WHAT CAN WE LEARN ABOUT R-PROCESS AND NUCLEAR EOS FROM NS-MERGER OBSERVATIONS?

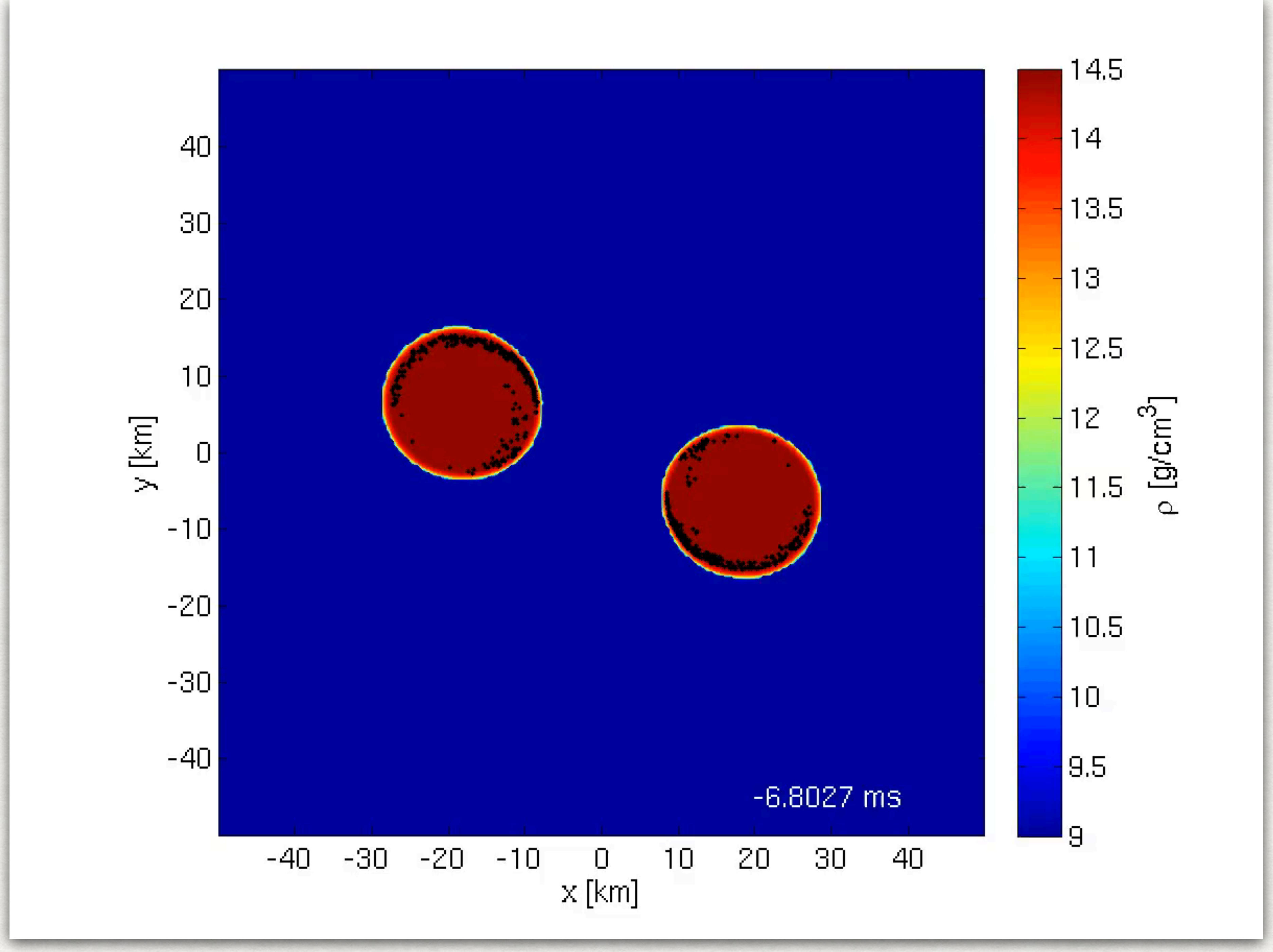
OLIVER JUST
ASTROPHYSICAL BIG BANG LABORATORY
RIKEN

6TH FAIRNESS WORKSHOP
GENOVA, MAY 20TH,

WITH: H.-TH.-JANKA, A. BAUSWEIN, S. GORIELY, R. ARDEVOL,
M. OBERGAULINGER, S. NAGATAKI, M. WU, I. TAMBORRA M., AND OTHERS

Movie: NS-NS Merger

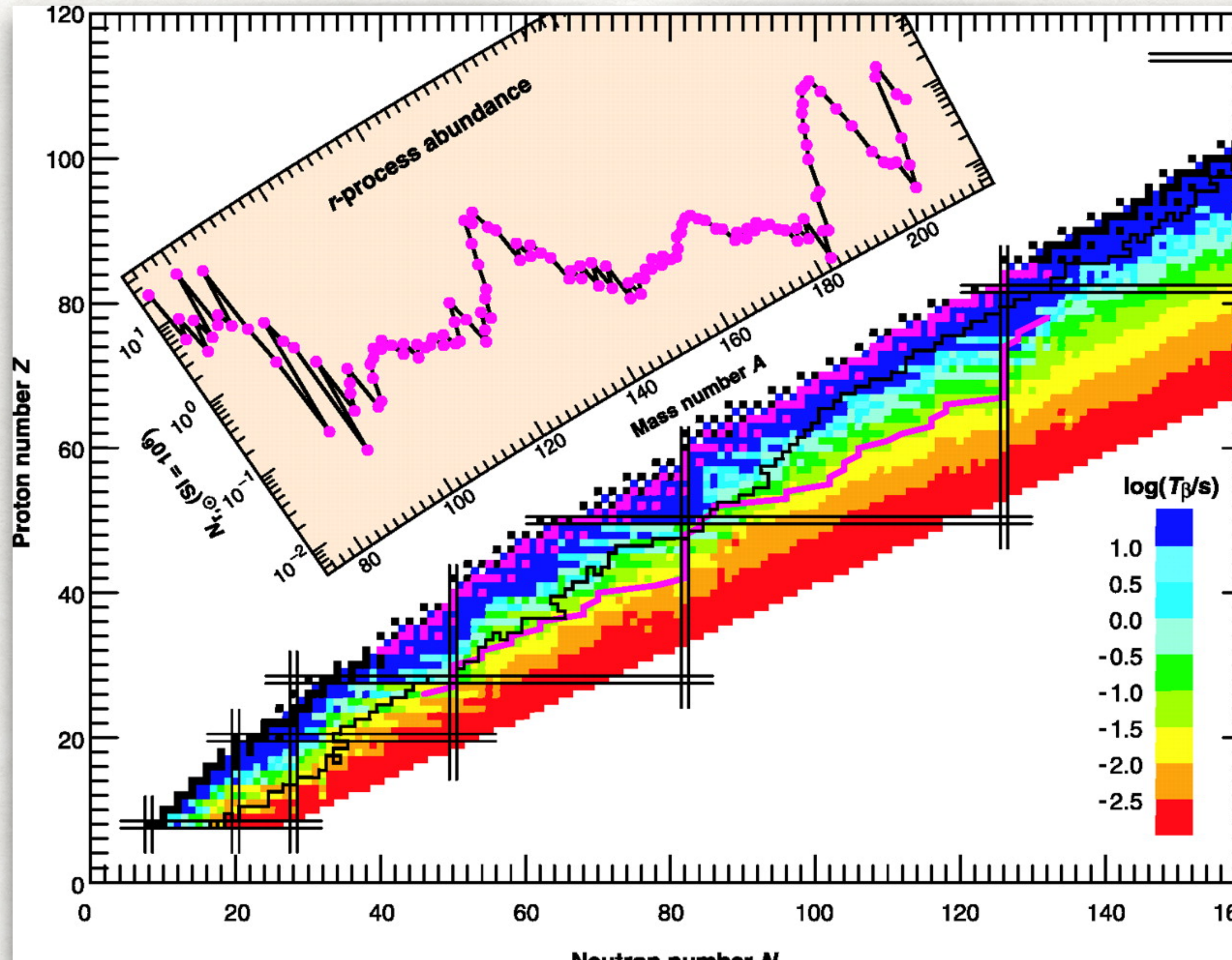
(SPH simulation by A. Bauswein)



NEUTRON-STAR MERGERS AS SOURCES OF R-PROCESS ELEMENTS

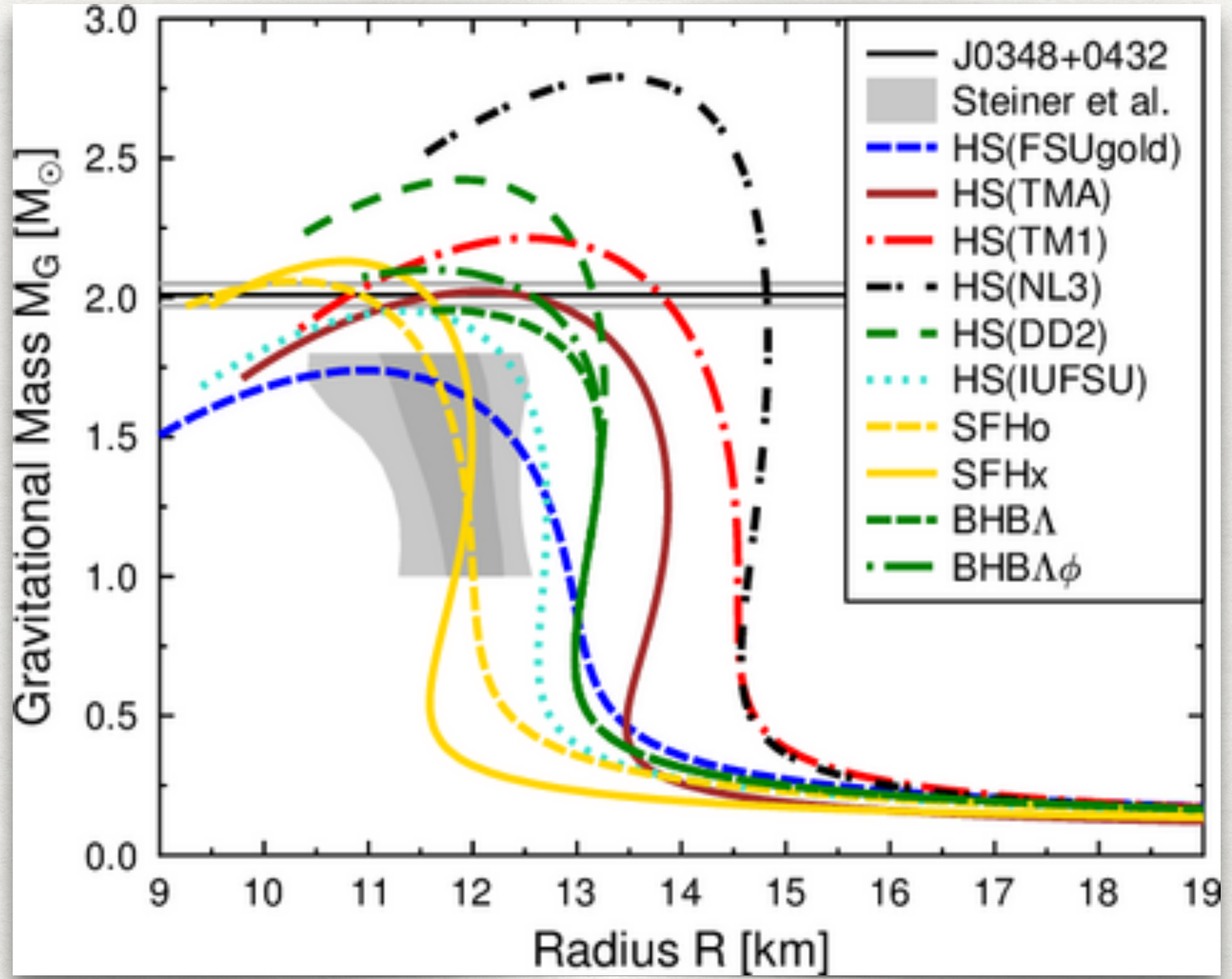
(...SUCH AS GOLD)

- 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



NS MERGERS AS KEY TOWARDS UNDERSTANDING THE NUCLEAR EOS?

