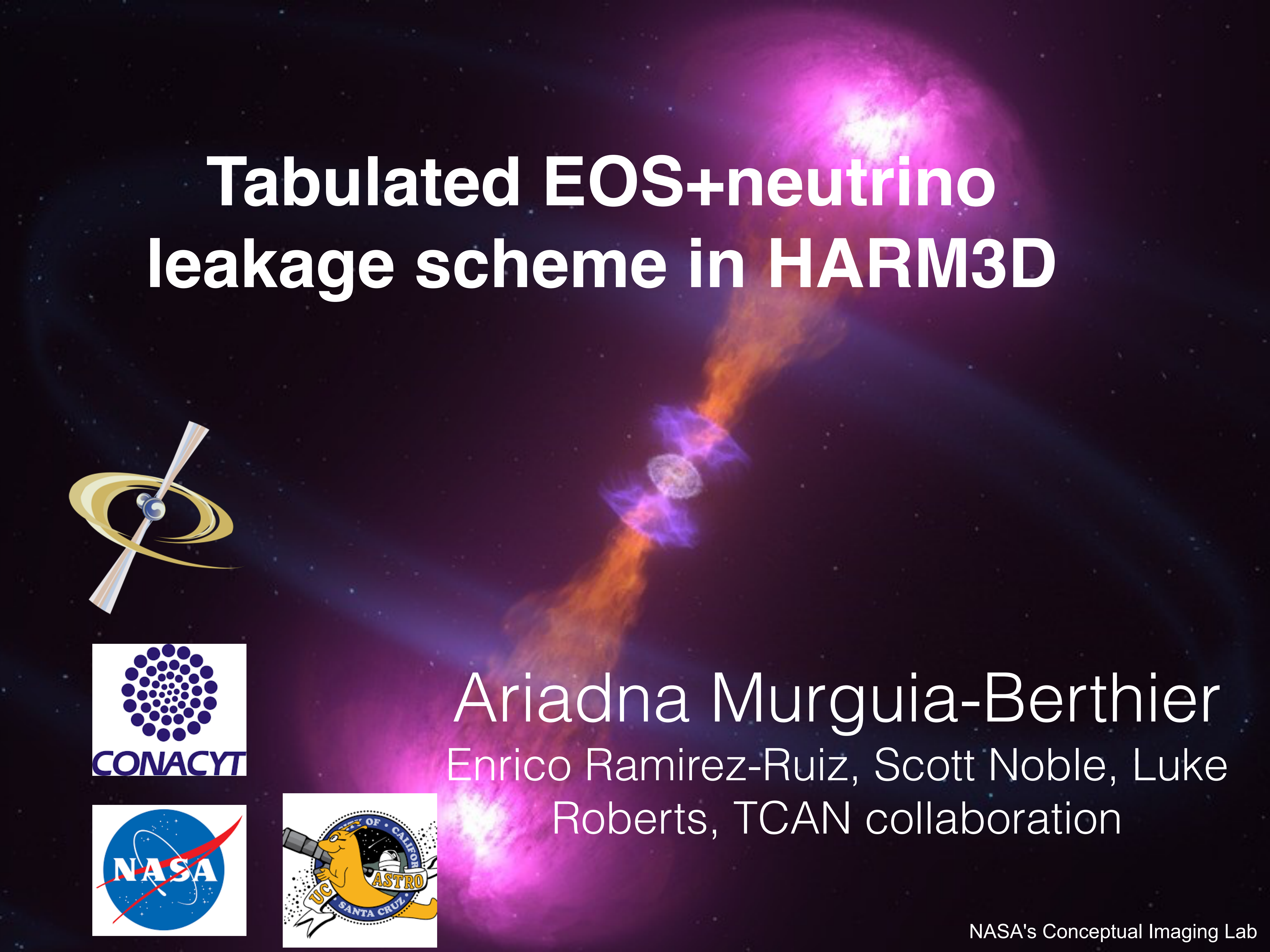


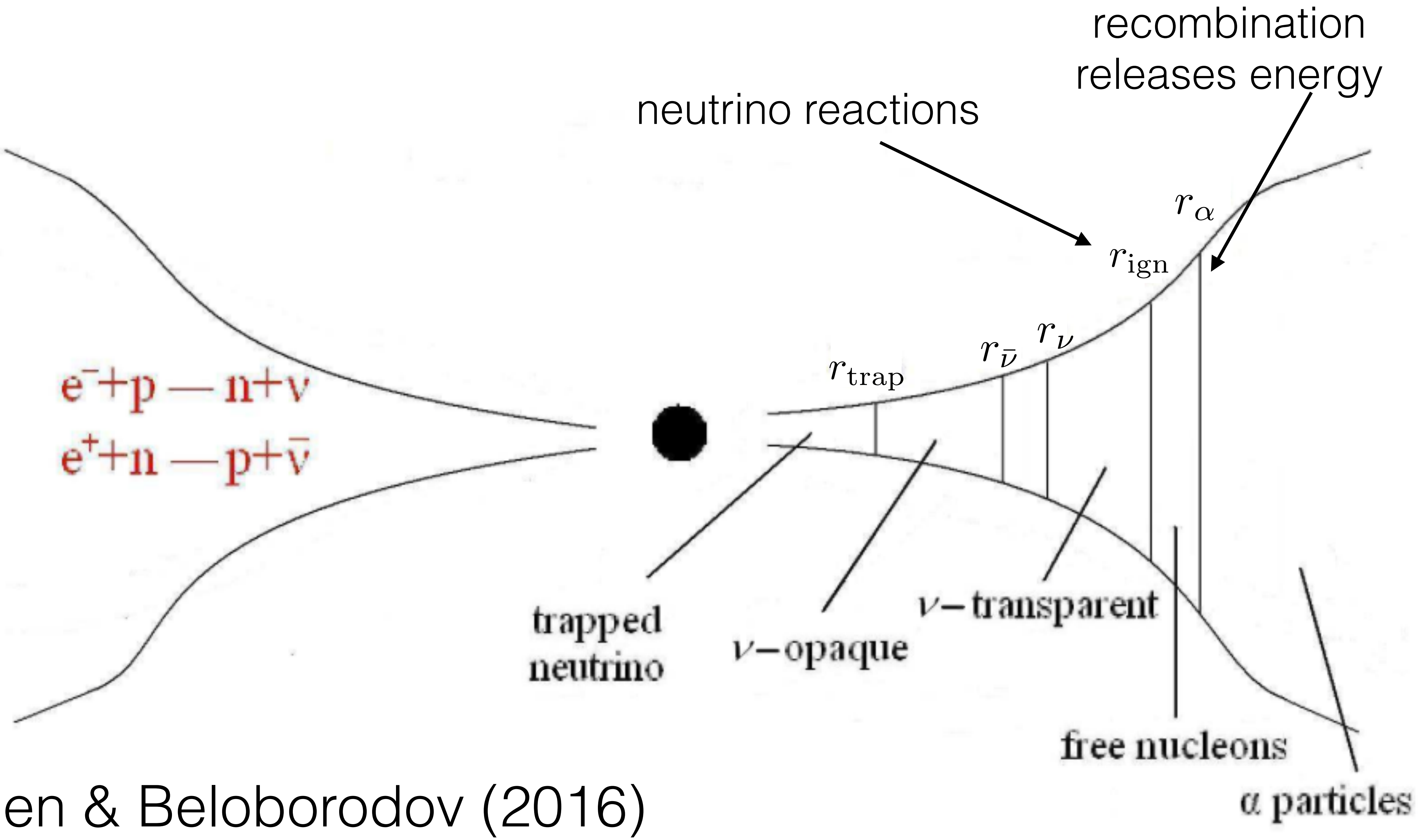
Tabulated EOS+neutrino leakage scheme in HARM3D

