Combined Analyses of Outflows from Neutron-Star Mergers

Oliver Just
Max-Planck-Institut für Astrophysik

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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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for Astrophysics

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Gravitational Wave Astronomy
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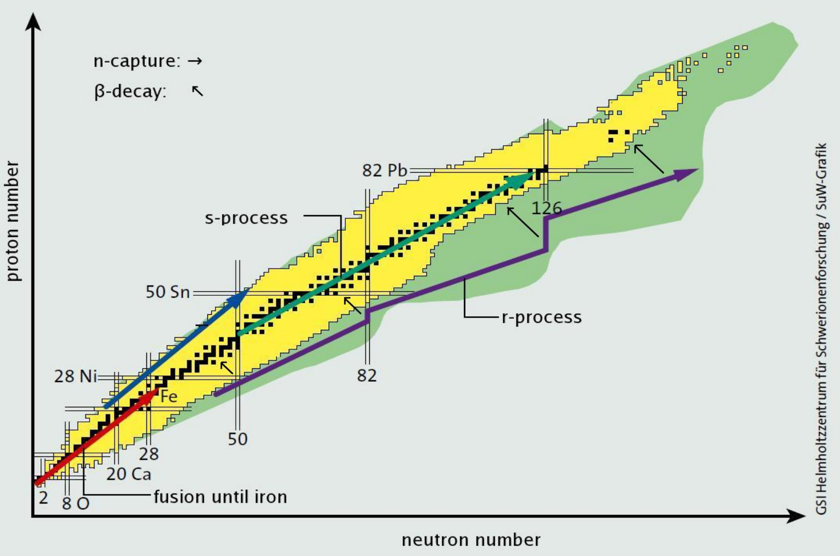
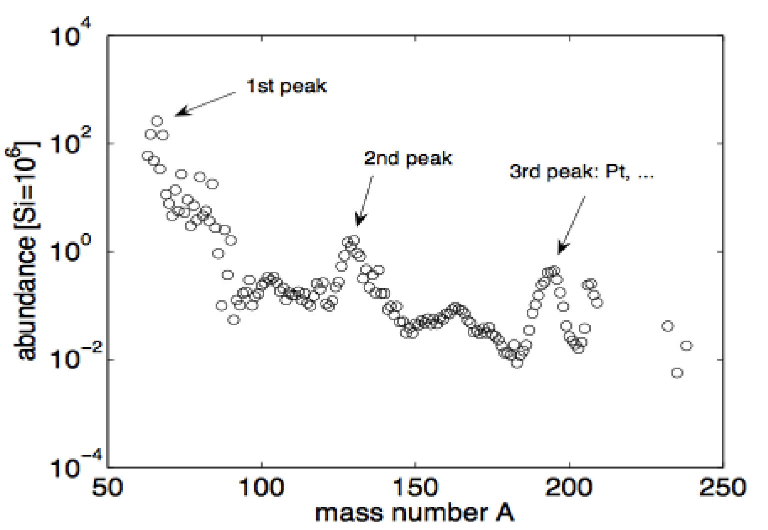
Why Study Outflows of NS-Mergers?

1) NS-mergers could be main / significant source of r-process elements in the universe!

➔ the nucleosynthesis process is identified: ***rapid neutron capture process***





Observed solar r-process abundance

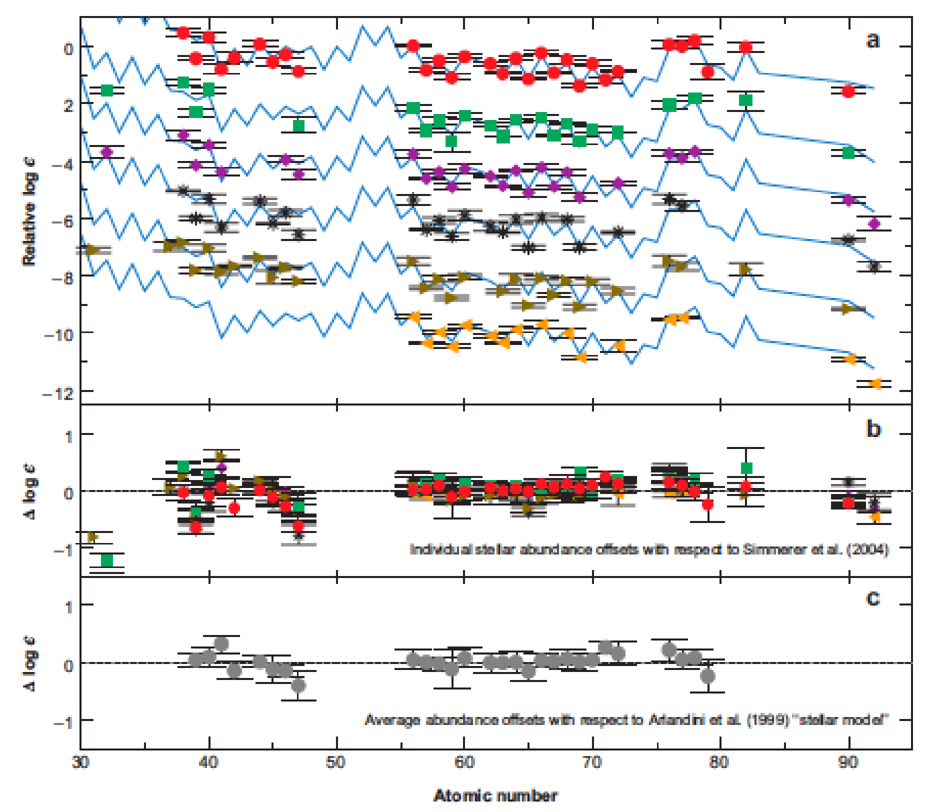
➔ **BUT: astrophysical site(s) not clearly identified so far!**

➔ winds from CCSNe are not neutron-rich enough and have too low entropies (at least for strong r-process)

Why Study Outflows of NS-Mergers?

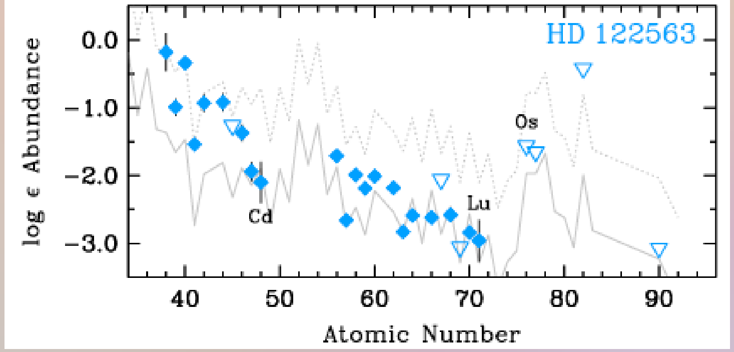
1) NS-mergers could be main / significant source of r-process elements in the universe!

"typical" observed pattern



➔ very robust for heavy, while larger scatter for lighter elements

… but exceptions exist



➔ typical in lighter, but deficient in heavier elements

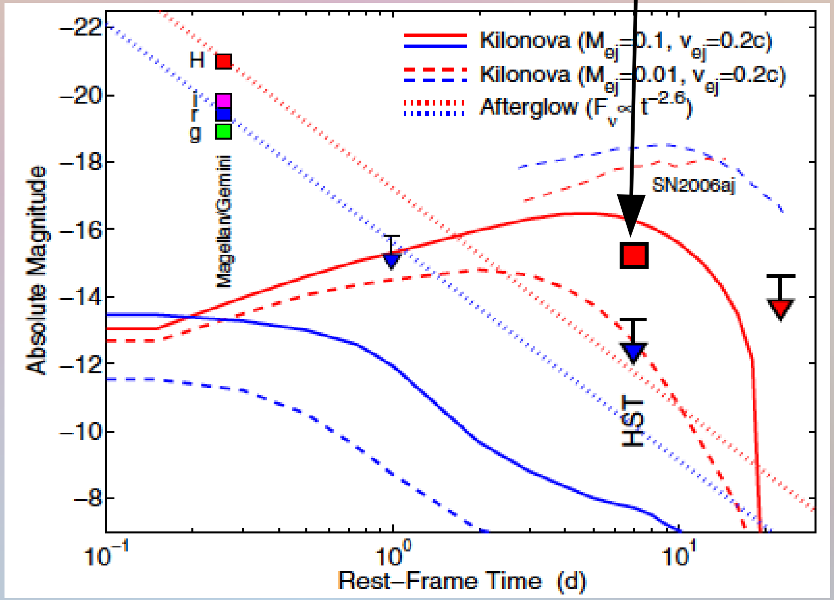
(Plots from Sneden '08)

Why Study Outflows of NS-Mergers?

