The Niels Bohr International Academy

DARK

The Ghostly Messengers of the Universe

Irene Tamborra

Niels Bohr Institute, University of Copenhagen

Second Conference of Nordic Network for Diversity in Physics

Helsinki, November 4, 2019

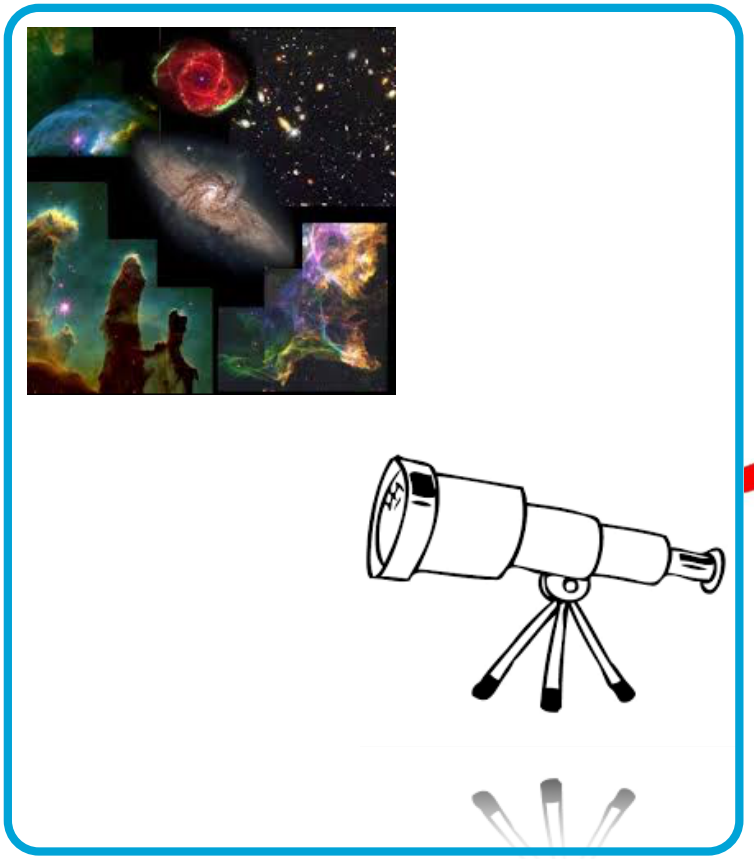
VILLUM FONDEN

Sapere Aude

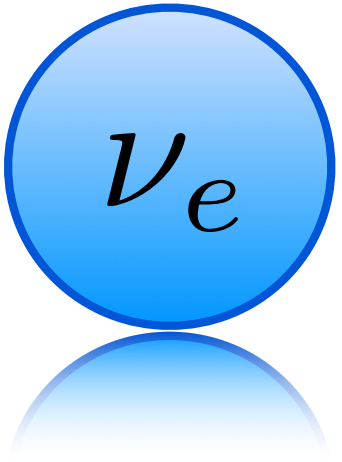
CARLSBERG FOUNDATION

SFB 1258 Neutrinos Dark Matter Messengers

From Macroscopic to Microscopic



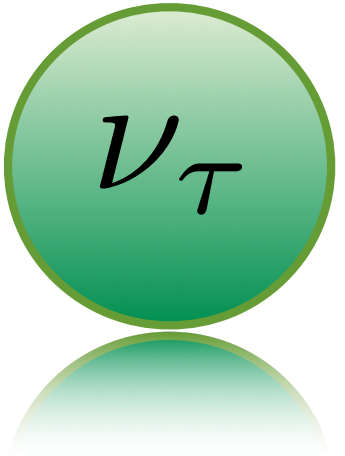
Neutrinos

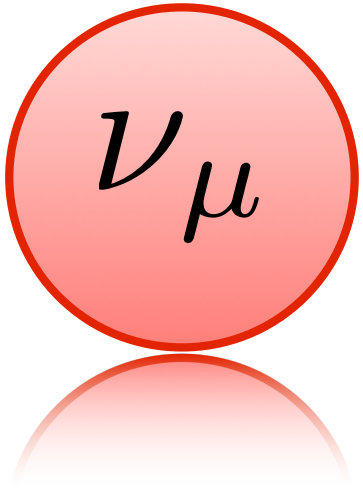


Ghostly

Abundant

Elusive





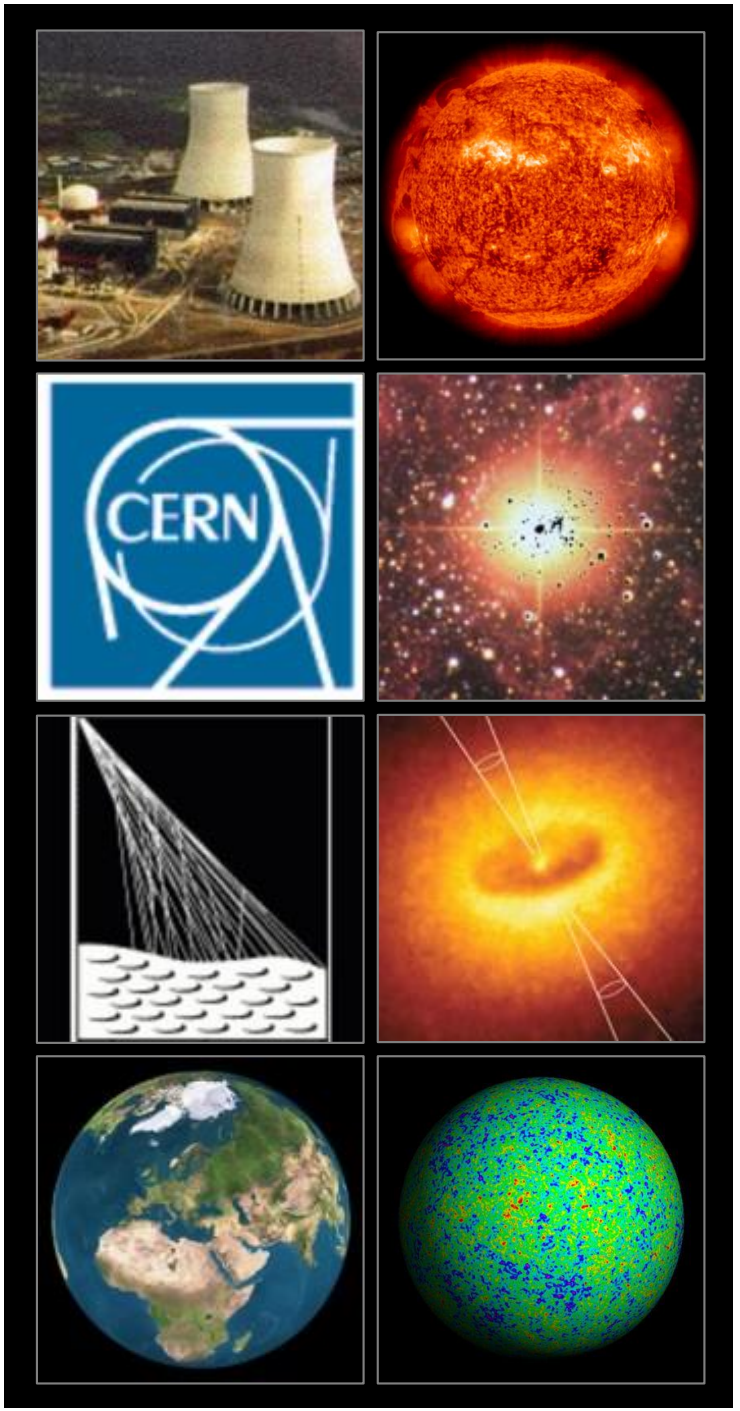
Where Are Neutrinos Produced?

Nuclear reactors

Particle accelerators

Atmosphere

Earth



Sun

Supernovae and binary mergers

Gamma-ray bursts and other cosmic accelerators

Big Bang

Grand Unified Neutrino Spectrum

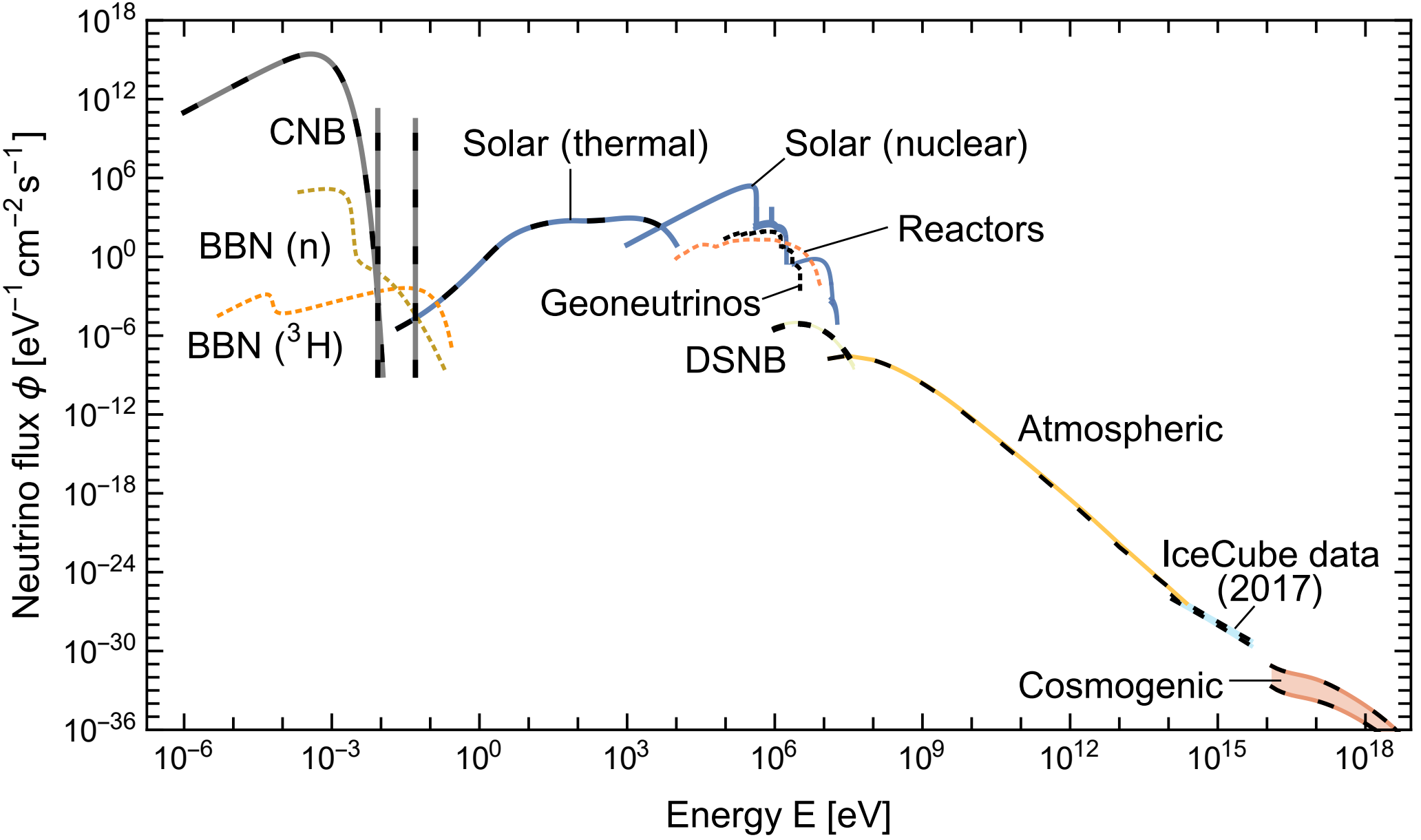


Figure from Vitagliano, Tamborra, Raffelt, arXiv: 1910.11878.

