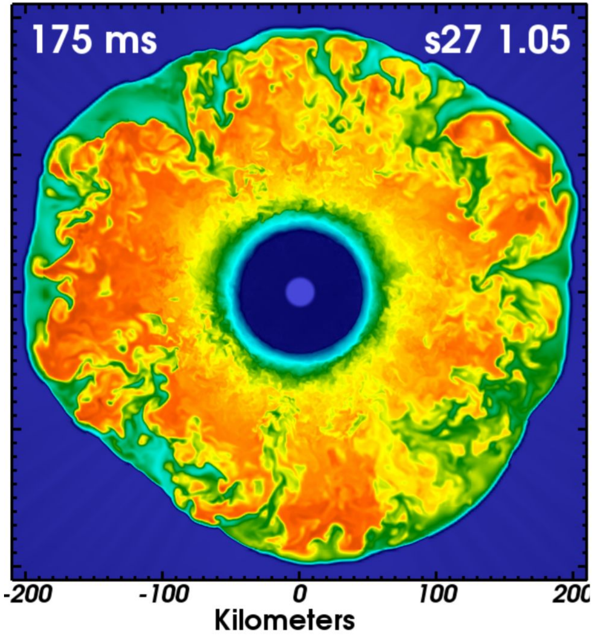
Accurate Neutrino Transport in Supernovae and Mergers

Sherwood Richers, NC State University
Gail McLaughlin, NC State University
Yonglin Zhi, NC State University
Hiroki Nagakura, Caltech

Neutrinos in Core-Collapse Supernovae

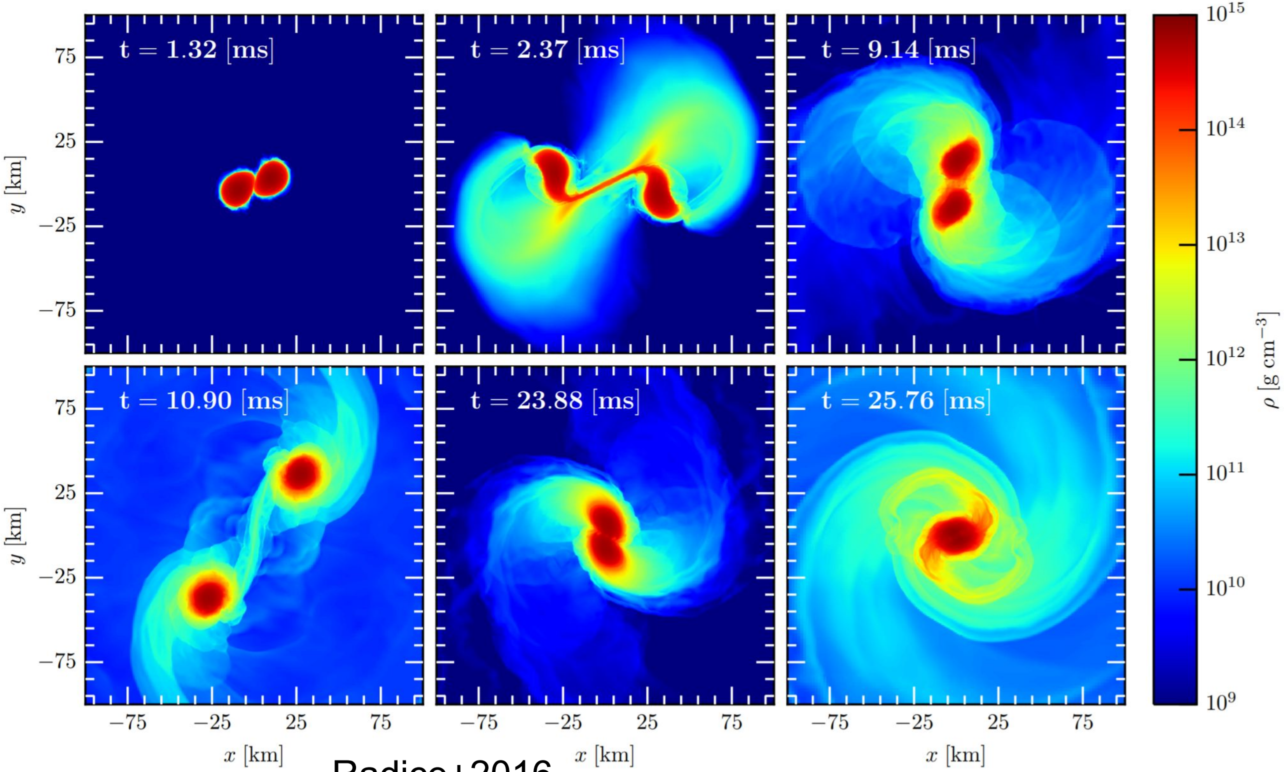


(Couch & O'Connor 2013)

Neutrinos drive explosion through **heating**, my drive neutron star **kick**, and may be observed soon.

- Turbulence/SASI drive asymmetric radiation
- Velocities few % speed of light
- Delicate balance determines explodability

Neutrinos in Neutron Star Mergers



Radice+2016

Neutrinos drive **outflows**, modify **composition**.

- Complex geometry
- Relativistic orbital velocity
- Strongly GR
- Smaller optical depth than CCSN (in disk)

Neutrino Transport

$f(x^\mu, p^\mu)$ is (# of neutrinos) per (volume) per (energy) per (solid angle)

Classical Boltzmann Equation

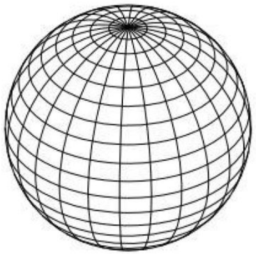
$$\frac{1}{c}\frac{\mathrm{df}}{\mathrm{d}\tau} = \mathcal{C}$$

Neutrino Transport

$f(x^\mu, p^\mu)$ is (# of neutrinos) per (volume) per (energy) per (solid angle)

Classical Boltzmann Equation

$$\frac{1}{c}\frac{\mathrm{df}}{\mathrm{d}\tau} = \mathcal{C}$$

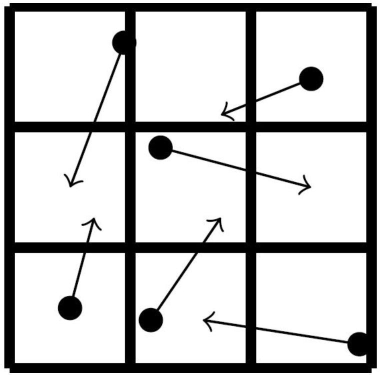
$f =$  Discrete Ordinates

Neutrino Transport

$f(x^\mu, p^\mu)$ is (# of neutrinos) per (volume) per (energy) per (solid angle)

Classical Boltzmann Equation

$$\frac{1}{c}\frac{\mathrm{df}}{\mathrm{d}\tau} = \mathcal{C}$$

$f =$ 

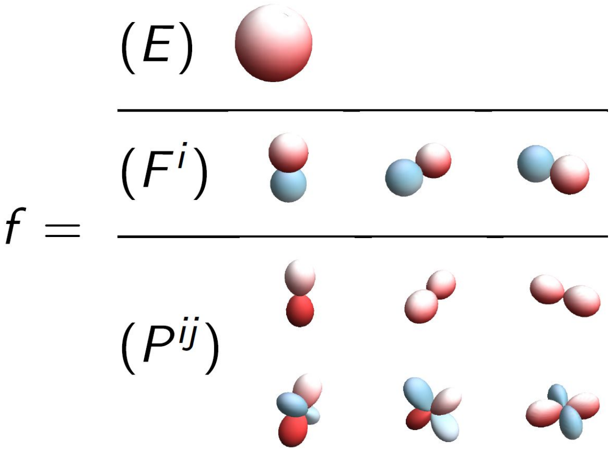
Monte Carlo
Ray-Tracing

Neutrino Transport

$f(x^\mu, p^\mu)$ is (# of neutrinos) per (volume) per (energy) per (solid angle)

Classical Boltzmann Equation

$$\frac{1}{c}\frac{\mathrm{df}}{\mathrm{d}\tau} = \mathcal{C}$$



Flux-Limited Diffusion
Two-Moment (M1)

Neutrino Transport

$f(x^\mu, p^\mu)$ is (# of neutrinos) per (volume) per (energy) per (solid angle)

