Neutrino flavor transformation in mergers

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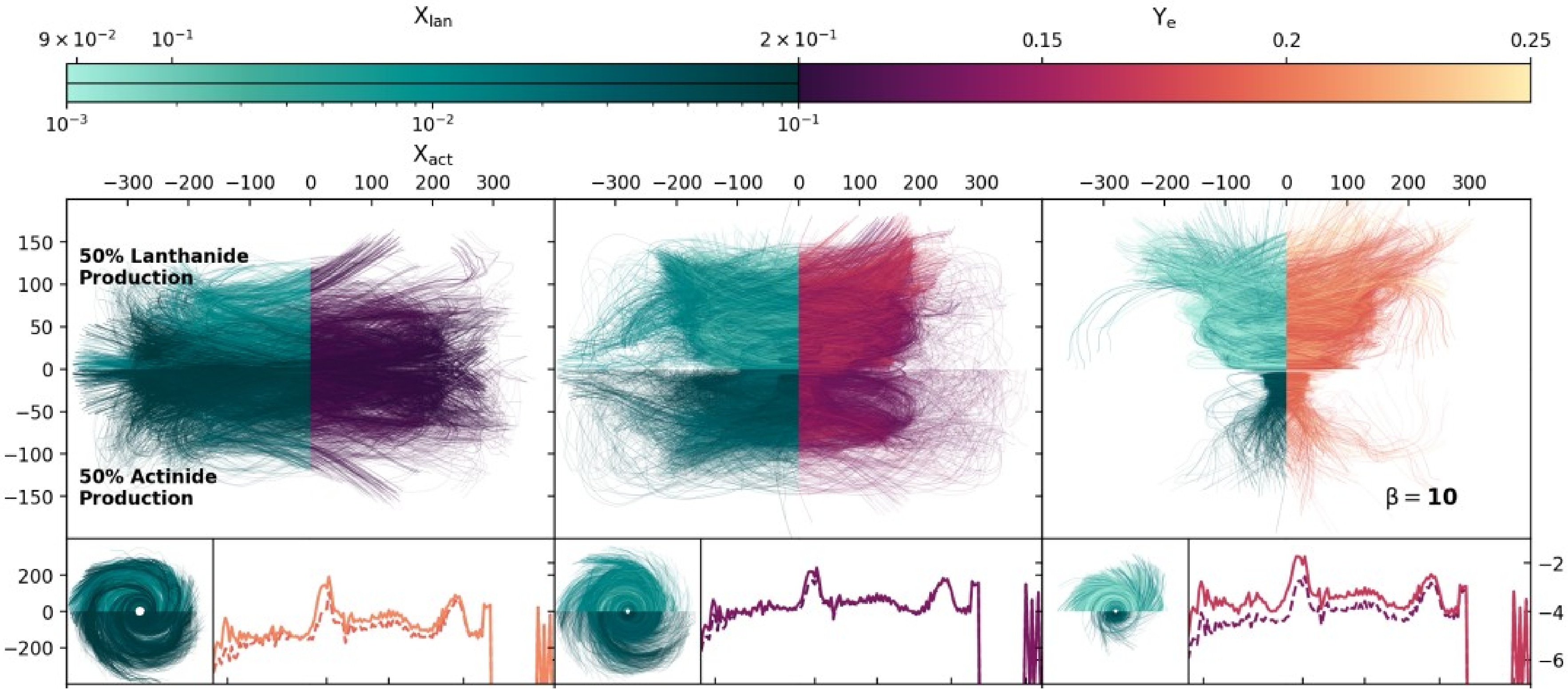
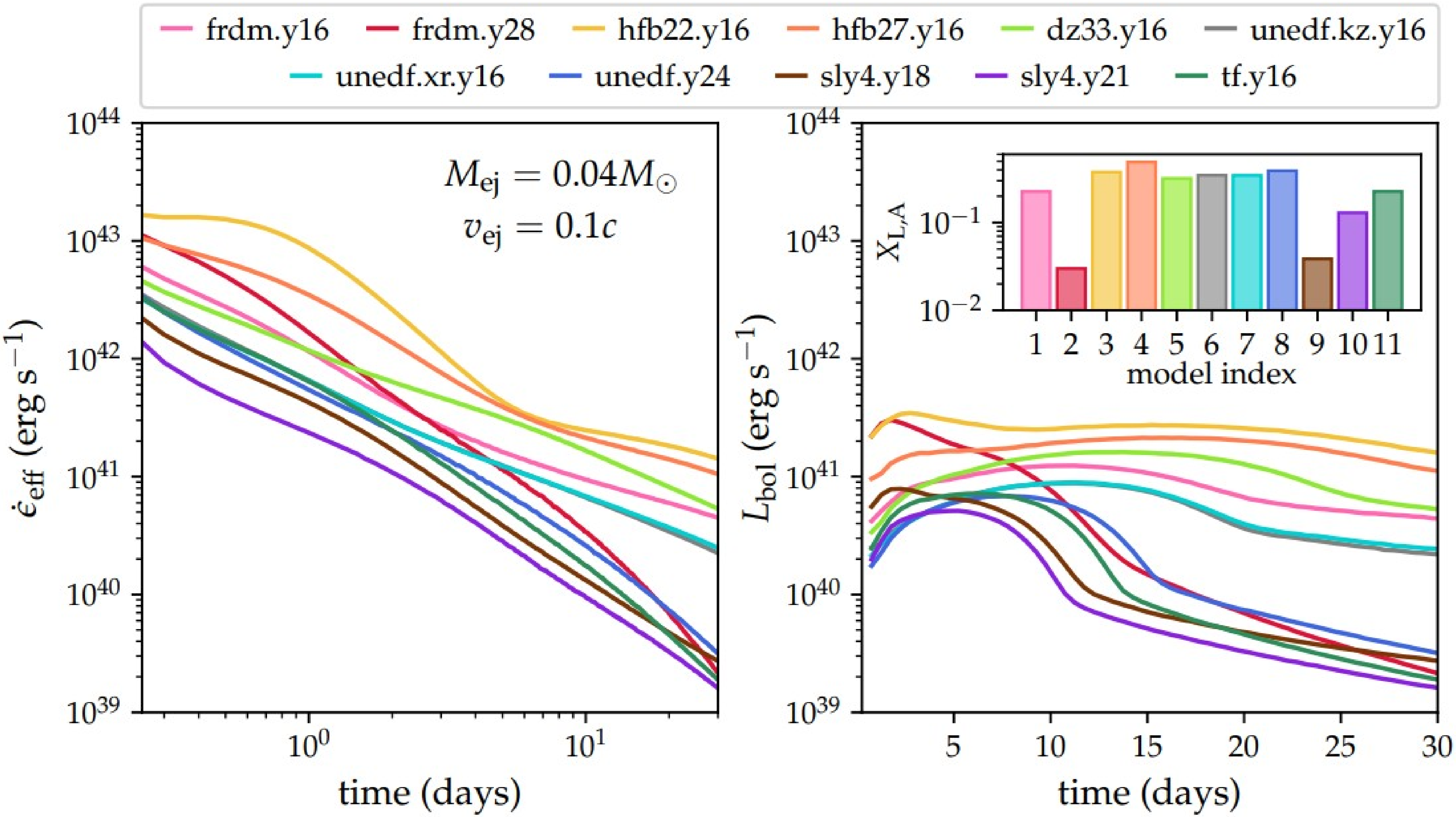
Black hole accretion disk tracer particles



Lund et al 2023

Fig. shows a subset of about 100,000 tracers.

Electromagnetic counterpart (kilonova) to a merger depends on the electron fraction



Barnes et al 2021, see also Zhu et al 2021

Flavor matters for nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

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

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

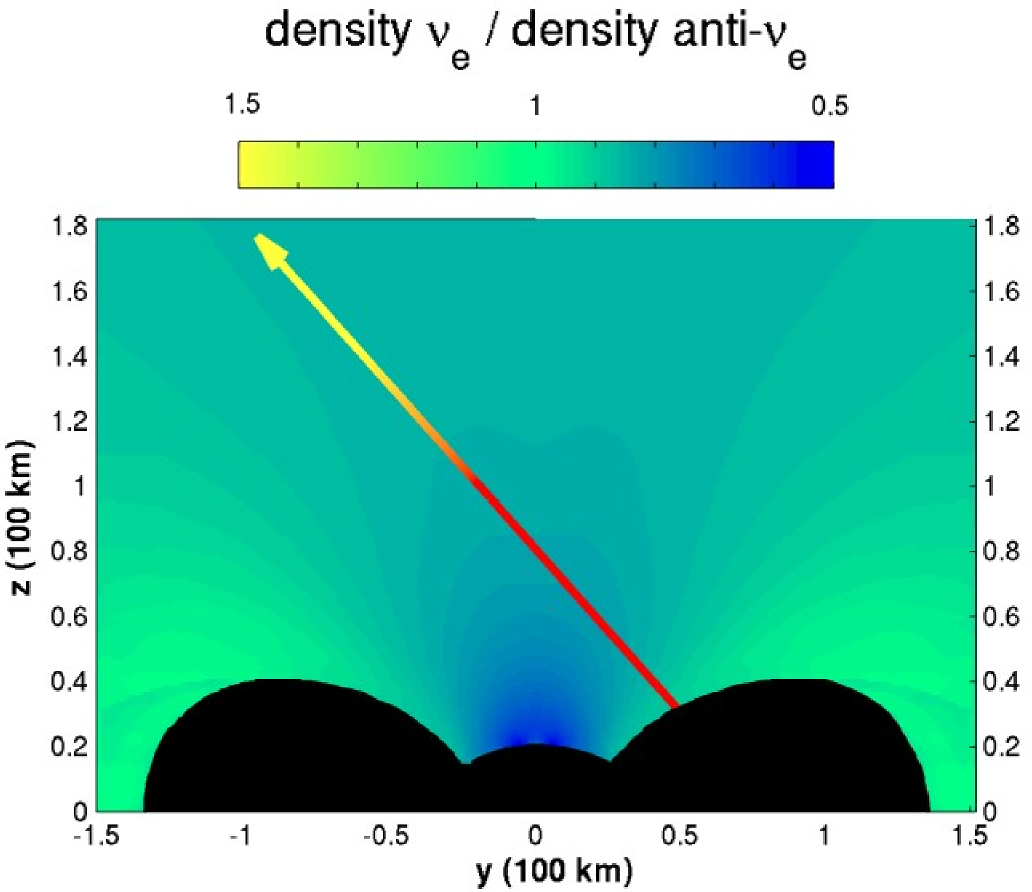
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

