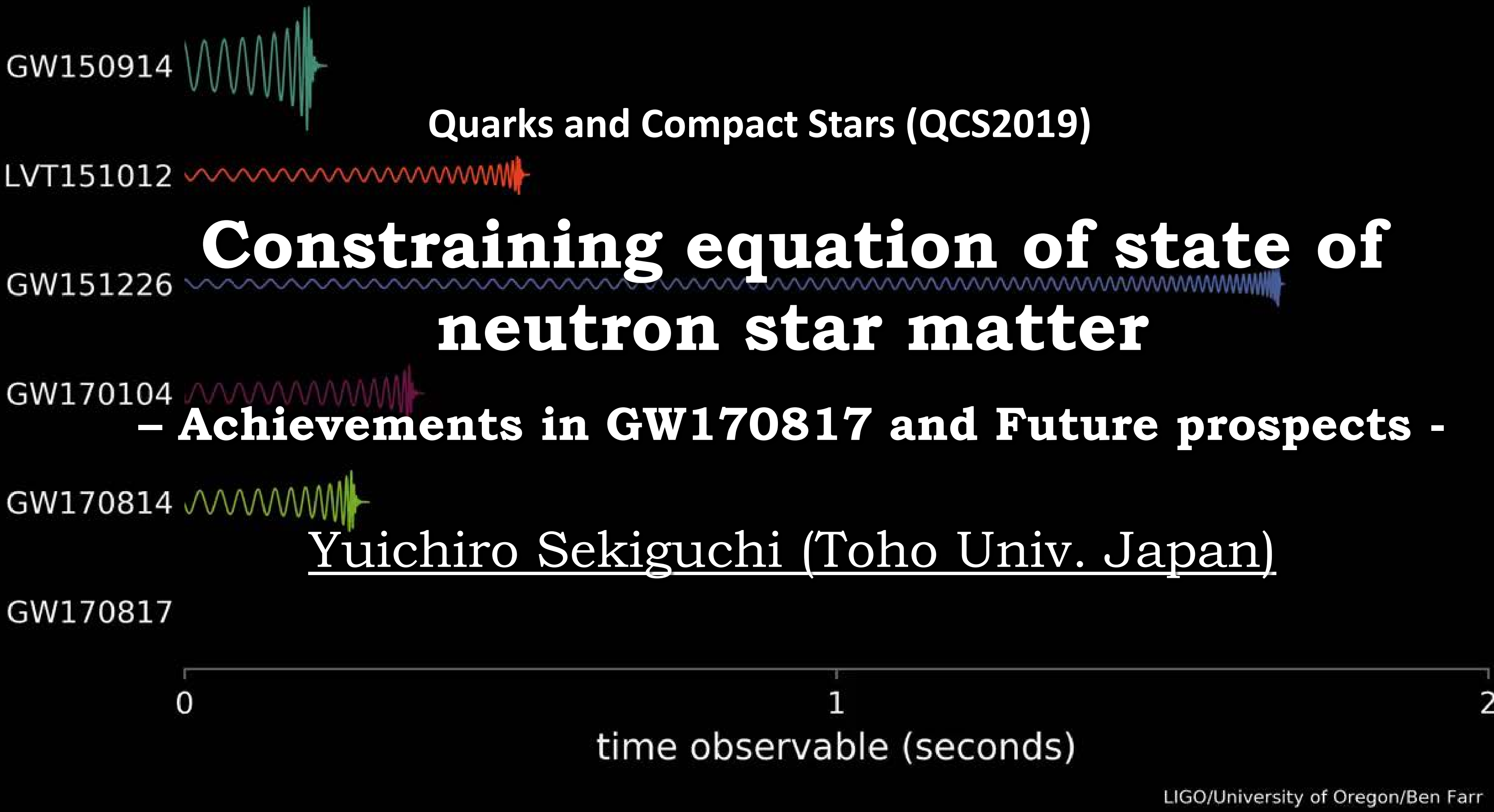
Quarks and Compact Stars (QCS2019)

Constraining equation of state of neutron star matter

– Achievements in GW170817 and Future prospects -

Yuichiro Sekiguchi (Toho Univ. Japan)



https://www.youtube.com/watch?v=vTeAFAGpfso&feature=share

Era of GW astronomy has come !

- The first direct GW detection **GW150914** : dawn of GW astronomy
  - GW from **BH-BH** : 10 events in O2 and 22 candidates in **O3 (started Apr, 2019)**
- The first **NS-NS** event **GW170817** opened the door to the multi-messenger astronomy with GW
  - Provides a way to constrain EOS of NS matter (topic of my talk)
  - Expected event rate $110 \sim 3840\ \mathrm{Gpc^{-3} yr^{-1}} \Rightarrow \underline{0.1 \sim 10\ \mathrm{yr^{-1}}}$ for adv. LIGO
- 5 NS-NS candidates in O3 (**S190425z, S190426c, S190510g, S190901ap, S190910h**)
  - If all these are the real event ⇒ event rate : $\underline{\sim 10\ \mathrm{yr^{-1}}}$
  - But, only **S190425z** has small false alarm rate (FAR) ($\sim 10^{-5} \mathrm{yr^{-1}}$, for other events FAR $\sim 0.2 - 1\ \mathrm{yr^{-1}}$: such a low S/N, fake event can happen once per year/5 years)

  ⇒ event rate : $\underline{\sim 1\ \mathrm{yr^{-1}}}$
- Two **BH-NS** candidates :
  - S190814bv (FAR $\sim 10^{-5} \mathrm{yr^{-1}}$), S190910d (FAR $\sim 10^{-1} \mathrm{yr^{-1}}$)

Era of GW astronomy has come !

- GW event rate for NS-NS, BH-NS may be large as $> 1\ \mathrm{yr}^{-1}$
- Event rate ∝ volume ∝ (sensitivity)^3
- Twice better sensitivity results in 8 times larger rate : $\sim 10\ \mathrm{yr}^{-1}$
  - Detector update are ongoing and planned

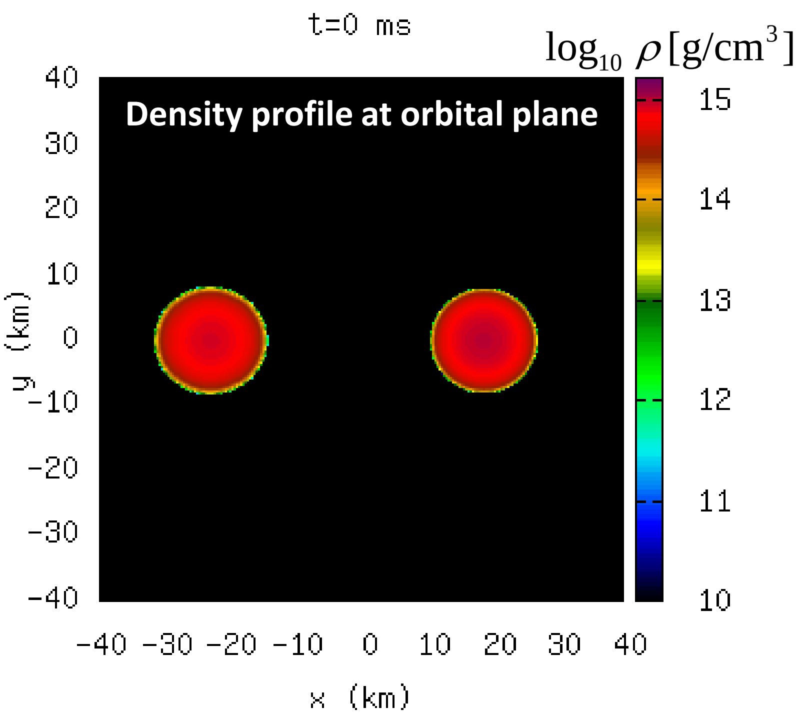
- **We are now stepping into the era of GW astronomy !**

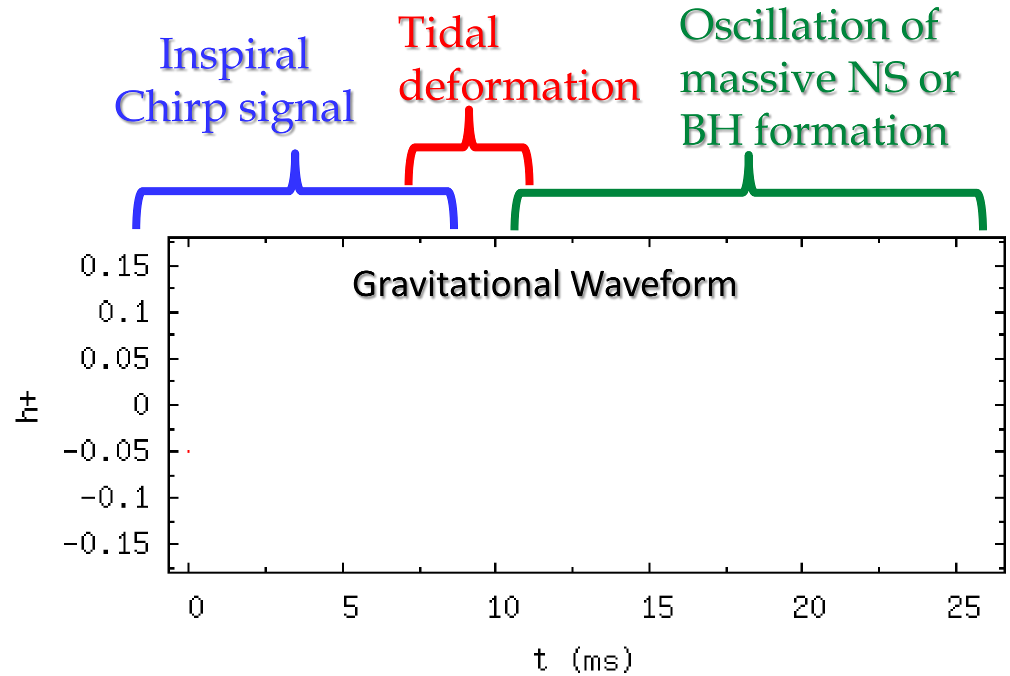
- In particular, physics of NS matter may be explored using GW from NS-NS/BH mergers
  - Indeed a constraint on EOS was obtained in GW170817

Sekiguchi et al, 2011; Hotokezaka et al. 2013

Gravitational waves from NS merger

Numerical relativity simulation modelling GW170817





- point particle approx.
- information of binary parameter (**NS mass**, etc)

- finite size effect
- **NS tidal deformability**
- ⇒ **NS radius**

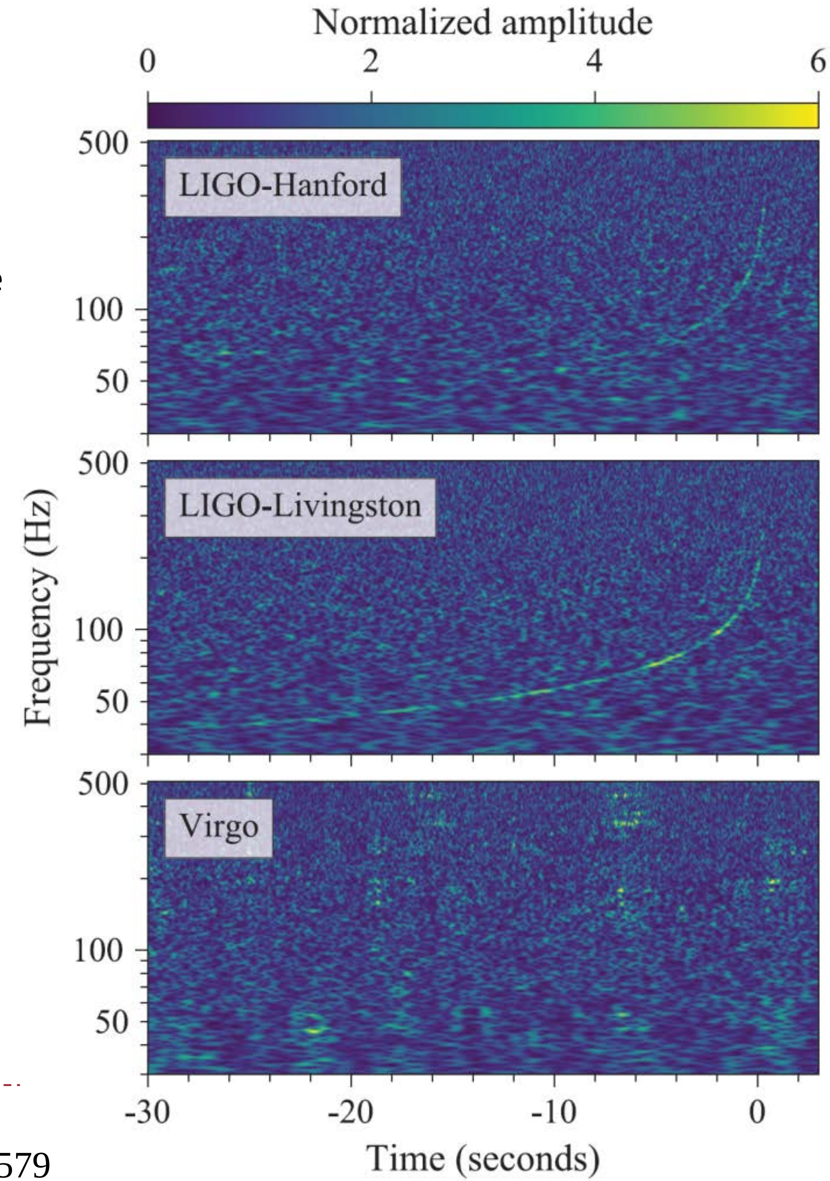
- BH or NS ⇒ **maximum mass**
- GWs from massive NS ⇒ **NS radius of *massive* NS**

Mass determination by the chirp signal

- S/N = 33.0 (signal to noise ratio)
  - Assumption/setup of data analysis :
    - NS is not rotating rapidly like BH
    - Using the EM counterpart SSS17a/AT2017gfo for the source localization
    - Using distance indicated by the red-shift of the host galaxy NGC 4993
- Chirp mass : $\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.186^{+0.001}_{-0.001} M_\odot$
  - Total mass : $2.74 M_\odot$ (1%)
  - Mass ratio : $m_1/m_2 = 0.7 - 1.0$
    - **Primary mass (m1) : $1.46^{+0.12}_{-0.10} M_\odot$**
    - **Secondary (m2) : $1.27^{+0.09}_{-0.09} M_\odot$**

90% C.L

- Luminosity distance to the source : 40^{+10}_{-10} Mpc



LIGO-Virgo Collaboration GWTC-1 paper
See also Abbott et al. PRL 119, 161101 (2017); arXiv:1805.11579

Tidal deformability

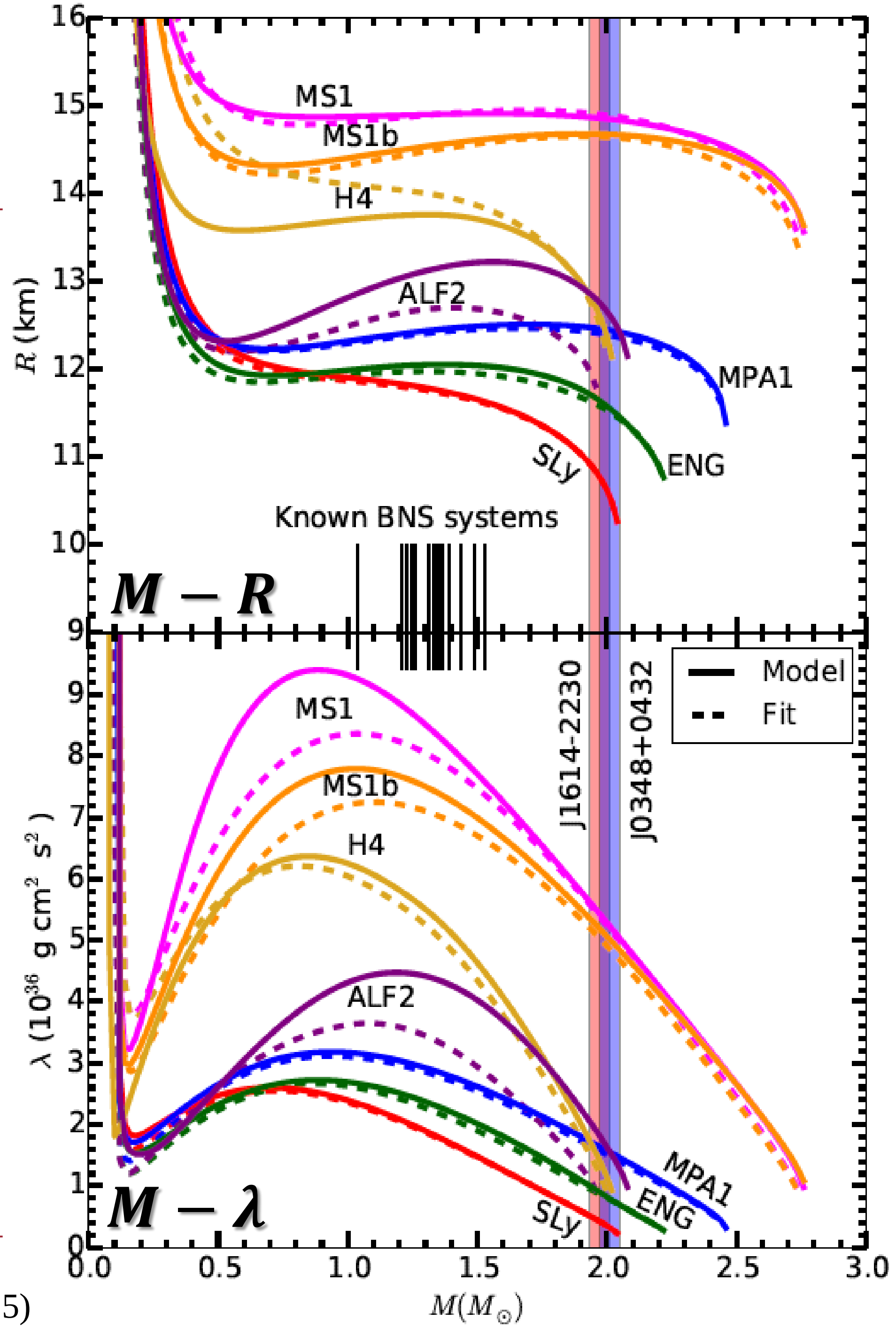
- Tidal Love number : λ
  - Response of quadrupole moment Q_{ij} to external tidal field E_{ij}

$$Q_{ij} = -\lambda E_{ij}$$

  - Stiffer NS EOS
  - $\Rightarrow$ NS Gravity can be supported with less contraction
  - $\Rightarrow$ larger NS radius
  - $\Rightarrow$ larger λ
  - $\Rightarrow$ larger deviation from point particle GW waveform
  - Tidal deformability (non-dim.) : Λ

$$\lambda = \frac{C^5}{G} \Lambda R^5 \qquad C = \frac{GM}{c^2 R}$$

Compactness parameter



Lackey et al. PRD 91, 043002(2015)

