Impact of Neutrinos in Neutron-Star Mergers

Oliver Just
RIKEN

With: A. Bauswein, J. Guilet, R. Ardevol,
M. Obergauliner, H.-Th. Janka, S. Goriely, and others

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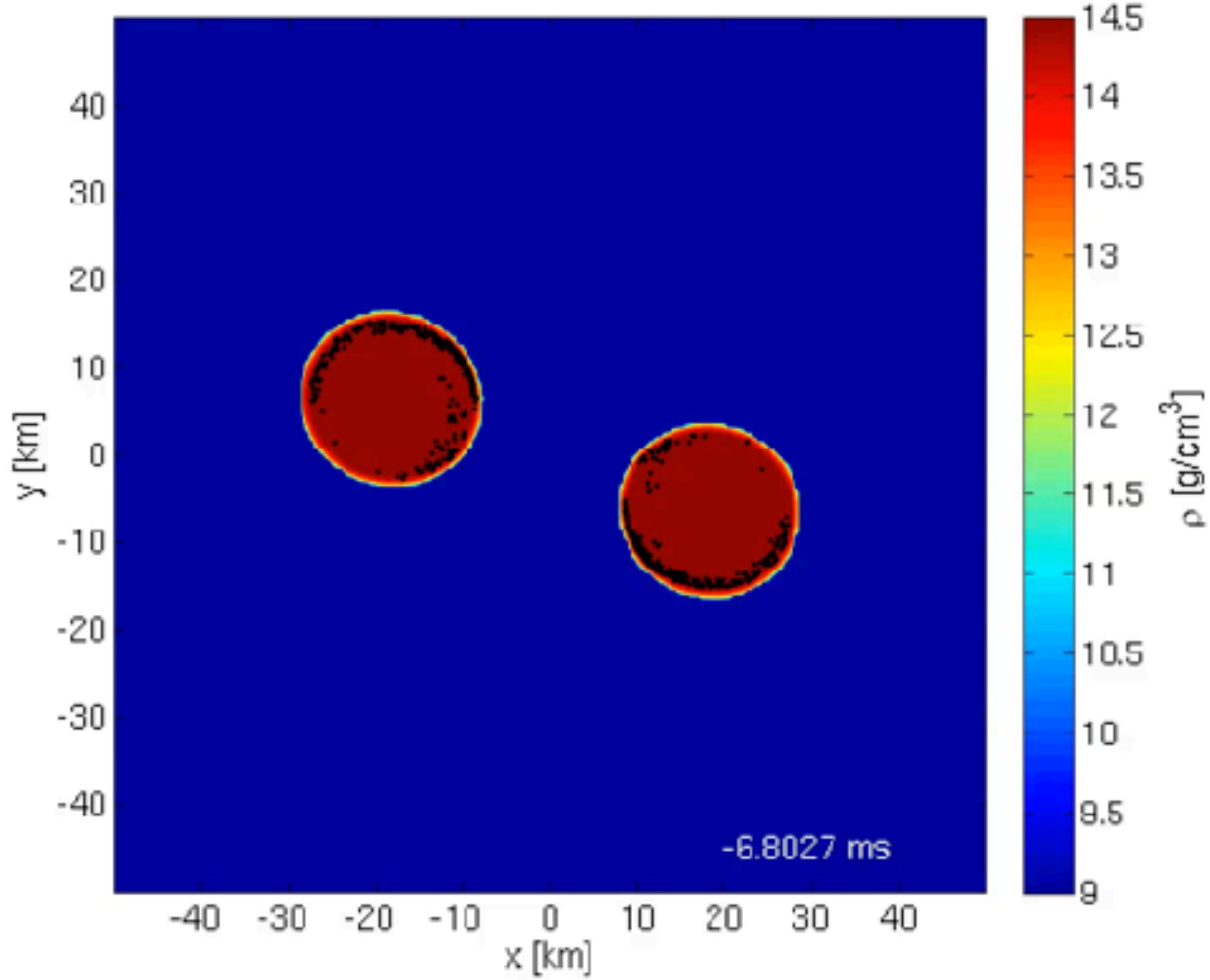
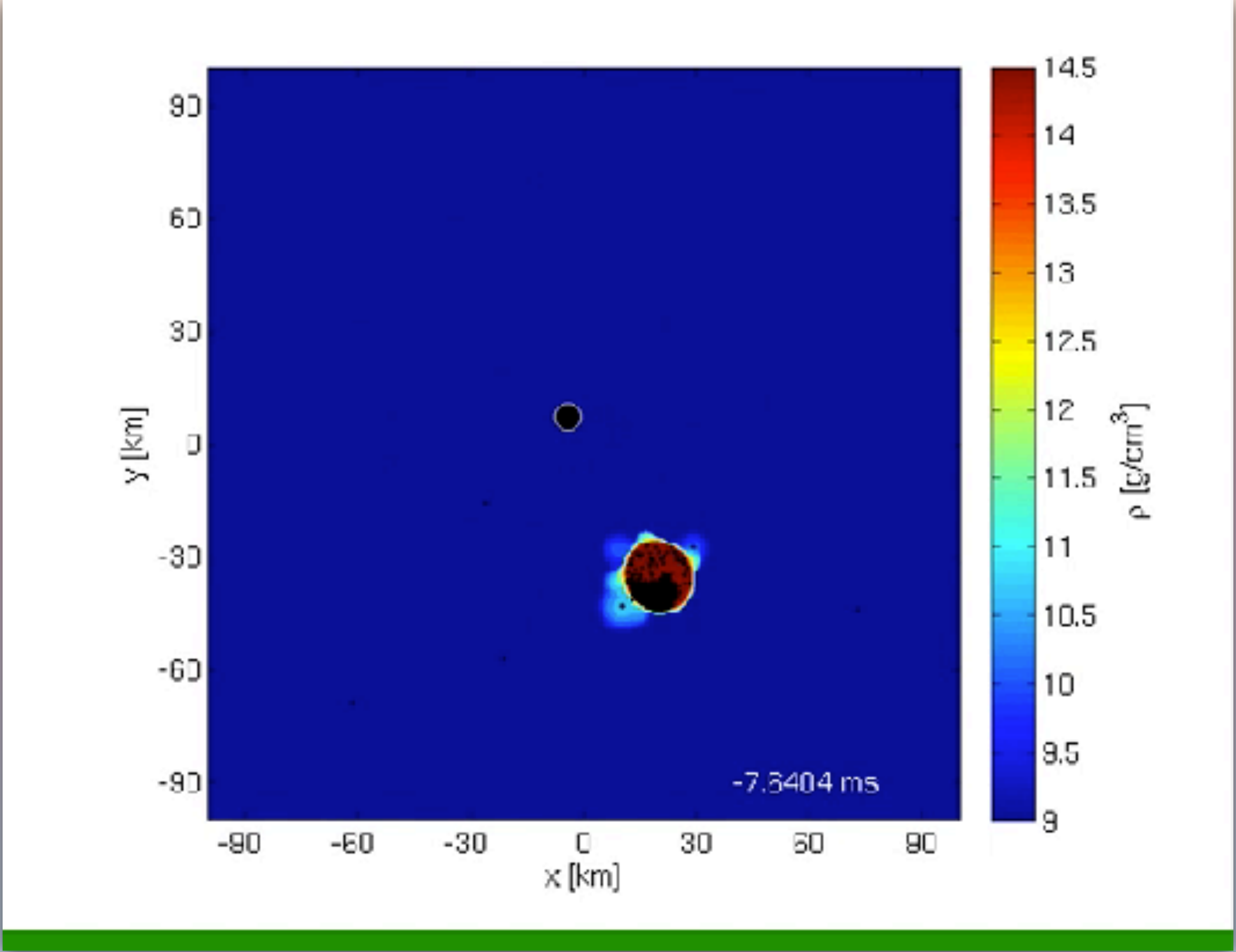
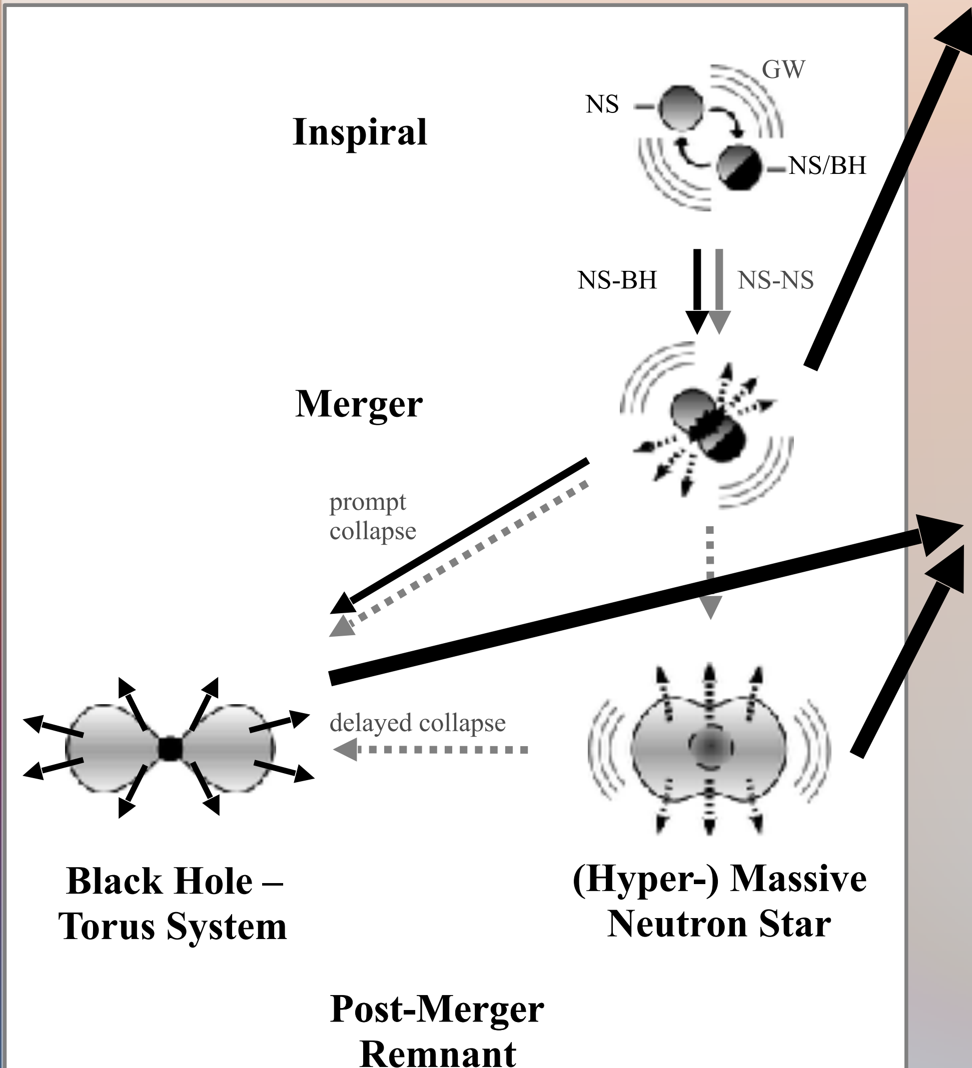
Movie: NS-NS Merger
(SPH simulation, by A. Bauswein)



