Neutrinos and element synthesis from neutron star mergers

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(For supernova see Tony Mezzacappa's talk on Tuesday)

Neutrino physics changes the outcome of element synthesis

- tidal ejecta
- collisional ejecta

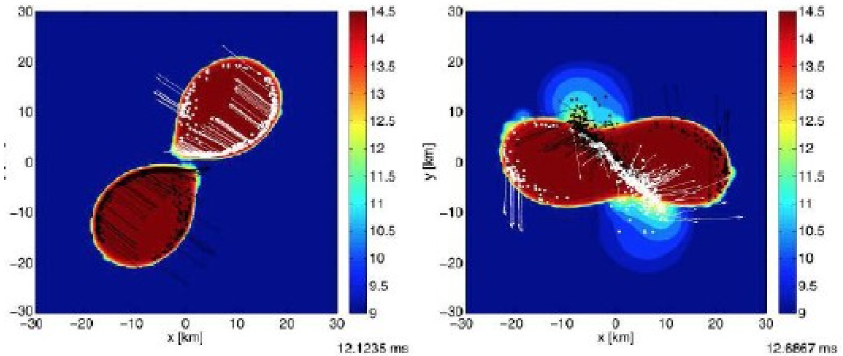


fig. from Bauswein et al 2013

- disk/hypermassive NS outflow
- outflow from viscous heating

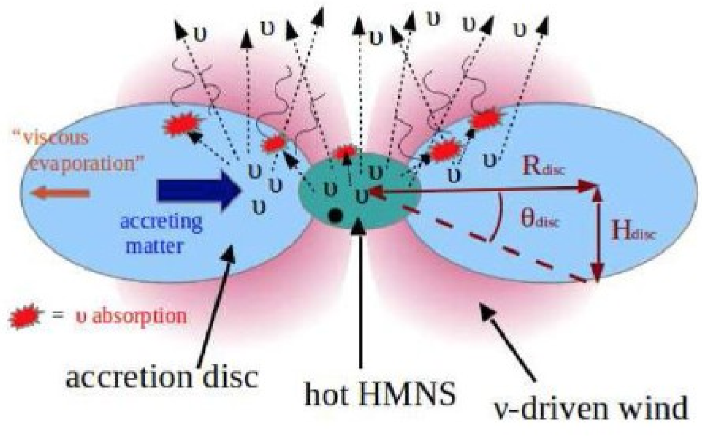


fig. from Perego et al 2014

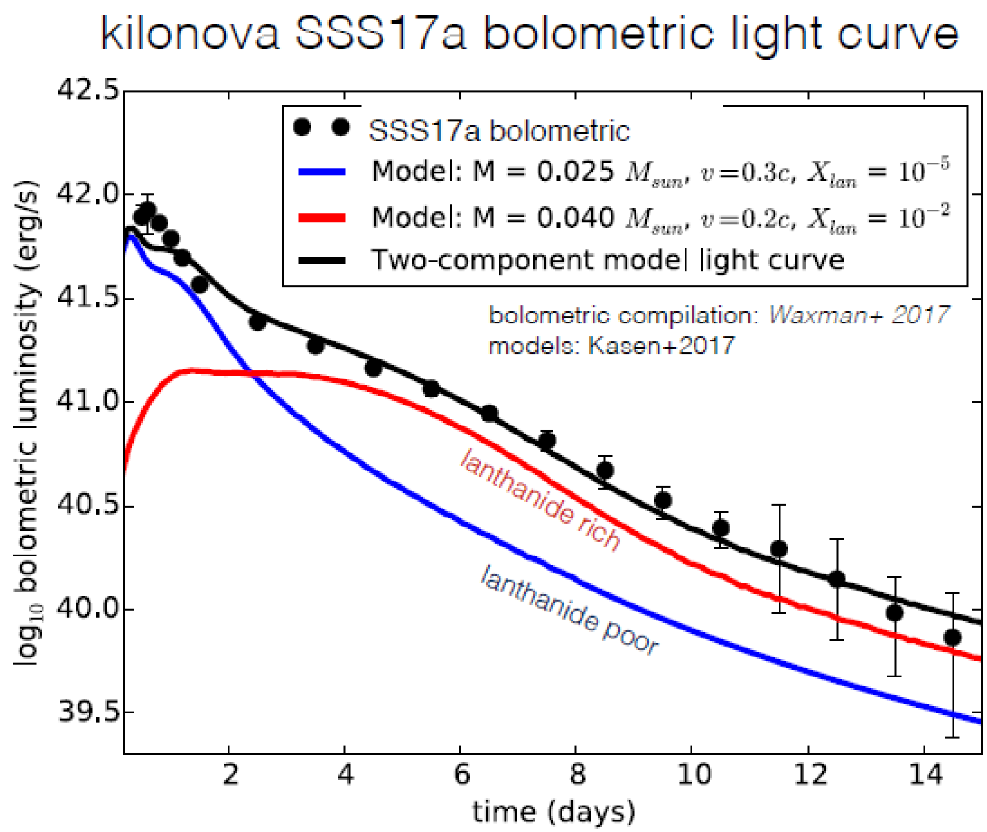
Neutrino physics matters for the outcome of element synthesis

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

Which r-process elements do neutron star mergers make?

