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Title: Nuclear Astrophysics and Astrophysical Transients

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Intended for: Invited Seminar at Hamburg Observatory. Talk is on December 2.

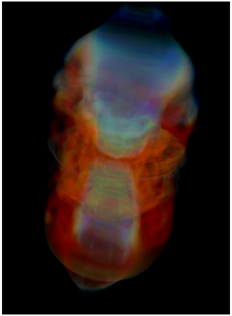
Issued: 2022-11-23

Los Alamos
NATIONAL LABORATORY

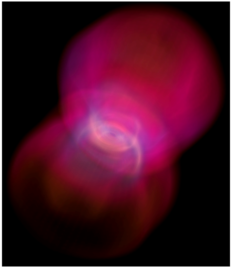
Nuclear Astrophysics and Astrophysical Transients

Jonah Miller

Los Alamos National Laboratory



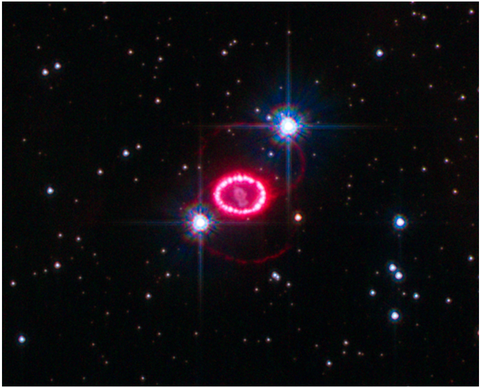
Hamburg



- Feb. 23, 1987

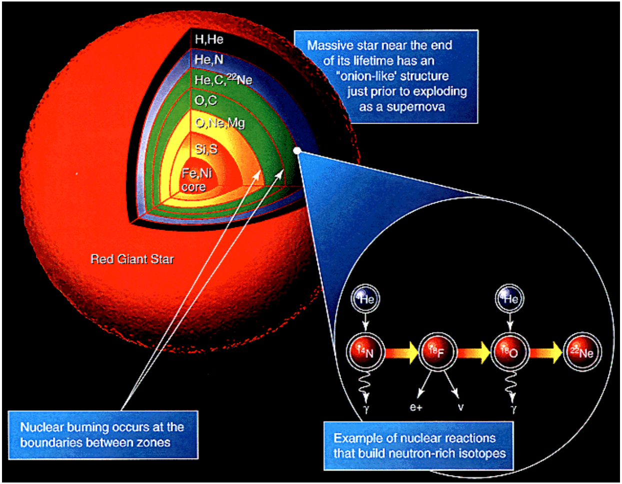
ESO/Schmidt

- Sept. 2, 2010



NASA/Hubble

Stellar structure primer



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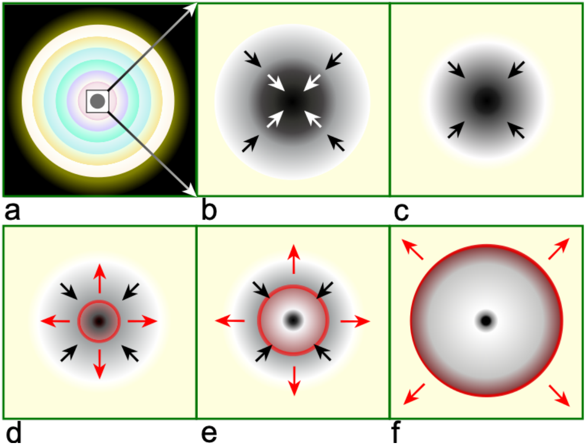
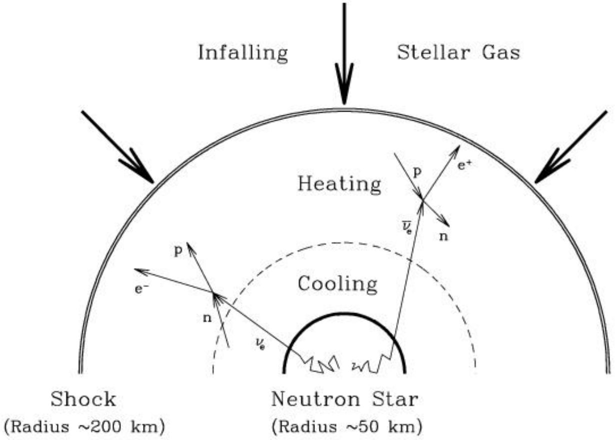
Collapse



Hall, Magasjukur2, Wikimedia Commons

Powering The Explosion



T. Janka

Neutron Stars

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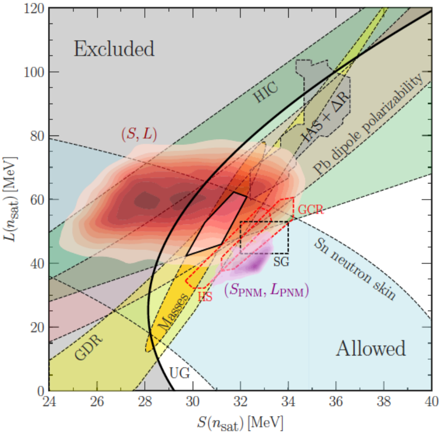


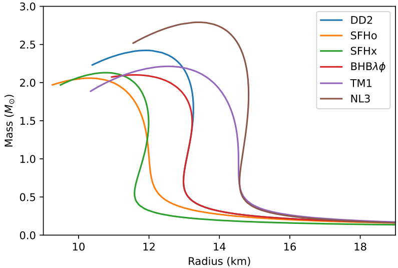
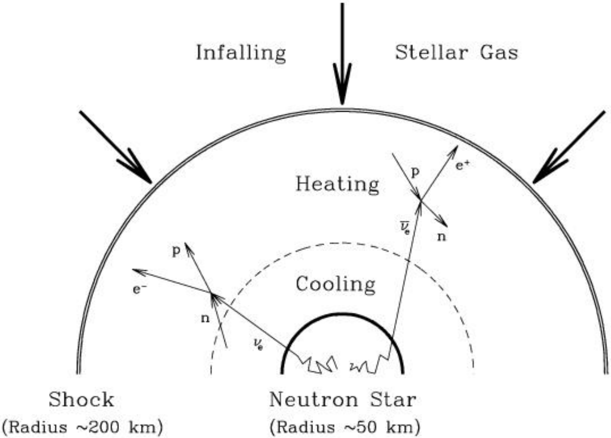


