Heavy Element Production and Neutrino-Driven Jets in Neutron-Star Merger

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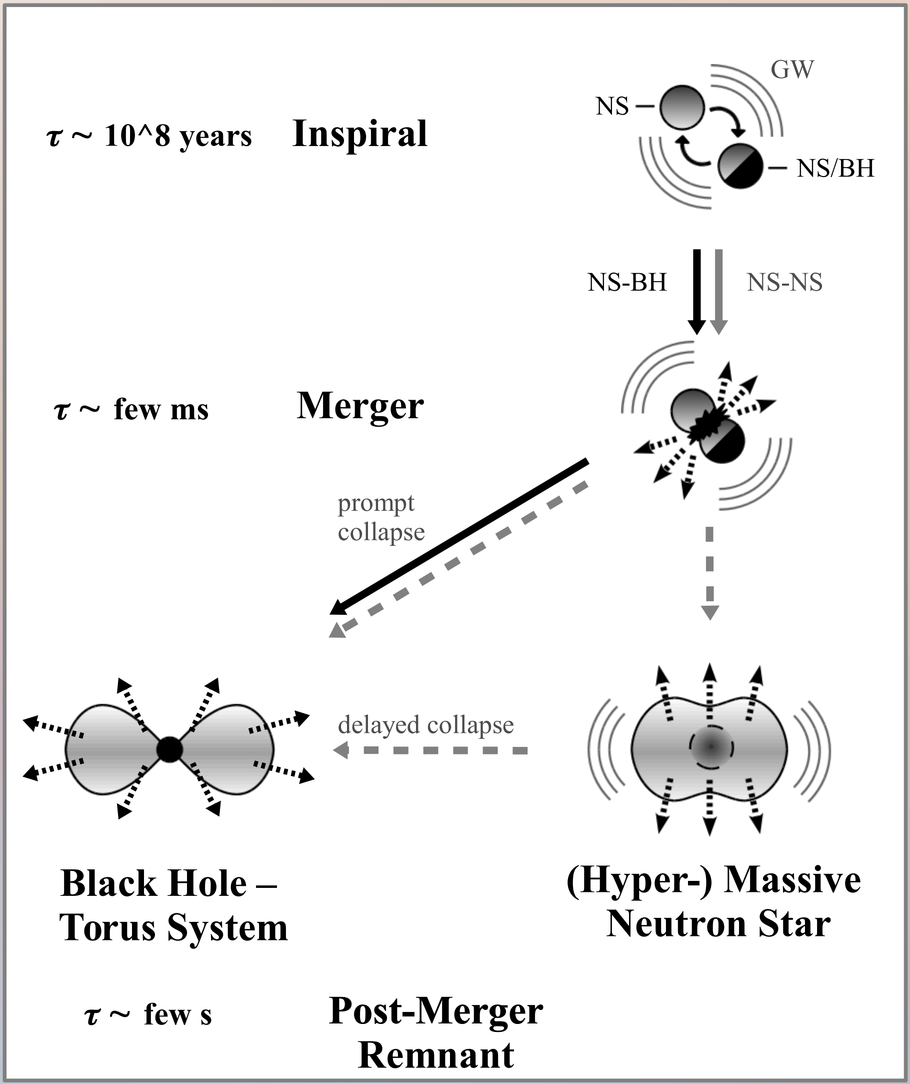
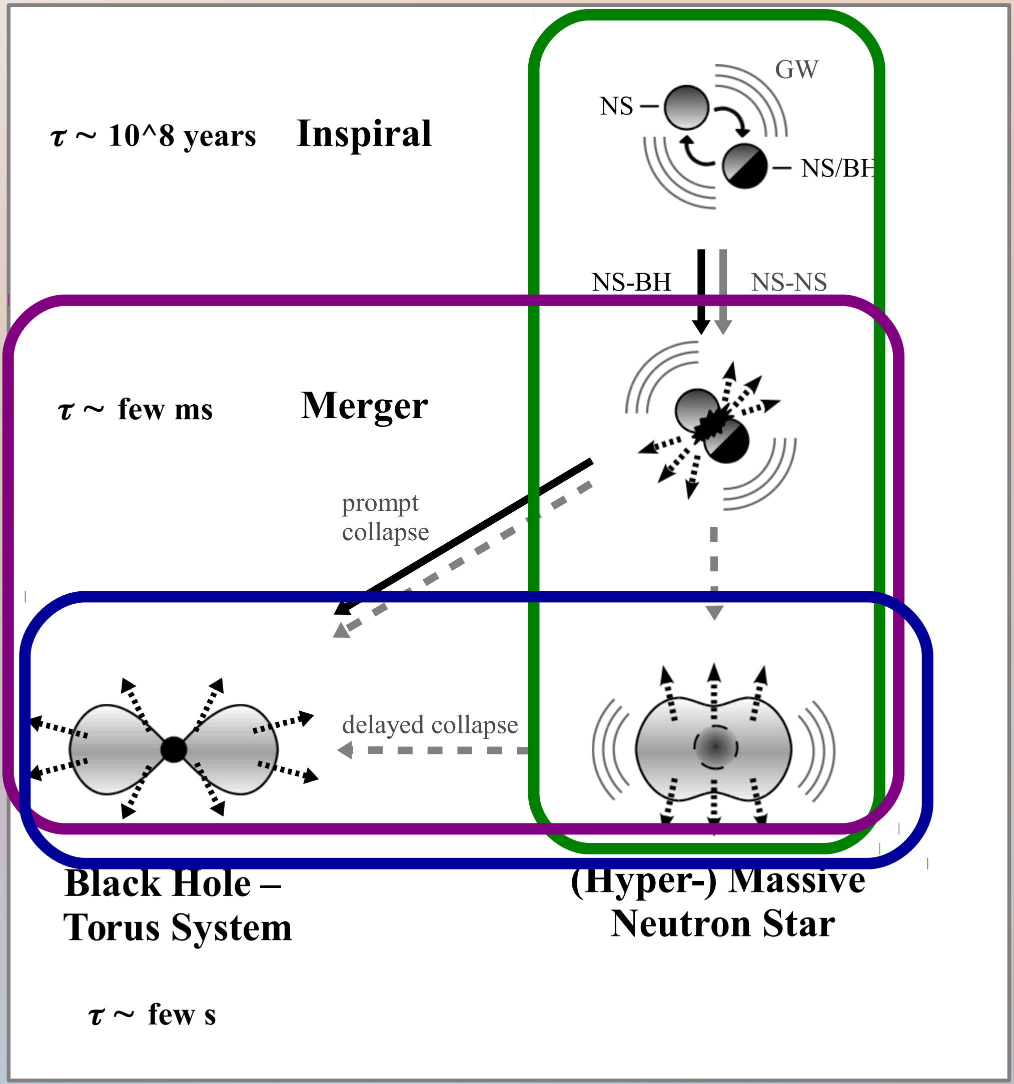
TUM LMU Excellence Cluster Universe

Evolution Channels, Multi-Messenger Astronomy



Evolution Channels, Multi-Messenger Astronomy



➔ GW signal

... binary parameters?

