Theoretical Nuclear and Particle Astrophysics Group at ASIoP

Meng-Ru Wu (Institute of Physics, Academia Sinica)

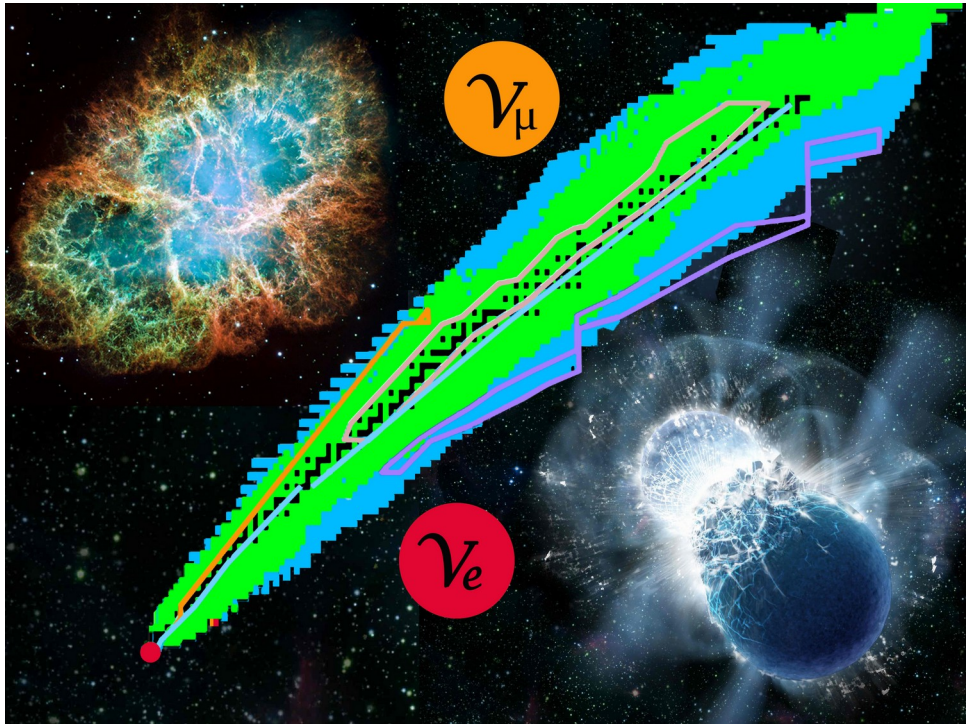
Taiwan Nuclear Physics Retreat, Jiaoxi, Yilan, Taiwan, April 20–22, 2026

Theoretical nuclear & particle astrophysics group @ ASIoP

https://mengruwuu.github.io/

Research interest & goals

- neutrino interaction & oscillations in dense matter
- multimessenger signals from supernovae and compact binary mergers
- nucleosynthesis of heavy elements in supernovae and mergers
- probing dark sector with stellar explosions



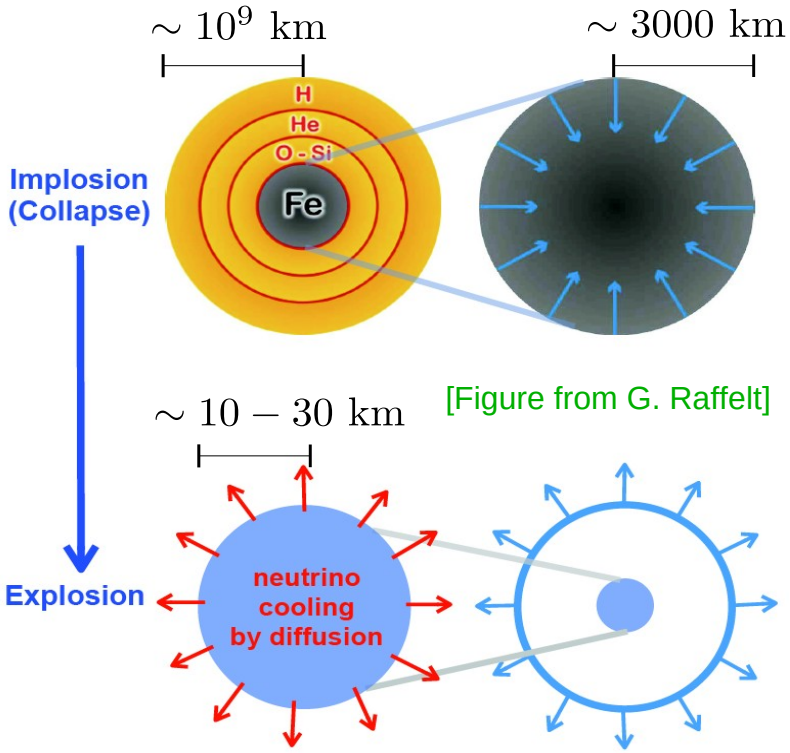
Collective neutrino oscillations in dense media

Group members: Soumya Bhattacharyya, Madhurima Chakraborty, Jakob Ehring, Shih-Jie Huang, Tzu-Chi Wang, Guan-Lin Wu

External collaborators: Oliver Just, Zewei Xiong (GSI Darmstadt), Sajad Abbar, Thomas Janka (MPA Garching), Ian Padilla-Gay (UCB), Tobias Fischer (U Wroclaw), Chun-Yu Lin (NCHC)

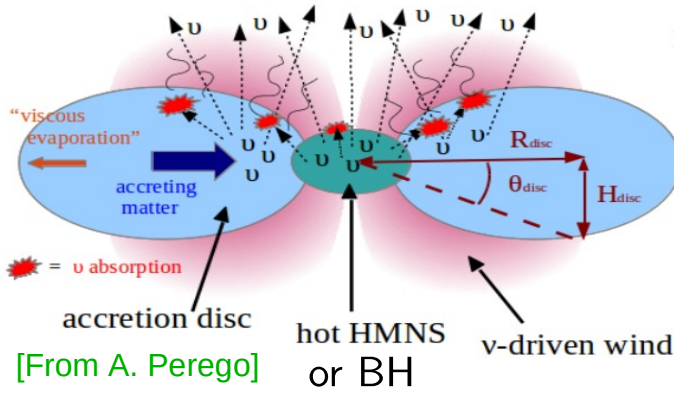
Neutrinos from SNe and from mergers

Core-collapse supernovae



[Figure from G. Raffelt]

Neutron star mergers



[From A. Perego]

inspiral

explosion

gravitational energy → thermal energy → neutrinos!