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

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

Do 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 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)

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

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

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

Types of transformations

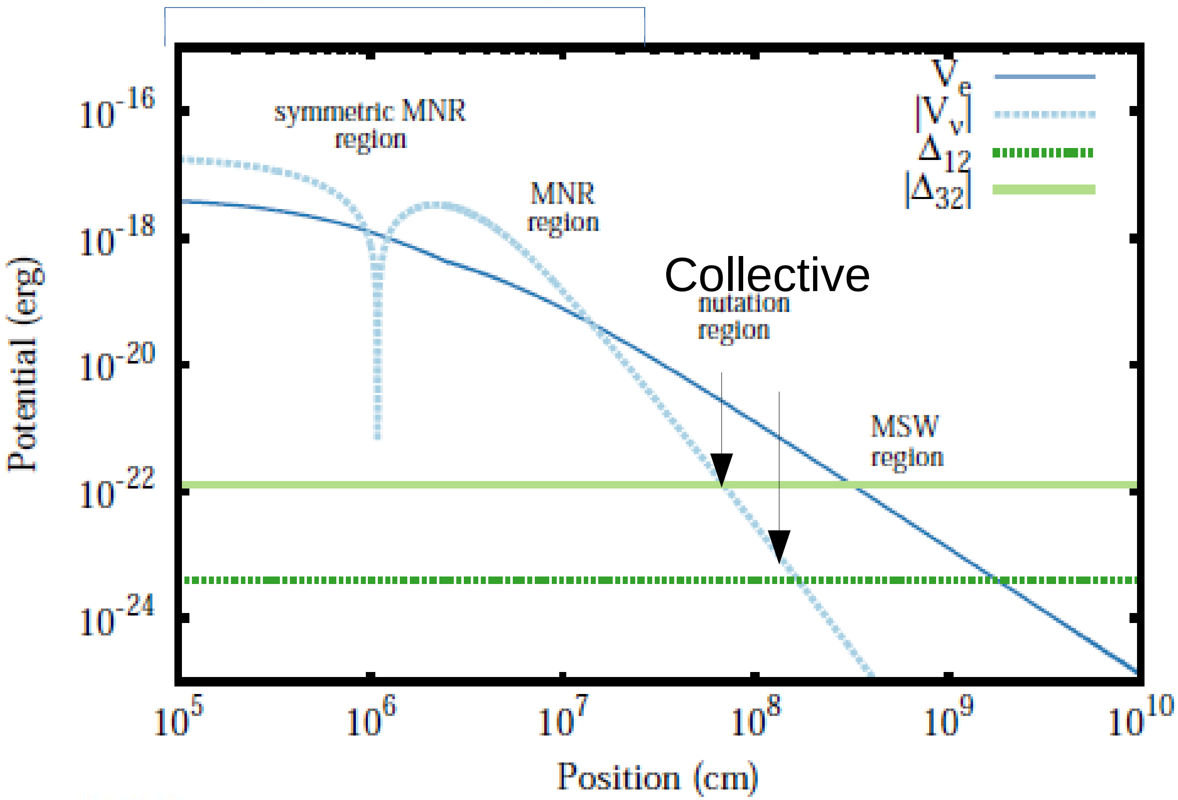
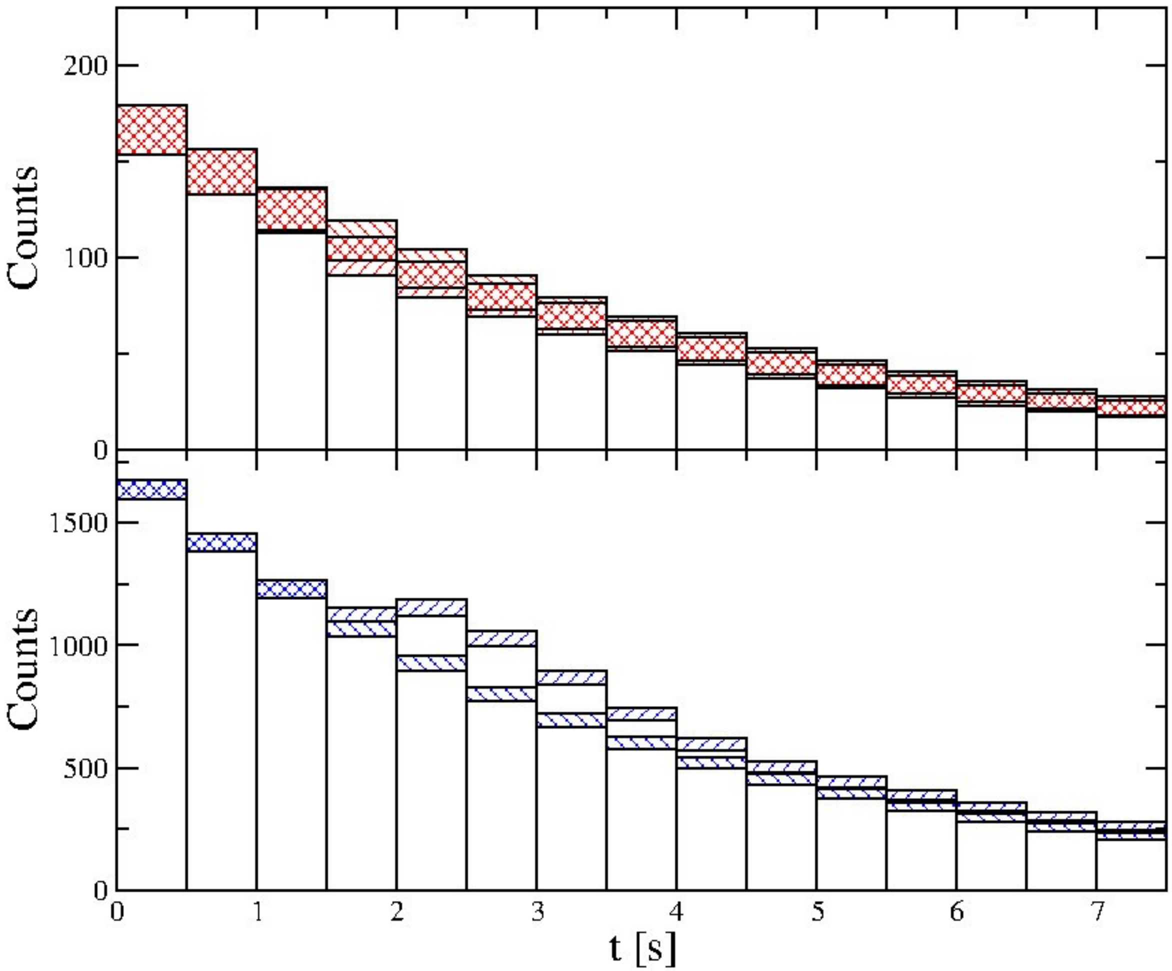


fig. from Malkus et al 2016

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

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

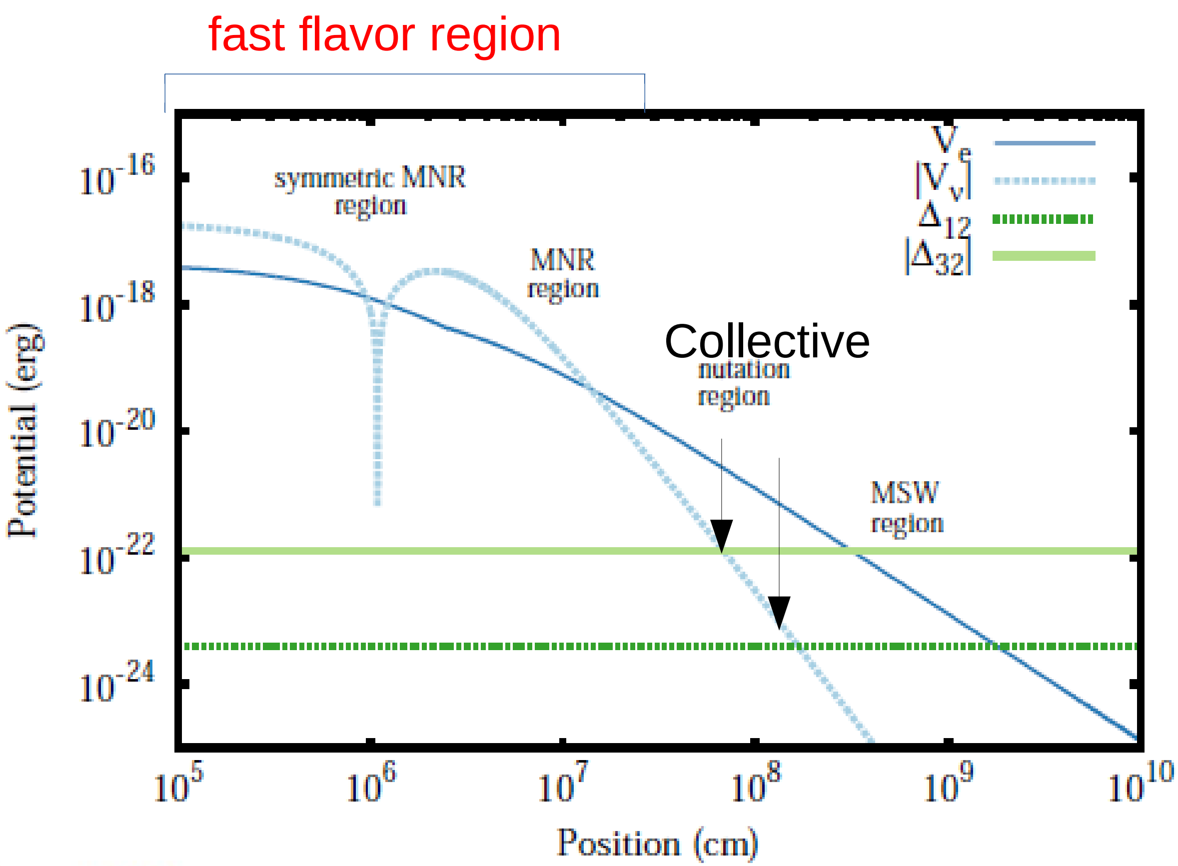
Collective and MSW change on the supernova neutrino time signal



