Neutrino Quantum Kinetics or Neutrino Transport

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Yonglin Zhu, NCSU
Alexey Vlasenko, NCSU
James Kneller, NCSU
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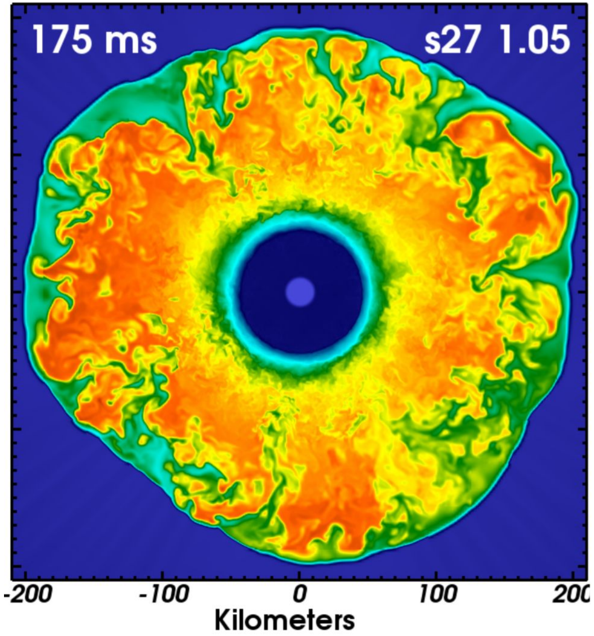
Outline

	Supernovae	Neutron Star Mergers
Transport		
Quantum Kinetics		

Neutrinos in Core-Collapse Supernovae

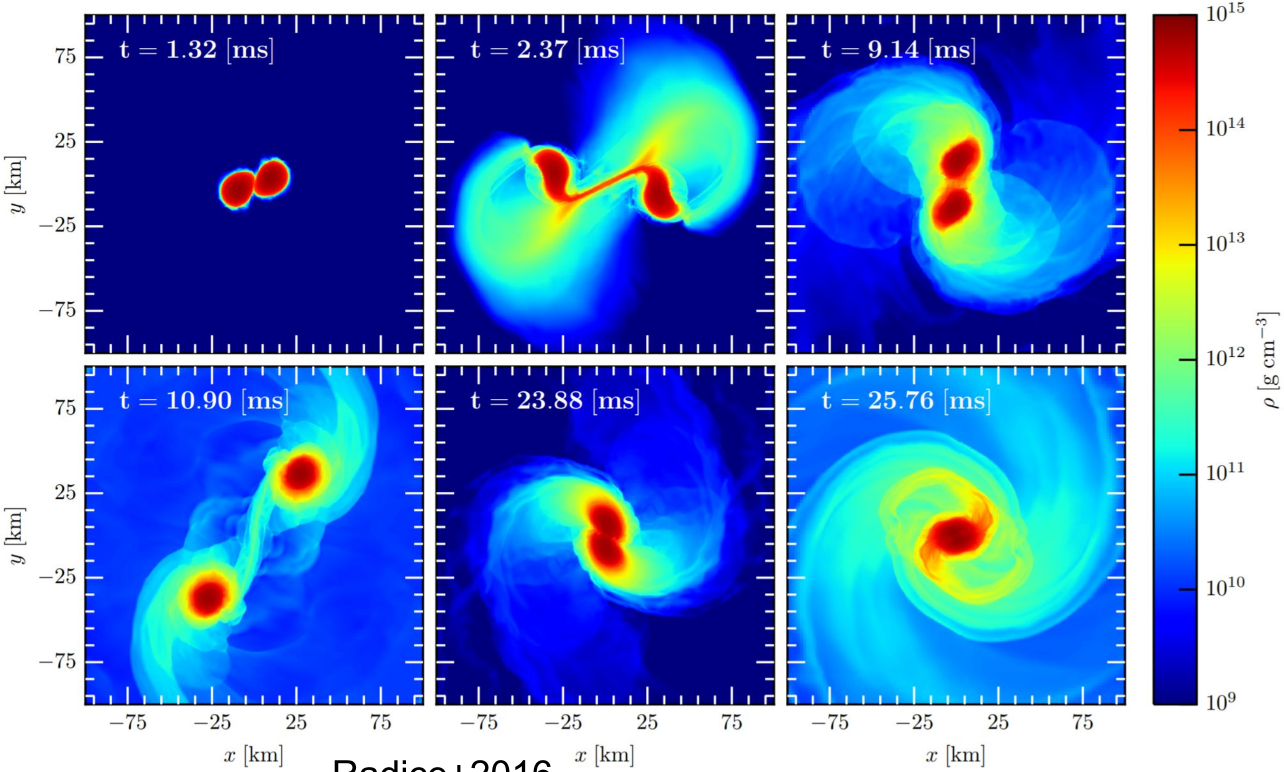


(Couch & O’Connor 2013)

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

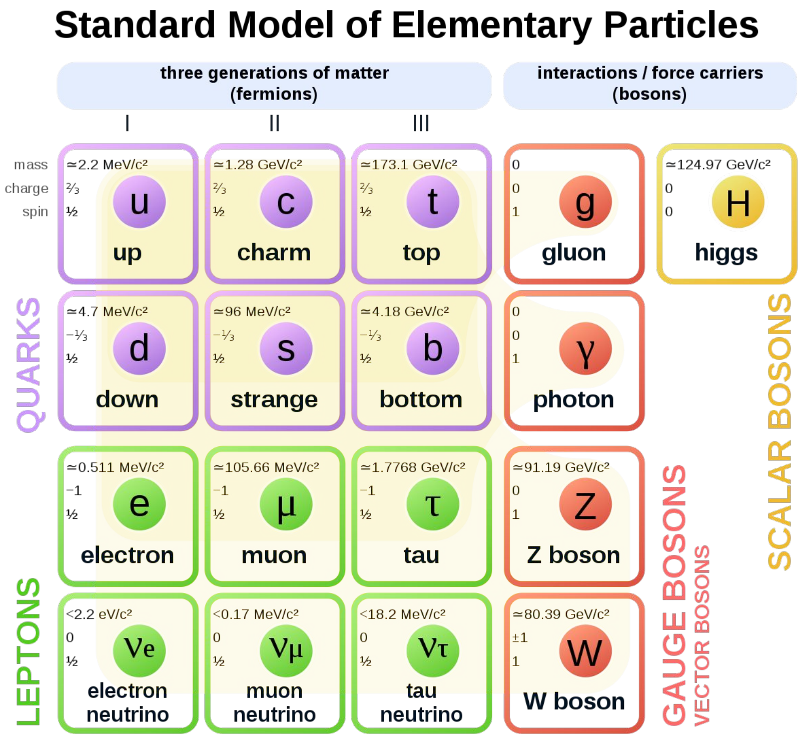
Neutrinos drive **outflows**, modify **composition**.

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

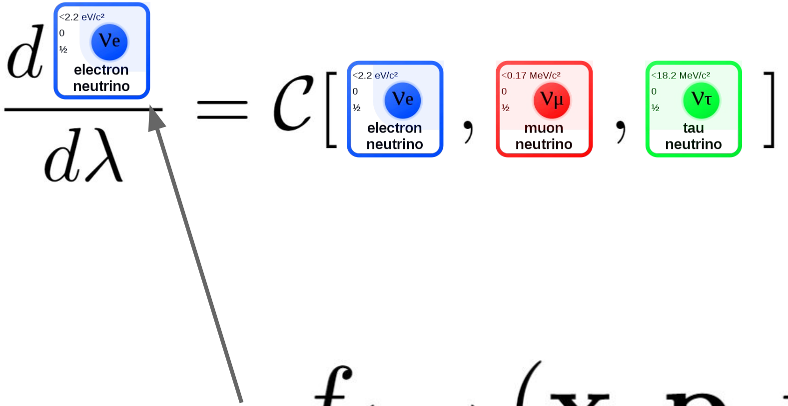
Part I:

Quantum Kinetics

Neutrino Radiation Transport



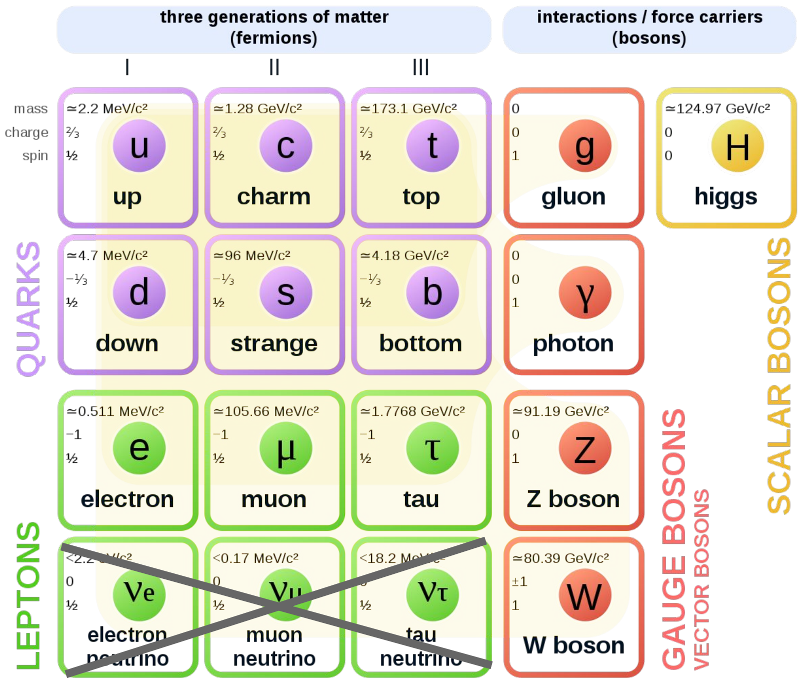
Treat each flavor separately:



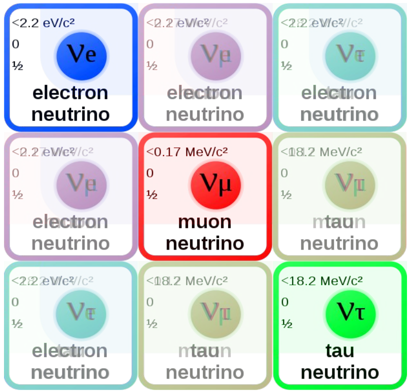
$$f_{(\nu_e)}(\mathbf{x}, \mathbf{p}, t)$$

Neutrino Quantum Kinetics

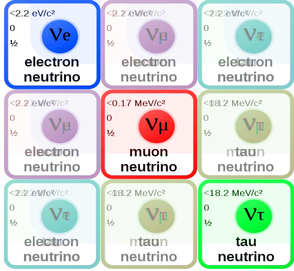
Standard Model of Elementary Particles

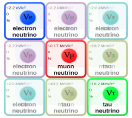
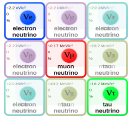
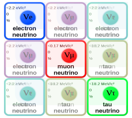


But the neutrino flavors are mixed!
(Pontecorvo 1968, Wolfenstein1978, Mikheev & Smirnov 1985)



Neutrino Quantum Kinetics



$\frac{d}{d\lambda}$  $= \mathcal{C}[$  $] - \frac{i}{\hbar c}[\mathcal{H},$  $]$

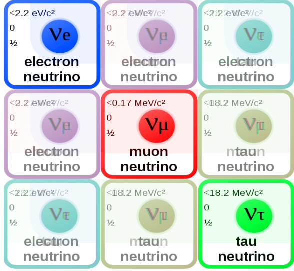
Cardall 2008
Vlasenko et al. 2014
Blaschke+Cirigliano 2016

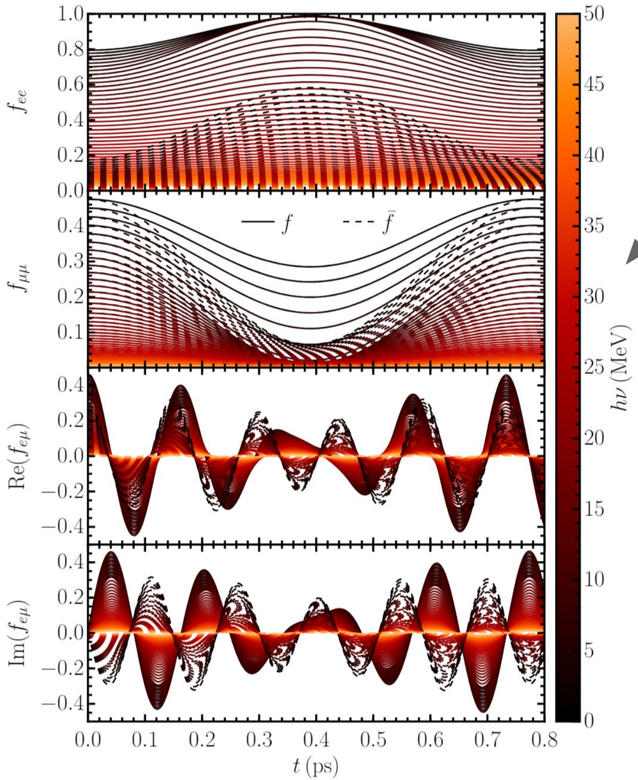
$$f_{ab}(\mathbf{x}, \mathbf{p}, t)$$

Different flavors experience different potentials.

Well, that's not too bad, right?

Interactions + Oscillations



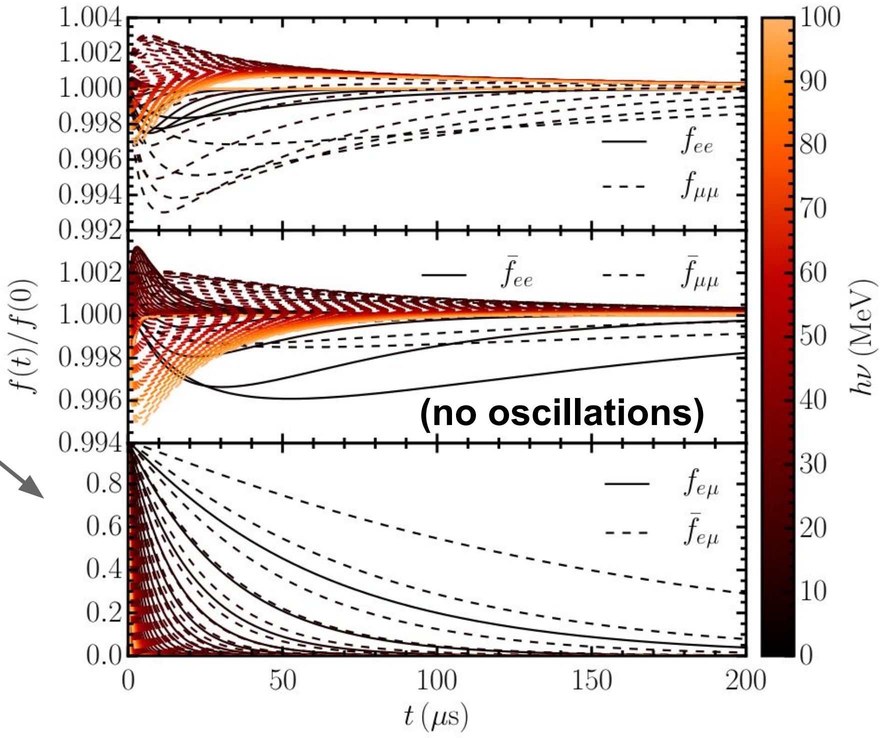


Oscillations are on extremely short timescales

Interactions take 10^7 times longer!

Not possible to evolve directly.

Richers+ (2019)



Outline

Supernovae

Neutron Star Mergers

Transport

Quantum Kinetics

Can use existing neutrino interaction physics to build **quantum collision terms**

Let's use them to understand mergers!
But the geometry is difficult.

Part II:

Just Transport

Neutrino Transport

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

Classical Boltzmann Equation

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

Neutrino Transport

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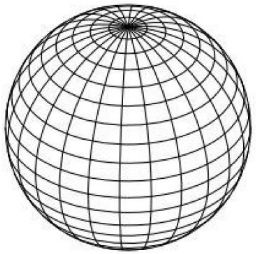
$f =$  Discrete Ordinates

Neutrino Transport

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

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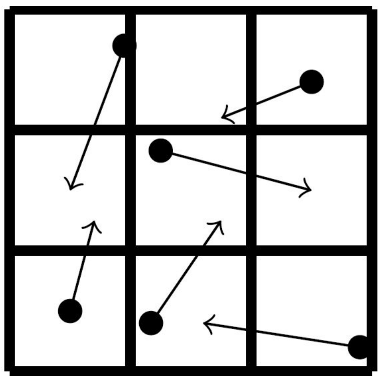
$f =$ 

Monte Carlo
Ray-Tracing

Neutrino Transport

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

Classical Boltzmann Equation

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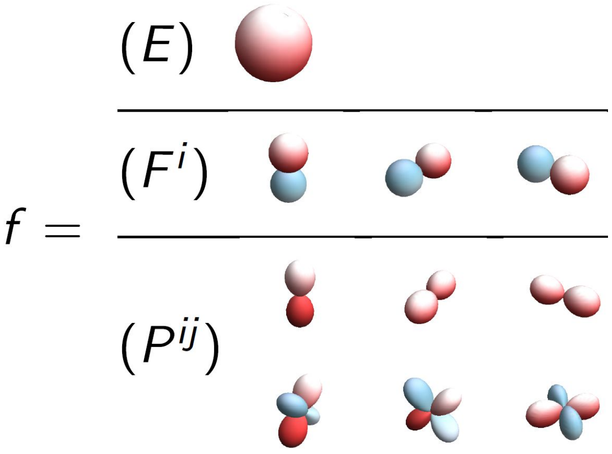


Flux-Limited Diffusion
Two-Moment (M1)

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

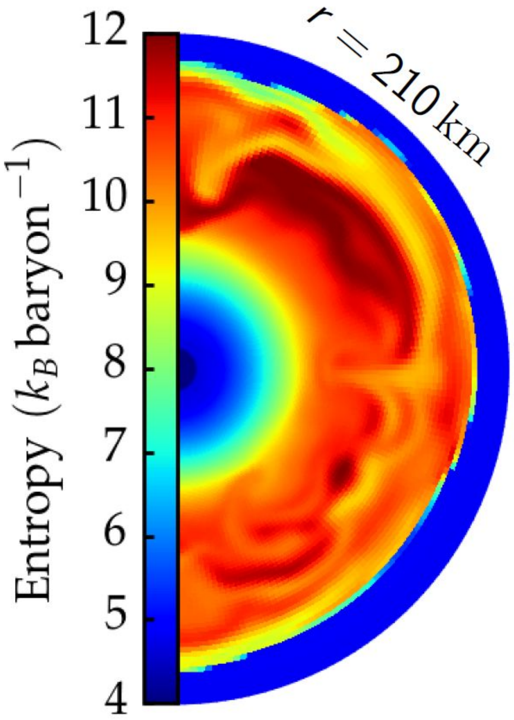
$$\frac{\mathrm{df}}{\mathrm{d}\tau} = \frac{\partial f}{\partial \tau} + \frac{\mathrm{dx}^\mu}{\mathrm{d}\tau}\frac{\partial f}{\partial x^\mu}$$

