連星中性子星合体に対する一般相対論的輻射磁気流体計算 ：コード開発の現状

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CGP
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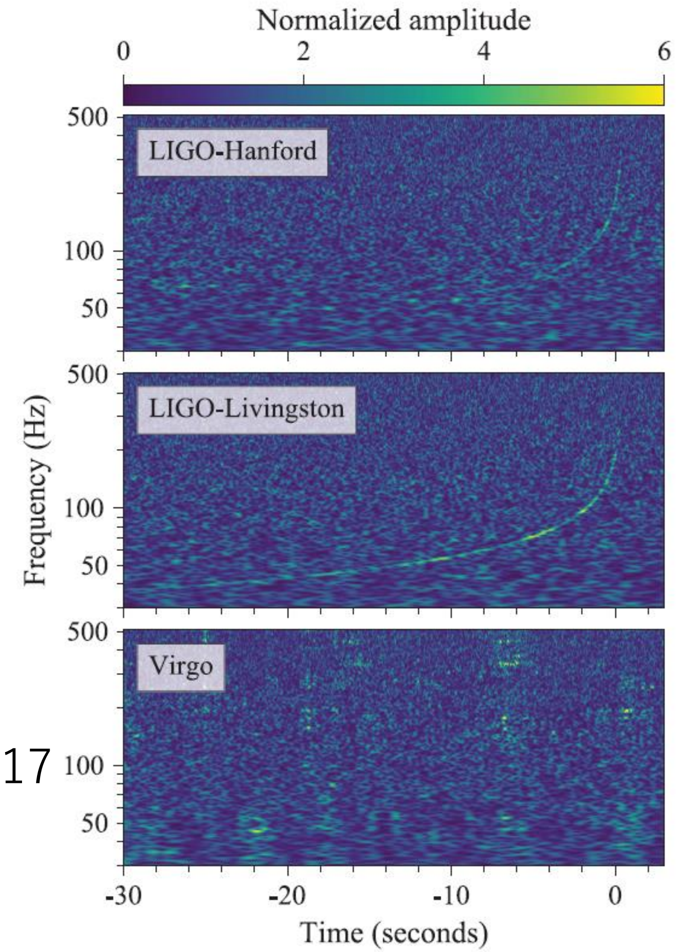
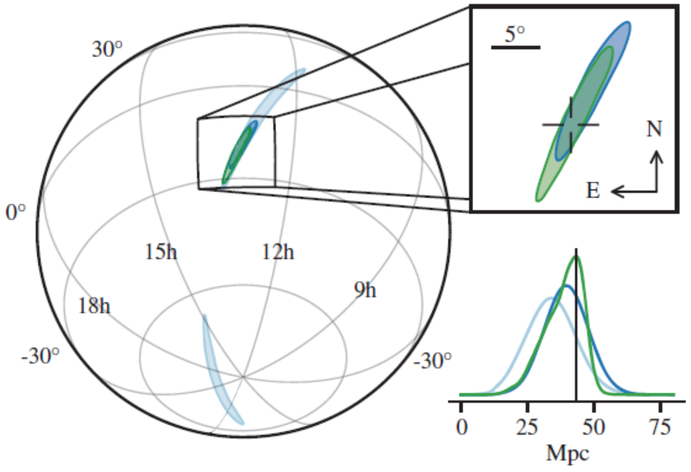
Gravitational Wave Physics and Astronomy Genesis

GW170817: First detection of gravitational waves from a binary neutron star mergers