Gava et al 2009

Neutrinos from BNS would also be detectable if in galaxy (Caballero et al 2009)

Types of transformations

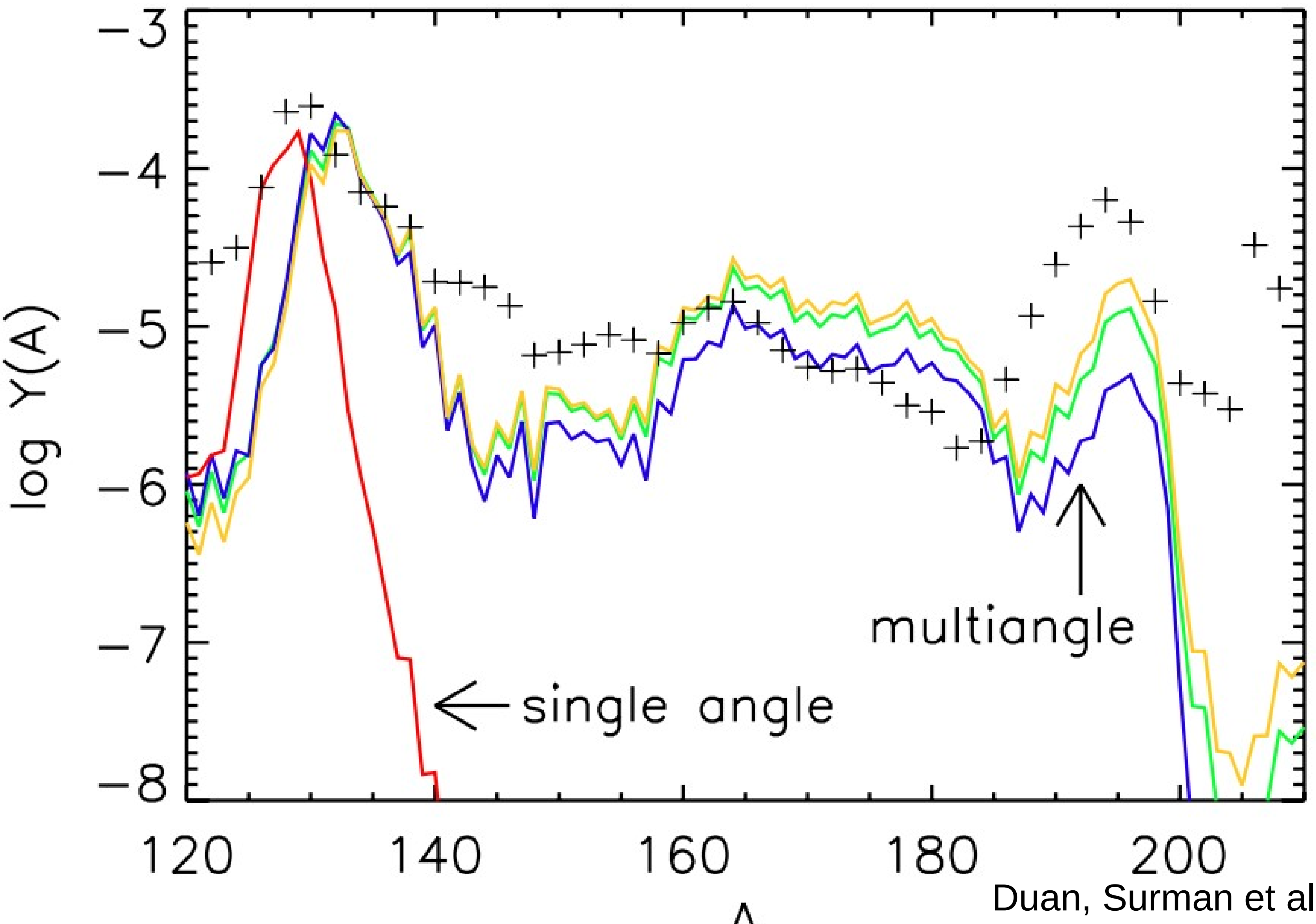


$$\mathbf{H} = \mathbf{H}_{\rm vac} + \mathbf{H}_{\rm M} + \mathbf{H}_{\rm SI}$$

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

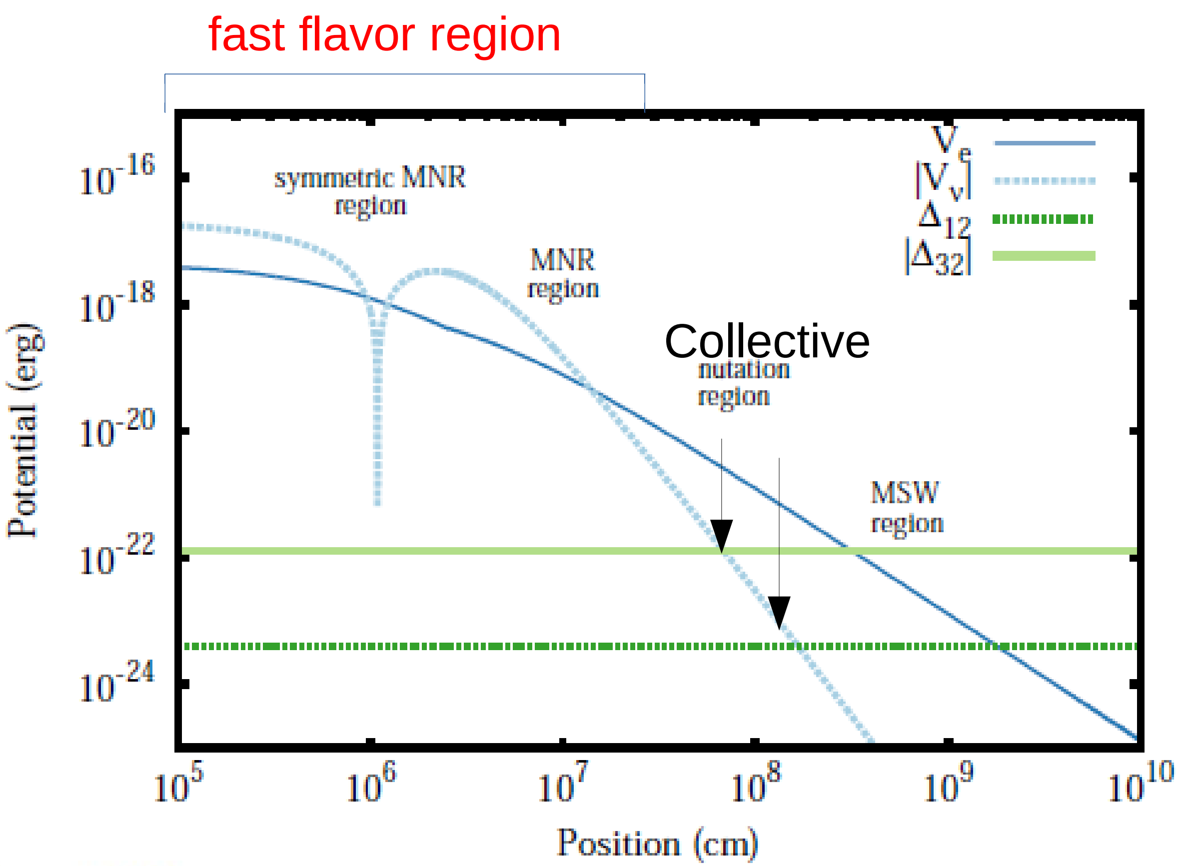
fig. from Malkus et al 2016

Collective oscillations for nucleosynthesis



Duan, Surman et al 2011

Types of transformations

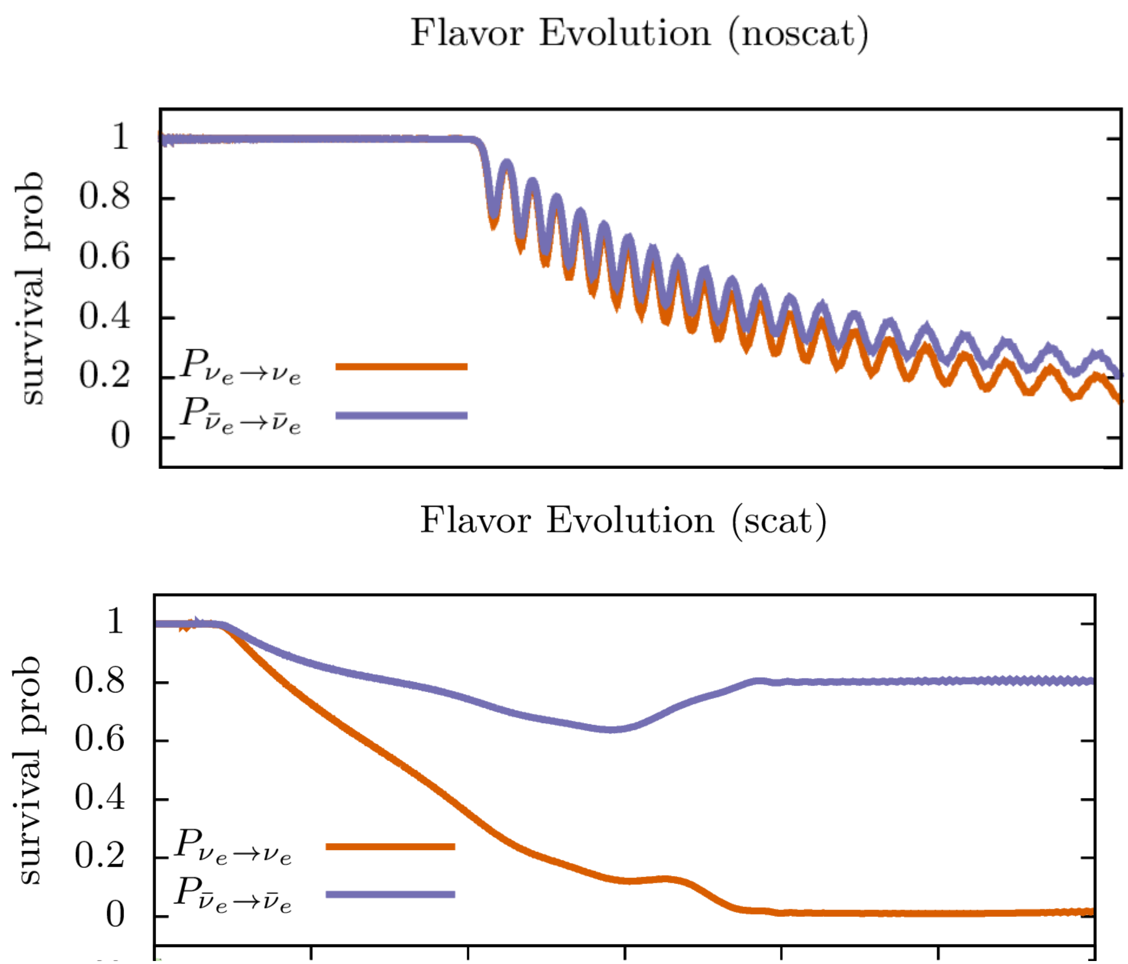


$$\mathbf{H} = \mathbf{H}_{\text{vac}} + \mathbf{H}_{\text{M}} + \mathbf{H}_{\text{SI}}$$

