Gravitational waves and Electromagnetic signals from Neutron Star binary mergers

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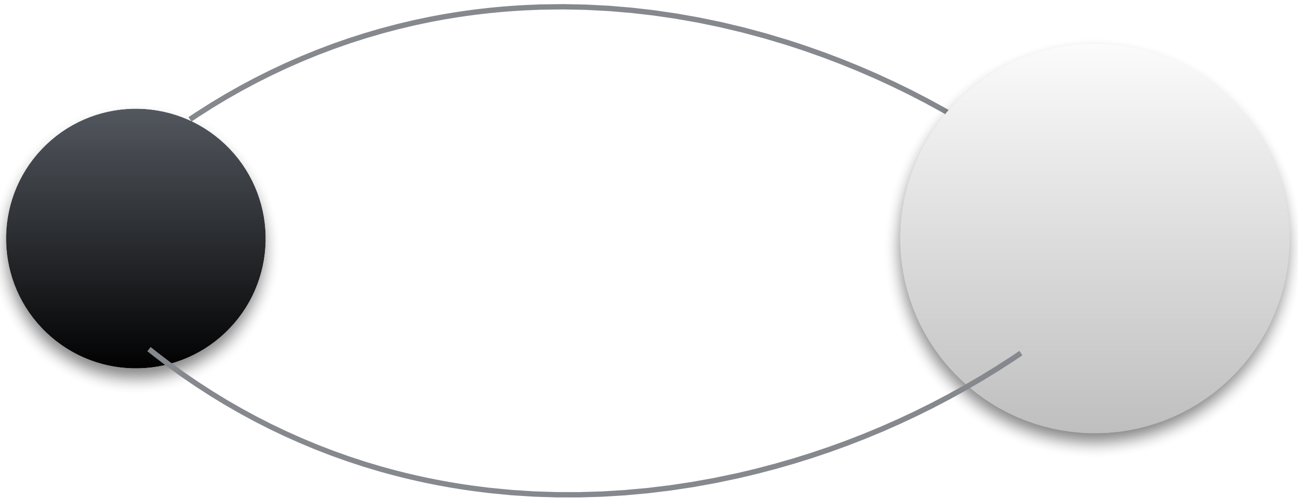
Introduction

Compact Binary



- A compact binary: A binary system composed of **compact objects**, such as a black hole (BH), a neutron star (NS), (and/or a white dwarf)

Black hole

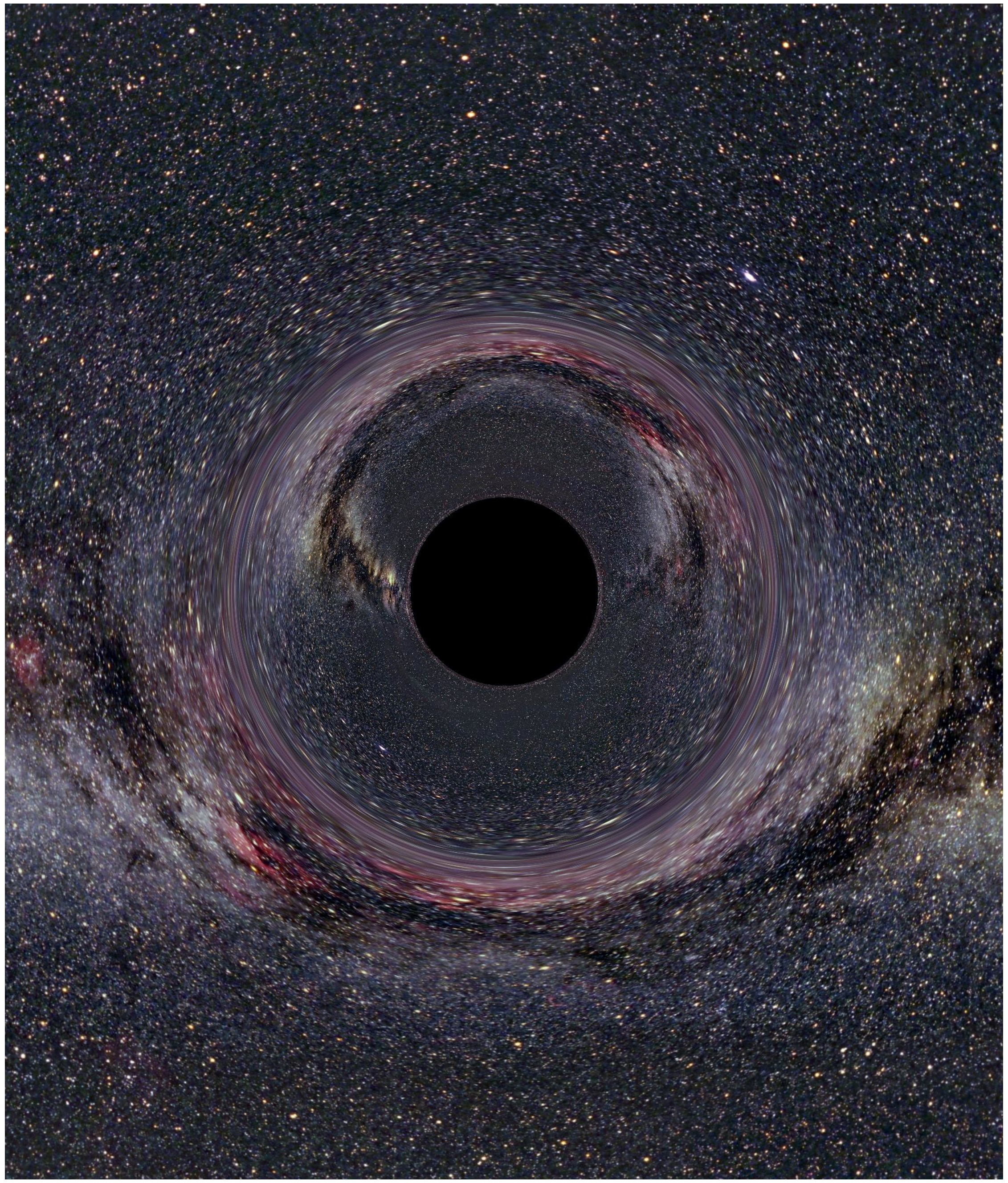
- A region of the space-time where anything, including lights, can not escape for its strong gravity.
  The surface of the region is called the Event horizon.

- Black hole can have only three physical parameters;

  The **mass**,

  spin angular momentum,

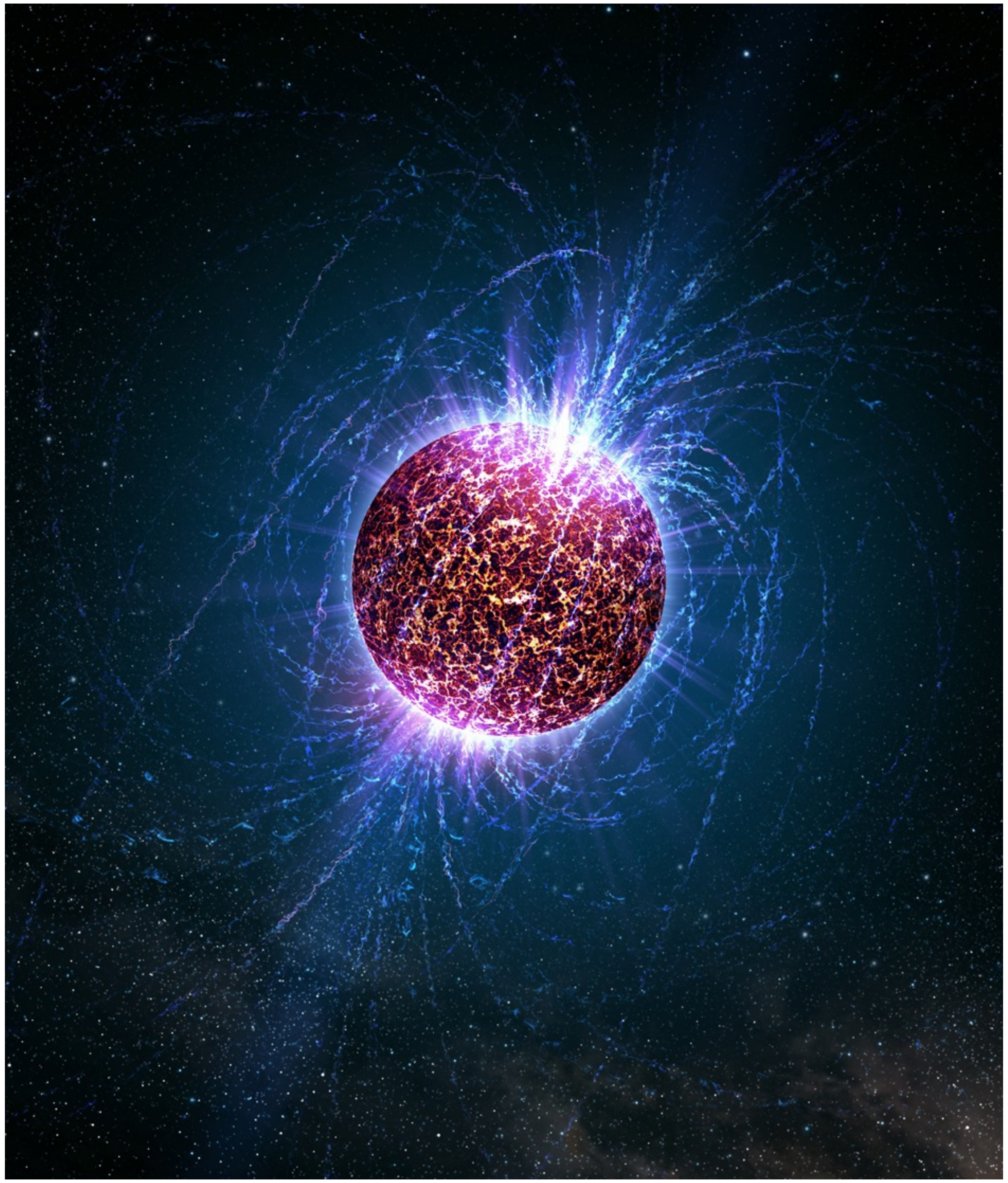
  and **charge**.
  For astronomical situations, the charge is consider to be neutralized.



ref) U. Kraus (2014)

Neutron star

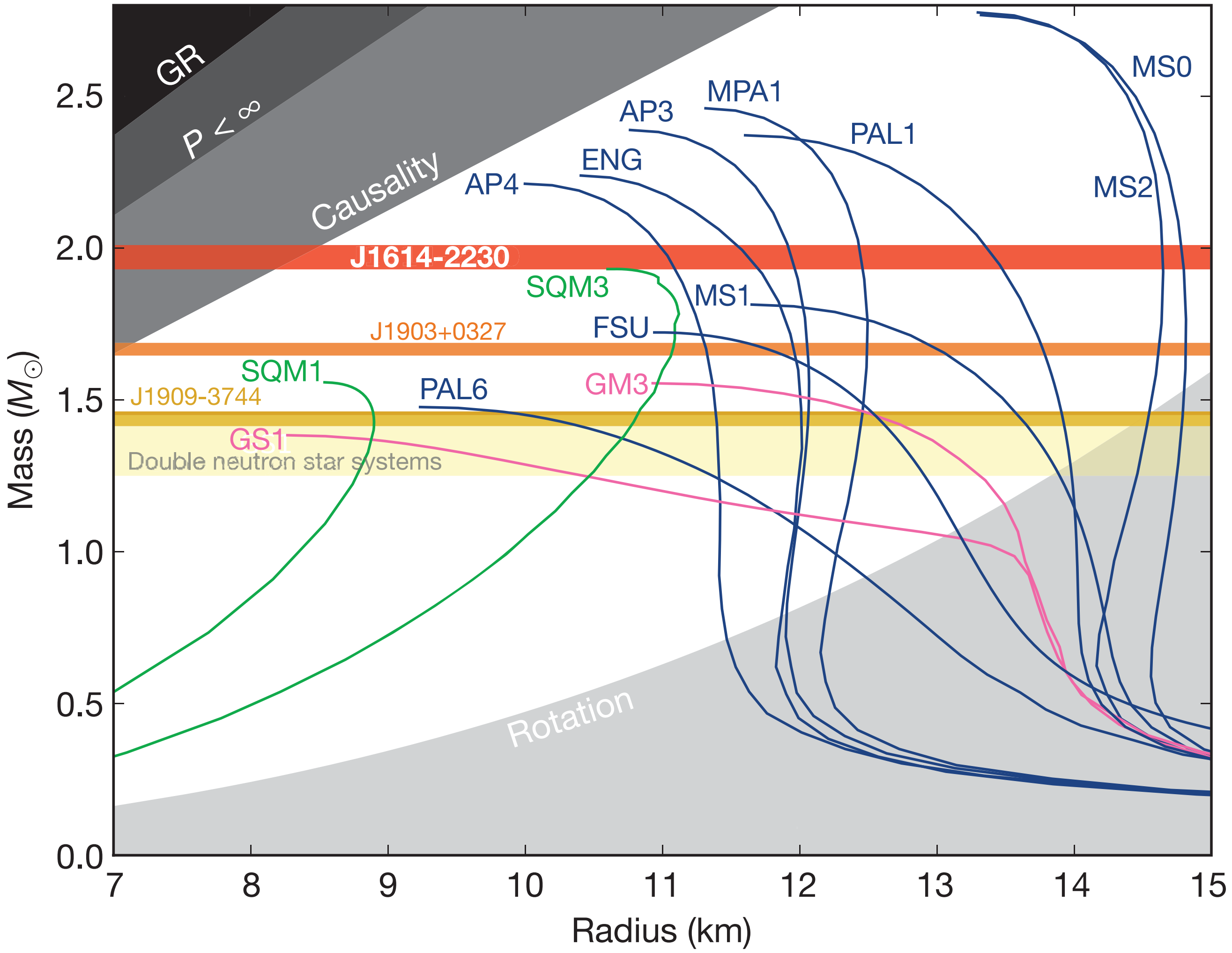
- A neutron star is an extremely dense star formed as the result of the collapse of a massive star.
- Most of them are observed as pulsars, which are rapidly rotating, highly magnetized neutron stars, emitting a strong beams.
- 1-2Msun, typically ~1.4 Msun, ~10 km



ref) http://essayweb.net/

NS equation of state (EoS)

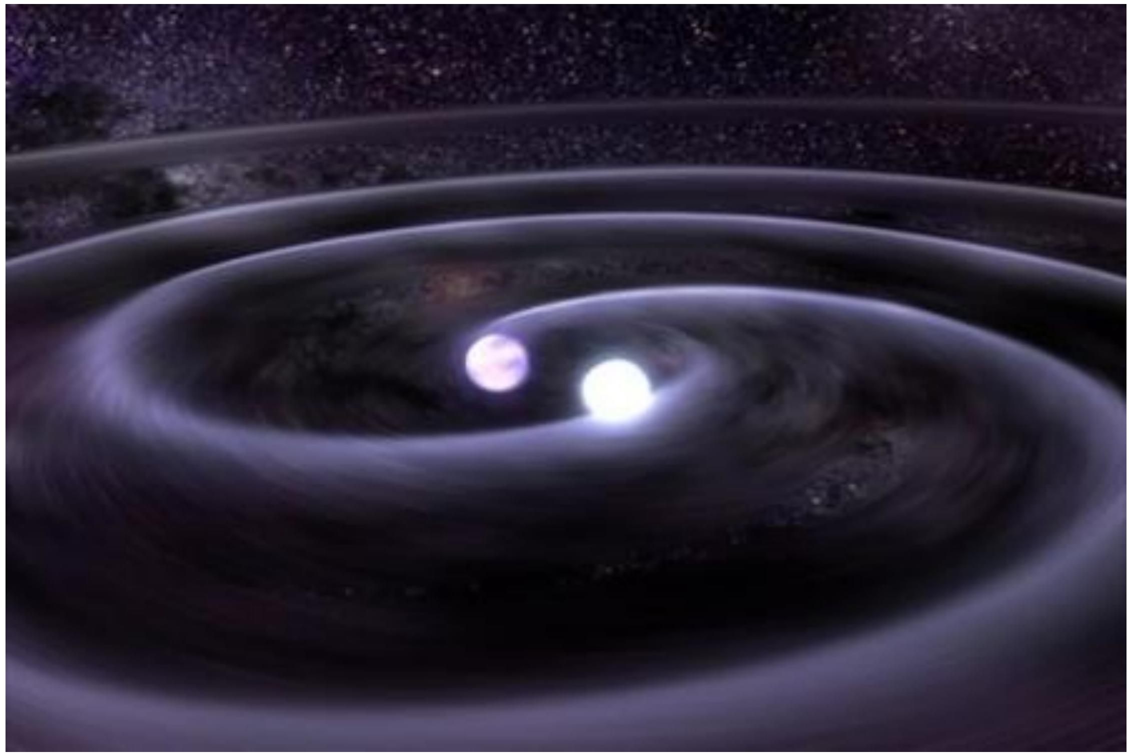
- The NS radius / maximum NS mass is sensitive to the equation of state (EoS) of NS, which is still not comprehended yet.
- Precise measurement of the NS radius / maximum NS mass provides us the information of the NS EoS.



ref) P. Demorest et. al. (2010)

Gravitational waves (GWs)

- Gravitational waves are the ripples of curvature that propagate at the speed of light, and their existence is predicted by general relativity.
- The binary system composed of compact objects, such as NS-NS, BH-NS and BH-BH binary, are the efficient sources of gravitational waves.



http://www.amnh.org/

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} + \mathcal{O}(h^2)$$

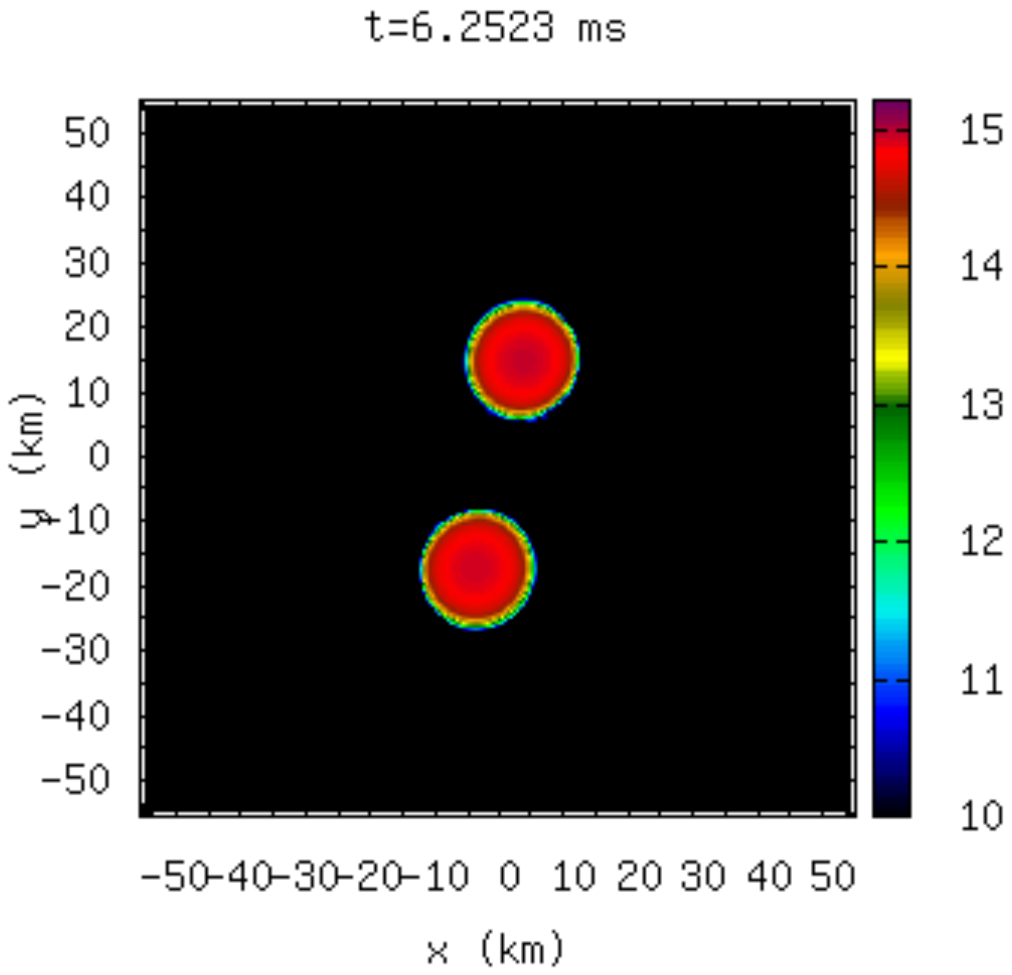
$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) h_{\mu\nu} = 0$$

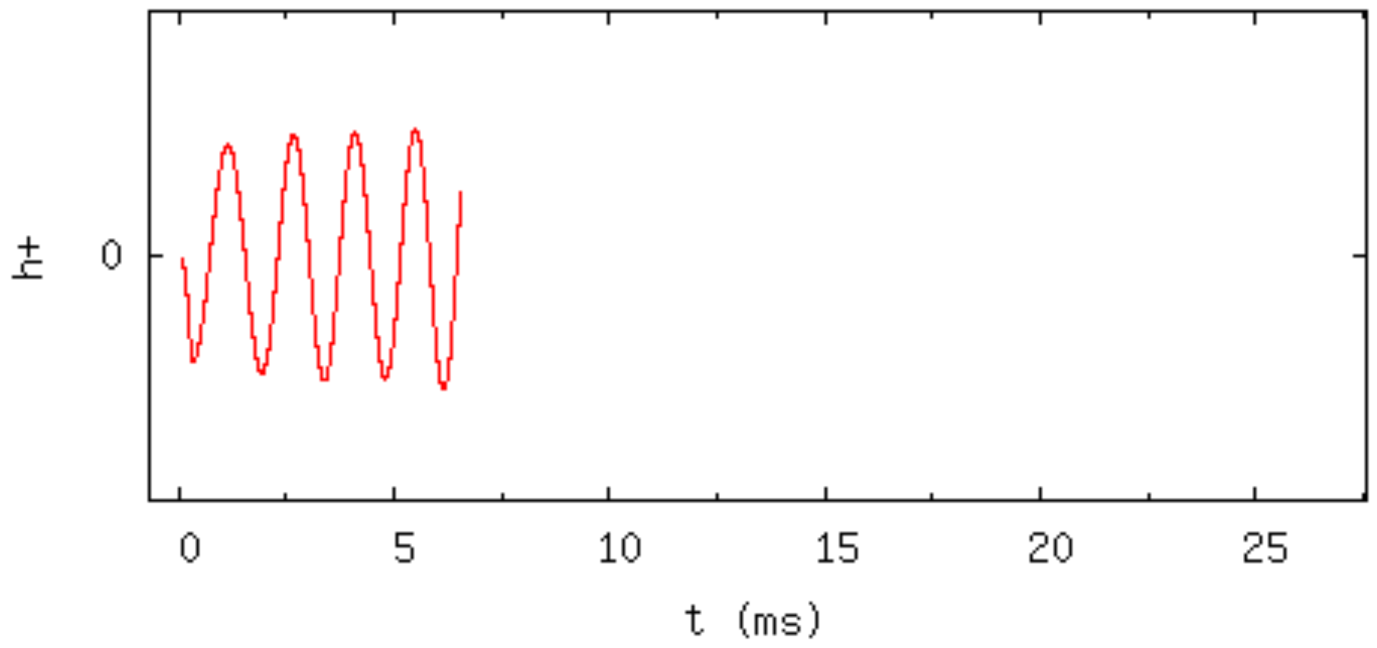
Compact binary mergers

- Compact binaries efficiently emit gravitational waves shrinking their orbital separation, and the objects eventually merge

  → **compact binary mergers**

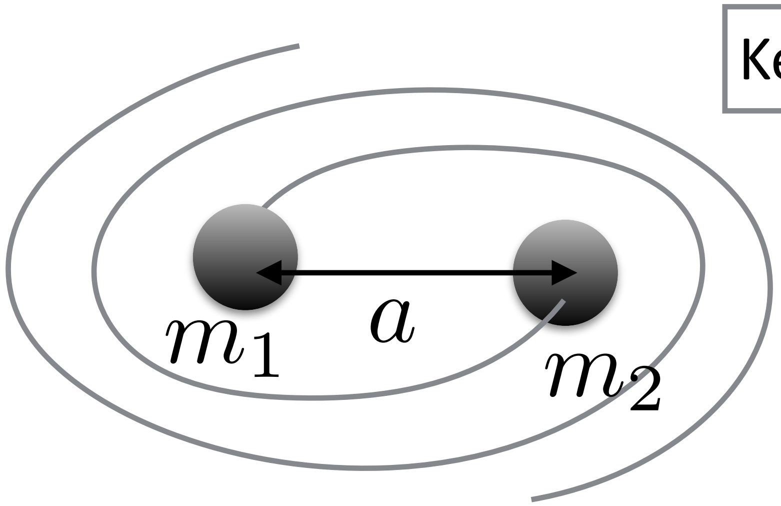
- Gravitational waveform from a binary merger contains rich physical information of the source (masses, spins, distance, inclination, etc…)





Ref: K. Hotokezaka et al. 2013

Gravitational waves from a compact binary merger (leading order)



Kepler's law

$$m = m_1 + m_2$$:total mass

$$\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$$:symmetric mass ratio

$$E = -\frac{\eta m^2}{a}$$:total energy

$$f = \frac{\Omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{m}{a^3}}$$:orbital frequency

Quadrupole formula

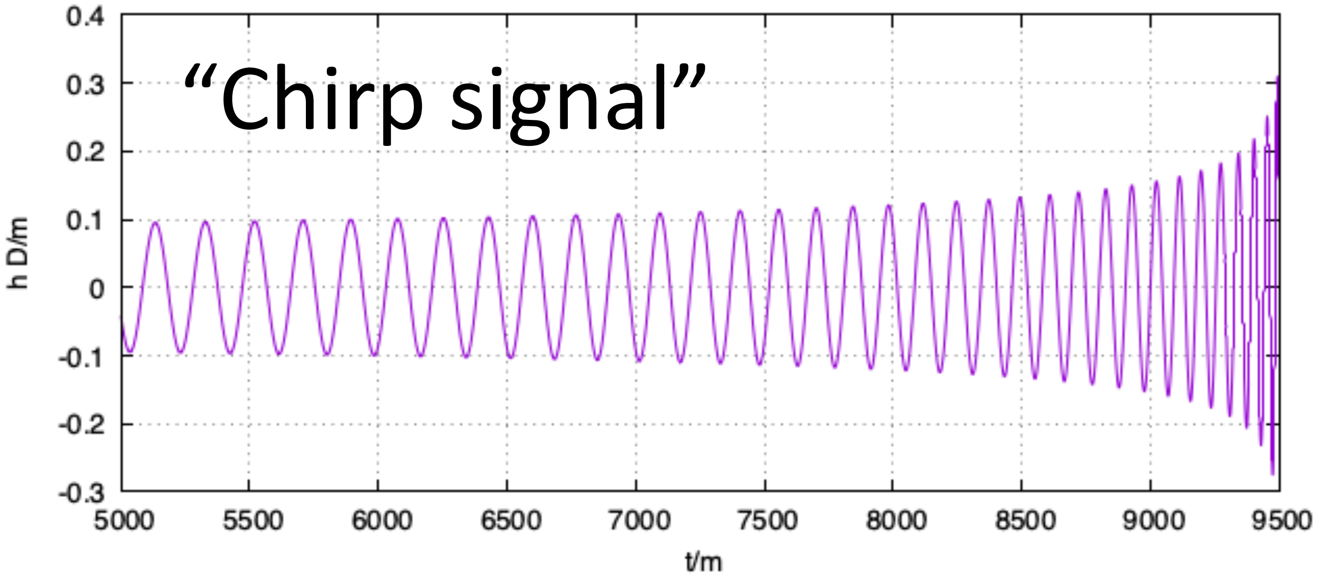
$$|h| \approx \frac{2\pi^{2/3}\mathcal{M}^{5/3}}{D} f_{\mathrm{GW}}^{2/3} \quad \dot{E}_{\mathrm{GW}} = -\frac{32\eta}{5}\left(\frac{m}{a}\right)^5$$:energy loss via GW emission

$$\frac{df_{\mathrm{GW}}}{dt} = \frac{96}{5}\pi^{8/5}\mathcal{M}_{\mathrm{chirp}} f_{\mathrm{GW}}^{11/3}$$

$$f_{\mathrm{GW}} = 2f$$:GW frequency

$$\mathcal{M}_{\mathrm{chirp}} = m\eta^{3/5}$$: chirp mass

D : luminosity distance



PostNewtonian expansion

PostNewtonian expansion:

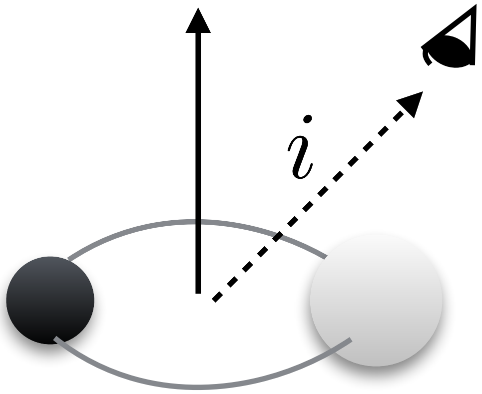
$$h = Ae^{i\phi_{\mathrm{GW}}}$$

$$A(x) = \frac{2m\eta}{D}x\left(A_0 + A_{0.5}x^{0.5} + A_1 x + A_{1.5}x^{1.5} + A_2 x^2 + \cdots\right)$$

$$\frac{dx}{dt} = \frac{64\eta}{5}x^5\left(1 + a_1 x + a_{1.5}x^{1.5} + a_2 x^2 + \cdots\right)$$

PostNewtonian Parameter: $x := (\pi m f_{\mathrm{GW}})^{2/3} \approx \left(\frac{m}{a}\right)$

※Note that amplitude factors depend on the inclination angle



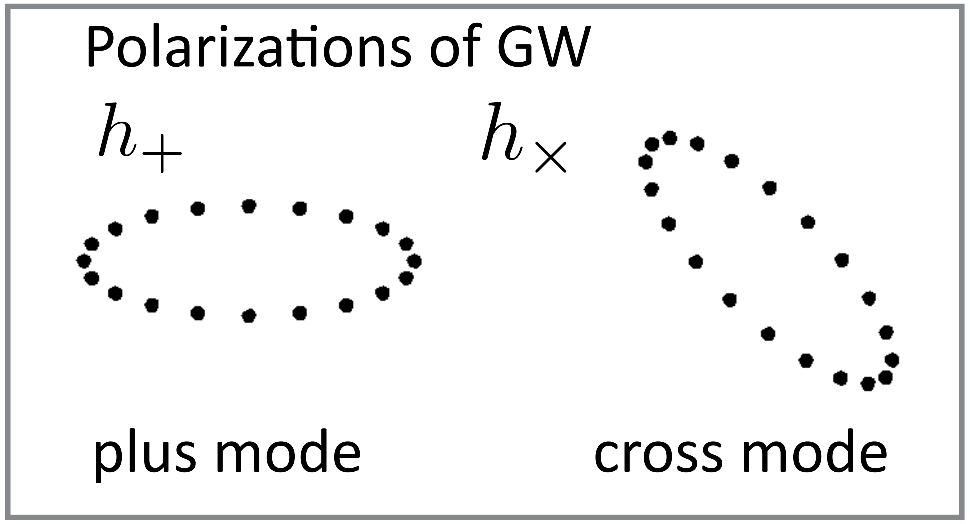
$$A_0^+ = -(1+\cos^2 i)$$

$$A_0^\times = -2\cos^2 i$$

- 0PN: chirp mass: $\mathcal{M}_{\mathrm{chirp}} = m\eta^{3/5}$
- 1PN: symmetric mass: $\eta = \frac{m_1 m_2}{(m_1+m_2)^2}$
- 1.5PN: spin: $\chi_i = \frac{S_i}{m_i^2}$
- **5PN: tidal deformability:** Λ_i

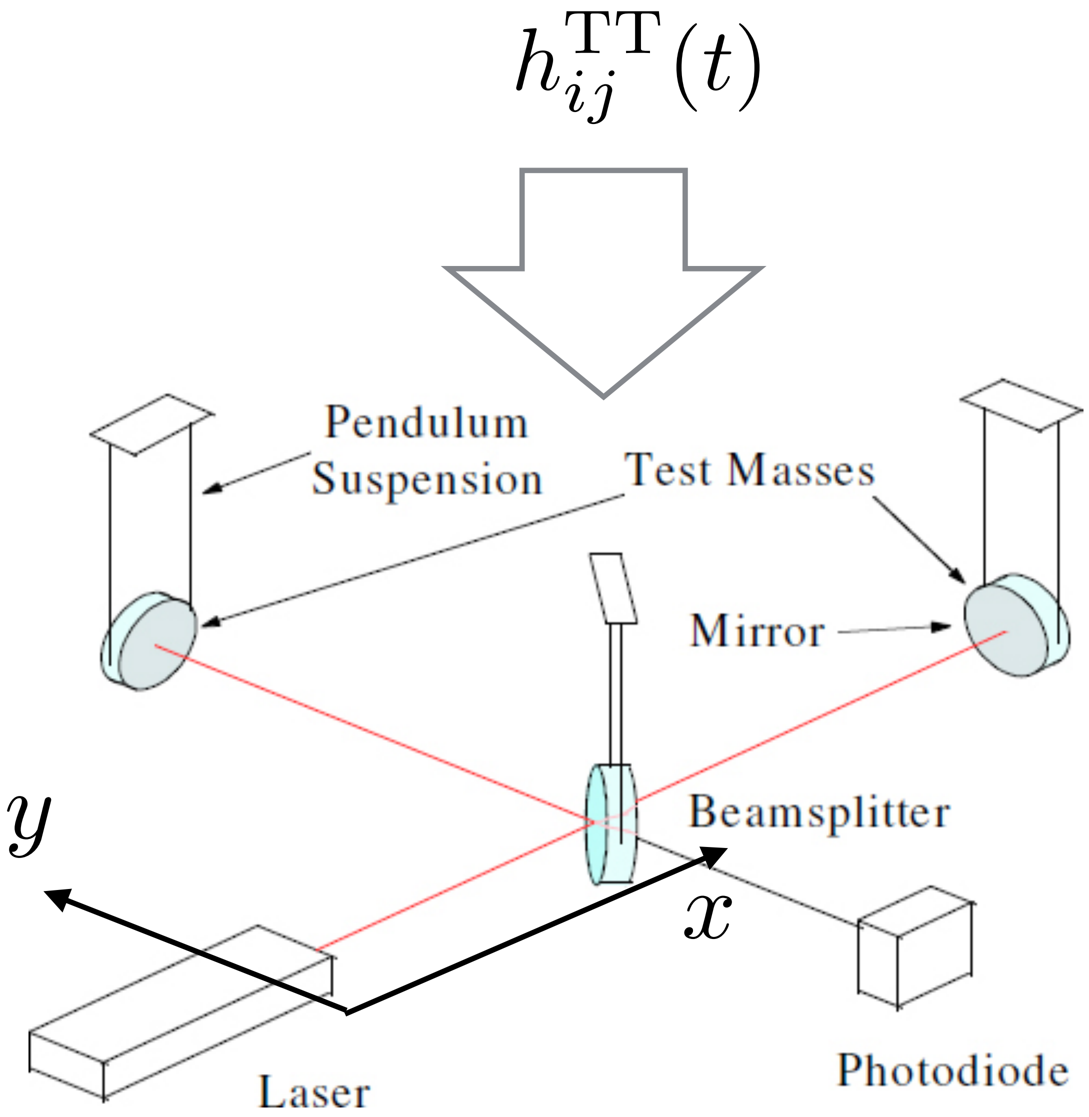
Detecting gravitational waves

- Gravitational waves are detected by measuring the change of the distance by laser interferometer



Transverse-Traceless gauge:

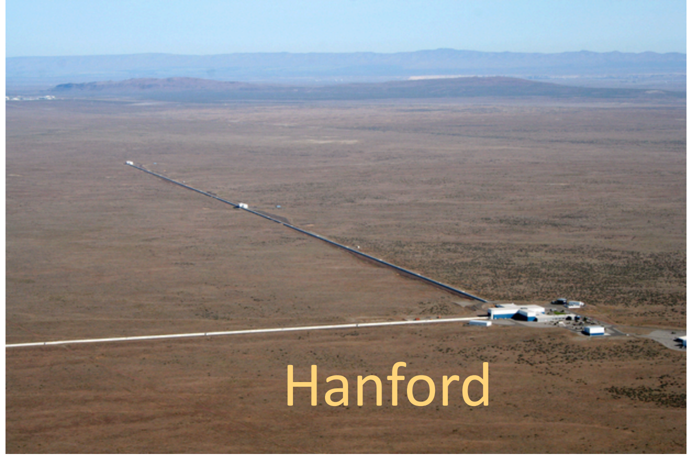
$$h_{\mu\nu}^{\mathrm{TT}} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



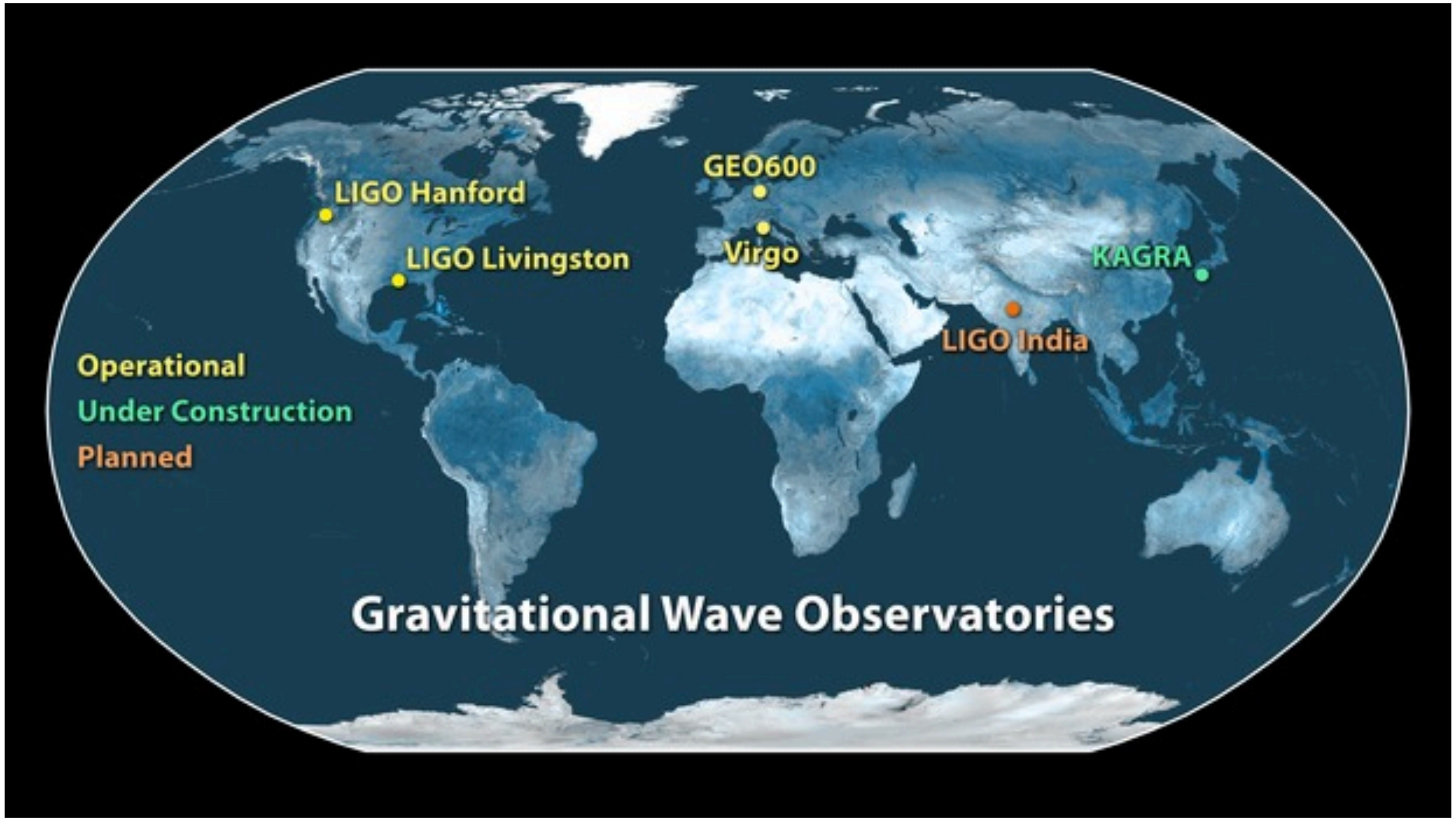
For face-on waves:
$$\frac{d^2 X^i}{dt^2} \approx \frac{1}{2}\ddot{h}_{ij}^{TT} X^j$$

Gravitational wave detectors

advanced LIGO



https://www.ligo.caltech.edu/



- GW sources for ground-based GW detectors
  - **Compact binary mergers**
  - Core collapse Super Novae
  - Rotating Neutron stars
  - Primordial GW (Inflation)
  - Cosmic Strings

http://www.virgo-gw.eu/

http://gwcenter.icrr.u-tokyo.ac.jp/

Gravitational wave events

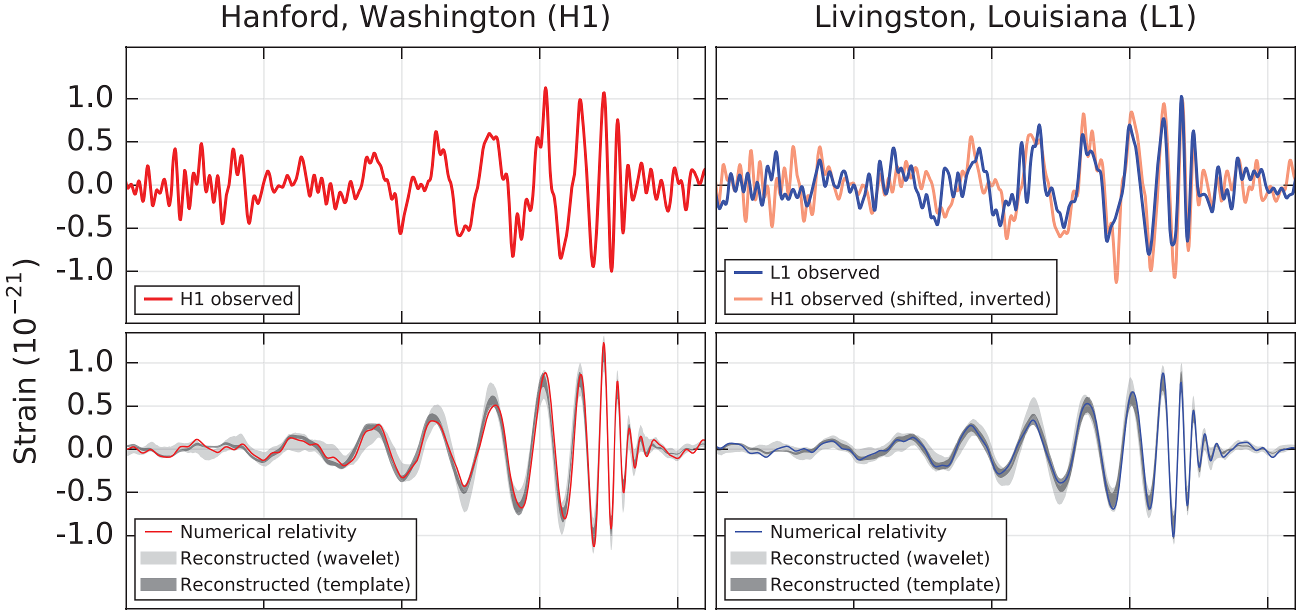
- Compact binary mergers are among the main targets of ground-based gravitational-wave detectors, such as **LIGO**, **Virgo**, and **KAGRA**

- Since 14th of September 2015, many GW events have been detected

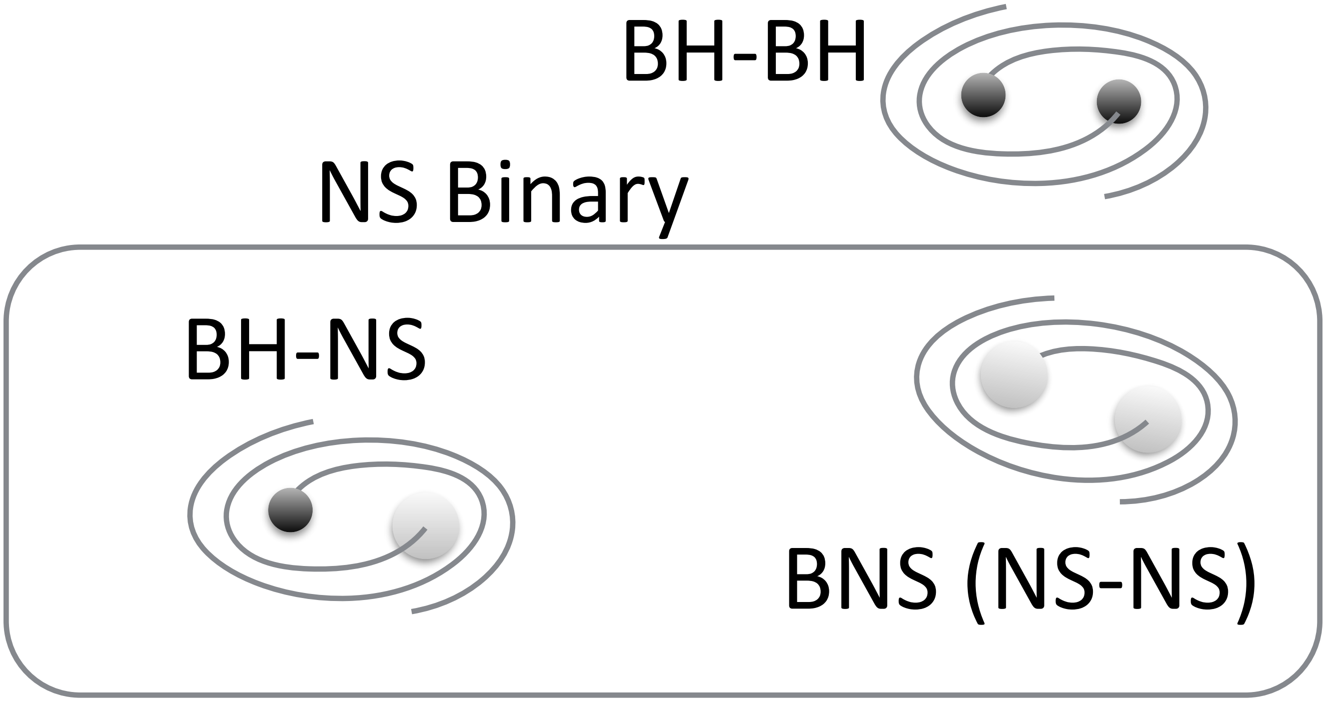
- Binary BH (BBH; BH-BH)
  - GW150914, GW151012, GW151226, GW170104, GW170608, GW170809, GW170814, GW170817, GW170818, GW170823

- **Binary NS (BNS; NS-NS) GW170817**

- GW150914 (The first GW event)