Movie: NS-BH Merger
(SPH simulation, by R. Ardevol, A. Bauswein)



Ejecta Components, Modeling Status



dynamical/prompt ejecta

→ tidal tails
→ shock-heated

3D, GR, ν-transport, MHD

(Rosswog & Korobkin, Bauswein & Janka, Sekiguchi & Shibata, Hotokezaka, Rezzolla, Radice, Kiuchi, Foucart, Duez, ...)

post-merger ejecta

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

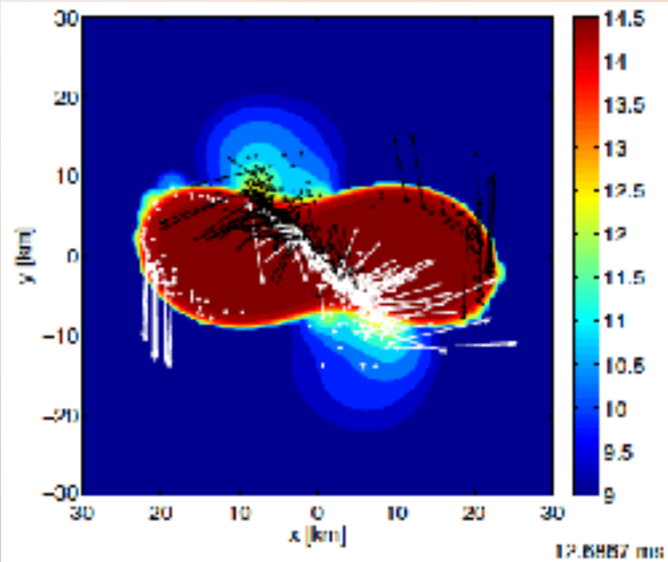
ν-tran, MHD/Vis, 3D, GR

(Fernandez & Metzger, Perego & Martin, Siegel, Kiuchi, Ru, Fujibayashi…)

Prompt/Dynamical Ejecta

(as obtained in OJ, Bauswein, Ardevol, Goriely, Janka ’15)

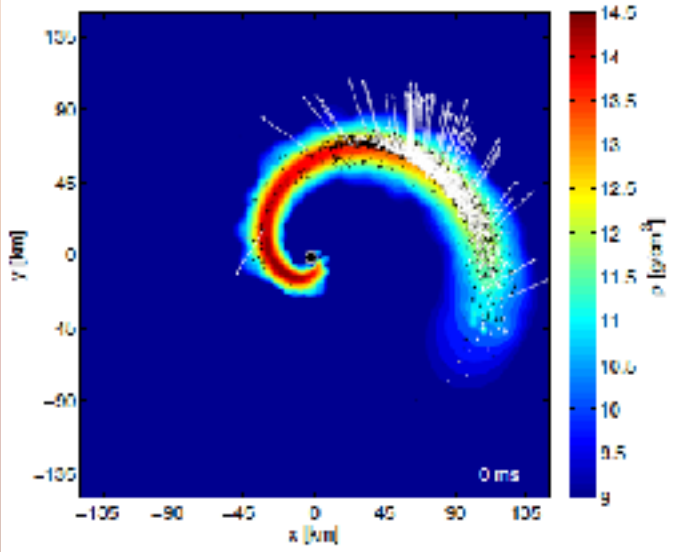
NS-NS



Typical outflow properties:

- outflow masses:
  M ~ 0.001 – 0.1 Msun
- electron fraction:
  Ye < 0.1 (*)
- entropy per baryon:
  s ~ 1 – 30 kB
- velocity:
  v ~ 0.2 – 0.4 c

NS-BH

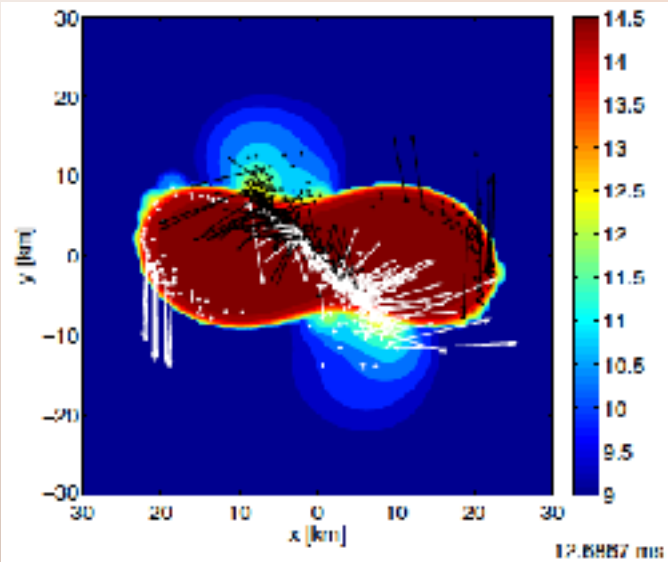


(* : Depends on neutrino treatment for NS-NS mergers)

Prompt/Dynamical Ejecta

(as obtained in OJ, Bauswein, Ardevol, Goriely, Janka '15)

NS-NS



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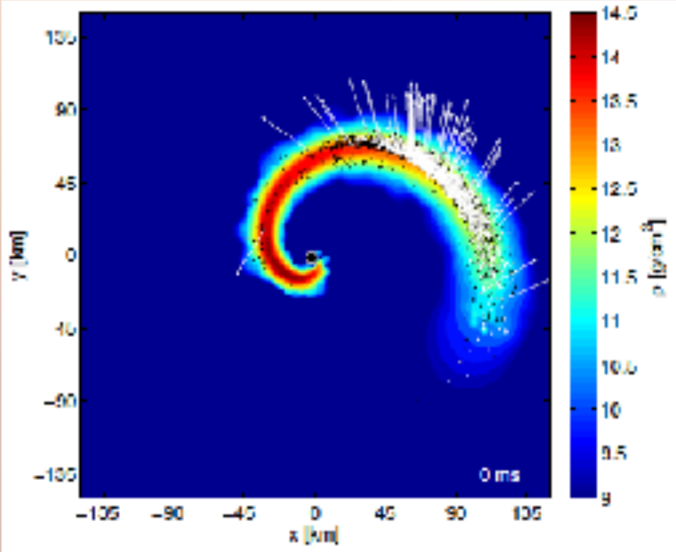
NS-BH



softer EOS yields…

- *larger* torus masses (in case of collapse)
- *larger* outflow masses
- *larger* outflow velocities

softer EOS yields…

- *smaller* torus masses (in case of collapse)
- *smaller* outflow masses

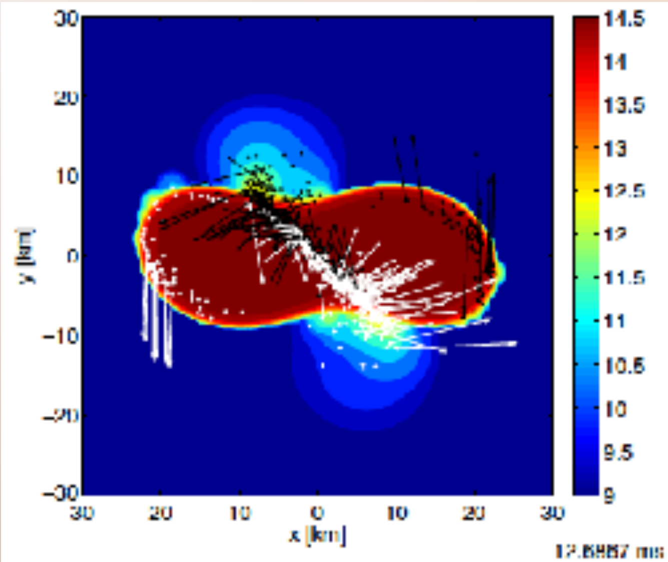
(* : Depends on neutrino treatment for NS-NS mergers)

Prompt/Dynamical Ejecta

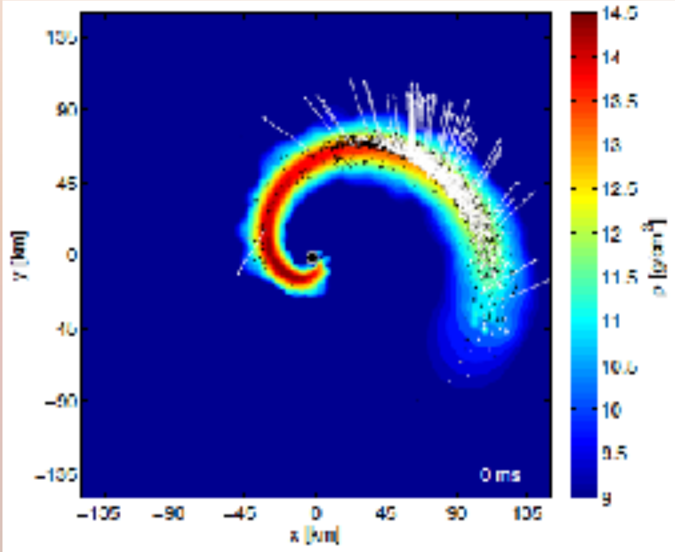
(as obtained in OJ, Bauswein, Ardevol, Goriely, Janka ’15)

Typical outflow properties:

NS-NS



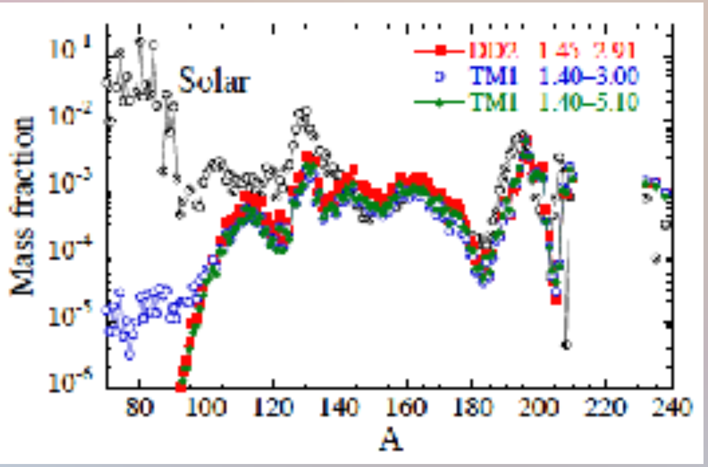
NS-BH



- outflow masses:
  M ~ 0.001 – 0.1 Msun
- electron fraction:
  Ye < 0.1 (*)
- entropy per baryon:
  s ~ 1 – 30 kB
- velocity:
  v ~ 0.2 – 0.4 c

