ショートガンマ線バースト中心動力源の数値モデリング

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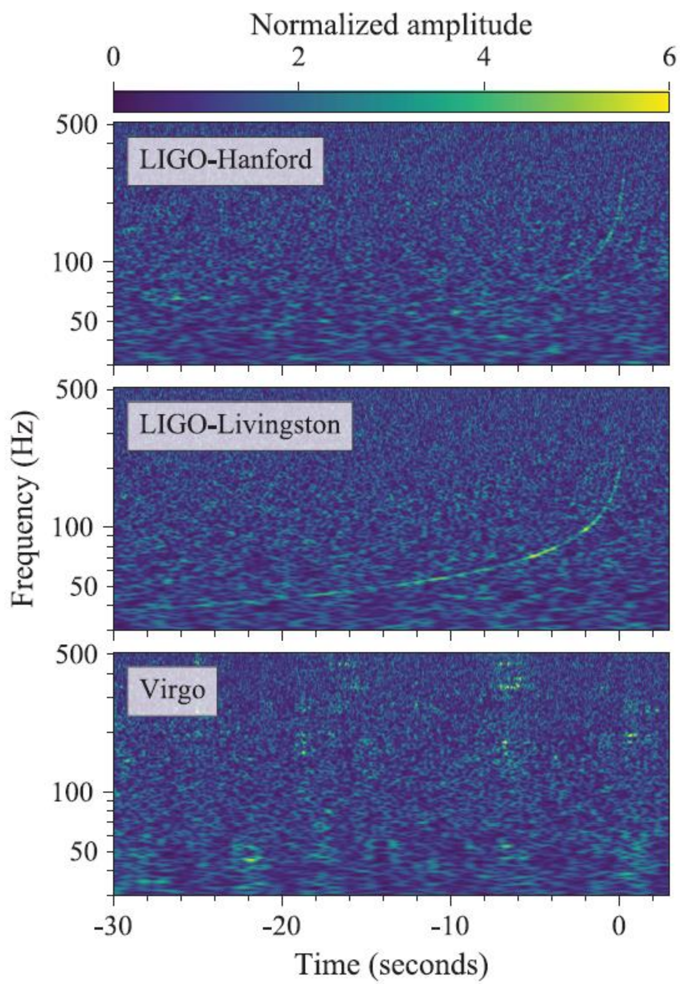
研究会「ガンマ線バースト研究の新機軸」

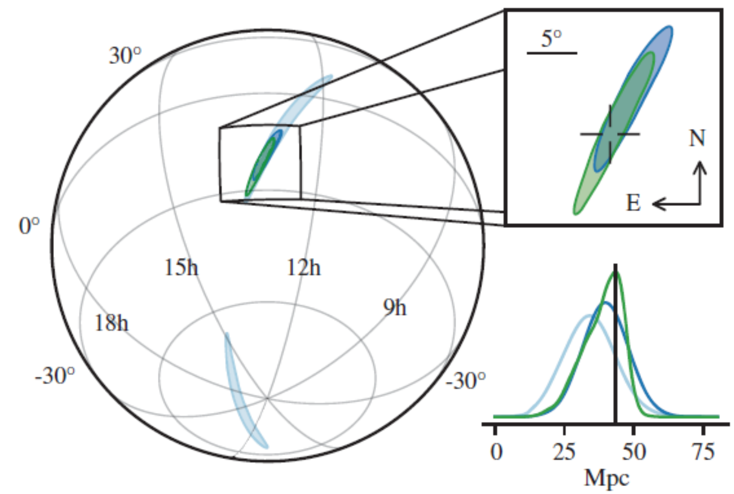
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP

GW170817 as a BNS merger event



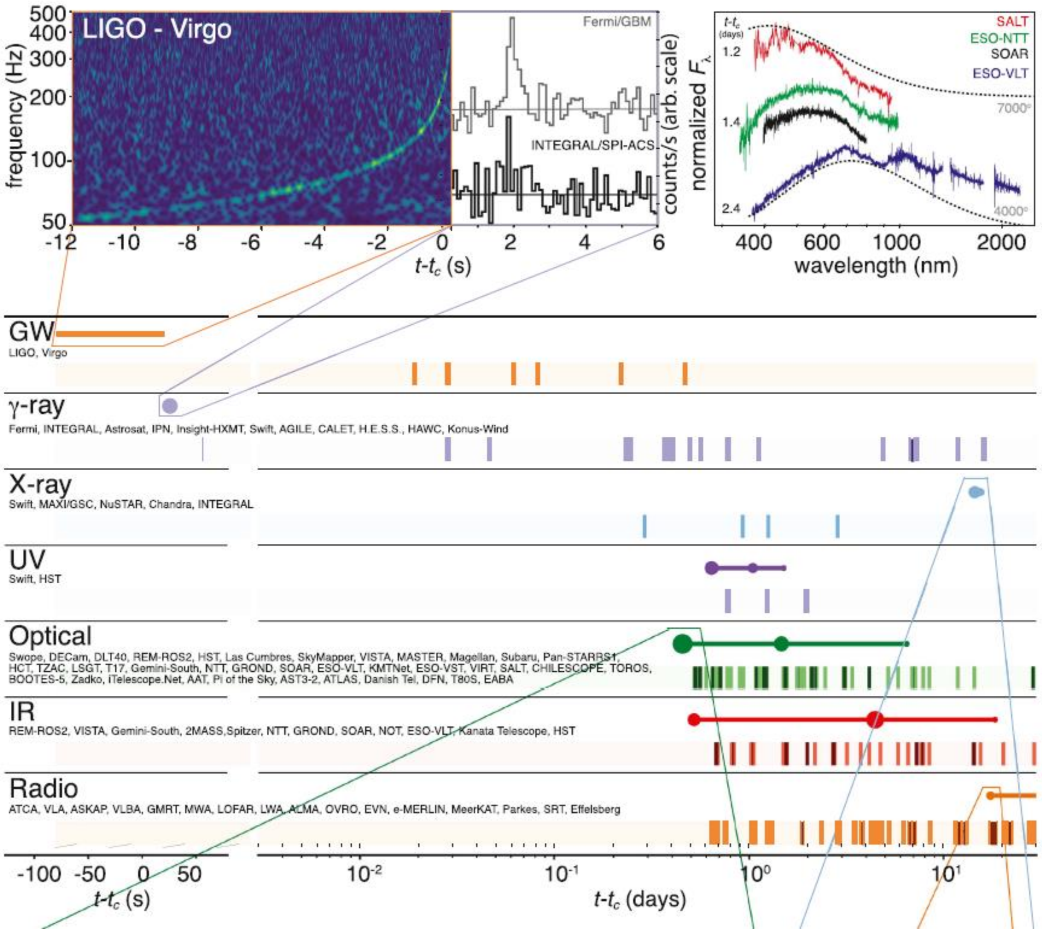
Sky map by LIGO + VIRGO

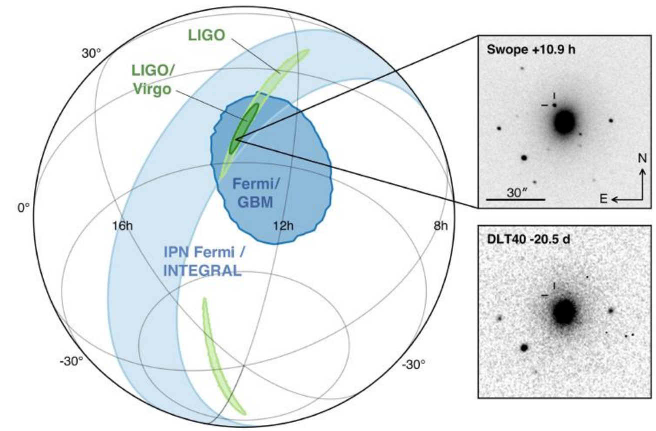


LSC-Virgo collaboration
PRL 2017

▶ Aug. 17th 2017, 74 sec. signals detected by LIGO-Hanford.
▶ S/N is 32.4 !

Real Multimessenger Astronomy Era

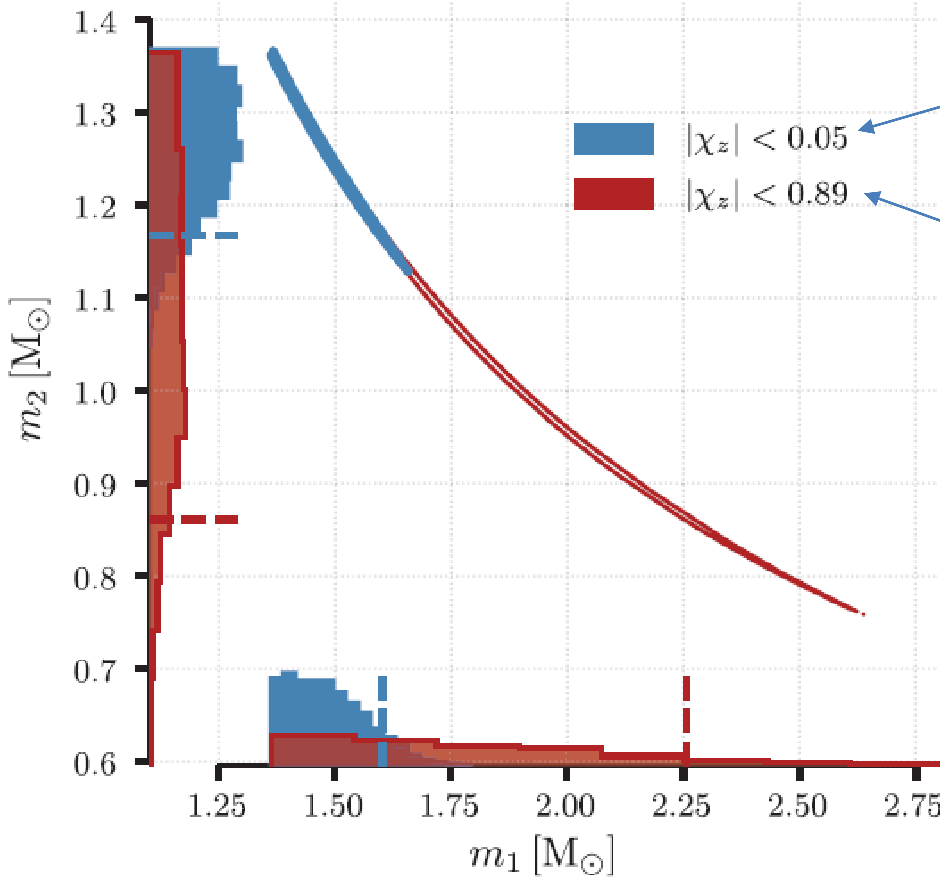




LSC-Virgo collaboration
APJ 848, L12, 2017

- GW ⇒ γ-ray ⇒ UV, Optical, IR ⇒ X-ray ⇒ Radio
- Host galaxy (NGC4993) was identified by the optical telescope (SSS17A)

Source properties of GW170817



low NS spin prior

high NS spin prior

LSC and Virgo collaboration PRL 119, 161101 (2017)

▶ Mass measurement of NSs.

