Neutron star mergers

Kenta Kiuchi

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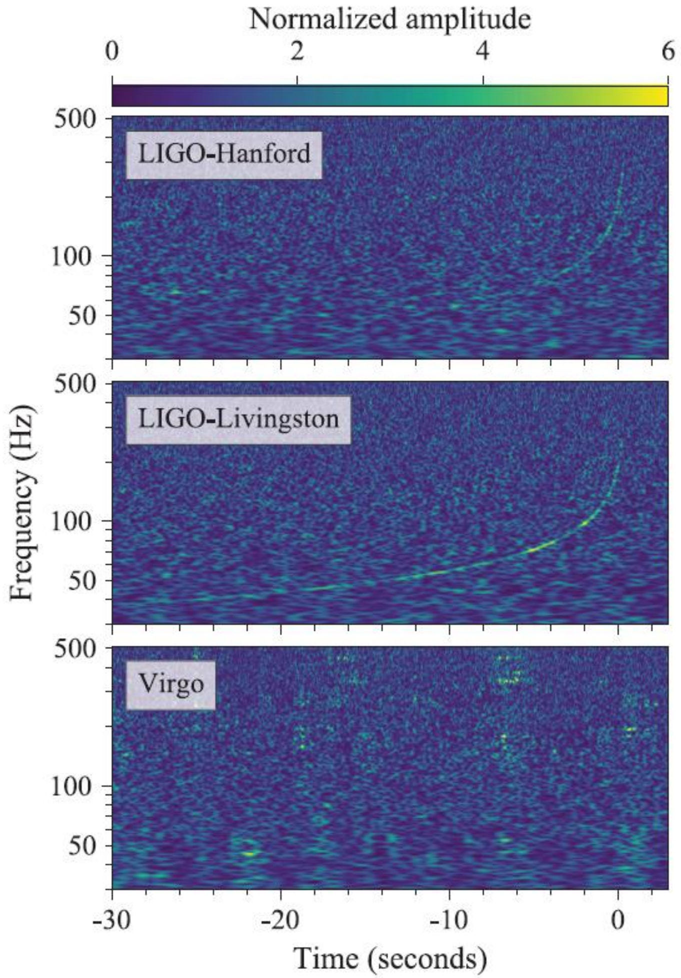
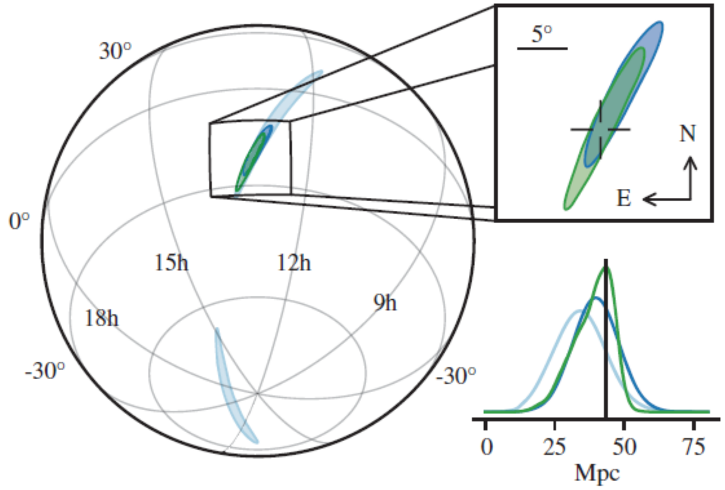
CGP

GW170817/AT2017gfo/GRB170817



Sky map by LIGO + VIRGO

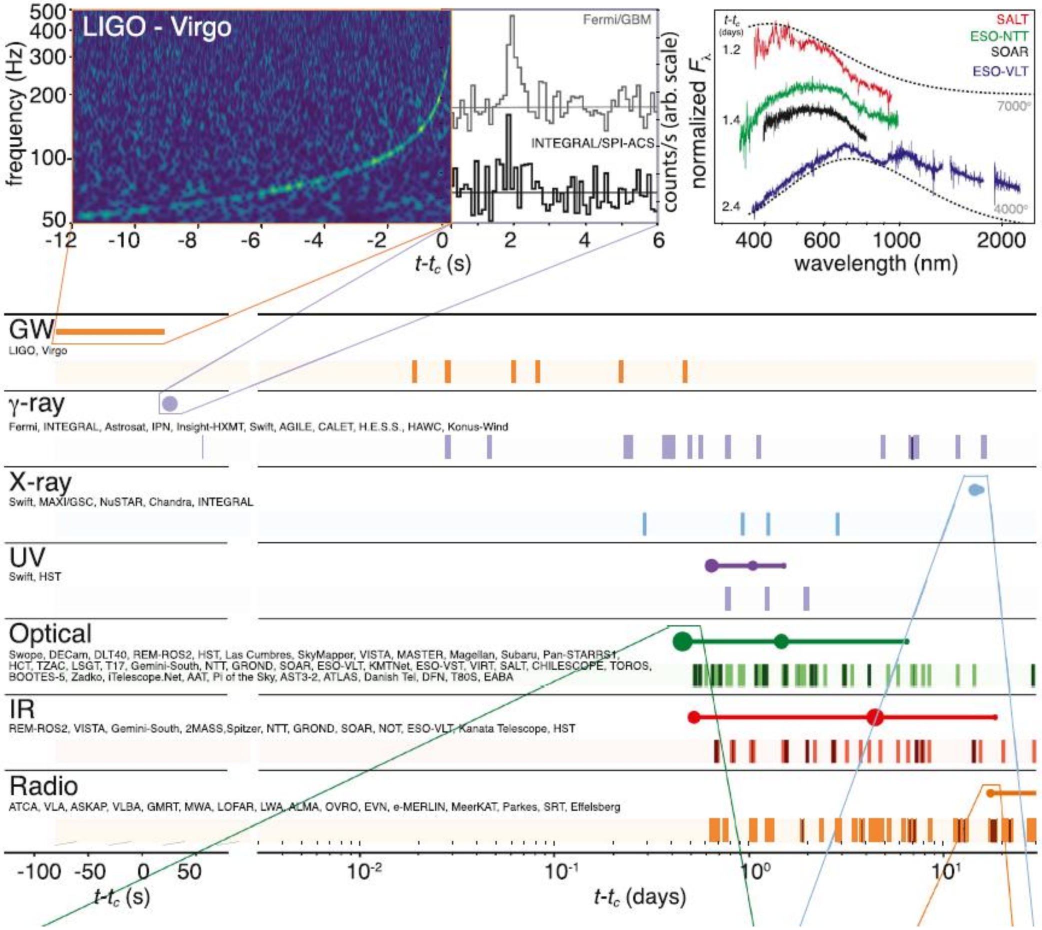


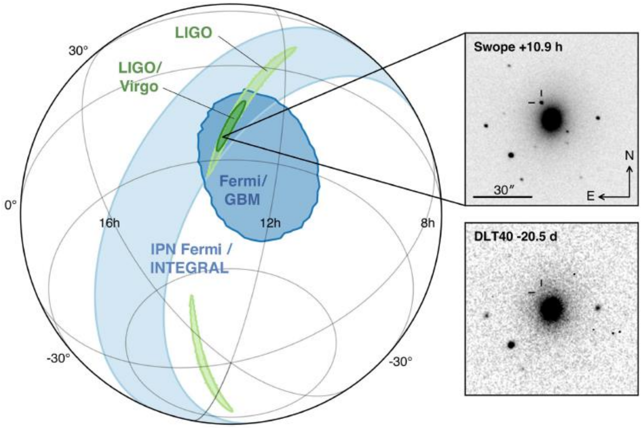
LSC-Virgo collaboration
PRL 2017

▶ Aug. 17th 2017, 74 sec. signals detected by LIGO-Hanford.

▶ S/N is 32.4 !

Real Multimessenger Astronomy Era

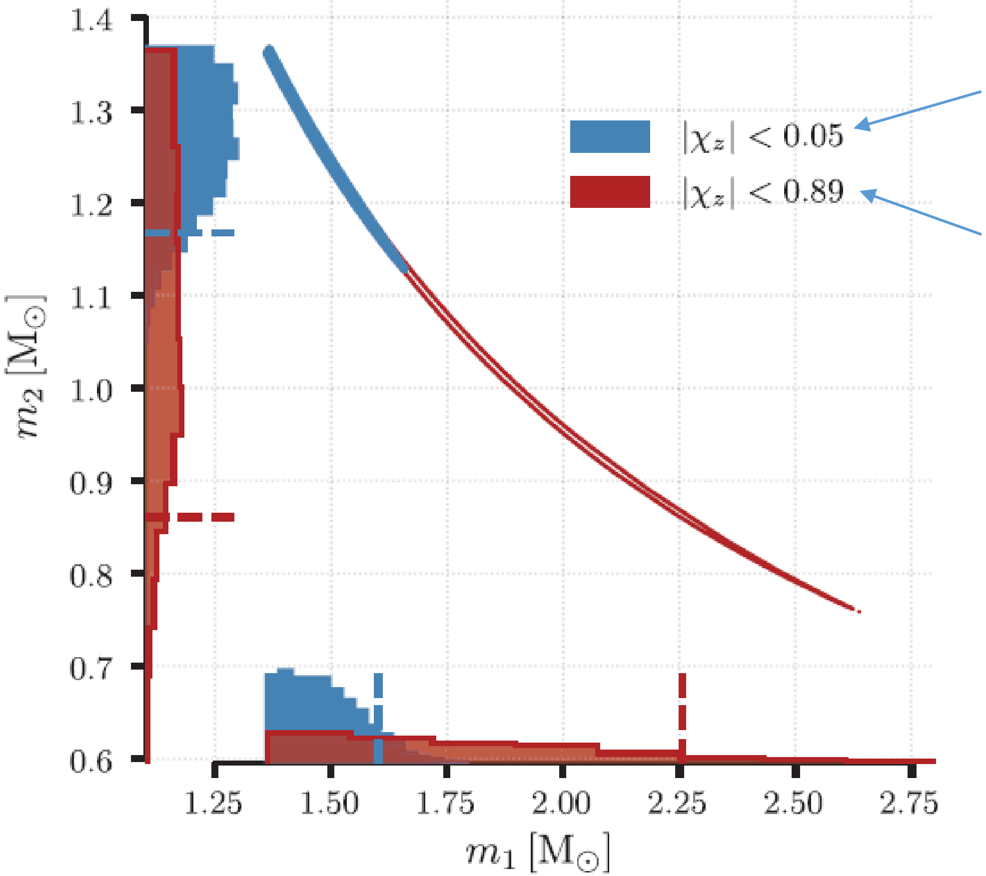




LSC-Virgo collaboration
APJ 848, L12, 2017

- 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)

