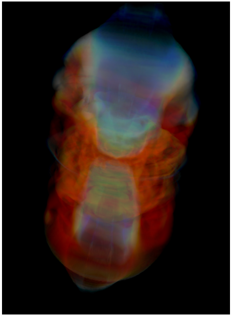
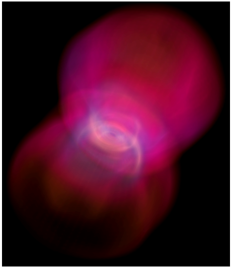
# Neutrino Transport and Effects on Observables in Compact Binary Mergers


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

Los Alamos National Laboratory

43rd International School of Nuclear Physics



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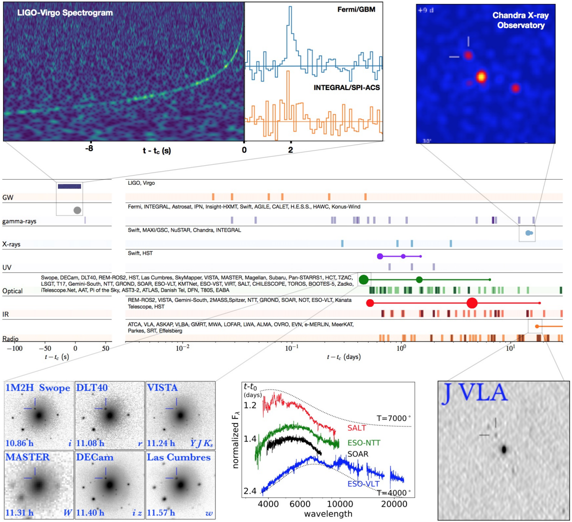
# Cosmic Gold

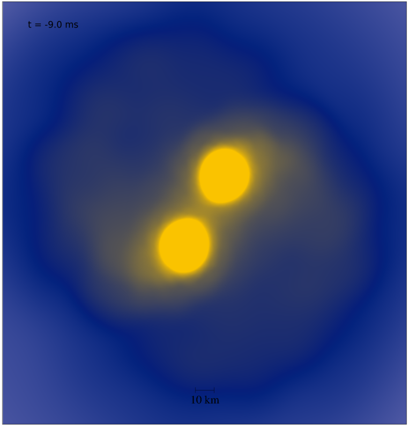
Ashley Mackenzie for Quanta Magazine, March 23, 2017


LIGO-Virgo Spectrogram
Fermi/GBM
INTEGRAL/SPI-ACS
t - tc (s)
Chandra X-ray Observatory
GW
gamma-rays
X-rays
UV
Optical
IR
Radio
LIGO, Virgo
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
Swift, HST
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t − tc (s)
t − tc (days)
1M2H Swope
DLT40
VISTA
MASTER
DECam
Las Cumbres
normalized Fλ
wavelength
SALT
ESO-NTT
SOAR
ESO-VLT
T=7000°
T=4000°
J VLA

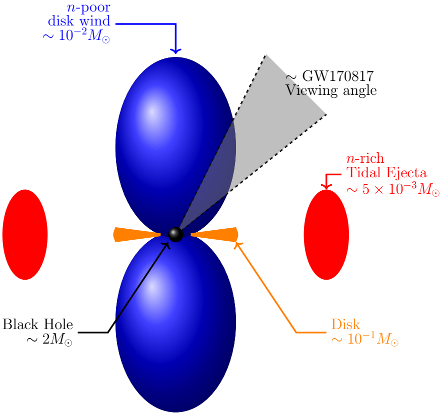
Abbot+, 2017

Wikimedia Commons

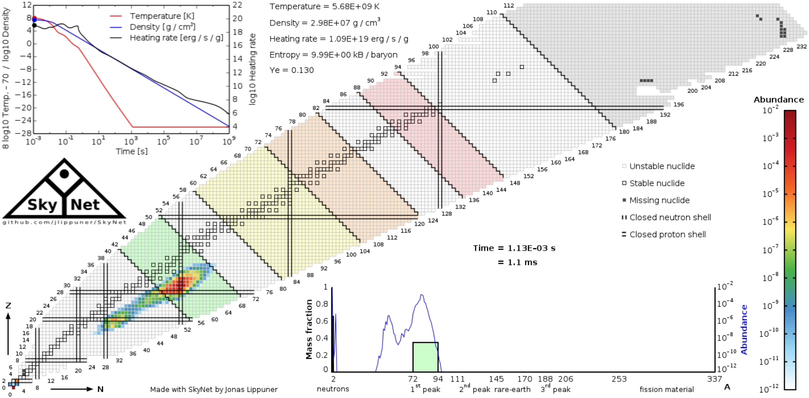
# Neutron Star Mergers: A 2+ Component Model