The first PRL paper : upper limit on $\tilde{\Lambda}$

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

$$\tilde{\Lambda} < 800 \quad \Longrightarrow \quad \Lambda_{1.4} \lesssim 800$$

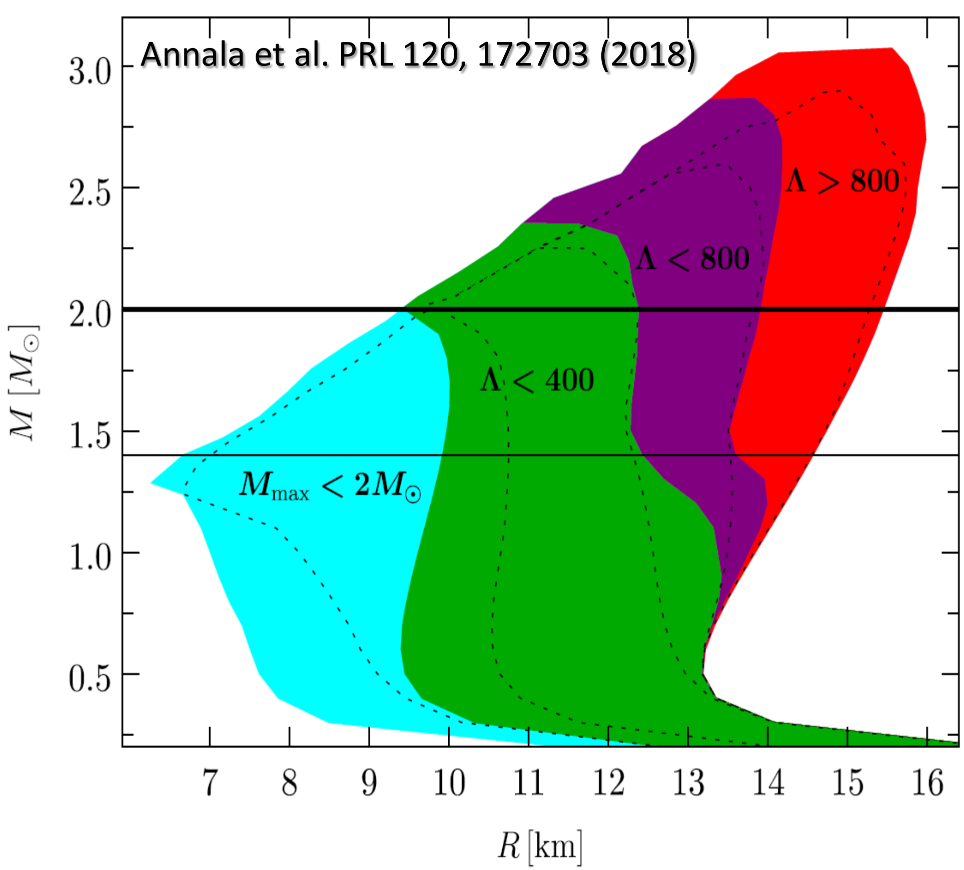
- The analysis with **GW data only**, the other constraints such as
  - causality ($c_S < c$), $M_{\mathrm{EOS,max}} \gtrsim 2M_{\odot}$, nuclear experiments
  - the two NS should obey the same EOS
  - use of mass distribution of the observed binary pulsar as prior
- were **NOT** taken into account

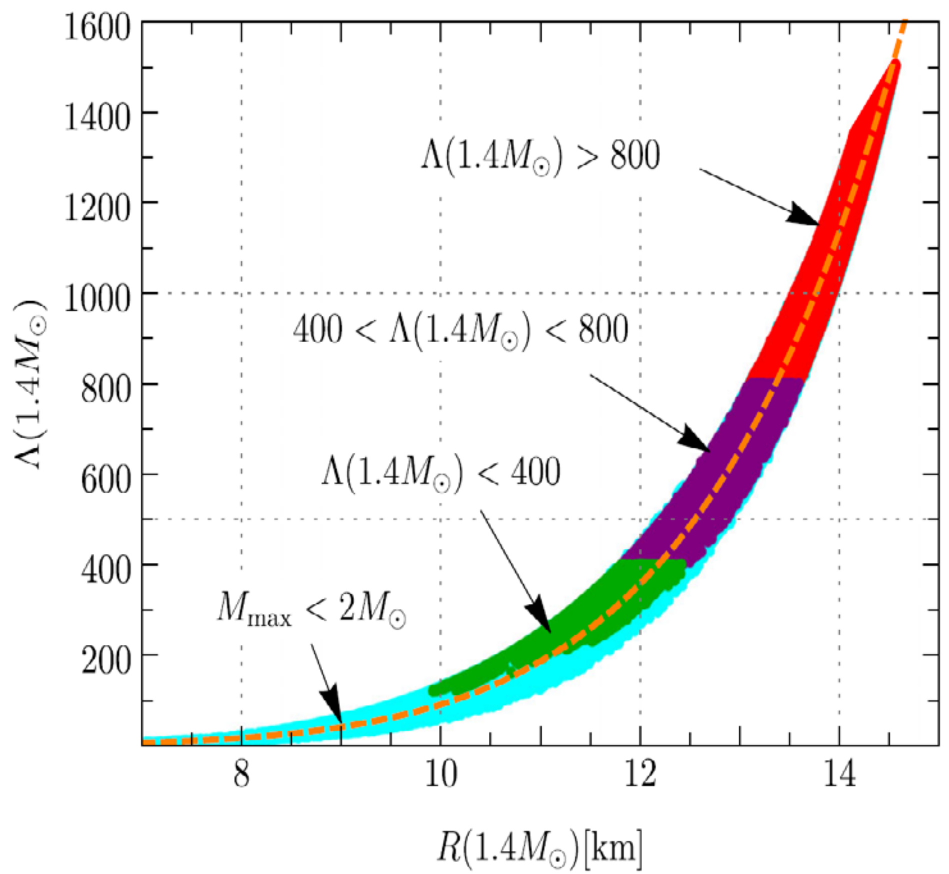
$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Annala et al. PRL 120, 172703 (2018)

Impact of $\tilde{\Lambda} < 800$ on NS radius & EOS

- **$\Lambda_{1.4} \lesssim 800$: in terms of NS radius $10 \lesssim R_{1.4M_\odot} \lesssim 13.5$ km for an EOS**
  - connects to the NNLO pQCD (Kurkela et al. 2010) and chiral EFT (Hebeler et al. 2013)
  - causality $c_s < c$ and $M_{\mathrm{EOS,max}} \gtrsim 2M_\odot$ constraints in the intermediate region

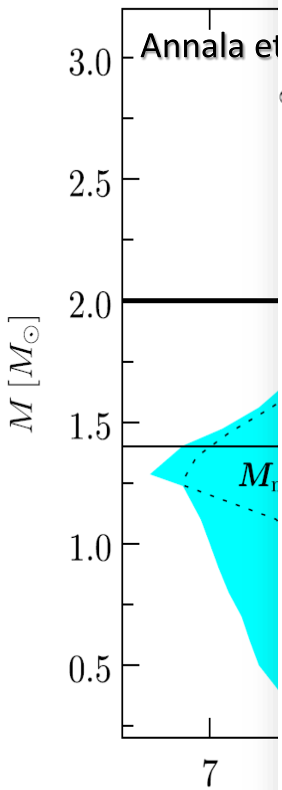


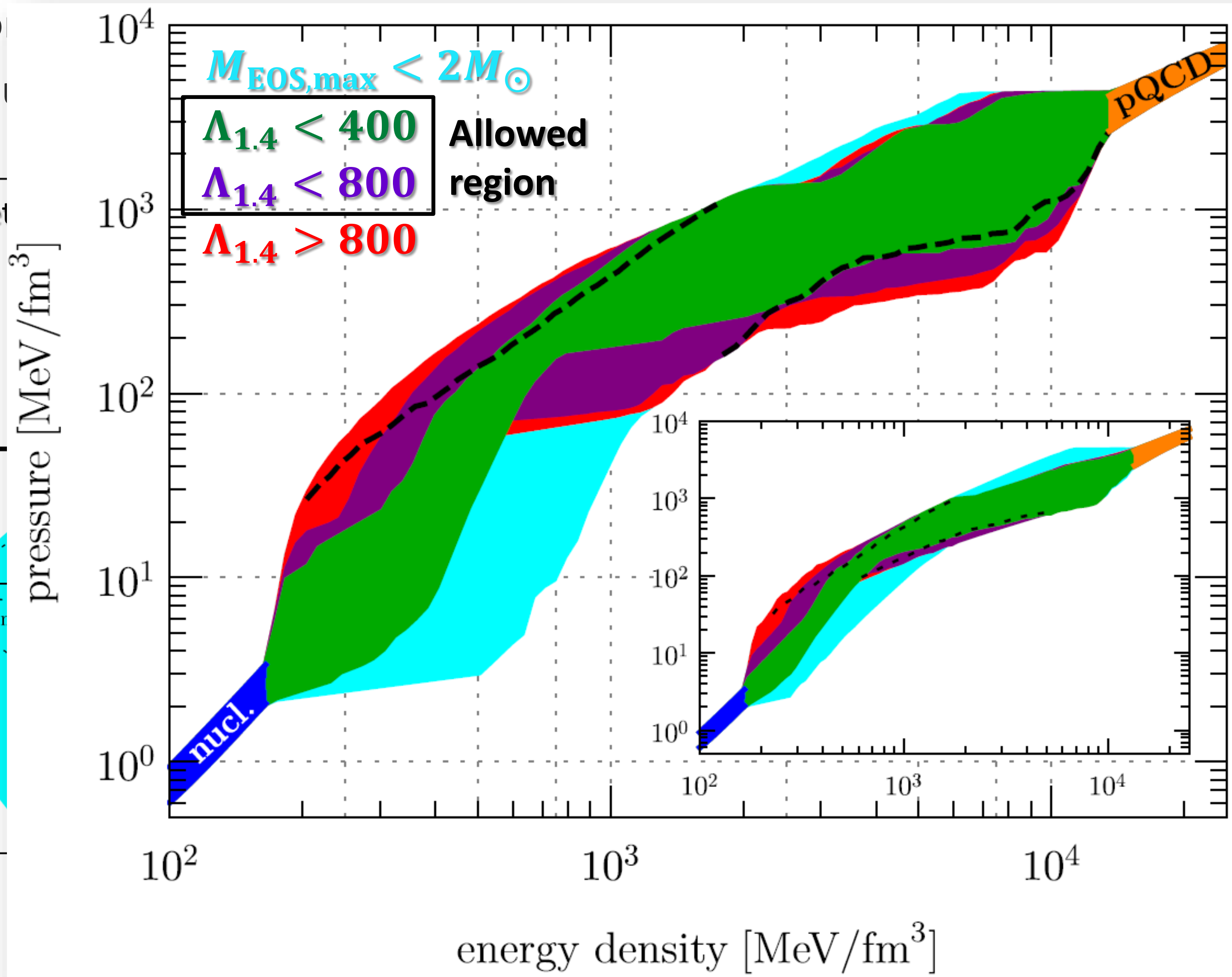


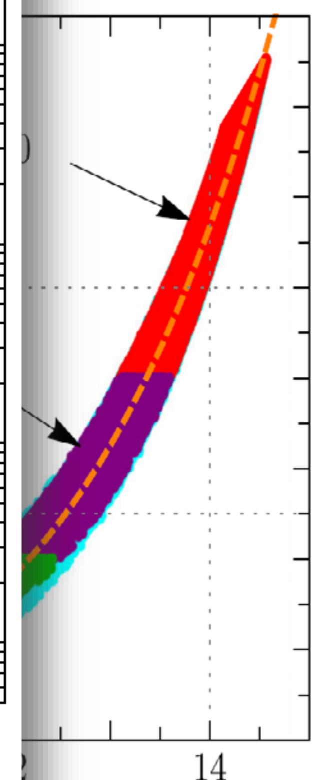
Annala et al. PRL 120, 172703 (2018)

Impact of $\tilde{\Lambda} < 800$ on NS radius & EOS

- $\Lambda_{1.4} \lesssim 800$: in terms of NS radius $10 \lesssim R_{1.4M_\odot} \lesssim 13.5$ km for an EOS
  - co … 2013)
  - ca … region







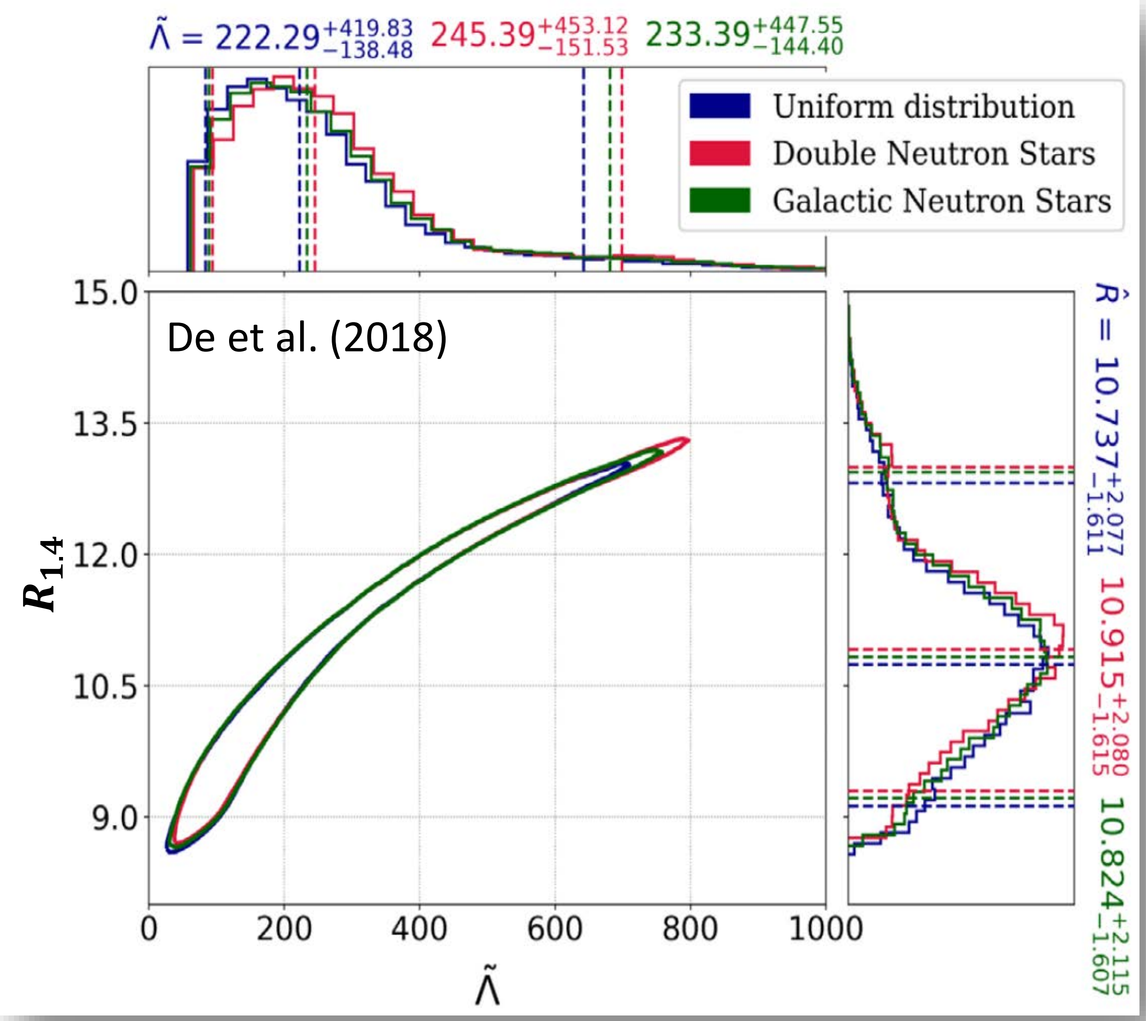
Impact of $\tilde{\Lambda} < 800$: the other studies

- Almost all studies assume some phenomenological EOS model as in Annala et al. (2018)
  - Annala et al. (2018) : chiral EFT (up to 1.1ns) + pQCD
    - $120 \lesssim \Lambda_{1.4} \lesssim 800$, $10 \lesssim R_{1.4} \lesssim 13.6$ km
  - Tews et al. (2018) : chiral EFT (up to 2ns !!)
    - $80 \lesssim \Lambda_{1.4} \lesssim 570$ (the upper limit from EOS model, not from GW data)
  - Fattoyev et al. (2018) : using results of PREX (Pb Rudius EXperiment)
    - $400 \lesssim \Lambda \lesssim 800$, $12 \lesssim R_{1.4} \lesssim 13.6$ km (lower limit from $R_{\rm skin}^{208} \gtrsim 0.15$fm)
    - suggest large symmetry energy $\Rightarrow$ larger NS radius
  - Malik et al. (2018) : using nuclear data (symmetry energy, incompressibility)
    - $12 \lesssim R_{1.4} \lesssim 14$ km
  - only an earlier studies are listed, there are many other studies

De et al. PRL 121, 091102 (2018)

Importance of the other constraints

- **GW data analysis** (not interpretation of $\tilde{\Lambda} < 800$) using constraints of
  - causality ($c_s < c$)
  - $M_{\mathrm{EOS,max}} \gtrsim 2M_\odot$
  - nuclear experiments
  - the two NS (Λ) should obey the same EOS
  - use of mass distribution of the observed binary pulsar as prior in the Bayesian analysis



$$\tilde{\Lambda} \sim 100 - 700$$

$$R_{1.4} \sim 9 - 13\ \mathrm{km}$$

- De et al. PRL 121, 091102 (2018)

Importance of GW template

- GW template used in the first PRL paper and De et al. was not good !
  - used **3.5PN**（Post-Newtonian）**point-particle** waveform (TaylorF2)
    - 3.5PN : relativistic correction up to $(v/c)^{2\times 3.5} \sim G^{3.5}$
  - **Tidal (non-point-particle) effects join at 5PN**
    - at least 5PN *point-particle* waveform is necessary to extract $\tilde{\Lambda}$ correctly
    - Otherwise $\tilde{\Lambda}$ will be overestimated because tidal effects would be contaminated by PN point particle corrections
  - ⇒ importance of adopting higher-order PN waveforms or **numerical-relativity (NR)** (calibrated) templates

Abbott et al. PRL 121, 161101 (2018)

Update analysis with NR waveform

PHYSICAL REVIEW LETTERS **121,** 161101 (2018)

Editors' Suggestion

GW170817: Measurements of Neutron Star Radii and Equation of State

B. P. Abbott *et al.**

(The LIGO Scientific Collaboration and the Virgo Collaboration)

(Received 5 June 2018; revised manuscript received 25 July 2018; published 15 October 2018)

