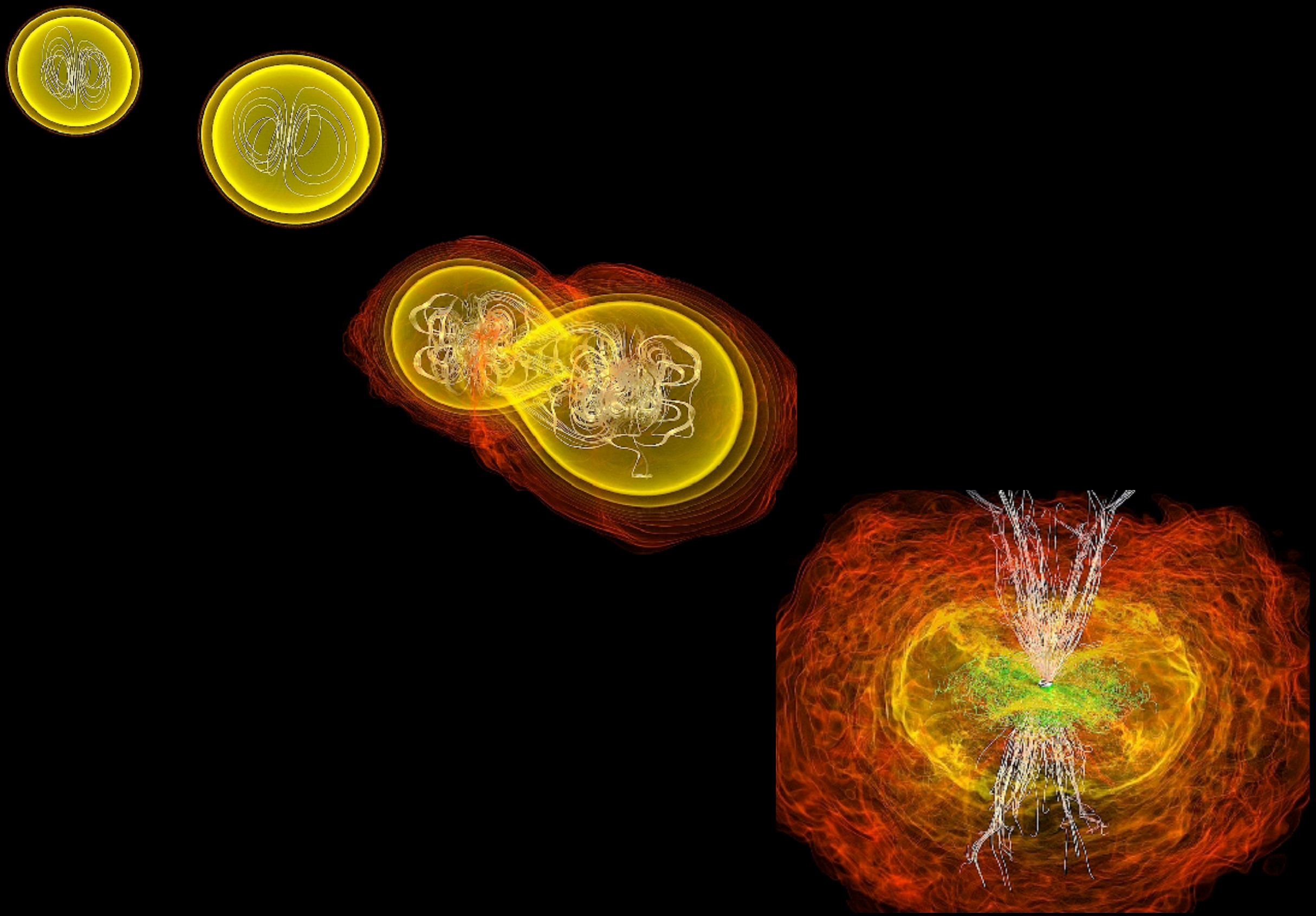
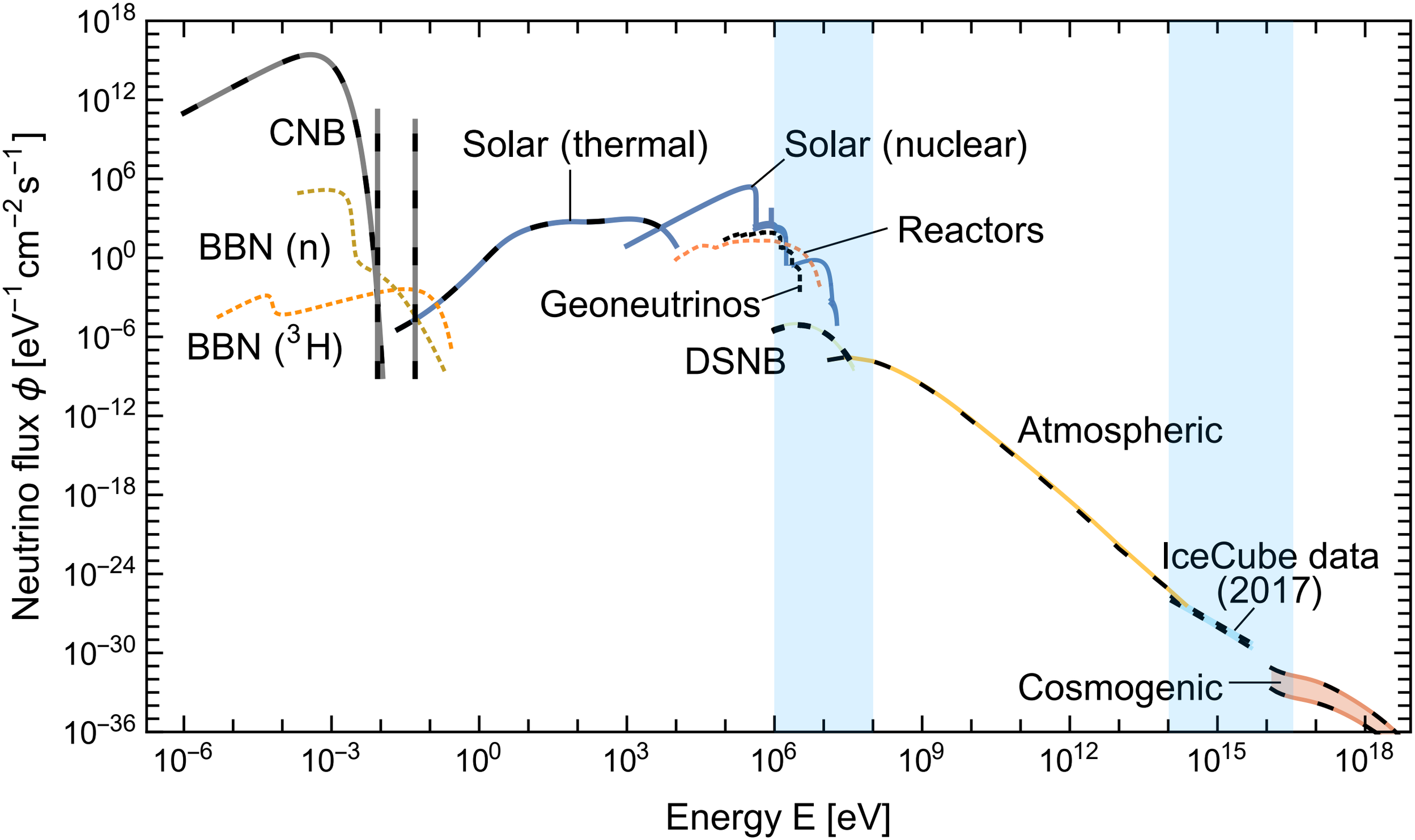


Figure credits: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

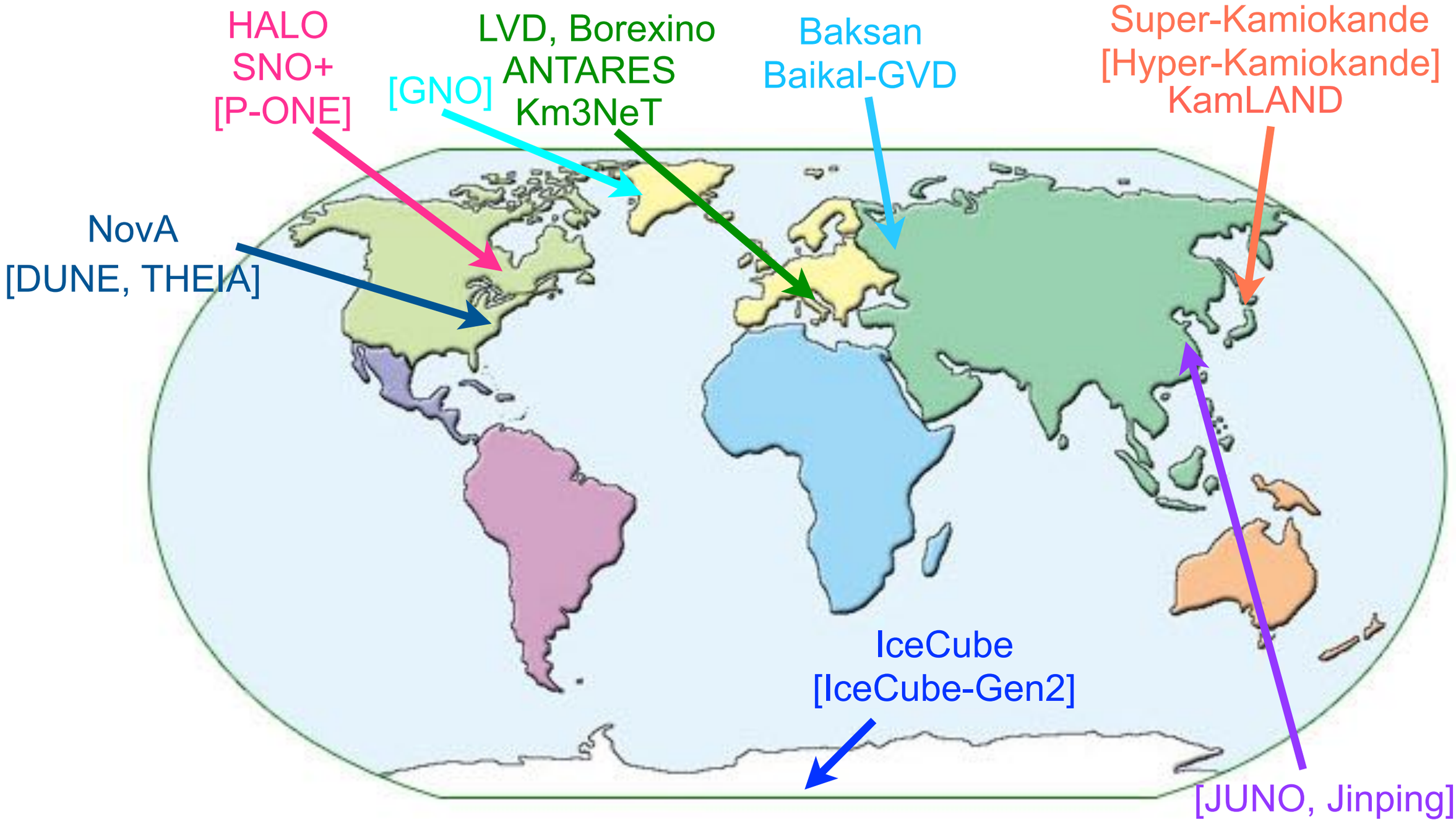
Neutrino Counterparts

Grand Unified Neutrino Spectrum



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

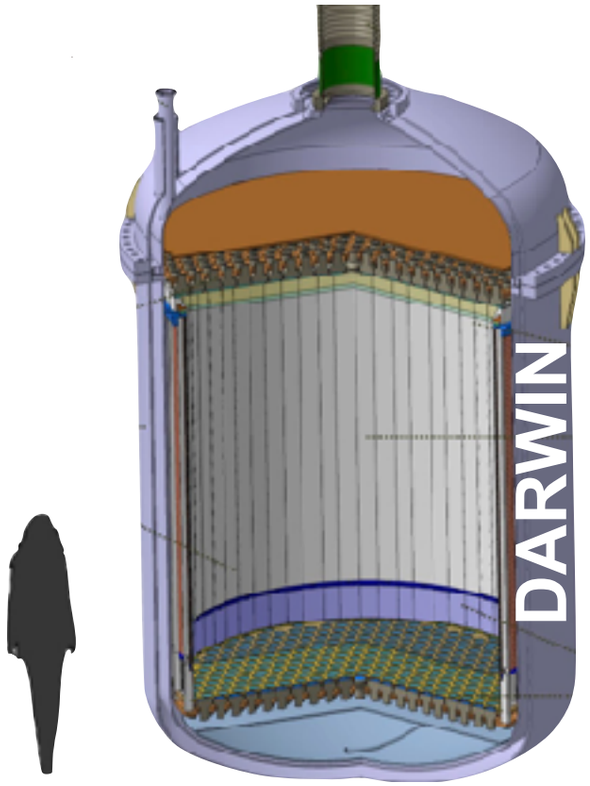
Neutrino “Telescopes”