Classical Boltzmann Equation

$$\frac{1}{c}\frac{\mathrm{df}}{\mathrm{d}\tau} = \mathcal{C}$$

Left Side: Expand the derivative

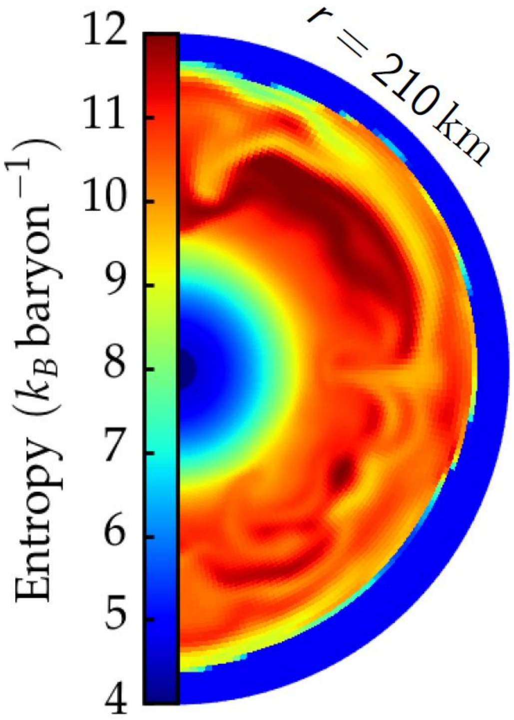
$$\frac{\mathrm{df}}{\mathrm{d}\tau} = \frac{\partial f}{\partial \tau} + \frac{\mathrm{dx}^\mu}{\mathrm{d}\tau}\frac{\partial f}{\partial x^\mu}$$

Right Side: Integrate collision rate with other things $(1 + 2 \leftrightarrow 3 + 4)$

$$C \sim \int \mathrm{d}^3\mathbf{p}_2 \int \mathrm{d}^3\mathbf{p}_3 \int \mathrm{d}^3\mathbf{p}_4 \; \mathrm{R}(\mathrm{f}_1,\, \mathrm{f}_2,\, \mathrm{f}_3,\, \mathrm{f}_4,\, \mathbf{p}_1,\, \mathbf{p}_2,\, \mathbf{p}_3,\, \mathbf{p}_4)$$

SEDONU: GR Monte Carlo Transport

1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter

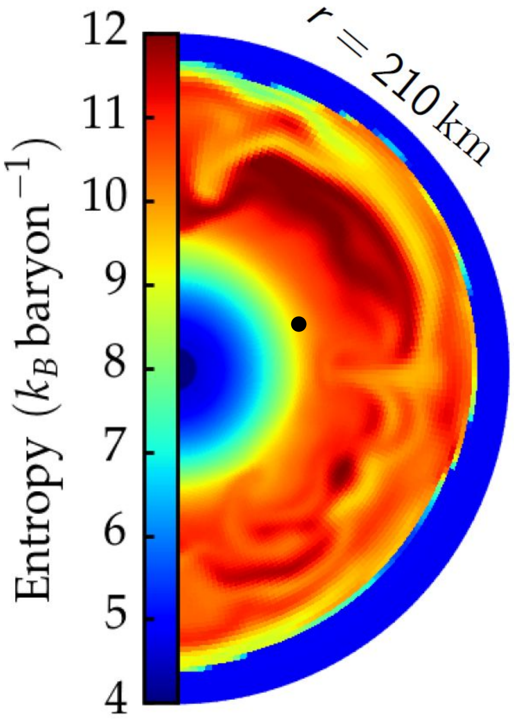


3D Interpolate:

- Metric (and derivatives)
- Opacities/Emissivities
- Scattering Kernels
- Velocity

SEDONU: GR Monte Carlo Transport

1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter

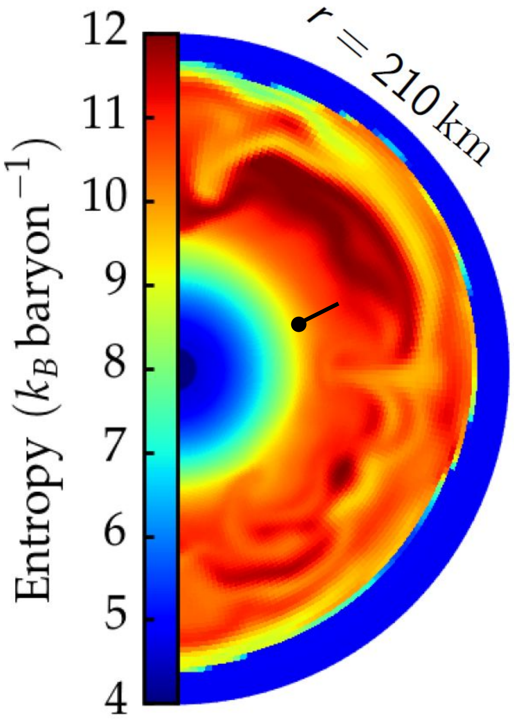


Emit:

- **Random** location
- **Random** direction
- **Random** energy

SEDONU: GR Monte Carlo Transport

1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter

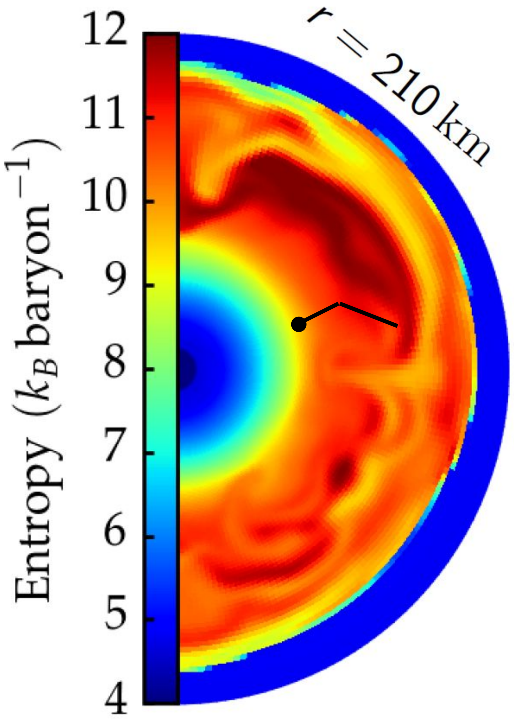


Propagate & Absorb:

- **Random** distance
  $$\mathrm{PDF}(d) = \sigma_s e^{-\sigma_s d}$$
- Absorb continuously
- Accumulate f

SEDONU: GR Monte Carlo Transport

1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter

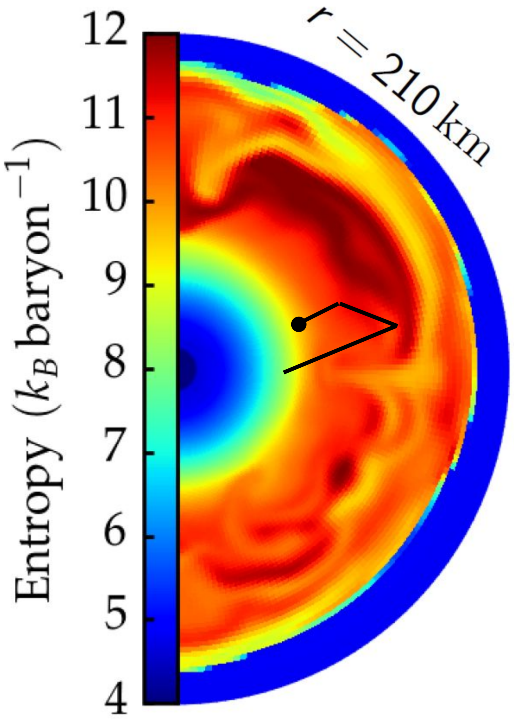


Scatter:

- **Random** direction & energy

SEDONU: GR Monte Carlo Transport

1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter

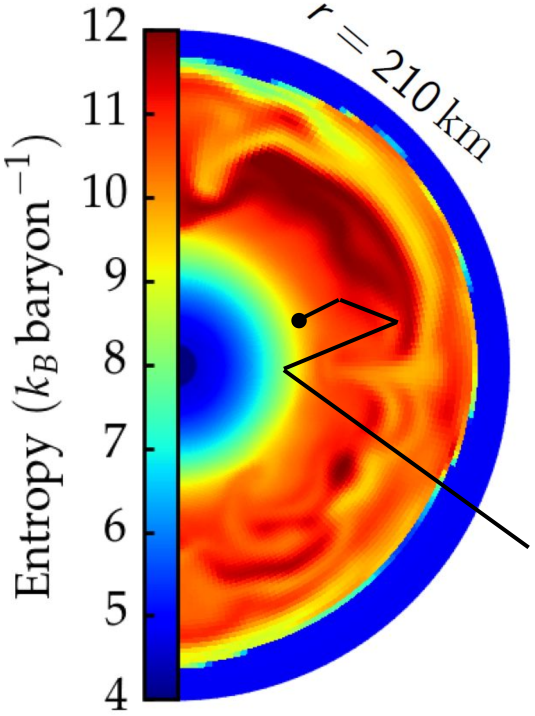


Scatter:

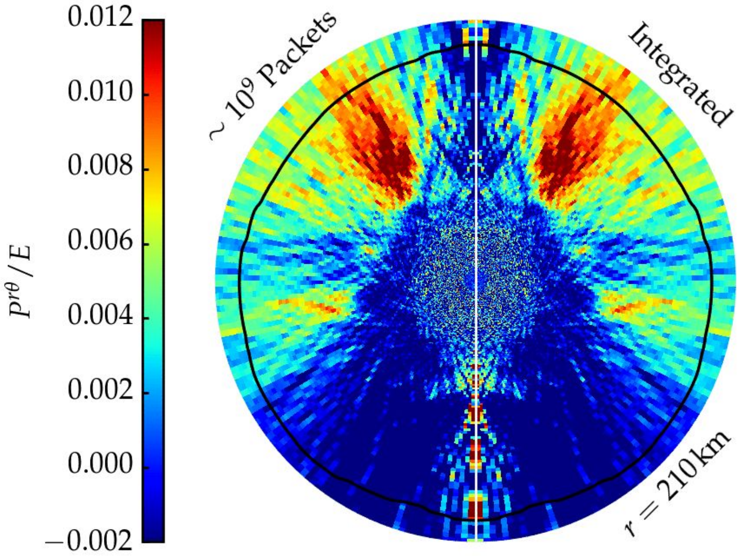
- **Random** direction & energy

SEDONU: GR Monte Carlo Transport

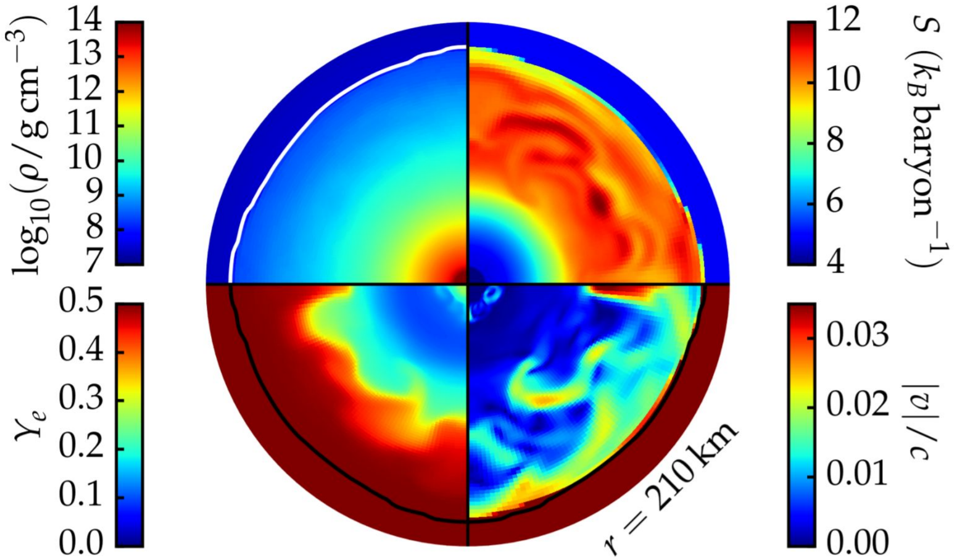
1. Take fluid snapshot
2. Emit
3. Propagate & Absorb
4. Scatter



