Neutrino flavor transformation in neutron star mergers (and supernovae)

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IReNA

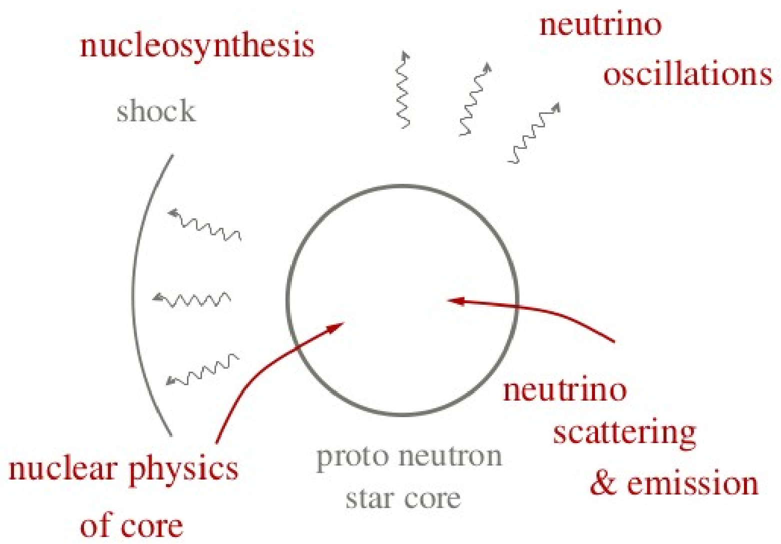
FIRE
Fission In R-process Elements
The FIRE collaboration explores the role of fission in the rapid neutron capture or r-process of nucleosynthesis

U.S. DEPARTMENT OF ENERGY | Office of Science

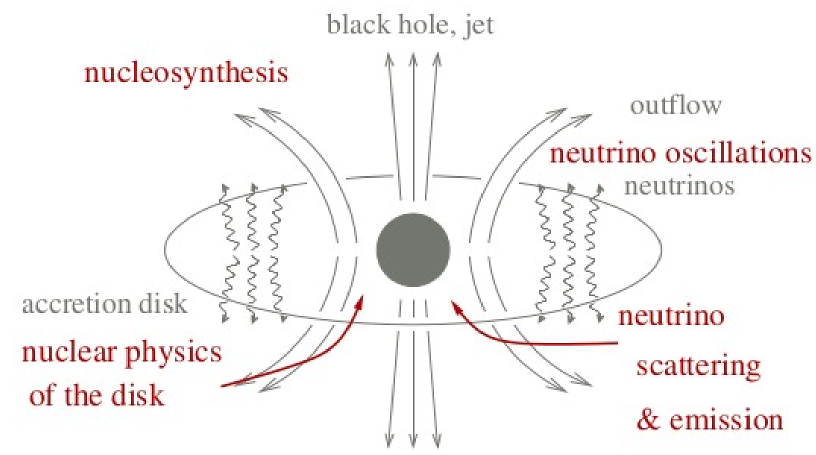
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Microphysics of explosions and mergers



Standard core core collapse SN



Accretion disk from core collapse SN or compact object merger

Specific examples of questions where neutrino physics is needed

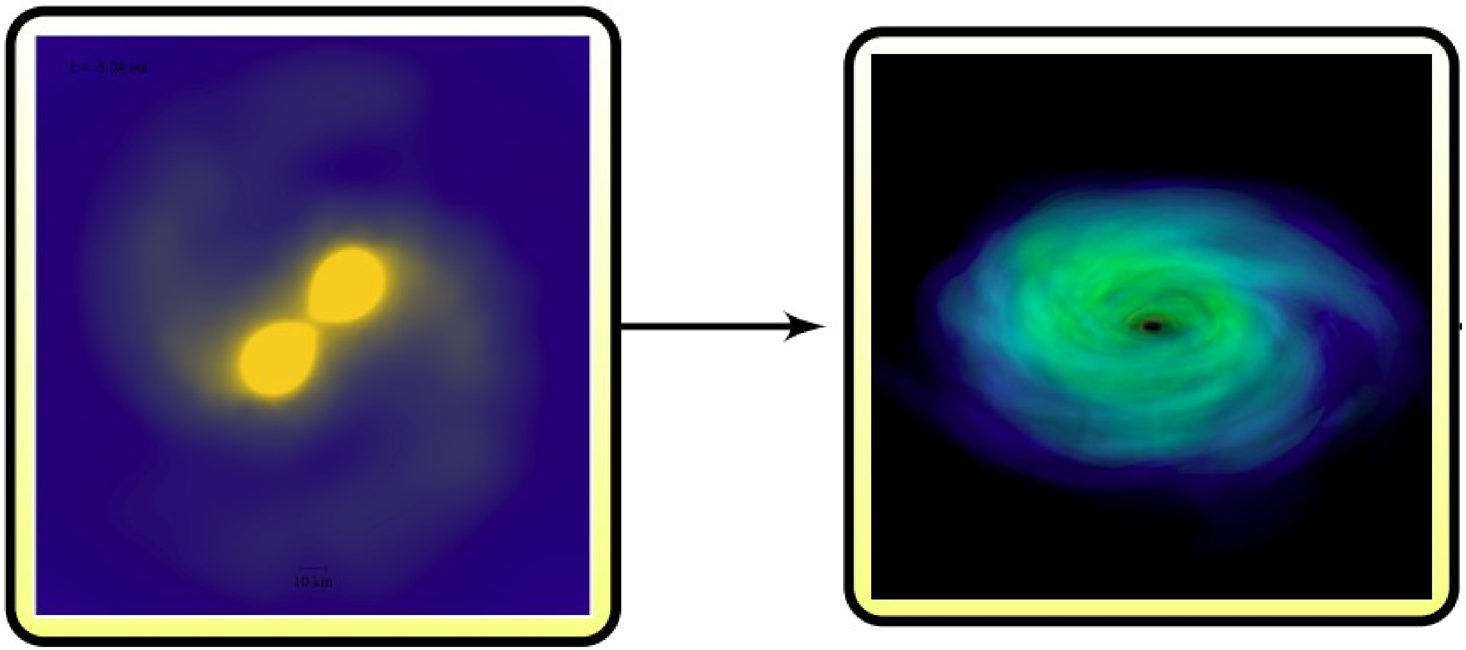
How do neutrinos affect the dynamics of both objects?

What is the spectrum of the emitted neutrinos?

Which r-process elements do neutron star mergers make?

What elements are made in winds?

Neutrino physics changes the outcome of element synthesis



Tidal and collisional ejecta

Wind and viscous evaporation

Fig from talk by Miller 2022

The weak interaction matters

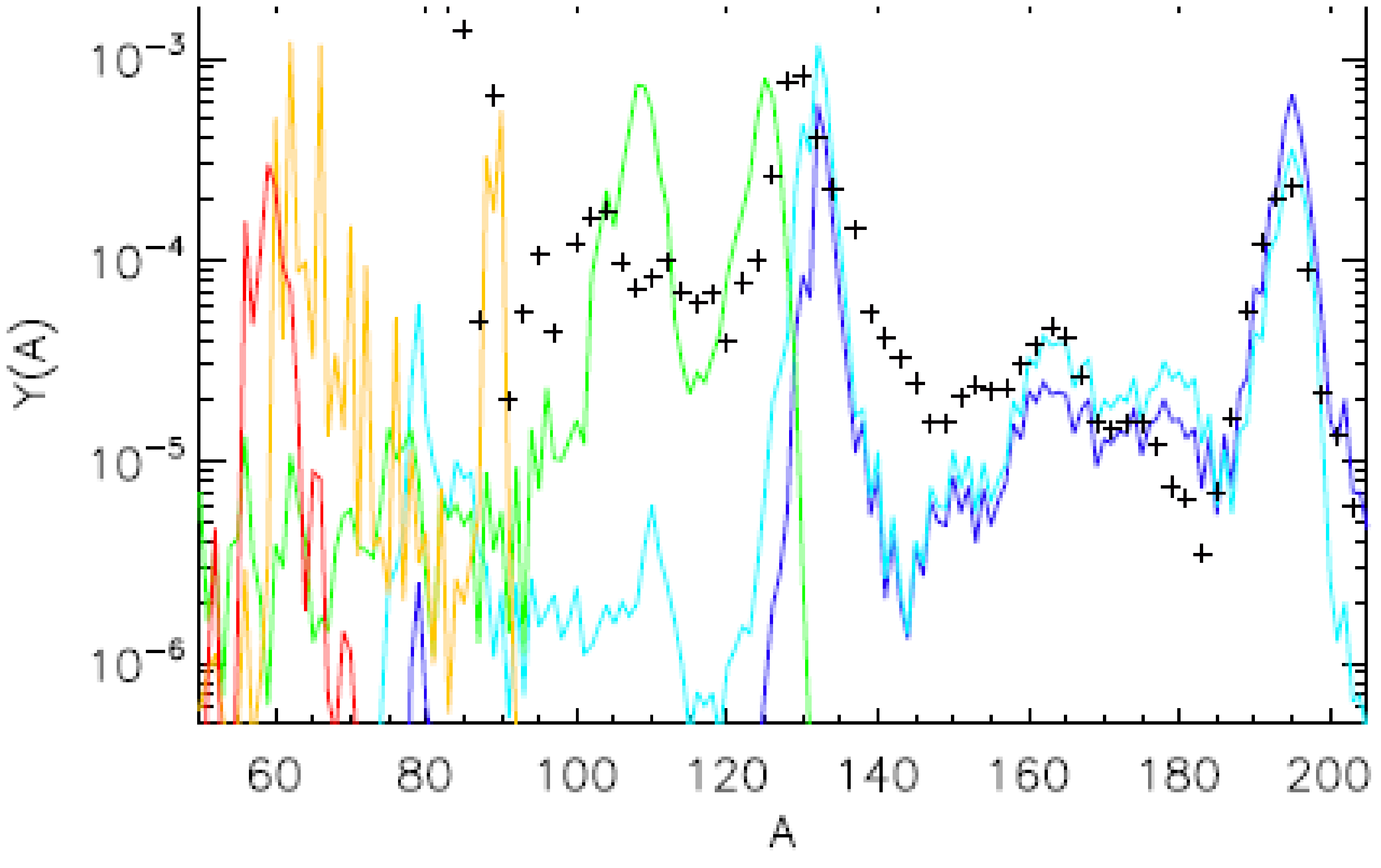
How neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

