Gravitational-waves/ Electromagnetic counterparts modeling for Neutron star binaries

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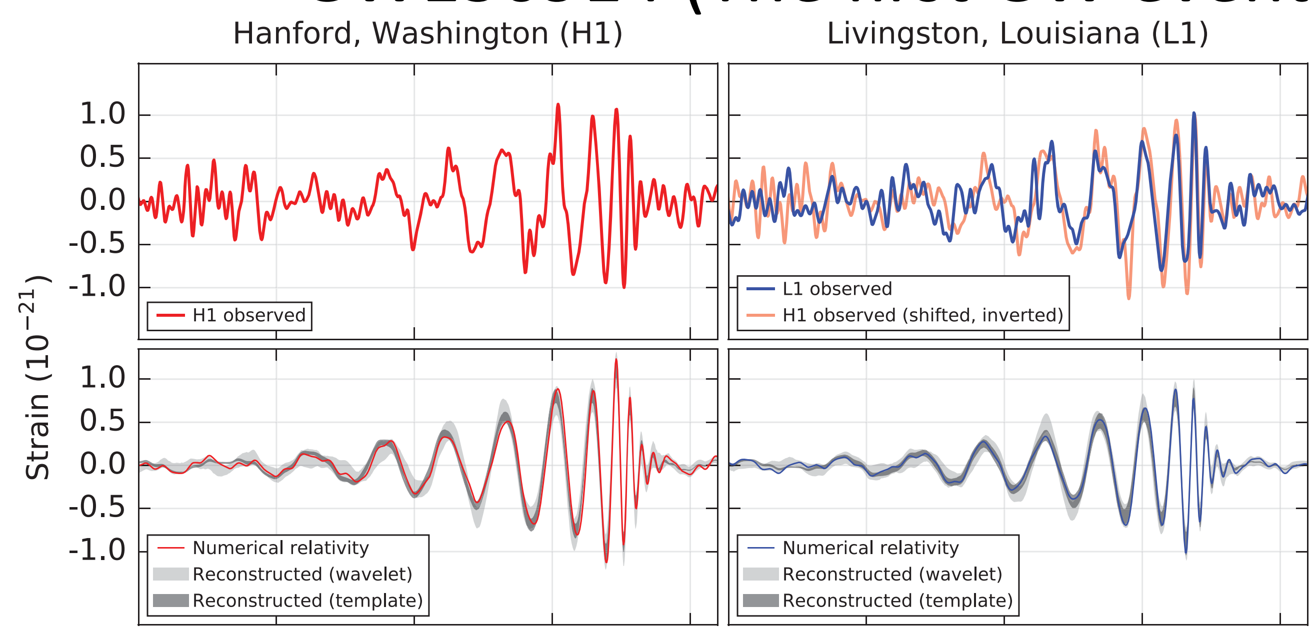
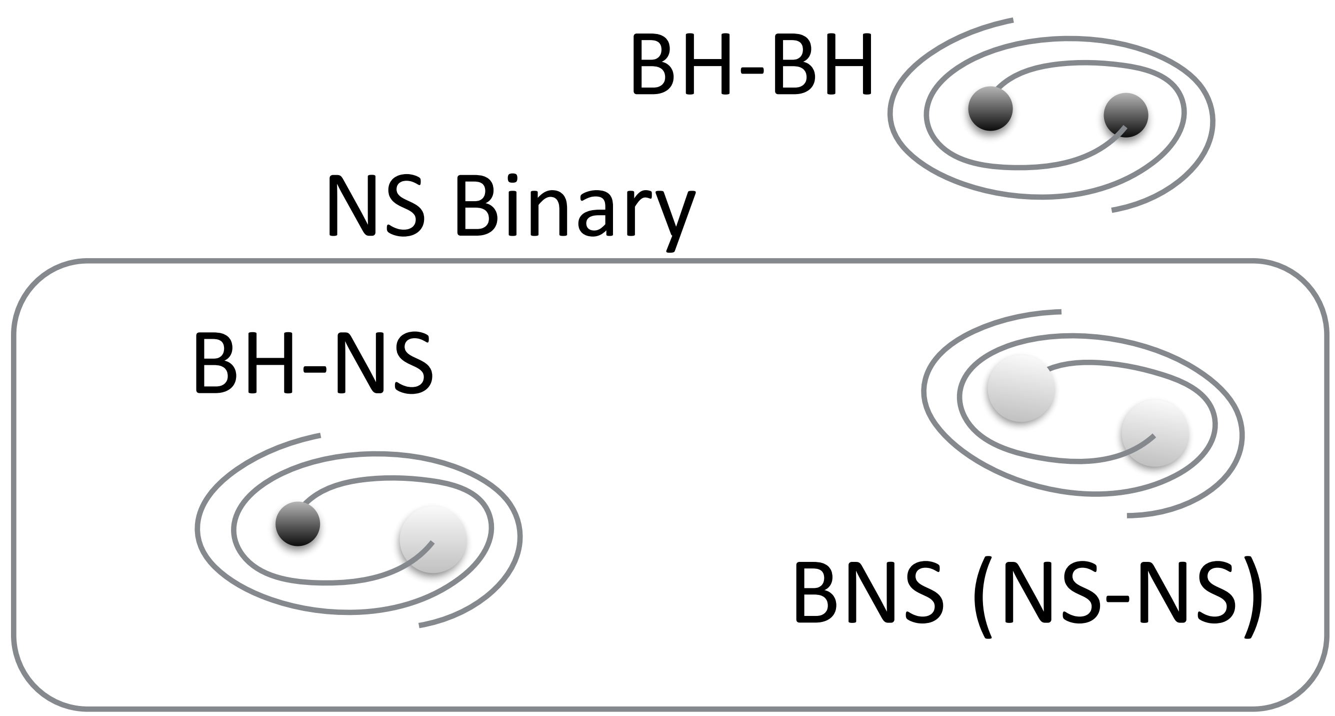
Compact binary mergers

- Compact Binaries: Binary system composed of black holes (BHs) and/or neutron stars (NSs)
- Compact binaries efficiently emit gravitational waves shrinking their orbital separation, and the objects eventually merge-> **compact binary mergers**
- Compact binary mergers are among the main targets of ground-based gravitational-wave detectors,
  such as **LIGO**, **Virgo**, **Ligo-India**, and **KAGRA**
- Since 14th of September 2015, many GW events have been detected
- Binary BH (BBH; BH-BH)
  - GW150914, GW151012, GW151226, GW170104, GW170608, GW170809, GW170814, GW170817, GW170818, GW170823
- **Binary NS (BNS; NS-NS) GW170817**

- GW150914 (The first GW event)



Ref: B.P.Abbot et al. 2016



Neutron star binary mergers

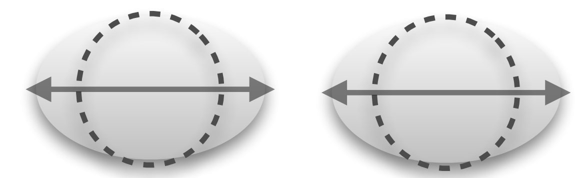
- Gravitational waveform of a binary merger contains rich physical information of the source (masses, spins, distance, inclination, etc…)

- In particular, **if the binary contains a NS**, the information of the internal structure of the NS can be extracted

- During the inspiral, a NS is deformed by the tidal force of the companion object. Deformation of a NS (s) accelerates the orbital shrinking, and modifies gravitational waveforms

- From the observed waveforms, *the tidal deformability* of a NS can be extracted

- The tidal deformability reflects the internal structure of a NS, and it can constrain **the NS equation of state (EOS)**



Tidal deformation

$$\Delta\Phi_{\mathrm{GW}}^{\mathrm{Tidal}}(t)$$

Modification in the GW phase

$$\Lambda = G\lambda\left(\frac{c^2}{GM_{\mathrm{NS}}}\right)^5 \sim \left(\frac{c^2 R_{\mathrm{NS}}}{GM_{\mathrm{NS}}}\right)^5$$

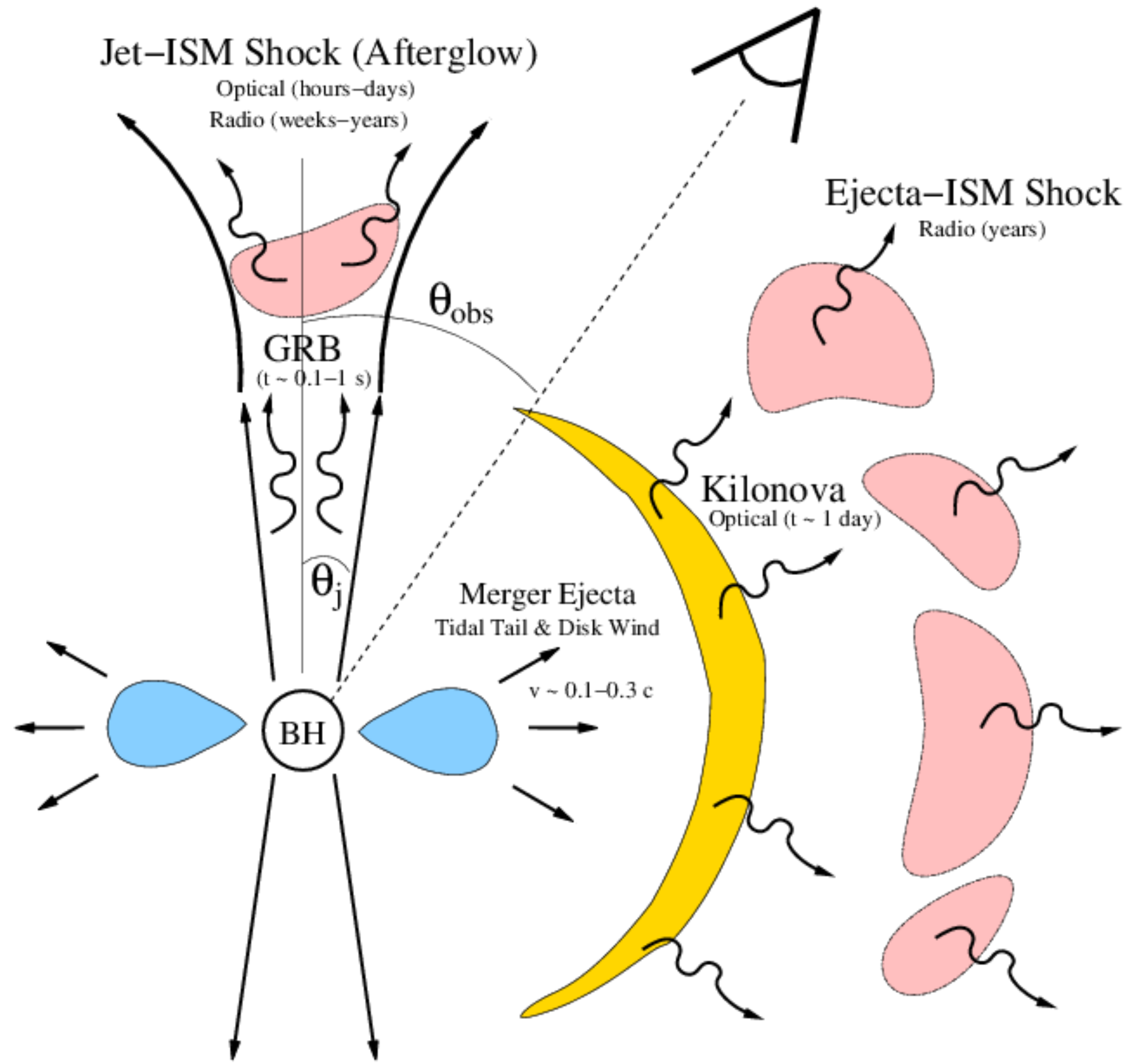
（dimensionless） tidal deformability

$$Q_{ij} = -\lambda\mathcal{E}_{ij} = -\lambda\partial_i\partial_j\Phi$$

Quadrupole tidal field

Electromagnetic Counterparts to NS binary mergers

- Various transient EM counterparts are proposed for NS binary mergers
- for example,
  - short-hard gamma-ray-burst
  - Afterglow
  - cocoon emission
  - kilonovae/macronovae
  - radio flare, etc.
- Host galaxy identification, remnant properties, source environment
- Possible synthesis site of r-process nuclei



