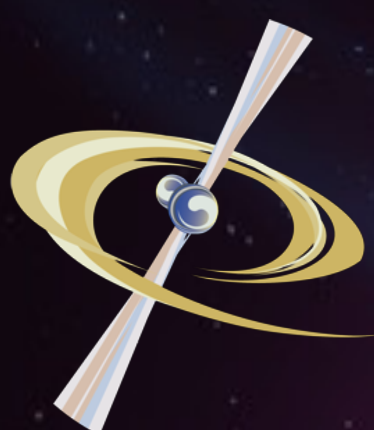
Neutrino-cooled accretion disks



Ariadna Murguia-Berthier

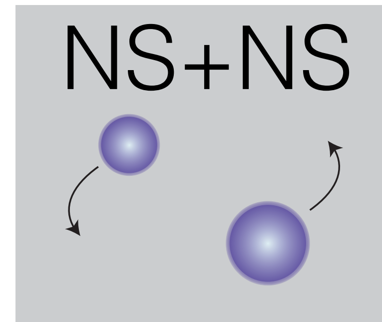
Enrico Ramirez-Ruiz, Scott Noble, Luke Roberts, TCAN collaboration

RIT College of Science Center for Computational Relativity and Gravitation

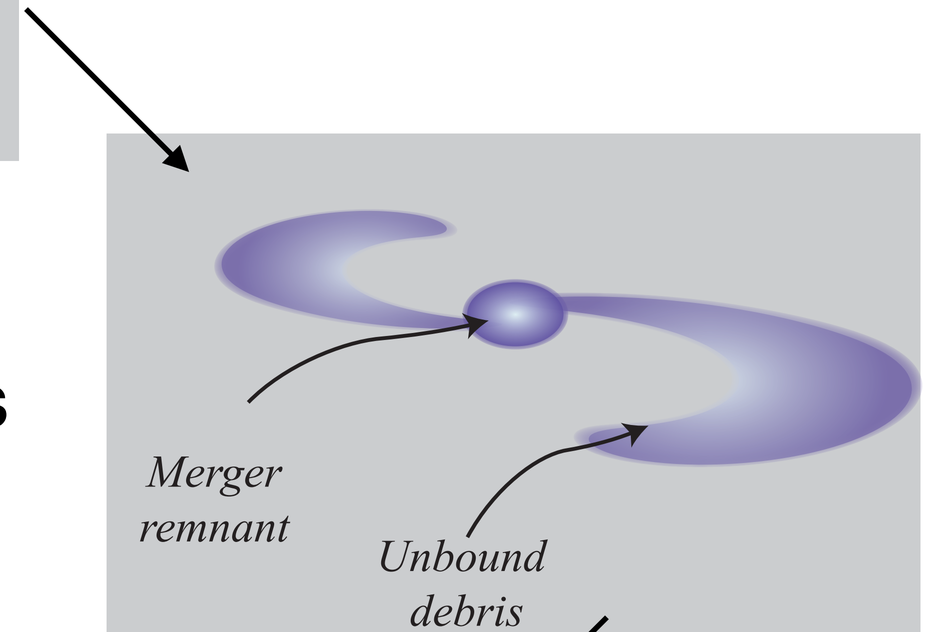
NASA's Conceptual Imaging Lab

Events in the life of GW170817

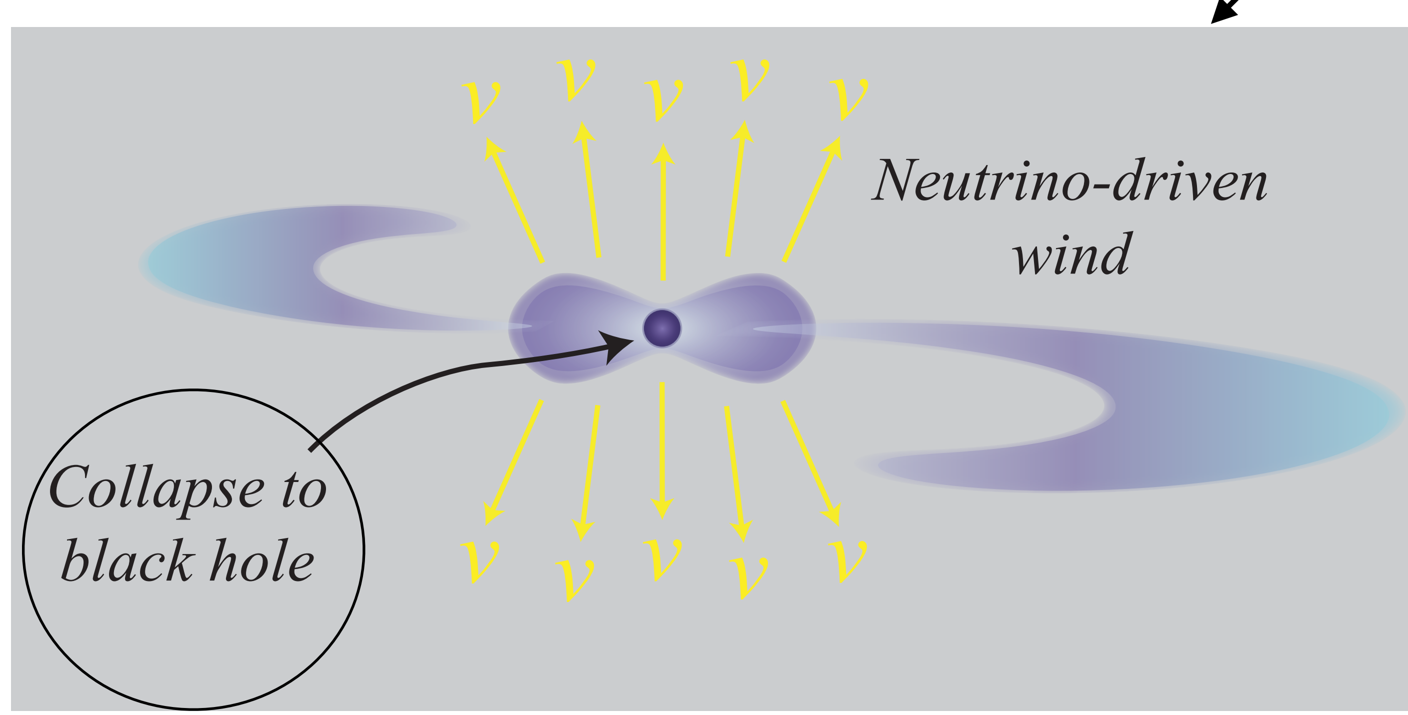
- Secular evolution



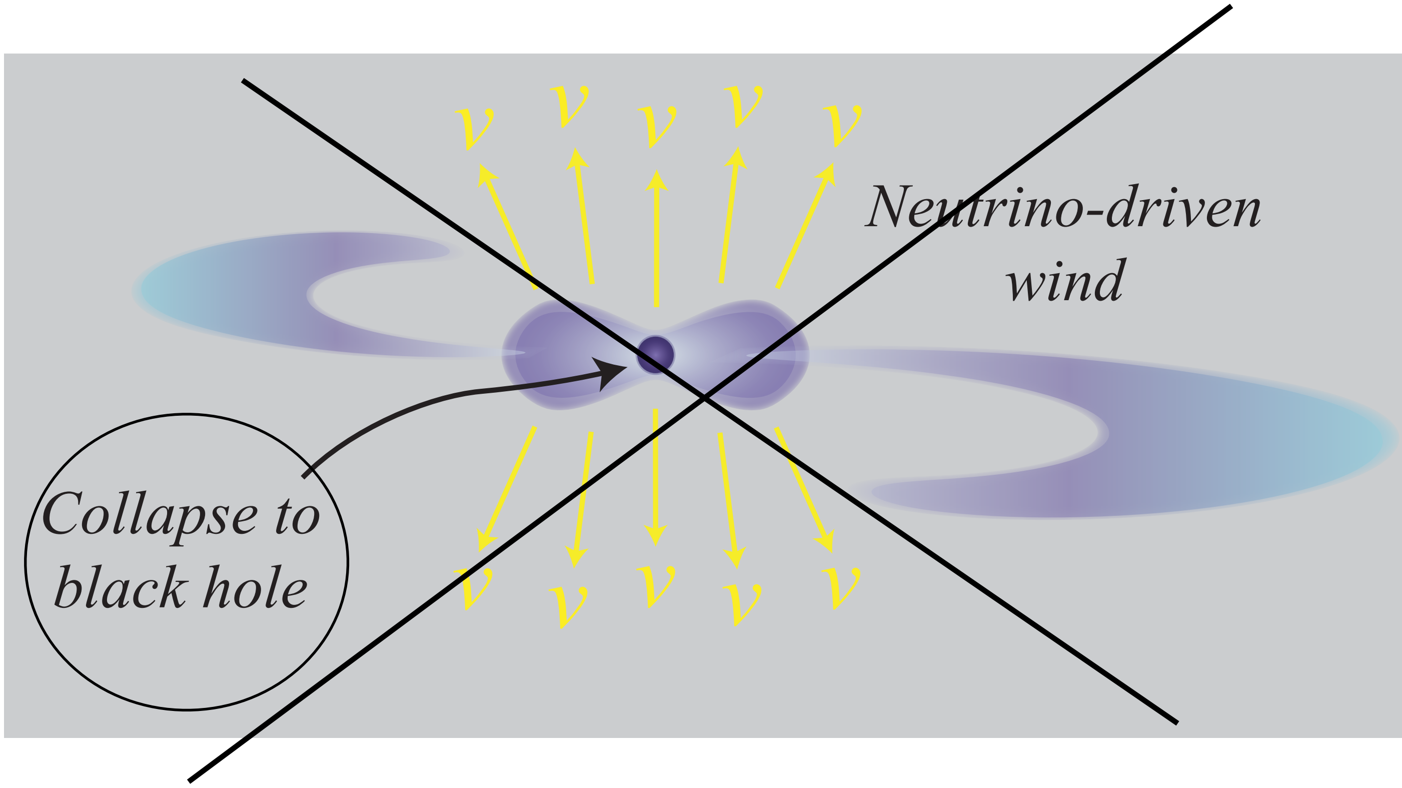
- Dynamical stability of close binaries



- Hyper-massive neutron star with accretion disk



$M_{\mathrm{GW170817}} > M_{\max}$ Mass at which self-gravitating objects collapse



$M_{\mathrm{GW170817}} \sim 2M_{\odot}$

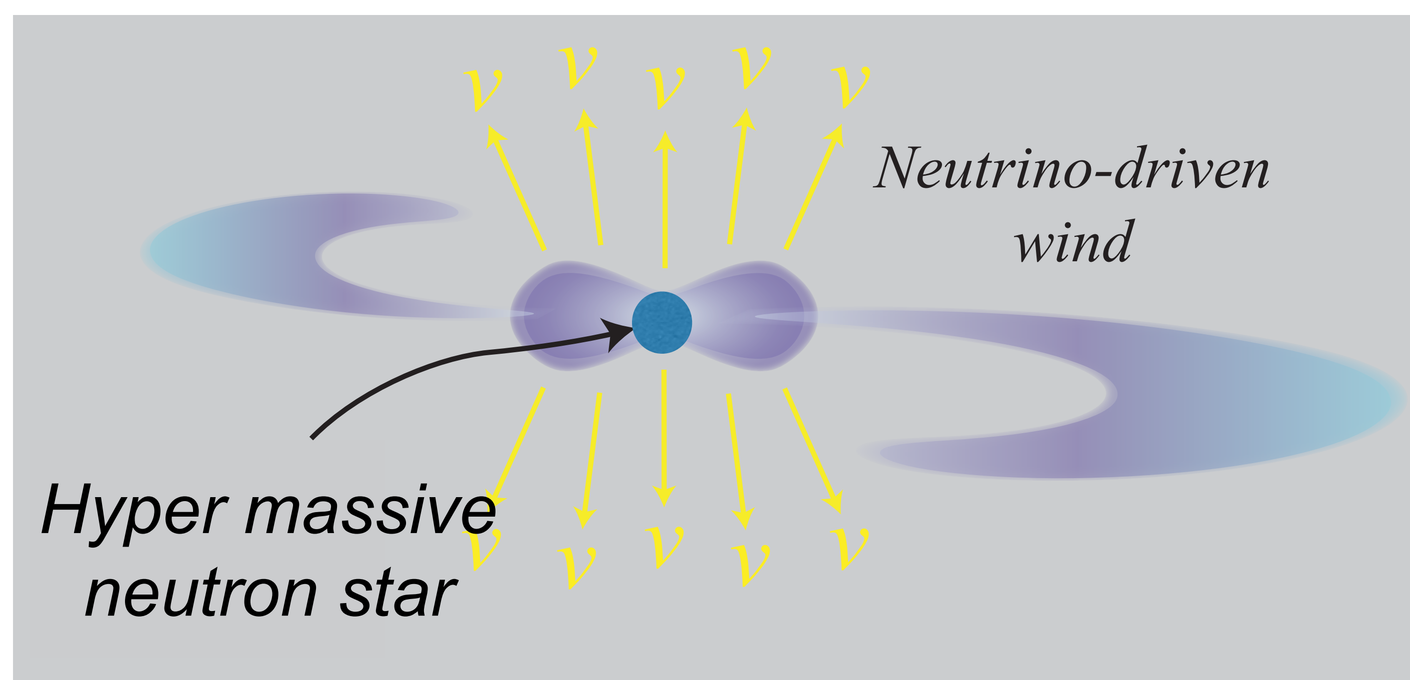
$M_{\max} \sim 2.8M_{\odot}$

Gill et al. (2019)

