Many faces of black hole accretion in gamma ray bursts

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Plan of the talk

1. Introduction, short and long GRBs, gravitational waves

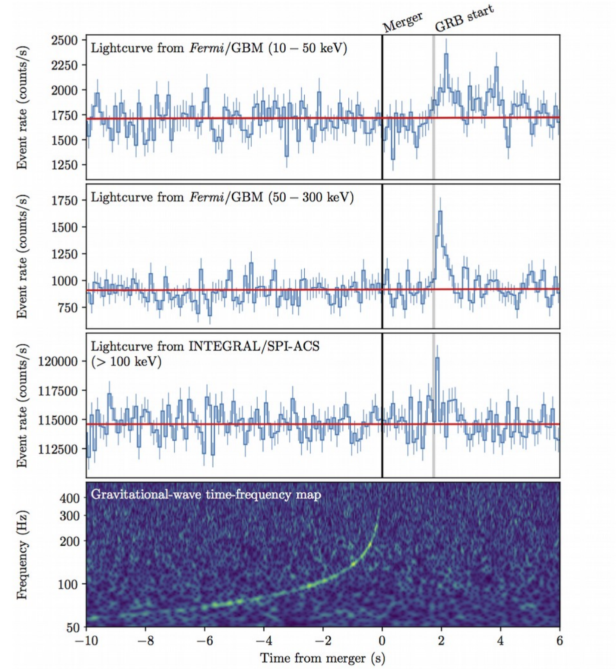
2. GRB central engine, numerical modeling

3. Nuclear physics and kilonova modeling

4. Jets and their variability

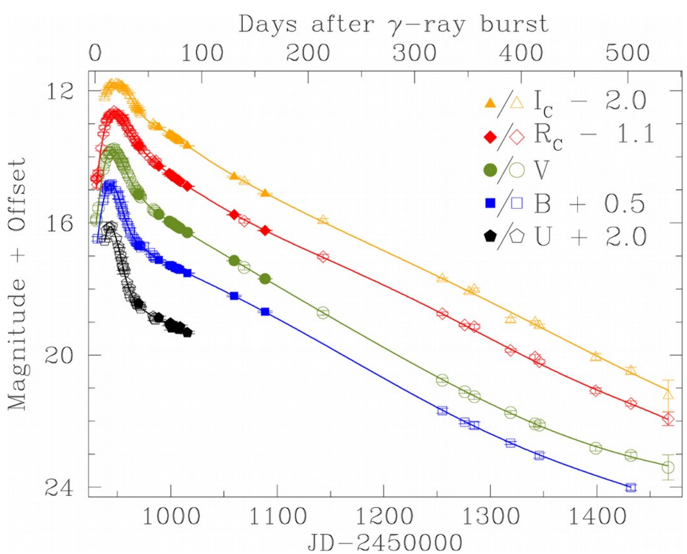
5. Spherical collapse, limits on stellar rotation and black hole spins

Gamma Ray bursts

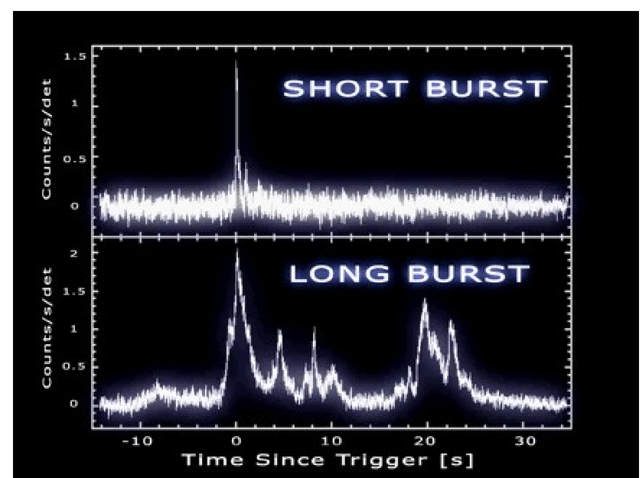


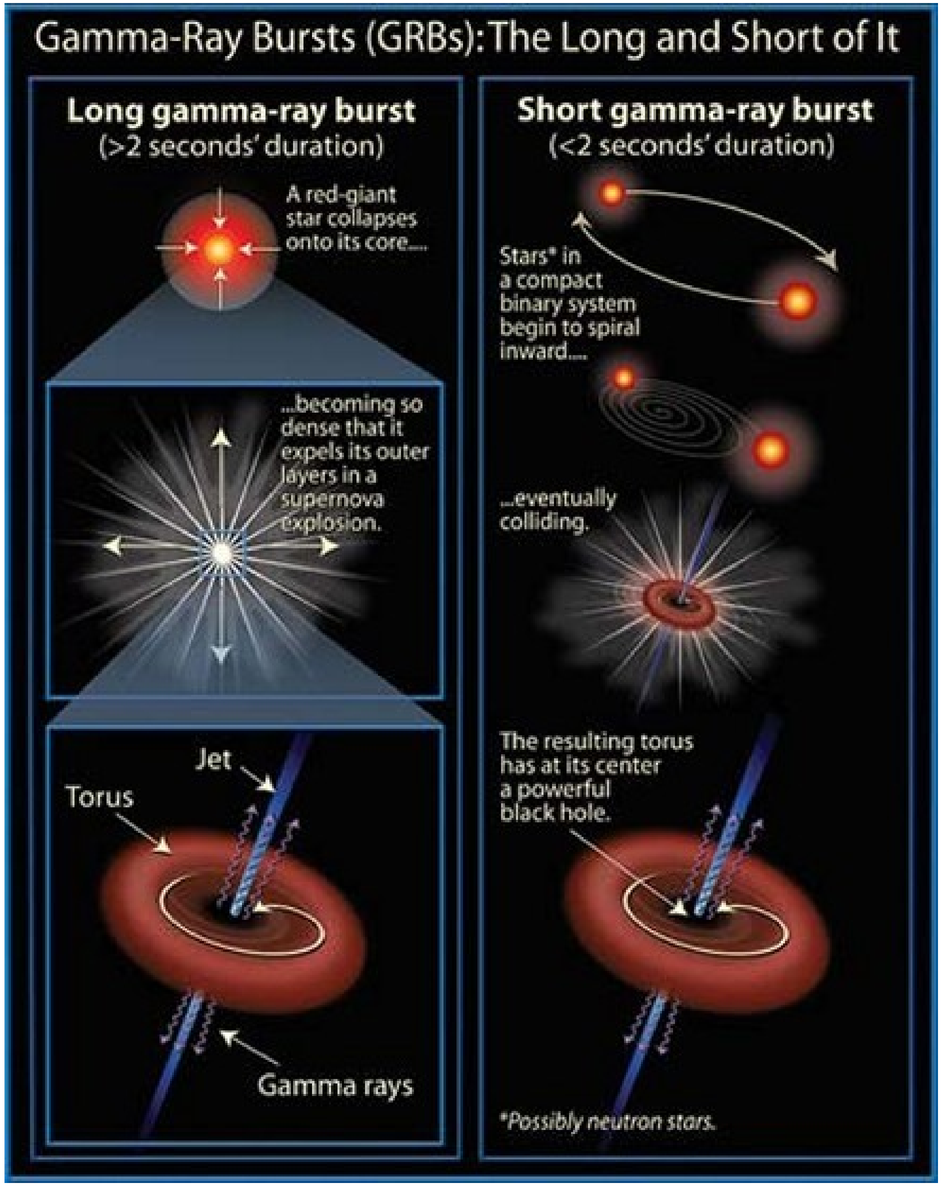
Rapid, bright flashes of radiation peaking in the gamma-ray band

First association of long event: GRB 980425 and SN 1998bw



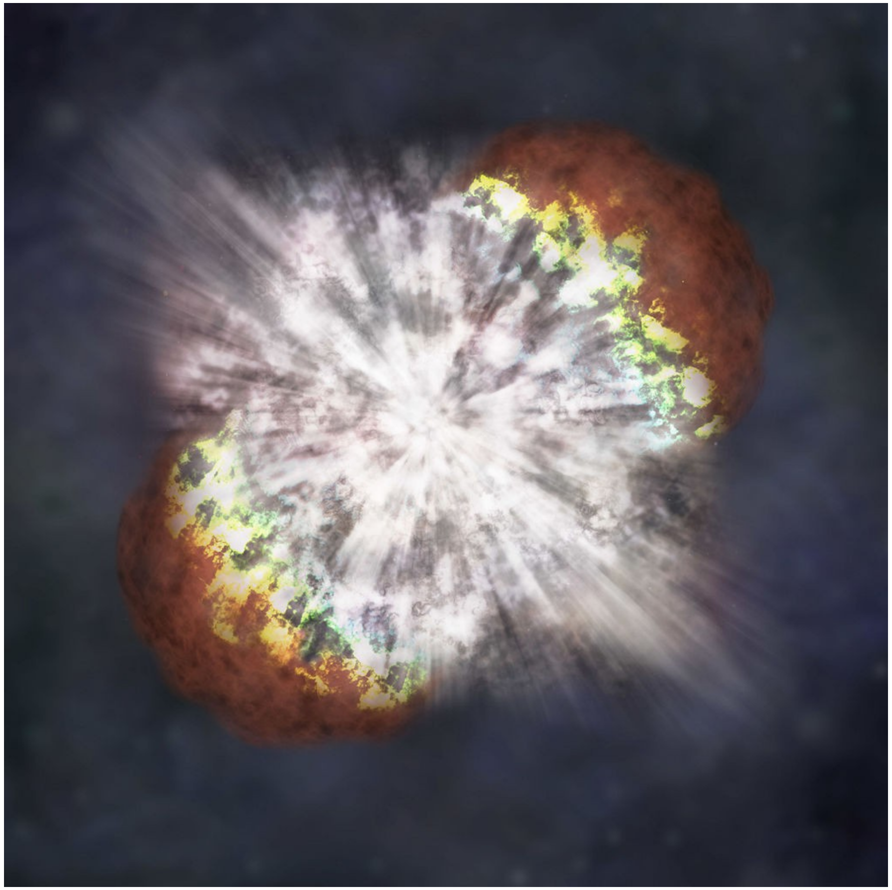
Confirmed source of short event: GRB/GW170817





- Short GRBs: mergers
- Long GRBs: collapsing massive stars
- Both involve jets launched through accretion onto black hole

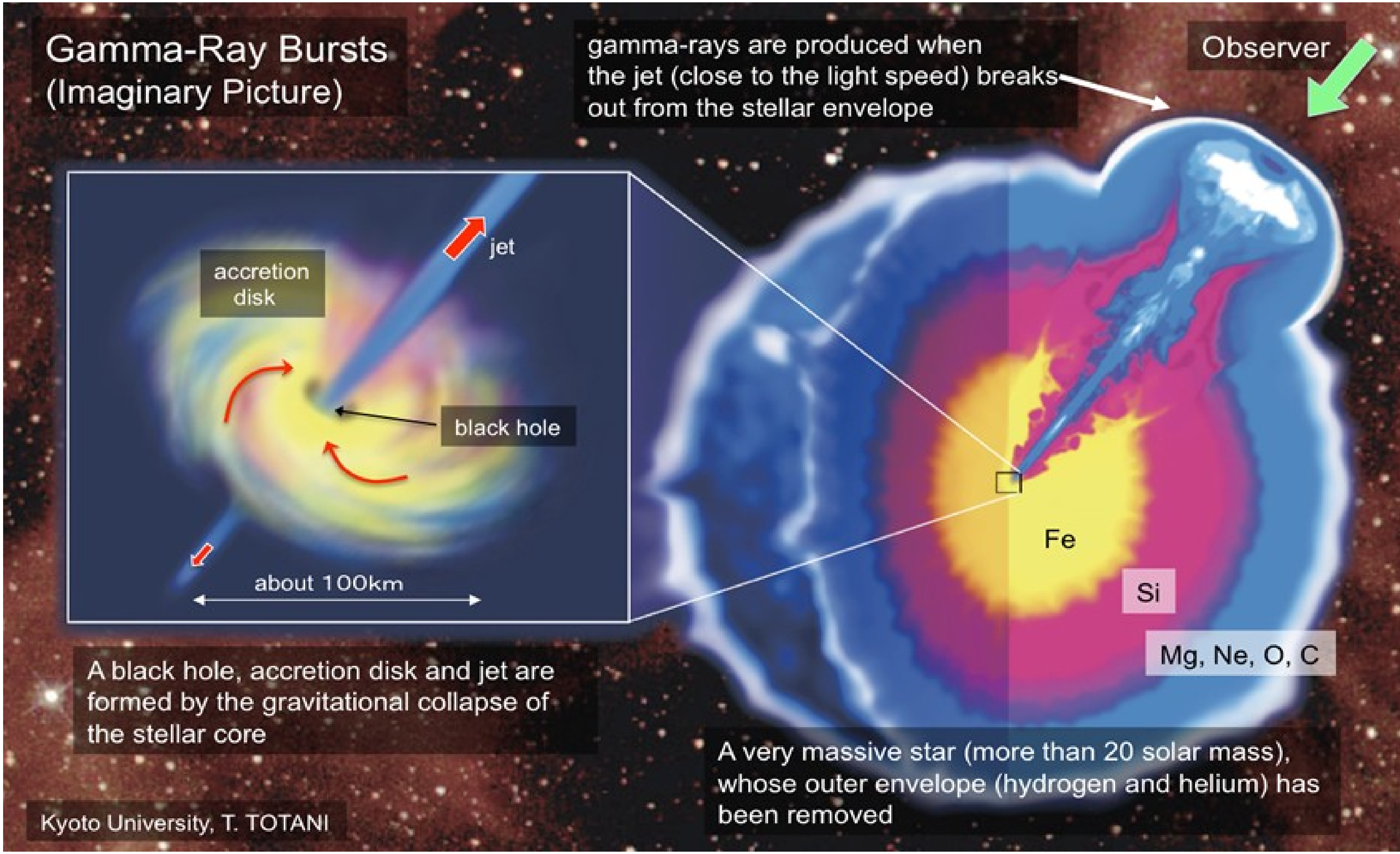
Explosion of the supernova



The remnant of the collapsed core may form a neutron star or a black hole

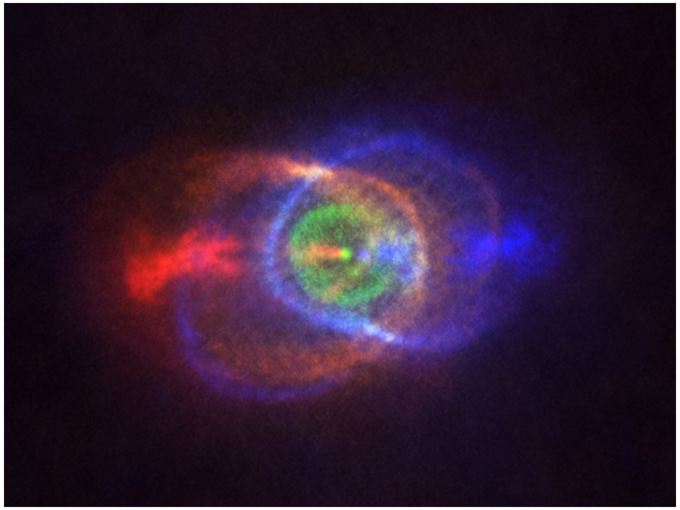
SNe of type Ib/c, are believed to mark the deaths of massive stars, stripped of their hydrogen (type Ib), and possibly helium (type Ic), envelope before explosion.