Ref: B. Metzger and E. Berger 2012

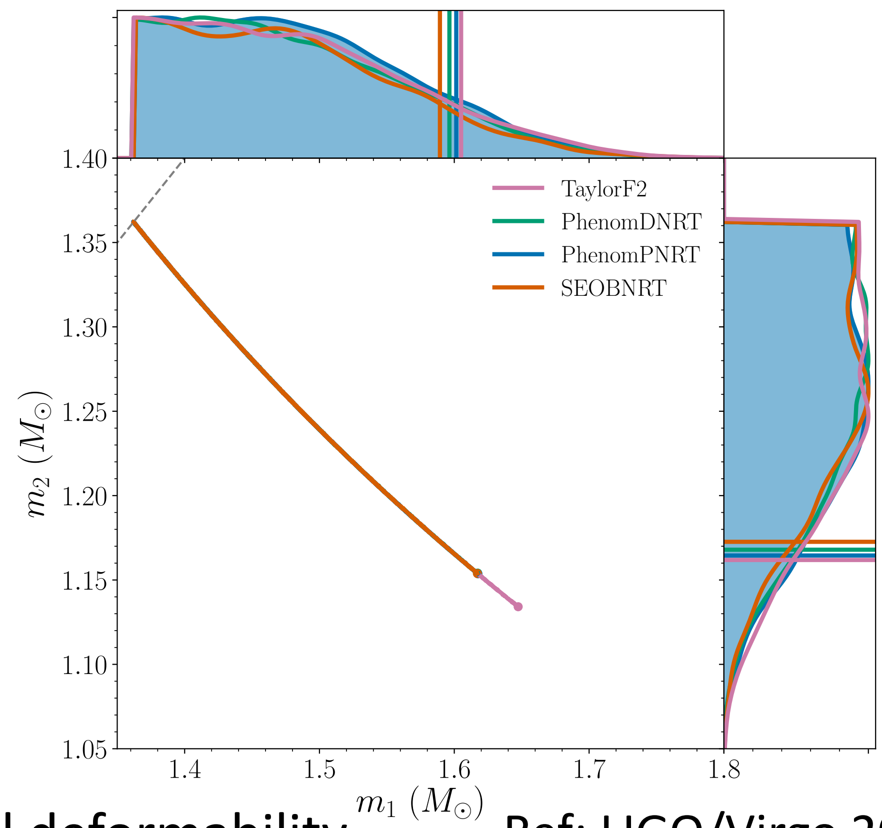
GW170817

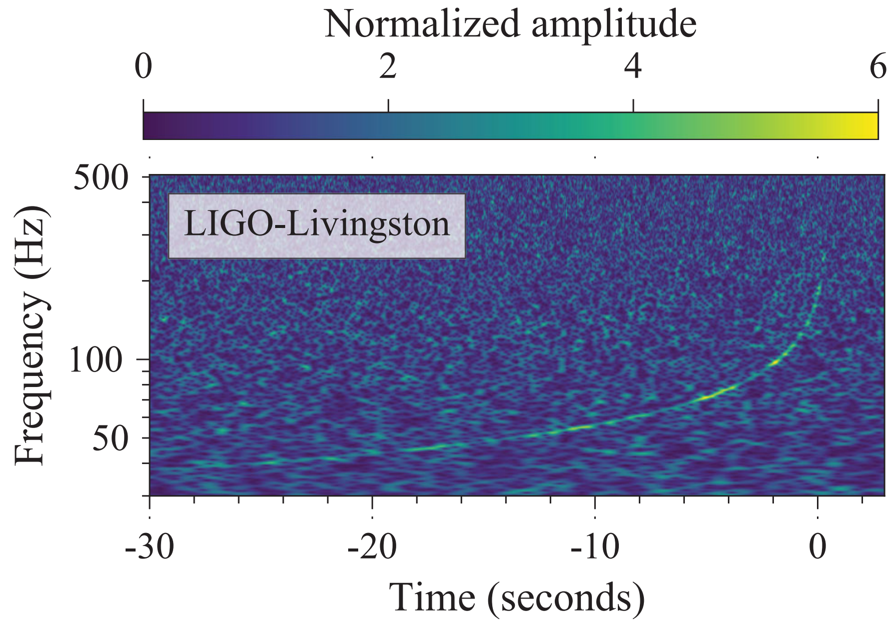
- On 17th of August 2017,
  LIGO and Virgo reported
  the first detection of gravitational waves from
  a binary NS (BNS; NS+NS binary) merger

- Binary parameters were constrained tightly as ever was, and **the tidal deformability** is indeed measured (constrained) in this event

- Independent analysis of parameter estimation is performed by several groups
  employing several waveform models
  and assumptions

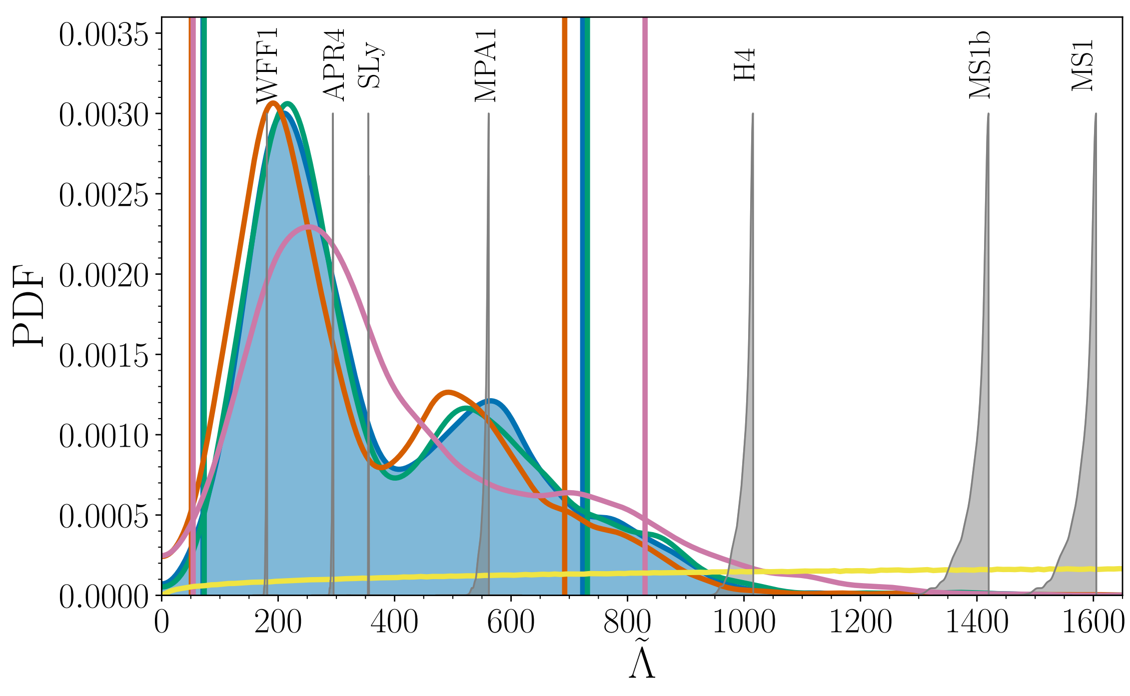
Masses of the binary components





Tidal deformability

Ref: LIGO/Virgo 2017,2018



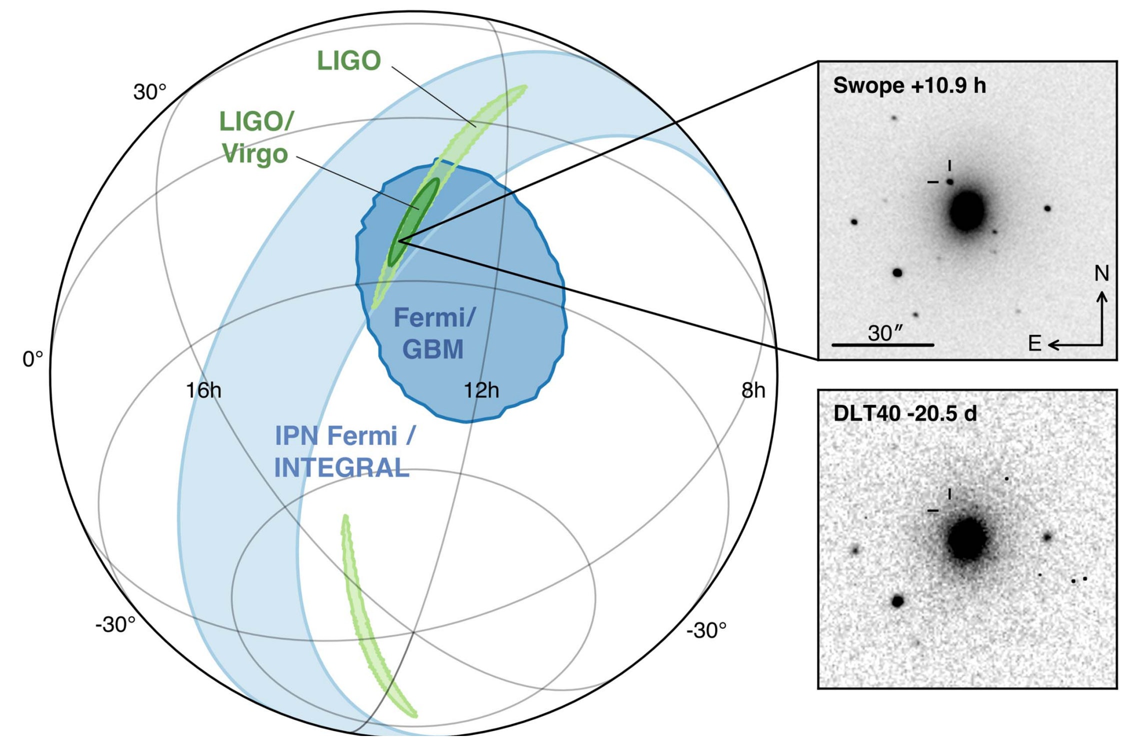
GW170817: Electromagnetic Counterparts

- Electromagnetic (EM) counterparts to GW170817 were observed simultaneously over the entire wavelength range
 (from radio to gamma wavelengths)