Image from Carla Frohlich

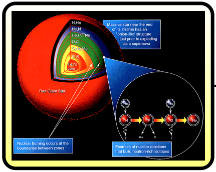
Lonardoni et al., PRR **2** 022033 (2020)

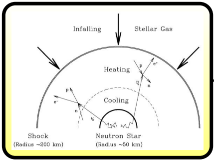
Nuclear EOS Impacts Explosion and Remnant

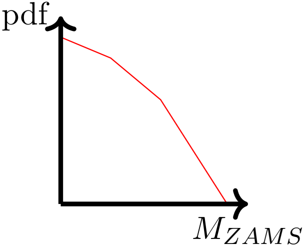


T. Janka

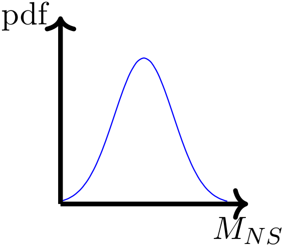
Observation vs Theory



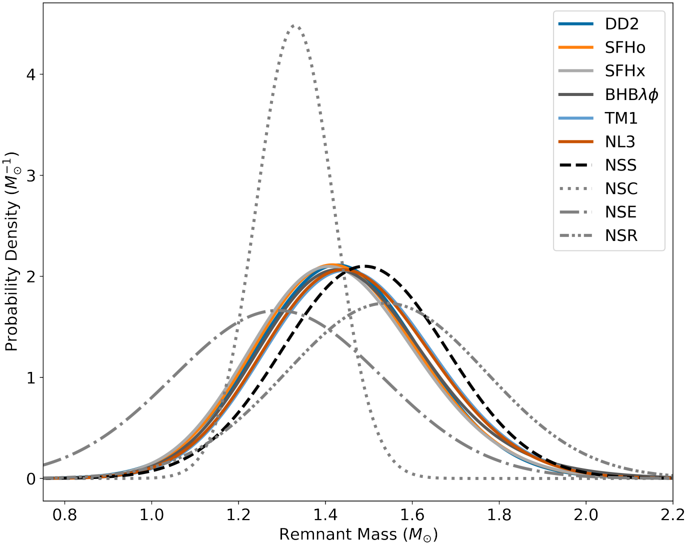




simulation

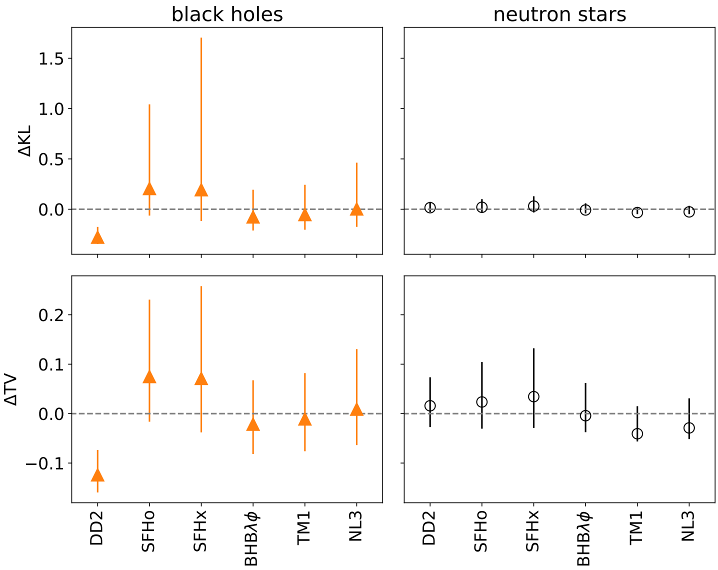


Compare Distributions!



Meskhi,...,**JMM** et al., ApJL **932** L3 (2022)

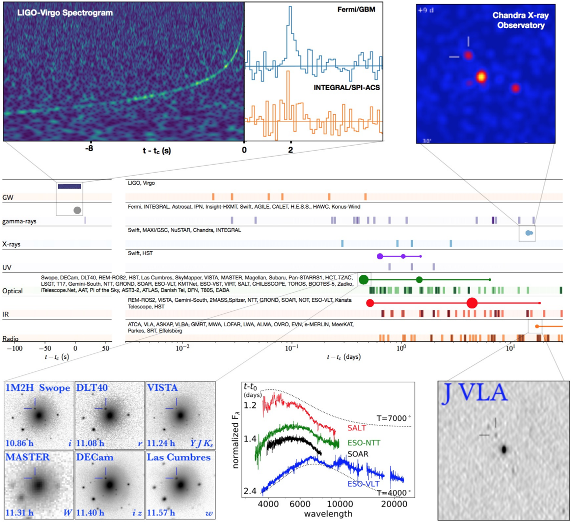
...Implies constraints on EOS!



