Tiny but Mighty: Neutrinos and Their Role in Neutron-Star Mergers

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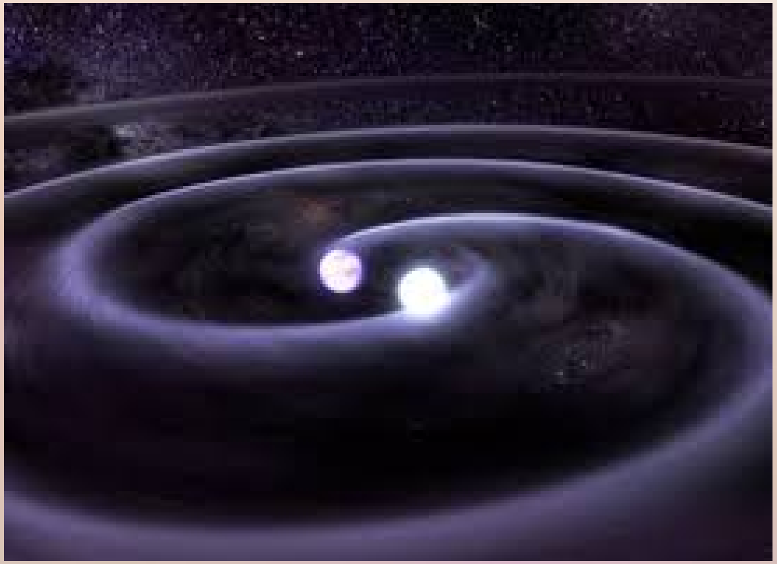
The Fate of Compact Object Binaries



- CBs emit **gravitational waves (GW)!**
  → **orbitial distance decays**
  → **merger inevitable**
- **bad news:** No NS merger has been safely observed so far, only ~10 NS-NS binaries known, 0 NS-BH binaries known
- **good news:** orbital decay is measured for the Hulse-Taylor pulsar and precisely confirms prediction by general relativity
- expected merger rate (Abadie 2010):
  ~ 1E-4 … 1E-6 per year per galaxy
- expected rate of GW observations:
  0.1...100 per year
- **RECENTLY: First GWs from BH-BH merger observed!!!**
-

(aLIGO Hanford, USA)

Where are heavy elements (e.g. gold) produced?

Origin of ~ half of trans-iron elements still unknown!

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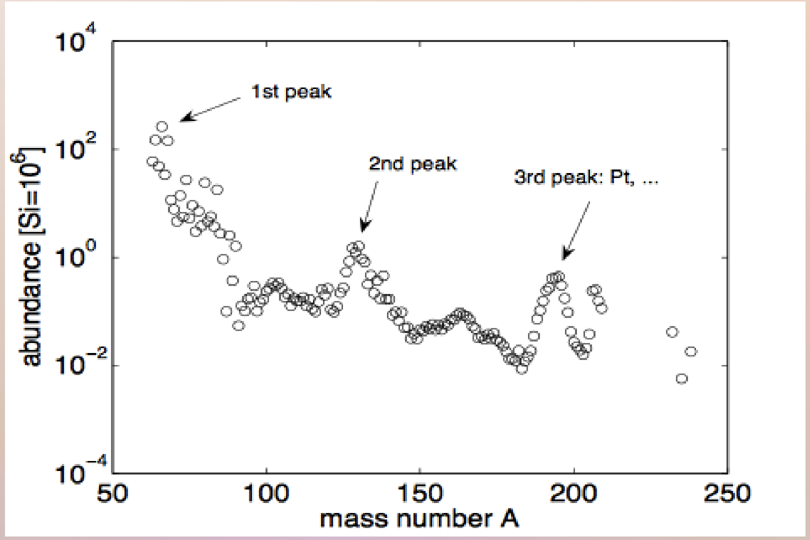
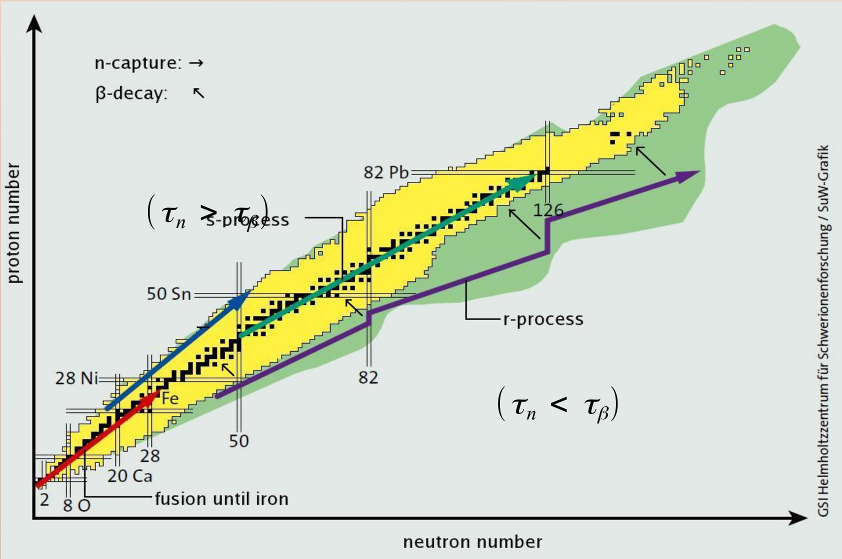
➔ nucleosynthesis process is basically known: ***rapid neutron capture process***



