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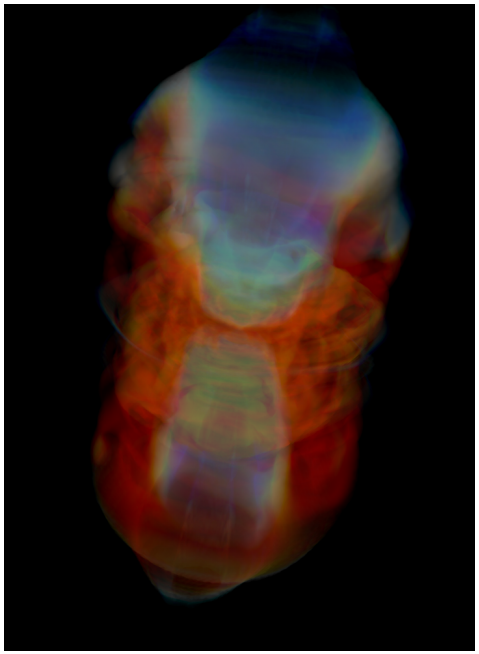
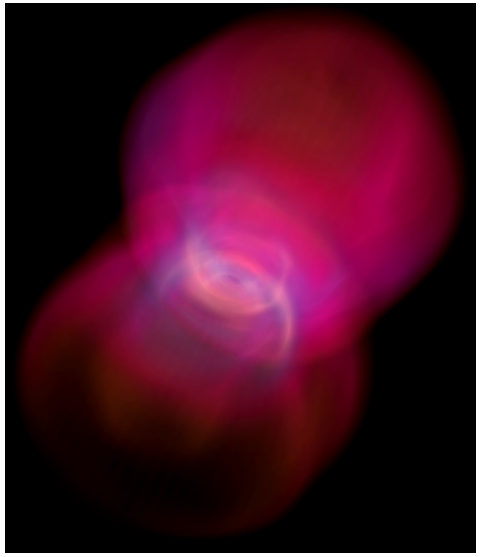
Fusion in Space: Nuclear Astrophysics, Neutron Star Mergers, and Accretion Disks

Jonah M. Miller

Los Alamos National Laboratory

SHI CRLC Virtual Seminar





A Deceptively Simple Question

- Where does stuff come from?

	1 IA	2 IIA	3 IIIA	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H Hydrogen																	2 4.0025 He Helium
2	3 6.941 Li Lithium	4 9.0122 Be Beryllium											5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Flourine	10 20.180 Ne Neon
3	11 22.990 Na Sodium	12 24.305 Mg Magnesium											13 26.982 Al Aluminium	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.065 S Sulphur	17 35.453 Cl Chlorine	18 39.948 Ar Argon
4	19 39.098 K Potassium	20 40.078 Ca Calcium	21 44.956 Sc Scandium	22 47.867 Ti Titanium	23 50.942 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.845 Fe Iron	27 58.933 Co Cobalt	28 58.693 Ni Nickel	29 63.546 Cu Copper	30 65.39 Zn Zinc	31 69.723 Ga Gallium	32 72.64 Ge Germanium	33 74.922 As Arsenic	34 78.96 Se Selenium	35 79.904 Br Bromine	36 83.8 Kr Krypton
5	37 85.468 Rb Rubidium	38 87.62 Sr Strontium	39 88.906 Y Yttrium	40 91.224 Zr Zirconium	41 92.906 Nb Niobium	42 95.94 Mo Molybdenum	43 96 Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.42 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.71 Sn Tin	51 121.76 Sb Antimony	52 127.6 Te Tellurium	53 126.9 I Iodine	54 131.29 Xe Xenon
6	55 132.91 Cs Caesium	56 137.33 Ba Barium	57-71 La-Lu Lanthanide	72 178.49 Hf Halfnium	73 180.95 Ta Tantalum	74 183.84 W Tungsten	75 186.21 Re Rhenium	76 190.23 Os Osmium	77 192.22 Ir Iridium	78 195.08 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.38 Tl Thallium	82 207.2 Pb Lead	83 208.98 Bi Bismuth	84 209 Po Polonium	85 210 At Astatine	86 222 Rn Radon
7	87 223 Fr Francium	88 226 Ra Radium	89-103 Ac-Lr Actinide	104 261 Rf Rutherfordium	105 262 Db Dubnium	106 266 Sg Seaborgium	107 264 Bh Bohrium	108 277 Hs Hassium	109 268 Mt Meitnerium	110 281 Ds Darmstadtium	111 280 Rg Roentgenium	112 285 Uub Ununbium	113 284 Uut Ununtrium	114 289 Uuq Ununquadium	115 288 Uup Ununpentium	116 293 Uuh Ununhexium	117 292 Uus Ununseptium	118 294 Uuo Ununoctium

57 138.91 La Lanthanum	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 145 Pm Promethium	62 150.36 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
89 227 Ac Actinium	90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 237 Np Neptunium	94 244 Pu Plutonium	95 243 Am Americium	96 247 Cm Curium	97 247 Bk Berkelium	98 251 Cf Californium	99 252 Es Einsteinium	100 257 Fm Fermium	101 258 Md Mendelevium	102 259 No Nobelium	103 262 Lr Lawrencium

- Alkali Metal
- Alkaline Earth Metal
- Metal
- Metalloid
- Non-metal
- Halogen
- Noble Gas
- Lanthanide/Actinide

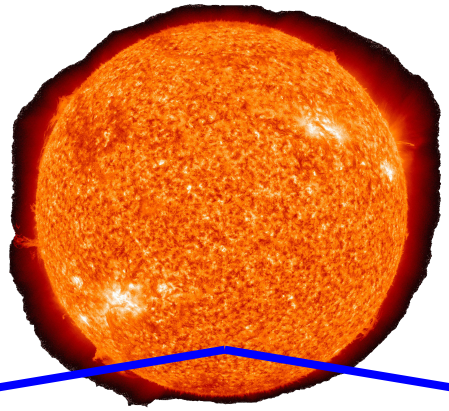
Z mass Symbol Name

man-made

D. Mendeleev, I. Griffin

What sets the relative abundances of elements?

- Observations of the sun one major way to measure abundances (but there are many others).



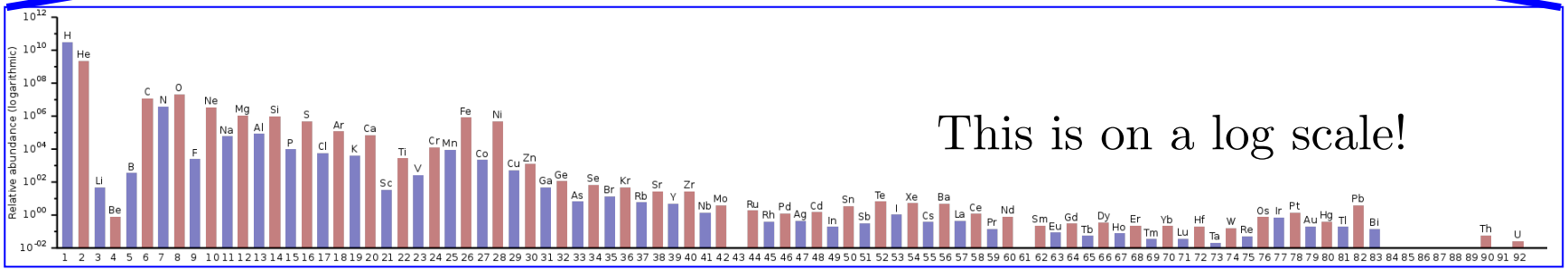


Image credit: NASA/APOD, Wikipedia

The Many Sources of the Elements in Our Universe

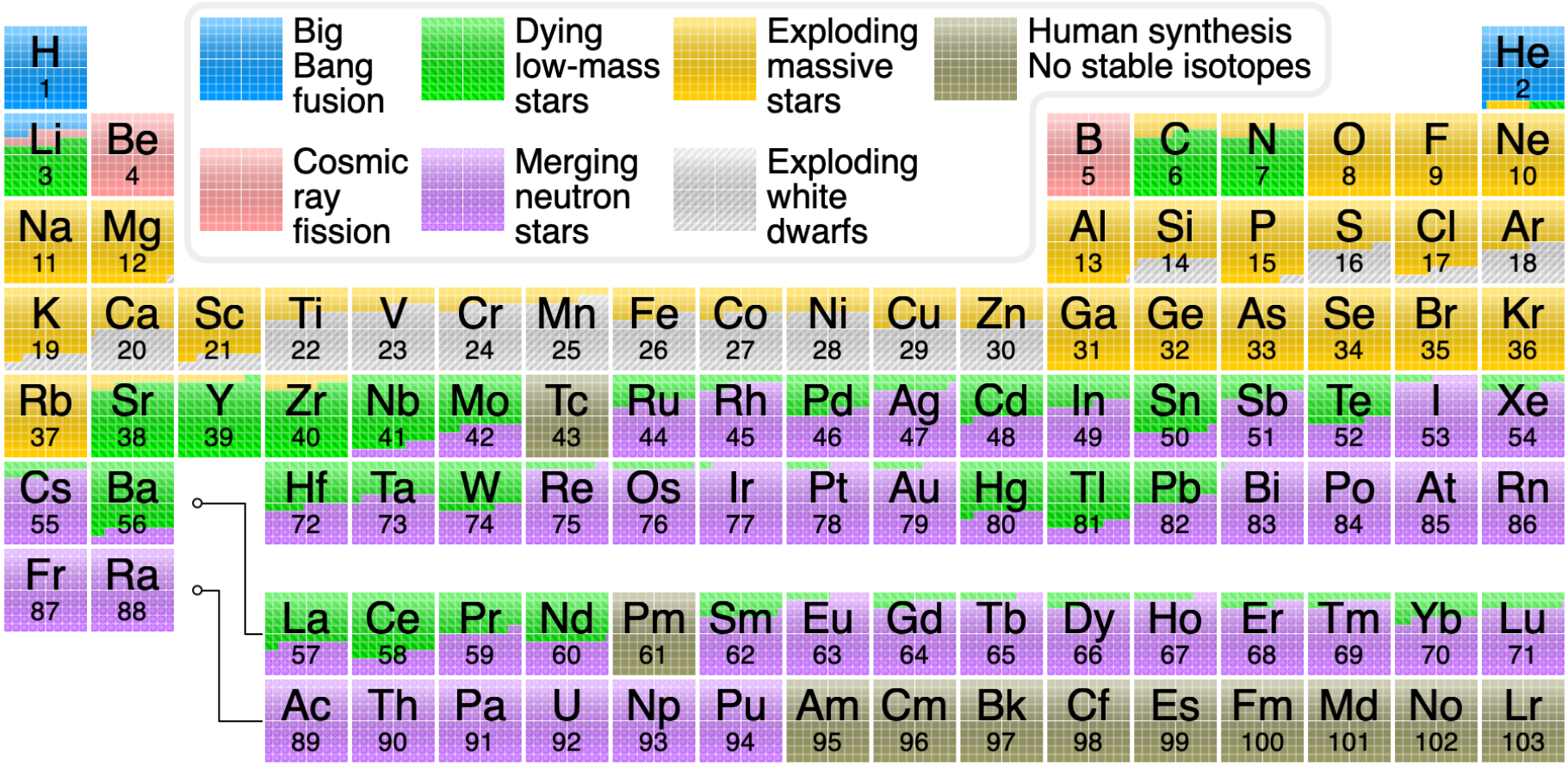


Image credit: Jennifer Johnson. Adapted by Wikipedia user cmglee.

The Many Sources of the Elements in Our Universe

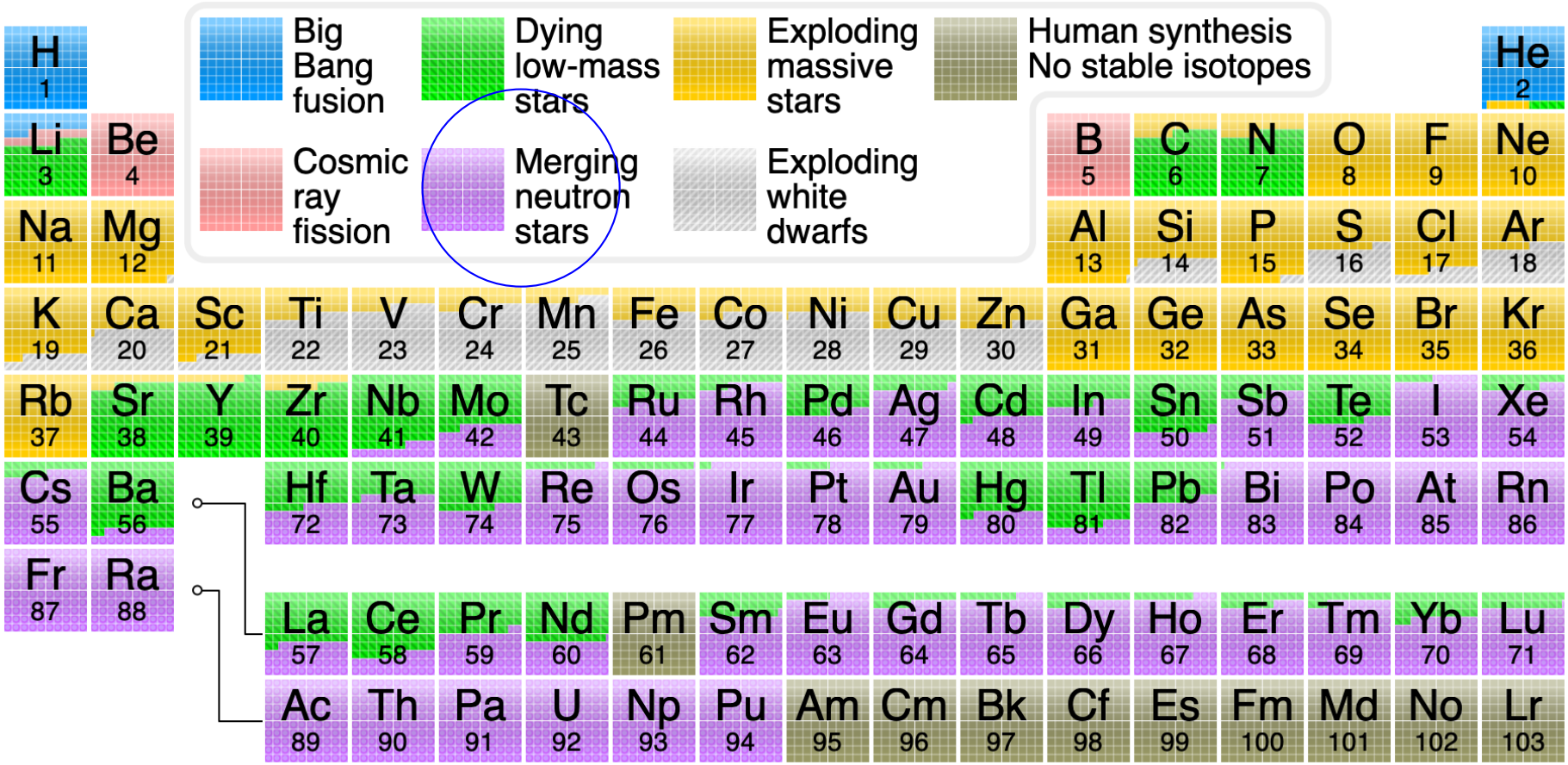


Image credit: Jennifer Johnson. Adapted by Wikipedia user cmglee.

The Many Sources of the Elements in Our Universe

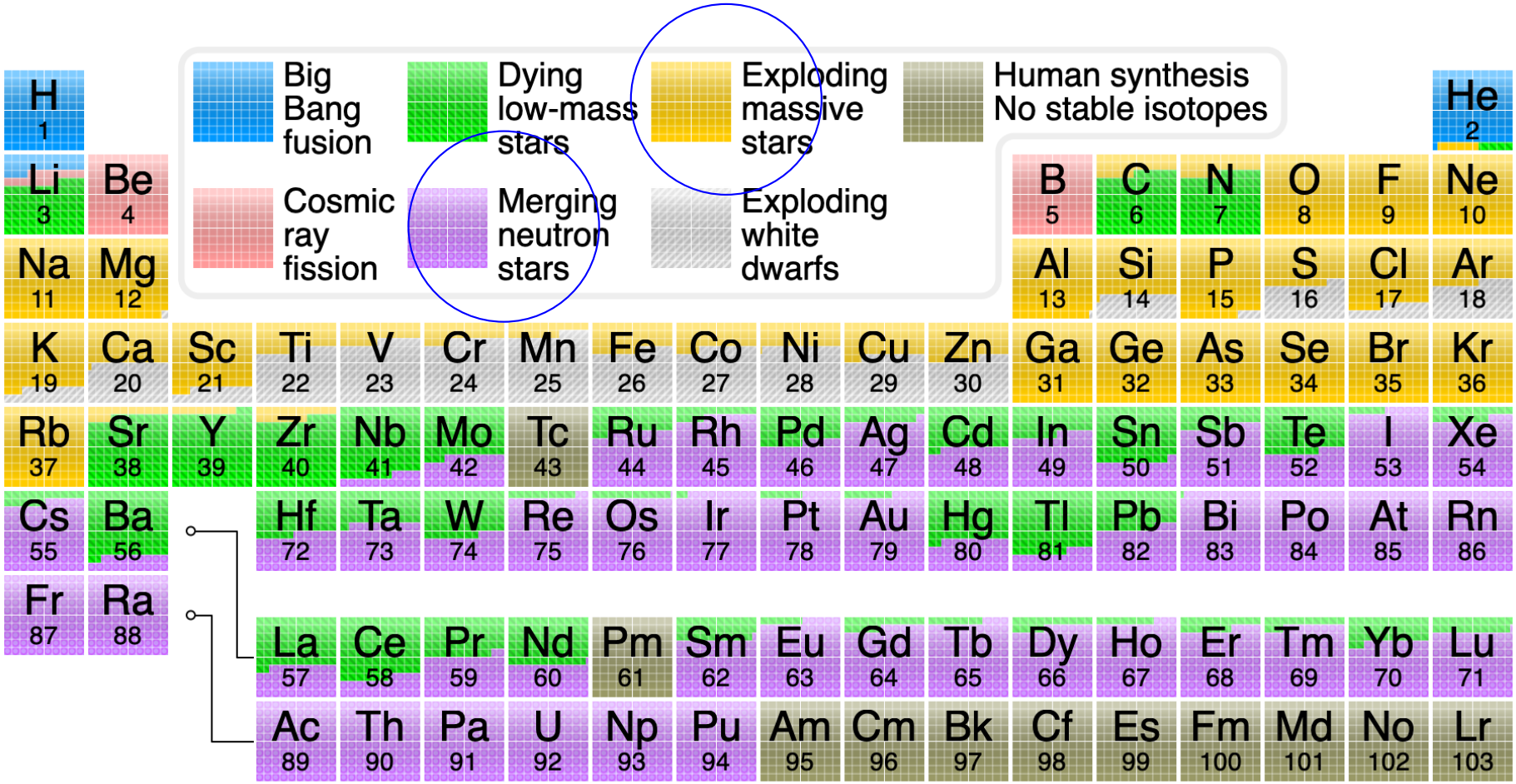
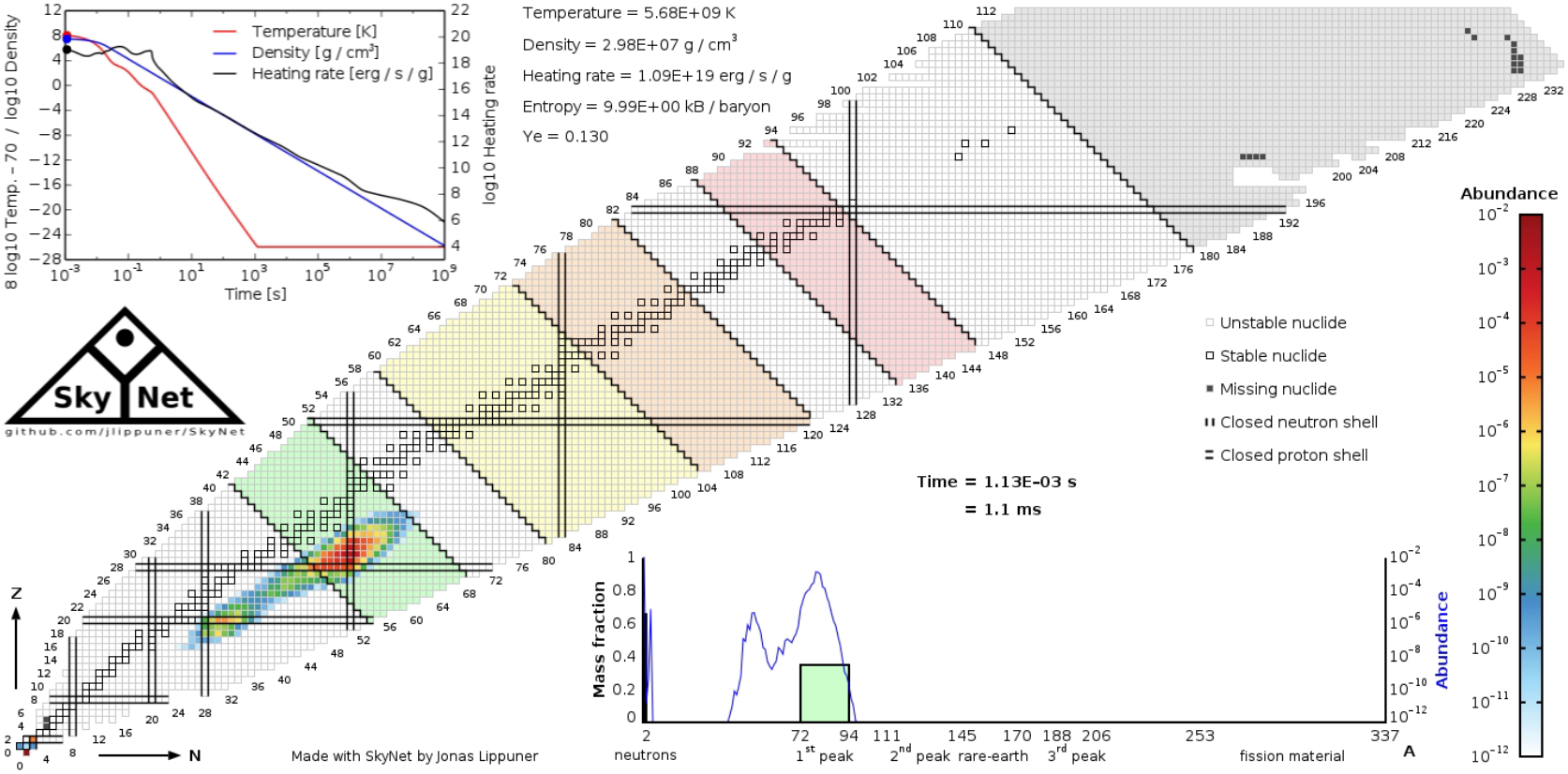