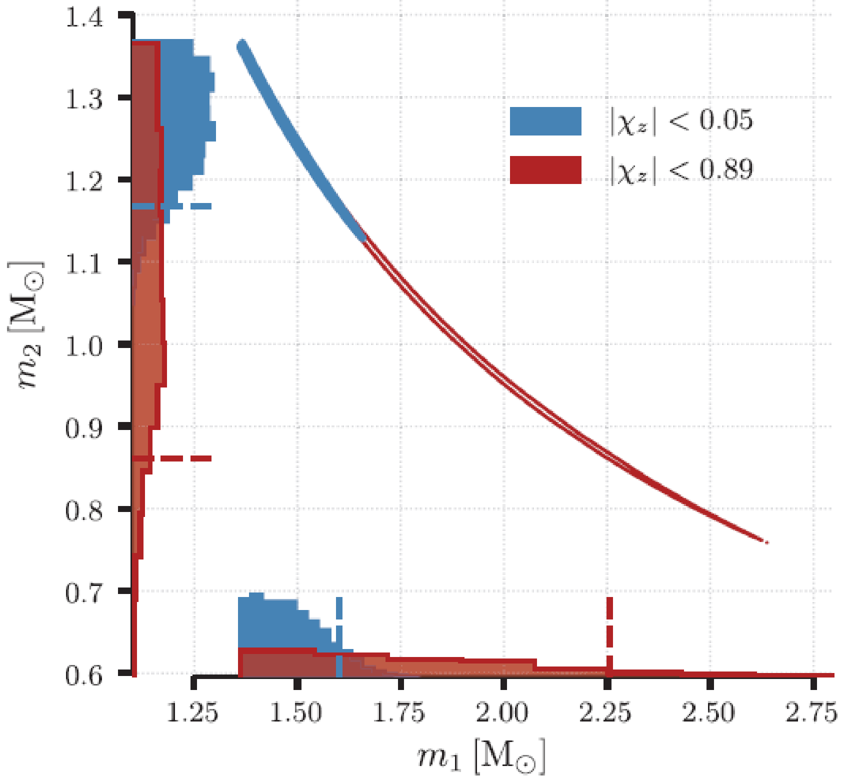
LSC, PRL 2017

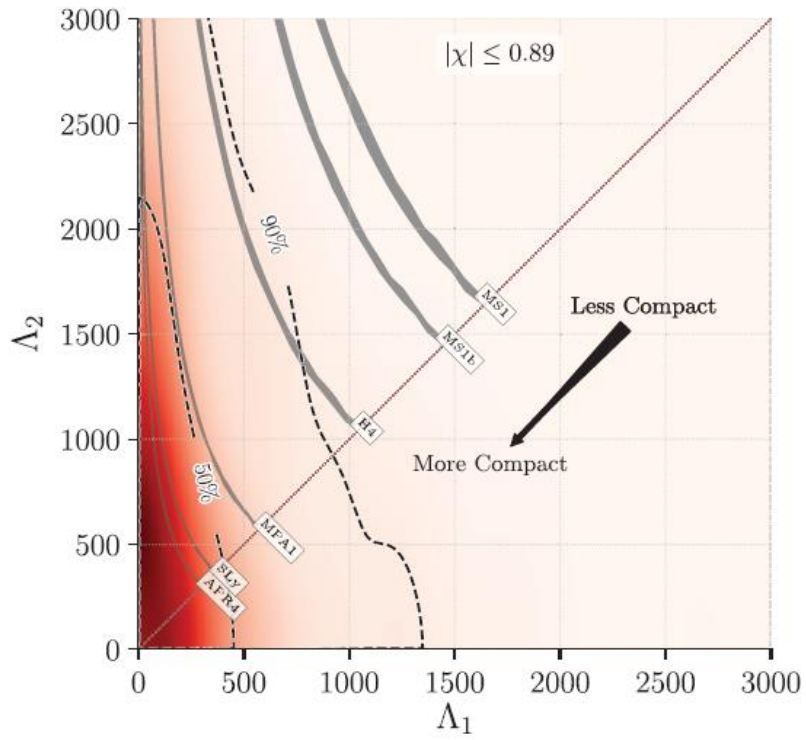


$$\mathcal{M}_{\mathrm{chirp}} = (m_1 m_2)^{5/3}/(m_1 + m_2)^{1/5} = 1.188^{+0.004}_{-0.002} M_\odot$$

Inspiral signals lasting for 74 seconds from 24 Hz ⇒ Binary Neutron Star Merger

First constraint on the equation of state of NS matter





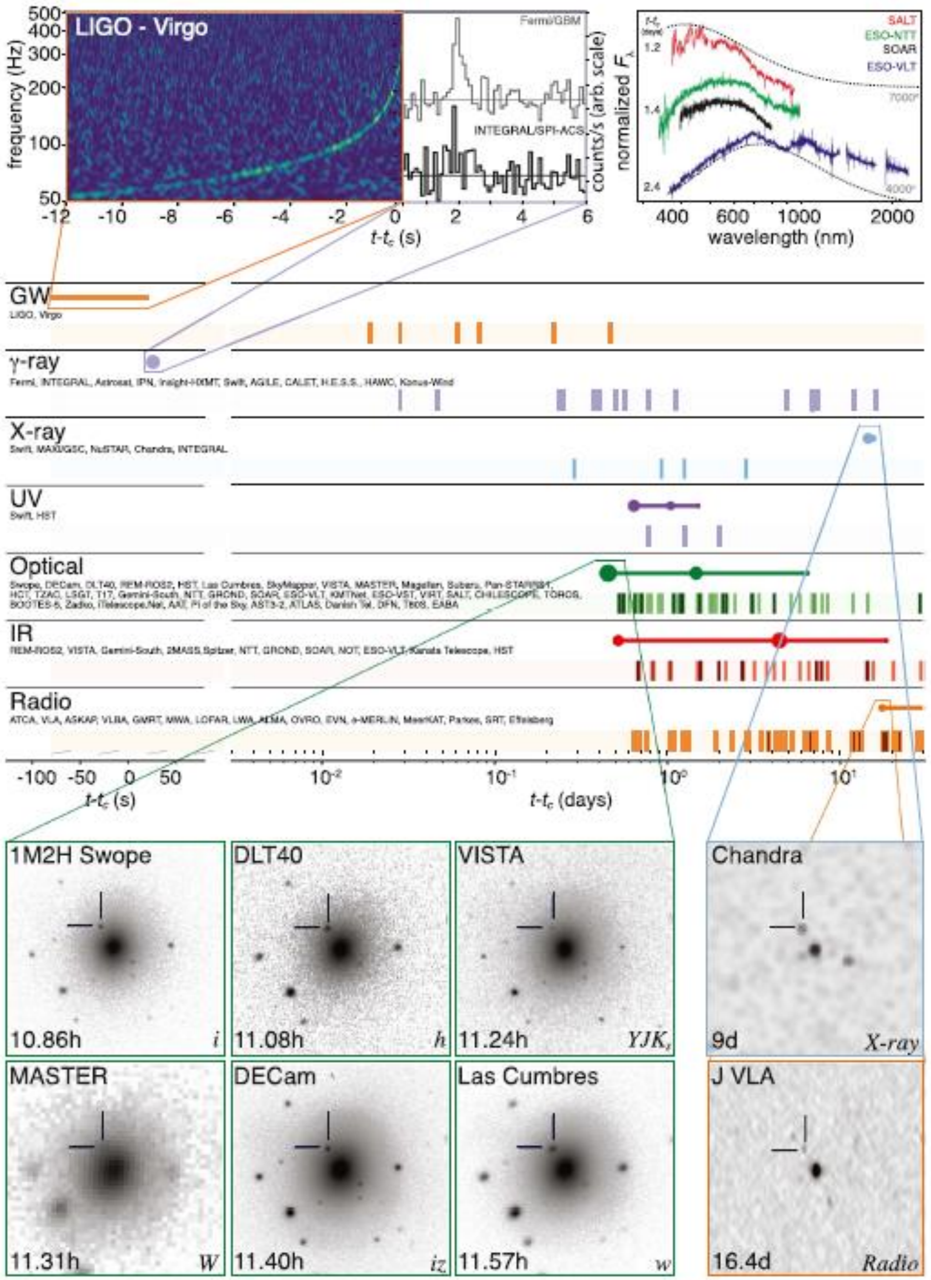
LSC, PRL 2017

$$m_1 = 1.36 - 1.60 M_\odot,\ m_2 = 1.17 - 1.36 M_\odot,$$

$$\tilde{\Lambda}(\Lambda_1, \Lambda_2) \leq 800 \Rightarrow R_{1.35 M_\odot} \leq 13.6\,\mathrm{km}$$

Consistent NS mass observed so far and a soft EOS is favored

Real Multimessenger Era (GW+EM)



