Neutrino-Driven Jets in Compact Object Mergers

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Motivation

- **central engine** and **launch mechanism** of short GRBs not safely identified yet
- two most likely systems: BH-tori and (H)MNS
- two most likely mechanisms: **neutrino-annihilation** and (several) **magneto-rotational processes**
- most previous studies compute annihilation rate using 1D models (Popham, DiMatteo, Liu, ...) or by post-processing individual snapshots (Ruffert, Dessart, Richers, …)
- other studies evolve jets without resolving the central engine (Aloy, Nagataki, Duffel, Murguia-Berthier, …)
- 2 necessary conditions to obtain about **$\sim 10^{48} - 10^{50}$ erg** in relativistic outflow material:
  - sufficient energy provided by nu-annihilation
  - sufficiently small energy loss during expansion
- What is the impact of the dynamical ejecta on the jet?

“ALCAR” Neutrino Transport Code

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

Radiation-hydro with Boltzmann solver too expensive!

Our approach (see also: O'Connor '14, Kuroda '15):

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

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

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

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

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

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

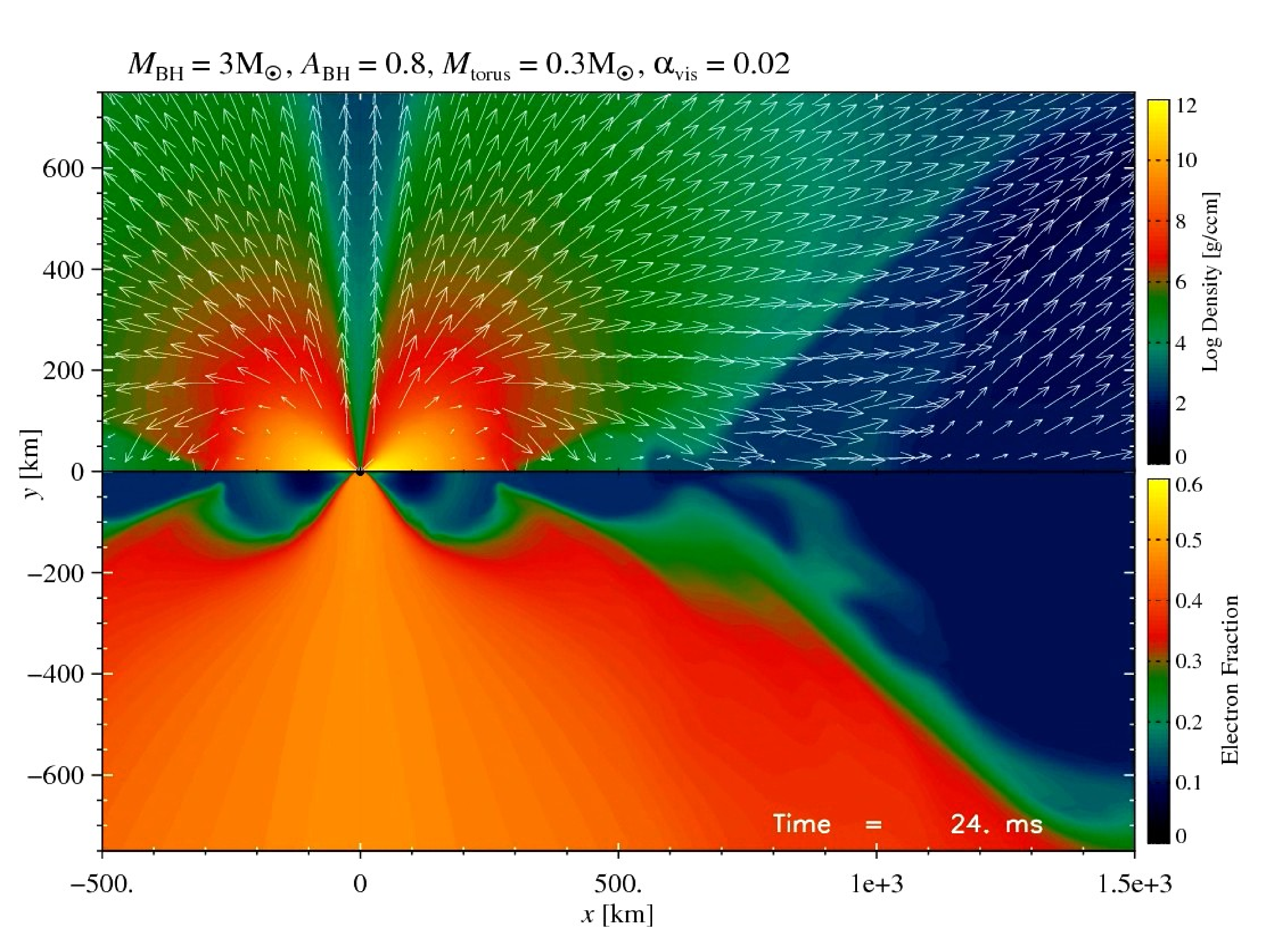
$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\} \quad \textbf{approximate algebraic closure relations (e.g. "M1 closure")}$$

