Relativistic MHD simulations of merging and collapsing stars

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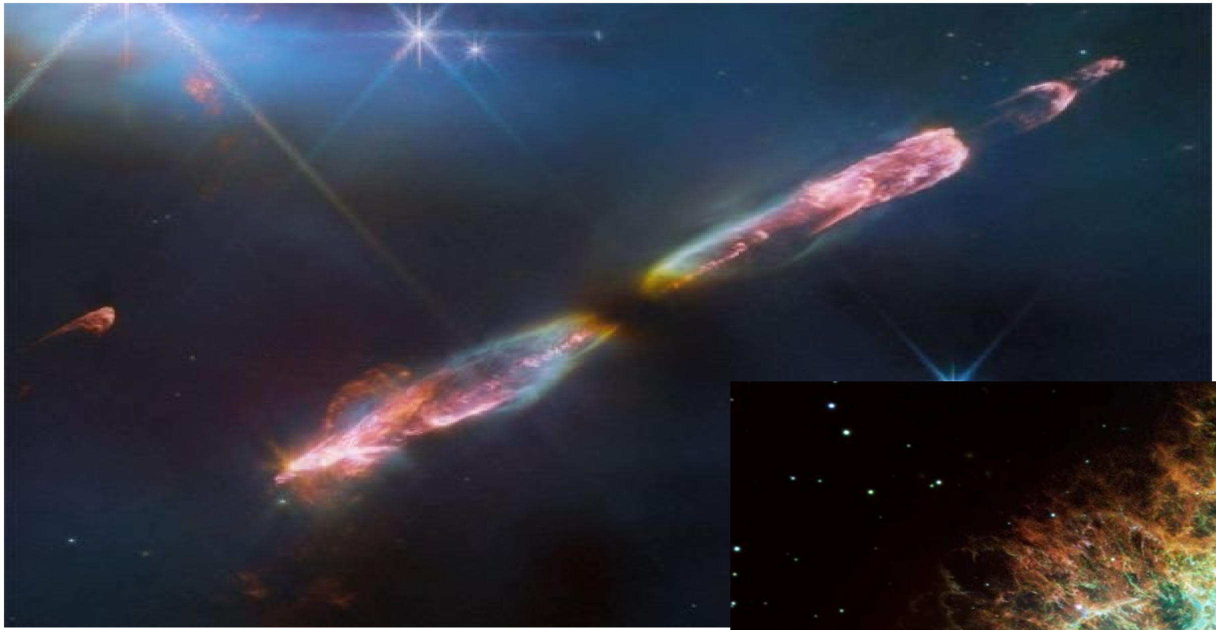
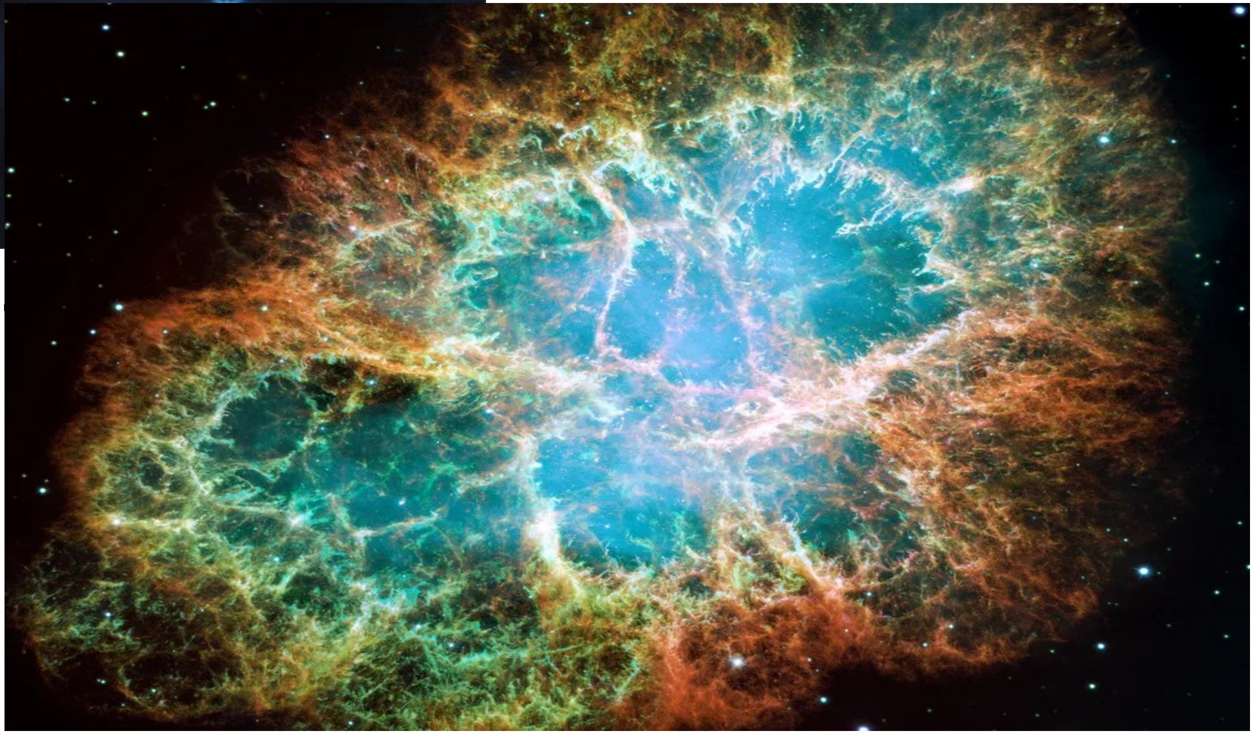
5th EPS conference on Gravitation
Prague, 11.12.2024

Cosmic explosions



HH221 by JWST



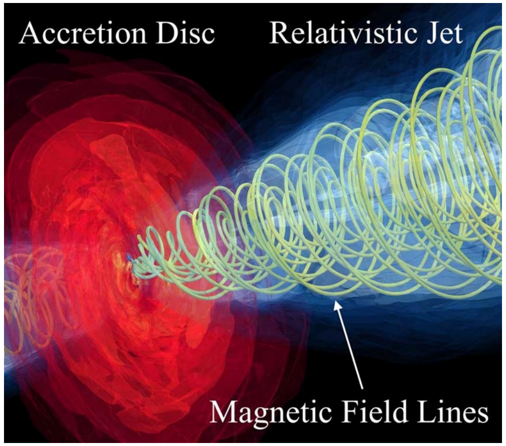
Crab Nebula by
Hubble Telescope

Transients and multimessenger astrophysics

Typically involve compact objects:
- black holes, neutron stars

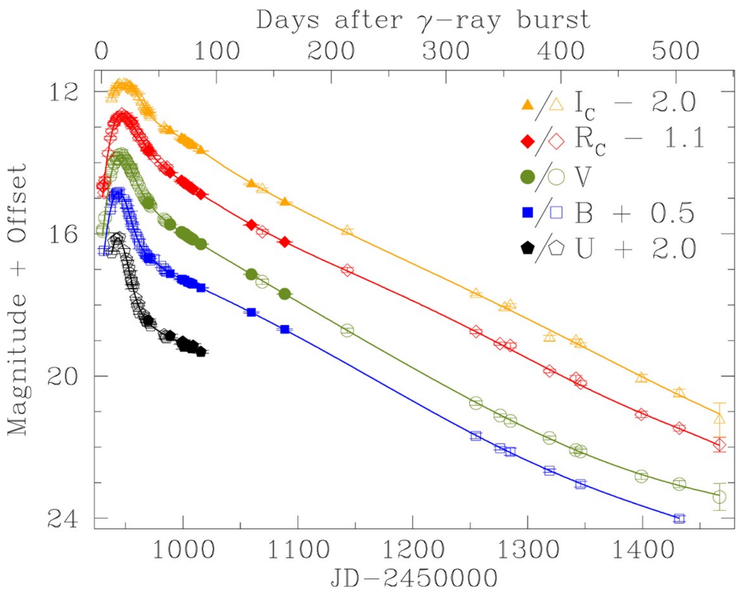
Gas propagates with relativistic velocities

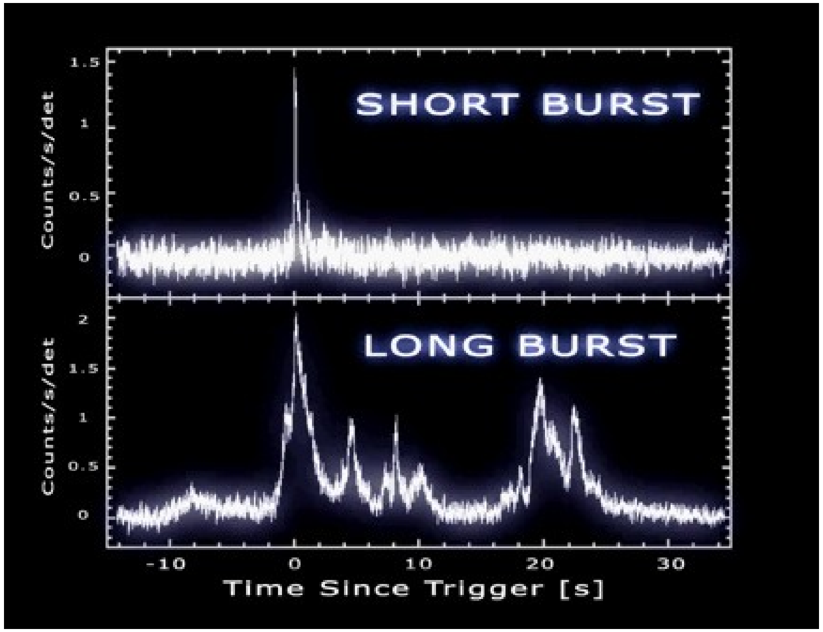
Few seconds/minutes to observe
the main characteristics



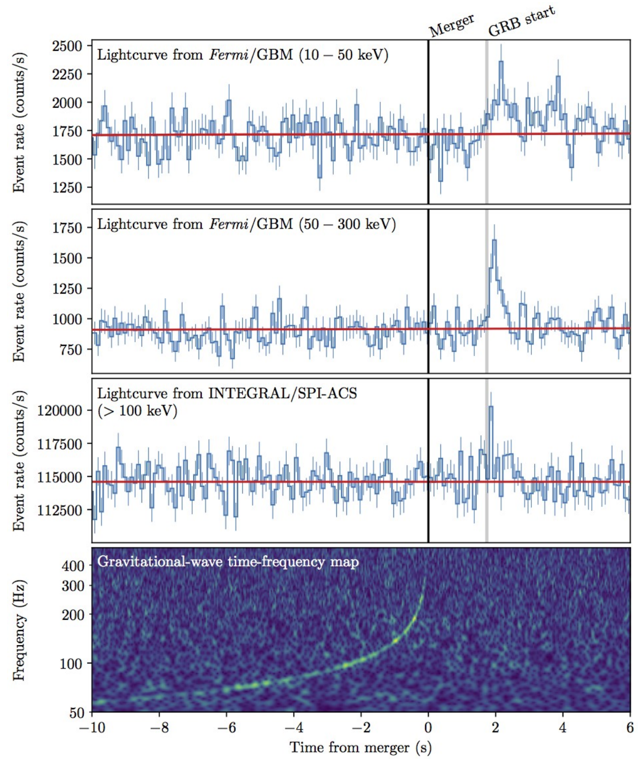
Complementary non-electromagnetic signals