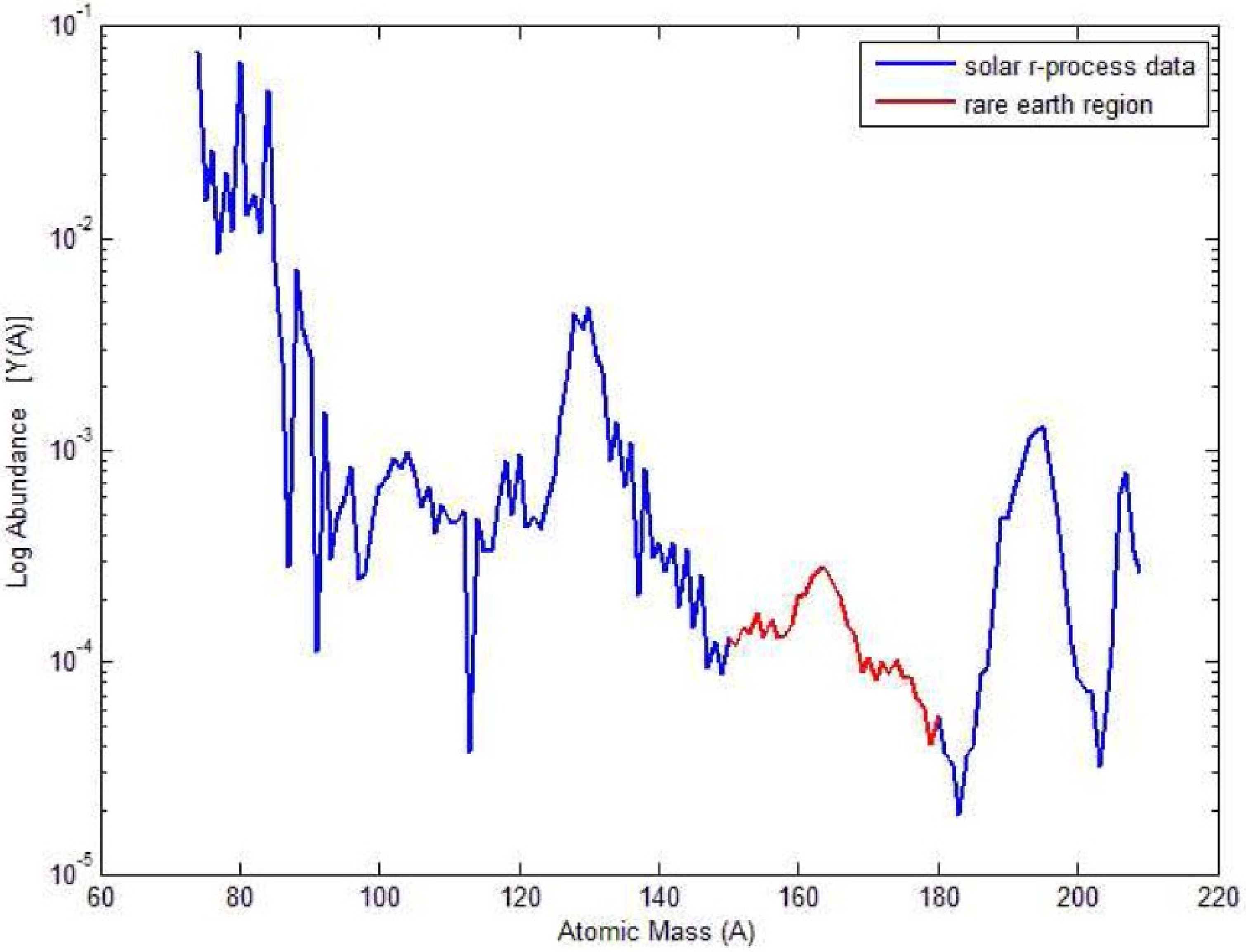
r-process: rapid neutron capture process of element synthesis.

Electromagnetic counterpart to the neutron star merger GW signal

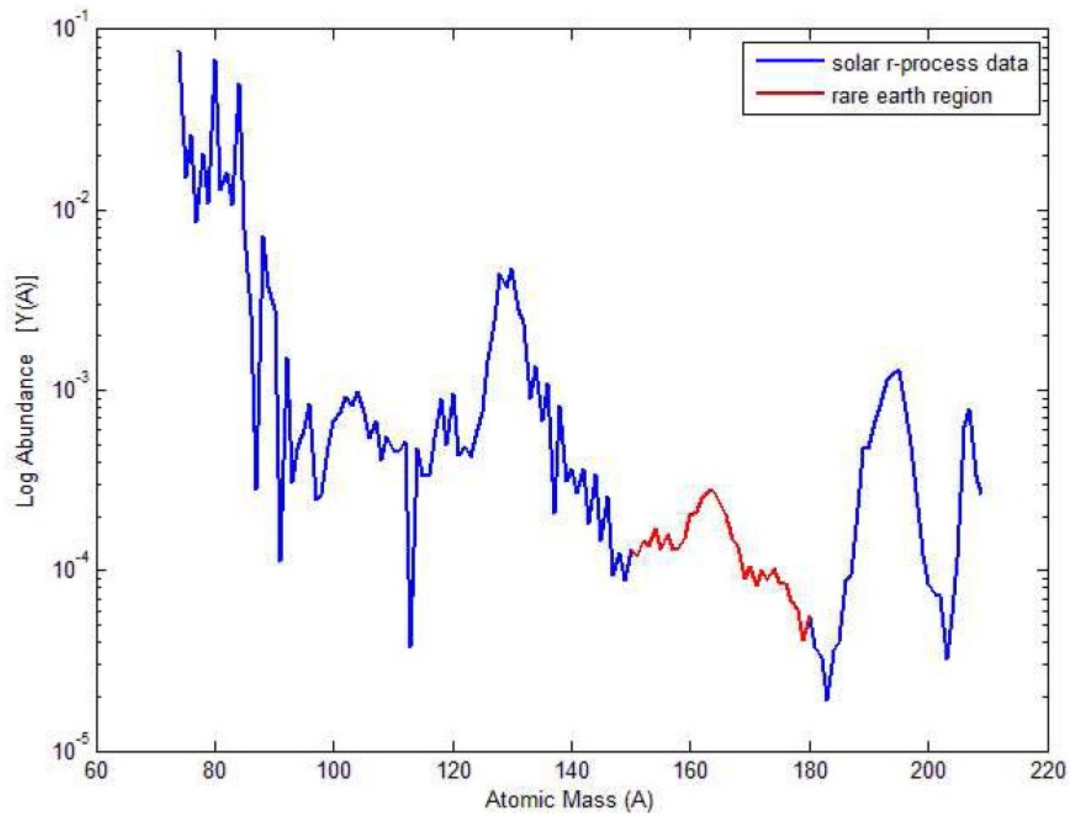


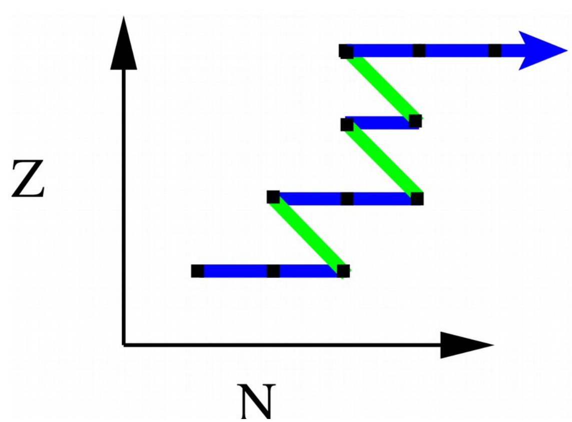
Material with significant opacity is the best fit to the data Slide credit: Dan Kasan Suggests lanthanides were made in the merger.