observed solar r-process abundance



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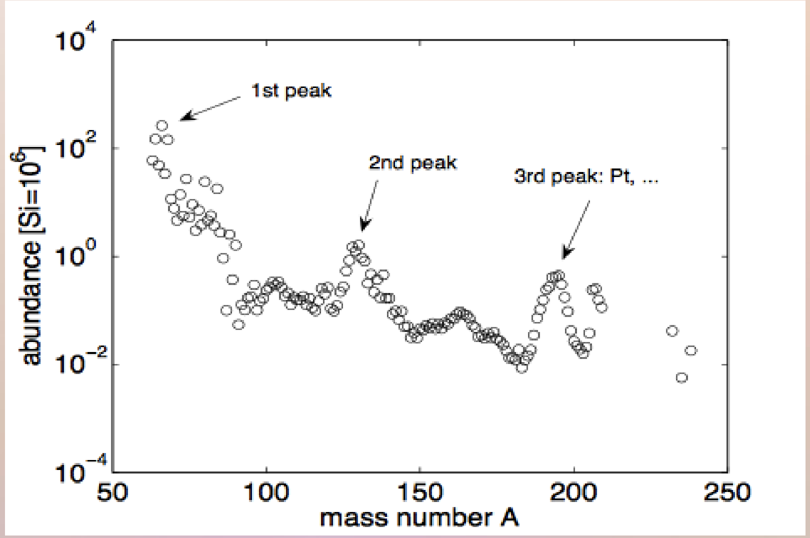
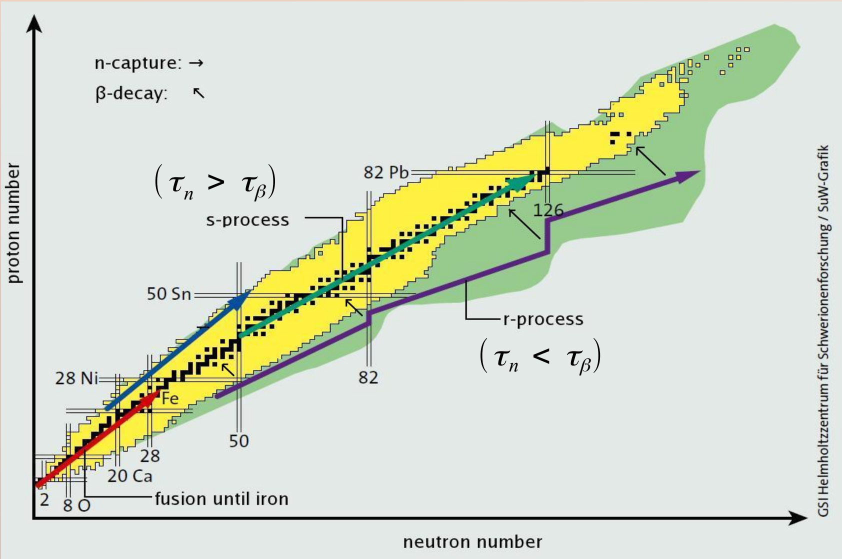




observed solar r-process abundance

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

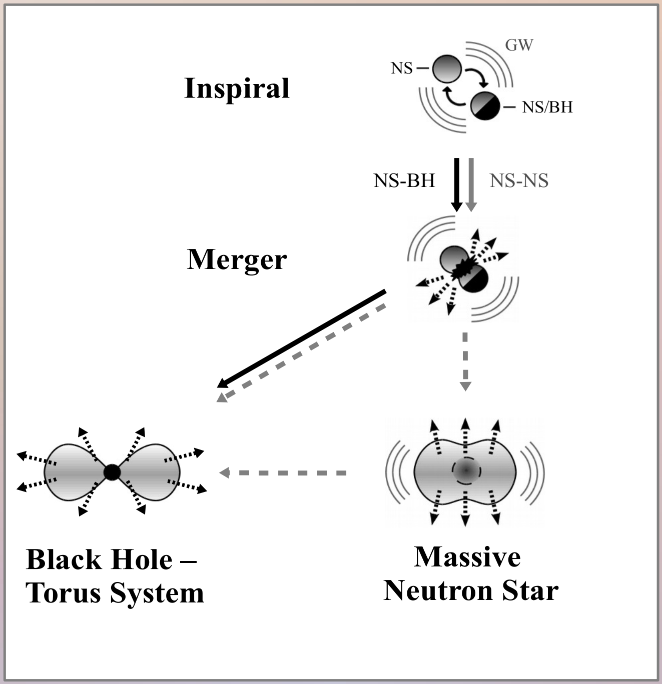
➔ **Requirements:** High neutron density → high-energy, explosive event
→ neutrino-interactions crucial

