OUTFLOWS FROM NEUTRON-STAR MERGERS (AND RELATED ISSUES)

OLIVER JUST
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RIKEN-RESCEU JOINT SEMINAR

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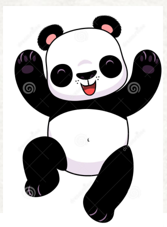
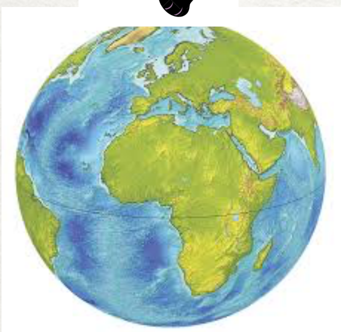
RIKEN MPPC iTHEMS Max Planck Institute for Astrophysics TUM LMU Excellence Cluster Universe erc European Research Council Established by the European Commission

ejecta
mass+velocity

ejection
mechanism



nucleosynthesis
yields



collapse time
of HMNS

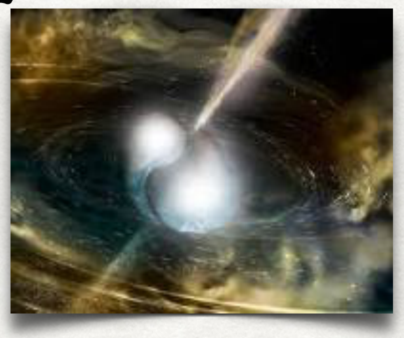
nuclear EOS
constraints

jet launching
mechanism

gravitational waves

radio

optical



UV

X-ray

gamma-ray

ejecta
mass+velocity

ejection
mechanism

nucleosynthesis
yields

collapse time
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jet launching
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modeling "black box"