2) NS mergers could be visible in optical and infrared!
("Kilonova" / "Macronova")

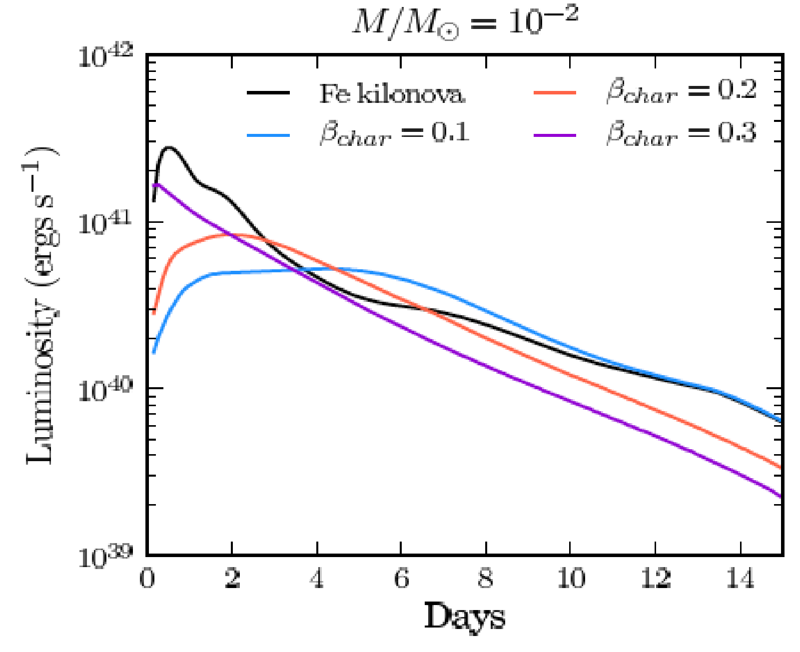
(Li&Paczynski, Kulkarni, Metzger)

- ➔ radioactive decay heats material
→ causes electromagnetic transient on
on timescale of several days
- ➔ possibly first Kilonova already measured
(Berger '13, Tanvir '13)



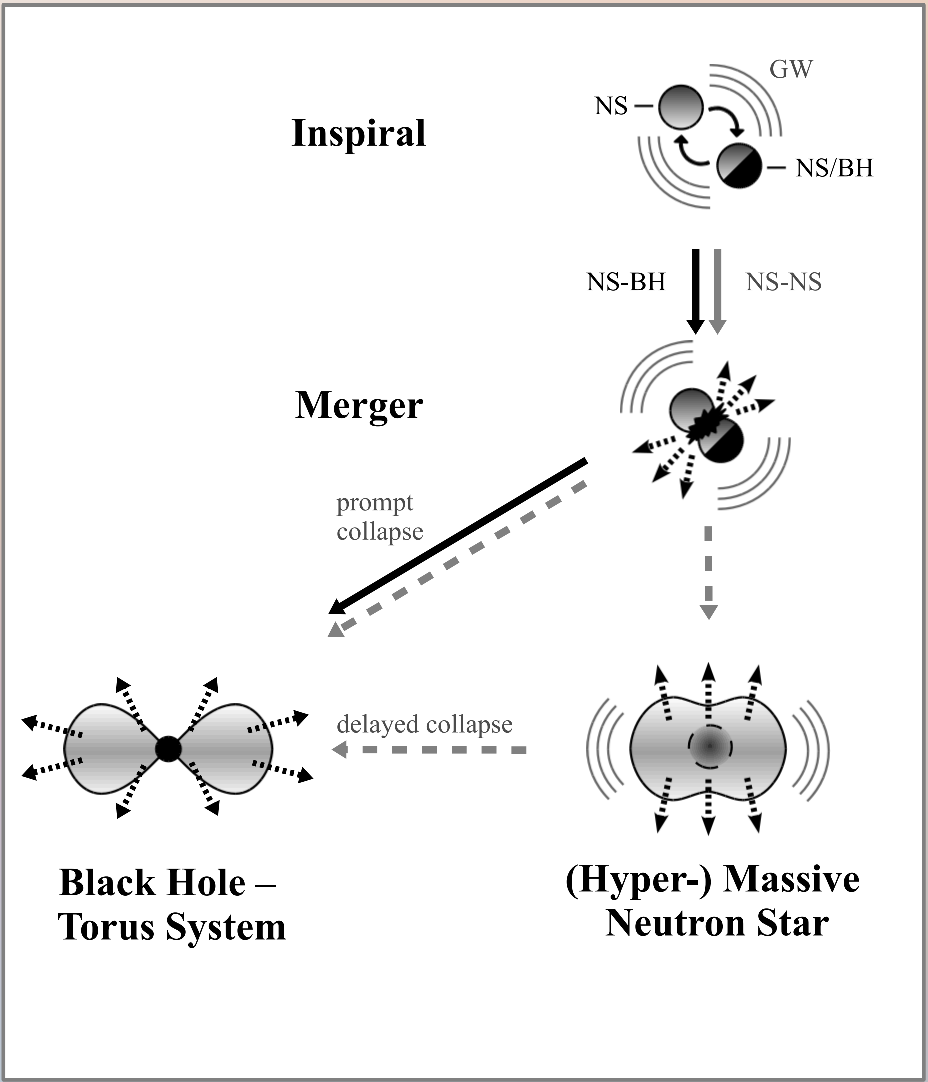
(Berger et. al. 2013)

theoretical lightcurve (Barnes & Kasen 2013)