Co-design summer school, 2016

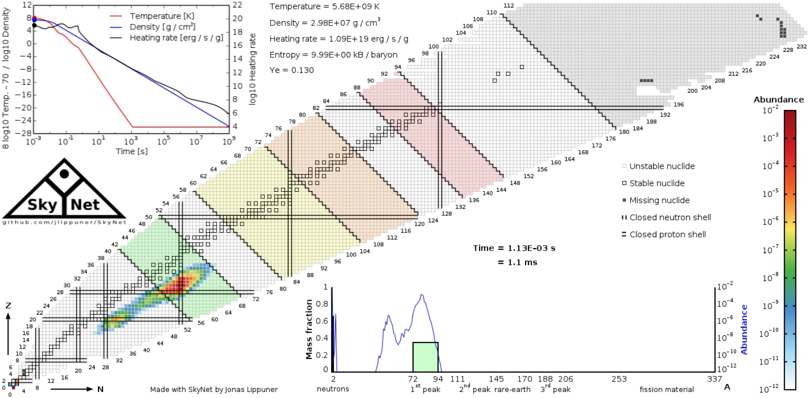


# The r-process

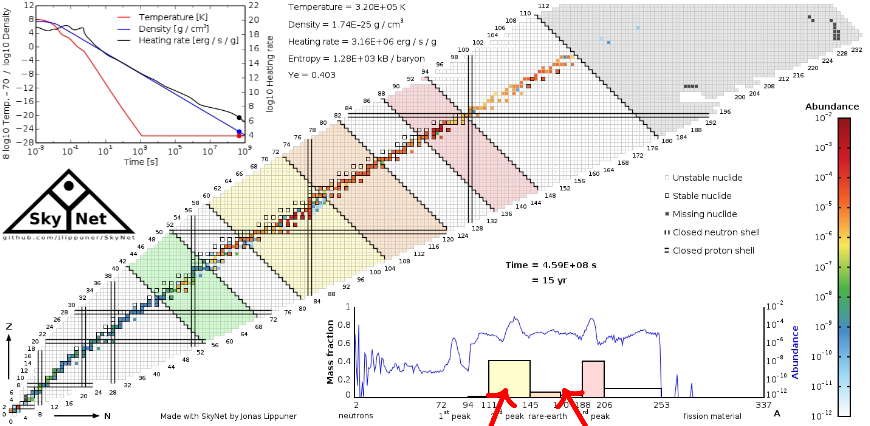



Courtesy of J. Lippuner

# The r-process

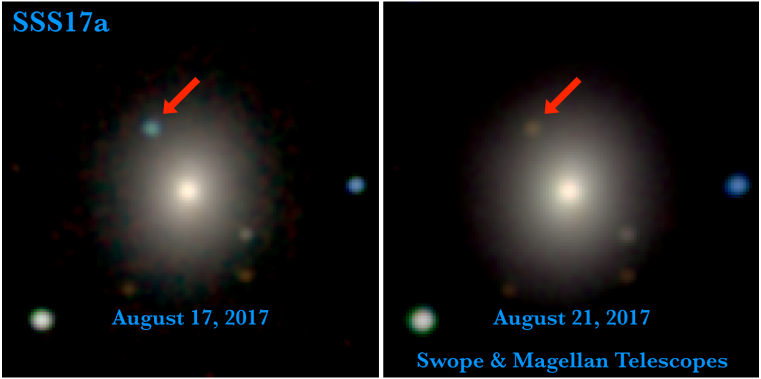



Courtesy of J. Lippuner



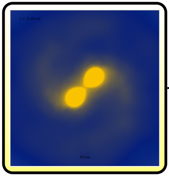

Not opaque

Opaque to visible light

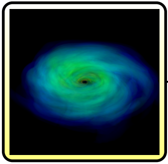



M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

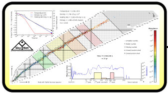
- Duration/relevant time scales
- Methods



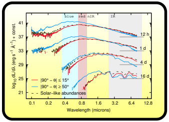
In-spiral:
$\sim \mu$s$\rightarrow$30 s
numerical relativity
ET, SpEC, etc.



Disk+GRB:
$\sim \mu$s$\rightarrow$1 s
GR$\nu$RMHD
$\nu$`bhlight`, `HARM`

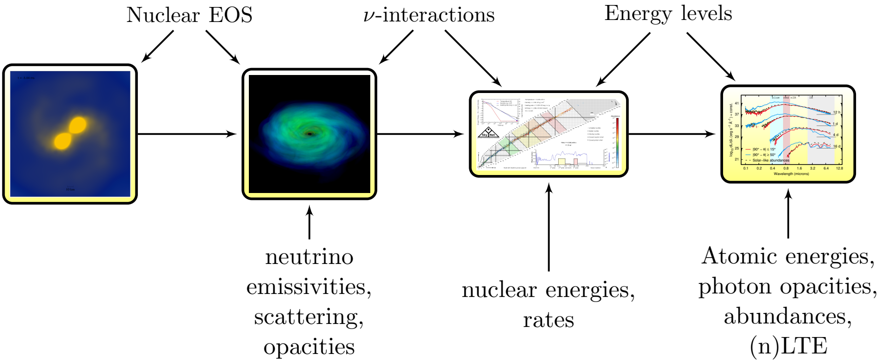


Non-equilibrium reactions:
$\sim$ s$\rightarrow$hours$\rightarrow$Myrs
Reaction network
PRISM, SkyNet

