Ejecta from Neutron-Star Mergers: Nucleosynthesis and Expansion Dynamics

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With: H.-Th. Janka, S. Goriely, A. Bauswein, R. Ardevol, M. Obergaulinger, N. Schwarz, C. Weinberger and others

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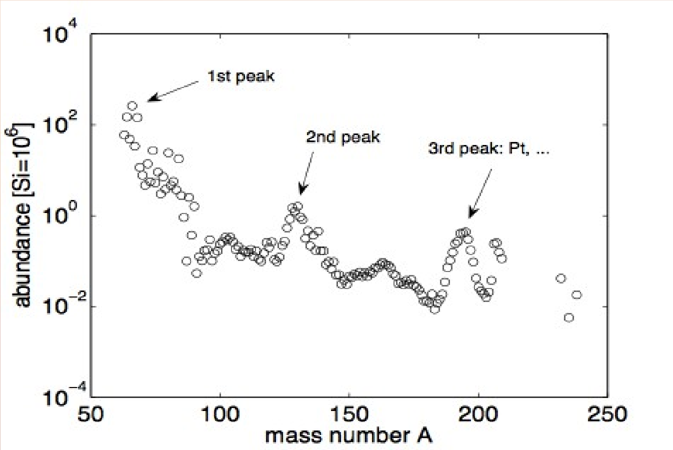
Motivation

1) Origin of r-process elements still unknown!

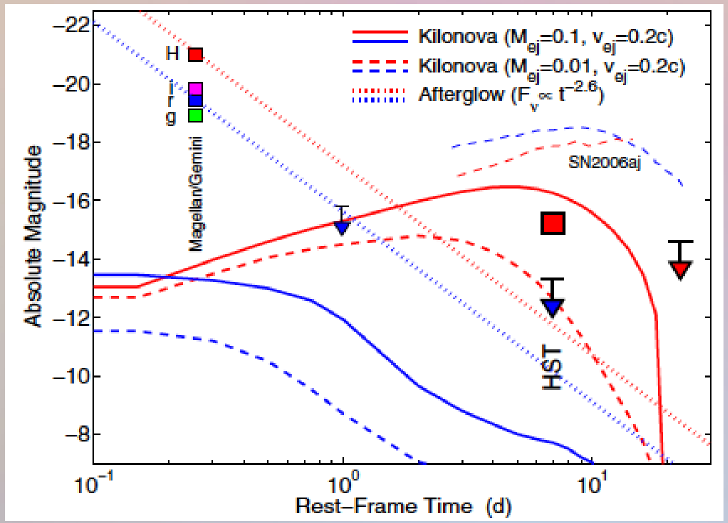
- **NS-mergers** seem to give favorable conditions
- still many uncertainties
- mostly only dynamical ejecta considered so far
- remnant evolution inevitably needs neutrino treatment



observed solar r-process abundance (Goriely '99)

2) Ejecta could be observable as short GRB, Kilonova, radio-transient etc.!

- observations provide information about the progenitor system, outflow mechanism, nuclear EOS etc.
- possibly first Kilonova already measured ⟶
- most Kilonova models concentrate only on single type of ejecta (mostly dynamical ejecta)
- what is the GRB jet launching mechanism?



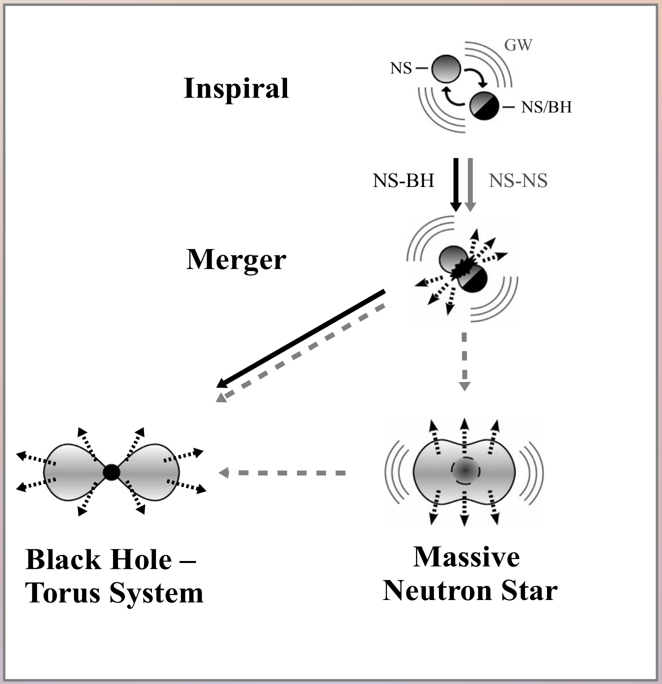
(Berger et. al. 2013)

Nucleosynthesis study

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

Main Question:

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



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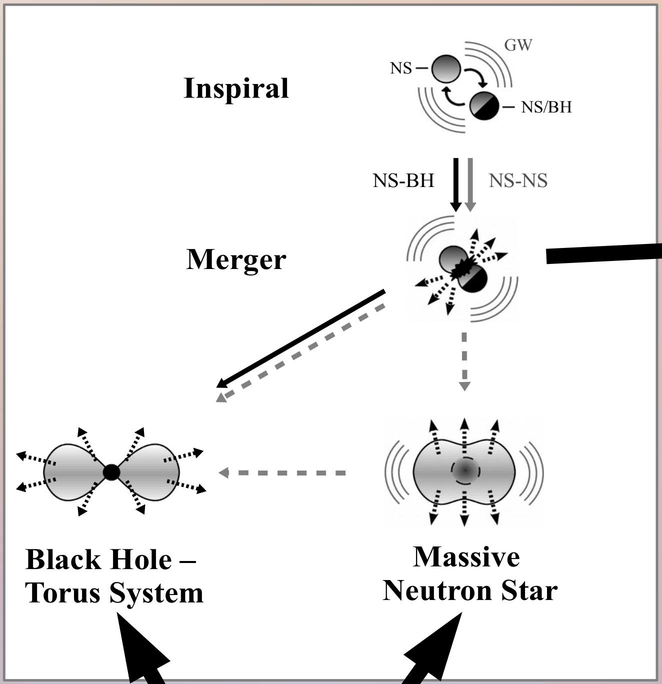

prompt / dynamical ejecta

ejecta due to neutrino heating, magnetic fields, viscous heating, (...)