Typical nucleosynthesis pattern:

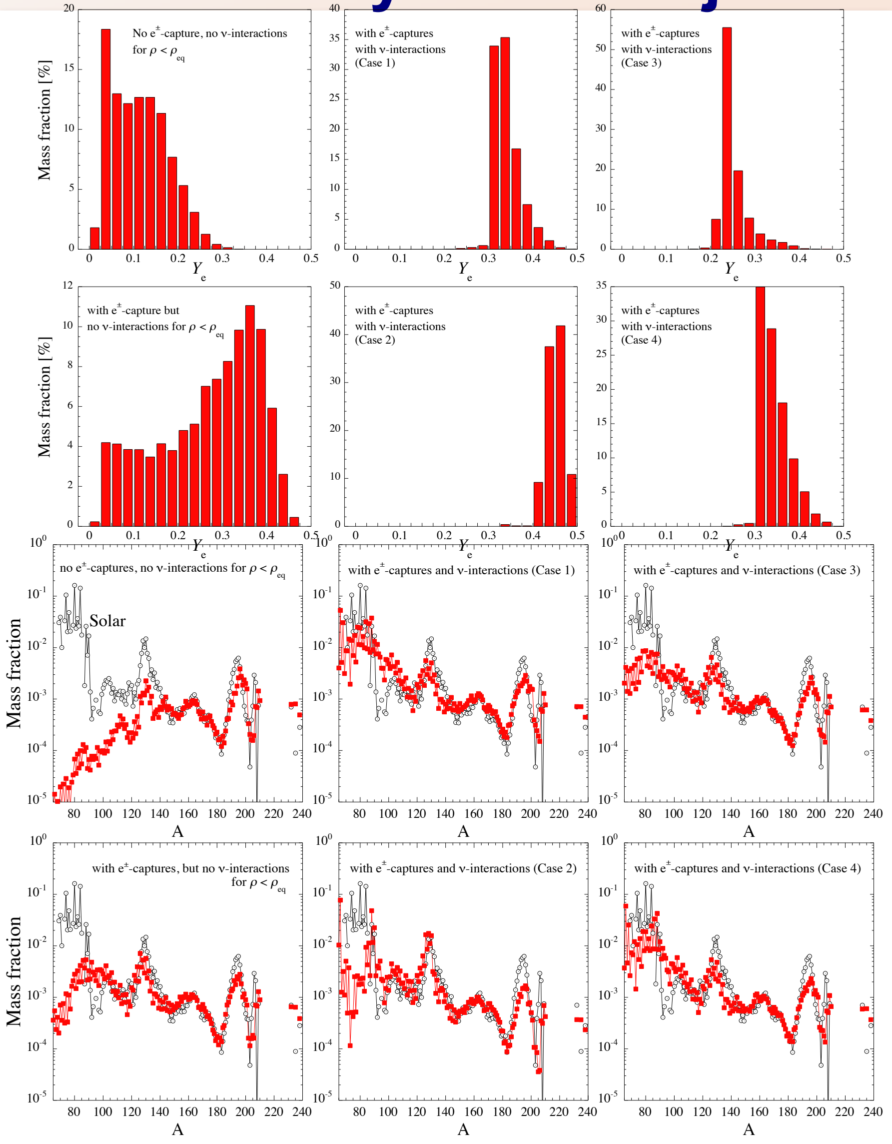
→ sub-solar for A < 140 (*)



→ solar-like for A > 140

(* : Depends on neutrino treatment for NS-NS mergers)

Impact of Weak Interactions on Dynamical Ejecta in NS-NS Mergers?



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

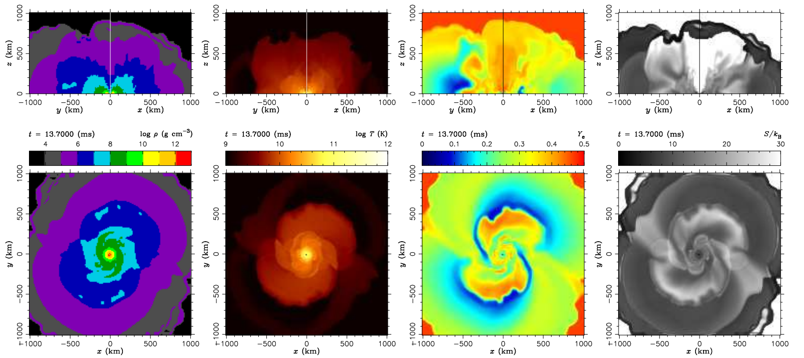
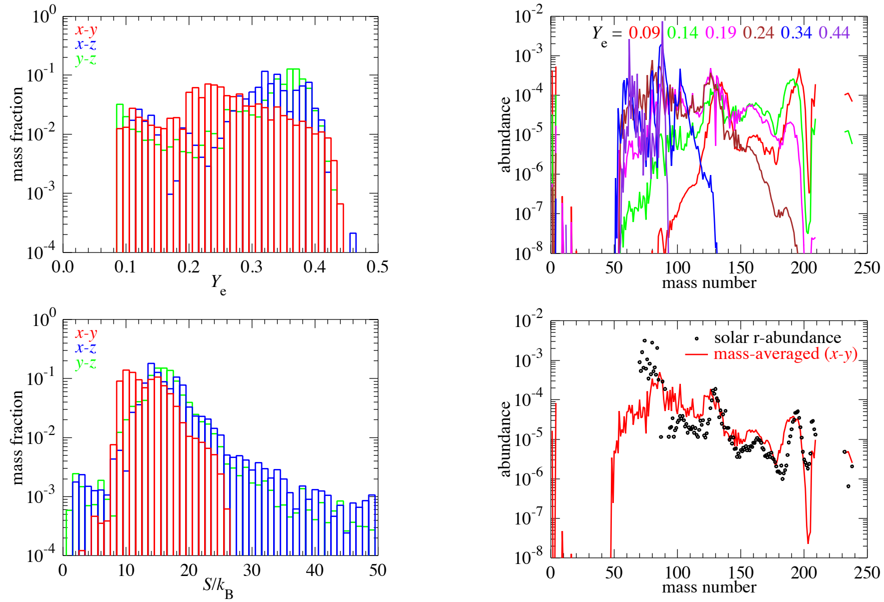


FIG. 2.— Color-coded distributions for density, temperature, Y_e, and S/k_B (from left to right) on the x-y (lower panels), x-z (positive sides of top panels), and y-z (negative sides of top panels) planes at the end of simulation.

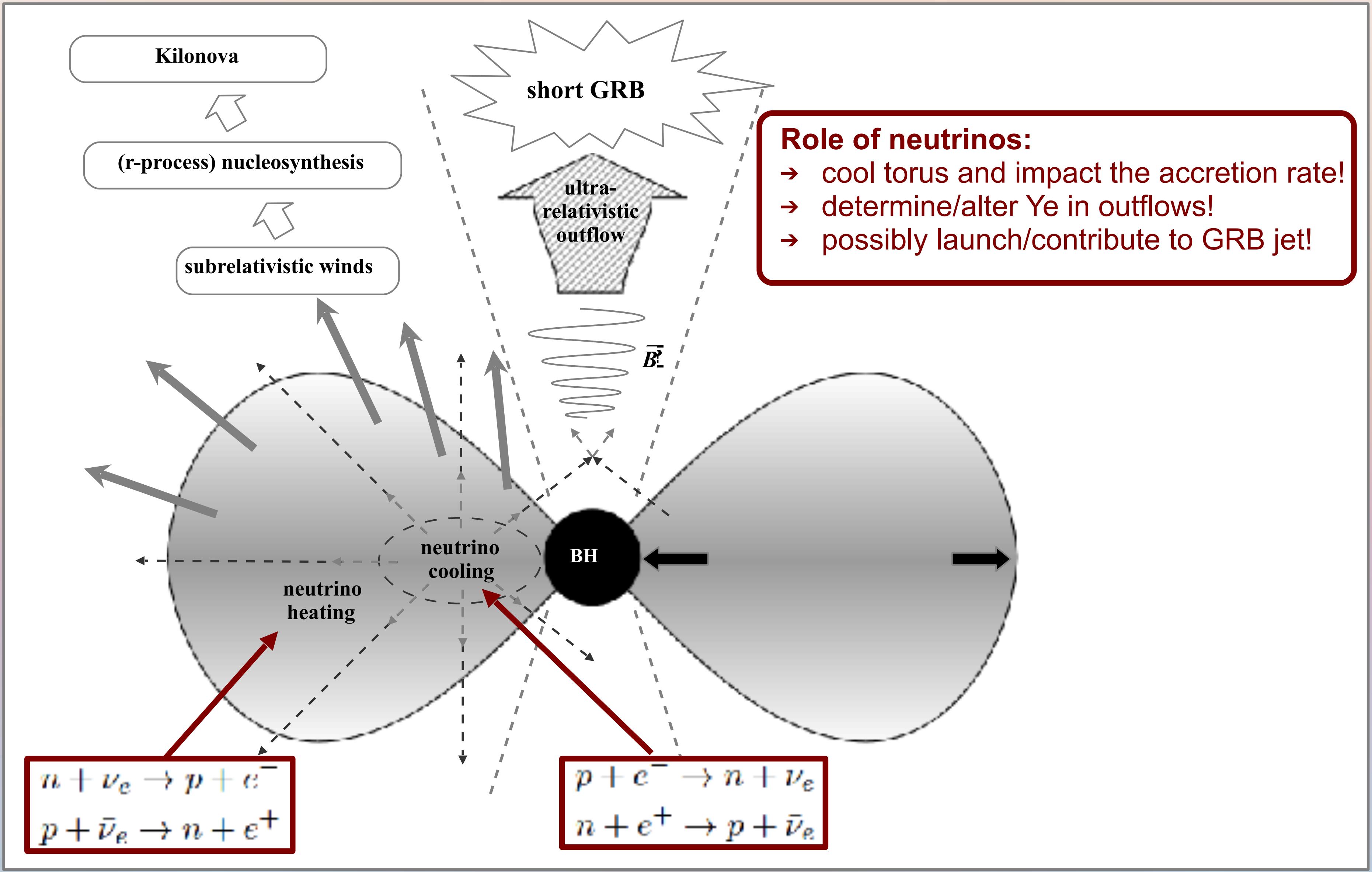


(Wanajo, Sekiguchi, Shibata, '14)

- ...can be quite significant. Dynamical ejecta may also produce lighter elements
- ***more simulations with accurate neutrino transport needed***

Post-Merger BH-Torus

(directly after its formation)



Role of neutrinos:

- → cool torus and impact the accretion rate!
- → determine/alter Ye in outflows!
- → possibly launch/contribute to GRB jet!

