Weakly Interacting Particles in Core Collapse Supernovae

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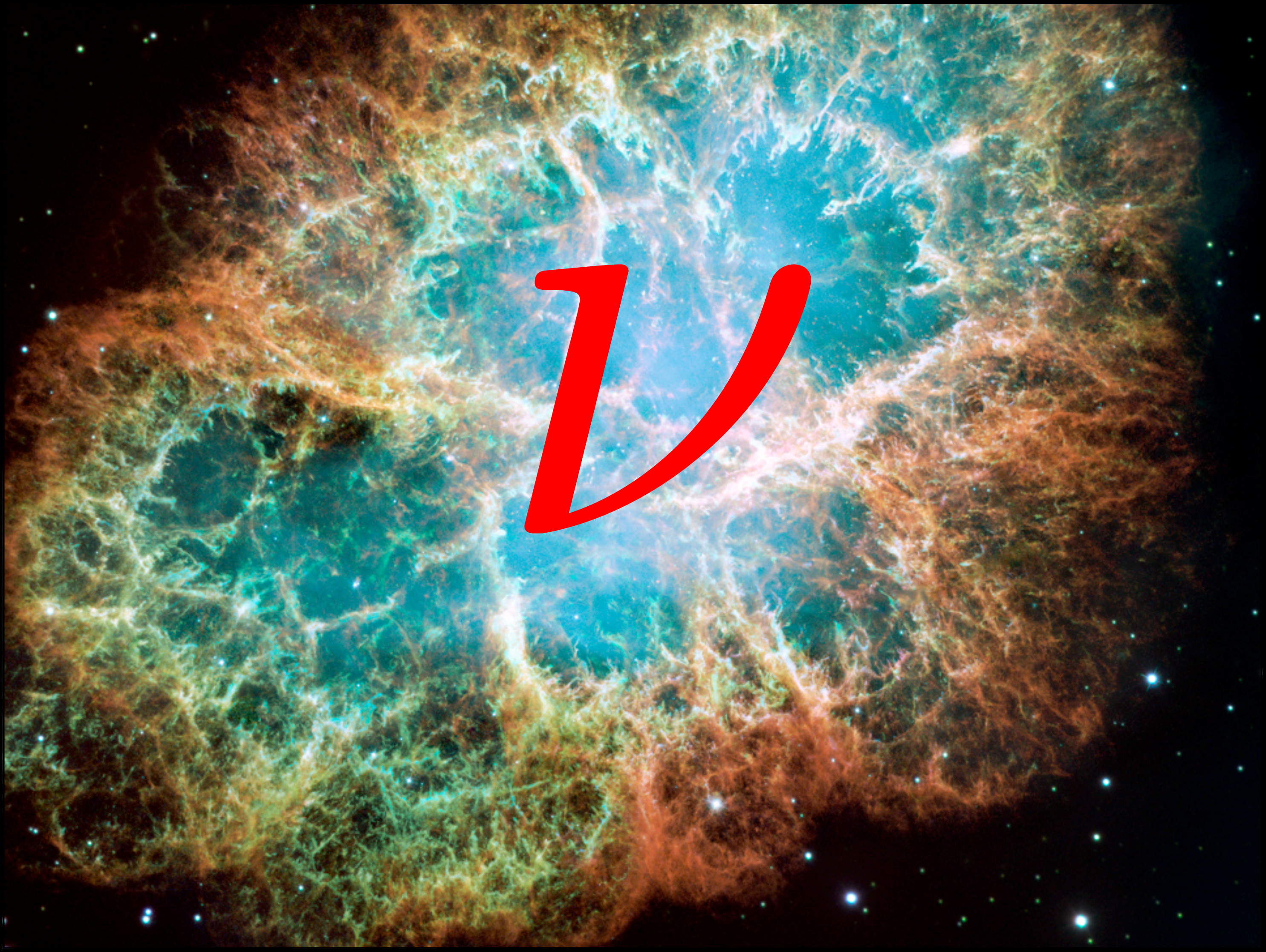

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VILLUM FONDEN
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SFB 1258 Neutrinos Dark Matter Messengers

Outline

- Core-collapse supernovae
- Standard weakly interacting particles from a supernova burst
- Non standard weakly interacting particles and supernovae
- Conclusions

Core Collapse Supernovae

Core Collapse Supernova

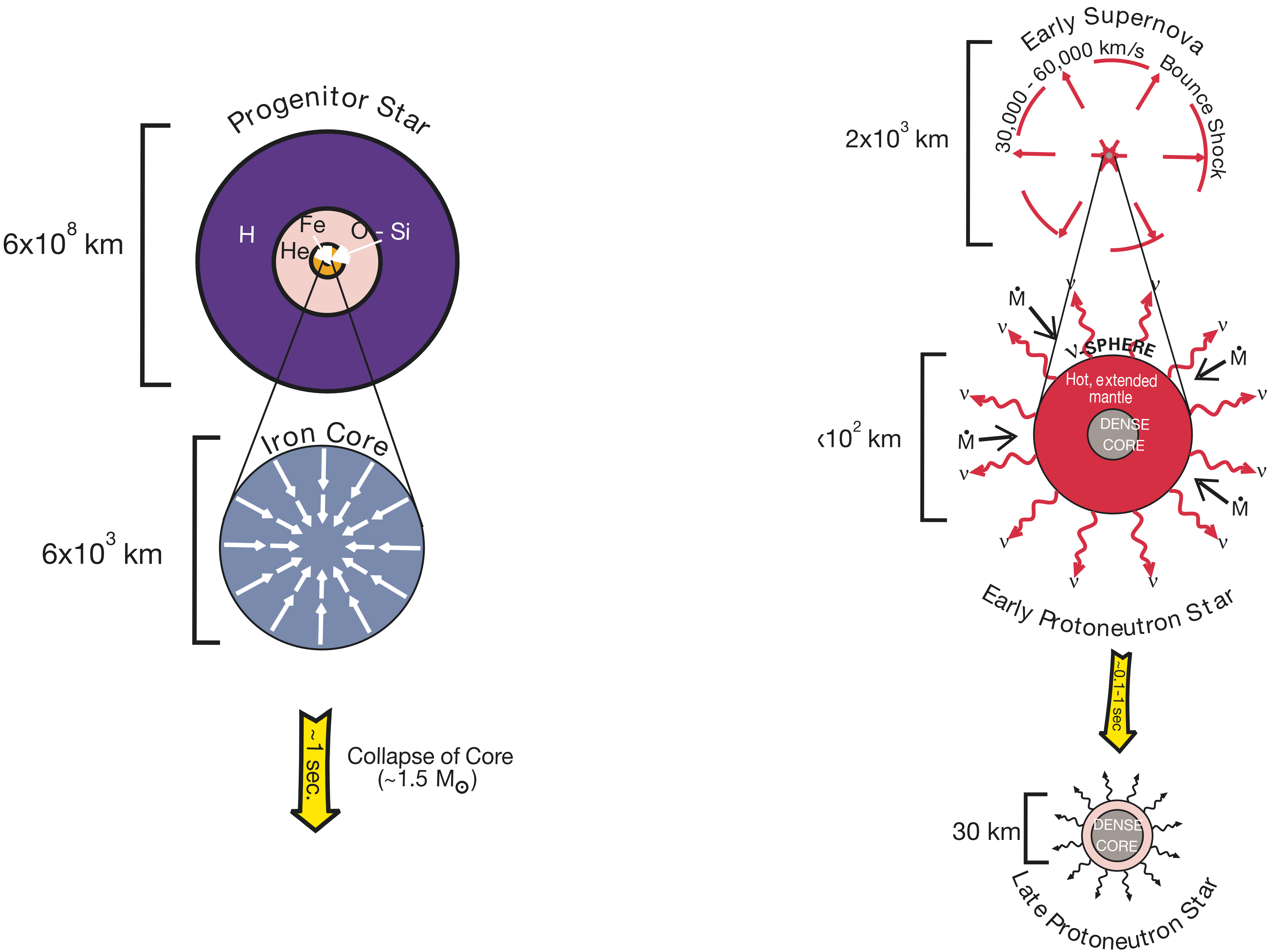
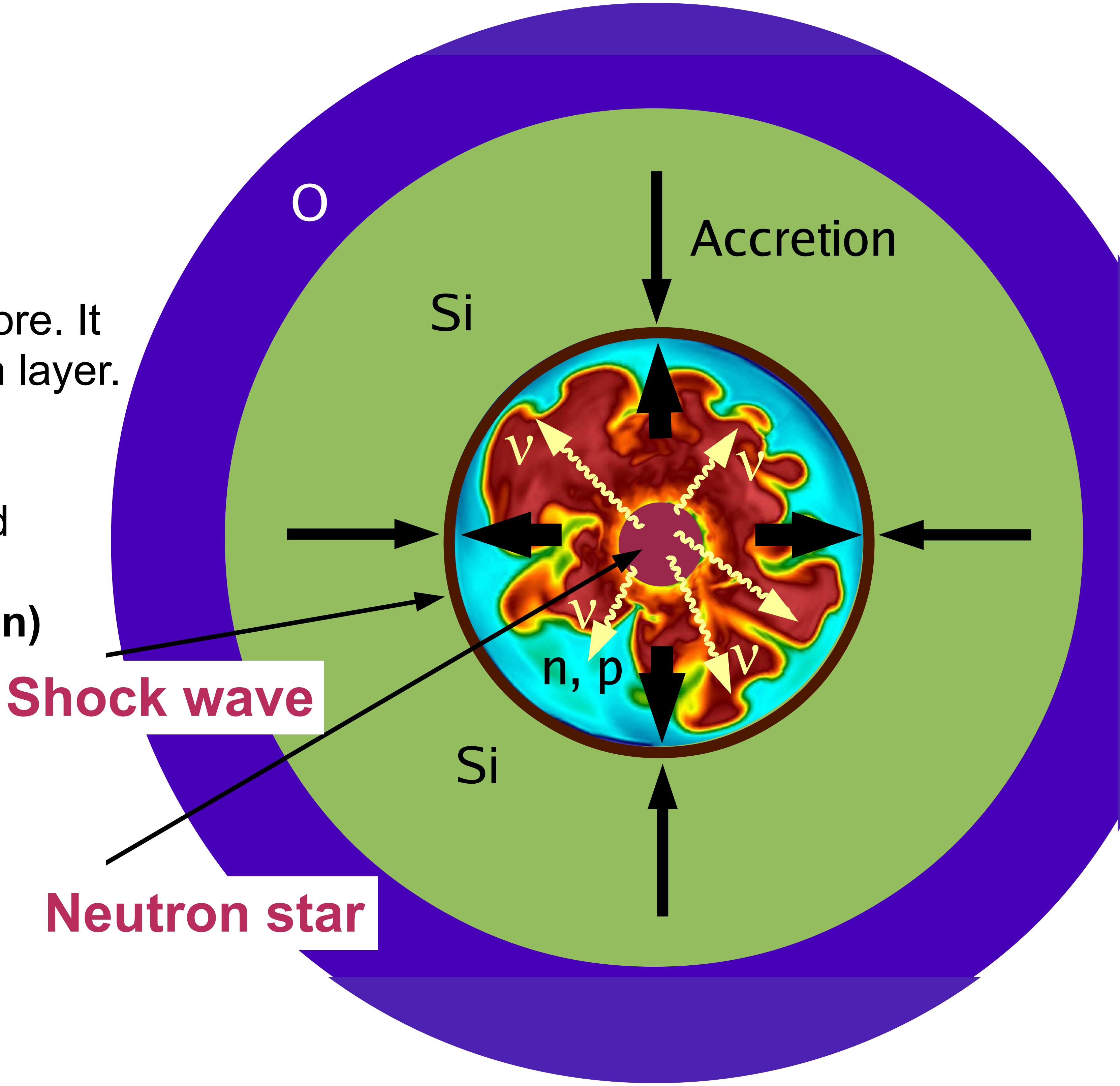