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

fig. from Malkus et al 2016

Matter neutrino resonance transformations in BNS



Collective

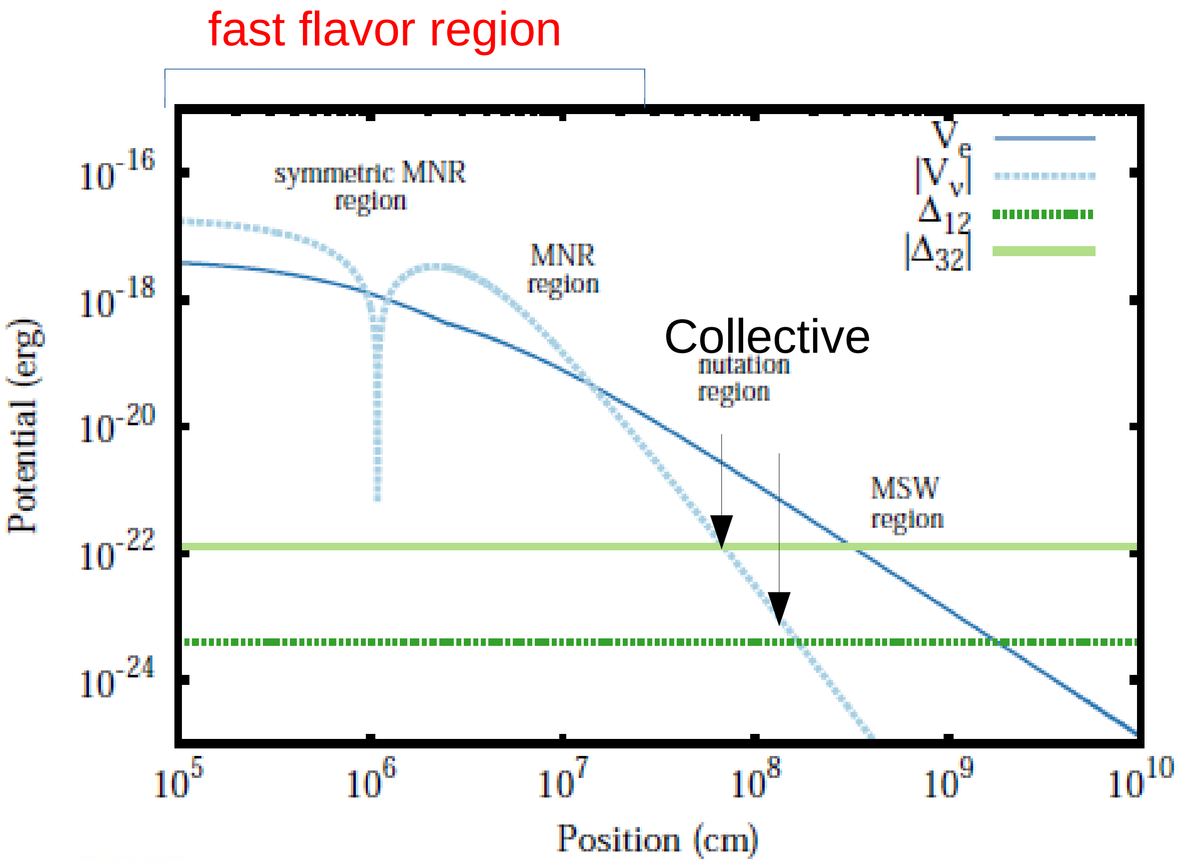
Matter-neutrino Resonance

300 km

1500 km

This is post-processing of a merger simulation from Deaton et al 2018

Types of transformations

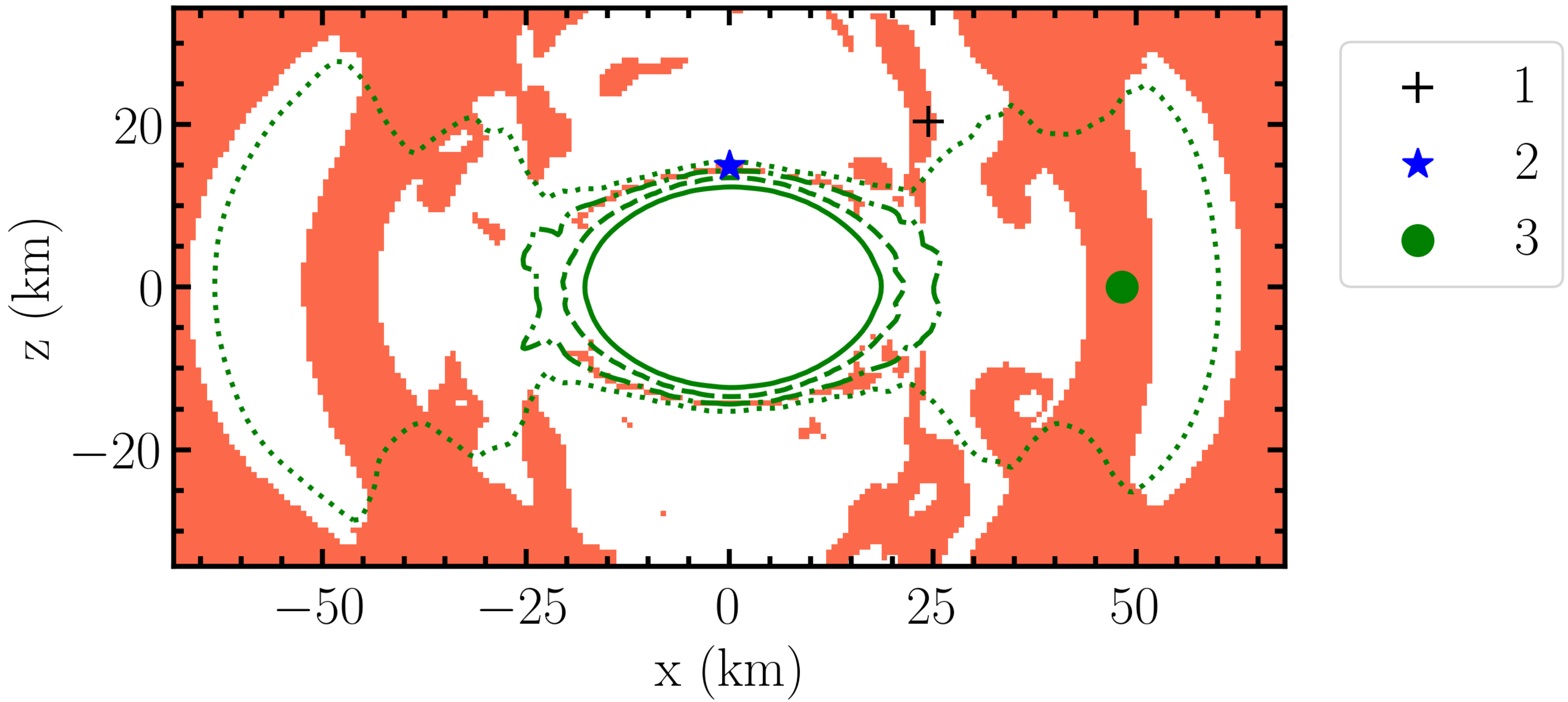


$$\mathbf{H} = \mathbf{H}_{\mathrm{vac}} + \mathbf{H}_{\mathrm{M}} + \mathbf{H}_{\mathrm{SI}}$$

