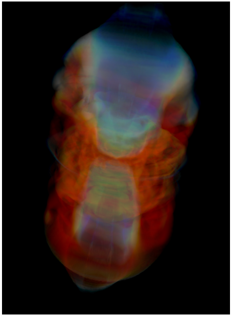
State of the Art and Future Prospects of Modeling Neutrinos in NS Mergers

Jonah M. Miller, in collaboration with:

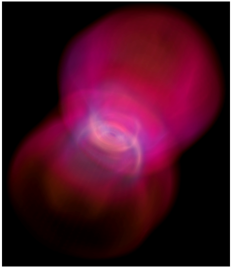
K. Lund, G. McLaughlin, M. Mumpower,

And Many More...

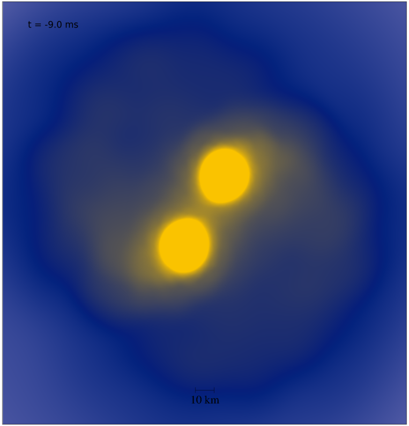
Los Alamos National Laboratory



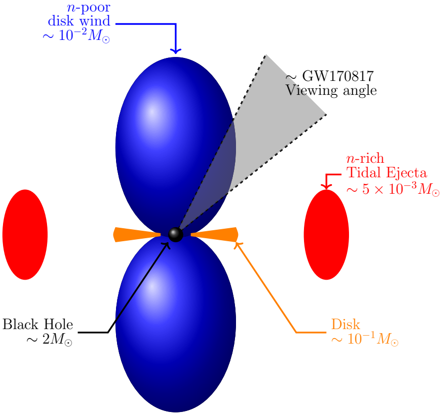
Astrophysical Neutrinos
and the Origin of the Elements