Figure credit: A. Burrows, Nature (2000).

Supernova Explosion Mechanism

- Shock wave forms within the iron core. It dissipates energy by dissociating iron layer.

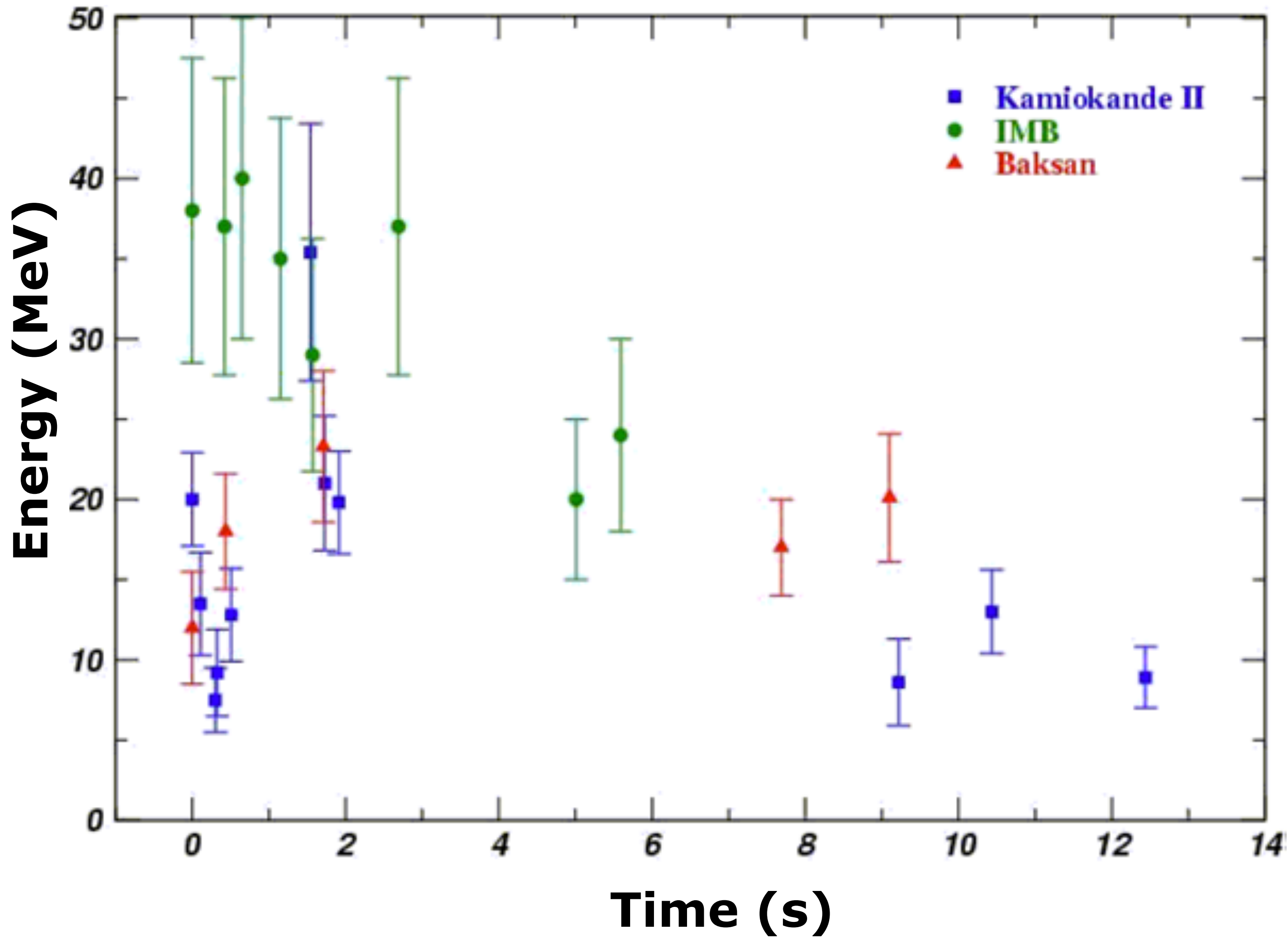
- **Neutrinos** provide energy to stalled shock wave to start re-expansion. **(Delayed Neutrino-Driven Explosion)**



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

Supernova 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).

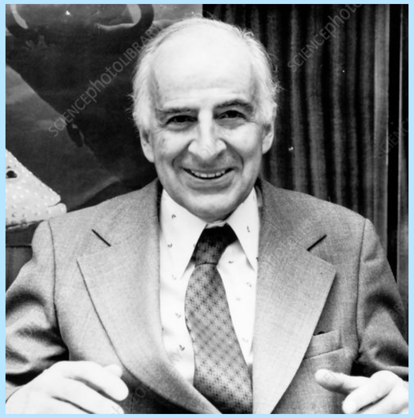
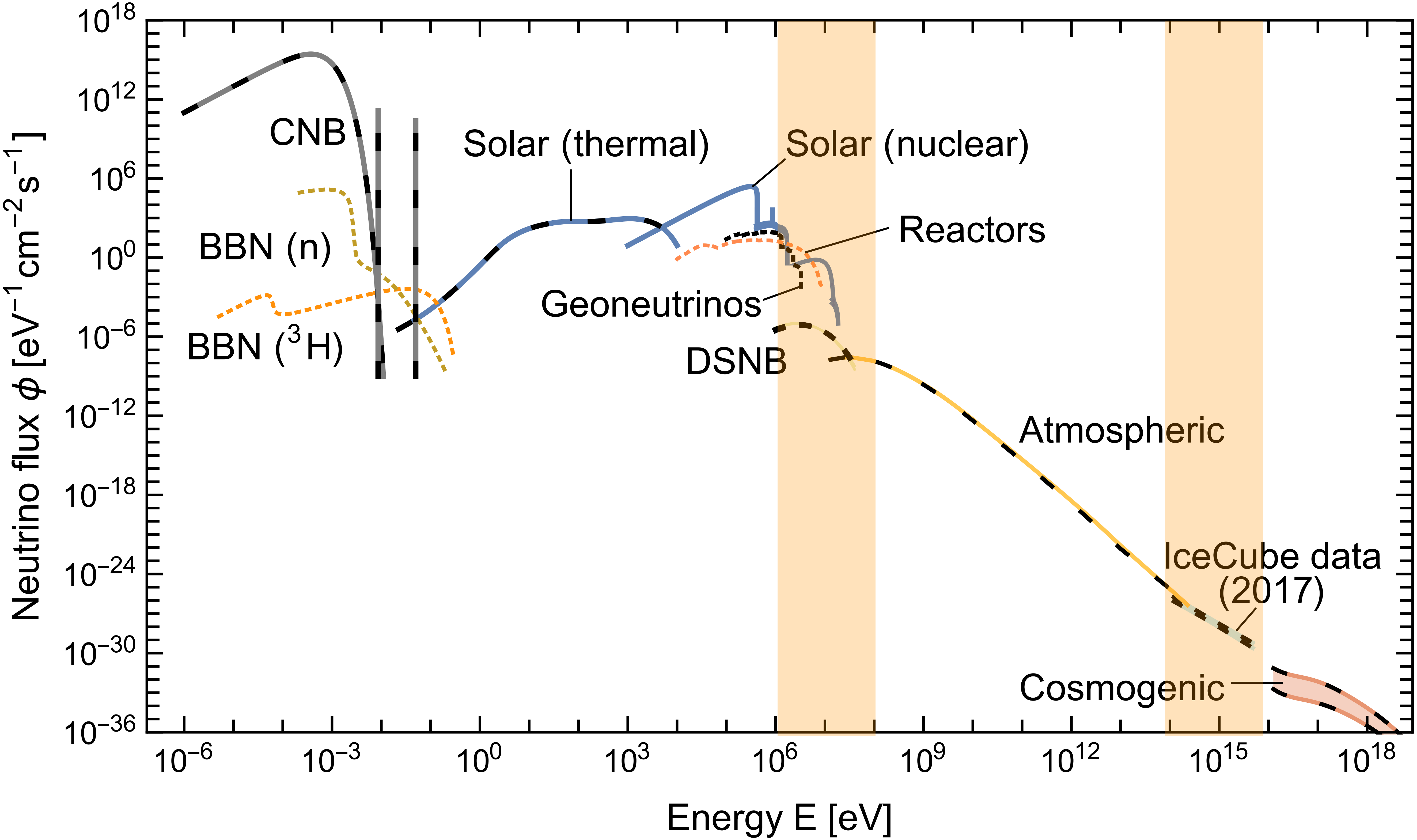


Image credits: NASA, CERNCOURIER.

