HOW TO DEAL WITH NEUTRINOS IN SIMULATIONS OF NEUTRON-STAR MERGERS AND CORE-COLLAPSE SUPERNOVAE?

(NO DEFINITIVE ANSWER GIVEN IN THIS TALK...)

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NUCLEAR AND ASTROPHYSICS ASPECTS FOR THE RAPID NEUTRON CAPTURE PROCESS IN THE ERA OF MULTIMESSENGER OBSERVATIONS

TRENTO, JULY 1ST

WITH: H.-TH.-JANKA, A. BAUSWEIN, S. GORIELY, R. ARDEVOL, M. OBERGAULINGER, S. NAGATAKI, R. GLAS, R. BOLLIG, AND OTHERS

RIKEN

MPPC

iTHEMS

Max Planck Institute for Astrophysics

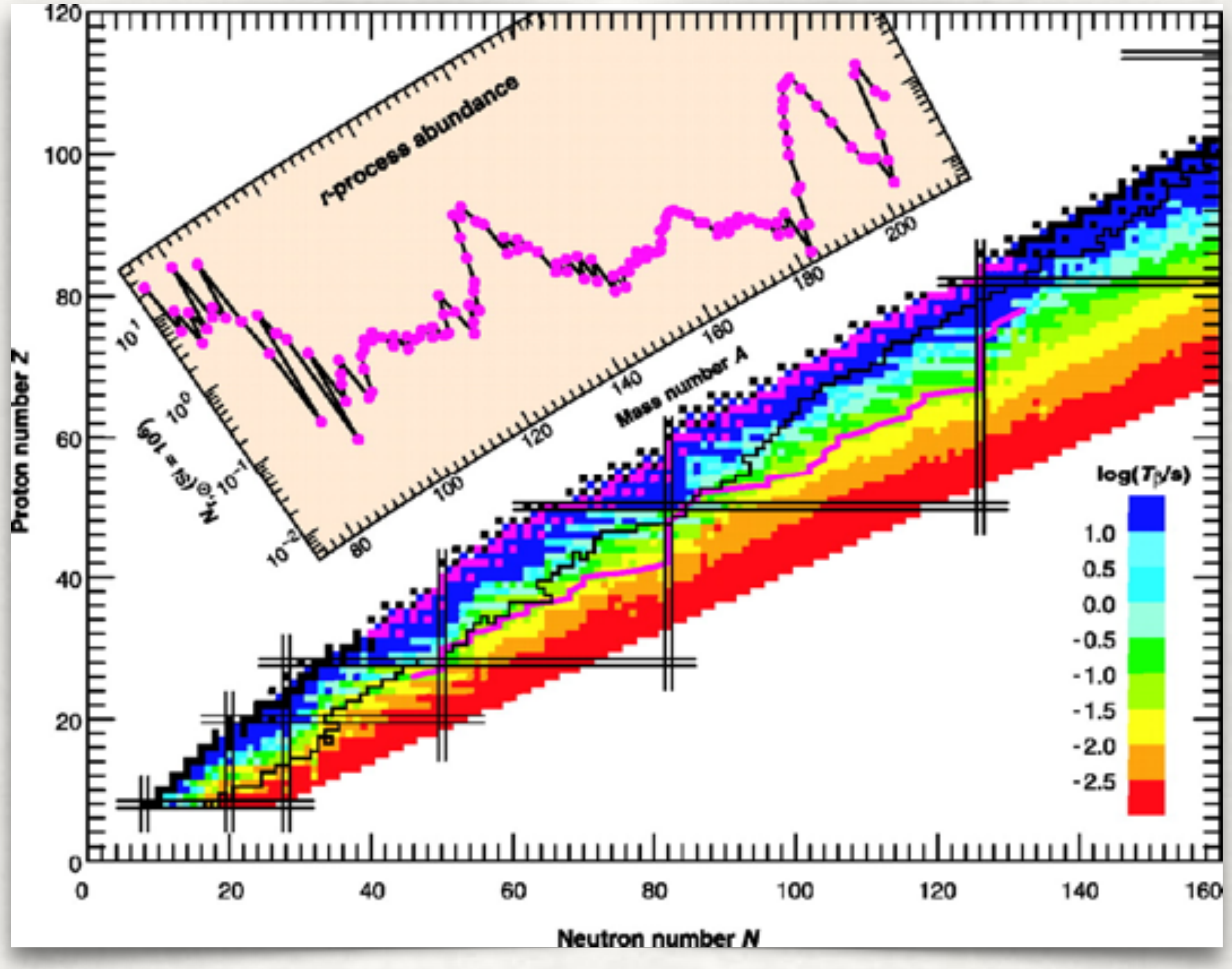
TUM LMU Excellence Cluster Universe

erc European Research Council Established by the European Commission

NEUTRON-STAR MERGERS AS SOURCES OF R-PROCESS ELEMENTS

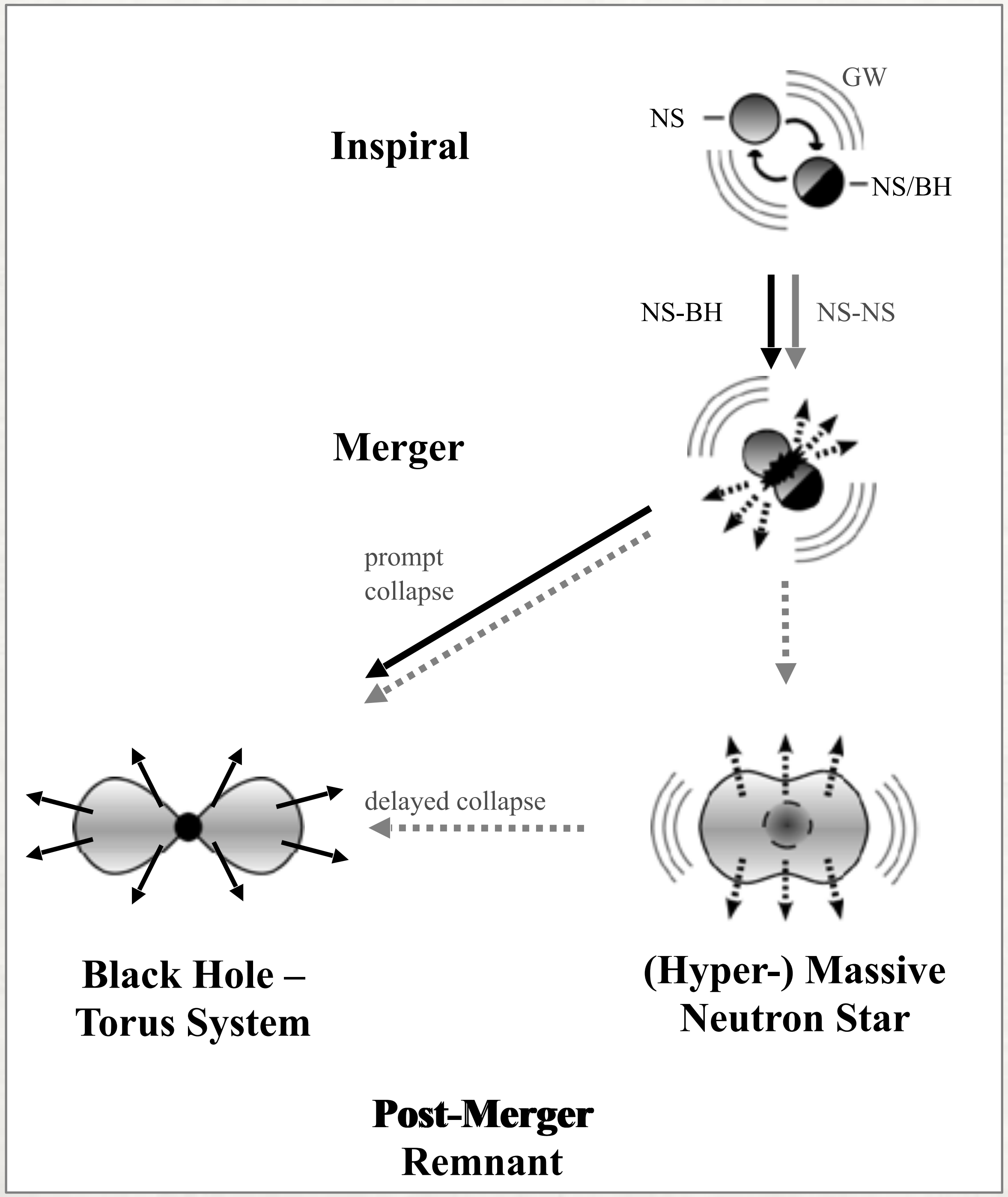
(...SUCH AS GOLD)

- Are neutron-star mergers significant/dominant sources?
- need explosive conditions with very high neutron densities
- neutron density depends sensitively on neutrino interactions
- suggested alternatives:
  - core-collapse supernovae
  - jets of magneto-rotational supernovae
  - accretion disks in collapsars