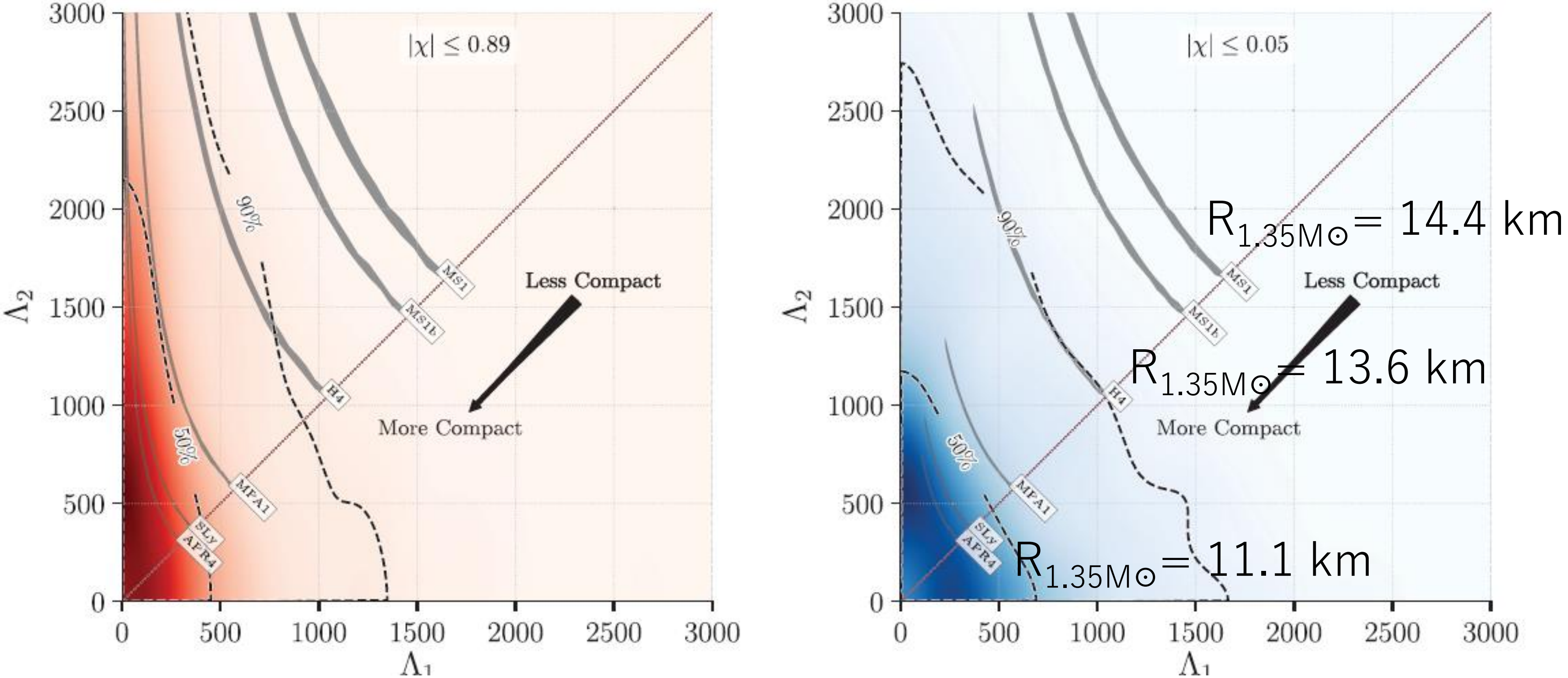
- Mass measurement of NSs.

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)



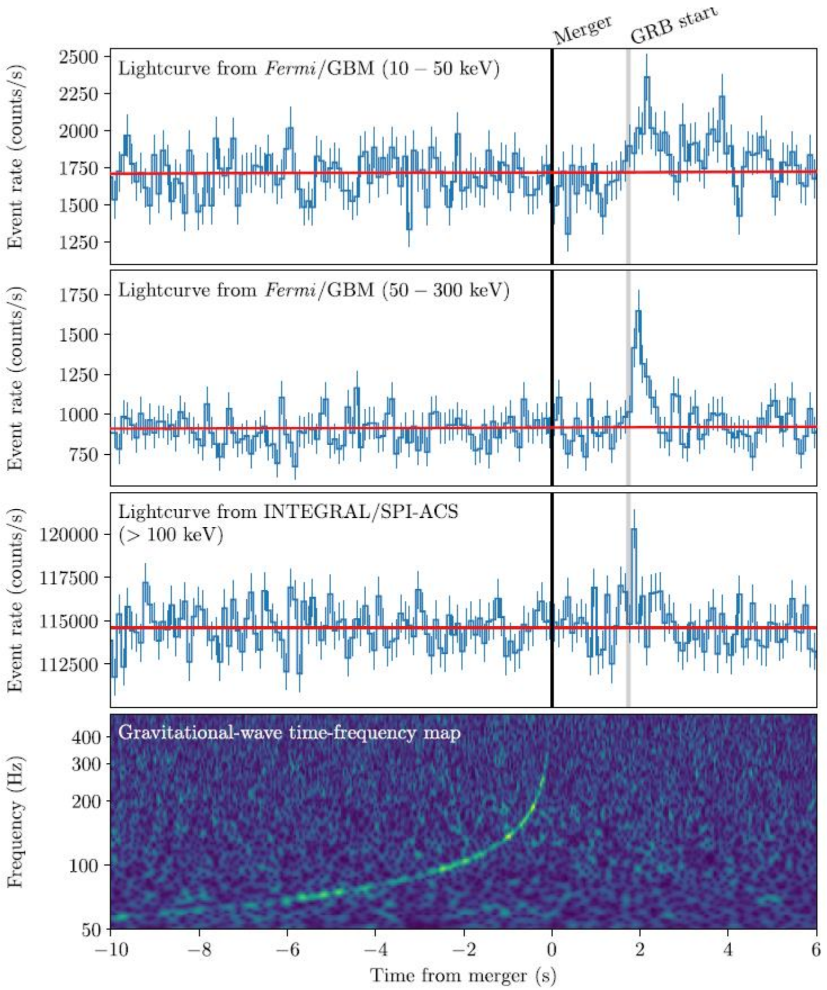
$R_{1.35M_\odot}$ = 14.4 km

$R_{1.35M_\odot}$ = 13.6 km

$R_{1.35M_\odot}$ = 11.1 km

- ▶ Tidal deformation Λ is related to a NS radius ⇒ Information of the NS equation of state.
- ▶ Soft EOS is favored ($\Lambda \leq 800$)

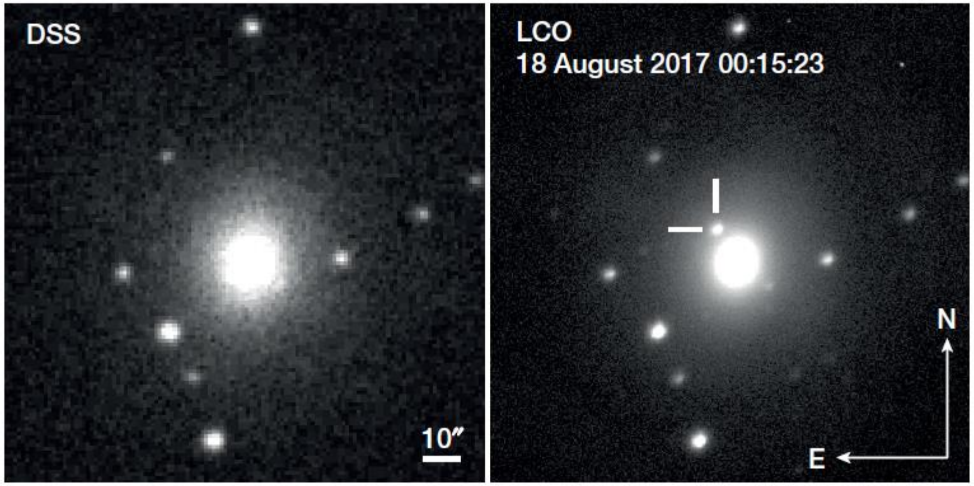
Detection of GRB170817A



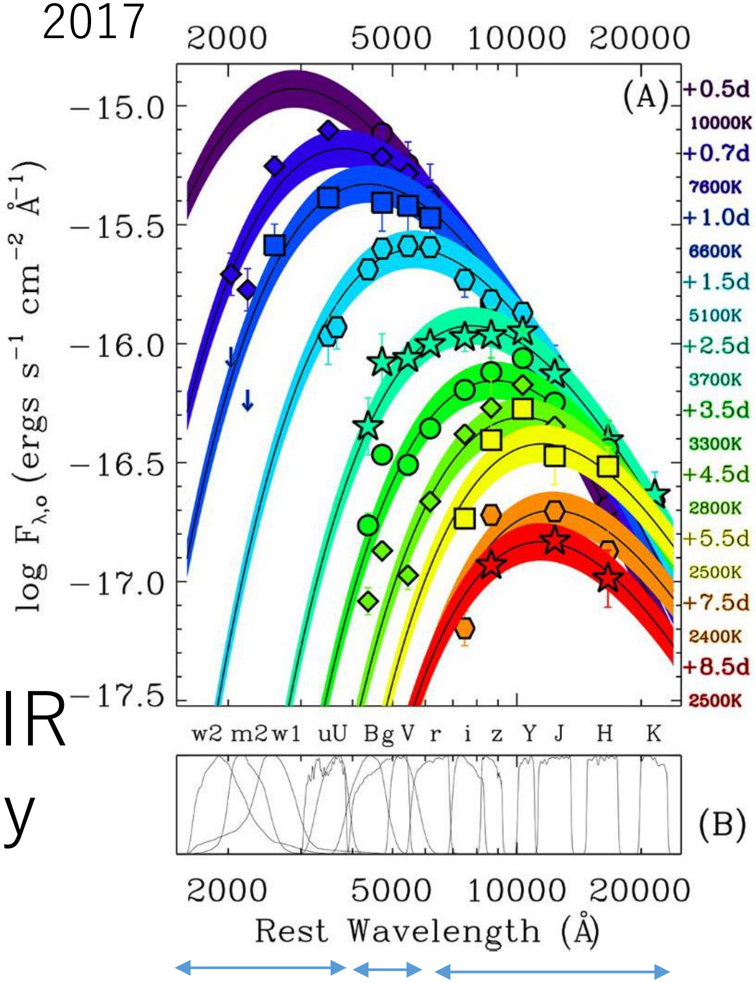
- ▶ $T_{90} = 2.0 \mp 0.5$ s, $T_0 = 1.7$s
- ▶ $E_{iso} \sim 5 \times 10^{46}$ erg (too dim)

Detected UV-Optical-Infrared emission

Arcavi et al. Nature 24291, 2017



Drout et al. Science (aaq0049) 2017



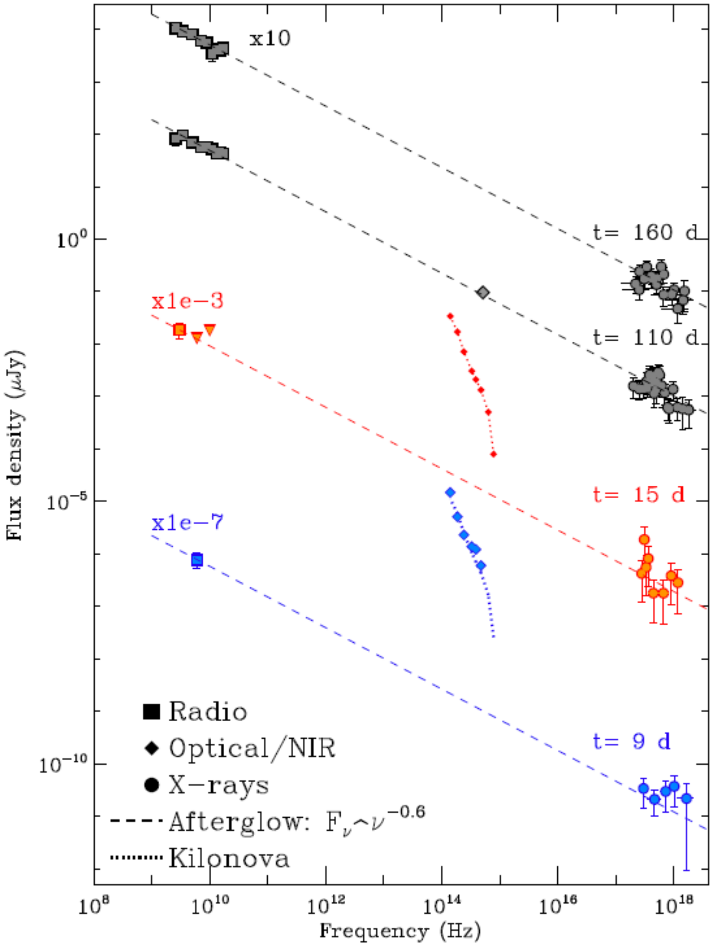
UV Optical IR

▶ Rapid reddening from UV to IR

▶ Spectrum is quasi-black body

▶ Long-duration IR component ($\sim 0.03M_\odot$)& short-duration UV-Optical component ($\sim 0.02M_\odot$)