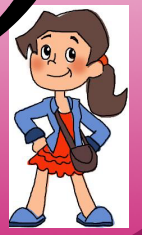
I Feel Like a Neutrino!

ν_e

ν_τ

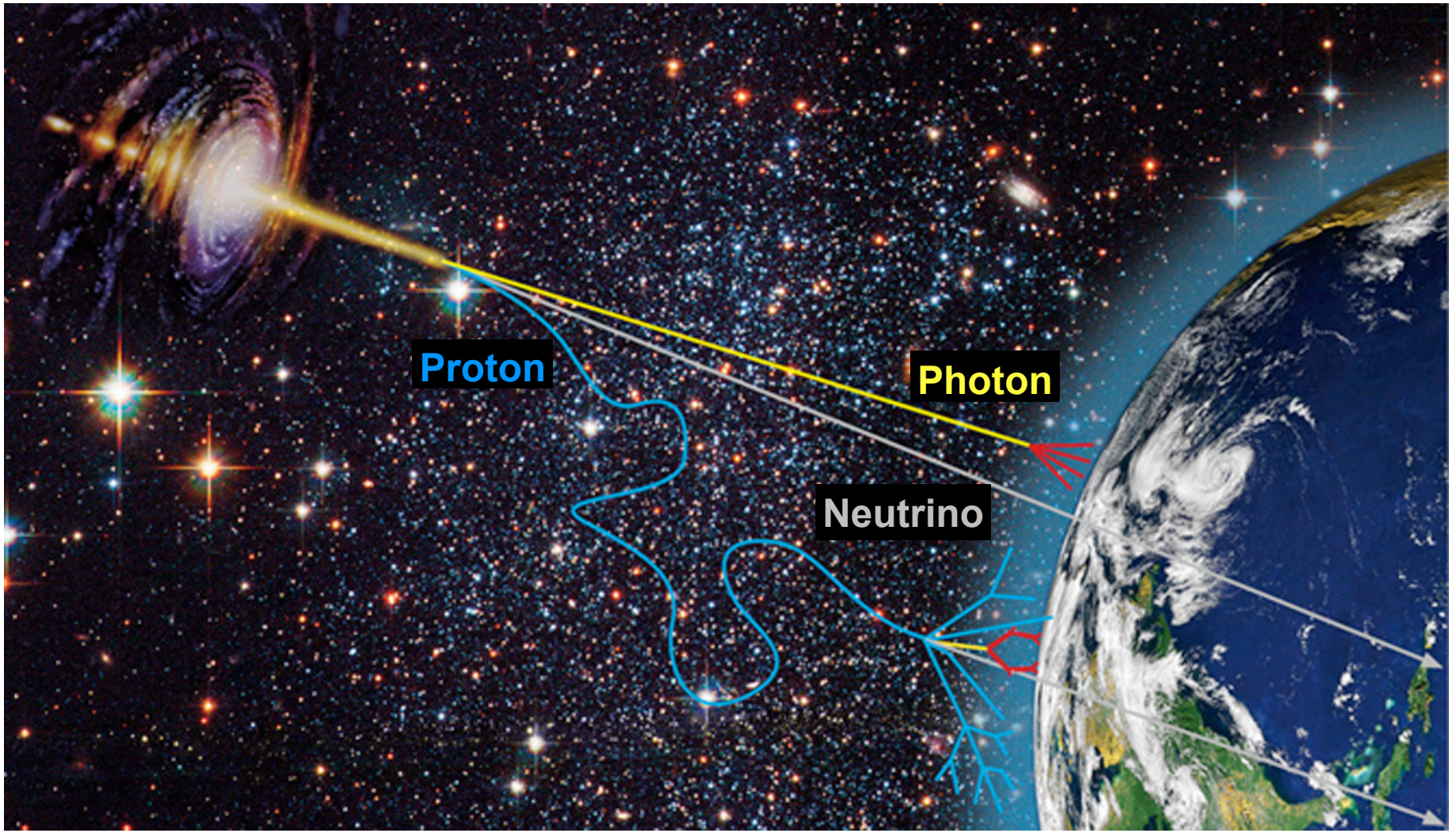
ν_μ

ν



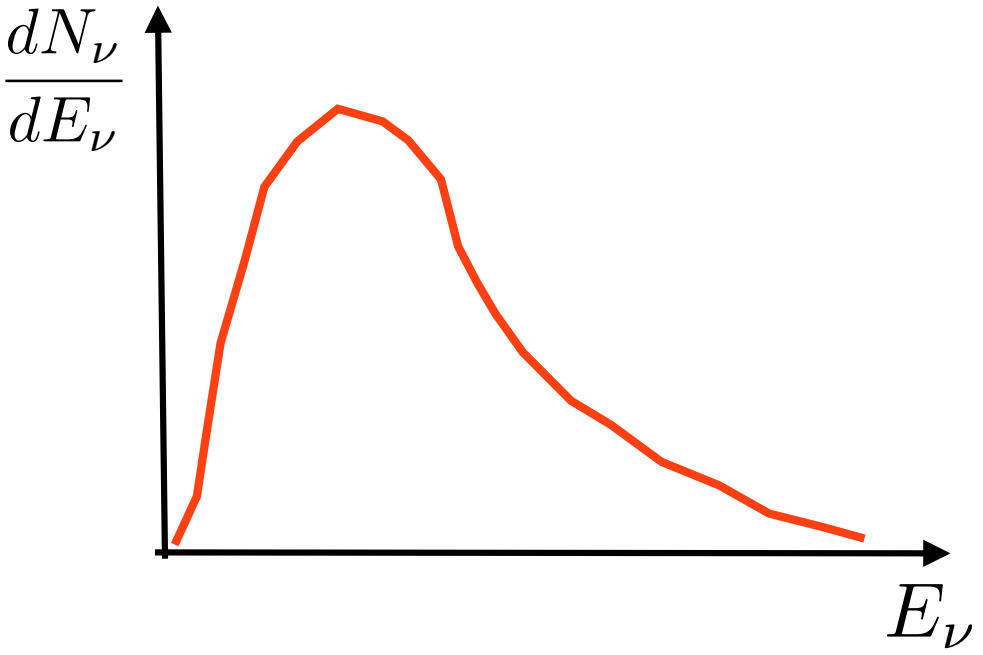
Ideal Messengers

Escaping unimpeded, neutrinos carry information about sources not otherwise accessible.