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

fig. from Malkus et al 2016

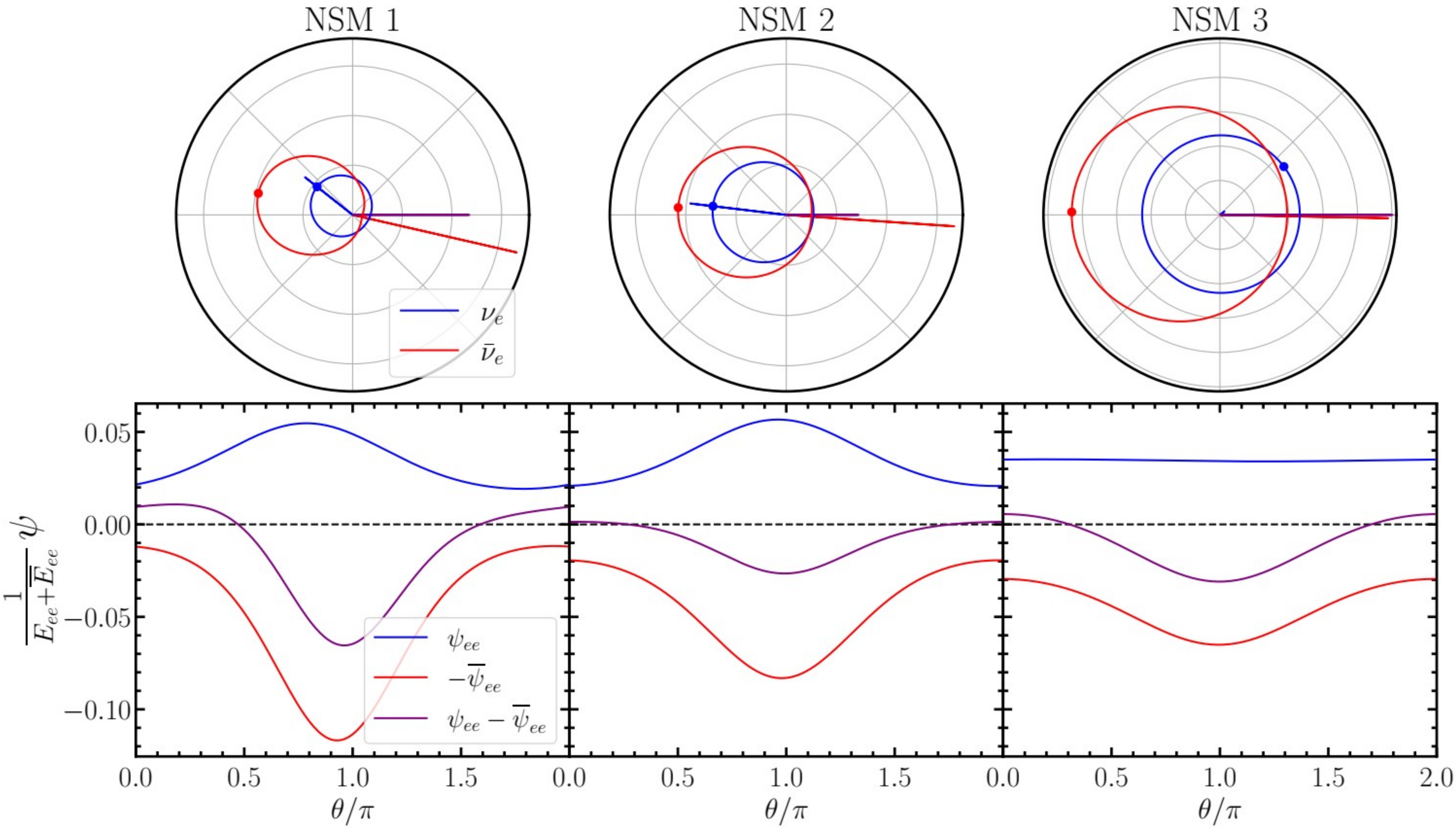
BNS remnant fast flavor regions



Orange region is where there are crossings, green contours are matter densities, $\{10^{11}, 10^{12}, 10^{13}, 10^{14}\}$ g/cm^3, classical simulation 5ms after merger by Foucart

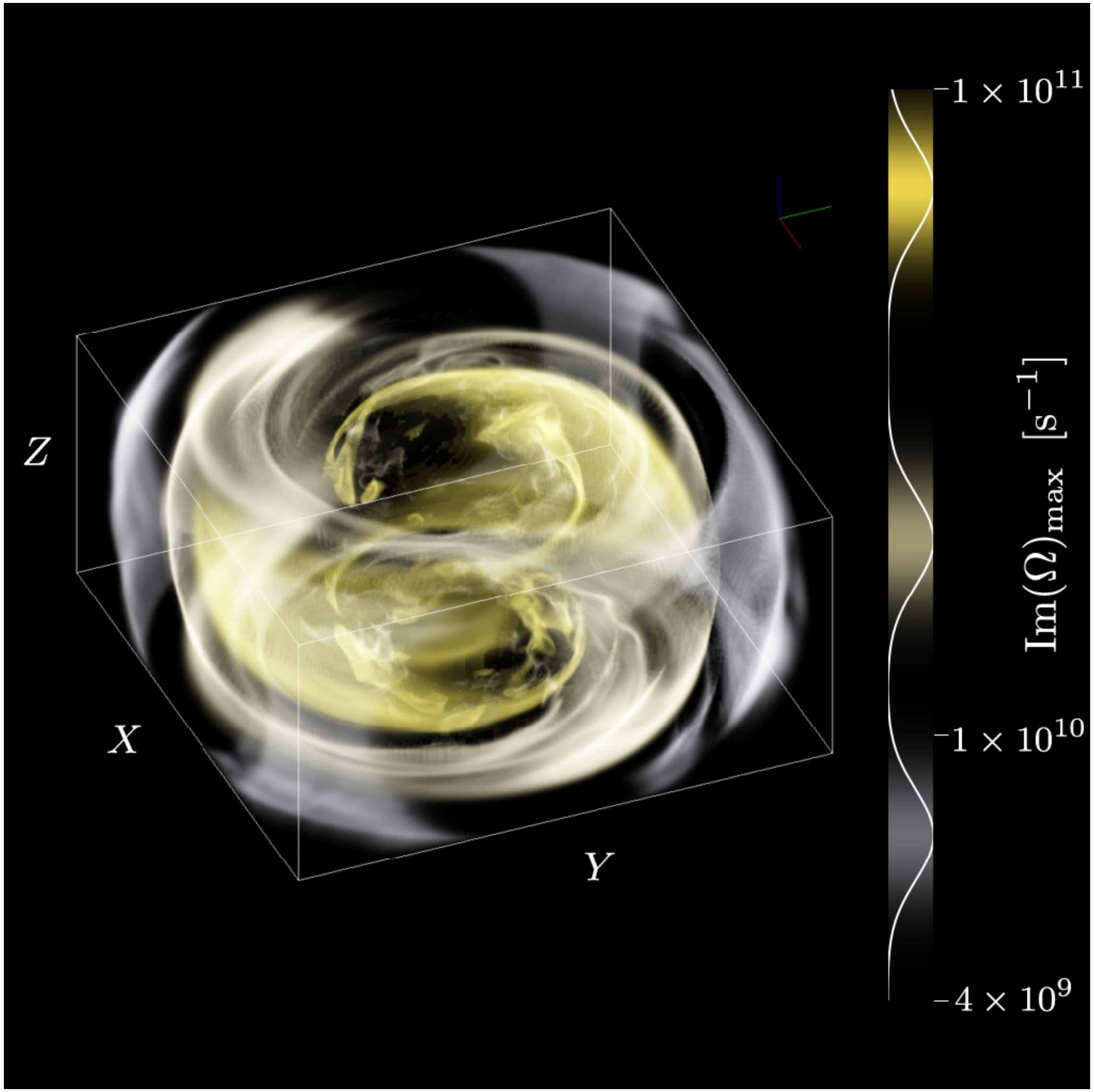
Fig. from Grohs, Richers et al 2023, see also Wu, Tamborra

Fast oscillation instability correlated with “crossings”



Plot from Grohs et at 2023, for supernovae see e.g. Abbar et al 2018

Instability growth rate



Froustey et al in prep 2023, see also Wu et al 2017, original stability analysis from Tamborra and collaborators

Angular moments

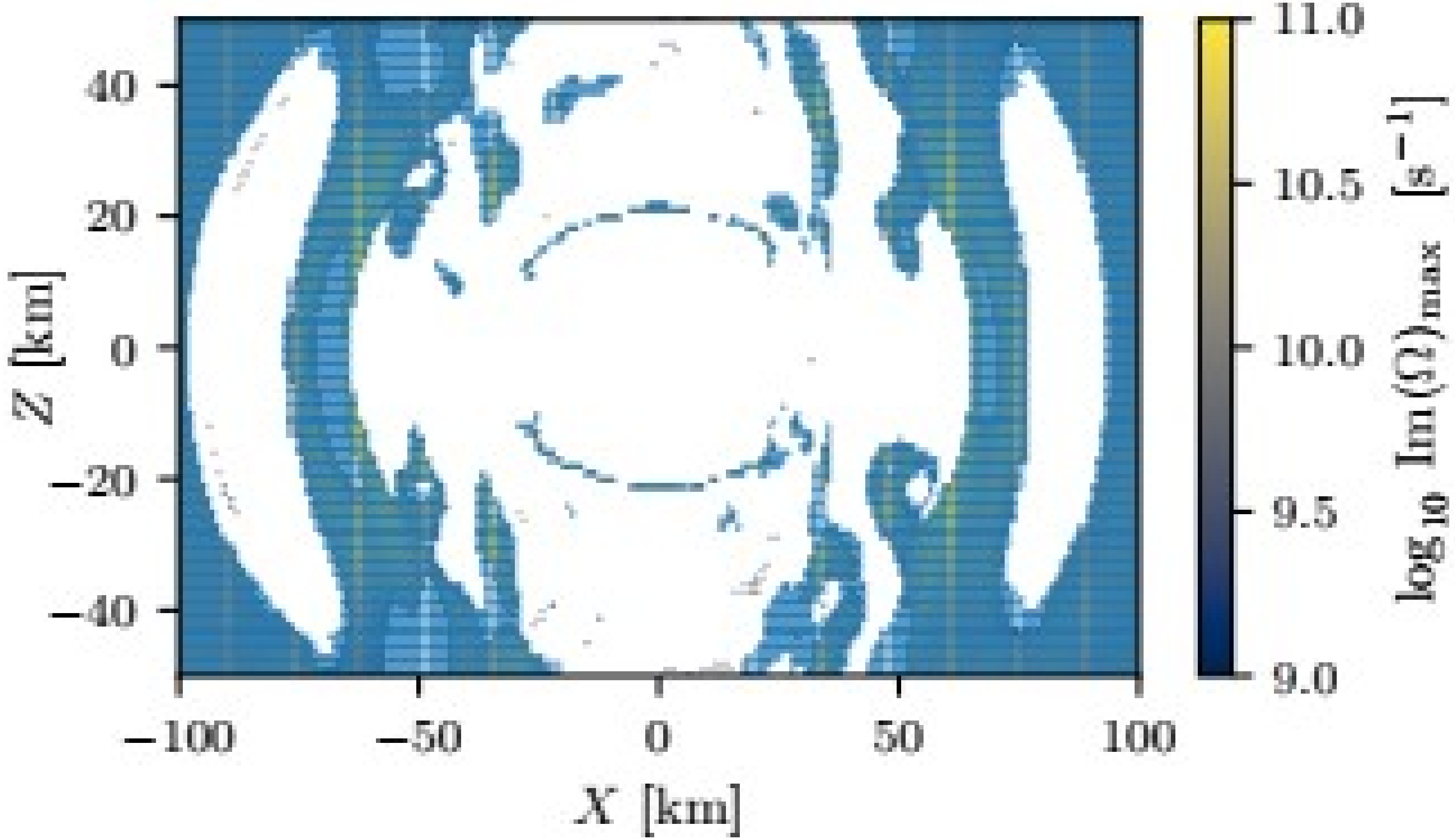
$$E(t,\vec{r},q) = \frac{1}{4\pi}\left(\frac{q}{2\pi\hbar c}\right)^3 \int d\Omega_p\, f(t,\vec{r},\vec{p})$$

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

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

Energy and flux moments

Instability growth rate, linear stability analysis **using moments**



Froustey et al in prep 2023, based on a classical simulation from Foucart.