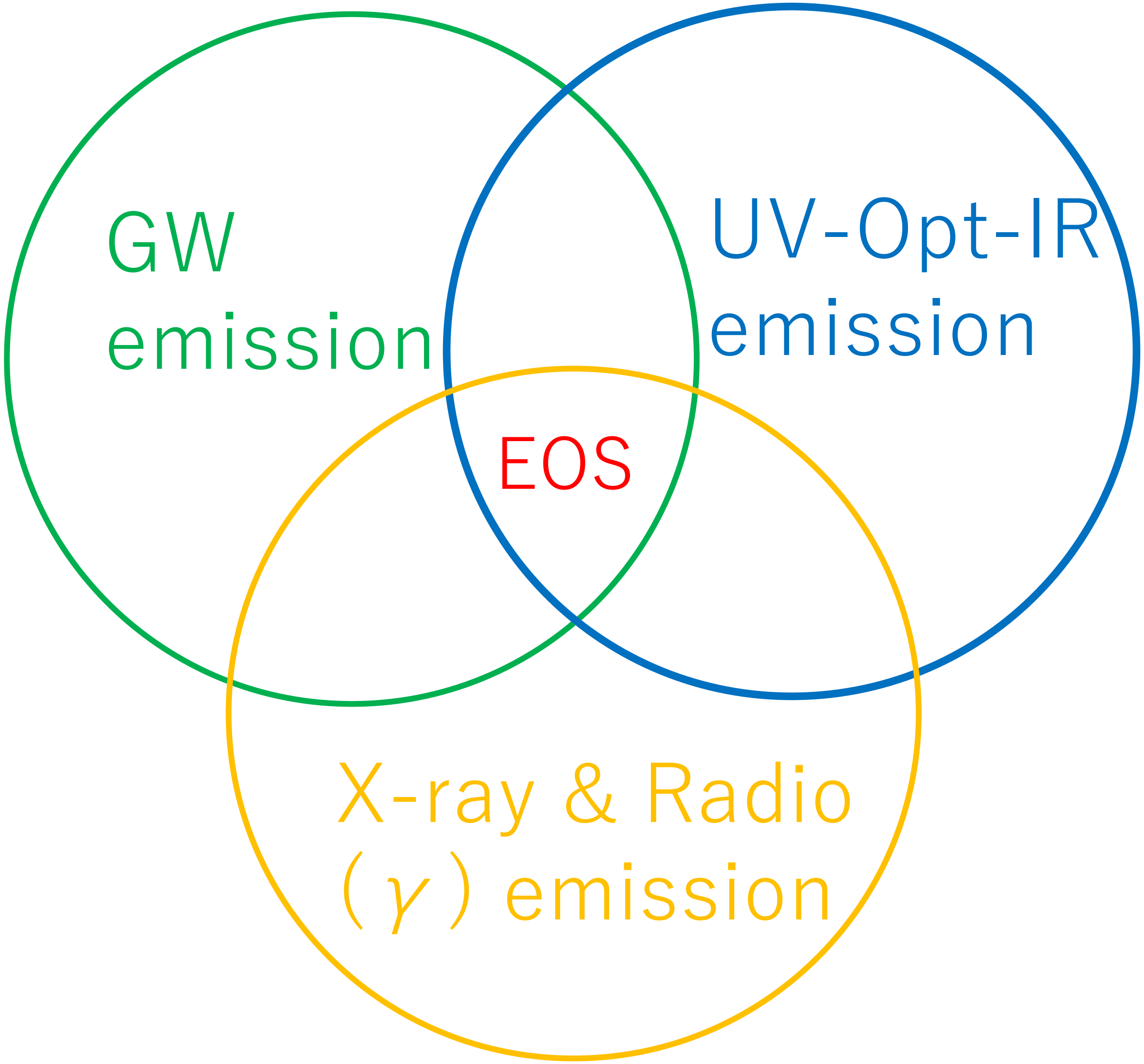
About 160 days observation @ Radio, X-ray observation after the merger



Margutti et al. 18
See also Mooley et al. 17, Troja et al. 17, Hallnan et al. 17
Very recent papers Alexander et al. 18, Dobie et al. 18

▶ Dynamical ejecta? Structured Jet? Cocoon emission?
(Margutti et al. 17, Gottleb et al. 17, Lazatti et al. 17)

Bottom line of this talk



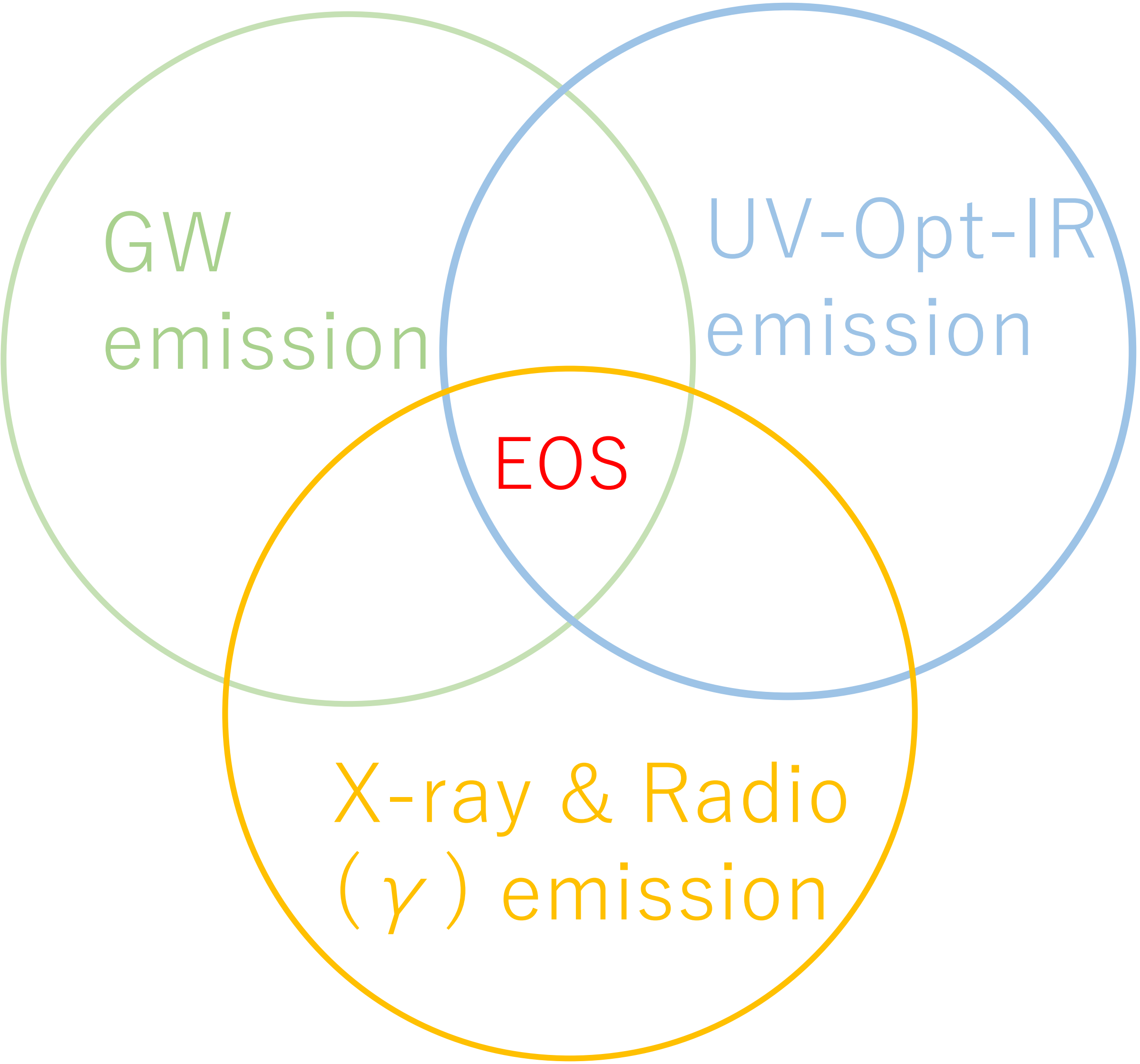
GW emission

UV-Opt-IR emission

X-ray & Radio (γ) emission

EOS

Bottom line of this talk



GW emission

UV-Opt-IR emission

X-ray & Radio (γ) emission

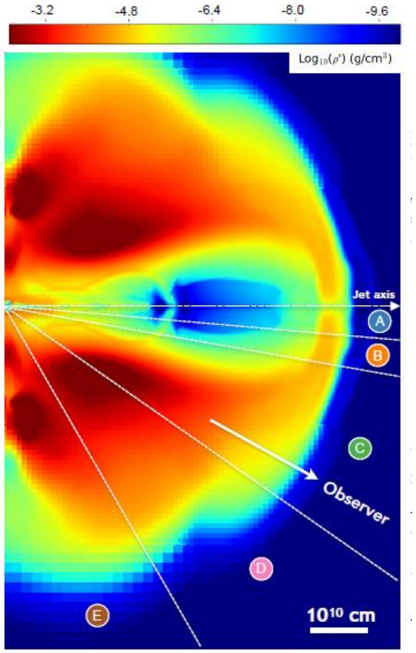
EOS

Three possibilities to explain X-ray and radio observations

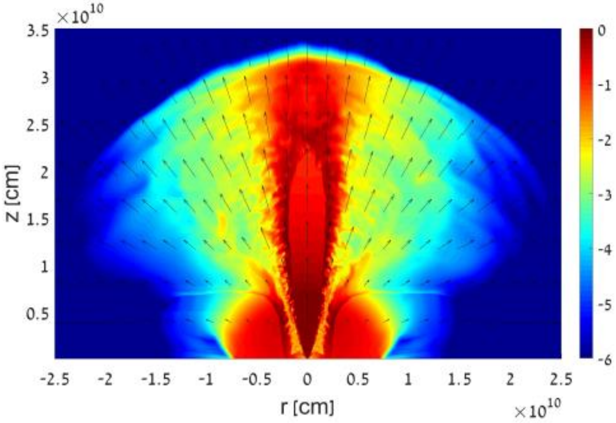
Structured Jet

Cocoon emission

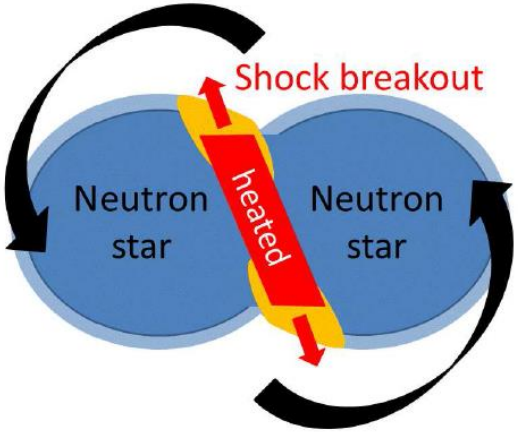
Fast tail of dynamical ejecta



Lazzati et al. 18



Gottieb, Nakar, Piran 18



Kyutoku, Ioka, Shiata 13

We explore the third possibility based on NR simulations.

