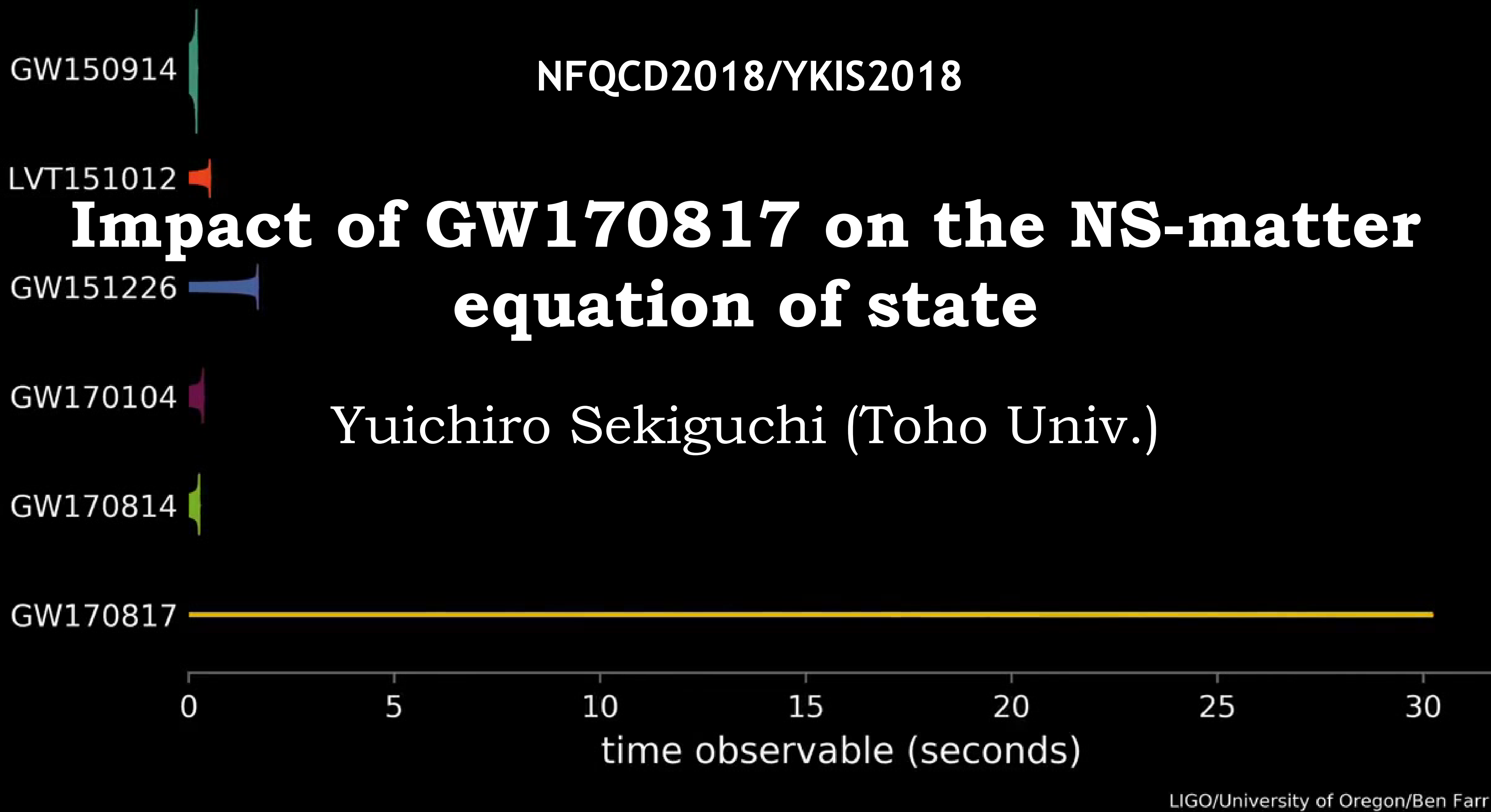
NFQCD2018/YKIS2018

Impact of GW170817 on the NS-matter equation of state

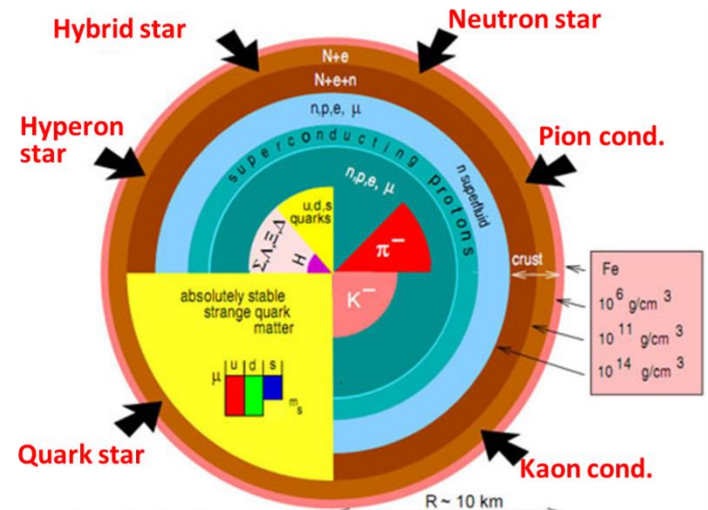
Yuichiro Sekiguchi (Toho Univ.)



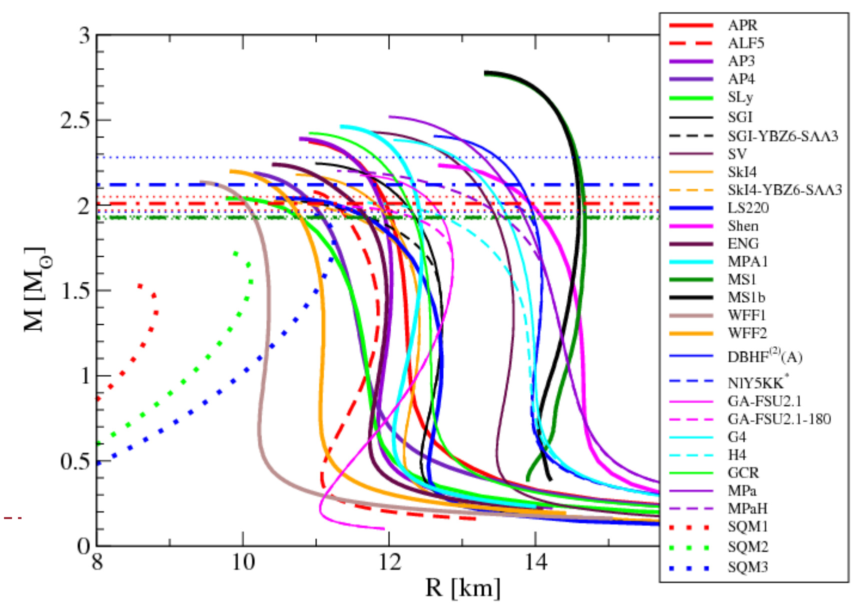
https://www.youtube.com/watch?v=vTeAFAGpfso&feature=share

Major scientific achievements: GW170817 provided us clues to

- **NS matter 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



Weber (2005)