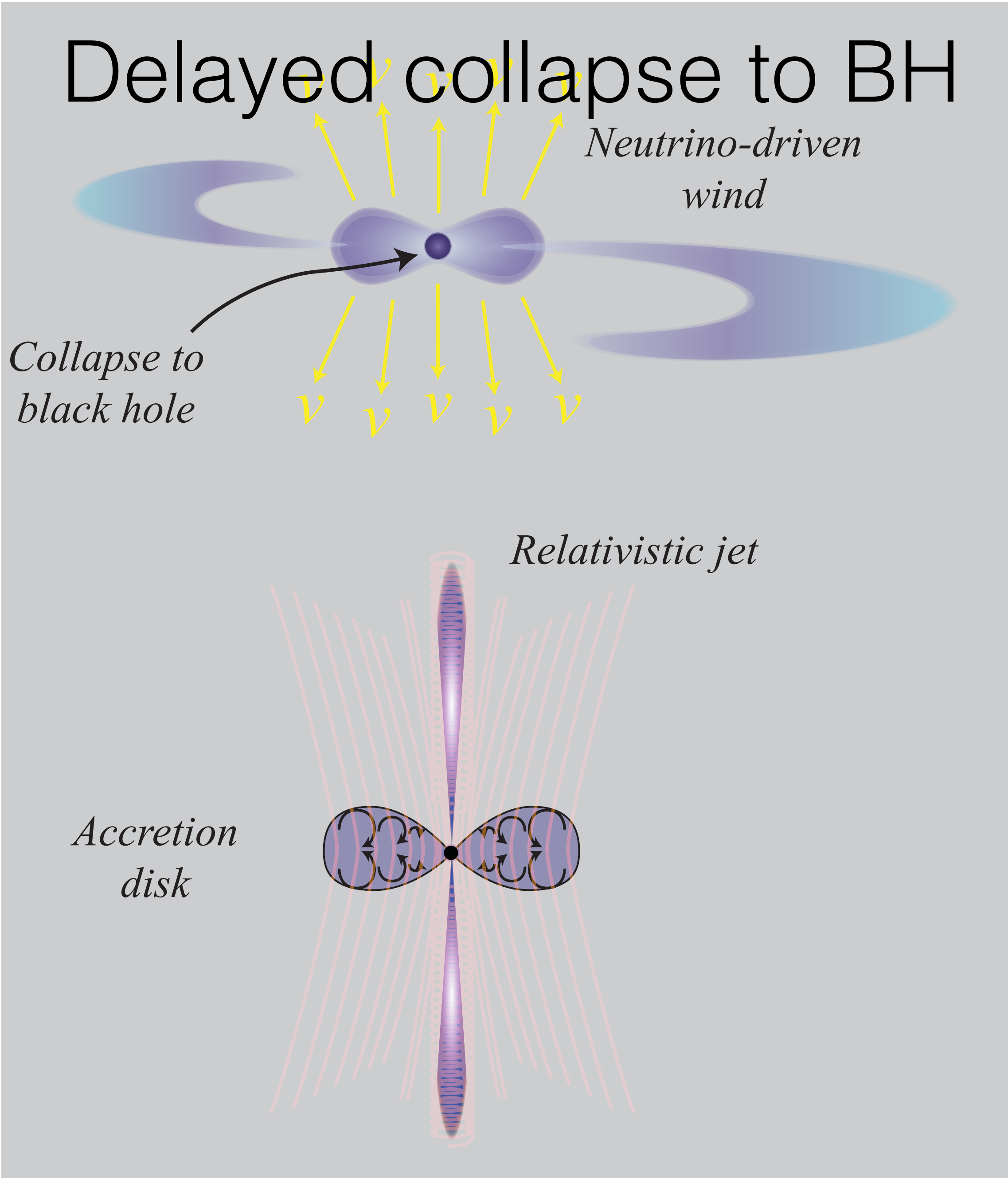
Prompt collapse to a BH

$M_{\mathrm{thres}} < M_{\mathrm{GW170817}} < M_{\max}$

Maximum mass for non-rotating NS



$$M_{\rm thres} < M_{\rm GW170817}$$

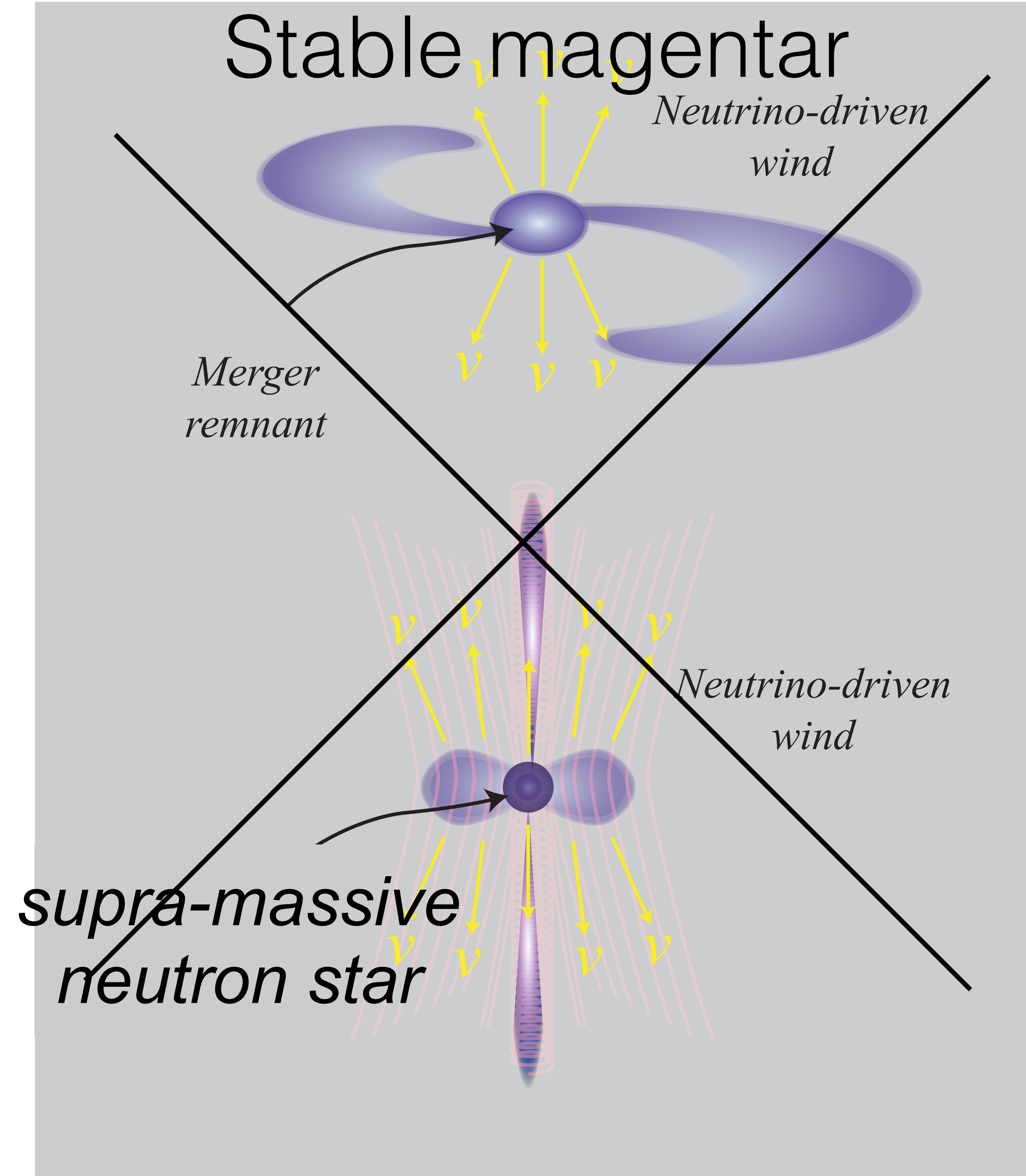


$$E \sim \epsilon(a) M_{\rm bh} c^2$$

$$t_\nu \approx 1s \left(\frac{\alpha}{0.01}\right)^{-1} \left(\frac{H/R}{0.5}\right)^{-2}$$

Courtesy of E. Ramirez-Ruiz

$$M_{\rm thres} > M_{\rm GW170817}$$



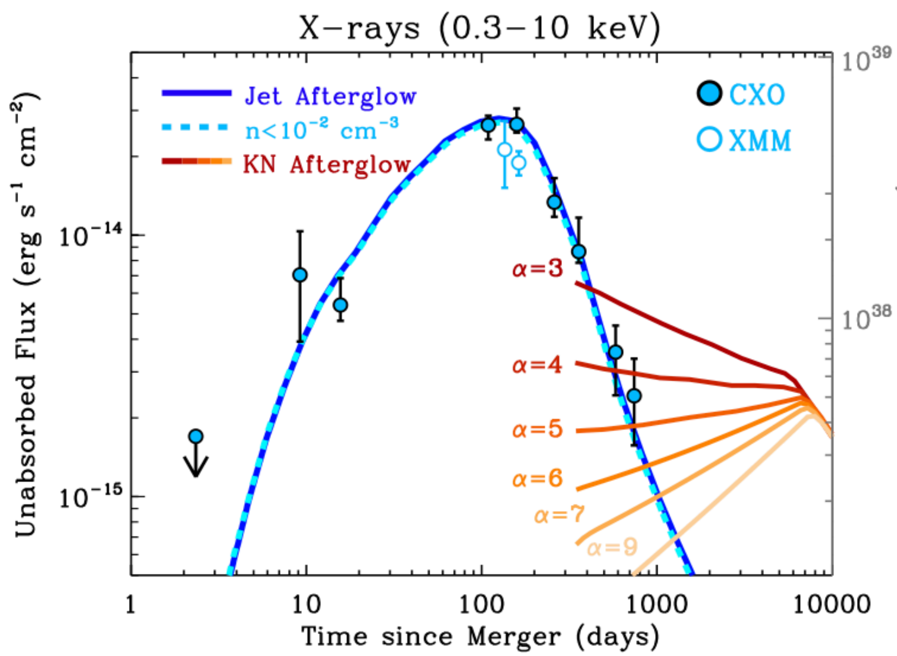
$$L >> 10^{42} {\rm erg/s}$$

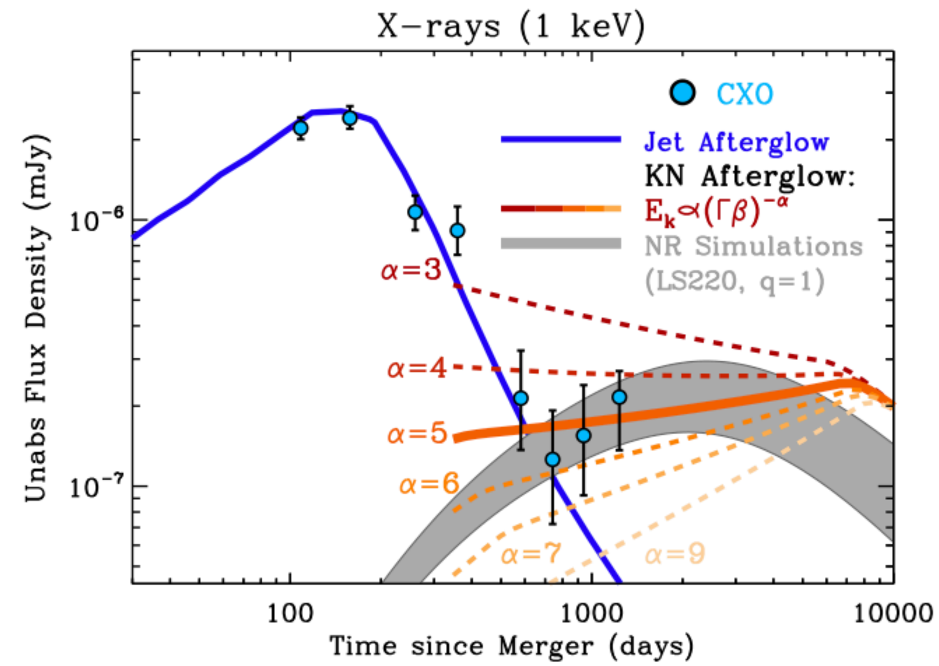
but

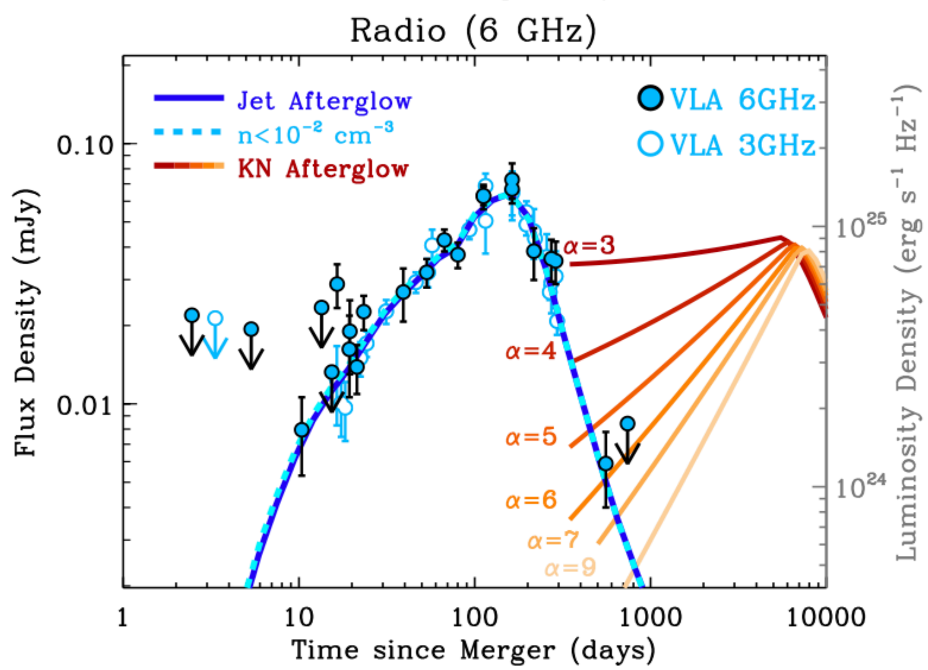
$$L_{\rm bol} < 10^{42} {\rm erg/s}$$

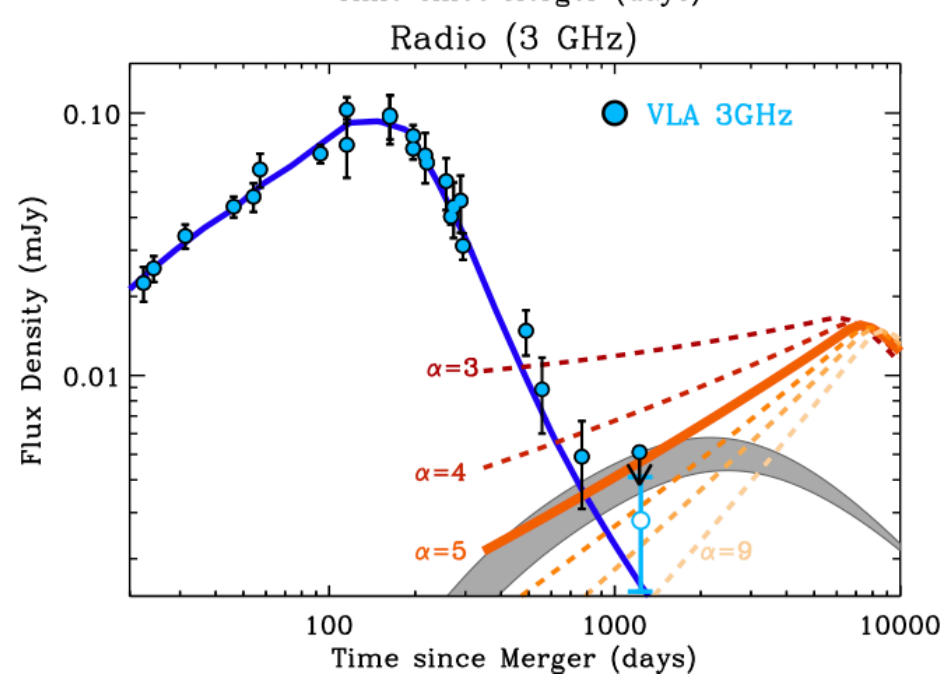
Gill et al. (2019)