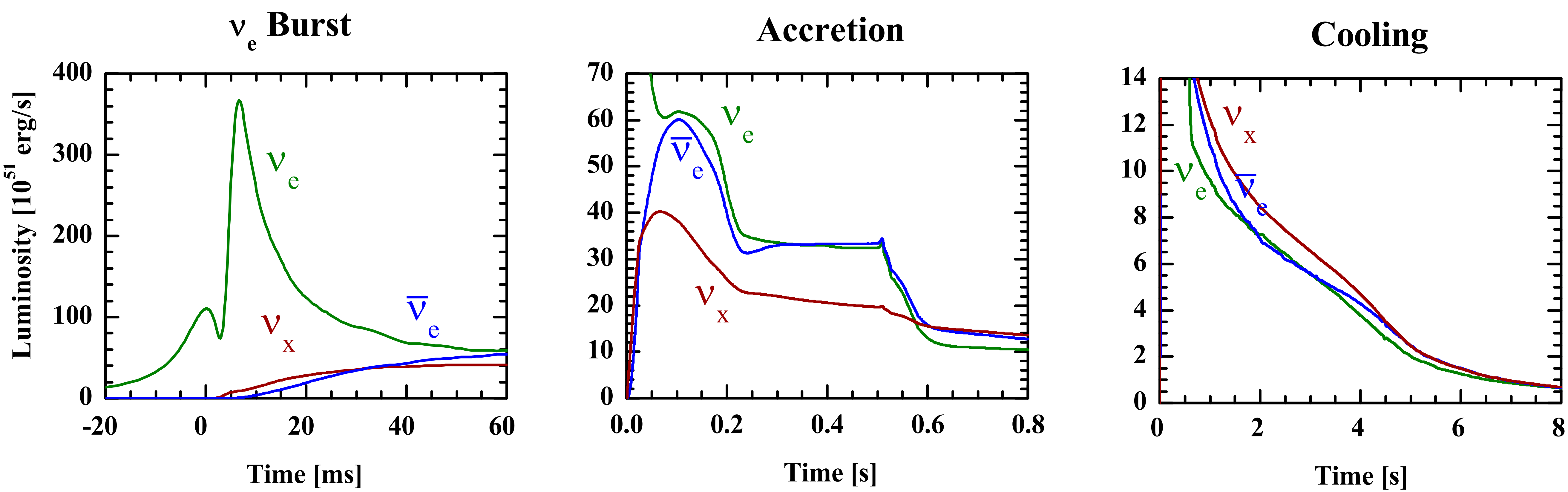
Grand Unified Neutrino Spectrum



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

Neutrinos from the Supernova Burst

Phases of Neutrino Emission



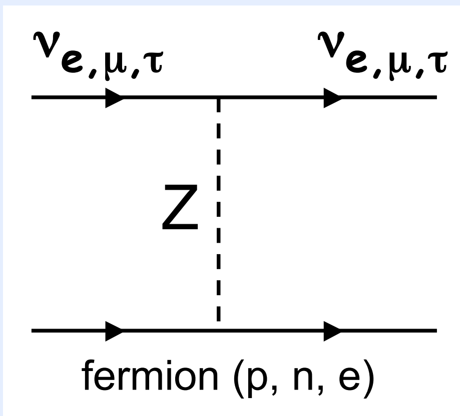
Signal independent on SN mass and EoS.

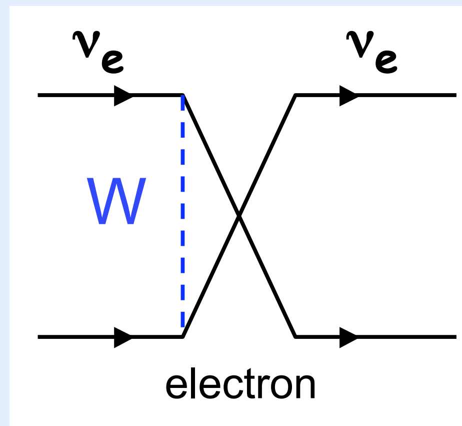
Signal has strong variations (mass, EoS, SN dynamics).

EoS and mass dependence.

Figure: 1D spherically symmetric SN simulation (M=27 M_{sun}), Garching group.

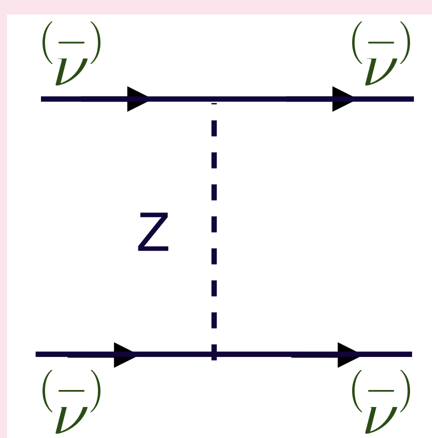
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

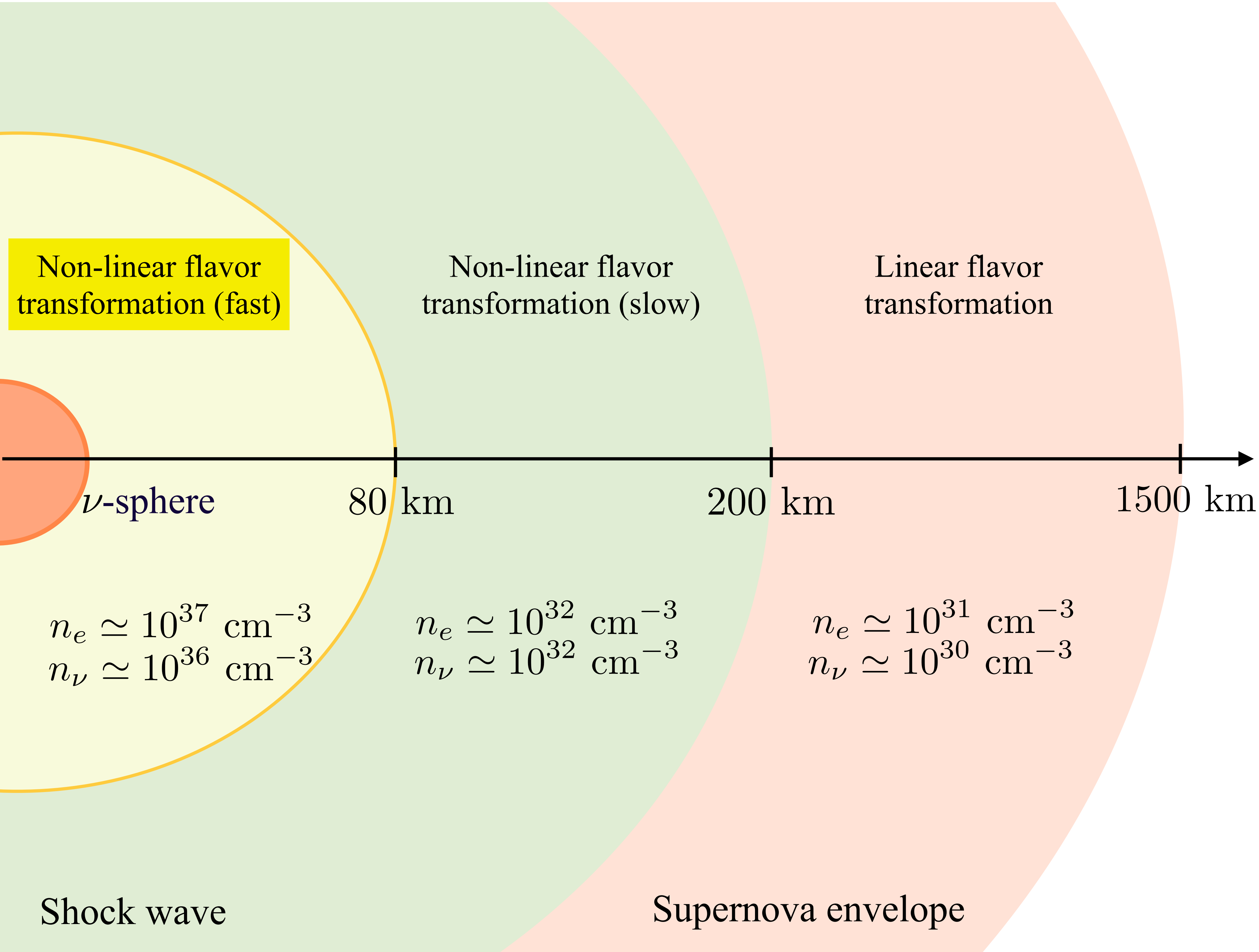


Neutrinos interact among themselves.