Gamma Ray Bursts



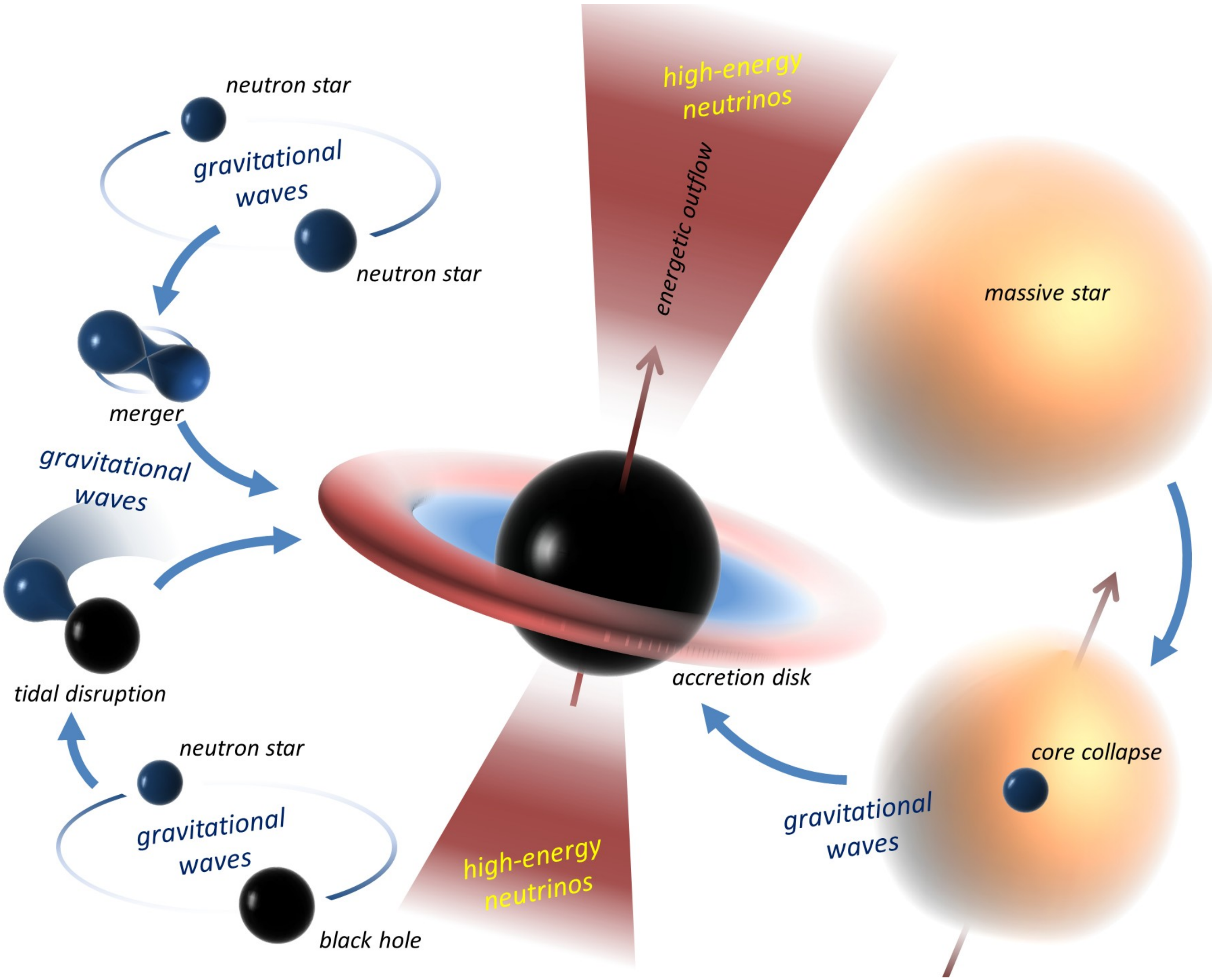


Long identified with core collapse Supernova (type I b/c ; Galama et al. 1998)



Short GRB identified with Neutron Star merger (GW170817; Abbott et al. 2017). 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

Possible scenarios for GRBs: mergers and collapsars



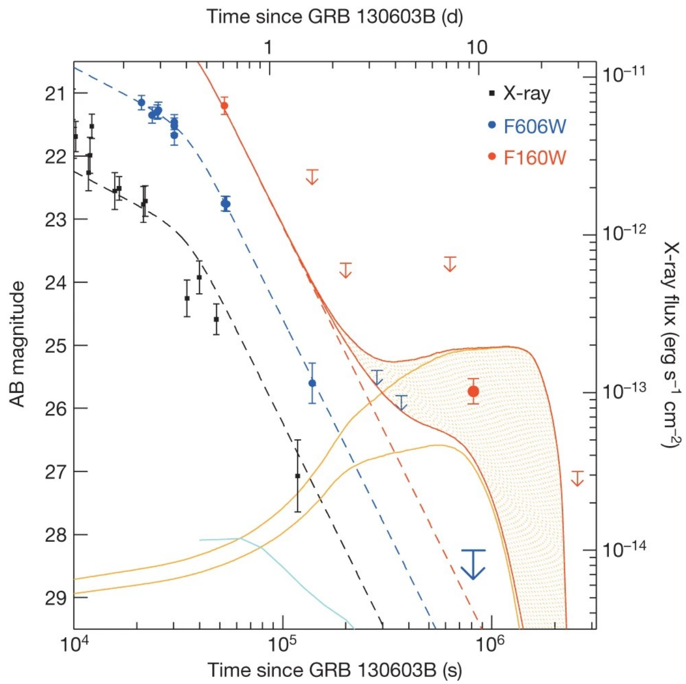
Kilonovae

NS-NS eject material rich in heavy radioactive isotopes.

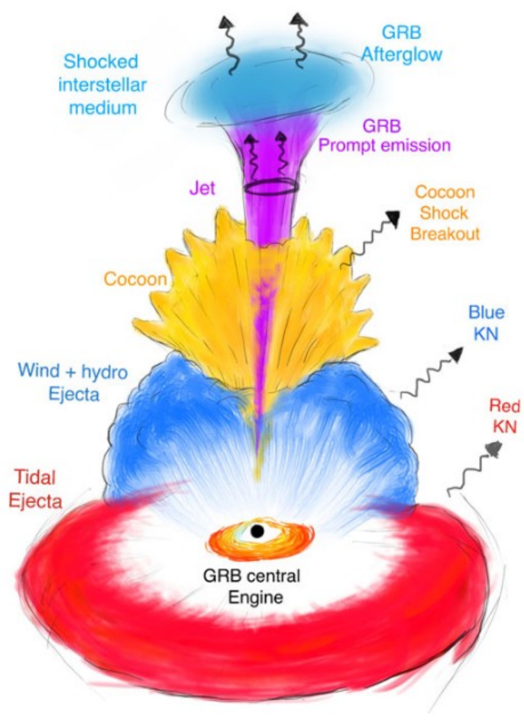
Can power an electromagnetic signal called a kilonova (e.g. Li & Paczynski 1998)

Dynamical ejecta from compact binary mergers, $M_{ej} \sim 0.01\ M_{Sun}$, can emit about 10^{40}-10^{41} erg/s in a timescale of 1 week

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

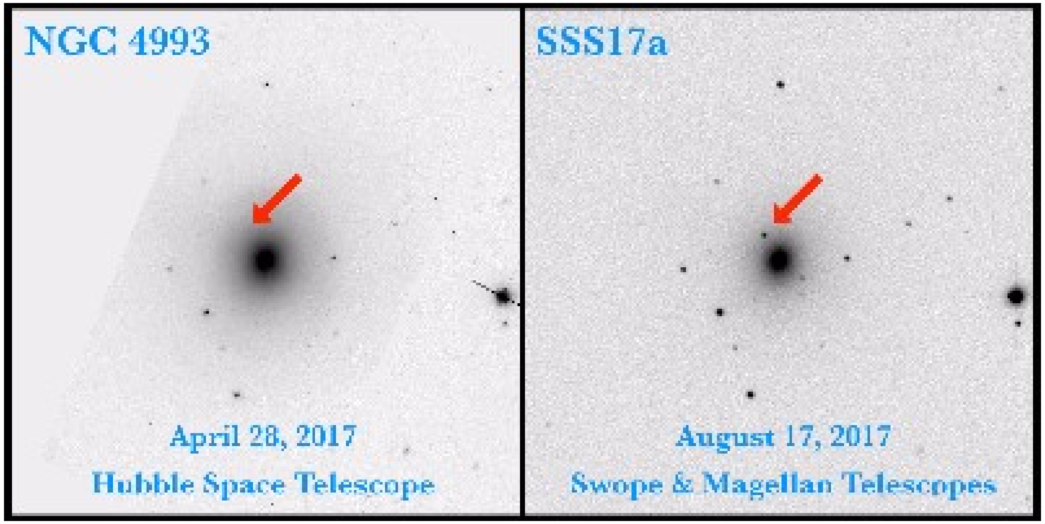


“Kilonova” associated with short GRB, Tanvir et al. 2013, Nature



Kilonova artistic plot,
Ascenzi, 2019

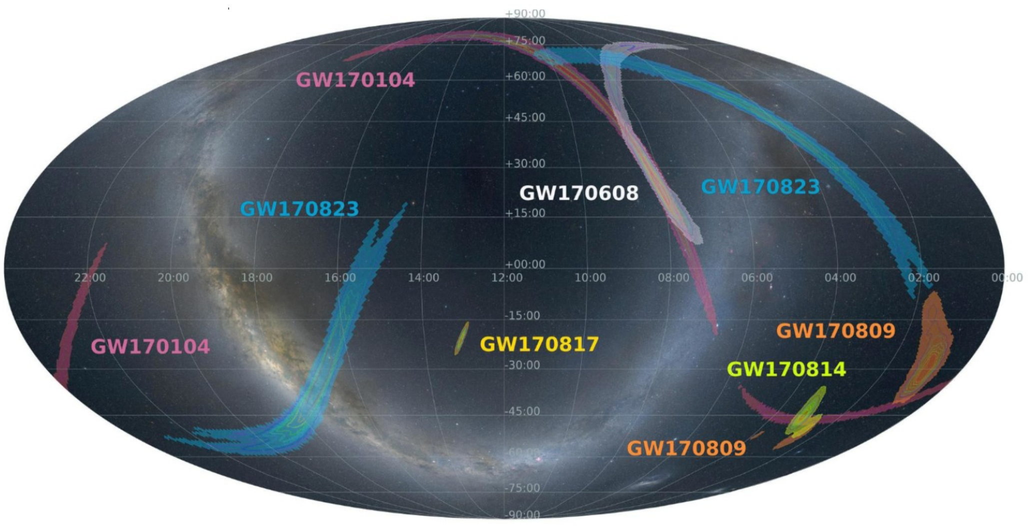
GW-GRB 170817



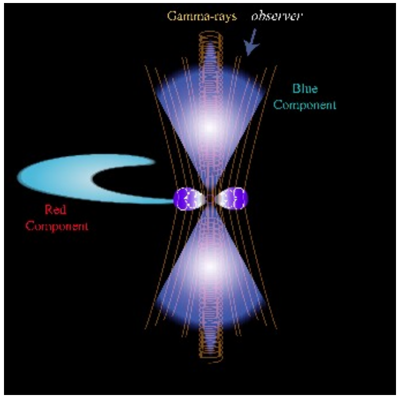
Rapidly fading electromagnetic transient in the galaxy NGC4993, was spatially coincident with GW170817 and a weak short gamma-ray burst (e.g., Smartt et al. 2017; Zhang et al. 2017, Coulter et al. 2017)

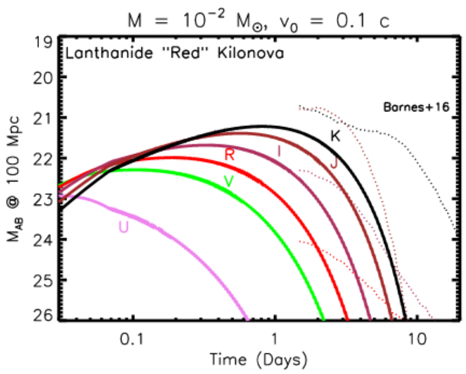
Double neutron stars formed a black hole after their merger.

