The r-process: neutrinos, gamma rays, neutron capture

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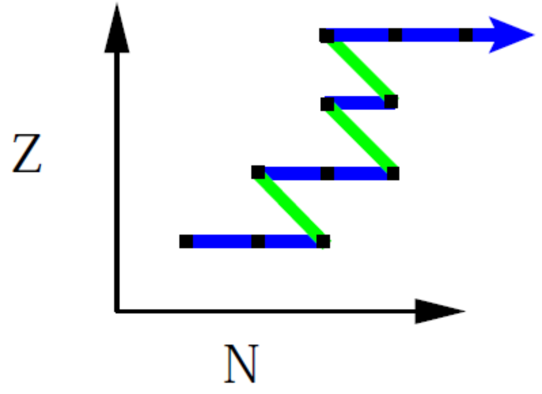
The r-process, what is it?

The rapid neutron capture process of nucleosynthesis

$$A(Z,N) + n \leftrightarrow A+1(Z,N+1) + \gamma$$

$$A(Z,N) \rightarrow A(Z+1,N-1) + e^- + \bar{\nu}_e$$



R-process is responsible for the rare earths (lanthanides), actinides as well as other nuclei

R-process solar system data

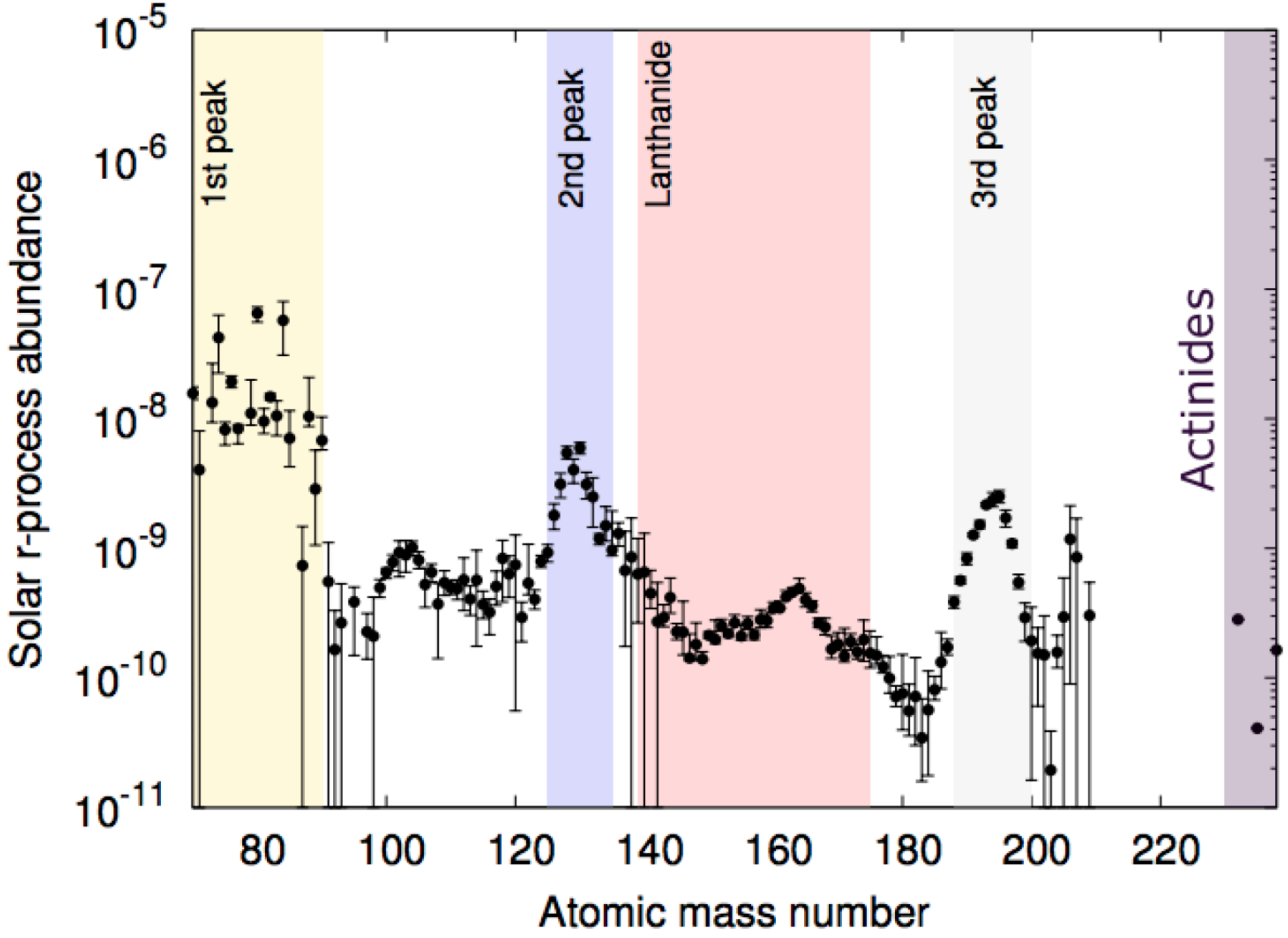
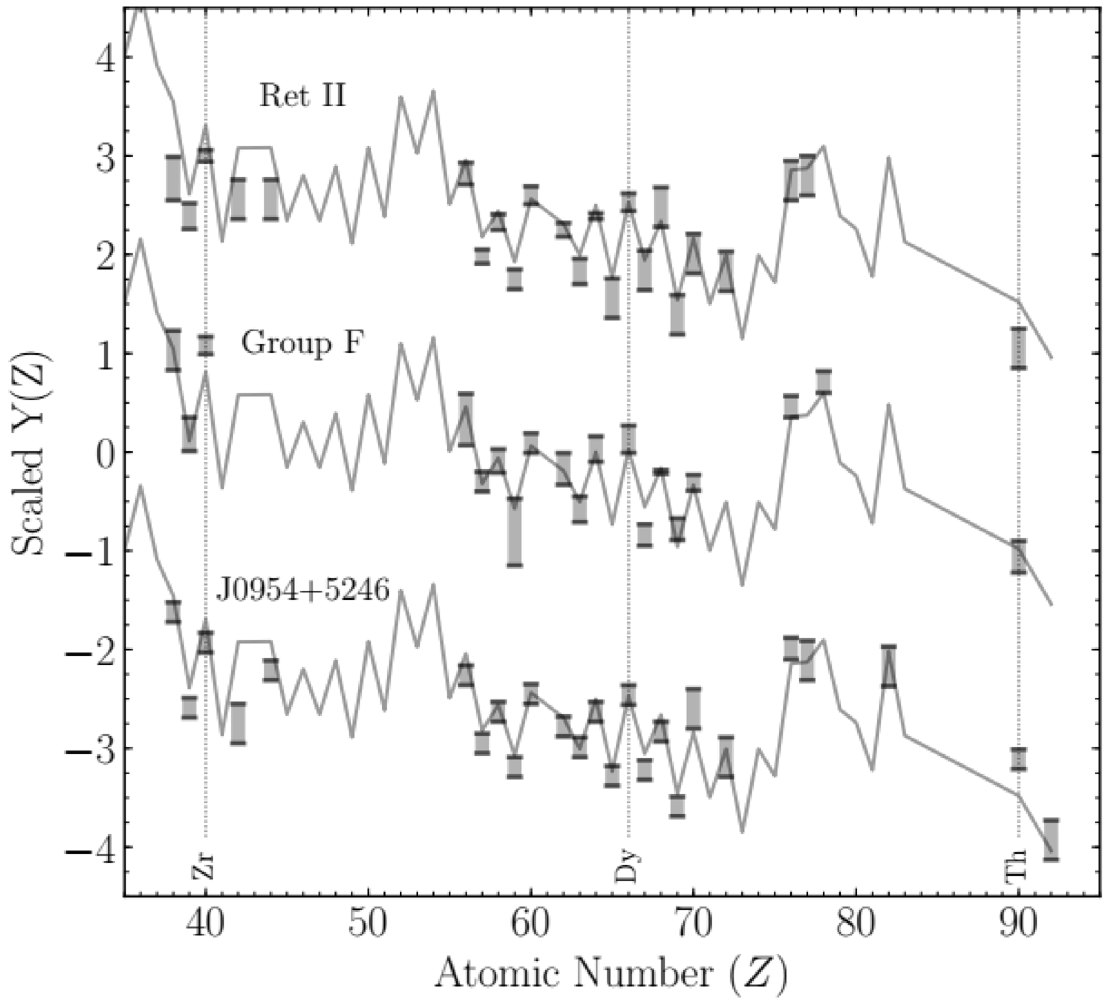


Fig from Bandyopadhyay and Beers 2025

Metal poor stars



Ret II, Ji et al, evidence for a rare event

Fig from Holmbeck et al 2019

There is evidence for r-process from a neutron star merger

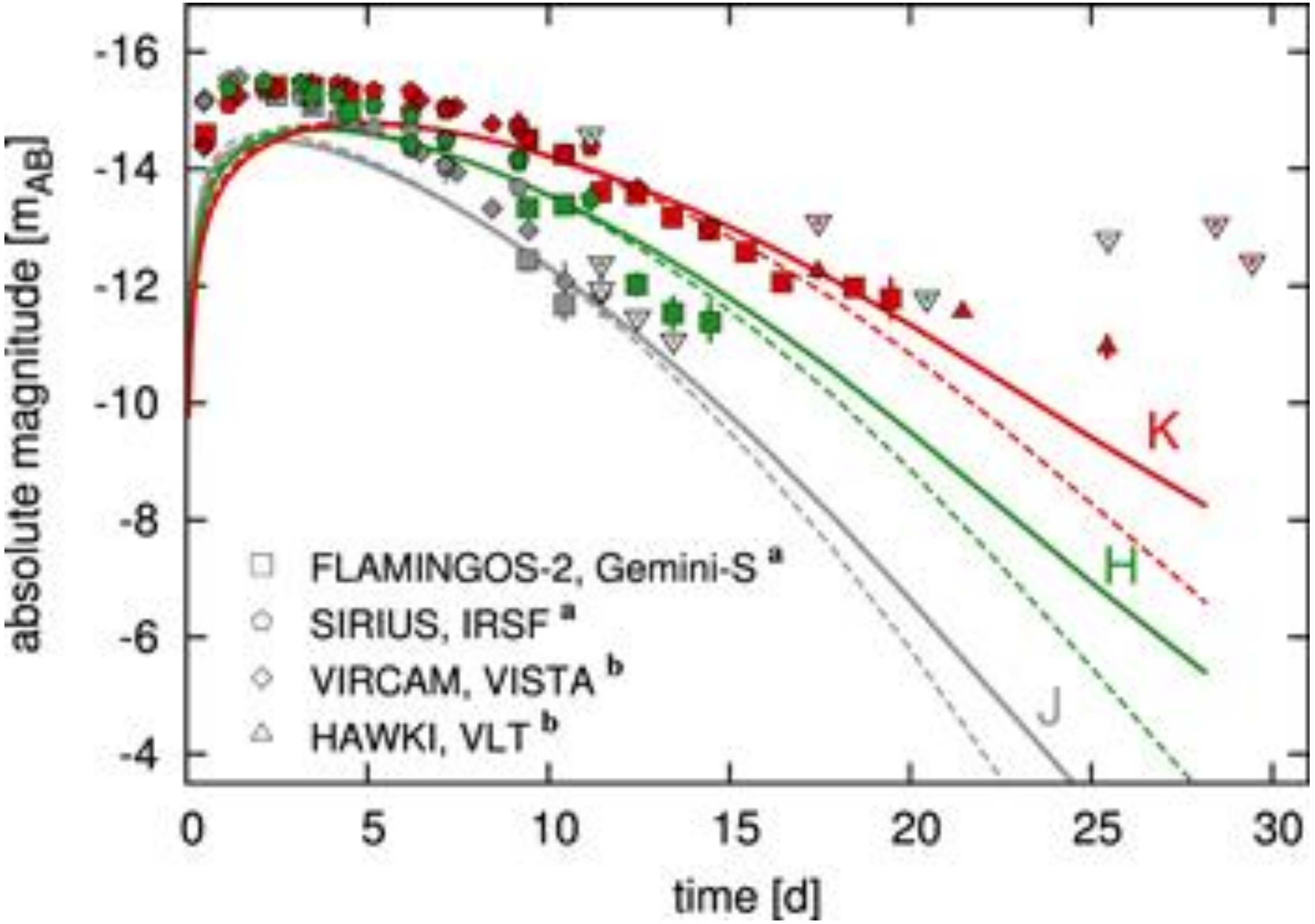
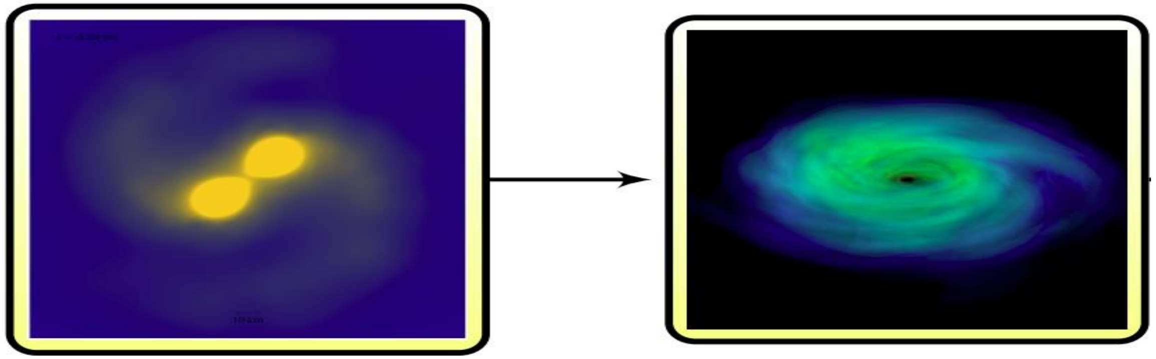


Fig. from Zhu et al 2019

A few explosive sites that could make r-process elements

Neutron star mergers

Fig from J. Miller



Core collapse supernovae

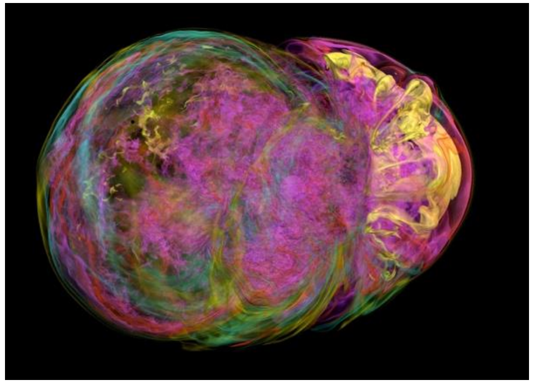


Fig. Blondin et al 2007

Core collapse supernovae with jets

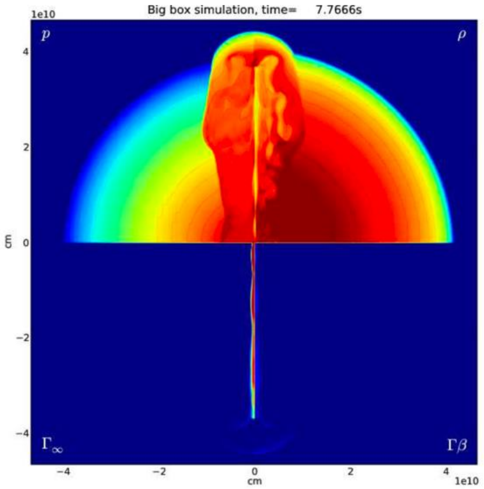


Fig. from Lazzati et al 2007

Black hole neutron star mergers

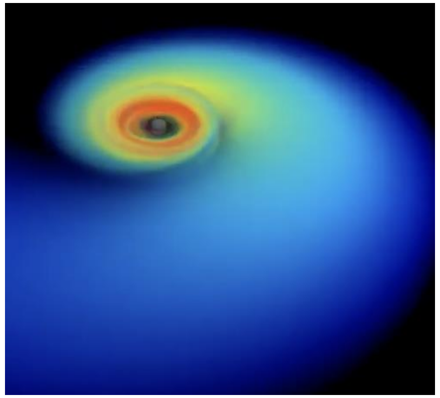


Fig from Hayashi and Shibata 2021

current questions

Does all the r-process material in the Galaxy come from neutron star mergers?