Non-linear phenomenon, trajectory is crucial!

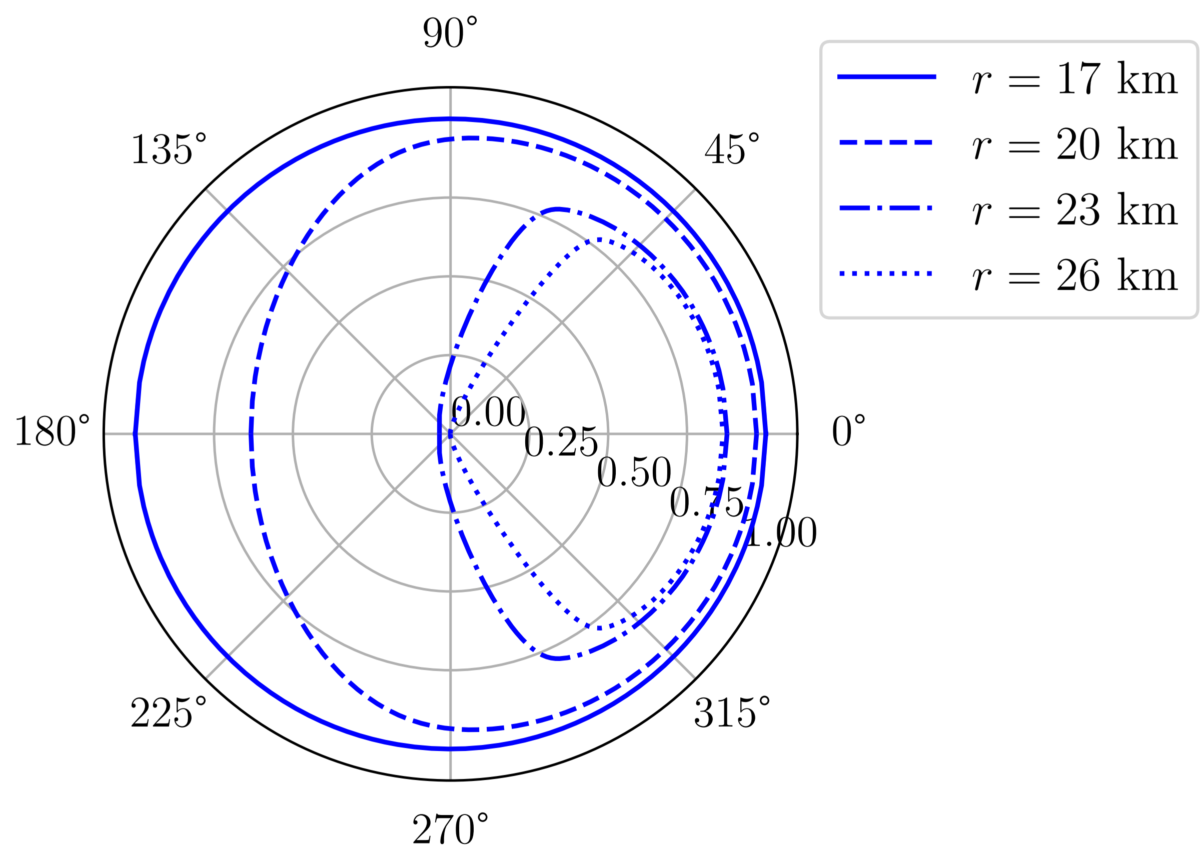
Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021).

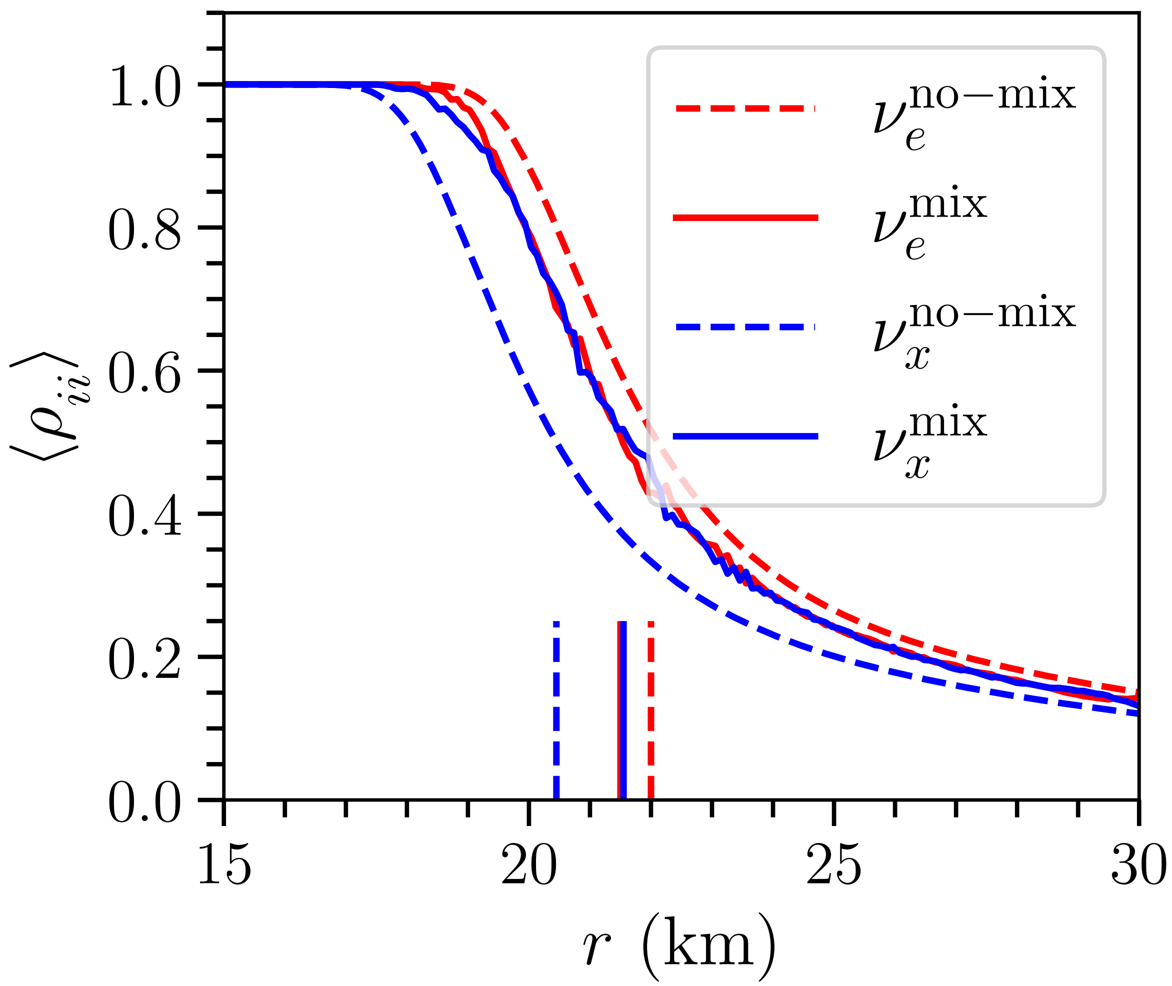
Simplified Picture of Flavor Conversions



