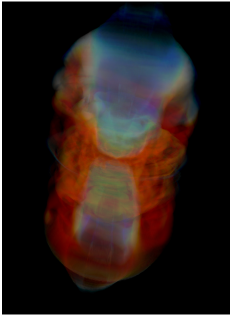
Neutrinos, Collapsars, Neutron Star Mergers, and You

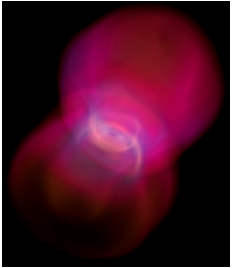
How neutrinos impact heavy element formation in the universe, and the resulting electromagnetic counterpart



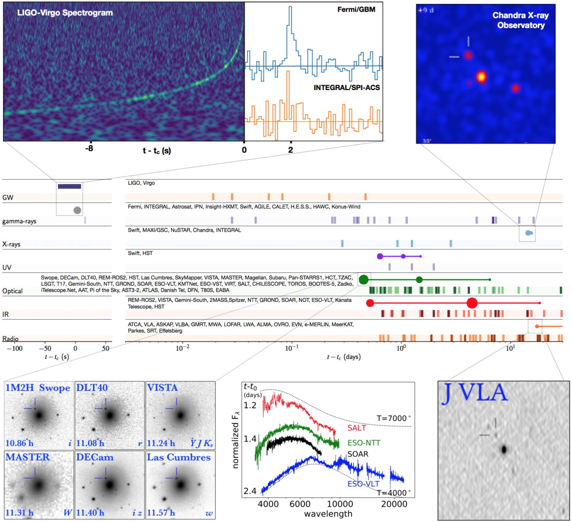
Jonah M. Miller,
And Many More...

