A few topics in neutrinos and nucleosynthesis in neutron star mergers

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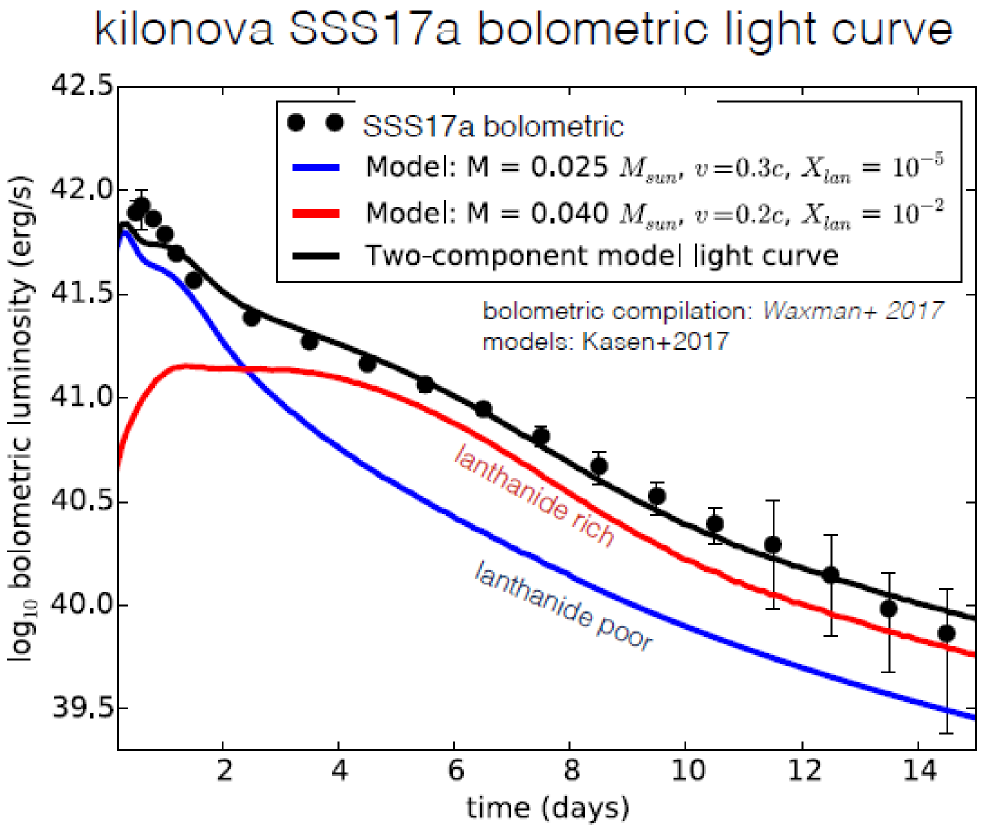
Specific examples of questions where neutrino physics is needed

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

Which r-process elements do neutron star mergers make?

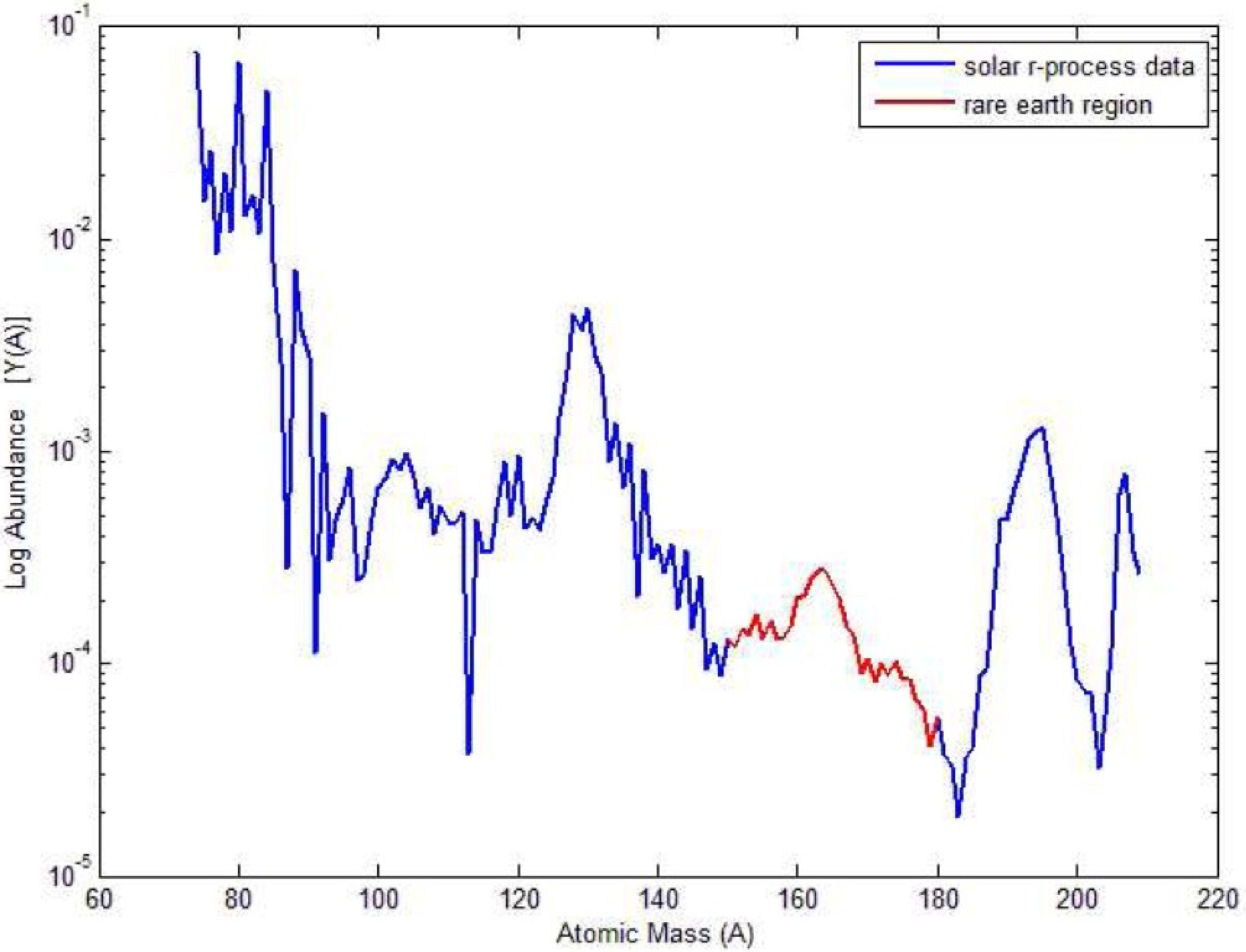
Alternate astrophysical sites: talks by Siegel on Thursday, Kajino and Anand on Friday

Electromagnetic counterpart to the neutron star merger GW signal



Material with significant opacity is the best fit to the data Slide credit: Dan Kasan Suggests lanthanides were made in the merger.

Where are the lanthanides?