Basics of synchrotron emission (Sari et al. 98)

Characteristic frequency

$$\nu(\gamma_e) = \Gamma \gamma_e^2 \frac{q_e B}{2\pi m_e c}, \ \gamma_e \ : \text{ electron Lotentz factor}$$

Electron power law distribution

$$N(\gamma_e) d\gamma_e \propto \gamma_e^{-p} d\gamma_e,$$

$$\gamma_e \ \geq \ \gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} (\Gamma - 1)$$

Critical Lorentz factor

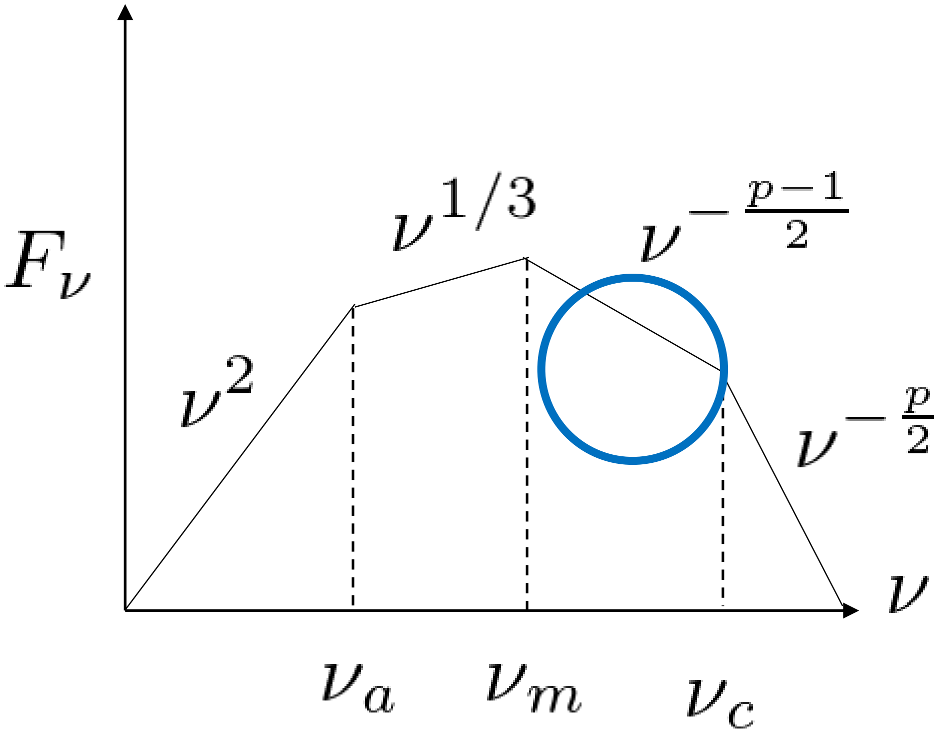
$$\gamma_c = \frac{3 m_e}{16 \epsilon_B \sigma_T m_p c} (t \Gamma^3 n)^{-1}$$

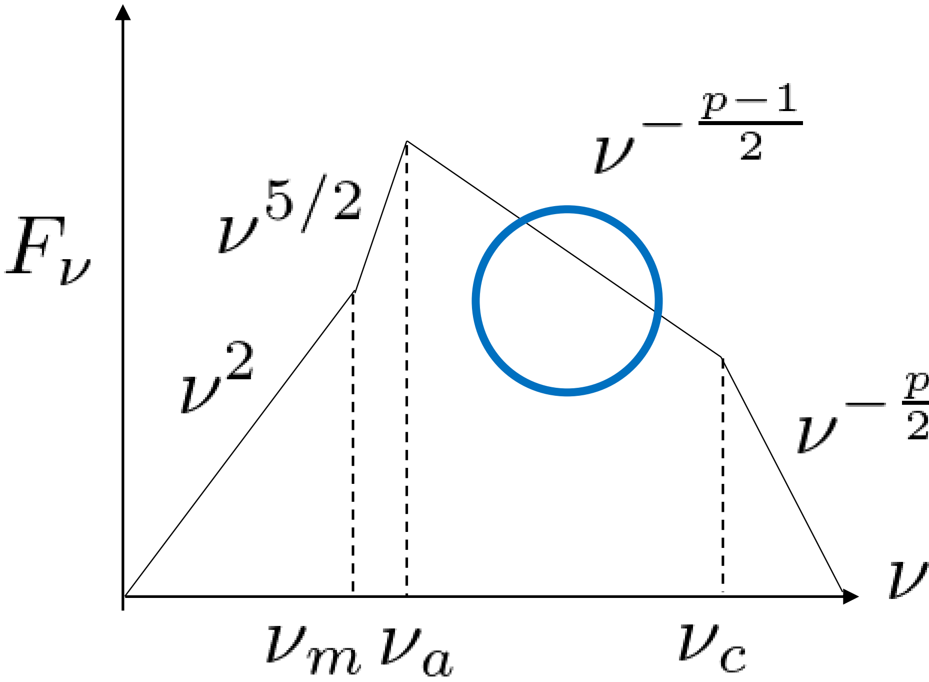
Electron with $\gamma_e \geq \gamma_c$ loses the energy within the time t.

Basics of synchrotron emission (Sari et al. 98)

$\nu_m = \nu(\gamma_m),\ \nu_c = \nu(\gamma_c),\ \nu_a$: self-absorption

Slow cooling （$\nu_c > \nu_m$）





$$\nu_c \approx 0.5\,\mathrm{keV}\left(\frac{n}{0.01\mathrm{cm}^{-3}}\right)^{-3/2}\left(\frac{\epsilon_B}{0.05}\right)^{-3/2}\left(\frac{t}{100\ \mathrm{day}}\right)^{-2}\left(\frac{\beta}{0.6}\right)^{-3}$$

$$\nu_m \approx 60\ \mathrm{MHz}\left(\frac{\epsilon_B}{0.05}\right)^{1/2}\left(\frac{\epsilon_e}{0.1}\right)^{2}\left(\frac{n}{0.01\mathrm{cm}^{-3}}\right)^{1/2}\Gamma^4$$

$$\nu_a \approx 30\ \mathrm{MHz}\left(\frac{E_{\mathrm{iso}}}{10^{49}\mathrm{erg}}\right)^{\frac{2}{3(p+4)}}\left(\frac{n}{0.01\ \mathrm{cm}^{-3}}\right)^{\frac{3p+4}{6(p+4)}}\left(\frac{\epsilon_B}{0.05}\right)^{\frac{2+p}{2(p+4)}}\left(\frac{\epsilon_e}{0.1}\right)^{\frac{2(p-1)}{p+4}}\left(\frac{\beta}{0.6}\right)^{\frac{15p-10}{3(p+4)}}$$

Basics of synchrotron emission (Sari et al. 98)

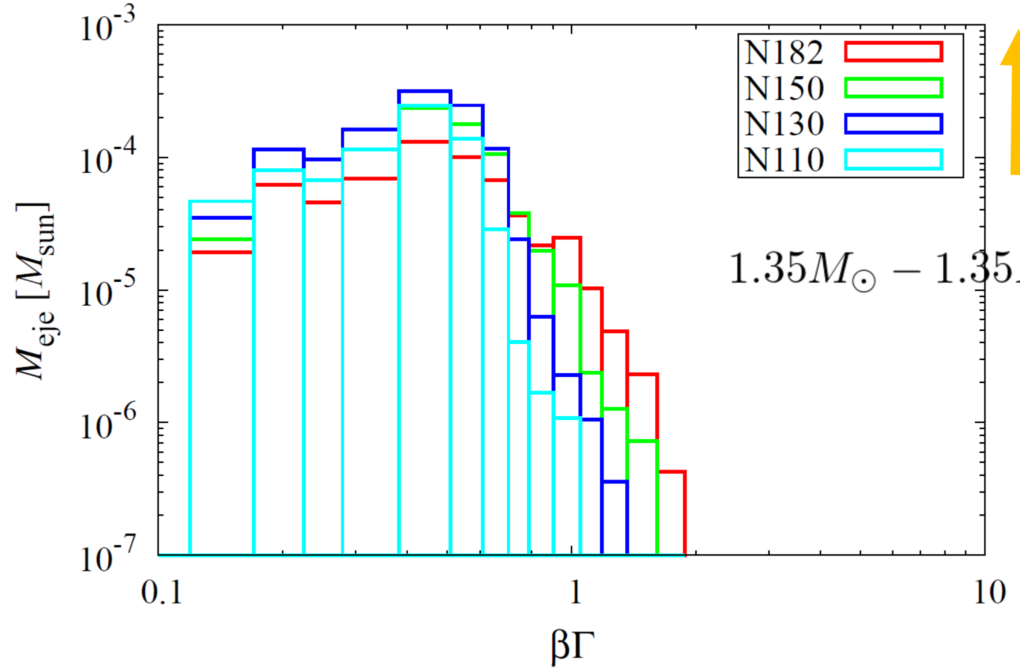
Given $E(>\Gamma\beta)$,

$$\frac{4}{3}\pi n m_p R^3 (c\Gamma\beta)^2 = E(>\Gamma\beta),$$

$$\frac{dR}{dt} = \frac{c\Gamma\beta}{\sqrt{1+(\Gamma\beta)^2}}$$

NR simulation found a fast component ($\Gamma\ \beta>1$)

(Kiuchi et al. 17, See also Hotokezaka et al. 13, Bauswein et al. 13)



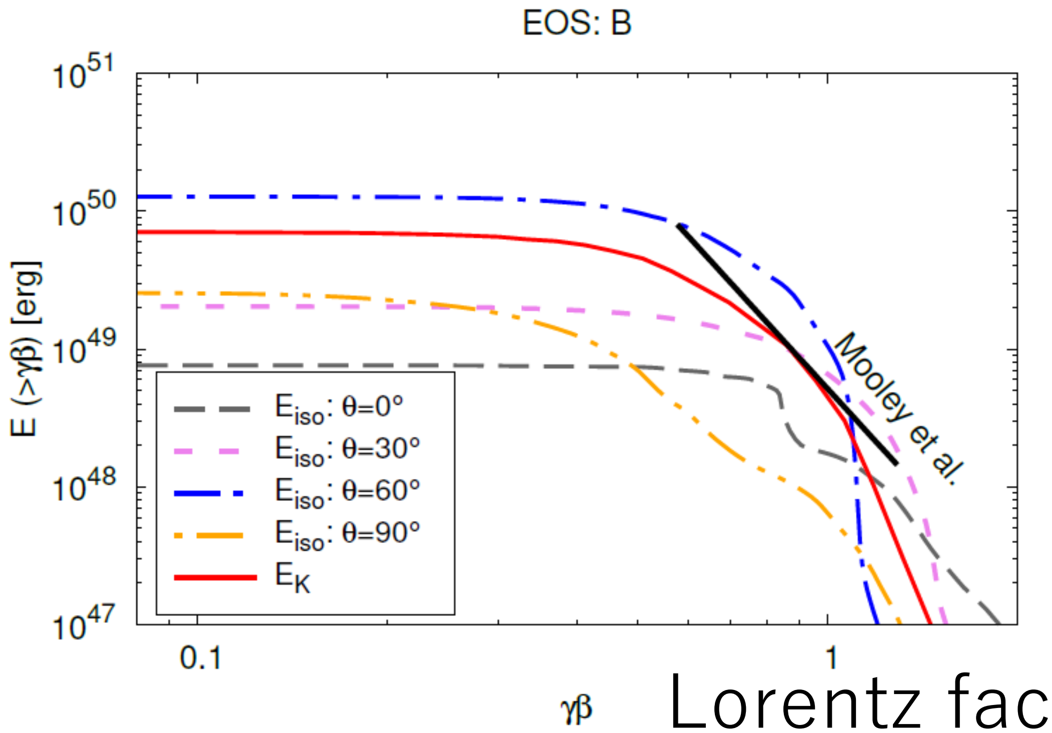
↑ Increasing the resolution

$1.35M_\odot - 1.35M_\odot,\ R_{1.35\mathrm{M}_\odot} \approx 11$ km

Long-term radio, X-ray observations

(Hotokezaka, KK et al. 18)