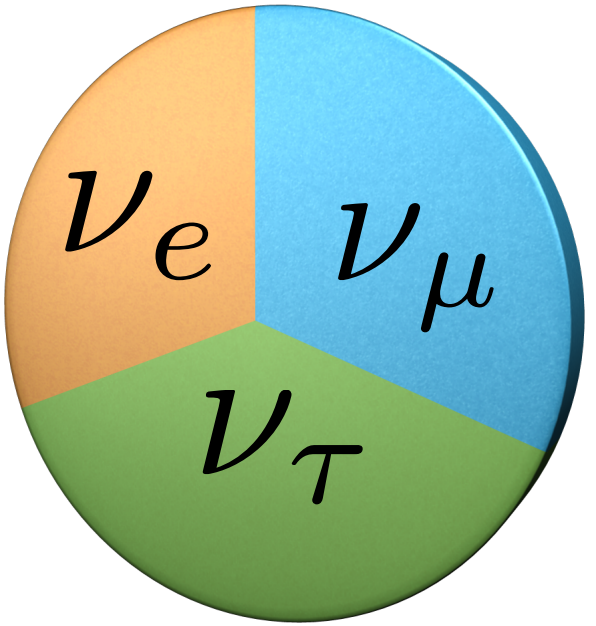
Powerful Probes in Astrophysics

Energy distribution



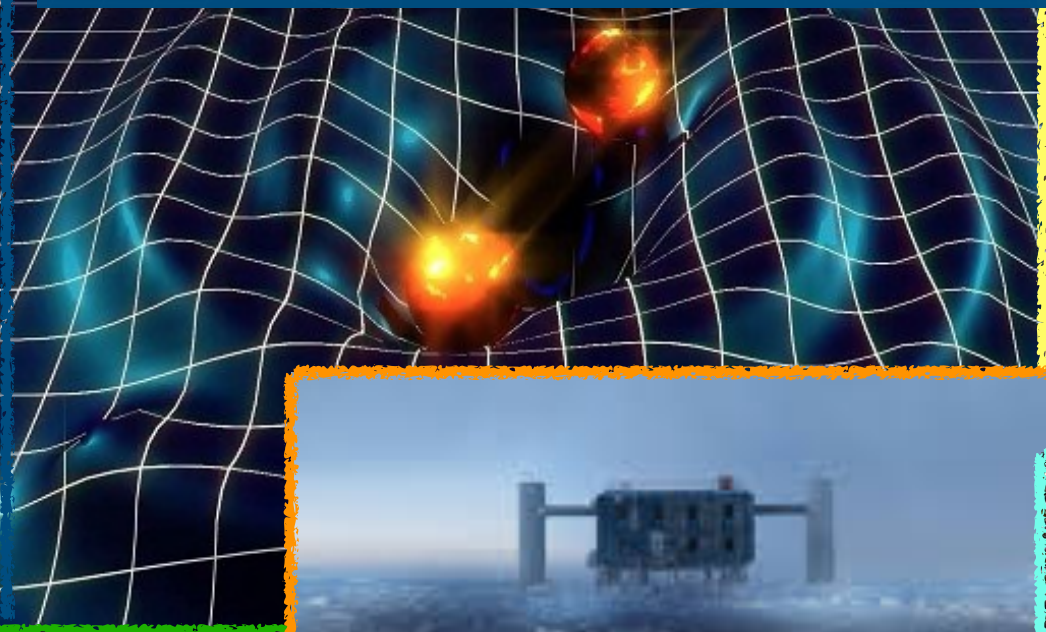
Similar to photons

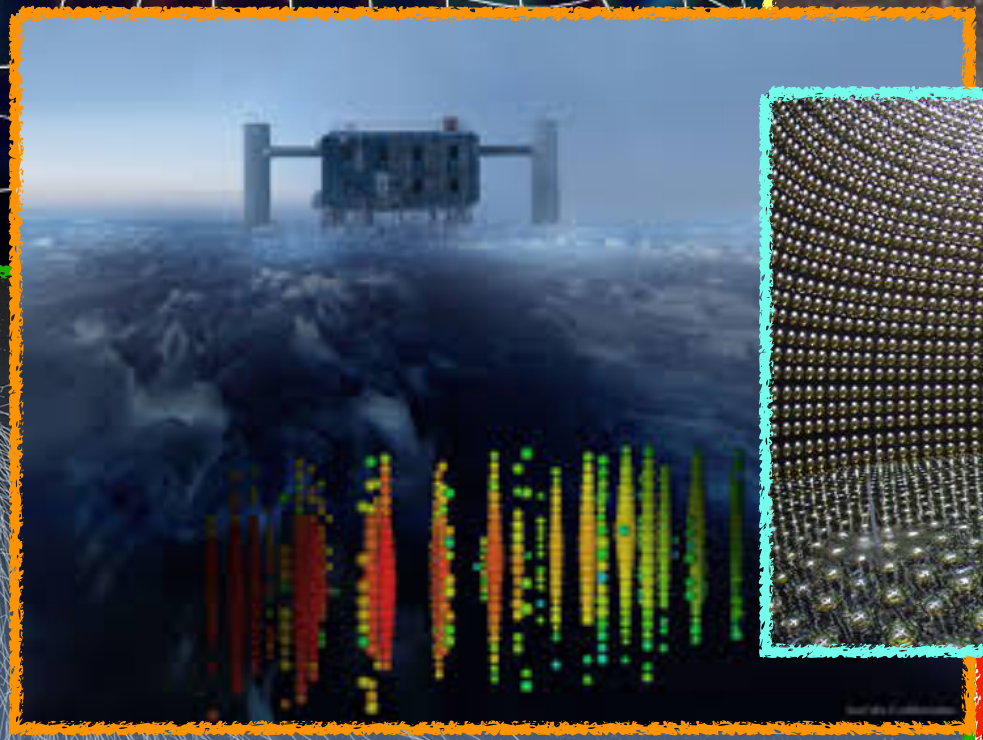
Flavor ratio

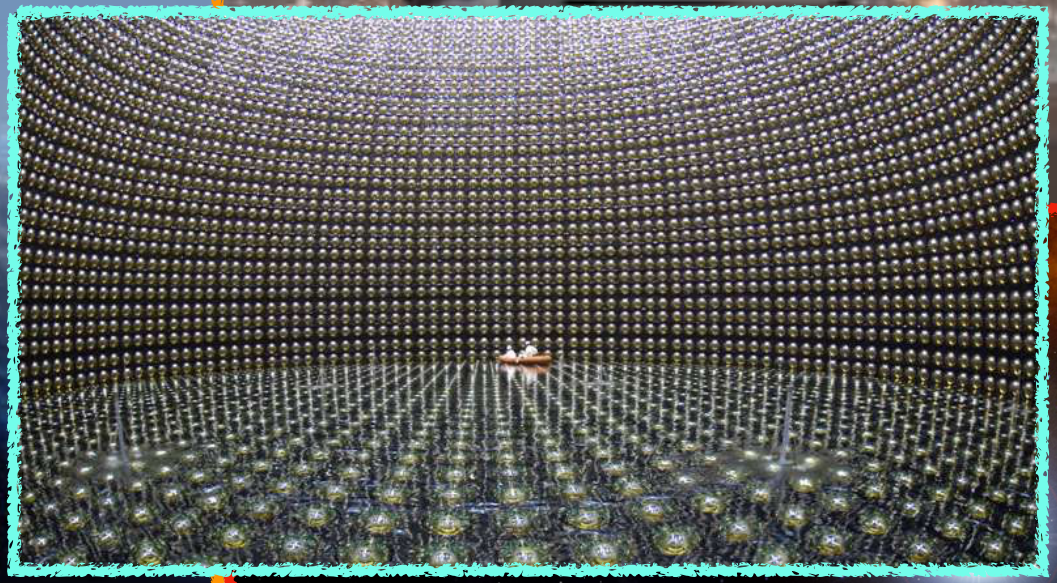


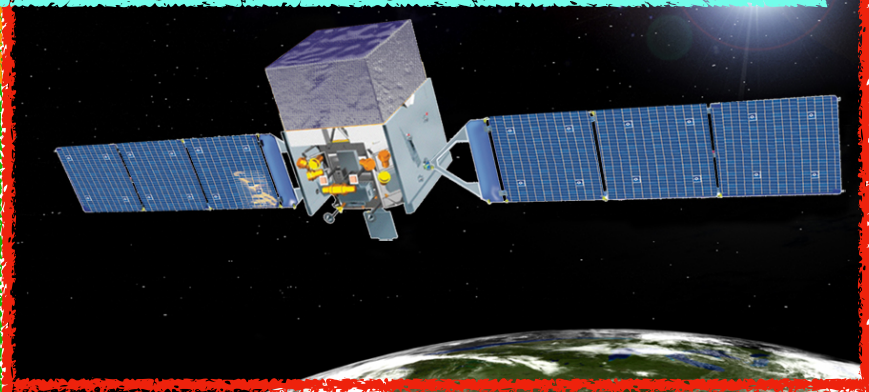
Neutrinos only!

Dawn of the Multi-Messenger Era



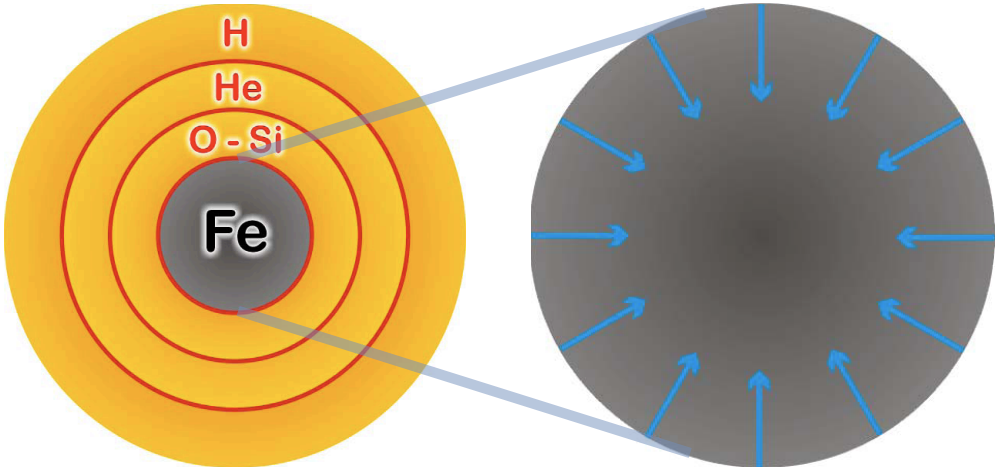






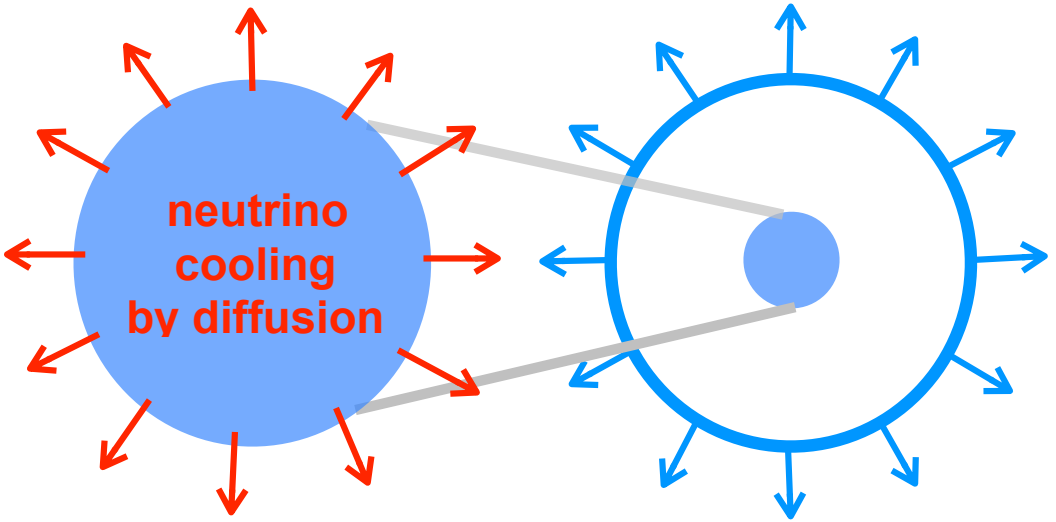

CORE COLLAPSE SUPERNOVAE

Core Collapse Supernova Explosion



Implosion (Collapse)