... nuclear EOS?

➔ short GRB

... from BH-torus system?

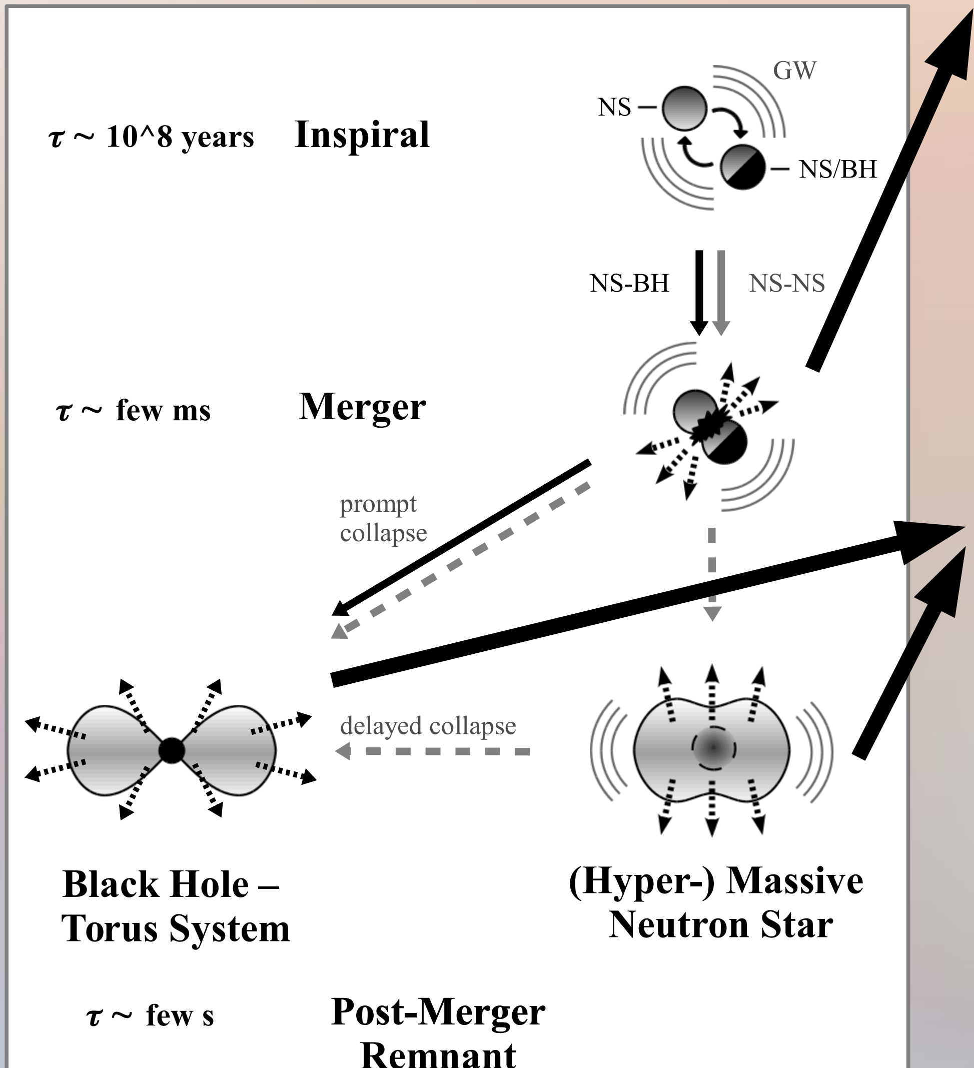
... from (H)MNS?

➔ Massive Ejecta

... sources for r-process elements?

... observable electromagnetic signals (Macro-/Kilonova)?

Ejecta Components, Modeling Ingredients



dynamical/prompt ejecta

→ tidal tails

→ shock-heated

***3D, GR**, ν-transport, MHD*

post-merger ejecta

→ neutrino-driven

→ viscous expansion

→ MHD turbulence

***ν-tran, MHD/Vis**, 3D, GR*

Ingredients For Modeling NSMs (and CCSNe)

- ✓ 6D neutrino transport
- ✓ nuclear EOS
- ✓ detailed weak interaction cross sections
- ✓ general relativistic effects
- ✓ magnetic fields
- ✓ sufficient (?) resolution
- ✓ ...

→ all combined only feasible with exa-scale computers (or even much bigger)

→ algorithms with reasonable compromise between accuracy and efficiency highly desired

"ALCAR" Neutrino Transport Module (OJ, Obergaulinger, Janka '15, MNRAS, 453, 3386)

Radiation-hydro with Boltzmann solver too expensive!