- The follow-up observation of the electromagnetic counterparts allowed us to identify the host galaxy (NGC4993: ~40 Mpc)

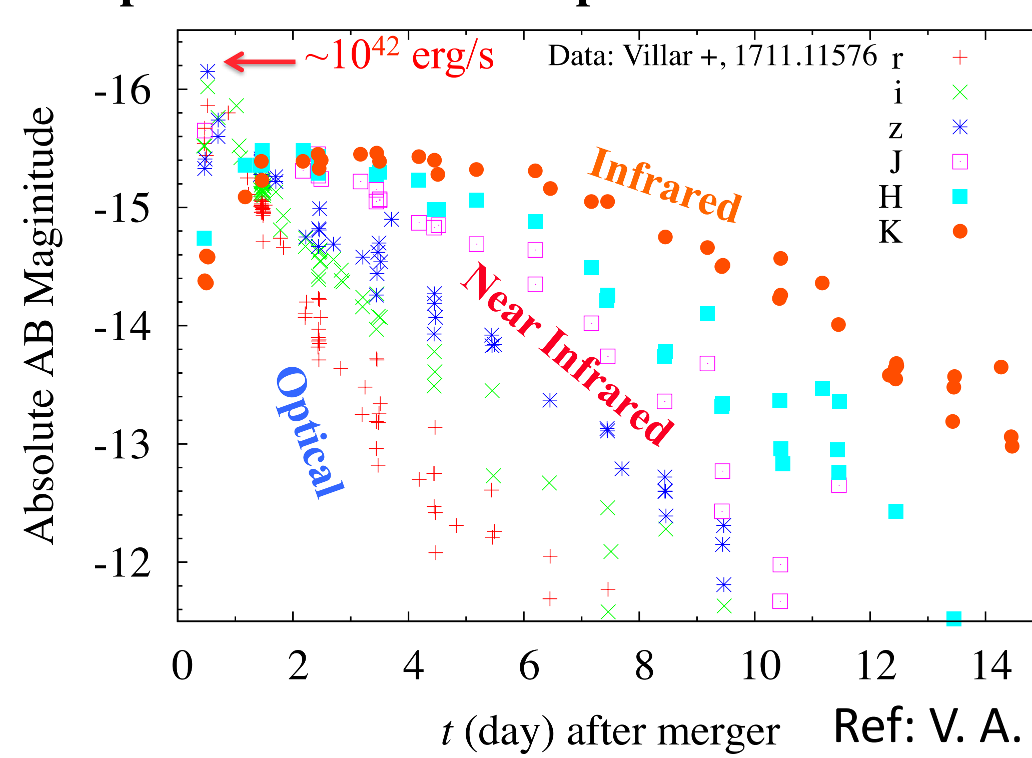
- Observed lightcurves and spectra provided the physical information of merger ~ post-merger dynamics of the system

  (property of merger remnant,
  r-process nucleosynthesis,
  existence of relativistic jets,...)



Ref: P. S. Cowperthwaite 2017

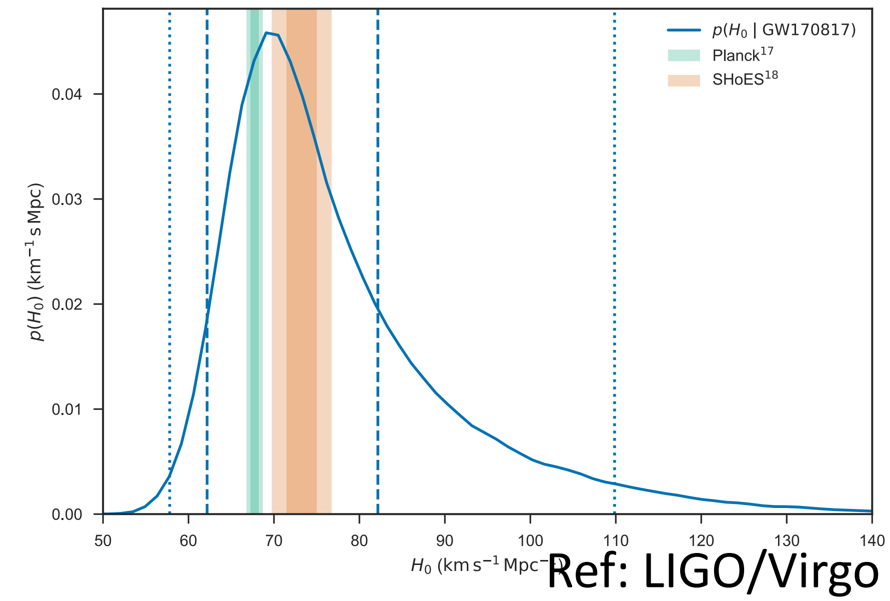
Optical-IR EM counterparts of GW170817



Ref: V. A. Villar 2017

Multi-messenger Astronomy

- The first opportunity of
  multi-messenger astronomy
  with the combination GW and EM observation



Ref: LIGO/Virgo 2017

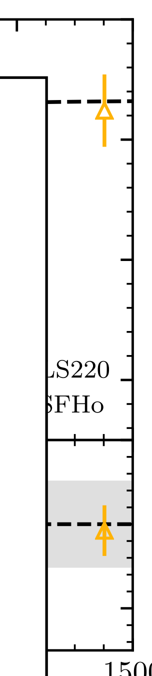
  - Host galaxy + GW luminosity distance
    → Hubble parameter

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

Ref: LIGO/Virgo/Fermi/INTEGRAL 2017

  - Time delay of Gamma ray observation:
    → GW propagation speed

- Tasks and problems:
  - **accurate GW template for NS binary mergers**
  - accurate prediction of ejecta profile
  - **accurate kilonovae/macronovae lightcurve prediction**
  - short GRB association?
  - etc…



Ref: Radice & Dai 2018

Gravitational waveform modeling for NS binaries

GW templates for BNS

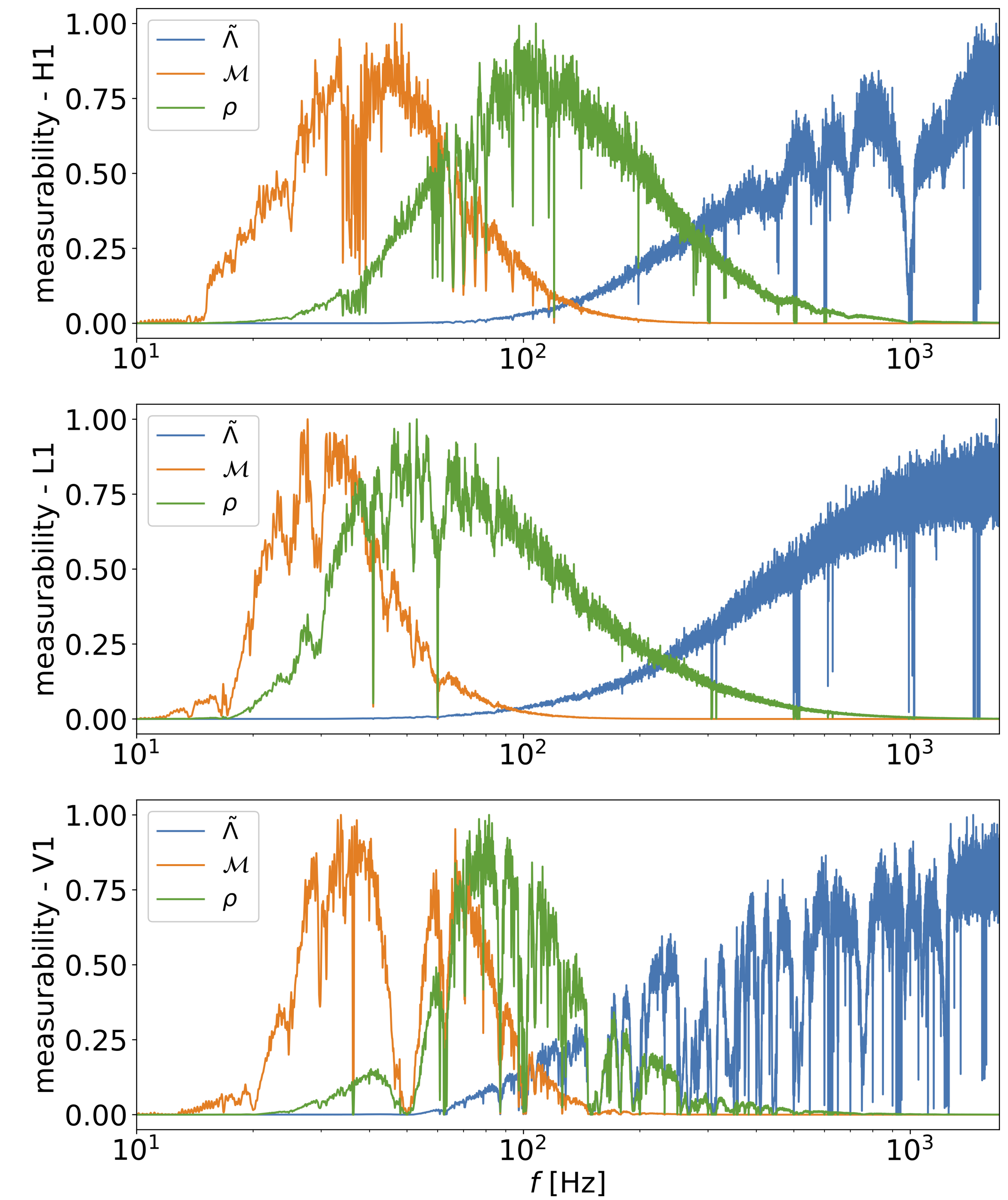
- Physical information is extracted from observed gravitational waves by the comparison with theoretical templates
  $\rightarrow$ **an accurate waveform templates are crucial for parameter estimation**

- The waveforms including the tidal effects are analytically derived by post-Newtonian (PN) calculation
  (and the Effective-One-Body formalism)

  - Newtonian (Flanagan et al. 2008)
  - 1 PN (Vines et al. 2011)
  - 2.5 PN (Damour et al. 2012)
  - Self force informed resum. (Bernuzzi et al. 2015, 2018)
  - Dynamical tide (Hinderer et al. 2016, Lackey et al. 2018)

- **Tidal effects become significant in the last part of the inspiral. However, the model based on PN calculation would not be accurate just before the merger.**

ref) De et al. 2018



Prediction by numerical simulations is important for modeling the tidal correction
(at least needed to be checked)

Numerical Relativity simulations

- **Numerical-relativity (NR) simulation** is the unique method to predict dynamics and gravitational waves in the late inspiral & merger phase.