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

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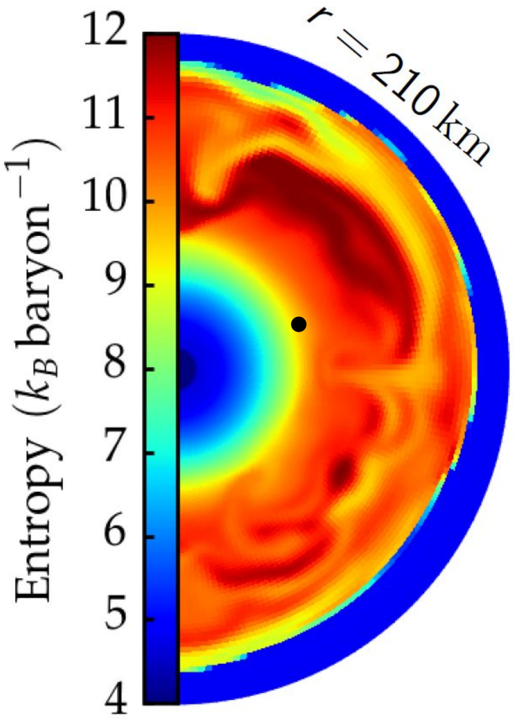

Emit:

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

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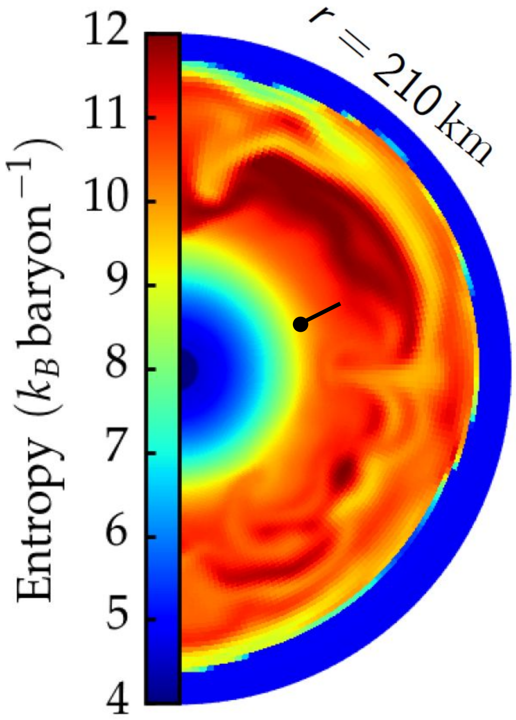

Propagate & Absorb:

- **Random** distance

$$\mathrm{PDF}(d) = \sigma_s e^{-\sigma_s d}$$

- Absorb continuously
- Accumulate f

SEDONU: GR Monte Carlo Transport

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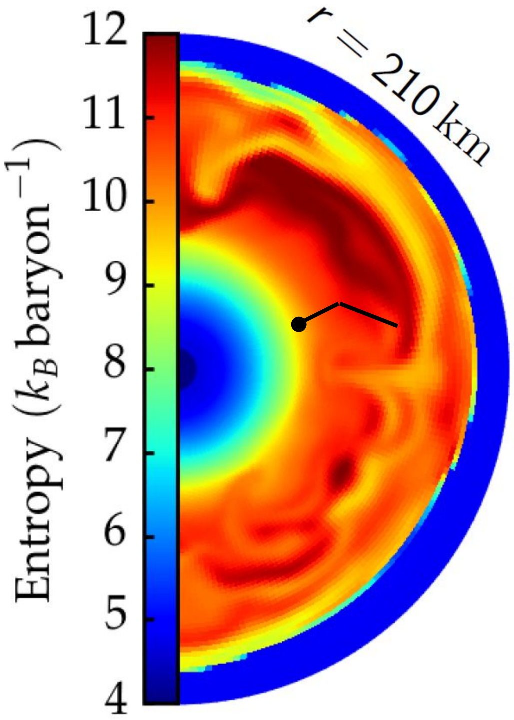

Scatter:

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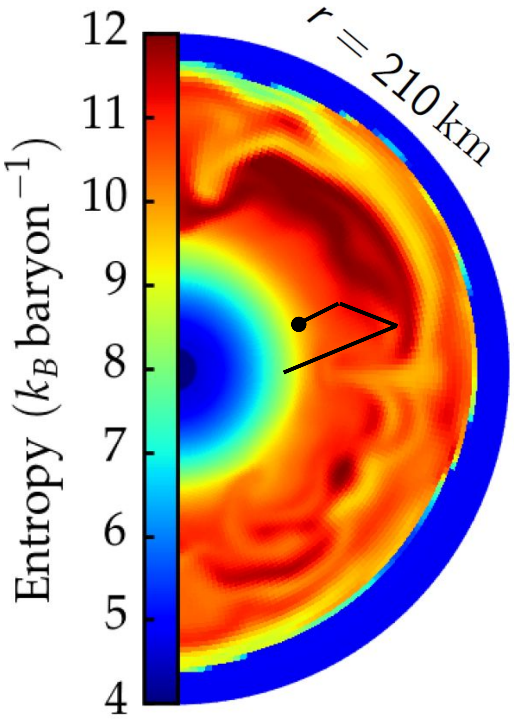

Scatter:

- **Random** direction & energy

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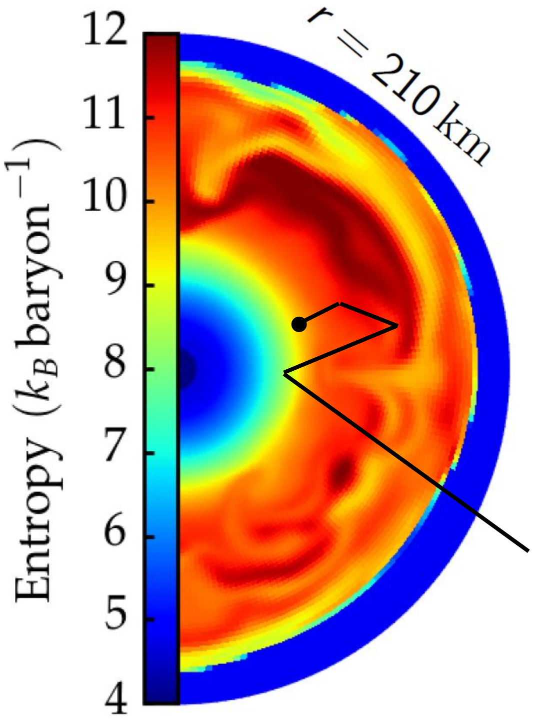
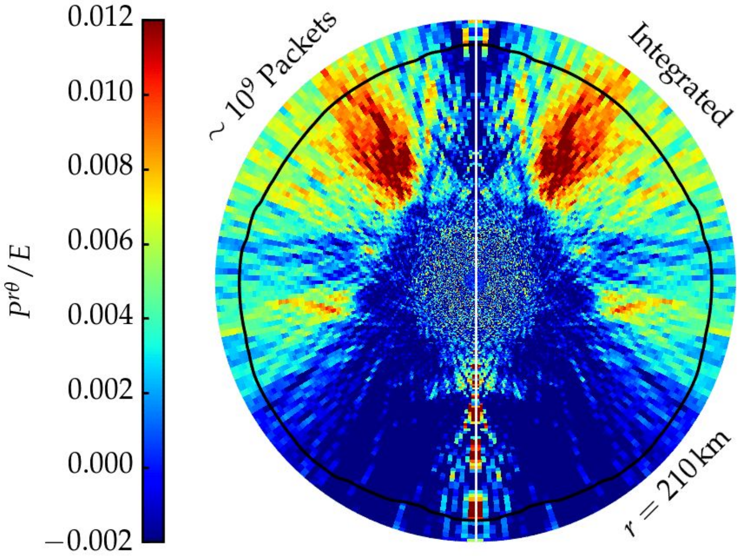
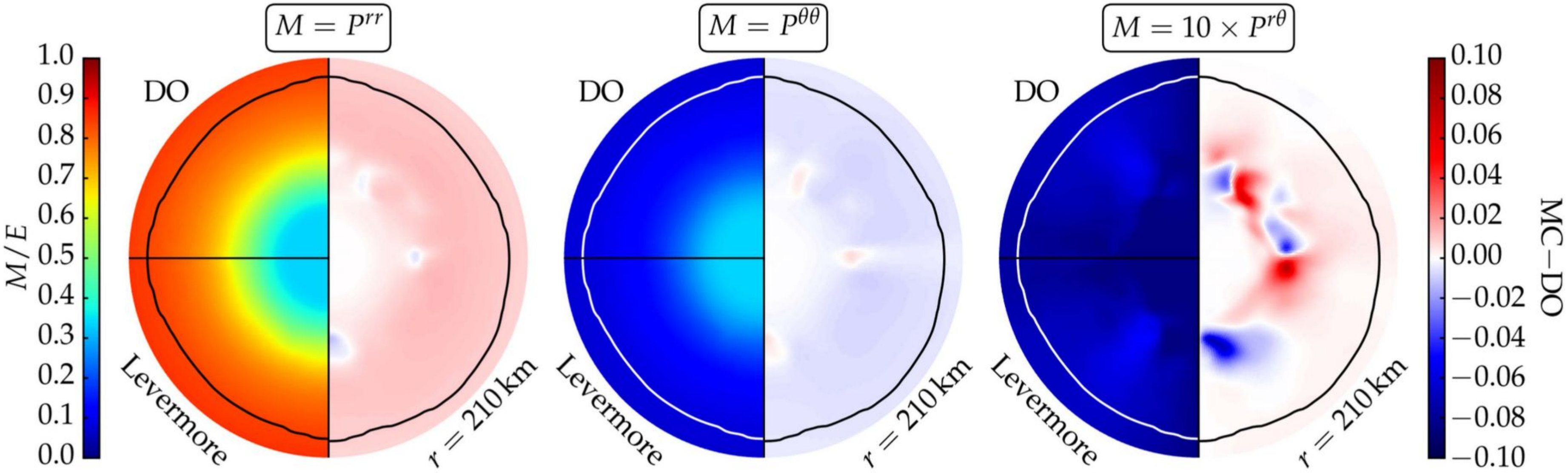


