Light Sterile Neutrinos in Compact Binary Merger Remnants

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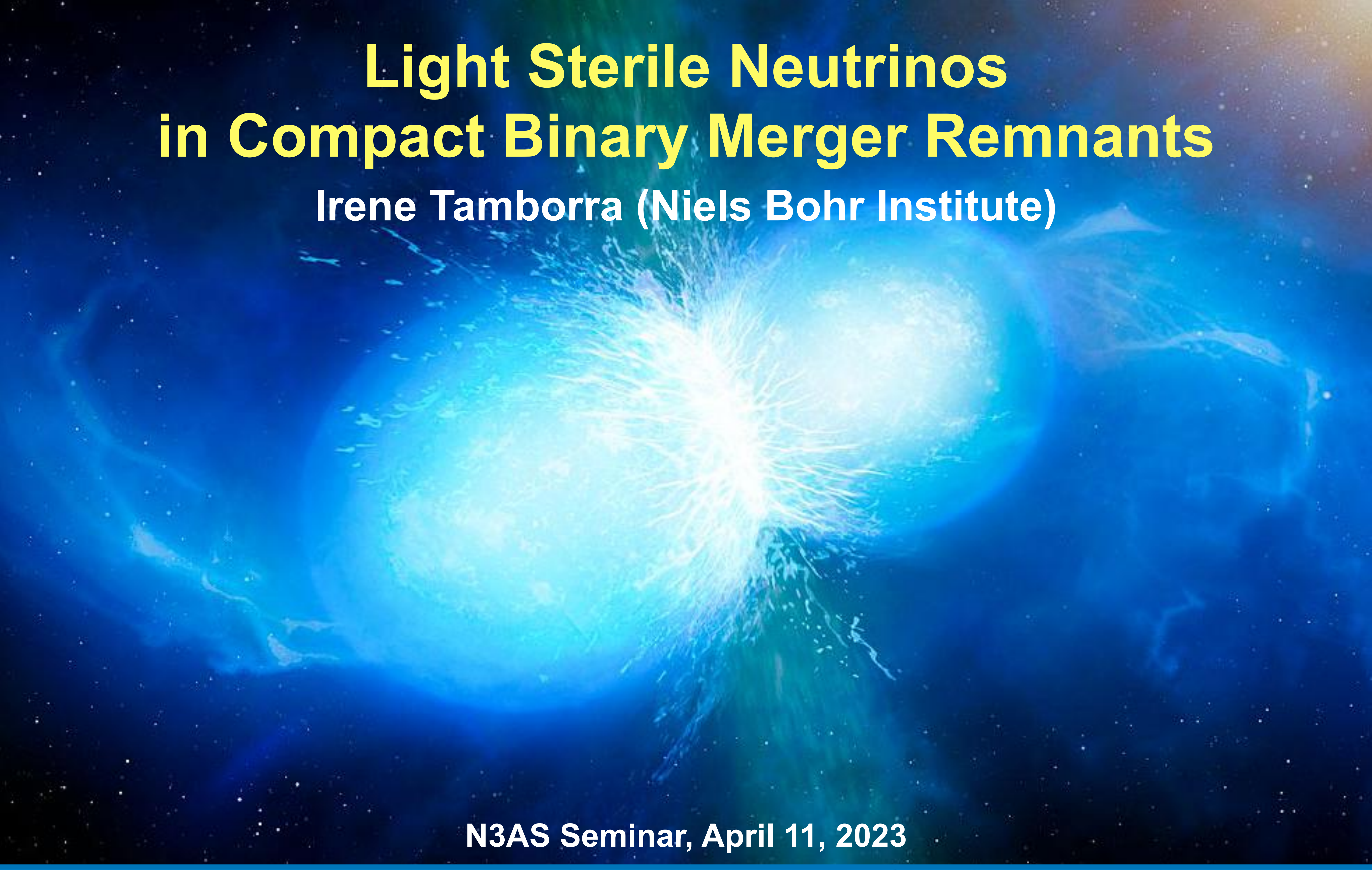

N3AS Seminar, April 11, 2023

VILLUM FONDEN

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SFB 1258 Neutrinos Dark Matter Messengers

Outline

- Properties of compact binary merger remnants
- Neutrinos and compact binary merger remnants
- Resonant production of sterile neutrinos
- Temporal evolution and implications on the merger physics
- Conclusions

Based on Sigurðarson, Tamborra, Wu, Phys. Rev. D 106 (2022) 123030.

Compact Binary Mergers

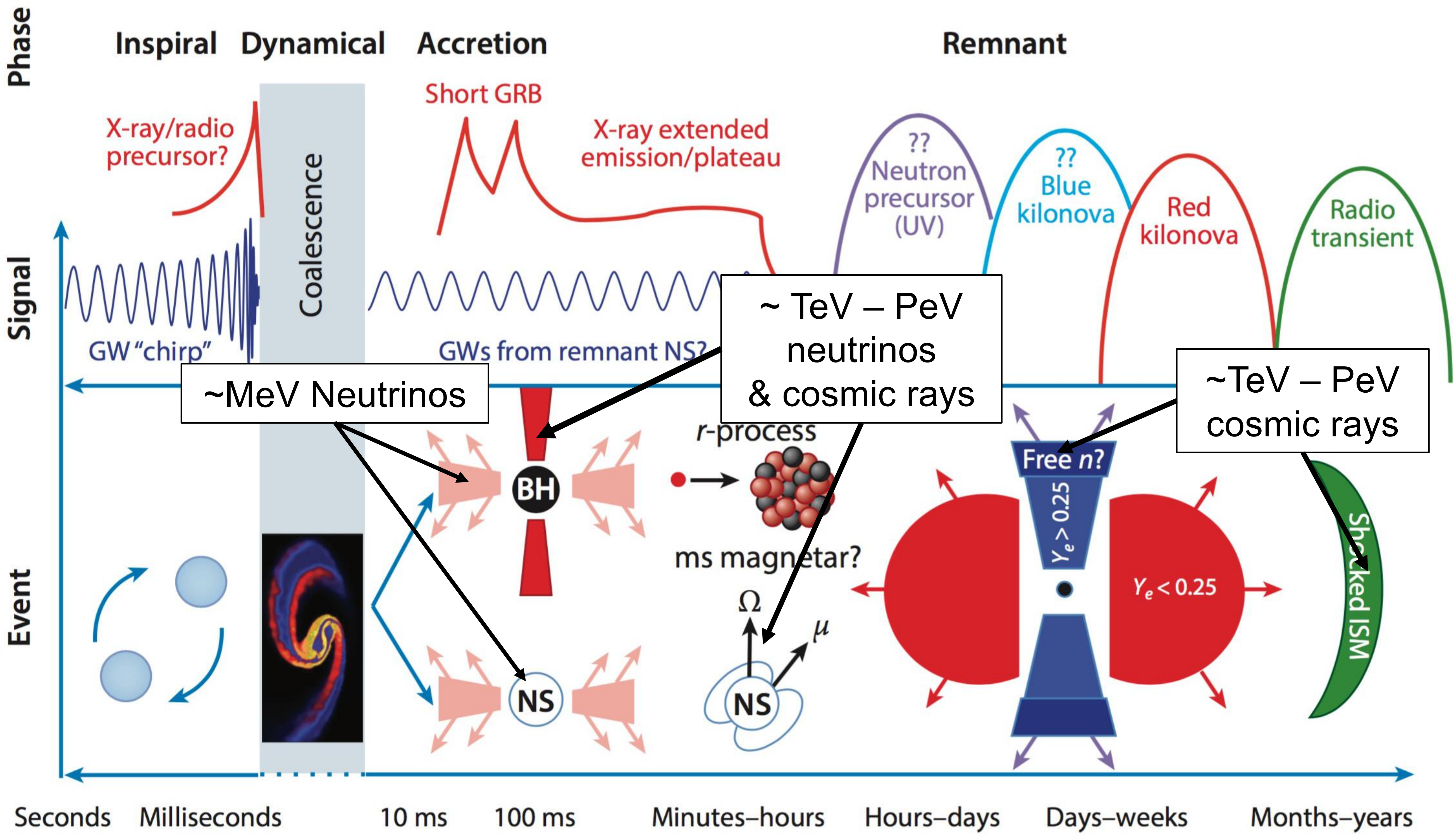
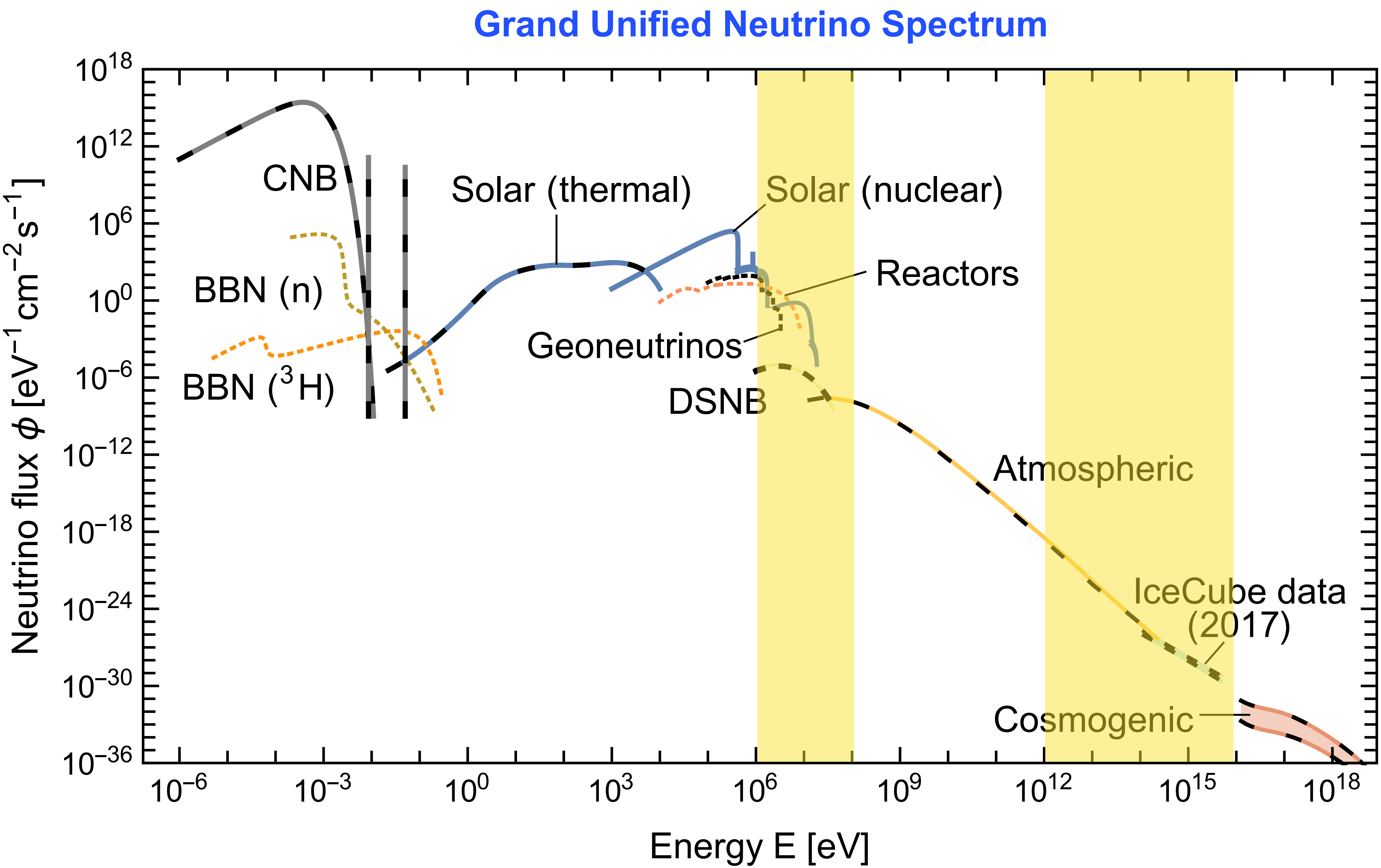


