Monte Carlo Neutrino Transport in Core-Collapse Supernovae

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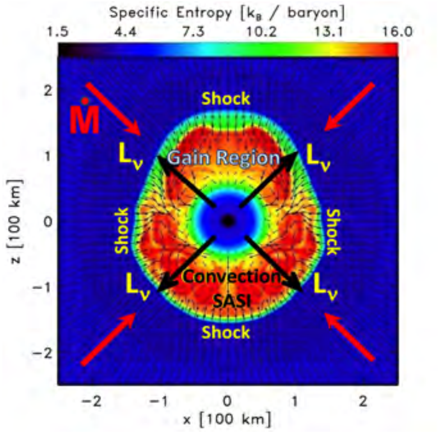
Core-Collapse Supernovae



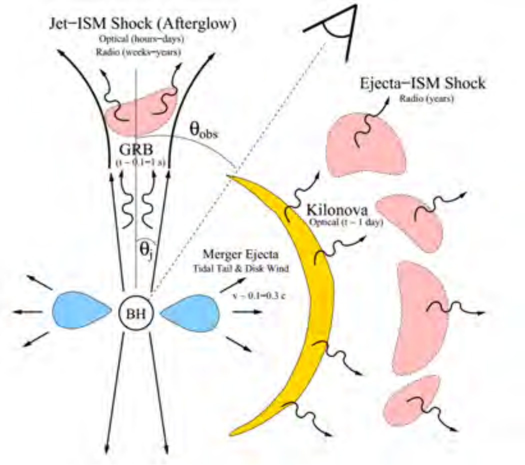
(Ott 2009)

- 10^{51} erg explosion energy
- 10^{53} erg neutrinos released

Neutrinos heat the matter under the shock and drive the explosion.

But how exactly does this work?

Neutron Star Mergers



Metzger and Berger (2012)

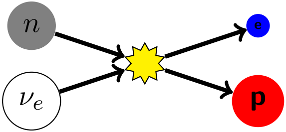
- **Neutrinos** drive outflows that make heavy elements.
- **Neutrinos** may drive relativistic jets.

Can computational models match this heuristic?

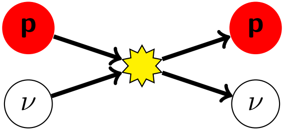
What is a neutrino?

$$\sigma_0 = \frac{4G_F^2 \cos^2(\theta_C)(m_e c^2)^2}{\pi(\hbar c)^4} \approx 1.705 \times 10^{-44}\,\mathrm{cm}^2$$

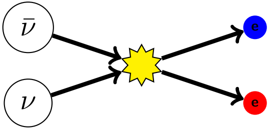
Moving



Absorption/Emission



Scattering



Pair Prod./Annihil.

Radiation Transport

3D

GRMHD

EOS

Nuclei

ν-Radiaton

Boltzmann Equation

$$\frac{\partial f}{\partial t} + \vec{\Omega} \cdot \vec{\nabla} f = C(f)$$

$$\vec{\Omega} = \text{direction}$$
$$C(f) = \text{collisional terms}$$
$$f(\vec{x}, \vec{\Omega}, E_\nu, t) = N_\nu/\text{str}/\text{Hz}/\text{cm}^3$$

7-D integro-differential equation!

Code Verification

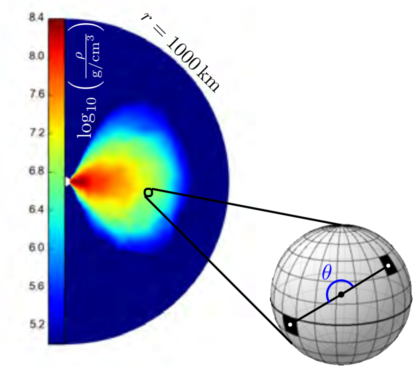
Neutrinos are fundamental to supernovae and neutron star mergers.

We need the *right* answer.

A Tale of Two Methods

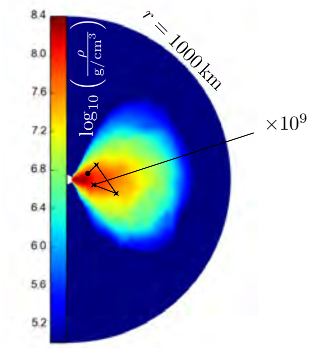
Two very different methods for solving the *same problem*:

Discrete Ordinates



Discretize into energy/angle bins.