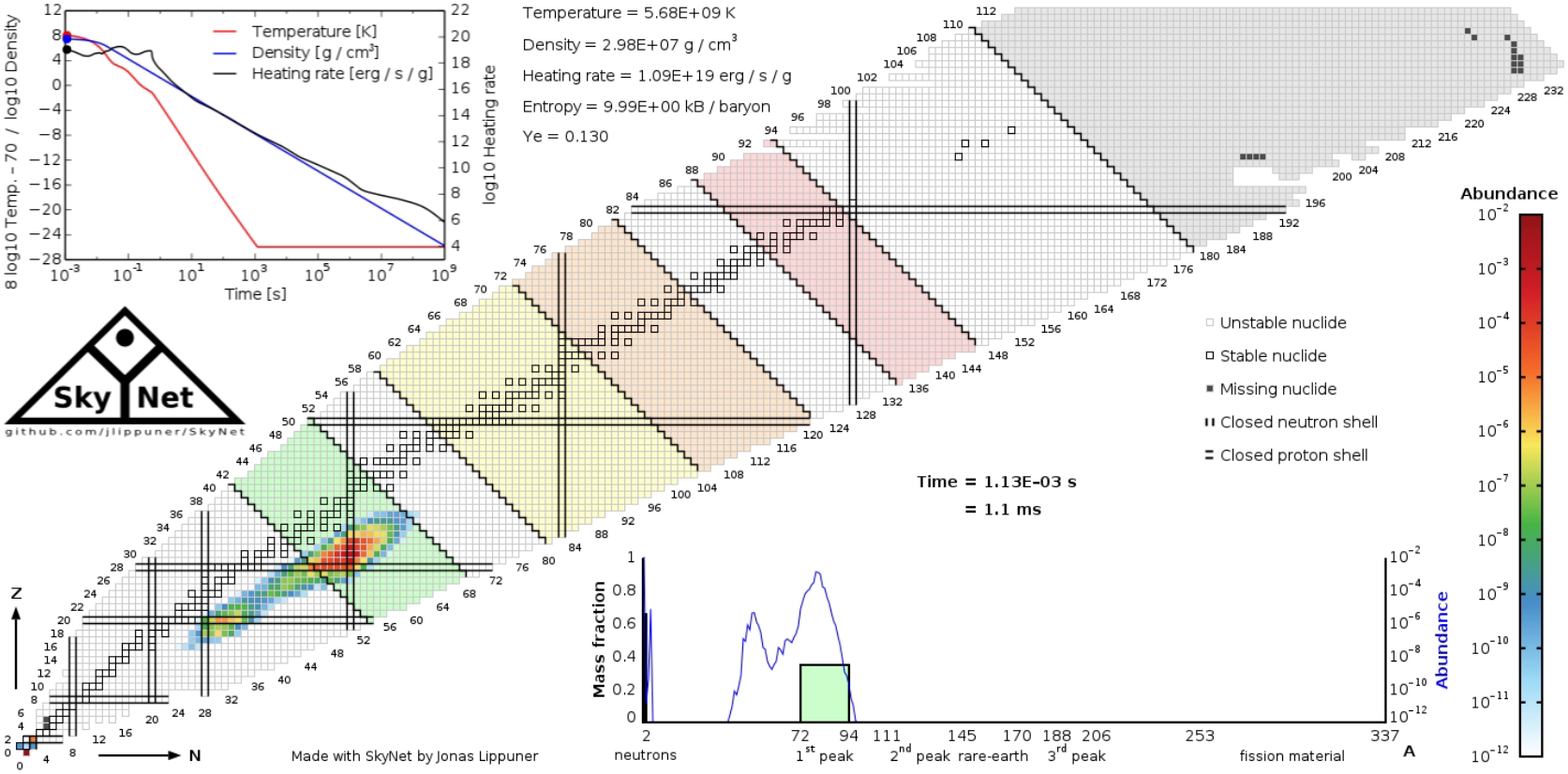
Image credit: Jennifer Johnson. Adapted by Wikipedia user cmglee.

The r-process



Courtesy of J. Lippuner

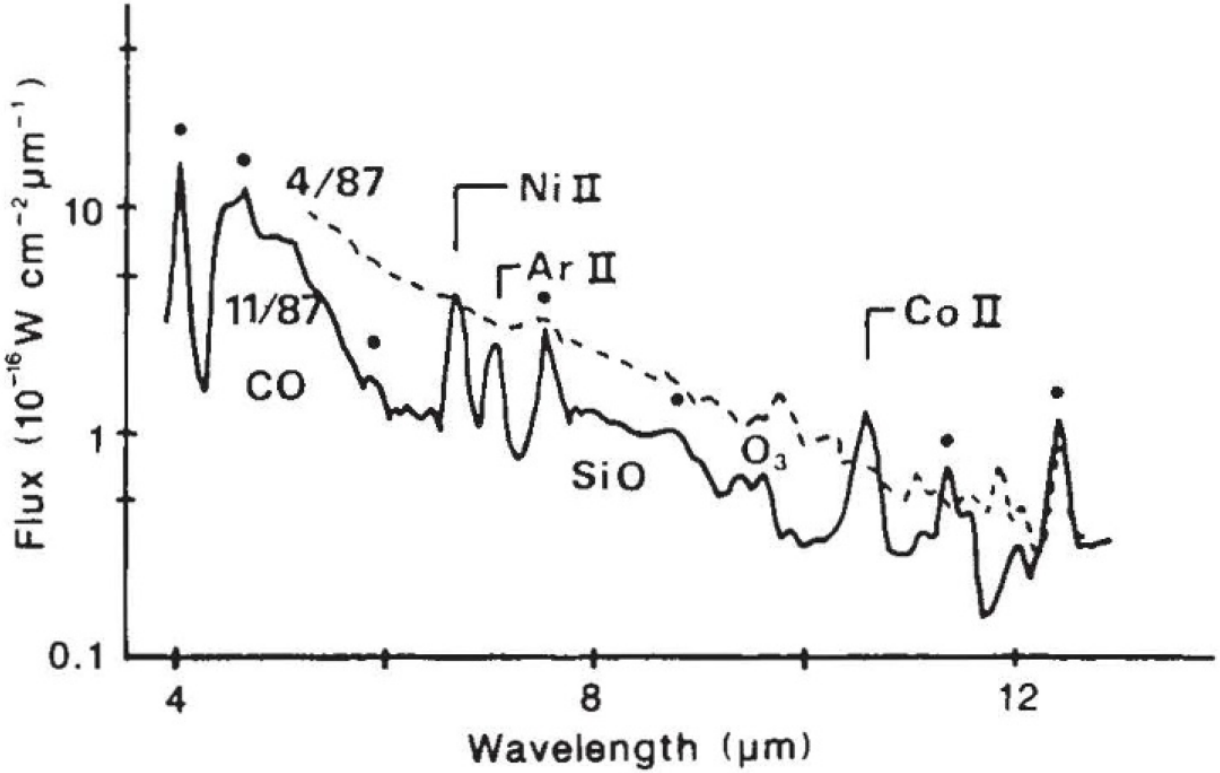
The r-process



Courtesy of J. Lippuner

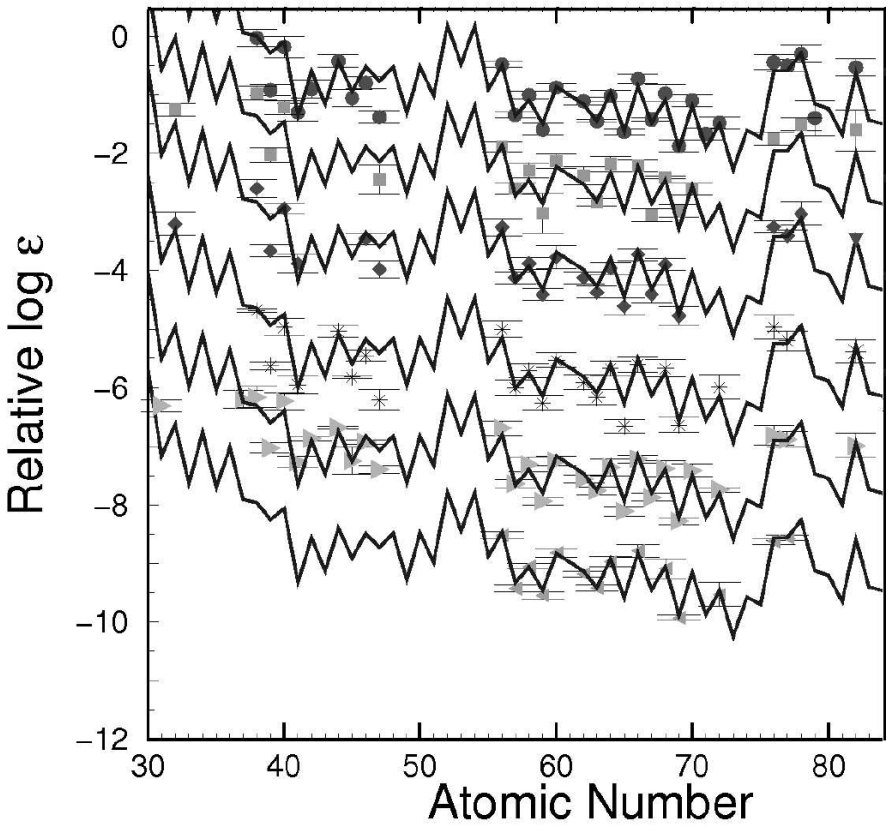
Nucleosynthesis in SN1987A

NASA/HUBBLE



Rank et al. *Nature* **331**, 505–506 (1988)

The Rare-Earth Peak and Metal-Poor Stars



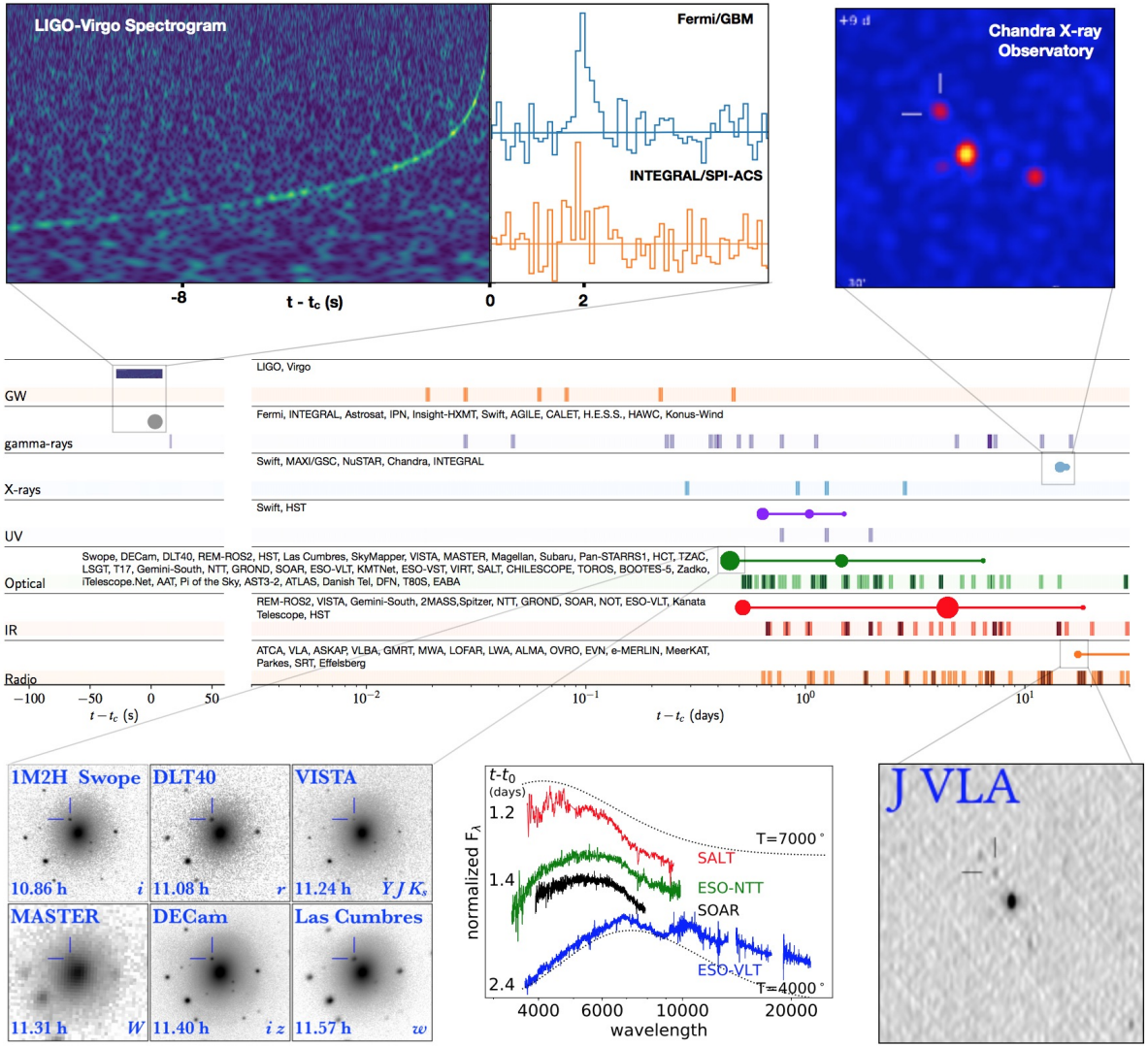
- Spectra from many stars available.
- Stars with not too many heavy elements show an interesting, repeatable pattern, which shows up in our sun too!
- Another source (beyond SN) needed!

J. J. Cowan

Striking Cosmic Gold With Neutron Star Mergers

Ashley Mackenzie for Quanta Magazine, March 23, 2017

Observations Galore!