Meskhi,...,**JMM** et al., ApJL **932** L3 (2022)

Cosmic Gold

Ashley Mackenzie for Quanta Magazine, March 23, 2017


LIGO-Virgo Spectrogram
Fermi/GBM
INTEGRAL/SPI-ACS
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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 (days)
1M2H Swope
DLT40
VISTA
MASTER
DECam
Las Cumbres
normalized Fλ
wavelength
T=7000°
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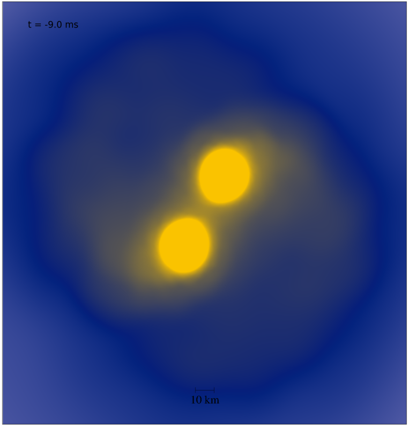
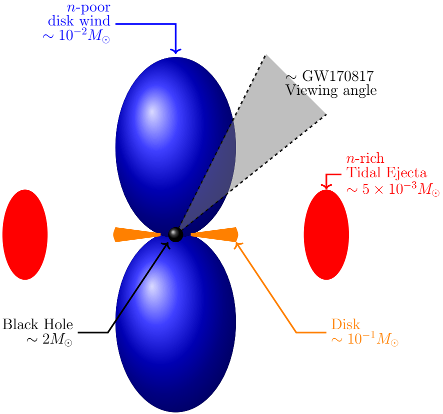
ESO-NTT
SOAR
ESO-VLT
J VLA