➔ **ejecta from CCSNe:** favored for decades, but not neutron-rich enough and too low entropies (at least to produce heaviest elements)

➔ **ejecta from NS-mergers???**

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

(Just+ '15, MNRAS 448, 541)



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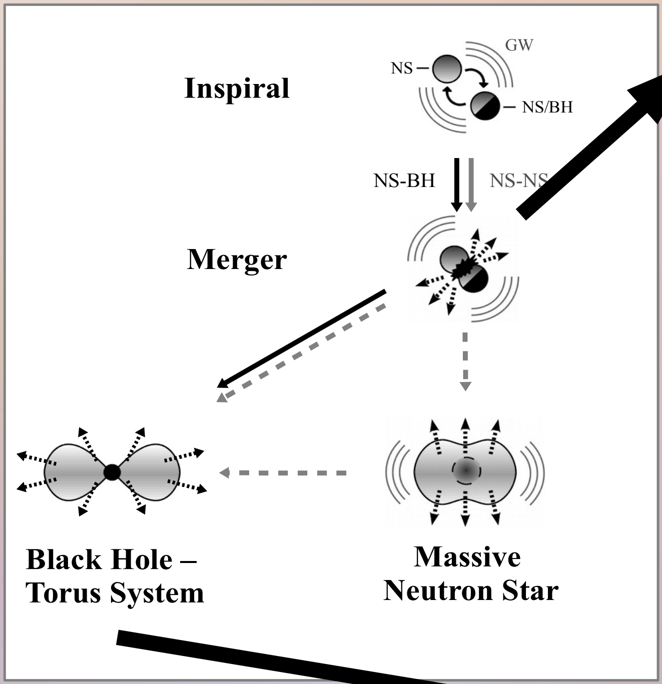


NS-NS and NS-BH merger phase modeled with CFC relativistic 3D SPH code (without neutrinos)

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

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

Radiation-hydro with Boltzmann solver too expensive!

Our approach:

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

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

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

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

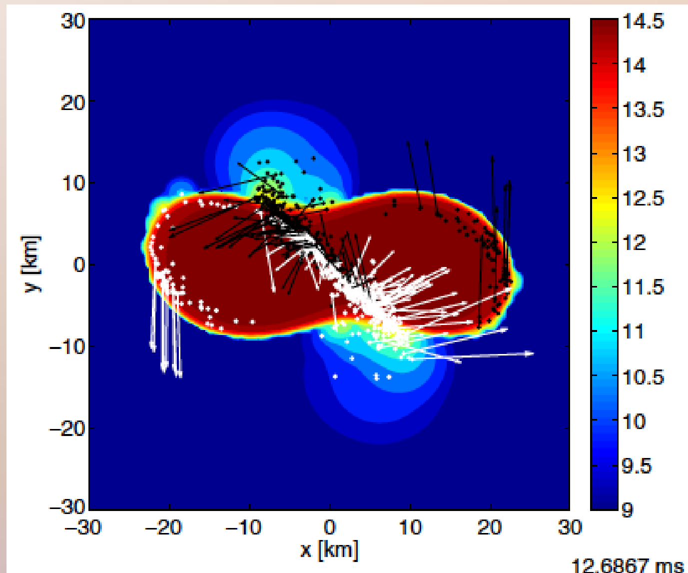
$$Q^{ijk} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k$$

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

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

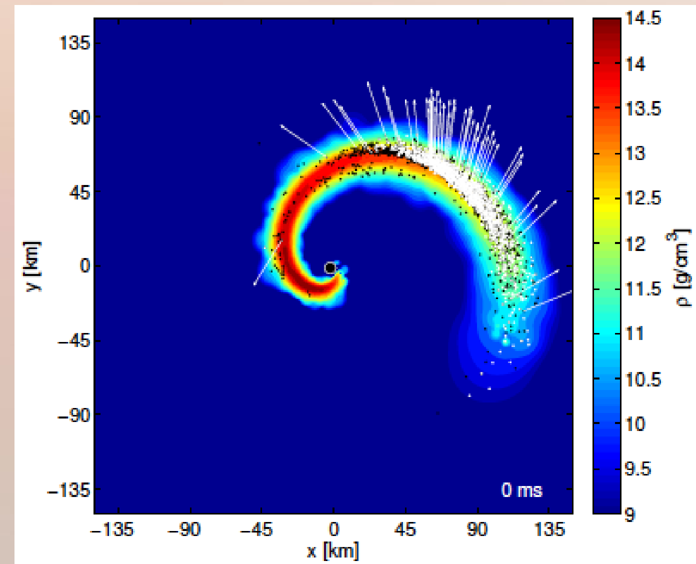
Dynamical ejecta launched during the merger