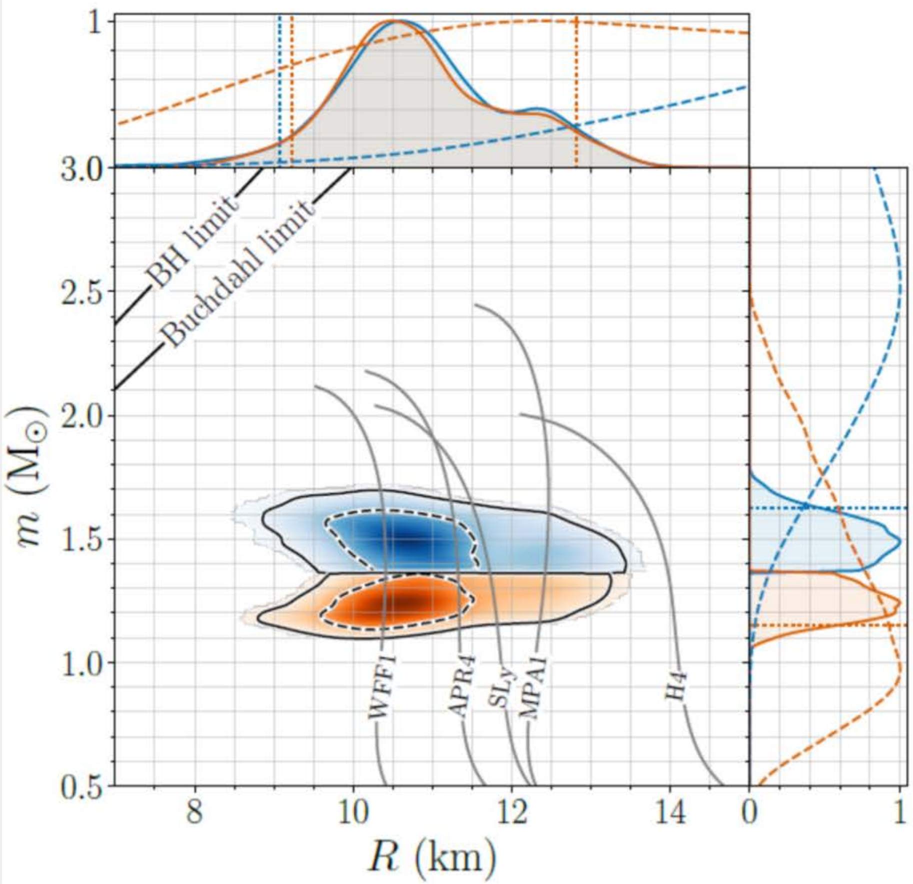
- waveform calibrated by **numerical relativity** simulations
- wider data range 30-2048 Hz ⇒ 23-2048 Hz (≈1500 cycle added)
- source localization from EM counterpart SSS17a/AT2017gfo
- the causality and maximum NS mass constraints are also considered

$$\tilde{\Lambda} < 800 \Rightarrow \tilde{\Lambda} \approx 300^{+400}_{-200}$$

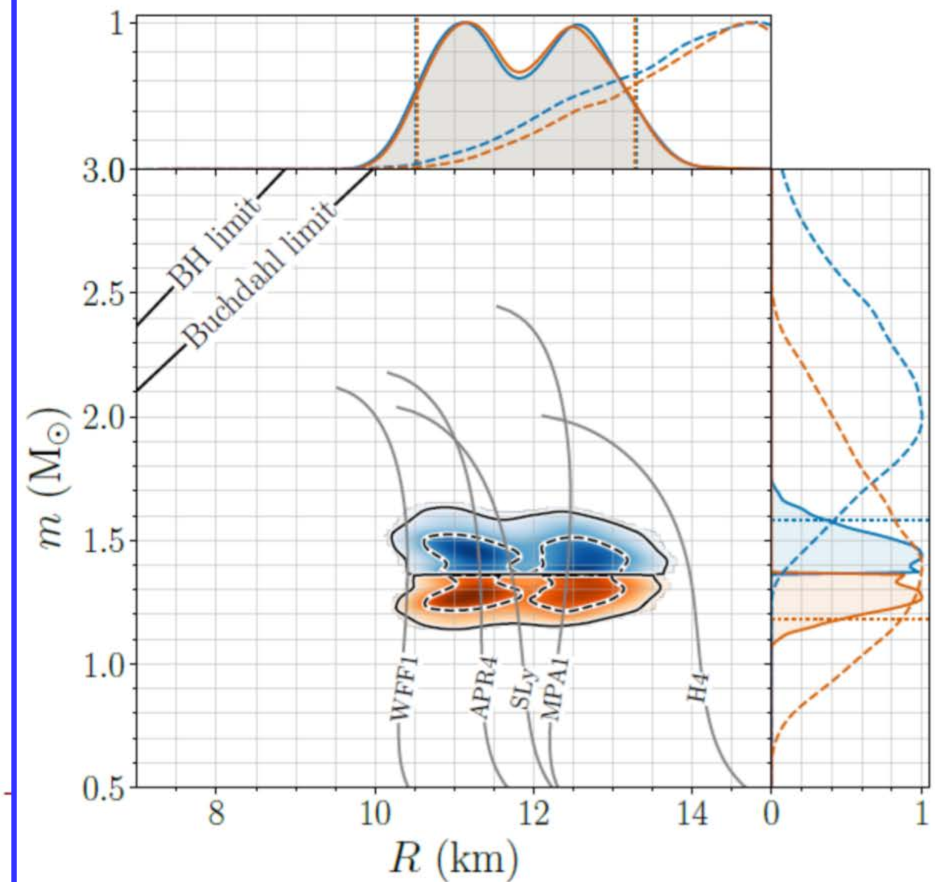
Abbott et al. PRL 121, 161101 (2018)

Update analysis with NR waveform

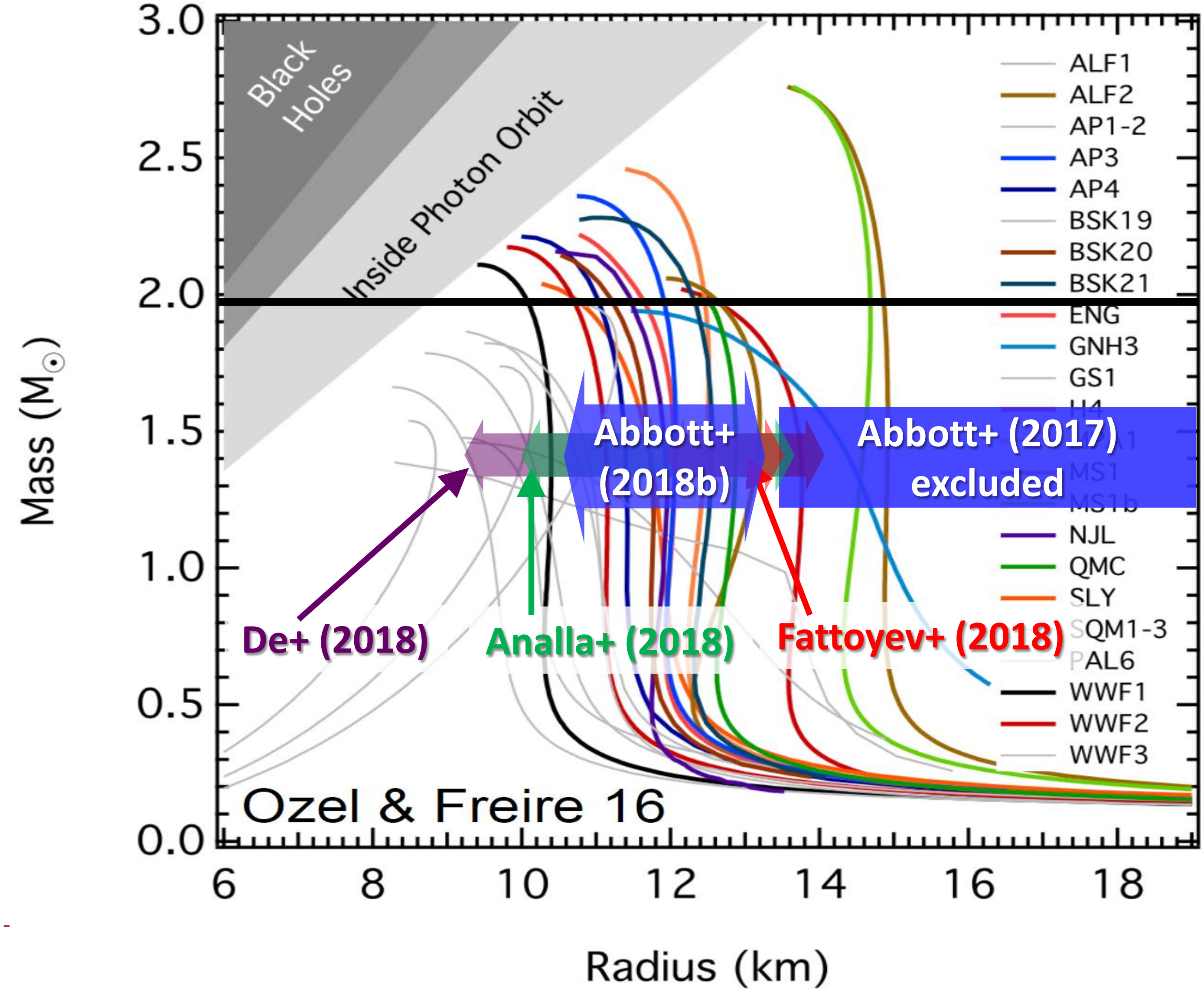
- Analysis without $2M_\odot$ constraint
  - $R_1 = 10.8^{+2.0}_{-1.7}$ km
  - $R_2 = 10.7^{+2.1}_{-1.5}$ km



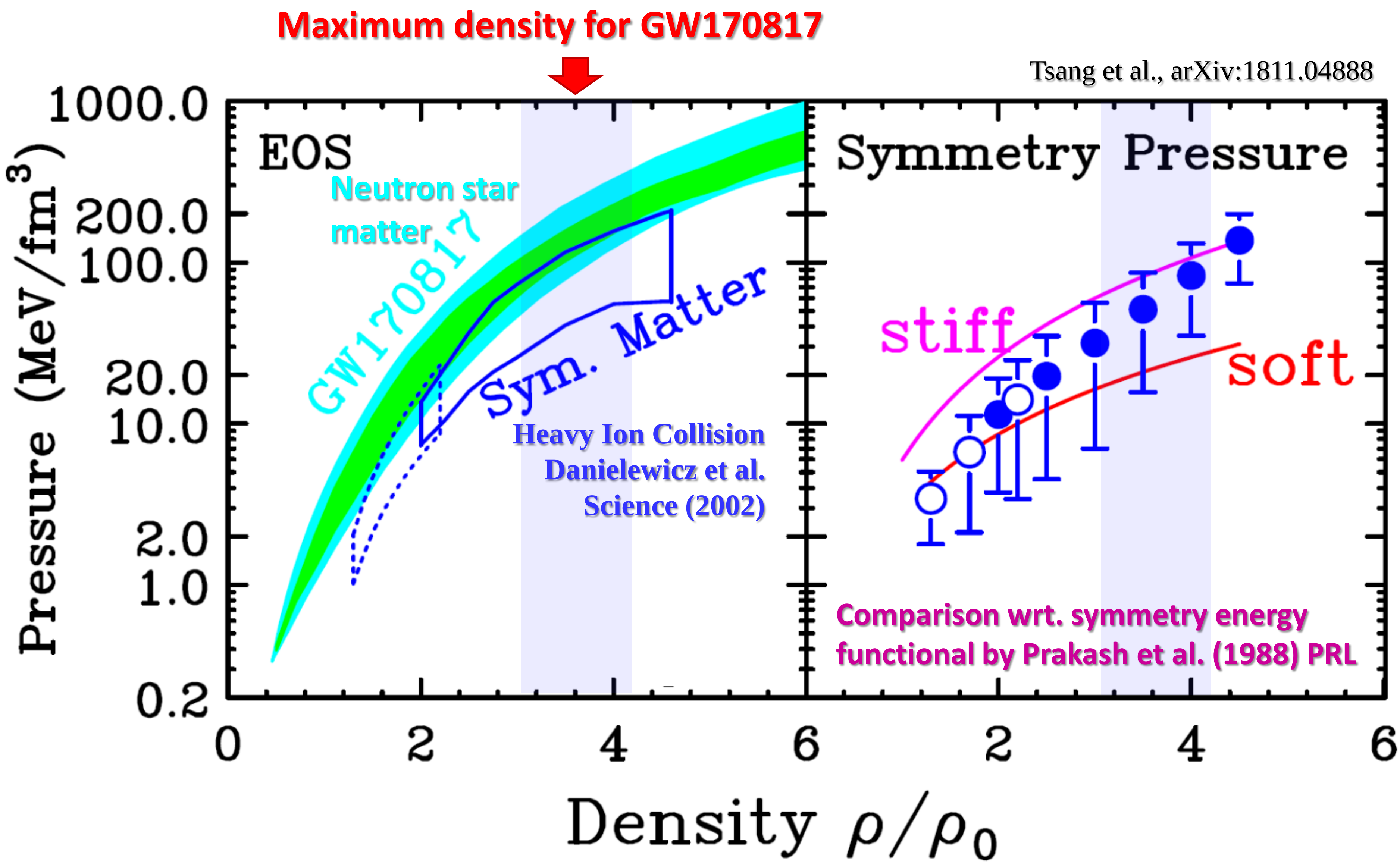
- Analysis with $2M_\odot$ constraint
  - $R_1 = 11.9^{+1.4}_{-1.4}$ km
  - $R_2 = 11.9^{+1.4}_{-1.4}$ km



A summary of NS structure constraint



EOS comparison : GW vs. Heavy Ion Col.

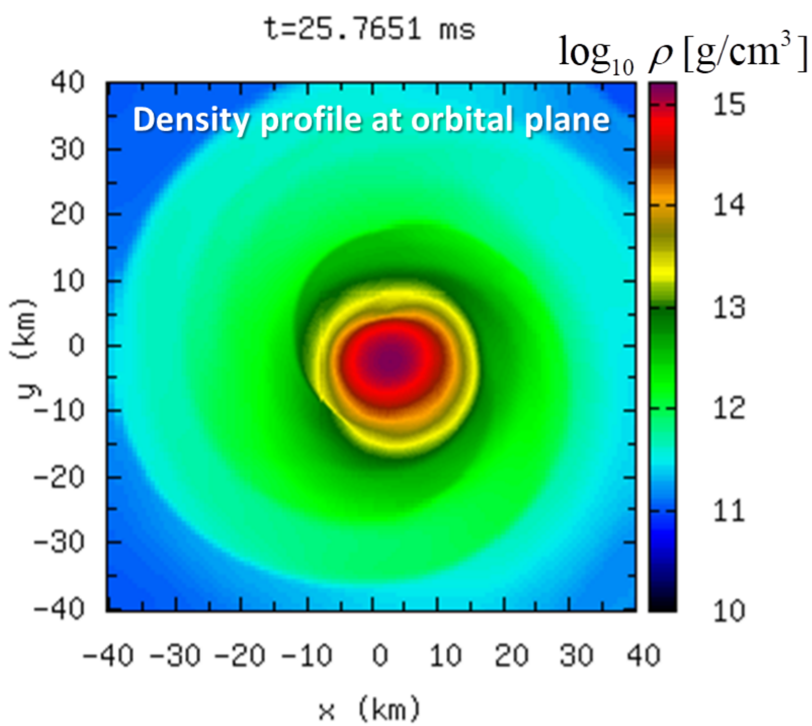


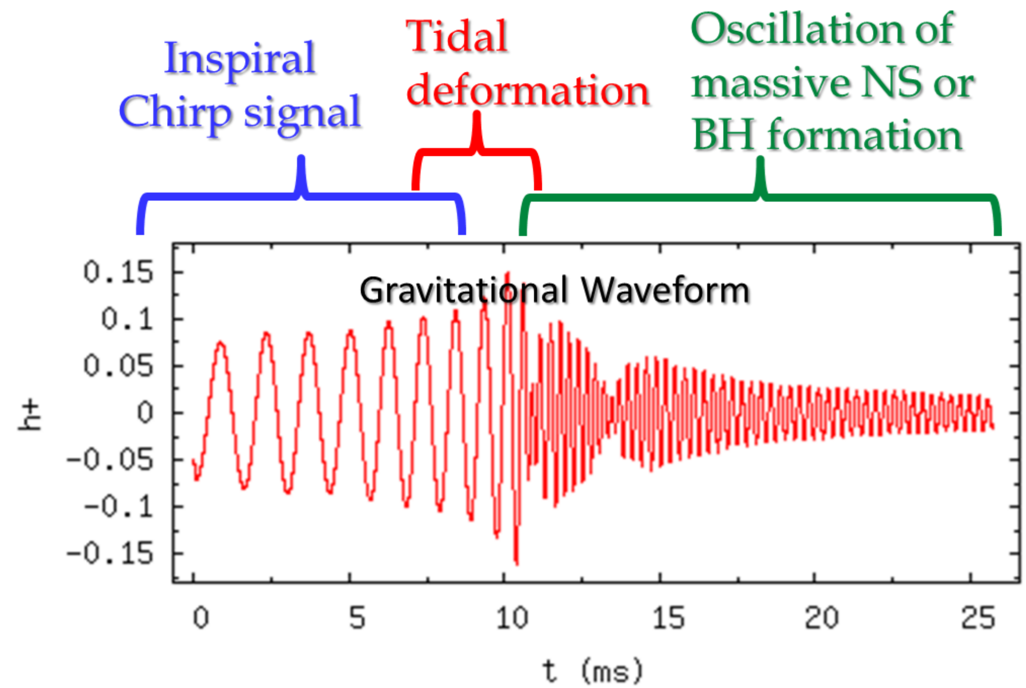
Q. How to explore the higher densities ?

A. Study GW from more massive NS for which the central density is higher

GW from post-merger phases

Numerical relativity simulation modelling GW170817





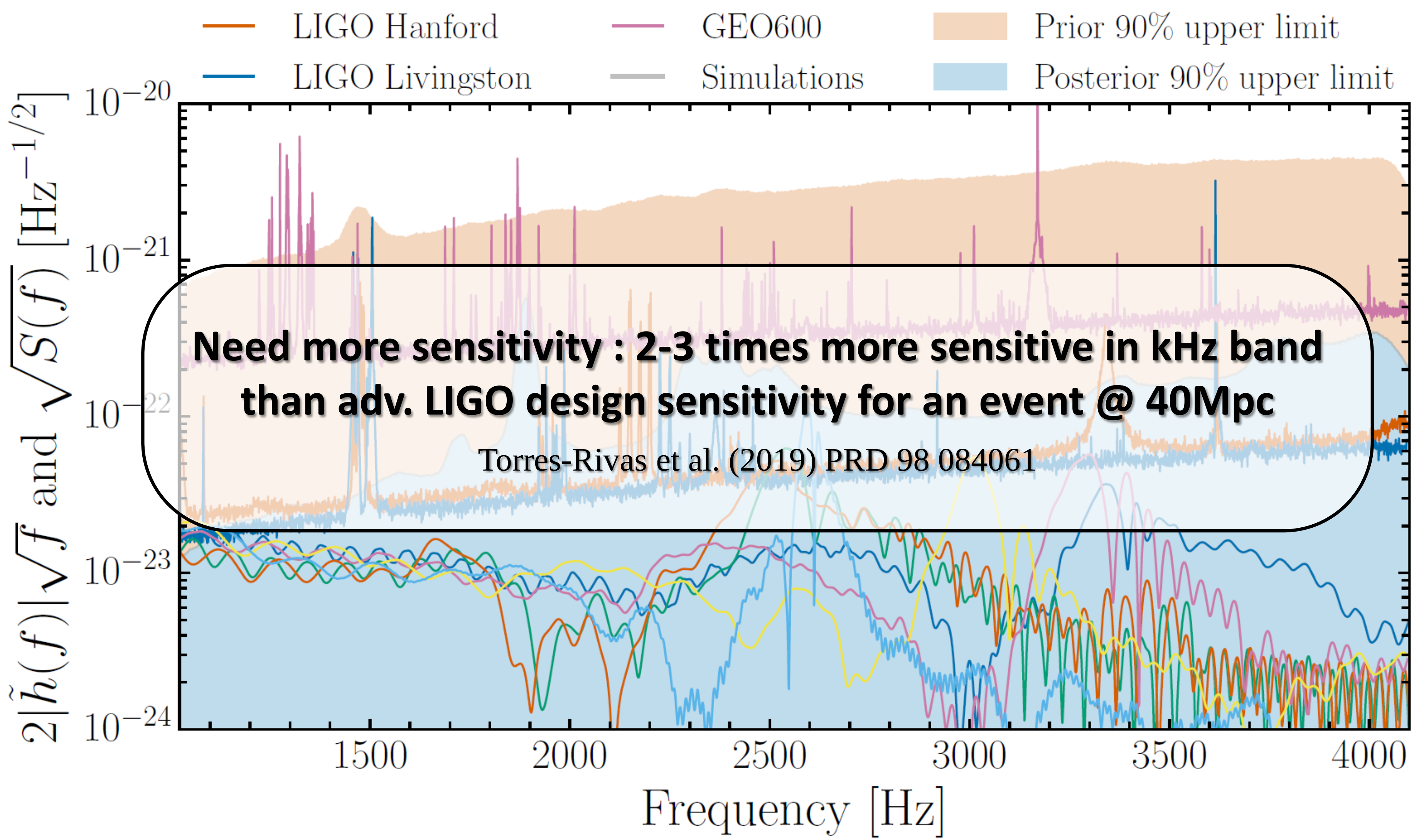
- point particle approx.
- information of binary parameter (**NS mass**, etc)

- finite size effect
- **NS tidal deformability**
- ⇒ **NS radius**

- BH or NS ⇒ **maximum mass**
- GWs from massive NS ⇒ **NS radius of *massive* NS**

