Jets and winds from gamma ray bursts

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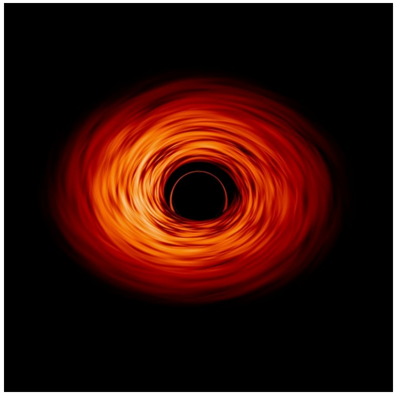
Plan of the talk

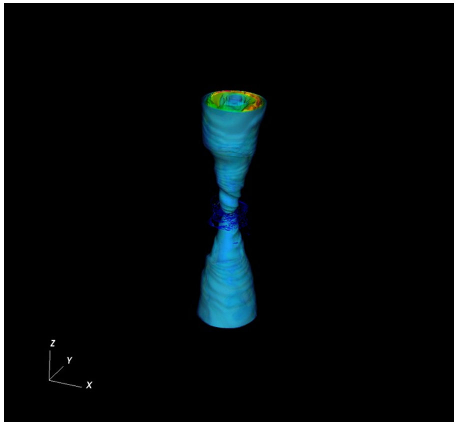
1. Introduction, short and long GRBs, gravitational waves

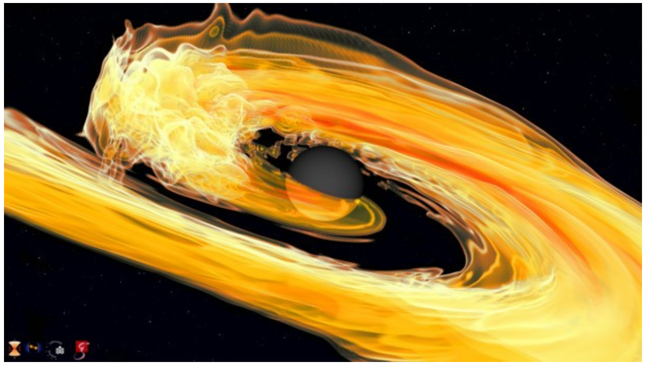
2. GRB central engine, numerical simulations

3. Nuclear physics and kilonova modeling

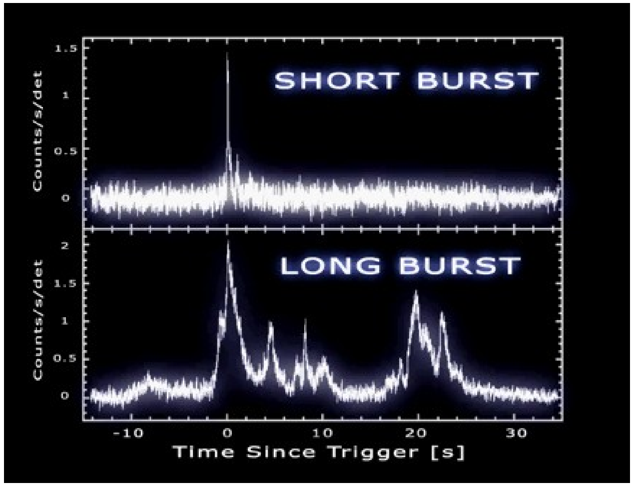
4. Jets and their variability





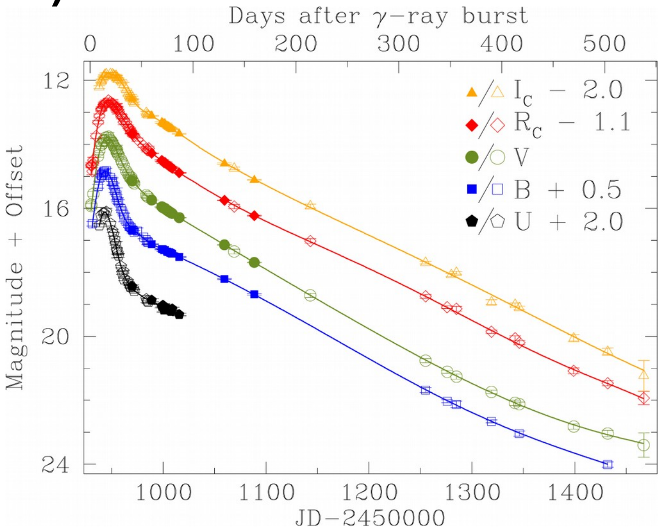


Gamma Ray bursts



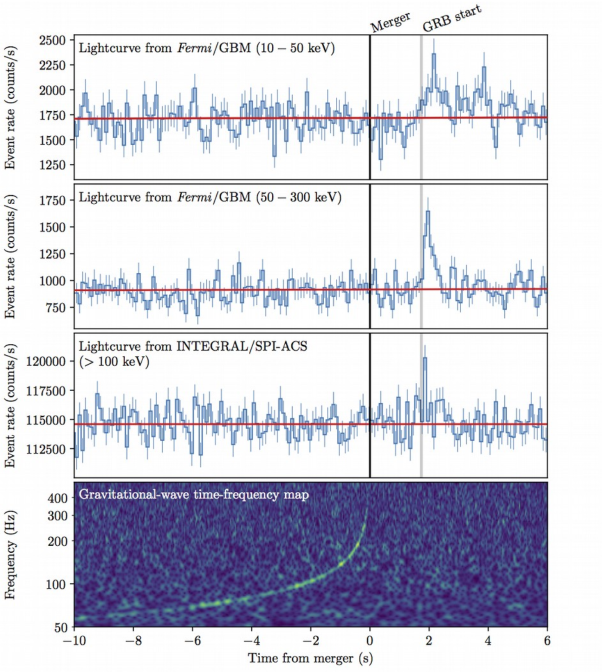
Rapid, bright flashes of radiation peaking in the gamma-ray band

First association of long event: GRB 980425 and SN 1998bw (Kuulkarni et al. 1998)

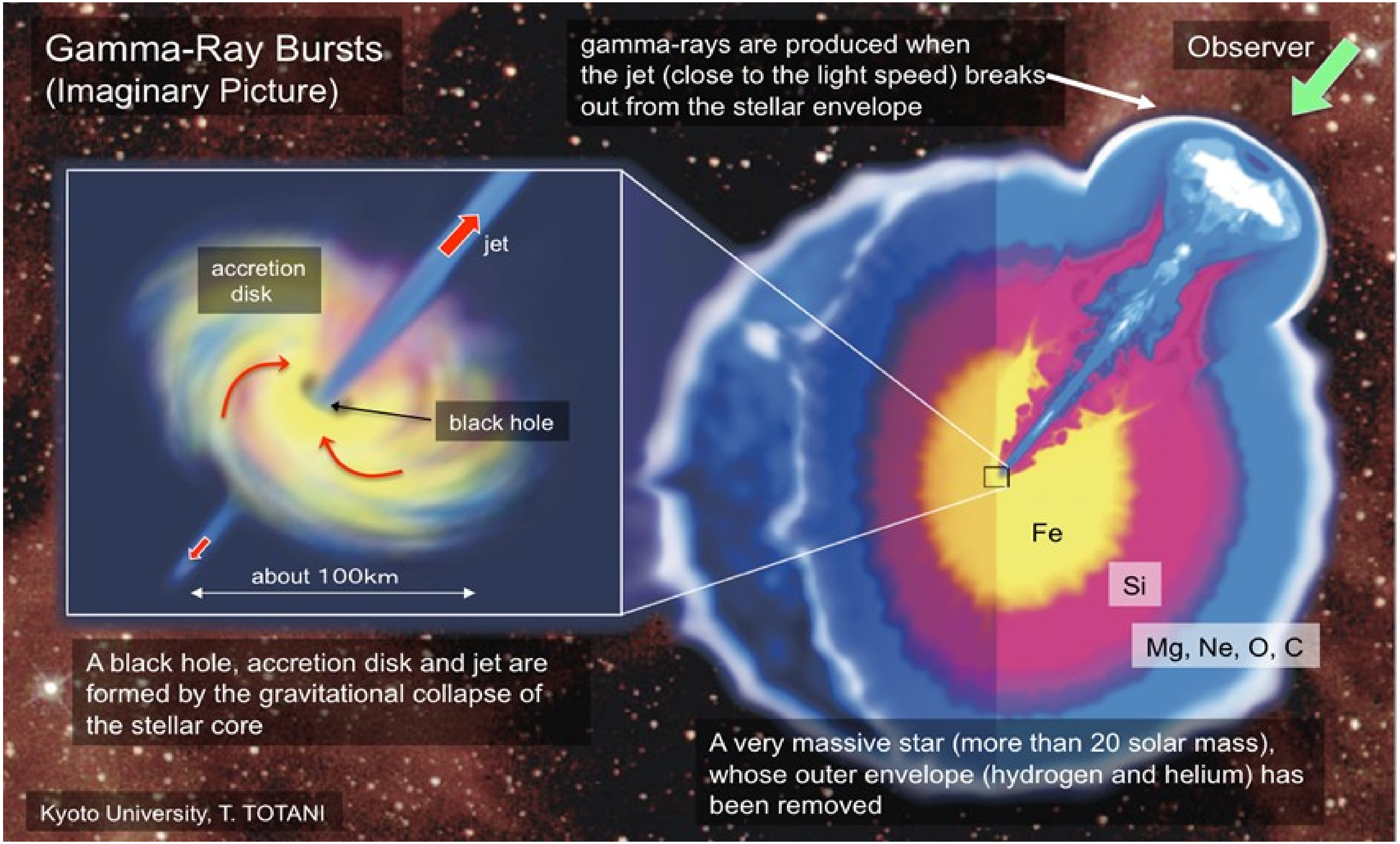


Complete lightcurve from Clochiatti et al. (2011)

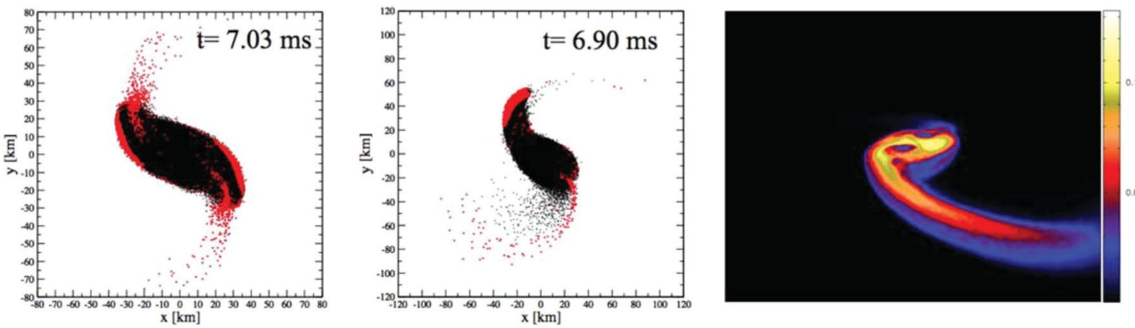
Confirmed source of short GRB: GW170817 (Abbott et al. 2017)