Ariadna Murguia-Berthier

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

NASA's Conceptual Imaging Lab

Physics in the accretion disk



recombination releases energy

neutrino reactions

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

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

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

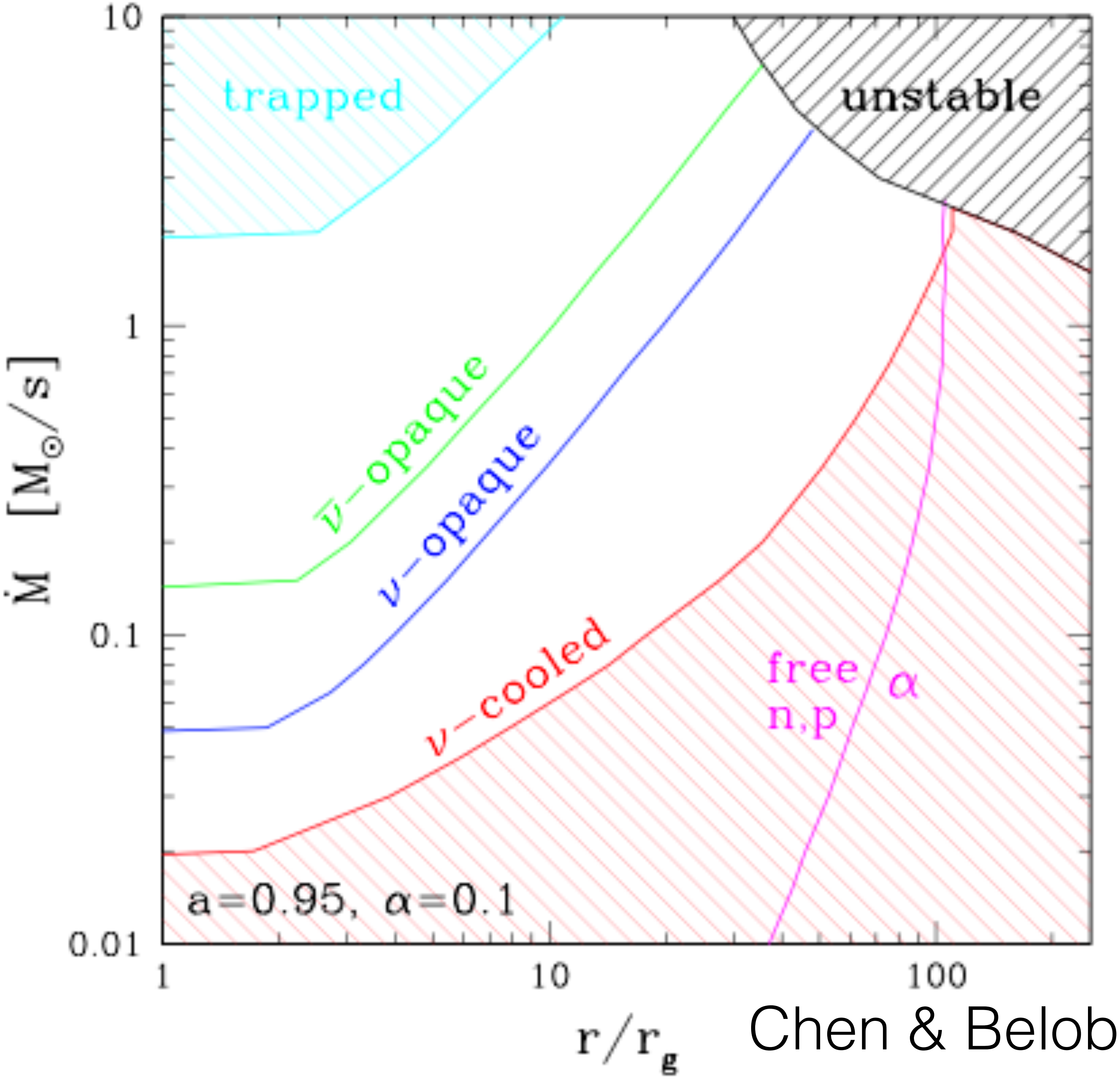
Absorption (opacity source)

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

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

Accretion disk

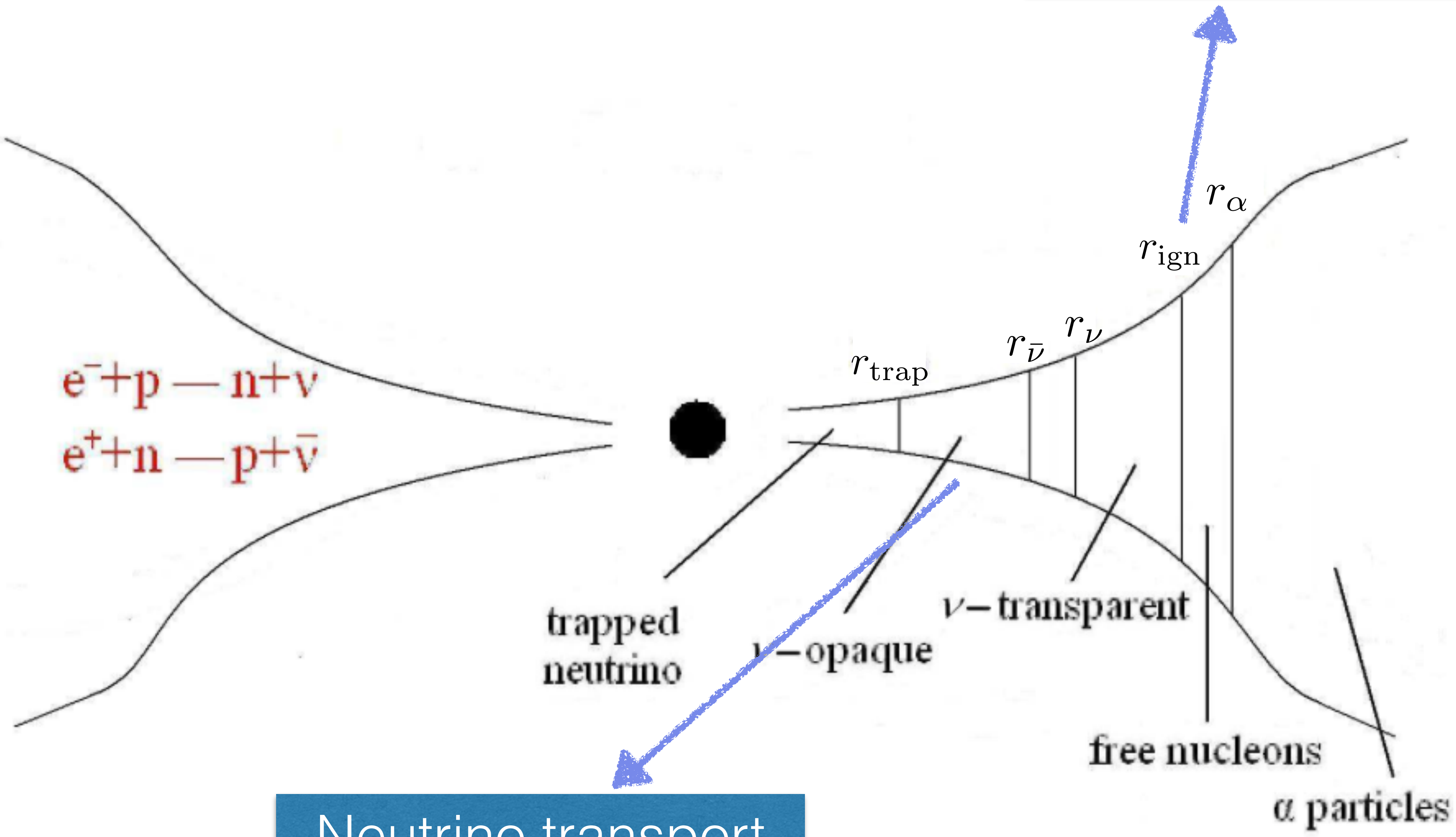
Gravitationally unstable (Toomre Q)



