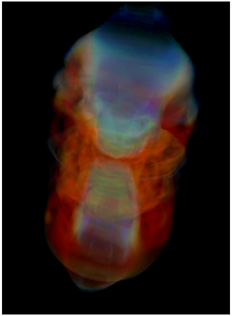
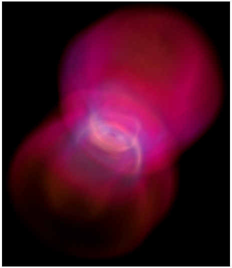
How full neutrino transport impacts heavy element formation in the universe and the resulting electromagnetic counterpart

Jonah M. Miller, in collaboration with:
Brandon Barker, Kelsey Lund,
Mariam Gogilashvili
And Many More...

Los Alamos National Laboratory



Einstein Toolkit Workshop



This should be a conversation!

- Please feel free to interrupt me and ask questions as I speak.
- I plan to leave lots of time for questions.

The required legalese:

- This Document cleared for unlimited release with LA-UR-24-25455
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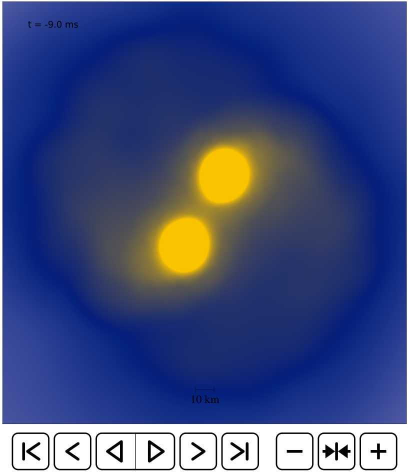
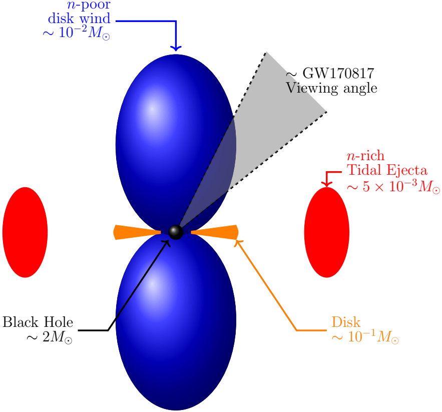
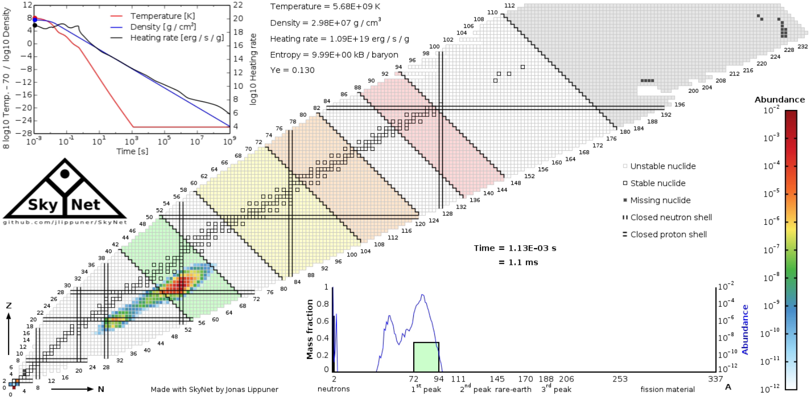