Our approach:

➔ **Spectral Two-moment scheme with algebraic Eddington factor (*AEF or M1 scheme*)**

$$E = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t) \quad \leftarrow \text{energy density}$$

$$F^i = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i \quad \leftarrow \text{momentum density}$$

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

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

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

$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\} \text{approximate algebraic closure relations (e.g. "M1 closure")}$$

(also several other realizations by Kuroda '15, O'Connor '15, Skinner '15, Foucart '15)

Algorithm Details

- **Advantages:**
  - effective save up of the two angular degrees of freedom
  - truly multidimensional instead of Ray-by-Ray(-plus)
  - computational costs: ~ hydro times # energy bins (more expensive with energy-bin coupling interactions)
  - since equations are hyperbolic they can be solved just like hydro-eq.
  - describes shadows better than FLD
  - better to parallelize than FLD, because advection is explicit in time

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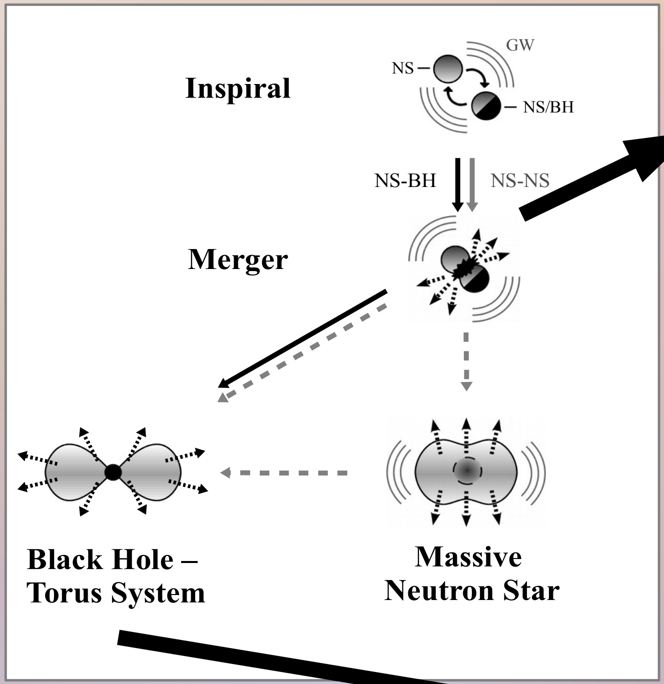
- **Disadvantages:**
  - less accurate for more complex geometries of radiation sources
  - AEF closure introduces non-linearity $\rightarrow$ light fronts interact with each other, unphysical shocks can develop ("two-beam instability")
  - accuracy for CCSNe and NSMs only partially explored so far

What and how many heavy elements are ejected in which phase of a NS-NS/BH merger?

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



NS-NS and NS-BH merger phase modeled with relativistic 3D code (without neutrinos) → Nucleosynthesis analysis of prompt ejecta

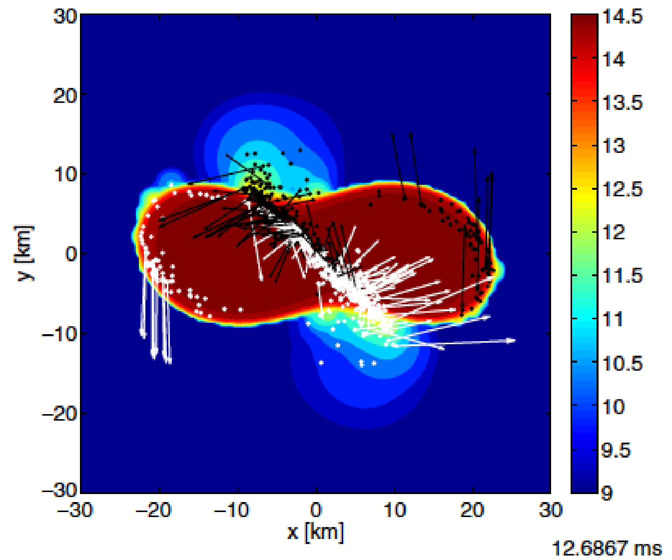
BH-torus phase modeled in 2D axisymmetry with spectral neutrino transport → Nucleosynthesis analysis of disk ejecta

Hydrodynamic simulations

Post-processing of ejecta

Dynamical Ejecta

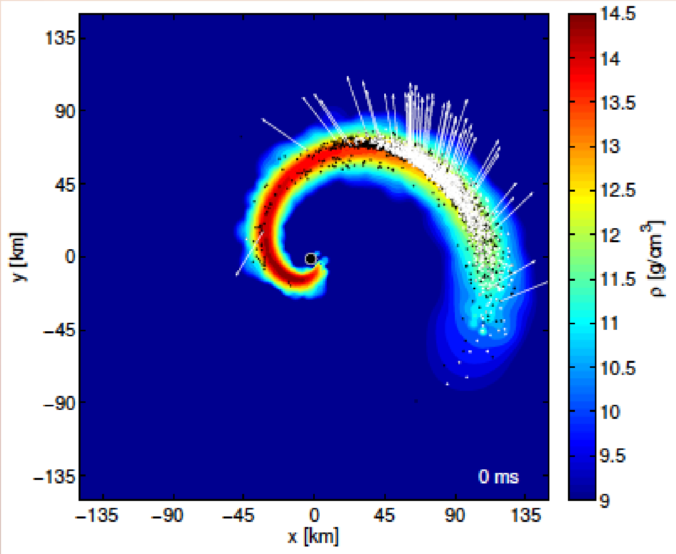
NS-NS

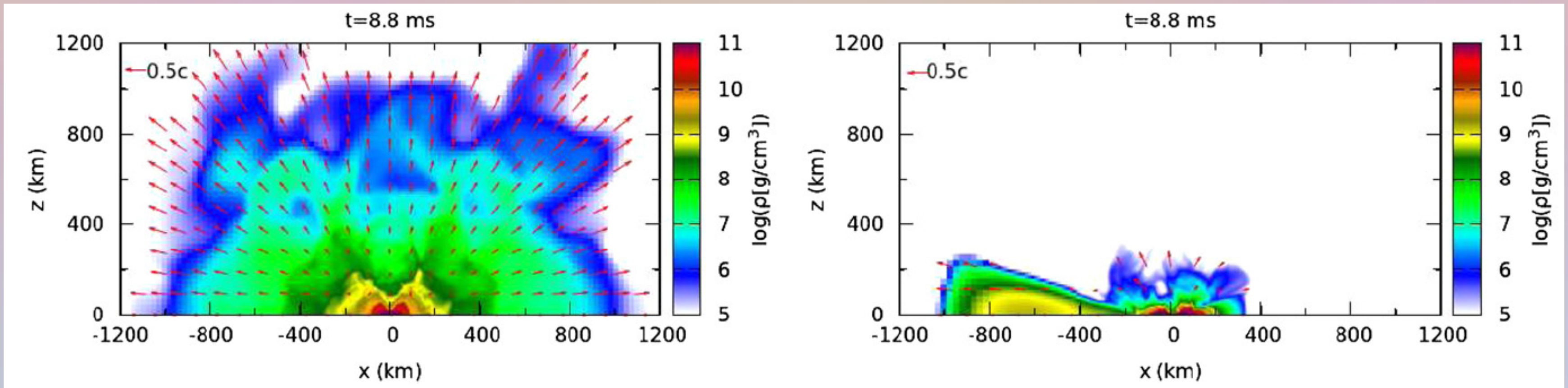


Typical properties:

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

NS-BH



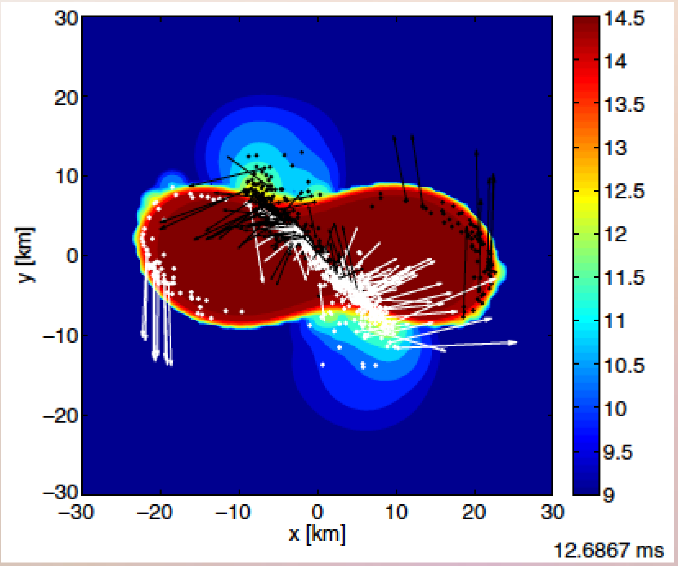


(Hotokezaka et. al. '13)

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

Dynamical Ejecta

NS-NS



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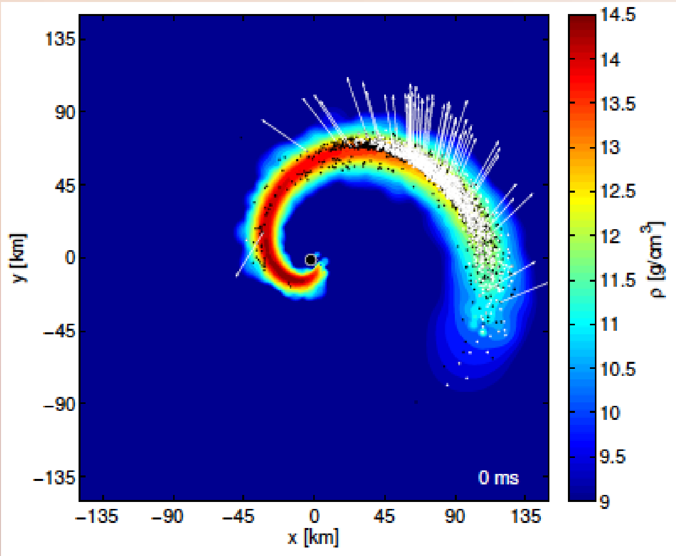
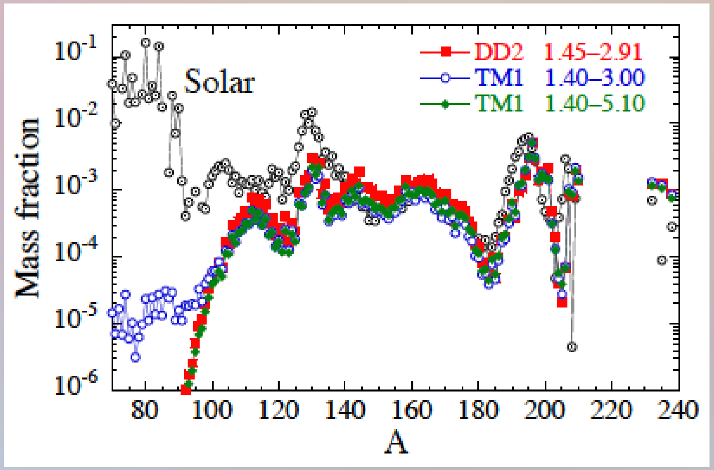
NS-BH



Typical nucleosynthesis pattern:

→ sub-solar for A < 140 (*)



→ solar-like for A > 140

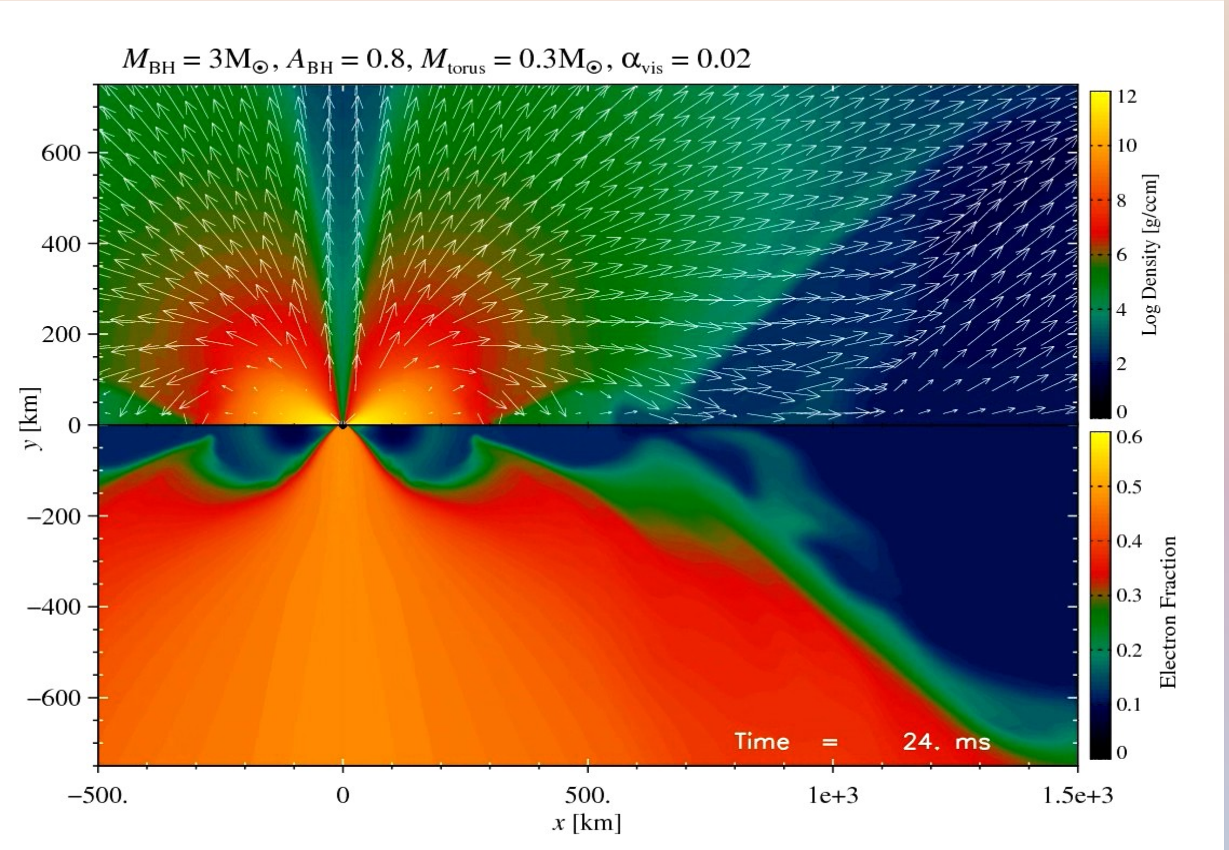
(* : Depends on neutrino treatment for NS-NS mergers)