Where are the lanthanides?



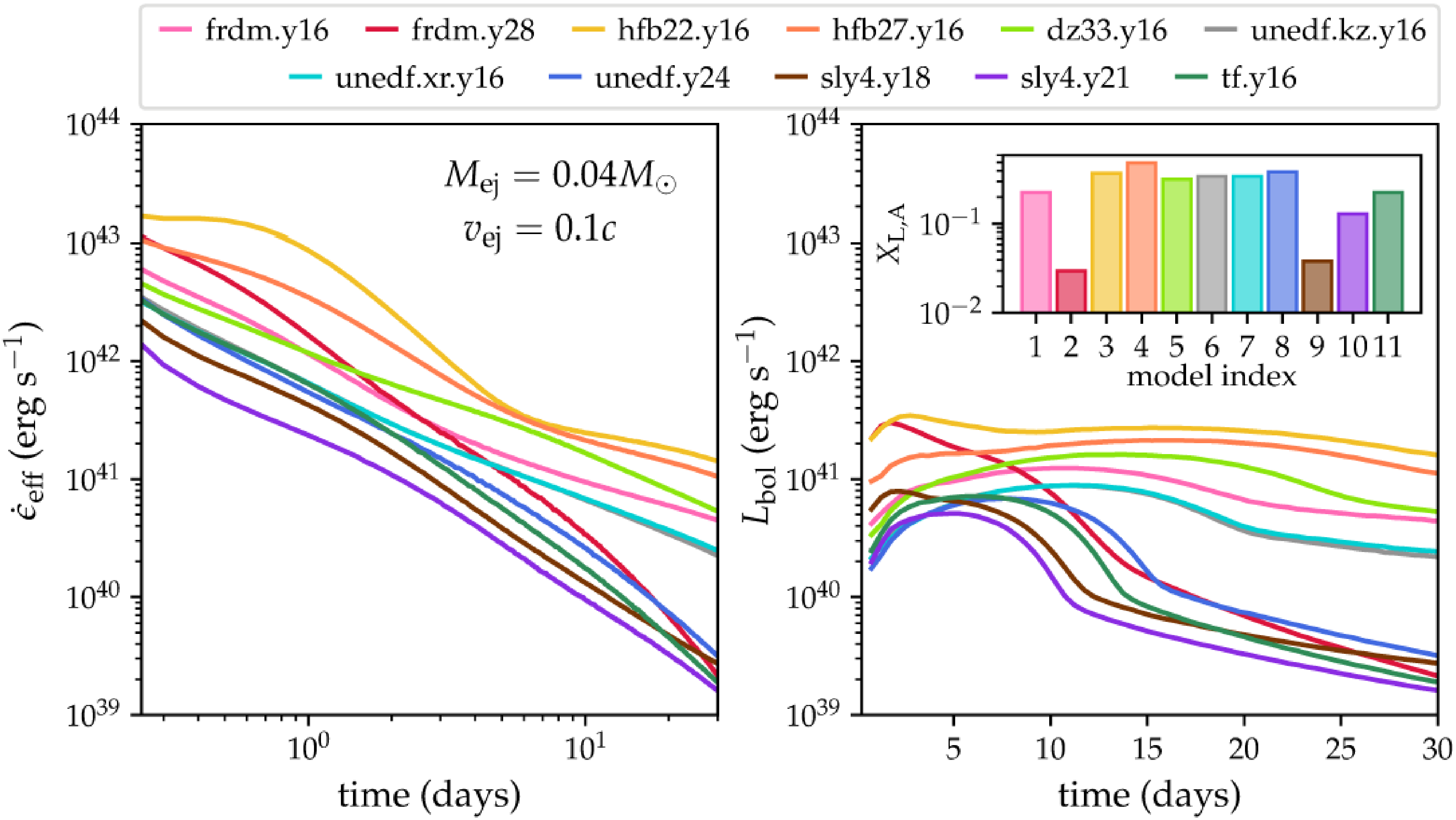
Whether you can get to fissioning nuclei or not depends on the number of neutrons available for capture





Fissions and alpha decays

Decaying nuclei leave an imprint (in principle) on the light curve



Barnes, Zhu, Lund et al 2021

See K. Lund's talk Tuesday afternoon

How many neutrons were captured?