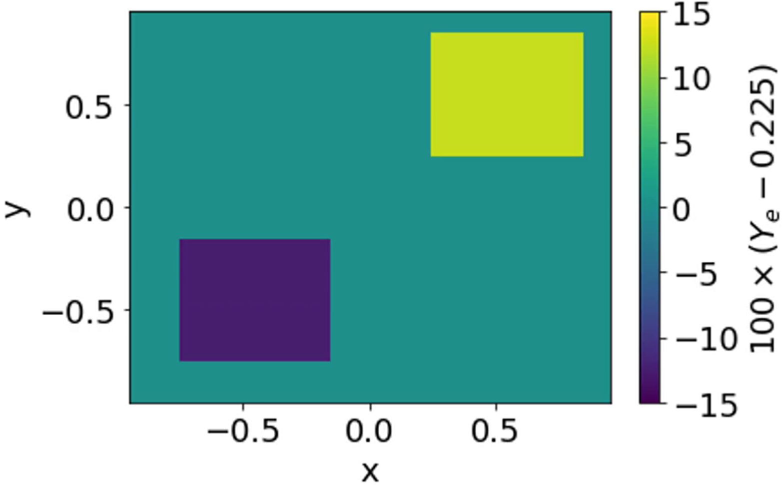



Photon transport:
$\sim$ Weeks
DDMC-IMC
`SuperNu`,`sedona`

# The Makings of a Kilonova



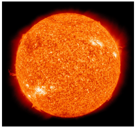
# Neutrino Transport Matters!

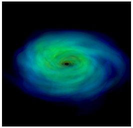


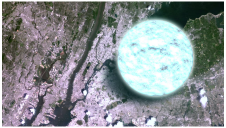

**JMM**, B. R. Ryan, J. C. Dolence. ApJS **241** 30 (2019)

# Transport Limits

- Characterized by optical depth $\tau$ 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.

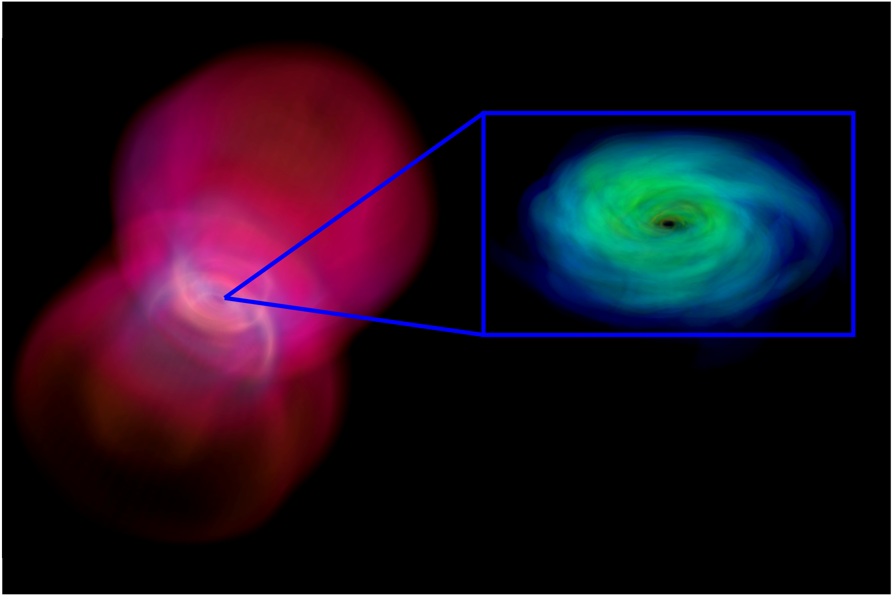
# Relevant Neutrino Interactions

| Type | Processes | Corrections/Approximations |
|---|---|---|
| Abs./Emis. on Neutrons | $\nu_e + n \leftrightarrow e^- + p$<br>$\nu_\mu + n \leftrightarrow \mu^- + p$ | Blocking/Stimulated Abs.<br>Weak Magnetism<br>Recoil |
| Abs./Emis. on Protons | $\bar{\nu}_e + p \leftrightarrow e^+ + n$<br>$\bar{\nu}_\mu + p \leftrightarrow \mu^+ + n$ | Blocking/Stimulated Abs.<br>Weak Magnetism<br>Recoil |
| Abs./Emis. on Ions | $\nu_e A \leftrightarrow A' e^-$ | Blocking/Stimulated Abs.<br>Recoil |
| Electron Capture on Ions | $e^- + A \leftrightarrow A' + \nu_e$ | Blocking/Stimulated Abs.<br>Recoil |
| $e^+ - e^-$ Annihilation | $e^+ e^- \leftrightarrow \nu_i \bar{\nu}_i$ | single-$\nu$ Blocking<br>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-$\nu$ Blocking<br>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<br>electron polarization<br>form-factor |

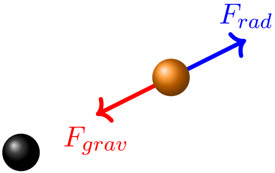
- And this is ignoring Neutrino oscillations!