Ejecta from BH-torus remnant

comparable to mass of dynamical ejecta!!!

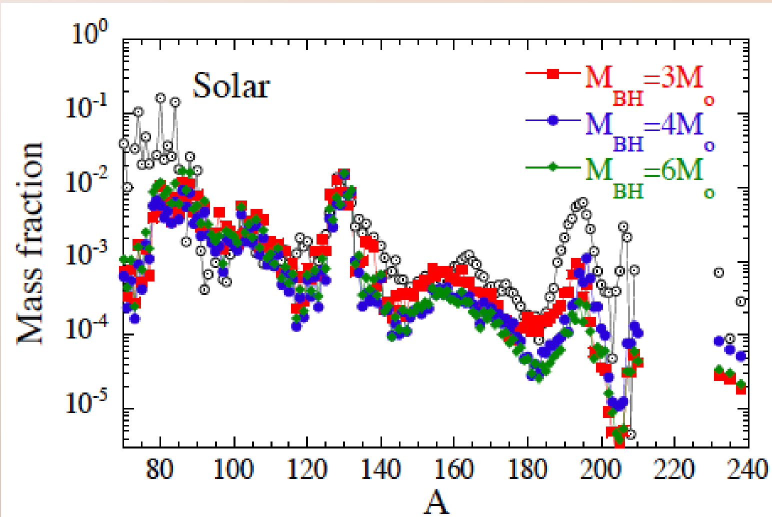
Typical properties:

- outflow masses: ~ 5-20% of initial disk 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

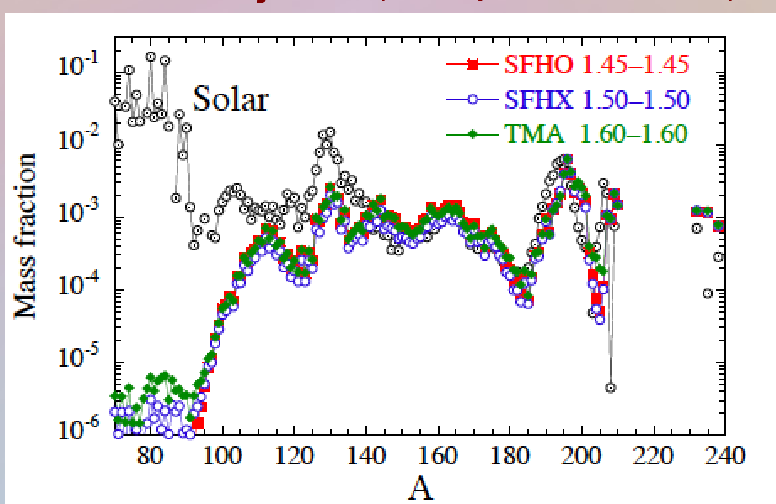


Combined nucleosynthesis yields

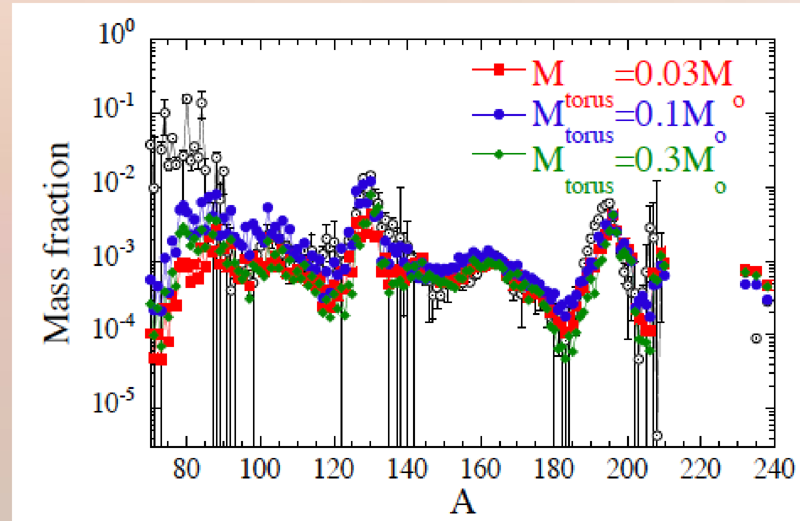
➔ DISK ejecta (mainly A ~ 90 - 140)



➔ PROMPT ejecta (mainly A ~ 140 - 210)