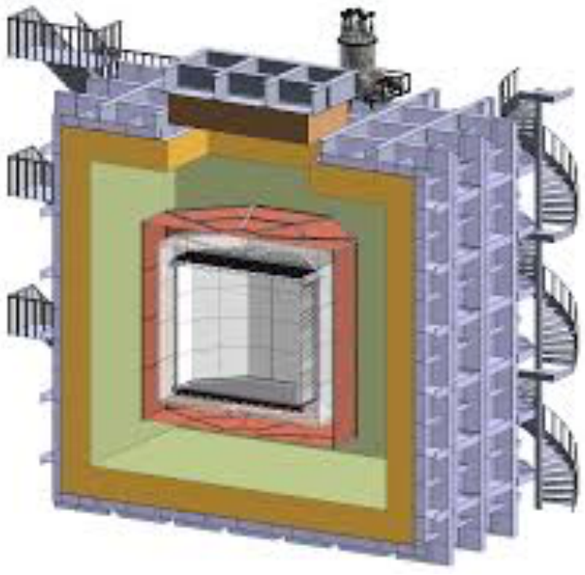
Fundamental to combine astrophysical signals from detectors employing different technologies (e.g., Cherenkov and liquid scintillator detectors).

Neutrino “Telescopes”

Neutrino Telescopes Based on Coherent Scattering



DarkSide-20k & ARGO



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

See talks by L. Pattavina, R. Peres

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.

Core-Collapse Supernovae

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

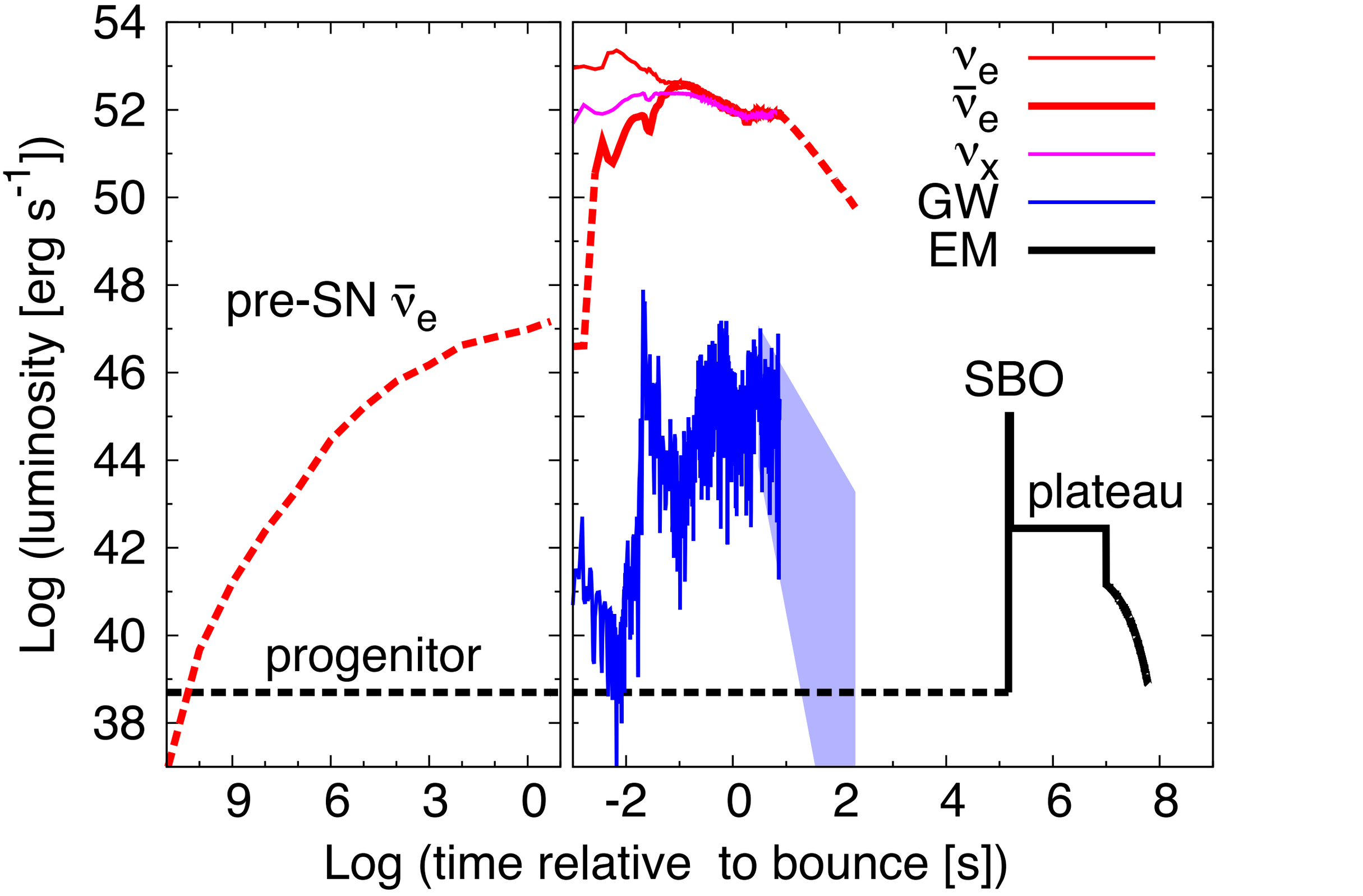
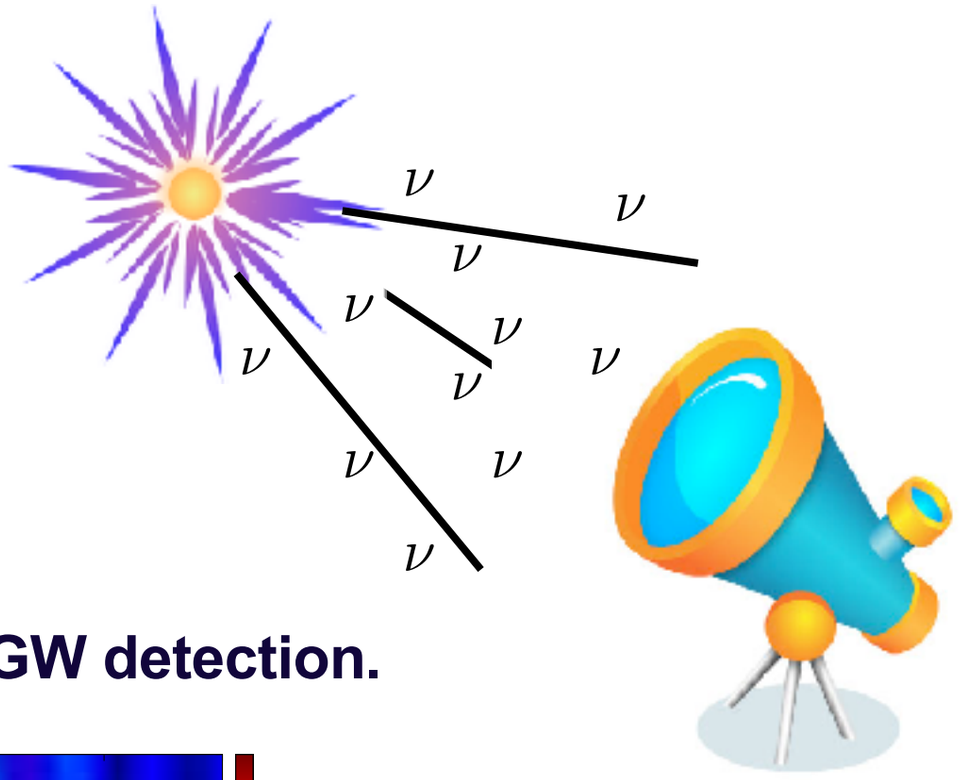


Figure from Nakamura et al., MNRAS (2016).

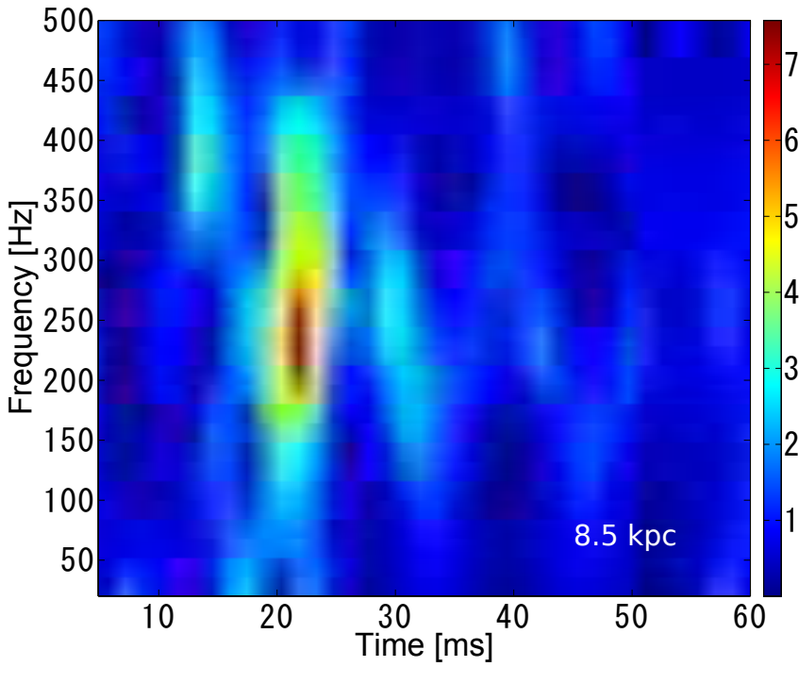
Neutrino Alert

SuperNova Early Warning System 2.0.

Supernova direction and distance.