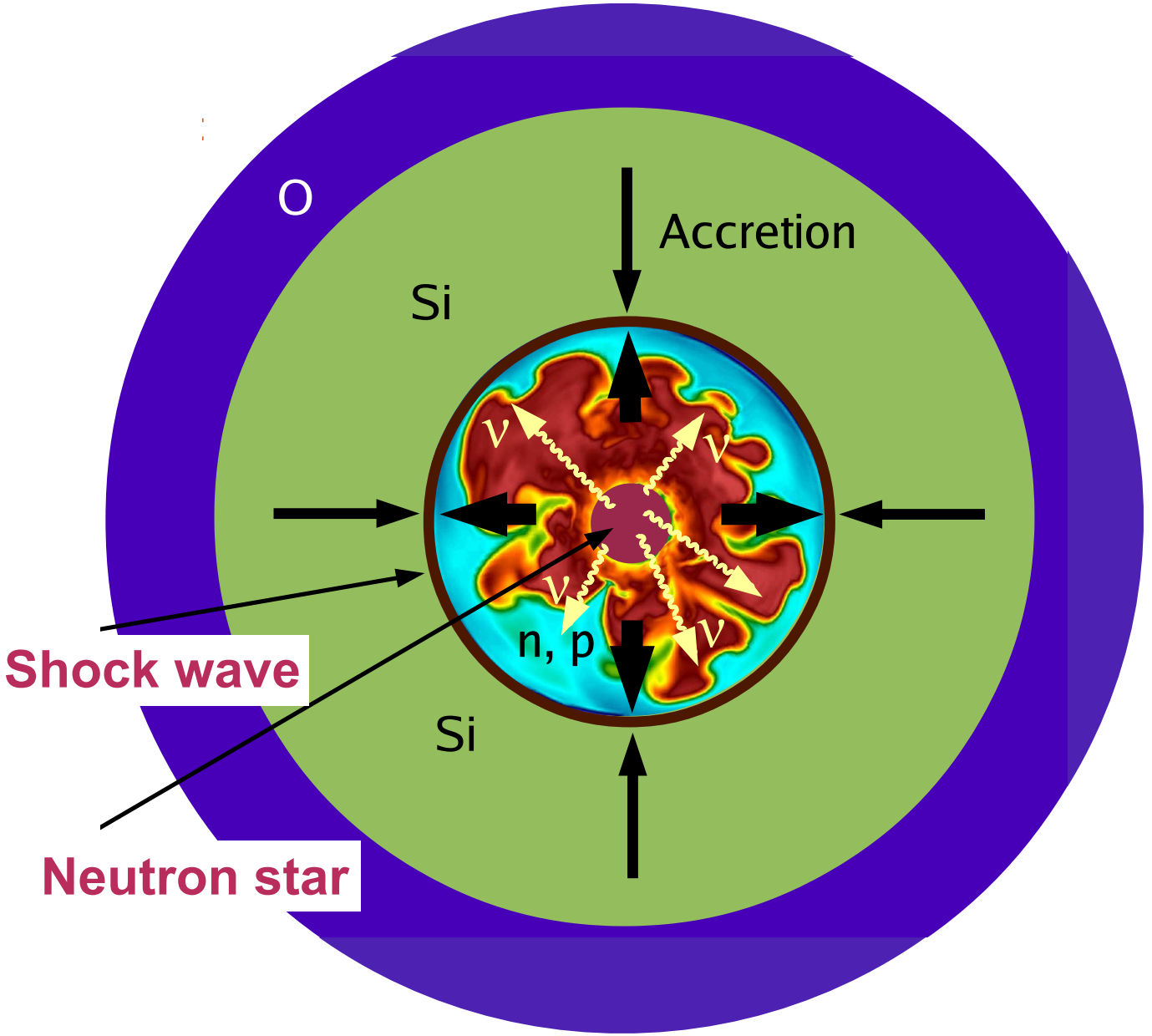
Explosion



Neutrinos carry 99% of the released energy (~ 10^{53} erg).

Supernova Explosion Mechanism

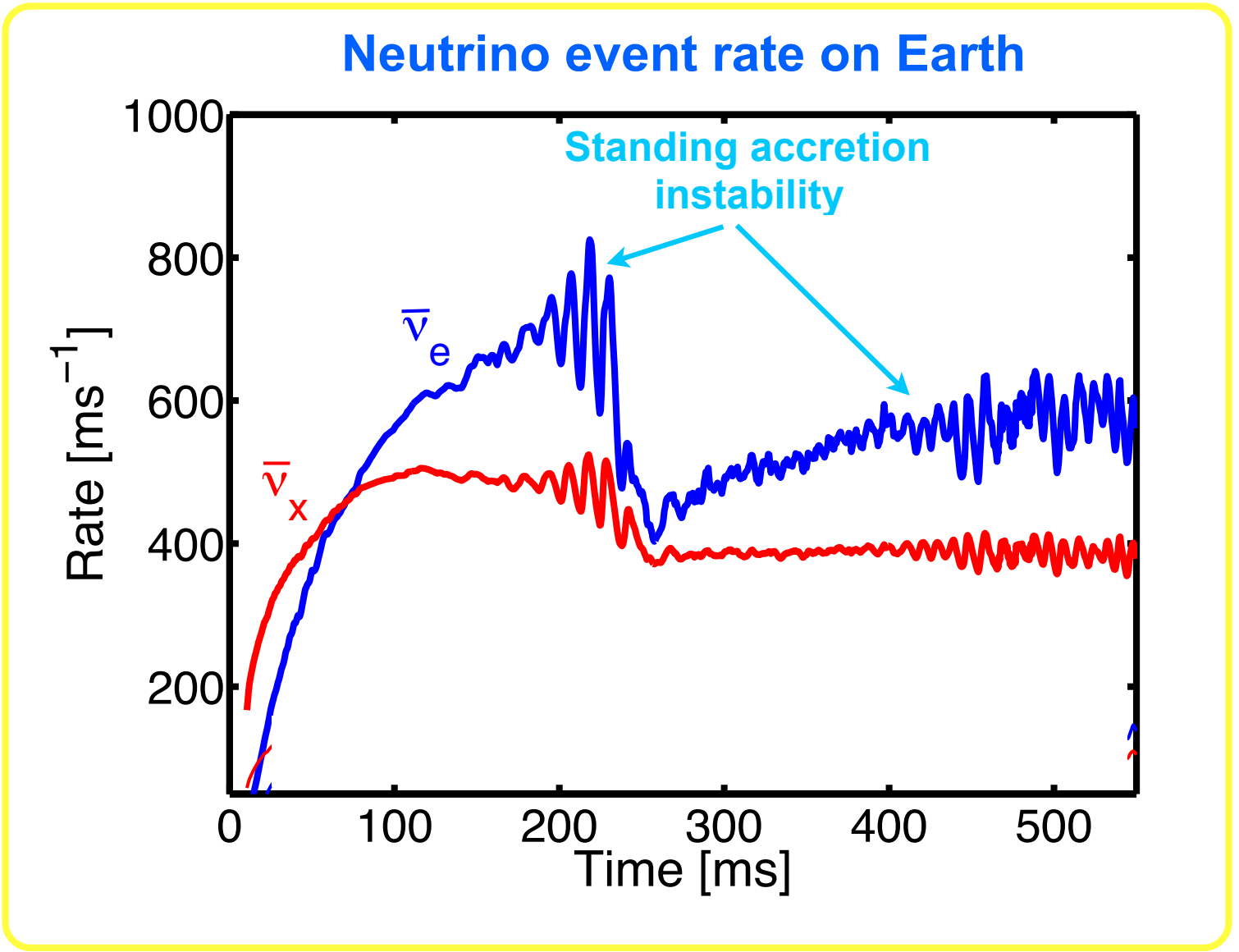
Shock wave forms within the iron core. It dissipates energy dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.



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

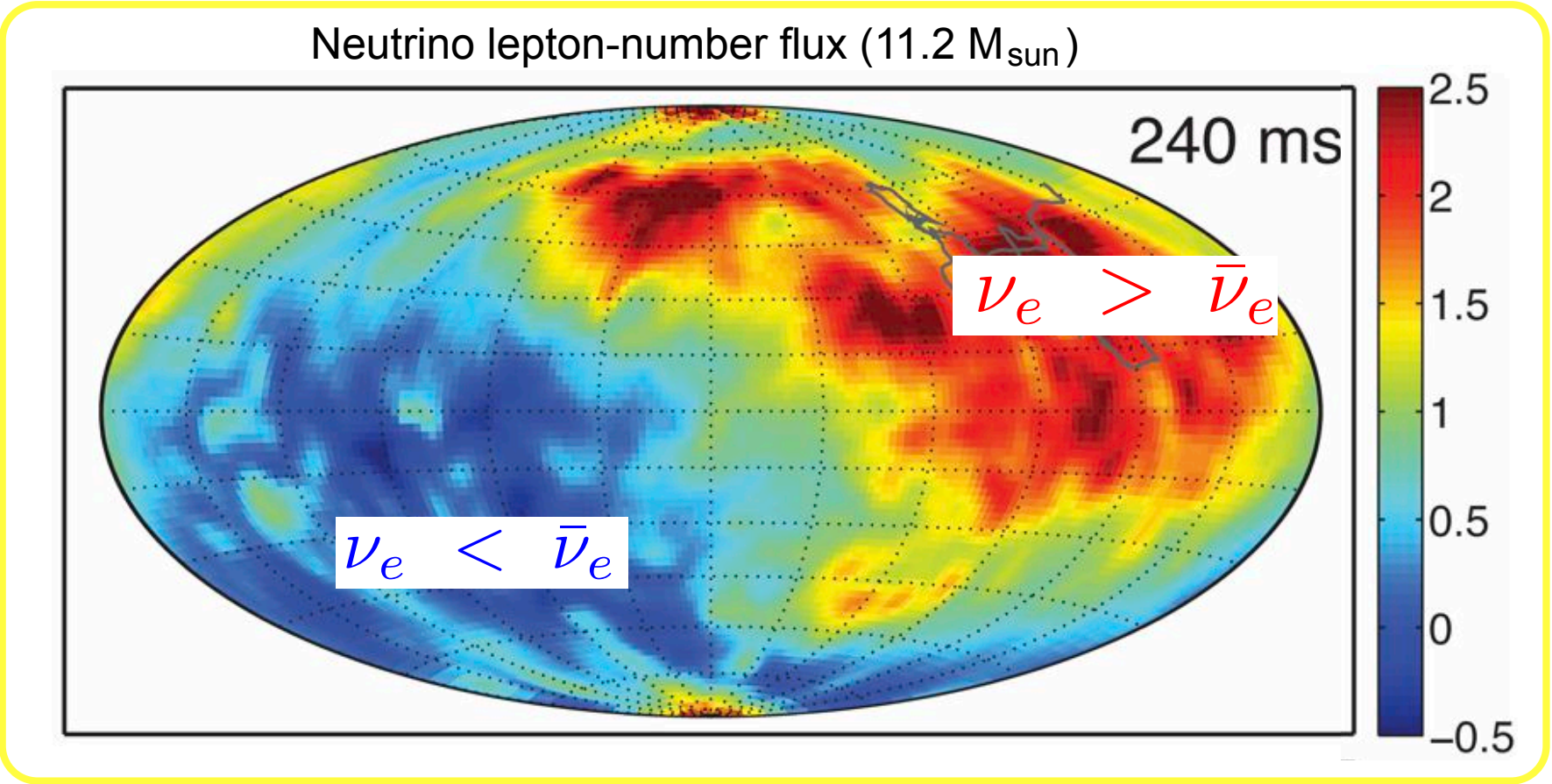
Neutrinos Probe Supernova Dynamics

Neutrinos (and gravitational waves) can probe the explosion mechanism.