Abbott et al. ApJL 851, L16 (2017); arXiv:1805.11579; see also arXiv:1810.02581

No GW from merger remnant detected



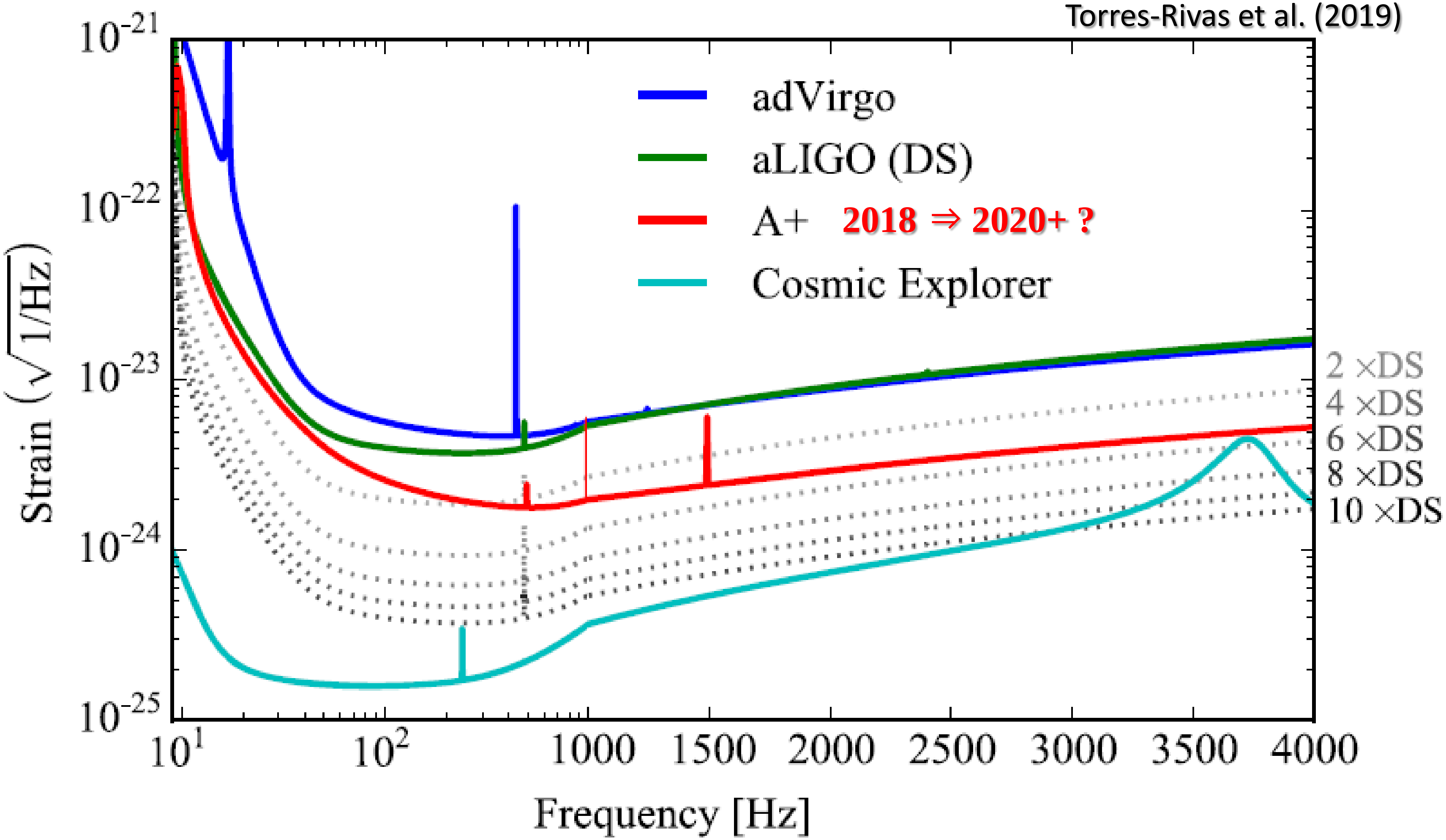
Need more sensitivity : 2-3 times more sensitive in kHz band than adv. LIGO design sensitivity for an event @ 40Mpc

Torres-Rivas et al. (2019) PRD 98 084061

Sensitivities of future detectors

- **LIGO A+** : a few times more sensitive in kHz band than adv. LIGO (Torres-Rivas et al. (2019) PRD 98 084061)

LIGO-T15TBI-v1 white paper
Torres-Rivas et al. (2019)



Constraints from EM signals

Constraints from EM observations

$$M_{\text{crit}} = M_{\text{EOS,max}} + \Delta M_{\text{rot,rig}} + \Delta M_{\text{rot,diff}} + \Delta M_{\text{therm}}$$

- **Condition 1 : BH should not form promptly after the merger**
  - need $M \gtrsim 0.01 M_\odot$ mass ejection to explain the observed kilonova

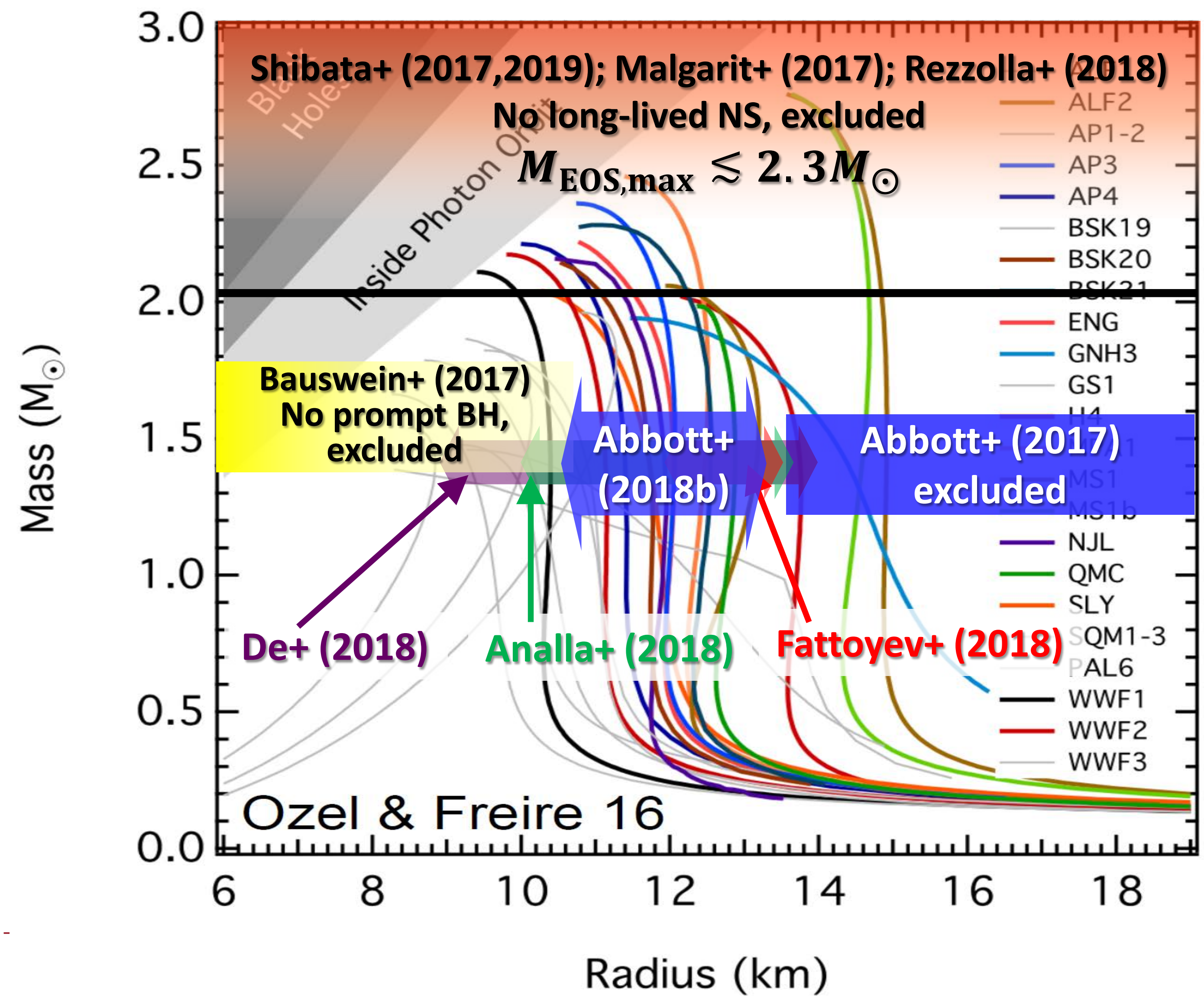
$$M_{\text{crit}} \gtrsim M_{\text{GW170817}} = 2.74 M_\odot$$

  - too soft EOS or too compact NS is excluded (e.g., Bauswein et al. 2017)
- **Condition 2 : massive NS formed after the merger should not be too long-lived**
  - No signal from long-lived NS (e.g. Sun et al. 2017)

$$M_{\text{EOS,max}} + \Delta M_{\text{rot,rig}} \lesssim 2.74 M_\odot$$

  - stiff EOS with $M_{\text{EOS,max}} \gtrsim 2.3 M_\odot$ is excluded
  - Margalit & Metzger 2017; Shibata et al. 2017; Rezzolla et al. 2018

Summary of constraint on NS structure using both GW and EM

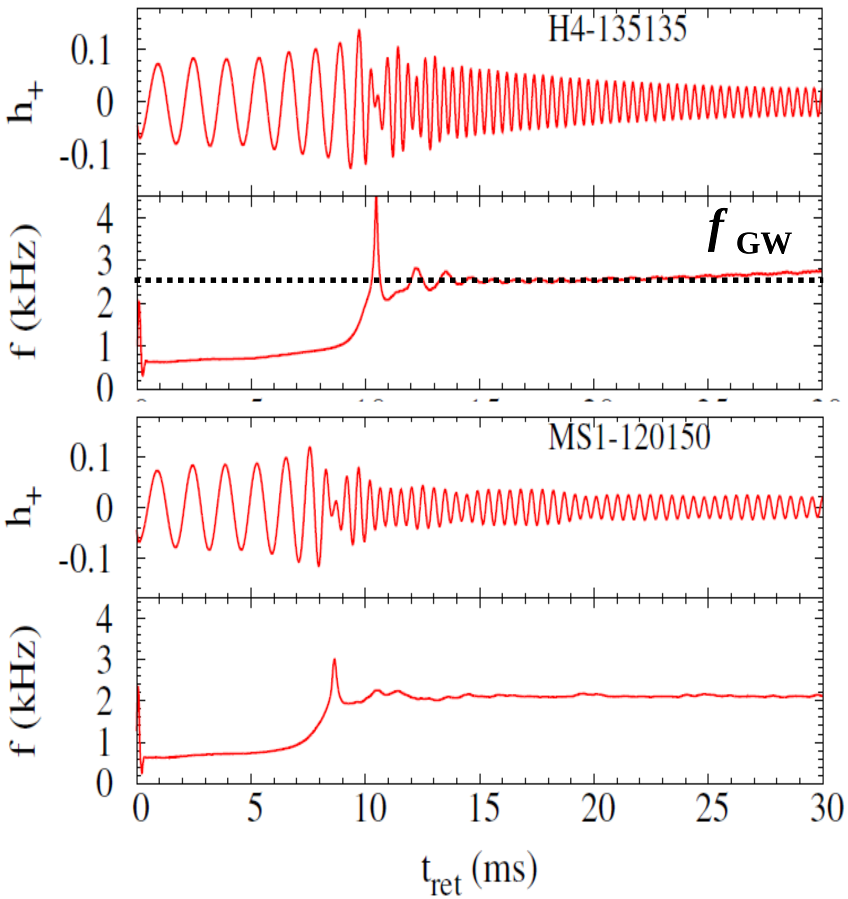


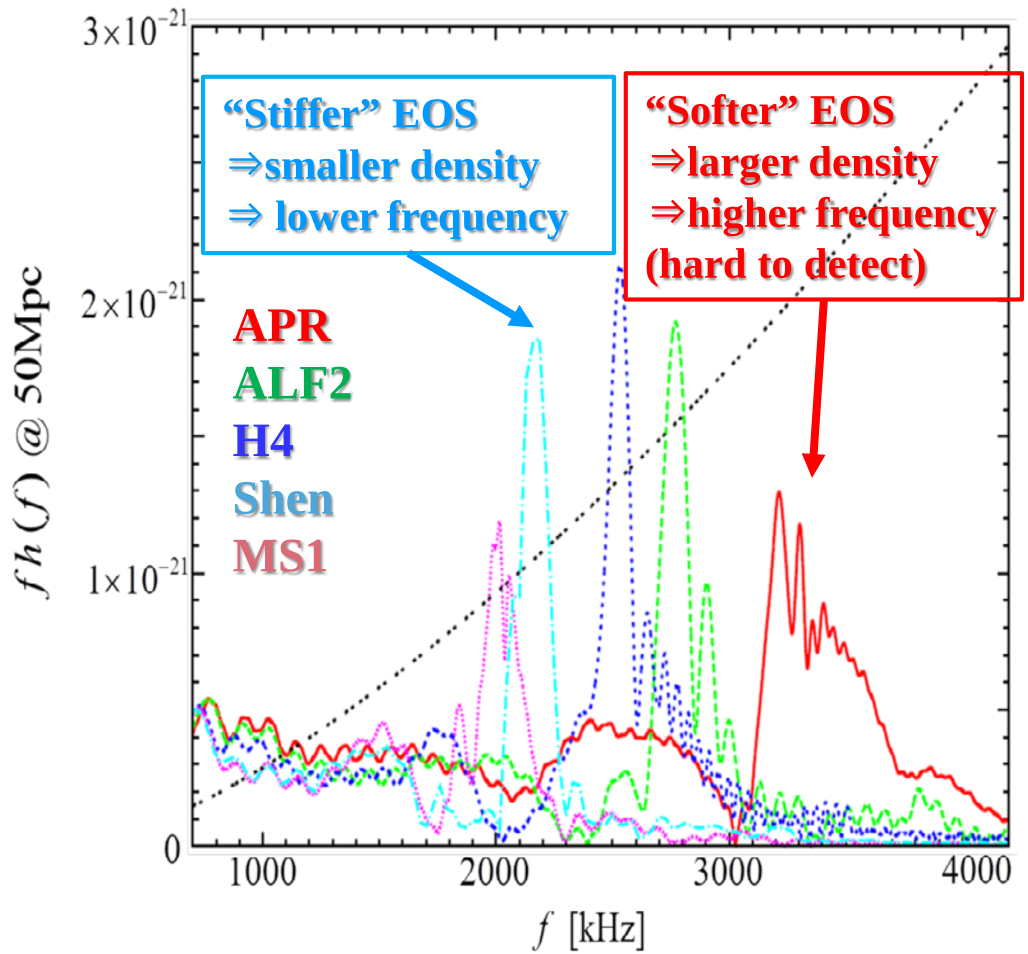
Future prospects

Listening GW from merger remnant NS

- Characteristic frequency of GW from merger remnant depends on EOS
  - If peak frequency can be determined within 10% error, then we could constrain radius of massive NS with $\Delta R \sim 1$ km

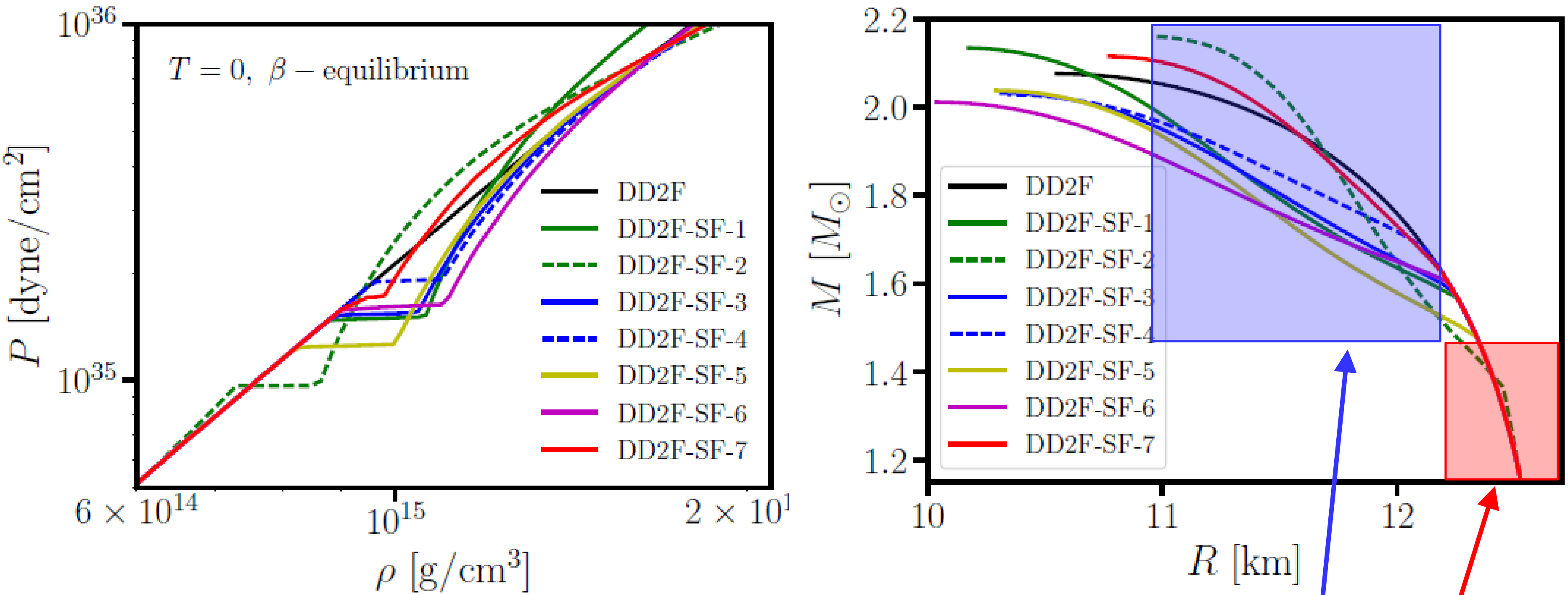
Hotokezaka et al. 2013; Bauswein et al. 2013





