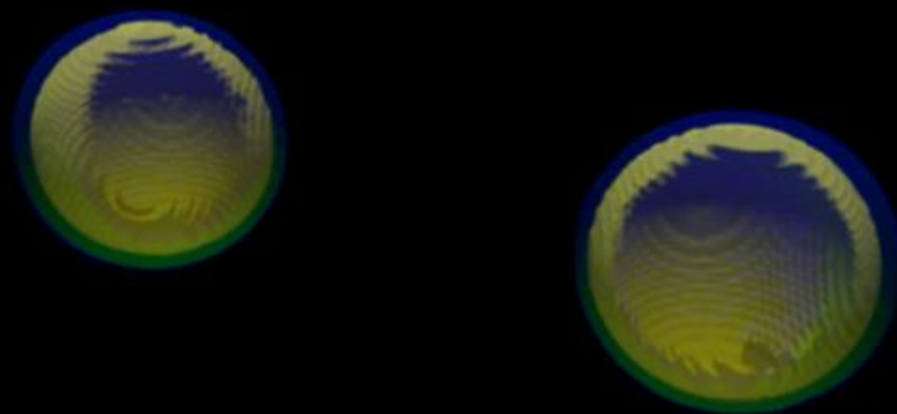
Revisting the lower bound on tidal deformability derived by AT 2017gfo and related topics

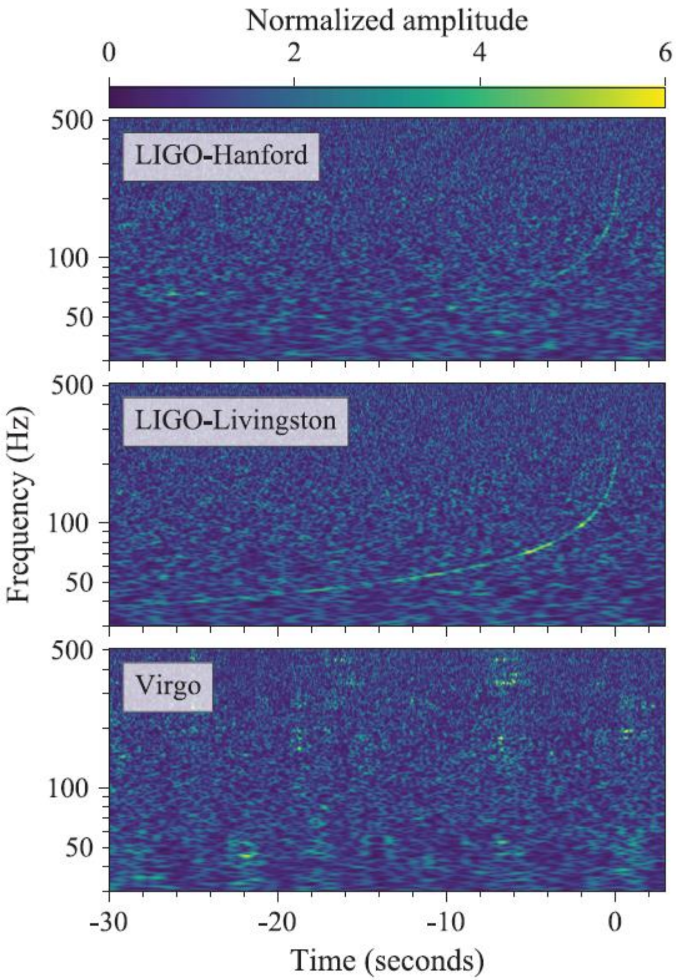


Kenta Kiuchi (AEI/YITP)

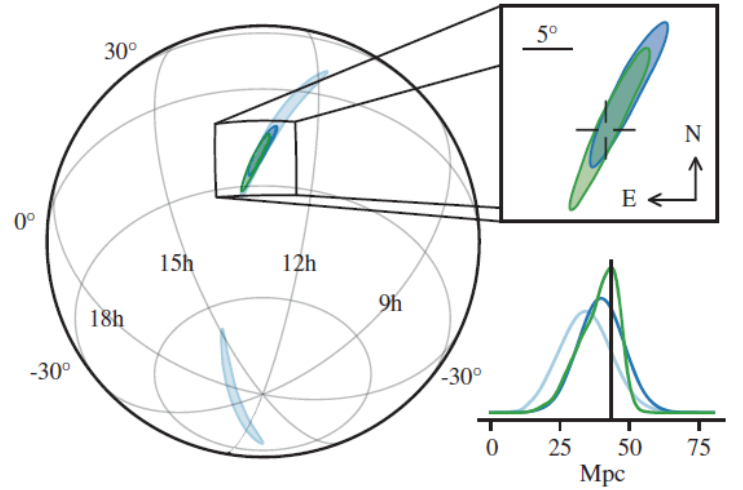
Max-Planck-Institut für Gravitationsphysik
Albert-Einstein-Institut

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

GW170817 as a BNS merger event



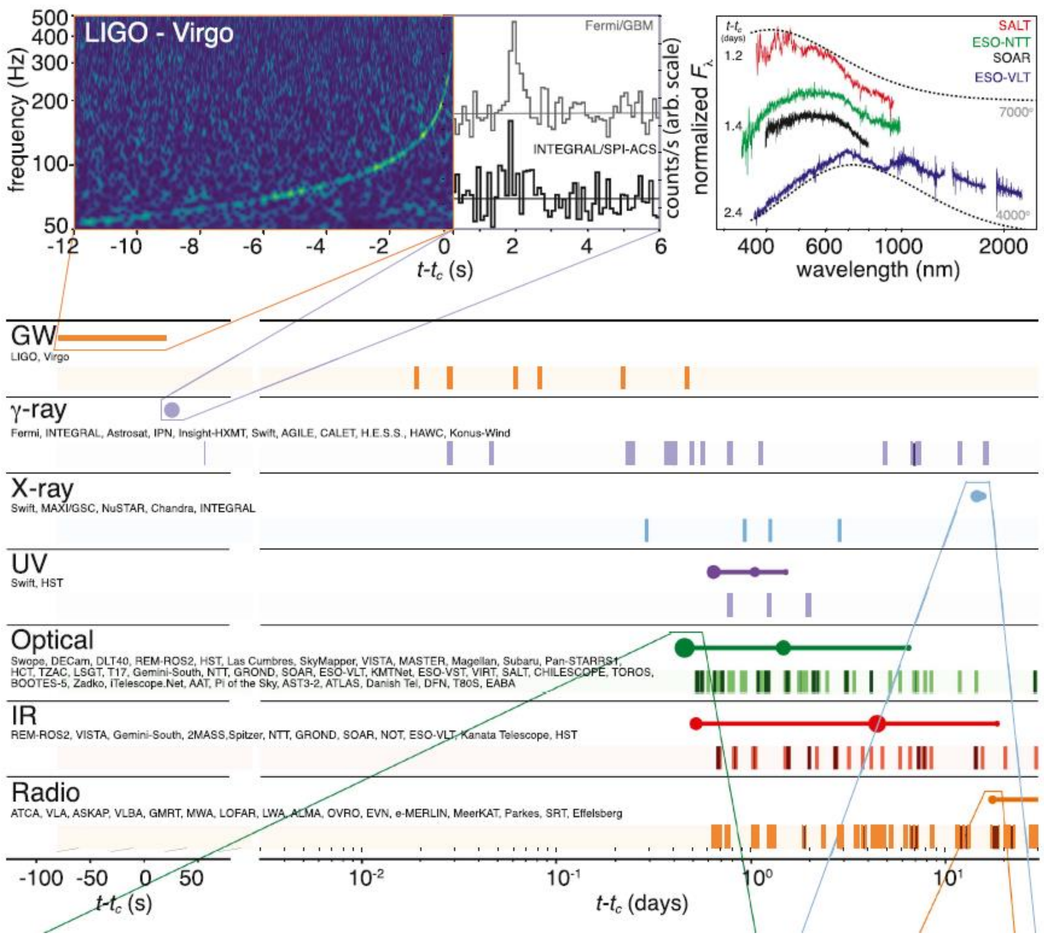
Sky map by LIGO + VIRGO

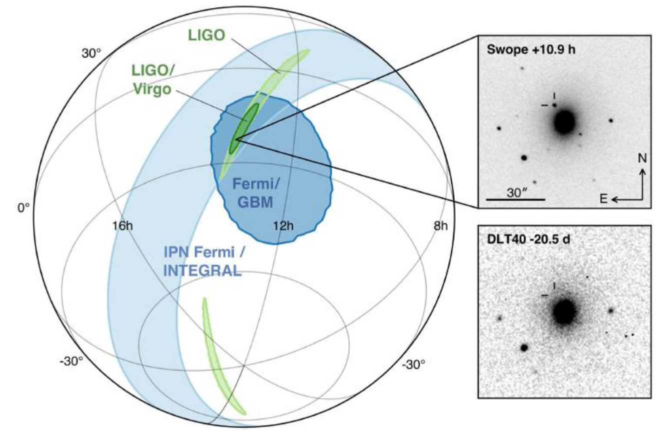


LSC-Virgo collaboration
PRL 2017

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

Real Multimessenger Astronomy Era

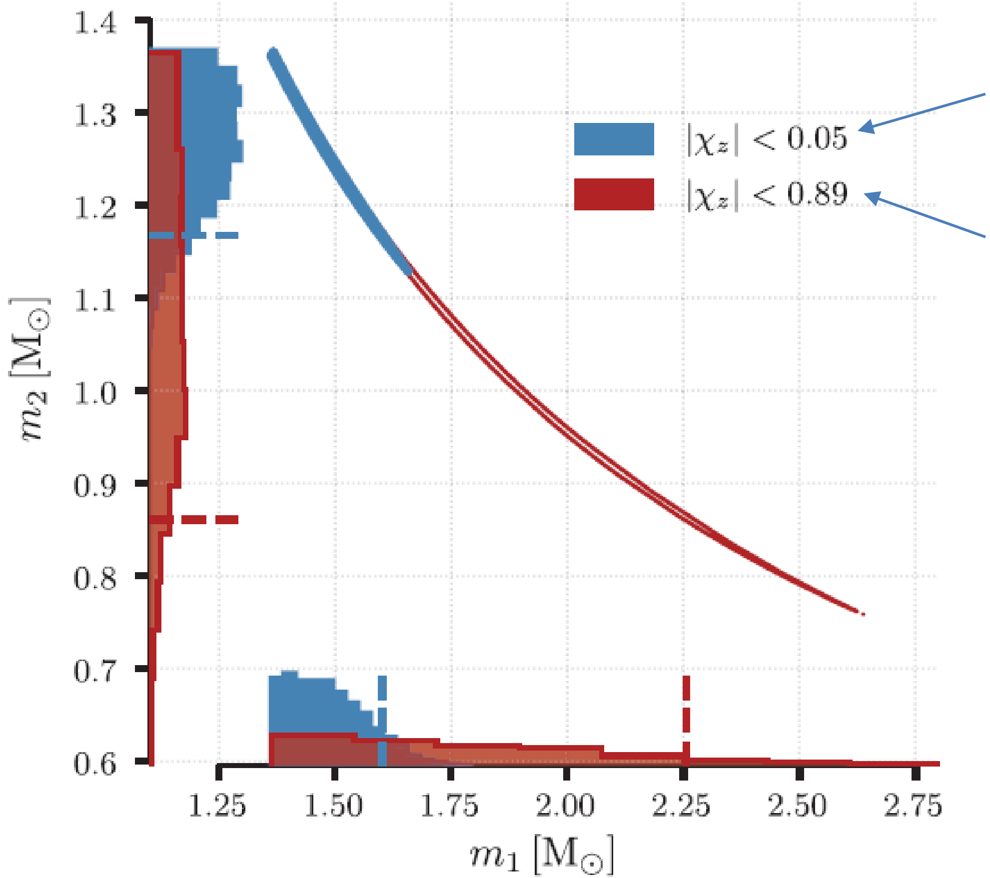




LSC-Virgo collaboration
APJ 848, L12, 2017

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

Source properties of GW170817



LSC and Virgo collaboration PRL 119, 161101 (2017)

▶ Mass measurement of NSs.

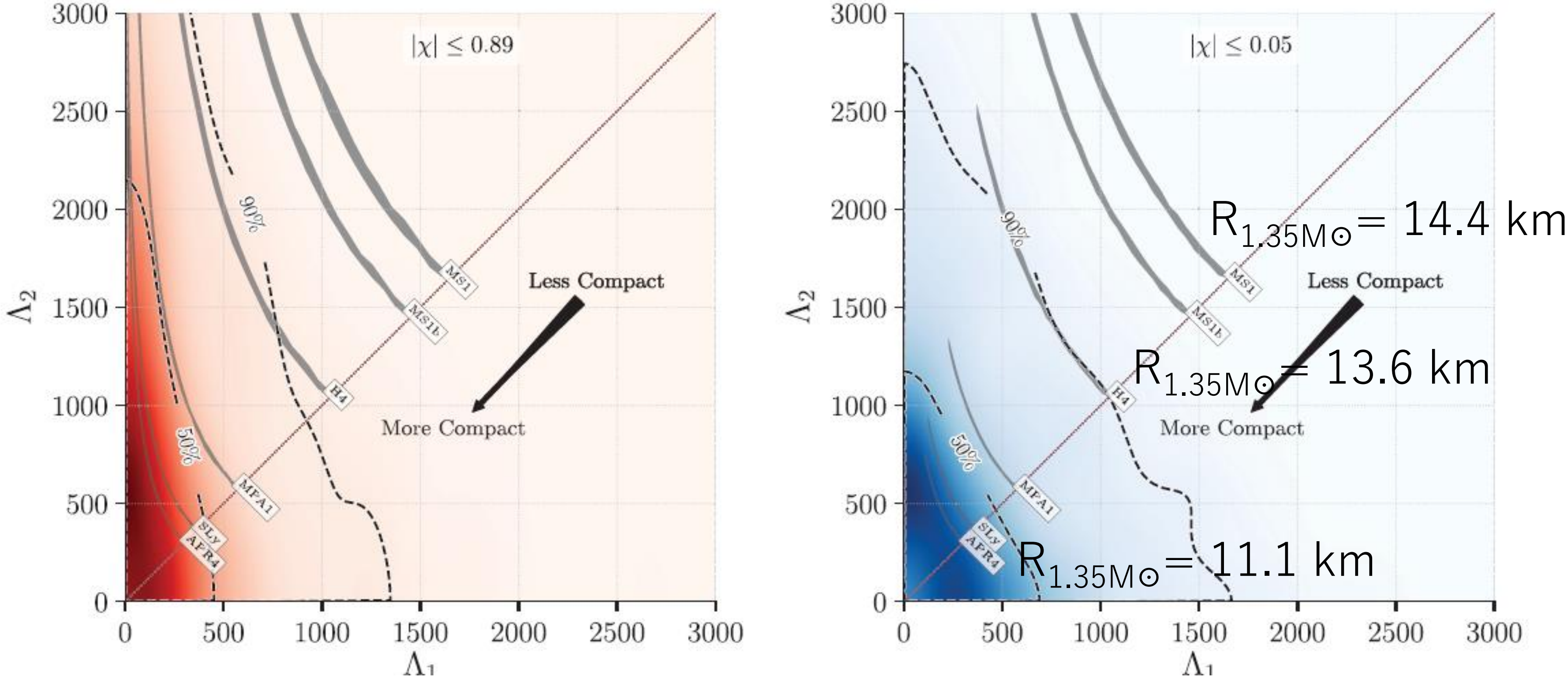
m_1: 1.36-1.60 $M_\odot$, m_2 : 1.17-1.36 $M_\odot$ (low spin prior)

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)

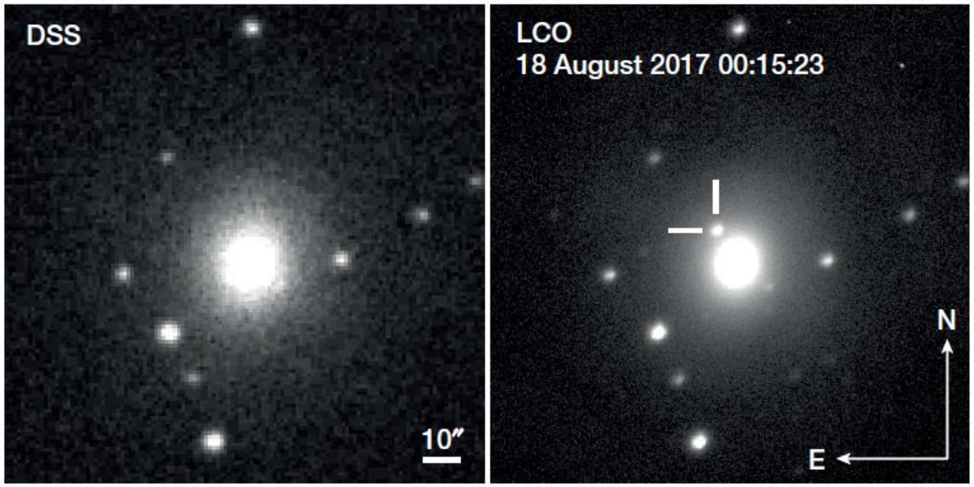


▶ Tidal deformation Λ is related to a NS radius ⇒ Information of the NS equation of state.

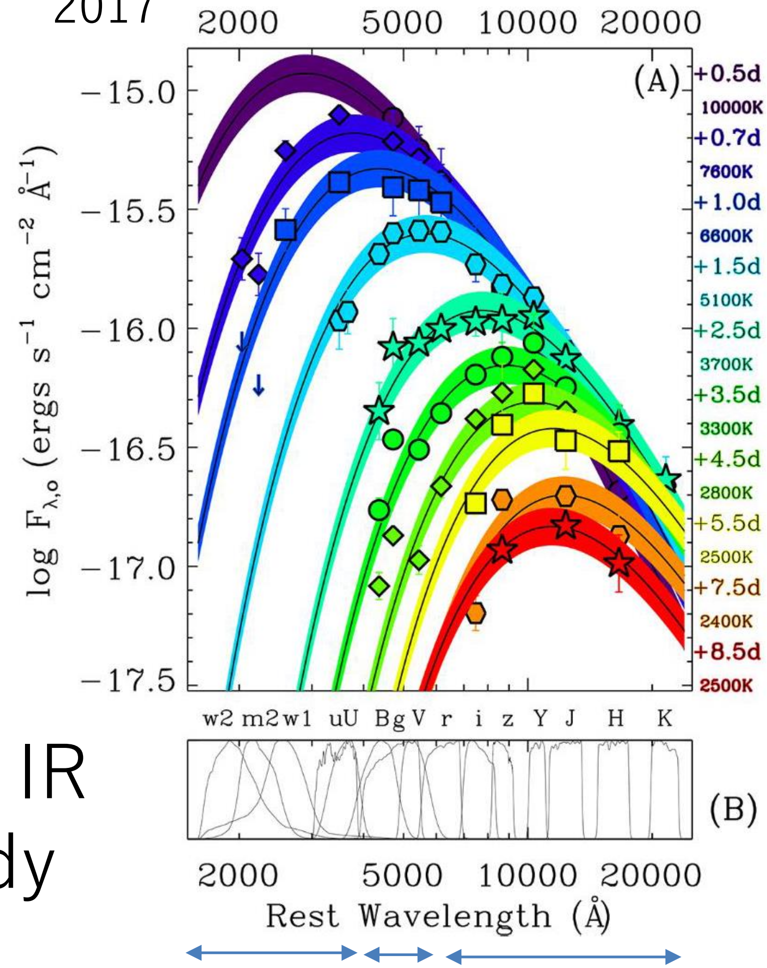
▶ Soft EOS is favored ($\Lambda \leq 800$)

Detected UV-Optical-Infrared emission

Arcavi et al. Nature 24291, 2017



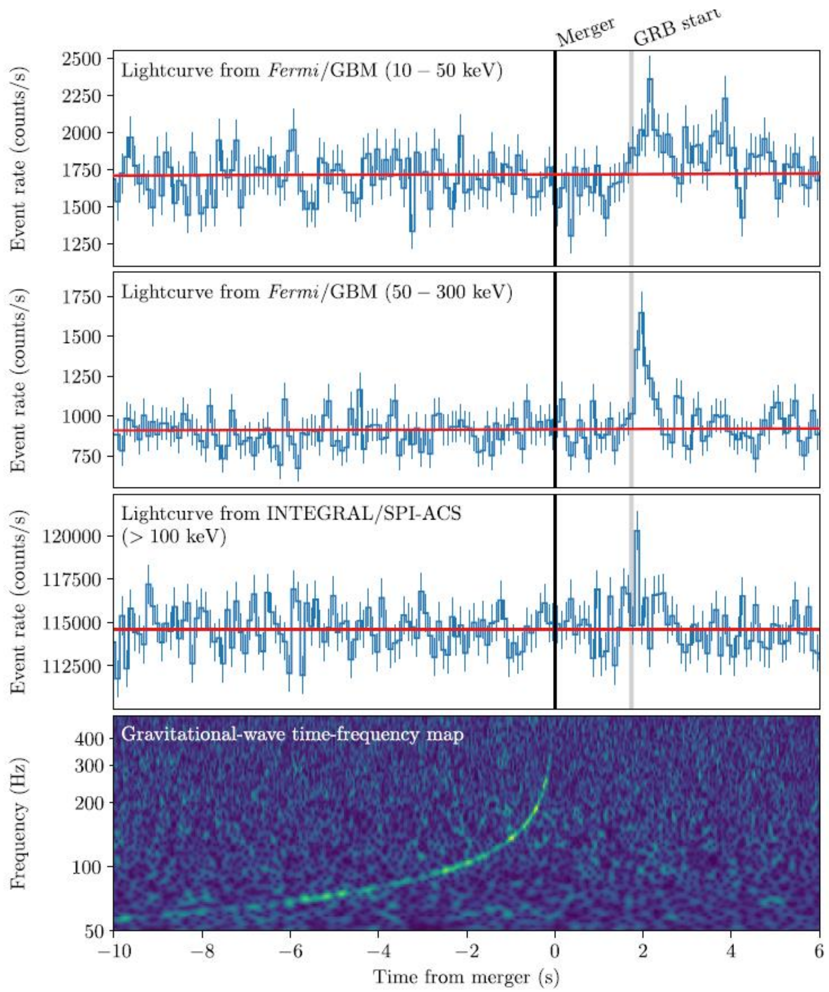
Drout et al. Science (aaq0049) 2017



UV Optical IR

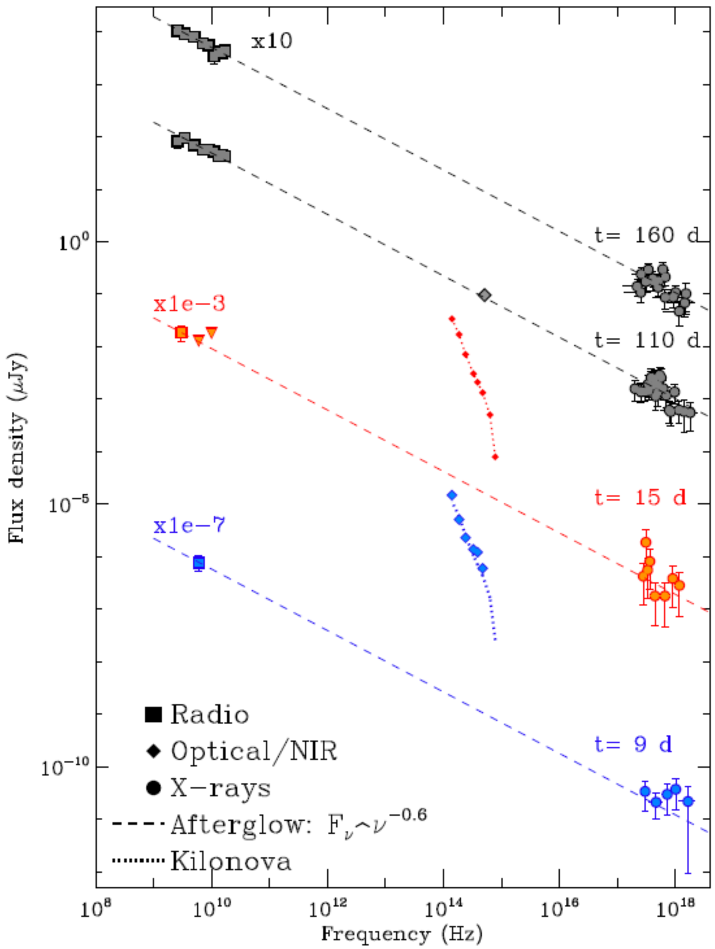
- ▶ Rapid reddening from UV to IR
- ▶ Spectrum is quasi-black body
- ▶ Long-duration IR component & short-duration UV-Optical component

Detection of GRB170817A



- $T_{90} = 2.0 \mp 0.5$ s, $T_0 = 1.7$s
- $E_{iso} \sim 5 \times 10^{46}$ erg (too dim)

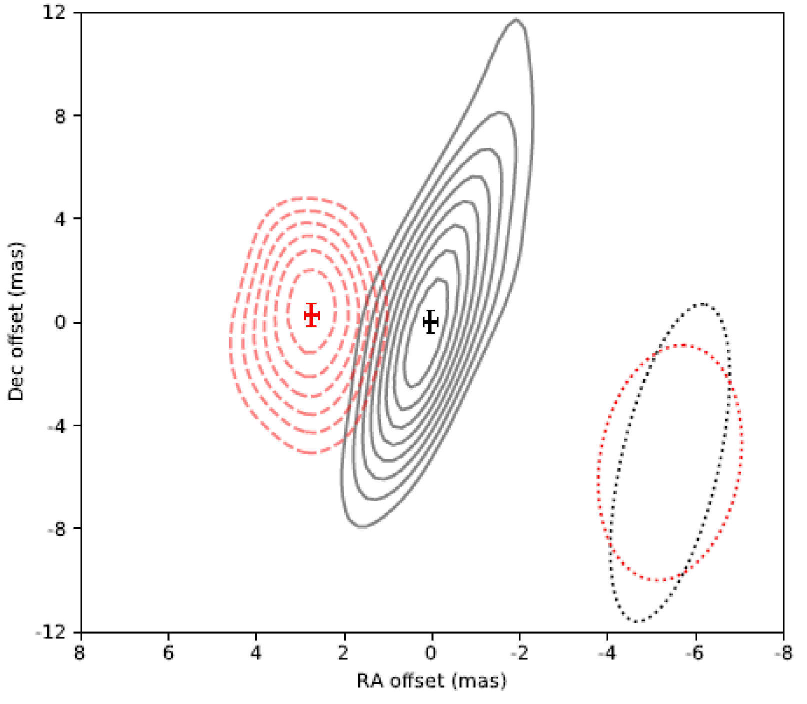
About 160 days observation @ Radio, X-ray observation after the merger

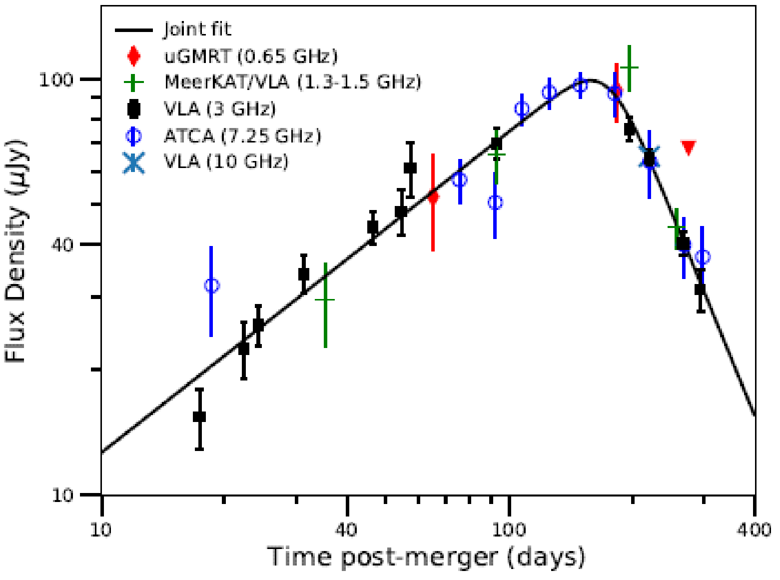


Margutti et al. 18
Mooley et al. 17
Troja et al. 17
Hallnan et al. 17

▶ Structured Jet (Margutti et al. 17, Gottleb et al. 17)

Superluminal motion of GW170817



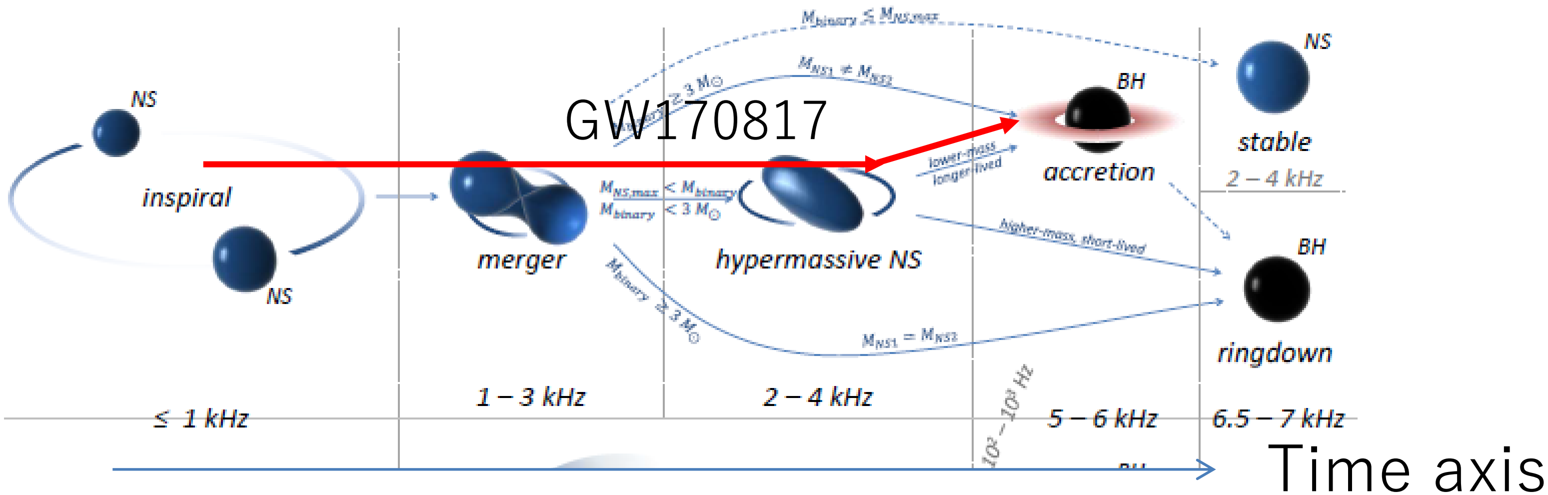


Mooley et al. 18a, b

▶ Superluminal motion of the source image in radio
▶ Light curve fitting suggests a sharp decline at 170 days after the merger

⇒ Strong suggestion of the relativistic jet

Can Joint analysis of GW+EM constrain the NS matter property?



