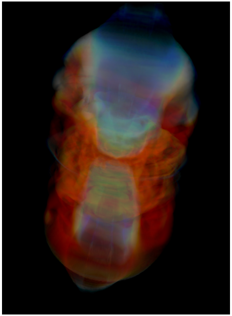
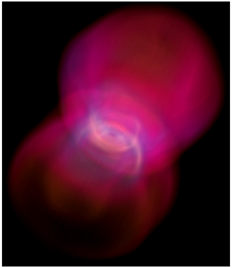
Kilonova and r-Process Nucleosynthesis

Jonah M. Miller, in collaboration with:
K. Lund, G. McLaughlin, M. Mumpower,
And Many More...

Los Alamos National Laboratory



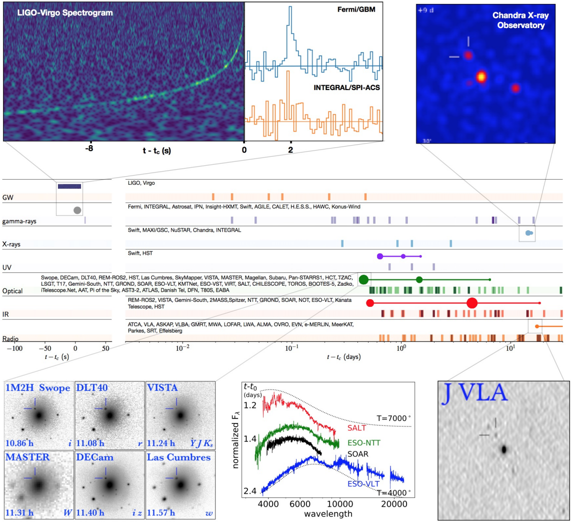
Astrophysical Neutrinos
and the Origin of the Elements