Chen & Beloborodov (2016)

Accretion disk

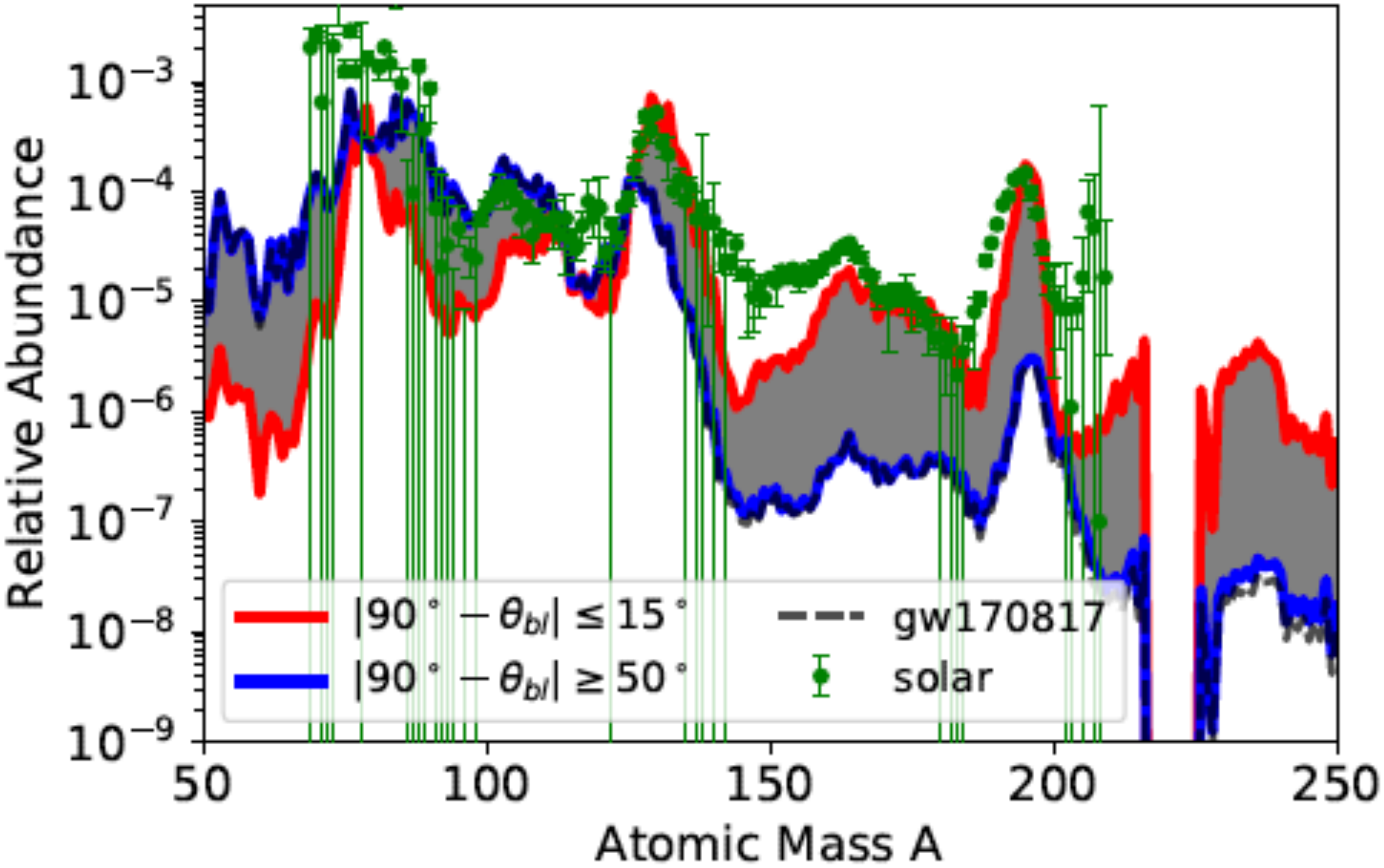
Realistic EOS



Neutrino transport
(or leakage scheme)

Chen & Beloborodov (2016)