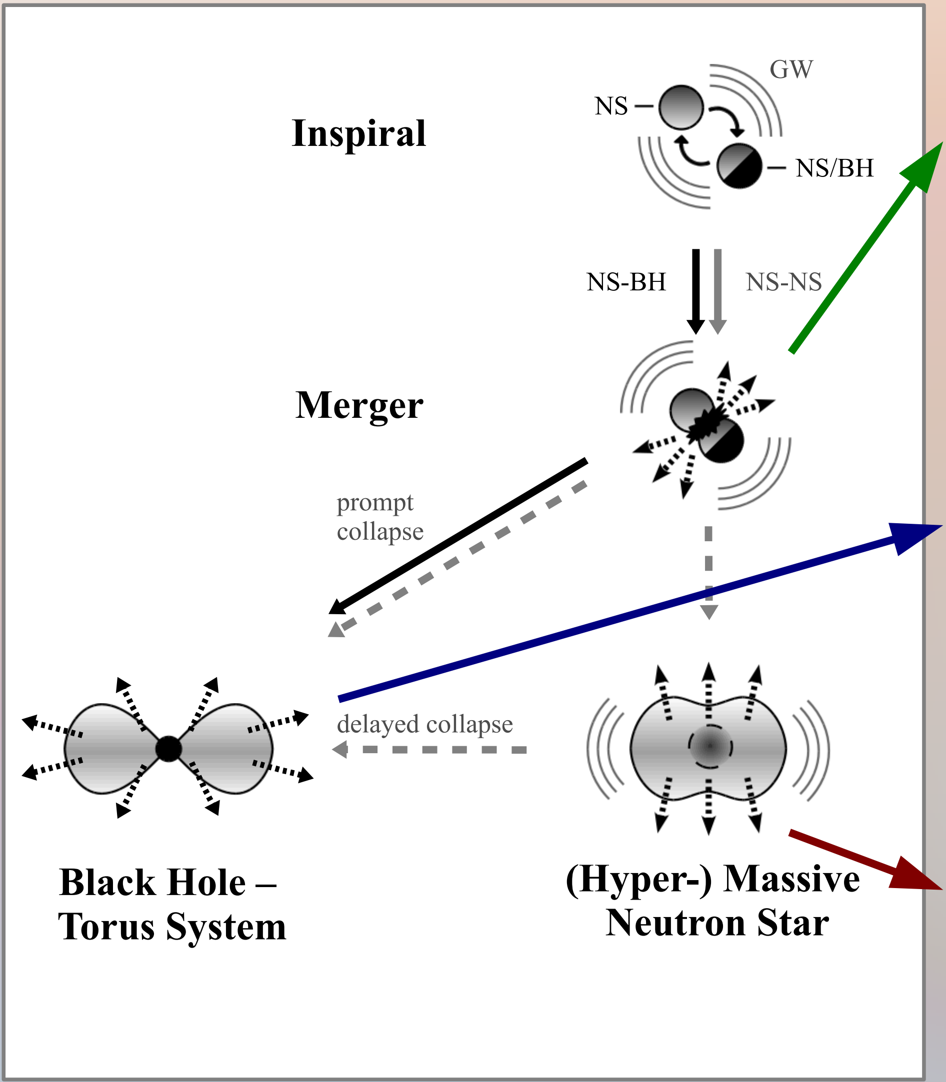


- ➔ opacity determined by lanthanides
- ➔ lightcurve carries information about
outflow mass, composition, velocity

Neutron-Star Mergers: Outflow Types



Neutron-Star Mergers: Outflow Types



➔ prompt/dynamical ejecta

... e.g. Rosswog, Janka, Shibata
... almost exclusively studied so far
... most studies find very low Ye →robust production A>140 elements
... *see Yuichiro's talk!*

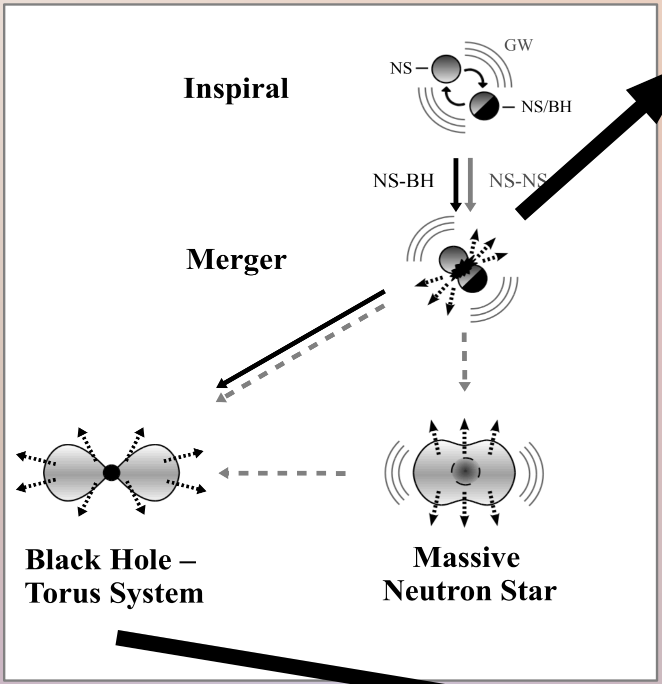
➔ BH-torus ejecta

... Surman, Wanajo, Fernandez&Metzger
... can be driven by neutrino heating, viscosity, B-fields, recombination...

➔ (H)MNS ejecta

... Dessart, Perego, Metzger&Fernandez
... mostly driven by neutrino heating
... *see Albino's talk!*

Study Overview



NS-NS and NS-BH merger phase modeled with CFC relativistic 3D SPH code (A.Bauswein, R. Ardevol)

Nucleosynthesis analysis of prompt ejecta (S. Goriely)

Hydrodynamic simulations

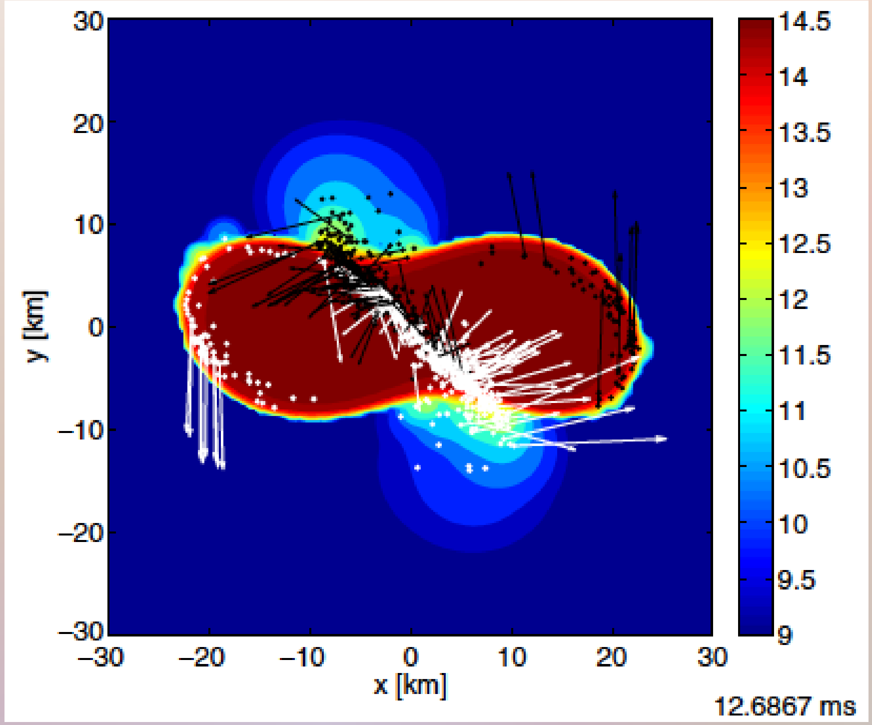
Post-processing

BH-torus phase modeled with 2D finite-volume neutrino-hydrodynamics code, global parameters consistent with merger simulations (OJ)

Nucleosynthesis analysis of prompt ejecta (S. Goriely)