Figure credit: Brian Metzger.

Compact Binary Mergers vs. Supernovae

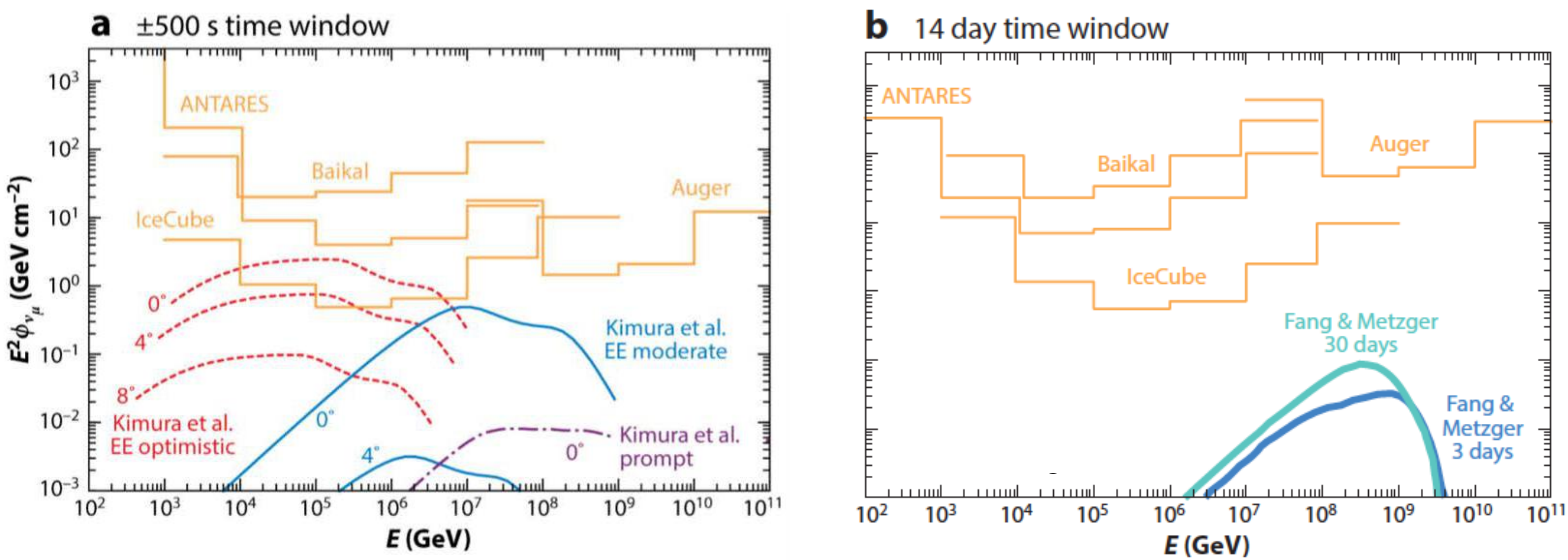
Event Type	Mergers	Core-Collapse SN
Physical Mechanism	Merging of two neutron stars	Core collapse of massive star
Neutrino Properties	Comparable	Comparable
Neutrinos Features	Antineutrino rich	Neutrino rich
LE-Detectability	Poor detection chances	Galactic source
HE-Detectability	sGRB or magnetar	Jets or shock-powered interactions

Neutrinos and Compact Binary Mergers



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

High Energy Neutrinos from GRB 170817A?

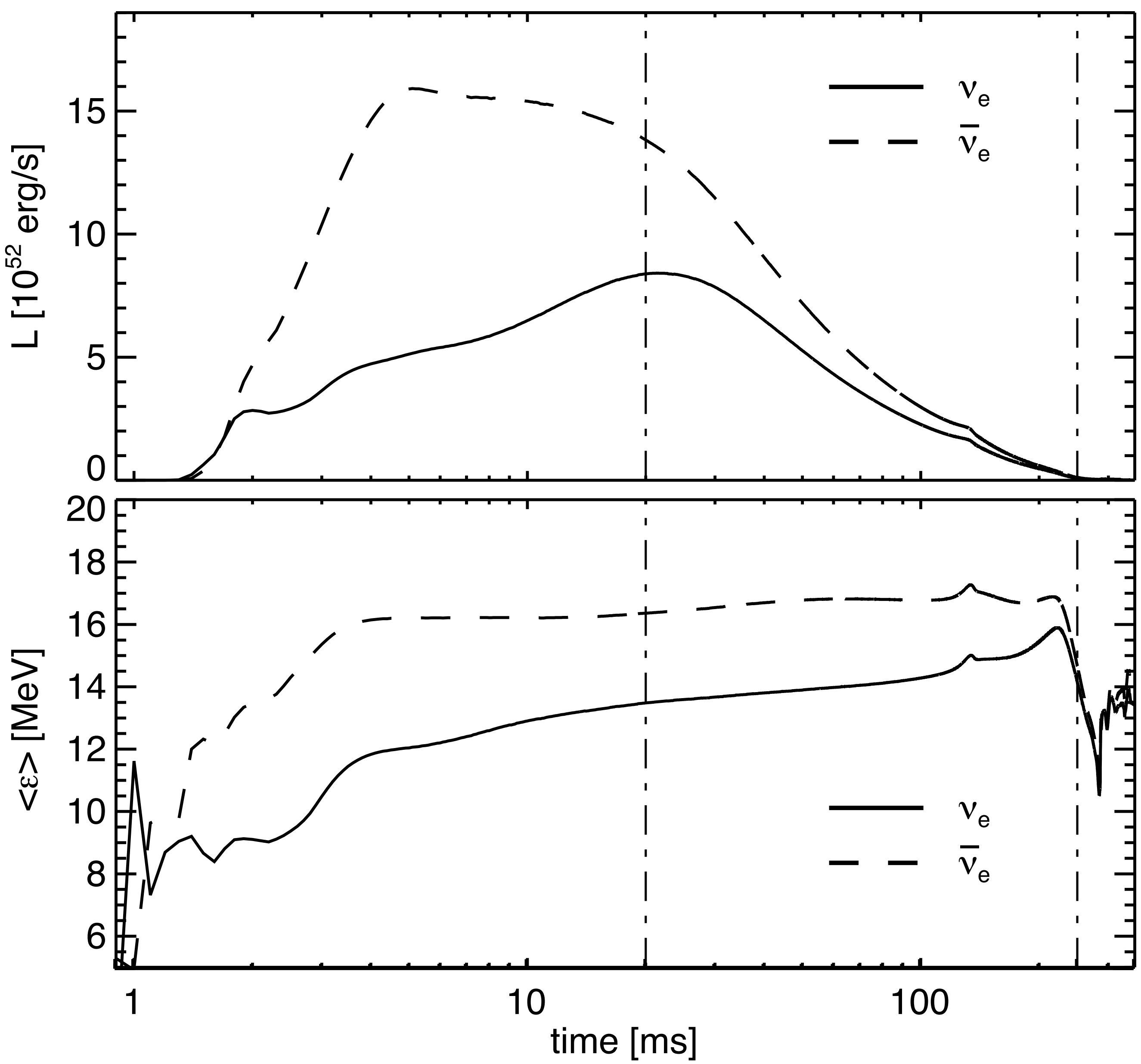


- No neutrinos detected from prompt short GRB phase yet.
- Neutrinos from long-lived ms magnetar and internal shock propagating in kilonova ejecta.
- Favorable detection opportunities with multi-messenger triggers.