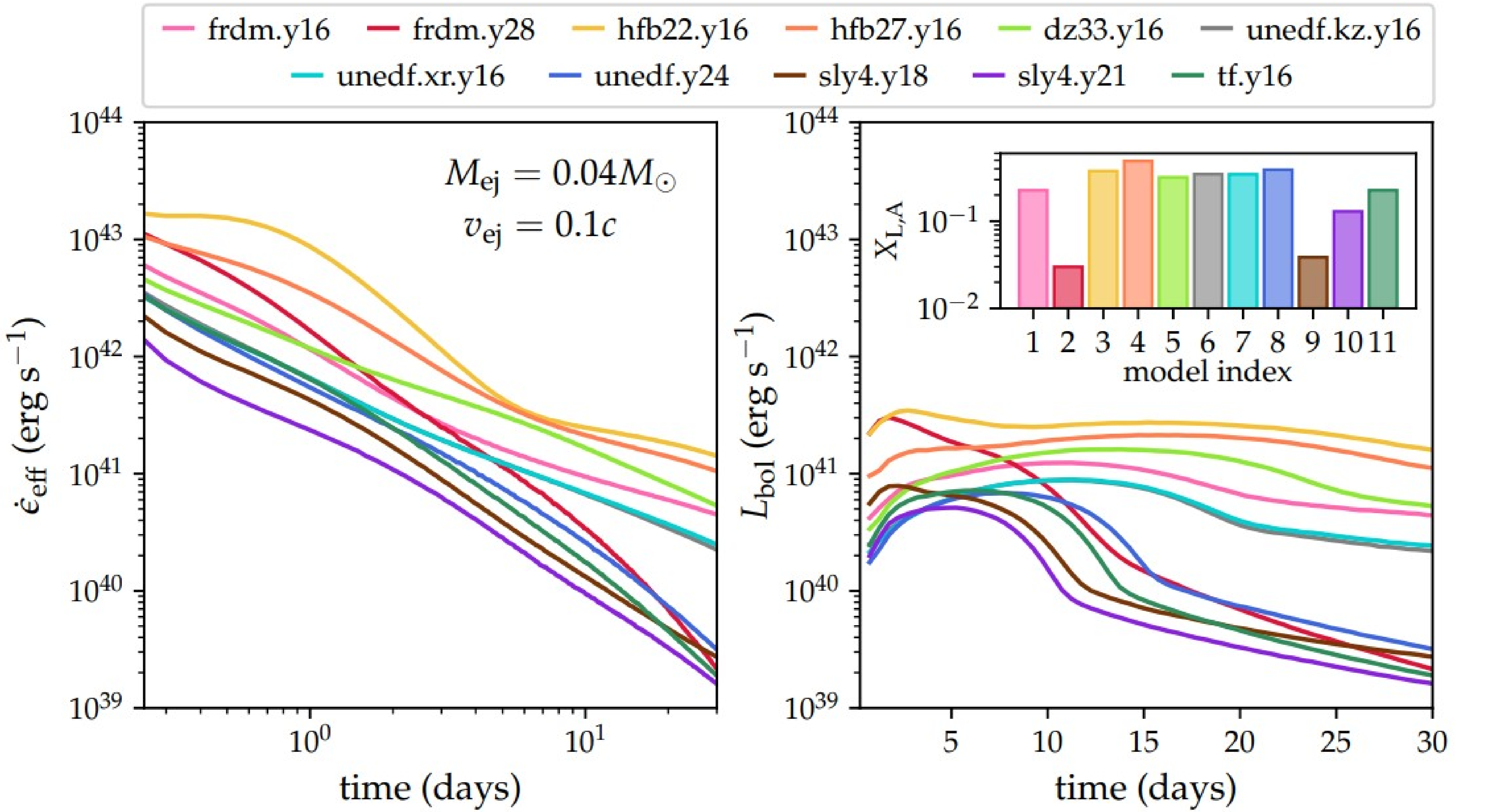
$$\bar{\nu}_e + p \rightarrow n + e^+$$

How much does it matter?



Malkus et al 2016

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



Barnes et al 2021, see also talk by K. Lund

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

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

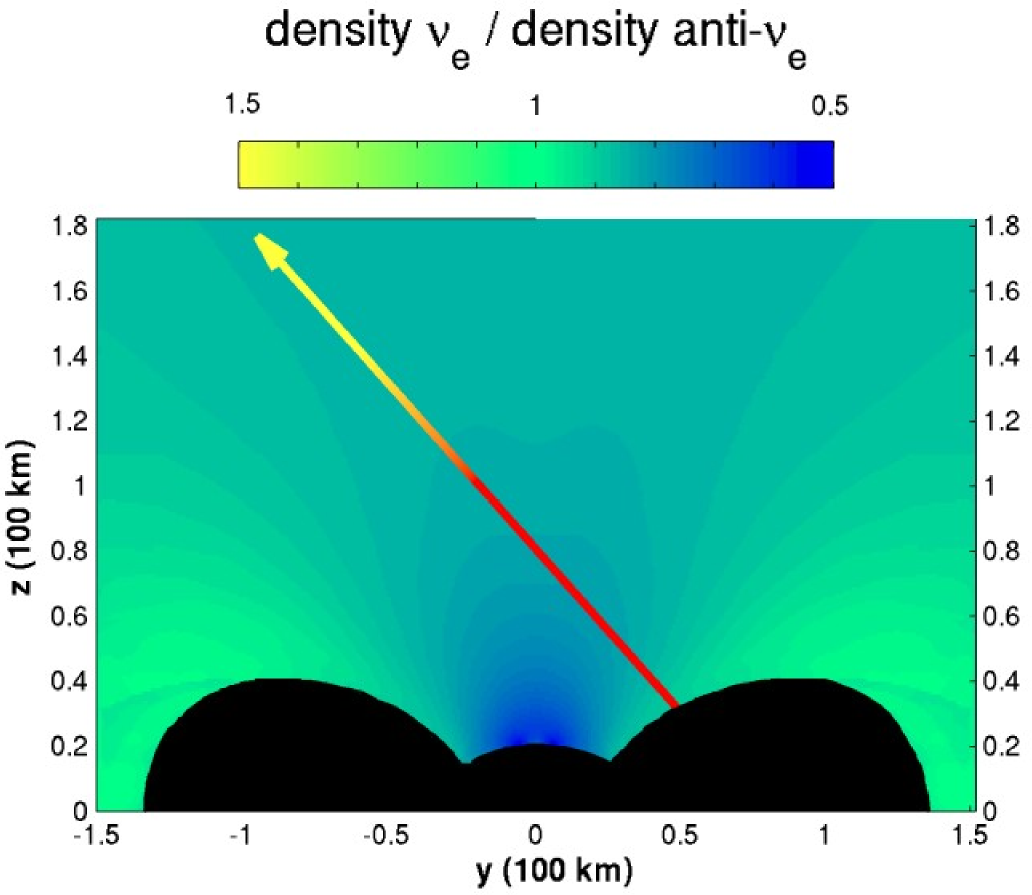
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

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 supernovae and 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)