NS-NS

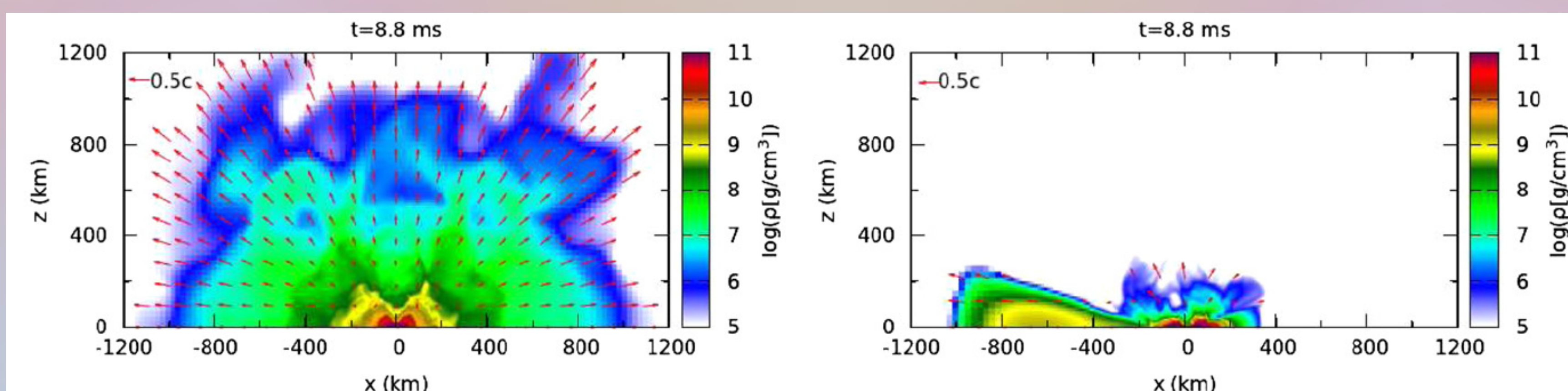


(Bauswein et. al. '13)

NS-BH

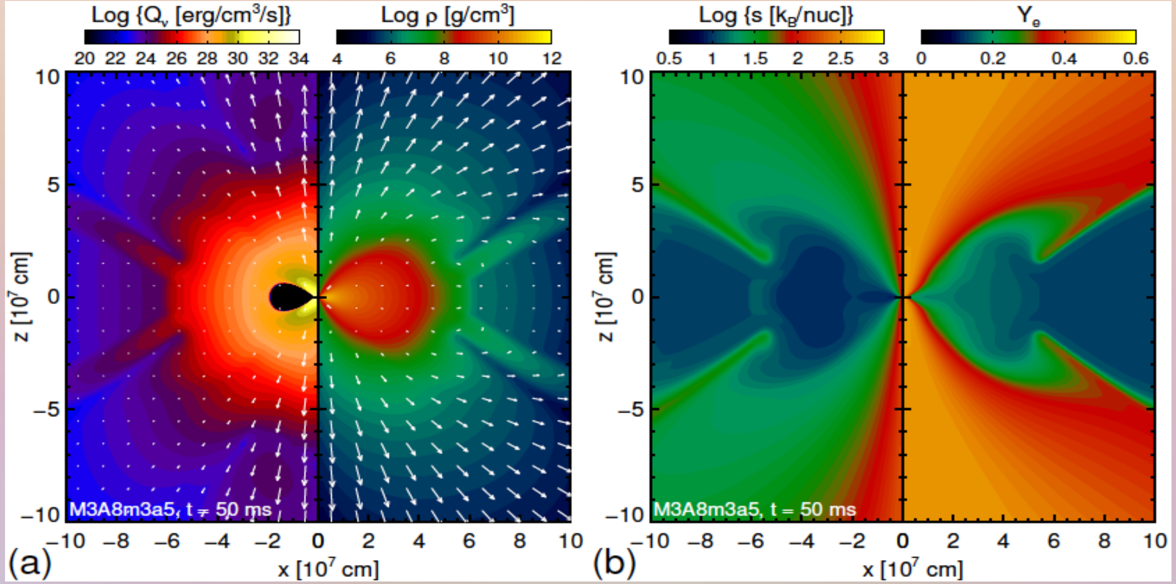


(Just et. al. '15)