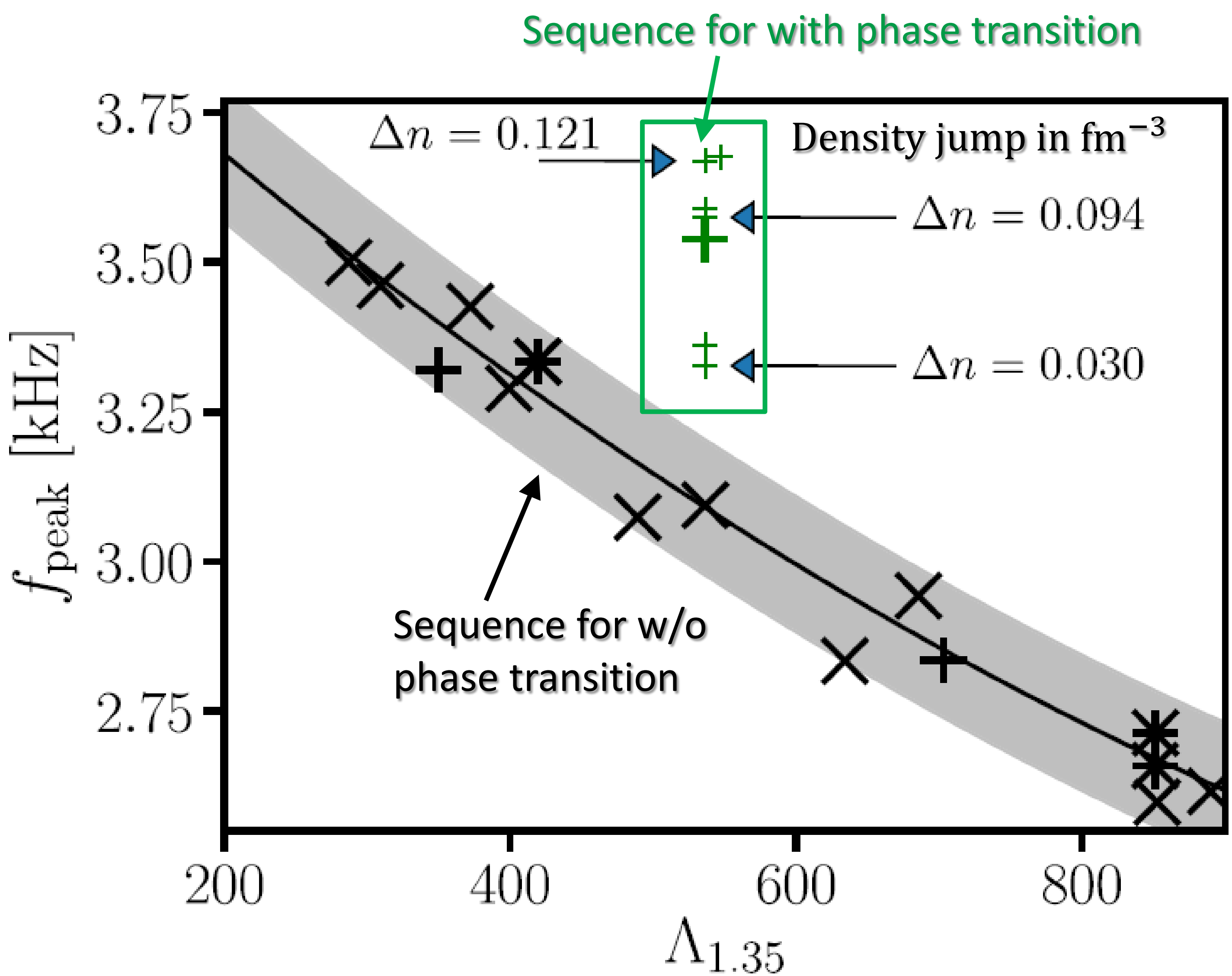
Bauswein et al. (2019) PRL 122 061102

Proving 1st order hadron-quark transition



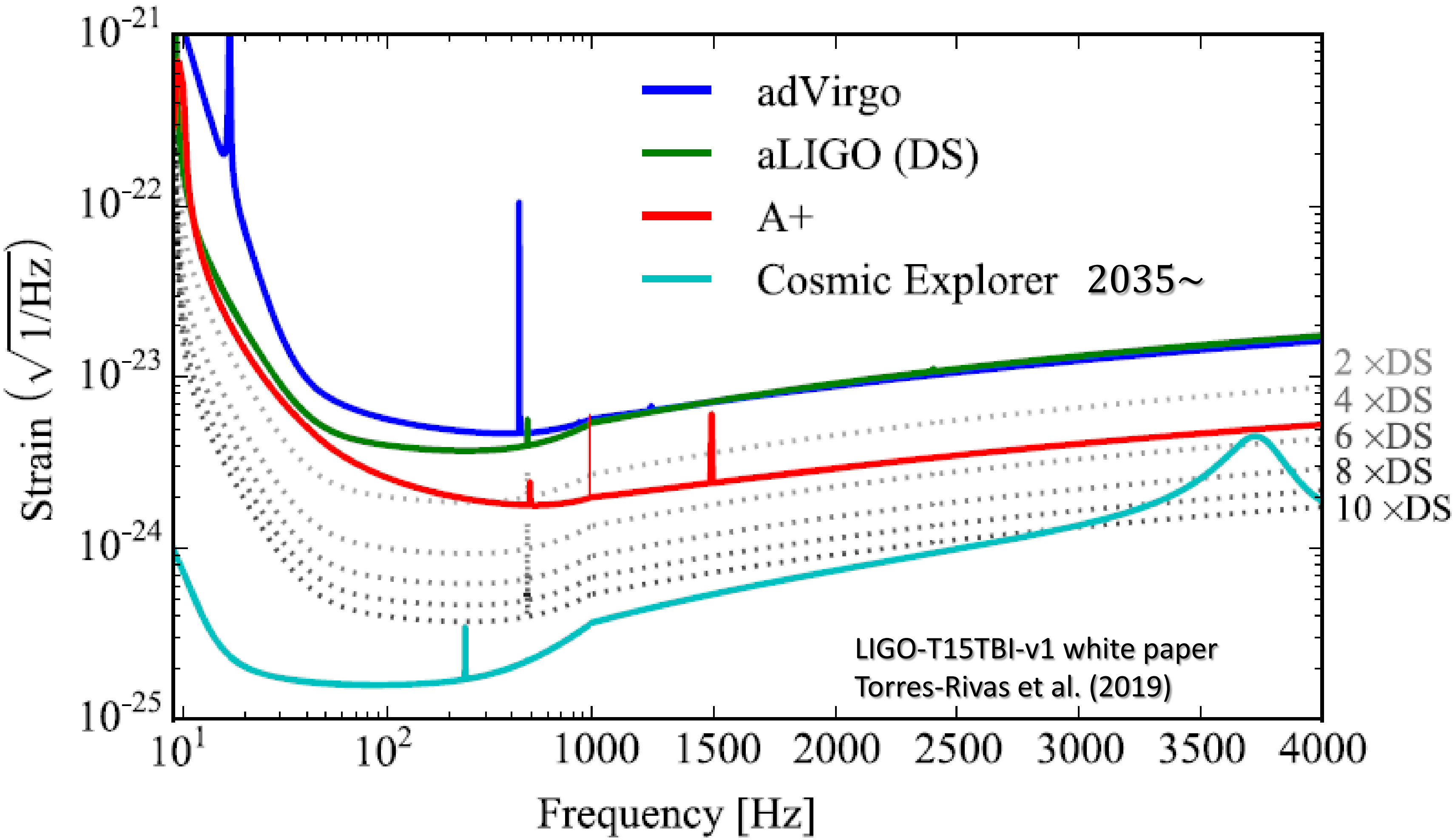
- If hadron-quark phase transition occurs at higher densities, so that the tidal deformability (structure) of $< 1.4 M_\odot$ NS is same
- On the other hand, structure of more massive NS is different $\Rightarrow$ the peak frequency of GW from post-merger system will be different

Proving 1st order hadron-quark transition

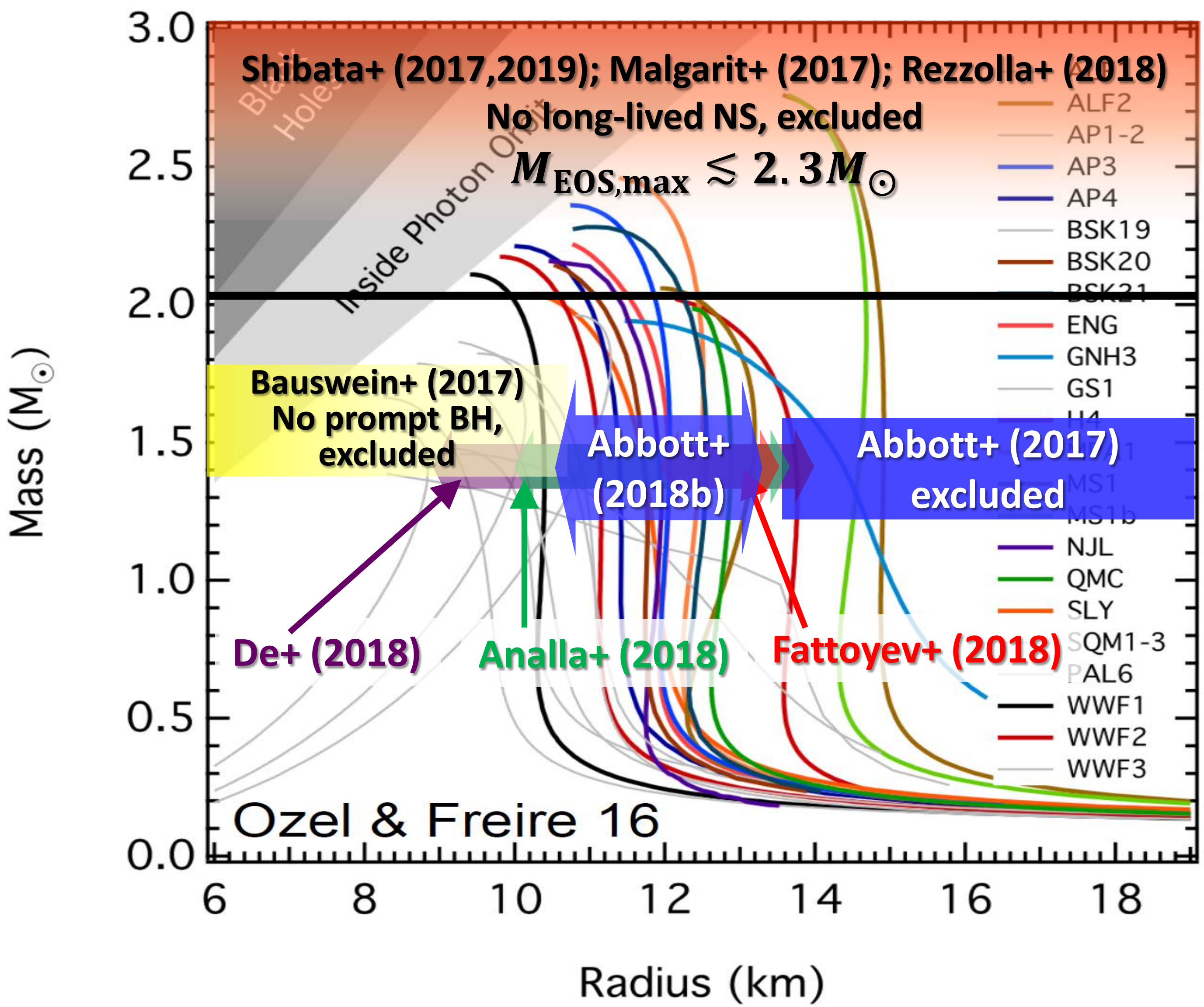


Sensitivities of future detectors

- Future detectors with 5-8 times more sensitive in kHz band (like Cosmic Explorer) will be necessary (Torres-Rivas et al. (2019) PRD 98 084061)



Summary of constraint on NS structure using both GW and EM



Summary

- Conservative result from tidal deformability extraction
  - Radius of $M = 1.4M_{\odot}$ NS : $10 \lesssim R_{1.4} \lesssim 13$ km
  - EOS constraint from GW is consistent with that from nuclear experiments and heavy ion collision
  - Using waveform calibrated by Numerical Relativity is very important
  - the results is not informative for $\rho > 3 - 4\rho_0$

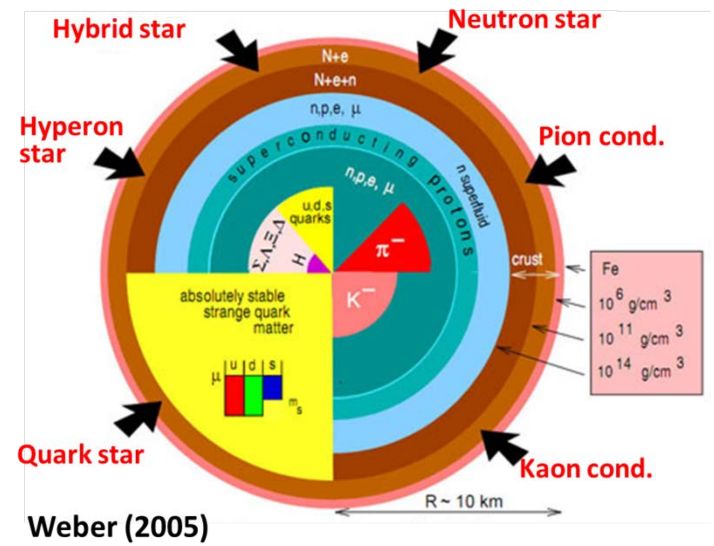
- To explore the higher density region, massive NS is necessary
  - GW from merger remnant NS , if detected, is a promising
  - Need 2-3 times higher sensitive that advanced LIGO $\Rightarrow$ next generation detector

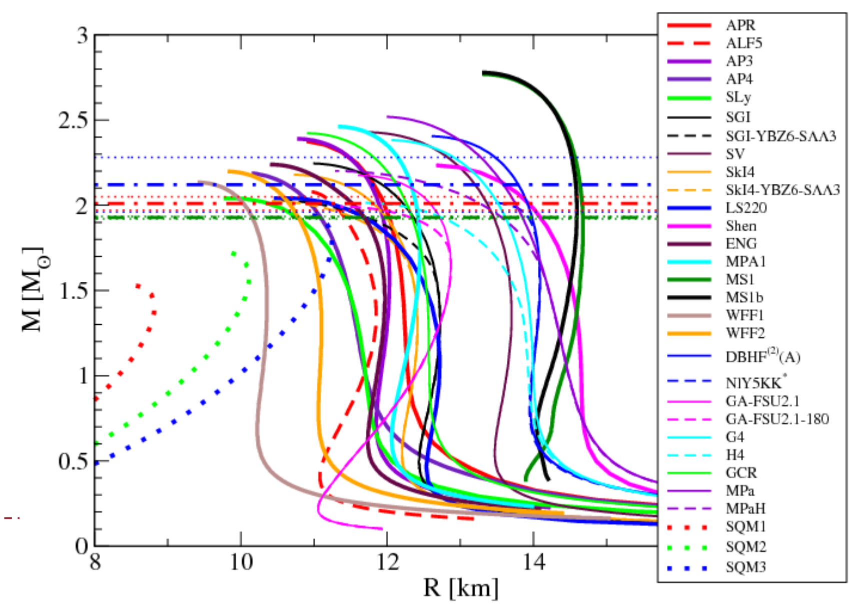
- Observation of EM signal will tell us about the maximum mass of NS
  - Estimated event rate is quite high 1-10/year
  - Numerical relativity simulation + theoretical modelling of EM signal is promising

Appendices

Major scientific achievements: GW170817 provided us clues to

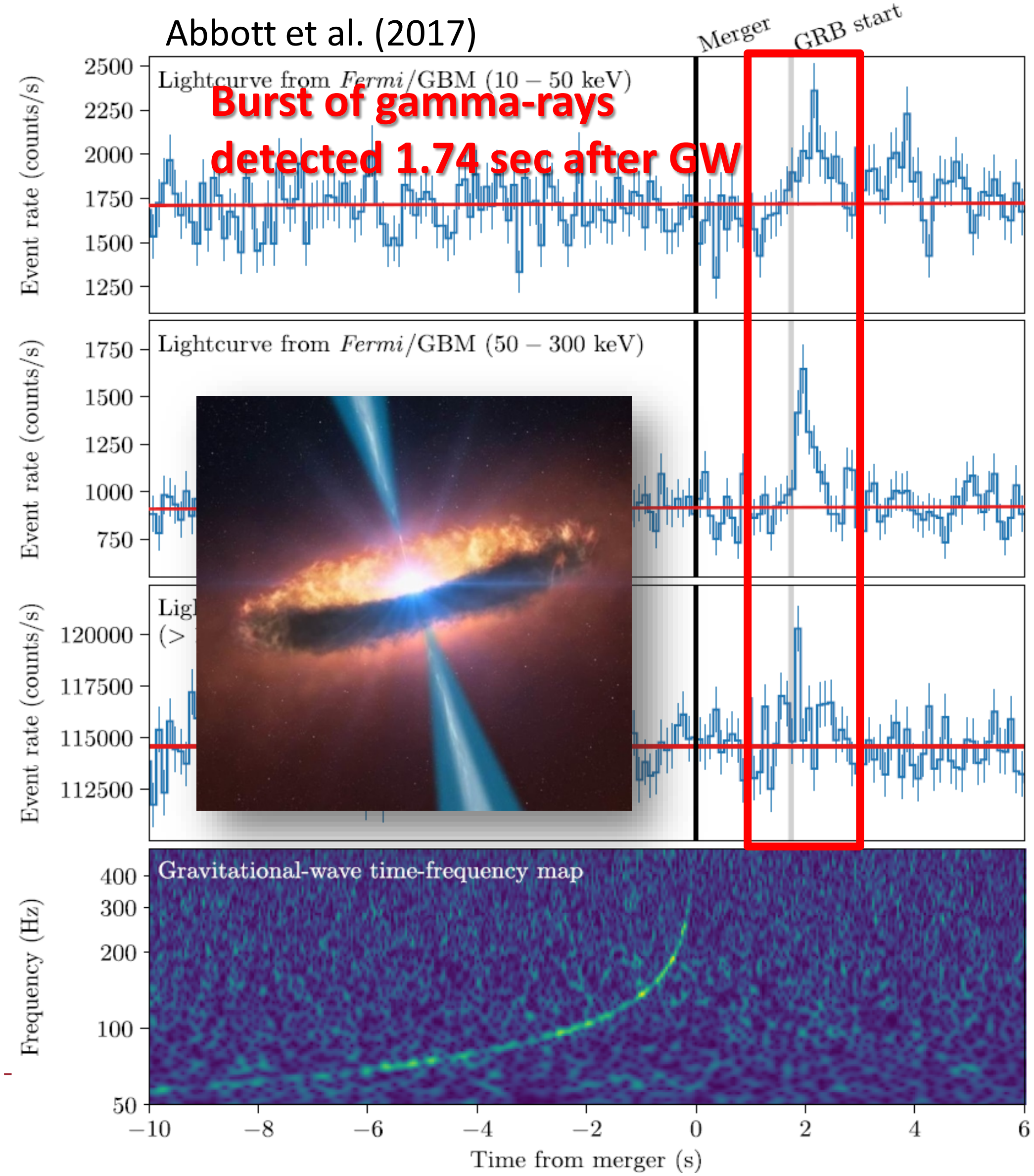
- **NS matter equation of state (EOS)**
  - **Tidal deformability extraction**
  - **Maximum mass constraint**
- Short gamma-ray bursts (SGRB) central engine
- Origin of heavy elements
  - r-process nucleosynthesis
  - kilonova/macronova from decay energy of the synthesized elements
- GW as standard siren
  - Hubble constant





Major scientific achievements: GW170817 provided us clues to

- NS matter equation of state (EOS)
  - Tidal deformability extraction
  - Maximum mass constraint
- **Short gamma-ray bursts (SGRB) central engine**
- Origin of heavy elements
  - r-process nucleosynthesis
  - kilonova/macronova from decay energy of the synthesized elements
- GW as standard siren
  - Hubble constant