GW detection

⇒ After 1.7s, Gamma-Ray detection

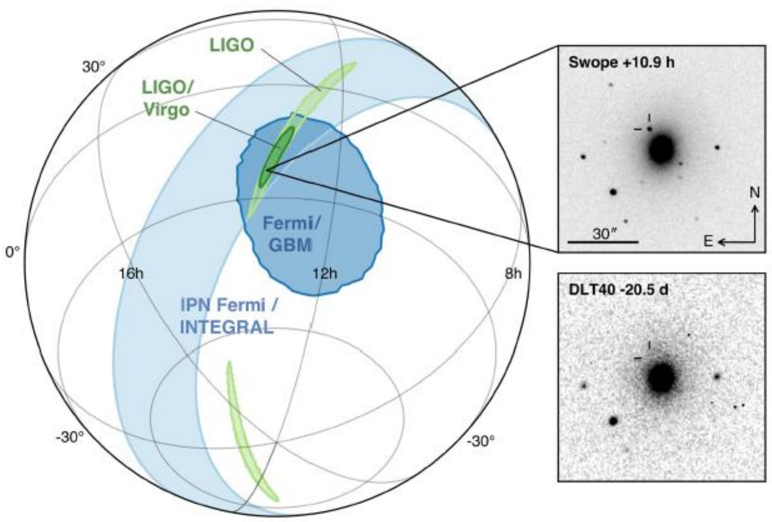
⇒ After 0.5 day, UV-Optical-NIR detection (source identification)

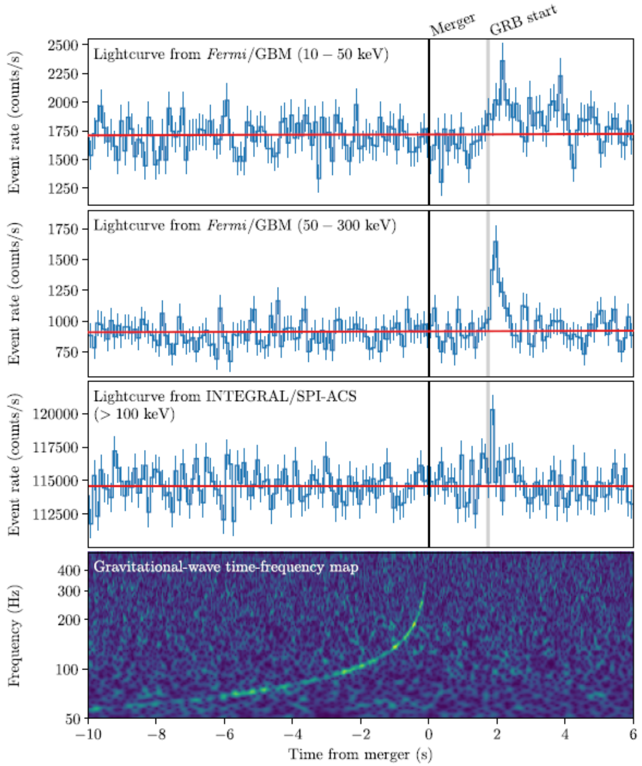
⇒ After 9 day, X-ray detection

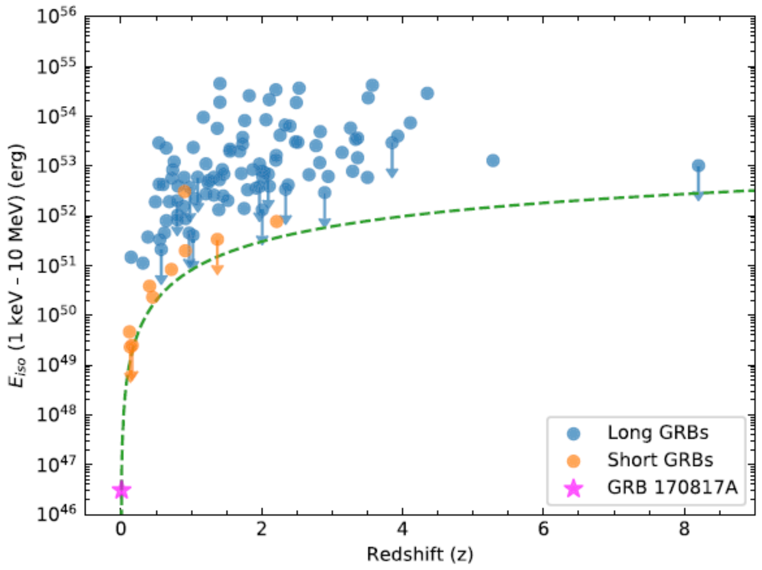
⇒ After 16 day, Radio detection

LSC+EM, APJL 2017

GRB170817A : Fermi Gamma-ray Burst Monitor detection







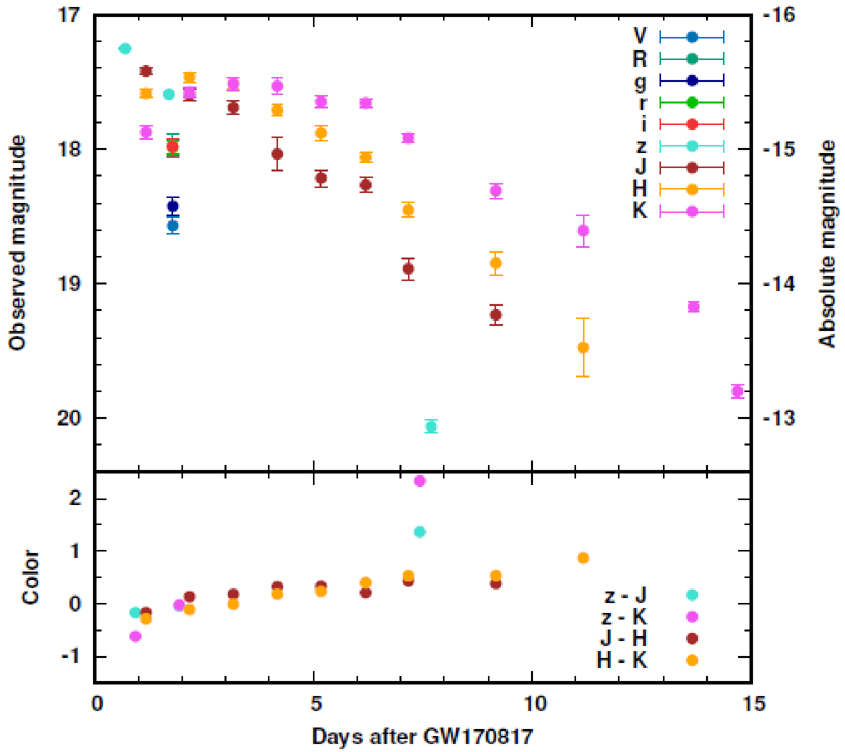
LSC+Fermi GBM, APJL 2017

▶ Coincidence detection with time lag of 1.7 second ⇒ Source position is consistent with GW170817