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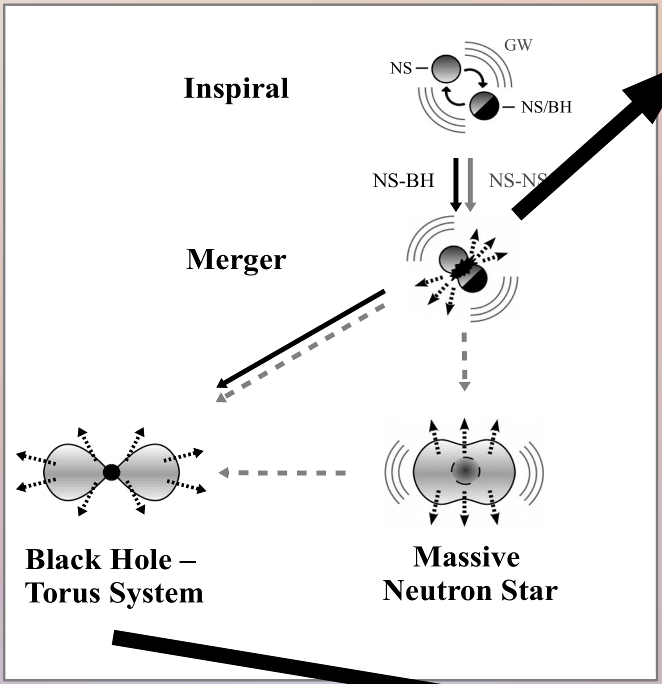


NS-NS and NS-BH merger phase modeled with CFC relativistic 3D SPH code (without neutrinos)

→ Nucleosynthesis analysis of prompt ejecta

Hydrodynamic simulations

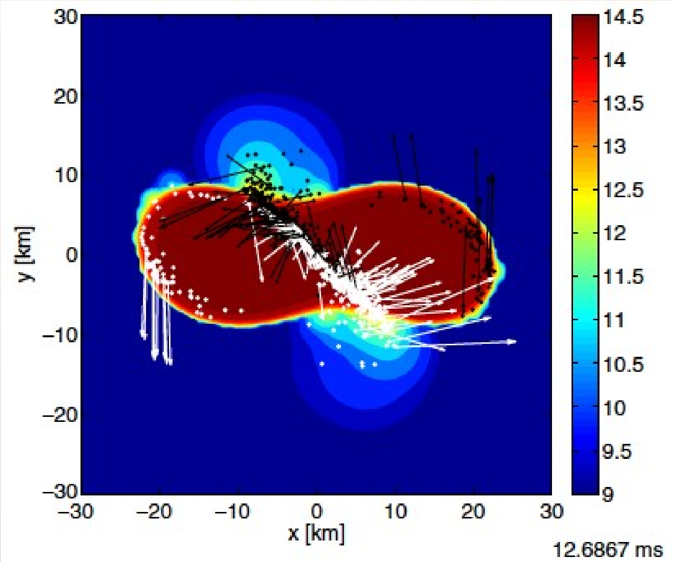
Post-processing of ejecta

BH-torus phase modeled with finite-volume neutrino-hydrodynamics code, global parameters consistent with merger simulations

→ Nucleosynthesis analysis of disk ejecta

Prompt/Dynamical Ejecta

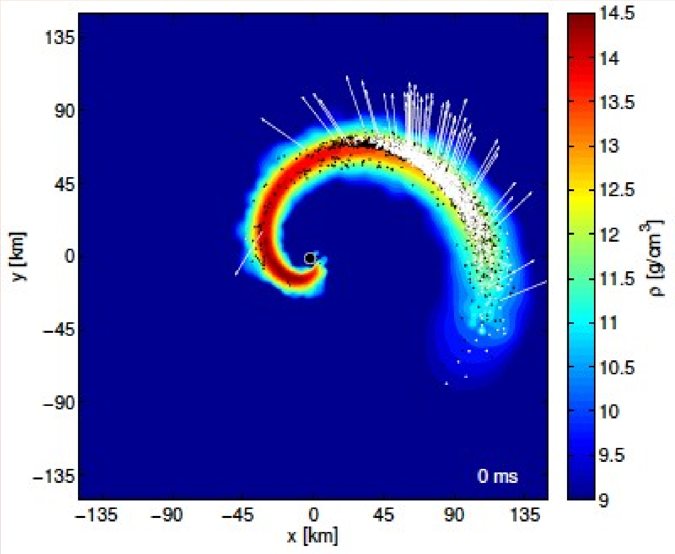
NS-NS



Typical outflow properties:

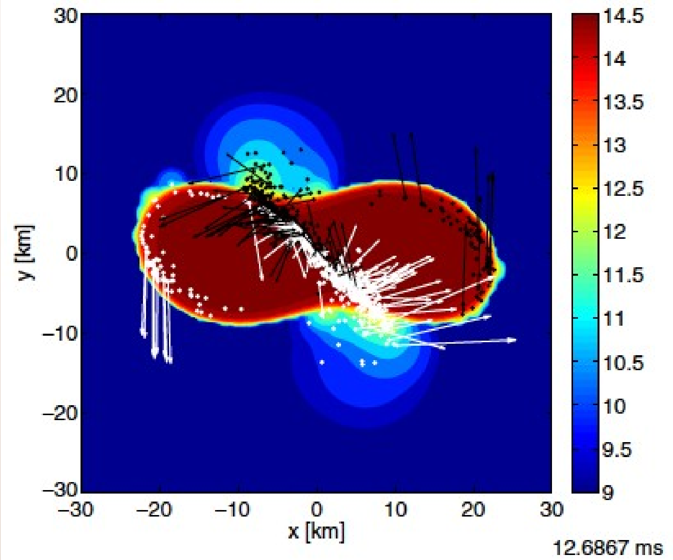
- outflow masses:
  ~ 0.001 – 0.1 Msun
- electron fraction:
  Ye < 0.1
- entropy per baryon:
  s ~ 1 – 30 kB
- velocity:
  v ~ 0.2 – 0.4 c