Co-design summer school, 2016

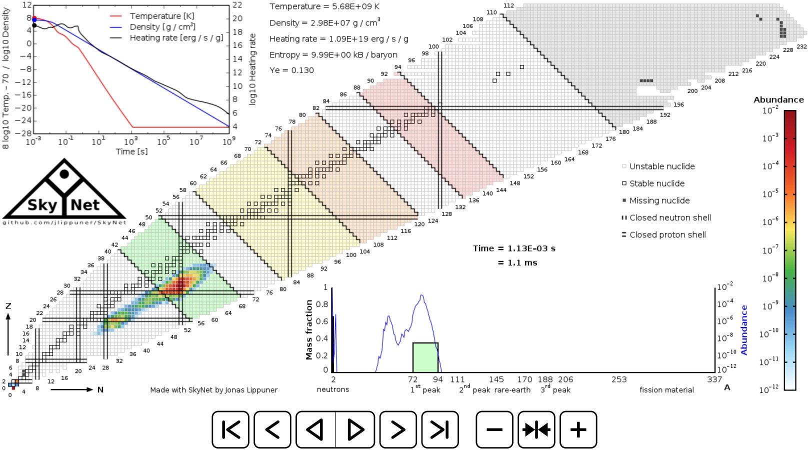


The r-process



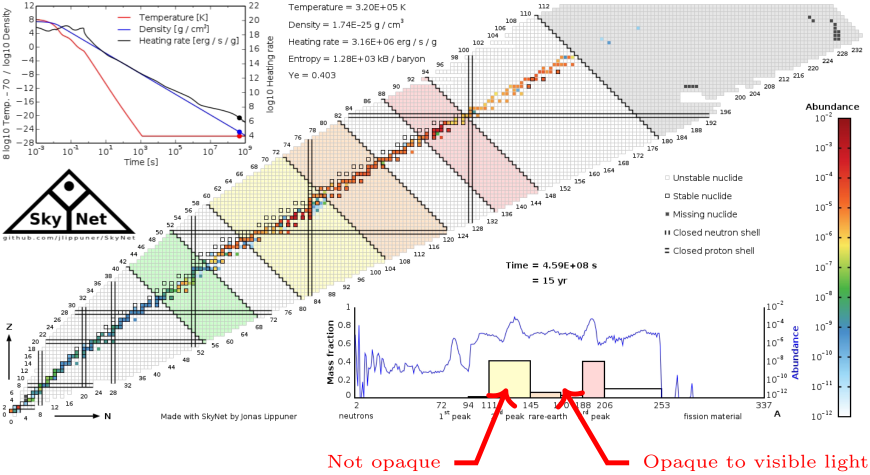
Courtesy of J. Lippuner

The r-process



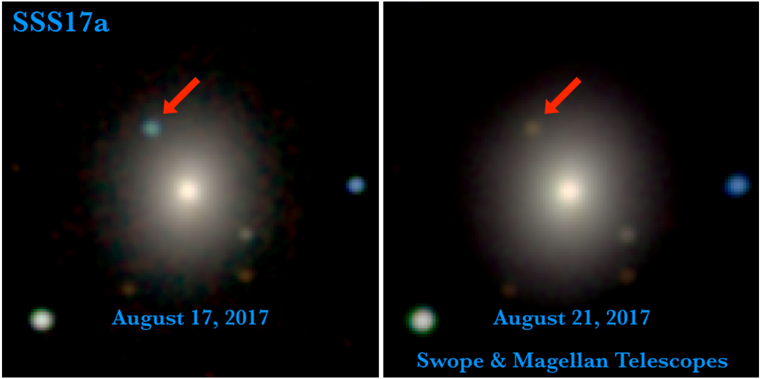
Courtesy of J. Lippuner

Opacity



Temperature [K]
Density [g / cm³]
Heating rate [erg / s / g]
Time [s]
8 log10 Temp. - 70 / log10 Density
log10 Heating rate
Temperature = 3.20E+05 K
Density = 1.74E-25 g / cm³
Heating rate = 3.16E+06 erg / s / g
Entropy = 1.28E+03 kB / baryon
Ye = 0.403
Sky Net
github.com/jlippuner/SkyNet
Abundance
Unstable nuclide
Stable nuclide
Missing nuclide
Closed neutron shell
Closed proton shell
Time = 4.59E+08 s
= 15 yr
Z
N
Made with SkyNet by Jonas Lippuner
Mass fraction
Abundance
neutrons
1st peak
2nd peak
rare-earth
3rd peak
fission material
A
Not opaque
Opaque to visible light

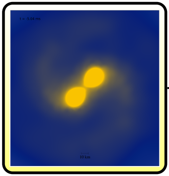
The Kilonova



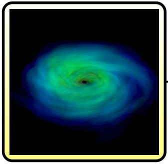
M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

The Makings of a Kilonova

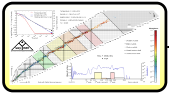
- Duration/relevant time scales
- Methods



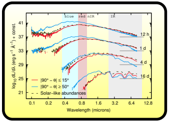
In-spiral:
$\sim \mu$s$\rightarrow$30 s
numerical relativity
ET, SpEC, etc.



Disk+GRB:
$\sim \mu$s$\rightarrow$1 s
GRνRMHD
ν`bhlight`, `HARM`



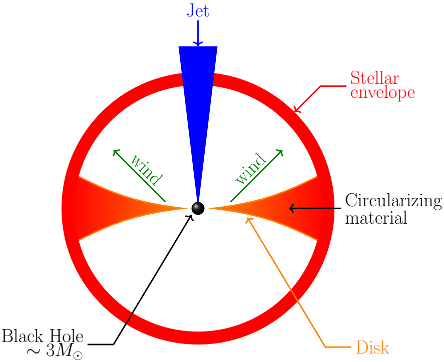
Non-equilibrium reactions:
$\sim$ s$\rightarrow$hours$\rightarrow$Myrs
Reaction network
PRISM, SkyNet



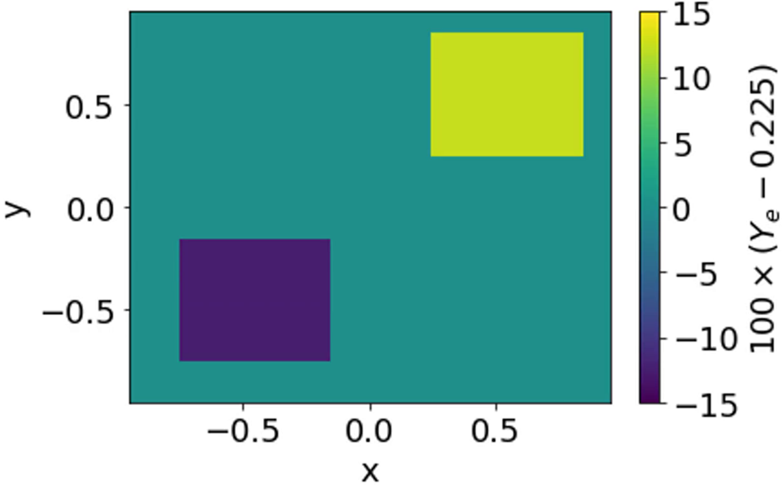
Photon transport:
$\sim$ Weeks
DDMC-IMC
SuperNu,Sedona

Collapsars: An r-Process Parallel

- Collapse of rapidly rotating massive star
- Accretion disk that forms:
  - potential engine of long gamma ray bursts
  - potential site of r-process
- See:
  - Siegel, Barnes, Metzger, *Nature* **569**, 241 (2019)
  - **JMM** et al., ApJ **902**, 66 (2020)
  - Much recent work. Just et al., Gottlieb et al., Barnes + Metzger, ...