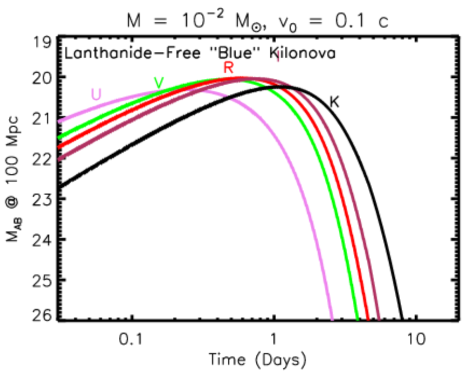
During the inspiral phase, **gravitational waves** were produced

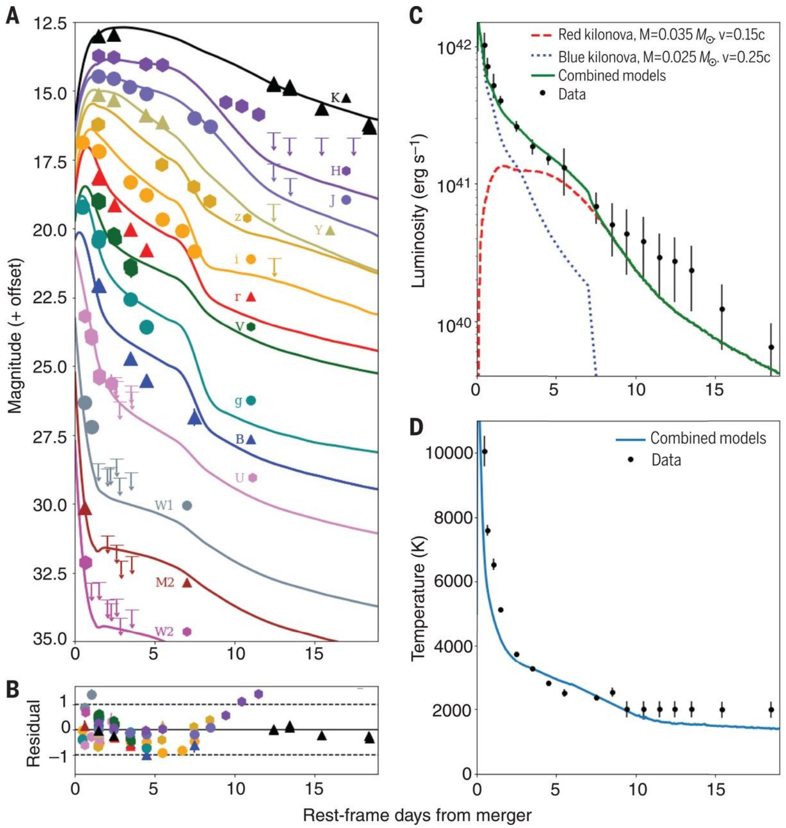


Blue and red kilonova lightcurves







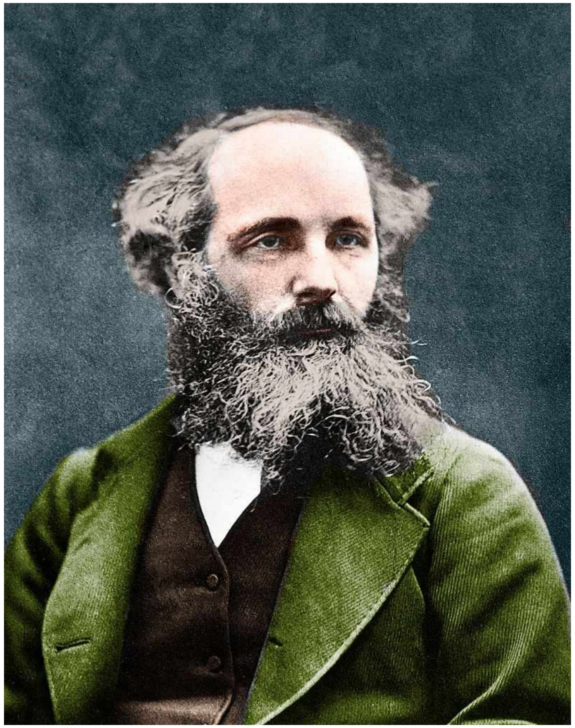


observational data for the transient SSS17a, associated with GW170817

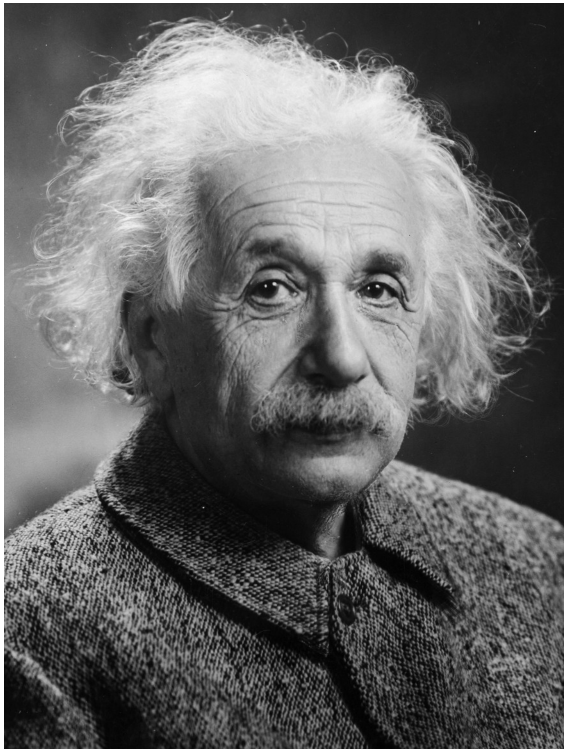
(Kilpatrick et al. 2017).

Relativistic Magnetohydrodynamics

Leonard Euler



James Maxwell

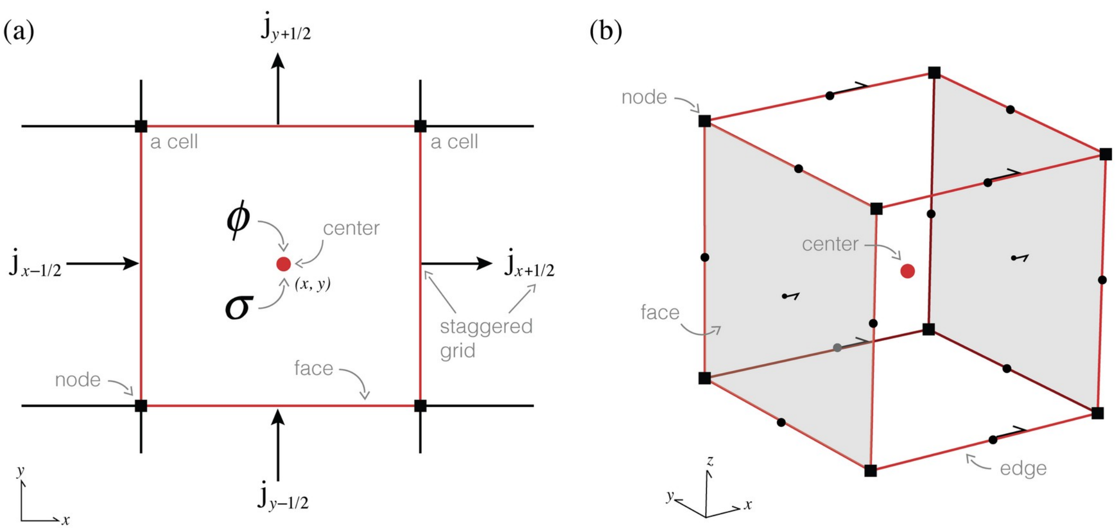


Albert Einstein

Describe motion of magnetized gas in gravitational field of a black hole

Numerical simulations

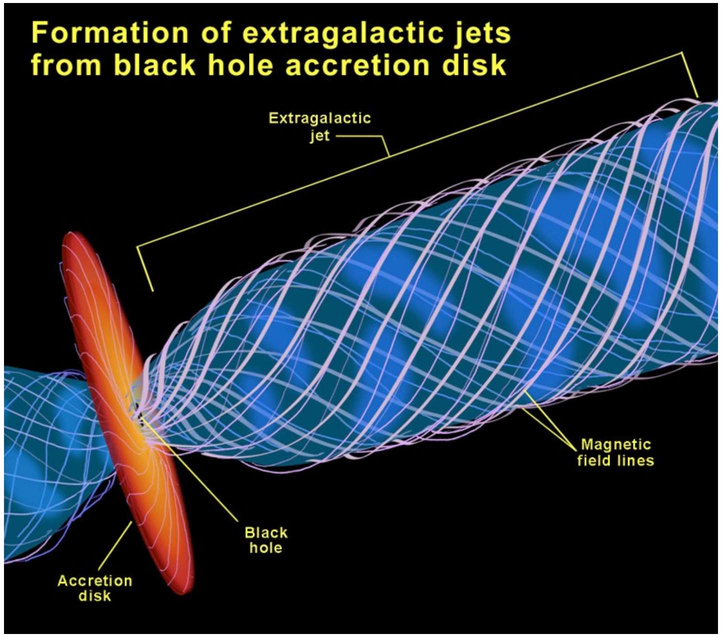
$$\partial_t \mathbf{U(P)} = -\partial_i \mathbf{F^i (P)} + \mathbf{S(P)}$$

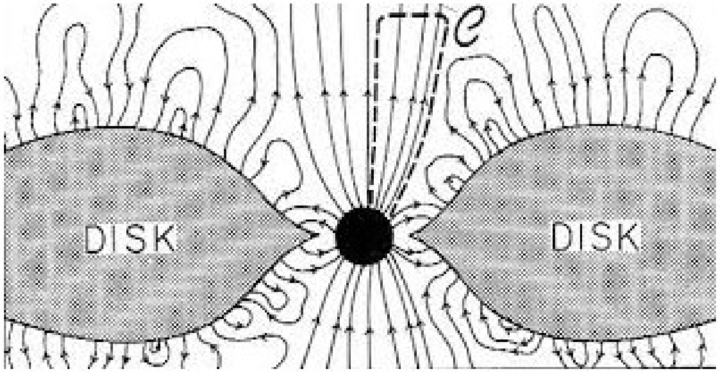


- Equations discretized on the grid
- Finite Volume methods
- Scheme advances conserved variables in time
- Inversion schemes used to recover primitive variables **P(U)** needed by the equation of state

Relativistic MHD jets

- Jets are common in the Universe, and observed at different mass scales from accreting black holes
- Need a central engine, with magnetic fields anchored in the accretion disk penetrate black hole’s ergosphere and mediate energy extraction

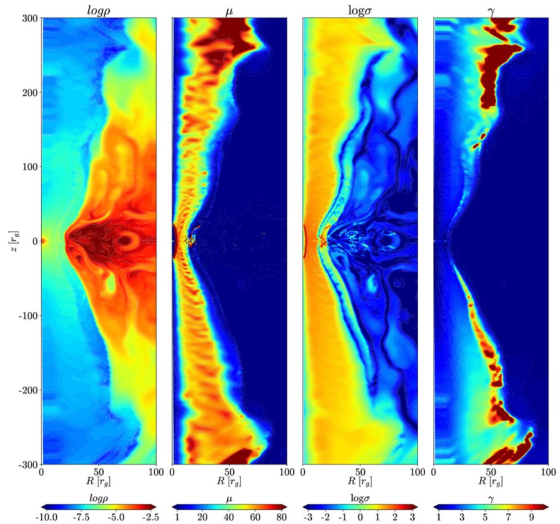




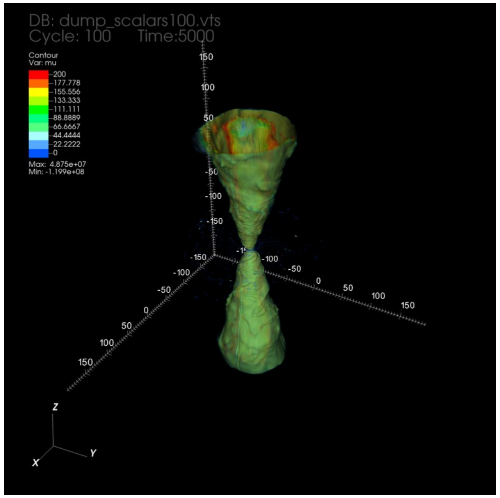
Thorne 1986

Jets from numerical simulations

- Jet launched when rotational frequency of magnetic field is large wtr. to BH angular velocity
- They are powered by Blandford-Znajek process (BZ) when the charged particles are accelerated in BH magnetosphere
- Energy in the simulated jet non-uniformly distributed → top-hat jet models excluded

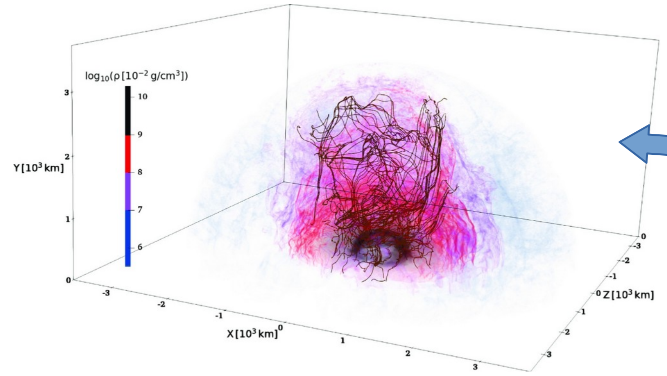


K. Sapountzis & AJ (2019)



B. James, AJ & F. Nouri (2022)

GR MHD, simple init.