Moment quantum kinetic equations

Zero moment (neutrino density)

First moment (flux)

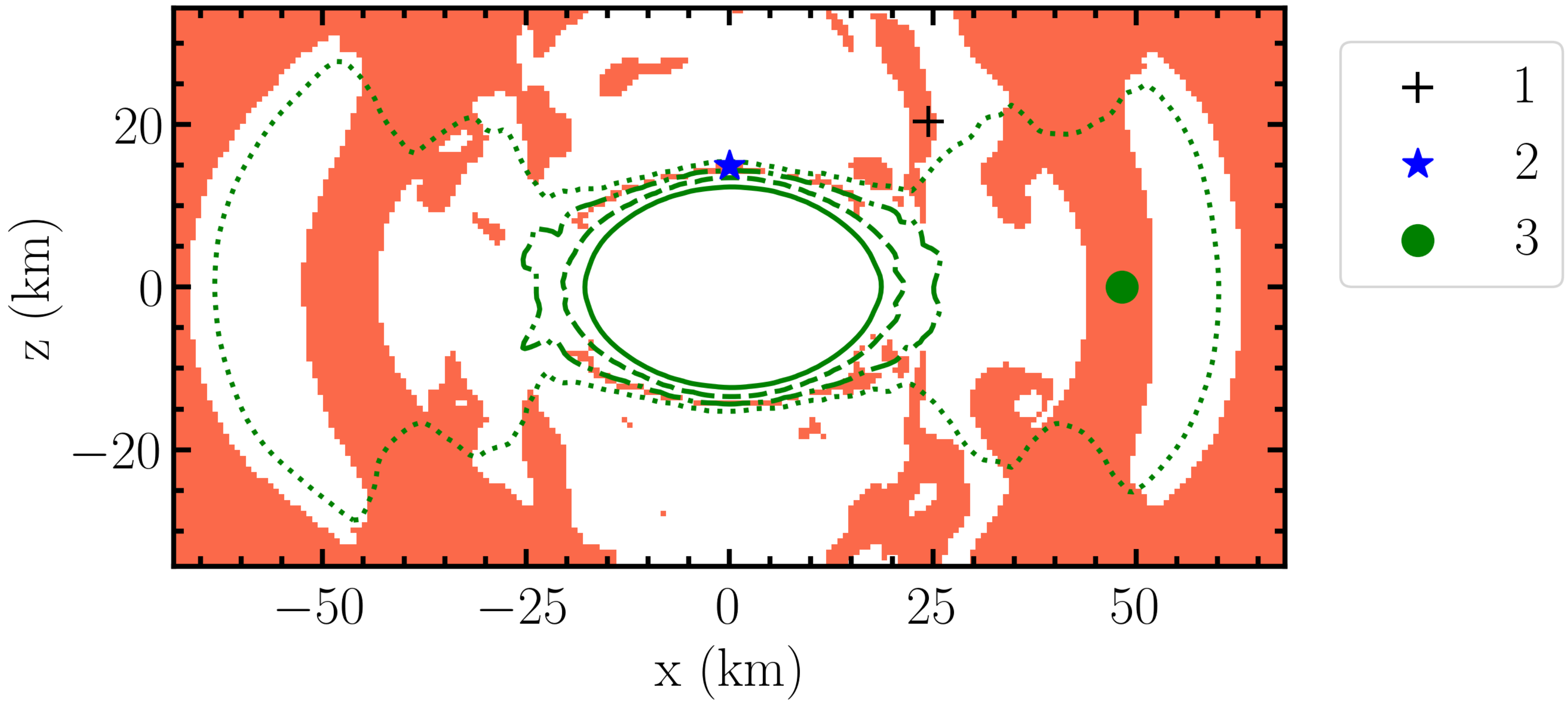
$$\frac{\partial E}{\partial t} + \frac{\partial F^j}{\partial x^j} = -\imath\,[H_V + H_M + H_E, E] + \imath\,[H_F^j, F_j],$$

$$\frac{\partial F^j}{\partial t} + \frac{\partial P^{jk}}{\partial x^k} = -\imath\,[H_V + H_M + H_E, F^j] + \imath\,[H_F^k, P_k^j]$$

Second moment (pressure)

Reduces the number of equations you need to 4, but you need a quantum closure.
Results in the following slides use a quantum adaption of the maximum entropy closure

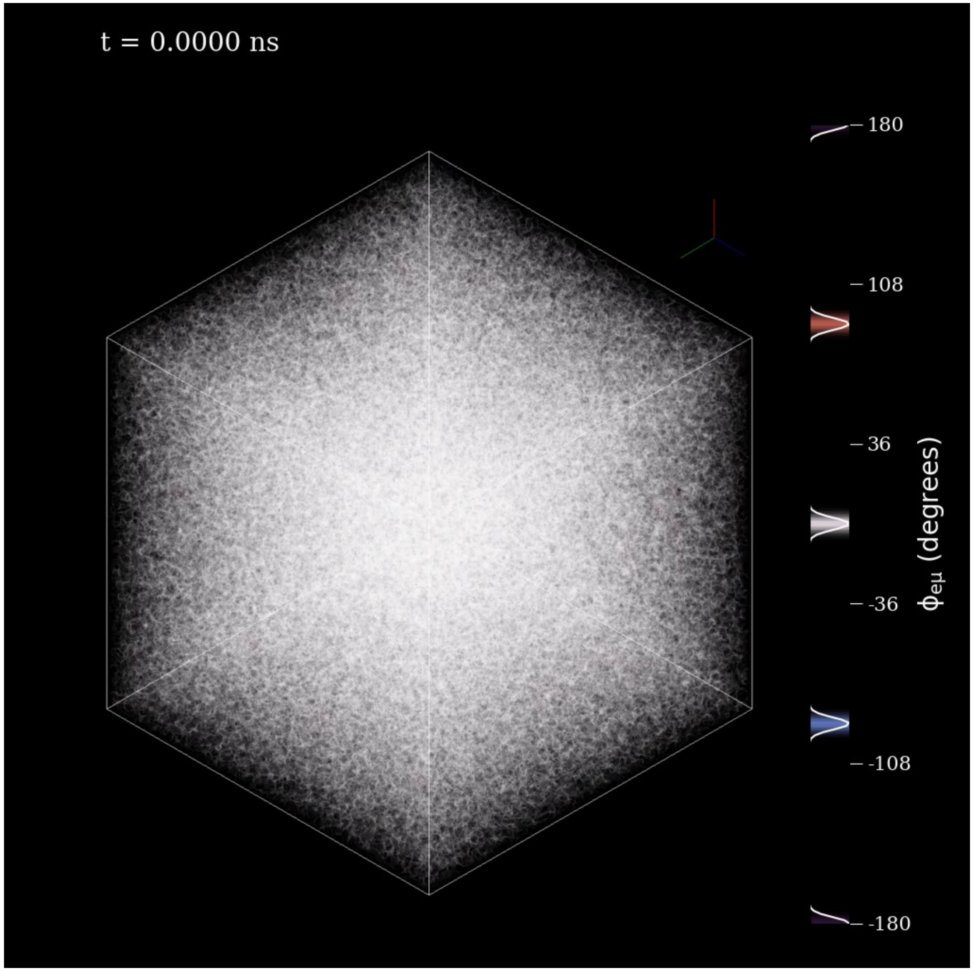
BNS remnant fast flavor regions



Orange region is where there are crossings

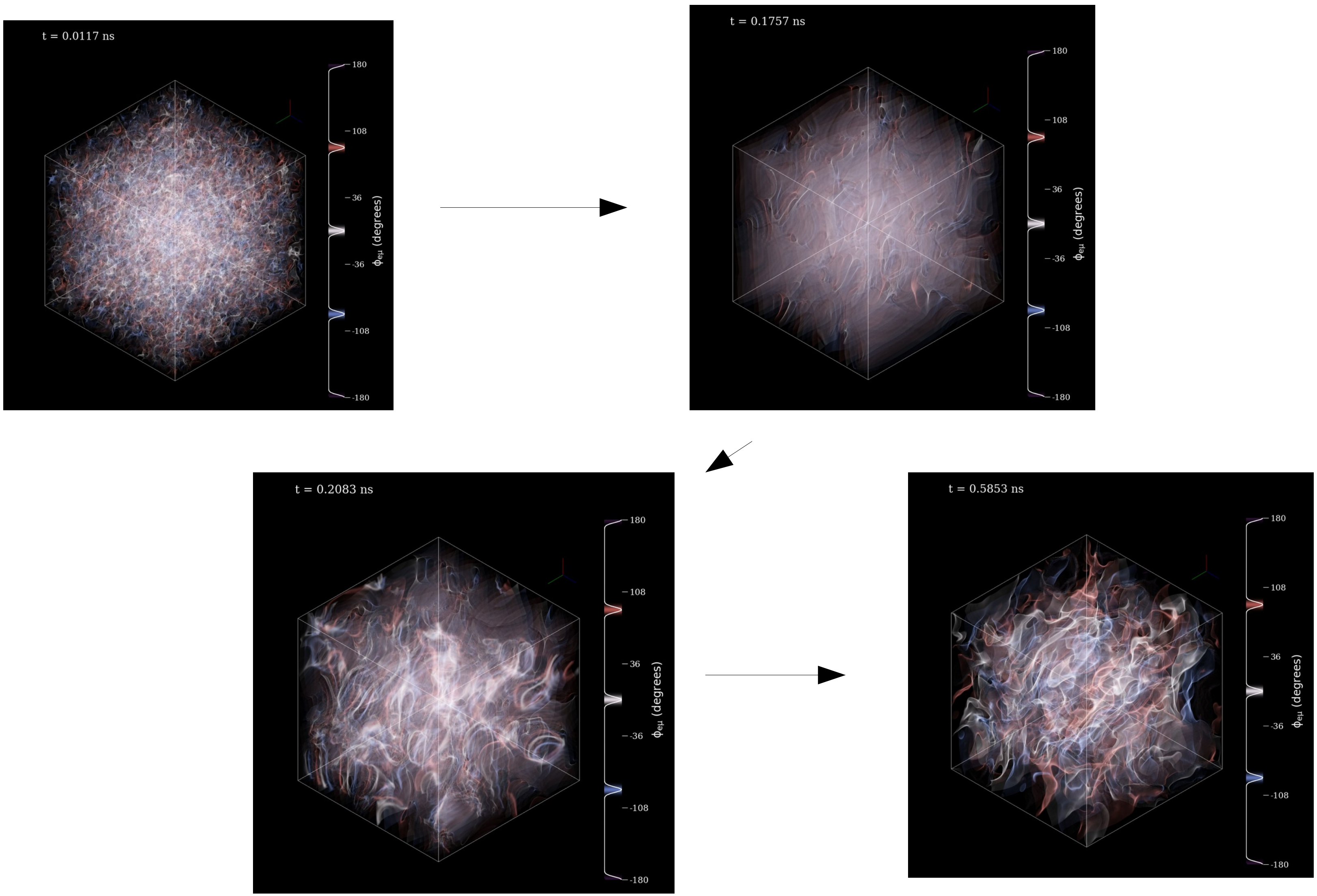
Grohs, Richers et al 2023

Fast flavor oscillations above a BNS merger (Grohs et al 2022)