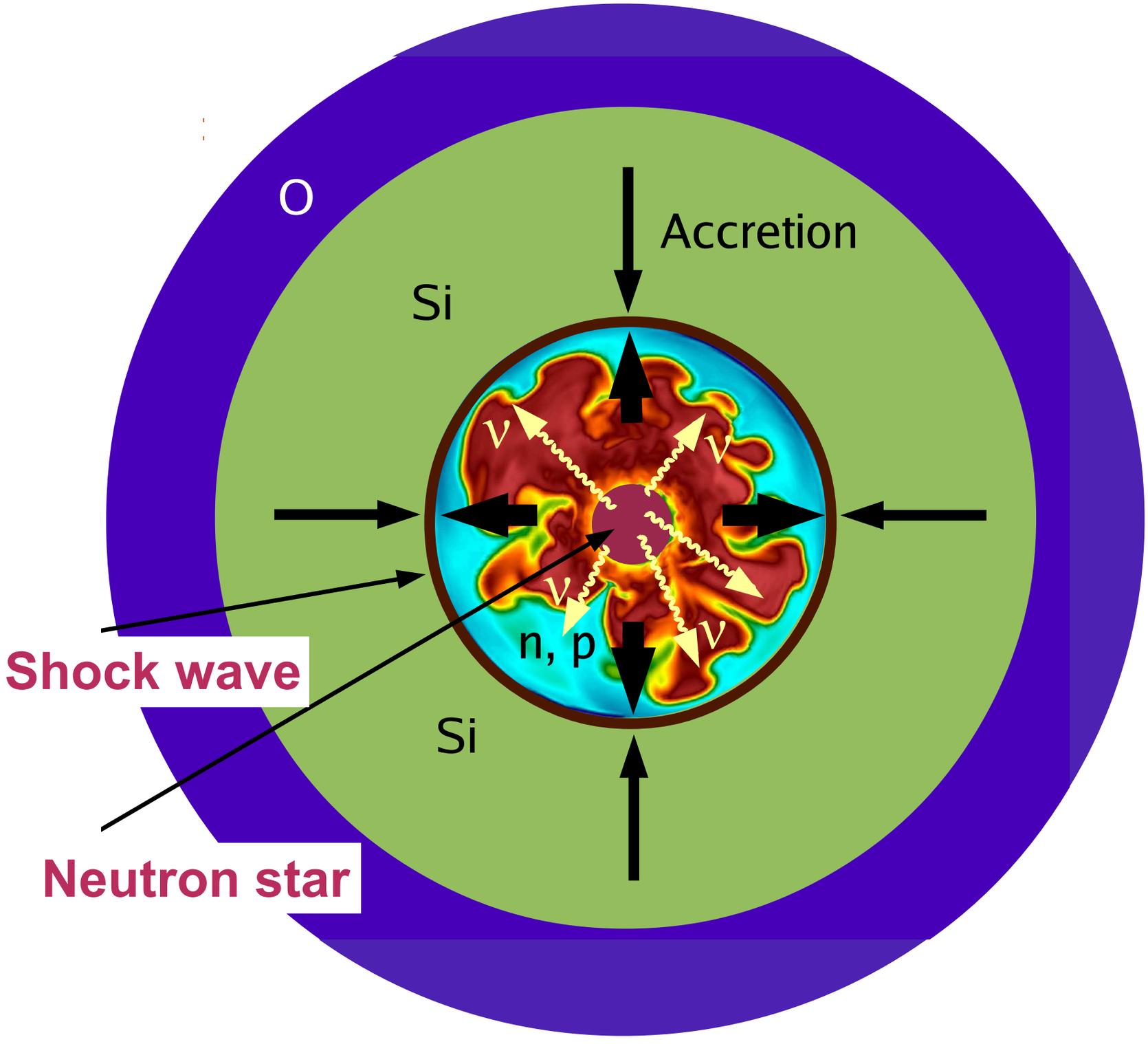
Neutrino timing for GW detection.



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

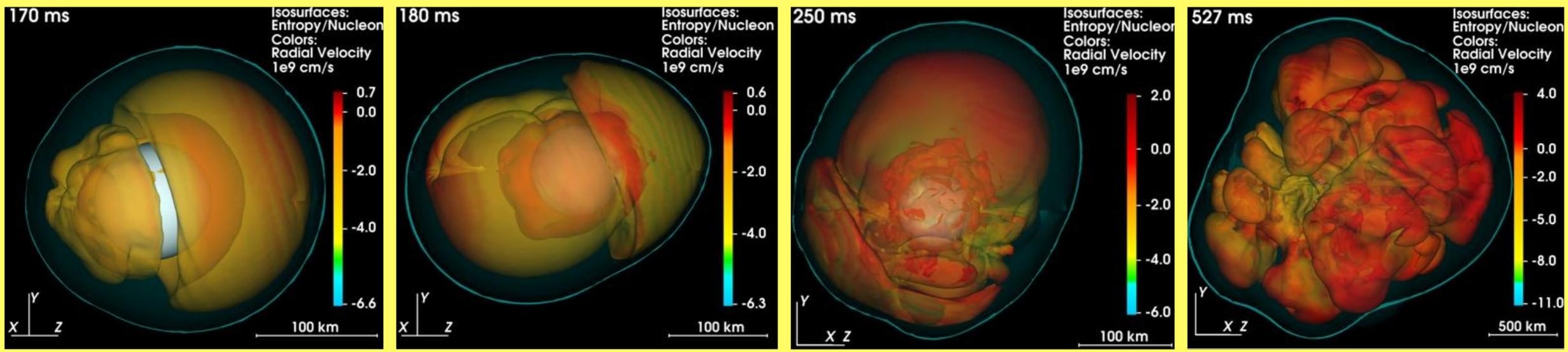
Shock wave forms within the iron core. It dissipates energy by dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.

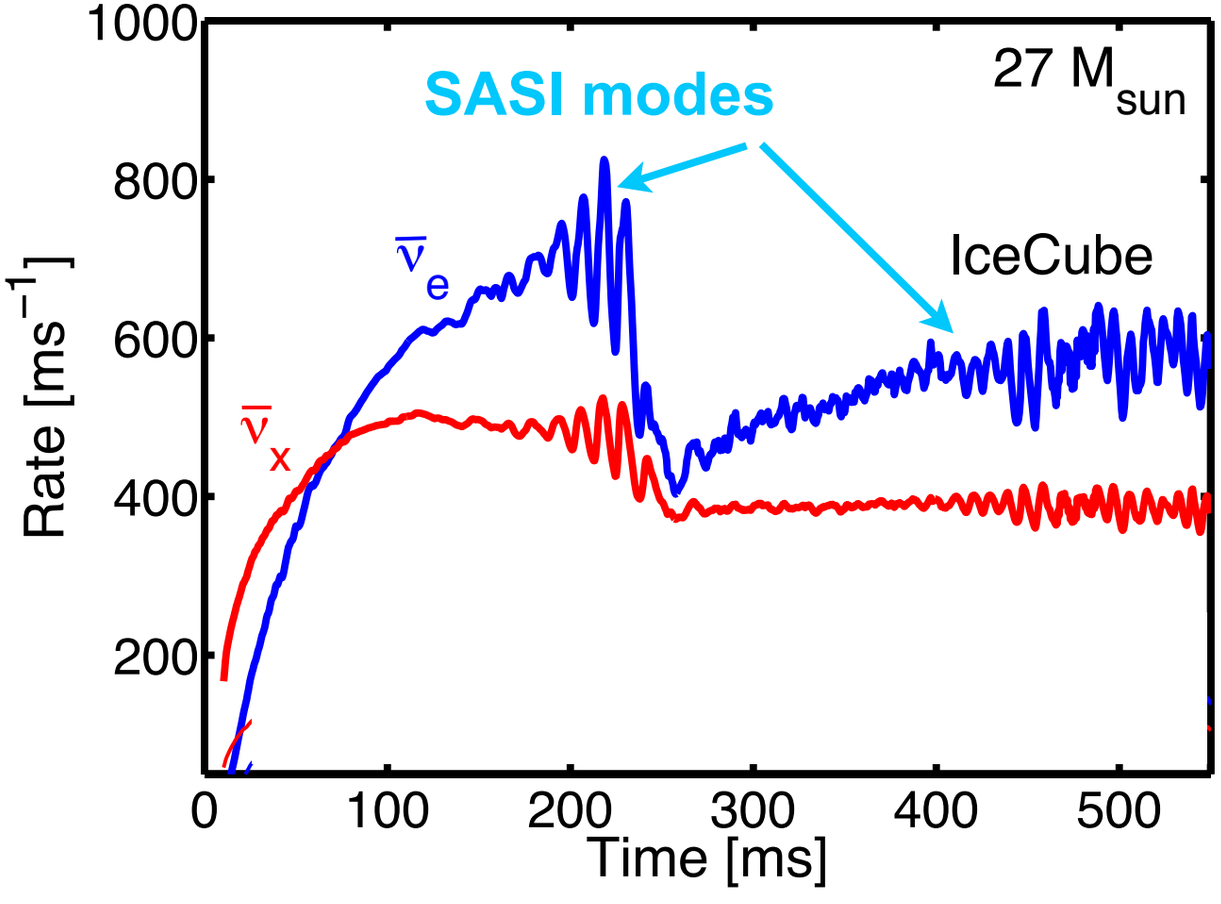


Recent reviews: Burrows & Vartanyan (2021). Janka (2017). Mirizzi, Tamborra et al. (2016).

Supernova Explosion Mechanism

Standing Accretion Shock Instability (SASI)

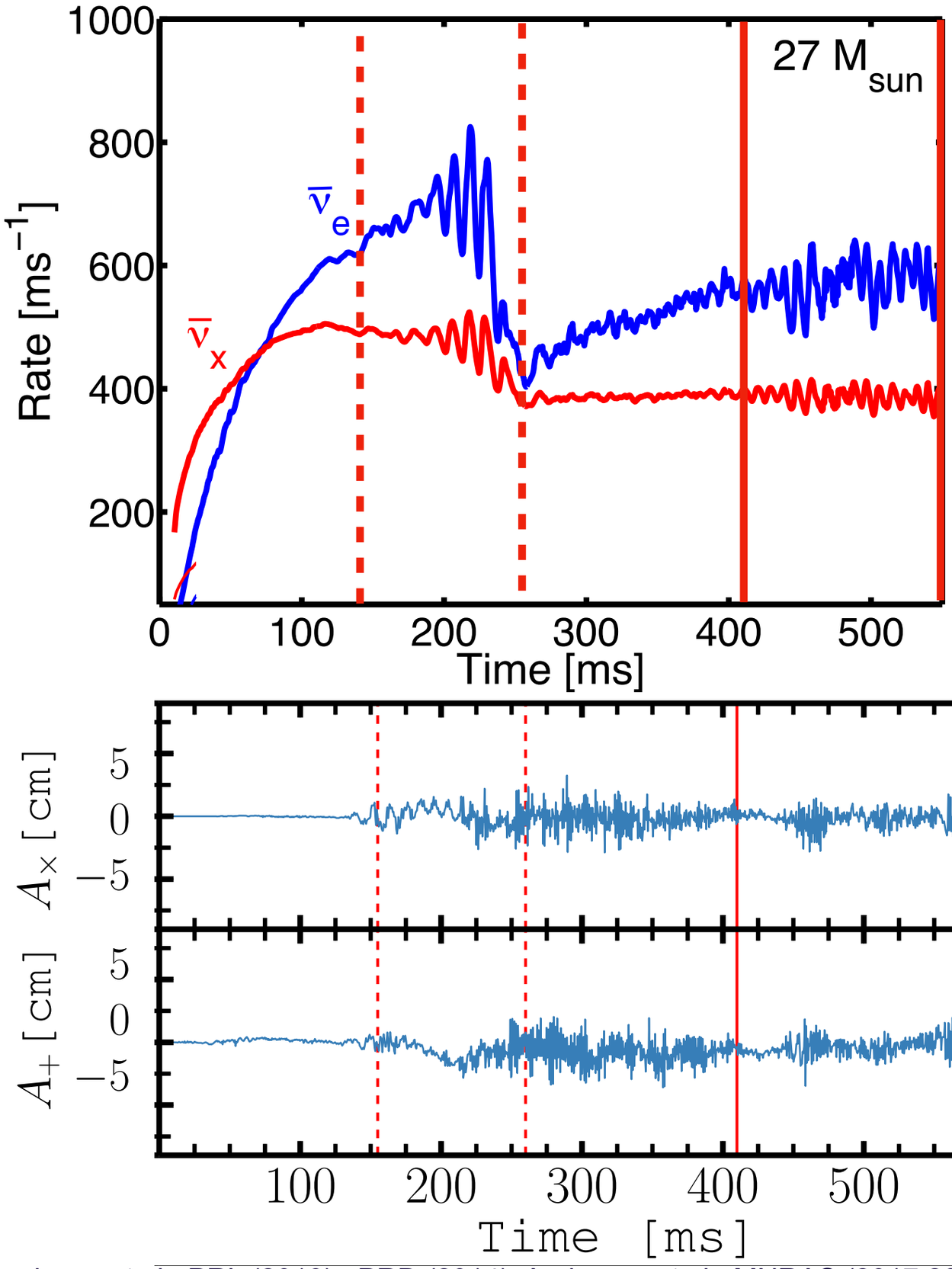




SASI frequency: O(85) Hz.