Einstein's equation

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Euler equation

$$\nabla_\mu \left(\rho u^\mu\right) = 0 \quad \nabla_\mu T^{\mu\nu} = 0$$

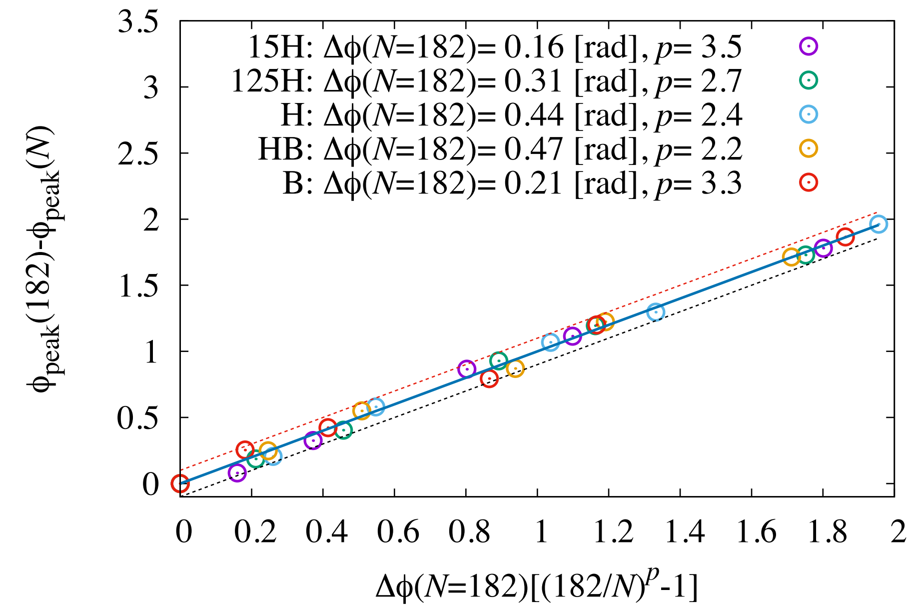
Equation of state (EOS)

$$P = P(\rho)$$

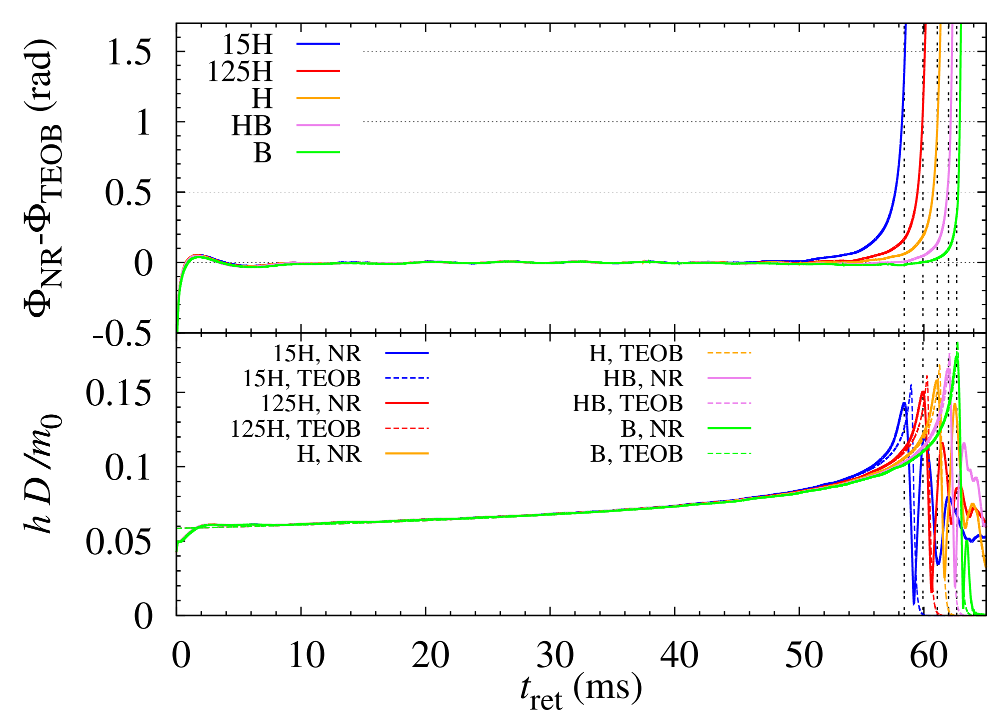
*neither MHD nor neutrino radiation are not considered in these simulations

phase at the time of the peak amplitude

1.21-1.51 M_sun



Ref: Kiuchi et al. 2017,KK et al. 2018



- Performing high-resolution NR simulations, waveforms of which phase errors are estimated to be sub-radian are obtained.

- The phase difference larger than ~1 rad is found between recent TEOB waveforms (SEOBNRv2T) and NR results for the case that Λ~850

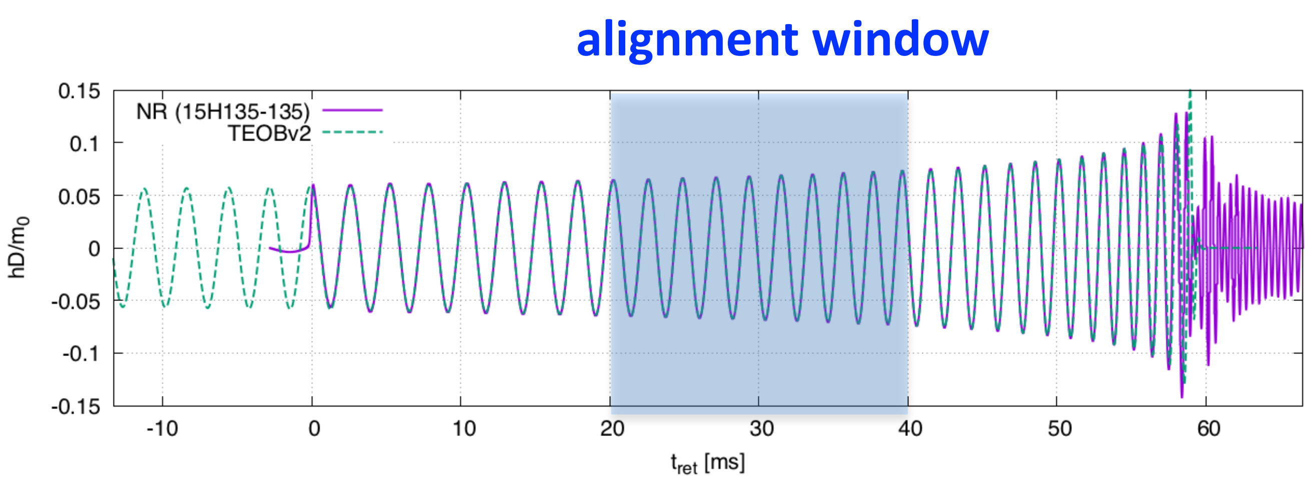
- See also Dietrich et al. 2016, Foucart et al. 2018, Haas et al. 2016 for recent high precision NR simulations for NS binary mergers

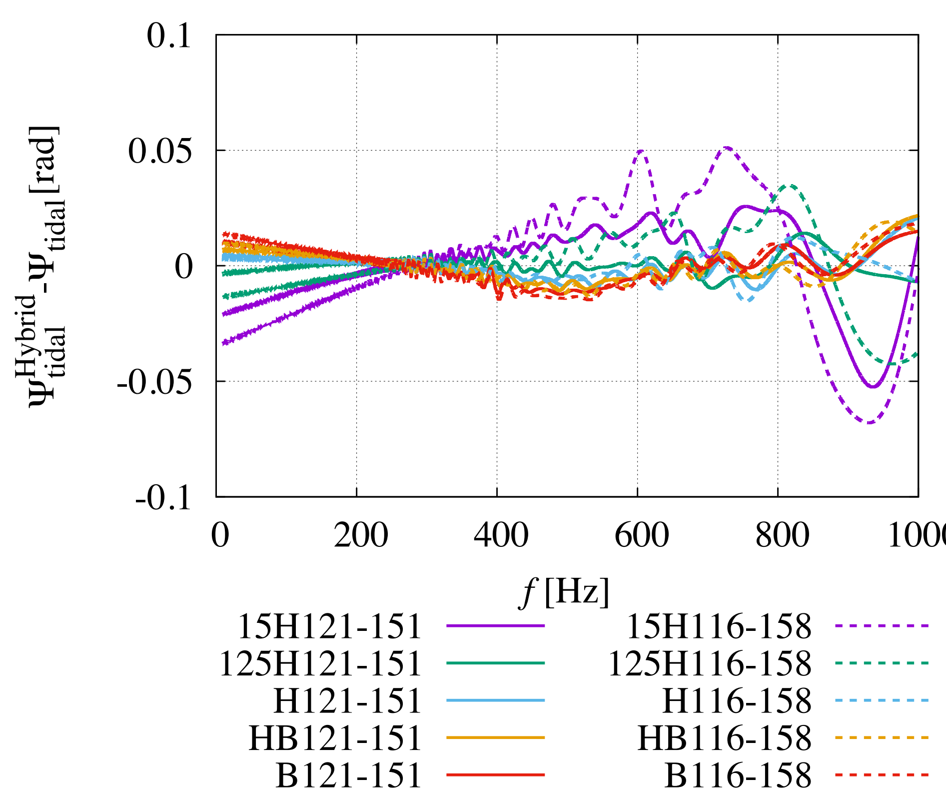
Frequency-domain waveform model

- Based on our latest numerical-relativity waveforms, a frequency domain waveform model for BNS mergers is derived, in particular, for the inspiral phase

- Our waveform model is calibrated to hybrid waveforms composed of our latest numerical-relativity waveforms (>400 Hz) and the EOB (SEOBNRv2T) waveforms (<400 Hz).