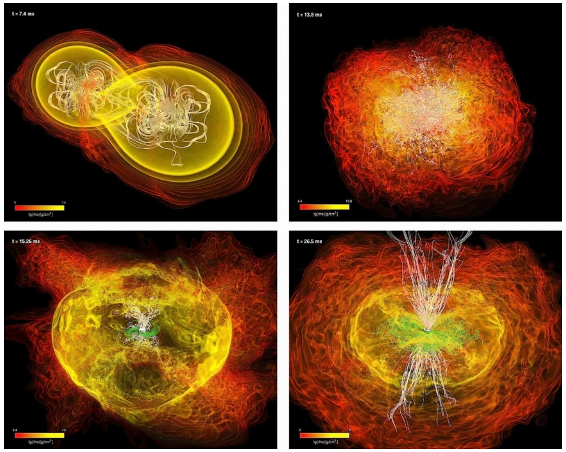
Long GRBs: collapsing massive stars



Short GRBs: Compact binary mergers

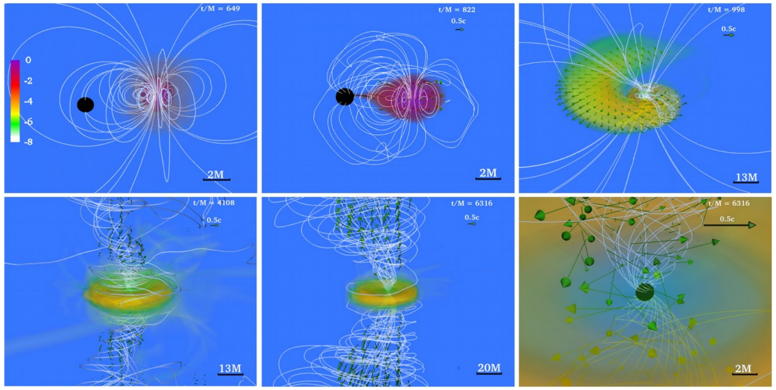


Korobkin et al. 2012

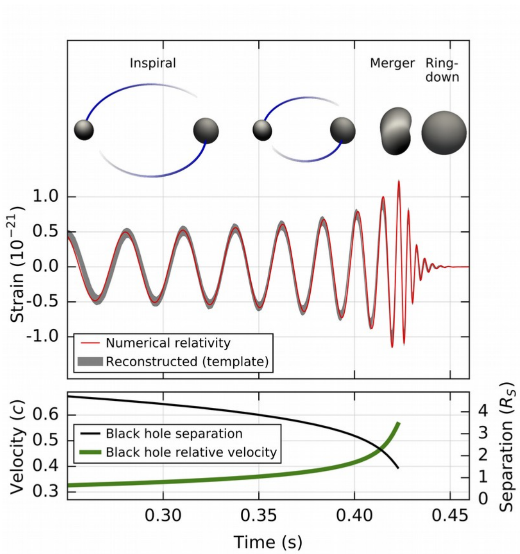


Rezzolla et al. 2014

Numerical simulations allow to study the mergers (or for a small fraction, collisions) of NSNS and NSBH systems (e.g. Shibata, Baumgarte & Shapiro 2000).



Paschalidis et al. 2015



Gravitational waves

Transverse deformation of the spacetime curvature, propagating with the speed of light

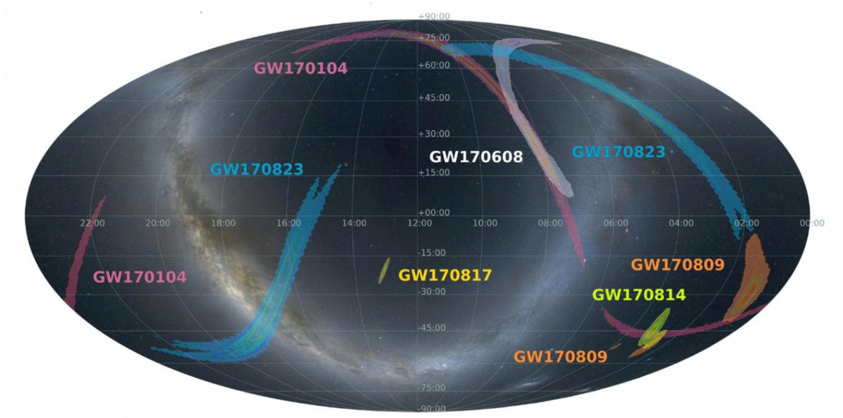
Source of gravitational waves is the mass moving with acceleration

Numerical relativity methods: 3+1 decomposition (Baumgarte, Shibata, Shapiro, Nakamura, 1990's); BBH spacetime evolution F. Pretorius (2005), M. Campanelli et al. (2006)

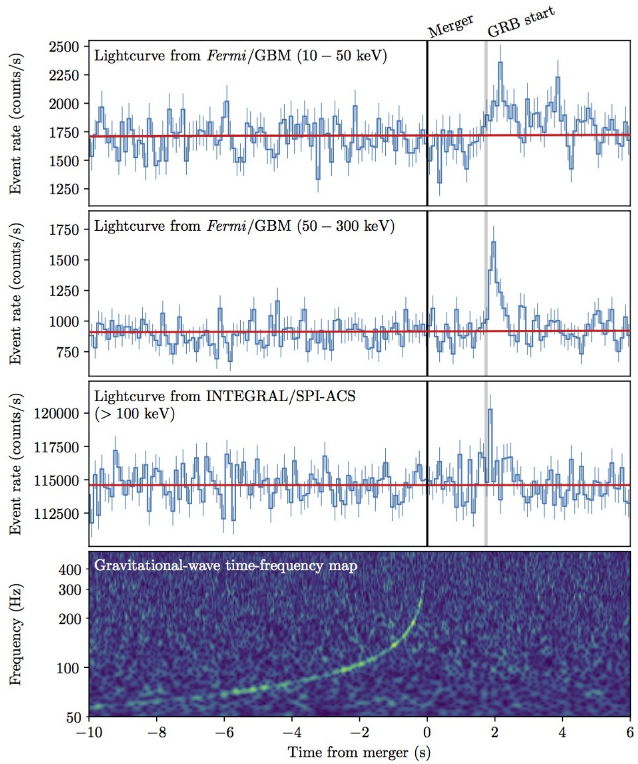
Nobel Prize in Physics: 2017 (K. Thorne, B. Barrish, R. Weiss)

GW 170817

Double neutron stars formed a black hole after their merger.
During the inspiral phase, **gravitational waves** were produced
After the merger, gamma-ray telescopes observed a **burst** of energy.
The time delay of 1.7 s may be associated with formation of HMNS



Rapidly fading electromagnetic transient in the galaxy NGC4993, was spatially coincident with GW170817 and a weak short gamma-ray burst (e.g., Smartt et al. 2017; Zhang et al. 2017, Coulter et al. 2017)



Other mergers: BNS and BH-NS

The first part of the O3 run (O3a) have led to the identification of 48 binary black hole (BBH) candidates (Abbott et al. 2019c, 2021b) and two BNS candidates (Abbott et al. 2017a, 2020d)

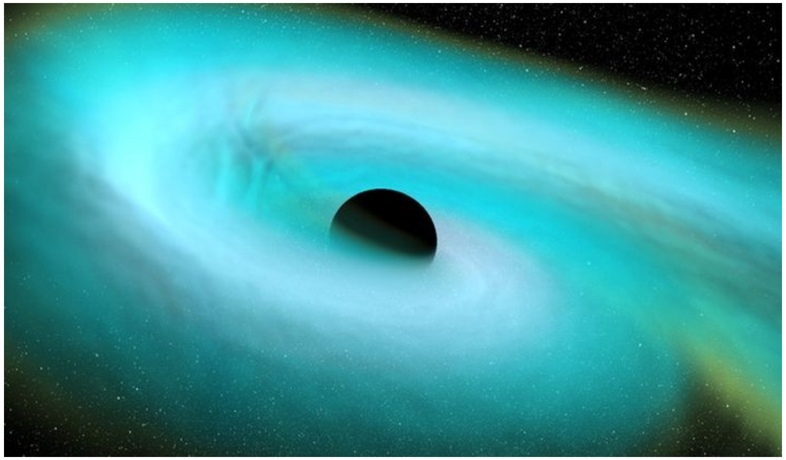
GW190814:

Gravitational Waves from the coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. The source was localized to 18.5 deg^2 at a distance of 241_{-45}^{+41} Mpc. The source has the most unequal mass ratio yet measured.

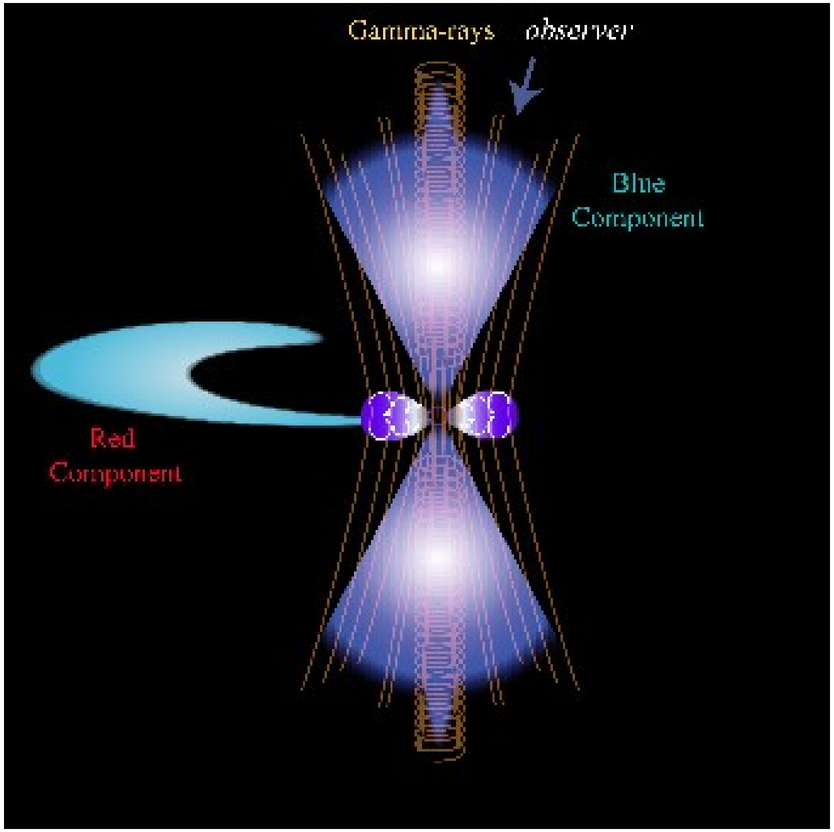
No electromagnetic counterpart has been confirmed to date.