Effective save up of the two angular degrees of freedom!

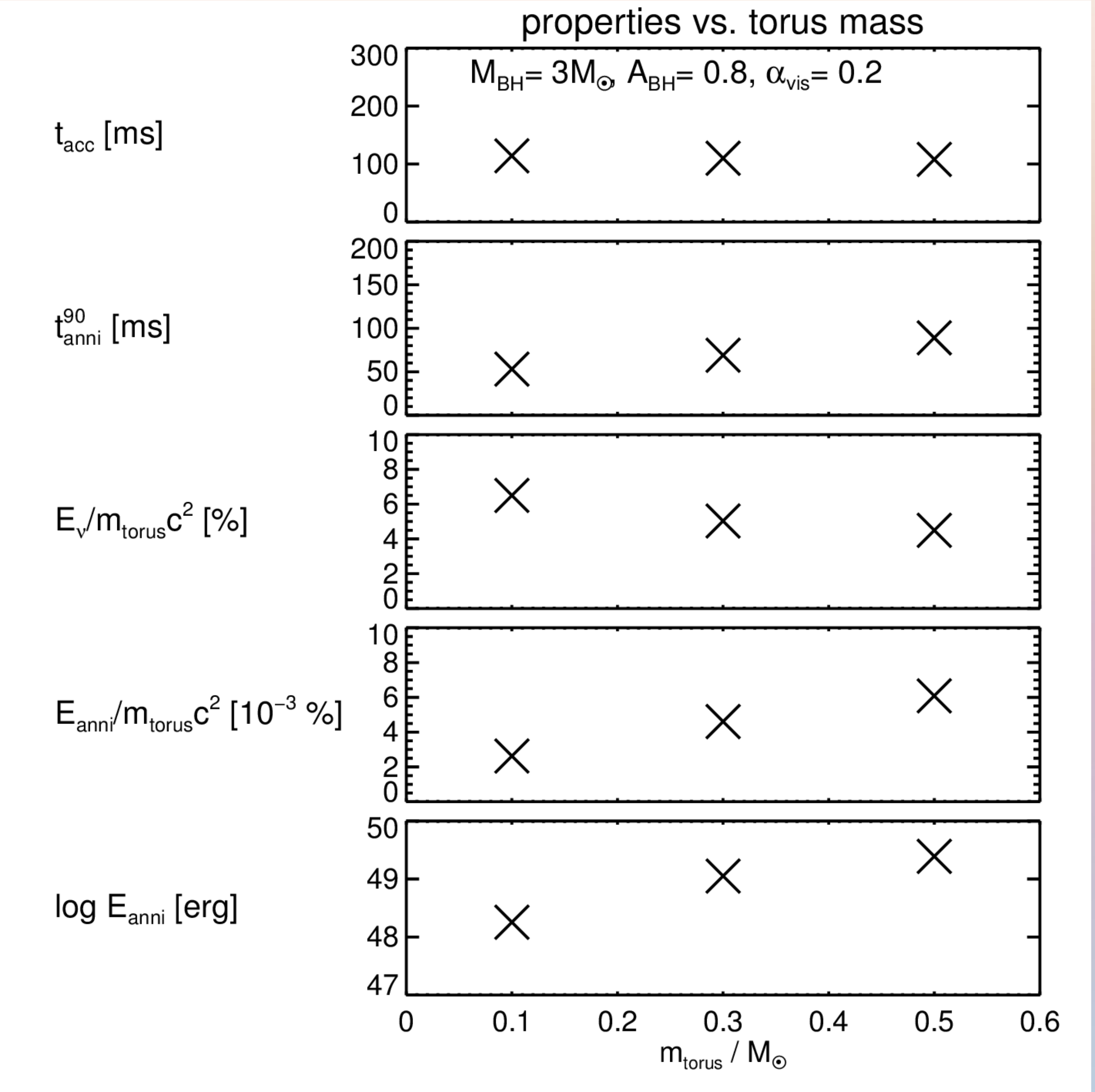
Setup of BH-Torus Models
(first without dynamical ejecta)