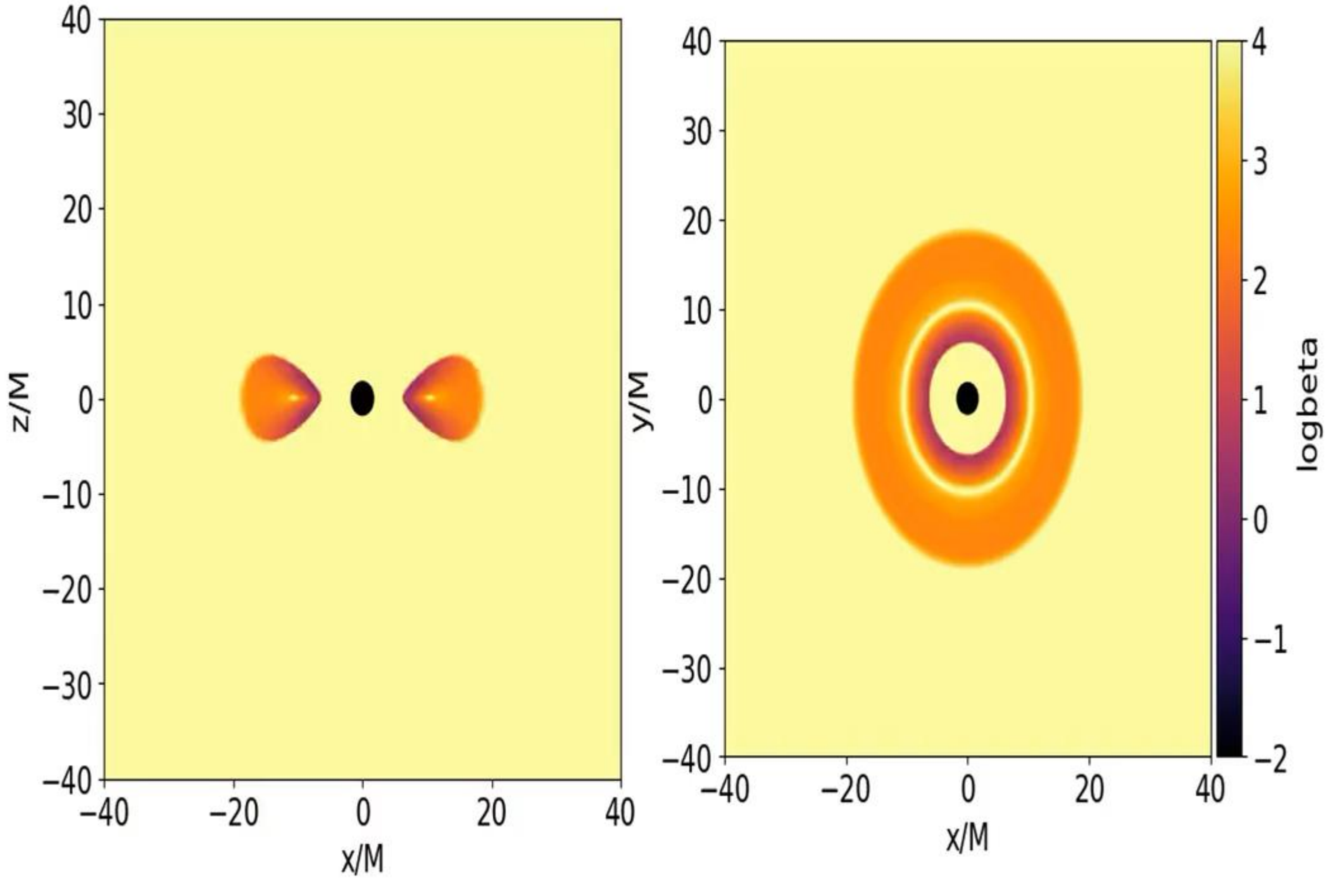
Which r-process elements do neutron star mergers make?

Which r-process elements do other sites make?

How do we evaluate how successful a candidate astrophysical site is for producing r-process elements?

One way is to create a simulation, calculate the element synthesis and compare with data

merger remnant



Video from
K. Lund, J
Miller

Spatial path of ejected mass

Tracer particles sorted by electron fraction, ejection angle, and nucleosynthetic outcome

Kelsey Lund
N3AS fellow

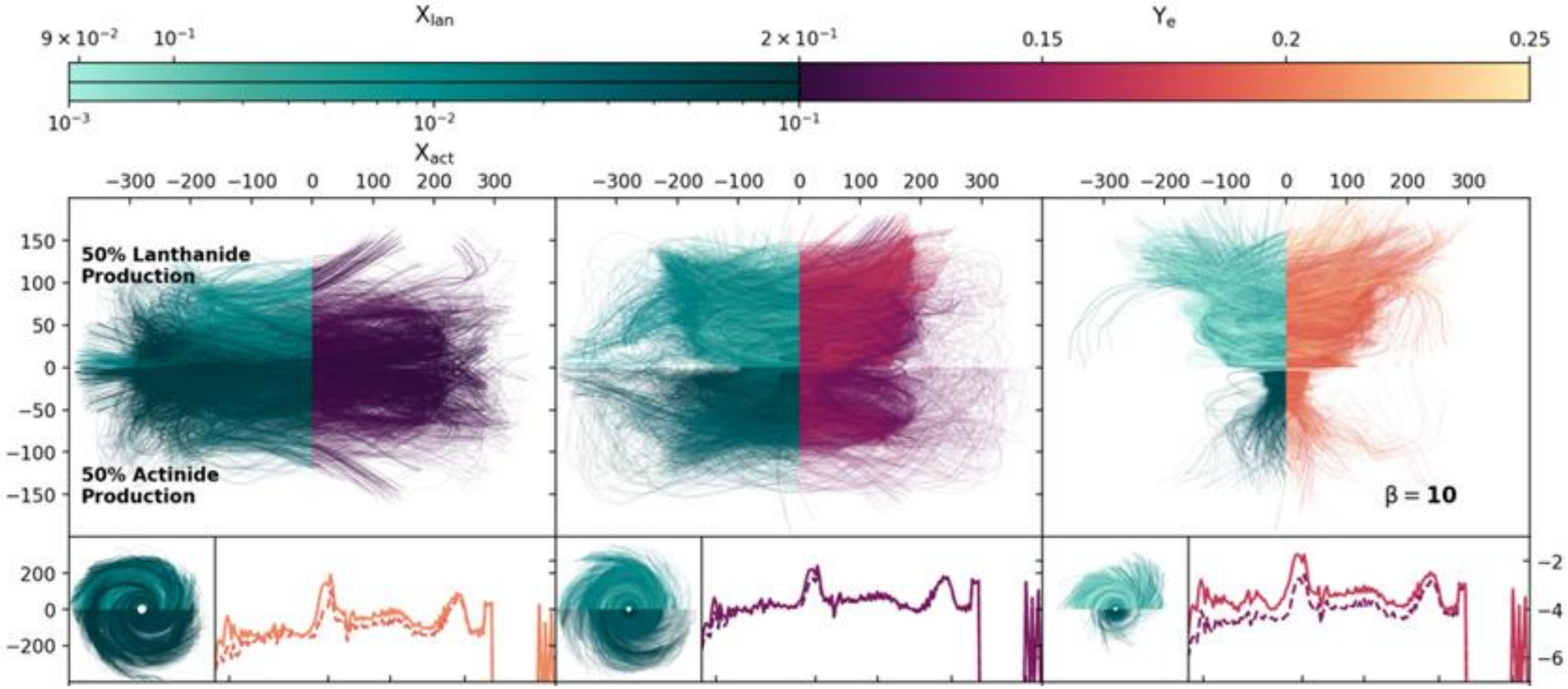
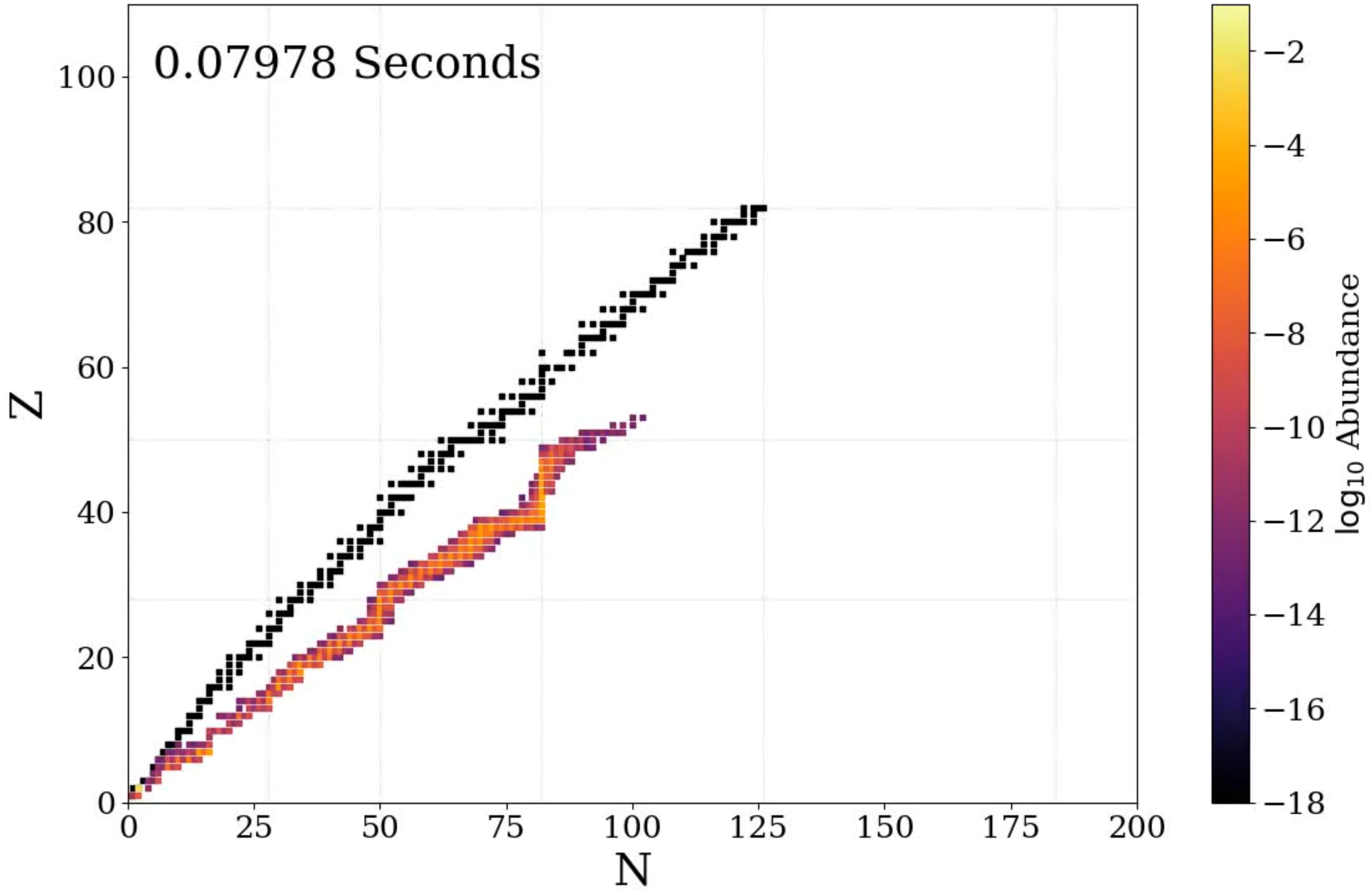


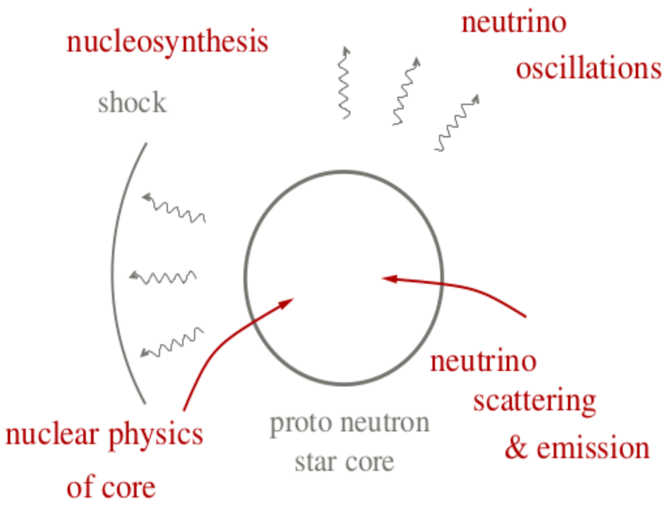
Fig. shows 100,000 tracers from Lund et al 2024

Neutron star merger ejecta makes elements, movie by Kelsey Lund

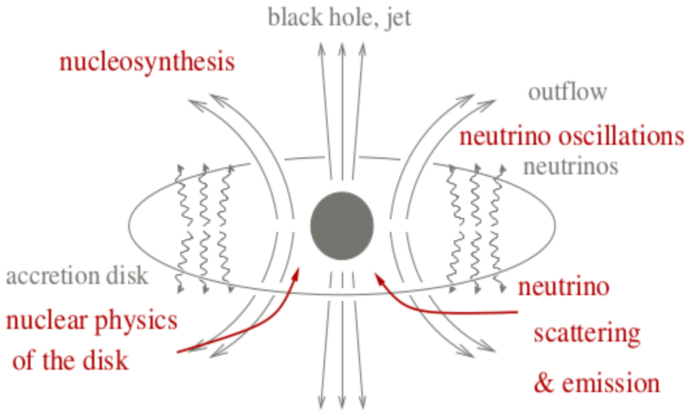


A view of the microphysics

What is the role of neutrinos, nuclear physics?