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

Supernova Explosion Mechanism

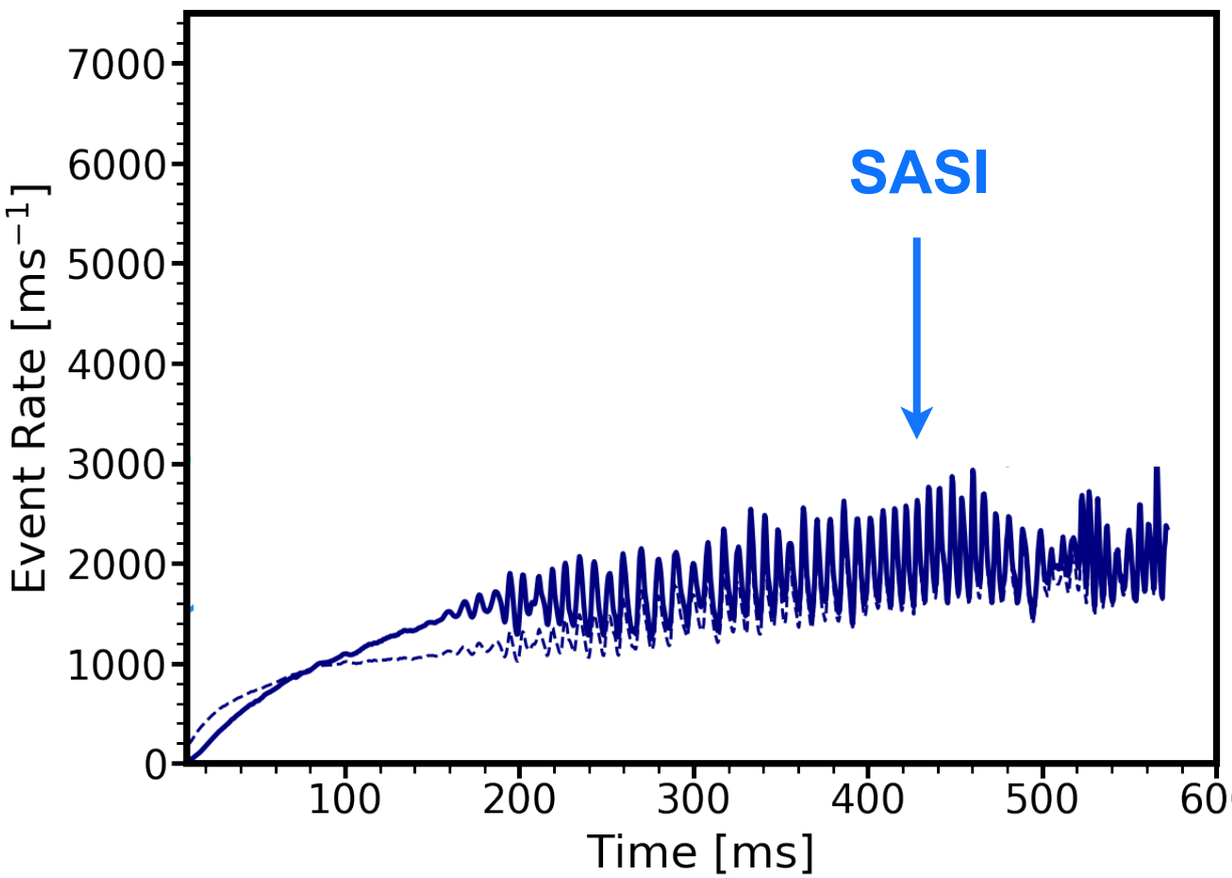


Neutrinos

Gravitational waves

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

Black Hole Forming Collapses

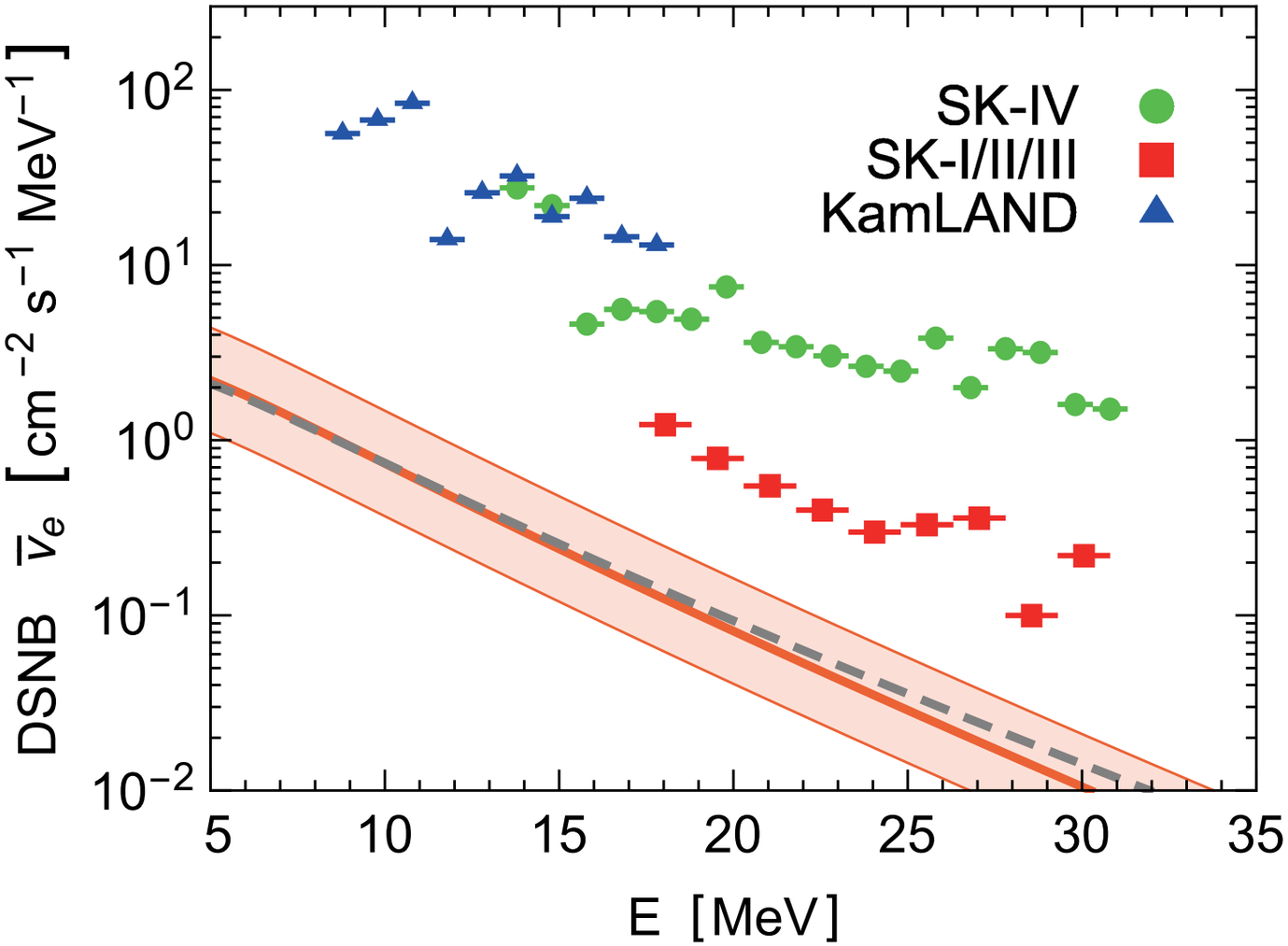


Neutrinos and gravitational waves probe black hole formation.

SASI frequency evolution
= Shock radius evolution

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

Diffuse Supernova Neutrino Background

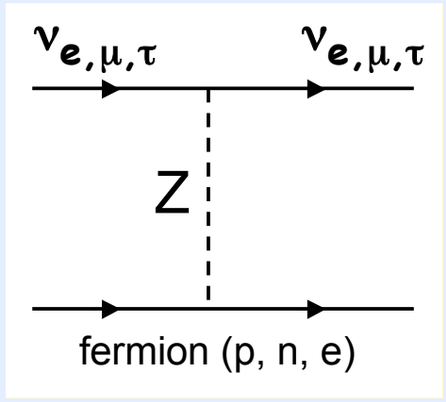


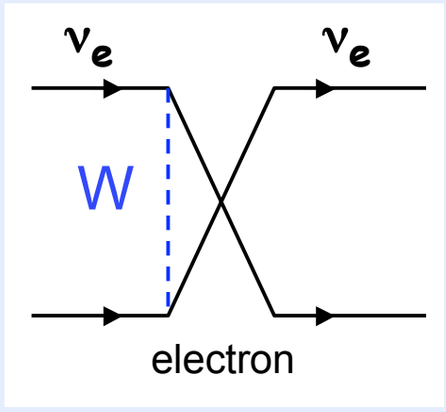
- The diffuse supernova neutrino background is a **guaranteed** signal!
- Independent test of supernova rate.
- Constraints on fraction of black hole forming collapses.
- Affected by binary interactions (mass transfer and mergers).

See talks by A. Giampaolo, H. Li

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).

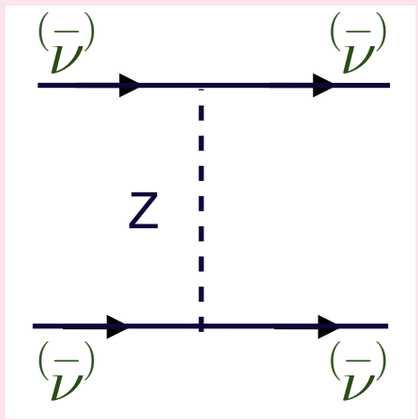
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