Observations show, that not all Ib/c SNe make a successful GRB jet, but a failed jet remains (e.g. SN2002ap; Berger et al. 2002; Mazzali et al. 2002; Soderberg et al. 2006; Piran et al. 2019)

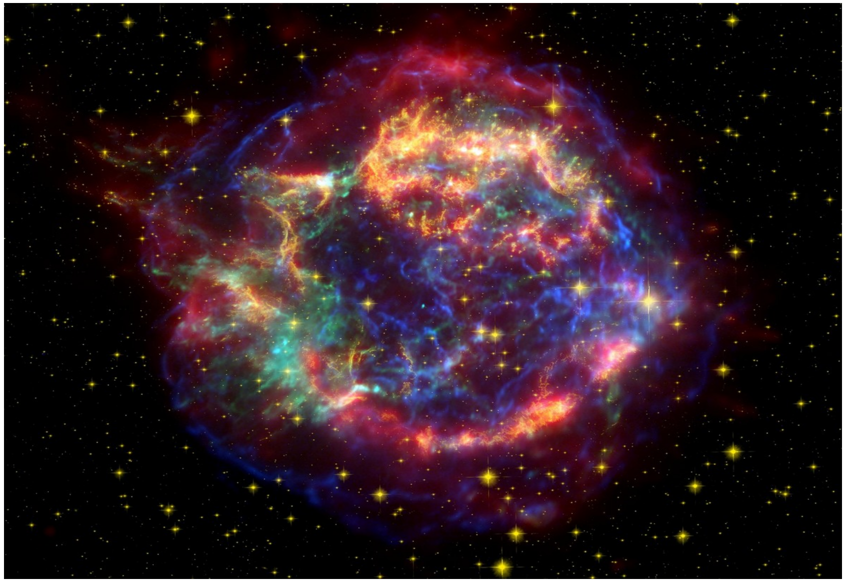

Gamma-Ray Bursts
(Imaginary Picture)
gamma-rays are produced when the jet (close to the light speed) breaks out from the stellar envelope
Observer
accretion disk
jet
black hole
about 100km
Fe
Si
Mg, Ne, O, C
A black hole, accretion disk and jet are formed by the gravitational collapse of the stellar core
A very massive star (more than 20 solar mass), whose outer envelope (hydrogen and helium) has been removed
Kyoto University, T. TOTANI

Black hole or neutron star?

After core-collapse supernova, the nature of compact remnant mostly depends on the progenitor mass on the Main Sequence, and is also dependent on its metallicity *(Nomoto et al. 2003; Ott et al. 2018)*



ALMA image of post-CE binary HD101584

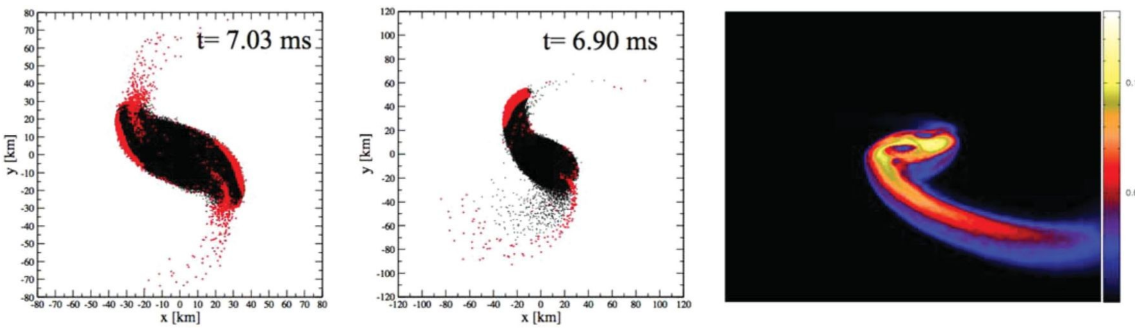


Composite (HST, Spitzer, Chandra) image of Cas A supernova remnant

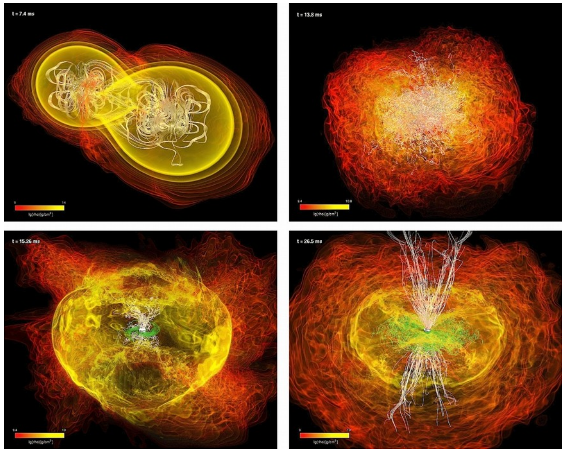
Massive stars heavier than 10 M_{Sun} are frequently born in binary systems, or in multiple stellar configurations (Sana et al. 2012; Taddia et al. 2019).

Evolution is driven by mass transfer (incl. unstable episode of Common Envelope; eg. *Fryer et al. 2013)*

Compact binary mergers

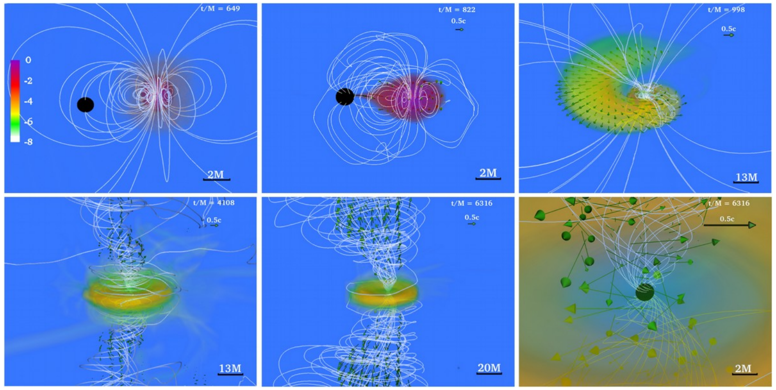


Korobkin et al. 2012



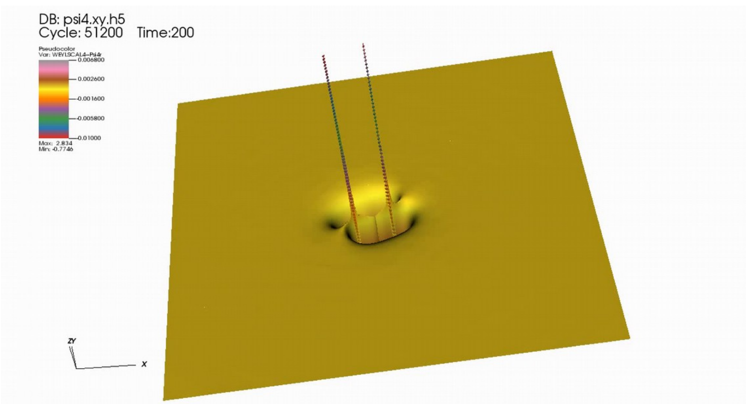
Rezzolla et al. 2014

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

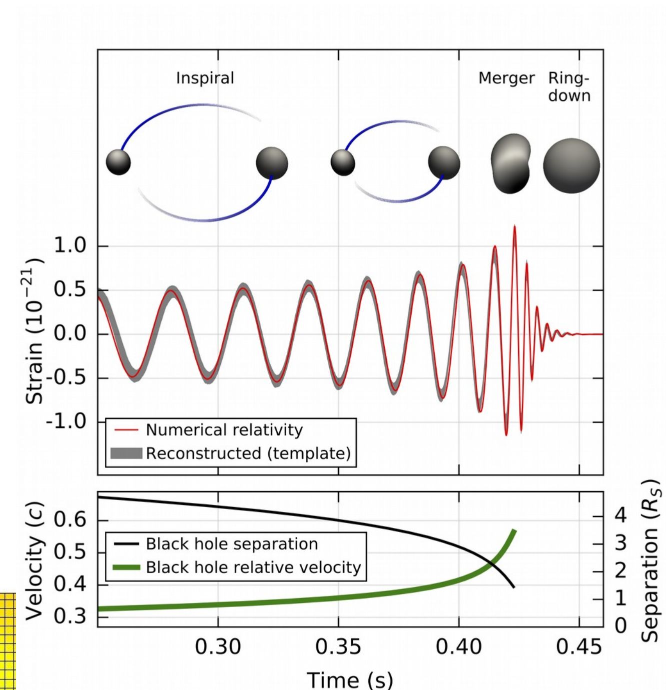
Nobel Prize in Physics: 2017 (K. Thorne, B. Barrish, R. Weiss)

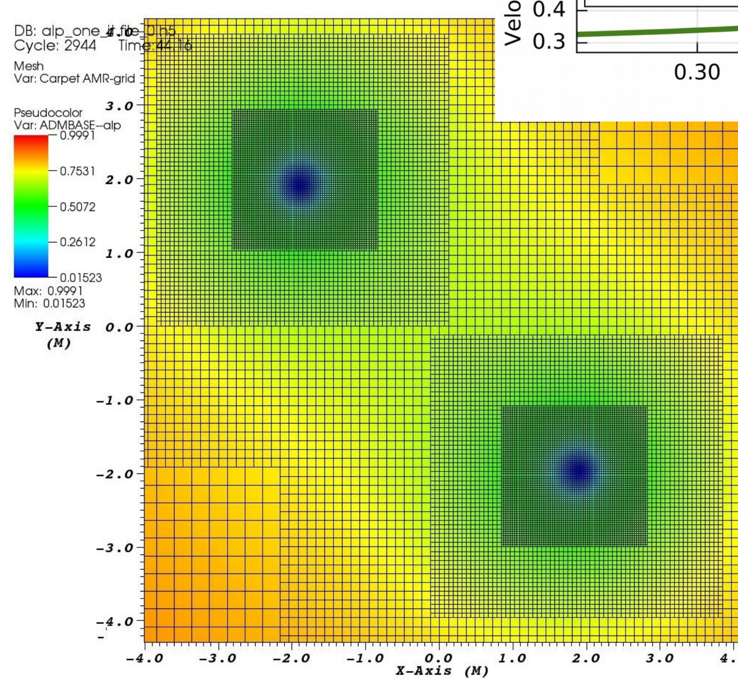
Numerical relativity

Two-body problem in GR has no analytic solution

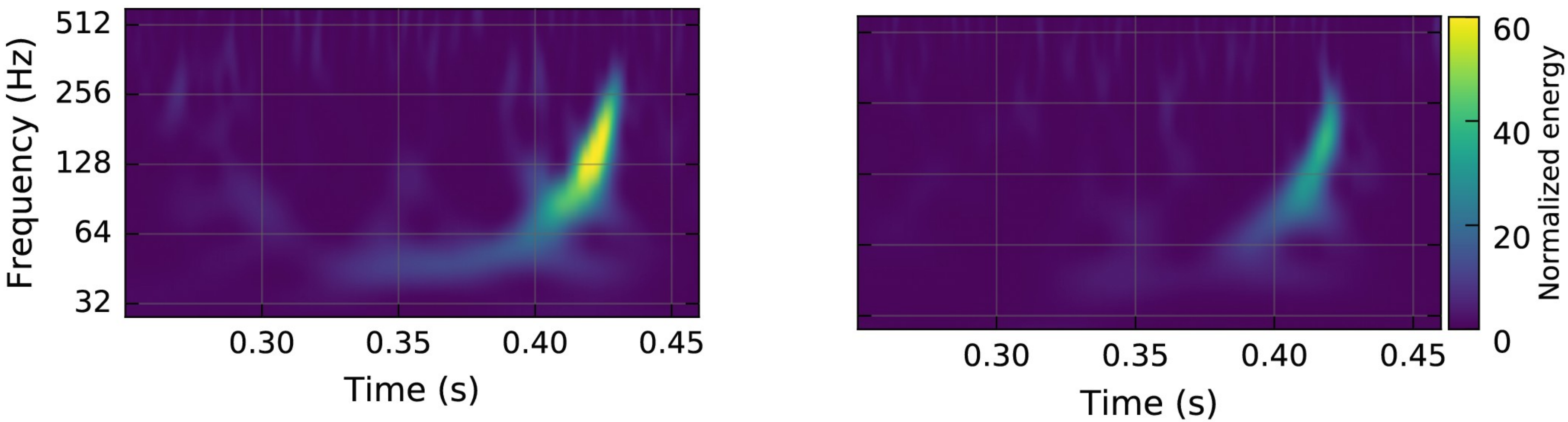
First methods that solve numerically the motion of black hole binary, were developed by (Pretorius 2005; Campanelli et al. 2006)

Technical issues: event horizon, singularity. Techniques: excision, AH finder, adaptive mesh refinement levels





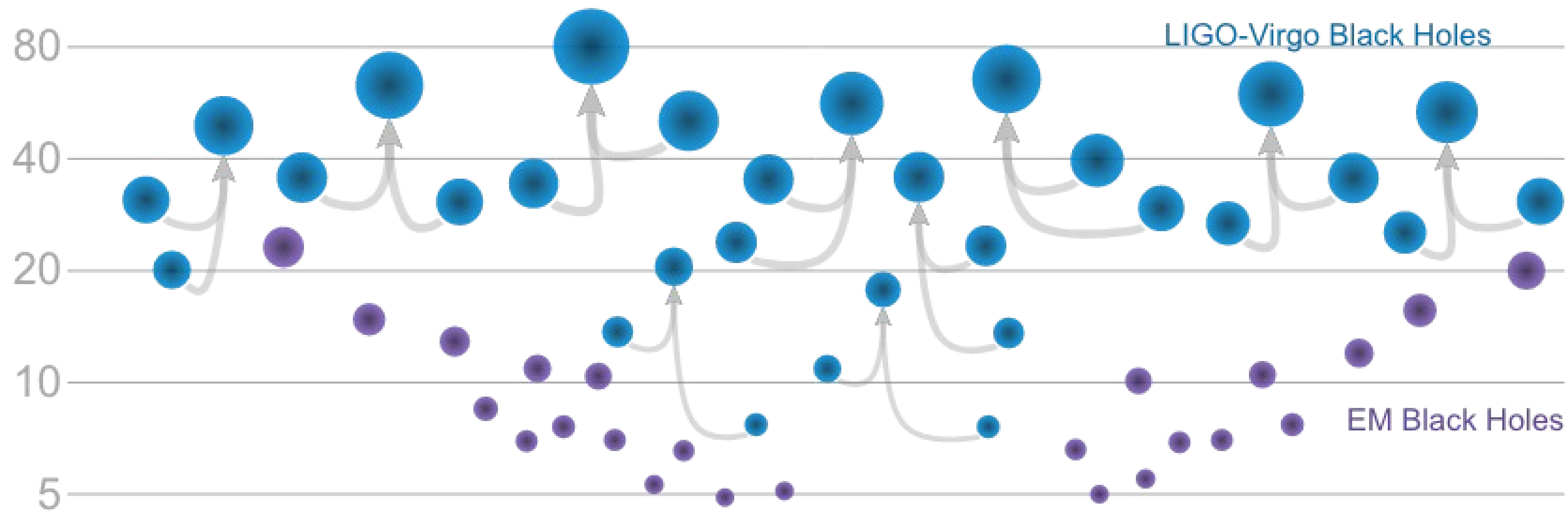
GW 150914



First detection of the gravitational wave in 2015: source GW150914.

Observed by LIGO detectors, located in Hanford (H1, left) and Livingston (L1, right). Time zero was on 14th September, 2015, at 09:50:45 UTC.