Repeat 10 billion times



CCSN: Neutrino Heating



Richers+ (2015)

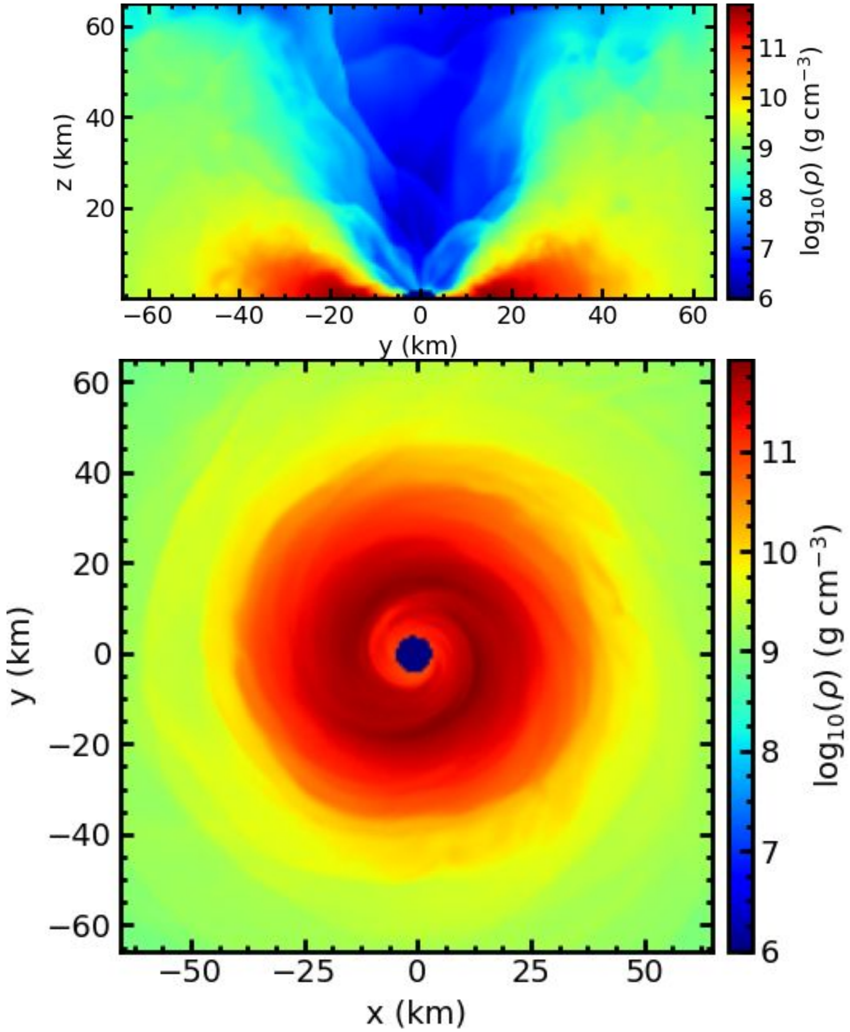
Few % difference in 2D as well!

Outline

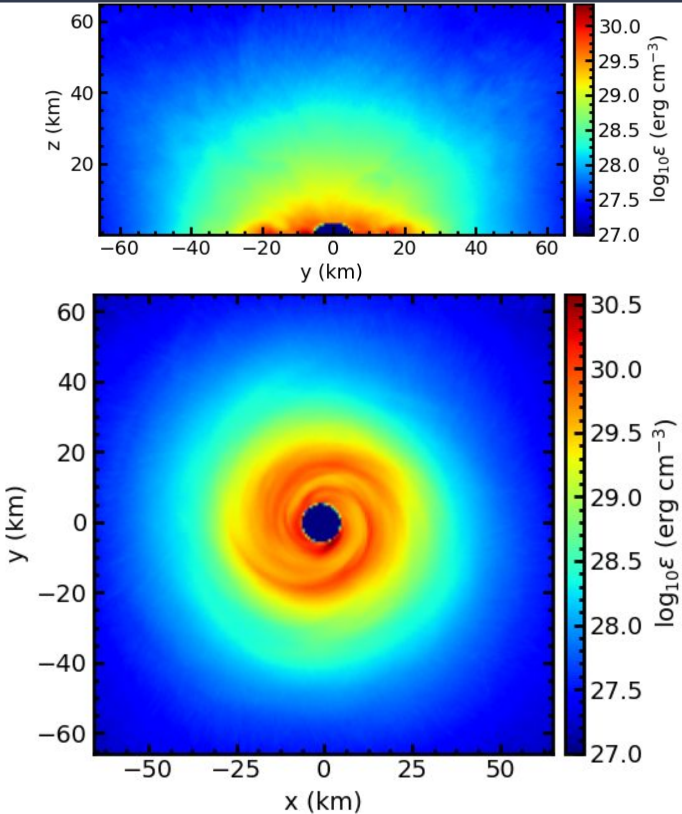
	<u>Supernovae</u>	<u>Neutron Star Mergers</u>
<u>Transport</u>	**Moments** work well in 1D (worse in multi-D) Do they work for mergers?	
<u>Quantum Kinetics</u>	Can use existing neutrino interaction physics to build **quantum collision terms** Let’s use them to understand mergers! But the geometry is difficult.	

What About Mergers?

Hydro: Radice+2017

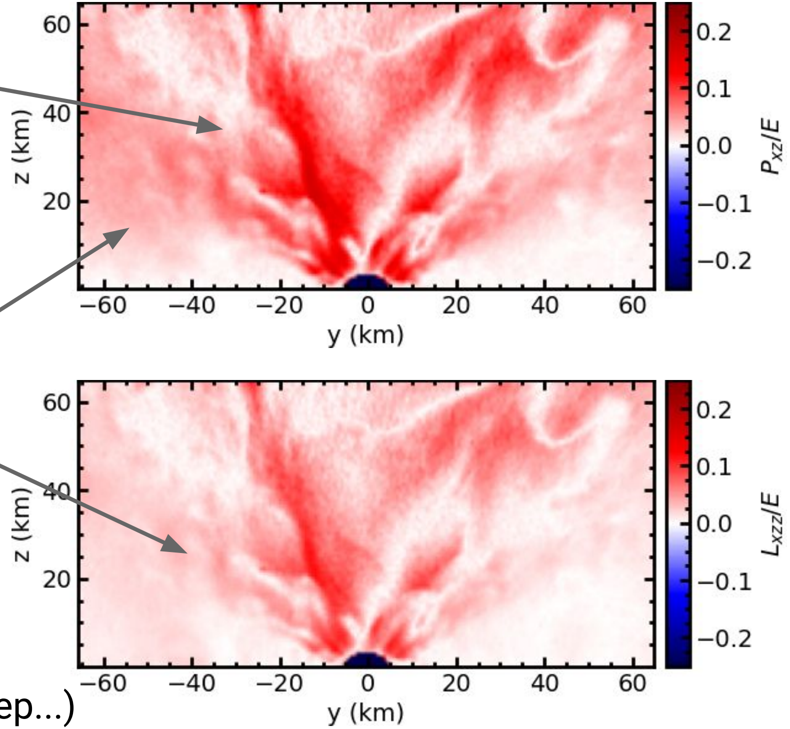


Lots of structure in higher moments.



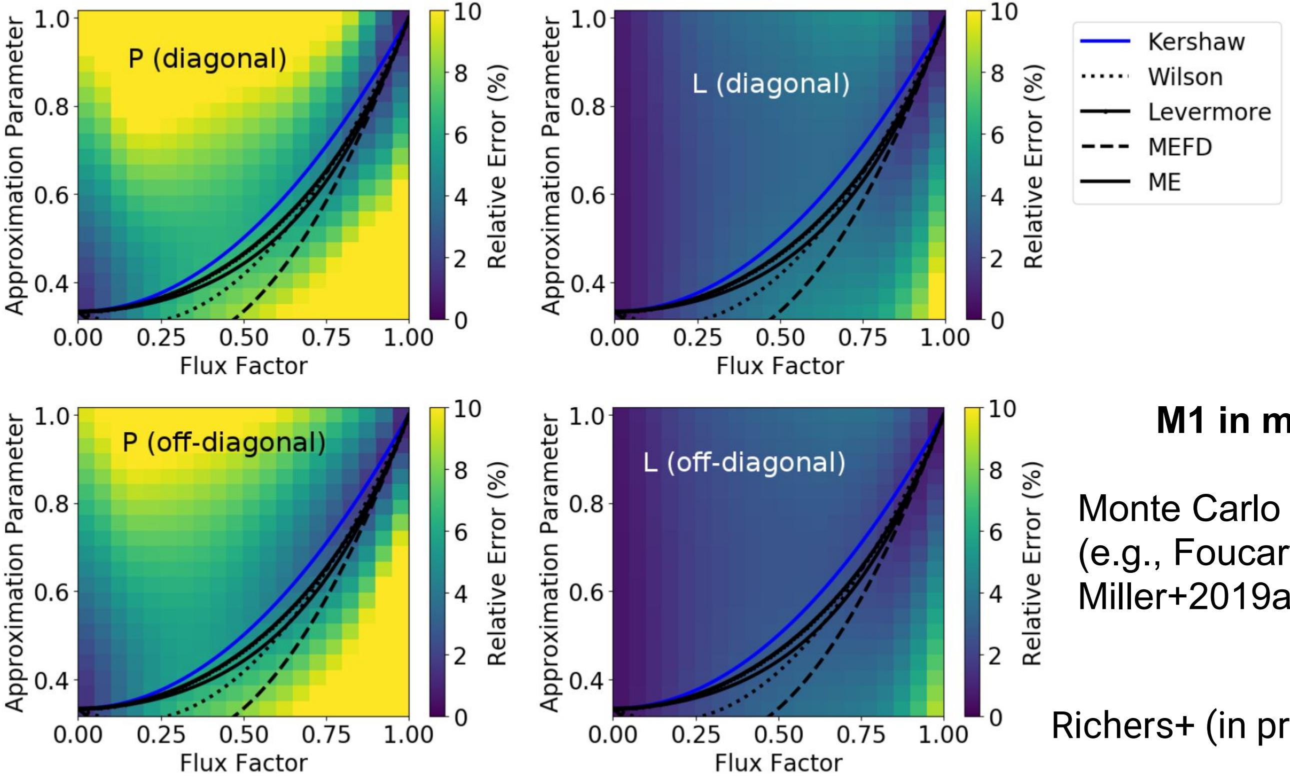
Compare to 0.01 for CCSN

0 for spherical radiation



Richers+ (in prep...)