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

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

Collision term

Convective derivative

Hamiltonian

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

Hamiltonian creates non-linearity

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

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

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

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

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

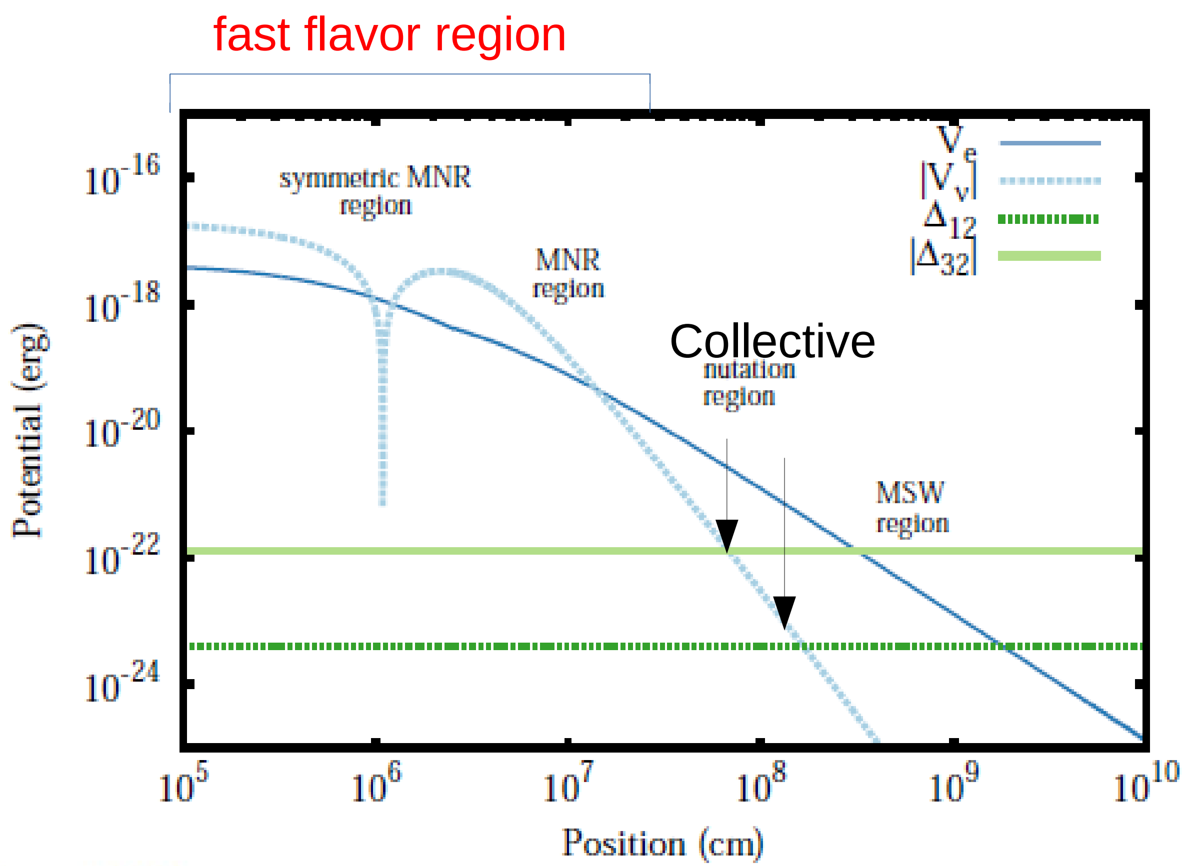


fig. from Malkus et al 2016

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

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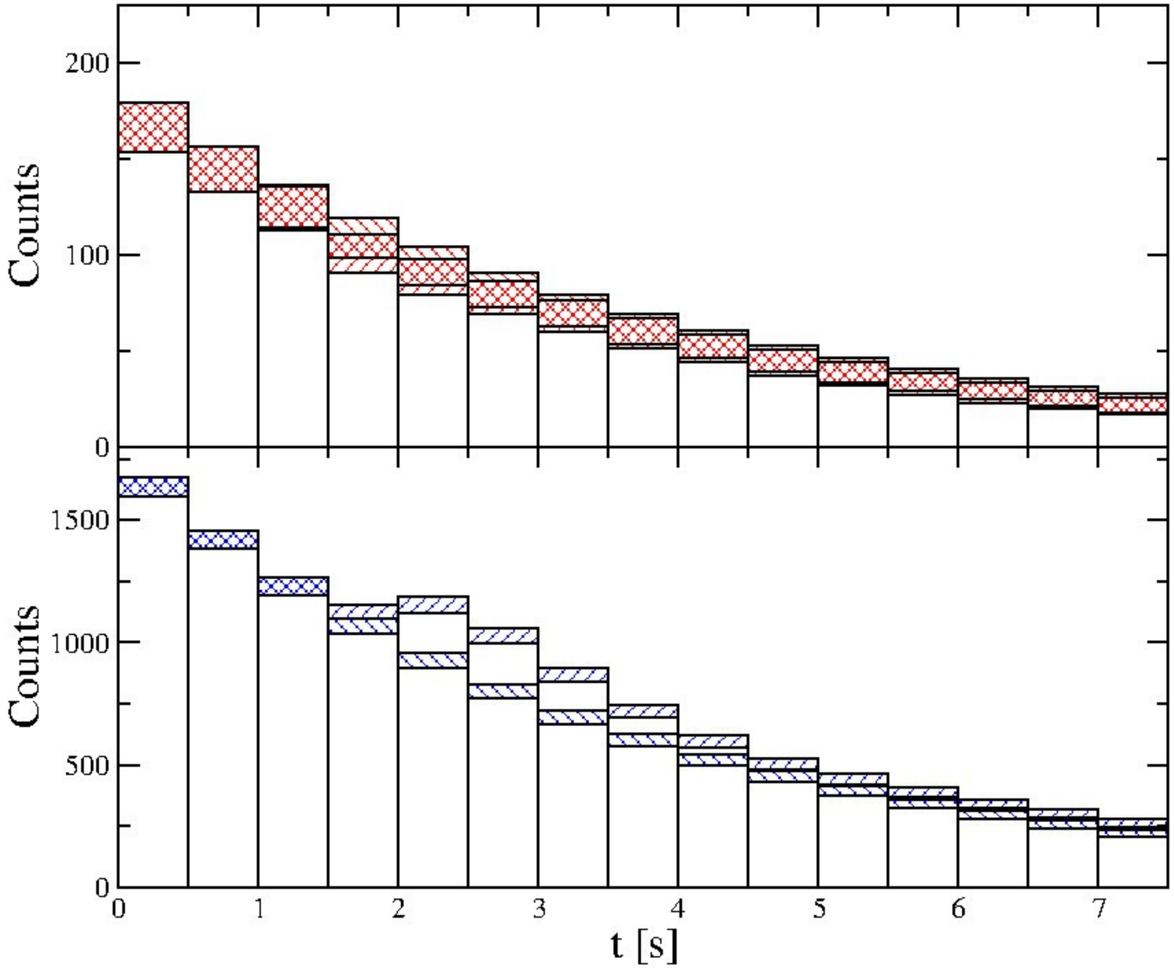
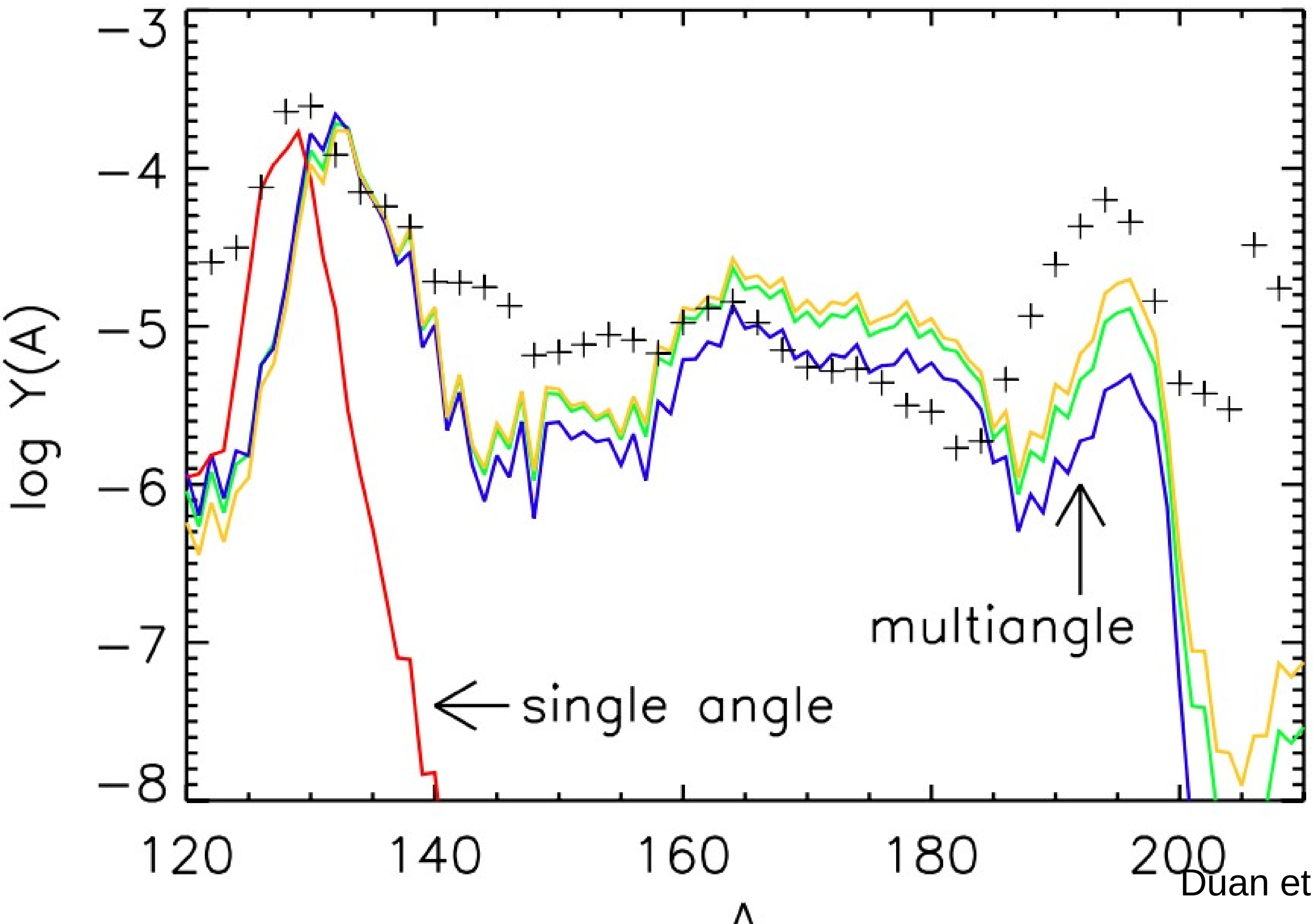
Collective and MSW change on the supernova neutrino time signal