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

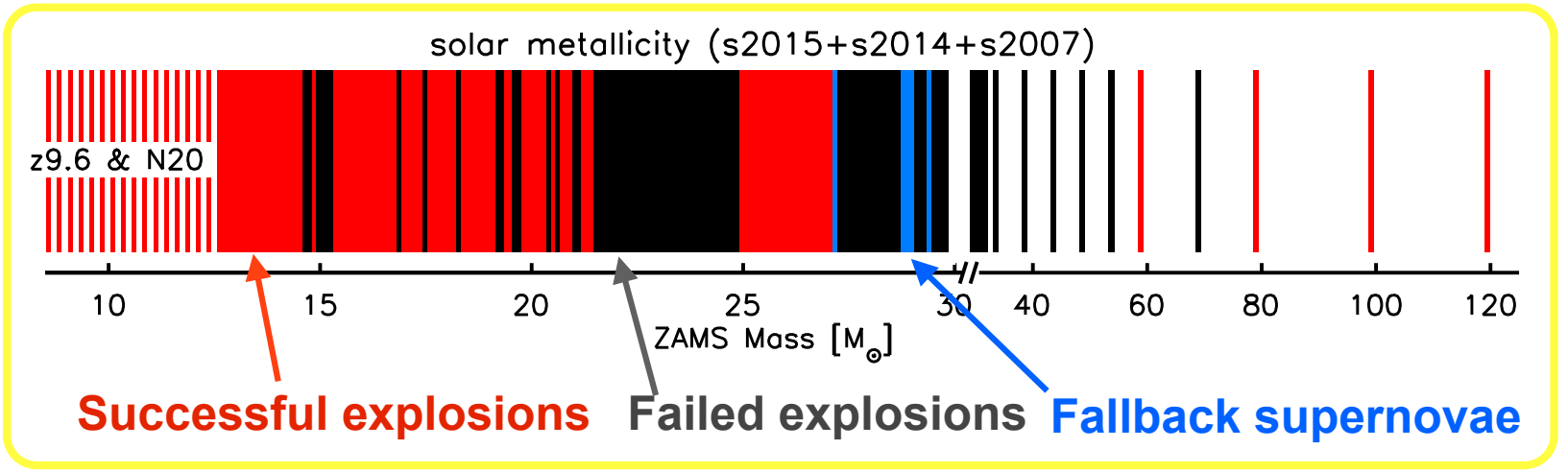
LESA: Neutrino-Driven Instability

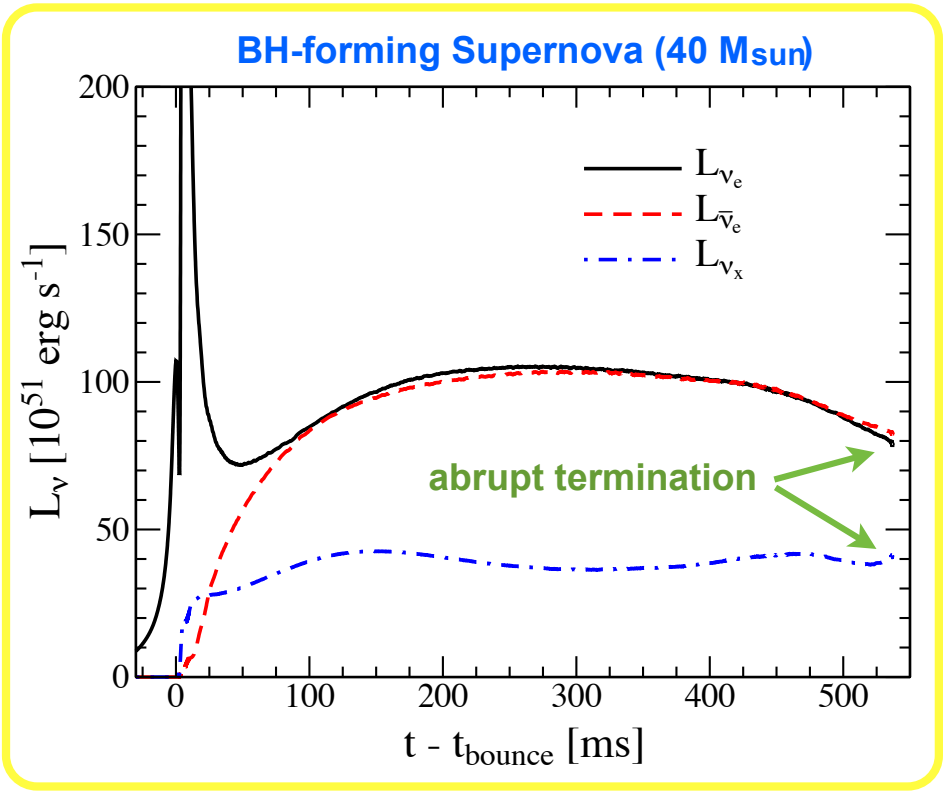


Lepton-number emission asymmetry (**LESA**): Large-scale feature with **dipole character**.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).
Janka et al., ARNPS (2016). Glas et al., (2018), Vartanyan et al., MNRAS (2019), O'Connor & Couch, ApJ (2018).

Neutrinos Probe Black Hole Formation





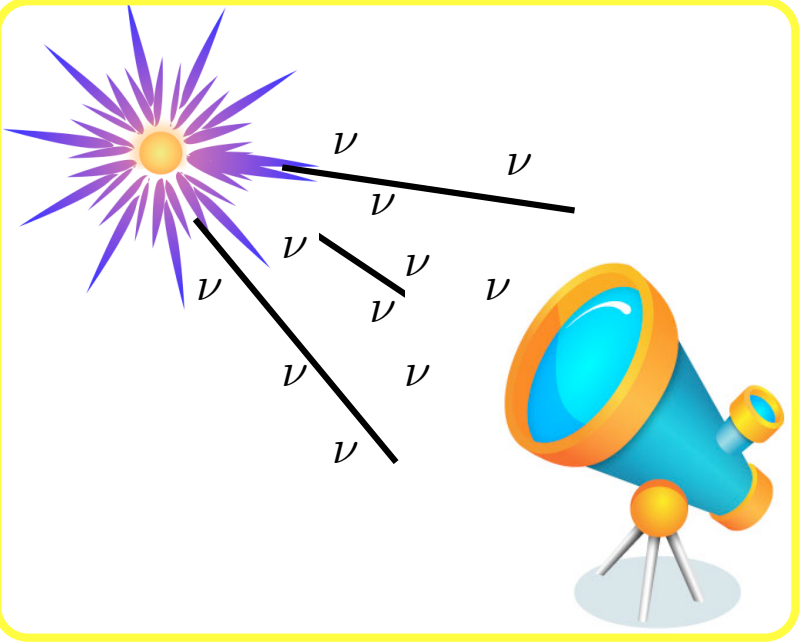
- Low-mass supernovae can form black holes.
- Neutrinos reveal black-hole formation.
- Failed supernovae up to 20-40% of total.

Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015). Kuroda et al., MNRAS (2018).

Neutrino Alert

SuperNova Early Warning System (SNEWS).

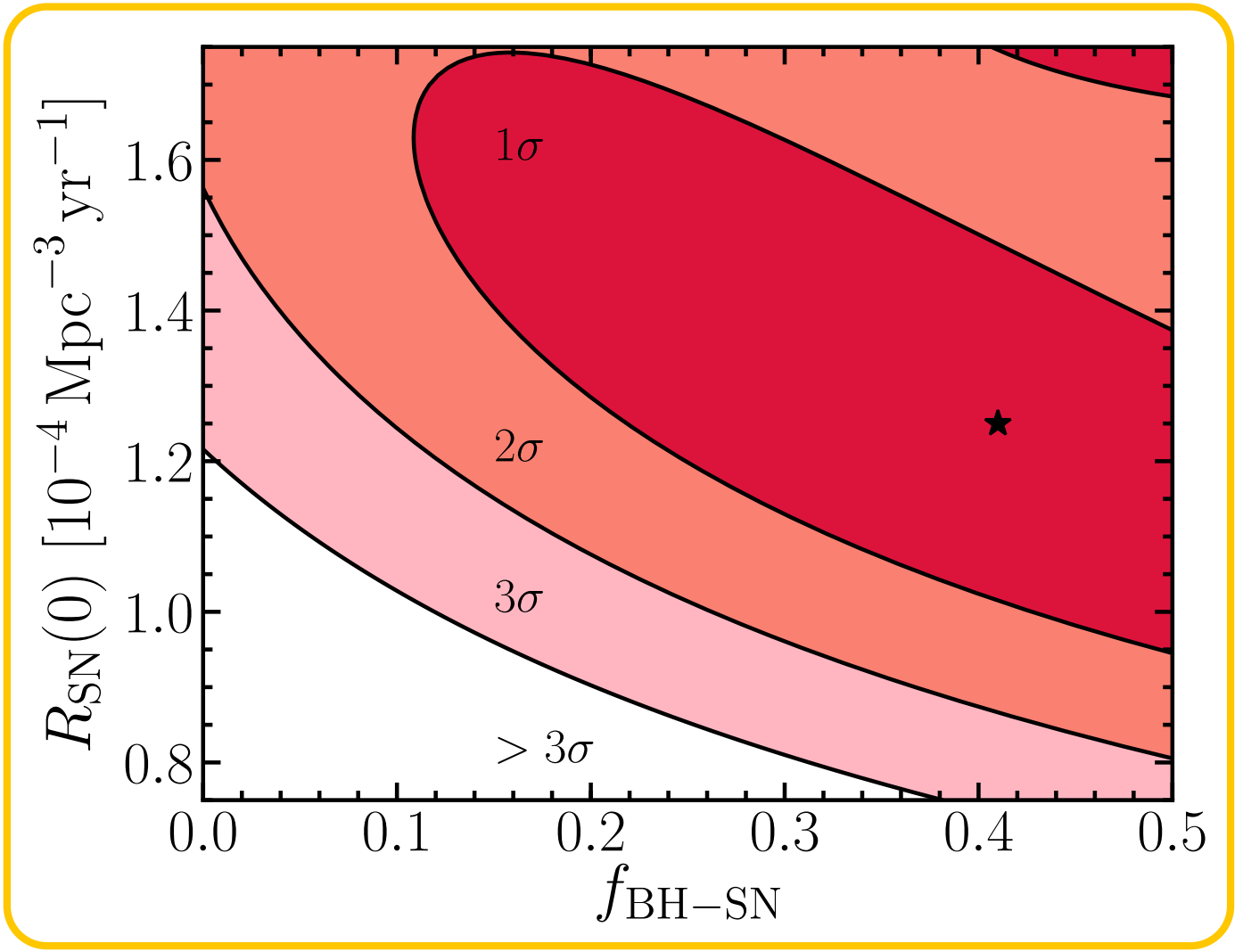
Network to alert astronomers of a burst
(neutrinos reach us earlier than photons).



Determination of **supernova direction** with neutrinos.

Crucial for vanishing or weak supernova.

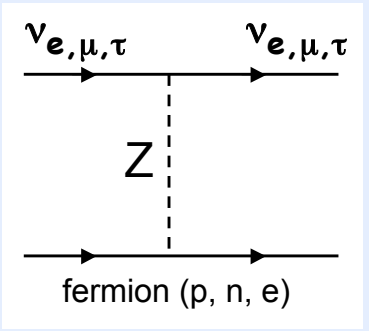
Neutrinos Probe Global SN Population

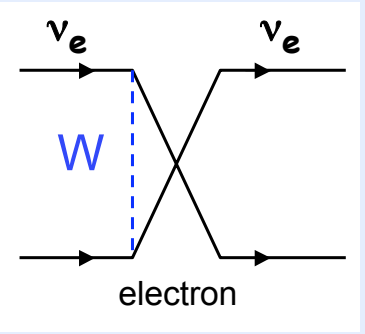


- Independent test of the local supernova rate.
- Constraints on the fraction of black hole forming supernovae.