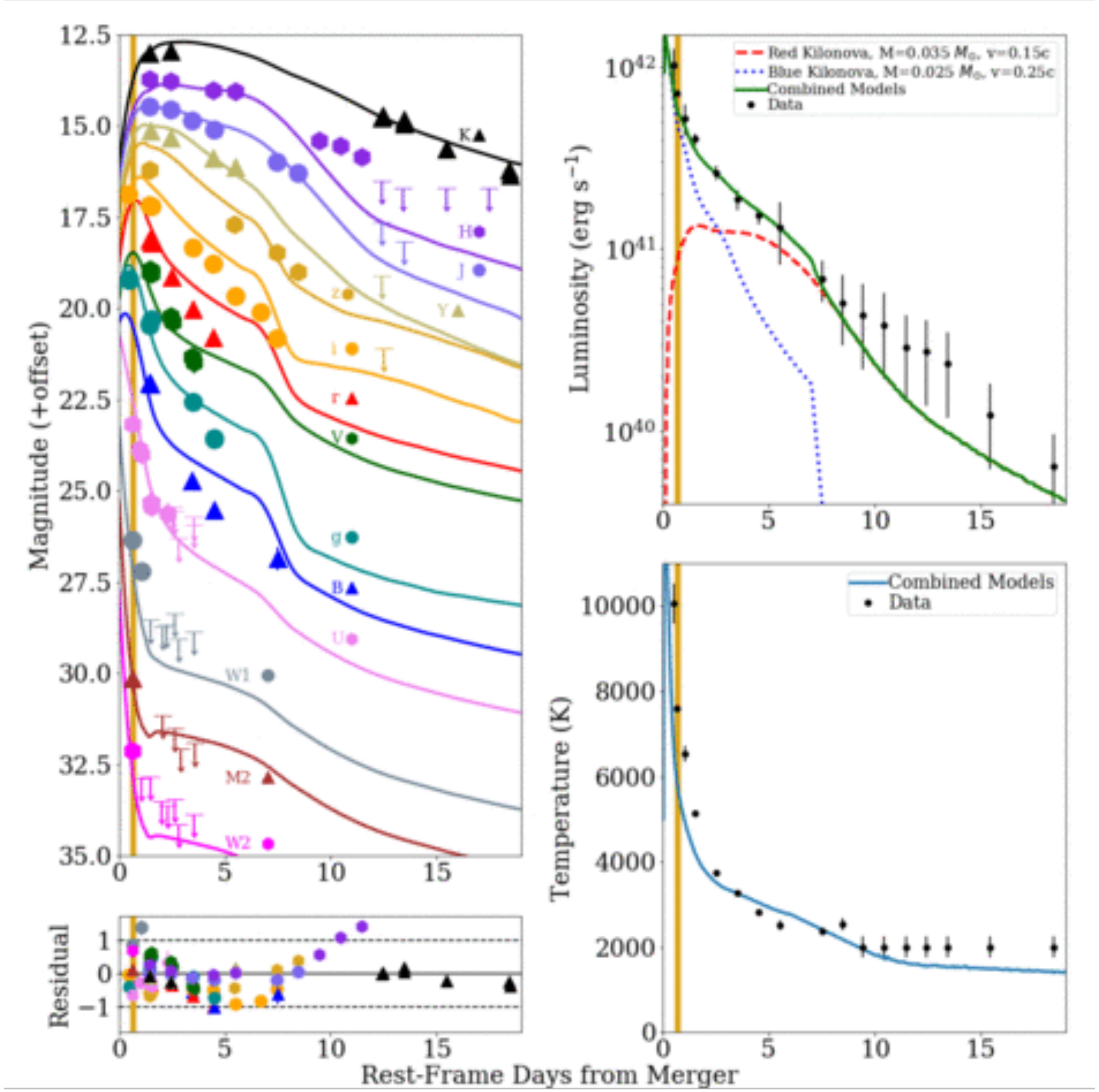
Nucleosynthesis in accretion disks



The final composition is still uncertain

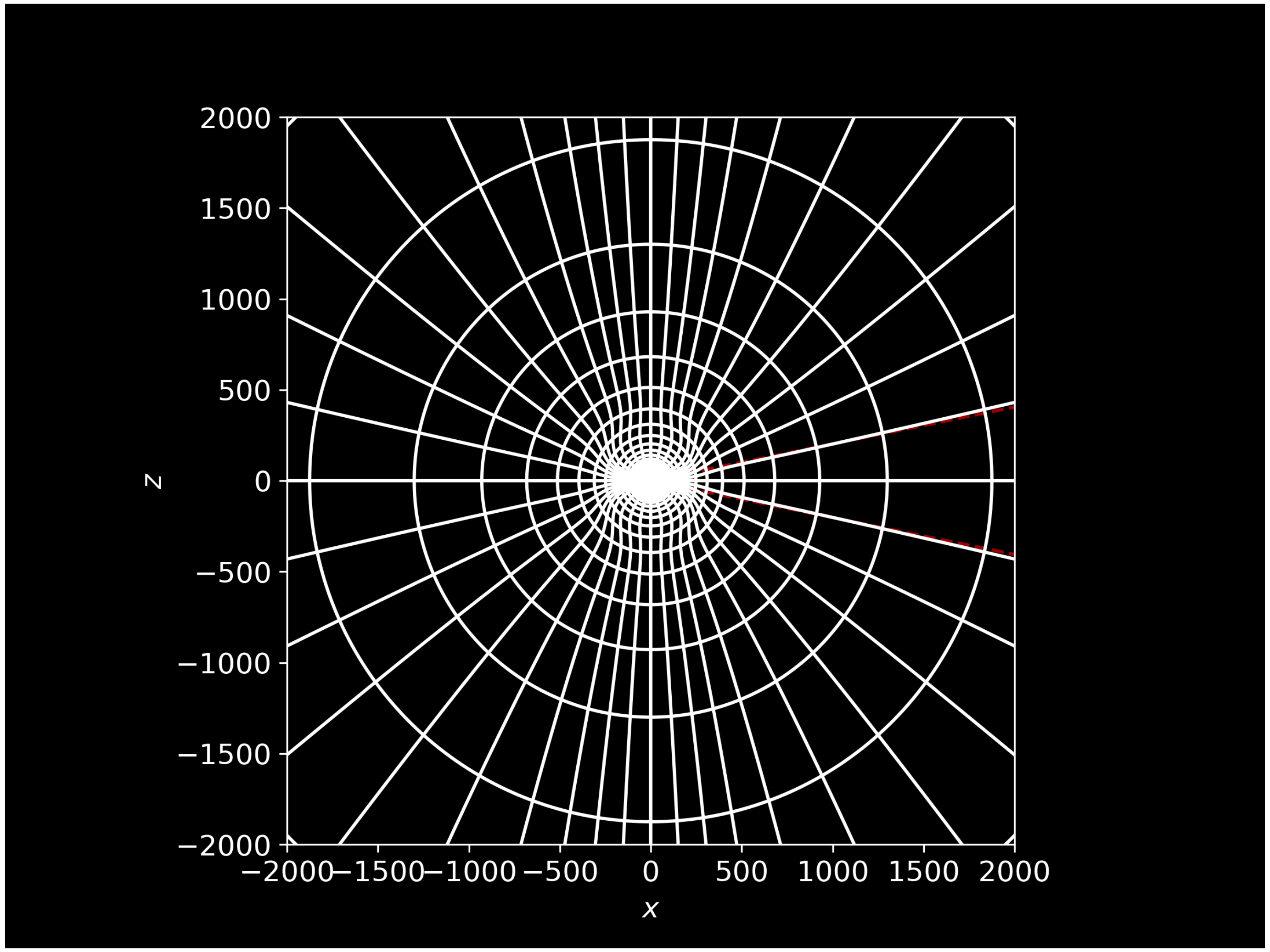
e.g. Janiuk et al. (2014) Wu et al. (2016), Siegel & Metzger (2018), Fernandez et al. (2018), Foucart et al. (2018), Miller et al. (2019a)

Kilonova emission: GW170817



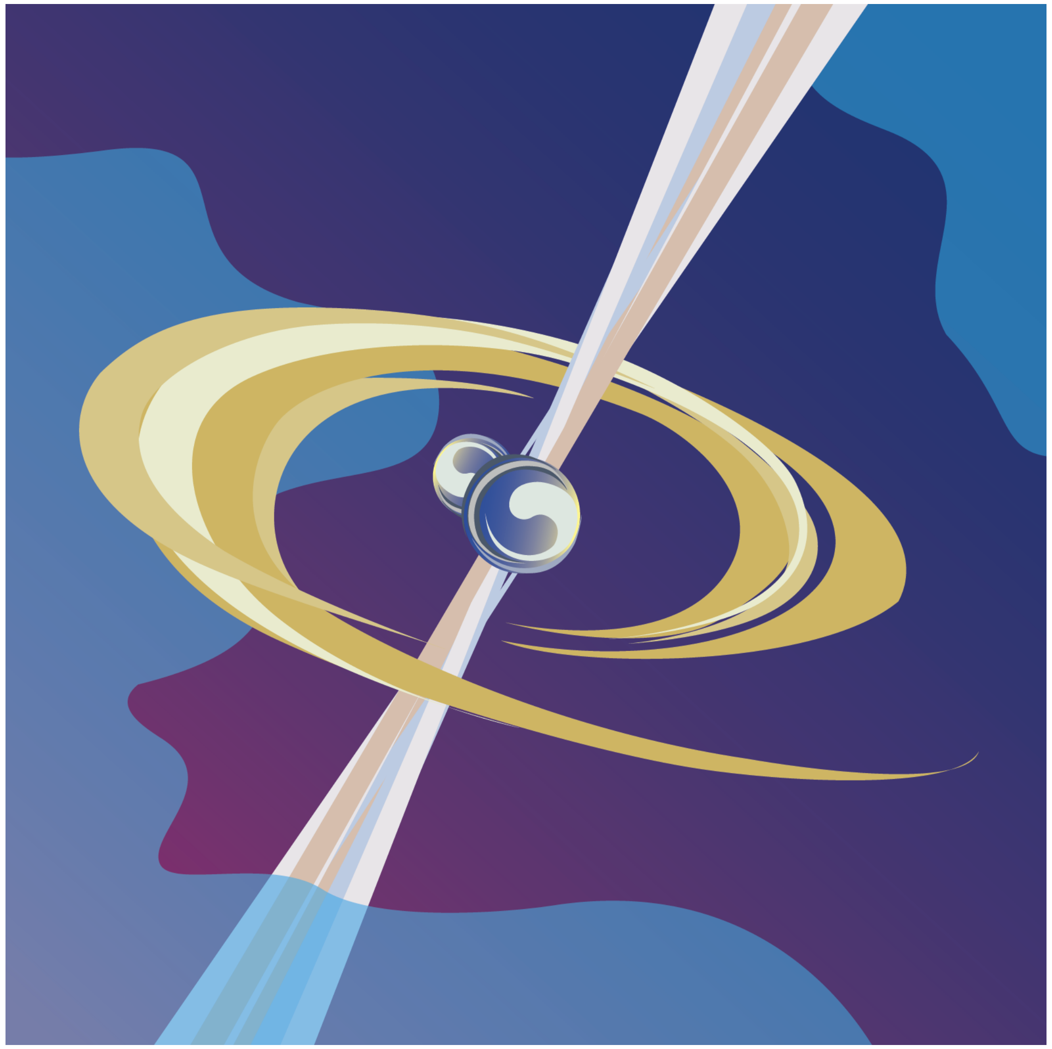
Kilpatrick & **1M2H, including Murguia-Berthier** (2017)