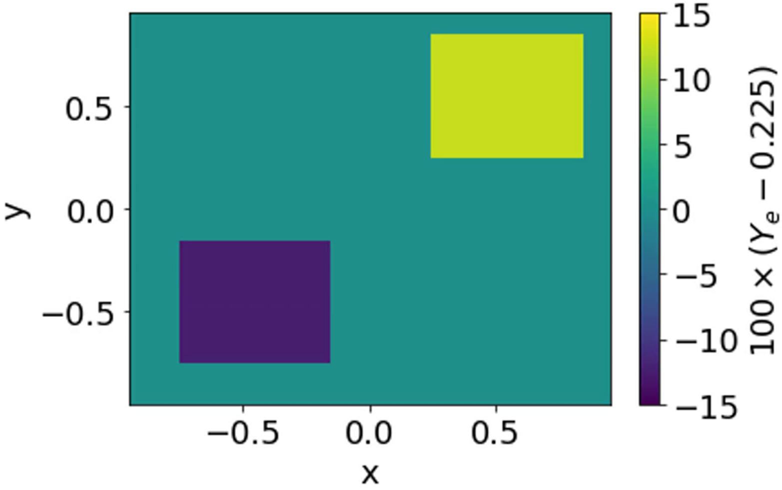


Neutrino Transport Matters!



JMM, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

Neutrino Transport Matters!



JMM, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

The Relevant Conservation Laws

- Neutrino Transport Equation (assumes massless)

$$\frac{D}{d\lambda}\left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3}\right) = \left(\frac{h^2 \eta_{\epsilon,f}}{\epsilon^2}\right) - \left(\frac{\epsilon \chi_{\epsilon,f}}{h}\right)\left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3}\right)$$

- Momentum and Internal Energy Conservation

$$\partial_t \left[\sqrt{-g}\left(T^t{}_\nu + \rho_0 u^t \delta^t_\nu\right)\right] + \partial_i \left[\sqrt{-g}\left(T^i{}_\nu + \rho_0 u^i \delta^t_\nu\right)\right] = \sqrt{-g}\left(T^\kappa{}_\lambda \Gamma^\lambda_{\nu\kappa} + G_\nu\right)$$

- Electron Number

$$\partial_t \left(\sqrt{-g}\rho_0 Y_e u^t\right) + \partial_i \left(\sqrt{-g}\rho_0 Y_e u^i\right) = \sqrt{-g} G_{\mathrm{ye}}$$

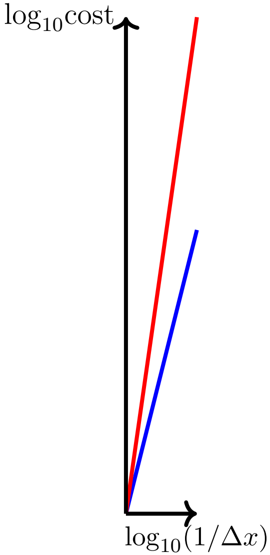
- Spacetime (actually much more complicated)

$$\begin{aligned}(\partial_t - \mathcal{L}_\beta)\gamma_{ij} &= -2\alpha K_{ij} \\ (\partial_t - \mathcal{L}_\beta)K_{ij} &= R_{ij} + \cdots + 4\pi\left[(S-\rho)\gamma_{ij} - 2S_{ij}\right]\end{aligned}$$

- And baryon number and magnetic flux conservation...

Why is Transport Hard?

- Fluid Equations:
  - Variables, e.g., ρ, depend on 3 spatial dimensions and time: $\sim \frac{1}{\Delta t}\frac{1}{\Delta x}\frac{1}{\Delta y}\frac{1}{\Delta z} \sim \left(\frac{1}{\Delta x}\right)^4$
- Boltzmann/Transport equation:
  - Variables, e.g., f, depend on 3 spatial dimensions, 3 momentum dimensions, and time.
  - Where am I and where am I going? $\sim \left(\frac{1}{\Delta t}\right)\left(\frac{1}{\Delta x}\right)^3\left(\frac{1}{\delta p_x}\right)^3$ $\sim \left(\frac{1}{\Delta x}\right)^7$



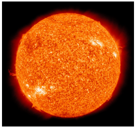
Relevant Neutrino Interactions

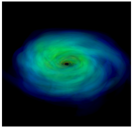
Type	Processes	Corrections/Approximations
Abs./Emis. on Neutrons	$\nu_e + n \leftrightarrow e^- + p$ $\nu_\mu + n \leftrightarrow \mu^- + p$	Blocking/Stimulated Abs. Weak Magnetism Recoil
Abs./Emis. on Protons	$\bar{\nu}_e + p \leftrightarrow e^+ + n$ $\bar{\nu}_\mu + p \leftrightarrow \mu^+ + n$	Blocking/Stimulated Abs. Weak Magnetism Recoil
Abs./Emis. on Ions	$\nu_e A \leftrightarrow A' e^-$	Blocking/Stimulated Abs. Recoil
Electron Capture on Ions	$e^- + A \leftrightarrow A' + \nu_e$	Blocking/Stimulated Abs. Recoil
$e^+ - e^-$ Annihilation	$e^+ e^- \leftrightarrow \nu_i \bar{\nu}_i$	single-ν Blocking Recoil
n_i-n_i Brehmsstrahlung	$n_i^1 + n_i^2 \rightarrow n_i^3 + n_i^4 + \nu_i \bar{\nu}_i$	single-ν Blocking Recoil
Proton scattering	$\nu_i + p \leftrightarrow \nu_i + p$	elastic/inelastic
Neutron scattering	$\nu_i + n \leftrightarrow \nu_i + n$	elastic/inealstic
Heavy ion scattering	$\nu_i + A \leftrightarrow \nu_i + A$	ion-ion correlation electron polarization form-factor

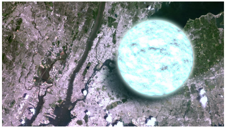
- And this is ignoring Neutrino oscillations!