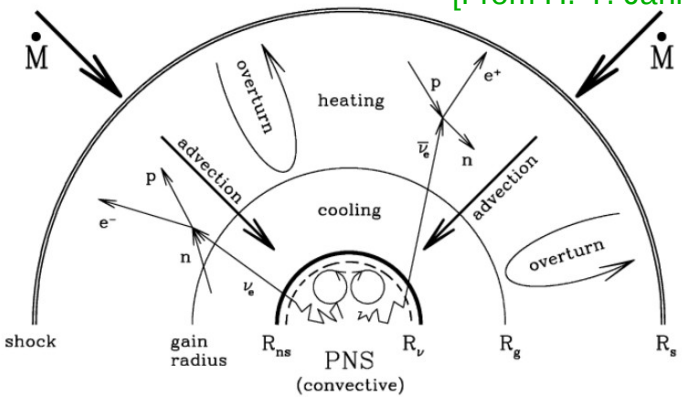
$L_\nu \sim 10^{51-53}$ erg/s, $N_\nu \sim 10^{56-58}$ of $\mathcal{O}(10)$ MeV emitted in $\sim \mathcal{O}(1-10)$ s

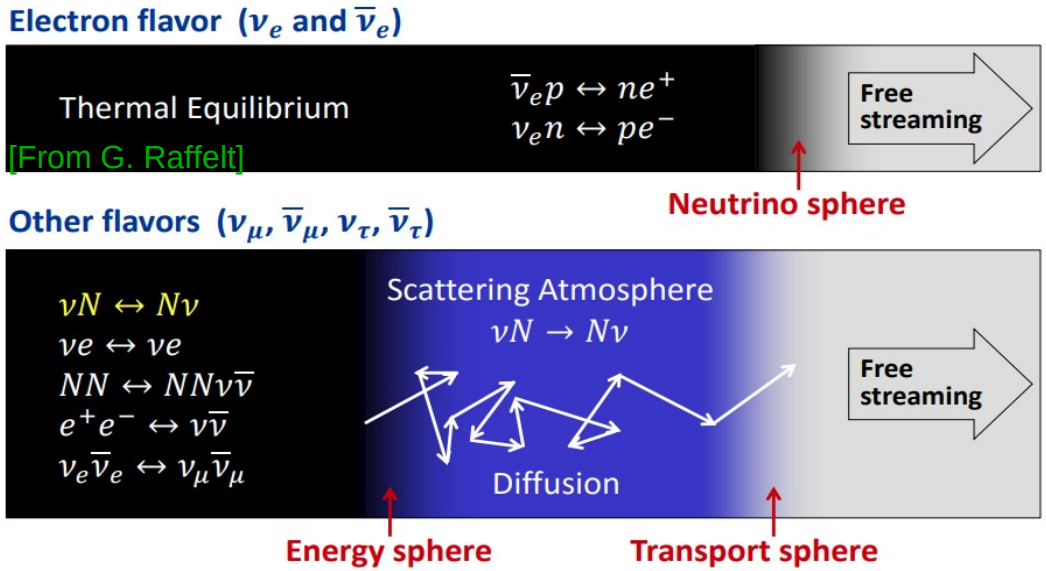
Modeling SNe and mergers with neutrinos

State-of-the-art general relativistic (magneto-) hydrodynamic simulations of supernovae and neutron star mergers include approximate treatment of classical Boltzmann transport of neutrinos

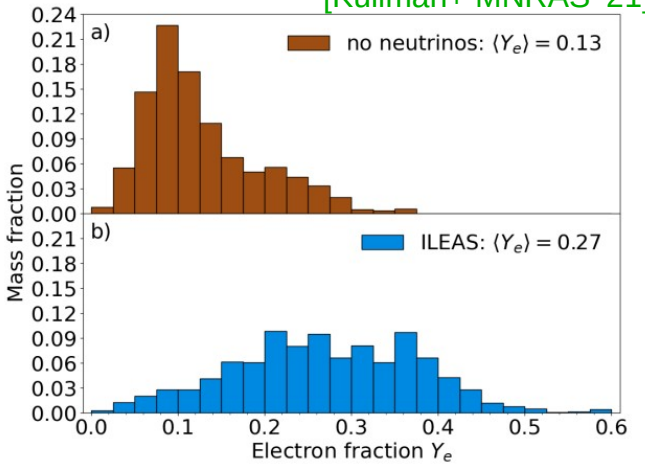
$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}}) f_{\nu_\alpha}(\mathbf{x},\mathbf{p},t) = \mathcal{C}$$

[From H.-T. Janka]





[Kullman+ MNRAS '21]



Accurate neutrino transport holds the key to model the evolution of these systems and predict reliable observables