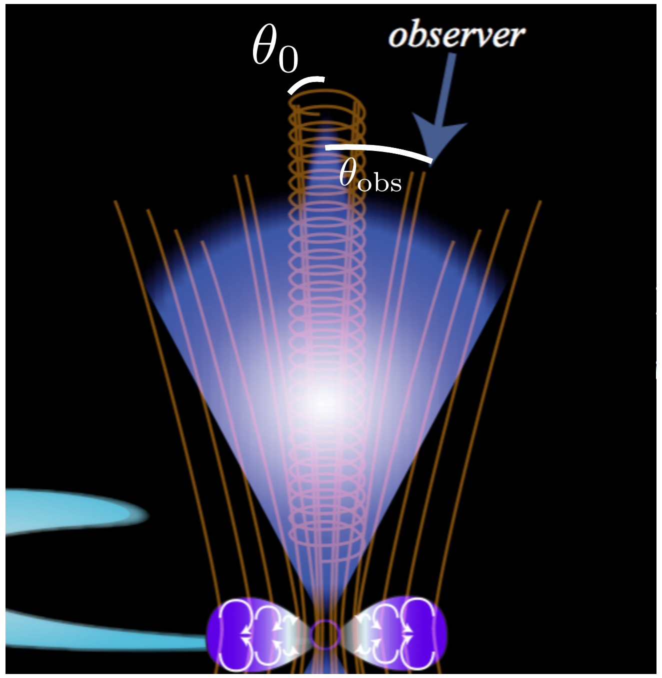
GW170817: Non-thermal emission





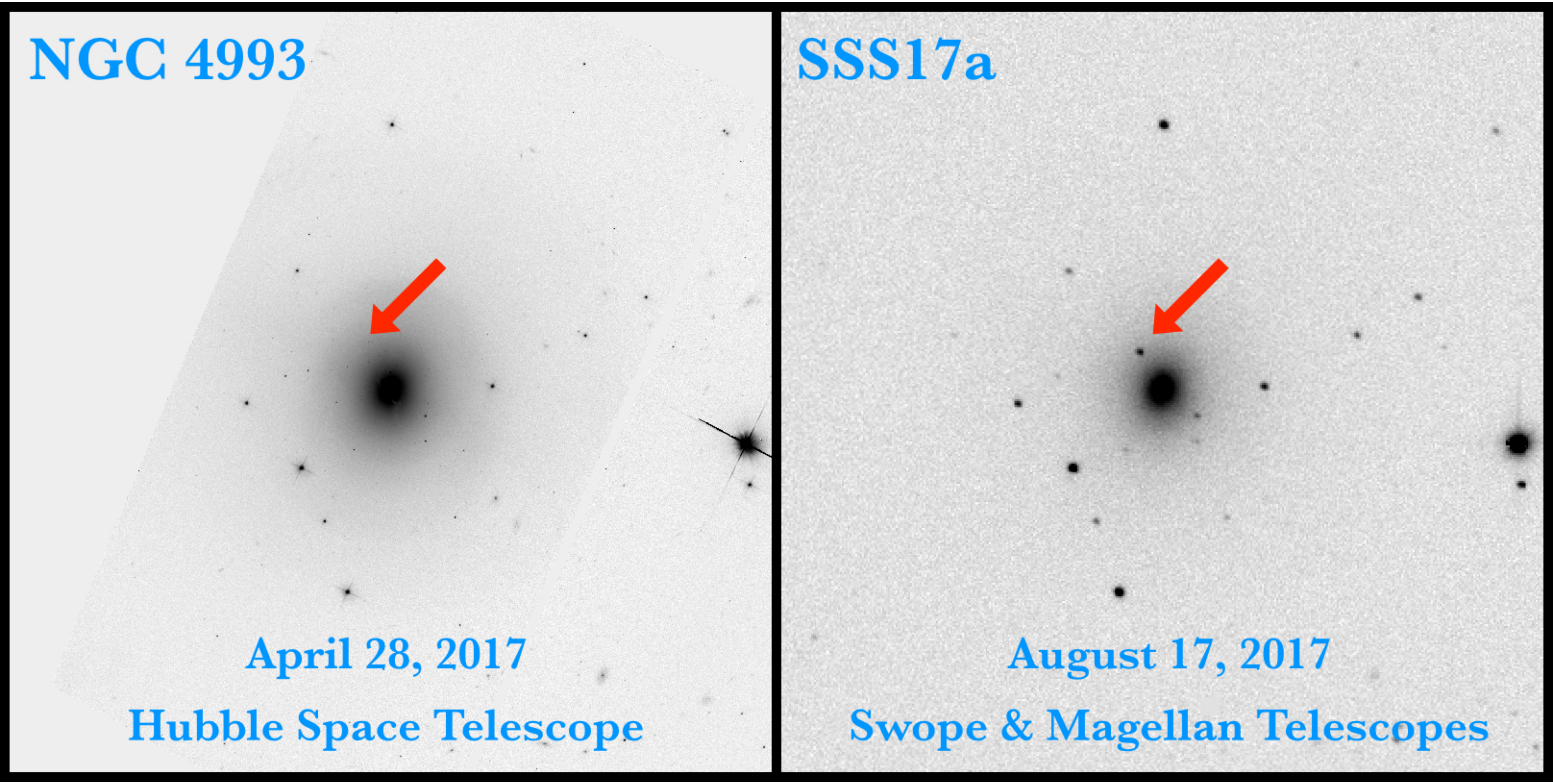






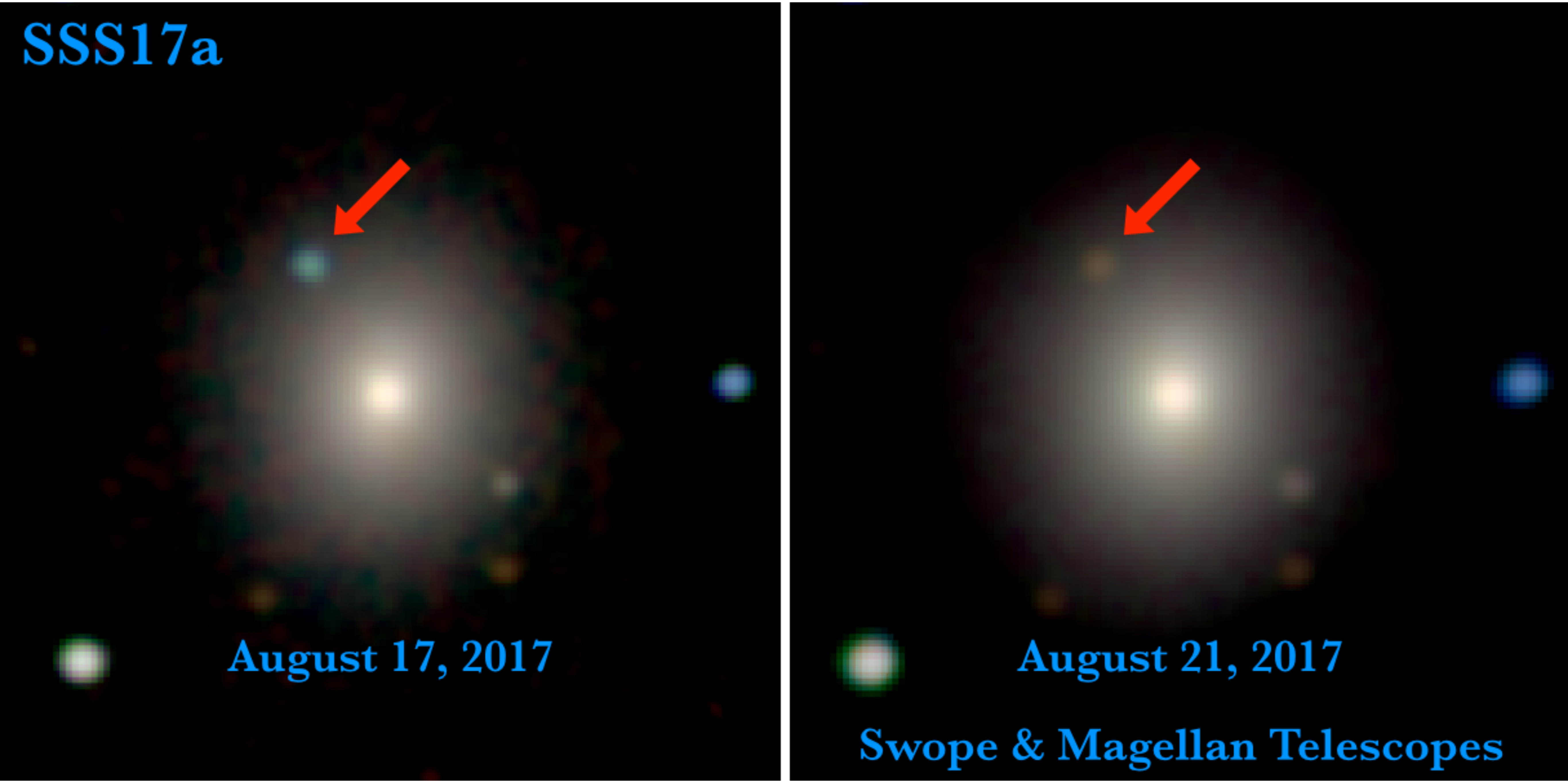
Hajela et al. (2020), (2021) & lots more

Kilonova

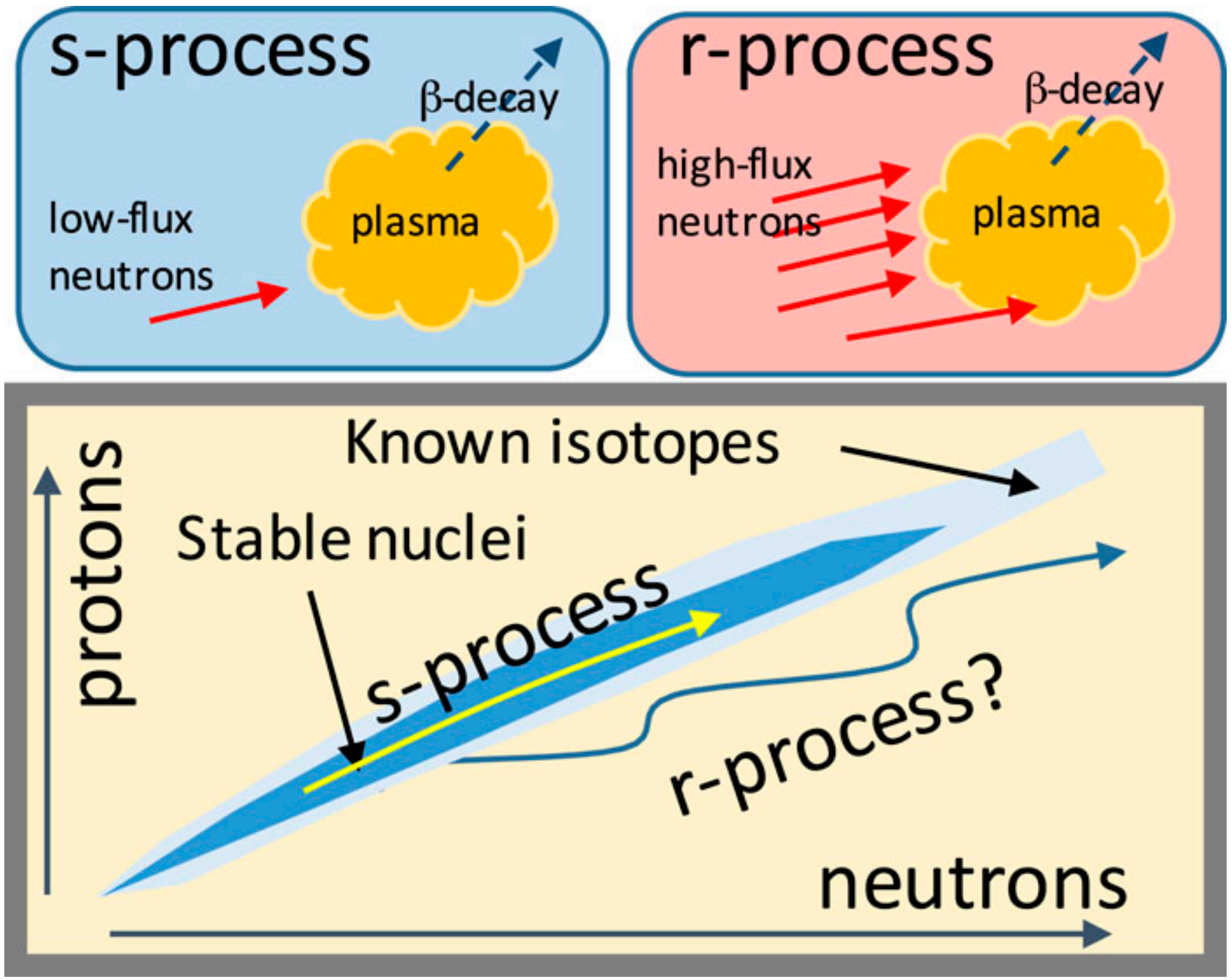


Coulter & **1M2H** (2017)

Optical/IR/UV emission: unlike anything we've seen

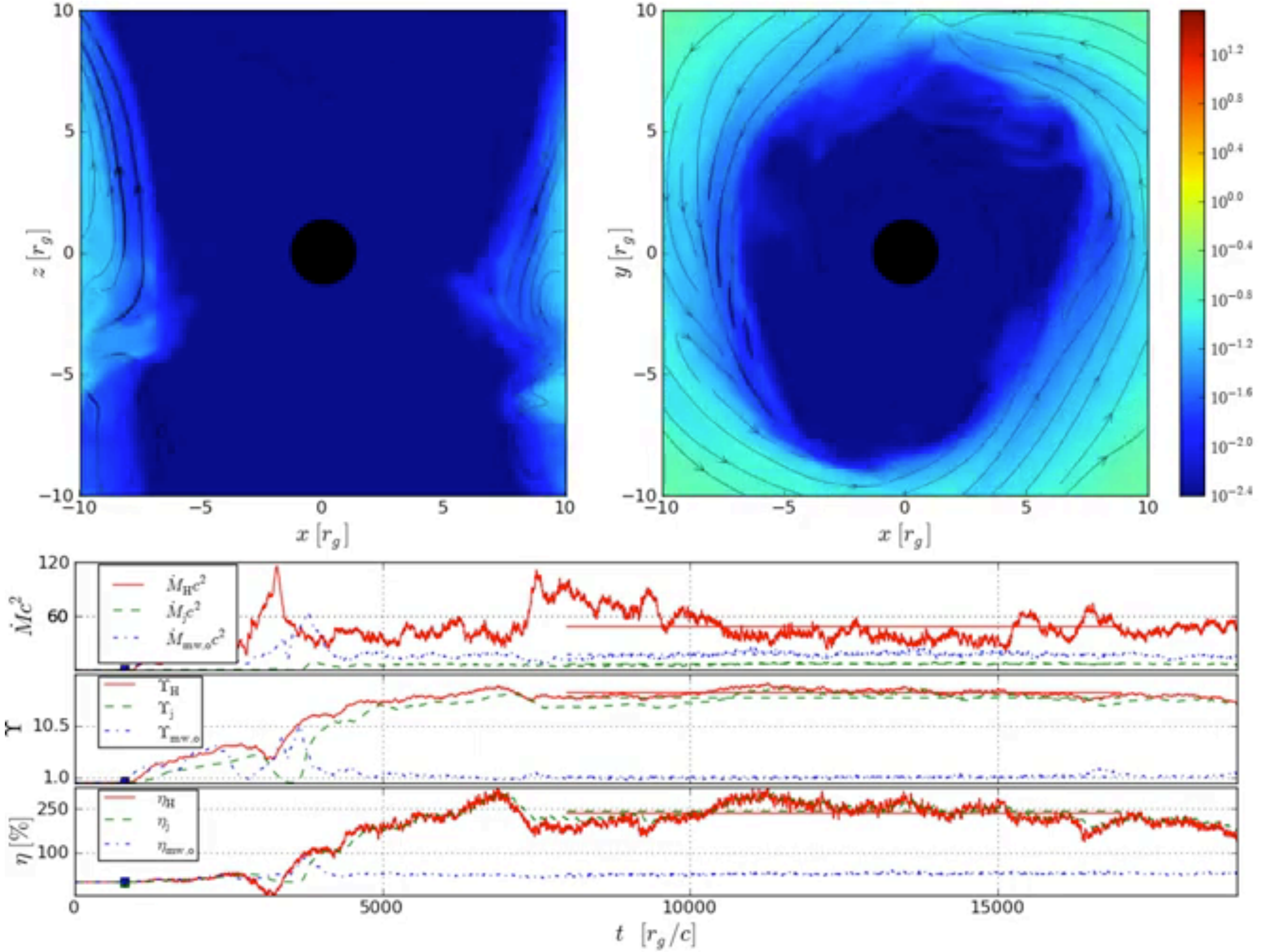


r-Process nucleosynthesis

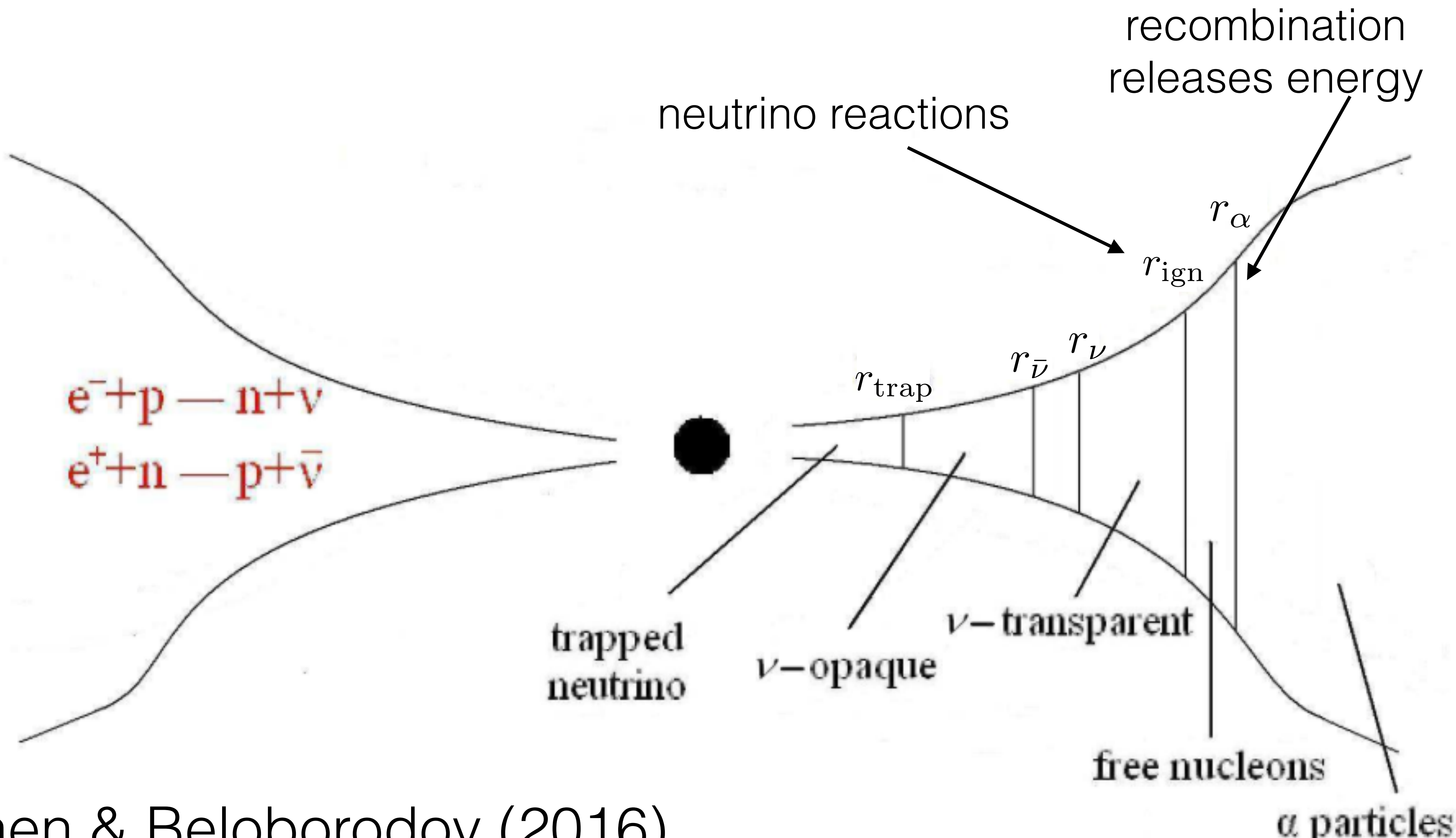


r-process-> Neutron capture> beta decay

MHD stress driven outflow



Physics in the accretion disk



Chen & Beloborodov (2016)

Di Matteo et al. (2002)

Narayan et al. (2001)