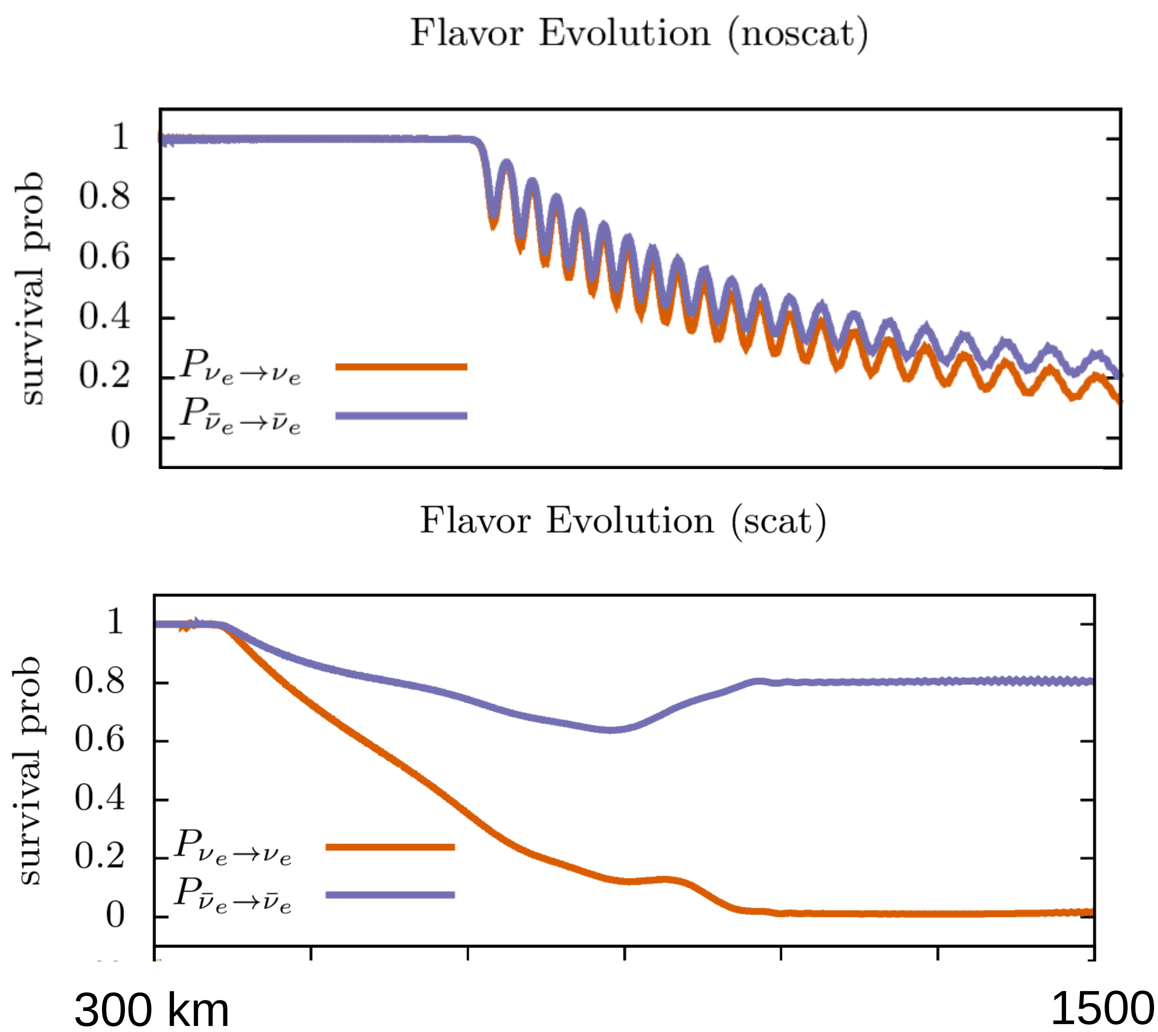
Gava et al 2009

Collective oscillations for supernova nucleosynthesis



Duan et al 2011

Transformation is sensitive to conditions, approximations



Collective

Matter-neutrino Resonance

Deaton et al 2018

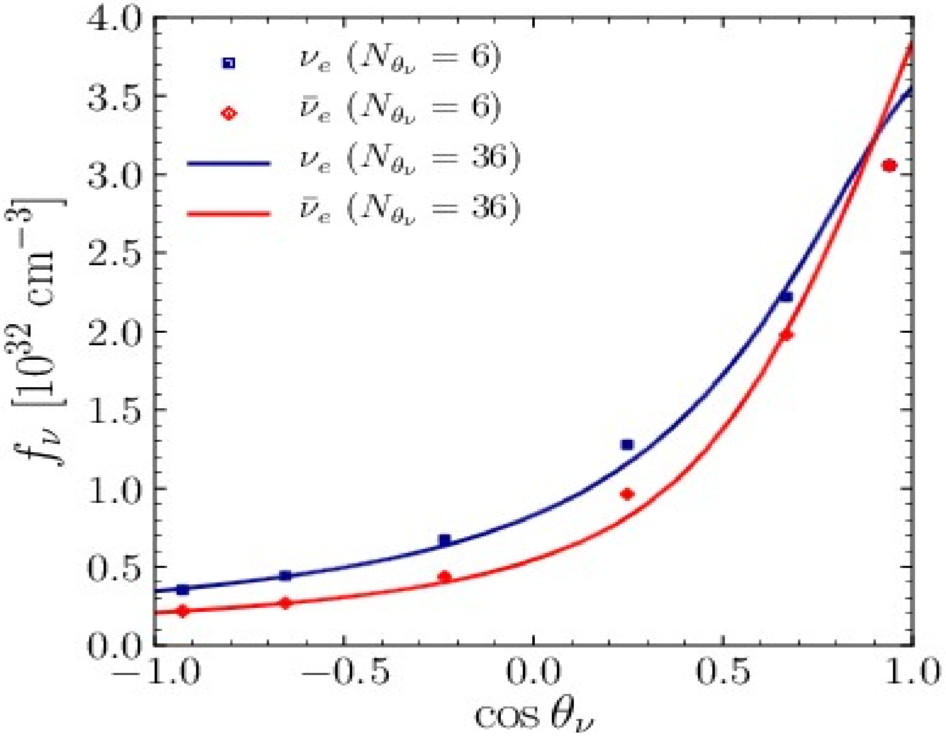
A few of the open issues in neutrino flavor physics

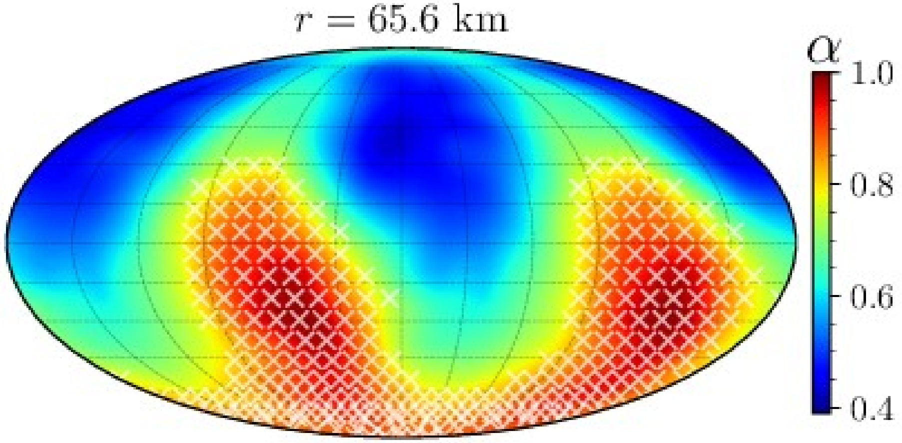
"Fast flavor" oscillations may occur close to the decoupling surface – how to account for these very small scale oscillations consistently

Energy, direction, and flavor changing collisions need to be included self consistently

Flavor transformation physics needs to be included in astrophysical simulations

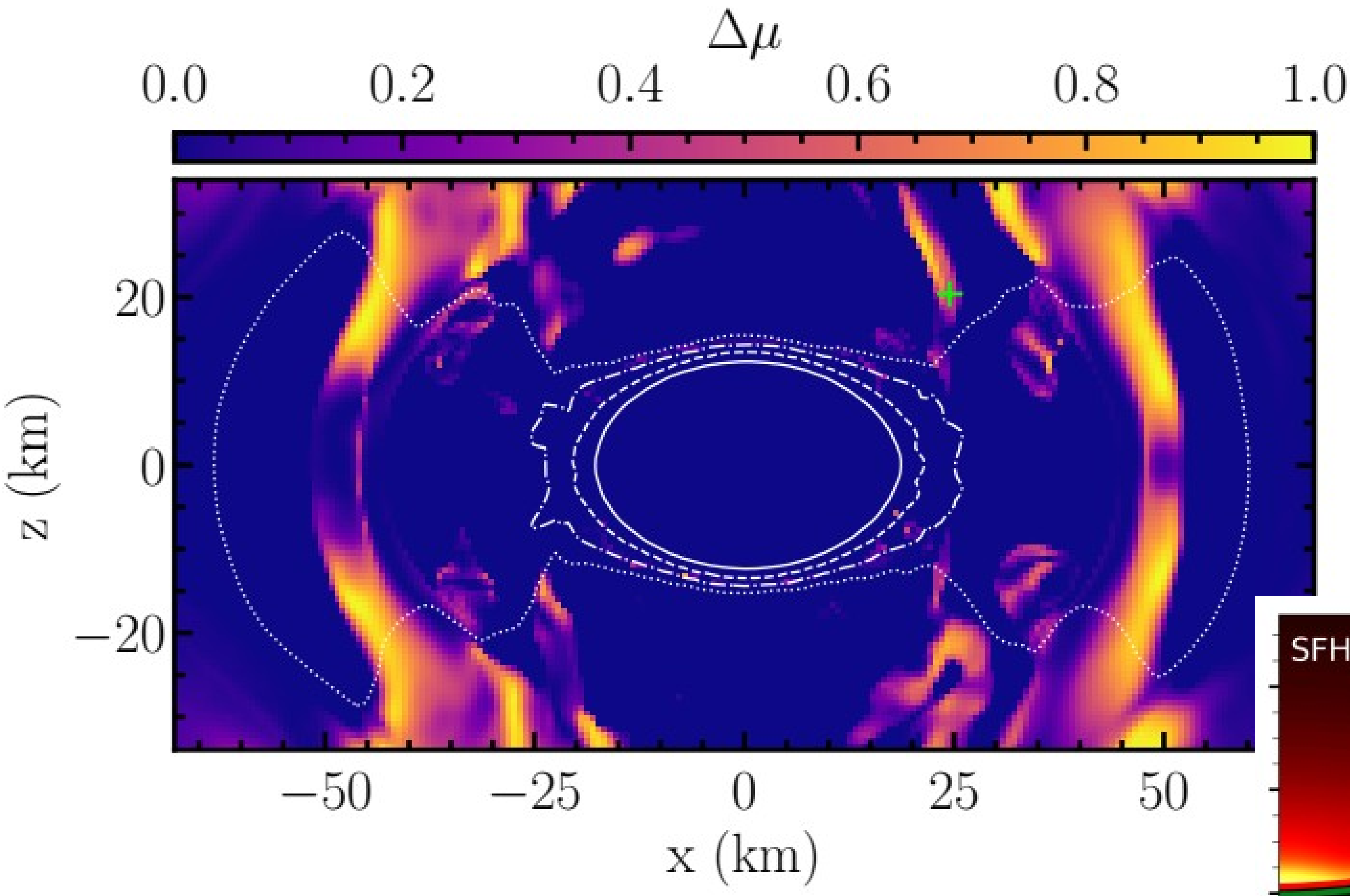
Fast oscillation instability correlated with “crossings”