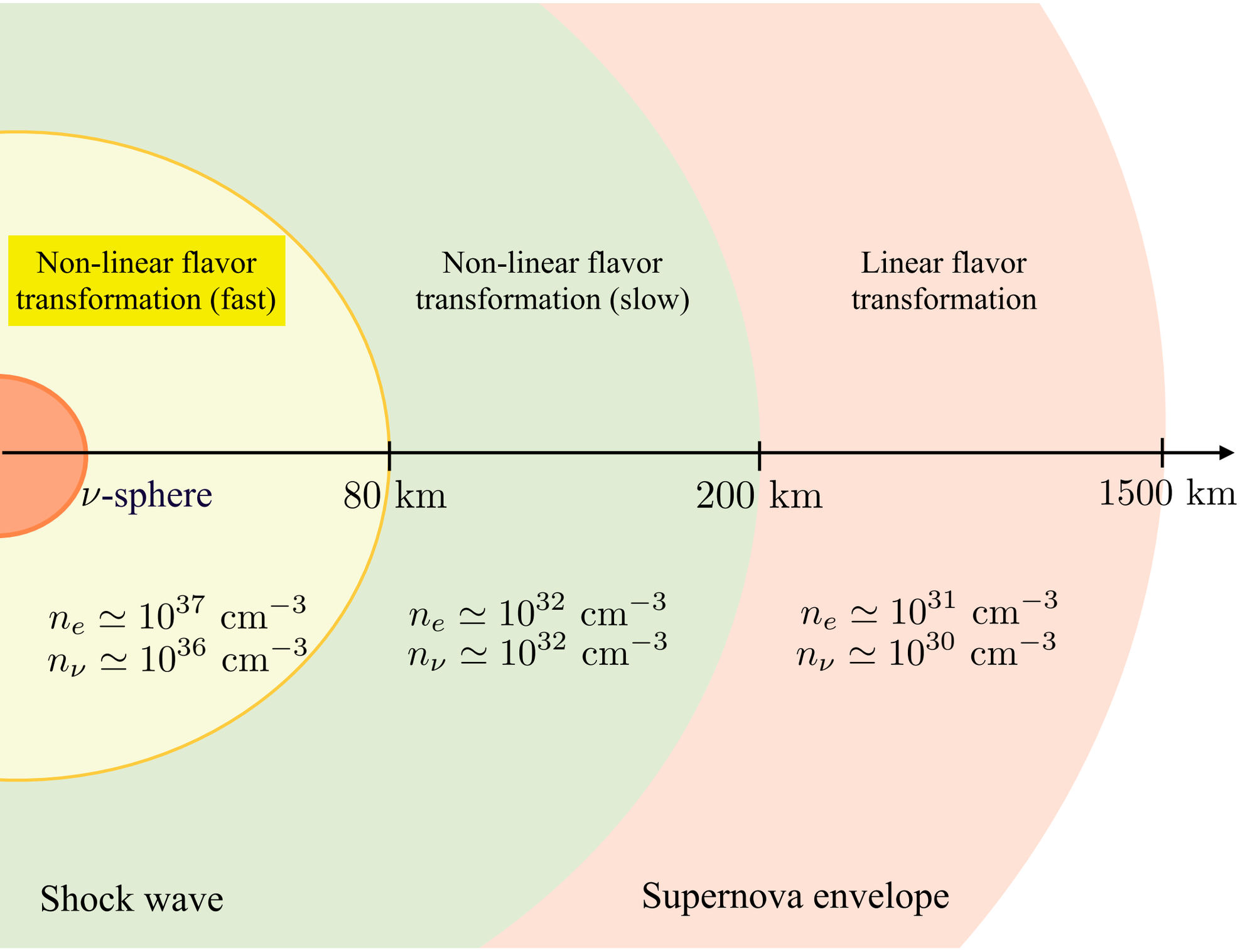


Neutrinos interact among themselves.

Non-linear phenomenon!

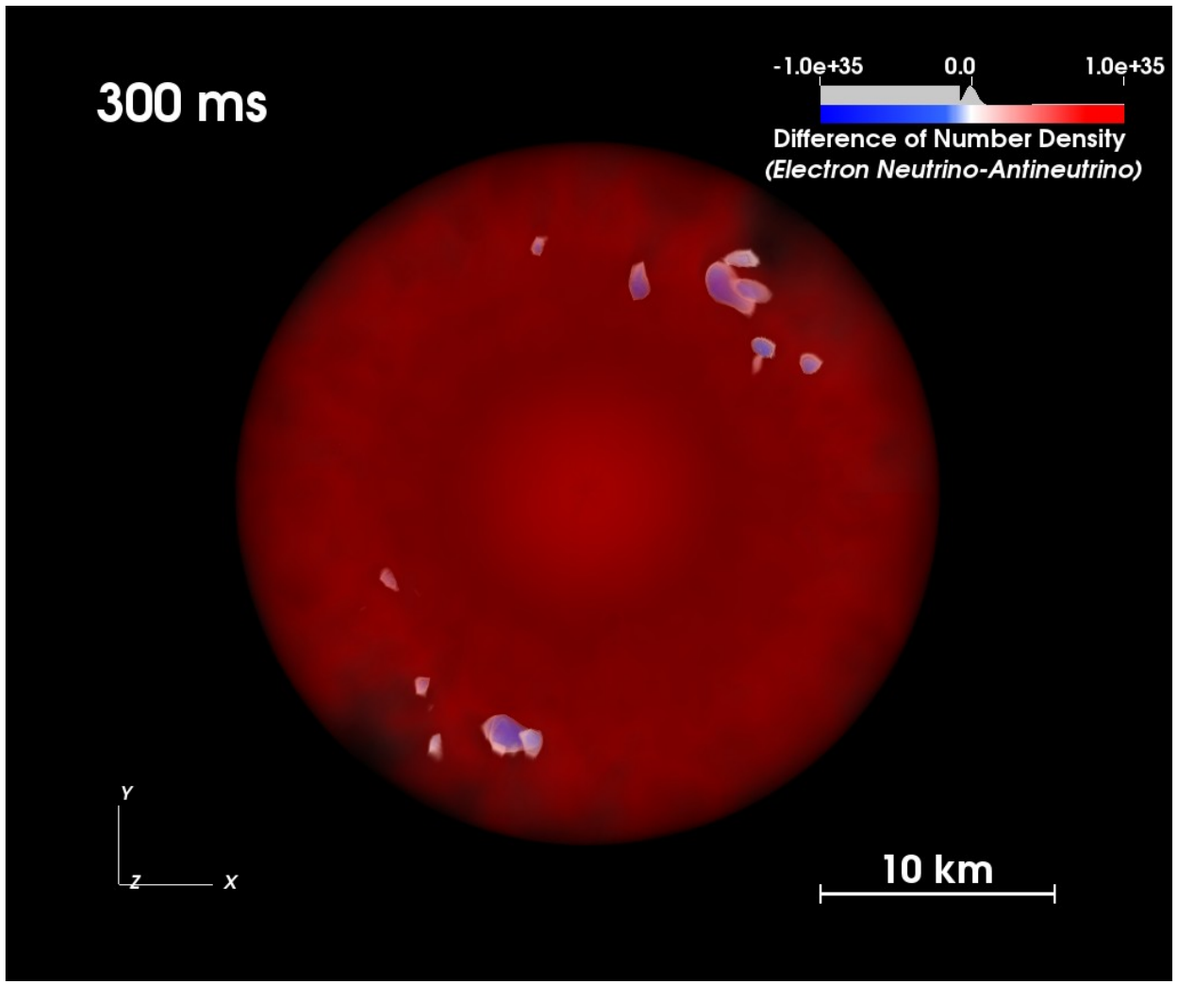
Recent review: Tamborra & Shalgar, Ann. Rev. (2021, in press).

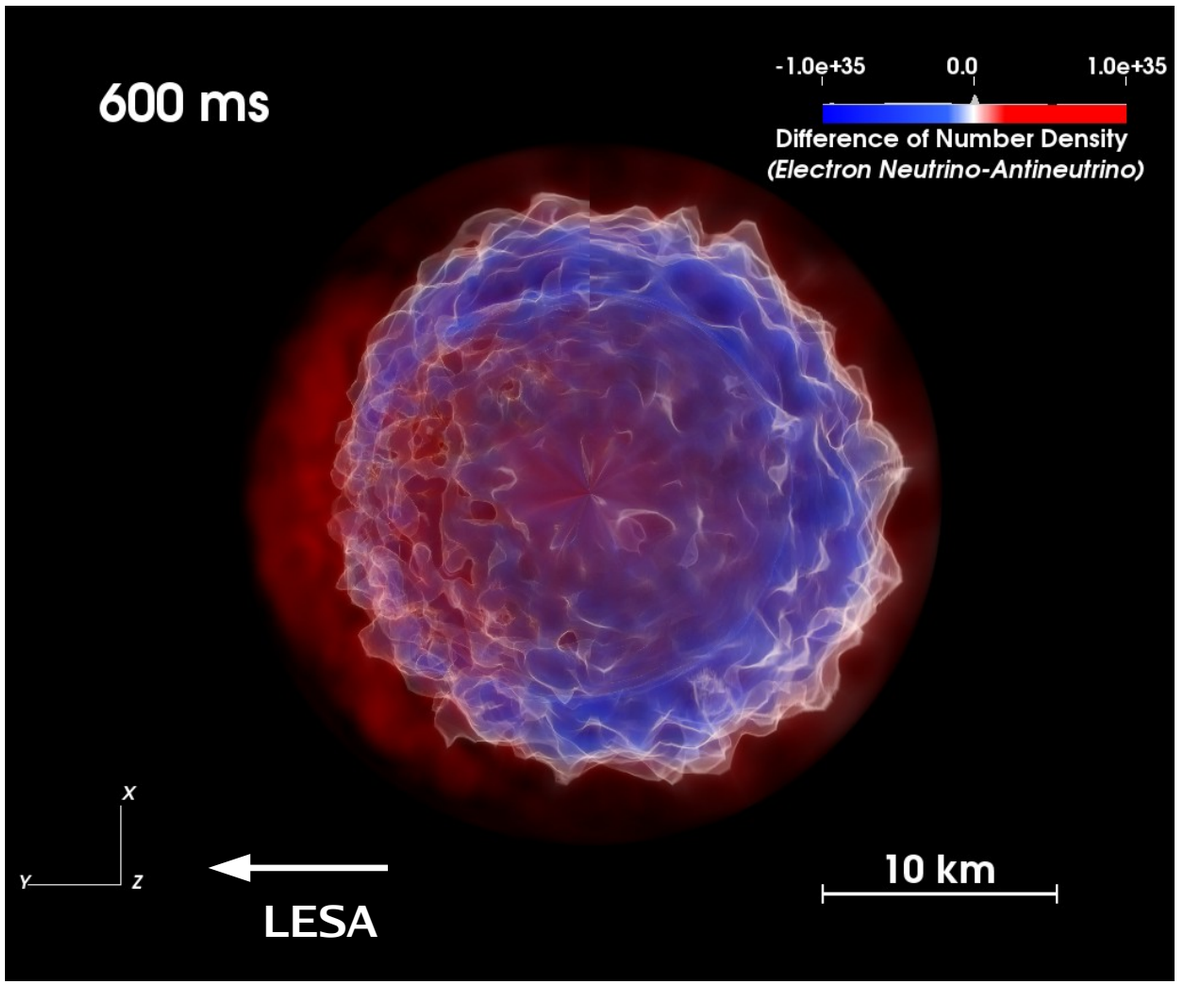
Simplified Picture of Flavor Conversions



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

Fast Flavor Instabilities in SN Simulations





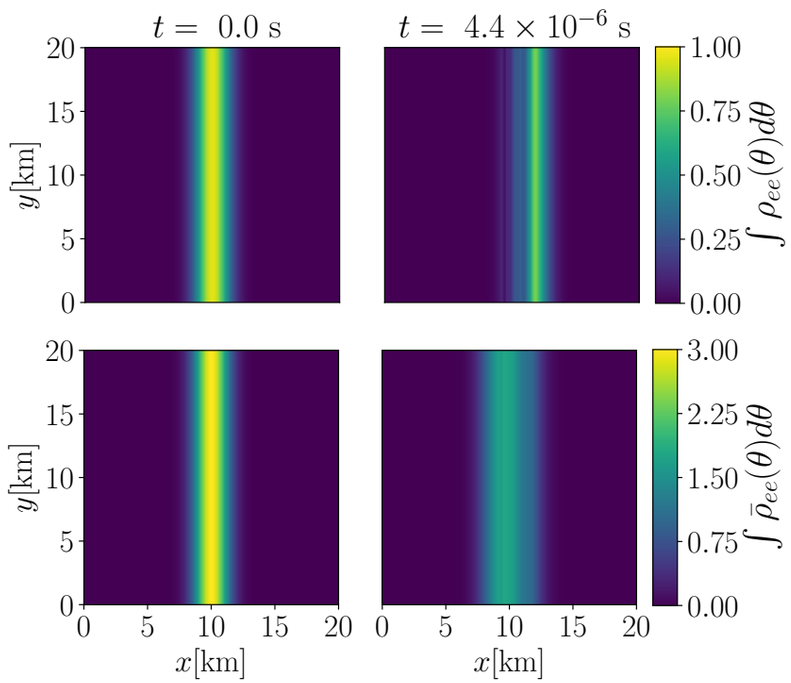
Regions of flavor instability diagnosed inside and outside the newly formed neutron star.