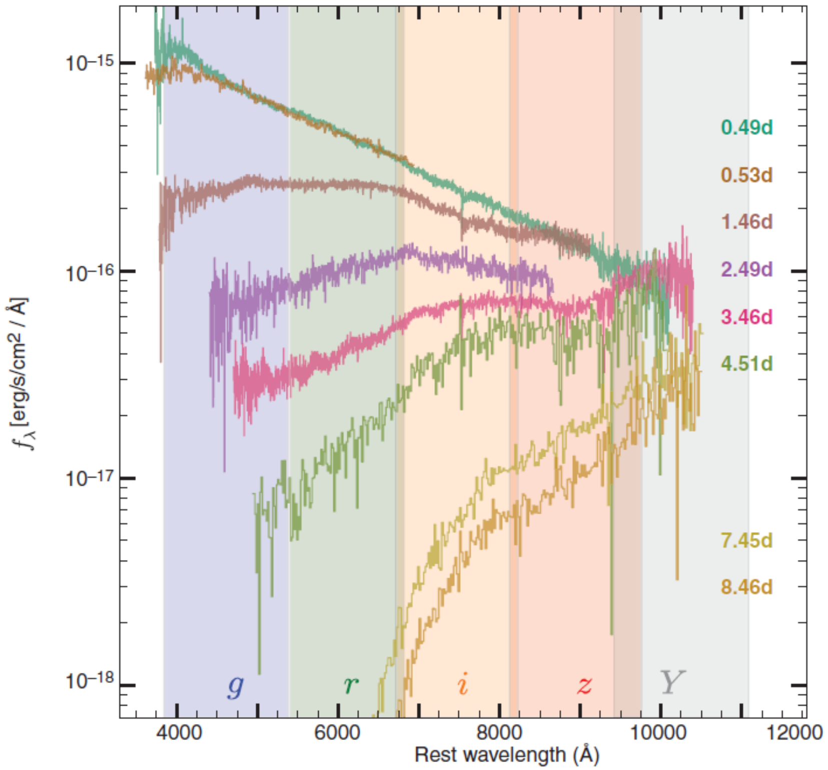
▶ $E_{iso} \sim 10^{46}$ erg which is much below typical short gamma-ray burst

Swope Supernova Survey 17a : Optical-NIR detection

Utsumi et al. PASJ 2017



Shappee et al. Science 2017

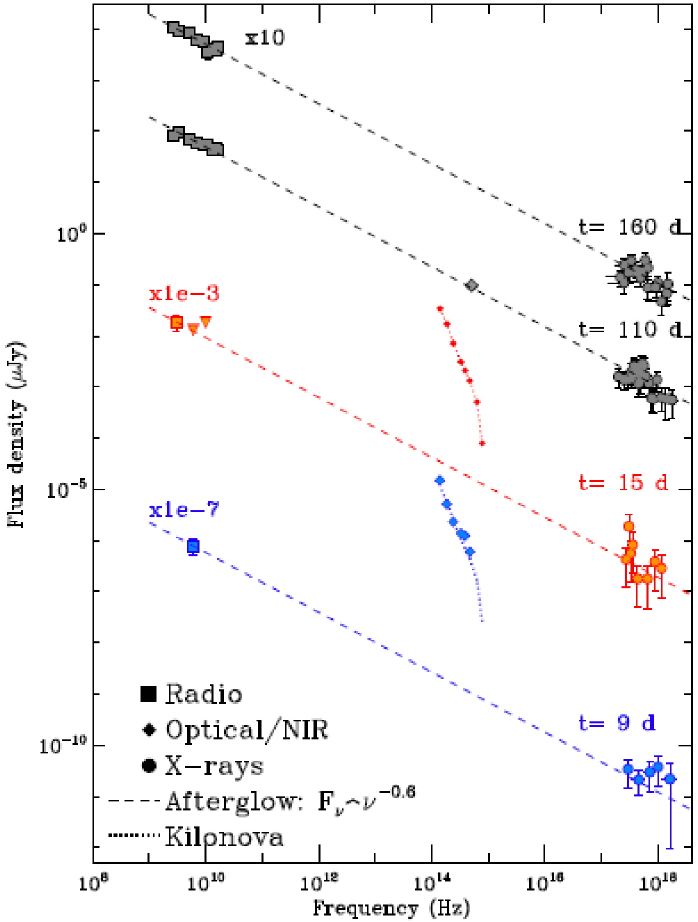


▶From UV-Optical emission at 0.5 day (Blue emission) to Near-Infrared emission at 9 days (Red emission) ⇒ Two components

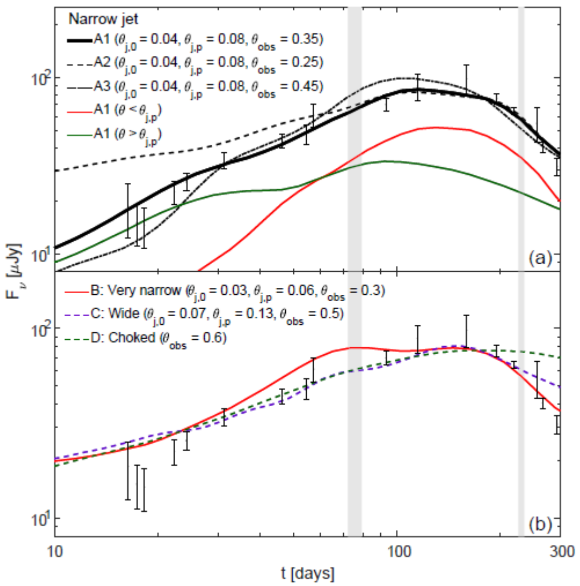
$$\text{Fast blue component} \sim 0.02M_\odot,\ v \sim 0.2 - 0.3c$$

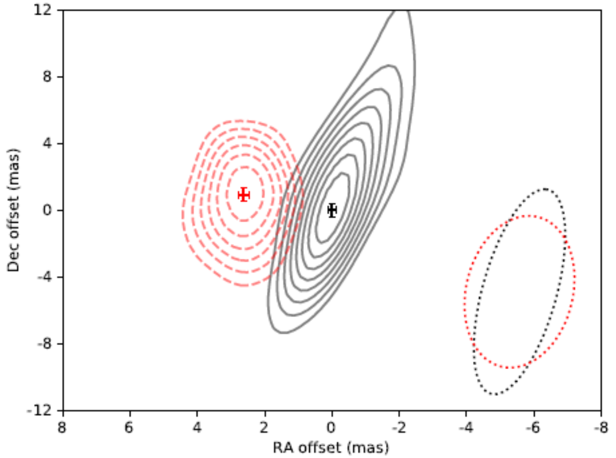
$$\text{Slow red component} \sim 0.03M_\odot,\ v \sim 0.1c$$