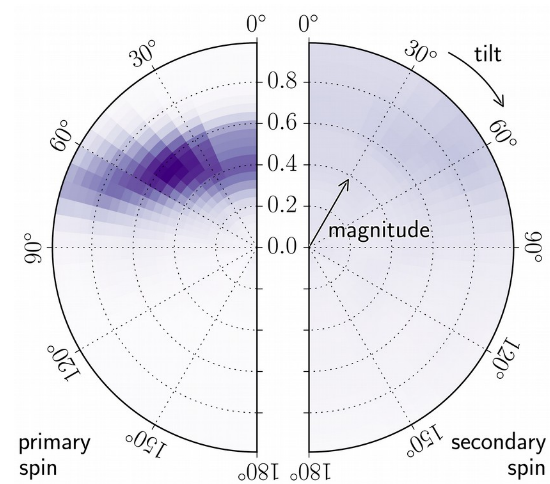
Mass assembly and spins of BBHs



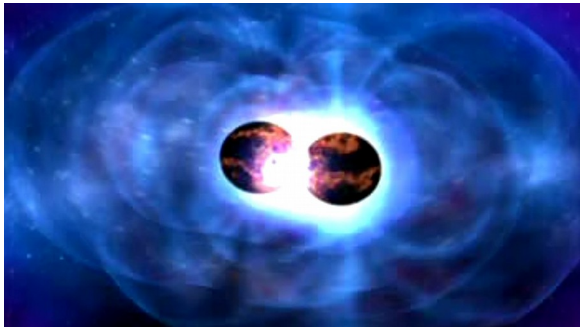
- In LIGO data, a negative correlation between mass and the mean effective spin is found (Safarzadeh et al. 2020).
- Data disfavour large spins.
- Typical spins are constrained to a<0.4. For aligned spins the constraints are tighter, spins required a ~ 0.1

(Rouet & Zaldarriaga, 2019).

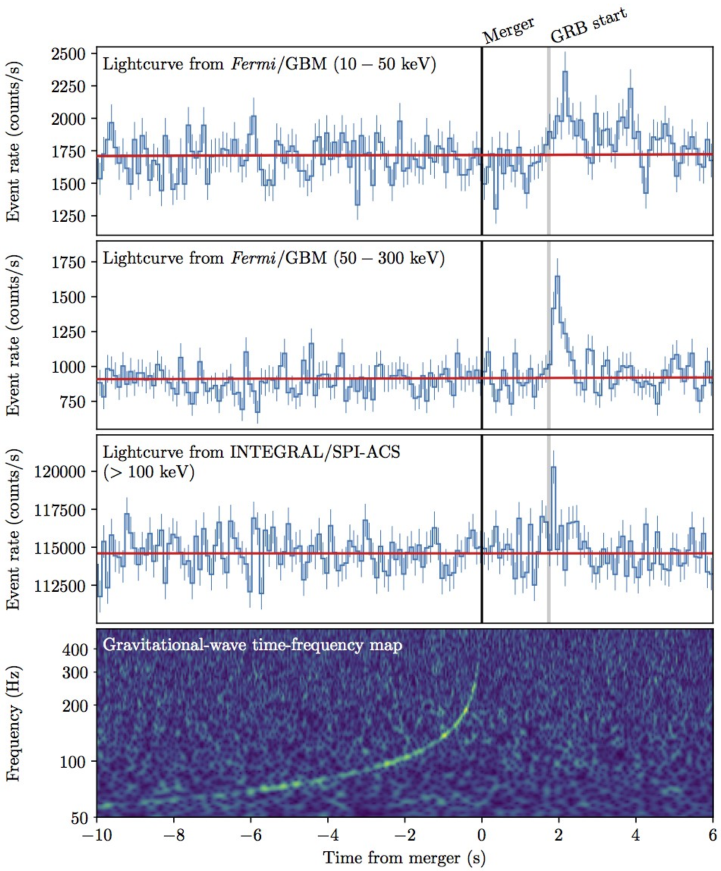
- The most-spinning objects are GW151226 and GW170729 (Biscoveanu et al. 2020)



GW 170817

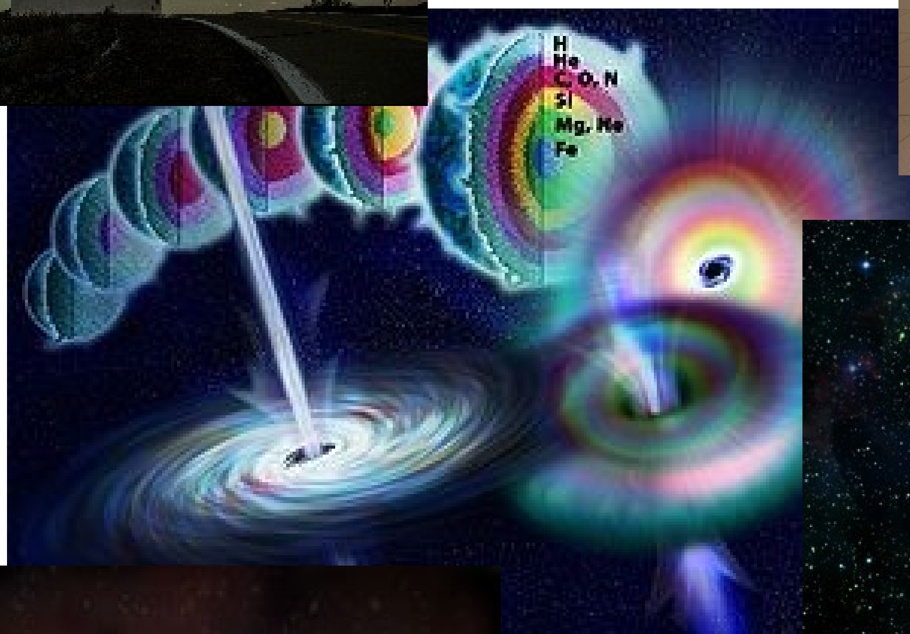


Double neutron stars formed a black hole after their merger.
During the inspiral phase, **gravitational waves** were produced
After the merger, we can observe a **burst** of energy.
The time delay of 1.7 s may be associated with formation of HMNS (*see talks by L. Rezzolla and M. Shibata at this conf.*)

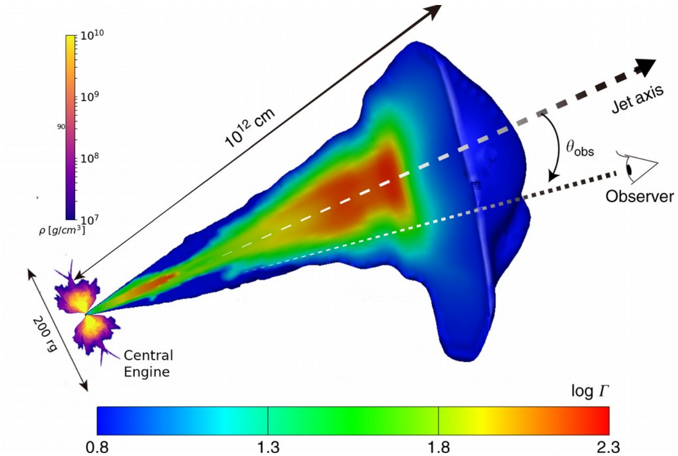


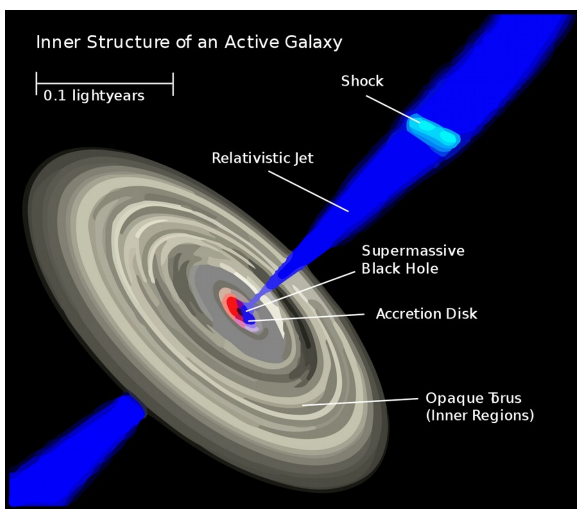
Rapidly fading electromagnetic transient in the galaxy NGC4993, was spatially coincident with GW170817 and a weak short gamma-ray burst (e.g., Smartt et al. 2017; Zhang et al. 2017, Coulter et al. 2017, Murguia-Berthier et al. 2017)


JAGUAR


H
He
C, O, N
Si
Mg, Ne
Fe

Central engine and jet





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

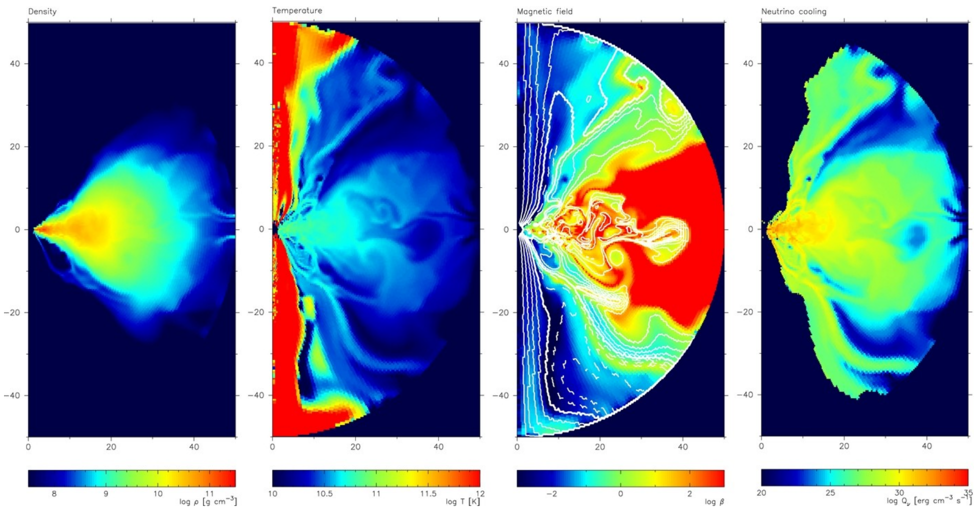
Jet is powered by the central engine.

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.

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

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

Accretion in GRB central engine



Janiuk, Mioduszewski & Mościbrodzka (2013)

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

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

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

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

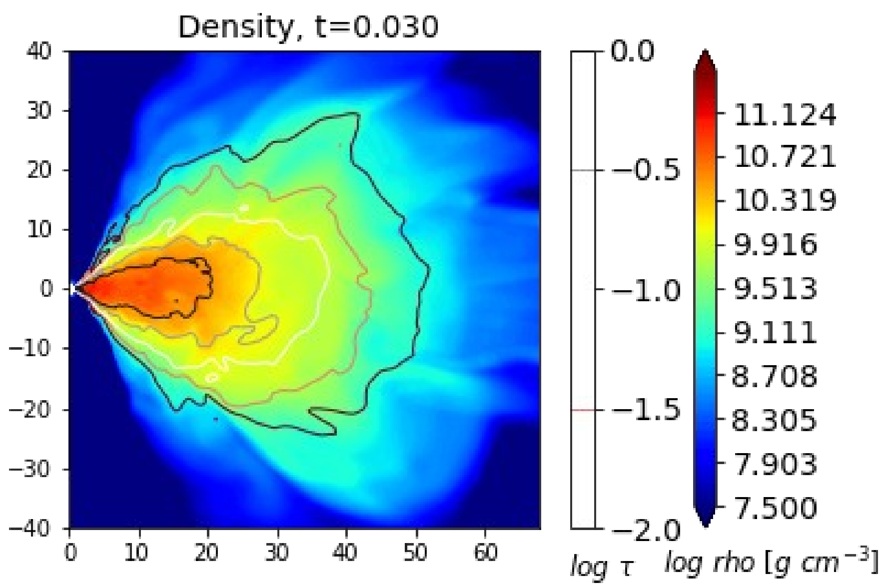
$$T^{\mu\nu} = T_{(m)}{}^{\mu\nu} + T_{(em)}{}^{\mu\nu},$$

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

- Hyperaccretion: rates of 0.01-10 M_S/s
- EOS is not ideal, plasma composed of n, p, e+, e−
- Chemical and pressure balance required by nuclear reactions: electron-positron capture on nucleons, and neutron decay (Reddy, Prakash & Lattimer 1998)
- Neutrino absorption & scattering

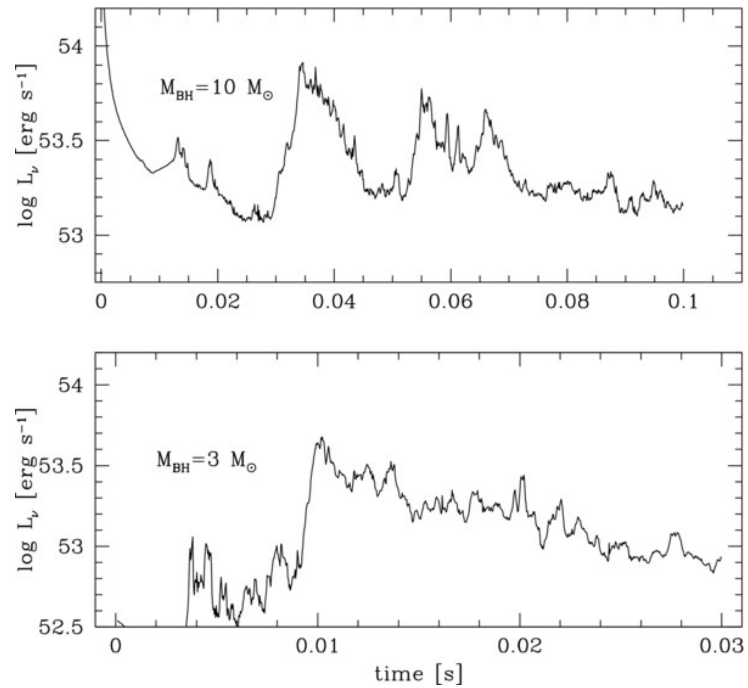
Steady state and time-dependent models
1-D hydro: DiMatteo et al. 2002; Kohri et al. 2002, 2005; Chen & Beloborodov 2007; Janiuk et al. 2007; Janiuk & Yuan 2010; Lei et al. 2009; Kawanaka et al. 2013, Janiuk 2014; Liang et al. 2015; 2017;
2D-(GRM)HD: Fernandez et al. 2015, Just et al. 2016, Janiuk et al. 2013; Siegel & Metzger 2017; Janiuk 2017, 2019, Fujibayashi et al. 2020

Neutrinos



Neutrino cooling and optical depth as in Yuan (2005); Reddy (1998)

Follow-up is the ongoing project on the neutrino leakage, F.H. Nouri et al. in prep. Need to optimize the code performance, i.e. inversion schemes, and test on supercomputers



Two-stream approximation:

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

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

$$q_{\mathrm{a},\nu_e} = q^{\mathrm{pair}}_{\nu_e} + q_{\mathrm{urca}} + q_{\mathrm{plasm}} + \frac{1}{3} q_{\mathrm{brems}},$$

$$\tau_\mathrm{s} = \tau_{\mathrm{s,p}} + \tau_{\mathrm{s,n}}$$

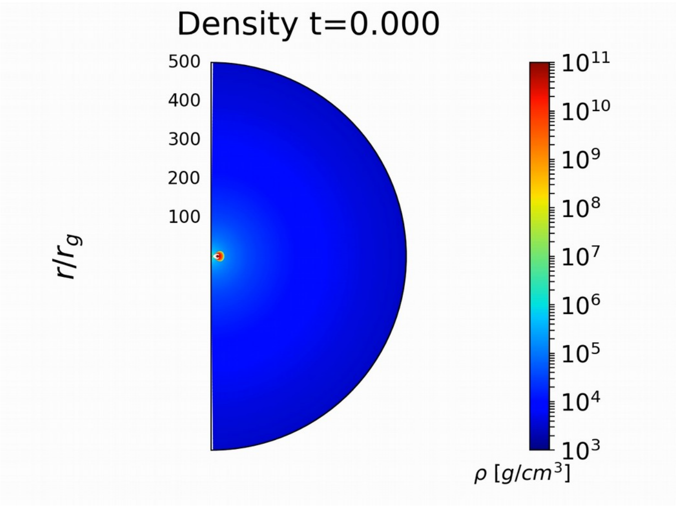
$$= 24.28 \times 10^{-5} \left[\left(\frac{kT}{m_\mathrm{e} c^2} \right)^2 H (C_{\mathrm{s,p}} n_\mathrm{p} + C_{\mathrm{s,n}} n_\mathrm{n}) \right]$$

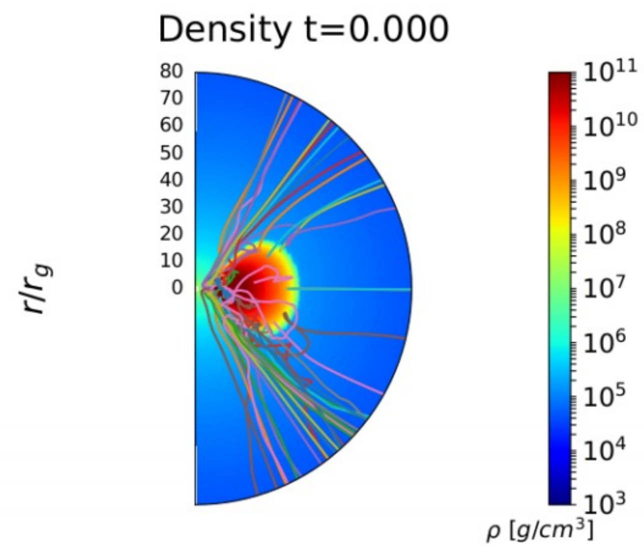
Magnetized disk wind

HARM-COOL (Janiuk, 2017, ApJ, 837, 39).