Does this mean that flavor conversion is not negligible in the decoupling region?

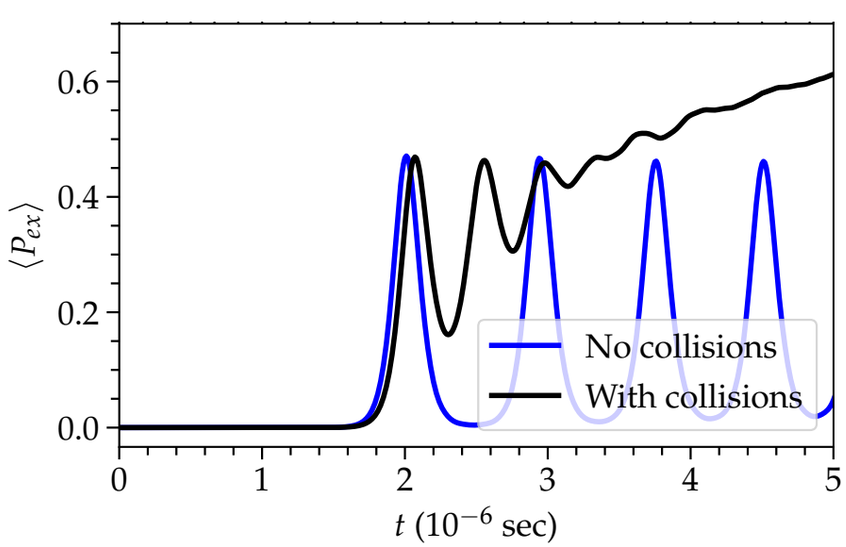
Glas et al., PRD (2020). Abbar et al., PRD (2019), PRD (2020). Azari et al., PRD (2020). Nagakura et al., ApJ (2019). Morinaga et al., PRR (2020). Shalgar & Tamborra, ApJ (2019). Tamborra et al., ApJ (2017). Abbar et al., PRD (2021, in press)….

Non-Linear Flavor Conversions

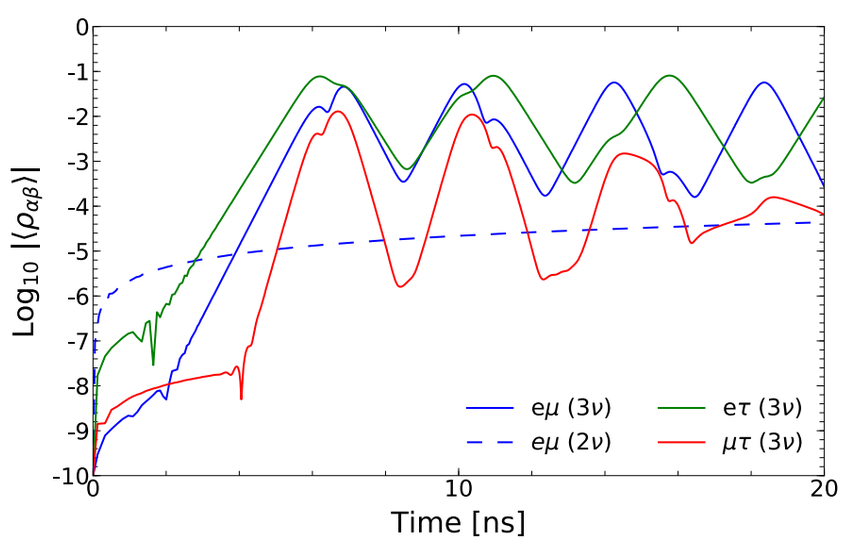
Neutrino advection



Collisions



Three flavor effects

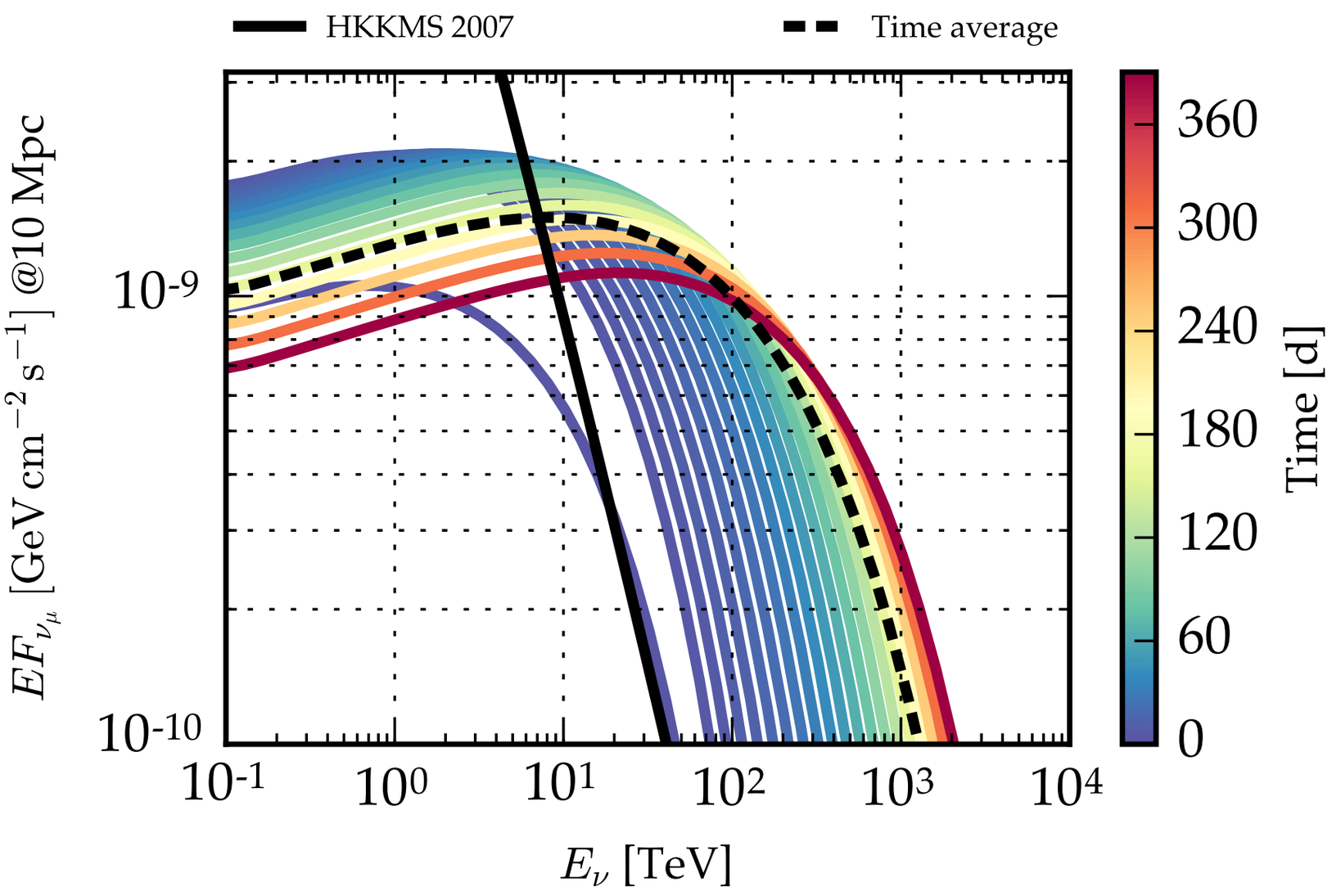


- Flavor instabilities are damped by neutrino advection.
- Neutrino conversions strongly affected by collisions.
- Three flavor effects can be large.
- Results not predicted by stability analysis, further work needed!

See talk by S. Bhattacharyya

Shalgar & Tamborra, PRD (2021, in press). Martin et al., arXiv: 2101.01278. Capozzi et al., PRL (2019). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Capozzi et al., PRL (2020). Bhattacharyya & Dasgupta, PRL (2021). Johns et al., PRD (2020).