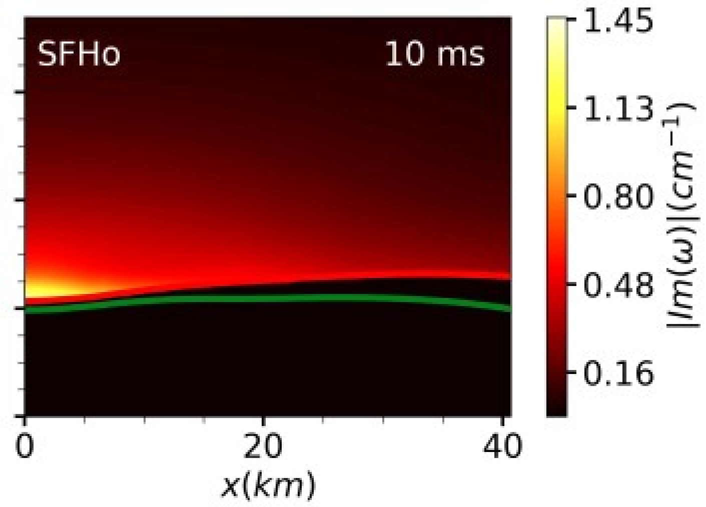


Figures from Abbar et al 2018,
supernova model from Sumiyoshi et al

Crossings in BNS remnant



Grohs, Richers et al 2022, simulation by Foucart



See also Wu et al 2020

Types of techniques for understanding flavor transformation

“Toy” models can be more easily Intepreted, e.g. pendulum below

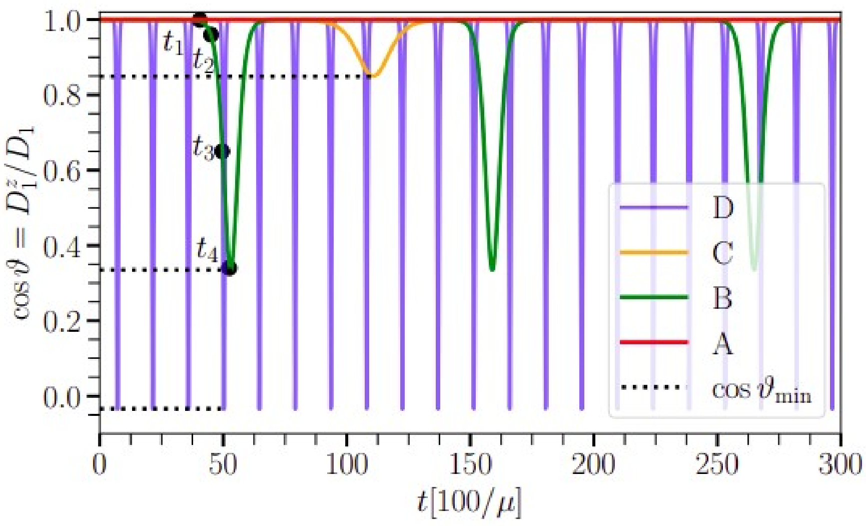


Fig. From Padilla-Gay et al 2021

Solving the QKEs – promises physical realisability

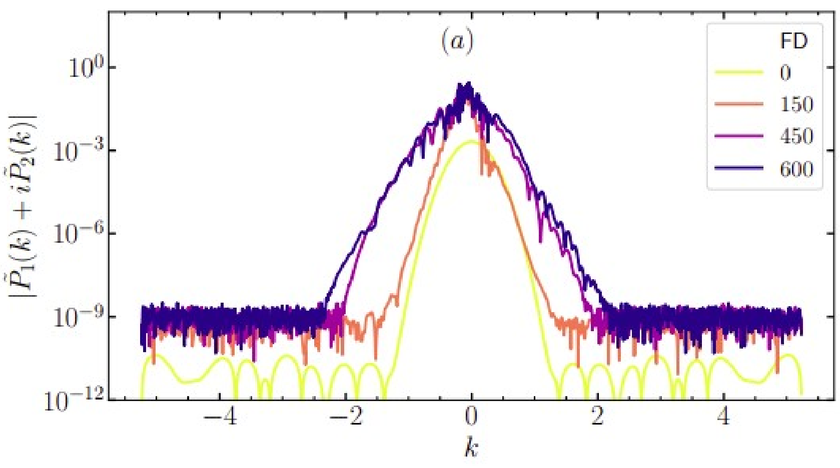
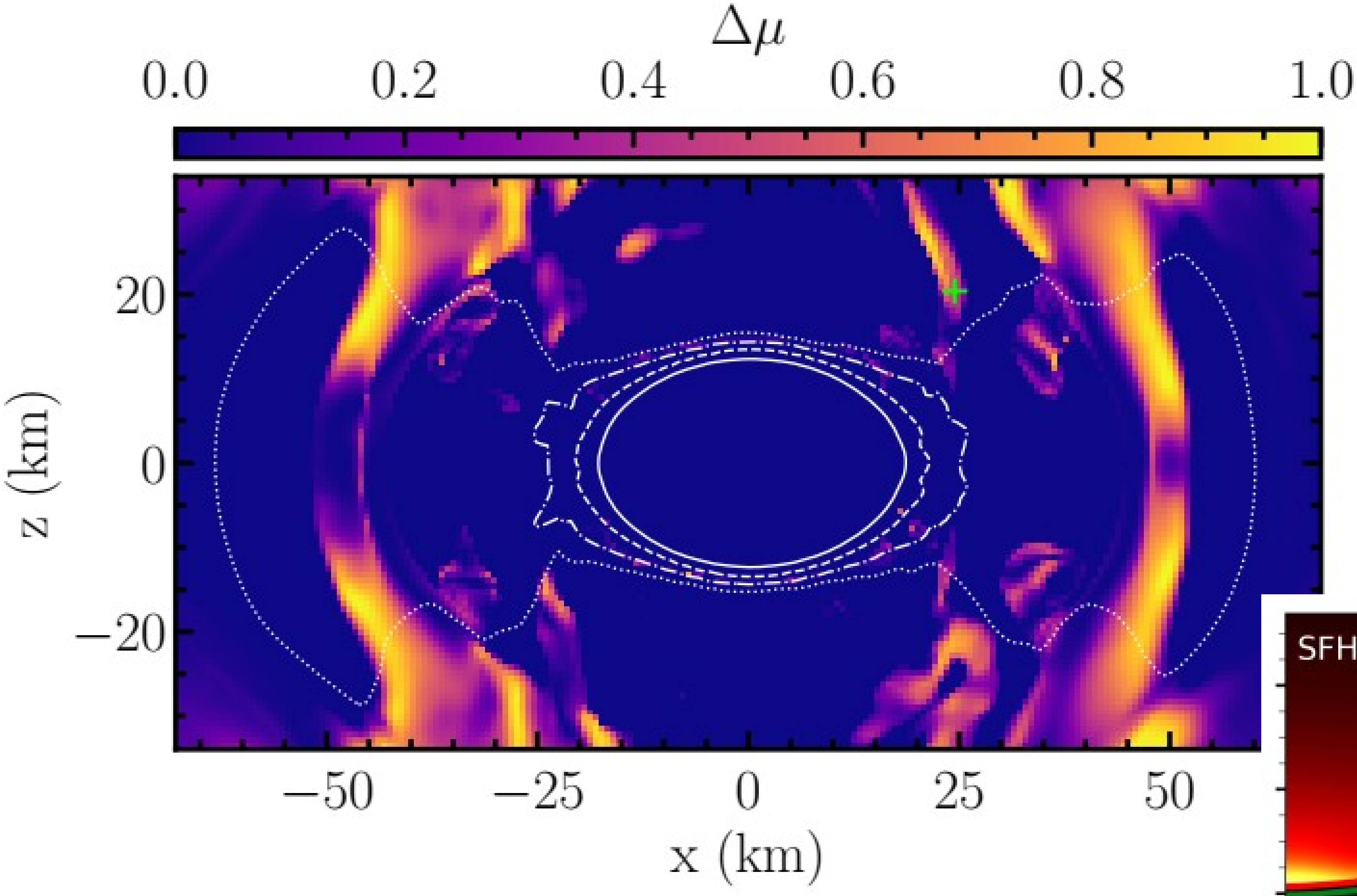
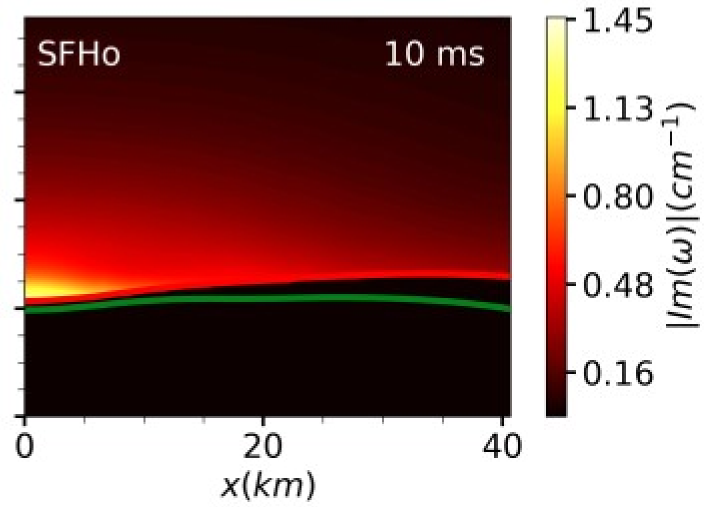