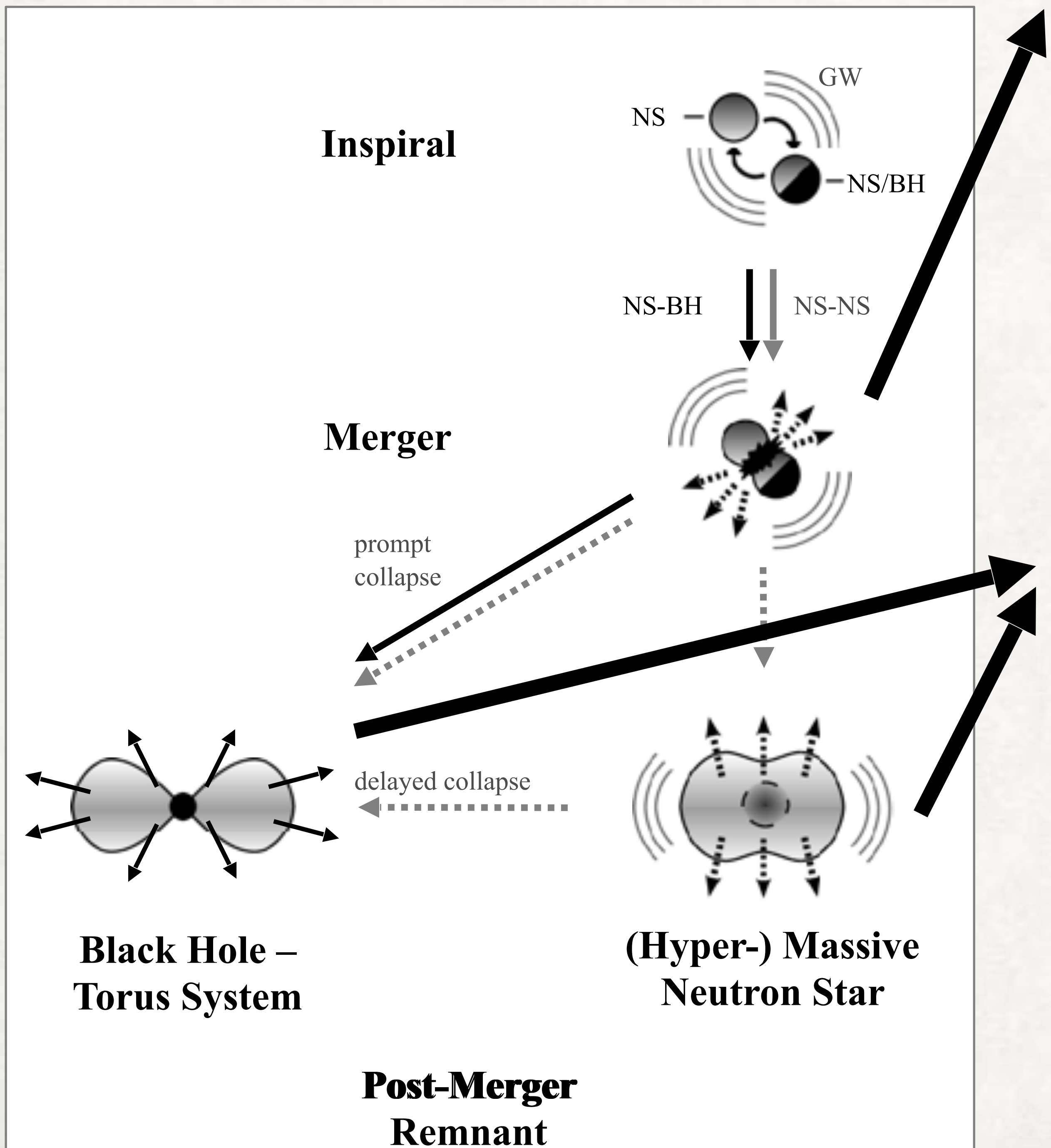


(e.g. Lattimer & Schramm, Freiburghaus, Goriely, Wanajo, Qian, Woosley, Martinez-Pinedo, Fischer, Metzger, Siegel, Pruet, McLaughlin, and many, many more)

Neutron-star mergers: ejecta components



Neutron-star mergers: ejecta components



dynamical/prompt ejecta

→ tidal tails
→ shock-heated

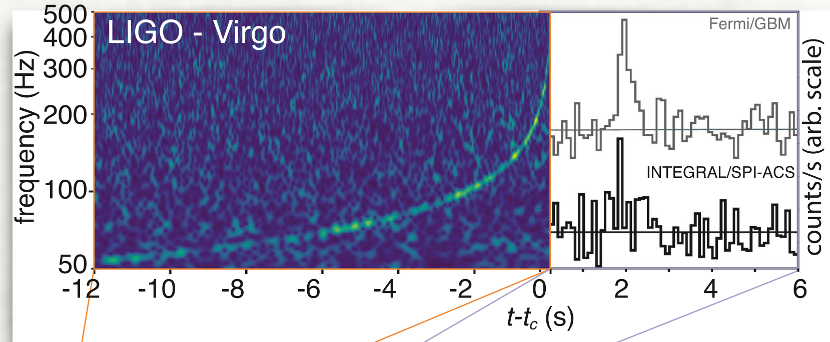
post-merger ejecta

→ neutrino-driven
→ viscous/turbulence driven
→ due to other (MHD) effects?

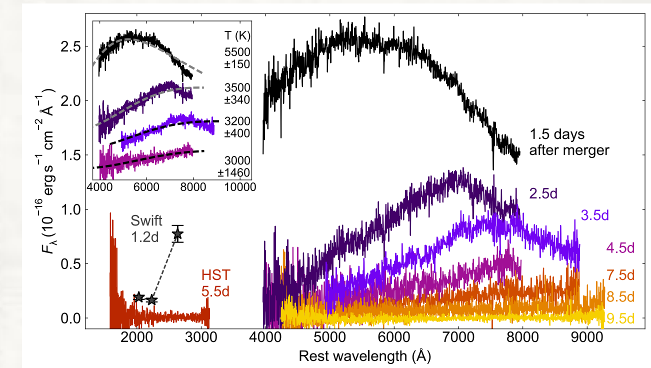
(see e.g. works by: Ruffert & Janka, Rosswog & Liebendoerfer, Freiburghaus, Shibata & Sekiguchi, Hotokezaka, Bauswein, Fernandez & Metzger, Surman, Just, Perego, Foucart, Siegel, Radice, Rezzolla, Giacomazzo, Ciolffi …)

GW170817 + EM COUNTERPARTS

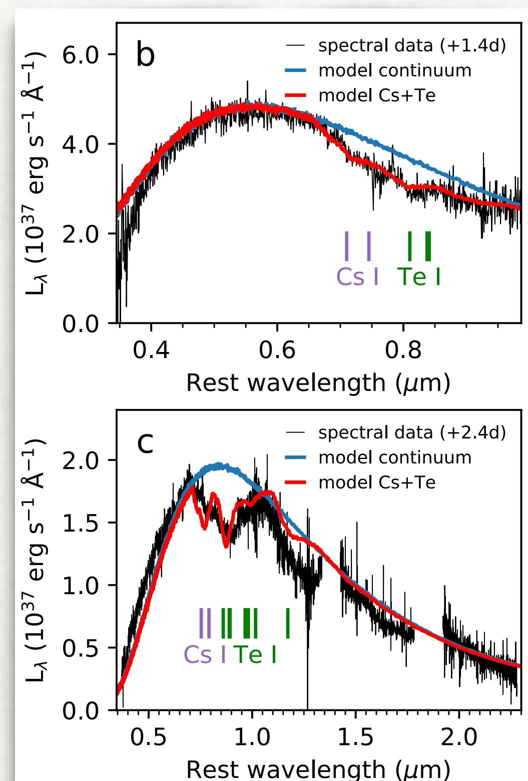
- Mtot = M1 + M2 ~ 2.74 Msun
- M1/M2 ~ 0.7 - 1
- **blue ejecta component** with
  $\langle Y_e \rangle > 0.25$
  M ~ 0.01-0.03 Msun
- **red ejecta component** with
  $\langle Y_e \rangle < 0.25$
  M ~ 0.01-0.03 Msun
- low-luminosity gamma-ray burst
  with E_{peak} ~ 100keV



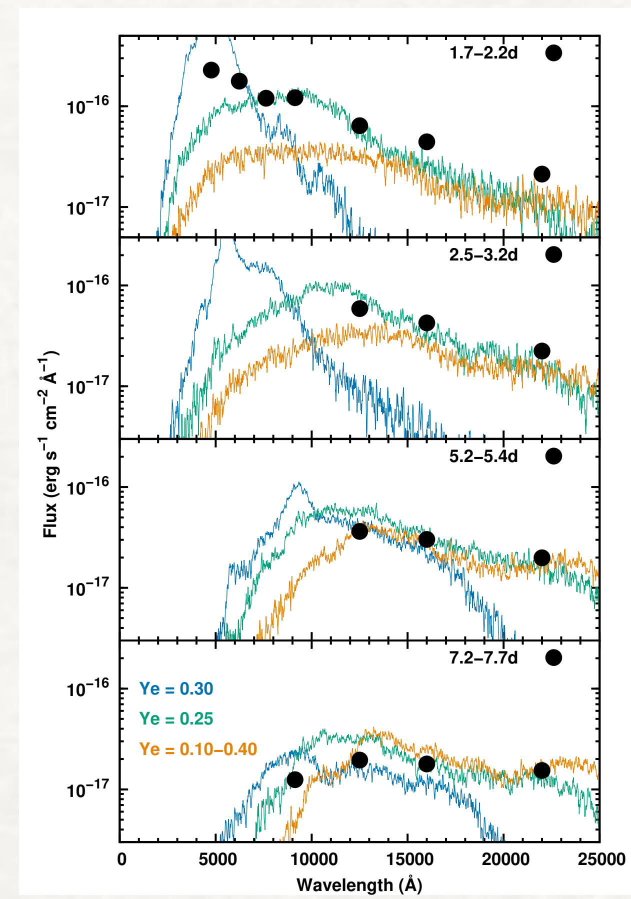
(LIGO Coll.+'17)



(Nicholl+'17)



(Smartt+'17)



(Tanaka+'17)

+ many other works by, e.g., Berger, Kasliwal, Kasen, Metzger, Mooley, Piran, Rosswog, Tanvir, Nakar, Gottlieb, MacFadyen, …

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➜ *many studies on* ***interpretation of EM*** *signals, e.g., Kasen '18, Shibata '18, Metzger '18, Mooley '18, Gottlieb '18, Bromberg '18, MacFadyen '18, …*

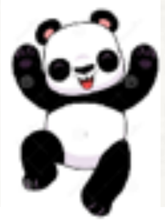
shock-heated dynamical ejecta and/or neutrino-processed ejecta launched from a HMNS remnant? *High mass and velocity still enigmatic…*

dynamical ejecta launched during merger or viscous ejecta from the remnant?