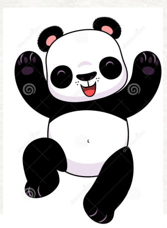
- EOS determines **Mass-Radius relationship** for neutron stars
- each EOS characterized by typical **NS radius** and **maximum mass**



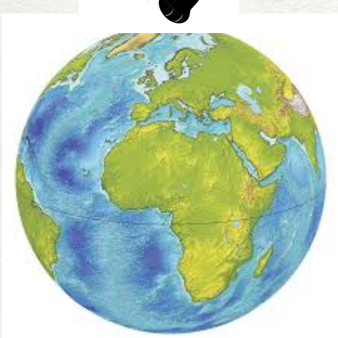
(M. Hempel)

ejecta
mass+velocity

ejection
mechanism



nucleosynthesis
yields



collapse time
of HMNS

nuclear EOS
constraints

jet launching
mechanism

gravitational waves

radio

optical

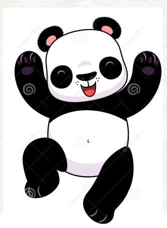
UV

X-ray

gamma-ray

ejecta mass+velocity

ejection mechanism



nucleosynthesis yields

collapse time of HMNS

nuclear EOS constraints

jet launching mechanism

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

radio

optical

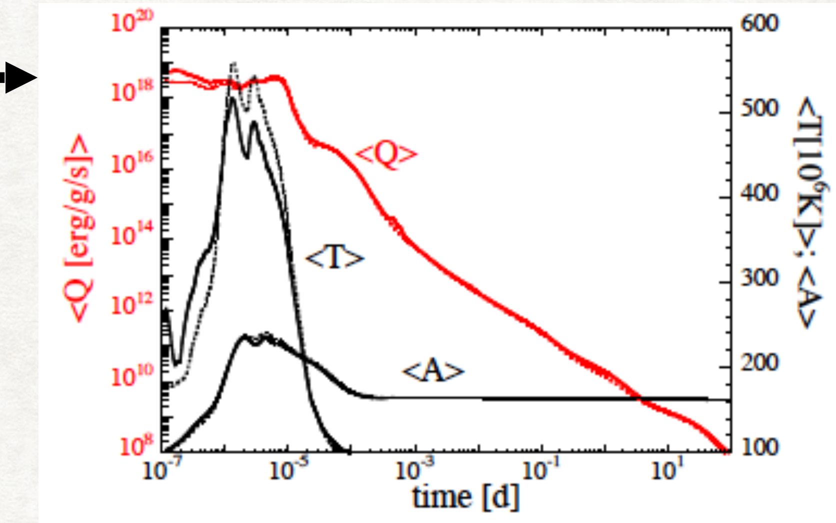
UV

X-ray

gamma-ray

Kilo- / Macronovae

- ➔ radioactive decay heats newly synthesized material
- ➔ light curves contain valuable information about mass, velocity, and composition

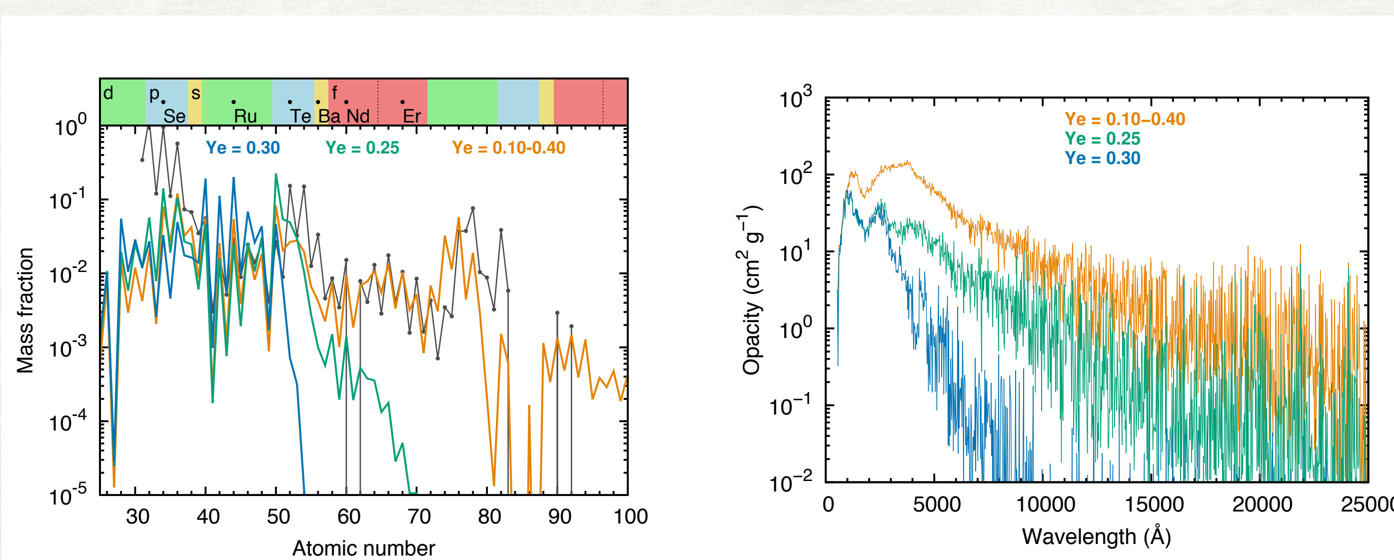


(Goriely et. al. 2011)

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

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

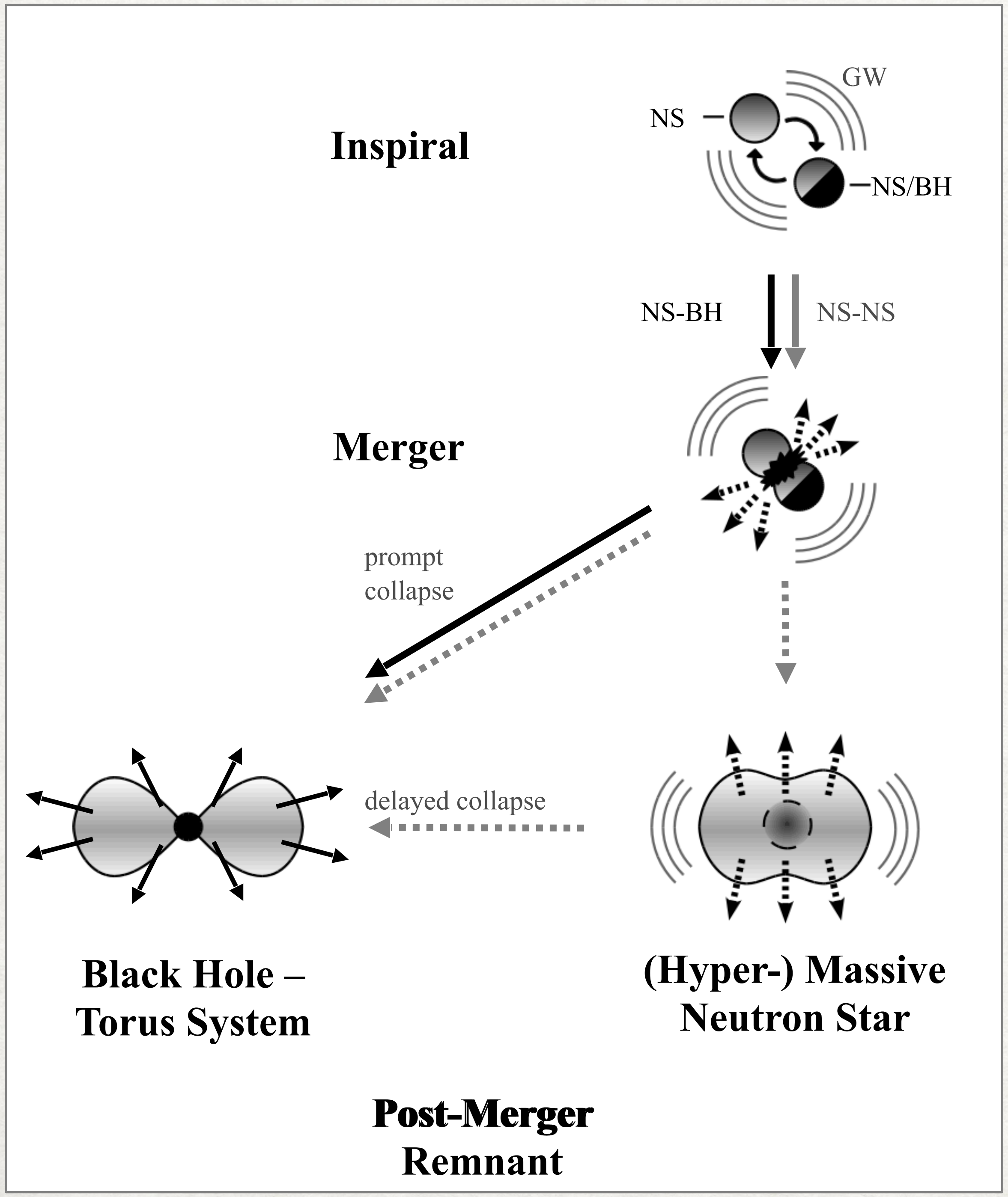
$$T_{\rm eff,peak} \approx \left[\frac{L_{\rm peak}}{4\pi (V_{\rm ej} t_{\rm peak})^2 \sigma_{\rm SB}}\right]^{1/4} \approx 8\times10^3\,{\rm K}\left(\frac{f}{10^{-6}}\right)^{1/4}\left(\frac{V_{\rm ej}}{0.1\,c}\right)^{1/8}\left(\frac{M_{\rm ej}}{0.03\,M_\odot}\right)^{-1/8}\left(\frac{\kappa}{0.3\,{\rm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



(Tanaka '18)

(Barnes & Kasen 2013)

Modeling challenges
(apart from nuclear physics challenges)



➜ *Neutrino transport:*

- ★ *full 6D Boltzmann eq. extremely expensive =>approximations inevitable*
- ★ *neutrino leakage schemes*
- ★ *one- or two-moment transport schemes*
- ★ *Monte-Carlo or ray-tracing schemes*
- ★ *neutrino oscillations???*

➜ *Magnetic fields and turbulence*

- ★ *extremely fine resolution needed to resolve all relevant length scales (e.g. magneto-rotational instability), particularly in the HMNS*
- ★ *many approaches employ effective (alpha-) viscosity*

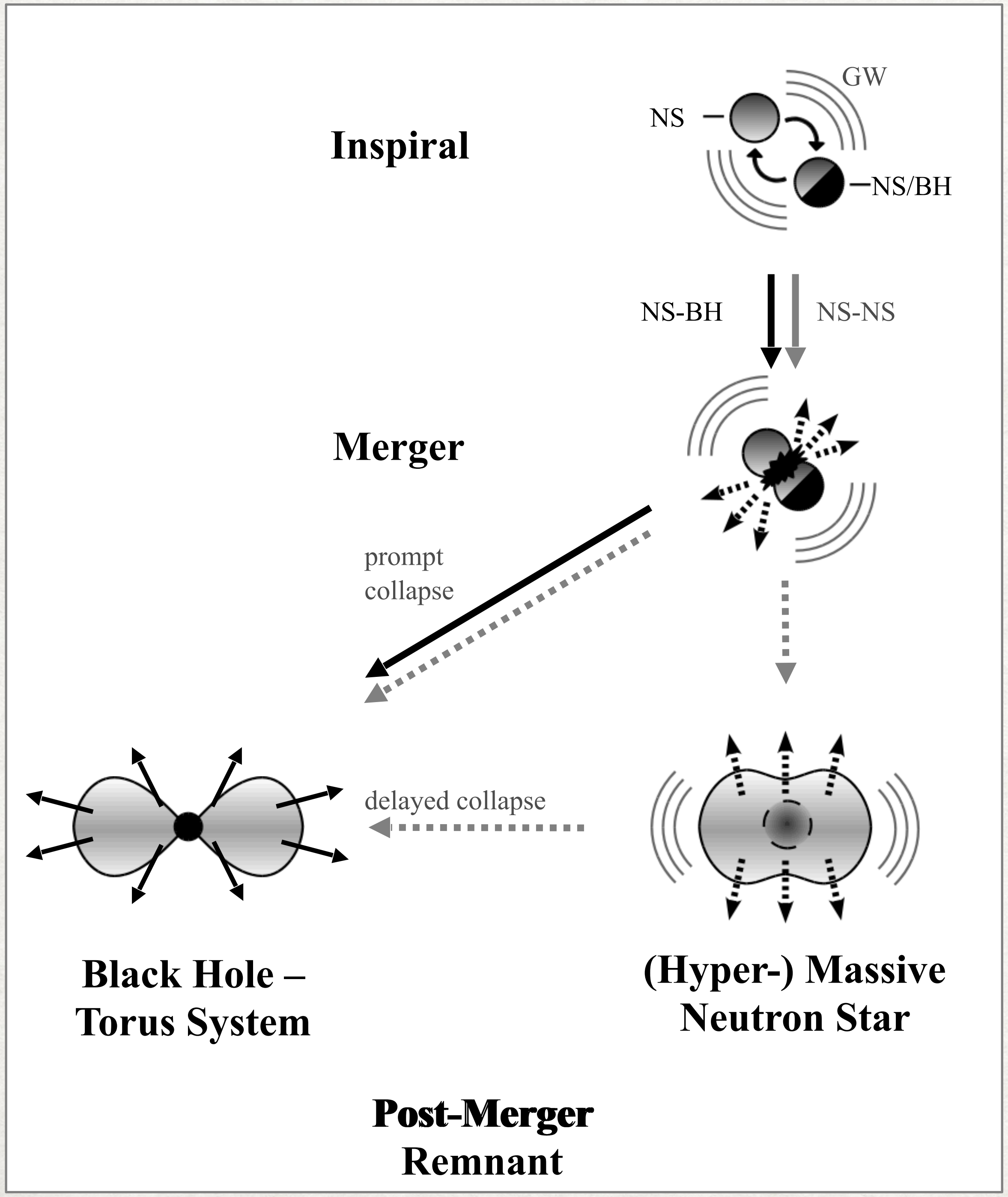
➜ *General/special relativistic effects*