Standard core core collapse SN



Accretion disk from core collapse SN or compact object merger

Today’s topics

What is the role of neutrino flavor transformation?

Can we use gamma rays to detect neutron rich elements?

Today's topics

What is the role of neutrino flavor transformation?

Can we use gamma rays to detect these elements?

Flavor matters for nucleosynthesis

Neutrinos change the ratio of neutrons to protons

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Oscillations change the spectra of ν_es and $\bar{\nu}_e$s

$$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$$

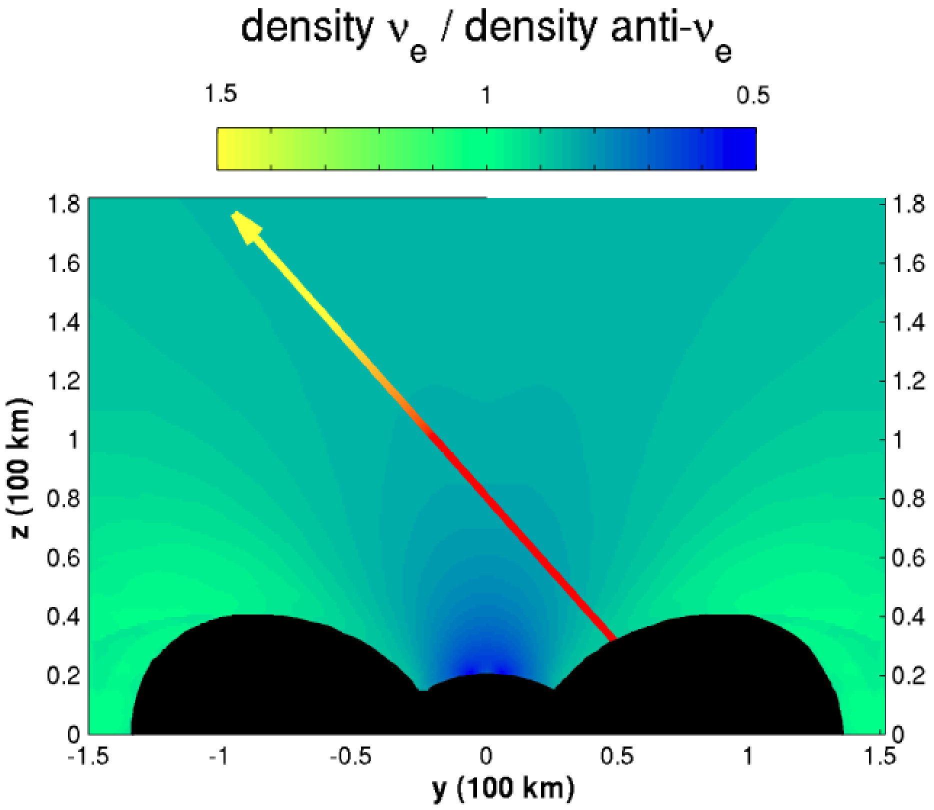
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

Mergers have less ν_μ, ν_τ than ν_e and $\bar{\nu}_e$

$\rightarrow$ oscillation reduces numbers of ν_e, $\bar{\nu}_e$

Will neutrinos transform in these explosive environments?

- Answer, almost certainly, is yes



Zhu et a 2016

(Quantum) kinetic equations

$$i\frac{D\rho}{Dt} = [\mathbf{H}, \rho] + iC$$

$$i\frac{D\bar{\rho}}{Dt} = [\bar{\mathbf{H}}, \bar{\rho}] + i\bar{C}$$

Collision term

Convective derivative

Hamiltonian

See work by Volpe

Hamiltonian creates non-linearity

$$\mathbf{H} = \mathbf{H}_{\mathrm{vac}} + \mathbf{H}_{\mathrm{M}} + \mathbf{H}_{\mathrm{SI}}$$

$$\bar{\mathbf{H}} = \mathbf{H}_{\mathrm{vac}} - \mathbf{H}_{\mathrm{M}} - \mathbf{H}^{*}_{\mathrm{SI}}$$

$$\imath \frac{D\rho}{Dt} = [\mathbf{H}, \rho]$$

$$\imath \frac{D\bar{\rho}}{Dt} = [\bar{\mathbf{H}}, \bar{\rho}]$$

Neutrinos see a potential due to other neutrinos

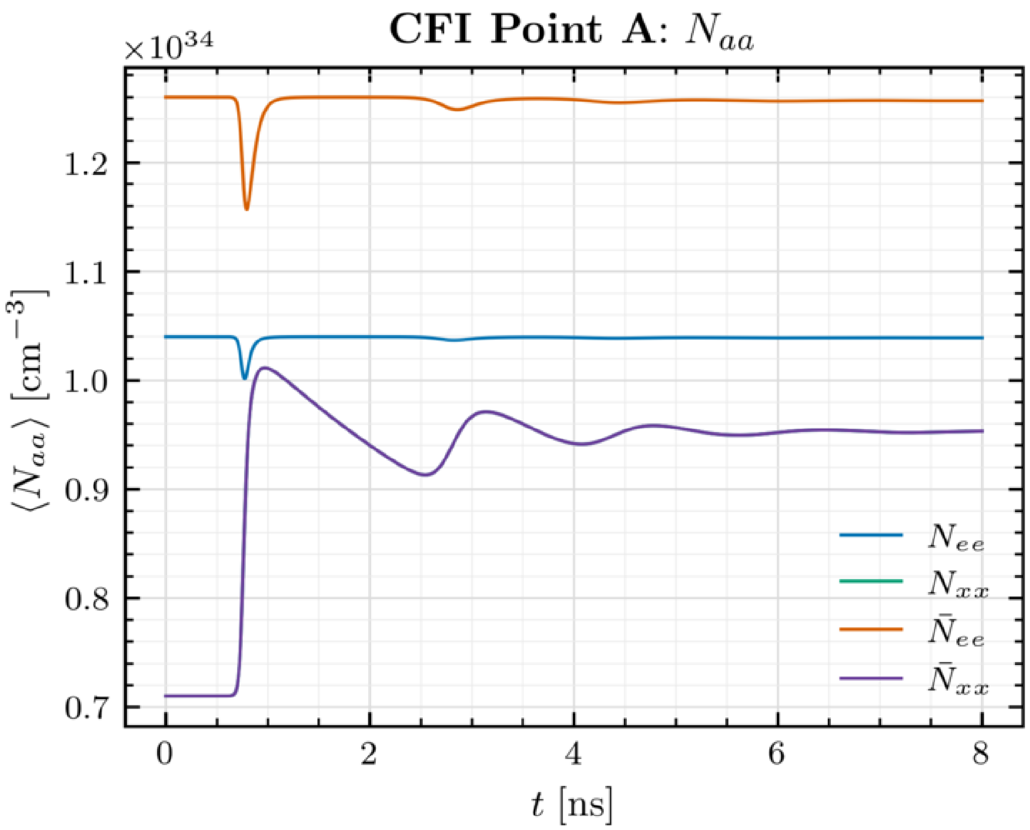
Neutrinos see a potential due to the matter

Flavor and mass are not the same

Glossary (see Cristina Volpe's talk)

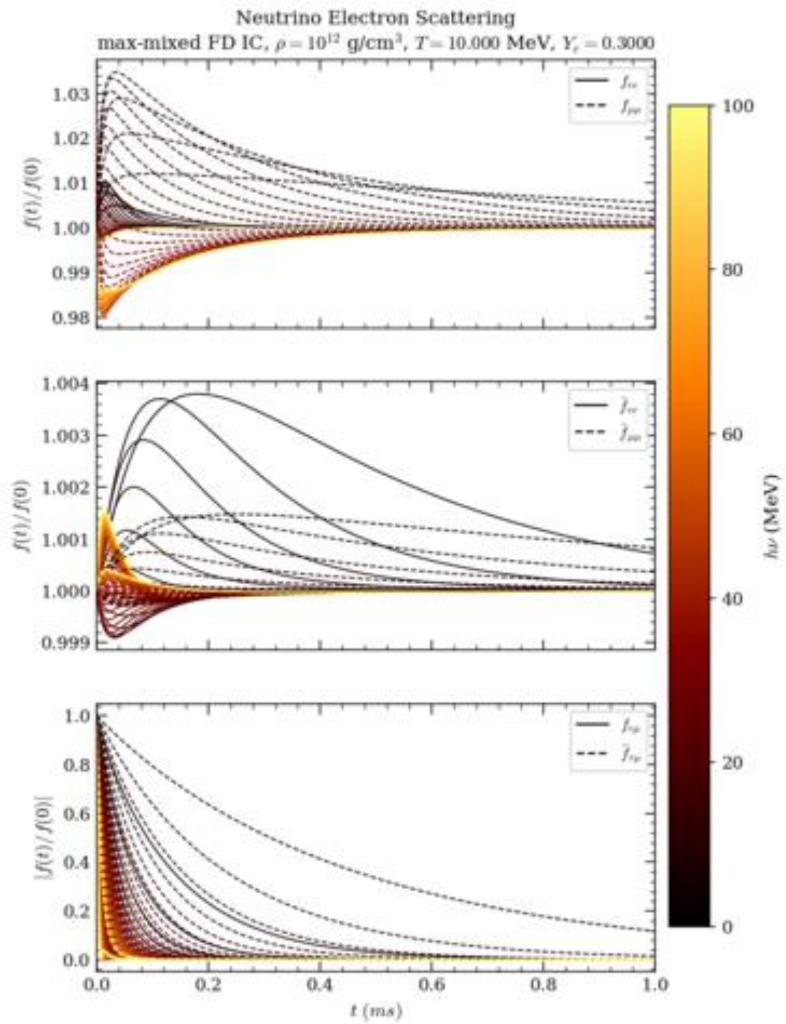
- **Fast flavor transformation** – driven by the "self interaction" Hamiltonian and differing electron neutrino and electron antineutrino distributions, oscillation occurs on timescale of nanoseconds
- **Collisional flavor transformation** – driven by the combination of the collision and the "self-interaction" Hamiltonian, time scales of tenths of milliseconds
- **Many body oscillations** – QKE formalism not used, timescale even faster than fast oscillations, all species equilibrate
- **Slow oscillations** – driven but the combination of the "self interaction" and vacuum mass splitting
- **Matter Neutrino Resonance** transformation – driven by the interaction between the "self-interaction" and the matter Hamiltonian
- **MSW oscillations** – driven by combination of the matter Hamiltonian and vacuum mass splitting
- **Neutrino-Antineutrino oscillations** – yesterday's talk by Huang

Examples of the role of collisions



Collisional flavor instability

Collisional flavor transformation originally introduced by L. Roberts



Collisional damping

Christian Hall
ENAF/SciDAC graduate student

Reproduction of Richers et al 2019

Hall et al in prep

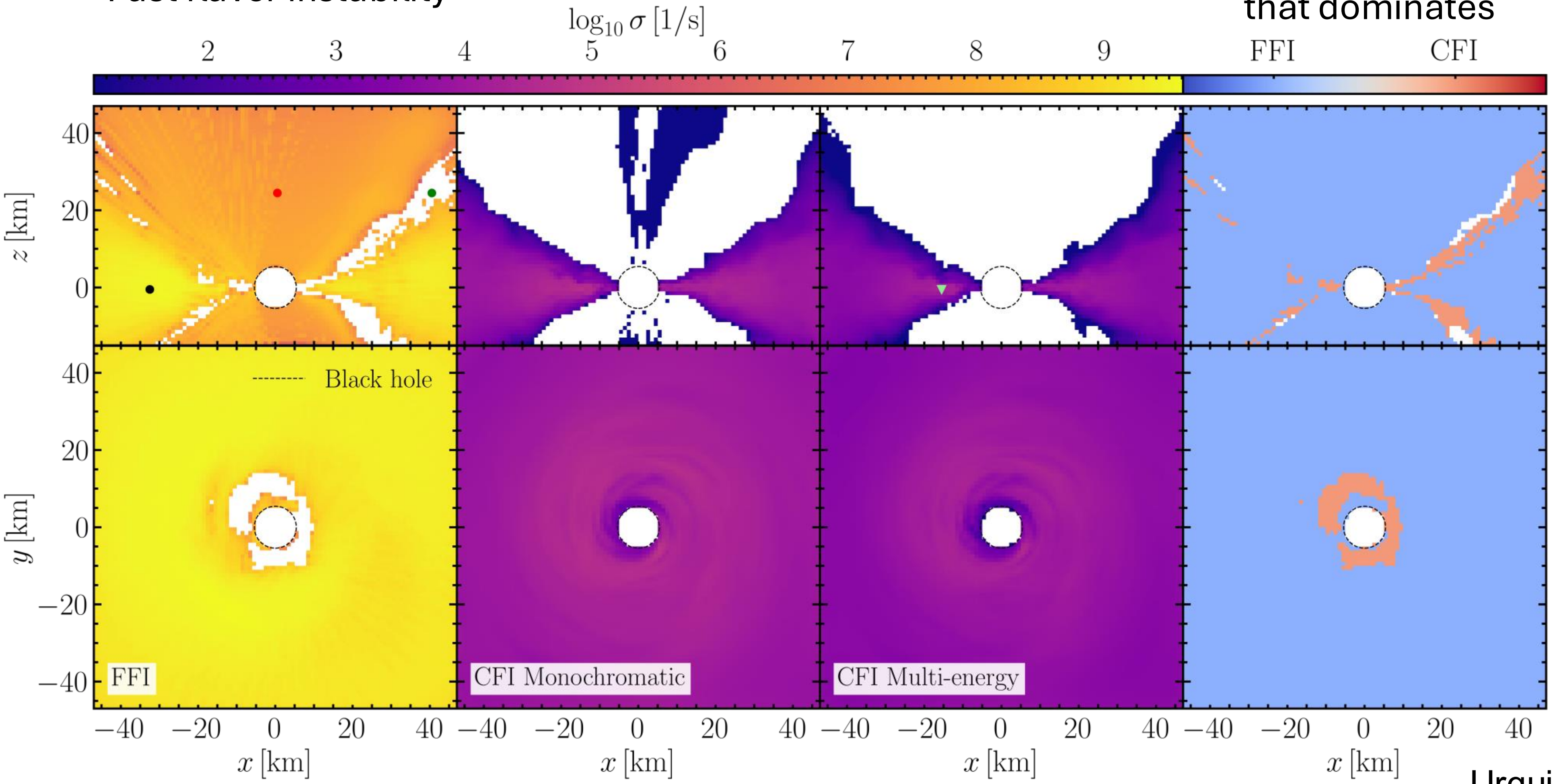
Regions of neutrinos transformation in mergers

