

Neutrino Quantum Kinetics

$$\frac{d}{d\lambda} \left[\begin{array}{c} \text{Electron Neutrino} \\ \text{Muon Neutrino} \\ \text{Tau Neutrino} \\ \text{Anti-Electron Neutrino} \\ \text{Anti-Muon Neutrino} \\ \text{Anti-Tau Neutrino} \end{array} \right] = \mathcal{C} \left[\begin{array}{c} \text{Electron Neutrino} \\ \text{Muon Neutrino} \\ \text{Tau Neutrino} \\ \text{Anti-Electron Neutrino} \\ \text{Anti-Muon Neutrino} \\ \text{Anti-Tau Neutrino} \end{array} \right] - \frac{i}{\hbar c} \left[\mathcal{H}, \begin{array}{c} \text{Electron Neutrino} \\ \text{Muon Neutrino} \\ \text{Tau Neutrino} \\ \text{Anti-Electron Neutrino} \\ \text{Anti-Muon Neutrino} \\ \text{Anti-Tau Neutrino} \end{array} \right]$$

$$f_{ab}(\mathbf{x}, \mathbf{p}, t)$$

Different flavors experience different potentials.

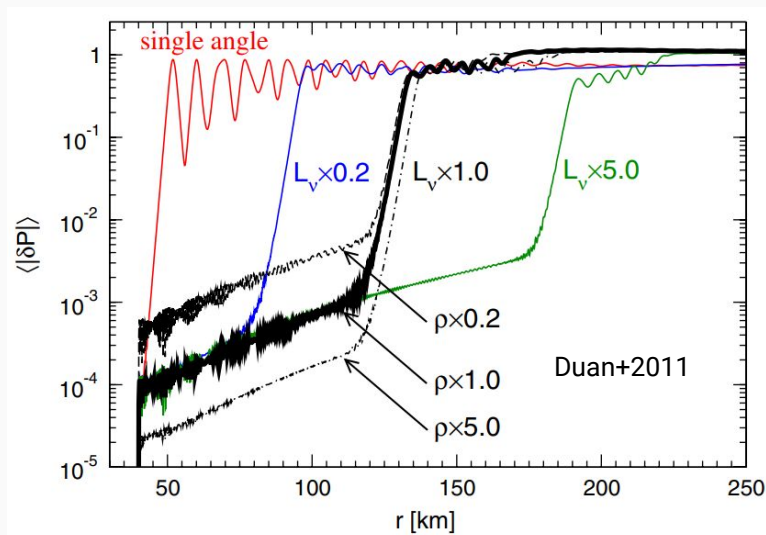
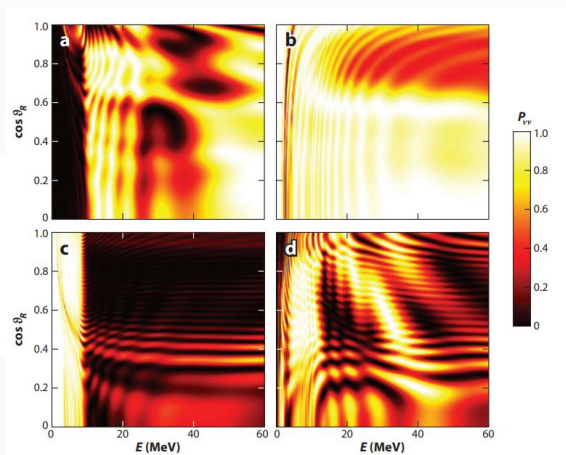
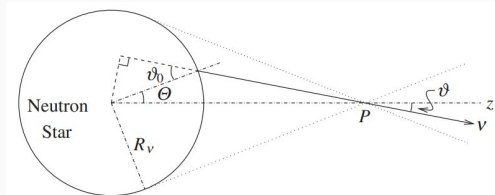
Cardall 2008
Vlasenko et al. 2014
Blaschke+Cirigliano 2016

Ten Years Ago

- Collective oscillations can modify supernovae / nucleosynthesis
 - Duan, Fuller, Quian 2010
- Many toy problems (bipolar, synchronized oscillations)
- Fast flavor instability unknown to everybody but Ray Sawyer
 - Sawyer 2005
- under-resolved bulb model
 - e.g. Duan+2006 10.1103/PhysRevD.74.105014