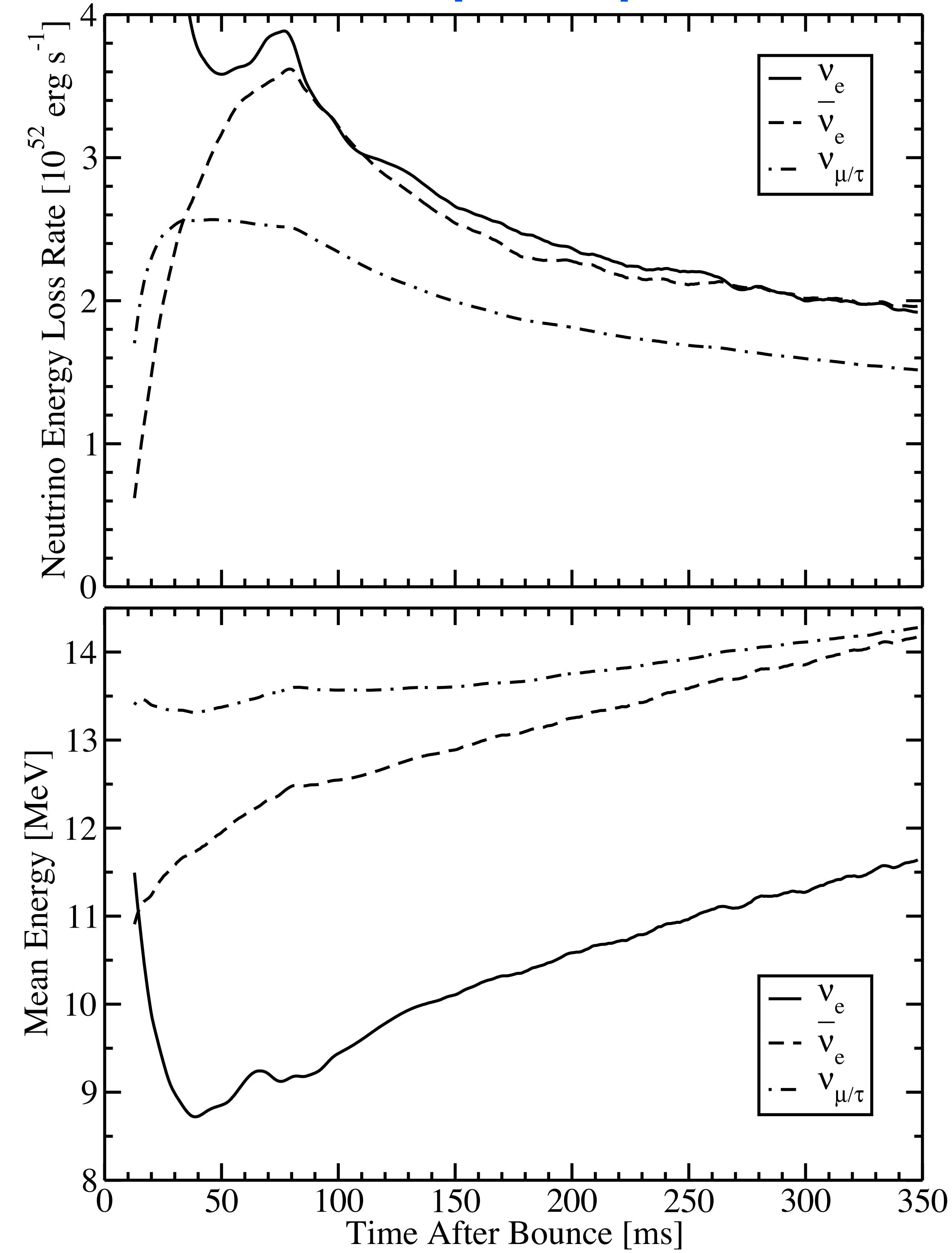
Figure credit: Christian Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku, Kashiyama, PRD (2018). Tamborra, Ando, JCAP (2015). Gottlieb, Globus, ApJL (2021).

Low Energy Neutrino Emission Properties

Neutron star merger remnant



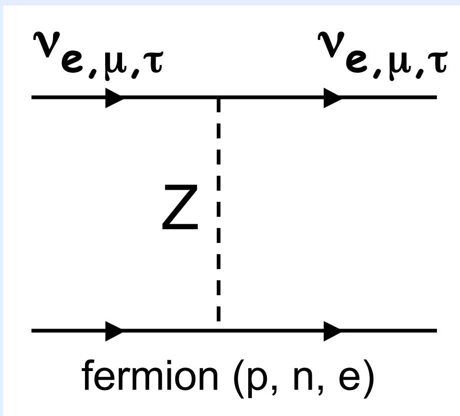
Core-collapse supernova

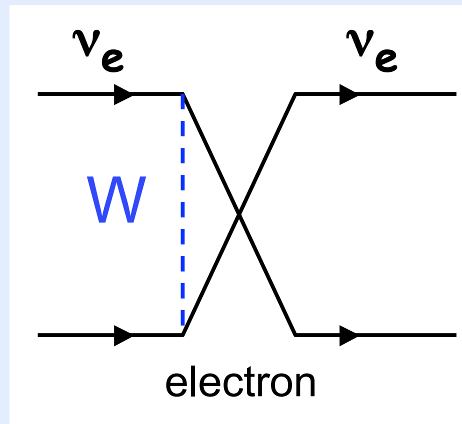


Mergers exhibit excess of antineutrinos over neutrinos (conversely to supernovae).

Figures from Wu, Tamborra et al., PRD (2017), Tamborra et al., PRD (2014).

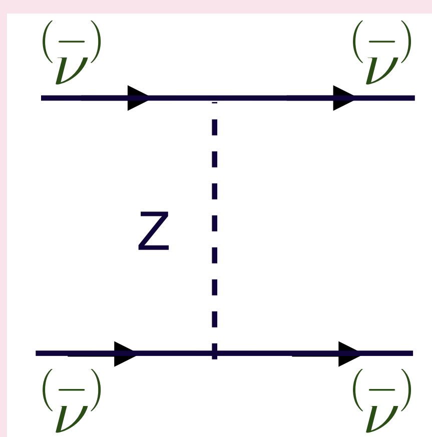
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

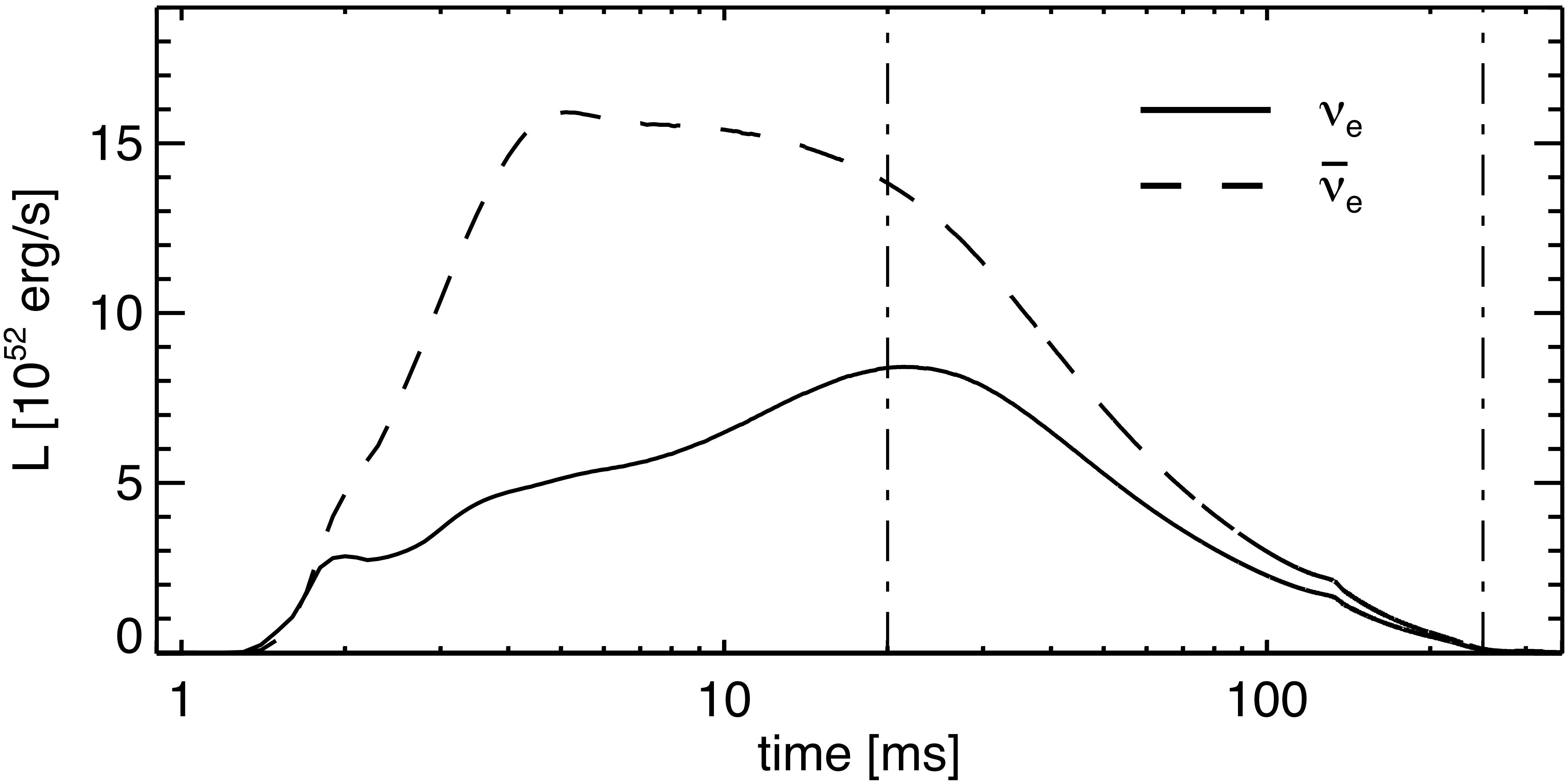


Neutrinos interact among themselves.