Los Alamos National Laboratory

Neutrinos in
Cosmology and Astrophysics

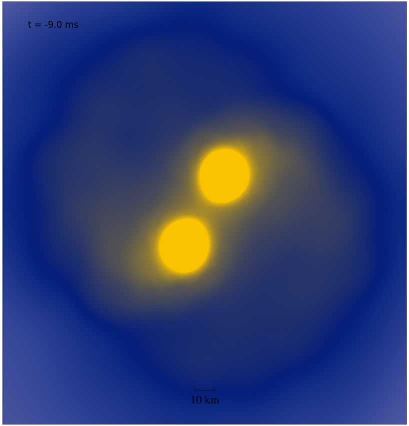


The 170817 Merger

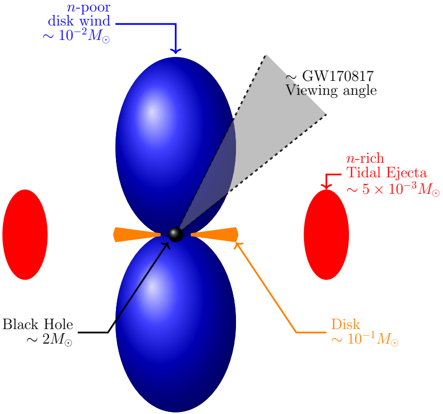


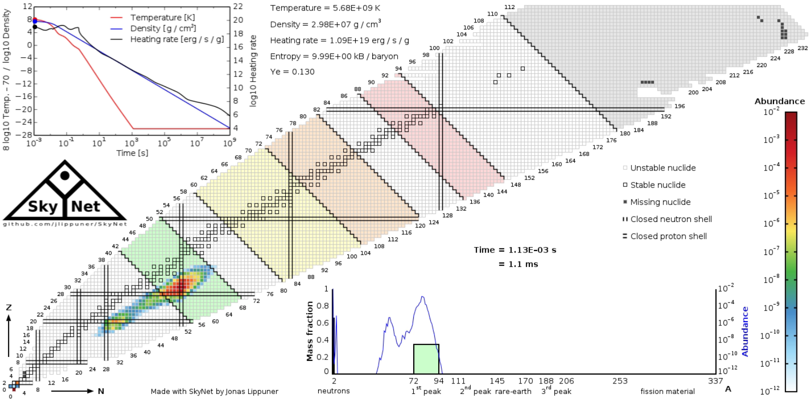
Abbot+, 2017

Neutron Star Mergers: A 2+ Component Model

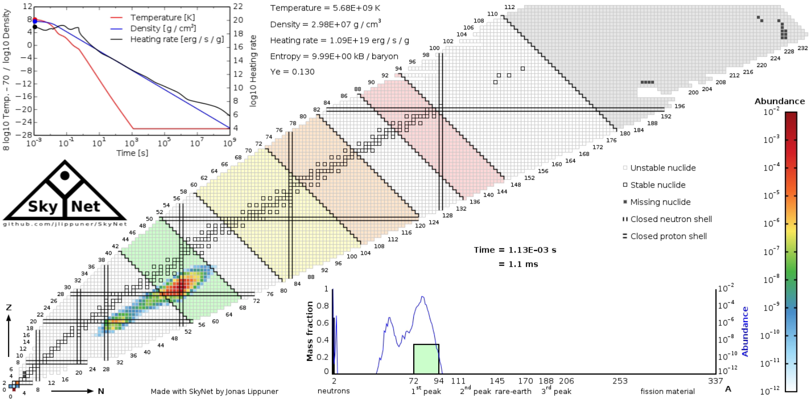


Co-design summer school, 2016





Courtesy of J. Lippuner



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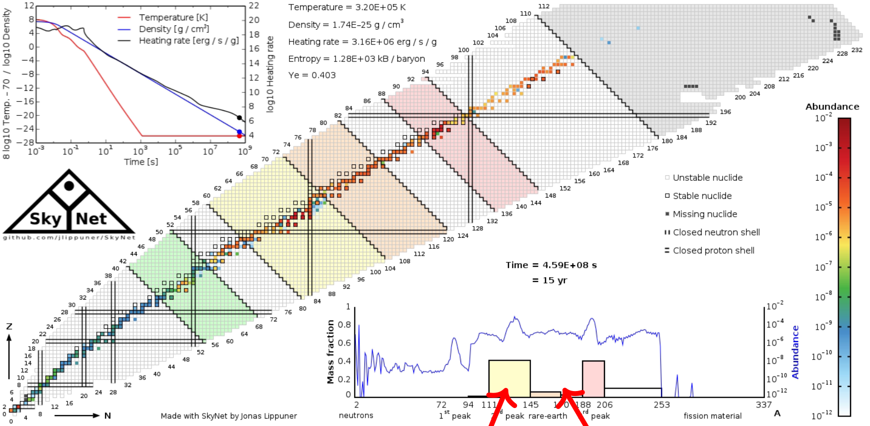
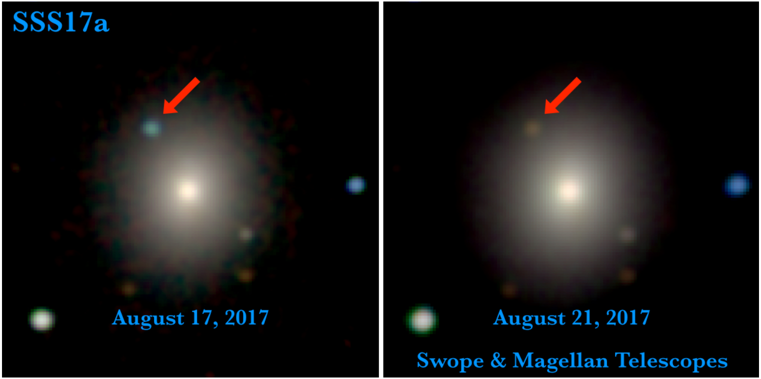


Not opaque

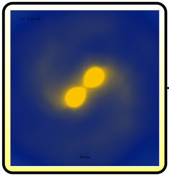
Opaque to visible light

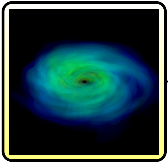


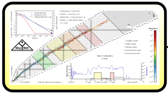
M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