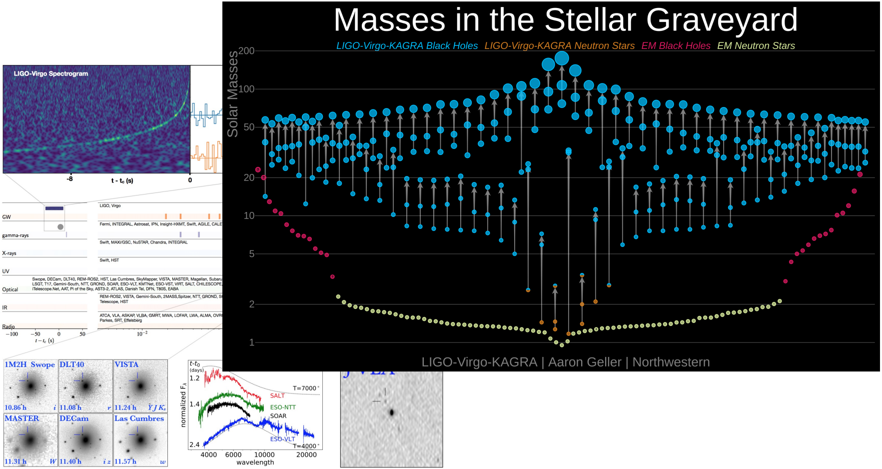
Cosmic Gold

Ashley Mackenzie for Quanta Magazine, March 23, 2017

The 170817 Merger

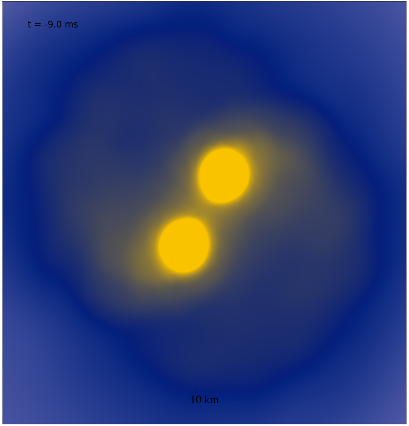


Abbot+, 2017

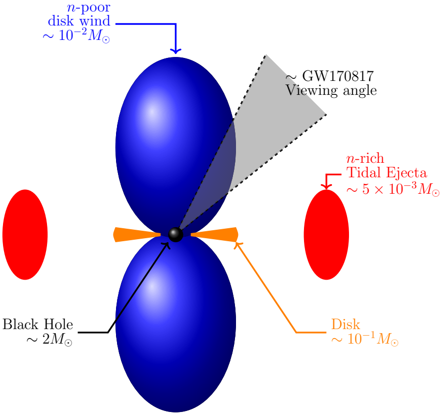


Abbot+, 2017, Aaron Geller/LIGO-VIRGO-KAGRA

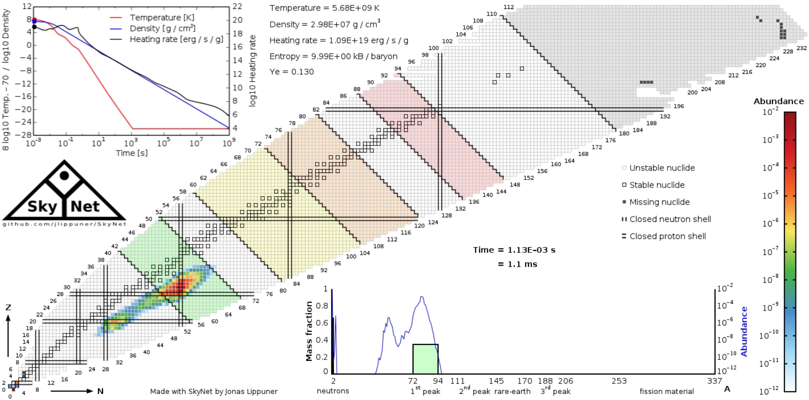
Neutron Star Mergers: A 2+ Component Model