Non-linear phenomenon, trajectory is crucial!

Recent reviews: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021). Richers & Sen, arXiv: 2207.03561.

Matter-Neutrino Resonance



$F_{\bar{\nu}} > F_{\nu}$ ⇨ Flavor conversion phenomenology not present in supernovae.

Figures from Wu, Tamborra et al., PRD (2017).

Matter-Neutrino Resonance

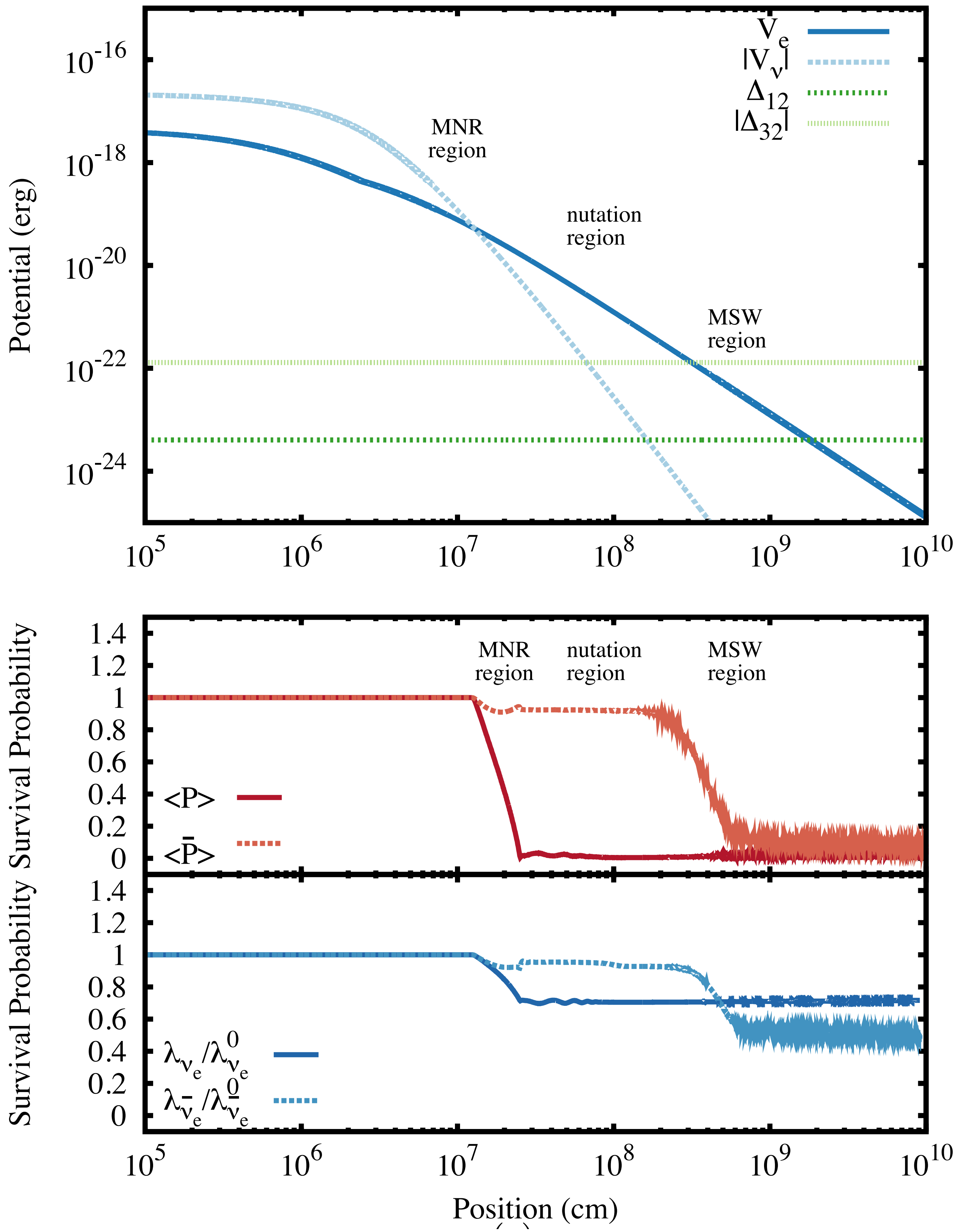
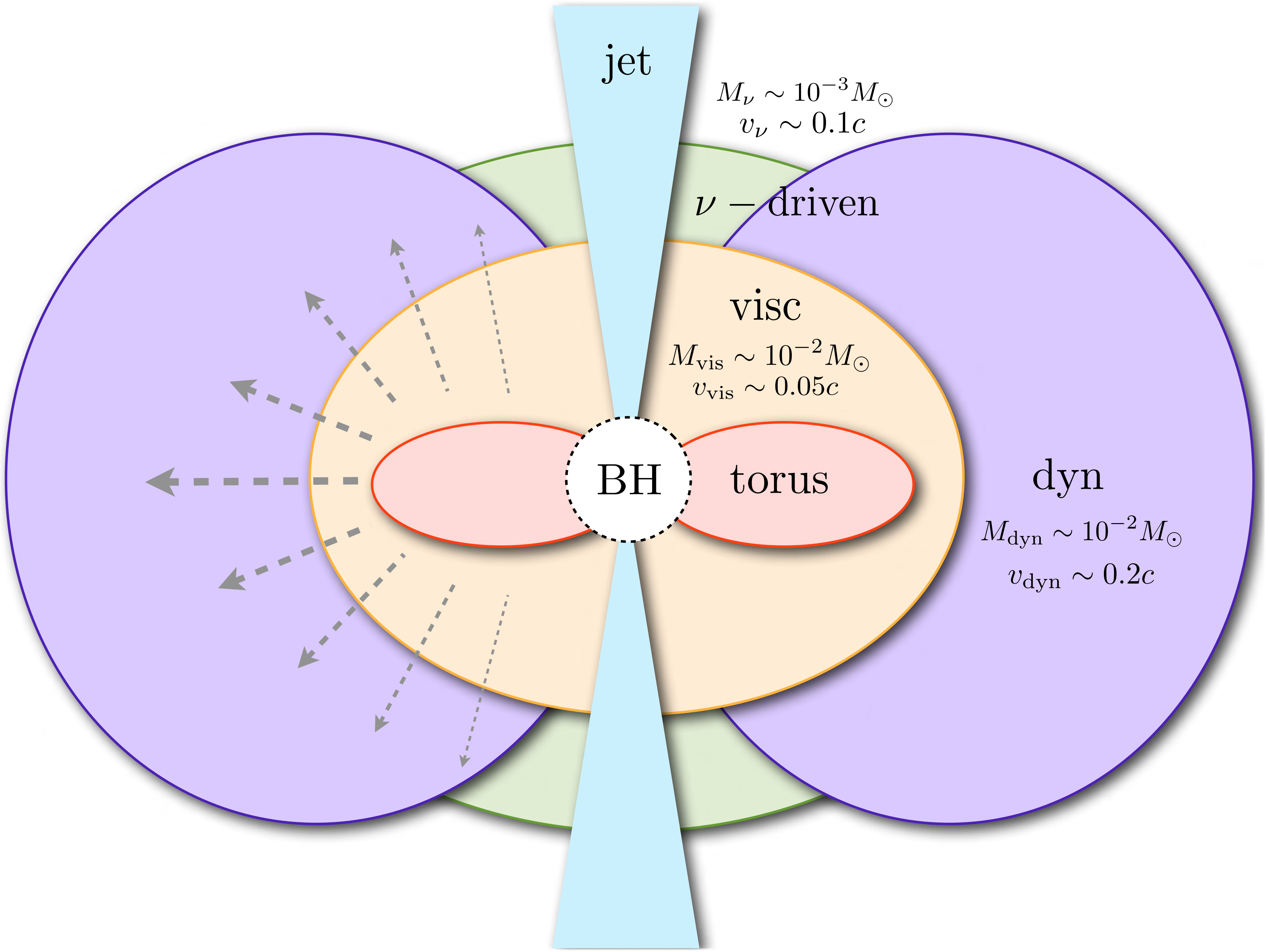


Figure from Malkus et al., PRD (2012).