Ref: KK et al. 2018





$$\Psi_{\rm tidal} = \frac{3}{128\eta}\left[-\frac{39}{2}\tilde{\Lambda}\left(1+a\tilde{\Lambda}^{2/3}x^{p}\right)\right]x^{5/2}$$
$$\times\left[1+\frac{3115}{1248}x-\pi x^{3/2}+\frac{28024205}{3302208}x^{2}-\frac{4283}{1092}\pi x^{5/2}\right]$$

$$a = 12.55,$$
$$p = 4.240.$$

- We check that our waveform is accurate than ~0.1 rad is for **300<Λ<1900 (~11-14 km)** , **0.7<q<0.1, m_tot~2.5-2.7 M_sun** with respect to the hybrid waveforms

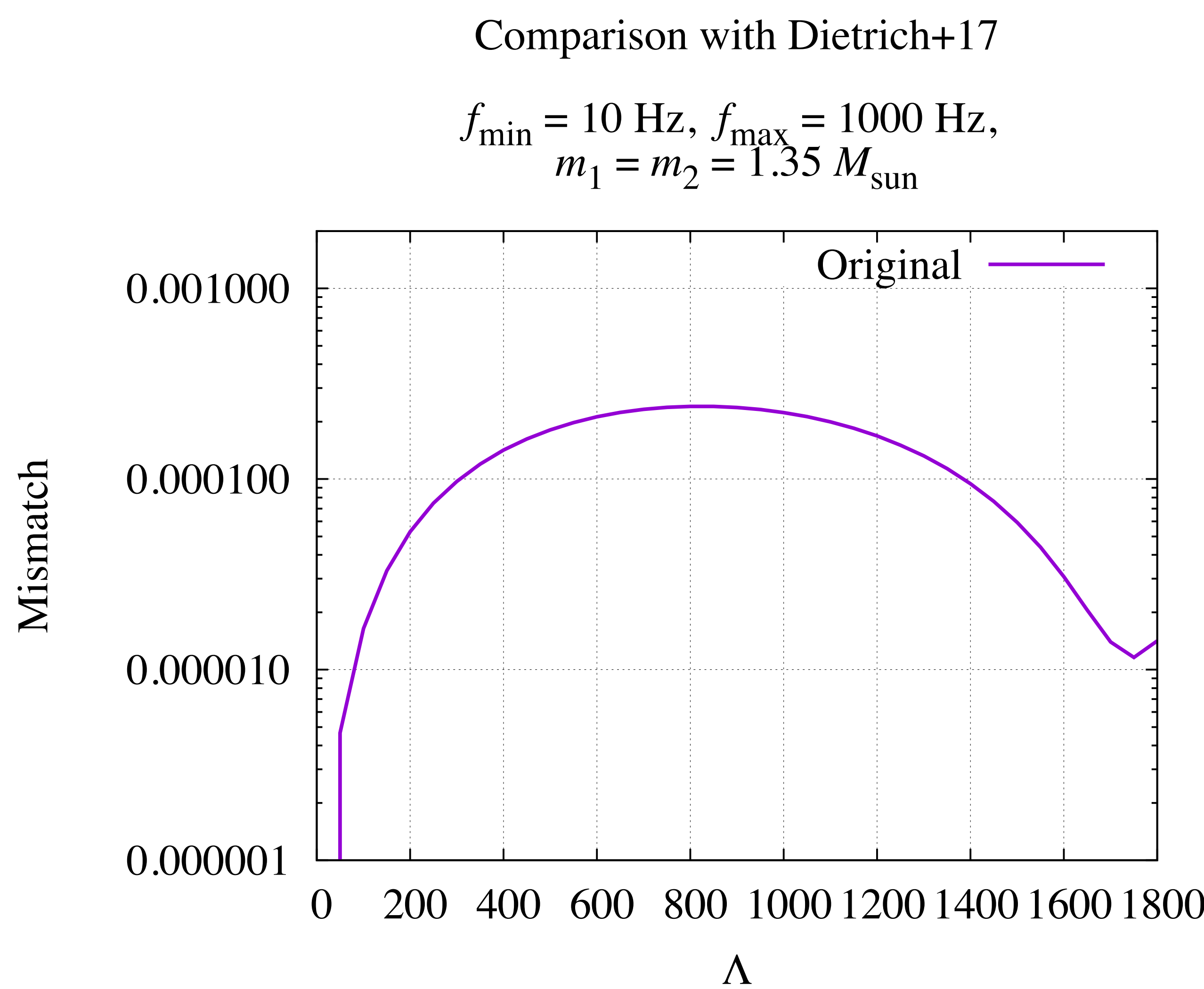
*post-merger waveforms are not included in the model

Comparison with Dietrich et al. 2017

- A BNS GW model is also derived in Dietrich et al. 2017 based on different NR waveforms and TidalEOB waveforms

- **Though their and our models are derived independently, two models give almost consistent results**

- Difference found for a large value of Λ, would be present with the improvement of the statistics (ΔΛ<~100)



Ref: KK et al. 2018

$$\left(\tilde{h}_1 \middle| \tilde{h}_2\right) = 4\mathrm{Re}\left[\int_{f_{\rm min}}^{f_{\rm max}} \frac{\tilde{h}_1(f)\,\tilde{h}_2^*(f)}{S_{\rm n}(f)}df\right] \qquad ||\tilde{h}|| = \sqrt{\left(\tilde{h}\middle|\tilde{h}\right)}$$

Mismatch: $$\bar{F} = 1 - \max_{\phi_0, t_0} \frac{\left(\tilde{h}_1 \middle| \tilde{h}_2(\phi_0, t_0)\right)}{||\tilde{h}_1||\,||\tilde{h}_2||}$$

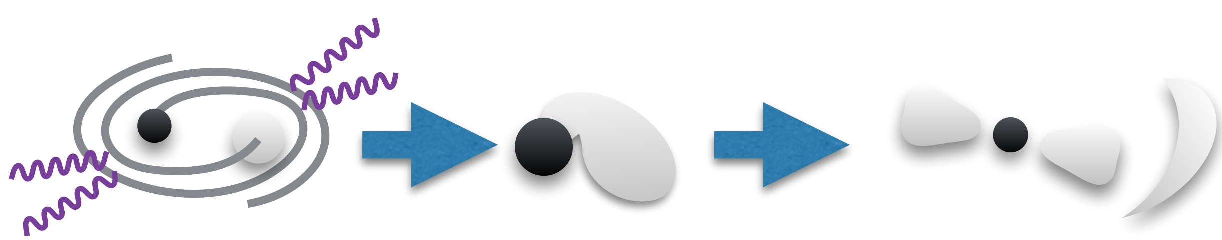
$$\Psi_T^{\rm NRP} = -\kappa_2^T \frac{\tilde{c}_{\rm Newt}}{X_A X_B} x^{5/2} \times \frac{1 + \tilde{n}_1 x + \tilde{n}_{3/2} x^{3/2} + \tilde{n}_2 x^2 + \tilde{n}_{5/2} x^{5/2}}{1 + \tilde{d}_1 x + \tilde{d}_{3/2} x^{3/2}}$$

Ref: Dietrich et al. 2017

Black hole-Neutron star (BH-NS) merger

- Though waveforms in the inspiral phase would have almost the same behavior as BNS or BBH,
  the merger part of the BHNS waveform could be different if the NS is **tidally disrupted**

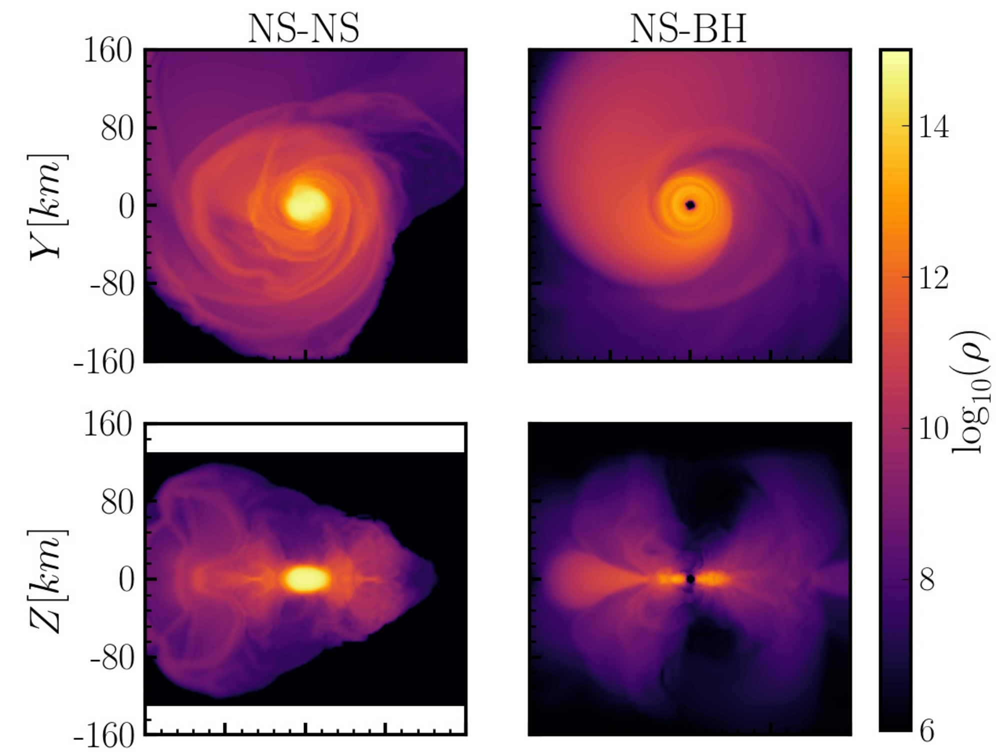
  →The high frequency part (>1kHz) of GW is important
  (see also e.g. Shibata et al. 2009, Lackey et al. 2014, Pannarale et al. 2015)



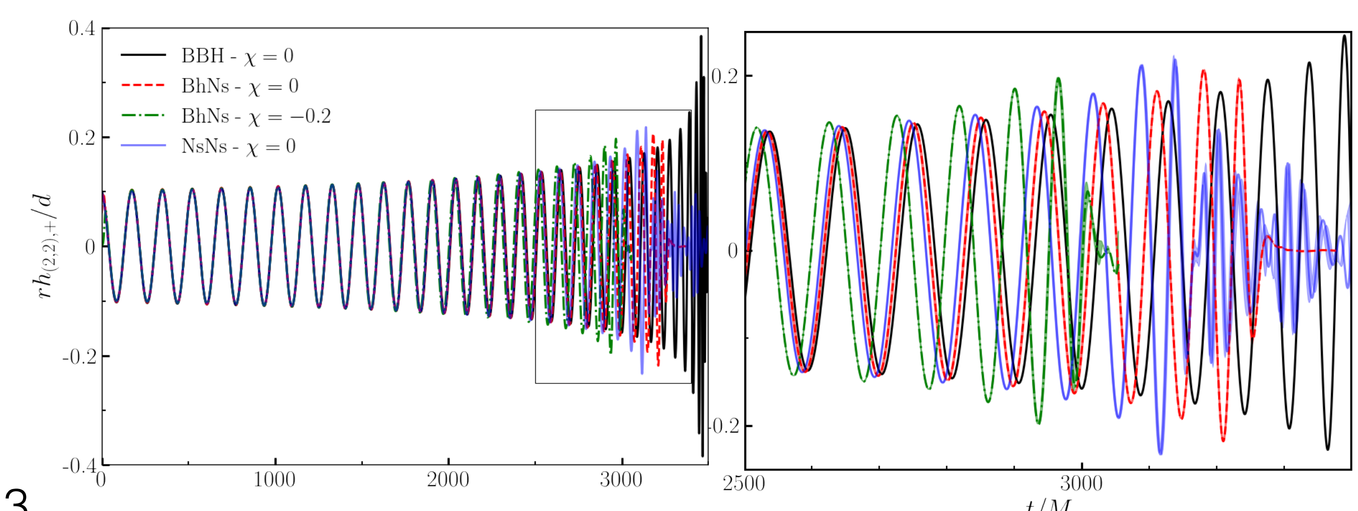
- Kilonova emission would also be different due to difference in the ejecta morphology and composition

- However…
  current GW constraint on tidal deformability (~<600-800) suggests that tidal disruption is difficult unless the mass ratio is small (<3) or the BH spin is high enough (>0.75)