SR MHD, complex init (BNS merger)

Pavan et al. (2023)

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

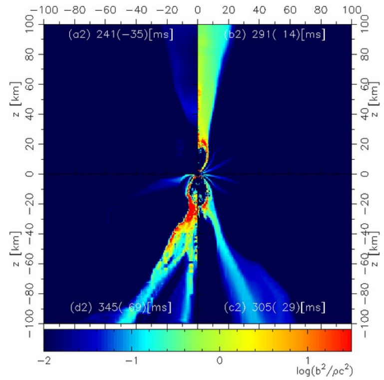
$$\Phi_{\rm BH} = \frac{1}{2}\int |B^r|\,{\rm d}A_{\theta\phi}$$

$$a = \frac{c\,J_{\rm BH}}{G\,M_{\rm BH}^2}$$

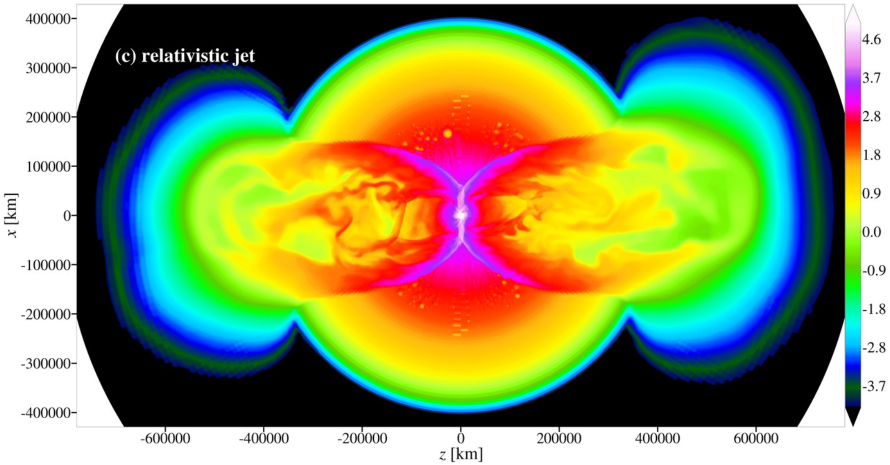
Collapsar modeling

Jet breakout process difficult to model due to multi-scale problem and computational complexity

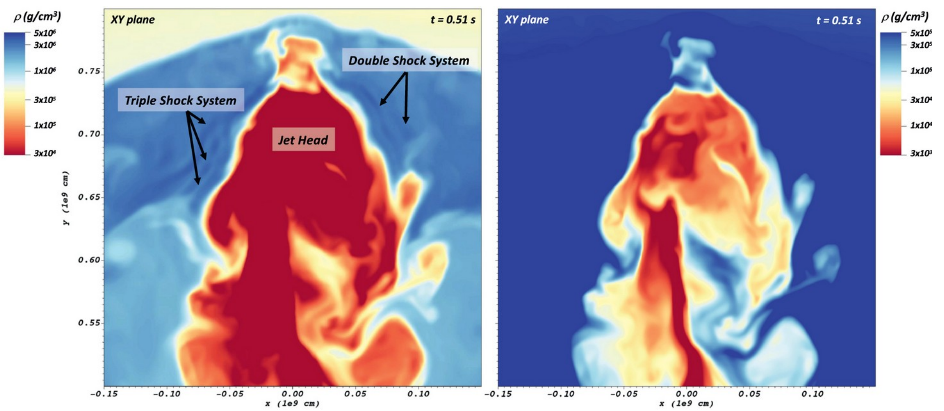
See also: Aloy & Obergaulinger (2020) Just et al. (2022); Fujibayashi et al. (2023); Kuroda & Shibata (2024)



3D hydrodynamic models shown that jet centroid oscillates around the axis of the system, due to inhomogeneities encountered in the propagation

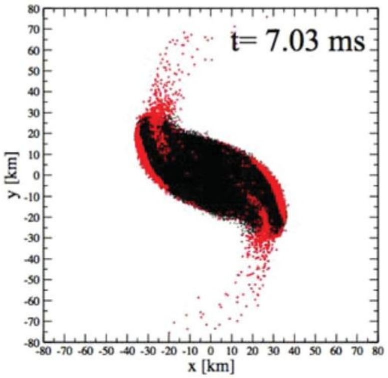


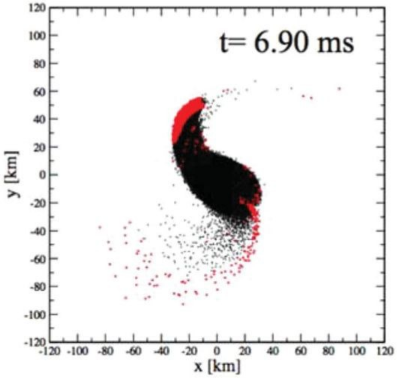
Gottlieb et al., 2022

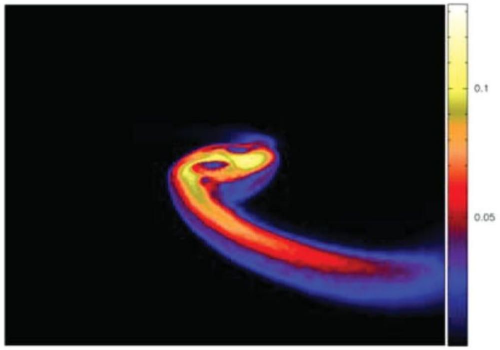


Lazzati et al., 2021

Mergers modeling



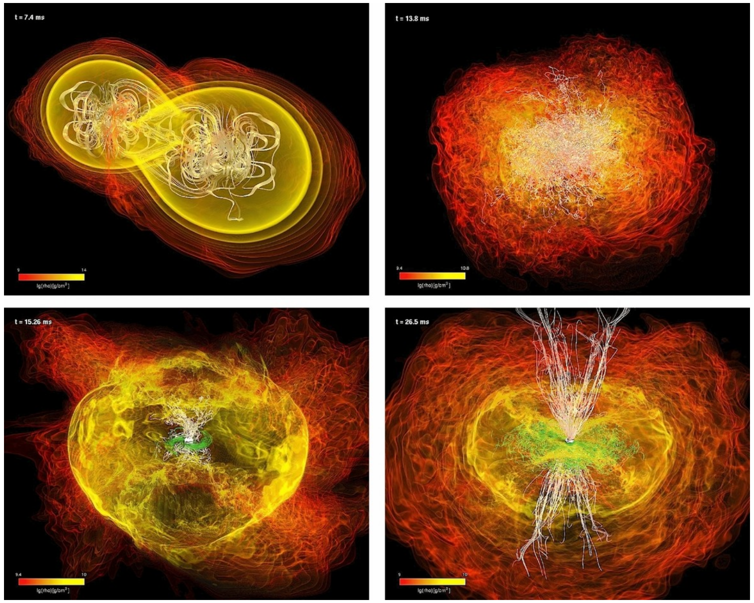




Binary NS merger simulations

→ SPH methods, eg. Korobkin et al. (2012)

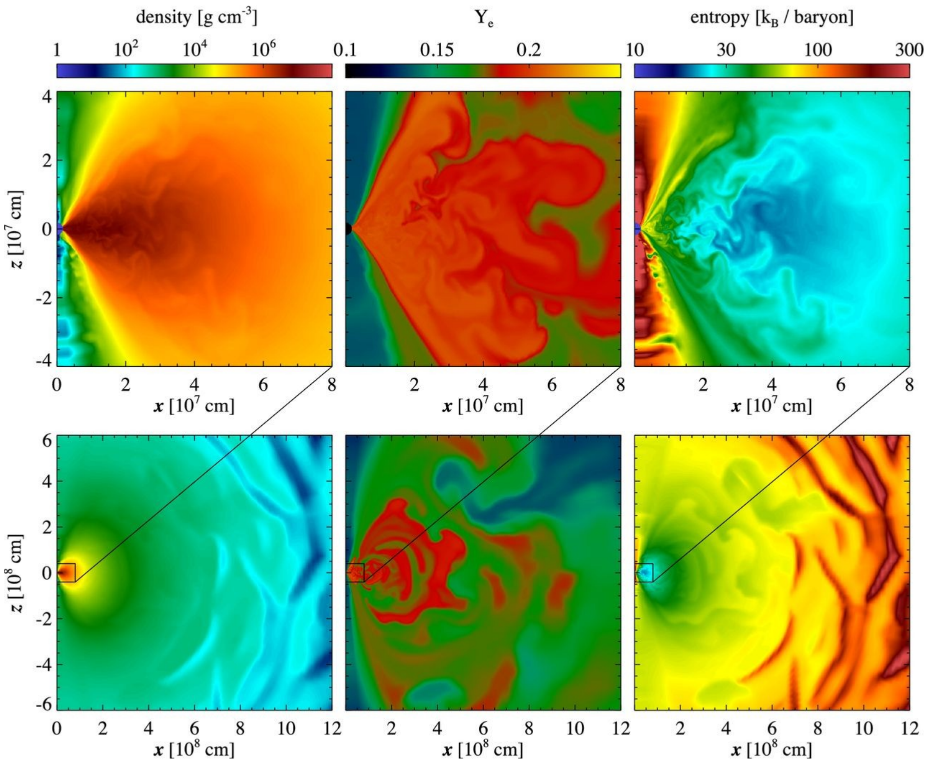
→ numerical relativity methods, e.g. Rezzolla (2014), Paschalidis et al. (2015), Aguilera-Miret, Vigano & Palenzuela (2021); Kawaguchi et al. (2024)

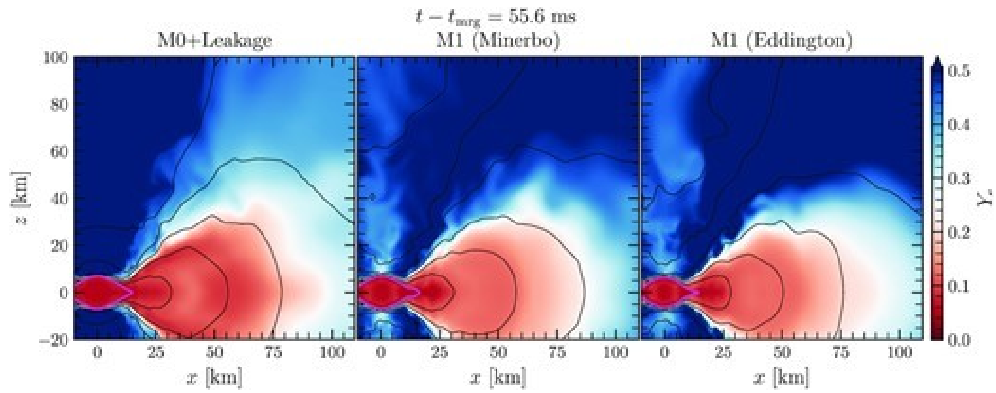


Post-merger systems

Accretion disk embedded in low density medium. MHD needed for MRI turbulent transport and outflow speeds compatible with observations.