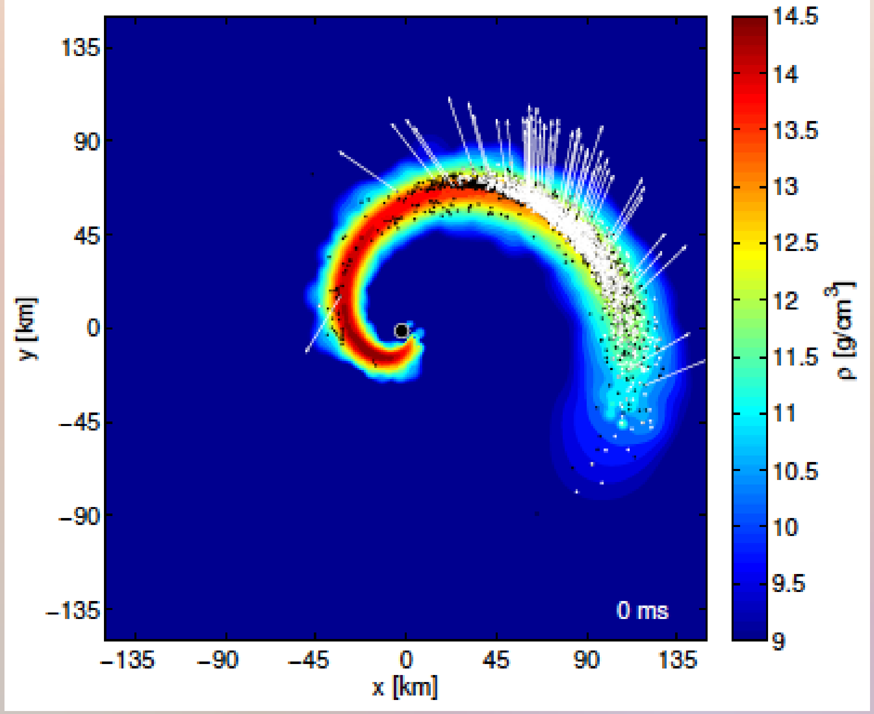
Dynamical Ejecta

NS-NS

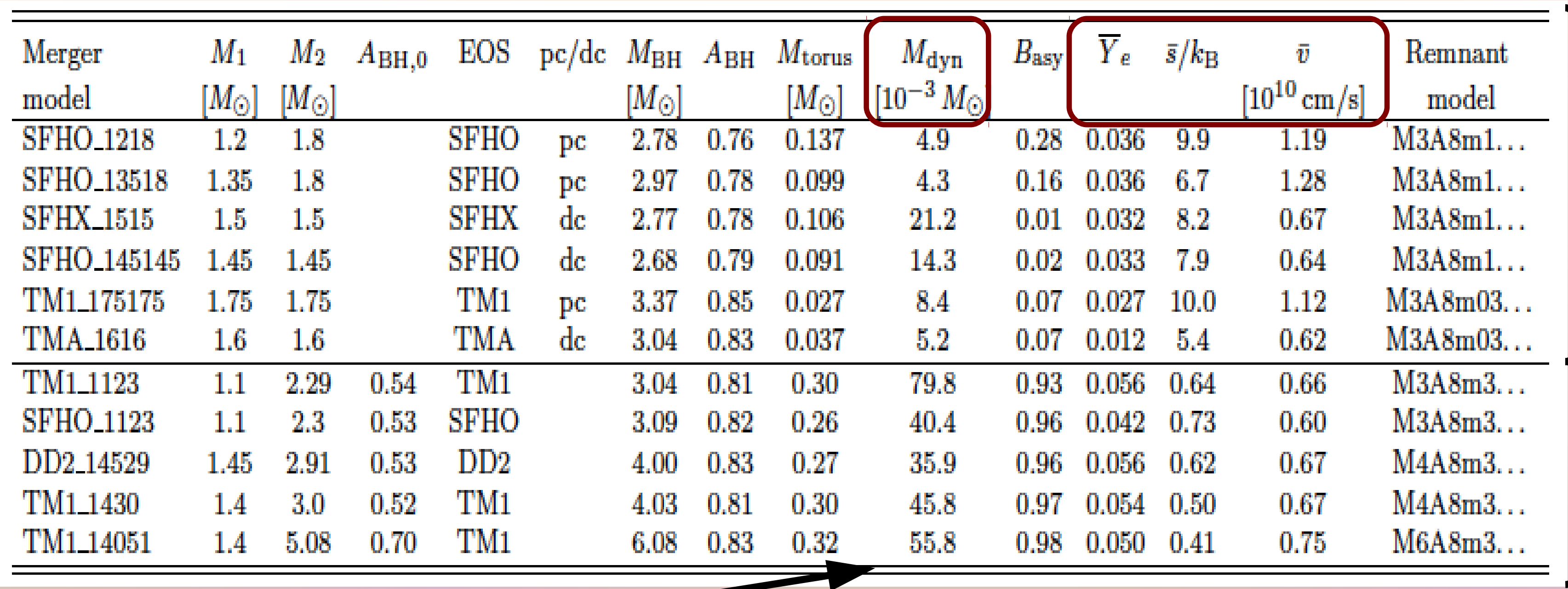


(Bauswein '13)

NS-BH



Dynamical Ejecta



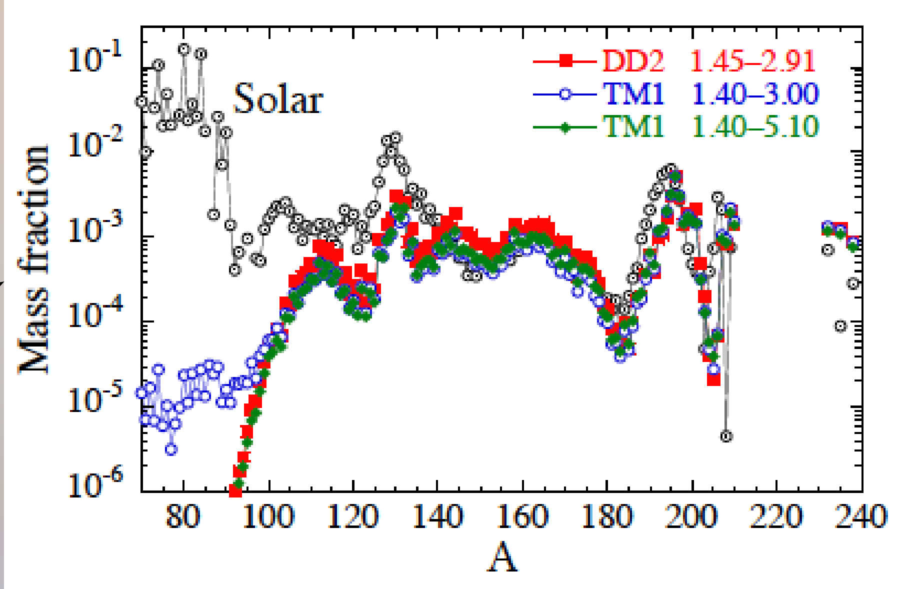
Merger model	M_1 $[M_\odot]$	M_2 $[M_\odot]$	$A_{\mathrm{BH},0}$	EOS	pc/dc	M_{BH} $[M_\odot]$	A_{BH}	M_{torus} $[M_\odot]$	M_{dyn} $[10^{-3}\,M_\odot]$	B_{asy}	$\overline{Y}_e$	$\bar{s}/k_{\mathrm{B}}$	$\bar{v}$ $[10^{10}\,\mathrm{cm/s}]$	Remnant model
SFHO_1218	1.2	1.8		SFHO	pc	2.78	0.76	0.137	4.9	0.28	0.036	9.9	1.19	M3A8m1...
SFHO_13518	1.35	1.8		SFHO	pc	2.97	0.78	0.099	4.3	0.16	0.036	6.7	1.28	M3A8m1...
SFHX_1515	1.5	1.5		SFHX	dc	2.77	0.78	0.106	21.2	0.01	0.032	8.2	0.67	M3A8m1...
SFHO_145145	1.45	1.45		SFHO	dc	2.68	0.79	0.091	14.3	0.02	0.033	7.9	0.64	M3A8m1...
TM1_175175	1.75	1.75		TM1	pc	3.37	0.85	0.027	8.4	0.07	0.027	10.0	1.12	M3A8m03...
TMA_1616	1.6	1.6		TMA	dc	3.04	0.83	0.037	5.2	0.07	0.012	5.4	0.62	M3A8m03...
TM1_1123	1.1	2.29	0.54	TM1		3.04	0.81	0.30	79.8	0.93	0.056	0.64	0.66	M3A8m3...
SFHO_1123	1.1	2.3	0.53	SFHO		3.09	0.82	0.26	40.4	0.96	0.042	0.73	0.60	M3A8m3...
DD2_14529	1.45	2.91	0.53	DD2		4.00	0.83	0.27	35.9	0.96	0.056	0.62	0.67	M4A8m3...
TM1_1430	1.4	3.0	0.52	TM1		4.03	0.81	0.30	45.8	0.97	0.054	0.50	0.67	M4A8m3...
TM1_14051	1.4	5.08	0.70	TM1		6.08	0.83	0.32	55.8	0.98	0.050	0.41	0.75	M6A8m3...