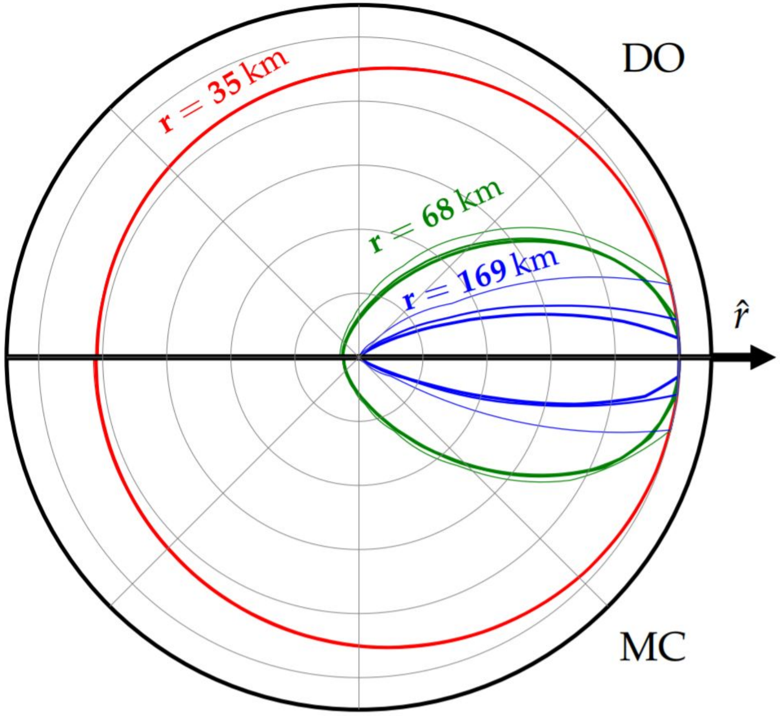
Repeat 10 billion times



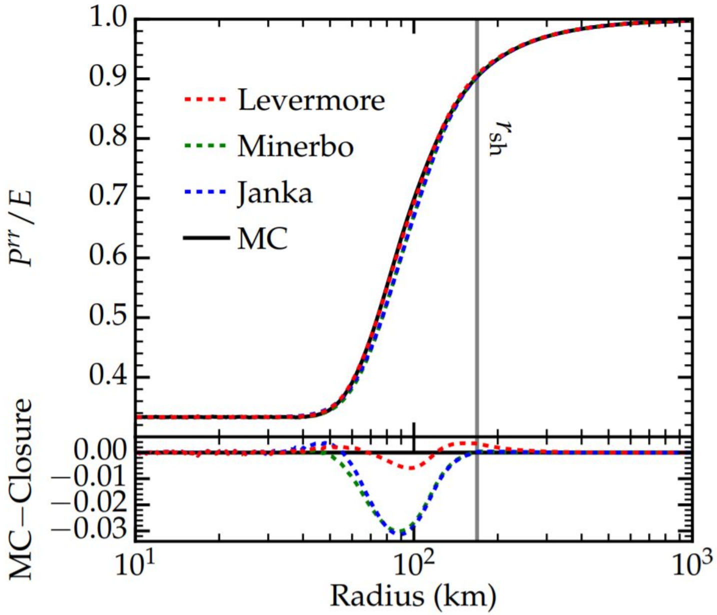
Let's Explore the CCSN Neutrino Field



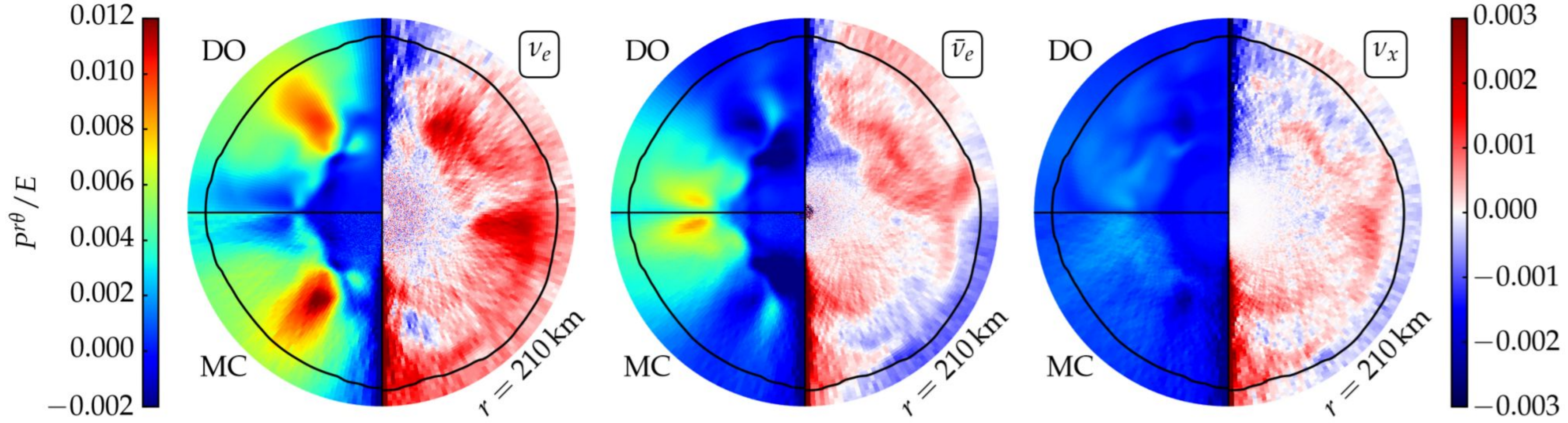
CCSN: Neutrino Field



Richers+2015

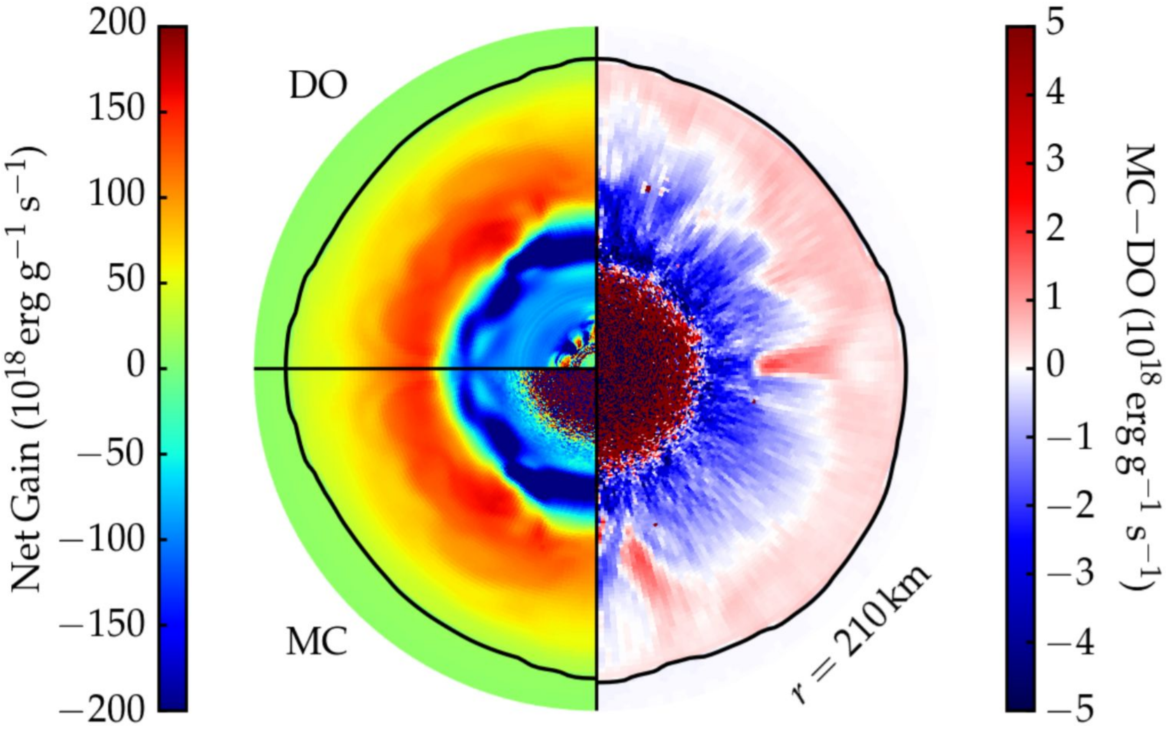


CCSN: Neutrino Field



M1-MC similar to DO-MC (i.e., **M1 does pretty well**)

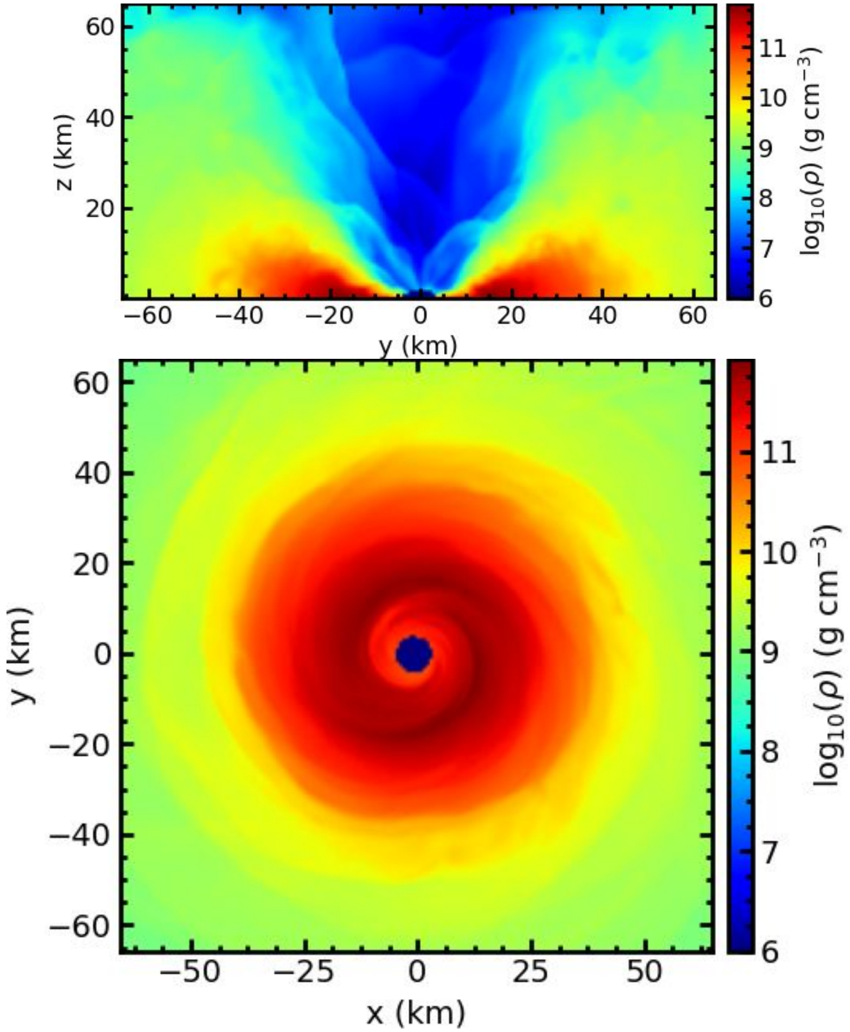
CCSN: Neutrino Heating



Few % difference in net gain between two “exact” methods

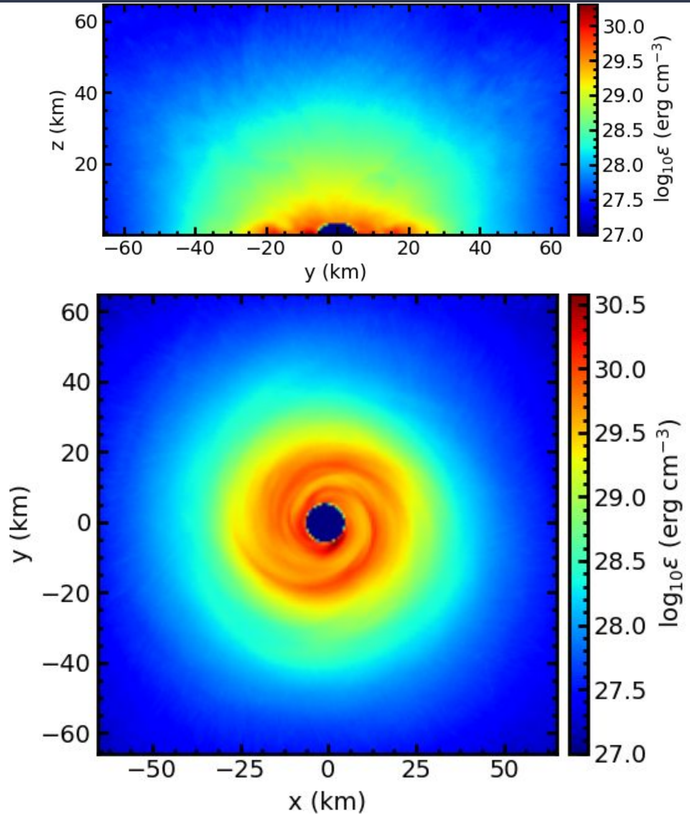
Heating in PNS is very stiff.

Let’s Explore the Merger Neutrino Field



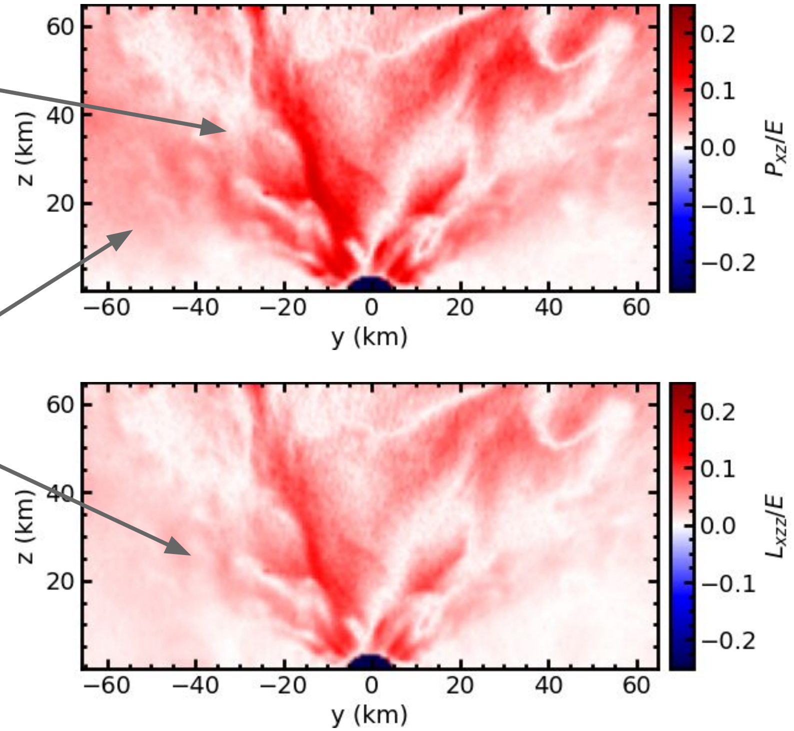
Hydro: Radice+2017

Lots of structure in higher moments.