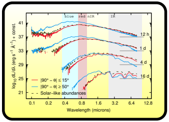
The Makings of a Kilonova

- Duration/relevant time scales
- Methods









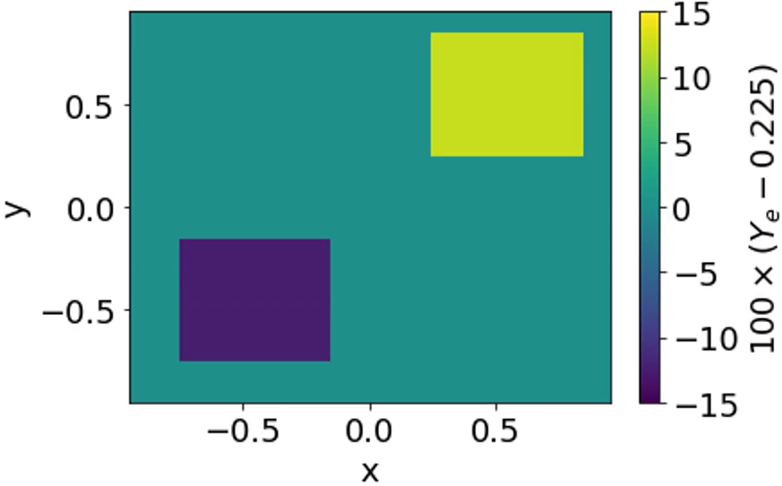
In-spiral:
$\sim \mu$s→30 s
numerical relativity
ET, SpEC, etc.

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

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

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

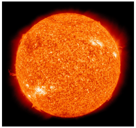
Neutrino Transport Matters!

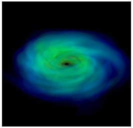


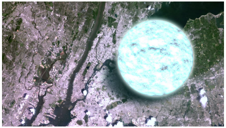
JMM, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

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

Transport Techniques

- Full Boltzmann Solvers
  - Mesh-based methods
    - Discrete ordinates
    - Sparse grids
    - Spectral and finite differences
  - Mesh-free
    - Monte Carlo

- Approximate methods
  - Cooling functions
  - Leakage
  - Flux-limited Diffusion
  - Analytic moment closures
- Hybrid methods
  - Moment methods with flexible closures
  - Diffusion + leakage, etc.

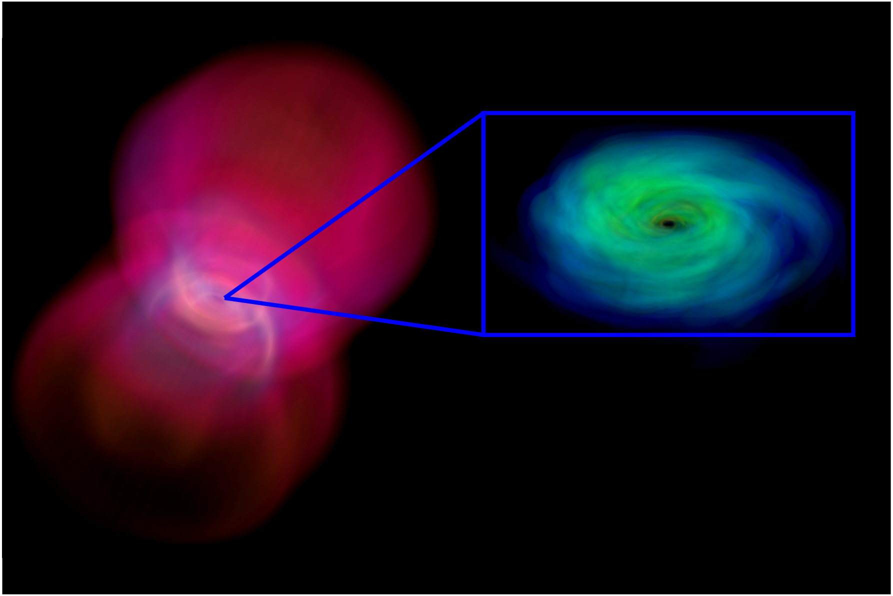
Relevant Neutrino Interactions

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!

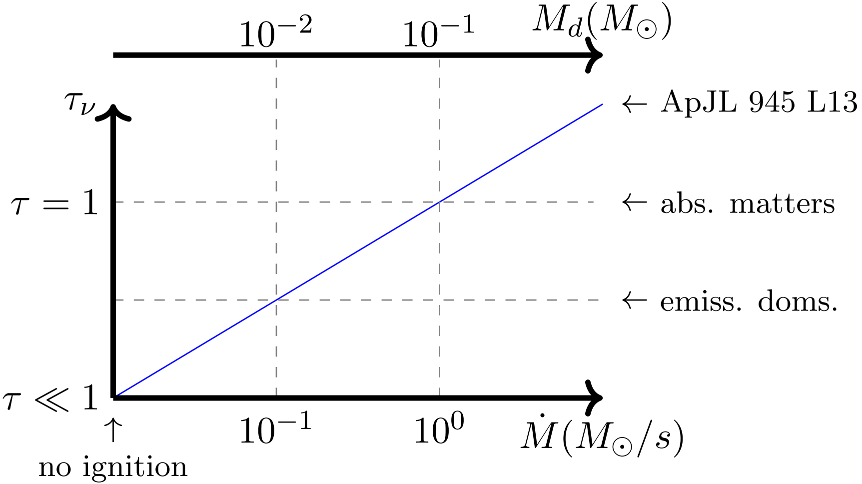
Burrows, Reddy, Thompson, NPA **177**, 356, (2006)