NS-NS

NS-BH

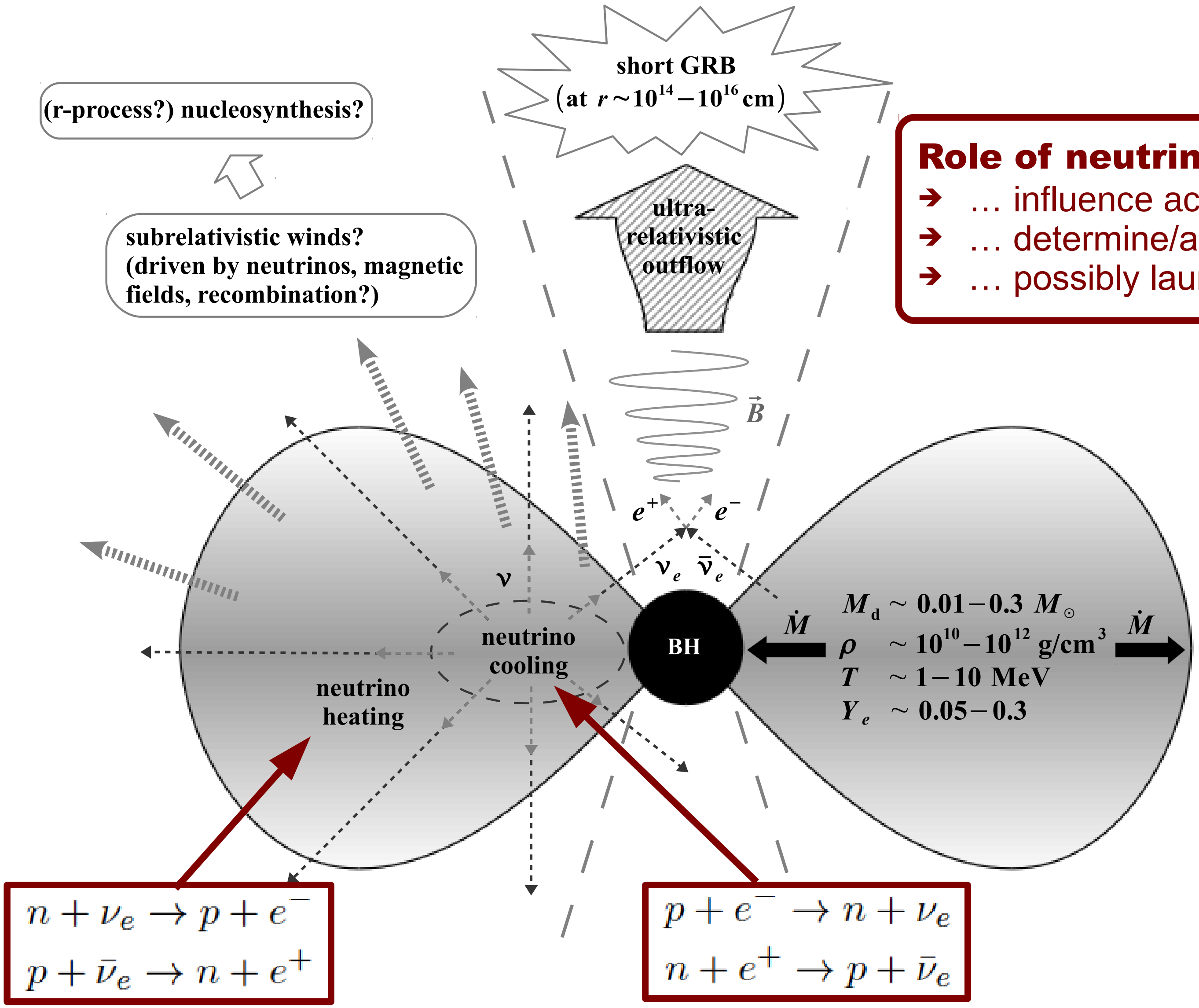
Typical properties:
- outflow masses ~ 0.001 – 0.1 Msun
- electron fraction Ye < 0.1
- entropy per baryon s ~ 1 – 10 kB
- velocity v ~ 0.2 – 0.4 c

Typical nucleosynthesis yields:
- solar deficient for A < 140
- solar like for A > 140 (robust)



Physics of Post-Merger BH-Torus

(short after its formation)



Role of neutrinos:

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

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

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

Neutrino Transport

Full Boltzmann equation too expensive!

Our approach:

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

$$
\begin{aligned}
E &= \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t) && \leftarrow \textbf{energy density} \\
F^i &= \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i && \leftarrow \textbf{momentum density} \\
P^{ij} &= \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j && \leftarrow \textbf{pressure} \\
Q^{ijk} &= \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k
\end{aligned}
$$

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

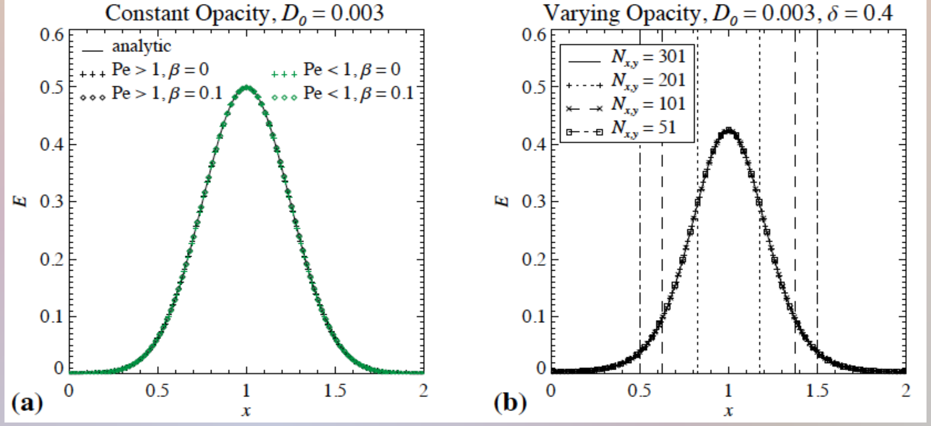
$$
\left.
\begin{aligned}
P^{ij} &= P^{ij}(E, F^i) \\
Q^{ijk} &= Q^{ijk}(E, F^i)
\end{aligned}
\right\} \quad \textbf{approximate algebraic closure relations (e.g. "M1 closure")}
$$

Computational save up of two degrees of freedom!

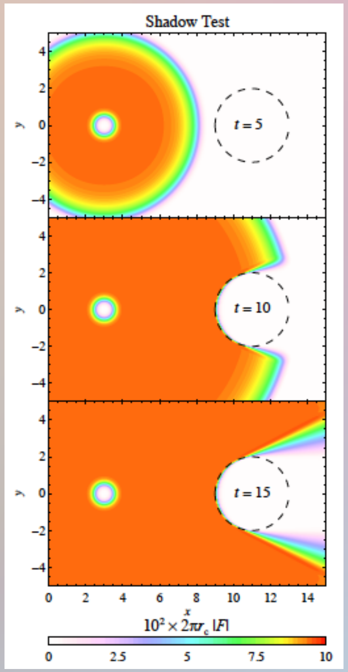
Neutrino Transport

Details of the algorithm:

- energy-dependent (multi-group), fully multidimensional
- O(v/c) effects advection, aberration and Doppler shift included
- IMEX scheme for time integration → efficiently scalable
- implemented most important neutrino-interaction channels
- extensively tested in 1D and 2D (Just, Janka, Obergaulinger, to be submitted)