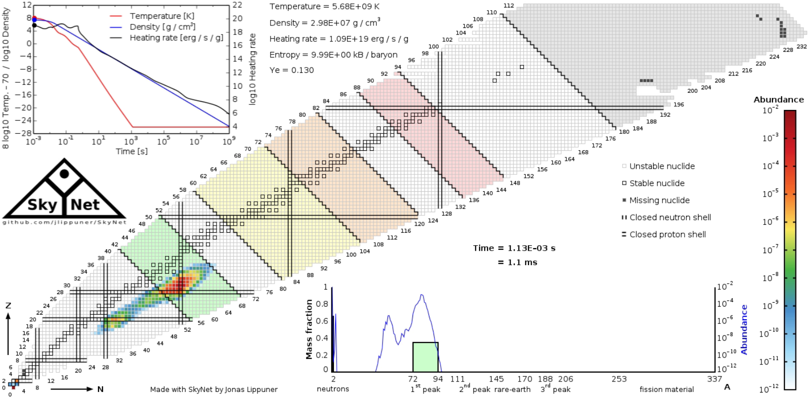


Neutron Star Mergers: A 2+ Component Model

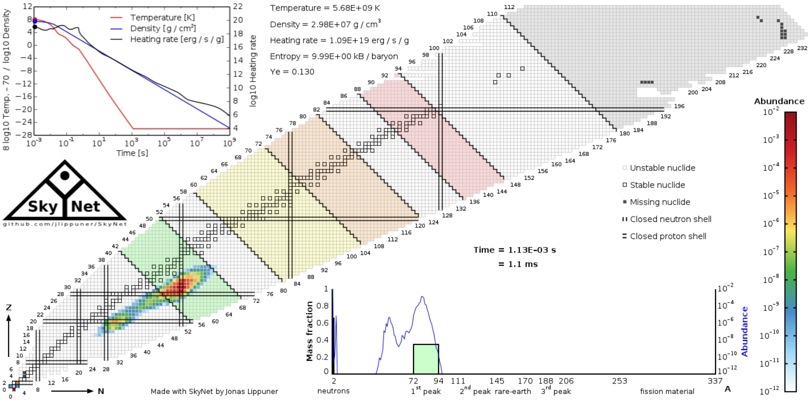


Co-design summer school, 2016



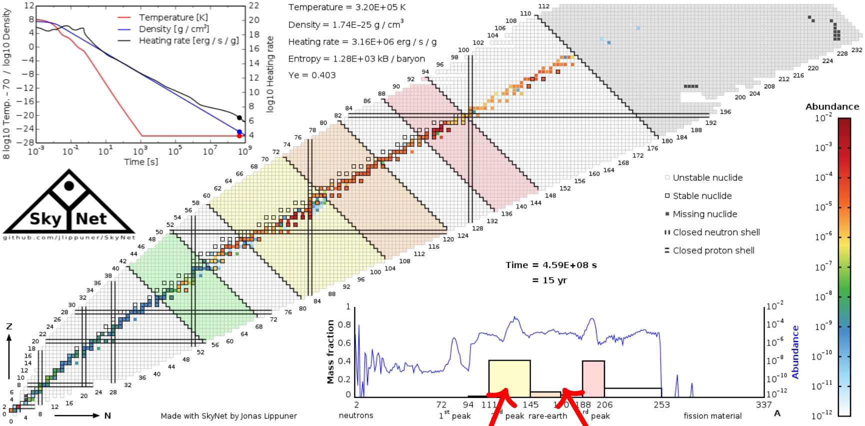


Courtesy of J. Lippuner



Courtesy of J. Lippuner

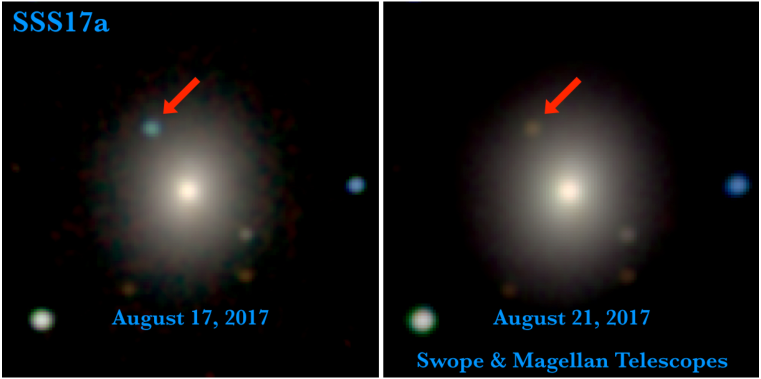
Opacity



Not opaque

Opaque to visible light

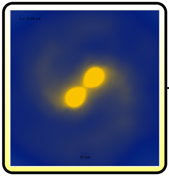
The Kilonova

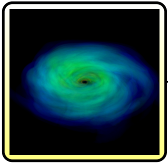


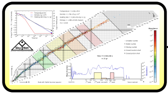
M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

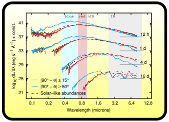
The Makings of a Kilonova

- Duration/relevant time scales
- Methods









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

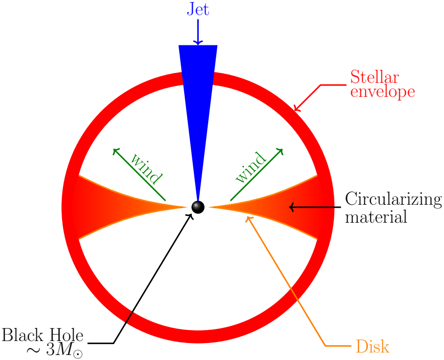
Disk+GRB:
$\sim \mu$s$\to$1 s
GRνRMHD
ν`bhlight`, `HARM`

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

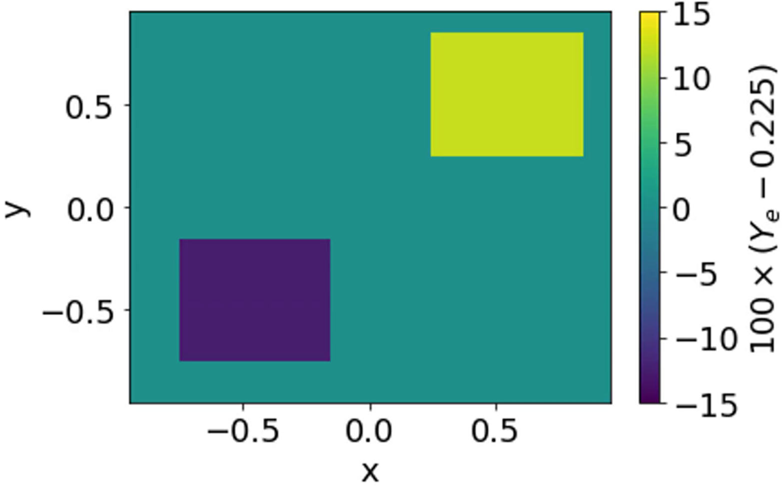
Photon transport:
$\sim$ Weeks
DDMC-IMC
SuperNu,Sedona

