Studying Post-merger Outflows from Magnetized Neutrino-cooled Accretion Disk Simulations

Fatemeh Hossein-Nouri, Agnieszka Janiuk, Michal Przerwa

Center for Theoretical Physics of the Polish Academy of Sciences

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Two ejecta components for Kilonova GW170817

- The light curves show a rapid decline in brightness and a rapid transition of the spectral peak from the UV to the IR.
- Both the light-curves and spectra resemble predictions for a ‘kilonova’ a transient powered by radioactive decay of heavy nuclei and isotopes synthesized through the *r*-process.
- This is the first demonstration that *r*-process nucleosynthesis occurs in neutron star binary mergers.
- The presence of transitory UV emission, followed by the longer term IR emission hints at two ejecta components:

1- **Dynamical ejecta**: Lower-mass, high-velocity, neutron-rich component (merger) => Dimmer and red/IR emission

2- **Disk winds outflows:** Slower, higher-mass, less neutron-rich component (post-merger) => Brighter and blue

The total ejected mass is ~ 0.03-0.06 of a solar mass.

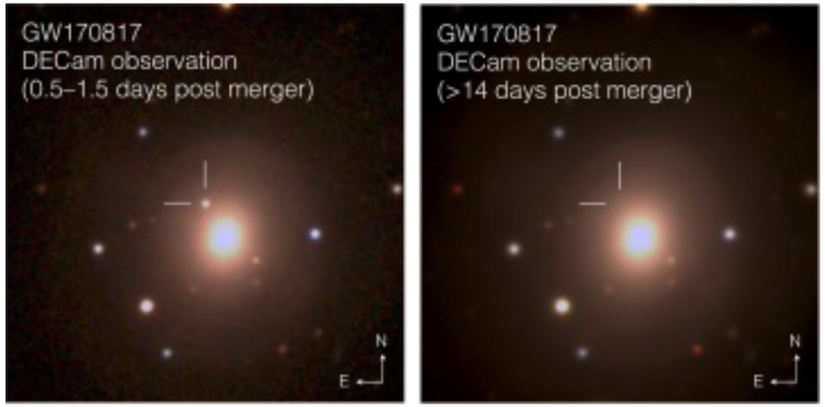
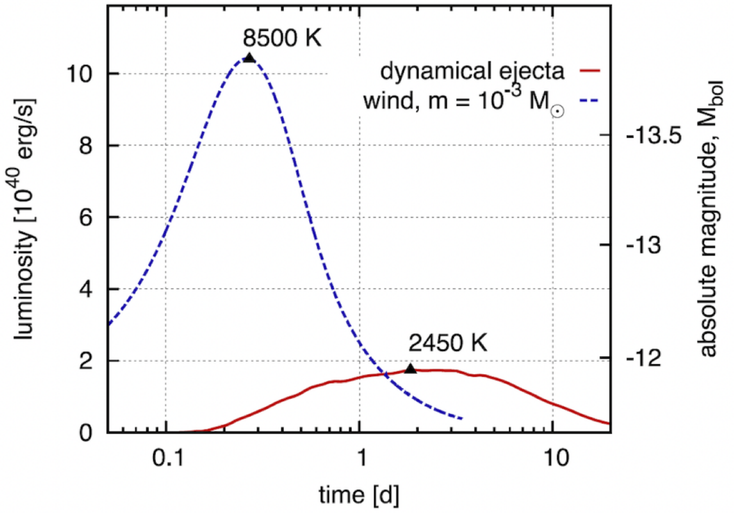


Figure 1 from Soares-Santos, M., et al. "The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera." 2017, ApJL, 848, L16.



Grossman et al. (2014)

Post-merger accretion disk systems are cool!

Magnetized BHNS/NSNS post merger accretion disks:

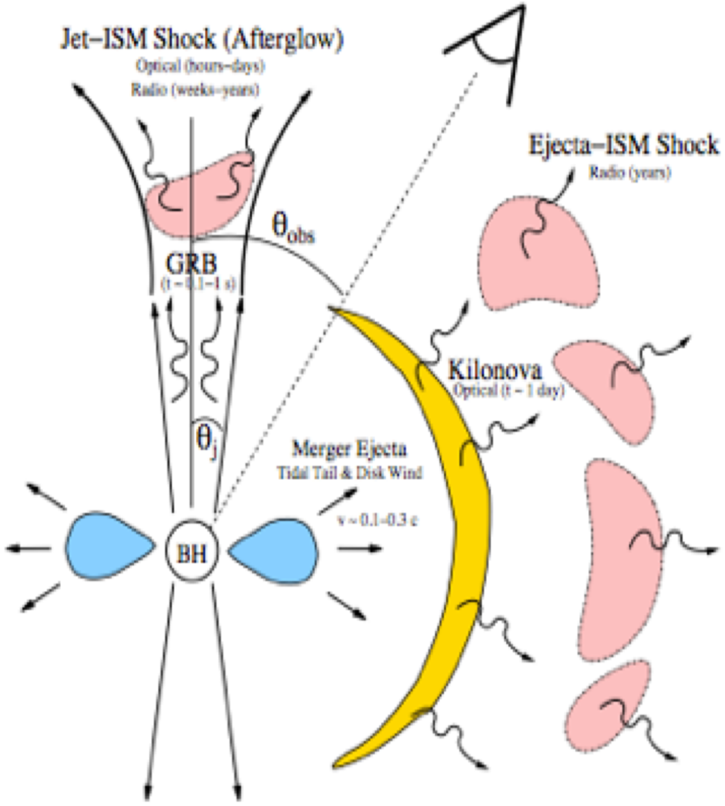
- Formation of the relativistic jets, short GRBs and afterglows through BZ mechanism
- Creating neutron-rich post-merger outflows (caused by MRI) for r-process to generate kilonova and other possible electromagnetic counterparts

➢ **Magnetic field**

- Magnetorotational instability (MRI), turbulence
- **Magnetically-driven winds**
- Viscous heating
- Create jets

➢ **Neutrinos**

- Disk cooling
- Composition evolution
- **Neutrino-driven winds**

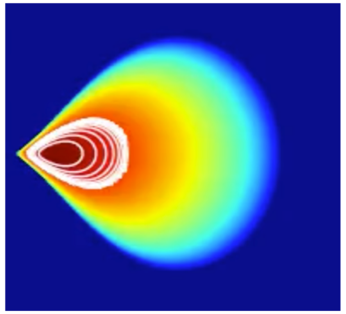


Metzger & Berger 2012

Numerical Setup and Initial Data

- HARM_COOL finite volume code with HLL shock capturing scheme.
- Using the analytical solution of accretion disk around and Kerr BH

  (Fishbone & Moncrief 1976)
- BH spin [-0.9,+0.98]
- Disk mass [0.01,0.3] $M_\odot$



Neutrino treatment (Janiuk et al. 2013)
The neutrino optical depth for different species are approximated as: (De Matteo et al. 2002)

$$\tau_{\mathrm{a},\nu_\mathrm{i}} = \frac{H}{4\frac{7}{8}\sigma T^4} q_{\mathrm{a},\nu_\mathrm{i}},$$

$$Q_\nu = \frac{(7/8)\sigma T^4}{(3/4)} \sum_{i=e,\mu,\tau} \frac{1}{0.5(\tau_{a,i} + \tau_s) + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_{a,i}}}$$

- **Equation of state:** Realistic nuclear matter composed of free protons, neutrons, electron–positron pairs, and helium nuclei. (Reddy et al. 1998), considering weak interactions to determine neutrino opacities in hot dense matter.
- **Initial magnetic field** has pure poloidal configuration and confined within the torus.

$$\beta = P_{\mathrm{gas,max}}/P_{\mathrm{B,max}} = 50$$

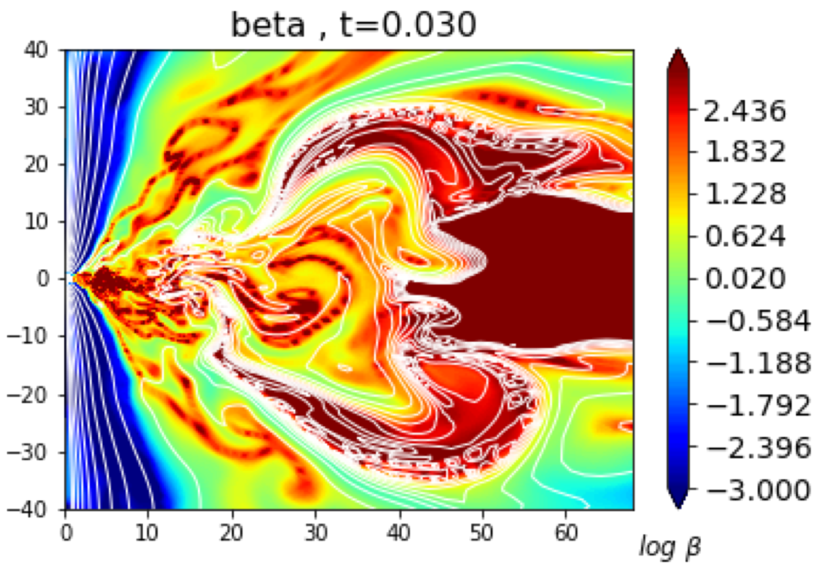
- The grid is 2D spherical coordinated with resolution 384*300 for (r, θ) running on 96 cores
- Evolution time: ~0.2 s
- Particle tracer technique is used to measure the outflows.