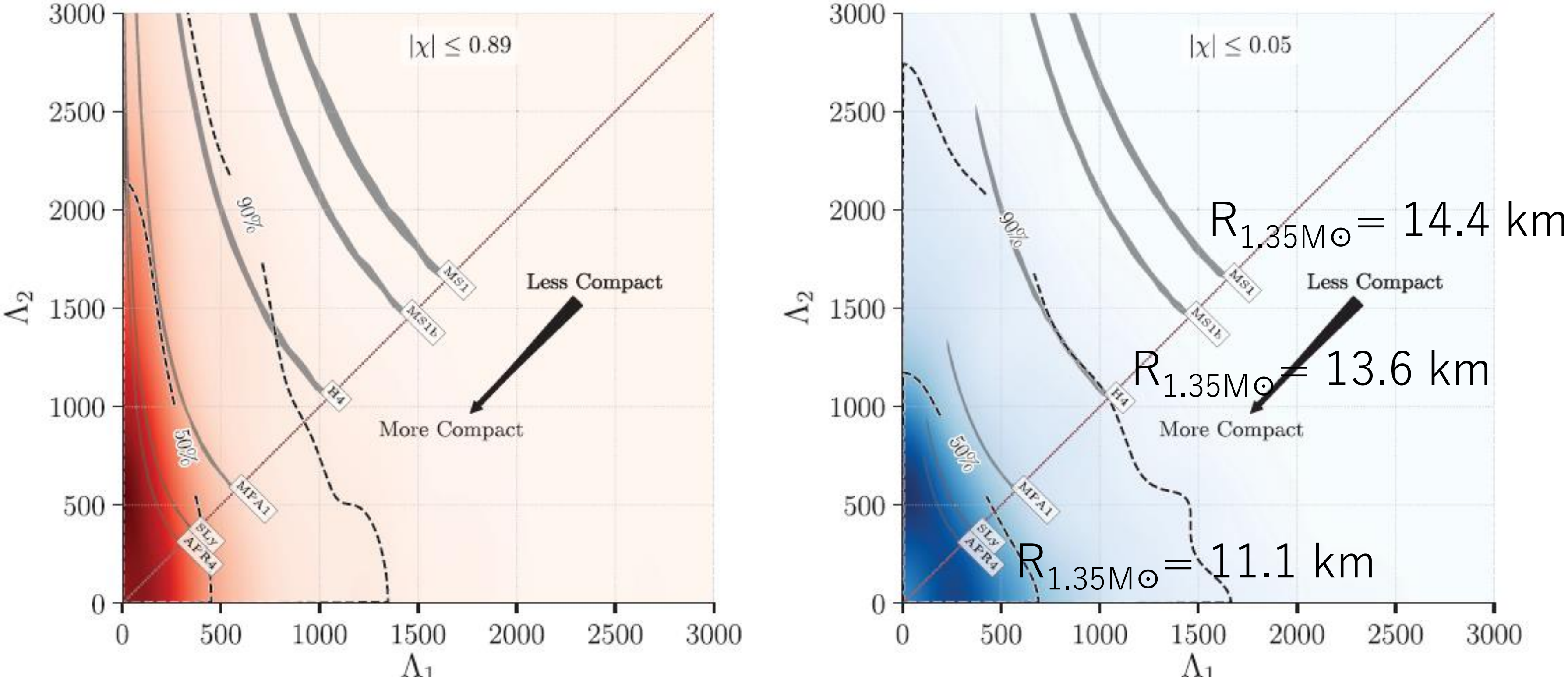
m_1: 1.36-1.60 $M_\odot$, m_2 : 1.17-1.36 $M_\odot$ (low spin prior)

m_1: 1.36-2.26 $M_\odot$, m_2 : 0.86-1.36 $M_\odot$ (high spin prior)

▶ Luminosity distance is 40^{+8}_{-14} Mpc

Tidal deformability measurement of NSs

LSC and Virgo collaboration PRL 119, 161101 (2017)

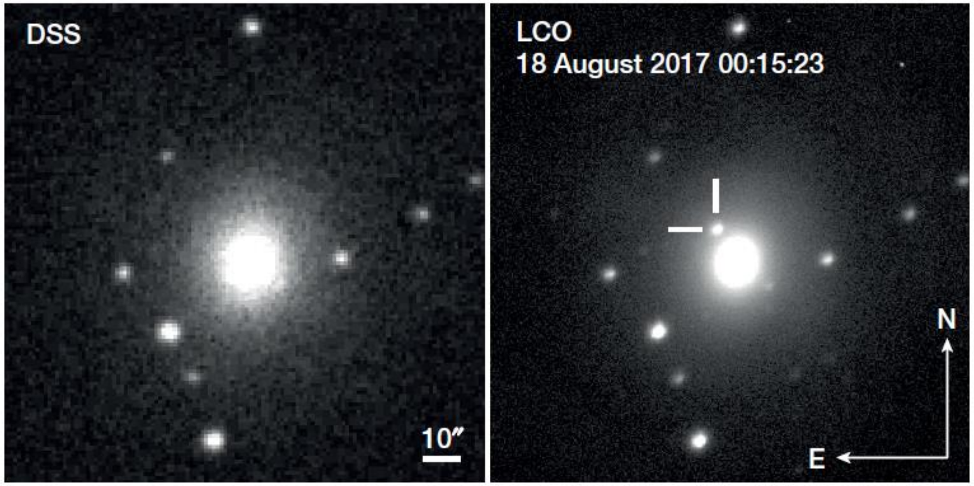


▶ Tidal deformation Λ is related to a NS radius ⇒ Information of the NS equation of state.

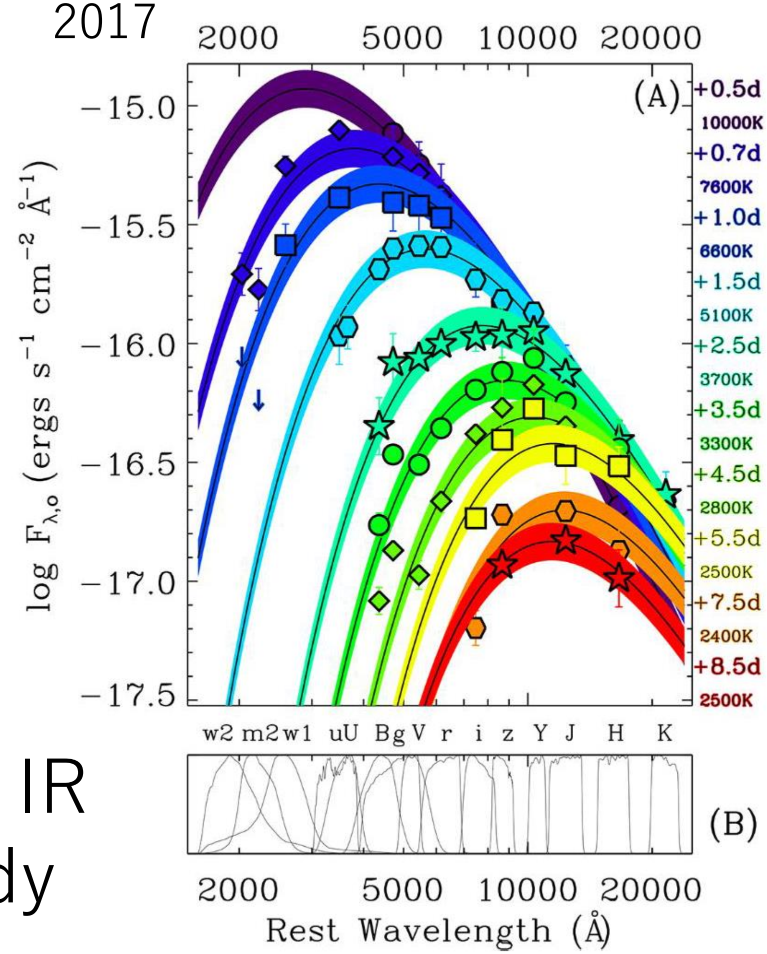
▶ Soft EOS is favored (Λ ≤ 800)

Detected UV-Optical-Infrared emission

Arcavi et al. Nature 24291, 2017



Drout et al. Science (aaq0049) 2017



UV Optical IR

- ▶ Rapid reddening from UV to IR
- ▶ Spectrum is quasi-black body
- ▶ Long-duration IR component & short-duration UV-Optical component (see also Tanaka kun's talk)

Science target of GWs from BNS merger

Revealing the central engine of SGRBs

▶Merger hypothesis (Narayan, Paczynski, and Piran 92)

Exploring the equation of state of neutron star matter

▶Determination of NS radius (NS tidal deformability) (Flanagan & Hinderer 08 etc.)

Origin of the heavy elements

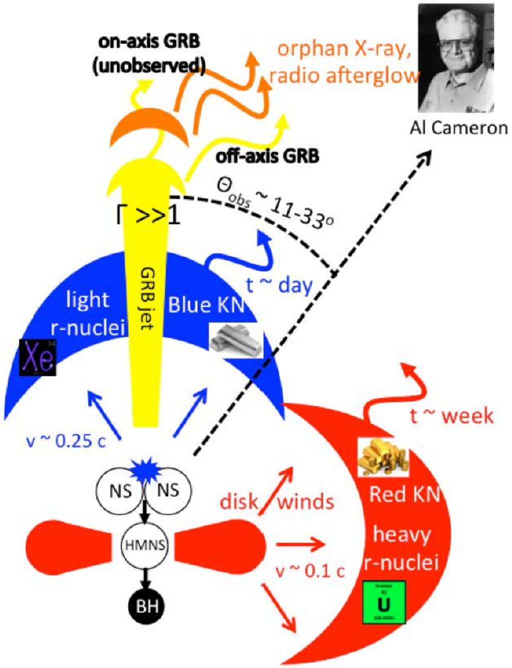
▶R-process nucleosynthesis site (Lattimer & Schramm 76)

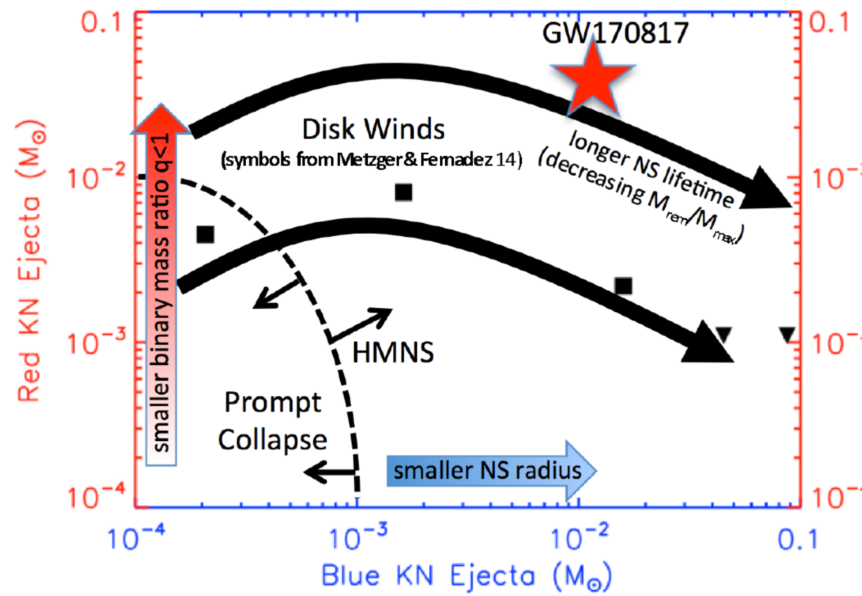
Electromagnetic counter part of GW sources

▶Optical-near infrared emission due to the radioactive heating source of r-process elements (Li & Paczynski 98, Metzger et al. 10)

GW170817 as a central engine of GRB170817A?