- initial configuration given by **equilibrium tori** with constant specific angular moment
- simulations performed in **2D axisymmetry**
- multi-group neutrino transport with **10 energy groups**
- most dominant **(electron) neutrino interactions** included:
  - ✔ *emission/absorption by nucleons*
  - ✔ *neutrino-nucleon scattering*
  - ✔ *neutrino-antineutrino annihilation*
- Newtonian hydrodynamics **with pseudo-Newtonian** gravitational potential by Artemova → mimics the ISCO and BH spin
- angular momentum transport: Shakura & Sunyaev **α-viscosity**
- variation of m_{torus}, M_{BH}, A_{BH}, α_{vis}
- similar models as used for **nucleosynthesis study** Just et al. '15 MNRAS 448, 541 and conceptually similar as in Fernandez '13, '14

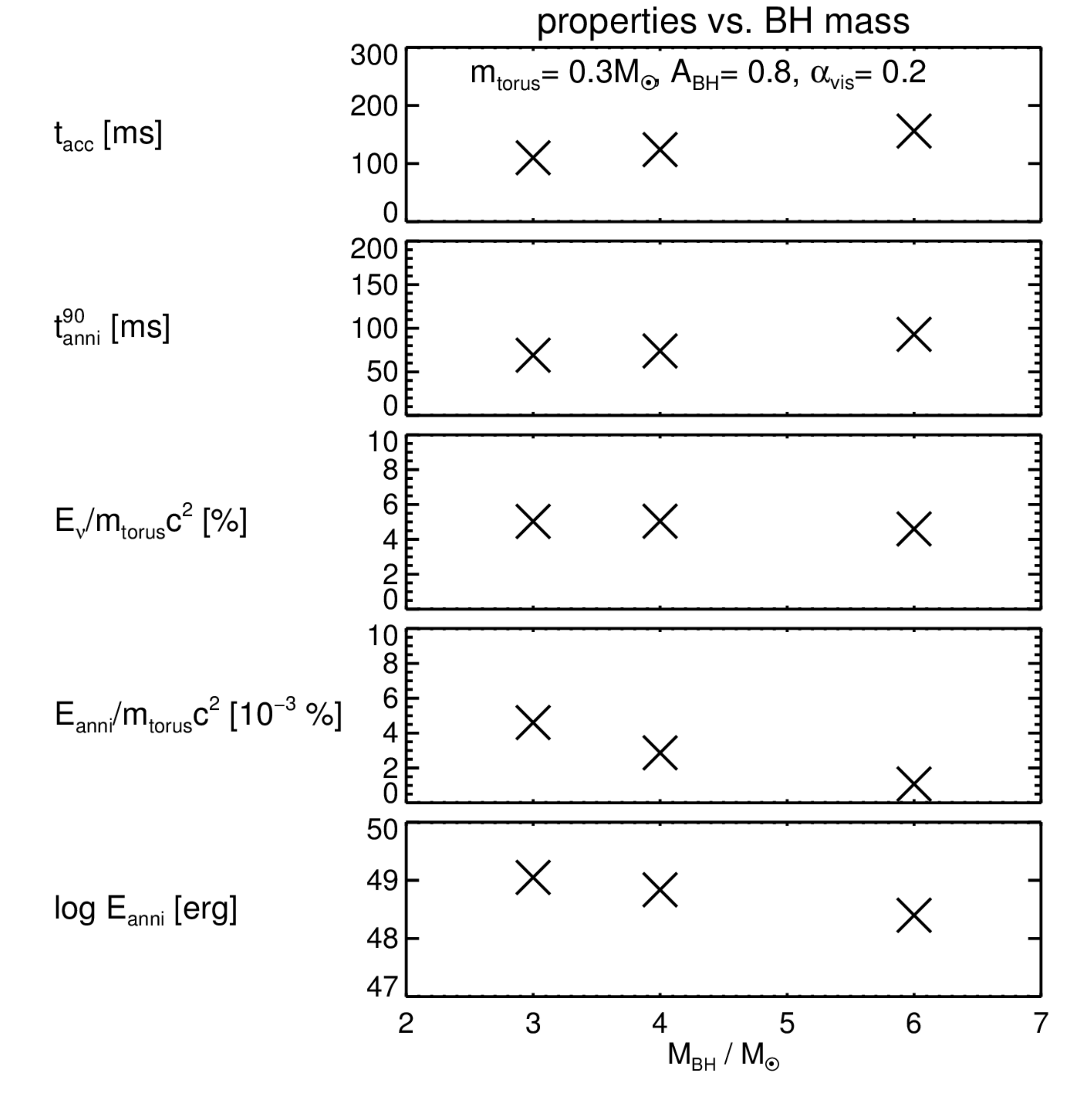
Movie: BH-torus without prompt ejecta



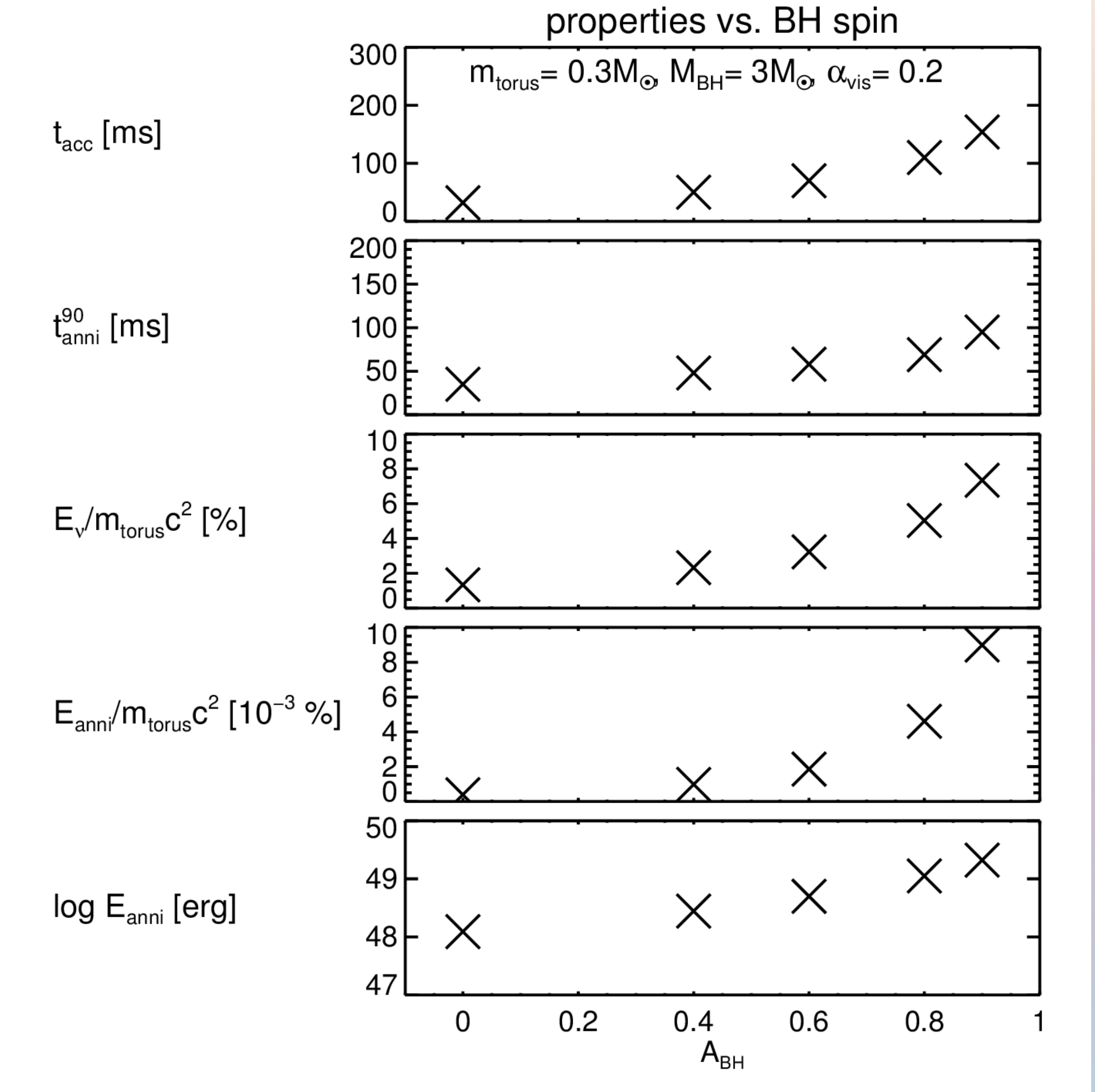
Neutrino emission properties vs. torus mass