➜ safe identification needs better modeling

ejecta
mass+velocity

ejection
mechanism



nucleosynthesis
yields

collapse time
of HMNS

nuclear EOS
constraints

jet launching
mechanism

gravitational waves

radio

optical

UV

X-ray

gamma-ray

ejecta mass+velocity

ejection mechanism

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modeling "black box"

- ★ **hydrodynamic models** from numerical simulations including GR, neutrino transport, MHD
- ★ nucleosynthesis yields from **nuclear physics** calculations
- ★ **atomic shell** calculations and **radiative transfer** for EM light curve

gravitational waves

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gravitational waves

radio

optical

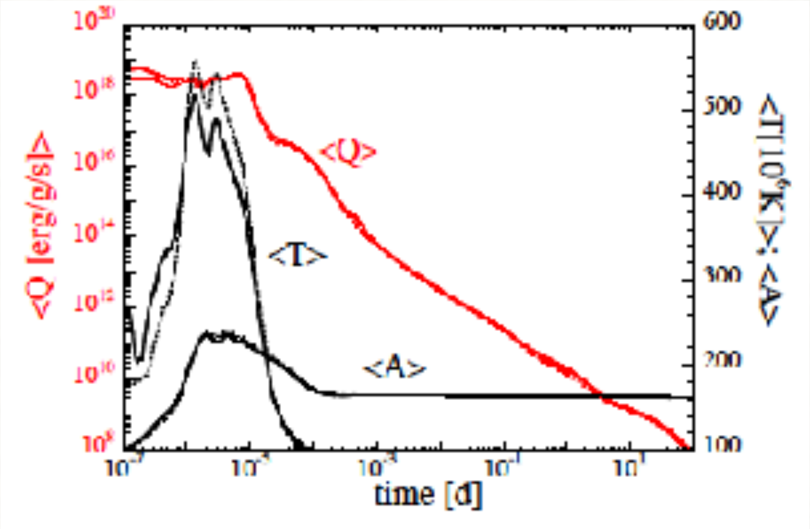
UV

X-ray

gamma-ray

Kilo- / Macronovae

- **radioactive decay** heats newly synthesized material



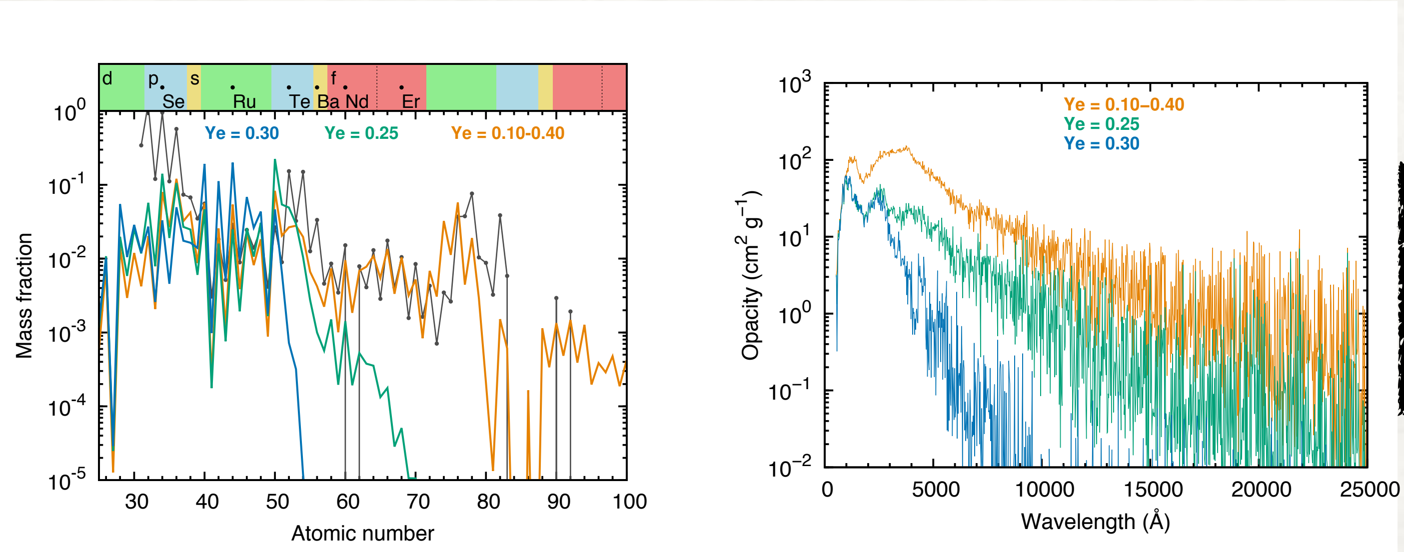
(Goriely et. al. 2011)

- light curves most sensitive to **mass, velocity, and composition**

$$t_{\rm peak} \approx \sqrt{\frac{\kappa M_{\rm ej}}{4\pi c V_{\rm ej}}\xi} \approx 1.5\,{\rm days}\left(\frac{V_{\rm ej}}{0.1\,c}\right)^{-1/2}\left(\frac{M_{\rm ej}}{0.03\;M_\odot}\right)^{1/2}\left(\frac{\kappa}{0.3\,{\rm cm^2\,g^{-1}}}\right)^{1/2}\xi^{1/2},$$

$$L_{\rm peak} \approx \frac{fM_{\rm ej}c^2}{t_{\rm peak}} \approx 4.3\times10^{41}{\rm erg\,s^{-1}}\left(\frac{f}{10^{-6}}\right)\left(\frac{V_{\rm ej}}{0.1\,c}\right)^{1/2}\left(\frac{M_{\rm ej}}{0.03\;M_\odot}\right)^{1/2}\left(\frac{\kappa}{0.3\,{\rm cm^2\,g^{-1}}}\right)^{-1/2}\xi^{-1/2},$$

$$T_{\rm eff,peak} \approx \left[\frac{L_{\rm peak}}{4\pi(V_{\rm ej}t_{\rm peak})^2\sigma_{\rm SB}}\right]^{1/4} \approx 8\times10^3\,{\rm K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{V_{\rm ej}}{0.1\,c}\right)^{1/8}\left(\frac{M_{\rm ej}}{0.03\;M_\odot}\right)^{-1/8}\left(\frac{\kappa}{0.3\,{\rm cm^2\,g^{-1}}}\right)^{-3/8}\xi^{-3/8}$$



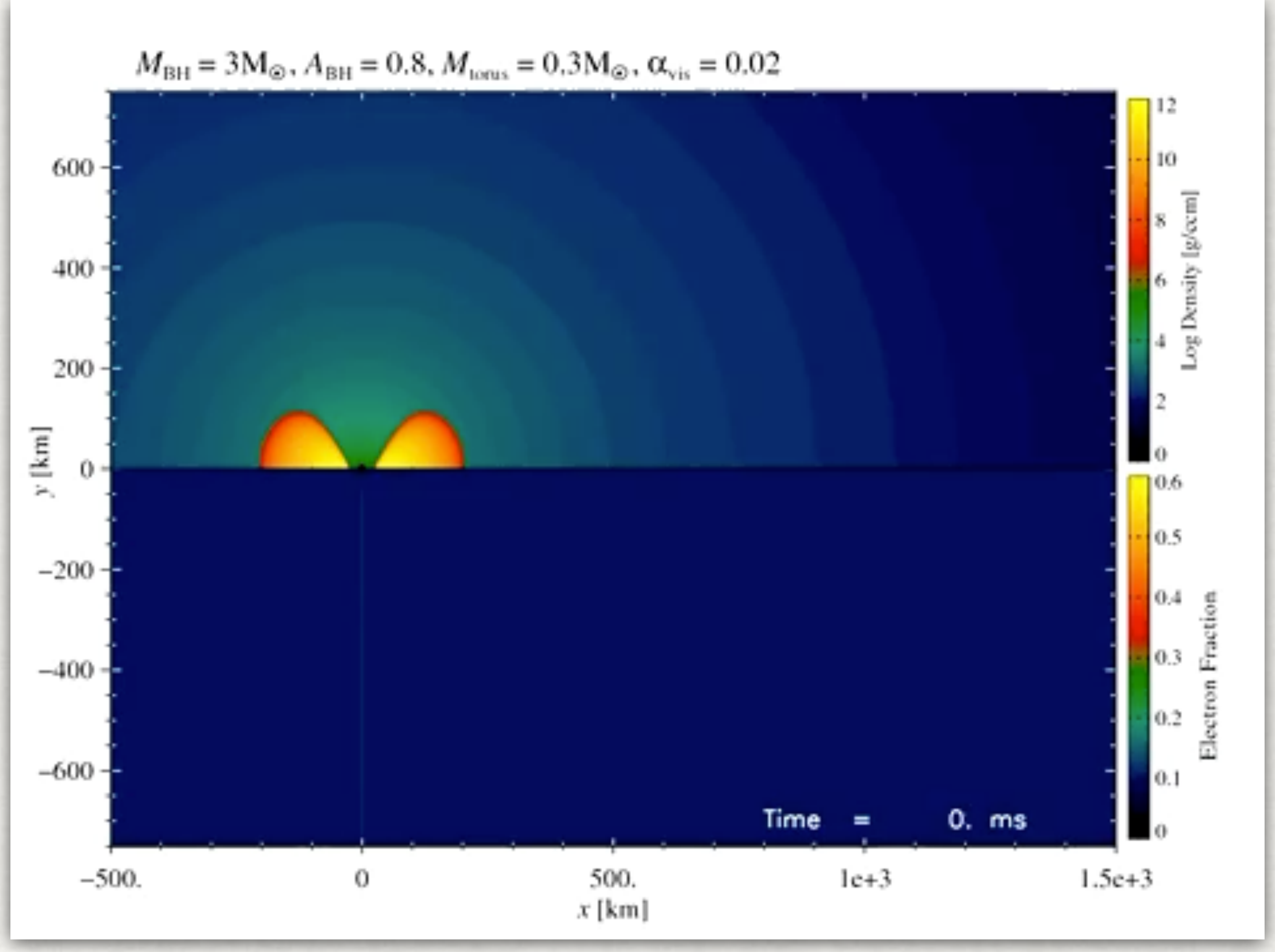
(Tanaka '18)

- **strong Ye dependence calls for reliable neutrino treatment in simulations**

Example: Post-merger BH-torus remnant

Mainly two ejecta components:

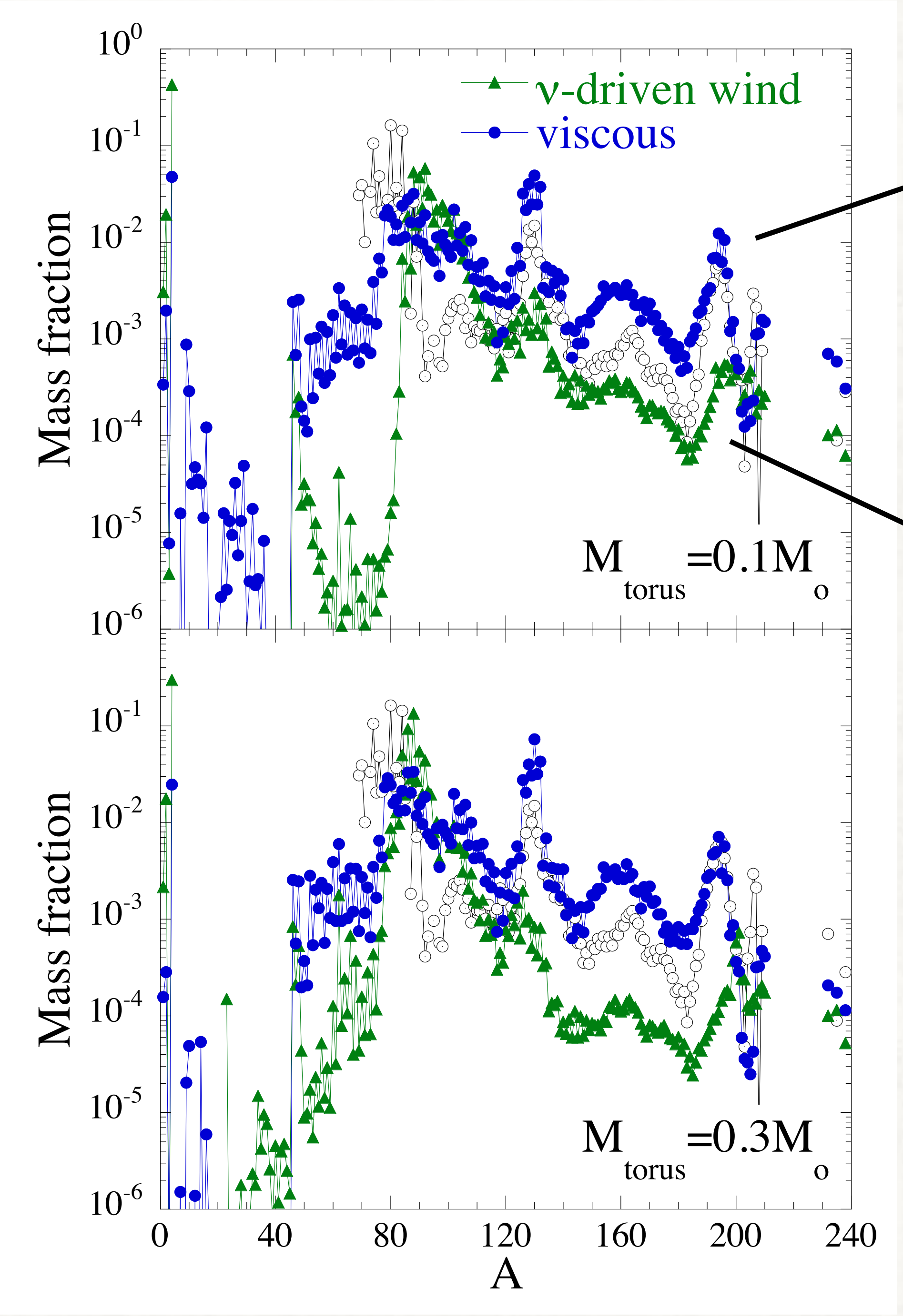
- **neutrino-driven wind,** Ye controlled by neutrino absorption
- **wind driven by viscous expansion and angular momentum transport,** Ye controlled by neutrino emission



(simulated with M1 neutrino transport code “ALCAR”, OJ, Bauswein, Ardevol, Goriely, Janka ’15)

(also: Fernandez ’13, Wu ’16, Siegel ’17)

Nucleosynthesis yields of BH-torus ejecta



(OJ, Bauswein, Ardevol, Goriely, Janka ’15)

viscous outflows:
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

neutrino-driven outflows:
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

BASIC TYPES OF NEUTRINO TREATMENTS

- Boltzmann-solvers (e.g. Monte-Carlo, S_n):

$$\partial_t I(x, y, z, \theta, \phi, \epsilon) + \ldots = Q_{\mathrm{emission}}(\rho, T, Y_e) - Q_{\mathrm{absorption}}(\rho, T, Y_e, I)$$

6 degrees of freedom
(3 spatial, 3 mom. coords.)

=> most accurate, most expensive

- Truncated moment methods \w local closure (e.g. M1, flux-limited diffusion):

$$\partial_t E(x, y, z, \epsilon) + \ldots = Q^0_{\mathrm{emission}}(\rho, T, Y_e) - Q^0_{\mathrm{absorption}}(\rho, T, Y_e, E, F, \ldots)$$

$$\partial_t F(x, y, z, \epsilon) + \ldots = Q^1_{\mathrm{emission}}(\rho, T, Y_e) - Q^1_{\mathrm{absorption}}(\rho, T, Y_e, E, F, \ldots)$$

4 degrees of freedom

=> less accurate, less expensive, but still expensive

- Leakage/trapping schemes:

optical depth

$$Q_{\mathrm{emission}} - Q_{\mathrm{absorption}} =: Q^{\mathrm{effective}}_{\mathrm{emission}} = f(\rho, T, Y_e, \tau)$$

=> no evolution equation for neutrinos, least expensive

WHY DIFFERENT NEUTRINO SCHEMES?

Approximate neutrino transport schemes:

- local cooling schemes
- neutrino-leakage schemes
- Flux-limited diffusion
- M1
- Ray-by-Ray approximation
- …

Boltzmann-solvers:

- discrete ordinate method
- Monte Carlo
- tangent-ray scheme (only Ray-by-Ray)
- …

😄 computationally efficient

😄 possible to explore larger parameter space

😄 accuracy may be sufficient for many questions

😄 potentially most accurate

😄 necessary when high accuracy is needed

😄 provide reference solutions for approximate methods

😩 potentially large uncertainties

😩 impact of each approximation must be tested individually for each application

😩 affordable resolution limited, impact not well known

😩 small number of available models: cross-comparisons and parameter exploration unfeasible

➡ cross-comparisons **invaluable** to assess reliability of each scheme

➡ **particular challenges in multi-D comparisons:** high computational costs per simulation, turbulence, resolution, stochasticity…

CLASSICAL LEAKAGE SCHEMES

(e.g. Ruffert & Janka, Rosswog & Liebend. ’01, see, however, ASL leakage by Perego ’15, Gizzi ’19, which is improved in several respects)

$\tau \approx 1$

PNS or HMNS

optical depth

$\tau \gg 1$

neutrinos emitted on diffusion timescale

$$t_{\rm diff} = \frac{3d}{c}\tau$$

optical depth

$\tau \ll 1$

neutrinos emitted on production timescale

$$t_{\rm prod} = \frac{E_\nu^{\rm eq}}{Q_{\rm emission}}$$

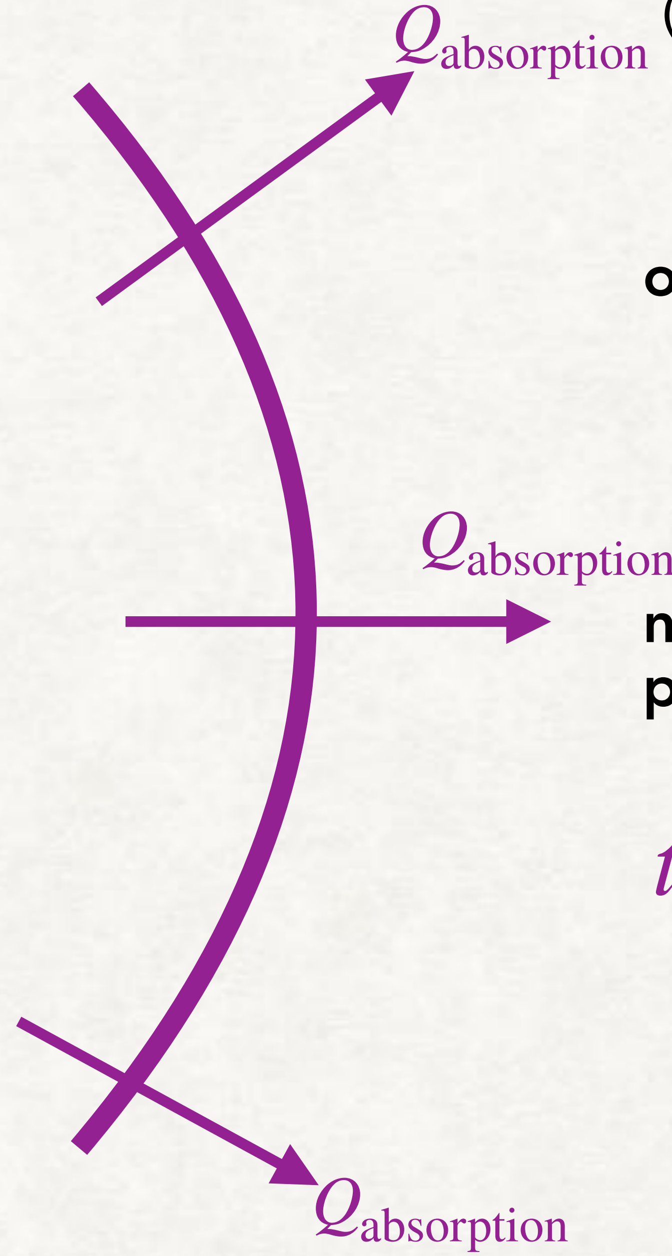
interpolation:

$$\partial_t Y_e + v\nabla Y_e = Q_{\rm emission}^{\rm effective} \equiv Q_{\rm emission}(1 + \frac{t_{\rm diff}}{t_{\rm prod}})^{-1}$$

=> free parameter “d”, no inclusion of neutrino equilibration, no absorption

NEW "ILEAS" LEAKAGE SCHEME

(Ardevol, Janka, OJ, Bauswein, '19)



PNS or HMNS

optical depth
$\tau \gg 1$

neutrinos emitted on diffusion timescale

$$t_{\text{prod}} = \frac{E_\nu^{\text{eq}}}{-c\frac{\nabla E_\nu^{\text{eq}}}{3\kappa}}$$

optical depth
$\tau \ll 1$

neutrinos emitted on production timescale

$$t_{\text{prod}} = \frac{E_\nu^{\text{eq}}}{Q_{\text{emission}}}$$

equilibrium regime:

$$\partial_t(Y_e + Y_\nu) + v\nabla(Y_e + Y_\nu) = Q^{\text{effective}}_{\text{emission}}$$

non-equil. regime:

$$\partial_t Y_e + v\nabla Y_e = Q^{\text{effective}}_{\text{emission}} + Q_{\text{absorption}}$$