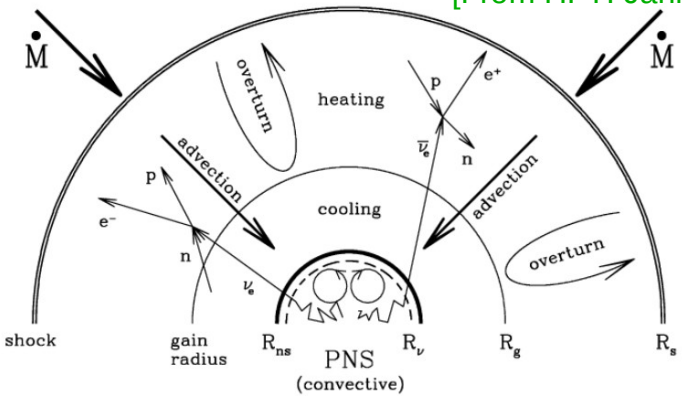
Modeling SNe and mergers with neutrinos

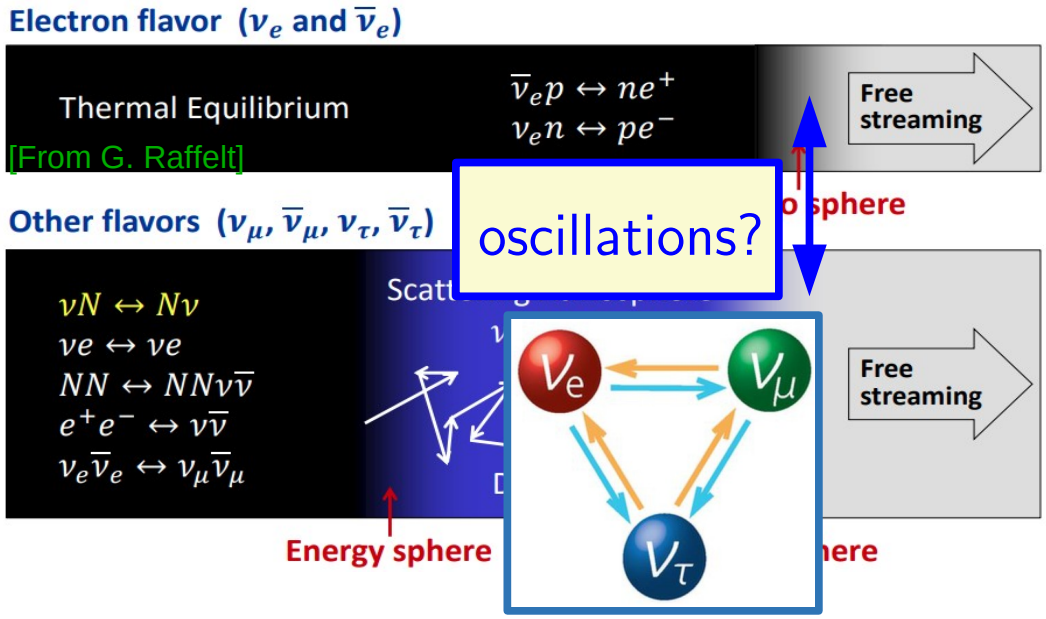
State-of-the-art general relativistic (magneto-) hydrodynamic simulations of supernovae and neutron star mergers needs to include (approximate) treatment of ~~classical Boltzmann~~ quantum transport of neutrinos

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\rho_\nu(\mathbf{x},\mathbf{p},t) = \mathcal{C} - i[H,\varrho_\nu]$$

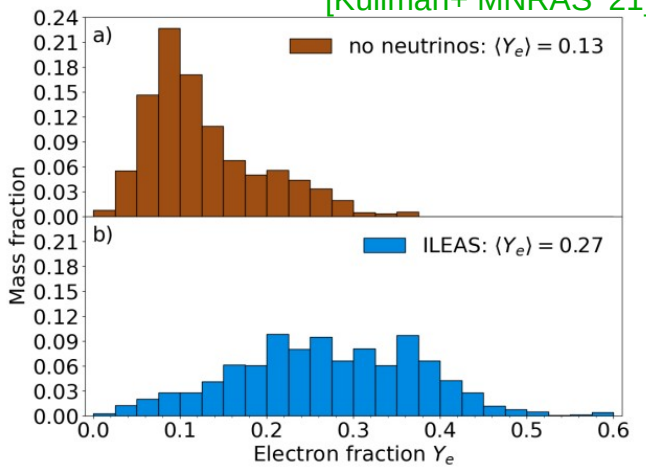
$$H \subset H_{\nu\nu} \propto G_F \int d^3q(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})[\varrho_\nu - \varrho^*_{\bar\nu}] \sim G_F n_\nu$$

[From H.-T. Janka]





[Kullman+ MNRAS '21]



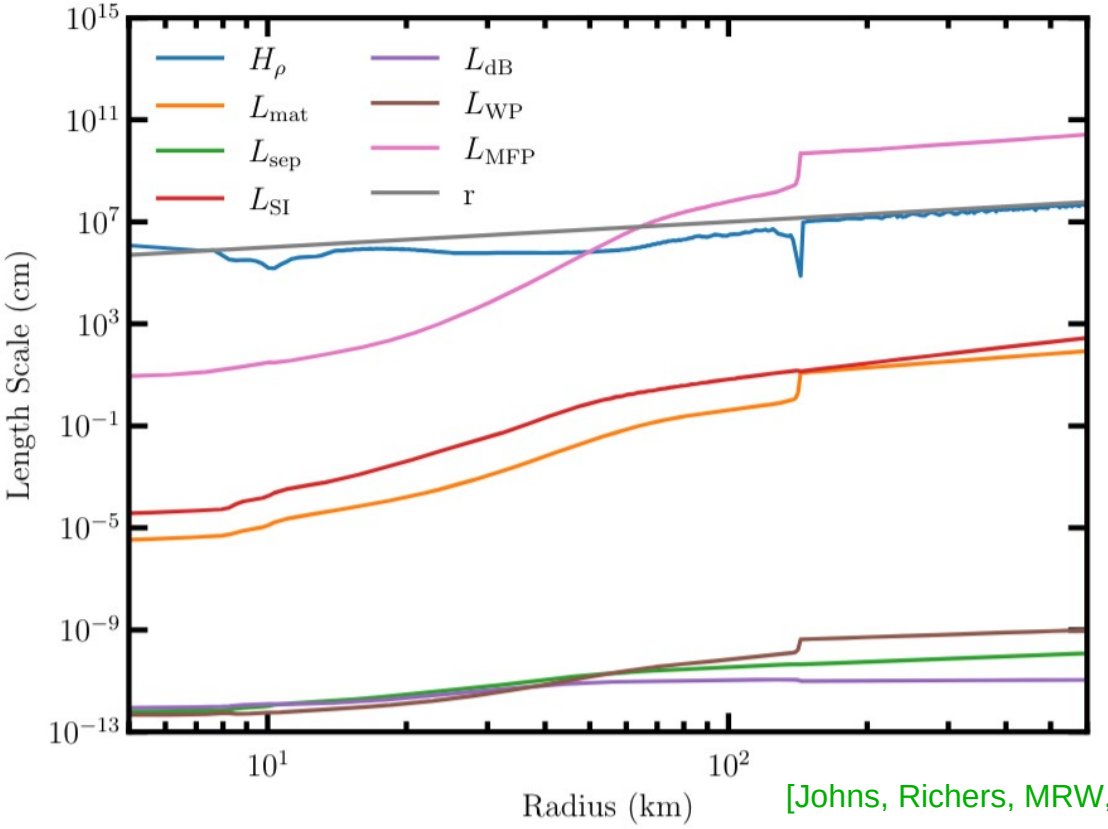
→ nonlinear collective phenomena in flavor space of neutrinos that can substantially impact SN explosion mechanism and nucleosynthesis [Johns, Richers, MRW, ARNPS '25 (2503.05959)]