Metal poor stars

Rare earths and third peak often seen together

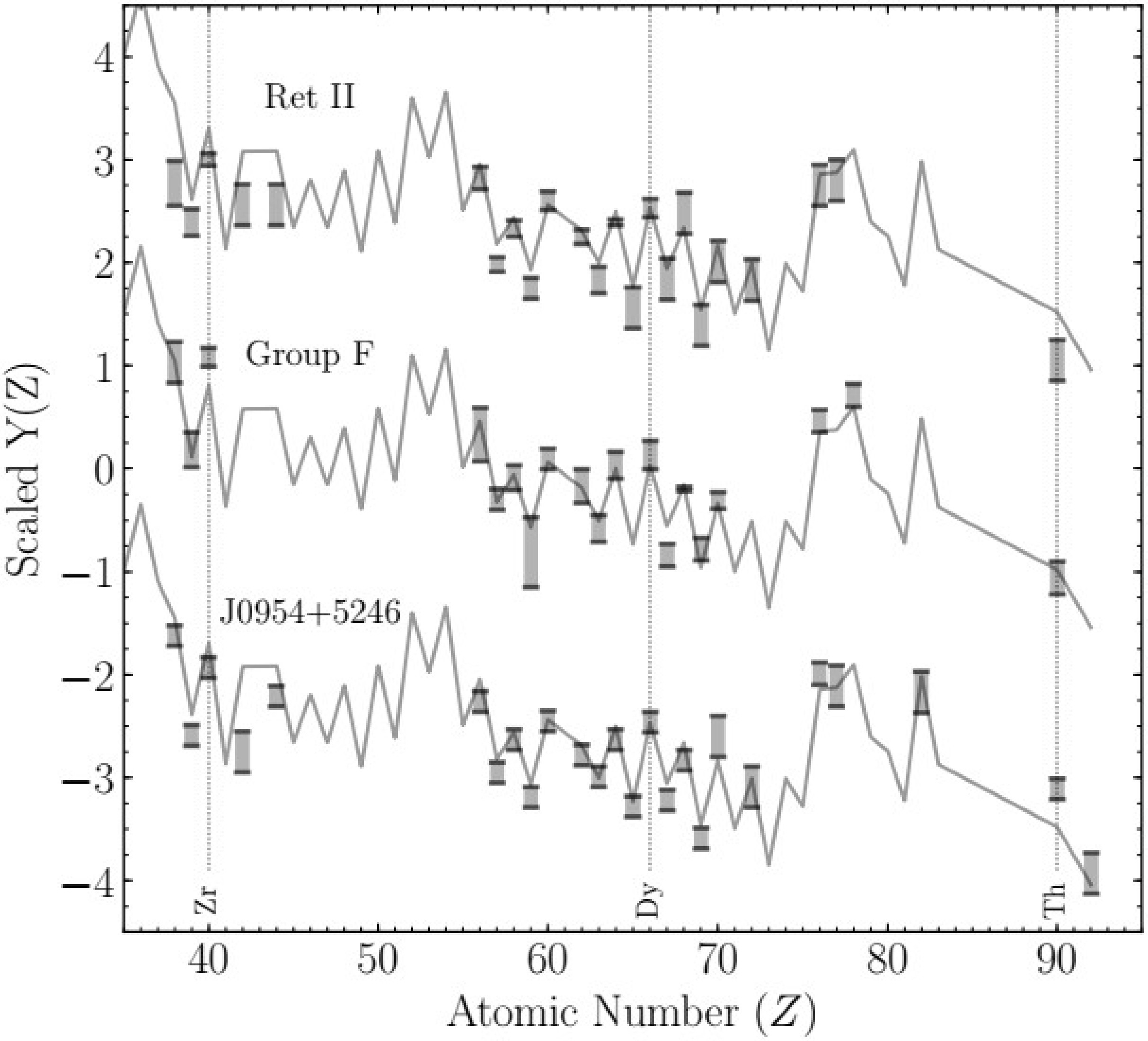


Fig from Holmbeck et al 2019

Some roles that microphysics plays

nuclear structure/reactions and the EM counterpart

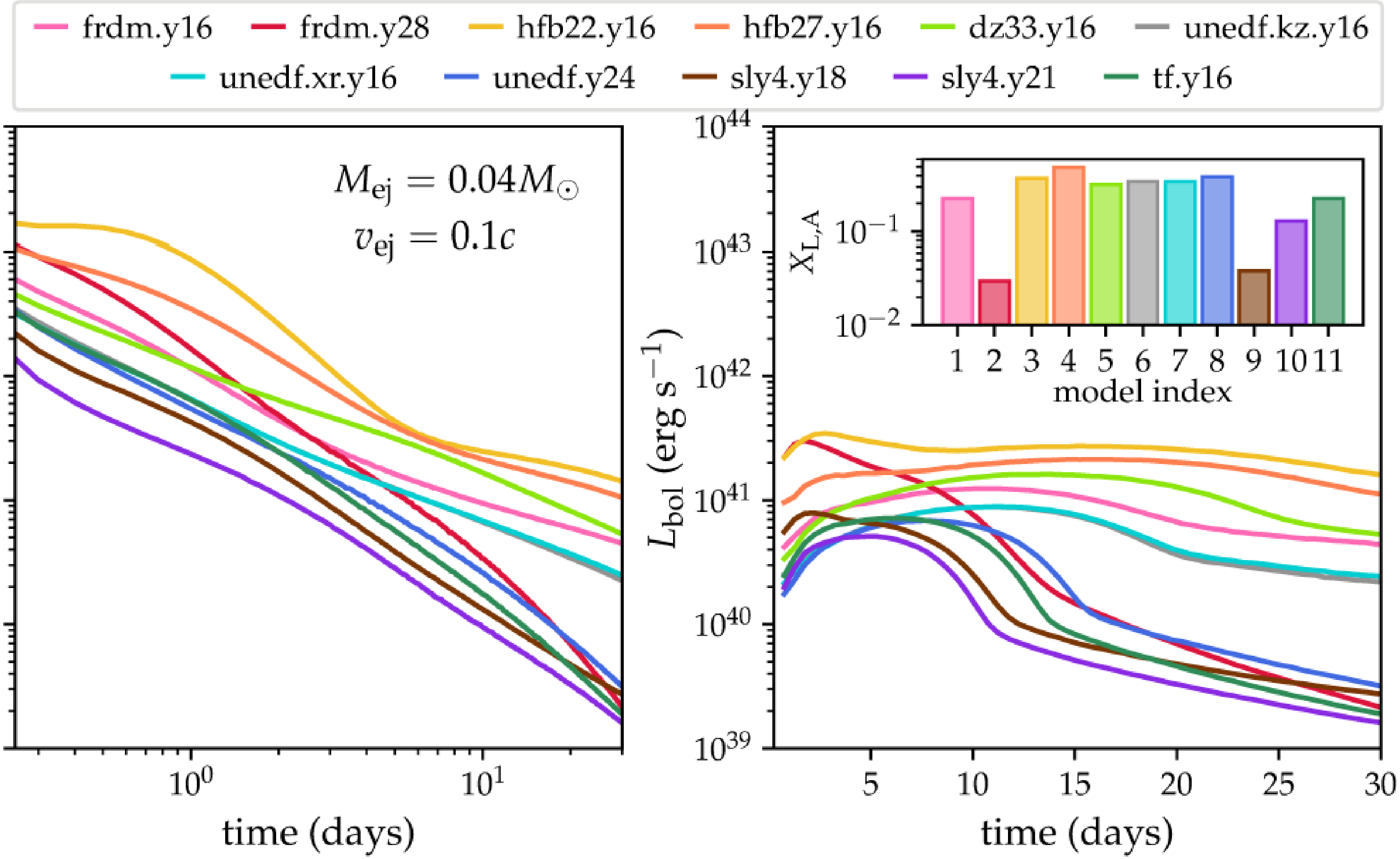
- freshly synthesized nuclei decay and release energy
- some fraction of this energy thermalizes in the ejecta
- thermalized energy diffuses out at a rate determined by the opacity

two primary ways the new elements are important

- they determine the nuclear heating
- they create the opacity : more lanthanides → higher opacity

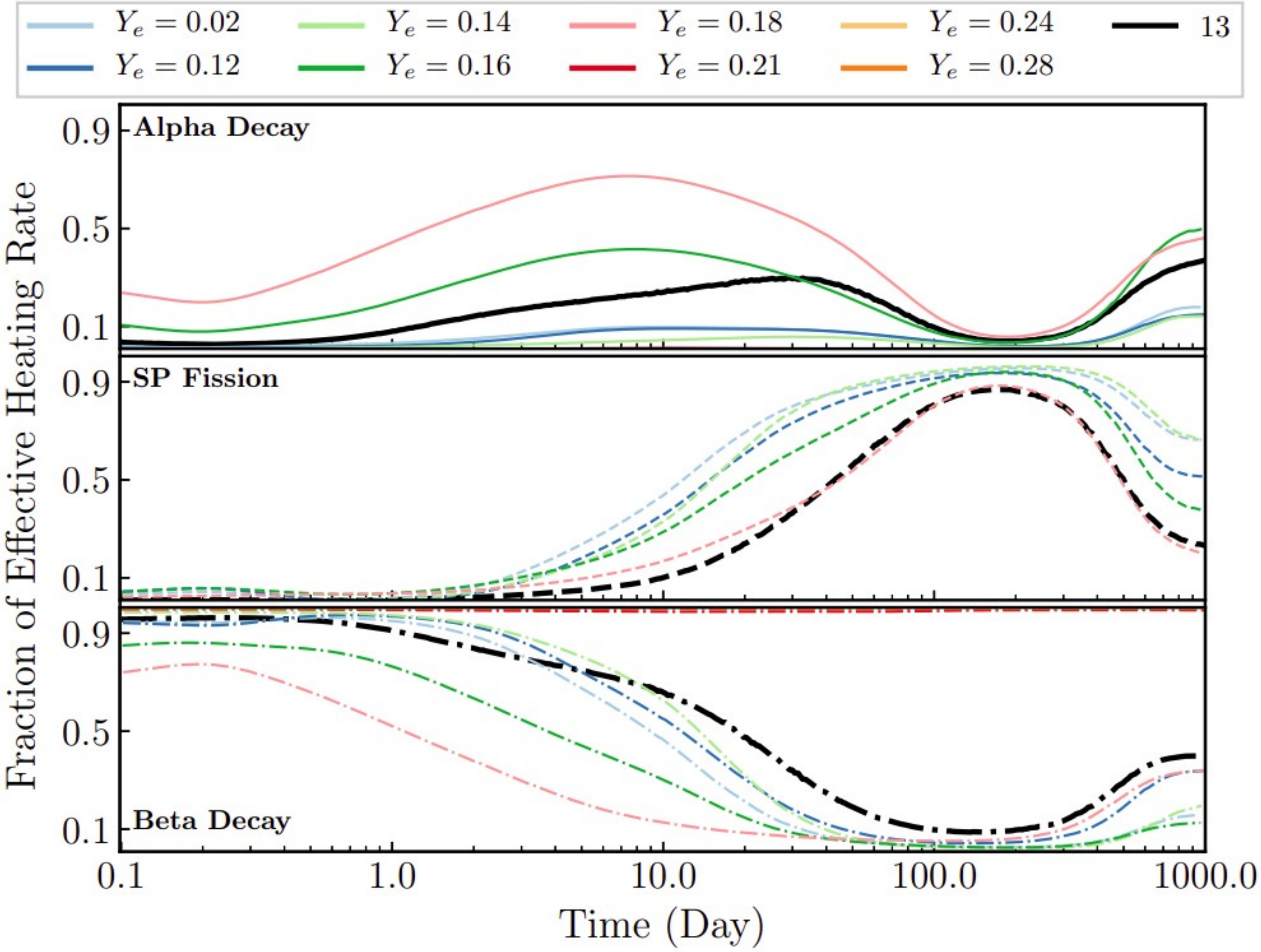
See Gabriel Martinez-Pinedo’s talk on Friday morning!