- ★ *Newtonian, post-Newtonian methods*
- ★ *Conformally flat general relativity*
- ★ *full general relativity*

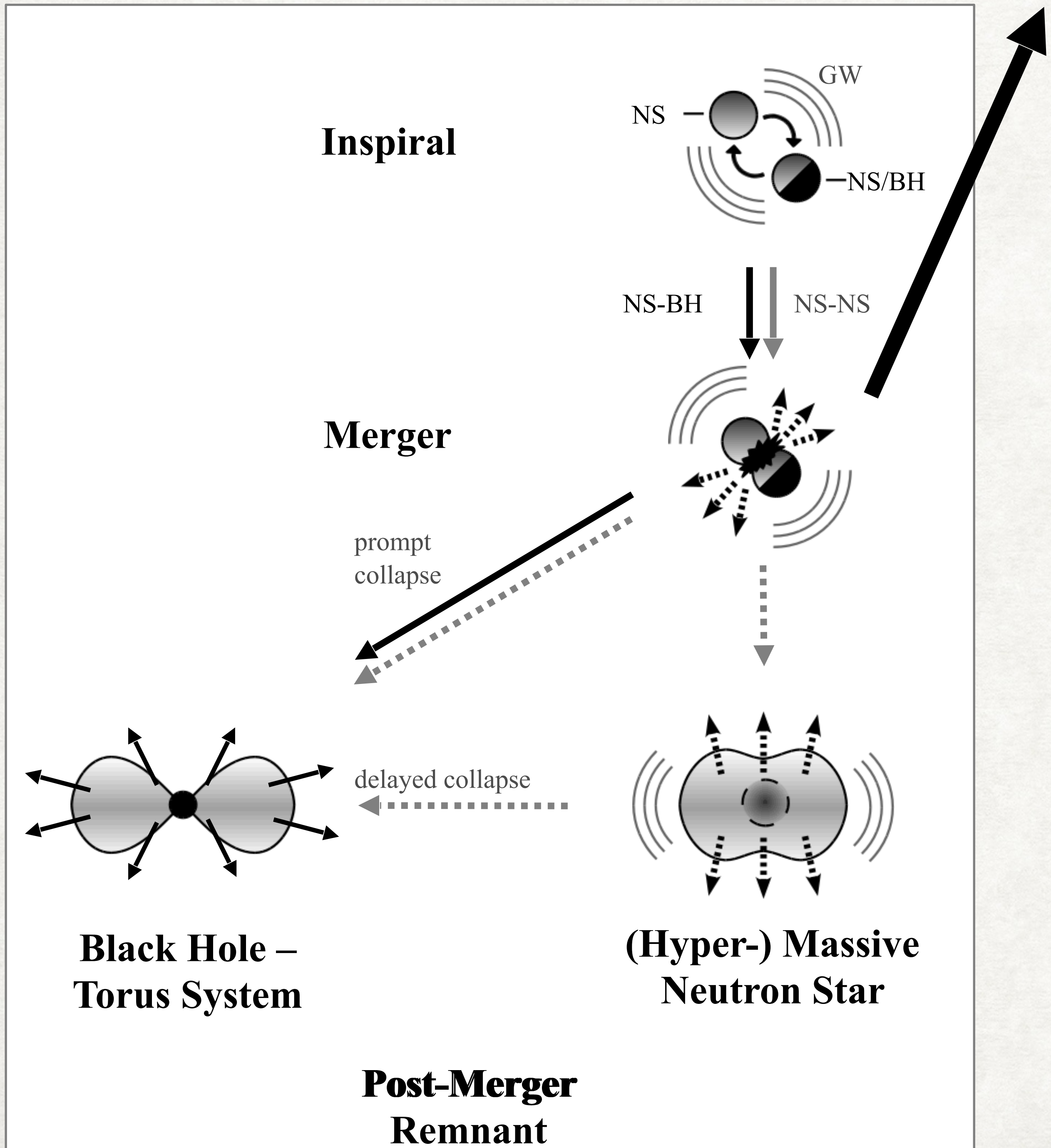
➜ *Photon transport for electromagnetic signal*

- ★ *opacities of heavy elements poorly known*
- ★ *computationally expensive*

Neutron-star mergers: ejecta components



Neutron-star mergers: ejecta components

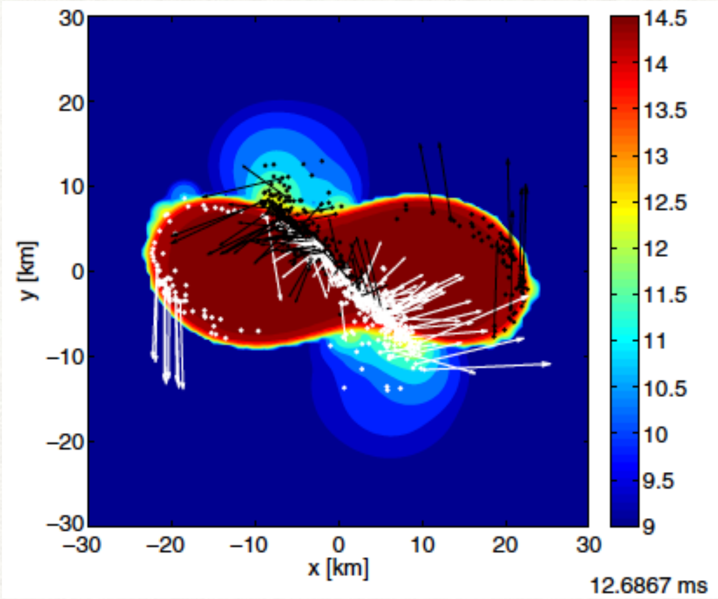


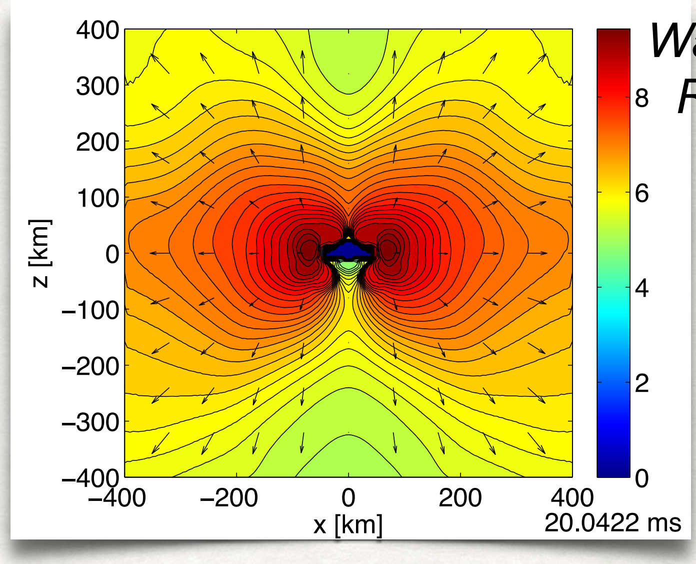
dynamical/prompt ejecta

→ tidal tails

→ shock-heated

Prompt / dynamical ejecta





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

Prompt / dynamical ejecta

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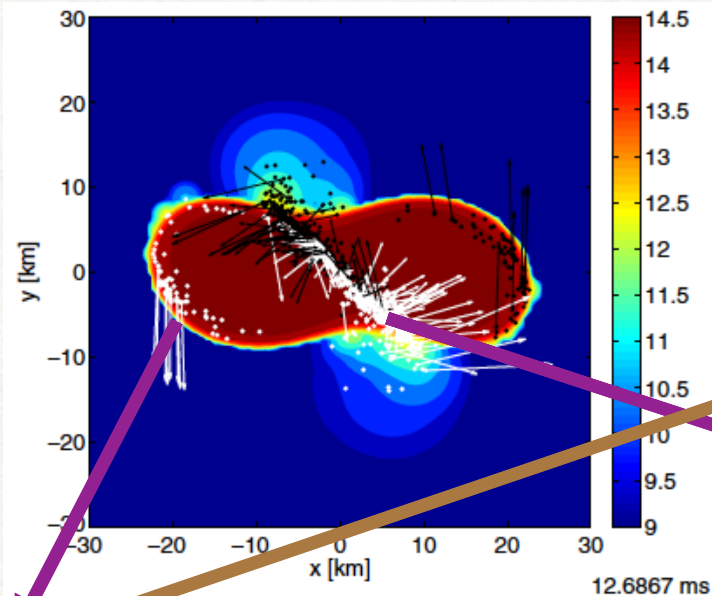
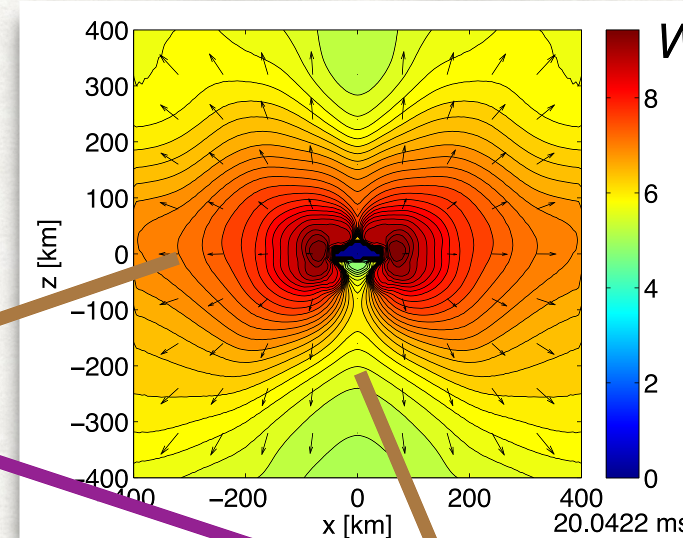


(Bauswein '13)



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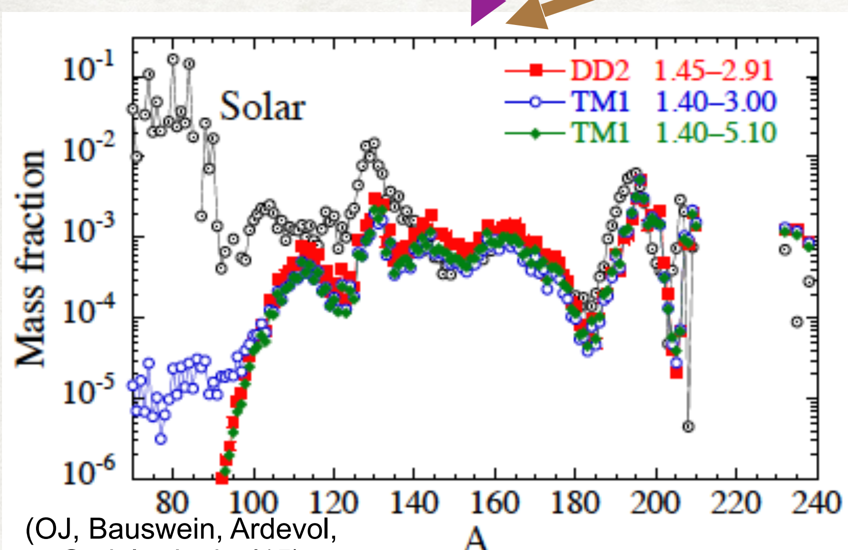
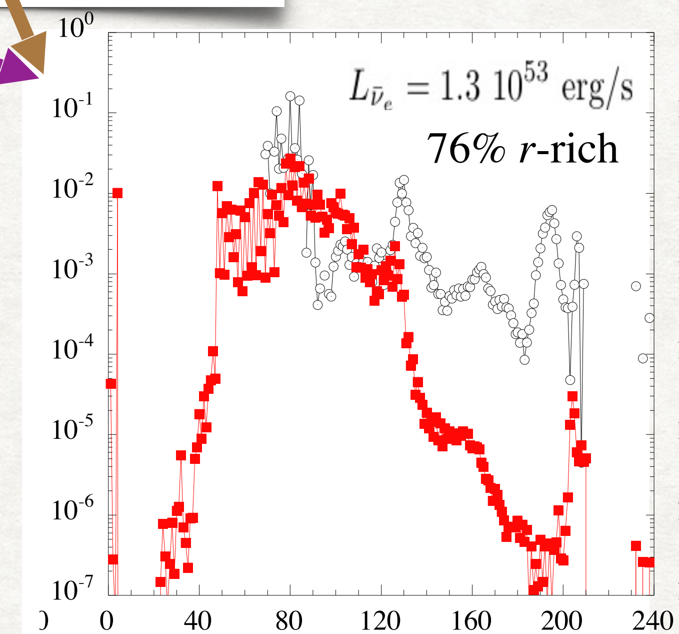


(OJ, Bauswein, Ardevol, Goriely, Janka '15)