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, ...
  - Coleman Dean's talk this afternoon

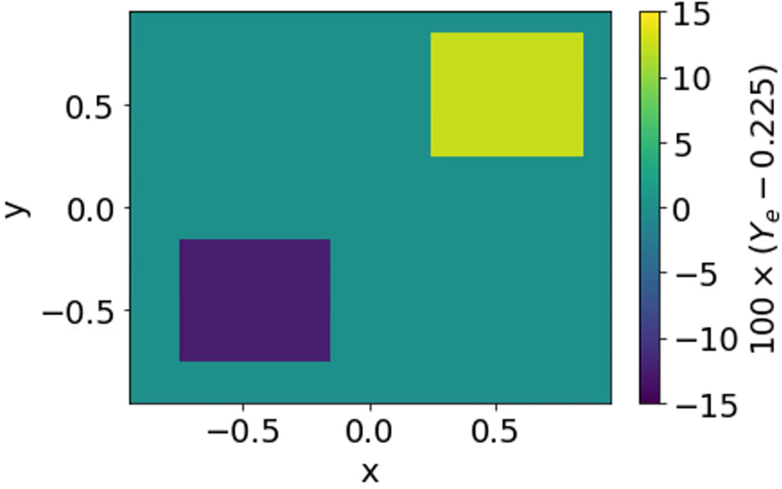


Neutrino Transport Matters!



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

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

- 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

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

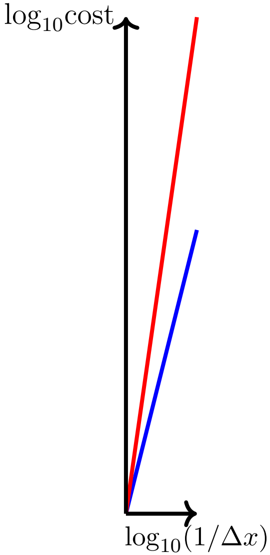
- Spacetime (actually much more complicated)

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

- 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

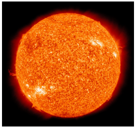
Type	Processes	Corrections/Approximations
Abs./Emis. on Neutrons	$\nu_e + n \leftrightarrow e^- + p$ $\nu_\mu + n \leftrightarrow \mu^- + p$	Blocking/Stimulated Abs. Weak Magnetism Recoil
Abs./Emis. on Protons	$\bar{\nu}_e + p \leftrightarrow e^+ + n$ $\bar{\nu}_\mu + p \leftrightarrow \mu^+ + n$	Blocking/Stimulated 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

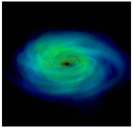
- And this is ignoring Neutrino oscillations!

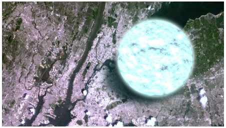
Burrows, Reddy, Thompson, NPA **177**, 356, (2006)

Transport Limits

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







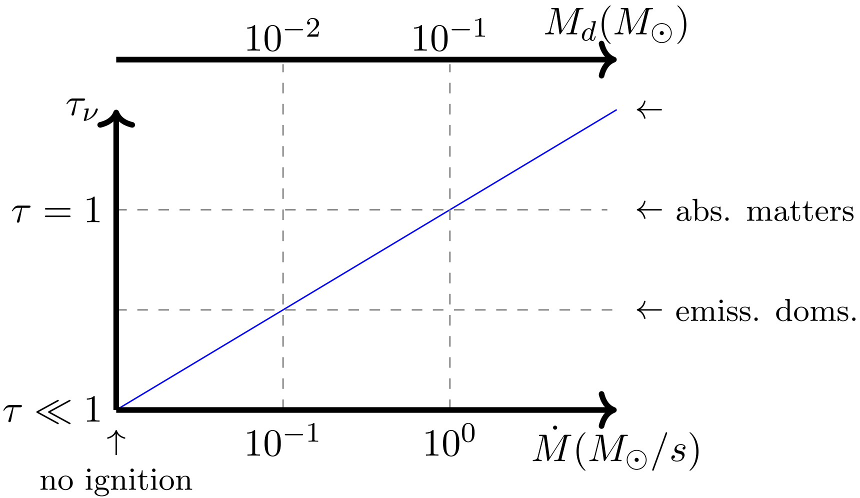
$\tau \ll 1$
free-streaming

Must solve
full Boltzmann
Equation

$\tau \gg 1$
diffusion

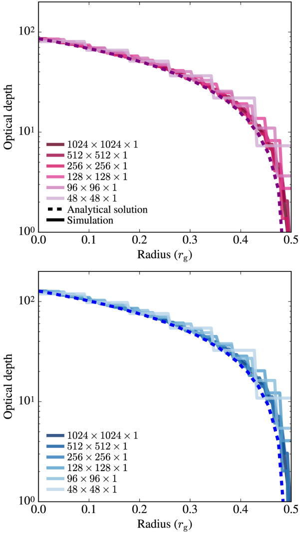
How Much Does Transport Matter for disks?