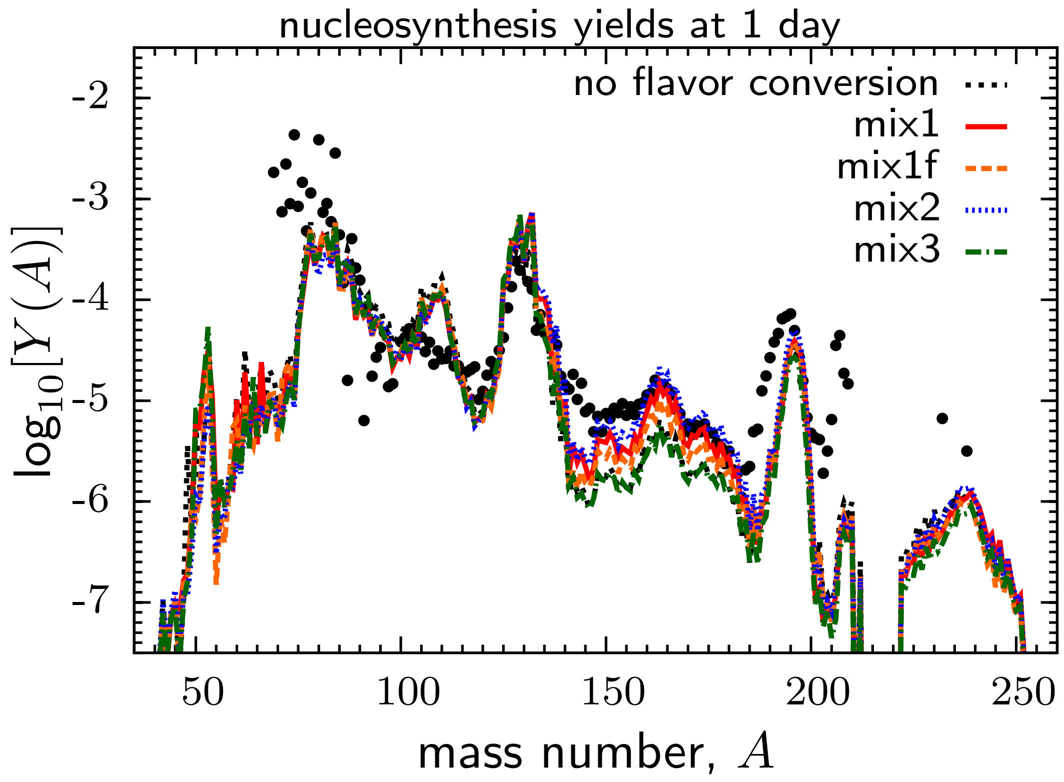
Because of antineutrino excess, the nu-nu potential enters in resonance with the matter one.

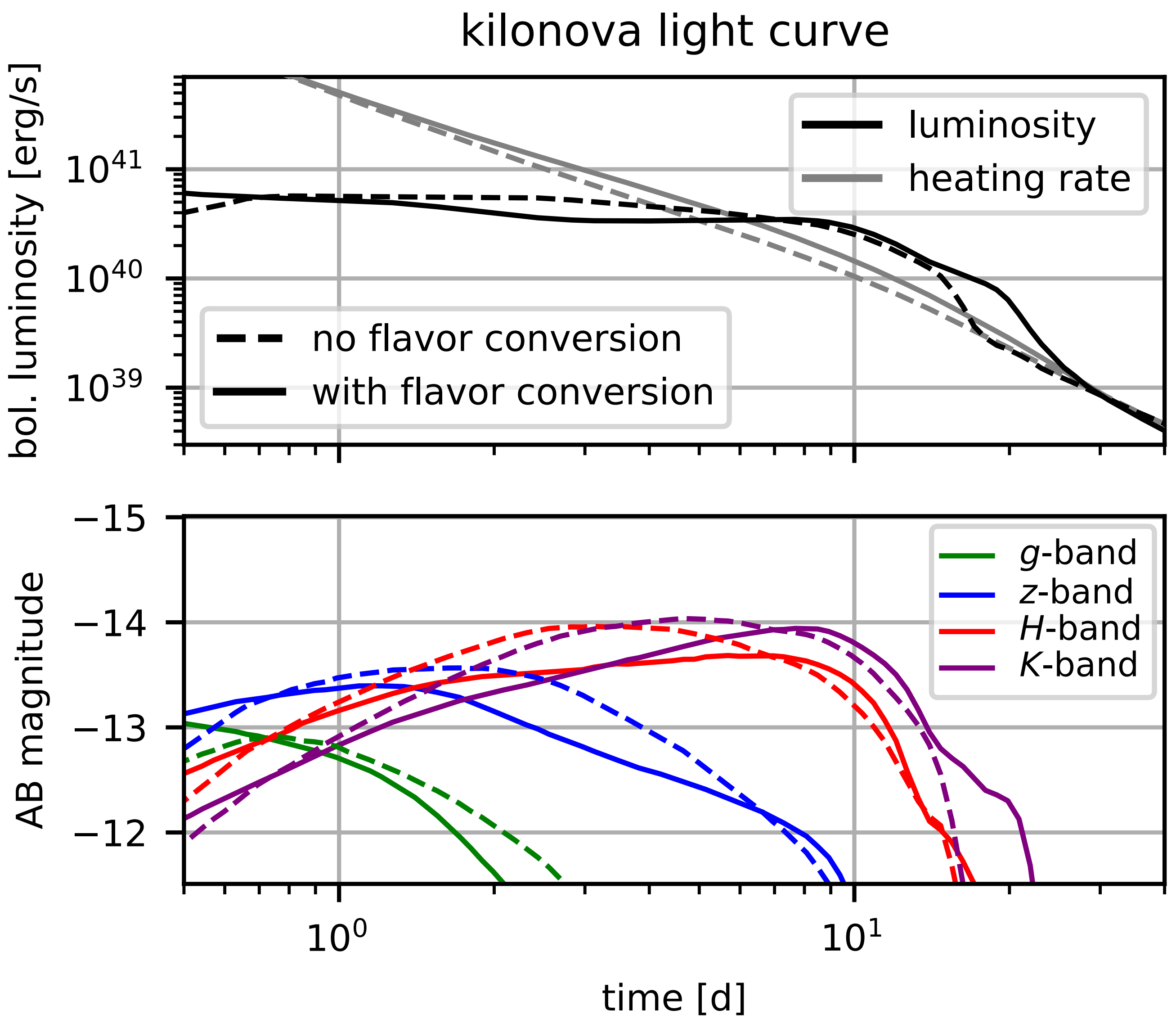
Do Neutrinos Affect Merger Physics?



Neutrino may play a major role especially for element production around the polar region and affect the cooling of the disk.

Neutrino Pairwise Conversion

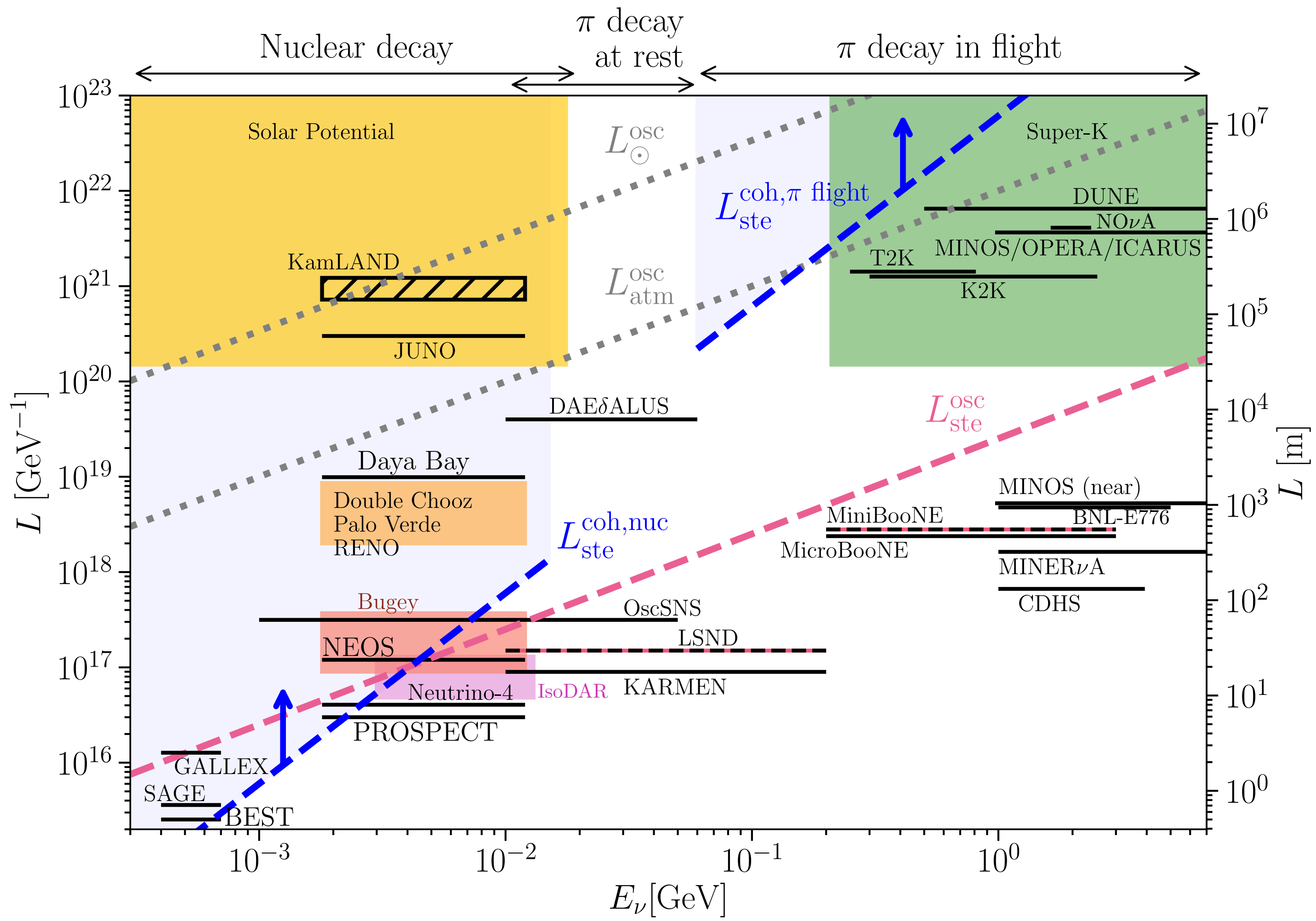




- Linear stability analysis suggest pairwise conversions may occur everywhere above the remnant disk.
- Flavor conversions may lead to an enhancement of nuclei with A>130 (kilonova implications).
- More work needed to grasp how neutrinos affect electromagnetic emission.