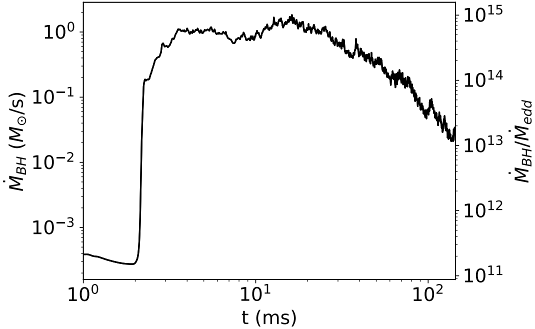
Burrows, Reddy, Thompson, NPA **177**, 356, (2006)

# Lets Start With the Disk

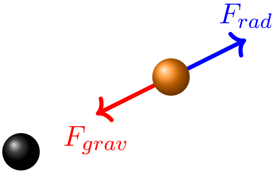


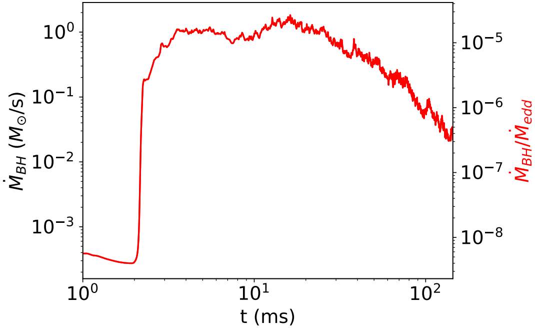
# Accretion Rates



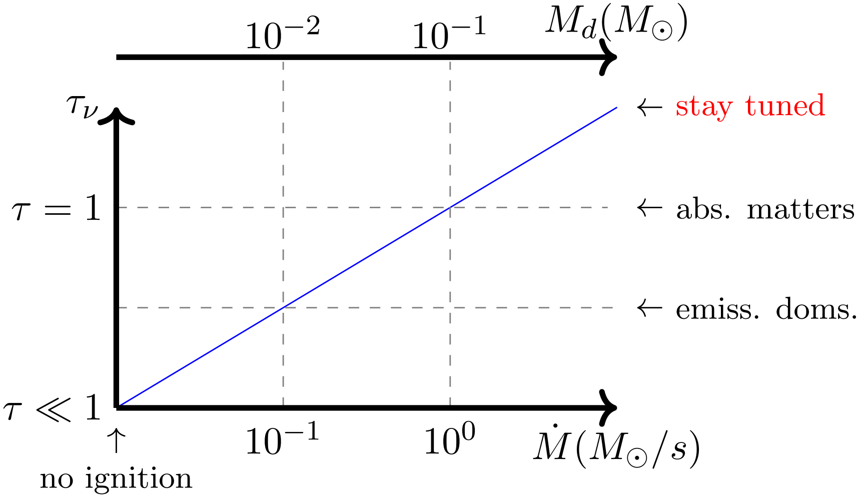
# Accretion Rates



# How Much Does Transport Matter for disks?

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



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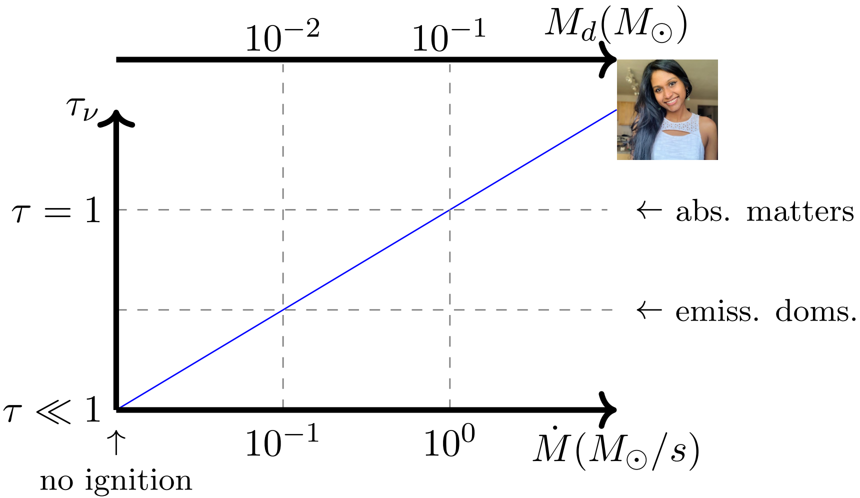