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



Technique: Leakage and Cooling

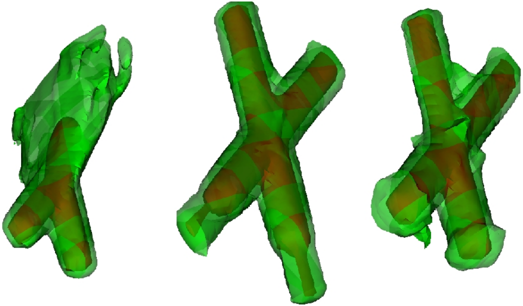
- Apply source terms but don't model radiation field
- Leakage corrects source terms by trying to account for re-absorption
- Requires calculation of optical depth
- Relatively simple to implement, potentially faster



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."

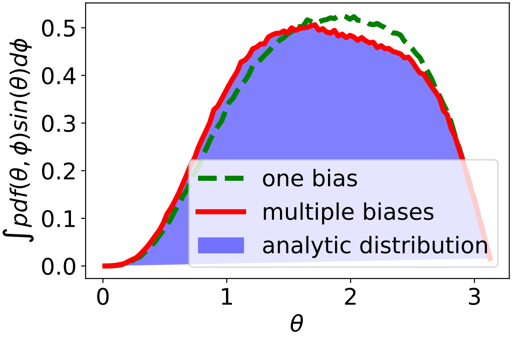


Foucart, MNRAS **475** 3 (2018)

Technique: Particles + Monte Carlo

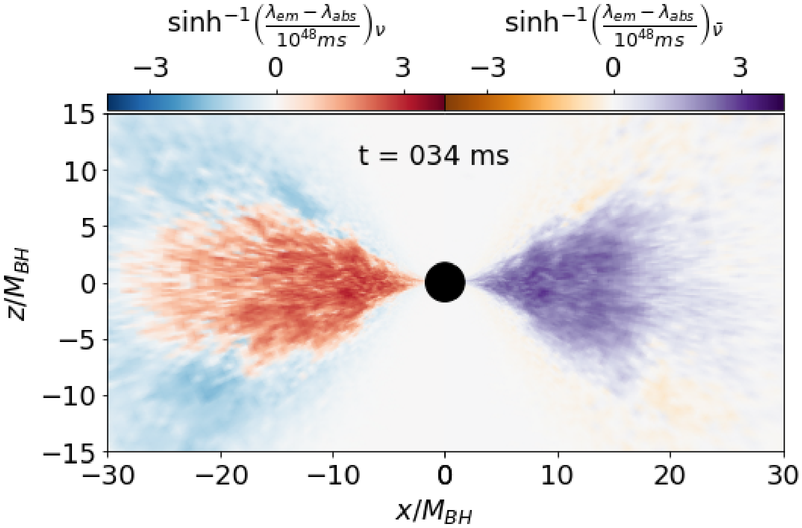
- $f = \sum_{i=1}^{N} w_i \delta^3(x - x_i)\delta^3(p - p_i)\delta(t - t_i)$
- Error scales as $1/\sqrt{N}$, no matter number of dimensions!

- Evolve particle paths *deterministically* $\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\mu}{d\lambda}\frac{dx^\nu}{d\lambda} = 0$
- Sample emission/absorption/scattering *probabilistically* $p(\text{scatt}) \sim \sigma(k^\mu, p_e^\nu)$
- Typicall struggles with large optical depths. But much recent progress. See, e.g., Foucart et al., PRD 107, 103055 (2023)



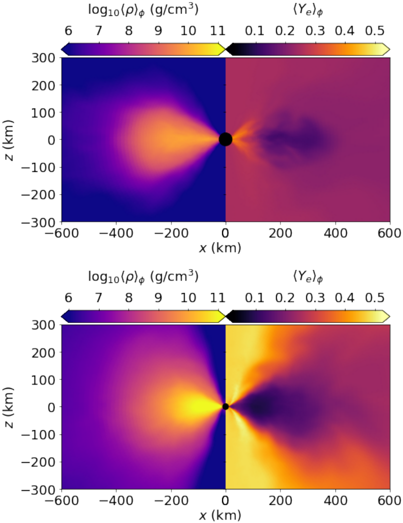
JMM, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