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

Flavor Conversion in the Supernova Core



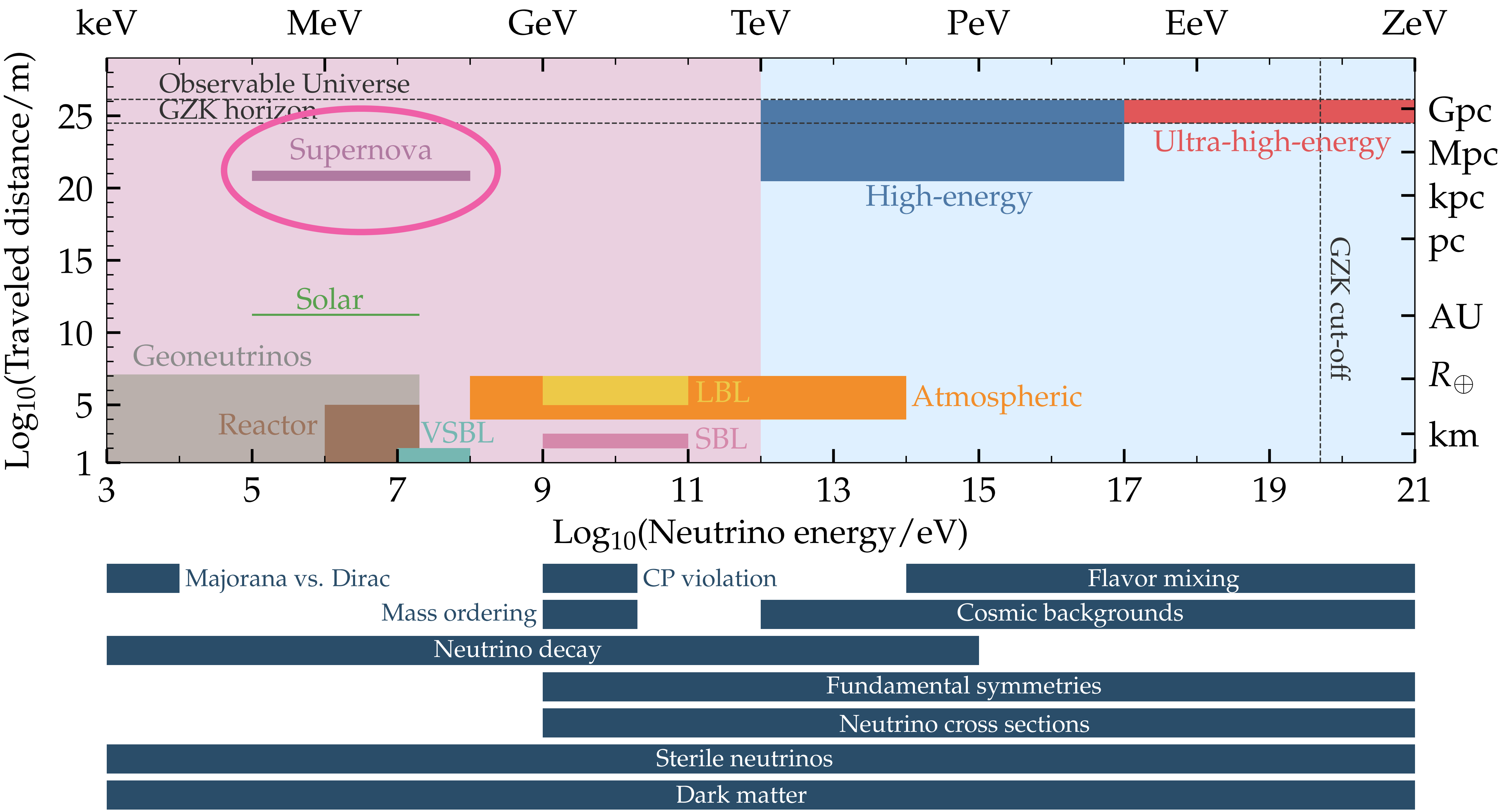


- Neutrino conversion is strongly affected by collisions and advection.
- Neutrino decoupling from matter is affected by flavor conversion.
- Implications yet to be determined.

Shalgar & Tamborra, arXiv: 2206.00676, arXiv: 2207.04058. Padilla-Gay, Tamborra, Raffelt, PRL (2022). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2020, 2021). Richers, Willcox, Ford, PRD (2021). Wu et al., PRD (2021). …

Non Standard Particles and Supernovae

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 supernova physics

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

Energy Loss Argument

Weakly interacting particles would take away energy from the standard neutrino burst and shorten it. Late time signal is one of the most sensitive observables.

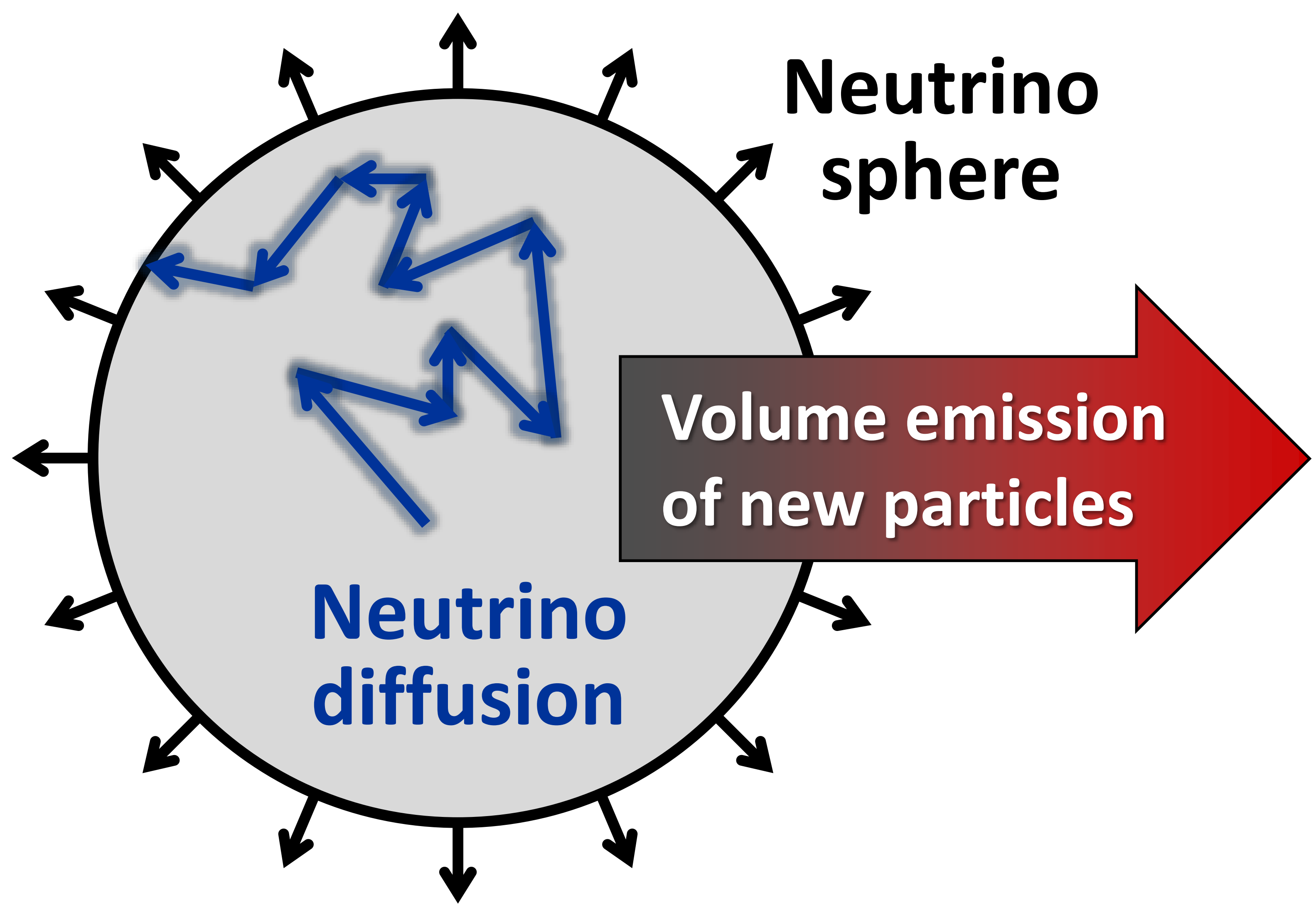
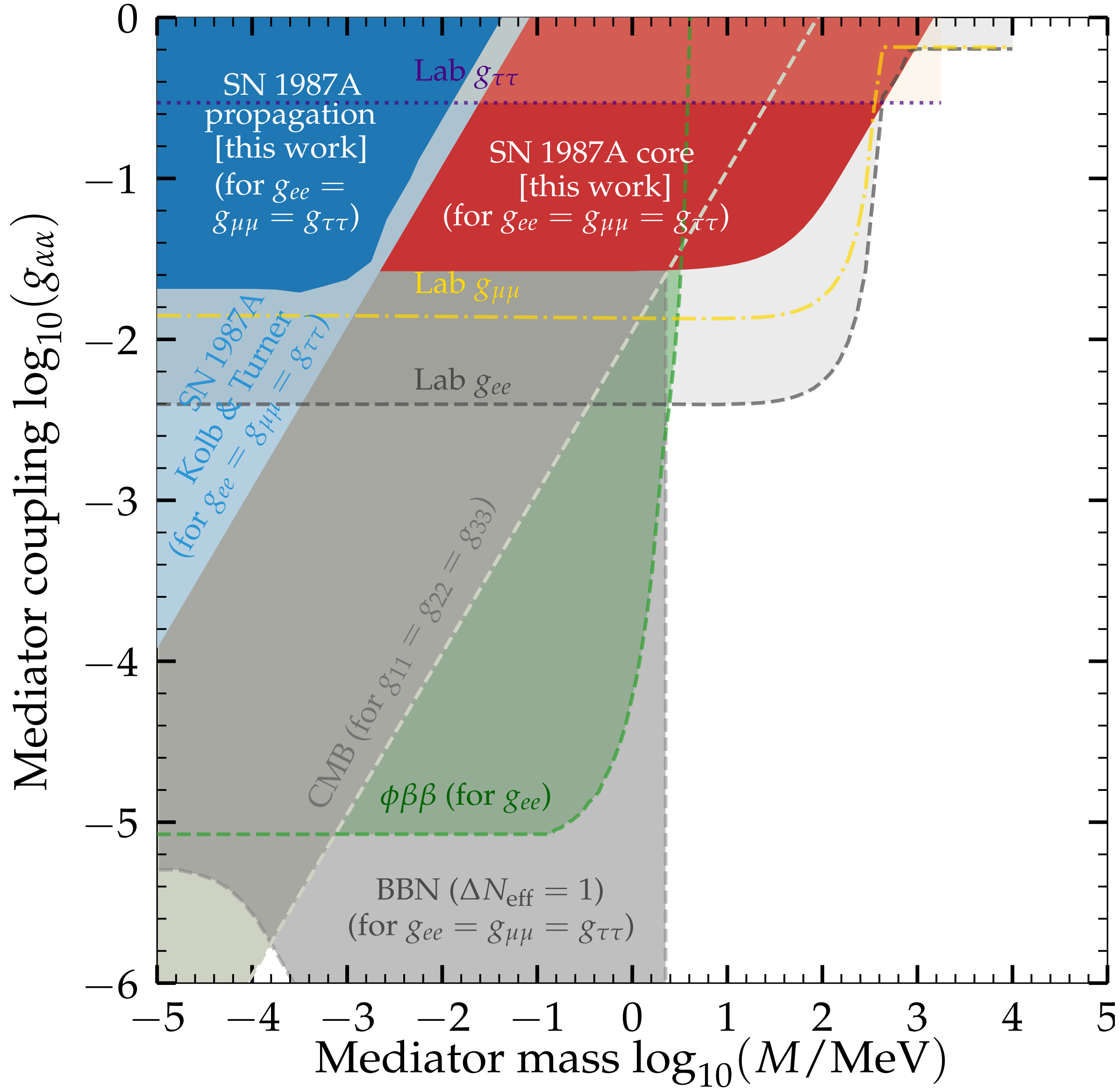