GW200105 and GW200115

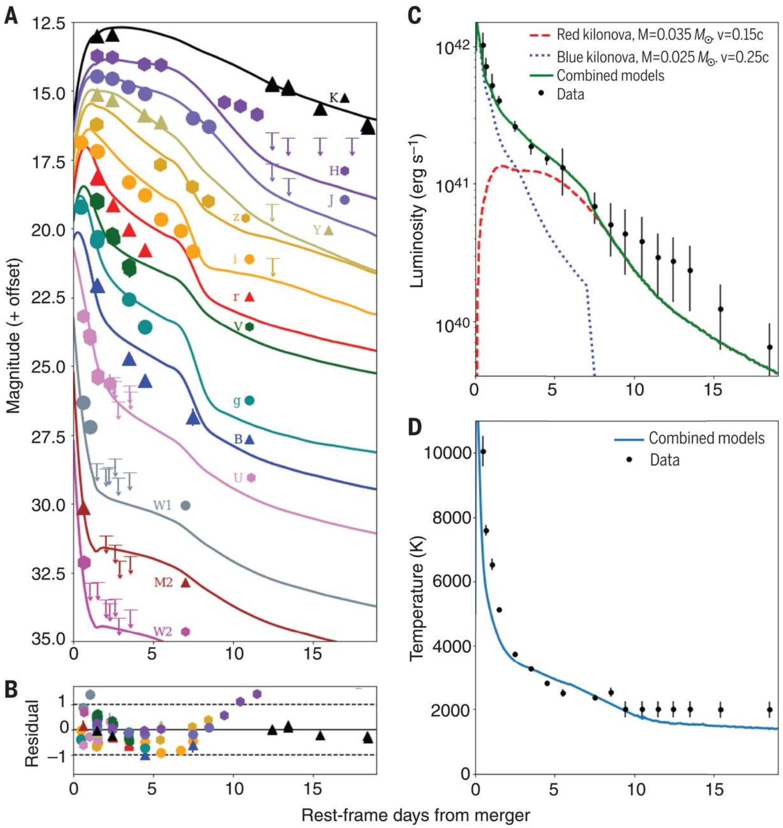
Gravitational Waves from Two Neutron Star–Black Hole Coalescences.



Blue and red kilonova lightcurve



Schematic idea of the GW170817 system
(Murguia-Berthier et al. 2017).



Blue and the red light from a kilonova, compared to observational data for the transient SSS17a, associated with GW170817 (Kilpatrick et al. 2017).

Disk wind and jet: two types of outflow in GRBs

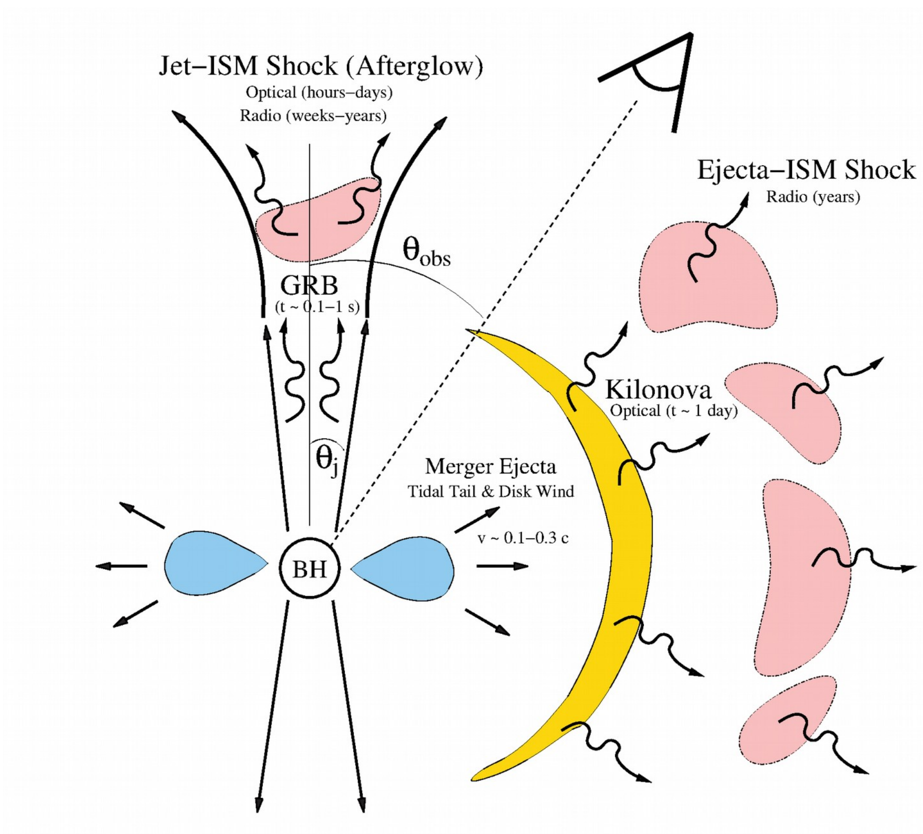


fig. B. Metzger (Living Reviews in Relativity, 2020).

Potential electromagnetic counterparts of compact object binary mergers as a function of the observer viewing angle.

Rapid accretion of a centrifugally supported disk (blue) powers a collimated relativistic jet, which produces a short GRB.

Equatorial outflows contribute to lower-energy signal.

Both are powered by the Central Engine.

GR MHD simulations of accretion

$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$

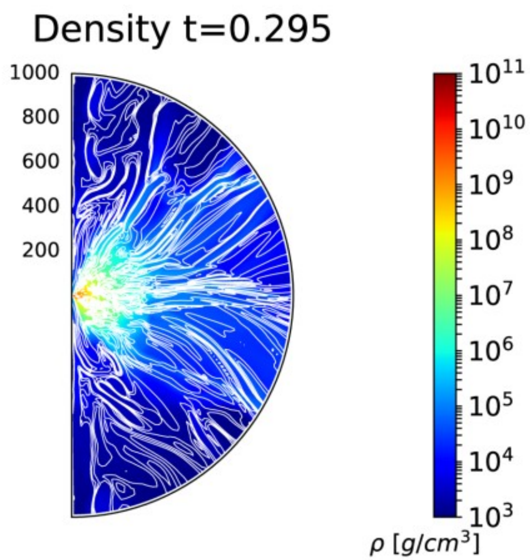
$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$

$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

$$(\rho u_\mu)_{;\nu} = 0$$

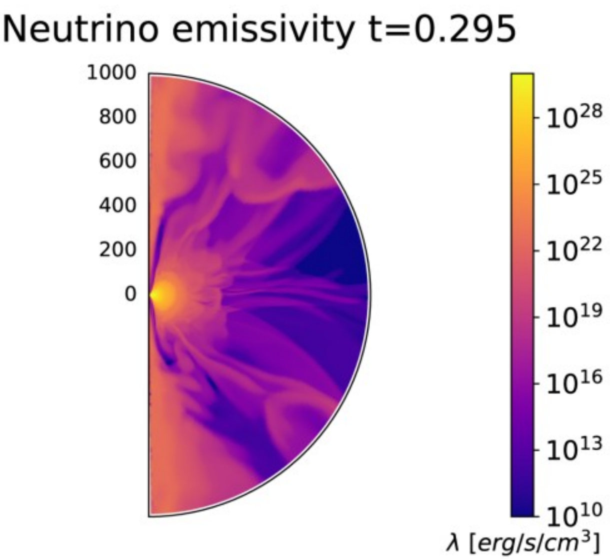
$$T^\mu_{\nu;\mu} = 0.$$

HARM scheme: Gammie et al.(2003)

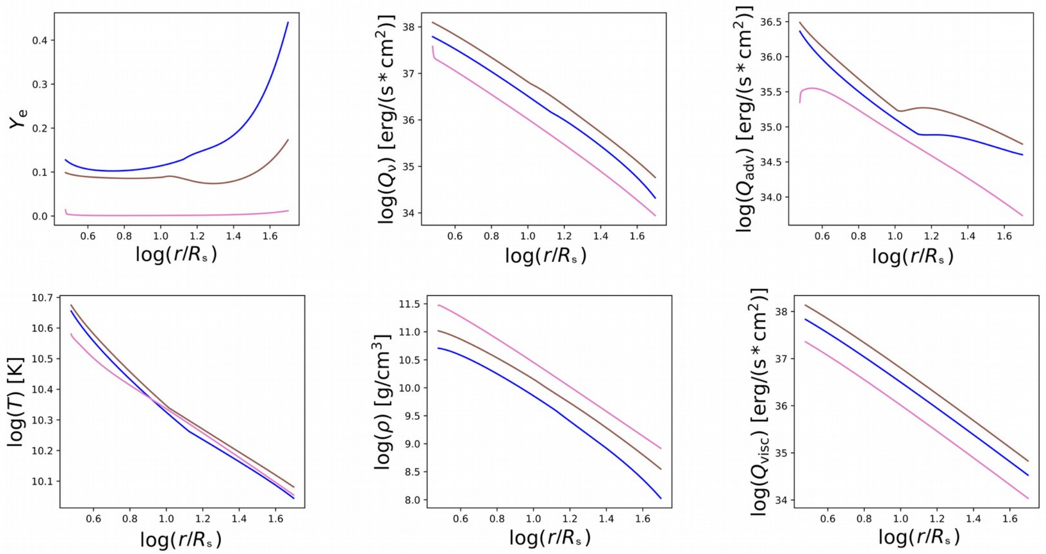


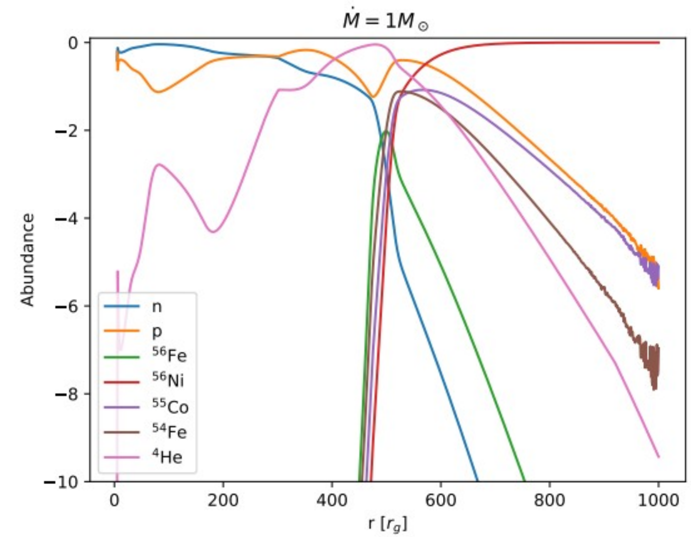
Tabulated Equation of State of Fermi gas is computed numerically by solving the balance of beta - reactions
(Yuan Y.-F. (2005); Janiuk, Yuan, Perna, DiMatteo (2007); Janiuk et al. 2013)