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

each item may contain considerable uncertainties

gravitational waves

radio

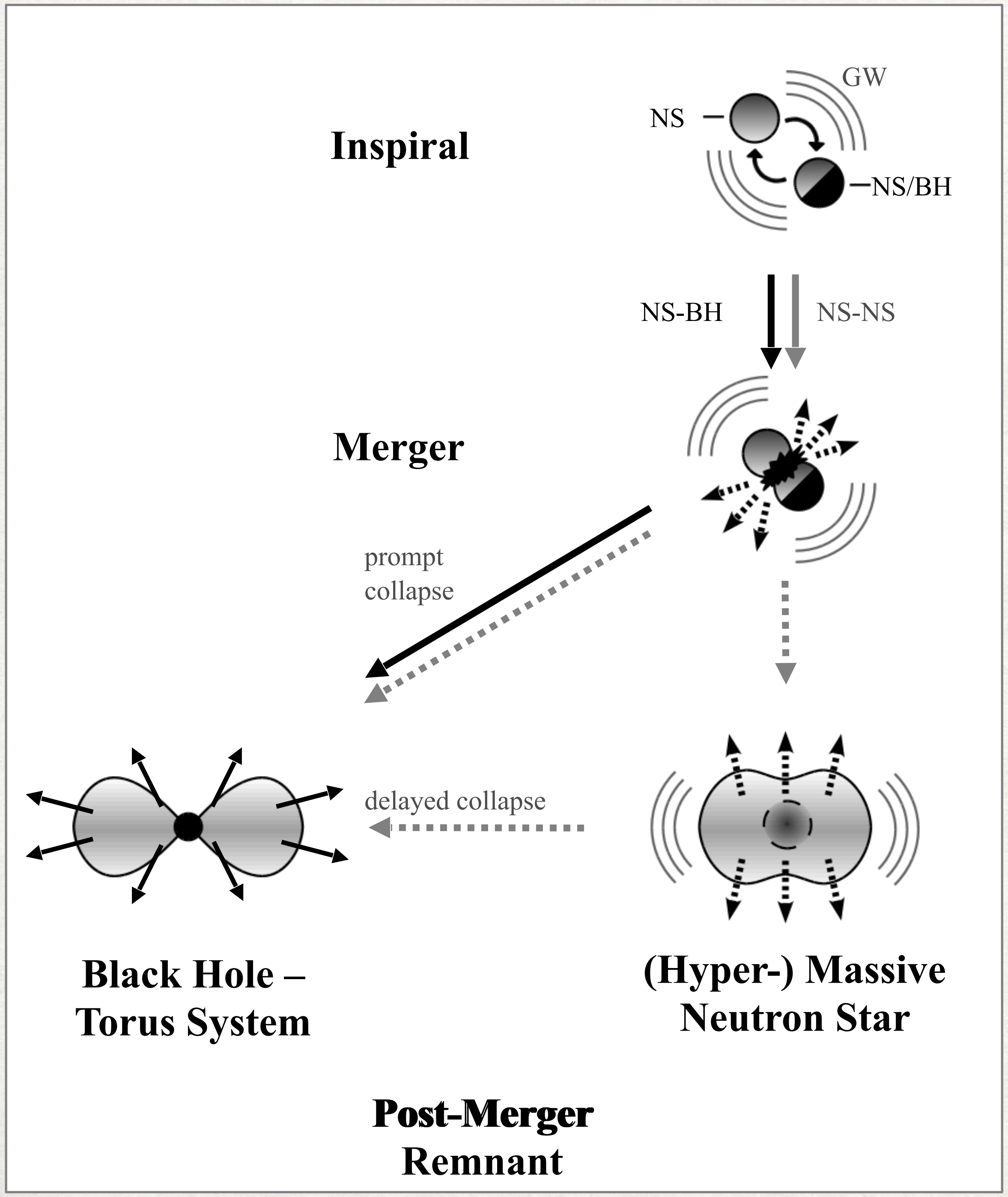
optical

UV

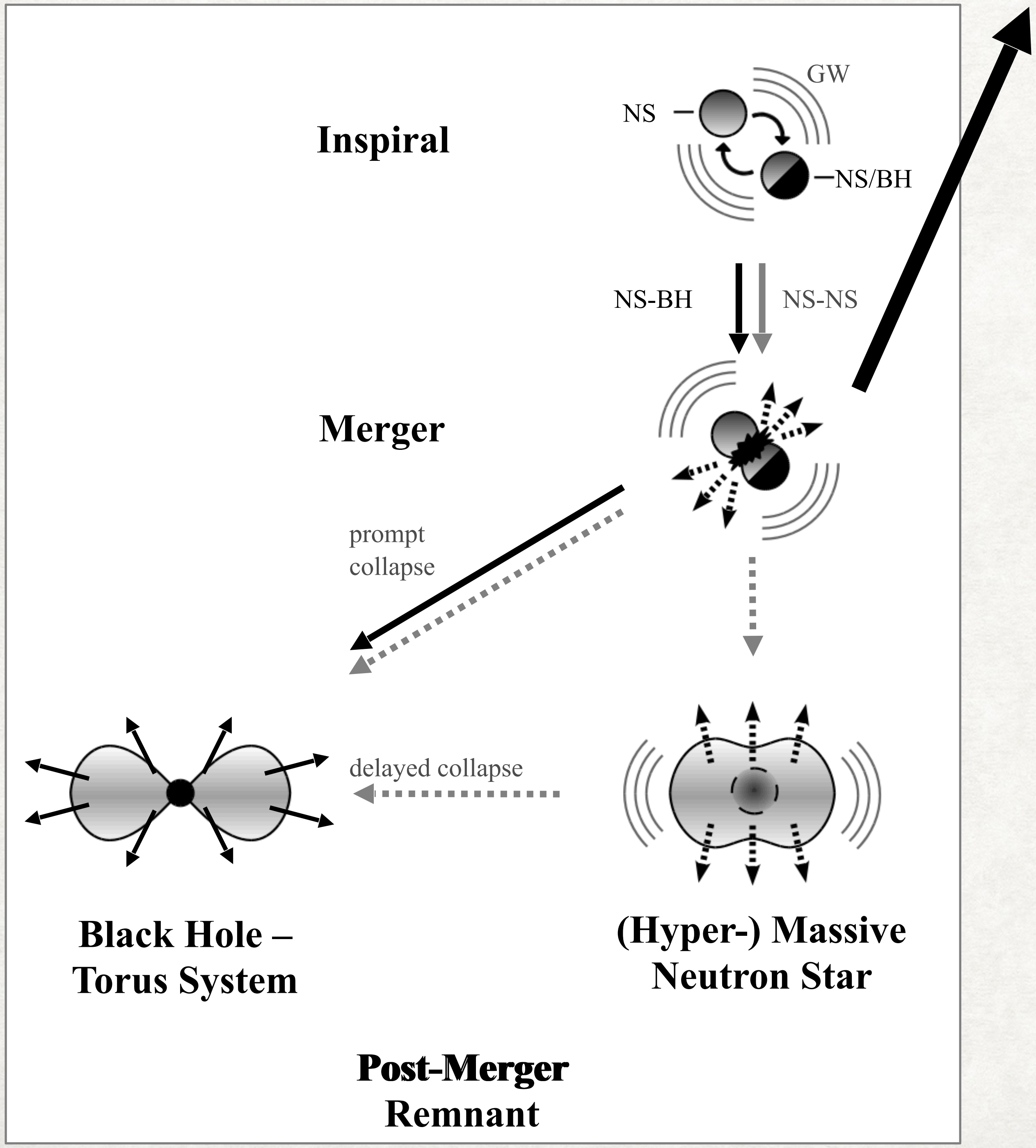
X-ray

gamma-ray

Neutron-star mergers: ejecta components



Neutron-star mergers: ejecta components

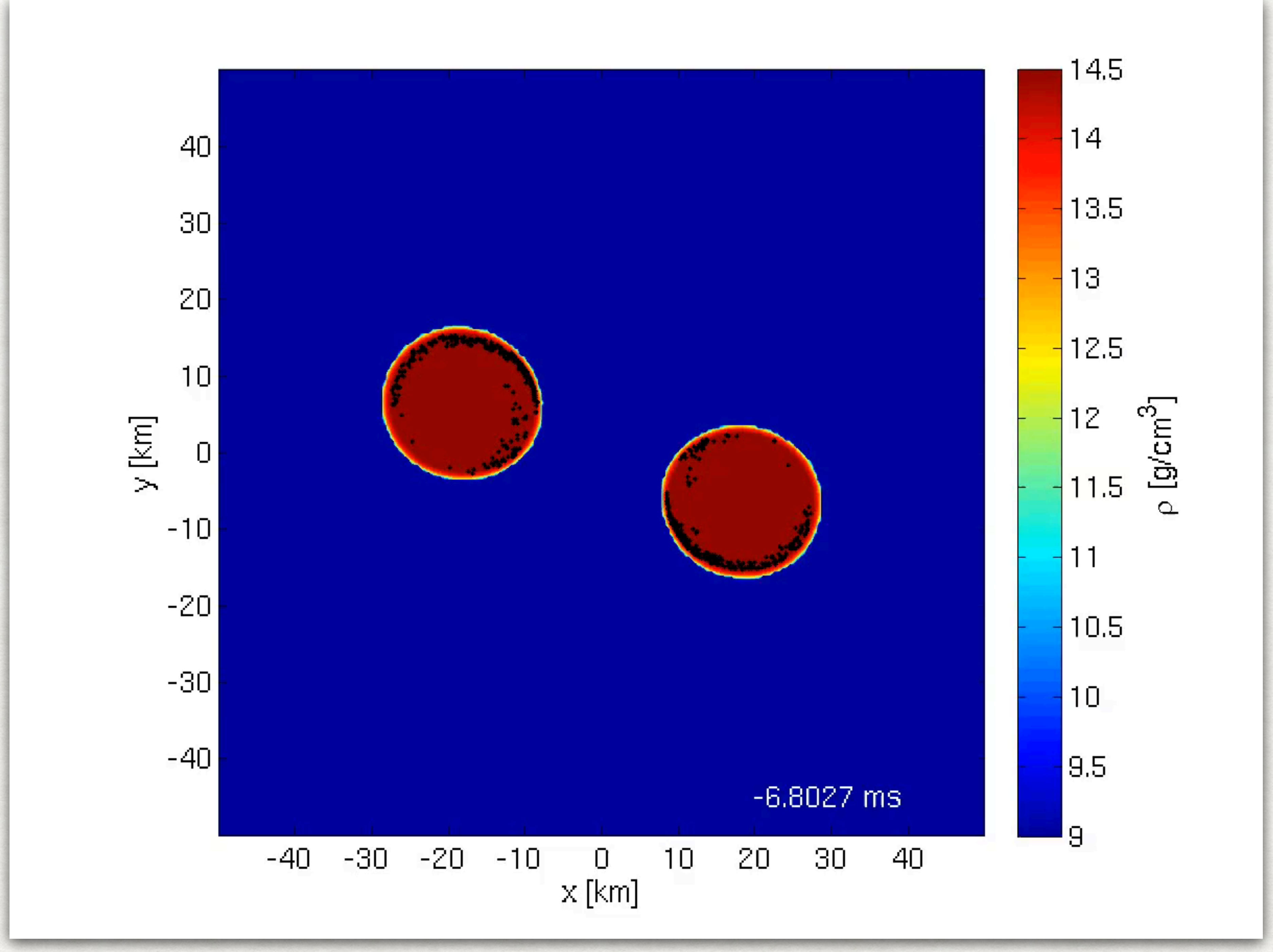


dynamical/prompt ejecta

→ tidal tails

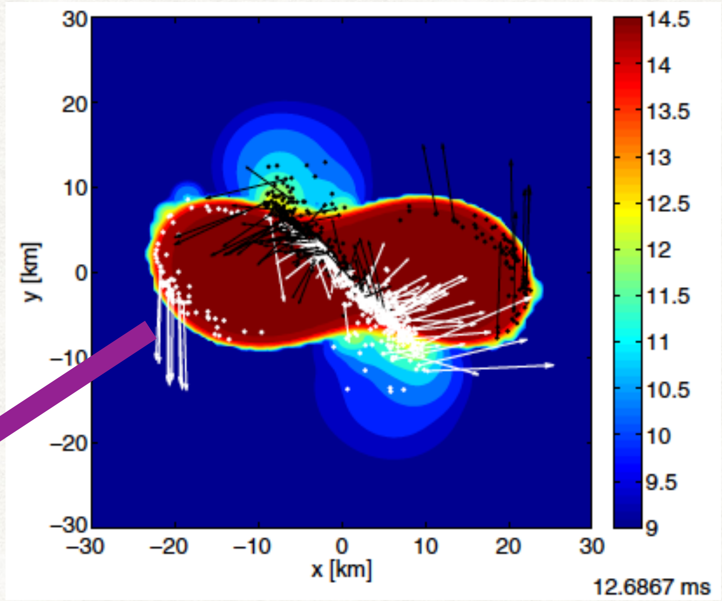
→ shock-heated

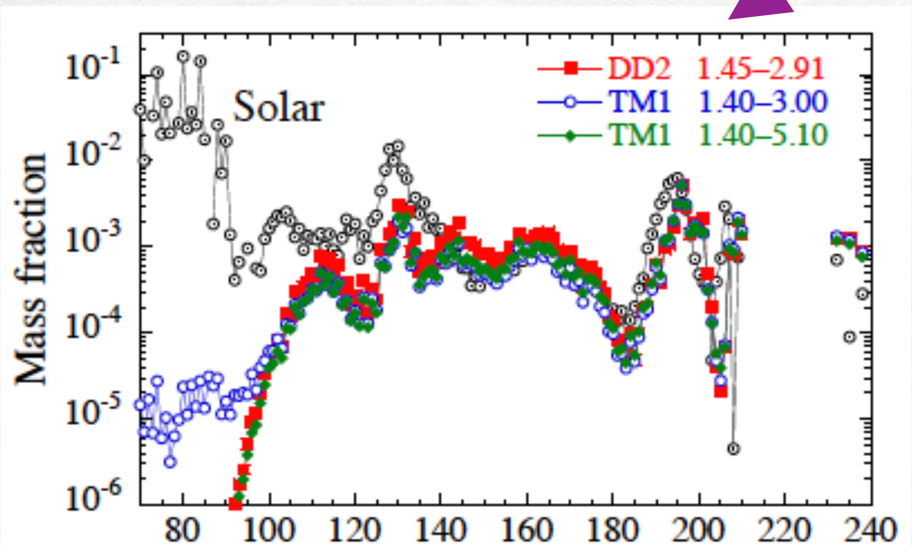
Movie: NS-NS Merger
(SPH simulation by A. Bauswein)



Prompt / dynamical ejecta

(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16, Martin '18)



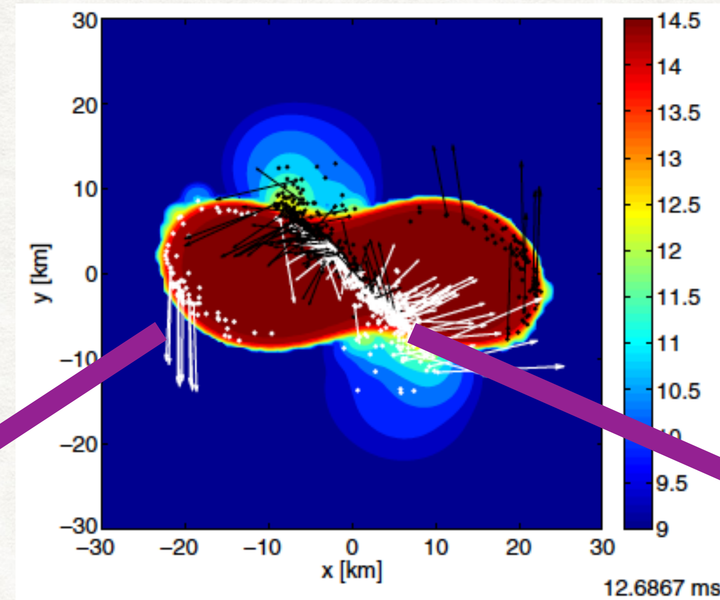


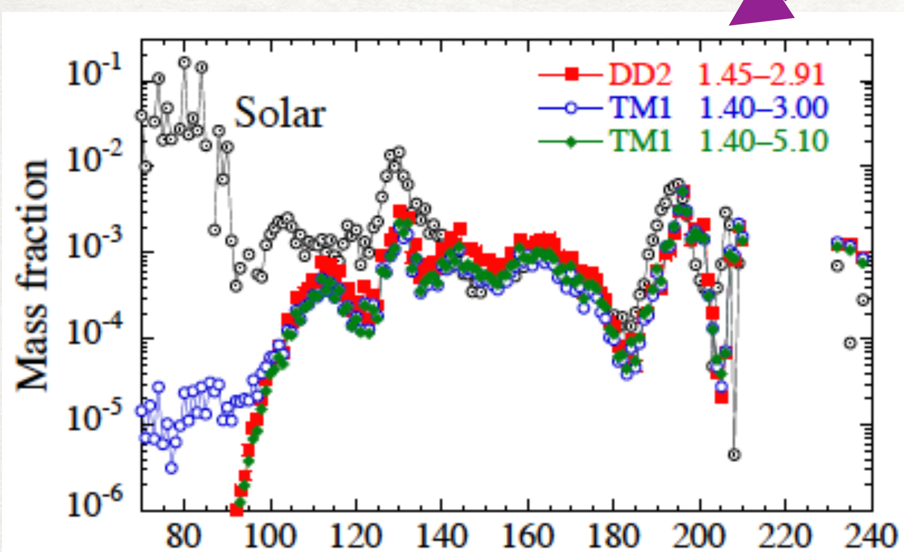
(OJ, Bauswein, Ardevol, Goriely, Janka '15)

from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

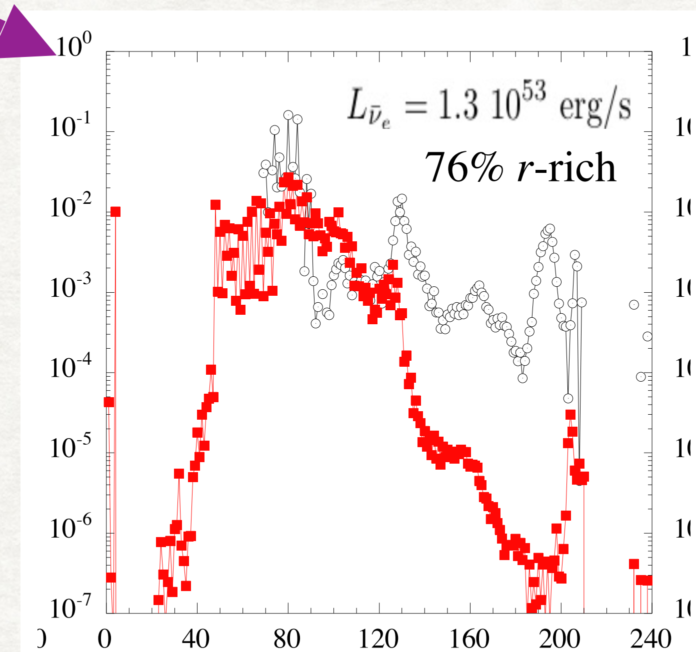
Prompt / dynamical ejecta

(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16, Martin '18)





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

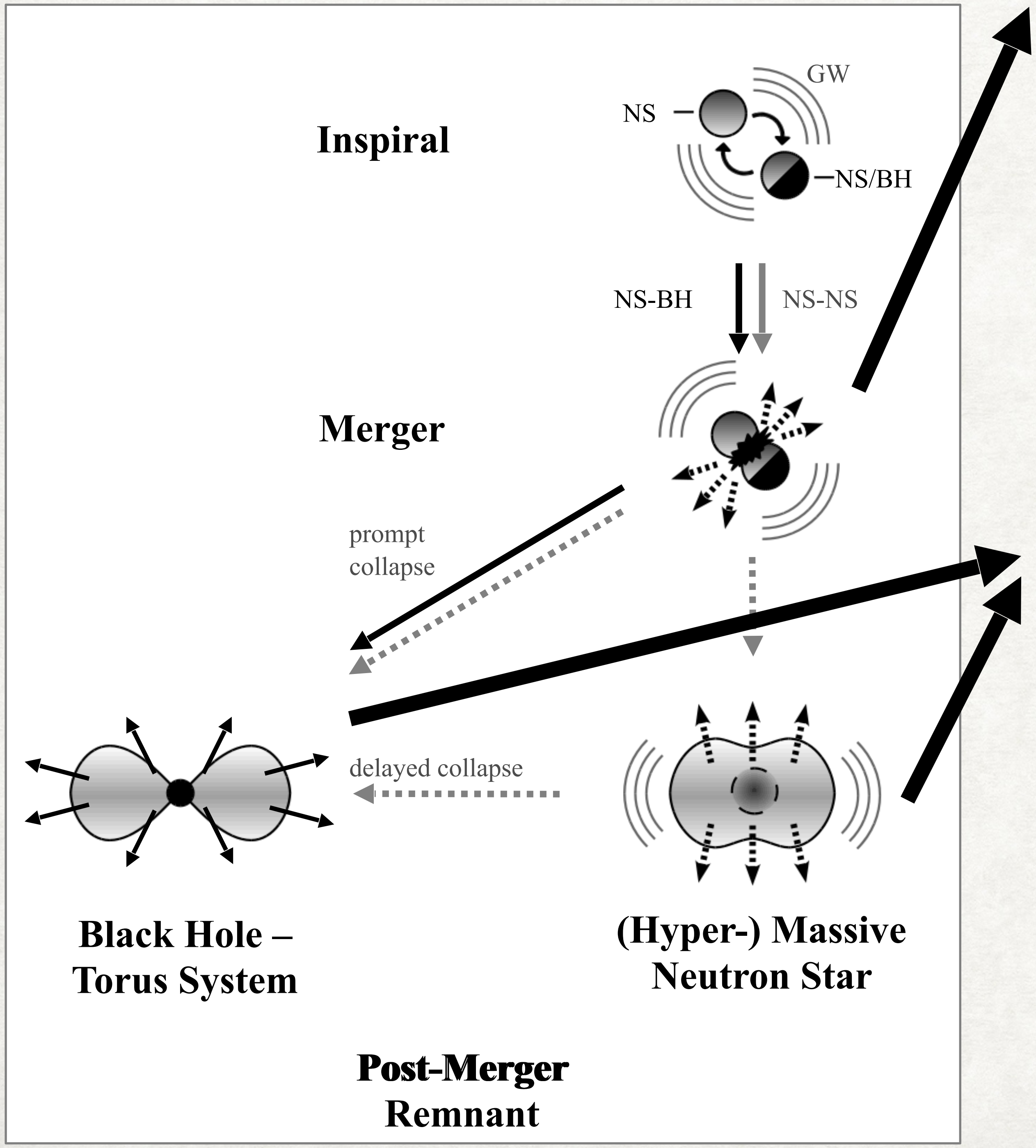


(Goriely et al '15+'18)