Movie shows the phase of E_{ex} (flavor off diagonal component of the zeroth angular moment)

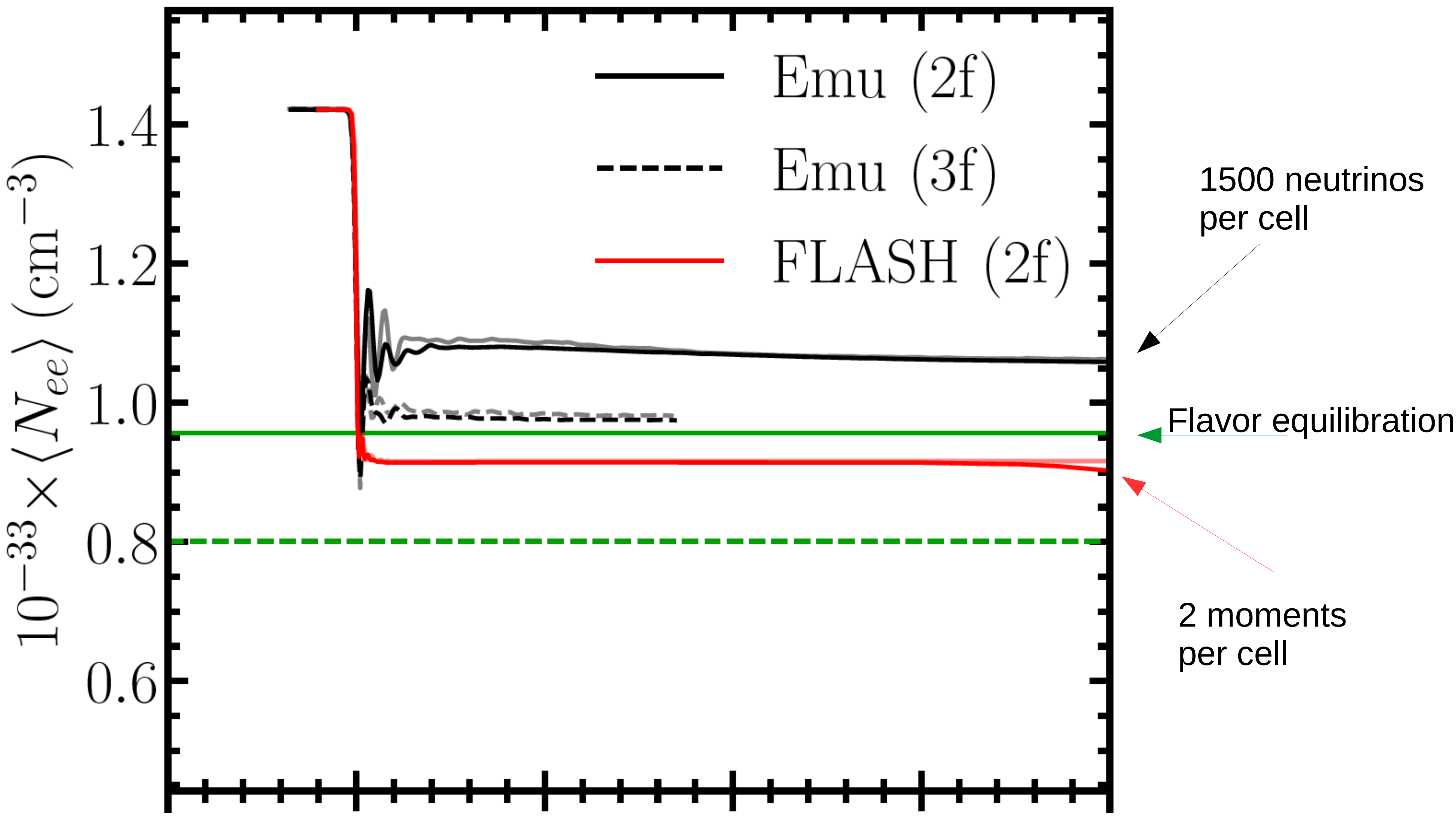
Fast flavor oscillations above a BNS merger (Grohs et al 2022)



Evolving angular moments is an approximation, so how well do key quantities stack up against particle in cell calculations?

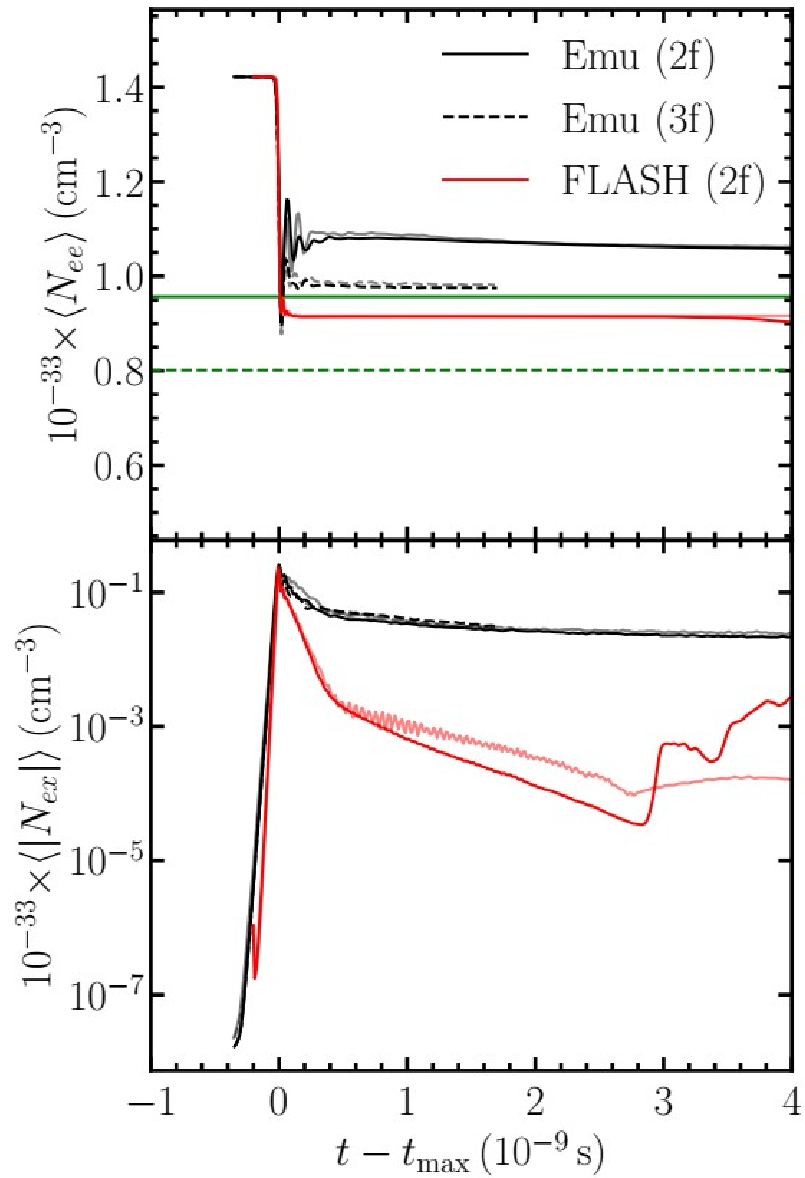
We investigate this by comparing key quantities against Sherwood Richers particle in cell code, EMU.