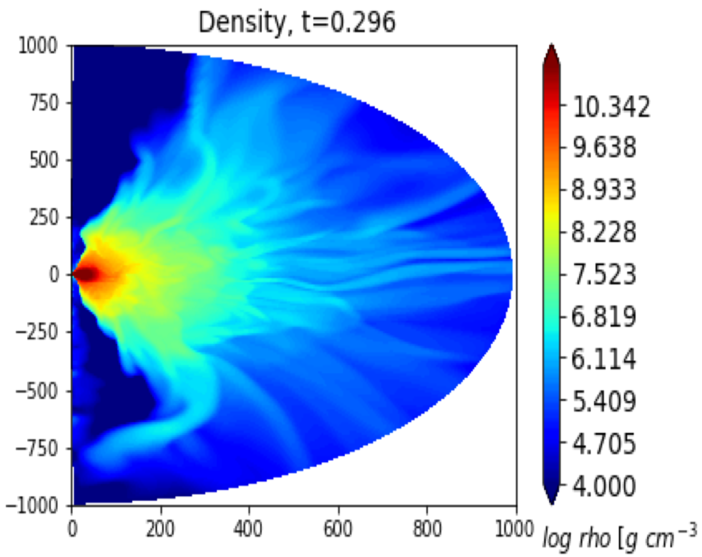
Magnetized Accretion Disk Models

Model	BH Mass [$M_\odot$]	BH Spin	M_{disk} [$M_\odot$]	r_{in}	r_{max}	l_{FM}	mass ratio
*M1.0-0.14-a0.98	1.0	0.98	0.14062	6	12	4.293	0.14
M1.0-0.14-a0.9	1.0	0.9	0.14062	6	12	4.293	0.14
M1.0-0.14-a0.6	1.0	0.6	0.14062	6	12	4.293	0.14
M1.0-0.14-a0.2	1.0	0.2	0.14062	6	12	4.293	0.14
*M5.0-0.3-a0.9	5.0	0.9	0.3120	6.5	13.4	4.44	0.3
M1.5-0.1-a0.9	1.5	0.9	0.09722	5.4	11	4.189	0.0635
M2.0-0.05-a0.9	2.0	0.9	0.04548	4.8	9.75	4.0617	0.0225
M2.65-0.1-a0.9	2.65	0.9	0.10276	3.8	9.75	4.0617	0.0265
*M6.0-0.14-aR0.6	6.0	0.6	0.14213	7.8	16.8	5.148	0.024
M6.0-0.14-a0.6	6.0	-0.6	0.14213	7.8	16.8	5.148	0.024
Cases to test the outflow measurements accuracy							
*High resolution 480*426 grid for M2.65-0.1-a0.9							
*Lower density threshold for tracers for M2.65-0.1-a0.9							
*Measuring tracers at $r = 400r_g$ for M2.65-0.1-a0.9							
*Measuring tracers at $r = 120r_g$ for M2.65-0.1-a0.9							

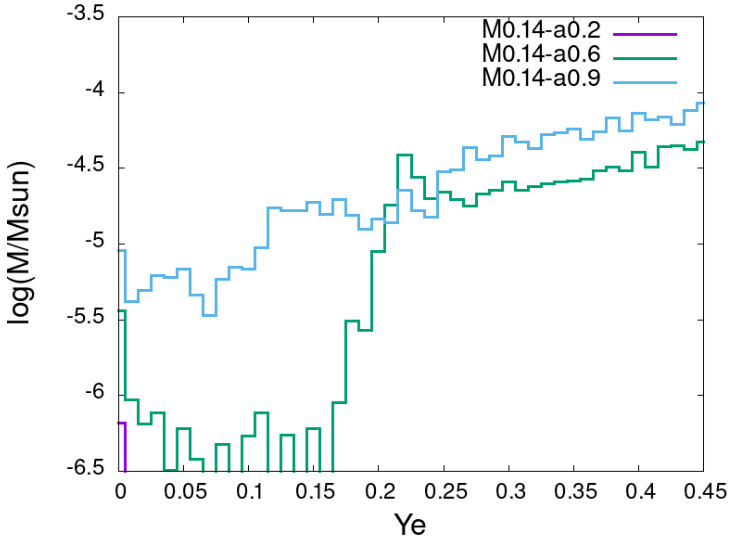
Table 1. Different disk setup for numerical simulations.