Lee, Ramirez-Ruiz, & Lopez-Camara (2009)
Fernandez & Metzger (2013)
Janiuk et al (2017, 2019), Nedora et al. (2021), Radice, Bernuzzi & Perego (2022)



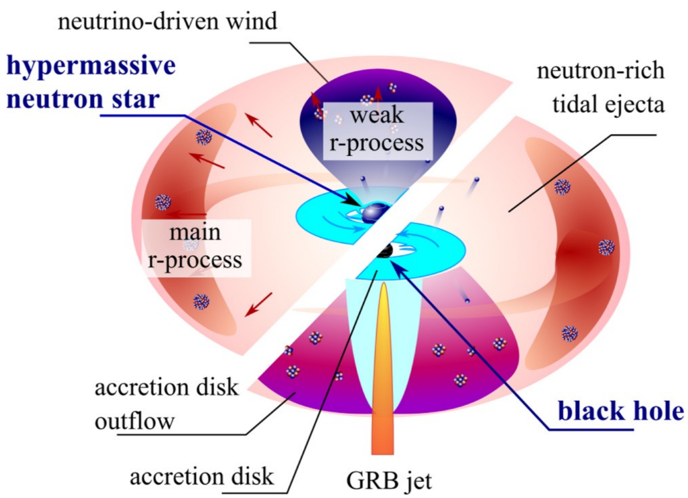


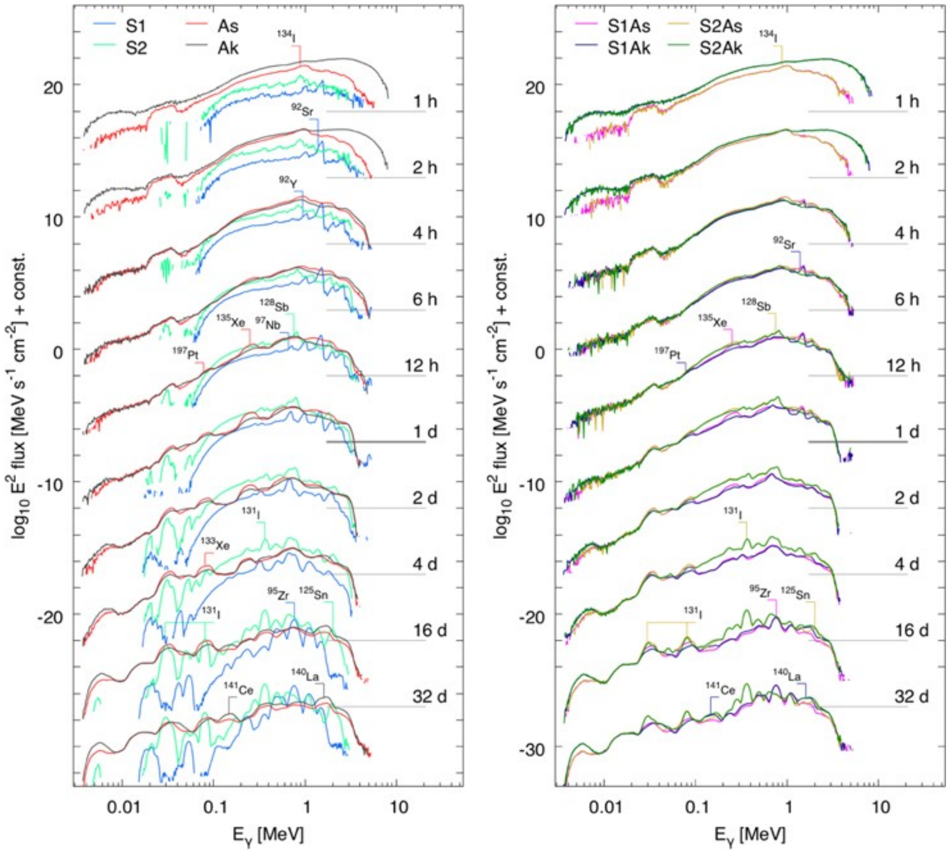
Gravity: pseudo-Newtonian, full GR

Neutrino treatment: averaged emissivity in opt. thin disk, leakage schemes, transport with M1 closure.

Radiation transport

In the two-component model (SPH simulation, *Korobkin et al. 2021*), 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).

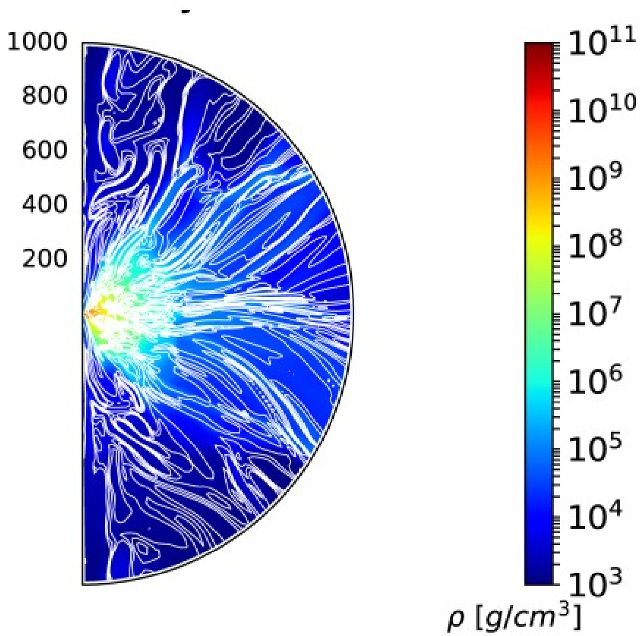




Recent works: Barnes et al. (2021); Just et al. (2022), Collins et al. (2023)

GR MHD simulations with HARM

$$(\rho u_\mu)_{;\nu} = 0$$
$$T^\mu_{\nu;\mu} = 0.$$
$$F^{*\mu\nu}{}_{;\nu} = 0\ .$$
$$F^{*\mu\nu} = b^\mu u^\nu - b^\nu u^\mu$$
$$T_{(m)}{}^{\mu\nu} = \rho\xi u^\mu u^\nu + p g^{\mu\nu}$$
$$T_{(em)}{}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$
$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$



HARM = Conserved scheme for High Accuracy Relativistic MHD *(Gammie et al. 2003)*

HARM-COOL = Accounts for neutrino cooling and Fermi gas EOS, computed numerically and **tabulated** during simulation with P(ρ, T), e(ρ,T) *(Janiuk et al. 2017; Janiuk 2019)*.

Publicly available code version

https://github.com/agnieszkajaniuk/HARM_COOL

- CPU only; - parallelized with MPI or hybrid with Open-MP
- outputs in ASCII or HDF5
- stationary or evolving Kerr metric (Król & Janiuk 2021)
- analytic or tabulated EOS (Janiuk 2019)

Equation of state

There can be two main types of EOS

1. Analytic
   - Polytrope $p(\rho) = \kappa\rho^{\Gamma}$, $\epsilon(\rho) = \frac{\kappa}{\Gamma-1}\rho^{\Gamma-1}$
   - Ideal gas (gamma-law): $p(\rho) = (\Gamma - 1)\rho\epsilon$
2. Tabulated
   - 1-parameter $\epsilon(\rho)$, $P_{\epsilon}(\rho)$
   - 2-parameter $\epsilon(\rho, T)$, $P_{\epsilon}(\rho, T)$
   - 3-parameter $\epsilon(\rho, T, Y_e)$, $P_{\epsilon}(\rho, T, Y_e)$

It is also possible to construct hybrid EOS, with analytic and tabulated components, e.g. depending on temperature range

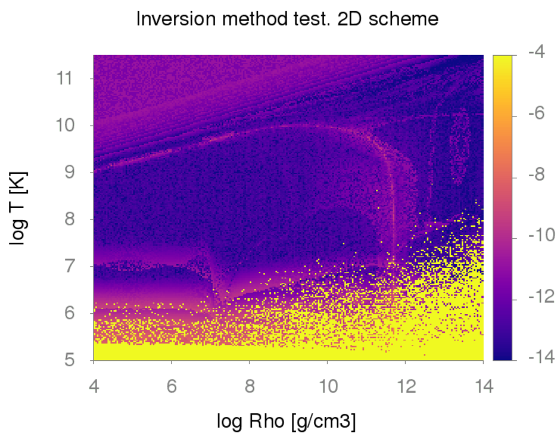
Non-trivial transformation between ‘conserved’ and ’primitives’ variables in GR MHD.
Various inversion schemes exist, needed to recover stress tensor and flux terms for fluid evolution

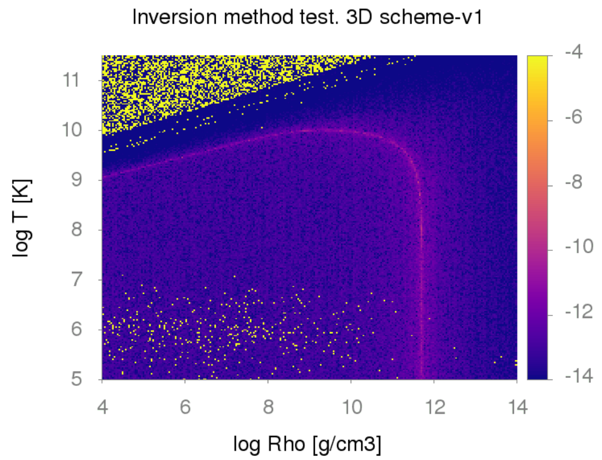
→ unbounded 2D and 3D (Siegel 2019). Faster but less stable

→ bracketed root-finding (Palenzuela et al. 2015). Slower but more robust

Tests of the scheme with composition dependent EOS

$$\partial_t \mathbf{U(P)} = -\partial_i \mathbf{F^i (P)} + \mathbf{S(P)}$$



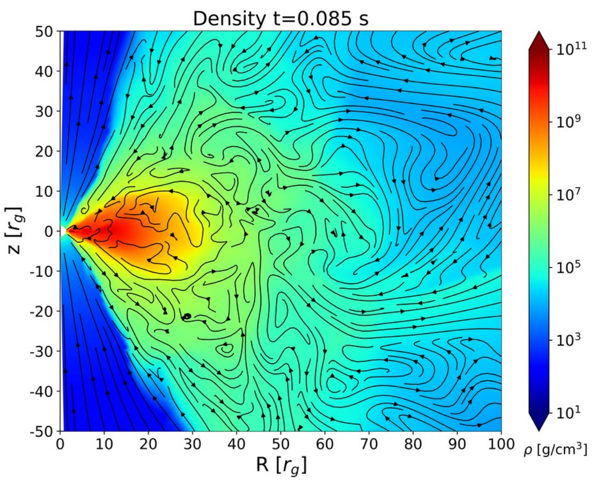


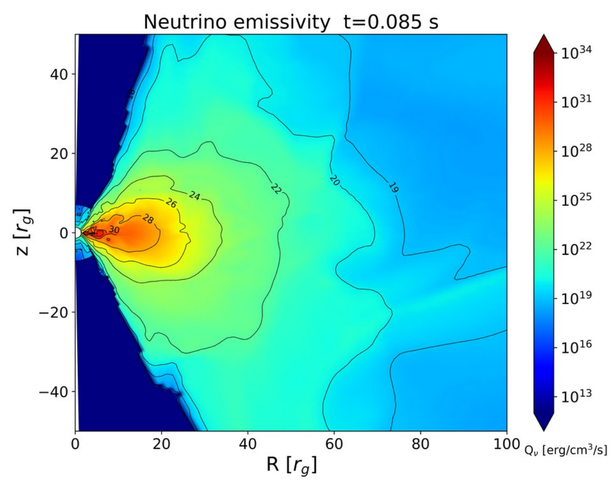
- Parameters: $Y_e = 0.1$, $\gamma = 2$, $p_{gas}/p_{mag} = 10^5$.
- Conserved variables derived in Kerr metric, then primitives perturbed by a factor of 1.05.
- Variables recovered through the 2D scheme compared to the unperturbed, to calculate $Err = \Sigma_{k=0.NPR}(P_k - \bar{P}_k)^2$

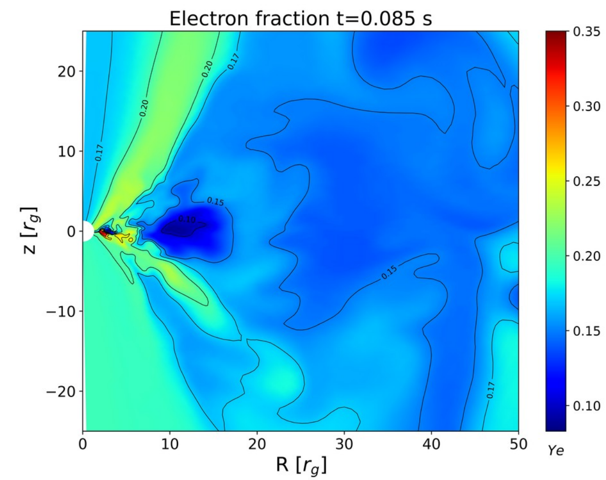
In HARM-EOS, we use the 3-parameter EOS adapted from **Helmholtz tables**, for wide range of densities and temperatures.