Neutrino reactions

Charged beta-process

$$e^- + p \rightarrow n + \nu_e$$

$$e^+ + n \rightarrow p + \bar{\nu}_e$$

Plasmon decay

$$\gamma \rightarrow \nu_e + \bar{\nu}_e$$

$$\gamma \rightarrow \nu_x + \bar{\nu}_x$$

Electron-positron pair annihilation

$$e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e$$

$$e^- + e^+ \rightarrow \nu_x + \bar{\nu}_x$$

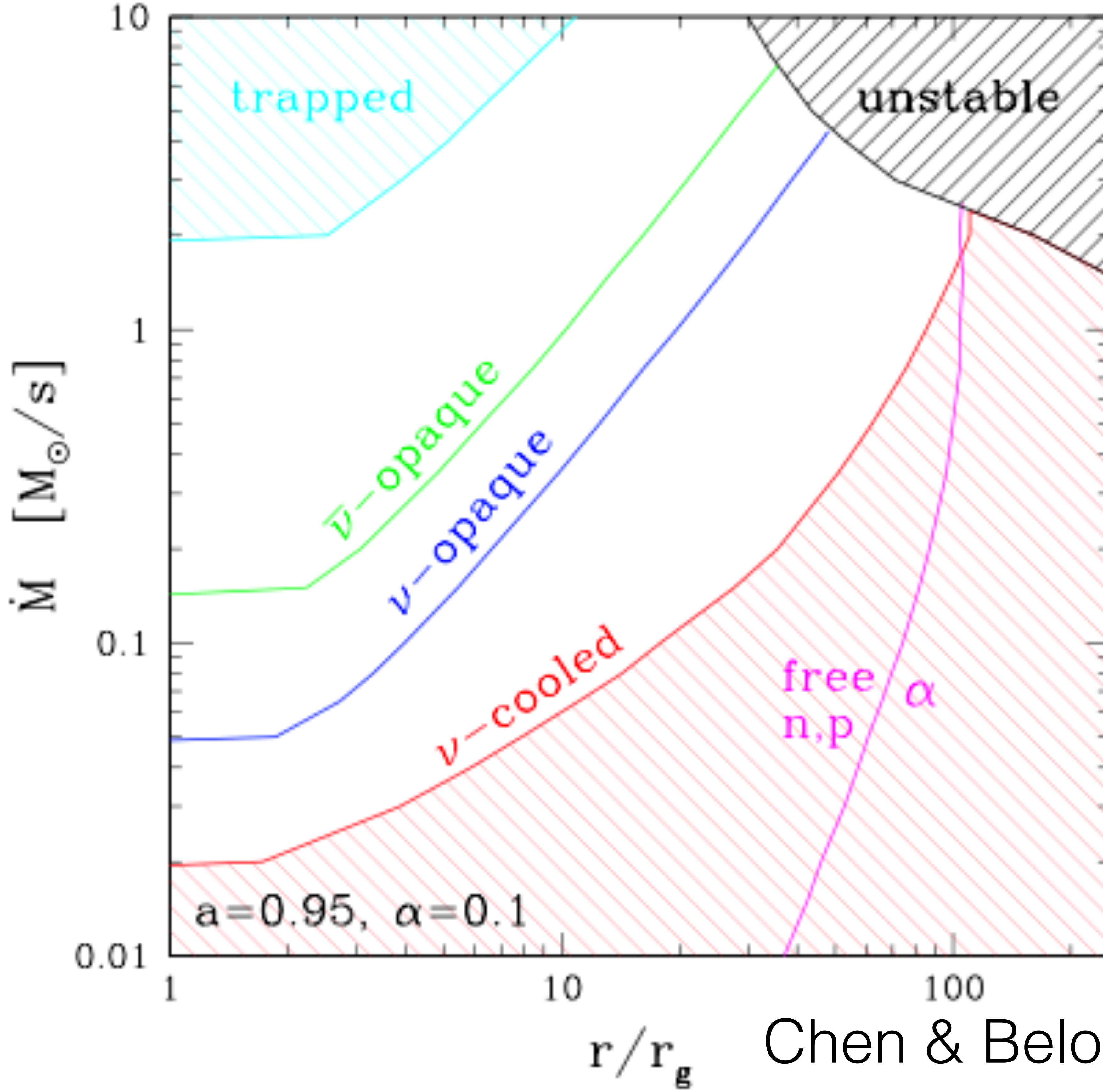
Absorption (opacity source)

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

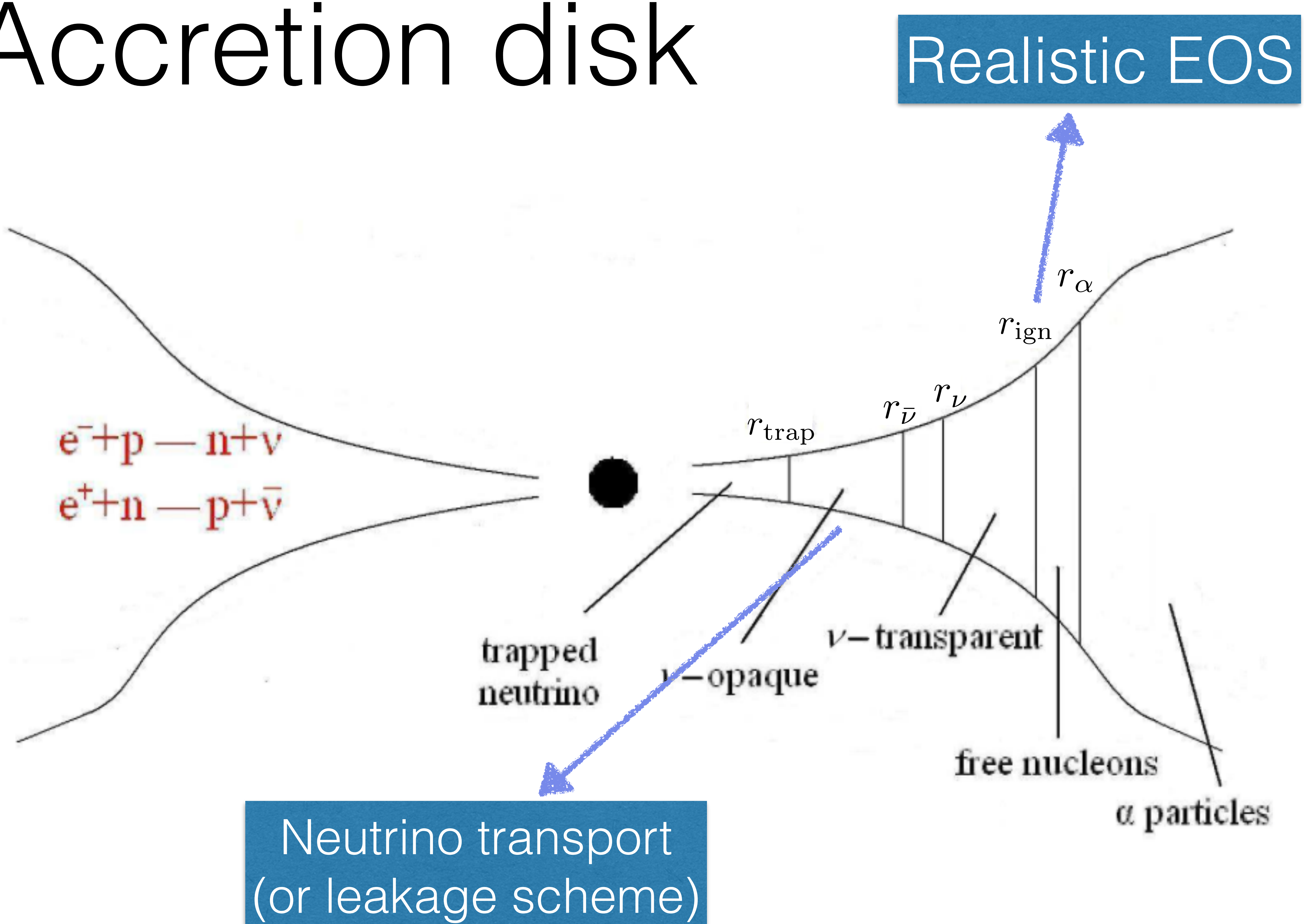
Accretion disk

Gravitationally unstable (Toomre Q)



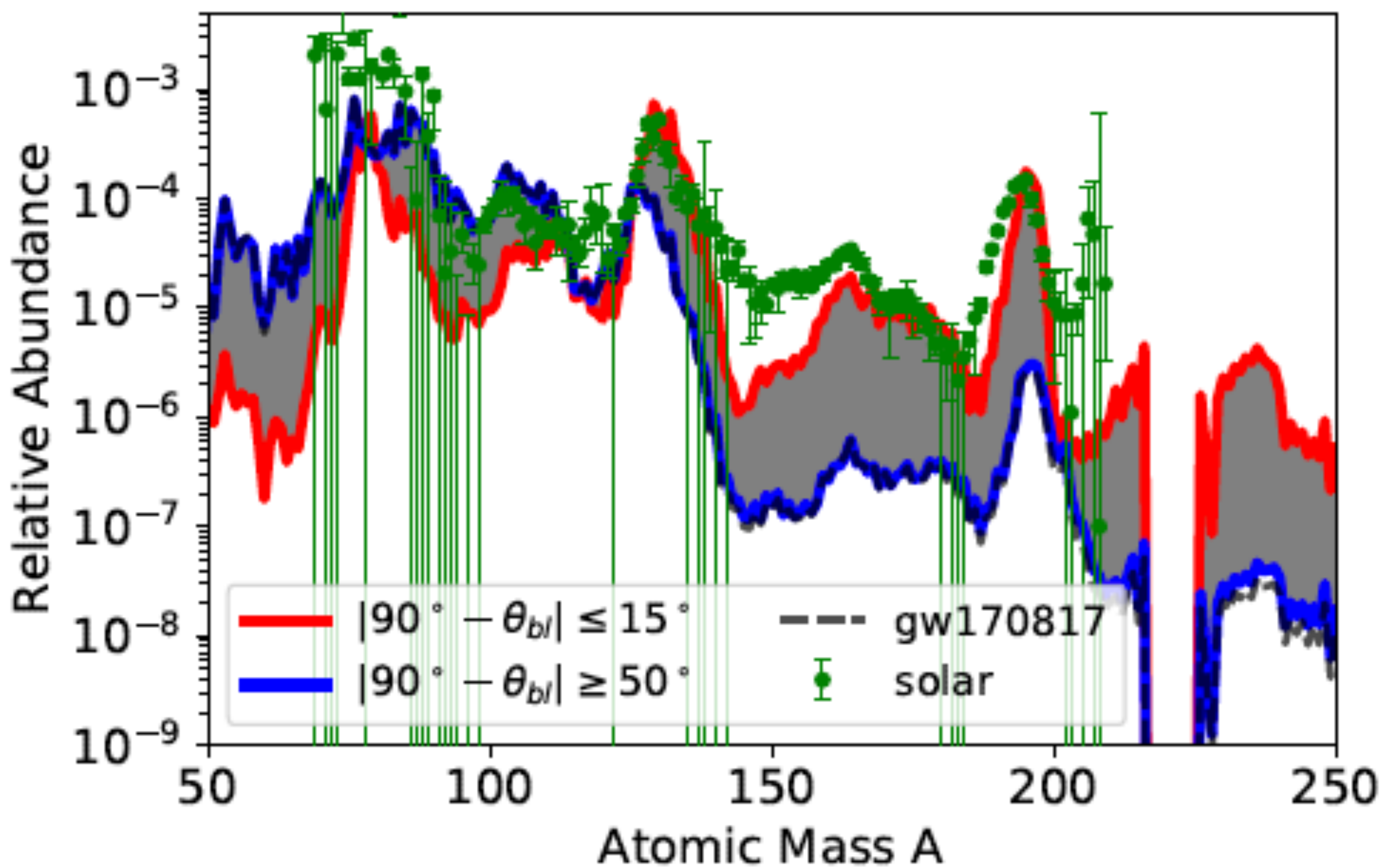
Chen & Beloborodov (2016)

Accretion disk



Chen & Beloborodov (2016)

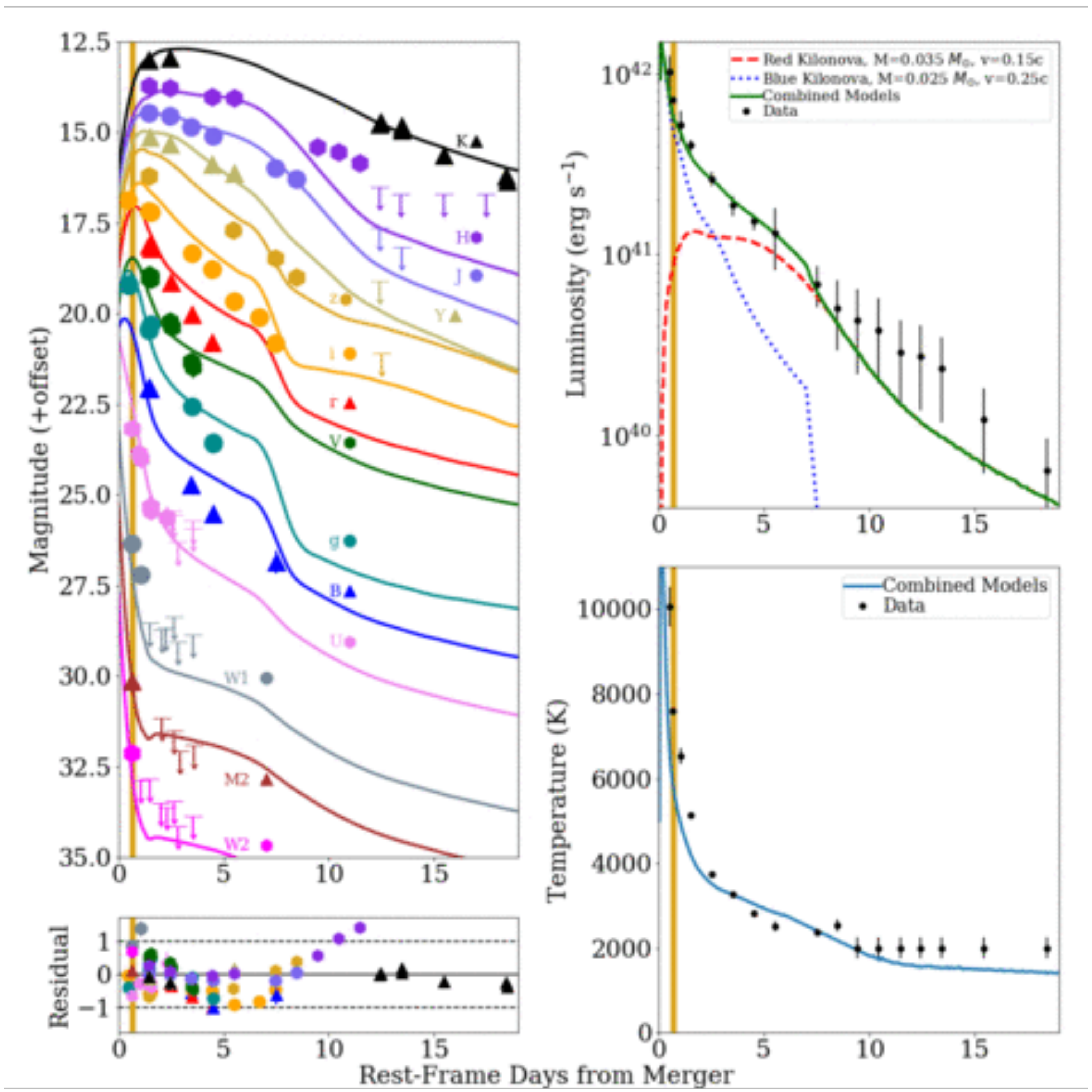
Nucleosynthesis in accretion disks



The final composition is still uncertain

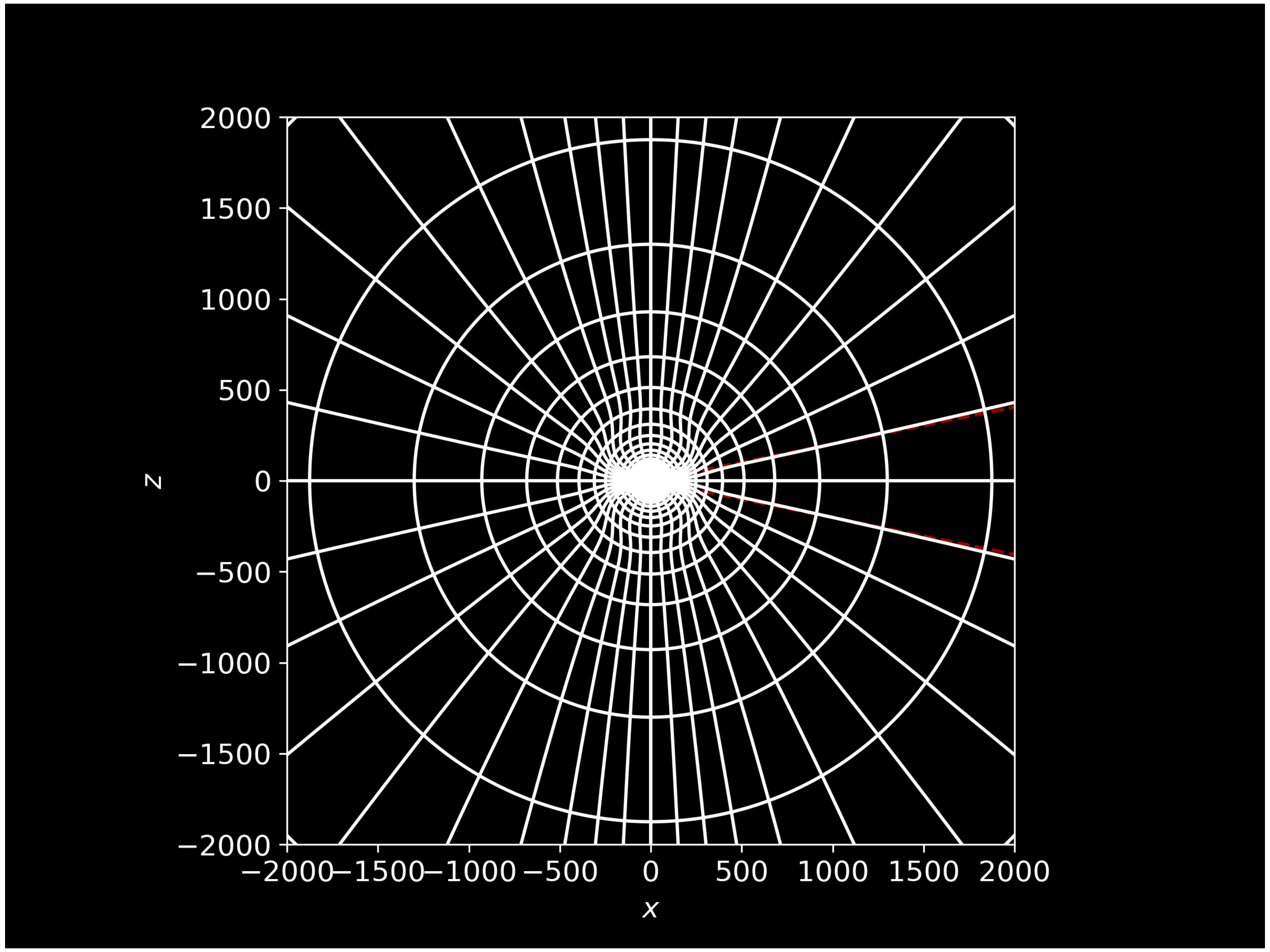
e.g. Janiuk et al. (2014) Wu et al. (2016), Siegel & Metzger (2018), Fernandez et al. (2018), Foucart et al. (2018), Miller et al. (2019a)