- $E_{\rm rot} \approx 10^{53}\,{\rm erg} \left(\frac{M_{\rm rem}}{2.7 M_\odot}\right)\left(\frac{R}{20\,{\rm km}}\right)^2\left(\frac{\Omega}{6000\,{\rm rad/s}}\right)^2$

If the remnant survives long enough, the dipole radiation injects the energy on the timescale,

$$t_{\rm sd} \approx 200\,{\rm s}\left(\frac{M_{\rm rem}}{2.7 M_\odot}\right)\left(\frac{R}{20\,{\rm km}}\right)^{-4}\left(\frac{\Omega}{6000\,{\rm rad/s}}\right)^{-2}\left(\frac{B_p}{10^{15}\,{\rm G}}\right)^{-2}$$

➡ Incompatible with the observation; $E_{\rm EM} \sim 10^{51}$erg

Optical-Infrared emission from BNS mergers
(Metzger et al. 10, Li & Paczynski 98)

Role of the r-process elements

▶ Heating source via radio-active decay

$$\dot{\epsilon} \approx 10^{10}\,\mathrm{erg\,s^{-1}\,g^{-1}} \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$$

▶ Opacity source (Lanthanide elements) (Barnes & Kasen 13, Tanaka & Hotokezaka 13)

$$\kappa \approx 10\,\mathrm{cm^2\,g^{-1}}$$

Properties of electromagnetic emission (Optical-IR)

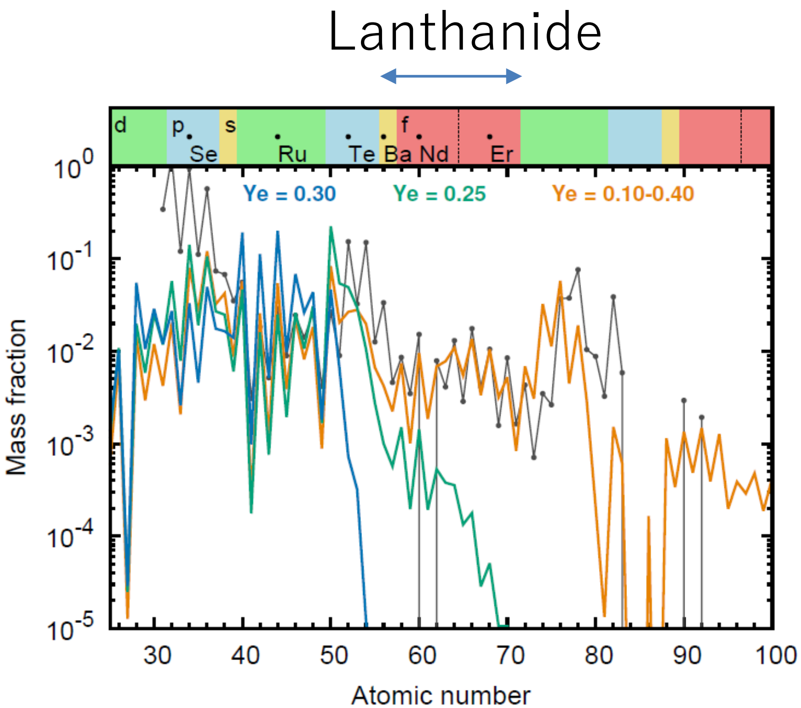
▶ Peak time (diffusion time = dynamical time)

$$t_{\rm peak} \approx 5.7\,\mathrm{day} \left(\frac{\kappa}{10\,\mathrm{cm^{-2}\,g^{-1}}}\right)^{1/2} \left(\frac{M_{\rm eje}}{0.03M_\odot}\right)^{1/2} \left(\frac{v_{\rm ej}}{0.2c}\right)^{-1/2}$$

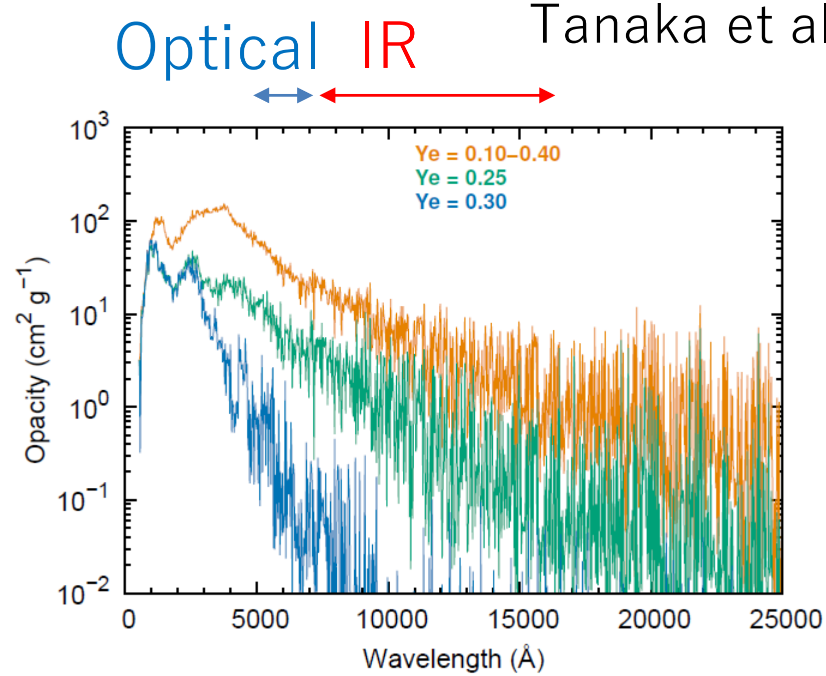
▶ Peak Luminosity

$$L \approx \dot{\epsilon} M_{\rm ej} \approx 6\times10^{41}\,\mathrm{erg\,s^{-1}} \left(\frac{M_{\rm eje}}{0.03M_\odot}\right) \left(\frac{t}{\mathrm{day}}\right)^{-1.3}$$

R-process nucleosynthesis and its opacity



Tanaka et al. 17

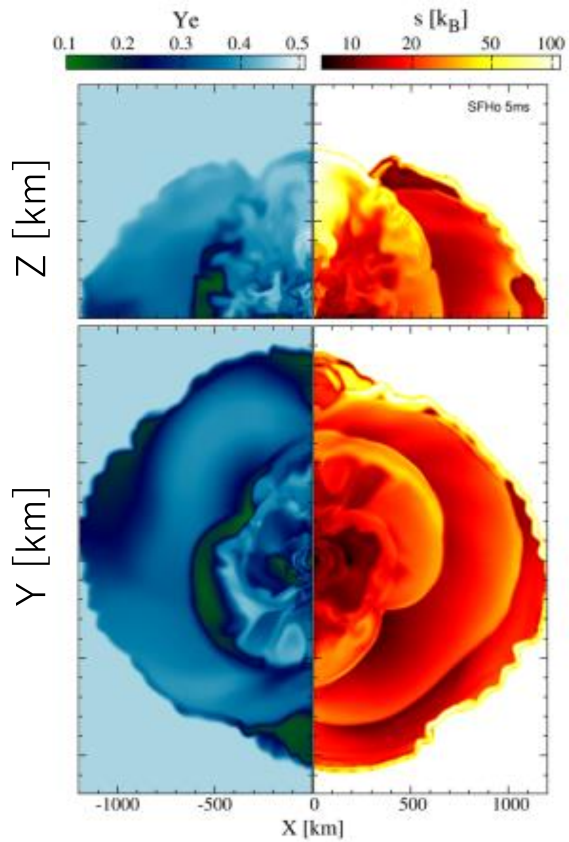


- ▶ Electron fraction Y_e is a key quantity
- ▶ $Y_e \gtrsim 0.25$ produces negligible / small amount of lanthanide ⇒ low opacity in optical
- ▶ $Y_e \lesssim 0.25$ produces lanthanide ⇒ high opacity in IR
- ▶ Neutrino reaction determine Y_e of the ejecta

Where does neutron rich ejecta come from?

▶Dynamical ejecta: Tidal component & Shocked component

▶Disk ejecta: Viscous heating/Angular momentum transfer with neutrino absorption



Sekiguchi, KK et al. 2015, 2016

Where does neutron rich ejecta come from?

▶Dynamical ejecta: Tidal component & Shocked component

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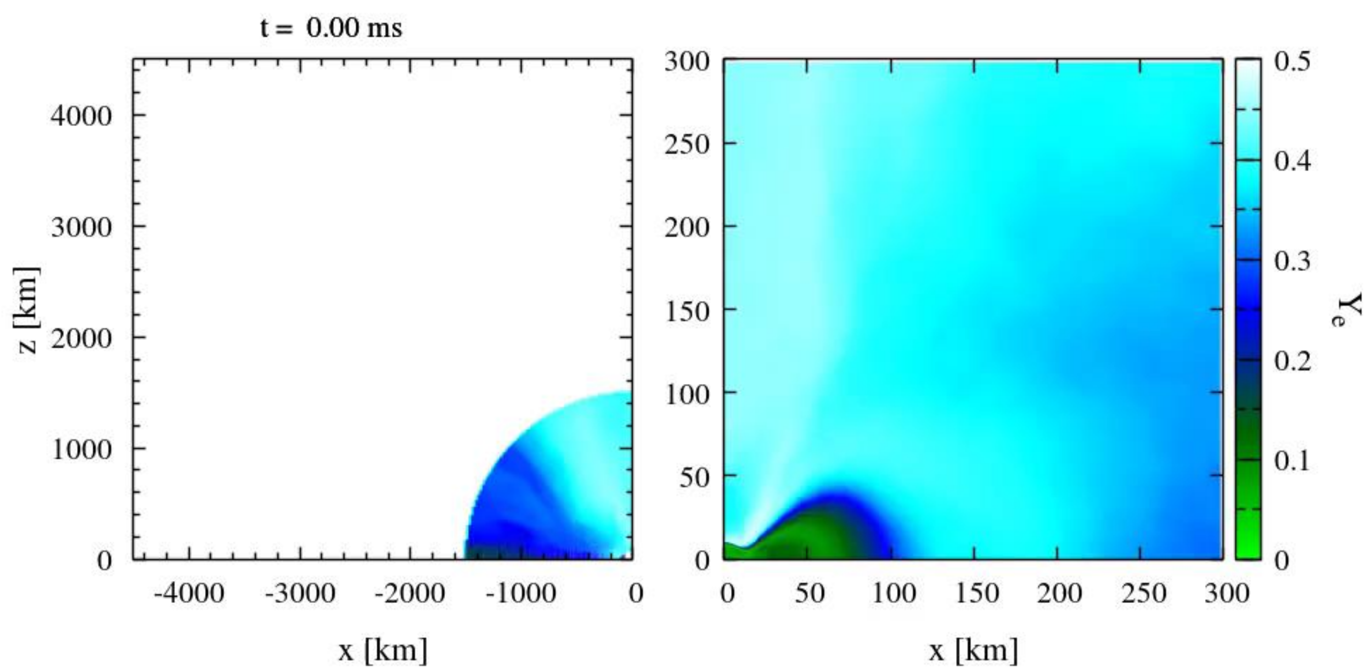
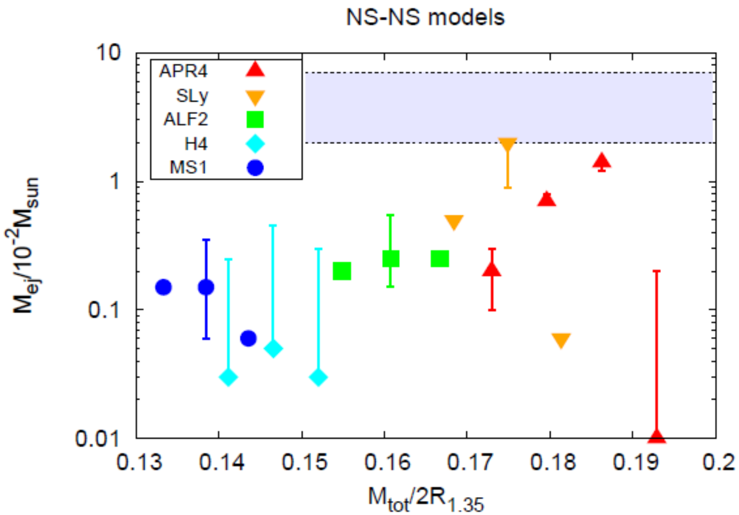


Viscosity = MHD instability-driven turbulent viscosity

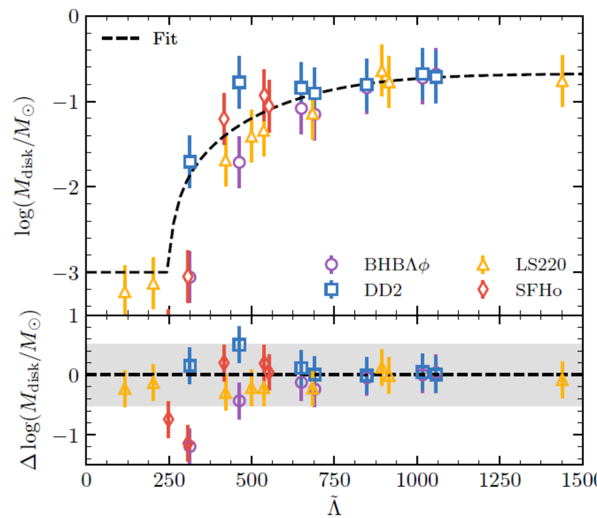
Fujibayashi, KK et al. 2018

Dependence M_{dyn} and M_{disk} on Λ

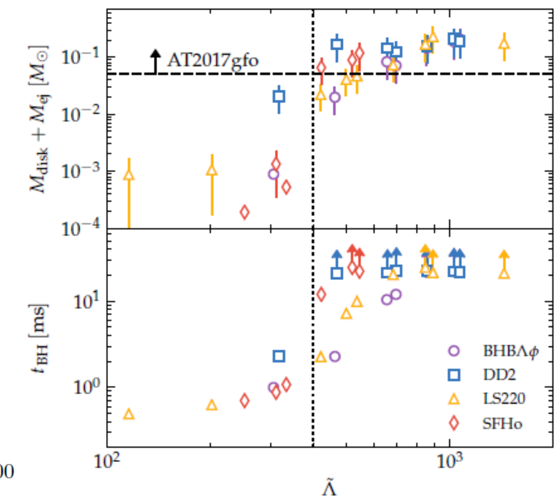
Hotokezaka, KK et al. 13



Radice & Dai 18



Radice et al. 18



▶ Small/Large Tidal deformability Λ favors large M_{dyn}/M_{disk}

Joint analysis of GW and EM gives a lower limit on $\Lambda \gtrsim 400$ (Radice et al. 17, Radice & Dai 19), (similar statement in Bauswein et al. 17)

Is it true? With their limited class of EOSs (Relativistic Mean Field), $M_{TOV,max}$ and Λ have a correlation.

Why is $M_{TOV,max}$ important ?

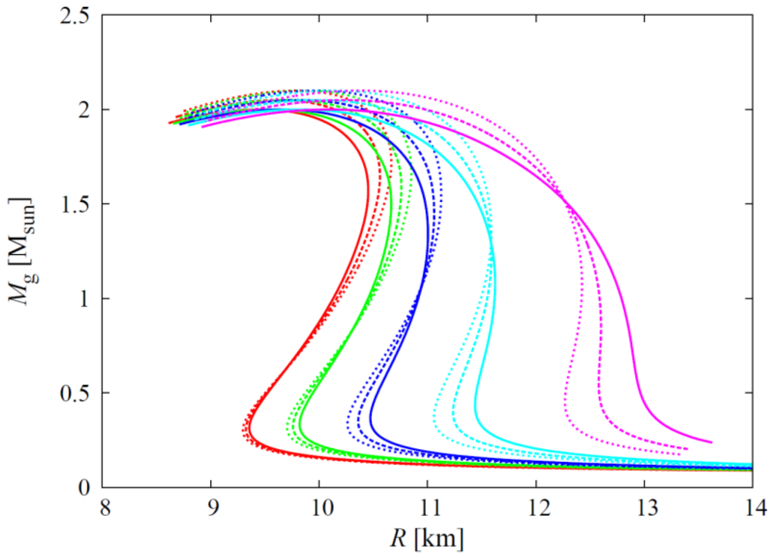
In general, a BNS with large $M_{TOV,max}$ tends to have a long lifetime after merger. ⇒ It has a chance to form a massive disk.

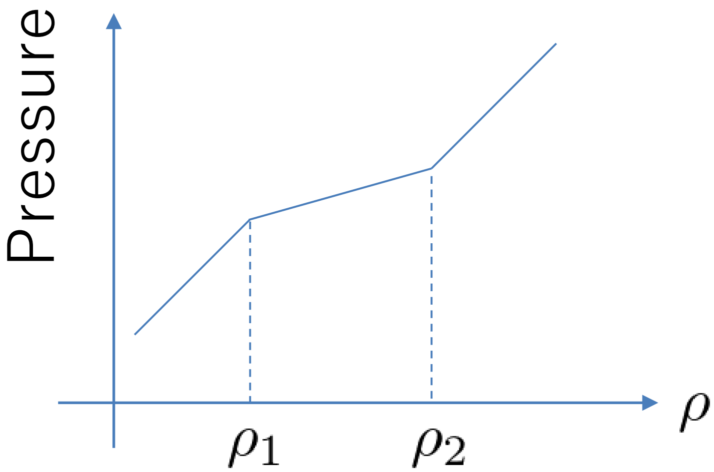
If $M_{TOV,max}$ correlates with Λ as the EOSs in Radice's paper, a model with small Λ tends to be rejected from AT2017 gfo observation.

We revisit this problem in NR simulation of BNSs with a Piece-Wise-Polytrope (PWP) prescription with which we can handle a correlation between $M_{TOV,max}$ and Λ.

Revisiting on the lower bound of Λ (KK et al. 19)

3 segments Piece-Wise Polytropic EOS (Read et al. 2009)





- ▶ $M_{TOV,\,max}$ = 2.00, 2.05, 2.10 $M_\odot$
- ▶ $\tilde{\Lambda}_{2.75M_\odot} \approx 200 - 600$
- ▶ 1.375-1.375$M_\odot$ (equal mass). 1.2-1.55$M_\odot$ (unequal mass) (cf. $2.74^{+0.04}_{-0.01}M_\odot$ for GW170817)

Three possibilities of a remnant

1. BNS collapses to a BH immediately after merger (we avoid calling it a prompt collapse as in Bauswein 17).

⇒No bounce case because there is no prominent bounce in α_{min}.

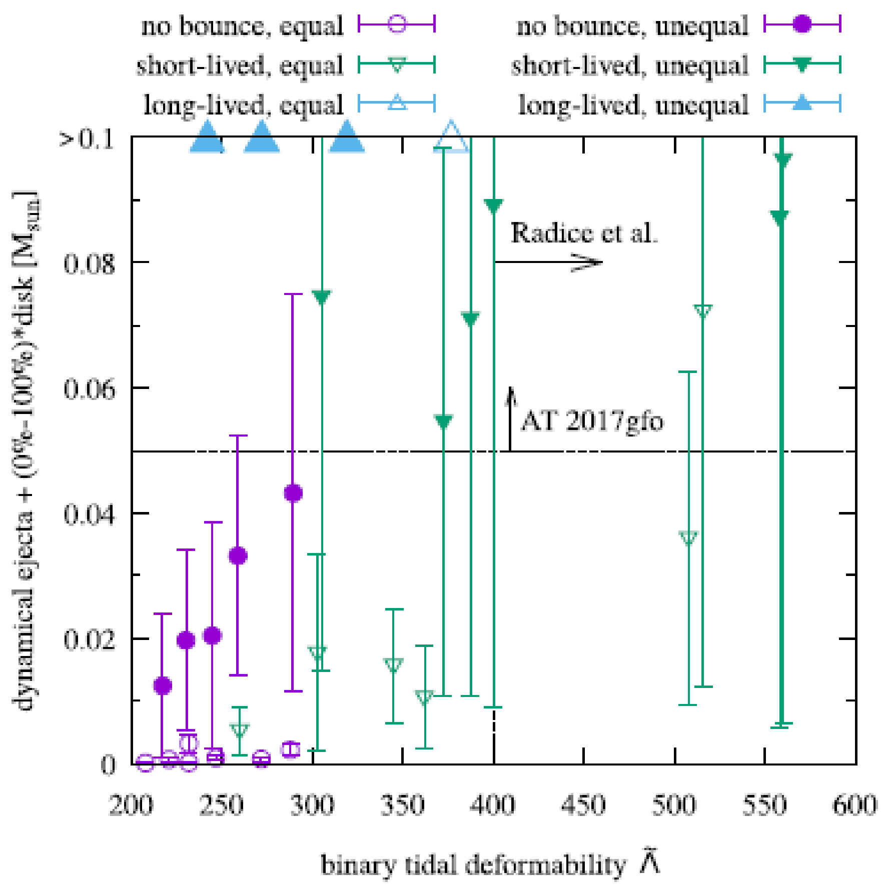
2. A transiently formed hyper massive NS collapses to a BH within 20 ms after merger. ⇒Short-lived case

3. A hyper massive NS never collapses to a BH ⇒ Long-lived case.

In this case, the disk is defined fluid elements with $\rho \lesssim 10^{13}$g/cc

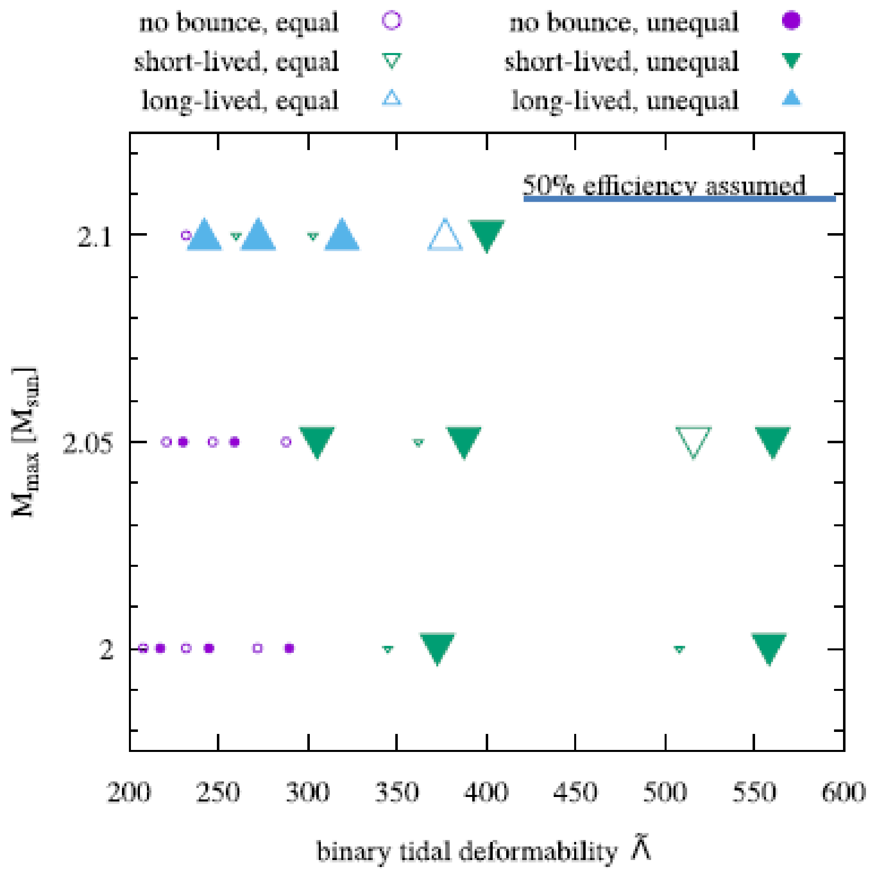
Result (KK et al. 19)

Total amount of the ejecta
(efficiency is 0-100%)



Explicit counter example for the claim by Radice et al.