Let's Talk Disks



How Much Does Transport Matter for disks?

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



Ingredients In Kilonova Disk Modeling

- General relativity
  - Rotating black hole spacetime
- Plasma physics
  - Ideal magnetohydrodynamics
- Nuclear physics
  - Hot gas treated as being in nuclear-statistical equilibrium via **equation of state**
  - Cooling outflow treated in postprocessing via **nuclear reaction networks**
- Radiation physics
  - Material is opaque to photons, can be incorporated in plasma physics
  - Material *not* opaque to **neutrinos**.
  - Neutrinos can *change the composition of the material* by converting neutrons to protons and vice versa.

Ingredients in Kilonova Disk Modeling

- Mass conservation:

$$\partial_t \left(\sqrt{-g}\rho_0 u^t\right) + \partial_i \left(\sqrt{-g}\rho_0 u^i\right) = 0$$

- Momentum and Internal Energy Conservation:

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

- Magnetic Fields

$$\partial_t \left(\sqrt{-g} B^i\right) - \partial_j \left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right] = 0$$

- Composition

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

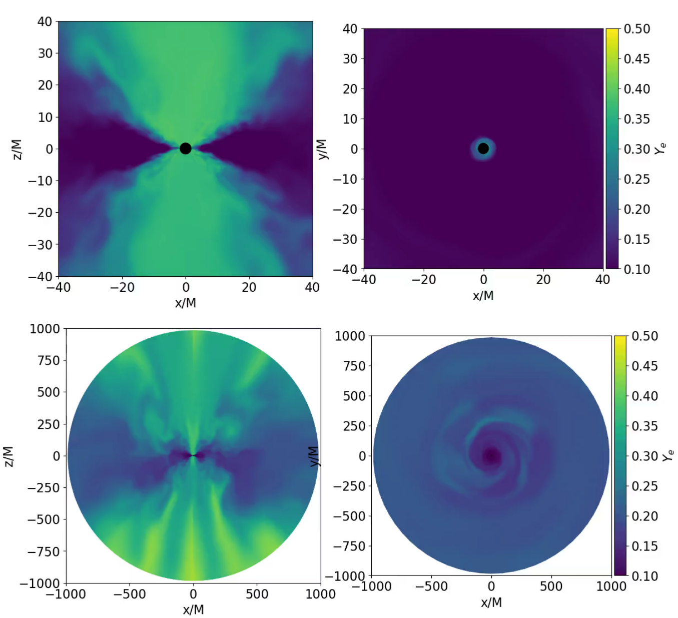
- Neutrino Transport

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

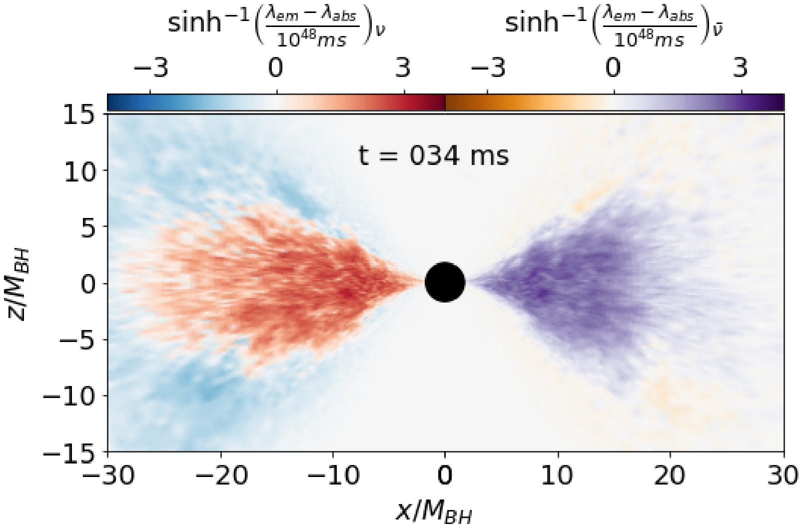
Presenting νbhlight!