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)

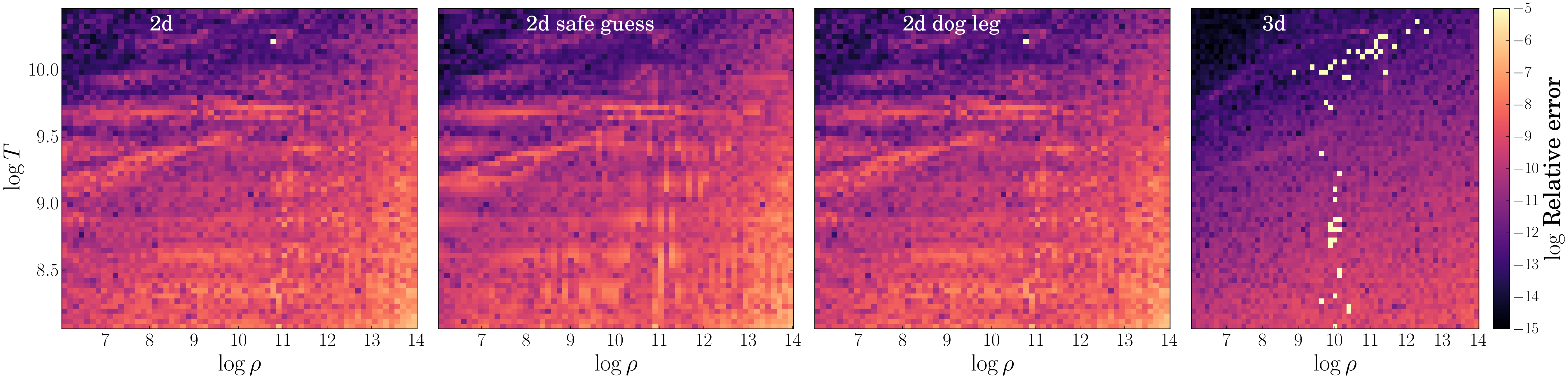
TCAN collaboration



- 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.



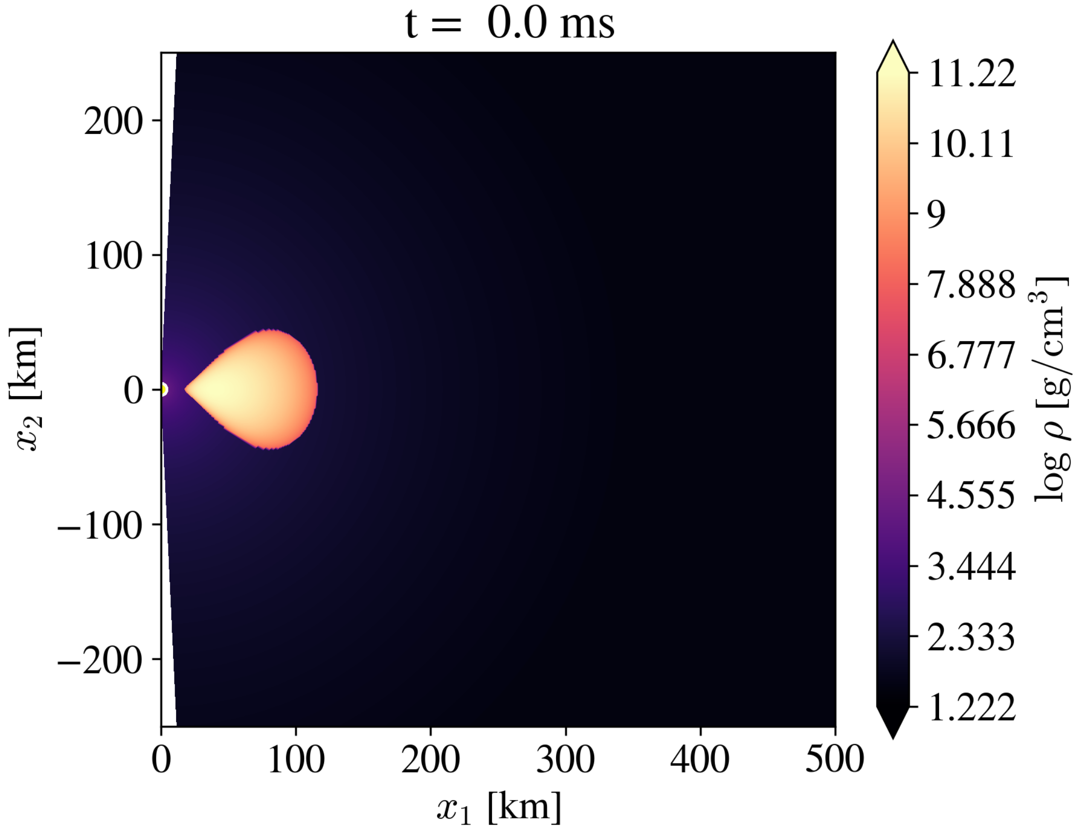
Based on Siegel et al. (2018)
Driver from O'Connor & Ott (2010),
Schneider et al. (2017)

Murguia-Berthier et al. (2021 in prep)

Lessons 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

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

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

The effective rates are an interpolation between the optically thin and thick regime