Ref: B.P.Abbot et al. 2016

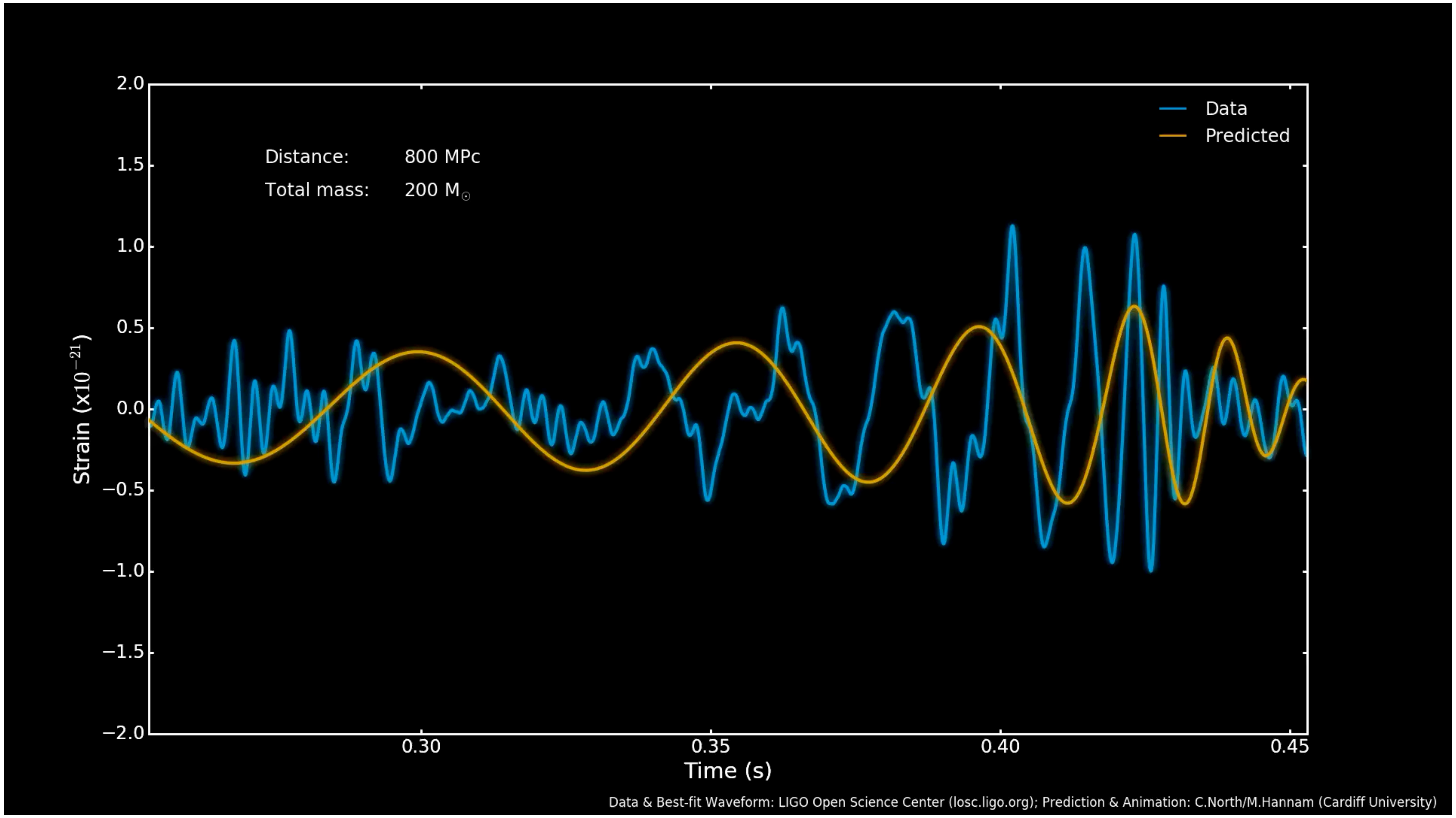

BH-BH

NS Binary

BH-NS

BNS (NS-NS)

Parameter estimation (intuitive picture)



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

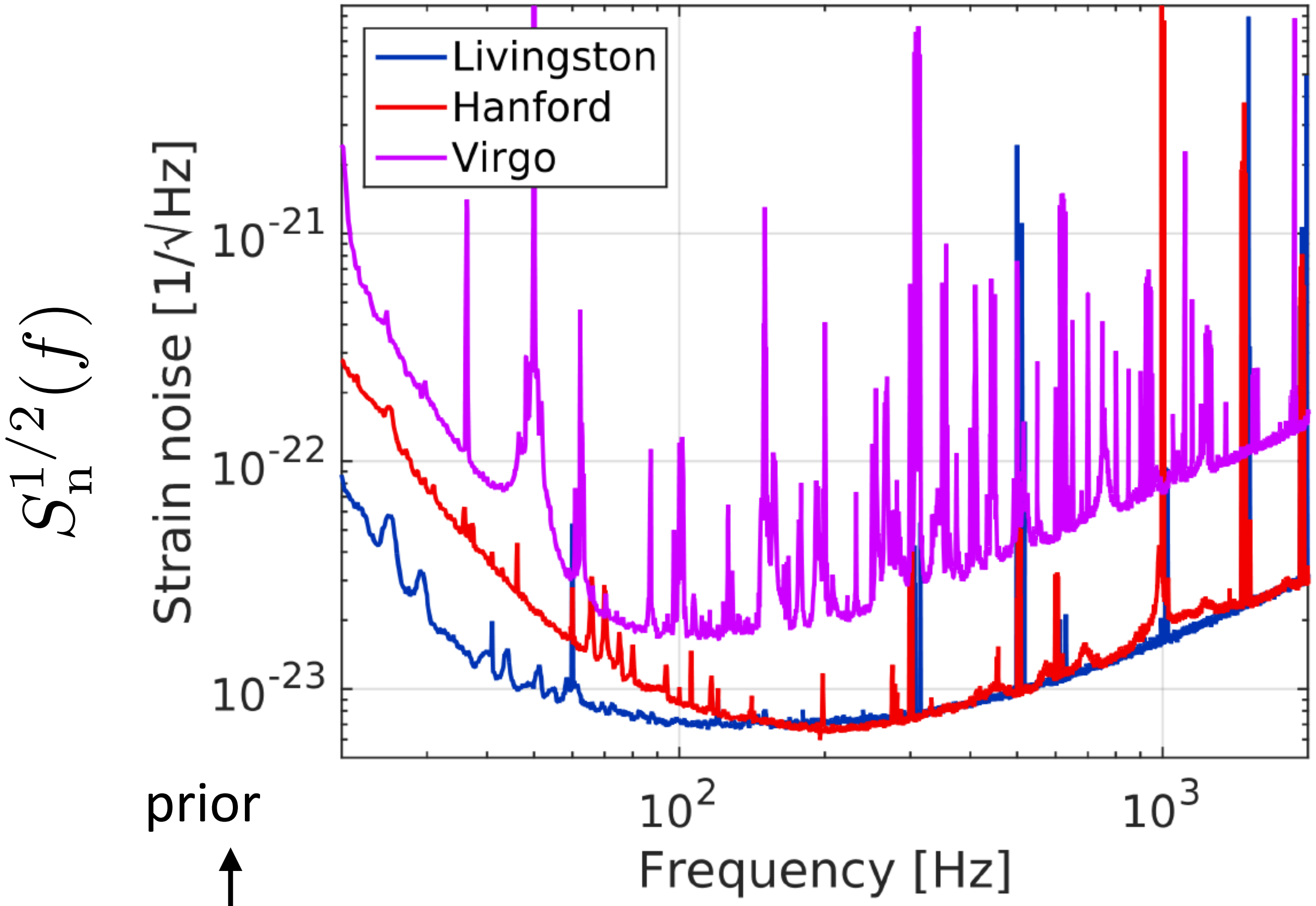
Ref: Gravitational Wave Open Science Center (https://www.youtube.com/watch?v=fiQtwPn6kfw)

- Physical information is extracted from the signal by the comparison with theoretical waveform templates

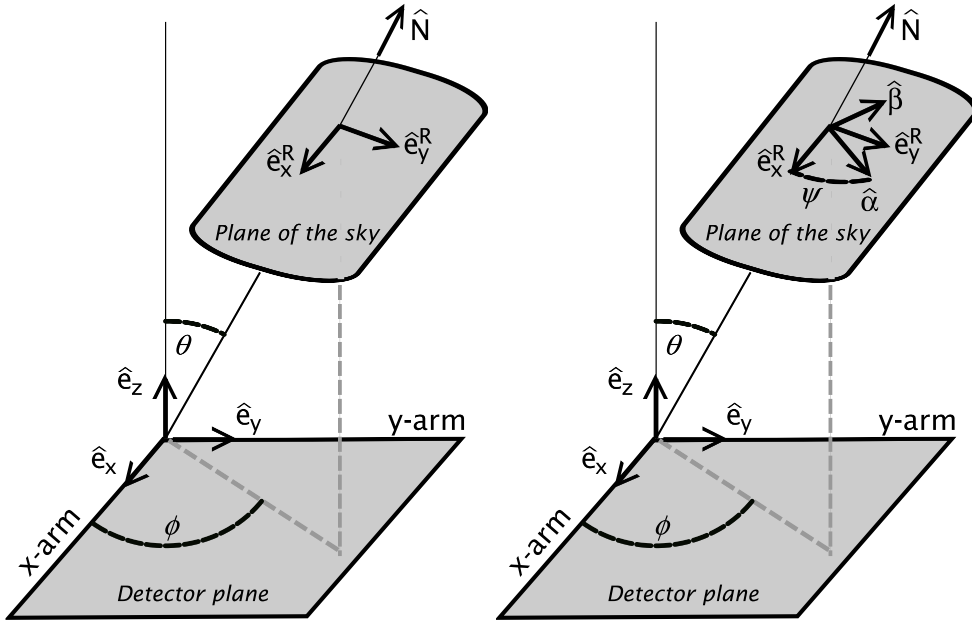
Parameter estimation

Detector sensitivity

Ref: B.P.Abbot et al. 2017



Ref: Sathyaprakash& Schutz 2009



posterior

prior

likelihood

signal

waveform template

$$\boxed{p(\vec{\theta}|\vec{d})} \propto \boxed{p(\vec{\theta})} \prod_{\rm det} \boxed{\mathcal{L}_{\rm det}(\vec{d}|\vec{\theta})} \qquad \mathcal{L}_{\rm det}(\vec{d}|\vec{\theta}) = \exp\left[-2\int_0^\infty \frac{\boxed{|\tilde{d}(f)} - \boxed{\tilde{h}(f;\vec{\theta})|^2}}{\boxed{S_{\rm n,det}(f)}} df\right]$$

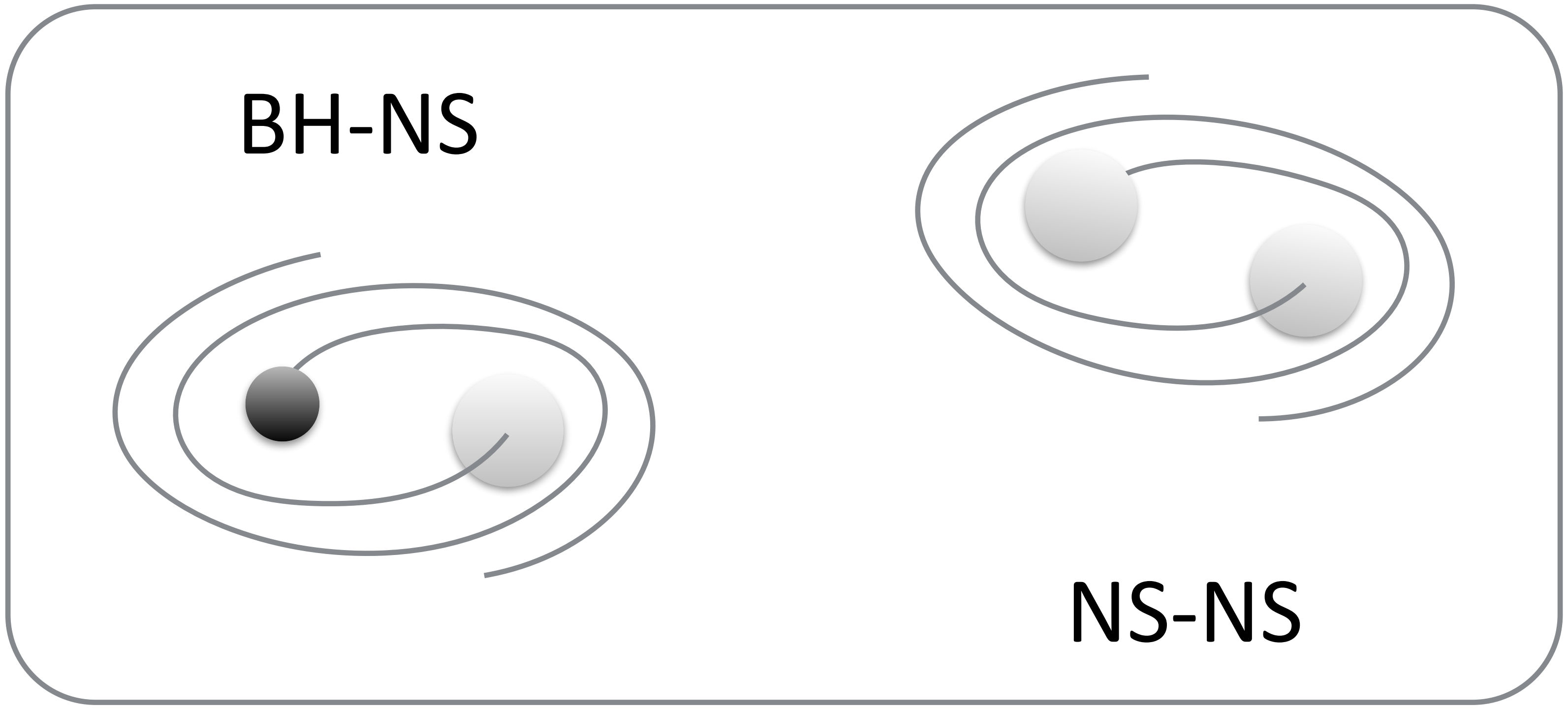
$\vec{\theta} = (m_1, m_2, \chi_1, \chi_2, \Lambda_1, \Lambda_2, \cdots$:intrinsic parameters

$, d_L, \theta, \phi, \psi, i \cdots)$:extrinsic parameters

detector noise spectrum

NS binary mergers

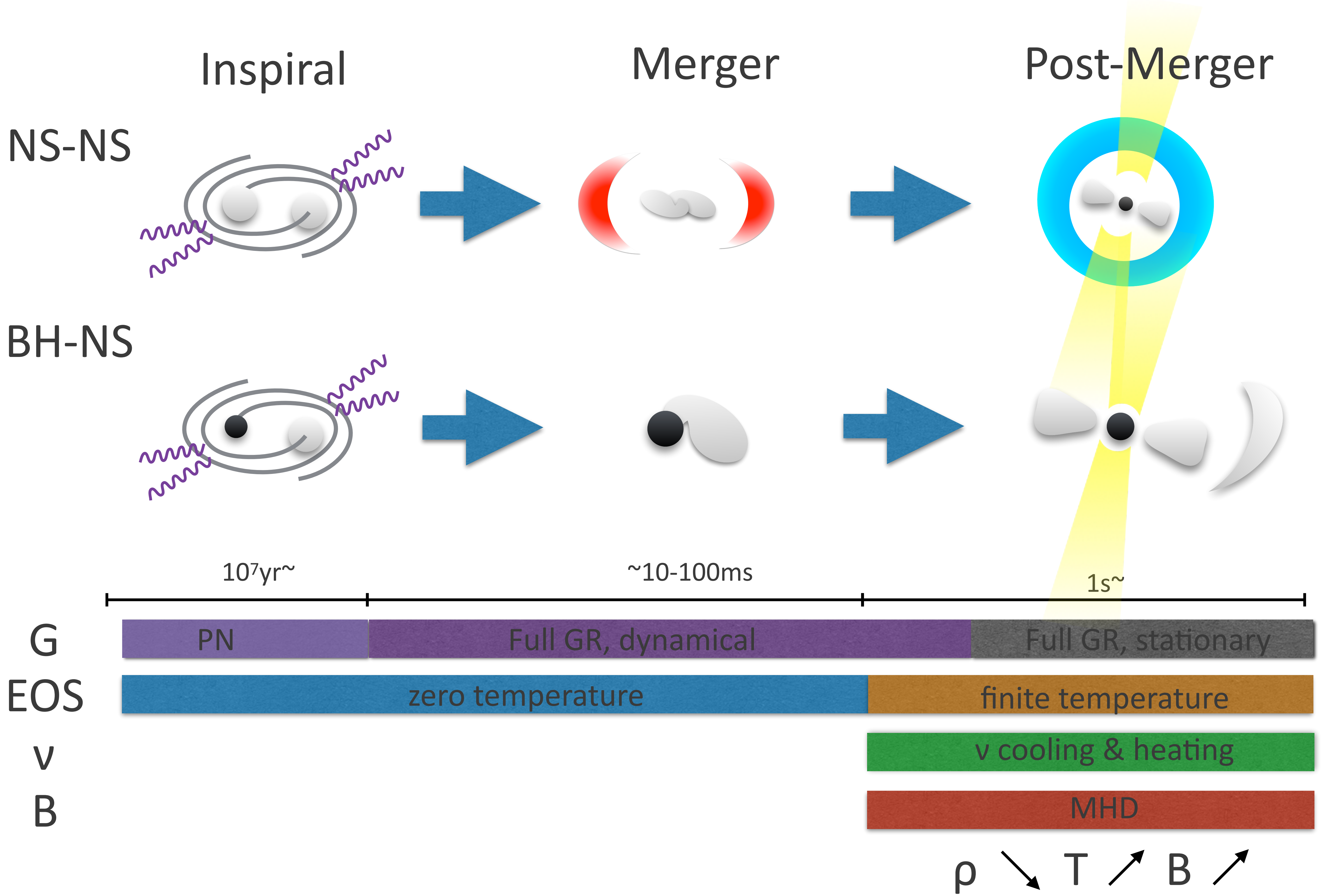
NS Binary



BH-NS

NS-NS

General picture



Inspiral

Merger

Post-Merger

NS-NS

BH-NS

10^7yr~

~10-100ms

1s~

G PN Full GR, dynamical Full GR, stationary

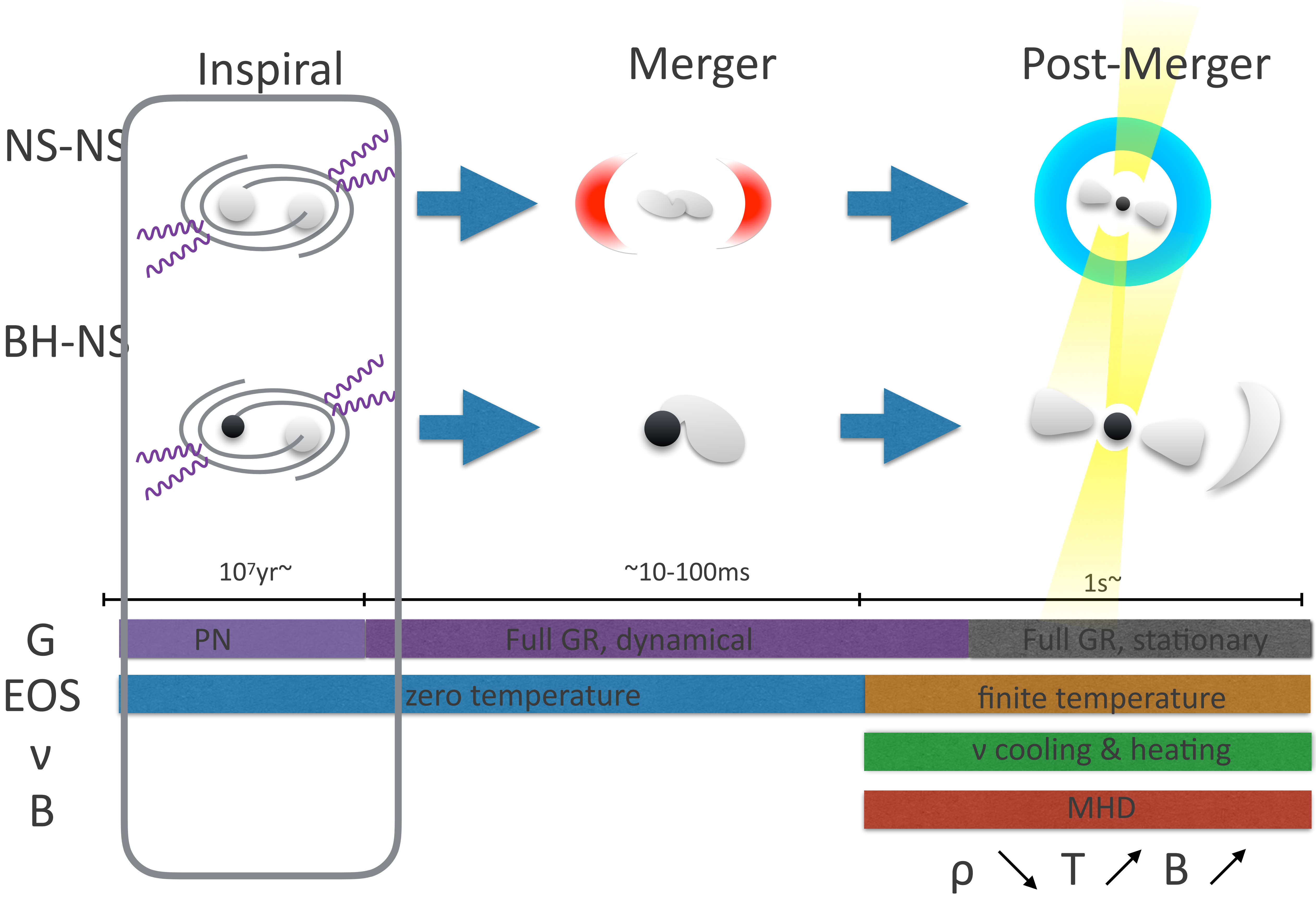
EOS zero temperature finite temperature

ν ν cooling & heating

B MHD

ρ ↘ T ↗ B ↗

General picture



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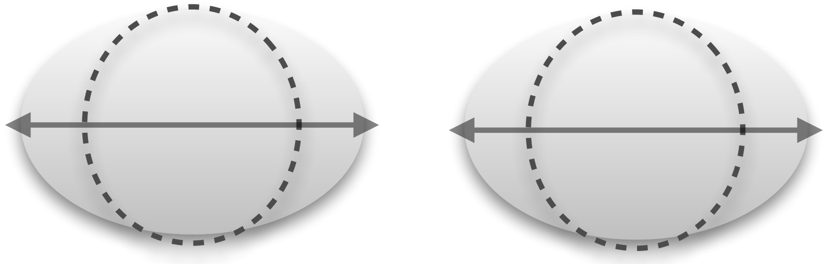
Inspiral phase:
Tidal deformation

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



Tidal deformation

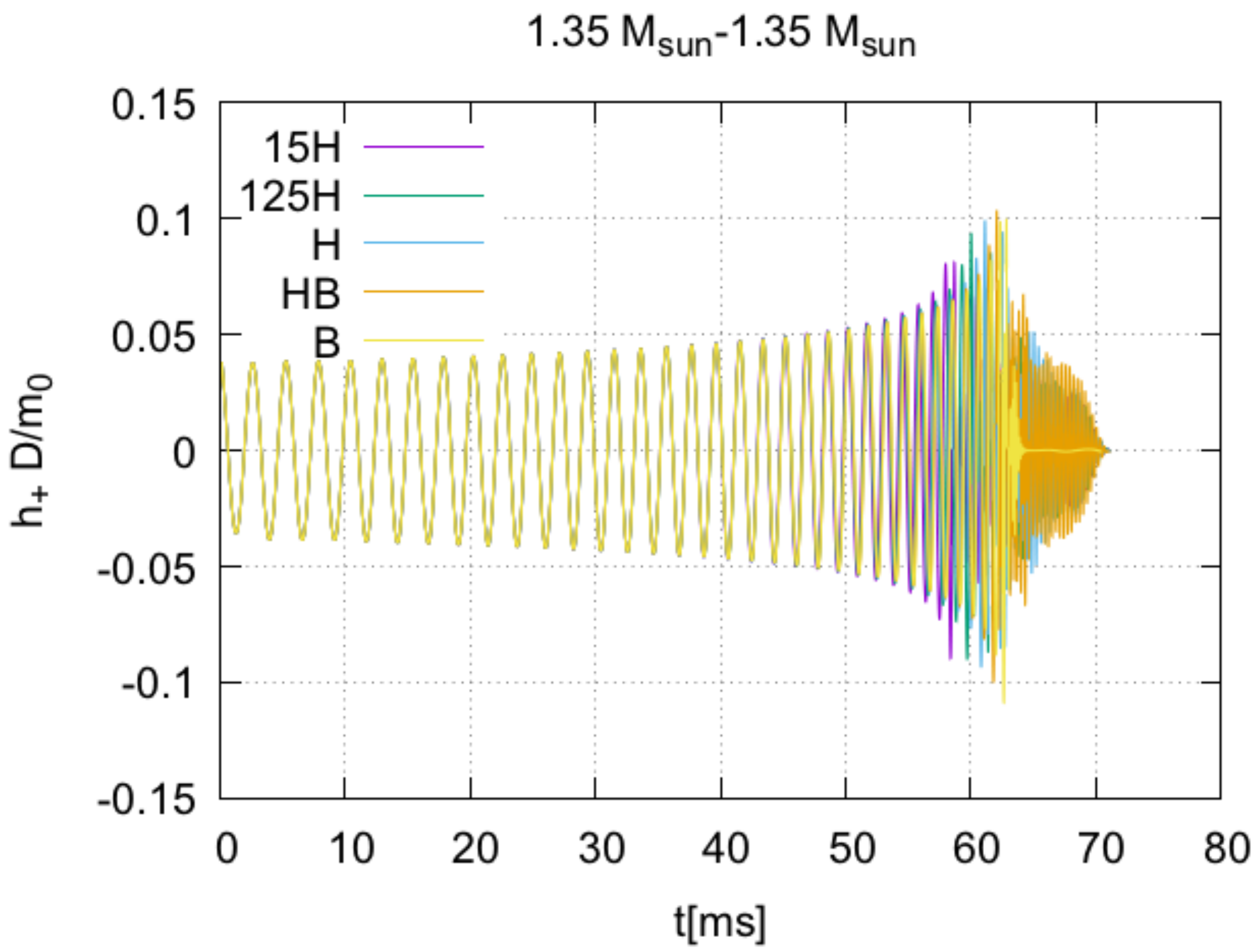
- In particular, **if the binary contains a NS**, the information of the internal structure of the NS can be extracted

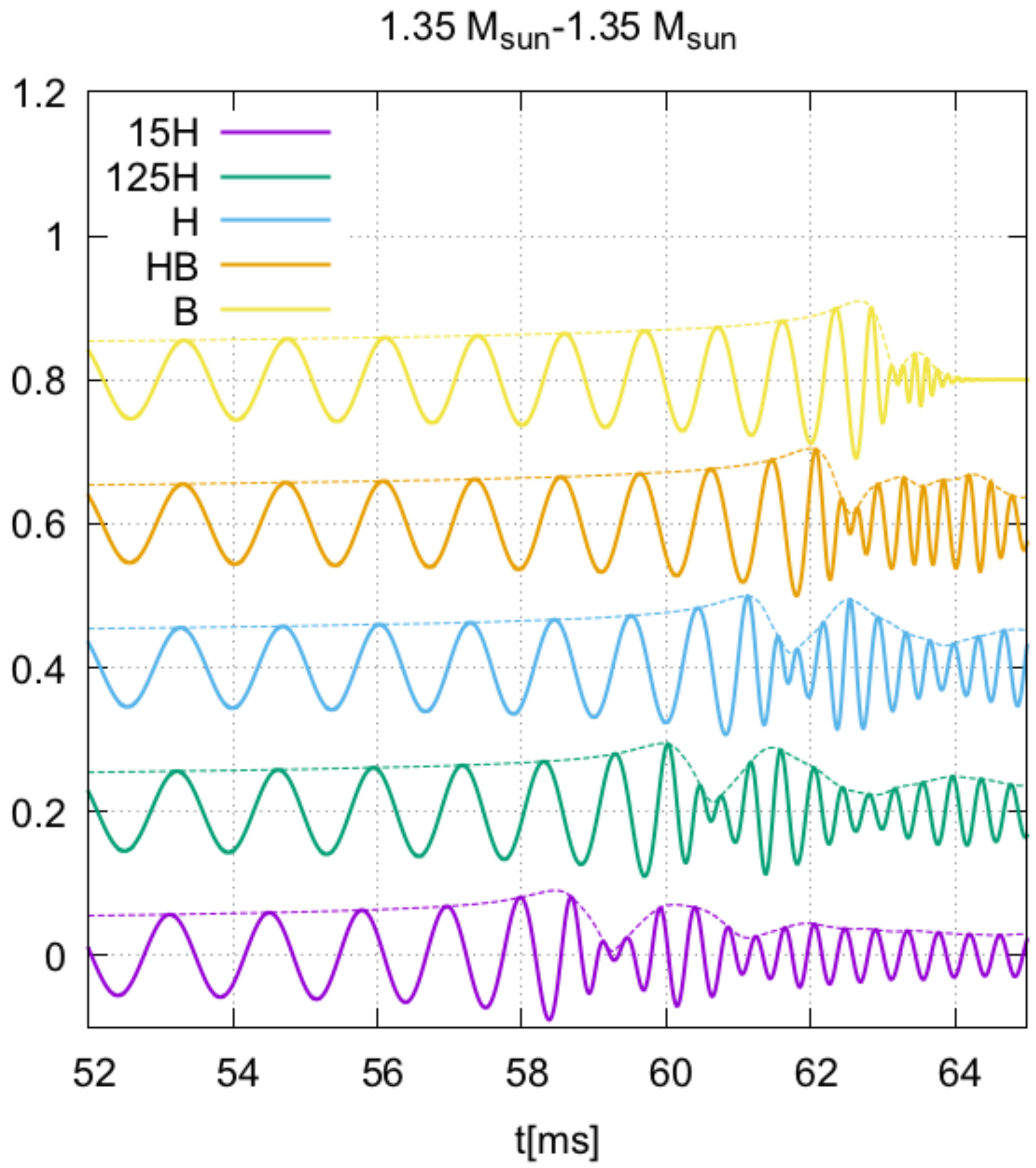
- During the inspiral, a NS is deformed by the tidal force of the companion object. Deformation of a NS (s) accelerates the orbital shrinking, and modifies gravitational waveforms

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

Modification in the GW phase

Effect of tidal deformation

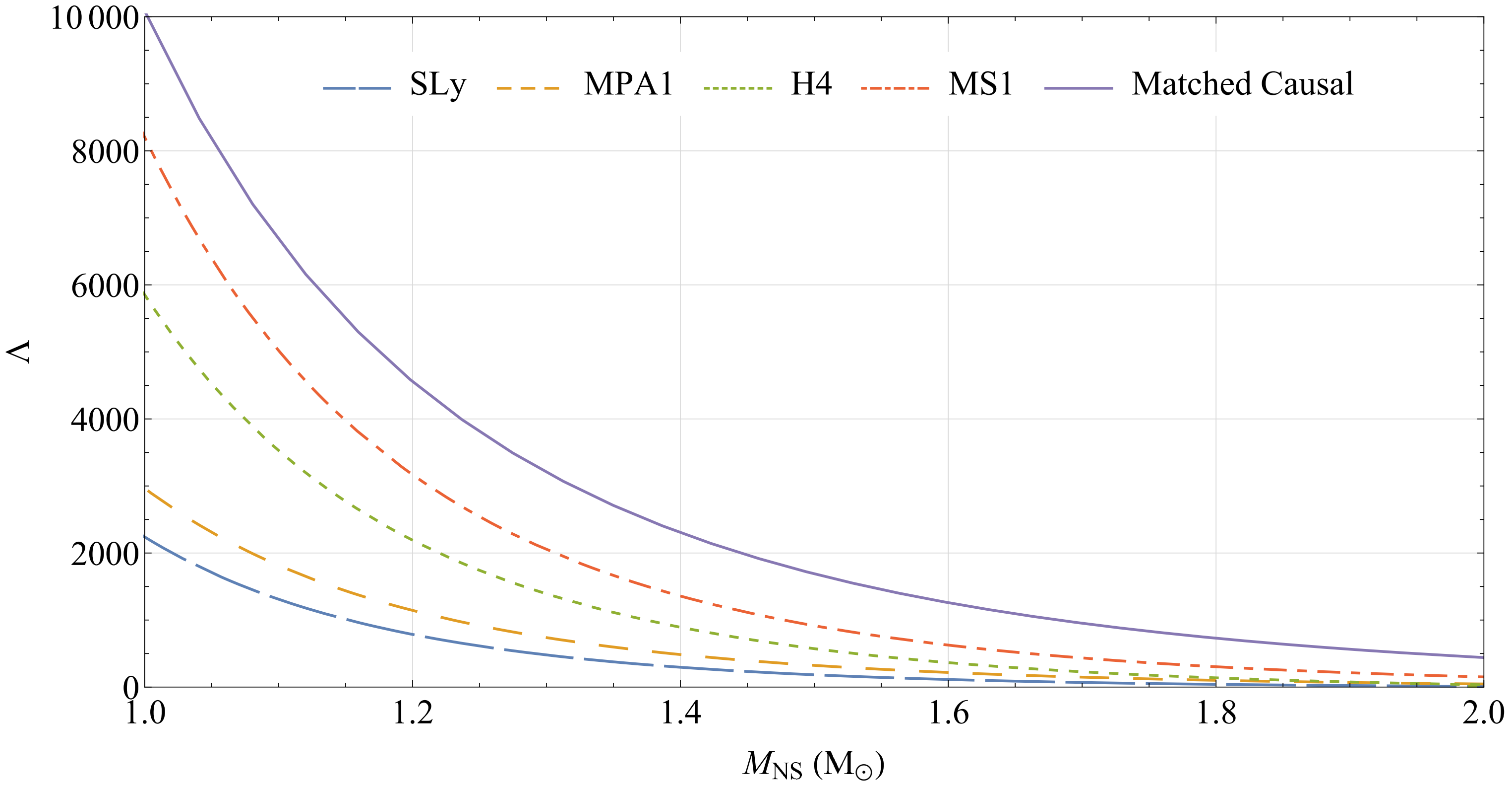




- Radius & Tidal deformability
15H>125H>H>HB>B

Ref) Kiuchi et al. 2017

Tidal deformability



Ref) Oeveren & Friedman 2017

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

（dimensionless） tidal deformability

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

Quadrupole moment tidal field

- From the observed waveforms, ***the tidal deformability*** of a NS can be extracted
- The tidal deformability reflects the internal structure of a NS, and its measurement can be used to constrain **the NS equation of state (EOS)**

GW templates for NS binaries

- Physical information is extracted from observed gravitational waves by the comparison with theoretical templates

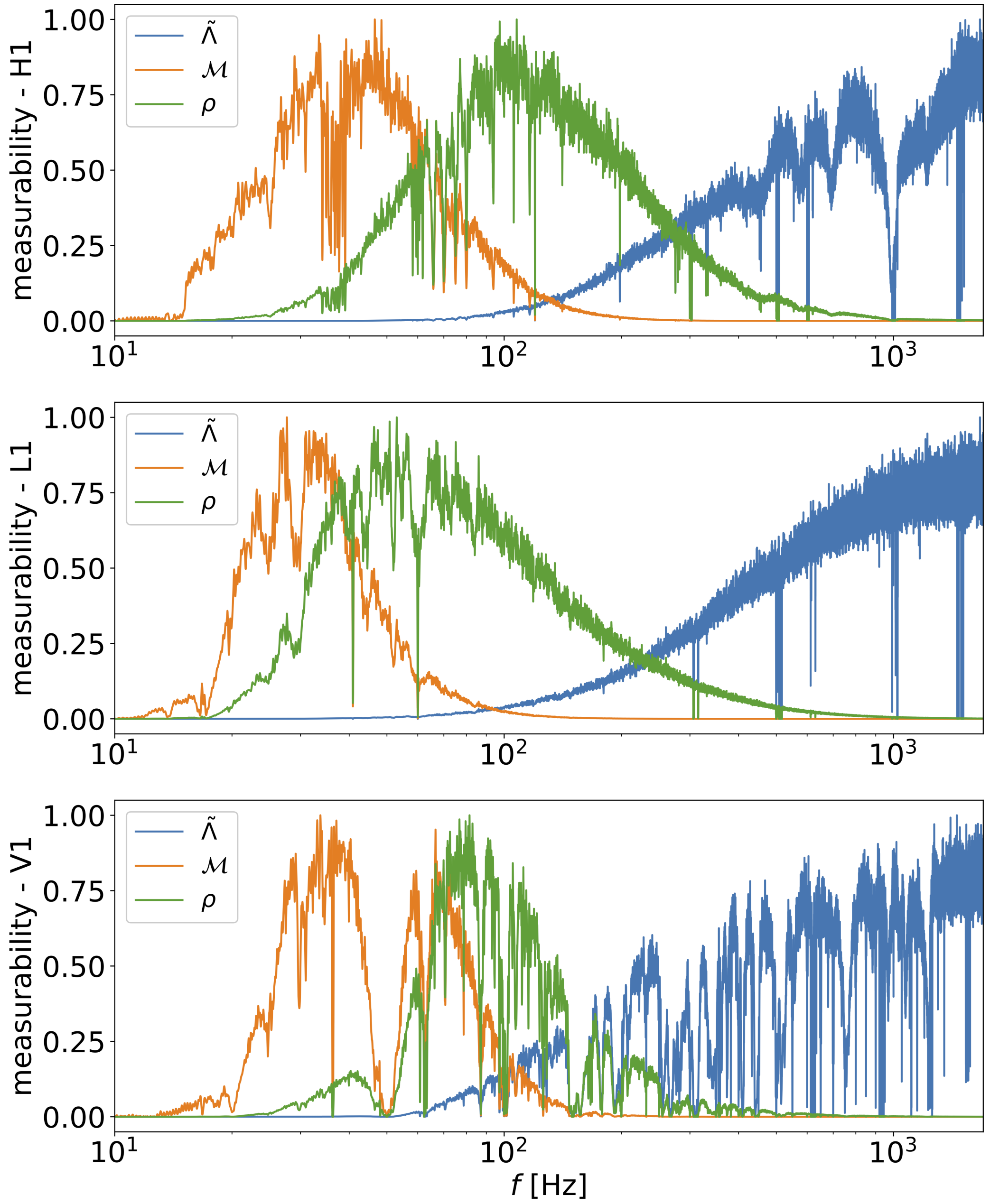
  → **an accurate waveform templates are crucial for parameter estimation**

- The waveforms **including the tidal effects** are analytically derived by post-Newtonian (PN) calculation
  (and by 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.**

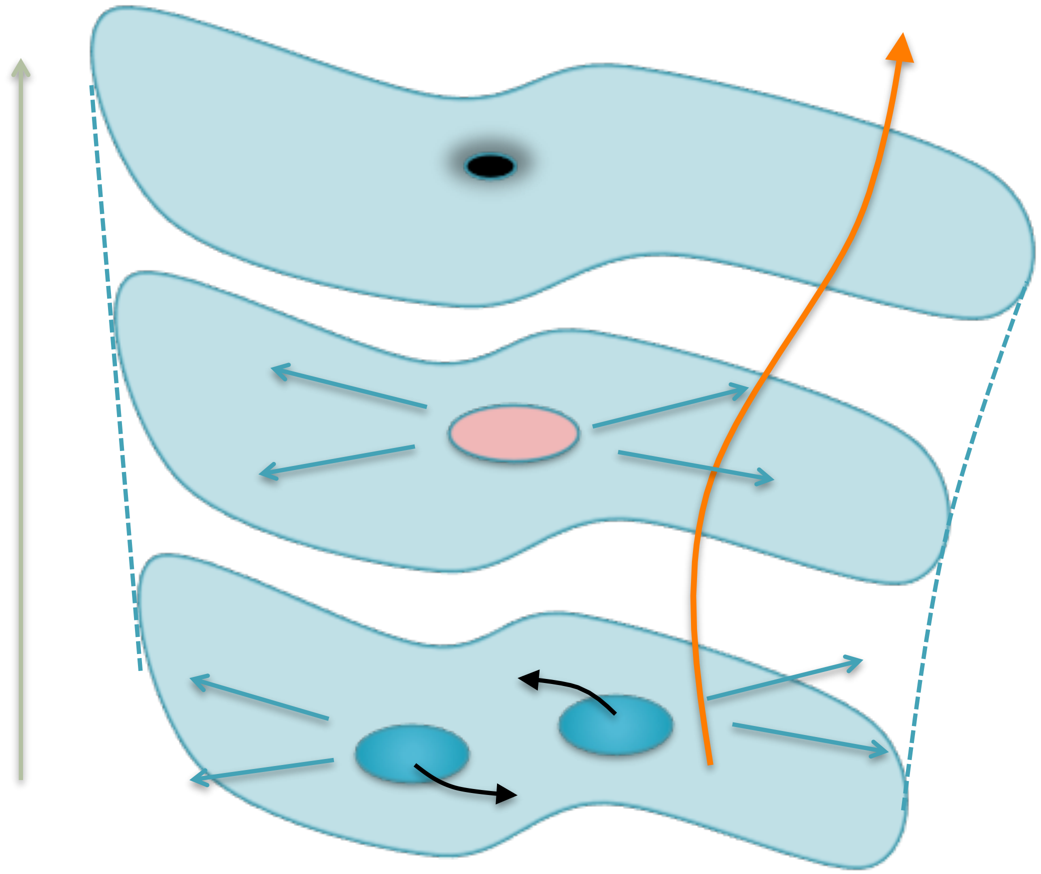
ref) De et al. 2018



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

Numerical Relativity Simulation

- **Numerical-relativity (NR) simulation** is the unique method to predict dynamics and gravitational waves in the merger phase—a regime where the non-linear effect of hydrodynamics should be taken into account in the framework of general relativity.