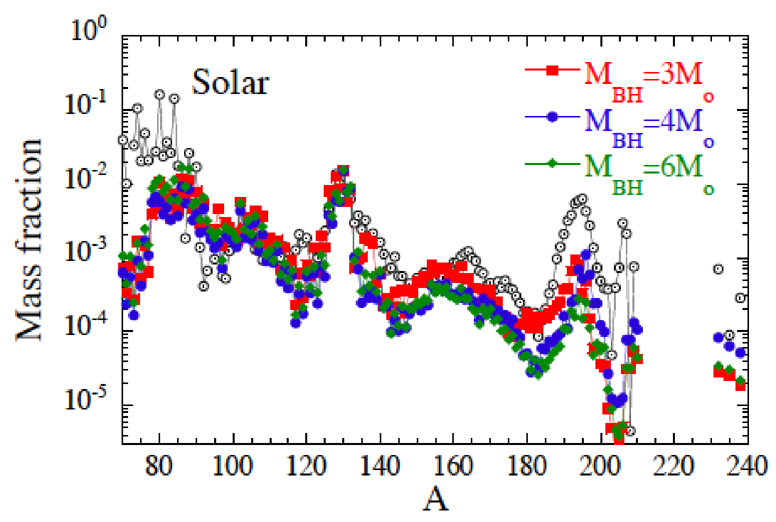
(Hotokezaka et. al. '13)

Ejecta from the remnant BH-torus system

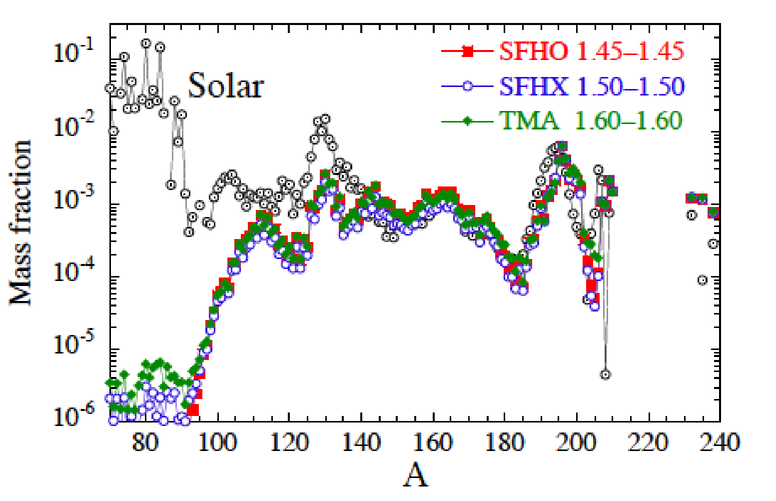


Combined nucleosynthesis yields

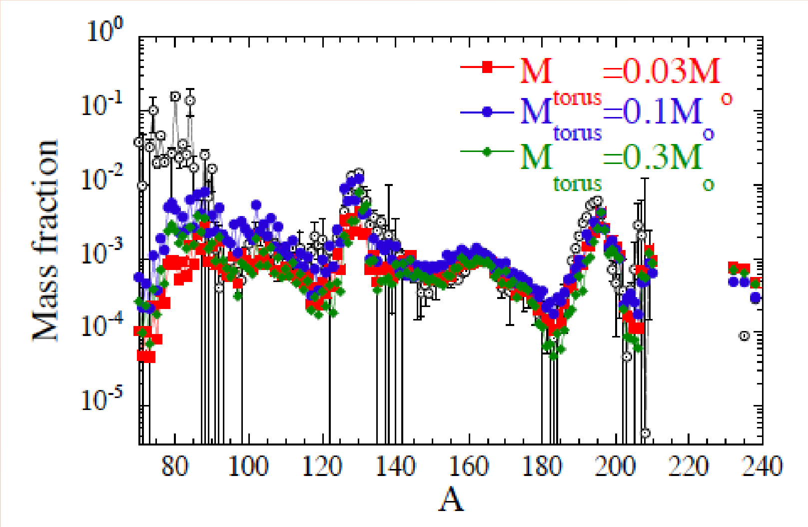
➔ DISK ejecta (mainly A ~ 90 - 140)



➔ PROMPT ejecta (mainly A ~ 140 - 210)



➔ DISK + PROMPT ejecta

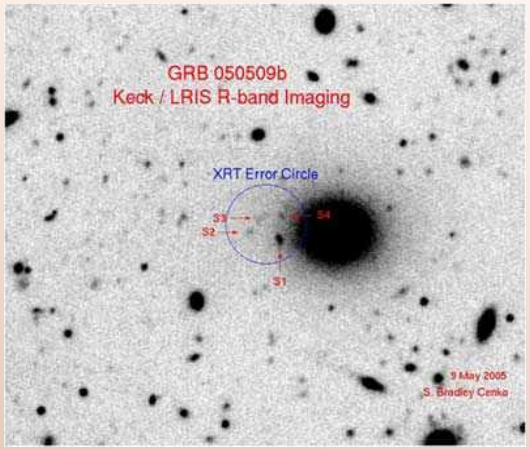


➔ nicely recovers the full mass range A > 90

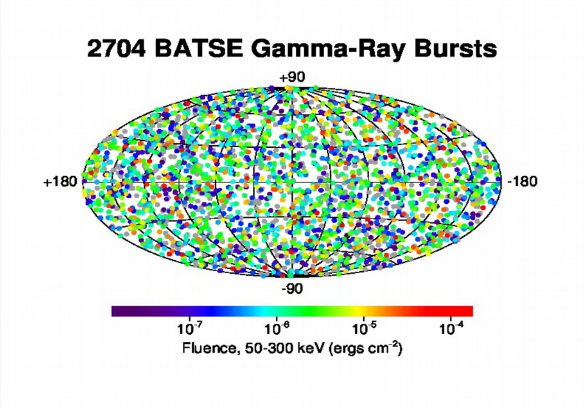
➔ BH-torus ejecta could be significant sources of intermediate mass elements with 90 < A < 140