Effects *both* light curve and abundances

The weak interaction matters

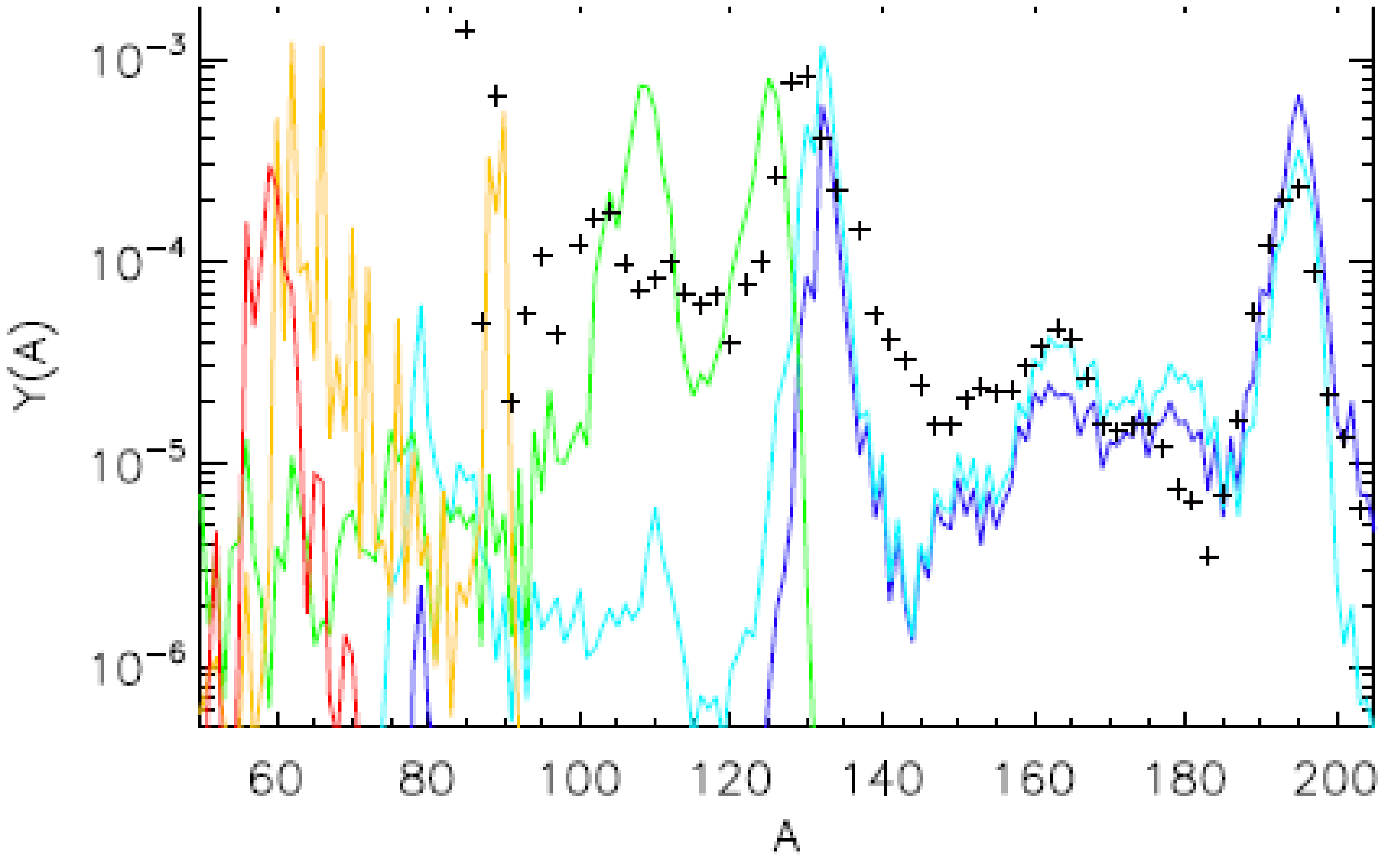
How neutrinos influence nucleosynthesis

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

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

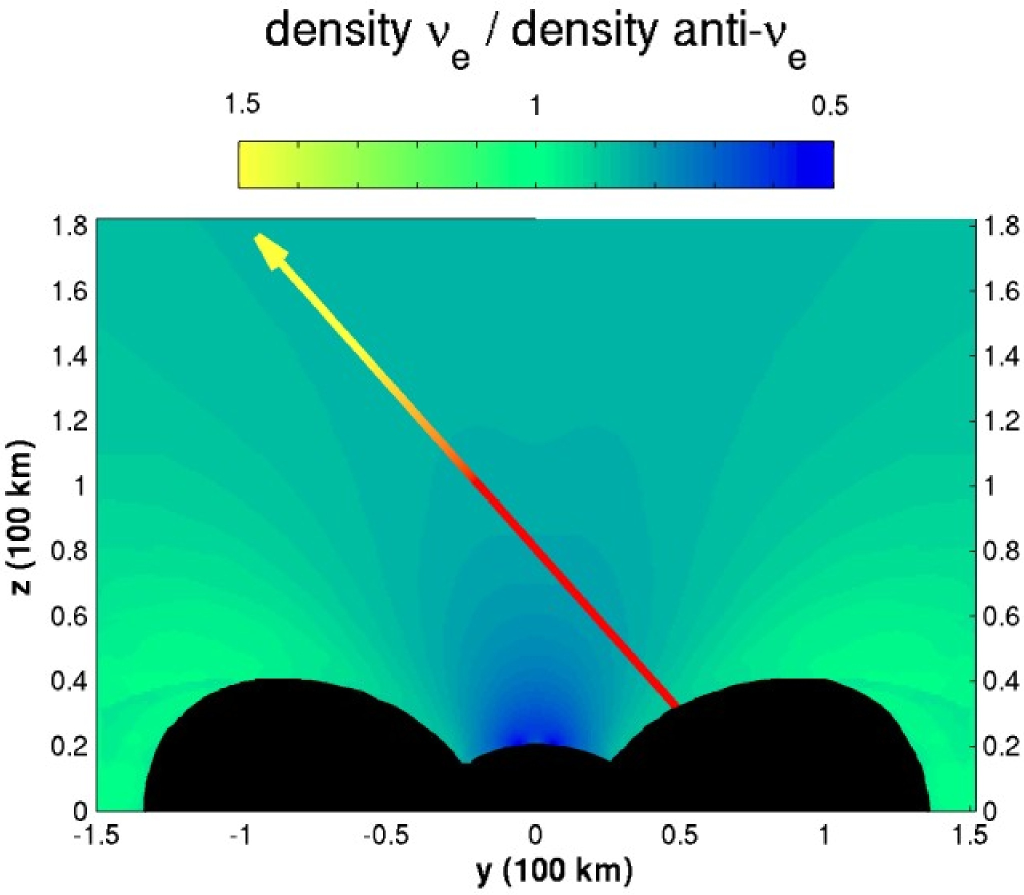
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

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 2016

Neutrinos can be described by a density matrix

Additional information about the phase

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

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

Tells you how likely you are to measure 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

For more complete quantum kinetic equations see work by Cirigliano, Fuller, 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