from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

from collision shock
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

Neutron-star mergers: ejecta components



dynamical/prompt ejecta

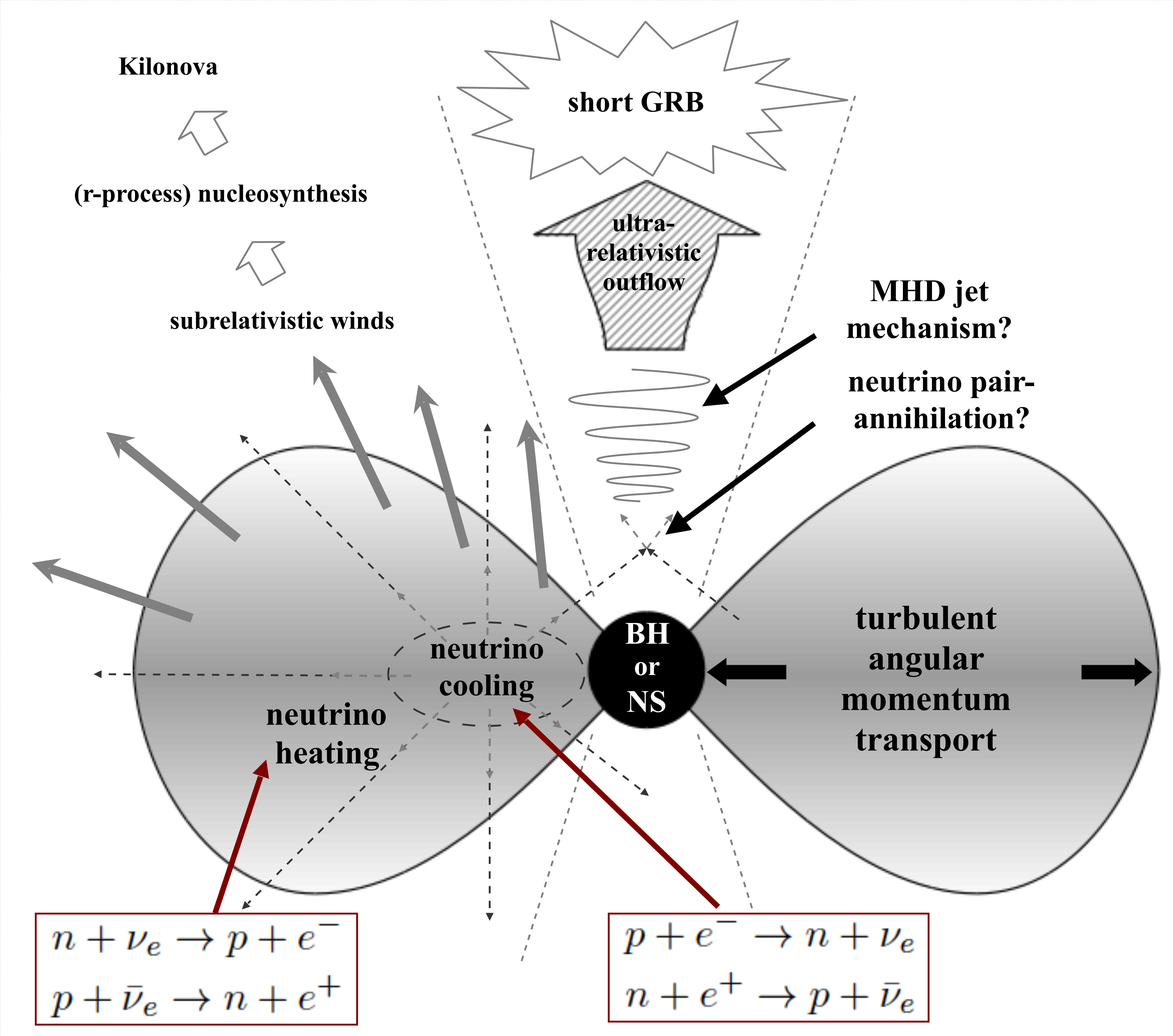
→ tidal tails
→ shock-heated

post-merger ejecta

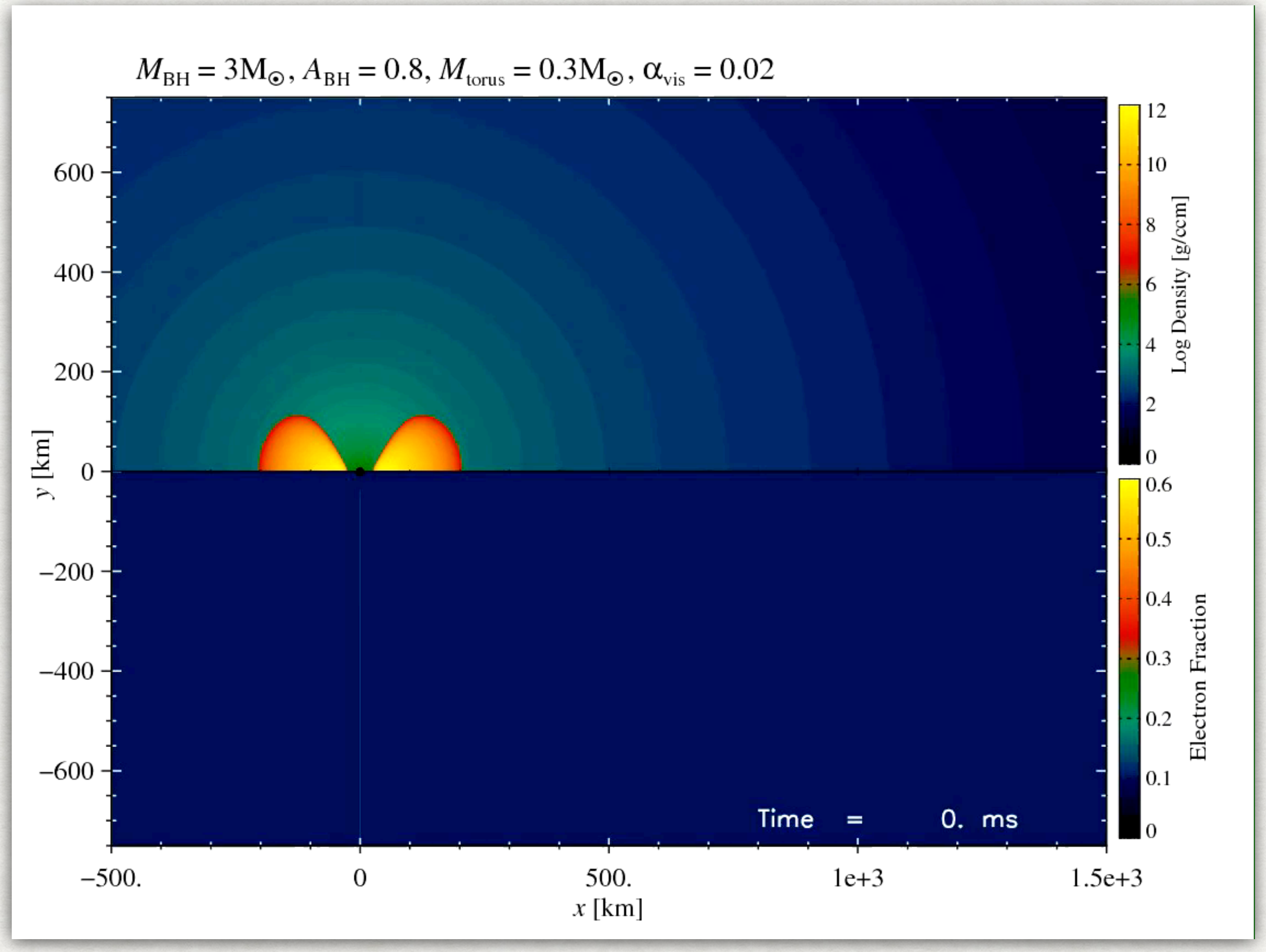
→ neutrino-driven
→ viscous/MHD driven expansion
→ MHD turbulence

PHYSICS OF POST-MERGER CONFIGURATION

Mass accretion, wind generation, and jet launching highly sensitive to angular momentum transport and neutrino cooling and heating



Post-merger BH-torus remnant



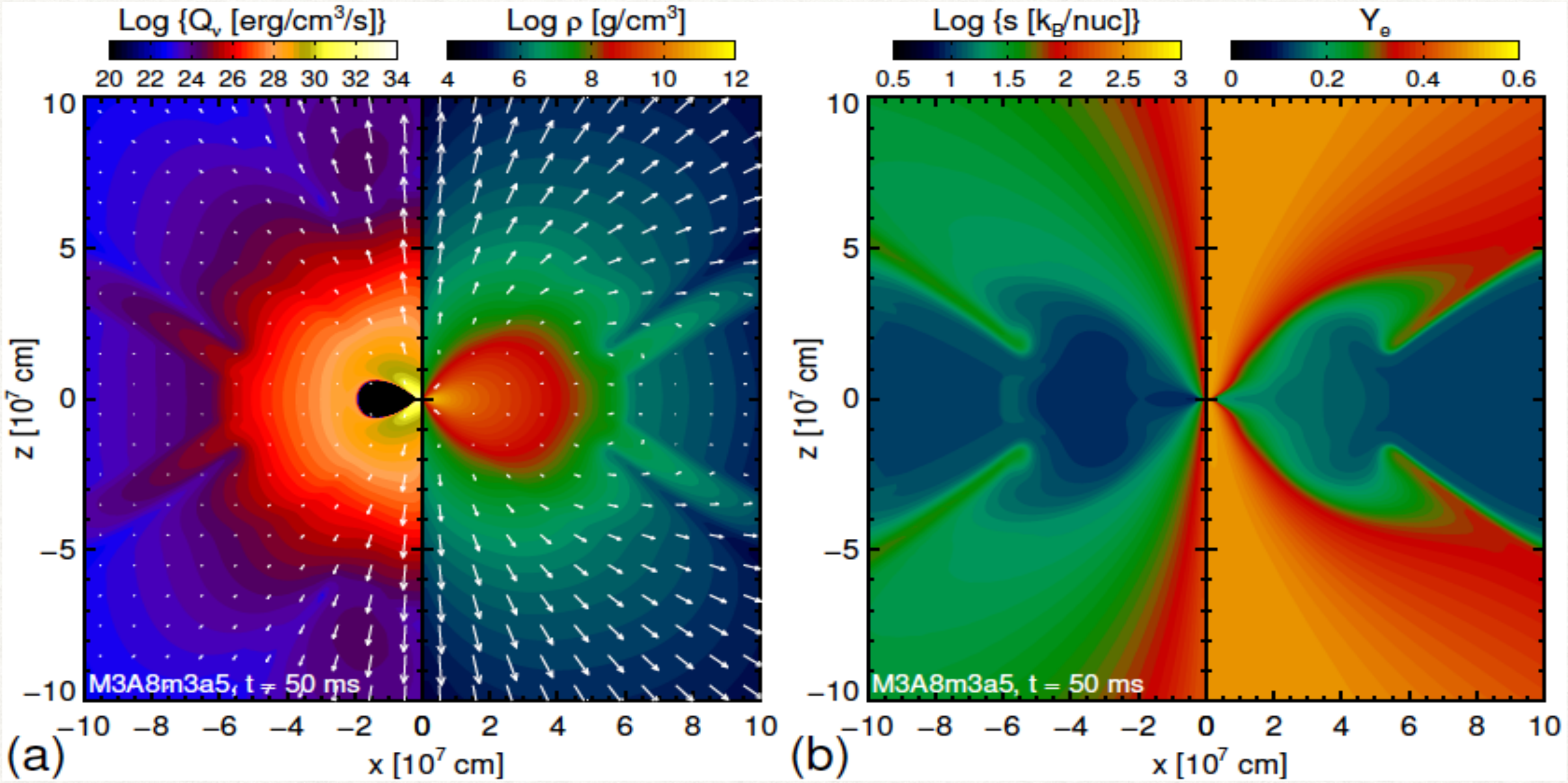
(OJ, Bauswein, Ardevol, Goriely, Janka '15)