2D static and dynamic diffusion



2D shadow test

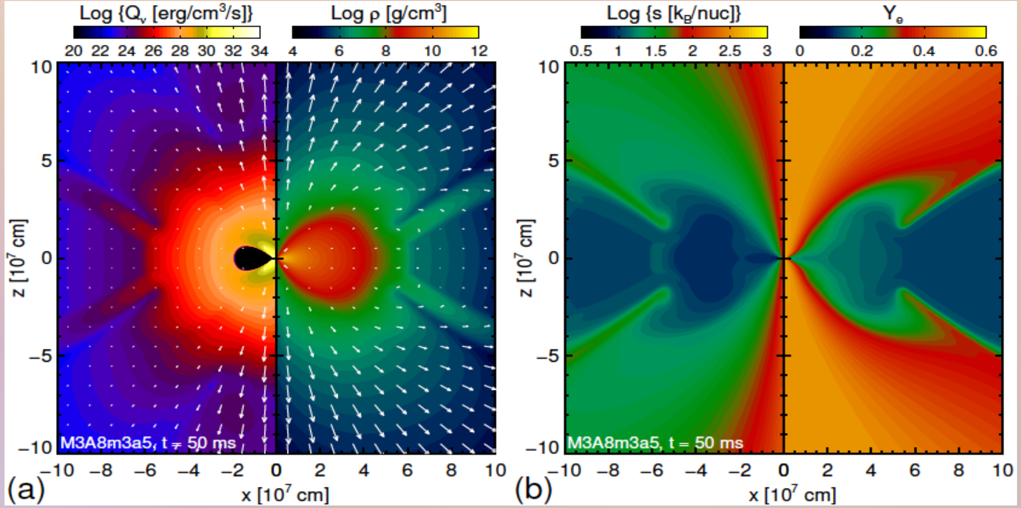
Setup of BH-Torus Models

- initial models: j-constant equilibrium tori
- axisymmetry
- angular momentum transport: Shakura & Sunyaev α-viscosity
- most dominant interactions included:
  - ✔ *beta-processes*
  - ✔ *neutrino-nucleon scattering*
  - ✔ *neutrino-antineutrino annihilation*
- pseudo-Newtonian gravitational potential (mimics the ISCO and BH spin)
- variation in M_{torus}, M_{BH}, α (adapted to merger simulations)

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**

$$\boxed{\begin{aligned} n + \nu_e &\rightarrow p + e^- \\ p + \bar{\nu}_e &\rightarrow n + e^+ \end{aligned}}$$

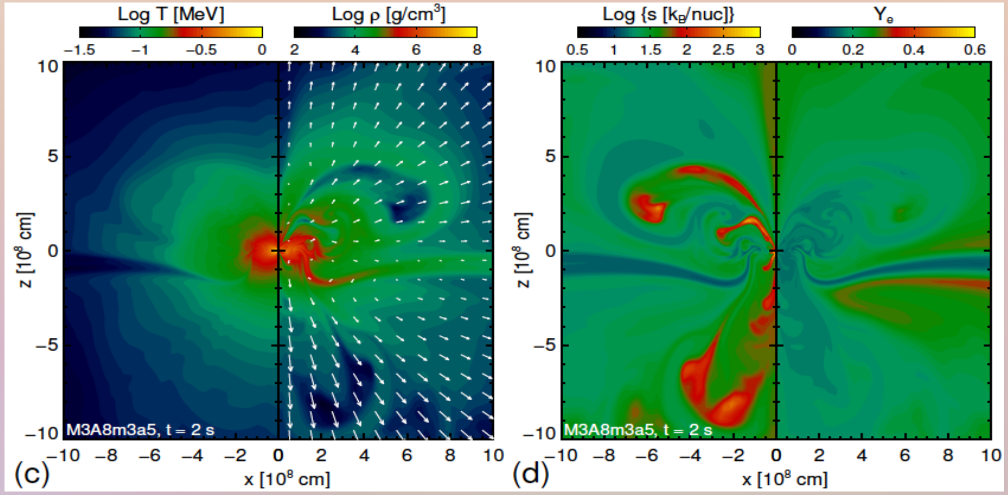
$$\boxed{Y_e \longrightarrow Y_e^\nu \simeq \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\varepsilon_{\bar{\nu}_e} - 2Q_{np}}{\varepsilon_{\nu_e} + 2Q_{np}}\right)^{-1}}$$

Disk Properties

2 main evolutionary phases:

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

➔ viscous heating dominates neutrino cooling



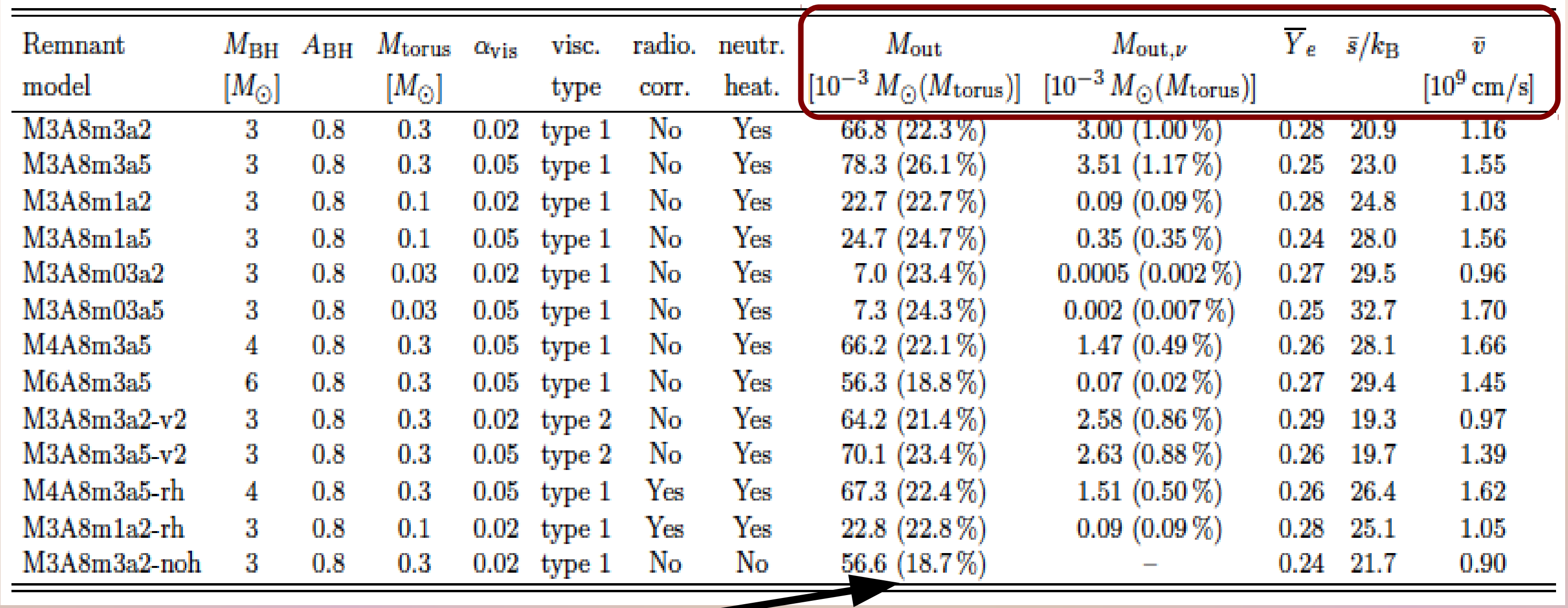
time = 2 s

➔ ejecta (mainly) driven by viscous effects

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

$$\boxed{\begin{array}{l} p + e^- \rightarrow n + \nu_e \\ n + e^+ \rightarrow p + \bar{\nu}_e \end{array}} \longrightarrow \boxed{Y_e \quad \longrightarrow \quad Y_e^{\beta} \quad = \quad Y_e(\rho, T, \mu_\nu = 0)}$$