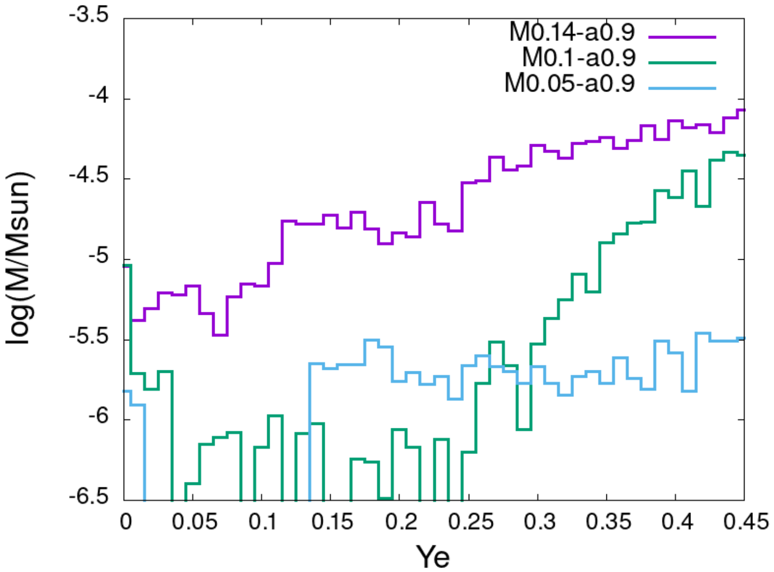
Disk Evolution and wind composition





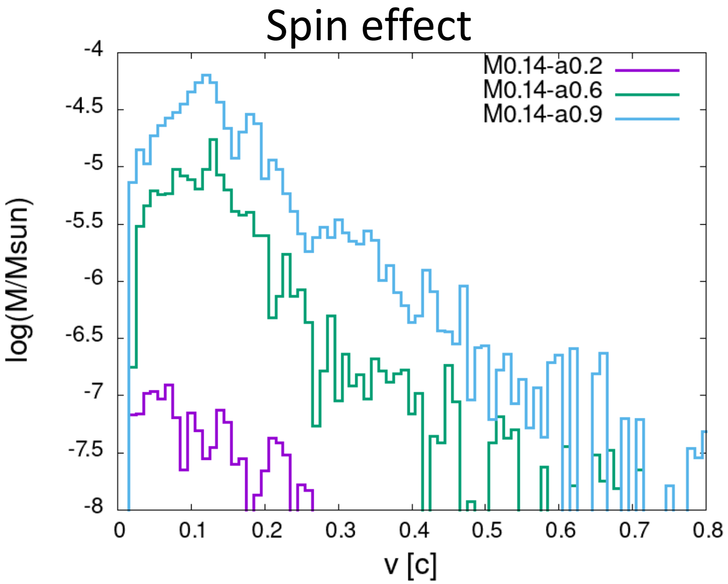
Magnetic field is amplified during the evolution and we have angular momentum transport cause by magnetorotational instability