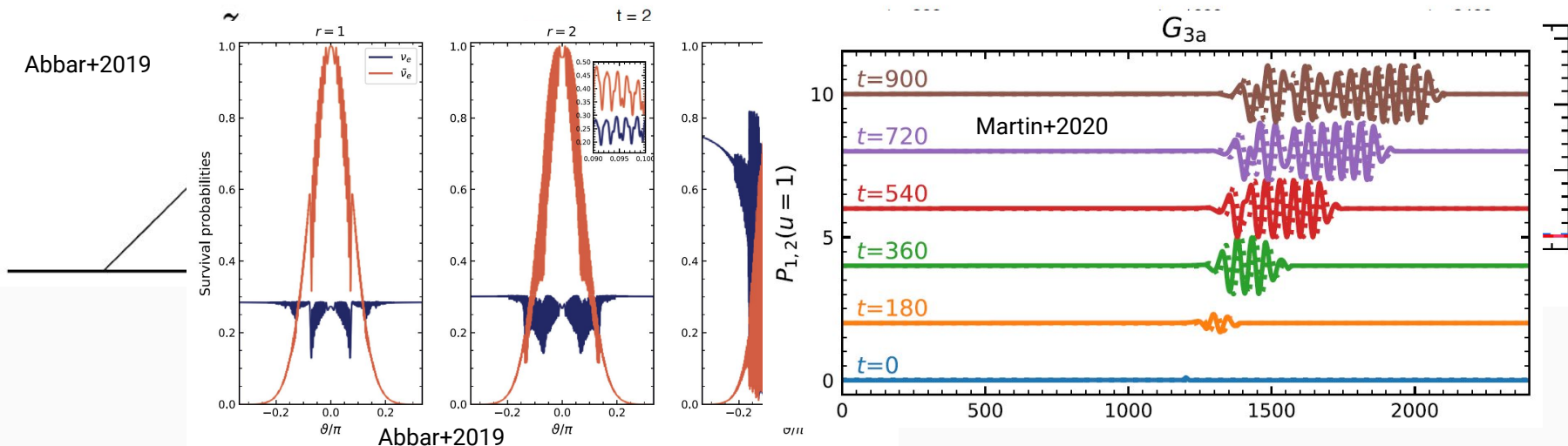
Questions Answered by Simulation

- Multi-angle bulb model simulations → collective oscillations from forward propagating neutrinos **not likely to affect CCSN** mechanism [Duan+2011, Dasgupta+2012, Vlasenko+2018, Zaizen+2020] but can probe non-standard interactions [Stapleford+2016]



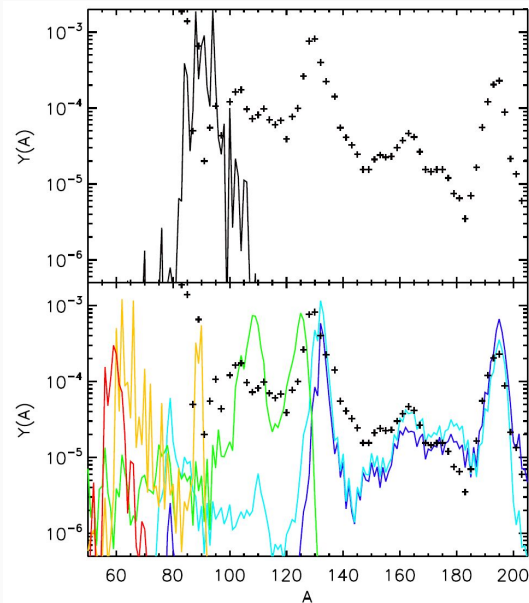
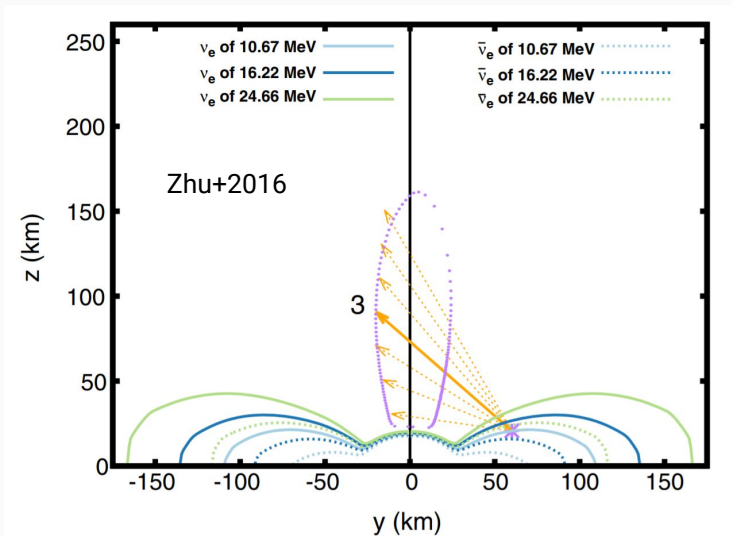
Questions Answered by Simulation