Collective ν oscillations: challenge & strategy

- Main challenge: Multi-scale problem

  The intrinsic oscillation length scale $\sim (G_F n_\nu)^{-1} \sim \mathcal{O}(1)$ cm, much smaller than the astrophysical scale of $\mathcal{O}(1)$ km

  $\rightarrow$ cannot brute-forcely implement νQKE in astrophysical simulations



(scale height, mean-free path, ...)
macroscopic scale
$\sim \mathcal{O}$(km)

(oscillation length)
mesoscopic scale
$\sim \mathcal{O}$(cm)

(particle separation, wave packet,...)
microscopic scale
$\sim \mathcal{O}$(pm)

[Johns, Richers, MRW, ARNPS '25 (2503.05959)]

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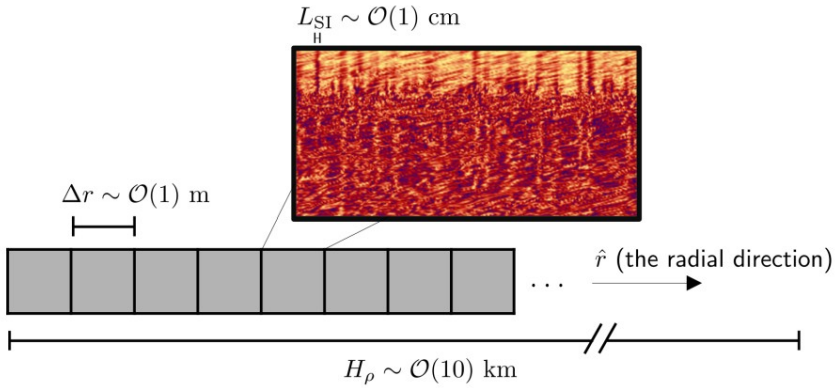
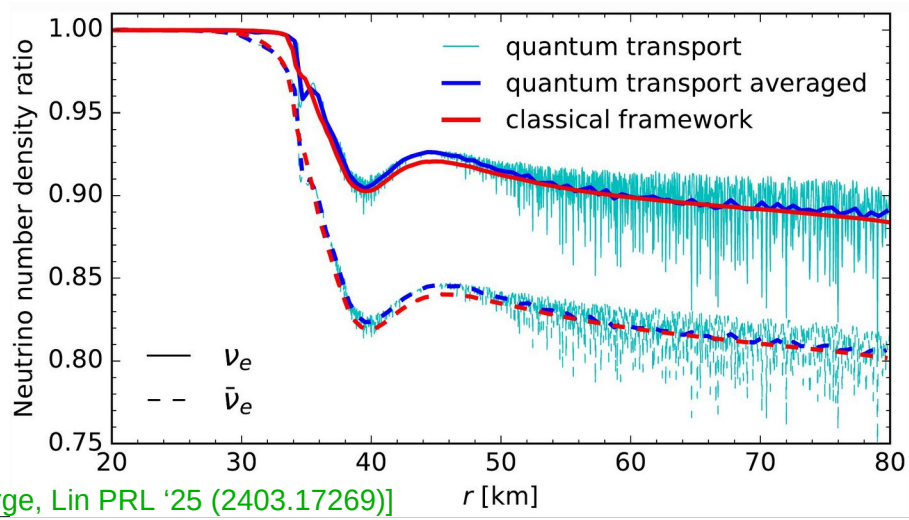
- Strategy: Sub-grid models guided by full νQKE simulations



global νQKE v.s. effective classical transport



[Xiong, MRW, George, Lin PRL '25 (2403.17269)]

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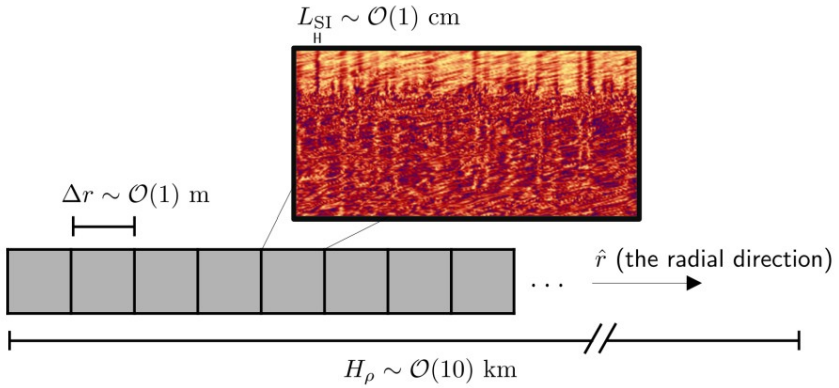