Einstein's equation

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

Euler equation

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

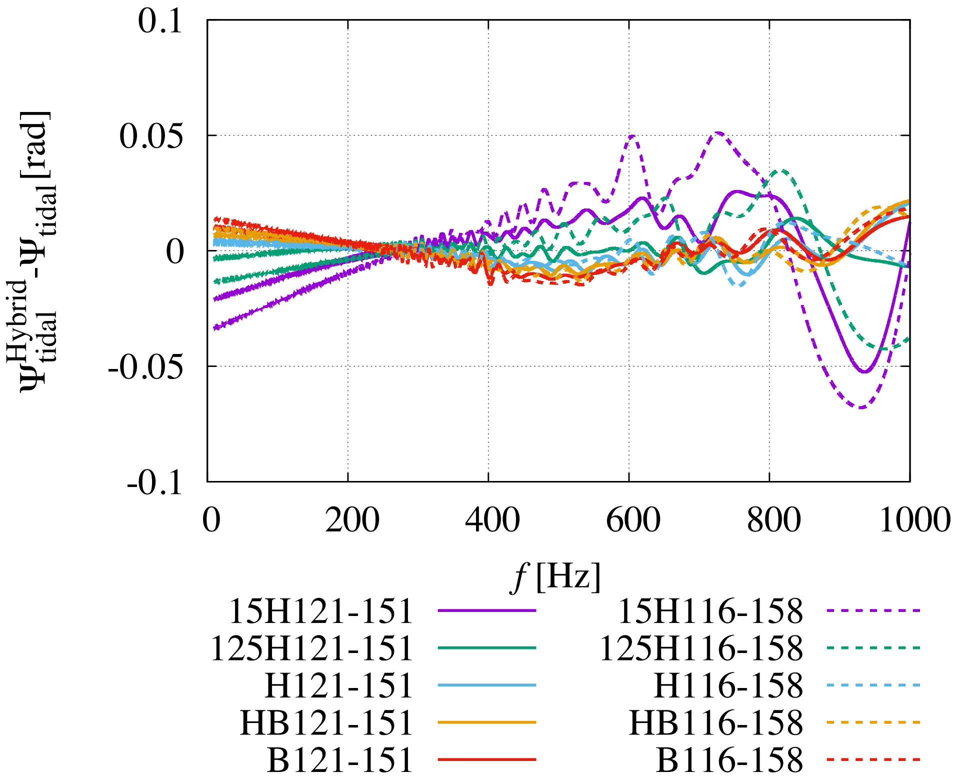
Equation of state (EOS)

$$P = P(\rho),\ P(\rho, T, Y_e), \cdots$$

(+MHD, viscosity, neutrino, etc.,)

NS-NS waveform model

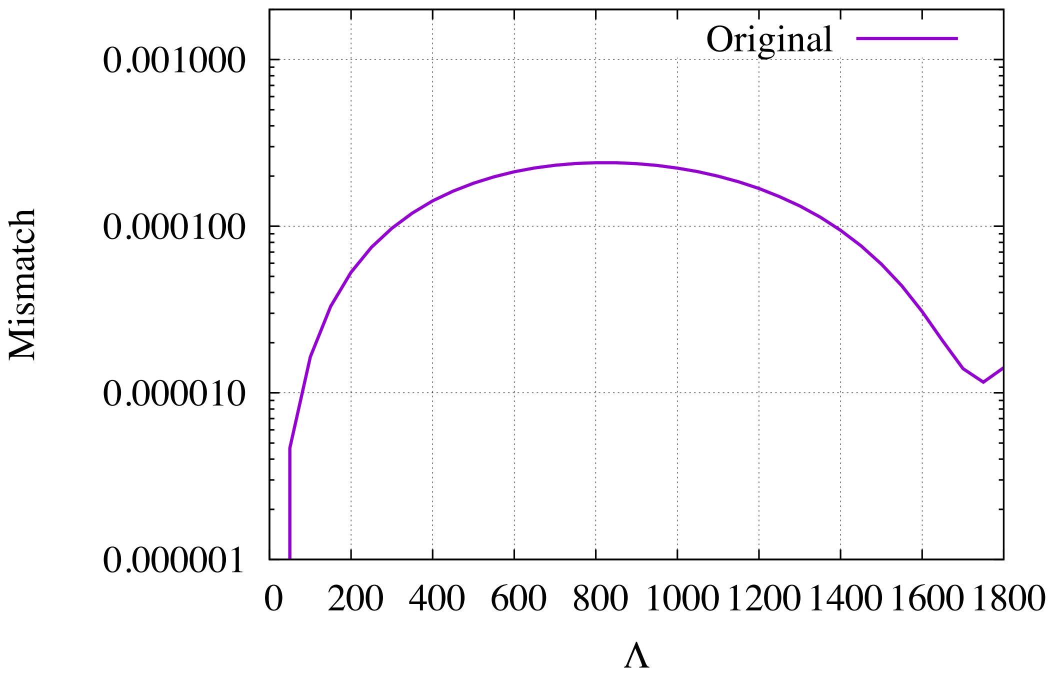
- Based on our latest numerical-relativity waveforms, a waveform model for NS-NS mergers is derived
- A NS-NS GW model is also derived in Dietrich et al. 2017 , 2019 based on different NR waveforms and TidalEOB waveforms
- Though their and our models are derived independently, two models give almost consistent results



Ref: KK et al. 2018, K. Kiuchi, KK et al. 2019

Comparison with Dietrich+17

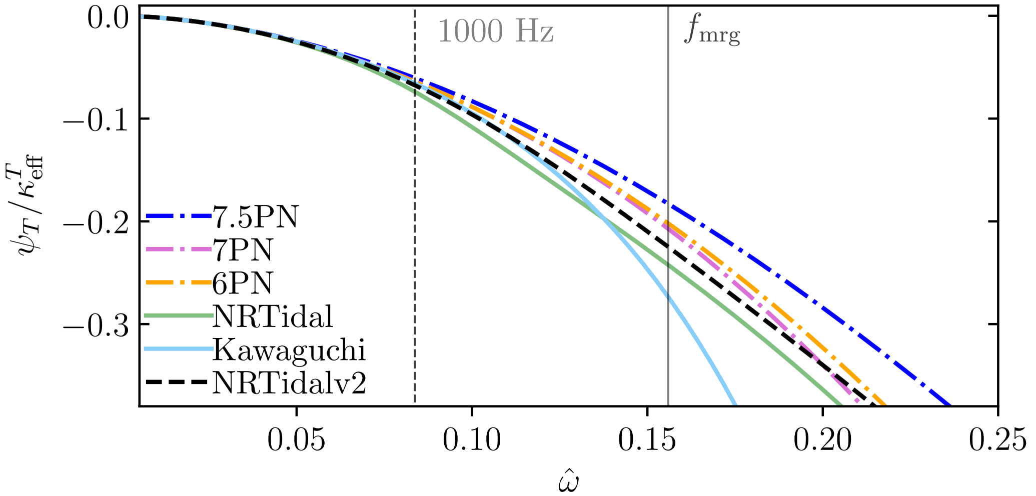
$f_{\rm min}$ = 10 Hz, $f_{\rm max}$ = 1000 Hz,
$m_1 = m_2$ = 1.35 $M_{\rm sun}$



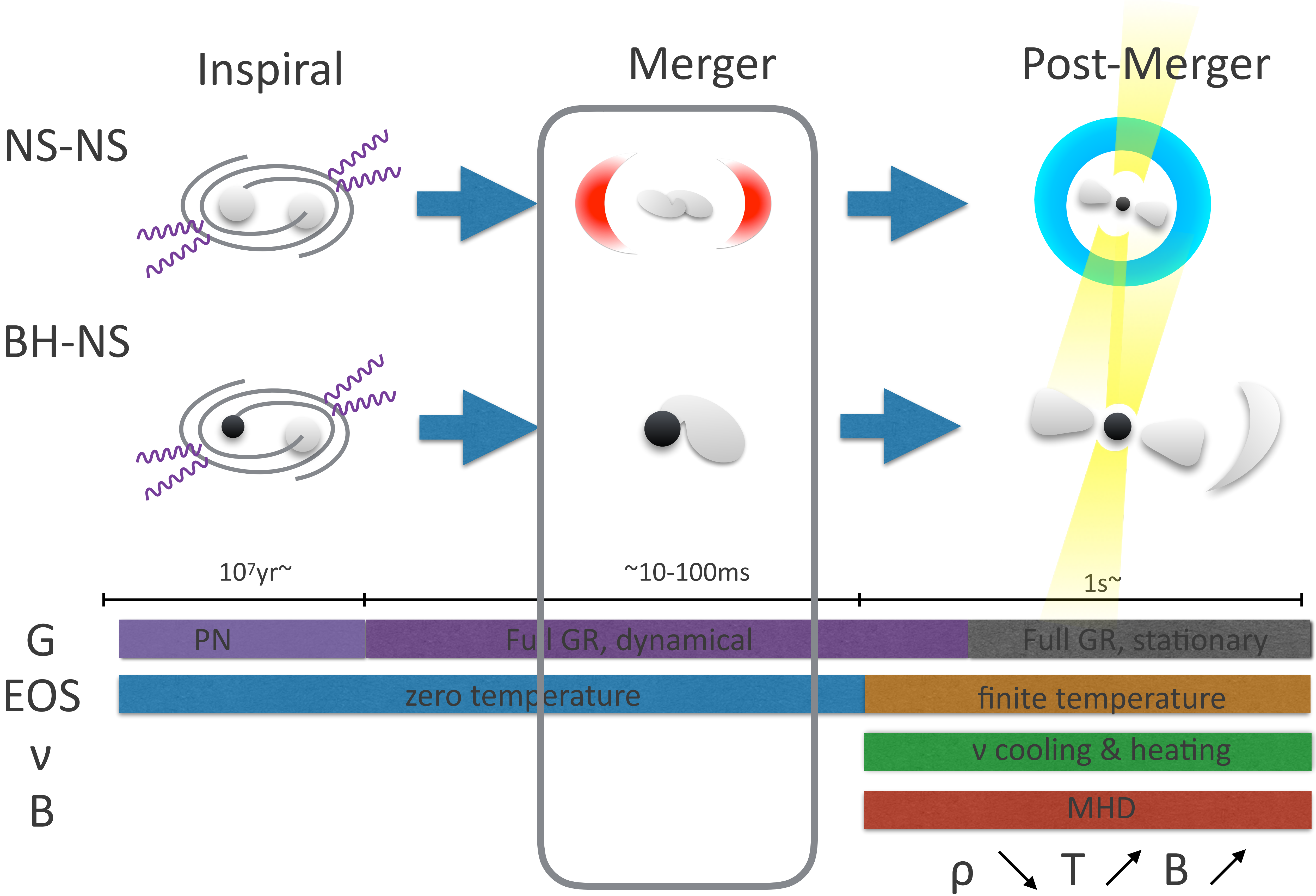
$$\Psi_{\rm tidal} = \frac{3}{128\eta}\left[-\frac{39}{2}\tilde{\Lambda}\left(1+a\tilde{\Lambda}^{2/3}x^{p}\right)\right]x^{5/2} \times\left[1+\frac{3115}{1248}x-\pi x^{3/2}+\frac{28024205}{3302208}x^{2}-\frac{4283}{1092}\pi x^{5/2}\right]$$

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

Ref: Dietrich et al. 2017, 201



General picture



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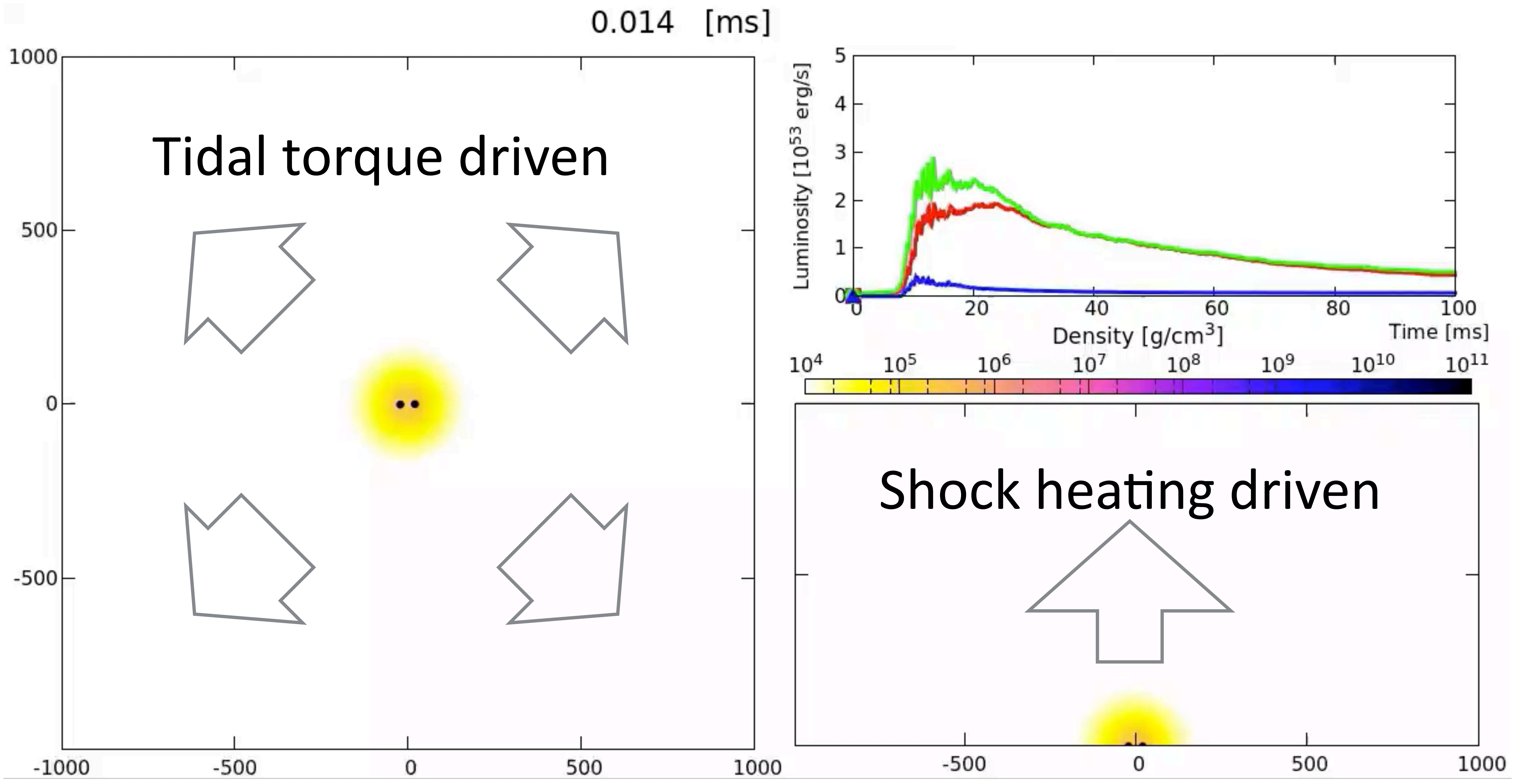
Mass ejection (NS-NS)

Ref: Y. Sekiguchi et al. 2015



Tidal torque driven

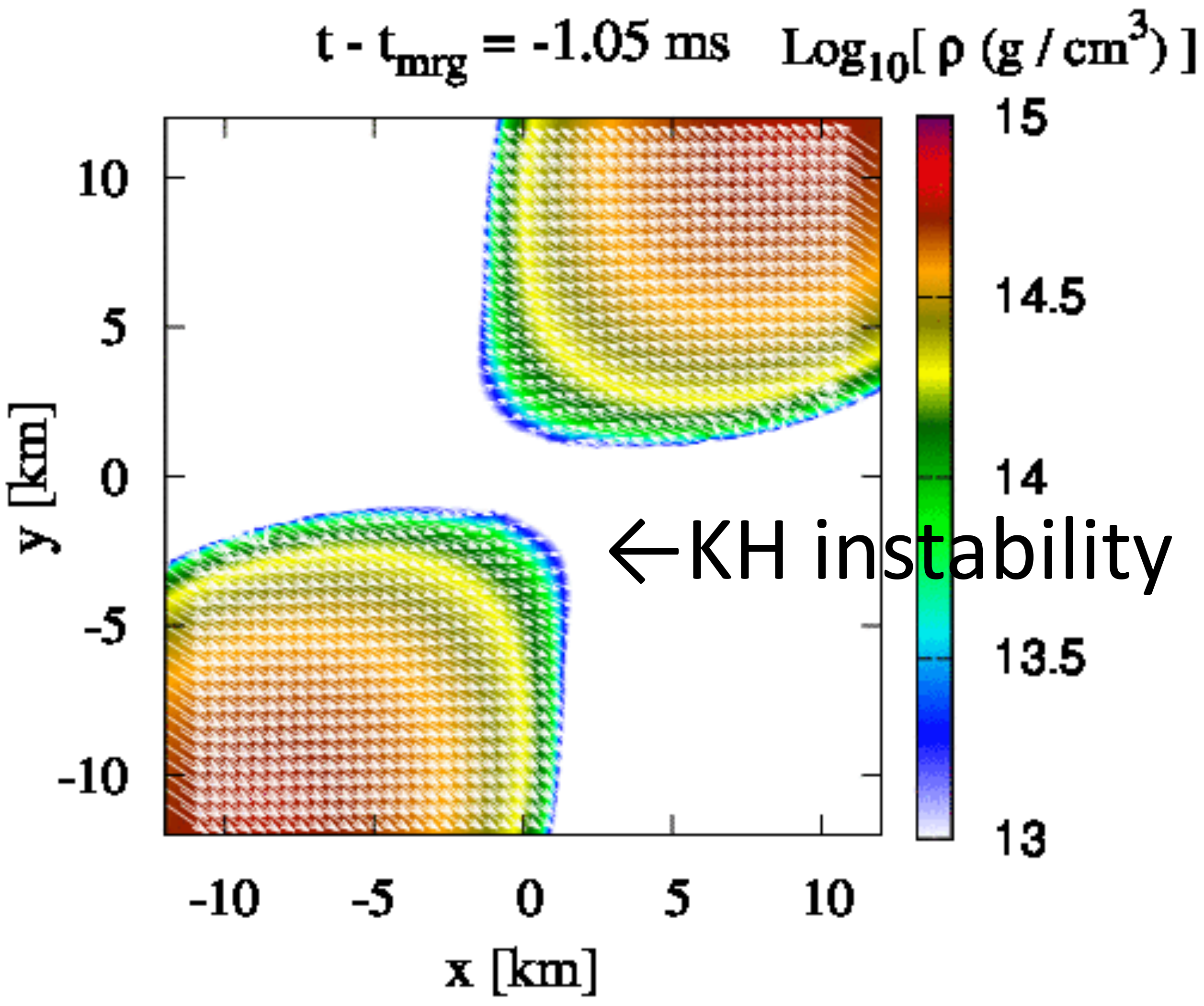
Shock heating driven

A fraction of NS material would be ejected from the system during the merger.
(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)

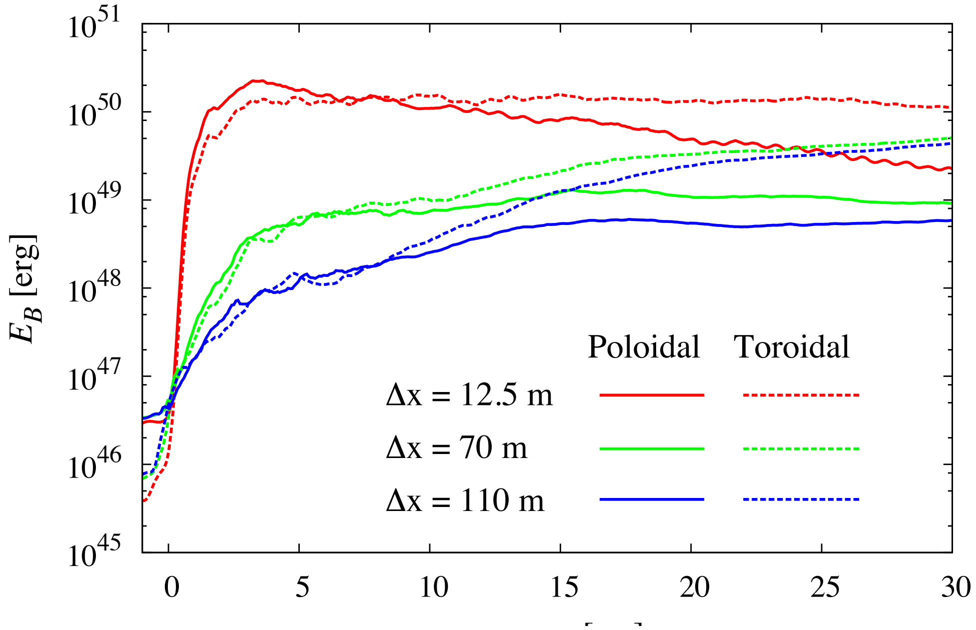
Remnant NS & torus

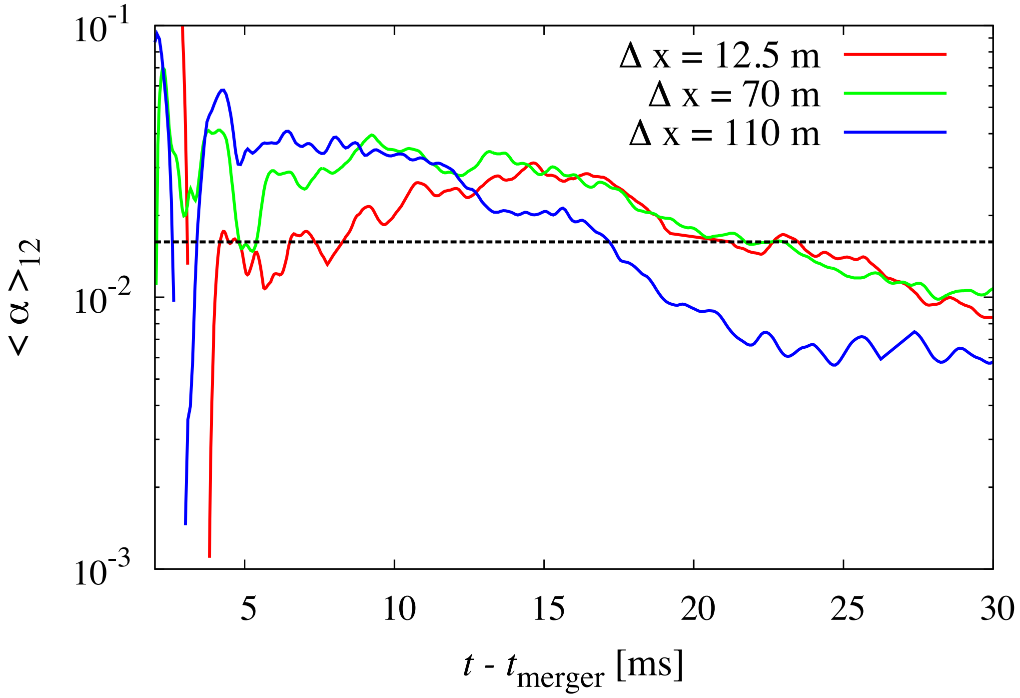
Turbulence in the contact surface→amplification of magnetic field

→The remnant NS and accretion torus would be highly magnetized.



←KH instability

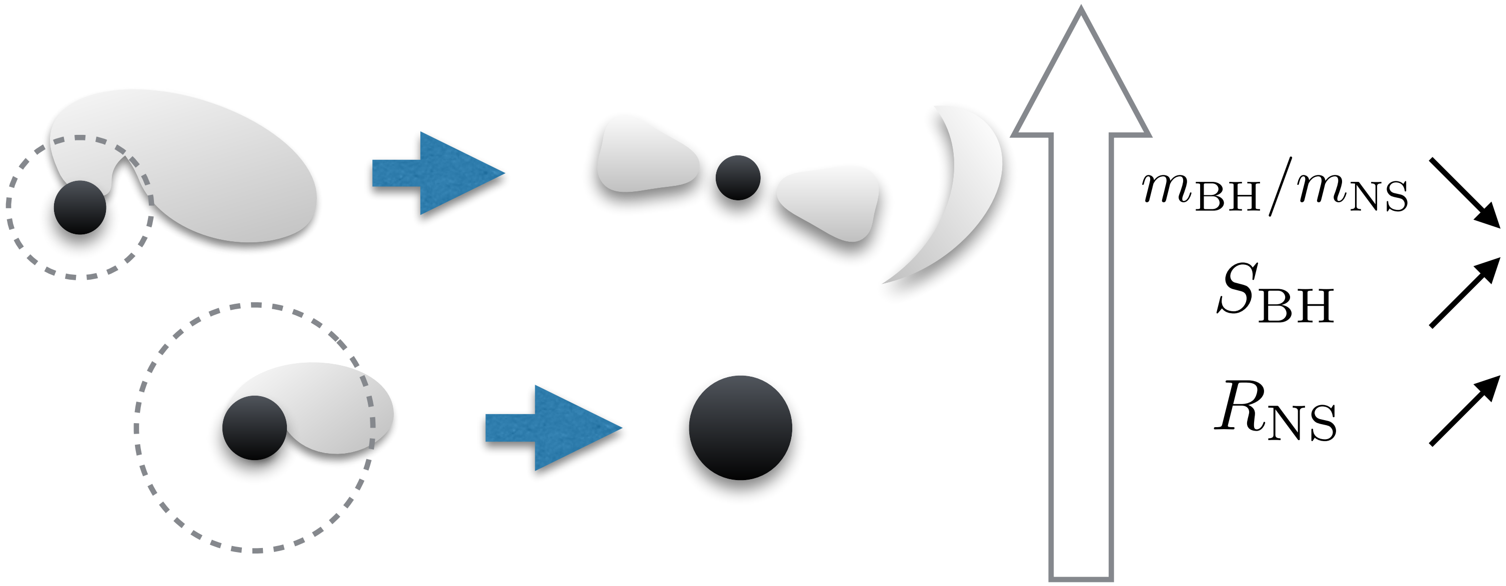




Ref: K. Kiuchi et al. 2015, 2017

Tidal disruption of NS (BH-NS)

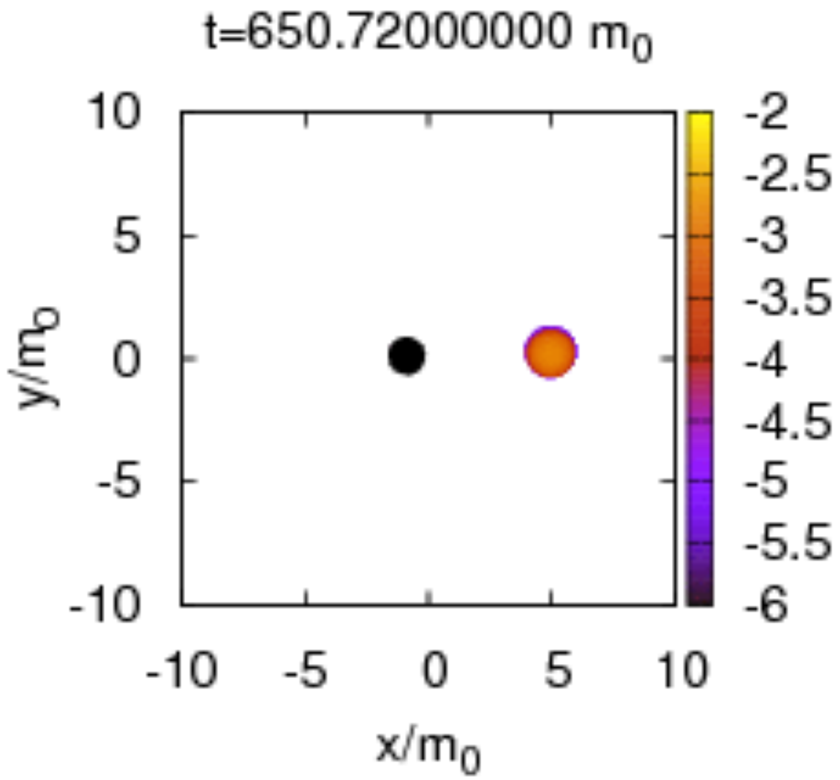
- If the tidal force of the BH exceeds the self-gravity of the NS, the NS is **tidally disrupted.**
- The NS should be tidally disrupted outside **the ISCO of the BH** to form **a ejecta or remnant torus,** otherwise entire NS material would be swallowed by the BH.
- Whether tidal disruption occurs or not depend on the binary parameters.

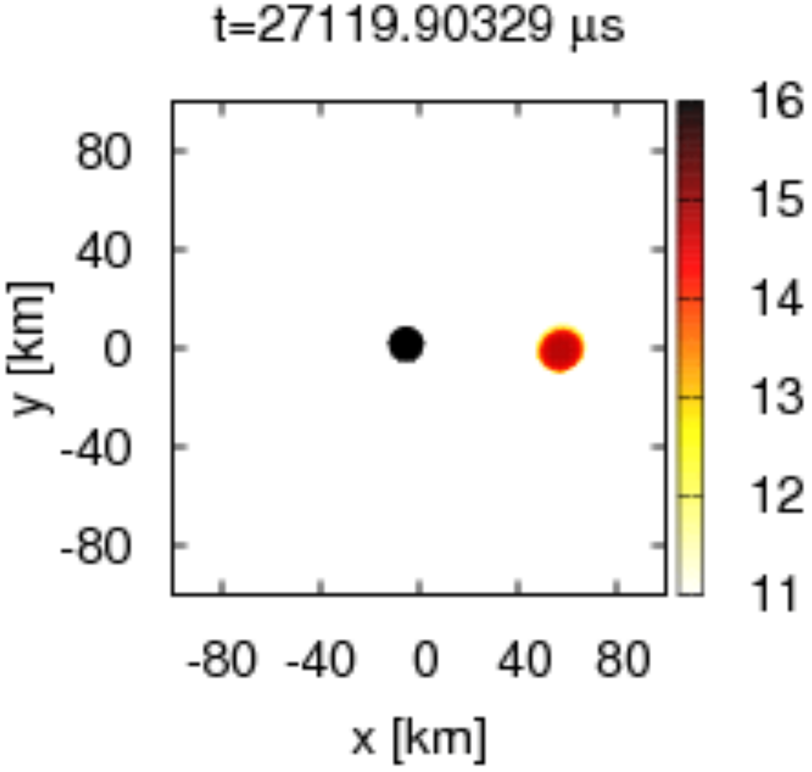


$m_{\rm BH}/m_{\rm NS}$ ↘

$S_{\rm BH}$ ↗

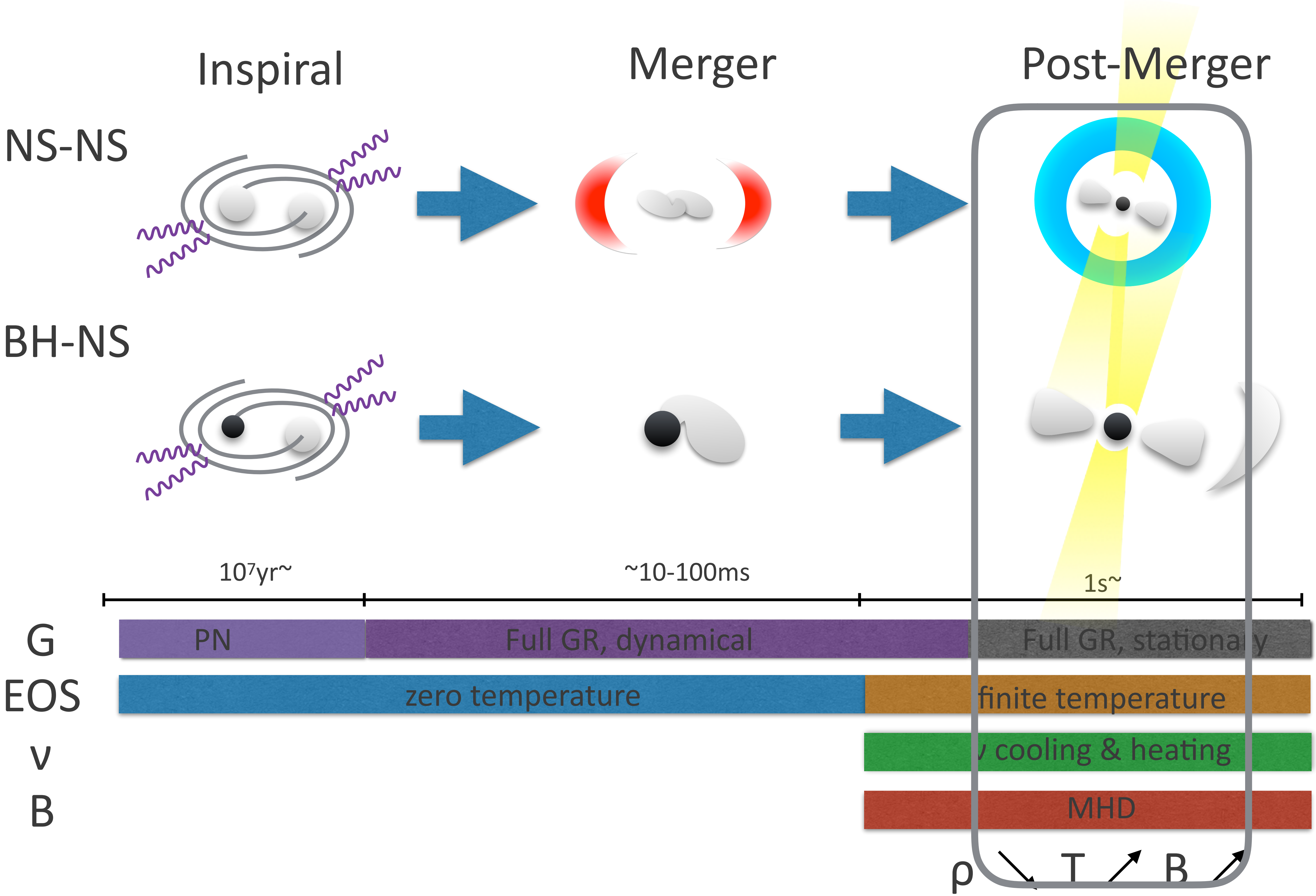
$R_{\rm NS}$ ↗





ref) Kyutoku et al. 2010, 2011

General picture



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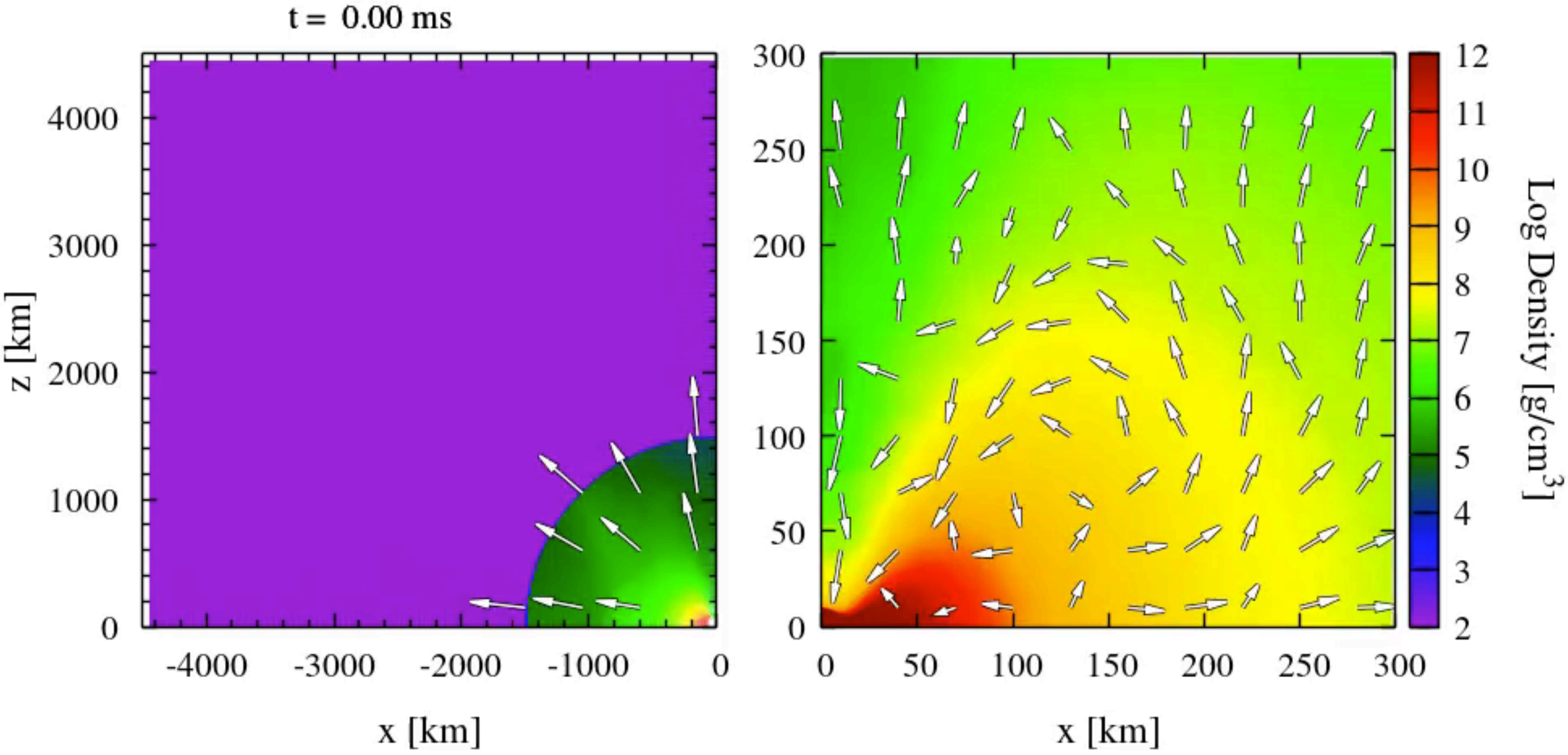
ρ ↘ T ↗ B ↗

Post-merger mass ejection

Viscous GRRHD simulation for merger remnant
(Ref: S. Fujibayashi et al. 2018)



Material ejection from the remnant torus would occur
driven by amplified magnetic fields or effective viscous heating due to magnetic turbulence

(see also e.g. Siegel et al. 2018, Fernandez et al.2018 for GRMHD simulations)

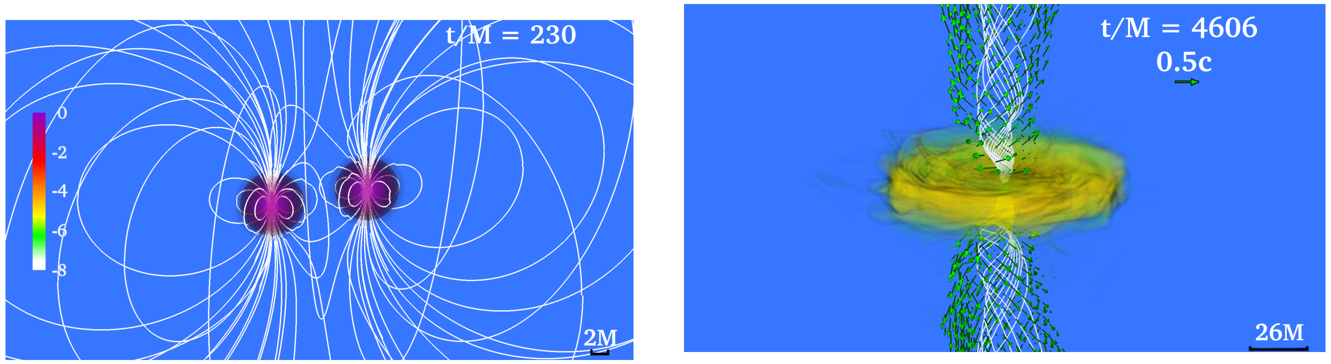
Relativistic jets

- Relativistic jets could be launched from the BH accretion torus system formed after the merger

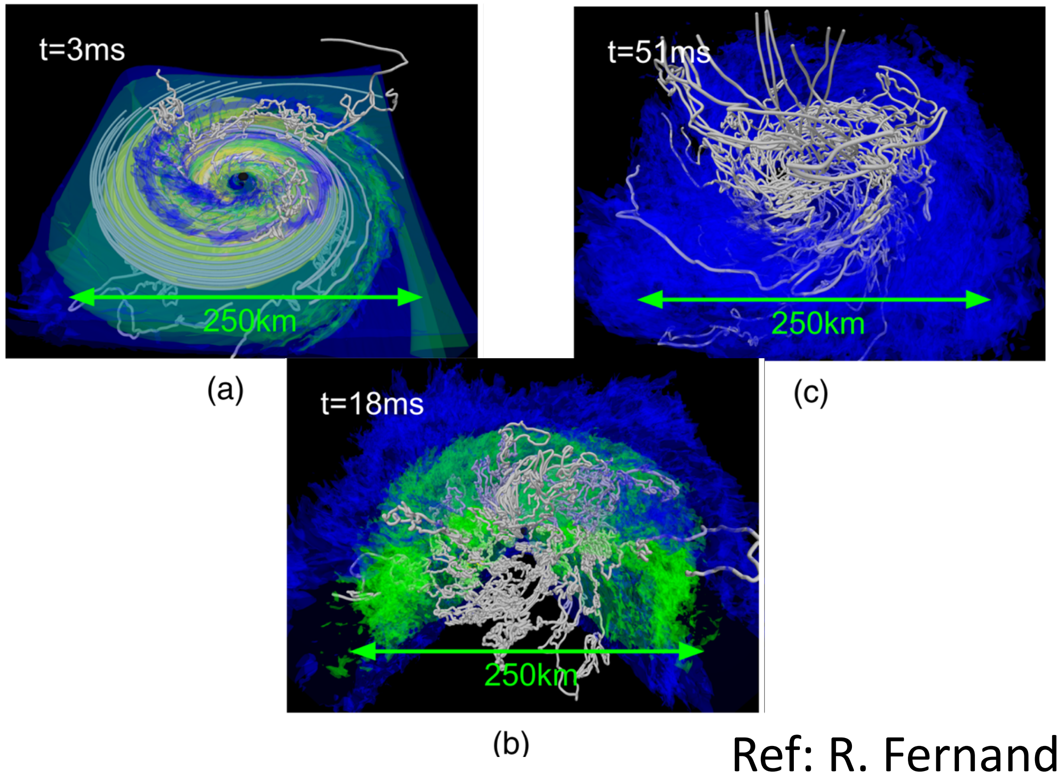
- global structure of the magnetic fields would play an important role

- contribution from neutrino pair annihilation seems to be sub-dominant

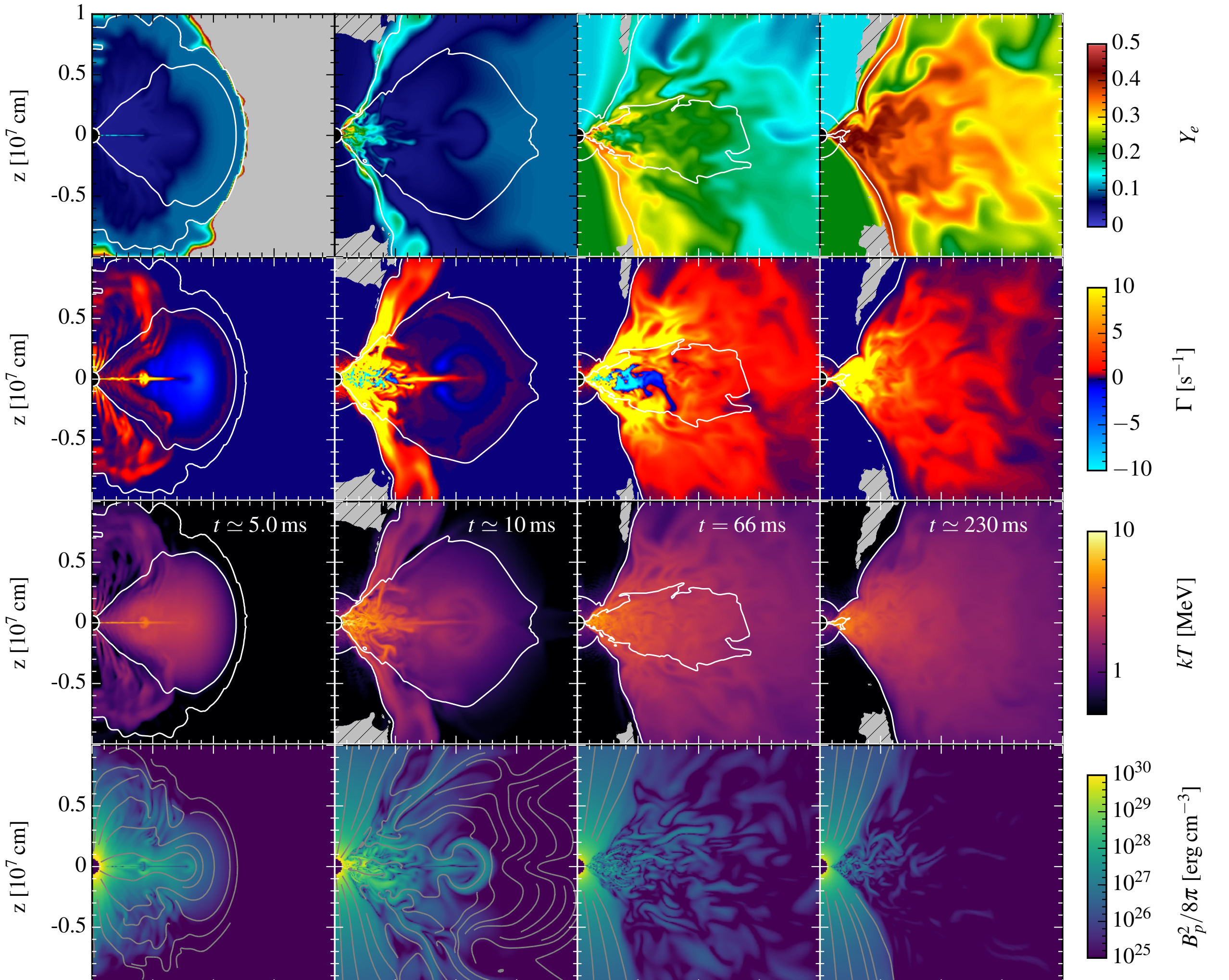
Ref: M. Ruiz et al. 2016



Ref: K. Kiuchi et al. 2015



Ref: R. Fernandez et al. 201



Post-merger waveforms (NS-NS)

- Post-merger waveforms would contain rich physical information,

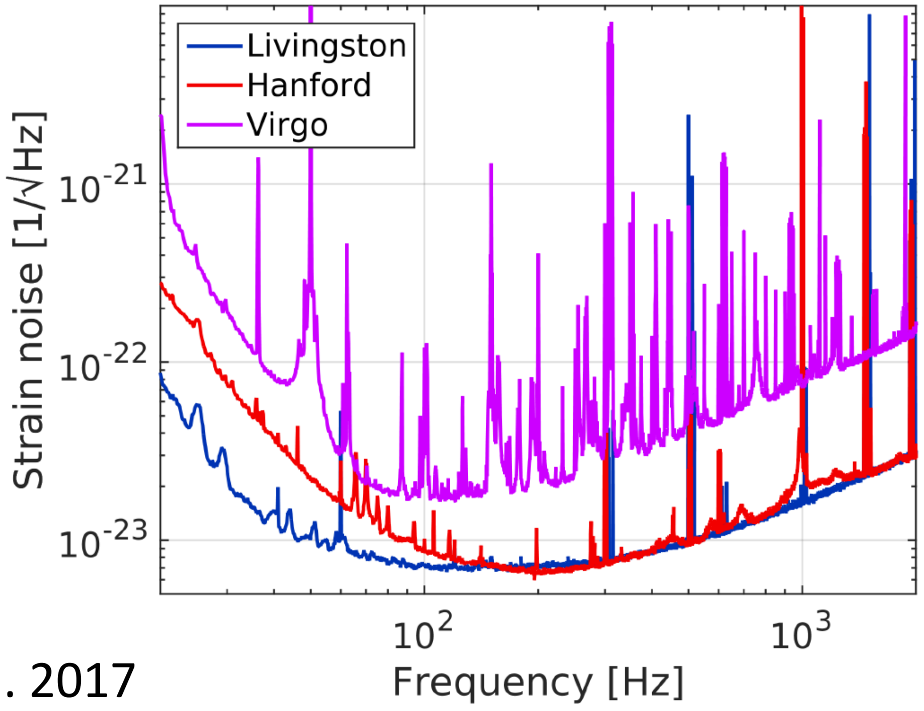
  such as **the evolution of the merger remnant** and

  information of high density part of NS EoS

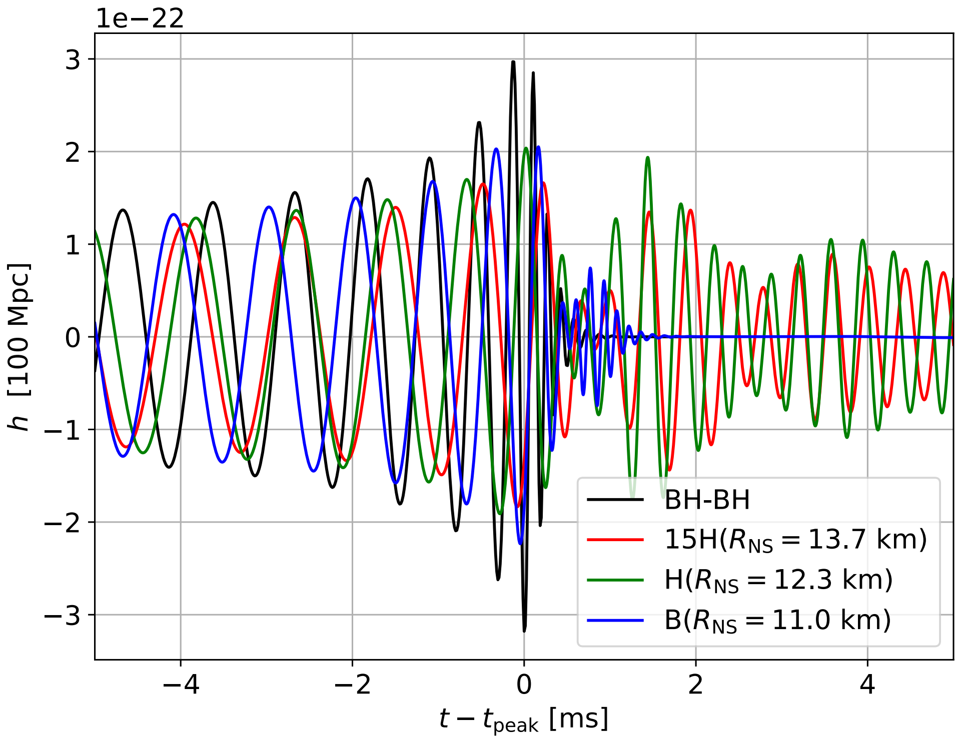
- Challenging for both detection and waveform modeling

- Complicated physical effects, such as MHD, thermal effect, and ν radiation, should be taken into account in the numerical simulations

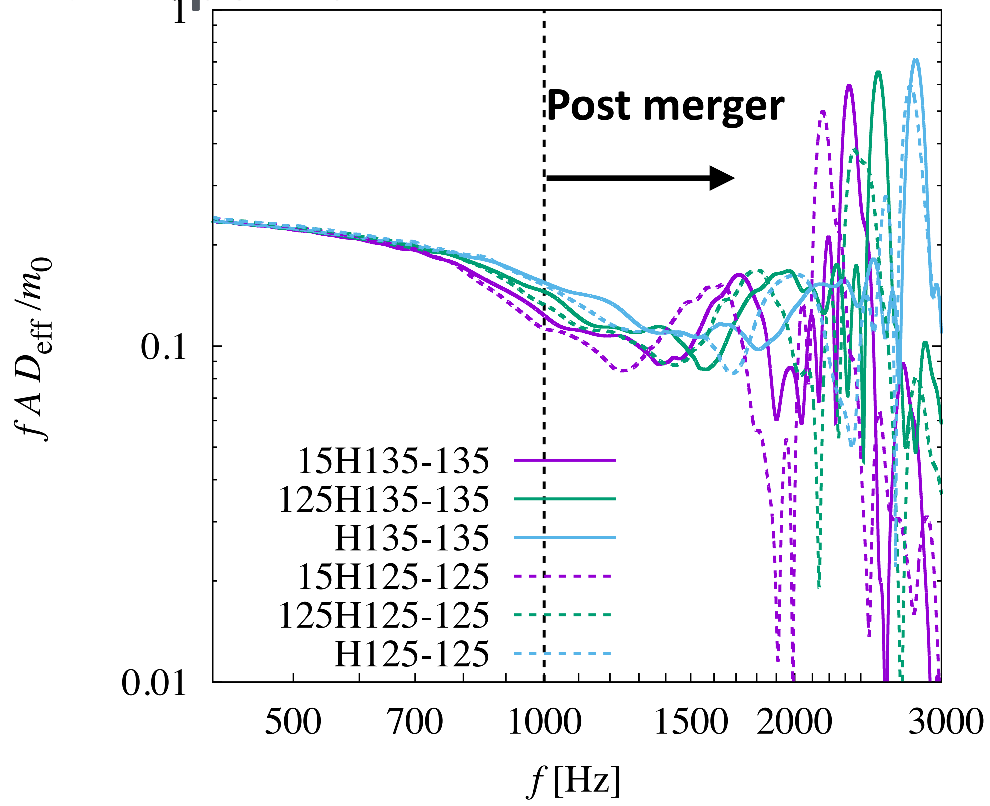
Detector sensitivity



Ref: B.P.Abbot et al. 2017



GW spectra



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

Post-merger waveforms (BH-NS)

- Waveforms in the inspiral phase would have almost the same behavior as BNS or BBH.