Result (KK et al. 19)



Small symbol ⇒ fail

Large symbol ⇒ success

For symmetric binary, there is no chance for the models with $\Lambda \lesssim 400$.

For asymmetric binary with large $M_{TOV,max}$, the models with $\Lambda \gtrsim 250$ still survive.

Open question

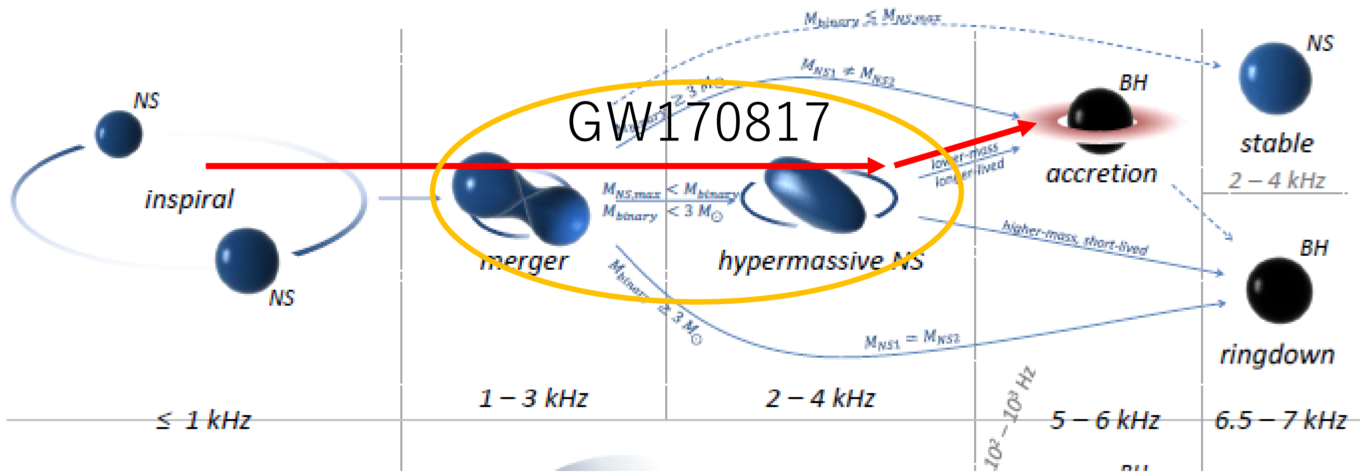
What is a realistic value of the fraction?

$$\text{fraction} \equiv \frac{M_{\text{wind}}}{M_{\text{disk}}}$$

MHD instability-driven turbulent viscosity ⇒ Main agent for the angular momentum transport and viscous heating

We don't know how large the effective turbulent viscosity should be.
⇒ Only (high-resolution) MHD simulation could give answer.

Assessment of the universality relations

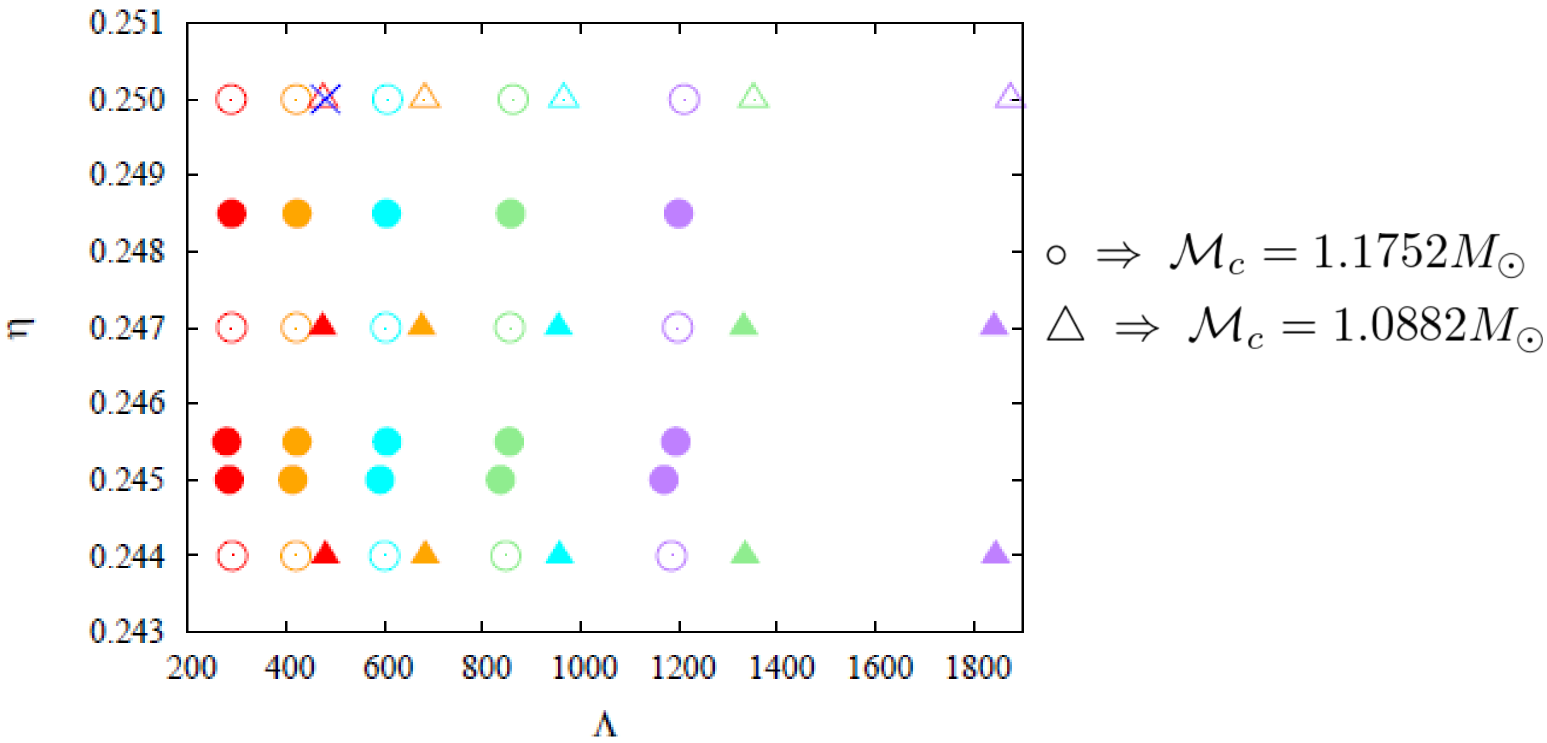


GWs in late inspiral and merger phase contain information of the NS matter.

There are a bunch of the proposed universal relations between f_{GW} and Λ (or R_{NS}), e.g., Rezzolla and Takami 16 and many references

⇒ Systematics were not well studied.

SACRA Gravitational Waveform Data Bank
(KK et al. 19)



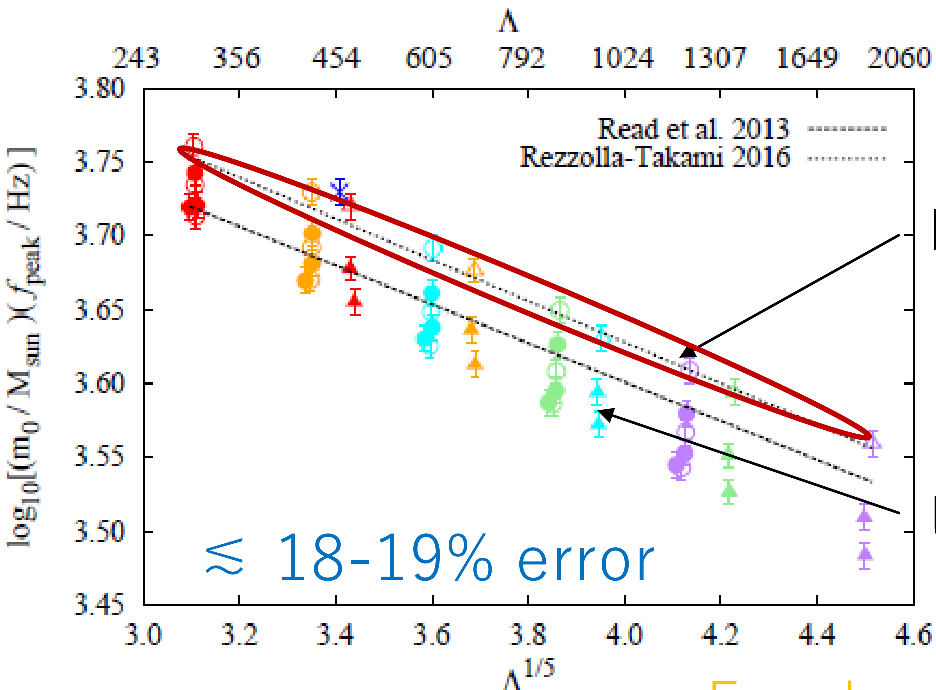
▶ 6 grid resolutions in each parameter points (Δx=64m for the best)

▶ 30-32 GW cycles

http://www2.yukawa.kyoto-u.ac.jp/~nr_kyoto/SACRA_PUB/catalog.html

Assessment of the universal relations for the post-merger signal (KK et al. 19.)

$f_{\rm peak} - \tilde{\Lambda}$ relation   Rezzolla & Takami 16, Read et al. 13



Equal mass binaries

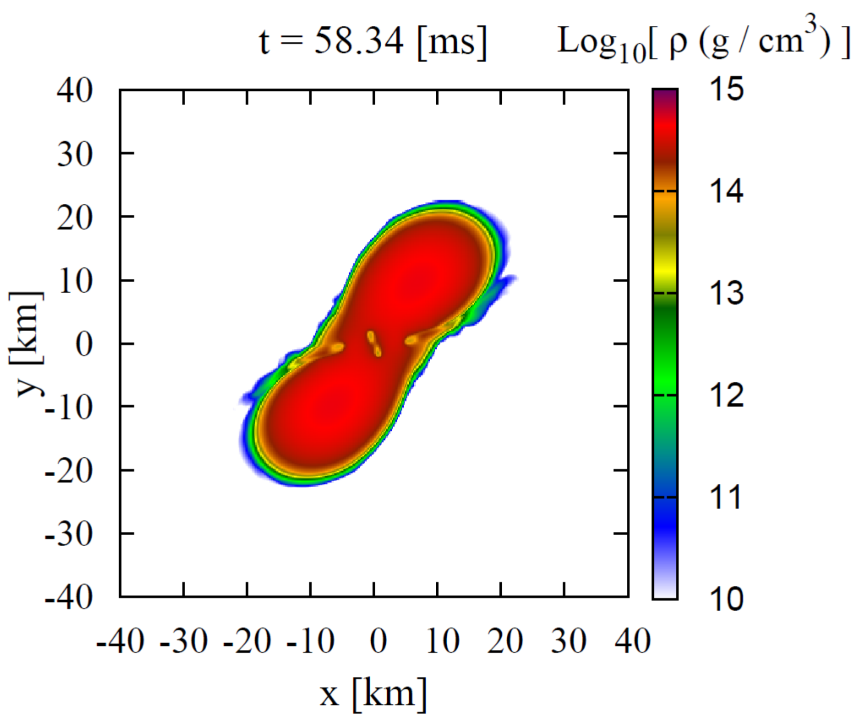
Unequal mass binaries

Error bar ⇒ finite difference error

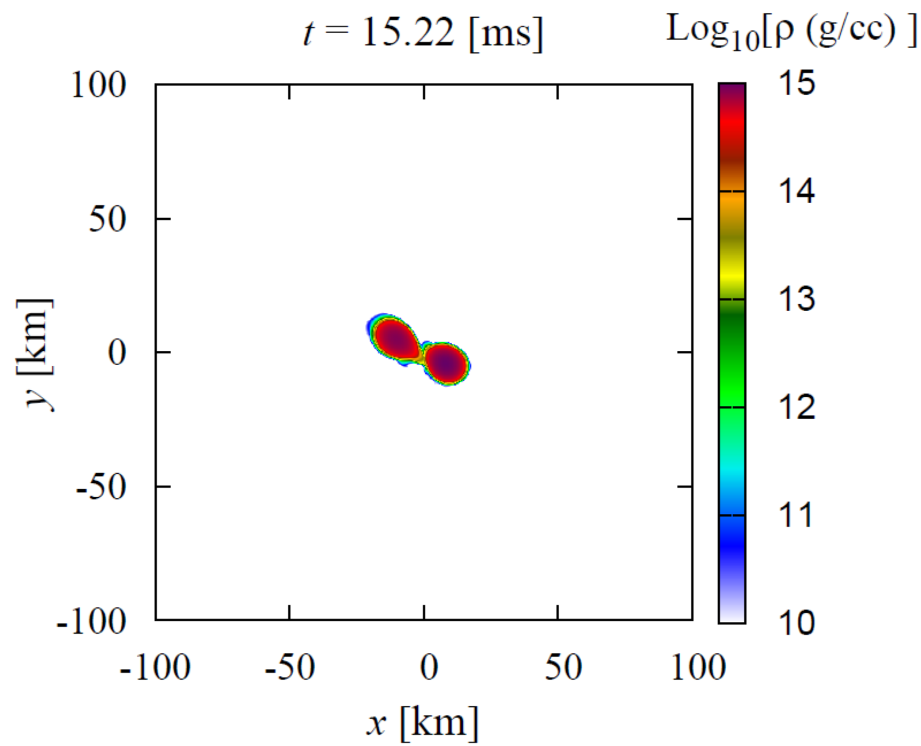
$f_{\rm peak}$ = GW frequency at the peak time of gravitational-wave amplitude

Why the universal relation doesn't hold for asymmetric binary?

Symmetric binary at $t=t_{peak}$



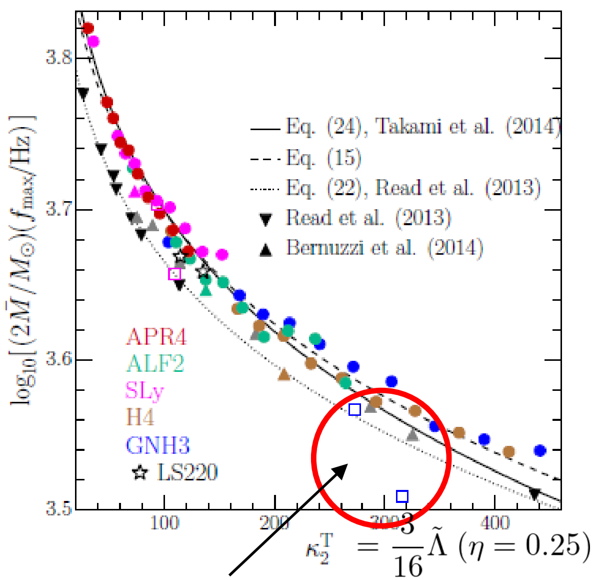
Asymmetric binary at $t=t_{peak}$



Tidal elongation for the asymmetric binary reduces f_{peak}.

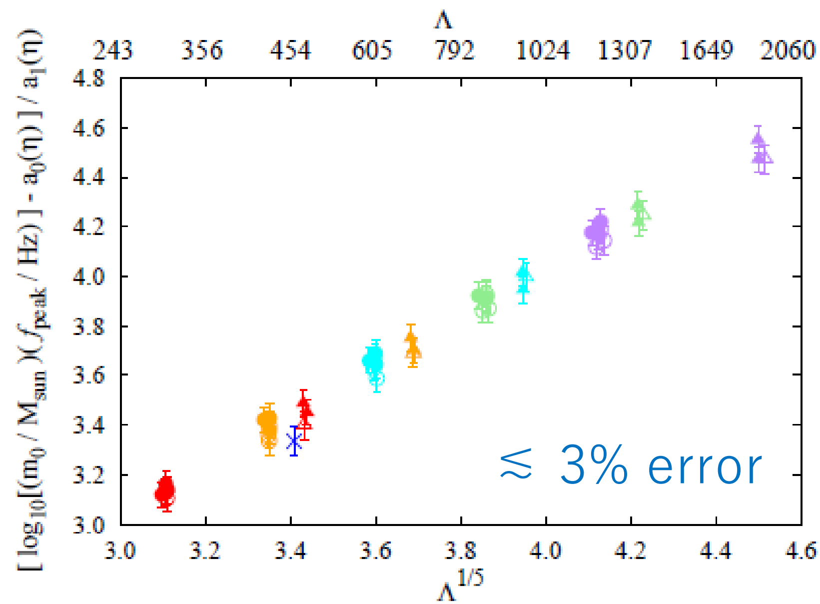
Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16



Unequal mass binaries

An improved relation



$$\log_{10}\left[\left(\frac{f_{\rm peak}}{\rm Hz}\right)\left(\frac{m_0}{M_\odot}\right)\right] = a_0(\eta) + a_1(\eta)\tilde{\Lambda}^{1/5}$$

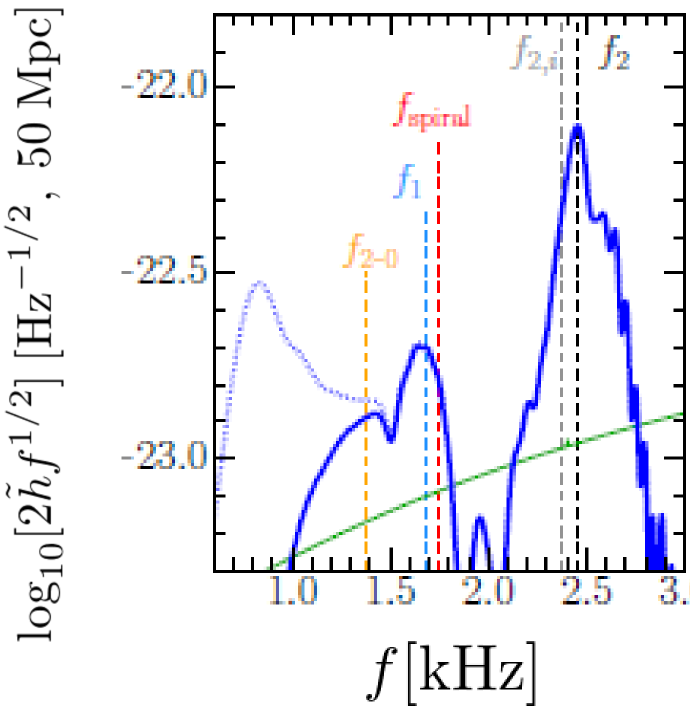
$$a_0(\eta) = 4.53582 - 1.22968\eta$$

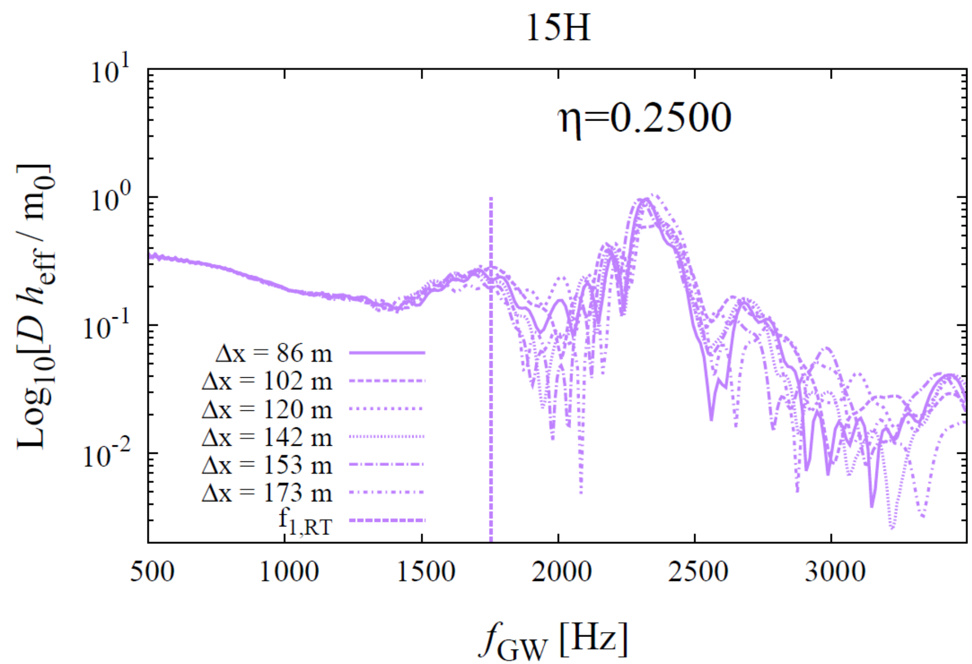
$$a_1(\eta) = -0.929178 + 3.1186\eta$$

Caveat: The improved relation could still suffer from the systematics (no B-field, no NS spin in this study).

Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16

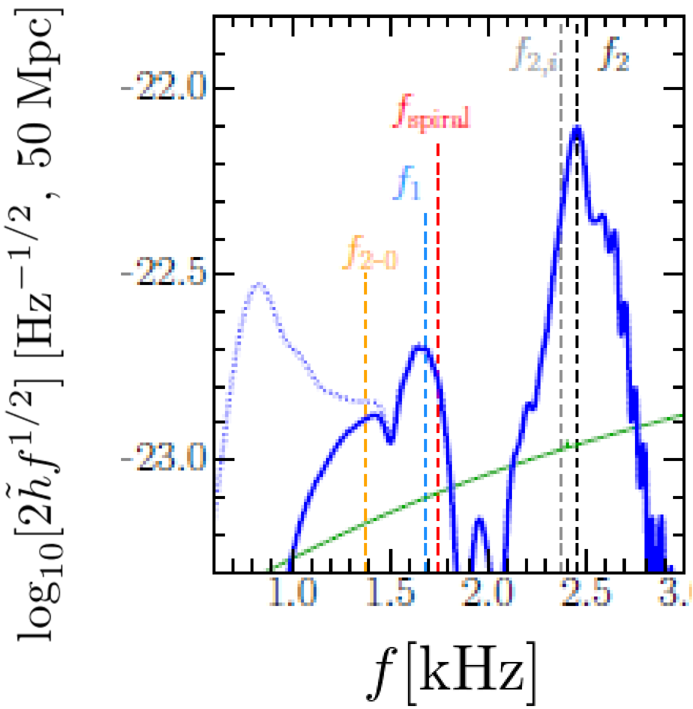


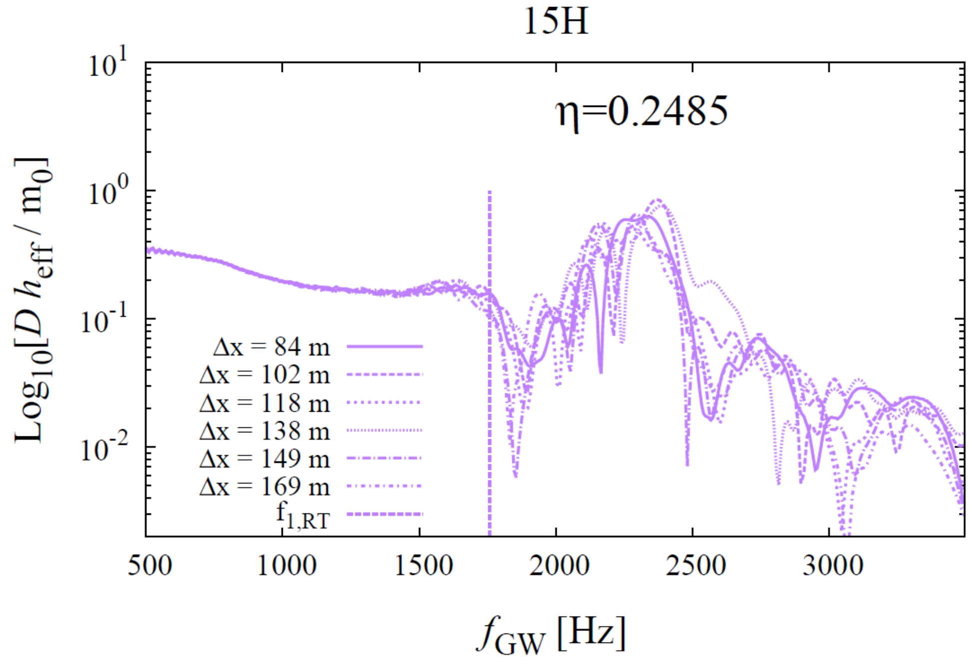


$$f_1 \approx 45.195 - 43.484(\kappa_2^T)^{1/5} + 14.563(\kappa_2^T)^{2/5} - 1.6623(\kappa_2^T)^{3/5}$$

Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16





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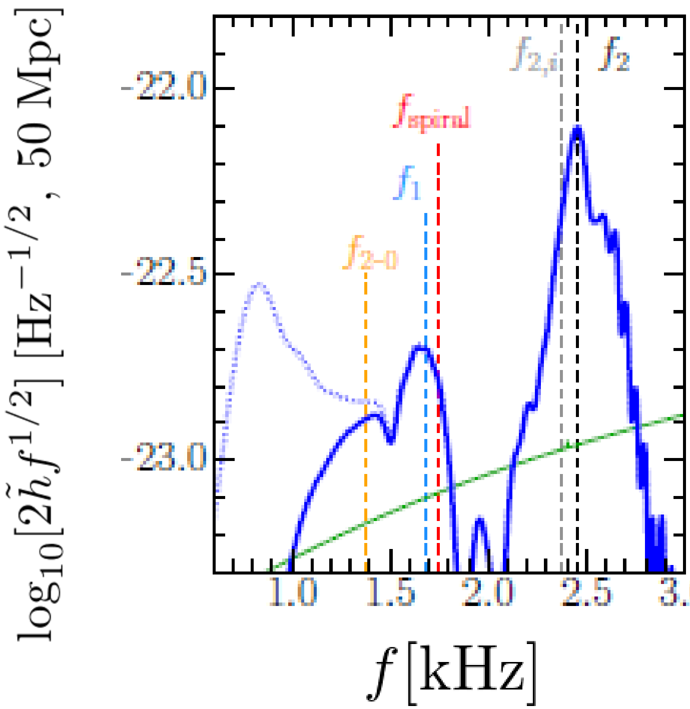