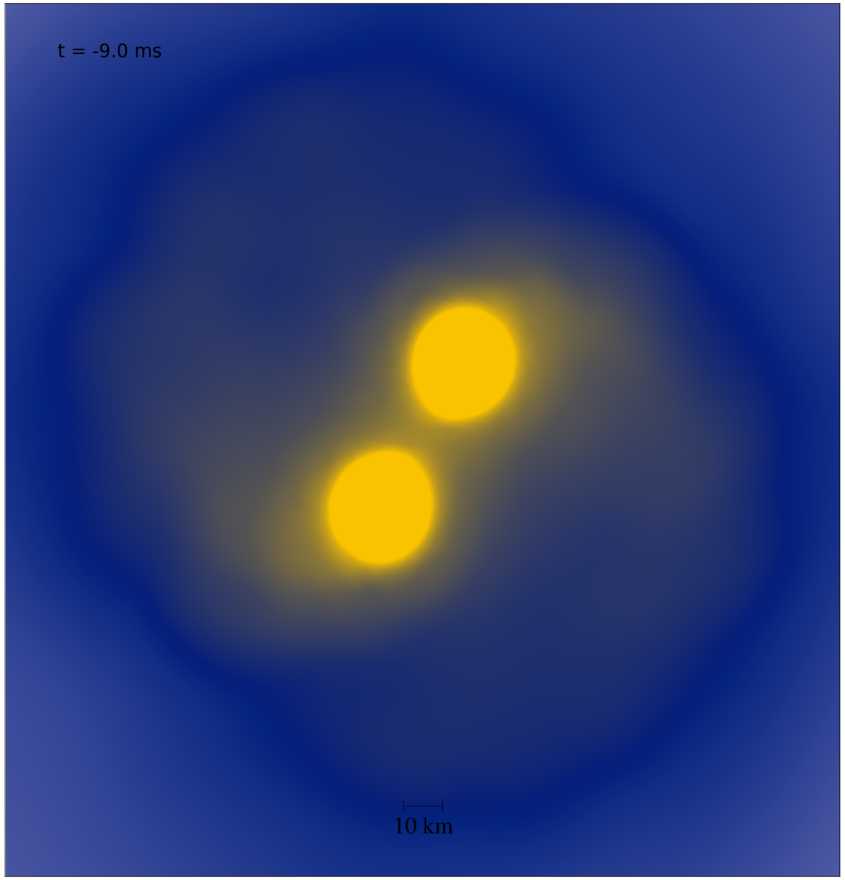


Abbot+, 2017

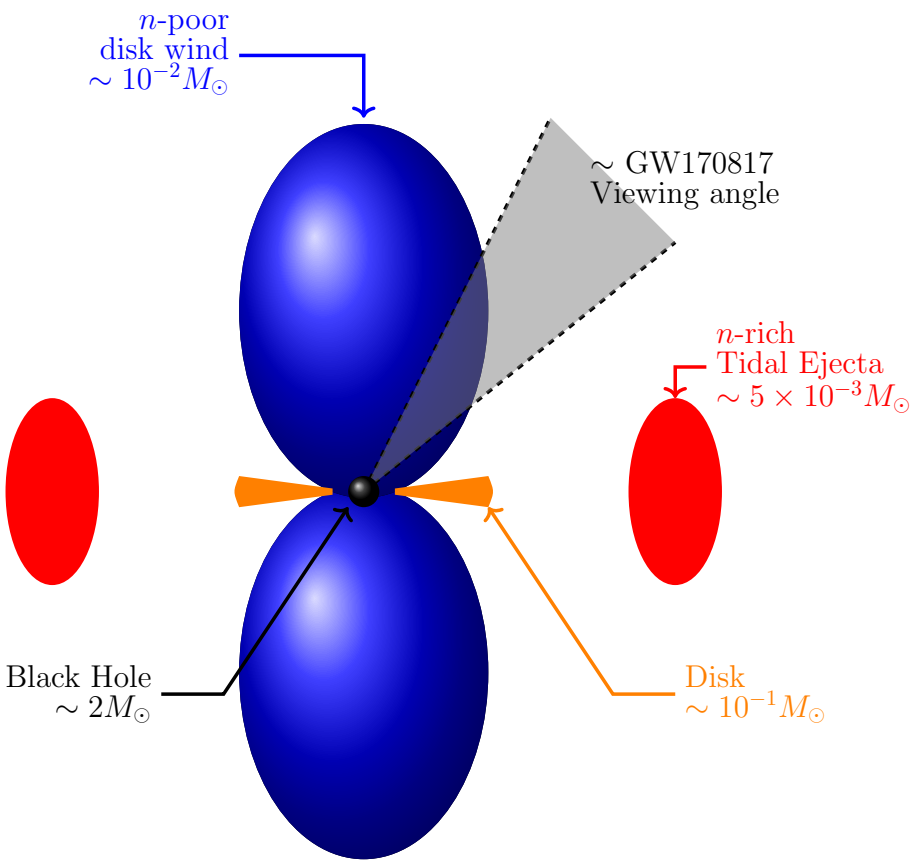
Neutron Stars

Wikimedia Commons

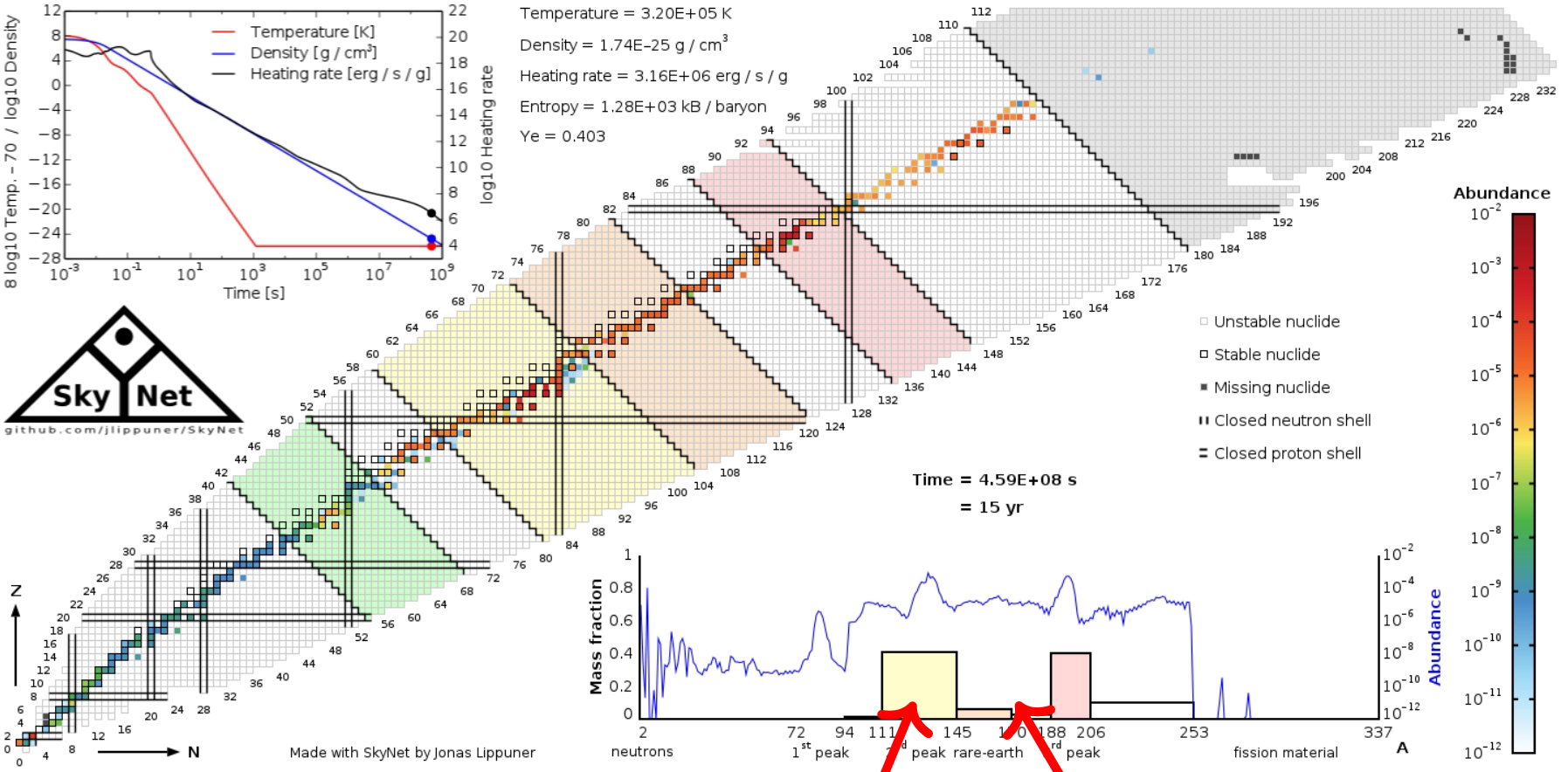
Neutron Star Mergers: A 2+ Component Model