Just, Abbar, Wu, Tamborra, Janka, Capozzi, PRD (2022). Wu, Tamborra et al. PRD (2017). Wu & Tamborra, PRD (2017). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). George, Wu, Tamborra, et al., PRD (2020). Fernandez, Richers, Mulyk, PRD (2022). Li & Siegel, PRL (2021).

Light Sterile Neutrinos



Various experimental neutrino anomalies remain unsolved:

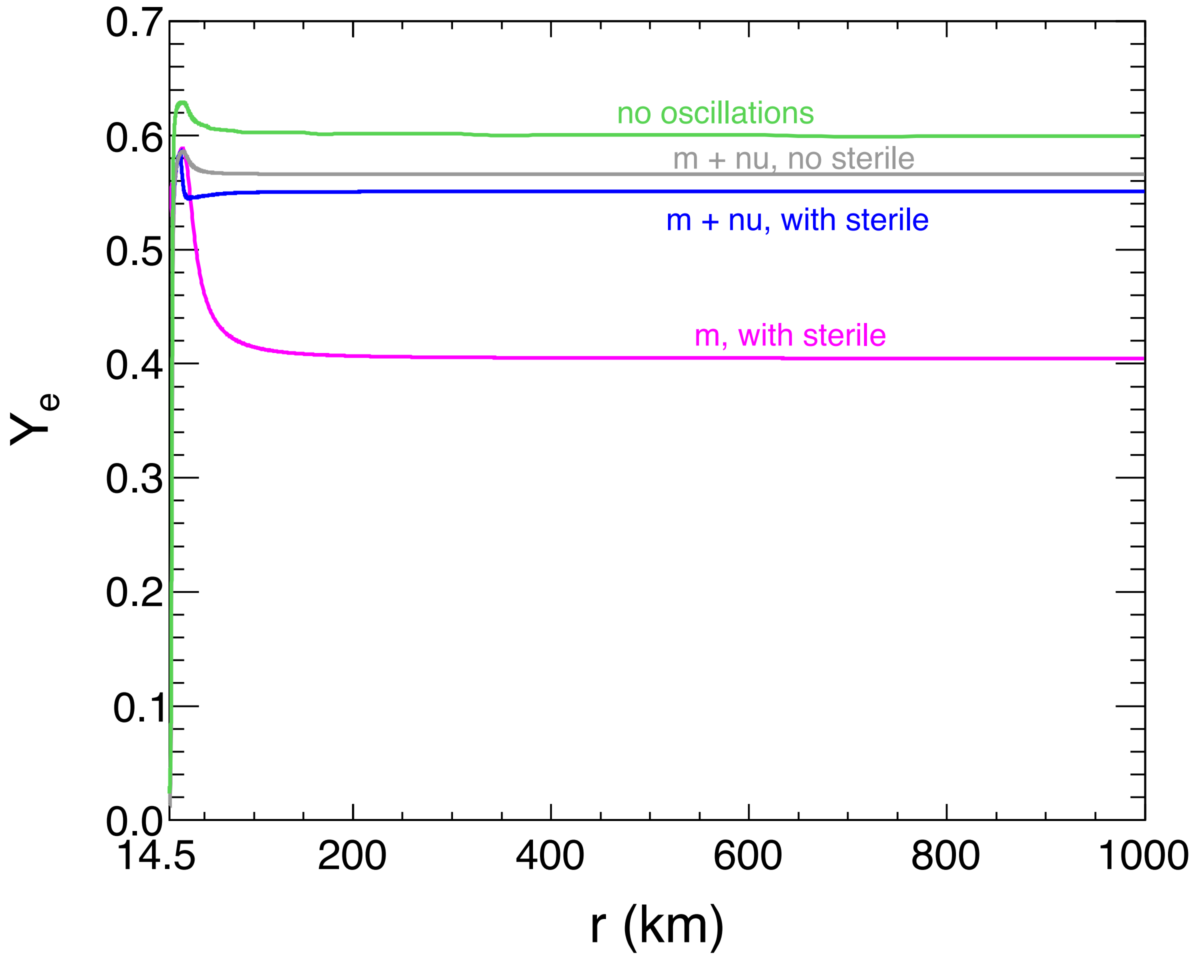
- LSND Anomaly & MiniBooNe low-energy excess—apparent oscillatory appearance of electron (anti)neutrinos.

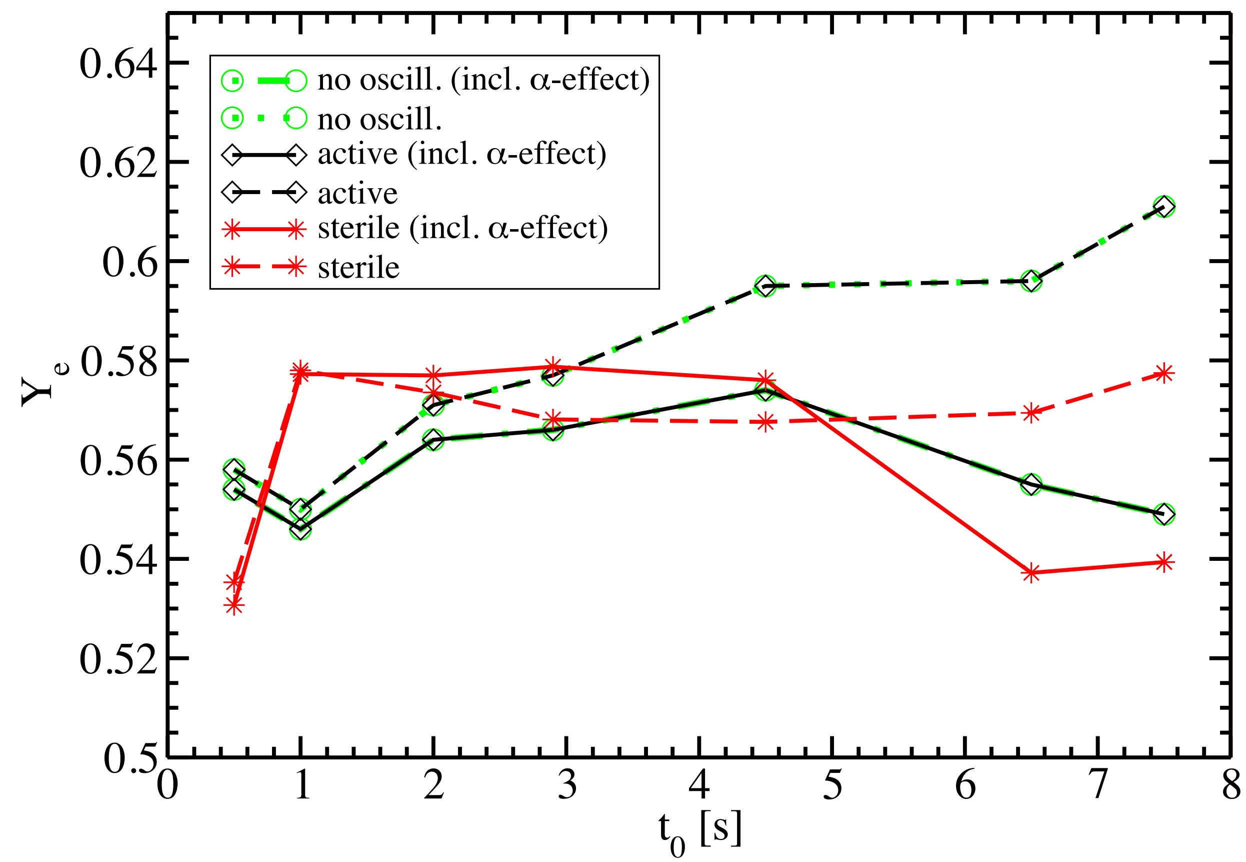
- Reactor Neutrino Anomaly (solved) & Gallium anomaly—overall normalization discrepancy of electron (anti)neutrinos expected from fission reactors.

- Cosmological data do not fully rule out sterile particles.

Acero et al., arXiv: 2203.07323.