Burrows, Reddy, Thompson, NPA **177**, 356, (2006)

- Characterized by optical depth τ s.t. $I_\nu = I_\nu(s_0)e^{-\tau(s_0,s)}$
  - Effective "scattering optical depth" also matters







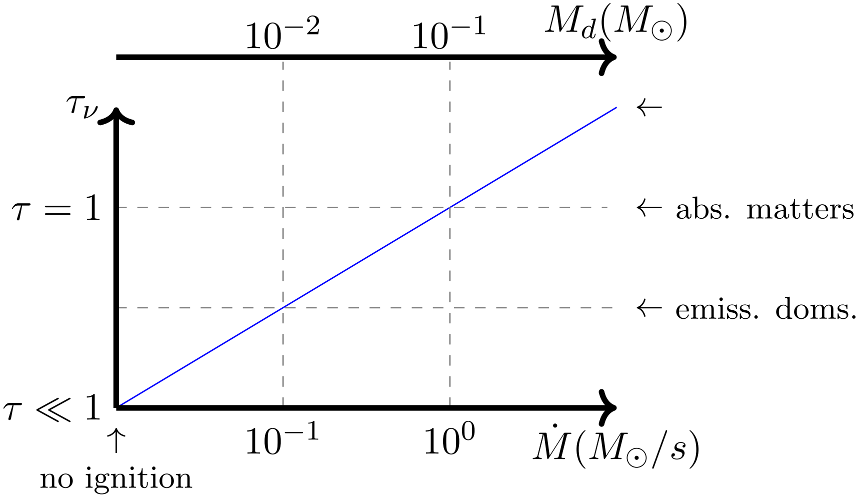
$\tau \ll 1$
free-streaming

Must solve
full Boltzmann
Equation

$\tau \gg 1$
diffusion

How Much Does Transport Matter for disks?

- Interactions scaling/nucleon:
  - T^6 typical in disks. Can be as sharp as T^8!



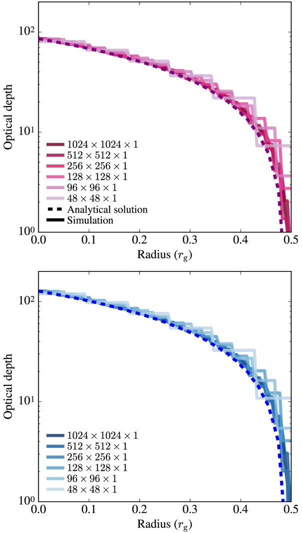
Transport Techniques

A zoo of techniques with various trade-offs

- Mesh-based methods, also called Short Characteristics
  - More expensive without some notion of sparsity or adaptivity
  - Discrete ordinates, also called S_N
  - Finite Elements
  - Finite Volumes
  - Finite Differences
  - Sparse grids
- Mesh-free, also called Long Characteristics
  - Often shot noise limited
  - Ray tracing
  - Monte Carlo
- Approximate methods
  - Approximation may or may not be appropriate
  - Cooling functions
  - Leakage
  - Flux-limited Diffusion
  - Analytic moment closures
- Hybrid methods
  - Potentially the best way to navigate the trade-space

Technique: Leakage and Cooling

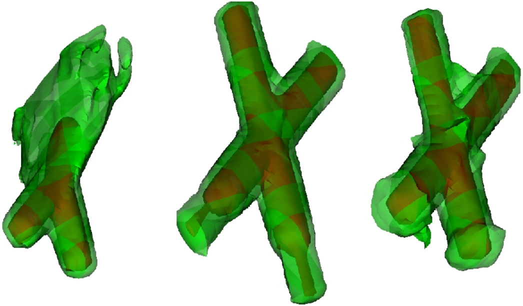
- Apply source terms but don't model radiation field
- Leakage corrects source terms by trying to account for re-absorption
- Requires calculation of optical depth
- Relatively simple to implement, potentially faster



Murguia-Berthier et al., ApJ **919**, 2 (2021)

Technique: Diffusion + Moments

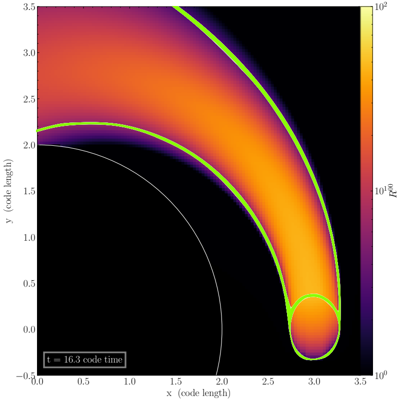
- Evolve *conserved* quantities of radiation field
  - Zeroth moment only: Conserve energy. Radiation field obeys diffusion equation
  - Zeroth + First moments; Conserve momentum too. Radiation field obeys “fluid” equations
- Information *lost* by dropping higher-order terms. System must be “closed.”



Foucart, MNRAS **475** 3 (2018)

More compute unlocks short characteristics

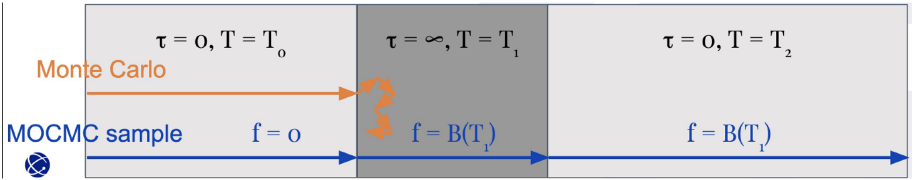
- Discretize full botlzmann on a grid. Typically in spherical coordinates (in momentum space).
- "Classic" discretization is finite differences S_N
- Finite volumes discretization (right)
- Finite elements discretization (see e.g., work by Maitraya Bhattacharya and David Radice)
- Sparsity such as sparse grids/tensor networks promising path forward



White et al., arXiv:2302.04283

A brief aside on Hybrid Methods

- Moment method closed with full transport solution or analytic solution, depending on region of interest
- Combines advantages of both approximate and exact methods, at cost of particles
- See, e.g., Foucart, MNRAS **475** 3 (2018); Izquierdo et al., 2024



;

Ryan and Dolence, ApJ **891** 118, (2020).