- Many toy problems to **demonstrate MNR, FFI** under loosening restrictions [Väänänen+2016; Dasgupta+2017; Abbar+2019,2019; Martin+2020; Shalgar+2020a,b,c; Johns+2020a,b; Padilla-Gay+2020; Bhattacharyya+2020a,b]



Questions Answered by Simulation

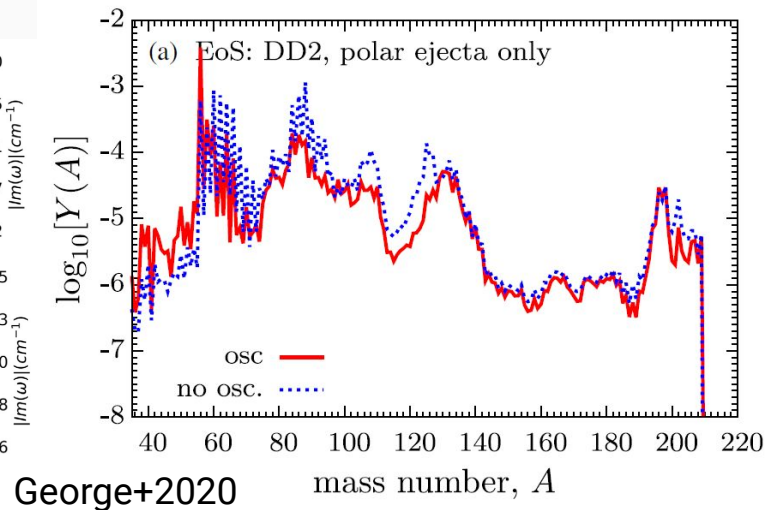
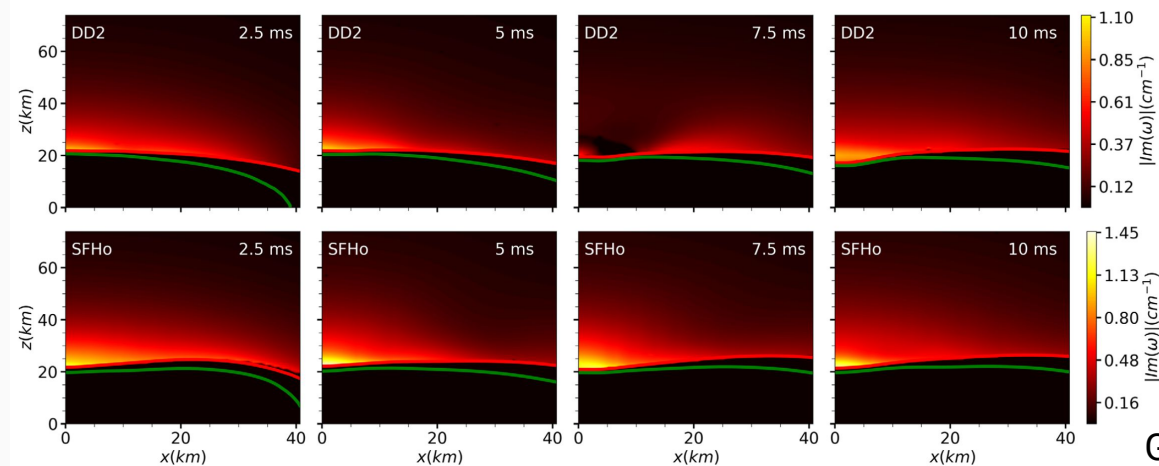
- Merger post-processing, ray tracing → **MNR may enhance or hurt r-process nucleosynthesis**
[Malkus+2012,2014,2016]



Malkus+2016

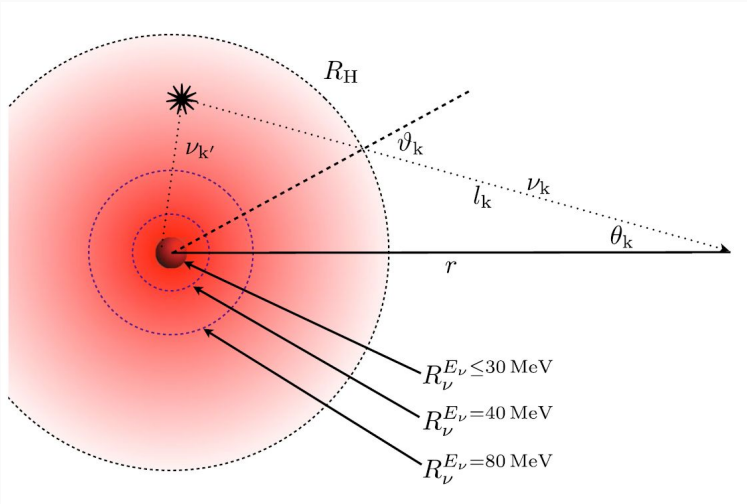
Questions Answered by Simulation

- Merger post-processing, ray tracing/tracers → **FFI likely diminishes r-process nucleosynthesis**
[Wu+ 2017, George+2020]