Where and how these transformations might occur

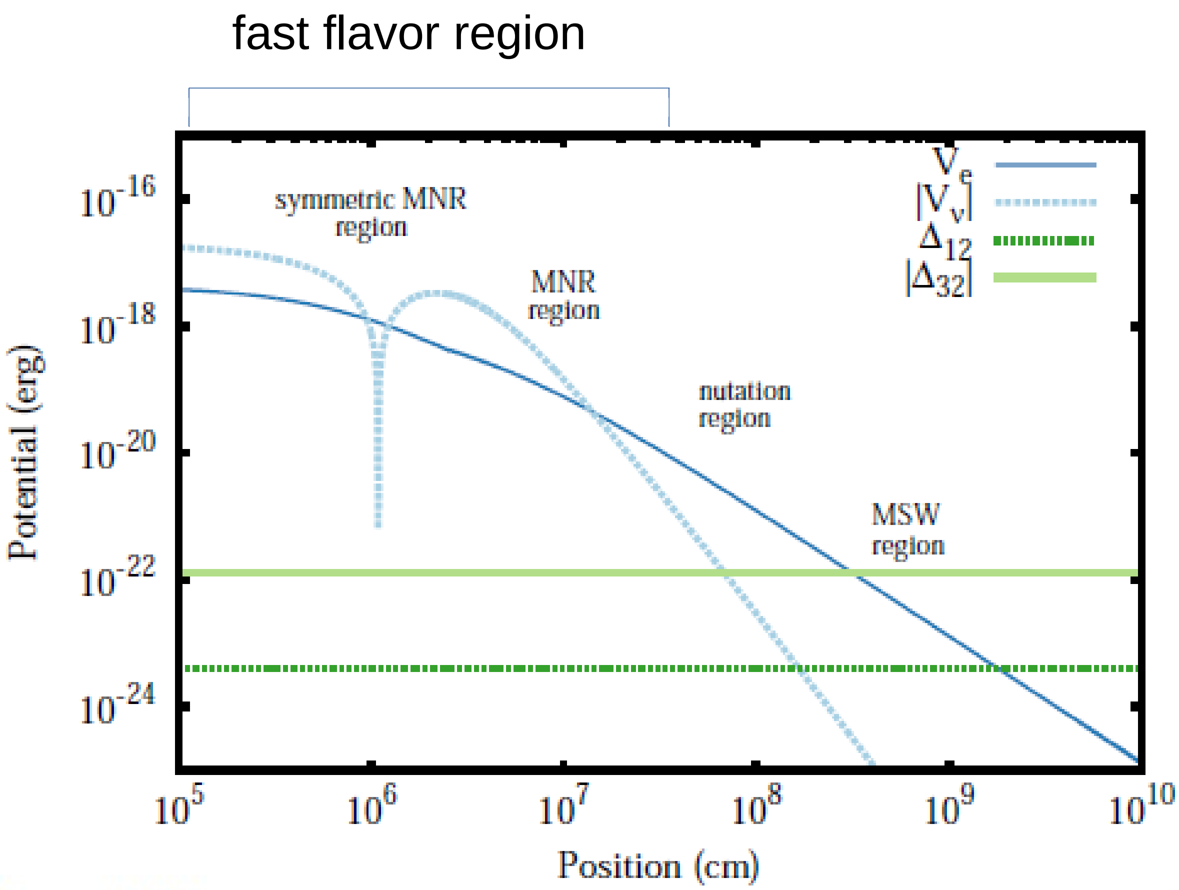


fig. from Malkus et al 2016

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

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

Transformation closest to the emission: “fast flavor”

Fast flavor:

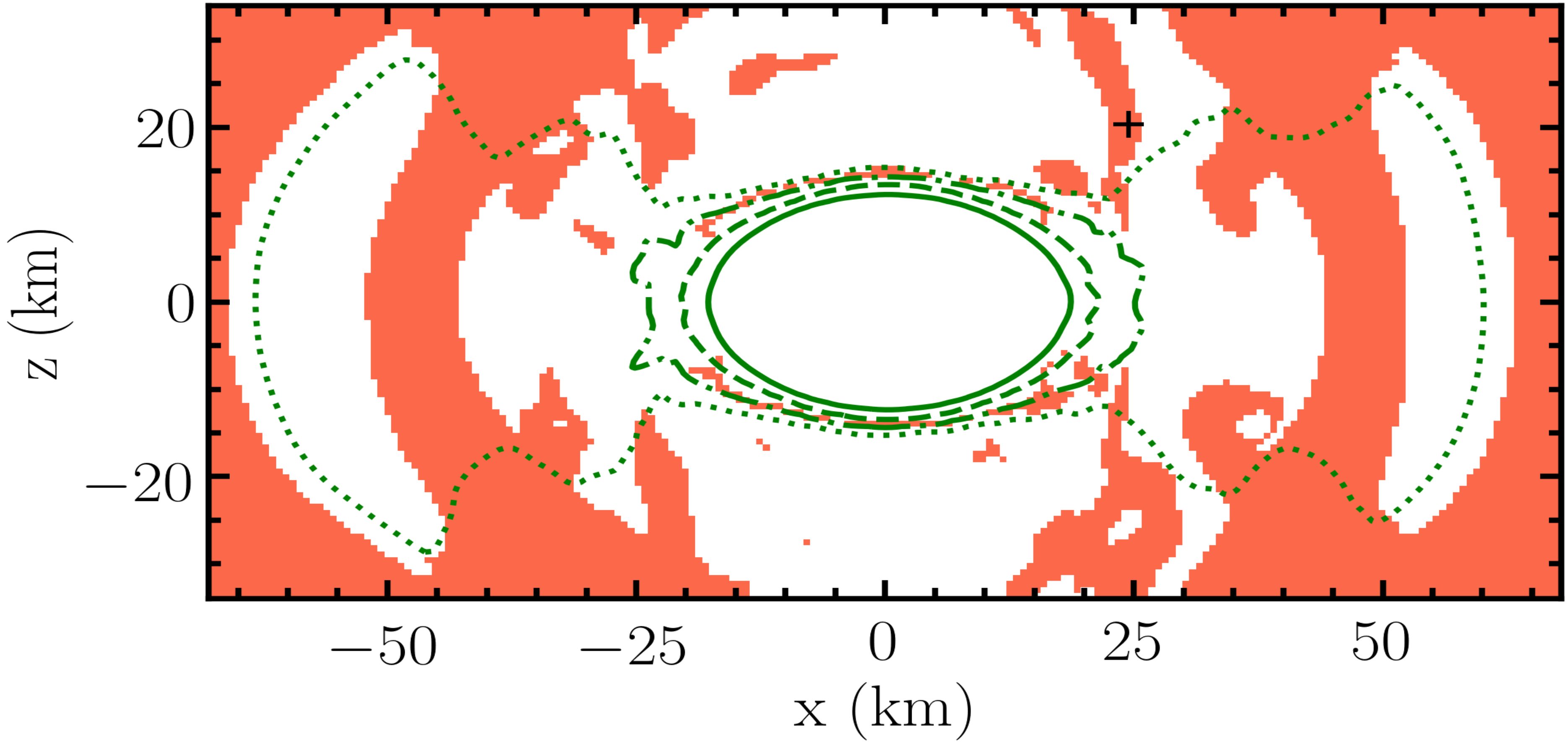
fastest transitions when inverse fluctuation wavelength (k) is similar to the difference in number density between neutrinos and antineutrinos

and

there is a “crossing”