Mildly relativistic dynamical ejecta



kinetic energy above $\gamma\,\beta$

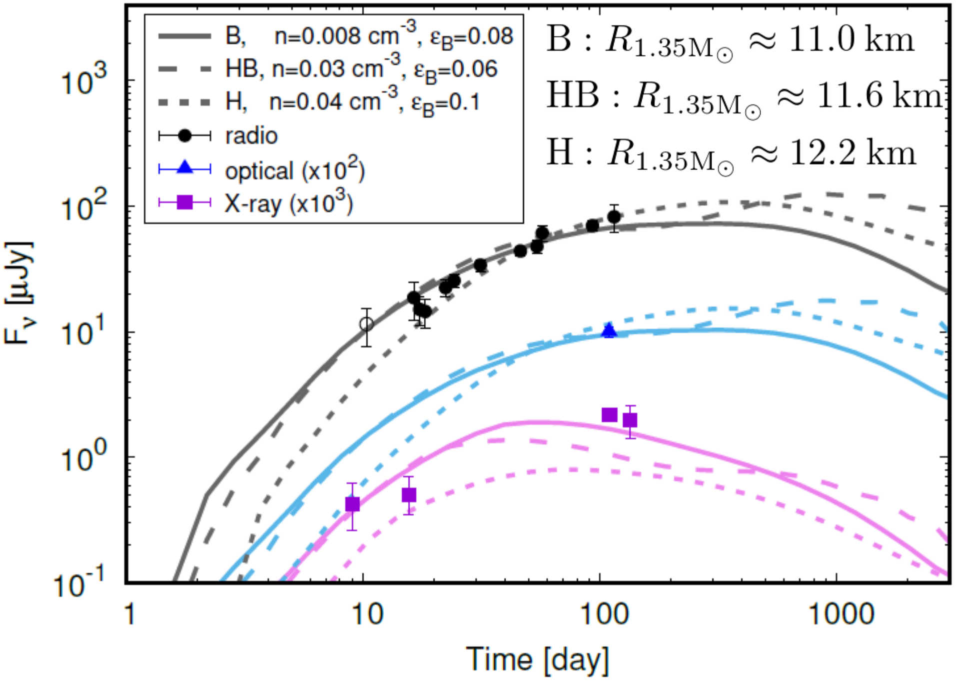
Lorentz factor × v/c

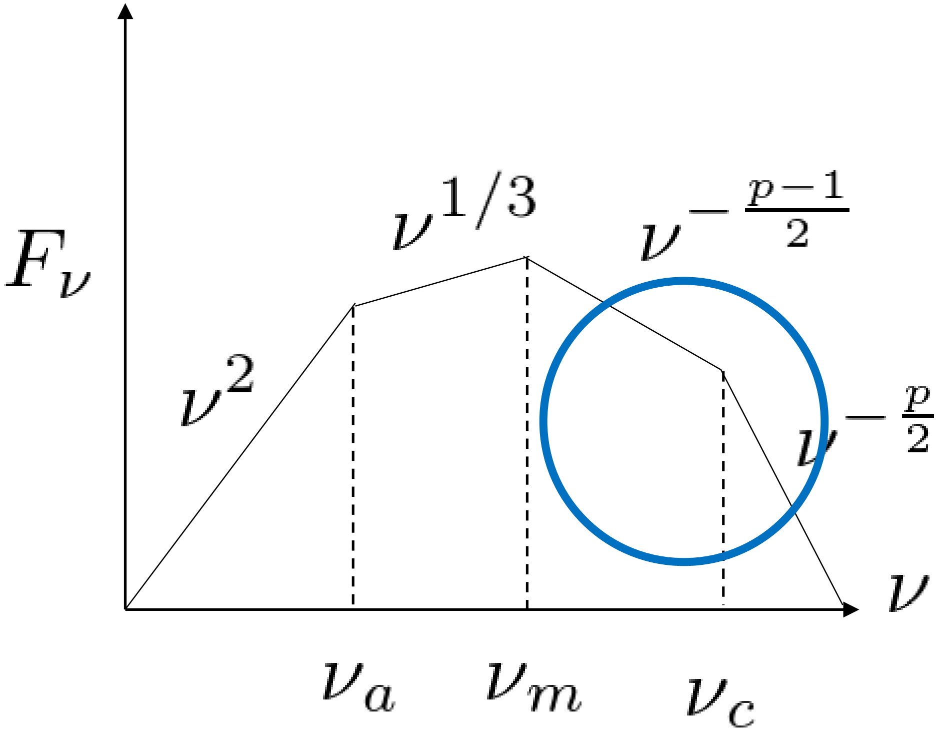
▶ Fast component coming from a contact interface

⇒ Mildly relativistic component $\beta = \mathrm{v}/\mathrm{c} \sim 0.6$

Long-term radio, X-ray observations

(Hotokezaka, KK et al. 18)

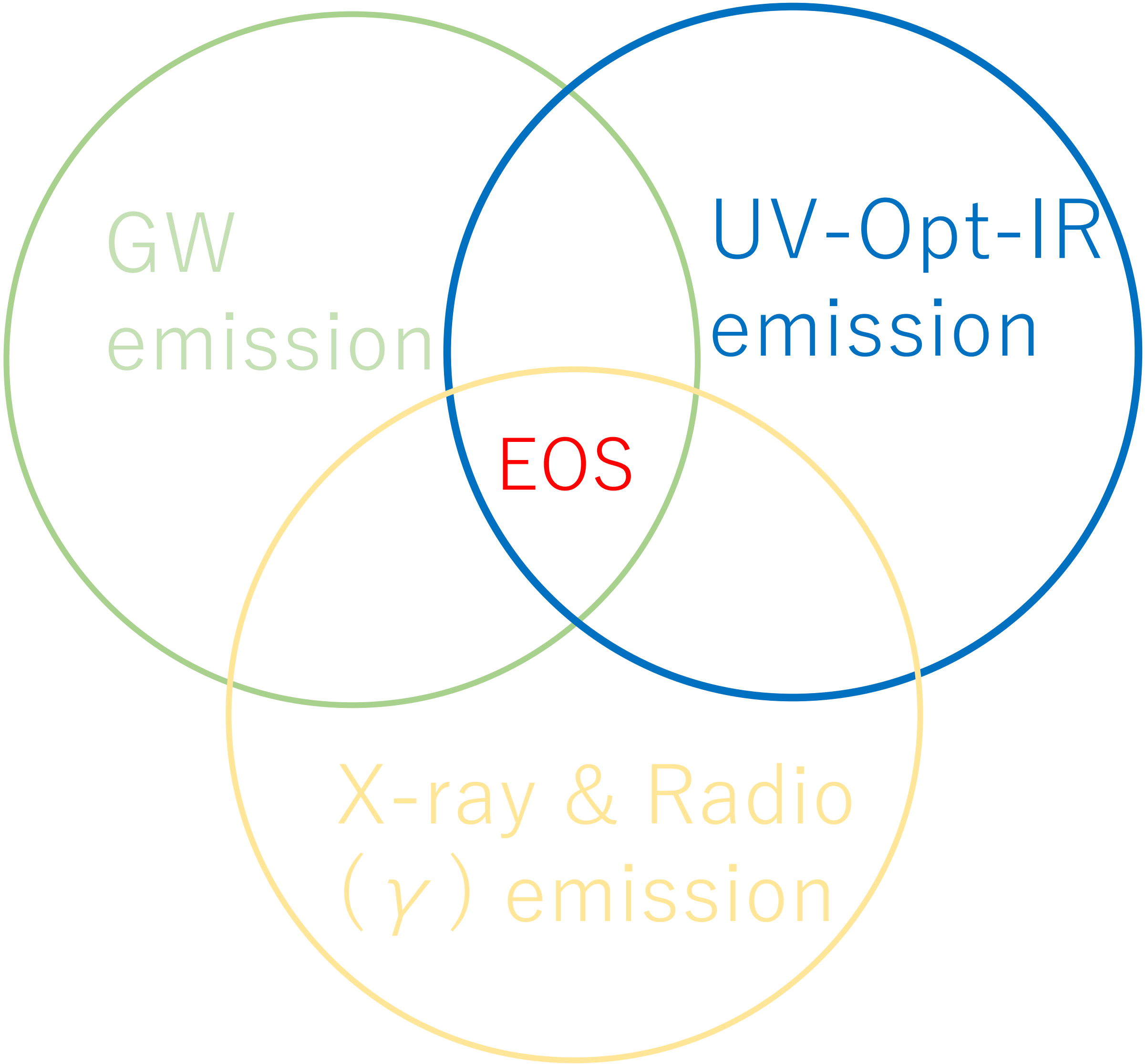




▶ Radio and X-ray emission favors a small NS radius.

▶ Prediction : Cooling frequency enters the X-ray band around t ∼ O(100)days

Bottom line of this talk



GW emission

UV-Opt-IR emission

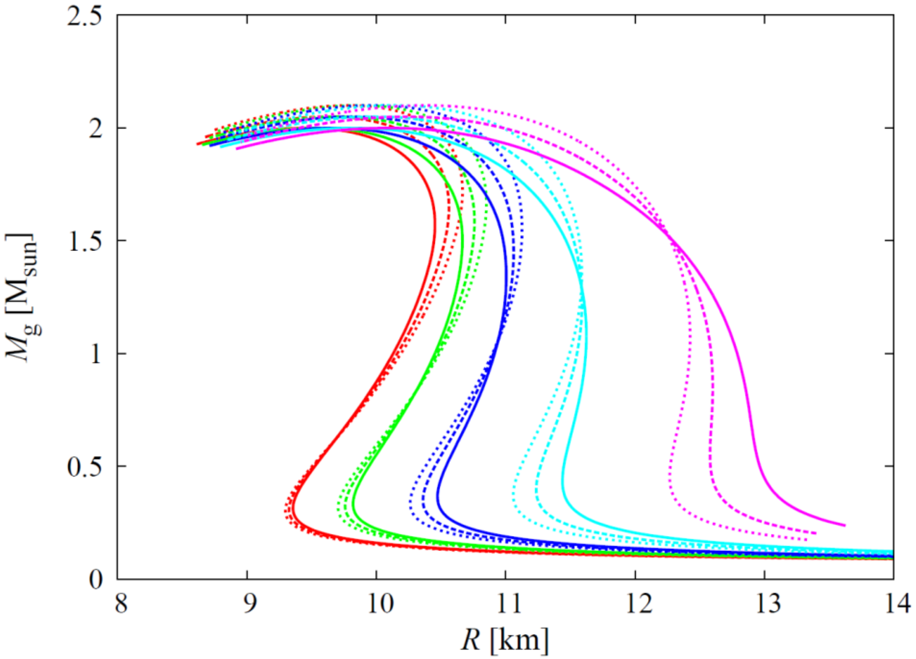
EOS

X-ray & Radio （γ） emission

Prompt BH formation is unlikely in GW170817

If $M_{total} > M_{thresh} = 1.2\text{-}1.7\ M_{TOV,max}$, a prompt collapse occurs (Shibata & Taniguchi 06).

▶ Ejecta in prompt BH formation could be small e.g., $M_{eje} \approx 0.05 M_{\odot}$ in AT2017gfo