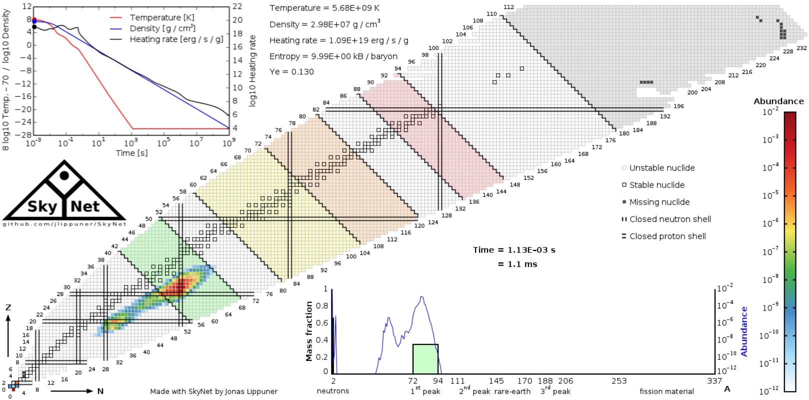
Co-design summer school, 2016



The r-process



Courtesy of J. Lippuner



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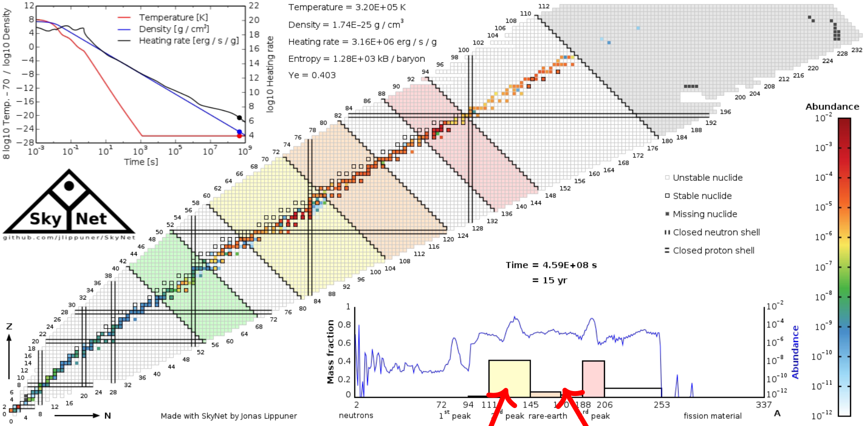
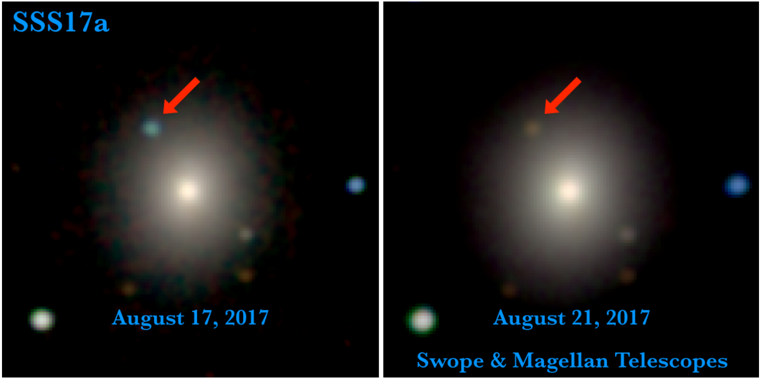


Not opaque

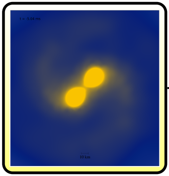
Opaque to visible light



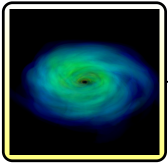
M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

The Makings of a Kilonova

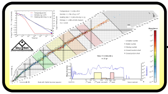
- Duration/relevant time scales
- Methods



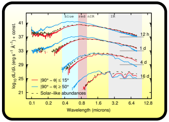
In-spiral:
∼ μs→30 s
numerical relativity
ET, SpEC, etc.



Disk+GRB:
∼ μs→1 s
GRνRMHD
`νbhlight, HARM`



Non-equilibrium reactions:
∼ s→hours→Myrs
Reaction network
PRISM, SkyNet



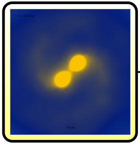
Photon transport:
∼ Weeks
DDMC-IMC
`SuperNu,sedona`

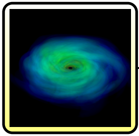
The Makings of a Kilonova

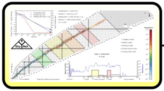
Nuclear EOS

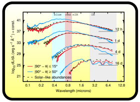
ν-interactions

Energy levels









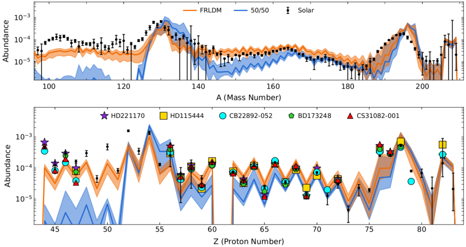
neutrino emissivities, scattering, opacities

nuclear energies, rates

Atomic energies, photon opacities, abundances, (n)LTE

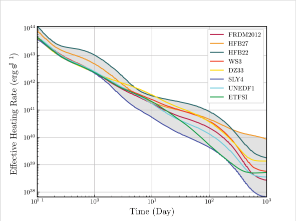
Nuclear Physics Feeds Directly into Observables

Fission Yields



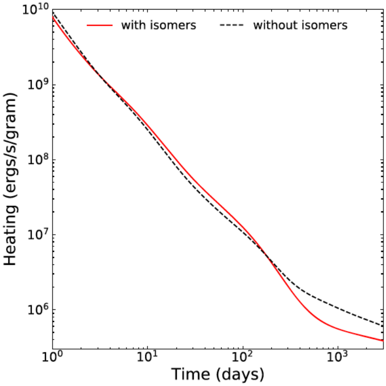
Vassh et al., ApJ **896** 28 (2020)