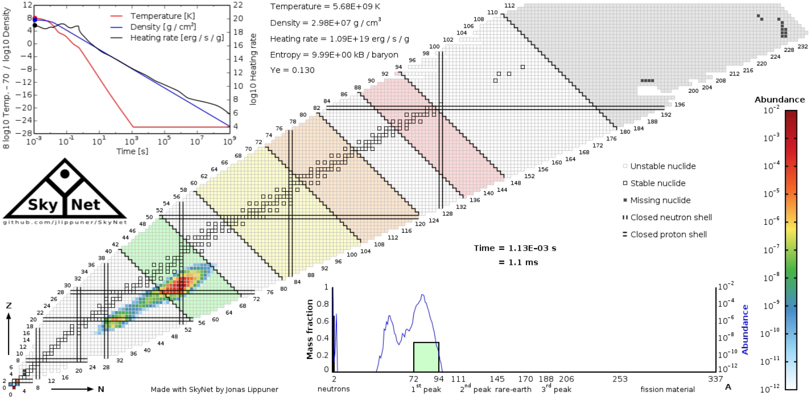
Abbot+, 2017

Neutron Star Mergers: A 2+ Component Model

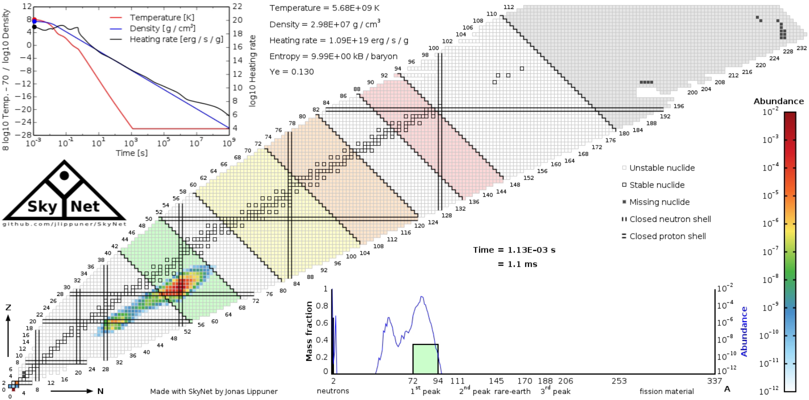


Co-design summer school, 2016



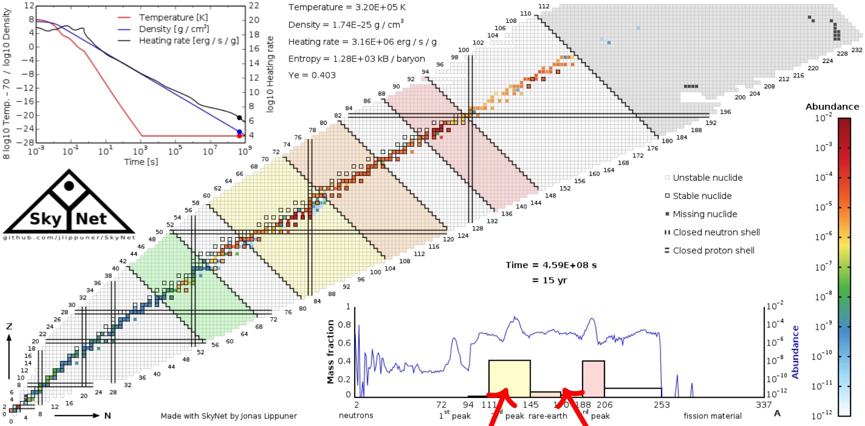


Courtesy of J. Lippuner



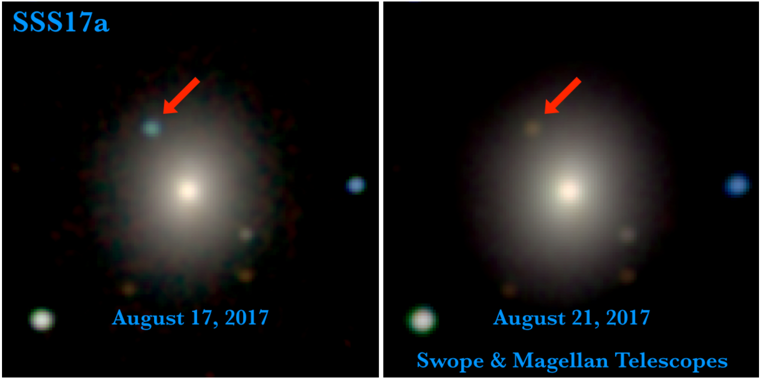
Courtesy of J. Lippuner

Opacity



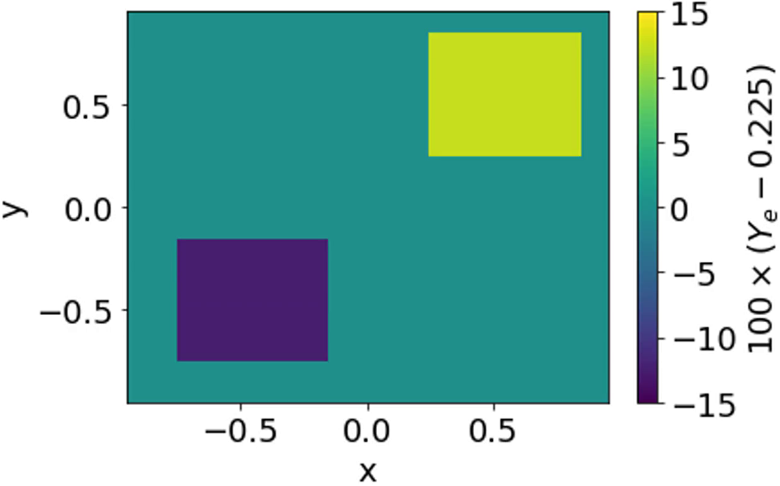
Not opaque

Opaque to visible light



M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

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

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

- 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 ν`bhlight`!

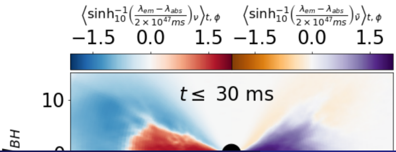
- General relativistic radiation magnetohydrodynamics for kilonova disks
- **Magnetized gas** via *finite volume methods*
  - Standard second-order Gudonov scheme
  - Cell-centered constrained transport for magnetic fields
  - WENO5 reconstruction
  - Local Lax-Friedrichs Riemann solver
- **Neutrinos** 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`.

Presenting νbhlight! github.com/lanl/nubhlight

core	minor formatting fix	7 months ago
data	add pretty picture to readme	10 months ago
prob	oops	2 days ago
script	Update capulin.py	7 days ago
test	fix tests to not call python explicitly and instead call the currentl...	7 months ago
.clang-format	added hidden files	10 months ago
.gitignore	added hidden files	10 months ago
.gitlab-ci.yml	added hidden files	10 months ago
.travis.yml	final changes to travis	10 months ago
LICENSE	newline at bottom of license	10 months ago
README.md	Update README.md	10 months ago
VERSION	first commit	10 months ago
eidr.md	Update eidr.md	8 months ago

README.md

nubhlight: General Relativistic Neutrino Radiation Magnetohydrodynamics with Monte Carlo Transport



Readme

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Contributors 4

jonahm-LANL Jonah Miller

Yurlungur Jonah Miller

soumide1102 Soumi De

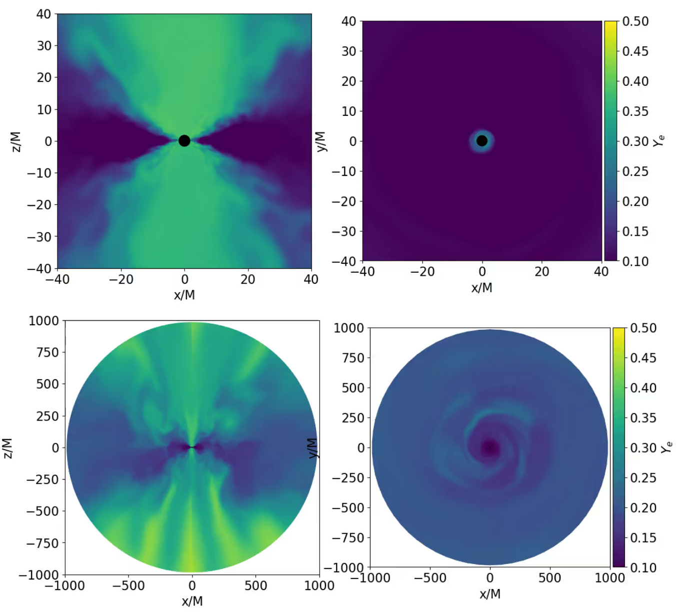
kinchb Brooks Kinch

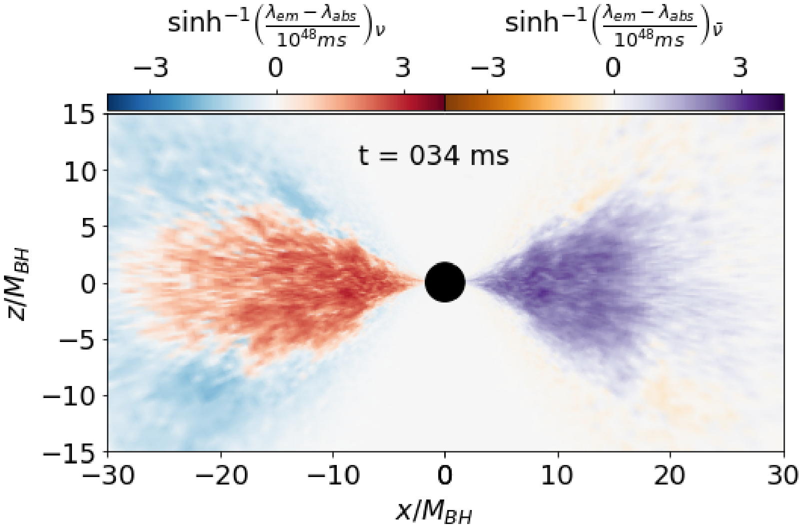
Languages

C 51.8% Python 43.3%

Fortran 3.8% Other 1.1%

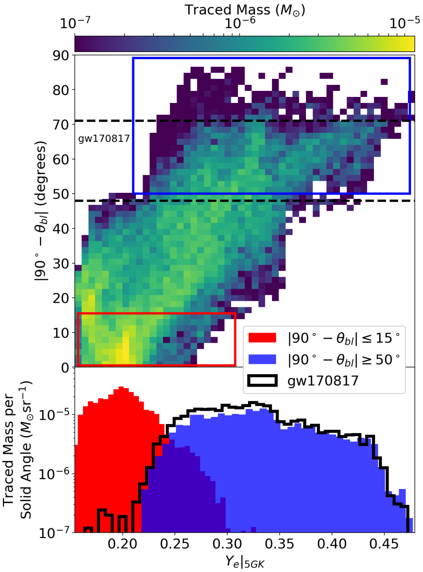
The August 2017 Disk (Miller et al., 2019)