=> more consistent inclusion of diffusion timescale and neutrino equilibration and 'ray-tracing' method for absorption

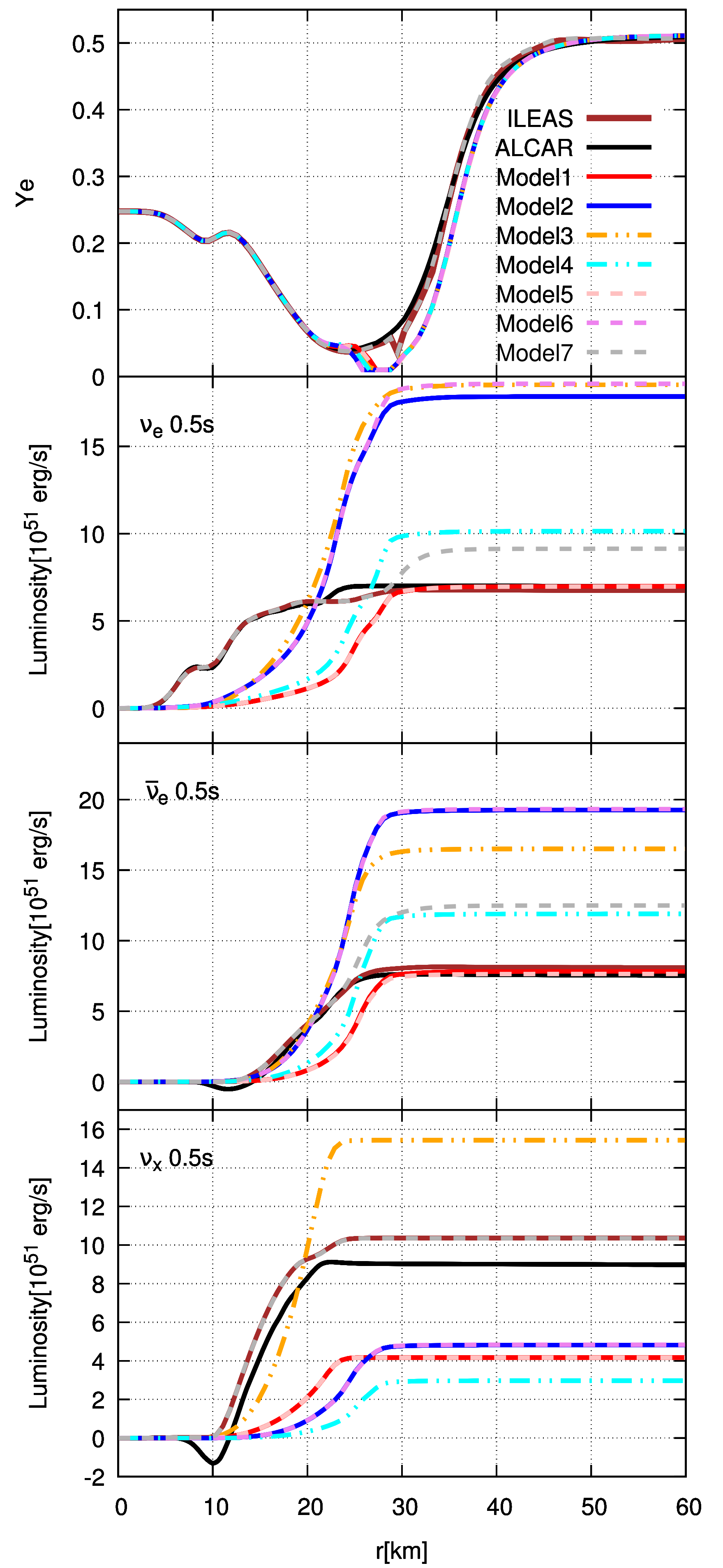
ILEAS: COMPARISON WITH CLASSICAL LEAKAGE SCHEMES AND M1 CODE (ALCAR)

(Ardevol, Janka, OJ, Bauswein, '19)

- stationary 1D hydro background taken from exploding CCSN at 0.5 s post-bounce
- new diffusion timescale improves fluxes at high optical depths (r<25km)
- new absorption treatment improves fluxes around the neutrino sphere (r~25km)

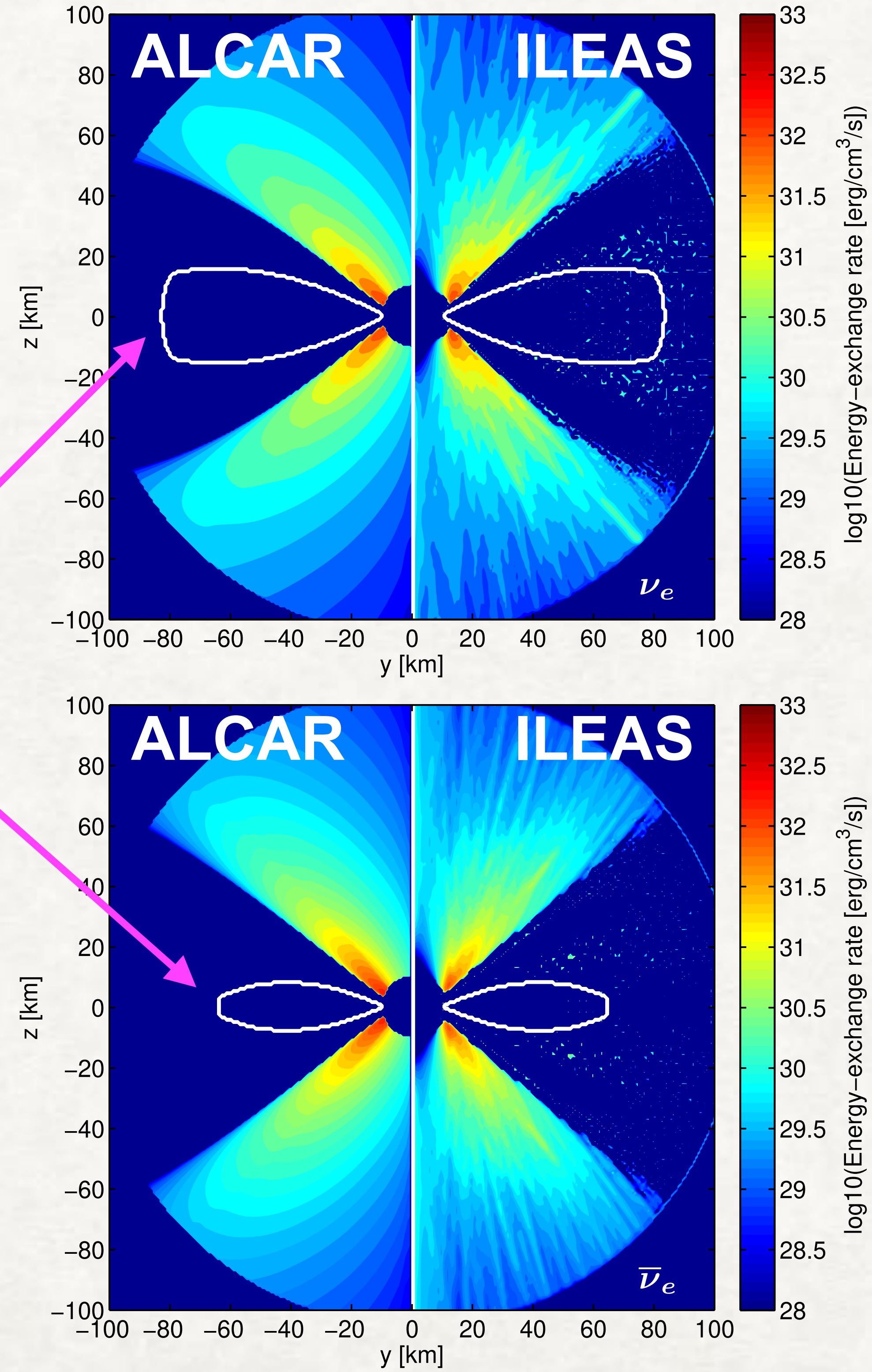
Model	$t^{\rm diff}_{\nu_i}$	Energy average	μ_ν	L_{ν_e} (10^{51} erg s^{-1})	$L_{\bar{\nu}_e}$ (10^{51} erg s^{-1})	L_{ν_x} (10^{51} erg s^{-1})
Model 1	RJS[a]	RJS	RJS	7.0	7.8	4.2
Model 2	RL[b]	RL	RL	17.9	19.3	4.8
Model 3	RL	RJS	RJS	18.5	16.5	15.4
Model 4	RJS	RL	RJS	10.1	11.9	3.0
Model 5	RJS	RJS	RL	7.0	7.6	4.2
Model 6	RL	RL	RJS	18.6	19.3	4.8
Model 7	AJJB[c]	AJJB	AJJB	9.1	12.5	10.4
ILEAS	AJJB	AJJB	AJJB	6.7	8.1	10.4
ALCAR	–	–	–	7.0	7.6	9.0

Notes: [a] Ruffert, Janka & Schäfer (Ruffert et al. 1996).
[b] Rosswog & Liebendörfer (Rosswog & Liebendörfer 2003).
[c] Ardevol, Janka, Just & Bauswein (this work).

