The equation of state of neutron star matter and gravitational waves

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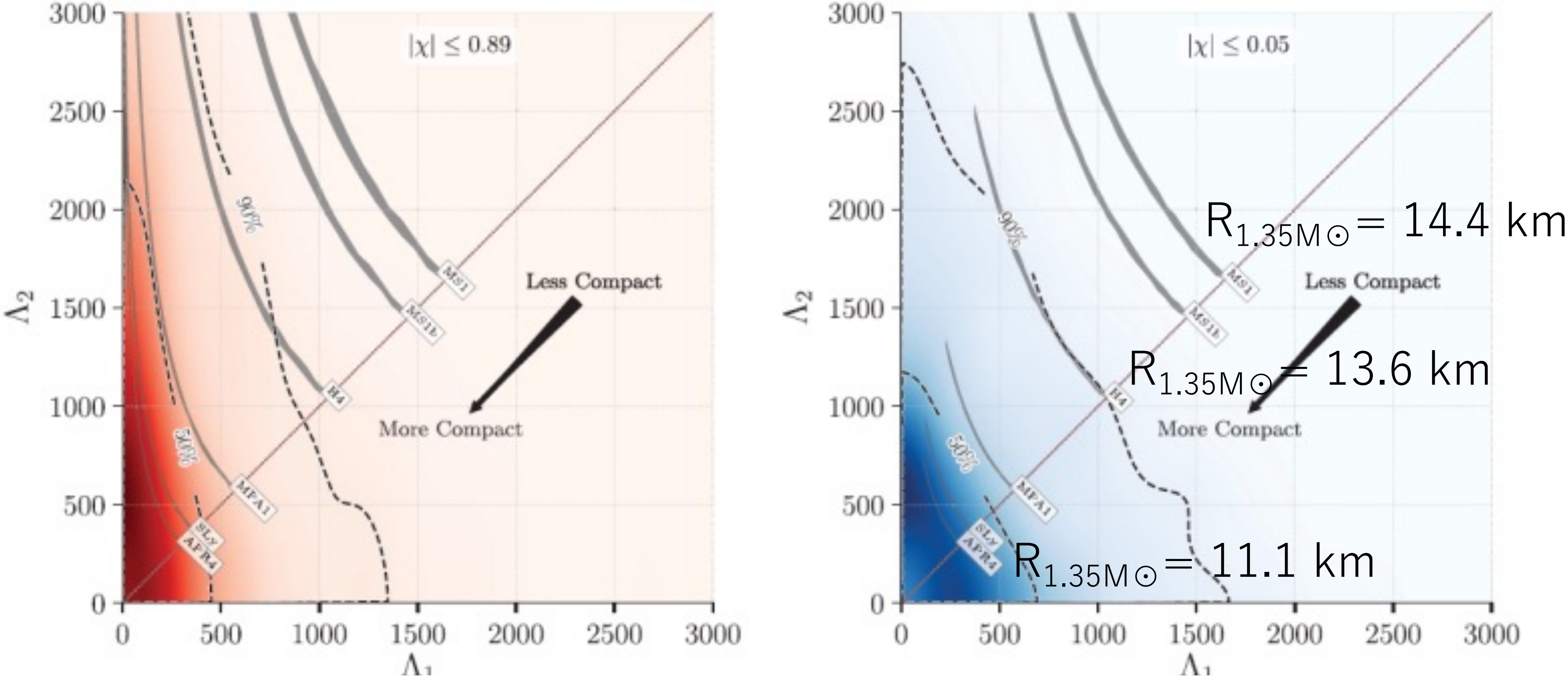
CGP

Tidal deformability measurement of NSs

LSC and Virgo collaboration PRL 119, 161101 (2017)



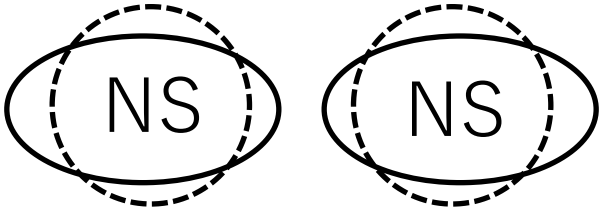
▶ Tidal deformation Λ is related to a NS radius ⇒ Information of the NS equation of state.

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

From inspiral to late inspiral phase

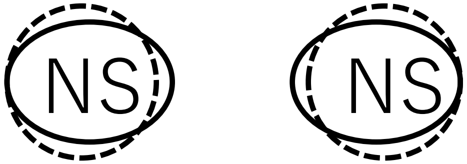
Tidal deformation

Stiff EOS (large R)



Easily tidally deformed

Soft EOS (small R)