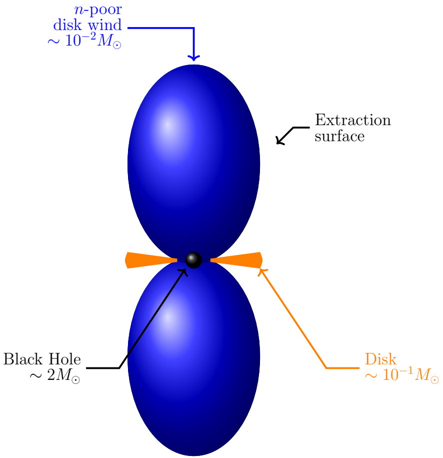




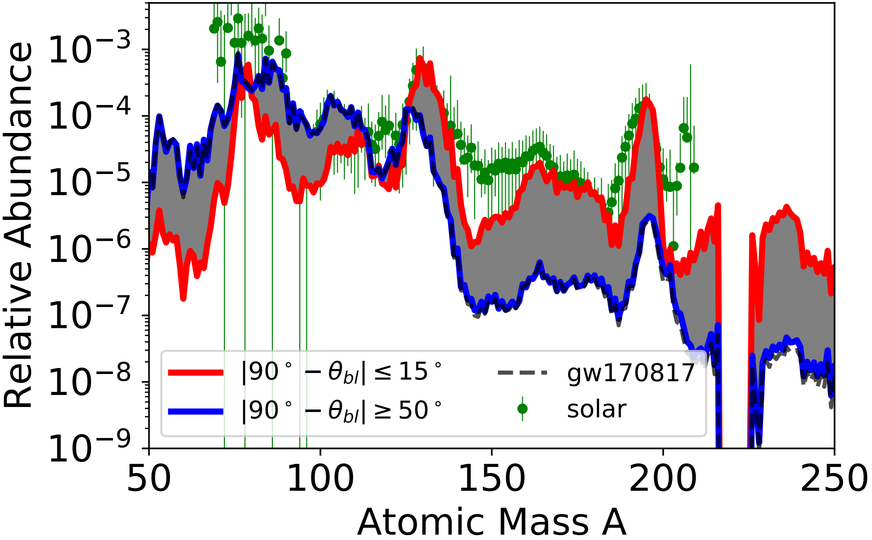
JMM et al. PRD **100** 023008 (2019)

Electron Fraction of the Outflow

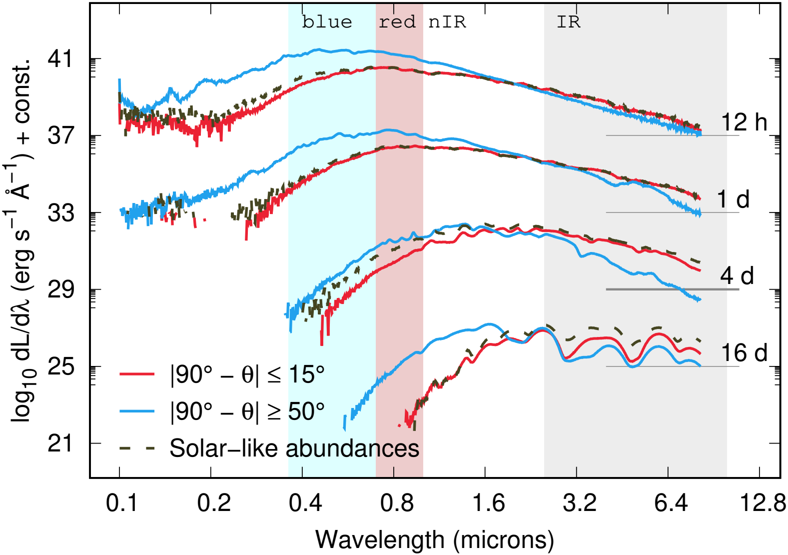




JMM et al. PRD **100** 023008 (2019)



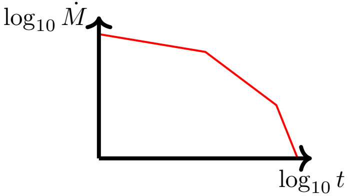
JMM et al. PRD **100** 023008 (2019)



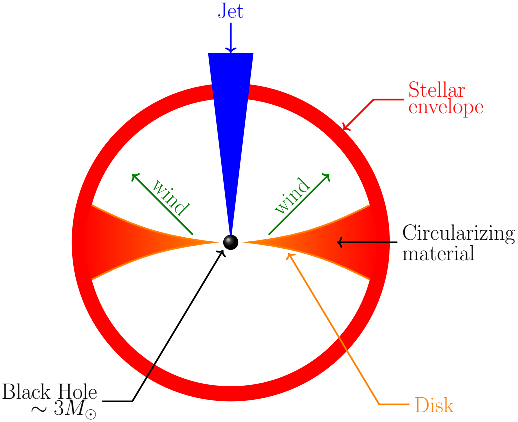
JMM et al. PRD **100** 023008 (2019)

Collapsars, and how it all circles back to supernovae

- Accretion times $t \sim 10s$
- $\dot{M}$ between
  - $10^{-4} M_\odot/s$
  - $10^{-1} M_\odot/s$
- $\rho \sim 10^{10}$ g/cm^3