Erick Urquilla: PhD student at UTK with Sherwood Richers

Fast flavor instability

Collisional flavor instability

Shows the instability that dominates



See also work by J. Froustey

Urquilla et al 2026

Glossary

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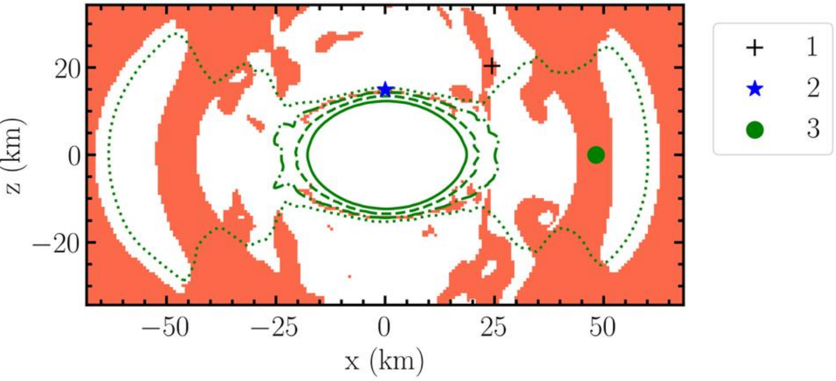
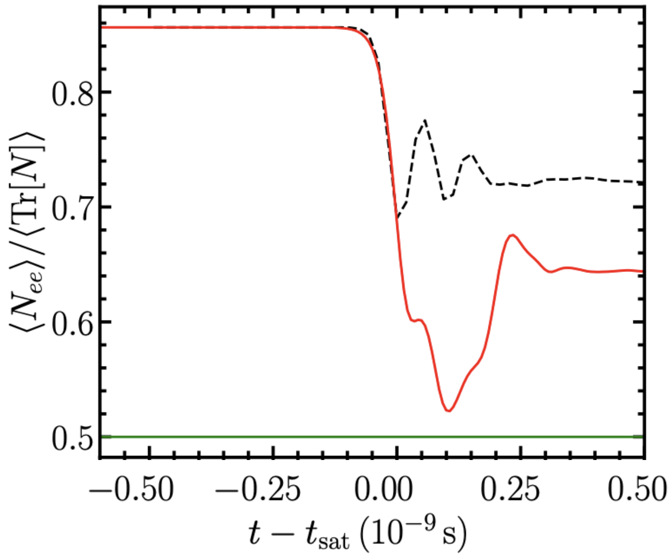
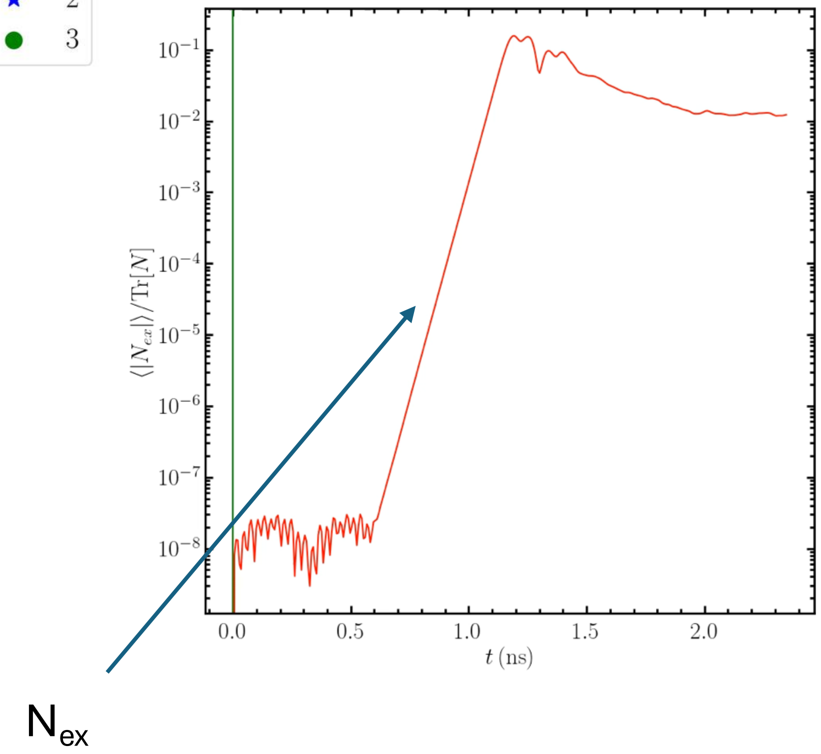
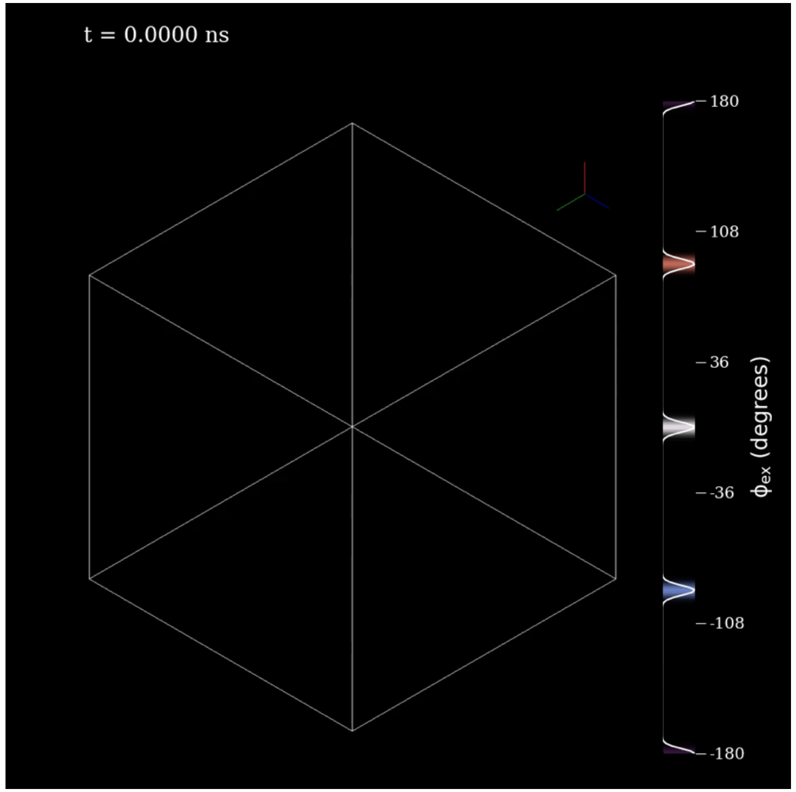
Small scale oscillation calculation (8 cm size box)

Movie shows the phase of the off diagonal component of the density matrix



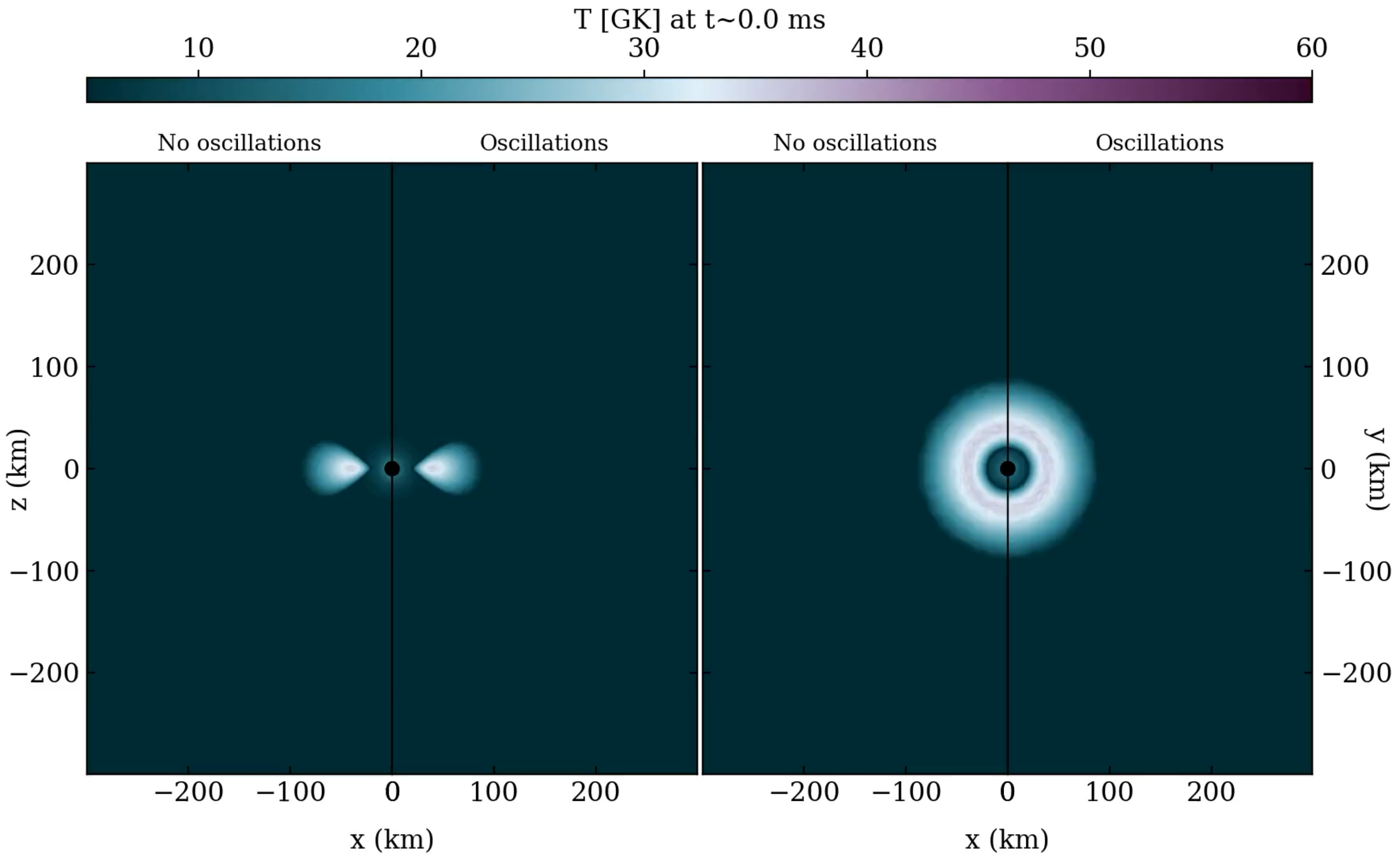






Gross et al 2025

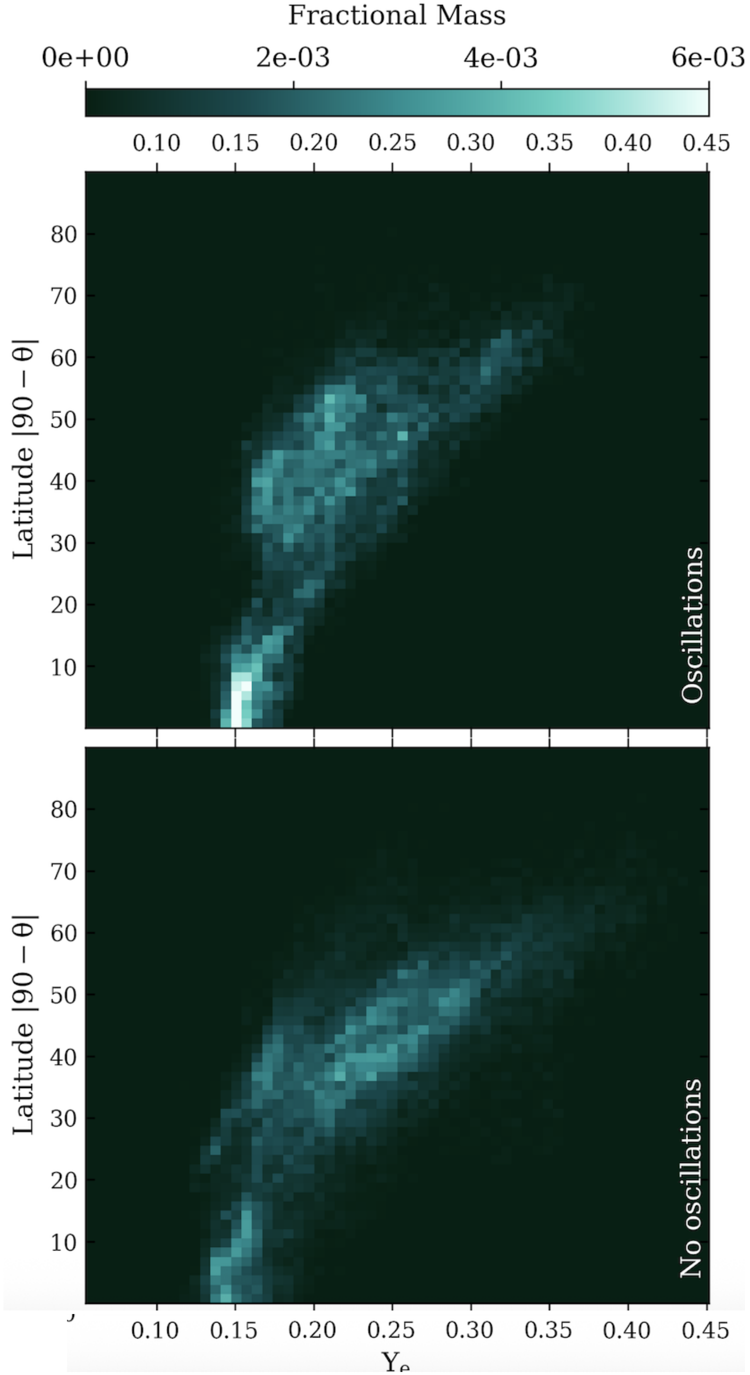
Implementing fast flavor oscillations in classical simulations