(qualitative agreement with Fernandez '13, Wu '16, Siegel '18)

Post-merger BH-torus remnant

early phase: ejecta (mainly) driven by neutrino-heating

time = 50 ms



Ye in ejecta determined by **neutrino captures**

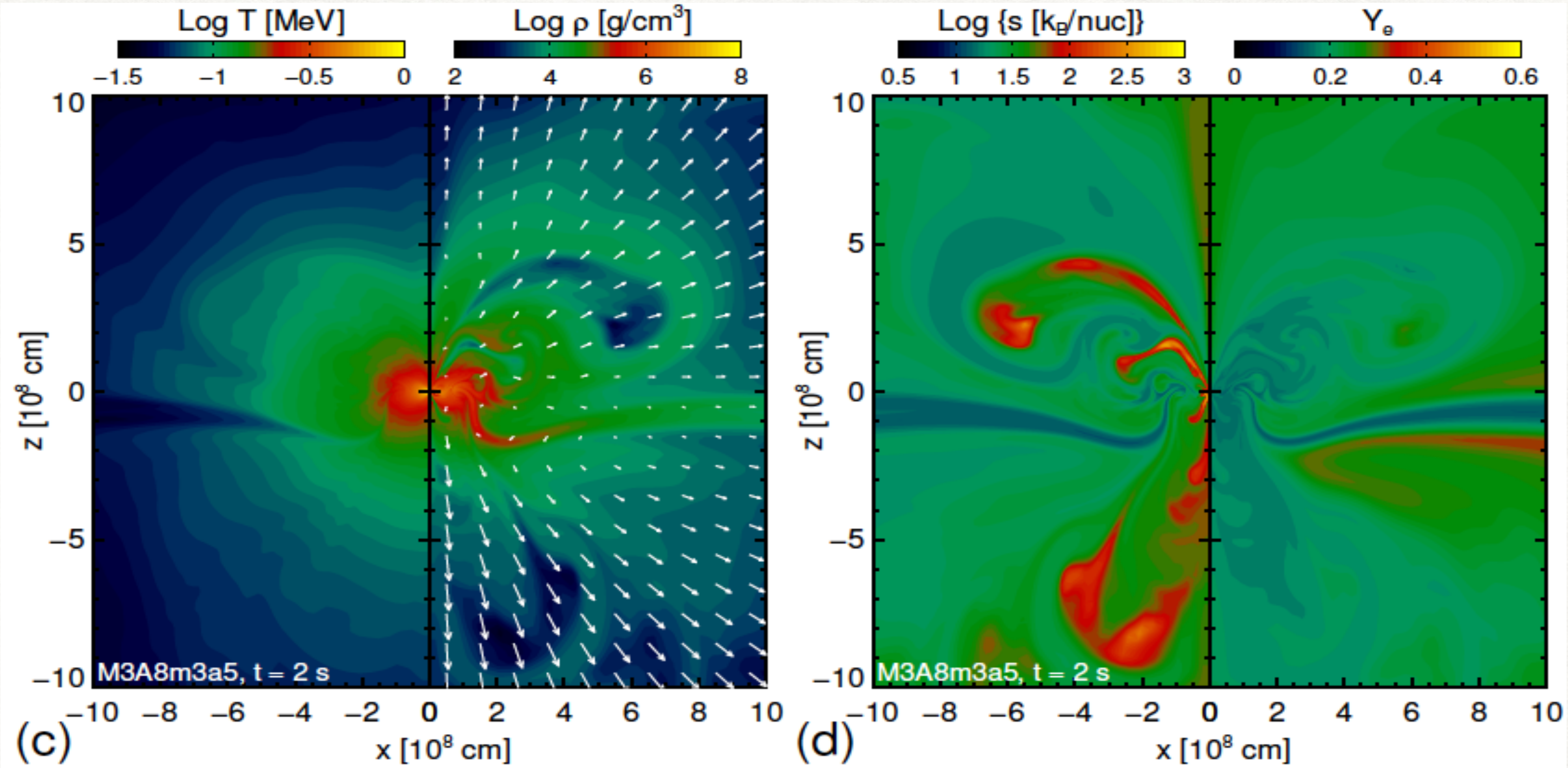
$$n + \nu_e \rightarrow p + e^-$$
$$p + \bar{\nu}_e \rightarrow n + e^+$$

$$Y_e \quad \longrightarrow \quad Y_e^\nu \quad \simeq \quad \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2Q_{np}}{\varepsilon_{\nu_e} + 2Q_{np}}\right)^{-1}$$

Post-merger BH-torus remnant

later phase: ejecta (mainly) driven by viscosity (turb. ang. mom. tr.)

time = 2 s

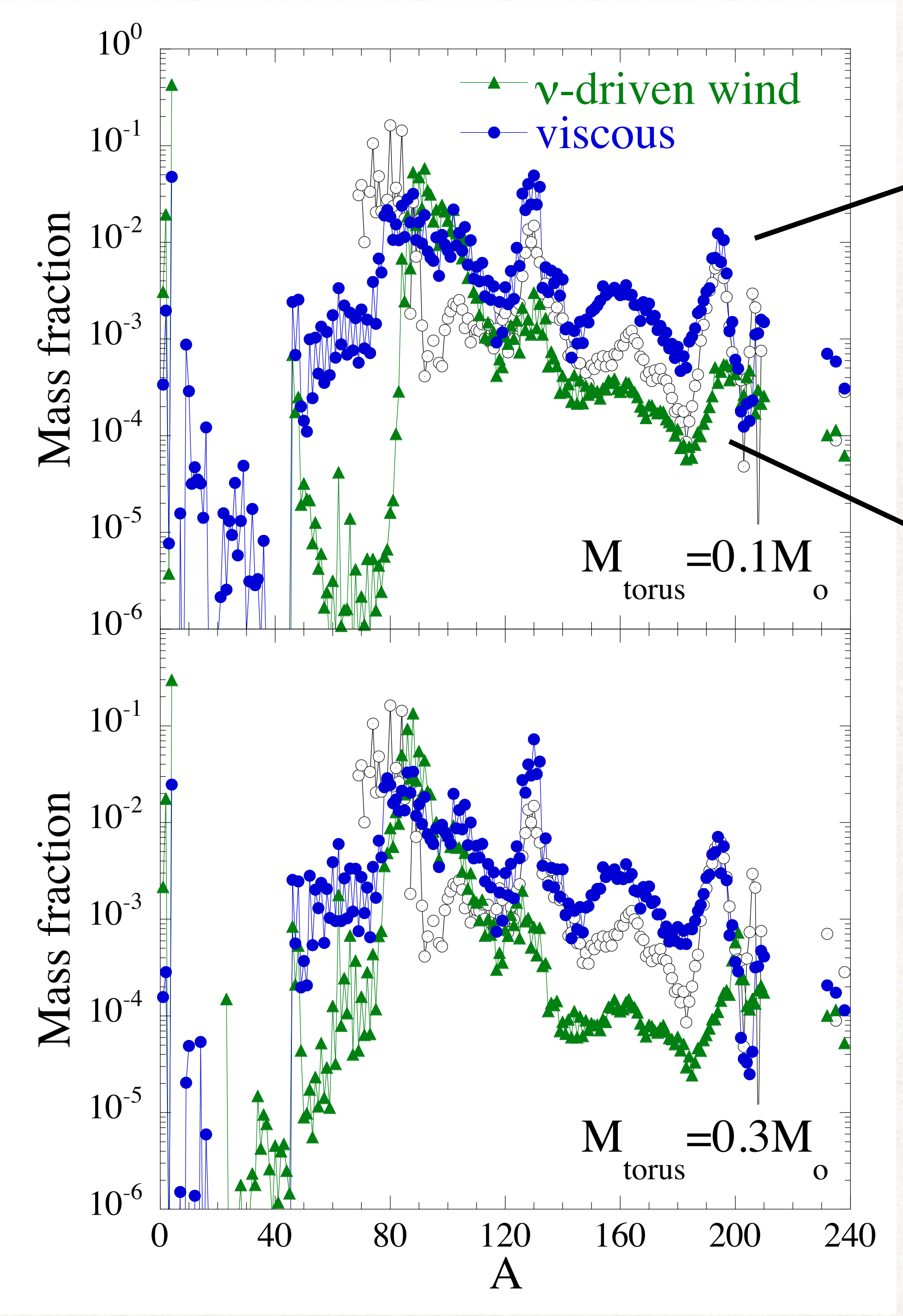


Ye in ejecta determined by **electron/positron captures**

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

$$Y_e \longrightarrow Y_e^\beta = Y_e(\rho, T, \mu_\nu = 0)$$

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)

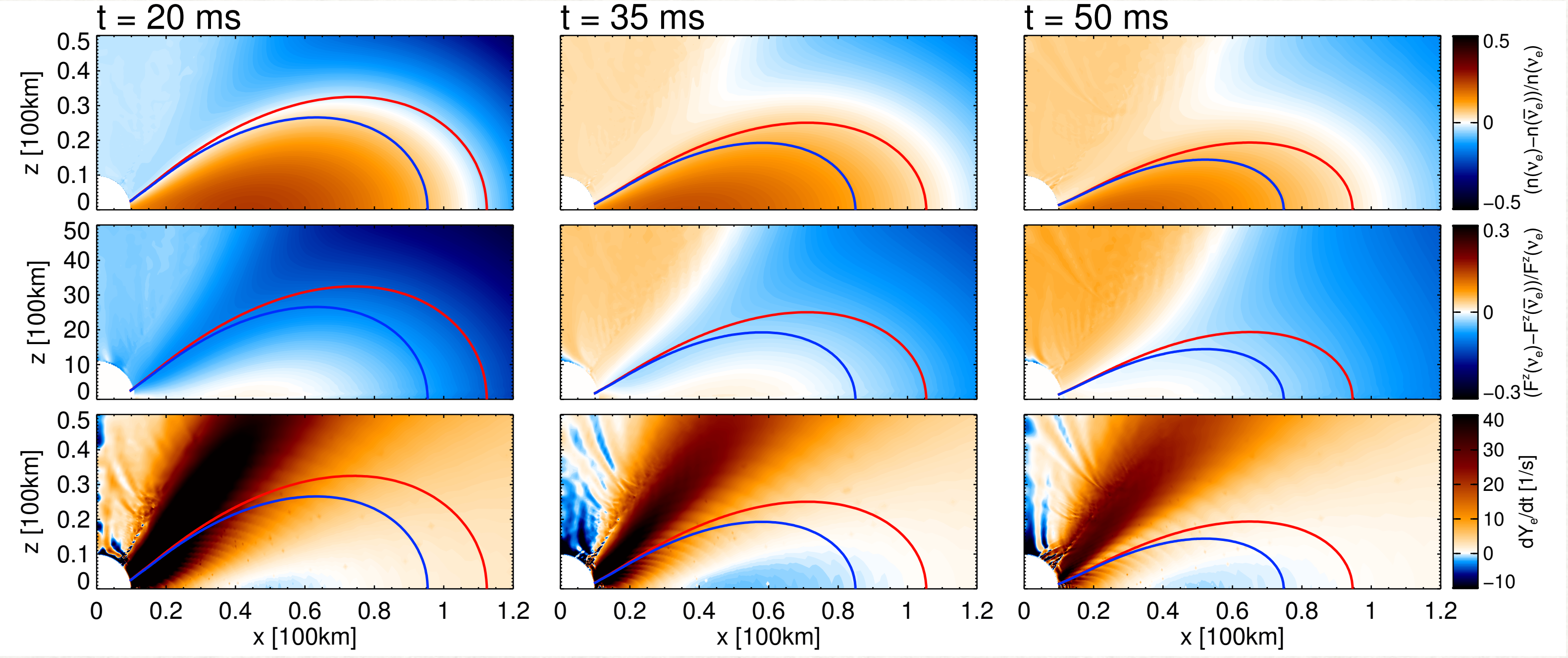
neutrino-driven outflows:
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