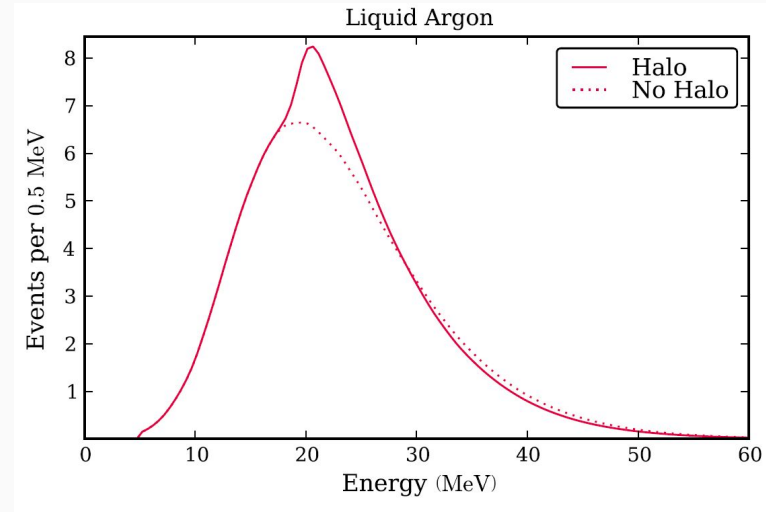


Questions Answered by Simulation

- **Halo effect** modifies neutrino signal [Cherry+2012,2013,2020; Sarikas+2012; Cirigliano+2018; Morinaga+2020]