Co-design summer school, 2016



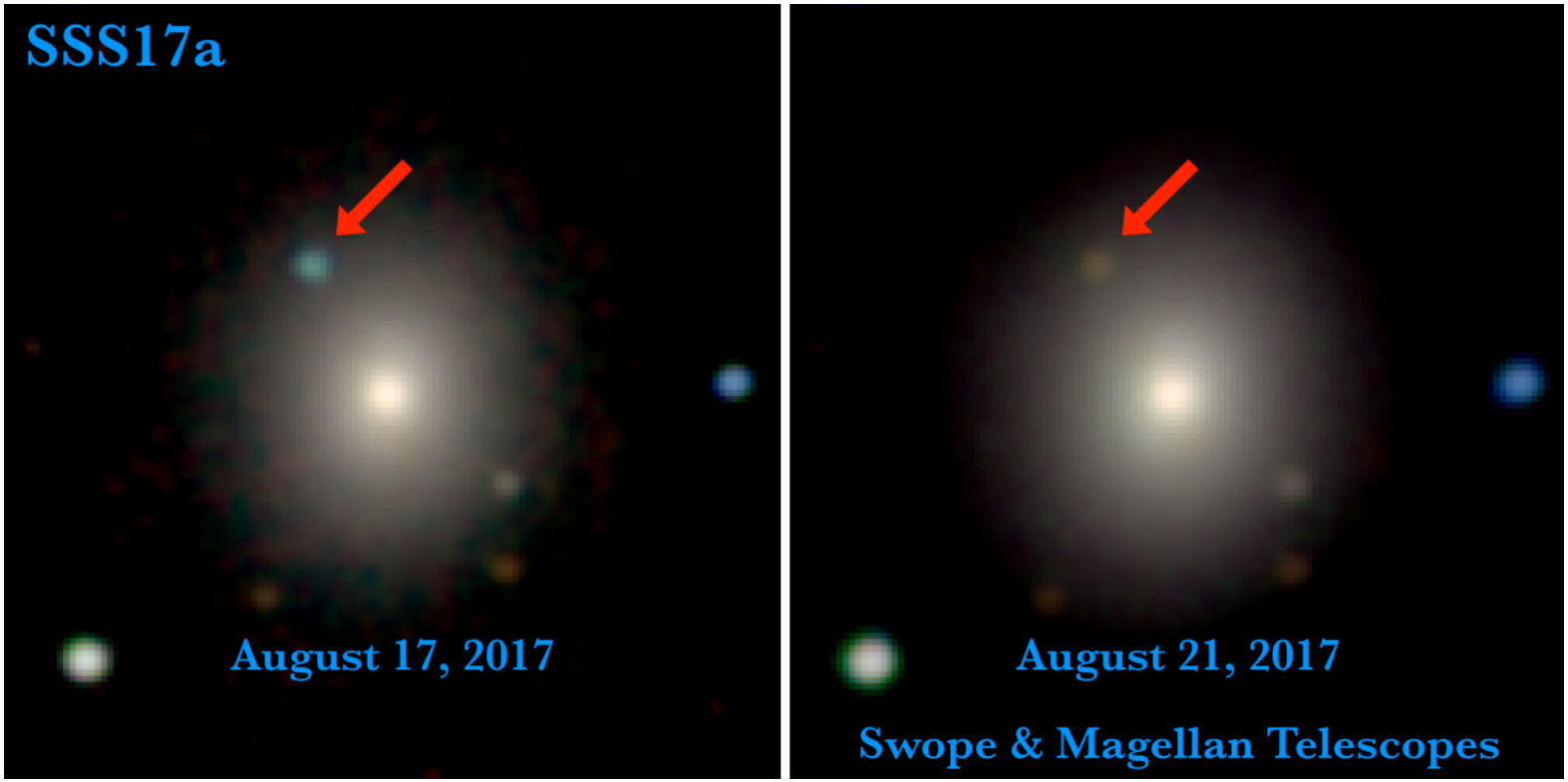
Opacity



Not opaque

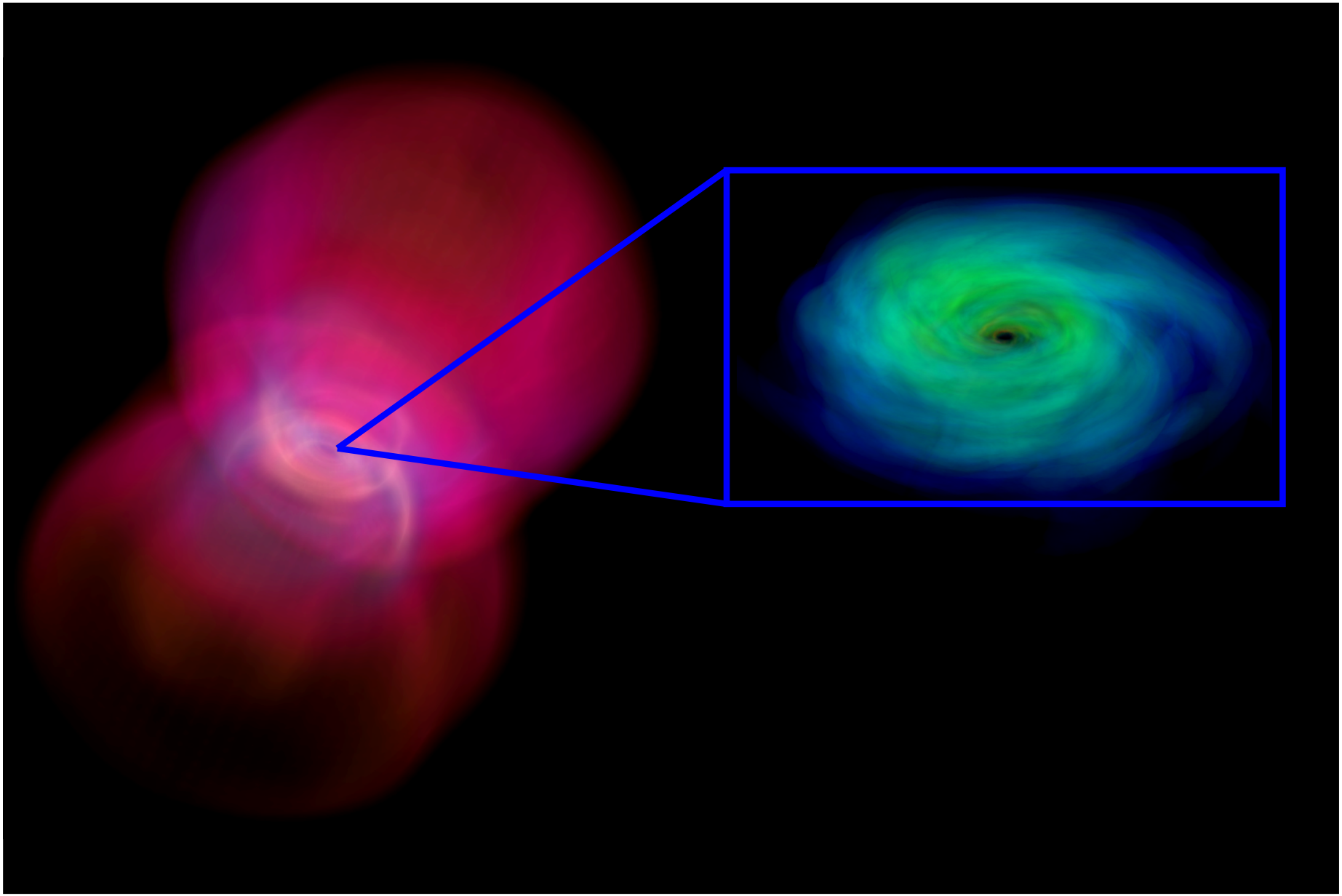
Opaque to visible light

The Kilonova

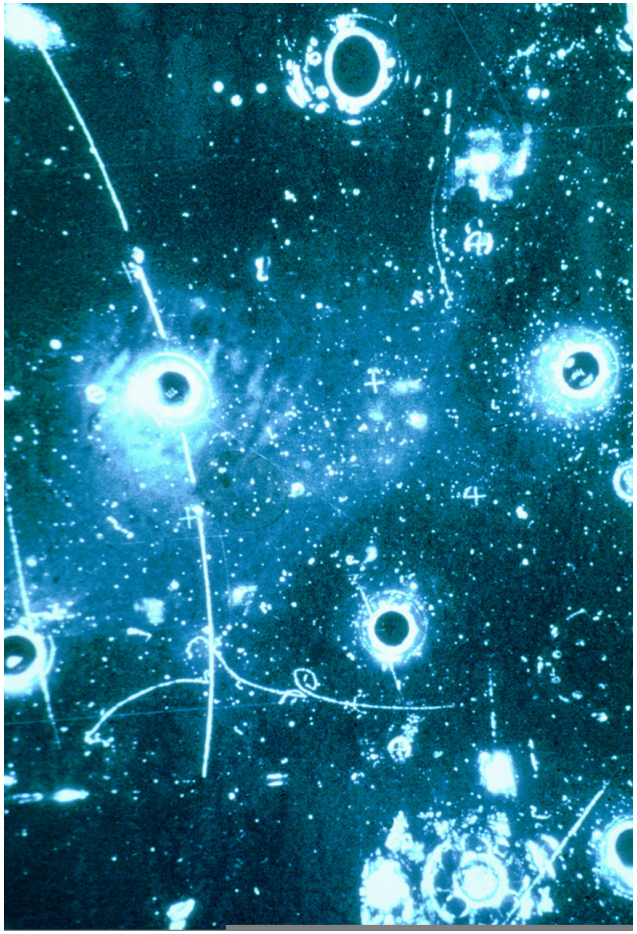


M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

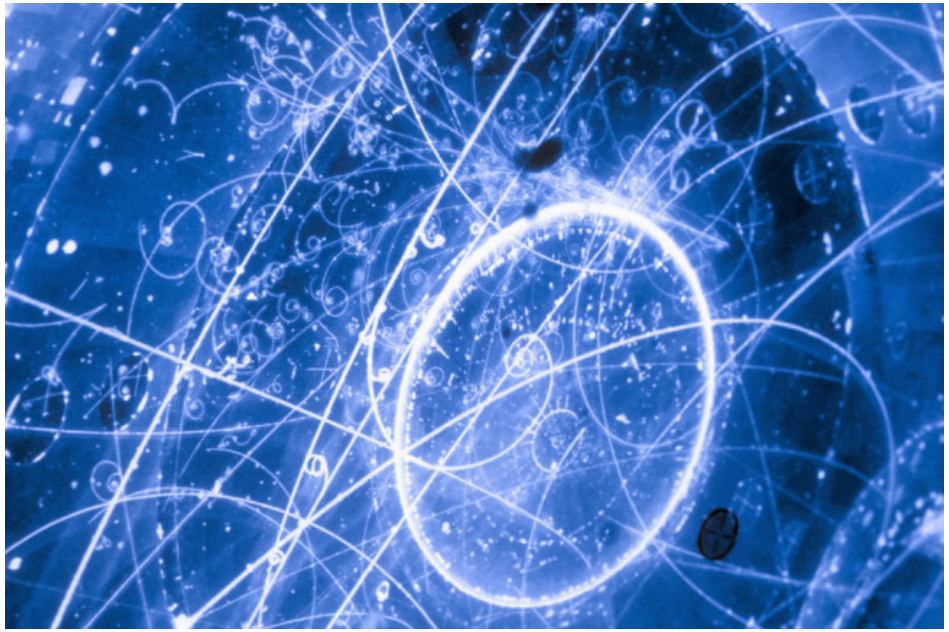
Lets Focus on the Disk



Enter the Neutrino

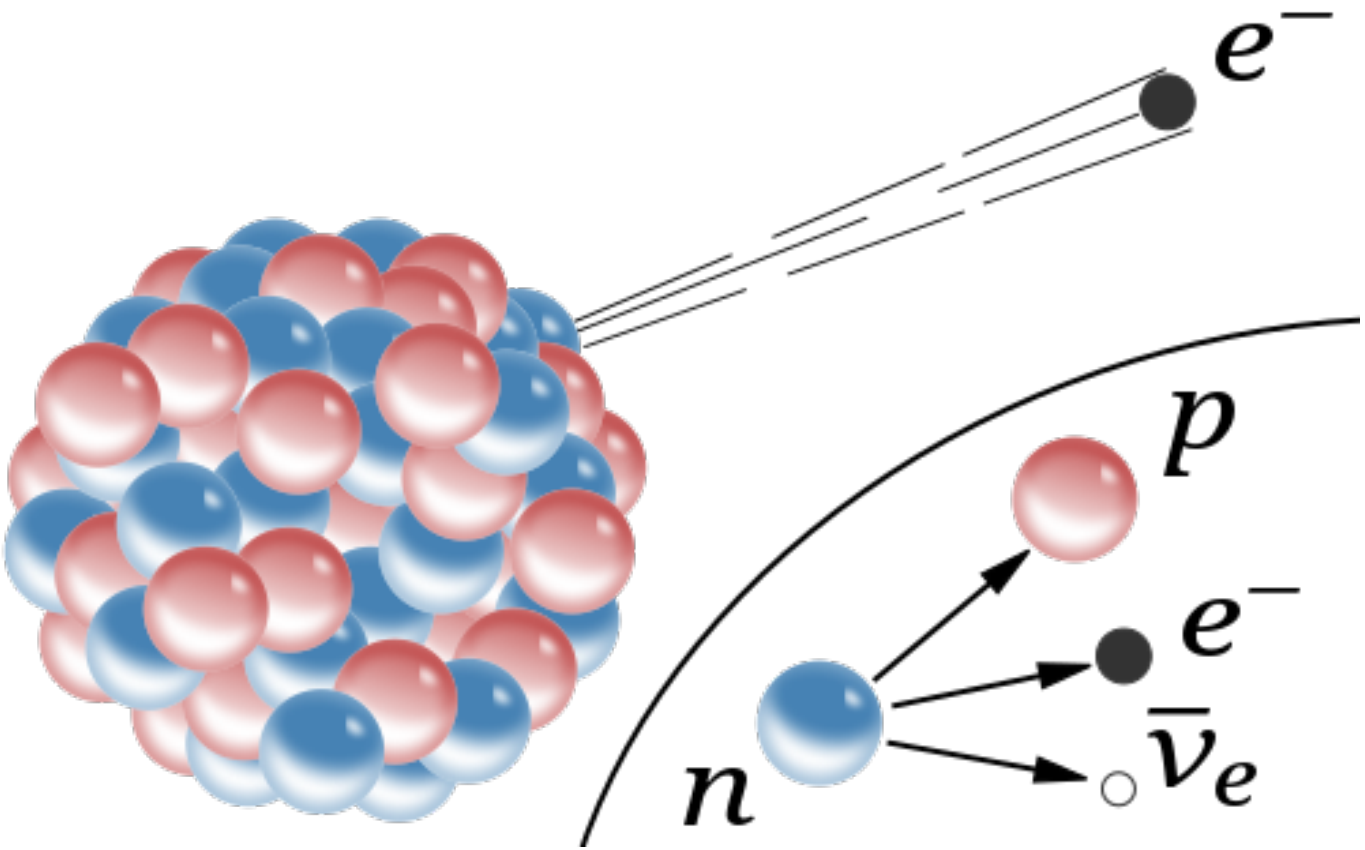


CERN/Gargamelle



Fermilab

Neutrinos are required for nuclear reactions



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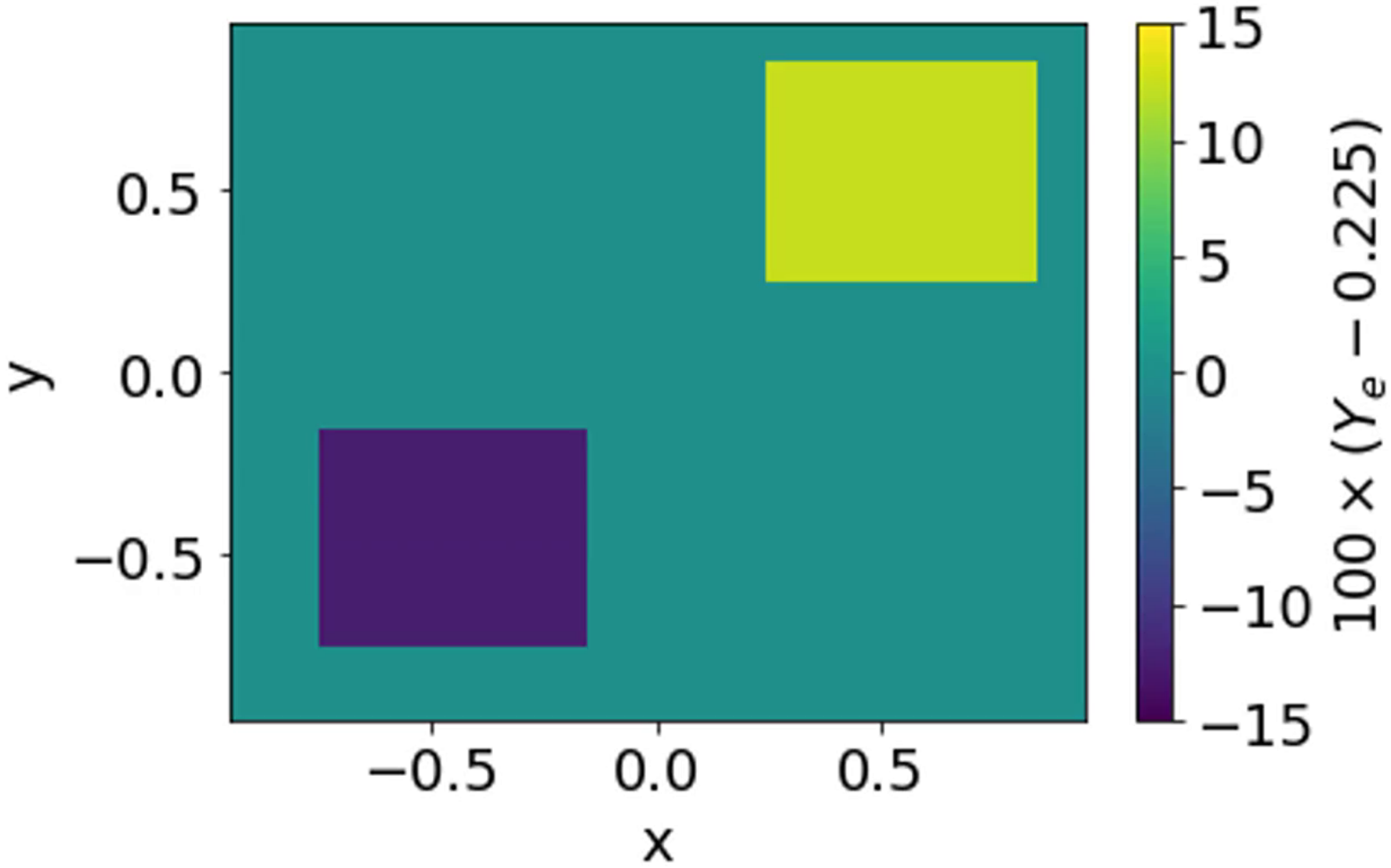
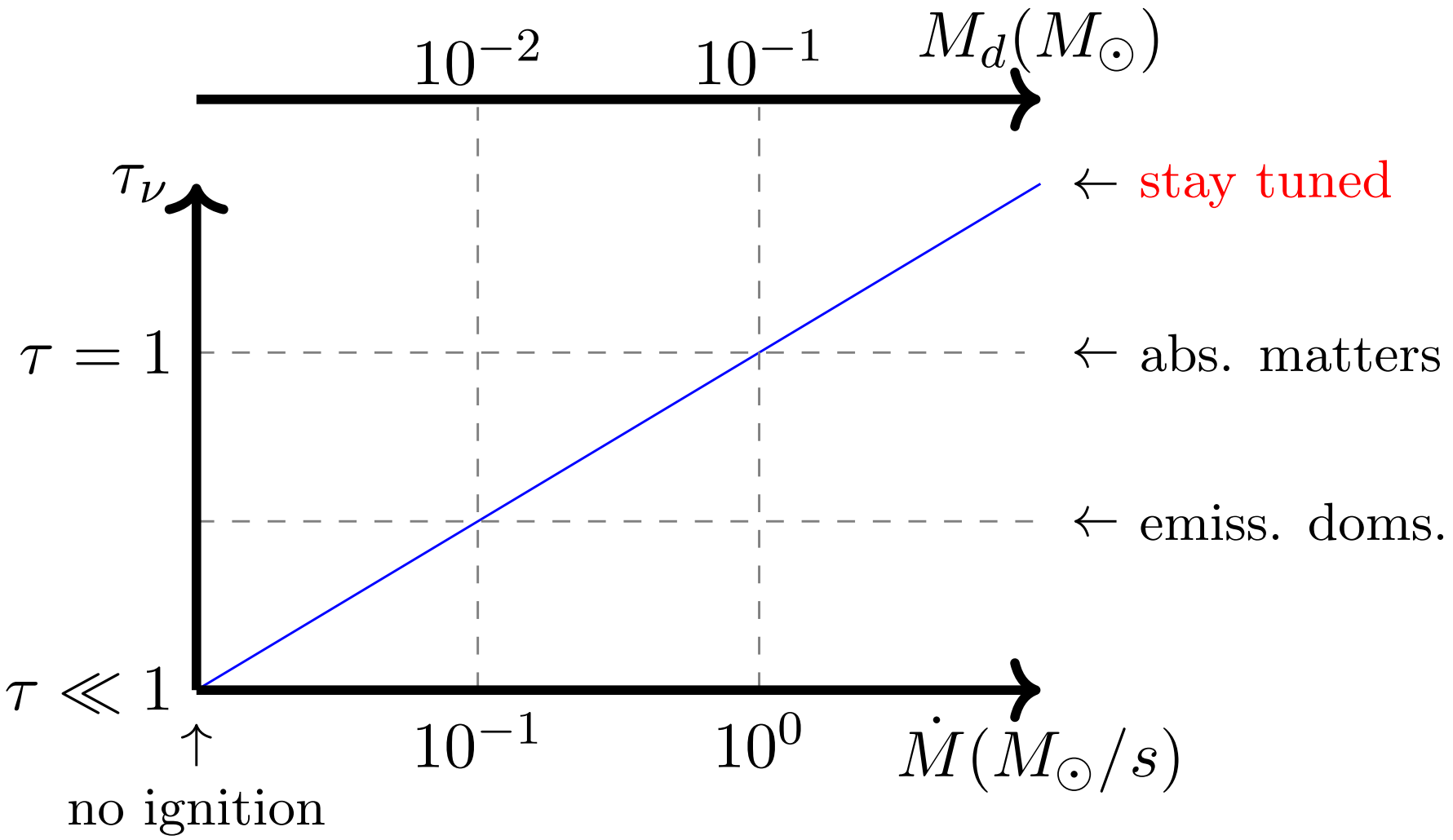
Neutrino Transport Matters!



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

How Much Does Transport Matter?



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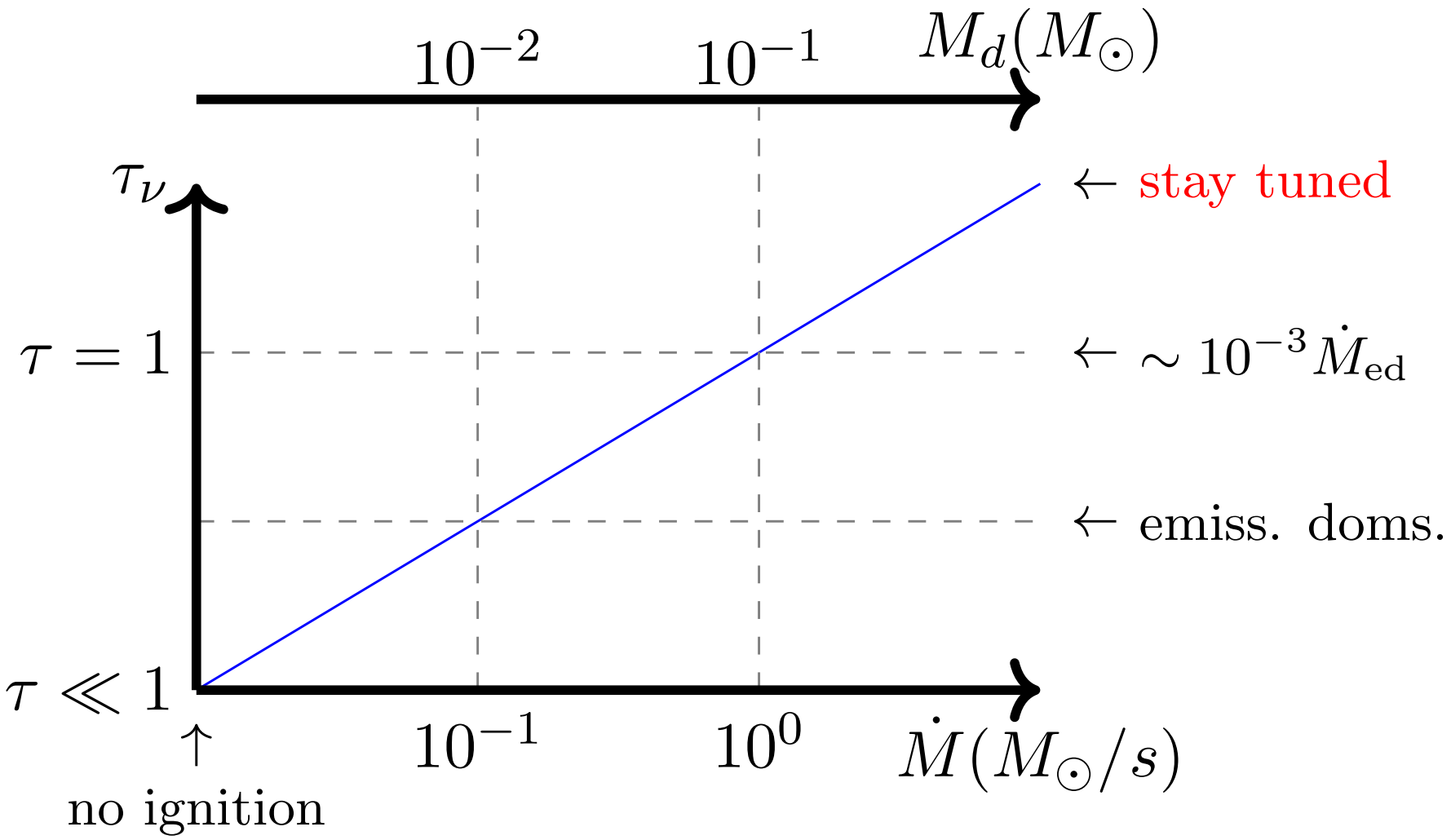
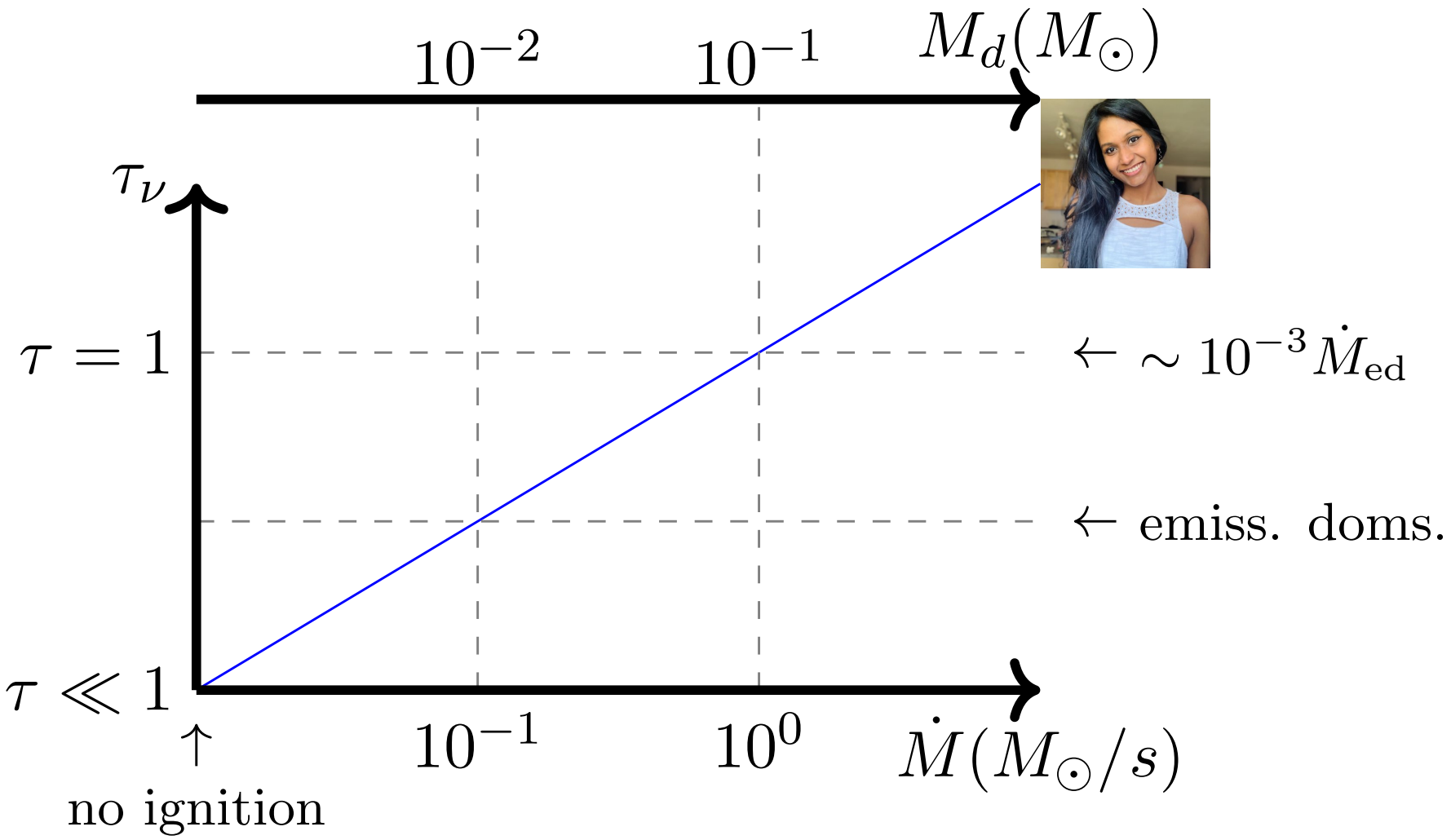


How Much Does Transport Matter?



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

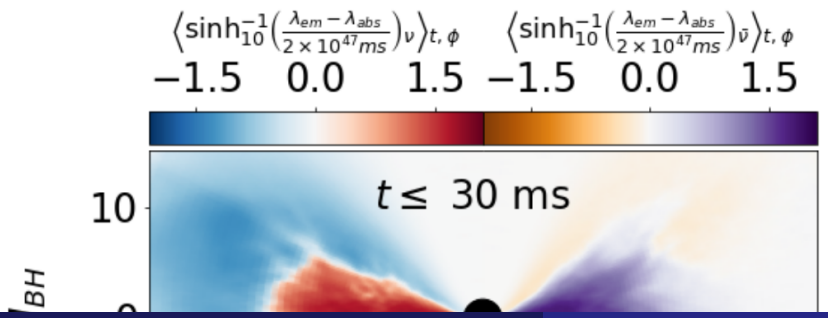
$$\frac{D}{d\lambda}\left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3}\right) = \left(\frac{h^2 \eta_{\epsilon,f}}{\epsilon^2}\right) - \left(\frac{\epsilon \chi_{\epsilon,f}}{h}\right)\left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3}\right),$$

Presenting νbhlight! 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



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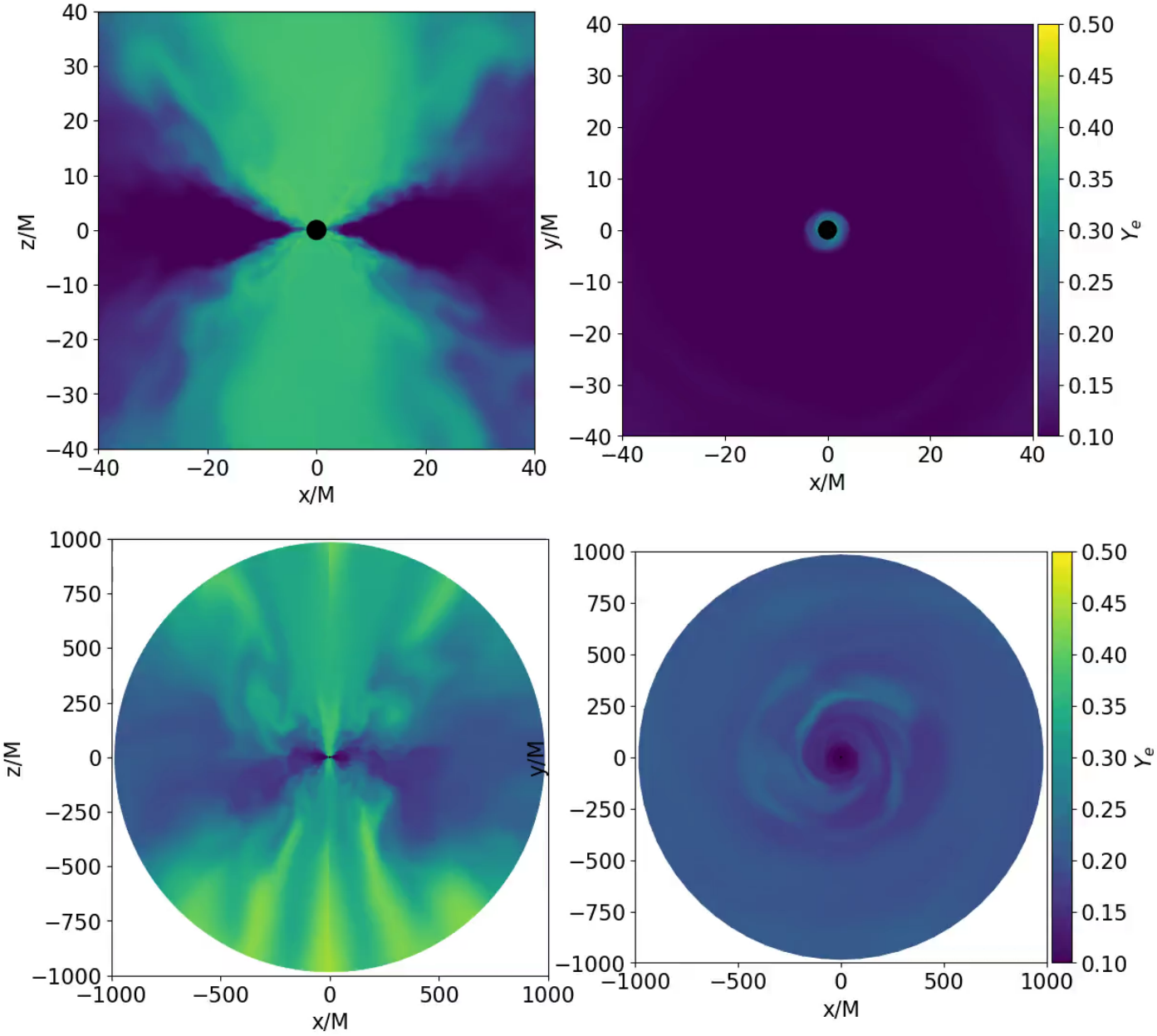
Contributors 4

- **jonahm-LANL** Jonah Miller
- **Yurlungur** Jonah Miller
- **soumide1102** Soumi De
- **kinchb** Brooks Kinch