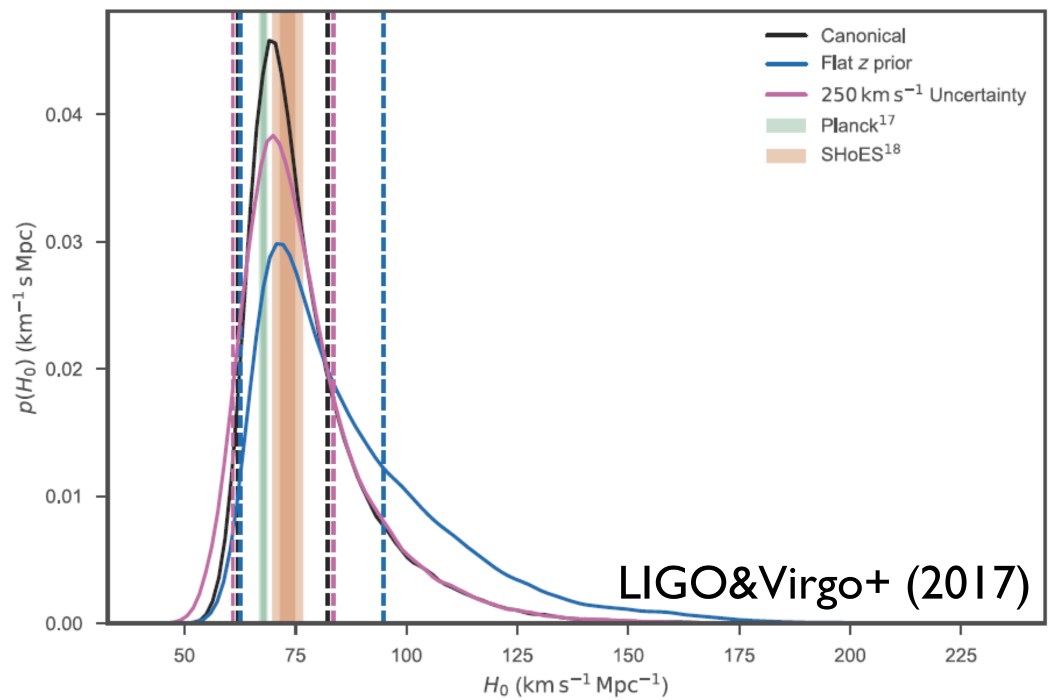


Major scientific achievements: GW170817 provided us clues to

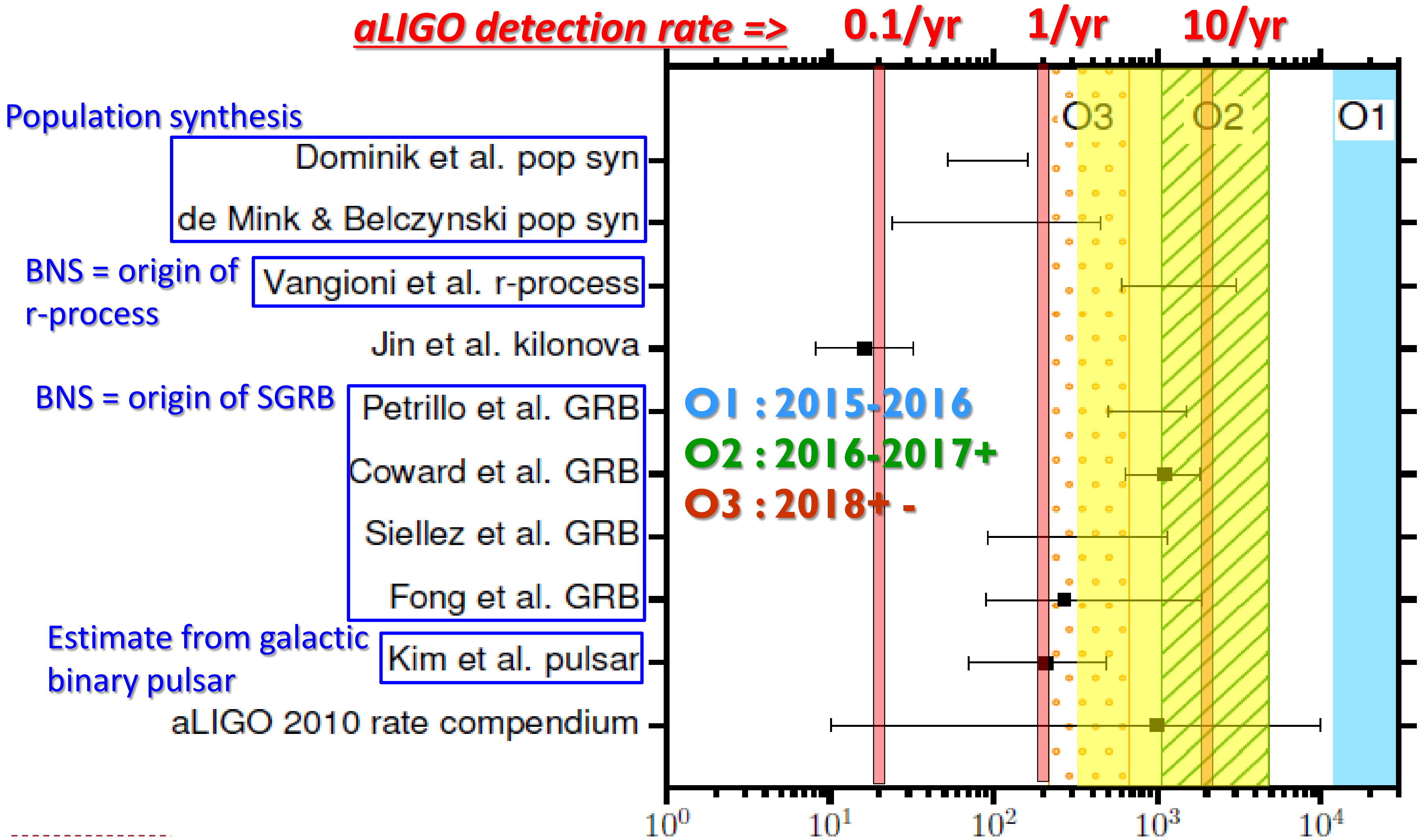
- NS matter equation of state (EOS)
  - Tidal deformability extraction
  - Maximum mass constraint
- Short gamma-ray bursts (SGRB) central engine
- **Origin of heavy elements**
  - **r-process nucleosynthesis**
  - **kilonova/macronova : UV-Infrared from decay energy of the synthesized elements**
- GW as standard siren
  - Hubble constant

Major scientific achievements: GW170817 provided us clues to

- NS matter equation of state (EOS)
  - Tidal deformability extraction
  - Maximum mass constraint
- Short gamma-ray bursts (SGRB) central engine
- Origin of heavy elements
  - r-process nucleosynthesis
  - kilonova/macronova from decay energy of the synthesized elements
- **GW as standard siren**
  - **Hubble constant**



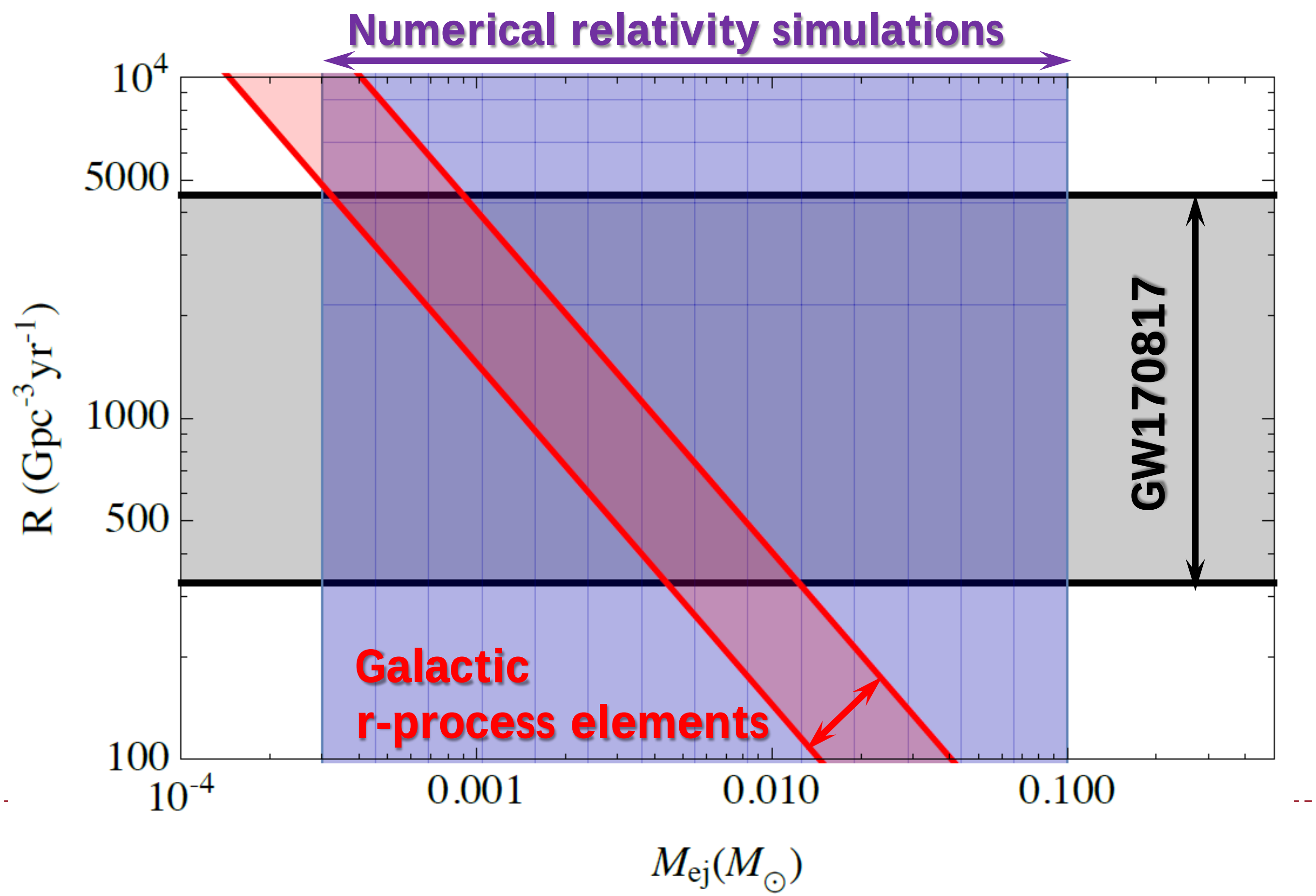
Expected NS-NS merger rate: **320-4740 $Gpc^{-3}yr^{-1}$**



Abbott et al. (2016)

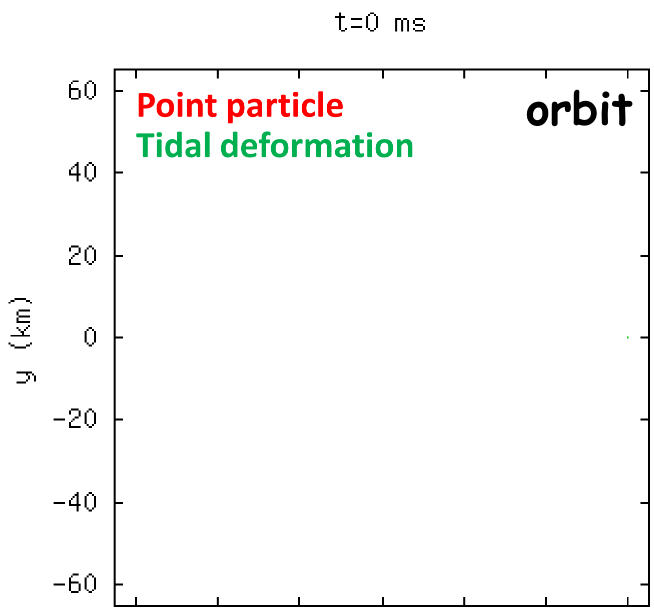
NS-NS merger as origin of r-process nucleosynthesis

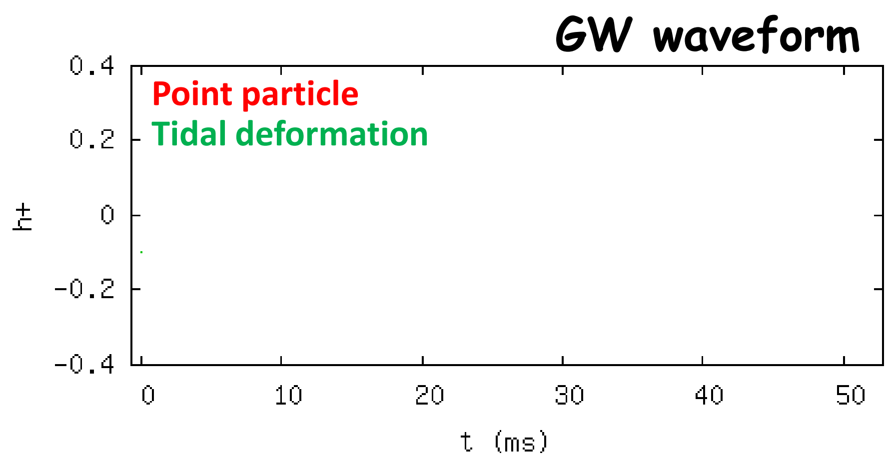
- NS-NS rate from GW170817 : 320-4740 $Gpc^{-3}yr^{-1}$
  - Mej ~ 0.01 Msun is sufficient for NS-NS merger to be the origin of r-process elements ! (Abbott et al. 2017)



Soft EOS (Smaller NS radius)

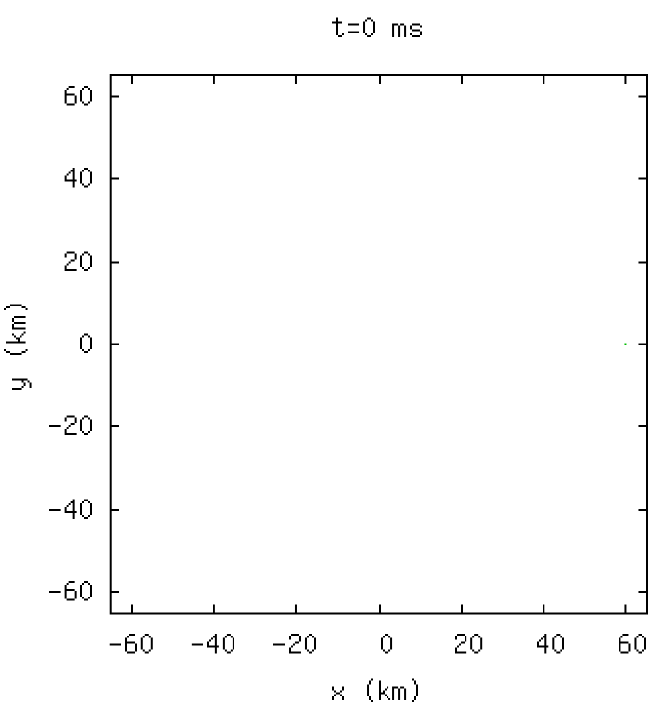
Effect of tidal deformation is not prominent

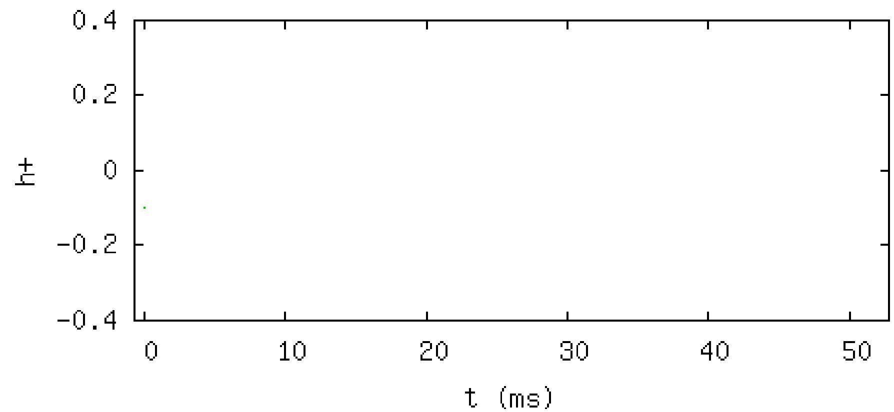




Stiff EOS (larger NS radius)

Deviation from point particle approximation can be clearly seen

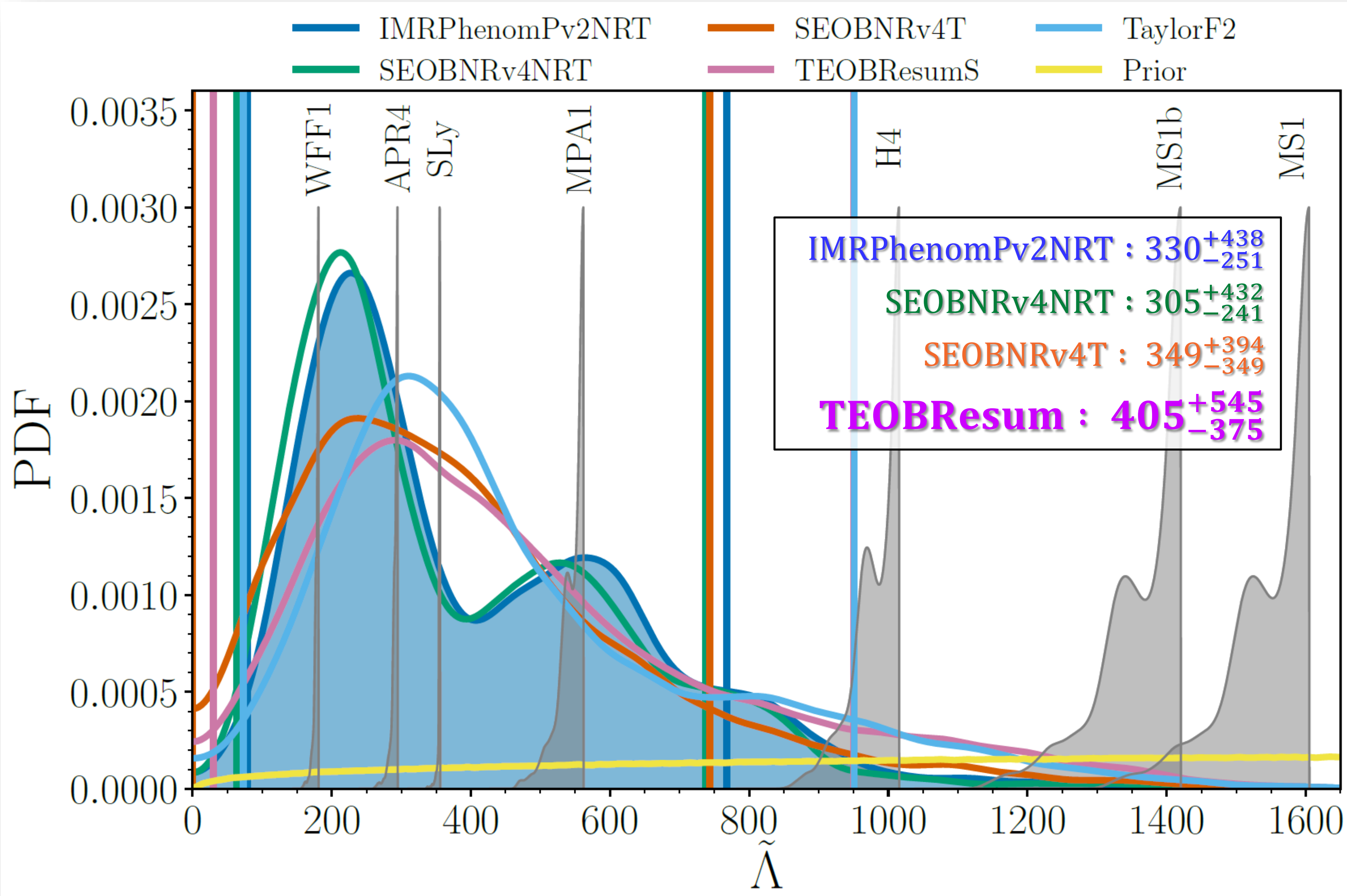




Importance of GW template

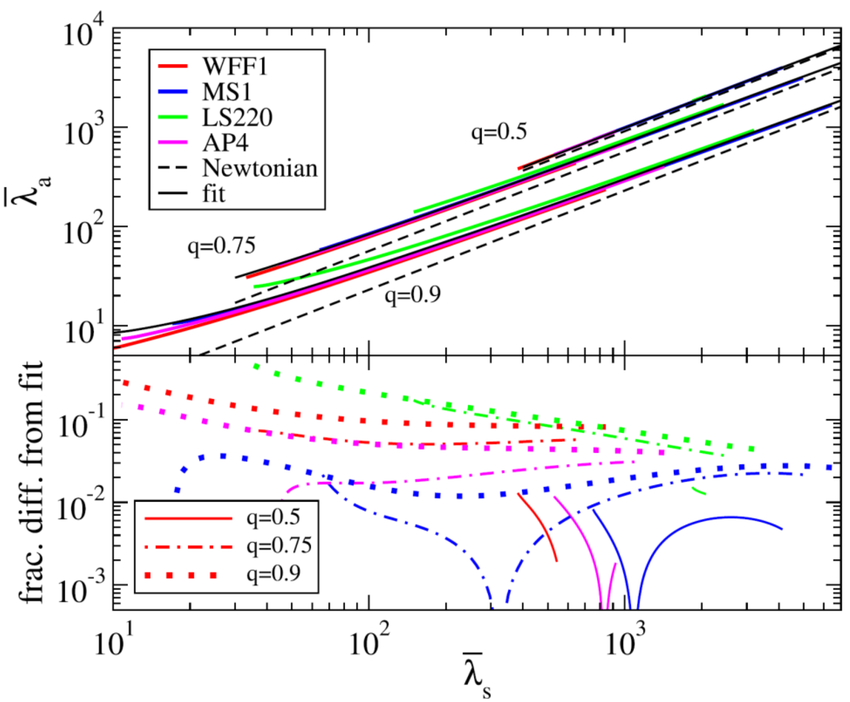
- Abbott et al. PRL (2017) : The 1st paper and the related papers
  - used **3.5PN** (Post-Newtonian) **point-particle** waveform (TaylorF2)
    - 3.5PN : relativistic correction up to $(v/c)^{2\times 3.5}$
  - **tidal effects** join at **5PN**
    - ⇒ at least 5PN *point-particle* waveform is necessary to extract $\tilde{\Lambda}$ correctly
    - Otherwise $\tilde{\Lambda}$ will be overestimated because tidal effects are contaminated by PN point particle corrections which are not taken into account
      - Modulations, which is due to 4-5PN+ point-particle corrections, are included in the tidal correction in an incorrect manner
  - Considerable difficulties in calculating higher order (> 4PN) waveform
    - No well-established PN waveform so far
      - But see 4.5PN waveform proposed in Messina & Nagar PRD 96, 049907 (2017)
    - ⇒ importance of **numerical-relativity (NR)** waveform