NS-BH



Prompt/Dynamical Ejecta

NS-NS



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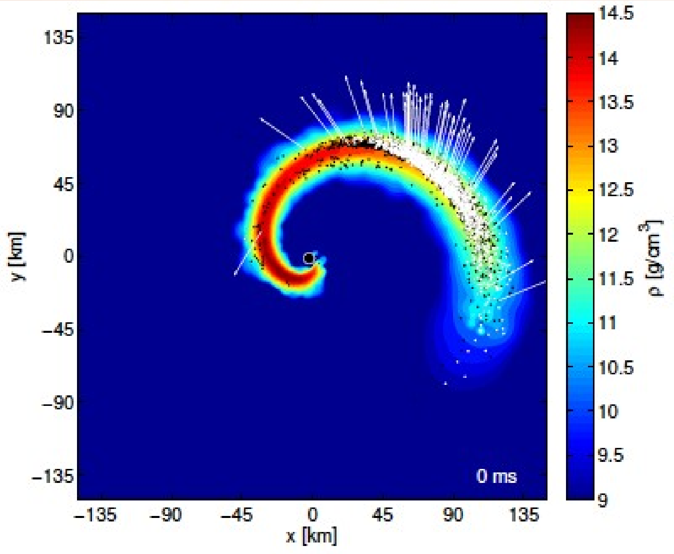
NS-BH

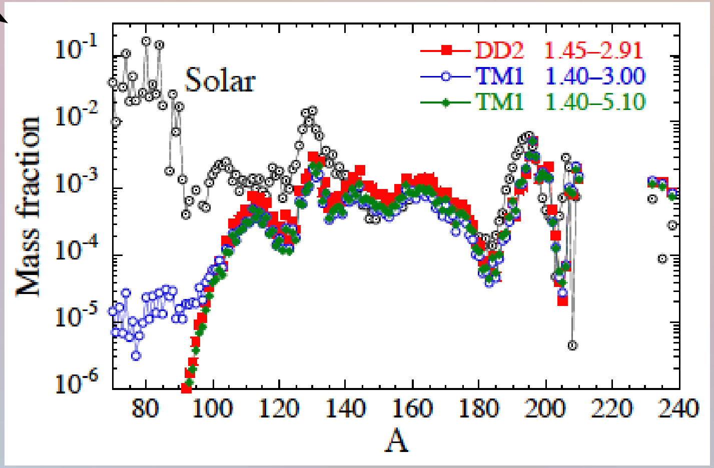


Typical nucleosynthesis pattern:

➔ sub-solar for A < 140

However, for ***NS-NS*** *case neutrino effects could* ***rise*** *Ye and result in* ***higher abundances for A<140!***

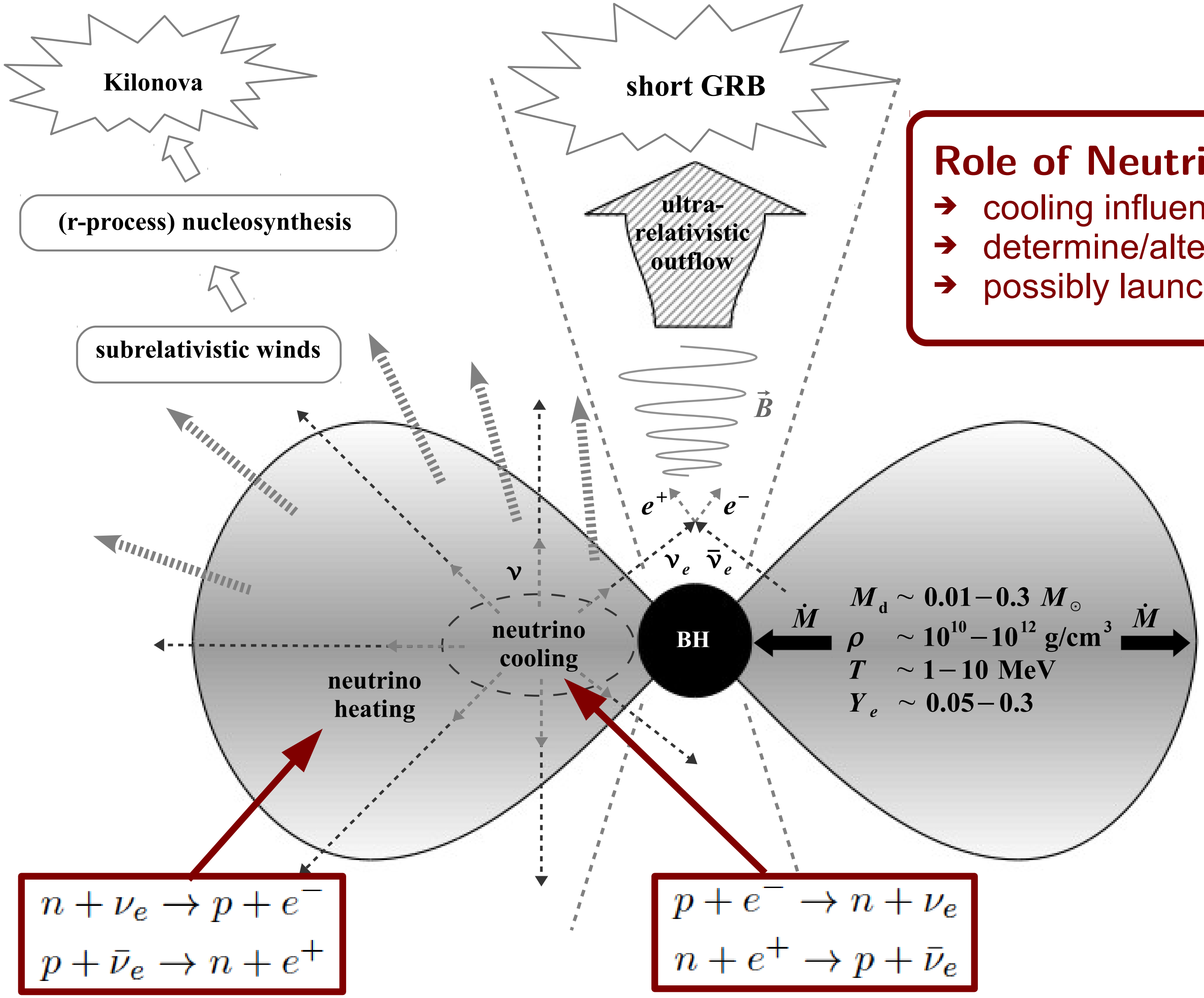
→ See Wanajo+ '14, Sekiguchi+15, Goriely+ '15 and talks by Thomas, Masaru