Ejecta Properties



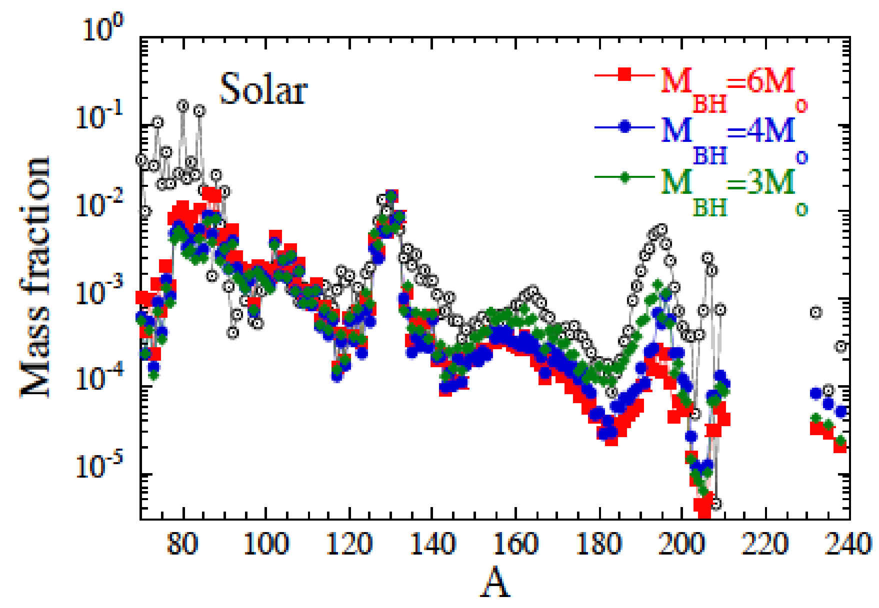
Remnant model	M_{BH} [$M_\odot$]	A_{BH}	M_{torus} [$M_\odot$]	α_{vis}	visc. type	radio. corr.	neutr. heat.	M_{out} [$10^{-3}\,M_\odot (M_{\mathrm{torus}})$]	$M_{\mathrm{out},\nu}$ [$10^{-3}\,M_\odot (M_{\mathrm{torus}})$]	$\overline{Y}_e$	$\bar{s}/k_{\mathrm{B}}$	$\bar{v}$ [10^9 cm/s]
M3A8m3a2	3	0.8	0.3	0.02	type 1	No	Yes	66.8 (22.3 %)	3.00 (1.00 %)	0.28	20.9	1.16
M3A8m3a5	3	0.8	0.3	0.05	type 1	No	Yes	78.3 (26.1 %)	3.51 (1.17 %)	0.25	23.0	1.55
M3A8m1a2	3	0.8	0.1	0.02	type 1	No	Yes	22.7 (22.7 %)	0.09 (0.09 %)	0.28	24.8	1.03
M3A8m1a5	3	0.8	0.1	0.05	type 1	No	Yes	24.7 (24.7 %)	0.35 (0.35 %)	0.24	28.0	1.56
M3A8m03a2	3	0.8	0.03	0.02	type 1	No	Yes	7.0 (23.4 %)	0.0005 (0.002 %)	0.27	29.5	0.96
M3A8m03a5	3	0.8	0.03	0.05	type 1	No	Yes	7.3 (24.3 %)	0.002 (0.007 %)	0.25	32.7	1.70
M4A8m3a5	4	0.8	0.3	0.05	type 1	No	Yes	66.2 (22.1 %)	1.47 (0.49 %)	0.26	28.1	1.66
M6A8m3a5	6	0.8	0.3	0.05	type 1	No	Yes	56.3 (18.8 %)	0.07 (0.02 %)	0.27	29.4	1.45
M3A8m3a2-v2	3	0.8	0.3	0.02	type 2	No	Yes	64.2 (21.4 %)	2.58 (0.86 %)	0.29	19.3	0.97
M3A8m3a5-v2	3	0.8	0.3	0.05	type 2	No	Yes	70.1 (23.4 %)	2.63 (0.88 %)	0.26	19.7	1.39
M4A8m3a5-rh	4	0.8	0.3	0.05	type 1	Yes	Yes	67.3 (22.4 %)	1.51 (0.50 %)	0.26	26.4	1.62
M3A8m1a2-rh	3	0.8	0.1	0.02	type 1	Yes	Yes	22.8 (22.8 %)	0.09 (0.09 %)	0.28	25.1	1.05
M3A8m3a2-noh	3	0.8	0.3	0.02	type 1	No	No	56.6 (18.7 %)	–	0.24	21.7	0.90

Typical properties:

- viscous ejecta dominant
- total outflow mass Mout ~ 20% Mtorus
- electron fraction Ye ~ 0.2 – 0.3
- velocity v ~ 10^9 cm/s

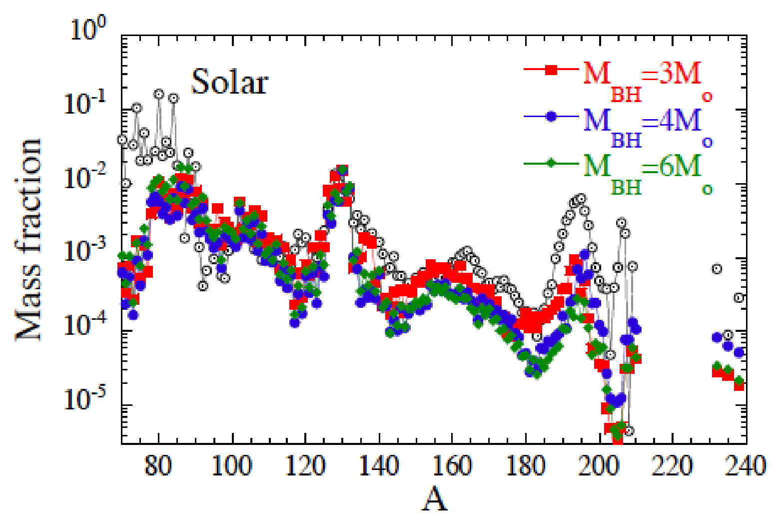
Typical nucleosynthesis yields:

- solar like for 90 < A < 140
- solar deficient for A > 140

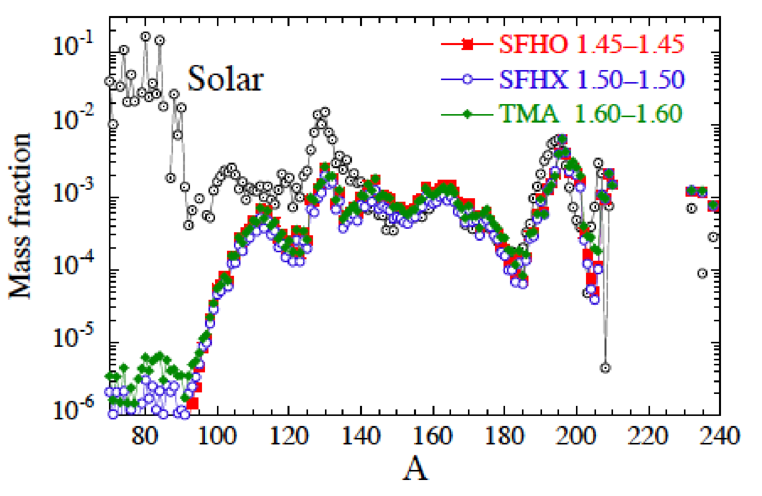


Combined Nucleosynthesis Yields

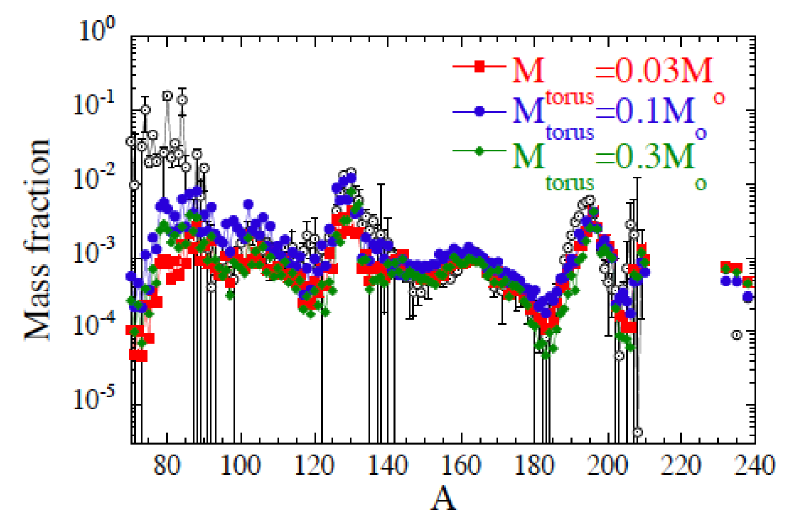
➔ DISK ejecta (mainly A ~ 90 - 140)