Siegel, Barnes, Metzger. Nature **241** (2019)

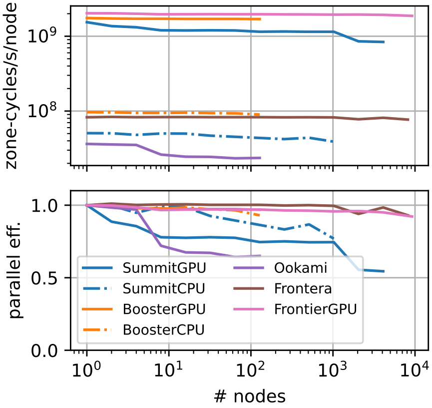


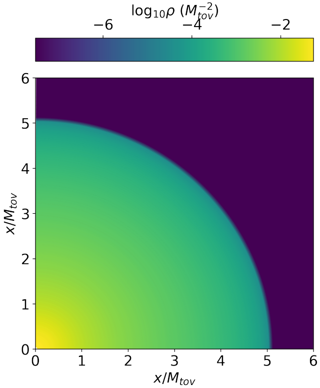
Big Open Questions and Uncertainties

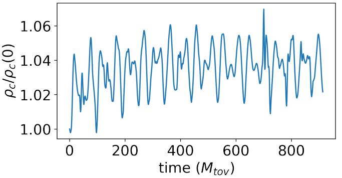
- Initial conditions matter. What are the right ones? Massive diversity:
  - BH mass and spin (V. Urrutia-Hurtado)
  - Disk mass (S. Curtis)
  - Magnetic field strength, topology. Transient due to MHD forces real? (K. Lund)
  - In collapsar case, disk feeding (B. Barker)
- Late time physics.
- Mapping the central engine to observations (Several topics by itself!)
- Neutrino oscillations—Elephant in the room. cm-scale physics impossible to treat.

Future: Leveraging Next-Generation HPC

- Parthenon AMR library: arXiv:2202.13209
- Fast logs: arXiv:2206.08957
- spiner performance-portable tables: joss.04367
- singularity-eos performance-portable EOS: `https://github.com/lanl/singularity-eos`
- Phoebus Performance portable GRνRMHD: `https://github.com/lanl/phoebus`







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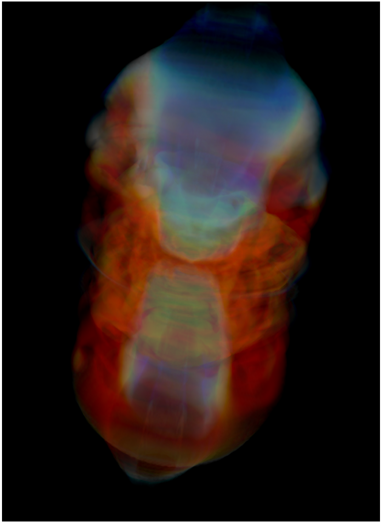
Conclusions

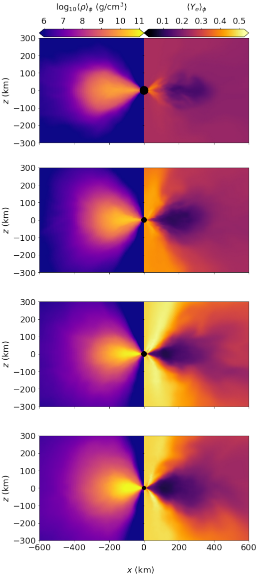
- Astrophysical transients are a rich laboratory!
- Very big things (stars, supernovae, neutron star mergers) tell us a lot about very tiny things (nuclear physics)
- Need GRRMHD and neutrino transport!
- NS Mergers are awesome!
  - Likely source of heavy elements in our universe
  - Disks can produce blue component of kilonova
- Stay tuned for more



The story differs for more massive disks, BHNS Mergers

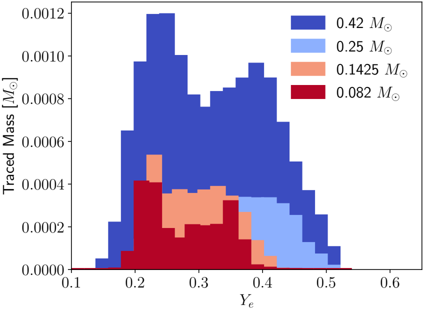
Remnant + Disk parameters, chosen to sample edge of what's possible:

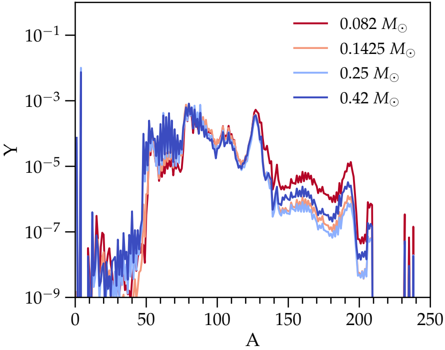
- $M_{BH} = 10, a = 0.8, M_d = 0.082$
- $M_{BH} = 6, a = 0.75, M_d = 0.1425$
- $M_{BH} = 7, a = 0.9, M_d = 0.25$
- $M_{BH} = 5, a = 0.9, M_d = 0.42$



Curtis, **JMM**, Frohlich. In Prep.