$$t_{\mathrm{diff}} = \frac{6\tau^2}{c\kappa_{\nu_i}}$$

$$t_{\mathrm{emission,R}} = R_{\nu_i} / n_{\nu_i}$$

$$t_{\mathrm{emission,Q}} = Q_{\nu_i} / \varepsilon_{\nu_i}$$

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

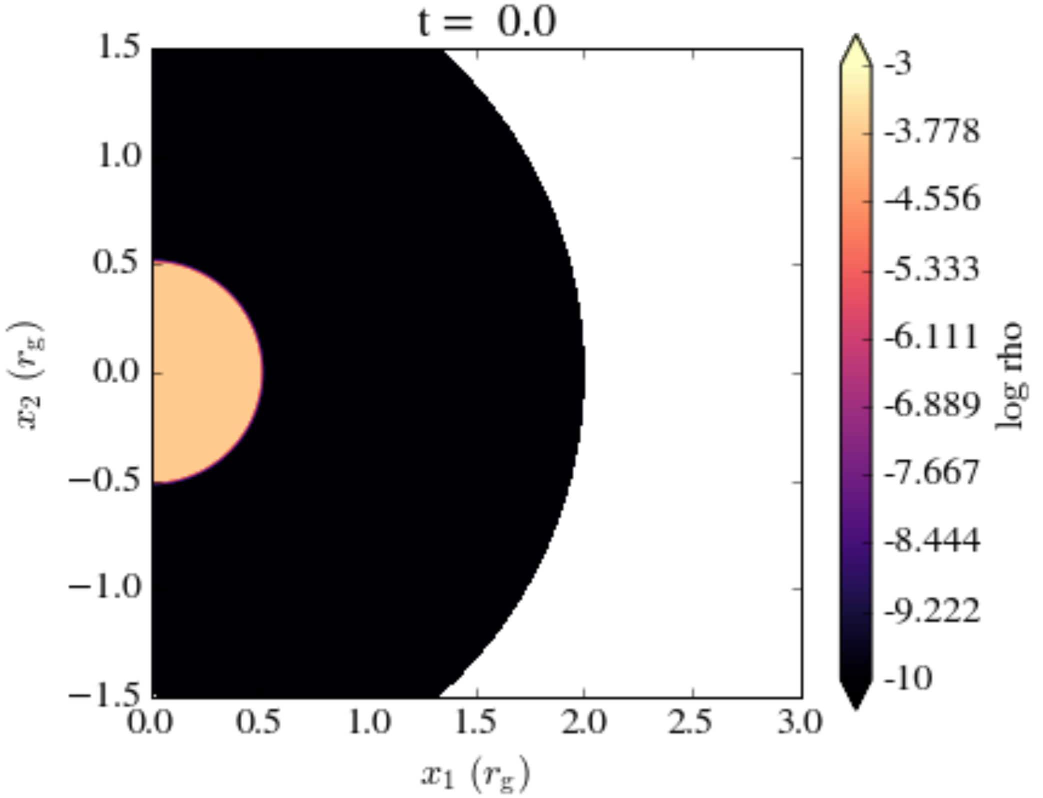
Optical depth

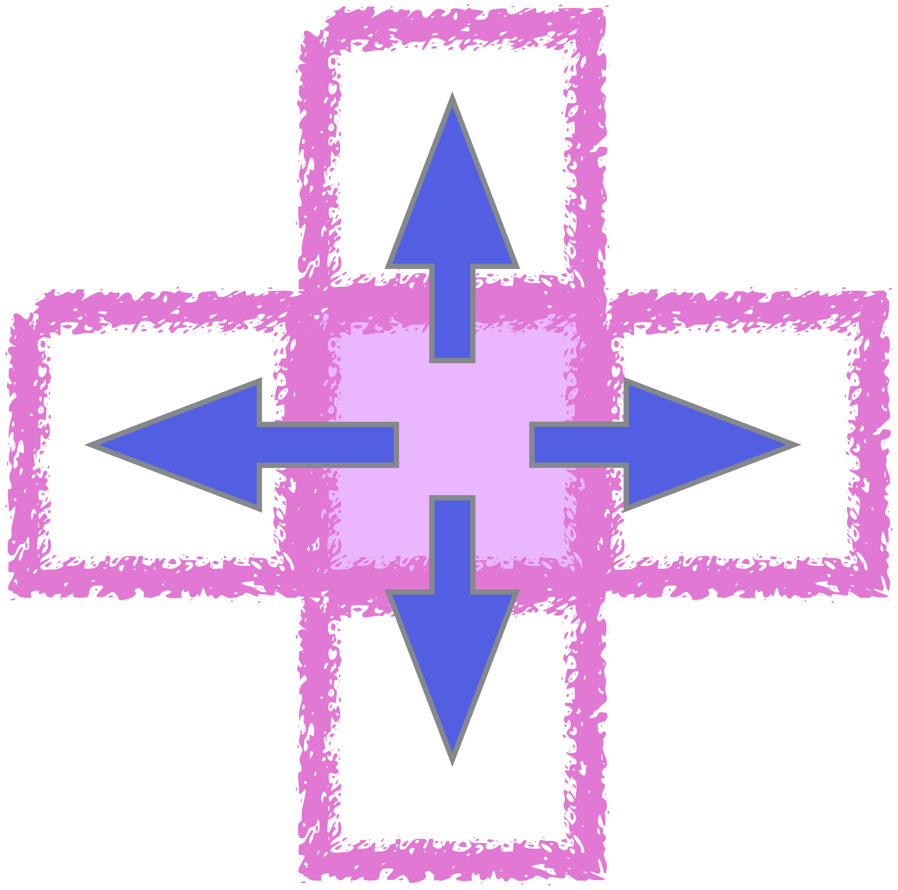
$$\tau = \int_{s_1}^{s_2} \kappa ds$$

Comes into the calculation of the diffusion time

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

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





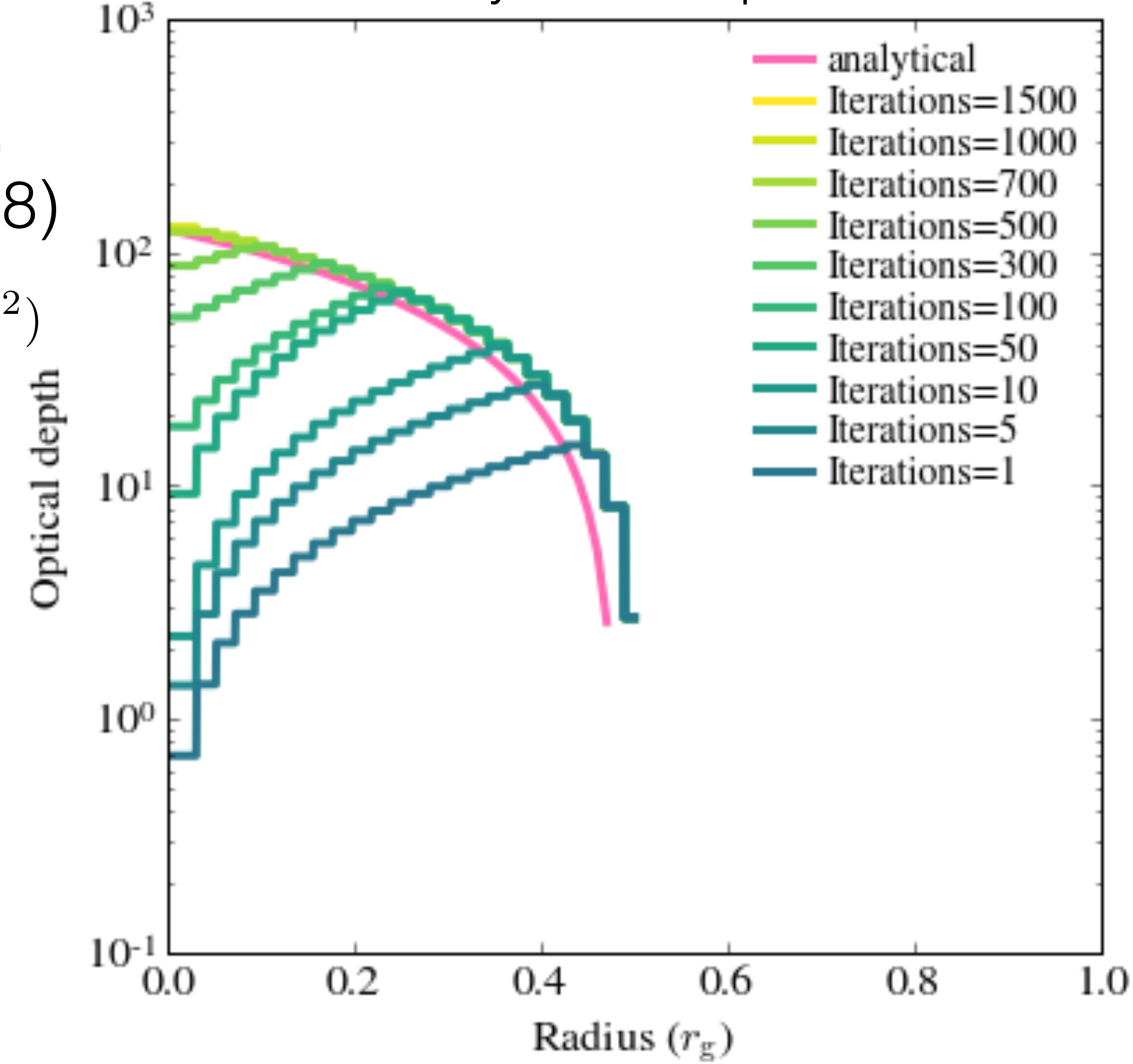
Leakage scheme: optical depth

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

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

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

Testing a sphere of constant density and temperature



Optical depth to electron neutrinos (R)