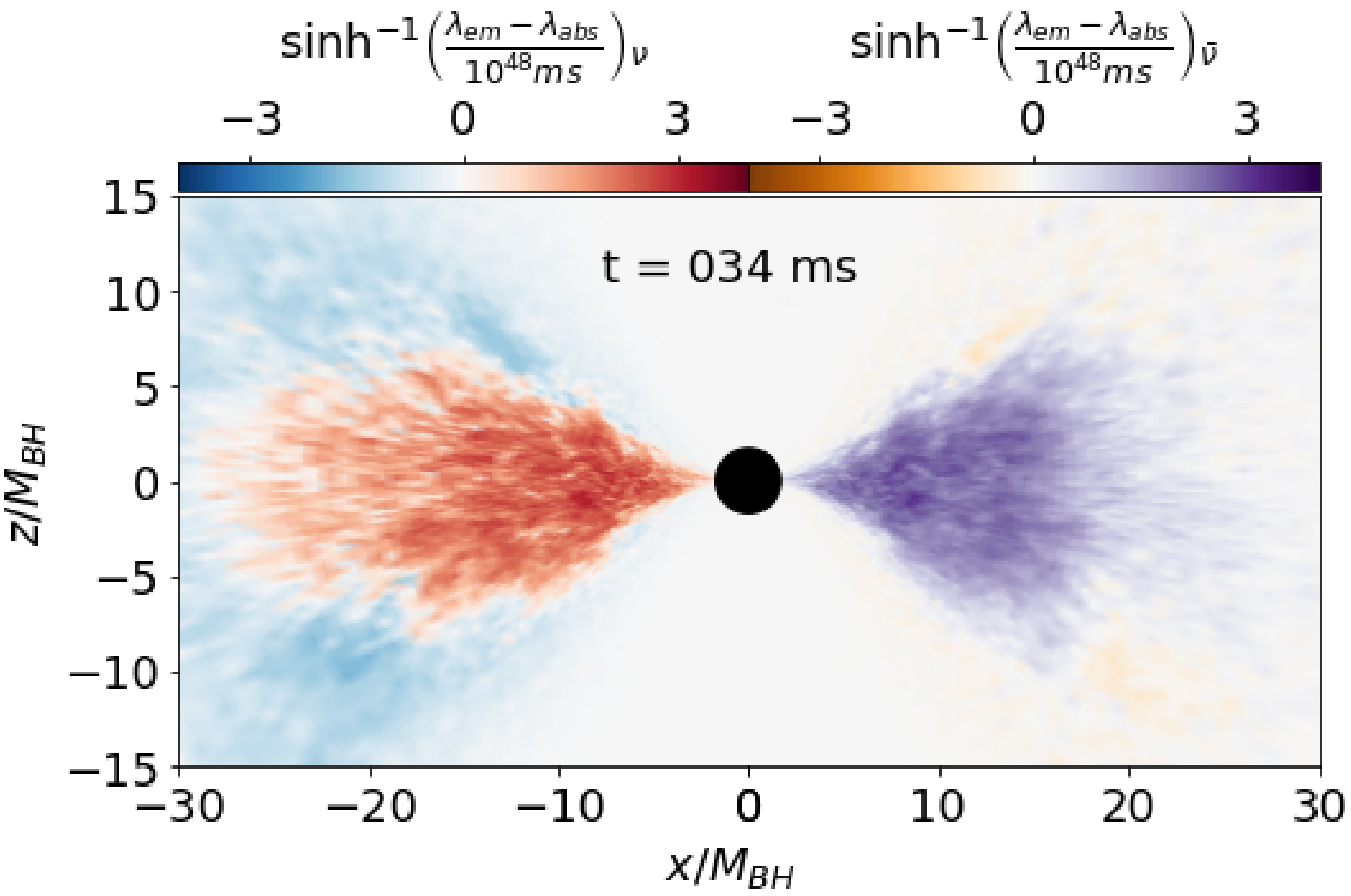
Languages

- C 51.8%
- Python 43.3%
- Fortran 3.8%
- Other 1.1%

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

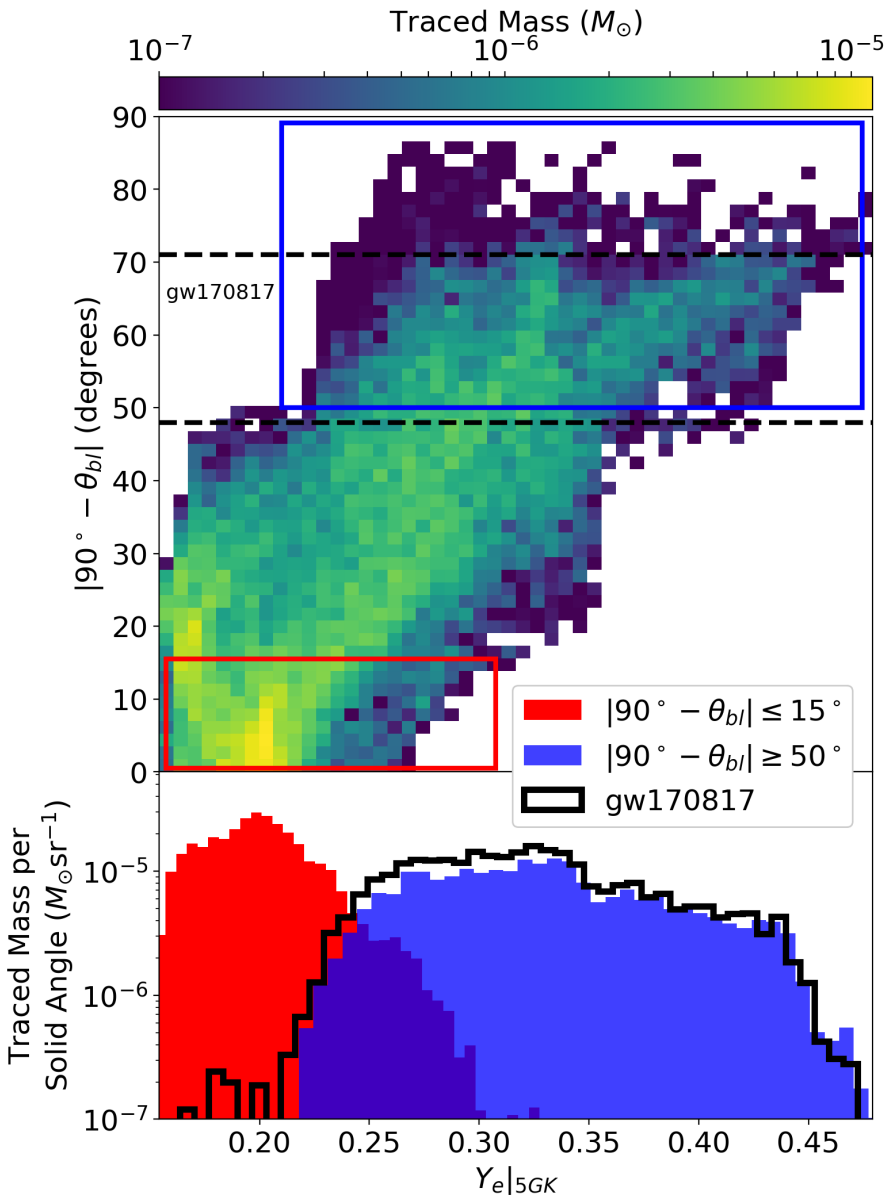


Neutrino Transport (Miller et al., 2019)

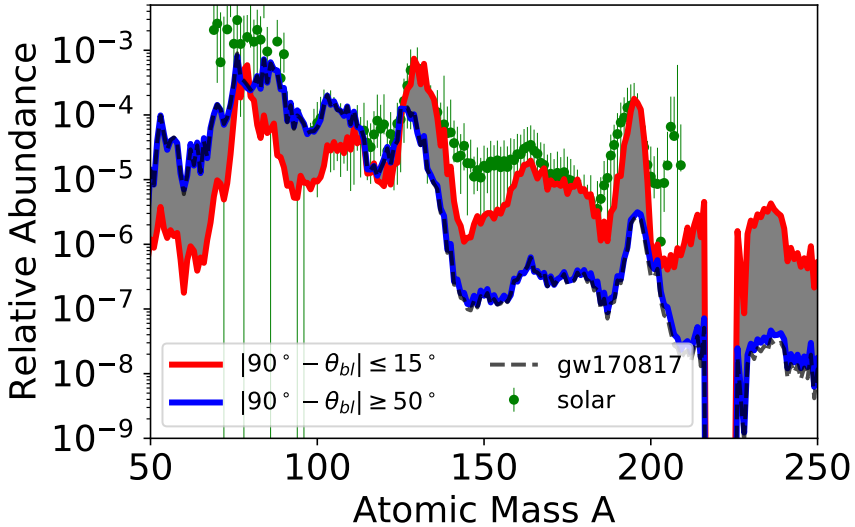


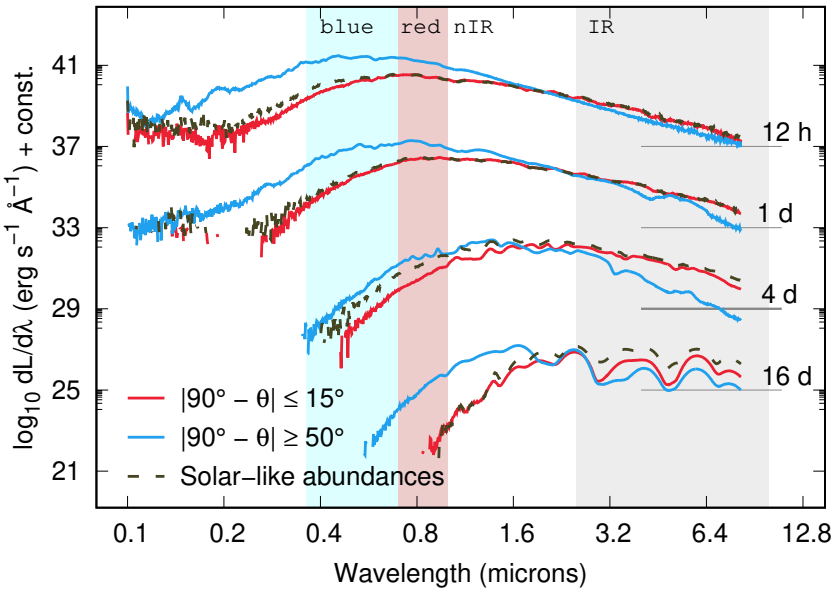
JMM et al. PRD **100** 023008 (2019)

Outflows, Nucleosynthesis, Observables

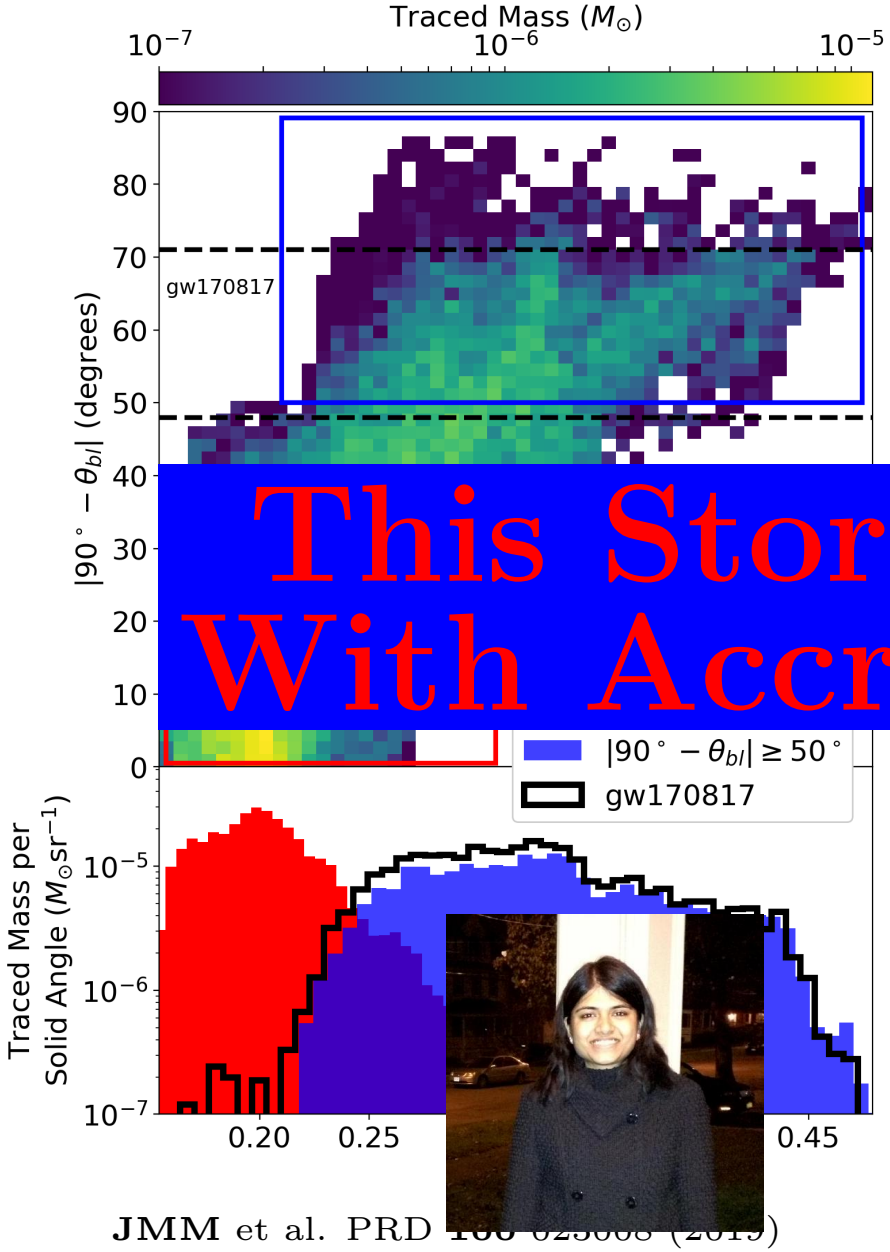


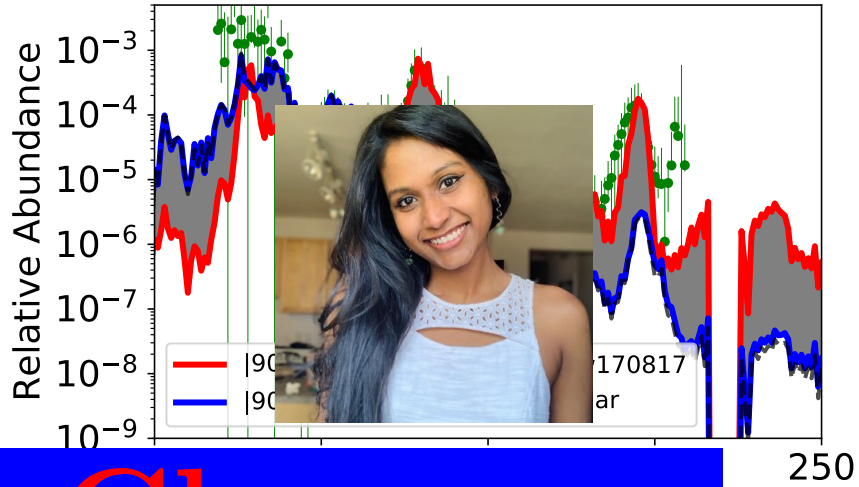
JMM et al. PRD **100** 023008 (2019)



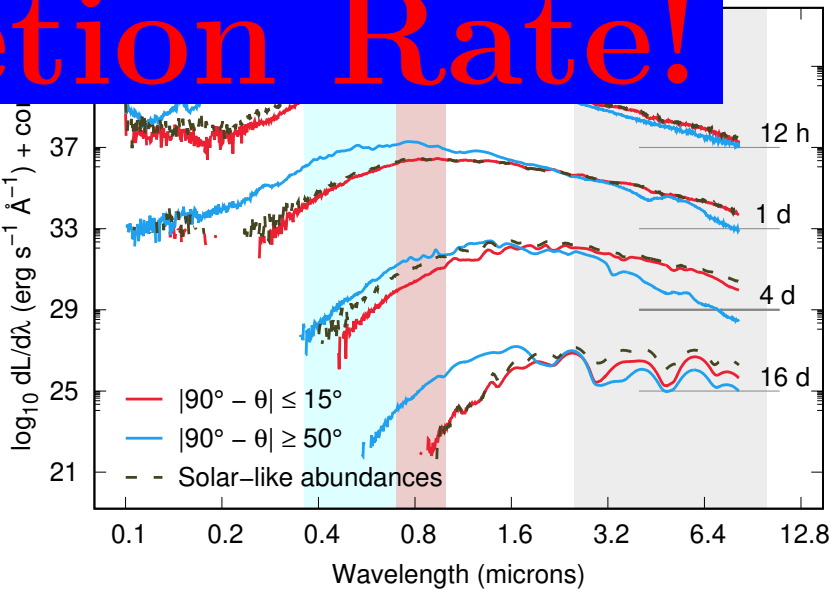


Outflows, Nucleosynthesis, Observables



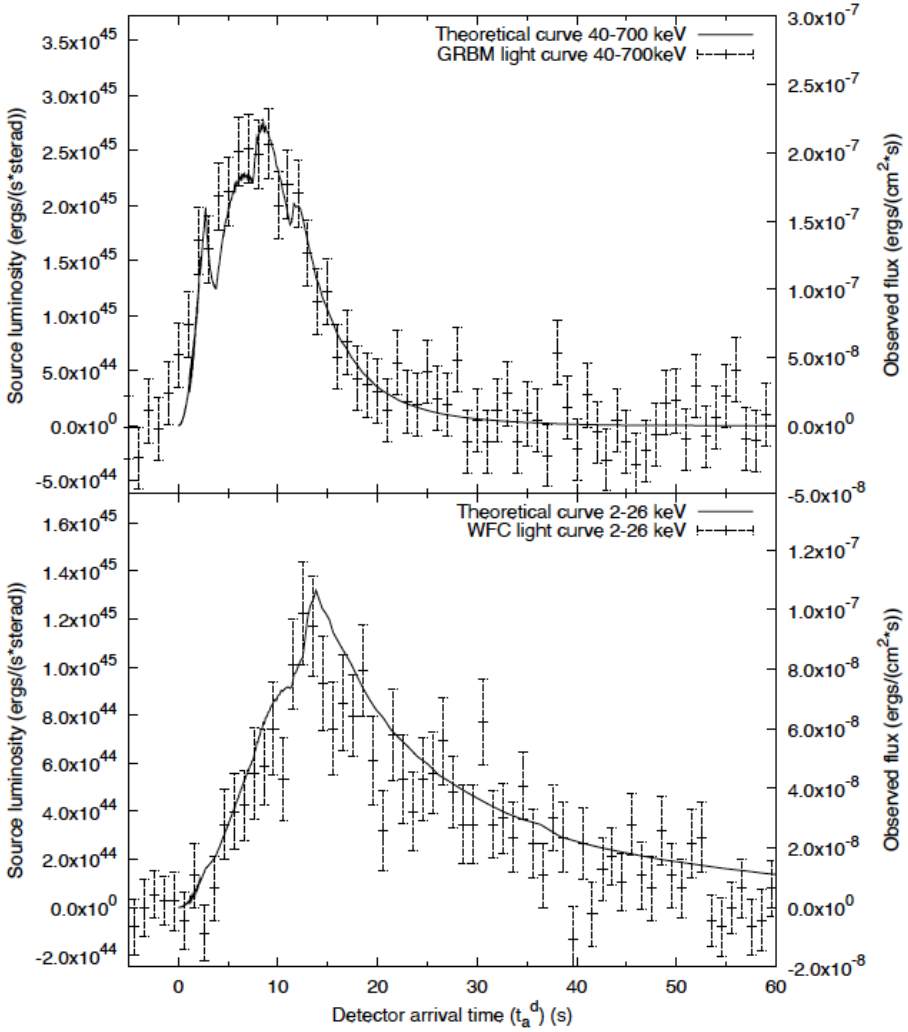


This Story Changes With Accretion Rate!



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

Accretion disks in supernovae?