➔ DISK + PROMPT ejecta



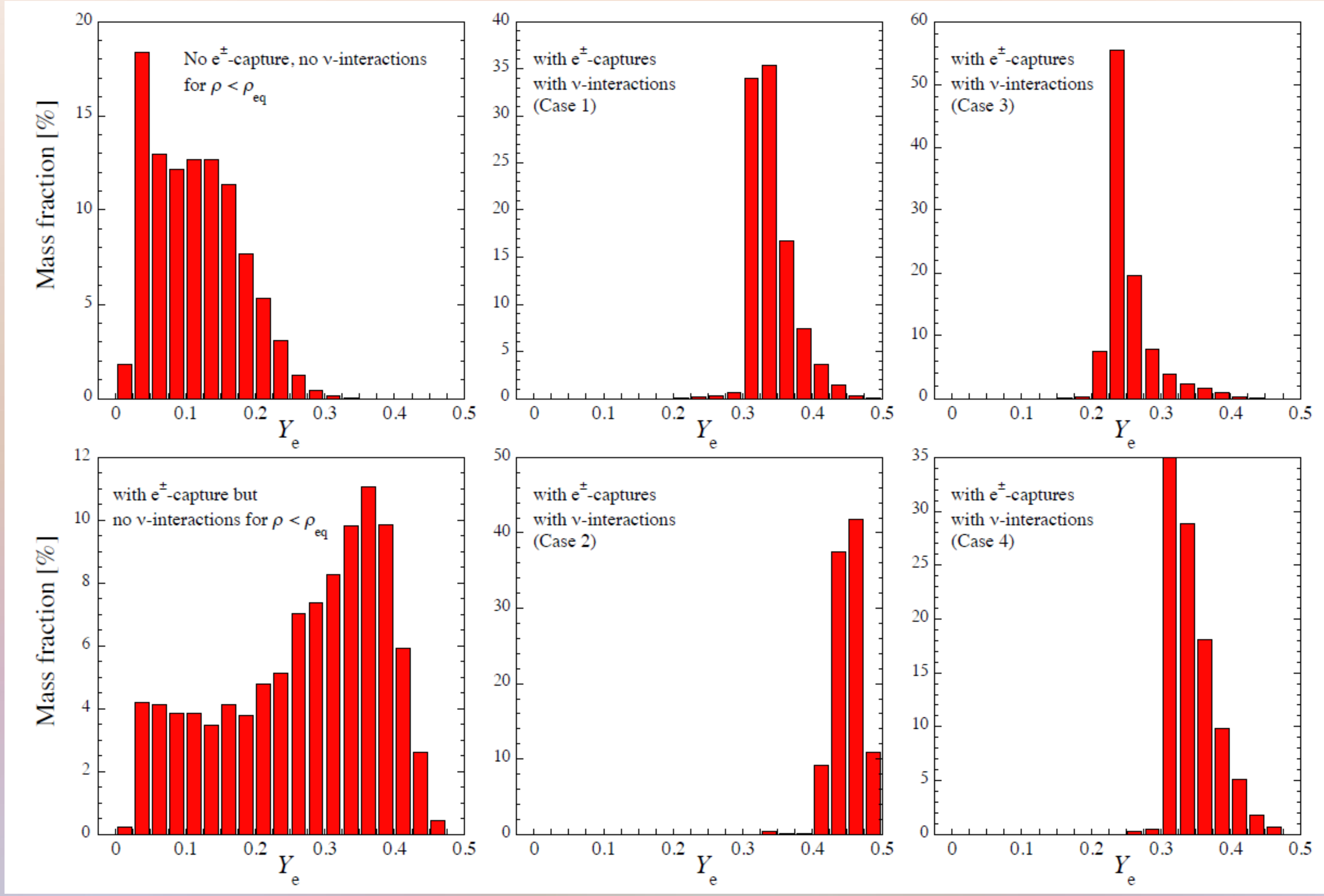
➔ nicely recovers the full mass range A > 90

➔ disk ejecta could be significant sources of intermediate mass elements with 90 < A < 140

➔ NS-remnant ejecta give similar pattern (Metzger+14, Perego+'14, Martin+'15)

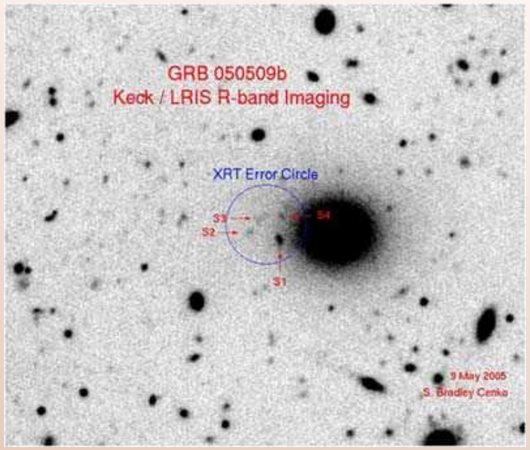
Impact of Weak Interaction on Dynamical Ejecta in NS-NS Mergers?

(Goriely, Bauswein, OJ, Pllumbi, Janka '15, MNRAS 452, 389)

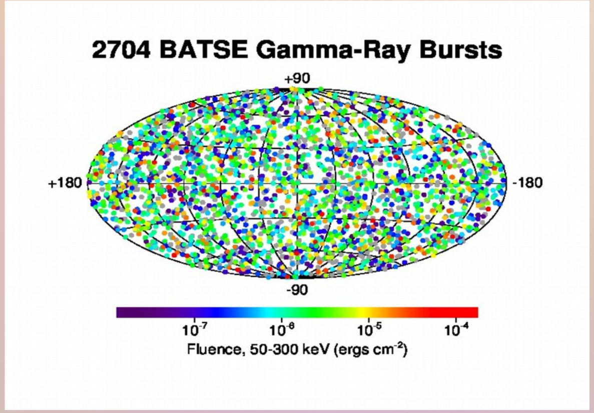


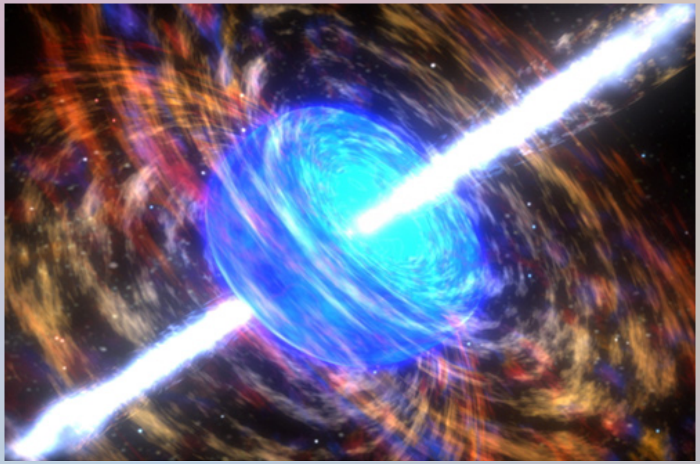
- ...can be quite significant!!! Dynamical ejecta may also produce lighter elements (consistent with Wanajo, Sekiguchi+'14,'15)
- more neutrino-transport simulations needed!