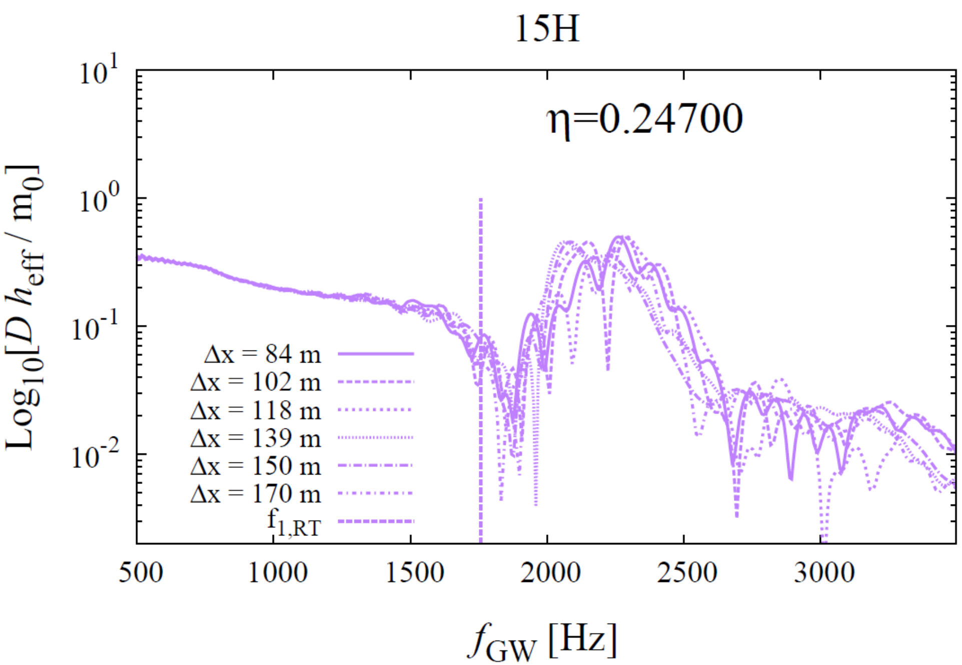

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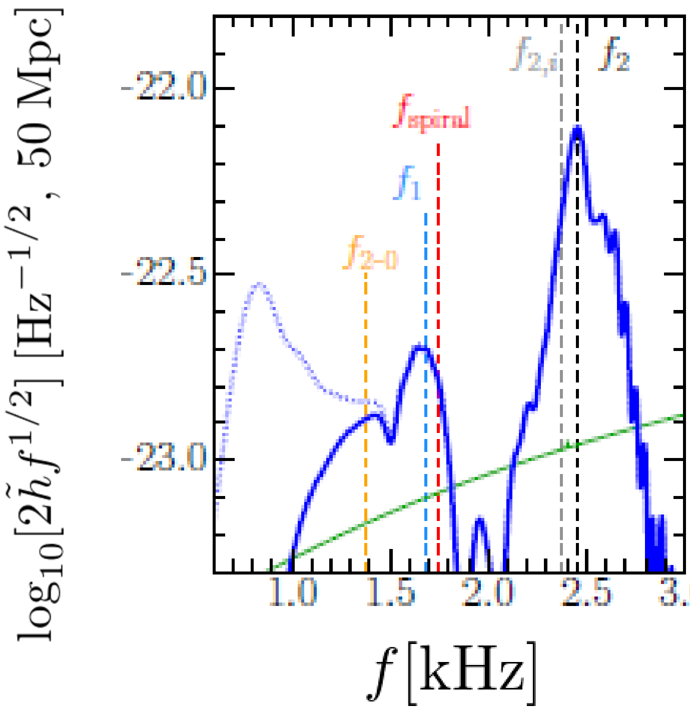

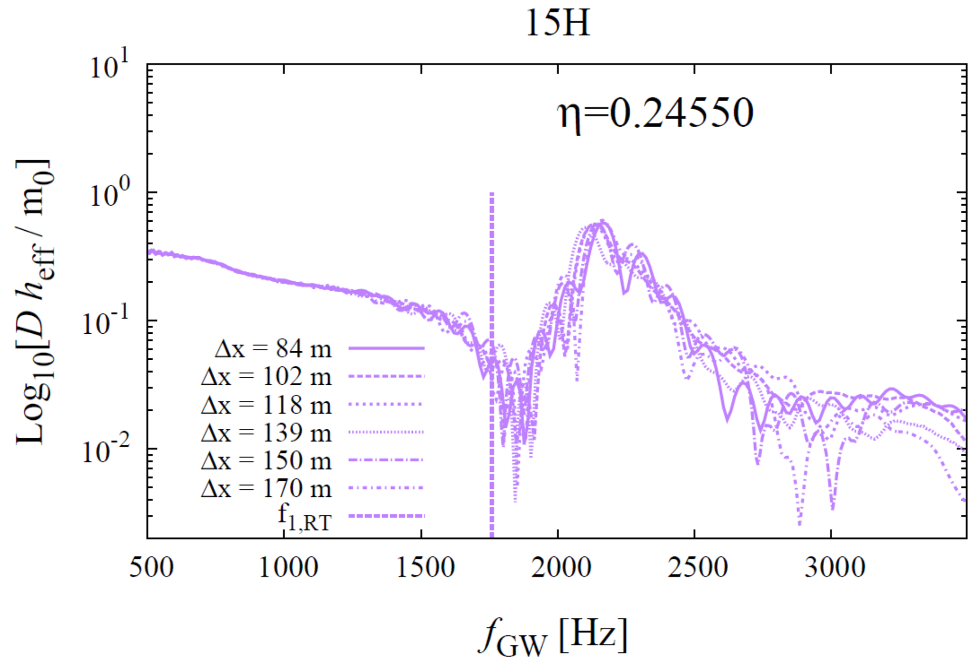

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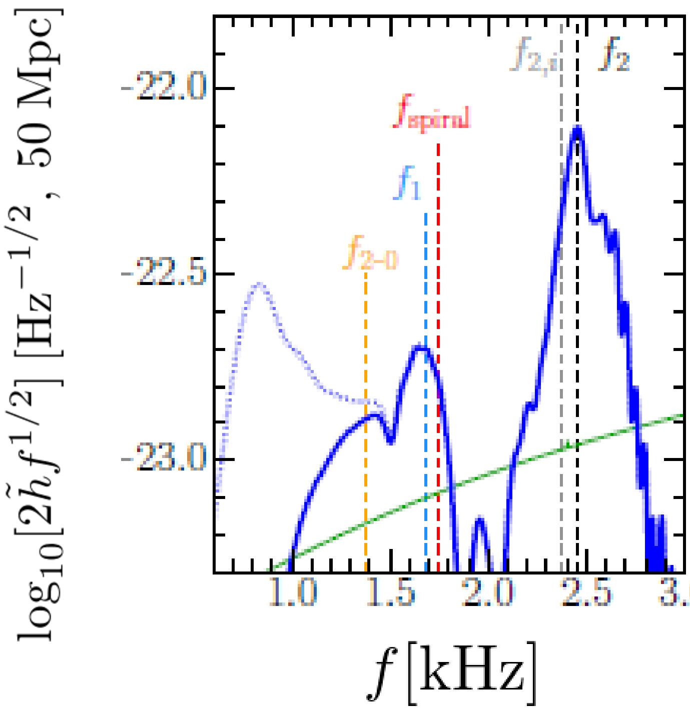

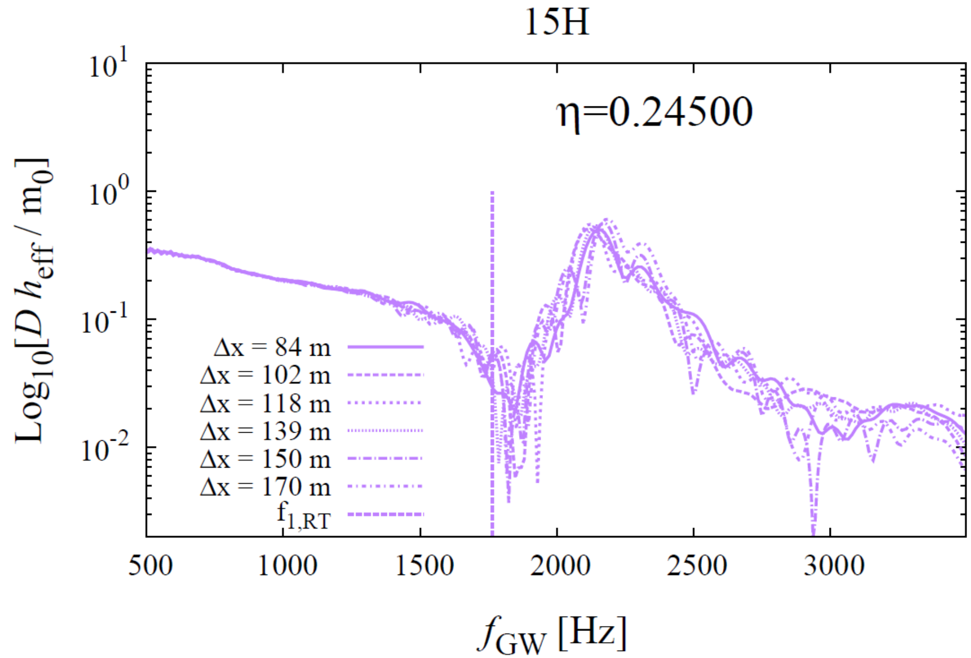

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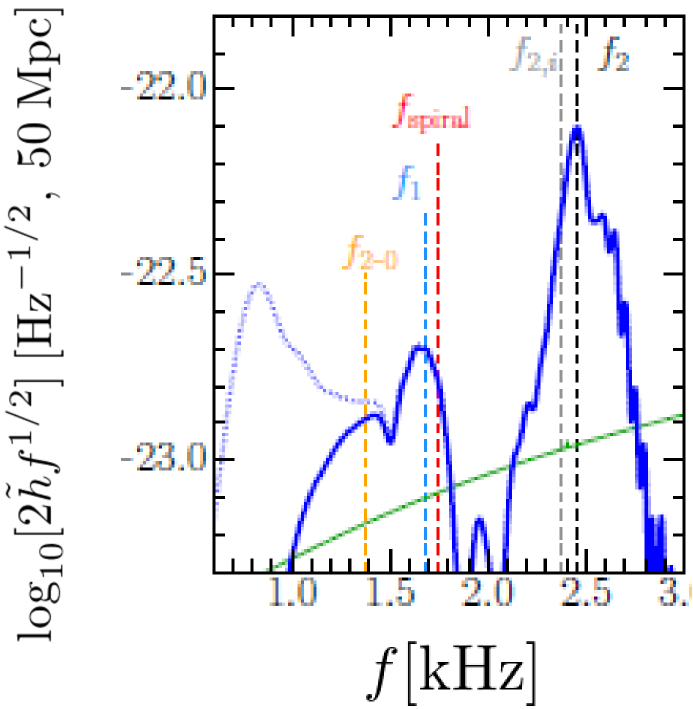
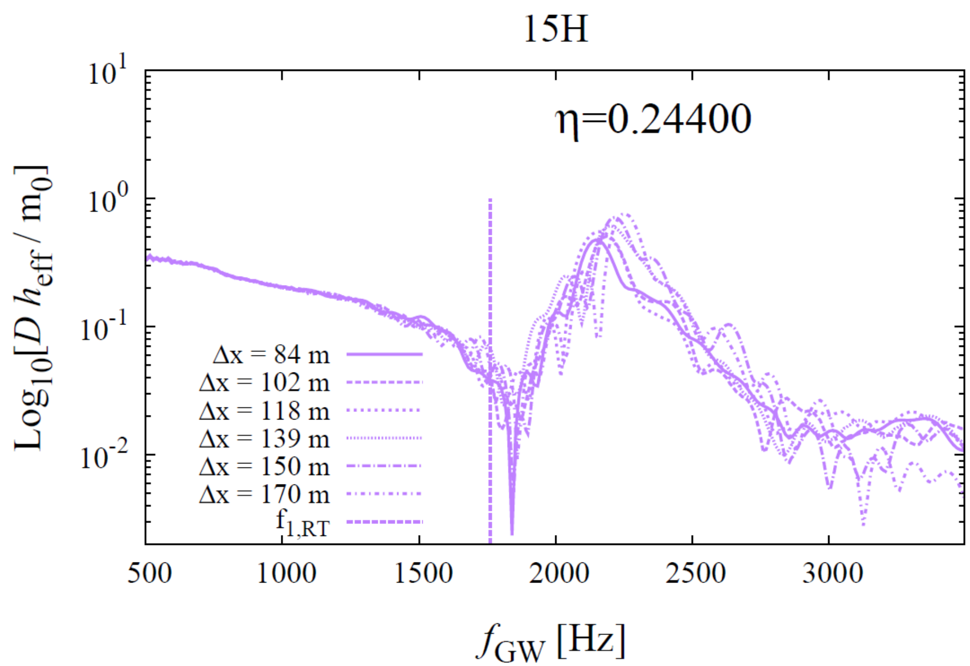
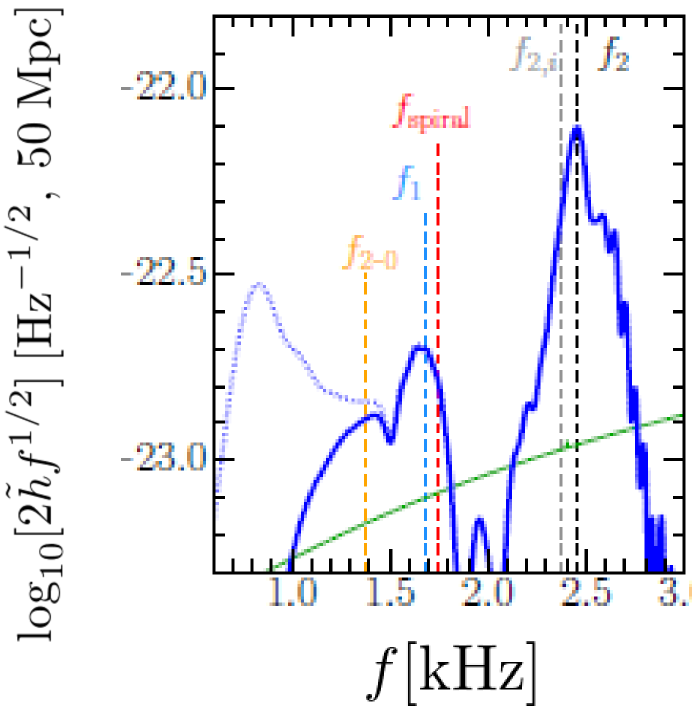


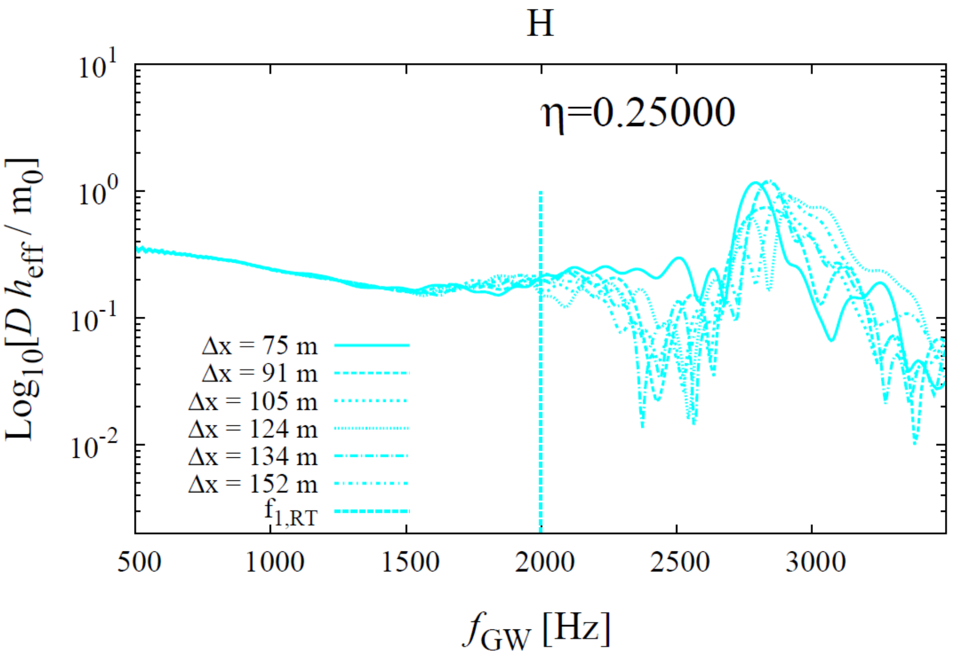


$f_1 - \tilde{\Lambda}$ relation is not universal (also pointed out in Dietrich et al. 15).

Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16





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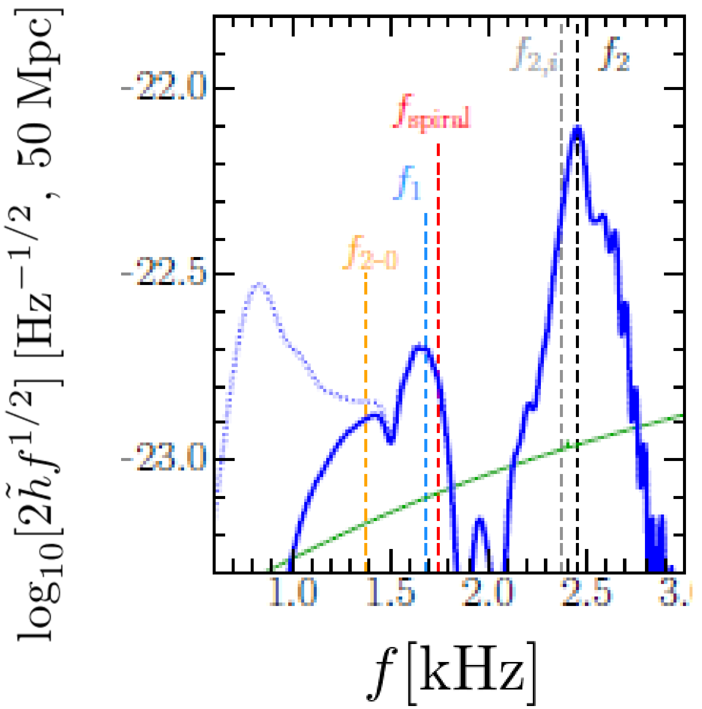
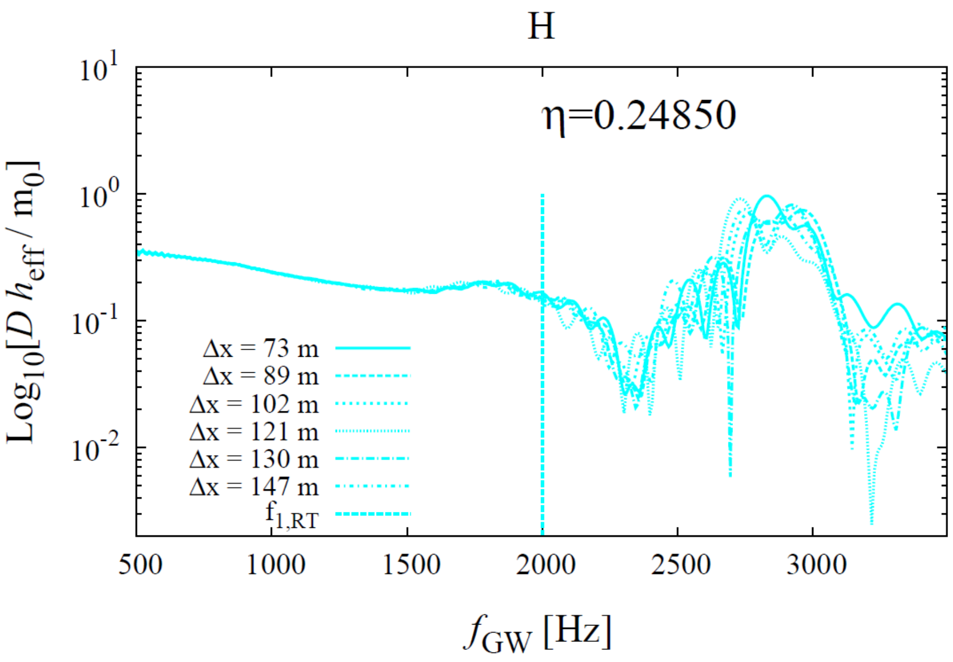
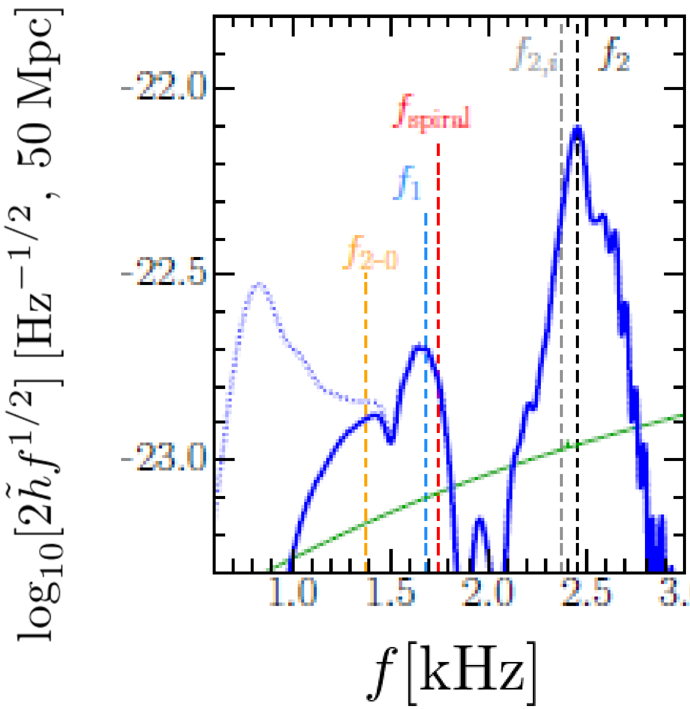
Rezzolla & Takami 16

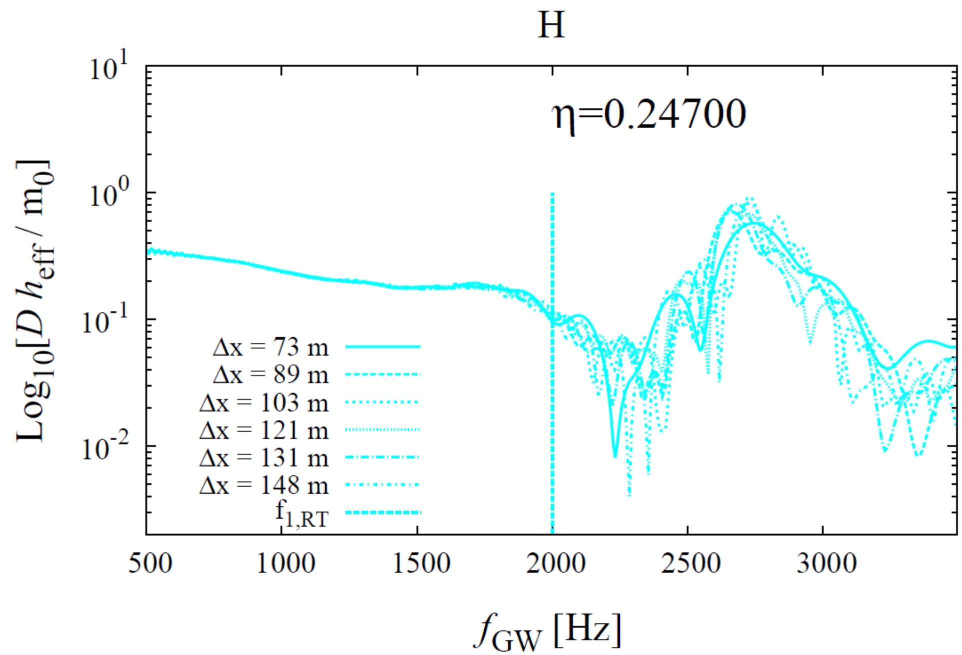




Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16





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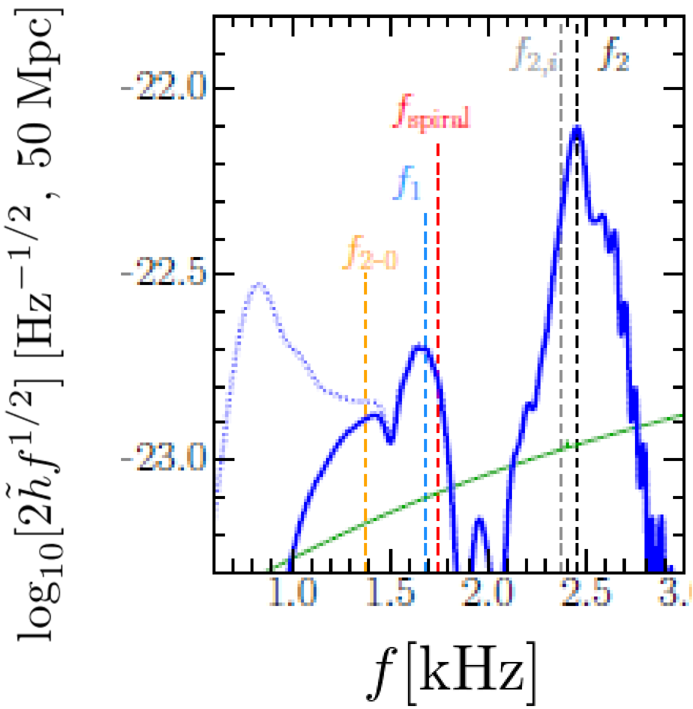

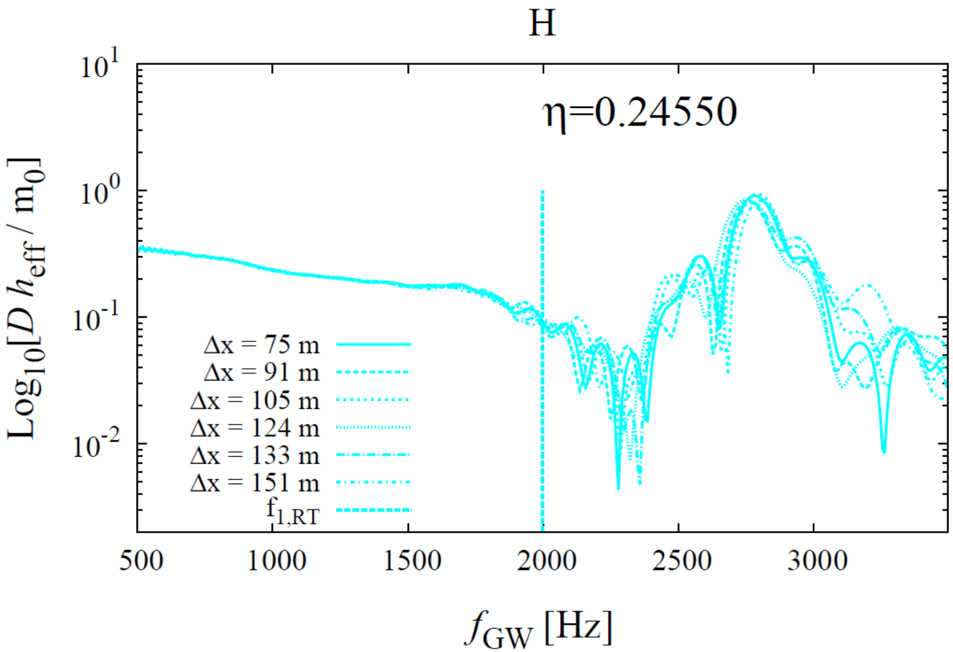

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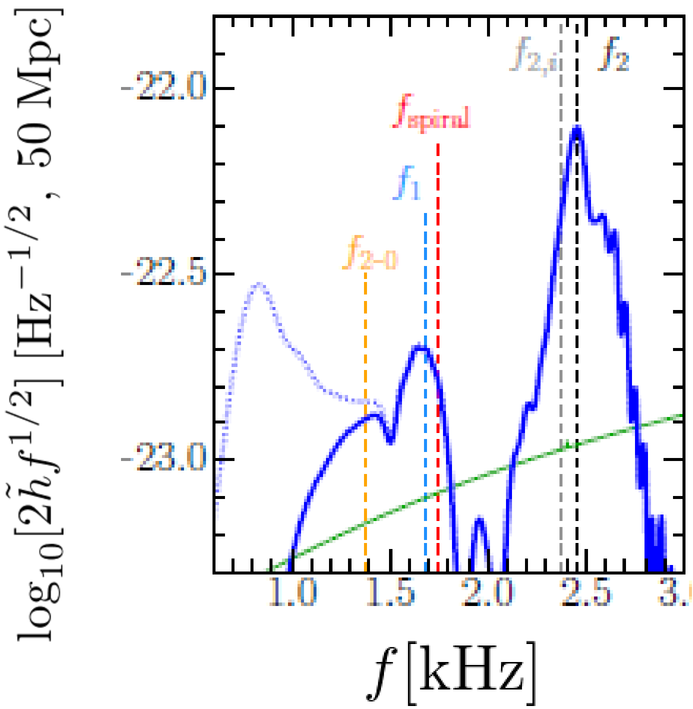