Heating rates
+mass models



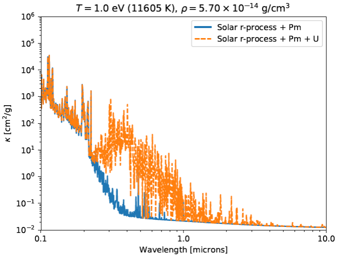
Zhu et al., ApJ **906** 94, (2021)

Astromers

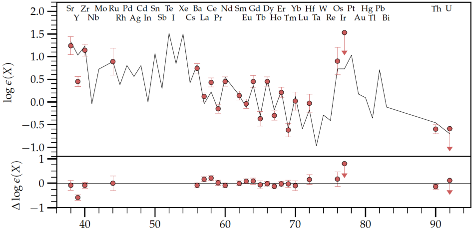


Misch et al., ApJL **913** L2, (2021)

Nucleosynthesis Feeds Directly into Observables

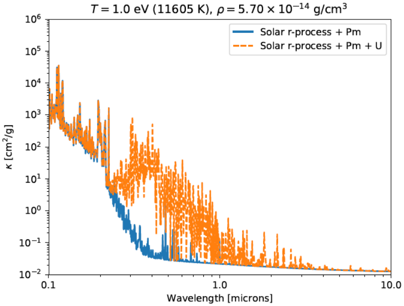


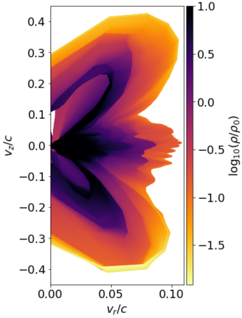
Even,...,**JMM**, et al. ApJ **899** 24 (2020)



Cain et al. ApJ **898** 40 (2020)

Major Uncertainties in Light Curve Modeling





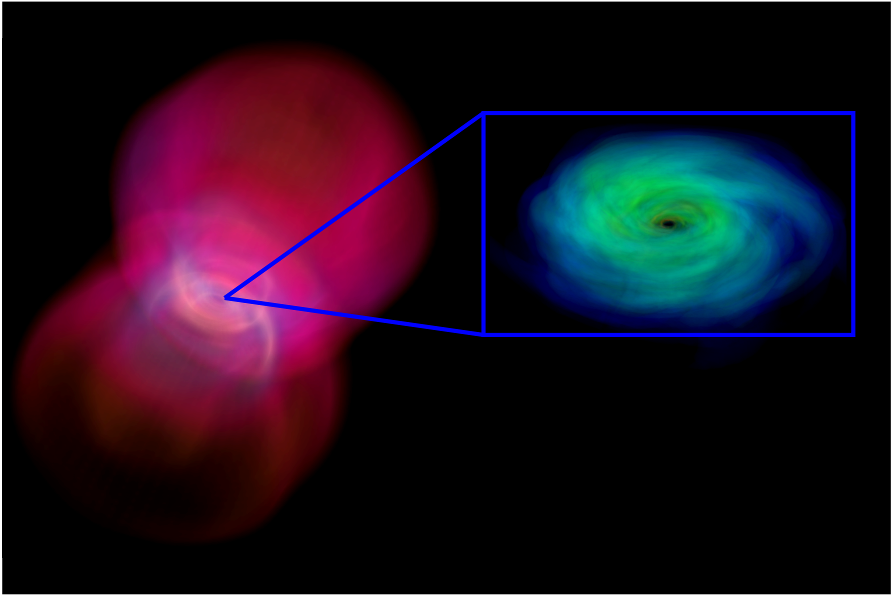
- Not all opacities known, so surrogates often used. Some elements matter more than others. Non-equilibrium (nLTE) effects important at late times.

- Geometric effects can be significant, are difficult to treat, and are degenerate with other parameters, such as ejecta mass.