➔ solar-like for A > 140

Post-Merger BH-Torus

(short after its formation)



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

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

Role of Neutrinos:

- ➔ cooling influences accretion dynamics!
- ➔ determine/alter Ye in outflows!
- ➔ possibly launch/contribute to GRB jet!

Neutrino Transport Scheme

(OJ, Obergaulinger, Janka '15, ArXiv:1501.02999)

Full Boltzmann equation too expensive!

Our approach:

- **Two-moment scheme with algebraic Eddington factor (aka *M1 scheme*)**

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

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

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

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

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

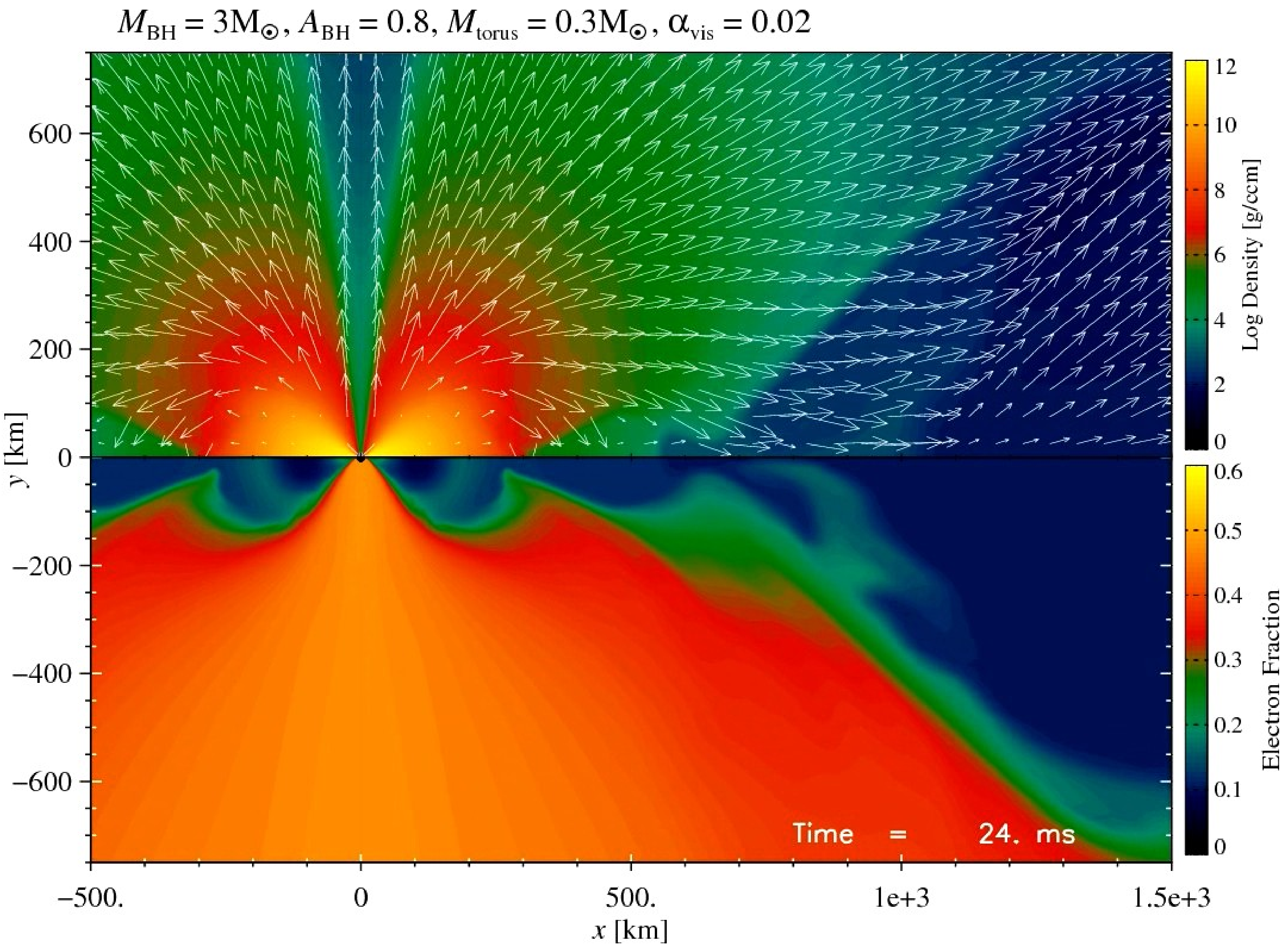
$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\} \quad \textbf{approximate algebraic closure relations (e.g. "M1 closure")}$$

Effective save up of the two angular degrees of freedom!