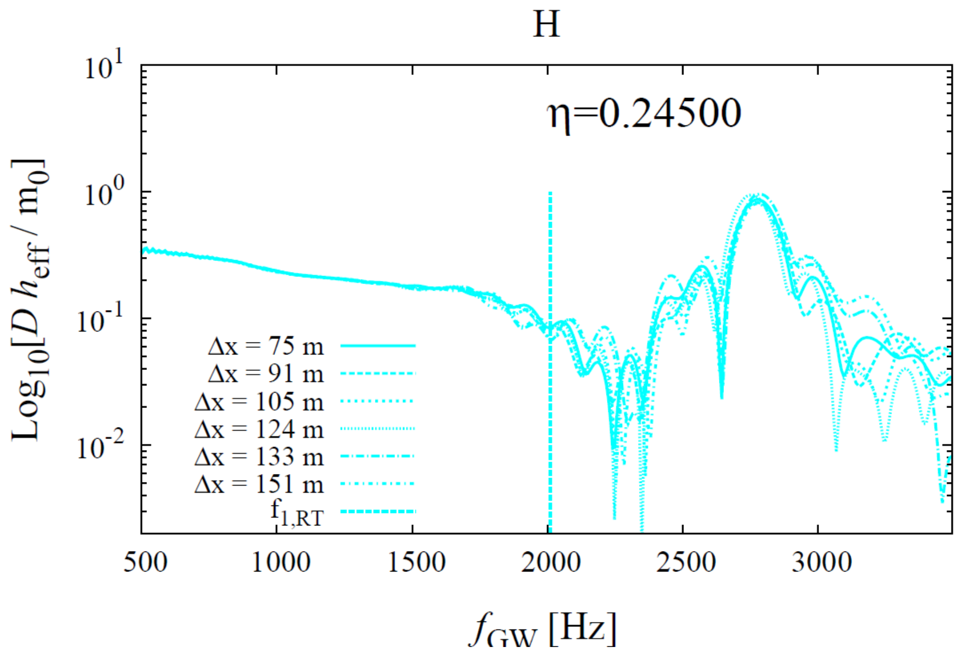

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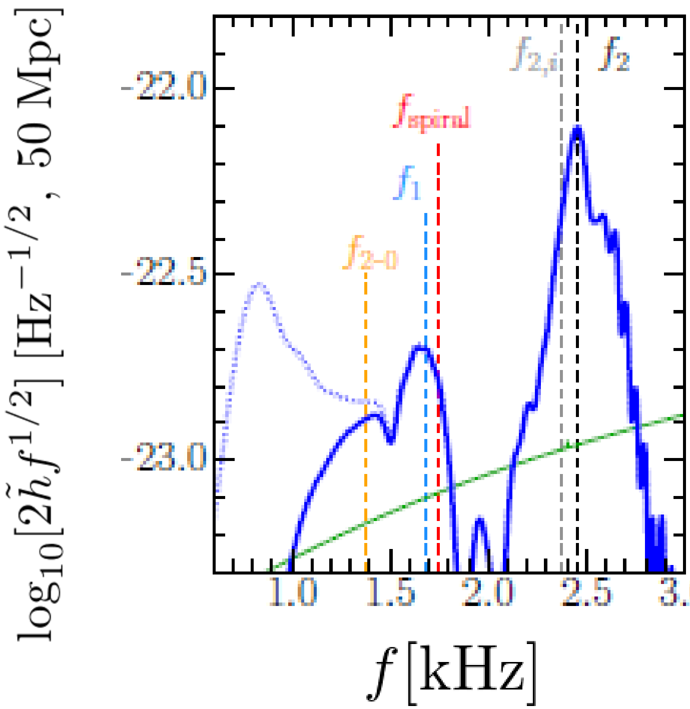
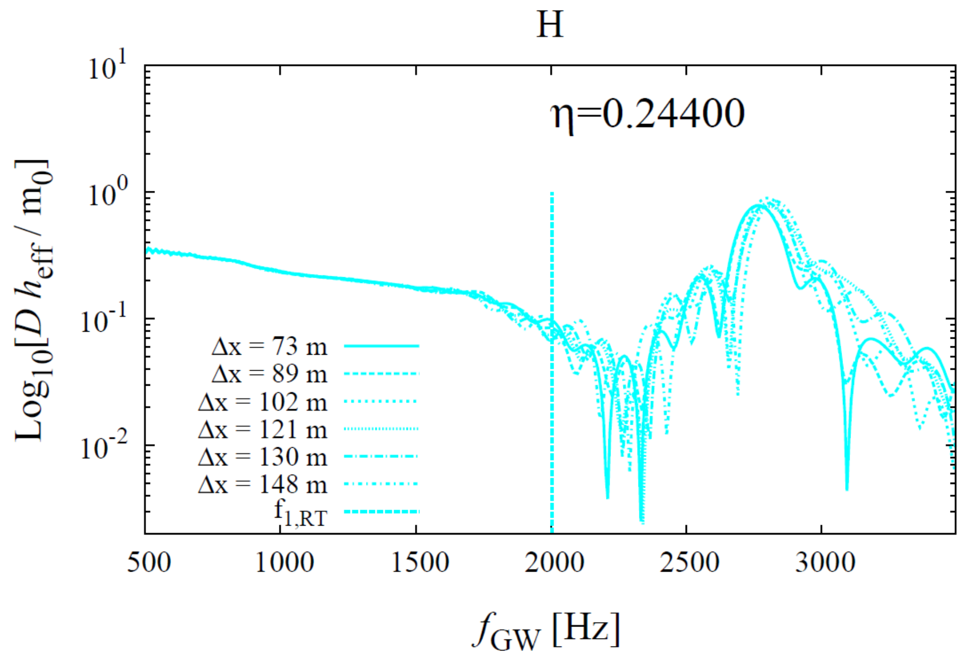
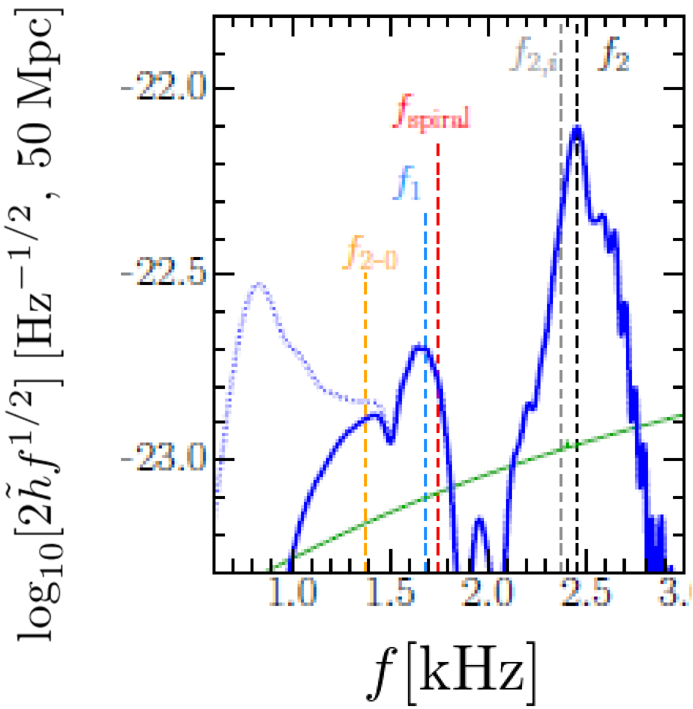


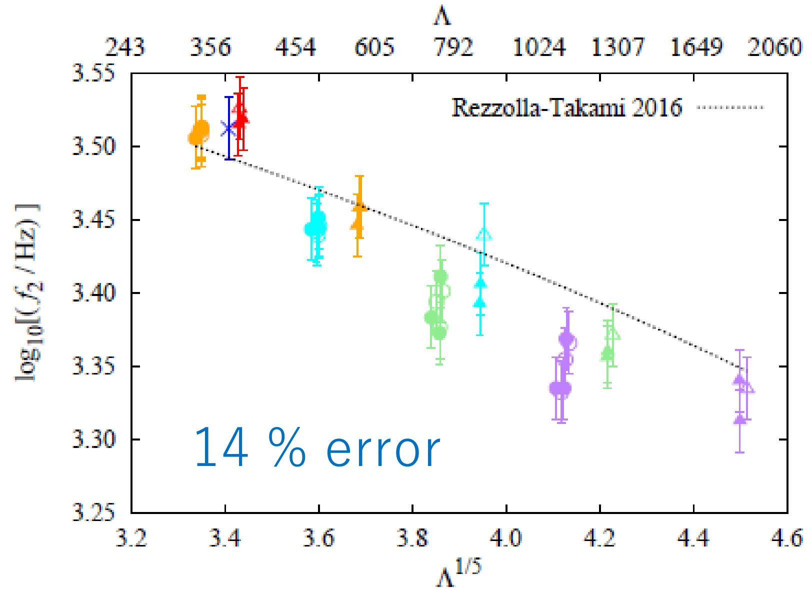


f_2 peak is affected by the finite difference error as well as the symmetric mass ratio.

Assessment of the universal relations for the post-merger signal (KK et al. 19)

Rezzolla & Takami 16

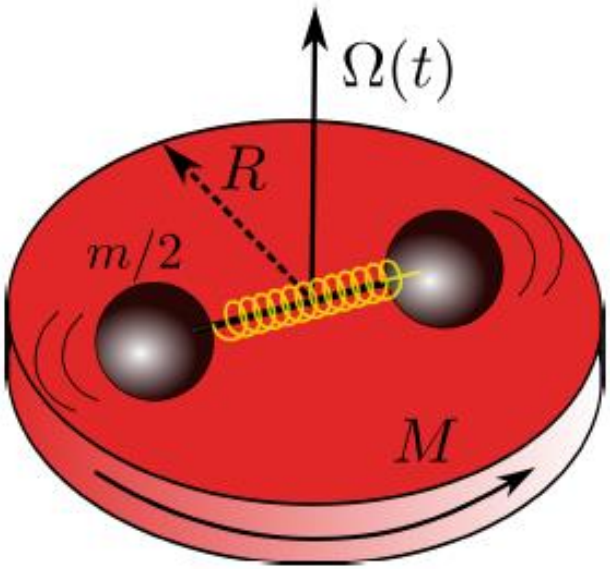


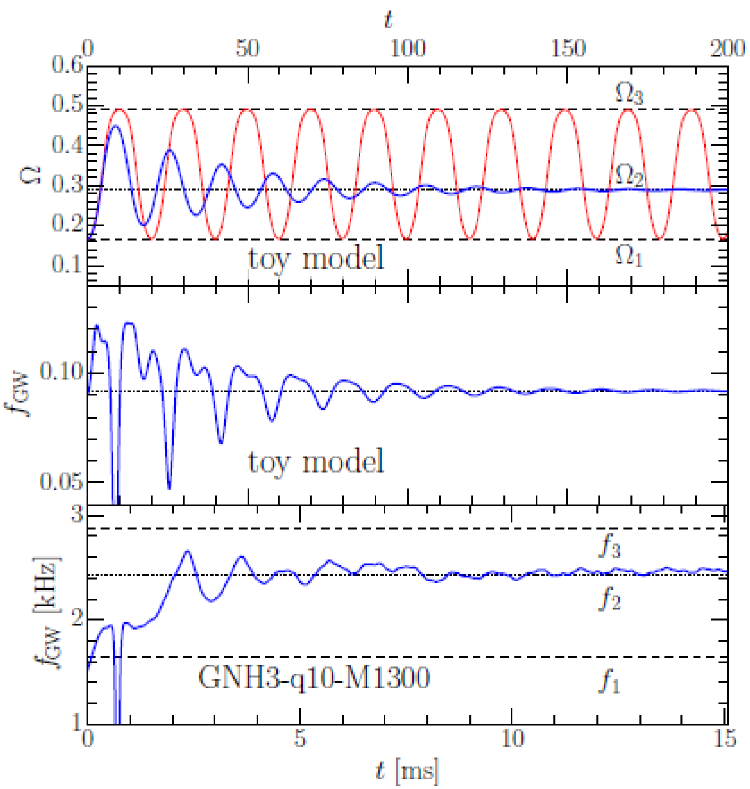


$$f_2 \approx 5.832 - 1.118(\kappa_2^T)^{1/5}\ \mathrm{kHz}$$

Why the universal relations don't hold?

Mechanical toy (Takami &Rezzolla 15)

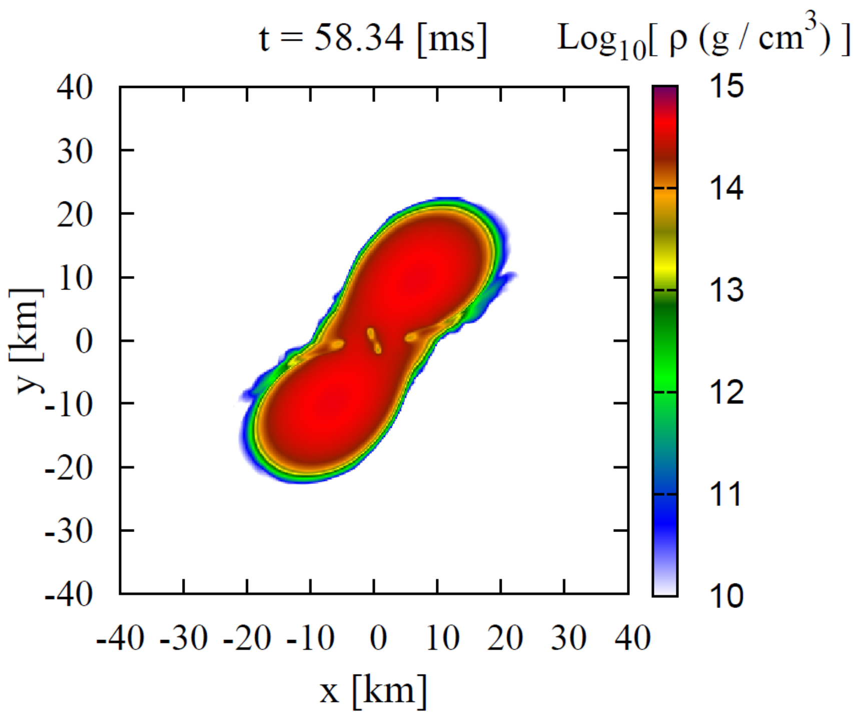




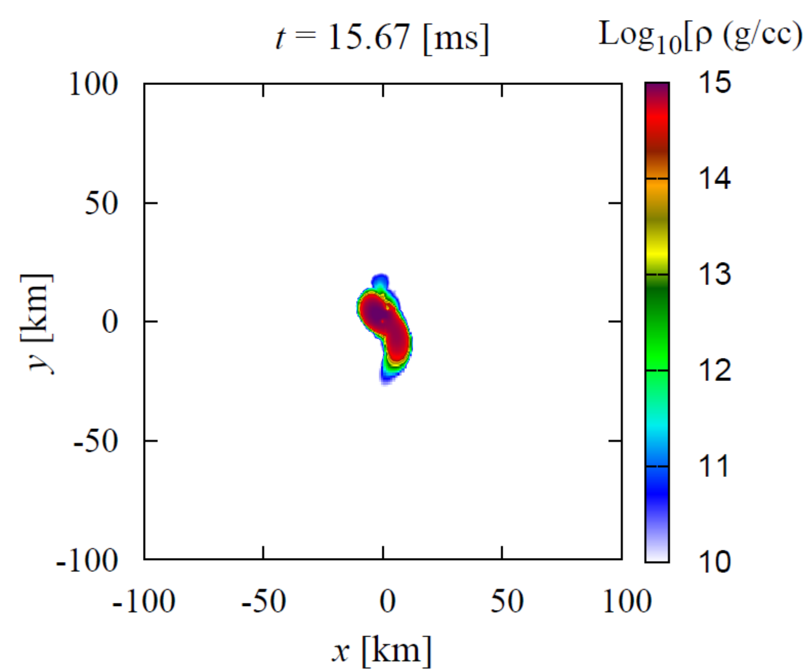
Given the angular momentum,
the smallest separation ⇒ Largest Ω ⇒ f_3
the largest separation ⇒ smallest Ω ⇒ f_1
$f_2 \simeq (f_1+f_3)/2$

Why the universal relations don’t hold?

Symmetric binary

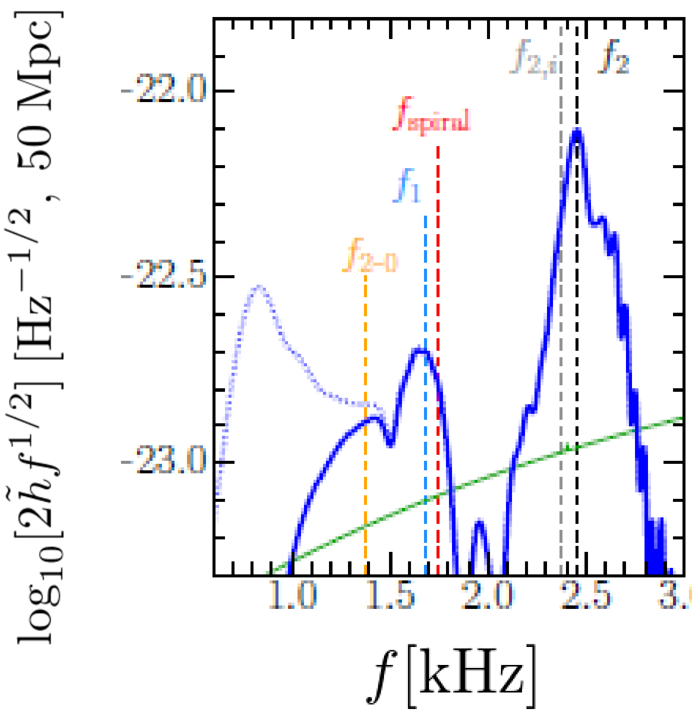


Asymmetric binary

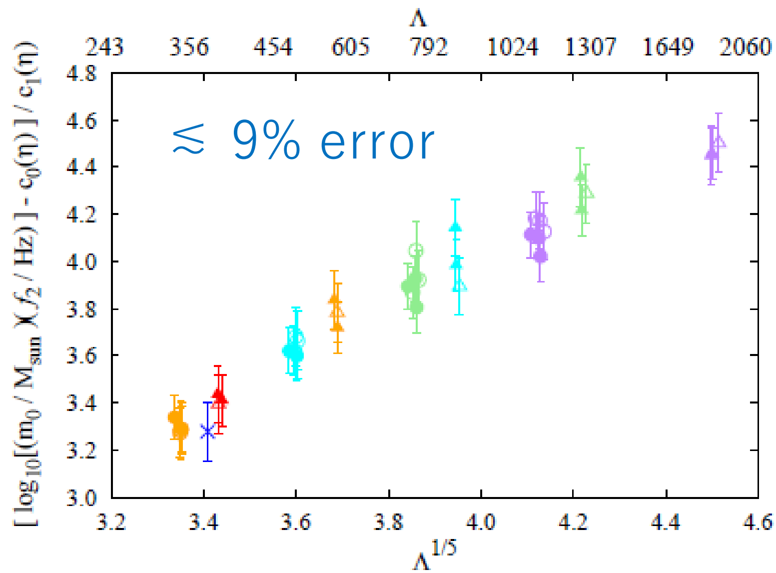


The mechanical toy model (two spheres with spring) could not describe the remnant of the asymmetric binaries.

Assessment of the universal relations for the post-merger signal (KK et al. 19)



An improved relation



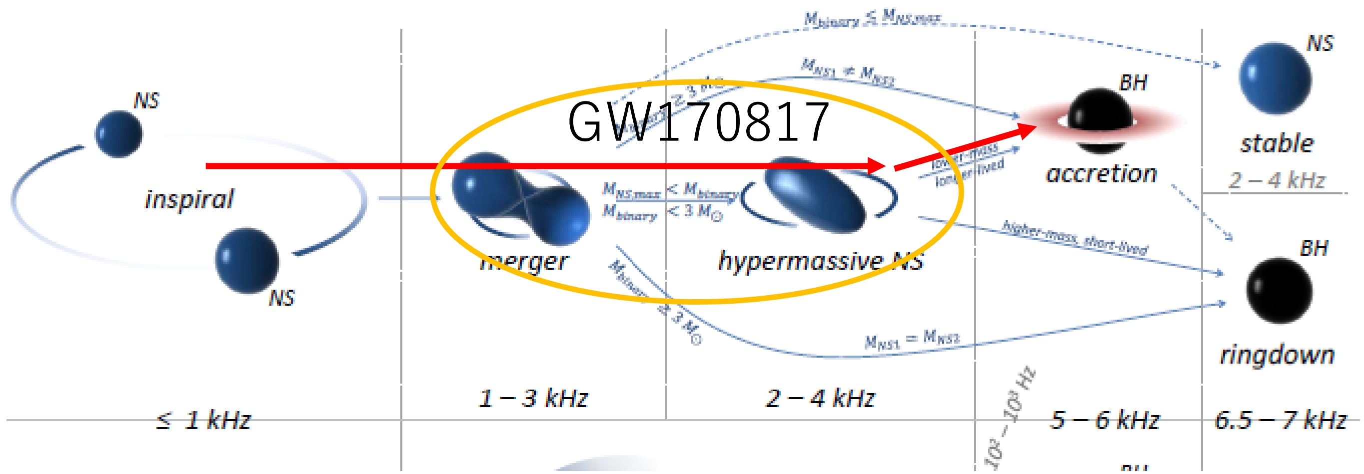
$$\log_{10}\left[\left(\frac{f_2}{\rm Hz}\right)\left(\frac{m_0}{M_\odot}\right)\right] = c_0(\eta) + c_1(\eta)\tilde{\Lambda}^{1/5}$$

$$c_0(\eta) = 11.3634 - 27.4181\eta$$

$$c_1(\eta) = -2.15771 + 7.94086\eta$$

Caveat: The improved relation could still suffer from the systematics (no B-field, no NS spin in this study).

How does the turbulence change the story?



Key ingredients

▶ Effective turbulent viscosity: MHD instability

MHD instability-driven turbulence

EOM : $\partial_t(\rho j) + \partial_R(\rho j v^R - \nu\rho R^2 \partial_R(j/R^2)) = 0$

ρ =density, j=specific angular momentum, ν = viscosity

▶ Angular momentum transfer by the viscous term.

▶ Energy dissipation due to the viscosity

Q. What is the “viscosity” ?

A. MHD turbulence :

$q = q_{ave} + \delta q$ s.t. $\langle q \rangle = q_{ave}$ and $\langle \delta q \rangle = 0$ where $\langle \cdot \rangle$ denotes time ensemble.

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

Reynolds+Maxwell stress : $W_{R\varphi} = \langle \delta v^R \delta v^\varphi - \frac{B^R B^\varphi}{4\pi\rho} \rangle$

To B or not to B in binary NS merger

▶ B-field in observed binary NSs : $10^{9.7} – 10^{12.2}$ G

Kinetic energy at the merger ∼ 10^{53} g cm^2 s^{-2} × $(M/2.7M_{sun})(v/0.3c)^2$

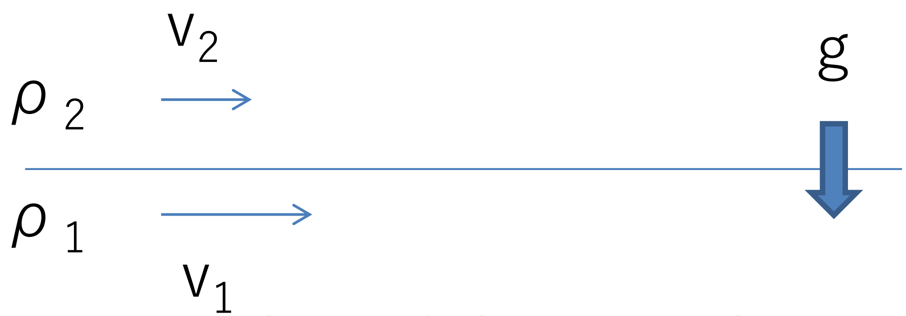
B-field energy ∼10^{41} g cm^2 s^{-2} $(B/10^{12}G)^2(R/10^5cm)^3$

B-field is irrelevant in BNS mergers ?