Tests performed to show the convergence of inversion schemes

Accretion disk & wind properties





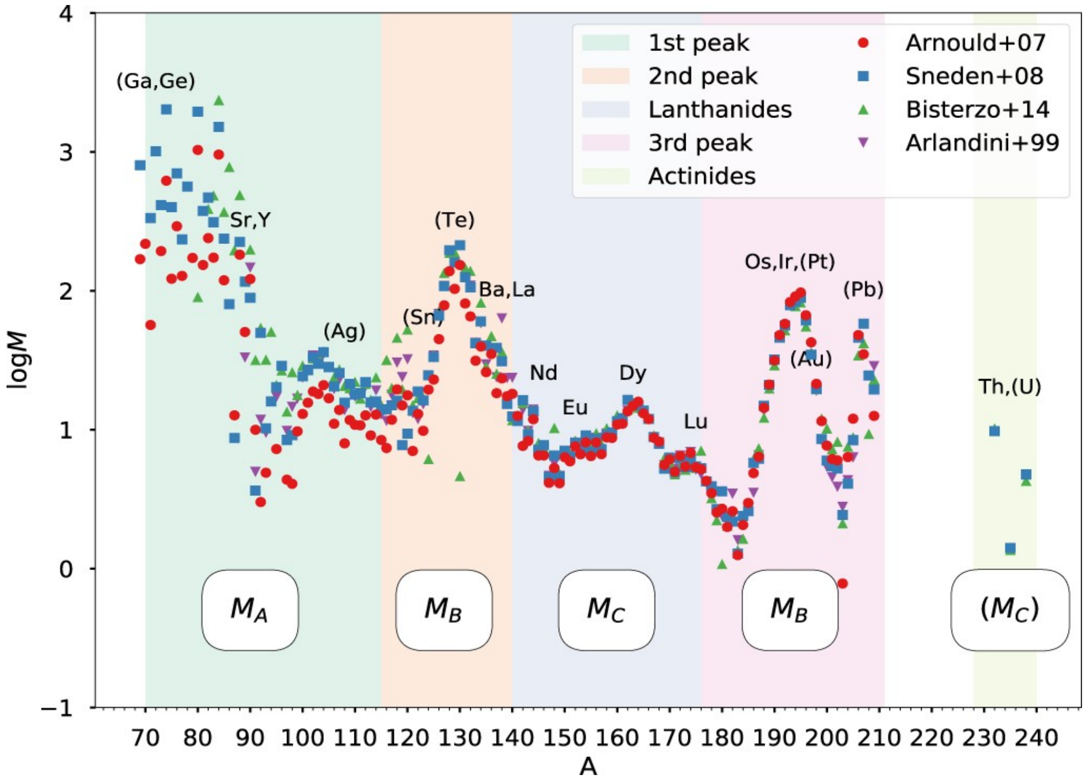


HARM-EOS results (with 3-parameter EOS)

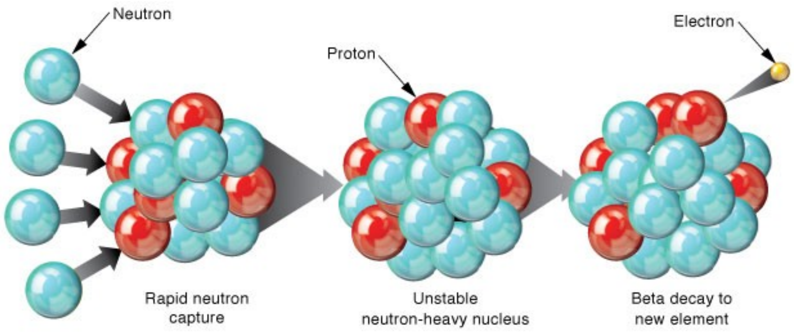
Additional source term in the energy-momentum conservation equation, due to heating and cooling by neutrinos.

Net rate of neutrino emission computed from lepton number conservation

r-process nucleosynthesis



Ji et al. 2019



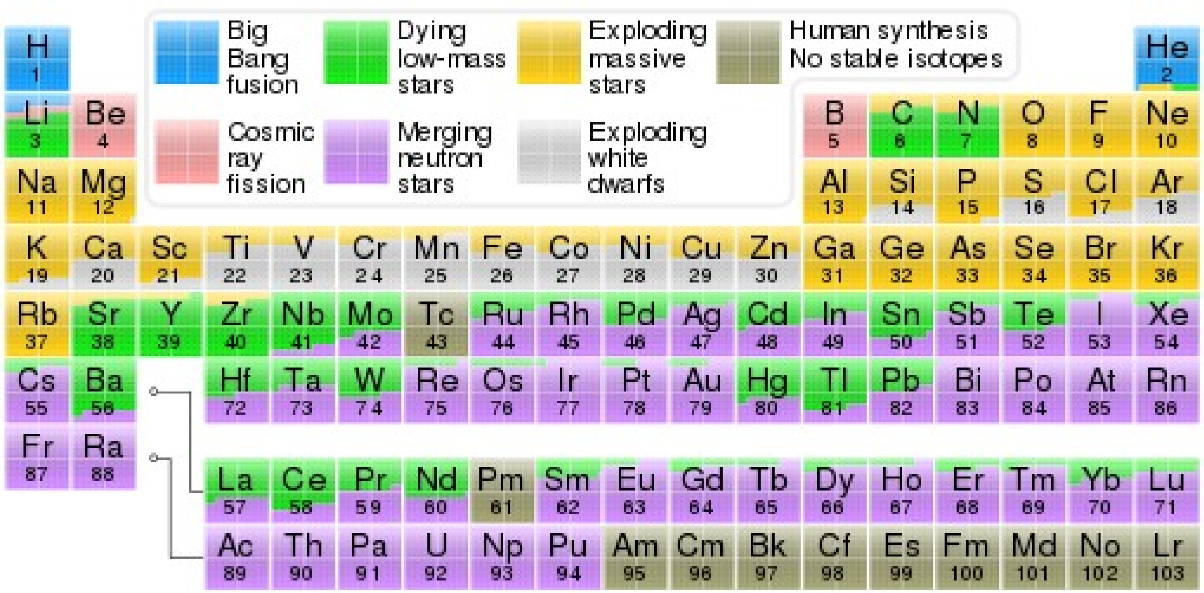
Matter is neutronized,
$Y_e = n_p/(n_p + n_n) < 0.5$

$Y_e > 0.25$: 1st peak

$Y_e = 0.15\text{-}0.25$: 2nd peak, Lanthanides

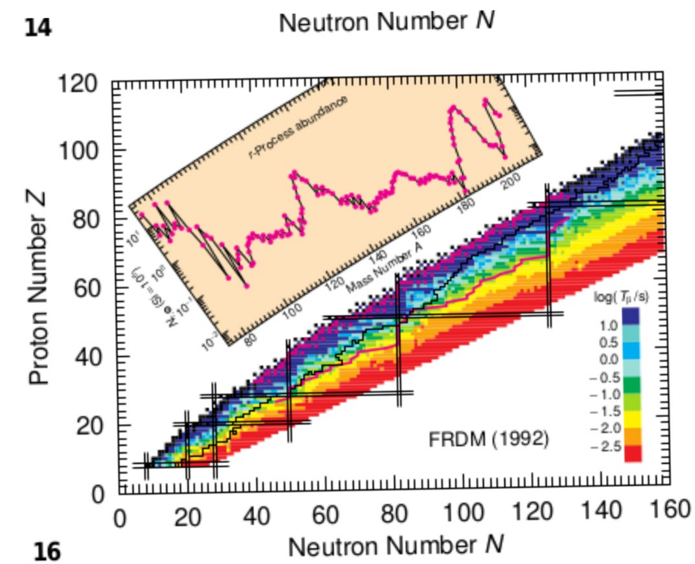
$Y_e < 0.15$: 3rd peak, Actinides

Heavy isotopes can be formed in the GRB environment



Astrophysical sites:

→ **supernovae explosions**
→ **compact binary mergers**

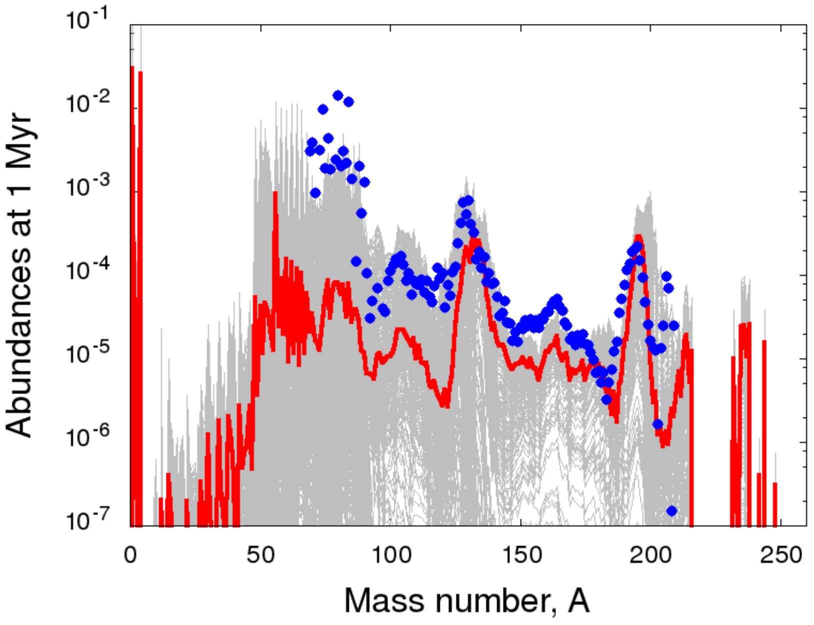


Moller et al., 1997

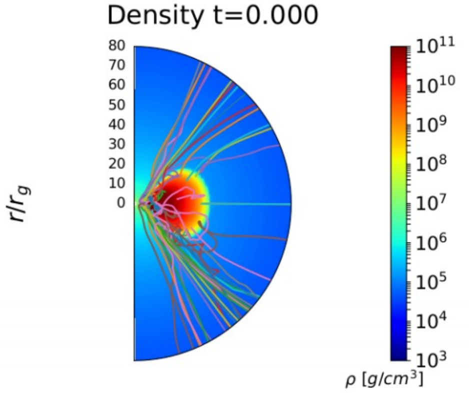
Nucleosynthesis in disk winds

Accretion disk winds traced by sampling the density, velocity, and composition over outflow trajectories (cf. Bovard & Rezzolla, 2015)

- Nucleosynthesis is computed by post-processing of results, by nuclear reaction network code (set of multiple ordinary differential eqs.)
- Heavy elements up to A ~ 200 (incl. Platinum, Gold; and Uranium, Thor) are produced in disk ejecta.
- They contribute to kilonova emitting radioactivities, along with dynamical ejecta produced before merger



R-process abundance pattern in disk wind (A. Janiuk, 2019)



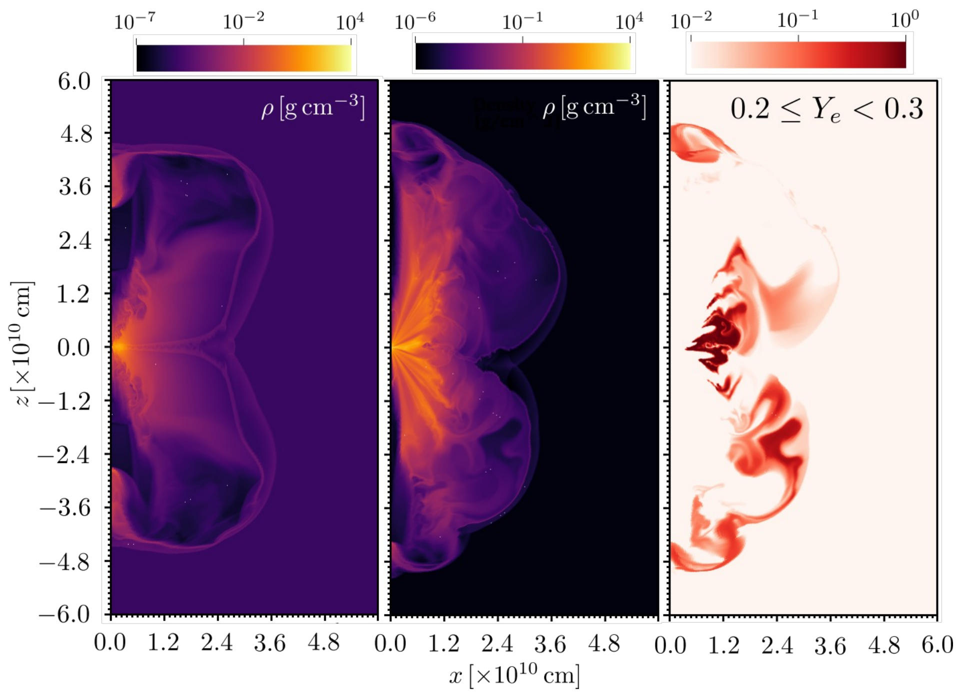
GRB jet collimation by post-merger ejecta