Kilonova emission: GW170817



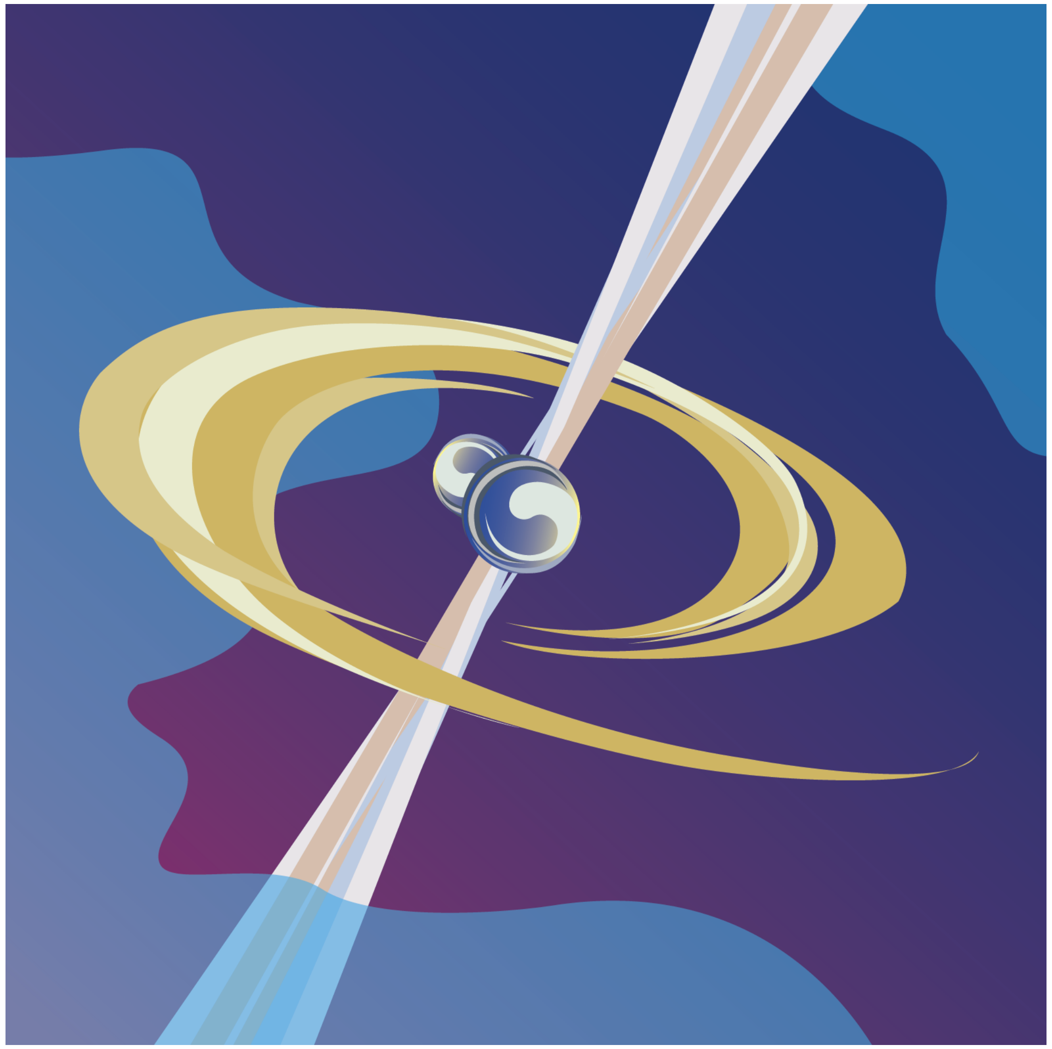
Kilpatrick & **1M2H, including Murguia-Berthier** (2017)

HARM3D



- Solves GRMHD equations
- Conservative
- Fully parallelized
- Well tested
- Evolves the electron fraction (new to this version)
- Patchworks included (new to this version, under construction)- multi patch infrastructure, more accuracy and efficiency for jets
- Arbitrary coordinate system (much less diffusion than a cartesian grid)

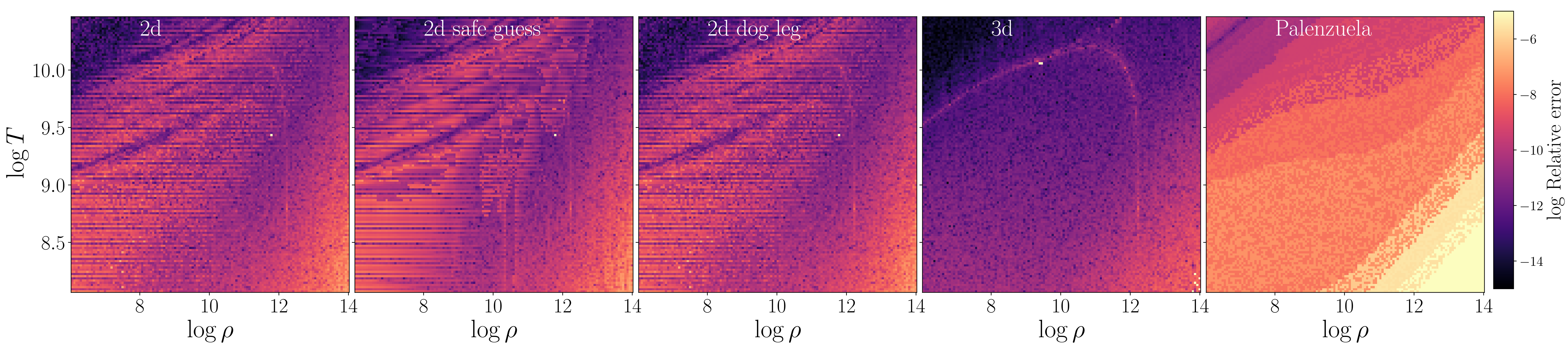
TCAN collaboration



- Goal: Do the most realistic simulations possible of NS mergers from a tight binary to a second after merger
- Using LORENE initial data to get two binary neutron stars.
- Evolve the initial data with IllinoisGRMHD/Spritz
- The simulation will be interpolated into HARM3d and used as initial conditions.
- Do different cases: direct collapse, delayed collapse, longer delayed collapse, stable NS, NSBH.
- Skynet used to obtain final nucleosynthesis
- For more information: compact-binaries.org

EOS interpolation

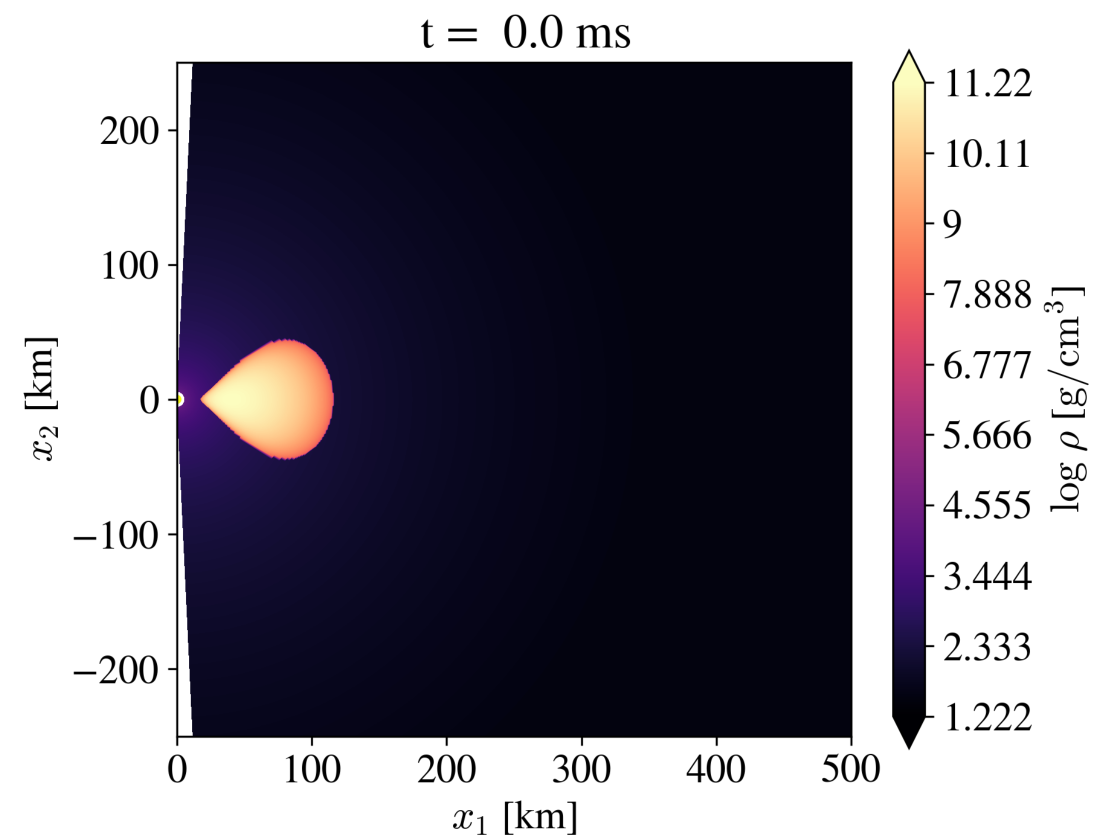
- Several con2prim routines added
- To test the EOS tables, we can use the relative error after the conversion from conserved variables to primitive variables.
- Here is the relative error comparing several routines. The density is in cgs, the temperature in K.



Based on Siegel et al. (2018)
Driver from O'Connor & Ott (2010), Schneider et al. (2017)

Murguia-Berthier et al. (2021)

Lessons/challenges about EOS



- Initial disk: isentropic with Fishbone-Moncrief enthalpy
- Disk boundary conditions: Enthalpy can be less than 1

- Atmospheric treatment: atmosphere can collapse!

Solution: set the density to decrease as a power+set the atmospheric density super low

- Need to add more robust con2prim

Leakage scheme

Charged beta-process

$$e^- + p \rightarrow n + \nu_e$$

$$e^+ + n \rightarrow p + \bar{\nu_e}$$

Plasmon decay

$$\gamma \rightarrow \nu_e + \bar{\nu_e}$$

$$\gamma \rightarrow \nu_x + \bar{\nu_x}$$

Electron-positron pair annihilation

$$e^- + e^+ \rightarrow \nu_e + \bar{\nu_e}$$

$$e^- + e^+ \rightarrow \nu_x + \bar{\nu_x}$$

Absorption (opacity source)

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu_e} + p \rightarrow n + e^+$$

Scattering with free nucleons

Based on Ruffert et al. (1996)
Galeazzi et al. (2013)
Bruenn (1985) and other papers

Leakage scheme

Source terms

$$\nabla_\mu T^{\mu\nu} = Q u^\nu$$

Heating/cooling rate

$$\nabla_\mu (n_\mathrm{e} u^\mu) = R$$

Absorption/emission rate

$$R_\nu^\mathrm{eff} = \frac{R_\nu}{1 + \frac{t_\mathrm{diff}}{t_\mathrm{emission,R}}}$$

$$Q_\nu^\mathrm{eff} = \frac{Q_\nu}{1 + \frac{t_\mathrm{diff}}{t_\mathrm{emission,Q}}}$$

Based on Ruffert et al. (1996)
Galeazzi et al. (2013), with modifications from Rosswog & Liebendörfer (2003),Siegel & Metzger (2018), O'Connor & Ott (2010)

Use spectrally averaged quantities

Leakage scheme

$$R_\nu^{\text{eff}} = \frac{R_\nu}{1 + \frac{t_{\text{diff}}}{t_{\text{emission,R}}}}$$

$$Q_\nu^{\text{eff}} = \frac{Q_\nu}{1 + \frac{t_{\text{diff}}}{t_{\text{emission,Q}}}}$$

Based on Ruffert et al. (1996)
Galeazzi et al. (2013)

If the diffusion timescale is large (opaque region):

$$R_\nu^{\text{eff}} = n_\nu / t_{\text{diff}}$$
$$Q_\nu^{\text{eff}} = \epsilon_\nu / t_{\text{diff}}$$

In transparent region:

$$\kappa(\bar{\nu}_e) = \kappa_s(\bar{\nu}_e, n) + \kappa_s(\bar{\nu}_e, p) + \kappa_a(\bar{\nu}_e, p)$$
$$\kappa(\nu_e) = \kappa_s(\nu_e, n) + \kappa_s(\nu_e, p) + \kappa_a(\nu_e, n)$$

Opacities for each neutrino/antineutrino and for each rate (R,Q)

$$R_\nu^{\text{eff}} = R_\nu$$

$$R_\nu = R_{\beta-\text{charged}} + R_{\text{plasmon decay}} + R_{e^- e^+}$$

(same for Q)

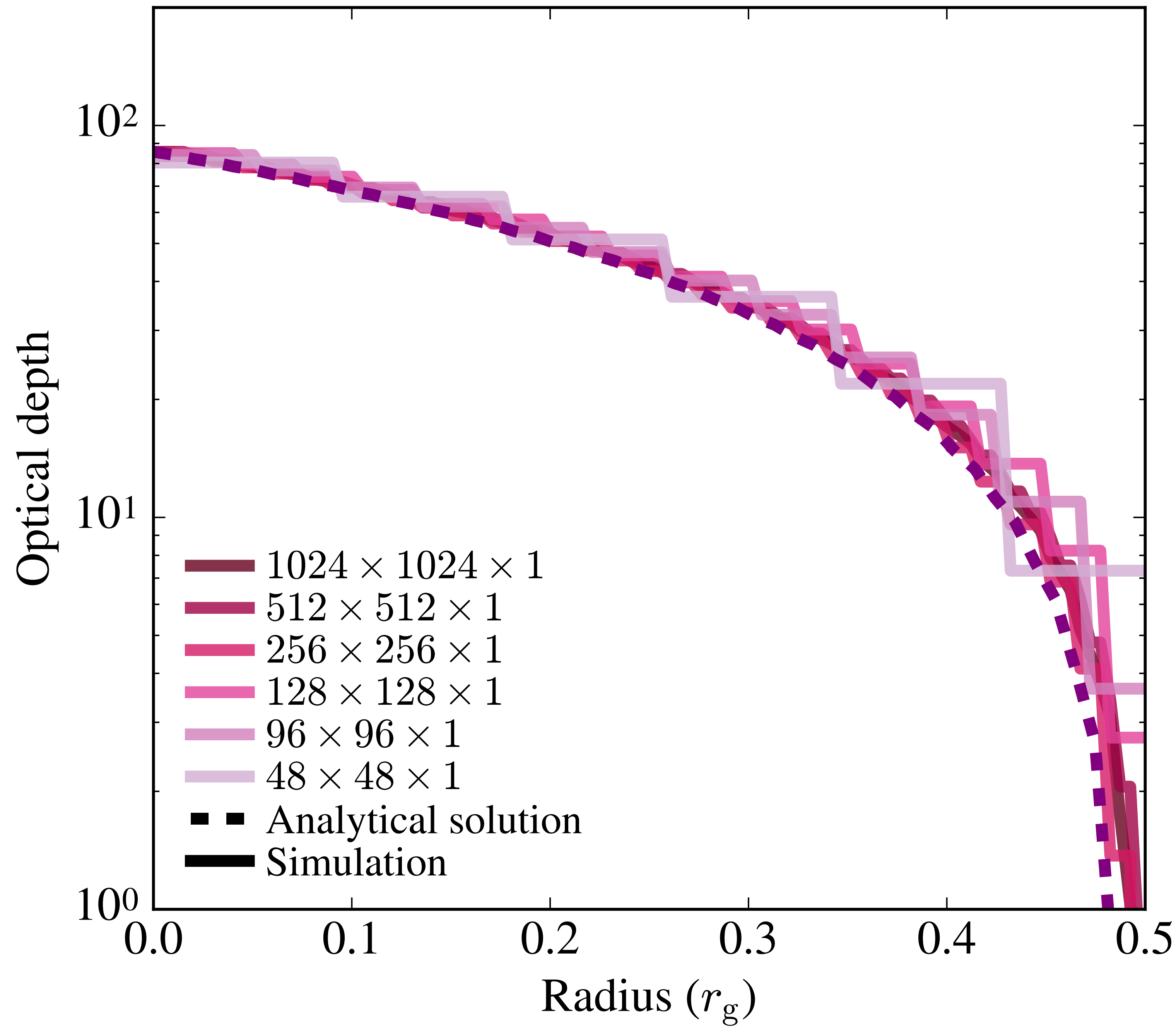
Leakage scheme: optical depth

$$\tau = \int_{s_1}^{s_2} \kappa ds$$

Testing a sphere of constant density and temperature

Neilsen et al. (2014), Siegel & Metzger (2018)

$$\min(\tau_{\nu,\mathrm{neigh}} + \bar{\kappa_\nu}(\bar{\gamma_{ab}} dx^a dx^b)^{1/2})$$