In the EOS, contribution to the pressure is by the free nuclei and e+ − e− pairs, helium, radiation and the trapped neutrinos:
P = Pnucl + PHe + Prad + Pν
Species are relativistic and partially degenerate.

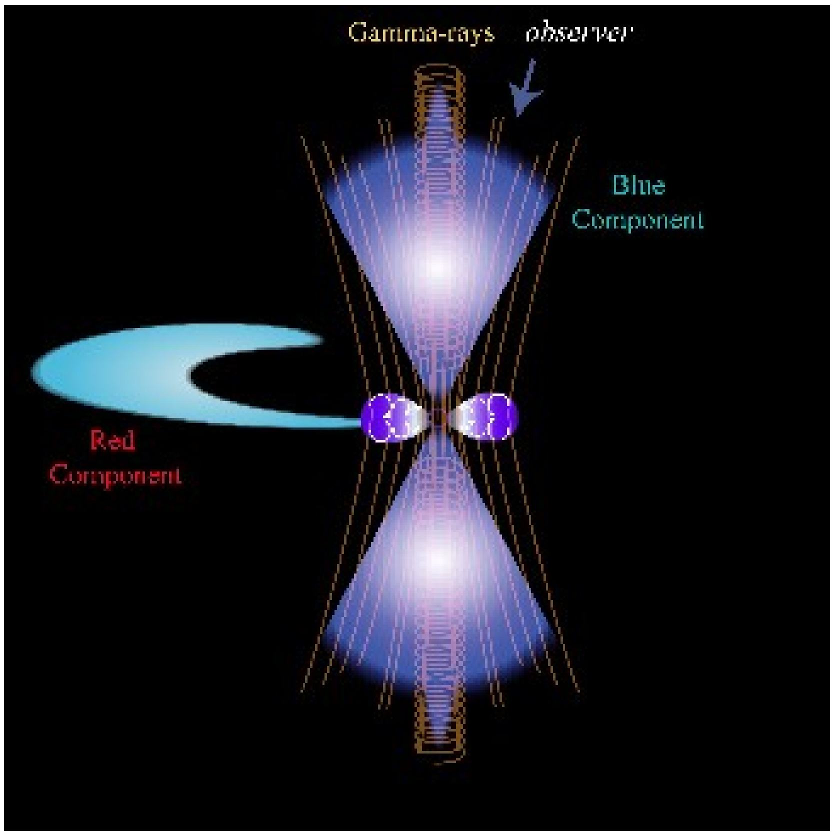
- EOS is implemented as tables, we use the *pthread* interpolation
- Matter is neutronized, $Ye = n_p/(n_p + n_n) < 0.5$
- Non-trivial transformation between conserved variables and 'primitives' in HARM due to GR MHD scheme (see Noble et al. 2006).
- Sound speed formula from Ibanez et al. (2015)





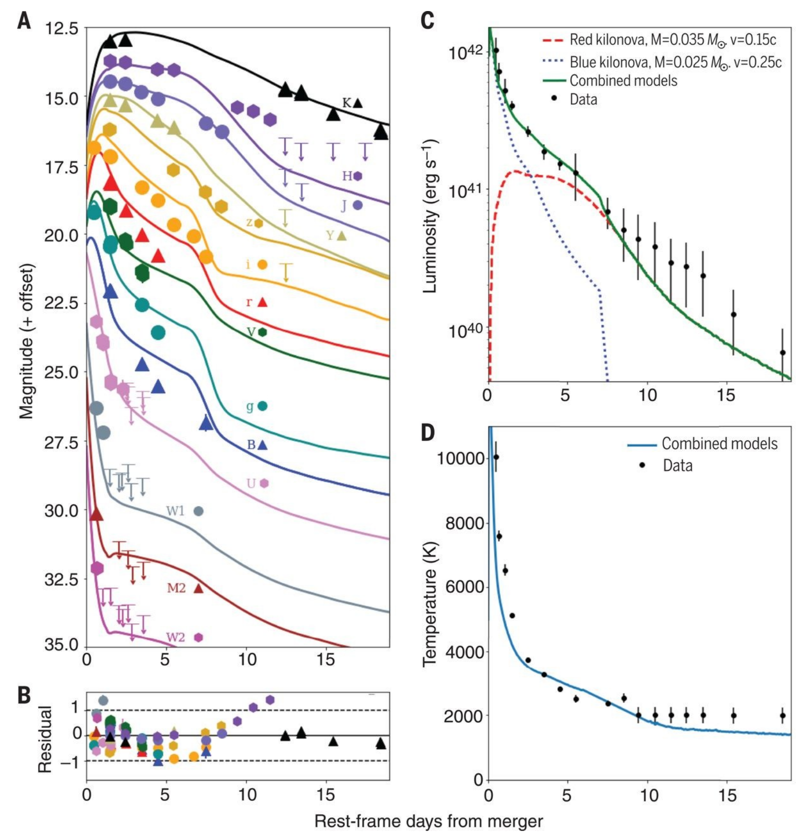
Now the code can follow the wind outflow, and compute the trajectories, where mass is ejected in sub-relativistic particles. The code distributes tracers uniformly in rest-mass density in flow (cf. Wu et al. 2016; Bovard & Rezzola 2017). We typically use about 2000 tracers (Janiuk, 2019, ApJ, 882, 163).

Blue and red kilonova lightcurve



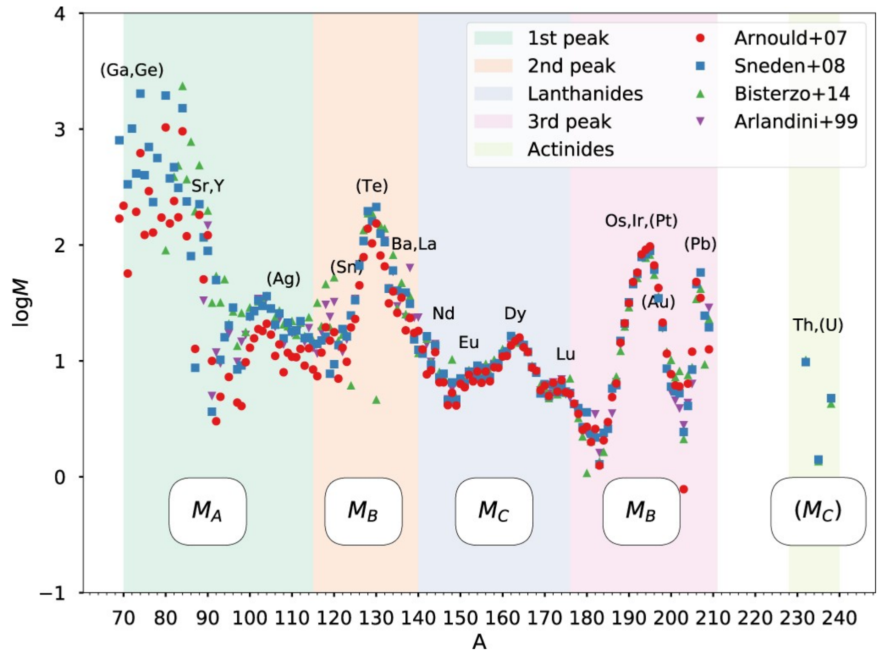
Schematic idea of the system
(Murguia-Berthier et al. 2017).

See talk by Ariadna Murguia at this conference

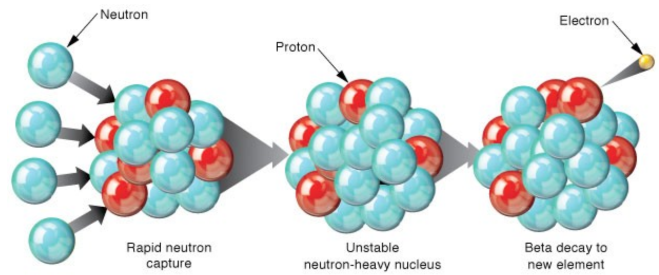


Blue and the red light from a kilonova, compared to observational data for the transient SSS17a, associated with GW170817 (Kilpatrick et al. 2017).

r-process nucleosynthesis



Ji et al. 2019



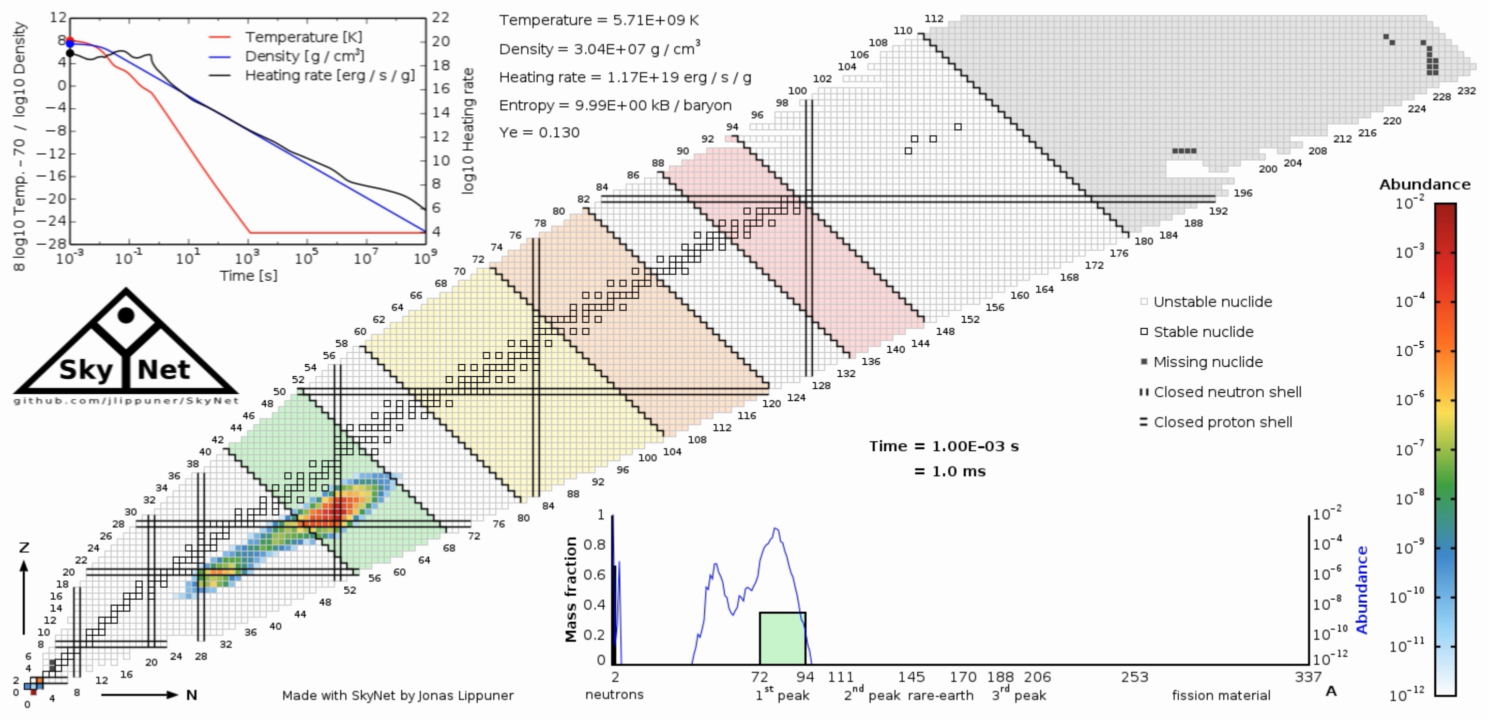
NS binary merger eject material rich in heavy radioactive isotopes.

They are formed in the rapid neutron capture process (r-process)

The decays can power an electromagnetic signal called kilonova

- 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)

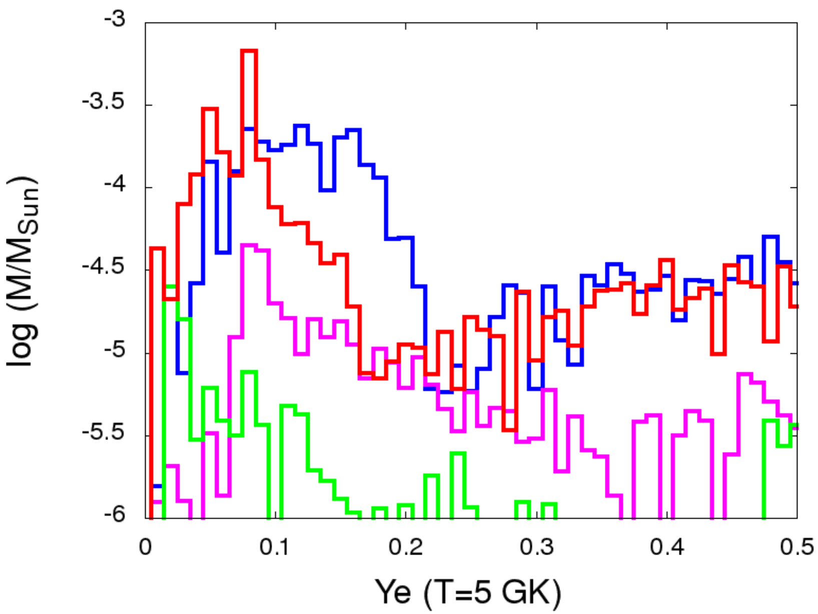
Nuclear reaction network

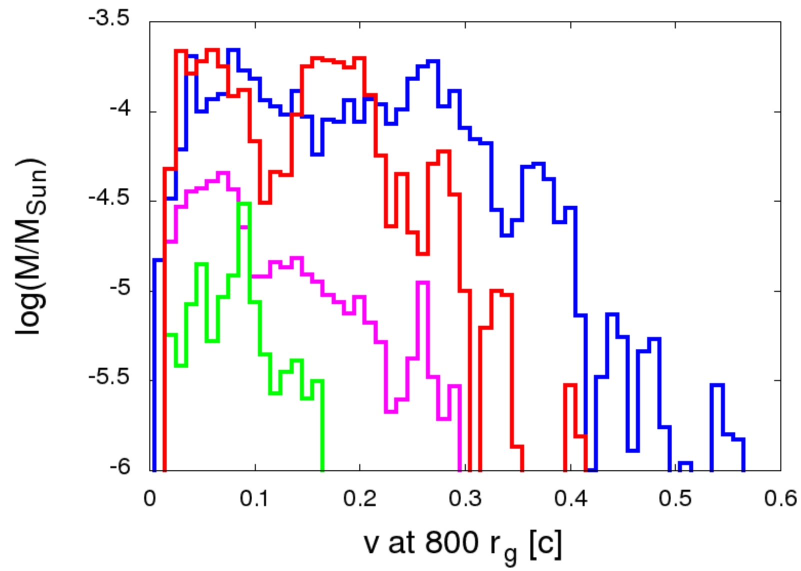


Code **SkyNet**, r-process nucleosynthesis; Lippuner & Roberts (2017).