Hard to be tidally deformed

Tidal deformability depends on NS EOSs

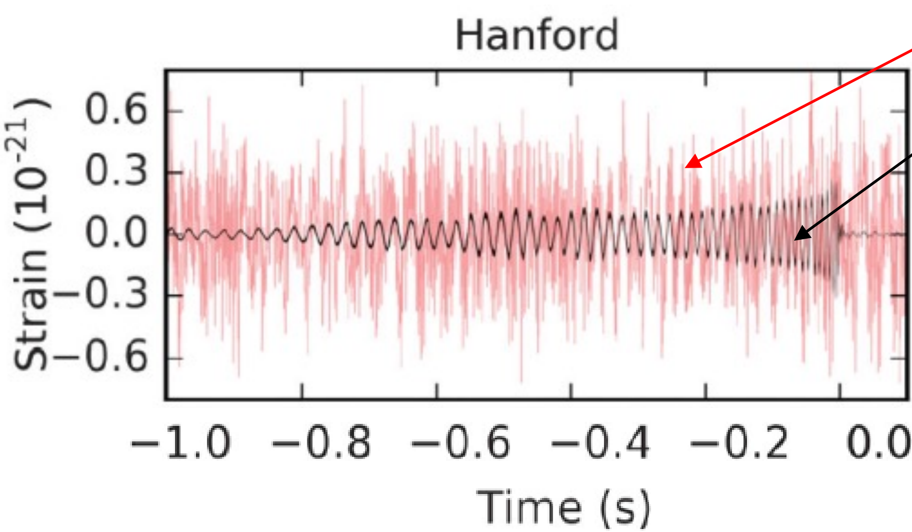
Tidal deformability imprinted in GWs

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

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

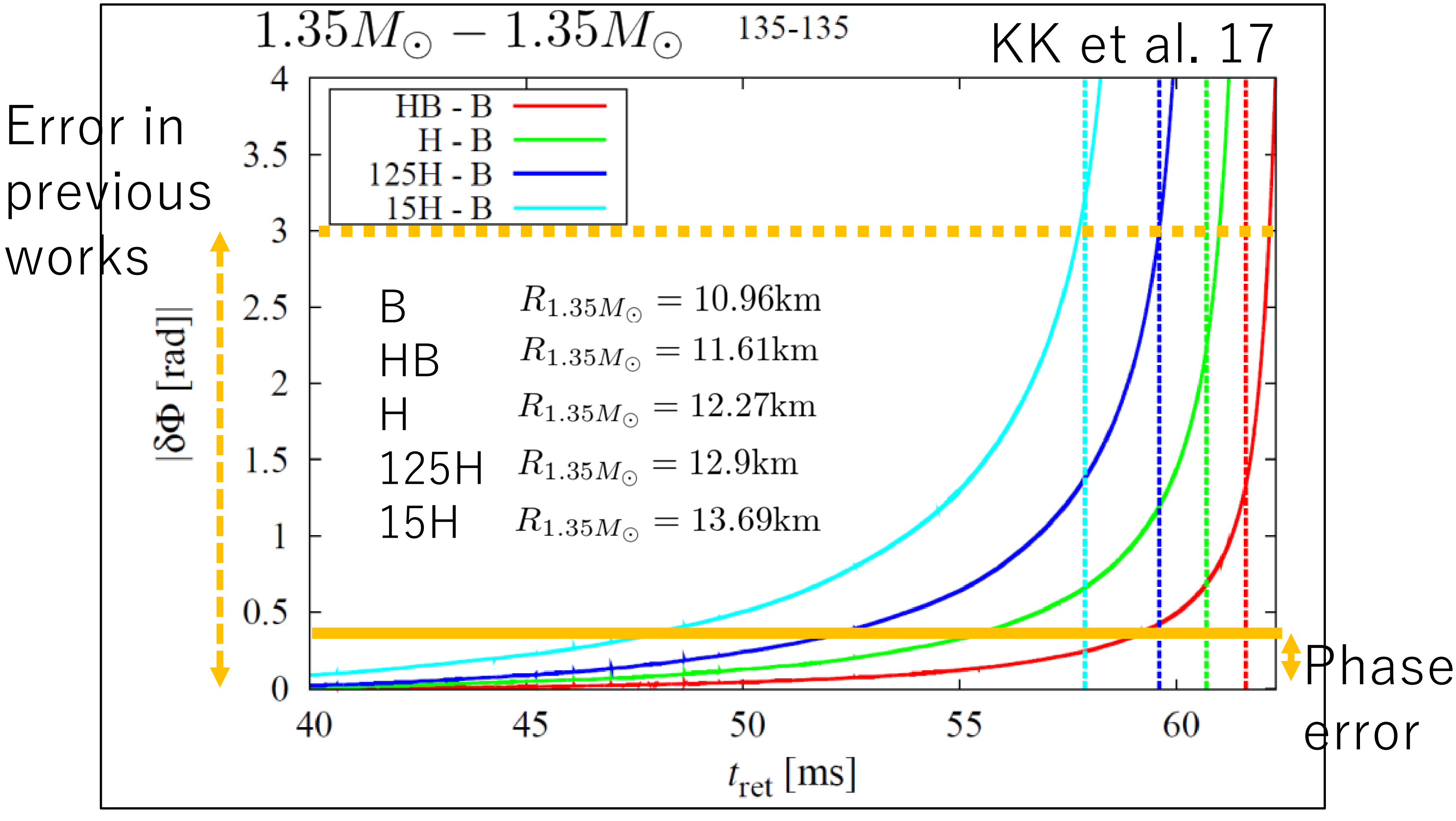
Theoretical template of GWs

Data + noise
Template



The phase error in a numerical simulation should be small enough. $\Delta\Phi_{\rm error} \ll \Delta\Phi_{\rm tidal}$