Exquisite Access to the Radiation Field

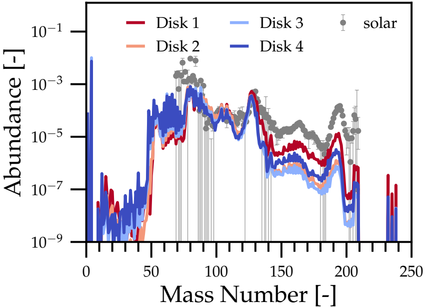


JMM et al. PRD **100** 023008 (2019)

Cool Science to Do



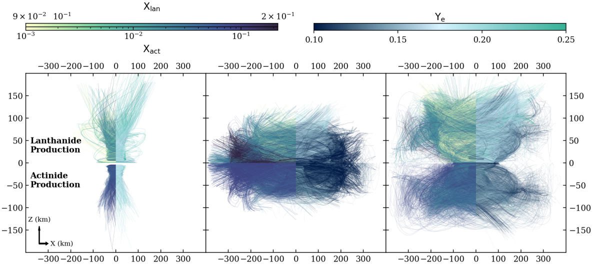
- Model a suite of exotic post-BHNS merger disks



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

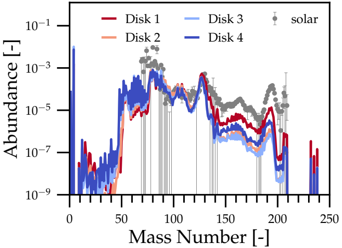
A Zoo of Possible Disks!

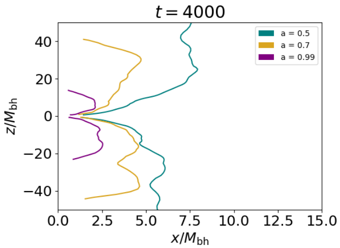
K. Lund,
In Prep



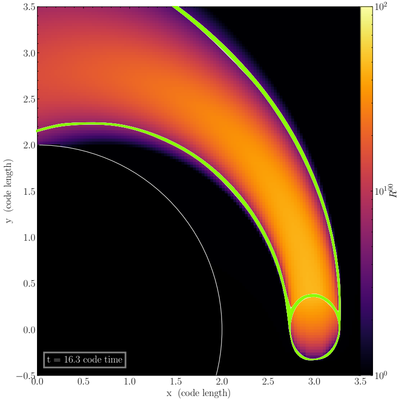
S. Curtis, **JMM**, et al., ApJL 945

V. Urrutia-Hurtado, In Prep



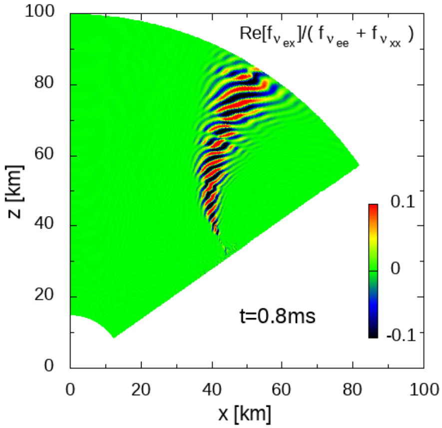


- Discretize full botlzmann on a grid. Typically in spherical coordinates (in momentum space).
- "Classic" discretization is finite differences S_N
- Finite volumes discretization (right)
- Finite elements discretization (see Maitraya Bhattacharyya this afternoon)



White et al., arXiv:2302.04283

Beyond the State of the Art: Oscillations

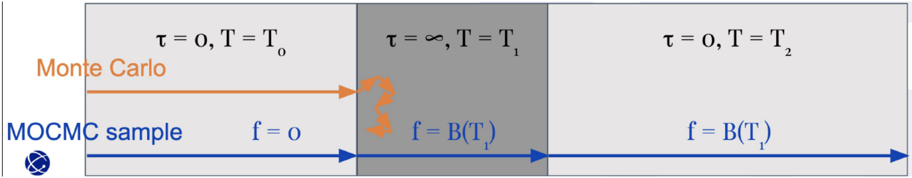


Nagakura, arXiv:2306.10108

- Separation of scales severely limiting: cm length scale for oscillations.
- Concerted effort in the community to treat phenomena anyway, both microscopically and through increasingly sophisticated approximations at macro scale.
- See lots of great talks tomorrow.