MERGERS: How well does M1 do?



Unlike CCSNe,
M1 in mergers has sizable errors

Monte Carlo transport may be able to fix it (e.g., Foucart+2018, Miller+2019a, Miller+2019b, Miller+2019c)

Richers+ (in prep...)

Outline

Supernovae | Neutron Star Mergers

Transport

Moments work well in 1D
(worse in multi-D)

Do they work for mergers?

Analytic closures
are inadequate for merger simulations

Solution: Monte Carlo transport

Quantum Kinetics

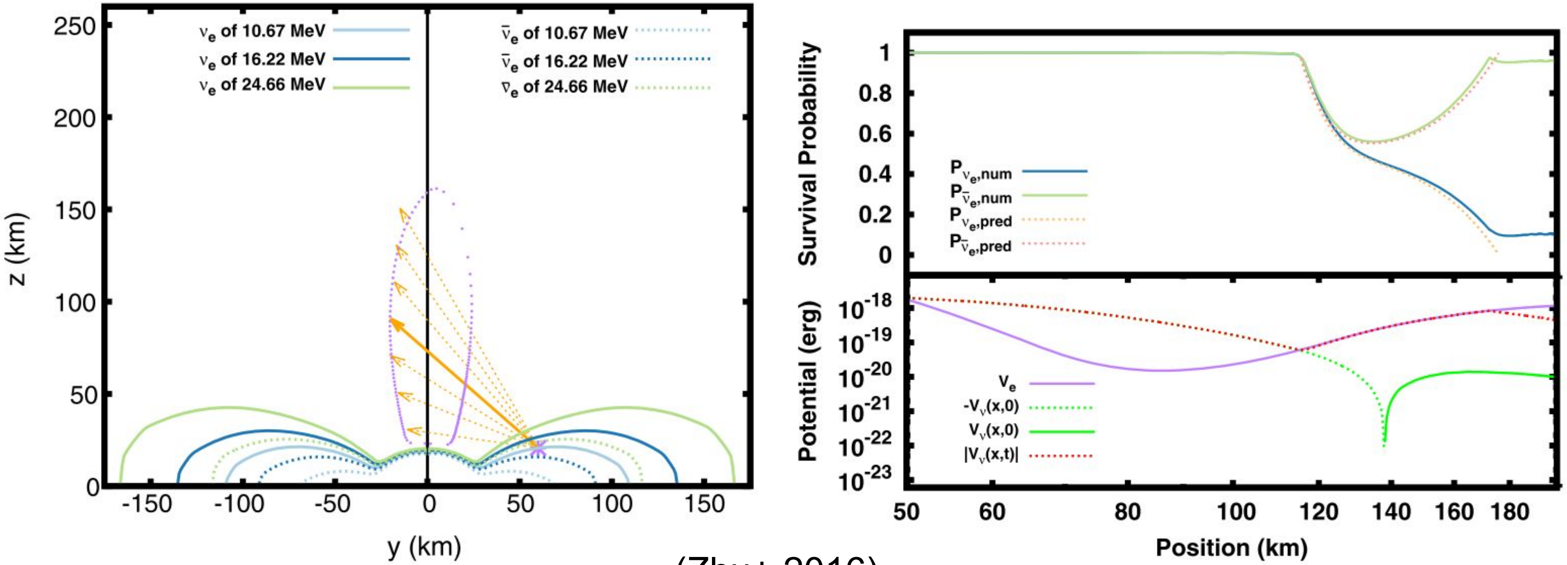
Can use existing neutrino
interaction physics to build
quantum collision terms

Let's use them to understand mergers!
But the geometry is difficult.

Part I:

Quantum Kinetics

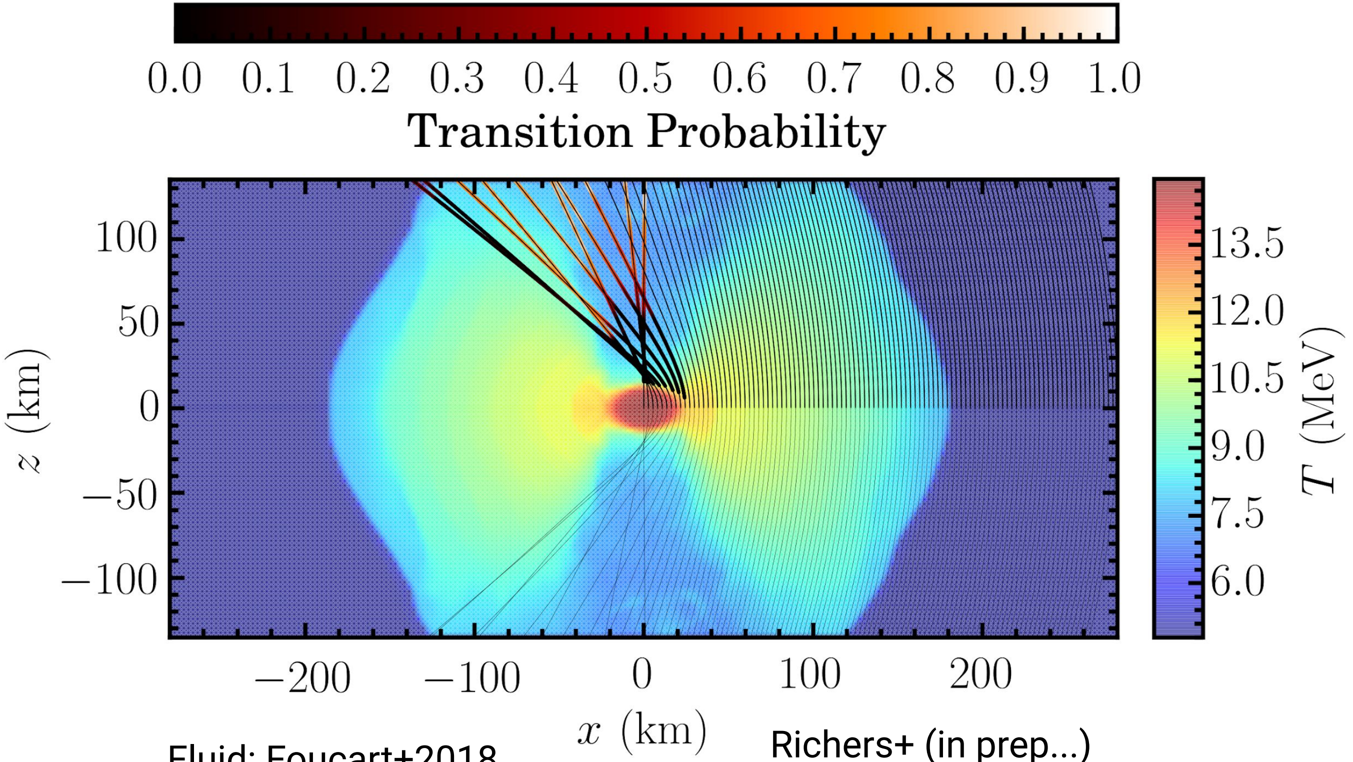
Pure oscillations in neutron star mergers



(Zhu+ 2016)

Neutrino-matter resonance efficiently transforms neutrinos.

Matter-Neutrino Resonance (3D GR)



Fluid: Foucart+2018

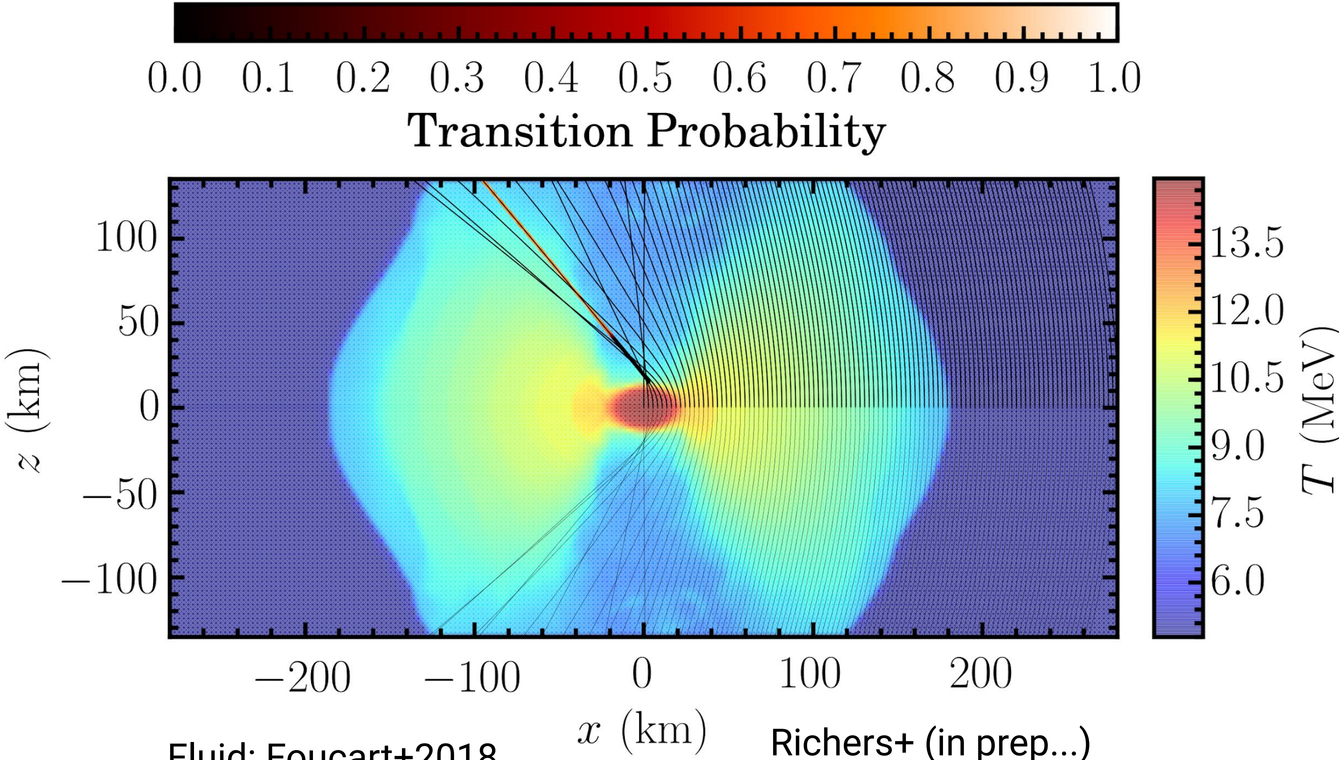
Richers+ (in prep...)