No ⇒ Several amplification mechanisms (Magneto Hydro Dynamical instabilities) could amplify the B-filed

B-field amplification @ the merger

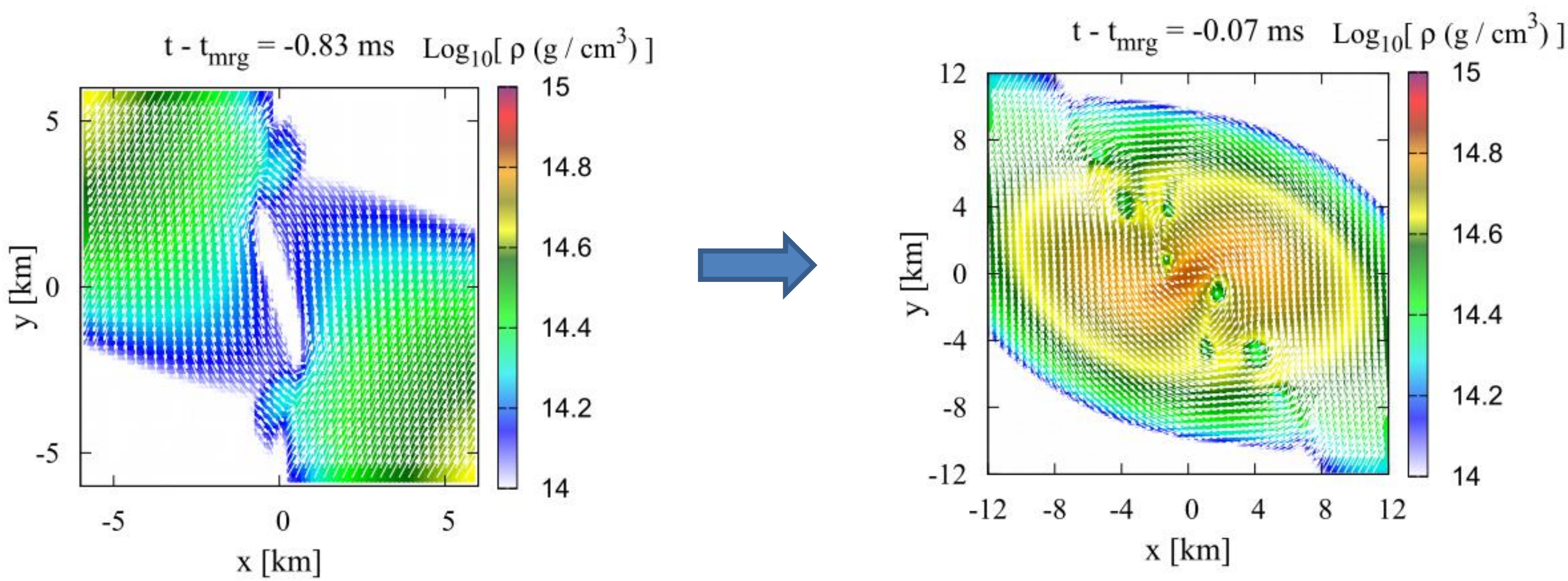
<u>Kelvin Helmholtz instability</u> (Rasio and Shapiro 99, Price & Rosswog 05)



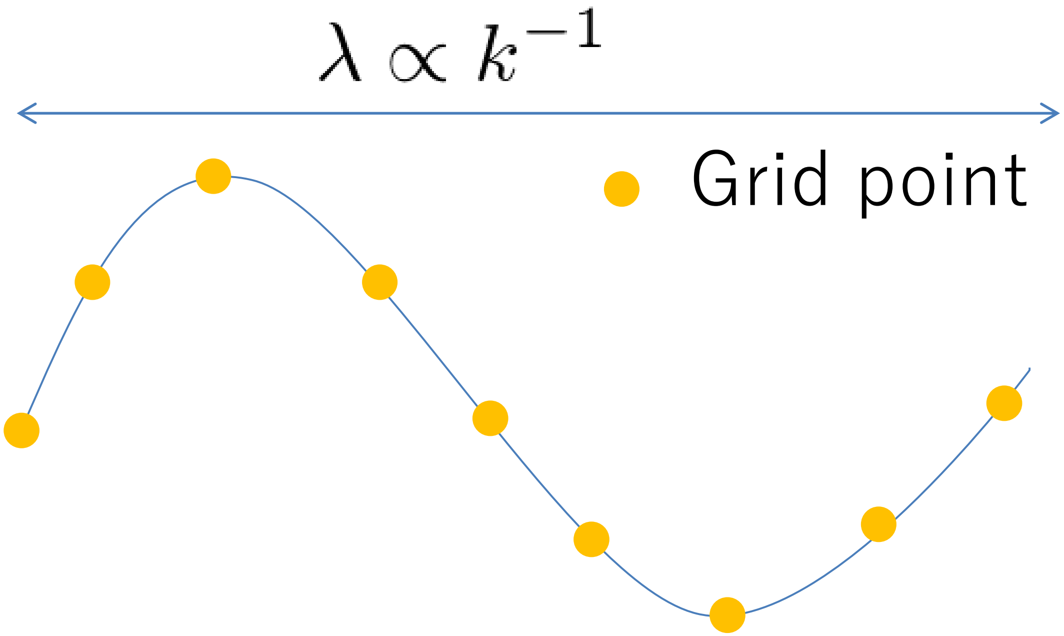
Minimum wave number of the unstable mode ;

$k_{min} \propto g(\rho_1 - \rho_2)/(v_1 - v_2)^2$

⇒ If g = 0, all the mode are unstable. $\sigma \propto k$



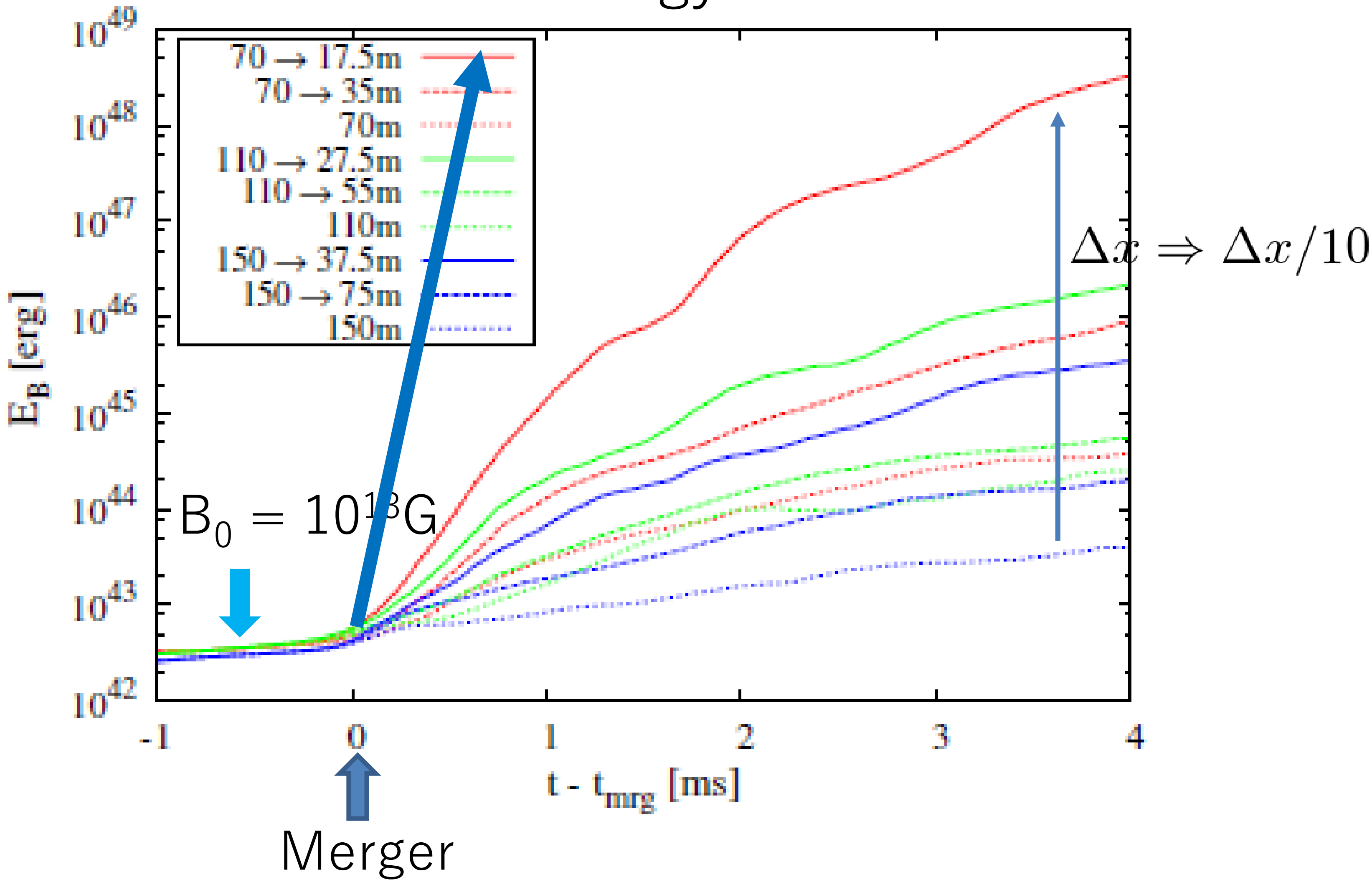
Explore the MHD instability-driven turbulence on K



Note : growth rate ∝ wave number in the KH instability ⇒ Large scale simulation is necessary

Magnetic field amplification

B-field energy evolution



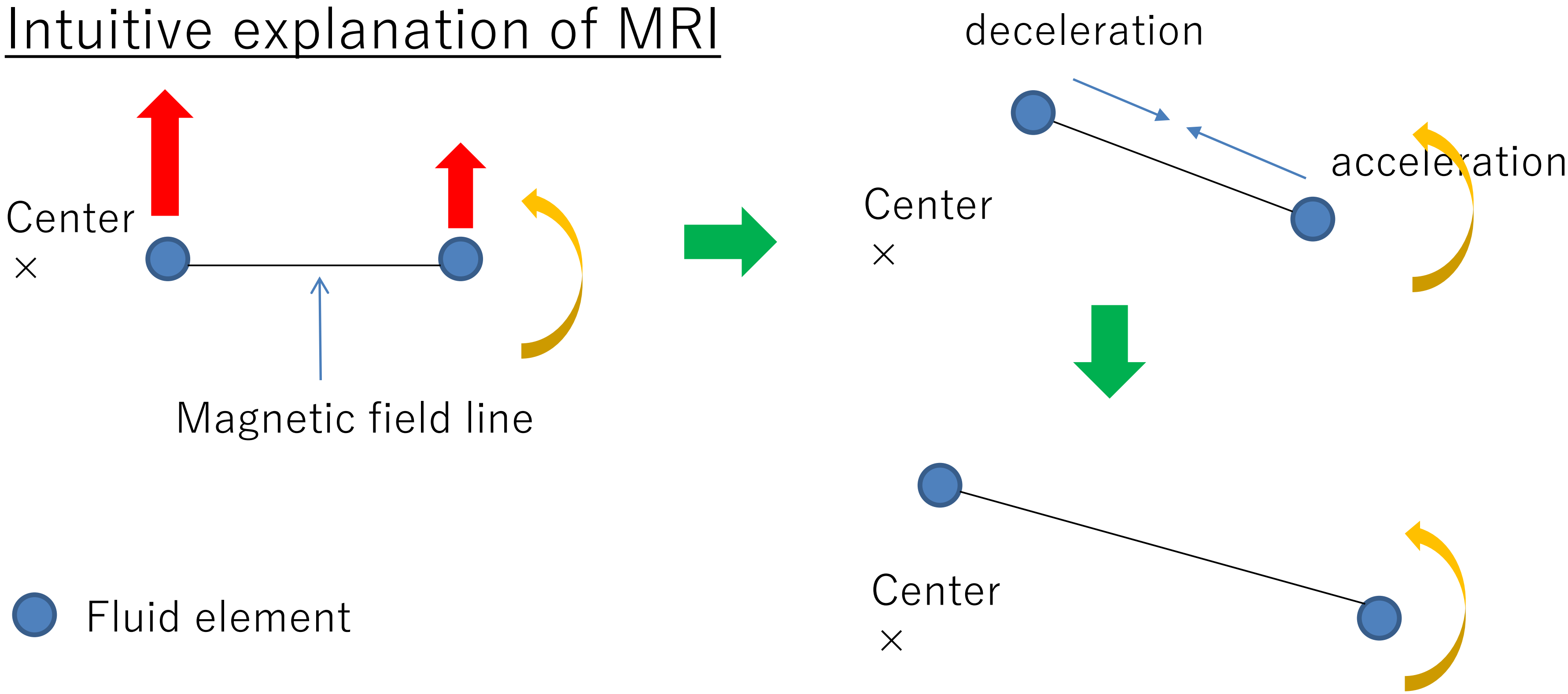
▶The growth rate shows the divergence. c.f. $\sigma \propto$ wave-number for KH instability.

Magneto Rotational Instability (MRI)

▶ (Balbus & Hawley 91)

Differential rotation $\nabla\Omega < 0 \Rightarrow B(t) \propto \exp(\sigma t),\ \sigma \approx \Omega$

Intuitive explanation of MRI



MRI produces turbulence as well.

Exploring the MHD instability-driven turbulence in BNS merger (KK et al. 2018)

To do list: Read α-viscosity parameter from MHD simulation data

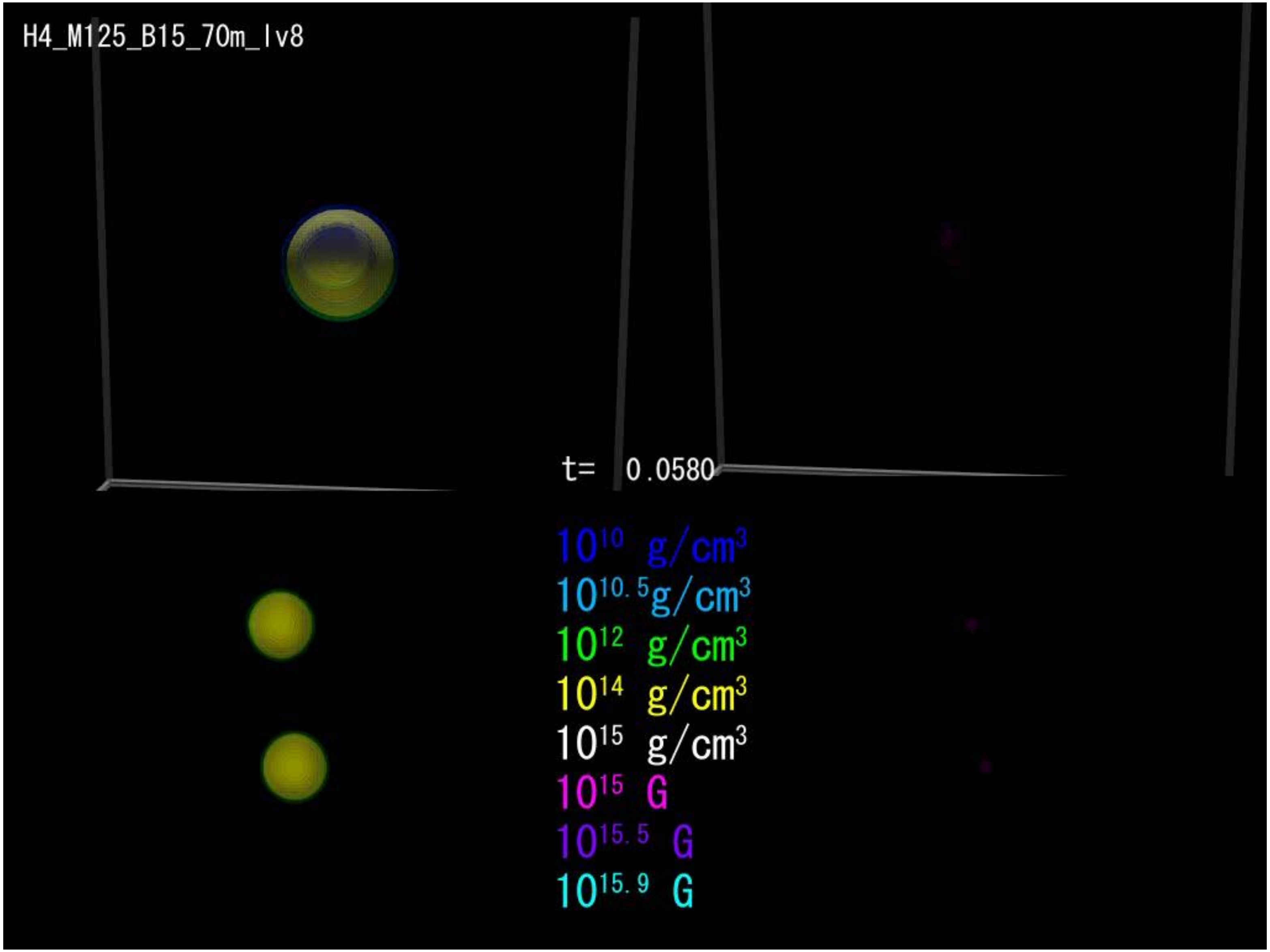
$$\alpha = \left\langle \frac{W_{R\varphi}}{P} \right\rangle$$

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

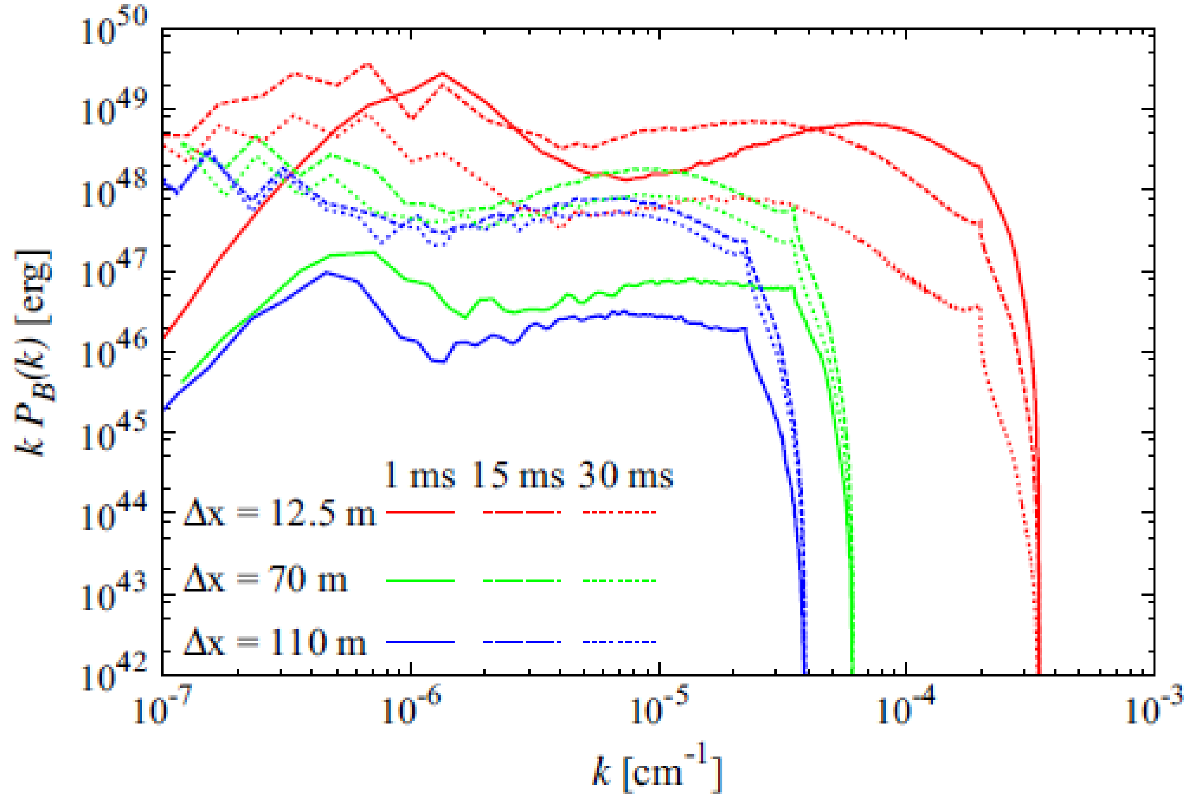
Caveat: Resolution study is essential because numerical diffusion kills the "turbulence",

i.e., underestimate the viscous parameter

Highest & longest simulation to date (70m & 200ms)



Power spectrum of the B field

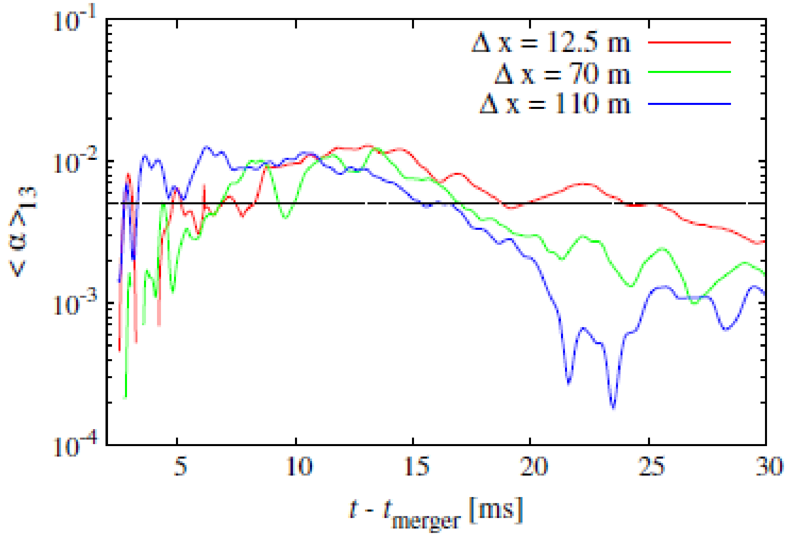


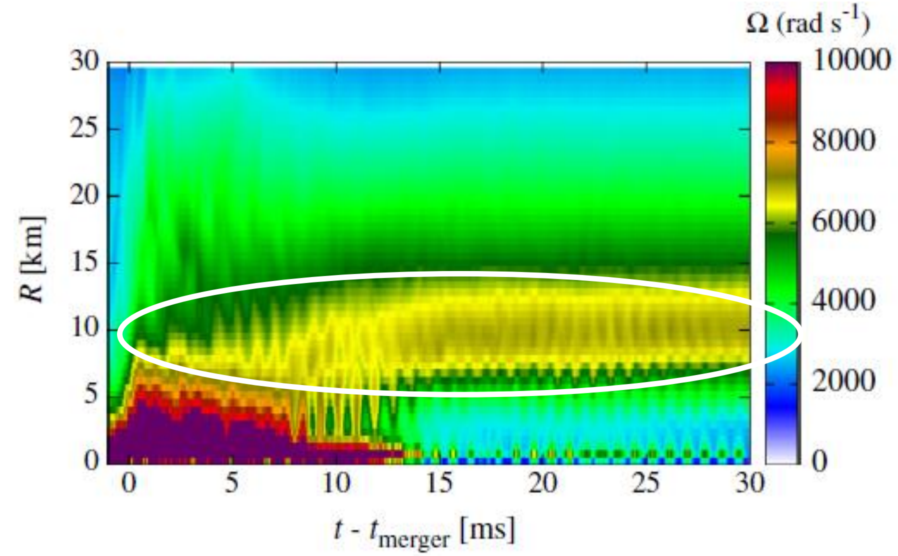
▶KH instability amplifies the small scale magnetic field efficiently

▶ Magneto Rotational Instability sustains the turbulence

α -viscosity parameter

$$13 \leq \log_{10}[\rho\,(\mathrm{g\,cm^{-3}})] < 14$$



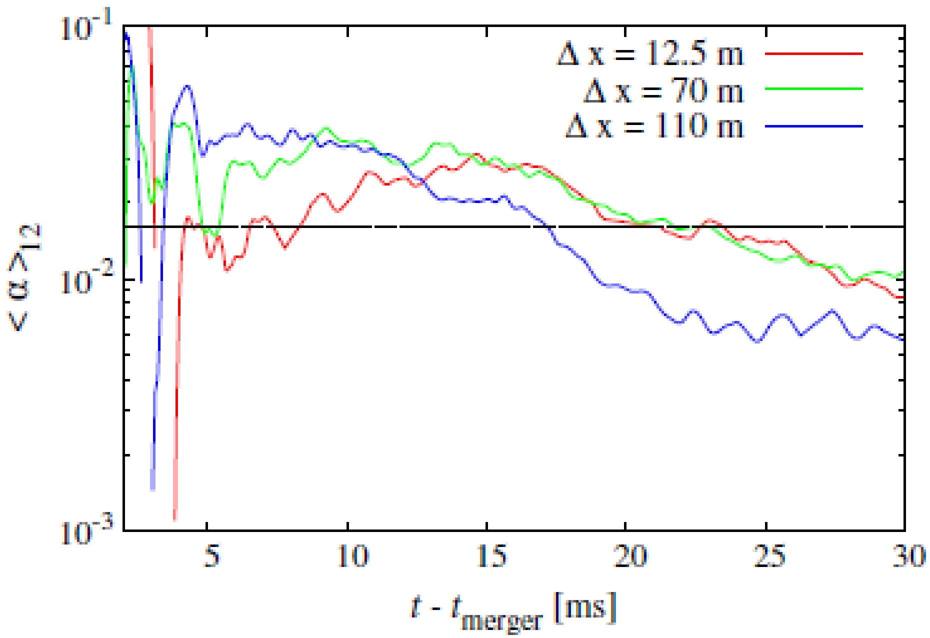


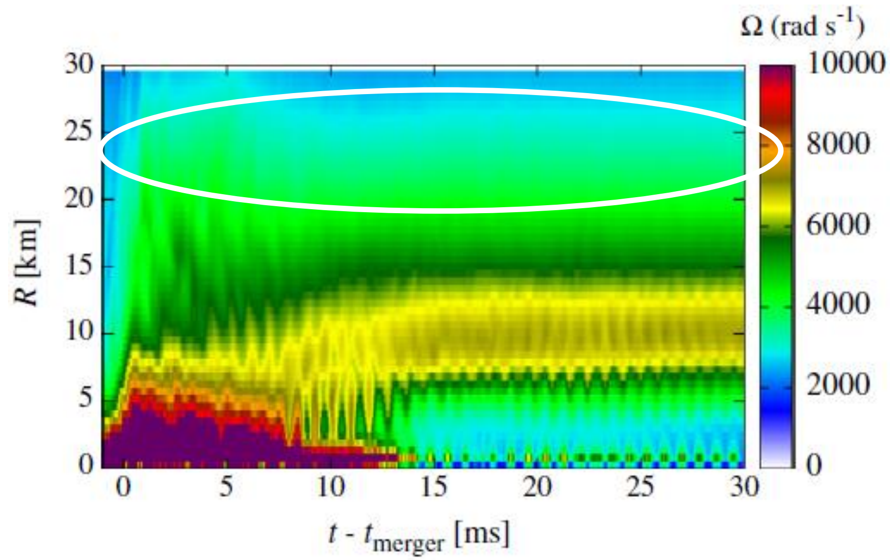
- $<< \alpha >> \gtrsim 4 \times 10^{-3}$ for the dense core
- $t_{vis} \lesssim 120$ ms $(<< \alpha >>/\ 4 \times 10^{-3})^{-1}$ $\times (<j>/1.7 \times 10^{16} \mathrm{cm^2 s^{-1}})(<c_s>/0.2c)^{-2}$

The turbulence dies away with the dx$\gtrsim$70m resolution, i.e., O(100ms) simulation with dx$\gtrsim$70m is unreliable.

α -viscosity parameter

$$12 \leq \log_{10}[\rho\,(\mathrm{g\,cm^{-3}})] < 13$$





▶ $<<\alpha>> \approx 1\times10^{-2}$ for the low-density envelope

Caveat: we cannot judge the reliability of the simulation with *one grid resolution simulation*.

Impact of the turbulent viscosity on the post-merger GWs (Shibata & KK 17a, b. Radice 17)

▶ α is likely to be $O(10^{-2})$ in merger remnants
⇒ Angular momentum transport may affect post merger GW signals.