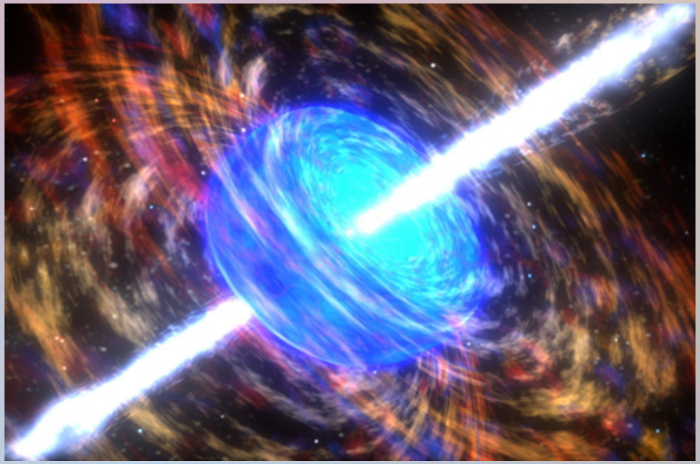
➔ observed scatter for 90 < A < 140 maybe explained by variable ratios of disk and prompt ejecta masses

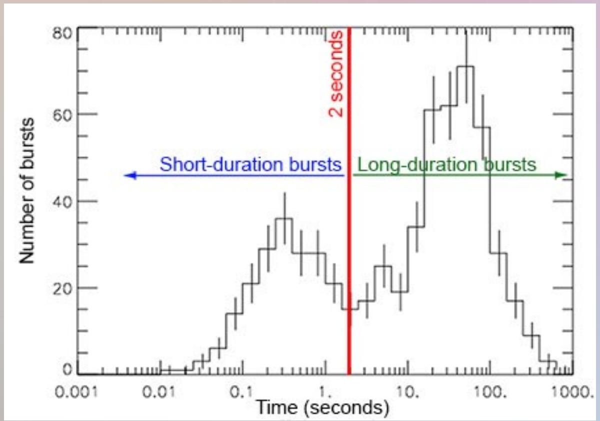
Gamma-Ray Bursts



- ➔ 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

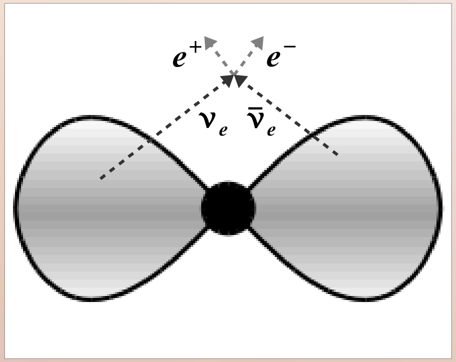






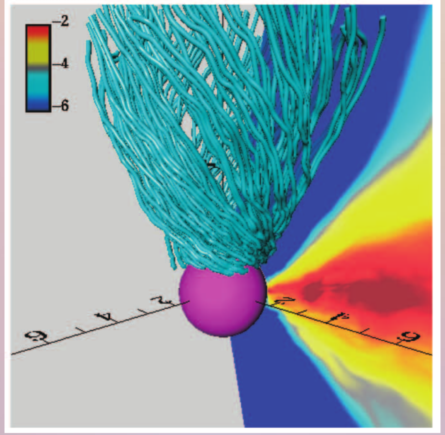
(NASA)

Popular central engine scenarios



➔ neutrino-pair annihilation

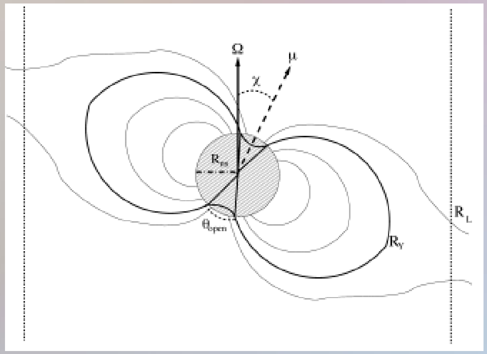
- neutrinos tap gravitational energy of disk
  e+-e- pairs thermalize → thermal fireball
- efficiency of converting gravitational energy into jet energy?
- baryon loading in the funnel?



(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?



(Metzger+ '11)

➔ magnetar spin-down emission

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

Is neutrino annihilation alone powerful enough to explain all sGRBs?

(Just+ '16, ApJL 816, 30)

- previous works mainly handicapped by complexity of radiation-HD
- conditions on the jet: **~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?