Long-term monitoring of X-ray and Radio



Mooley et al. 2018





Margutti et al. APJL 2018

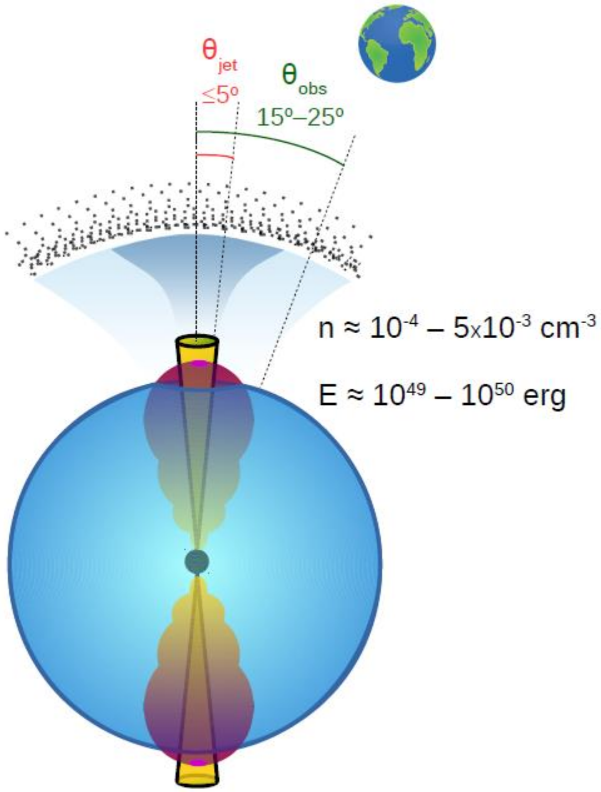
▶Synchrotron emission model nicely fits a single power law spectrum

▶Turnover in the light curve at 200 days ⇒ Suggestion of relativistic motion

▶ Image of the emission region in radio ⇒ Superluminal motion

A consistent picture of GW170817 and AT2017gfo

Mooley et al. 2018



Ioka and Nakamura PTEP 2018

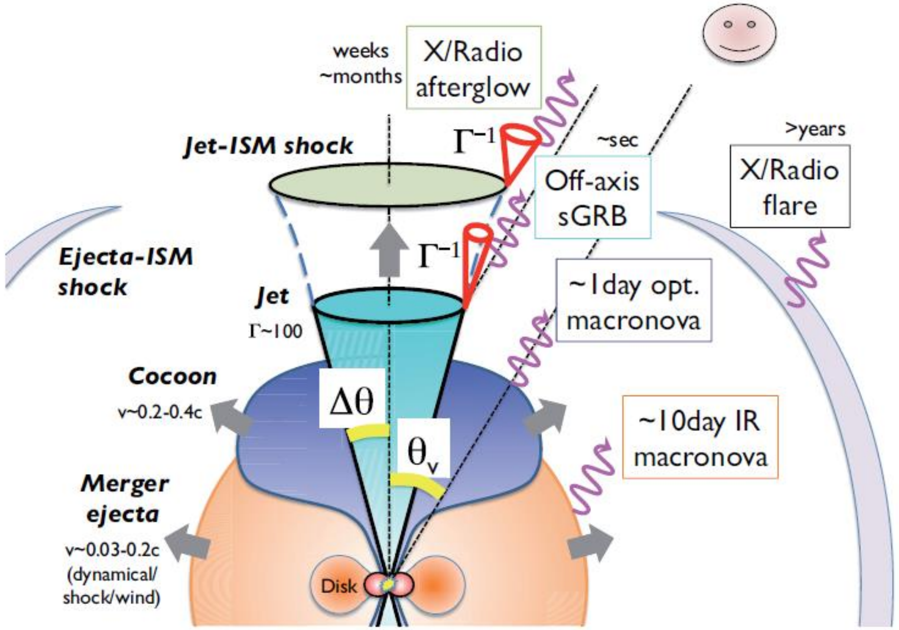


Fig. 1 Schematic figure of our unified picture.

▶ In GW170817, relativistic jet was launched and significant amount of the ejecta mass was emitted.

▶ Numerical modeling based on NR simulations can explain the ejecta from GW170817. (Sekiguchi, KK et al. 17a,b, Fujibayashi, KK et al. 18, Shibata et al. 17)

Challenge : Building a consistent numerical model

$$G_{\mu\nu} = 8\pi(T^{(\mathrm{hyd})}_{\mu\nu} + T^{(\nu\text{-rad})}_{\mu\nu} + T^{(EM)}_{\mu\nu})$$

$$\nabla_{\mu}(T^{\mu\nu}_{(\mathrm{hyd})} + T^{\mu\nu}_{(\mathrm{EM})}) = -G^{\nu}$$

$$\nabla_{\mu}T^{\mu\nu}_{(\nu\text{-rad})} = +G^{\nu}$$

$$\nabla_{\mu}(\rho u^{\mu}) = 0$$

$$\nabla_{\mu}(Y_l u^{\mu}) = 0$$

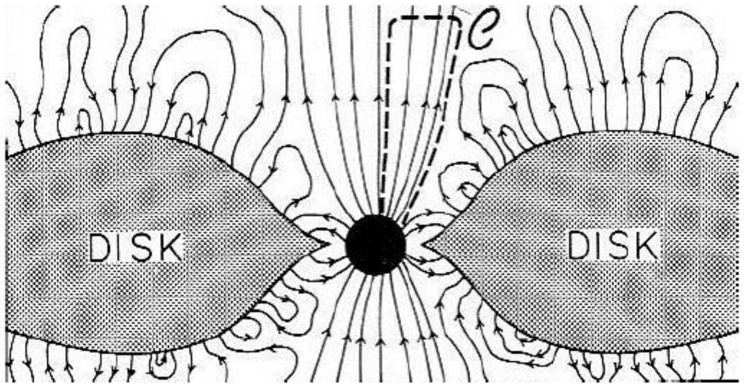
$$\nabla_{\mu}F^{\mu\nu} = -4\pi j^{\nu},\ \nabla^{*}_{\mu}F^{\mu\nu} = 0$$

▶ In K project, we neglect EM field or neutrino radiation.