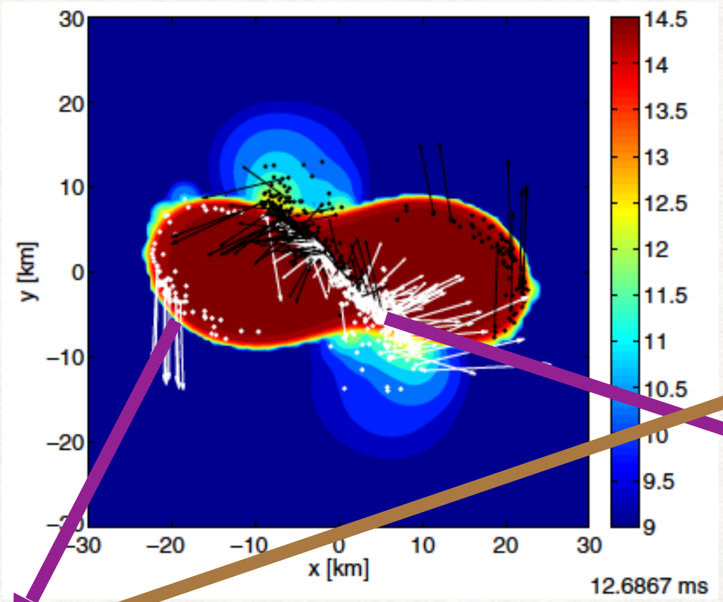
(Goriely et al '15+'18)

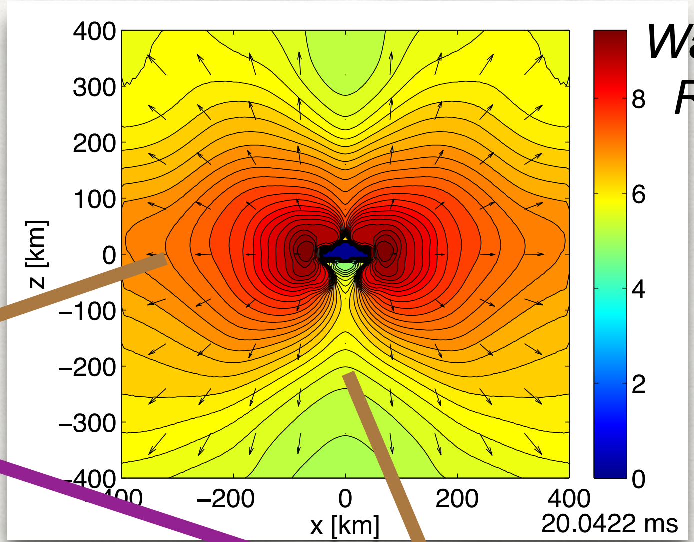
from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

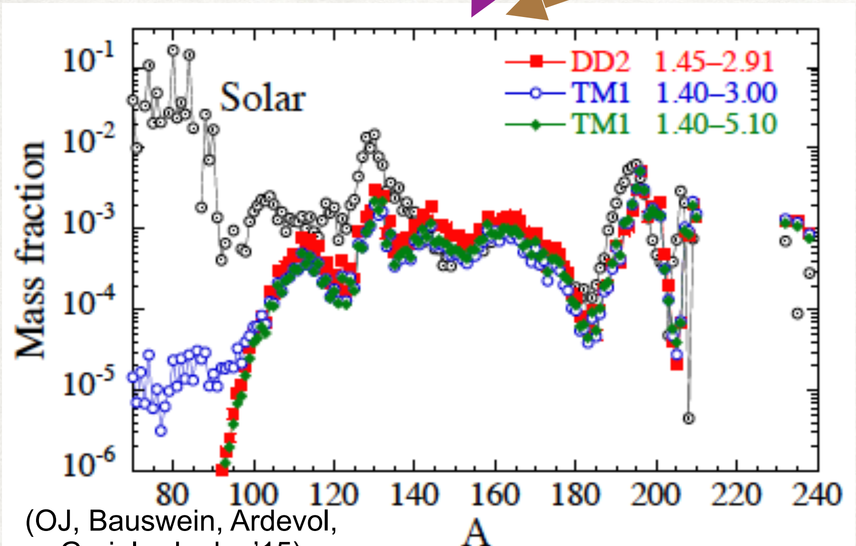
from collision shock
-> high Ye
-> less lanthanides
-> lower opacity
-> blue Kilonova
(if observed independently)

Prompt / dynamical ejecta

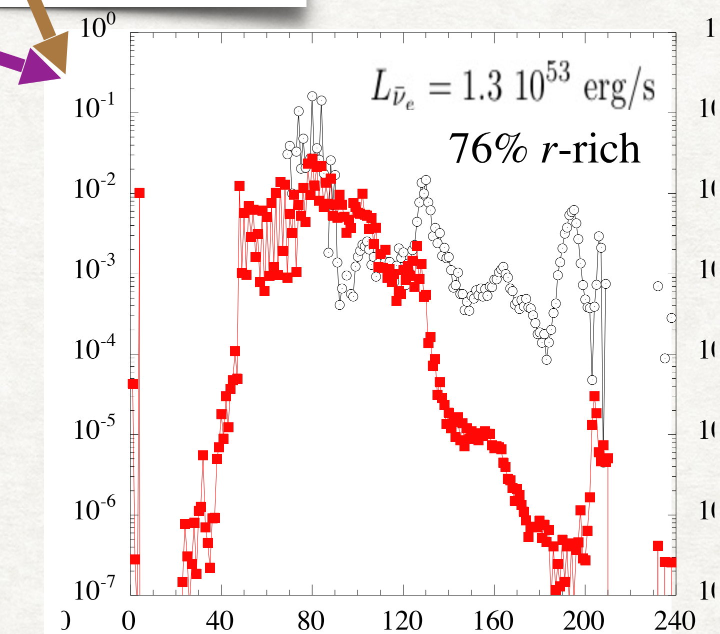
(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16, Martin '18)







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

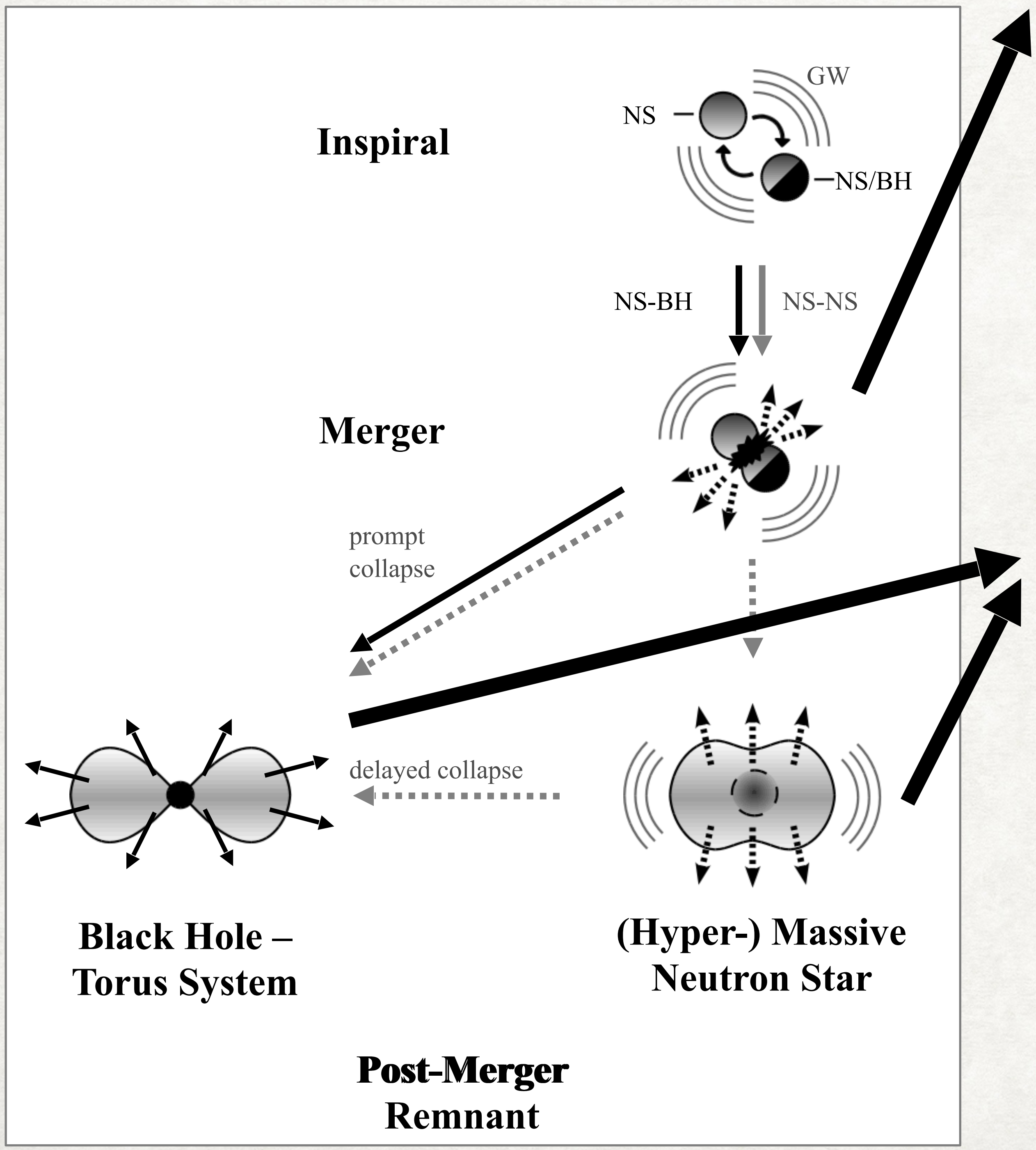


(Goriely et al '15+'18)

Further properties:

- ★ v ~ 0.1-0.3 c
- ★ M ~ 1E-4 - 1E-2 Msun
- ★ typically **larger** mass for **softer** EOS
- ★ very low mass for prompt collapse