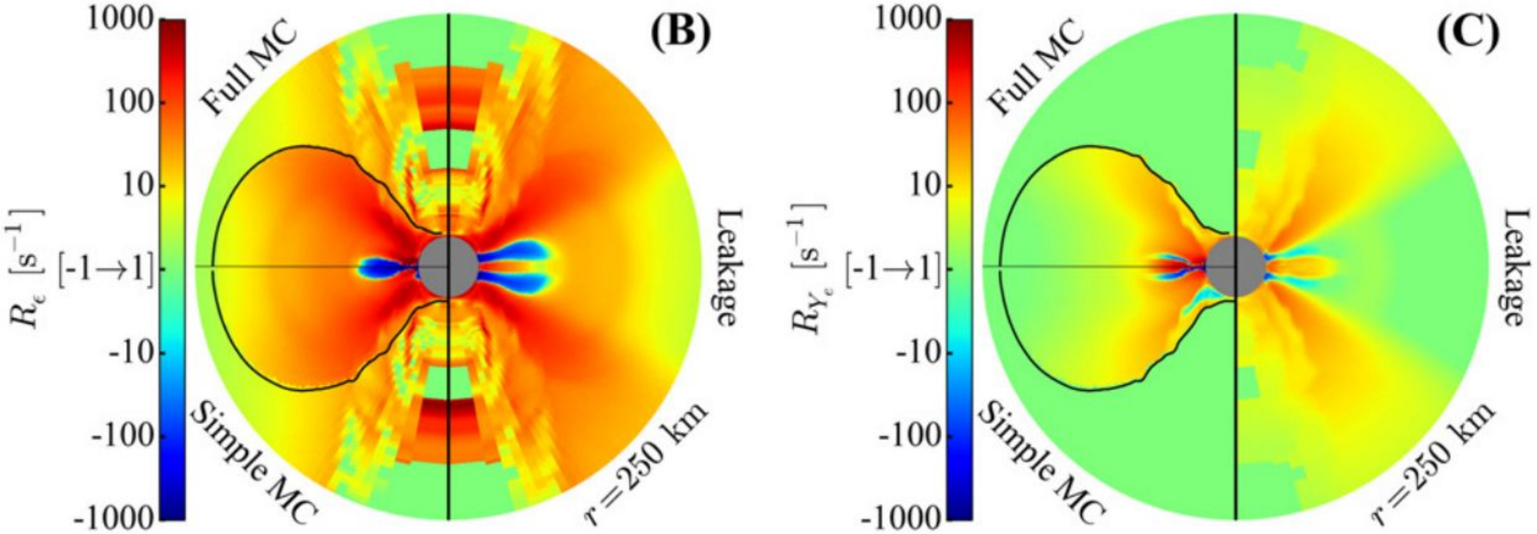


Compare to 0.01 for CCSN

0 for spherical radiation



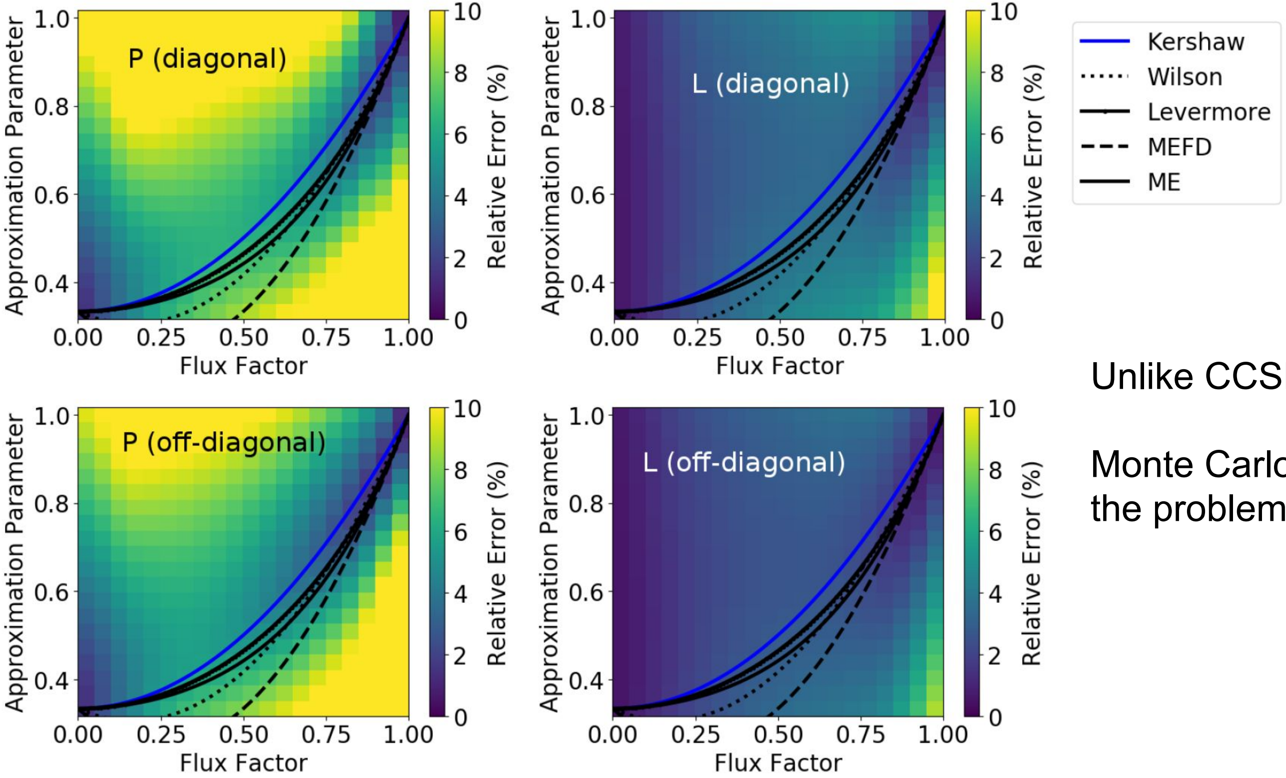
MERGERS: How well does leakage do?



Richers+2015

Yes, there are differences that should be checked.

MERGERS: How well does M1 do?



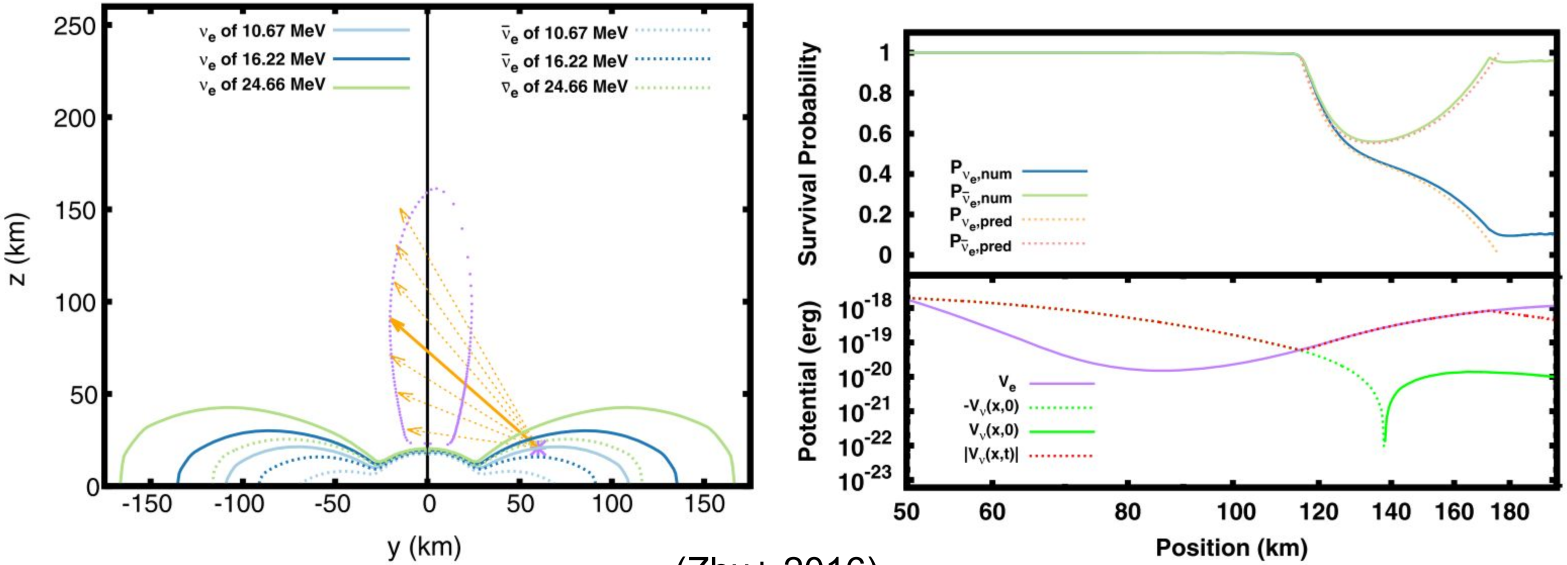
Unlike CCSNe, **M1 has sizable errors**

Monte Carlo transport may be able to fix the problems (e.g., Foucart+2018)

But wait...