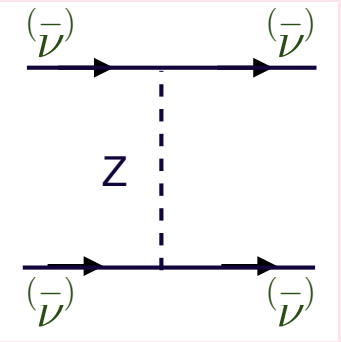
Moller, Suliga, Tamborra, Denton, JCAP (2018).

Neutrino Interactions





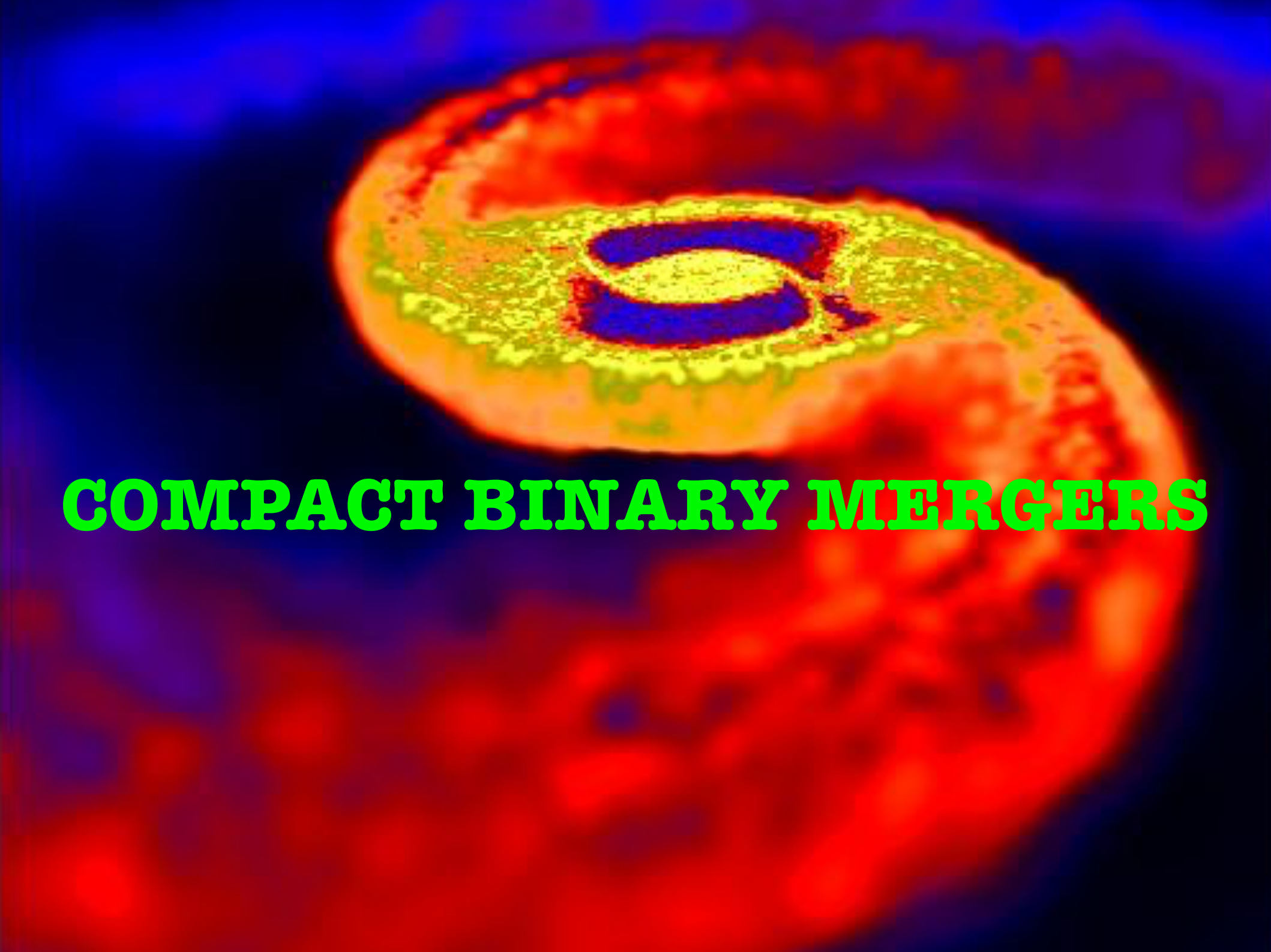
Neutrinos interact with neutrons, protons and electrons.



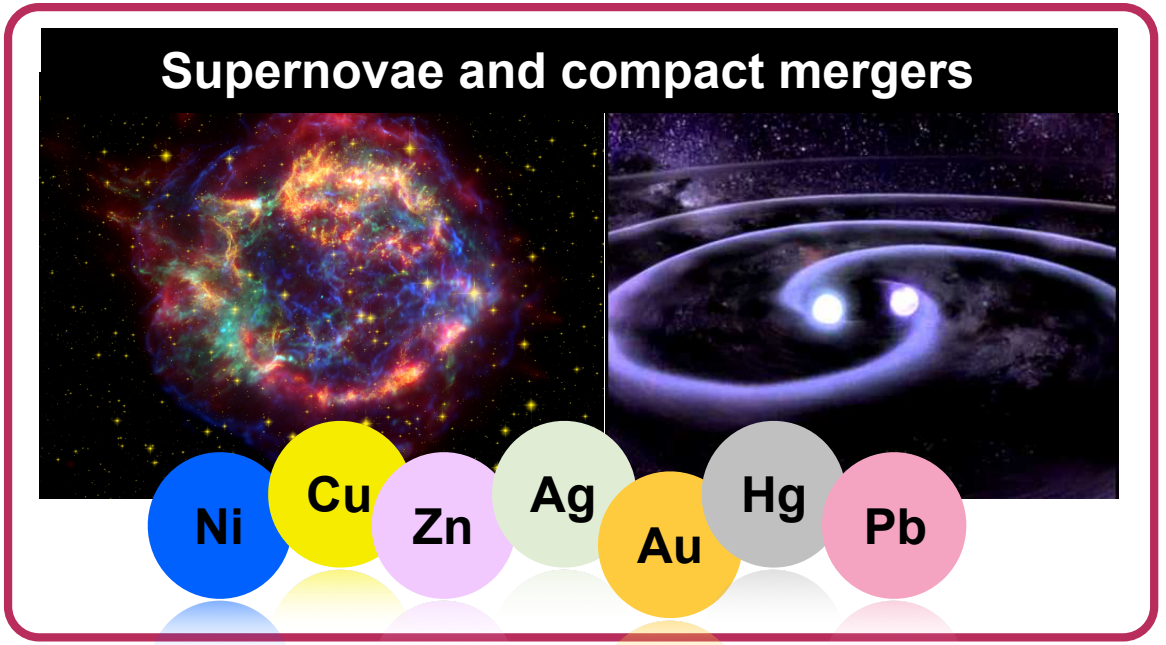
$\nu - \nu$ interactions

Non-linear phenomenon

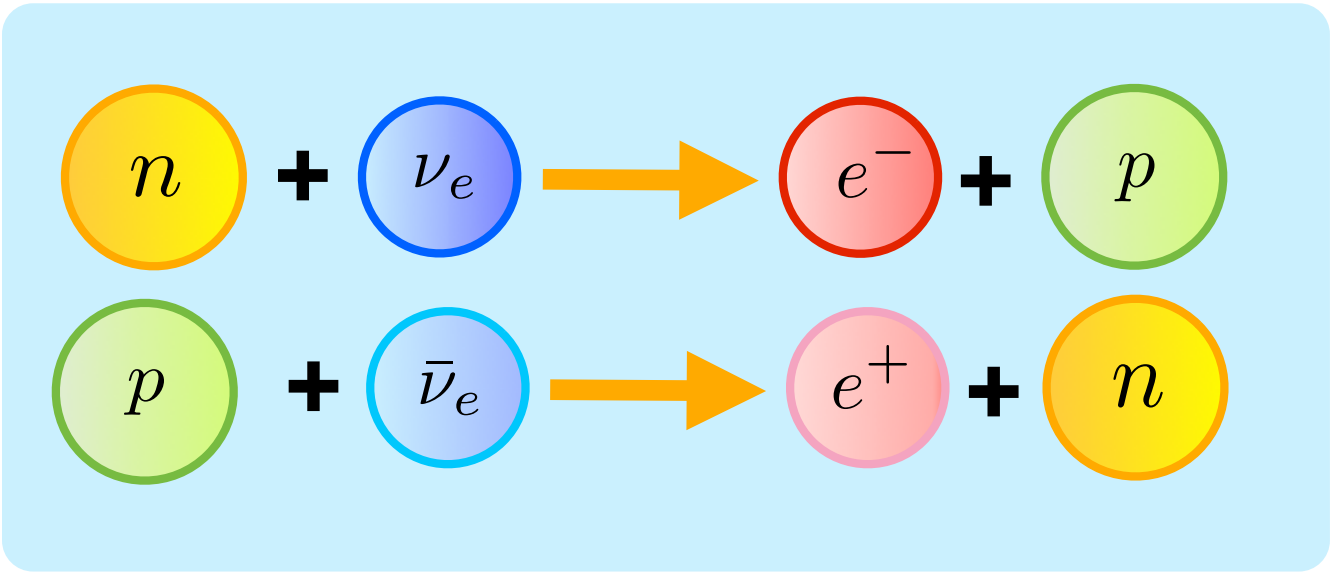
Izaguirre, Raffelt, Tamborra, PRL (2017). Tamborra et al., ApJ (2017). Shalgar & Tamborra, ApJ (2019).