Setup of BH-Torus Models

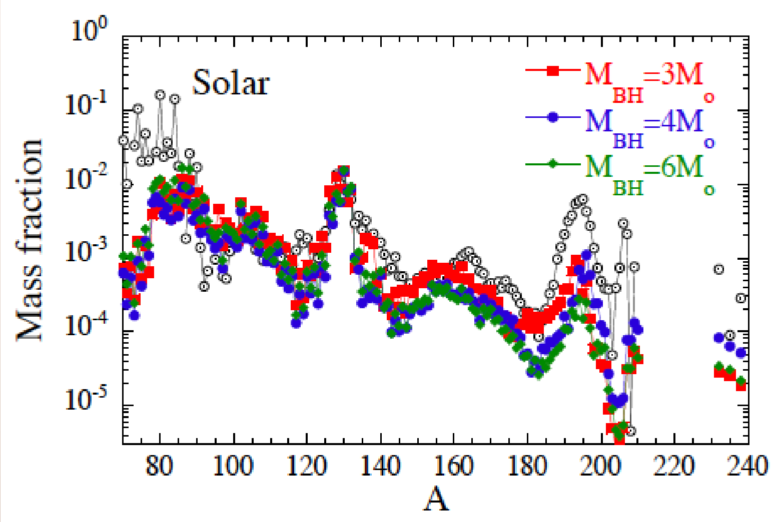
- multi-group neutrino transport with **10 energy groups**
- most dominant **neutrino interactions** included:
  - ✔ *emission/absorption by nucleons*
  - ✔ *neutrino-nucleon scattering*
  - ✔ *neutrino-antineutrino annihilation*
- Newtonian hydrodynamics **with pseudo-Newtonian** gravitational potential → mimics the ISCO and BH spin
- angular momentum transport: Shakura & Sunyaev **α-viscosity**
- variation in M_{torus}, M_{BH}, α (adapted to merger simulations)
- simulations performed in **2D axisymmetry**

Movie: BH-torus system

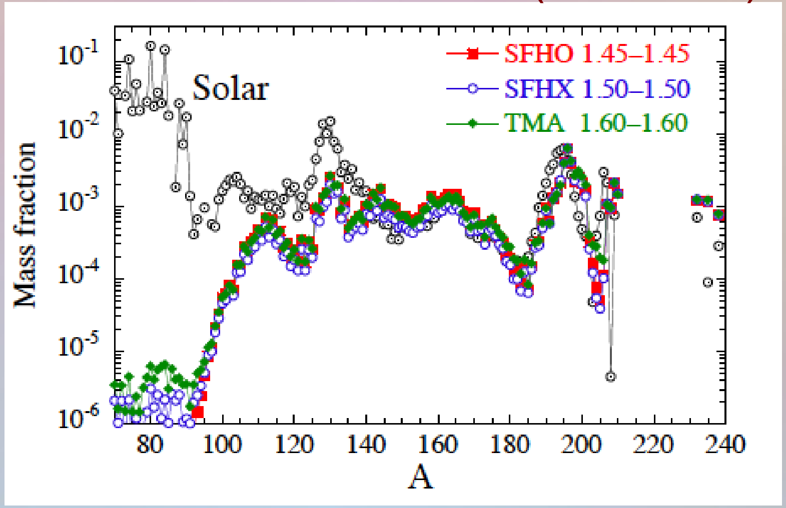


Combined Nucleosynthesis Yields

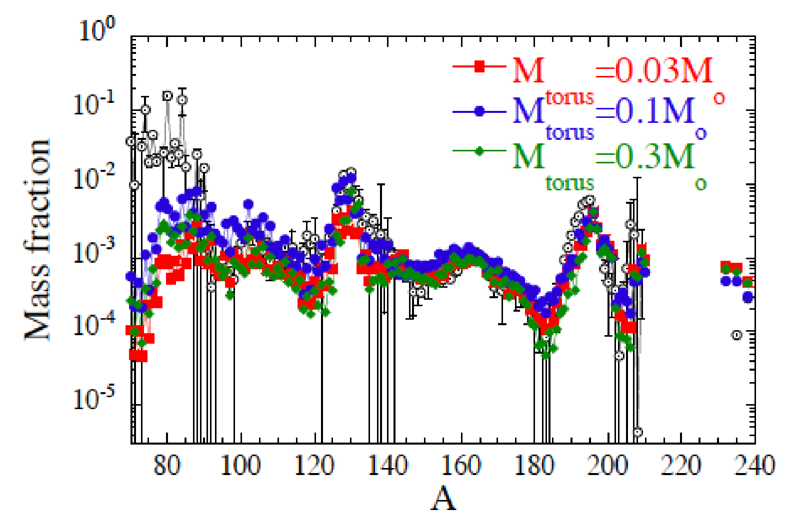
➔ DISK ejecta: Ye = 0.1 - 0.3
M ~ O (1% Msun)



➔ PROMPT ejecta: Ye < 0.1
M ~ O (1% Msun)



➔ DISK + PROMPT ejecta



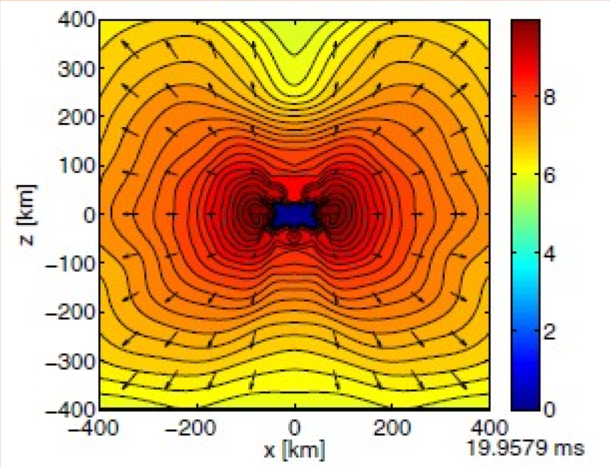
➔ nicely recovers the **full mass range** A > 90

➔ BH-torus systems could **significantly contribute** intermediate mass elements 90 < A < 140 to the r-element repertoire in the universe

➔ not considered here: additional contribution from (H)MNS → see Metzger, Fernandez '13,'14 and Perego '14, see talk by Brian