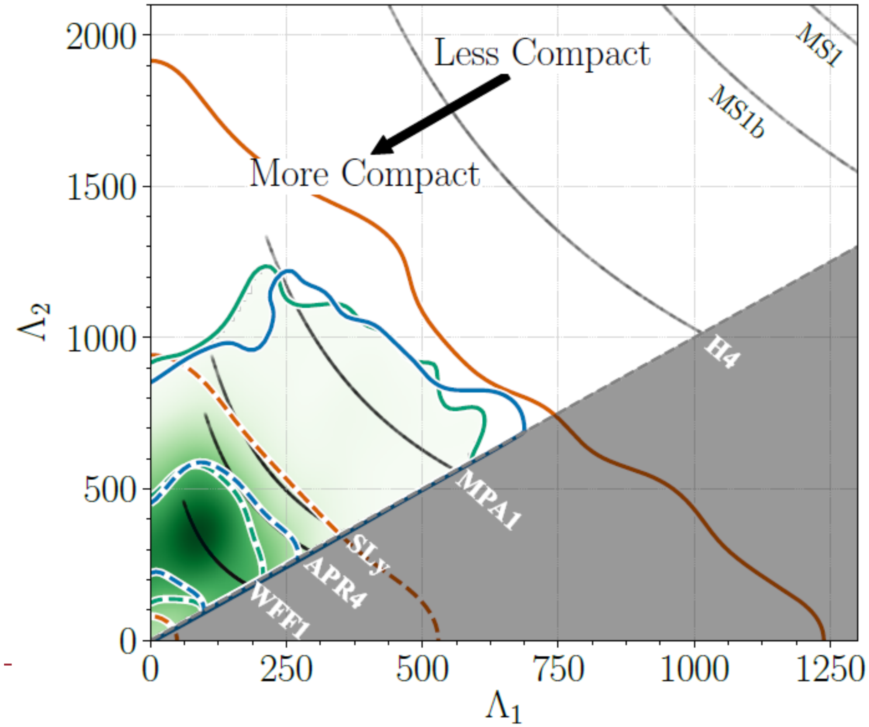
Update analysis with NR waveform



LIGO and Virgo Collaboration 1805.11581

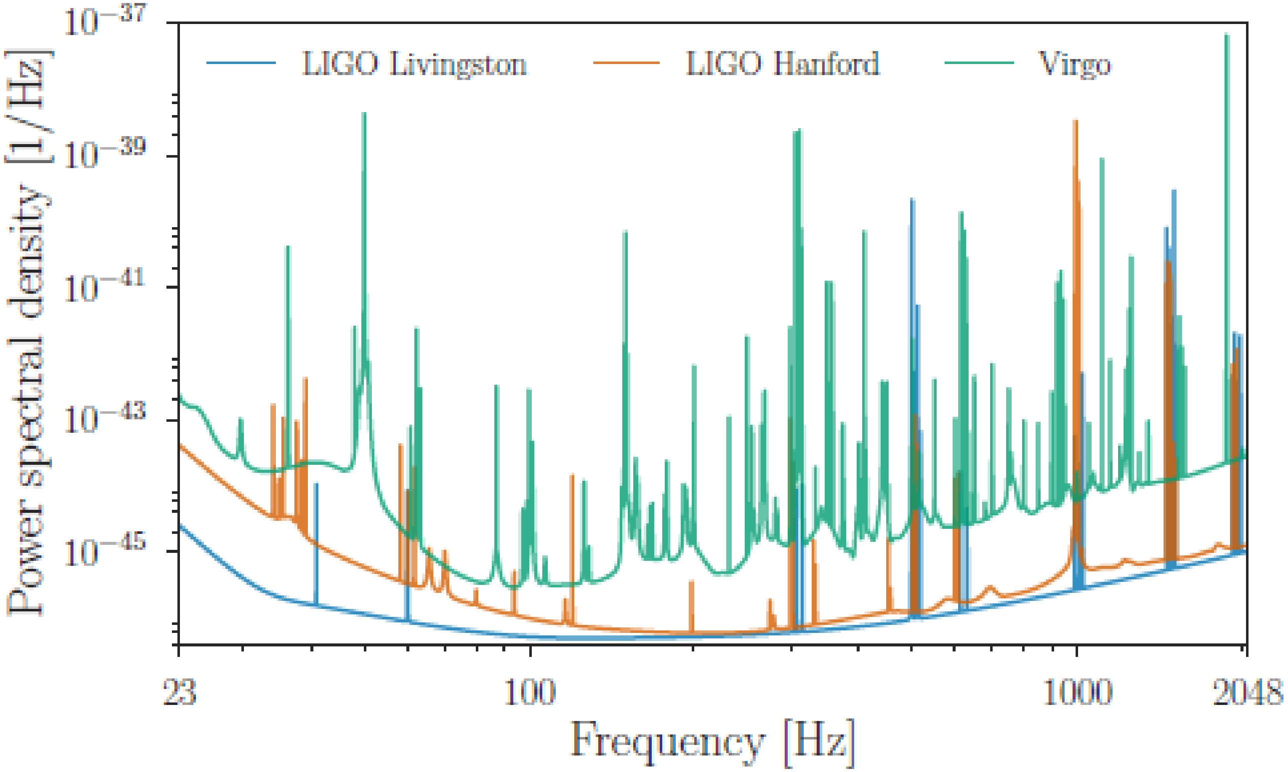
- orange: previous PRL
- Blue: parametrized EOS model by Lindblom (similar to piecewise Polytoric EOS) without 2Msun NS constraint
- Green: EOS independent relation by Yagi-Yunes





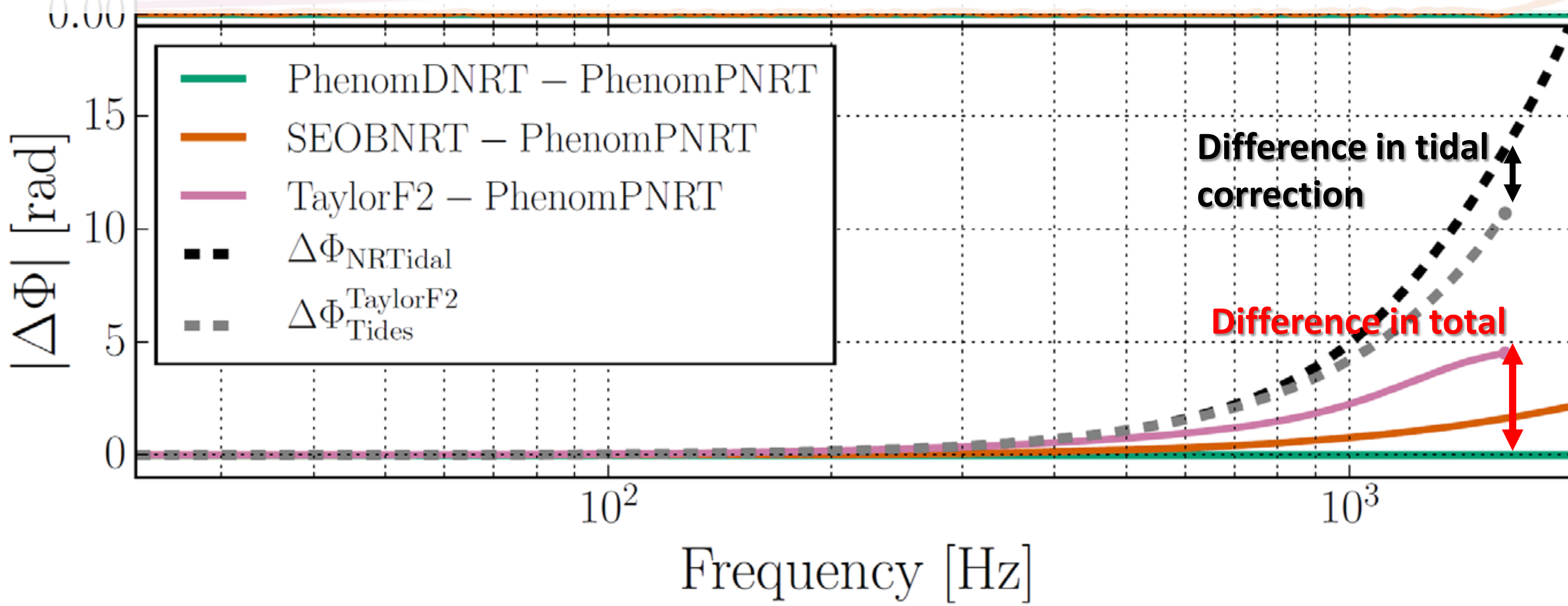
LIGO and Virgo Collaboration 1805.11579

- Basic update f-range : 30-2048Hz to 23-2048Hz, about (2700 (original)) + 1500 additional GW cycles
  - Improved 90% sky localization from 28 deg^2 to 16 deg^2
- Using



LIGO and Virgo Collaboration 1805.11579

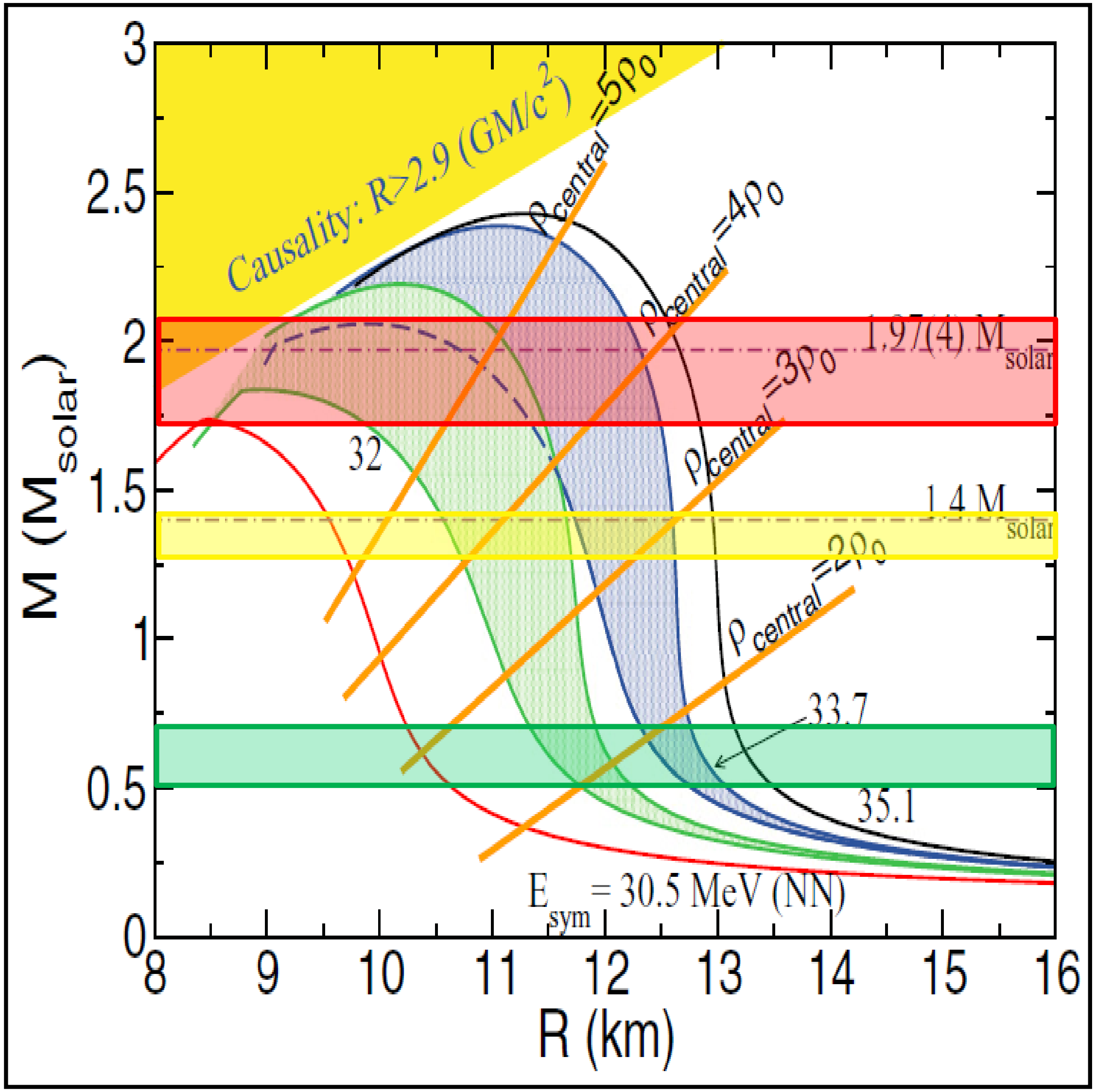
- Tidal effect is larger in NR calibrated waveform than previous model
- PN effects in point particle is also different
  - Stronger constraint on lambda for NR calibrated waveform

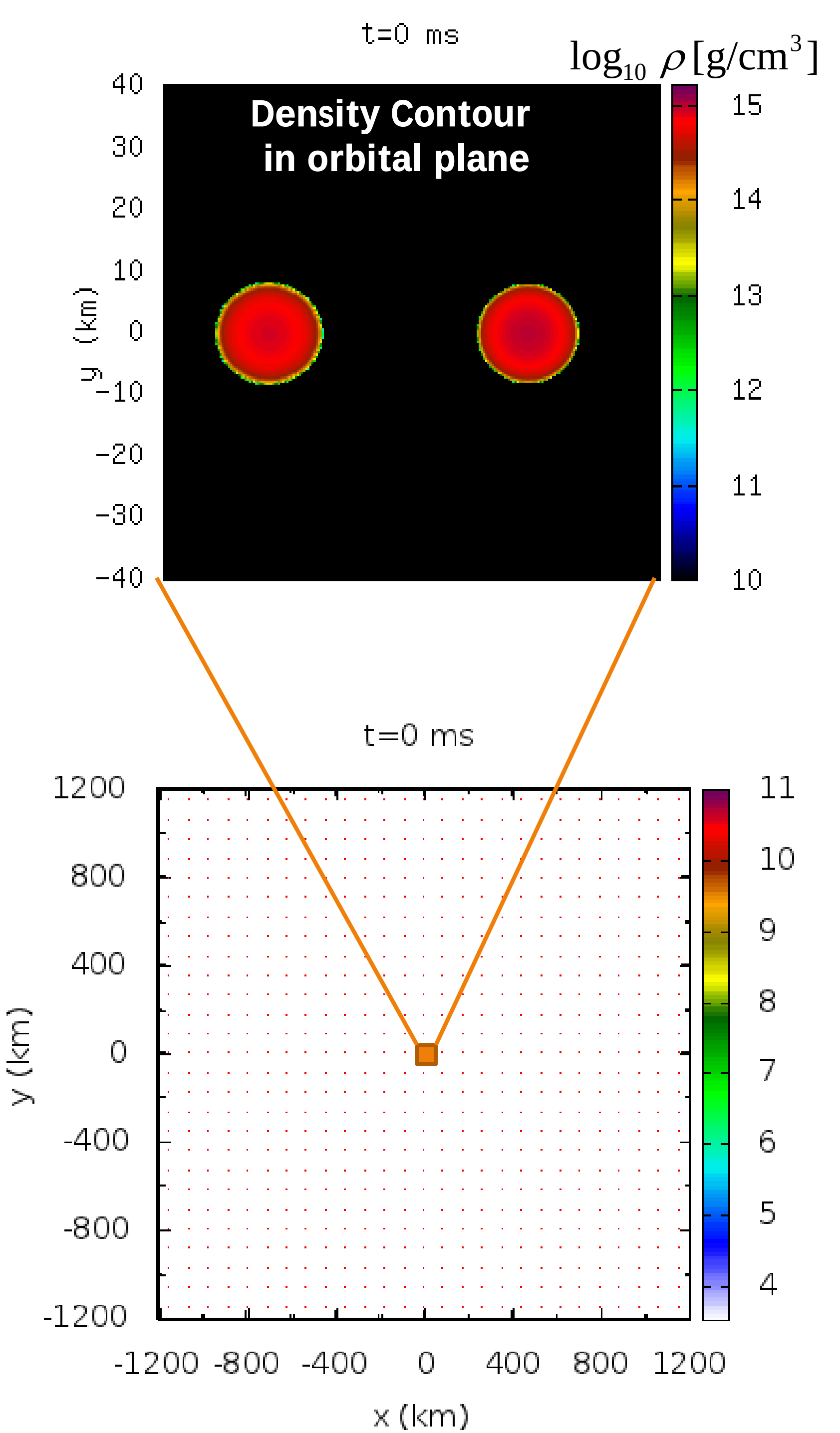


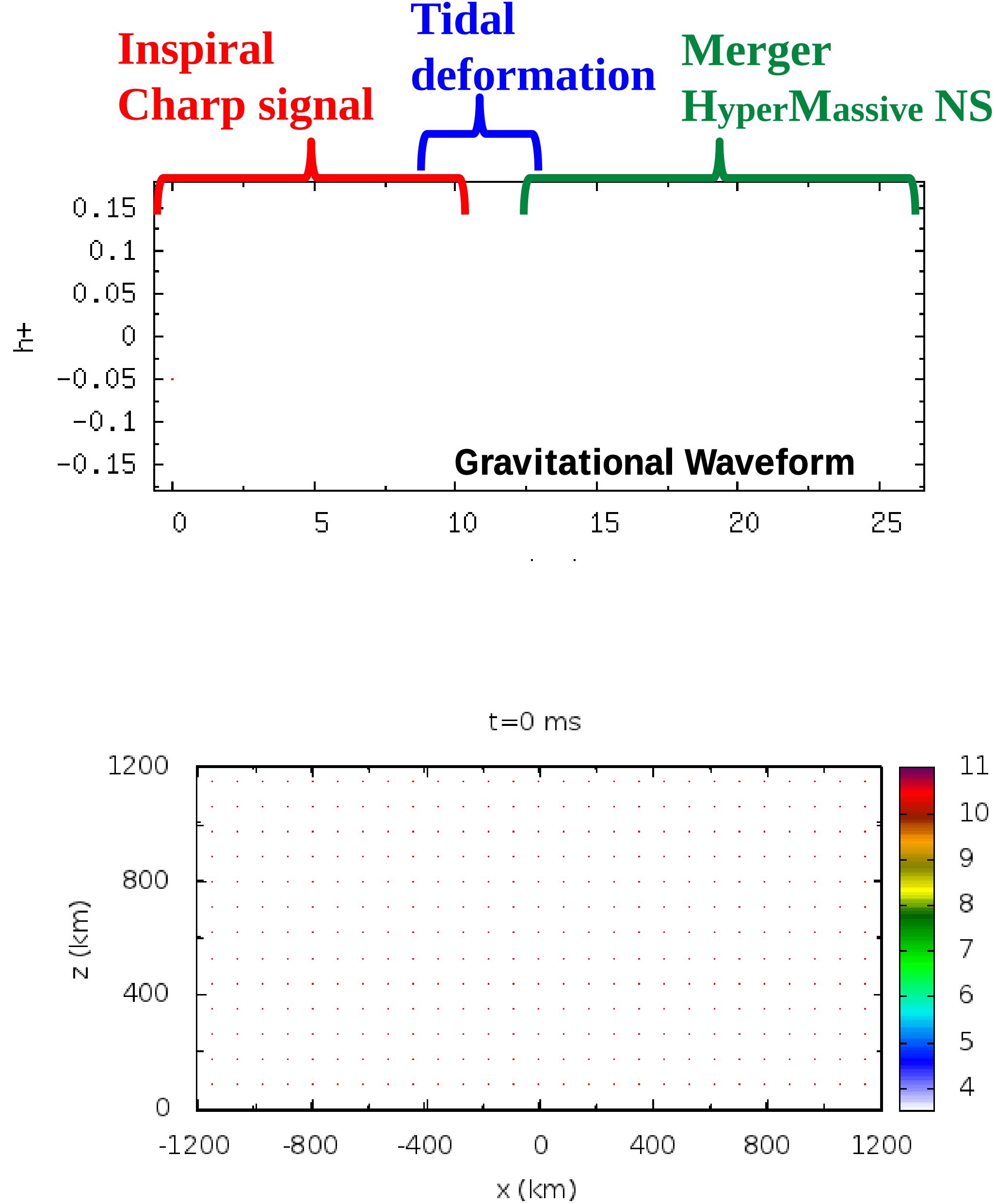
Massive NS is necessary to explore high density region