- General relativistic radiation magnetohydrodynamics for kilonova disks
- Open Source! https://github.com/LANL/nubhlight
- **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`.
- Ask me about our next gen code `Phoebus`.

The August 2017 Disk

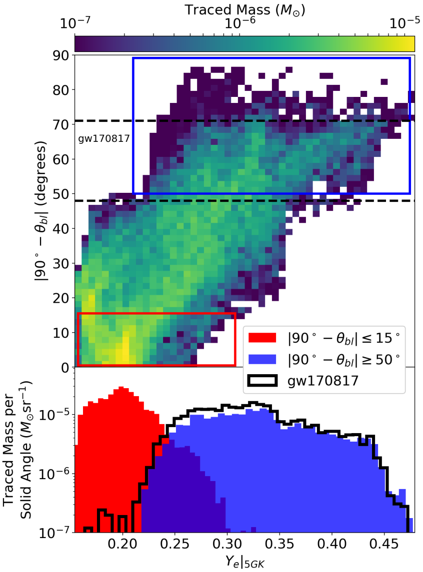


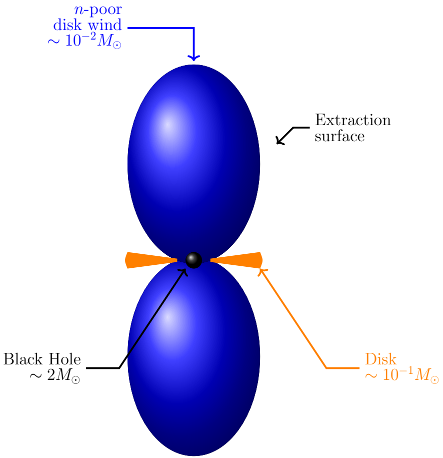
Neutrino Transport in the Disk



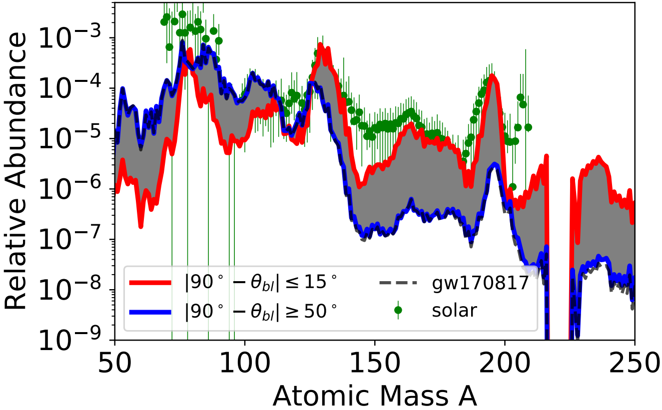
JMM et al. PRD **100** 023008 (2019)

Electron Fraction of the Outflow





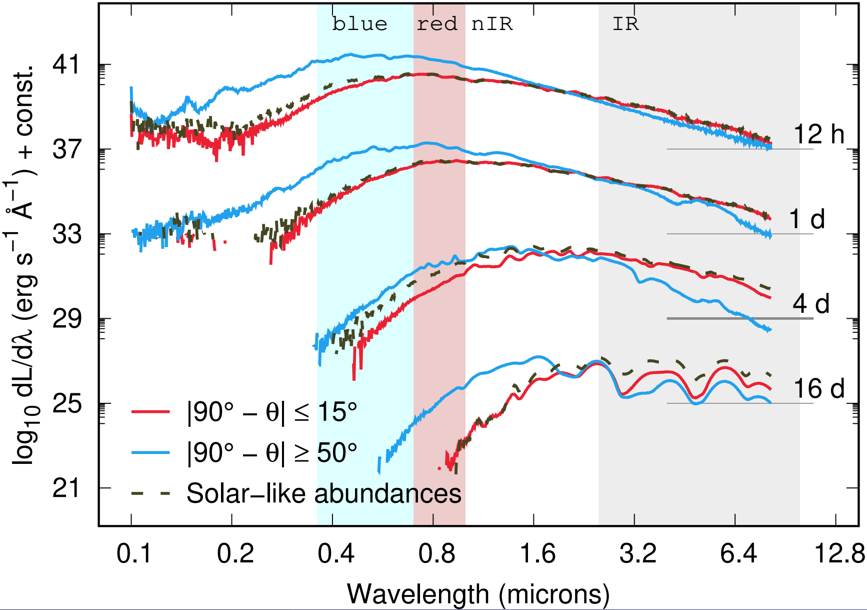
JMM et al. PRD **100** 023008 (2019)