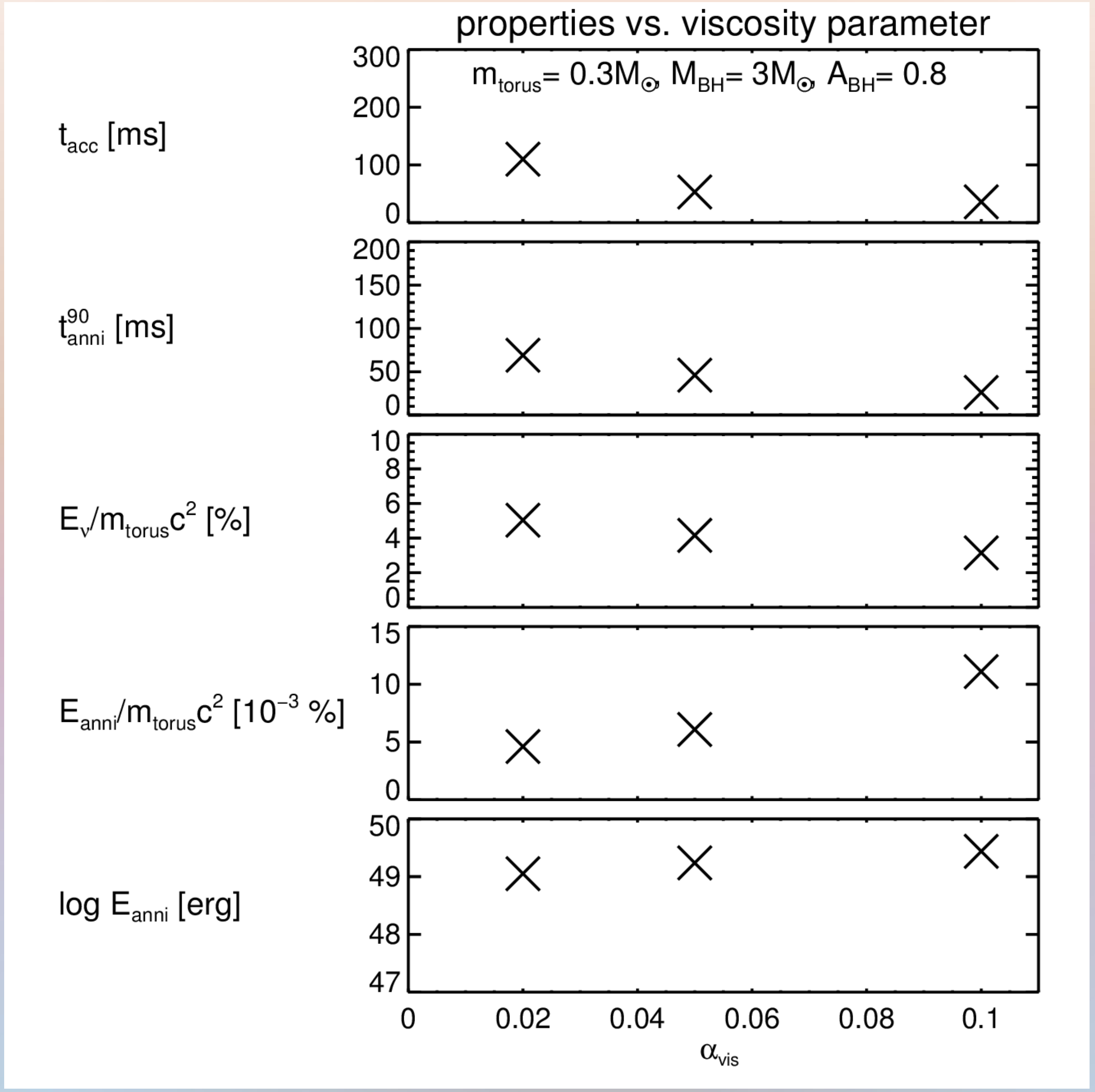
Neutrino emission properties vs. BH mass