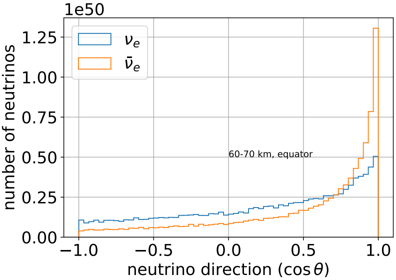
Technique: Particles + Monte Carlo

- Assume distribution function described by sum over delta functions:

$$f = \sum_{i=1}^{N} w_i \delta^3(x - x_i)\delta^3(p - p_i)\delta(t - t_i)$$

- Weight w_i for a given particle is the number of *physical* particles a single Monte Carlo packet (sometimes called *superphoton*) represents.
- For technical reasons, can struggle with large optical depths.

- A *fundamentally statistical* approach. Meaningful predictions recovered by *integration* over f.
- Error scales as $1/\sqrt{N}$, no matter number of dimensions!



Monte Carlo Transport Basics

Interactions with the gas are *probabilistic.*

- Weights w_i chosen at particle emission to fix number of particles created in a time step, and thus accuracy/cost:

$$N_{s,t} = \Delta t \sum_f \int \sqrt{-g} d^3x d\nu d\Omega \frac{1}{w} \frac{j_{\epsilon,f}}{h\nu}$$

- Created particle direction, energy, sampled from emissivity, treating it as a pdf.

Gotcha!

Resolution controls are heuristic and maintaining appropriate resolution can be a problem dependent puzzle. Expect growing pains.

Scattering and Absorption

Also probabilistic. But can be *biased*

- Important for accurately sampling scattering processes!
- Can be used to *de-enhance* too. Can stabilize in, e.g., a neutron star.

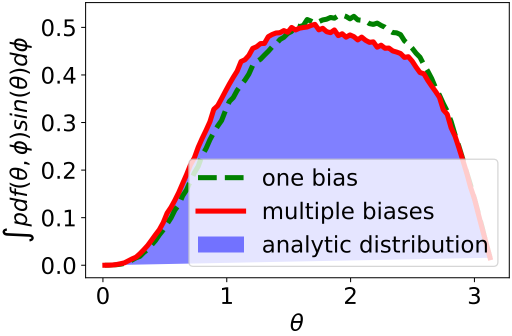
- For absorption:

$$\Delta\tau_a > -\ln(r_a)$$

- For scattering:

$$\Delta\tau_p > -\ln(r_s)/b_s(\nu, f, p)$$

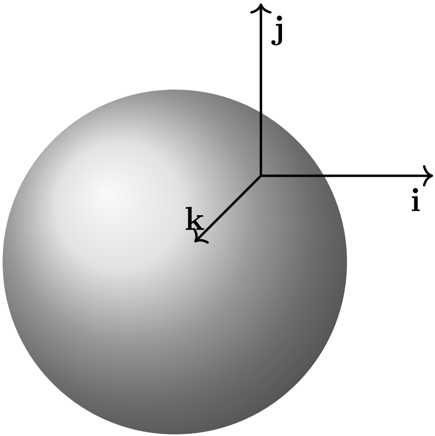
- For scattering to play a *fair game*, particles *split* upon scattering.



JMM, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

Gotcha! Tetrads and Units

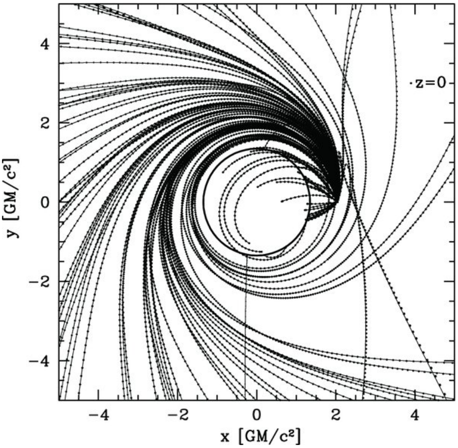
- Tetrads
  - Above interactions all expressed in *Minkowski* space, where algebra is simpler
  - To get away with this, we transform into a *tetrad* frame comoving with the fluid to process radiation-matter interactions
- Units
  - GR frequently scale-free.
  - Matter-radiation interactions not scale-free. CGS is natural.
  - Do "lab-frame" physics in natural units. Move to CGS to process, e.g., emissivity.



- Particle paths evolved *deterministically*:

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\mu}{d\lambda}\frac{dx^\nu}{d\lambda} = 0$$

- Assume neutrinos are massless (not quite true but good enough)