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.

Post-merger ejecta





Janiuk (2019, ApJ, 882, 163)

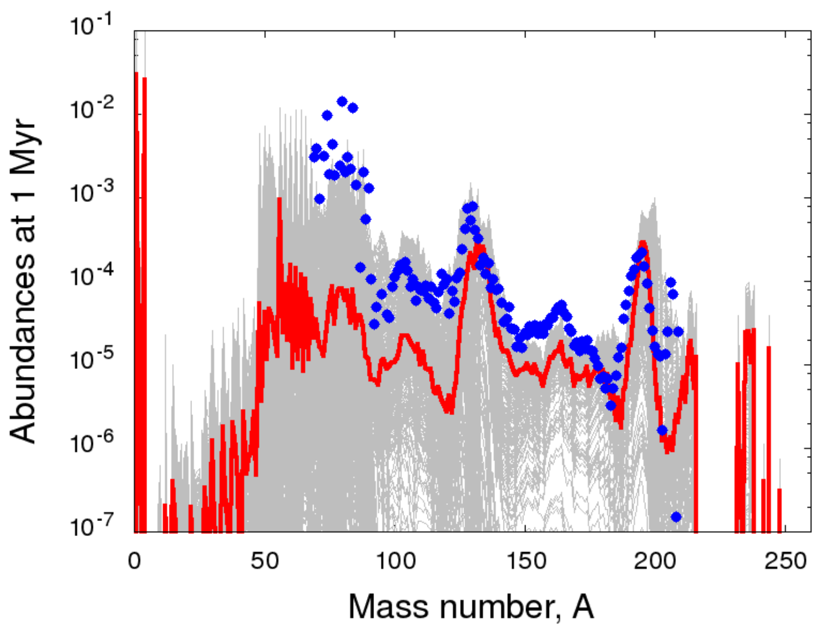
Density and electron fraction distributions are traced on the unbound outflows. The details are sensitive to engine parameters: BH spin and magnetisation of the disk (a=0.9 and a=0.6, for blue/magenta and red/green histograms).

We calculate the r-process nucleosynthesis on these outflows.

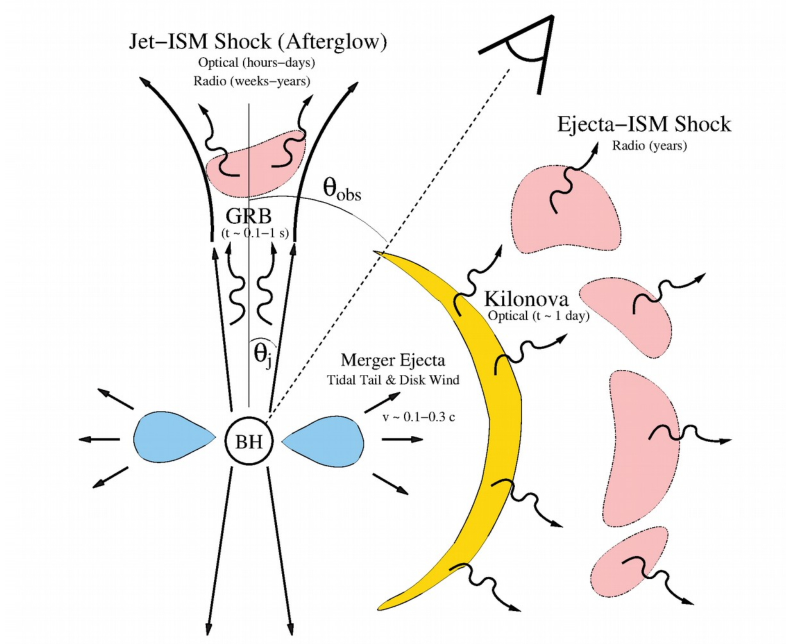
Magnetized outflows in gamma ray bursts engines contribute to the kilonova signals.

Nucleosynthesis in the disk outflows

Abundance pattern of r-process elements synthesized in the magnetically driven outflows in our simulations (lines) and Solar abundance pattern (points).



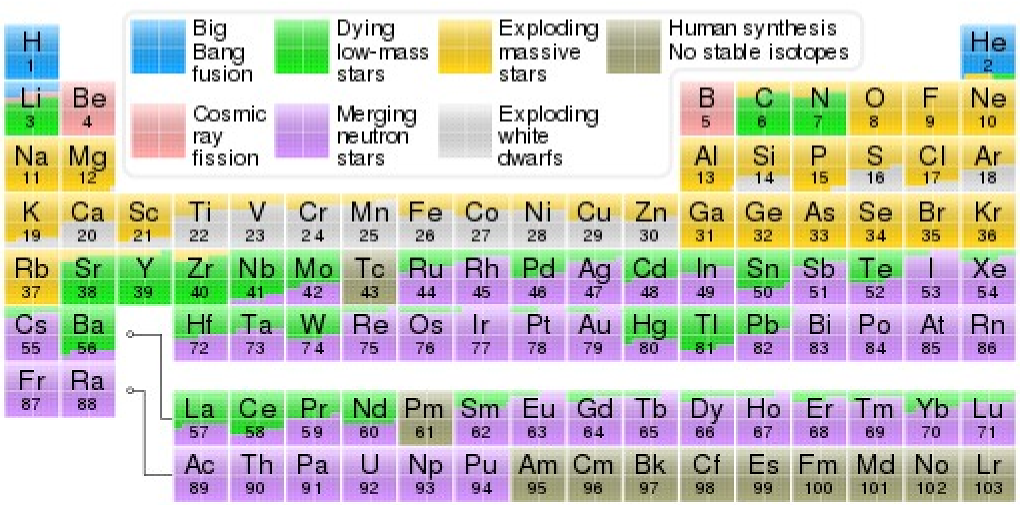
(Janiuk, 2019, ApJ, 882, 163)



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 (Metzger & Berger 2012).

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

Conclusions from our 2D simulations

- We implemented the nuclear EOS with arbitrary degeneracy of e,n,p, to the HARM GRMHD scheme and compute the evolution of black hole accretion flows in GRB engines

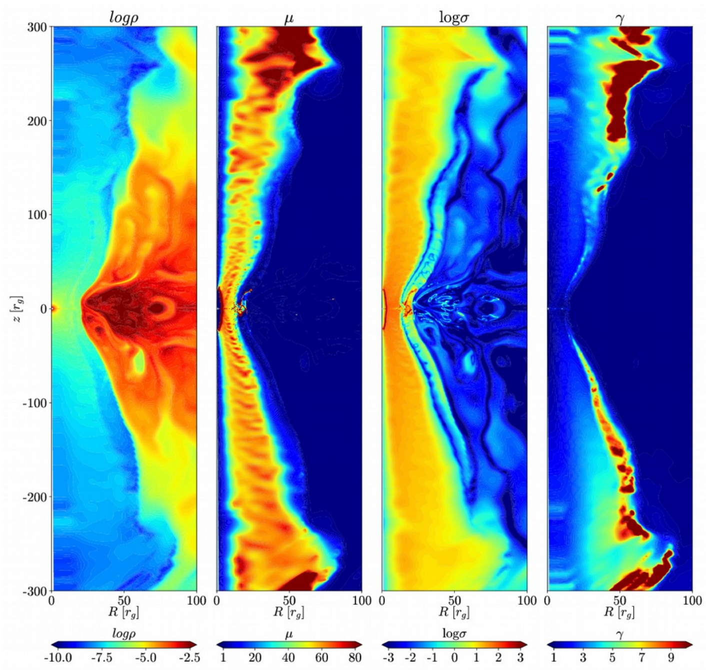
- The $r-$process nucleosynthesis, motivated by the recently discovered electromagnetic counterparts of gravitational waves, is studied via nuclear reaction network. Extrapolation of outflow trajectories, computed within the HARM models, can provide observationally testable results.

- The disk winds are able to launch fast wind outflows ($v=c \sim 0.11 - 0.23$) with a broad range of electron fraction $Ye \sim 0.1 - 0.4$, and help explain the multiple components observed in the kilonova lightcurves. The total mass loss from the post-merger disk via unbound outflows is between 2% and 17% of the initial disk mass.

- We observe dependence on black hole spin parameters and disk magnetisation, and elements up to $A \sim 200$ are produced in disk ejecta

- Results are to be verified with 3D simulation and neutrino transport/heating

Jet launching and energetics



Sapountzis & Janiuk (2019)

- If the black hole starts fastly rotate, jet ejection is inevitable

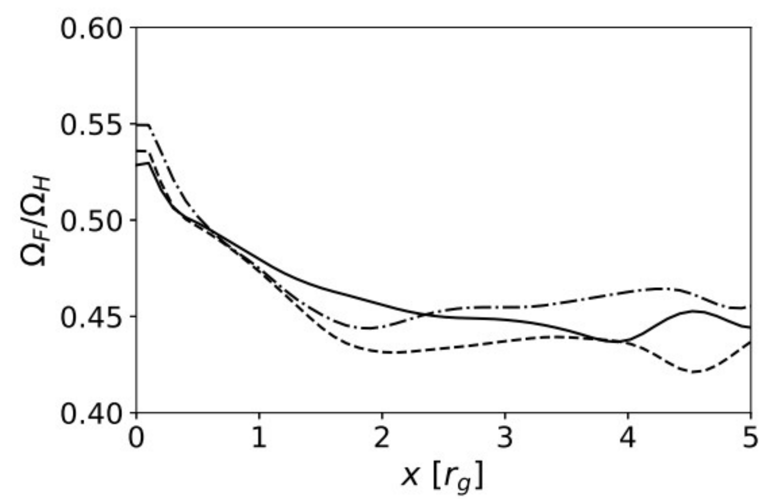
- The presence of magnetic fields powers the jet acceleration

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

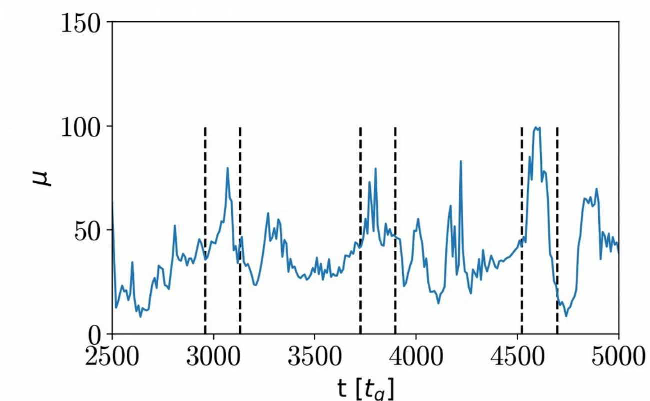
$$\mu = - T^r{}_t / \rho u^r$$

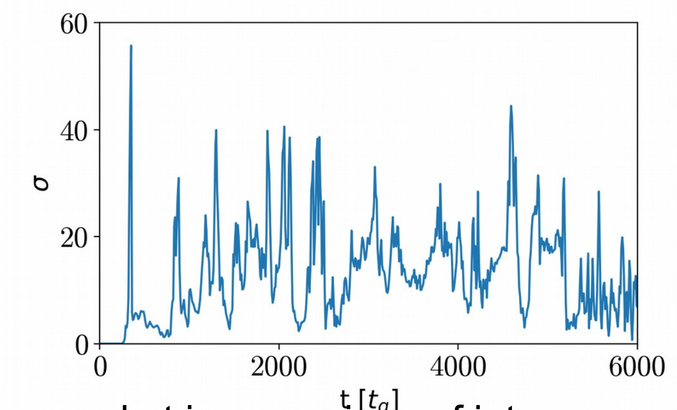
- Blandford-Znajek process, efficient if the rotational frequency of magnetic field is large wtr. to angular velocity of the black hole

Energetics of jets and energy extraction from the rotating black holes in gamma ray bursts

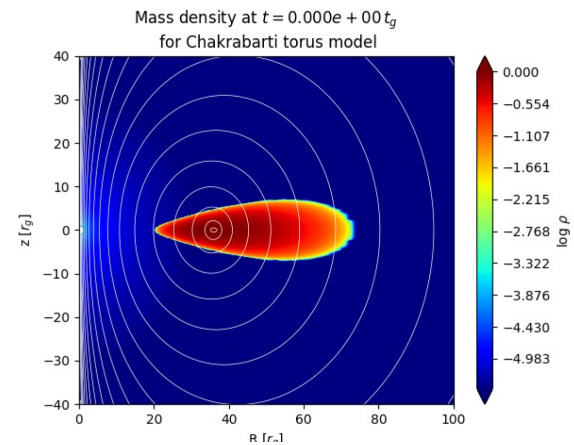


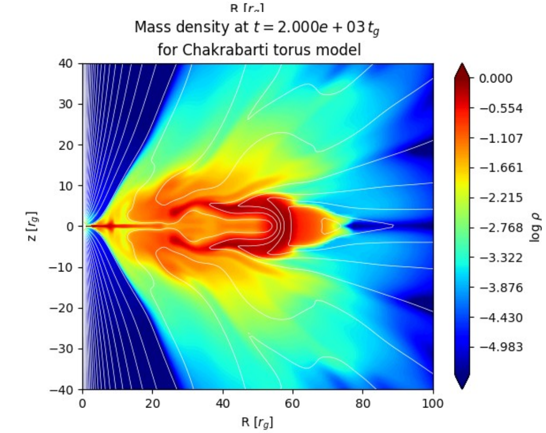
Variability of jets

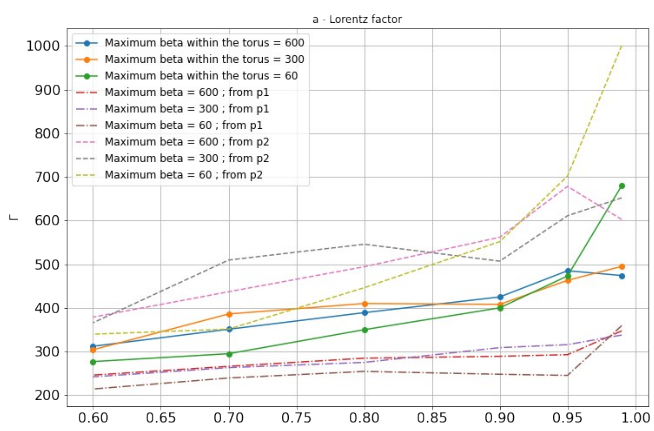


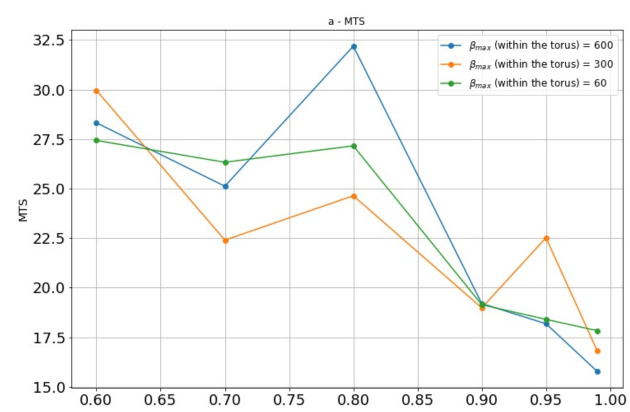


Time variability of σ and μ as measured at inner regions of jet . Left: variability as correlated with T_{MRI}, timescale of the fastest growing mode (Sapountzis & Janiuk, 2019).