  →it is important to distinguish it from BNS or BBH

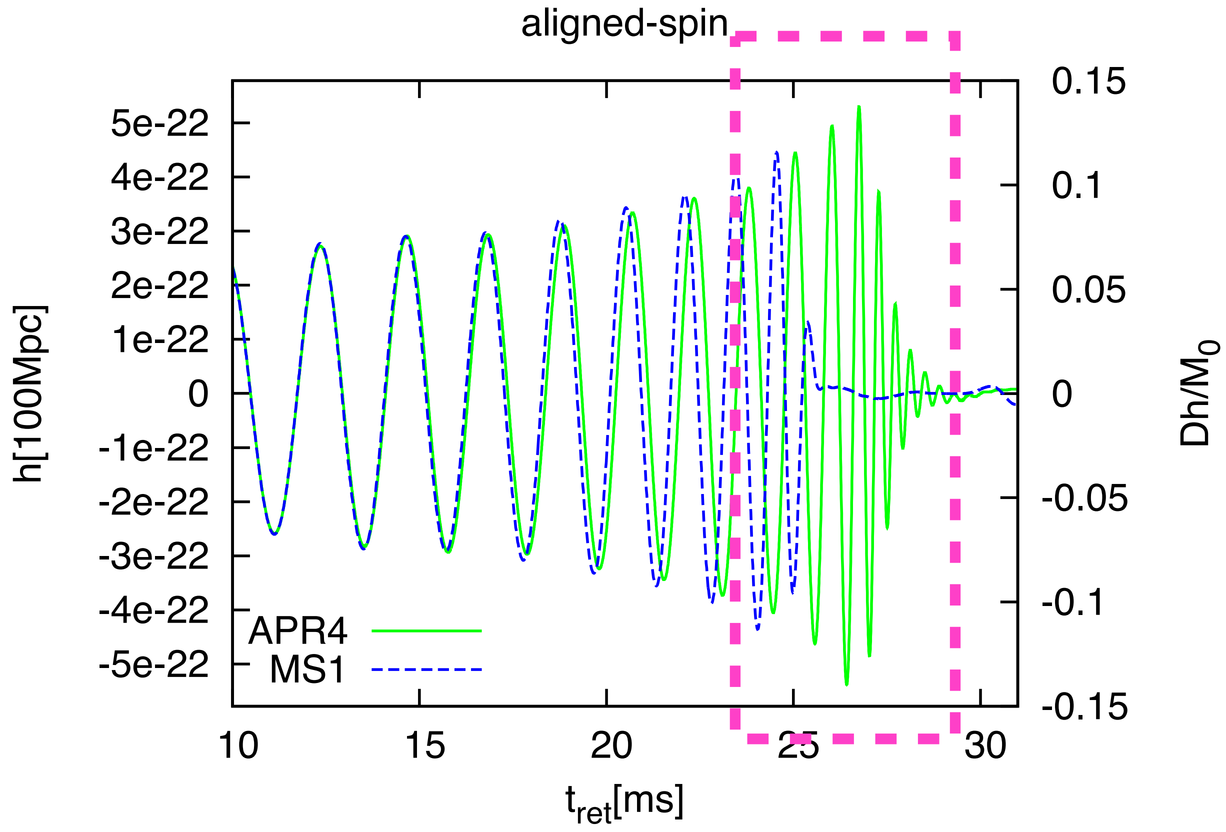
- The merger~post merger part of the BHNS waveform could be different if the NS is

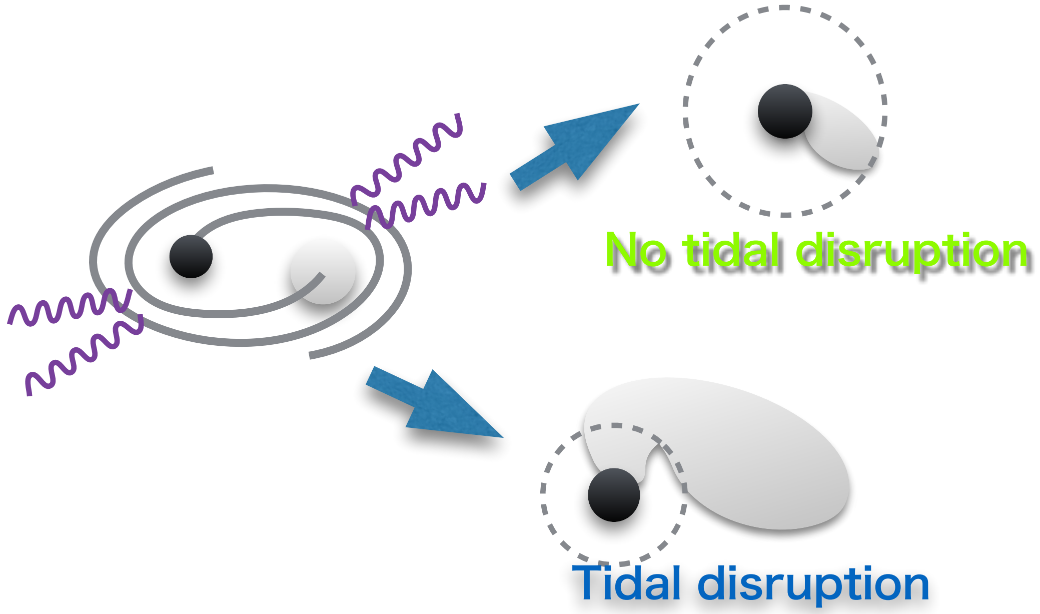
  tidally disrupted

  →The high frequency part (>1kHz) of GW is important

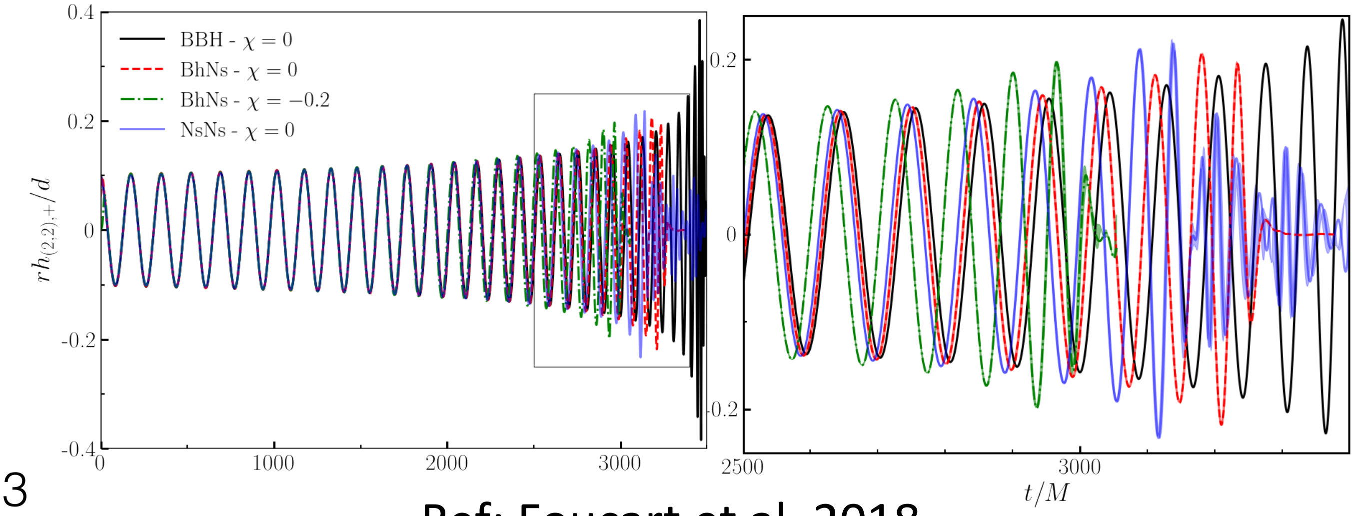
  (see also e.g. Shibata et al. 2009, Lackey et al. 2014, Pannarale et al. 2015)

ref) Kyutoku et al. 2015





GW comparison between different binary components (Q=1)



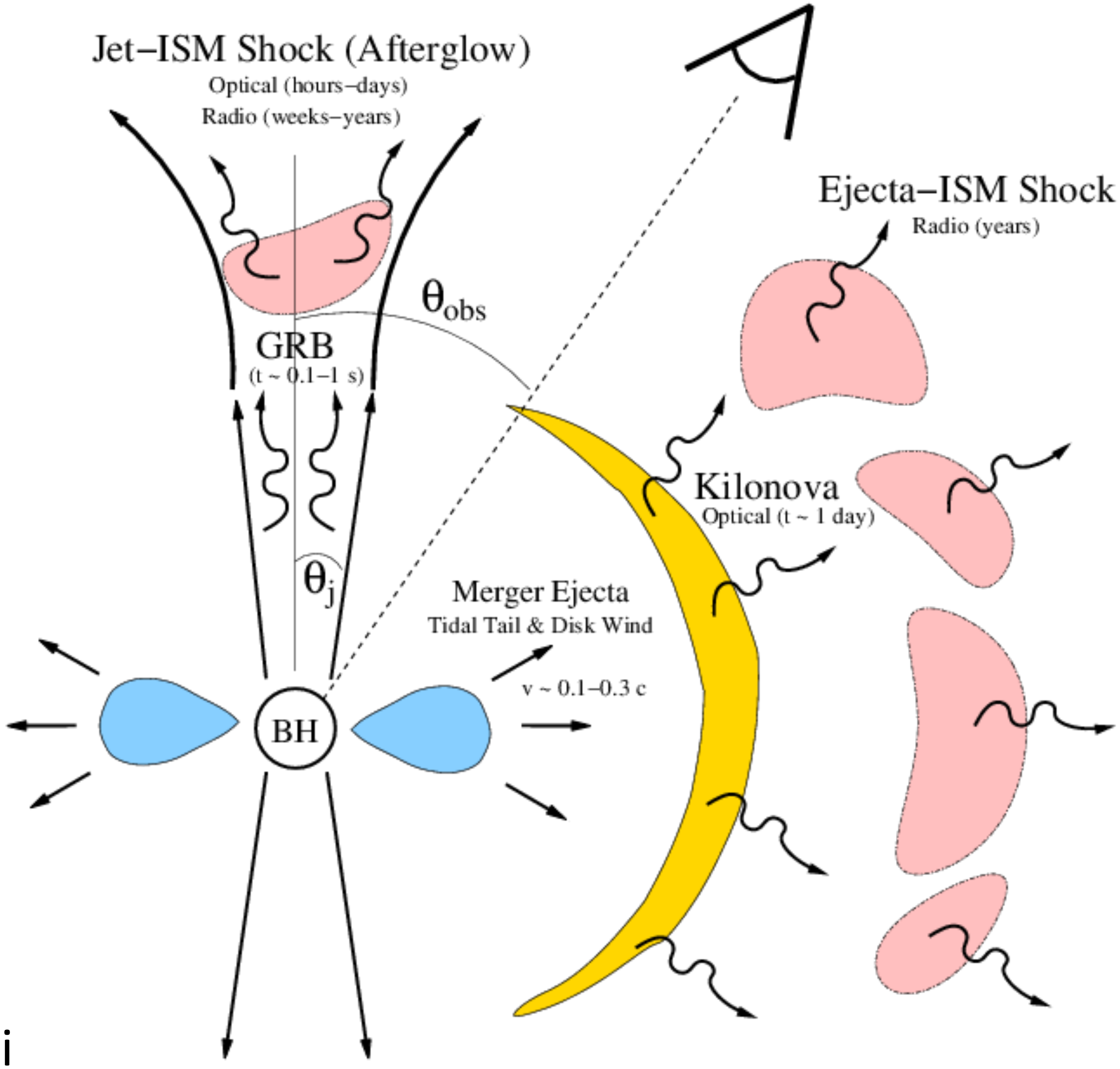
Ref: Foucart et al. 2018

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, environment

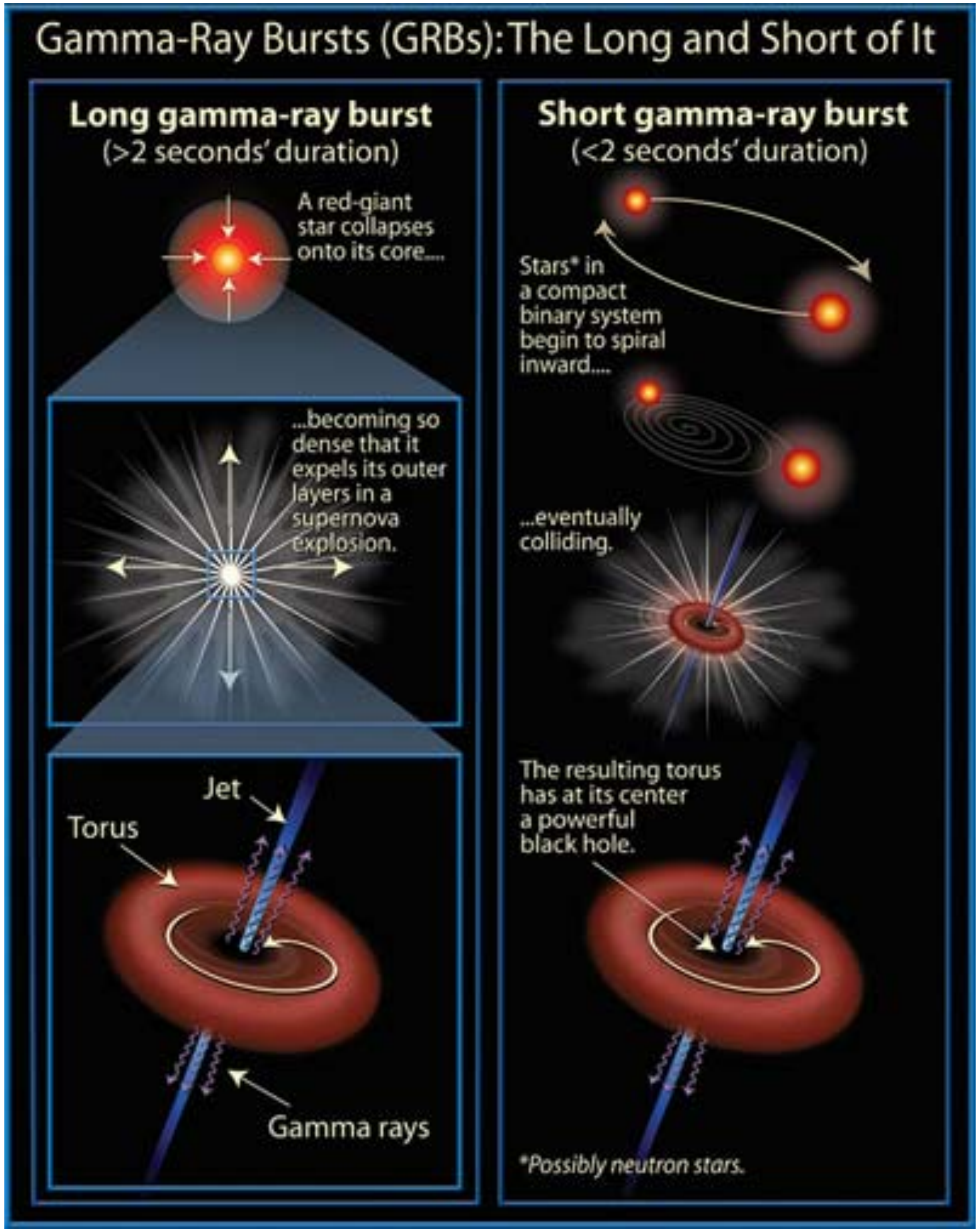
- Possible synthesis site of r-process nuclei



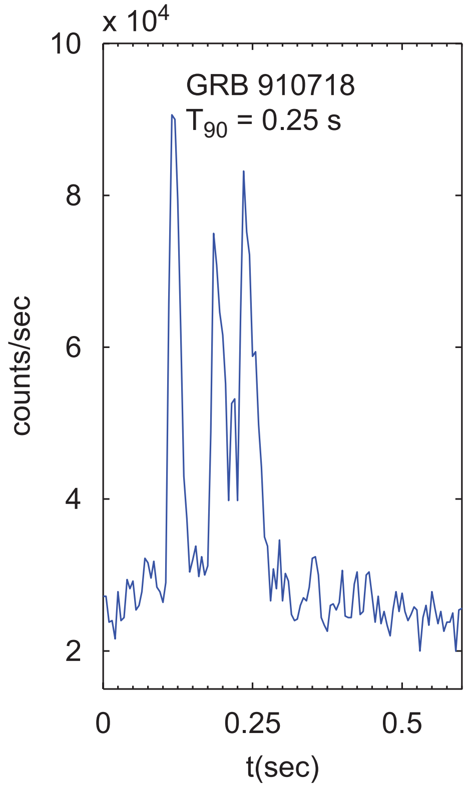
Ref: B. Metzger and E. Berger 2012

short-hard gamma-ray burst

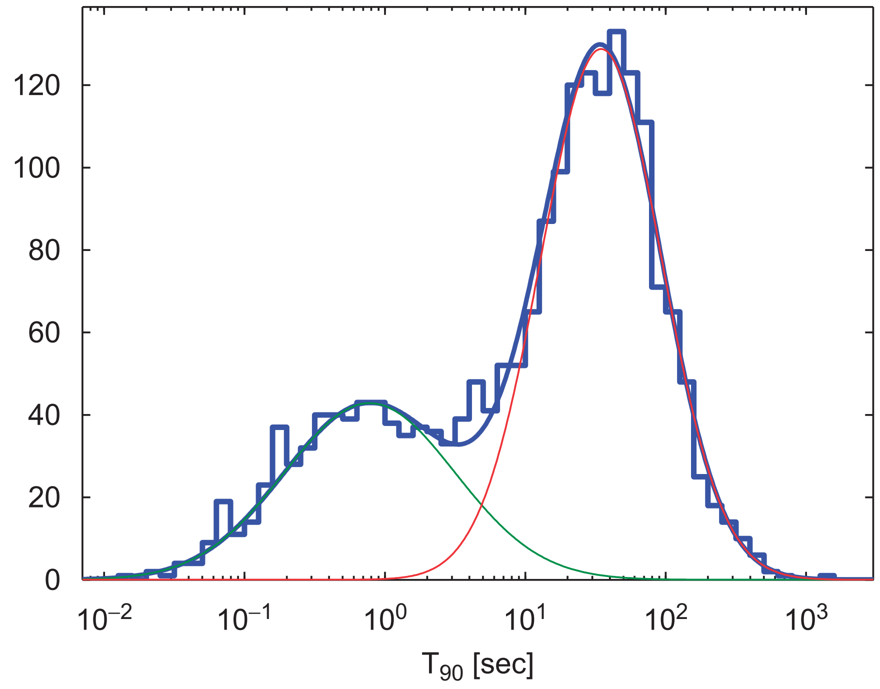
- $L \sim 10^{51}$erg/s, Δt=0.01-1000 s
- launched by highly relativistic jet ($\Gamma \sim$100-1000)
- Long-soft GRB: ≥ 2s
  deaths of massive stars
- Short-hard GRB: ≤ 2s
  neutron star binary merger?



sGRB light curve



Duration distribution of GRBs



ref) Nakar 2007

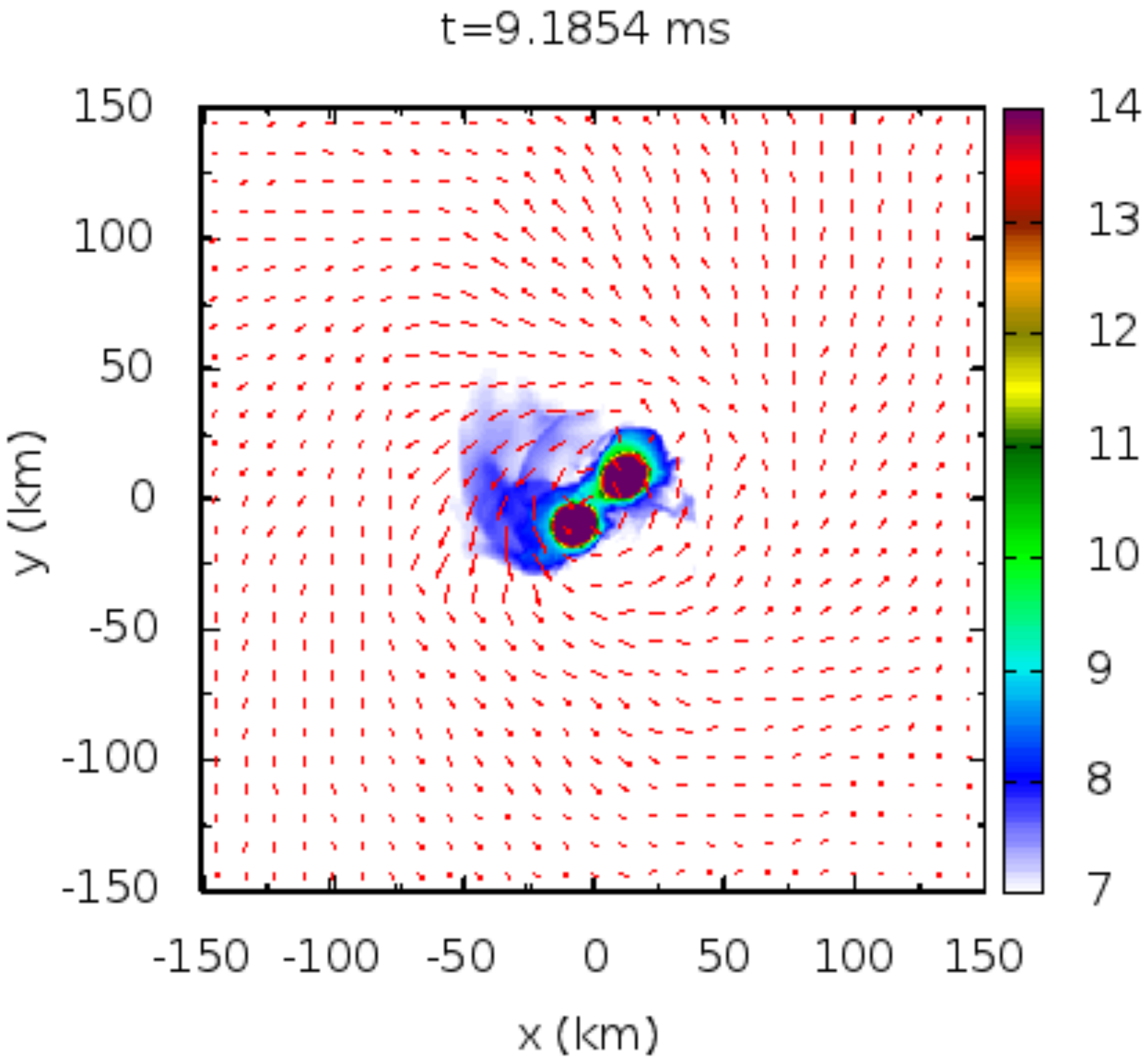
Kilonova/Macronova

- **A Kilonova/macronova** is a electromagnetic (EM) emission which expected to be associate with a NS binary merger.

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

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

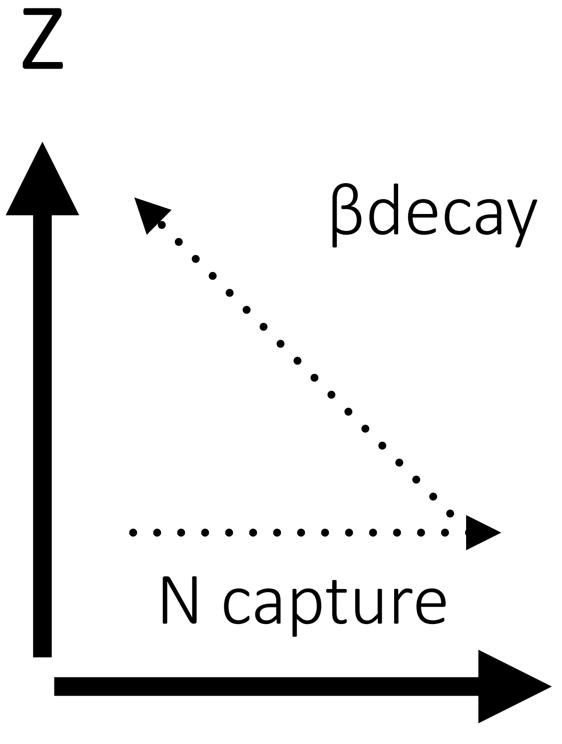
Li & Paczyński 1998, Kulkarni 2005,
Metzger et al. 2010 …



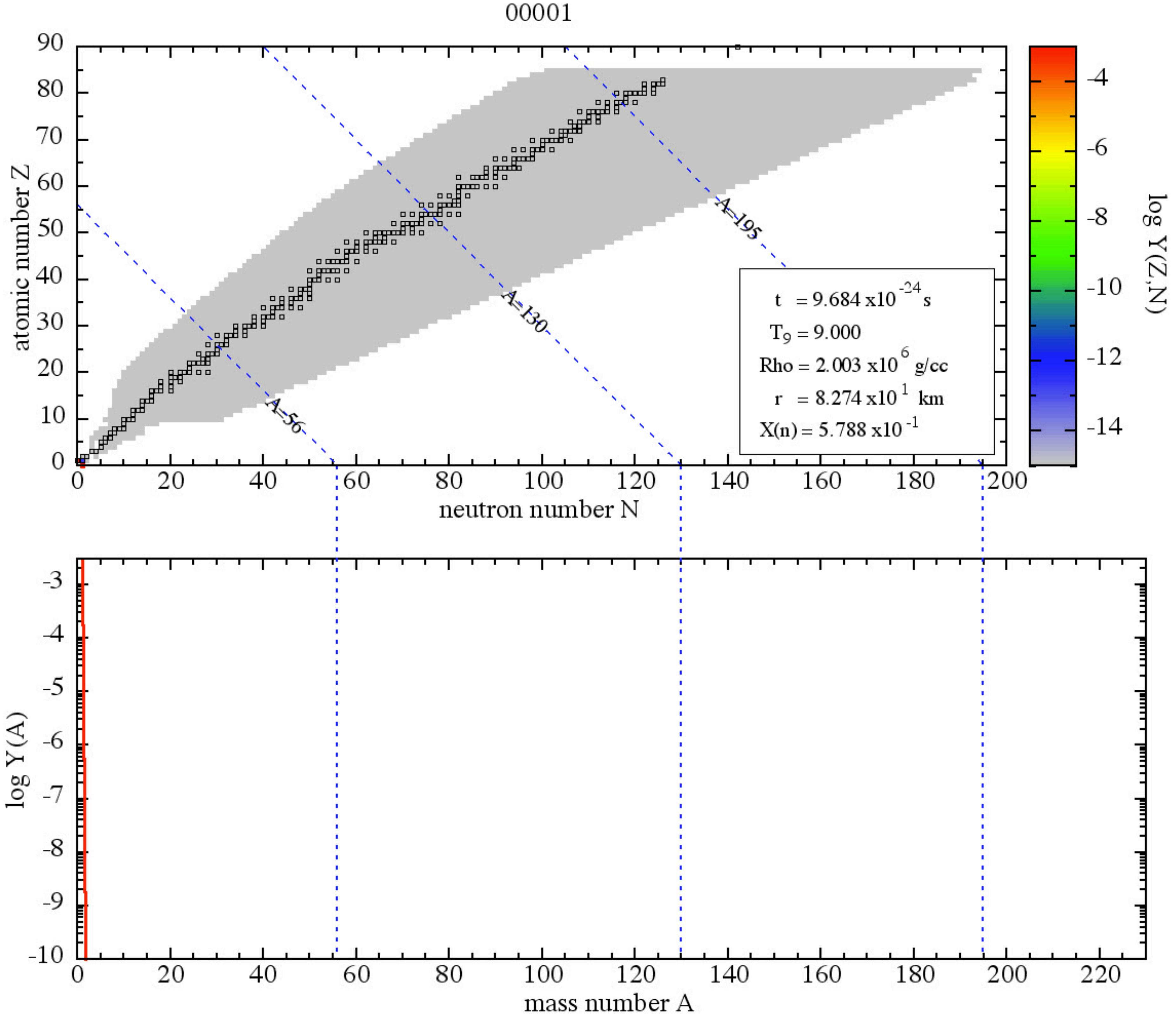
Ref: K. Hotokezaka et al. 2013

R-process nucleosynthesis

Credit) Sho Fujibayashi

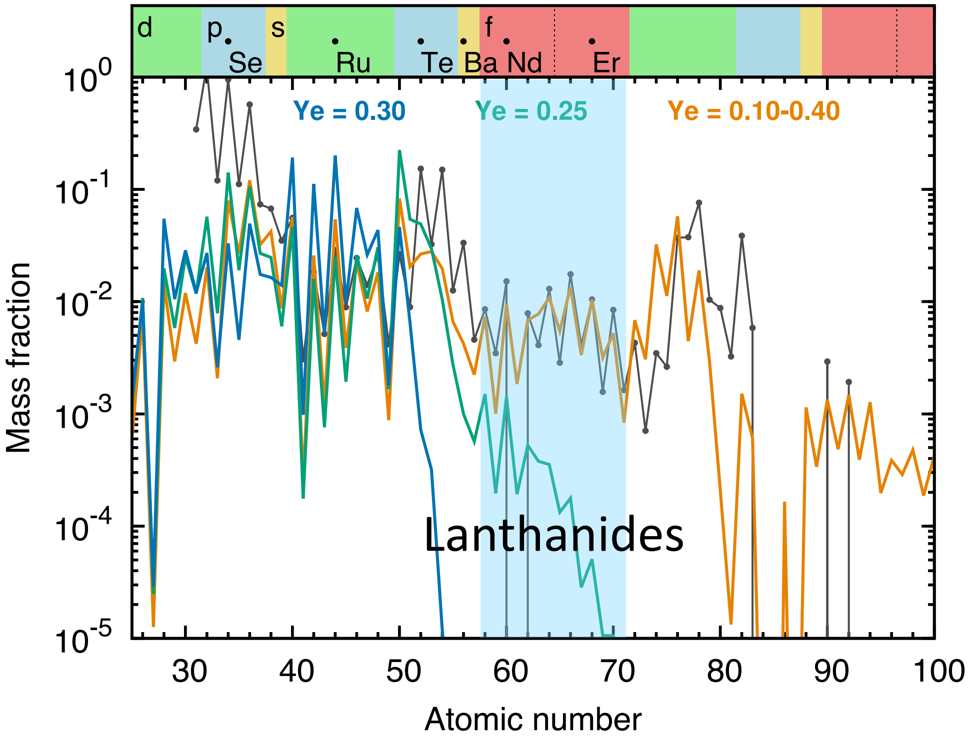


$$\tau_{\rm Ncap} \ll \tau_{\beta\rm dec}$$

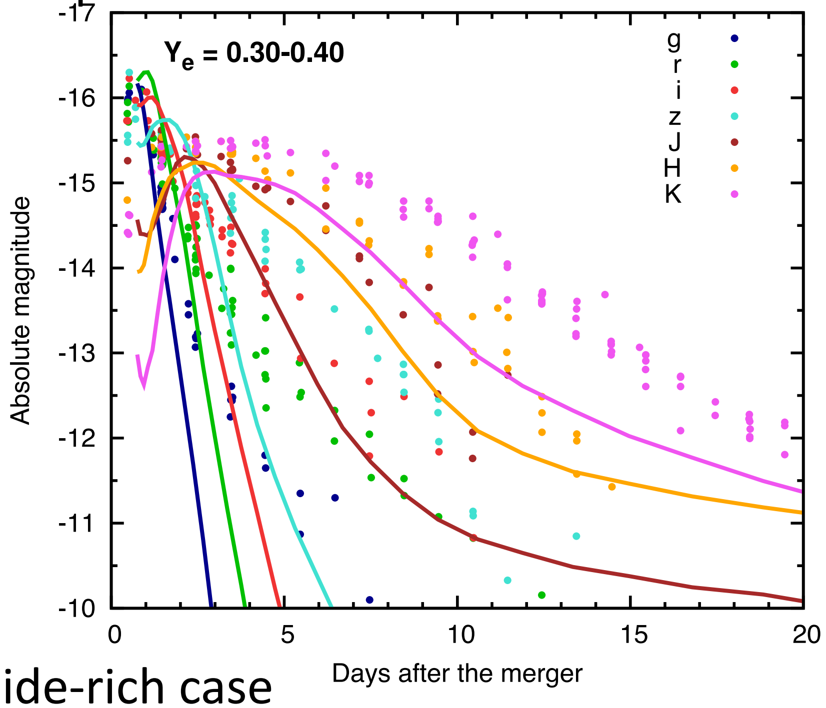


Ejecta opacity

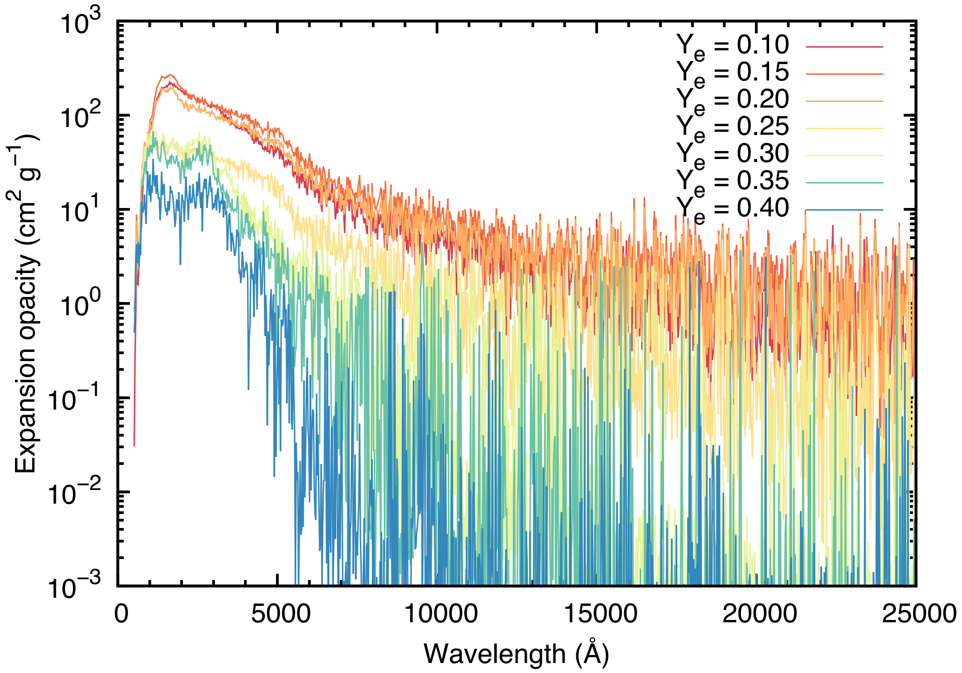
ref) Tanaka et al. 2018,2019

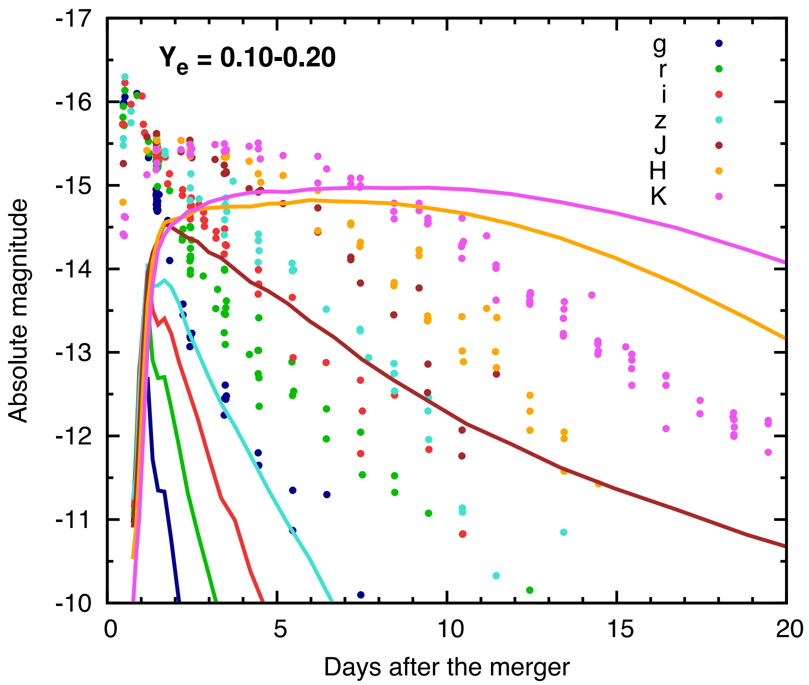


Lanthanide-poor case



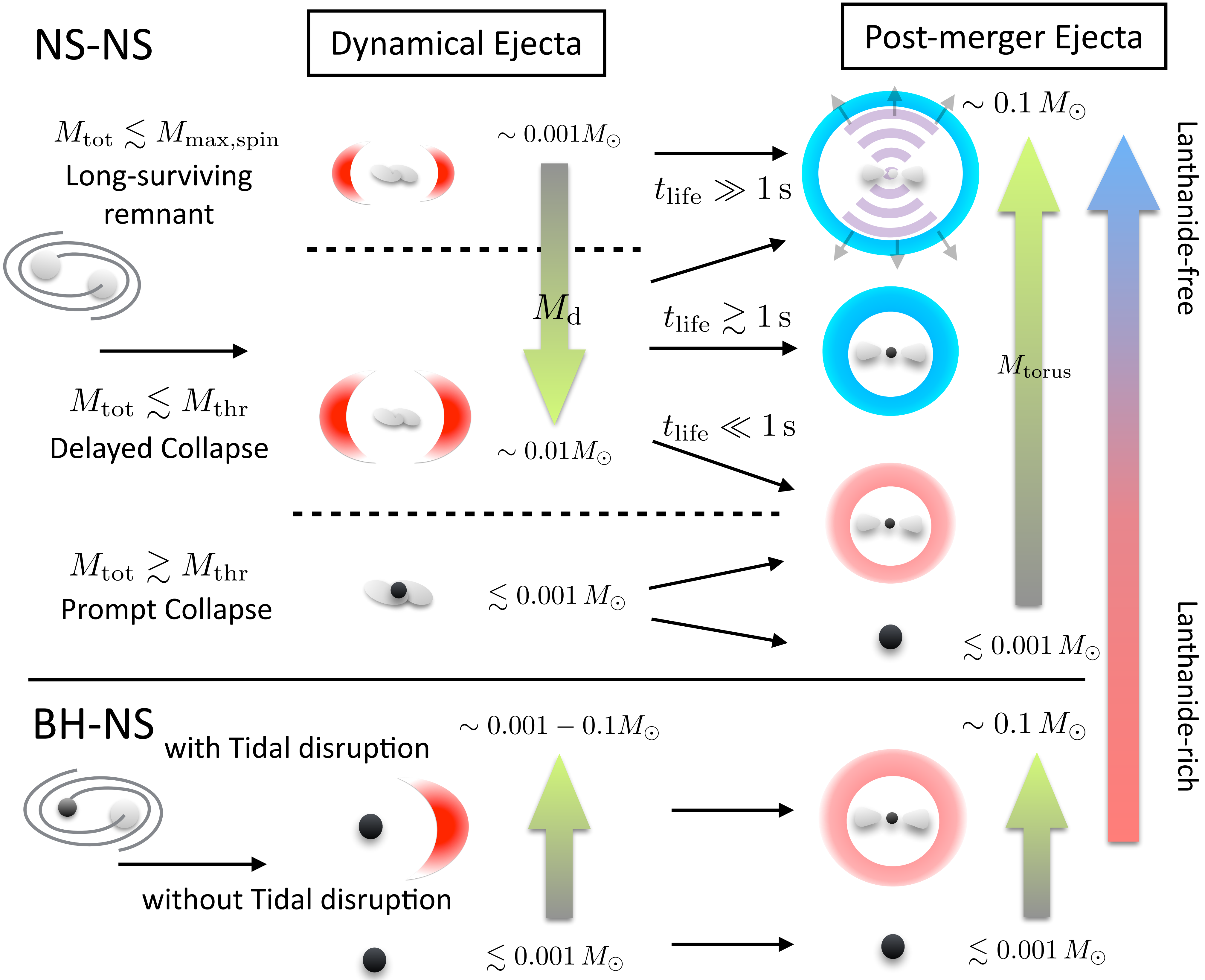
Lanthanide-rich case





$$Y_e = \frac{[p]}{[p] + [n]}$$

The ejecta opacity varies significantly (0.1—10 cm^2/g) depending on whether **lanthanide elements** are synthesized or not, which reflects the electron fraction, Ye, of ejecta. (Kasen et al. 2013, Barnes et al. 2013, Tanaka et al. 2013)



NS-NS

Dynamical Ejecta

Post-merger Ejecta

$M_{\rm tot} \lesssim M_{\rm max,spin}$

Long-surviving remnant

$\sim 0.001 M_\odot$

$t_{\rm life} \gg 1\,{\rm s}$

$\sim 0.1\, M_\odot$

$M_{\rm d}$

$t_{\rm life} \gtrsim 1\,{\rm s}$

$M_{\rm torus}$

$M_{\rm tot} \lesssim M_{\rm thr}$

Delayed Collapse

$\sim 0.01 M_\odot$

$t_{\rm life} \ll 1\,{\rm s}$

$M_{\rm tot} \gtrsim M_{\rm thr}$

Prompt Collapse

$\lesssim 0.001\, M_\odot$

$\lesssim 0.001\, M_\odot$

Lanthanide-free

Lanthanide-rich

BH-NS

with Tidal disruption

$\sim 0.001 - 0.1 M_\odot$

$\sim 0.1\, M_\odot$

without Tidal disruption

$\lesssim 0.001\, M_\odot$

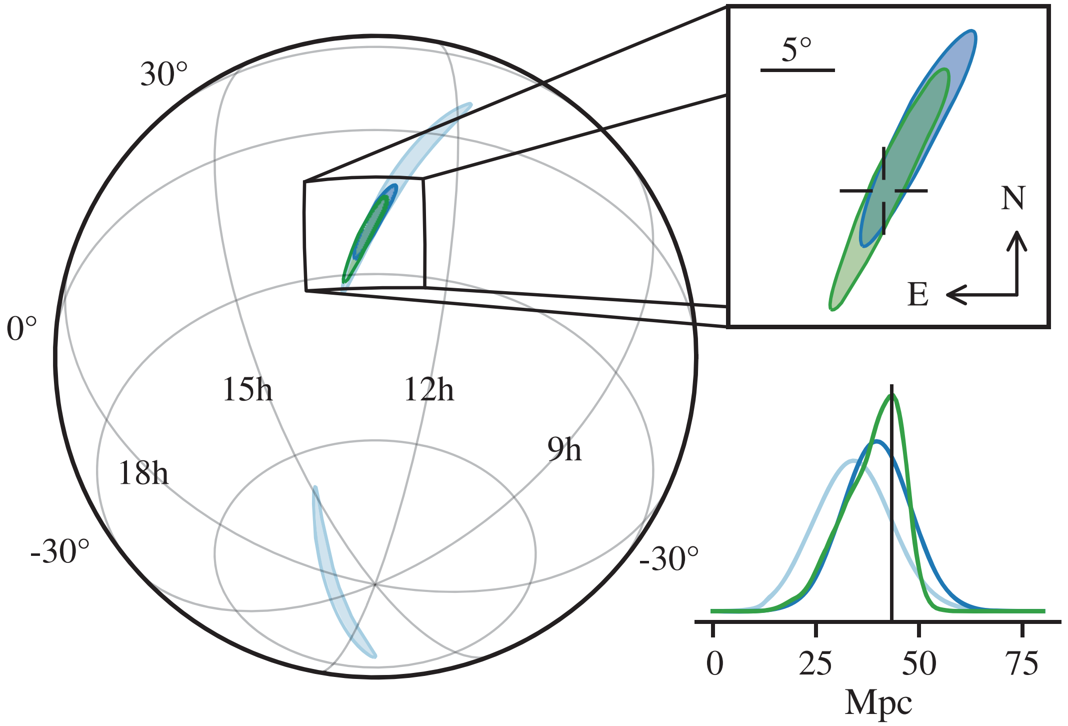
$\lesssim 0.001\, M_\odot$

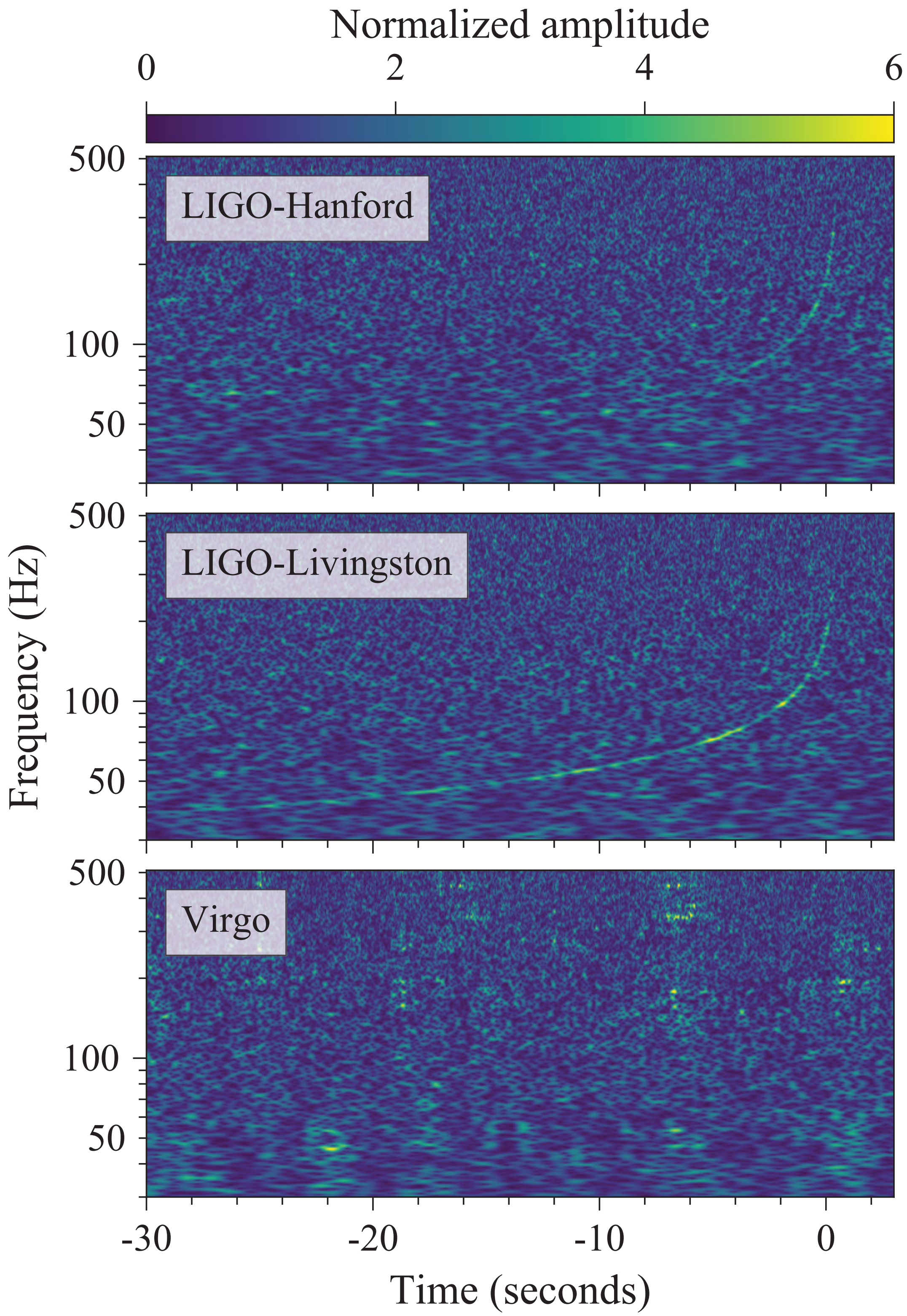
Kilonova lightcurves could show large diversity reflecting the variety in the binary parameters or the binary composition

The first NS-NS merger event: GW170817

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
- SNR=32.4
- Distance ~40 Mpc
- Sky localization: 28 deg^2





Ref: LIGO/Virgo 2017

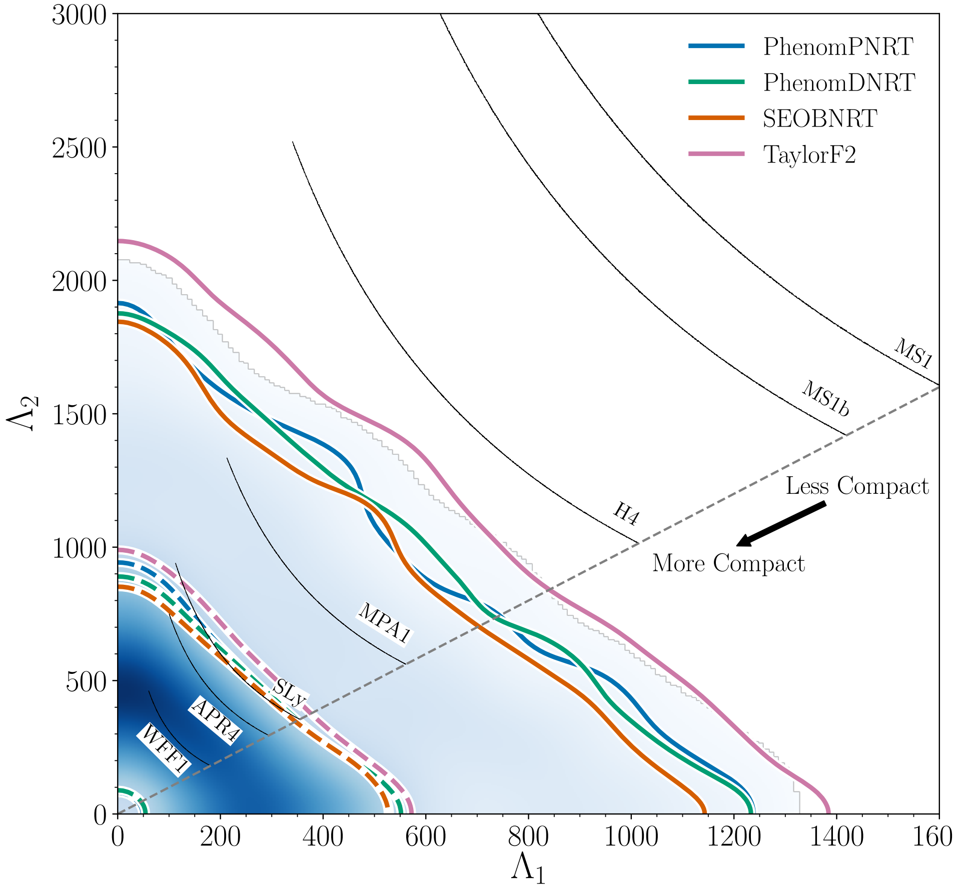
GW170817:Constraints on binary parameters