Neutron-star mergers: ejecta components



dynamical/prompt ejecta

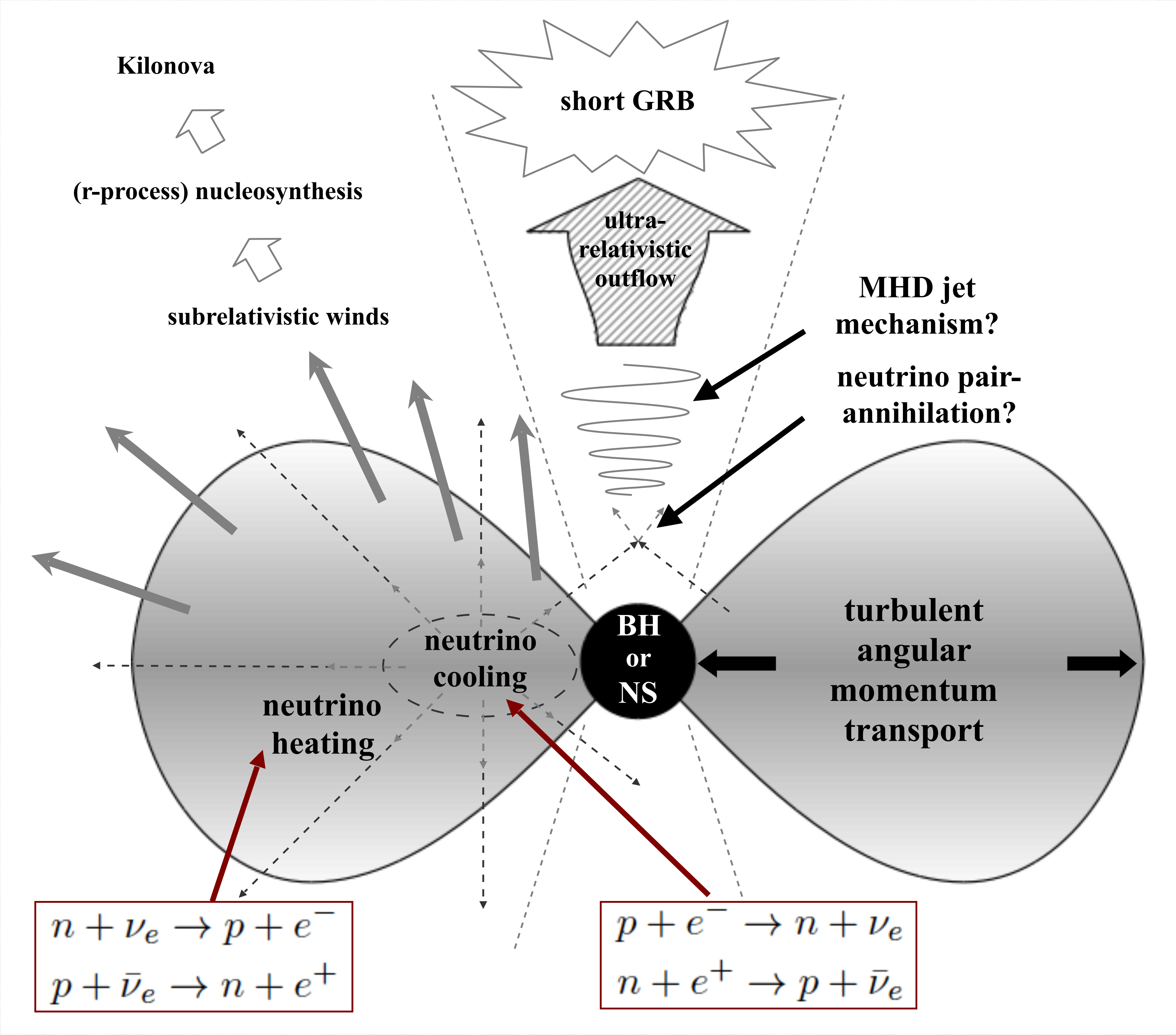
→ tidal tails
→ shock-heated

post-merger ejecta

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

PHYSICS OF POST-MERGER CONFIGURATION

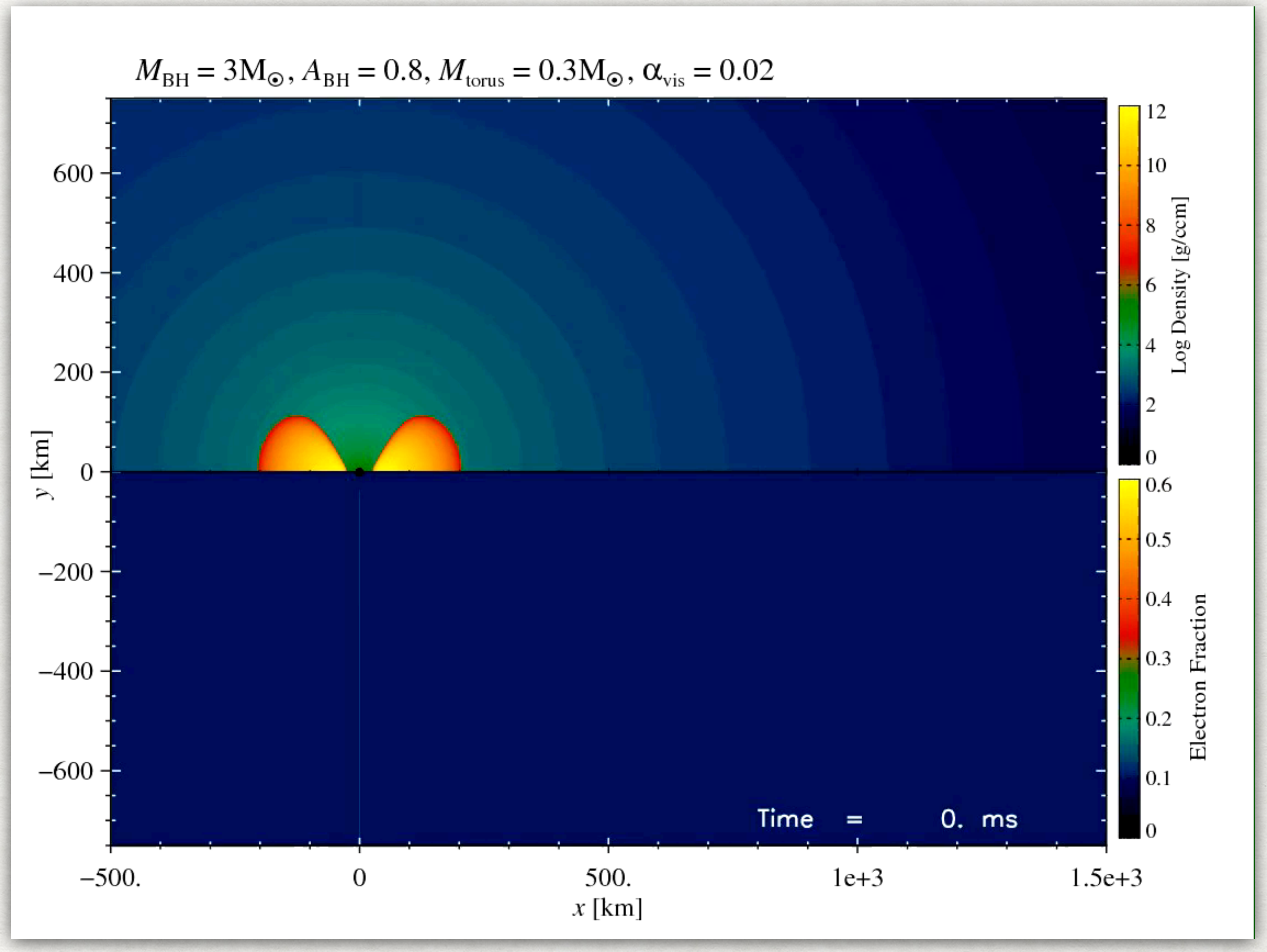
Mass accretion, wind generation, and jet launching highly sensitive to angular momentum transport and neutrino cooling and heating



Post-merger BH-torus remnant

Typical ejecta properties:

- outflow masses:
  ~ 5-20% of torus mass
  ~ 1E-4 - 1E-2 Msun
- electron fraction:
  <Ye> ~ 0.1-0.3
- entropy per baryon:
  <s> ~ 10 – 30 kB
- velocity:
  <v> ~ 0.05– 0.1 c
- **small** neutrino-driven component
- large viscous component



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

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

"ALCAR" NEUTRINO TRANSPORT MODULE

(OJ, OBERGAULINGER, JANKA '15, MNRAS, 453, 3386)

TWO-MOMENT TRANSPORT WITH ALGEBRAIC EDDINGTON FACTOR (*AEF OR M1 SCHEME*)

$$E = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)$$ ← **energy density, 0th-angular moment**

$$F^i = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i$$ ← **momentum density, 1st-angular moment**

$$P^{ij} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j$$ ← **pressure, 2nd-angular moment**

$$Q^{ijk} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k$$

evolution equations

$$\begin{cases} \partial_t E + \nabla_j \left(\alpha F^j + v^j E\right) + P^{ij}\nabla_i v_j + F^i \nabla_i \alpha \\ \qquad - \partial_\epsilon \left[\epsilon \left(P^{ij}\nabla_i v_j + F^i \nabla_i \alpha\right)\right] = \alpha S^{(0)}\,, \\ \partial_t F^i + \nabla_j \left(\alpha c^2 P^{ij} + v^j F^i\right) + F^j \nabla_j v^i + c^2 E \nabla^i \alpha \\ \qquad - \partial_\epsilon \left[\epsilon \left(Q^{ijk}\nabla_j v_k + c^2 P^{ij}\nabla_j \alpha\right)\right] = \alpha S^{(1),i} \end{cases}$$

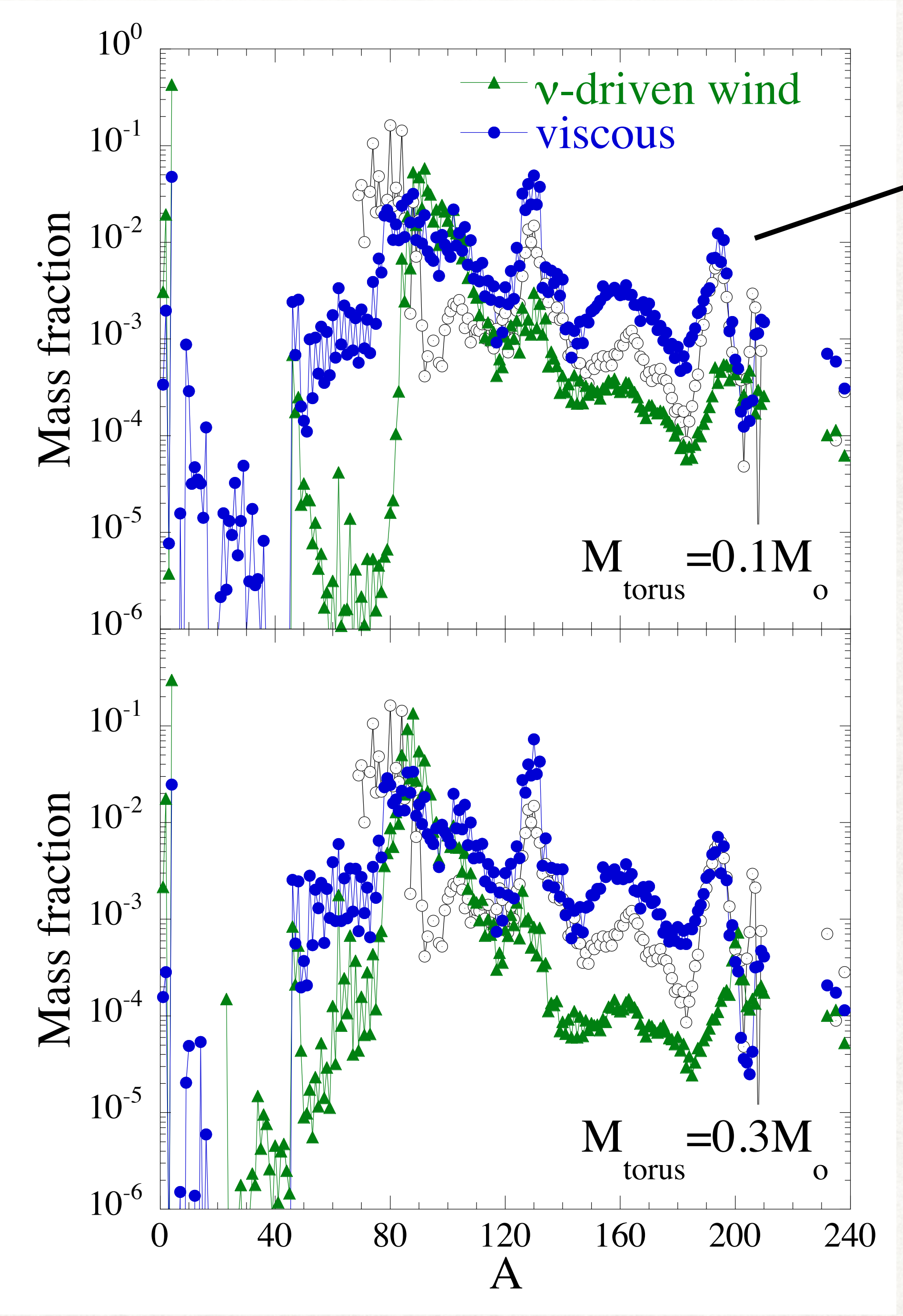
$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\}$$

central approximation of M1:
local closure relation for higher moments
(e.g. "M1 closure")

=> removes two degrees of freedom of nu-phase space
large gain of computational efficiency

=> trade-off: potential loss accuracy
(at least in optically thin regions)

Nucleosynthesis yields of BH-torus ejecta



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

viscous outflows:

-> low Ye

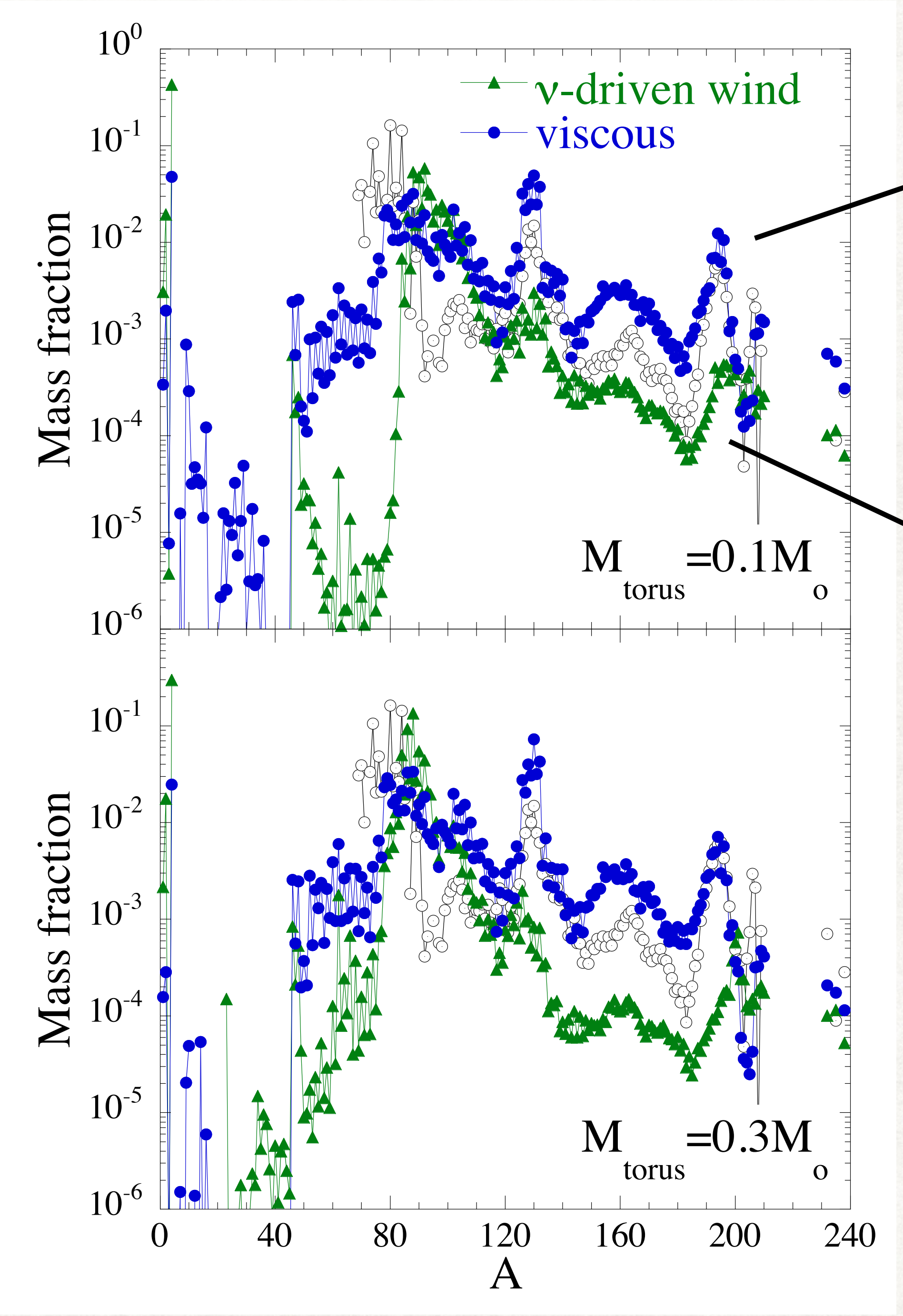
-> more lanthanides

-> higher opacity

-> red Kilonova

(if observed independently)