Beyond the State of the Art: 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)



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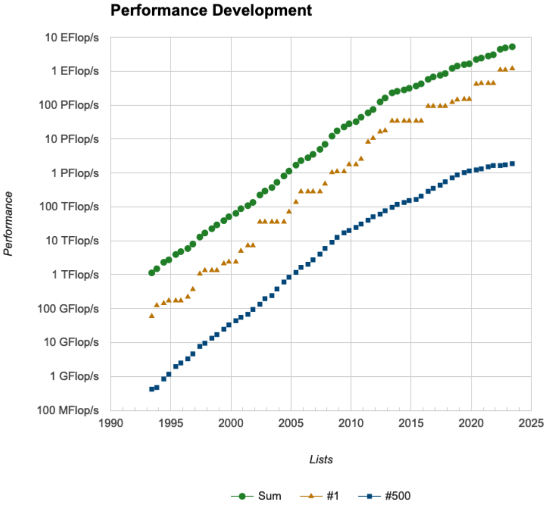
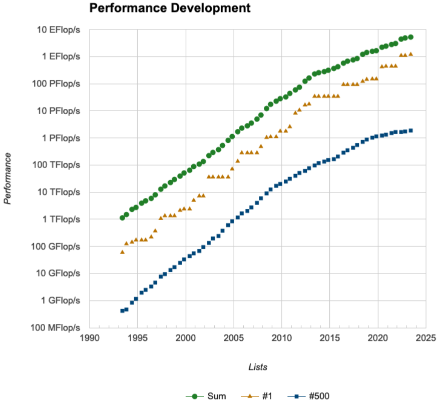
Ryan and Dolence, ApJ **891** 118, (2020).

Growth of Computing Power

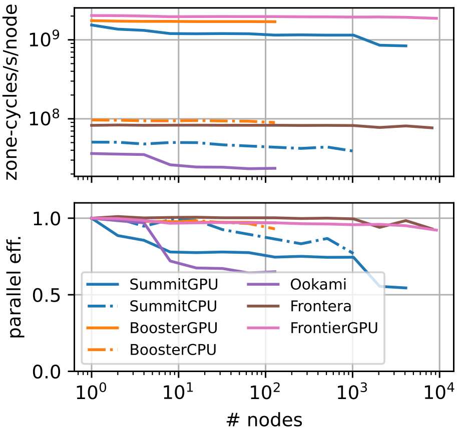


Top500 List

Parthenon: Unlocking GPU Cycles



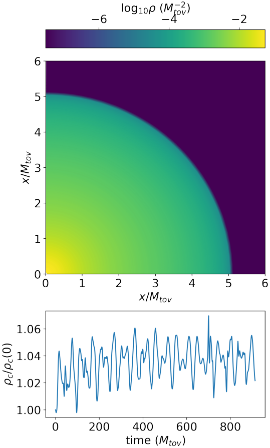
Top500 List



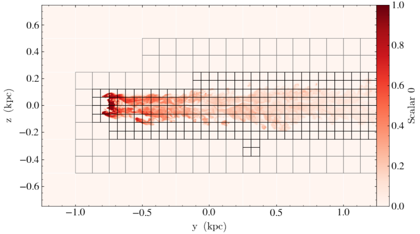
Grete, **JMM**, et al., ArXiv:2202.12309

Tools built on top of Parthenon

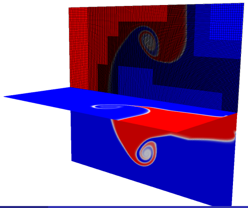
- Phoebus, neutron star



- Athena-PK, turbulence

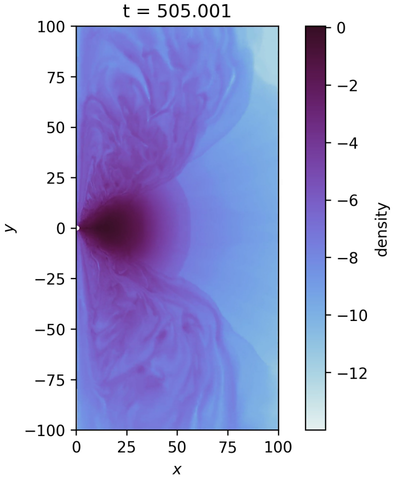


- Riot, triple point

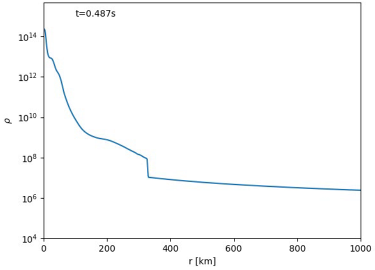


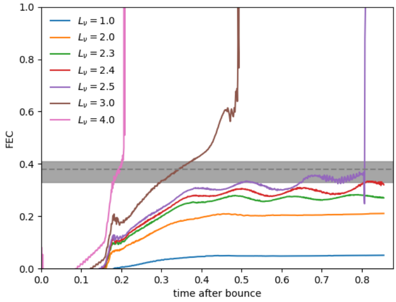
Next Generation of Full-Transport Disks in Phoebus