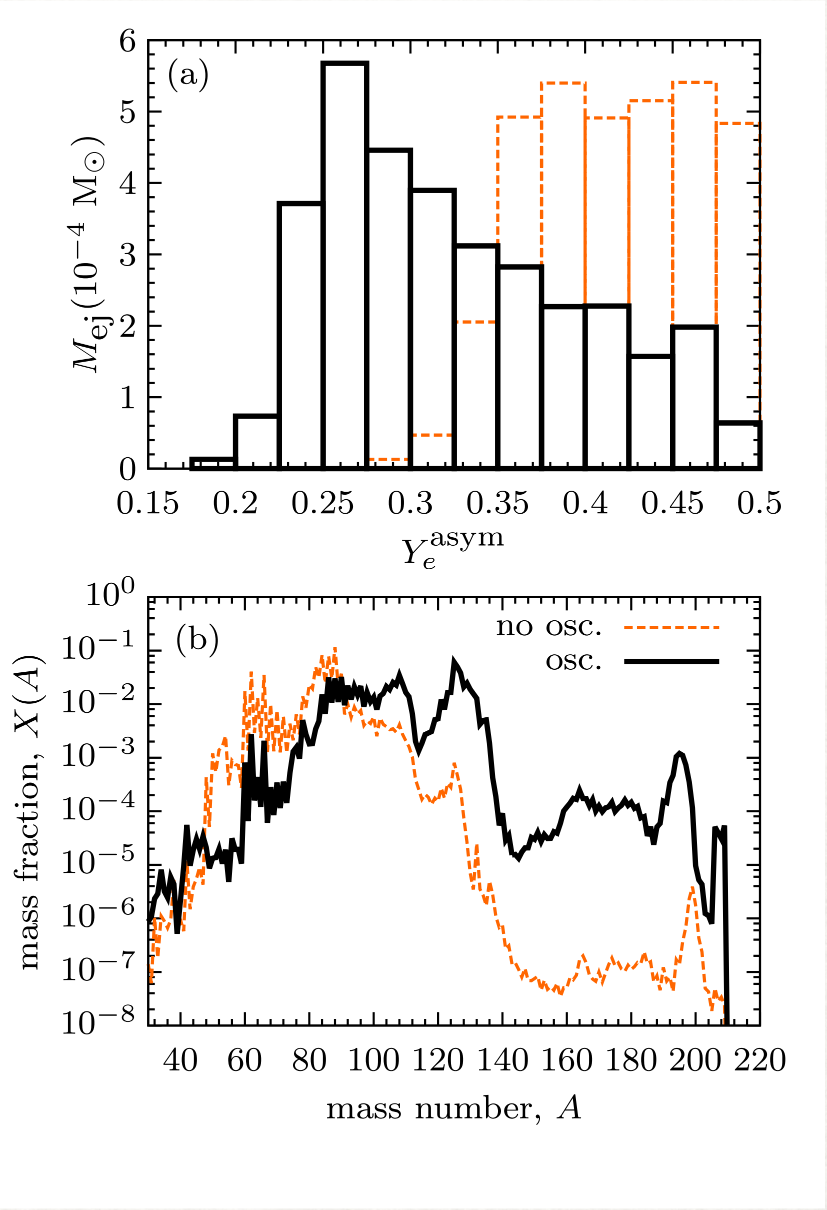
(similar qualitative tendency for outflows from a HMNS-torus system, e.g. Fujibayashi '17, Perego '14)

IMPACT OF NU-NU OSCILLATIONS ON THE NEUTRINO-DRIVEN WIND COMPONENT

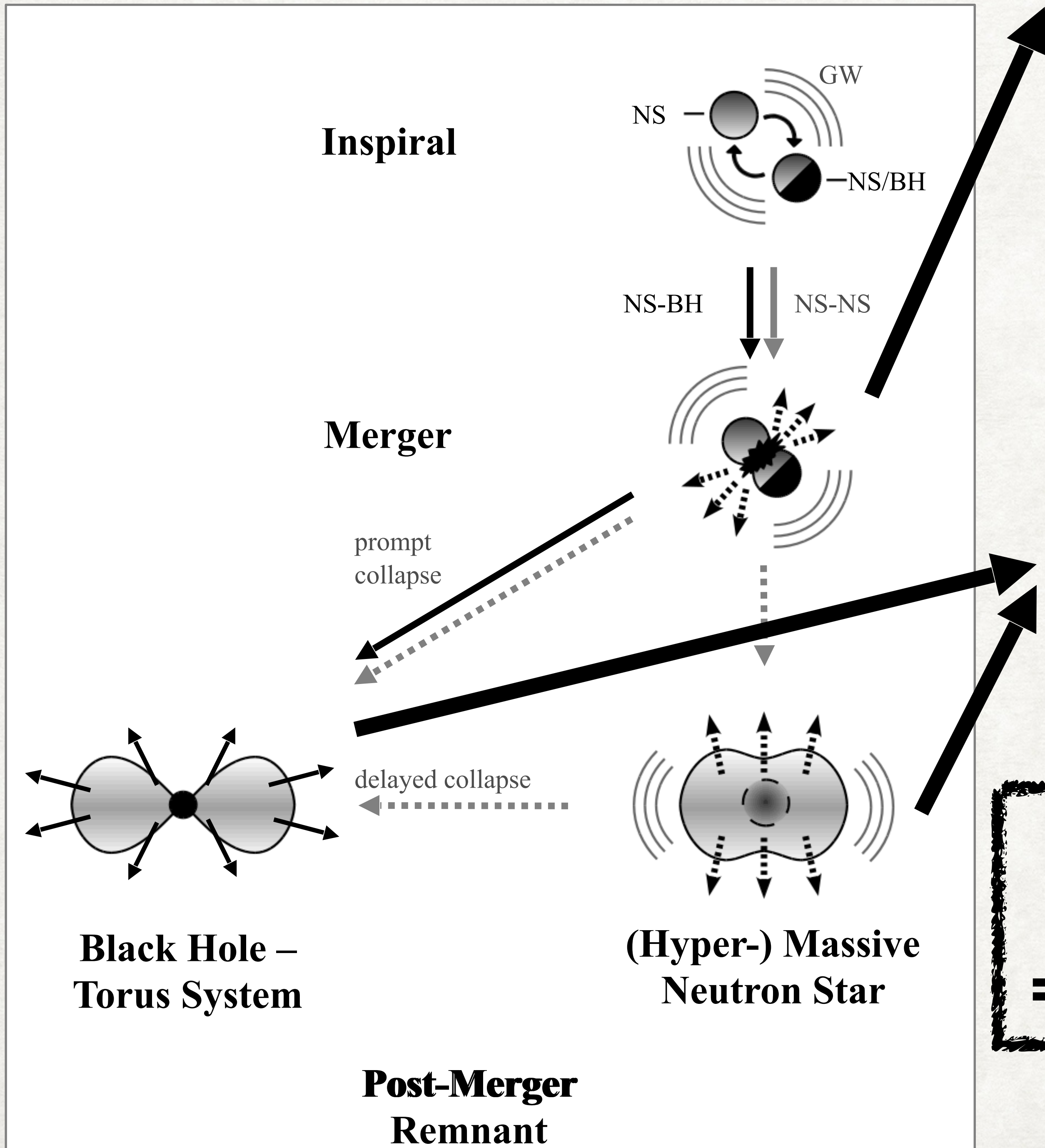
(Wu, Tamborra, OJ, Janka, 2017PhRvD, 96I3015W)

- ***"fast pairwise flavor conversions"*** may lead to flavor equilibration on length scales of **O(10cm)** (e.g. Sawyer+ 05, 09, 16)
- our simplified, exploratory study indicates that neutrino-driven ejecta may remain **more neutron rich**





Neutron-star mergers: ejecta components

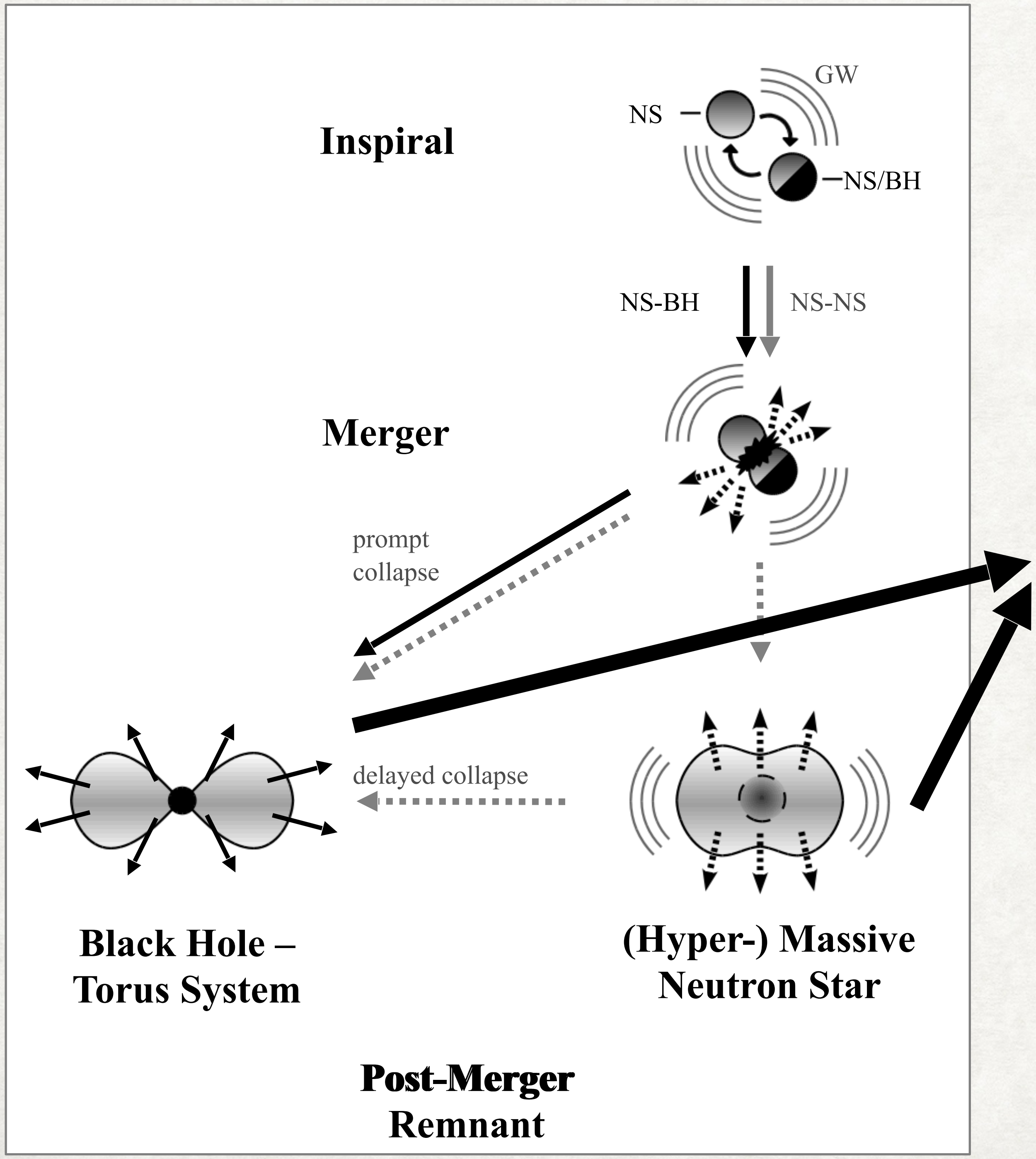


dynamical/prompt ejecta
→ tidal tails
→ shock-heated

post-merger ejecta
→ neutrino-driven
→ viscous/MHD driven expansion
→ MHD turbulence

BOTH ejecta types can contain
high-Ye and low-Ye components
=> observational distinction difficult

Neutron-star mergers: ejecta components



(short gamma-ray burst) jet?