The nuclei which decay leave an imprint on the light curve



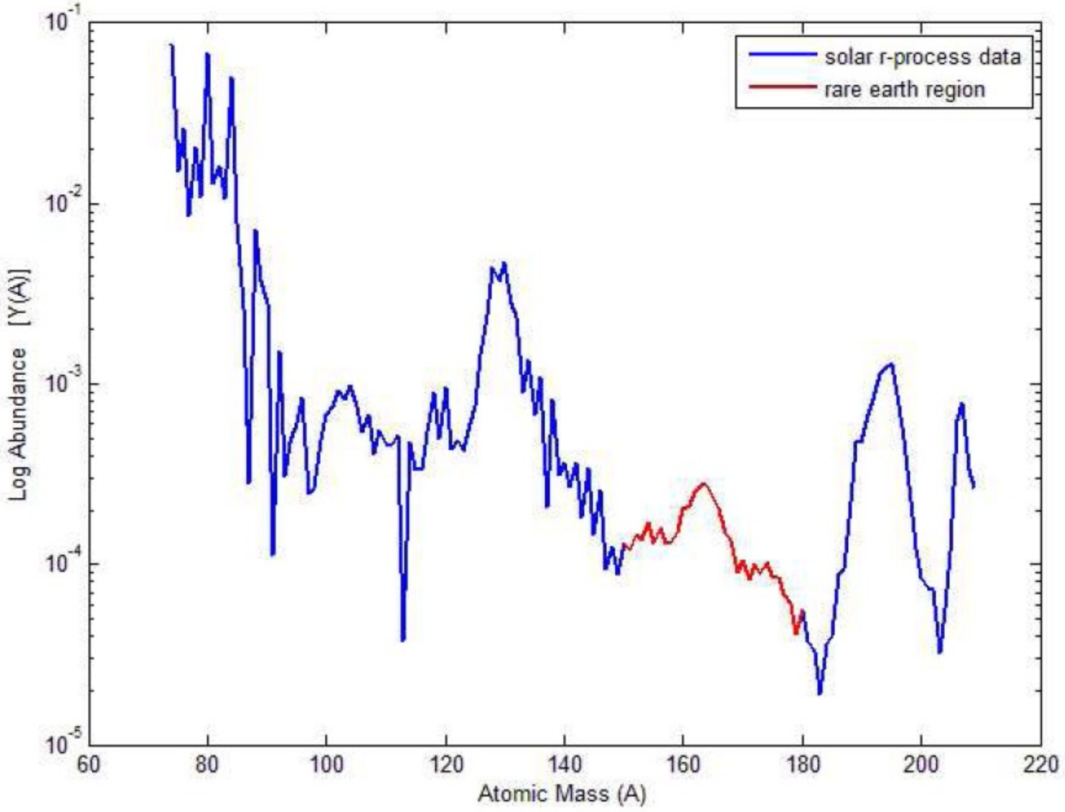
Barnes, Zhu, Lund et al

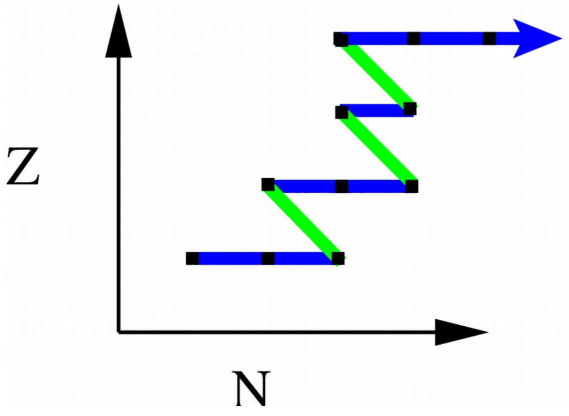
Beta decay, alpha decay and fission contribute to the heating



Using UNEDF, Fig from Zhu et al 2021

Whether you can get to fissioning nuclei or not depends on the electron fraction





Fissions and alpha decays

Fission of 254Cf changes the heating curve

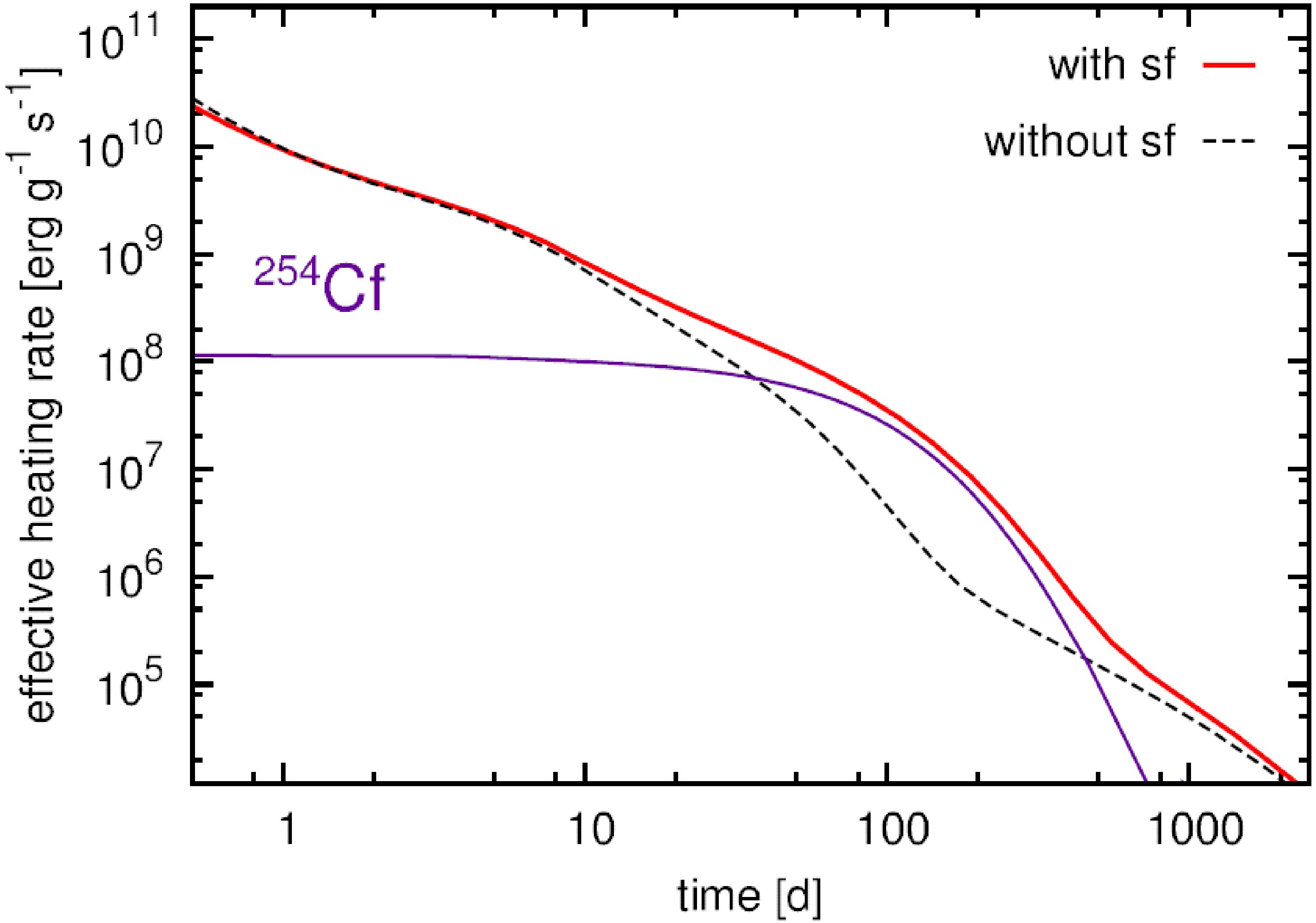


fig. from Zhu et al 2018. The FIRE collaboration isolated the extra heating to come largely from a single nucleus.