Metzger 17



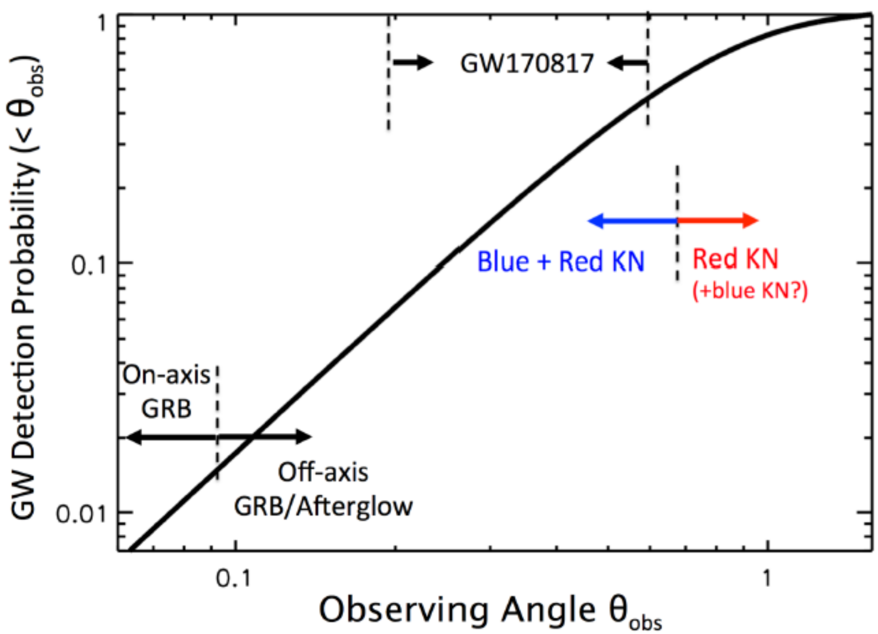


- Off-axis GRB? (Ioka san's talk)
- Rapid Blue Kilonova/Slow Red Kilonova

Uncertainity of heating rate : factor 2-3 (blue), < 2 (red), Thermalization efficiency : Uncertain (blue), Robust(red), Geometry factor ≈ 2

⇒ factor of 2-3 (blue) , 3-10 (red) in estimated M_{eje}

GW170817 as a central engine of GRB170817A?



Metzger 17

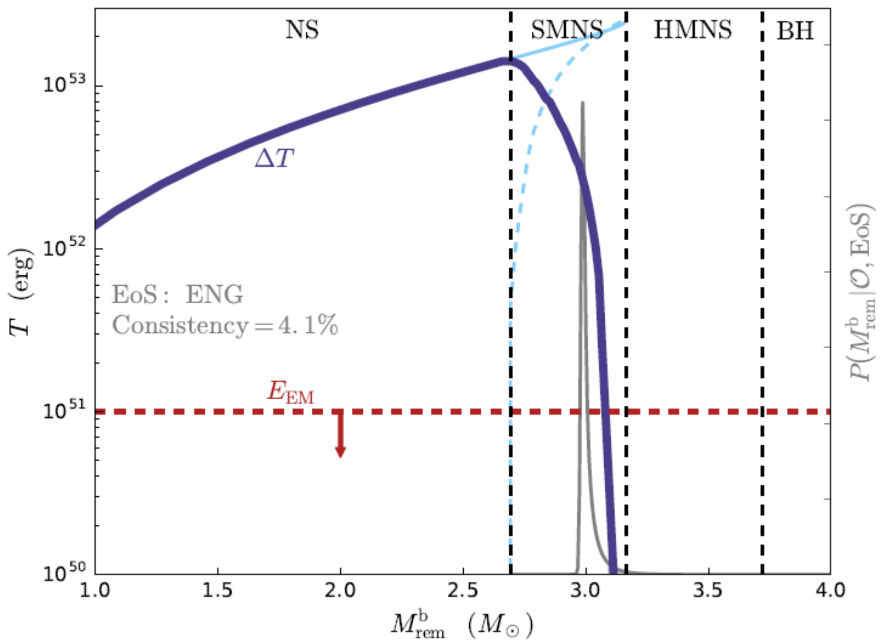
▶ SGRB rate observed on-axis : $f_{on}R_{SGRB} \approx 2 - 6$ Gpc^{-3} yr^{-1}

▶ Merger rate of BNS : $R_{BNS} \approx 1540^{3200}_{-1220}$ Gpc^{-3} yr^{-1}

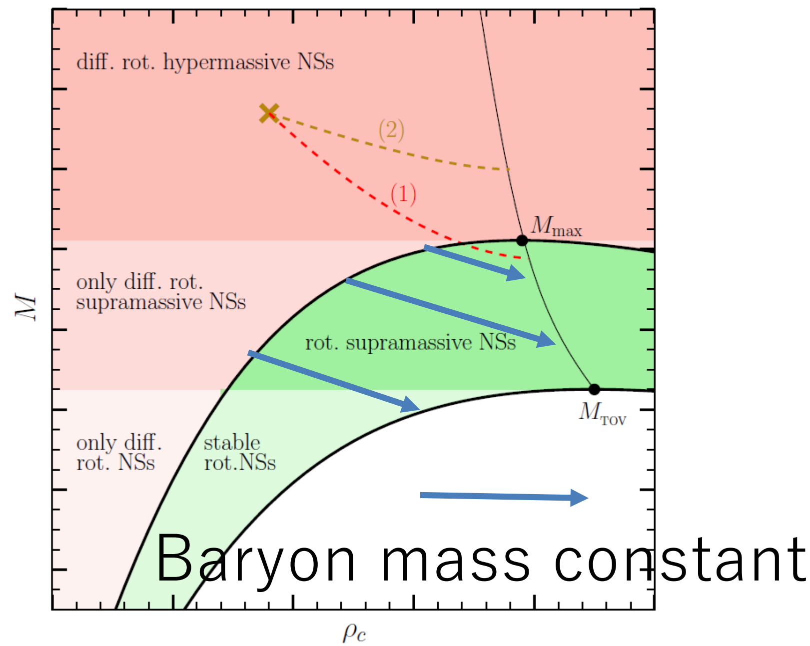
⇒ beaming fraction $f_b \approx f_{on}R_{SGRB}/R_{BNS} \sim 10^{-4} - 2 \times 10^{-2}$ ⇒ jet half-opening angle $\theta_j = (2 f_b)^{1/2} \approx 0.02\text{-}0.2$

An inferred remnant of GW170817

Given EOS



Margalit & Metzger 17



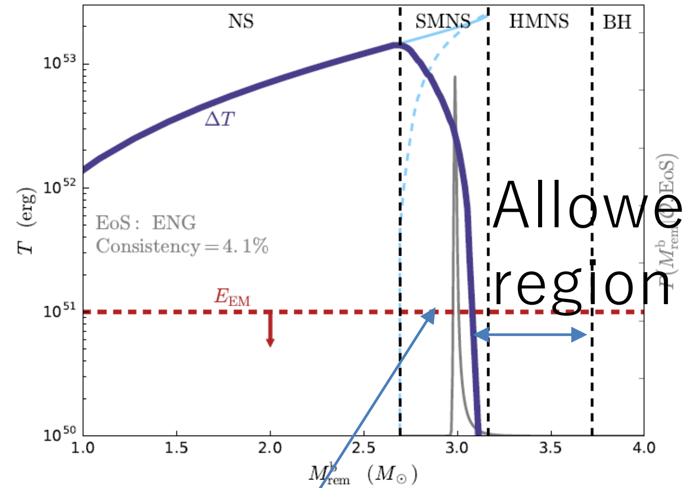
▶ ΔT: Maximum released rotational energy for HMNS⇒Rigidly rotating NS

▶ Observed kinetic energy of the ejecta E_{kin} =1/2 (M_{blue} v_{blue}^2 + M_{red} v_{red}^2) ≈10^{51} erg

Probability distribution of the baryon mass of merger remnant

$$P\left(M^{\rm b}_{\rm rem}|\mathcal{O},{\rm EoS}\right) = \int dM^{\rm b}_1 \int dM^{\rm b}_2\ \delta(M^{\rm b}_1 + M^{\rm b}_2 - M_{\rm ej} - M^{\rm b}_{\rm rem}) \times P\left(g_{\rm EoS}(M^{\rm b}_1), g_{\rm EoS}(M^{\rm b}_2)|\mathcal{O}\right) \left|g'_{\rm EoS}(M^{\rm b}_1)\right| \left|g'_{\rm EoS}(M^{\rm b}_2)\right|$$

Posterior from GW170817、
gEoS:M_b->M_g



Probability of the baryon mass

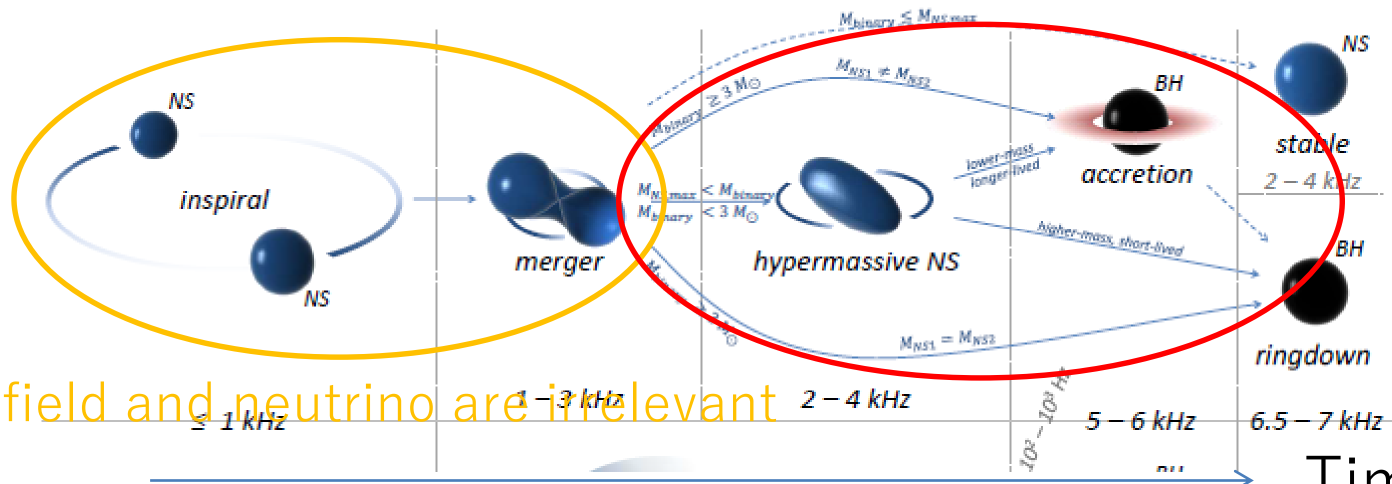
- M_{eje} = 0.02 $M_\odot$
- Consistency check of the probability of the baryon mass and $\Delta T < 10^{51}$erg ⇒ $M_{g,max} < 2.17 M_\odot$
- No significant post-merger signal (LSC collaboration 17)