Image credit: G. Raffelt

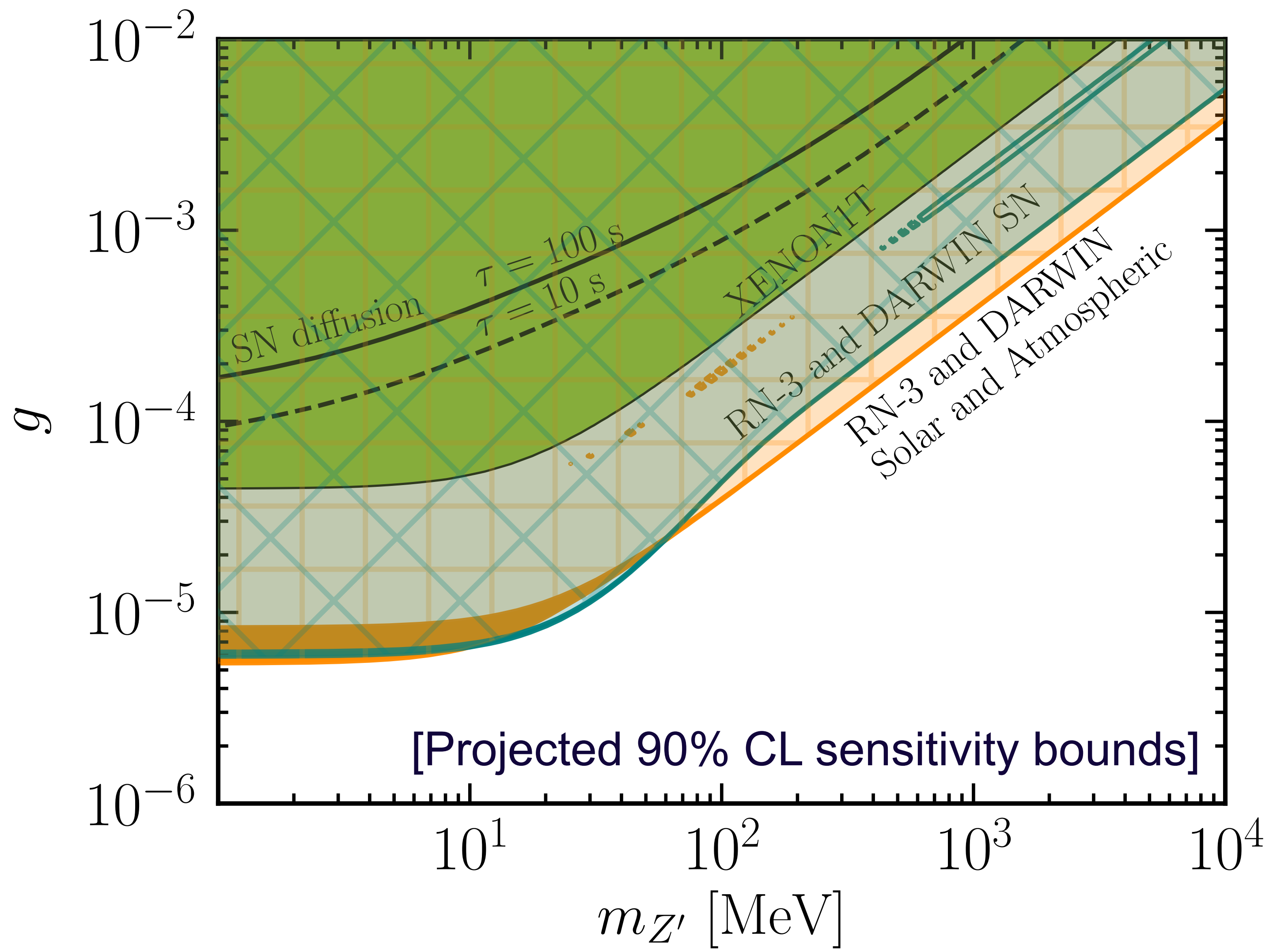
Non Standard Neutrino Interactions

Neutrino secret interactions



Shalgar, Tamborra, Bustamante, PRD (2021).

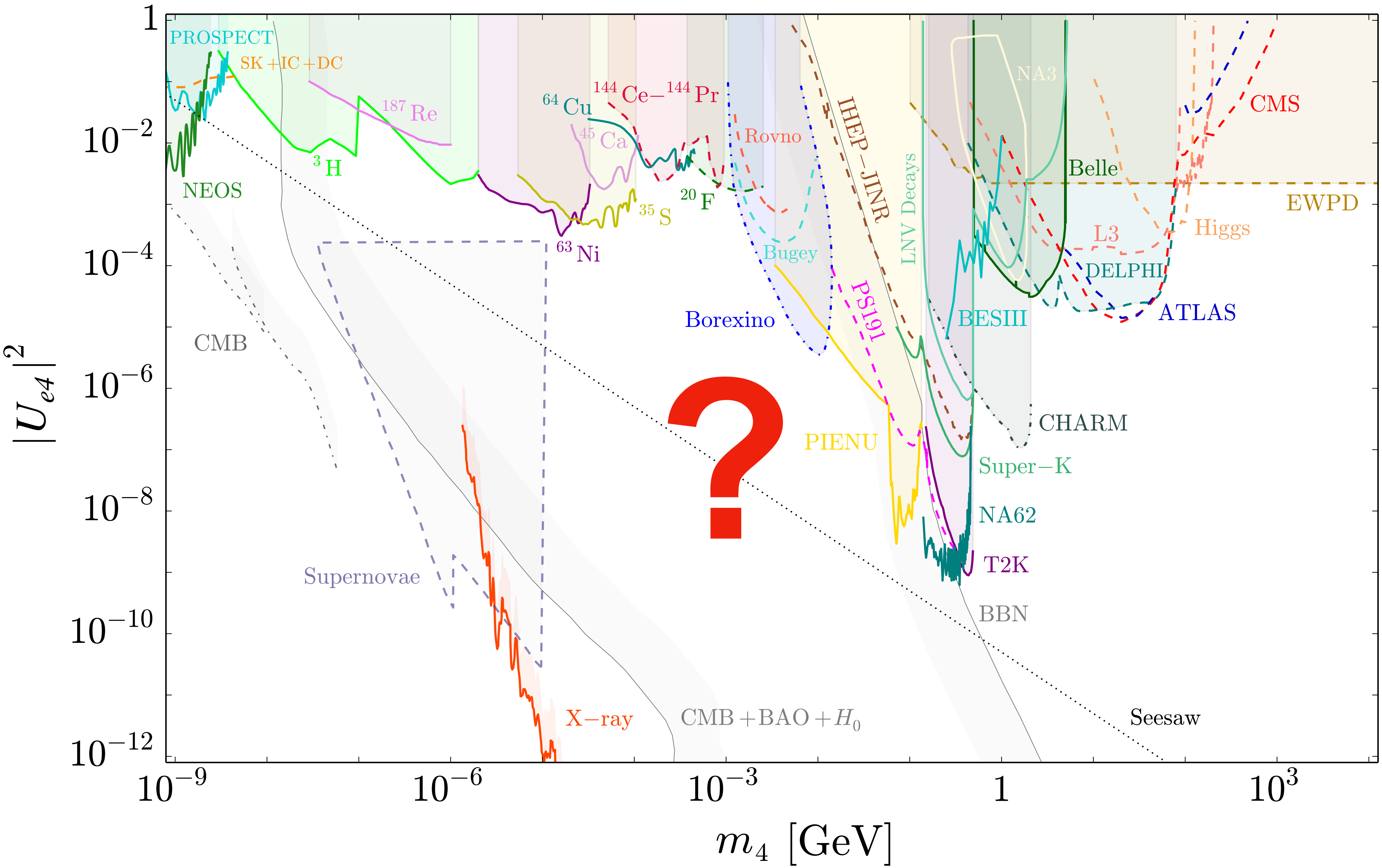
Non-standard coherent neutrino nucleus scattering



Suliga & Tamborra, PRD (2021).