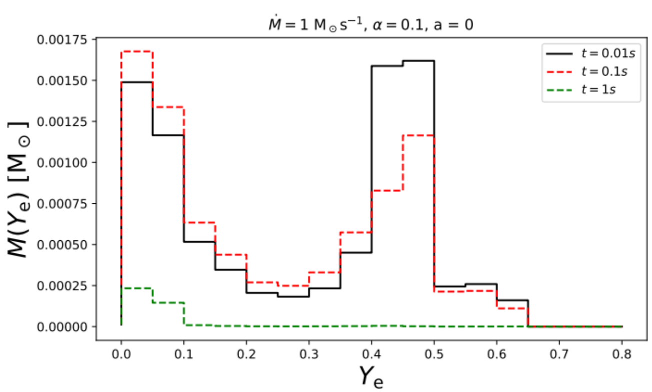
- Hyperaccretion: rates of 0.01-10 M_s/s
- Plasma composed of free n, p, e+, e− pairs
- Chemical and pressure balance required by nuclear reactions: electron-positron capture on nucleons, and neutron decay (Reddy, Prakash & Lattimer 1998)
- Neutrino absorption & scattering, treated by grey-body approximation

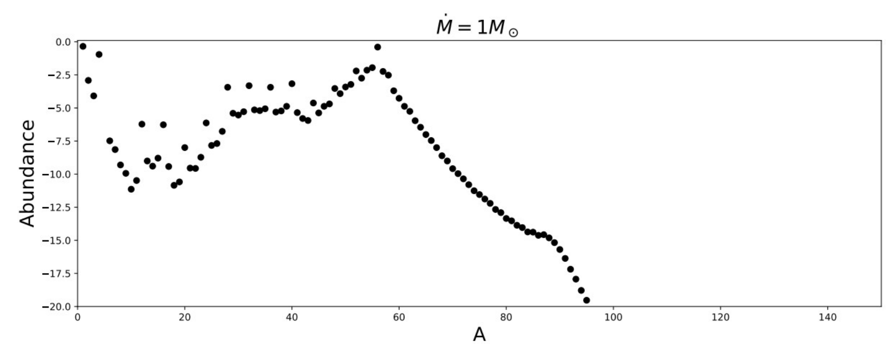


Properties of the disk and nucleosynthesis under NSE



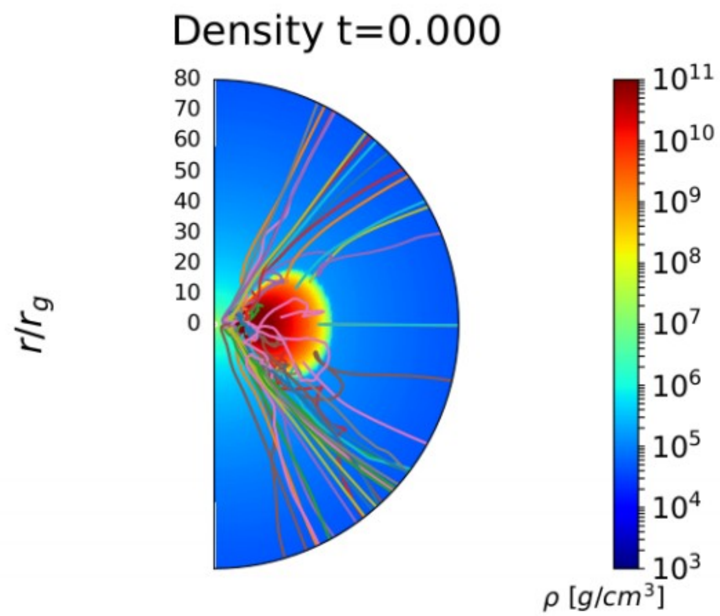






Results from student's project: Michal Przerwa (Warsaw Univ.)

Outflow via disk wind



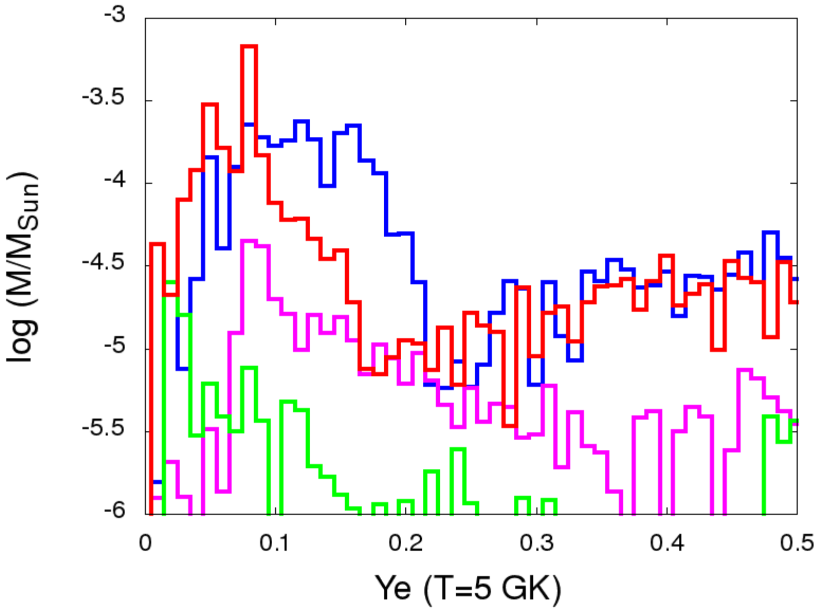
HARM-COOL (Janiuk, 2017, 2019).

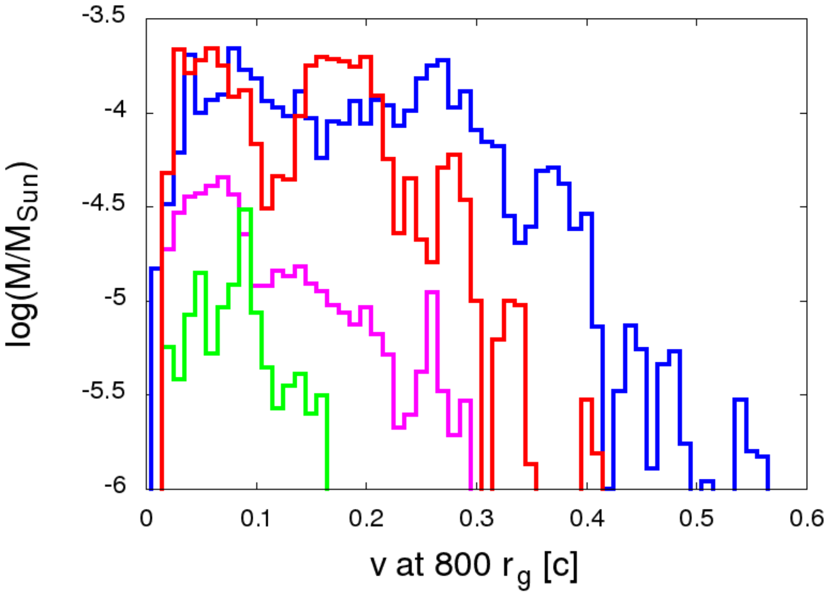
- EOS is implemented as tables, dynamically computed and filled with pressure, and entropy values as function of density and temperature
- Non-trivial transformation between ‘conserved’ and ’primitives’ variables in GR MHD. Various inversion schemes tested (see Siegel 2019).

Code follows the wind outflow, and computes the trajectories, where mass is ejected in sub-relativistic particles.
Tracers disributed uniformly in rest-mass density inside initial torus (cf. Wu et al. 2016; Bovard & Rezzola 2017). We typically use about 2000 tracers.

Matter is neutronized, $Ye = n_p/(n_p + n_n) < 0.5$.
Tracers store data about density, velocity, and electron fraction in the outflow.
R-process nucleosynthesis is calculated to obtain chemical evolution of the wind.