High Energy Supernova Neutrinos

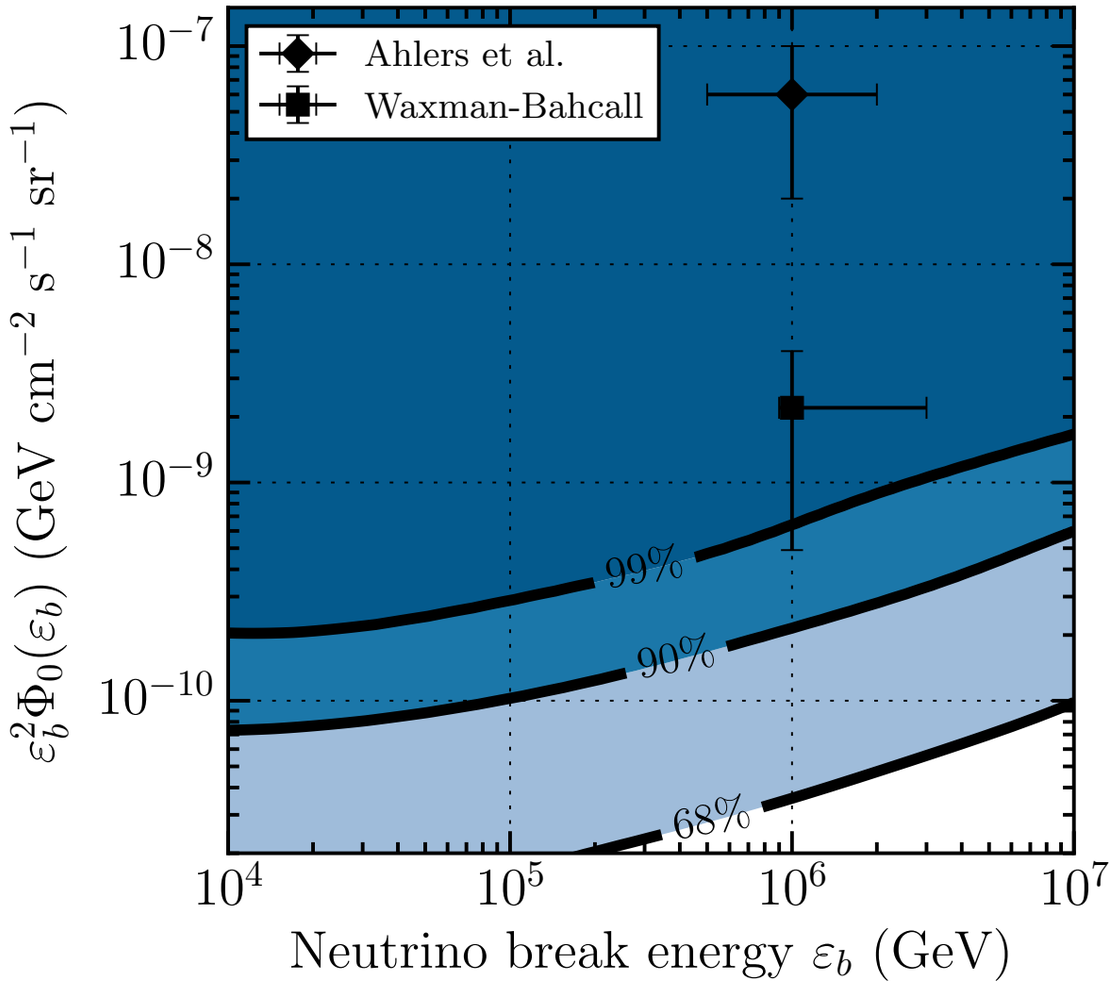


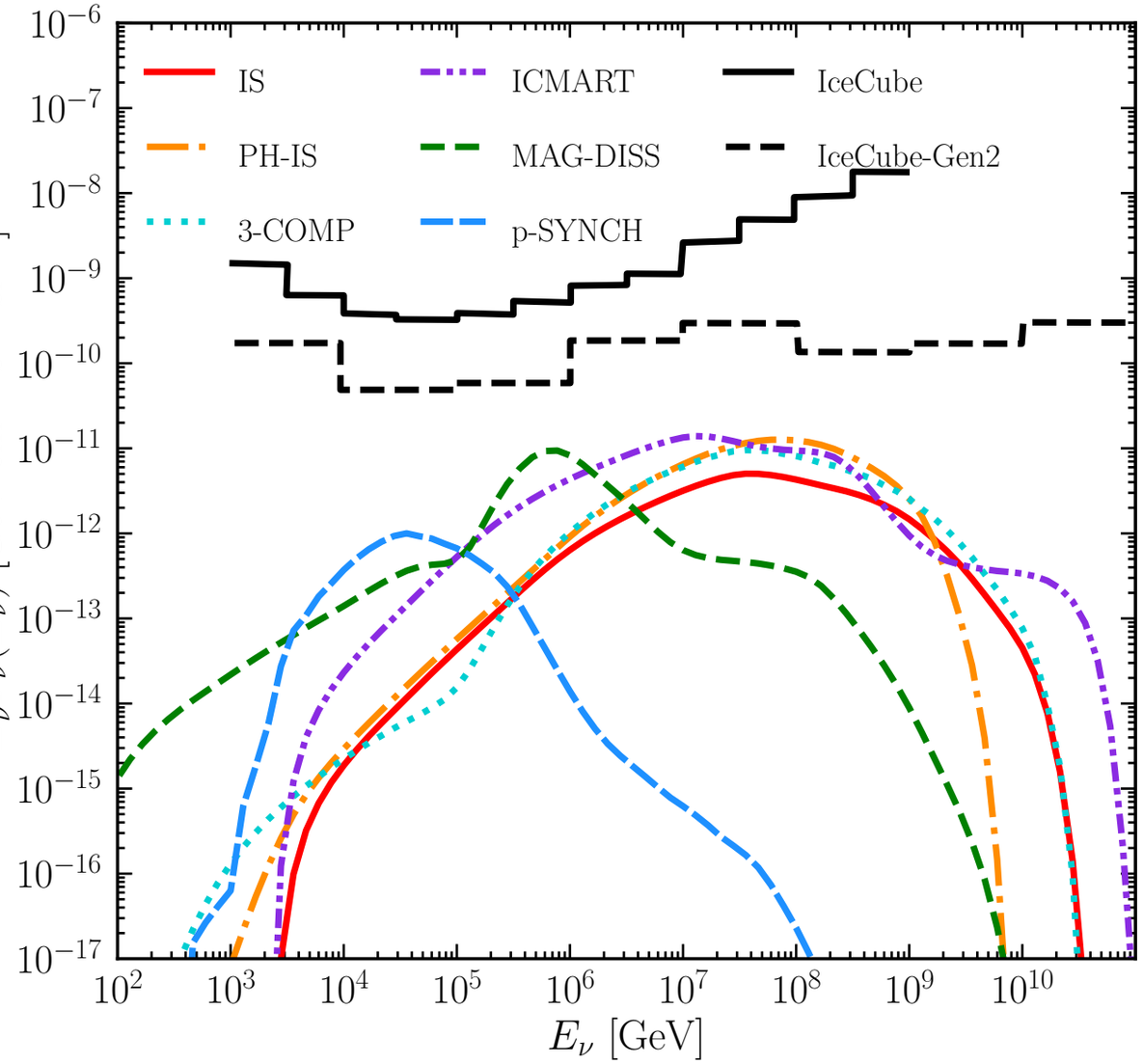
- Neutrinos from freely expanding supernova ejecta interacting with circumstellar medium.
- Neutrino non-detection constrains fraction of shock energy channeled to accelerated protons.

See talk by K. Murase

Petropoulou et al., MNRAS (2017). Murase, PRD (2018). Murase et al., PRD (2011), Zirakashvili & Ptuskin ApJ (2016).

High Energy Neutrinos from Long GRBs





- No successful detection of high energy neutrinos from long GRBs.
- Neutrino emission is strongly dependent on GRB emission mechanism.
- Neutrino emission from low-power GRBs can be copious.

See talks by K. Murase, I. Florou, T. Pitik, A. Rudolph, A. Zegarelli

ANTARES Coll., MNRAS (2020). IceCube Coll., ApJ (2017). Pitik, Tamborra, Petropoulou, arXiv: 2102.02223.

Compact Binary Mergers

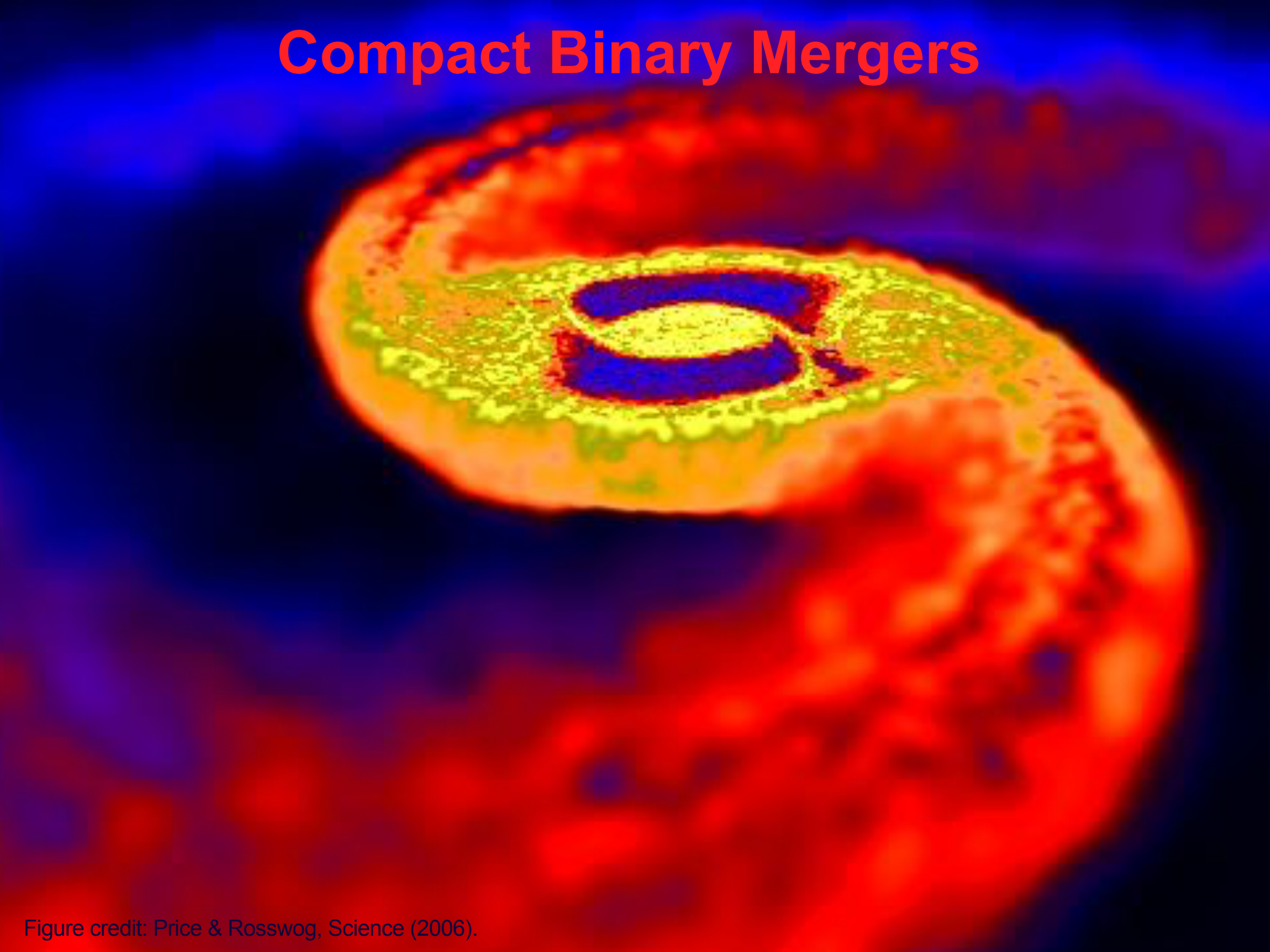
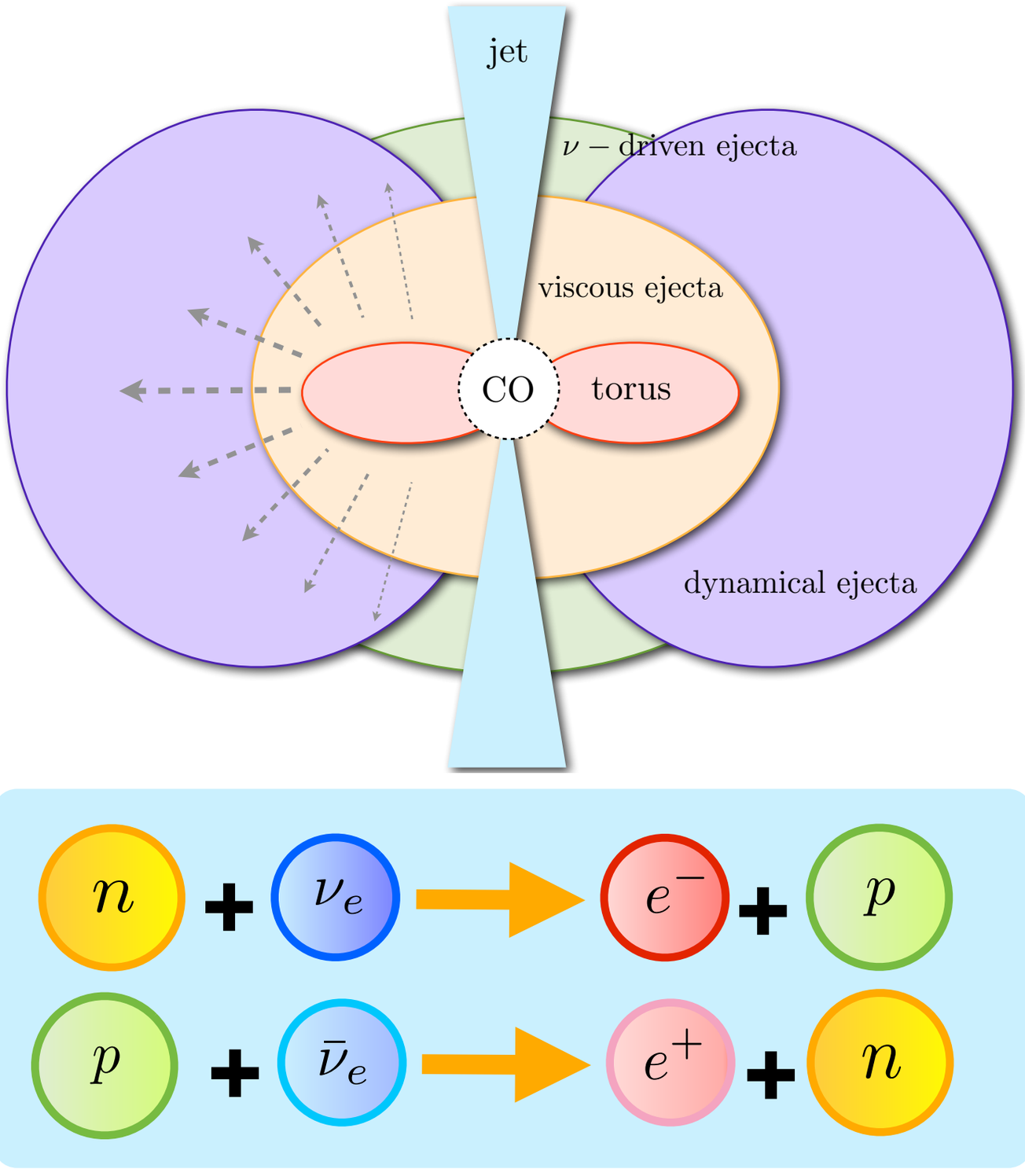


Figure credit: Price & Rosswog, Science (2006).