Nucleosynthesis yields of BH-torus ejecta



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

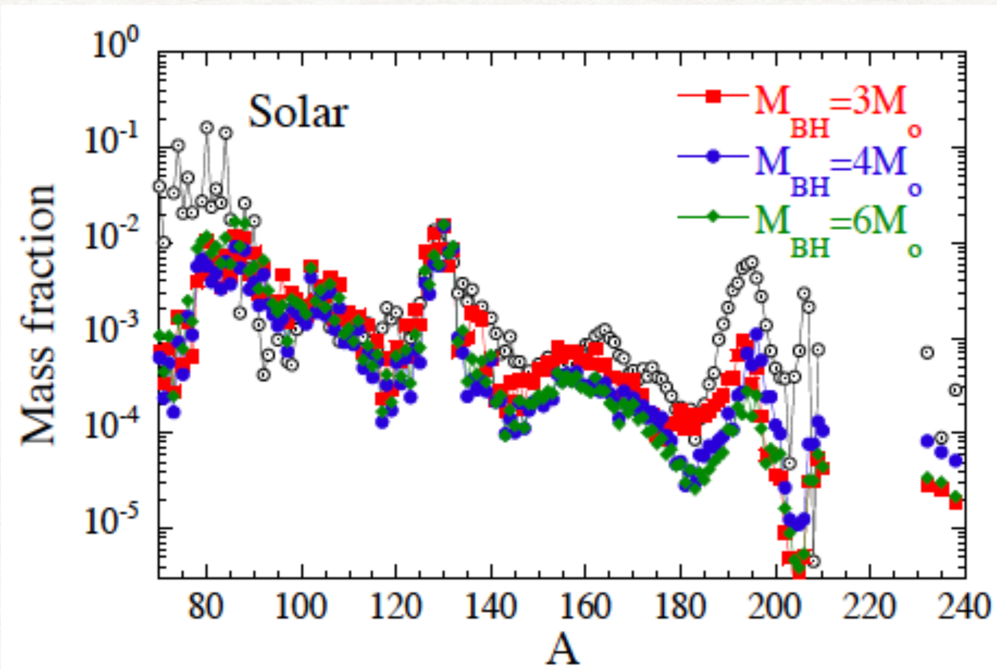
viscous outflows:
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

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

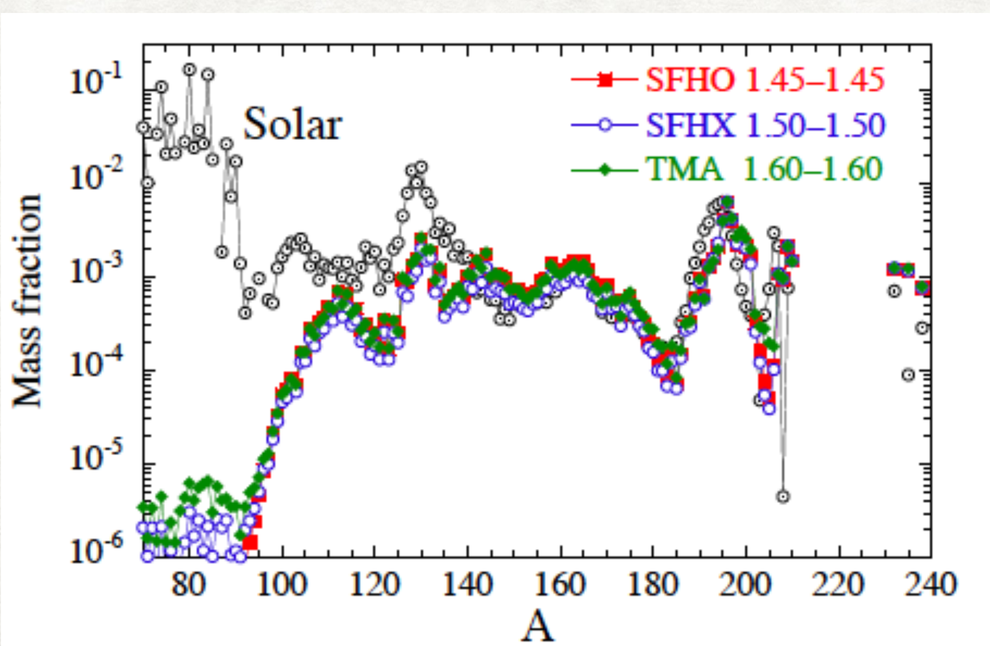
COMBINED NUCLEOSYNTHESIS YIELDS OF PROMPT AND TORUS EJECTA

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

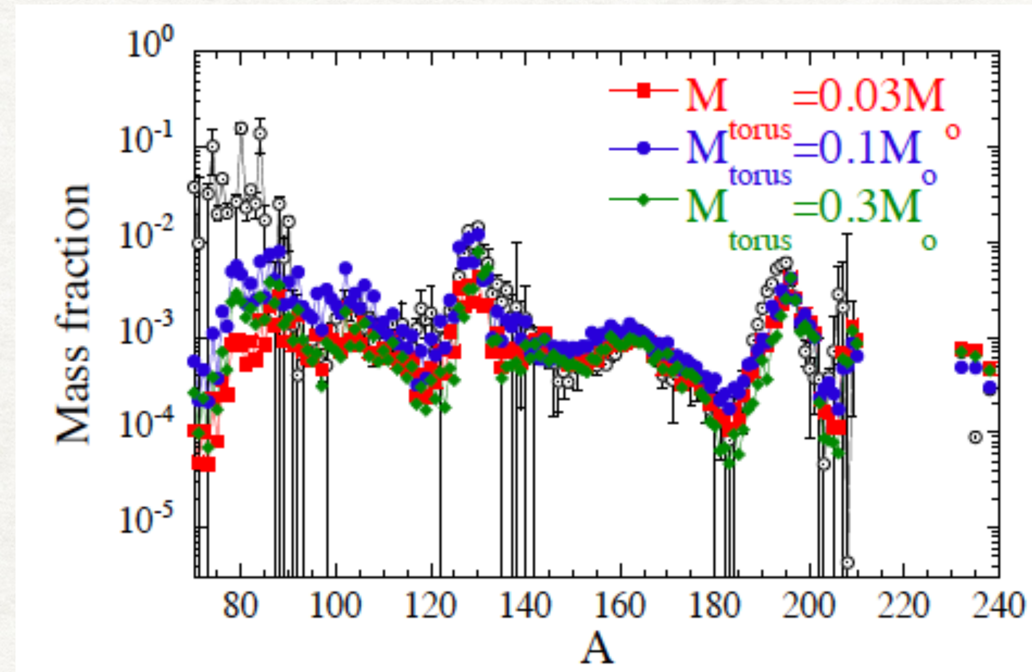
➔ DISK ejecta (mainly A ~ 90 - 140)



➔ PROMPT ejecta (mainly A ~ 140 - 210)



➔ DISK + PROMPT ejecta

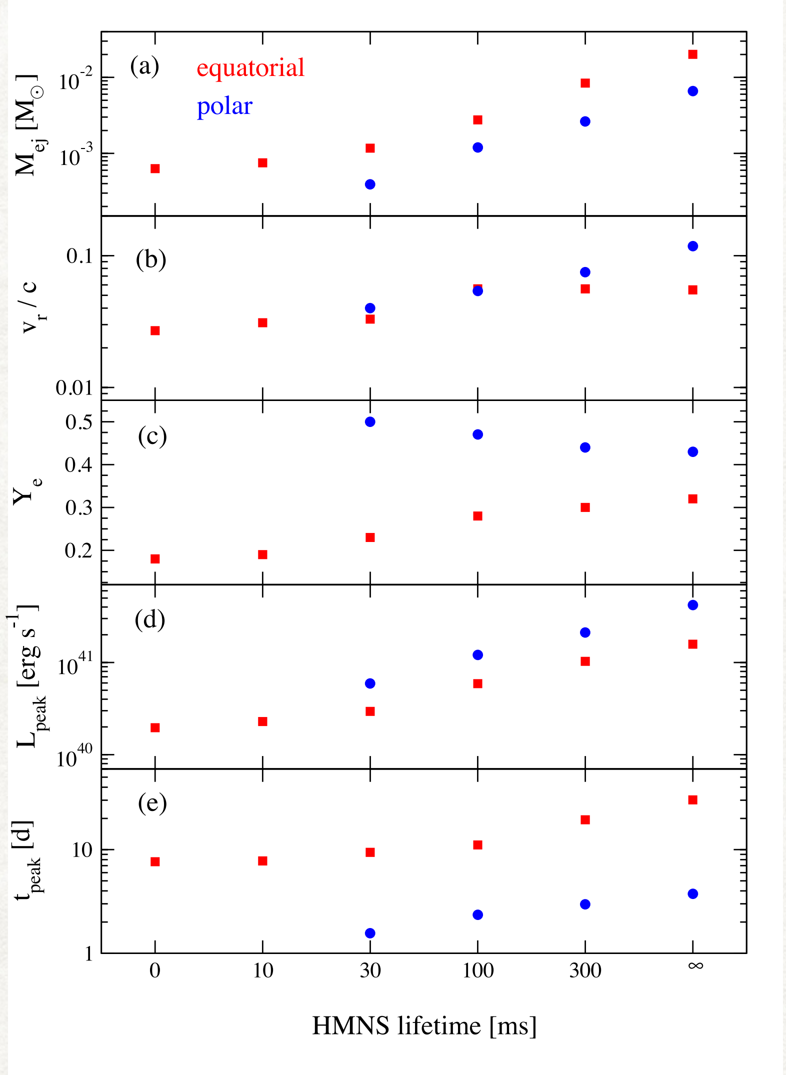


➔ nicely recovers the full mass range A > 90

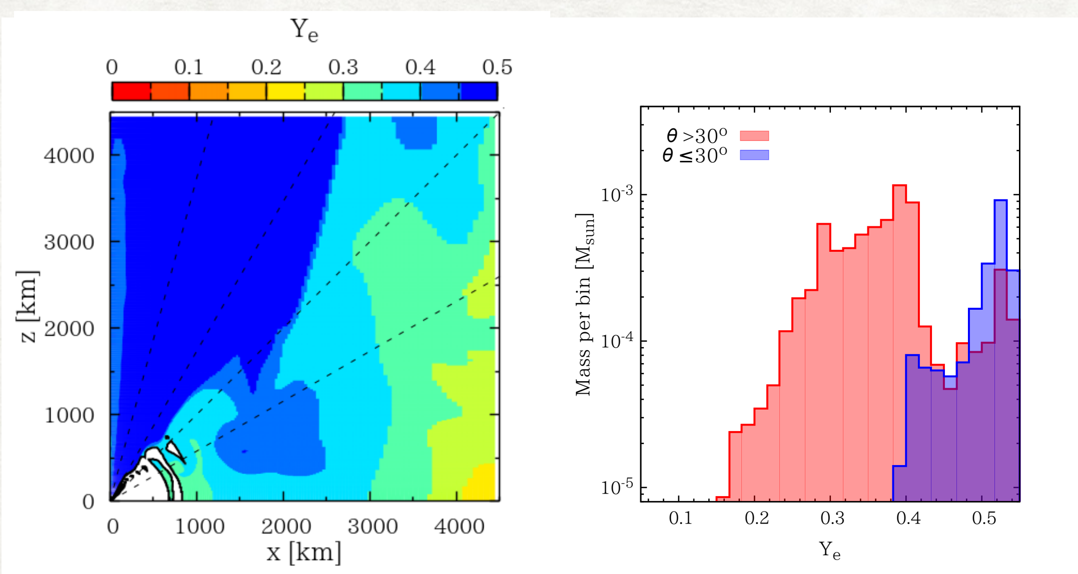
➔ strong support for idea that multiple ejecta components of NS mergers are significant sources of r-process elements