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

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

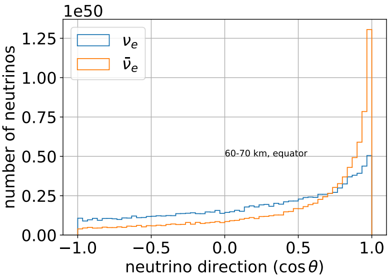
Spectra


blue
red
nIR
IR
41
37
33
29
25
21
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)
log10 dL/dλ (erg s−1 Å−1) + const.

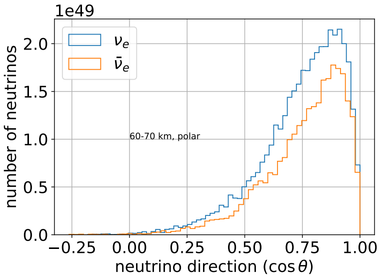
What about Oscillations?

- Due to length/time scales, impossible to treat from first principles
- Leverage ν**bhlight**'s unprecedented accuracy in neutrinos to look for type of oscillation instability, fast flavor (Payel Mukhopadhyay)

Equatorial



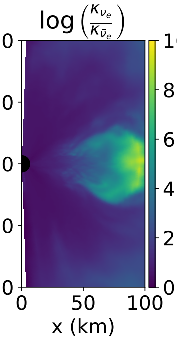
Polar



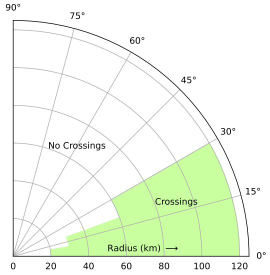
Crossings Ubiquitous? Not Always!

- Common wisdom is that crossings are ubiquitous for disks around HMNS remnants
- Not so for disks around BH remnants!
- Crossings caused by opacity structure in disk, and region with crossings depends on space and time

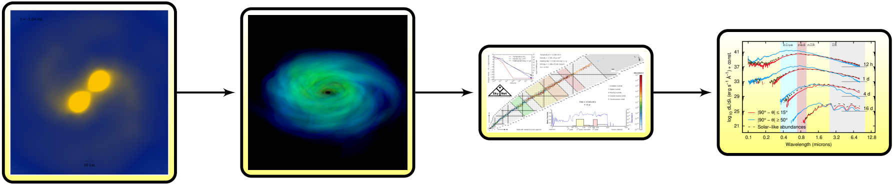
11ms 65ms



Crossing locations



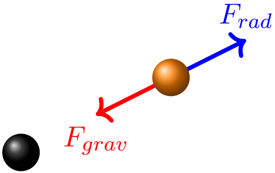
Summary

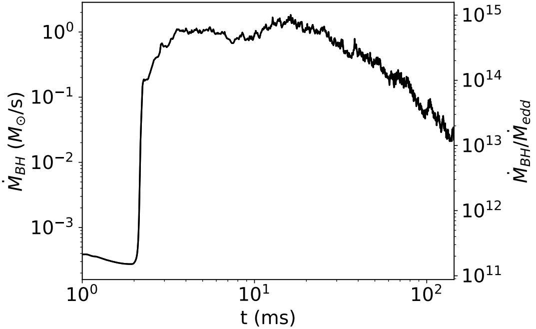


- Neutron star mergers are awesome!
  - Source of GRBs, heavy elements, kilonova afterglow, gravitational waves
- Despite huge successes so far, connecting an observation to an astrophysical system is complicated and challenging:
  - Oscillations big open question, but progress being made.
  - Ask me about other projects! Lots of exciting work going on.