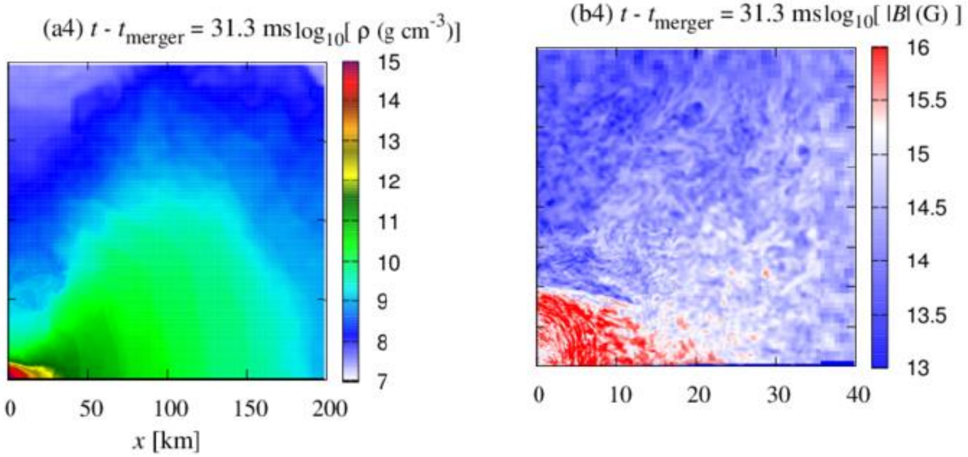
However, all the components should be included to build a central engine of SGRBs.

Challenge : Building a consistent numerical model

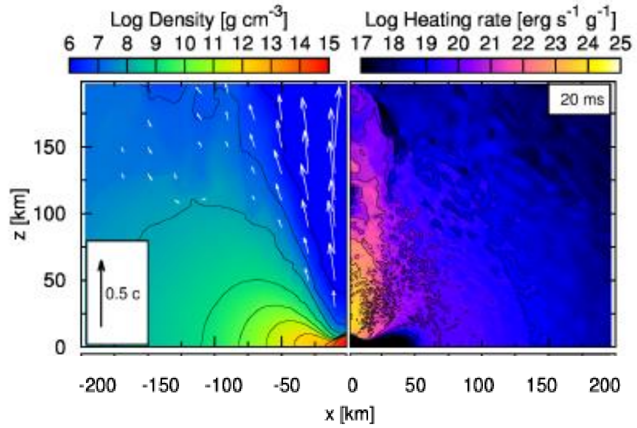
Blandford-Znajek mechanism as a key ingredient for relativistic jet launching



Thorne & Macdonald 1986



KK et al. 2018



Fujibayashi KK et al. 2017

▶Extracting BH rotational energy via coherent B fields

▶In BNS merger, the matter inertia dominate the B fields (randomly oriented B field is developed).

▶ Neutrino heating drives a disk wind in a polar direction.

⇒ Poloidal field generation because of the B-file lines frozen into the matter

Code develop : Numerical Relativity-neutrino Radiation Magneto Hydro Dynamics

▶ Einstein Solver based on Baumgarte-Shapiro-Shibata-Nakamura formulation ⇒ Tuning is OK

▶ Neutrino Radiation Hydrodynamics Solver based on M1-scheme ⇒ Tuning is OK

▶ B-field Solver based on Constraint-Transport method ⇒ Tuning is OK

▶ Nested grid (Fixed mesh refinement) implementation ⇒ Tuning is OK

▶ Tuning target is Primitive Recovery Solver with a tabulated EOS table

Code develop : Primitive Recovery Solver

We evolve the spatial components of the four velocity and energy weighted by the specific enthalpy.

$$\rho w,$$

$$\hat{u}_i = h u_i,$$

$$\hat{e} = hw - P(\rho, T, Y_e)/\rho w$$

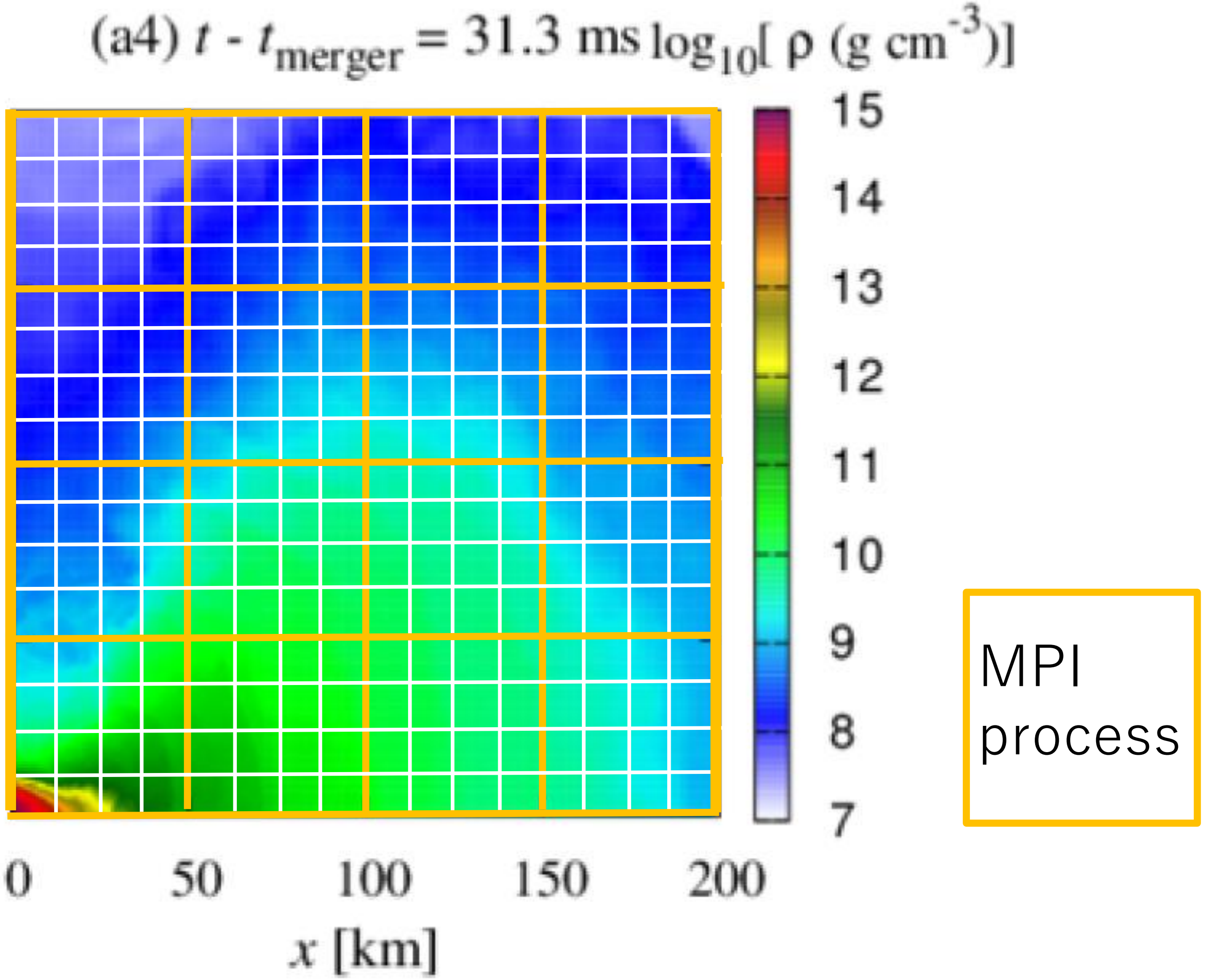
$$h(\rho, T, Y_e) = 1 + \epsilon + \frac{P}{\rho}, \; w^2 = 1 + \gamma^{ij} u_i u_j$$