⇒ BH is an inferred remnant of GW170817

Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)

B-field and neutrino play an essential role



B-field and neutrino are irrelevant

Time axis

Total mass vs Maximum mass of NSs (EOS)

▶ EOS produces a systematic error for modeling the central engine ⇒ Constraining a tidal deformability of NS

▶ MHD effect: Effective turbulent viscosity and/or large scale dynamo

▶ Neutrino reaction : Pair annihilation

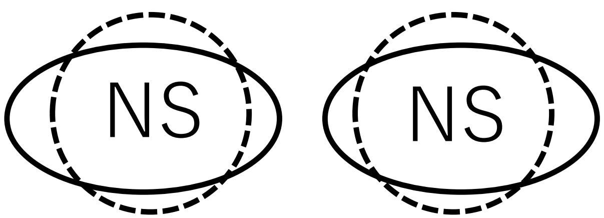
From inspiral to late inspiral phase

Tidal deformation : NS just before the merger could be deformed by a tidal force of its companion.

Tidal deformability depends on NS constituent, i.e., EOS.

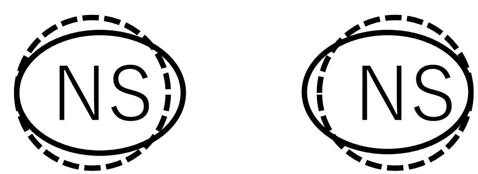
Tidal deformation

Stiff EOS (large R)



Easily tidally deformed

Soft EOS (small R)



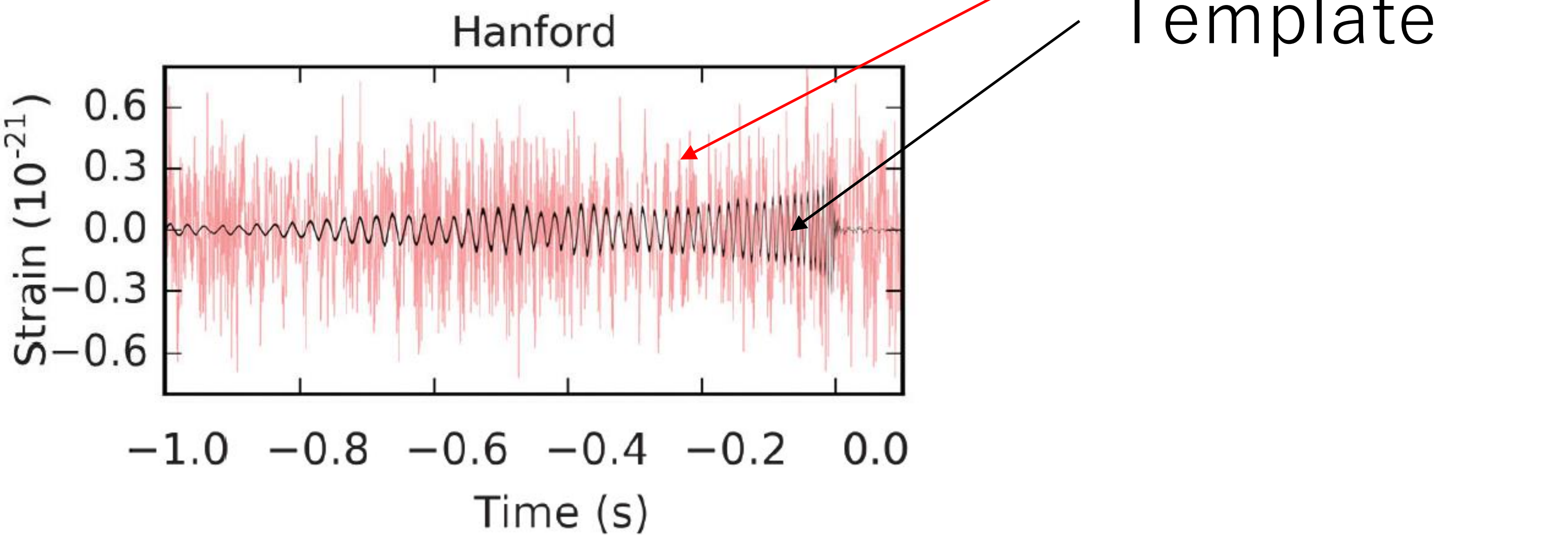
Hard to be tidally deformed

Tidal deformability imprinted in GWs

$$h = \underbrace{A(t)}_{\text{Amplitude}} e^{i \underbrace{\Phi(t)}_{\text{Phase}}}$$

Tidal force is attractive force ⇒
Tidal deformation accelerates the phase evolution