Fig. from George 2022

Crossings in BNS remnant



Grohs, Richers et al 2022



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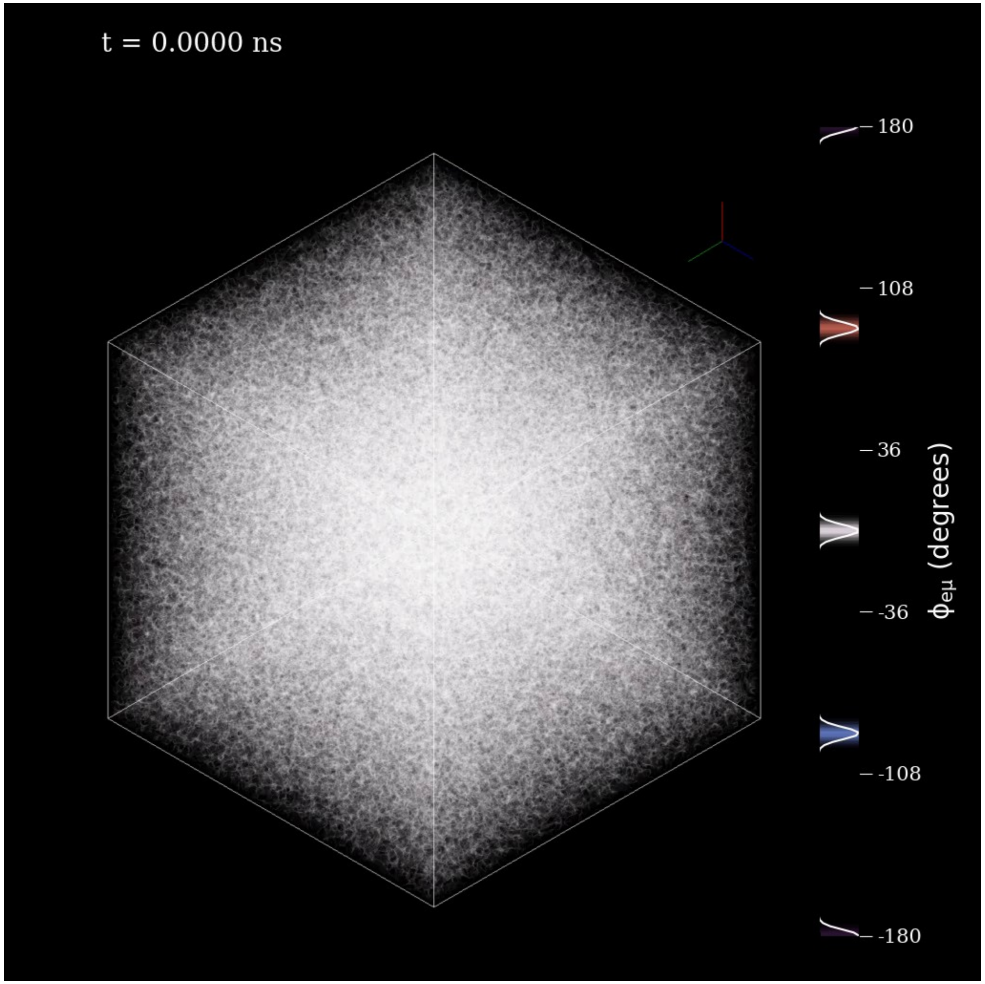
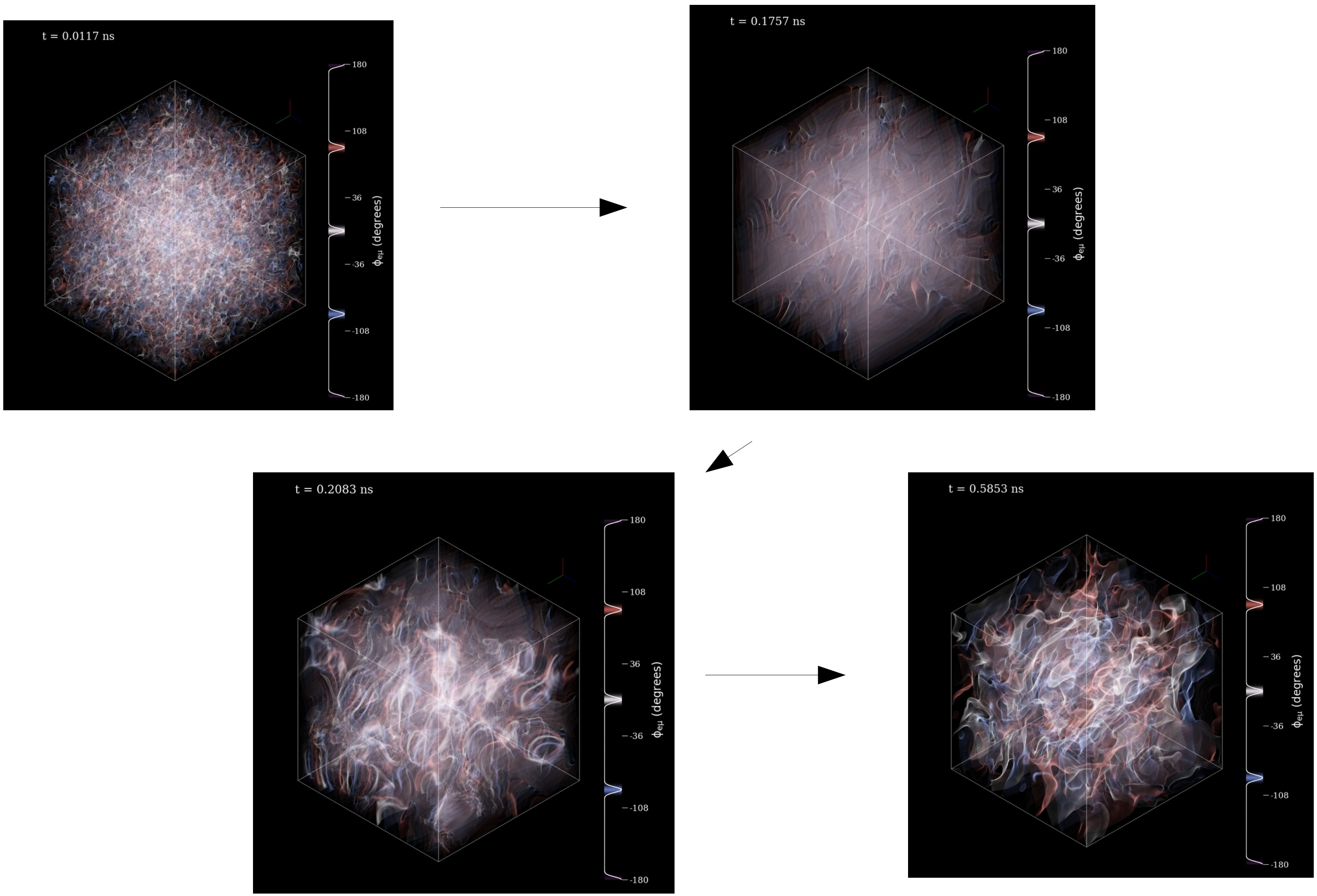
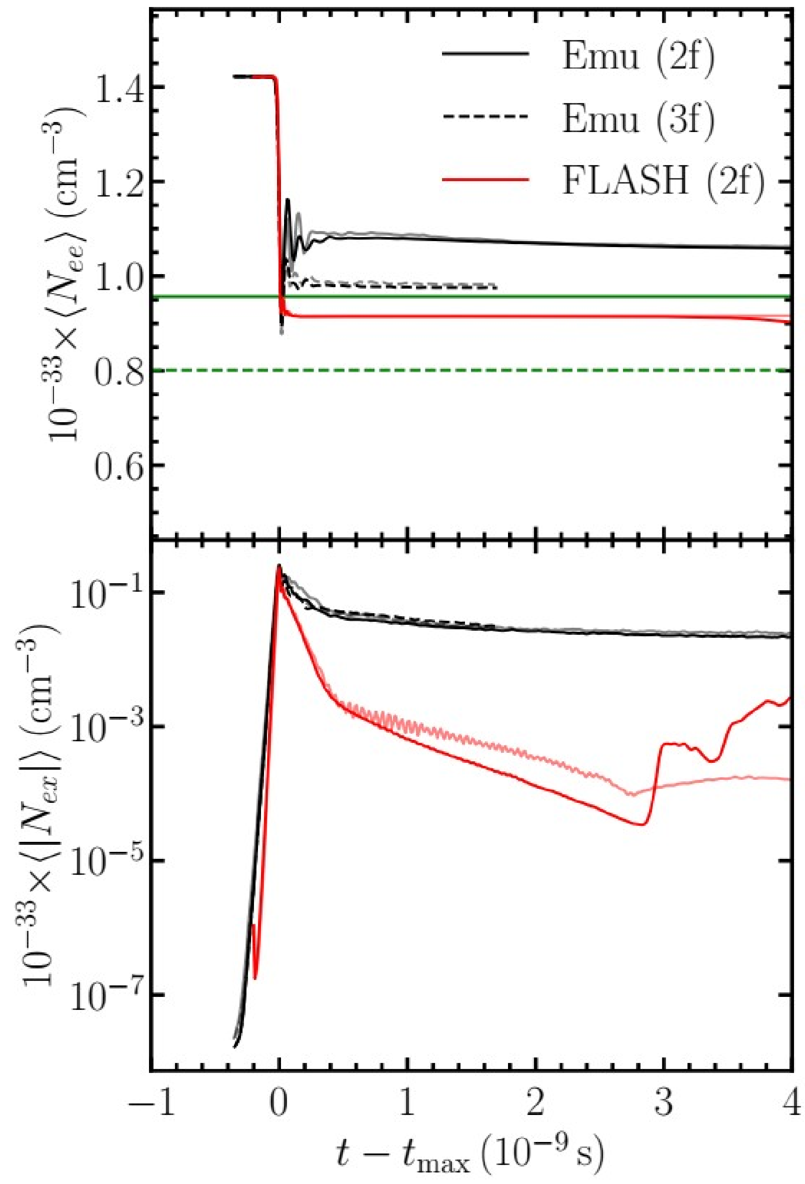
Fast flavor oscillations above a BNS merger (Grohs, Richers et al 2022)