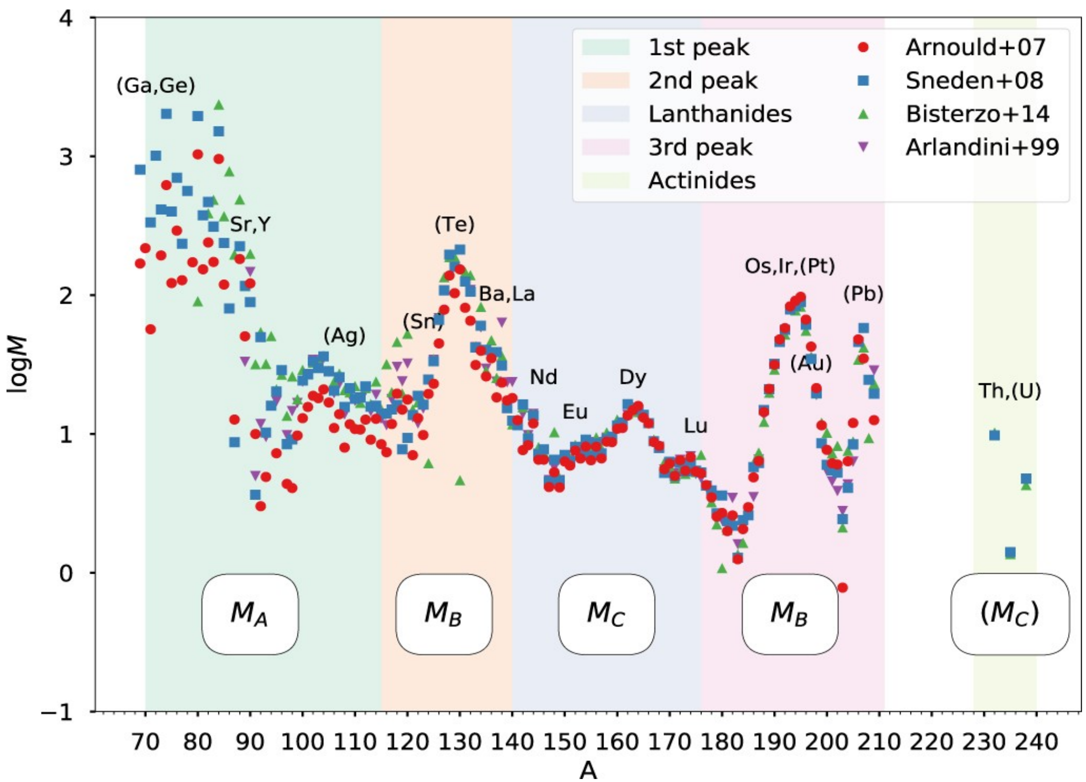
Post-merger ejecta



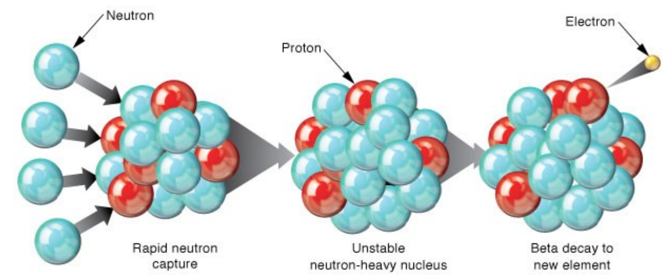


The disk launch fast wind outflows (v=c $\sim$ 0.11 − 0.23) with a broad range of electron fraction Ye $\sim$ 0.1 − 0.4. Mass loss via unbound outflows is between 2% and 17% of the initial disk mass. The details are sensitive to engine parameters: BH spin and magnetisation of the disk (a=0.9 and a=0.6, for blue/magenta and red/green histograms). More magnetized disk produce faster outflows. They should contribute to the kilonova signal, due to radioactive decay of r-process isotopes

r-process nucleosynthesis



Ji et al. 2019



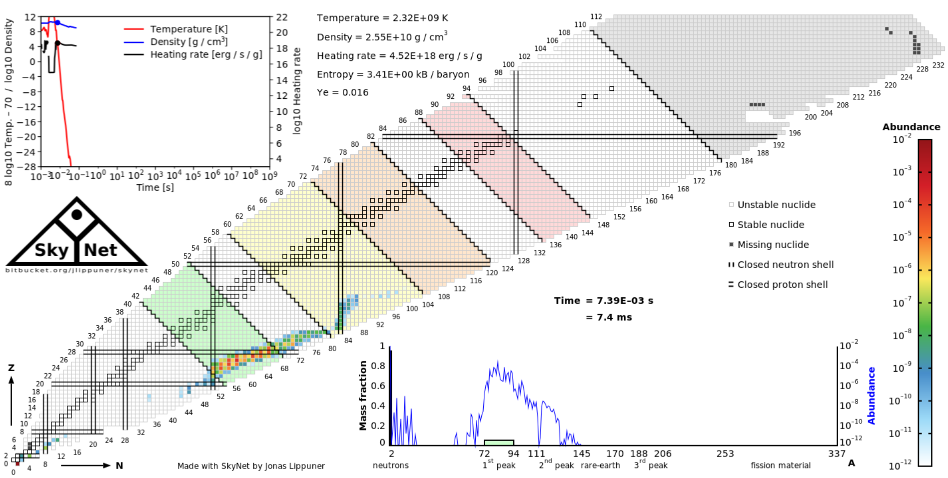
Ye > 0.25: 1st peak

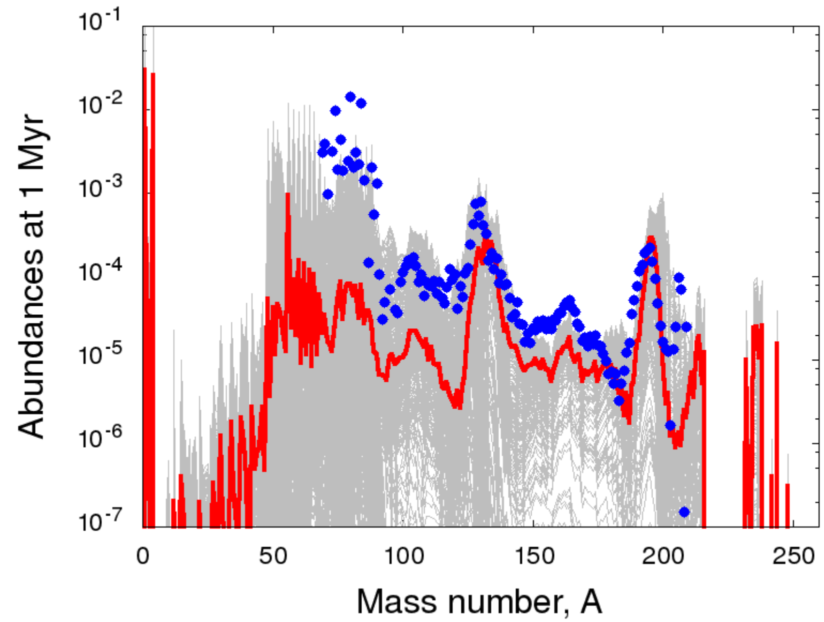
Ye = 0.15-0.25: 2nd peak, Lanthanides

Ye < 0.15: 3rd peak, Actinides

Nucleosynthesis in disk wind

Heavy elements up to A ~ 200 (incl. Platinum, Gold) are produced in disk ejecta.



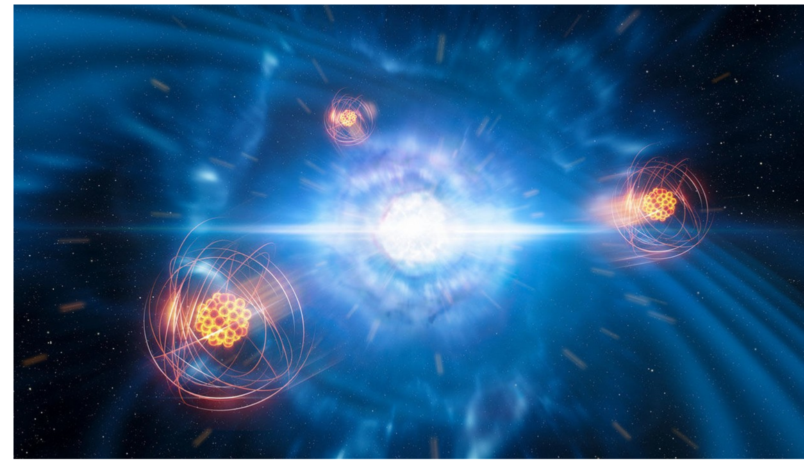


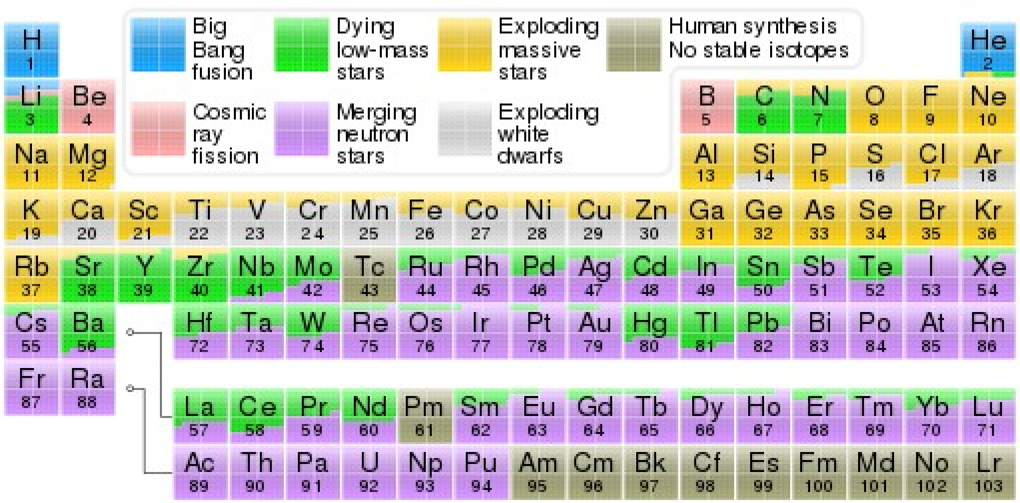
Nucleosynthesis in disk wind
(Janiuk, 2019, ApJ, 882, 163)

Code **SkyNet**, provides a nuclear reaction network; Lippuner & Roberts (2017). Publicly available, with a user-friendly python interface.
Capable to trace the nucleosynthesis in the rapid neutron capture process, icluding self-heating. Involves large database of over a thousand isotopes.
Takes into account the fission reactions and electron screening.