Observable consequence

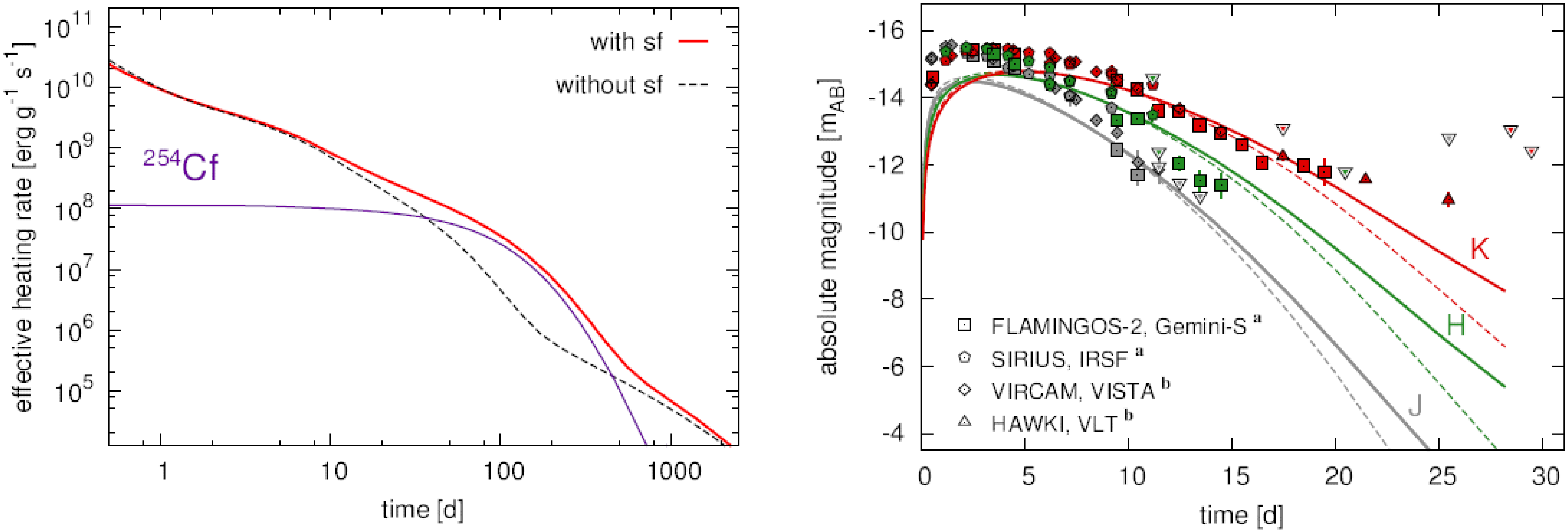


fig. from Zhu et al 2018.

How many neutrons were captured?

Effects *both* light curve and abundance pattern

Neutrino physics changes the outcome of element synthesis

- tidal ejecta
- collisional ejecta

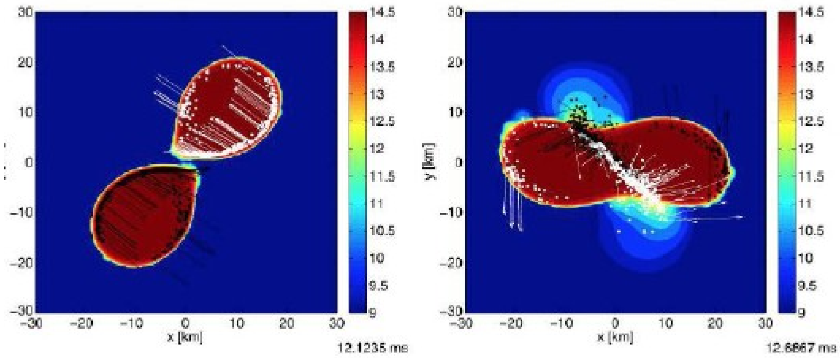


fig. from Bauswein et al 2013

- disk/hypermassive NS outflow
- outflow from viscous heating

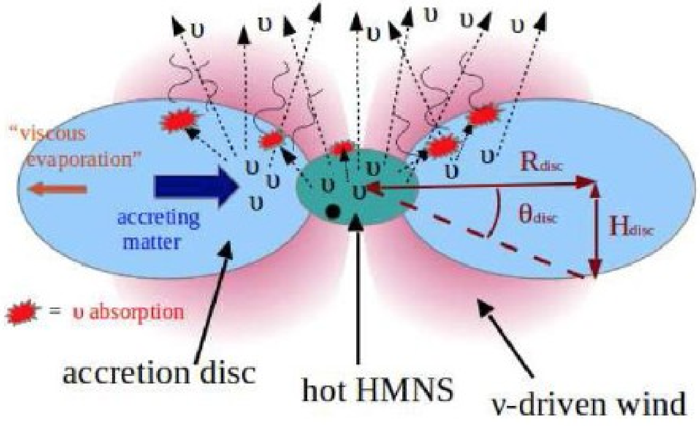
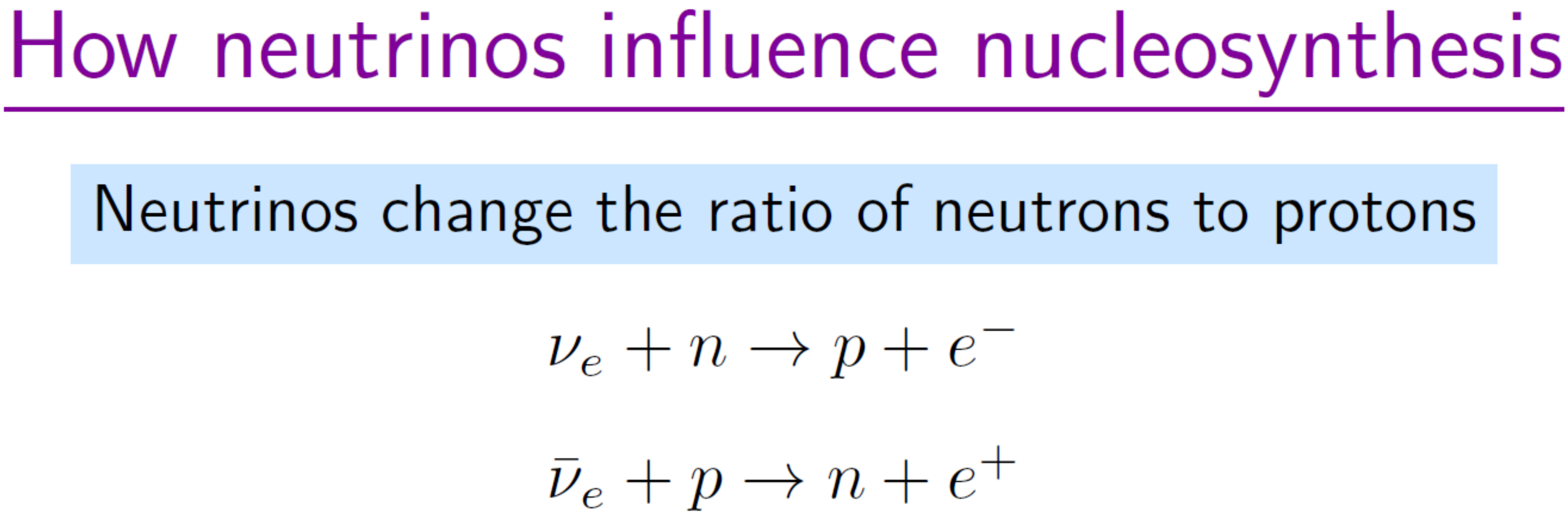


fig. from Perego et al 2014

The weak interaction matters



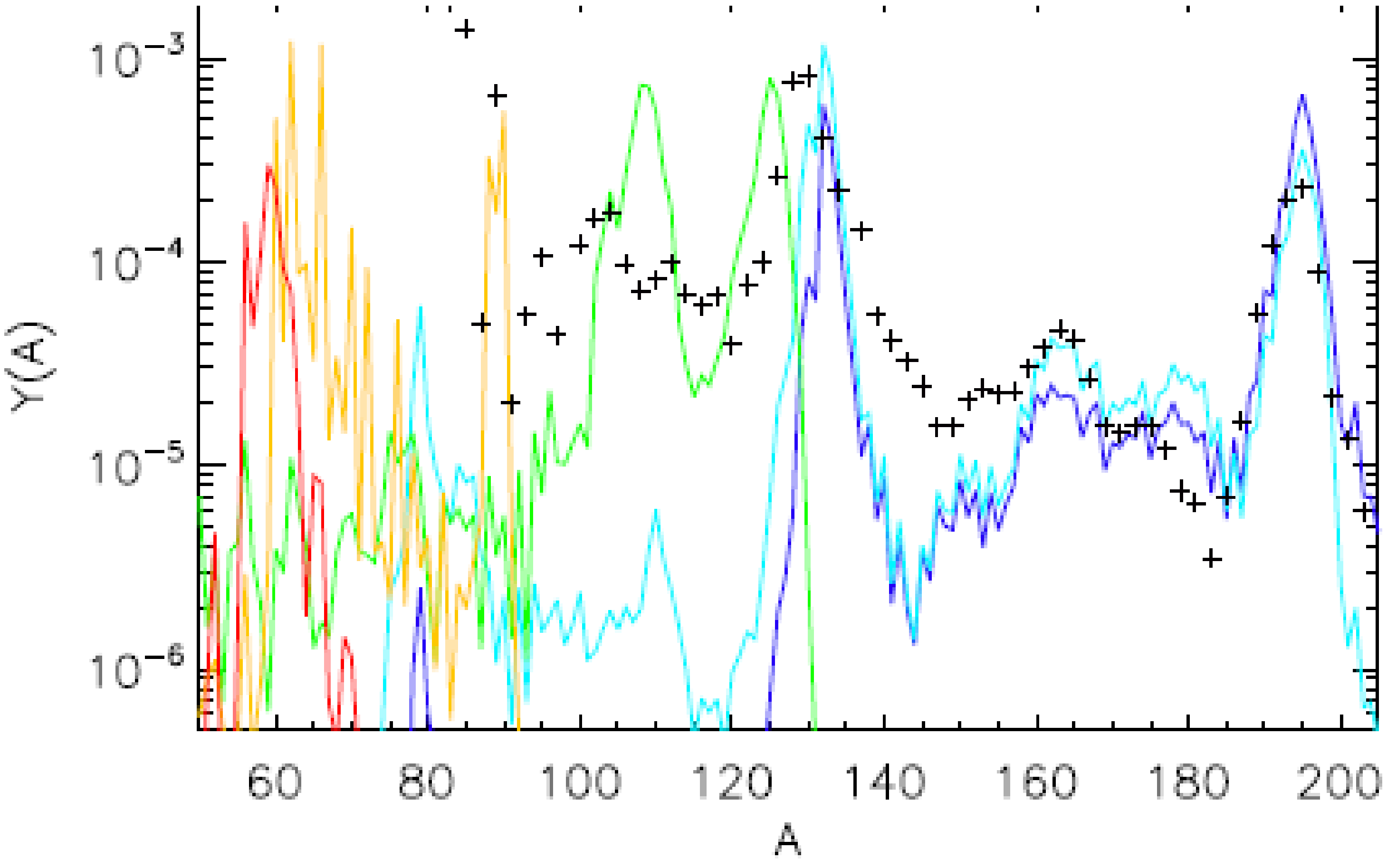
How neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