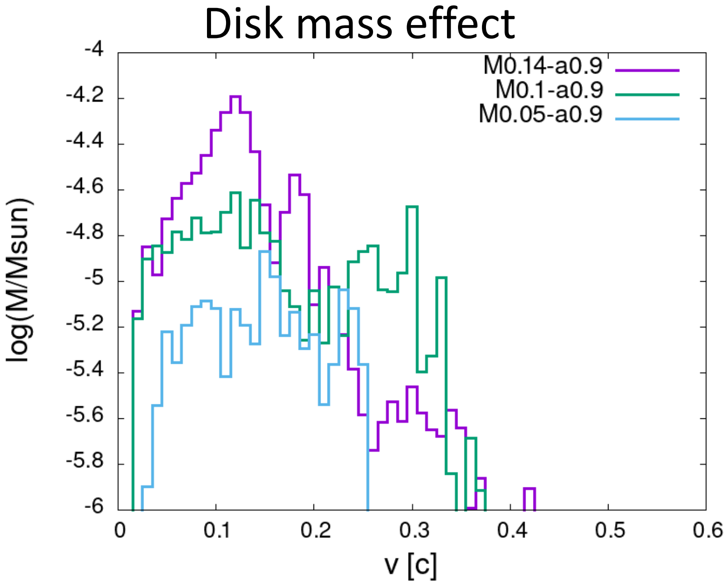




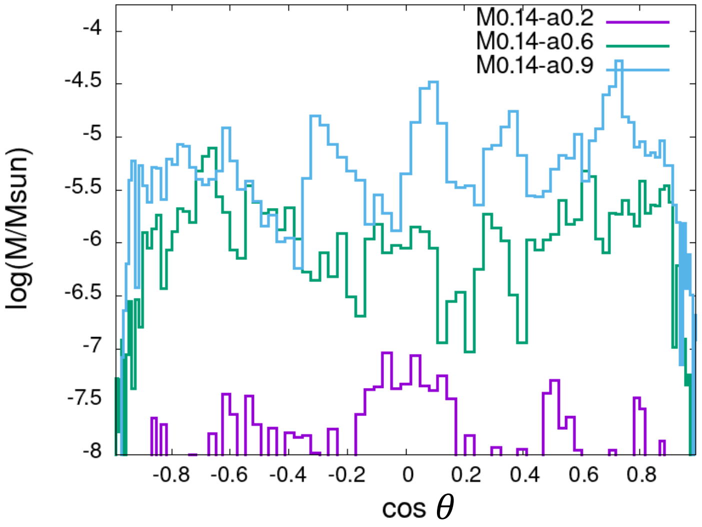
The outflow is dominated by less neutron rich matter $Y_e > 0.25$

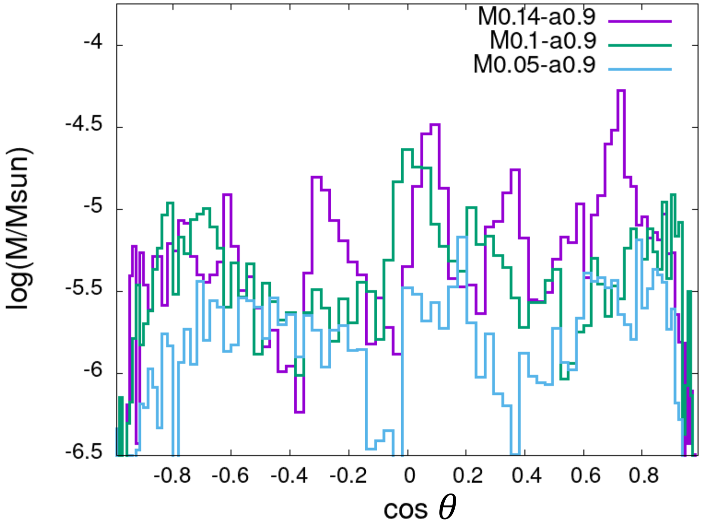
Outflows: Velocity and Geometry





Mass distribution verses velocity histogram.





Mass distribution verses polar angel histogram.

Outflows: General features

Model	Outflow Mass [$M_\odot$]	average Y_e	average v [c]
M1.0-0.14-a0.9	8.387×10^{-4}	0.37	0.2017
M1.0-0.14-a0.6	1.828×10^{-4}	0.4	0.1745
M1.0-0.14-a0.2	1.24×10^{-6}	0.43	0.1430
M2.0-0.05-a0.9	2.466×10^{-4}	0.39	0.1987
M1.5-0.1-a0.9	7.513×10^{-4}	0.39	0.1692
M6.0-0.14-aR0.6	3.927×10^{-5}	0.42	0.1284
M2.65-0.1-a0.9	5.654×10^{-4}	0.4	0.1532

The model with higher BH spin and disk mass generates winds with higher mass and higher velocity.

Estimating peak values for transients:

Grossman et al. (2014)

$$t_{\rm peak} = 4.9\ {\rm d} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{\frac{1}{2}} \left(\frac{\kappa}{10\ {\rm cm^2 g^{-1}}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm ej}}{0.1}\right)^{-\frac{1}{2}},$$

$$L_{\rm peak} = 2.5 \cdot 10^{40}\ {\rm erg\ s^{-1}} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{1-\frac{\alpha}{2}} \left(\frac{\kappa}{10\ {\rm cm^2 g^{-1}}}\right)^{-\frac{\alpha}{2}} \left(\frac{v_{\rm ej}}{0.1}\right)^{\frac{\alpha}{2}},$$

$$T_{\rm peak} = 2200\ {\rm K} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{-\frac{\alpha}{8}} \left(\frac{\kappa}{10\ {\rm cm^2 g^{-1}}}\right)^{-\frac{\alpha+2}{8}} \left(\frac{v_{\rm ej}}{0.1}\right)^{\frac{\alpha-2}{8}}.$$

$$\alpha = 1.3$$

Model	t_{peak}[d]	L_{peak} [erg/s]	T_{peak} [K]
M1.0-0.14-a0.9	0.27	6.62×10^{40}	8430
M1.0-0.14-a0.6	0.15	2.825×10^{40}	11350
M1.0-0.14-a0.2	0.016	5.15×10^{39}	...
M2.0-0.05-a0.9	0.13	4.04×10^{40}	10567
M1.5-0.1-a0.9	0.24	5.16×10^{40}	9106
M6.0-0.14-aR0.6	0.086	1.89×10^{40}	13689
M2.65-0.1-a0.9	0.298	5.39×10^{40}	8738