Toward a theoretical template bank



▶ 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 (Kawatuchi, KK et al 18)

GW phase

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

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

Tidal part (Damour et al 12)

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

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

Λ : Tidal deformability

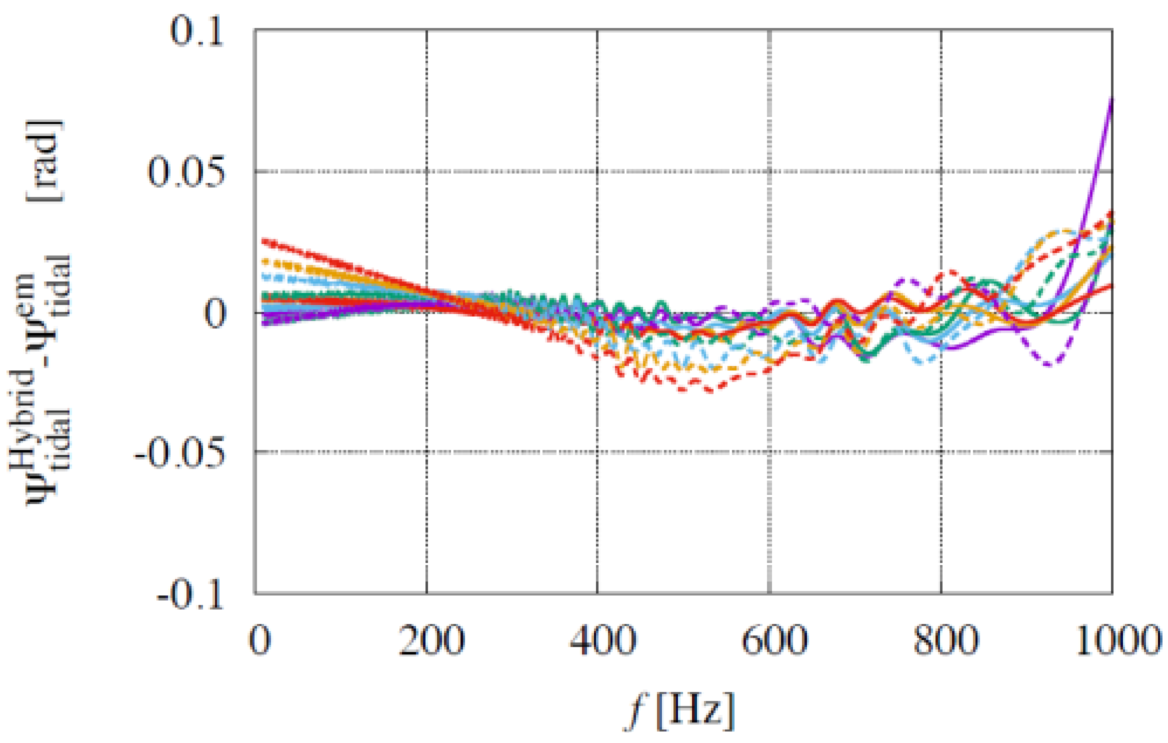
$x = (\pi m_0 f)^{3/2}$: Post-Newtonian parameter

Kyoto template (Kawaguchi, KK et al 18)