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

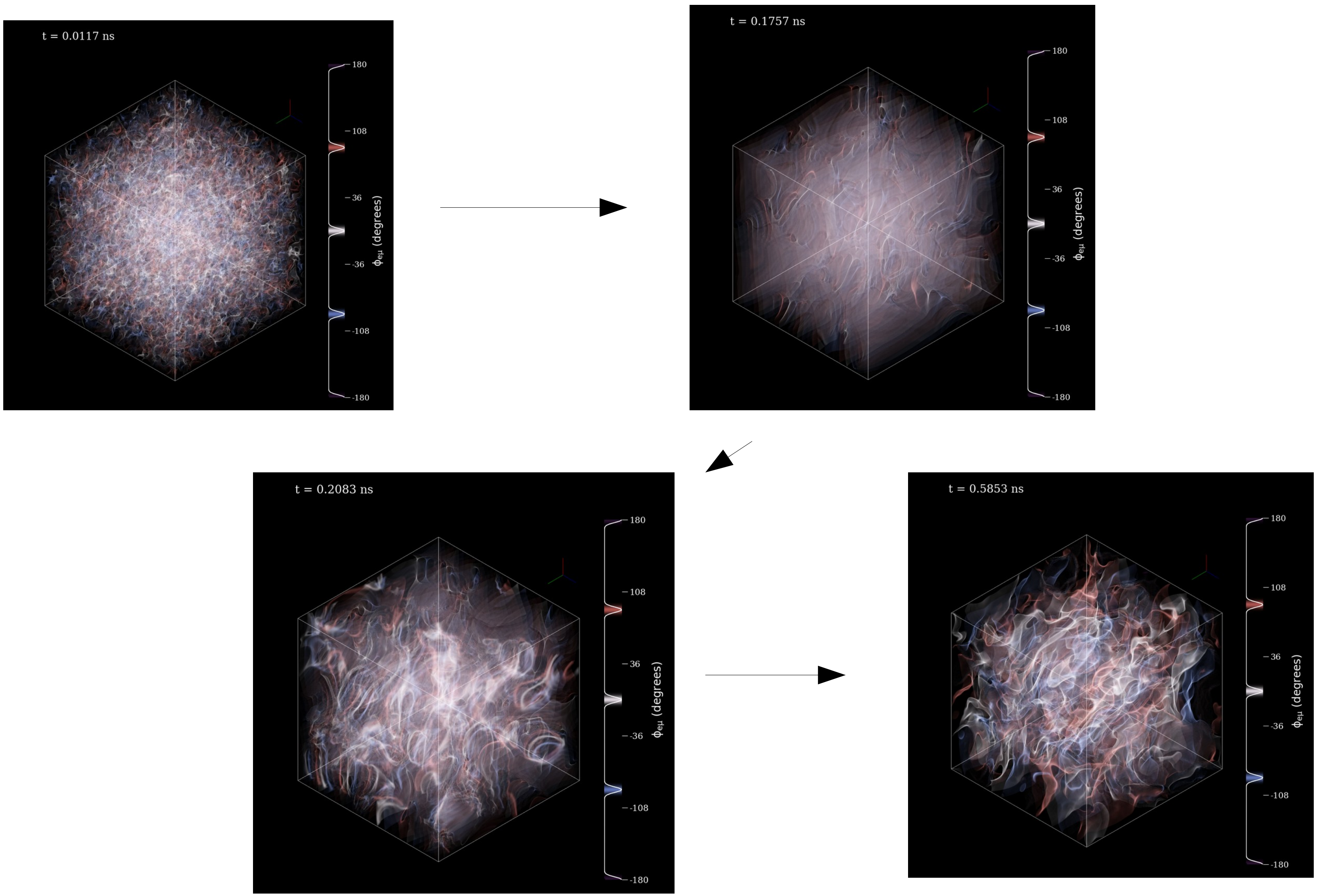
Crossings in BNS remnant



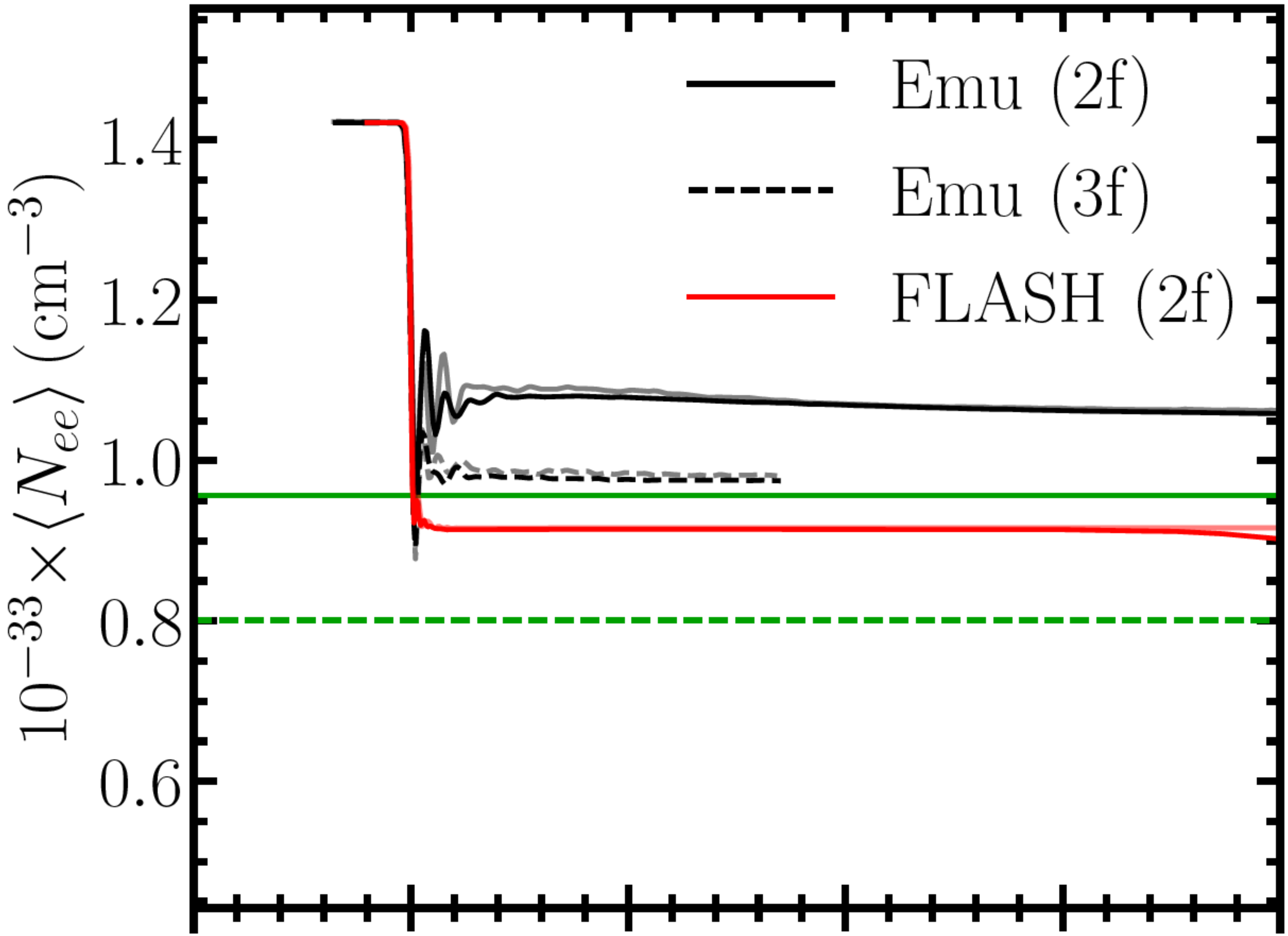
Grohs et al 2022

Fast flavor oscillations above a BNS merger with moments using FLASH

(Grohs et al 2022)