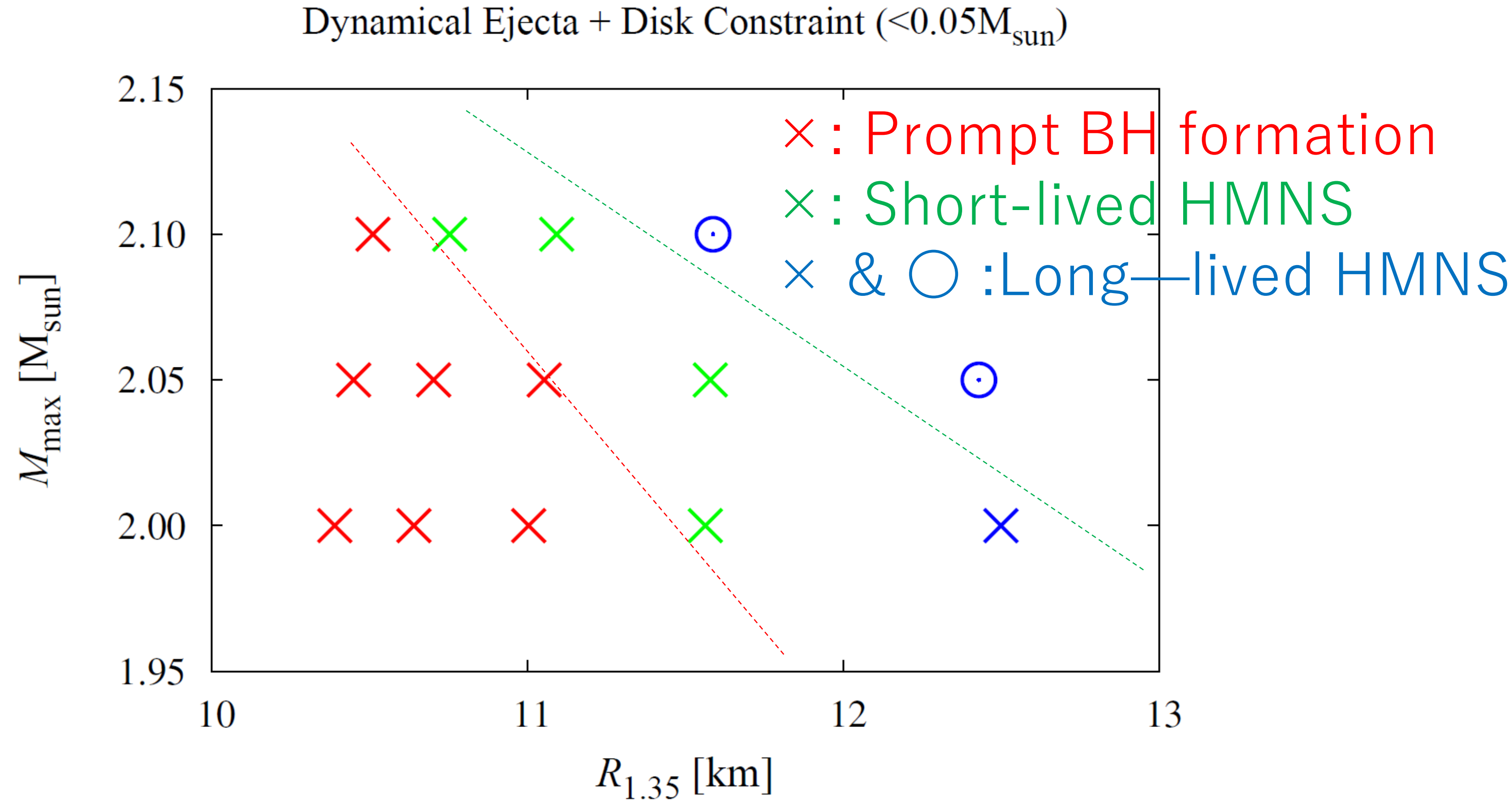
Parameterized EOS

▶ $M_{max} = 2.00\text{-}2.10\ M_{\odot}$

▶ $R_{1.35M\odot} \approx 10.4\text{-}12.4$ km

Unlikely prompt BH formation

$1.375 - 1.375 M_\odot$

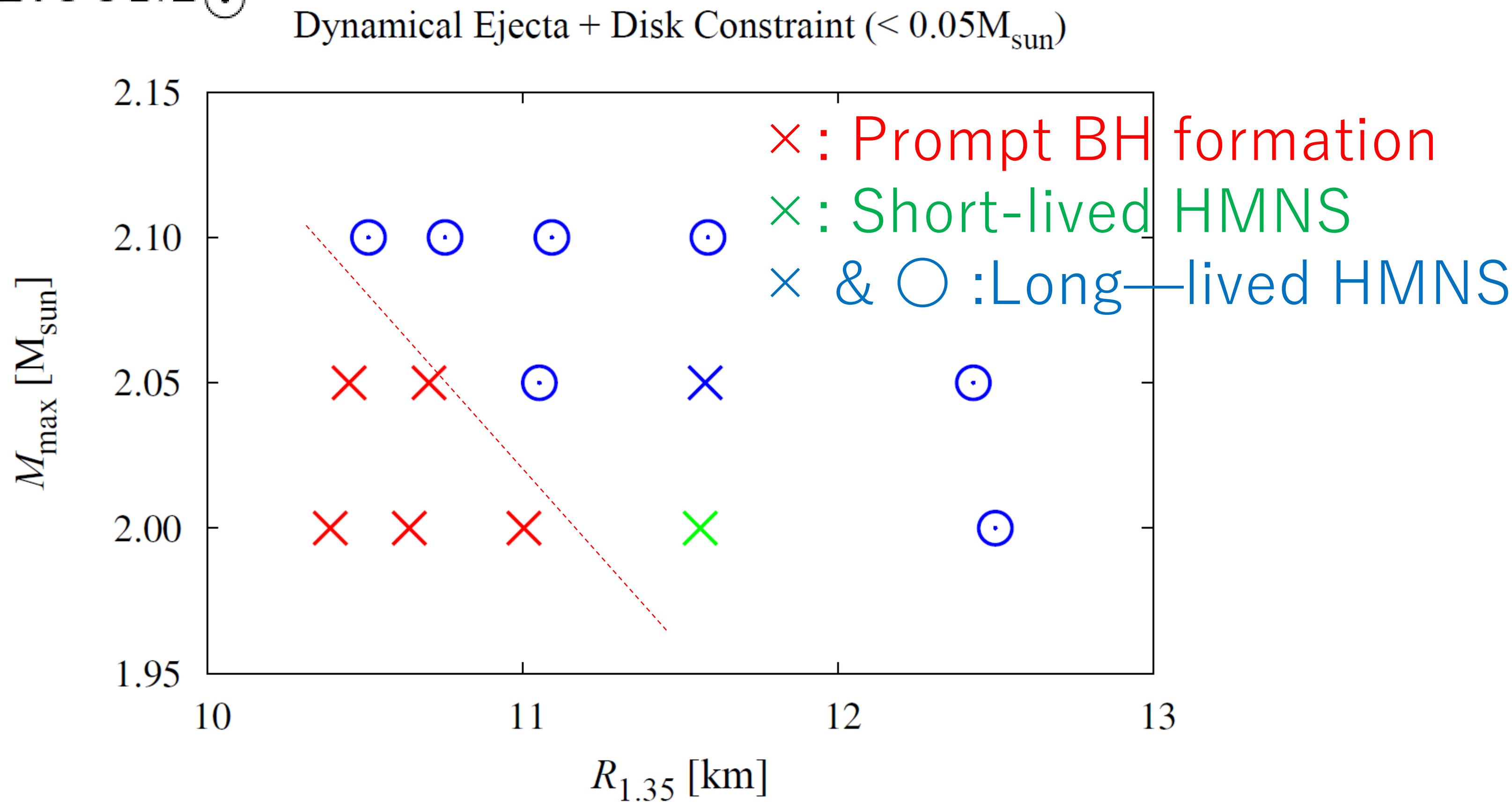


×: Dynamical Ejecta + 50 % of disk mass < 0.05 $M_\odot$

○: Dynamical Ejecta + 50 % of disk mass > 0.05 $M_\odot$

Unlikely prompt BH formation

$1.2 - 1.55 M_\odot$



× : Prompt BH formation

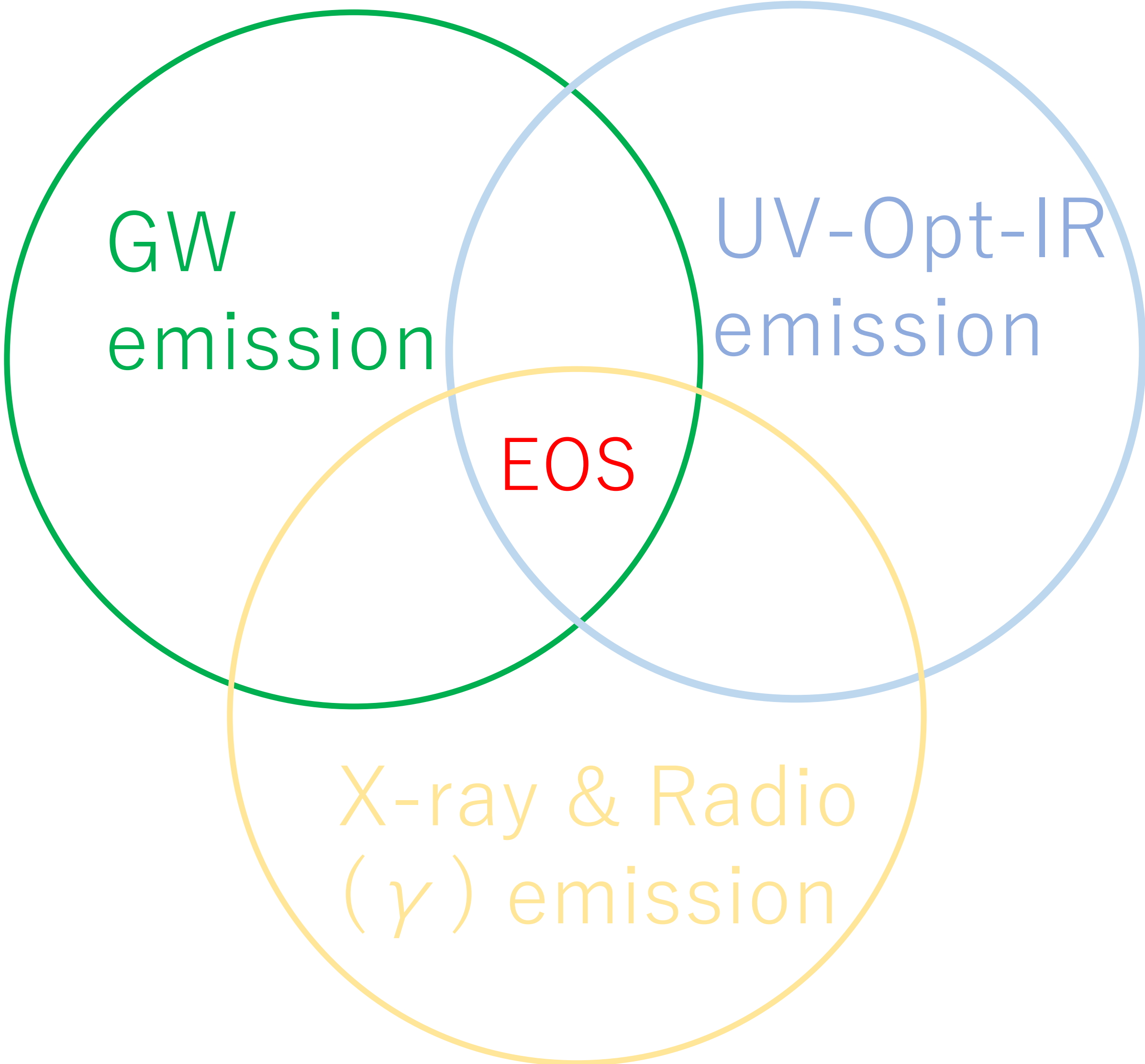
× : Short-lived HMNS

× & ○ :Long-lived HMNS

× : Dynamical Ejecta + 50 % of disk mass < 0.05 $M_\odot$

○: Dynamical Ejecta + 50 % of disk mass > 0.05 $M_\odot$

Bottom line of this talk



GW emission

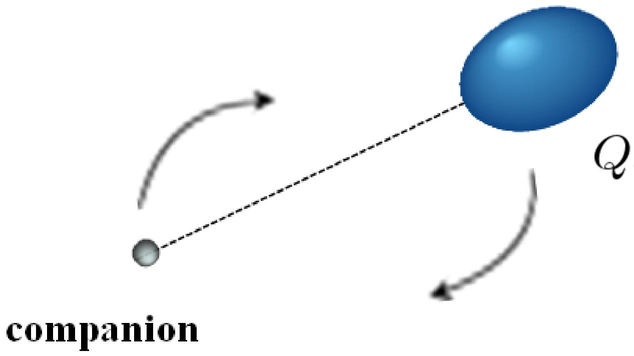
UV-Opt-IR emission

X-ray & Radio (γ) emission

EOS

Tidal deformation of NSs

non spinning NS in a binary



Q_{ij} : Quadrupole moment of a NS

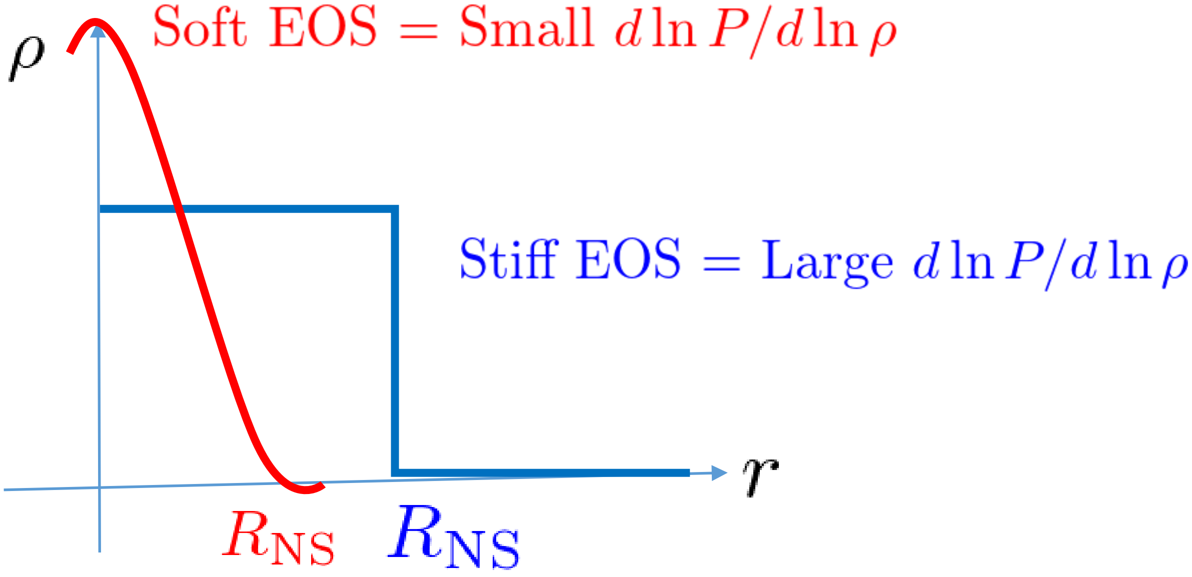
NS just before the merger could be deformed by a tidal force of its companion. (Flanagan & Hinderer 08).