- Binary parameters were constrained tightly as ever was (SNR~32), and **the tidal deformability** is indeed measured (constrained) in this event

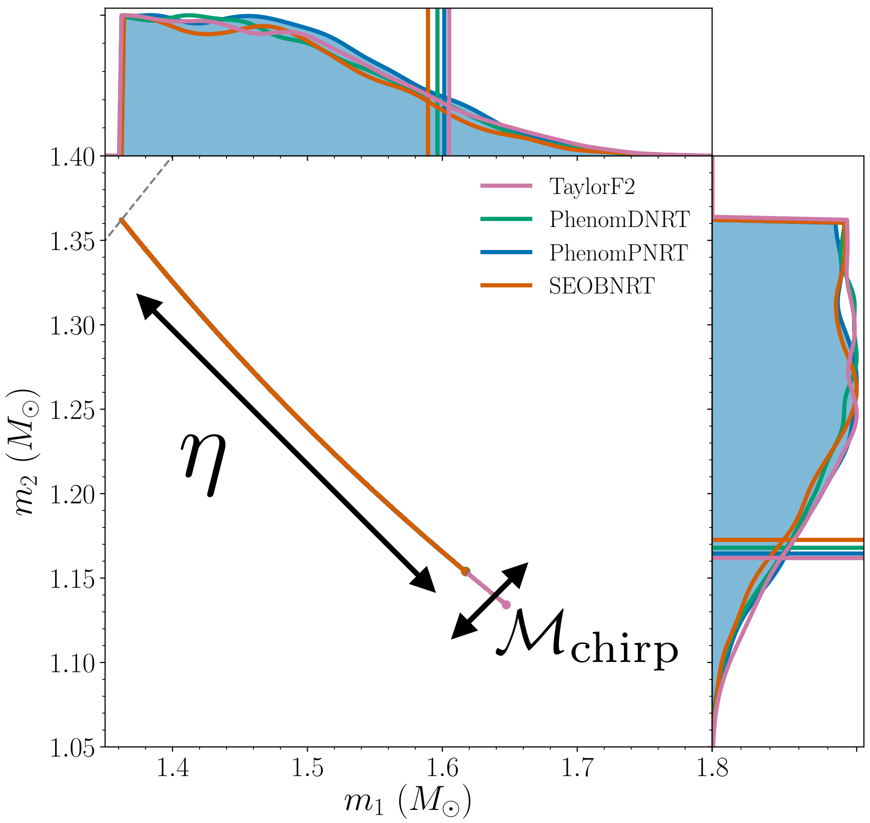
$$\tilde{\Lambda} = \frac{16}{13(1+q)^5}\left[(1+12q)\Lambda_1 + (12+q)q^4\Lambda_2\right]$$

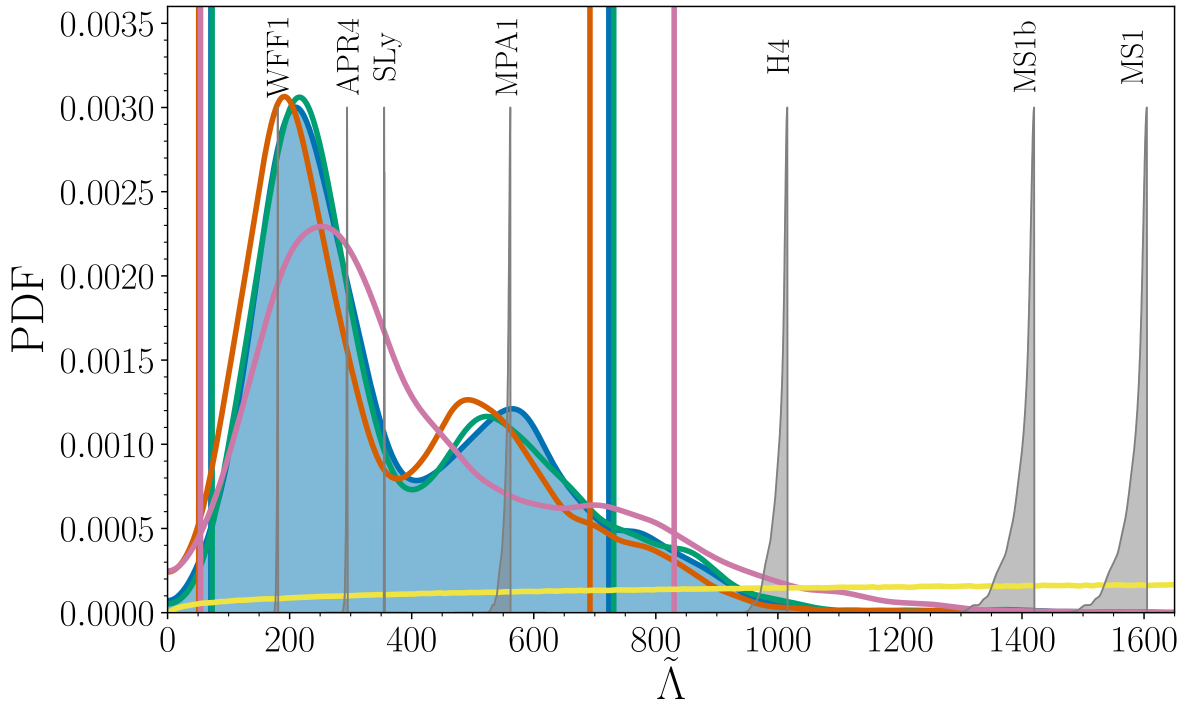
Tidal deformability

Ref: LIGO/Virgo 2017,2018



Masses of the binary components





GW170817: Constraints on binary parameters

Ref: LIGO/Virgo 2018

	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination $\theta_{\rm JN}$	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination $\theta_{\rm JN}$ using EM distance constraint [104]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001} {\rm M}_\odot$	$1.1976^{+0.0004}_{-0.0002} {\rm M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$	$1.186^{+0.001}_{-0.001} {\rm M}_\odot$
Primary mass m_1	$(1.36,\ 1.60)\ {\rm M}_\odot$	$(1.36,\ 1.89)\ {\rm M}_\odot$
Secondary mass m_2	$(1.16,\ 1.36)\ {\rm M}_\odot$	$(1.00,\ 1.36)\ {\rm M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01} {\rm M}_\odot$	$2.77^{+0.22}_{-0.05} {\rm M}_\odot$
Mass ratio q	$(0.73,\ 1.00)$	$(0.53,\ 1.00)$
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	$(0.00,\ 0.04)$	$(0.00,\ 0.50)$
Secondary dimensionless spin χ_2	$(0.00,\ 0.04)$	$(0.00,\ 0.61)$
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/ 300^{+420}_{-230}(HPD)	$(0, 630)$

- Chirp mass gives rigid lower limit to the total mass

$$m = \mathcal{M}_{\rm chirp}\eta^{-3/5} \geq 2.72\,M_\odot$$

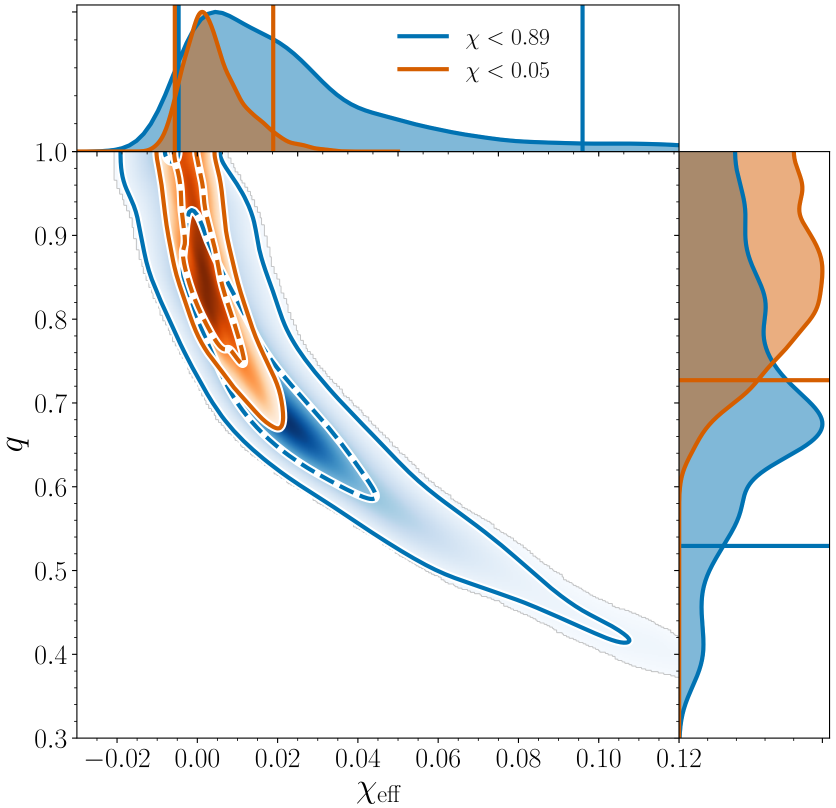
- Tidal deformability: $\tilde{\Lambda} < 800\,(90\%)$

or

$$\Lambda_{1.4} < 800\,(90\%)$$

※ $\tilde{\Lambda}$ depends only weakly on the mass ratio for fixed chirp mass

Mass ratio-spin degeneracy



GW170817: Electromagnetic Counterparts

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

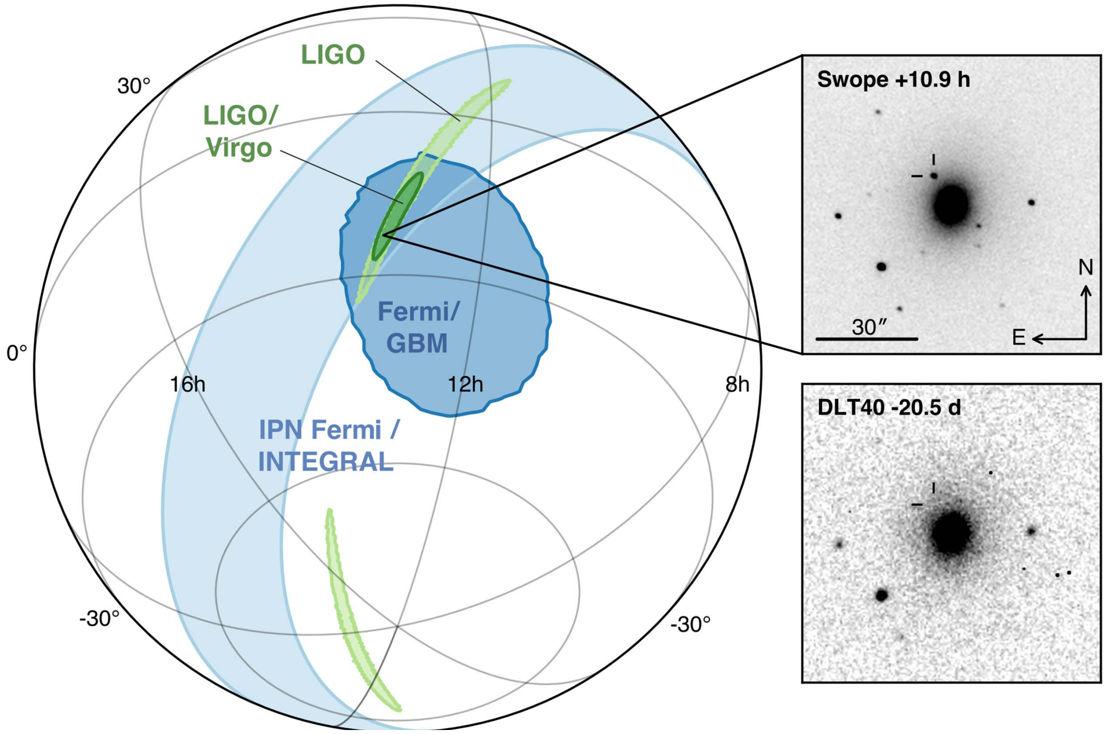
- The follow-up observation of the electromagnetic counterparts allowed us to identify the host galaxy (NGC4993: ~40 Mpc)

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

  (property of merger remnant,

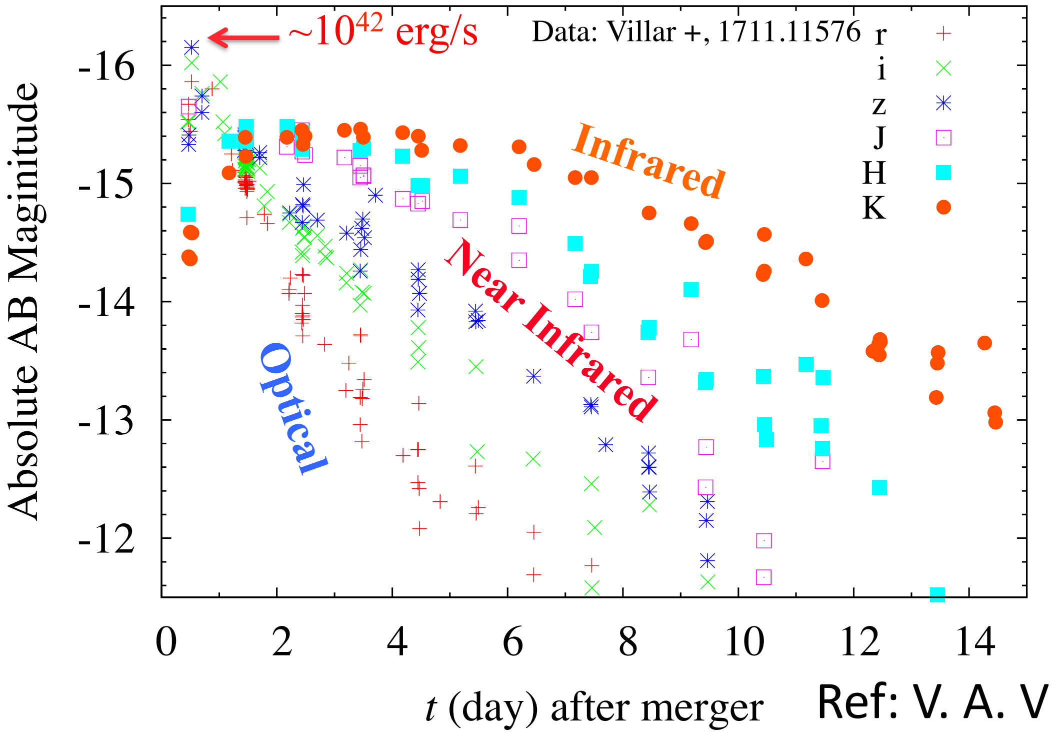
  r-process nucleosynthesis,

  existence of relativistic jets,...)



Ref: P. S. Cowperthwaite 2017

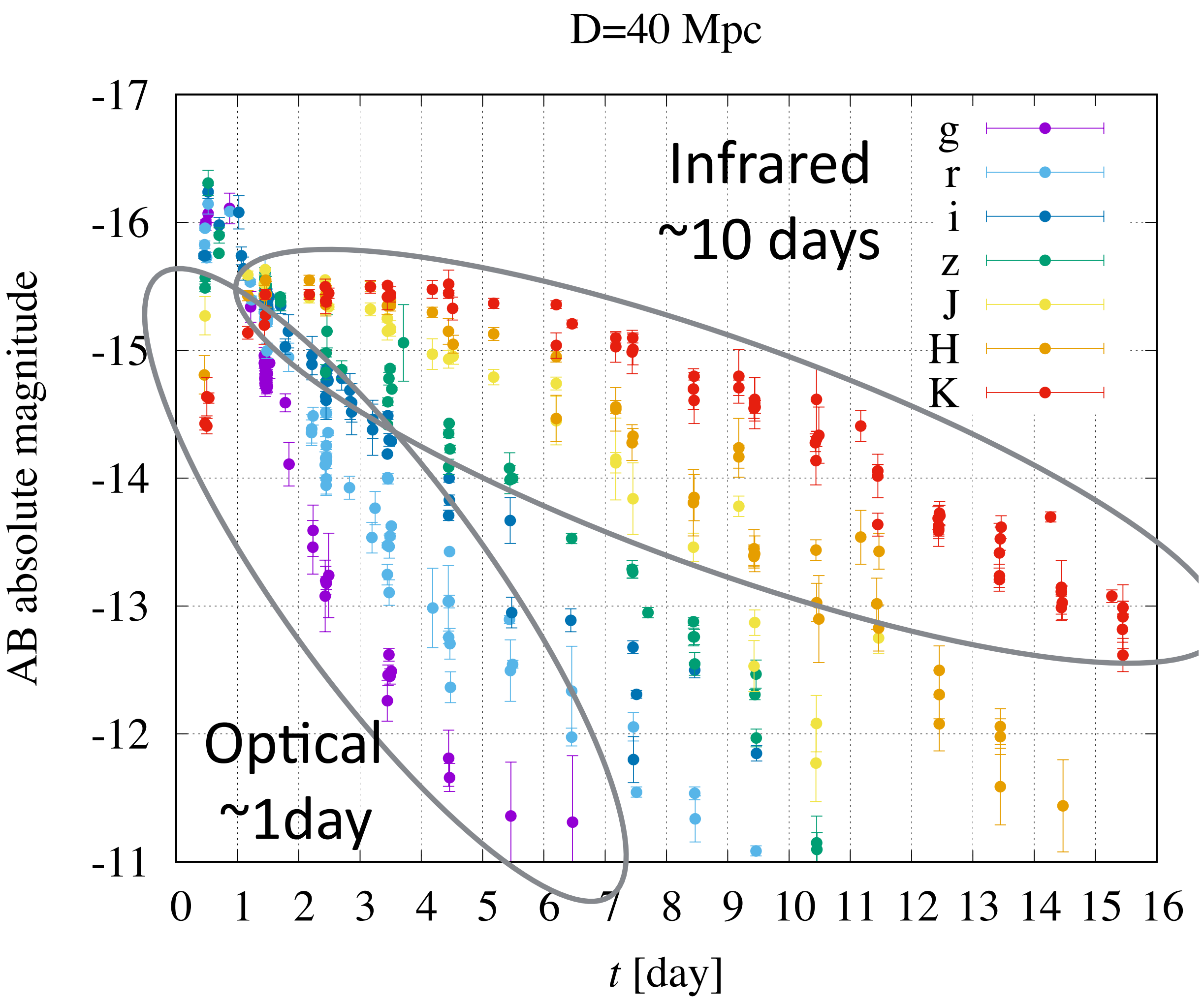
Optical-IR EM counterparts of GW170817



Ref: V. A. Villar 2017

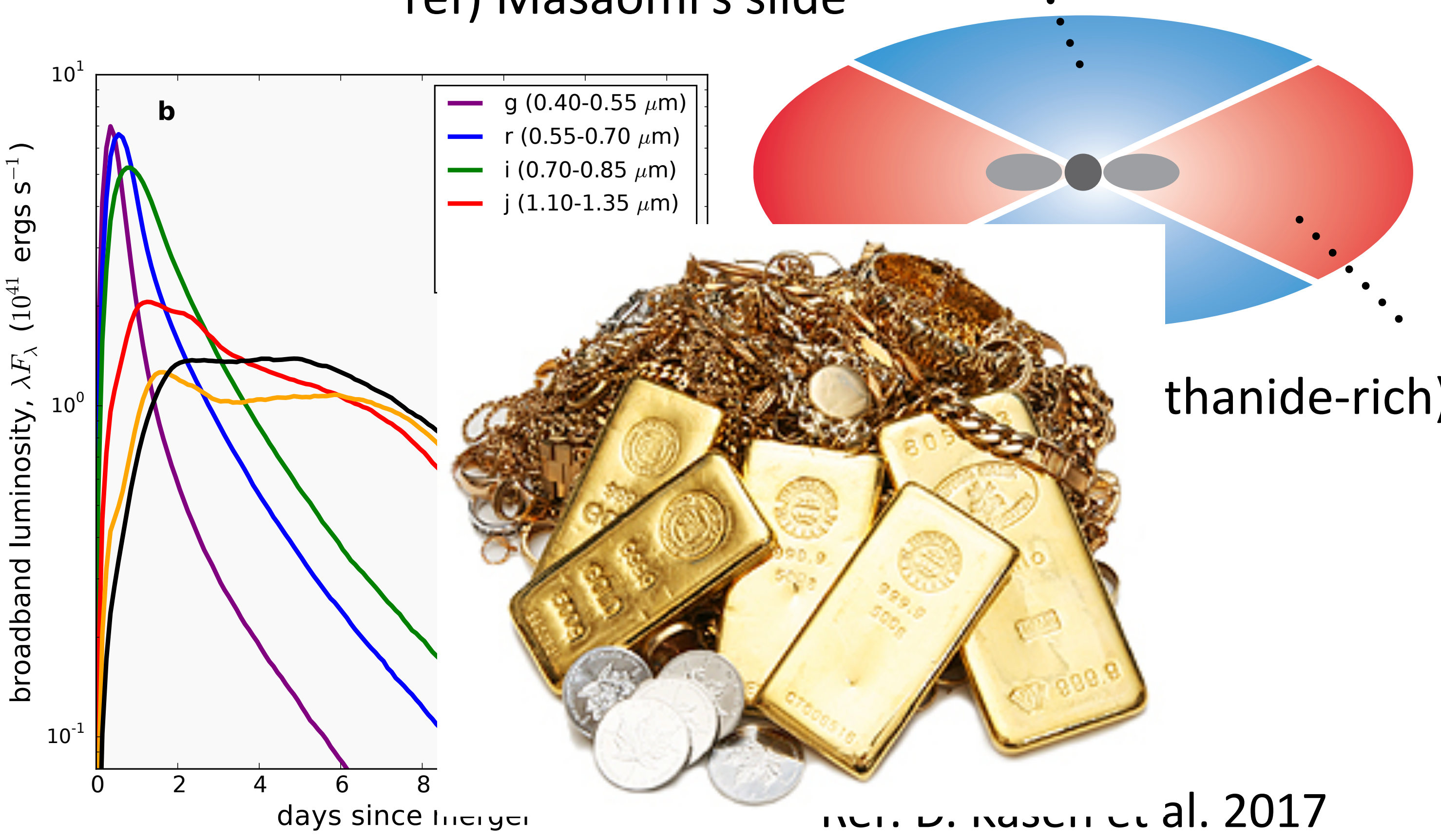
GW170817:
Kilonova/macronova with multiple components

Data: Summarized in Villar et al. 2017



ref) Masaomi’s slide

Blue (lanthanide-free)



thanide-rich

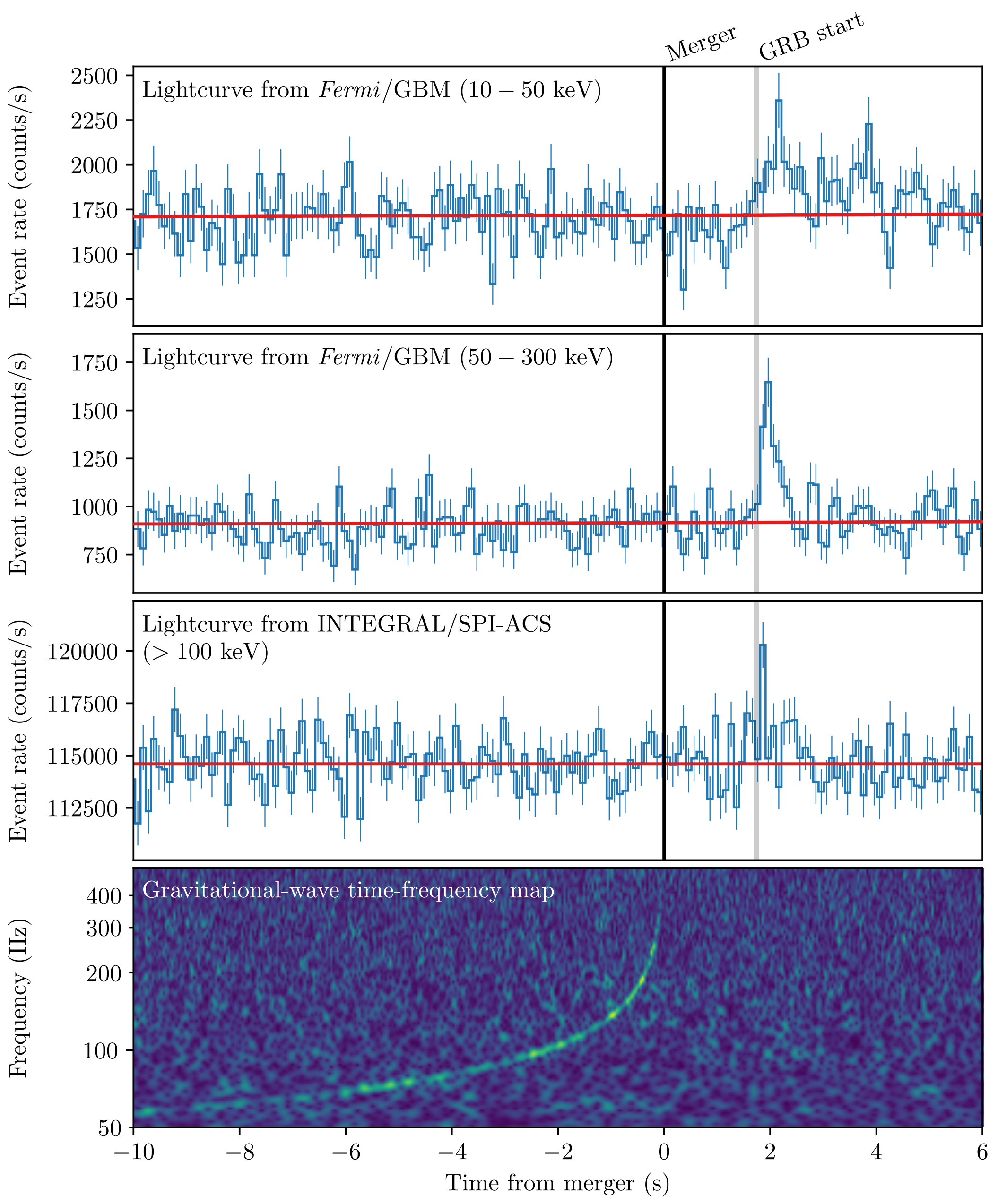
al. 2017

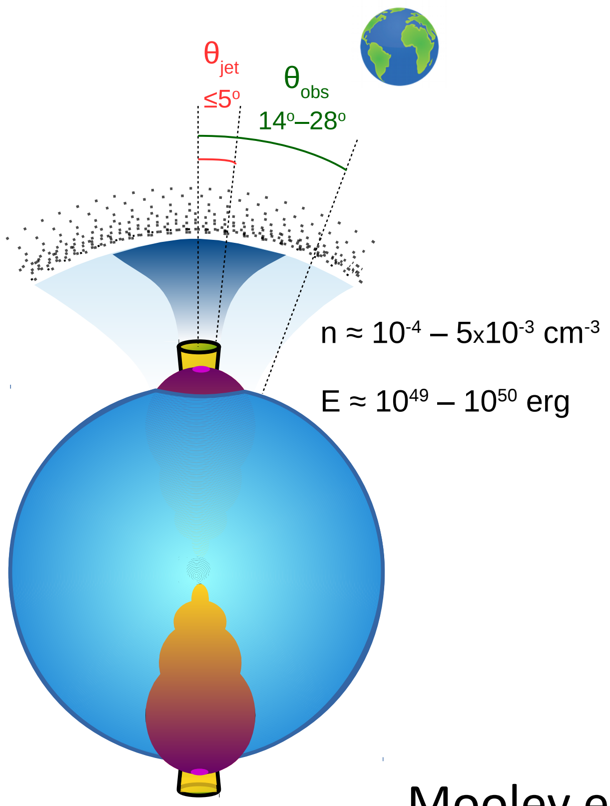
- **A Kilonova/macronova** model with multiple components well interprets the optical-Infrared observation (see e.g., Kasliwal et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017)
  - early-blue component (~1day) from **lanthanide-free ejecta (~0.01 M_sun, opacity ~0.1-1 cm^2/g)** + long-lasting red component (~10days) from **lanthanide-rich ejecta (~0.04 M_sun, opacity ~10 cm^2/g)**

※radiation transfer effect among the multiple ejecta components would change the ejecta mass estimation

Gamma ray burst?

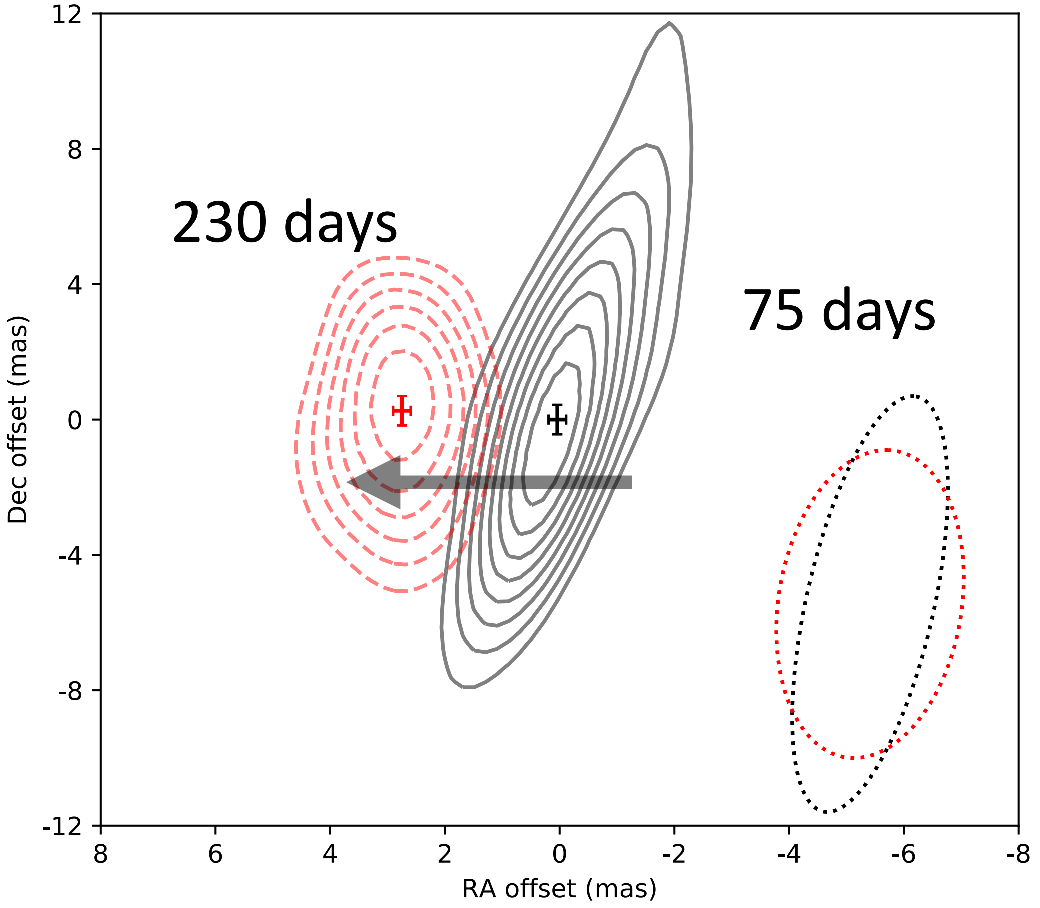
Ref: LIGO/Virgo/Fermi/INTEGRAL 2017





Mooley et al. 2018

Radio observation (VLBI)



- Gamma ray signal was detected 1.7s after the GW trigger …however, not typical short hard GRB?
- Superluminal motion of the radio counterpart → existence of a relativistic jet

Multi-messenger Astronomy

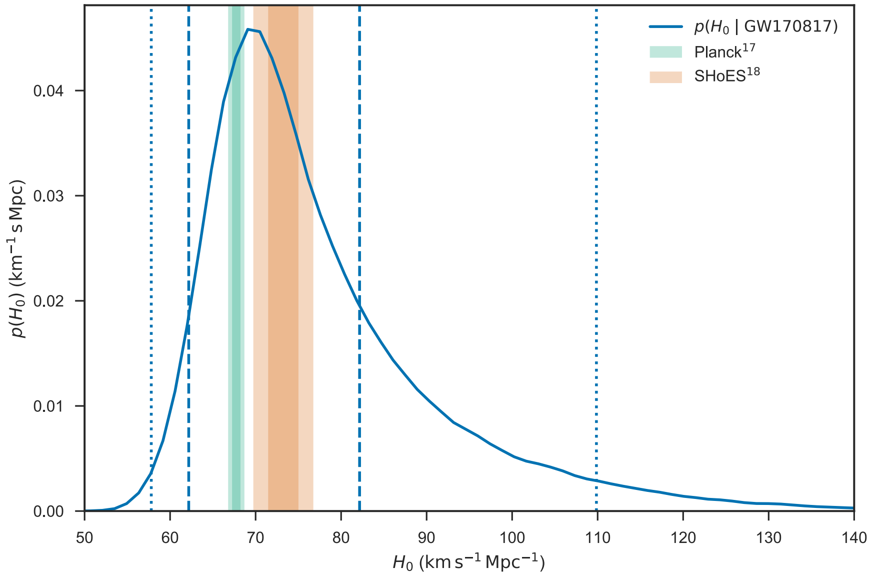
- The first opportunity of

  multi-messenger astronomy
  with the combination GW and EM observation

  - Host galaxy + GW luminosity distance
    → Hubble parameter

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

  - Tidal deformability + EM Constraint
    → Tighter limit on the NS property
    (e.g. Radice & Dai 2018, Kiuchi et al. 2019)

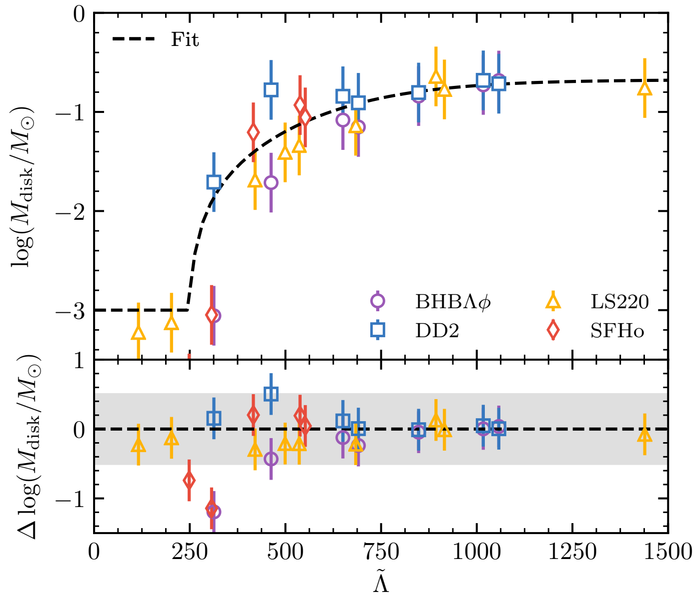


Ref: LIGO/Virgo 2017

$$-3\times10^{-15} \le \frac{\Delta v}{v_{\mathrm{EM}}} \le +7\times10^{-16}$$

$$\Delta v = v_{\mathrm{GW}} - v_{\mathrm{EM}}$$

Ref: LIGO/Virgo/Fermi/INTEGRAL 2017



Ref: Radice & Dai 2018

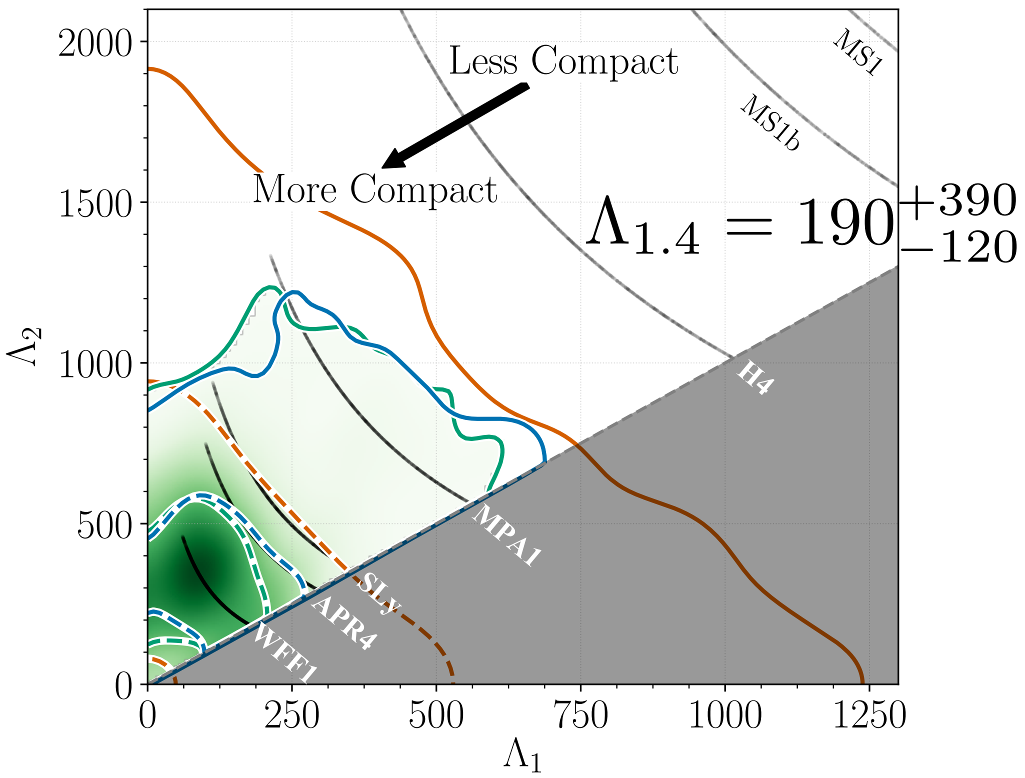
GW170817:Further constraints on Λ/Radius/Maximum mass

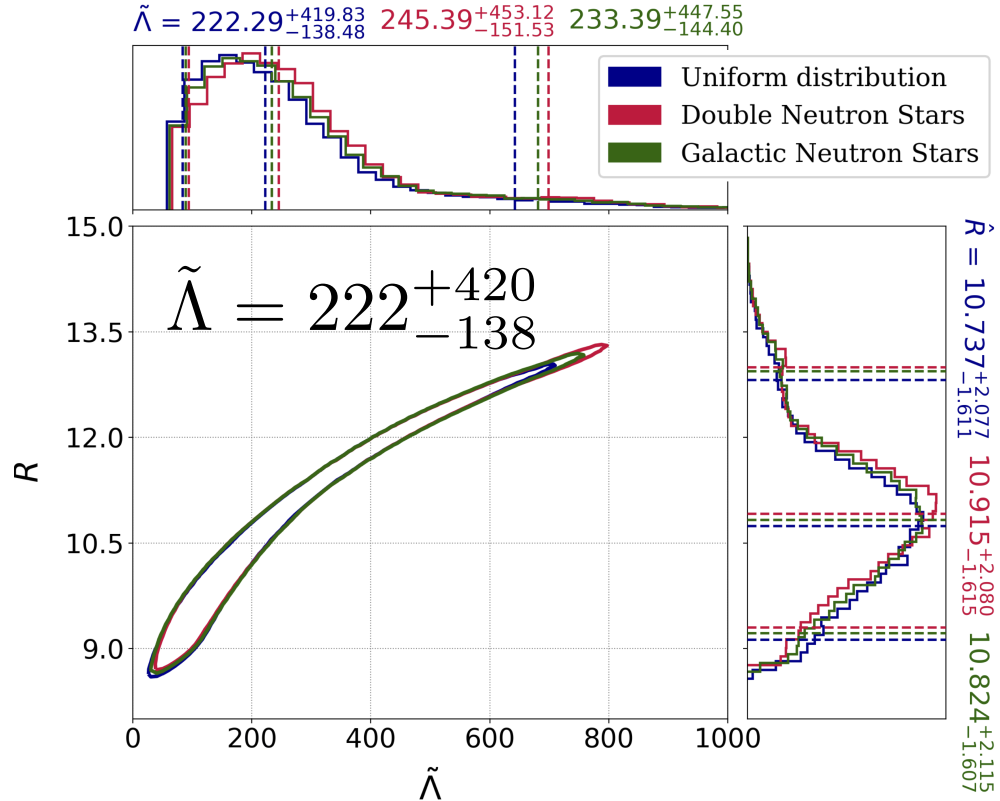
- Analysis of GW data with further assumptions
- Lower limit on the NS tidal deformability / radius
  based on EM observation
- Upper limit on the maximum mass
  based on EM observation

Analysis of GW data with further assumptions

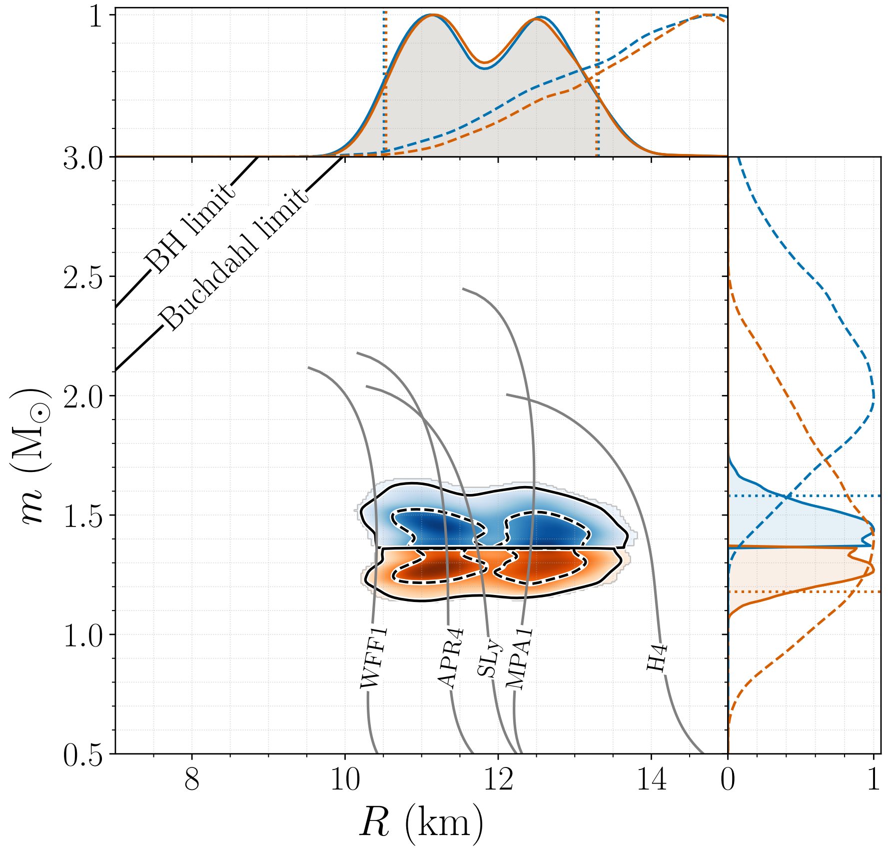
- Tighter constraints on the NS tidal deformability and radius are obtained by considering
  - the same NS EoS for two objects (c.f. twin stars)
  - current lower limit for the NS maximum mass (Mmax > 1.97 Msun : Antoniadis et al. 2013)

Ref: LIGO/Virgo 2018





Ref: De et al. 2018

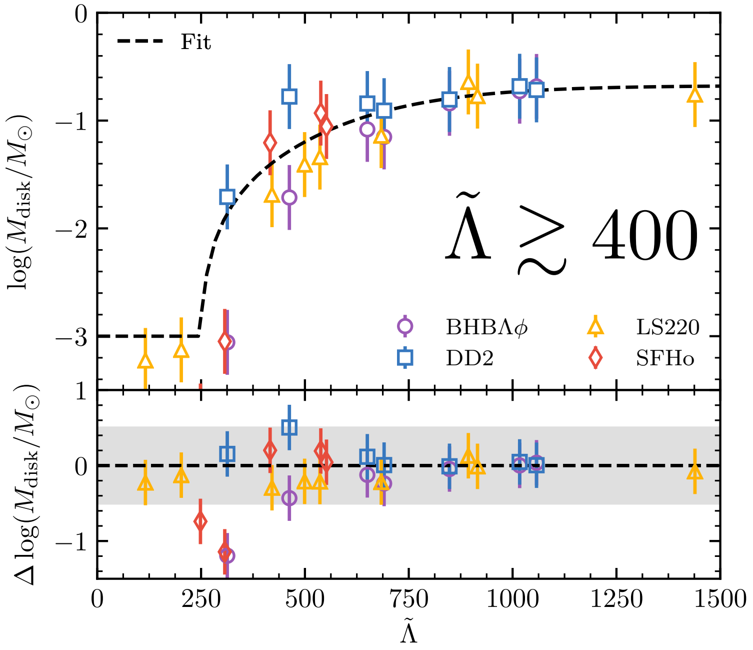


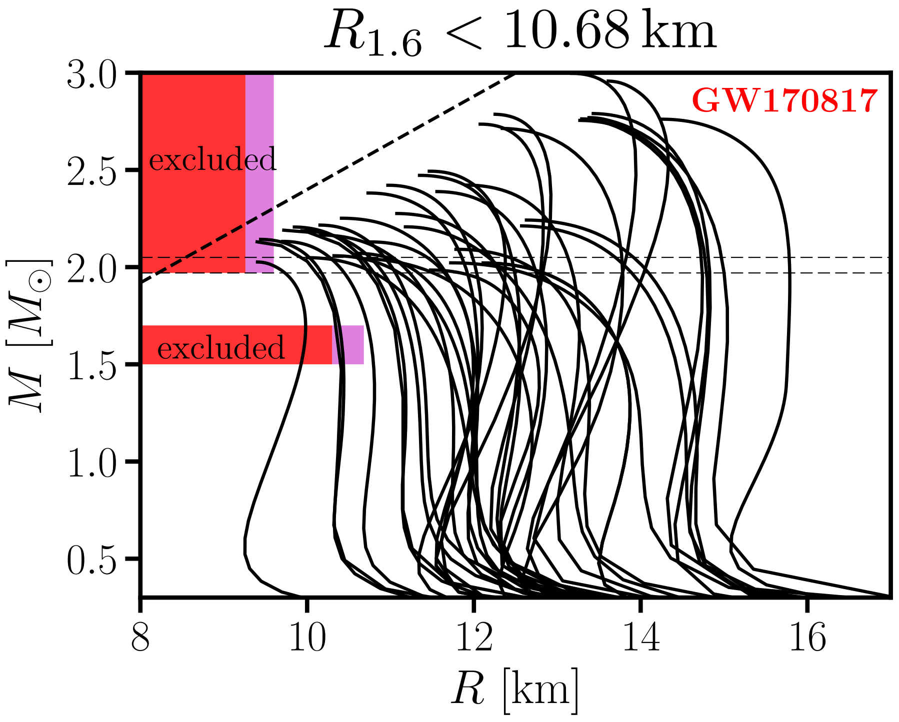
Lower limit on the NS tidal deformability / radius