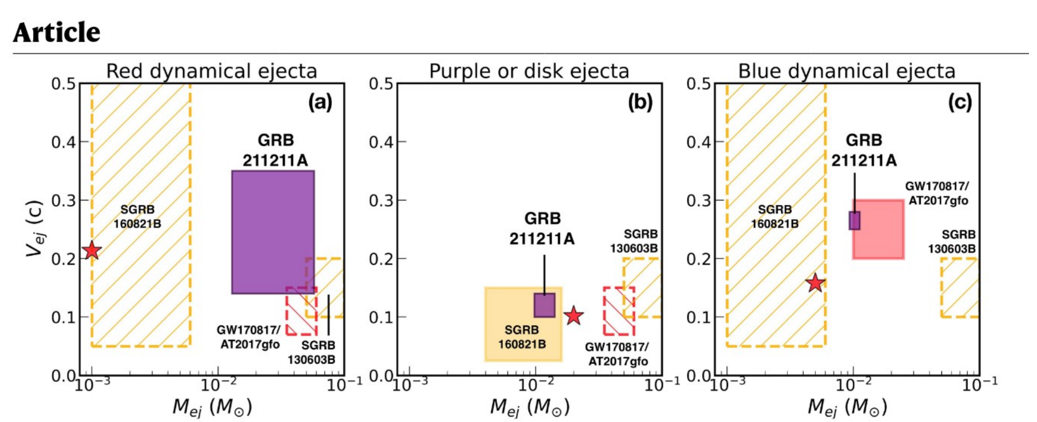
→ Jet shape and collimation due to spherical ejecta, or accretion disk wind
(Urrutia et al. 2024)

→ Disk wind mass estimated by various methods is between 4.e-4 and 4.e-2 Solar mass.
(Nouri et al. 2023).

→ Observables (lightcurve peak magnitude, spectra) need proper amount of wind mass and composition.

→ Kilonova colors still a puzzle
(Rastinejad et al. 2022)



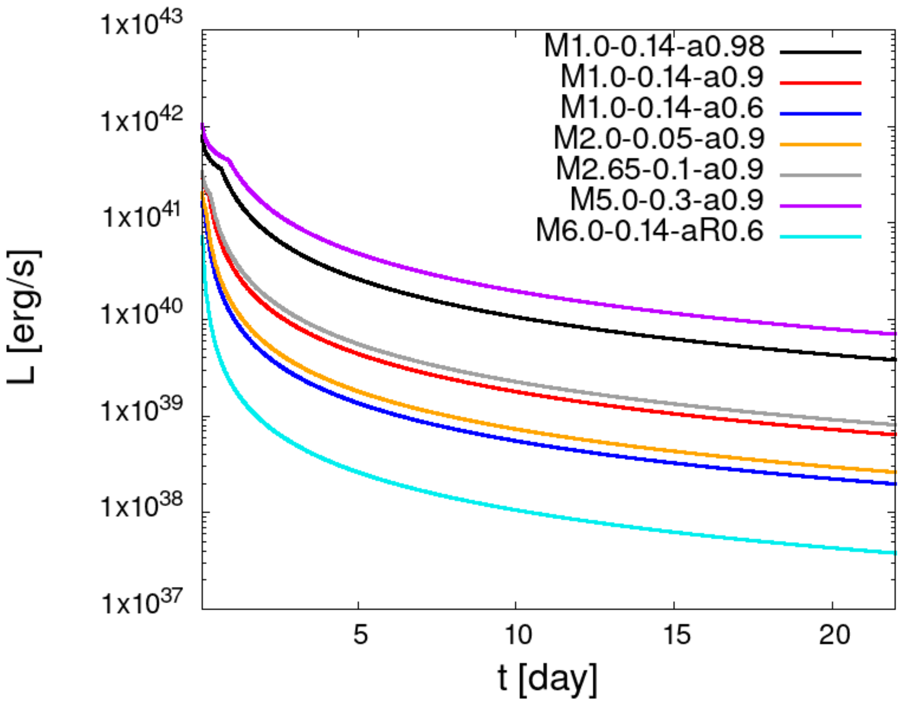


Kilonova lightcurves

- Synthetic kilonova ligtcurves for a range of BH-disk mass ratios and range of black hole spin parameters.
- We use method by Kawaguchi et al. (2016)

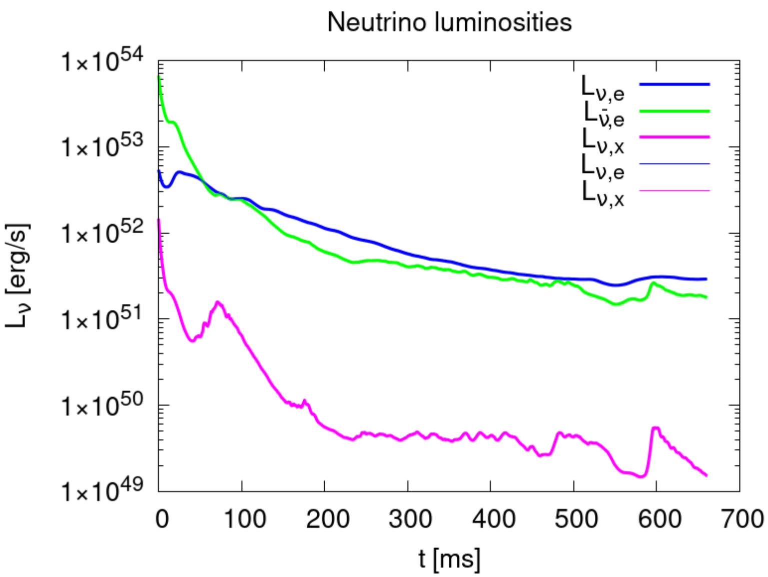
- Models aim to **distinguish between BH-NS and NS-NS** progenitors, eg. by measuring LC slopes (Kasen et al. 2015).
- Simulations show a **correlation between the black hole's spin** and ejected wind mass

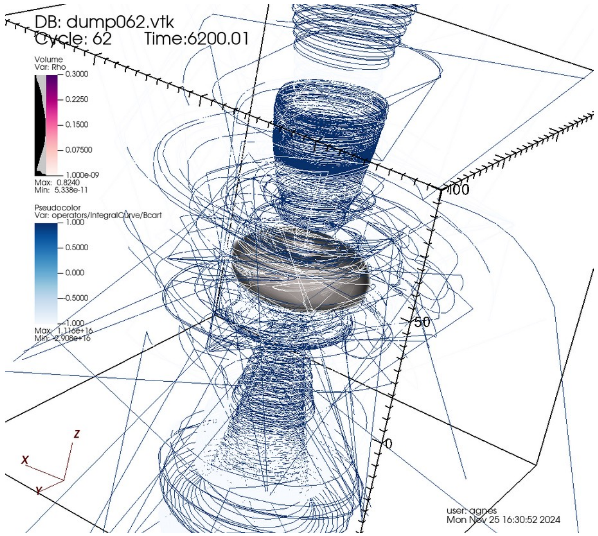
- Only a fraction (∼20%) of BHNS binaries gain a high BH spin (Drozda et al. 2022), so majority of these GRBs will not contribute to KN signals



Nouri, Janiuk & Przerwa (2023)

Neutrinos: extra power source to the jets





→ Neutrino leakage scheme (Ott et al. 2021).

→ Computes a gray optical depth estimate along radial rays for electron neutrinos, electron antineutrinos, and heavy-lepton neutrinos (nux), and computes local energy and lepton number loss terms.

→ This sample 3-D simulation with 3-parameter EOS used over 2 mln core-hours on LUMI supercomputer in Finland

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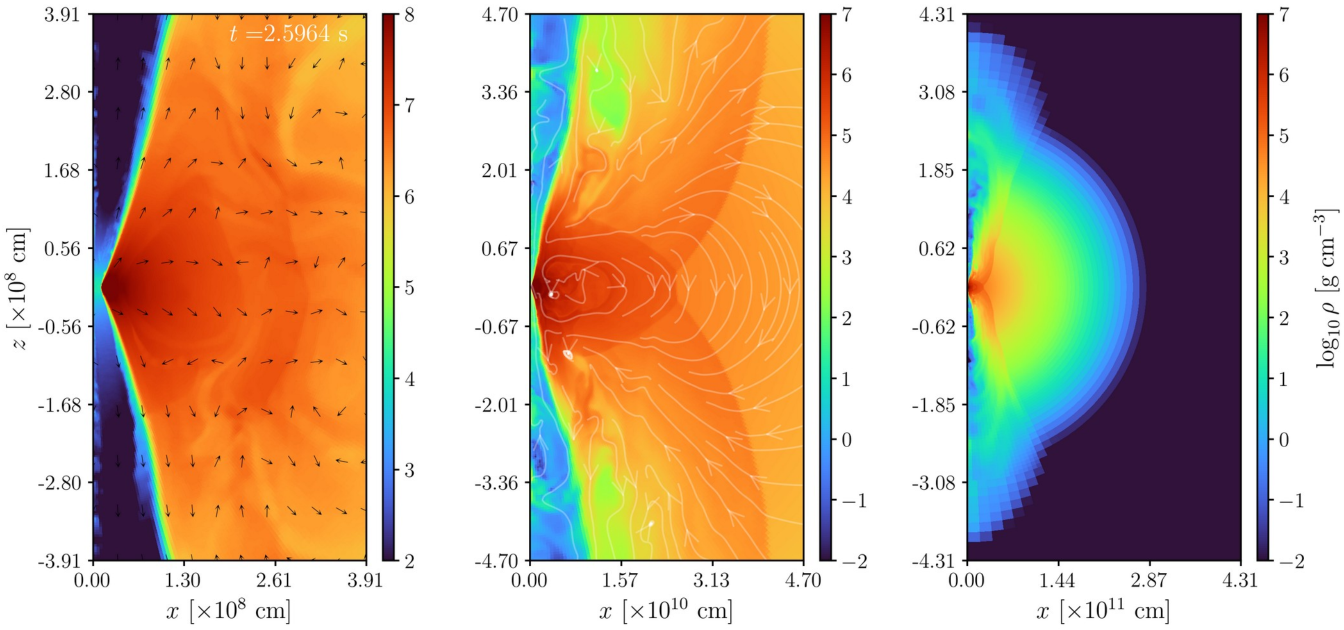
Collapsar simulations

→ Code BHAC, with adaptive mesh, allow to cover large scale (Porth & Olivares 2016) and reach jet breakout

→ Initial condition: evolved star models, either from pre-supernova (Woosley & Heger 2006) or evolved with MESA: no clue which is better (cf. Aloy & Obergaulinger 2021)

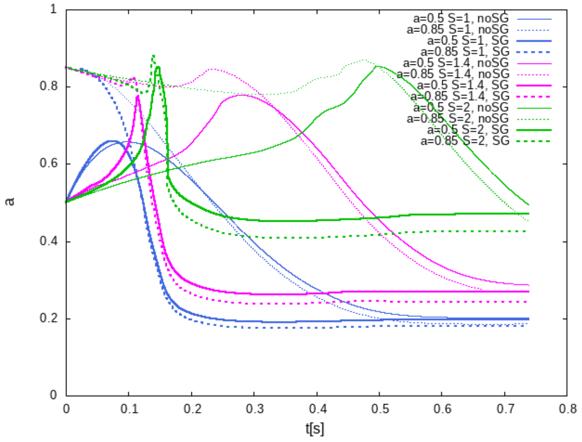
→ stellar core: rotating and magnetized (hybrid field, Moesta et al. 2015)

→ Kerr black hole, large spin (constant), put „by hand”



Urrutia, Olivares, Janiuk (2025, in prep)