$$Q_{ij} = -\lambda \mathcal{E}_{ij},$$

$$\Lambda = \frac{2}{3} k_2 \left(\frac{GM}{Rc^2} \right)^{-5}, k_2 = \frac{3}{2} \lambda R^{-5}$$

Tidal deformation of NSs

Hydrostatic eq. $\nabla P = -\rho \nabla \phi_g$



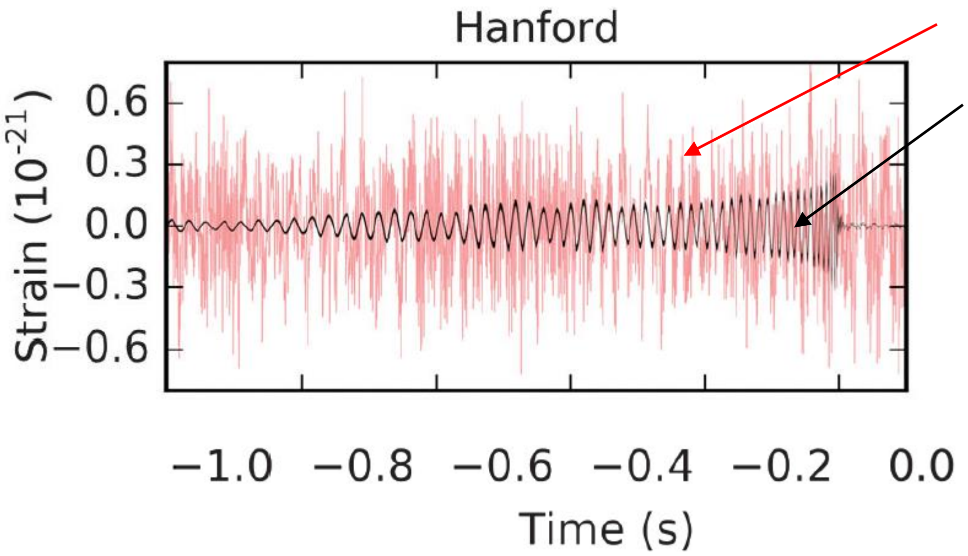
Stiff EOS ⇒ Uniform ρ (large R) ⇒ Easy to be tidally deformed

Soft EOS ⇒ Centrally concentrated ρ (small R) ⇒ Hard to be tidally deformed

Tidal deformability imprinted in GWs

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

Theoretical template of GWs



Data + noise

Template

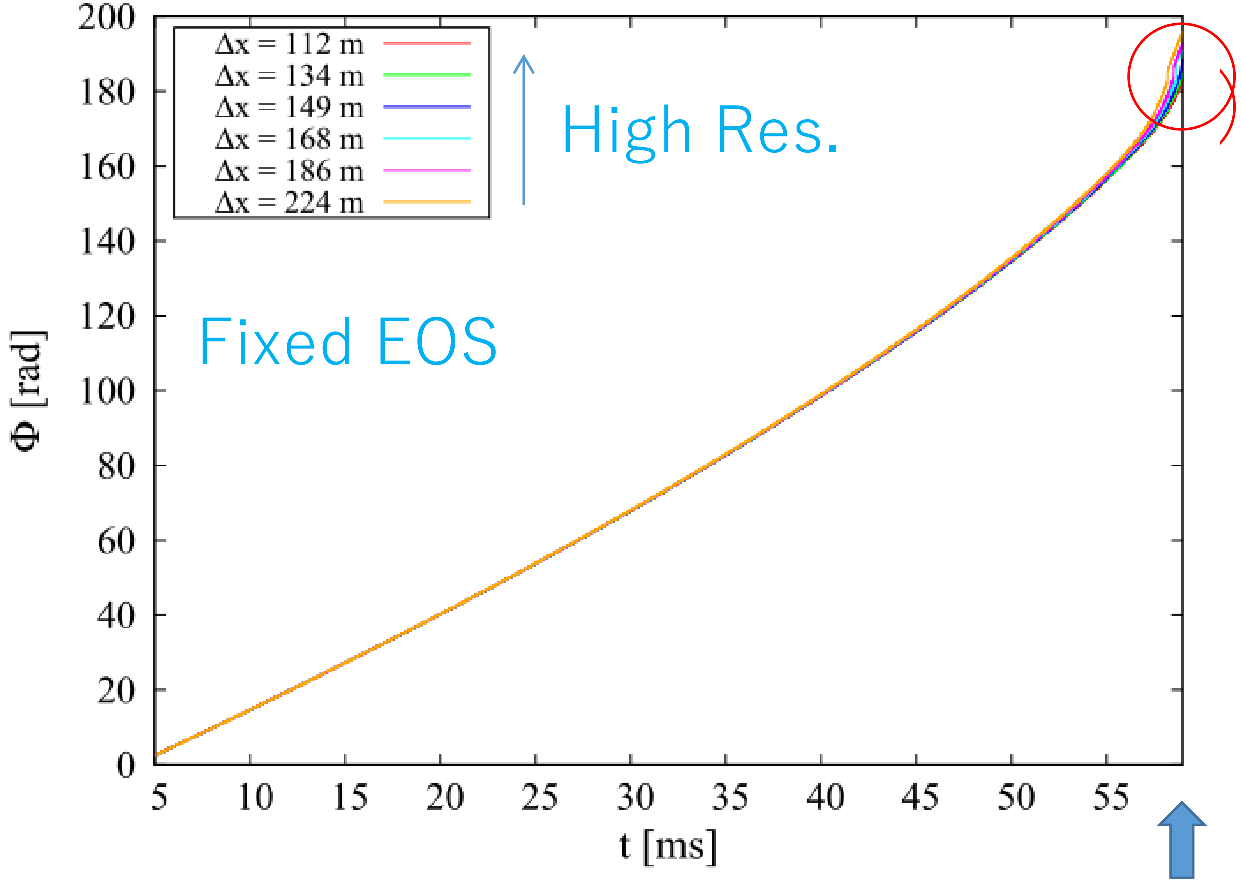
Tidal force is attractive force ⇒
Tidal deformation accelerates the phase evolution

Necessary to model evolution of the GW phase

Toward a theoretical template bank

Large tidal deformability ⇒ Rapid phase evolution

Numerical diffusion ⇒ Rapid phase evolution



High Res.

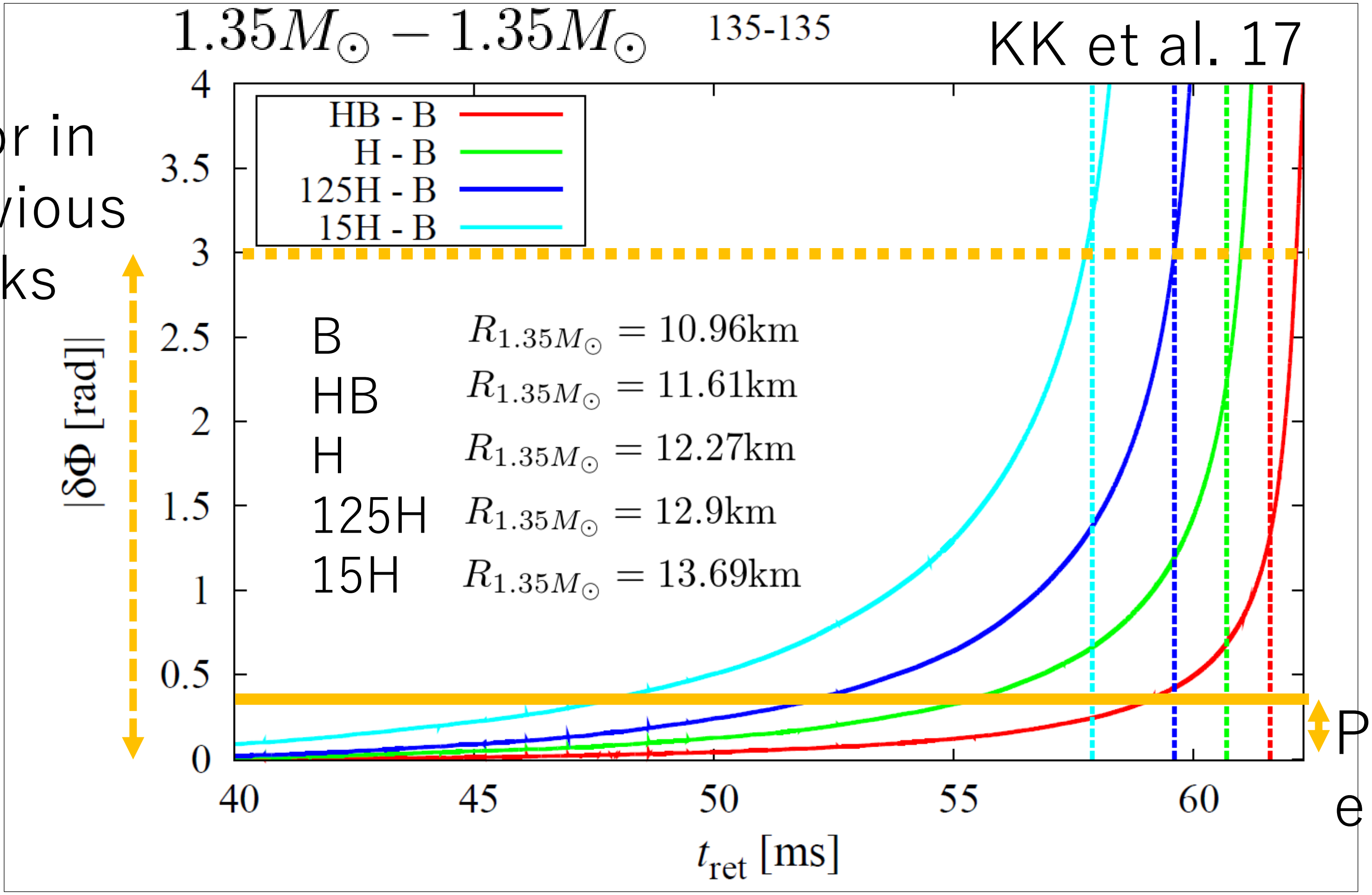
Fixed EOS

Merger

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

Convergence study ⇒ Continuum limit

Toward a theoretical template bank



Error in previous works

Phase error

▶ Phase error is significantly suppressed.

c.f. 3-4 radian (Hotokezaka et al. 13) , 0.5-1.5 rad. (Dietrich et al. 17)

Kyoto template (Kawaguchi, KK et al 18)

GW phase

$$\Phi_{\mathrm{GW}} = \underline{\Phi_{\text{point particle}}} + \Phi_{\mathrm{tidal}}$$

Modeling in binary black hole systems (Nagar et al. 16)