Long-term ejecta dynamics:
Include dynamical ejecta in BH-torus simulations

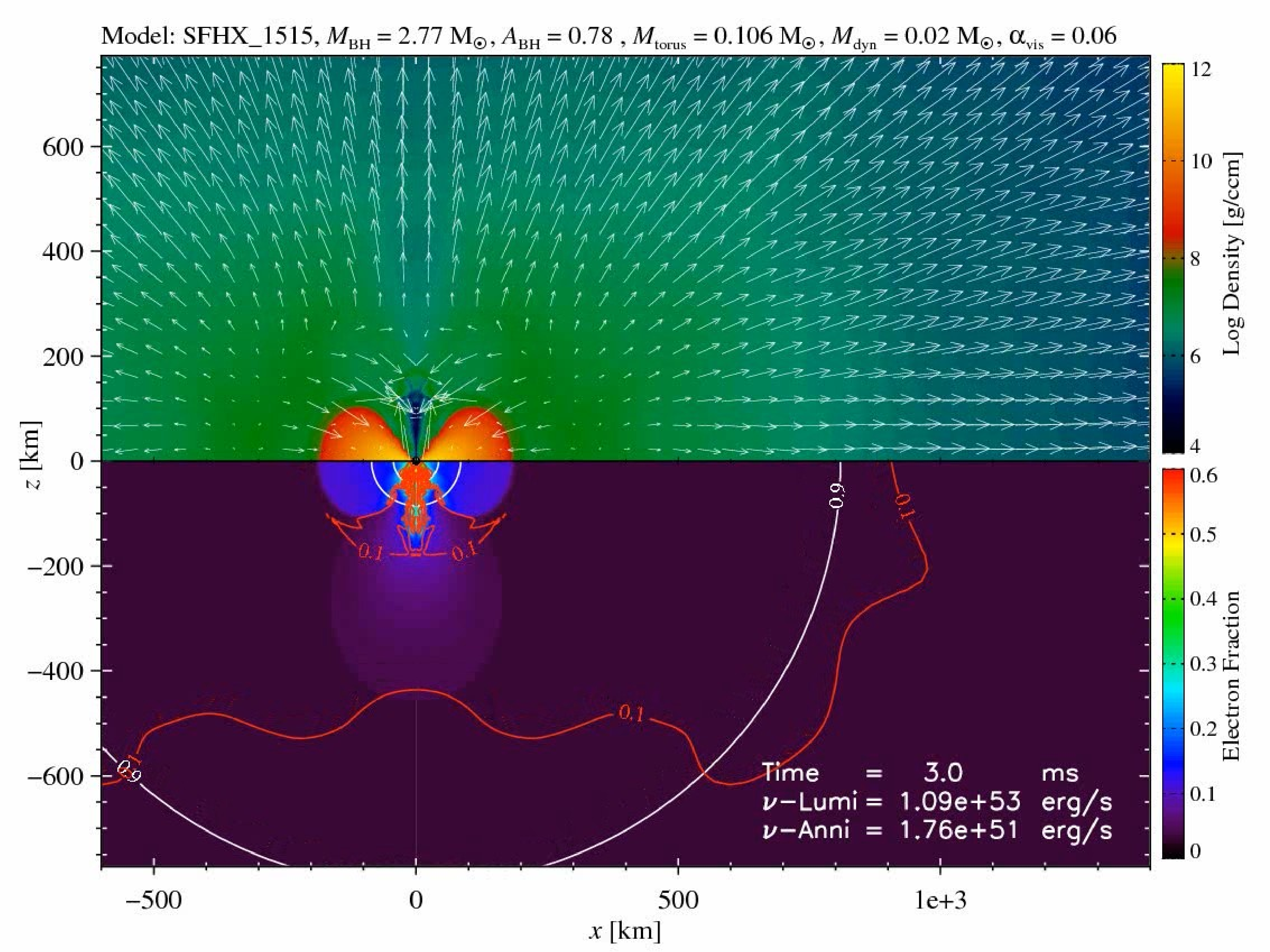
- dynamical ejecta are quasi-spherical
- data for dynamical ejecta mapped from SPH onto 2D grid to be evolved together with BH-torus systems
- extend EOS to low densities, include electron recombination, radioactive heating



(Bauswein et. al. '13)

Merger model	M_1 [$M_\odot$]	M_2 [$M_\odot$]	$A_{\mathrm{BH},0}$	EOS	pc/dc	M_{BH} [$M_\odot$]	A_{BH}	M_{torus} [$M_\odot$]	M_{dyn} [$10^{-3}\,M_\odot$]	B_{asy}	$\overline{Y}_e$	$\bar{s}/k_{\mathrm{B}}$	$\bar{v}$ [10^{10} cm/s]
SFHO_1218	1.2	1.8		SFHO	pc	2.78	0.76	0.137	4.9	0.28	0.036	9.9	1.19
SFHO_13518	1.35	1.8		SFHO	pc	2.97	0.78	0.099	4.3	0.16	0.036	6.7	1.28
SFHX_1515	1.5	1.5		SFHX	dc	2.77	0.78	0.106	21.2	0.01	0.032	8.2	0.67
SFHO_145145	1.45	1.45		SFHO	dc	2.68	0.79	0.091	14.3	0.02	0.033	7.9	0.64
TM1_175175	1.75	1.75		TM1	pc	3.37	0.85	0.027	8.4	0.07	0.027	10.0	1.12
TMA_1616	1.6	1.6		TMA	dc	3.04	0.83	0.037	5.2	0.07	0.012	5.4	0.62