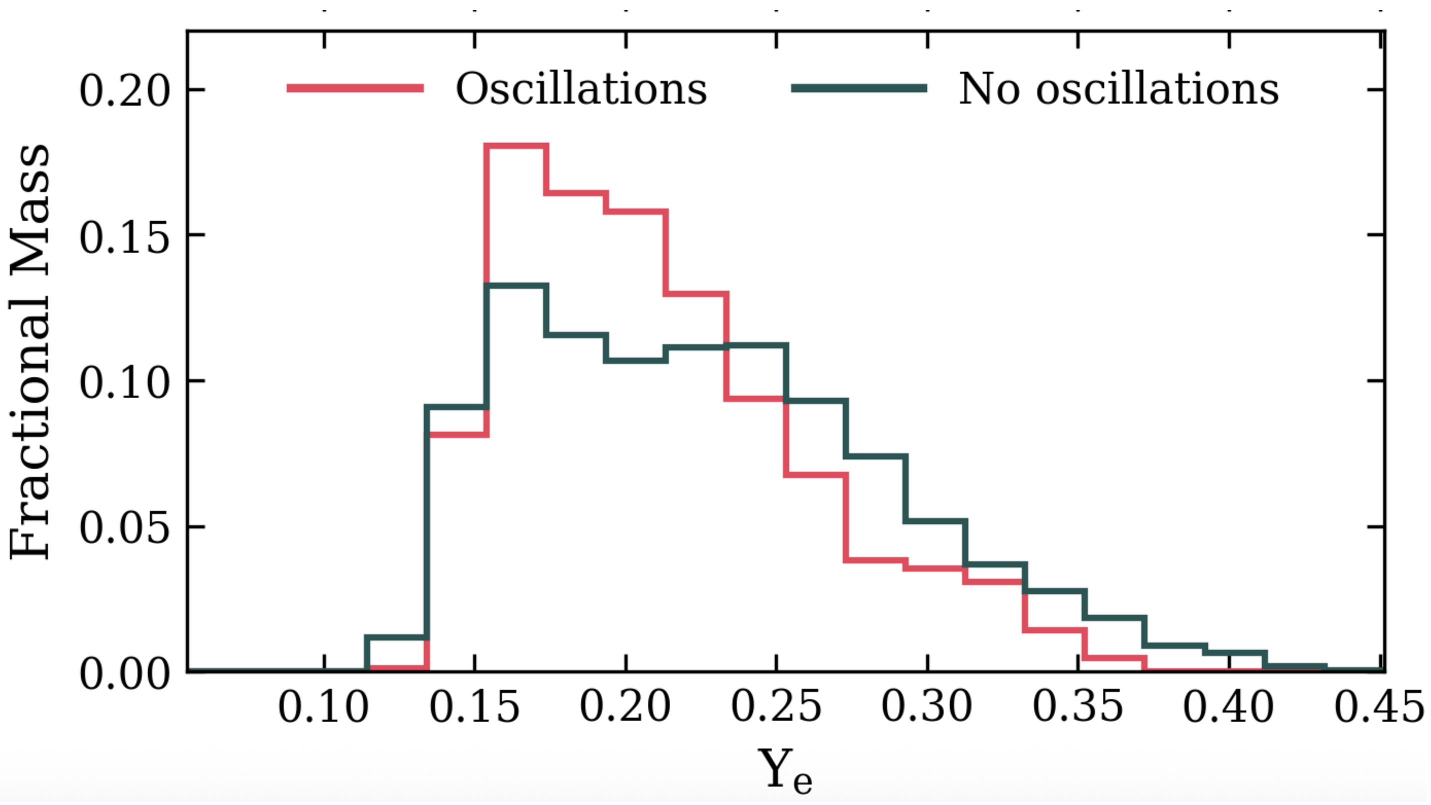


Kelsey Lund
N3AS fellow

Lund et al 2025

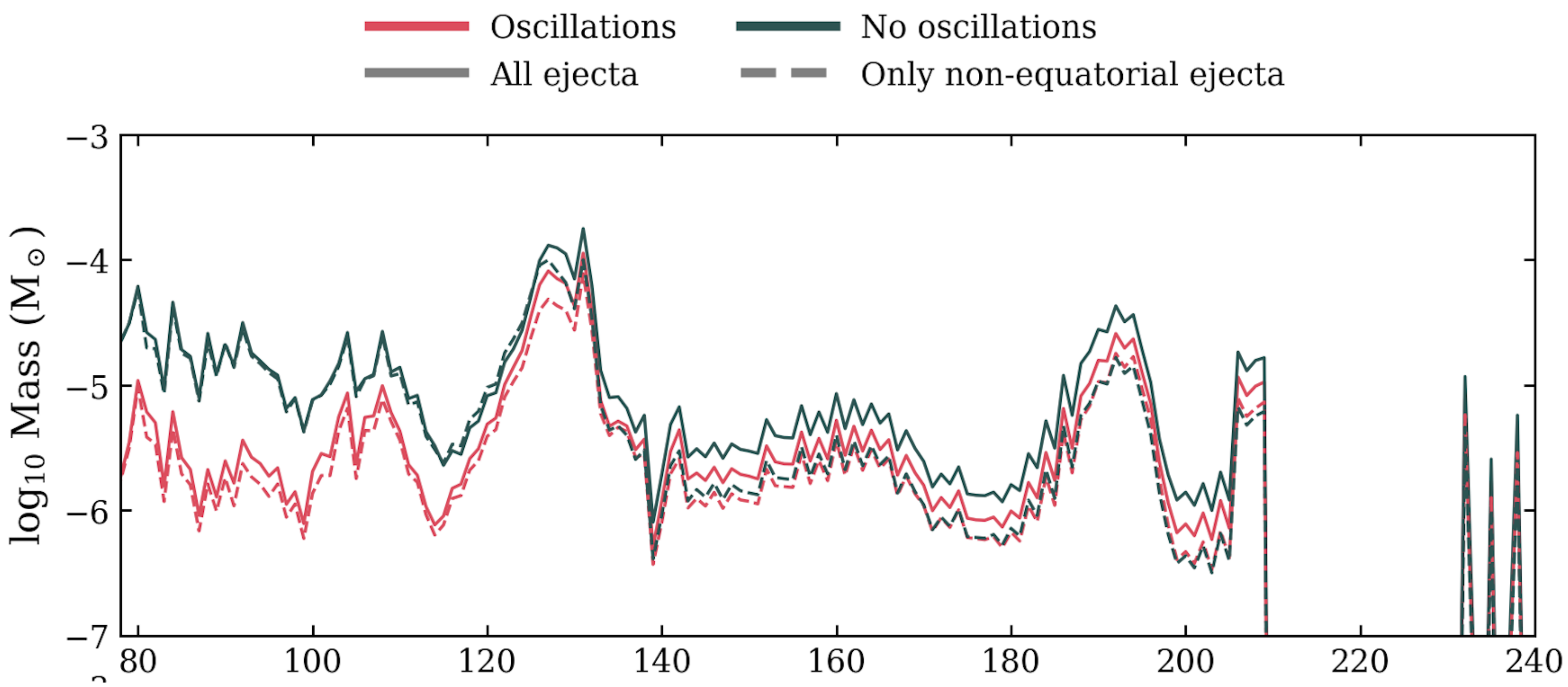
Consequences: wind shifts in angle and neutron richness





Electron fraction of ejected material

r-process: mass vs. A



Overall r-process mass is lower, especially in the weak r-process region

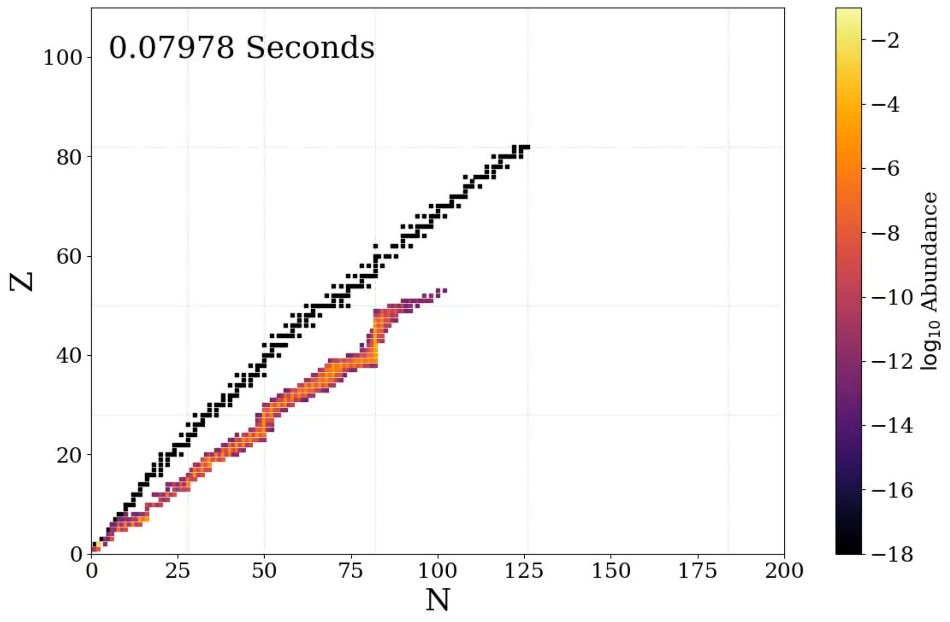
Today’s topics

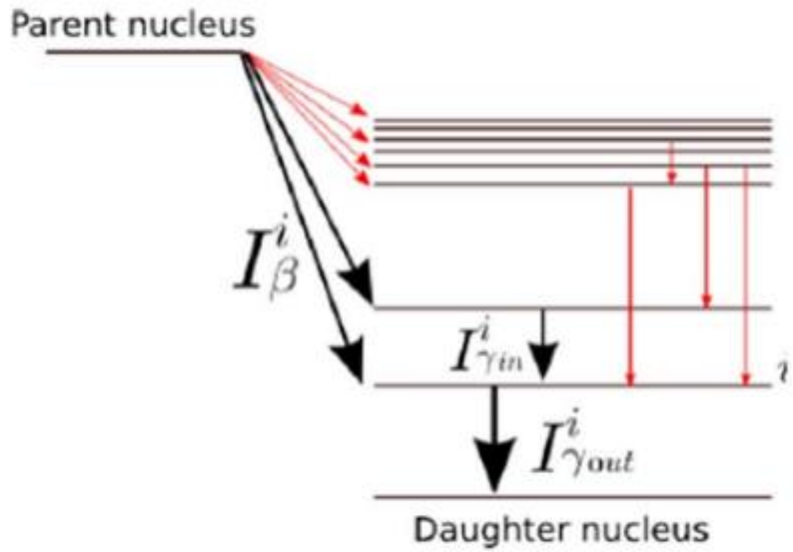
What is the role of neutrino flavor transformation?

Can we use gamma rays to detect r-process elements?

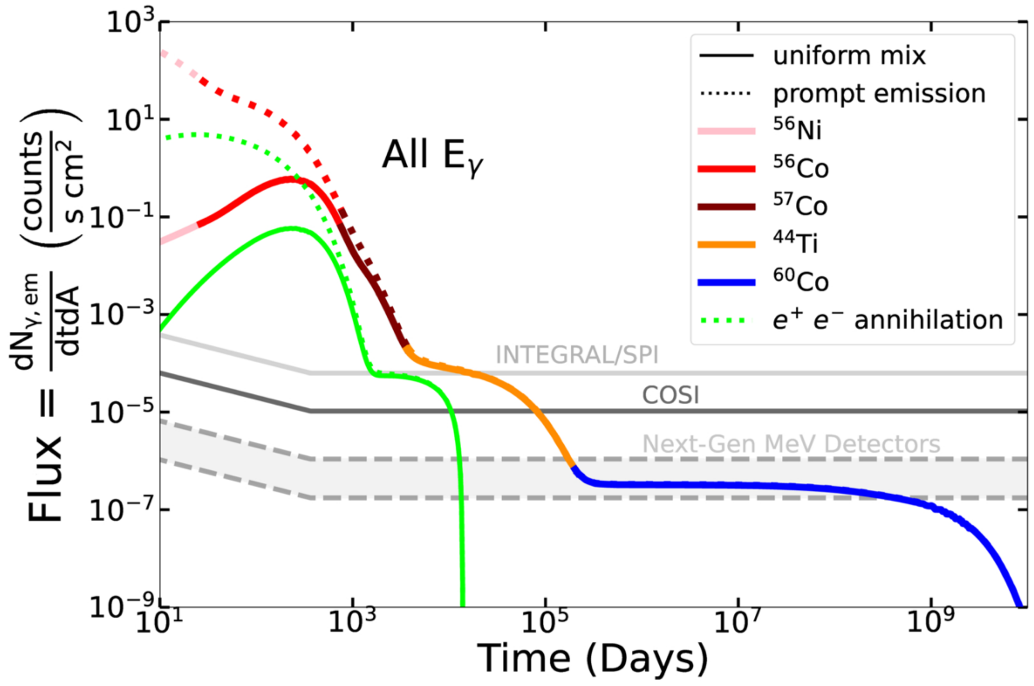
Gamma ray signatures

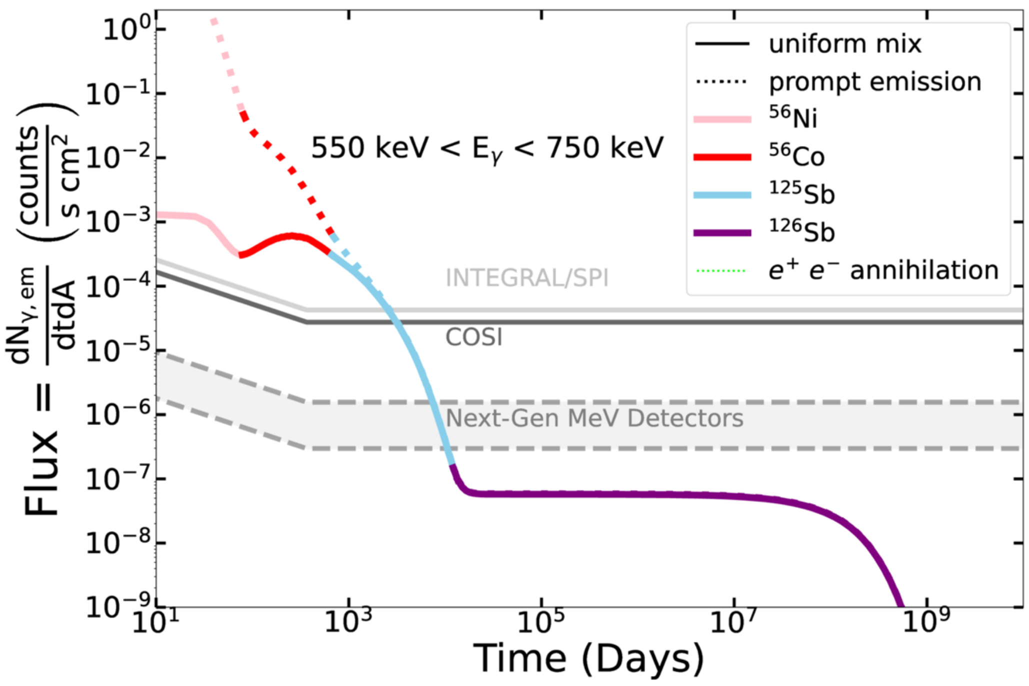
After a cosmic explosion, radioactive elements remain and slowly decay, producing gamma rays