- Constraints from the fact that EM counterparts are observed

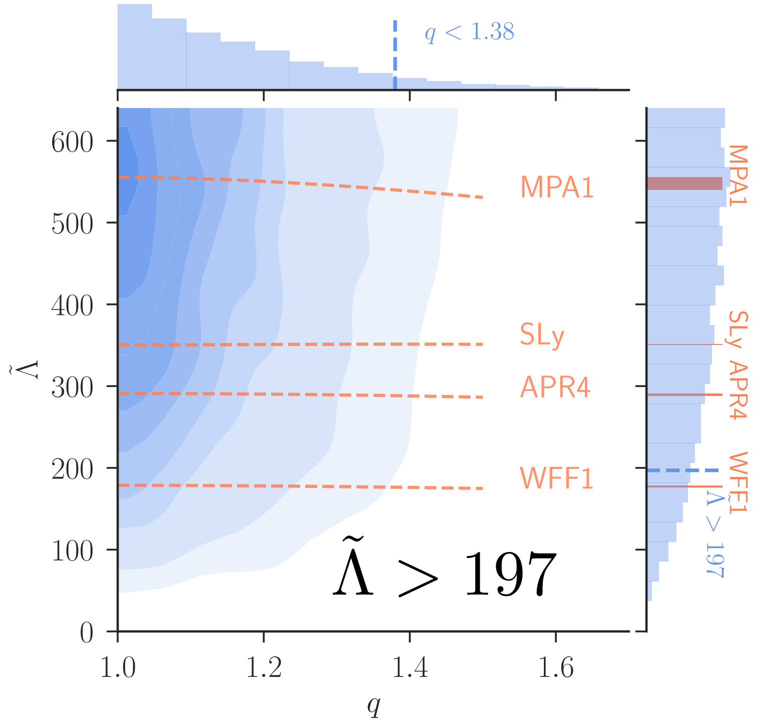
- Lower limit on the NS tidal deformability / radius based on the prediction of numerical relativity simulations

Ref: Radice & Dai 2018

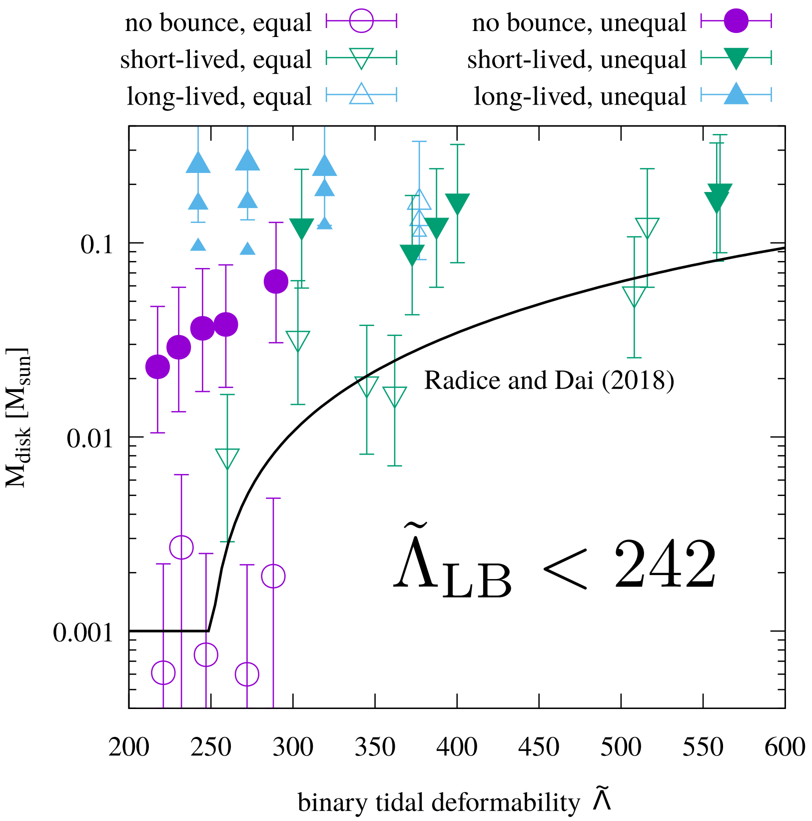




Ref: Bauswein et al. 2017



Ref: Coughlin et al. 2018



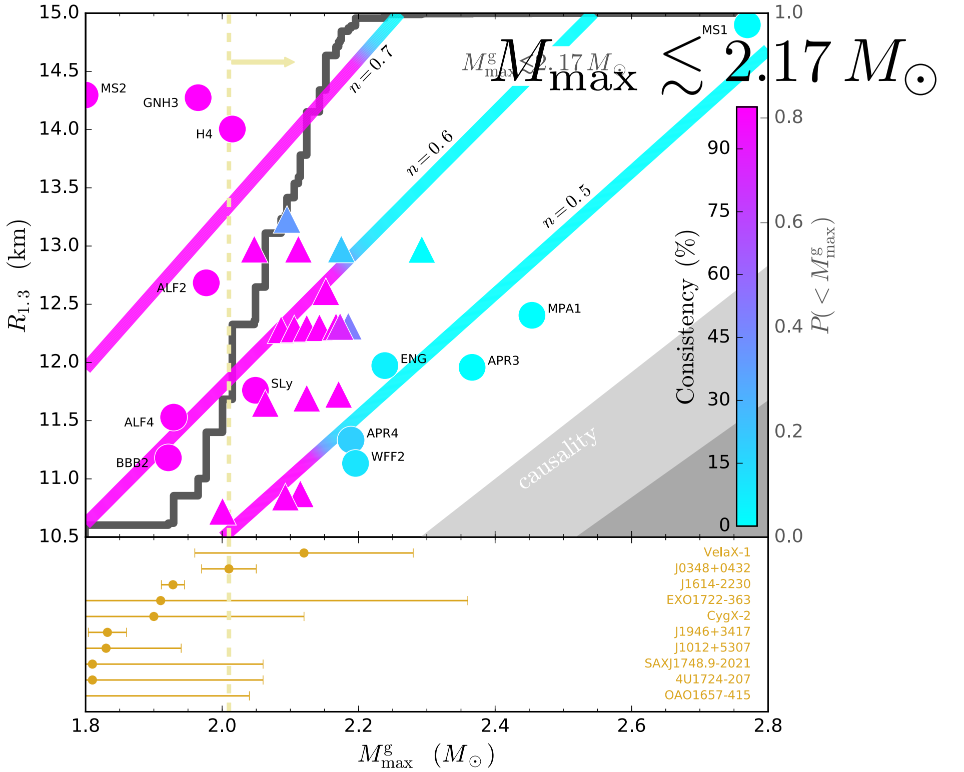
Ref: Kiuchi et al. 2019

Upper limit on the NS maximum mass

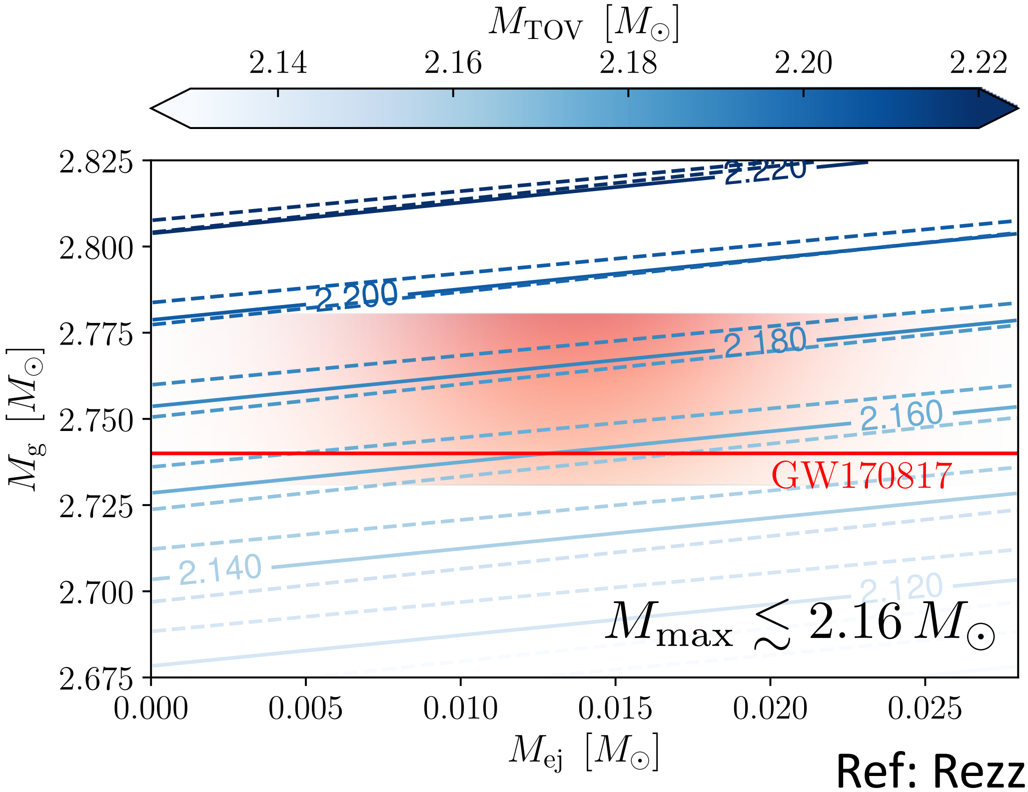
- Upper limit on the NS maximum mass from the fact that the remnant NS is likely to be temporarily survived and collapsed eventually to a BH
  - Presence of EM counterparts
  - No observation of magnetor-like activity
  - GRB association

$$M_{\rm max,rot} \approx 1.2 M_{\rm max}$$

Ref: Margalit & Metzger 2017

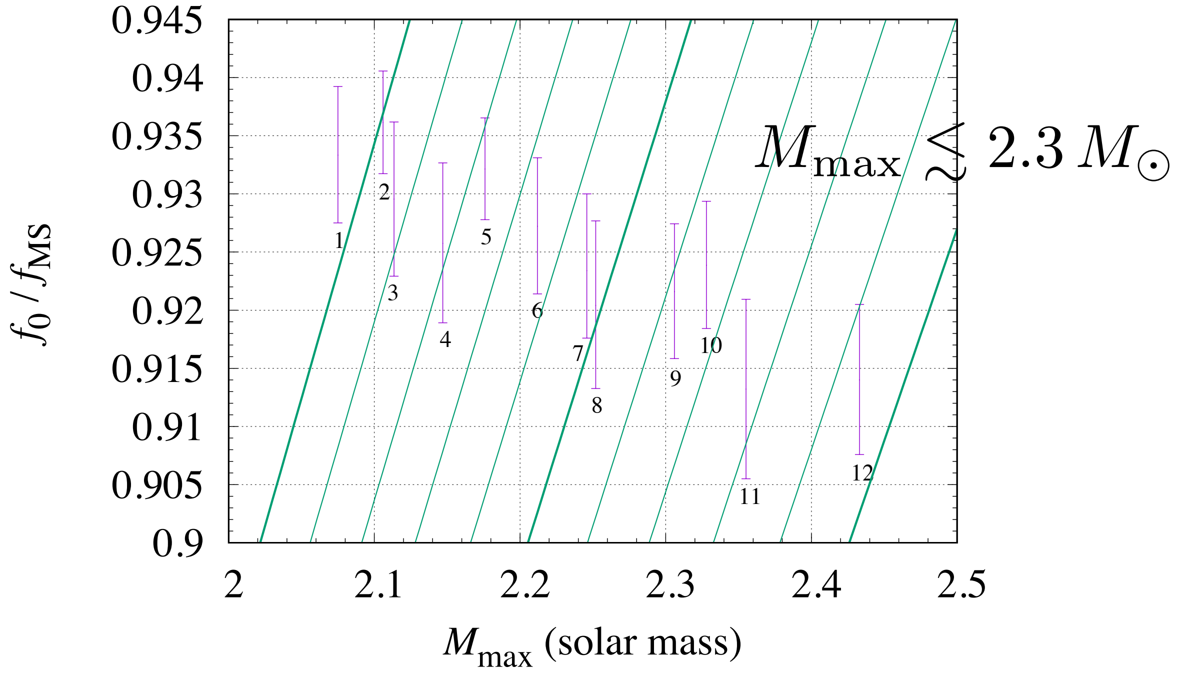


$M_{\rm max} \lesssim 2.17\, M_\odot$



$M_{\rm max} \lesssim 2.16\, M_\odot$

Ref: Rezzolla et al. 2018



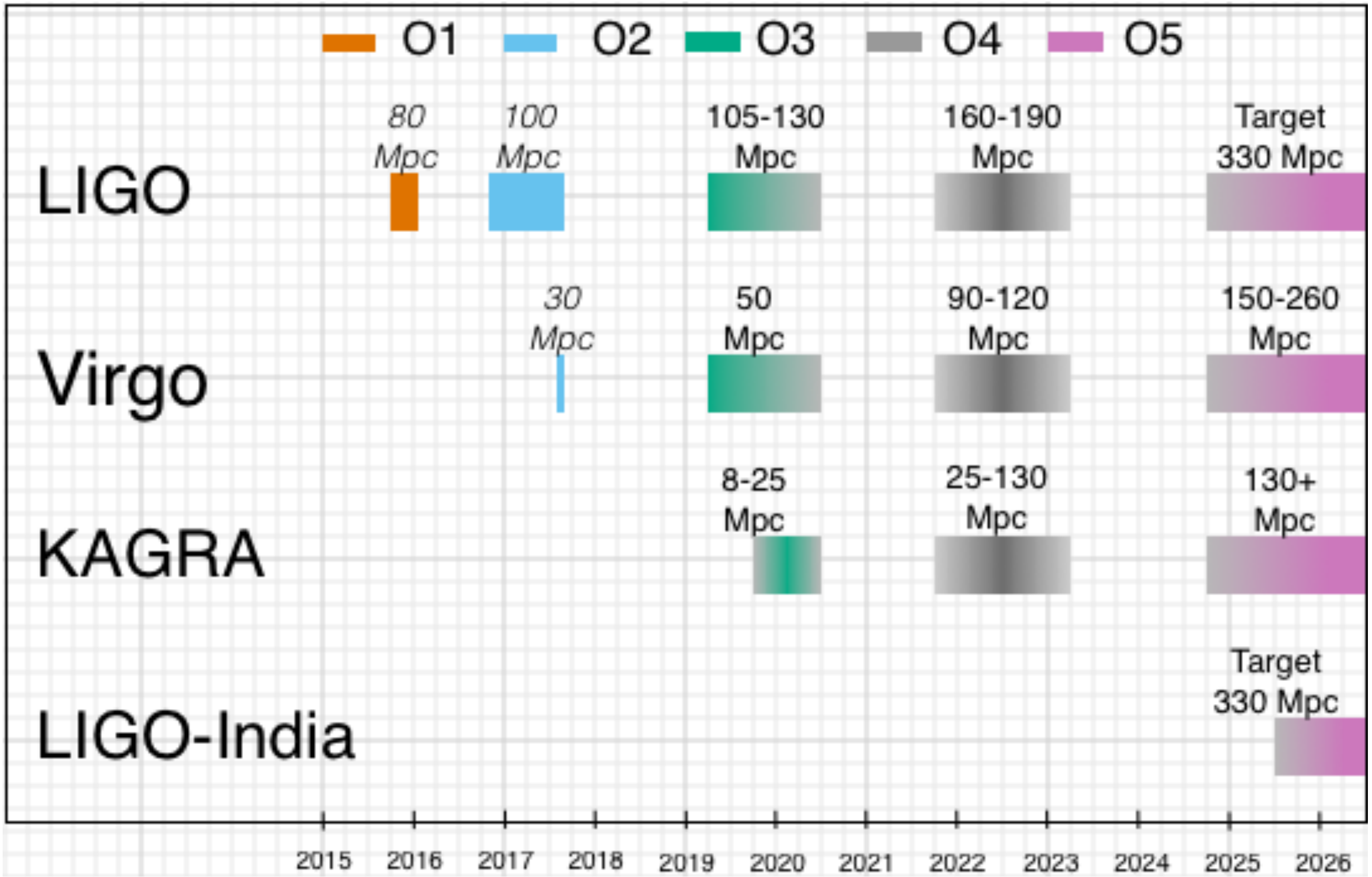
$M_{\rm max} \lesssim 2.3\, M_\odot$

Ref: Shibata et al. 2019

O3 observation

Third observing run (O3)

Ref: https://www.ligo.org/scientists/GWEMalerts.php

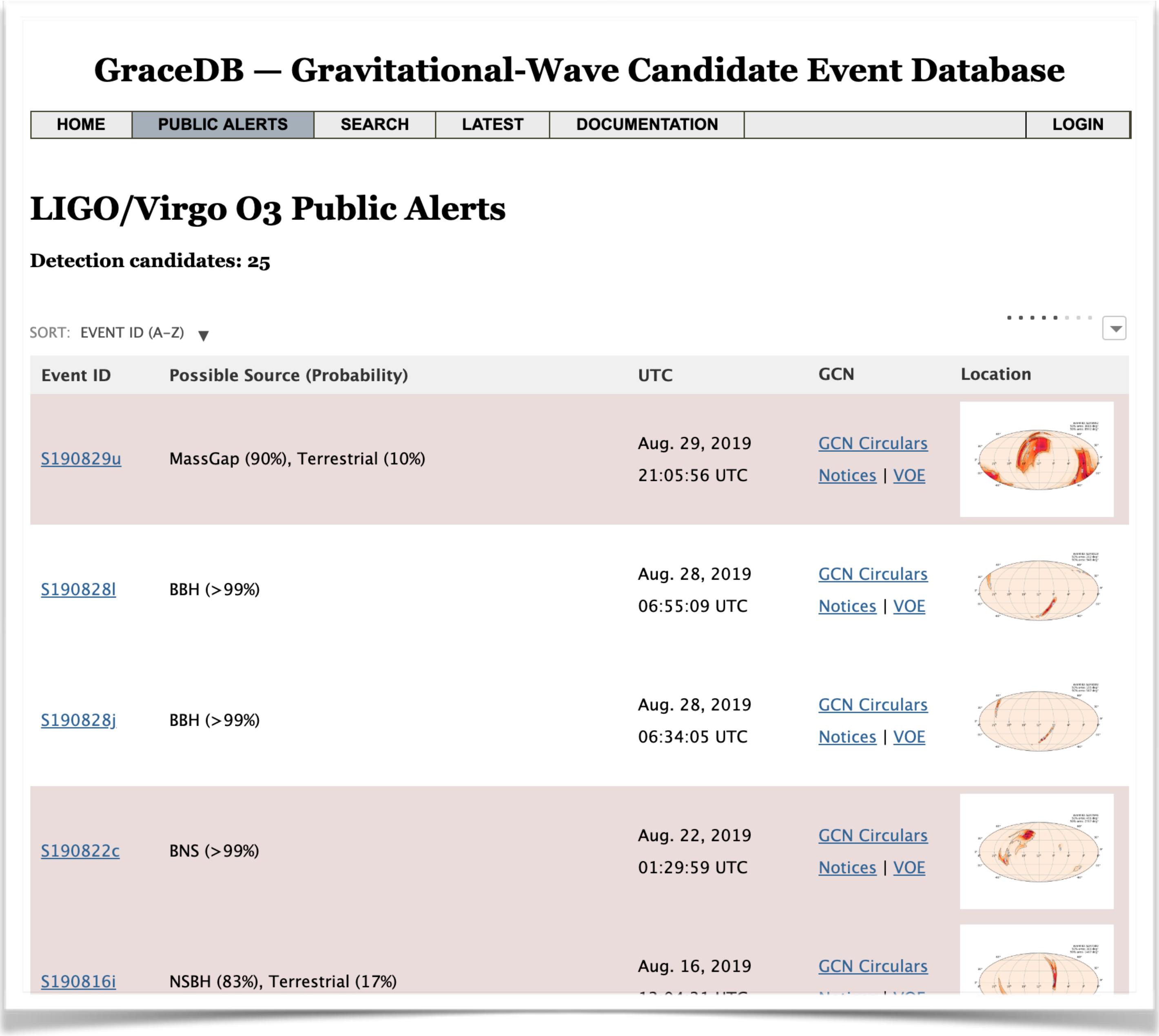


- The third observing run has been started from this April.

O3 detection candidates

https://gracedb.ligo.org/superevents/public/O3/

- BH-BH: 20 (21) candidates
  - S190828l, S190828j, S190728q, S190727h, S190720a, S190707q, S190706ai, S190701ah, S190630ag, S190602aq, S190521r, S190521g, S190519bj, S190517h, S190513bm, S190512at, S190503bf, S190421ar, S190412m, S190408an
    (, S190426c)
- NS-NS: 1 (4) candidates
  - **S190425z** (, S190718y, S190510g, S190426c)
- BH-NS: 1 (3) candidates
  - **S190814bv** (, S190901ap, S190426c)



GraceDB — Gravitational-Wave Candidate Event Database

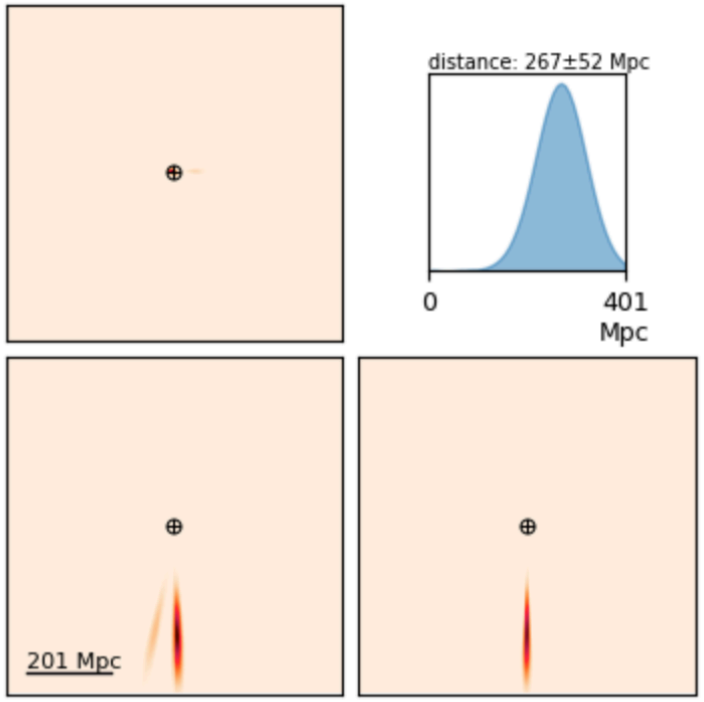
LIGO/Virgo O3 Public Alerts

Detection candidates: 25

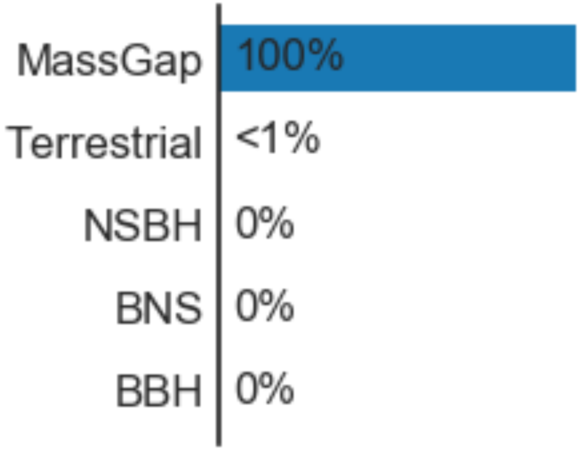
Event ID	Possible Source (Probability)	UTC	GCN	Location
S190829u	MassGap (90%), Terrestrial (10%)	Aug. 29, 2019 21:05:56 UTC	GCN Circulars Notices | VOE	
S190828l	BBH (>99%)	Aug. 28, 2019 06:55:09 UTC	GCN Circulars Notices | VOE	
S190828j	BBH (>99%)	Aug. 28, 2019 06:34:05 UTC	GCN Circulars Notices | VOE	
S190822c	BNS (>99%)	Aug. 22, 2019 01:29:59 UTC	GCN Circulars Notices | VOE	
S190816i	NSBH (83%), Terrestrial (17%)	Aug. 16, 2019	GCN Circulars	

BH-NS candidate: S190814bv

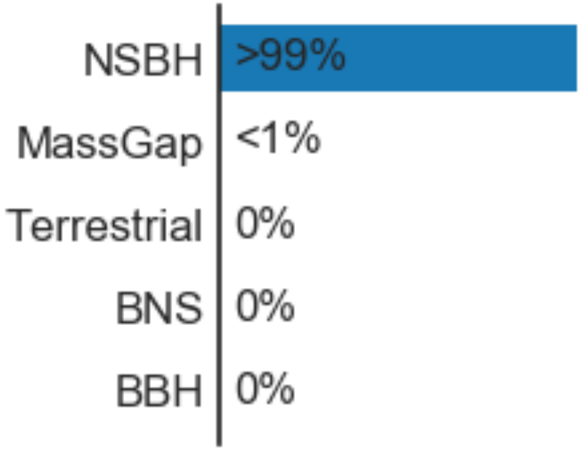
- Detection candidates of BH-NS merger has been reported at Aug. 14, 2019 21:10:39 UTC
- False alarm rate~1 per/ 10^{25} yrs.
- D~267±52 Mpc. (GW170817: ~40 Mpc)
- Sky localization: 23 deg^2 (90%)

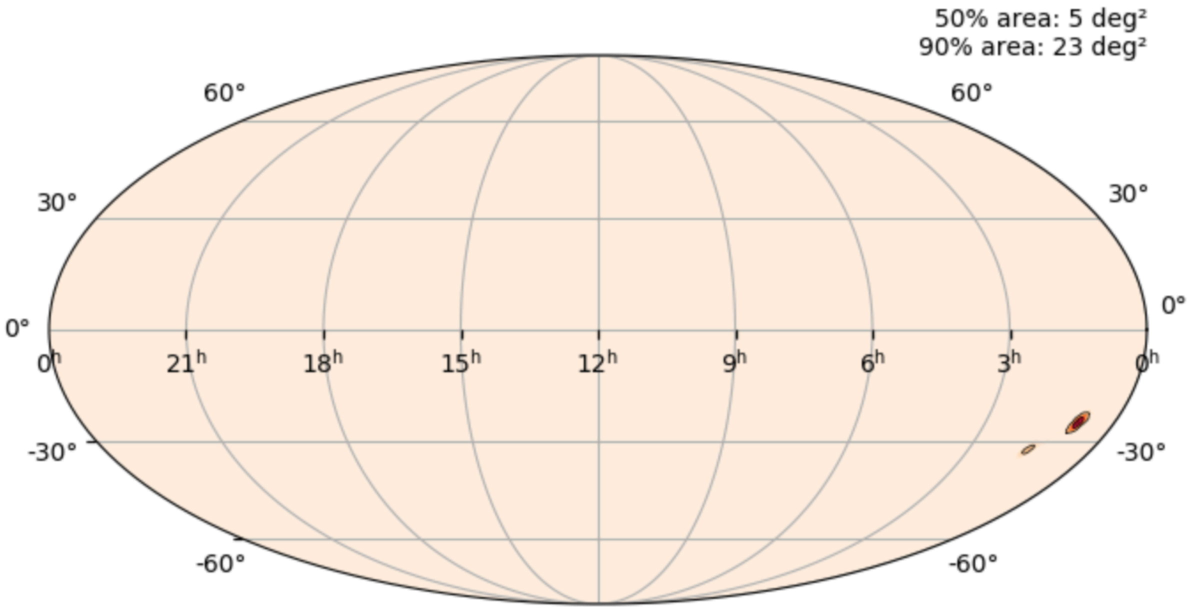


2019/8/14



2019/8/15

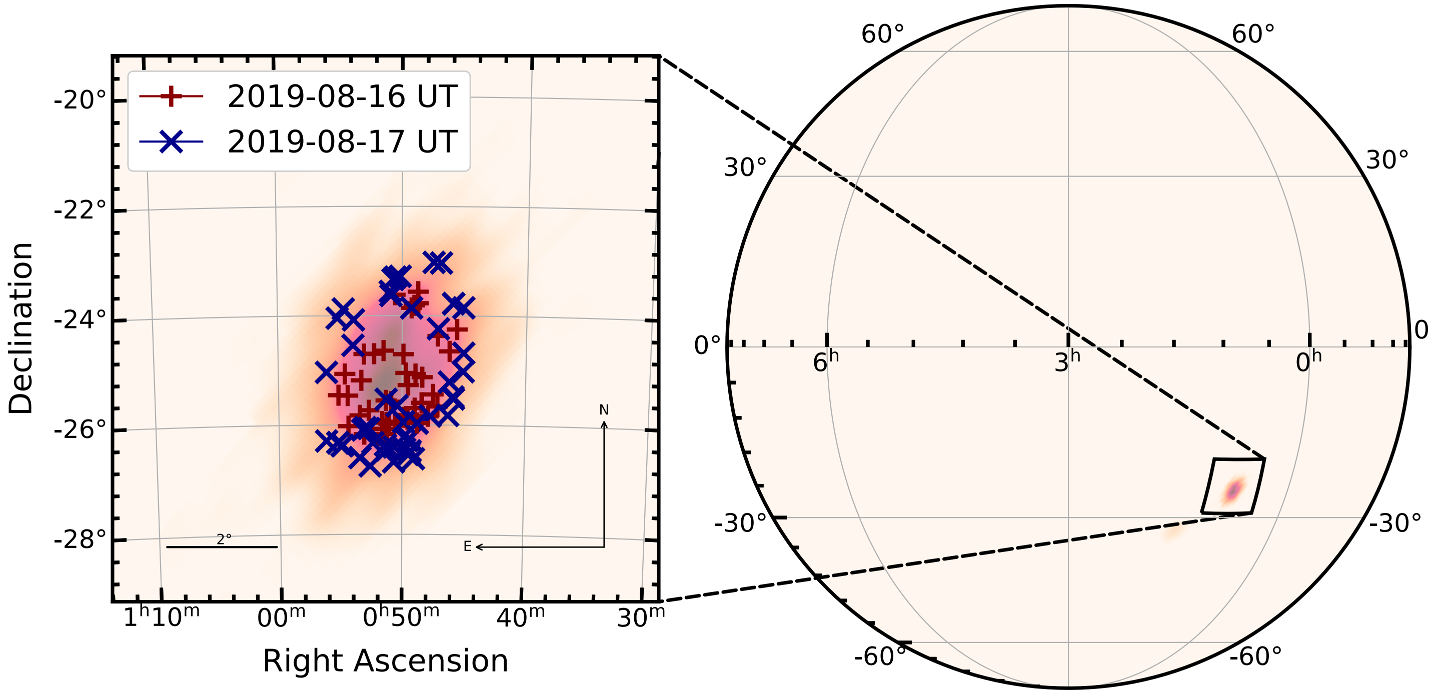


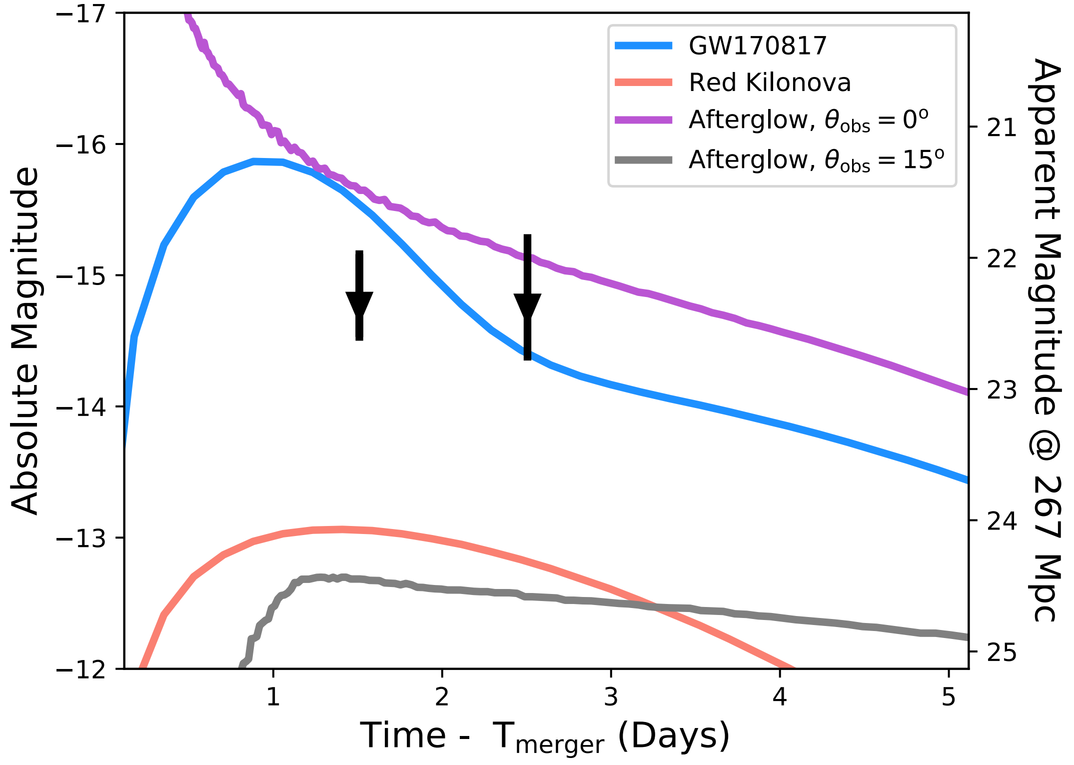


Mass gap: one of objects is 3 Msun < M < 5 Msun

NSBH: one of objects is M< 3 Msun and the another is M > 5 Msun

S190814bv: EM follow up



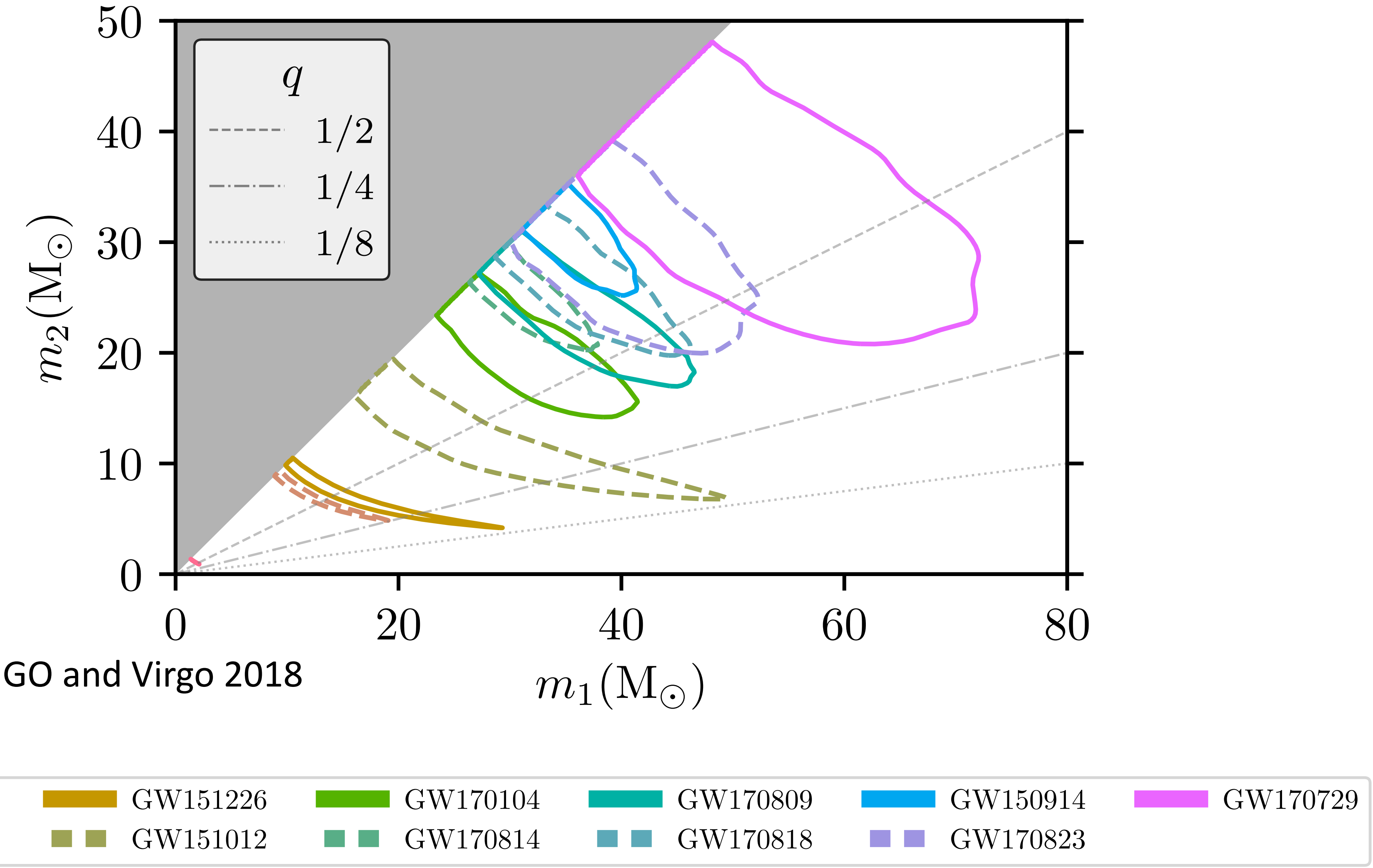


Gomez et al. 2019 (arXiv:1908.08913)

- No electromagnetic counterpart has been observed
- ~200 galaxies in 50% confident volume (1.8x10^{4} Mpc^{3})
- Optical counterparts similar to /brighter than GW170817 are not likely

S190814bv: Implication

Mass measurement for O2 events:

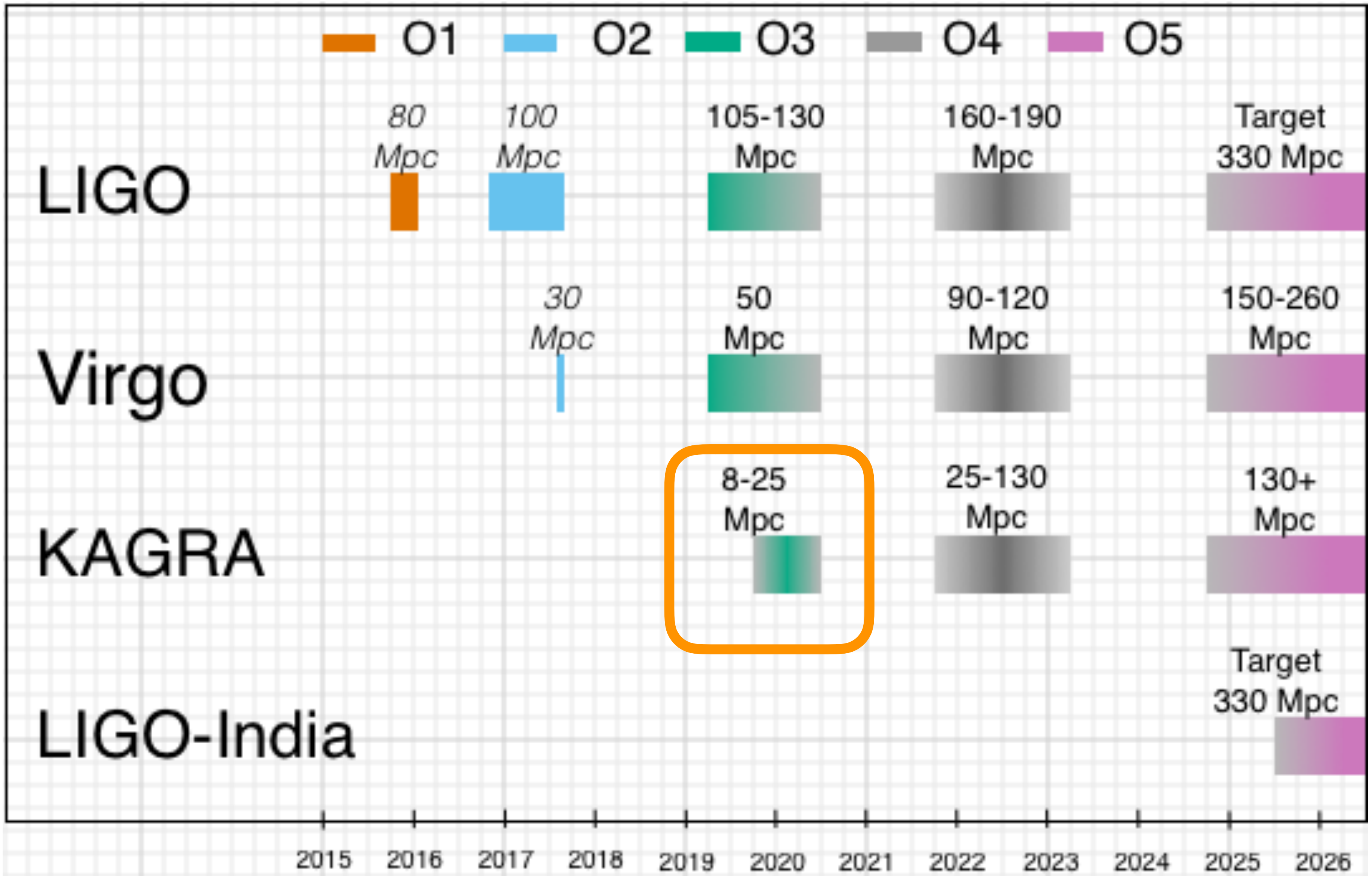


Ref) LIGO and Virgo 2018

- S190814bv could be the first event which does not support q~1

KAGRA joining O3

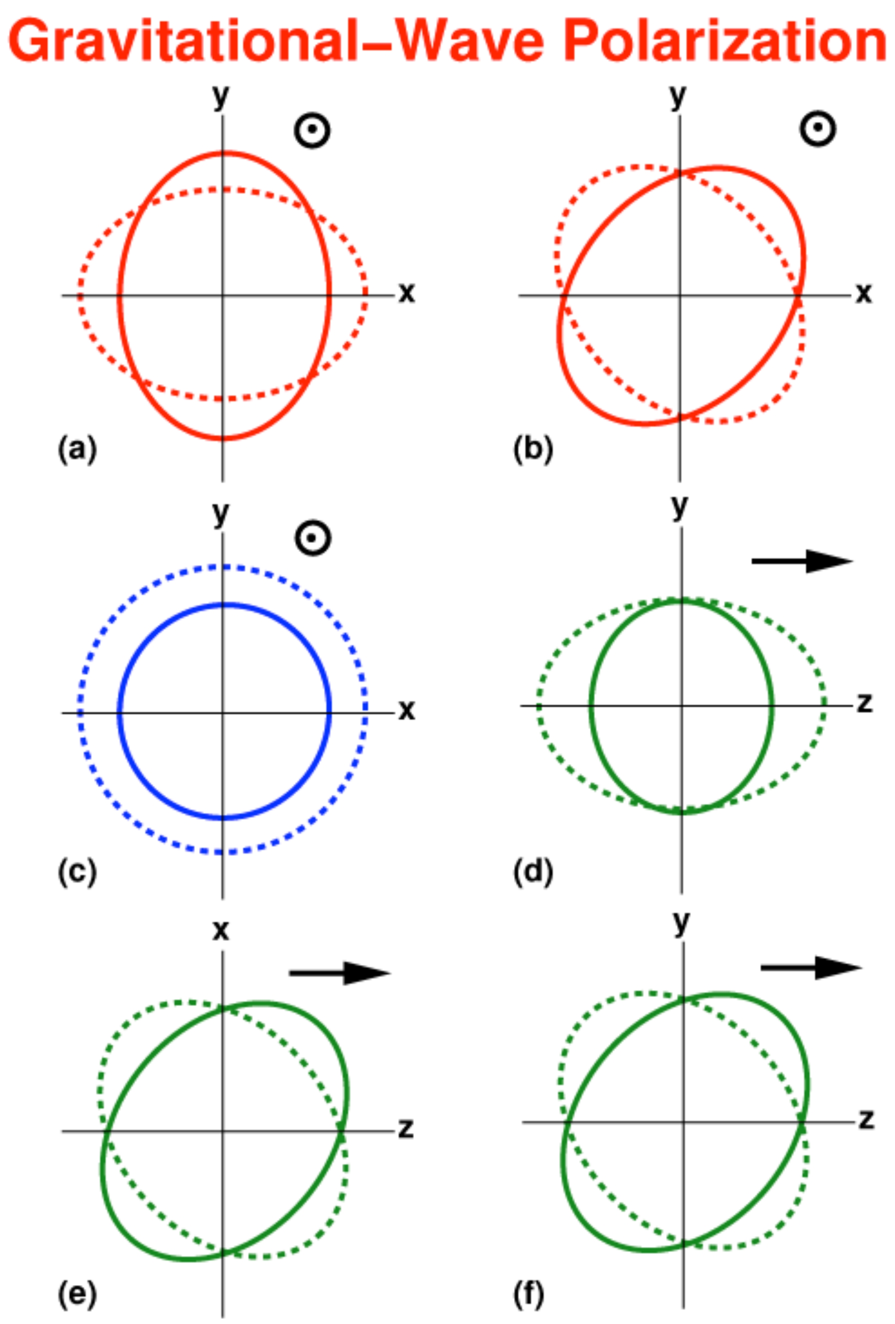
Ref: https://www.ligo.org/scientists/GWEMalerts.php



- KAGRA is planning to join O3 at the end of this year

Importance of KAGRA

- KAGRA joining to the detector network will contributes to the improvement of sky localization
- Enables to test the polarization modes of GW beyond GR (e.g., H. Takeda et al. 2018)



C. M. Will 2014

Improvement in sky localization for BNS
(assuming HL~K~I)

	HLV			HKLV			HIKLV		
SNR	0	0.05	0.4	0	0.05	0.4	0	0.05	0.4
12	74	80	80	30	34	34	12	13	12
14	43	56	58	21	21	22	9.3	8.1	9.0
16	37	35	45	15	13	15	6.1	5.8	5.9
20	22	24	24	8.0	7.8	8.3	3.1	3.8	3.9

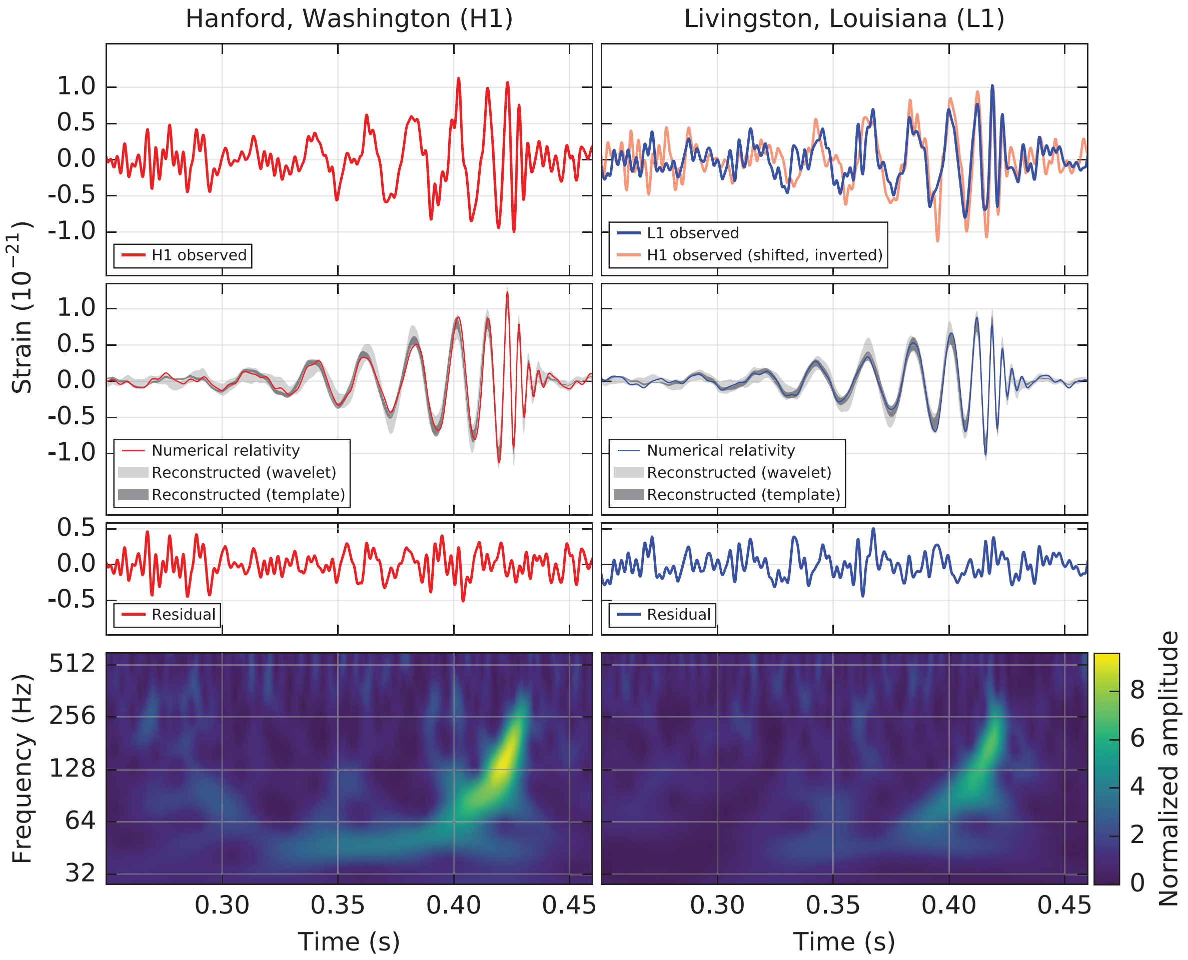
C. Pankow et al. 2018

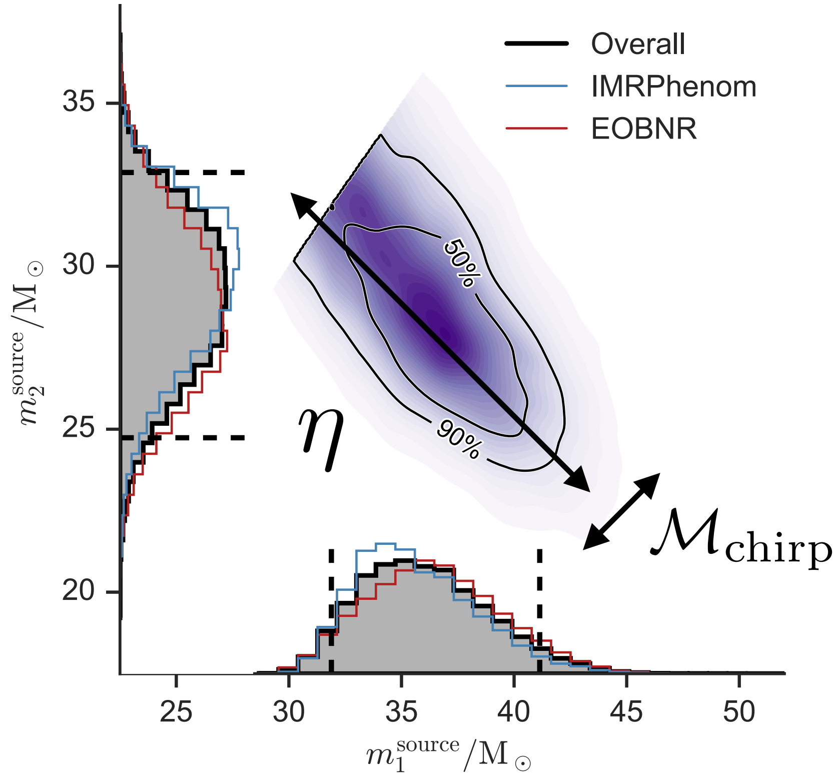
Summary

- Analytical/numerical studies for compact binary mergers have been enable us to achieve comprehensive understanding of observations.
- GW170817 achieved the measurement of the NS tidal deformability and confirmed that GW observation has a great impact on NS physics.
- The simultaneous observation of EM counterparts to GW170817 marked up the beginning of multi-messenger astronomy era.
- More and more GW events with more precise measurements of physical parameters would be achieved in the future.
- Further theoretical investigation is needed to maximize the scientific returns from the GW/EM events.