BNS vs. BHNS just after the mergers (Q=1.2) Hinderer et al. 2018



GW comparison between different binary components (Q=1)



Ref: Foucart et al. 2018

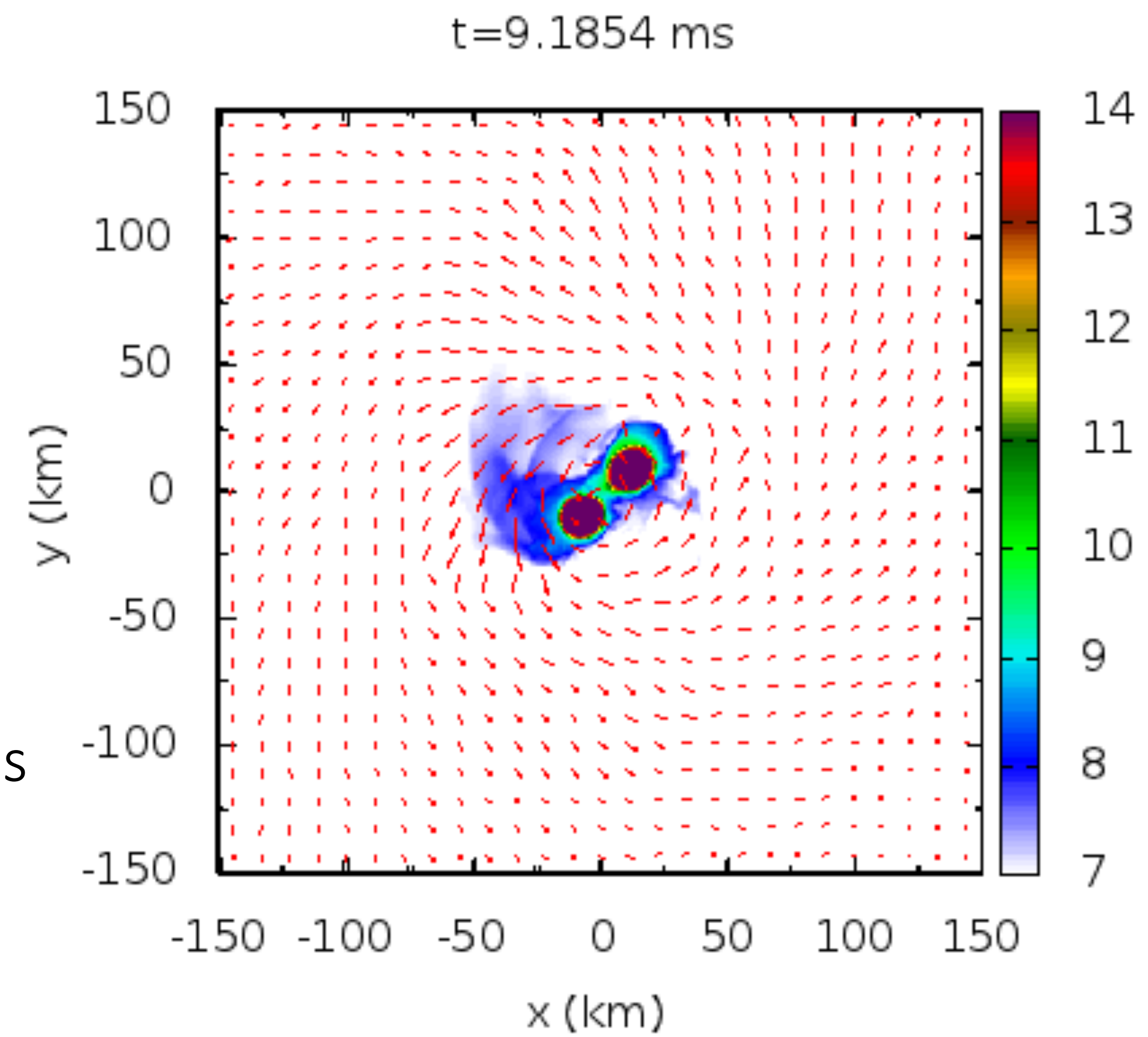
Kilonovae/Macronovae lightcurve modeling

Kilonova/Macronova

- A fraction of NS material would be ejected from the system during the merger

- Ejected material is neutron-rich
→heavy radioactive nuclei would be synthesised in the ejecta by the so-called r-process nucleosynthesis

  →EM emission in optical and NIR wavelengths could occur by radioactive decays of heavy elements
  : **kilonova/macronova**



Li & Paczyński 1998, Kulkarni 2005, Metzger et al. 2010 …

Ref: K. Hotokezaka et al. 2013

Properties of kilonovae / macronovae

- Kilonova/macronova is expected to be nearly **isotropic** emission.
  (cf. $\theta_{\rm jet} \sim 10^\circ$ for sGRB)
- The peak time of the emission will come in **~1—10 days**.
  (cf. ~1 year for radio flare)
- The most of the emission occurs in around **optical and infrared**.
- **The mass, velocity, morphology, and <u>the composition(electron fraction)</u>** of the ejecta characterize the lightcurve of the kilonova/macronova.

Rough Estimation

$$t_{\rm peak} \approx 3.3\,{\rm days} \times \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{1/2}$$

$$L_{\rm peak} \approx 2.0\times10^{41}\,{\rm ergs/s} \times \left(\frac{f}{10^{-6}}\right) \left(\frac{M}{0.03M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-1/2}$$

$$T_{\rm peak} \approx 3.1\times10^{3}\,{\rm K} \times \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{M}{0.03M_\odot}\right)^{-1/8} \left(\frac{v}{0.2c}\right)^{-1/8} \left(\frac{\kappa}{1\,{\rm cm^2/g}}\right)^{-3/8}$$

$M_{\rm eje}$:ejecta mass

κ :opacity

$v_{\rm eje}$:expanding velocity

f : energy conversion rate

The value of ejecta opacity (κ) can vary significantly depending on **the lanthanide fraction** of the ejecta
(Kasen et al. 2013, Barnes et al. 2013, Tanaka et al. 2013)

Mass Ejection Mechanisms

- NR simulations in the last decades revealed various mass ejection processes and the property of the ejecta

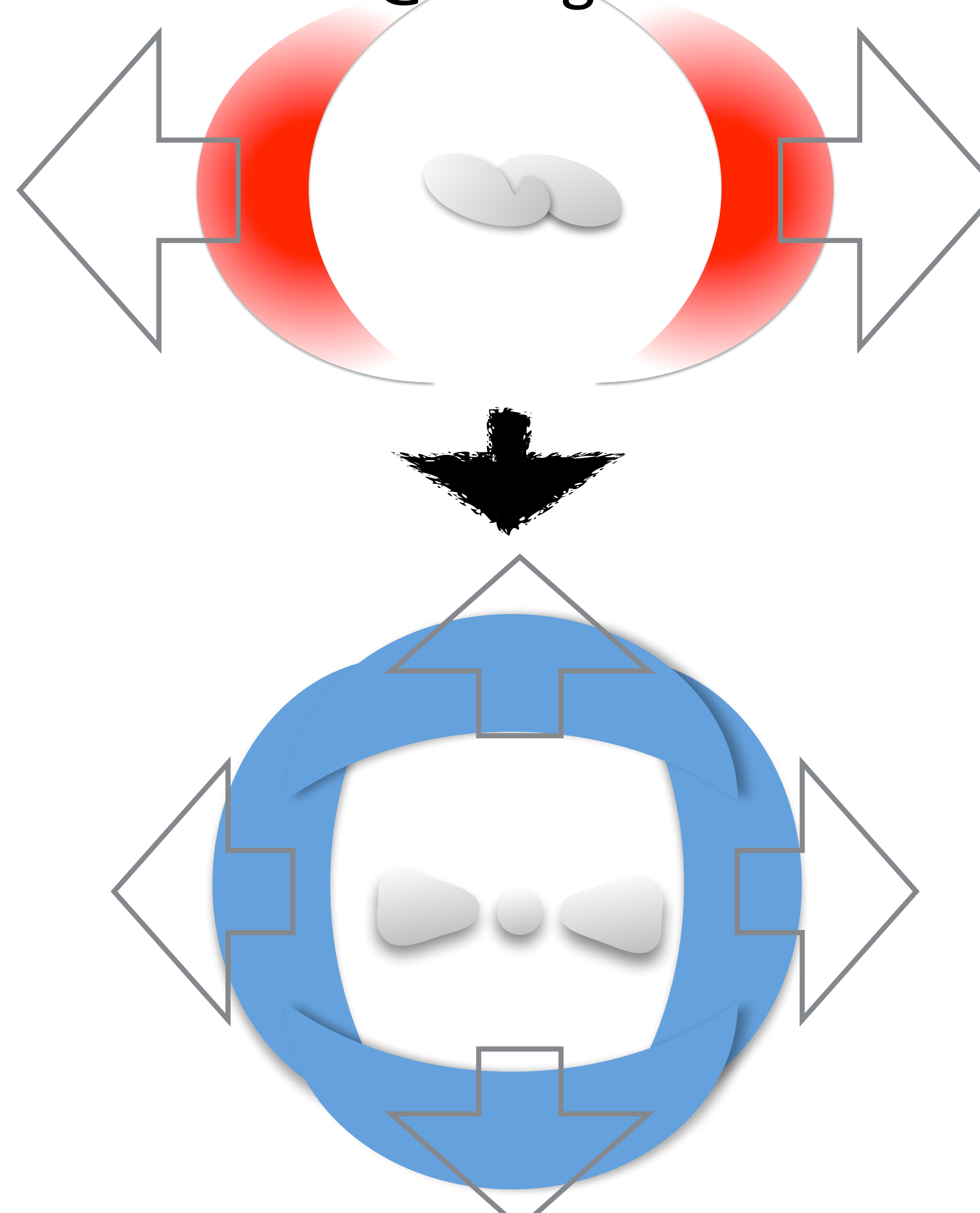
- **Dynamical mass ejection**
  mass ejection driven by tidal interaction
  or
  shock heating during the collision
  →lanthanide rich ejecta: **Red kilonova**

  (e.g., Hotokezaka et al. 2013; Bauswein et al. 2013; Sekiguchi et al. 2016; Radice et al. 2016; Dietrich et al. 2017; Bovard et al. 2017)

- **Post-merger mass ejection**
  mass ejection from the merger remnant driven by magnetic force, viscosity or neutrino radiation
  →lanthanide free ejecta: **Blue kilonova**
  (*if the remnant NS survives for sufficiently long time)

  (e.g., Dessart et al. 2009; Metzger & Fern´andez 2014; Perego et al. 2014; Just et al. 2015; Shibata et al. 2017; Lippuner et al. 2017; Fujibayashi et al. 2018, Siegel et al. 2018, Fernandez et al.2018)