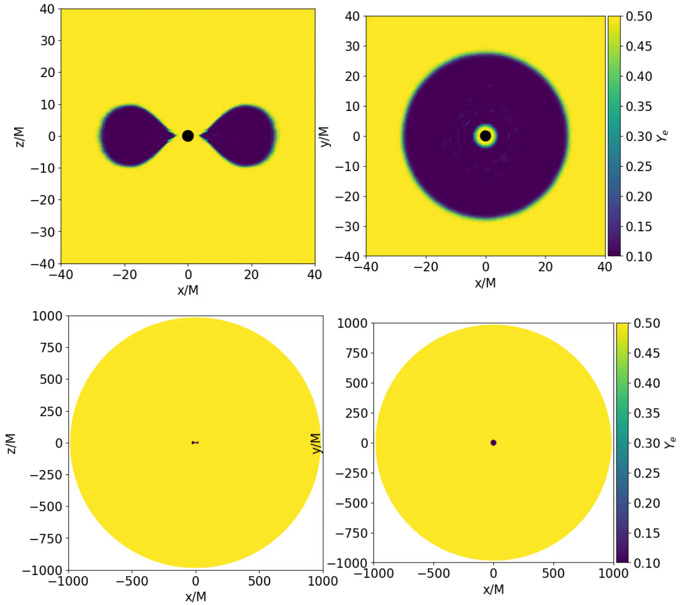


Dolence et al., (2009) ApJS **184** 387

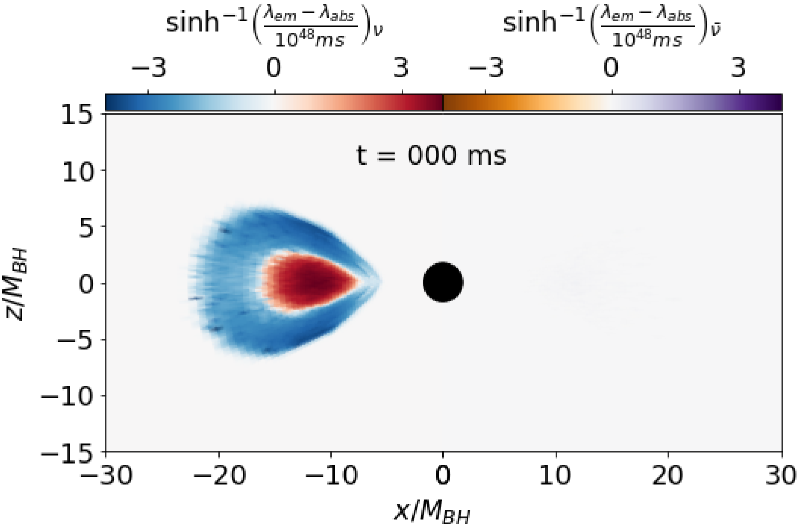
Putting it all together in ν`bhlight`!

- **Magnetized gas** via *finite volume methods*
  - Standard second-order Gudonov scheme
  - Cell-centered constrained transport for magnetic fields
  - WENO5 reconstruction
  - Local Lax-Friedrichs Riemann solver
- **Neutrinos** via *Monte Carlo methods*
  - Explicit integration along geodesics
  - Probabilistic emissivity, absorption, and scattering
  - Novel biasing scheme ensures all processes well-sampled
- **Coupled** via *operator splitting*
- Built on top of `HARM`, `grmonty`, and `bhlight`.

The August 2017 Disk

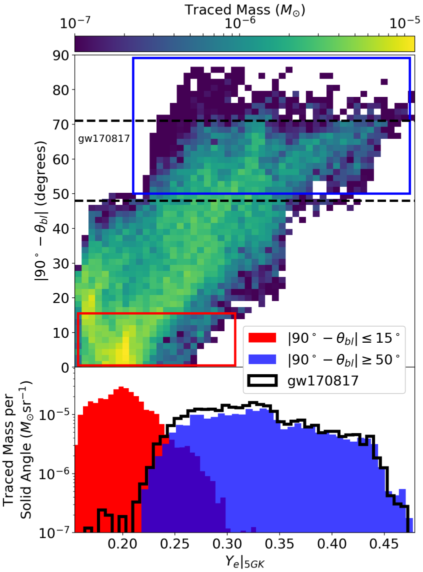


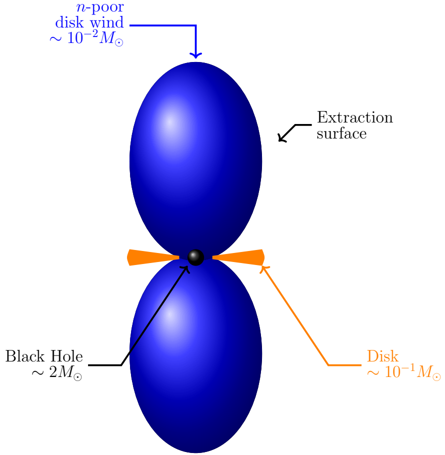
Exquisite Access to the Radiation Field



JMM et al. PRD **100** 023008 (2019)

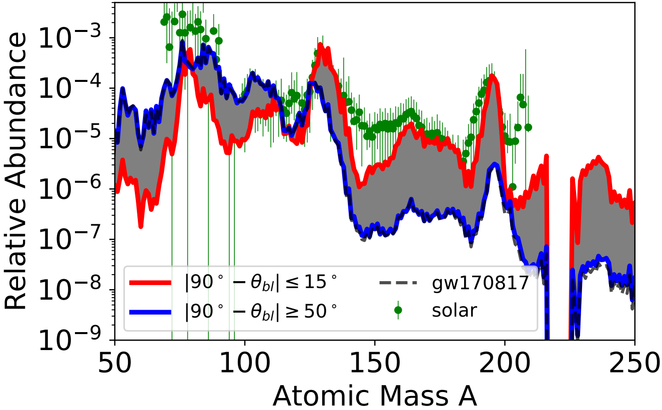
Electron Fraction of the Outflow





JMM et al. PRD **100** 023008 (2019)