Neutrinos can change flavor.

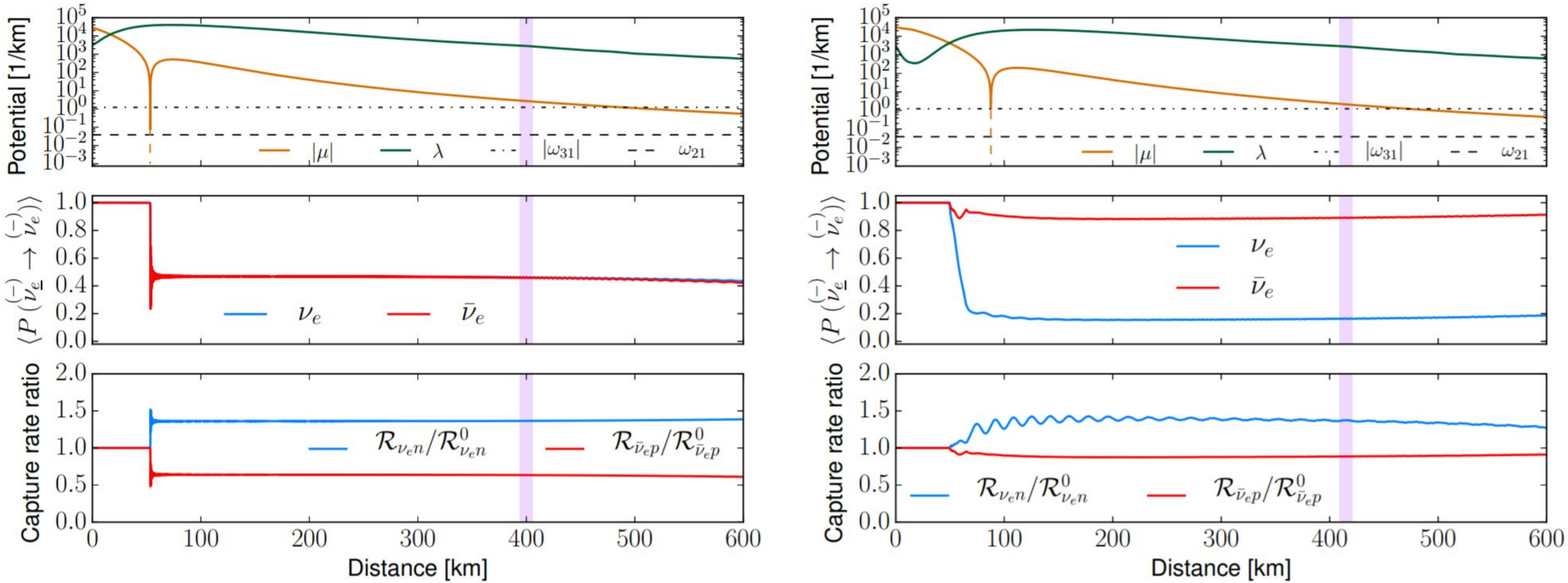
Pure oscillations in neutron star mergers



(Zhu+ 2016)

Neutrino-matter resonance efficiently transforms neutrinos.

Oscillations could affect outflows



(Frensel+2017)

Neutrinos can change flavor!

$$\frac{1}{p_0} p^i \partial_i f = -i[H, f] + \mathcal{C}[f, \bar{f}, \rho, Y_e, T]$$

Hacking Quantum Kinetics

$$\frac{1}{p_0} p^i \partial_i f = -i[H, f] + \mathcal{C}[f, \bar{f}, \rho, Y_e, T]$$

(See Vlasenko et al. 2014)

$$\frac{df}{dr} = \begin{bmatrix} \epsilon_e & 0 \\ 0 & \epsilon_\mu \end{bmatrix} + \int \frac{d\Omega}{4\pi} \begin{bmatrix} \kappa_{e,s} f_{b,ee} & 0 \\ 0 & \kappa_{\mu,s} f_{b,\mu\mu} \end{bmatrix} - \begin{bmatrix} \kappa_e f_{ee} & 0 \\ 0 & \kappa_\mu f_{\mu\mu} \end{bmatrix}$$

Emission **In-Scattering** **Absorption & Out-Scattering**

Hacking Quantum Kinetics

$$\frac{1}{p_0} p^i \partial_i f = -i[H, f] + \mathcal{C}[f, \bar{f}, \rho, Y_e, T]$$

(See Vlasenko et al. 2014)

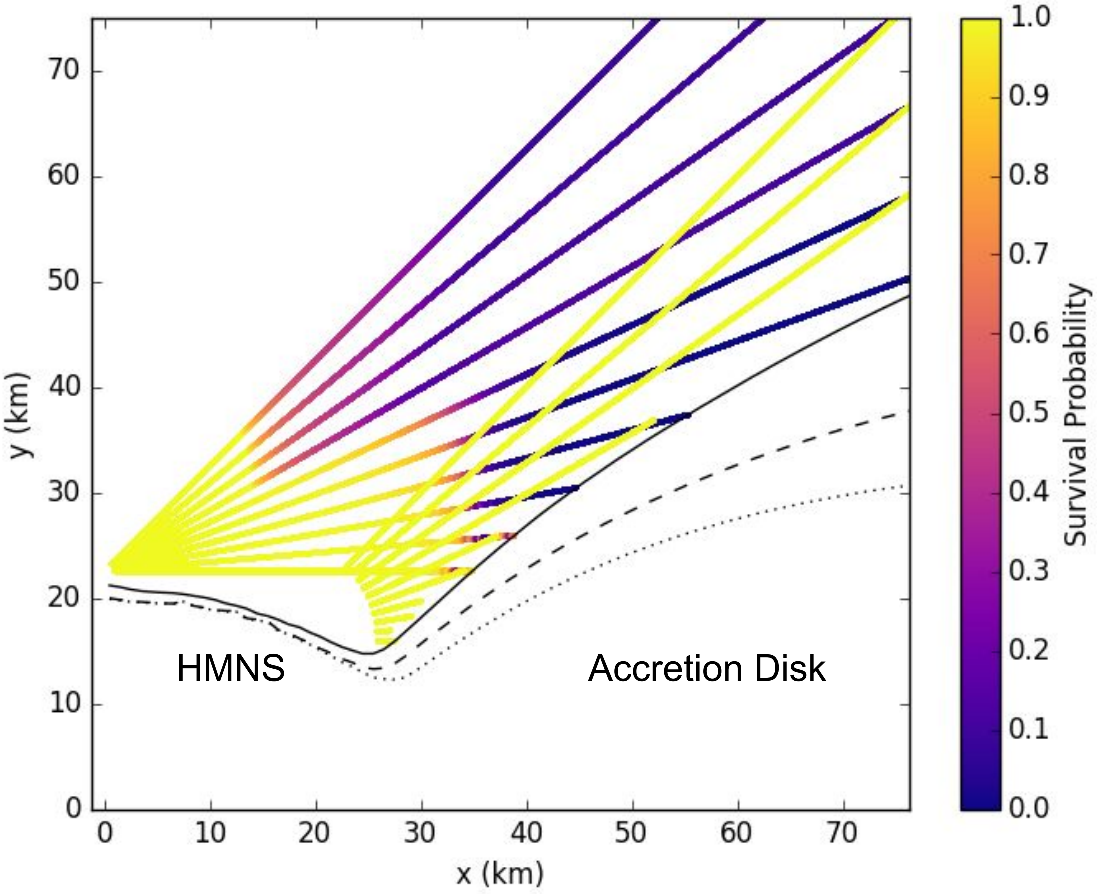
$$\frac{df}{dr} = \begin{bmatrix} \epsilon_e & 0 \\ 0 & \epsilon_\mu \end{bmatrix} + \int \frac{d\Omega}{4\pi} \begin{bmatrix} \kappa_{e,s} f_{b,ee} & \kappa_{\mu,s} f_{b,e\mu} \\ \kappa_{\mu,s} f_{b,\mu e} & \kappa_{\mu,s} f_{b,\mu\mu} \end{bmatrix} - \begin{bmatrix} \kappa_e f_{ee} & \frac{\kappa_e + \kappa_\mu}{2} f_{e\mu} \\ \frac{\kappa_e + \kappa_\mu}{2} f_{\mu e} & \kappa_\mu f_{\mu\mu} \end{bmatrix}$$