Neutrino emission properties vs. BH spin

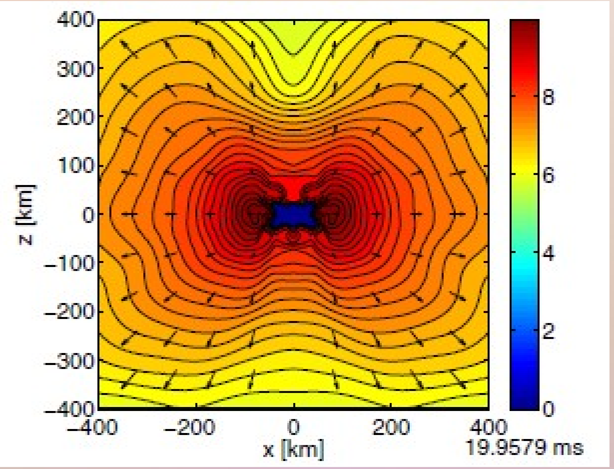


Neutrino emission properties vs. visc. parameter



Relativistic ejecta expansion into dynamical ejecta

- we now extend Newtonian to **special relativistic hydro**
- data for dynamical ejecta **mapped from SPH** simulations **onto 2D BH-torus grid**
- 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

Model TM11451: NS-BH remnant

- **MOVIE**
- dynamical ejecta are ignored since they are almost exclusively ejected in equatorial plane
- thermal fireball is successfully launched
- annihilation energy is efficiently converted to relativistic kinetic energy
- jet can expand almost unimpeded
- amount of energy sufficient at least to explain low-luminosity sGRBs

Model TM113520: NS-NS remnant

- **MOVIE**
- dynamical ejecta are slightly equatorially dominated
  $\longrightarrow$ favorable for jet launch
- jet is successfully launched, but only after significant energy input by annihilation
- in the **jet beam**, annihilation energy is efficiently converted to relativistic kinetic energy
- however, during expansion the **jet beam** dissipates almost all kinetic energy due to interaction with the **cocoon** and **jet head**
- amount of energy not sufficient to explain sGRBs