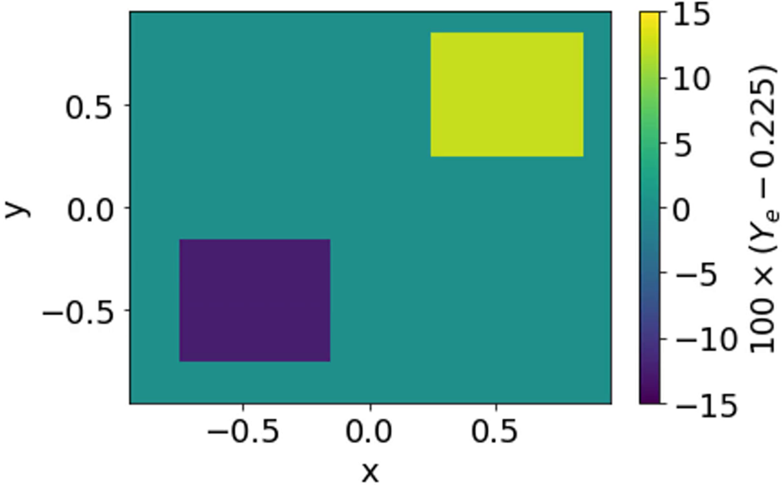
arXiv:204.00102

arXiv:1904.13298

Lets Talk About the Disk



Neutrino Transport Matters!



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

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

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

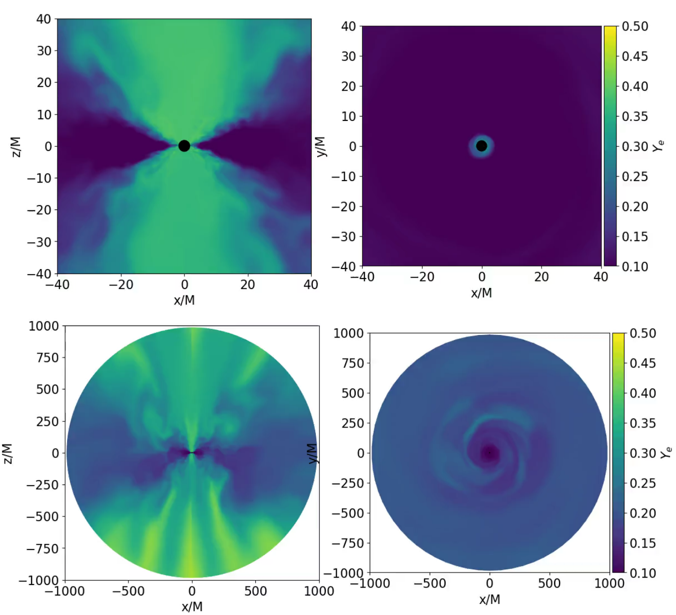
- Neutrino Transport

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

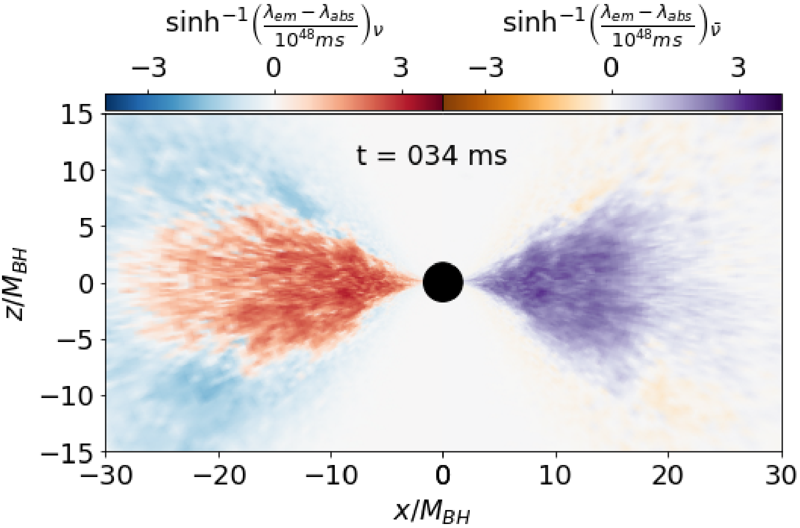
Presenting νbhlight!

- 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`.