Leakage scheme: optical depth

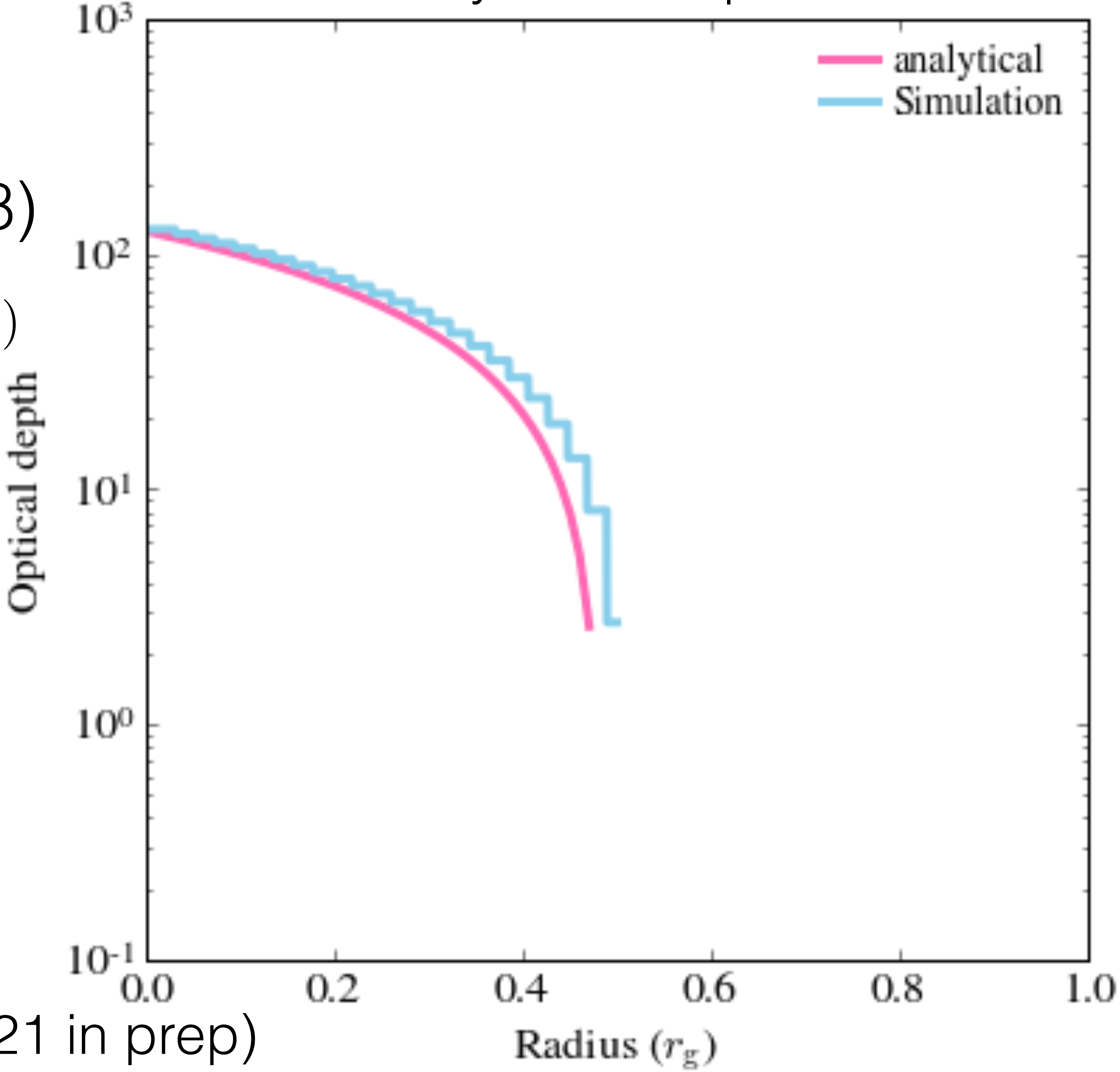
$$\tau = \int_{s_1}^{s_2} \kappa ds$$

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:

Testing a sphere of constant density and temperature



Optical depth to electron neutrinos (R)

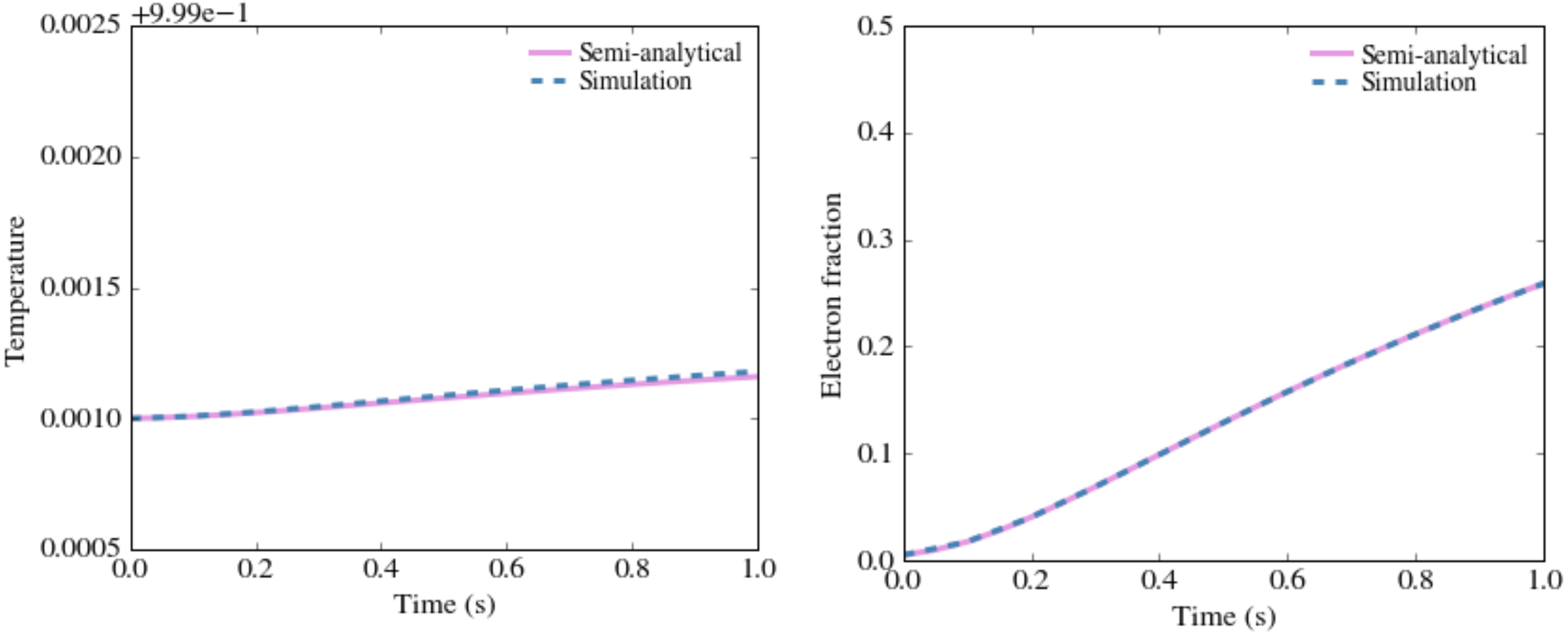
Murguia-Berthier et al. (2021 in prep)