How much does it matter?



Malkus '16

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

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

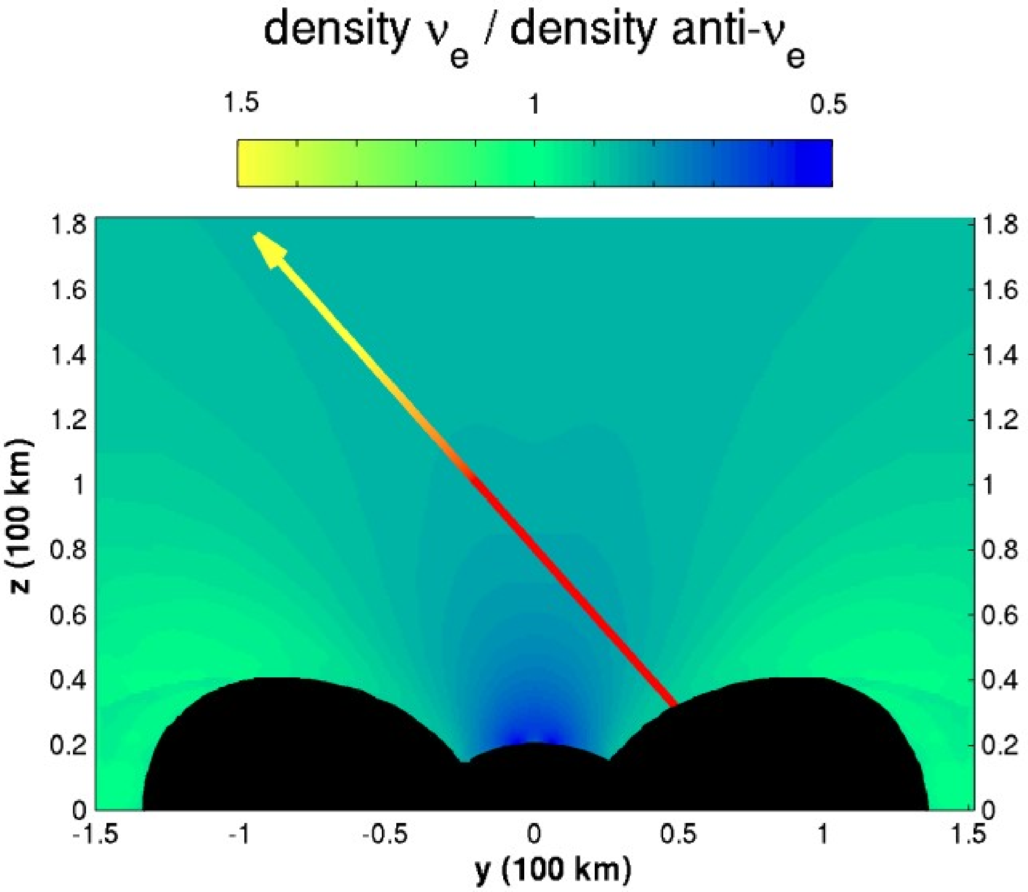
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

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 mergers?

Answer, almost certainly, is yes



Zhu et al

Neutrinos can be described by a density matrix

Additional informatio
about the phase

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{ex}^{*} & \rho_{xx} \end{pmatrix}$$

Tells you how likely you are to
measure the neutrino as electron type

Tells you how likely you
are to measure the neutrino
In an x (mu or tau) state

Neutrinos can oscillate (flavor transform)

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

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

Collision term

Convective derivative

Hamiltonian

Hamiltonian creates non-linearity

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

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

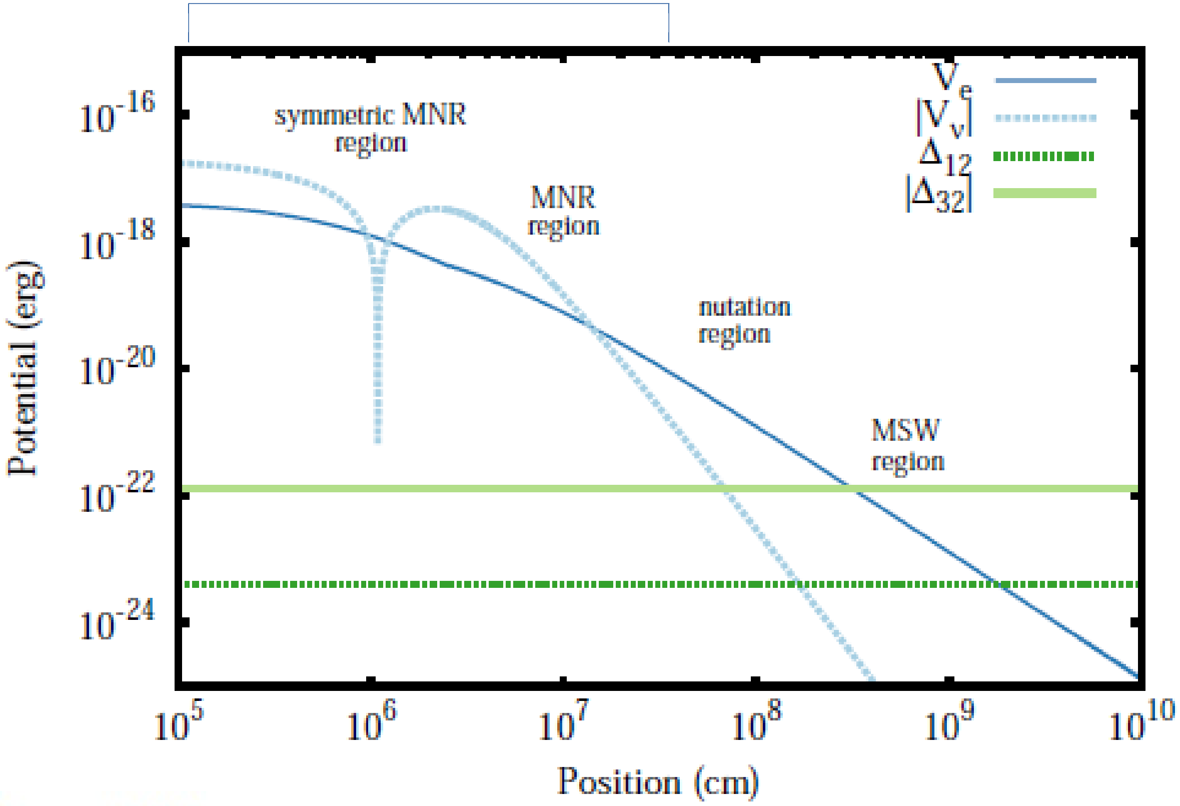
Neutrinos see a potential due to other neutrinos