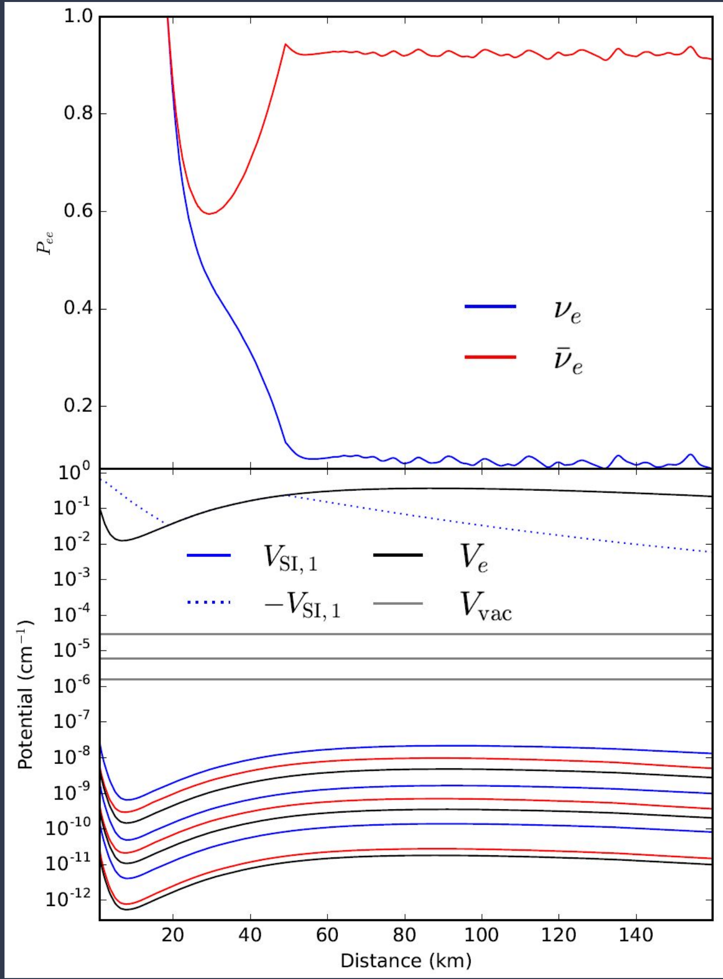
Emission — In-Scattering — Absorption & Out-Scattering

Note:

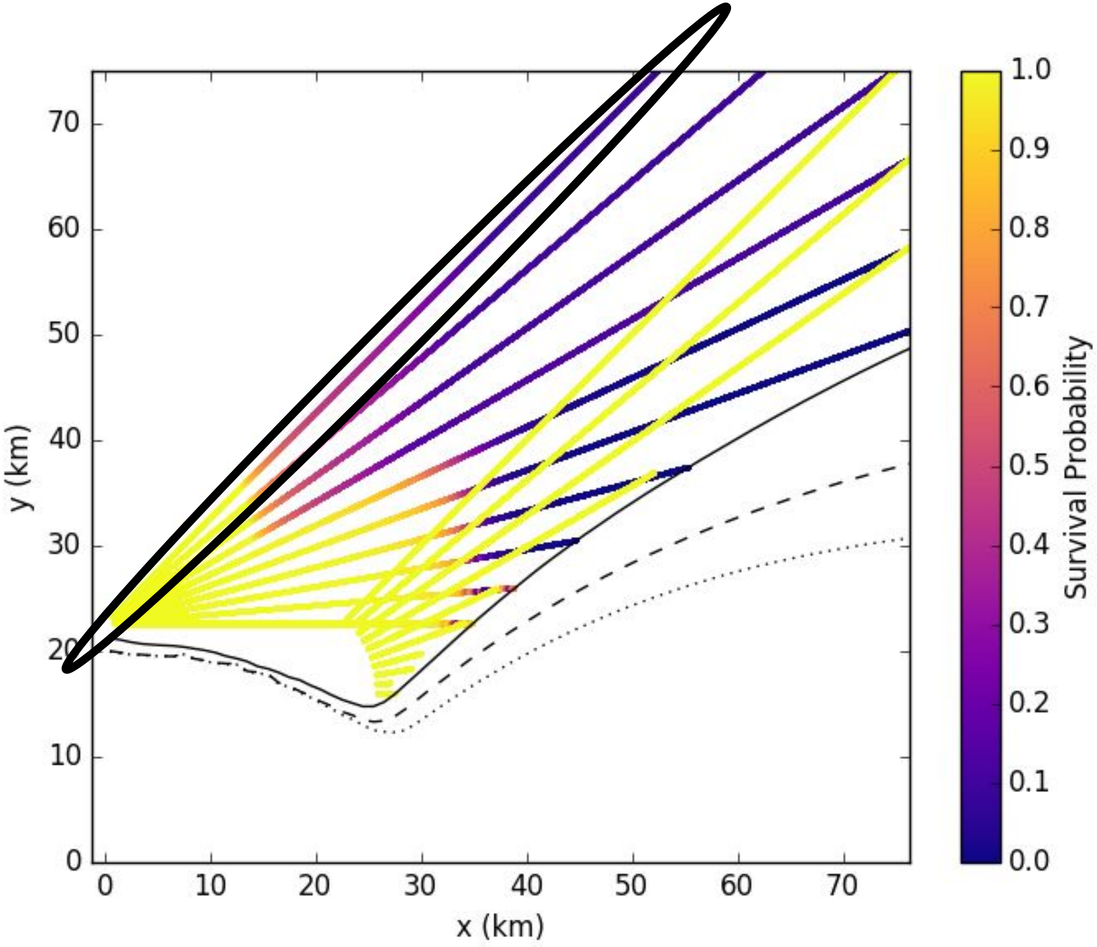
- pair annihilation is treated as absorption
- neutrino-neutrino scattering is ignored
- scattering is elastic and isotropic