The August 2017 Disk

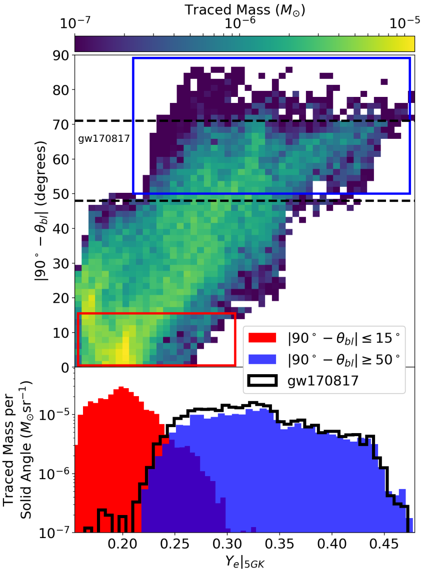


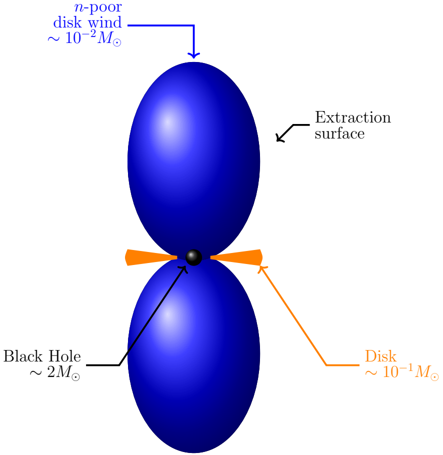
Neutrino Transport in the Disk



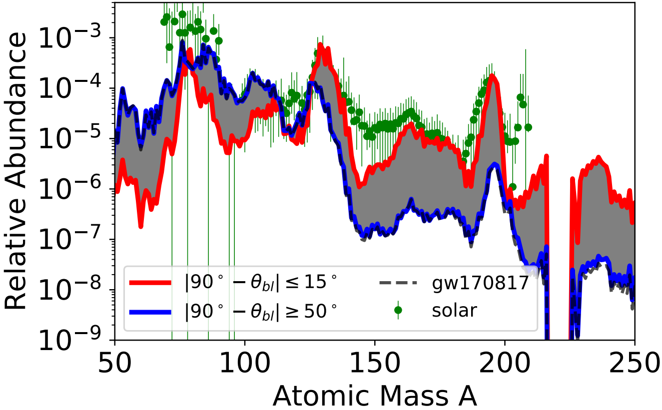
JMM et al. PRD **100** 023008 (2019)

Electron Fraction of the Outflow



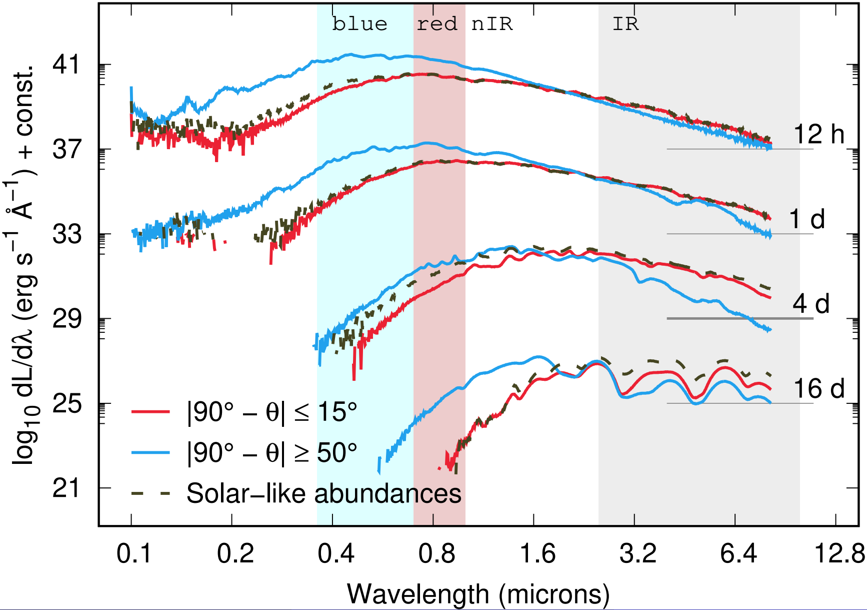


JMM et al. PRD **100** 023008 (2019)