With our convergence criterion:

Murguia-Berthier et al. (2021)

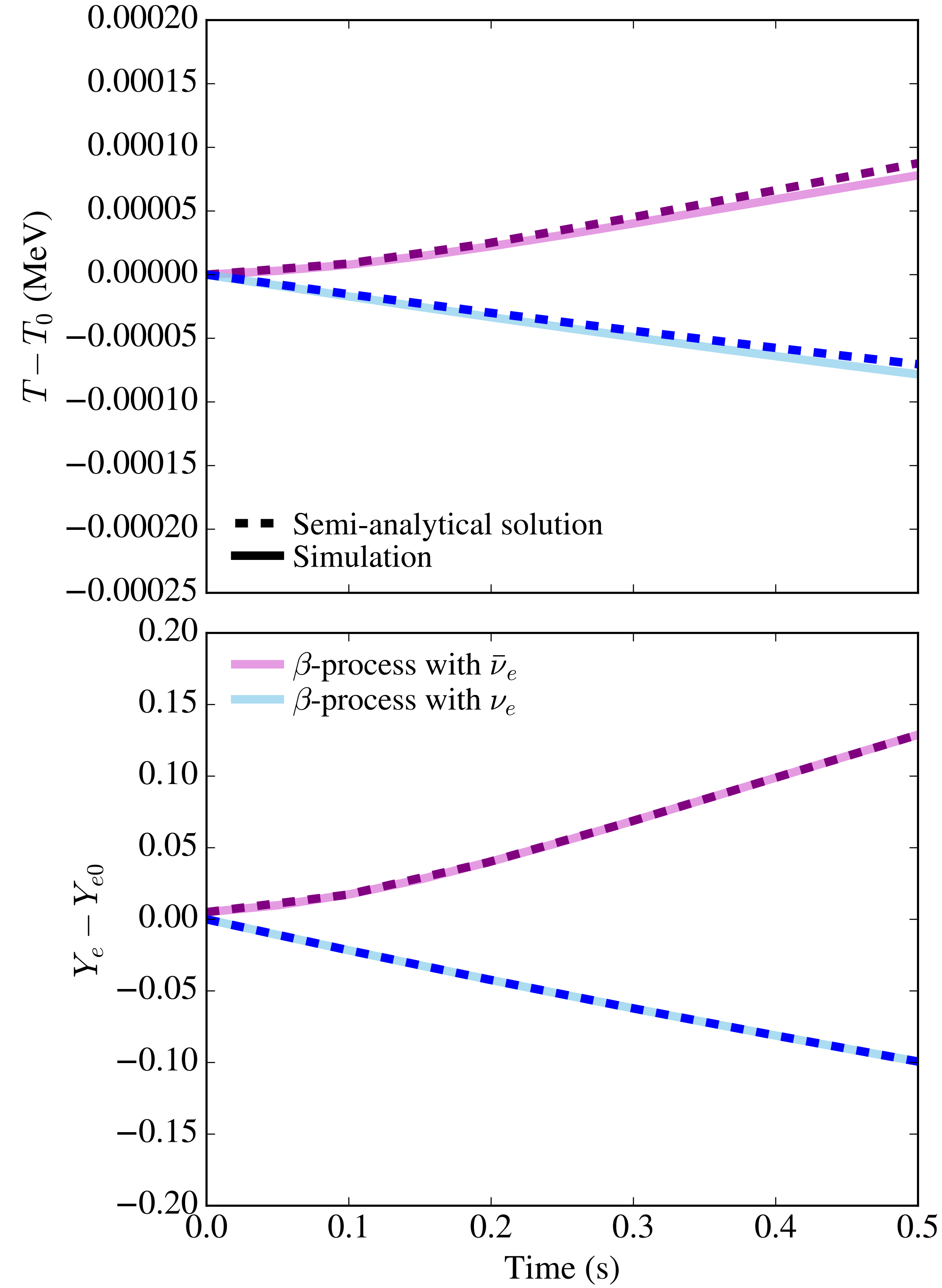
Optical depth to electron antineutrinos (R)

Leakage scheme testing

Evolution of isotropic, optically thin, constant density gas

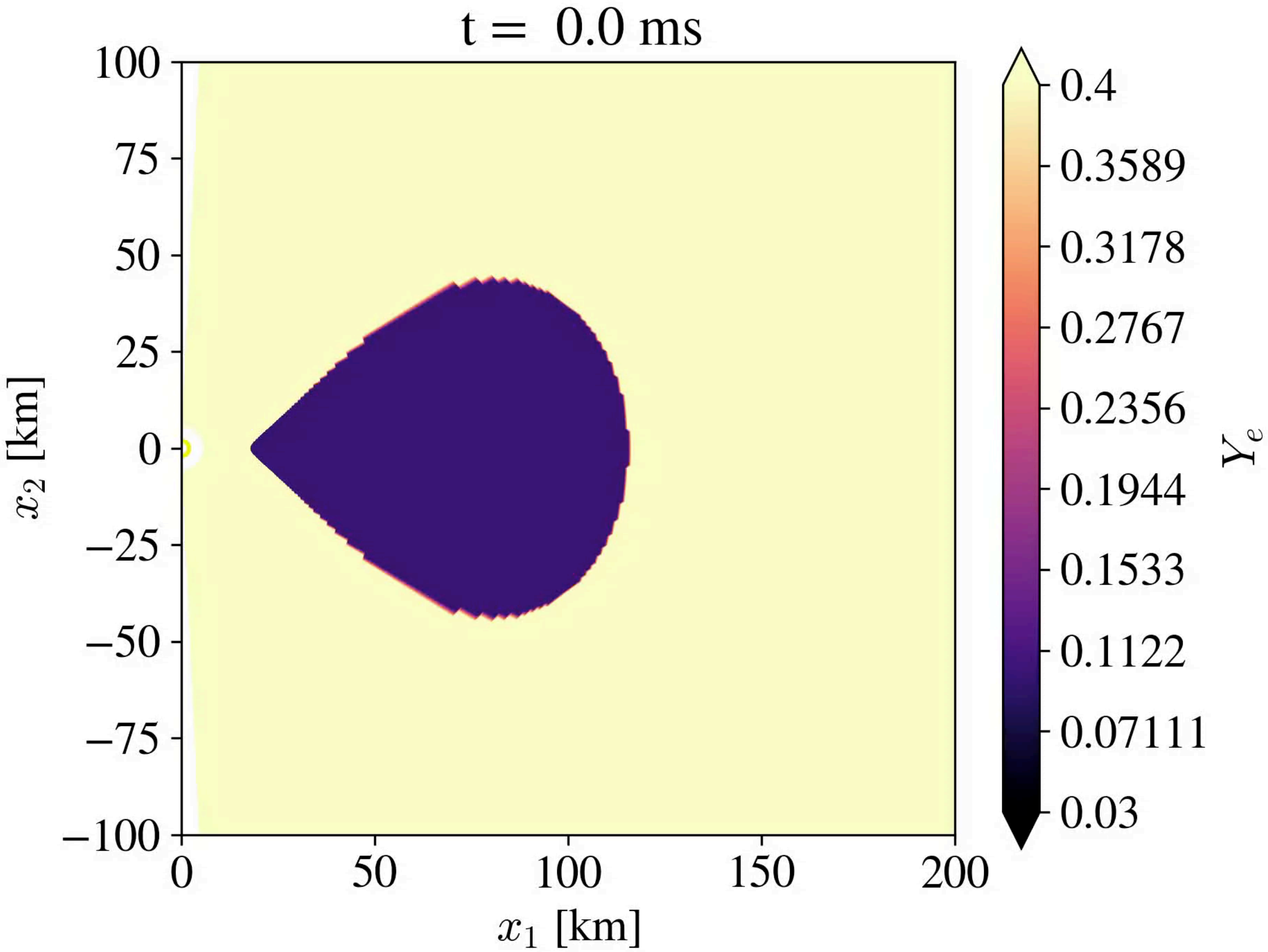
Ryan et al. (2015)
Miller at al. (2019)

$$\partial_t u = Q$$
$$\partial_t Y_e = R/\rho$$



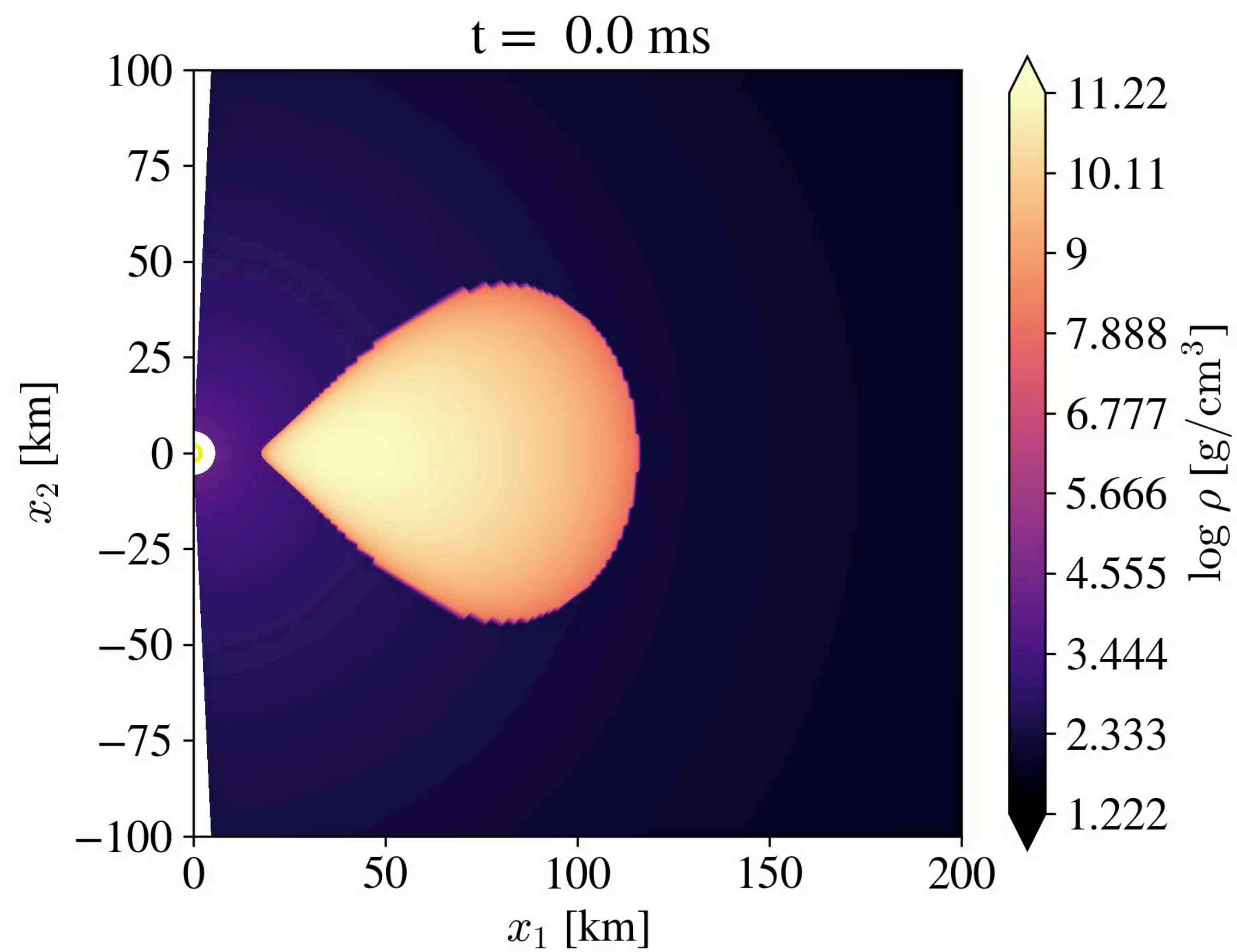
Murguia-Berthier et al. (2021)

Results: magnetized accretion disk with HARM3D+NUC



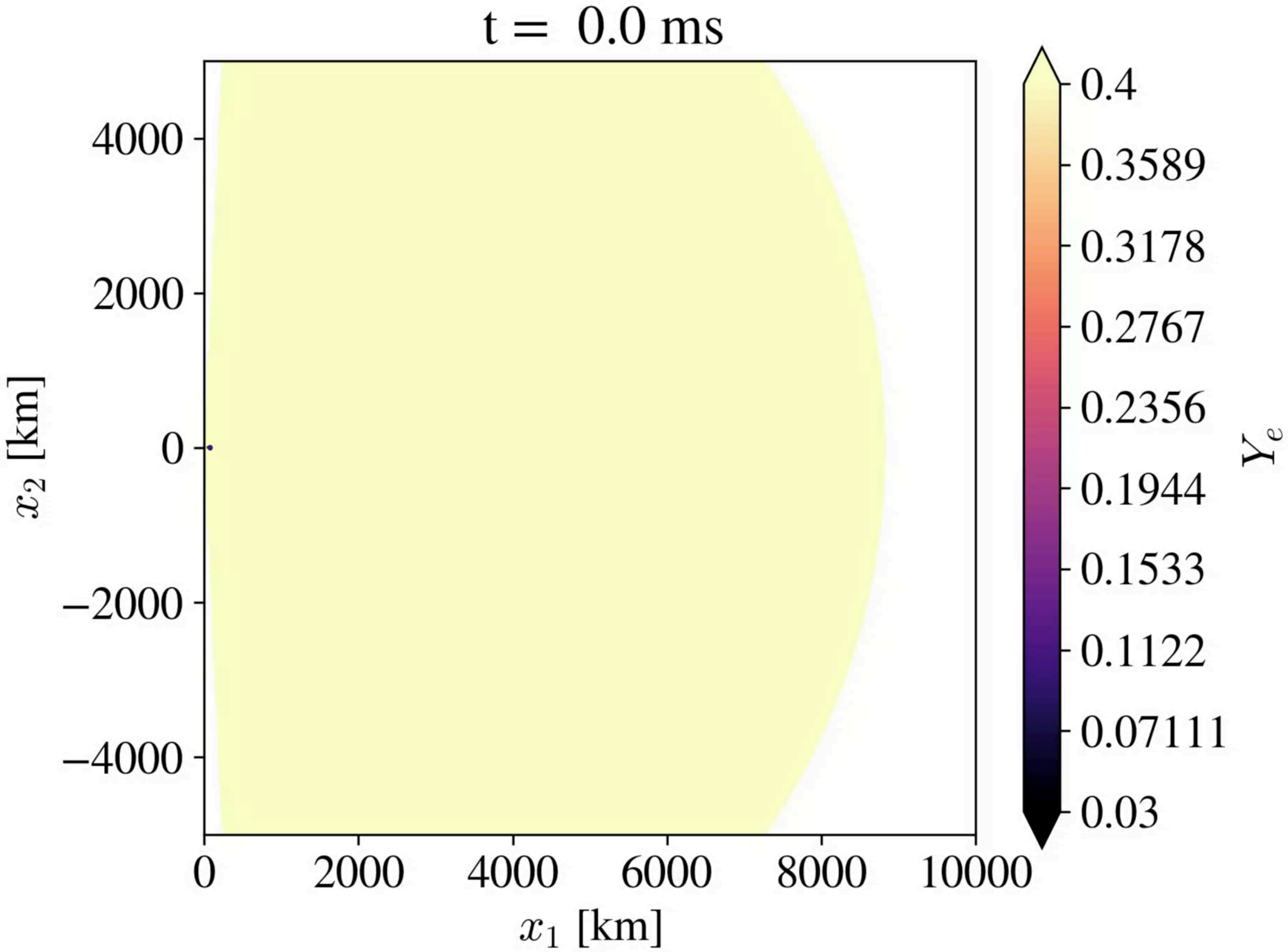
Parameter	Value
Disk radius of maximum pressure	$9r_g$
Disk inner radius	$4r_g$
Mass of disk	$0.03M_\odot$
Y_e in the disk	0.1
Specific entropy in the disk	7 k_b/baryon
β	100
BH spin	0.9375
BH mass	$3M_\odot$
Specific enthalpy at boundary	0.9977 [code units]
Temperature at radius of maximum pressure	4.4 MeV

Isentropic, FM magnetized torus (poloidal magnetic field) with realistic EOS+neutrino cooling



Murguia-Berthier et al. (2021)