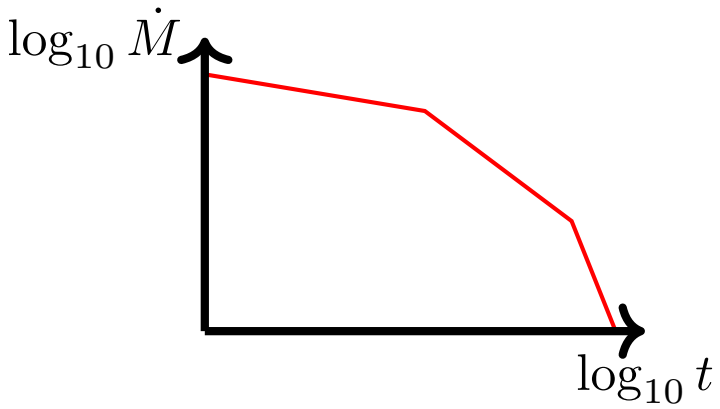


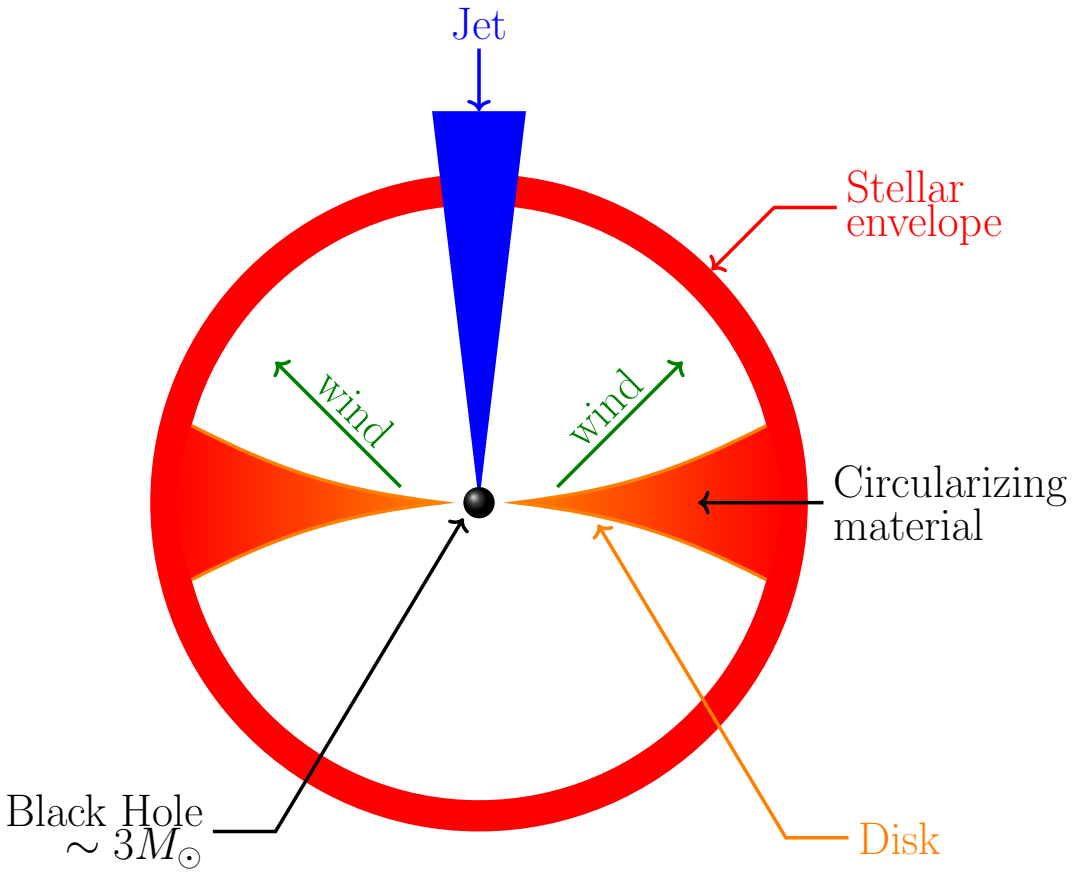
European Southern Observatory

Ruffini et al. BepoSAX telescope.
arXiv:0705.2456

Collapsars: Failed Supernovae

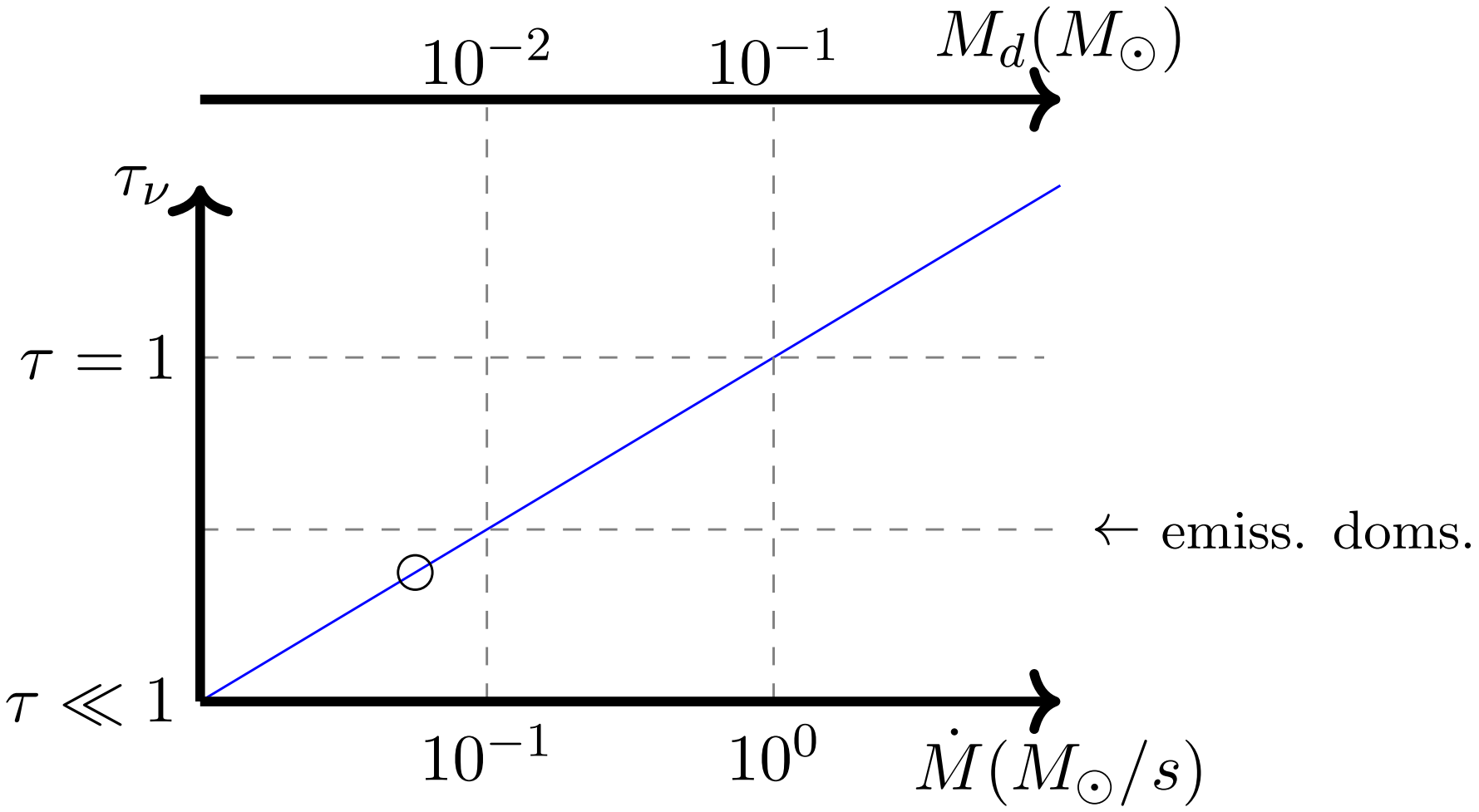
- Accretion times $t \sim 10s$
- $\dot{M}$ between
  - $10^{-4} M_\odot/s$
  - $10^{-1} M_\odot/s$
- $\rho \sim 10^{10}$ g/cm^3



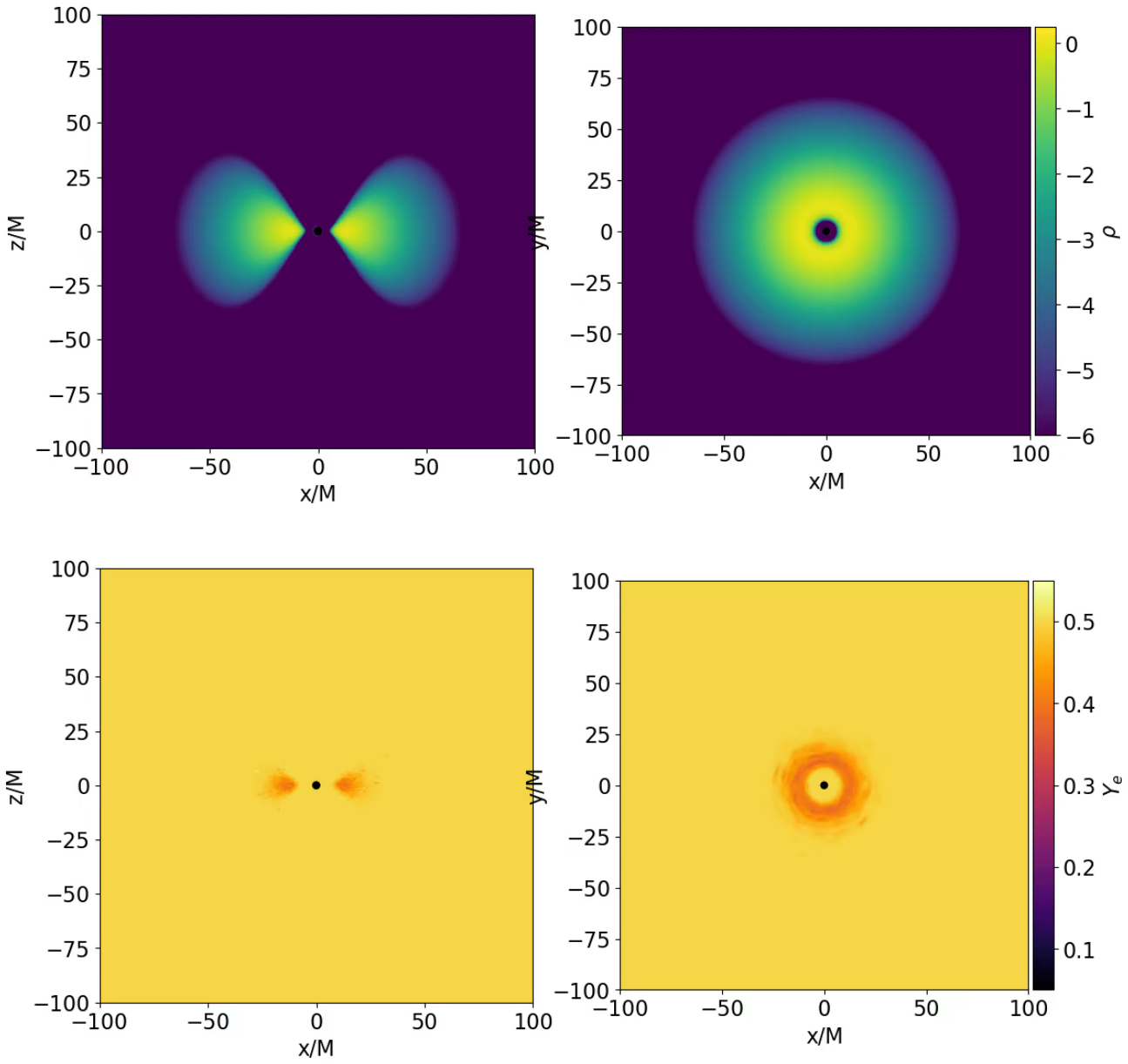


Siegel, Barnes, Metzger. Nature **241** (2019)

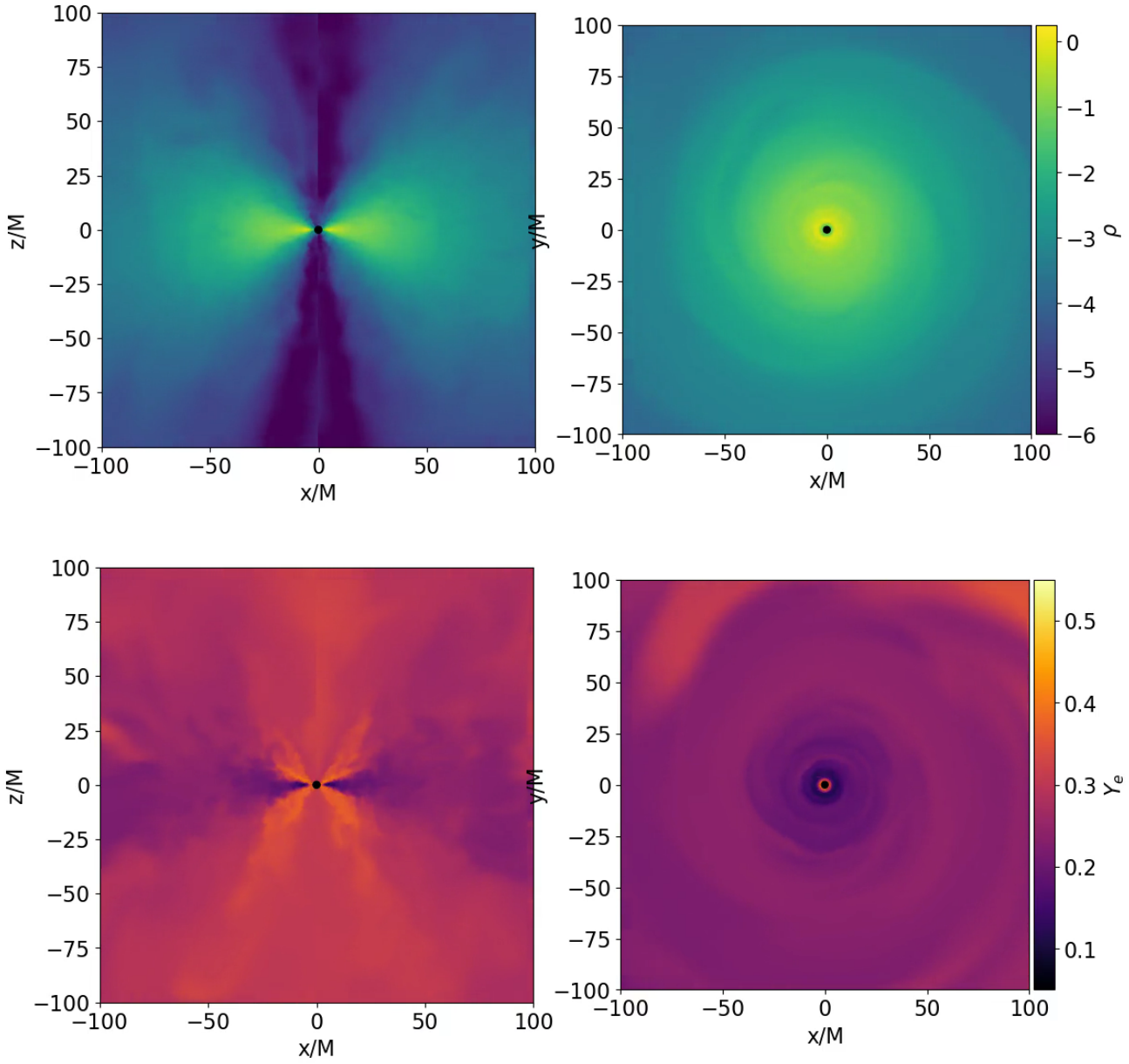
Neutrinos matter differently for collapsars!