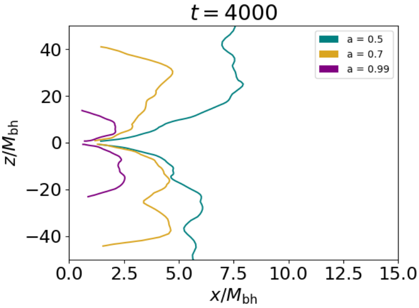
Electron Fractions and Yields

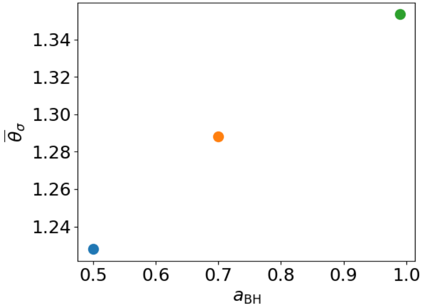




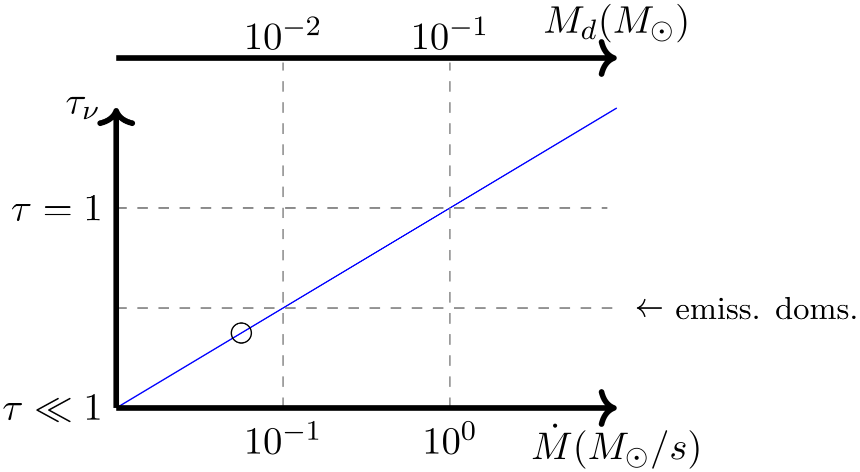
Curtis, **JMM**, Frohlich. In Prep.

- Black hole properties, such as spin change jet opening angle, and interaction of jet with wind.
  (Preliminary. V. Urrutia-Hurtado et al.)