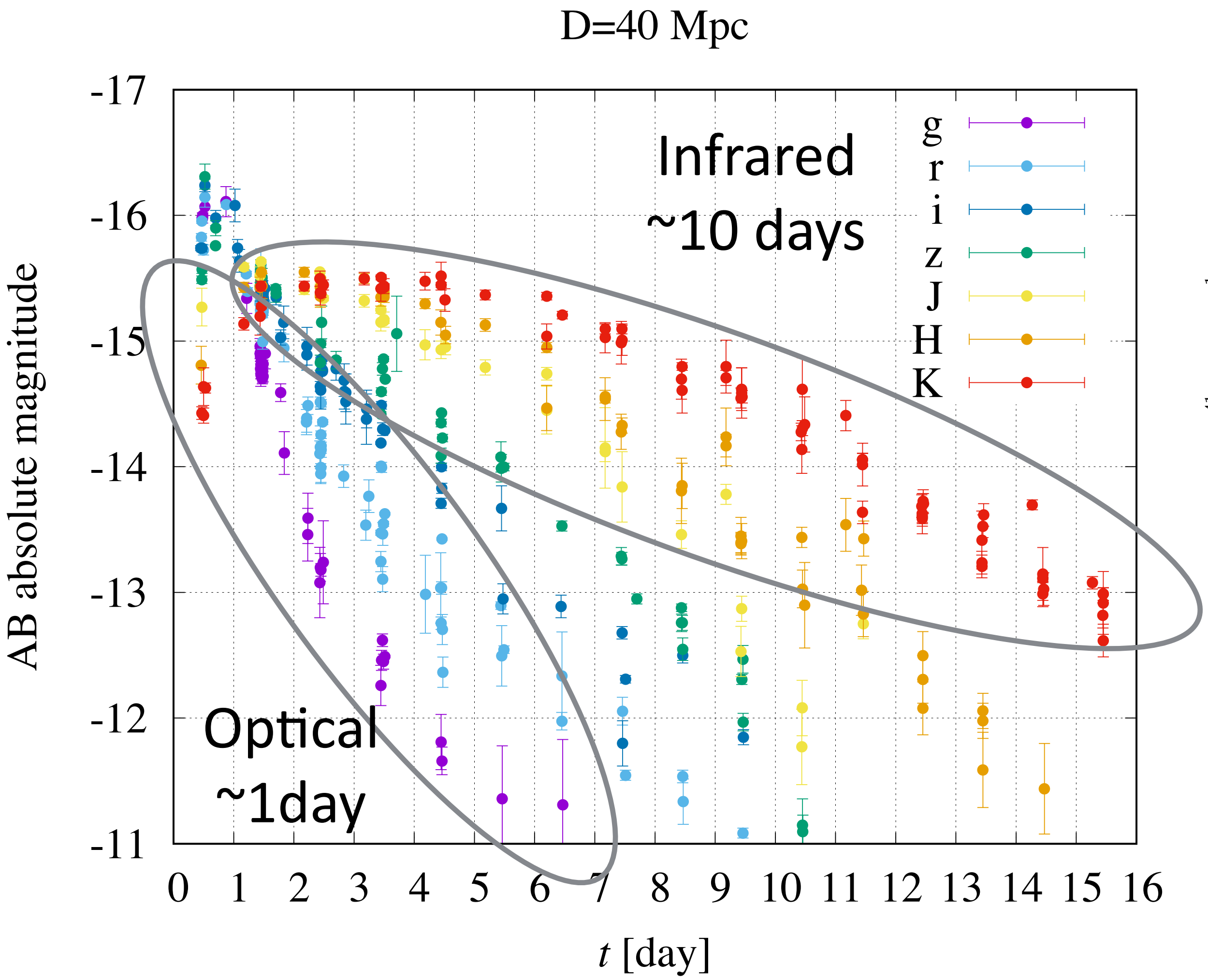
Dynamical mass ejection
@merger



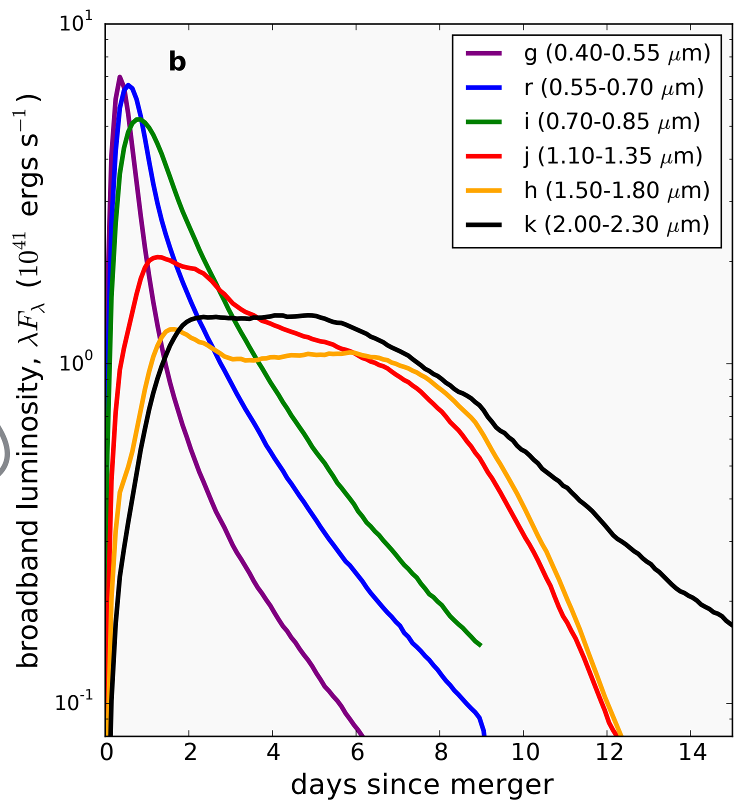
Post-merger mass ejection
@after merger

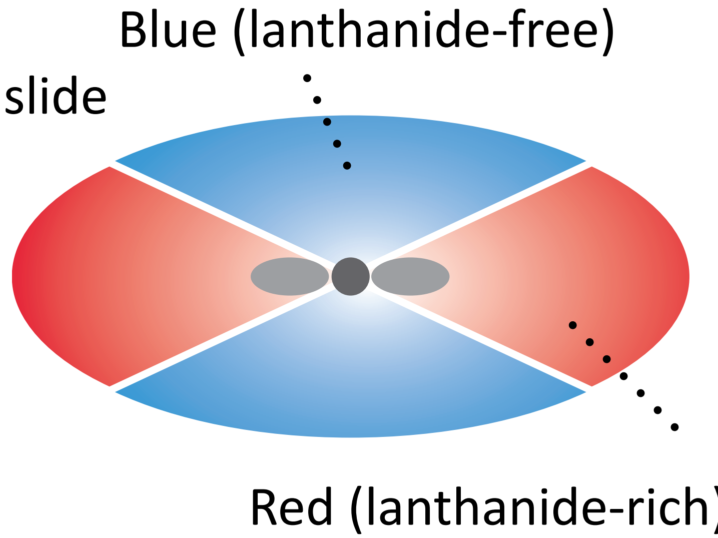
GW170817:
Kilonova with multiple components

Data: Villar et al. 2017



ref) Masaomi's slide



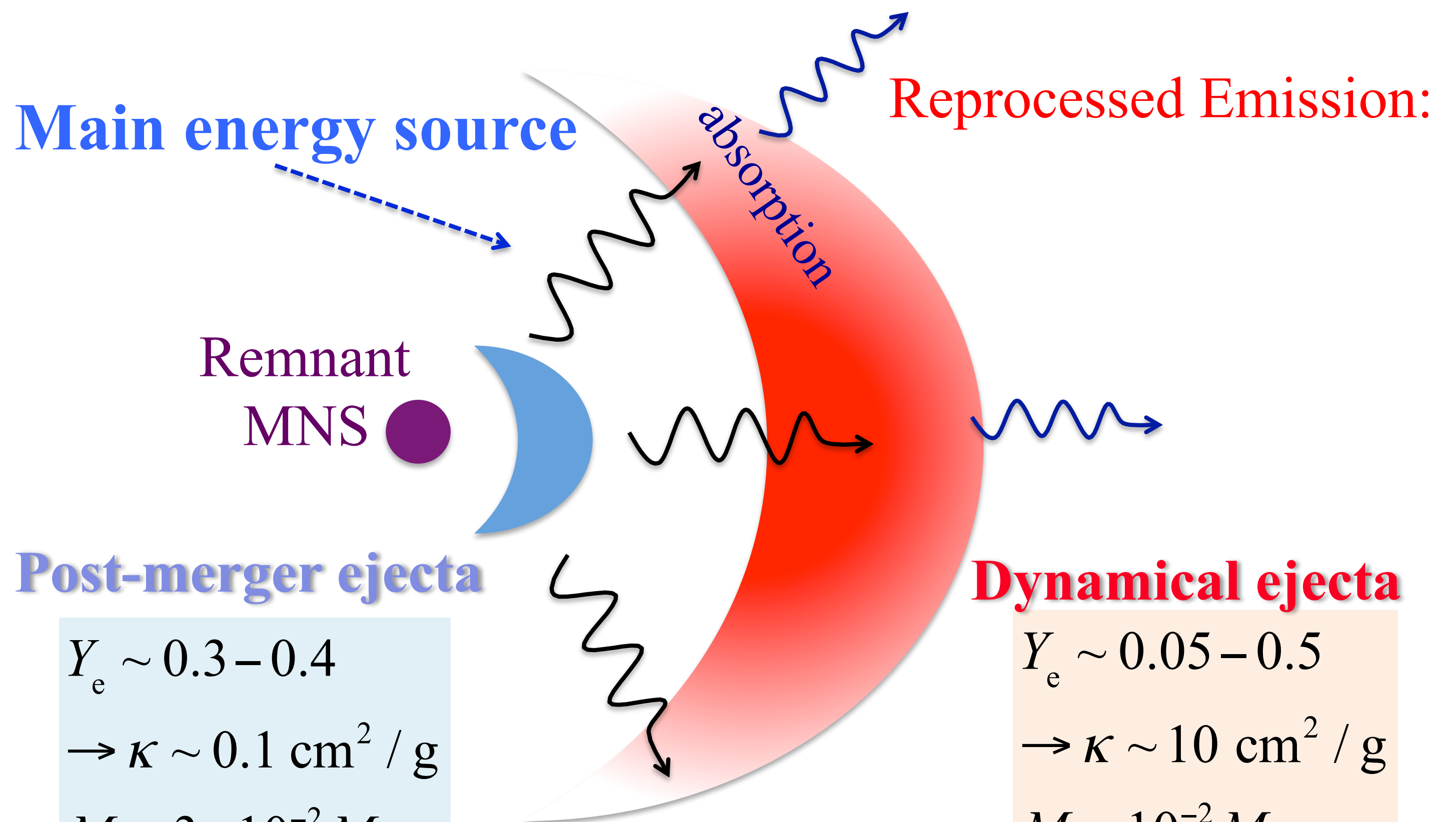


Ref: D. Kasen et al. 2017

- Kilonova/macronova model with multiple components well interprets the observation (see e.g., Kasliwal et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)
    - early-blue component (~1day) from **lanthanide-free ejecta**