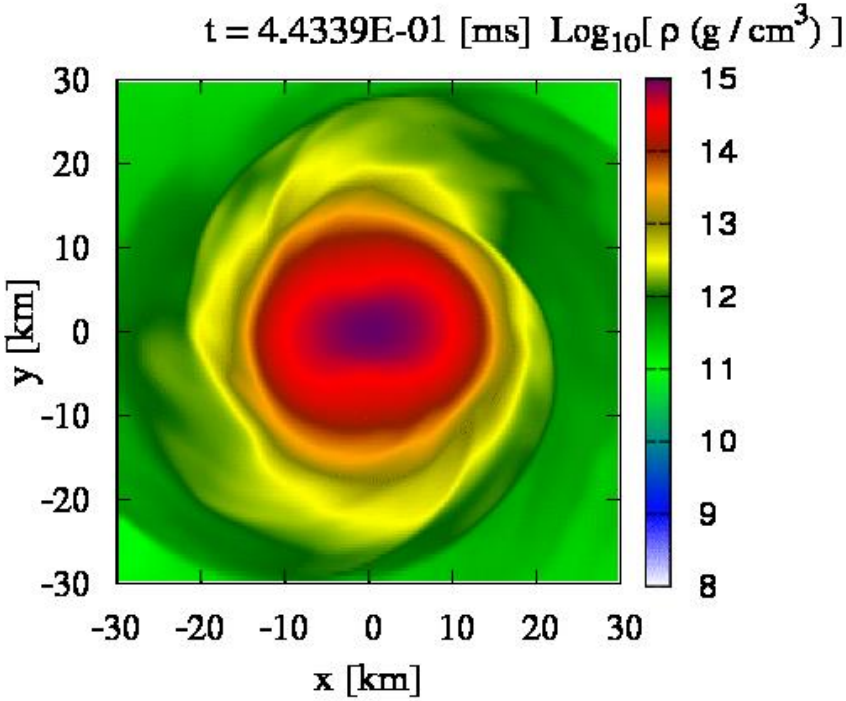
<u>Simulation</u>

3D GR viscous hydrodynamics simulation of BNS merger;

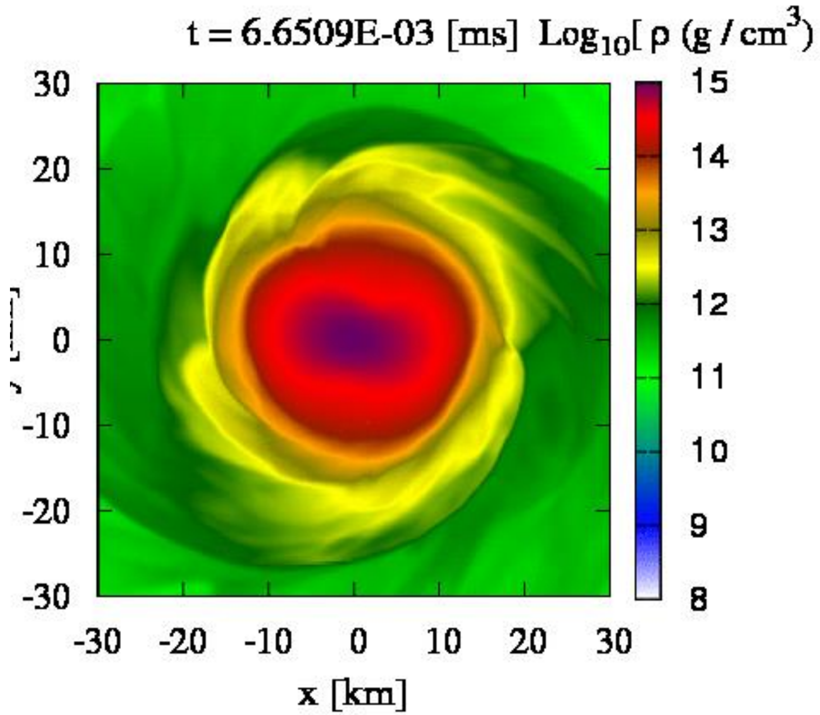
$$\nu = \alpha \frac{c_s^2}{\Omega}$$

Impact of the turbulent viscosity on the post-merger GWs (Shibata & KK 17a, b. Radice 17)

$\alpha = 0$



$\alpha = 0.02$

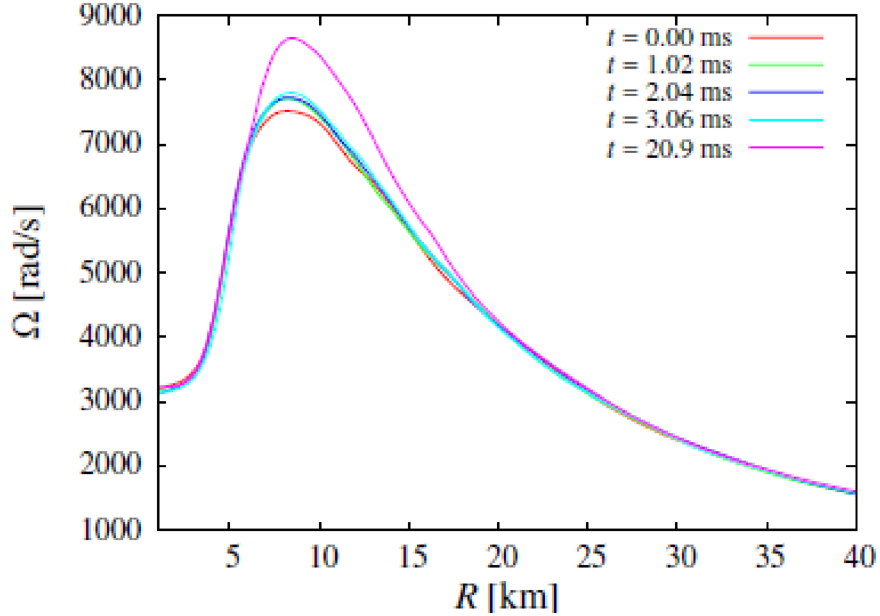


▶ Non-axisymmetric structure of the HMNS remains for the inviscid case (many references).

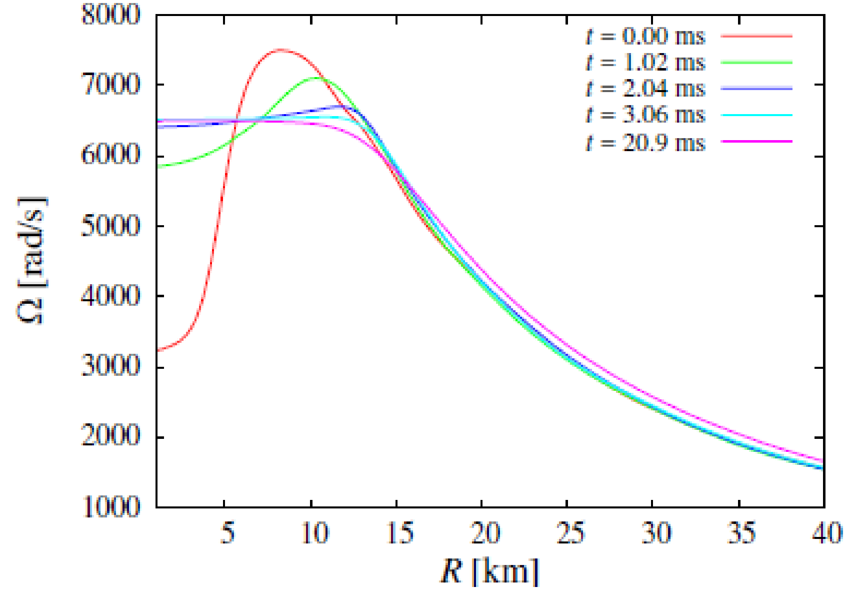
▶ Nearly axi-symmetric structure for the viscid case

Angular velocity evolution

$\alpha\ = 0.00$



$\alpha\ = 0.02$



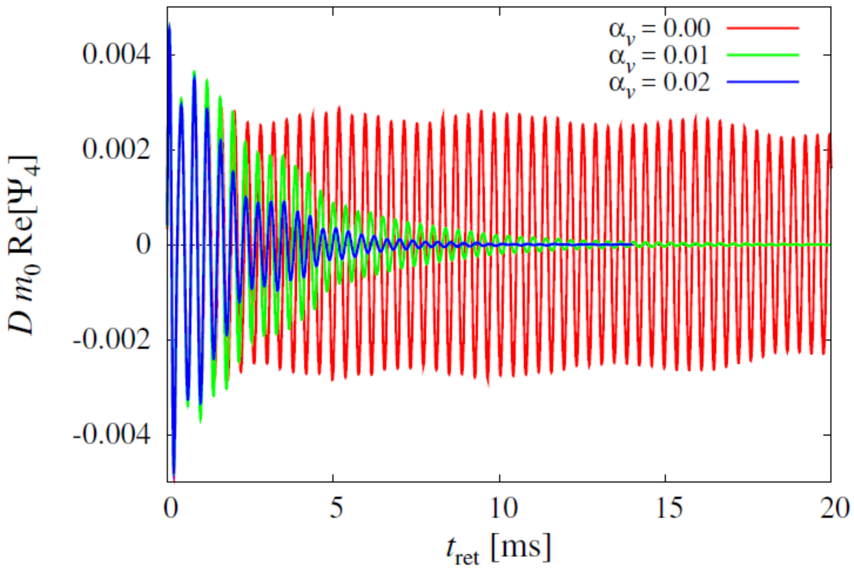
▶ Inner part quickly relaxes into an uniform rotation

cf. $t_{\rm vis} \approx 4.4\,{\rm ms}(\alpha/0.01)^{-1}(c_s/0.5\,c)^{-2}(R/10\,{\rm km})^2(\Omega/10^4\,{\rm rad/s})$

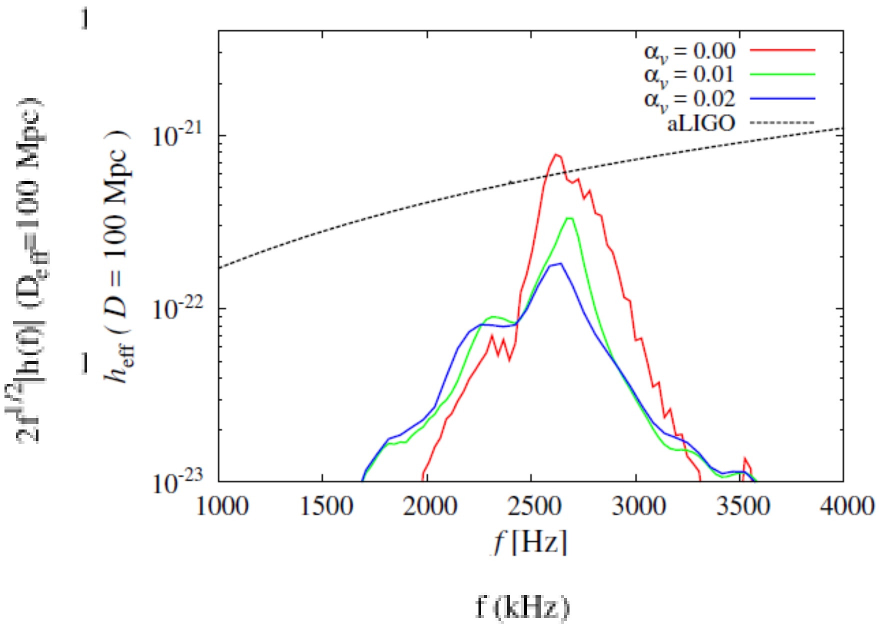
▶ The density structure relaxes into an axi-symmetric structure.

Impact of the turbulent viscosity on the post-merger GWs (Shibata & KK 17a, b. Radice 17)

Waveforms



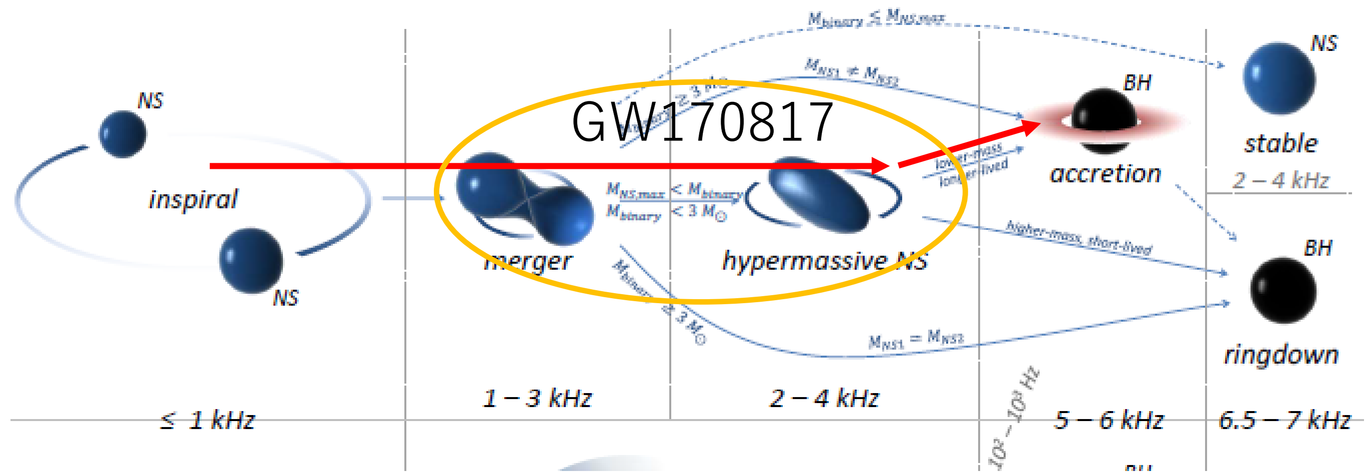
Spectrum



▶ Quasi periodic GWs for the inviscid case.

▶ No post merger signal from GW170817 (LSC collaboration 17)

How does the turbulence change the story?



<u>Open questions</u>

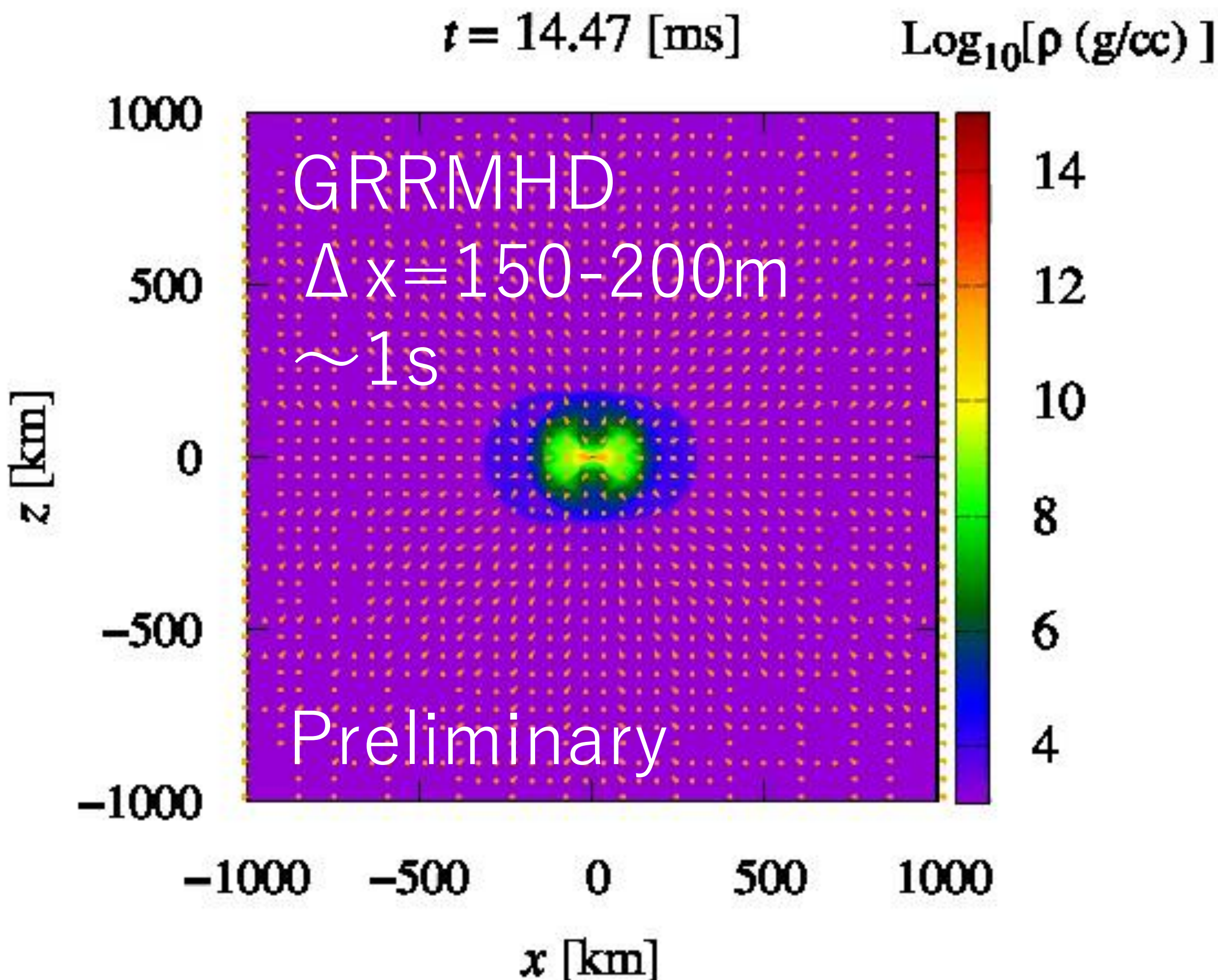
▶f_{peak}-Λ relation could be modified due to the KH-induced B-field, B_{local}∼$10^{16\text{-}17}$G

▶f_2-Λ relation could be modified due to the MHD instability-driven turbulence, only amplitude? or frequency?

▶ How large is the wind component?

To answer these questions

3D General Relativistic neutrino Radiation Magneto Hydrodynamics (with high spatial resolution and for long term) is necessary



Summary

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

▶ Numerical modeling is necessary to predict and understand observed events

▶ More sophisticated model ⇒ control the systematics stemming from the numerics, unimplemented physics, binary model and etc.

Turbulence is a key quantity for building a sophisticated model of the post-merger!

Science target of compact binary mergers

Exploring the theory of gravity

▶GW150914 etc. is consistent with GR prediction
(Abott et al. 16, 18)

But, it does not imply that GR is the theory of gravity in a strong gravitational field.

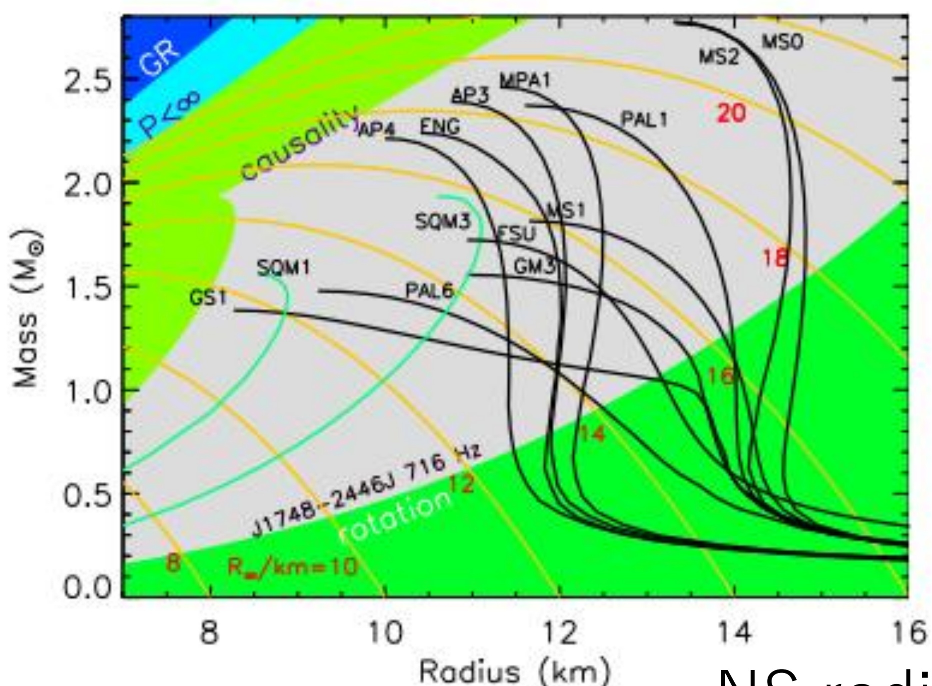
cf. Quasi normal mode from a merger remnant of BBH could prove the theory of gravity (Nakano et al. 16)

Science target of compact binary mergers

Exploring the Equation of State (EOS) of NS matter

NS interior state is poorly known

NS mass



NS radius

▶ Extraction of the information of NS mass and radius imprinted in merger waveforms ⇒ The EOS of NS matter (Flanagan & Hinderer 08 etc.)

Science target of compact binary mergers

Mystery of the central engine of Short-hard Gamma Ray Burst

- $E_{iso,\gamma} \sim 10^{49}$-$10^{51}$ g cm^2 s^{-2}, Duration ~ 0.1-2 s

They release the huge energy in a short time scale ⇒ A compact object could drive them.

Light curve of GRB

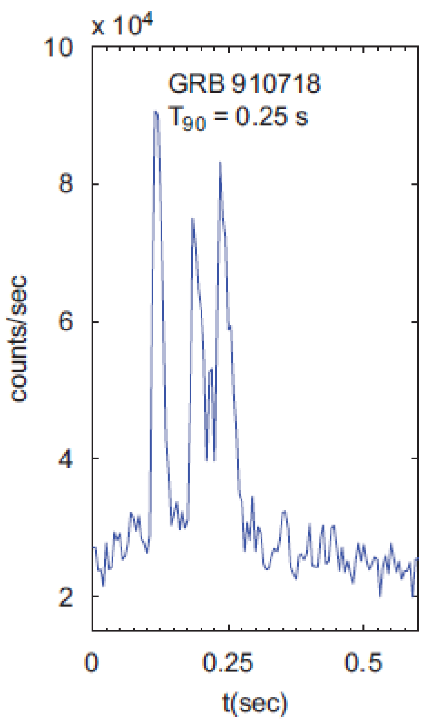
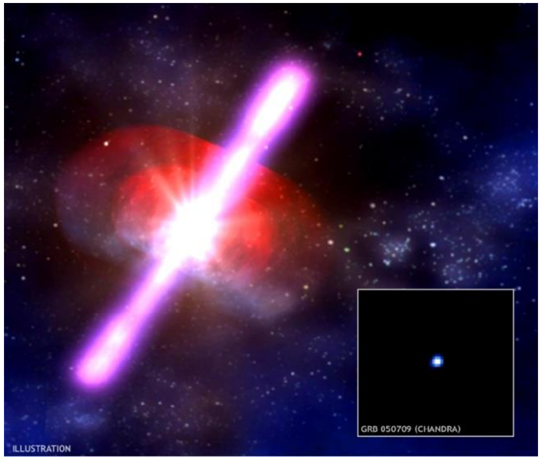
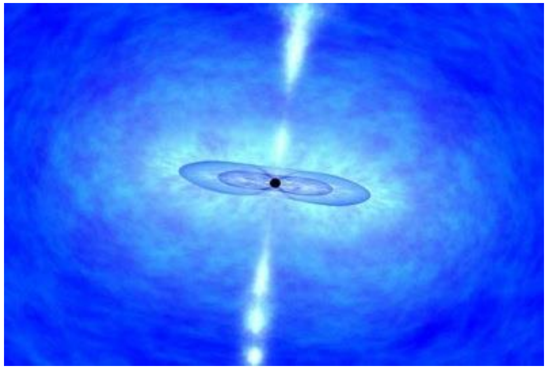


Image of GRB



Black-hole – Torus ?



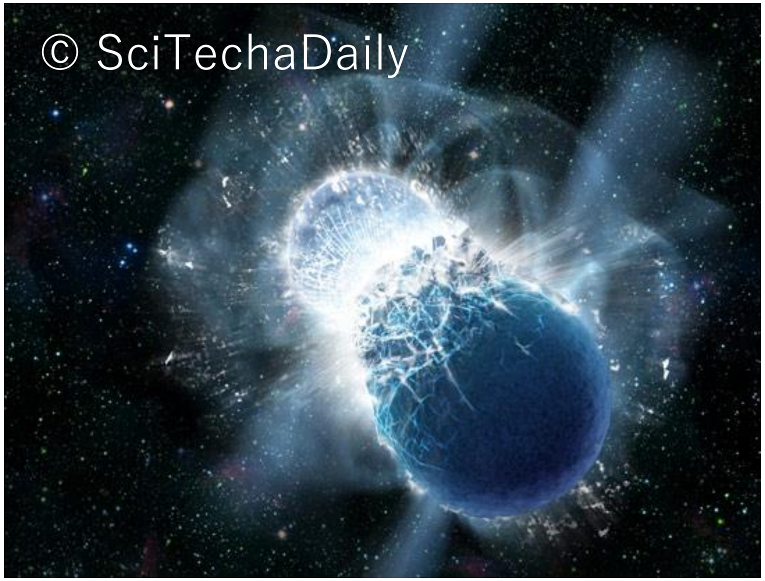
NS-NS or BH-NS merger could drive the GRBs.

Science target of compact binary mergers

Origin of heavy elements in the Universe

Nucleosynthesis by rapid neutron capture process

⇒ Mystery of the nucleosynthesis site



▶NS-NS/BH-NS merger⇒Mass ejection of the neutron rich matter⇒R-process nucleosynthesis

(Lattimer & Schramm 76, Wanajo et al. 14)

Detected UV-Optical-Infrared emission

- Long-duration IR component (Red)

$$t_{\rm peak} \approx 7.1\,{\rm day}\left(\frac{\kappa}{10\,{\rm cm^2 g^{-1}}}\right)^{1/2}\left(\frac{M}{0.035M_\odot}\right)^{1/2}\left(\frac{v_{\rm eje}}{0.25c}\right)^{-1/2}$$

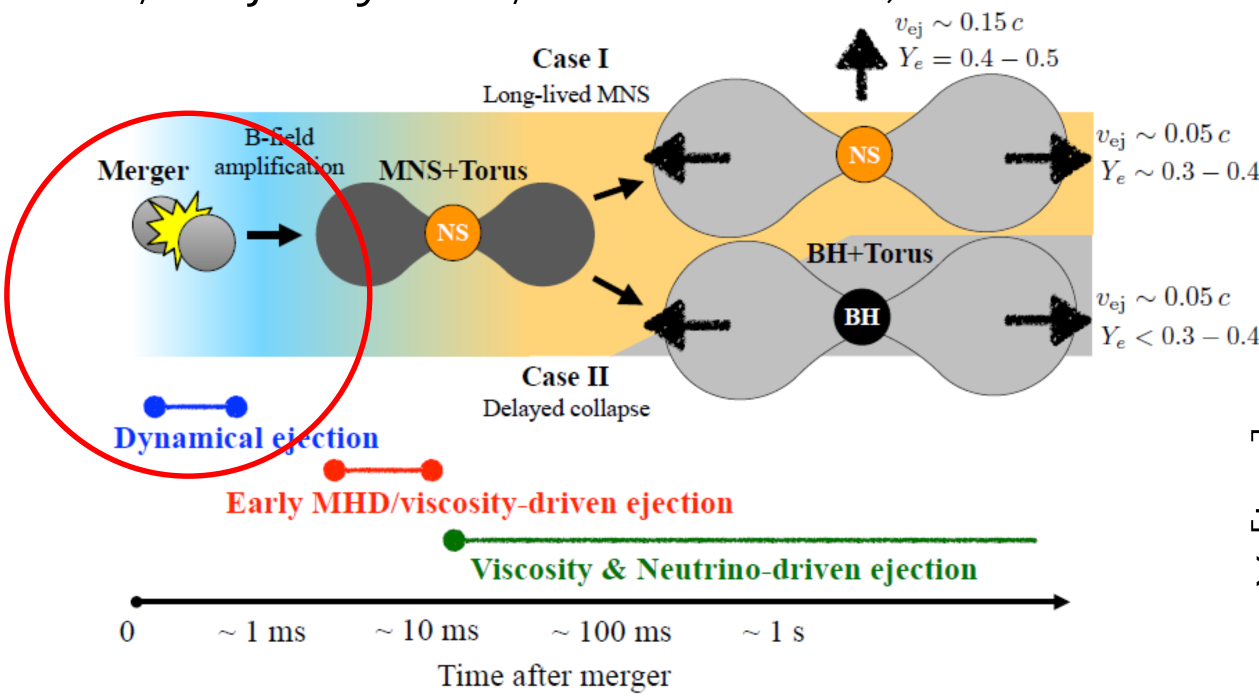
- Short-duration UV-IR component (Blue)

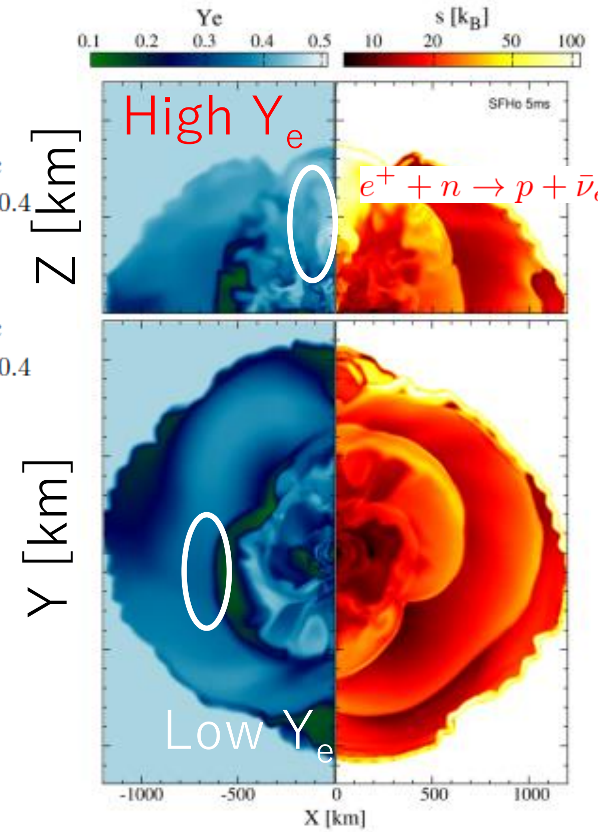
$$t_{\rm peak} \approx 1.5\,{\rm day}\left(\frac{\kappa}{1\,{\rm cm^2 g^{-1}}}\right)^{1/2}\left(\frac{M}{0.025M_\odot}\right)^{1/2}\left(\frac{v_{\rm eje}}{0.25c}\right)^{-1/2}$$

Short-duration blue component suggests the low-opacity (Lanthanide-free elements) ejecta.