Leakage scheme testing

Evolution of isotropic, optically thin, constant density gas

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

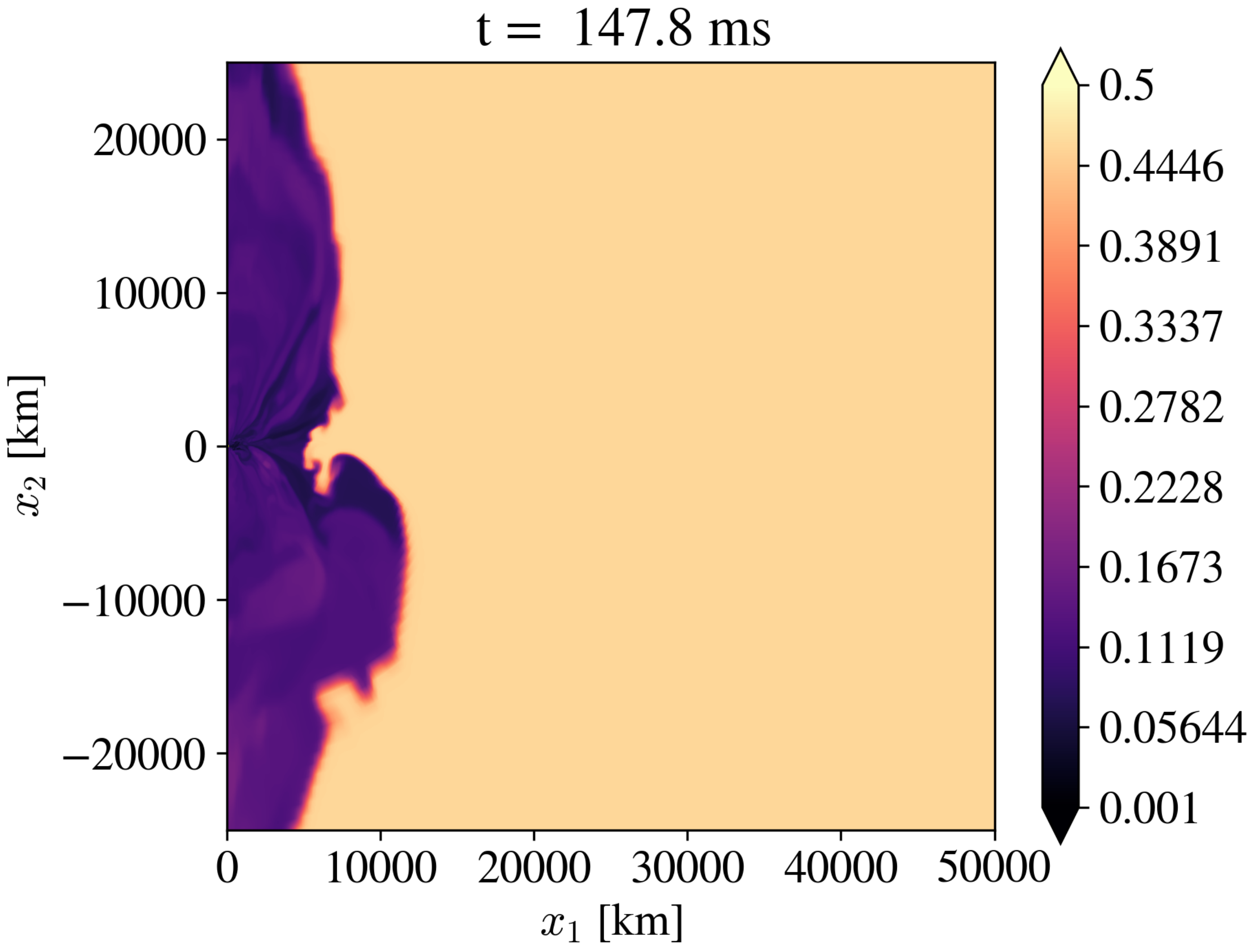
Ryan et al. (2015)
Miller at al. (2019)

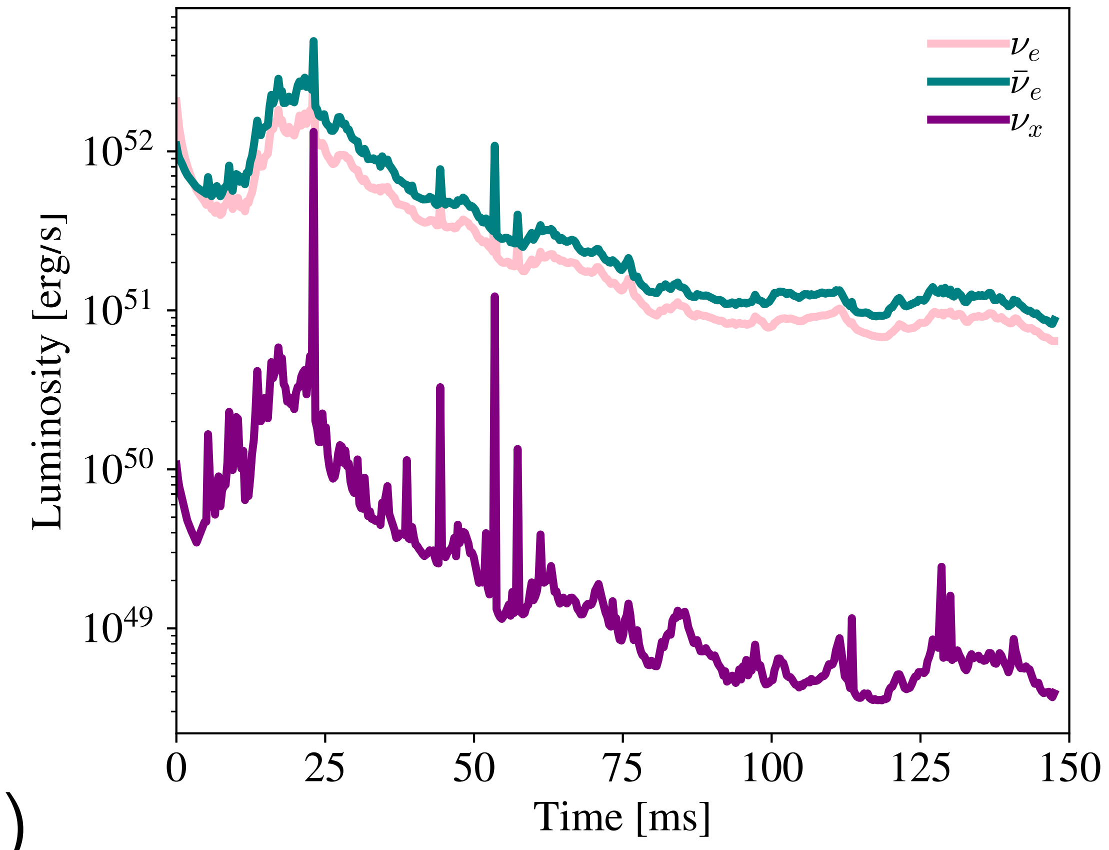


Beta process for electron antineutrino

Murguia-Berthier et al. (2021 in prep)

Results: magnetized accretion disk





Murguia-Berthier et al. (2021 in prep)

Conclusions and future work

- Tabulated EOS and neutrino leakage scheme are ready to work in HARM3D!
- Future work: get final abundances with Skynet
- Future work: TCAN science run with better initial conditions

¡Gracias!