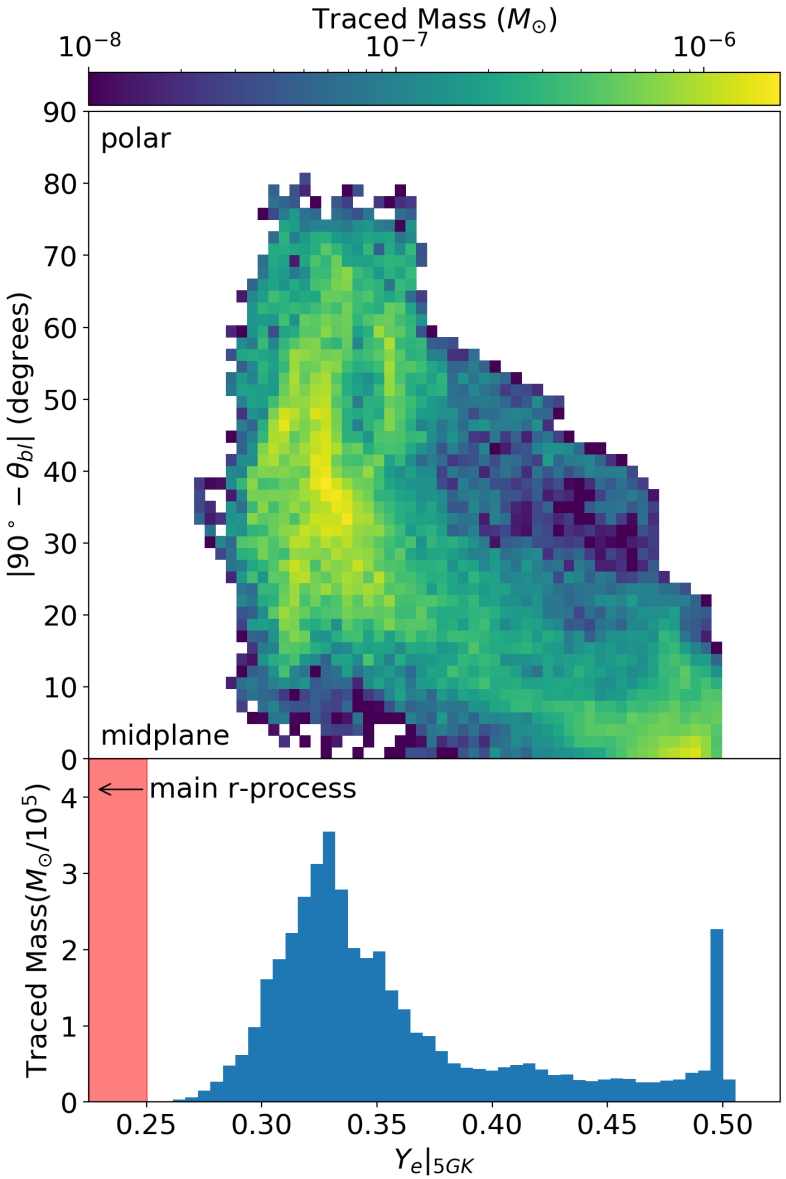
Building a Collapsar Disk

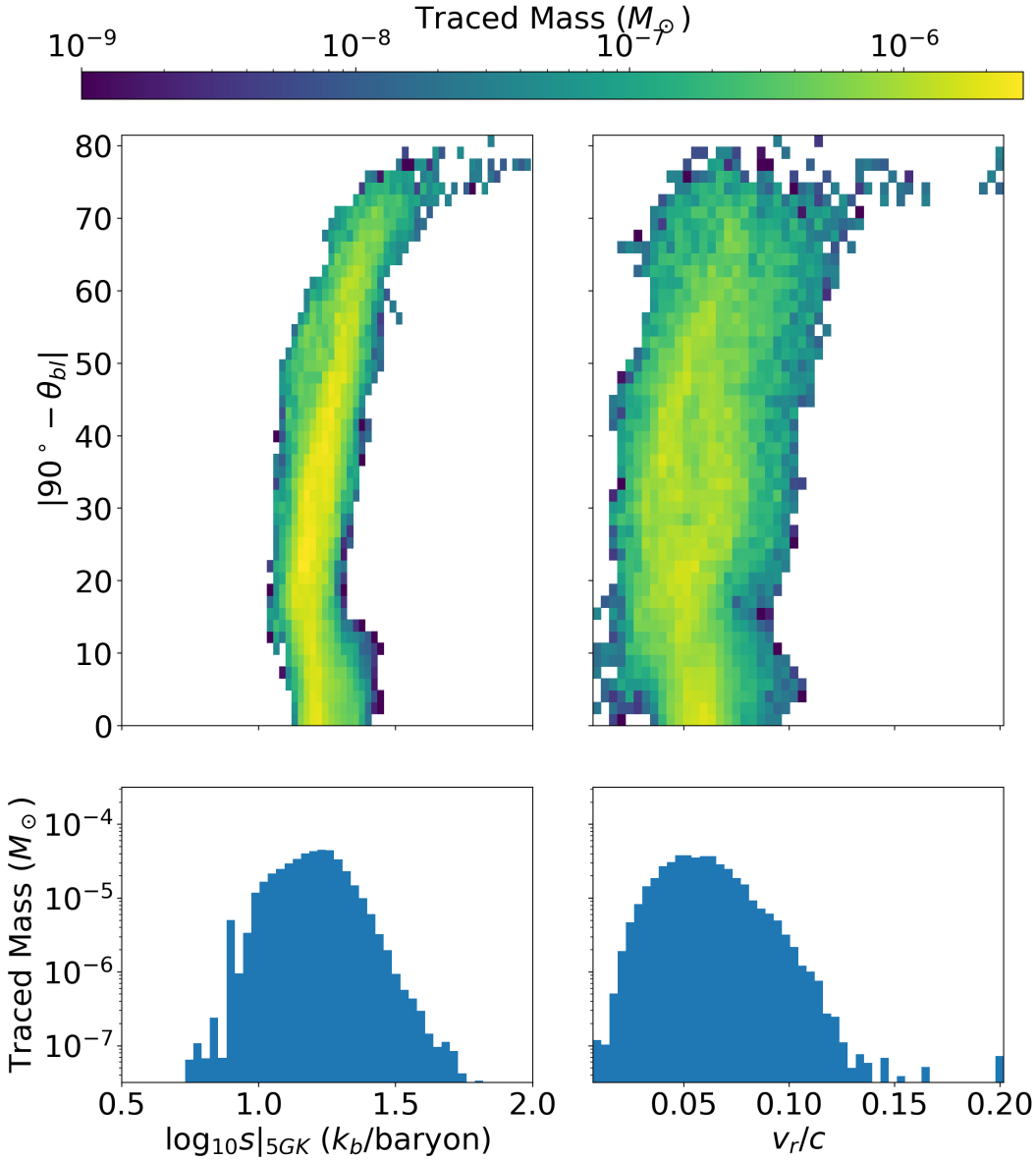


Building a Collapsar Disk

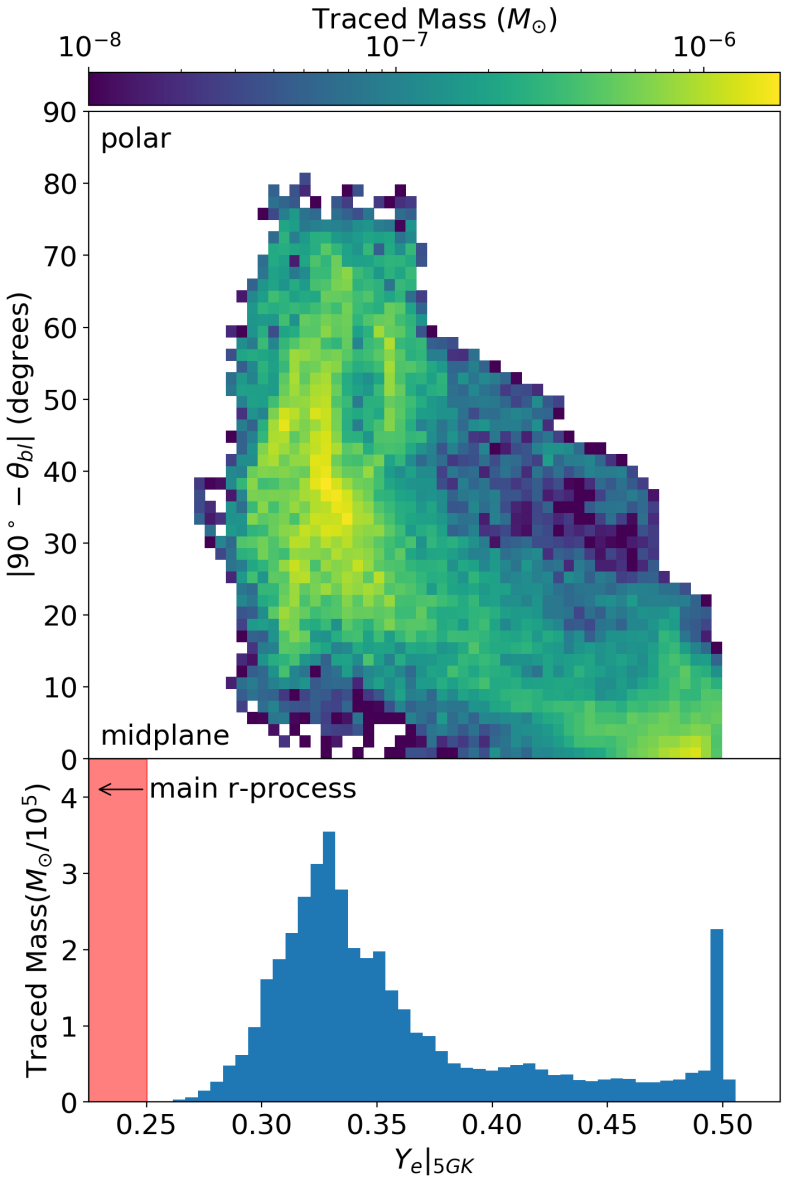


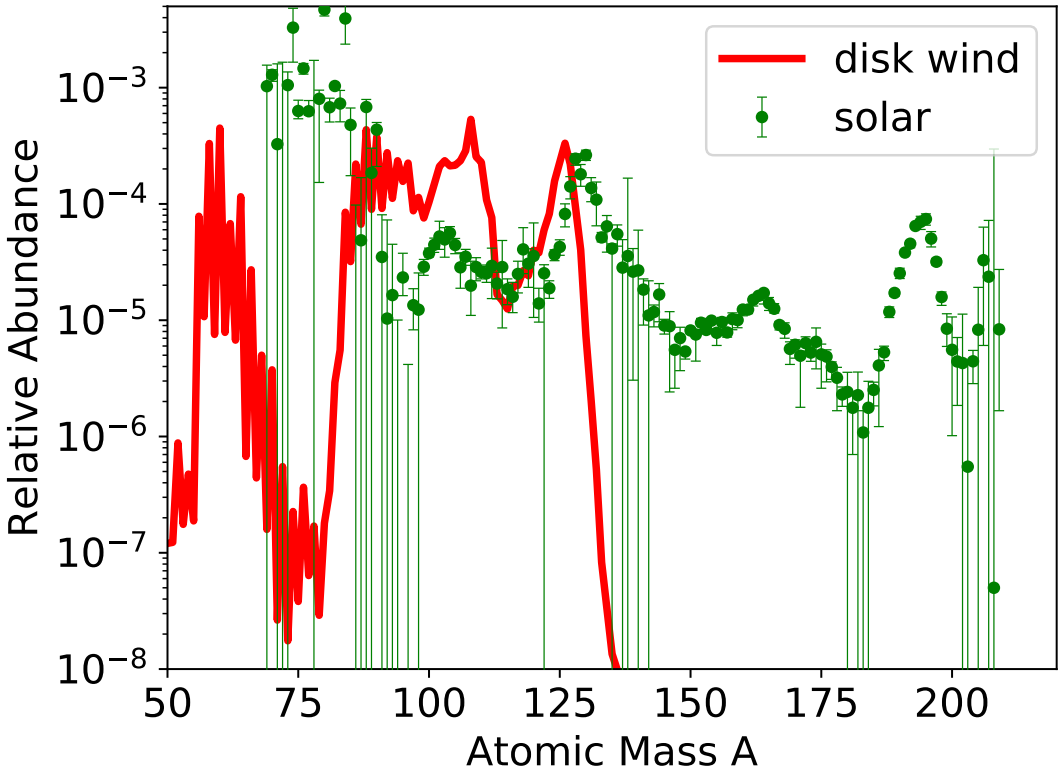
Outflow Properties





Electron Fraction and Nucleosynthesis





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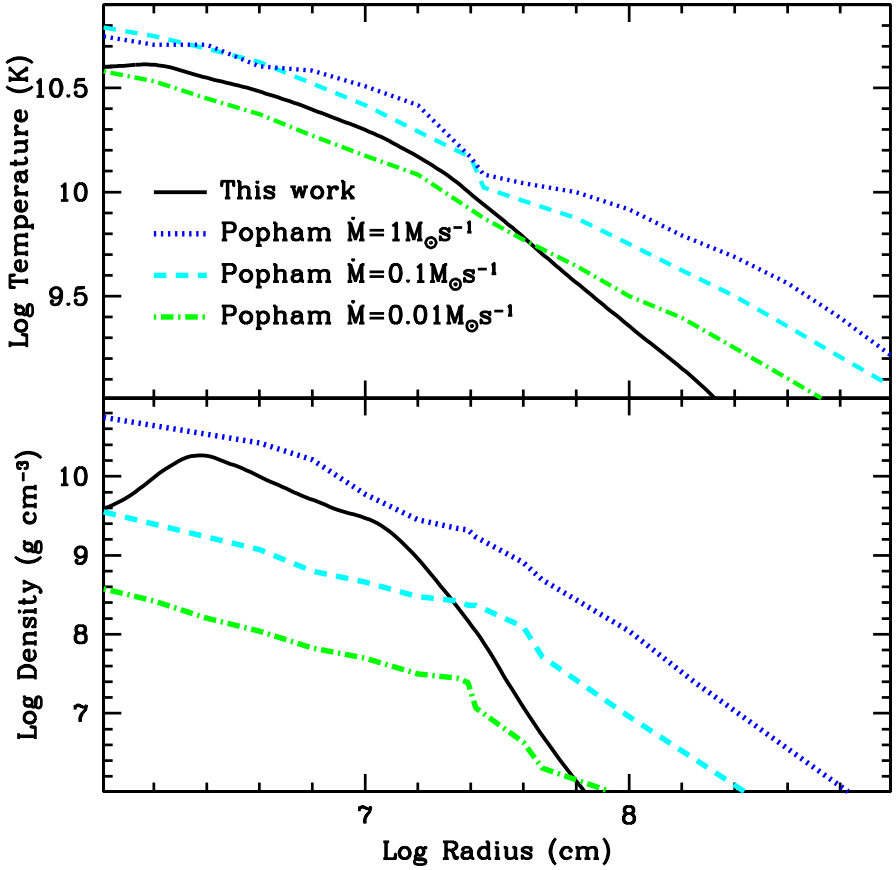
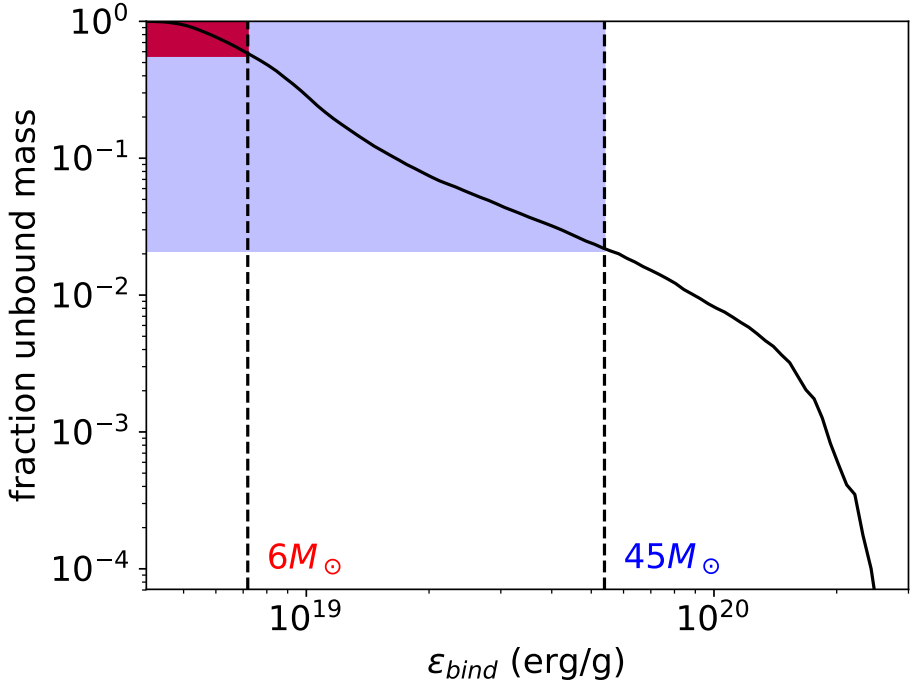
Limits of the Setup





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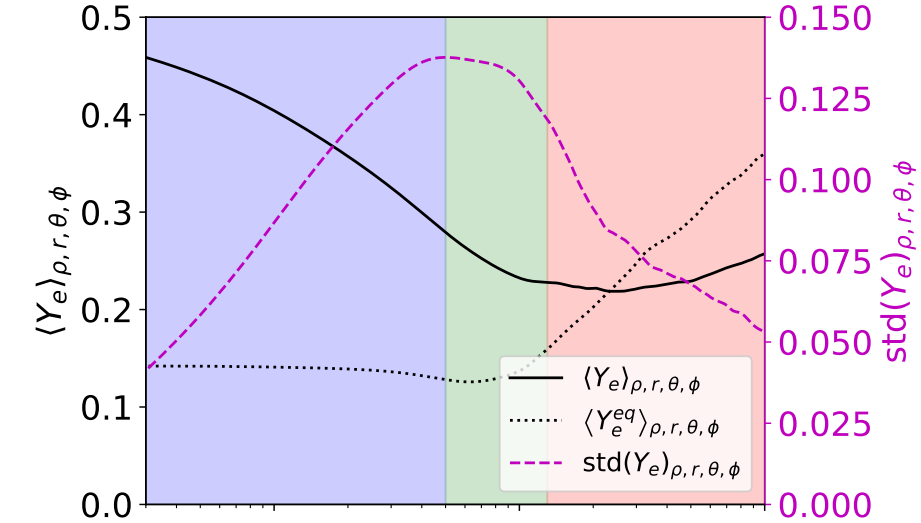
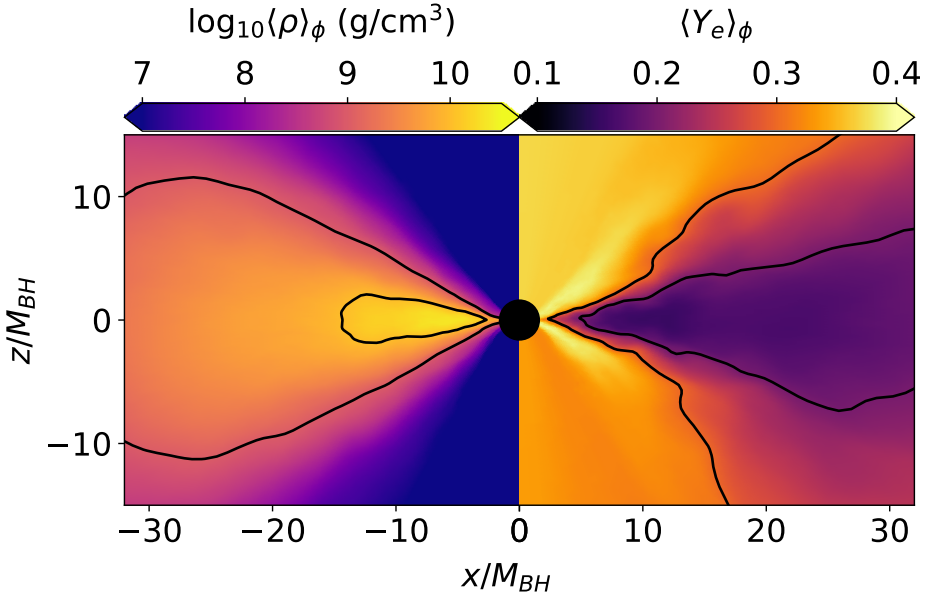
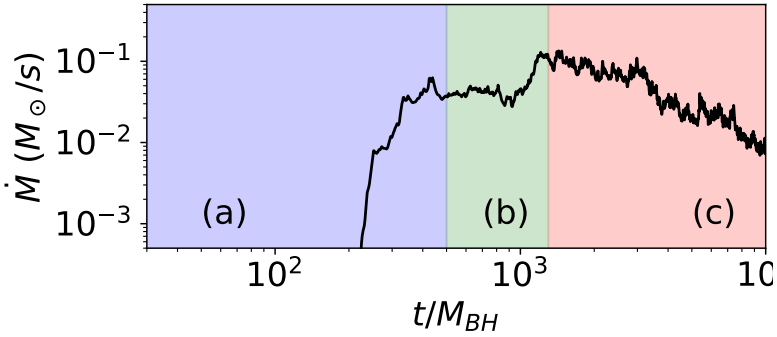
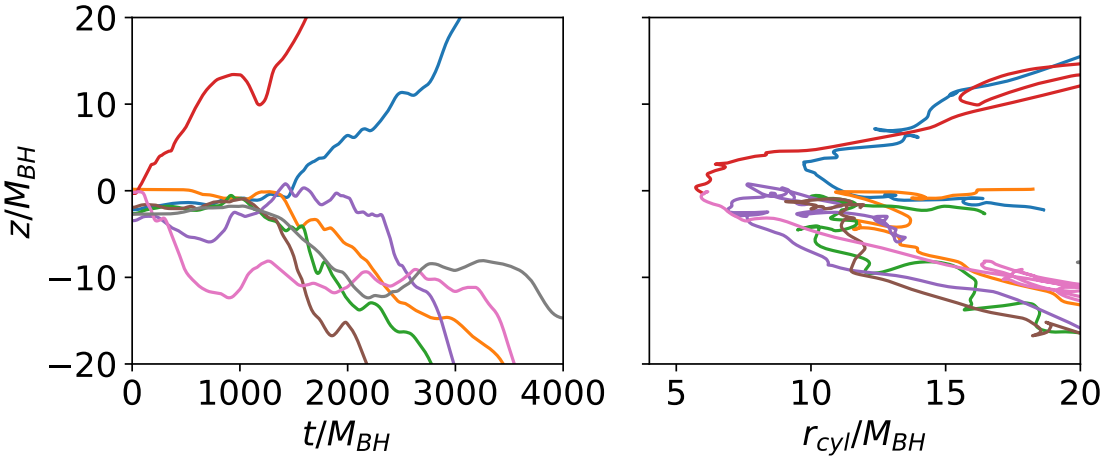
Lots of fun science!









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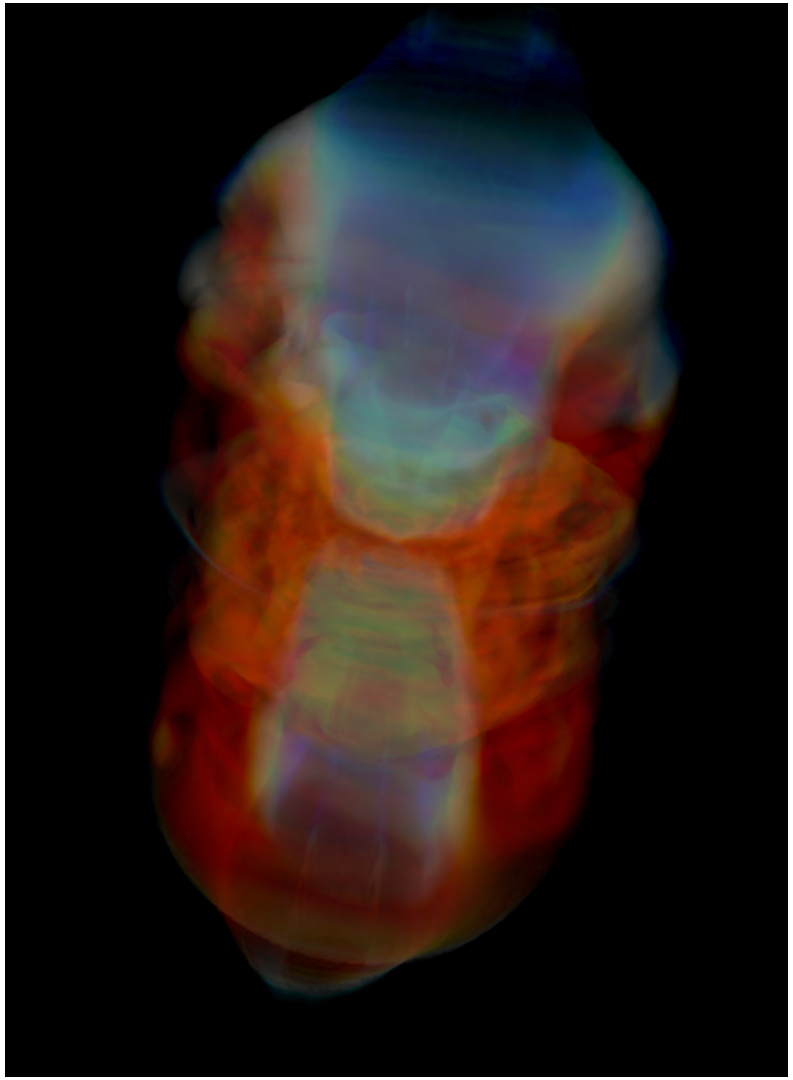
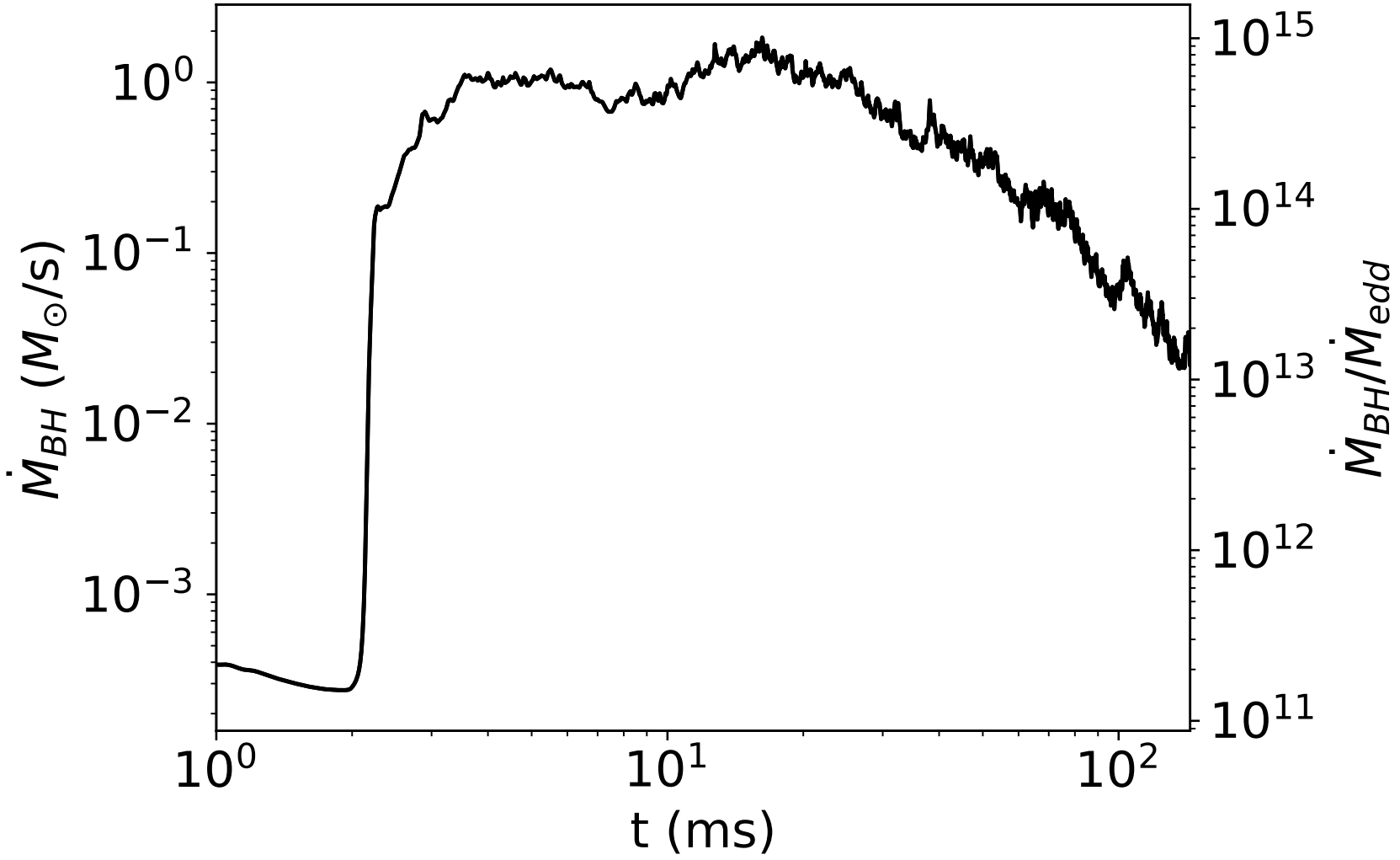
Conclusions