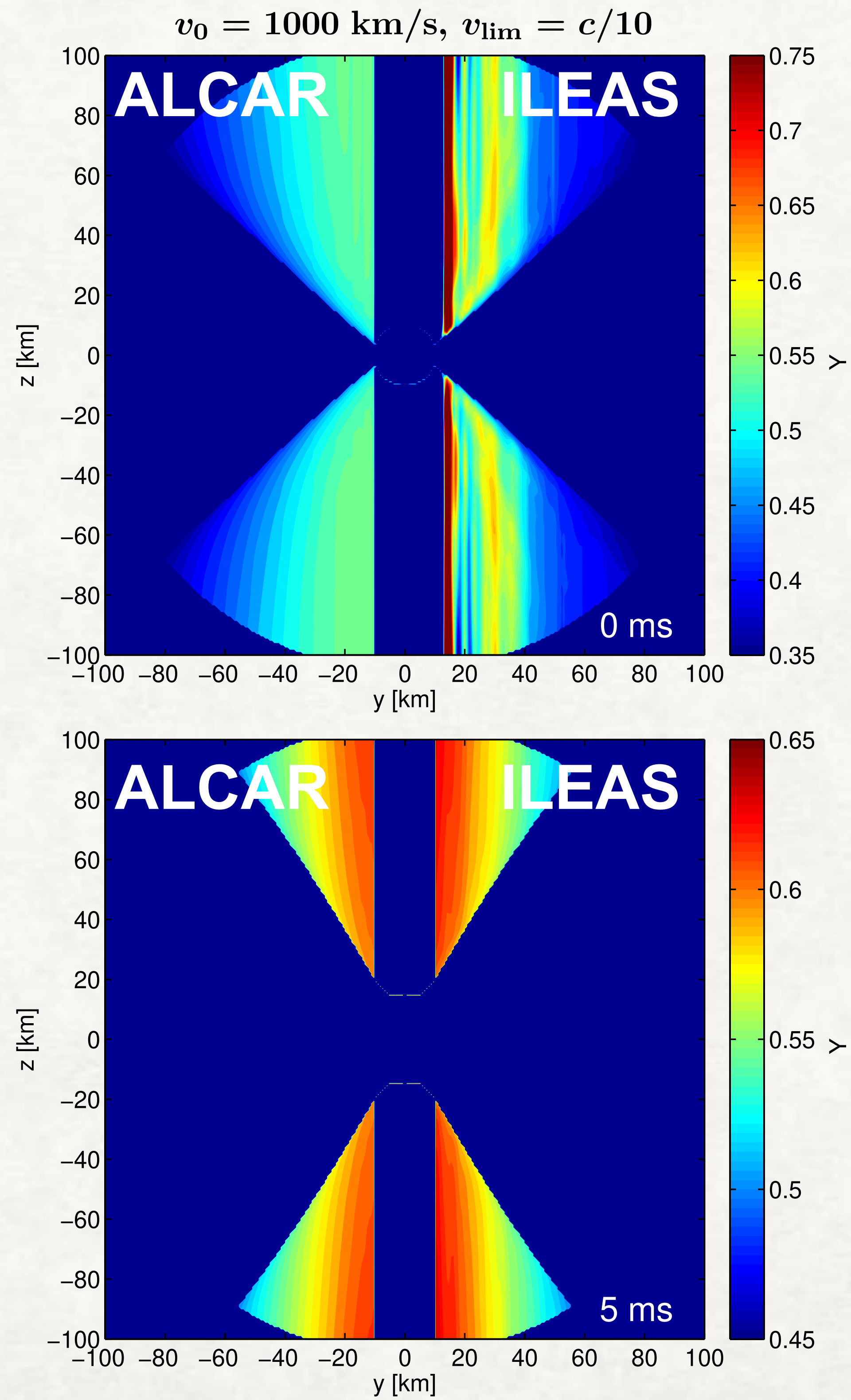


ILEAS: COMPARISON WITH M1 CODE (ALCAR) FOR A STATIONARY POST-MERGER BH-TORUS

neutrino-spheres



absorption rates

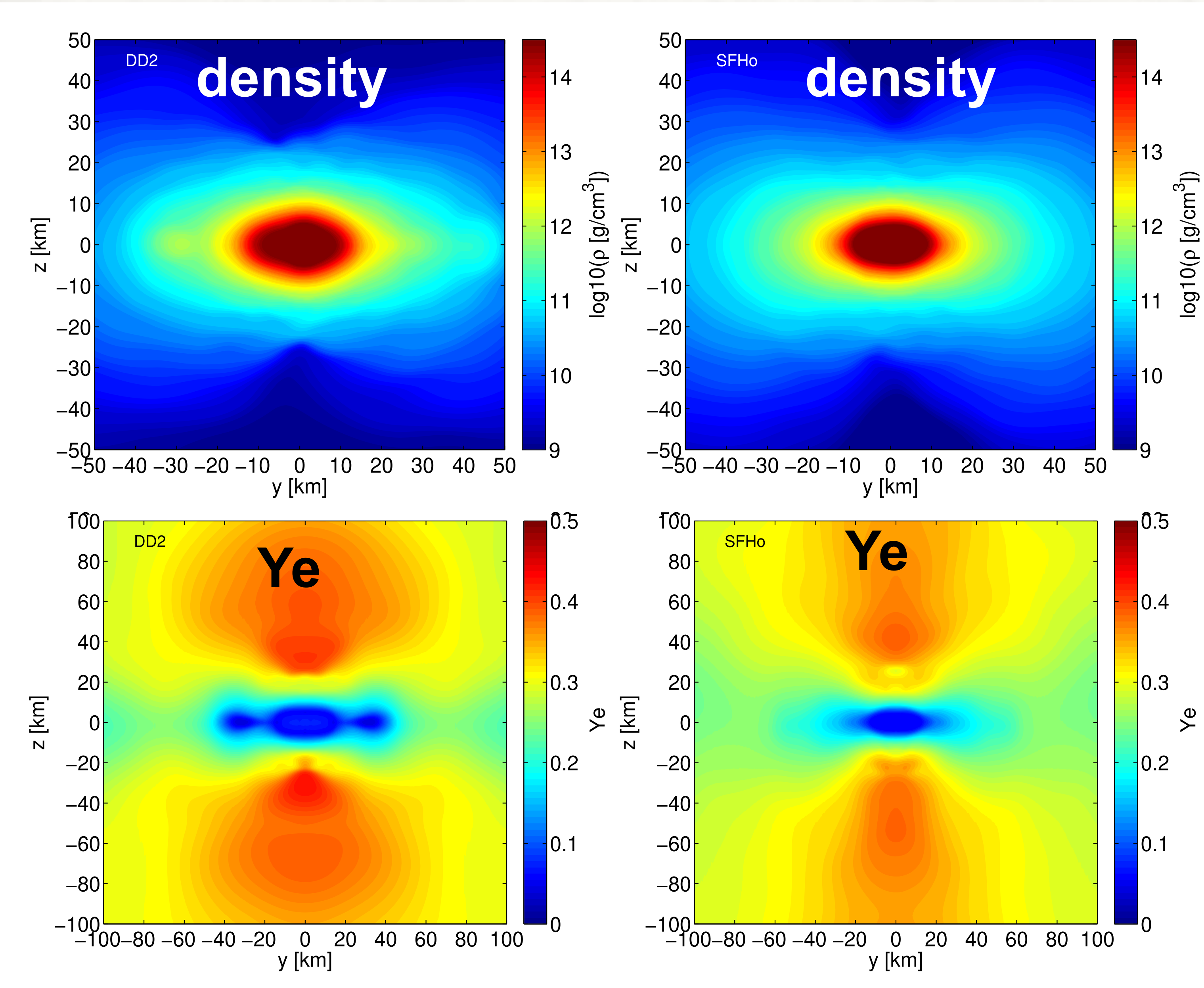


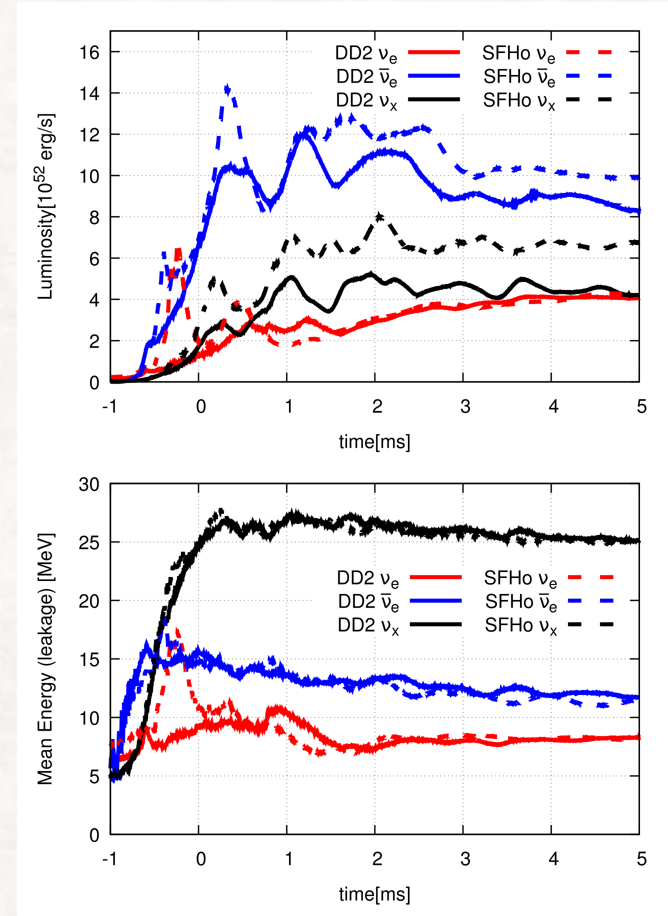
resulting Ye of ejecta

ILEAS: FULLY DYNAMIC MERGER SIMULATION

(WITH CFC-SPH HYDRO CODE)