COMPACT BINARY MERGERS

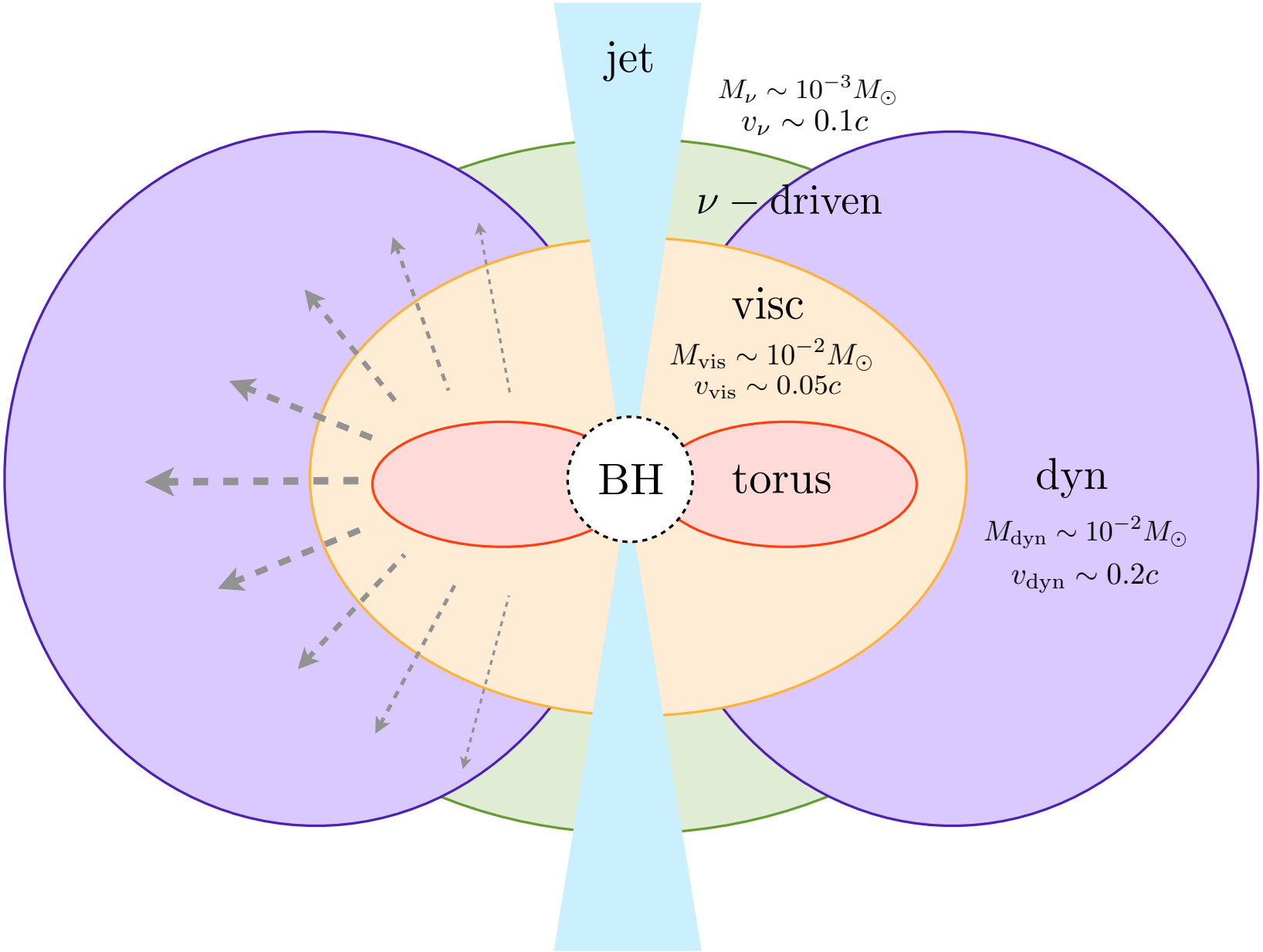
Nucleosynthesis



Synthesis of new elements could not happen without neutrinos.



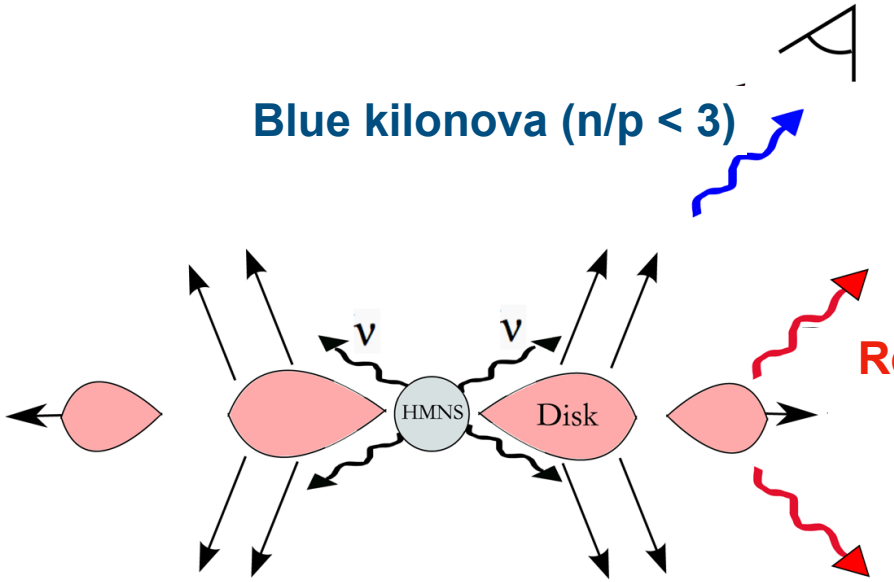
Neutrinos Affect Nucleosynthesis

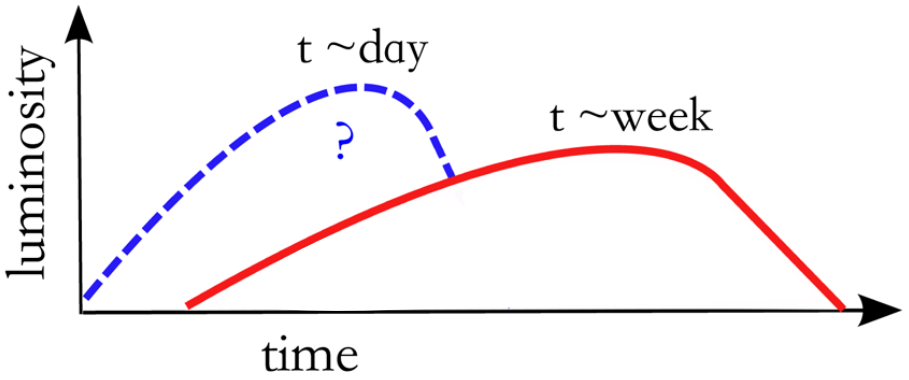


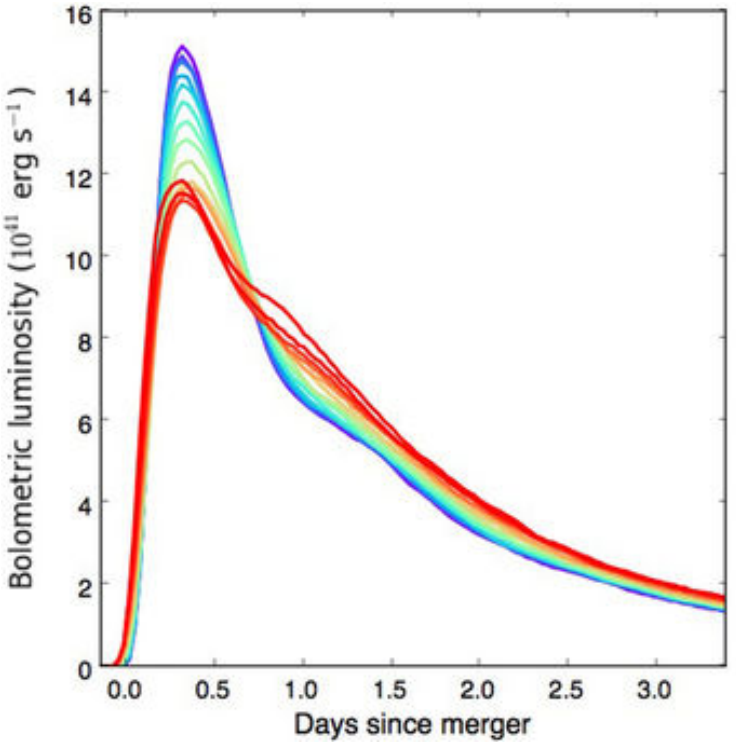
Neutrino may play a major role especially for element production around the polar region.

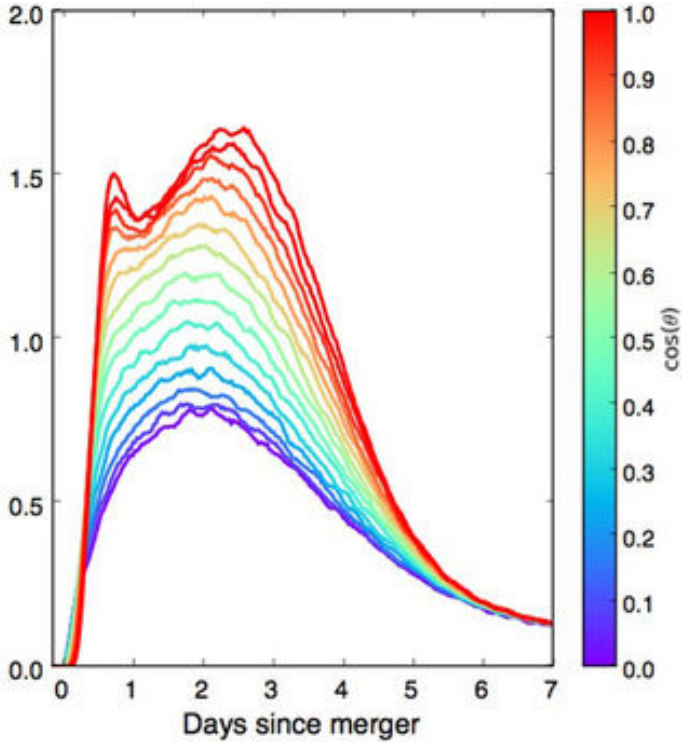
Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017).