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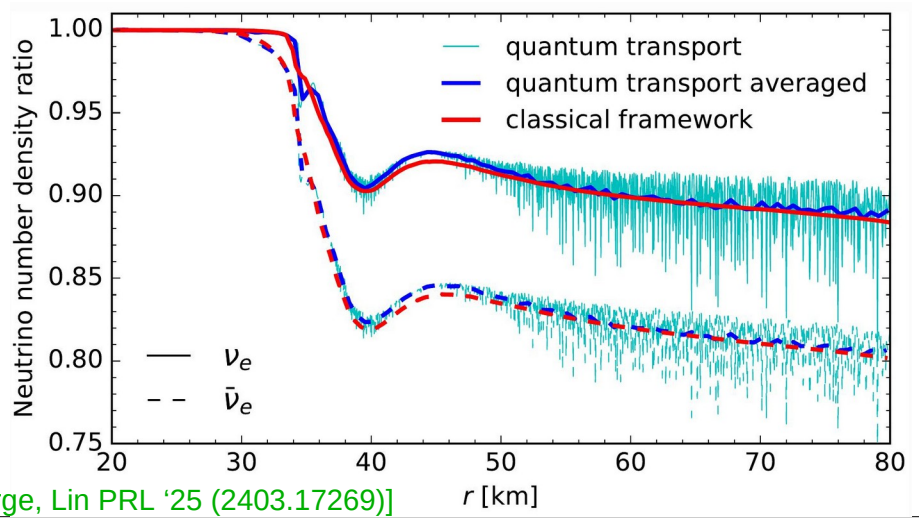


[Xiong, MRW, George, Lin PRL '25 (2403.17269)]

Many issues remaining going forward:

implementaion in real simulations? beyond simple coarse-grained equilibration? new formalisms? pairing & helicity correlations? beyond mean-field effect?

Rapid neutron-capture nucleosynthesis (r process)

Group members: Dhruv Desai (to join in June), Tsung-Han Yeh (to join in December)

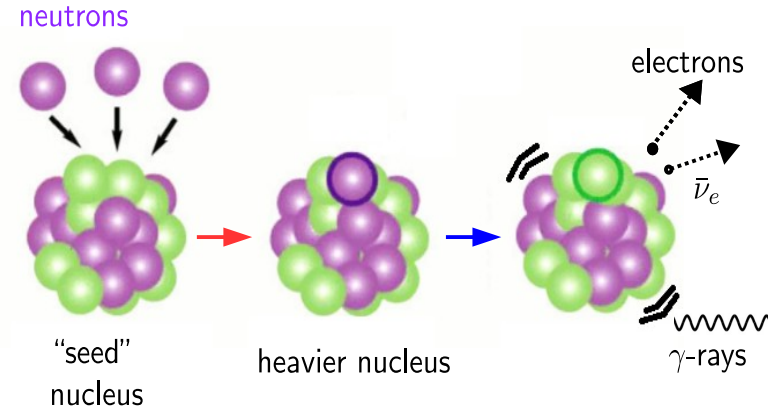
External collaborators: Gabriel Martinez-Pinedo (GSI Darmstadt), Li-Ting Ma, Kuo-Chuan Pan (NTHU), Tobias Fischer (U Wrowclaw), Yong-Zhong Qian (Minnesota), Gang Guo (Chinese U of Geoscience), Projjwal Banerjee (IIT Palakaad)

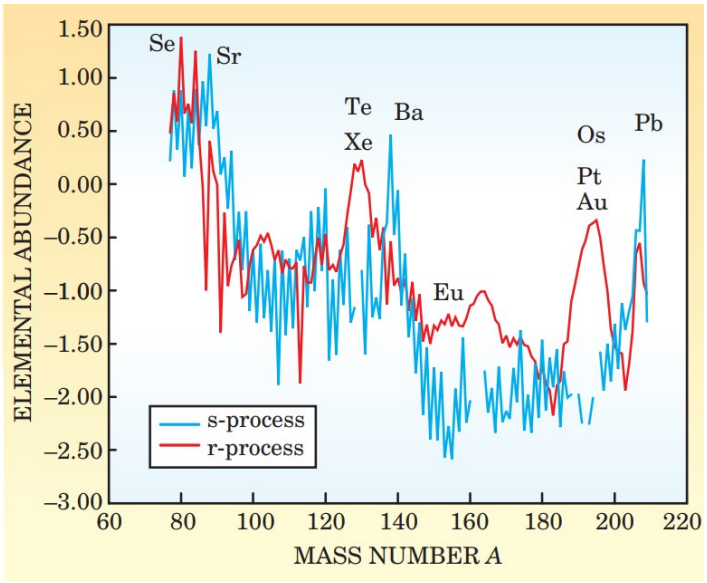
r process nucleosynthesis

The multimessenger event GW170817 provided evidences that binary neutron star mergers are r-process sites by observing the electromagnetic output from decays of unstable nuclei