# Ingredients In Kilonova Disk Modeling

- 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

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

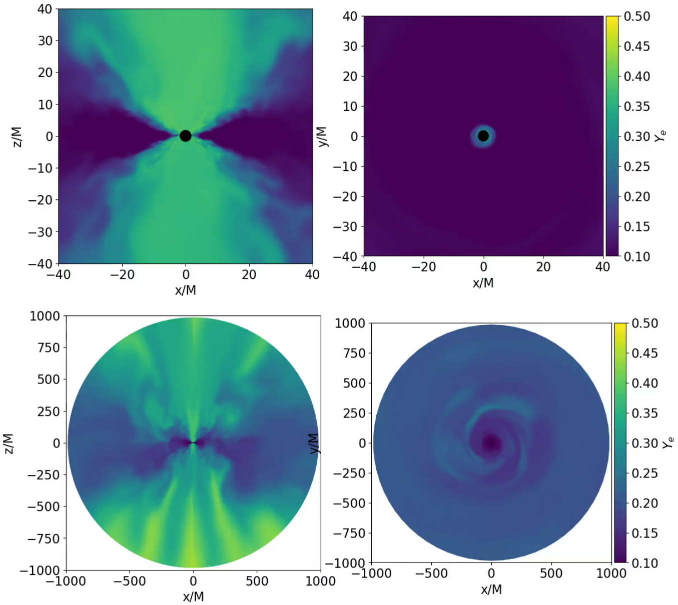
- Neutrino Transport

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

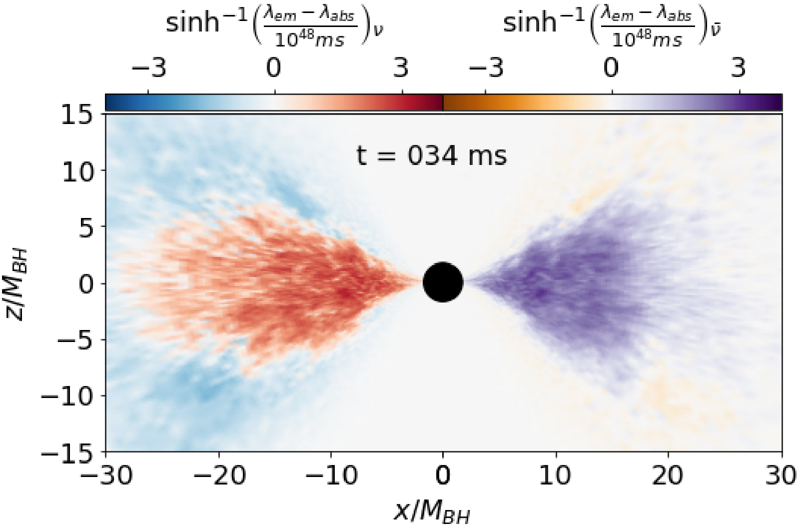
# Presenting $\nu$bhlight!