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

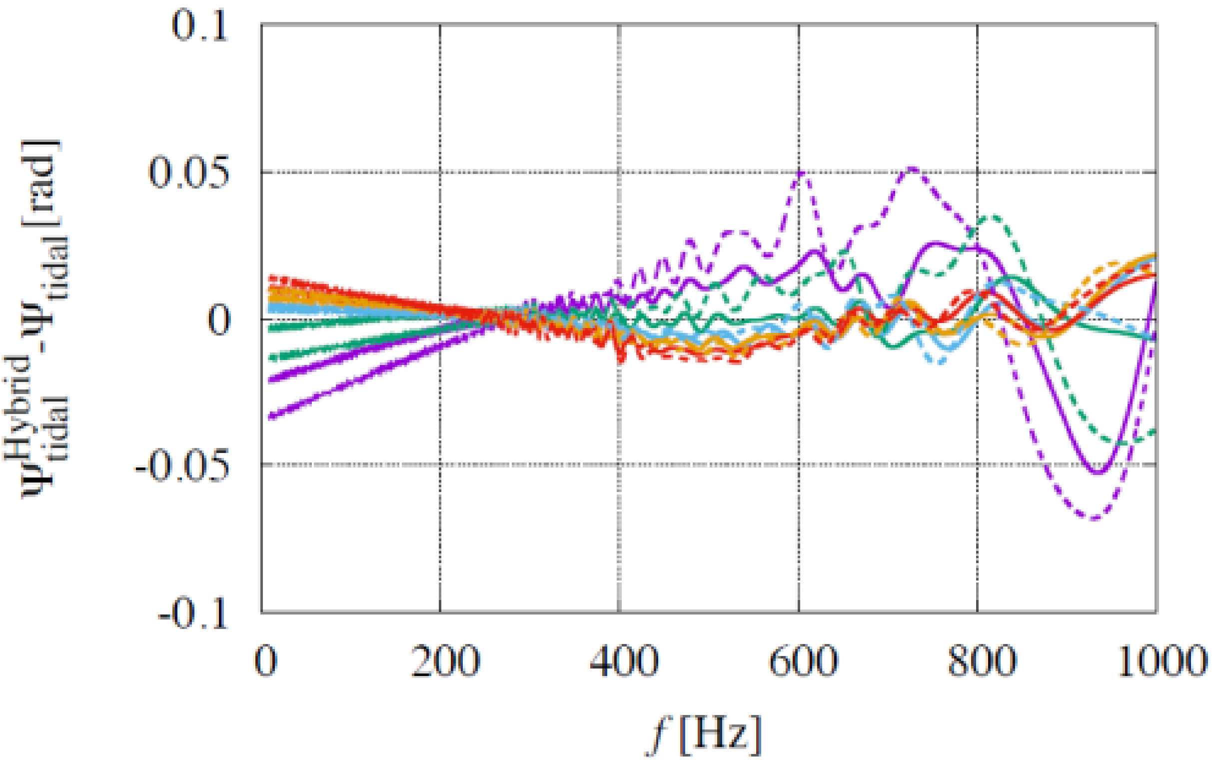
Fitting by a NR simulation $a = 12.55, p = 4.24$

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



Kyoto template (Kawaguchi, KK et al 18)

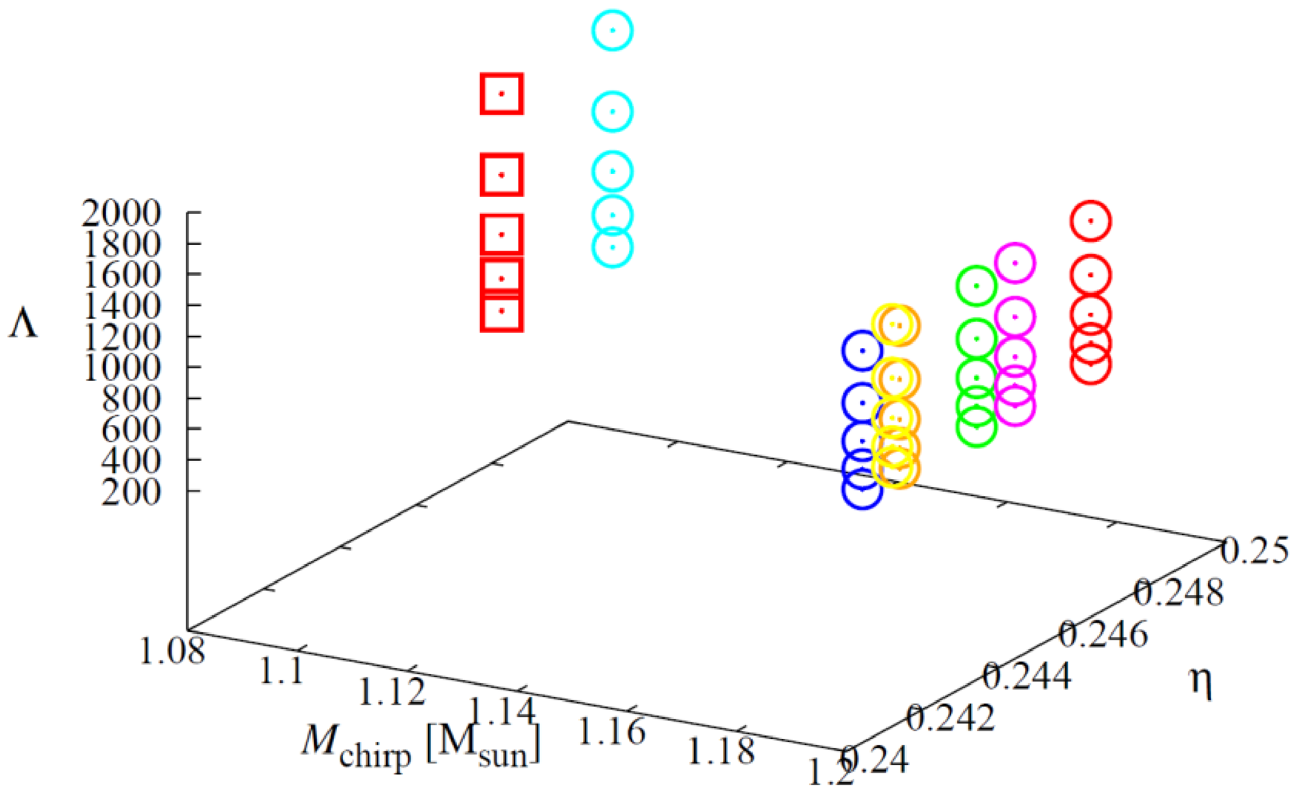
$1.21M_\odot$-$1.51M_\odot$, $1.16M_\odot$ -$1.58M_\odot$ with 5 EOSs