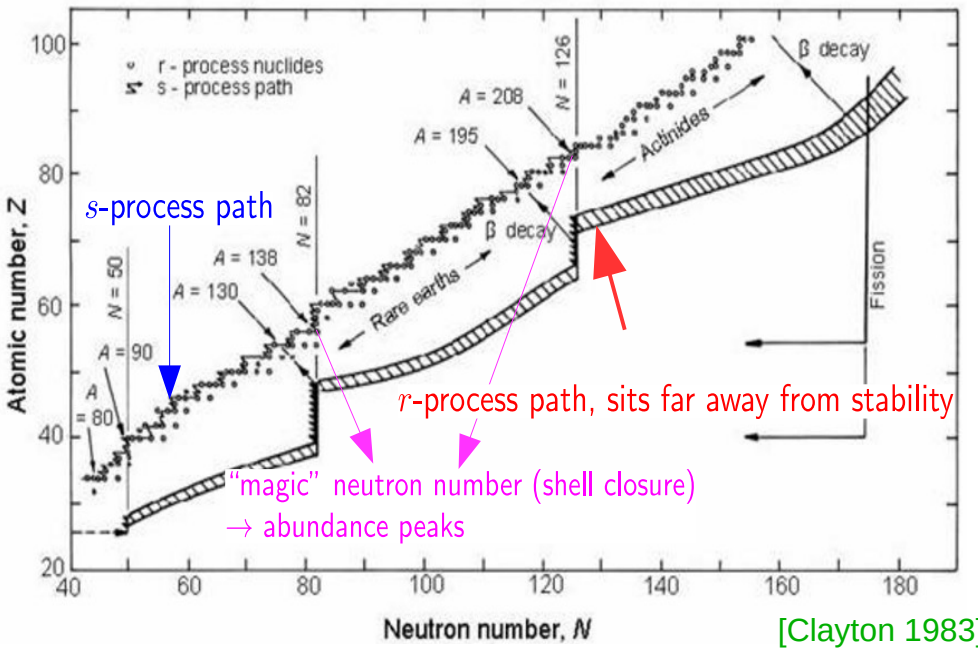
Key questions remain unanswered:

- Do we need other r process sources?
- Can we identify traces of specific elements?
- Imprints of r process nuclei in other observables?





[Figure from Cowen & Thielemann, 2004]



[Clayton 1983]

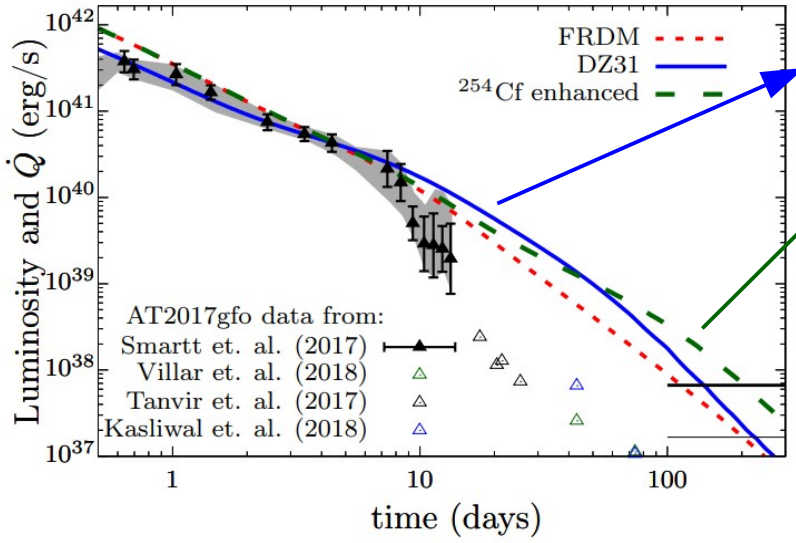
Potential signatures of actinide production?

[Barnes+2016, Rosswog+2017, Zhu+ 2018, 2021, MRW+ 2019, Giuliani+ 2020, Barnes+ 2021]

The amount of certain actinide isotopes with halflives of $\mathcal{O}(10-100)$ days can largely affect the late-time radioactive decay energy inputs in kilonovae

Bolometric lightcurve:

[MRW+ PRL '19 (1808.10459)]



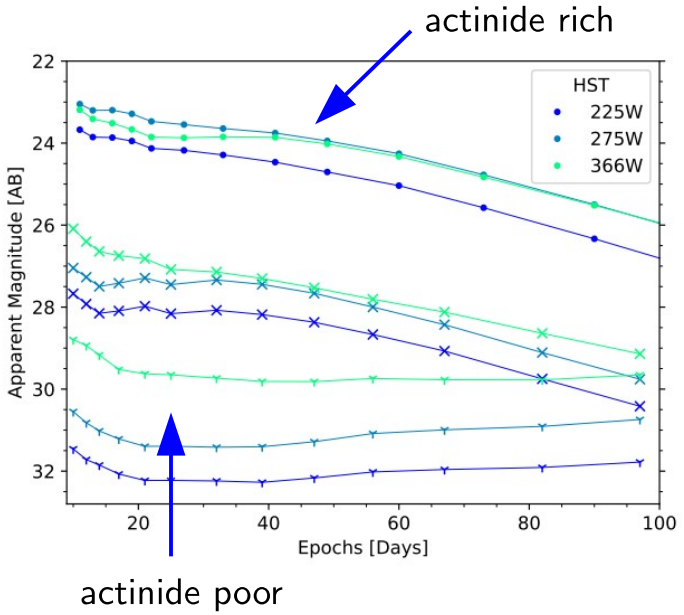
with $Y(^{222}\mathrm{Rn})$ and $Y(^{223-225}\mathrm{Ra}) \sim 3 \times 10^{-5}$

with $Y(^{254}\mathrm{Cf}) \sim 2 \times 10^{-6}$

JWST MIR limits

JWST NIR limits (at 100 Mpc)

Broadband lightcurves:



[Pognan, MRW+ MNRAS '24 (2409.16210)]