Neutrinos see a potential due to the matter

Flavor and mass are not the same

Where and how these transformations might occur

fast flavor region

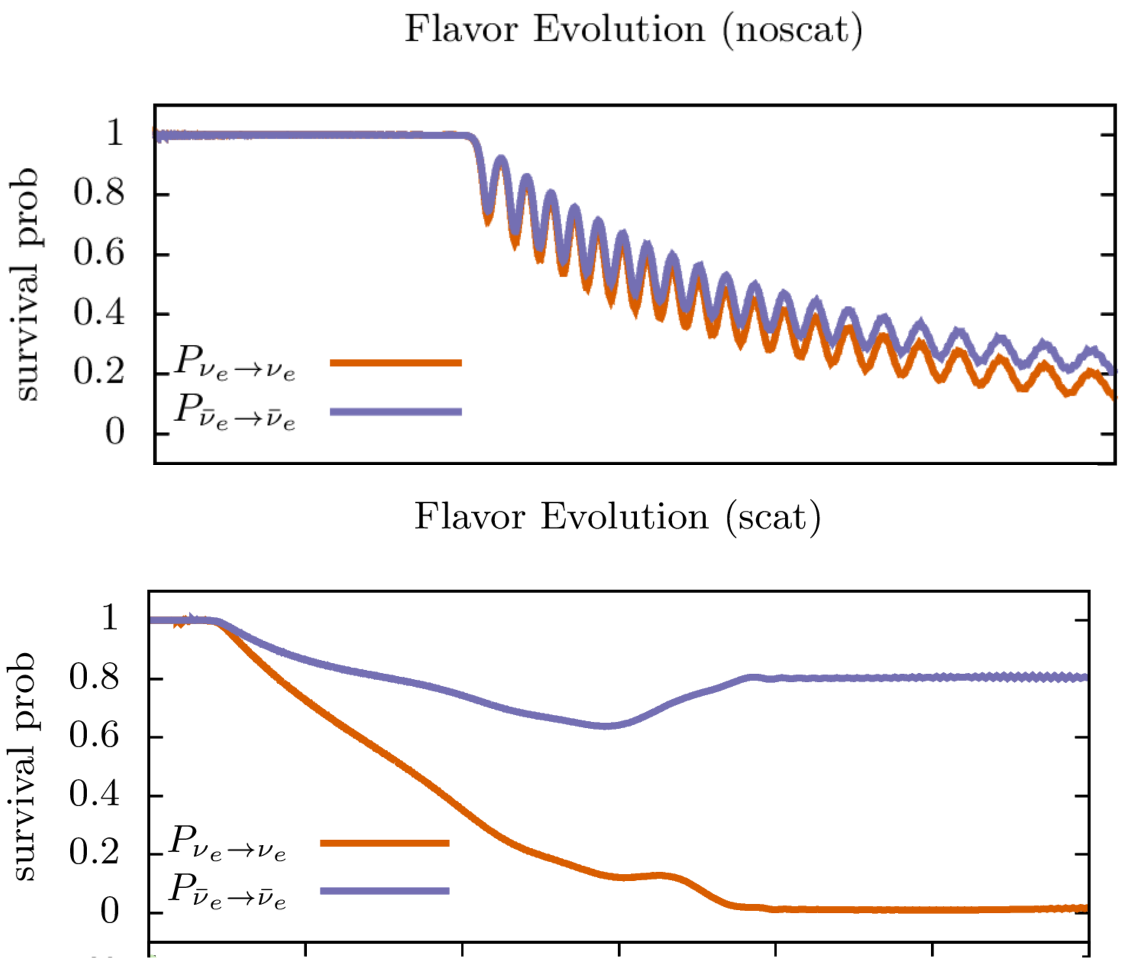


$$\mathbf{H} = \mathbf{H}_{\mathrm{vac}} + \mathbf{H}_{\mathrm{M}} + \mathbf{H}_{\mathrm{SI}}$$

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

fig. from Malkus et al 2016

Transformation is sensitive to conditions, approximations



Collective

Matter-neutrino Resonance

300 km

1500 km

Fig from Deaton et al

Transformation closest to the emission: “fast flavor”

Fast flavor:

fastest transitions when inverse fluctuation wavelength (k) is similar to the difference in number density between neutrinos and antineutrinos

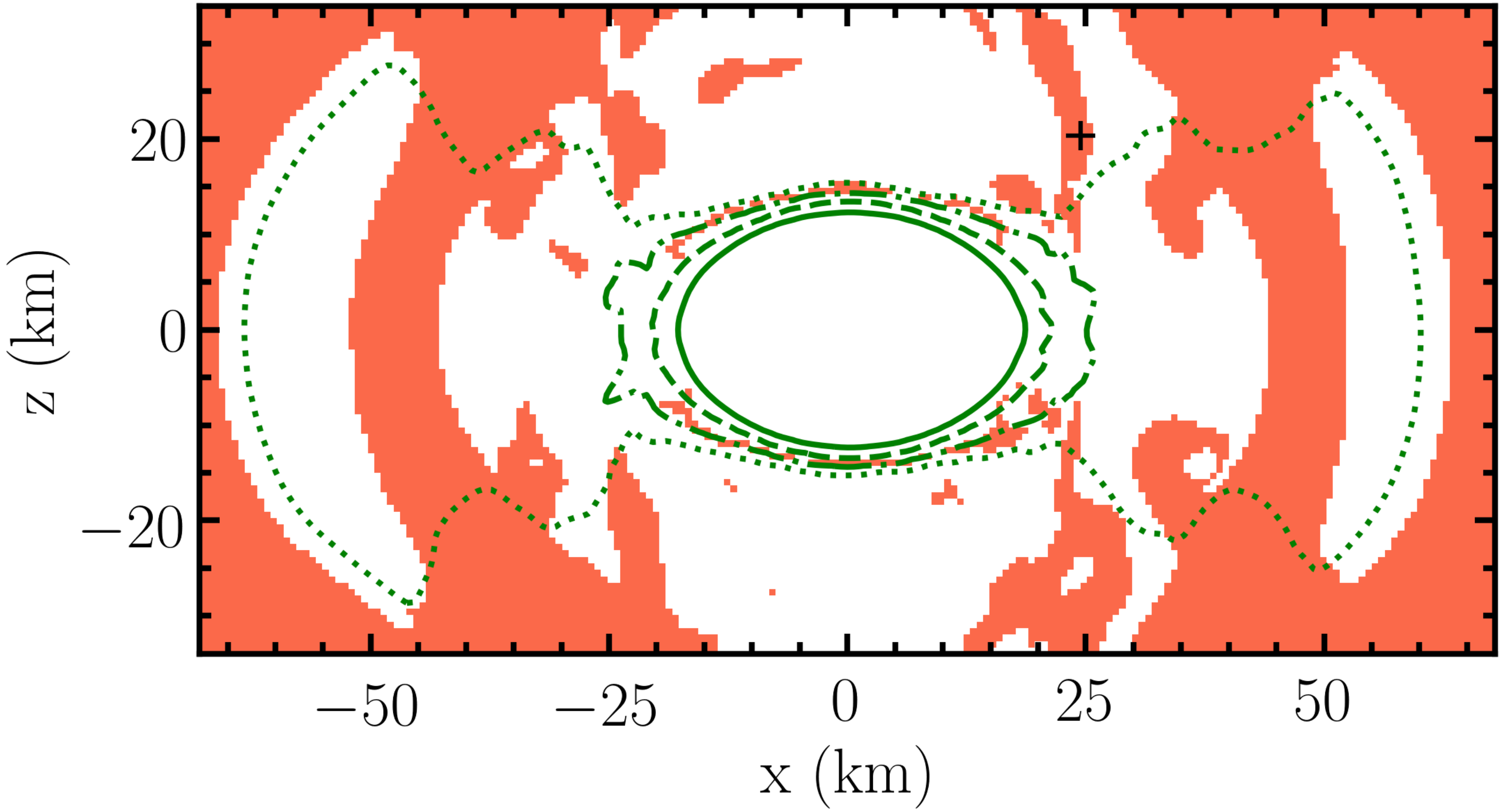
and

there is a “crossing”

(Sawyer, Friedland, Johns, Fuller, Balantekin, Patwardhan, Suliga and many more)

See Meng-Ru Wu’s talk tomorrow!

Crossings in BNS remnant



Grohs, Richers et al in prep, original (classical)
simulation from Francois Foucart

Ways to analyze flavor transformation

- Stability analysis → Find a growth rate
- (Toy Models)
- Particle in cell methods → track everything about every neutrino

- More approximate methods → moments

Toward inclusion in simulation: less exact methods: e.g. moments

What? Represent all the neutrinos at each point in space as four quantities (e.g. energy density and flux) and evolve these

Why? Possible way to eventually integrate into neutron star merger, supernova simulations

Numerical risk: Truncating an infinite tower of moments
(Fuller, Johns, Burrows, Duan ...)

Use two moments

$$E(t,\vec{r},q) = \frac{1}{4\pi}\left(\frac{q}{2\pi\hbar c}\right)^3 \int d\Omega_p\, f(t,\vec{r},\vec{p})$$

$$\vec{F}(t,\vec{r},q) = \frac{1}{4\pi}\left(\frac{q}{2\pi\hbar c}\right)^3 \int d\Omega_p\, \hat{p}\, f(t,\vec{r},\vec{p})$$

$$P(t,\vec{r},q) = \frac{1}{4\pi}\left(\frac{q}{2\pi\hbar c}\right)^3 \int d\Omega_p\, \hat{p}\otimes\hat{p}\, f(t,\vec{r},\vec{p})$$