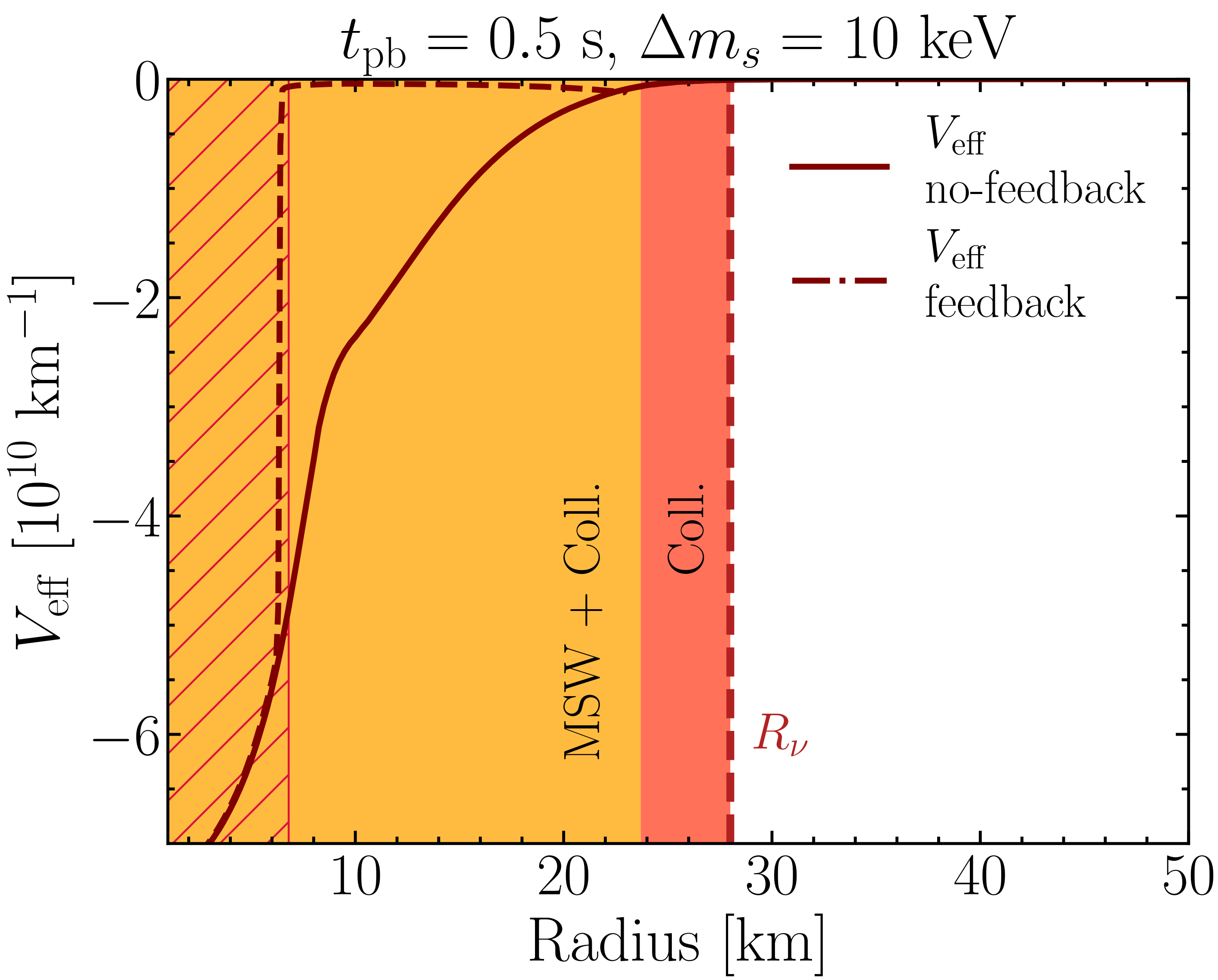
Kolb, Turner, PRD (1987). Fuller, Mayle, Wilson, ApJ (1988). Kachelreiss, Tomas, Valle, PRD (2000). Tarzan, PRD (2000). Farzan et al., JHEP (2018). Grifols, Masso, Peris, Mod. Phys. Lett. (1989). Rrapaj, Reddy, PRC (2016). Heurtier, Zhang, JCAP (2017). Chang et al., arXiv: 2206.12426 …

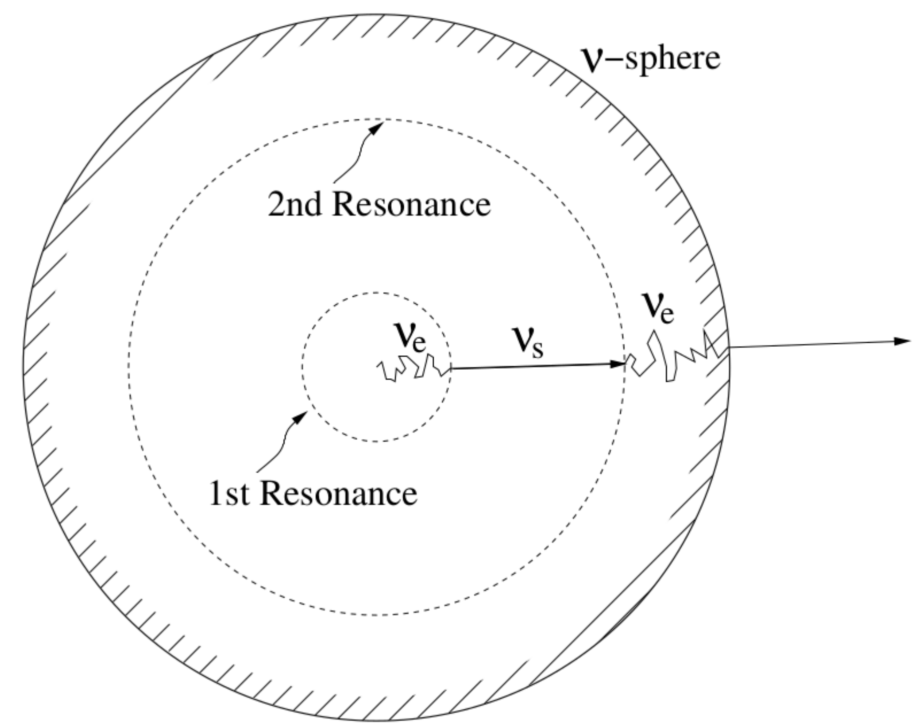
Sterile Neutrinos



Recent reviews: Dasgupta, Kopp, Phys. Rept. (2021). A. Merle, Sterile Neutrino Dark Matter (2017). Boeser et al., Progr. Part. Nucl. Phys. (2020).

KeV Mass Sterile Neutrinos



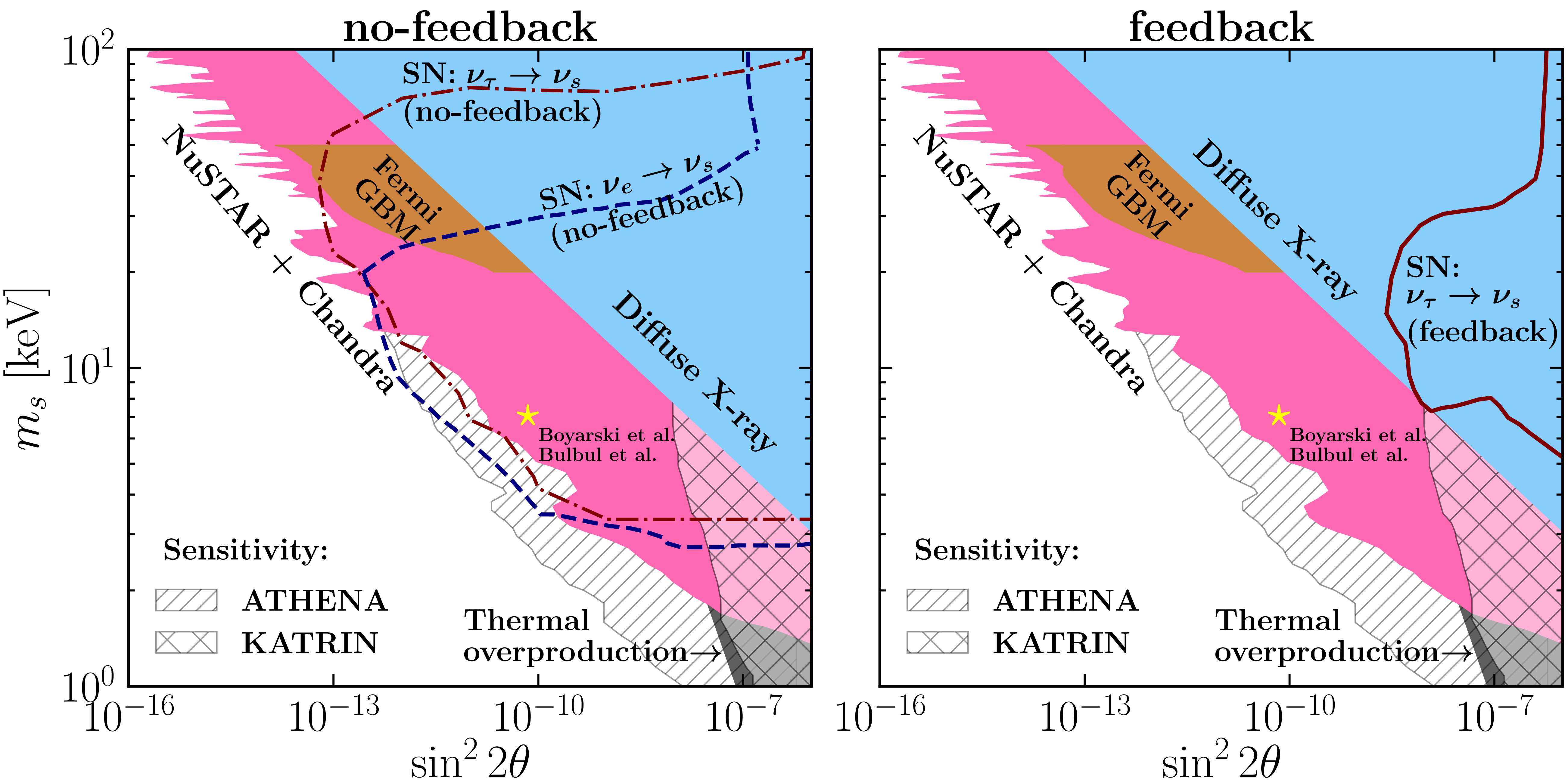


$$V_{\rm eff} = \sqrt{2} G_F n_B \left[-\frac{1}{2} Y_n + Y_{\nu_e} + Y_{\nu_\mu} + 2Y_{\nu_\tau} \right]$$

Sterile neutrinos modify the lepton asymmetry ➡ Changes in the effective potential

Suliga, Tamborra, Wu, JCAP (2019), JCAP (2020). Hidaka & Fuller (2006). Warren et al. (2016). Arguelles et al. (2016). Abazajian et al. (2001). Nunokawa et al. (1997). Hidaka & Fuller (2006). Raffelt & Zhou (2011).