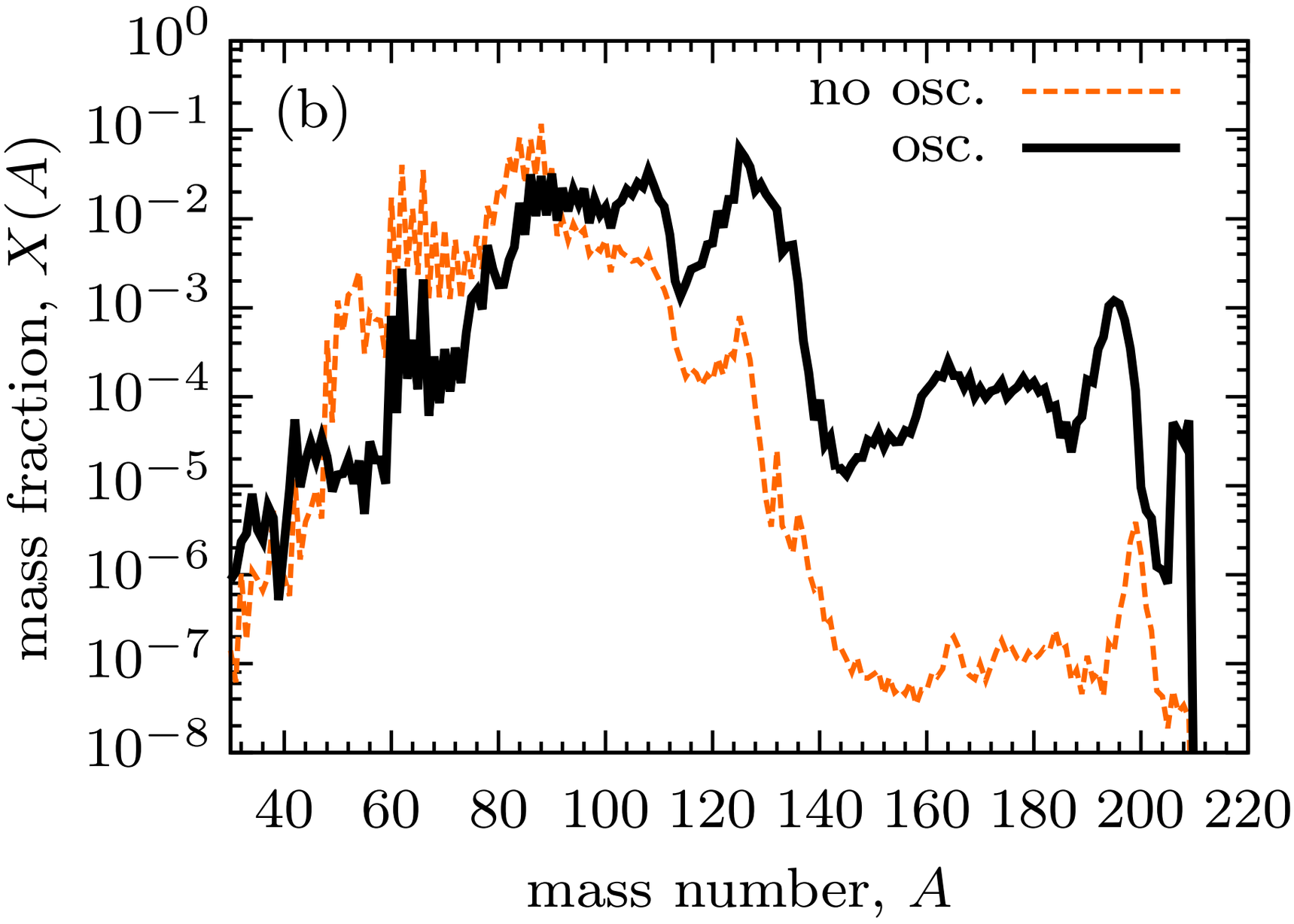
Do Neutrinos Affect Element Production?



Neutrino may play a major role especially for element production around the polar region.

Wu, Tamborra, Just, Janka, PRD (2017). Wu, Tamborra, PRD (2017).

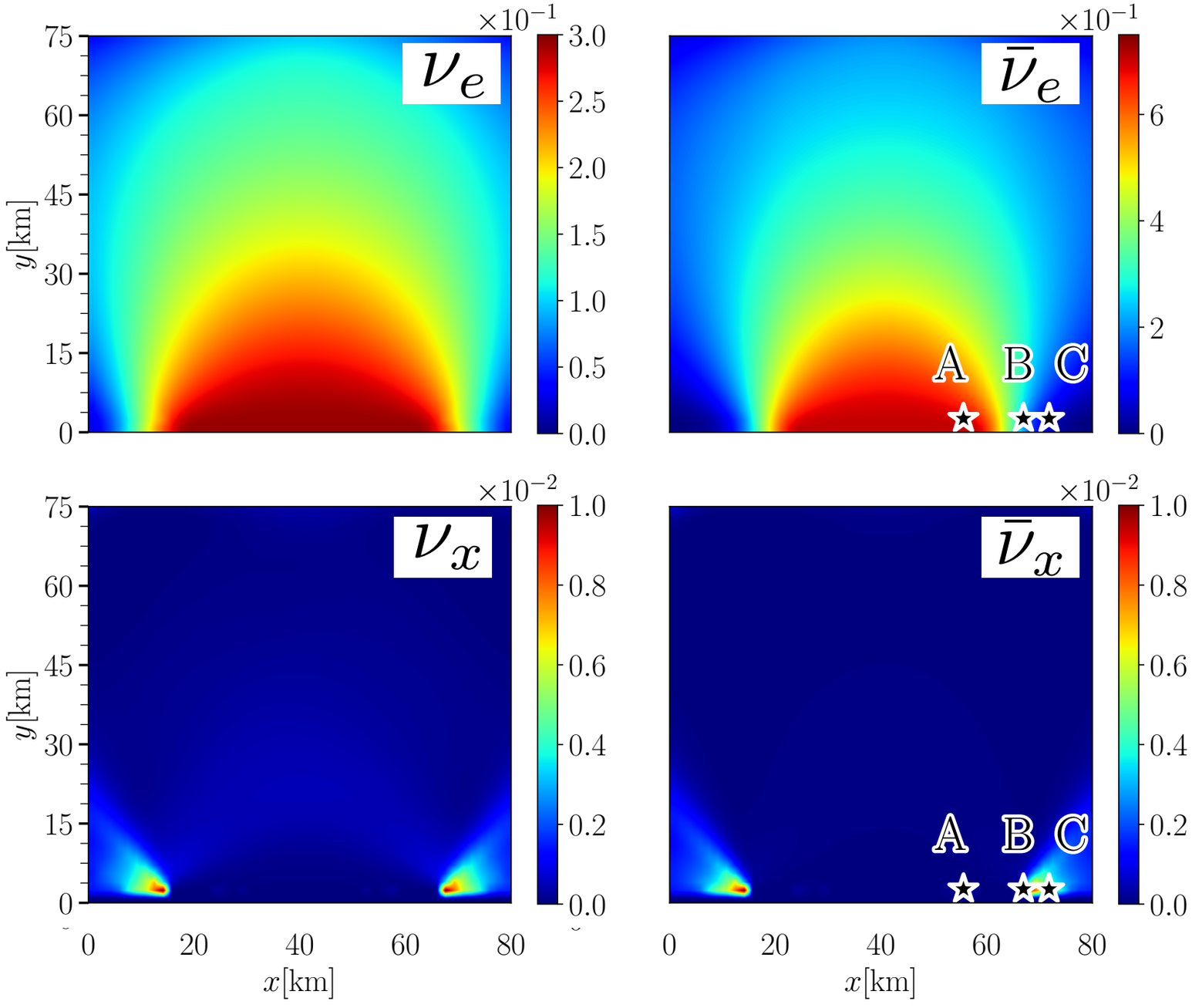
Do Neutrinos Affect Element Production?



Flavor conversions may lead to an enhancement of nuclei with A>130 (kilonova implications).

Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). George et al., PRD (2020).

Multi-Dimensional Numerical Solution

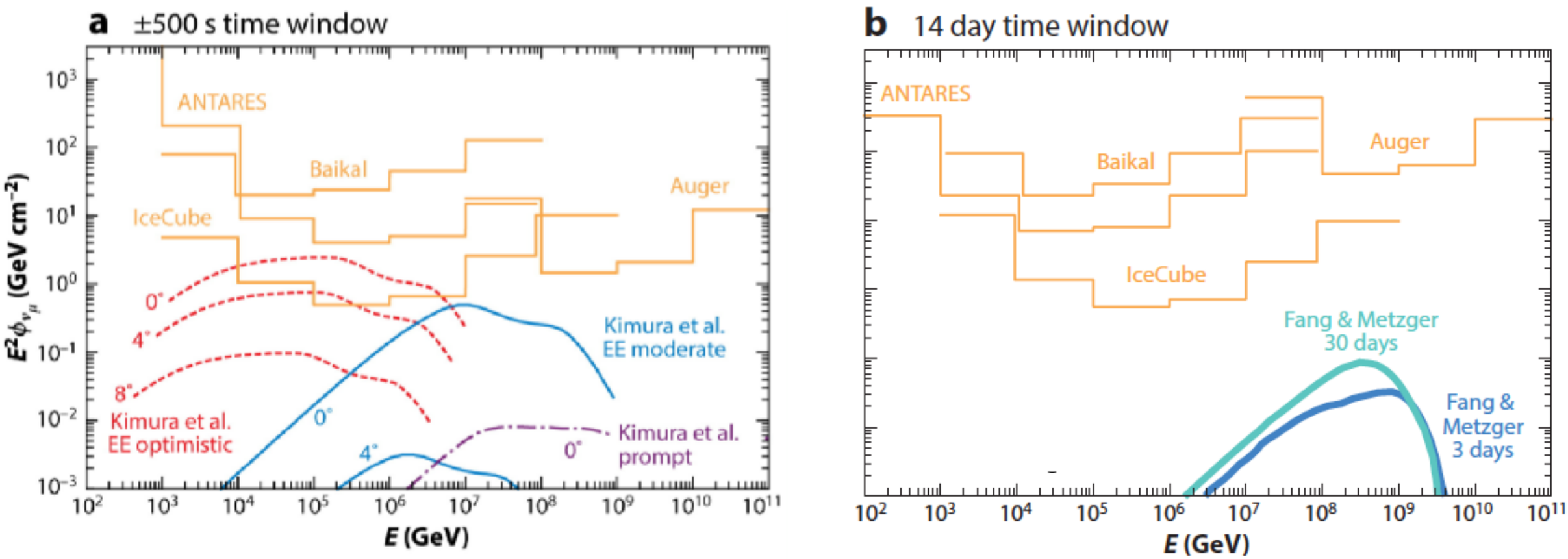


- Minimal flavor mixing in the polar region.
- Flavor mixing < 1%.
- More work needed!

See talk by I. Padilla-Gay

Padilla-Gay, Shalgar, Tamborra, JCAP (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 credits: 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).

Conclusions

- **Neutrinos are fundamental particles in GW sources.**
- **Low energy neutrinos carry imprints of the source engine.**
- **Neutrino conversions relevant, not yet complete understanding.**
- **High energy neutrinos carry information on source aftermath.**

Thanks!