▶ Systematic error is less than 0.1 rad

⇒ Independent analysis of adv. LIGO data (Narikawa et al in prep)

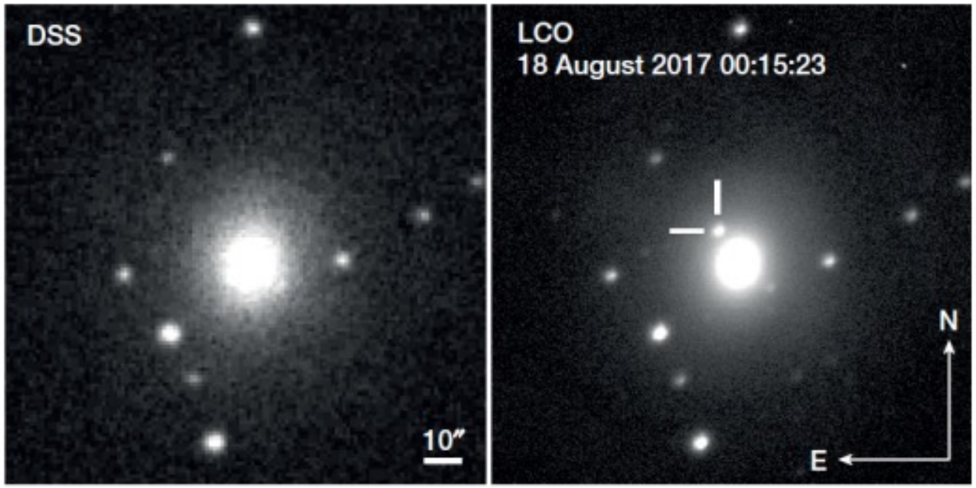
Toward a theoretical template bank



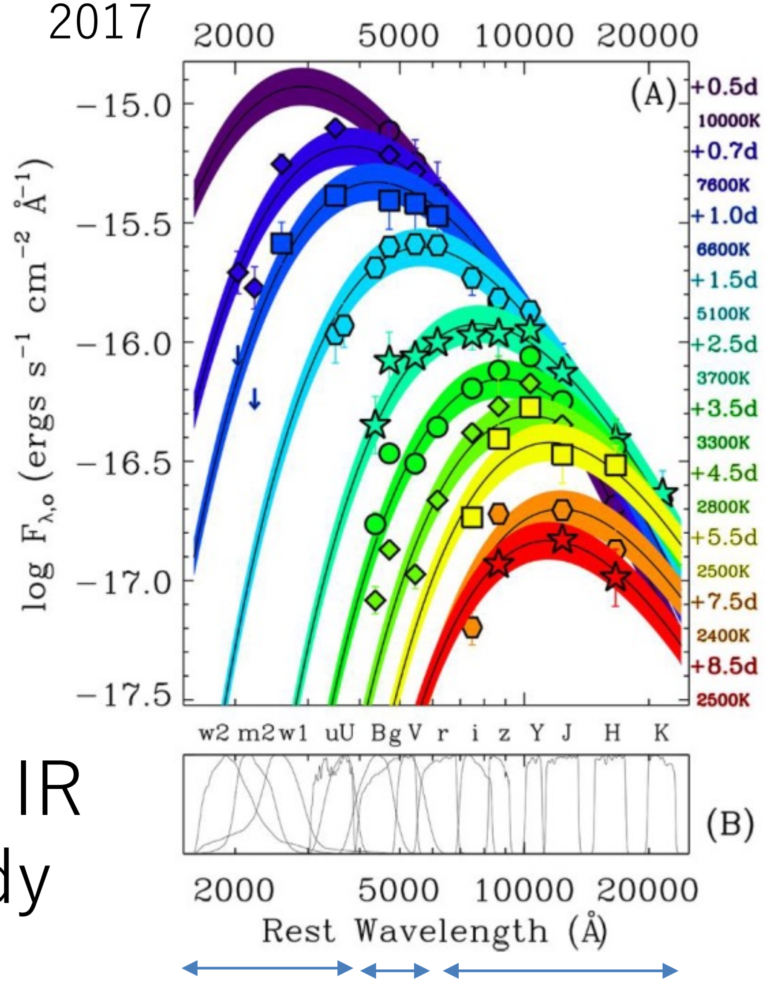
▶ Parameter space we've simulated so far.
On each grid point, we require phase error of O(0.1) rad.