- 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

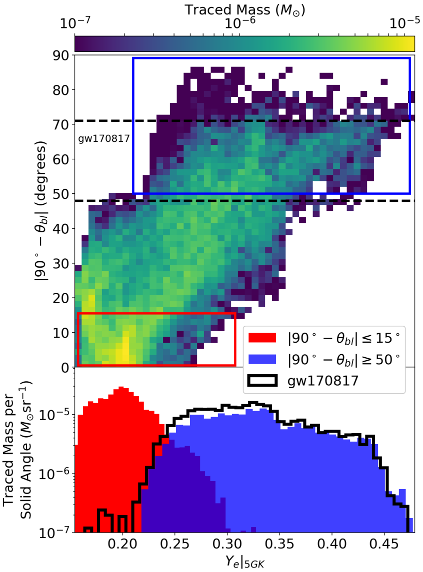


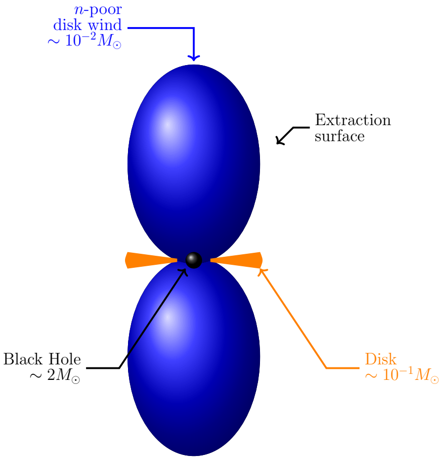
# Neutrino Transport in the Disk



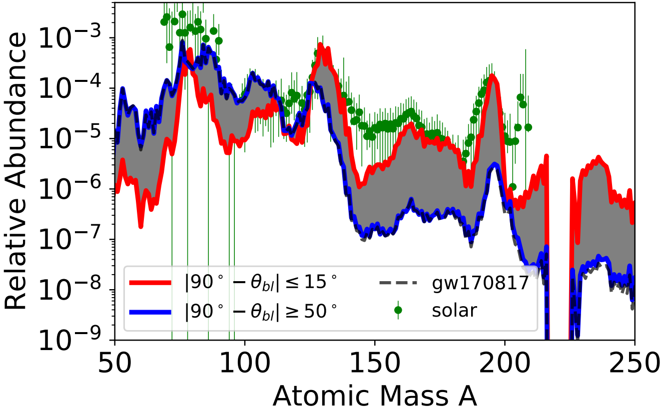

**JMM** et al. PRD **100** 023008 (2019)

# Electron Fraction of the Outflow



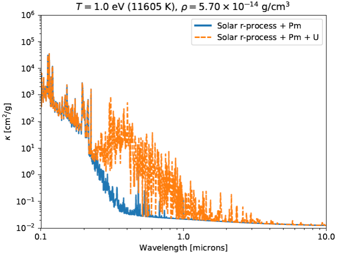

**JMM** et al. PRD **100** 023008 (2019)



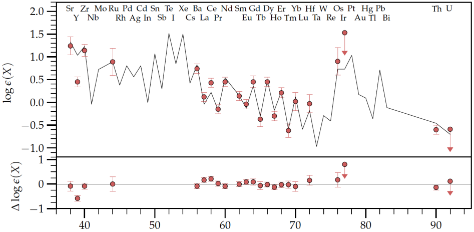

- r-process networks:
  - SkyNet
  - PRISM
  - CFNET
  - etc.

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

# Nucleosynthesis Feeds Directly into Observables



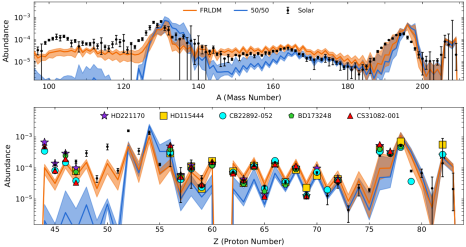

Even,...,**JMM**, et al. ApJ **899** 24 (2020)




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

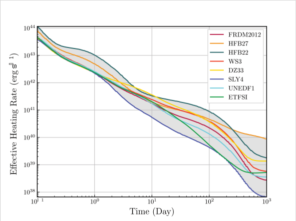
# A Sampling of What's Possible (Not my work)

Fission Yields



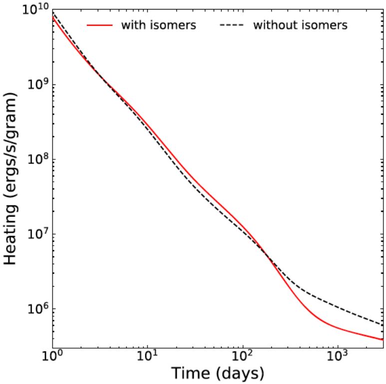

Vassh et al., ApJ **896** 28 (2020)

Heating rates +mass models

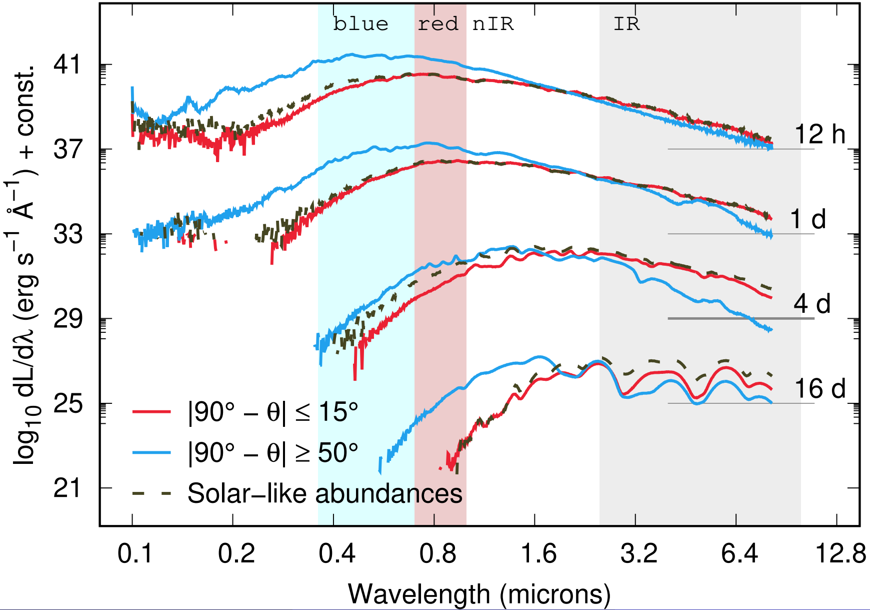



Zhu et al., ApJ **906** 94, (2021)

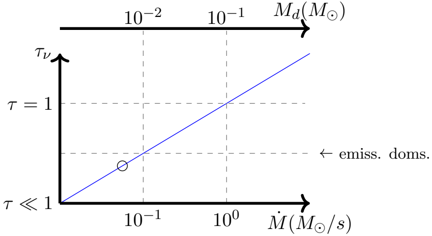
Astromers

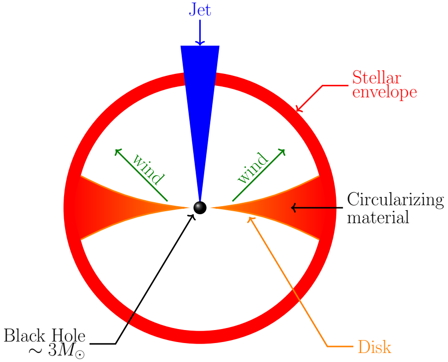



Misch et al., ApJL **913** L2, (2021)