κ=1 cm^2 g^{-1} is the average opacity for lanthanide-free ejecta (more transparent compared with dynamical ejecta)

Estimating Light-curves from the ejected matter:

Kawaguchi et al. (2016):

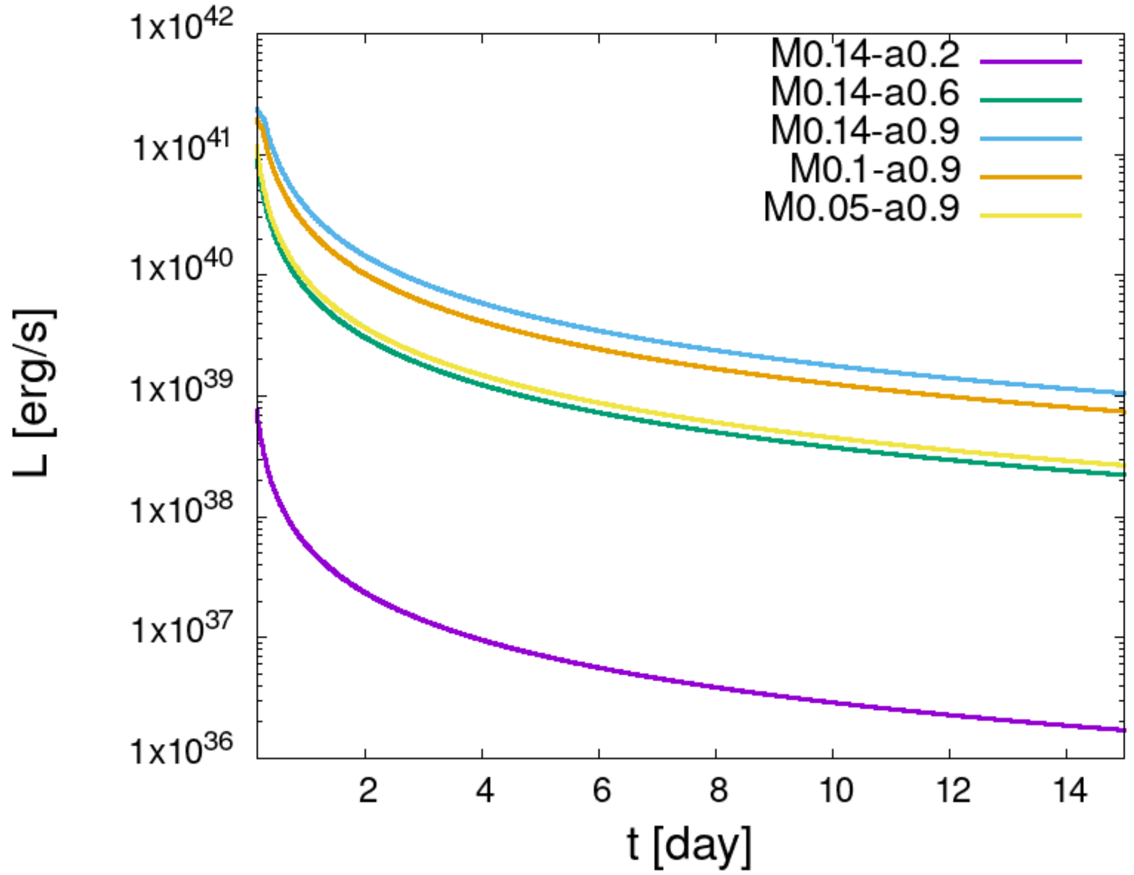
$$L_{\rm bol}(t) = (1+\theta_{\rm ej})\epsilon_{\rm th}\dot{\epsilon}_0 M_{\rm ej} \begin{cases} \frac{t}{t_c}\left(\frac{t}{1\ \rm d}\right)^{-\alpha}, & t \leqslant t_c \\ \left(\frac{t}{1\ \rm d}\right)^{-\alpha}, & t > t_c \end{cases},$$

Specific heating for energy release caused by radioactive decay:

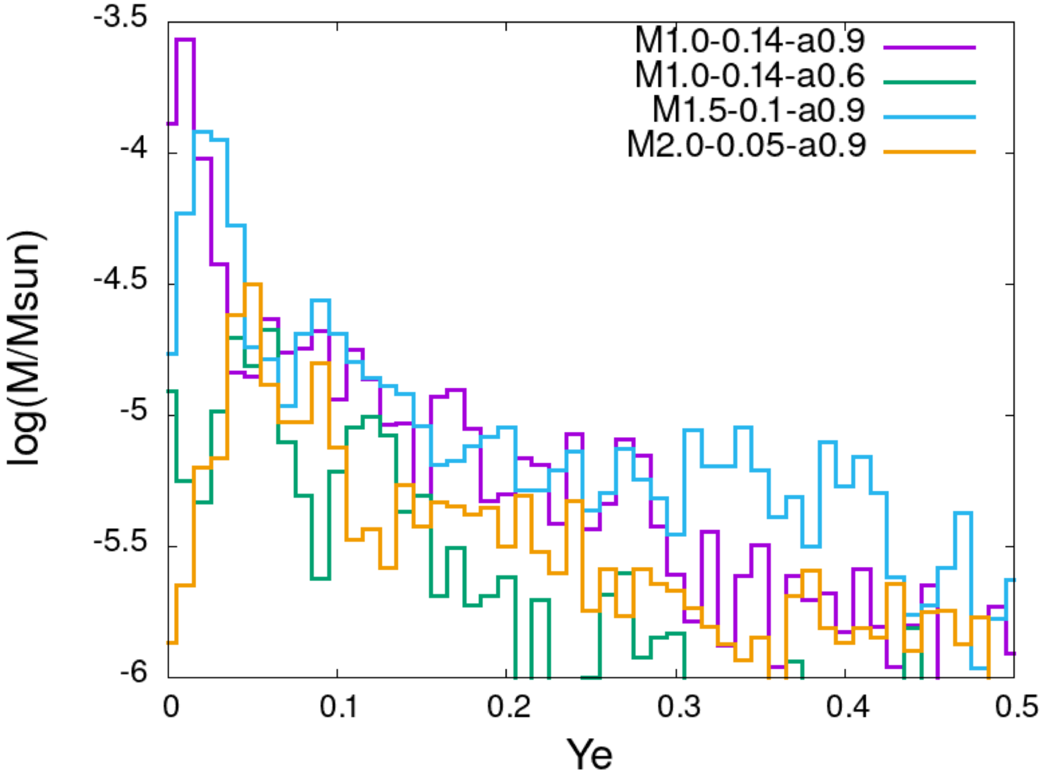
$$\dot{\epsilon}_0 = 1.58 \times 10^{10} \mathrm{erg\ g^{-1}\ s^{-1}}$$

The efficiency of thermalization $0.5 < \epsilon_{\rm th} < 1$

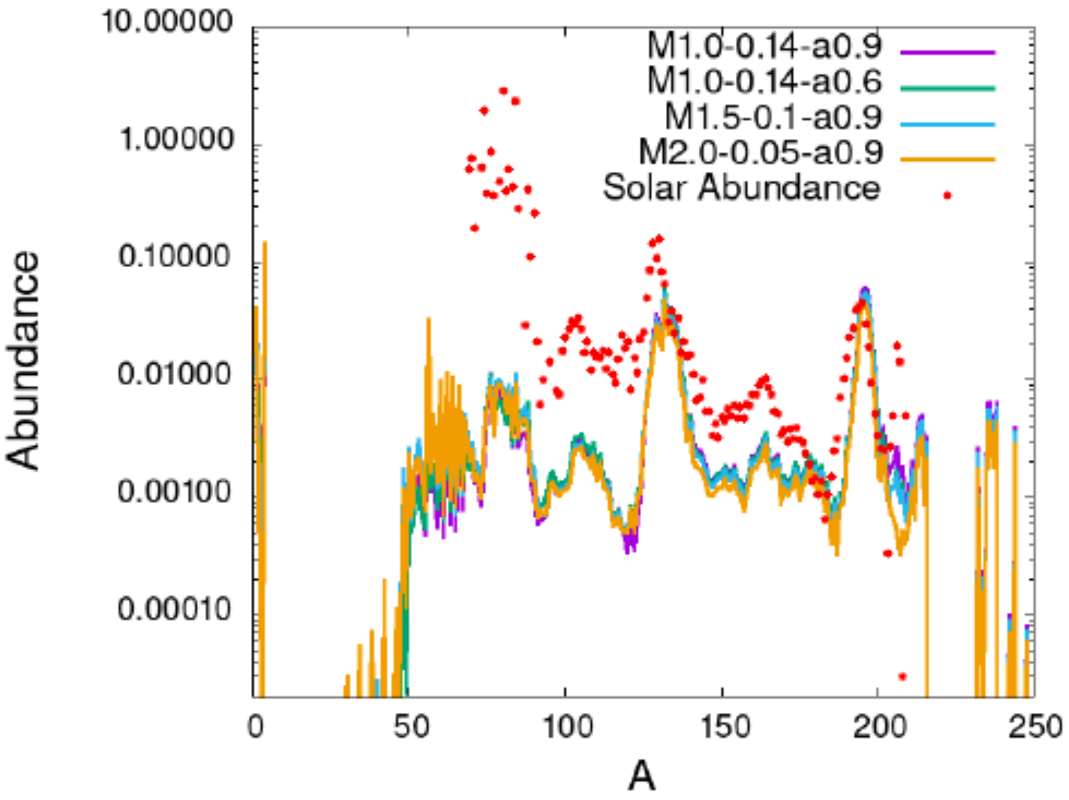
$$t_c = \sqrt{\frac{\theta_{\rm ej}\kappa M_{\rm ej}}{2\phi_{\rm ej}(v_{\rm max} - v_{\rm min})}},$$