"ALCAR" Neutrino Transport Module

(OJ, Obergaulinger, Janka '15, MNRAS, 453, 3386)

Radiation-hydro with Boltzmann solver too expensive!

Our approach:

➔ **Energy-dependent two-moment scheme with local closure (*M1 scheme*)**

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

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

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

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

$$\begin{aligned} \partial_t E + \nabla_j F^j + \nabla_j (v^j E) + (\nabla_j v_k) P^{jk} - (\nabla_j v_k) \partial_\epsilon (\epsilon P^{jk}) &= C^{(0)} \\ \partial_t F^i + c^2 \nabla_j P^{ij} + \nabla_j (v^j F^i) + F^j \nabla_j v^i - (\nabla_j v_k) \partial_\epsilon (\epsilon Q^{ijk}) &= C^{(1),i} \end{aligned}$$

} **evolution equations**

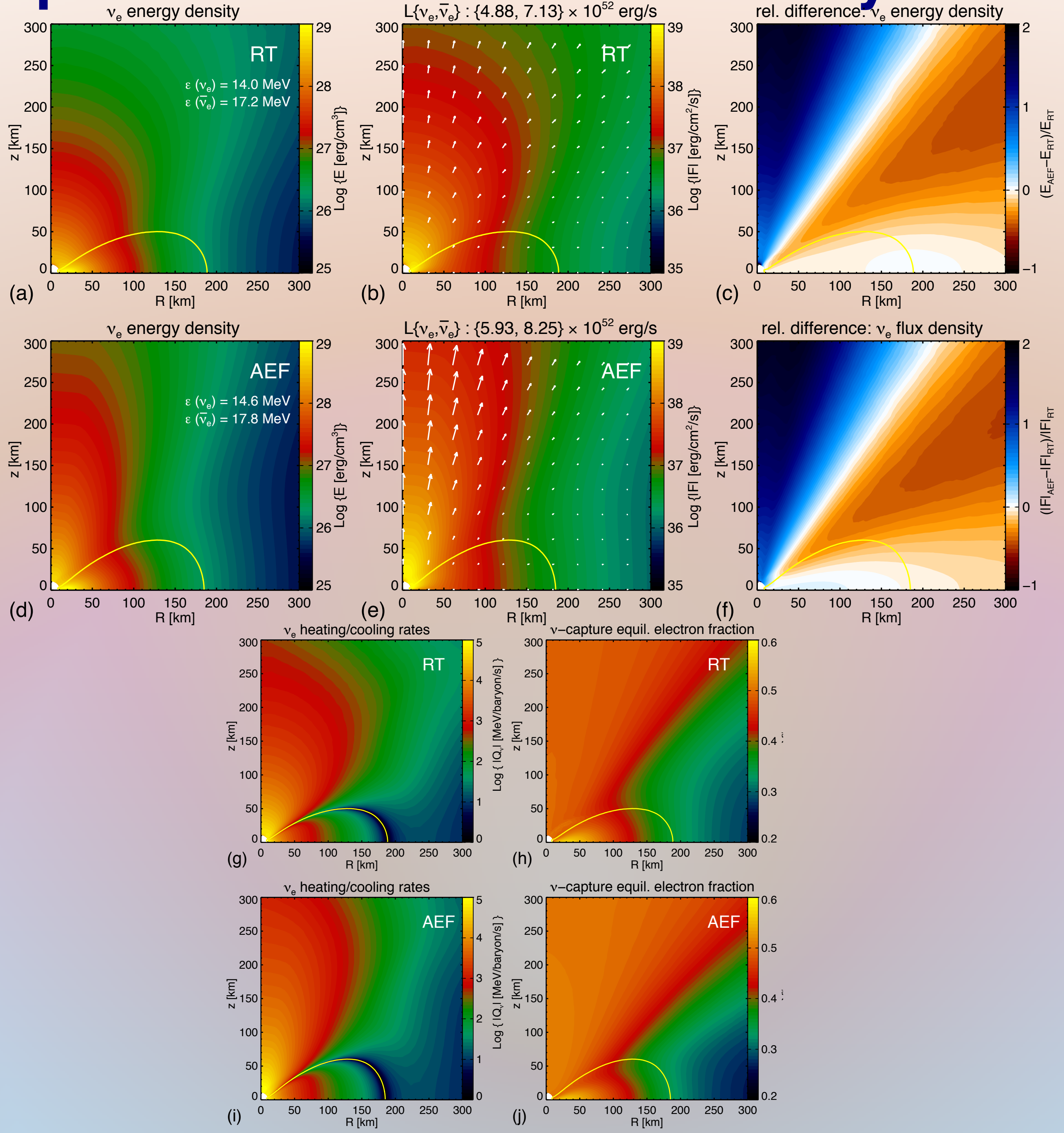
$$\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}$$

} **approximate algebraic closure relations (e.g. "Minerbo closure")**

Saves two degrees of freedom of nu-phase space!

BUT: Limited accuracy in optically thin regions

Comparison Between M1 and Ray Tracing



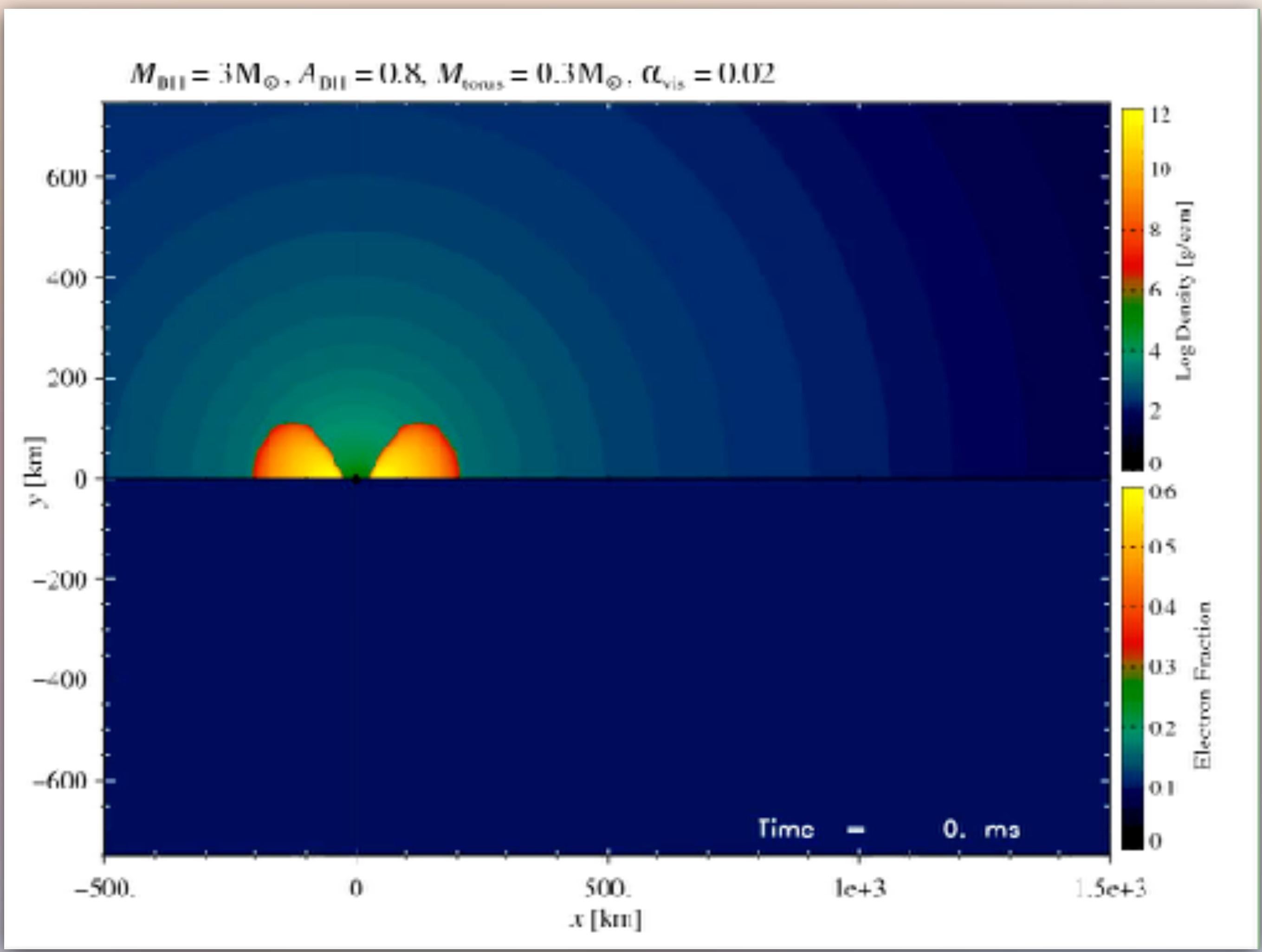
Post-Merger BH-Torus Remnant

Typical ejecta properties:

- outflow masses:
  ~ 5-20% of torus mass
- 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

- **dominant** viscous component

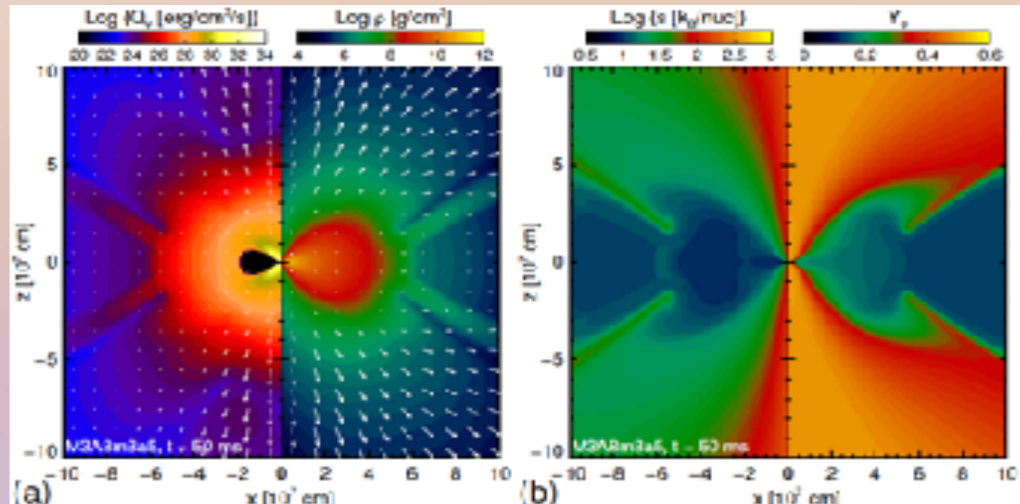


Disk Properties

2 main evolutionary phases:

→ first few 100 ms: *"Neutrino-dominated accretion flow"* **(NDAF)**

→ neutrino cooling balances viscous heating



time = 50 ms

→ ejecta (mainly) driven by neutrino-heating

→ Ye in ejecta determined by **neutrino captures**

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

→

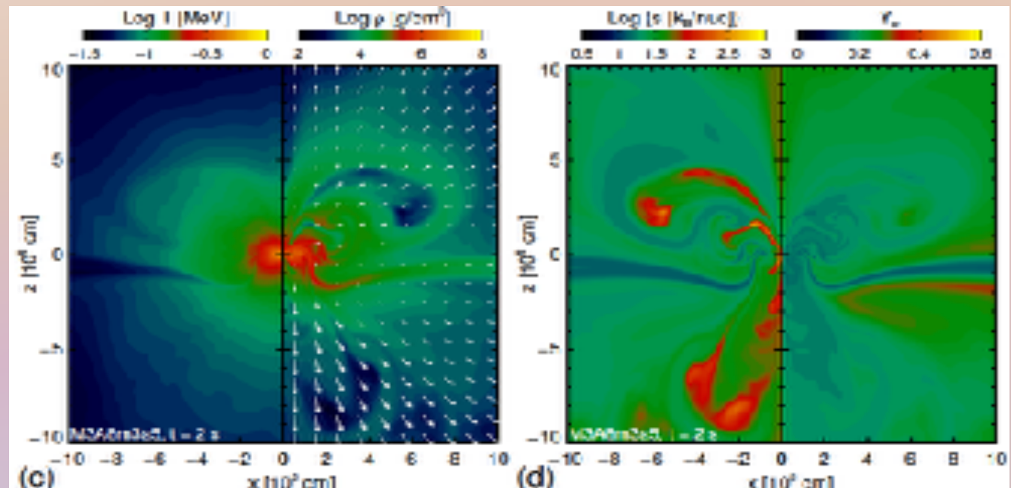
$$Y_e \longrightarrow Y_e^{\nu} \sim \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2Q_{np}}{\varepsilon_{\nu_e} + 2Q_{np}}\right)^{-1}$$

Disk Properties

2 main evolutionary phases:

➔ subsequently: *"Advection-dominated accretion flow"* **(ADAF)**

➔ viscous heating dominates neutrino cooling



time = 2 s

➔ ejecta (mainly) driven by viscous effects

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

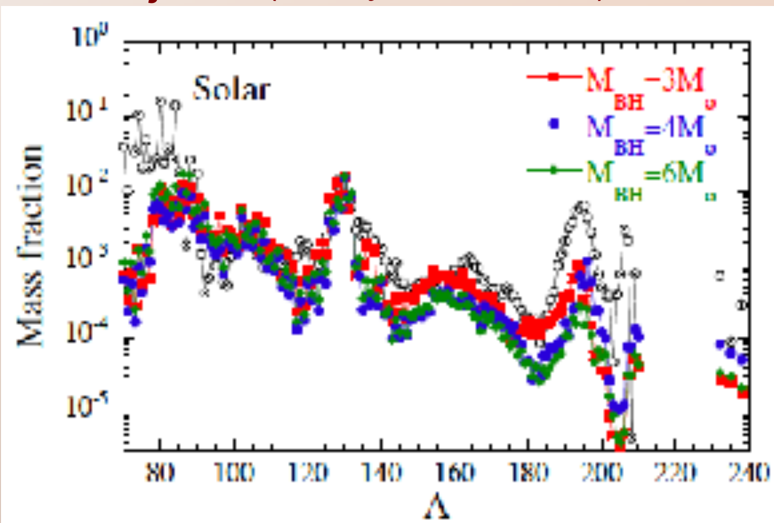
$$p + e^- \rightarrow n + \nu_e$$
$$n + e^+ \rightarrow p + \bar{\nu}_e$$

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

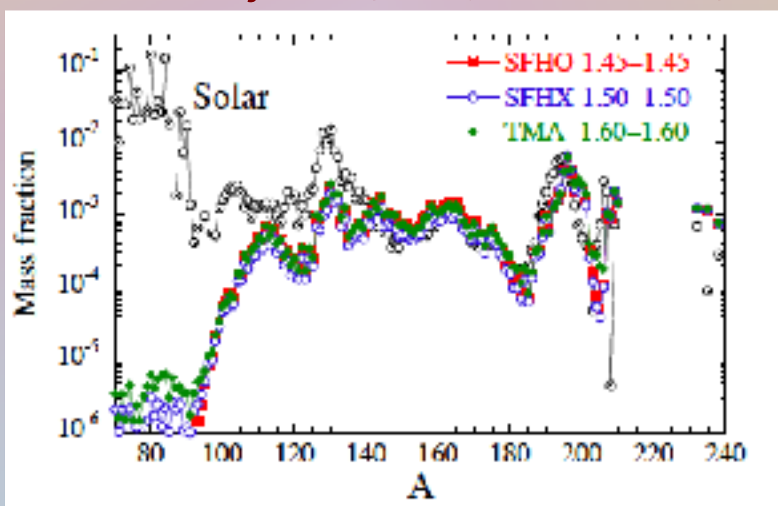
Combined nucleosynthesis yields

(OJ, Bauswein, Ardevol, Goriely, Janka '15, MNRAS 448, 541)

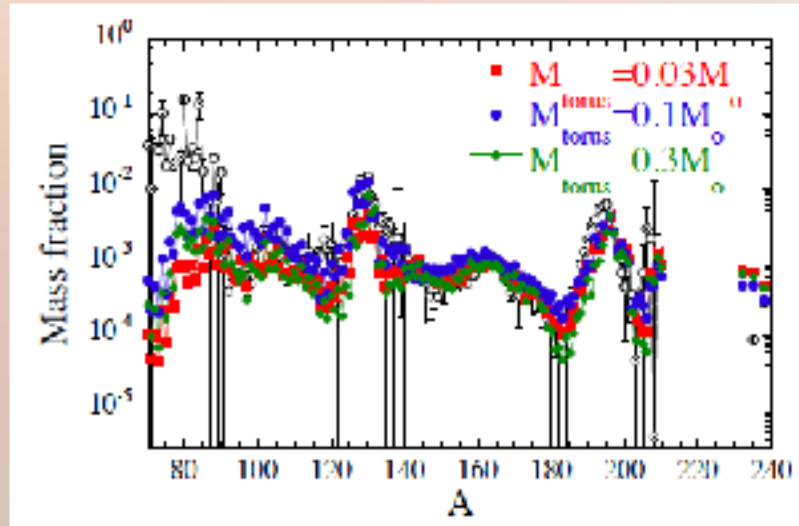
➔ DISK ejecta (mainly A ~ 90 - 140)



➔ PROMPT ejecta (mainly A ~ 140 - 210)



➔ DISK + PROMPT ejecta



➔ nicely recovers the full mass range A > 90

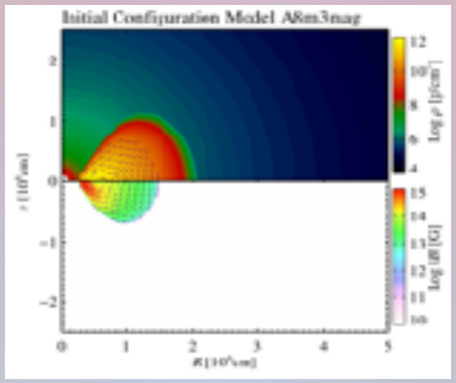
➔ BH-torus ejecta could be significant source of intermediate mass elements with 90 < A < 140

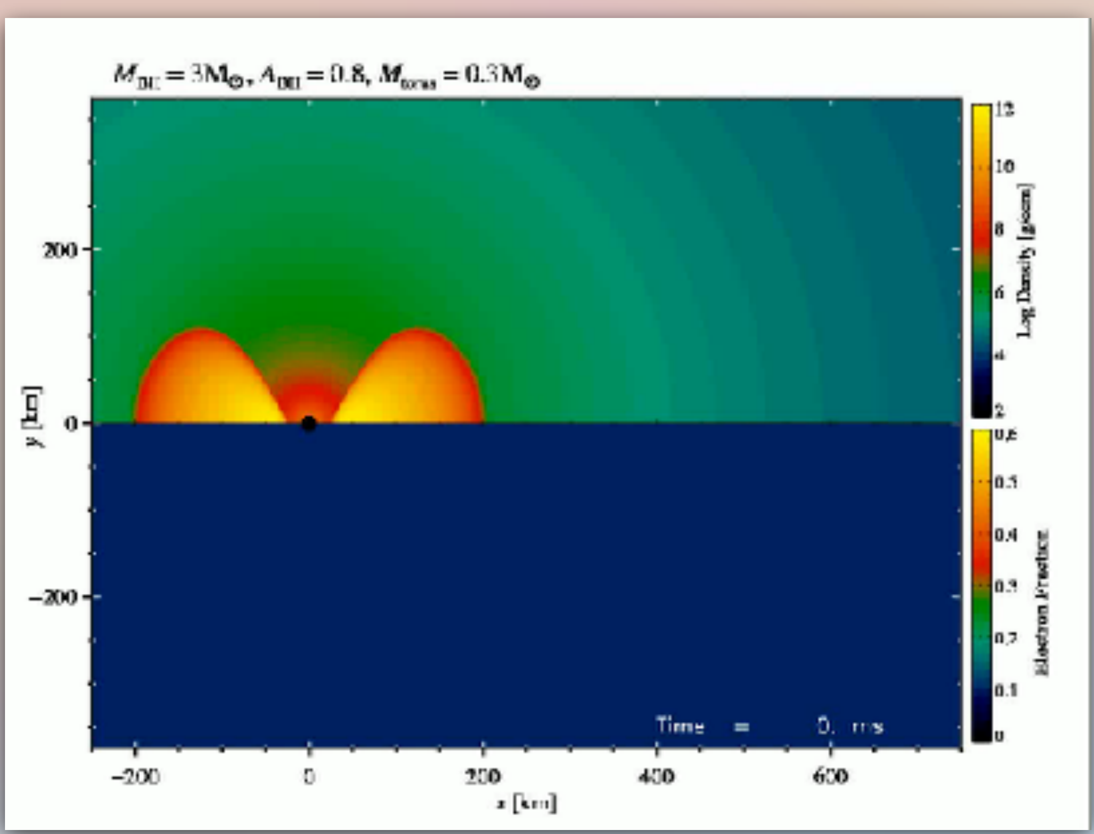
Magnetic fields?