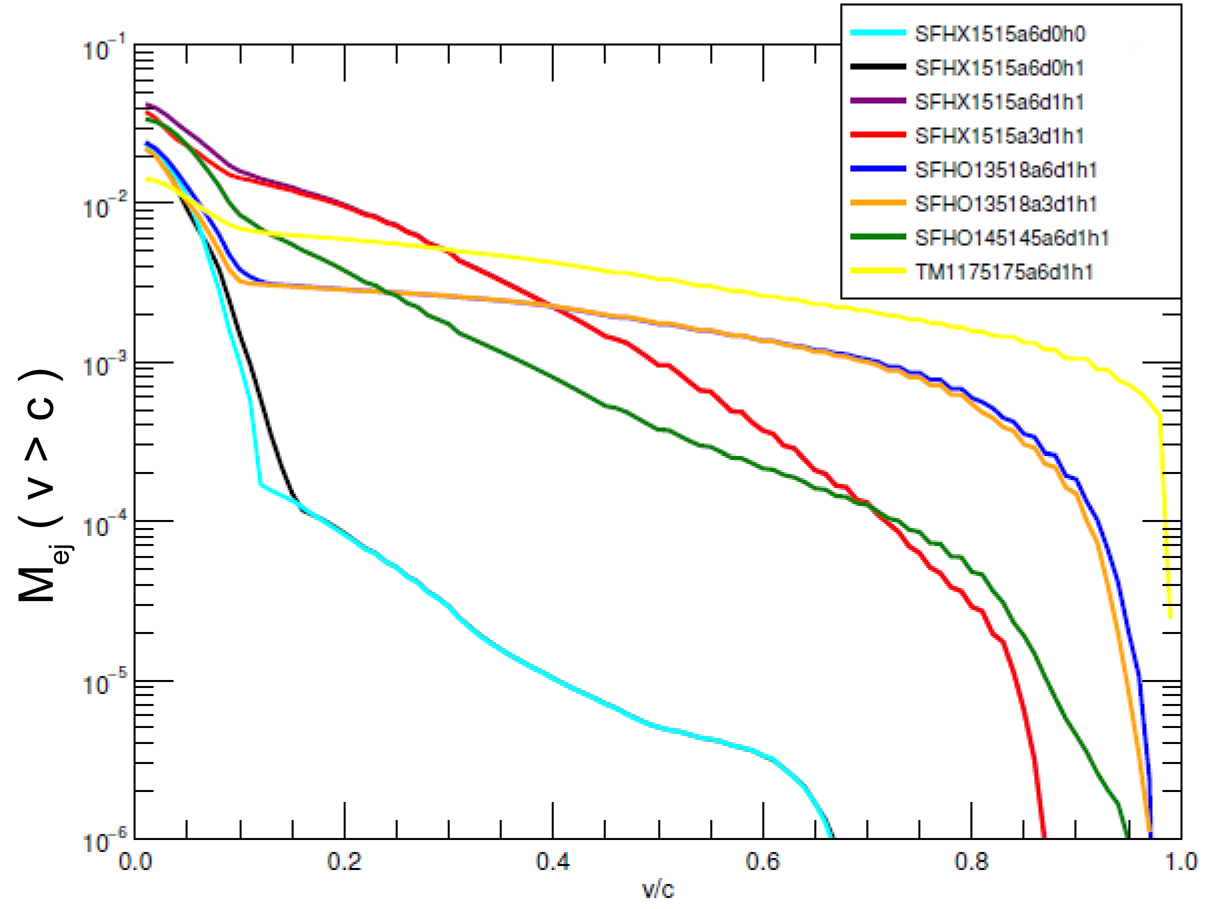
Movie: BH-torus with dynamical ejecta



Long-term ejecta dynamics

- bulk of dynamical ejecta faster than bulk of torus ejecta
- interaction is small, dynamical ejecta “cloak” torus ejecta
- dynamical ejecta shell may act as “Lanthanide curtain” (Kasen+ '14)