We need h to disentangle $\hat{u}_i$ and ρw. But, h is a function of ρ and T.

Therefore, iteration is needed.

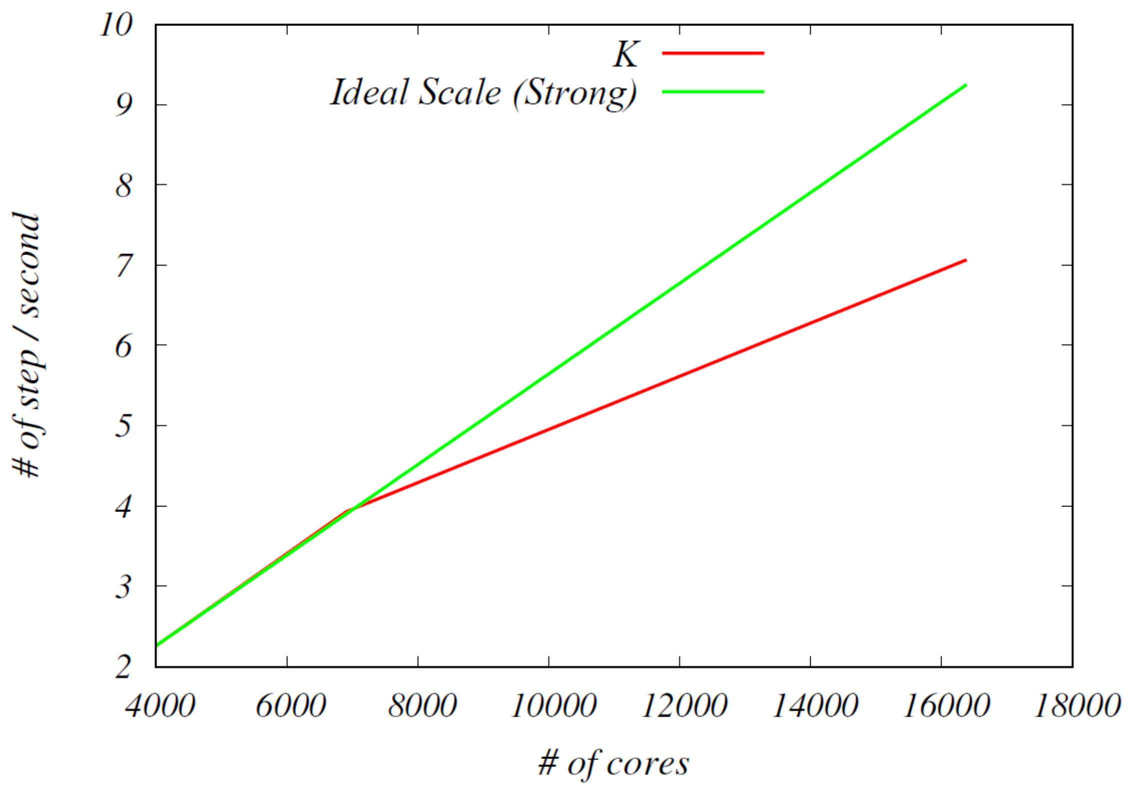
Data size of the tabluated EOS is large, e.g., 400Mbyte for SFHo EOS

Code develop : Block division of EOS table



If we focus on a specific MPI process, the density range is not so large. ⇒ We dynamically make a block EOS table.

Code develop : Scaling



- Strong scaling up to 32,000 cores.
- Parallelization efficiency is ～76%.