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

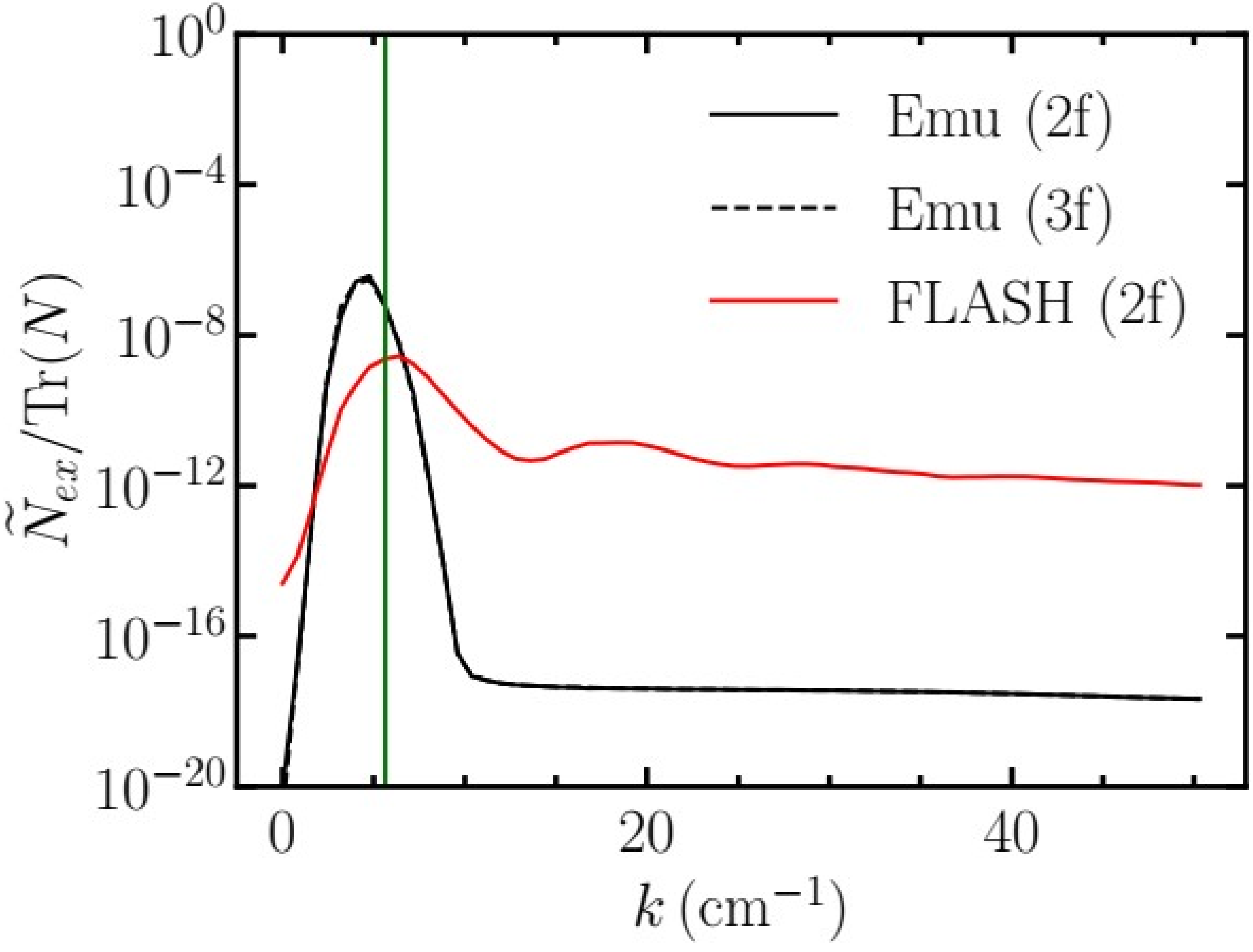


Growth and saturation, BNS, moments vs PIC



Grohs et al 2022

Fourier transform
BNS, moments vs PIC



Collisions

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

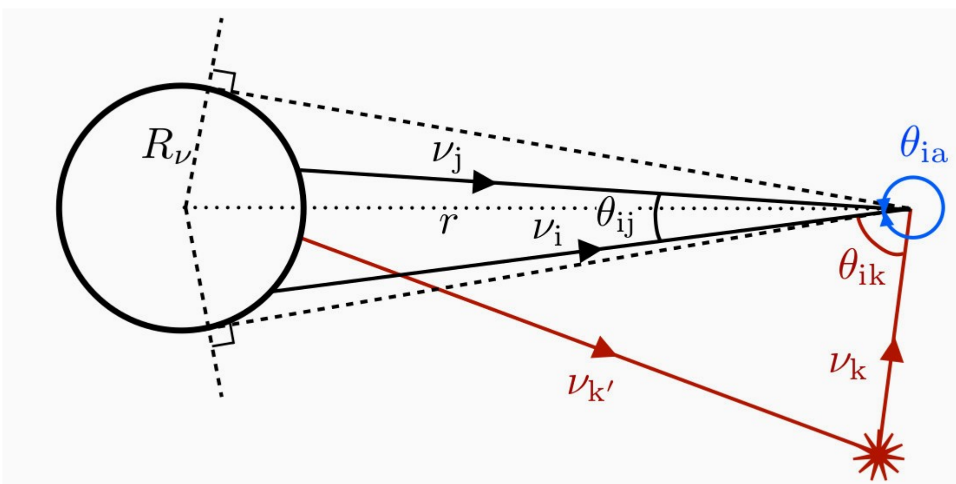
Collision term

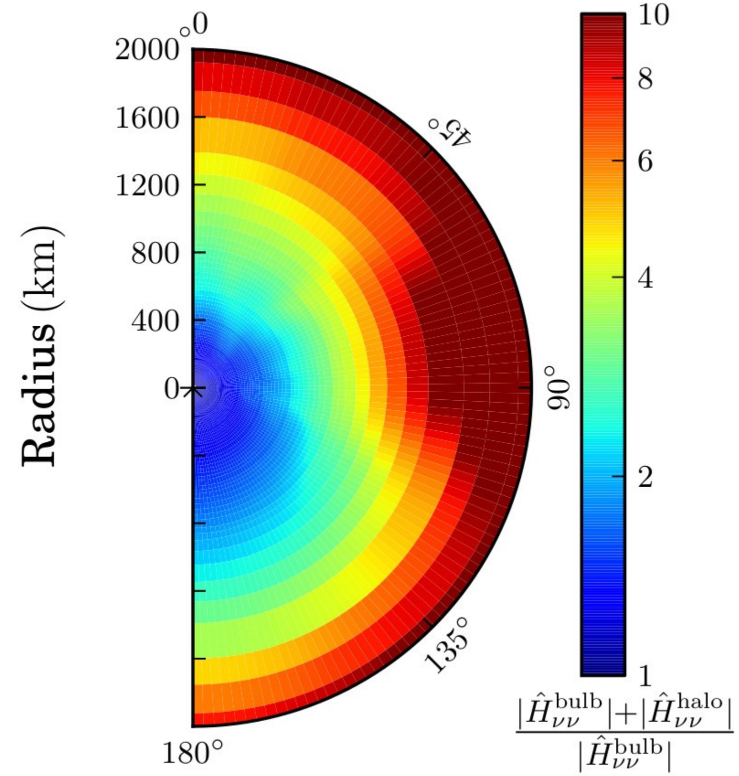
Convective derivative

Hamiltonian

Halo effect, collisions matter

Significant numbers of neutrinos can scatter "backward"