Tidal part (Damour et al 12)

$$\Phi_{\mathrm{tidal}}^{2.5PN} = \frac{3}{32}\left(-\frac{39}{2}\Lambda\ \left(1 + a\Lambda^{2/3}x^{p}\right)\right)x^{5/2}$$

$$\times\left(1 + \frac{3115}{1248}x - \pi x^{3/2} + \frac{28024205}{3302208}x^{2} - \frac{4283}{1092}\pi x^{5/2}\right)$$

Λ : Tidal deformability

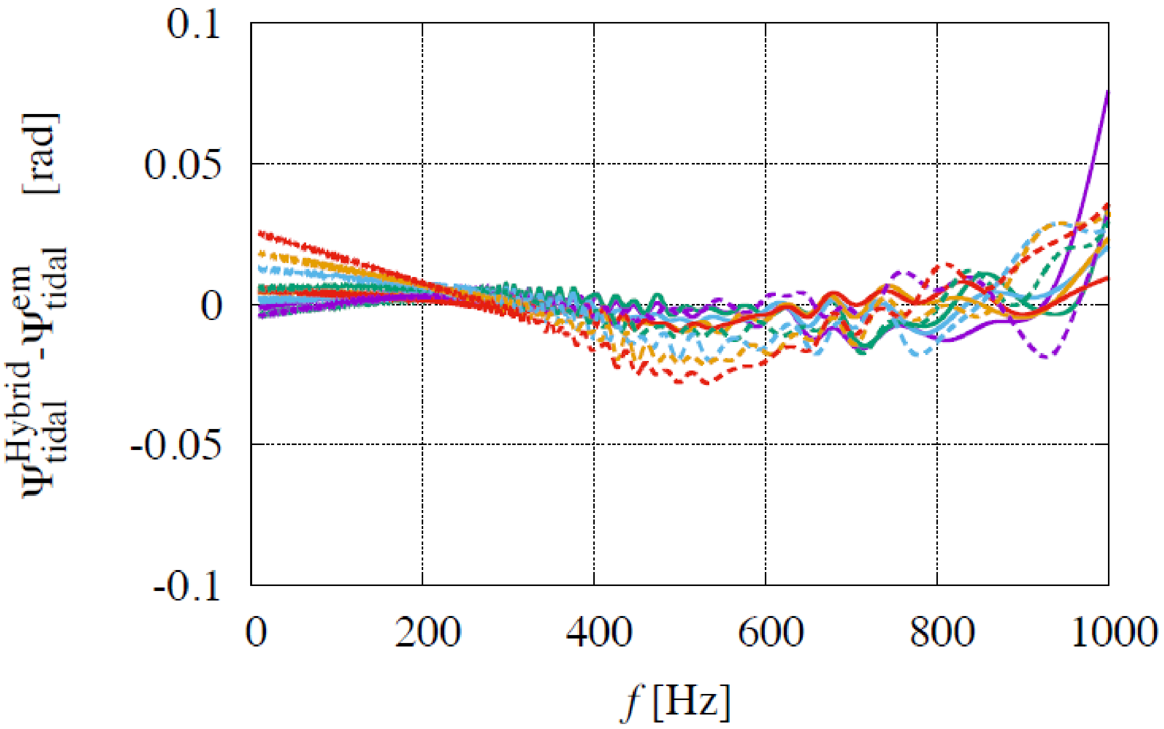
$x = (\pi m_0 f)^{3/2}$: Post-Newtonian parameter

Kyoto template (Kawaguchi, KK et al 18)

$$\Phi_{\mathrm{tidal}}^{2.5PN} = \frac{3}{32}\left(-\frac{39}{2}\Lambda(1+a\Lambda^{2/3}x^{p})x^{5/2} \times \cdots\right)$$

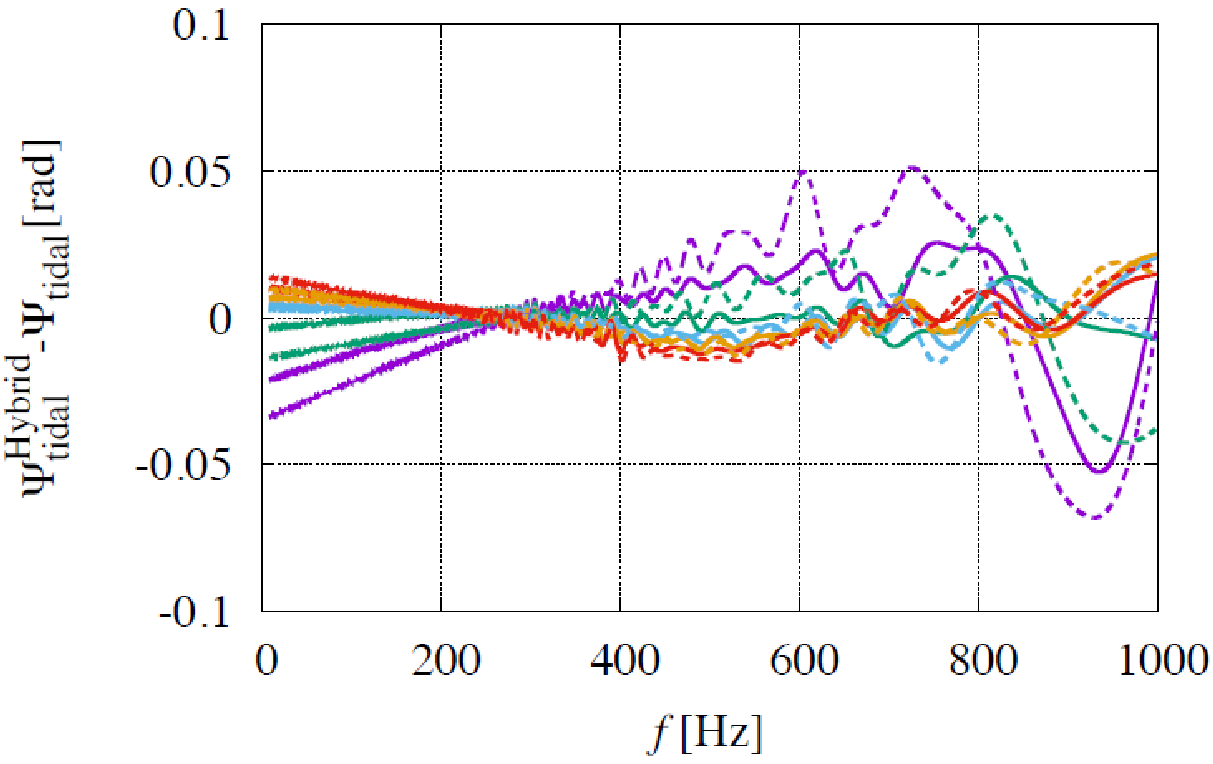
Fitting by a NR simulation $a = 12.55, p = 4.24$

$1.25M_{\odot}$-$1.25M_{\odot}$, $1.35M_{\odot}$ -$1.35M_{\odot}$ with 5 EOSs



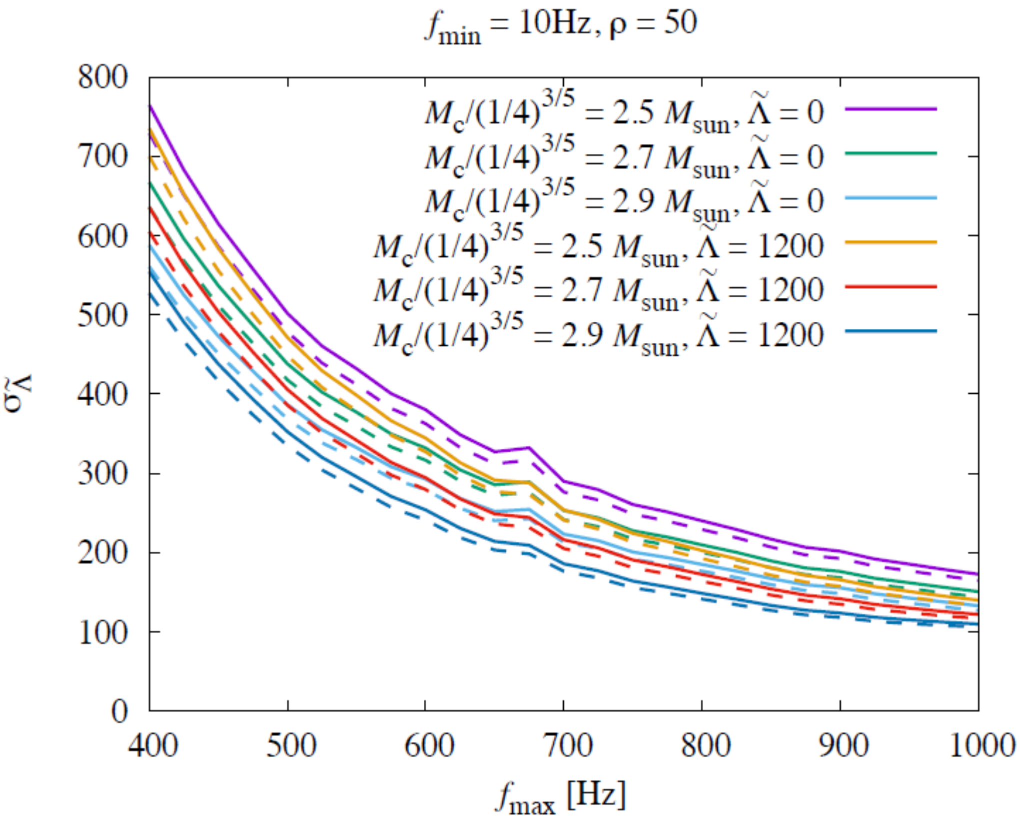
Kyoto template (Kawaguchi, KK et al 18)

$1.21M_\odot$-$1.51M_\odot$, $1.16M_\odot$ -$1.58M_\odot$ with 5 EOSs



▶ Systematic error for modeling is less than 0.1 rad

Statistical error in the measure ment



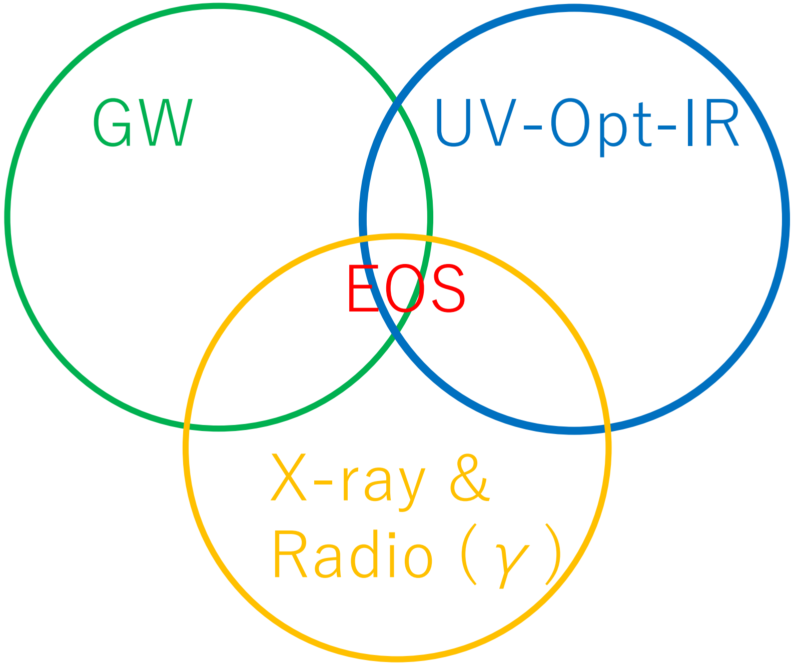
▶ Statistical error is improved as increasing $f_{\rm max}$

⇒ Independent analysis of adv. LIGO data

(Narikawa et al in prep.)

▶ LIGO result $\tilde{\Lambda} \lesssim 800 \Rightarrow R_{1.35 M_\odot} \lesssim 13.6\,\mathrm{km}$

Summary



▶ Fast dynamical ejecta (shock breakout) to explain the X-ray and radio observation favors a small Λ.

▶ Unlikely prompt collapse in GW170817 gives the constraint on the M_{max}-$R_{1.35}$ plane.

▶ Tidal deformability measurements in GW170817 indicate $\Lambda \lesssim 800$.