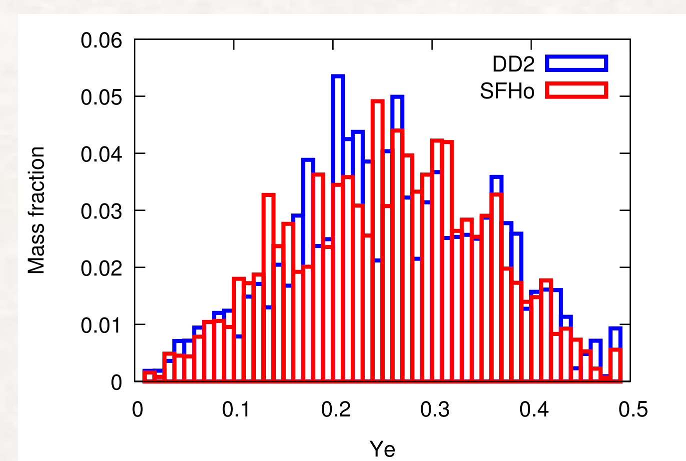
DD2 EOS **SFHO EOS**





neutrino luminosities

mean energies

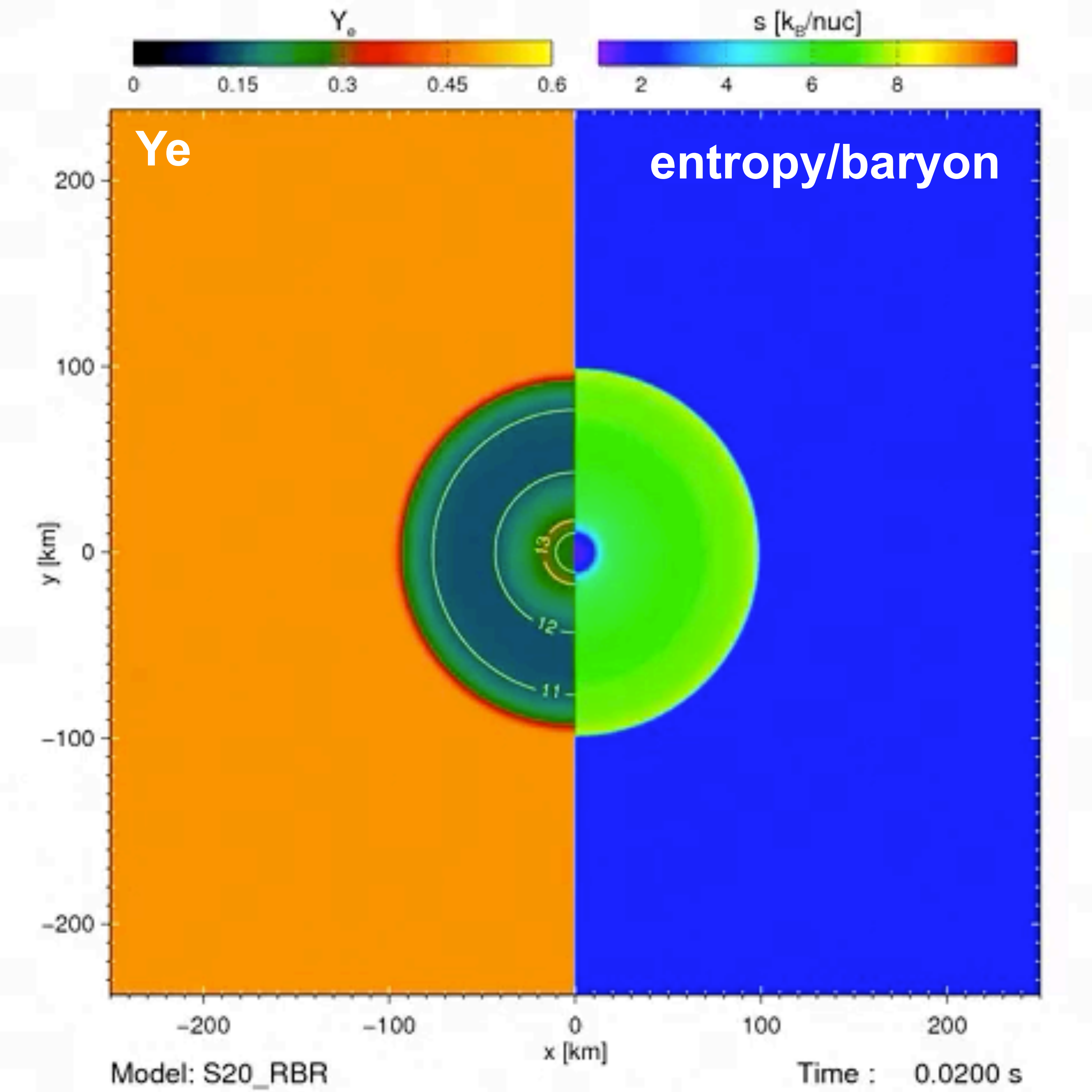


ejecta Ye distribution

- results qualitatively consistent with previous studies (e.g. Sekiguchi, Foucart, Palenzuela et al)
- quantitative differences (must be understood in future work)

(Ardevol, Janka, OJ, Bauswein, '19)

NEUTRINO TRANSPORT IN CCSNE: IMPACT OF RAY-BY-RAY APPROXIMATION



20 Msun model, simulated with M1 code ALCAR using ray-by-using (OJ, Bollig, Janka et al 2018)

Neutrinos…

- … cool down PNS and thereby regulate its size
- … heat up post-shock material in “gain layer”
- …control the Ye of PNS and ejecta

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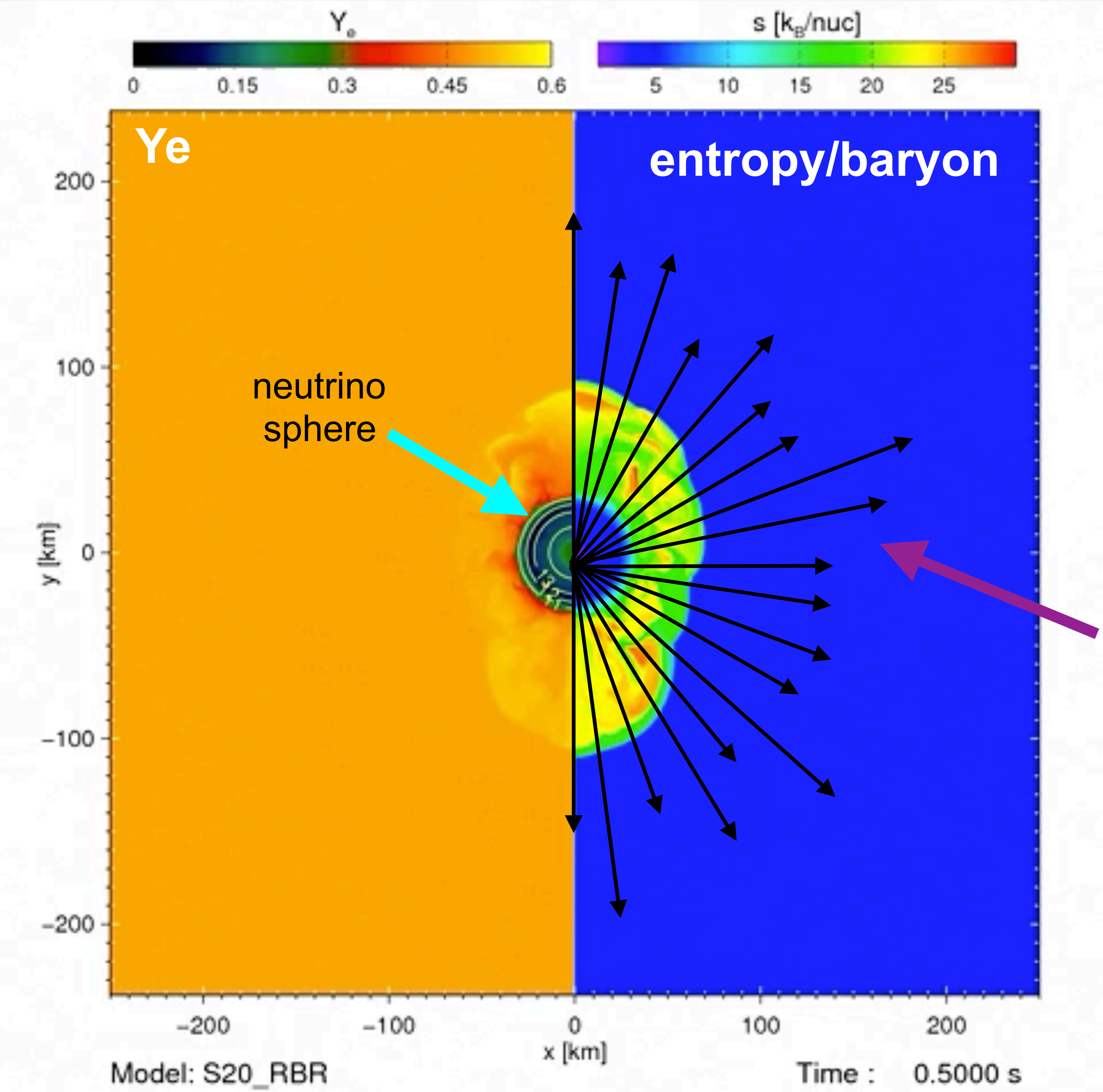