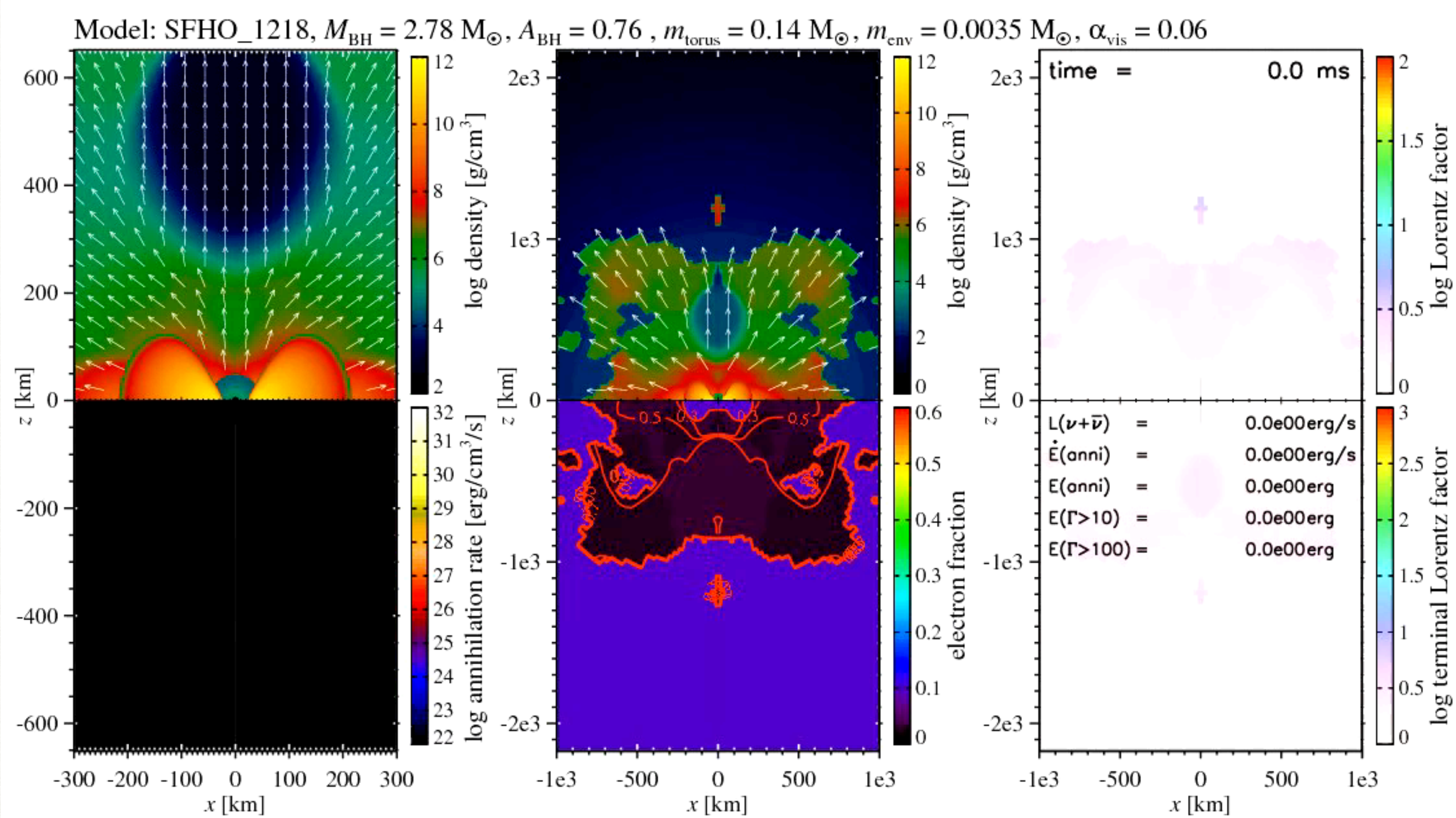
→ from neutrino pair annihilation?

→ from MHD Blandford-Znajek mech.?

→ Magnetar spindown?

(ASYMMETRIC) NS-NS MERGER

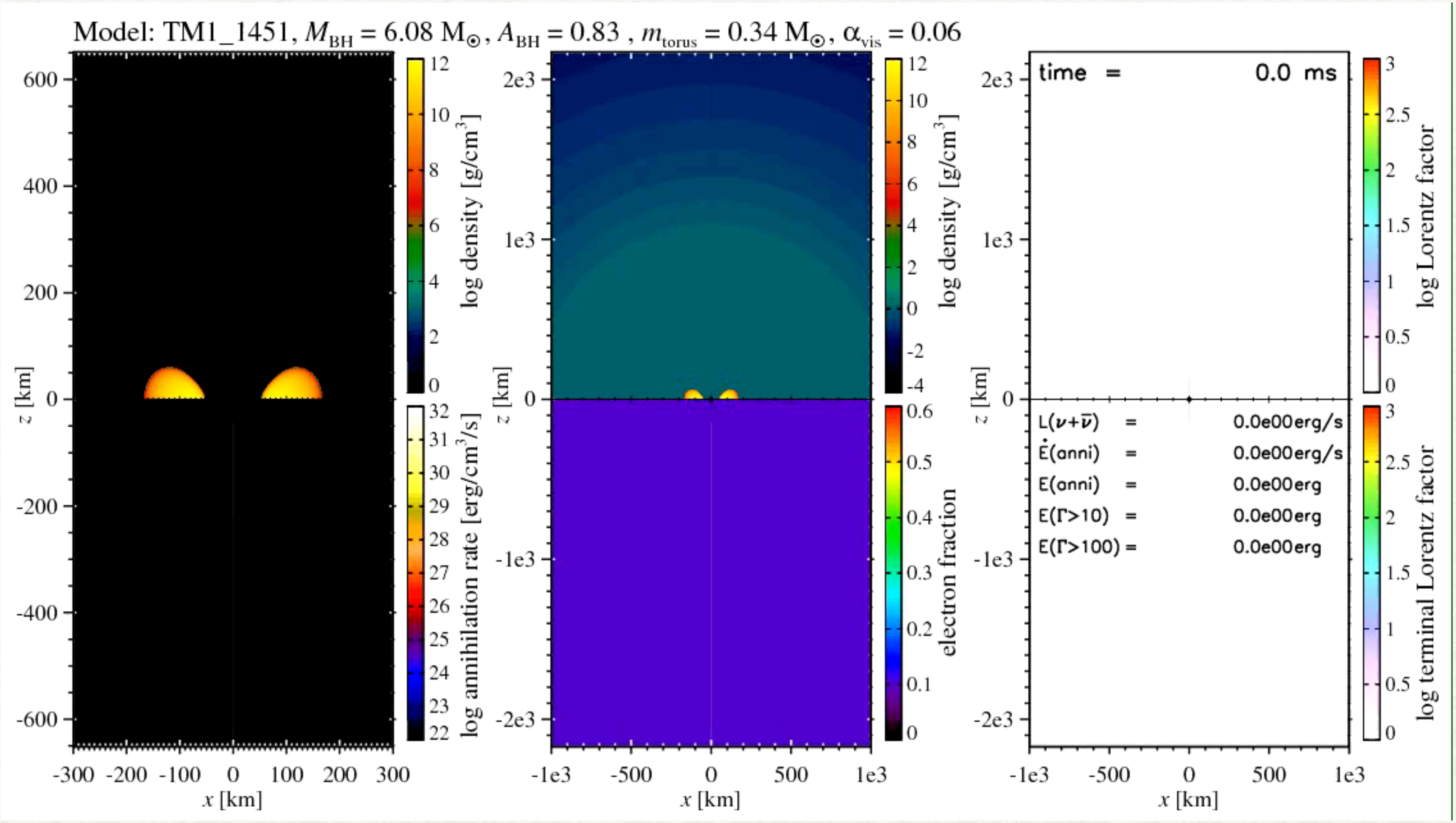
(OJ, Obergaulinger, Bauswein, Janka '15)



- ➡ jet is **successfully launched**, but then dissipates most of its kinetic energy into cloud of dynamical ejecta
- ➡ **choked jet, pair-annihilation NOT powerful enough**

NS-BH MERGER

(OJ, Obergaulinger, Bauswein, Janka '15)



- ➡ no dynamical ejecta in polar regions → jet can expand freely
- ➡ but energy still too low to explain majority of sGRBs
- ➡ **neutrino pair-annihilation not powerful enough to explain sGRBs**

GW170817/AT2017GFO

GW170817 + EM COUNTERPARTS

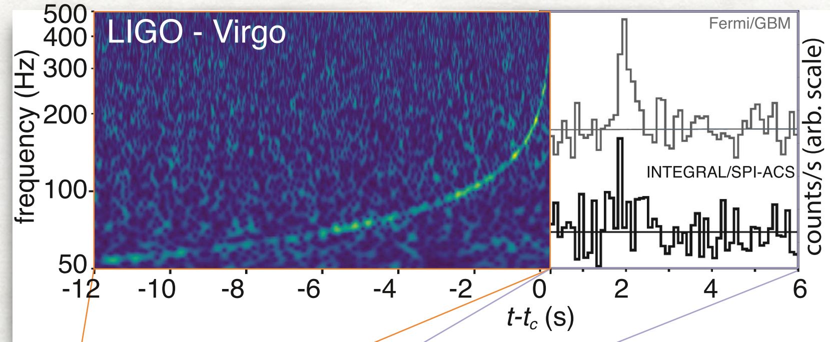
- Mtot = M1 + M2 ~ 2.74 Msun

- M1/M2 ~ 0.7 - 1

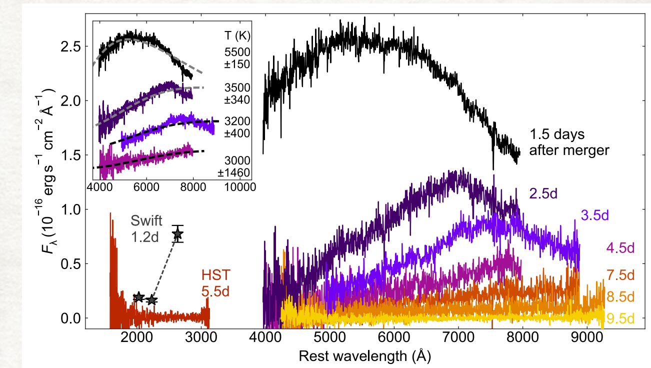
- **blue ejecta component** with
  $\langle Y_e \rangle > 0.25$
  M ~ 0.01-0.03 Msun

- **red ejecta component** with
  $\langle Y_e \rangle < 0.25$
  M ~ 0.01-0.03 Msun