Setup of BH-Torus Models

- initial configurations are manually constructed **equilibrium tori** with properties given by simulations of **NS-NS and NS-BH** mergers
- **dynamical ejecta** mapped from SPH merger simulations performed by A. Bauswein
- special relativistic hydrodynamics **with pseudo-Newtonian** gravitational potential by Artemova → mimics the ISCO and BH spin
- most dominant **(electron) neutrino interactions** included:
  - ✔ *emission/absorption by nucleons*
  - ✔ *neutrino-nucleon scattering*
  - ✔ *neutrino-antineutrino annihilation*
- angular momentum transport: Shakura & Sunyaev **α-viscosity**
- simulations performed in **2D axisymmetry**

Model SFHO_145145: NS-NS Remnant

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

Model SFHO_1218: NS-NS Remnant

- **MOVIE**
- dynamical ejecta are slightly equatorially dominated
  $\rightarrow$ 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 TM1_1451: NS-BH Remnant

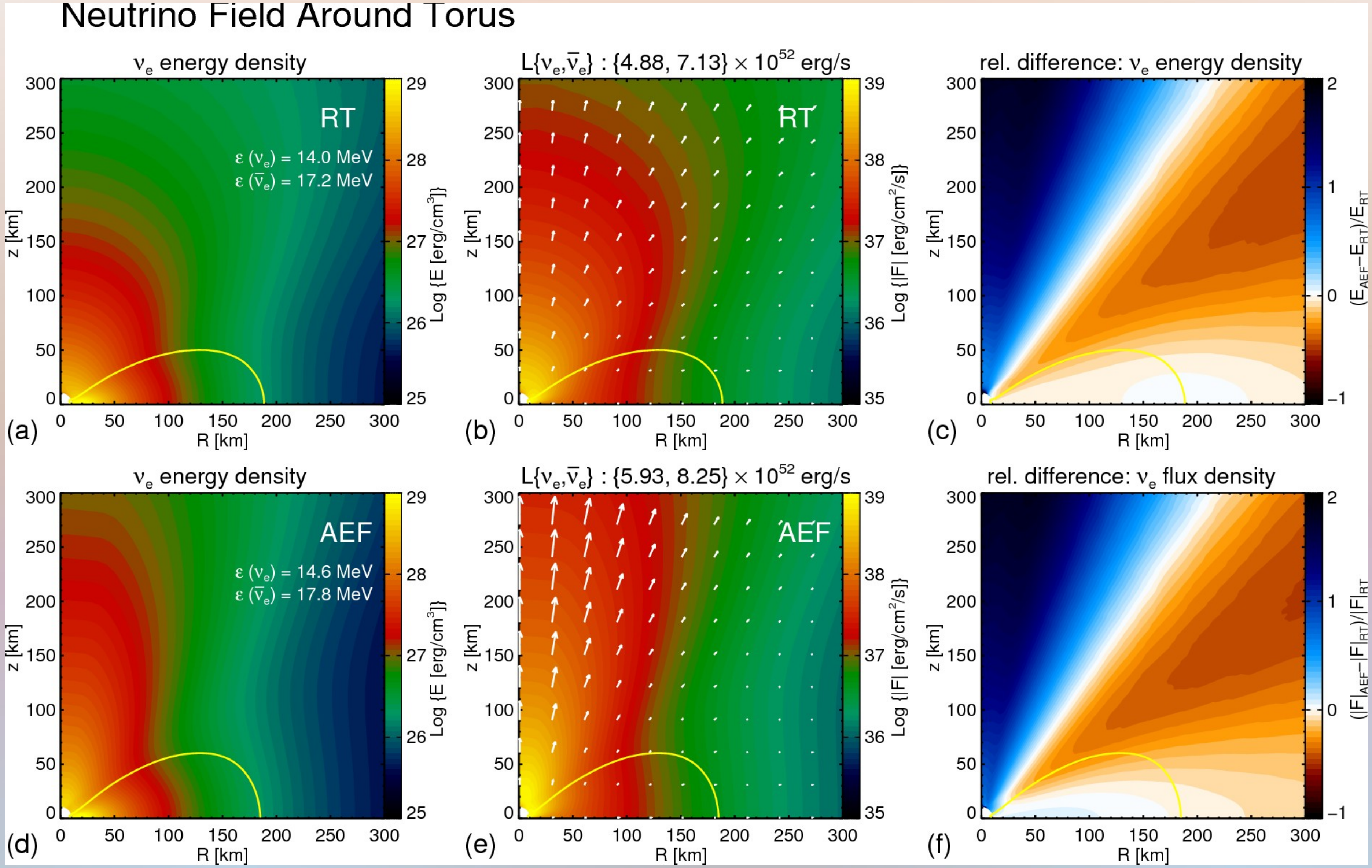
- **MOVIE**
- dynamical ejecta are ignored since they are almost exclusively ejected in equatorial plane
- **thermal fireball** is successfully launched
- annihilation energy is **efficiently converted to kinetic energy**
- jet can expand almost **unimpededly**
- amount of energy **sufficient** at least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