Red and Blue Kilonova Components





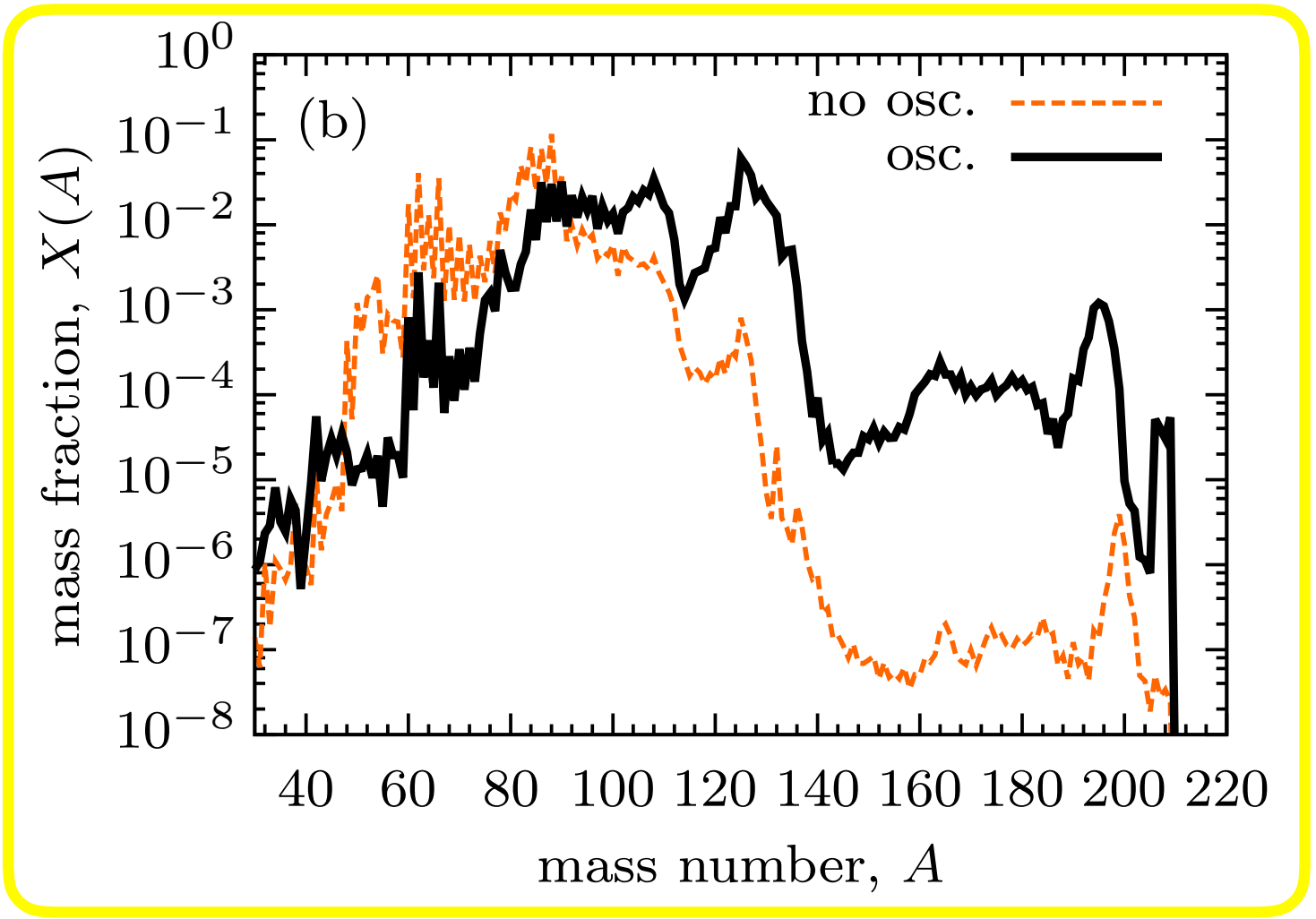




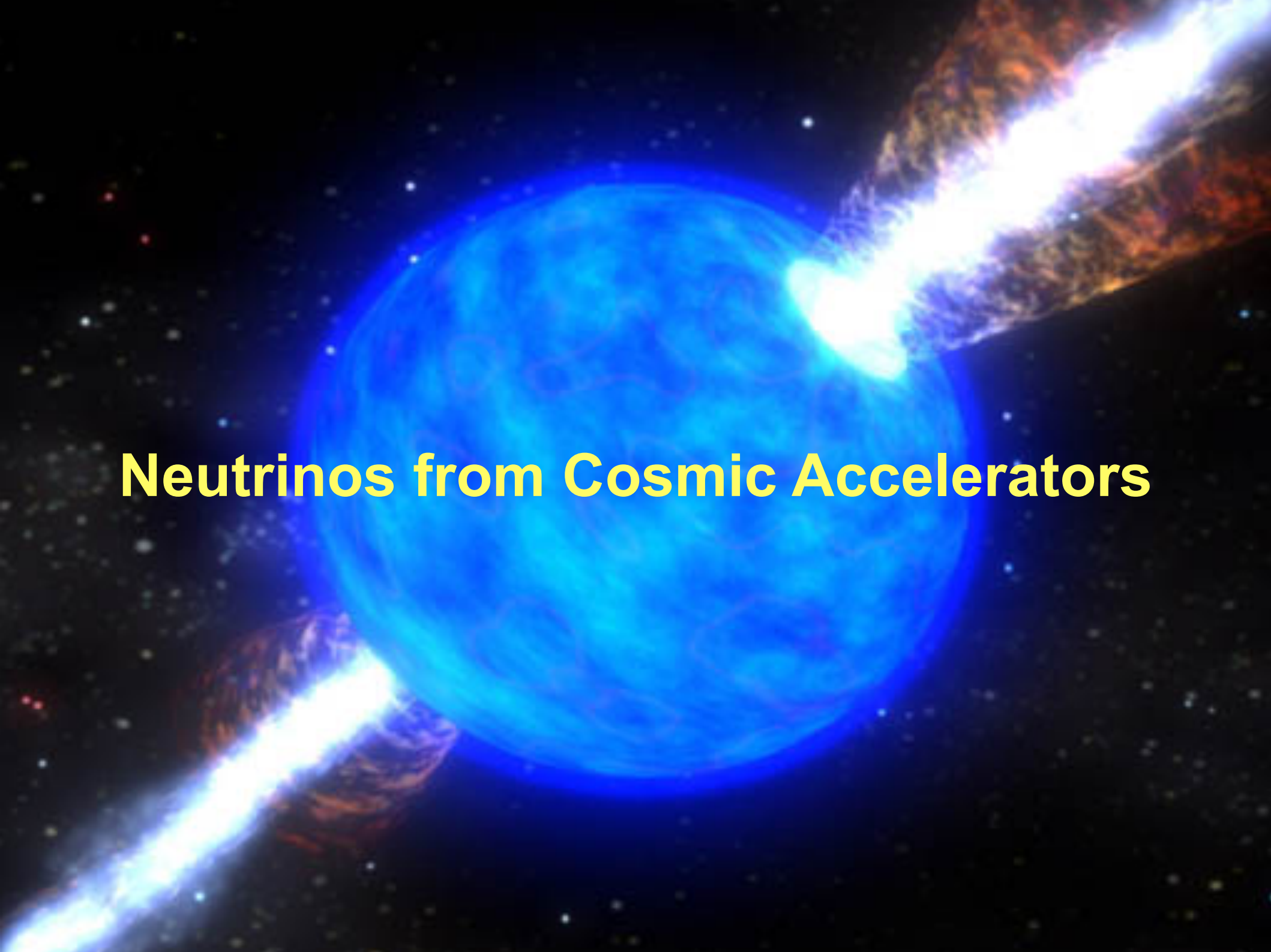
Figures taken from: Metzger & Fernandez, MNRAS (2014); Kasen et al., Nature 2017.

Neutrinos Affect Nucleosynthesis

Neutrino flavor conversions affect element production.

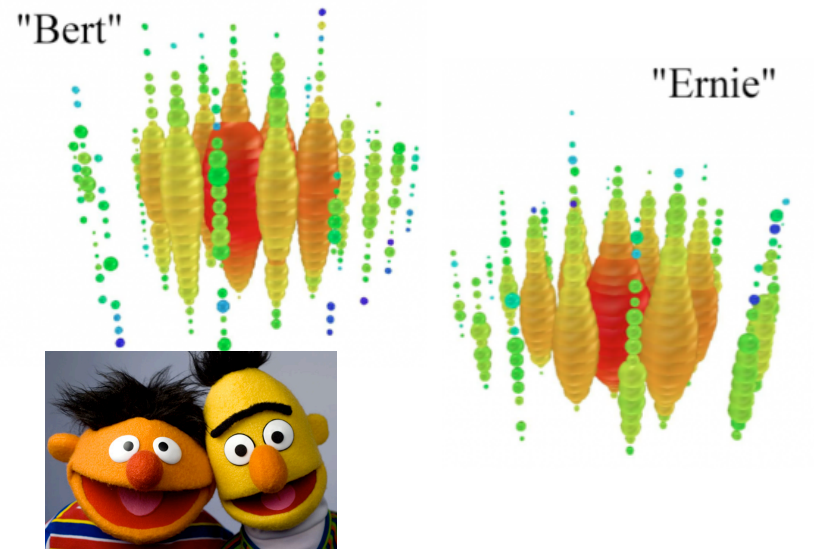


Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017).

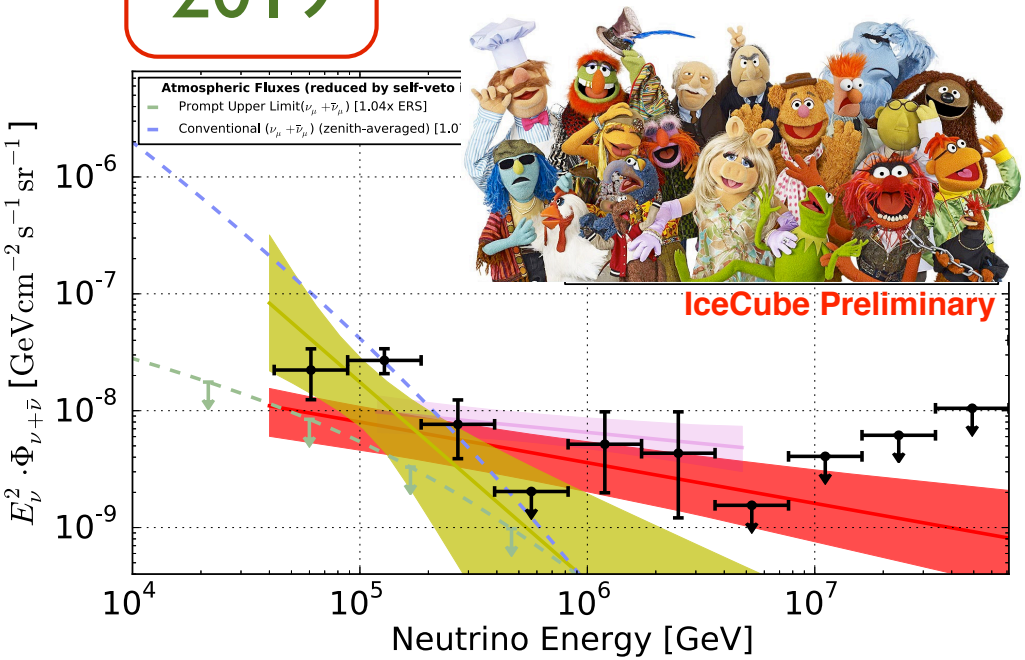

Neutrinos from Cosmic Accelerators

Upper Limit on Neutrino Emission

2013



2019



- ★ IceCube observed O(100) events in the TeV-PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

Evidence for astrophysical flux

IceCube Collaboration, Science (2013), PRL (2014), PRD (2015). IceCube Collaboration, ApJ (2015); PRL (2015). Ahlers & Halzen, Prog. Part. Phys. (2018).

Where Are These Neutrinos Coming From?

★ New physics?

★ Galactic origin [sub-dominant contribution]

★ **Extragalactic origin**
- Star-forming galaxies
- Gamma-ray bursts
- Active galactic nuclei, blazars
- Low-power or choked sources

More statistics needed! No strong preference so far.

Denton, Tamborra, JCAP (2018), ApJ (2018). Feyereisen, Tamborra, Ando, JCAP (2017).
Mertsch, Rameez, Tamborra JCAP (2017).

Conclusions

Neutrinos:

- **Fundamental in most energetic phenomena in our Universe.**
- **Ideal messengers.**
- **Carry imprints of the engine behind astrophysical sources.**
- **Affect element formation in astrophysical sources.**
- **Being a neutrino-like scientist helps to see things others don't see!**

Thank you!