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（～0.03M$_{\odot}$）

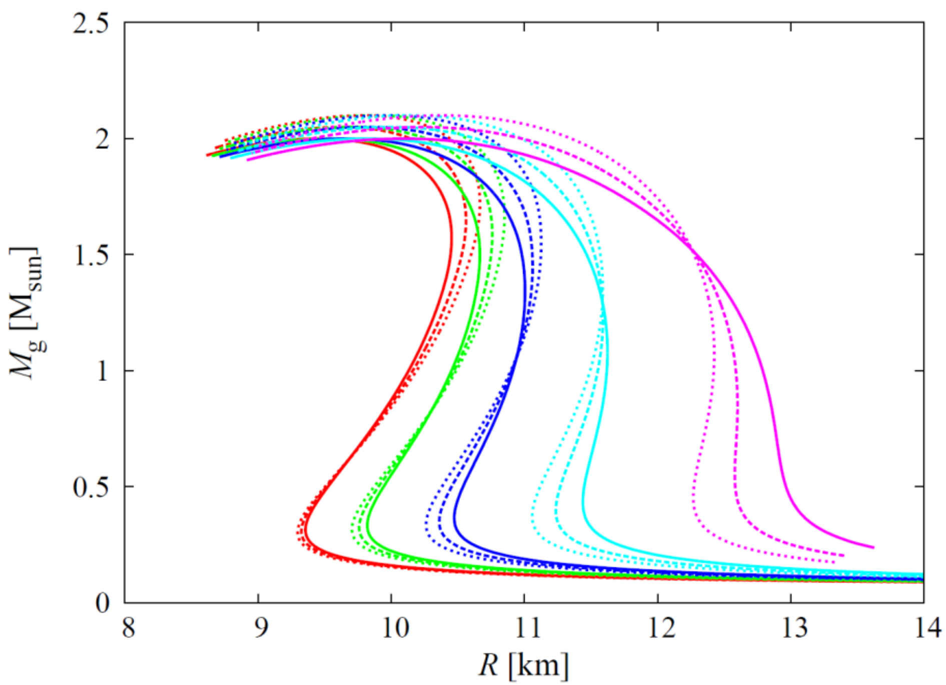
& short-duration UV-Optical component (～0.02M$_{\odot}$)

Prompt BH formation is unlikely

If $M_{total} > M_{thresh}$ = 1.2-1.7 $M_{TOV,max}$, a merger remnant collapses to a BH within a dynamical timescale (Shibata & Taniguchi 06).

▶ Ejecta in prompt BH formation could be small.