- **…are essential for angular momentum transport and MHD-driven Jet**
- **Major challenges:**
  - need 3D because of anti-dynamo theorem
  - need high resolution to resolve relevant scales

(see talks by Siegel and Tchekovskoy)

- **2D M1-MHD simulations (not sufficient to obtain long-term ejecta):**





Magnetic fields?

(Guliet, Bauswein, OJ, Janka, ’16)

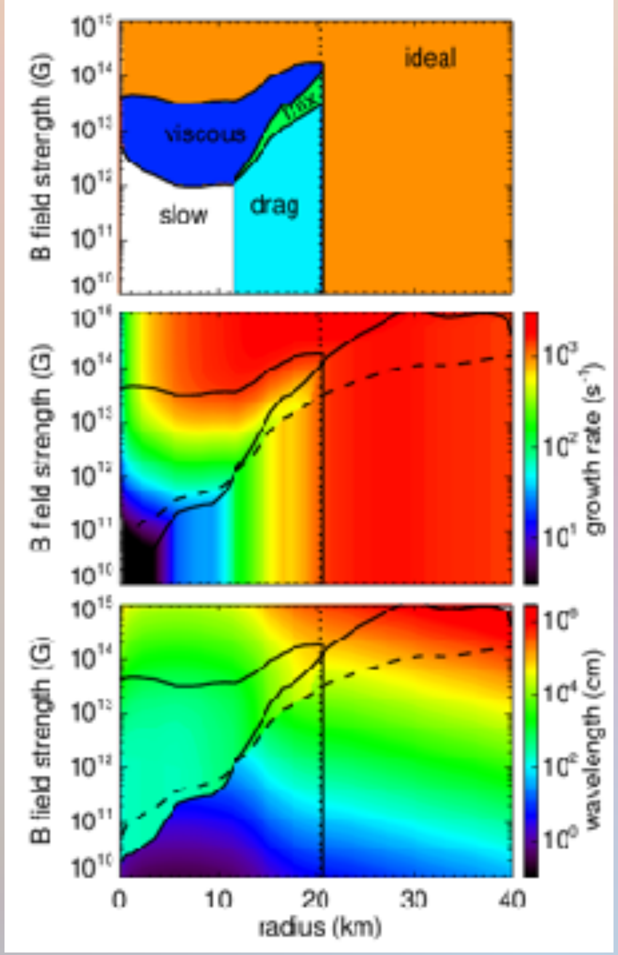
- **Can the Magnetorotational instability grow in remnants of NS-mergers?**
  - *In NS remnants:* slowed down by neutrino-viscosity and -drag
  - *In BH-torus remnants:* ideal growth

Neutrino viscosity (on length scales longer than neutrino mean free path):

$$\nu = 1.2 \times 10^{10} \left(\frac{T}{10\,\mathrm{MeV}}\right)^2 \left(\frac{\rho}{10^{13}\,\mathrm{g\,cm^{-3}}}\right)^{-2} \mathrm{cm^2\,s^{-1}}, \quad (2)$$

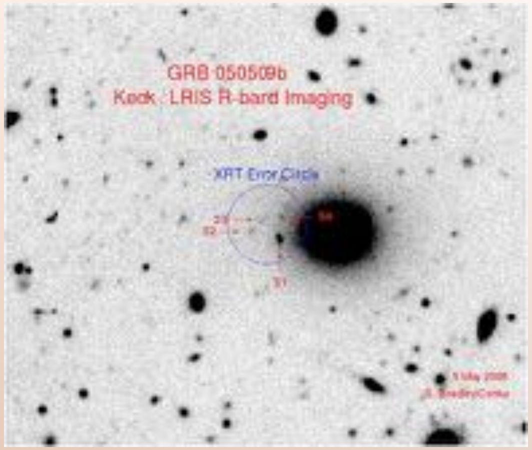
Neutrino drag damping rate (on length scales shorter than neutrino mean free path):

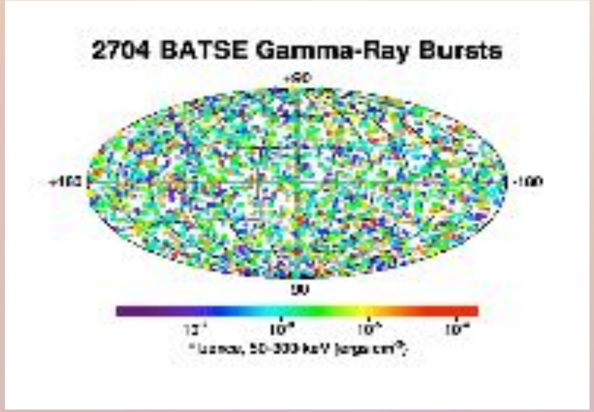
$$\Gamma = 6 \times 10^3\,(T/10\,\mathrm{MeV})^6\,\mathrm{s^{-1}}.$$



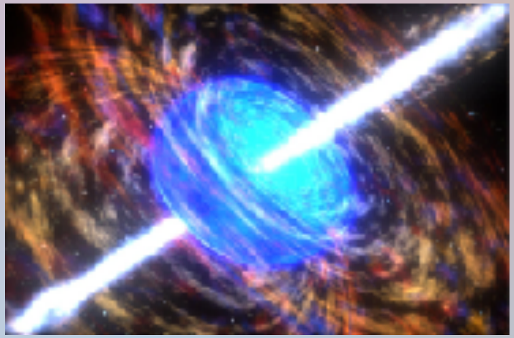
Gamma-Ray Bursts

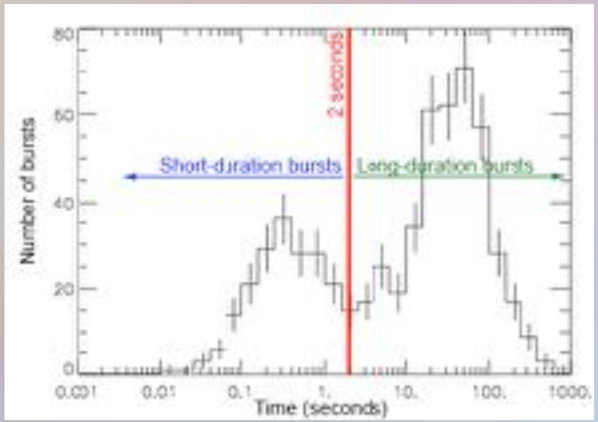
- ➔ first detected 1967 by VELA satellites
- ➔ since then ~ few 100 suggested possibilities for
- ➔ central engines
- ➔ since BATSE: must be of cosmological origin
- ➔ source is moving highly relativistically
- ➔ natural suggestion: jet from rotating compact object
- ➔ long bursts (T>2s): connection to death of massive stars
- ➔ short bursts (T<2s) still mysterious, most likely from NS mergers



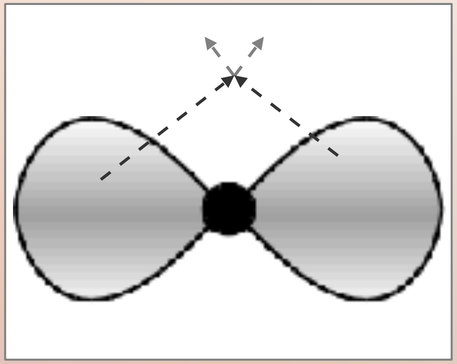


(NASA)



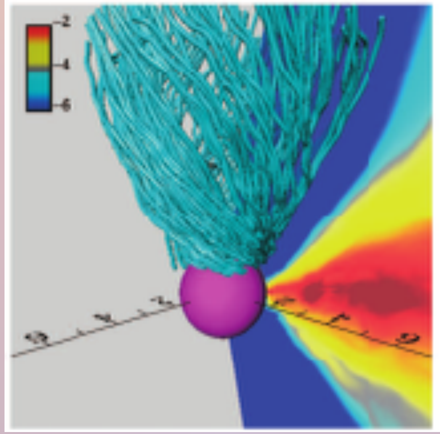


Popular central engine scenarios



➔ neutrino-pair annihilation

- neutrinos tap gravitational energy of disk
  e+-e- pairs thermalize → thermal fireball
- efficiency of converting gravitational energy into jet energy?
- baryon loading in the funnel?



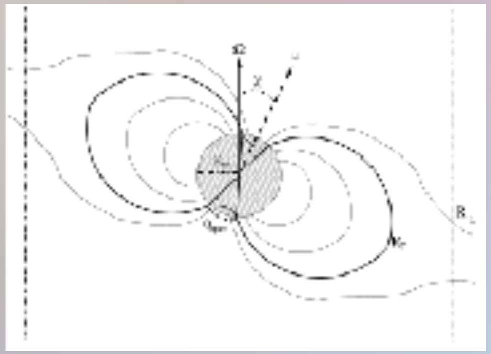
(Hirose+ '04)

➔ Blandford-Znajek process

- B-field taps rotation energy of central BH
  → Poynting-dominated jet
- efficient only for large-scale poloidal B-fields
- can large-scale fields be produced and sustained? MRI? Dynamo?

➔ magnetar spin-down emission

- B-field taps rotation energy of central NS
  → Poynting dominated jet
- is dipole model applicable?
- consistent with short burst timescale?



(Metzger+ '11)

EM Counterparts: Short Gamma-Ray Bursts

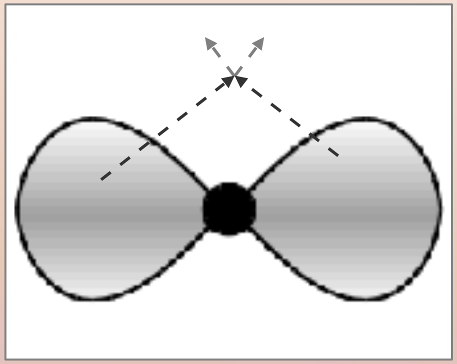
- **Suggested models:**

???