R-process and Abundances



Mass distribution verses electron fraction after applying r-process nucleosynthesis.



Nuclear abundances as a function of mass number A, based on average of tracers sampling the outflows.

Alternative ways to measure outflows

Ideally we want long-term 3D simulations (few seconds) with r-process heating and neutrino cooling source terms included in the hydro evolution equations.

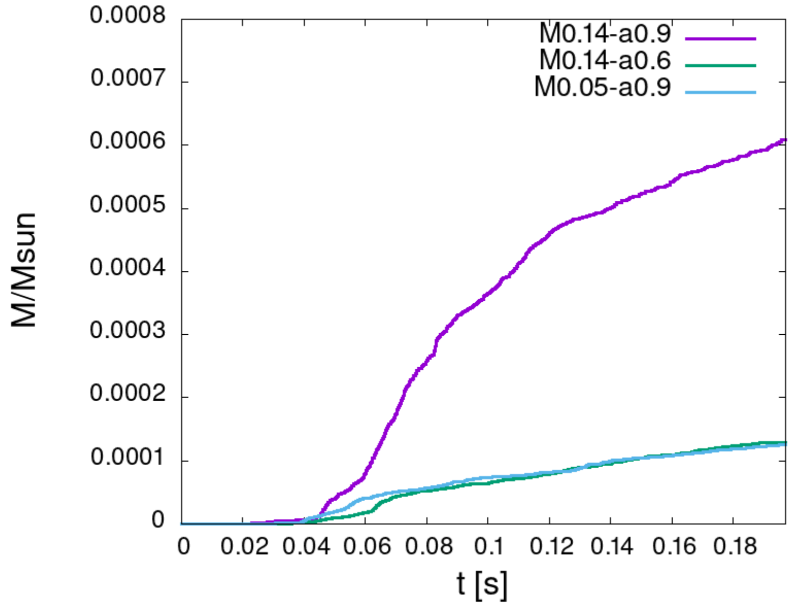
Criteria to identify the unbound matter, Foucart et al. (2021):

A: Geodesic: $u_t < -1$

B: Bernoulli: $hu_t < -1$

C: Modified Bernoulli (r-process heating and neutrino cooling are including) $hu_t\,(0.9968+0.0085\,Y_e) < -1$

Model	$M_{ej,tracers}$	$M_{ej,B}$
$M1.0-0.14-a0.9$	6.076×10^{-4}	0.003740



Evolution of the cumulative outflow mass launched from the disk measure by tracers.

Other tests: Grid resolutions, radius of extracting the outflow tracers and density thresholds to mark the active tracers.

Summary and Conclusions

- We observed our models generate winds with moderate velocity ($v/c \sim 0.1$-0.2).
- Disks with higher mass and spin generates more outflows with higher speed.
- Disks with higher mass and spin produce more neutron-rich outflows.
- For all cases, the average Y_e stands higher than the threshold $Y_e \sim 0.25$, where the ejecta is likely lanthanide free.
- We use these results to estimate the luminosity and light curves of possible radioactively powered transients. We found the luminosity peaks within the range of $\sim 10^{40}$-10^{41} erg/s, which agrees with previous studies for neutrino-driven and viscous disk wind models.

Thank you for your attention!