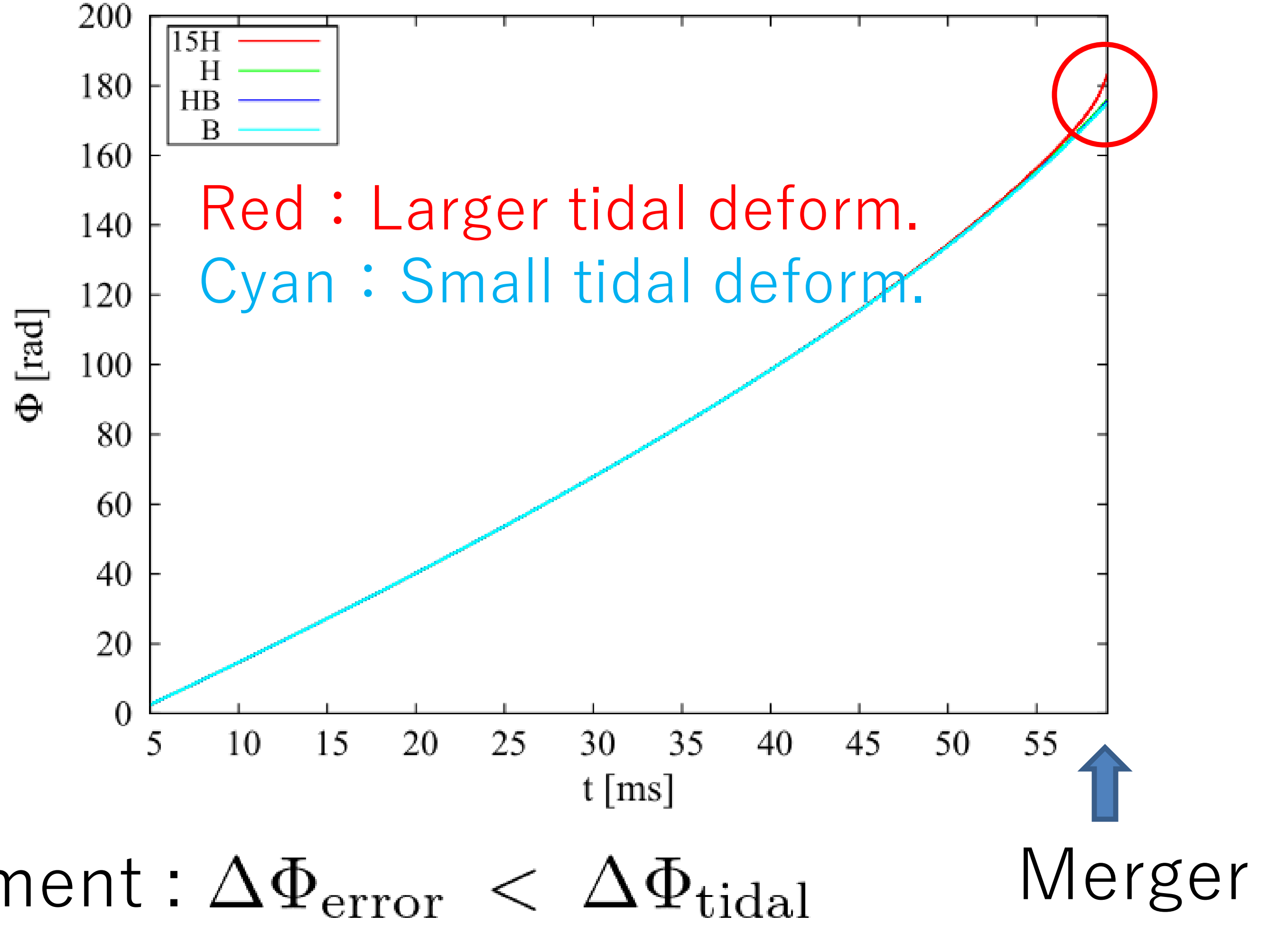
Theoretical template of GWs



To measure a tidal deformability

Large tidal deformability ⇒ Rapid phase evolution

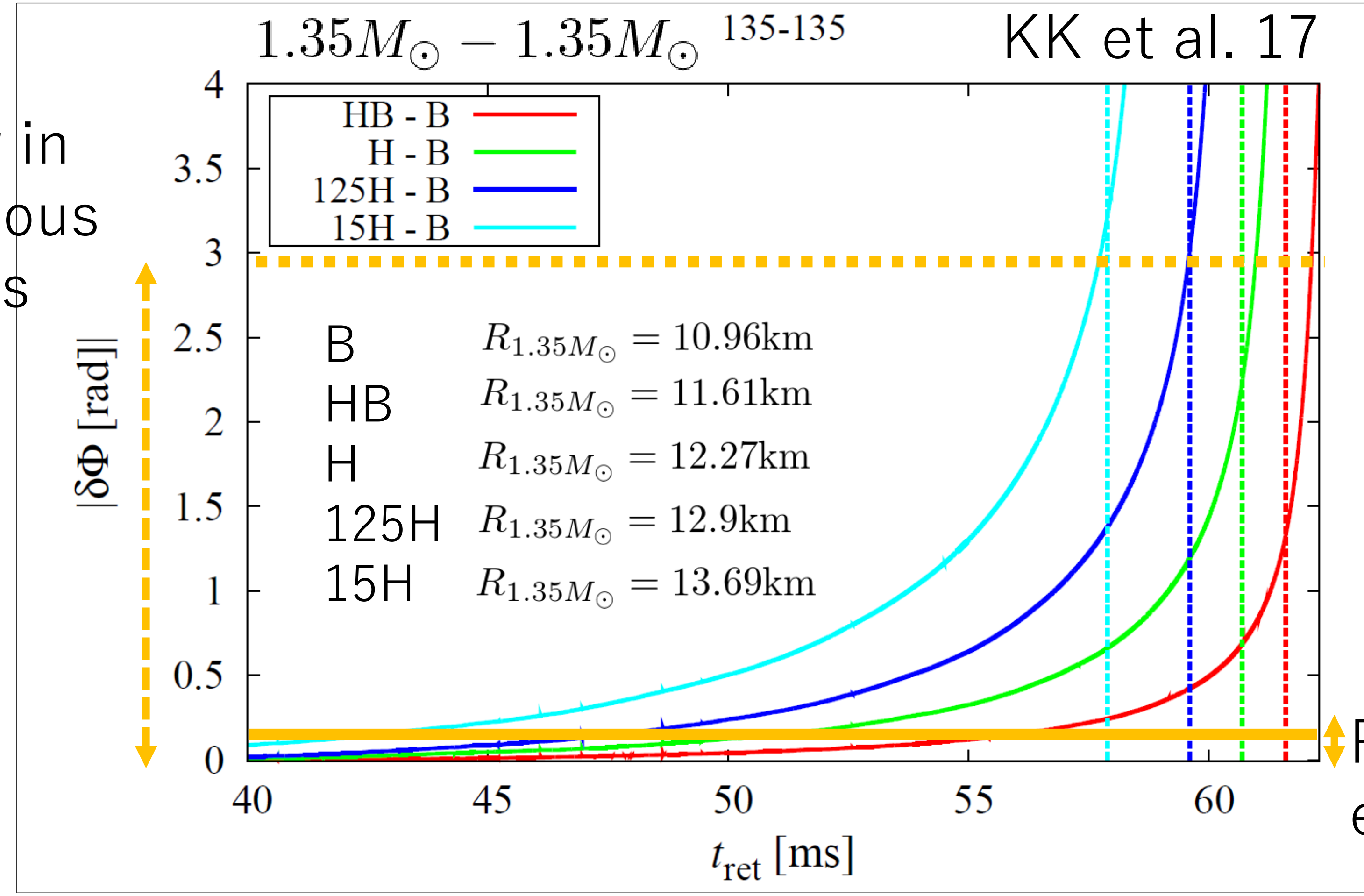
Numerical diffusion ⇒ Rapid phase evolution



Requirement : $\Delta\Phi_{\rm error} < \Delta\Phi_{\rm tidal}$

Toward a theoretical template bank

Error in previous works



Phase error

▶ We construct a phenomenological waveform template (Kawaguchi, KK et al. in prep.) ⇒ Data analysis of released LIGO data

Importance of MHD

Effective turbulent viscosity

$$\partial_t \langle \rho j \rangle + \partial_R (\langle \rho j v^R \rangle + R W_{R\varphi}) = 0$$

$$W_{R\varphi} = \langle \delta v^R \delta v^\varphi - \frac{B^R B^\varphi}{4\pi\rho} \rangle$$

▶ Angular momentum transfer by the stress
▶ Energy dissipation due to the effective turbulent viscosity

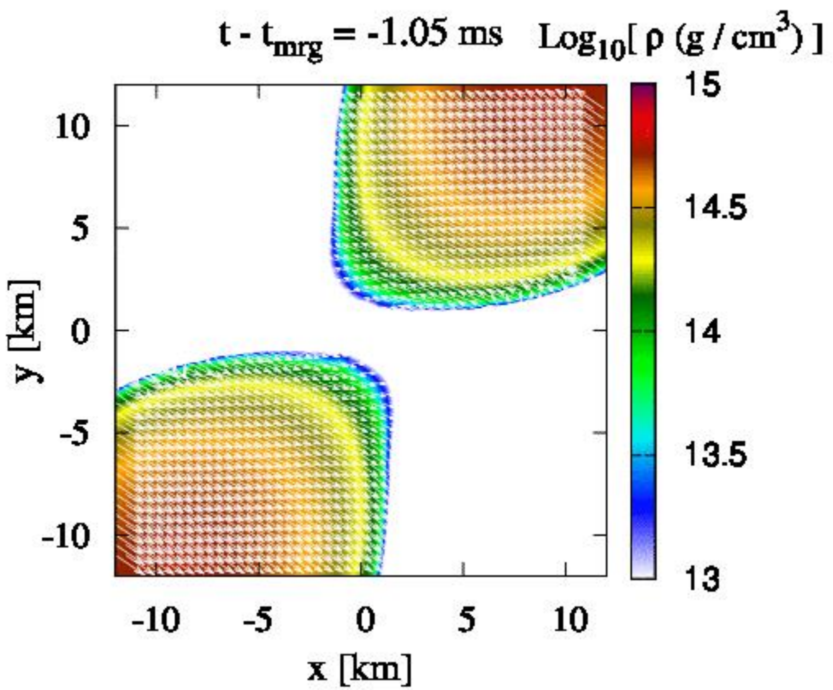
Generation of large scale field

▶ Coherent poloidal field is necessary for a jet launch via the Blandford-Znajek process (BH formation case) / Magnetar model (dipole radiation)

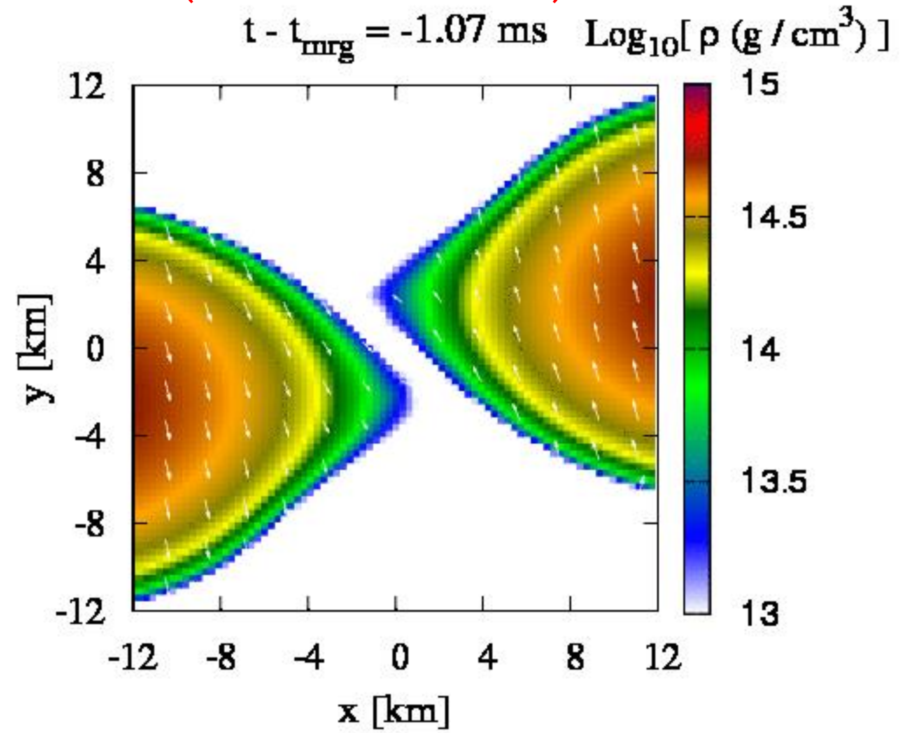
Magnetization of the remnant massive NS

Kelvin-Helmholtz instability (KK et al. 14, 15)

Fine resolution
(Δx=17.5m)



Low resolution
(Δx=150m)