- Graduate student at MSU: Brandon Barker
- Current capabilities:
  - Curvilinear coordinates
  - nuclear EOS
  - Monte Carlo transport
  - GPUs
- Soon to be ready:
  - Adaptive mesh refinement



- Graduate Student: Mariam Gogilashvili
- Connecting pen-and-paper model (FEC) to simulations: Gogilashvili and Murphy, MNRAS **515** 2, (2022)





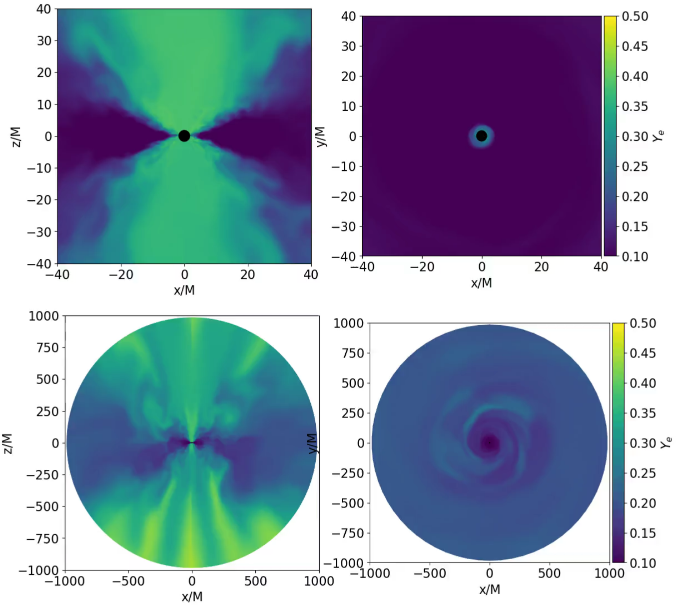
Get Involved

- 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`

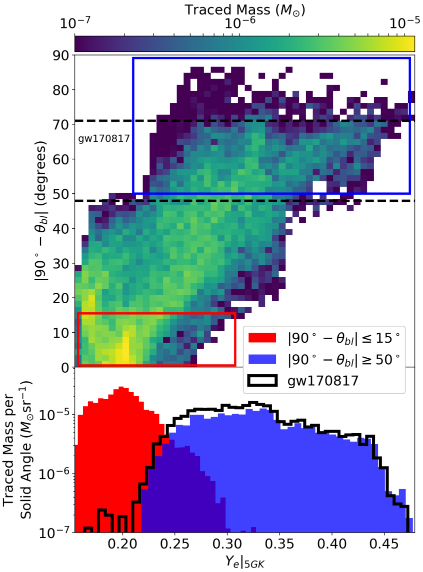
Summary.

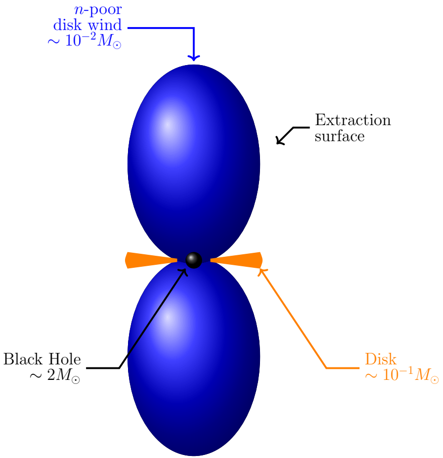
- Neutron star mergers definitively a source of r-process elements
- Mapping merger parameters to observables has many uncertainties and degeneracies. Neutrinos are key!
- Transport is hard: real transport has been computationally intractable until very recently.
- We've hit a phase transition. Better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