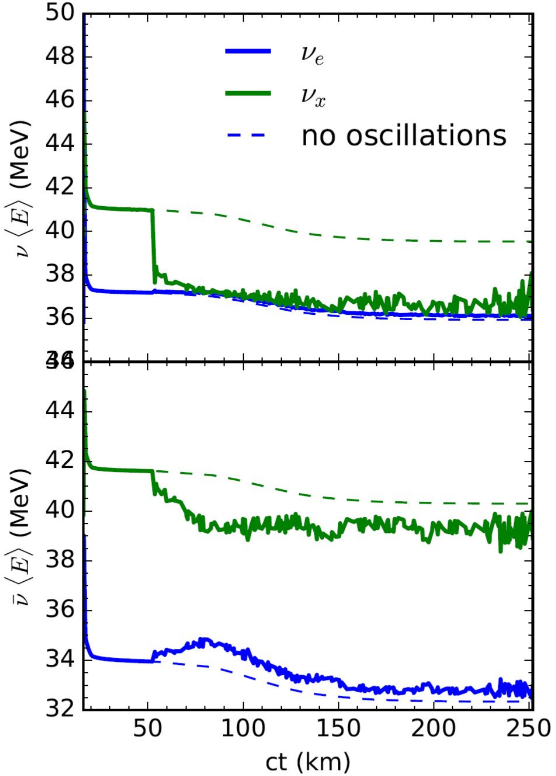
1) Use Monte Carlo to get neutrino field

2) Shoot rays using single-angle approximation

The same process occurs in 3D and GR!

Simultaneous Oscillations and Collisions





Fluid: Foucart+2018

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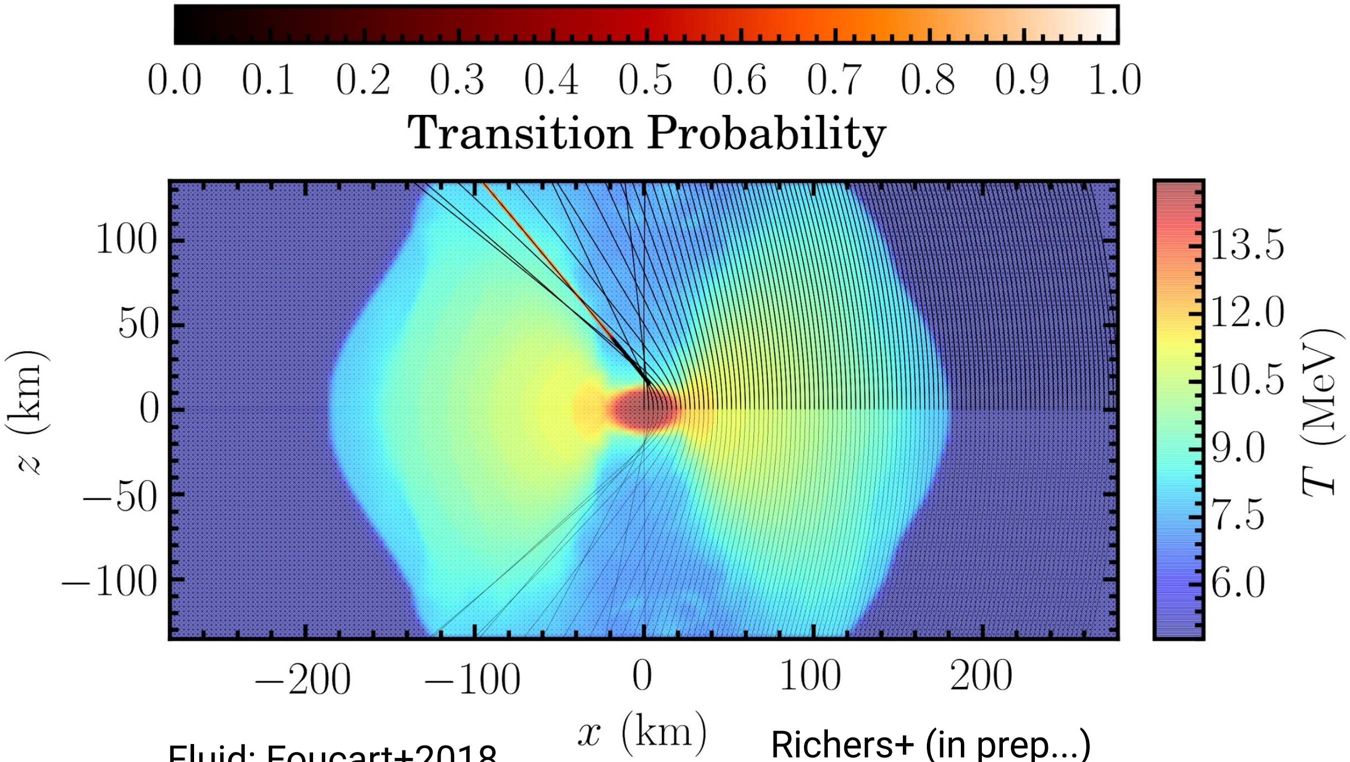
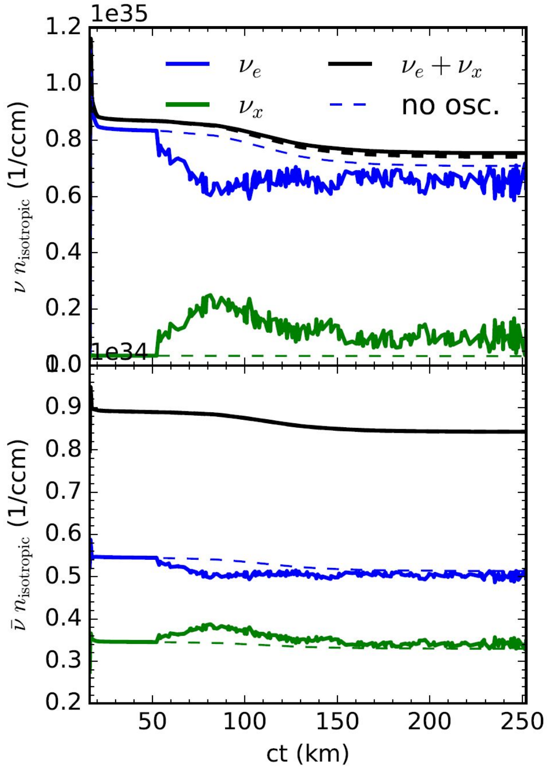
Simultaneous Oscillations and Collisions





Fluid: Foucart+2018

Richers+ (in prep...)

Outline

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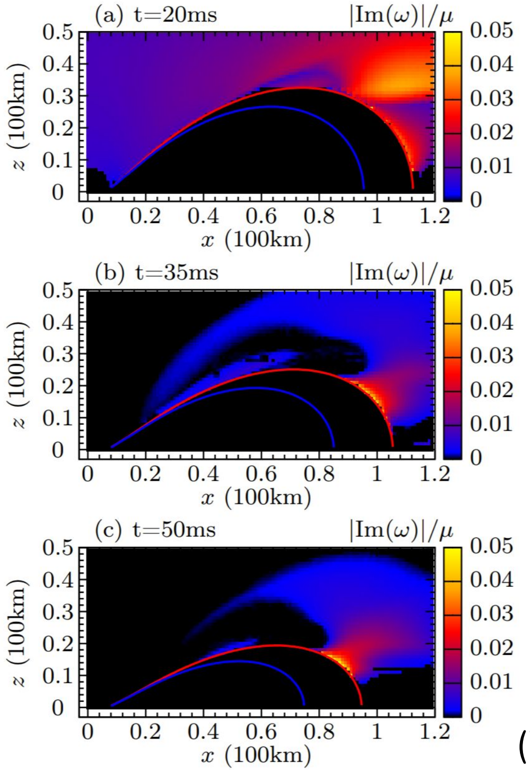
Transport	**Moments** work well in 1D (worse in multi-D) Do they work for mergers?	**Analytic closures** are inadequate for merger simulations Solution: Monte Carlo transport
Quantum Kinetics	Can use existing neutrino interaction physics to build **quantum collision terms** Let's use them to understand mergers! But the geometry is difficult.	Neutrino **oscillations and collisions** occur simultaneously This is gonna be tough.