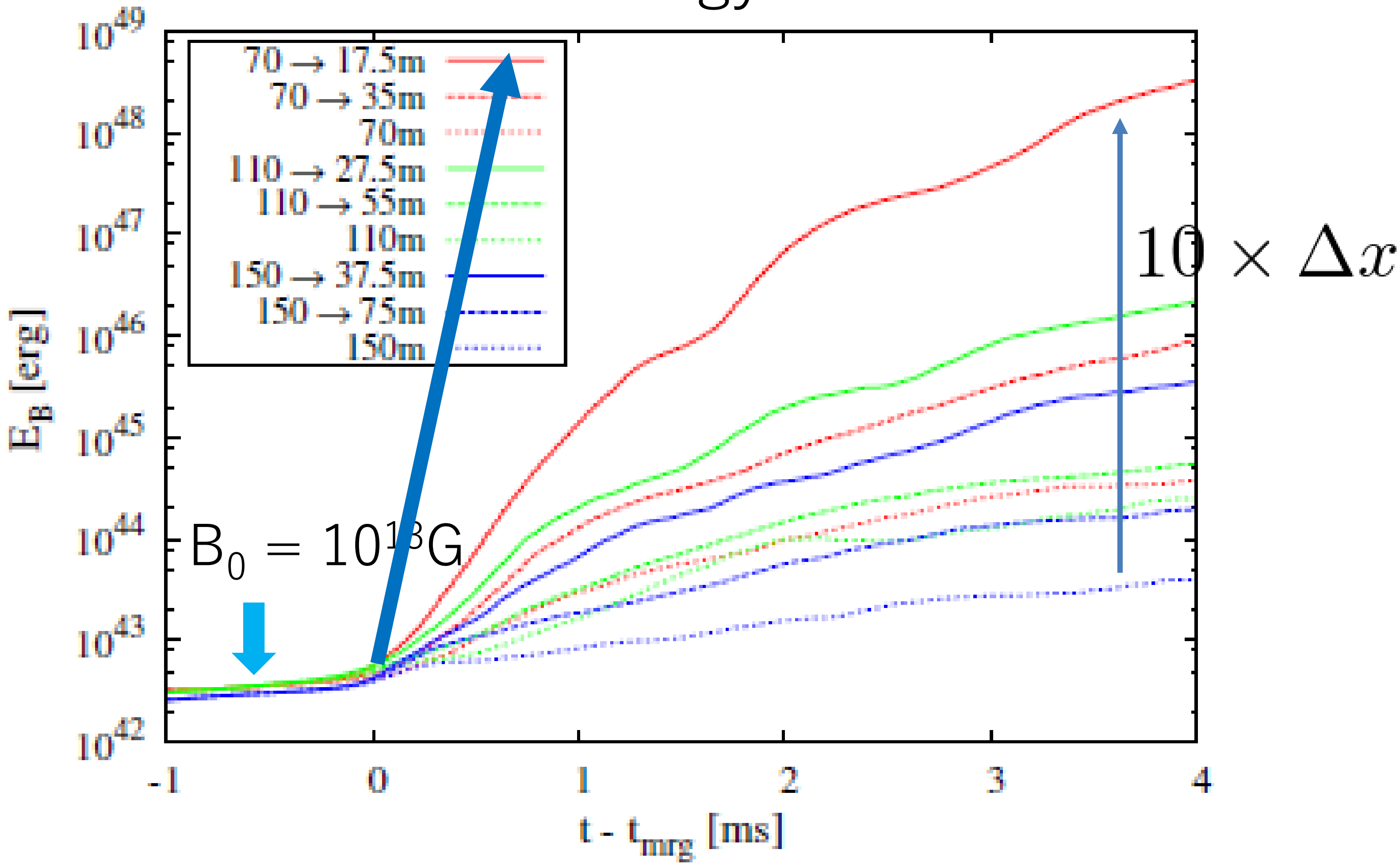


▶Small scale vortices develop rapidly ⇒ Efficient amplification of the B-field

▶ Low res. run cannot reproduce vorticity formation

Magnetization of the remnant massive NS

B-field energy evolution

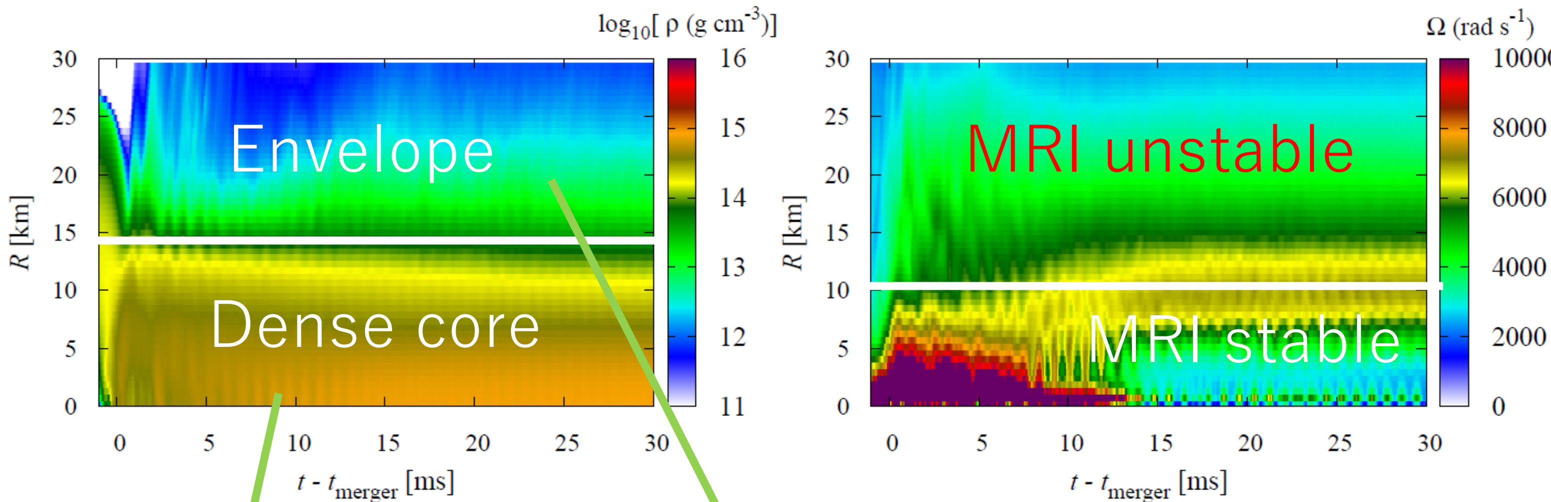


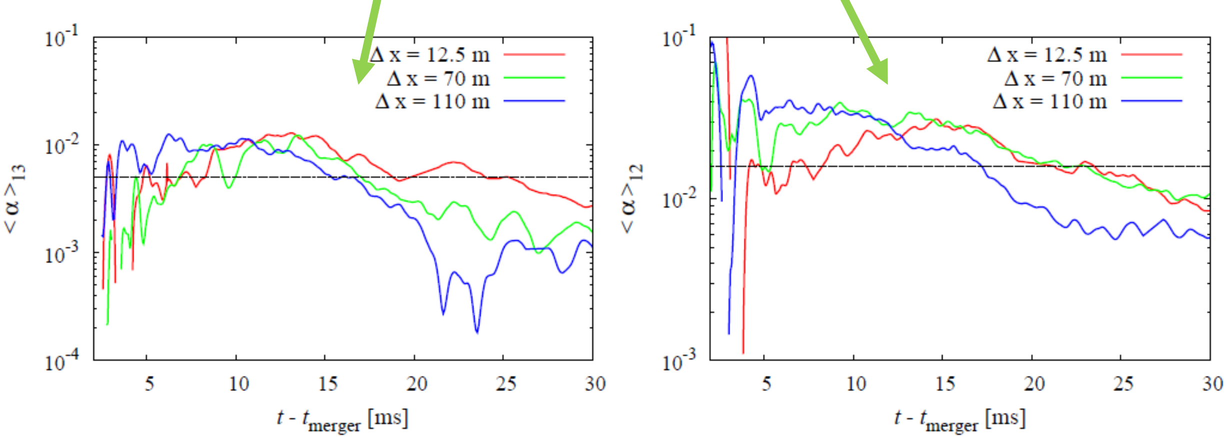
▶ The growth rate shows the divergence. c.f. $\sigma \propto$ wave-number for KH instability.

▶ Strong, but randomly oriented B-field

Effective turbulent viscosity in merger remnants

Space time diagram of merger remnant (KK et al. 17)





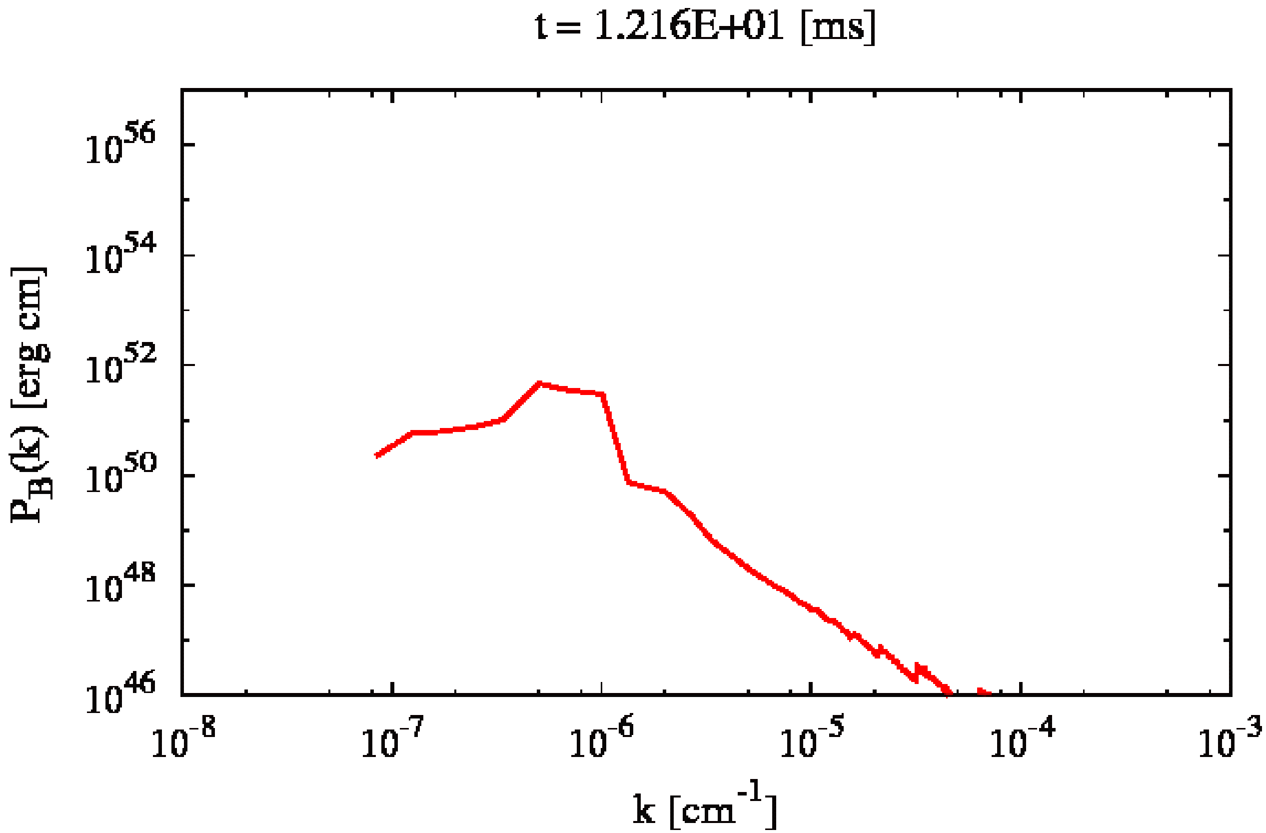
$$\alpha = \left\langle \frac{W_{R\varphi}}{P} \right\rangle$$

$W_{R\phi}$: Reynolds + Maxwell stress

- ▶ α inside a core $\gtrsim 5\times10^{-3}$
- ▶ α inside an envelope ≈ 0.01-0.02

Power spectrum evolution of B-fields

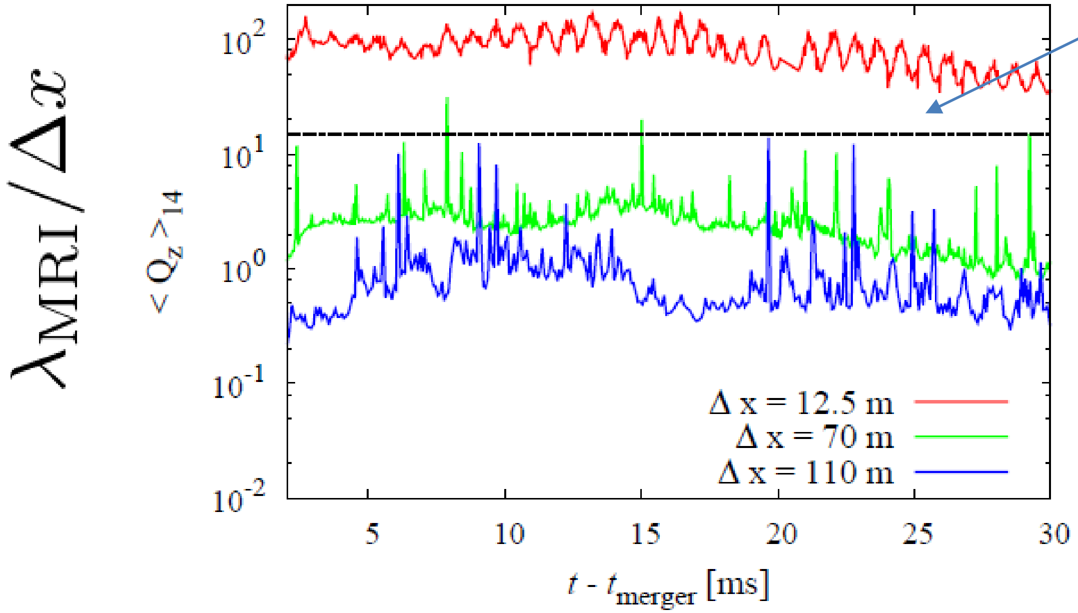
Poloidal component



- ▶ Early phase : KH instability amplifies the small scale magnetic field efficiently
- ▶ Late phase : Inverse cascade of MRI?
- ▶ No prominent signal of the generation of coherent field

What we learn from these numerical experiments

▶ Non-linear phase of the MRI is essential : Magneto-turbulent state should be sustained to generate effective turbulent viscosity
⇒ Fate of a remnant of BNS mergers