The August 2017 Disk



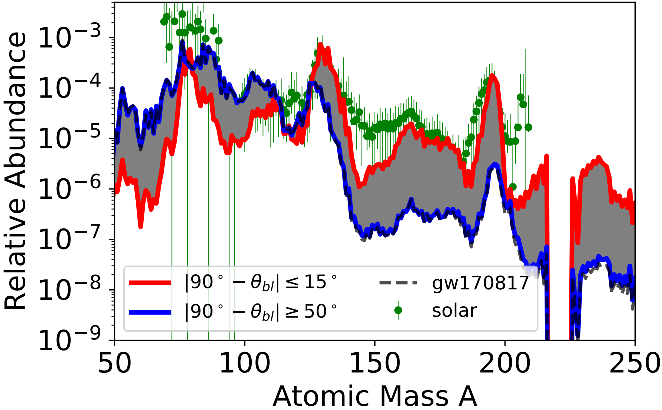
Electron Fraction of the Outflow





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

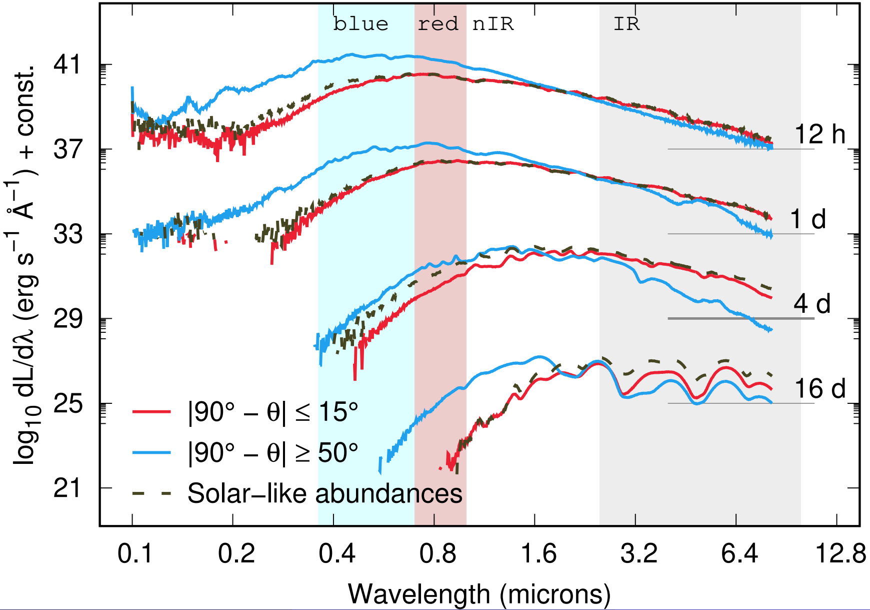
Nucleosynthesis



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

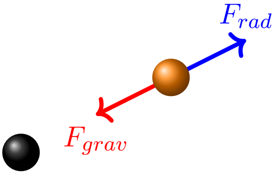
JMM et al. PRD **100** 023008 (2019)

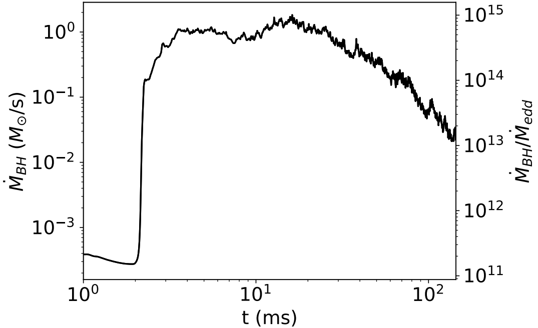
Spectra



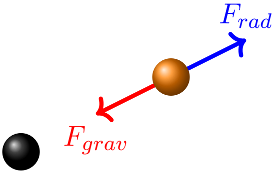
blue
red
nIR
IR
41
37
33
29
25
21
log10 dL/dλ (erg s−1 Å−1) + const.
12 h
1 d
4 d
16 d
|90° − θ| ≤ 15°
|90° − θ| ≥ 50°
Solar−like abundances
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12.8
Wavelength (microns)

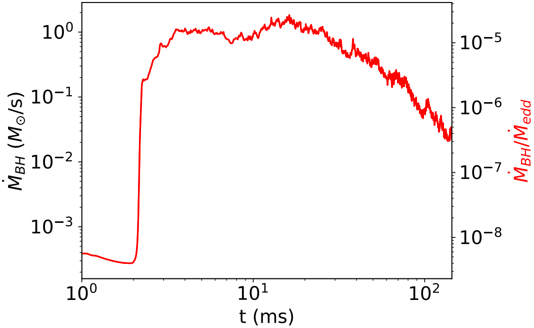
Accretion Rates





Accretion Rates





Transport Techniques

- Full Boltzmann Solvers
  - Mesh-based methods, also called Short Characteristics
    - Discrete ordinates, also called S_N
    - Finite Elements
    - Finite Volumes
    - Finite Differences
    - Sparse grids
  - Mesh-free, also called Long Characteristics
    - Ray tracing
    - Monte Carlo
- Approximate methods
  - Cooling functions
  - Leakage
  - Flux-limited Diffusion
  - Analytic moment closures
- Hybrid methods
  - Moment methods with flexible closures
  - Diffusion + leakage, etc.