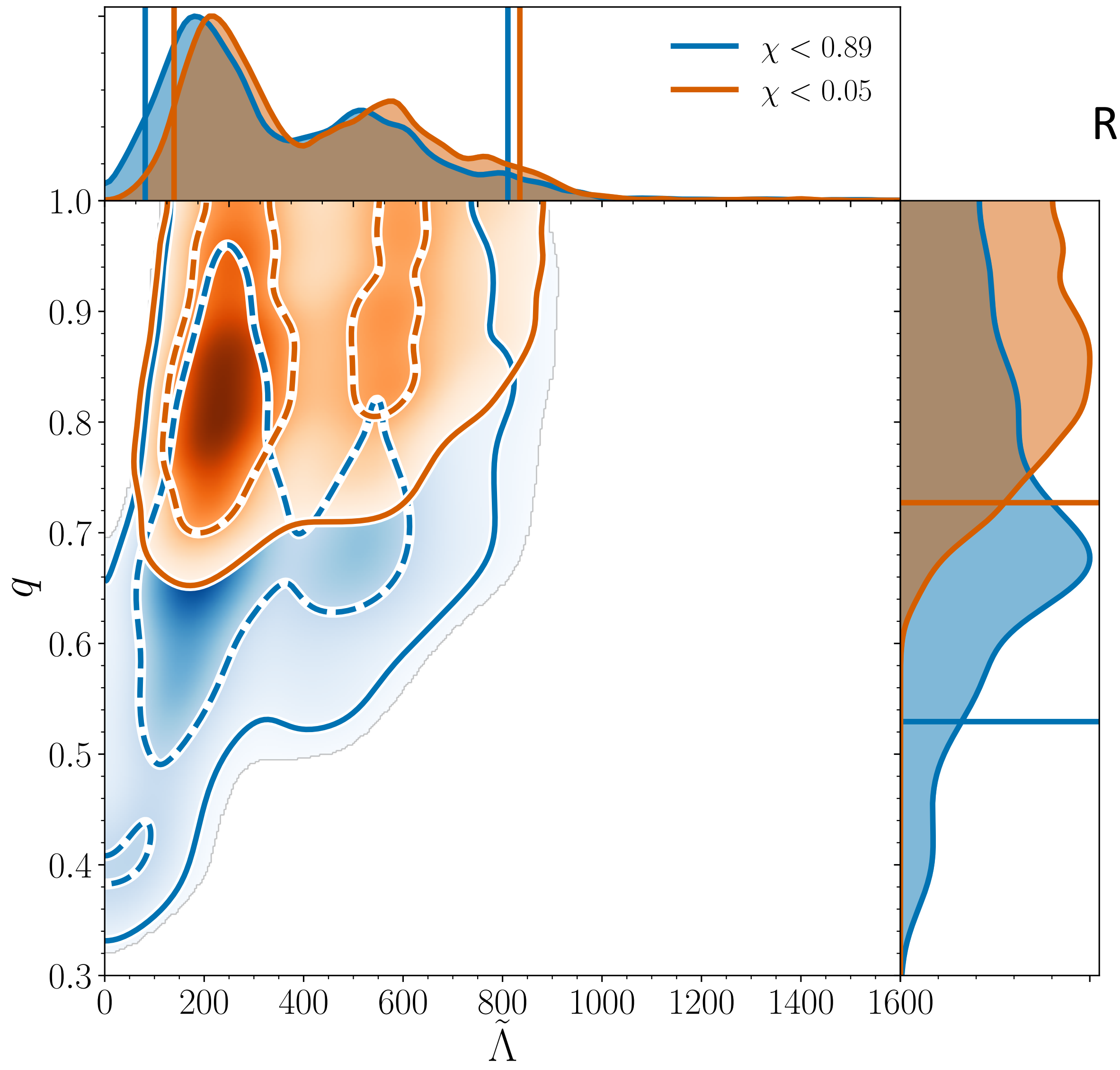
Appendix

First GW event: GW150914



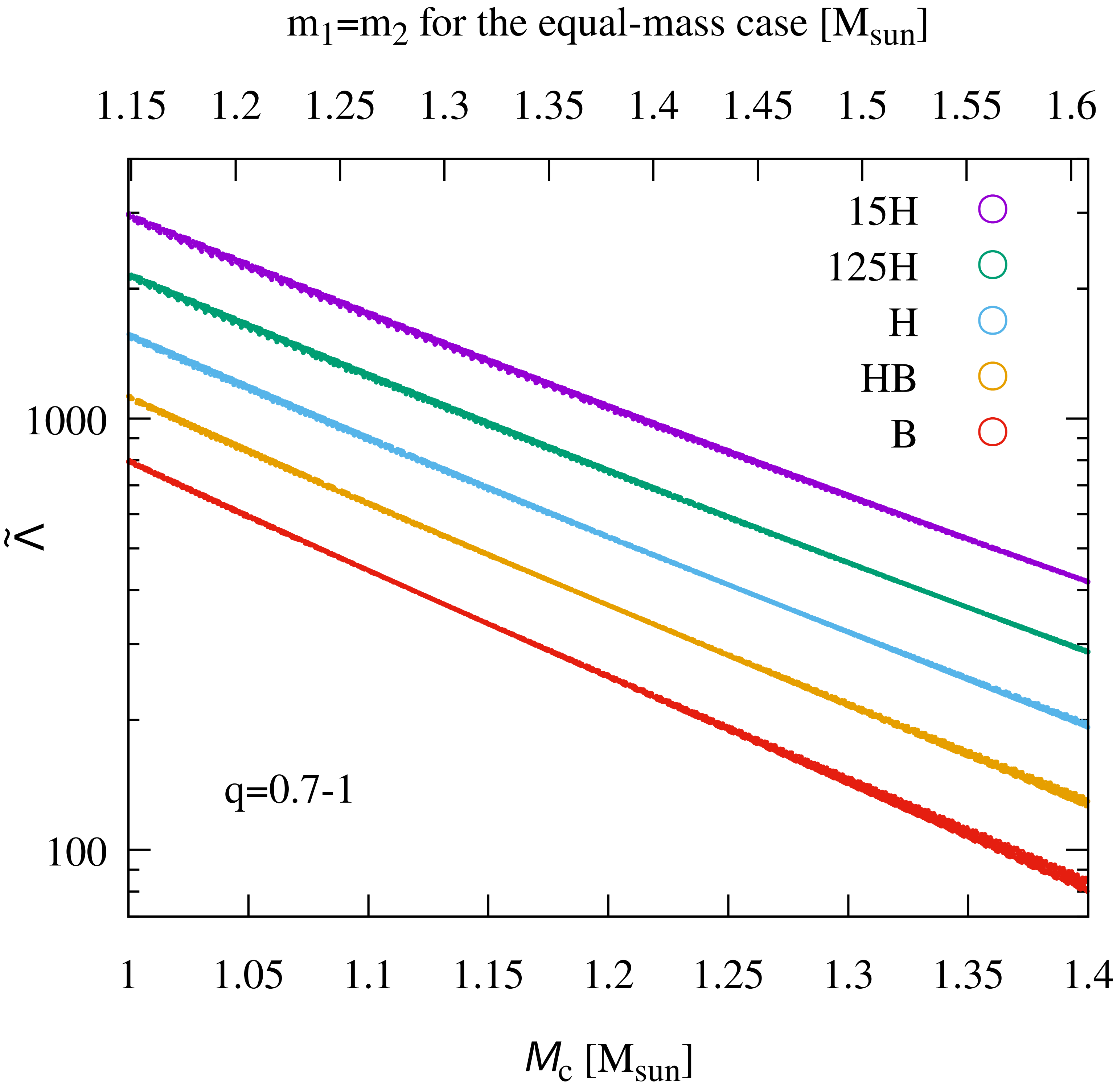


GW170817: upper limit to Λ



Ref: LIGO/Virgo 2017,2018

$\tilde{\Lambda} - \mathcal{M}_{\rm chirp}$ relation

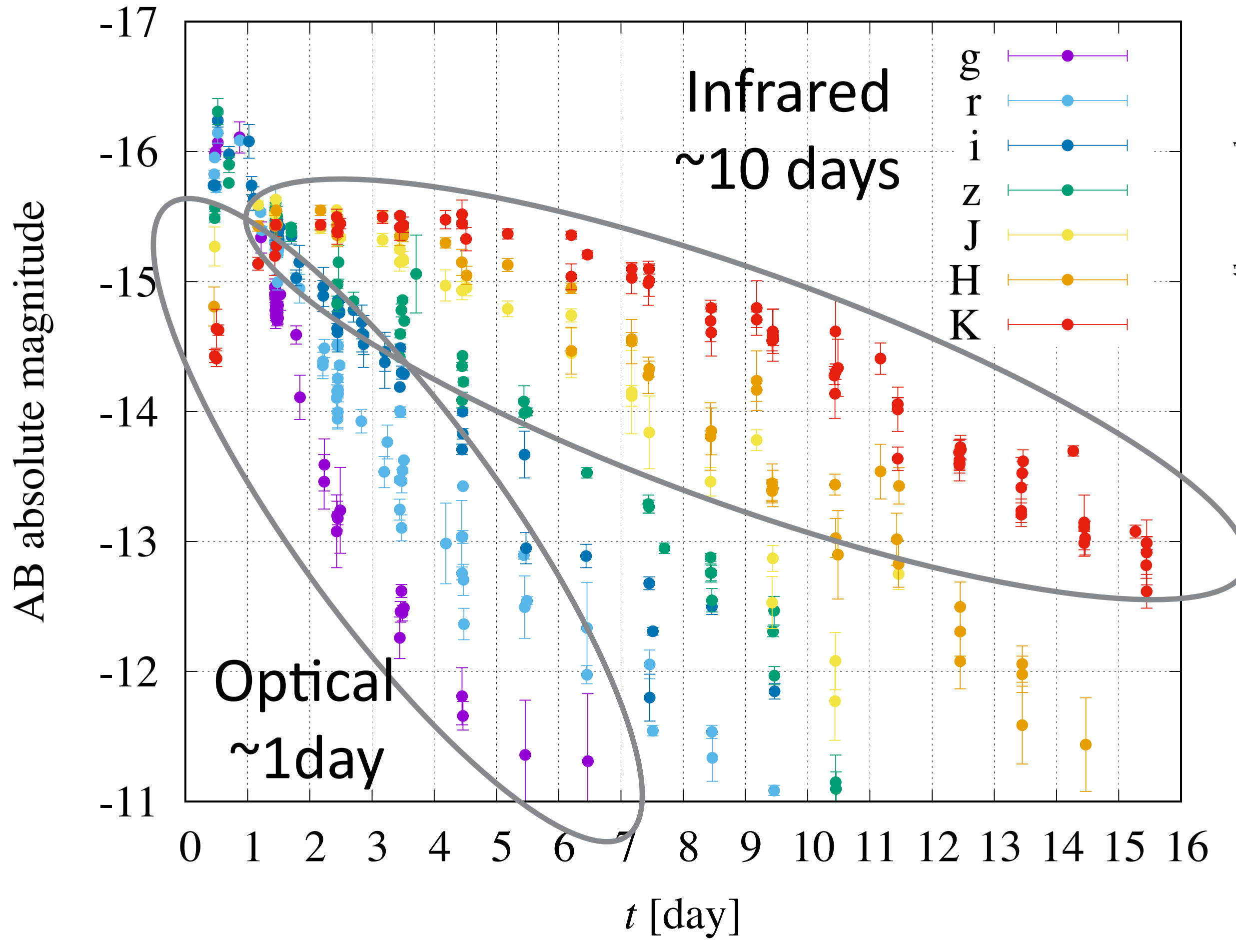


Ref: KK et al. 2018

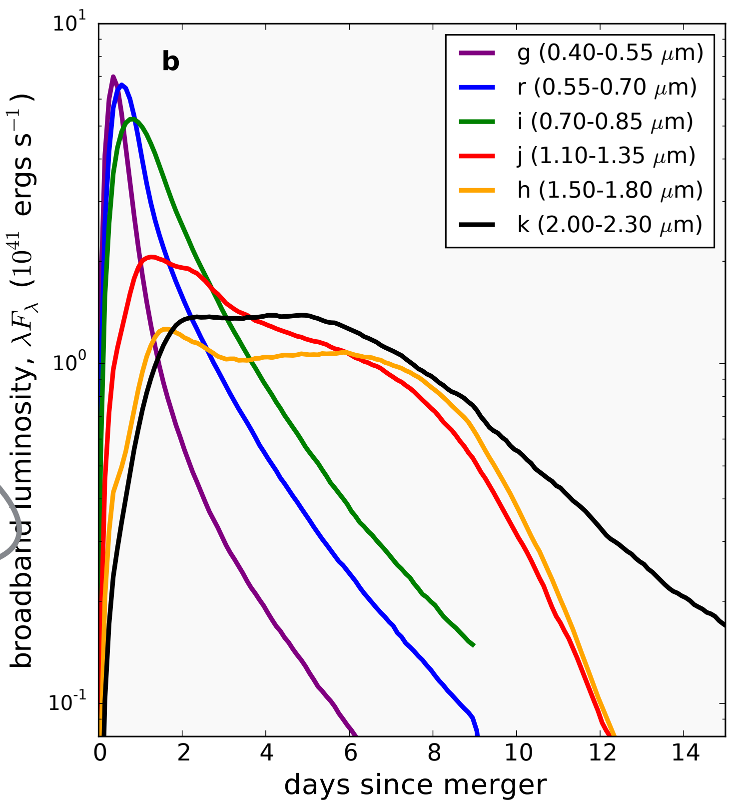
GW170817:
Kilonova/macronova with multiple components

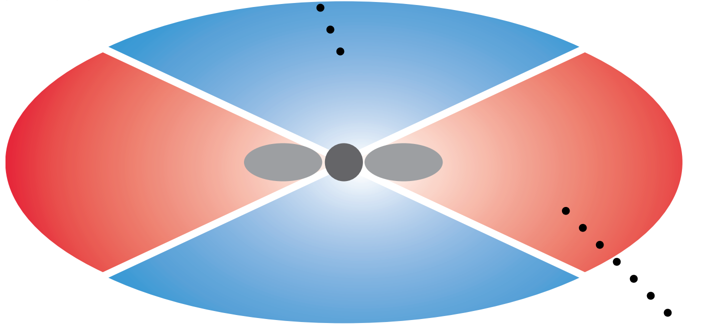
Data: Summarized in Villar et al. 2017

D=40 Mpc



ref) Masaomi's slide





Ref: D. Kasen et al. 2017

- Electromagnetic (EM) counterparts to GW170817 were observed simultaneously over the entire wavelength range (from radio to gamma wavelengths)
- **A Kilonova/macronova** model with multiple components well interprets the optical-Infrared 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 (~0.01 M_sun, opacity ~0.1-1 cm^2/g)** + long-lasting red component (~10days) from **lanthanide-rich ejecta (~0.04 M_sun, opacity ~10 cm^2/g)**

Properties of kilonovae / macronovae

ref) Li & Paczyński 1998

Order Estimation

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

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

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

$M_{\rm eje}$:ejecta mass

$v_{\rm eje}$:expanding velocity

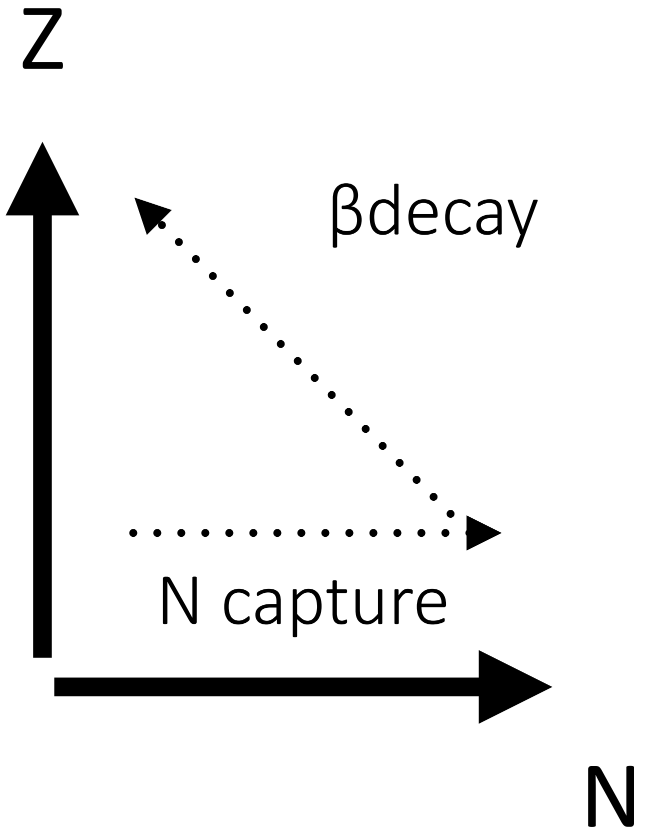
κ :opacity

f : energy conversion rate

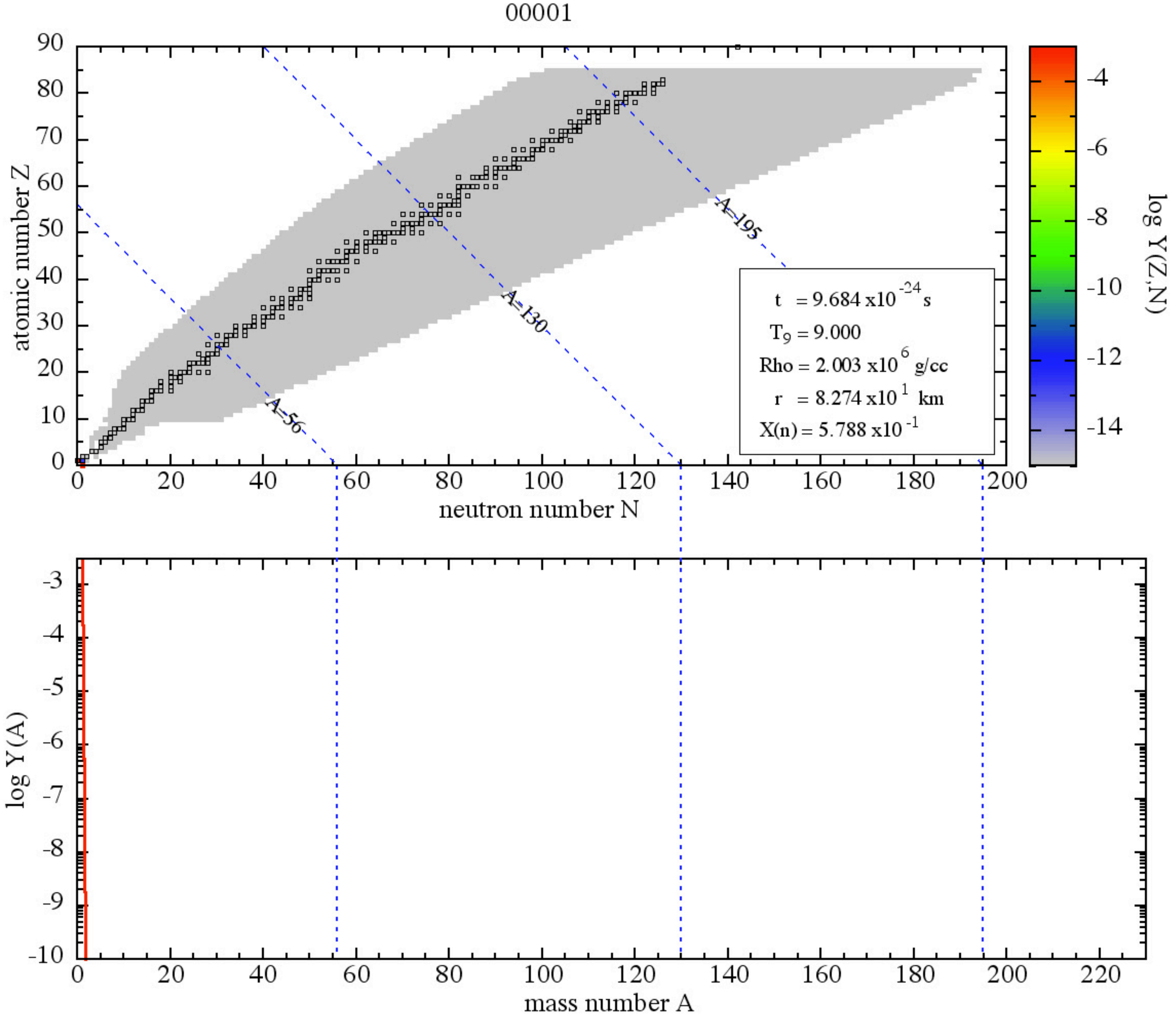
- The emission is expected to be bright in **the optical and infrared wavelength**.
- **The mass, velocity, morphology, and the composition(electron fraction)** of the ejecta characterize the lightcurve of the kilonova/macronova.

R-process nucleosynthesis

Credit) Sho Fujibayashi

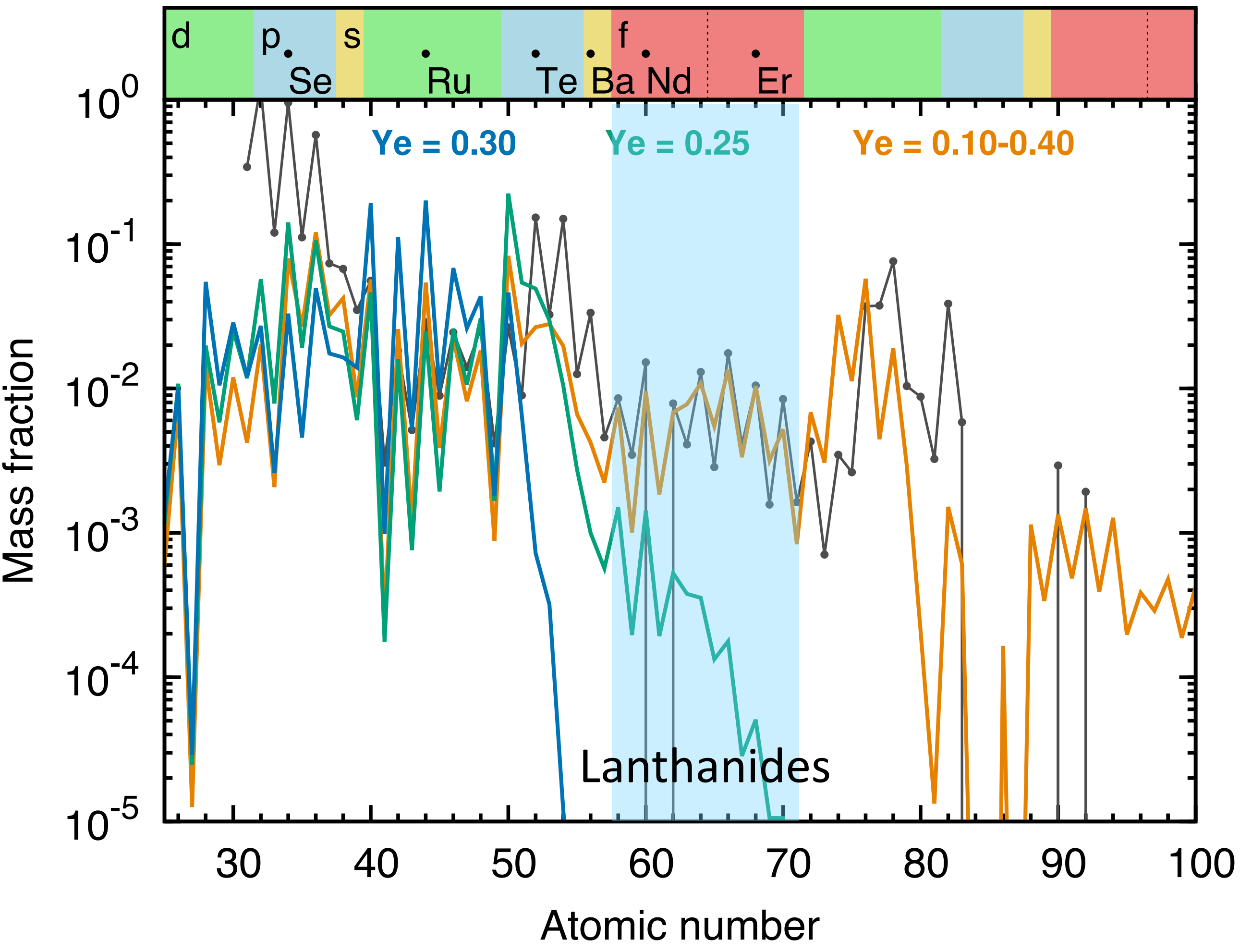


$$\tau_{\rm Ncap} \ll \tau_{\beta{\rm dec}}$$

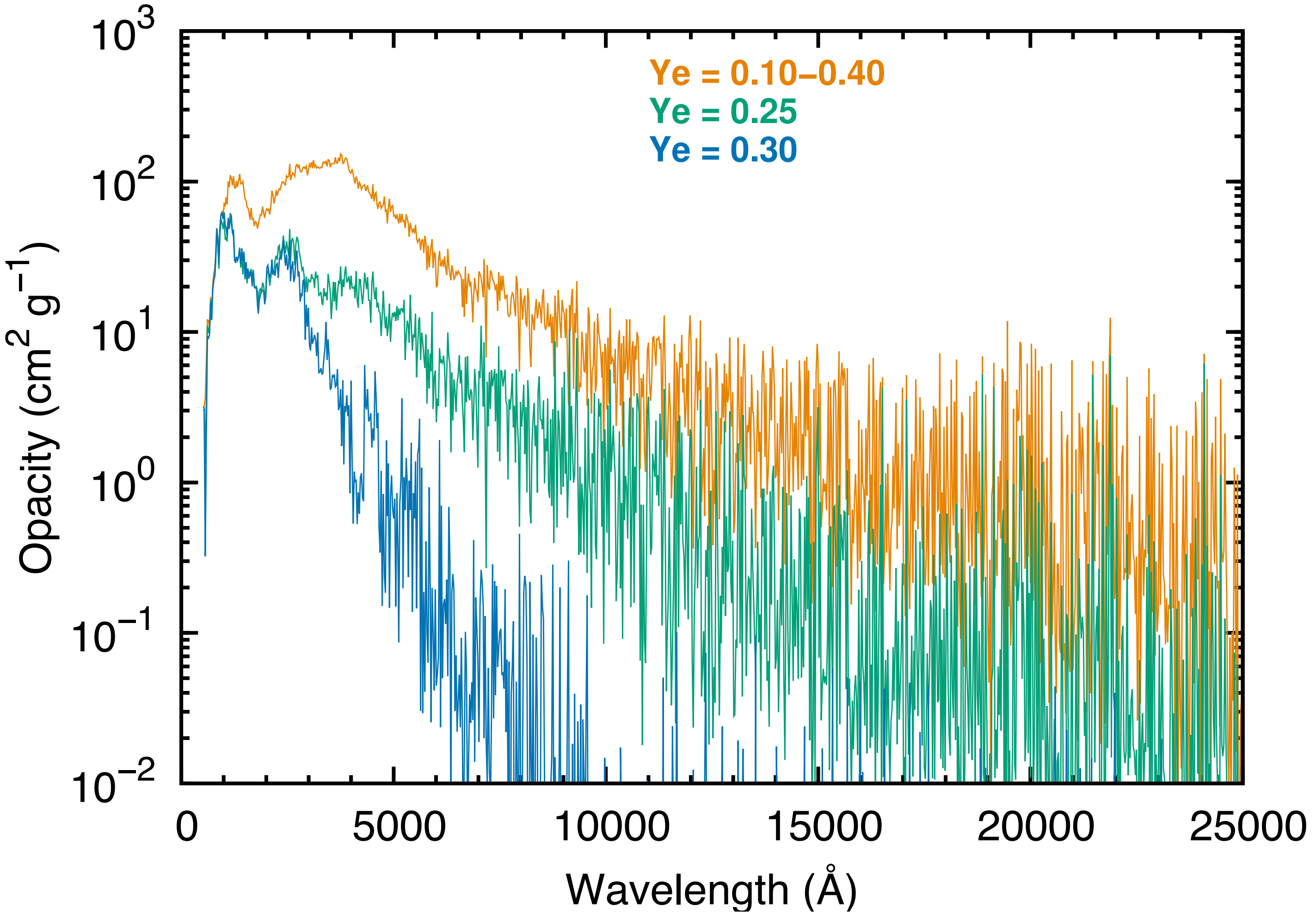


Ejecta opacity

$$Y_e = \frac{[p]}{[p]+[n]}$$



ref) Tanaka et al. 2018



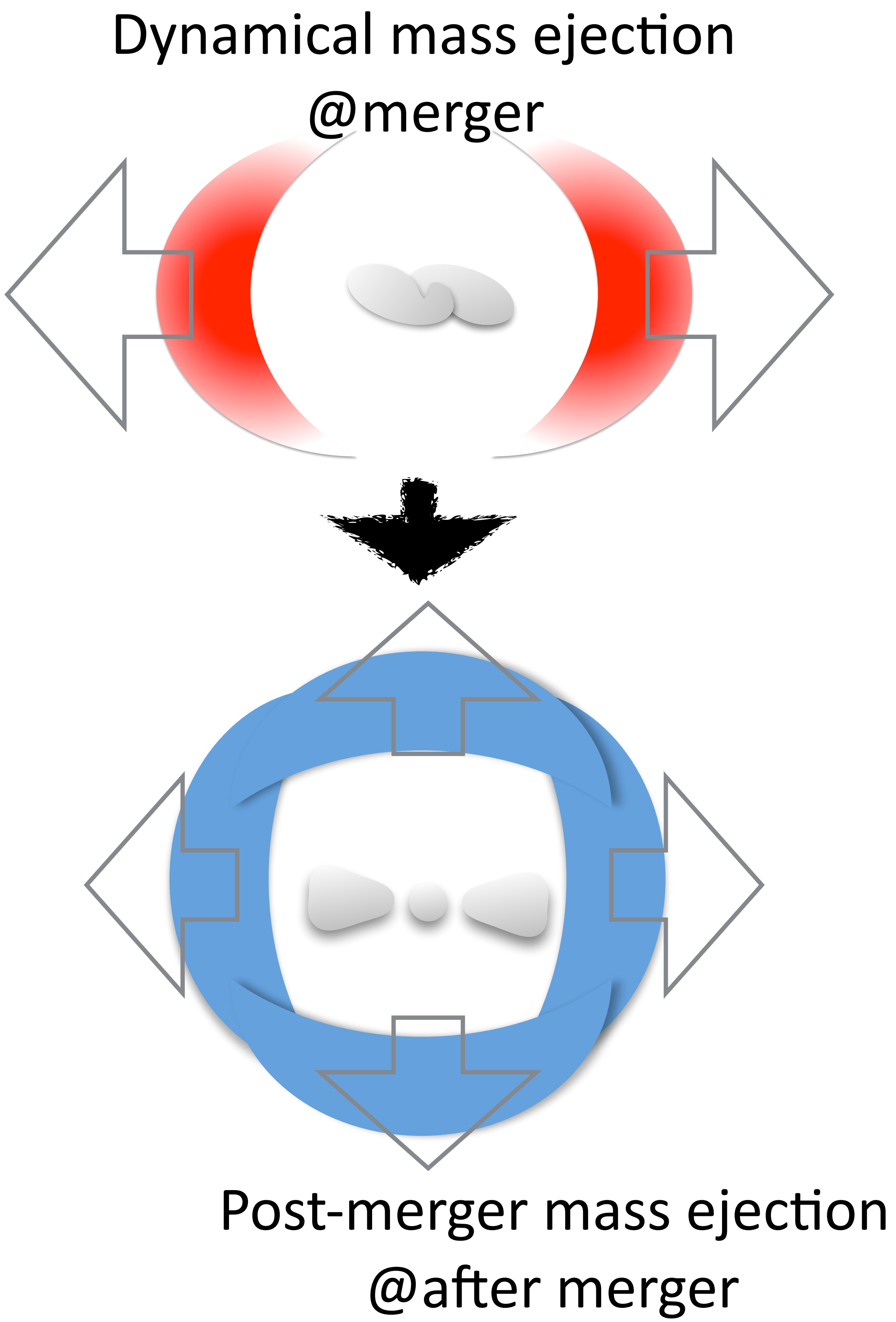
The ejecta opacity varies significantly (0.1—10 cm^2/g) depending on whether **lanthanide elements** are synthesized or not, which reflects the electron fraction, Ye, of ejecta. (Kasen et al. 2013, Barnes et al. 2013, Tanaka et al. 2013)

Mass Ejection Mechanisms

- In the last decades, many efforts have been made to study the mass ejection process and evolution of the merger remnant performing numerical-relativity simulations

- **Dynamical mass ejection**
  mass ejection driven by tidal interaction
  or
  shock heating during the collision
  (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 effective viscosity and/or neutrino heating
  (e.g., Dessart et al. 2009; Metzger & Fernández 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)

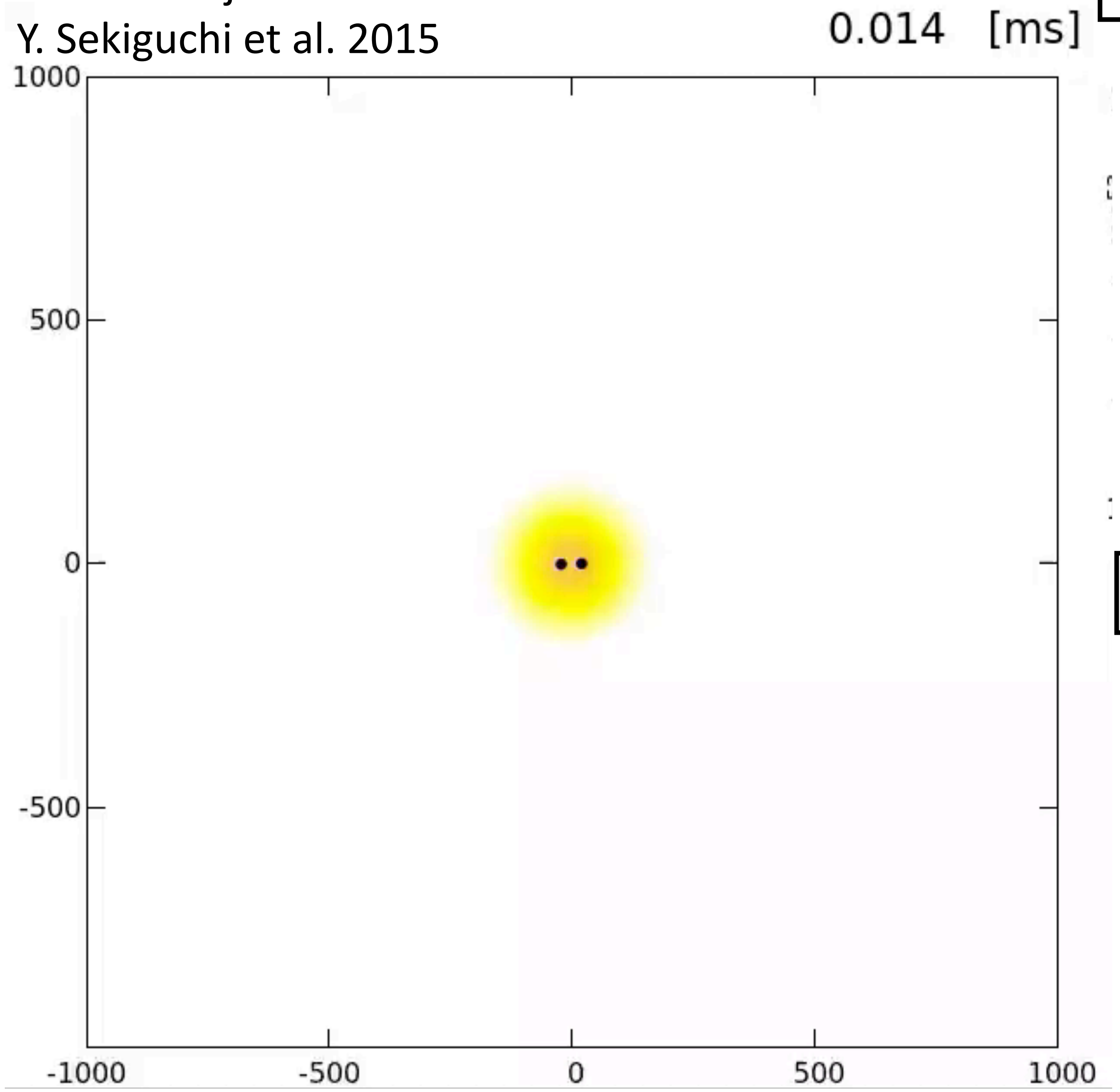


Dynamical mass ejection
@merger

Post-merger mass ejection
@after merger

Dynamical ejecta

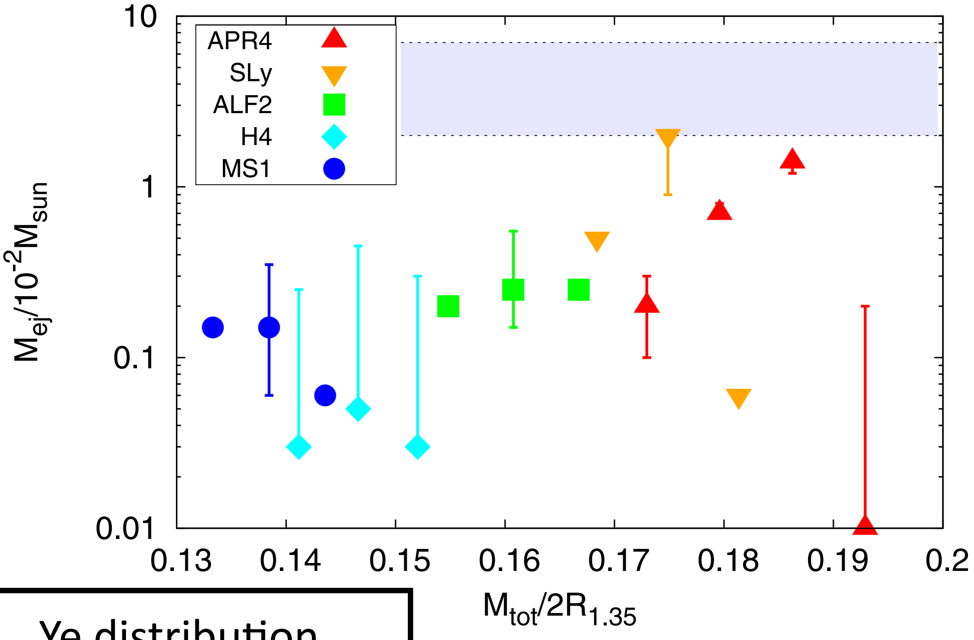
Ref: S. Wanajo et al. 2014
Y. Sekiguchi et al. 2015



Dynamical ejecta mass

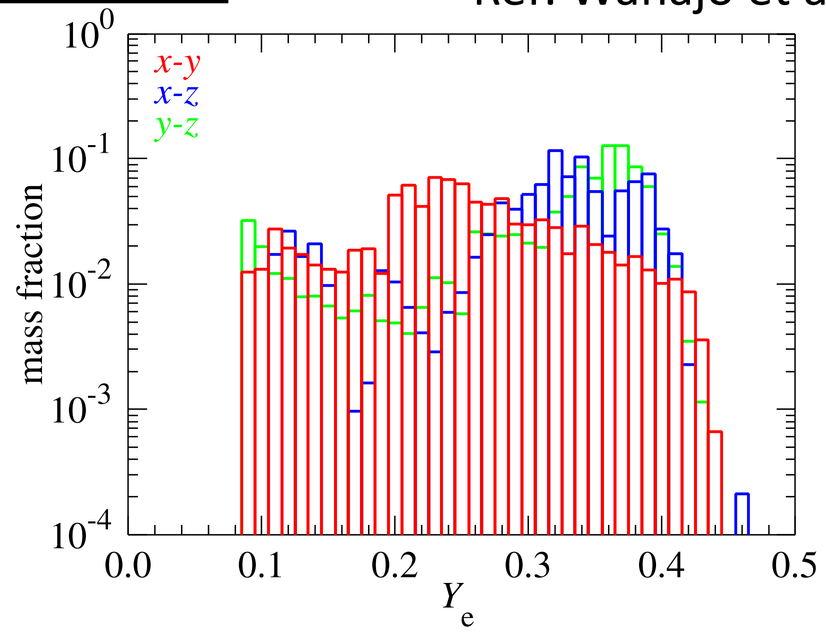
Ref: Hotokezaka et al. 2013

NS-NS models



Ye distribution

Ref: Wanajo et al. 2014



Dynamical ejecta of mass <~10^{-3}—10^{-2} M_{sun} is typically formed, depending on the NS masses and EOS.