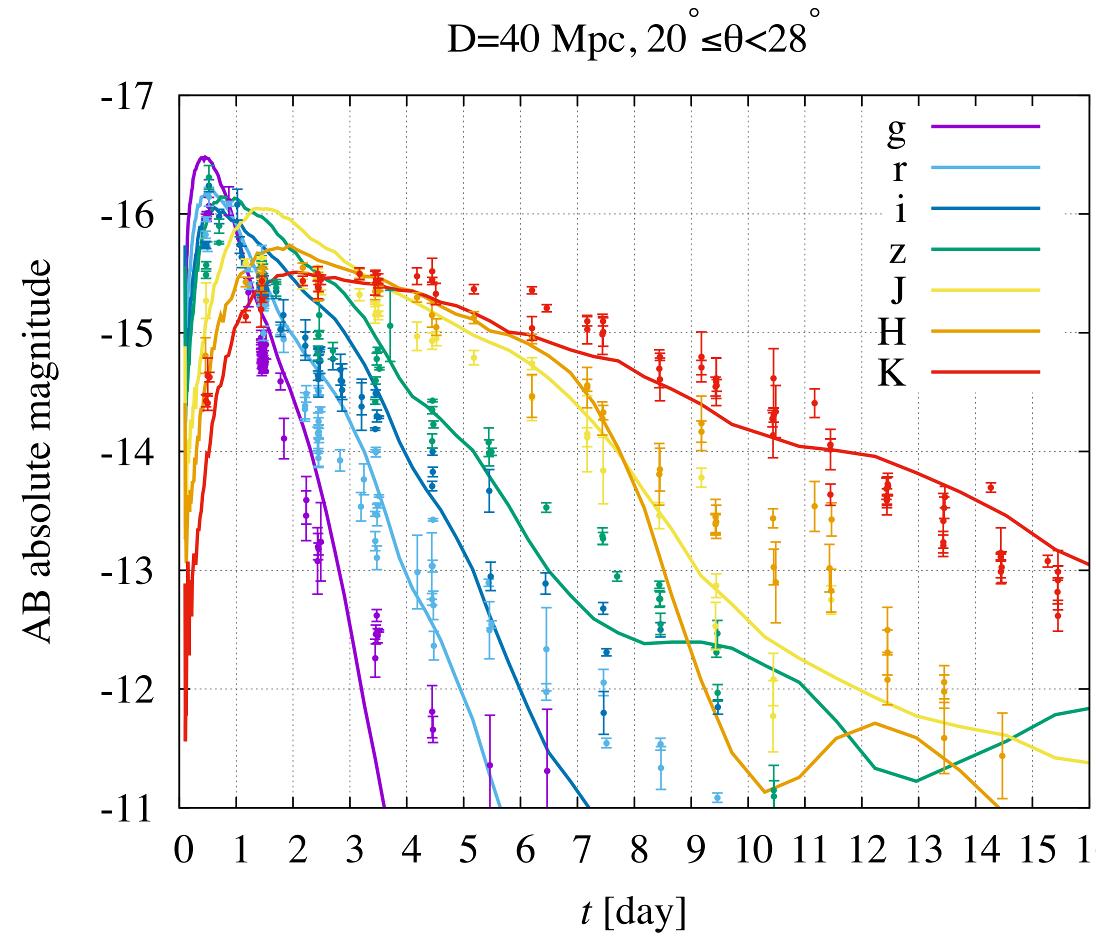
      + long-lasting red component (~10days) from **lanthanide-rich ejecta**
- Properties of ejecta inferred from the lightcurve
  tell us the information about the post-merger evolution of the binary merger

Photon interaction between different ejecta components



$Y_e \sim 0.3 - 0.4$
$\rightarrow \kappa \sim 0.1\ \mathrm{cm}^2/\mathrm{g}$
$M \sim 3\times10^{-2} M_\odot$
$v/c = 0.03 - 0.1$

$Y_e \sim 0.05 - 0.5$
$\rightarrow \kappa \sim 10\ \mathrm{cm}^2/\mathrm{g}$
$M \sim 10^{-2} M_\odot$
$v/c = 0.1 - 0.9$

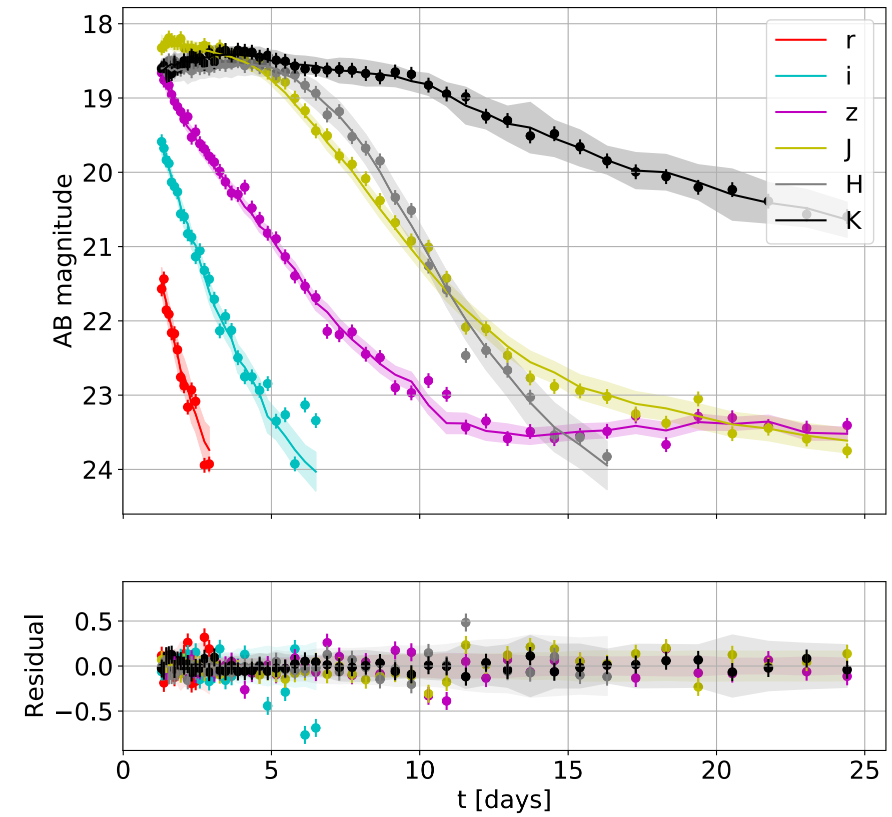


Ref: KK et al. 2018

We perform an axisymmetric radiative transfer simulation for kilonovae/macronovae taking photon interplay between multiple ejecta components into account, and showed its importance for estimating the ejecta mass and velocity. (see Perego et al. 2017, Wollaeger et al. 2017 for studies with similar setups and also Matsumoto et al. for reprocessing models in different context)

MCMC Parameter Inference

- Radiative transfer simulations are computational expensive to perform parameter estimation
  → fitting model employing **GPR modeling**
  (Gaussian Process Regression)
  - RT simulation ~1 Day /model
    → ~1 s/model
  - Photon interaction between different ejecta components are taken into account
- We are developing a MCMC parameter inference code based on the GPR fitting model
  - Systematics of the prediction should be studied (heating rate, thermalization efficiency, atomic line table, etc…)
  - (See also Villar et al. 2017,
    Coughlin et al. 2017, 2018
    for MCMC parameter inference
    based on GPR modeling)



Application to GW170817

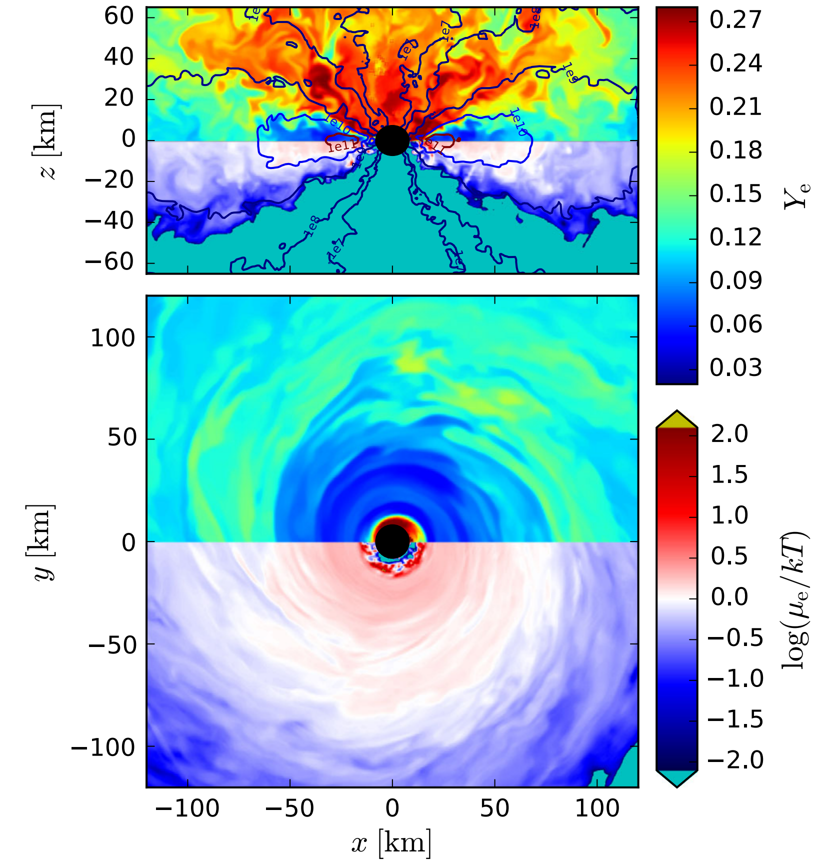
Preliminary

Variation of Kilonovae
BNS prompt collapse /BH-NS case

- If the merger remnant collapses
  to a black hole promptly,
  (or a BH-NS merger case)
  the post-merger ejecta would also be lanthanide-rich
  (see e.g., Wu et al. 2016, Siegel et al. 2018, Fernandez et al. 2018)

- For BHNS merger,
  lanthanide fraction of the ejecta
  would be higher in the absent of shock heating
  and neutrino irradiation
  →kilonova of BHNS dynamical ejecta would be bright in NIR

- **Kilonova emission would have variety depending on the components of the binary and its post-merger evolution**



Ref: Siegel et al. 2018

Summary

- Gravitational waveform model in the inspiral phase including the tidal effect are improved base on numerical relativity simulations
  - Consistent results are obtained between waveform models derived independently
  - Further improvements for both tidal part and point particle part waveform models would be needed to achieve tight constraint on the NS EOS in the future
- Kilonovae modeling considering multiple ejecta components is now in progress
  - Systematics on the lightcurve prediction should be studied
    (heating rate, thermalization efficiency, atomic line table, etc…)
  - Variety of kilonovae should also be studied
    (lanthanide fraction, morphology, connection to the binary parameters)
- GW from a BHNS merger would be detected in not so far future
  → How can we distinguish an event of a BHNS from a BH-BH or a NS-NS
  Merger waveforms?
  Electromagnetic counterparts?
  Further theoretical modeling and understanding of both GW and EM of BHNS are crucial

Thank you for listening!