➔neutrino pair annihilation

➔Blandford-Znajek process

➔magnetar dipole emission



Tested using for the first time time-dependent neutrino-hydrodynamics simulations

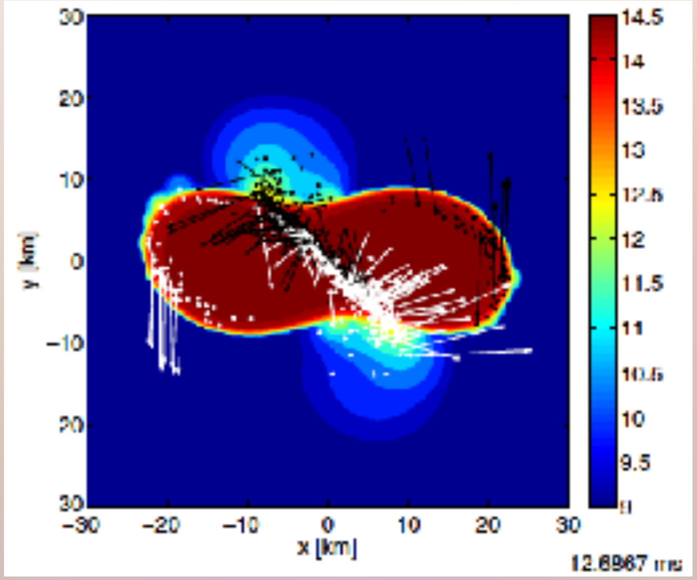
(OJ, Obergaulinger, Janka, Bauswein ApJ, 816, L30)

Necessary conditions for the jet to explain sGRB:

- Total energy: $\mathbf{E \sim 10^{48} – 10^{50}}$ **erg**
- Lorentz factor: $\mathbf{\Gamma \sim 10\text{-}100}$

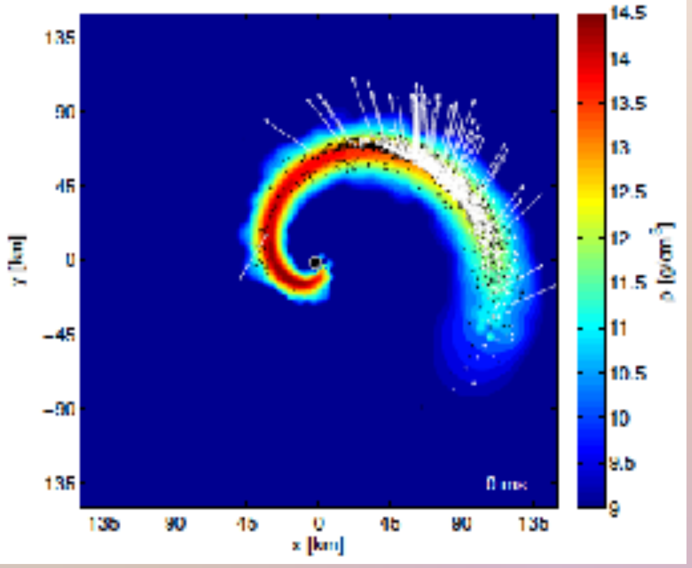
Geometry of Dynamical Ejecta

NS-NS

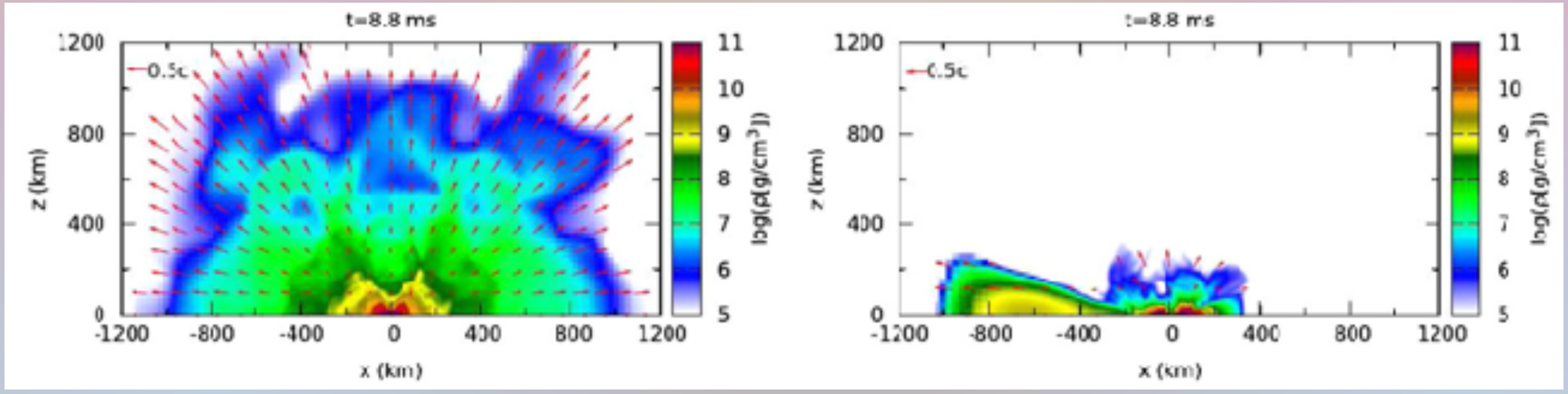


(Bauswein et. al. '13)

NS-BH



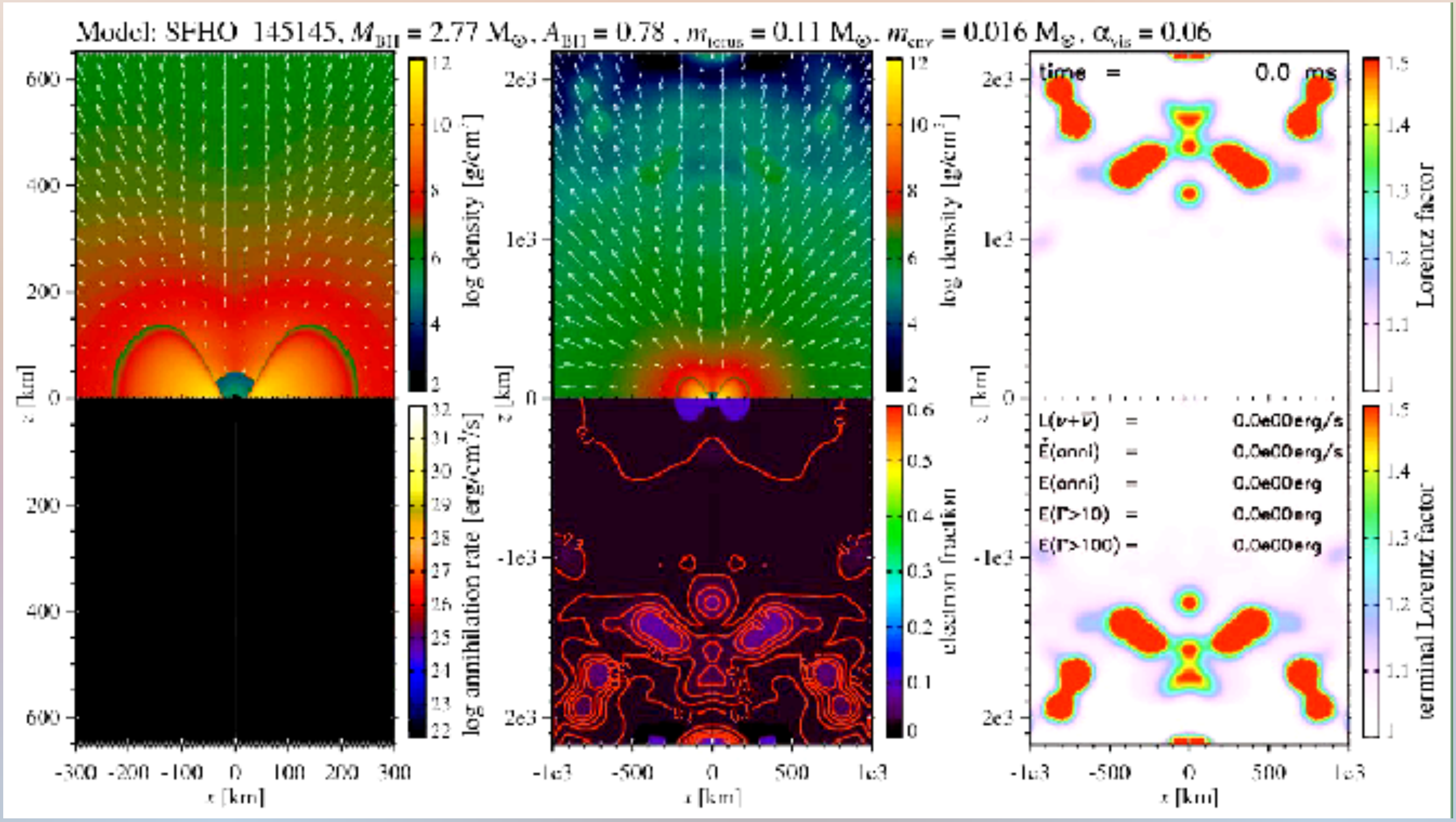
(Just et. al. '15)



(Hotokezaka et. al. '13)