Growth and saturation, BNS, moments vs PIC



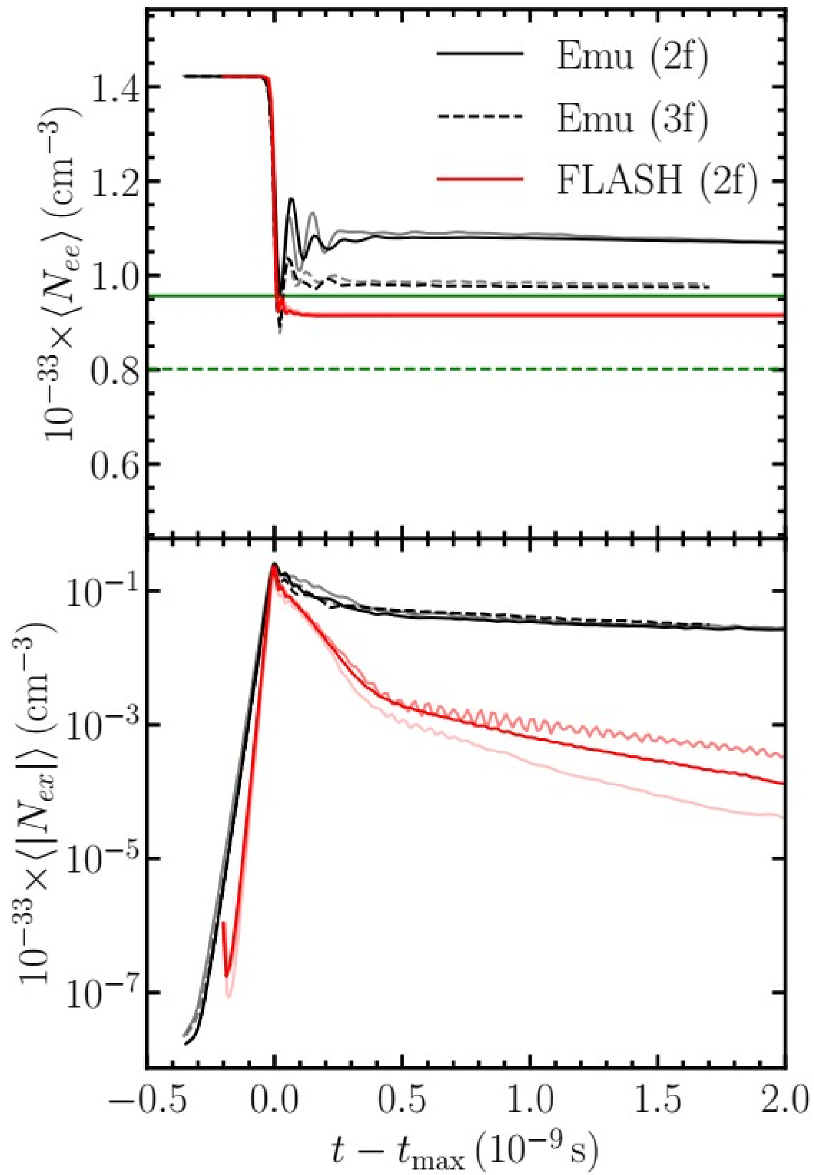
1500 neutrinos per cell

Flavor equilibration

2 moments per cell

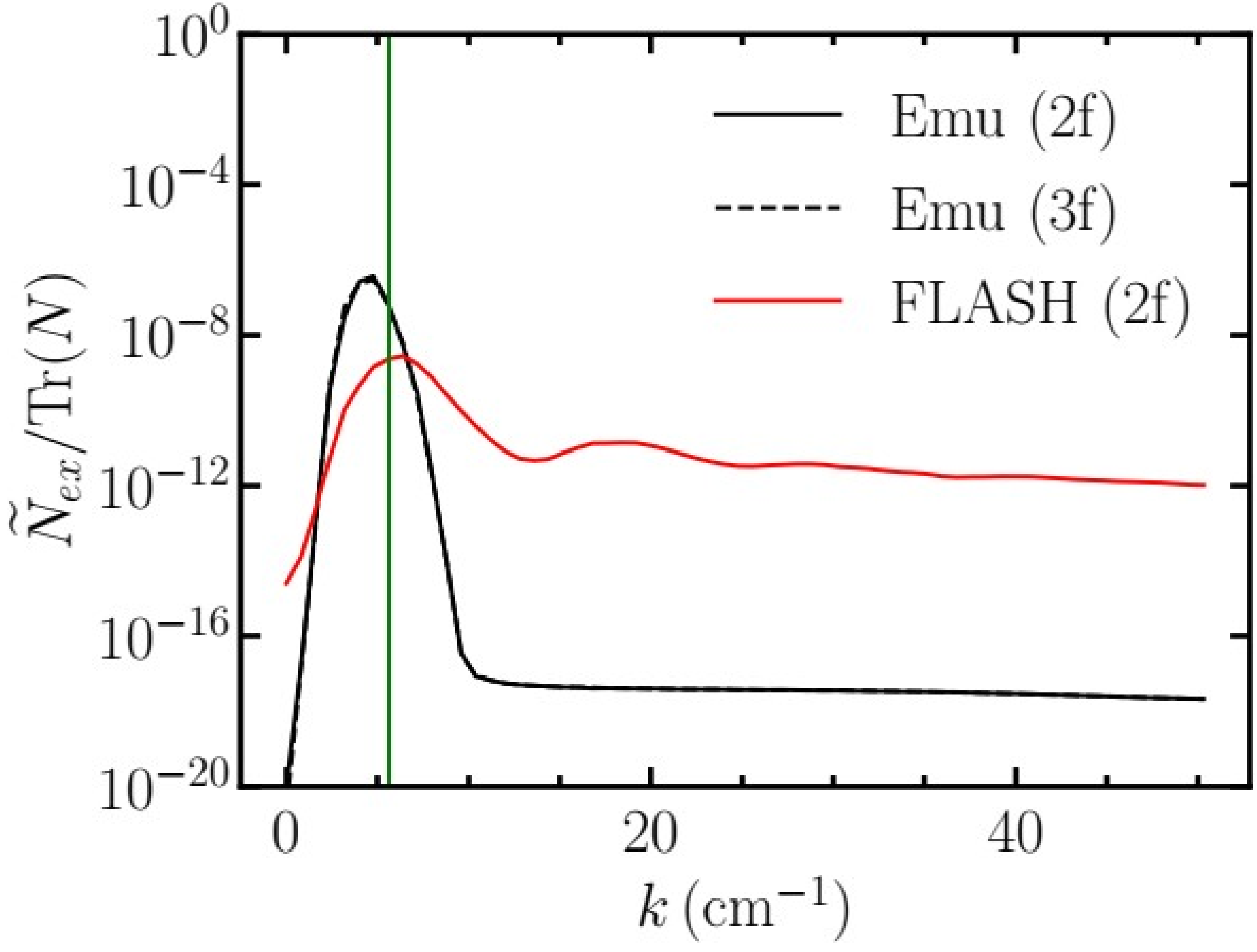
Grohs et al 2022

Growth and saturation, BNS, moments vs PIC



Grohs et al 2022

Fourier transform BNS, moments vs PIC

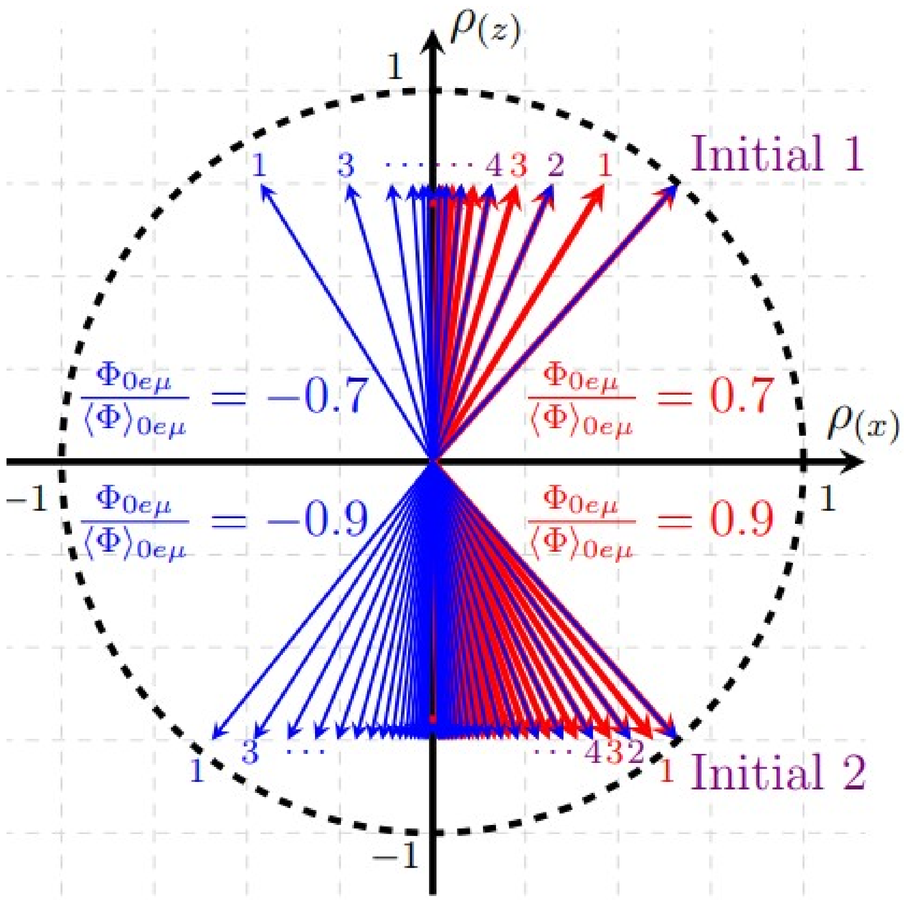


Collisions

Collisions: scatterings which change energy, momentum, type of particle

Collisions damp out “mixed” states and send the neutrino system toward pure flavor states (or not! Shalgar et al, Johns et al)

A neutrino in a mixed state under the influence of collisions



Evolution of flavor vector due to collisions, Fig. from Richers et al, 2019

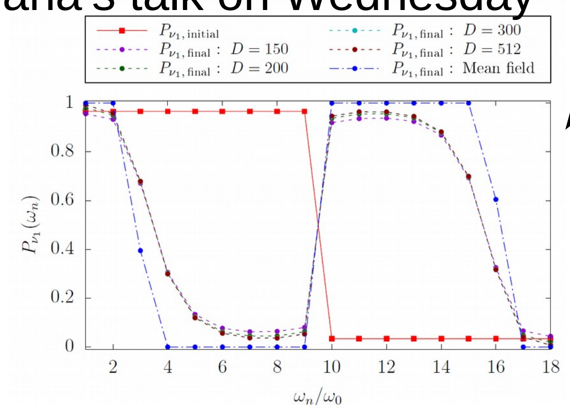
Conclusions

We need to understand neutrinos in astrophysical systems to accurately many observables. This involves solving the quantum kinetic equations in astrophysical environments

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

Looking to the future

Baha's talk on Wednesday



Jonah's talk earlier today