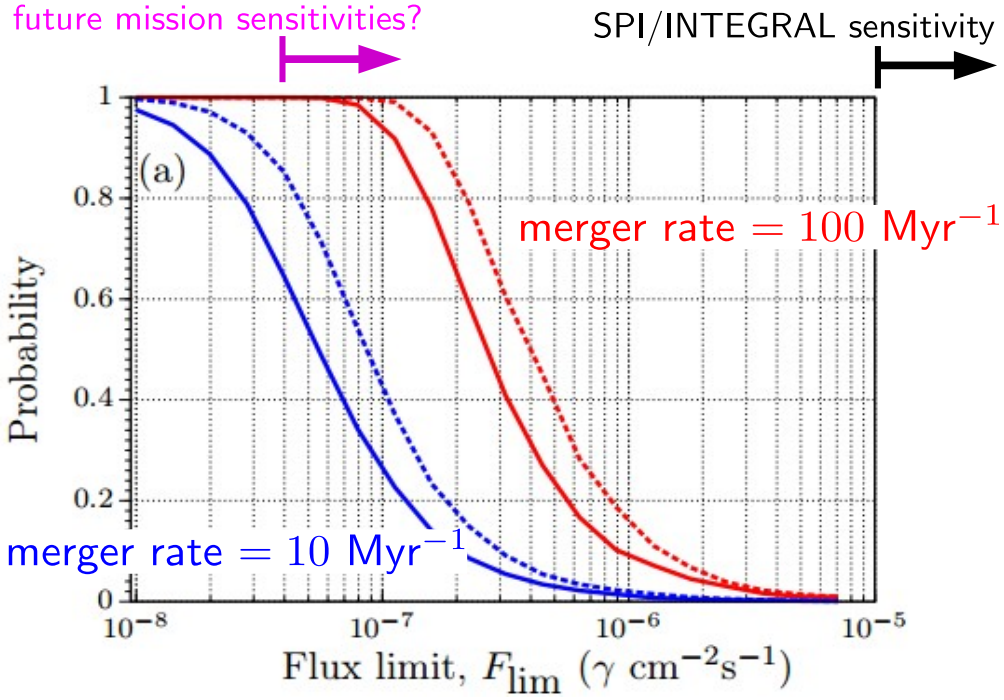
Detection of these features may offer implications to the nucleosynthesis condition in mergers as well as to the unknown nuclear physics property of exotic neutron-rich nuclei

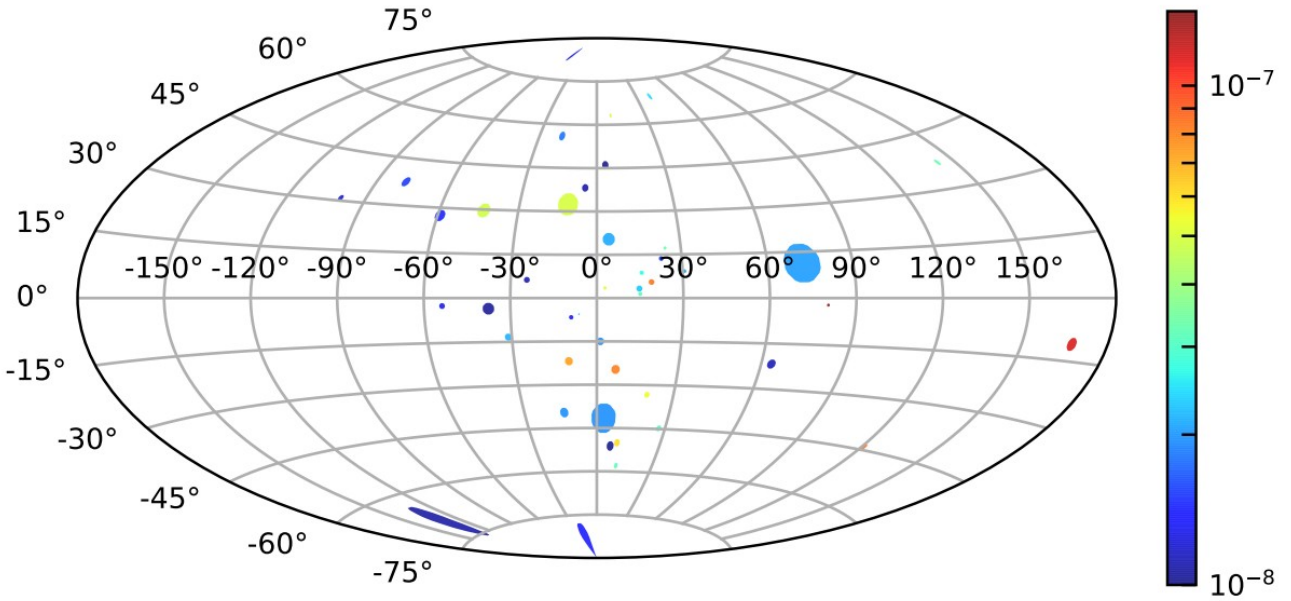
Gamma-rays from mergers?

Live events need to be close-by ($\lesssim 10$ Mpc), no distinct γ lines

Chances may be better with old ($\sim 10^5$ yr) merger nemnants!

primary candidate: ^{126}Sn ($t_{1/2} = 2.3 \times 10^5$yr) with strong lines at sub-MeV





[MRW, Banerjee, Metzger+ ApJ '19 (1905.03793)]