Summary

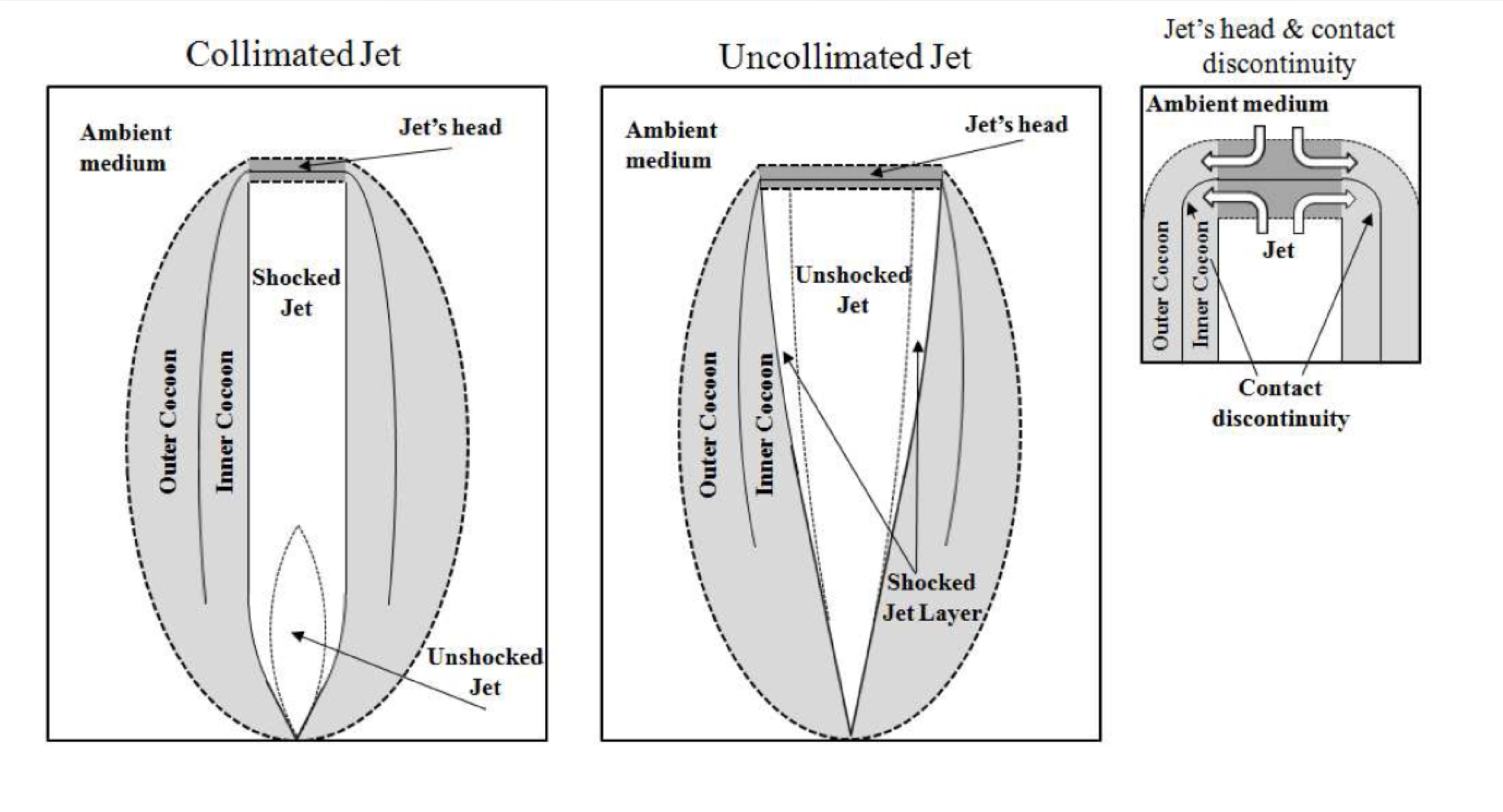
- NS mergers could be efficient "heavy element factories"
- using the **ALCAR** code we performed the first multi-group, neutrino-transport simulations of post-merger BH-torus systems
- *combined ejecta for both reproduce solar pattern in the full range of 90 < A < 240 → NS-mergers may well be main productions sites for all of these elements!*
- we also followed the relativistic jet expansion
- *results suggest that annihilation alone is insufficient and that MHD processes might be indispensable to explain sGRBs from NS-NS mergers and high-energy sGRBs from NS-BH mergers!*
- ***Exciting prospects: Hopefully very soon we will obtain GWs (and Kilonovae) from NS-NS/BH mergers → will allow us to test our models!***

Thank you for your attention!

Comparison Between M1 and Ray Tracing



Appendix: Jet expansion in external medium



(Bromberg et. al. '11)