Variability of jets in blazars and gamma ray bursts: correlations between Lorentz factor, minimum variability timescale and black hole spin

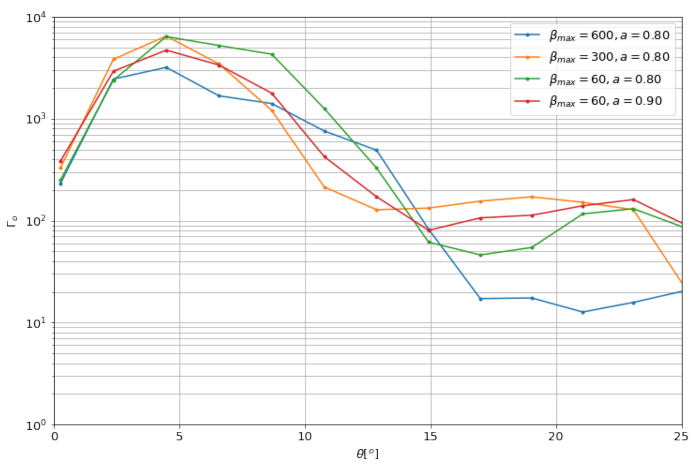
We calculate the μ at two chosen points along the jet direction located at r = 150 r_g, θ = 5° and θ = 10° and we take the average value.

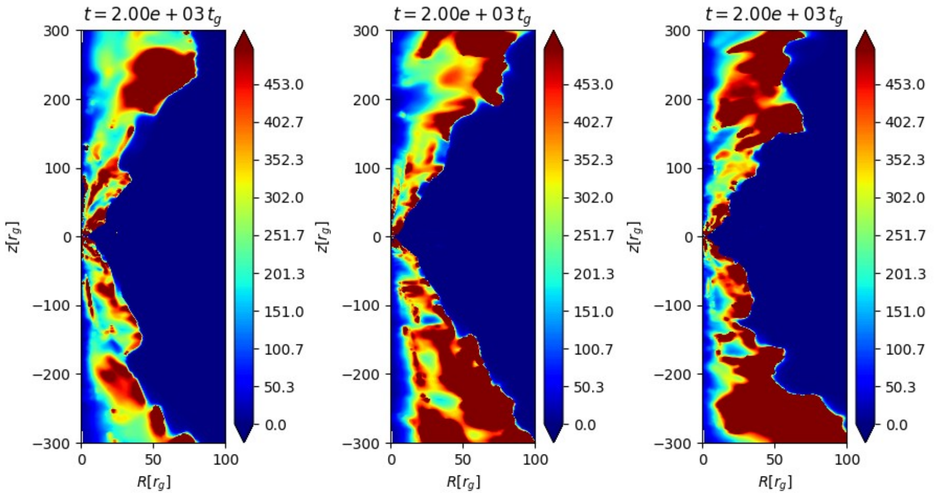
(Janiuk, James & Palit, 2021, ApJ, 917, 102).

Structure of the jet

● We note highly inhomogeneous outflows, where larger values of μ are reached at the edges of the jets rather than at the z polar axis.

● Time-averaged profile of jet as function of polar angle, at a large distance (~2000 rg) from the central engine shows that the most energetic part of the jet is located inside a narrow region of θ < 15o





Instantaneous jet energetics distribution, in 2D MHD simulation. Jet structure at time t=2000 M. Plot shows distribution of μ for models with β_{max} = 600; Models display jets launched from spinning black holes with the Kerr parameter, a = 0.6 (left), a = 0.8 (middle), and a = 0.95 (right).

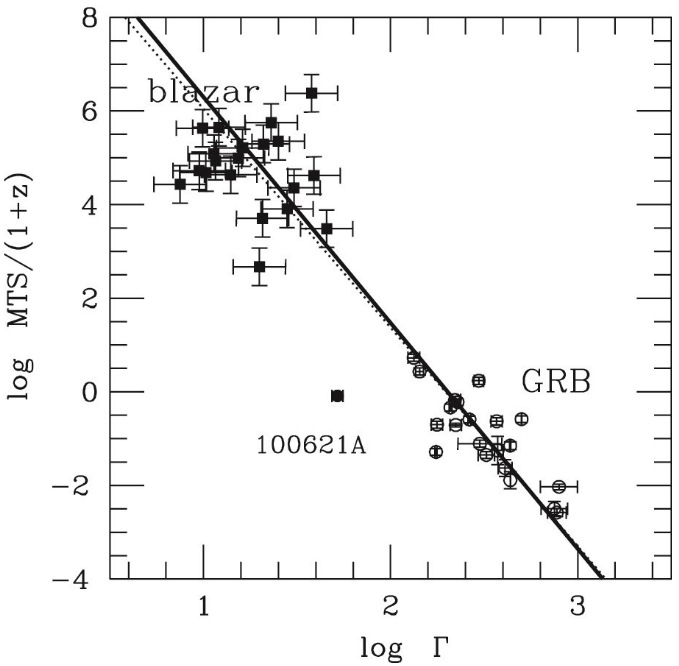
(Janiuk, James & Palit, 2021, ApJ).

Comparison to observations

● The Lorentz factor is calculated as the average of μ in time, $\Gamma = <\mu>_t$. This will be in geometrical units.

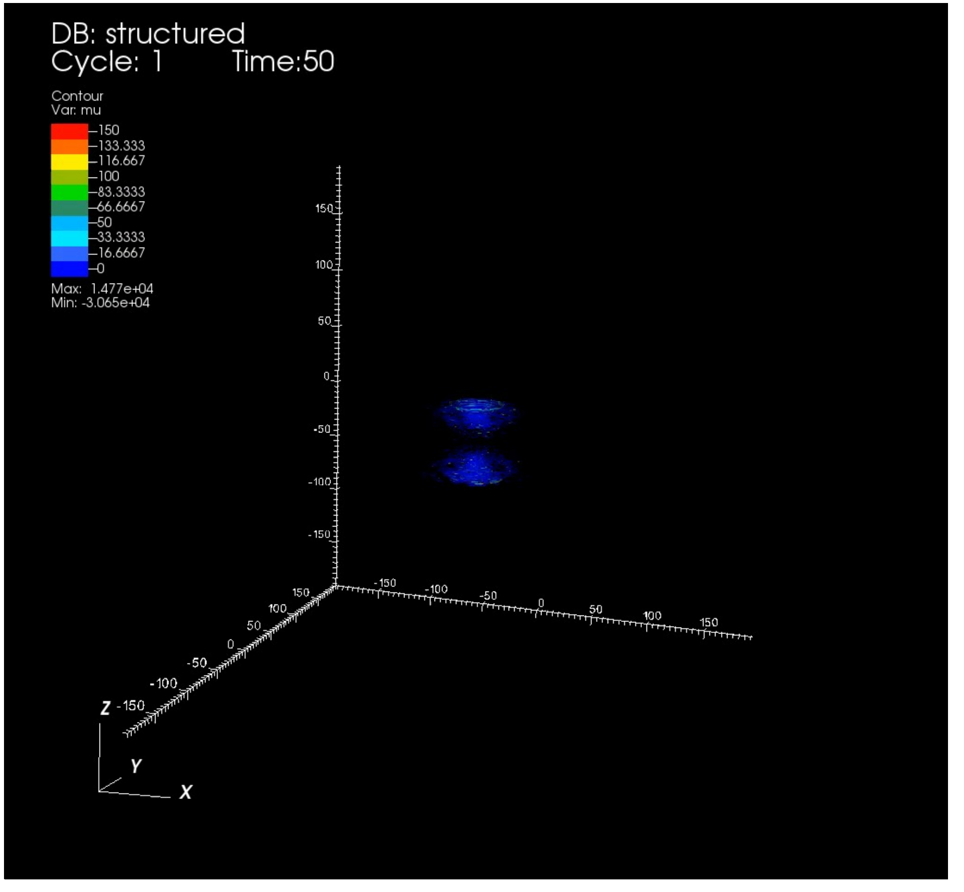
● The Minimum variability Time Scale (MTS) ~ peak widths at their half maximum on the μ – t plot

● Results scale with black hole mass. ($MTS_s = MTS_{MBH} \times GM_{BH}/c^3$)



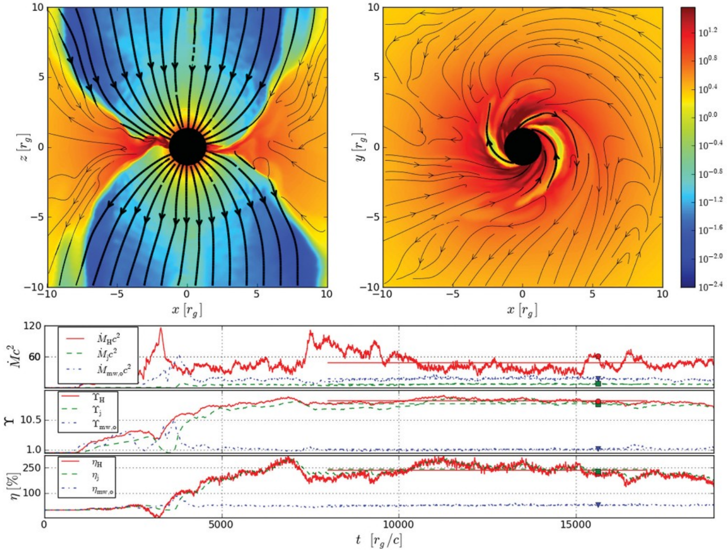
The MTS versus Lorentz factor, Γ, for GRBs and blazars. The solid line represents the best linear fit for 21 GRB. The dotted line represents the best fit for GRBs (excluding GRB100621A) and blazars in their sample. They find a joint correlation of a joint correlation of MTS ∝ $\Gamma^{-4.7}$±0.3 (Wu et al. 2016)

3D jet structure evolution



MAD states

- Initially toroidally-dominated models lead to only patches of magnetic flux, and transient outflows or weak jets.
- For initially poloidally-dominated models, magnetic flux builds up to a saturation point near BH
- High black hole spins a > 0:5, lead to formation of persistent relativistic jets, and highly non-axisymmetric magnetically chocked accretion flows



(McKinney et al. 2012)

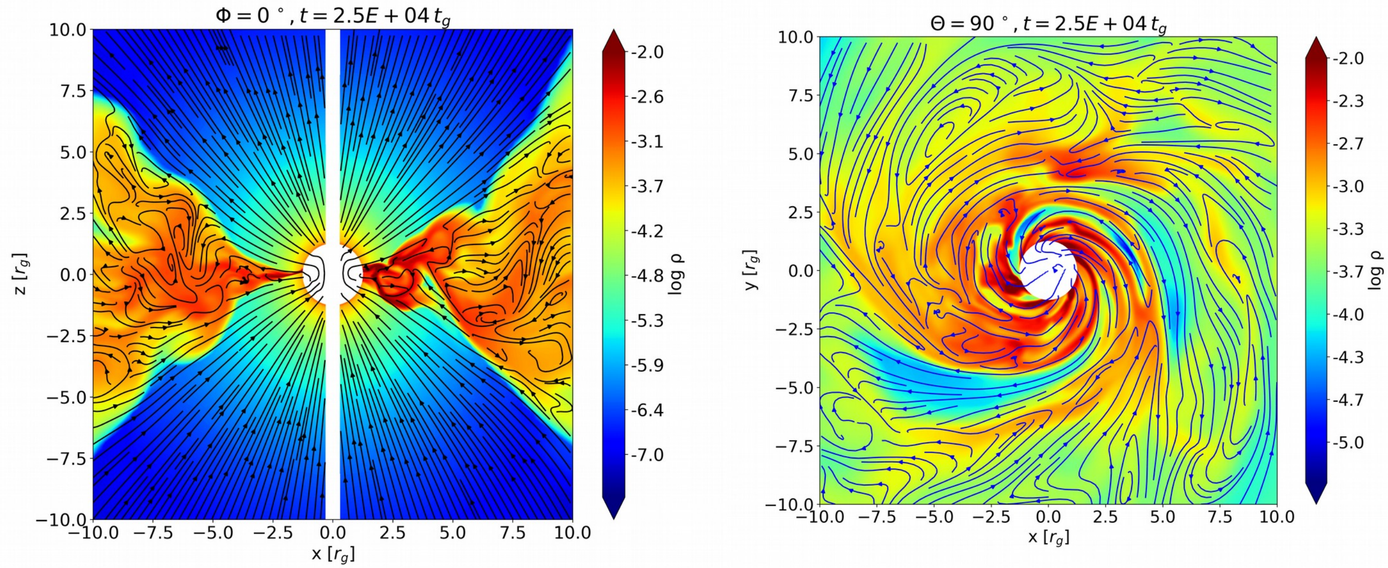
Force-free magnetosphere and activation of BZ-driven jet when dimensionless specific magnetic flux on horizon:

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

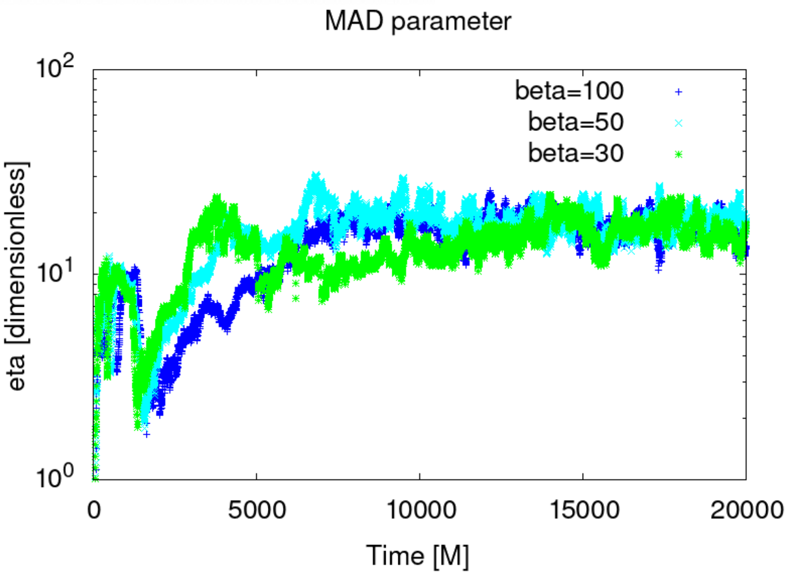
has characteristic value of > 1.

Works for long GRBs, microquasars, or Galactic center where Φ is on the order 10^{-9}; 10^{-12}, and 0.01-0.1 pc^2 G, respectively.