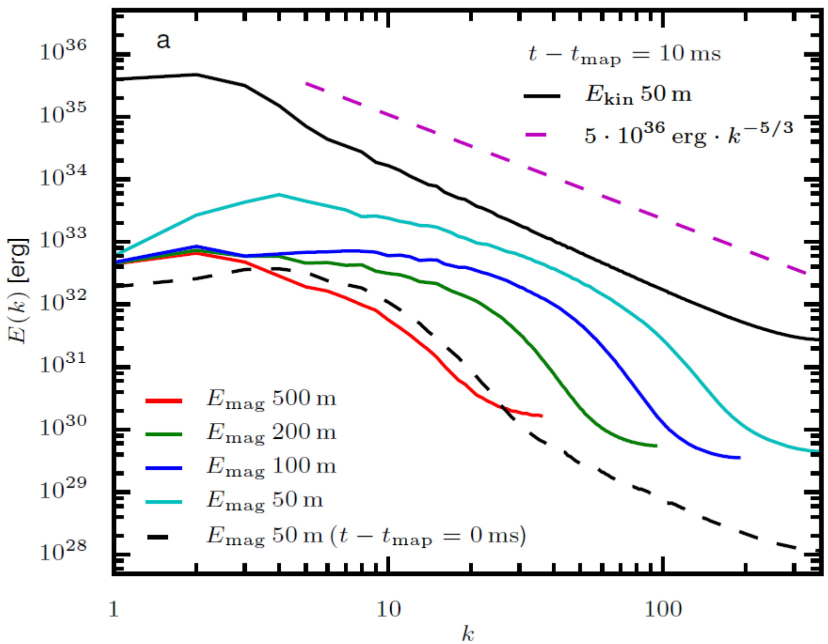


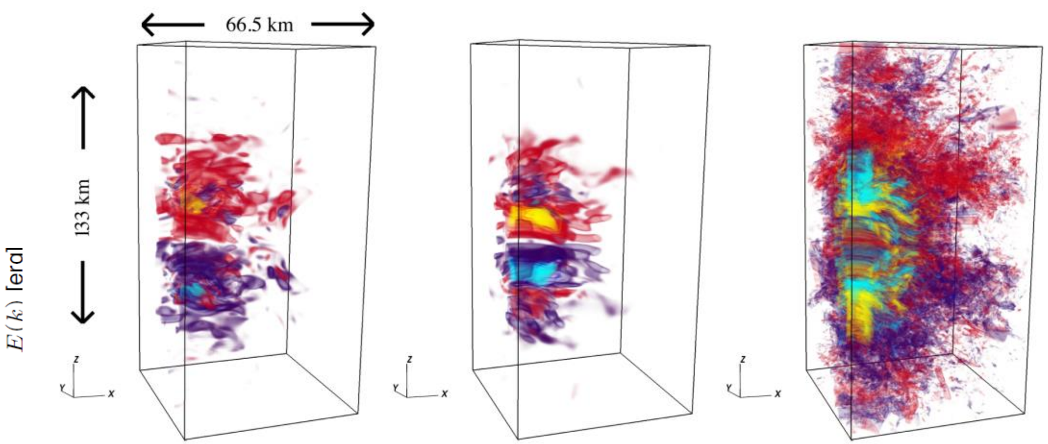
Criterion to resolve the linear phase of MRI

It generally requires much finer resolution.

What we learn from these numerical experiments

▶ Large scale dynamo is still challenging problem. In particular, poloidal B-field



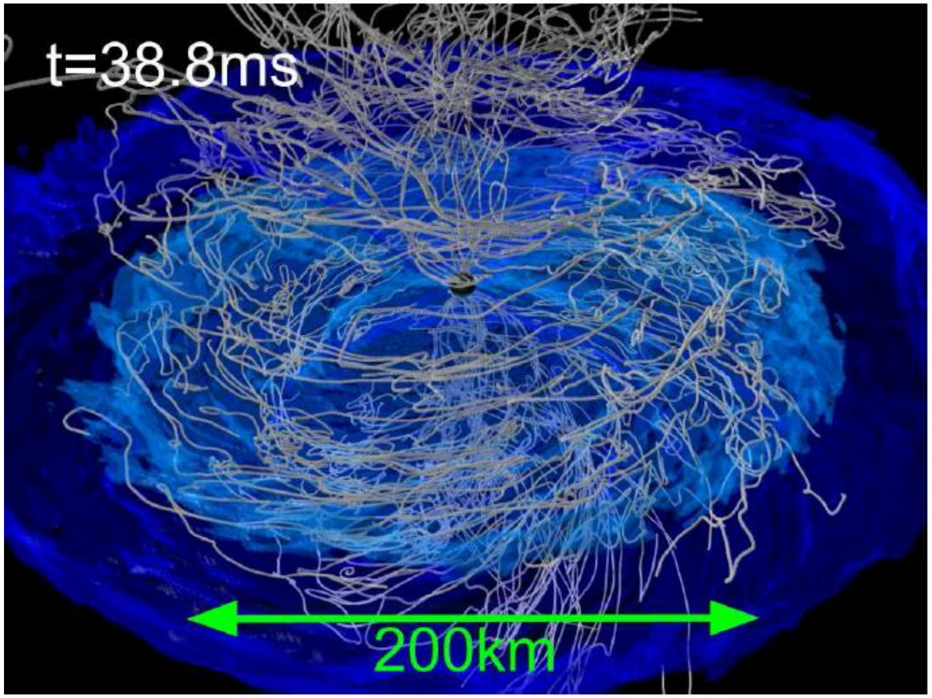


Mosta et al 15

▶ A magnetized SN simulation suggests a generation of coherent toroidal field via large scale dynamo.

What we learn from these numerical experiments

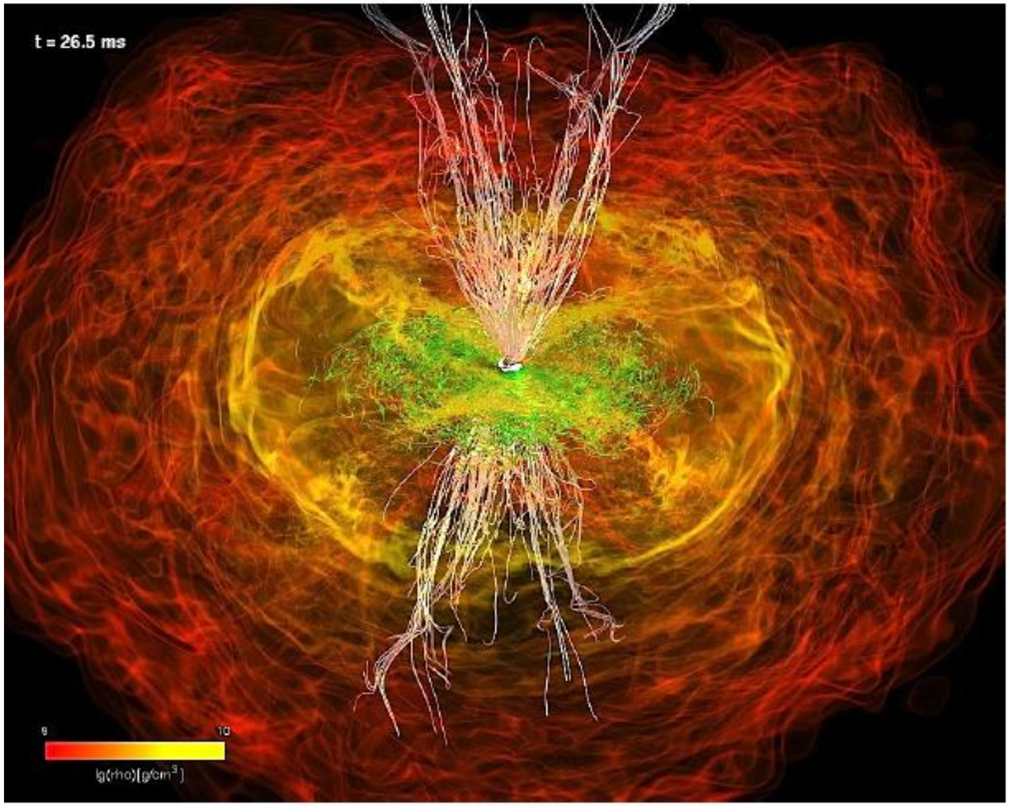
▶ After a BH formation case, jet launch is still non-trivial problem



▶ Jet launch is not found in our simulation;

$$P_{\rm ram} \approx 10^{29} {\rm dyn\ cm^{-2}} \left(\frac{\rho}{10^9 {\rm g\ cm^{-3}}}\right) \left(\frac{v}{0.3c}\right)^2 >> P_{\rm mag} \approx 10^{27} {\rm dyn\ cm^{-2}} \left(\frac{B}{10^{14}\ {\rm G}}\right)^2$$

Frankfurt group (AEI)



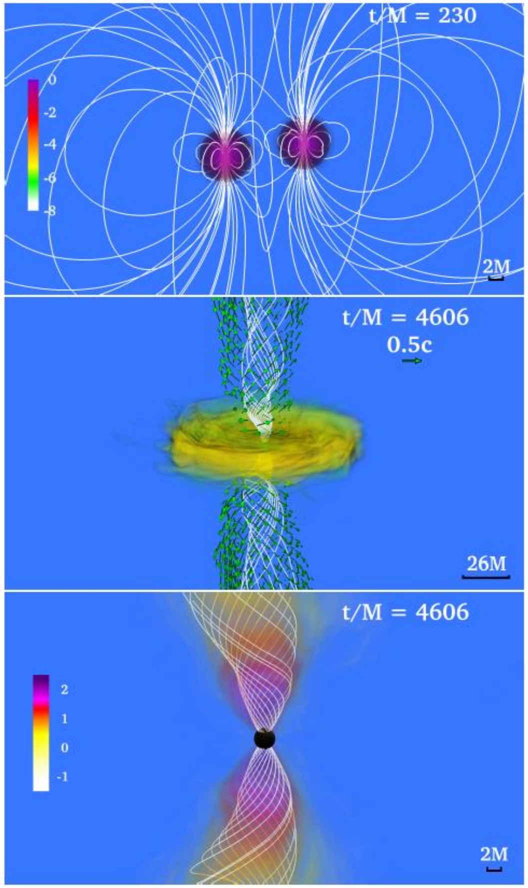
Rezzlla et al 11

- Jet launch is found at t ≈10 ms after a BH formation
- MRI is not resolved
- No fall back matter
- No clear explanation of a jet launch