Heavy elements in the Universe

Heavy isotopes formed in binary mergers enrich the Universe, including elements on Earth





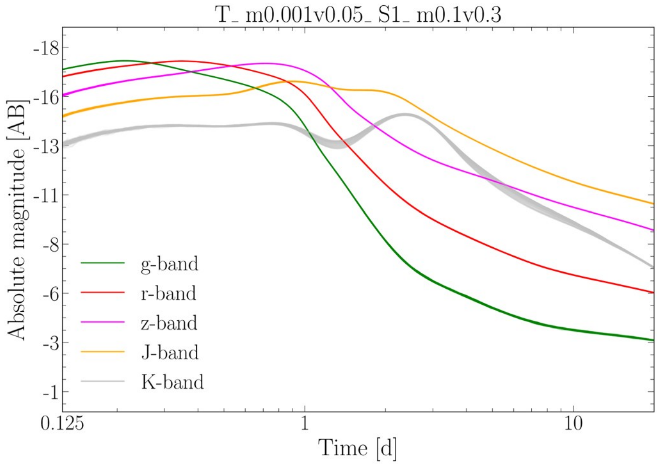
Old Uranium mine in Kowary, Poland, where Uranium-235 was extracted until 1958

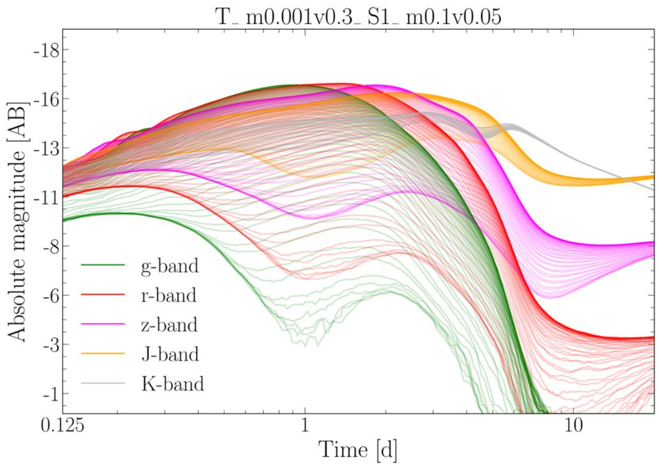
Kilonova emission

- Radioactivities from dynamical ejecta after first NS disruption power an electromagnetic signal (e.g. Li & Paczynski 1998; Tanvir et al. 2013; Korobkin et al. 2012)

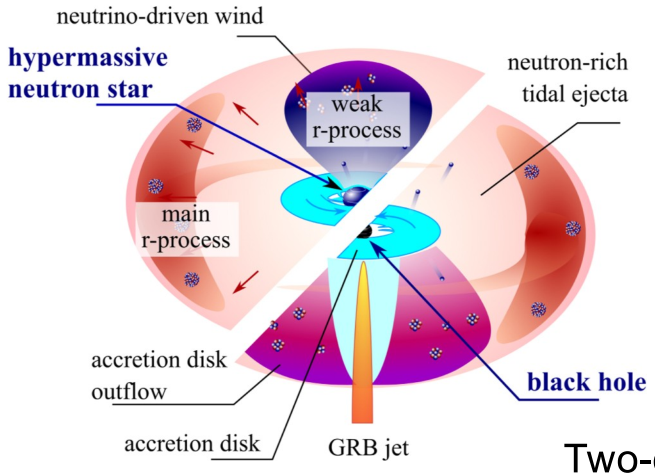
- Subsequent accretion can provide bluer emission, if it is not absorbed by precedent ejecta (Tanaka M., 2016, Berger 2016, Siegel & Metzger 2017)

- Day-timescale emission comes at optical wavelengths from lanthanide-free components of the ejecta, and is followed by week-long emission with a spectral peak in the near-infrared (NIR).



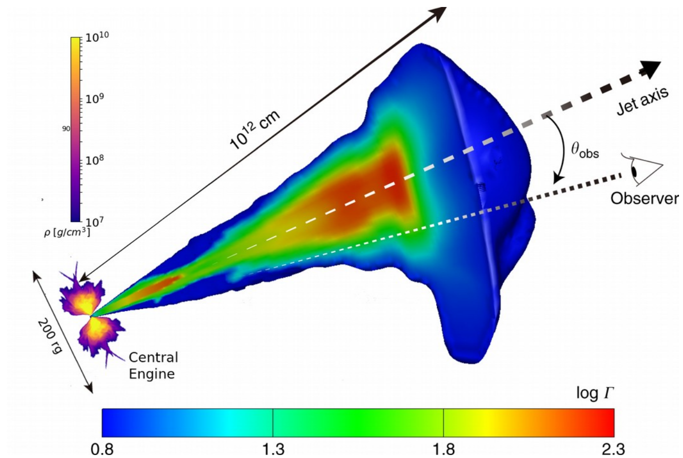


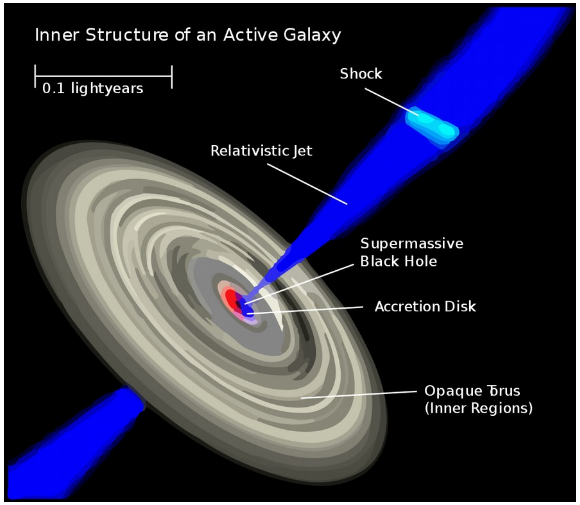
Monte Carlo radiative transfer software SuperNu (Wollaeger & van Rossum 2014) . Two models with 0.001 M⊙ and 0.1 M⊙ in the low-Ye and high-Ye component, respectively. Top: low-Ye and high-Ye ejecta speed of 0.05 c and 0.3 c, respectively. Bottom: low-Ye and high-Ye ejecta speed of 0.3 c and 0.05 c, respectively.



Two-component model scheme (Korobkin et al. 2021)

GRB Central engine and jet





Gamma ray emission comes from the photosphere of a collimated relativistic outflow pushing through the interstellar medium.

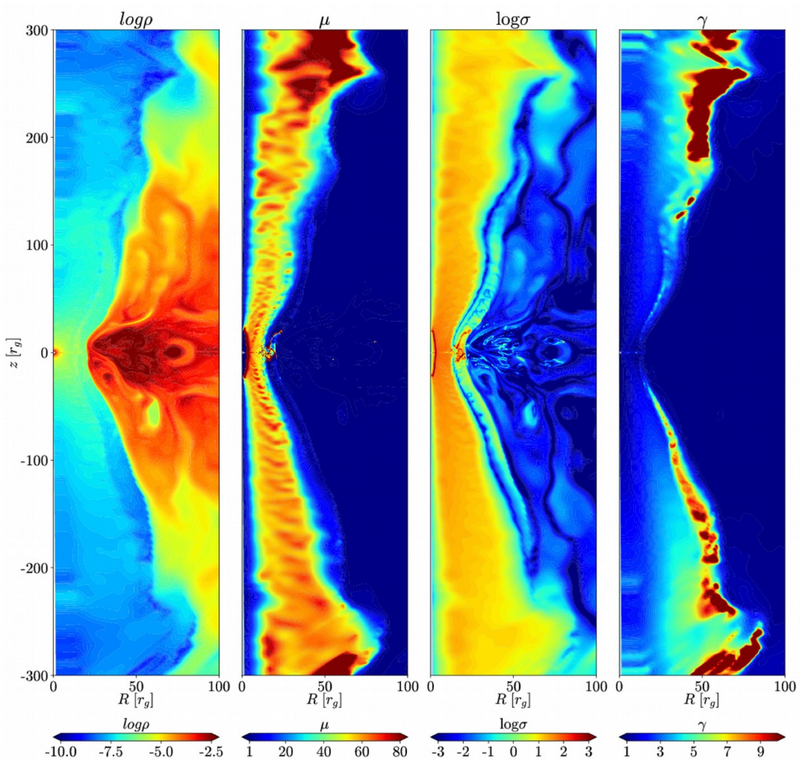
Jet is powered by the central engine.

This engine power is extracted from the spinning black hole, surrounded by an accretion disk and magnetic fields. Launching mechanism similar as in AGN jets.

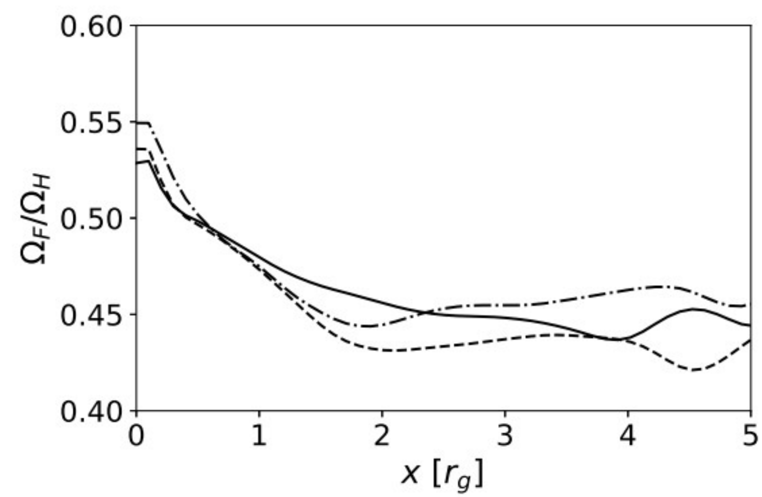
$$\dot{E}_{\rm BZ} = \frac{\kappa}{4\pi}\Phi_{\rm BH}^2 \frac{a^2 c}{16 r_{\rm g}^2}$$

$$\Phi_{\rm BH} = \frac{1}{2}\int |B^r|\, \mathrm{d}A_{\theta\phi} \qquad a = \frac{c\, J_{\rm BH}}{G\, M_{\rm BH}^2}$$

Jet launching and energetics



- If the black hole starts fastly rotate, jet ejection is inevitable
- The presence of magnetic fields powers the jet acceleration
- Blandford-Znajek process, efficient if the rotational frequency of magnetic field is large wtr. to angular velocity of the black hole

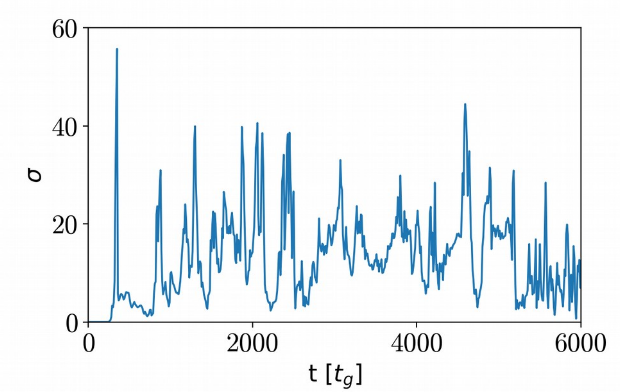


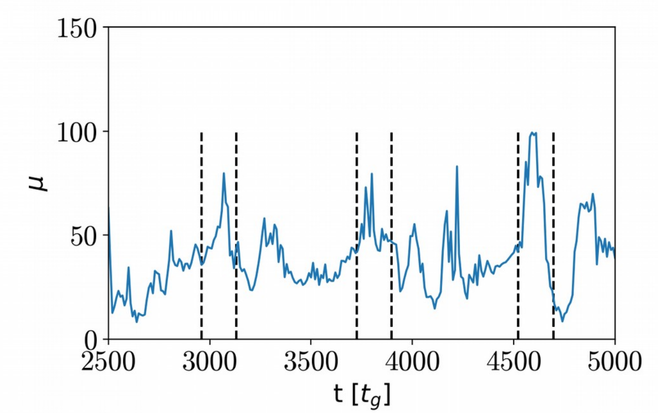
$\sigma = (T_{EM})^r{}_t / (T_{gas})^r{}_t$