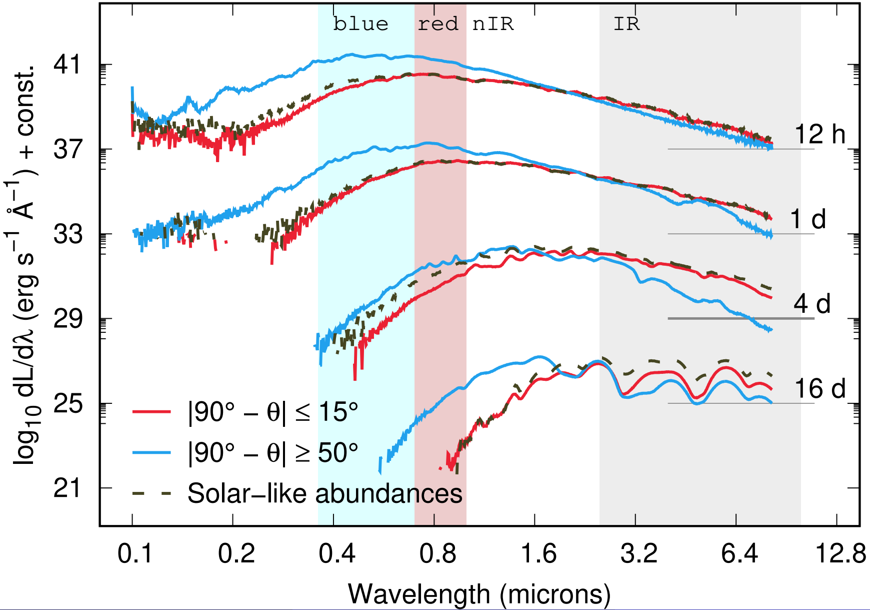
Nucleosynthesis



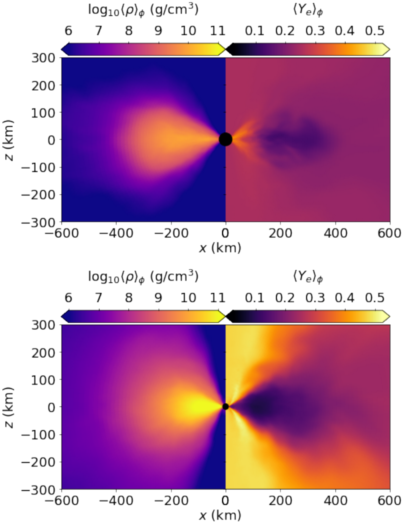
- r-process networks:
  - SkyNet
  - PRISM
  - CFNET
  - etc.

JMM et al. PRD **100** 023008 (2019)

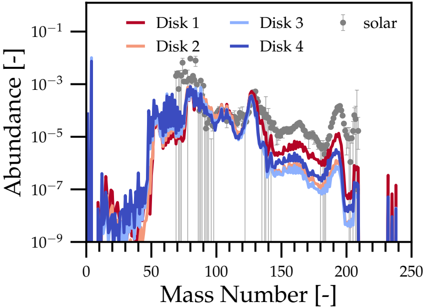
Spectra



blue
red
nIR
IR
41
37
33
29
25
21
$\log_{10} dL/d\lambda$ (erg s^{-1} Å^{-1}) + const.
12 h
1 d
4 d
16 d
$|90° - \theta| \leq 15°$
$|90° - \theta| \geq 50°$
Solar–like abundances
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12.8
Wavelength (microns)



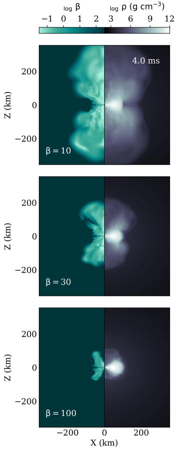
- Model a suite of exotic post-BHNS merger disks



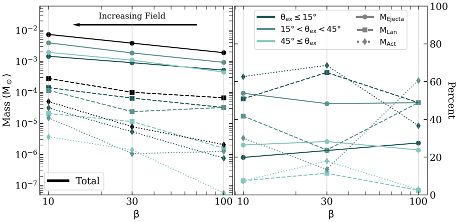
Curtis, **JMM**, et al., ApJS 945 L13 (2023)

Impact of Magnetic Field

- Magnetically-driven turbulence drives angular momentum transport.
- *Dr.* Kelsey Lund (defended yesterday!)



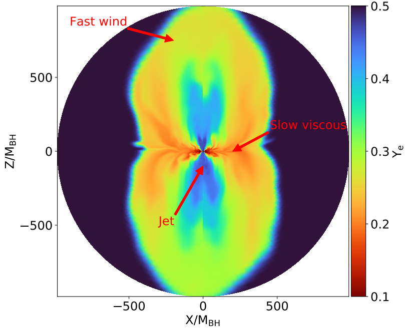
- Field must "spin up" due to turbulent instability.
- Larger fields mean less spin-up time, also more "memory" of initial configuration.
- Impacts yields, outflow morphology.

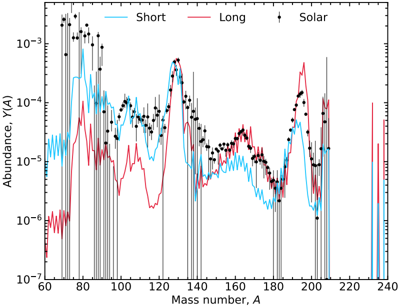


Lund, **JMM**, et al., (2024) ApJ **964** 111

Ultra Late-Time Outflow

- Original models of post-merger disks (and collapsars) only run for very short time: ~ 120ms.
- Outflow not finished by this time. Late-time outflow may look very different.
- Extended simulation to 1.2s physical time. 7 months required on supercomputer.

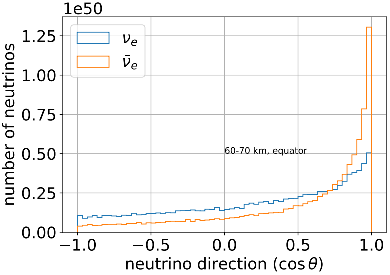


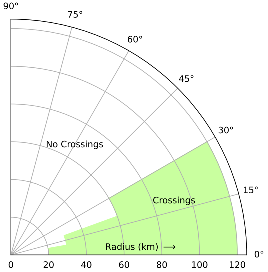


Sprouse, **JMM**, et al., (2024) ApJ **962** 79

Fast Flavor Transformations

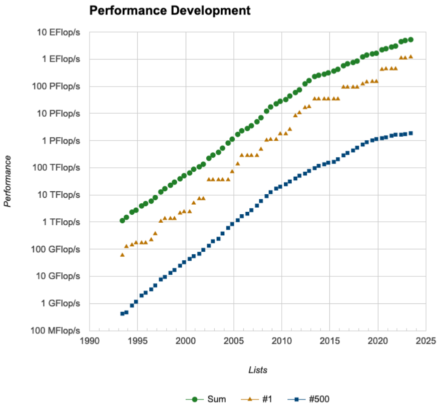
- Neutrinos can *oscillate* from one flavor to another. This can impact nucleosynthesis.
- Due to length/time scales, impossible to treat from first principles