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

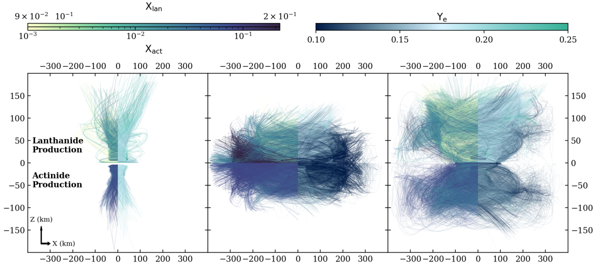
JMM et al. PRD **100** 023008 (2019)



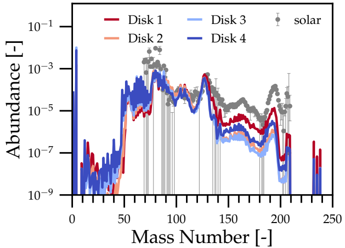
blue
red
nIR
IR
12 h
1 d
4 d
16 d
41
37
33
29
25
21
log10 dL/dλ (erg s−1 Å−1) + const.
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12.8
Wavelength (microns)
|90° – θ| ≤ 15°
|90° – θ| ≥ 50°
Solar–like abundances

A Zoo of Possible Disks!

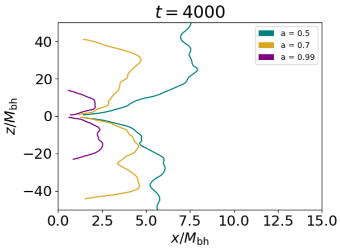
K. Lund, In Prep



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



V. Urrutia-Hurtado, In Prep

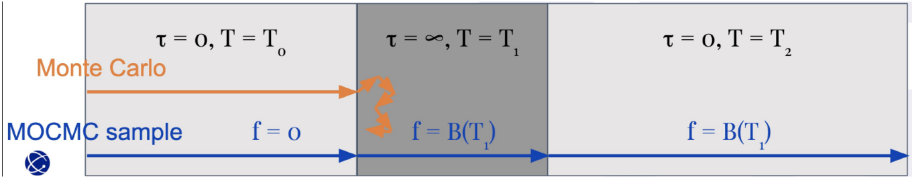


Big Open Questions and Modeling Uncertainties

- Oscillations! Great recent work by many people! Including lots of those here!
  - See P. Mukhopadhyay and L. Johns at this workshop
- Huge zoo of possible set of merger parameters
  - See M. Ristic, S. Curtis, K. Lund, B. Barker
- Nuclear reaction rates and r-process
  - K. Lund, G. McLaughlan, M. Mumpower
- Mapping from disk/merger outflow to homologous expansion phase
  - S. Curtis
- Opacities and composition of elements
- Multi-dimensional radiation transport
- Nuclear equation of state

The Future

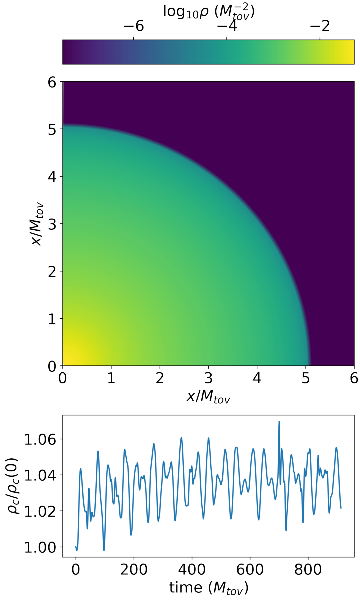
- Large optical depths, such as inside a neutron star present issues for Monte Carlo
- Need a method that can span the range of optical depths and solve the full transport equation
- A few flavors. See, e.g., Foucart, Radice, Mullen. My favorite is MOCMC.