Results: magnetized accretion disk with HARM3D+NUC



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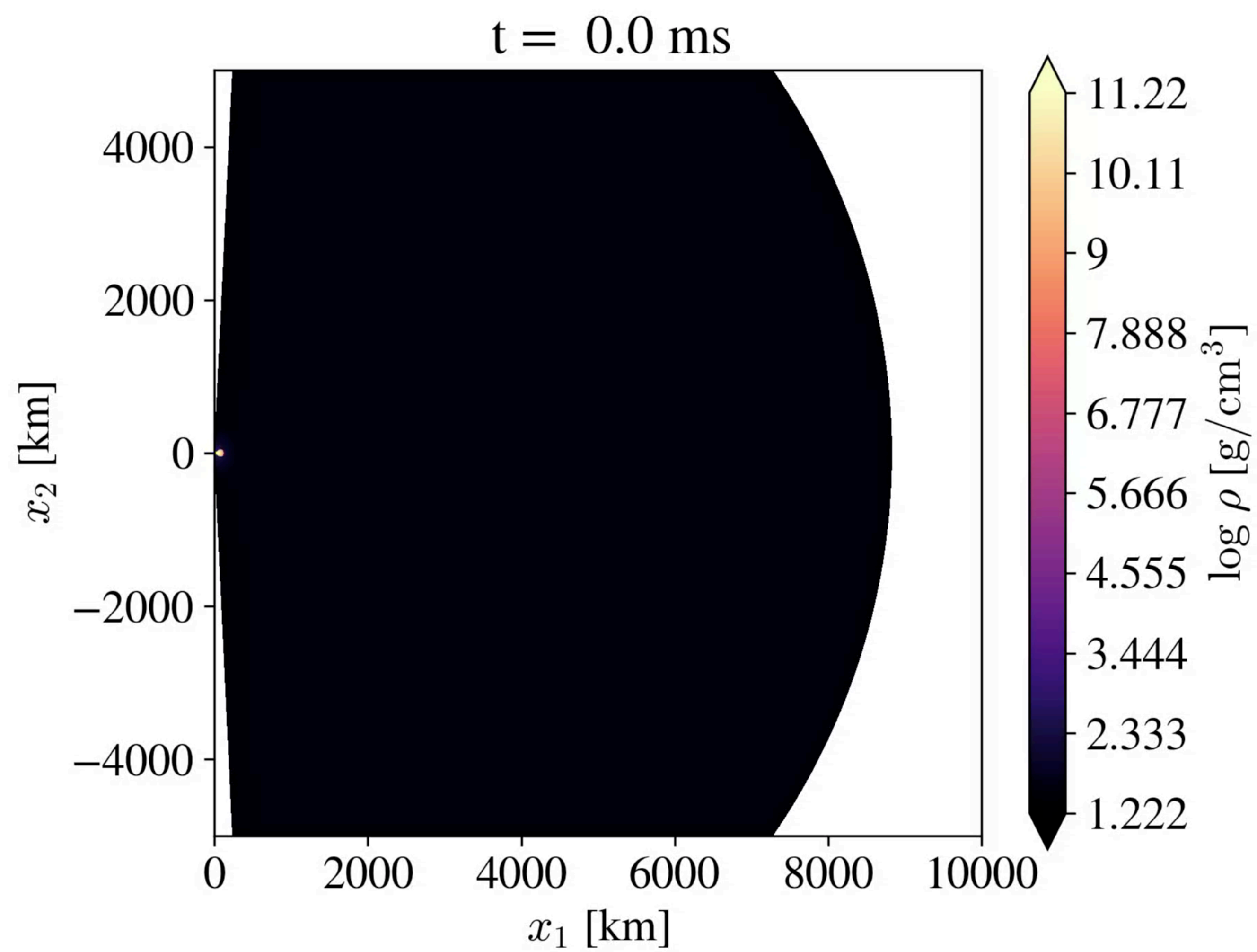
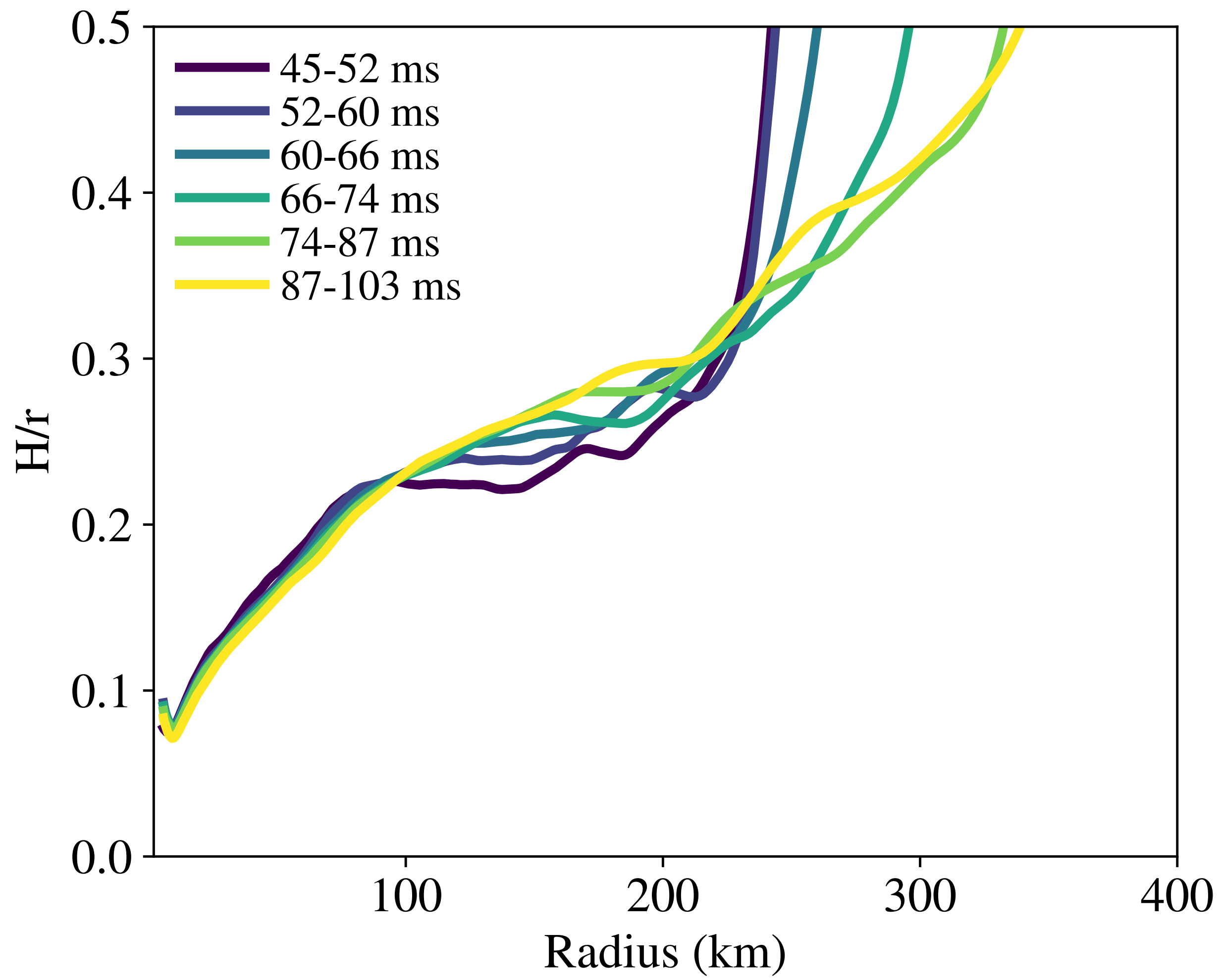
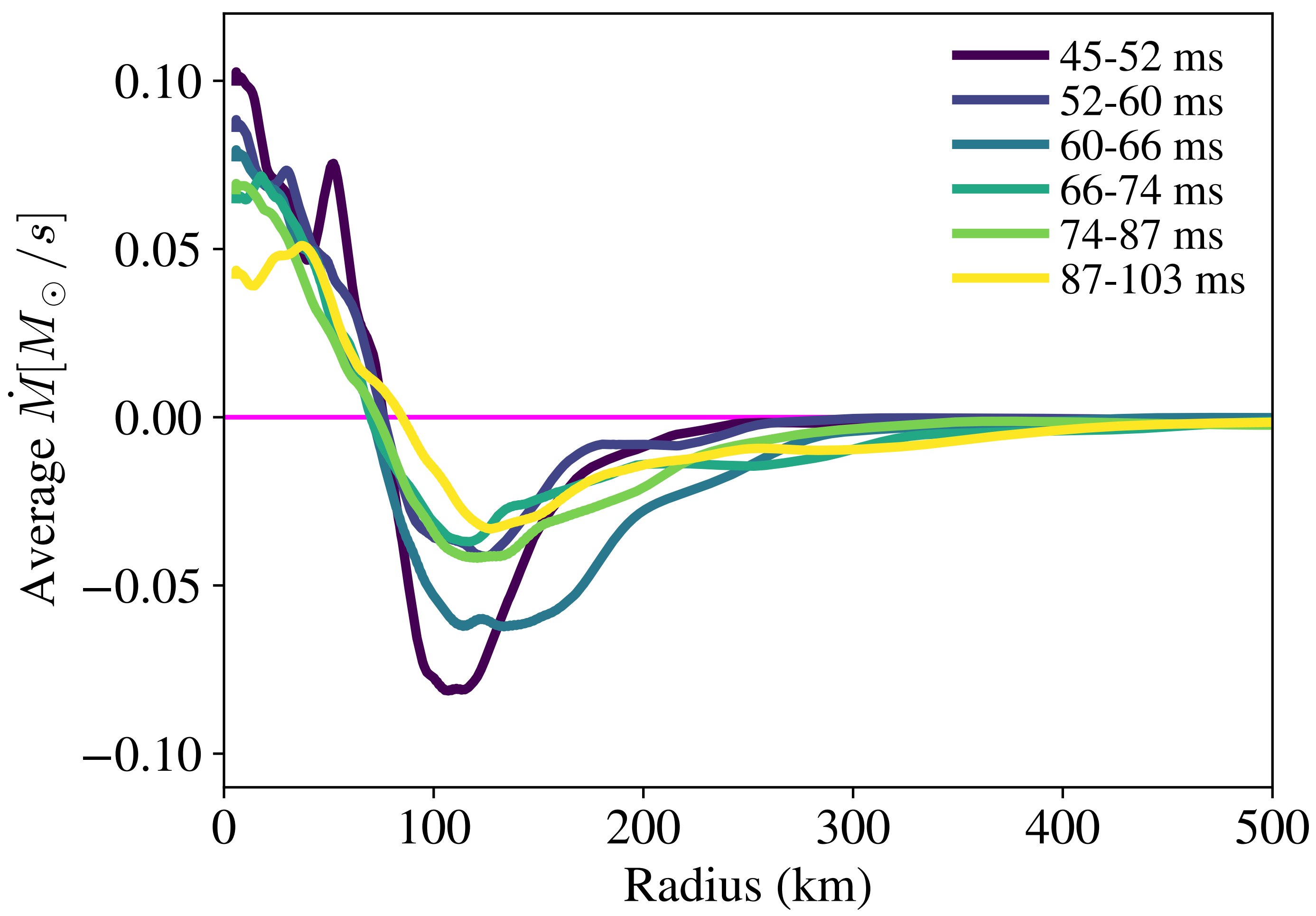


Isentropic, FM magnetized torus (poloidal magnetic field) with realistic EOS+neutrino cooling

Murguia-Berthier et al. (2021)

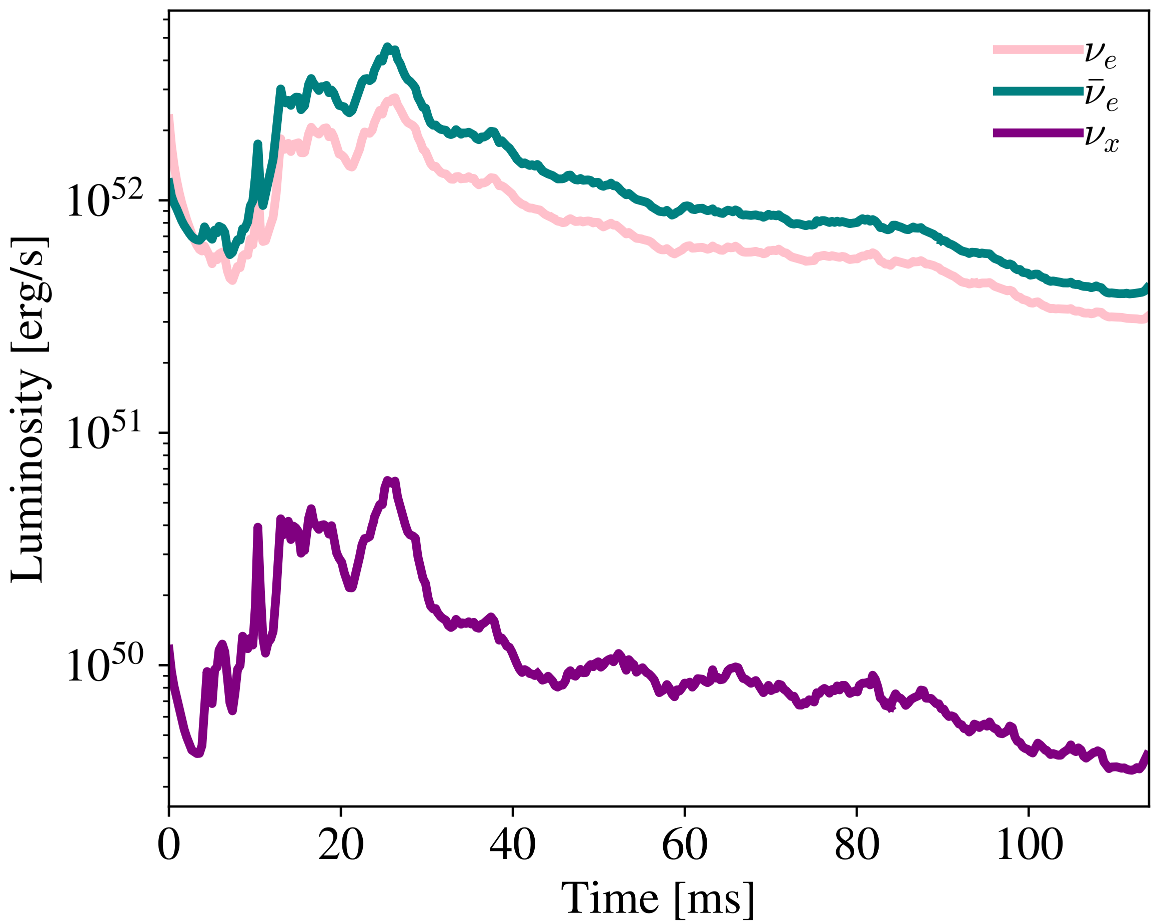
Results: magnetized accretion disk with HARM3D+NUC

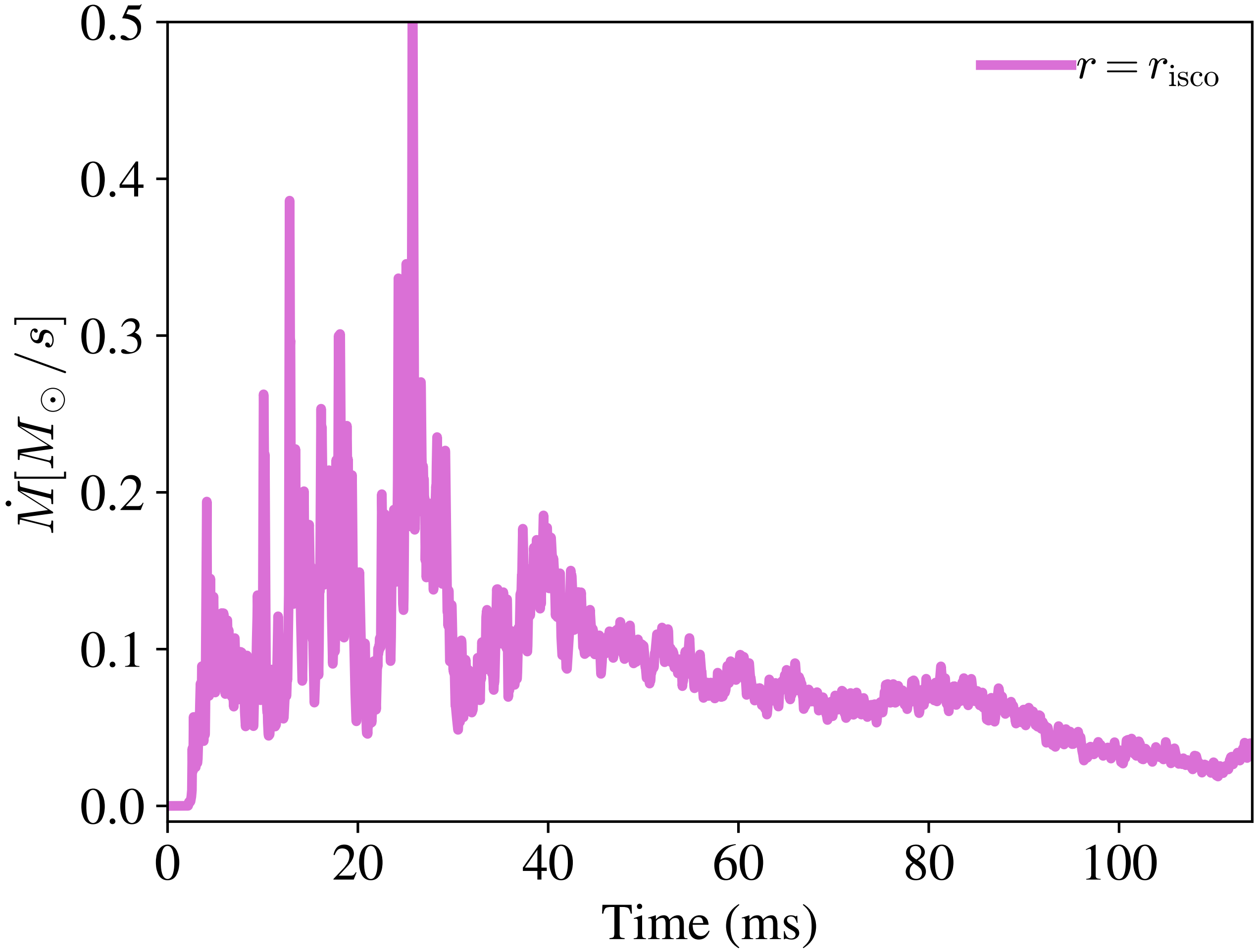




Murguia-Berthier et al. (2021)