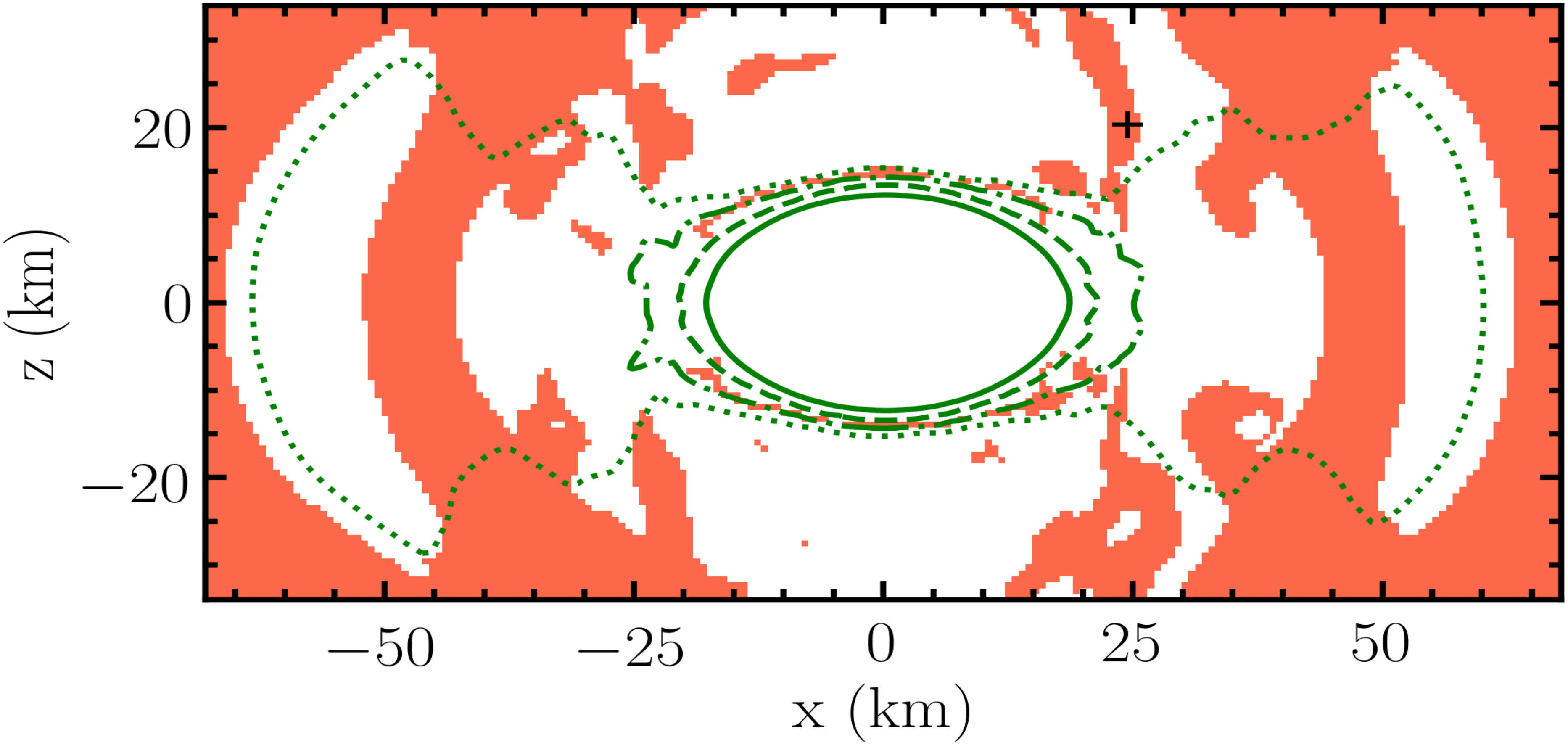
Energy and flux moments

Closure

$$P = F_{\text{closure}}(\text{energy, flux})$$

Choose the max entropy closure, consistent with the original classical simulation