Magnetically arrested accretion



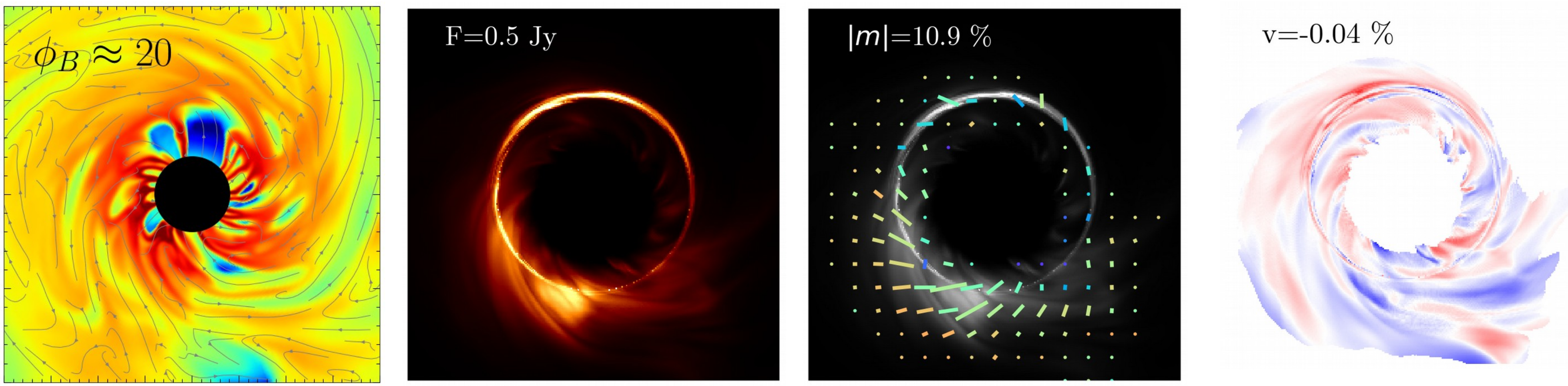
3D simulations of magnetically arrested accretion mode: Janiuk & Sapountzis (2021, in prep.)



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) around a black hole (Lloyd-Ronning et al., 2016)

Circular polarisation of synchrotron light

Mościbrodzka, Janiuk & de Laurentis
(2021,MNRAS accepted, arXiv:2103.00267)

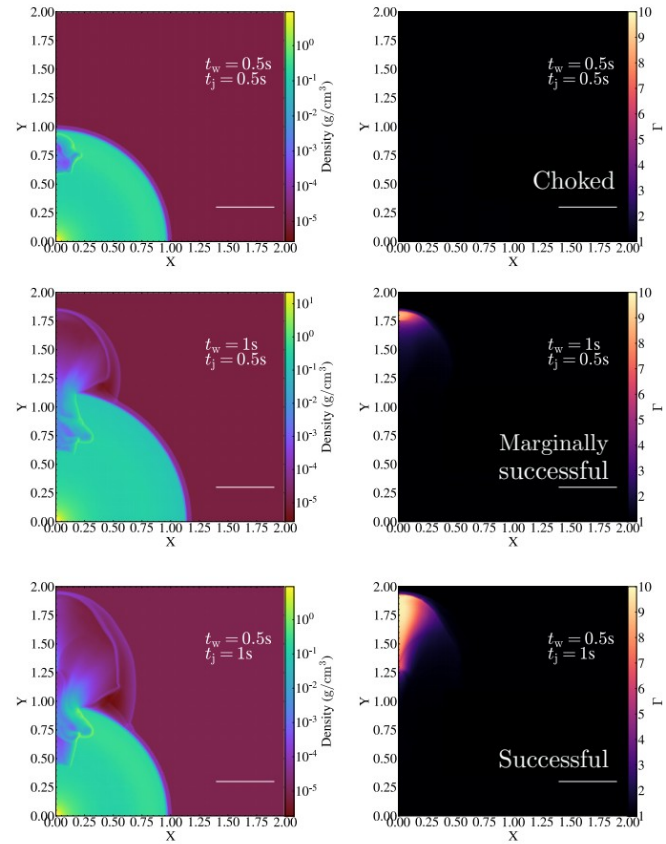


Polarimetric images of MAD model with β = 30 for ion to electron temperature ratio, Rh = 1, and nearly face-on viewing angle, i = 160 deg.
The left-most panel shows density distribution at the equatorial plane together with projected magnetic field lines. Second, third and fourth panels display the total intensity (Stokes I), linear and circular polarimetric images.

Calculations made with code iPole, the new ray-tracing code for covariant, polarized radiative transport (Mościbrodzka & Gammie, 2018).

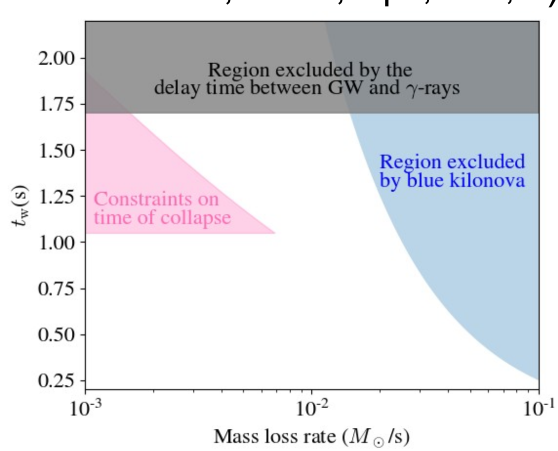
Chocked jets

- 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 $Mdot_w=10^{-2}\ M_{Sun}/s$ and $v_w= 0.3c$.
- Various models of wind: neutrino-driven, magnetically driven



(Murguia-Berthier 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 deg, Lorentz factor of jet Gamma=100-1000



Conclusions from the jet and central engine studies

1 GRB engine is a multi-scale problem.

2 Fundamental interactions between elementary particles in the plasma drive the microphysics of the engine.

3 Microphysics leads to direct observable tests (kilonovae).

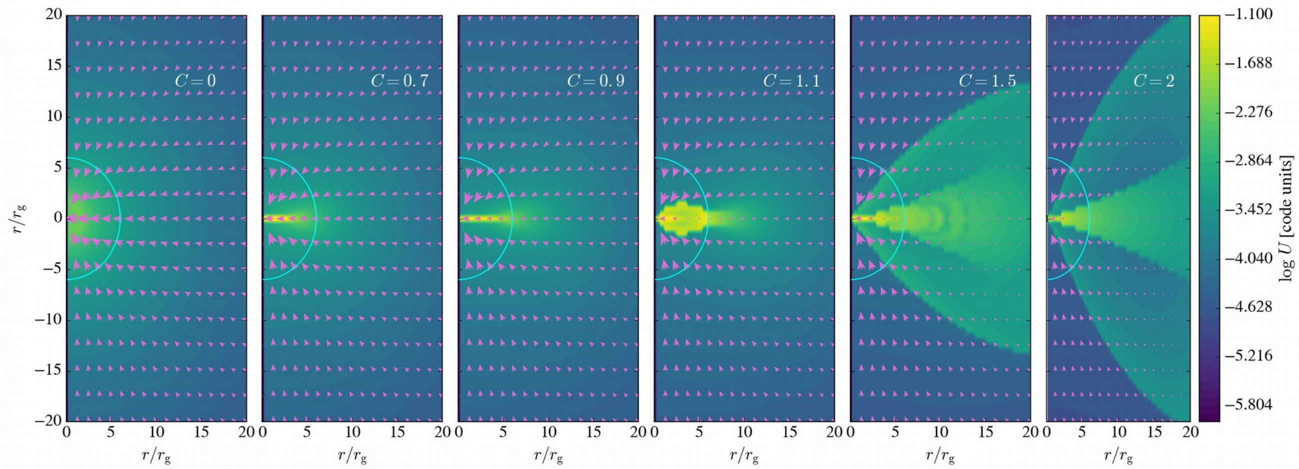
4 The MHD simulations show that rotational instabilities have imprint on the variability of the jet.

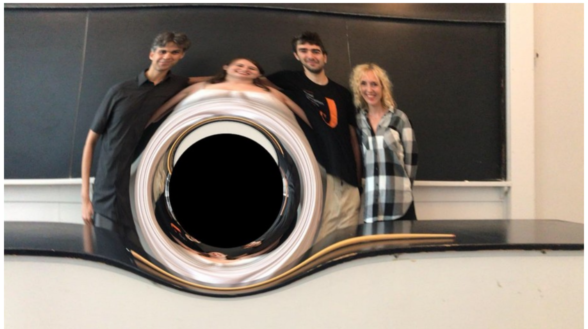
5 The same MHD mechanism drives uncollimated outflows

where the r-process elements are synthesized.

6 Magnetically arrested accretion mode may bring additional effects, icl. variability and spectral properties

Missing GRBs. How to leave a black hole without a trace?





Murguia-Berthier et al. (2020, ApJ Letters)

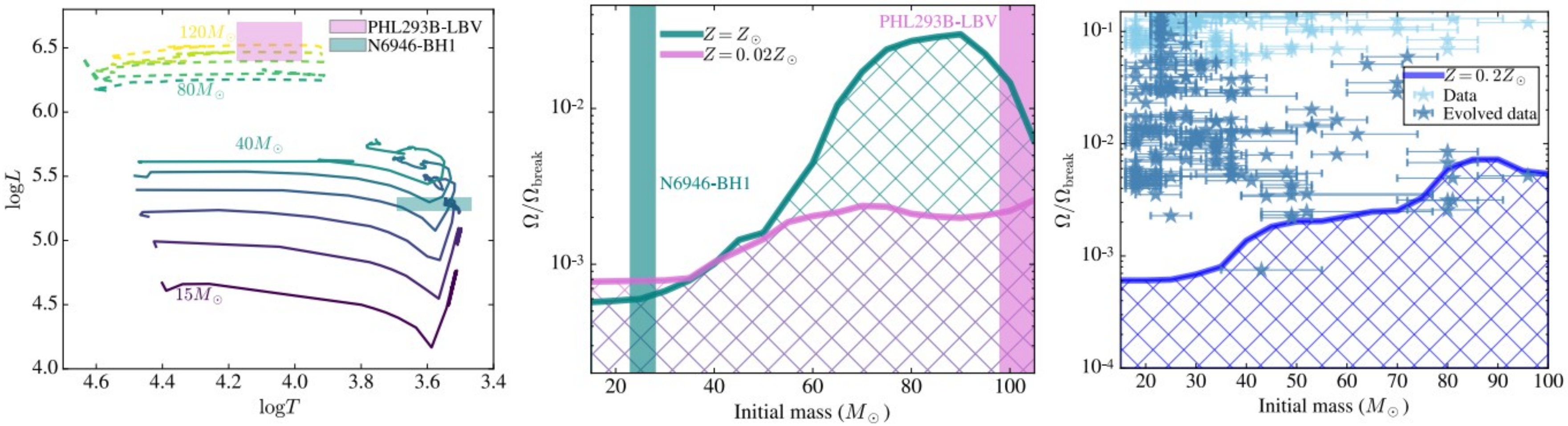
- Mini disk: energy can steadily accumulate in the equatorial region

- We find that above the critical specific angular momentum, C = 1.2, accretion onto a BH can generate feedback.

- For flows with C > 1.2, we expect feedback to likely halt the collapse.

- Any additional accumulation of energy will result in the disruption of the entire star, with a bright transient from the expanding cooled envelope

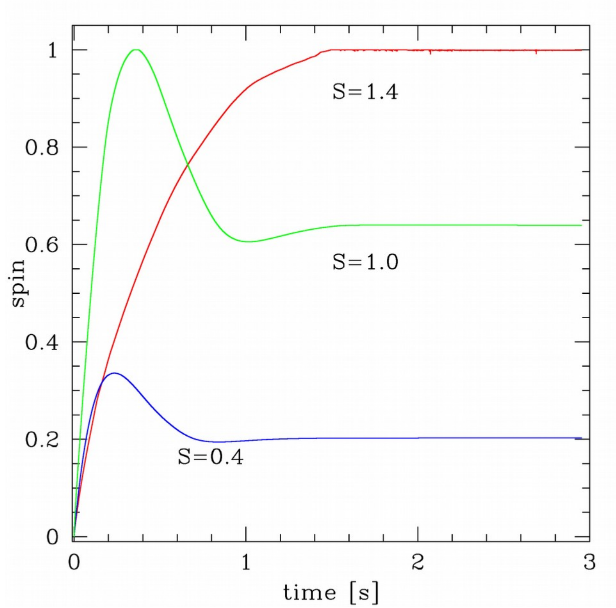
Limits on stellar rotation

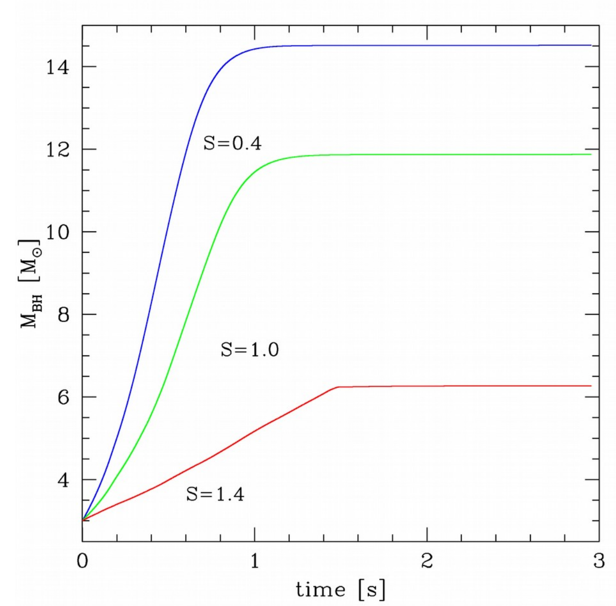


- We find that about 5% of the stars evolved with MESA code, have $\Omega/\Omega_{\rm break}$ below the critical value and will leave no accompanying transient.
- Models were constrained with the two observed ‘disappearing stars’, N6946-BH1 and PHL293B-LBV (Gerke et al. 2015; Adams et al. 2017; Allan et al. 2020)
- Sample of O stars taken from Ramirez-Agudelo et al. (2013) and Weidner & Vink (2010)

Change of mass and spin of the black hole during collapse

Black hole accretes both mass and angular momentum.
The Kerr metric coefficients are changed accordingly, during the collapse simulation
Increase of black hole mass is anti-correlated with spin increase
For high initial spins, also spin-down is possible

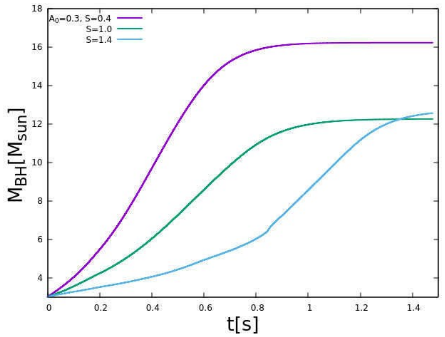


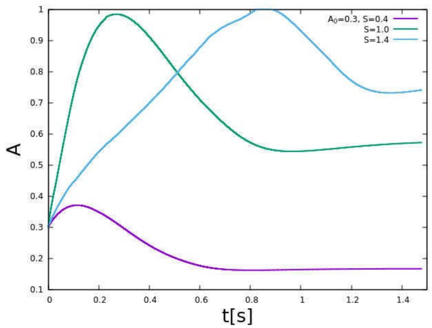


Lines correspond to 3 values of star's angular momentum magnitude.

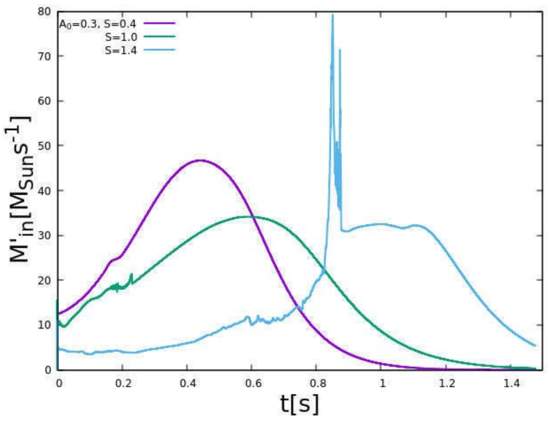
Black hole mass and spin change, flaring accretion rate

We compute the collapsar model with slowly-rotating quasi-spherical collapse with changing black hole spin and mass





Our test models out some constraints on the angular momentum content of the collapsing progenitor star, with the resultant mass and spin of the BH.