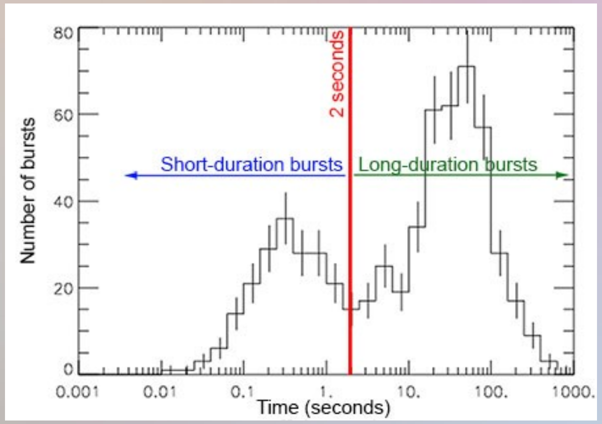
Gamma-Ray Bursts



- ➔ 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





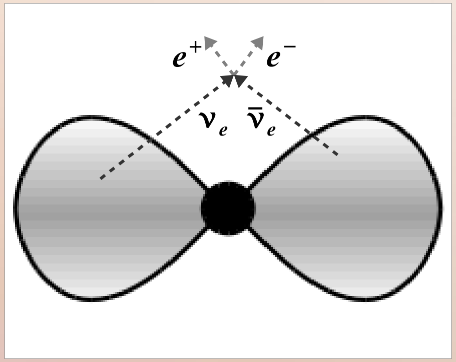


(NASA)

Popular central engine scenarios

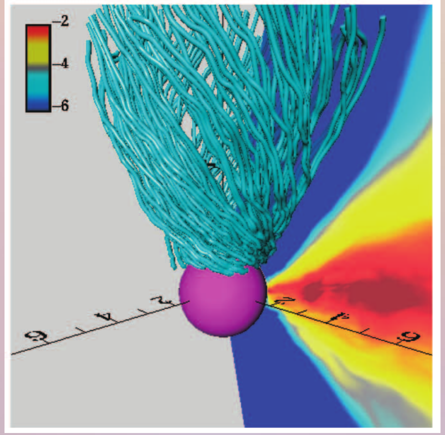
➔ neutrino-pair annihilation

- 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?



➔ Blandford-Znajek process

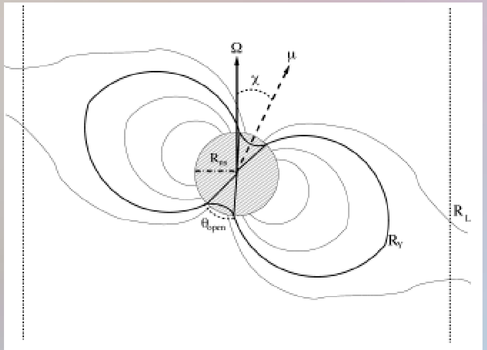
- B-field taps rotation energy of central BH
  → Poynting-dominated jet
- efficient only for large-scale poloidal B-fields
- can large-scale fields be produced and sustained? MRI? Dynamo?



(Hirose+ '04)

➔ magnetar spin-down emission

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



(Metzger+ '11)

Is neutrino annihilation alone powerful enough to explain all sGRBs?

(Just+ '16, ApJL 816, 30)

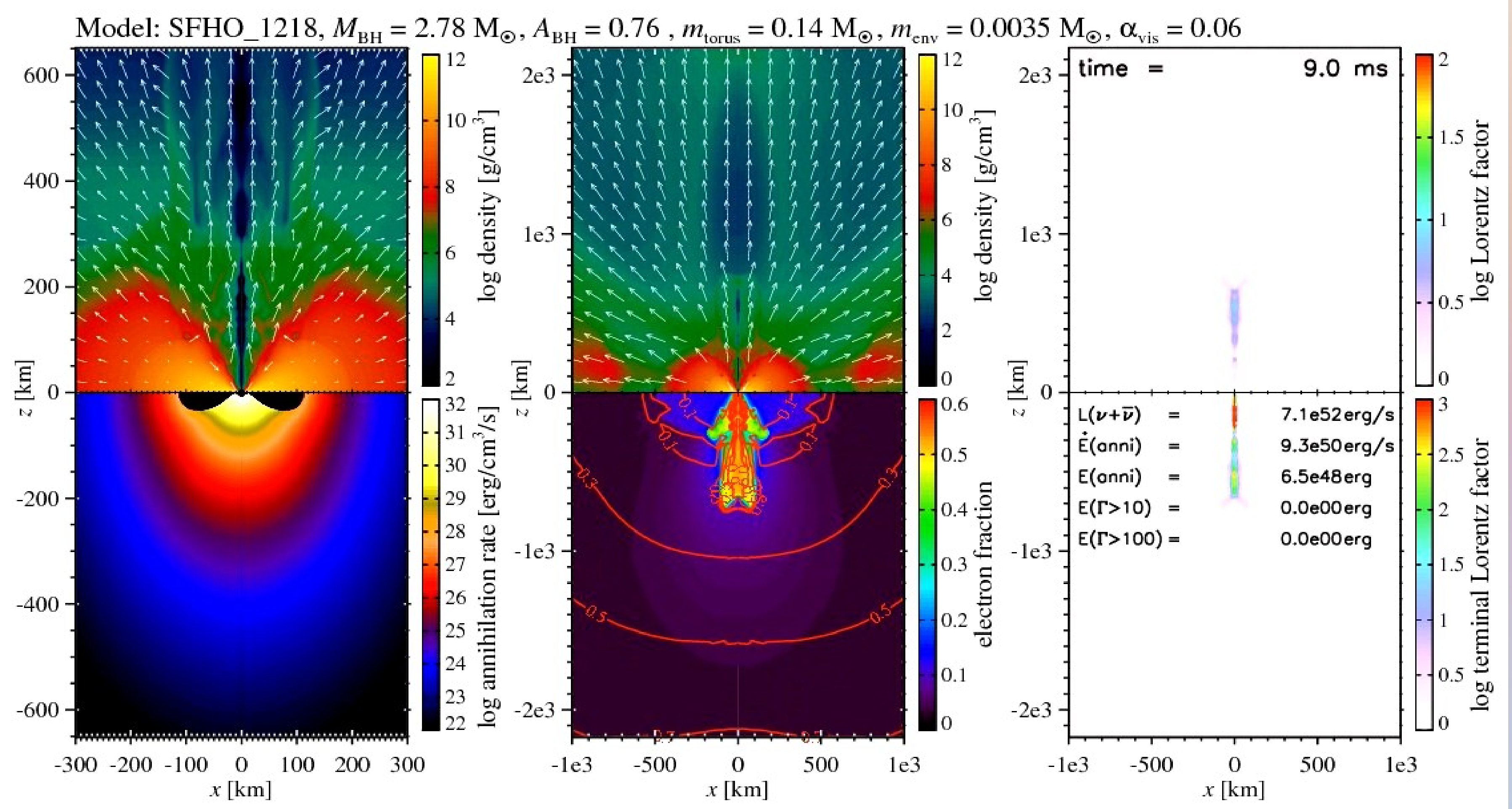
- properties of observed sGRB jets:
  energies **~10^{48}–10^{50} erg** and Lorentz factors **Γ>10-100**