$\mu = - T^r{}_t / \rho u^r$

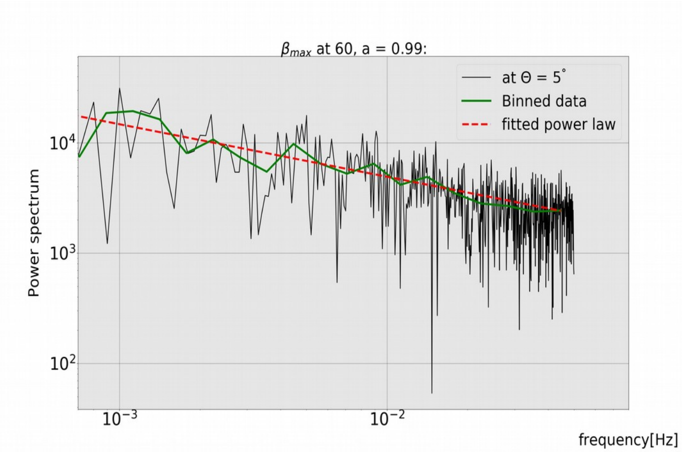
Fig from Sapountzis & Janiuk (2019, ApJ)

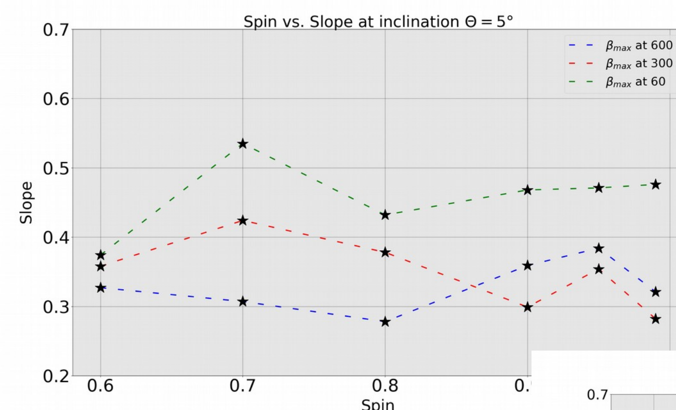
Variability of jets

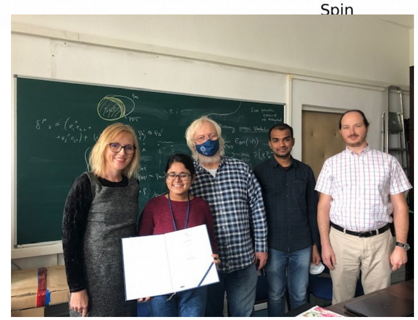


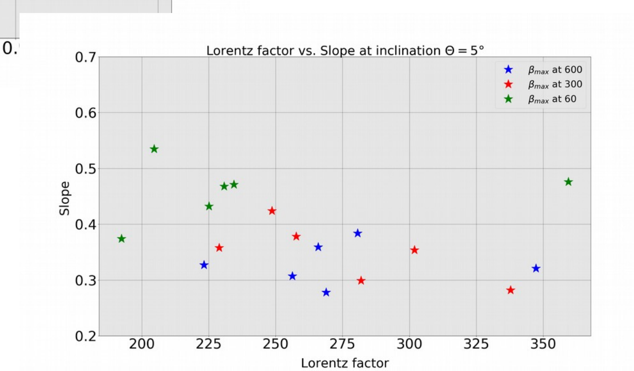


Time variability of σ and μ as measured at inner regions of jet . Variability is correlated with T_{MRI}, timescale of the fastest growing mode









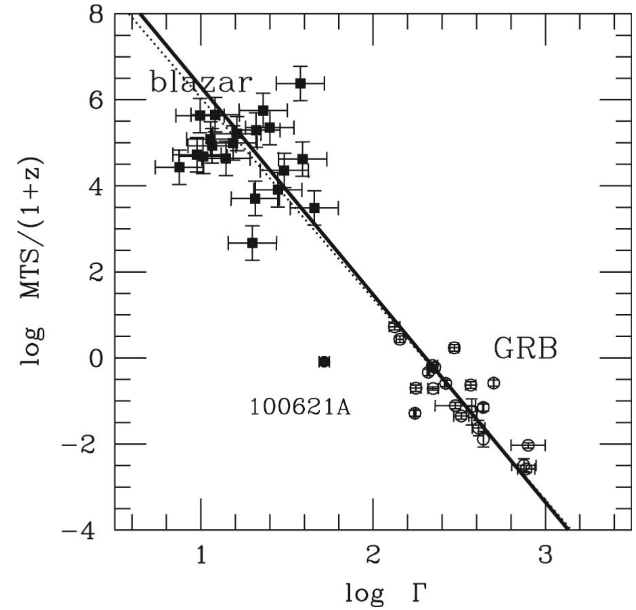
Power spectrum of model lightcurves. Power-law slope weakly depends on the black hole spin, while it seems to depend on jet Lorentz factor.

Comparison to observations

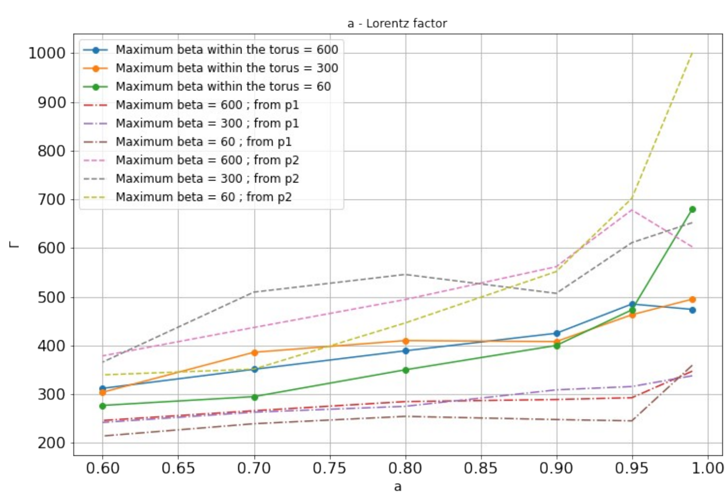
- In our simulation, jet Lorentz factor is calculated as the average of μ in time, $\Gamma = \langle \mu \rangle_t$.

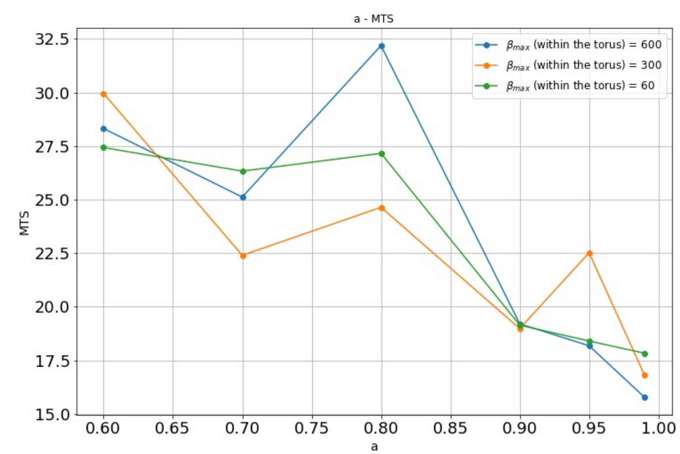
- The Minimum variability Time Scale (MTS) ~ peak widths at their half maximum on the μ – t plot

- Correlations Γ-a and a-MTS are confirmed. Results scale with black hole mass: $MTS_s = MTS_{MBH} \times GM_{BH}/c^3$



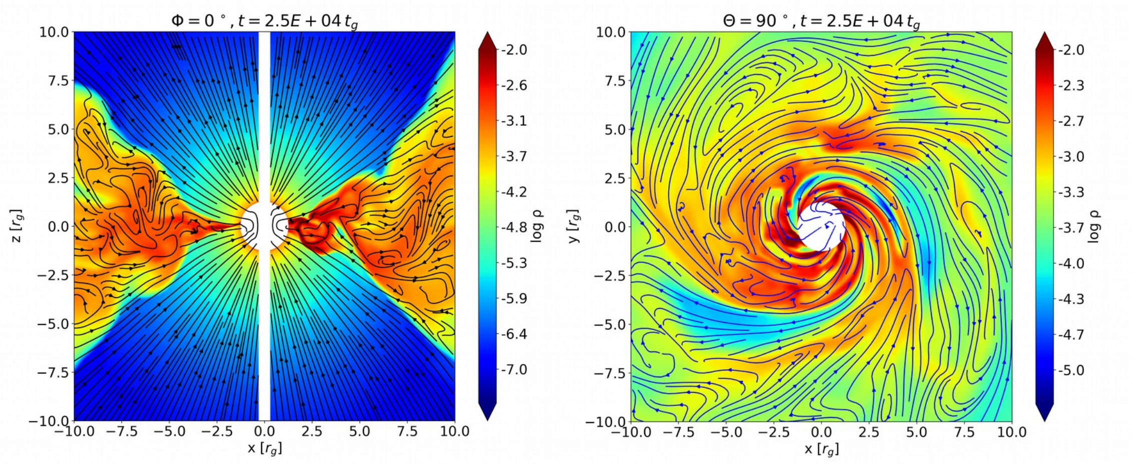
Joint correlation of MTS ∝ $\Gamma^{-4.7} \pm 0.3$ for blazar and GRB samples (Wu et al. 2016)

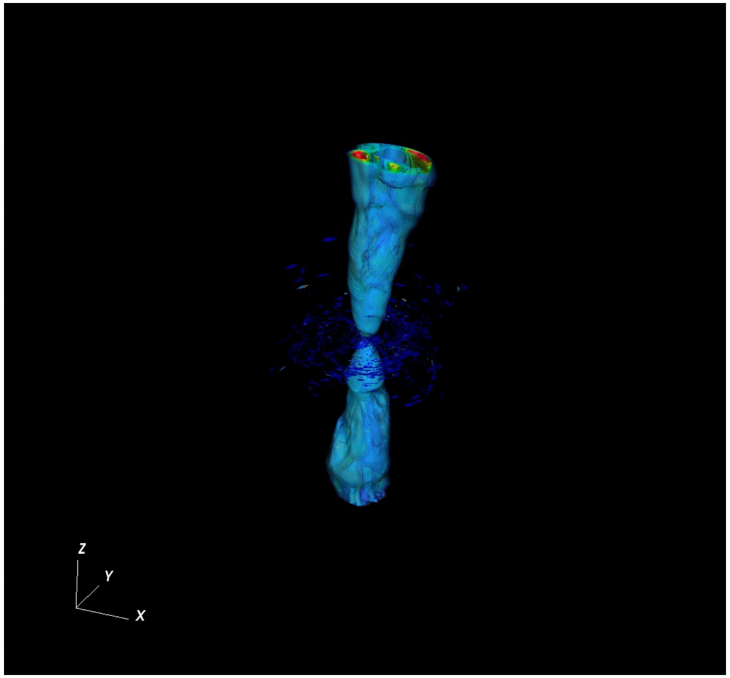




(Janiuk, James & Palit, 2021, ApJ, 917, 102)