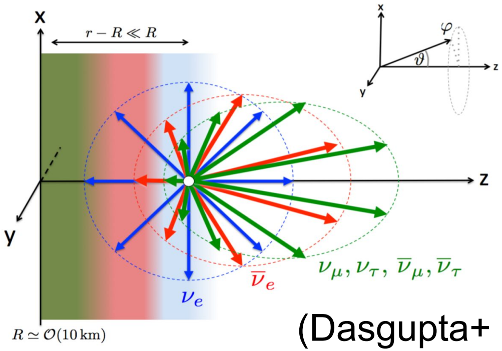
Supernovae and Mergers are Unstable! (since 2015)



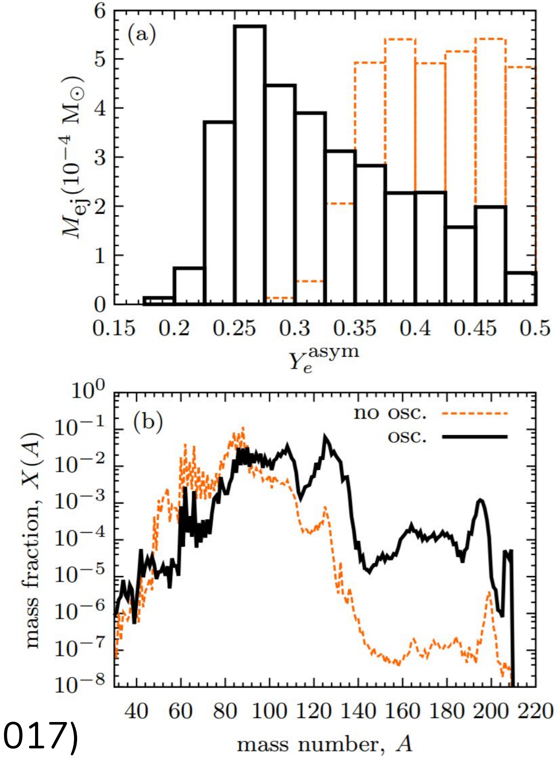
(Wu+ 2017)

Oscillations

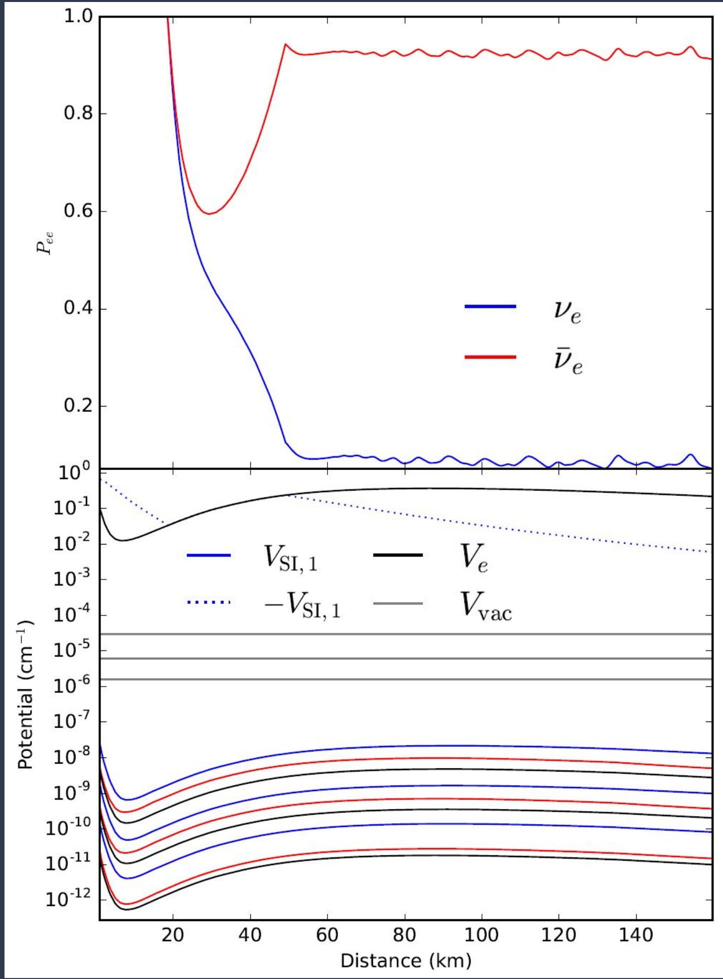
Less r-process



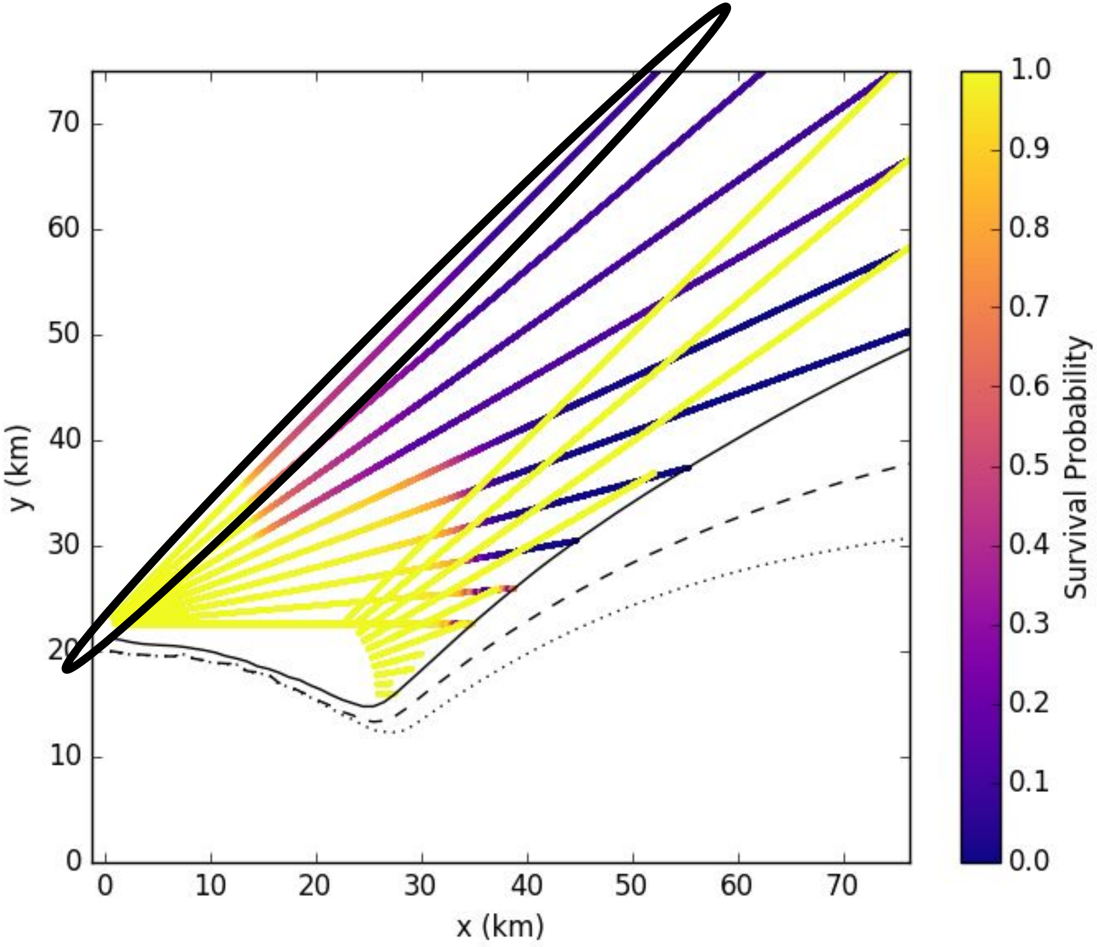
(Dasgupta+ 2017)

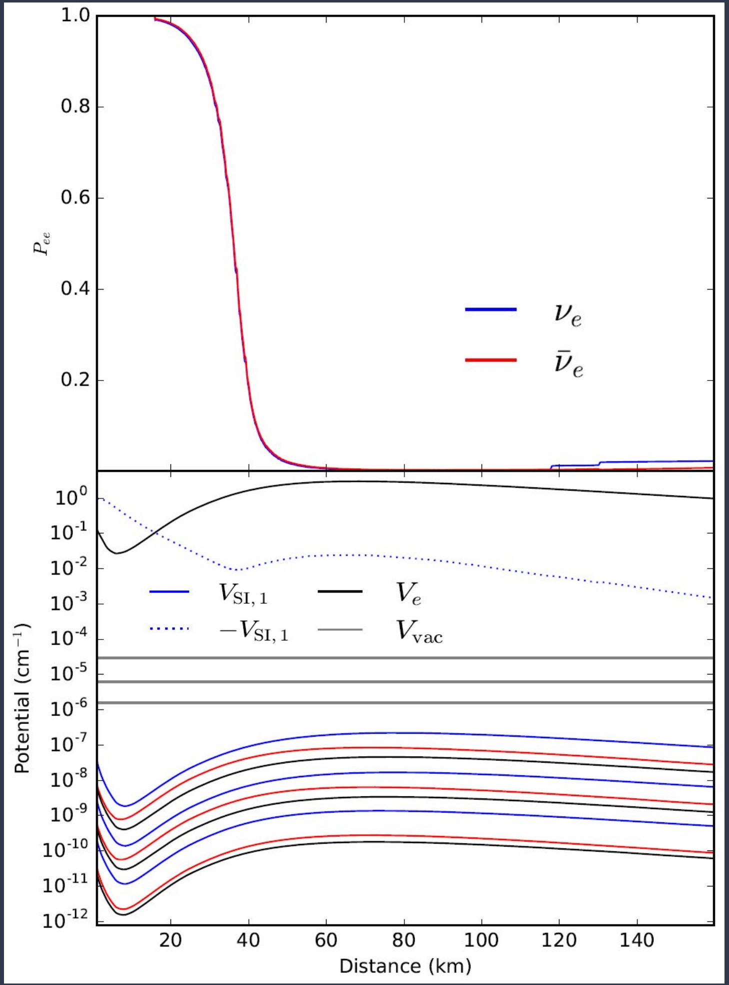


(Wu+ 2017)