Light Sterile Neutrinos in Supernovae

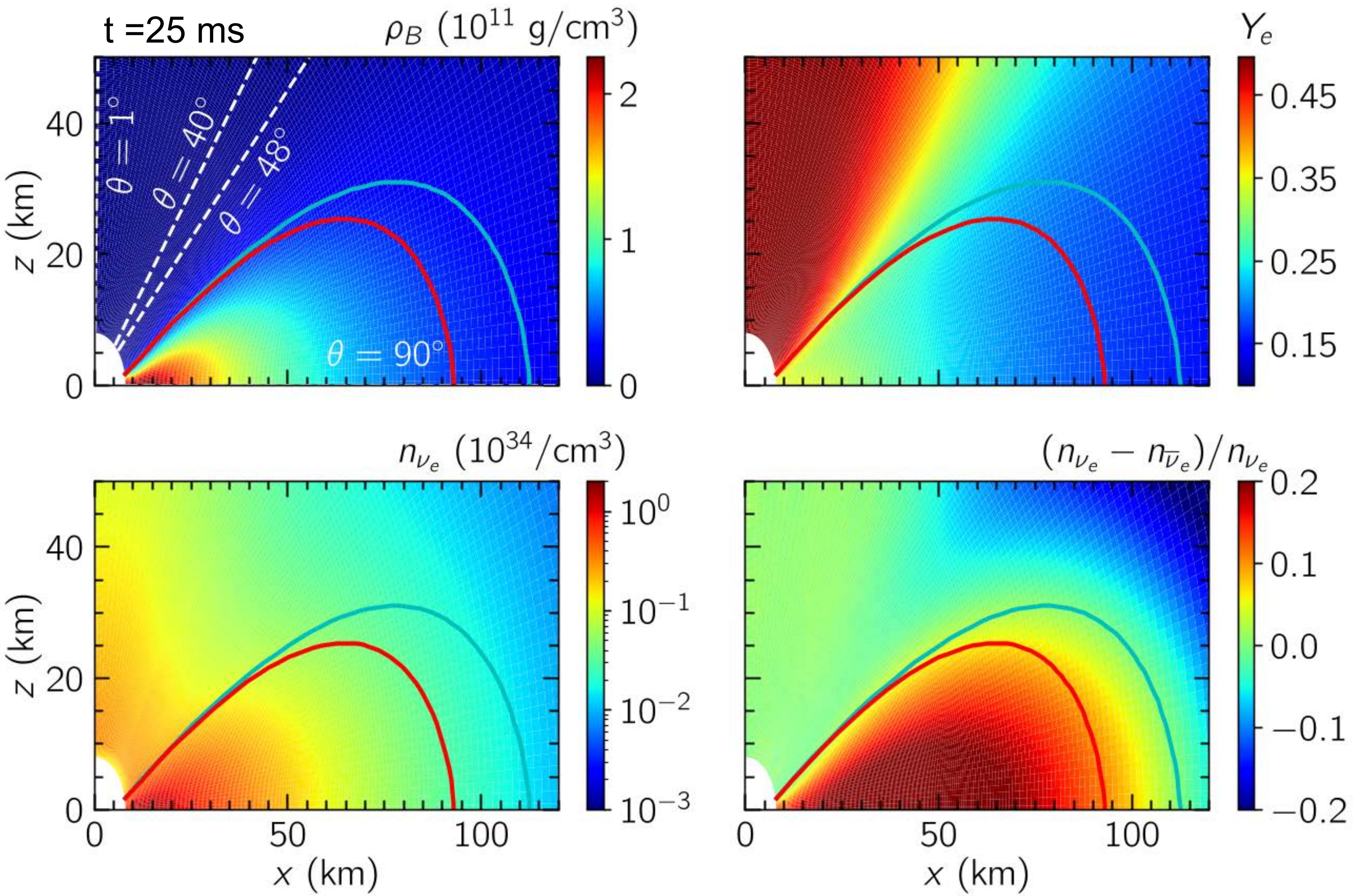




- Active-sterile flavor conversion has non-trivial feedback on electron abundance.
- Changes in the electron fraction impact nucleosynthesis (not enough to enable r-process).
- Active-sterile flavor conversion affects the mass loss rate and the wind velocity.

Tamborra et al., JCAP (2011). Pllumbi, Tamborra et al., ApJ (2014). Wu et al., PRD (2013), Xiong et al., ApJ (2019). Nunokawa et al., PRD (1997). McLaughlin et al., PRD (1999).

Black Hole Remnant Disk



Sigurðarson, Tamborra, Wu, PRD (2022). Just et al., MNRAS (2015).

Active-Sterile Flavor Evolution

$$\underbrace{\partial_r \rho_E = -i[H_E, \rho_E]}_{\text{Hamiltonian}} + \underbrace{\mathcal{C}(\rho_E, \bar{\rho}_E)}_{\text{Collision term}} \text{ and } \partial_r \overline{\rho}_E = -i[\overline{H}_E, \overline{\rho}_E] + \mathcal{C}(\rho_E, \bar{\rho}_E)$$

$$H_E = H_{v,E} + H_m = \omega \begin{pmatrix} -\cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & \cos 2\theta_v \end{pmatrix} + \begin{pmatrix} \lambda & 0 \\ 0 & -\lambda \end{pmatrix}$$