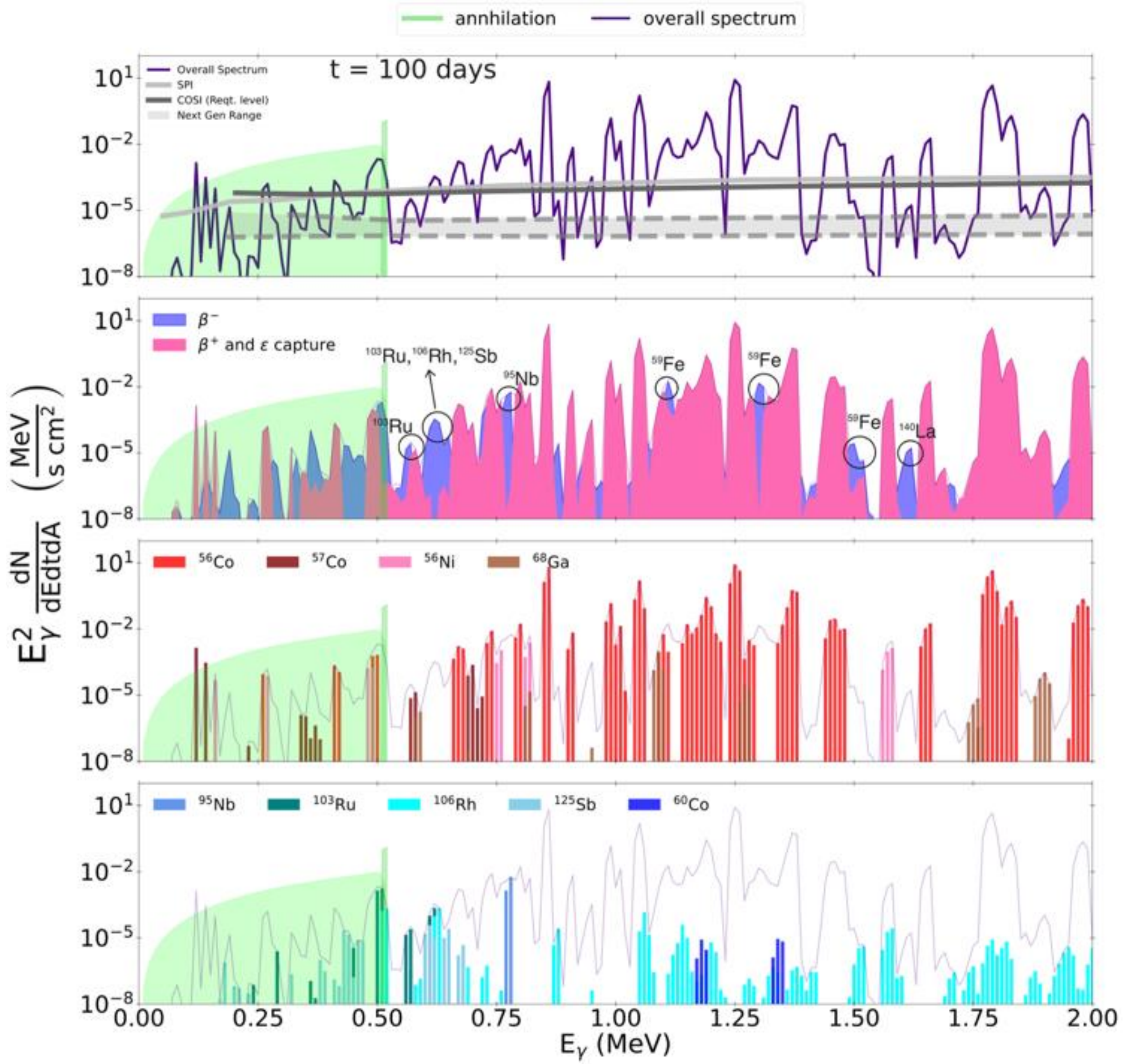
Example of a time profile in gammas in a supernova r-process producing event at 10 kpc





Liu et al 2025

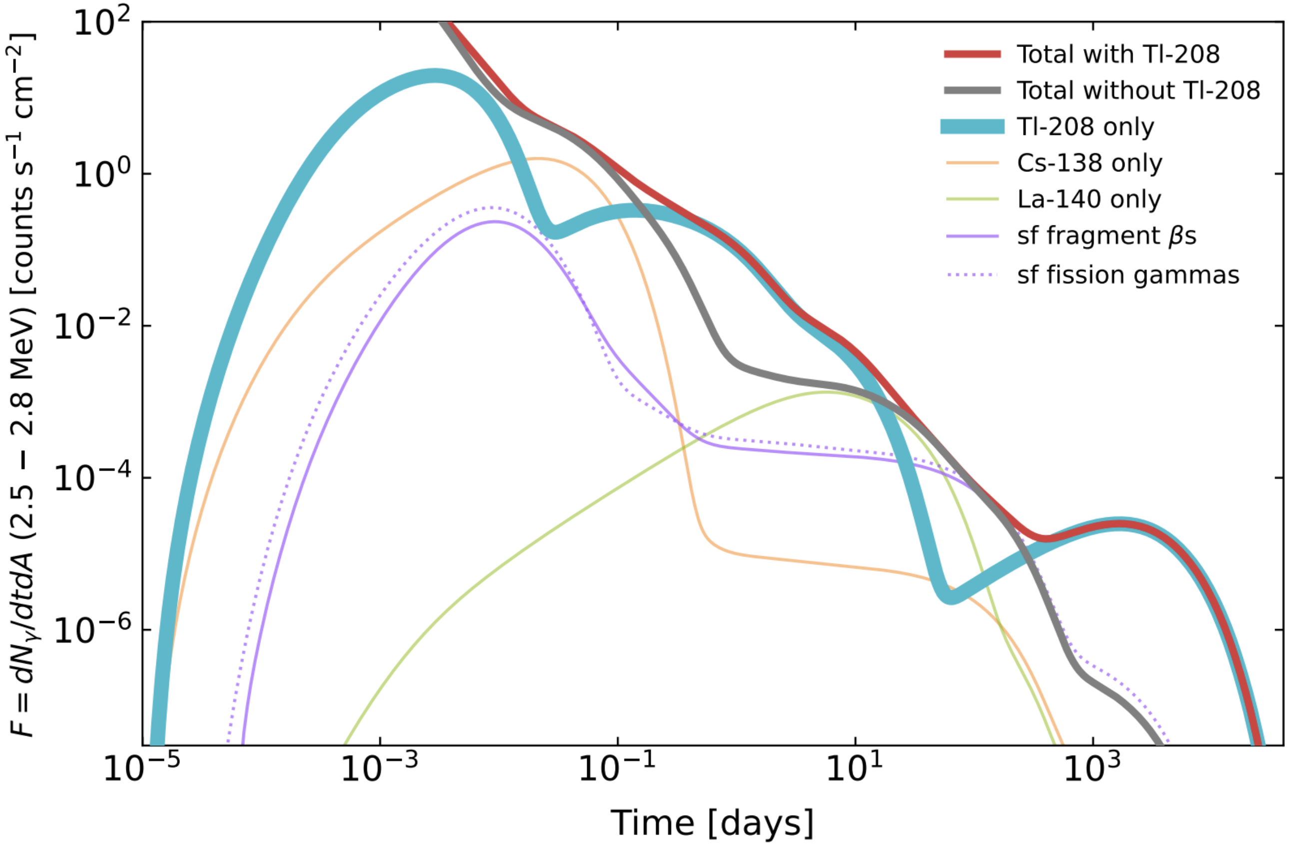
Prompt SN signal would be visible should we have Galactic core collapse SN



Shows expected signal at 100 days

Liu et al 2025

Example: Thallium-208 from a neutron star merger



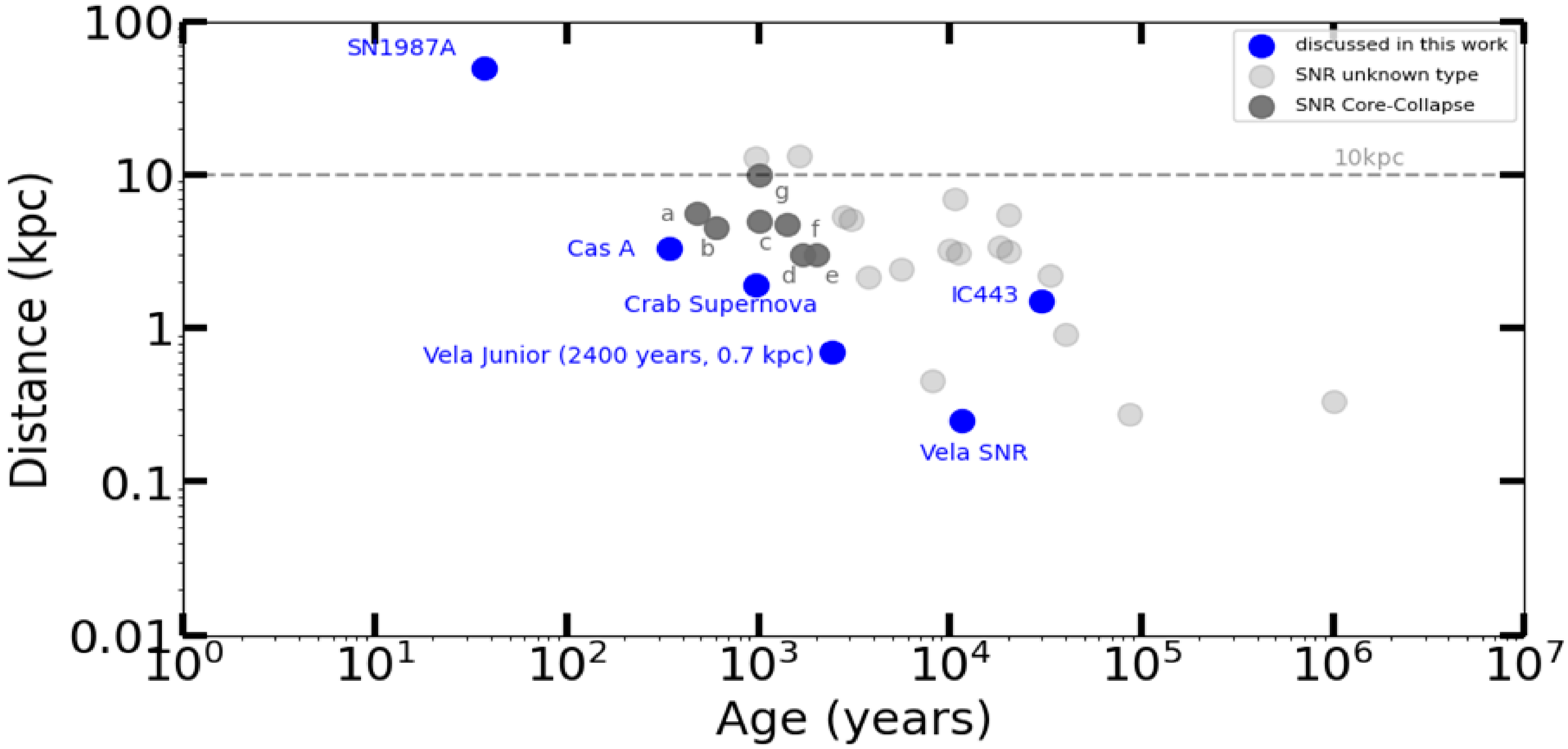
Energy region 2.5 MeV – 2.8 MeV is dominated by Thallium-208 decay (beta decay and then gamma decay) at certain times

Would show how far the r-process progressed – an important open question

Caveat: event must happen in the Galaxy

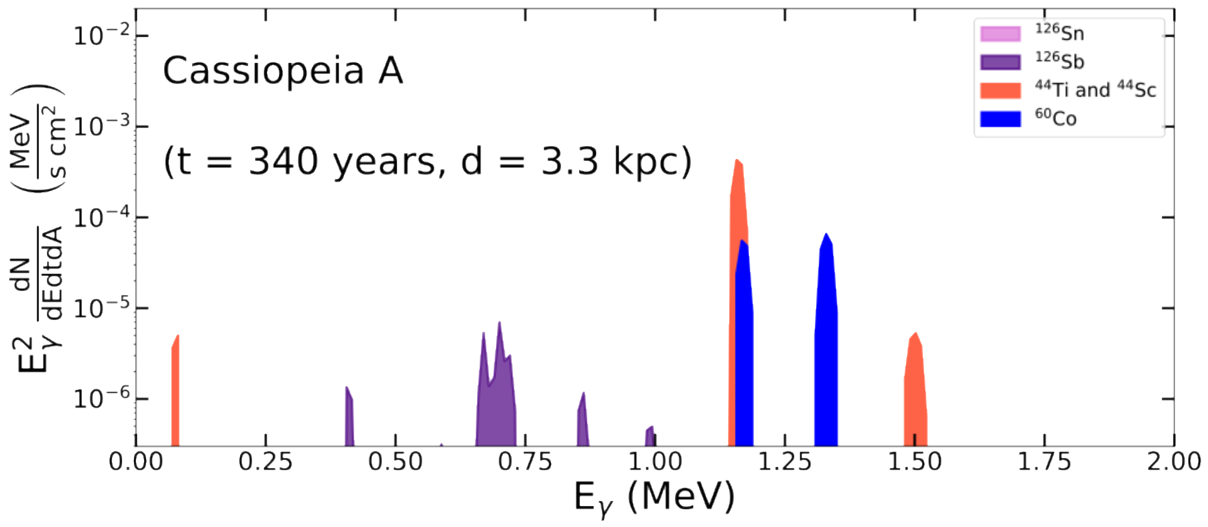
Vassh et al 2024

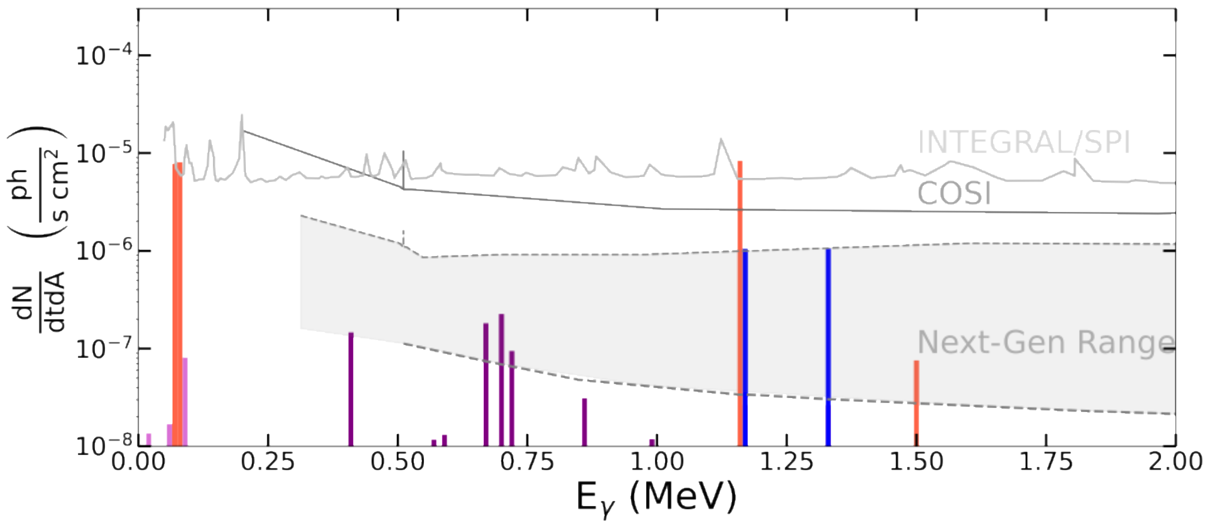
Nearby core collapse supernova remnants



Liu et al 2025

What would Cas A look like in gammas if it produced r-process?