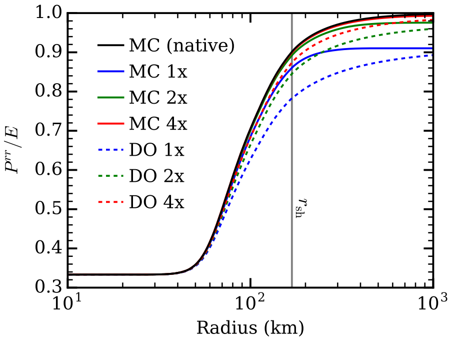
Monte Carlo



Discretize into particles.

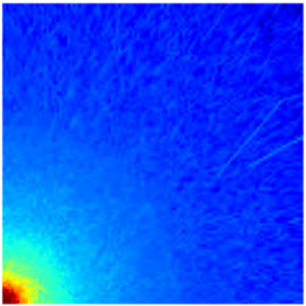
Key Challenge: Radiation transport is expensive!

DO is diffusive.



(Low resolution used in multi-D)

MC is noisy.



(Must do this $\sim 10^5$ times.)

Large per-node memory required for MC replication parallelism.

A Tale of Two Methods

Blue Waters is enabling the first verification of **multidimensional** Boltzmann-level neutrino transport codes.

Discrete Ordinates (dynamical)

Nagakura, Yamada, Sumiyoshi

- 1D: **74k** core-hours on Japanese FX
- 2D: **9M** core-hours on Japanese K

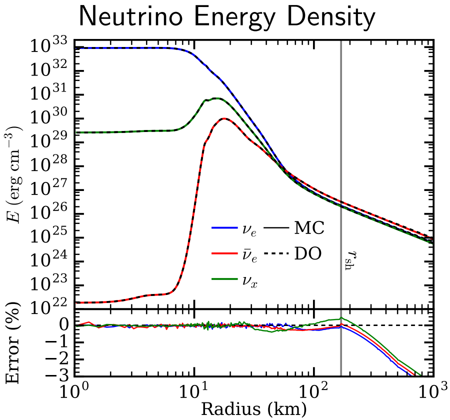
Monte Carlo (static)

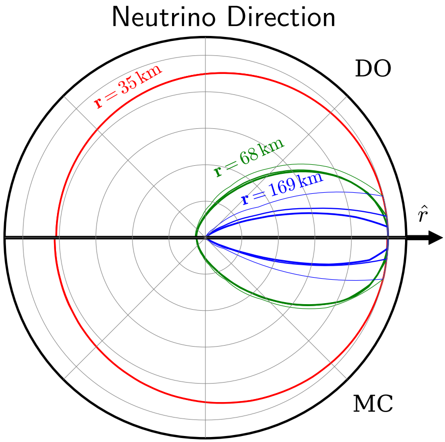
`Sedonu` (Open Source!)

- 1D: **6k** core-hours on BW
- 2D: **768k** core-hours on BW

We apply both codes to a **snapshot** during a supernova simulation.

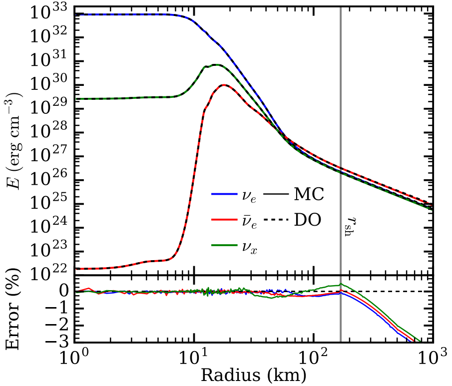
Monte Carlo vs Discrete Ordinates (1D)



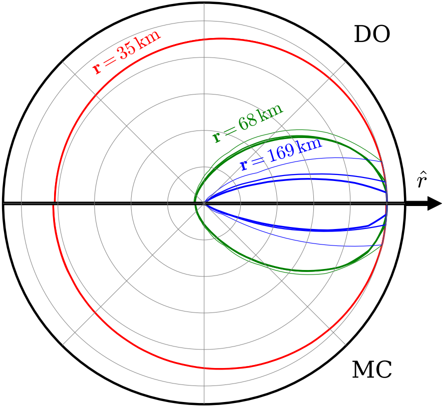


Monte Carlo vs Discrete Ordinates (1D)