Model SFHO145145: NS-NS remnant

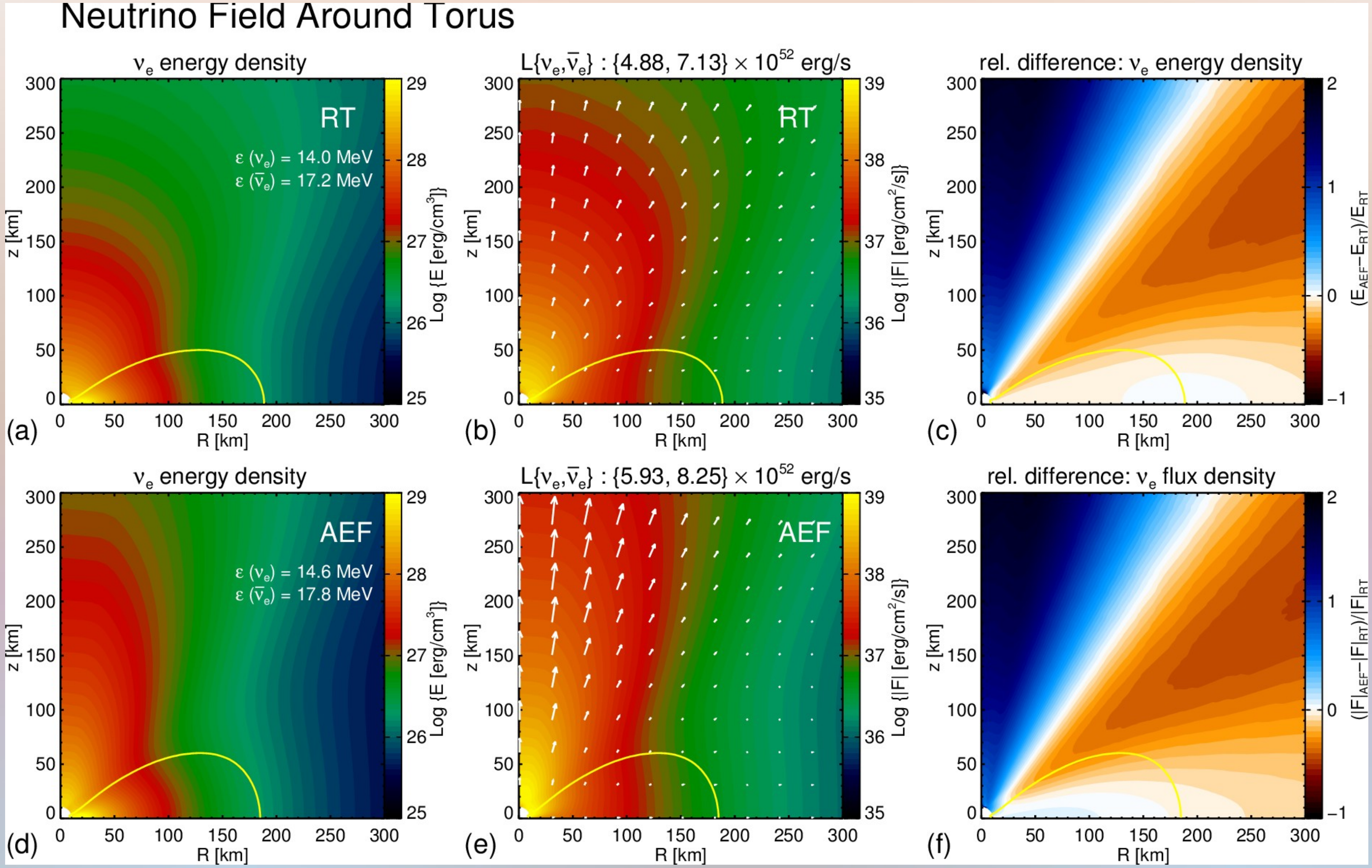
- **MOVIE**
- dynamical ejecta are almost spherical
  $\longrightarrow$ not favorable for jet launch
- annihilation only deposits thermal energy into dynamical ejecta
- however, **not powerful enough to launch a jet**