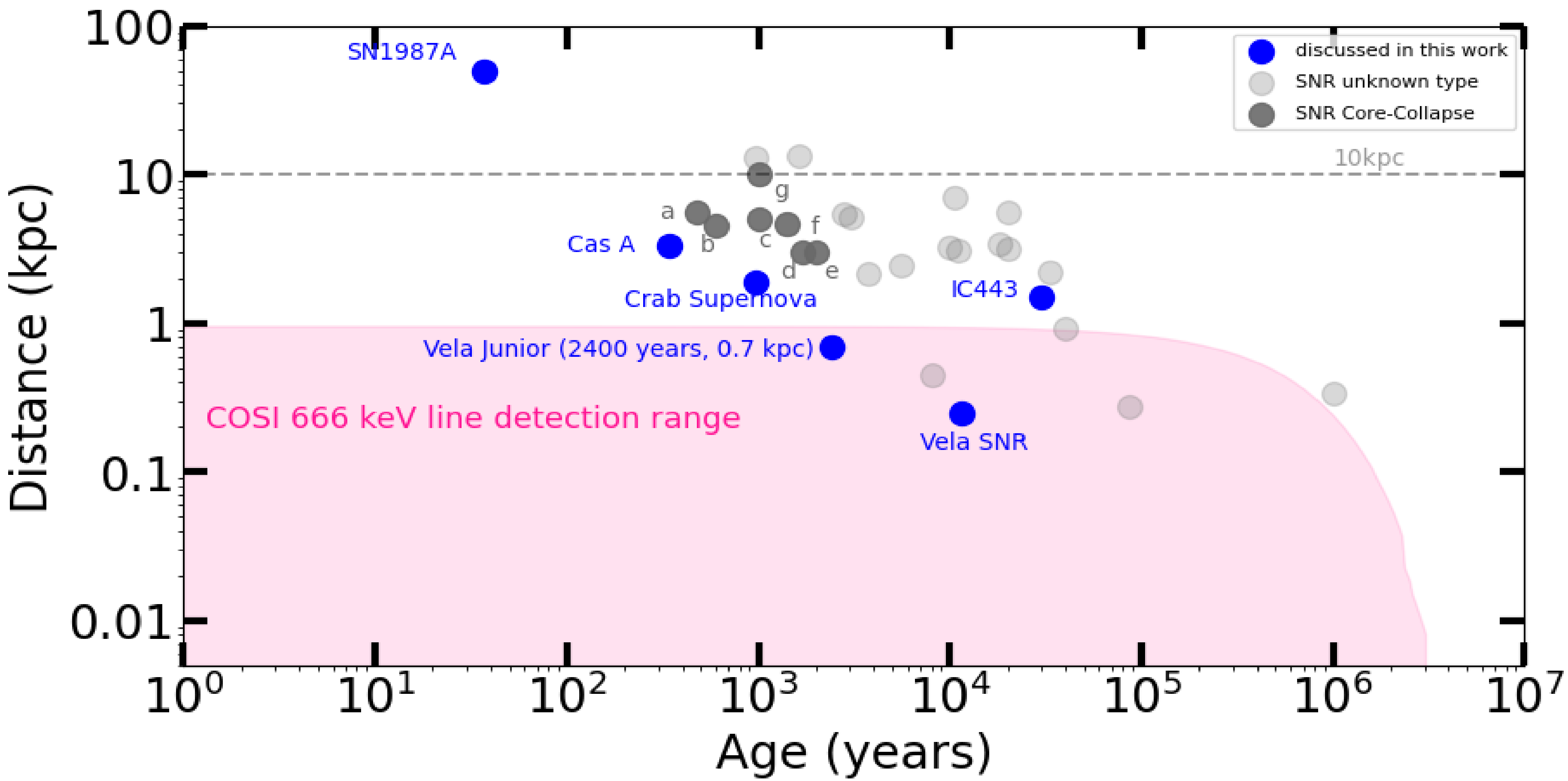




These results assume an magneto-hydrodynamical supernova that produces r-process

Liu et al 2025

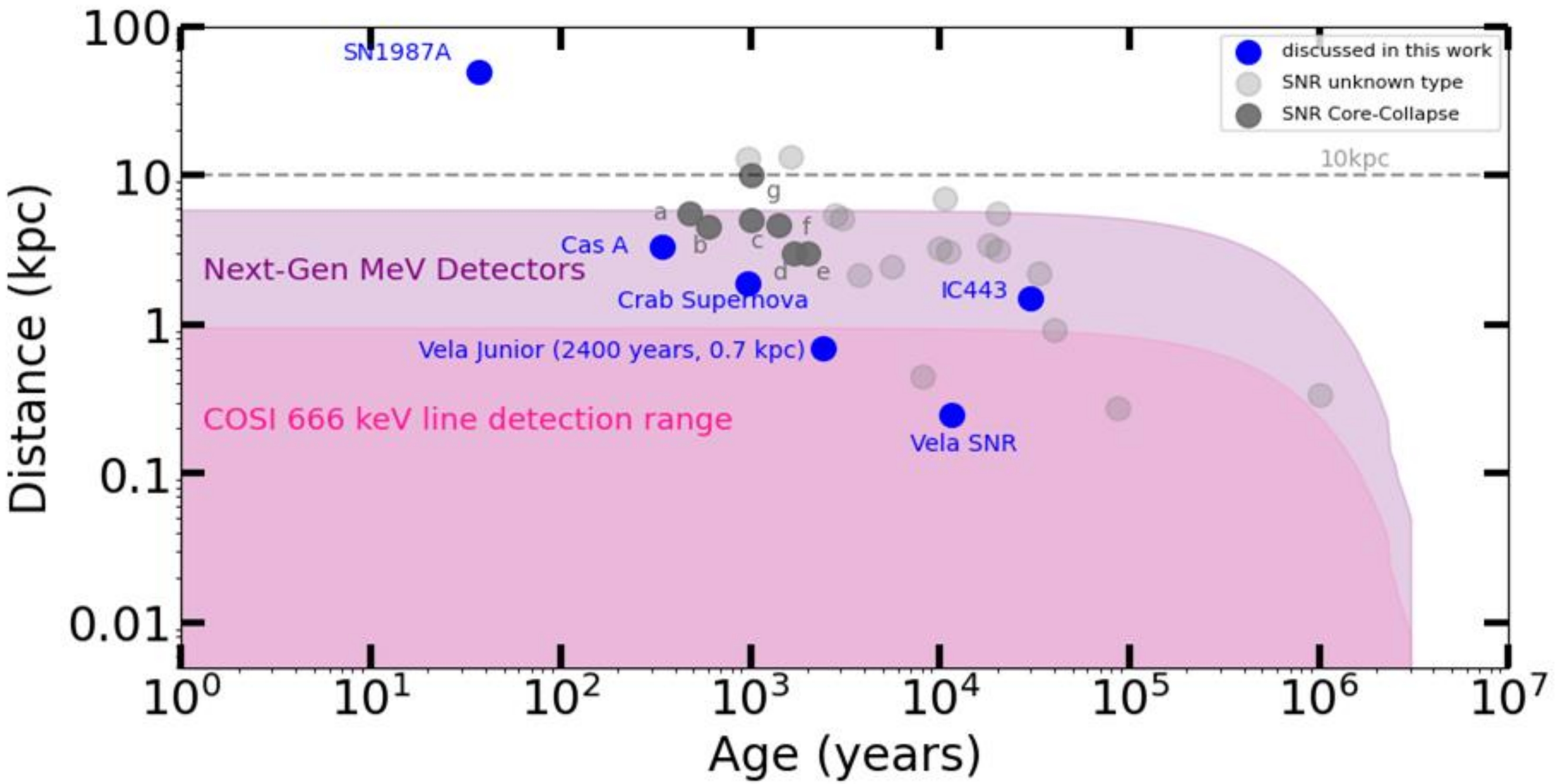
COSI may detect 126Sn if these supernovae made r-process



Zhenghai Liu

Liu et al 2025

Next generation gamma ray satellites could detect Sn if these supernovae made r-process



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60Fe – r-process producing supernovae make a lot

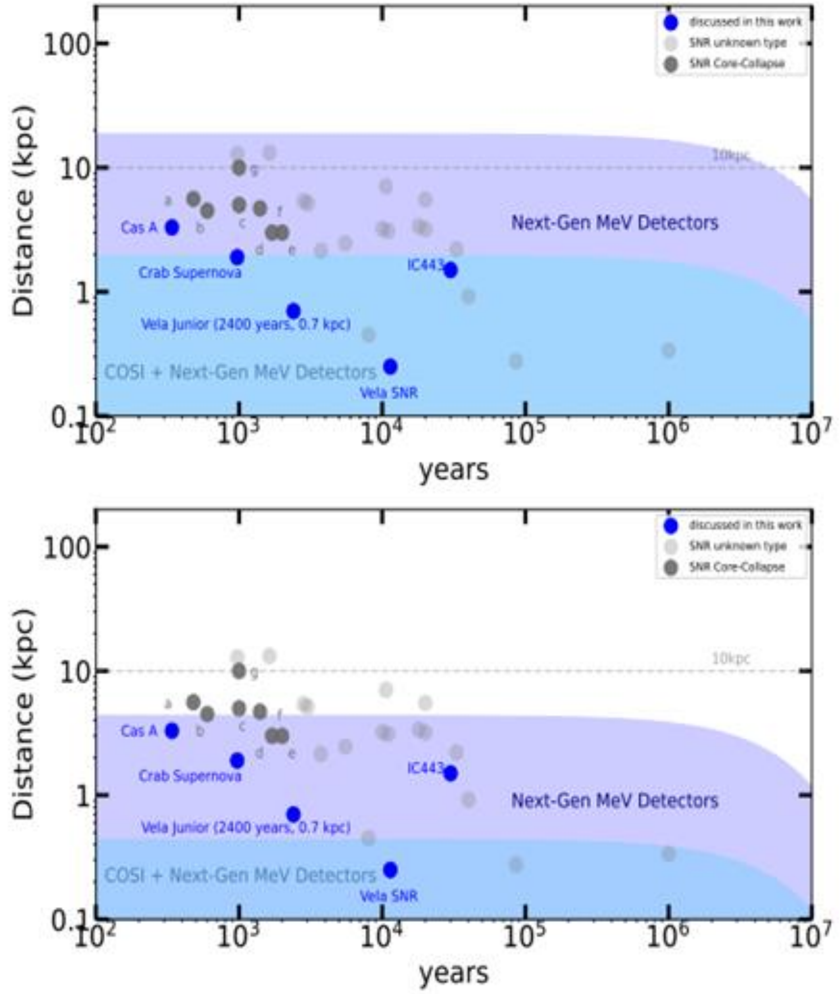


Figure 6. Top panel: same as Figure 5 but for the observability of ^{60}Co 1332 keV line using the ^{60}Fe yield from the MN-SN model. Bottom panel: same as the top panel, but for CCSN. The ^{60}Fe yield is taken from M. Limongi & A. Chieffi (2018) as $3.7 \times 10^{-5}\ M_{\odot}$.

Liu et al 2025

Conclusions

- The origin of the r-process elements is still an unresolved question

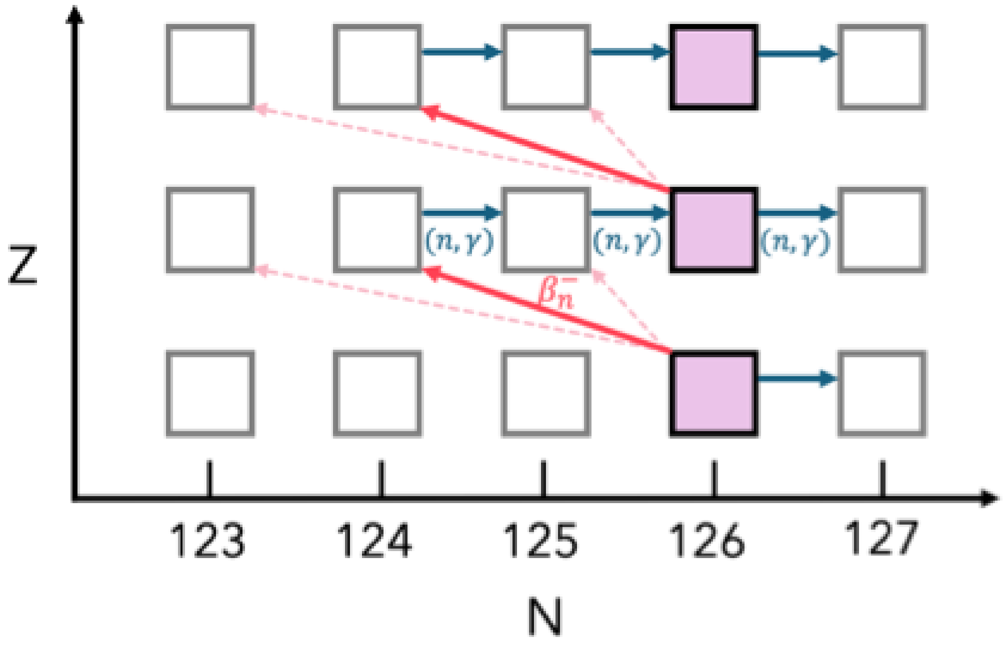
- We need more effort to understand the microphysics,
  e.g. neutrino flavor transformation
  e.g. neutron capture rates
  e.g. masses

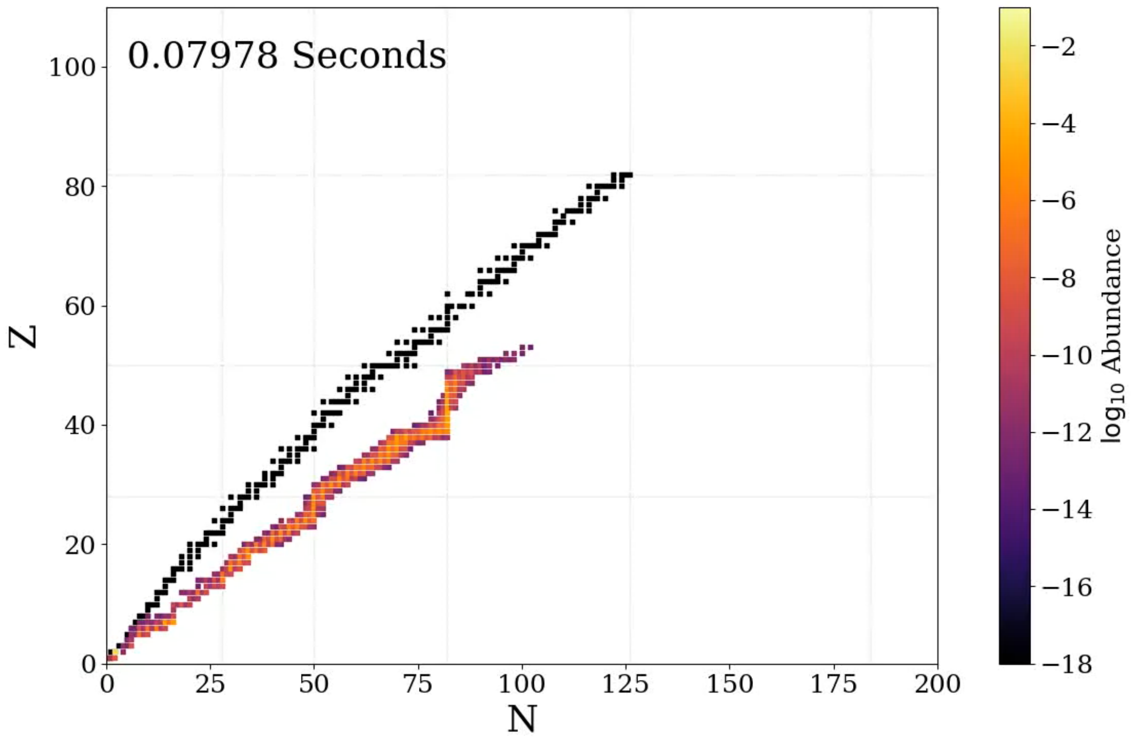
- We have exciting new possibilities for detecting r-process elements,
  e.g. gamma rays

Back up slides

What can be learned from mass measurements at the N=126 shell?