Test simulation

$$\text{EOS} = \text{SFHo with Timmes}$$

$$m_1 = m_2 = 1.34 M_\odot,$$

$$\Delta x_{lv=10} = 200 \text{ meter},$$

$$10 \text{ nested grid levels},$$

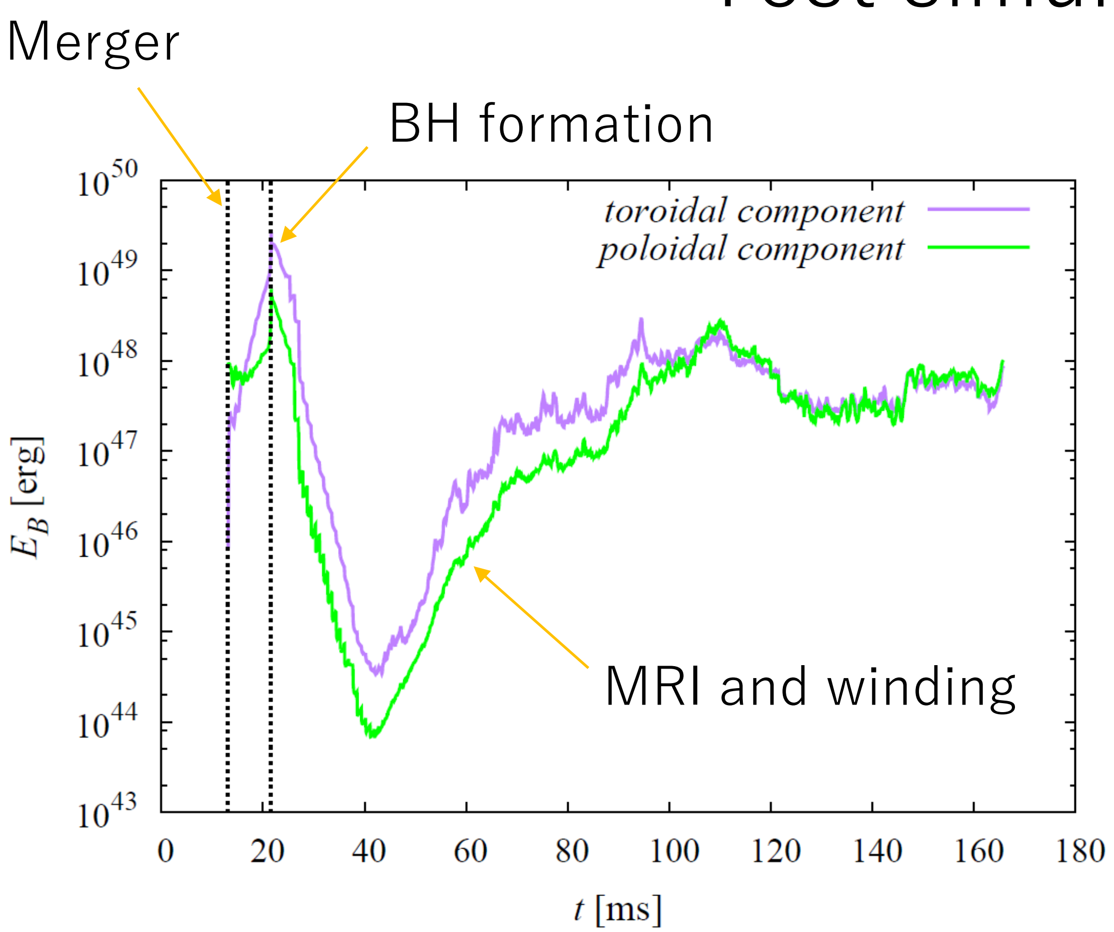
$$\# \text{ of grid in x,y,z in one nested grid level} \in [-178 : 178]$$

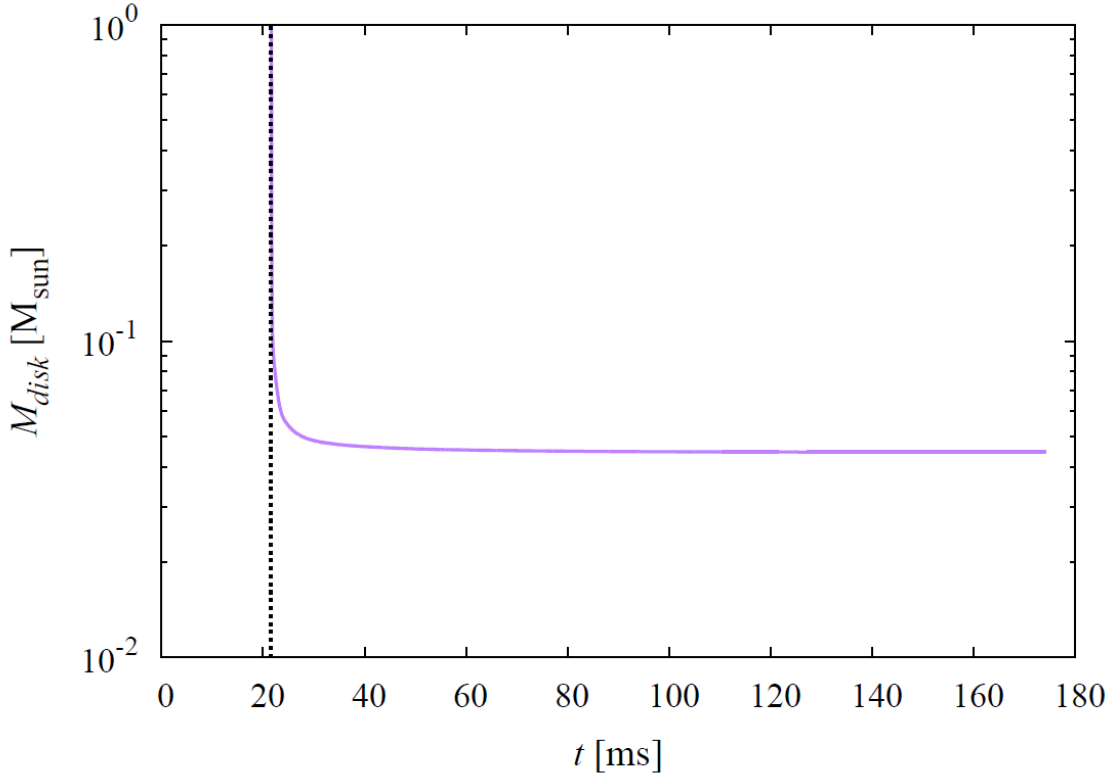
We intentionally selected a model with short-lived remnant because the condition to resolve the MRI is relaxed.

$$\lambda_{\rm MRI} \approx 500 \text{ m } (B/10^{16}\text{G})(\rho/10^{15} \text{ g cm}^{-3})^{-1/2}(\Omega/6000 \text{ rad } s^{-1})$$

$$\approx 3,000 \text{ m } (B/10^{16}\text{G})(\rho/10^{12} \text{ g cm}^{-3})^{-1/2}(\Omega/6000 \text{ rad } s^{-1})$$

Test simulation





$$M_{\rm disk} \approx 0.04 M_\odot,$$

$$E_{\rm rot,BH} \approx 2.5\times 10^{53}\,{\rm erg}(M_{\rm BH}/2.5M_\odot)(\chi/0.6)^2$$

Test simulation

But, I found the BH moves in z direction secularly and the code crashed at t ≈ 160 ms. cf. Accretion time scale is ≈ 400 ms. Time delay between GW170817 and GRB170817A is 1.7s.

▶ Maybe, we need switch to a staggered grid to ensure the linear momentum conservation or enlarge the numerical domain.

▶ Resolution study is mandatory.

▶ More systematic study for BNS models