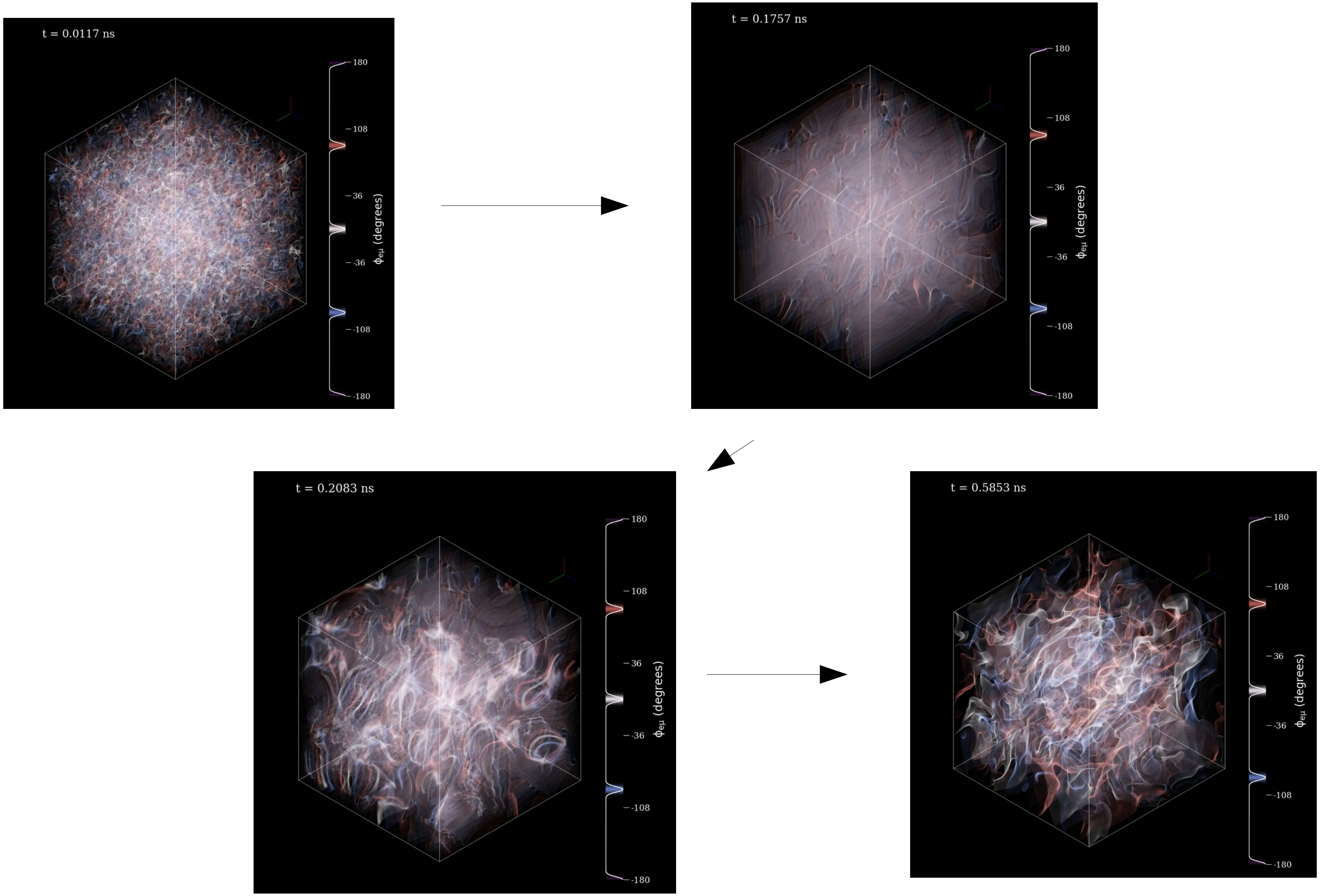
Crossings in BNS remnant



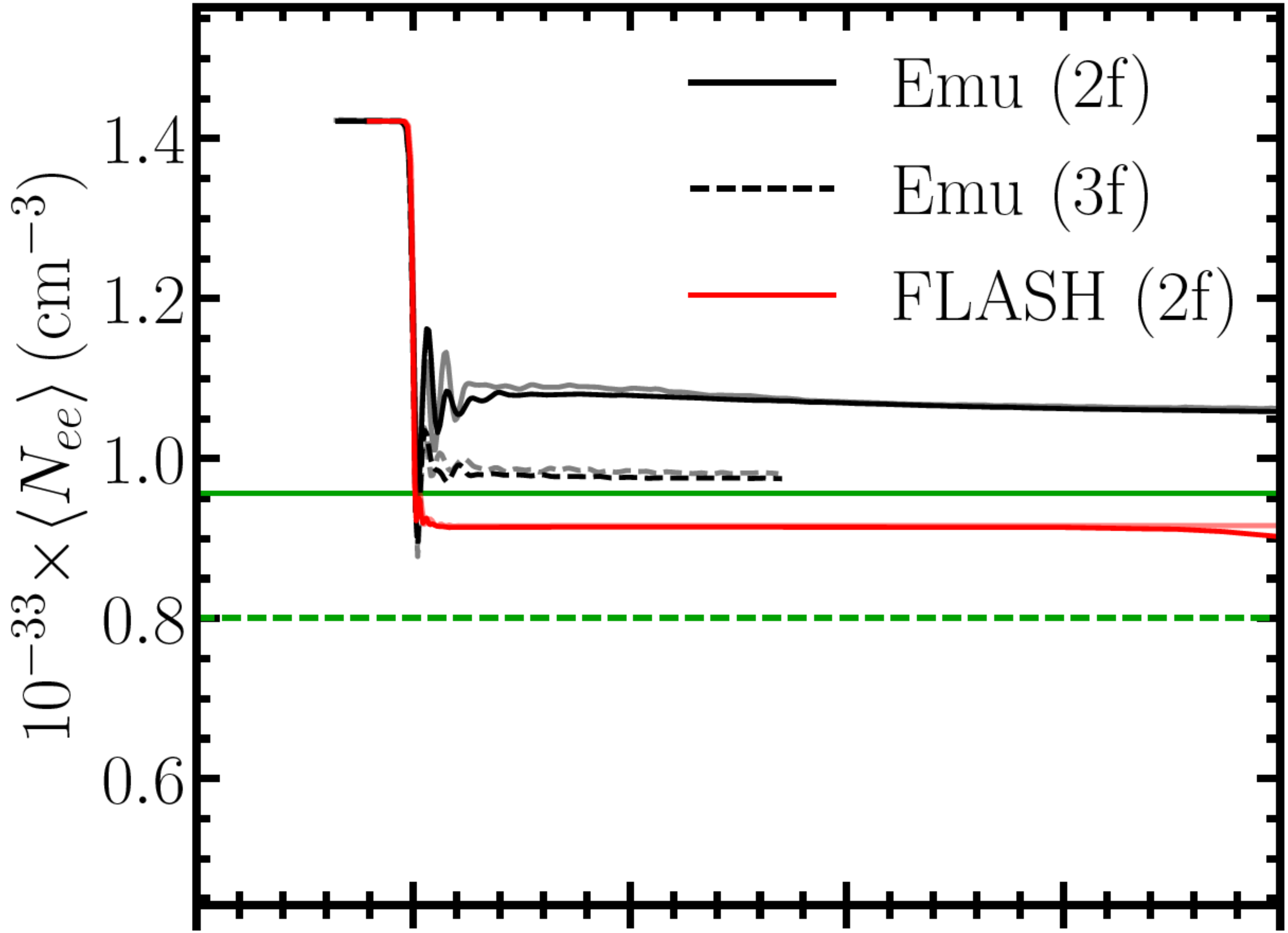
Grohs et al in prep

Fast flavor oscillations above a BNS merger with moments using FLASH

(Grohs et al in prep.)



Growth and saturation, BNS, moments vs PIC



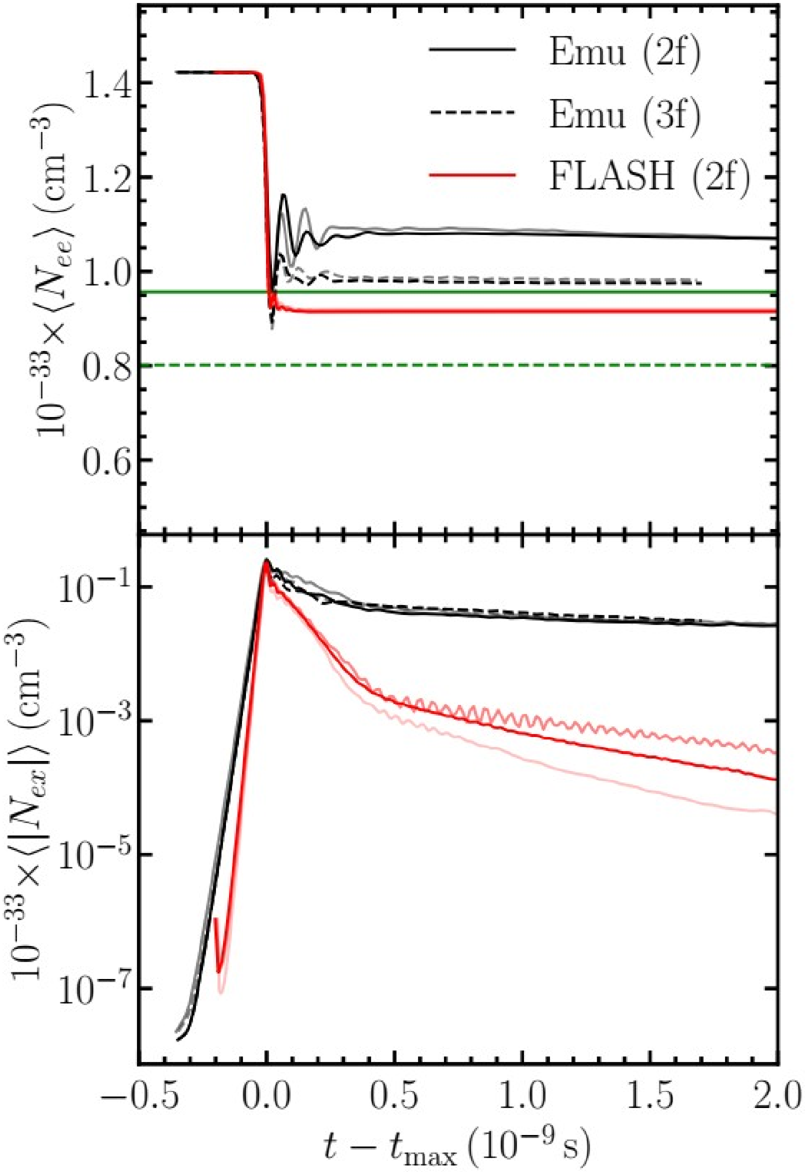
1500 neutrinos per cell

Flavor equilibration

2 moments per cell

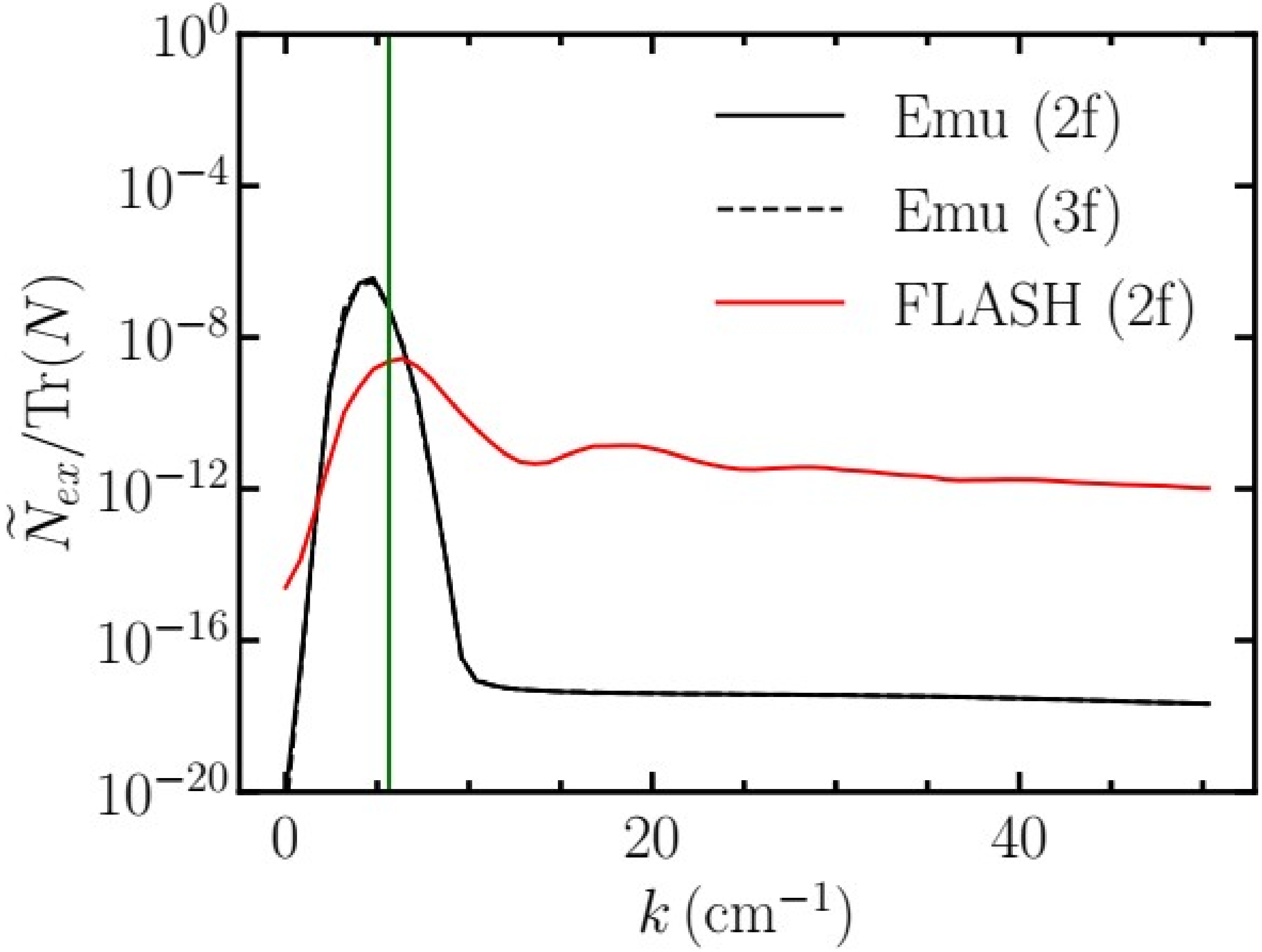
Grohs et al in prep

Growth and saturation, BNS, moments vs PIC



Grohs et al in prep

Fourier transform
BNS, moments vs PIC



Conclusions

We need to understand neutrinos in astrophysical systems to accurately predict observables including r-process

Involves solving the quantum kinetic equations in astrophysical environments

Starting to make progress on this using moment based methods

To keep mind: Astrophysical objects will make better laboratories for neutrino physics if we make progress on understanding systems with large numbers of neutrinos