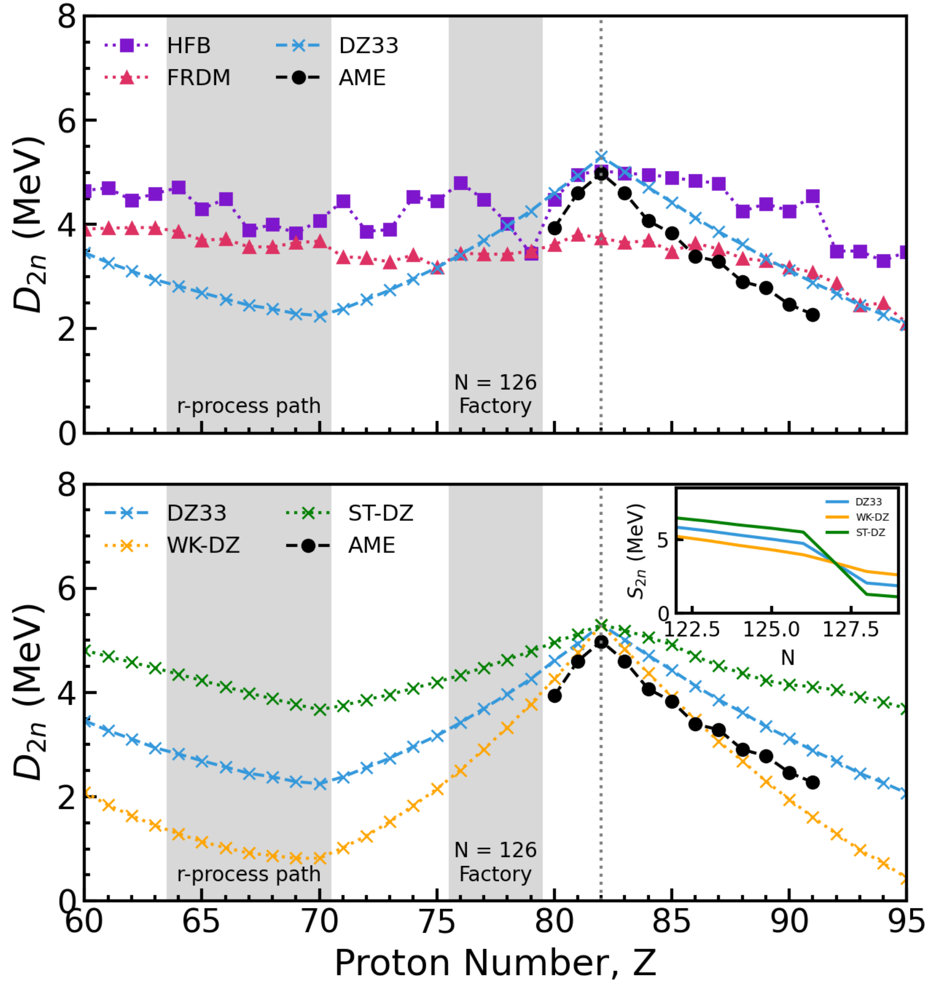
The 126 mass shell





“The two-neutron shell gap” for N=126

$$D_{2n}(Z, N) = S_{2n}(Z, N) - S_{2n}(Z, N + 2)$$



A few commonly used mass models

Black dots show the AME

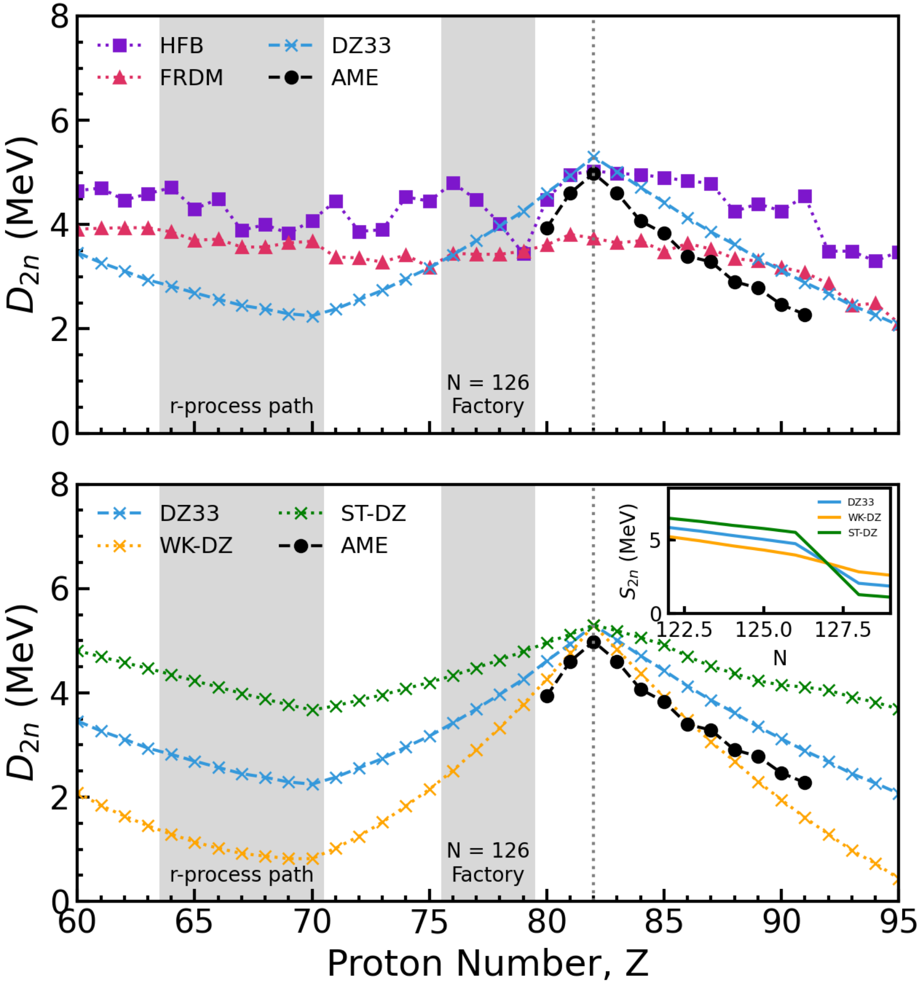
Green and yellow curves are modifications to DZ33 which change the slope

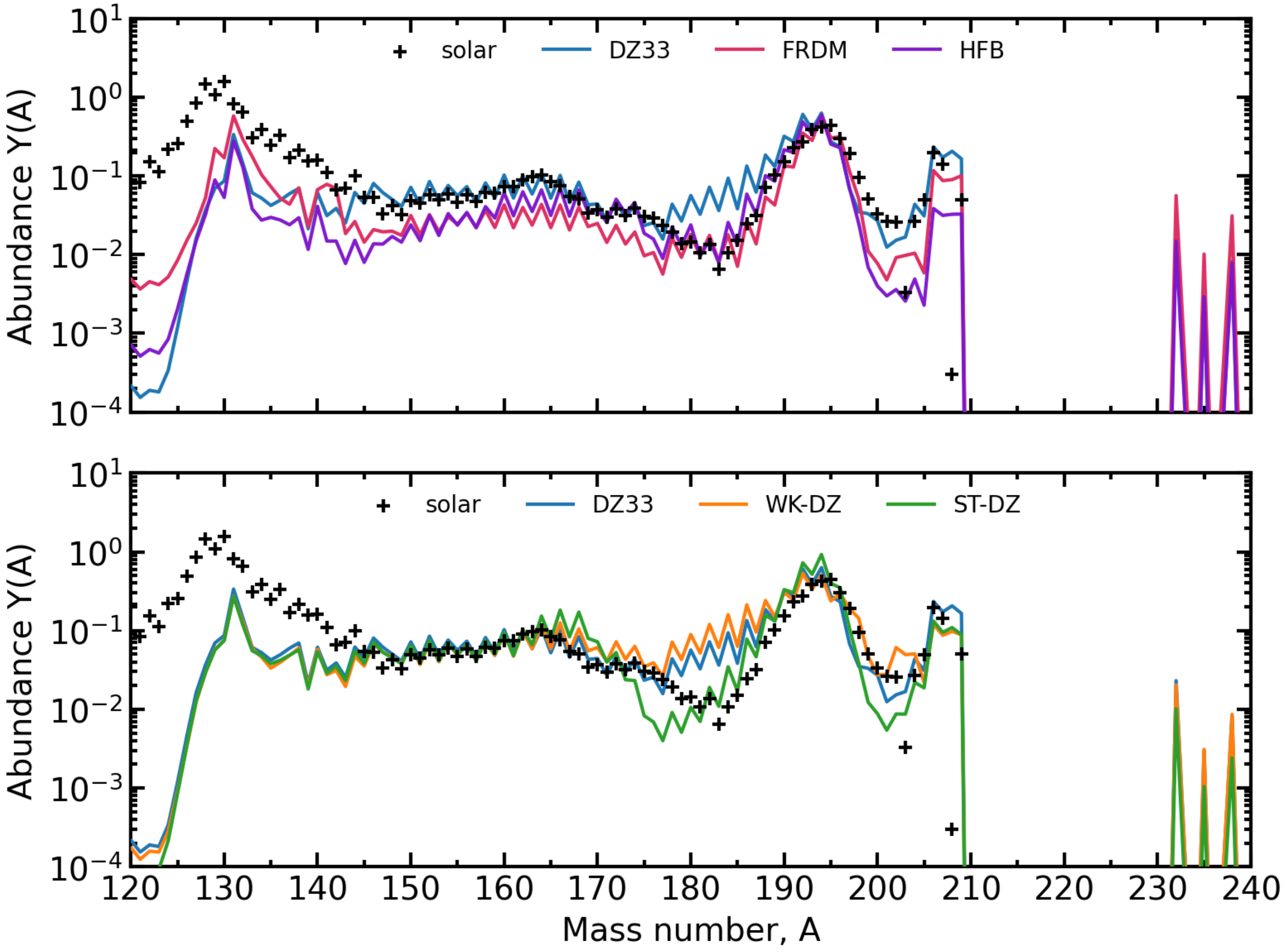
Li et al 2026

Effect of the two-neutron shell gap on the abundance pattern

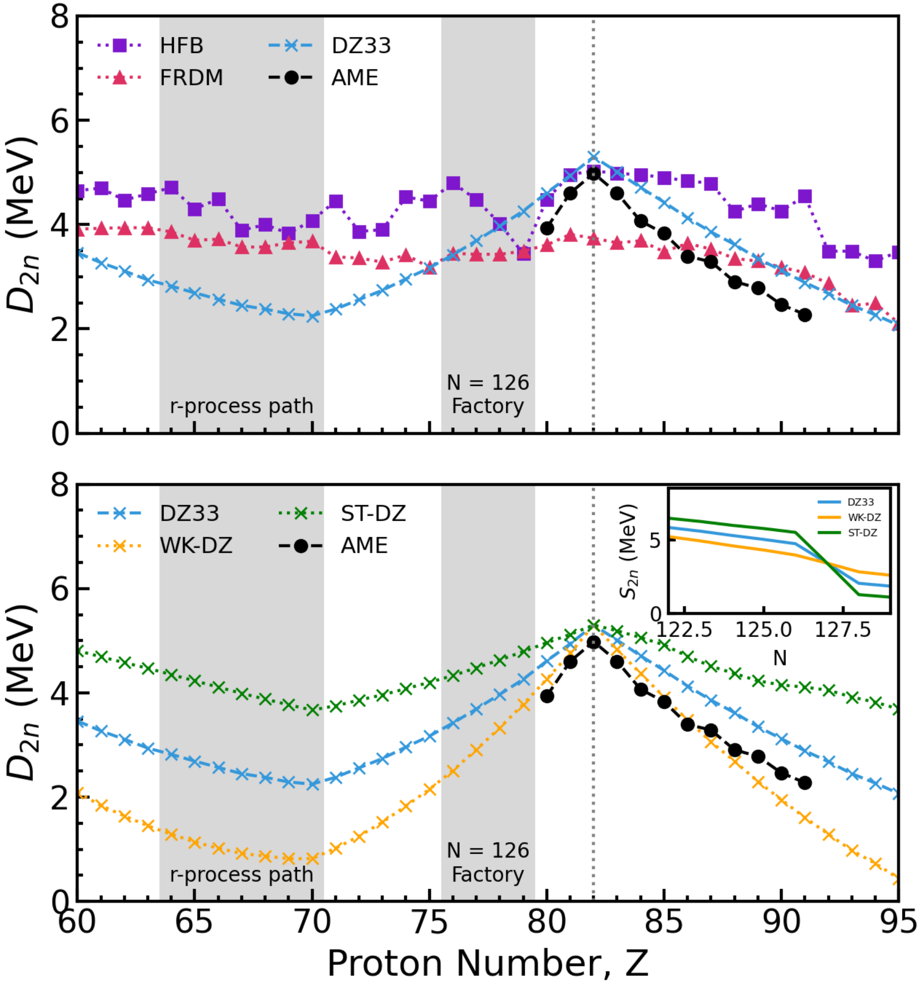
Mengke Li, N3AS fellow

Li et al 2026





A strong closure works great, a weak closure is constraining



- Strong closure - robust 126 peak
- Weak closure - requires very neutron rich astrophysical conditions