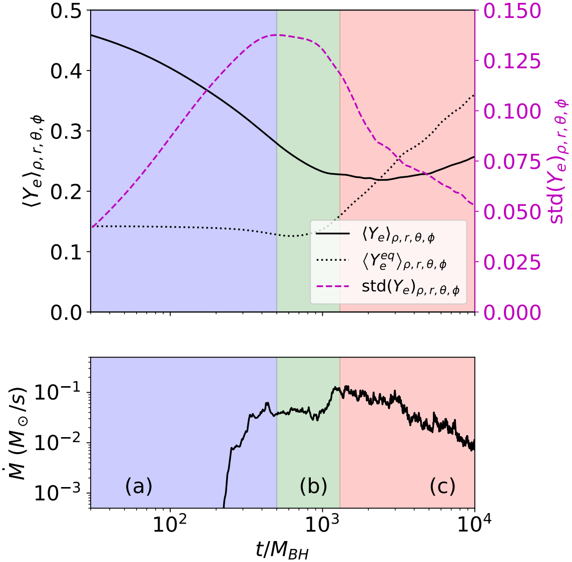

blue
red
nIR
IR
41
37
33
29
25
21
$\log_{10} dL/d\lambda$ (erg s$^{-1}$ Å$^{-1}$) + const.
12 h
1 d
4 d
16 d
|90° – θ| ≤ 15°
|90° – θ| ≥ 50°
Solar–like abundances
0.1
0.2
0.4
0.8
1.6
3.2
6.4
12.8
Wavelength (microns)

# Digging a Little Deeper with a Collapsar Disk



# Stationary Disk, No Ye equilibrium!



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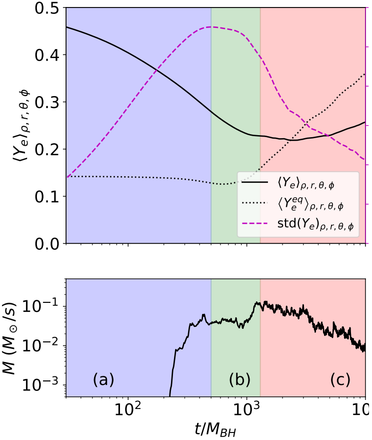
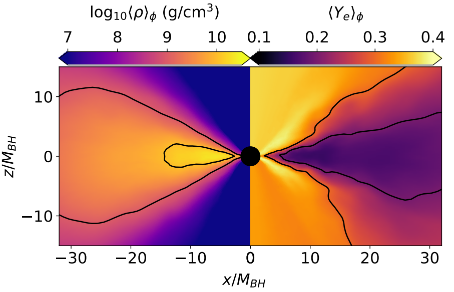
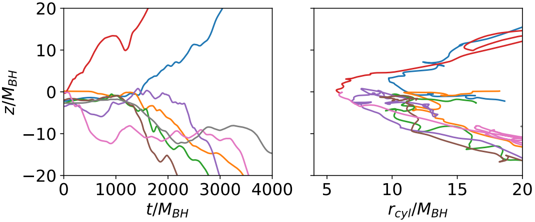
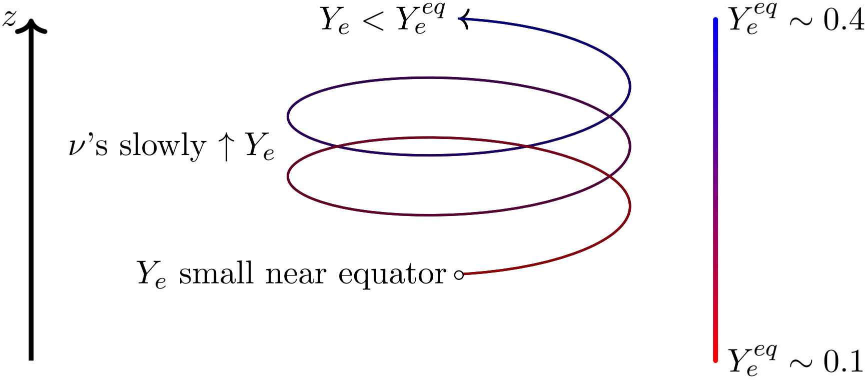


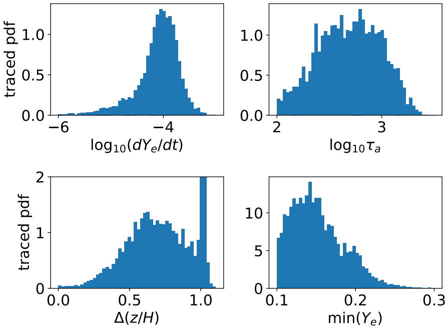

Miller et al., ApJ **902**, 66 (2020)