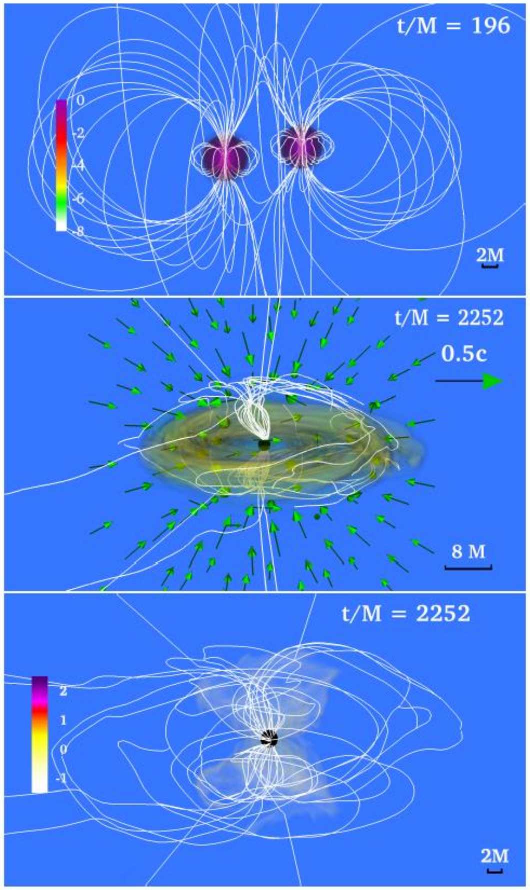
Illinois group

Milton et al 16, 17

HMNS ⇒ BH



Prompt collapse



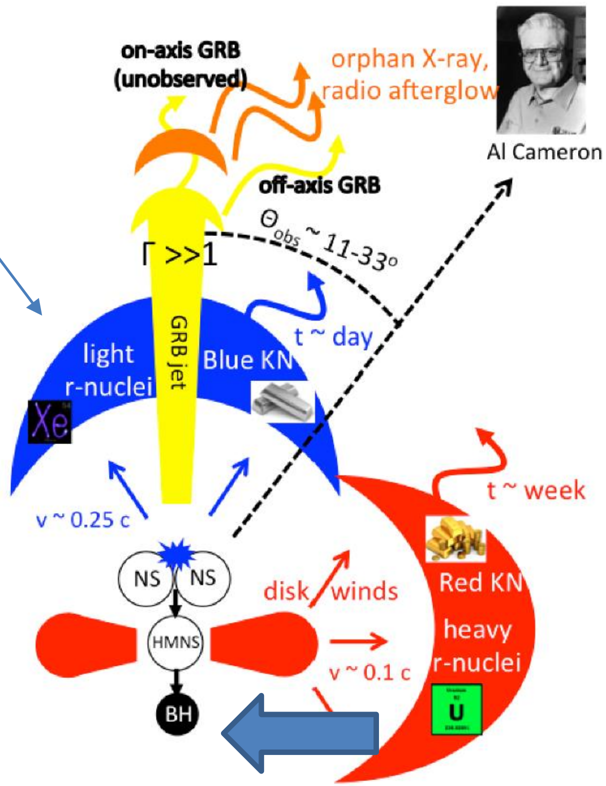
▶ Jet launch for delayed collapse, no jet for prompt collapse; small disk mass (EOS depend)

▶ Negligible amount of fall back matter (?)

Toward a modelling of GRB170817A

Blue component
0.01-0.02 $M_{\odot}$?

P_{ram} in initial phase should be large

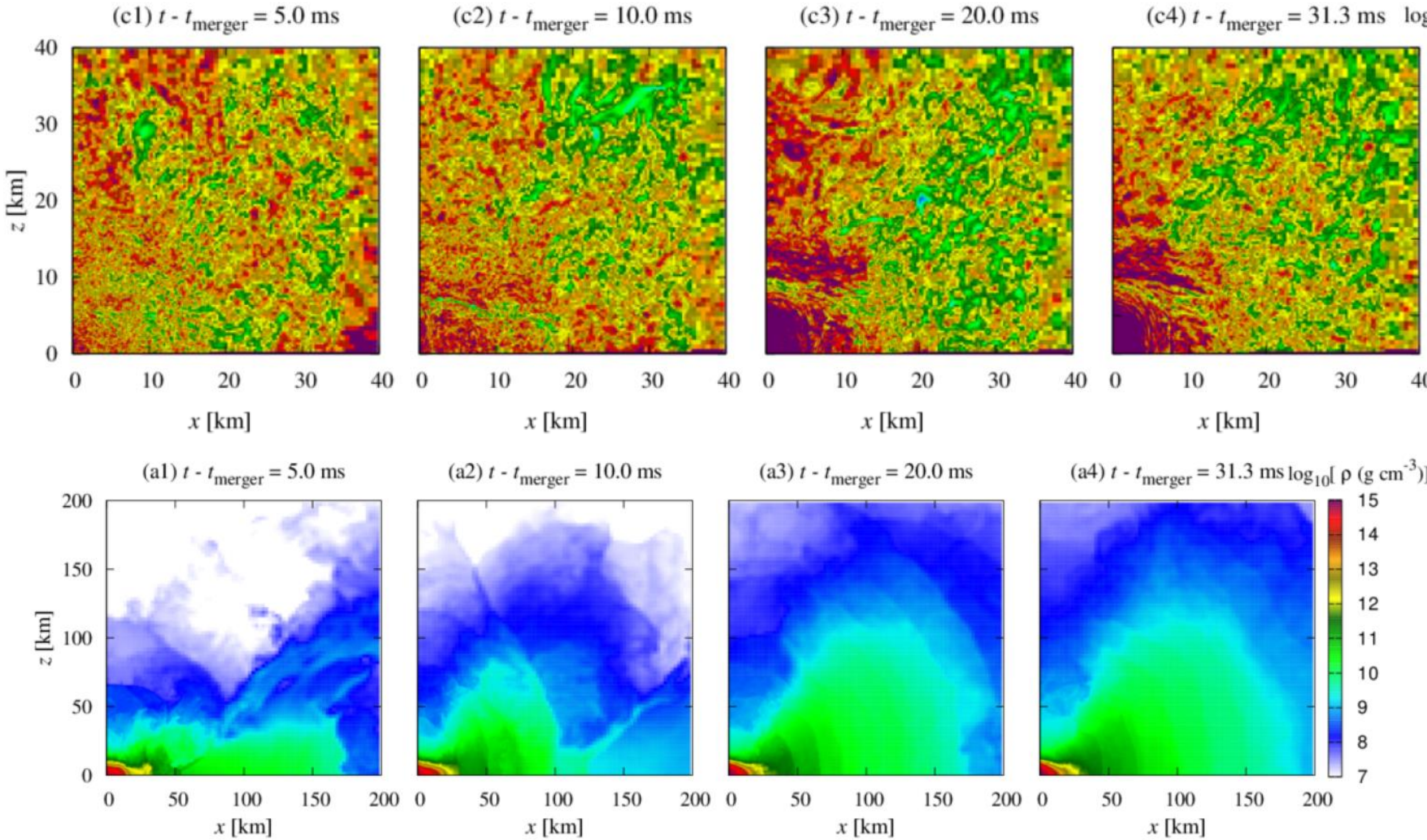


Accretion time should be determined by α

▶ Condition for a generation of poloidal field via only MHD process : $t_{fall} < t_{vis}$

Long-lived remnant case

$\beta = \frac{P}{P_{\rm mag}}$ on x-z plane for a long-lived remnant

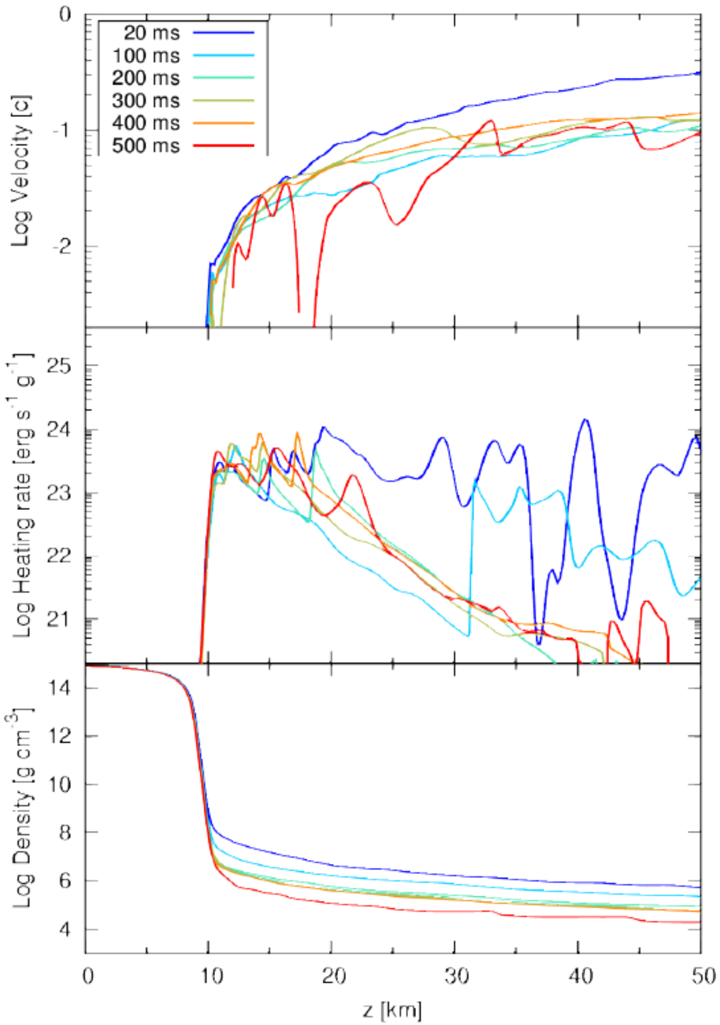


▶ Force free condition is hard to be built in a short time scale after merger

Long-lived remnant case

▶ Pair annihilation heating drives an outflow to a polar direction

Fujibayashi et al. 17a



$$\Gamma_f \approx 1.1 \left(\frac{Q/\rho}{10^{24}\ \mathrm{erg\ g^{-1}\ s^{-1}}} \right) \left(\frac{\tau_{\mathrm{heat}}}{1\ \mathrm{ms}} \right)$$

$$\tau_{\mathrm{heat}} = \frac{z}{v_{\mathrm{eje}}} \sim \frac{30\ \mathrm{km}}{0.1c} \approx 1\mathrm{ms}$$

▶ ρ ↘is necessary with keeping the heating rate, c.f. $\rho \sim 10^5\ \mathrm{g\ cm^{-3}}$ with $Q \sim 10^{31}\ \mathrm{erg\ cm^{-3}\ s^{-1}}$ is for $\Gamma \sim 100$

⇒ Still difficult even with a viscous heating (Just et al 15, Fujibayashi et al. 17b)

Long-lived remnant case

▶ Pair annihilation-driven wind may help to generate a coherent field

For instance,

$$\left(\frac{B^2/8\pi}{\rho c^2}\right) \approx 1 \left(\frac{B}{10^{13.5}\ \mathrm{G}}\right)^2 \left(\frac{\rho}{10^5\ \mathrm{g\ cm^{-3}}}\right)^{-1}$$

Force-free magnetic field could be build with the assist of neutrino pair annihilation.

Ultimately, NR-neutrino Radiation transfer MHD simulation is necessary (e.g., Siegel & Metzger 17).

Summary

▶ Opening of the real multi messenger astronomy of compact binary merger (rich information!)

▶ Equation of state of neutron star matter (tidal deformability) is constrained for the first time.
⇒ We build a template band based on NR simulations and data analysis is on going.

▶ Numerical modeling of a central engine is still on the way.

Pure MHD or neutrino pair annihilation is not likely to be sufficient to launch a relativistic jet.
GRRMD simulation is awaited.