NS-torus remnant

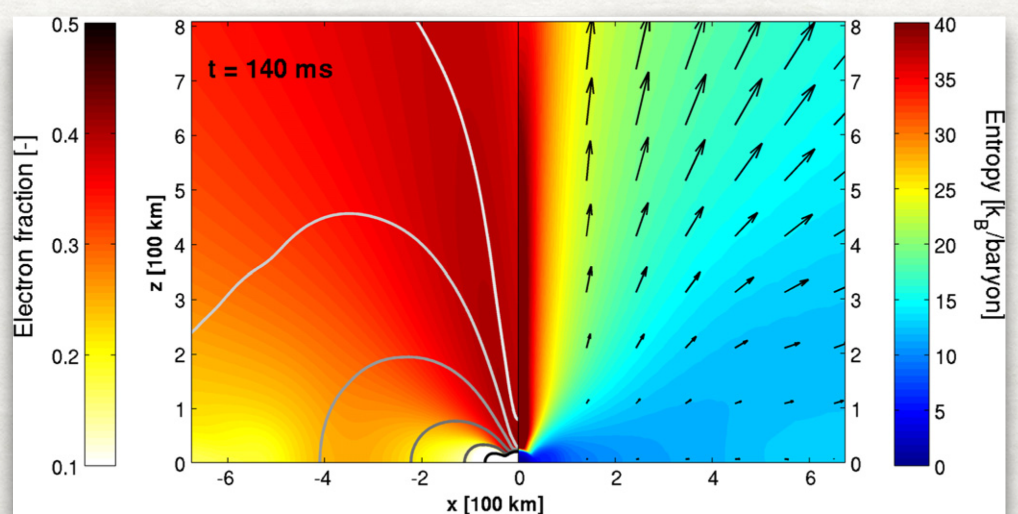
- **very challenging** to model, because of extremely small MRI length scales and complicated high-density neutrino physics
- NS represents **much larger** energy reservoir than BH-torus
- hence, ejecta mass likely **grows with HMNS lifetime**
- relative amount of **(blue) neutrino-driven** to **(red) viscous** ejecta higher



(Metzger '14)



(Fujibayashi '17)

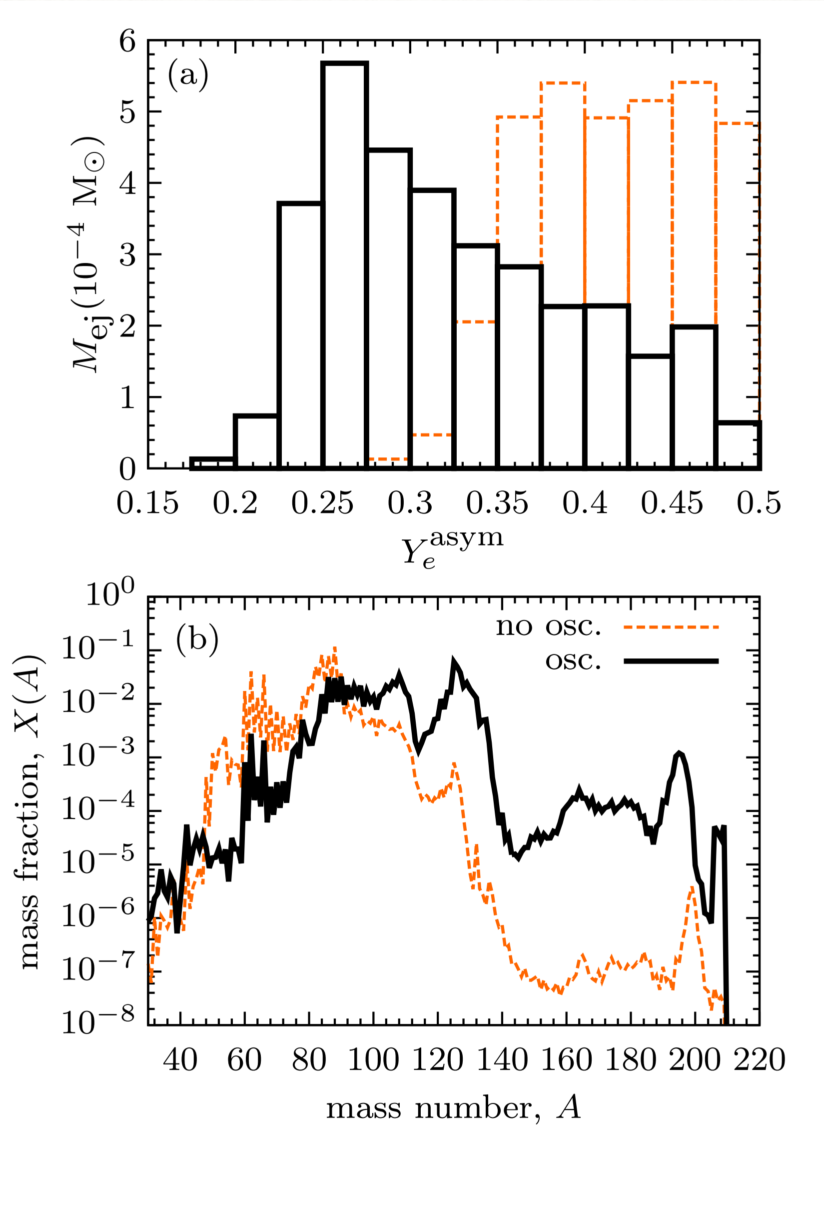


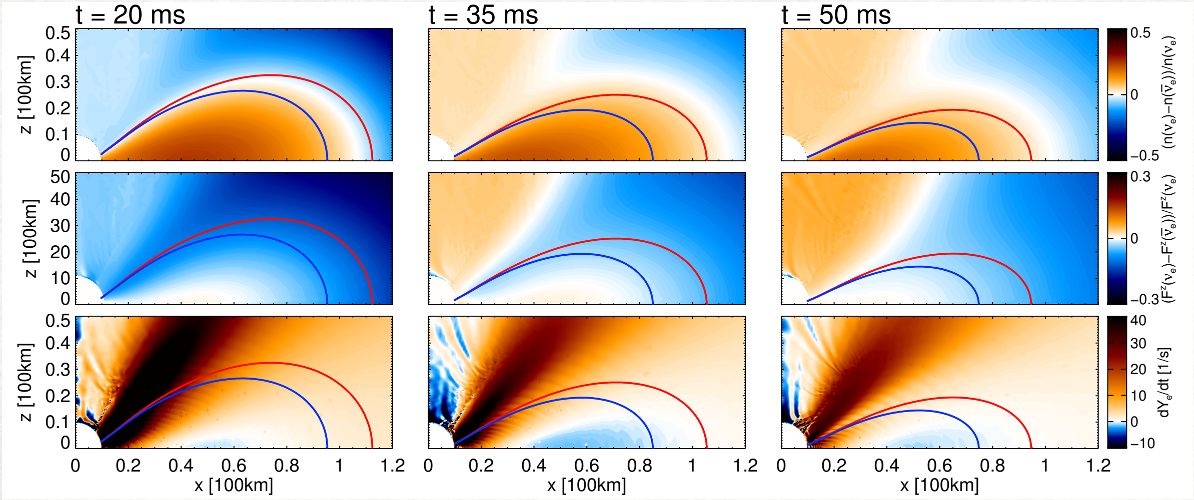
(Martin '15)

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

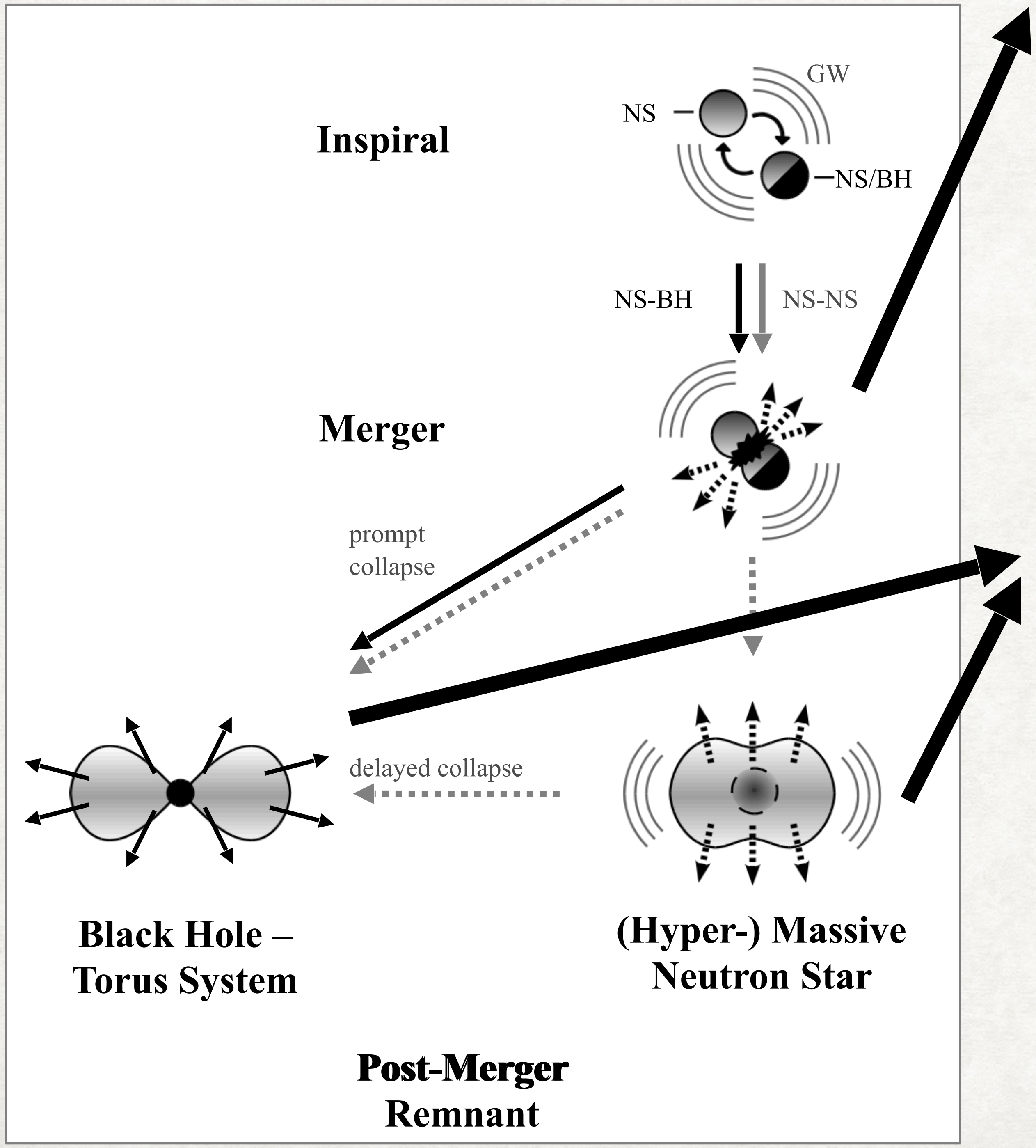
(Wu, Tamborra, OJ, Janka, 2017PhRvD, 96l3015W)

- recently (re-)discovered ***"fast pairwise flavor conversions"*** may lead to flavor equilibration on length scales of **O(10cm)** (e.g. Sawyer+ 05, 09, 16)
- take place whenever $n(\nu_e) - n(\bar{\nu}_e)$ changes sign in angular space
- our simplified, exploratory study indicates that neutrino-driven ejecta may remain **more neutron rich**
- ***neutrino oscillations remain major open question for neutrino effects in NS mergers***





Neutron-star mergers: ejecta components



dynamical/prompt ejecta

→ tidal tails
→ shock-heated

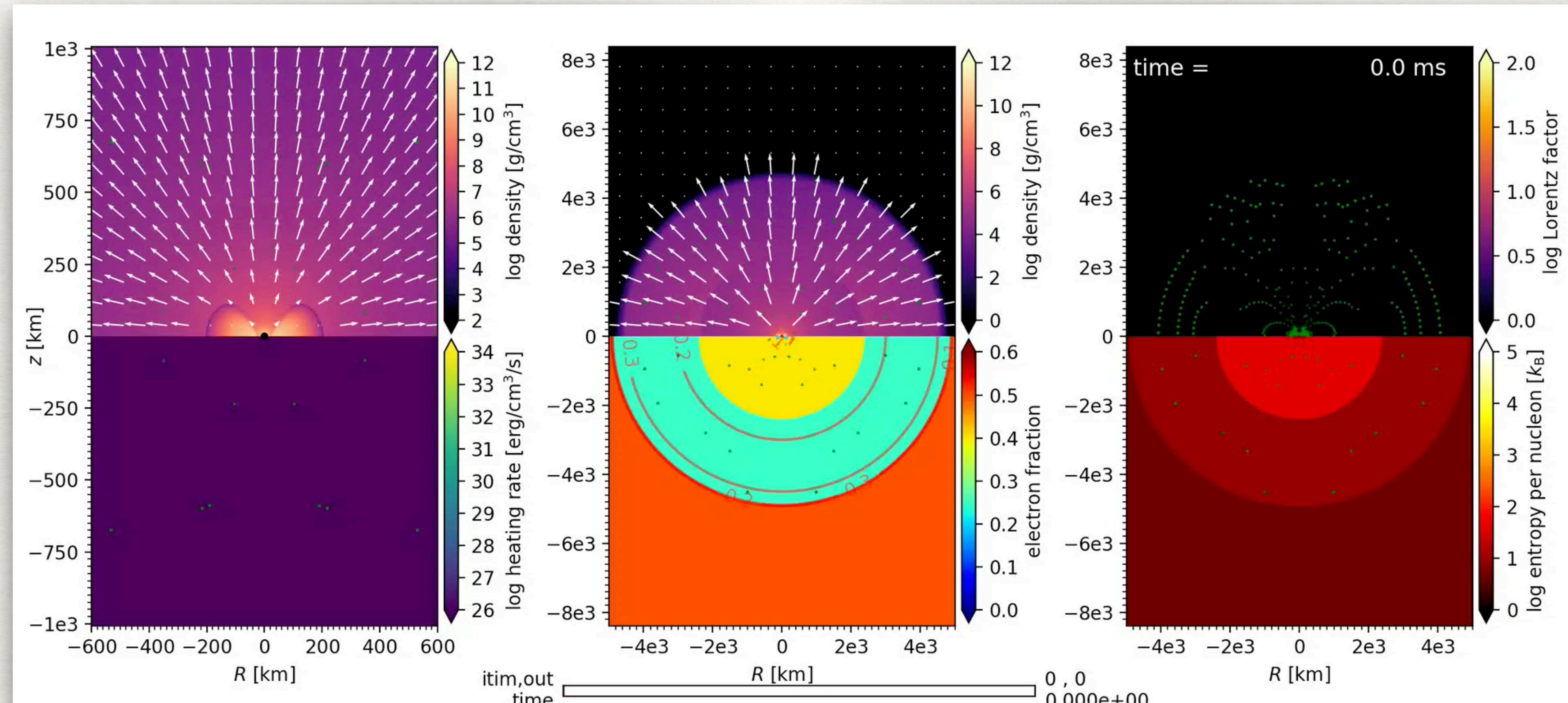
post-merger ejecta

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

(short gamma-ray burst) jet

→ from BH by what mechanism?
→ Magnetar spindown?
→ choked or successful?