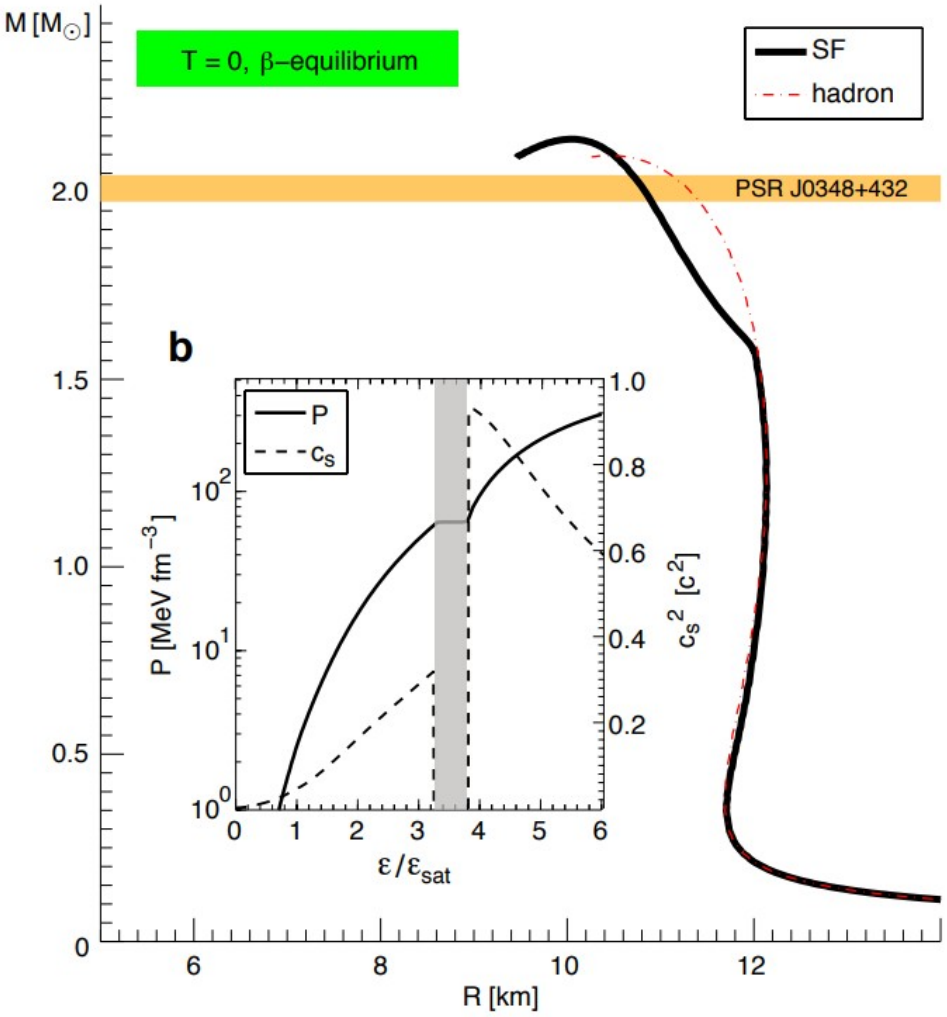
next-generation γ-ray telescope can probe this possibliity

Others research interests

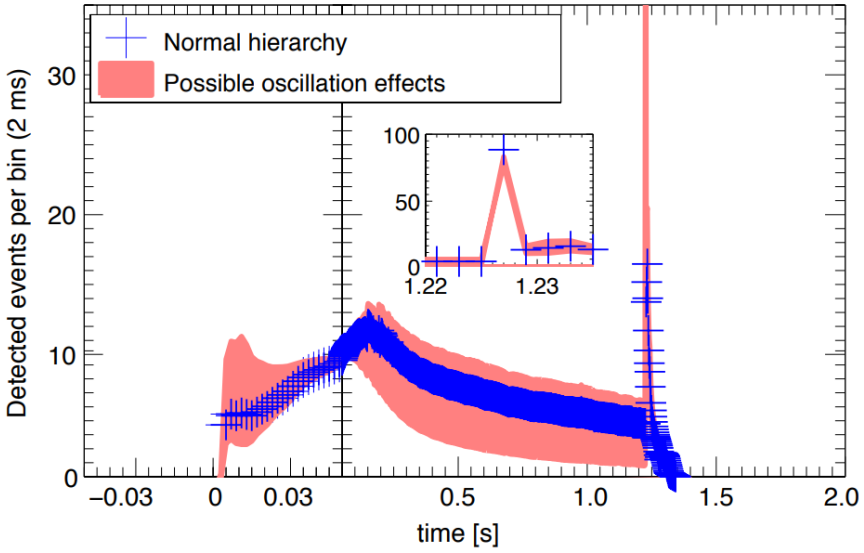
Nuclear astrophysics

- Impact of a first order hadron-quark phase transition in supernovae?

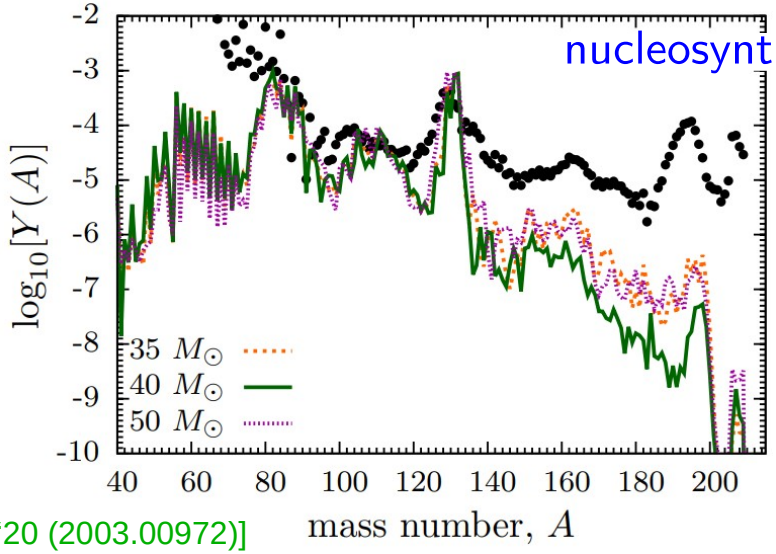
[Fischer, Bastian, MRW+ Nat. Astro. '18 (1712.08788)]



neutrino signals



nucleosynthesis



[Fischer, MRW, Wehmeyer+ ApJ '20 (2003.00972)]

Nuclear astrophysics

- Impact of a first order hadron-quark phase transition in supernovae?
- nuclear heating impact on NS merger ejecta property?
- potential r-process imprints on high-energy neutrino signals?
- chemical evolution of heavy elements
- Nuclear EoS and gravitational waves (group member: Hung Tan)

Astroparticle physics (group member: Yen-Hsun Lin)

- exotic particle production and signature in supernovae and NS mergers
- dark matter searches with astrophysical observables