20 Msun model, simulated with M1 code ALCAR using ray-by-ray (OJ, Bollig, Janka et al 2018)

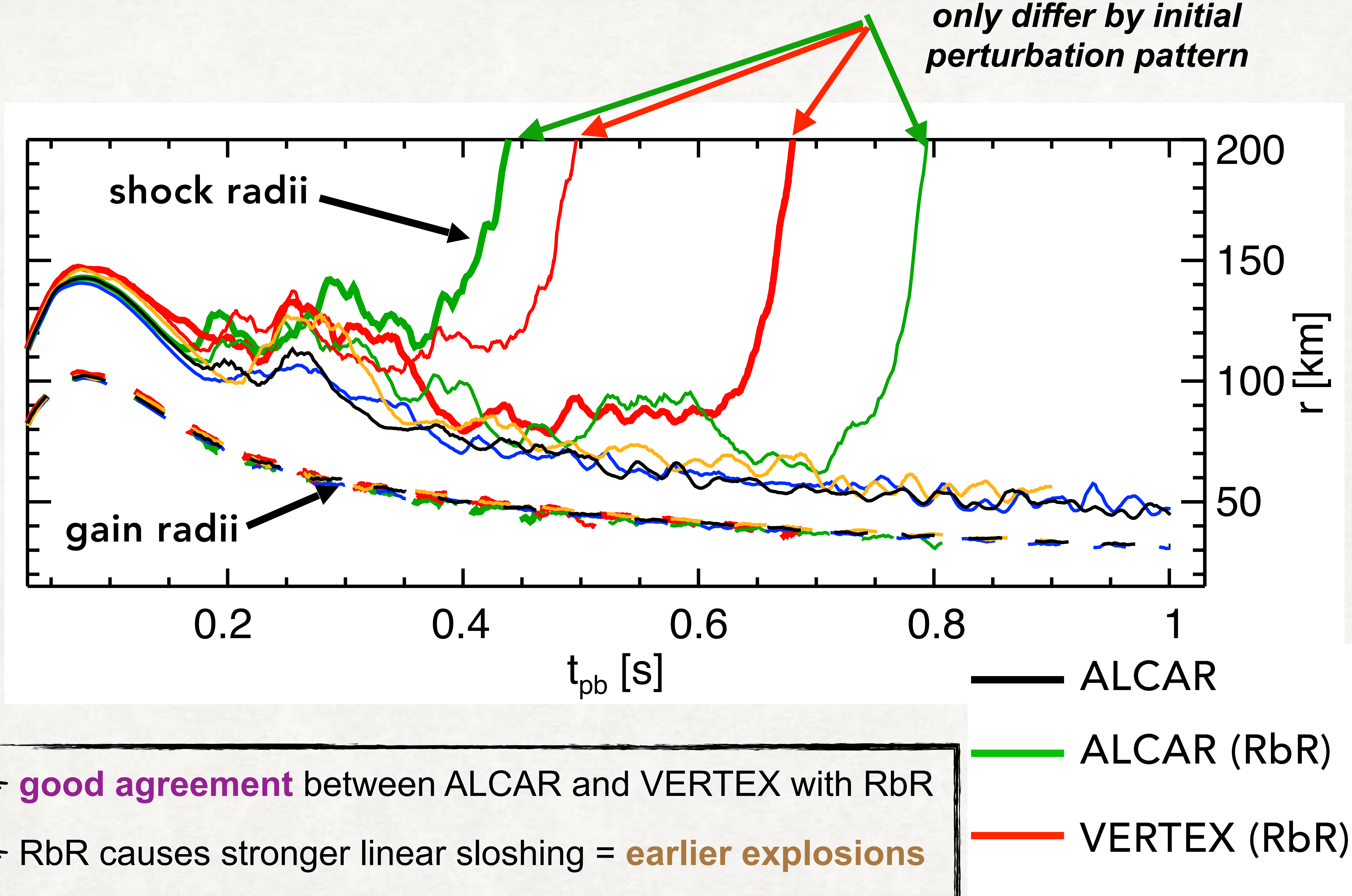
Neutrinos…

- … cool down PNS and by that regulate its size
- … heat up post-shock material in “gain layer”
- …control the Ye of PNS and ejecta

Ray-by-ray approximation:

- neutrino distribution along each radial ray assumed to be axisymmetric around ray
- motivated by spherical shape of neutrino sphere
- large computational savings
- ***one of most often employed approximations in CCSN simulations***

AXISYMMETRIC S20 MODEL



- ☛ **good agreement** between ALCAR and VERTEX with RbR
- ☛ RbR causes stronger linear sloshing = **earlier explosions**
- ☛ **large stochastic scatter** of explosion times

(OJ, Bollig, Janka et al, '18)

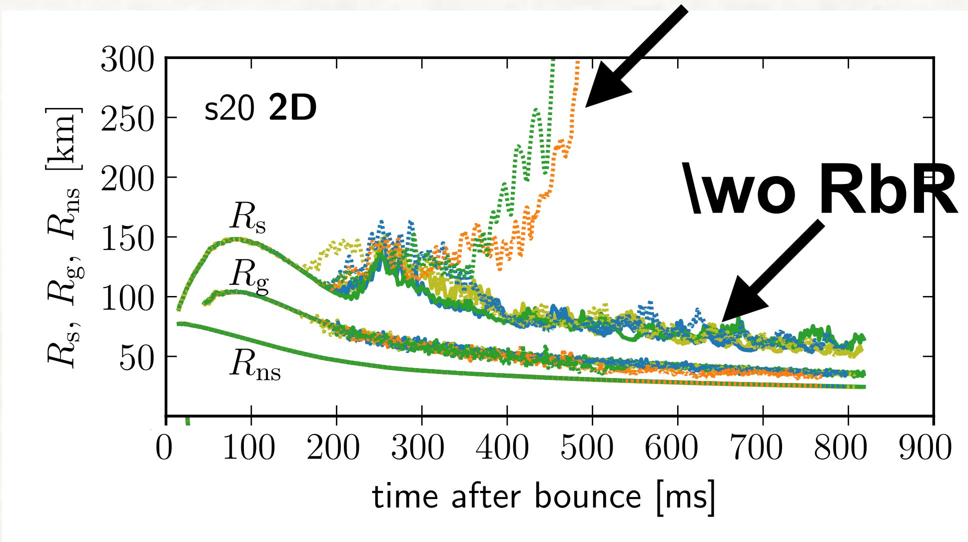
AND IN 3D? MUCH SMALLER IMPACT OF RBR

(Glas, OJ, Janka, Obergaulinger 2019, all simulations done with ALCAR code)

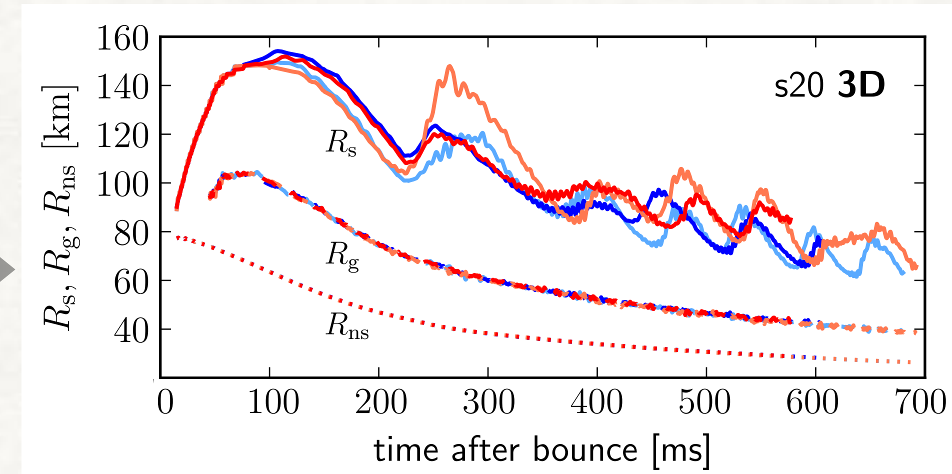
S20, 2D:

\w RbR

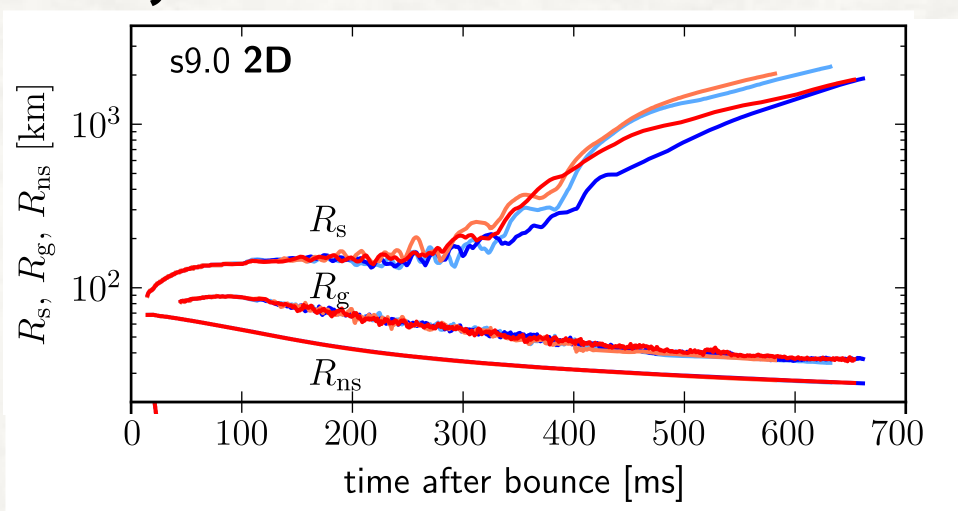
\wo RbR



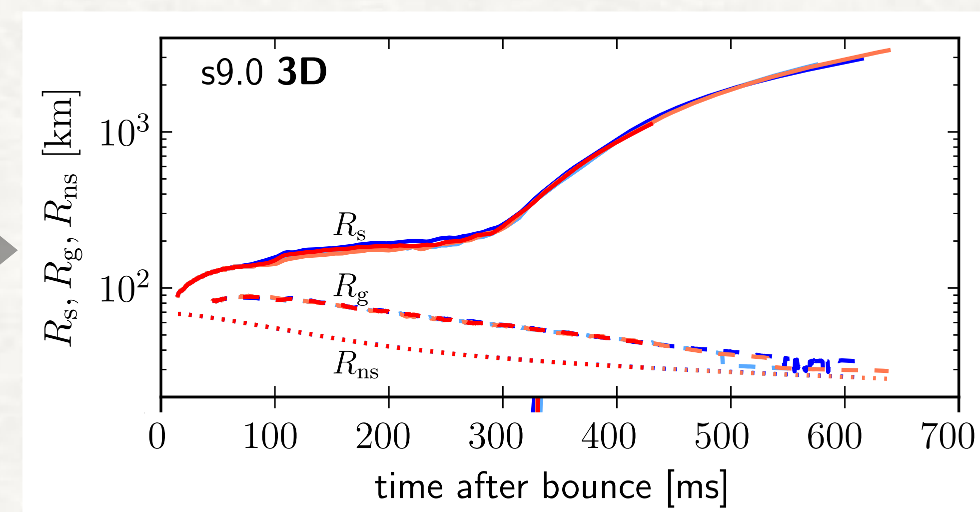
S20, 3D:



S9, 2D:



S9, 3D:



- FMD L \wo RbR, low resolution
- FMD H \wo RbR, high resolution
- RbR+ L \w RbR, low resolution
- RbR+ H \w RbR, high resolution

- ☛ overall **weaker oscillation amplitudes** in 3D than in 2D
- ☛ **small impact of RbR** in 3D
- ☛ **lends credibility** to most existing RbR models

Take Home Messages

- NS mergers produce a **variety of different outflow components**, each with individual nucleosynthesis signature as well es EM signal
- reliable determination of ejecta properties from multi-messenger observations calls for **reliable and robust neutrino schemes** (also holds for CCSNe)
- new scheme “ILEAS” incorporates important effects due to **equilibration, neutrino absorption, and diffusion** in a computationally efficient leakage method
- first results look qualitatively consistent with previous works, but still need to find reason for quantitative differences
- we tested the commonly employed **ray-by-ray (RbR) approximation** for CCSNe in 2D and 3D
- RbR **facilitates explosions in 2D**, at least in sloshing-dominated (“SASI”) cases
- in 3D **almost no sensitivity to RBR** because of absence of artificial symmetry axis