KeV Mass Sterile Neutrinos



The dynamical feedback due to flavor conversions in sterile states considerably relaxes the excluded region of the parameter space of sterile neutrinos.

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

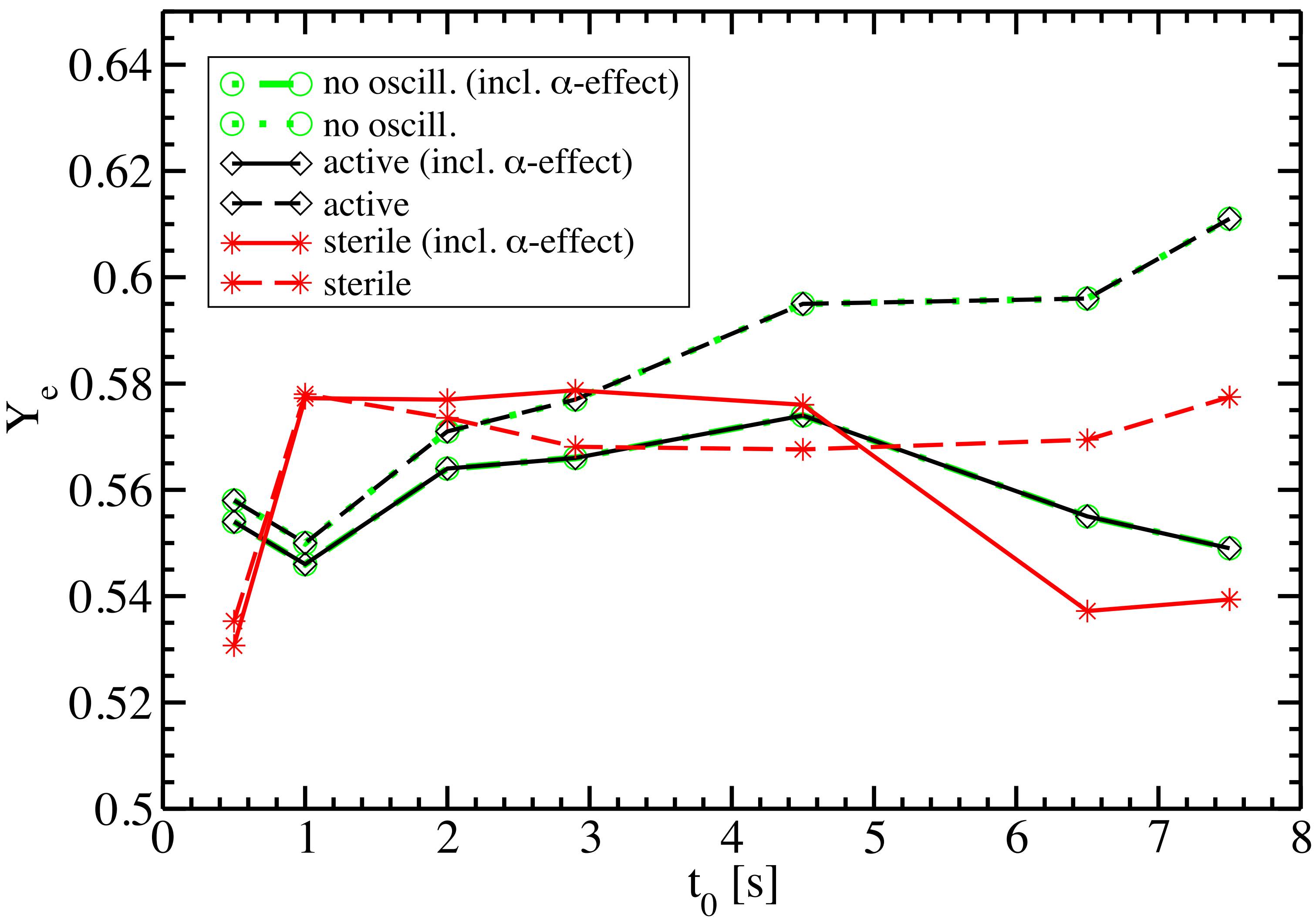
eV Mass Sterile Neutrinos

Flavor mixing affects element production mainly via

$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$Y_e(r) = \frac{N_e(r)}{N_e(r) + N_n(r)}$$

$$\mathrm{H}^{\mathrm{m}} = \sqrt{2} G_{\mathrm{F}} N_b \, \mathrm{diag}\left(\frac{3}{2}Y_e - \frac{1}{2}, \frac{1}{2}Y_e - \frac{1}{2}, 0\right)$$

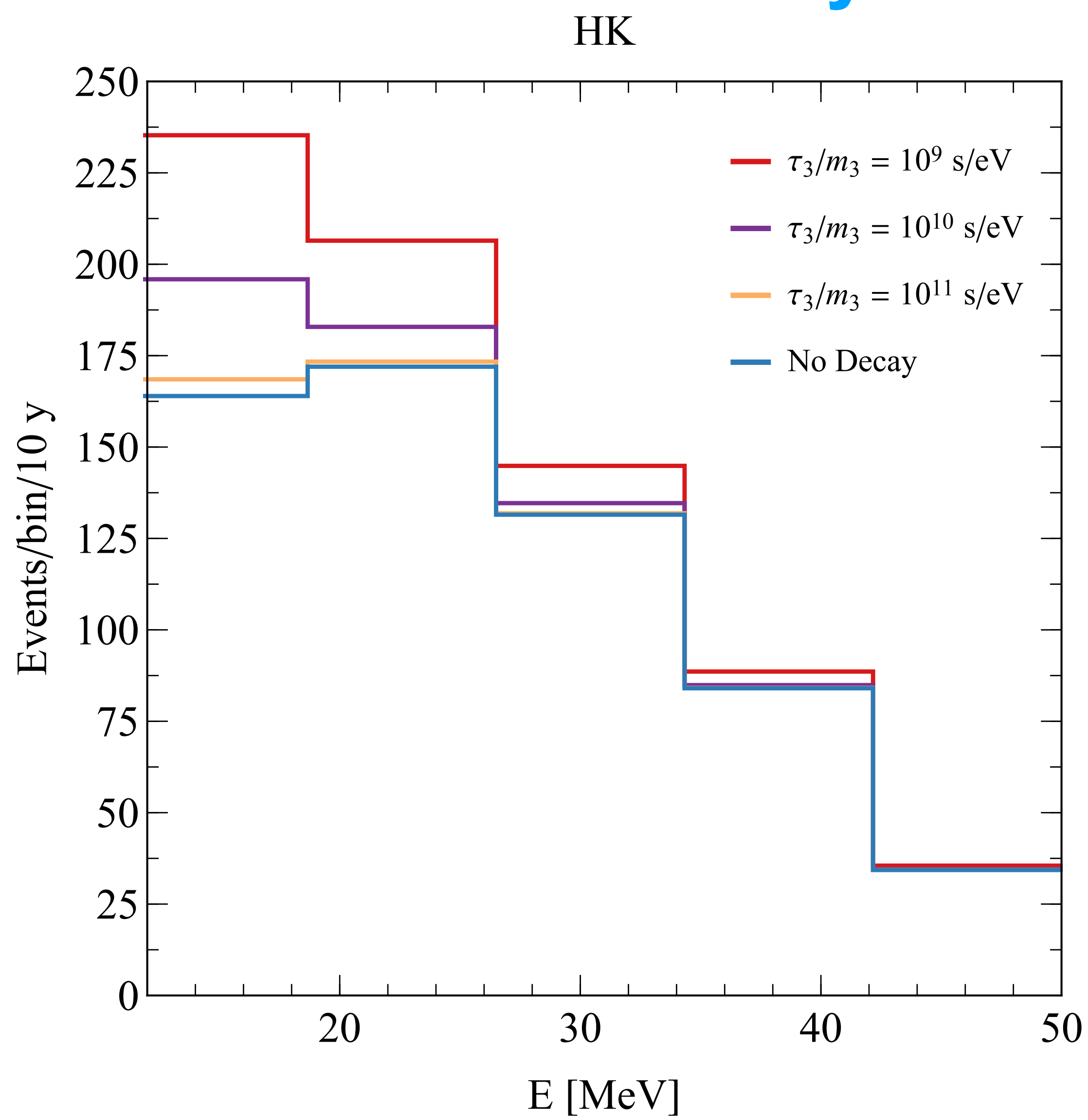


Light sterile neutrinos have small impact on the element formation and do not make the post-explosion wind outflow neutron rich enough to activate a strong r-process.

Tamborra et al., JCAP (2013). Pllumbi, Tamborra et al., ApJ (2015). Wu et al., PRD (2015). Xiong et al., ApJ (2019). Nunokawa et al., PRD (1997).

Diffuse Supernova Neutrinos & New Physics

Neutrino decay



- Independent constraints on supernova population and non-standard particles.
- Detection expected to happen soon.
- Modeling uncertainties are to be reduced.

de Gouvea et al., PRD (2020). Abe et al., PRD (2021). Moller et al., JCAP (2018). Kresse et al., ApJ (2021). Lunardini & Tamborra, JCAP (2012). Horiuchi et al., PRD (2021).

Conclusions

- Core-collapse supernovae are driven by neutrinos
- Neutrino physics in the supernova core remains to be understood
- Complementary bounds on non-standard scenarios from core-collapse supernovae
- DSNB allows to test physics of (non-)standard weakly interacting particles

Thank you!