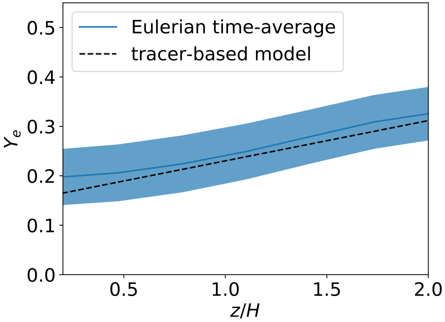
# Turbulence and $Y_e$



# $Y_e$ is set by the balance of Turbulence and Neutrinos!

$$Y_\mathrm{e}(z/H) = \langle \min(Y_\mathrm{e}) \rangle_\mathrm{trc} + \langle \frac{dY_\mathrm{e}}{dt} \rangle_{t,\mathrm{trc}} \left( H \, \langle \frac{dz}{dt} \rangle_{t,\mathrm{trc}}^{-1} \right) \left( \frac{z}{H} - \langle \min(z/H) \rangle_\mathrm{trc} \right)$$



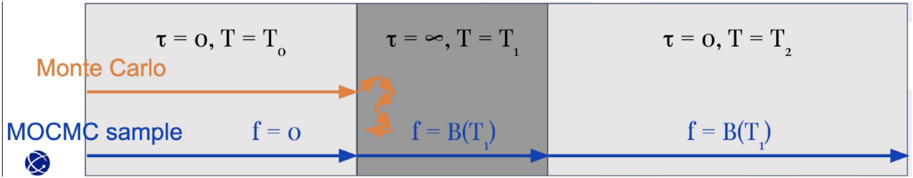

Miller et al., ApJ **902**, 66 (2020)

# Big Open Questions and Modeling Uncertainties

- Oscillations (Great recent work by S. Richers, V. Cirgliano, M.-R. Wu, X. Li, and D. Siegel)
- 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
- 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.



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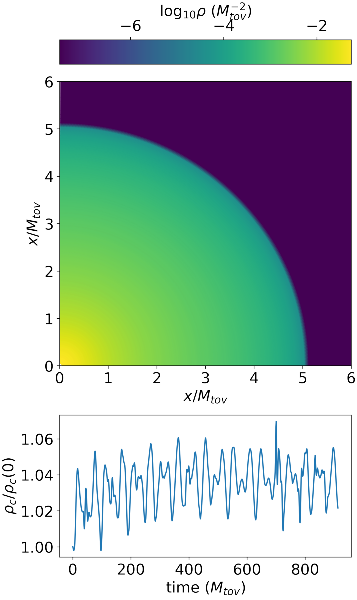
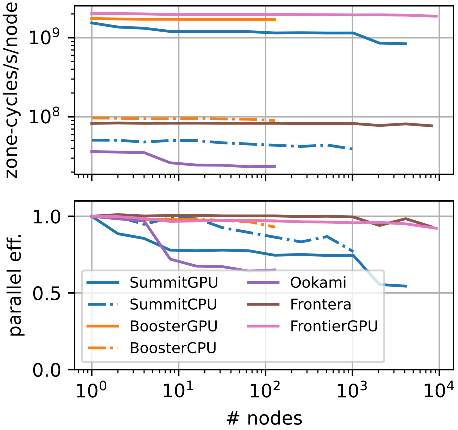
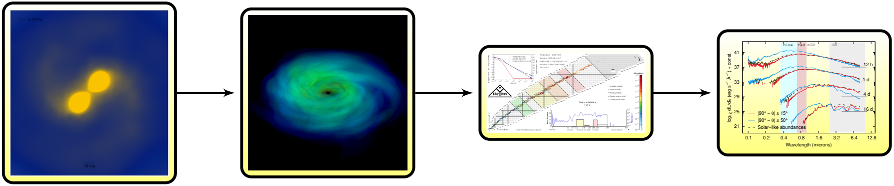
Ryan and Dolence, ApJ **891** 118, (2020).



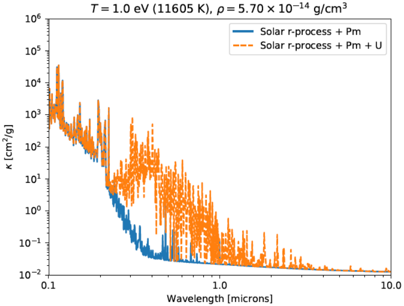

Grete, **JMM**, et al., ArXiv:2202.12309

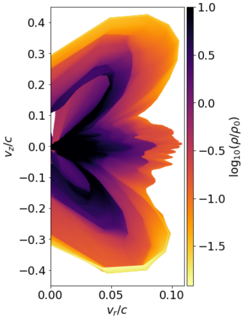
# Take-home Message




- 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

# Uncertainties




- Not all opacities known, so surrogates often used. Some elements matter more than others.

arXiv:1904.13298

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

arXiv:204.00102