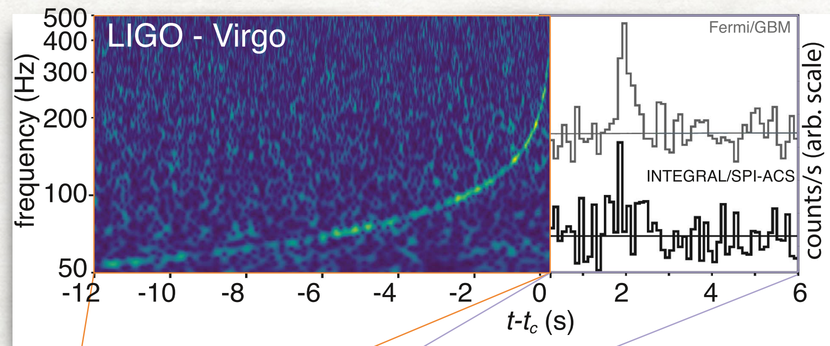
ONGOING WORK:
IMPACT OF JET ON NUCLEOSYNTHESIS?



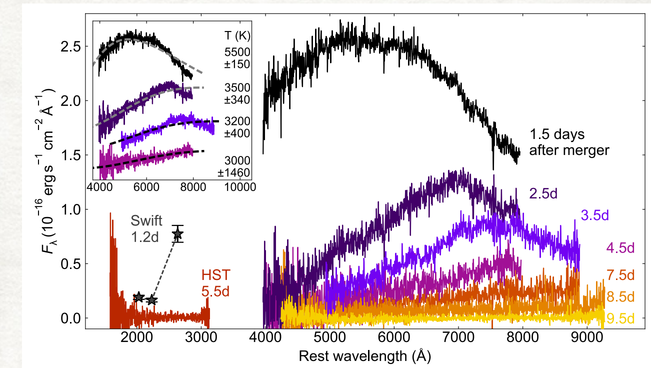
GW170817/AT2017GFO

GW170817 + EM COUNTERPARTS

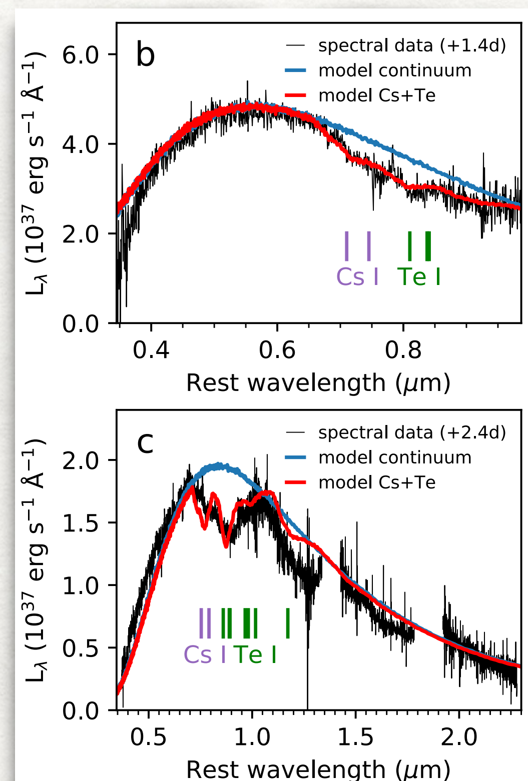
- Mtot = M1 + M2 ~ 2.74 Msun
- M1/M2 ~ 0.7 - 1
- **blue ejecta component** with
  $\langle Y_e \rangle$ > 0.25
  M ~ 0.01-0.03 Msun
- **red ejecta component** with
  $\langle Y_e \rangle$ < 0.25
  M ~ 0.01-0.03 Msun
- low-luminosity gamma-ray burst
  with E_{peak} ~ 100keV



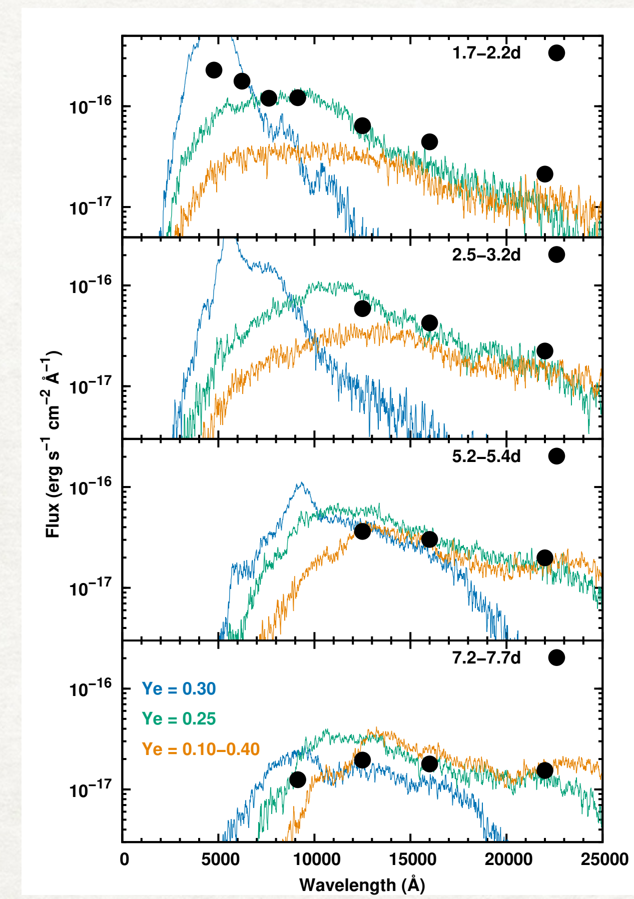
(LIGO Coll.+'17)



(Nicholl+'17)



(Smartt+'17)



(Tanaka+'17)

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

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

➜ *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 from choked jet or cocoon emission from structured jet. Recent observations favor successful jet (Mooley+18). *High E_{peak} still puzzling…*

➜ major open questions remain…better models needed

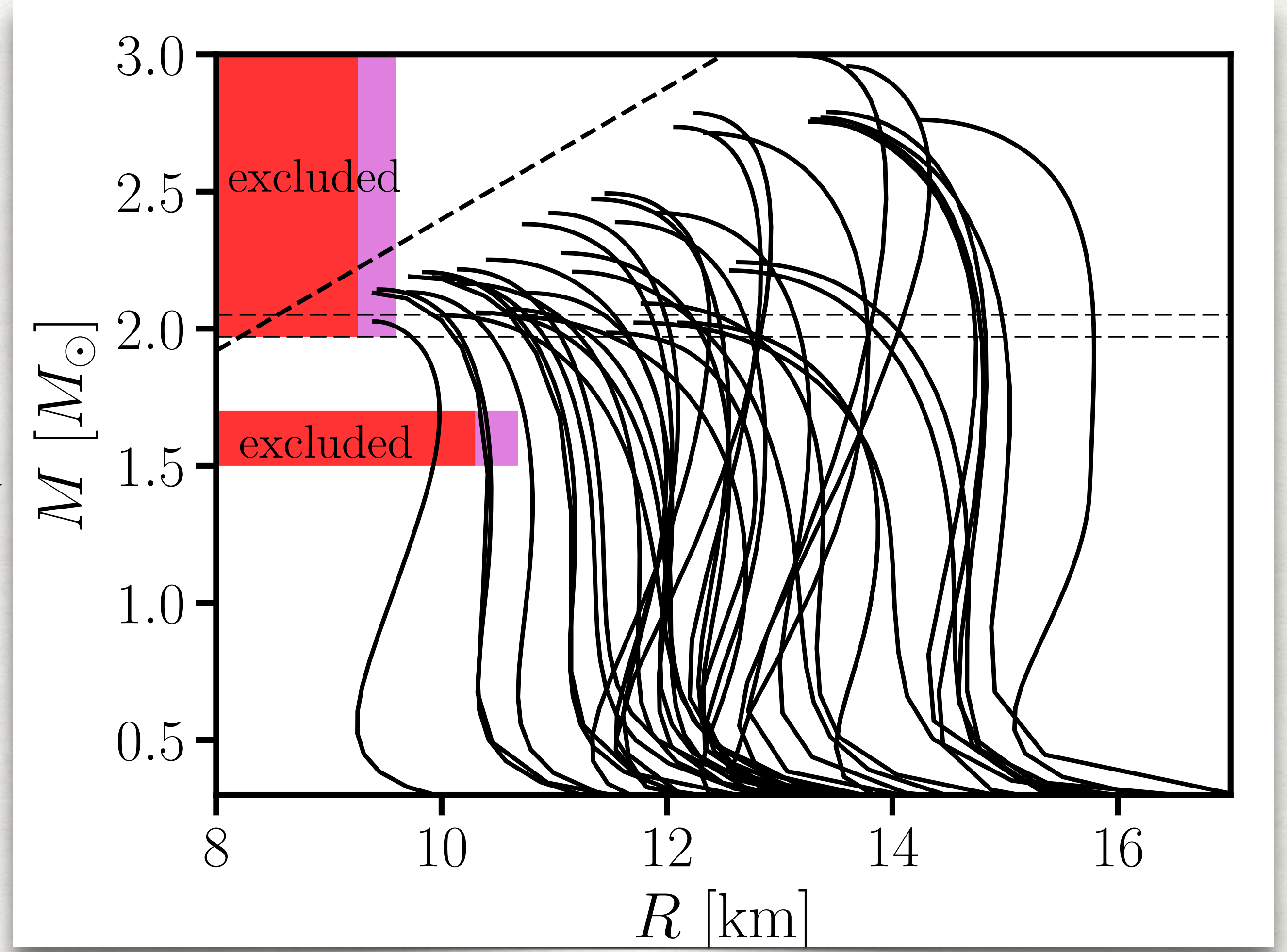
DELAYED COLLAPSE IS VERY LIKELY FOR GW170817: IMPLICATION FOR NUCLEAR EOS

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

empirical relation deduced from NS merger simulations (Bauswein+'13, PRL 111, 131101)

$$M_{\mathrm{thres}} = \left(-3.606\frac{GM_{\mathrm{max}}}{c^2 R_{1.6}} + 2.38\right) \cdot M_{\mathrm{max}}$$

$$M_{\mathrm{thres}} = \left(-3.38\frac{GM_{\mathrm{max}}}{c^2 R_{\mathrm{max}}} + 2.43\right) \cdot M_{\mathrm{max}}$$



***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)

Take Home Messages

- NS mergers produce a **variety of different outflow components**, each with individual nucleosynthesis signature as well es EM signal
- ejecta are less neutron-rich **(i.e. blue)** if illuminated by neutrinos, e.g. for shock-heated dynamical ejecta or neutrino-driven winds from remnant
- ejecta more neutron-rich **(i.e. red)** if neutrino illumination is low, e.g. for tidal dynamical ejecta or viscous remnant ejecta
- ejecta **more massive for longer lifetime** of HMNS
- GW170817 suggests large amount of both red and blue ejecta, hence **likely a delayed collapse**
- likely mixture of dynamical, neutrino-driven, viscously driven, MHD-driven ejecta **=>** however, **safe identification not yet possible** **=>** **better models needed**
- new radius constraint: **delayed collapse suggests R_NS > 10.7 km**
- neutrino oscillations **might have strong impact on Y_e**, however, still extremely uncertain