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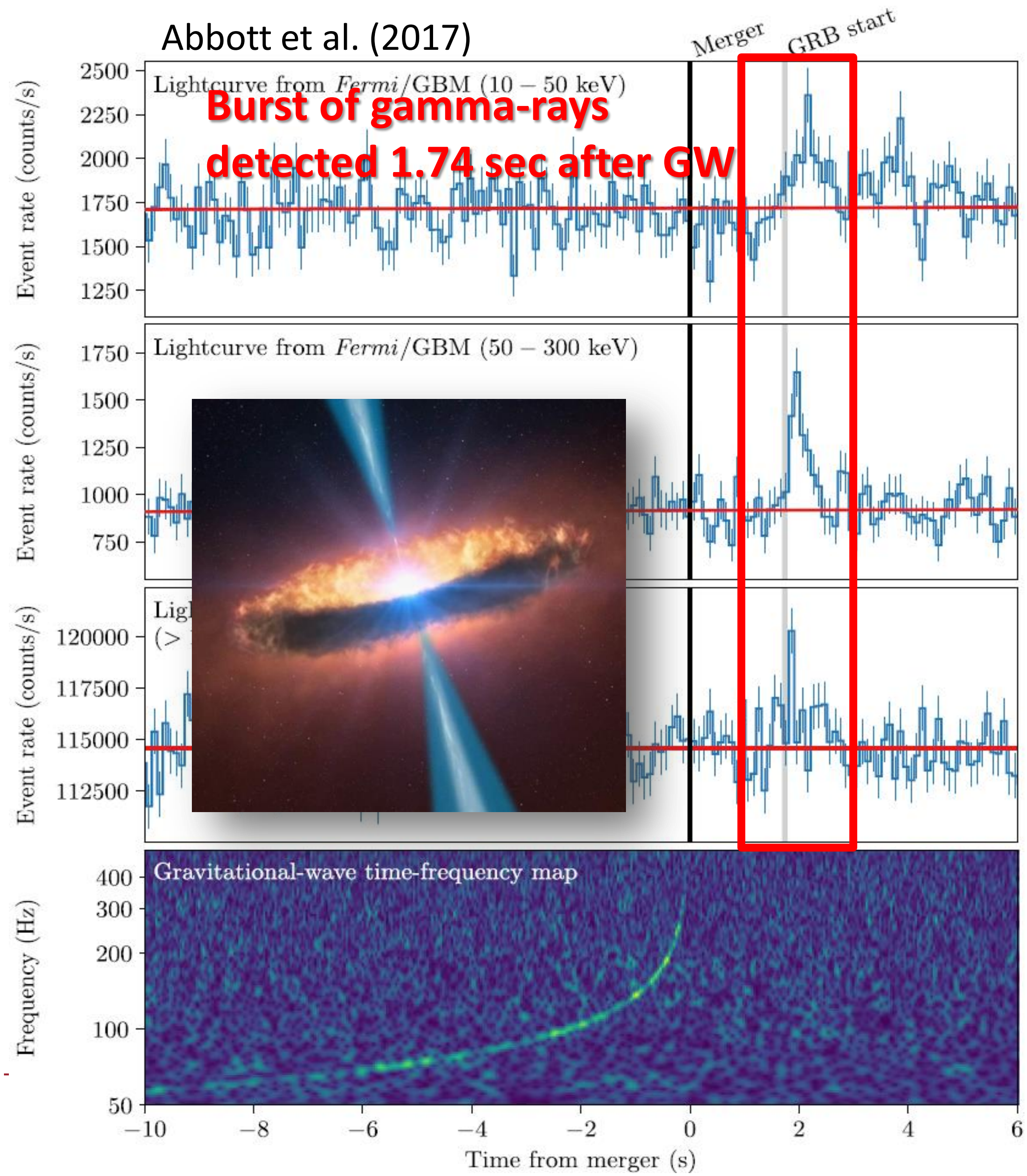

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  - **kilonova/macronova : UV-Infrared from decay energy of the synthesized elements**
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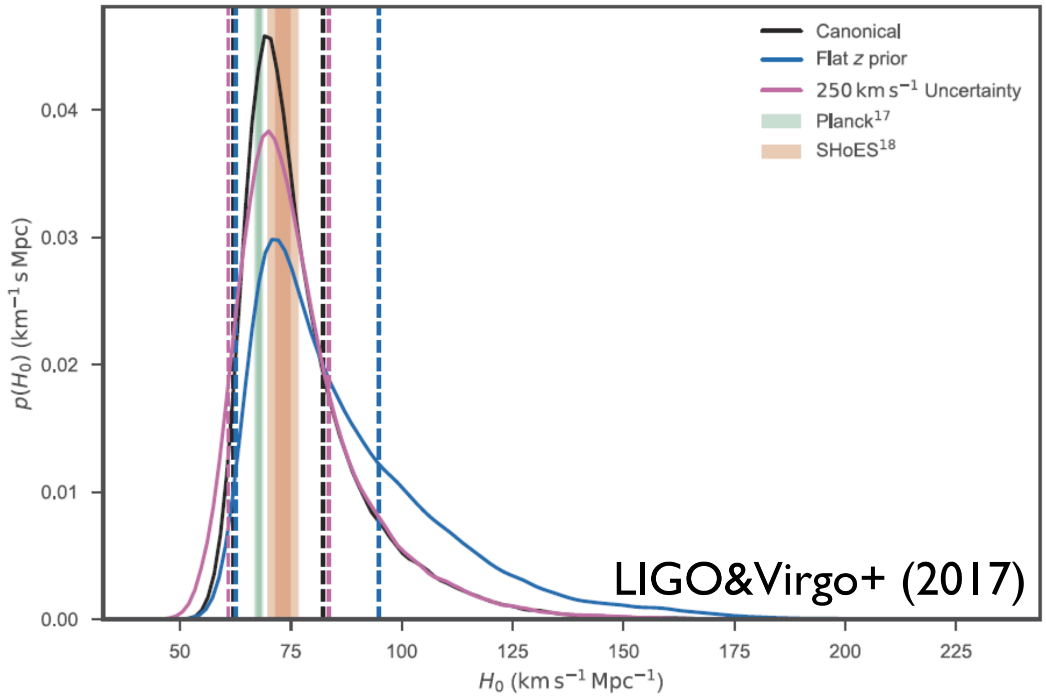