- Are necessary condition(s) fulfilled?:
  - sufficient energy provided by nu-annihilation *and / or*
  - sufficiently small energy loss during expansion

- What is the impact of the dynamical ejecta on the jet?

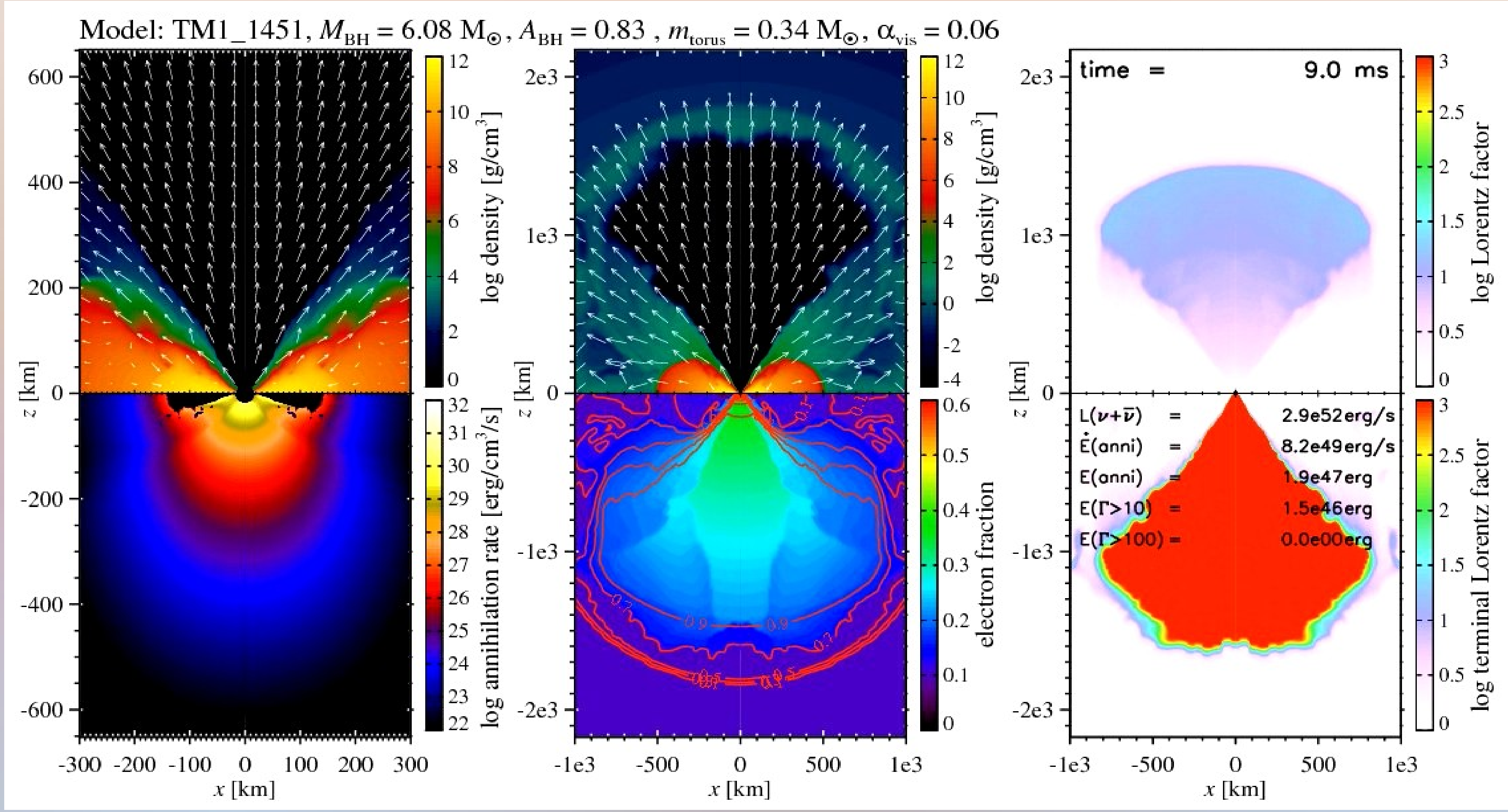
NS-NS Merger

- 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

- several types of ejecta with large spread in Ye, s, v
- each component with characteristic abundance pattern and Kilonova signal
- each component potentially relevant for chemogalactic evolution
- so far only tidal ejecta have robustly predictable nucleosynthesis
- large uncertainties for other components
- post-merger ejecta probably dominantly produce intermediate mass elements
- sGRB jet probably not launched by neutrino-annihilation alone
- *better modeling of neutrino transport combined with MHD, GR needed!*

Thank you for your attention!