Results: magnetized accretion disk with HARM3D+NUC





Murguia-Berthier et al. (2021)

Challenges regarding the neutrino treatment

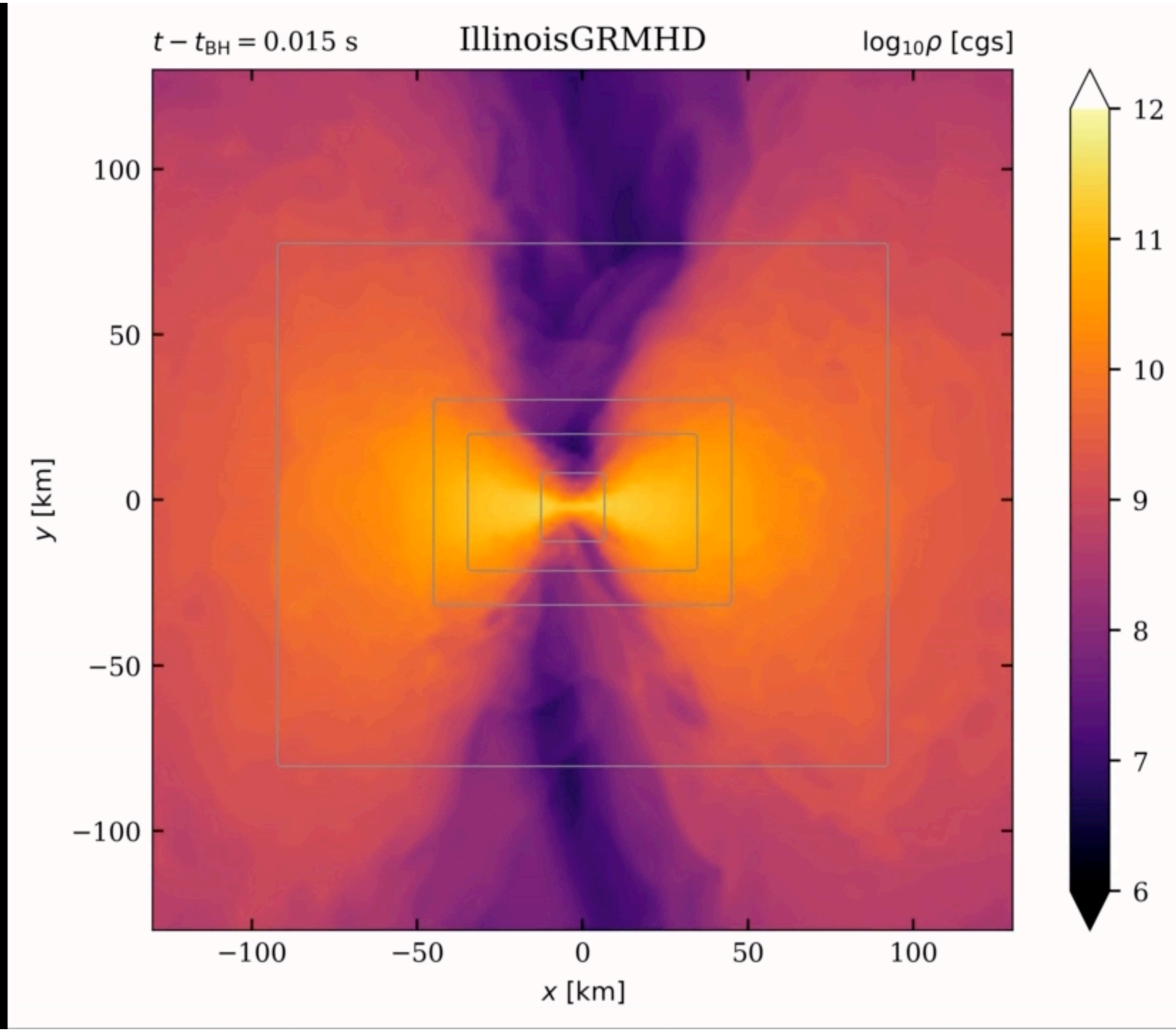
Neutrino leakage is very simple, grey, yet computationally efficient

Moment based transport has to be closed with an analytical closure, leading to non-convergence in the Boltzmann equation.

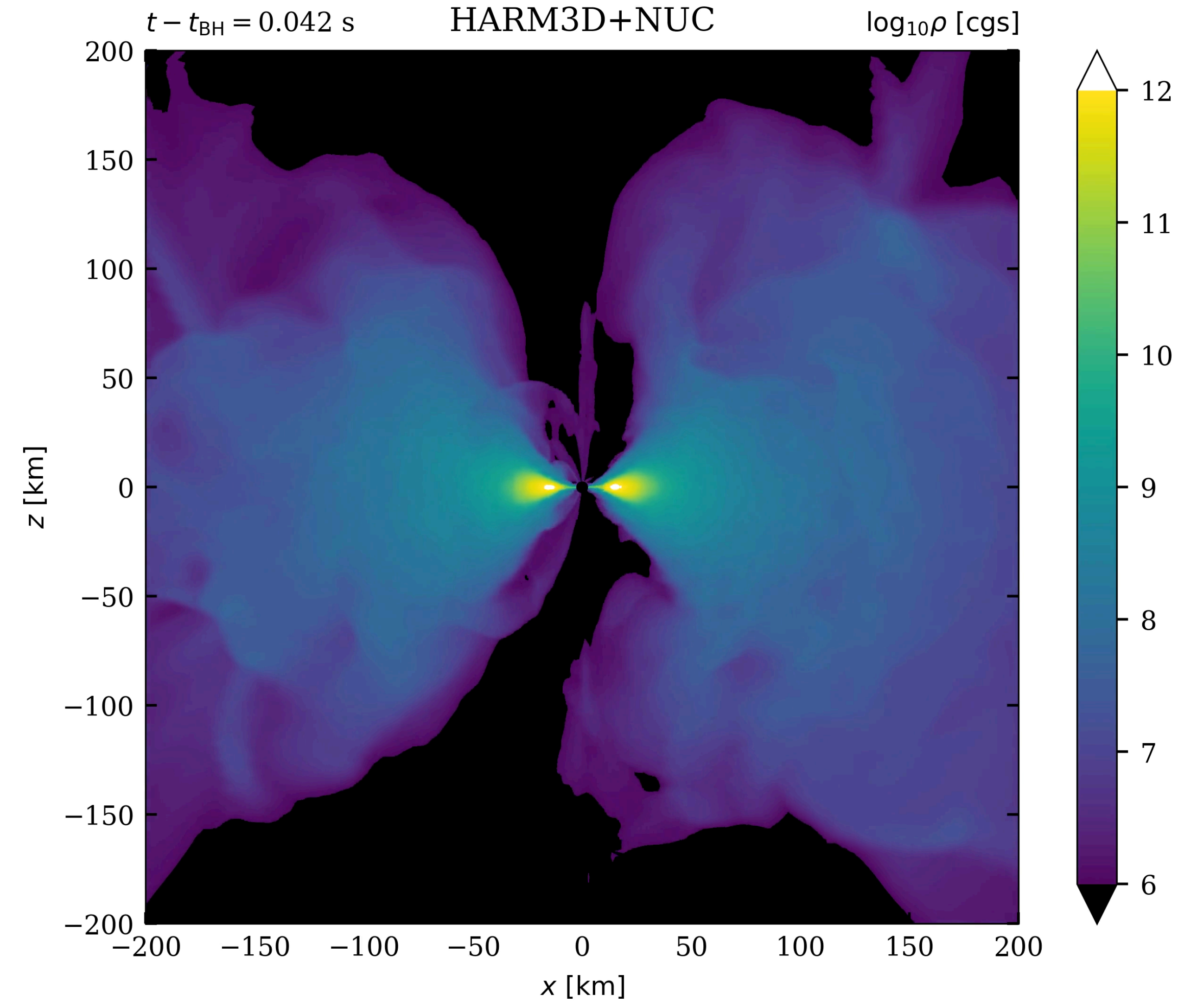
Monte Carlo methods are still under development

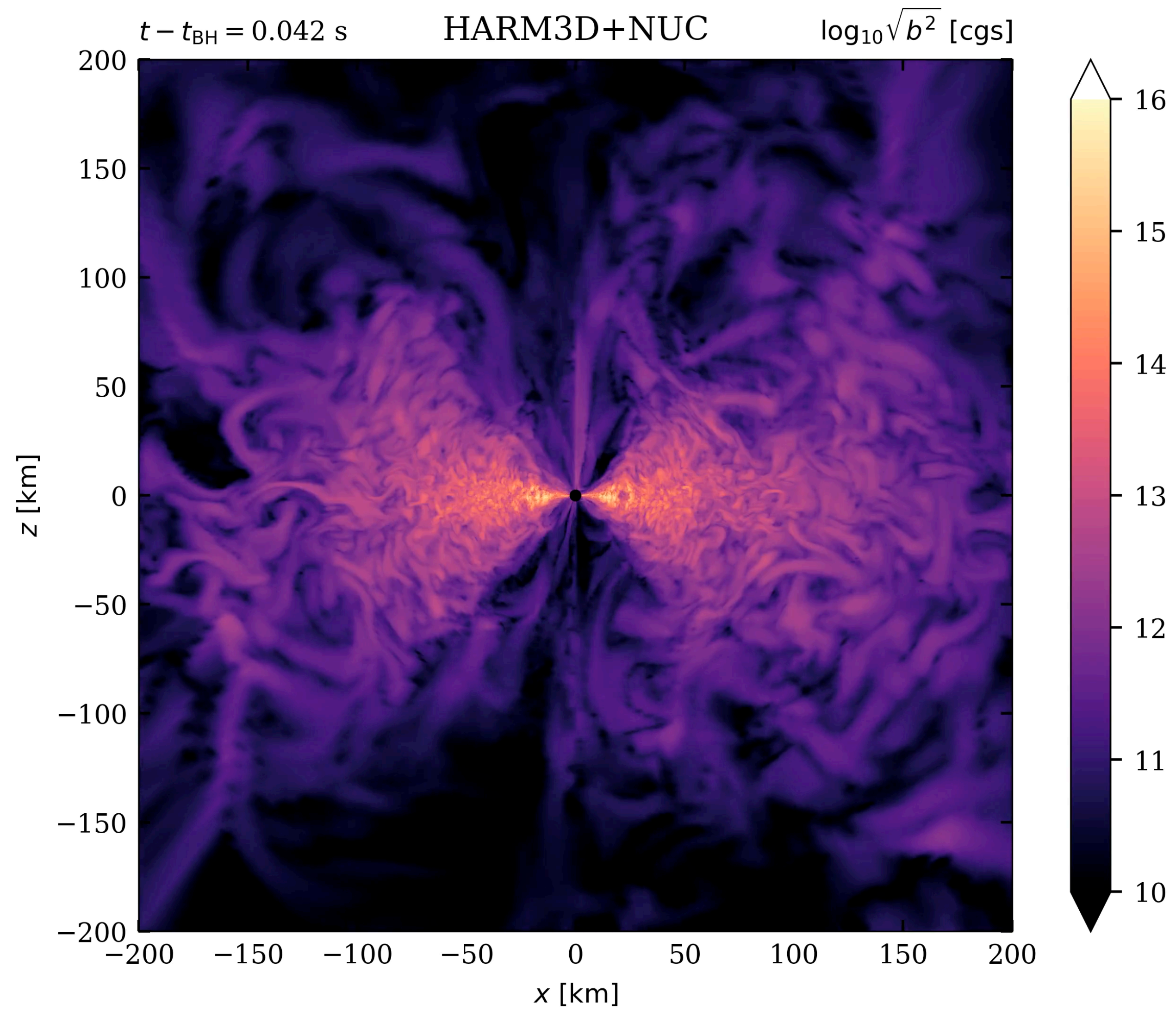
See Foucart 2022 for a review

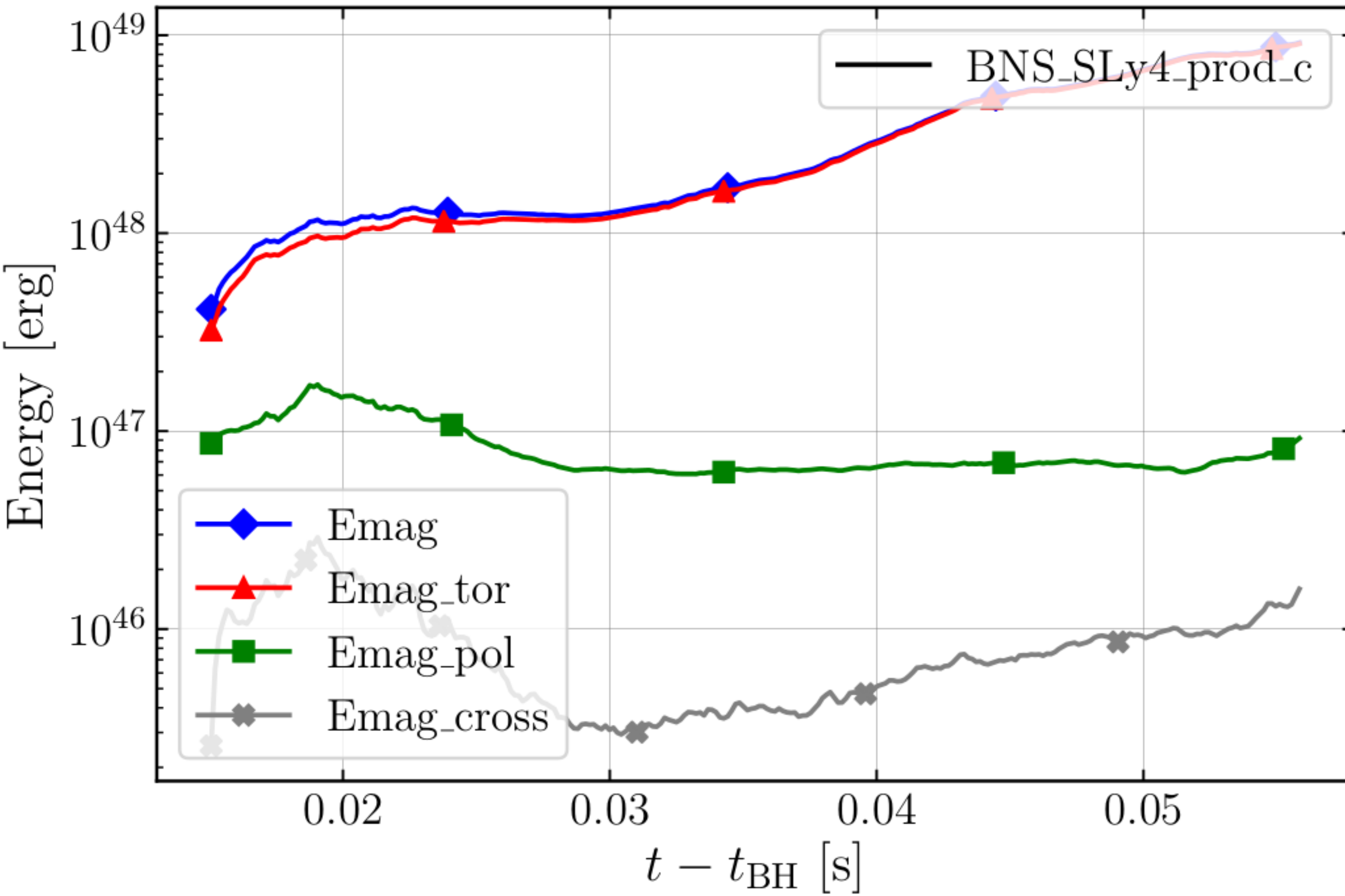
The future: TCAN collaboration



Courtesy of Federico Lopez Armengol


$t - t_{BH} = 0.042$ s
HARM3D+NUC
$\log_{10}\rho$ [cgs]
z [km]
x [km]


$t - t_{BH} = 0.042$ s
HARM3D+NUC
$\log_{10}\sqrt{b^2}$ [cgs]
z [km]
x [km]



BNS_SLy4_prod_c
Emag
Emag_tor
Emag_pol
Emag_cross
Energy [erg]
10^{49}
10^{48}
10^{47}
10^{46}
0.02
0.03
0.04
0.05
$t - t_{\rm BH}$ [s]

Conclusions

- We performed simulations on a magnetized torus and studied the impact of neutrinos and recombination to alpha-particles.

- We have the code HARM3D+NUC with tracer particles ready and tested to perform GRMHD simulations with a tabulated EOS and neutrinos!

- We are performing the hand-off in TCAN.

¡Gracias!