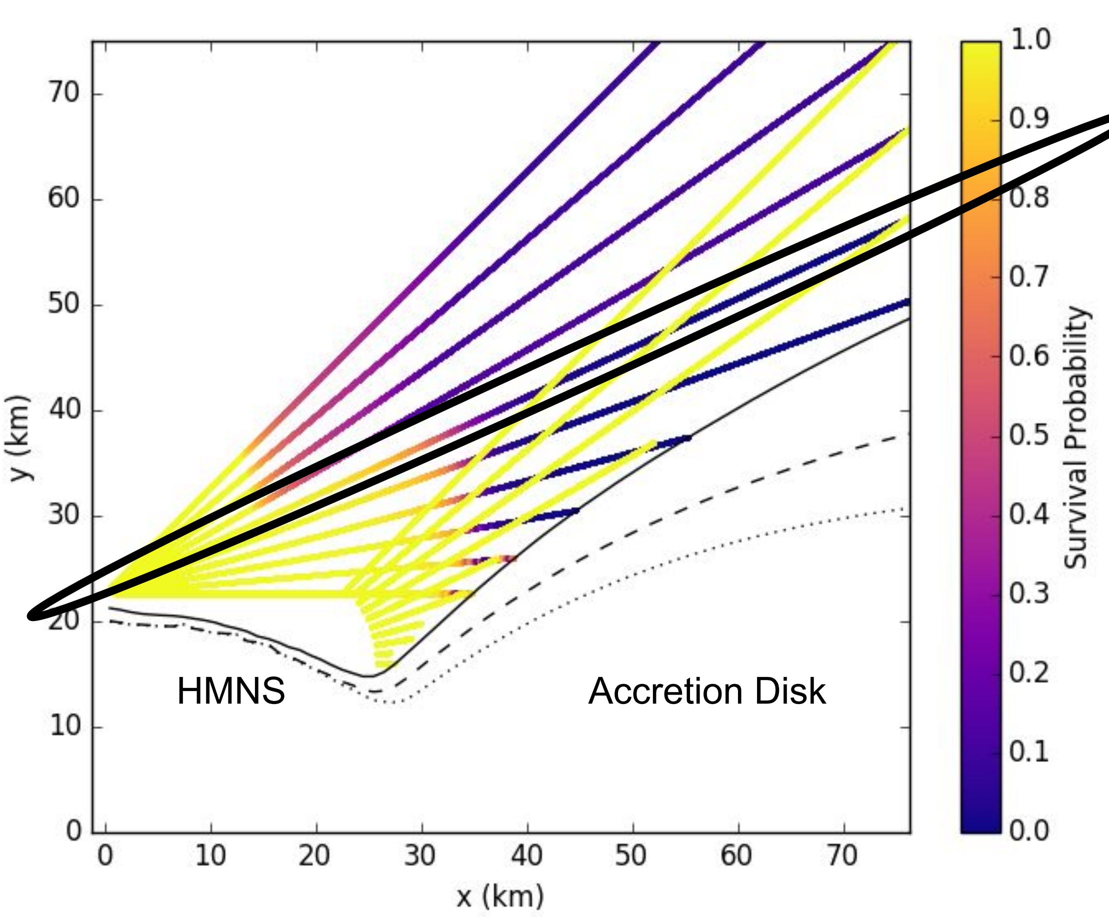


Matter-Neutrino Resonance!

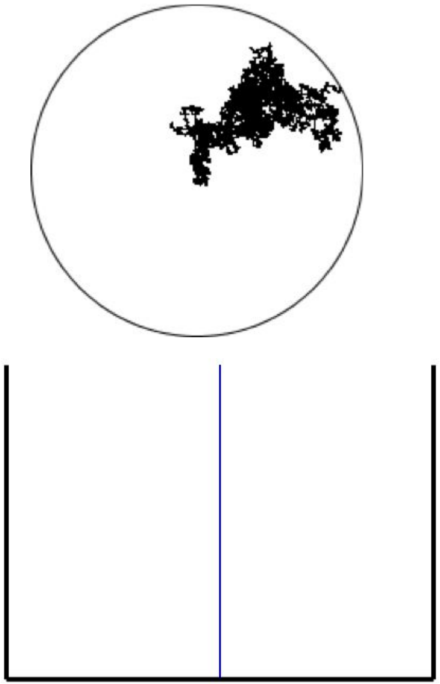


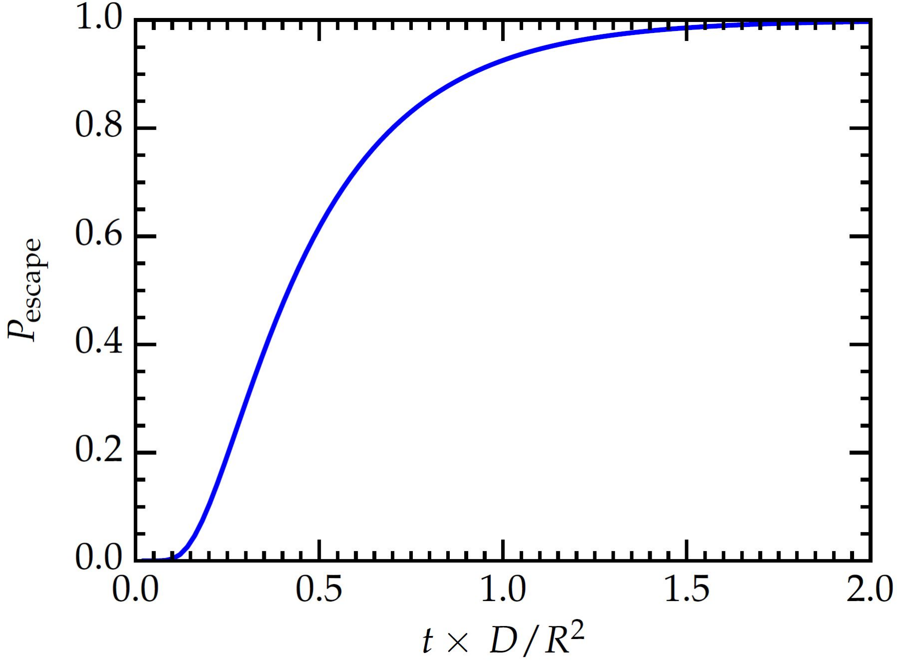


Synchronized MSW

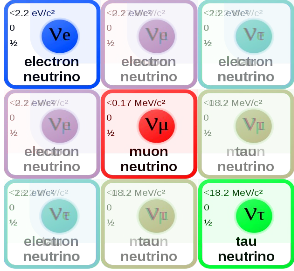


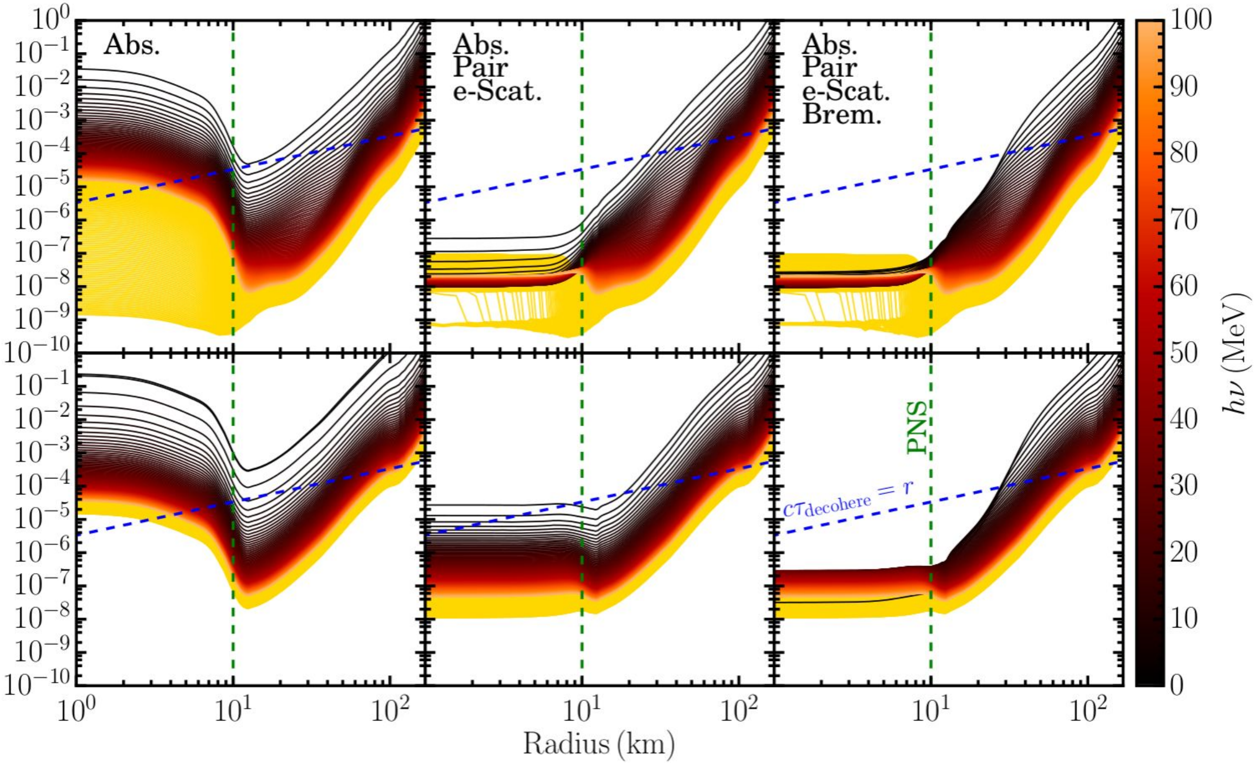
Monte Carlo Random Walk Approximation





Many collision processes are important!





Core:

- Absorption/Emission
- Pair Processes
- Scattering
- Bremsstrahlung
- Neutrino-Neutrino

Heating Region:

- Absorption/Emission