⇒ Constraining EOS



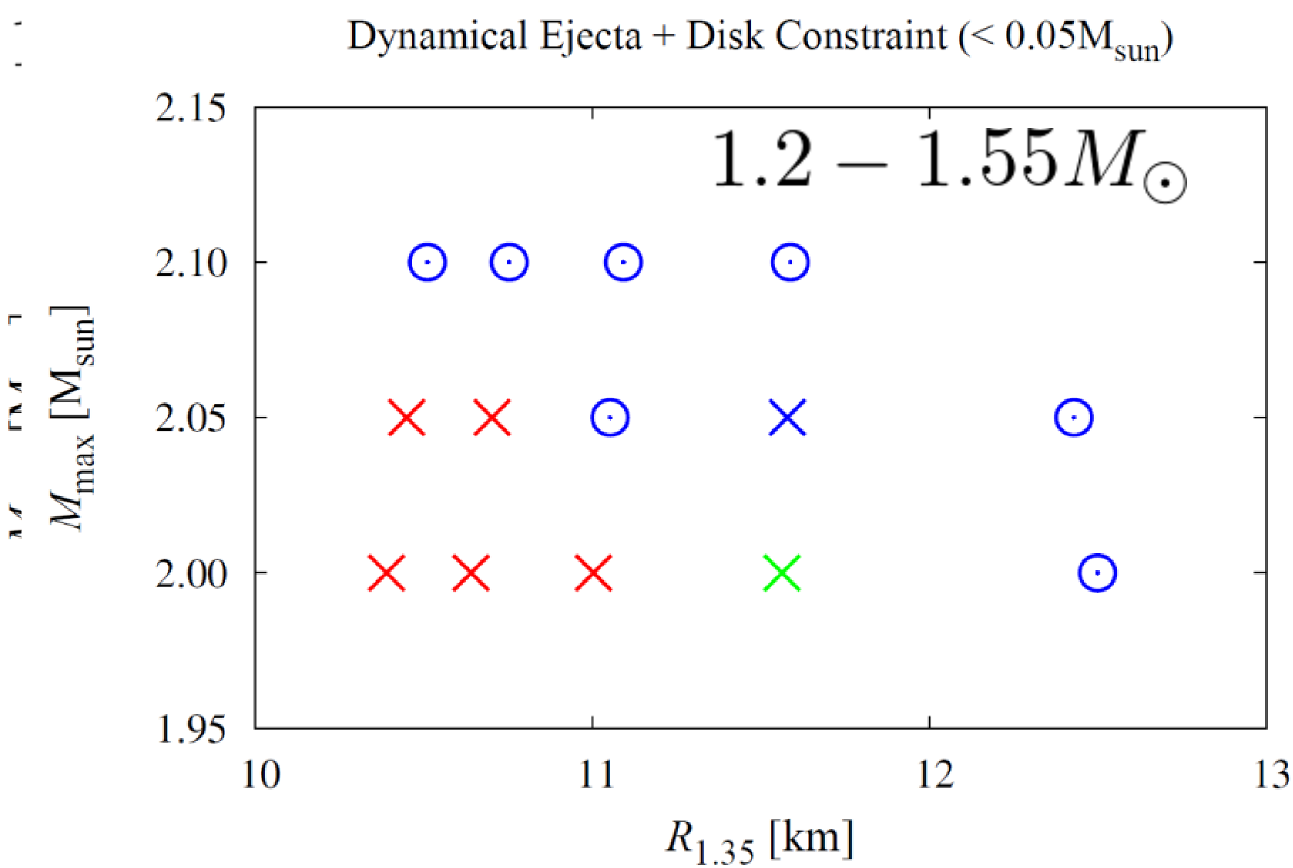
PWP framework

▶ M_{max} = 2.00-2.10 $M_\odot$

▶ $R_{135} \approx$ 10.4-12.4 km

NS radius constraint from a prompt BH formation (KK et al. 18 in prep)

$1.375 -$

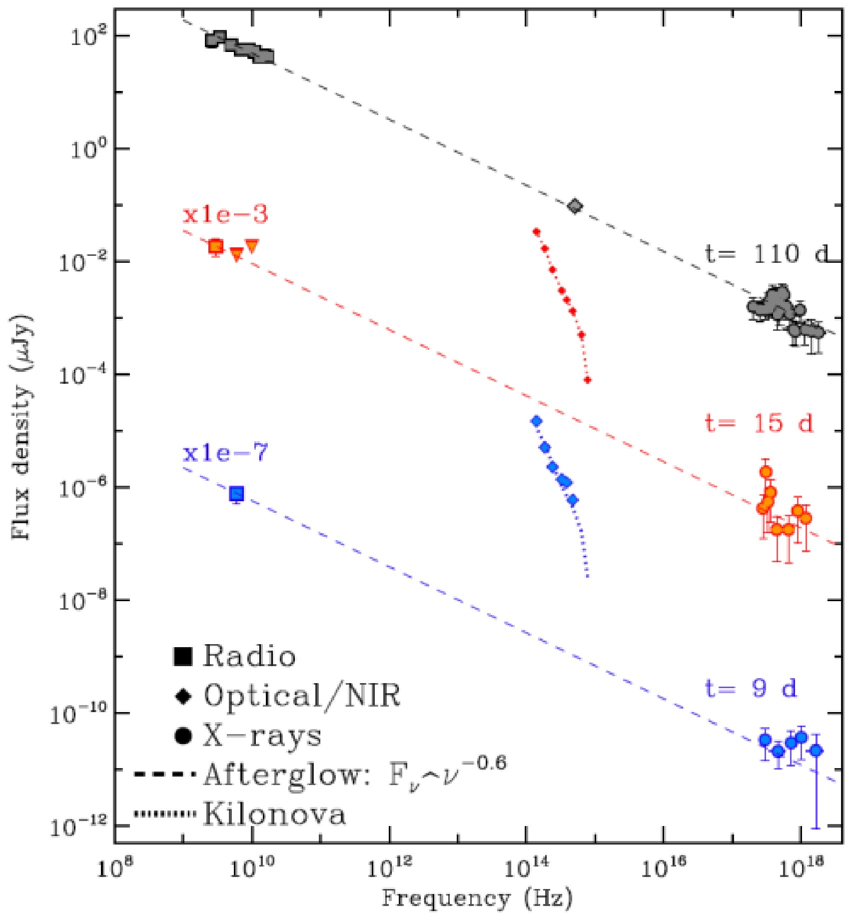


mation
/INS
ed HMNS

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

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

About 100 days observation @ Radio, X-ray observation after the merger



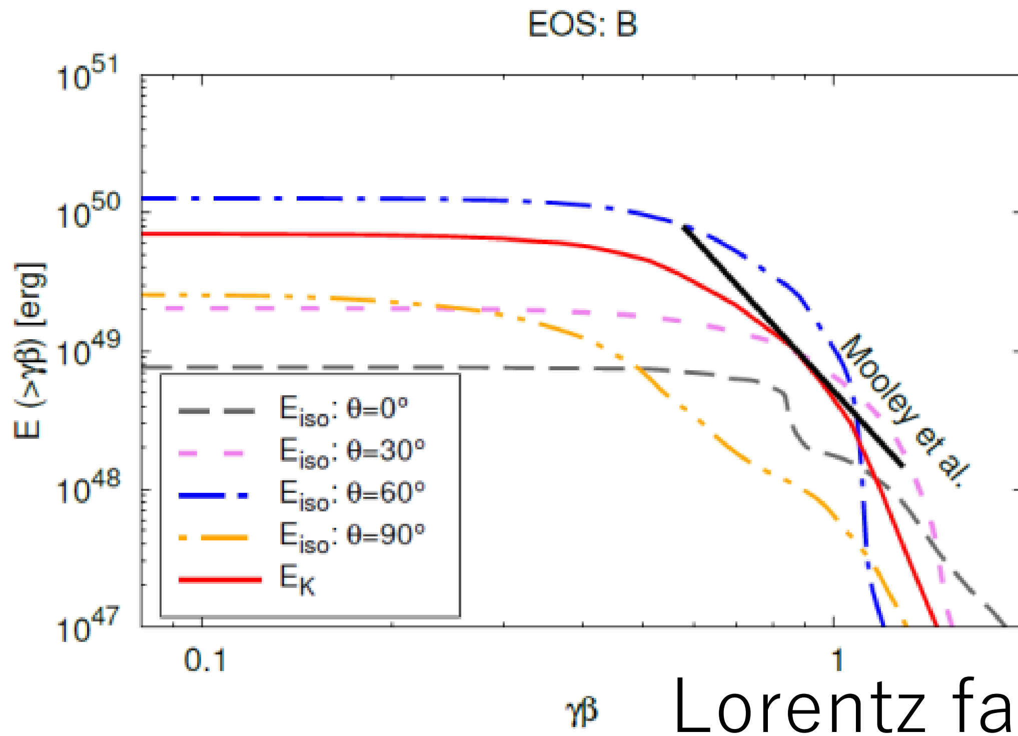
Margutti et al. 18
Mooley et al. 17
Troja et al. 17
Hallnan et al. 17