(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)

Ye partially becomes large due to shock heating and neutrino irradiation

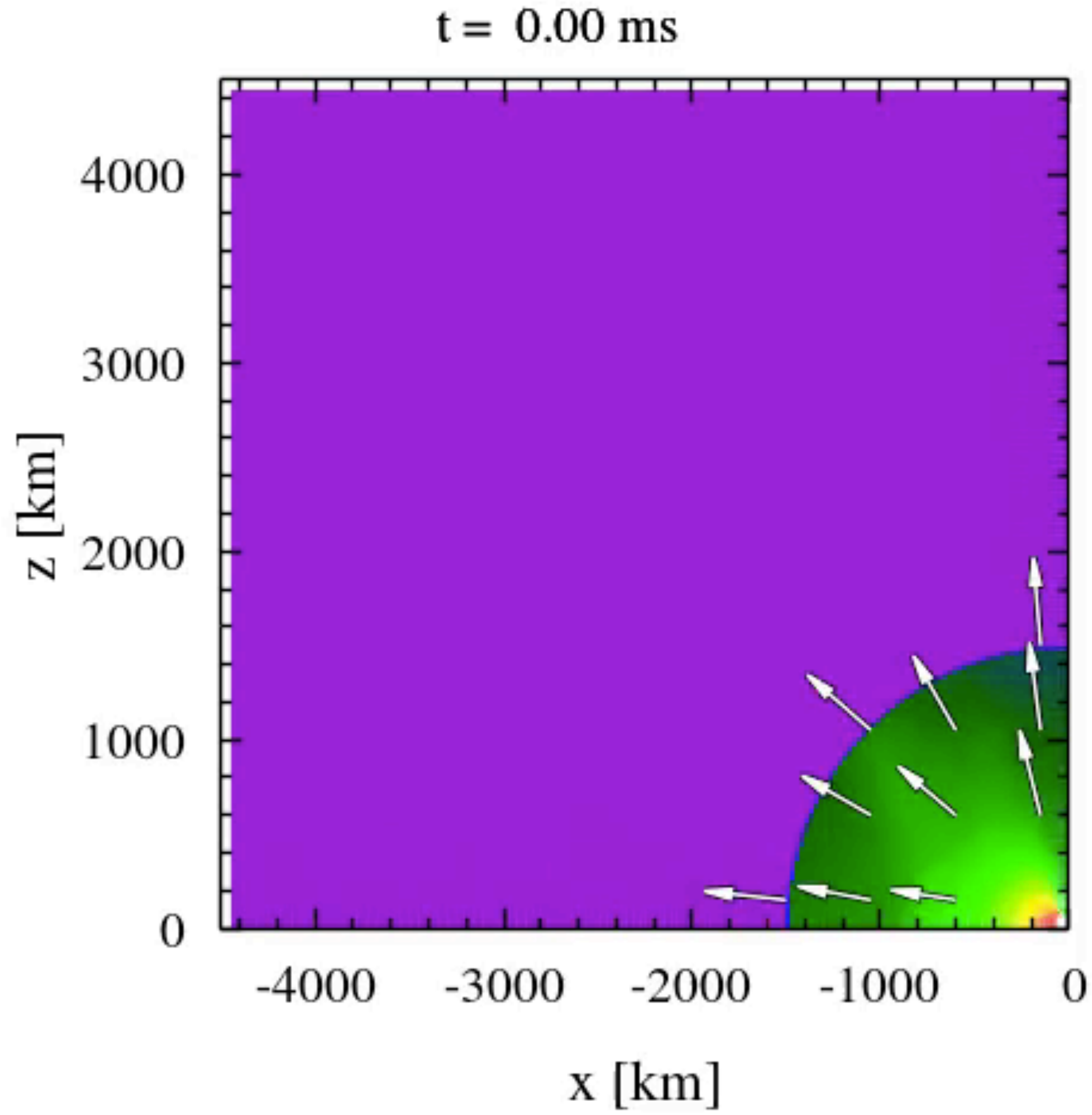
(cf. NS Ye~<0.1) Yet, substantial amount of ejecta remains to be Ye<0.25 and lanthanide is synthesized

Post-merger ejecta

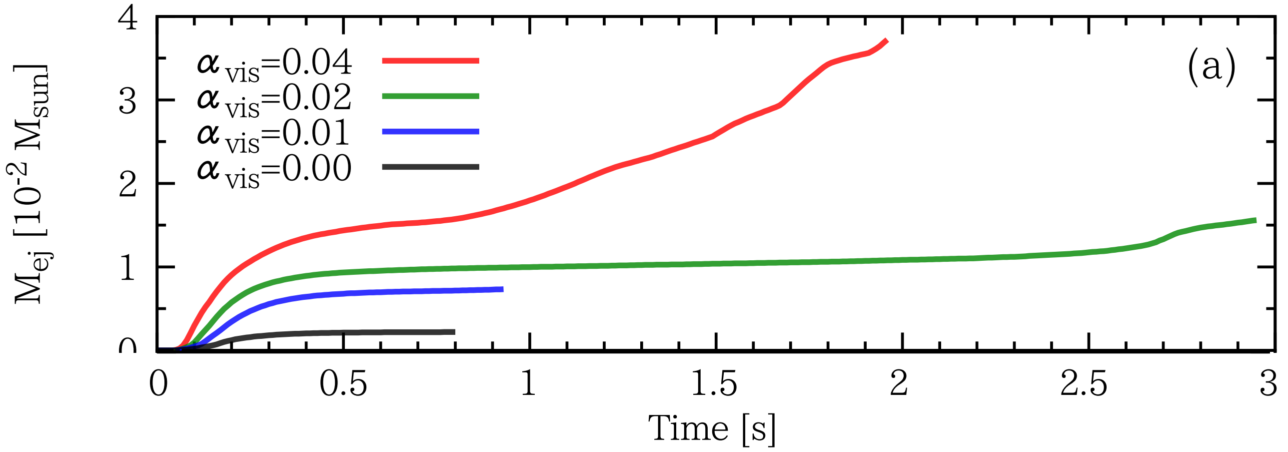
$$p+\bar{\nu}_e \rightarrow n+e^+$$

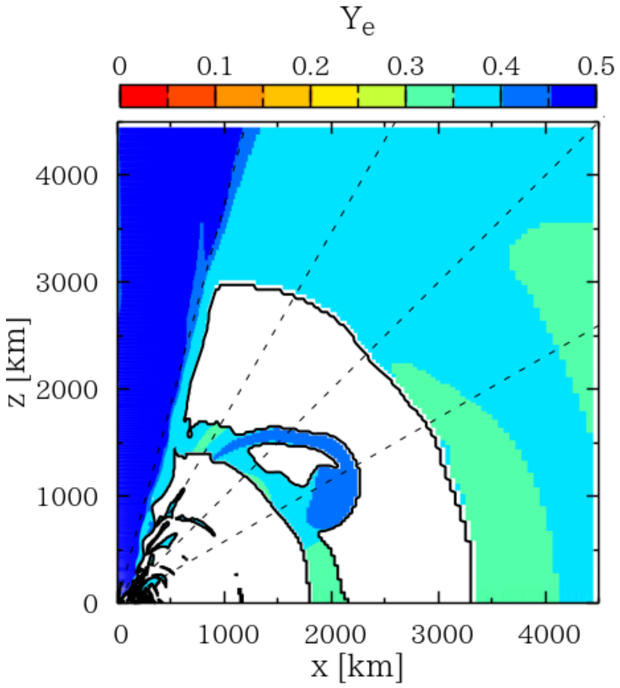
$$n+\nu_e \rightarrow p+e^-$$

Viscous GRRHD simulation for merger remnant
(Ref: S. Fujibayashi et al. 2018)

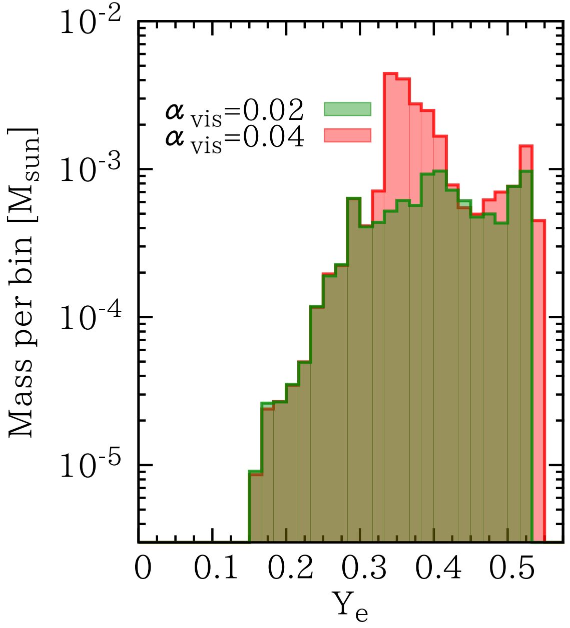


Ejected mass





Ye distribution of ejecta

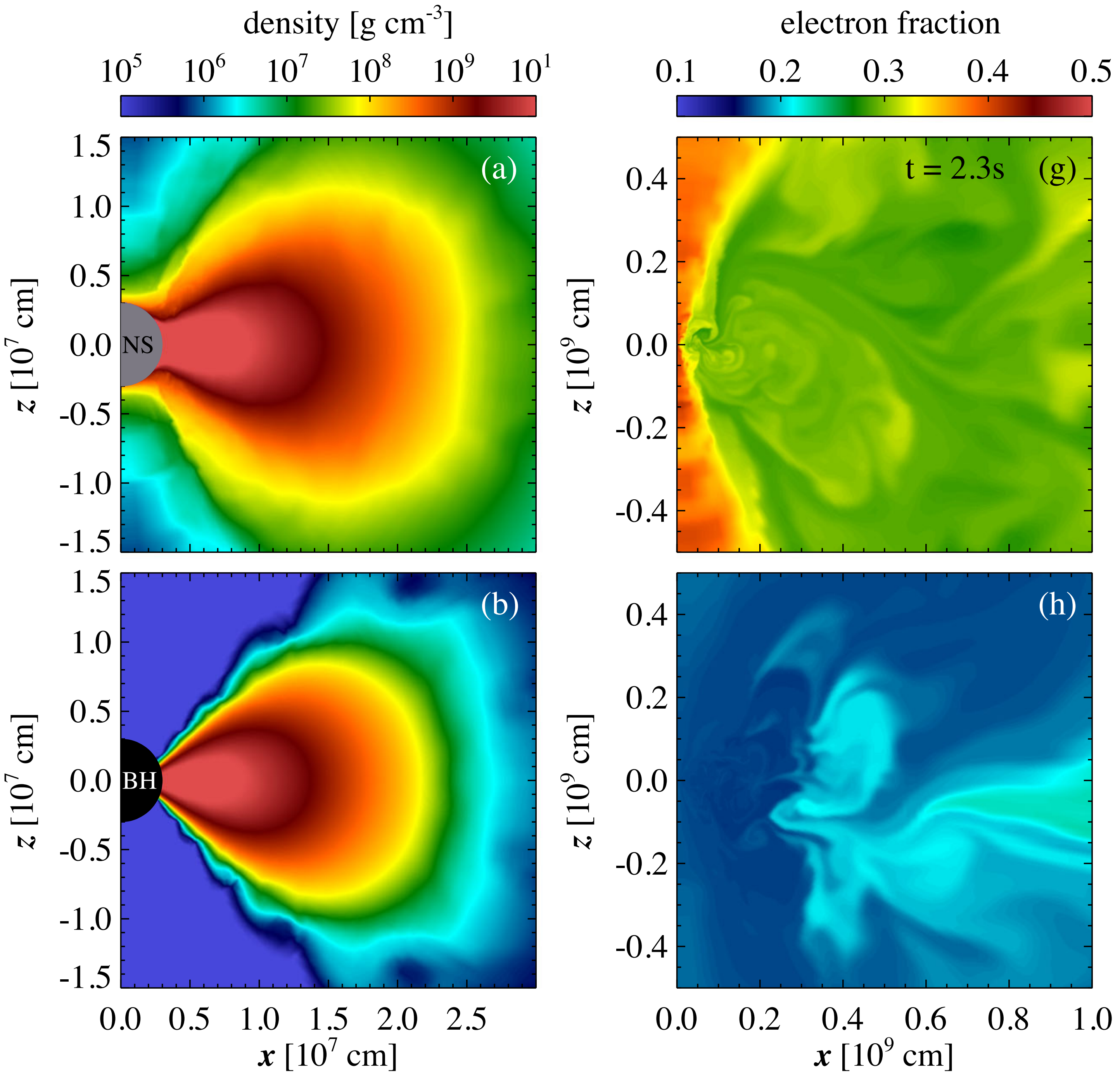


~10^{-2}—10^{-1} M_{sun} is ejected from the remnant torus, depending on the effective viscous parameter and the lifetime of the remnant NS. (see also e.g. Siegel et al. 2018, Fernandez et al.2018 for GRMHD simulations)

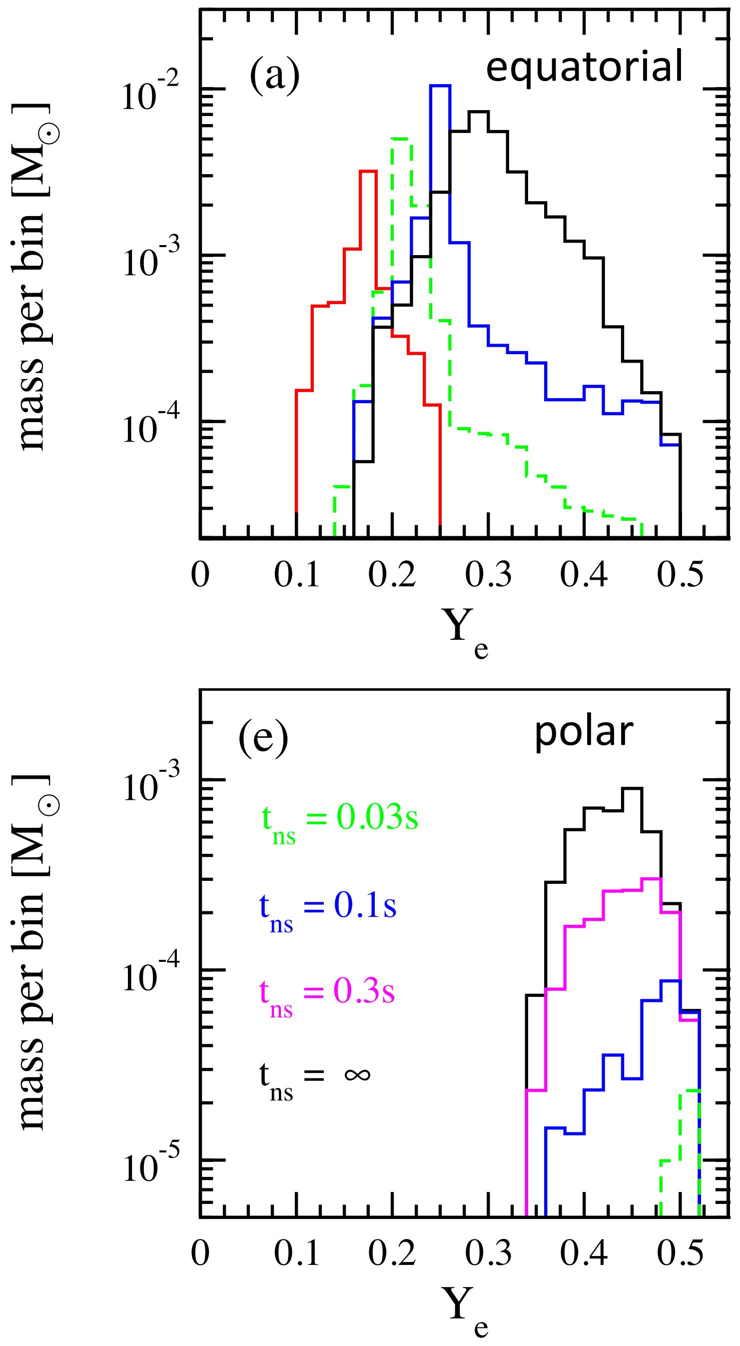
post-merger ejecta would typically have Ye>0.25 due to neutrino irradiation

if remnant neutron star is sufficiently long-lived (t>~1sec.).→ lanthanide-poor ejecta

Remnant NS Lifetime



Ye distribution of ejecta



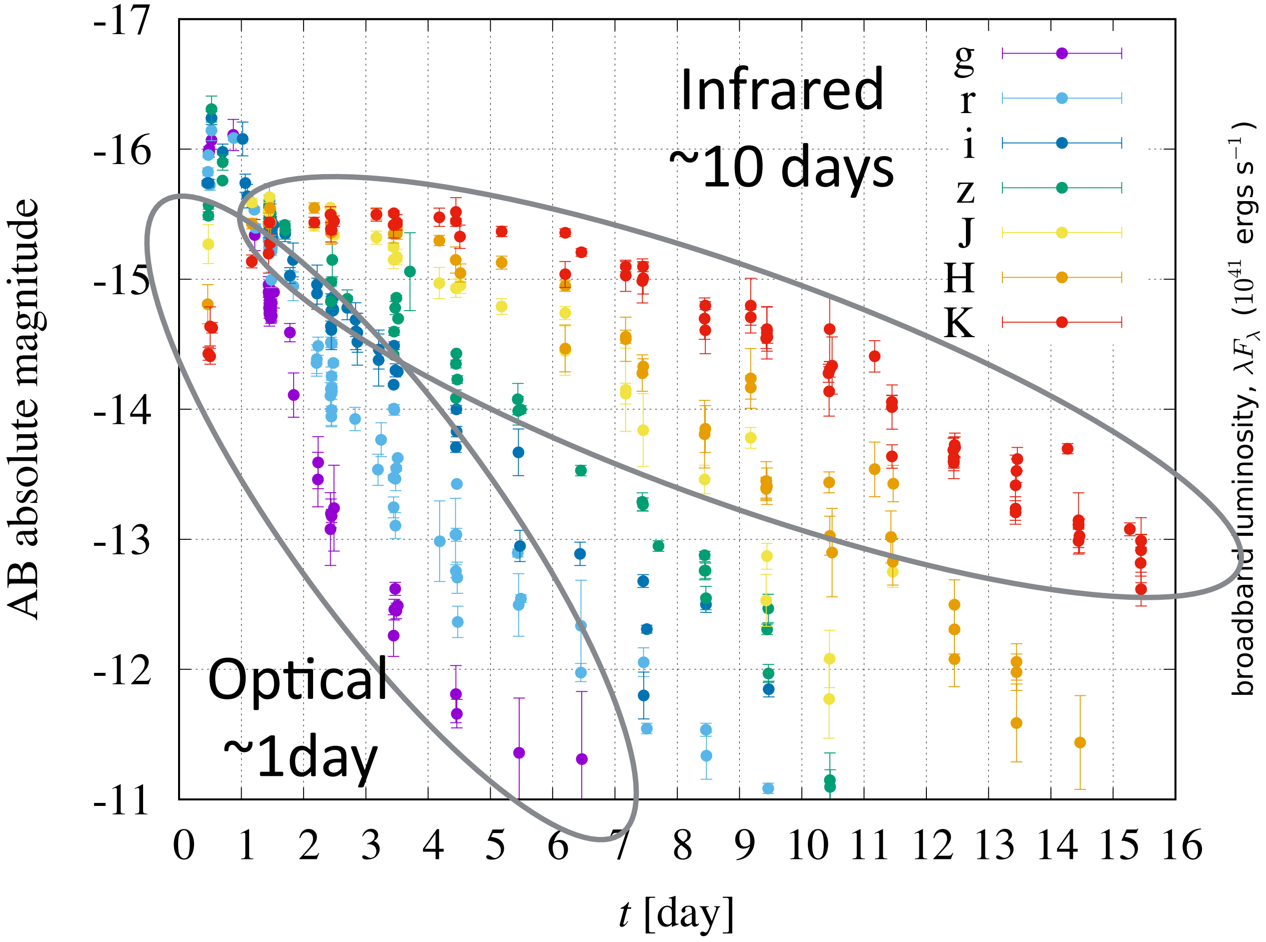
Ref: Metzger & Fernández et al. 2014

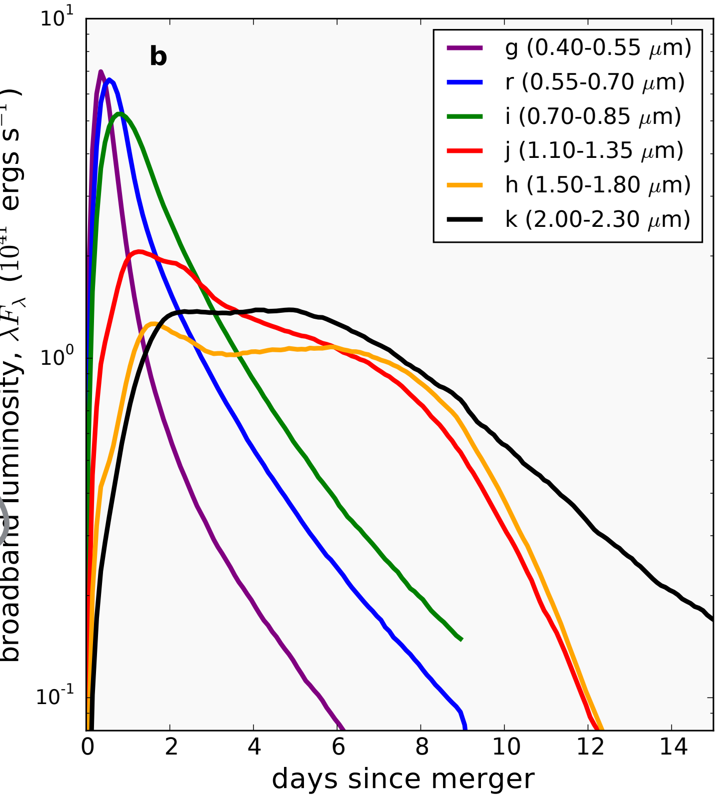
- Life time of the remnant NS has a large impact on the Ye distribution of the post merger ejecta (See also Lippuner et al. 2017)

GW170817:
Kilonova/macronova with multiple components

Data: Summarized in Villar et al. 2017

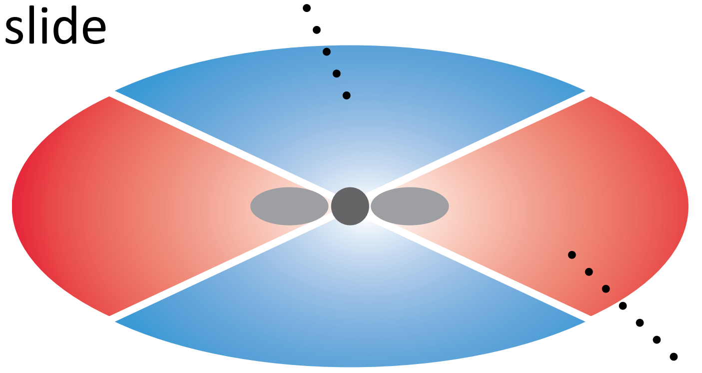
D=40 Mpc





ref) Masaomi's slide

Blue (lanthanide-free)



Red (lanthanide-rich)

Ref: D. Kasen et al. 2017

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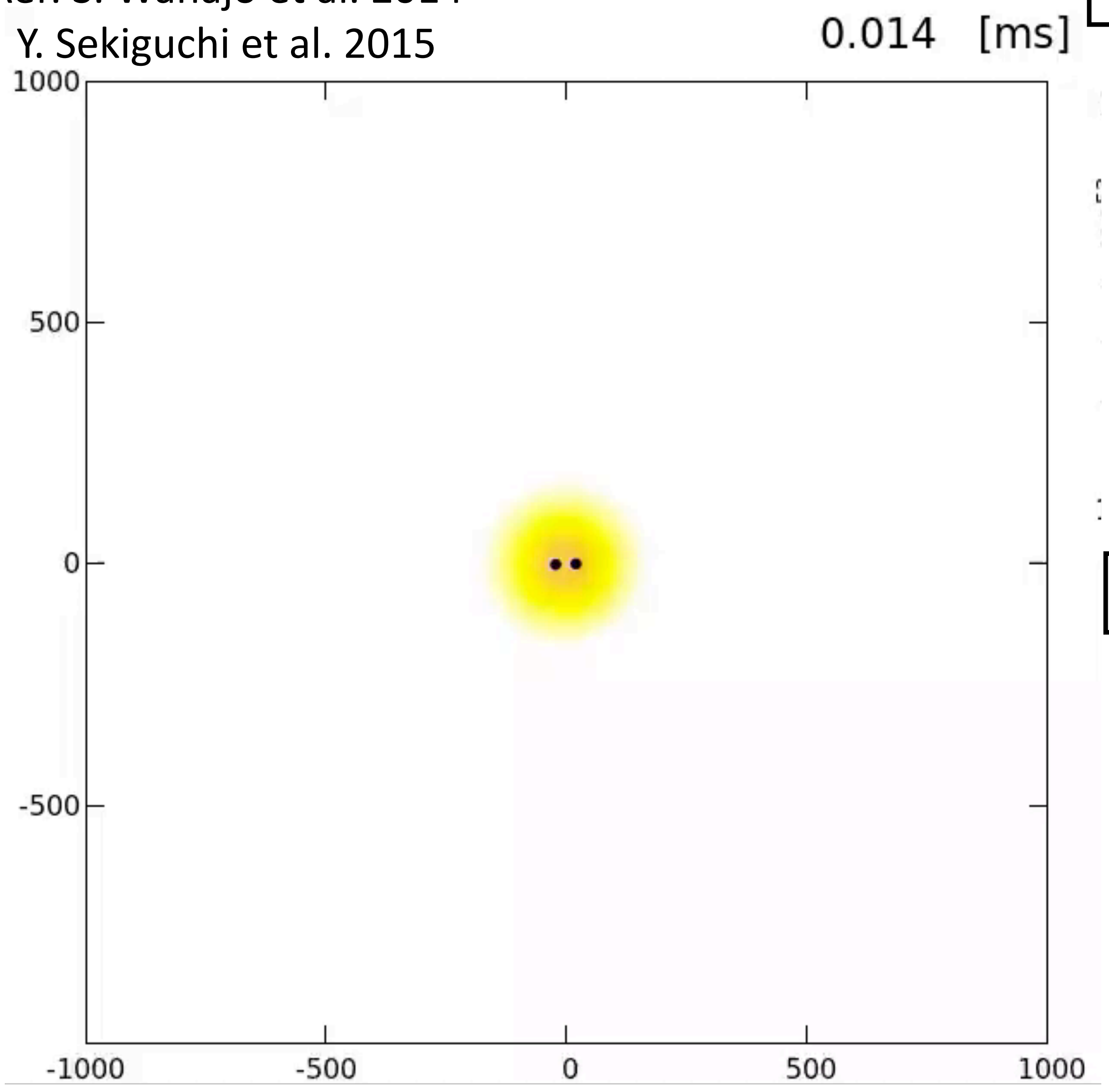
  - early-blue component (~1day) from **lanthanide-free ejecta (~0.01 M_sun, opacity ~0.1-1 cm^2/g)** + long-lasting red component (~10days) from **lanthanide-rich ejecta (~0.04 M_sun, opacity ~10 cm^2/g)**

Dynamical ejecta

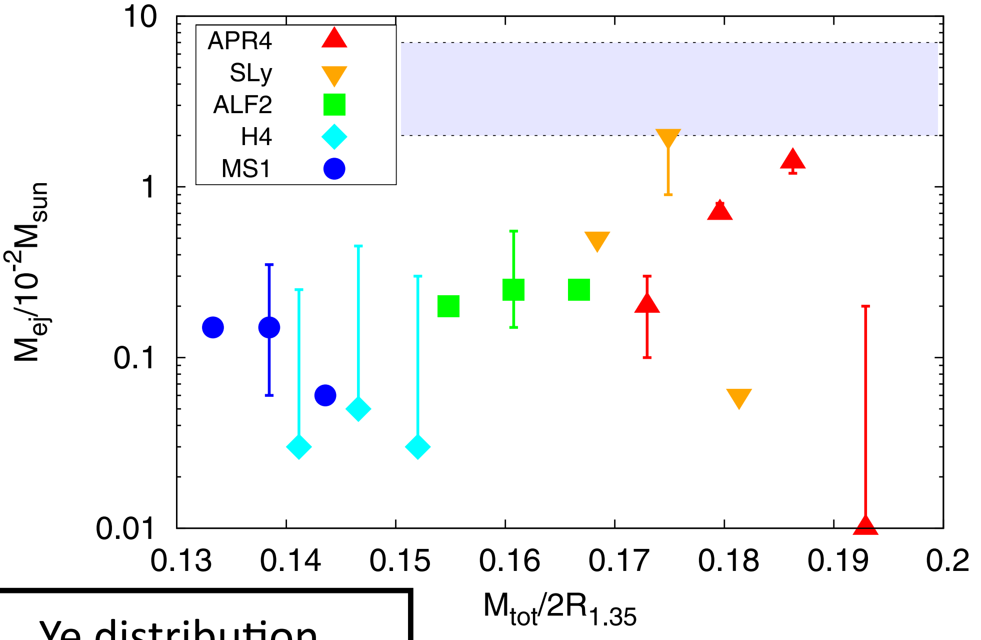
Ref: S. Wanajo et al. 2014
Y. Sekiguchi et al. 2015



Dynamical ejecta mass

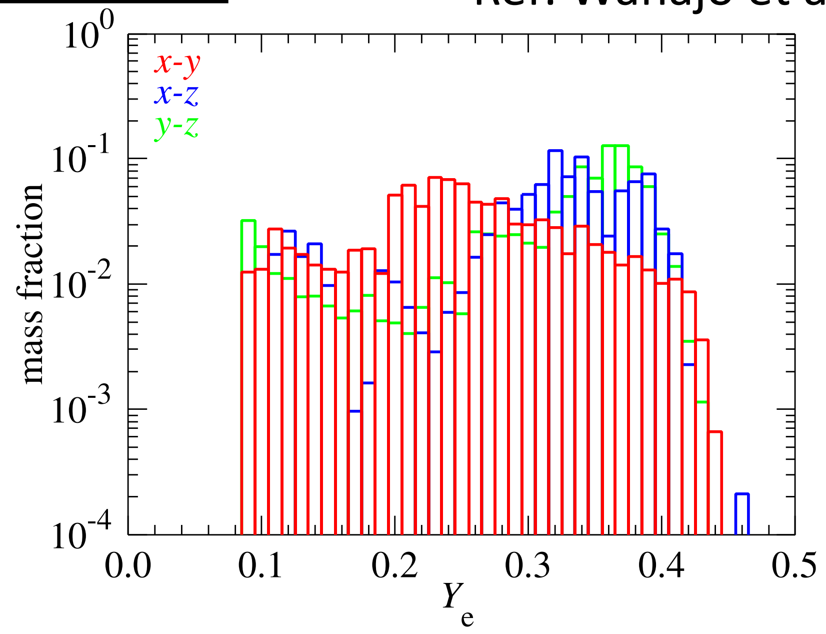
Ref: Hotokezaka et al. 2013

NS-NS models



Ye distribution

Ref: Wanajo et al. 2014



Dynamical ejecta of mass $<\sim 10^{-3}$—10^{-2} M_{sun} is typically formed, depending on the NS masses and EOS.

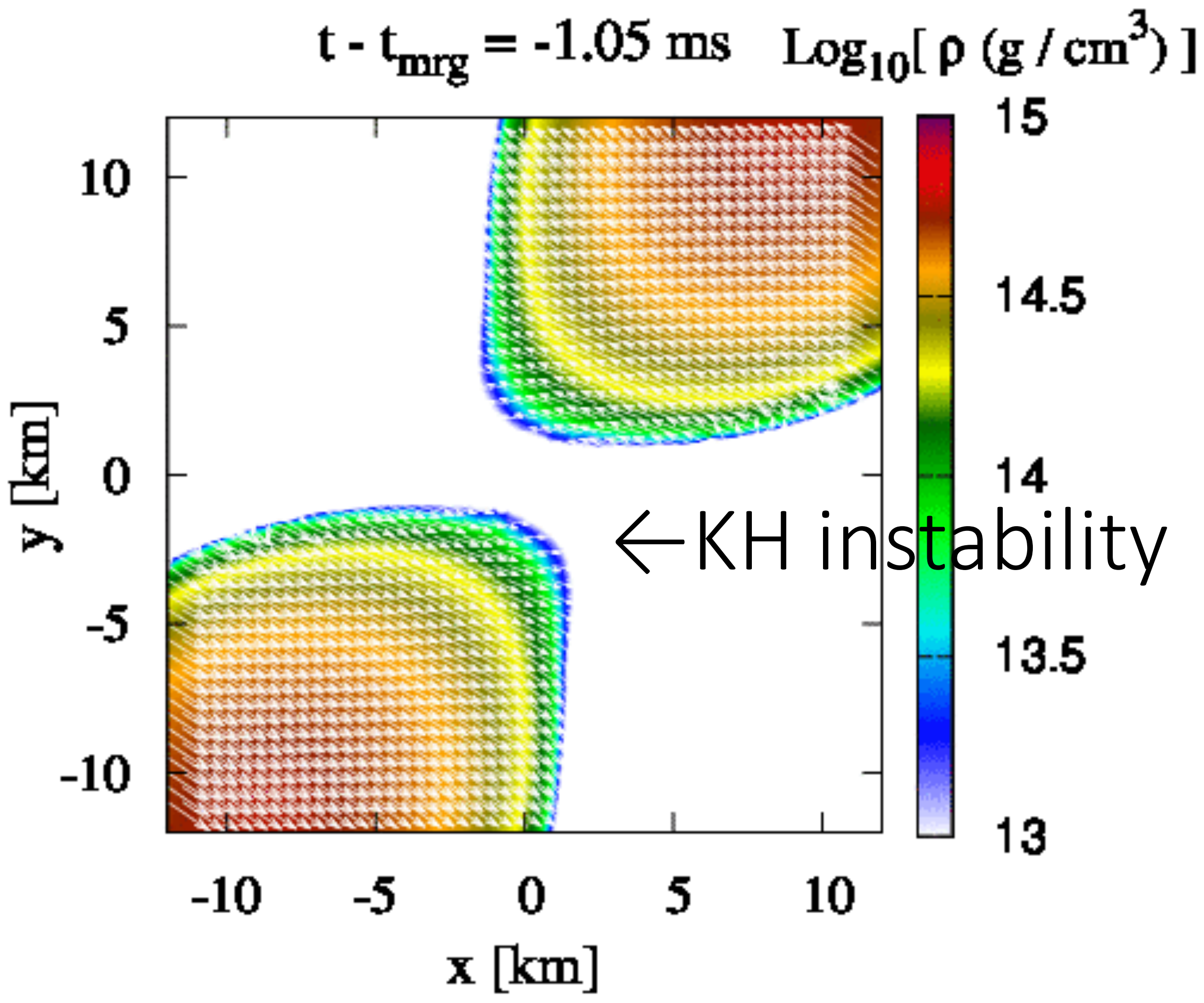
(e.g. Hotokezaka et al. 2013; Bauswein et al. 2013; Sekiguchi et al. 2016; Radice et al. 2016; Dietrich et al. 2017; Bovard et al. 2017)

Ye partially becomes large due to shock heating and neutrino irradiation

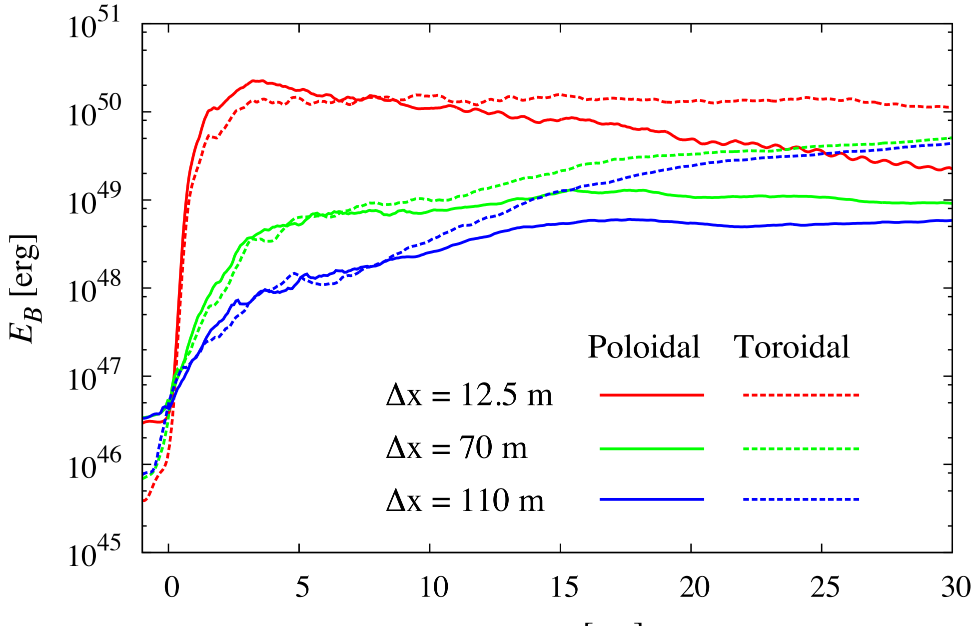
(cf. NS Ye~<0.1) Yet, substantial amount of ejecta remains to be Ye<0.25 and lanthanide is synthesized

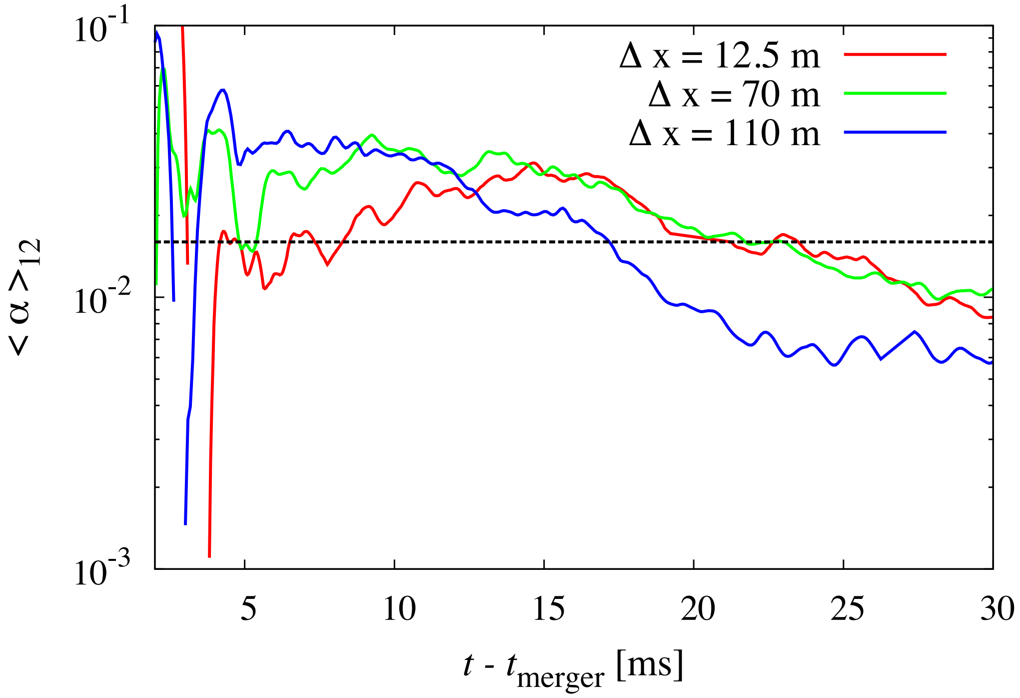
Evolution of Remnant NS & torus: Effective viscosity

Turbulence in the contact surface→amplification of magnetic field →effective viscosity would play a role



←KH instability





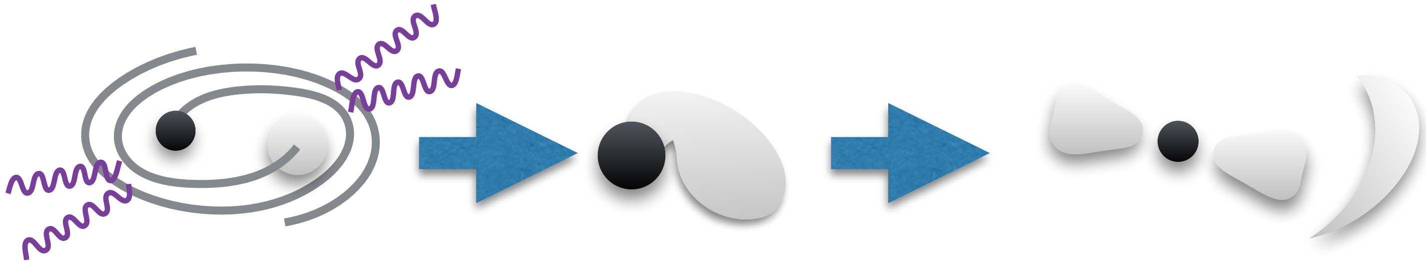
Ref: K. Kiuchi et al. 2015, 2017

Relativistic jets

Black hole-Neutron star (BH-NS) merger

Ref: Kyutoku et al. 2018

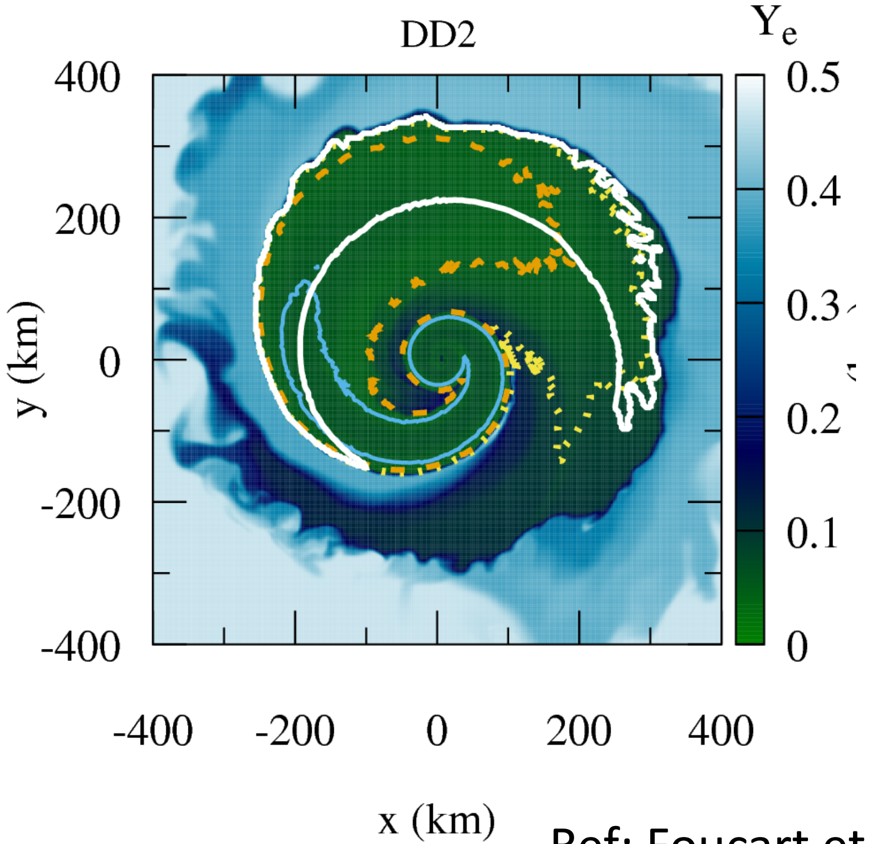
- If the NS is **tidally disrupted**
  substantial amount of material would remain/ejected after the merger



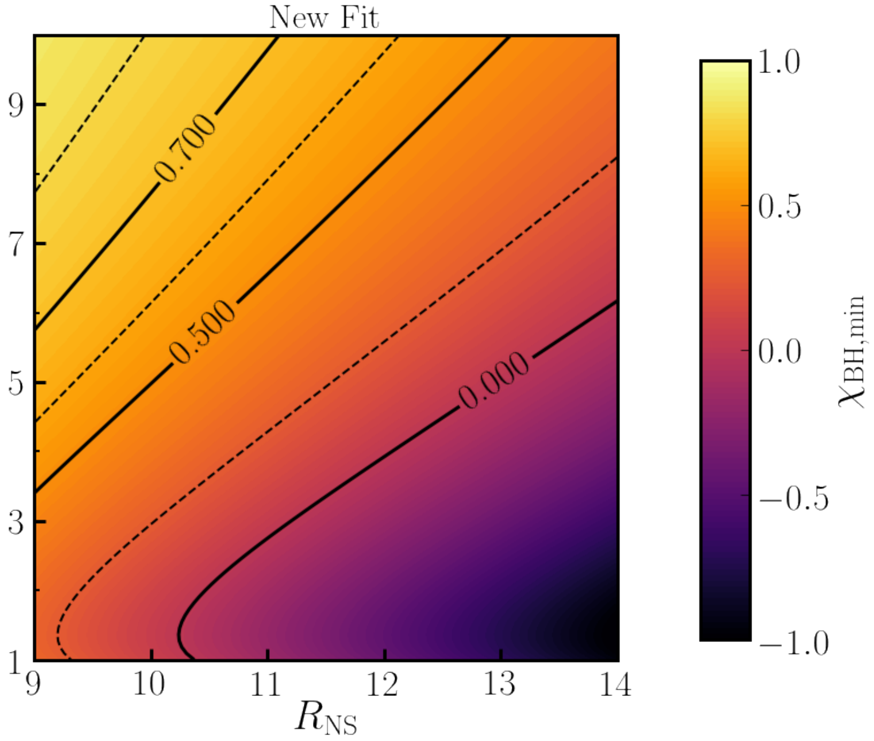
For BHNS merger, lanthanide fraction of the ejecta would be higher in the absent of shock heating and neutrino irradiation
(e.g. Just et al. 2015, Foucart et al. 2017,Kyutoku et al. 2018)

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

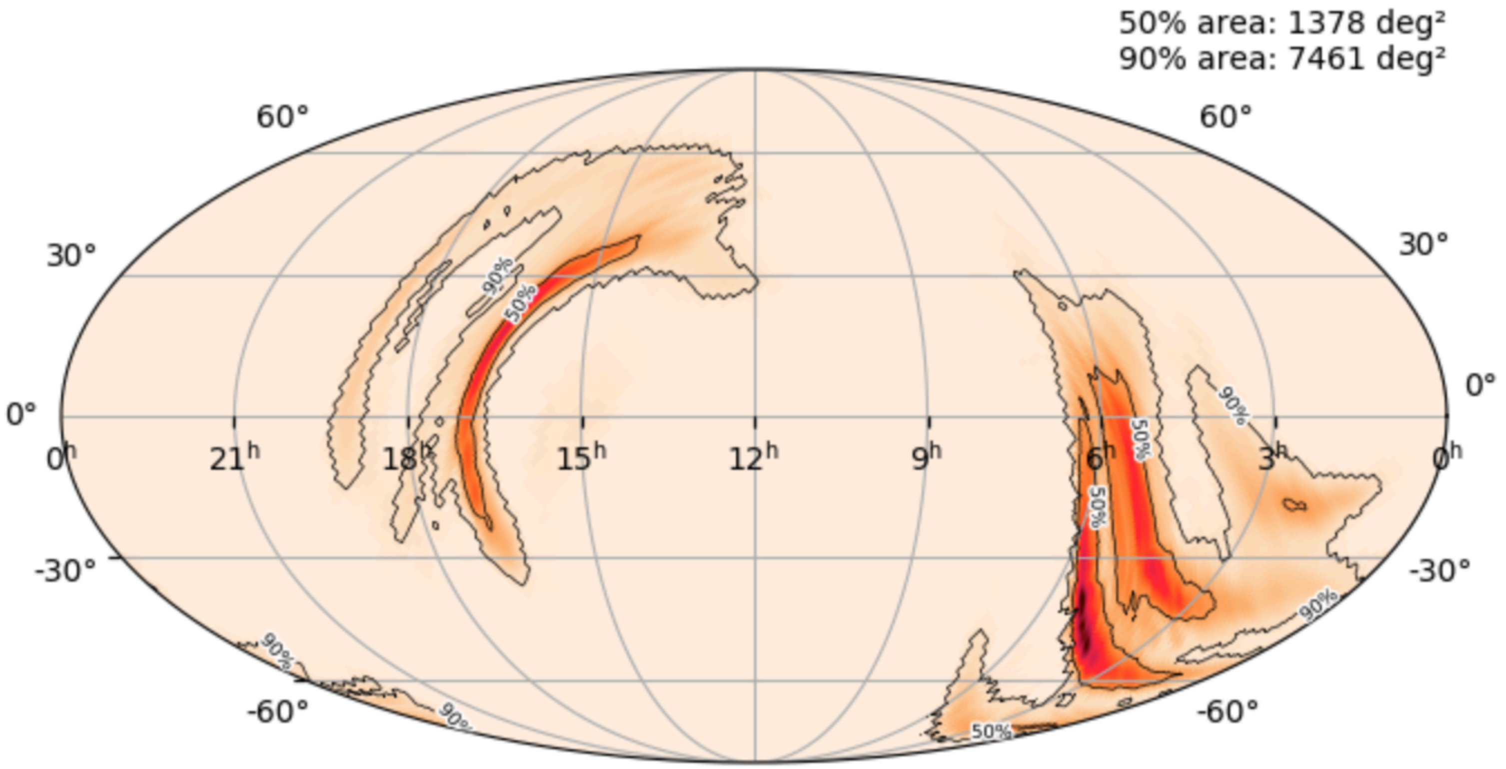
- Whether NS is tidally disrupted or not, and the remnant disk/ejecta mass depends strongly on the binary parameters.

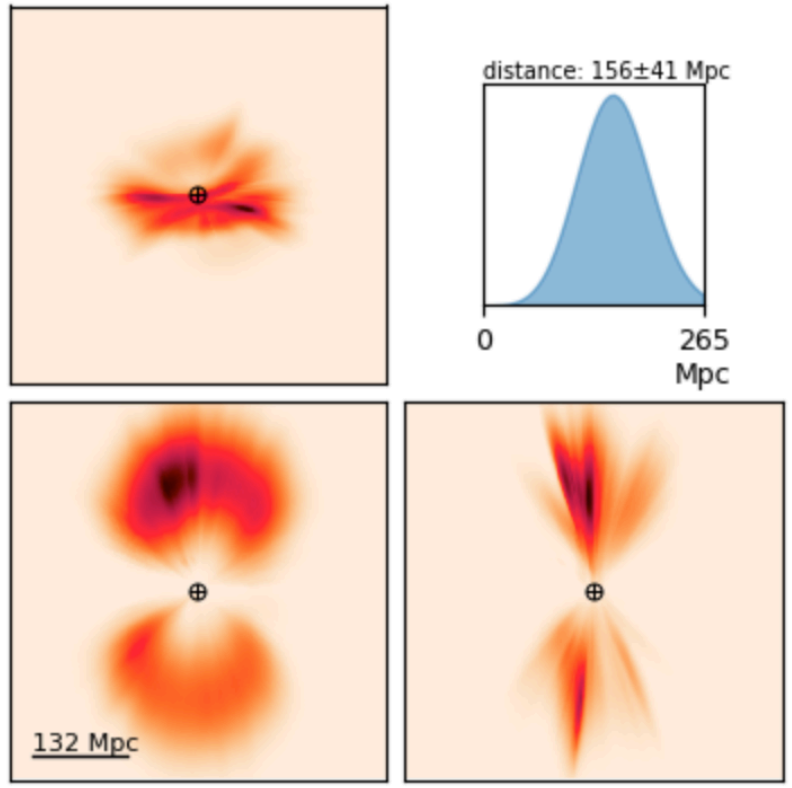


Ref: Foucart et al. 2018



NS-NS candidate: S190425z





BH-BH Candidates: S190828l, S190828j