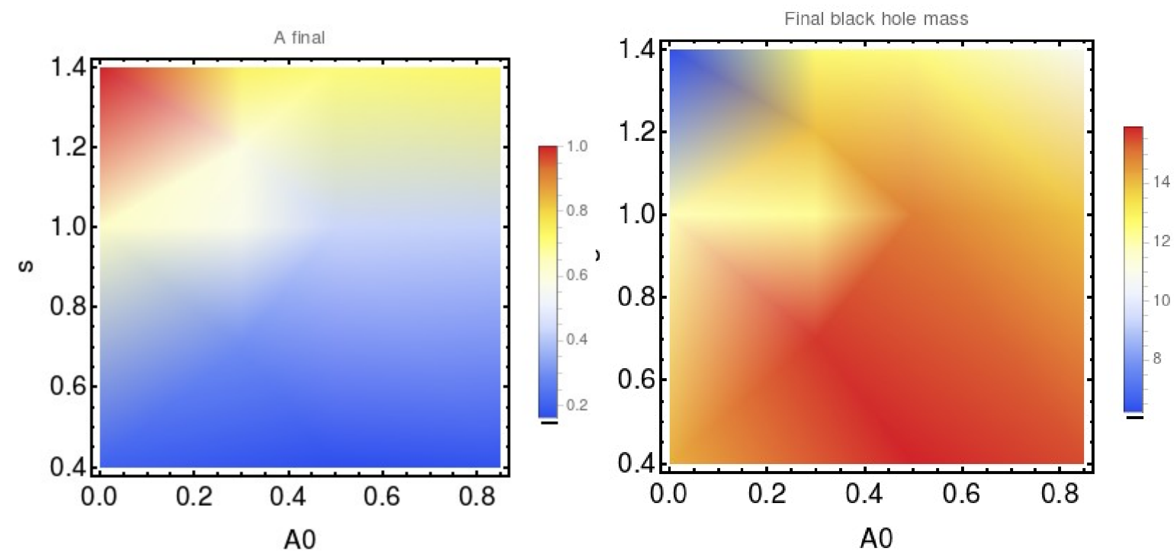


The code built upon the old HARM-2D scheme, but with own MPI implementation, 3D-extension, plus Kerr metric evolution method:
A. Janiuk, P. Sukova, I. Palit, (2018, ApJ,868, 68)

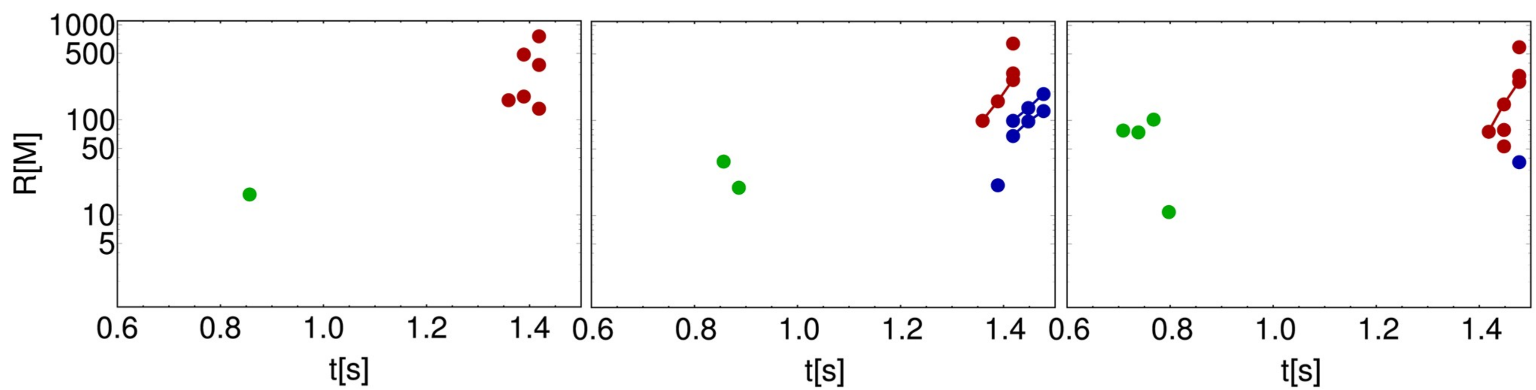
Król & Janiuk. (2021, ApJ, 912, 132)

Parameter space study and shocks

• Supercritical rotation always spins up the black hole maximally, but dependence on the initial spin is not monotonic.
• Only if the initial spin was small, the black hole will remain maximally spinning. Otherwise, it spins down again.
• Growth of black hole mass is largest when envelope rotation is slow, and the black hole was at least moderately spinning.

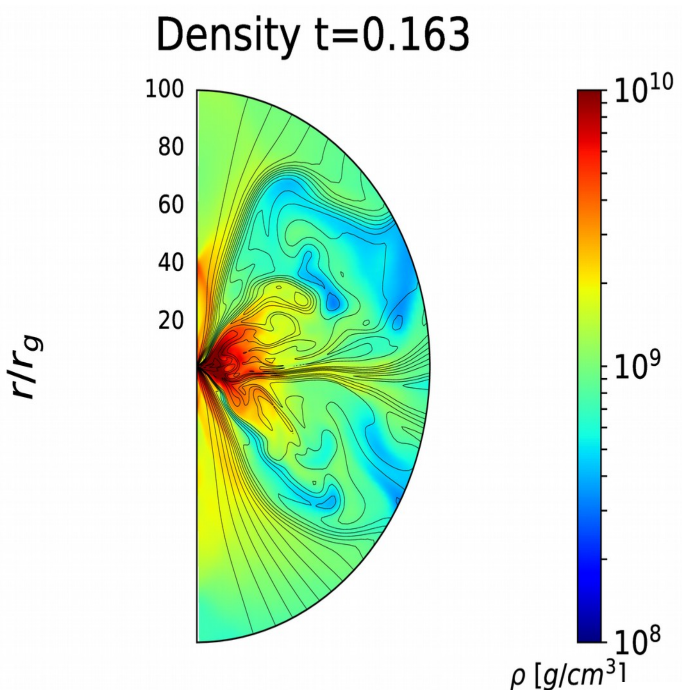


Król & Janiuk. (2021, ApJ, 912, 132)

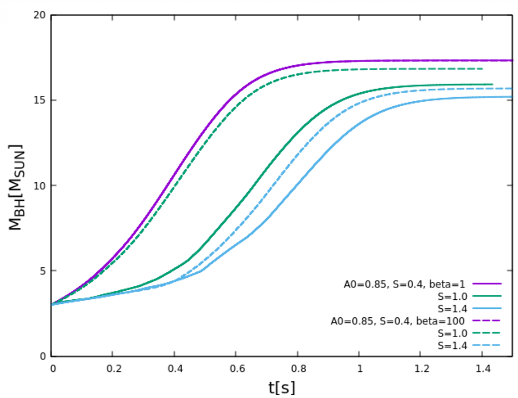


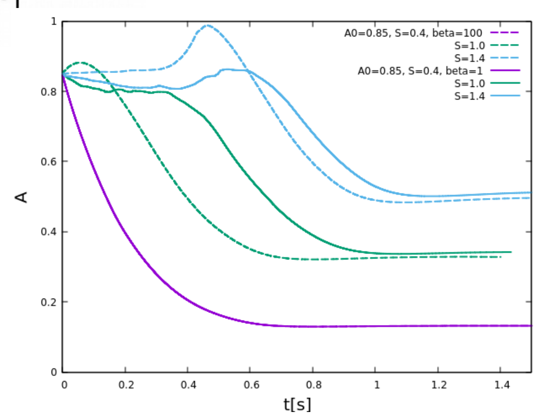
Shock front velocities (about 0.04c) are smaller if BH is fast spinning, than in simulations with spin-less black hole

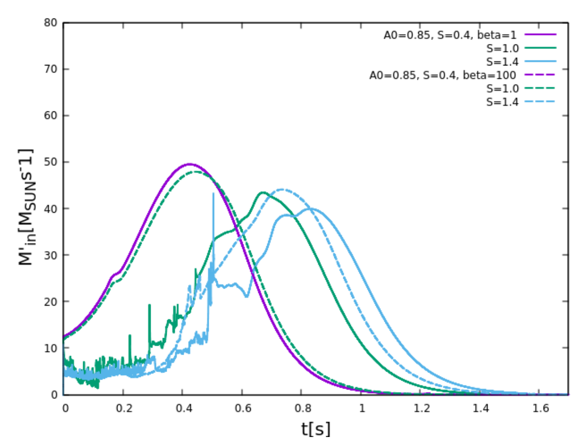
What if the black hole spins up and matter is magnetized?



- We simulate collapsar model with initial BH spin A=0.85,
- parabolic magnetic field normalized to β = 1.0 (solid) and β = 100 (dashed), and three magnitudes of angular momentum

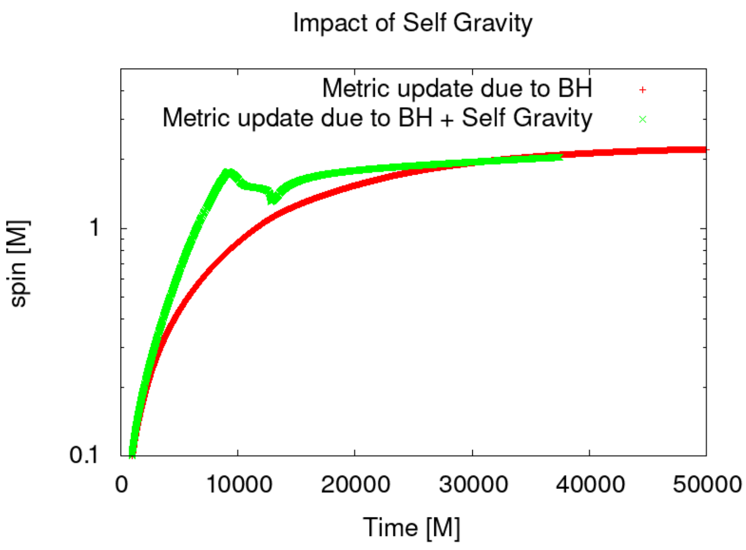


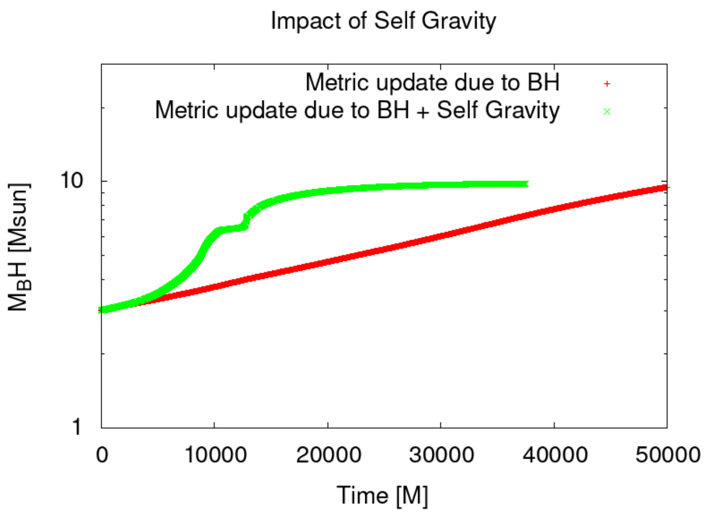




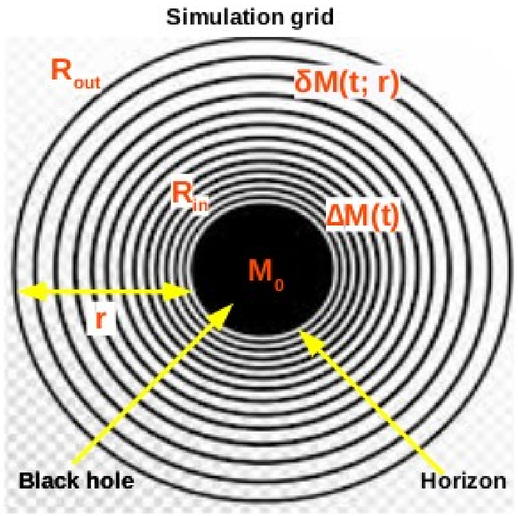
Król & Janiuk. (2021, ApJ, 912, 132)

Effects of self-gravity





In Król & Janiuk. (2021), we neglected the collapsars self-gravity.
This effect does add a perturbation in the first phase of collapse (study in detail by Janiuk et al. in prep.; see Palit, Janiuk and Sukova 2020, APPA, arXiv:2005.07824)



Computational astrophysics group at CTP

Postdocs: Fatemeh Hossein-Nouri, Przemysław Figura

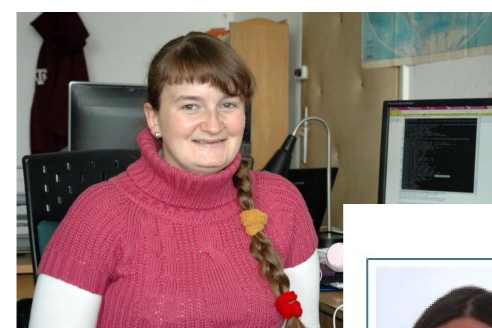
PhD students: Ishika Palit, Bestin James

Interns: Michał Przerwa

Former members and interns: Kostas Sapountzis, Petra Sukova, Szymon Charzyński, Mikołaj Grzędzielski, Dominika Król, Katarzyna Wojczuk, Patryk Mioduszewski

http://www.cft.edu.pl/astrofizyka

Access to supercomputing facilities in Poland and EU: ICM-Okeanos; Cyfronet, PRACE grant on HAWK supercomputer at Stuttgart Univ.



Machine learning algorithms will help search for GW

We propose to develop new quantum algorithms and quantum computer systems in order to demonstrate that a fast and reliable data analysis for the detection of gravitational waves from space (LISA mission) or from the ground (Einstein's Telescope) can be done more efficiently using quantum machine learning

Quantum neural networks have the ability, besides the potentially significant increase in speed, to extract reliable information from very small data sets and also show very good stability to noisy training data, all important characteristics when working on gravitational waves data sets.

The focus is on training the quantum machine learning algorithms for the detection of prospective gravitational wave signals, which will be observable together with their counterparts by future observatories and cosmic missions.

In particular, introducing new data analysis methods to improve the localization uncertainties for the weaker GW signals based on LIGO-Virgo/KAGRA observing runs, will overall increase the number of detection and hence facilitate the observation of electromagnetic counterparts.

QUANTERA
ERA-NET Cofund in Quantum Technologies

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)

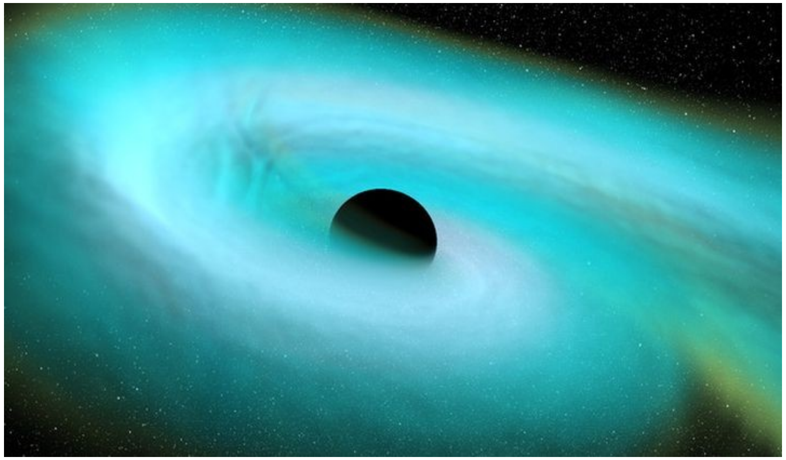
GW190814:

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.



Thank you for your attention!