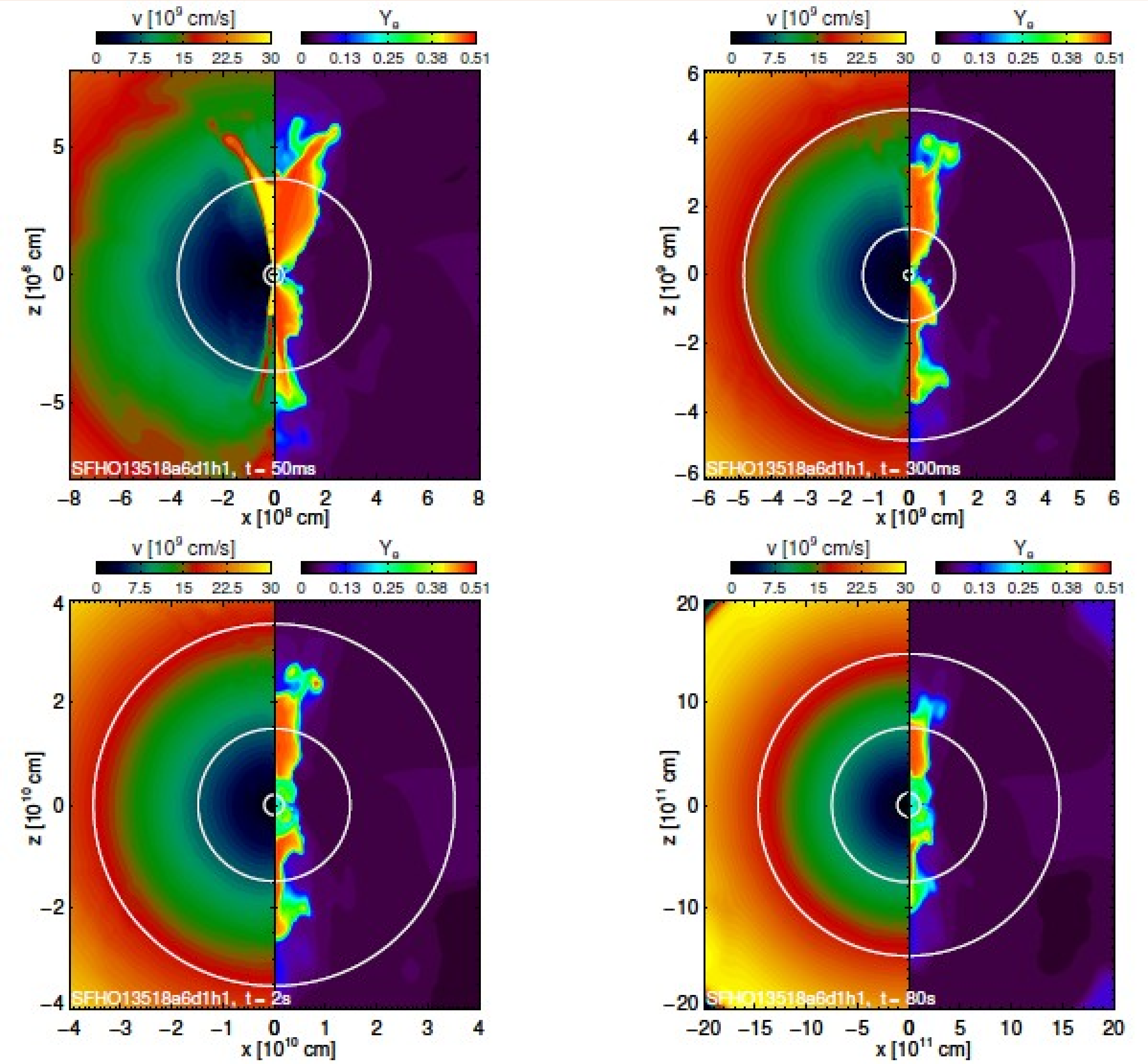
velocity distribution of ejecta



(N. Schwarz, master thesis)

Long-term ejecta dynamics

- only neutrino-driven component drills (partially) through dyn. ej.
- but not energetic enough to become highly relativistc
- preliminary result: nu-annihilation probably not energetic enough to explain short GRB jet!

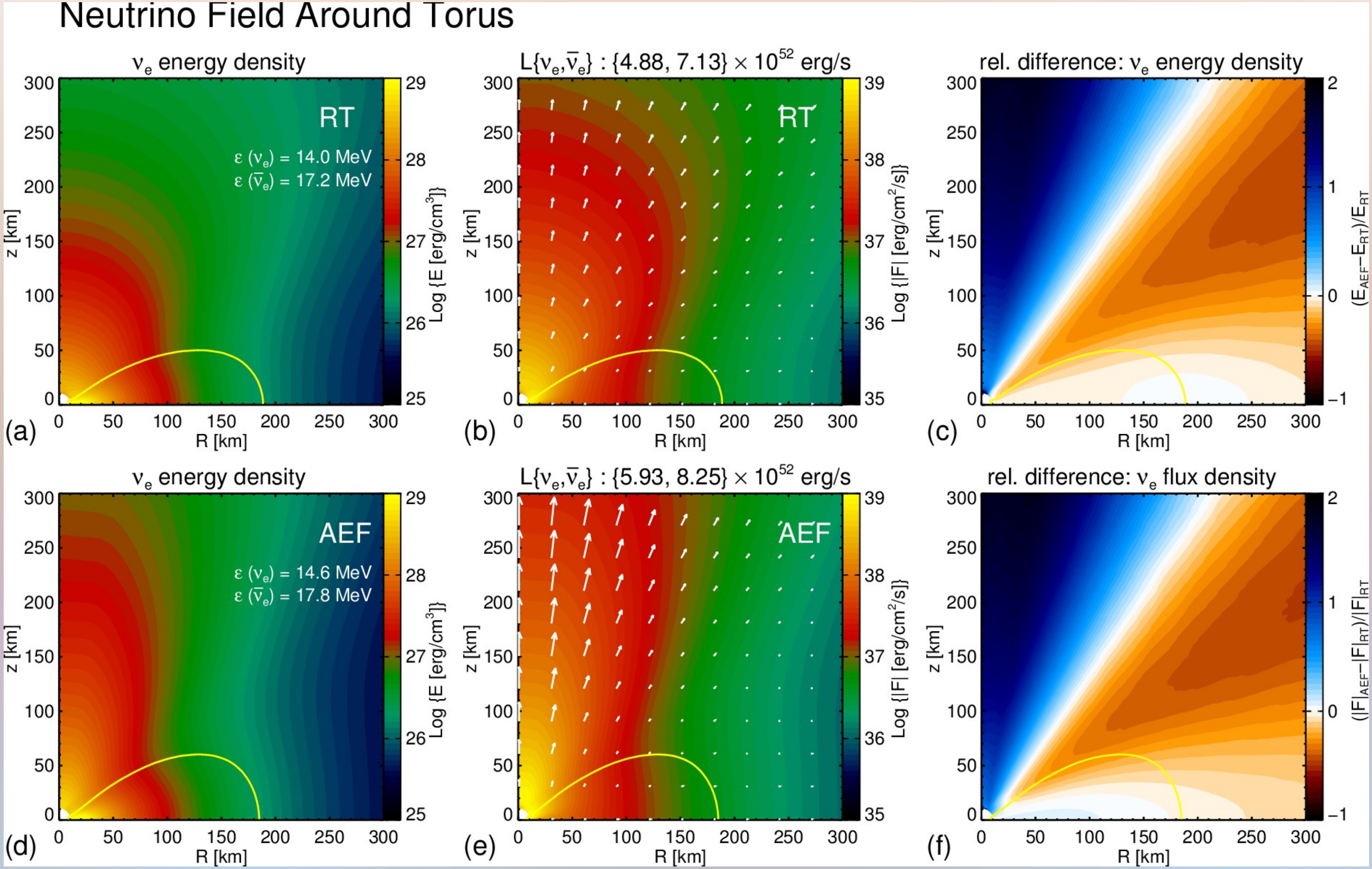


(N. Schwarz, master thesis)

Summary

- we examined NS-NS, NS-BH mergers with BH-torus remnants
- dynamical ejecta → more neutron-rich → heaviest elements
- BH-torus ejecta with masses comparable to dynamical ejecta → moderately neutron-rich → intermediate mass elements
- *results support idea that NS mergers could be main productions sites for all elements $90 < A < 240$!*
- we consistently evolved dynamical ejecta together with BH-torus system
- surrounding shell of dynamical ejecta evolve faster and mainly decoupled from torus ejecta
- only small amount of neutrino-driven ejecta partially penetrates dynamical ejecta
- ***preliminary** results indicate that neutrino-annihilation not powerful enough to give rise to GRB jet*

Appendix: Test of Neutrino Scheme



Appendix: Test of Neutrino Scheme 2