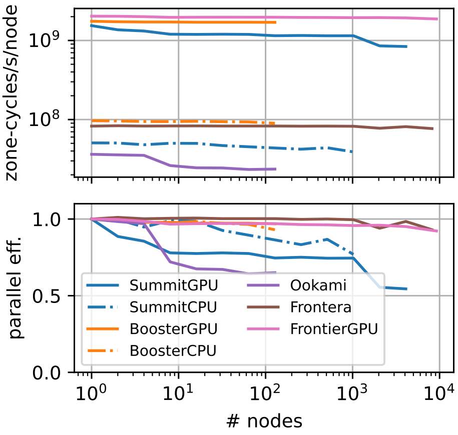


;

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

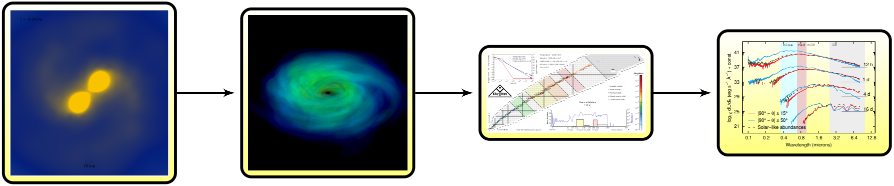
The Future





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

Take-home Message



- 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:
  - Involves **all four fundamental forces**, many different physical processes, modeled by very different codes/capabilities
  - Many **degeneracies** between astrophysical uncertainty, microphysical uncertainty, etc.
- Now must tamp down on these uncertainties in each domain

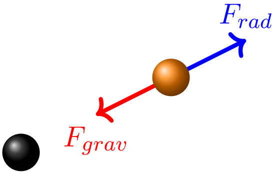
Relevant Neutrino Interactions

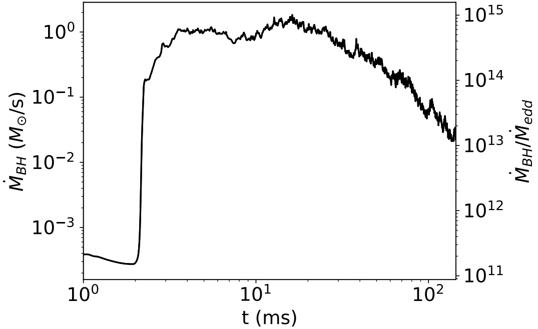
Type	Processes	Corrections/Approximations
Abs./Emis. on Neutrons	$\nu_e + n \leftrightarrow e^- + p$ $\nu_\mu + n \leftrightarrow \mu^- + p$	Blocking/Stimulated Abs. Weak Magnetism Recoil
Abs./Emis. on Protons	$\bar{\nu}_e + p \leftrightarrow e^+ + n$ $\bar{\nu}_\mu + p \leftrightarrow \mu^+ + n$	Blocking/Stimulated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

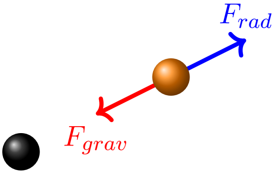
Burrows, Reddy, Thompson, NPA **177**, 356, (2006)

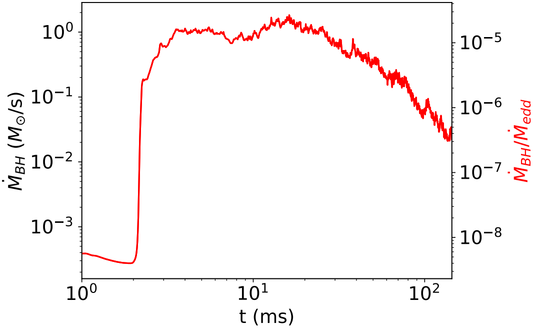
Accretion Rates





Accretion Rates





How Much Does Transport Matter for disks?

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