Growing BH in collapse



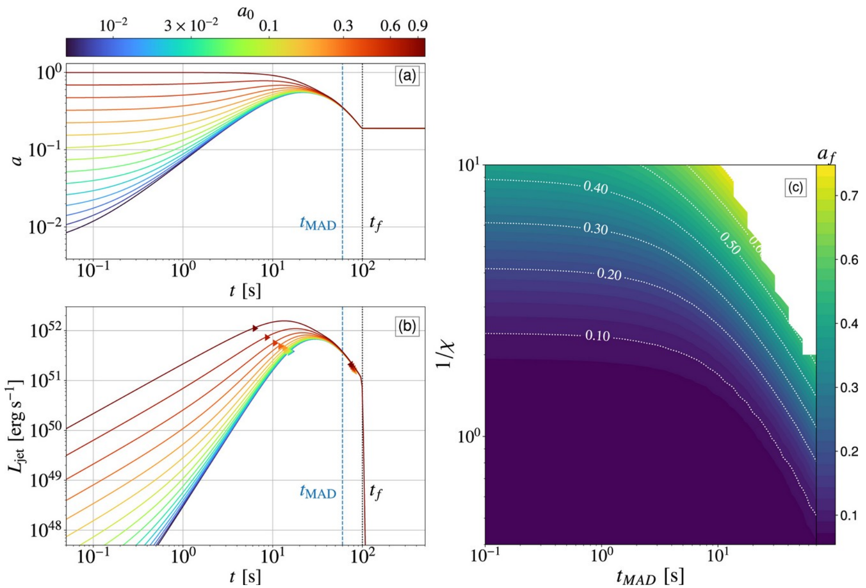
- Core rotation leads to formation of mini-disk at equatorial plane.
- Angular momentum is accreted into BH

  (cf. Barkov & Komissarov 2010, AJ, Charzyński & Bejger 2013, Król &AJ 2021)
- Space-time Kerr metric is changing due to changing mass and spin of newly formed black hole in collapsar.

$$\dot{M}_{BH} = \int d\theta d\phi \, \sqrt{-g} \, T^r{}_t,$$

and

$$\dot{J} = \int d\theta d\phi \, \sqrt{-g} \, T^r{}_\phi,$$



Black hole spin down during collapse after MAD state.

Equilibrium spin value a~0.2

Jaquemin-Ide, et al. (2024)

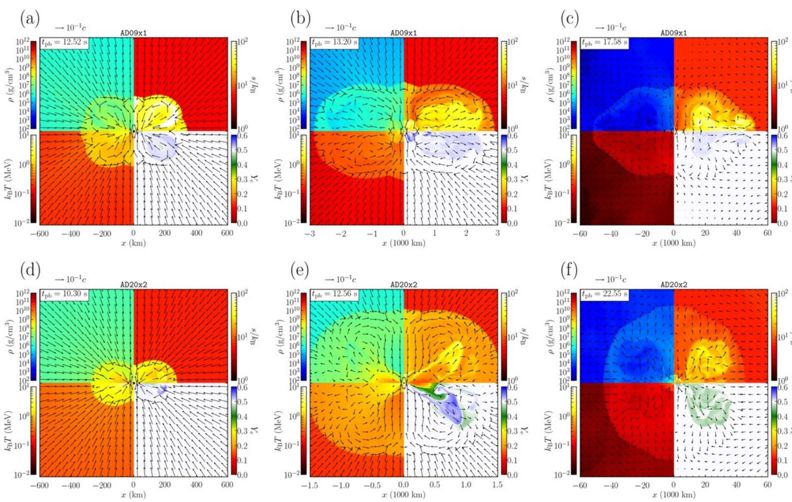
Self-Gravity in the collapsar

HARM-SELFG

→ Space-time Kerr metric is evolving due to changing mass and spin of black hole

→ Perturbative terms due to self gravity of collapsing core (Janiuk et al. 2023)

→ Inhomogeneities and accretion shocks



→ Evolved stellar core

→ BSSN method, GR Hydro+neutrinos

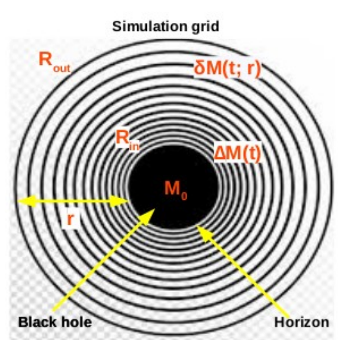
→ Accretion shocks form

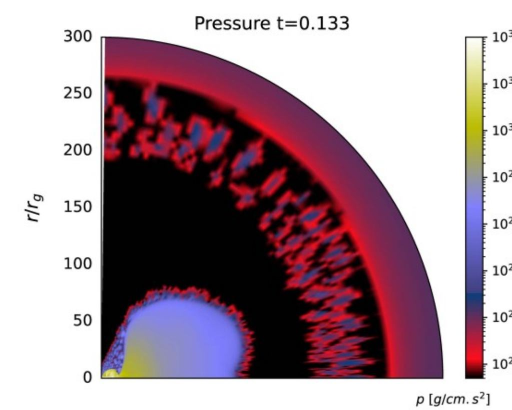
Fujibayashi et al. 2023

$$\dot{M}_{BH} = \int d\theta d\phi \sqrt{-g}\, T^r{}_t,$$

and

$$\dot{J} = \int d\theta d\phi \sqrt{-g}\, T^r{}_\phi,$$



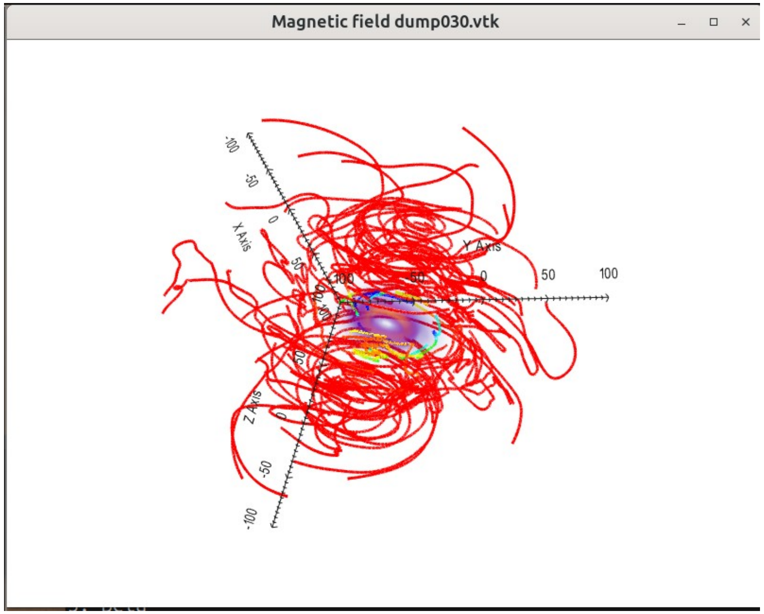


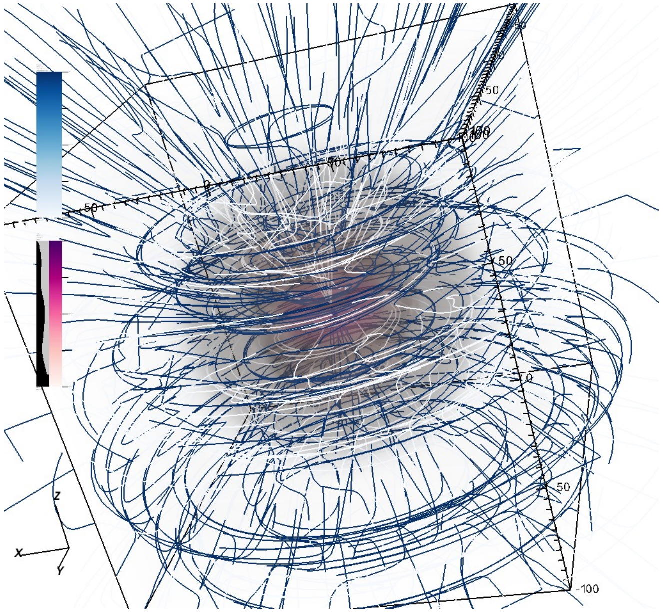
Summary

- Cosmic explosions related to deaths of massive stars, birth of black holes and neutron stars, or their mergers, are spectacular phenomena that lead to variety of observables.

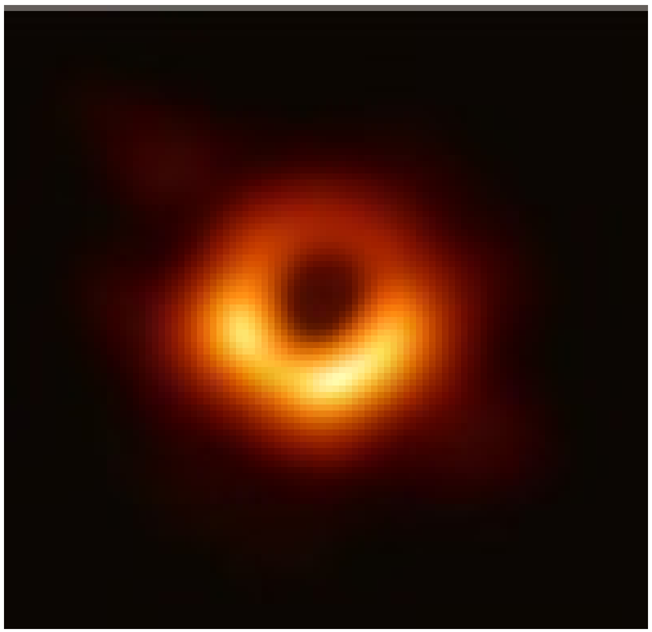
- Computational astrophysics methods and massive GR MHD simulations are great tool to model these events.

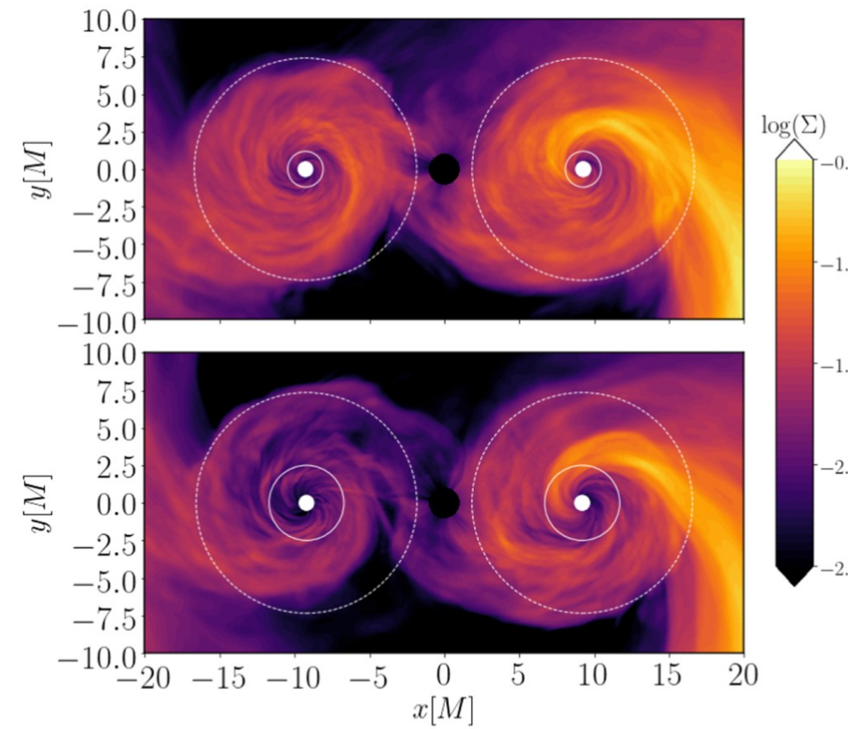
- Complexity of the problem is due to interactions of strongly magnetized plasmas in extreme gravity. The multiscale nature of the problem, from micro scale (fm) up to cosmic distances (billions km) poses biggest technical challenge.





Not covered in this talk





Relativistic Astrophysics group at CTP PAS

- please visit our website.
https://ra.cft.edu.pl/

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NARODOWE CENTRUM NAUKI

3D models: SG effects, collapse, EOS

- Works in progress
- Need much more computational resources
- Role of magnetic fields and self-gravity
- Search for non-axisymmetric modes in the SGI
- Search for plausible conditions for jet breakout
- Role of SGI shocks for nucleosynthesis