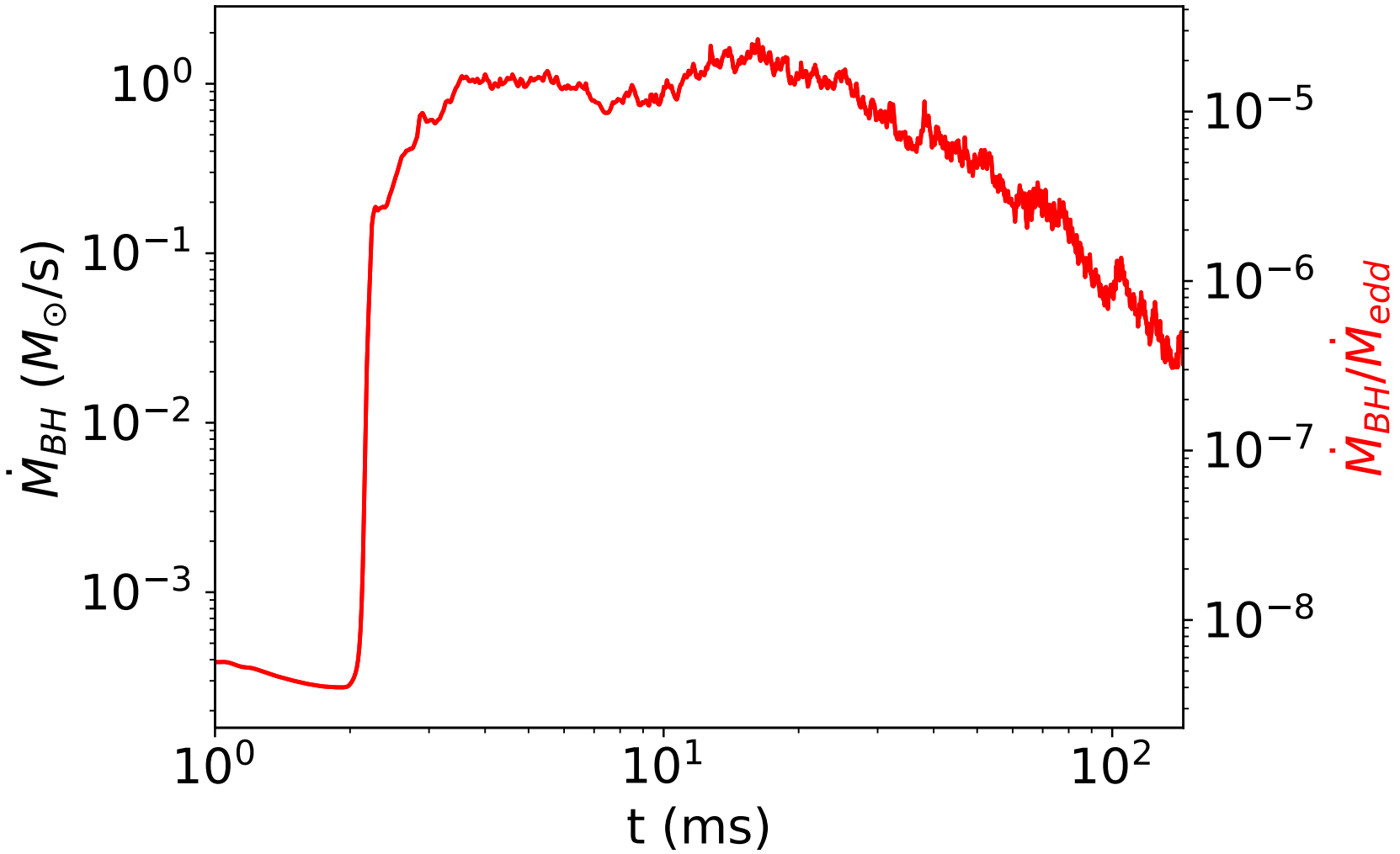
- The heaviest elements in the universe produced in some crazy cool systems!
- Need GRRMHD and neutrino transport!
- NS Mergers:
  - Likely source of heavy elements in our universe
  - Disks can produce blue component of kilonova
- Large diversity in outflows and disk physics
  - Angular structure in the outflow is generic.
  - Set by balance between MHD turbulence and neutrino physics



Accretion Rates



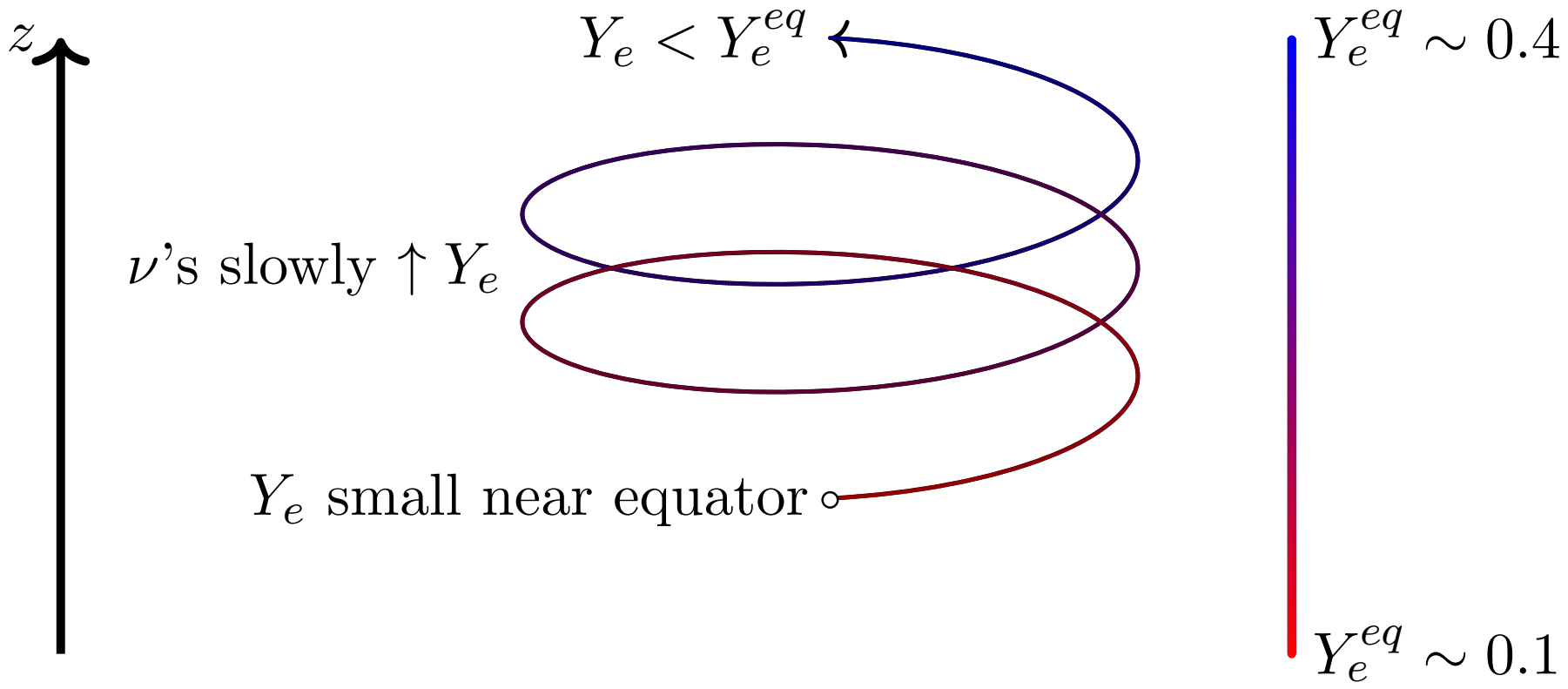
Accretion Rates



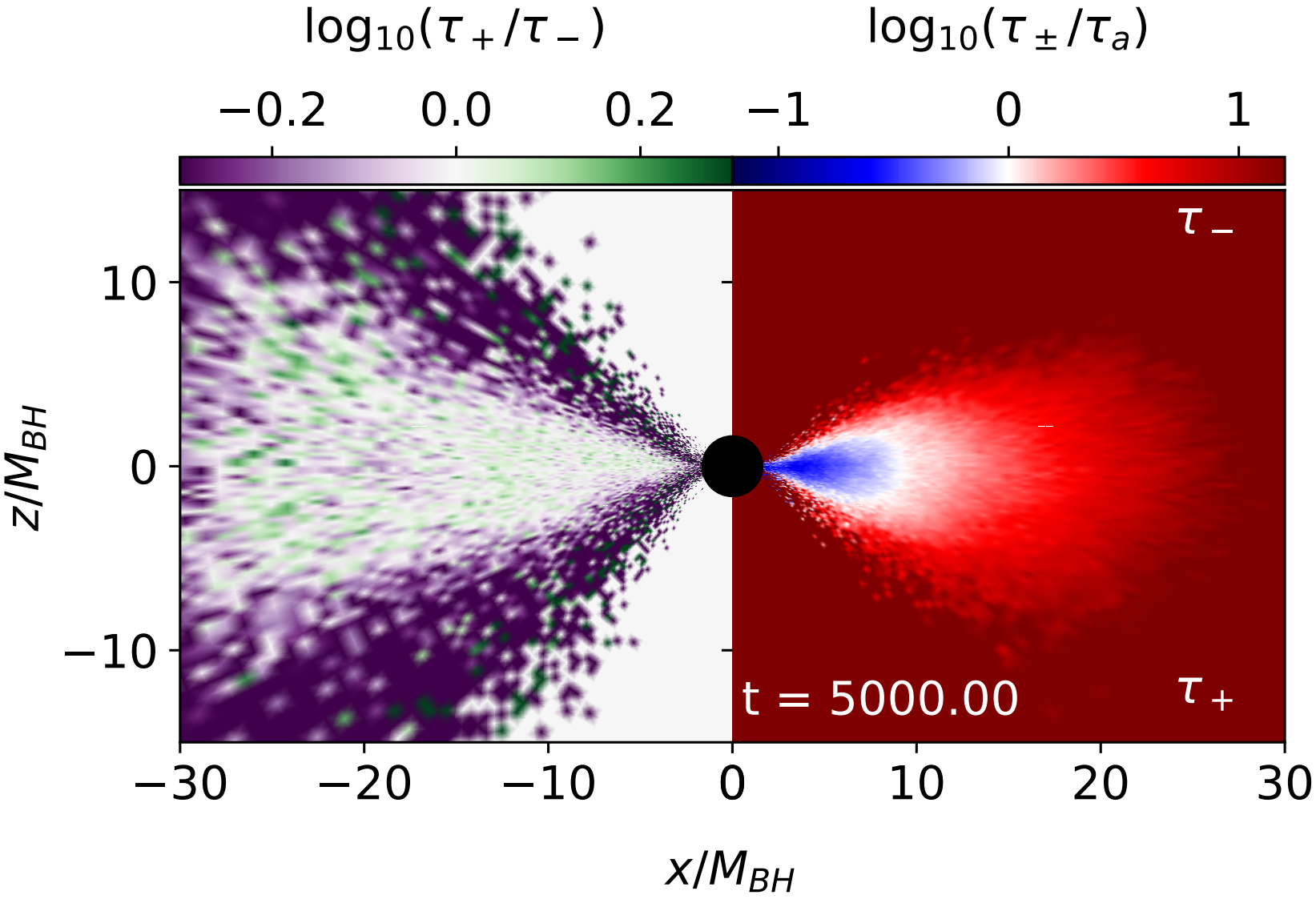
Presenting νbhlight!

- 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`.

Turbulence and Y_e



Y_e is set by the balance of Turbulence and Neutrinos!



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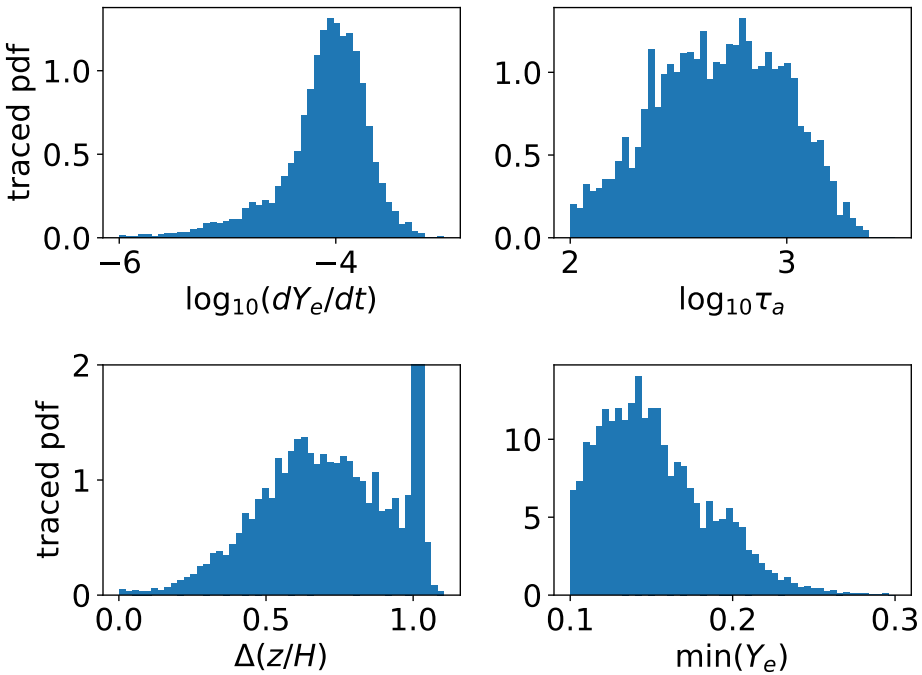
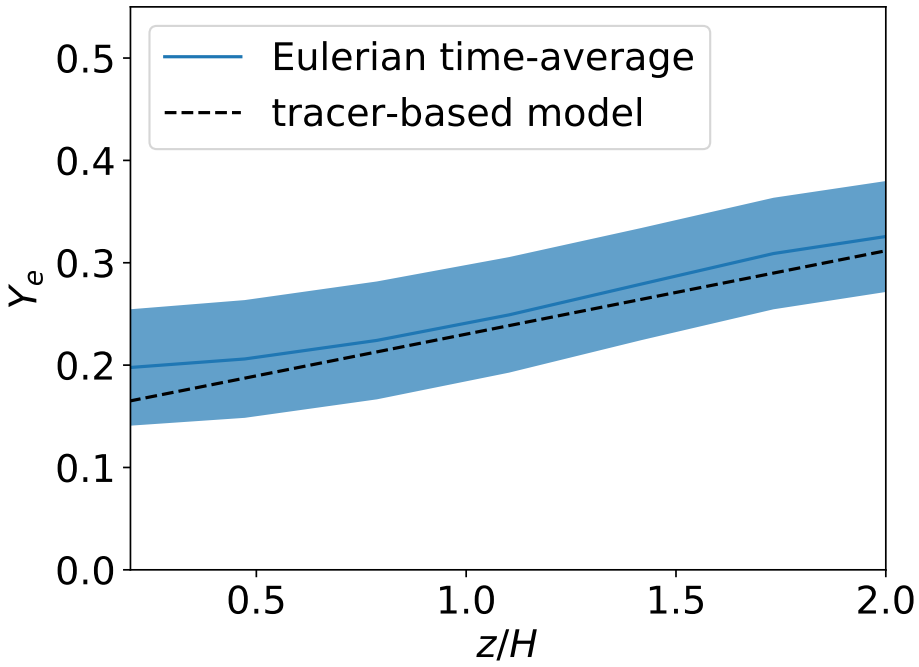
Y_e is set by the balance of Turbulence and Neutrinos!

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





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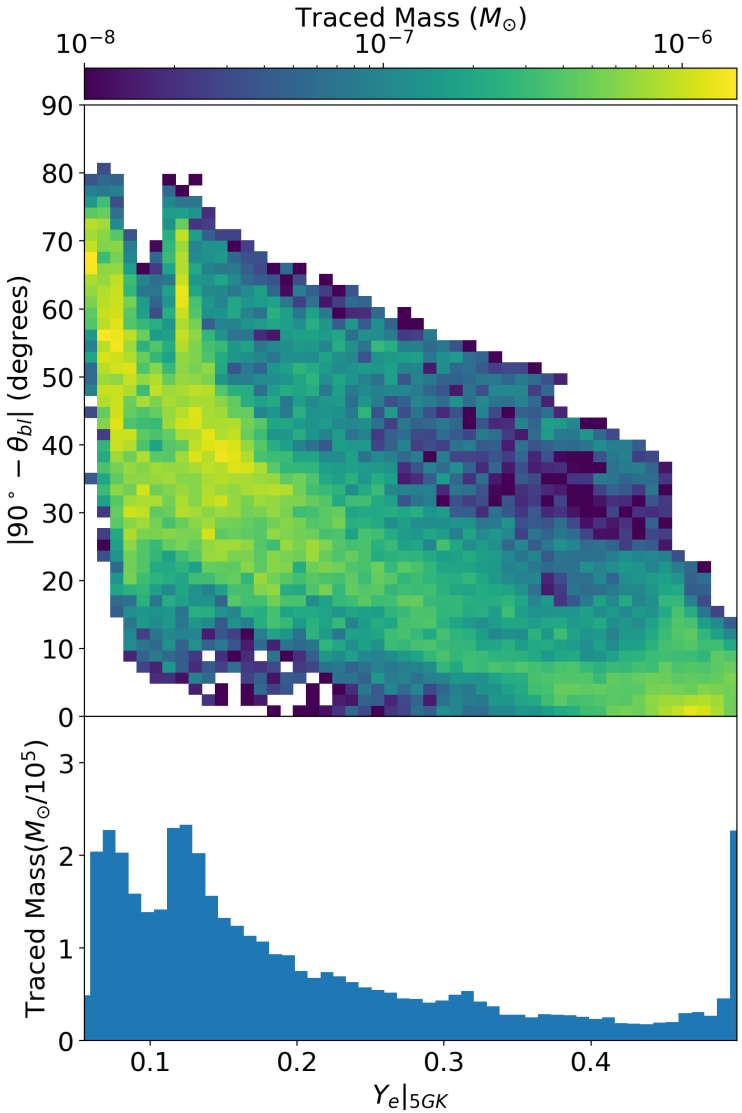
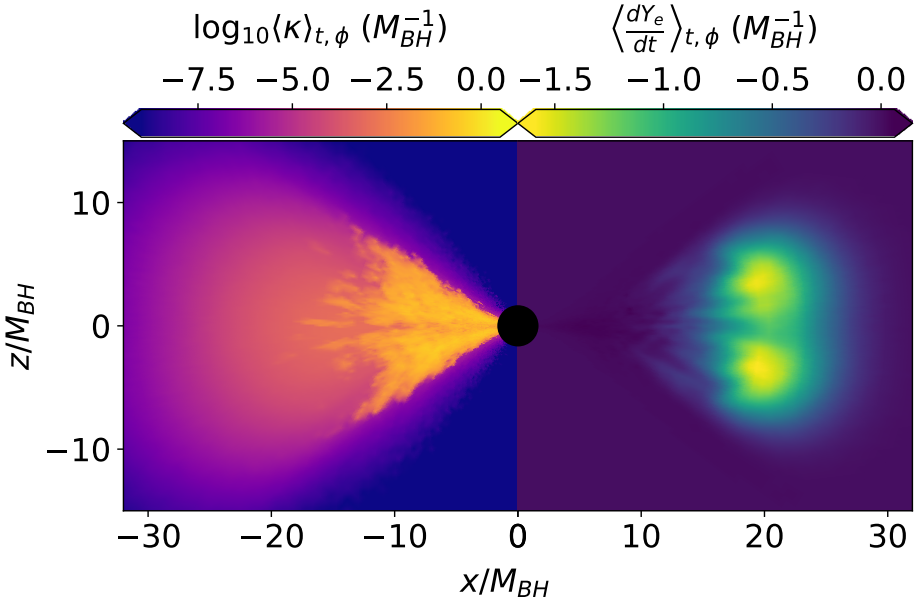
How Important is Absorption?

- With no absorption:



- Opacity suppresses change in Y_e



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