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

Long-term radio, X-ray, optical observations
(Hotokezaka, KK et al. 18)

Mildly relativistic dynamical ejecta

kinetic energy above $\gamma\ \beta$

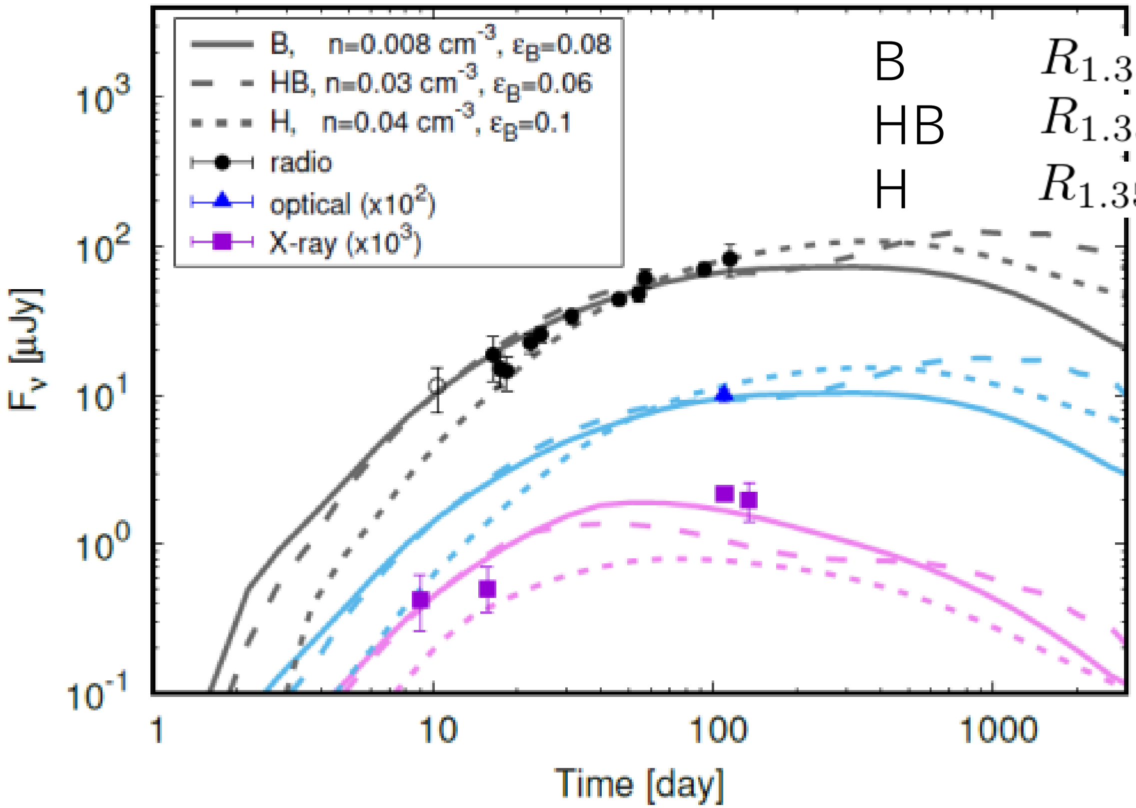


Lorentz factor × v/c

▶ Fast component coming from a contact interface

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

Long-term radio, X-ray, optical observations
(Hotokezaka, KK et al. 18)



B $R_{1.35M_\odot} = 10.96\mathrm{km}$
HB $R_{1.35M_\odot} = 11.61\mathrm{km}$
H $R_{1.35M_\odot} = 12.27\mathrm{km}$

▶ Our model can fit radio, X-ray, optical data
▶ Prediction : X-ray starts to decline around t ～ 100days

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 the data analysis is on going.

▶ Prompt BH formation is unlikely in GW170817 ⇒ lower bounds in NR radius

▶ Long-term observation in radio, X-ray, and optical signal can be explained by a mildly dynamical ejecta
⇒ Soft EOS is favored.