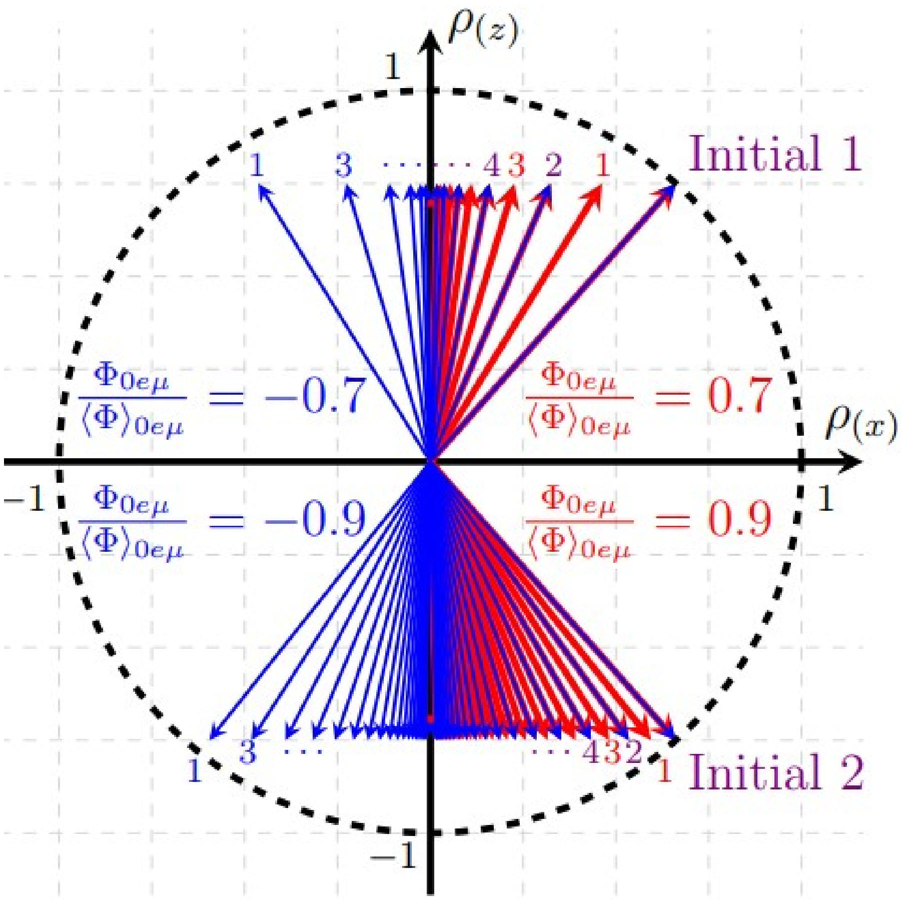
Cherry et al 2012

Collisions

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

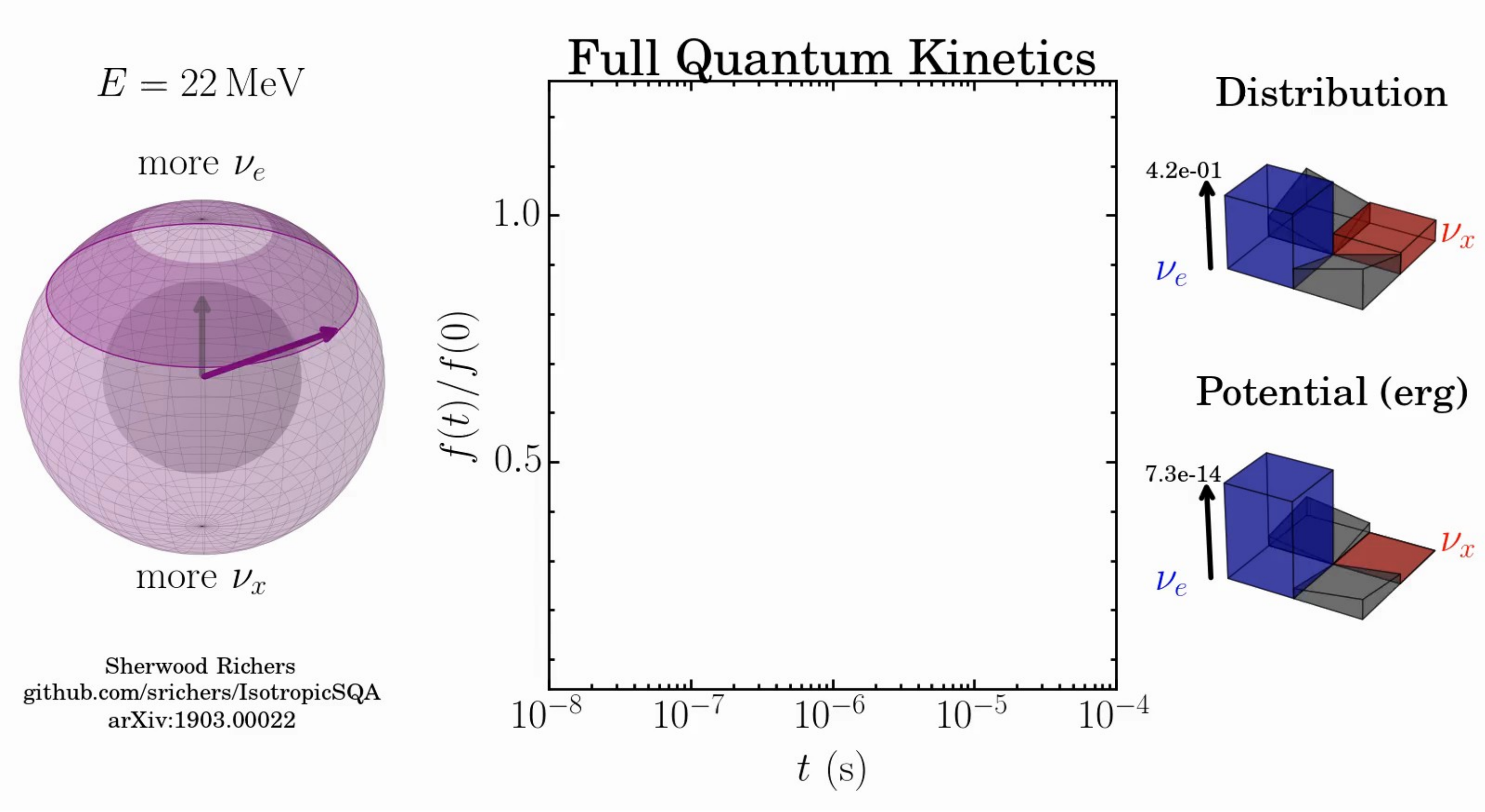
Collisions damp out “mixed” states and send the neutrino system toward pure flavor states (or not! Shalgar et al, Johns et al, talk by Zewei Xiong tomorrow)

A neutrino in a mixed state under the influence of collisions



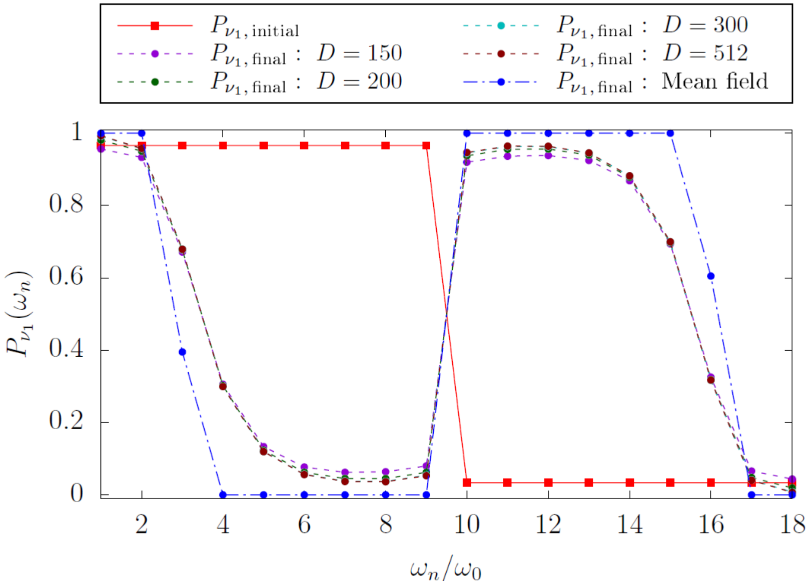
Evolution of flavor vector due to collisions, Fig. from Richers et al, 2019

Oscillations with collisions, isotropic



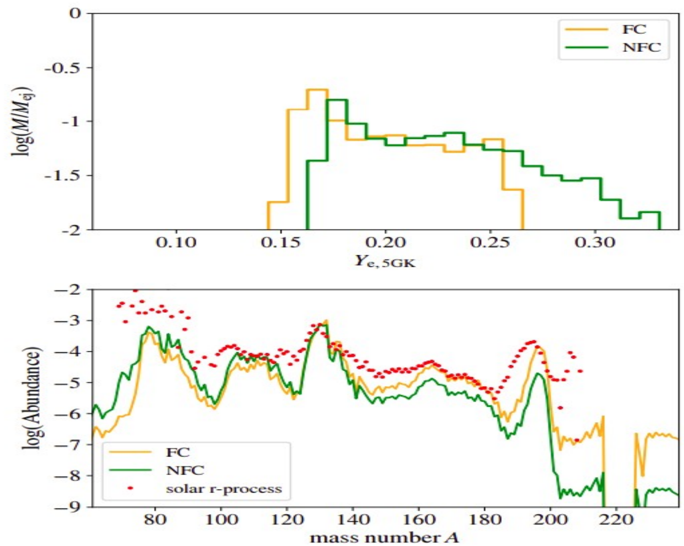
Where we are headed – near term

Testing our assumptions



Cervia, Siwach et al 2022

Inclusion in BNS simulation in approximate way



Li et al 2022

Conclusions

We need to understand neutrinos in astrophysical systems to accurately predict observables including element synthesis, neutrino signals

Involves solving the quantum kinetic equations in astrophysical environments

Starting to make progress on this by understanding fast flavor, making efforts to include full QKEs, understand the usefulness of the mean field approximation

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