➔ DYNAMICAL ejecta (mainly A ~ 140 - 210)



➔ DISK + DYNAMICAL ejecta



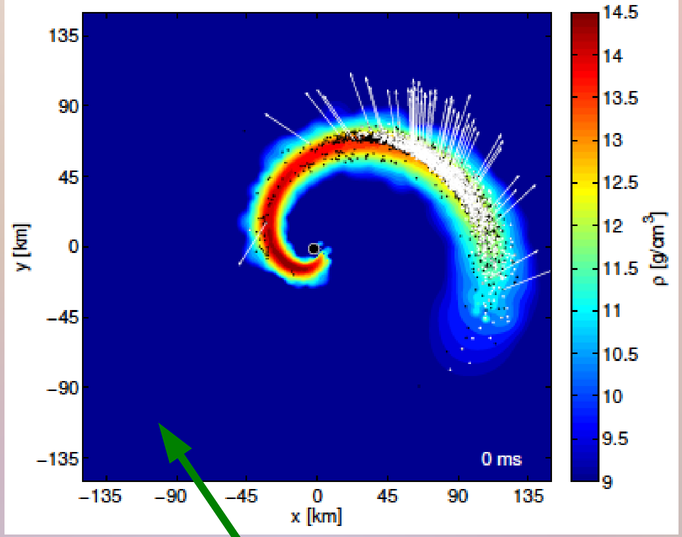
➔ nicely recovers the full mass range A > 90

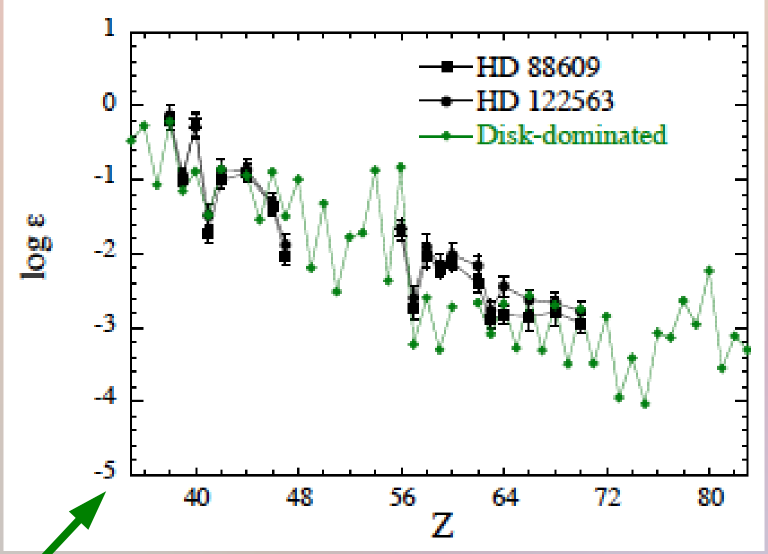
➔ BH-torus ejecta could be significant sources of intermediate mass elements with 90 < A < 140

➔ observed scatter for 90 < A < 140 maybe explained by variable ratios of disk and prompt ejecta masses

Heavy-Element Deficient Stars

… could perhaps be explained by asymmetric mass ejection in NS-BH mergers





stars located here are primarily enriched by disk ejecta only

Summary

- ➔ NS mergers could be main/significant sources of r-process elements in the universe
- ➔ all outflow components potentially important and each could have individual nucleosynthesis signatures
- ➔ we analyzed prompt ejecta from NS-NS / NS-BH mergers as well as ejecta from relic BH-torus system
- ➔ prompt ejecta typically few % Msun and give solar-like yields for $A > 140$
- ➔ disk ejecta typically few % Msun, subdominantly neutrino-driven and dominantly viscously-driven, and give solar-like yields for $90 < A < 140$
- ➔ combinations of dynamical + disk ejecta reproduce solar pattern within $90 < A < 210$

Conclusions

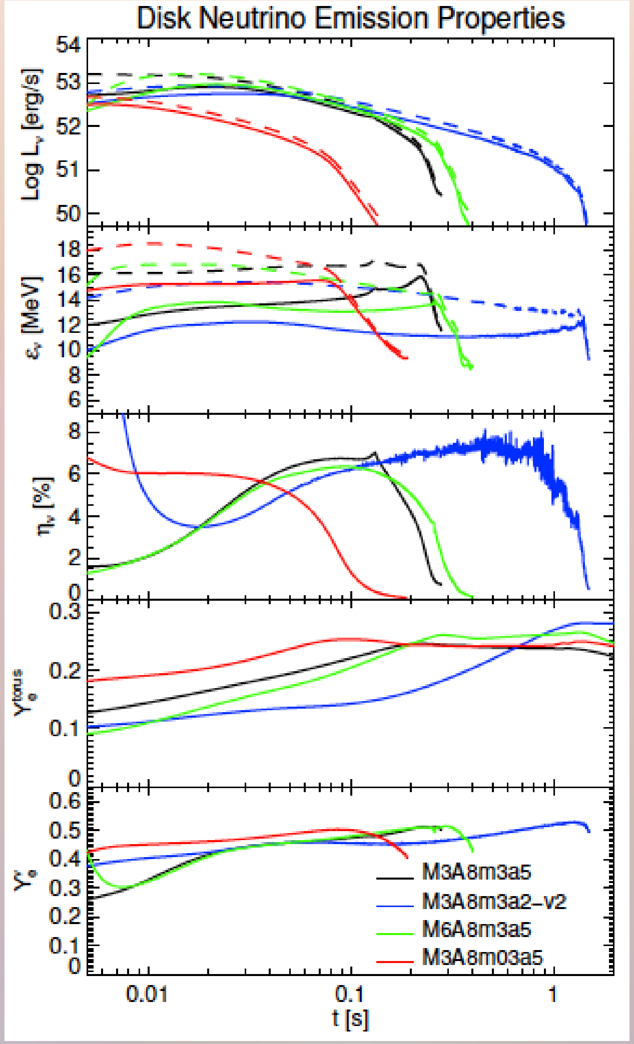
- ➔ dynamical ejecta from NS-BH mergers could be significant/main sources of r-process elements in the range A > 140
- ➔ ejecta from BH-torus remnants could be significant/main sources of r-process elements in the range 90 < A < 140
- ➔ observed star-to-star scatter for the lighter elements could be explained by different ratios of dynamical-to-disk ejecta masses
- ➔ heavy-element deficient stars possibly explained by asymmetric mass ejection in NS-BH mergers

- ➔ several aspects of our study can still be improved, e.g.:
  - add ejecta from (H)MNS
  - include neutrinos in merger-phase simulations
  - take BH-torus configuration as resulting from merger model
  - include relativity and MHD in BH-torus models

More details in arXiv:1406.2687

Supplementary Material

Emission Properties



Disk Neutrino Emission Properties

Ejecta Properties