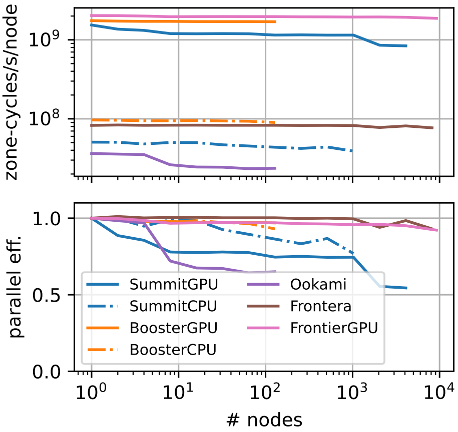


Mukhopadhyay, **JMM**, McLaughlin, ArXiv:2404.17938

Parthenon: Unlocking GPU Cycles



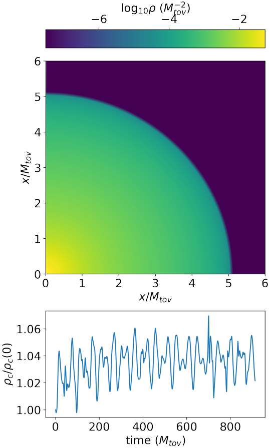
Top500 List



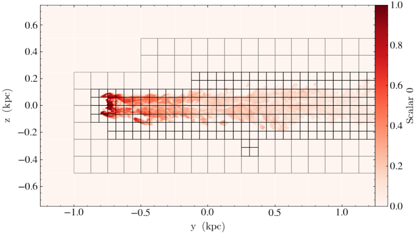
Grete, **JMM**, et al., ArXiv:2202.12309

Tools built on top of Parthenon

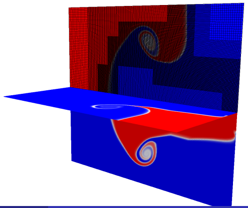
- Phoebus, neutron star



- Athena-PK, turbulence

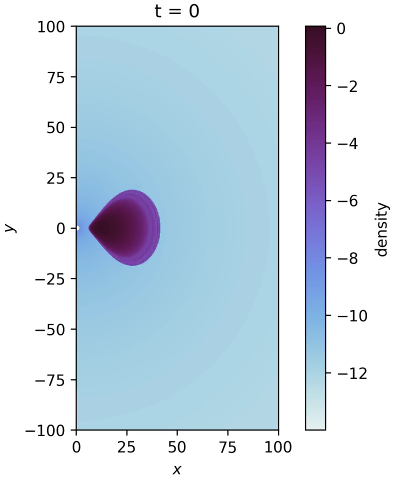


- Riot, triple point



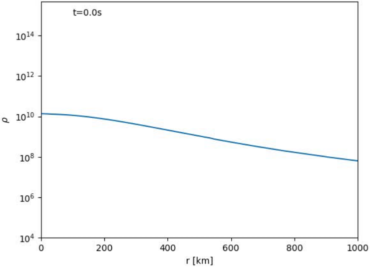
Next Generation of Full-Transport Disks in Phoebus

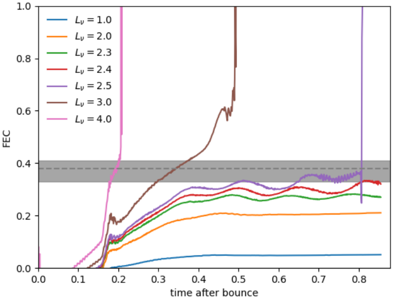
- *Dr.* Brandon Barker (just defended his thesis)
- Current capabilities:
    - Curvilinear coordinates
    - nuclear EOS
    - Monte Carlo transport
    - GPUs
- Soon to be ready:
    - Adaptive mesh refinement



Supernovae in Phoebus

- *Dr.* Mariam Gogilashvili (just defended her thesis)
- Connecting pen-and-paper model (FEC) to simulations: Gogilashvili and Murphy, MNRAS **515** 2, (2022)
- Gogilashvili, Murphy, **JMM**, (2024) ApJ **962** 110





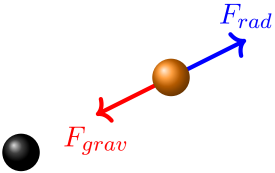
Get Involved

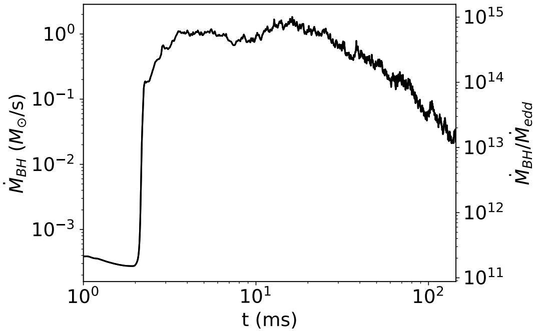
- Parthenon:
  `https://github.com/parthenon-hpc-lab/parthenon`
- Phoebus: `https://github.com/lanl/phoebus`
- νbhlight: `https://github.com/lanl/nubhlight`
- singularity-eos: `https://github.com/lanl/singularity-eos`
- singularity-opac: `https://github.com/lanl/singularity-opac`
- Spiner: `https://github.com/lanl/spiner`

Summary.

- Neutron star mergers definitively a source of r-process elements
- Mapping merger parameters to observables has many uncertainties and degeneracies. Neutrinos are key!
- Transport is hard: real transport has been computationally intractable until very recently.
- We've hit a phase transition. Better computers and better numerical methods have converged and model fidelity is improving very rapidly.
- The future is (neutrino) bright!

Accretion Rates





Accretion Rates