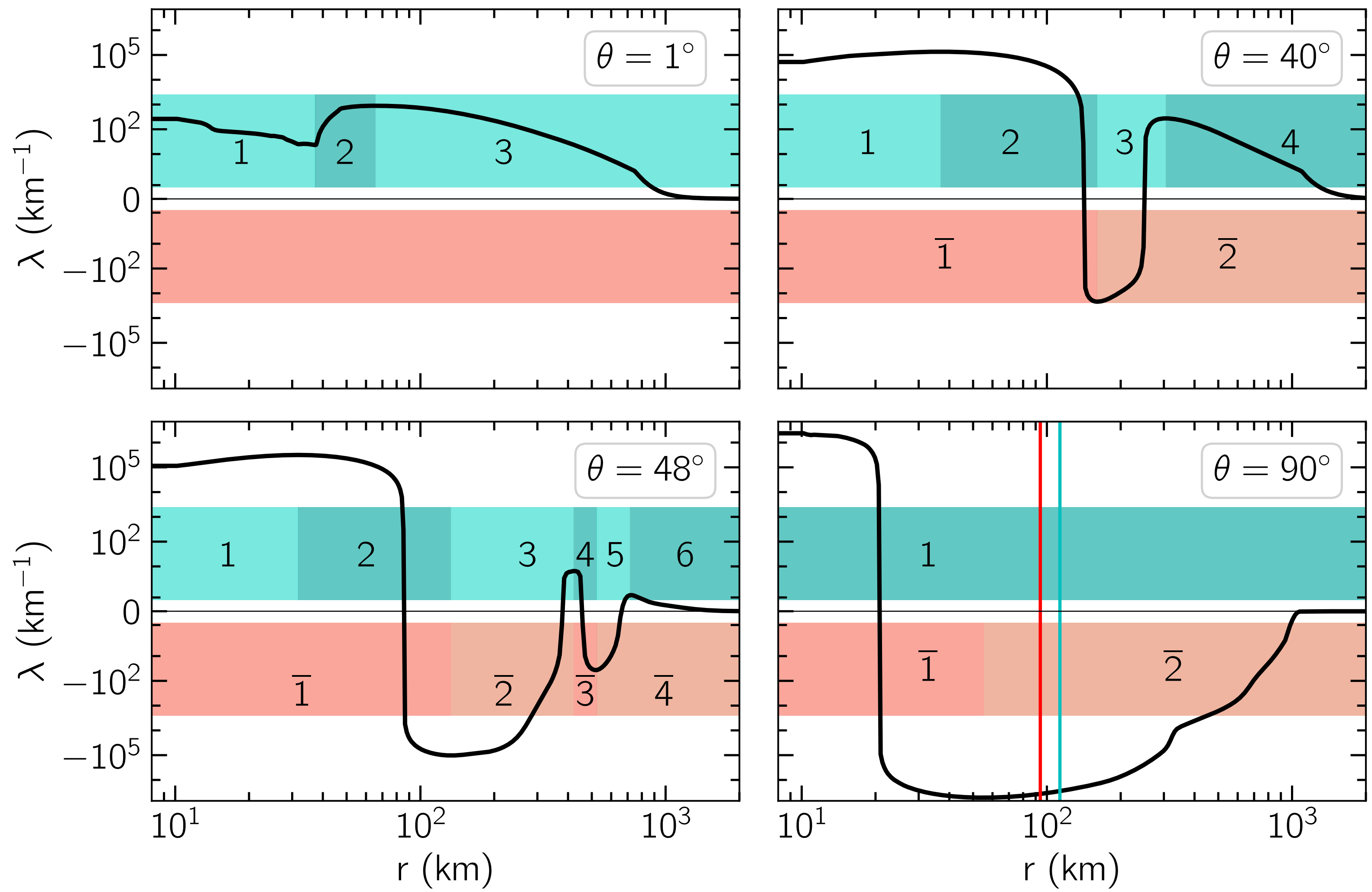
with

$$\lambda = \frac{\sqrt{2} G_F \rho_B}{2 m_N}(3Y_e - 1)$$

MSW resonance: $\lambda_{\rm res} = \pm\omega \cos 2\theta_v$

Active-Sterile Flavor Evolution

$\sin^2 \theta_V = 10^{-2}$ and $\Delta m^2 = 10^{-1}$ eV^2

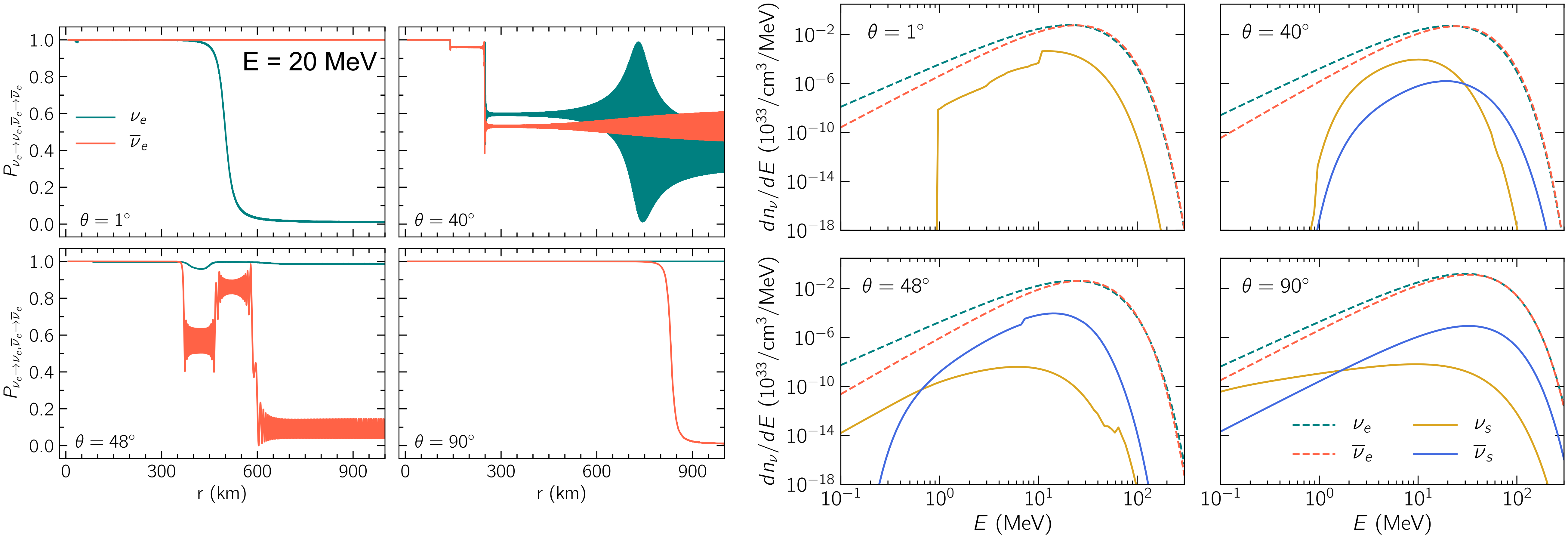


- Flavor conversion physics is highly dependent on the emission direction. Multiple resonances could occur for some directions.
- Sterile neutrinos are minimally produced in the equatorial plane. Sterile antineutrinos are not produced in the polar region.
- Flavor conversion phenomenology in NS merger remnants differs from the SN one. Similar to the SN case, the innermost resonances are less adiabatic than the outer ones.

Sigurðarson, Tamborra, Wu, PRD (2022).

Flavor Conversion Phenomenology

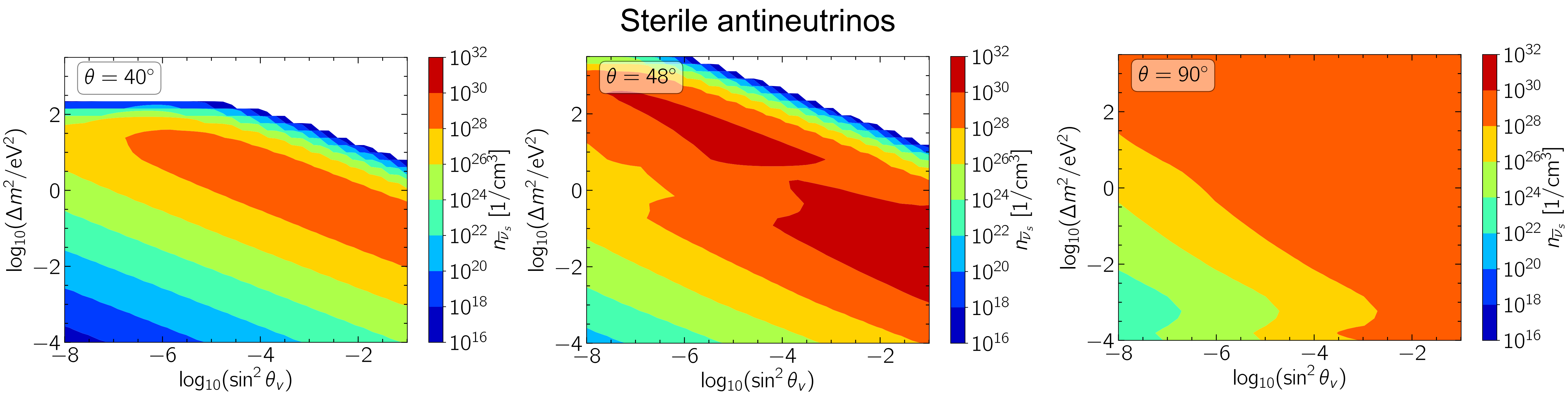
$\sin^2\theta_V = 10^{-2}$ and $\Delta m^2 = 10^{-1}$ eV^2



- Energy dependent features appear due to multiple resonances.
- Sterile antineutrinos are not produced in the polar region.
- More sterile antineutrinos than neutrinos are produced in the equatorial region.

Sigurðarson, Tamborra, Wu, PRD (2022).

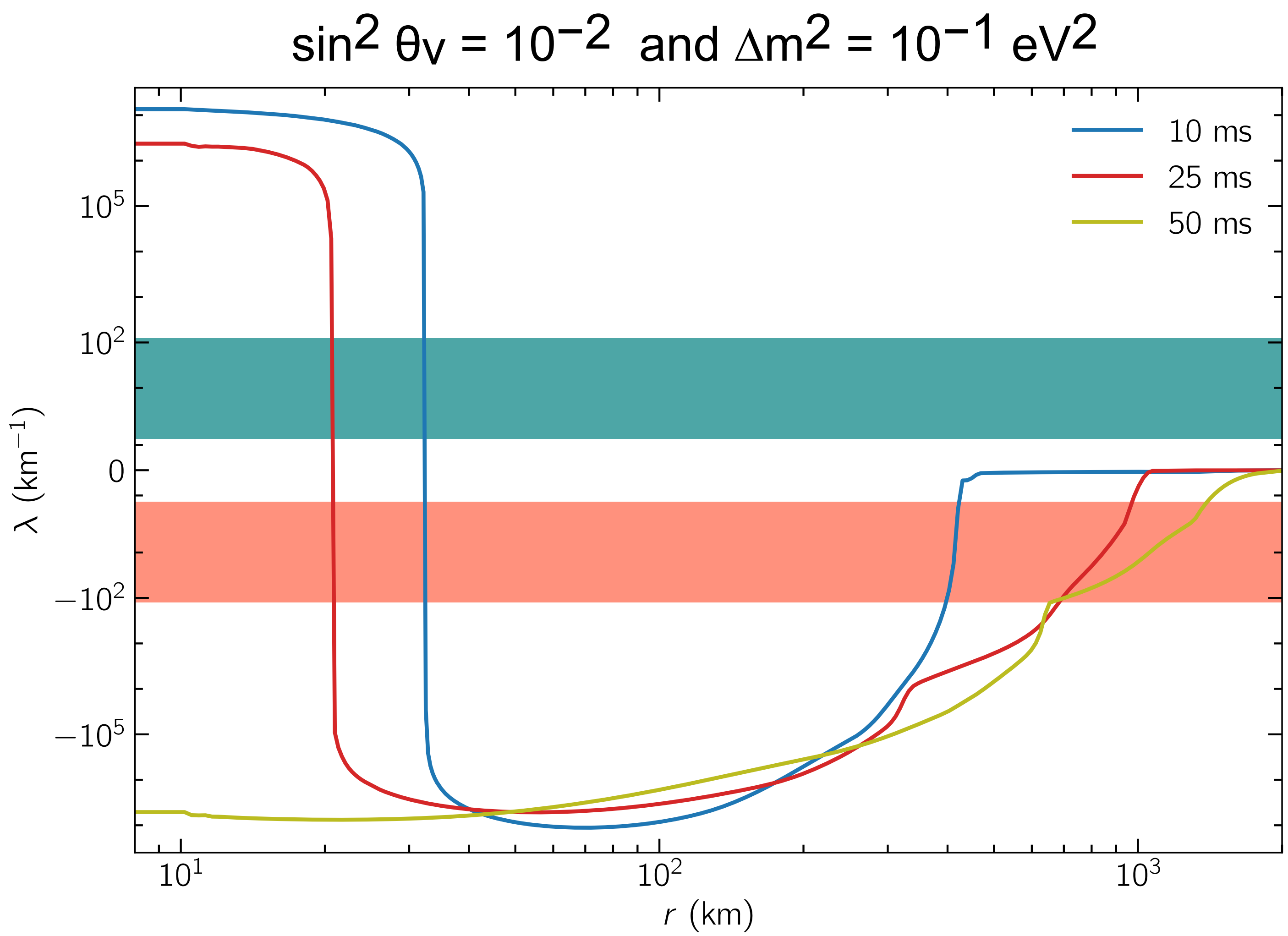
Flavor Conversion Phenomenology



- The adiabaticity of the MSW resonance increases as $\sin^2\theta_V$ and/or Δm^2 increase.
- A high Δm^2 causes λ_{res} to exceed the minimum value of λ, resulting in the absence of resonances for the upper part of the parameter space.
- The lowest number density of resonantly produced sterile particles is visible in the bottom left corner of the ($\sin^2\theta_V$,Δm^2) plane.

Sigurðarson, Tamborra, Wu, PRD (2022).

Phenomenology: Time Dependence



Fixed emission angle: $\theta = 90°$

- In the proximity of the equatorial plane, the electron fraction drops causing λ to change sign in the innermost regions for t > 25 ms.
- As t increases, the matter gradient becomes gentler, resulting in adiabatic resonances.
- As t increases, a larger region of the parameter space is affected by flavor conversion.

Sigurðarson, Tamborra, Wu, PRD (2022).

Conclusions

- Compact binary merger remnants are as rich in neutrinos as supernovae.
- The impact of neutrino physics on the merger physics remains to be understood.
- The merger setup favors multiple active-sterile MSW resonances.
- Sterile (anti)neutrino production is strongly direction dependent.
  Large production of sterile (anti)neutrinos in the polar (equatorial) region.
- As the BH torus evolves, the active-sterile phenomenology remains unchanged qualitatively.
- Active-sterile conversion can have implications on the disk cooling rate and its outflows.

Thank you!