We build a model of GW170817 based on the NR simulations : neutrino radiation transfer & effective turbulent viscosity

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)



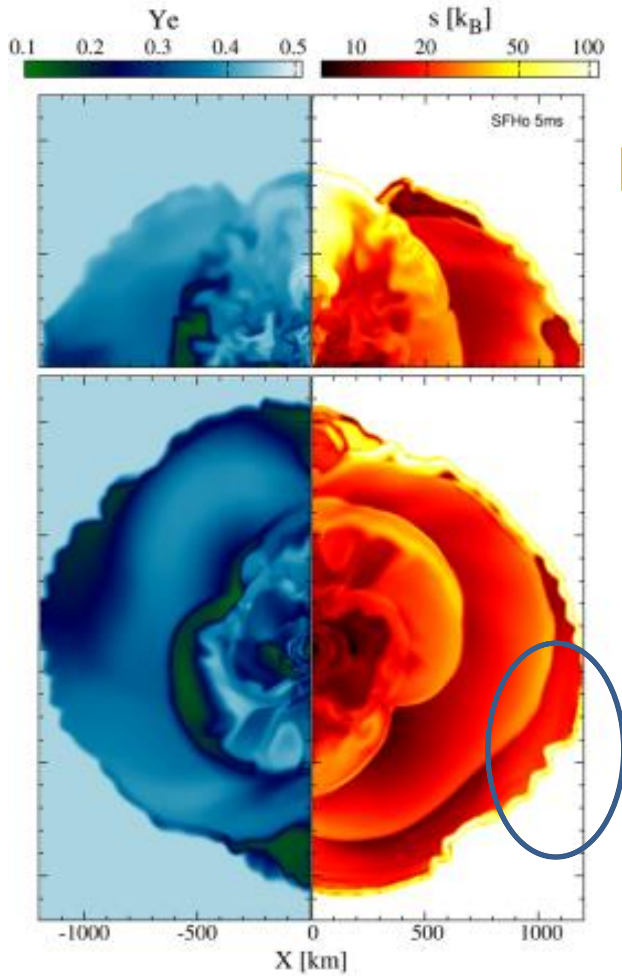


- ▶ $Y_e \lesssim 0.1$ before the merger
- ▶ The positron capture ($n+e^+ \Rightarrow p+\nu_e$) and neutrino absorption ($n+\nu_e \Rightarrow p+e^-$) increases Y_e.
- ▶ Dynamical ejection is primarily driven by tidal torque (orbital direction) ⇒ $M_{eje} \sim O(10^{-3}) M_\odot$, $Y_e \approx 0.05\text{-}0.5$, $\theta \gtrsim 45°$ ⇒ High opacity (red component)

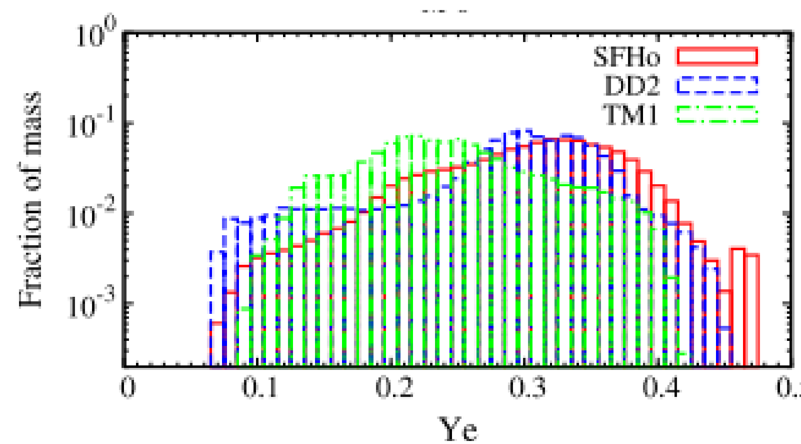
Neutrino radiation transport simulation of BNS mergers (Sekiguchi, KK et al. 15, 16, Wanajo et al. 14)

EOS : SFHo (Steiner et al. 2013), NS mass : 1.35-1.35$M_\odot$

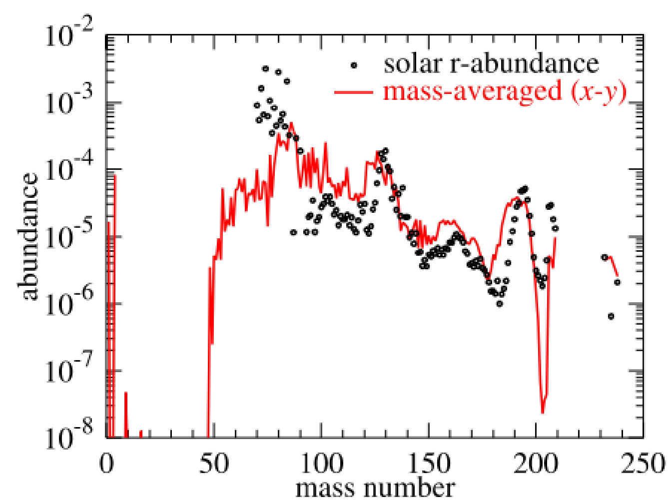
Ye Entropy



Mass histogram of Ye

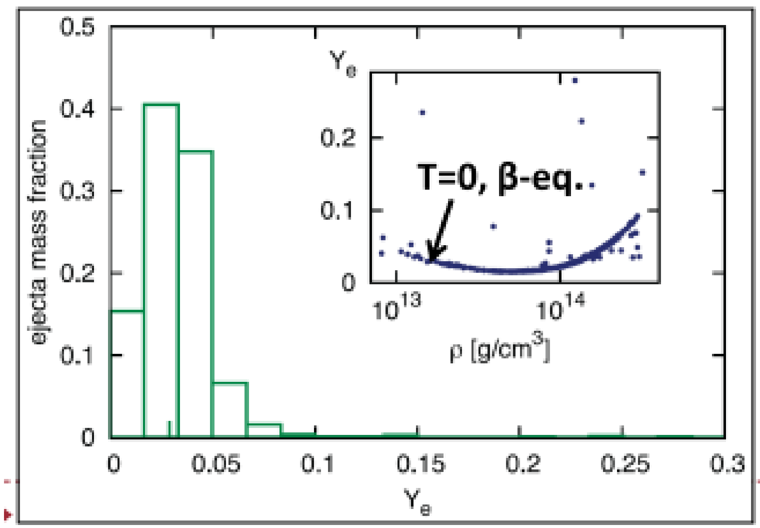


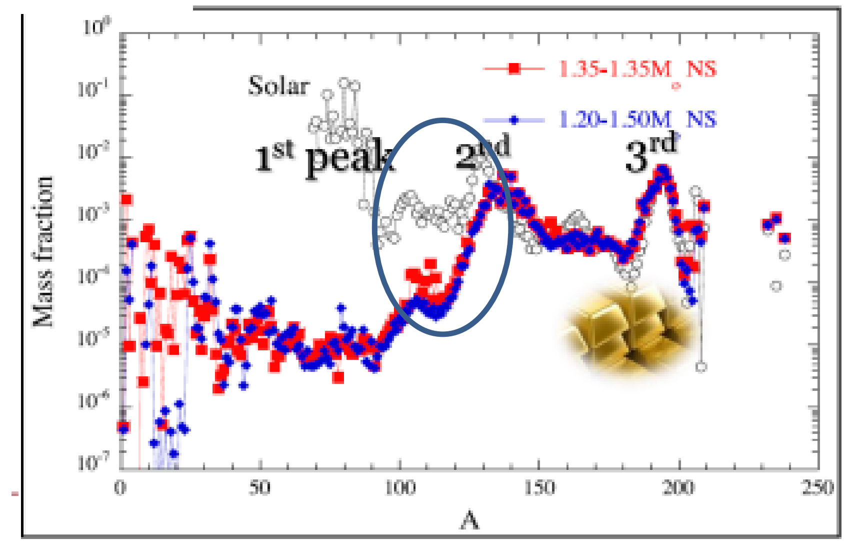
R-process



Neutrino radiation transport simulation of BNS mergers (Sekiguchi, KK et al. 15, 16, Wanajo et al. 14)

Previous works in which the neutrino effect is neglected (Korobkin et al. 12)

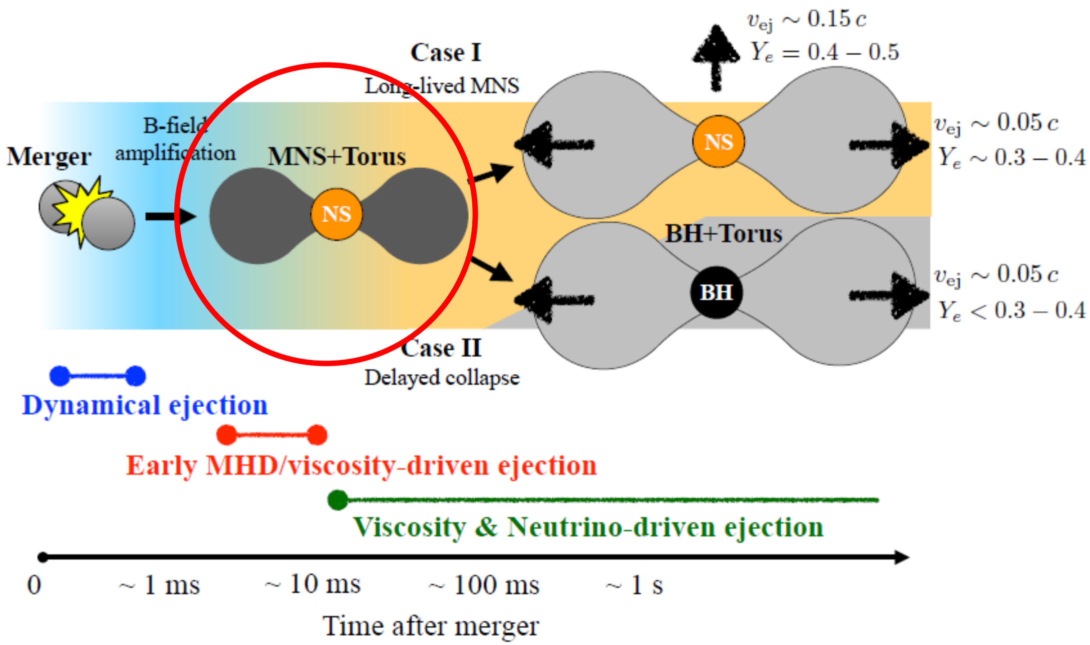


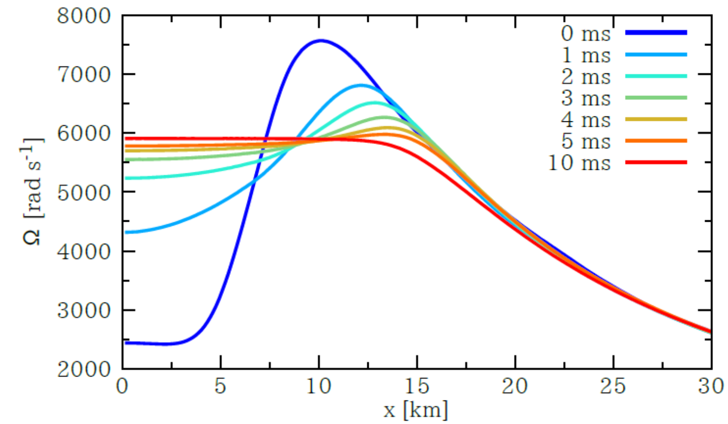


Similar result is obtained in Newtonian neutrino radiation transport simulation.

Caveat : Neutrino radiation transport (and GR) is essential to reproduce the solar abundance of the r-process elements.

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)

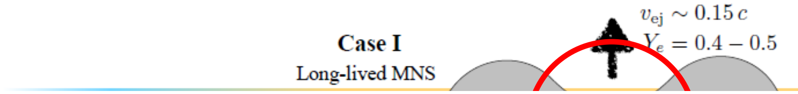


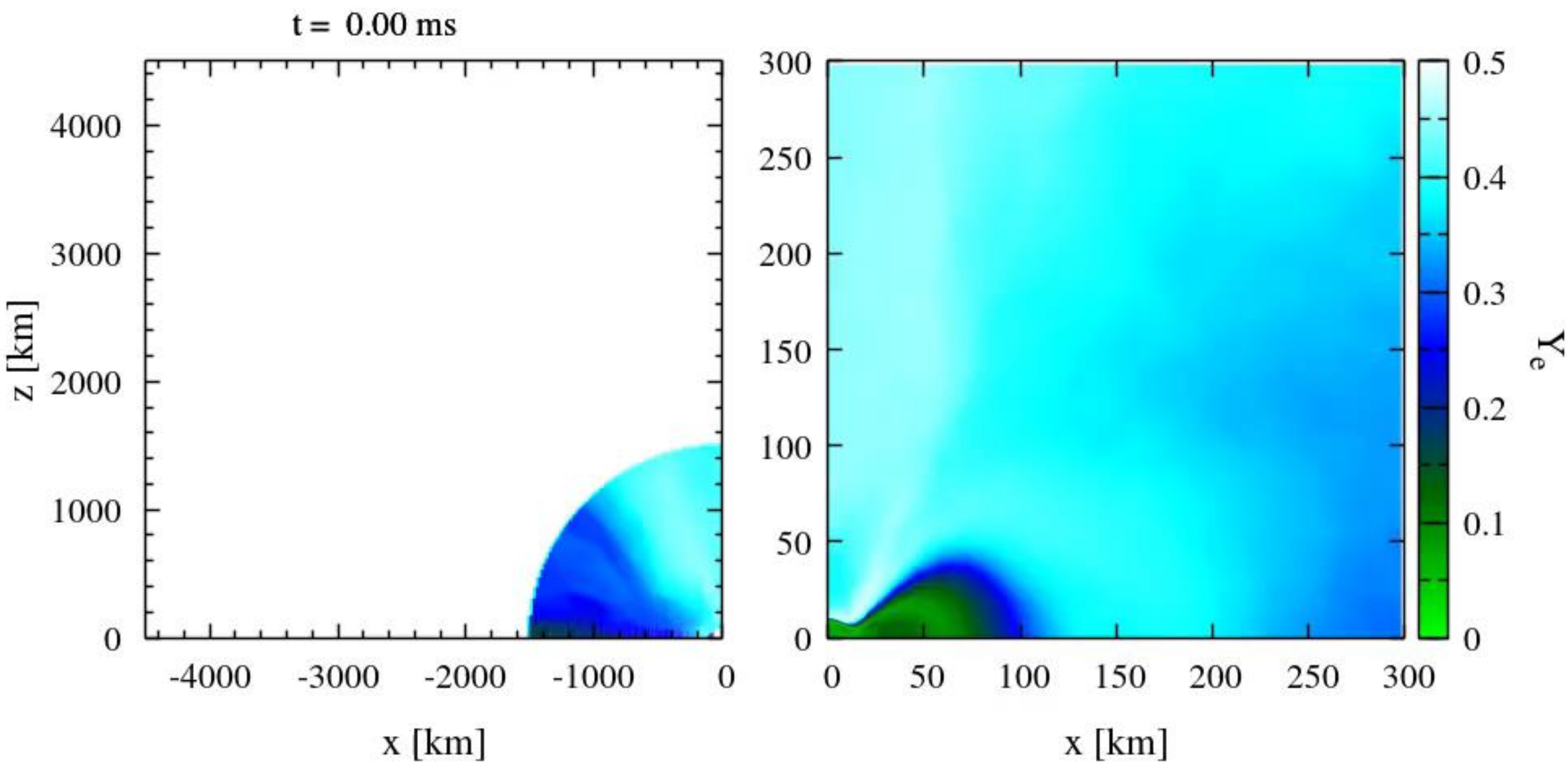


- Magneto-turbulent viscosity drives a quick angular momentum transport ⇒ Revelation of the differential rotational energy ⇒ Sound wave generation

$M_{eje} \sim 10^{-2} M_\odot (\alpha/0.02)$, $Y_e \approx 0.2$-0.5, $\theta \gtrsim 30°$, $v \sim 0.15$-$0.2c$ ⇒ Low opacity (blue component)

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)

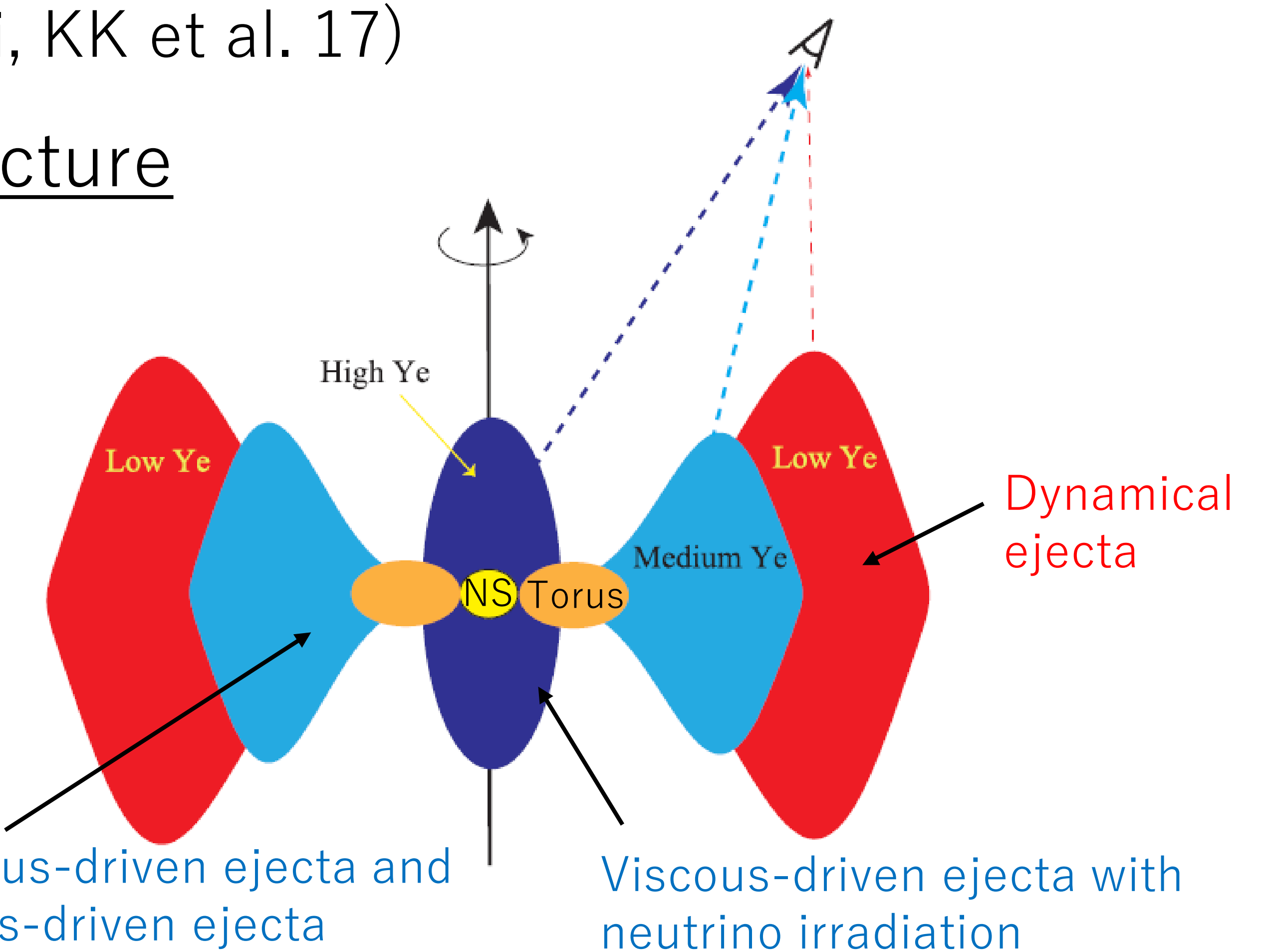




of the torus) ⇒ $\gtrsim 10^{-2}\,M_\odot$, $Y_e \approx 0.3$-0.4, $\theta \gtrsim 30°$ ⇒ Low opacity (blue component)

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)

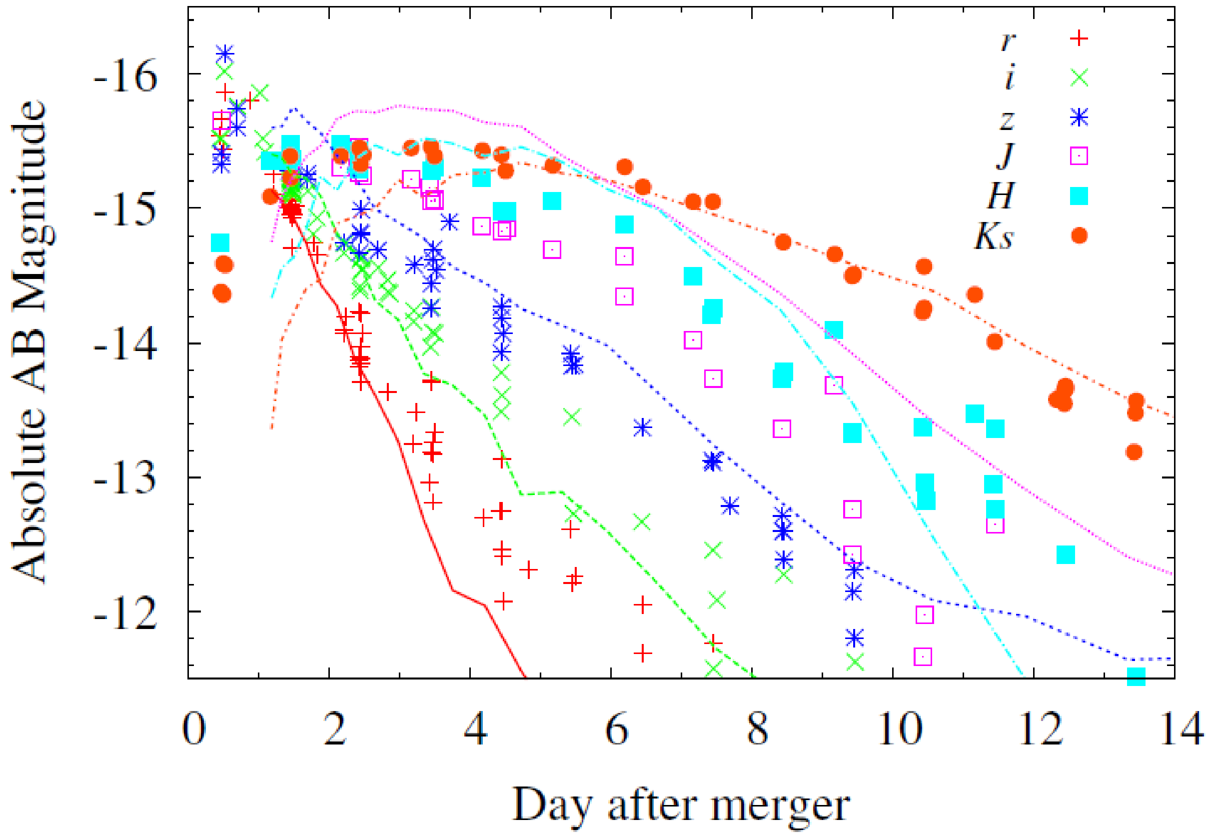
Schematic picture



▶ Ejecta has several components and red/blue depends on the viewing direction.

⇒GW and EM observations suggest the viewing angle is $\leq 28°$

Optical-Infrared emission from GW170817
(Tanaka et al. 17)



▶ Light curve (HSC) fitting by a photon radiation hydro. simulation with Ye of ～0.25

⇒ Agree with our numerical modeling

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)

▶ If a merger remnant is a very/permanently long-lived NS, the rotational energy of 10^{53} erg may be released by a magnetic dipole radiation.
⇒ Energy injection to ejecta
⇒ Optical counterpart of GW170817 did not show such an feature ($E_{kin} \approx 10^{50}$ erg)
⇒ Inferred merger remnant is a BH

▶Binary mass of GW170817 ≈ 2.73-2.78$M_\odot$
▶Mass (energy) radiated from a remnant via GW, neutrino, and ejecta ≈ 0.15∓0.03 $M_\odot$
⇒ Estimated remnant mass ≈ 2.60∓0.05 $M_\odot$
⇒ $M_{max,sph} = M_{max,rigid} / 1.2 = 2.15\text{-}2.25\ M_\odot$

Numerical modeling of GW170817 (Shibata et al. 18, Fujibayashi, KK et al. 17)

▶ Estimated merger rate from GW170817
⇒ $R \approx 0.8^{+1.6}_{-0.6} \times 10^{-4}\ \mathrm{yr}^{-1}/\mathrm{gal}$

▶ Assuming all the r-process elements are synthesized in BNS mergers,

$$R_{\text{r-process}} \approx 10^{-4}\ \mathrm{yr}^{-1}/\mathrm{gal}\ (M_{A\geq 90}/5\times 10^{-3} M_{\odot})$$

Consistent in order of magnitude estimation