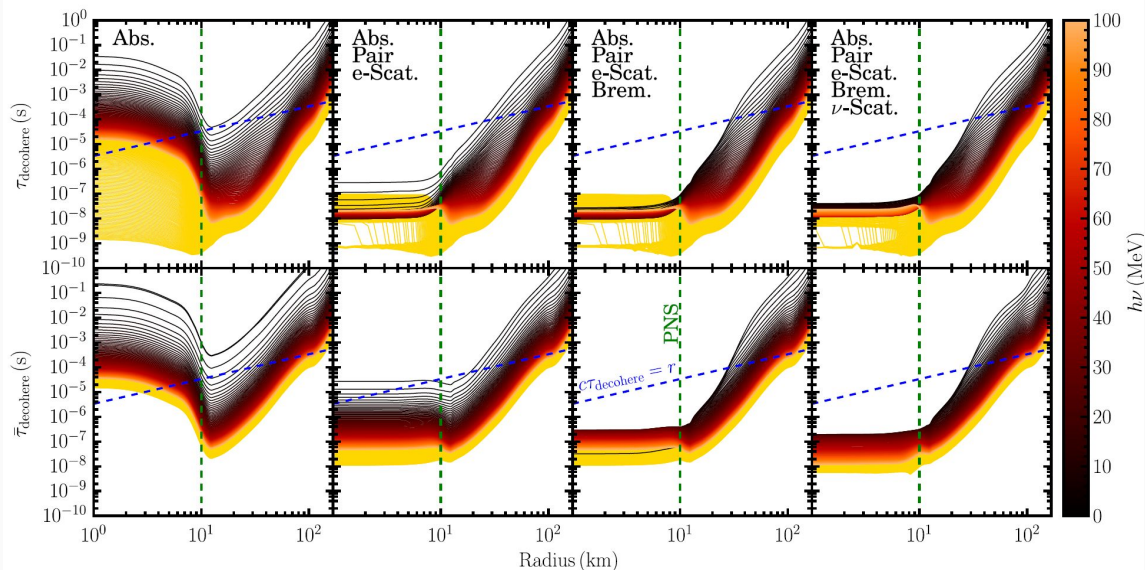


Cherry+2013



Questions Answered by Simulation

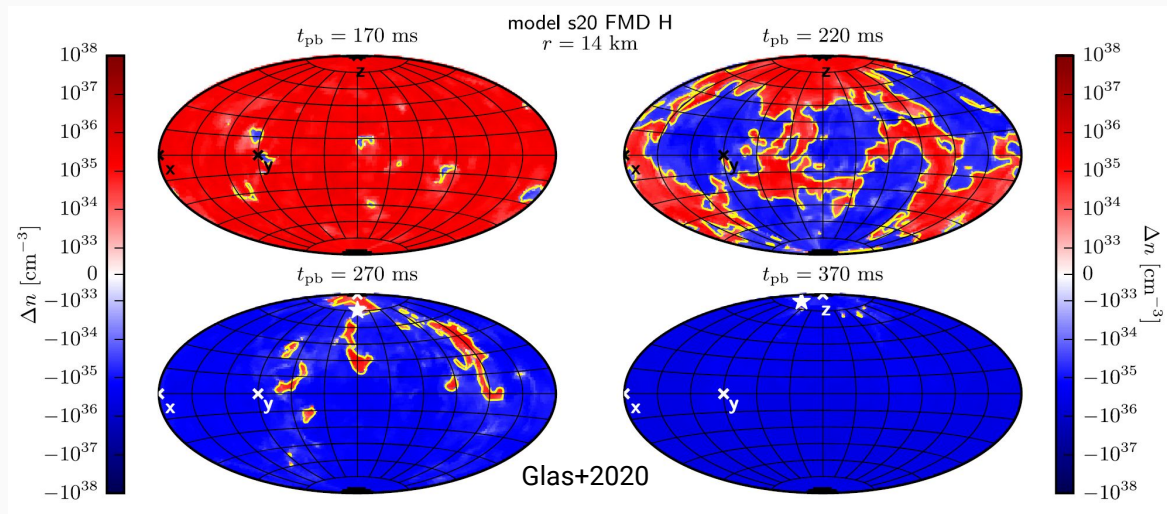
- Coupling reaction rates to oscillation calculations → **we can simulate quantum kinetics**
[Capozzi+2019, Richers+2019, Shalgar+2020]



Richers+2019

Questions Answered by Simulation

- Multi-dimensional CCSN/merger simulations used in post-processing to **predict instabilities**
[Tamborra+2017; Abbar+2019,2020; Azari+2019,2020; Nagakura+2019; Xiong+2020; Morinaga+2020; Glas+2020]



10-year Questions

- What does the **FFI** do to neutrino distributions?
- What **information about a supernova** can be interpreted from neutrinos that have undergone FFC, MNR, halo effect, etc?
- Should we expect a substantial departure from our understanding of the **CCSN mechanism** and CCSN/merger **nucleosynthesis** if {NSIs, FFI, spin coherence, sterile neutrinos, MNR, Halo Effect} exist?
- How do **collisions and oscillations** modify each other?
- In addition to state of the art simulations, can we produce a state of the art “**error bar**”?
- How do we cultivate an ecosystem of **open codes and data**.

10-year Questions

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Parameter sweep using
**direct flavor
transformation
simulations.**

10-year Questions

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2D, 3D simulations with
**sub-grid flavor
transformation**

1D time-dependent
neutrino halo simulation

10-year Questions

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Parameter sweep using **direct flavor transformation simulations.**

2D, 3D simulations with **sub-grid flavor transformation**

1D **full-star quantum kinetics** simulations

2D, 3D simulations coupling flavor transformations to **tracer particles**

Improved **“regular” neutrinos** in simulations

10-year Questions

- How do **collisions and oscillations** modify each other?

2D, 3D simulations with
**sub-grid flavor
transformation**

1D **full-star quantum
kinetics** simulations

10-year Questions

- In addition to state of the art simulations, can we produce a state of the art “**error bar**”?

2D, 3D simulations
coupling flavor
transformations to **tracer
particles**

Standard **test problems**,
code comparisons,
open codes/data

Available Codes

- Convert “regular” neutrino transport to include oscillations (sub-grid or direct)
 - Bolztran, FLASH, ALCAR, Fornax, Sedonu, “The Boltzmann code”, ...
- Convert oscillation codes to include collisions
 - IsotropicSQA
- Write custom kinetics codes
 - a few are being worked on

Cost Estimate

- Multi-angle bulb model - thousands of core-hours
- Isotropic quantum kinetics - thousands of core-hours
- Two-beam neutrino oscillations
 - [[Starting at 10km in a CCSN, 2-beam 1-energy transport, based on 1D CCSN snapshot]]
 - [[Scaling up actual simulations of neutrino flavor transformation]]
 - 200,000 Exa-byte memory required
 - 6e40 core-hours for 1ms of evolution.

To-Do List

Standard **test problems**,
code comparisons,
open codes/data

1D time-dependent
neutrino halo simulation

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direct flavor
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