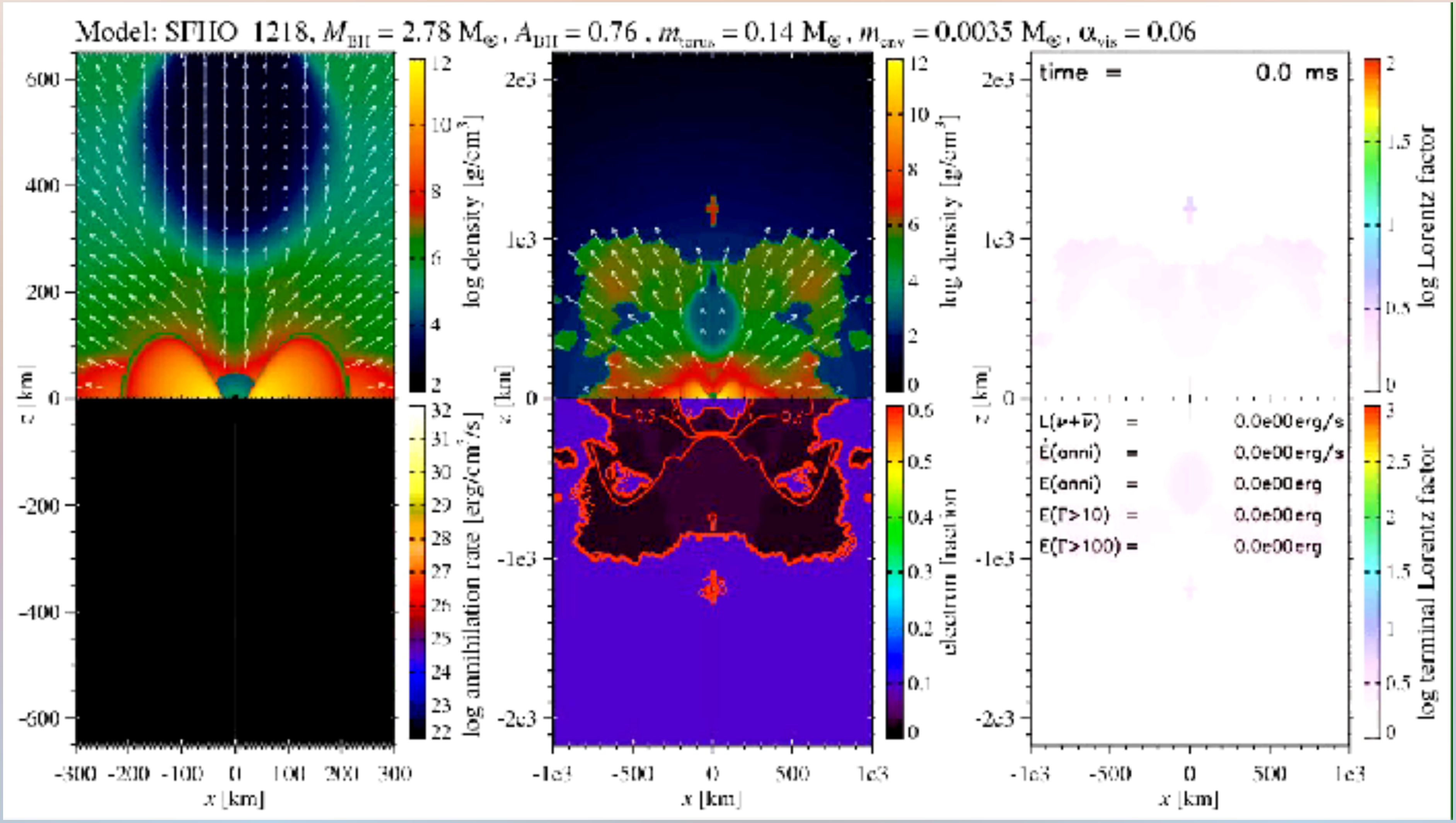
Symmetric NS-NS Merger

- baryon loading in the funnel too high, **no jet launched**



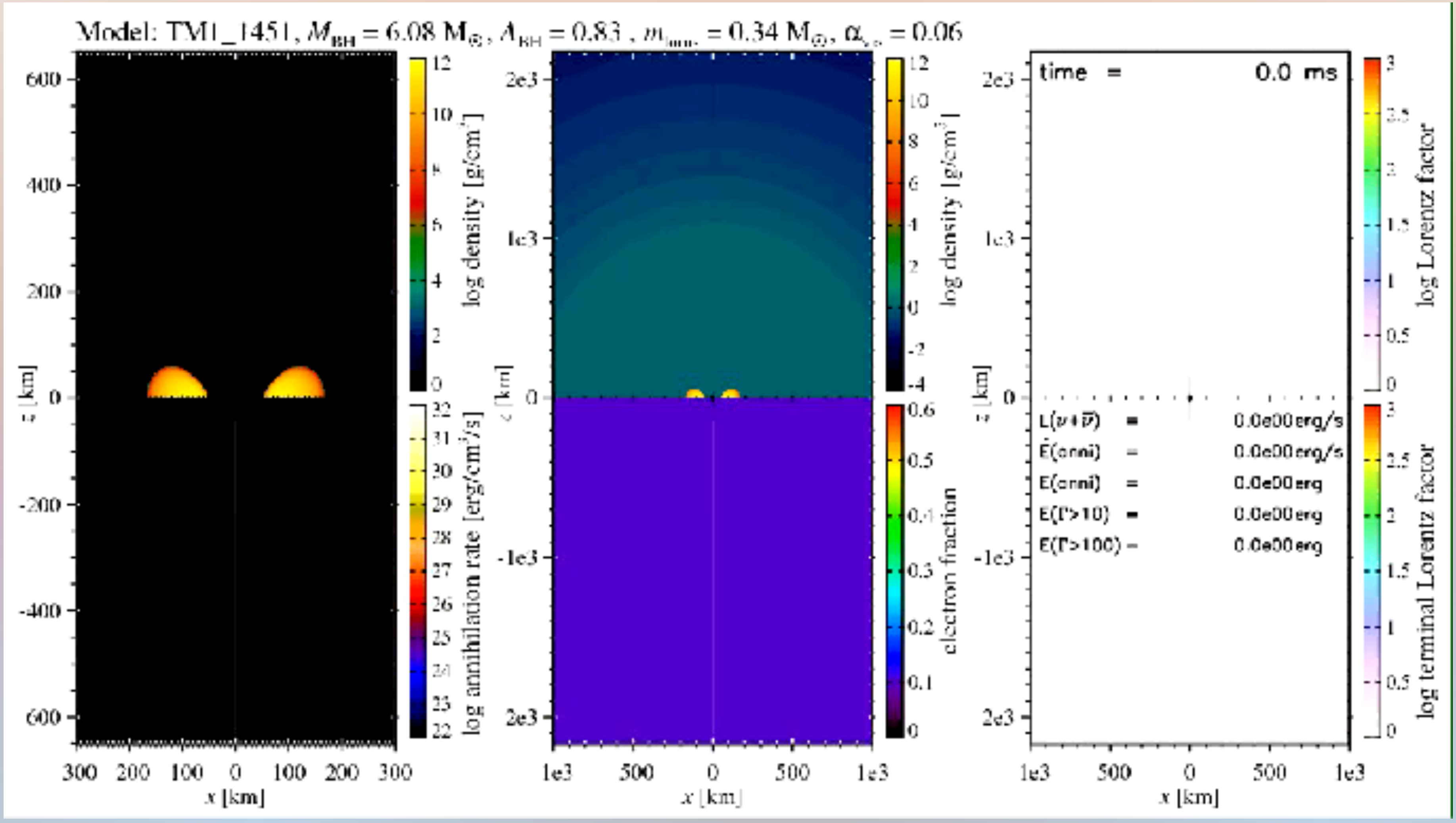
Asymmetric NS-NS Merger

- jet is **successfully launched**, but then dissipates most of its kinetic energy into cloud of dynamical ejecta



NS-BH Merger

- no dynamical ejecta in polar regions → jet can expand freely
- however, energy too low to explain majority of sGRBs

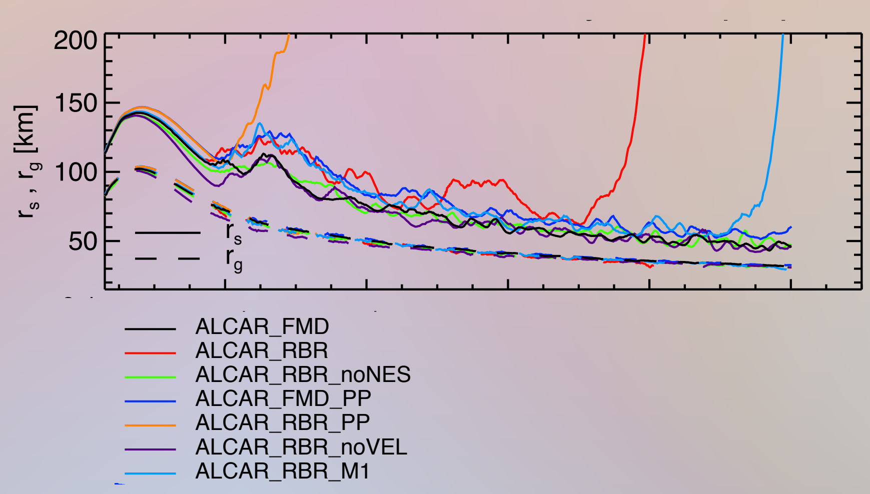


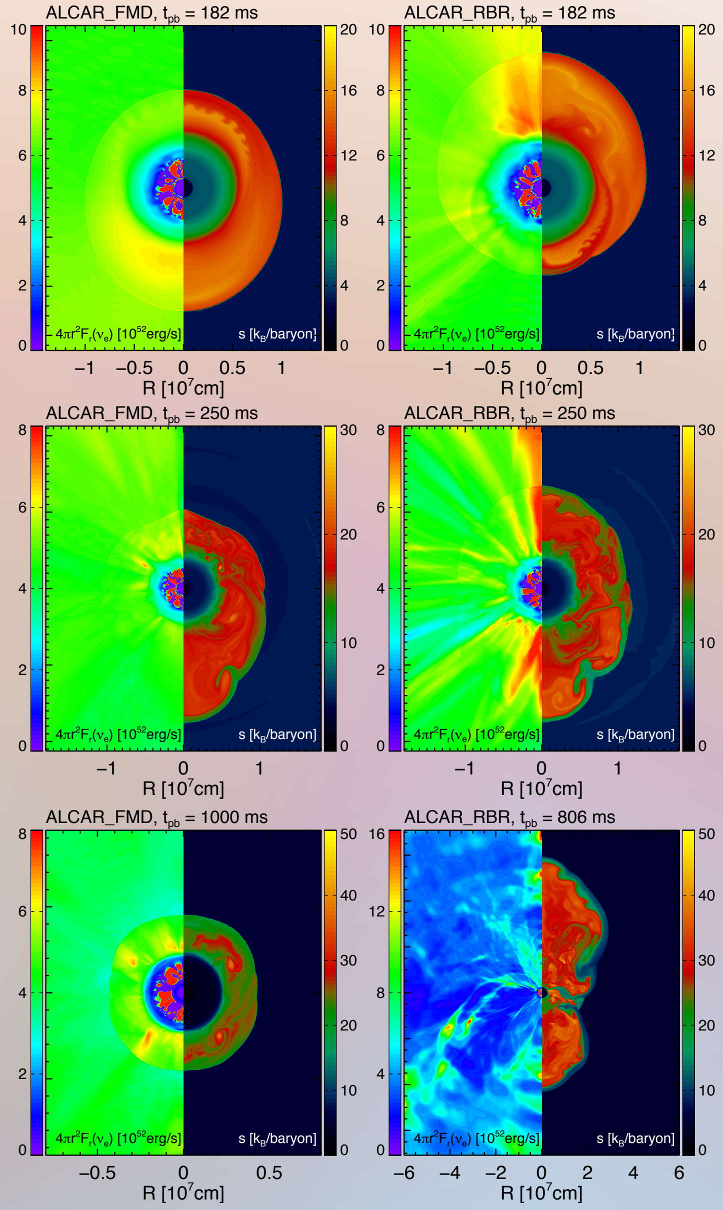
Summary

- neutrinos can have strong impact on Ye, ejecta mass, remnant cooling, MRI, and jet
- r-process nucleosynthesis:
    - for neutrino-driven winds (from HMNS or disk): energy-dependent neutrino transport inevitable
    - for viscous-like winds: maybe no transport needed, leakage sufficient
    - for dynamical ejecta from NS-NS: e-dependent nu-transport desirable
    - for dynamical ejecta from NS-BH: nu-transport probably negligible
- jets:
    - neutrino annihilation probably not the main agent, but could help clearing the funnel
    - for accurate annihilation rate: e-dependent nu-transport desirable
- MRI in the remnant:
    - slowed down by neutrinos in the HMNS
- still major challenge to combine nu-transport with GR and MHD but major steps have been taken by various groups

It could be worse…

- … in (2D) core-collapse supernovae ***small*** modifications in the nu-transport can decide if star explodes or not





(Just et al, in prep)