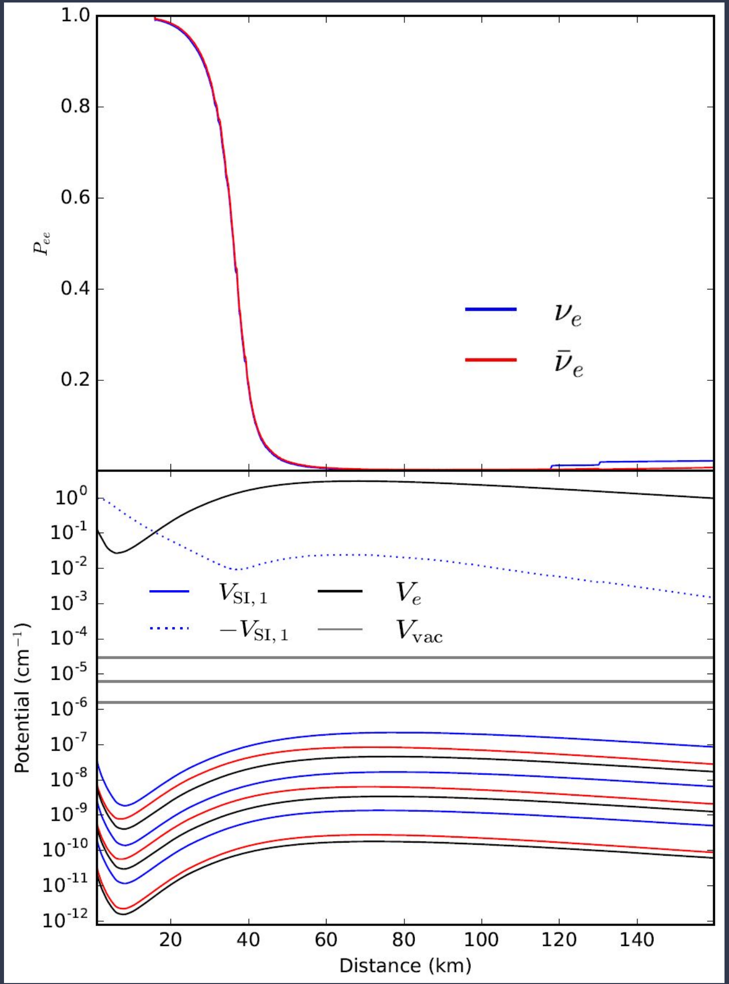
Multiple Oscillations Modes



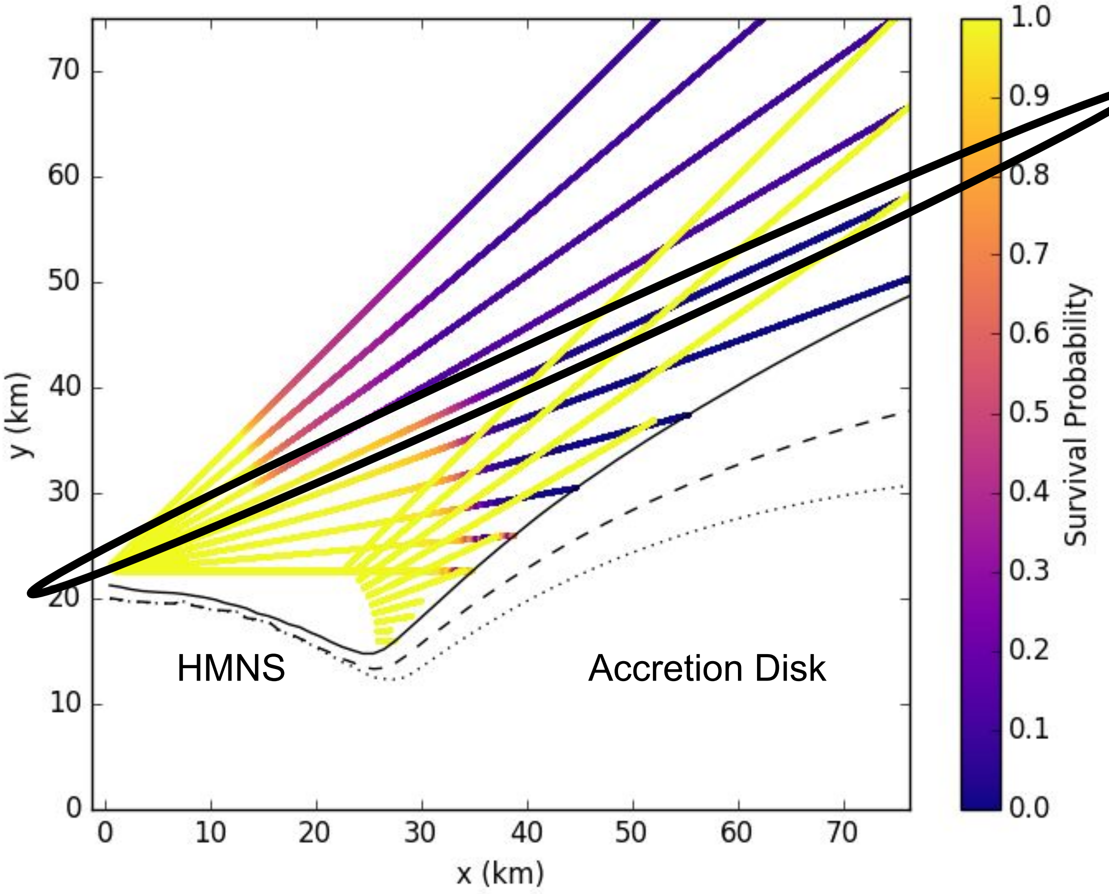


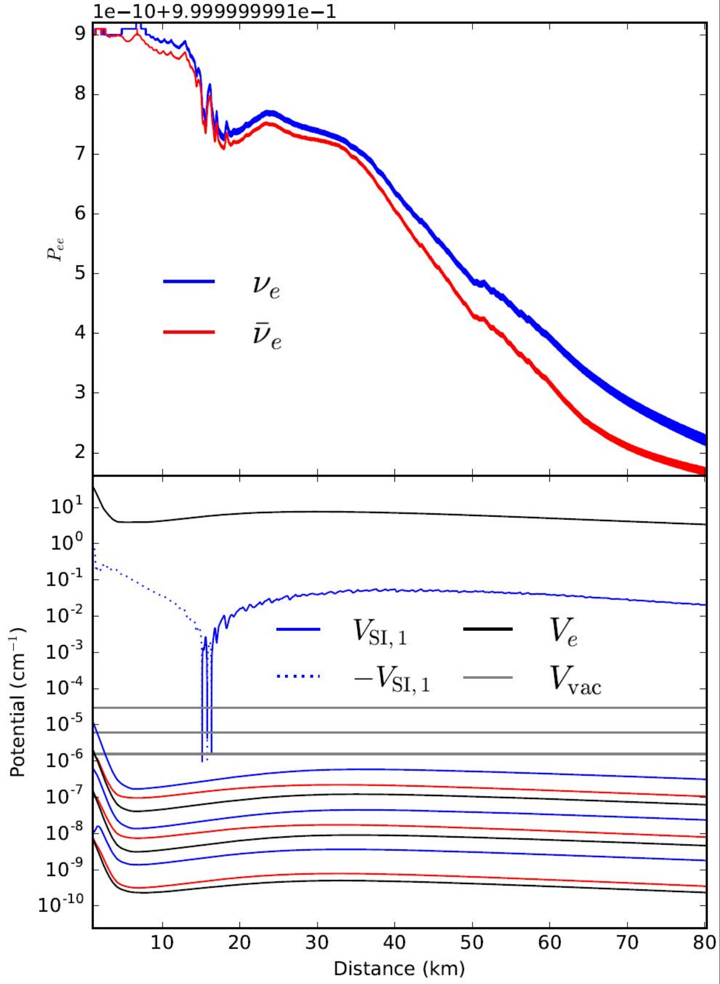
Matter-Neutrino Resonance!



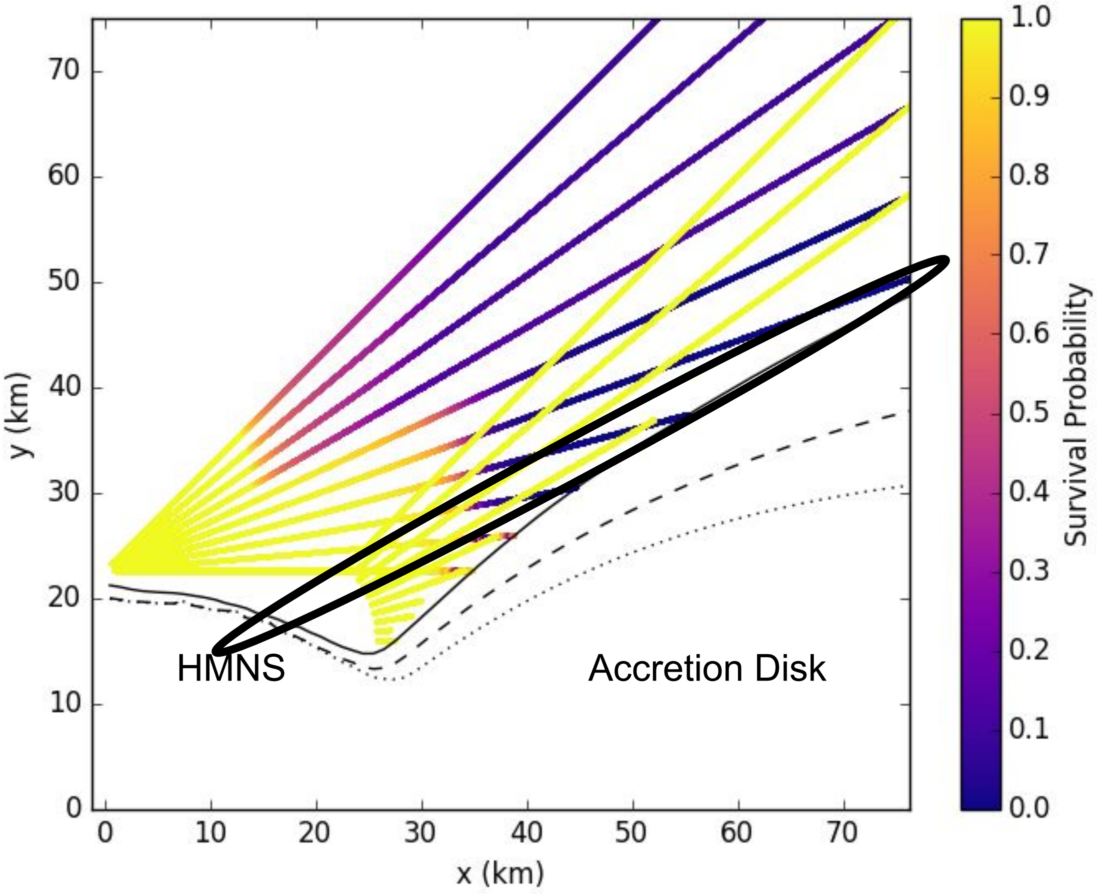


Synchronized MSW





Too many electrons!



Conclusions and Caveats

- Monte Carlo gives detailed **angular information**.
- **Two-moment transport** seems to work decently in CCSNe.
- Mergers simulations can greatly benefit from **better neutrino transport**.
- **Neutrinos change flavor** - dynamics/composition effects is an open question!
- **QKE Improvement Needs:**
  - The **single-angle** approximation.
  - The **two-flavor** approximation.
  - The **scattering kernels** lack phase information and fermi-blocking.
  - Background neutrino field is **inconsistent** with the interaction rates.
  - Background neutrino/matter field is **axisymmetric**.
  - Only one background tested.

Monte Carlo Random Walk Approximation