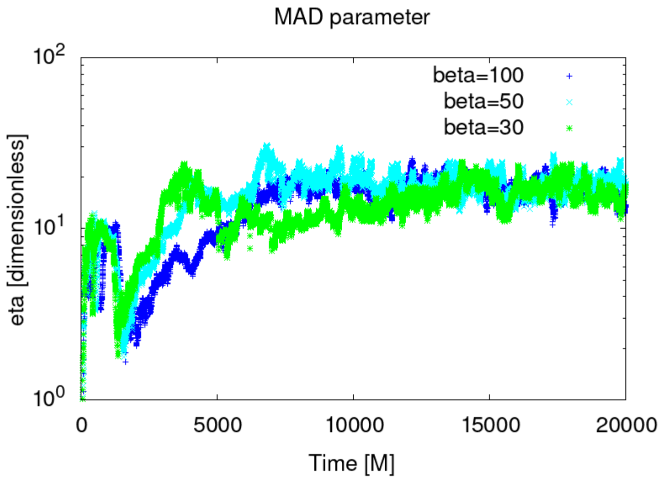
Jets from MAD disks





3D simulations of MAD accretion mode: Janiuk (2022, ApJ, submitted); James et al. (in prep)

Models for the temporal variability of long gamma-ray bursts (GRBs) during the prompt phase (the highly variable first 100 s or so), were proposed in the context of a magnetically arrested disc (MAD, cf. McKinney et al. 2012) around a black hole (Lloyd-Ronning et al., 2016)

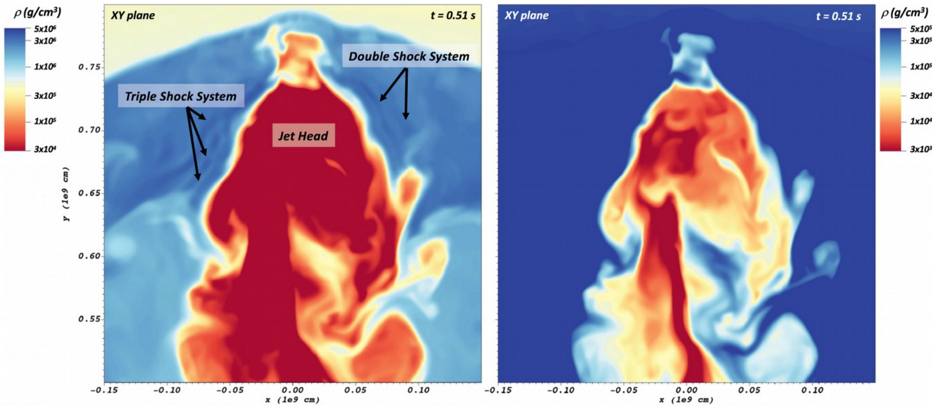


$$\Psi_{BH} = \Phi_{BH} / 5 (r_g^2 c\ Mdot)^{1/2}$$

Jet interactions with BNS ejecta

In BNS merger, the interaction of a relativistic jet with the binary ejecta shapes the structure of outflow and its radiation properties.

3D simulations show that jet centroid oscillates around the axis of the system, due to inhomogeneities encountered in the propagation

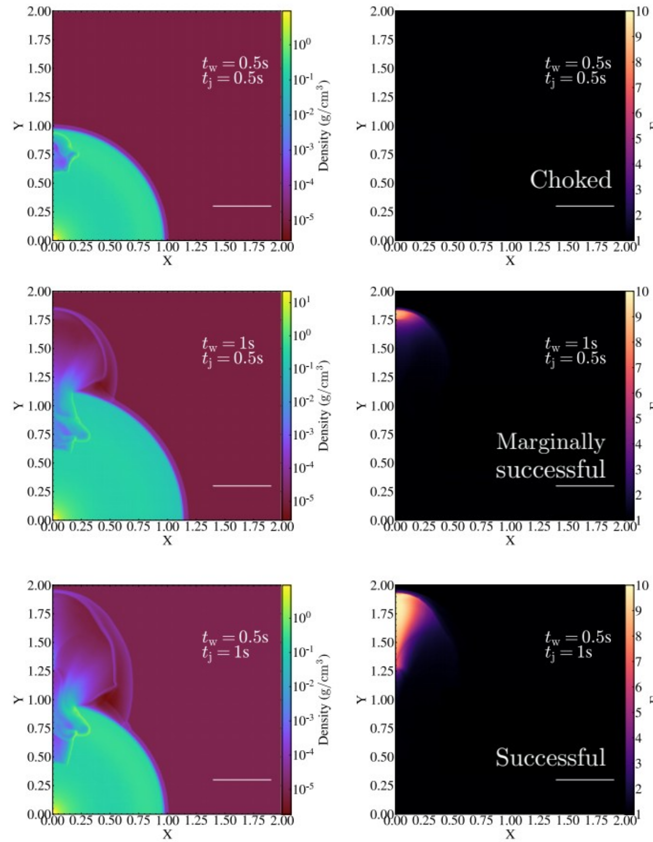


Lazzati et al., 2021

The breakout time is comparable to the central engine duration in SGRBs and possibly a non-negligible fraction of the total delay between the gravitational and gamma-ray signals.

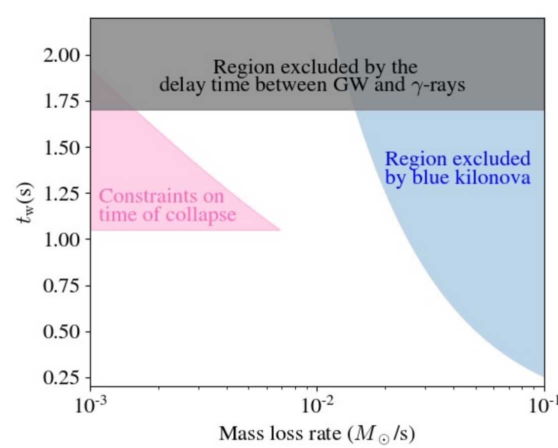
Chocked jets

- Expansion of the jet is affected by the properties of the wind through which it propagates
- We made simulations of jets propagating within a spherical wind with a mass loss rate of $\dot{M}_w=10^{-2}$ M_{Sun}/s and v_w= 0.3c.
- Various models of accretion disk wind: neutrino-driven, magnetically driven



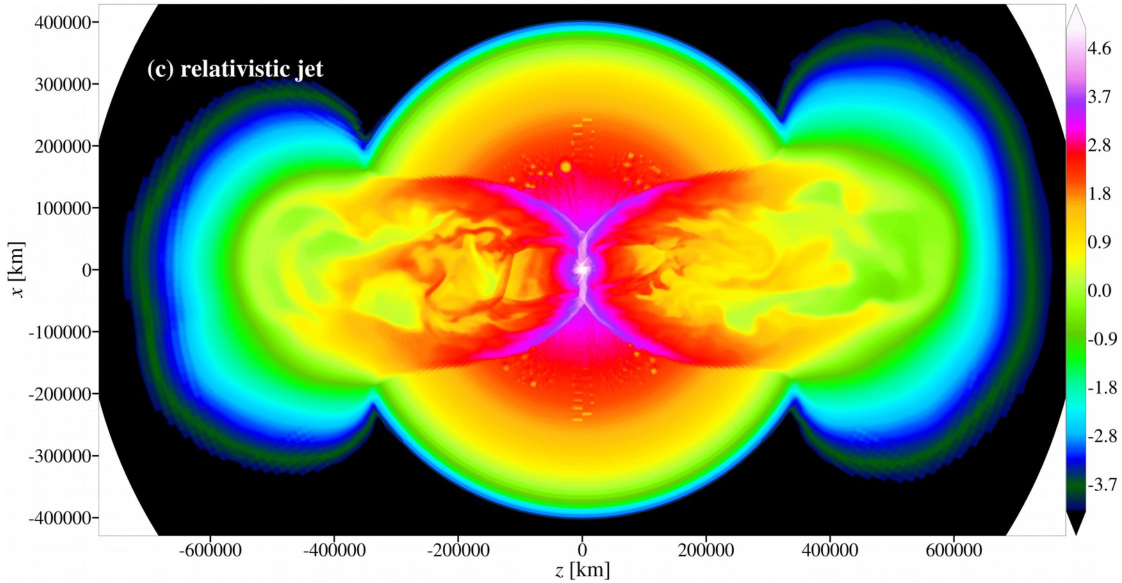
(**Murguia-Berthier, Ramirez-Ruiz, Janiuk, et al., 2021, ApJ, 908, 2)**

Constraints for wind time t_w as a function of mass loss. **GW 170817:** jet energy of $5x10^{48}$-10^{50} erg, initial opening angle: 9-20°, Lorentz factor Γ=100-1000



3D jet structure and collapsar breakout

Gottlieb et al. (2022, MNRAS). The first 3D GRMHD collapsar simulations, which extend from the self-consistent jet launching by an accreting Kerr black hole (BH) to the breakout from the star.



Magnetically arrested accretion mode may bring additional effects, icl. variability and spectral properties. Very high resolution 3D simulations show also importance of plasmoid reconnection (Ripperda et al. 2021, arXiV)

Summary

NS binary merger ejects material rich in heavy radioactive isotopes. They are formed in the rapid neutron capture process (r-process). The decays can power an electromagnetic signal called kilonova

- The r − process nucleosynthesis in the accretion disk outflows can provide additional contribution to the kilonova emission. Observationally testable results, motivated by the recently discovered electromagnetic counterparts of gravitational wave source GW170817, require two-component modeling.

- The MHD simulations show that rotational instabilities have imprint on the variability of the jet. The same MHD mechanism drives the disk-wind.

- Jet interactions with wind shape its radiative properties and together with pre-merger dynamical ejecta may explain time-delay between GW and GRB signals