Neutrino Energy Density

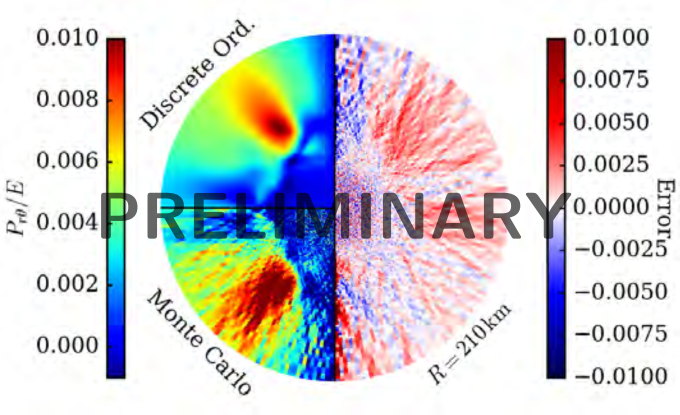


Neutrino Direction



Monte Carlo vs Discrete Ordinates (2D)

$P_{r\theta}$ - sensitive metric of multidimensional **anisotropy**



Good agreement in most difficult metrics.

The Third Wheel: Approximate Moment Methods

1. Rewrite Boltzmann equation in terms of angular moments of f

$$E := \nu^3 \int d\Omega f(\nu, \Omega, x^\mu)$$

$$F^\alpha := \nu^3 \int d\Omega f(\nu, \Omega, x^\mu) l^\alpha$$

$$P^{\alpha\beta} := \nu^3 \int d\Omega f(\nu, \Omega, x^\mu) l^\alpha l^\beta$$

$$N^{\alpha\beta\gamma} := \nu^3 \int d\Omega f(\nu, \Omega, x^\mu) l^\alpha l^\beta l^\gamma$$

$$\text{...etc}$$

$$\frac{dE}{dt} = S_0(E, F^\alpha, P^{\alpha\beta})$$

$$\frac{dF^\alpha}{dt} = S_1(E, F^\alpha, P^{\alpha\beta}, N^{\alpha\beta\gamma})$$

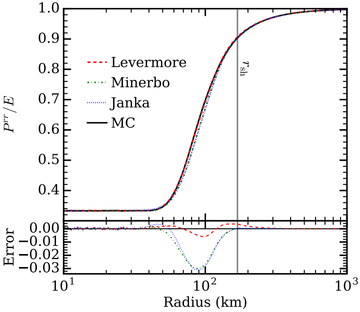
$$\text{...etc}$$

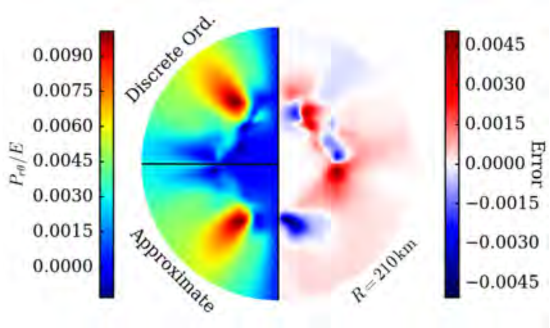
(Thorne 1981, Shibata 2011)

2. Make a guess for $L^{\alpha\beta}(J, H^\alpha)$ and $N^{\alpha\beta\gamma}(J, H^\alpha)$
3. Evolve J and H^α *only*

The Third Wheel: Approximate Moment Methods

How good is the approximation?



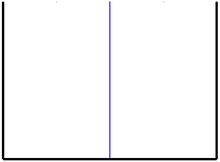


Monte Carlo and **Discrete Ord.** can make *approximate* transport *better*!

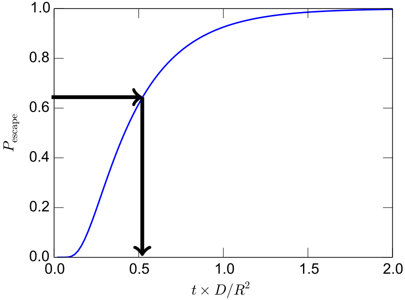
random walk

⇓

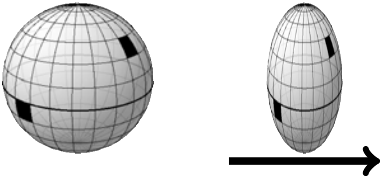
diffusion



1) Use analytic solution to find travel time.



2) Transform out of the comoving frame.



Take Away

- **Blue Waters Fellowship** is funding development and *rigorous* verification of new methods.
- **Blue Waters hardware** is optimal for MC radiation transport.
- **Blue Waters support** has been instrumental in aiding optimization and implementation ideas.
- **Open-source code** and **open data** aid verification efforts community-wide.

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