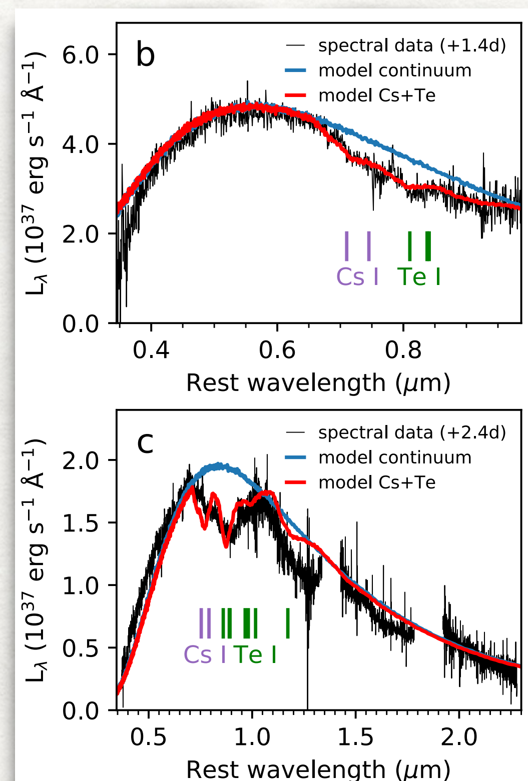
- low-luminosity gamma-ray burst
  with E_{peak} ~ 100keV



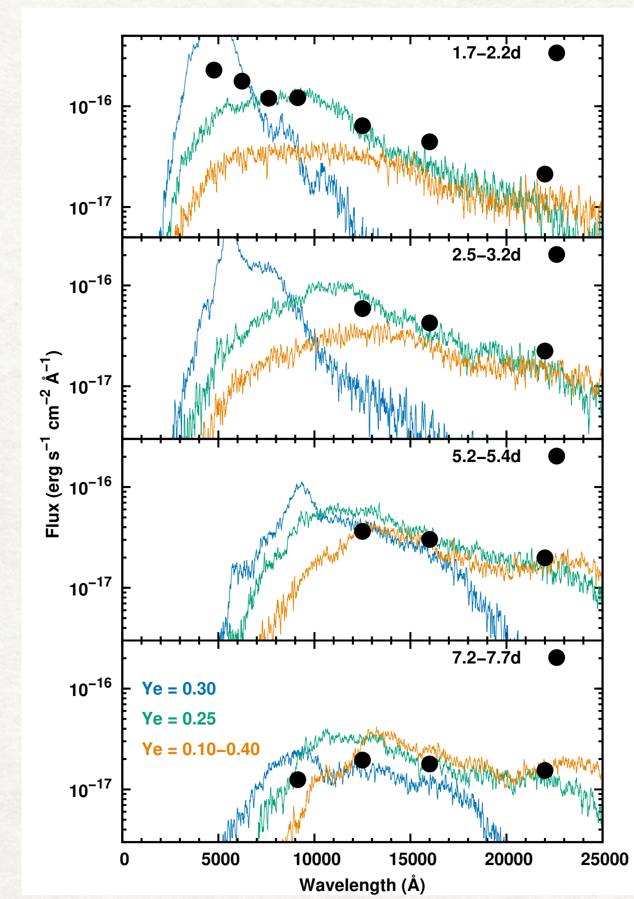
(LIGO Coll.+'17)



(Nicholl+'17)



(Smartt+'17)



(Tanaka+'17)

GW170817 + EM COUNTERPARTS

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

➜ *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…*

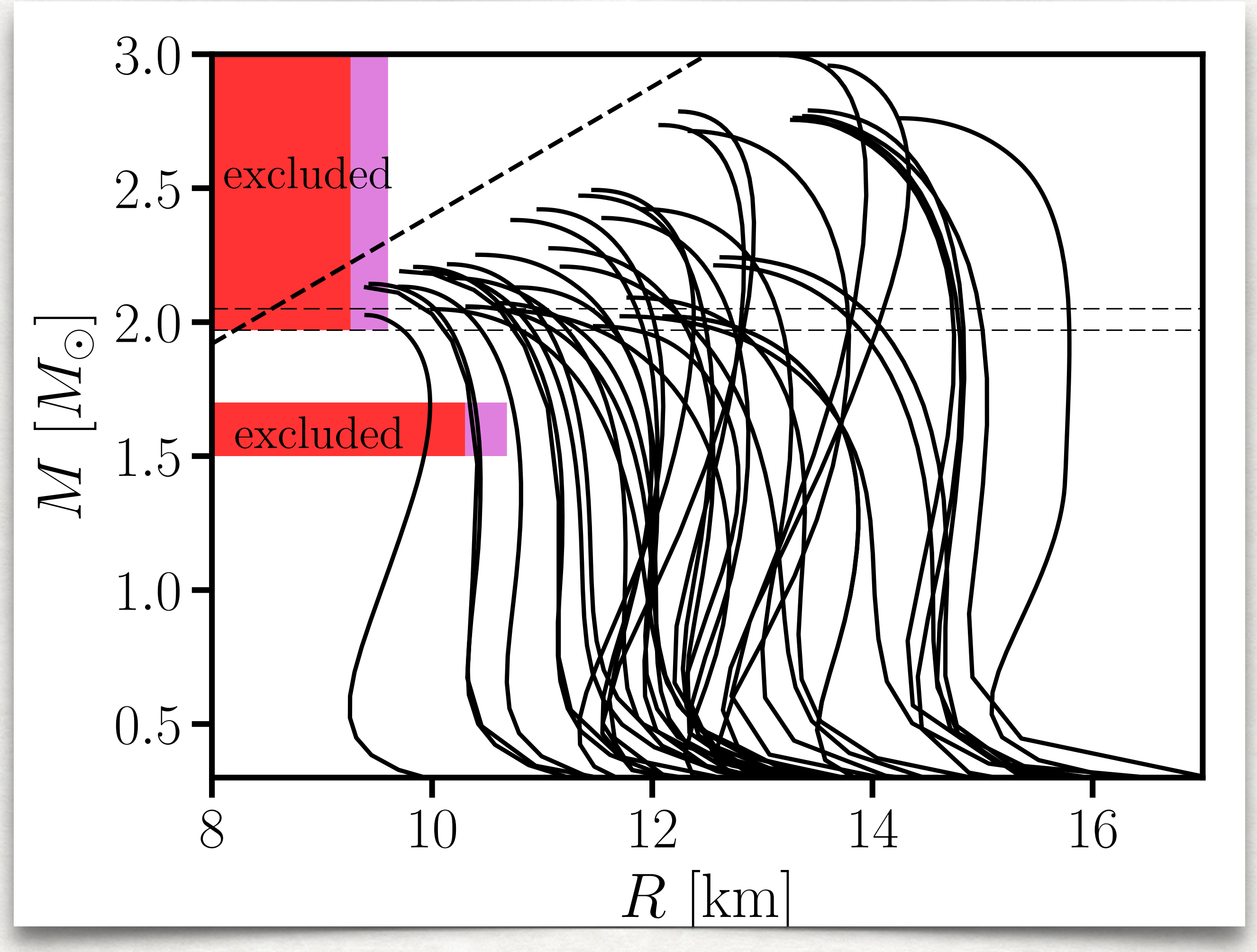
dynamical ejecta launched during merger or viscous ejecta from the remnant?

shock breakout emission or cocoon emission from structured jet. *High E_{peak} still puzzling…*

➜ *major open questions remain…better models needed*

DELAYED COLLAPSE IS VERY LIKELY FOR GW170817: IMPLICATION FOR NUCLEAR EOS

(Bauswein, OJ, Janka, Stergioulas, 2017ApJ, 850L, 34B)



very conservative *constraint*
assuming HMNS lifetime > 0 ms

R_{16} > 10.3 km
R_{max} > 9.3 km

conservative *constraint*
assuming HMNS lifetime > 10 ms

R_{16} > 10.7 km
R_{max} > 9.6 km

(also several other EOS studies, e.g., Margalit+ '17, Rezzolla+ '17, Ruiz+ '17, Radice+ '17)

CCSN EXPLOSION MECHANISM: CODE COMPARISON

WHY CODE COMPARISONS?

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

😄 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

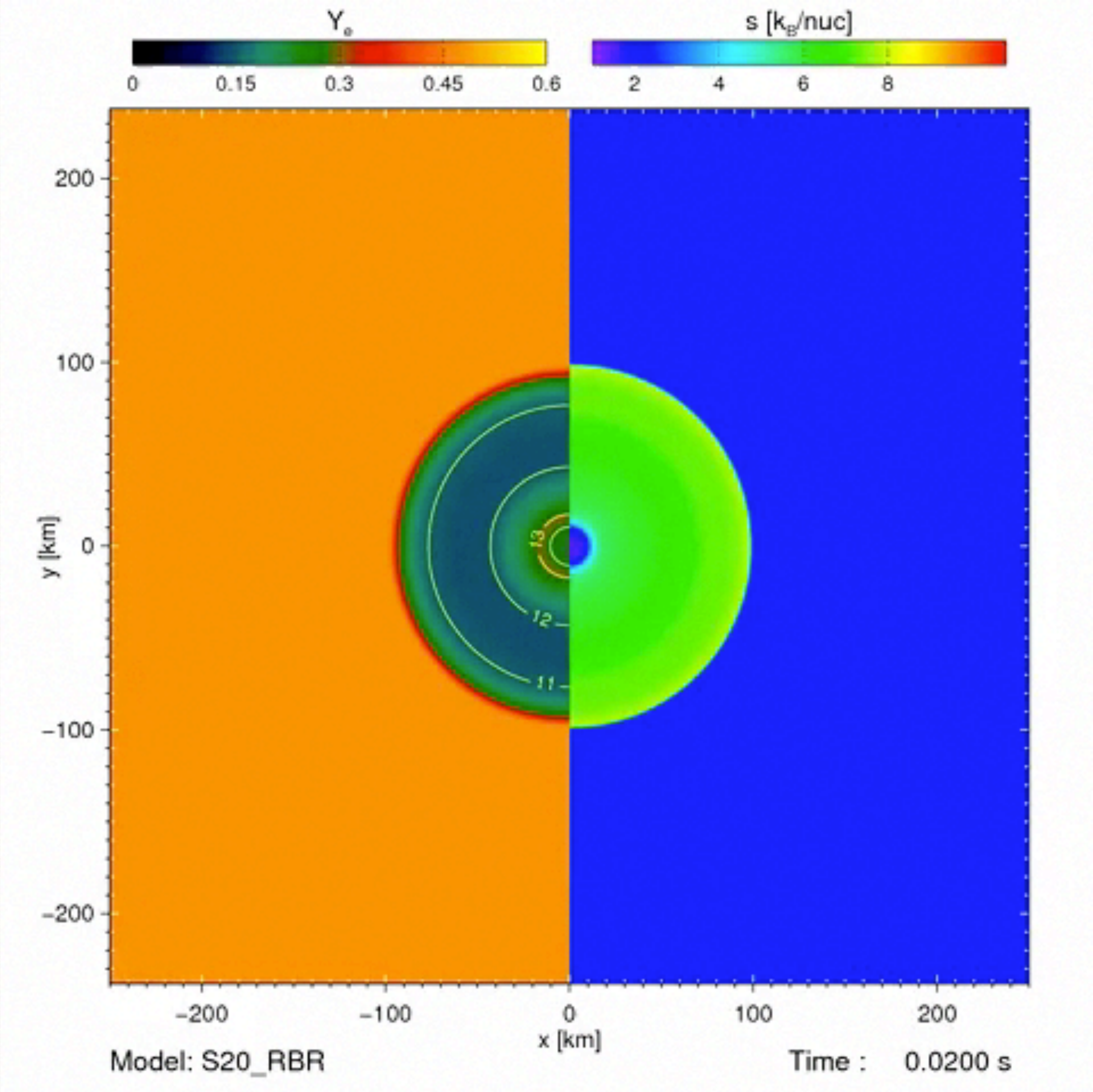
😩 small number of available models: cross-comparisons and parameter exploration unfeasible