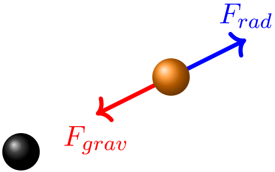
Wikimedia Commons

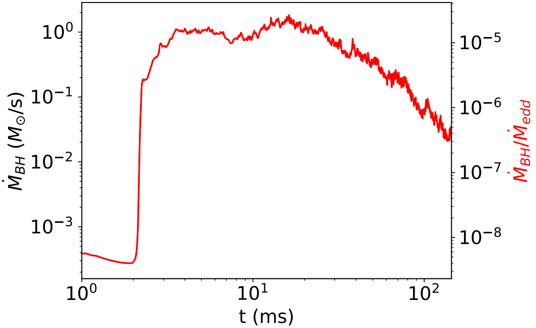
Accretion Rates



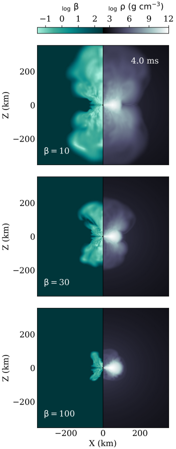


Accretion Rates

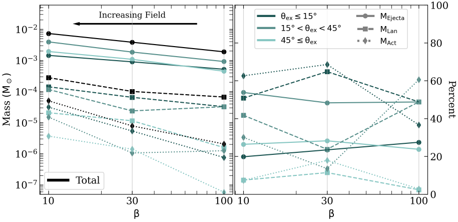




- Magnetically-driven turbulence drives angular momentum transport.



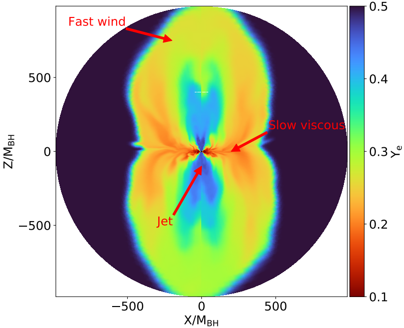
- Field must “spin up” due to turbulent instability.
- Larger fields mean less spin-up time, also more “memory” of initial configuration.
- Impacts yields, outflow morphology.

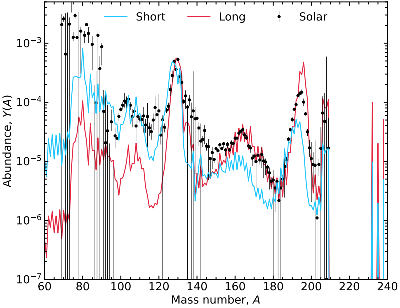


Lund, **JMM**, et al., ArXiv:2311.05796

Ultra Late-Time Outflow

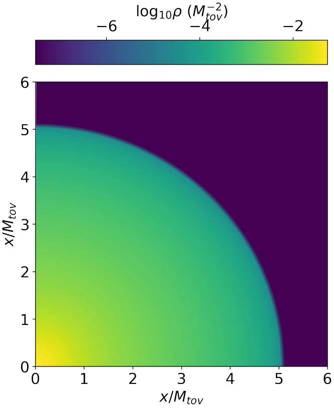
- Original models of post-merger disks only run for very short time: ~ 120ms.
- Outflow not finished by this time. Late-time outflow may look very different.
- Extended simulation to 1.2s physical time. 7 months required on supercomputer.

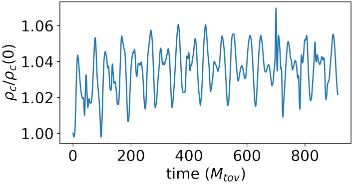


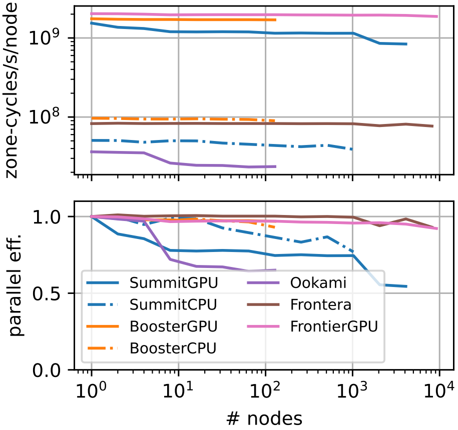


Sprouse, **JMM**, et al., 2024 ApJ **962** 79

The Future







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