Gandolfi et al. (2012) PRC 85 032801(R)

- core bounce in supernovae
  - mass：0.5~0.7Msun
  - ρc：a few ρs
- canonical neutron stars
  - mass： 1.35-1.4Msun
  - ρc：several ρs
- massive NS (> 1.6 Msun)
  - ρc ：> 4ρs
- massive NSs are necessary to explore higher densities
  - We can use GW from NS-NS merger remnant:
  - NS with M > 2 Msun





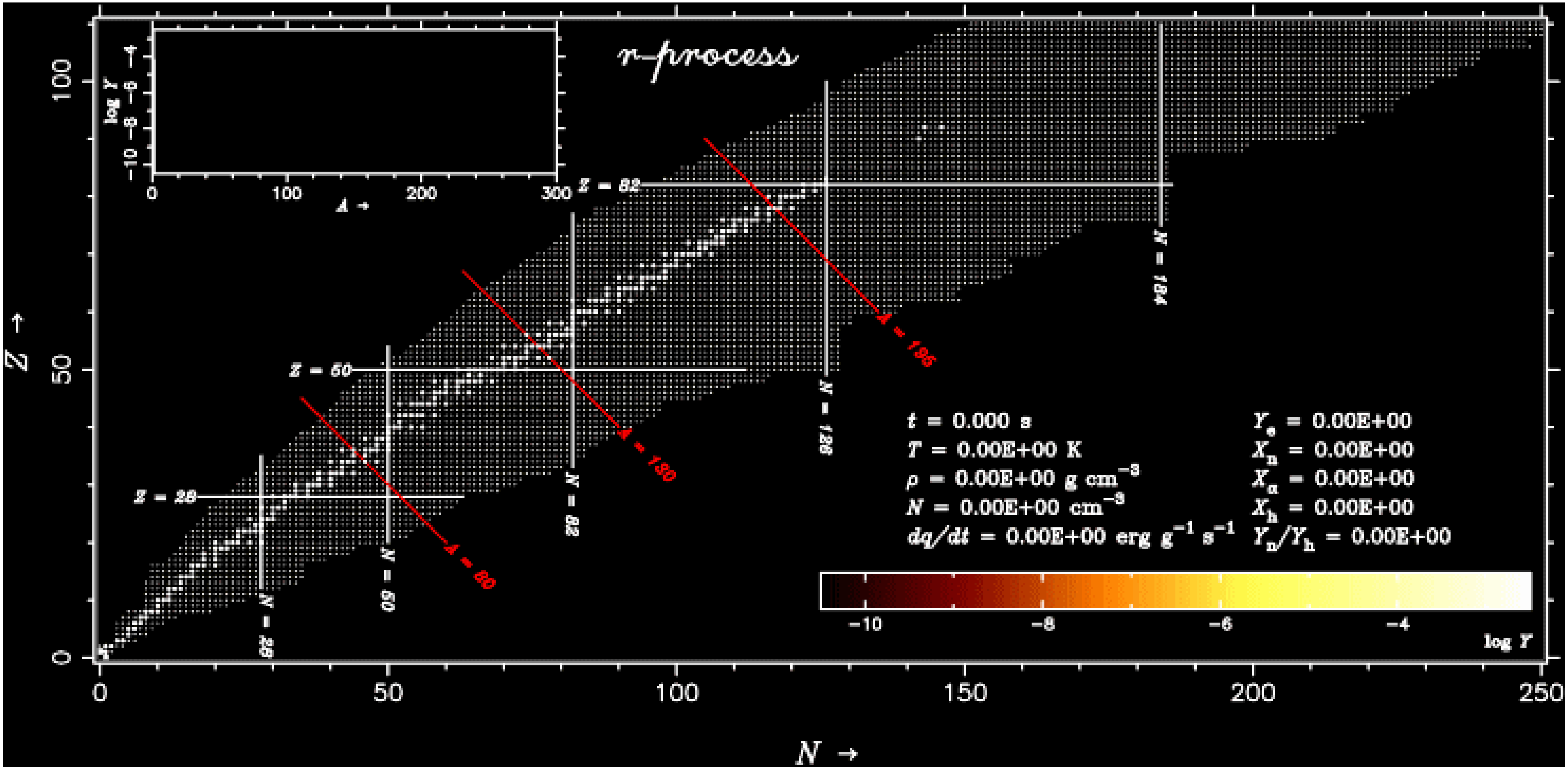


Animation by Hotokezaka

Sekiguchi et al. PRL (2011a, 2011b)
Kiuchi et al. PRL (2010); Hotokezaka et al. (2013)

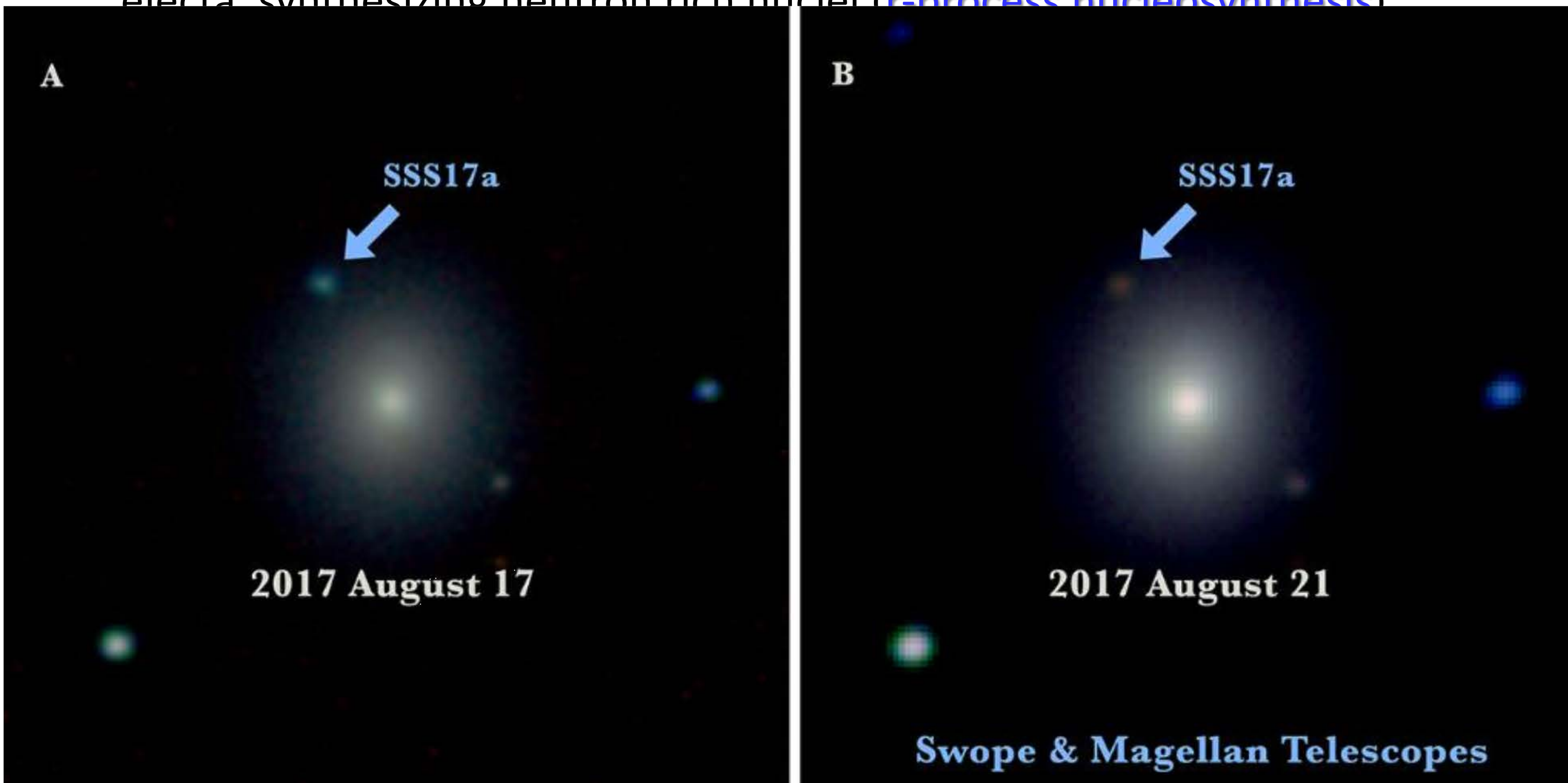
Kilonova from NS-NS merger

- Ejecta from NS-NS merger is very neutron rich
- Rapid (faster than β decay) neutron capture proceeds (r-process) in the ejecta, synthesizing neutron rich nuclei (r-process nucleosynthesis)



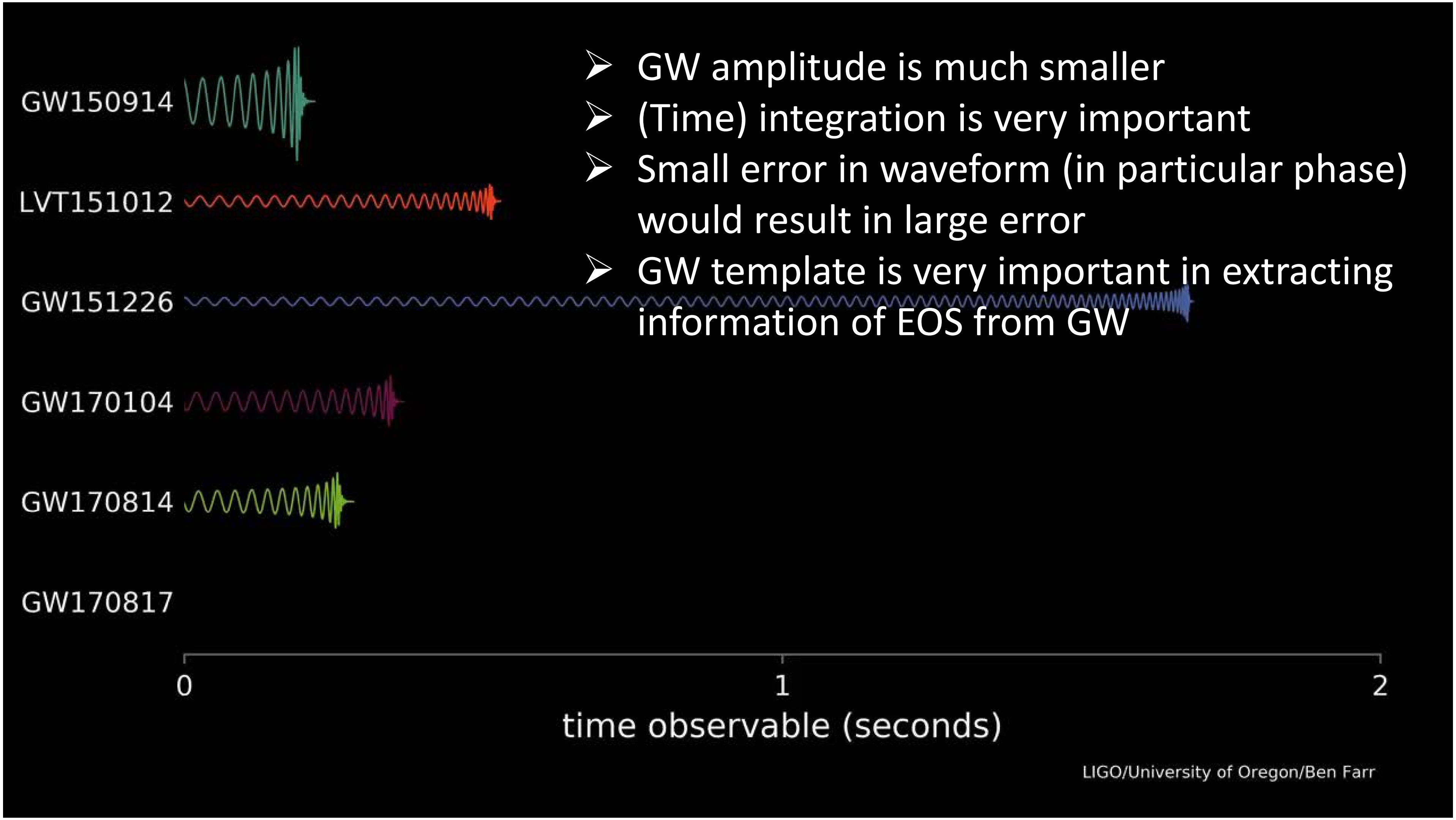
Kilonova from NS-NS merger

- Ejecta from NS-NS merger is very neutron rich
- Rapid (faster than β decay) neutron capture proceeds (r-process) in the ejecta, synthesizing neutron rich nuclei (r-process nucleosynthesis)



Importance of GW template

- **For GW from NS-NS, template is much more important than BH-BH**



- GW amplitude is much smaller
- (Time) integration is very important
- Small error in waveform (in particular phase) would result in large error
- GW template is very important in extracting information of EOS from GW

Constraints from EM observations

- **Electromagnetic (EM) observations can be used to tell weather BH is formed after the merger**
  - Although no GW from post-merger phase is detected
  - Modelling based on Numerical Relativity is necessary

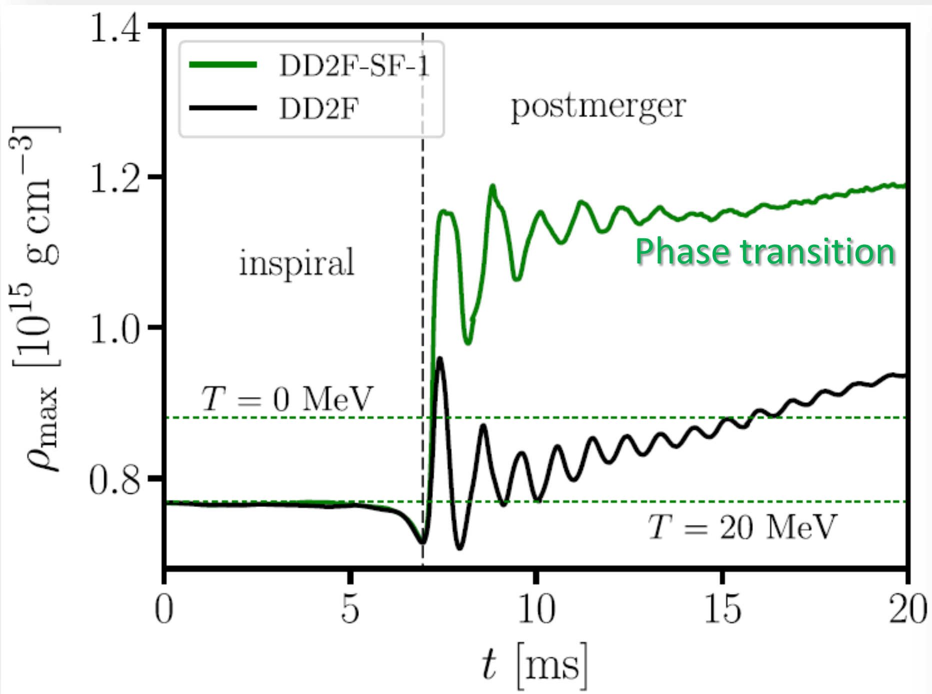
- **Threshold mass for the BH formation**

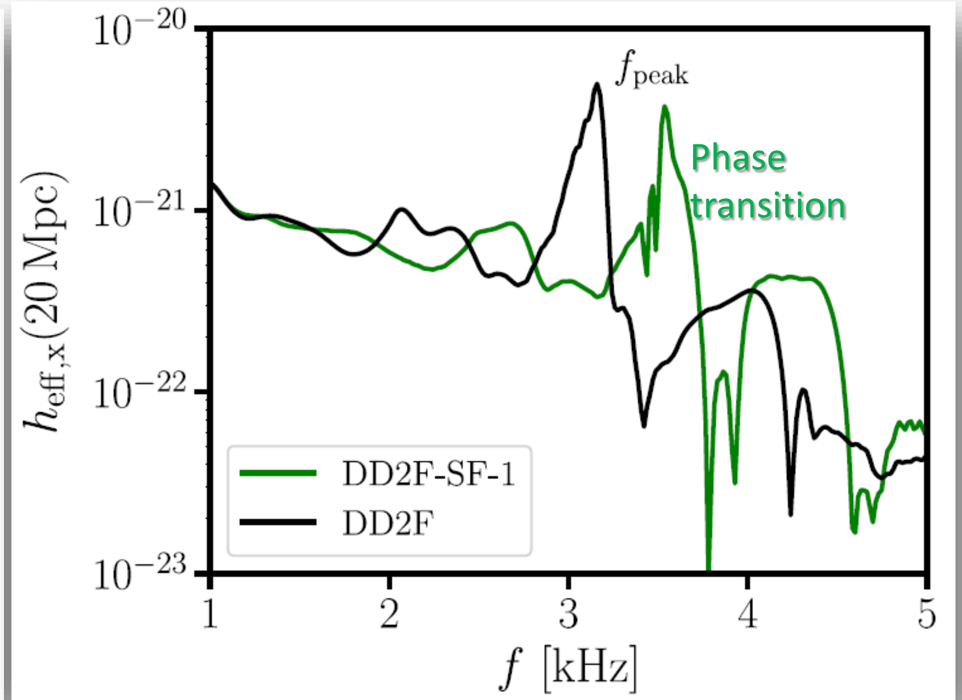
$$M_{\rm crit} = M_{\rm EOS,max} + \Delta M_{\rm rot,rig} + \Delta M_{\rm rot,diff} + \Delta M_{\rm therm}$$

  - $M_{\rm EOS,max}$: maximum mass of cold spherical NS determined by EOS
  - $\Delta M_{\rm rot,rig}$: additional support from rigid rotation
  - $\Delta M_{\rm rot,diff}$: additional support from differential rotation
    - Short-time support : magnetic field will destroy differential rotation
  - $\Delta M_{\rm therm}$: additional thermal support
    - Short-time support : emission of neutrinos will remove thermal support

Numerical relativity simulation

Proving 1^{st} order hadron-quark transition





- If hadron-quark phase transition occurs at higher densities, so that the tidal deformability of $< 1.4 M_\odot$ NS is same
- On the other hand, structure of more massive NS is different $\Rightarrow$ the peak frequency of GW from post-merger system will be different