Summary

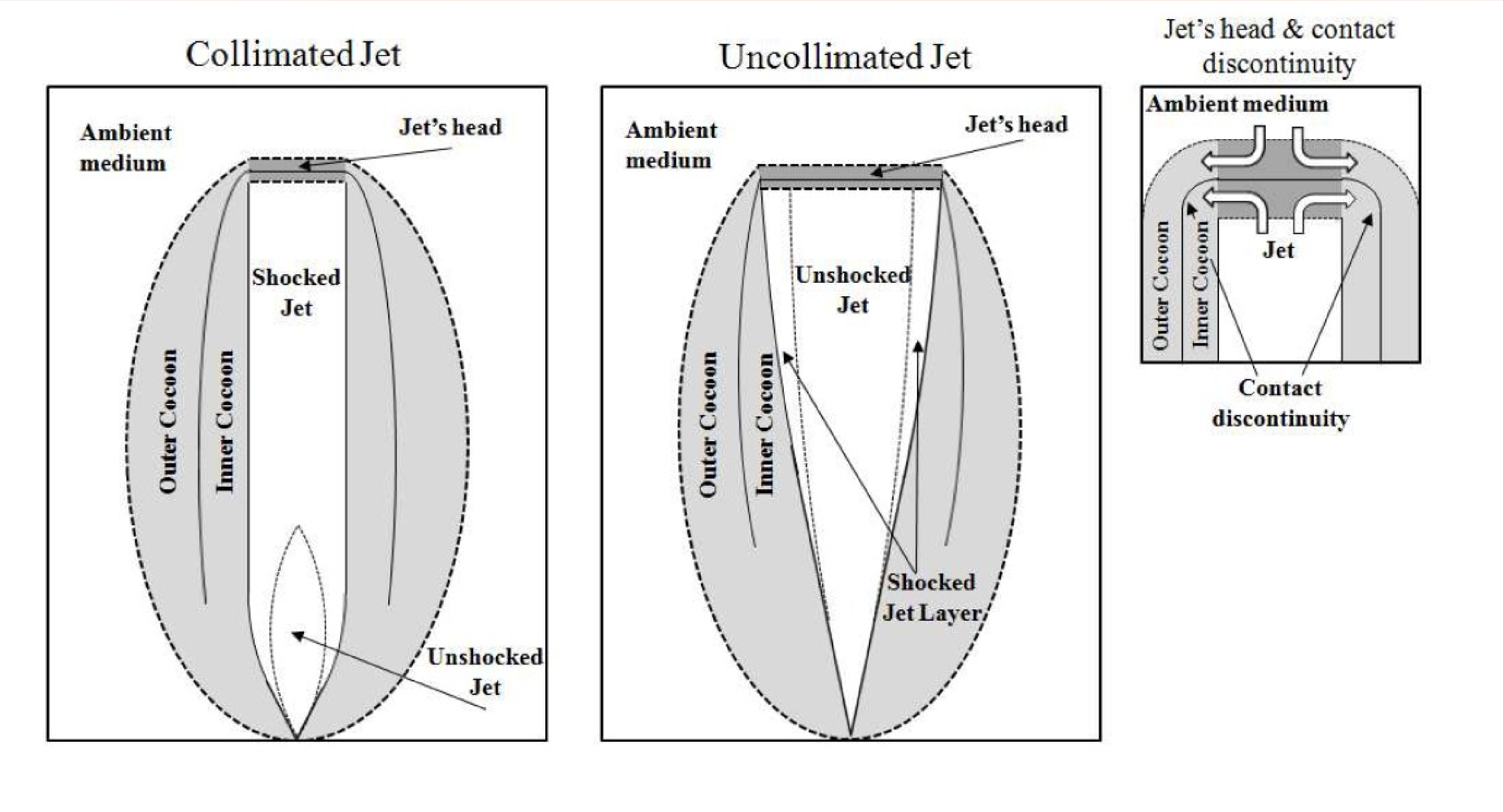
- using the M1 code **ALCAR** we examined neutrino emission + annihilation in BH-torus systems as functions of m_{torus}, M_{BH}, A_{BH}, α_{vis}
- typical annihilation energies are $10^{47} - 10^{49}$ erg and efficiencies are $10^{-5} - 10^{-4}$, while high values favor **high m_{torus}**, **low M_{BH}**, **high A_{BH}**, **high α_{vis}**
- for selected models we followed the relativistic jet expansion into the dynamical ejecta
- **NS-BH mergers:** major fraction of anni. energy may end up in relativistic ejecta → could explain at least low-luminosity sGRBs
- **NS-NS mergers:** either no jet is launched or the major fraction of anni. energy is dissipated in the dynamical ejecta → annihilation too weak
- for a delayed collapse in NS-NS mergers, the situation is likely even worse due to additional neutrino-driven winds
- *results suggest that **other mechanisms are needed** to explain sGRBs in NS-NS mergers and high-energy sGRBs in NS-BH mergers!*

Thank you for your attention!

Appendix: Test of Neutrino Scheme



Appendix: Jet expansion in external medium



(Bromberg et. al. '11)