➡ cross-comparisons **invaluable** to assess reliability of final conclusions

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

COMPARISON STUDY IN 2D

(OJ, Bollig, Janka et al, ’18)

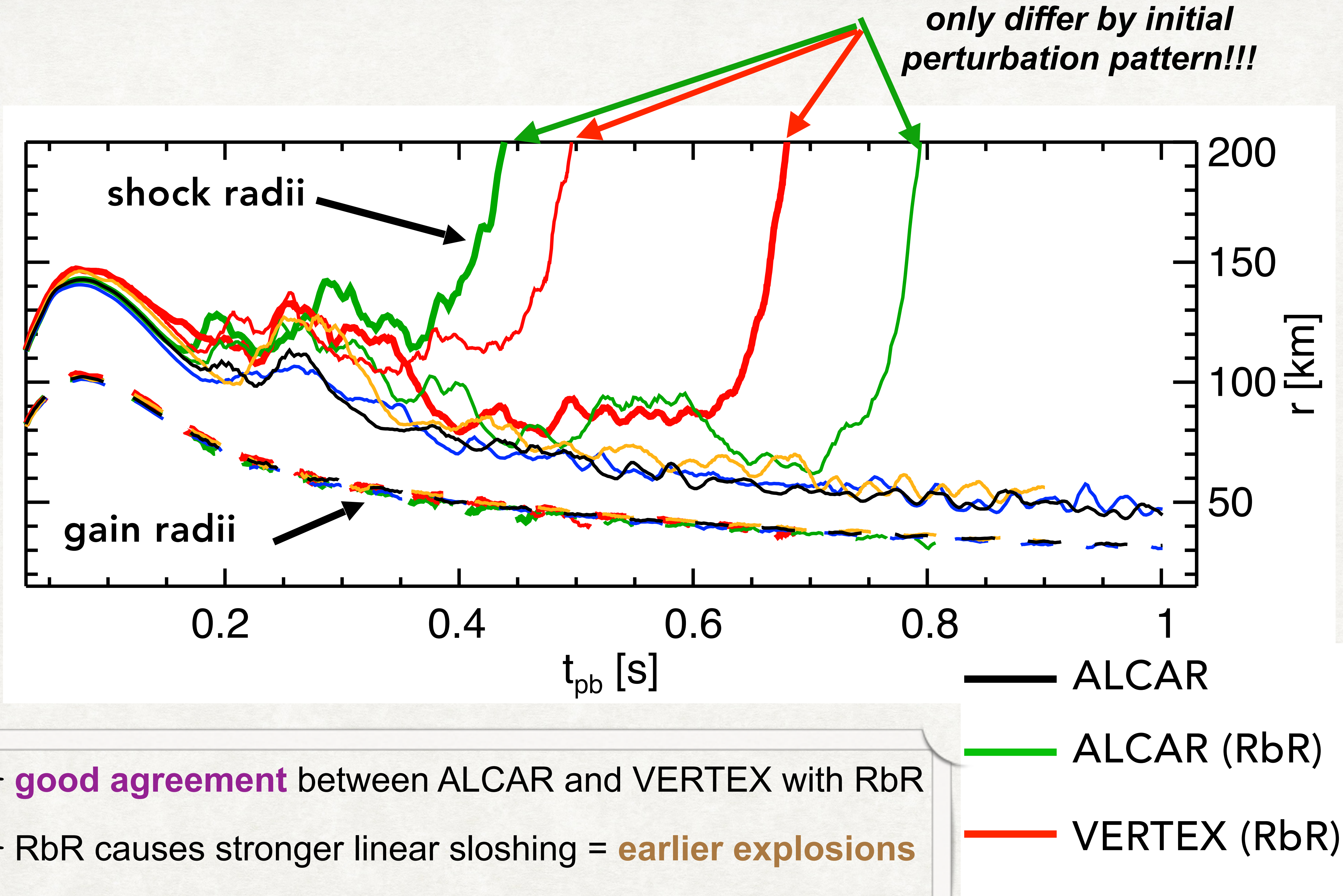


(20 Msun model, simulated with “ALCAR” code, M1 approximation, with ray-by-ray+)

Aims:

- compare M1-RbR (ALCAR) with Boltzmann-RbR (VERTEX)
- compare M1-RbR with unconstrained M1
- test other common approximations used for neutrino transport

ALCAR VS VERTEX VS RBR+: 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)

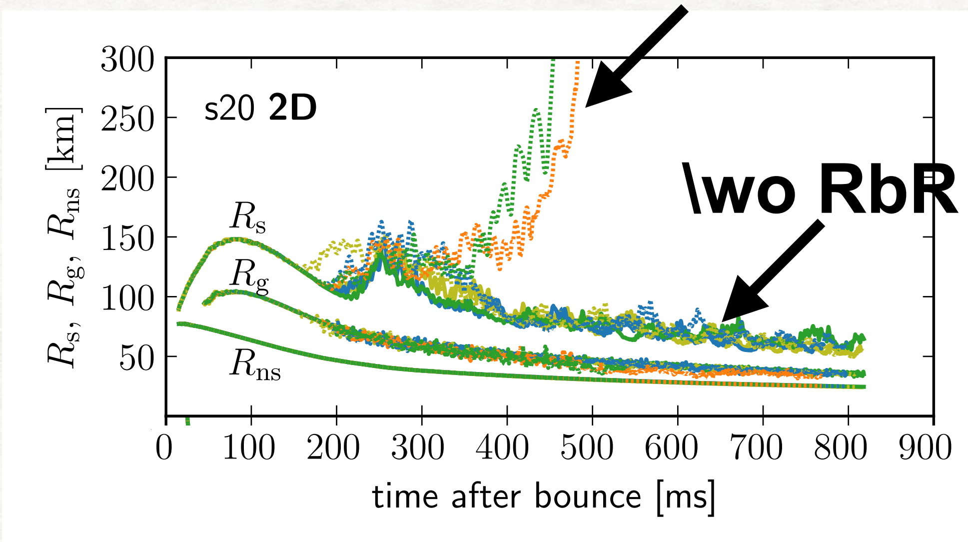
WHAT ABOUT IMPACT OF RBR IN 3D?

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

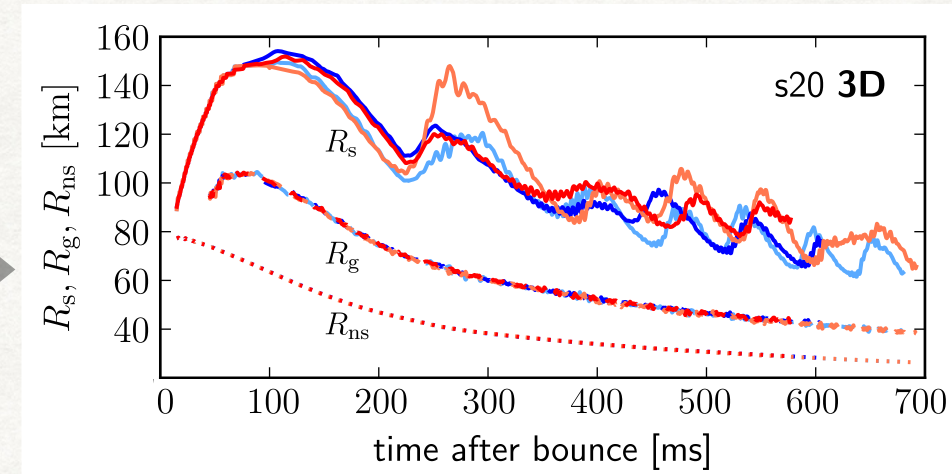
S20, 2D:

\w RbR

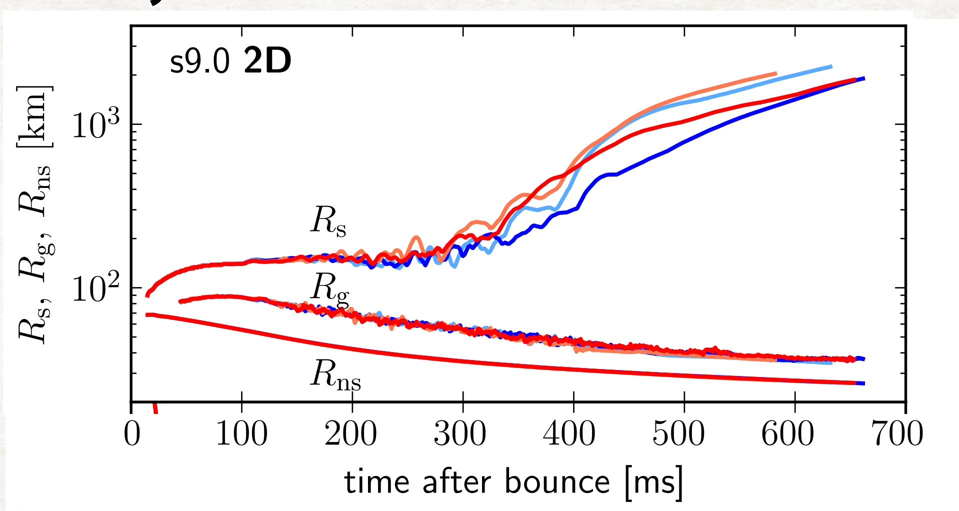
\wo RbR



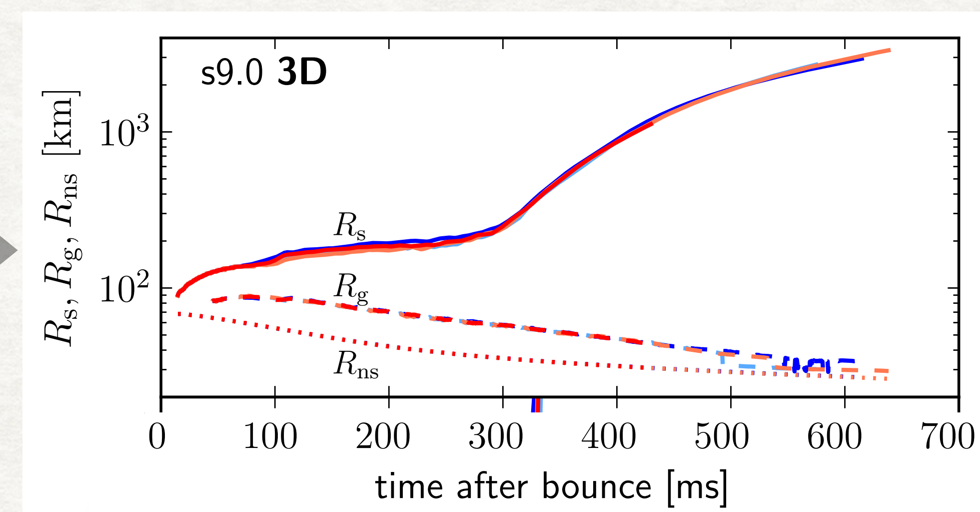
S20, 3D:



S9, 2D:



S9, 3D:



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

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

Summary

- NS mergers produce a **variety of different outflow components** with characteristic nucleosynthesis signature as well es EM signal
- observed Kilonova for GW170817 is probably due to a **mixture of dynamical, neutrino-driven, viscously driven, MHD-driven ejecta** **=>** **however, safe identification not yet possible** **=>** **better models needed**
- **the sGRB jet most likely not** powered by neutrino pair-annihilation
- **new method** to constrain NS radius, R_NS > 10.7 km if GW170817 was a delayed collapse
- neutrino oscillations **might have strong impact on Y_e**

- CCSNe: **M1 code ALCAR** compares well with **Boltzmann code VERTEX** using RbR approximation
- RbR approximation facilitates explosions **in 2D, but not in 3D**
- **significant stochastic scatter of explosion times** for same initial conditions => need to be careful when comparing models in the literature