Growth and saturation, BNS, moments vs PIC



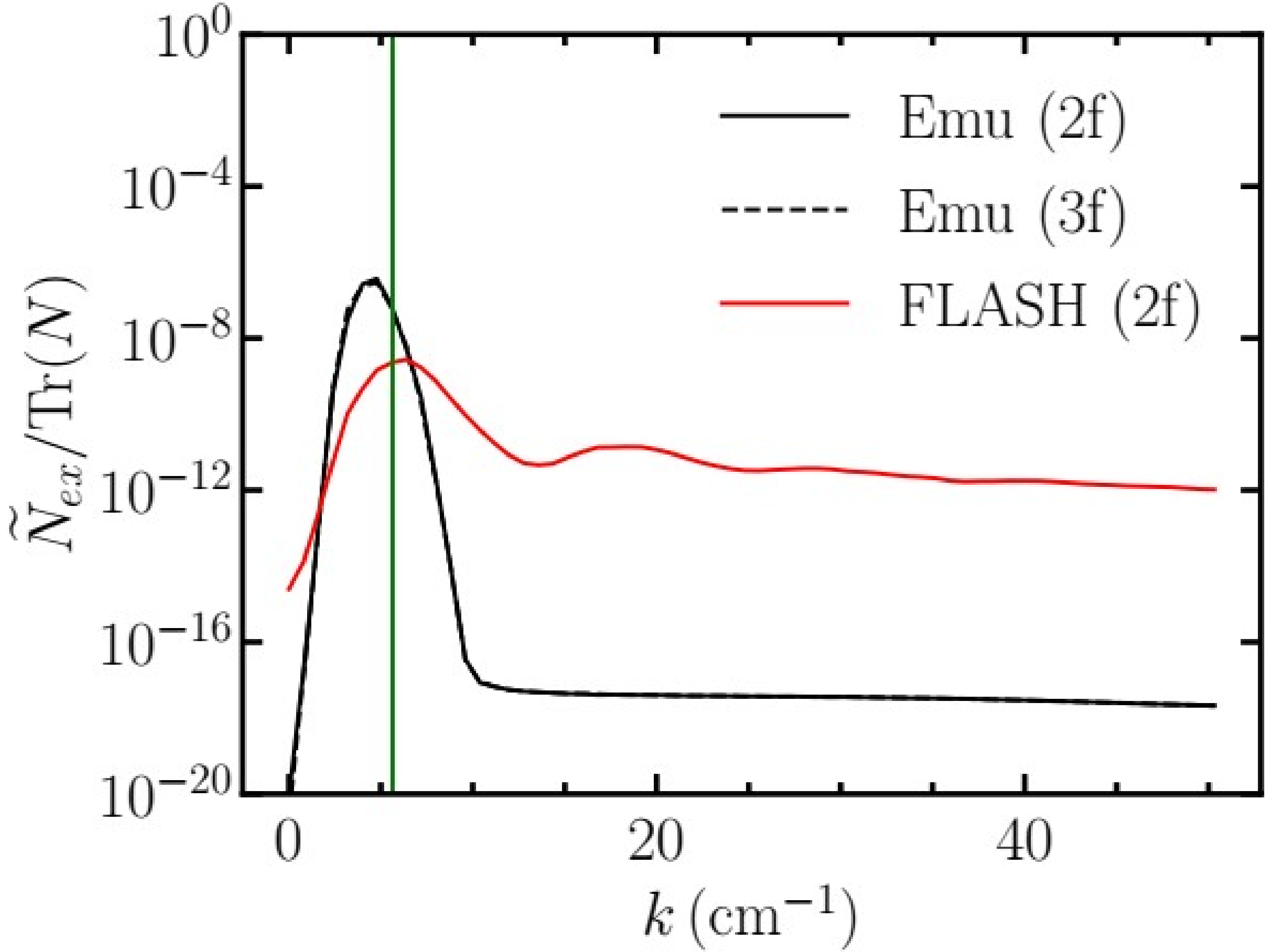
Grohs et al 2022

Growth and saturation, BNS, moments vs PIC



Grohs et al 2022

Fourier transform
BNS, moments vs PIC



Collisions

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

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

Collision term

Convective derivative

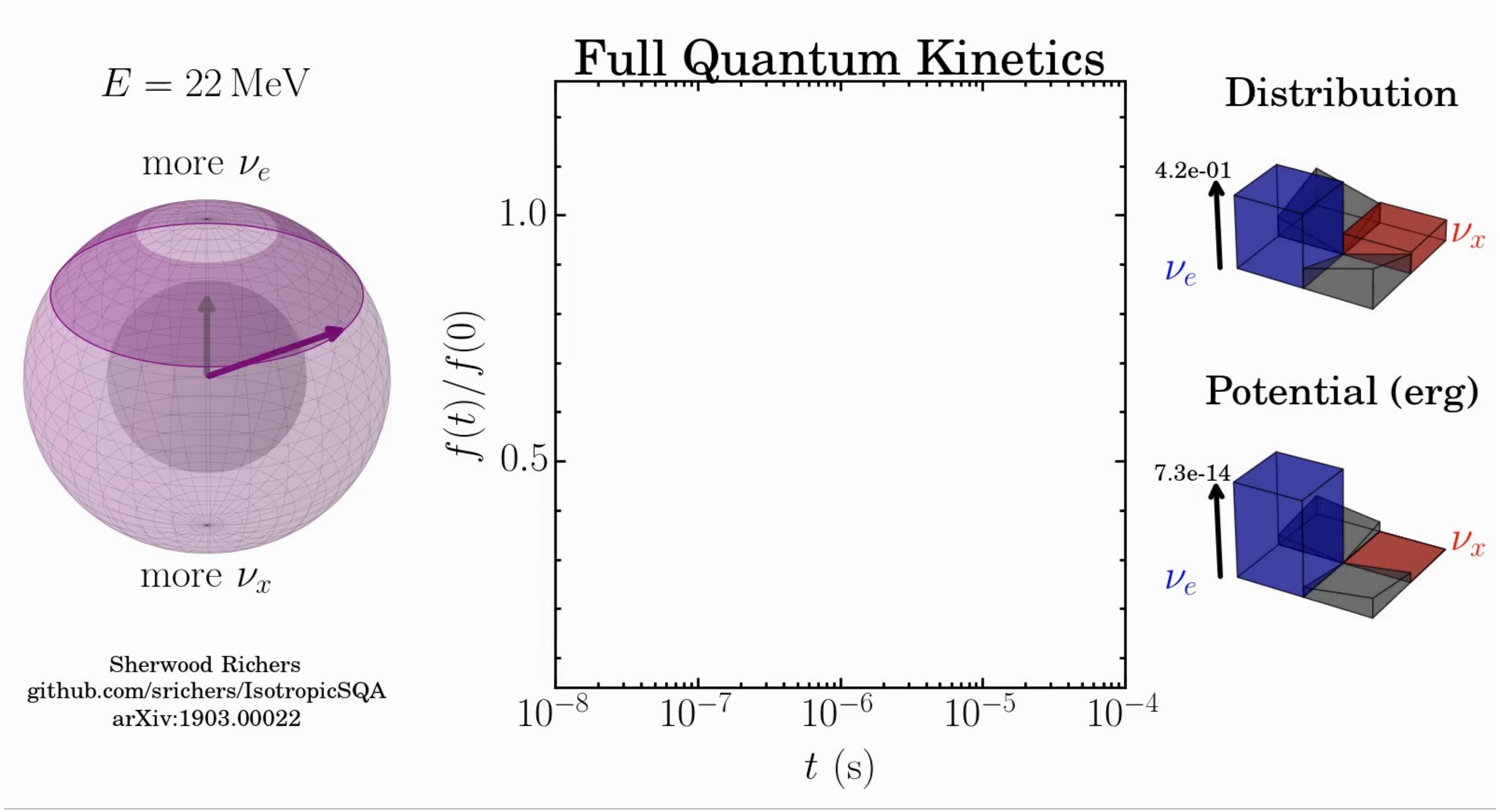
Hamiltonian

Collisions

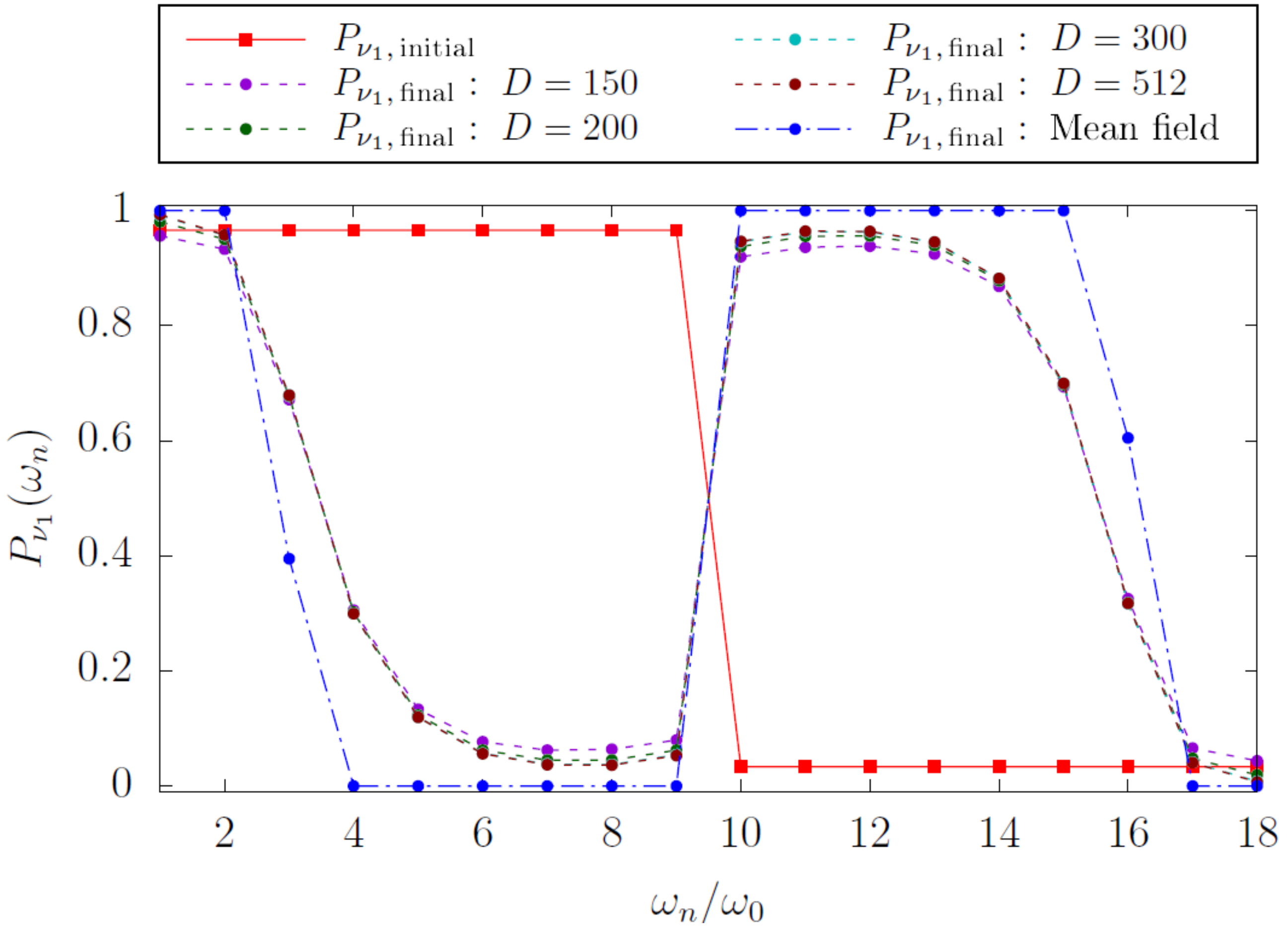
Collisions: scatterings which change energy, momentum, type of particle

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

Oscillations with collisions, isotropic



Alternate approach: many body neutrinos (continuously interacting)



Cervia, Siwach et al 2022

Conclusions

We need to understand neutrinos in astrophysical systems to accurately predict observables including element synthesis, electromagnetic signatures

Involves solving the quantum kinetic equations in astrophysical environments

Starting to make progress on this by examining fast flavor, role of collisions

Some efforts to include flavor transformation in simulations (topic saved for discussions). An essential feature to capture is that a fast flavor conversion eradicates a crossing so global advection is key to understanding what happens (Nagakura 2023)

Lots of activity in this field and also a long way to go