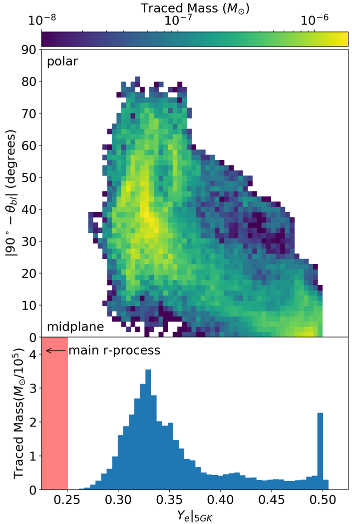


Collapsar Disks: A Cautionary Tail

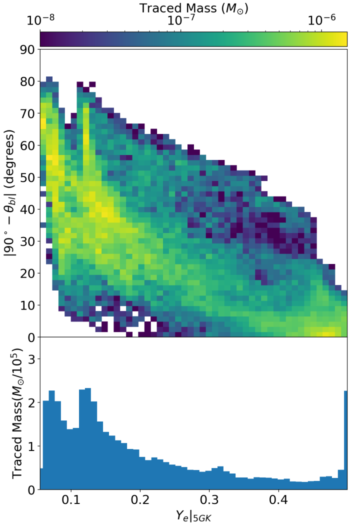


Electron Fraction With and Without Absorption

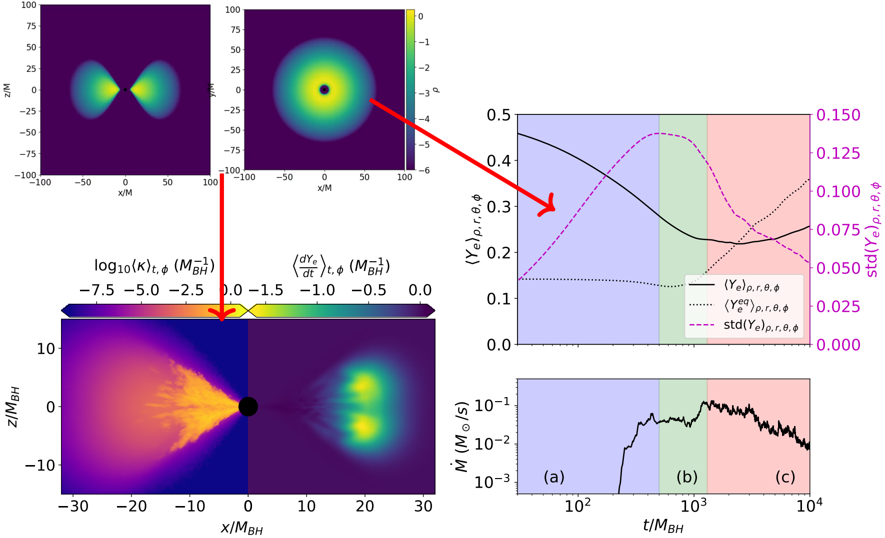
- Electron Fraction With Absorption



- Electron Fraction With Optically thin Cooling



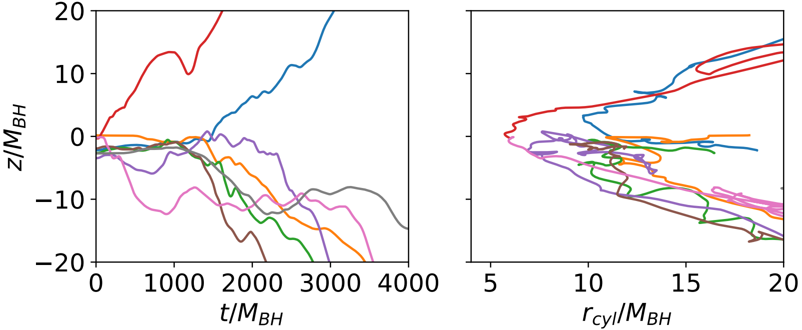
Absorption and Initial Conditions



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

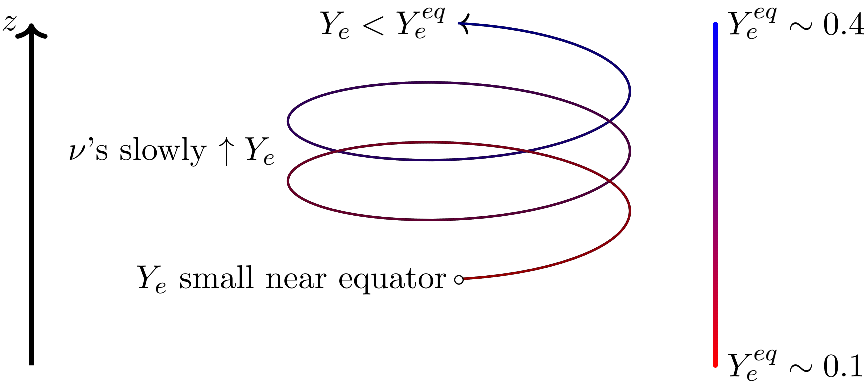
How is Y_e vs Lattitude Set?

- Traced paths of Lagrangian fluid packets through the disk.

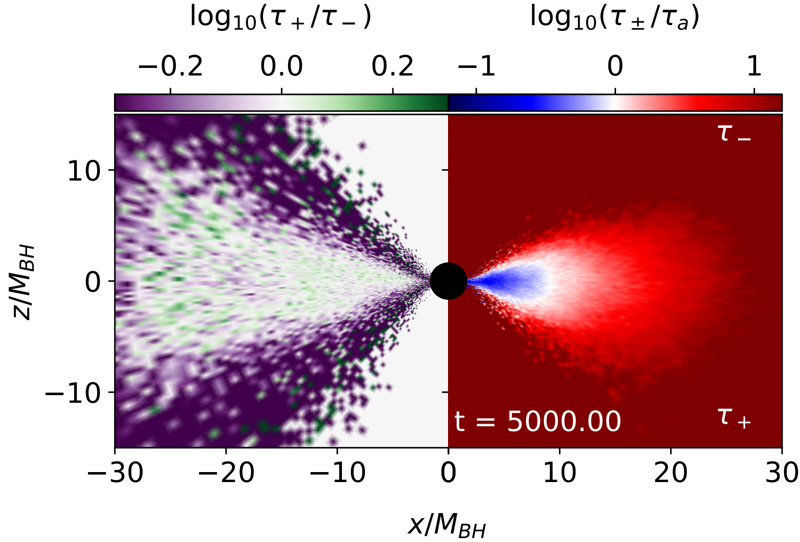


Miller et al., ApJ **902**, 66 (2020)

Turbulence and Y_e



Y_e is set by the balance of Turbulence and Neutrinos!



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

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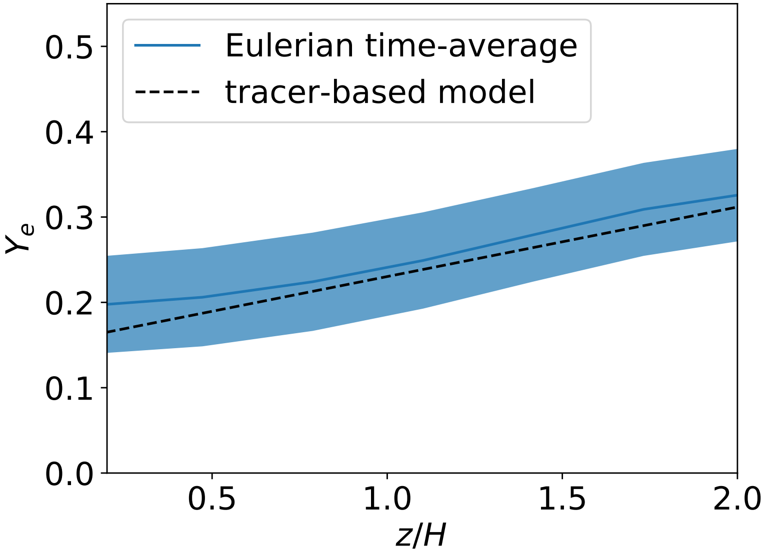
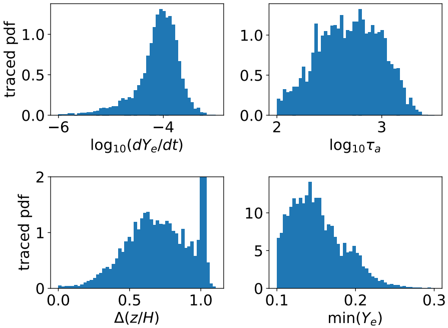


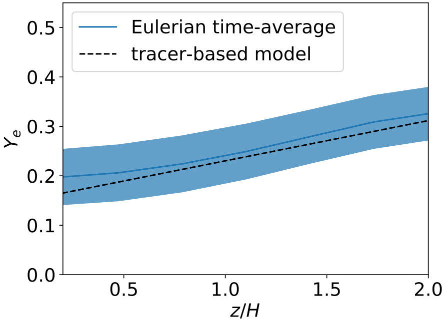
Miller et al., ApJ **902**, 66 (2020)

Y_e is set by the balance of Turbulence and Neutrinos!

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

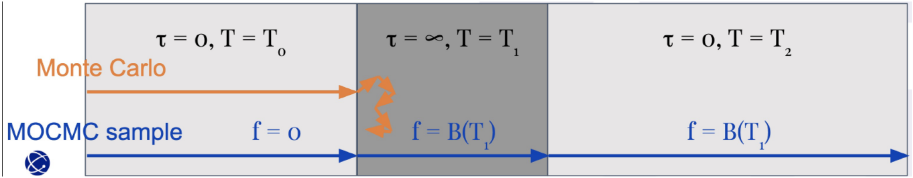


Miller et al., ApJ **902**, 66 (2020)



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
- Great progress community. See work by Radice, Mullen, Foucart, others.



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