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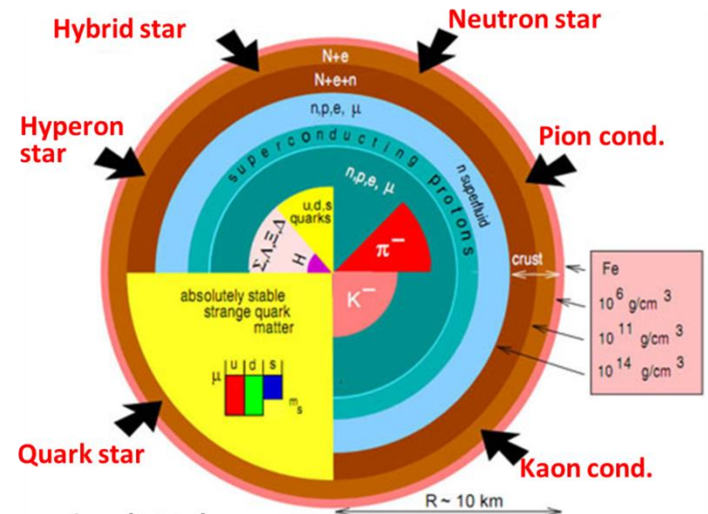

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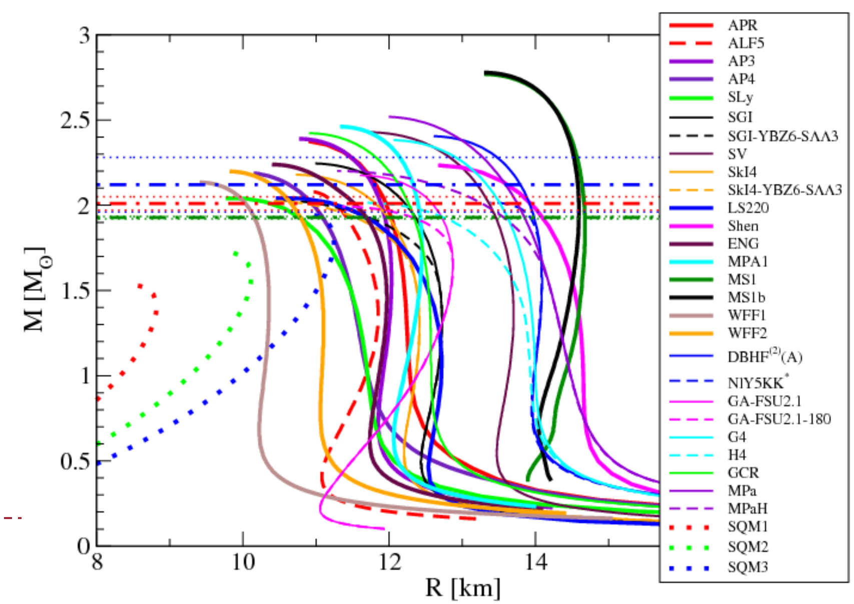
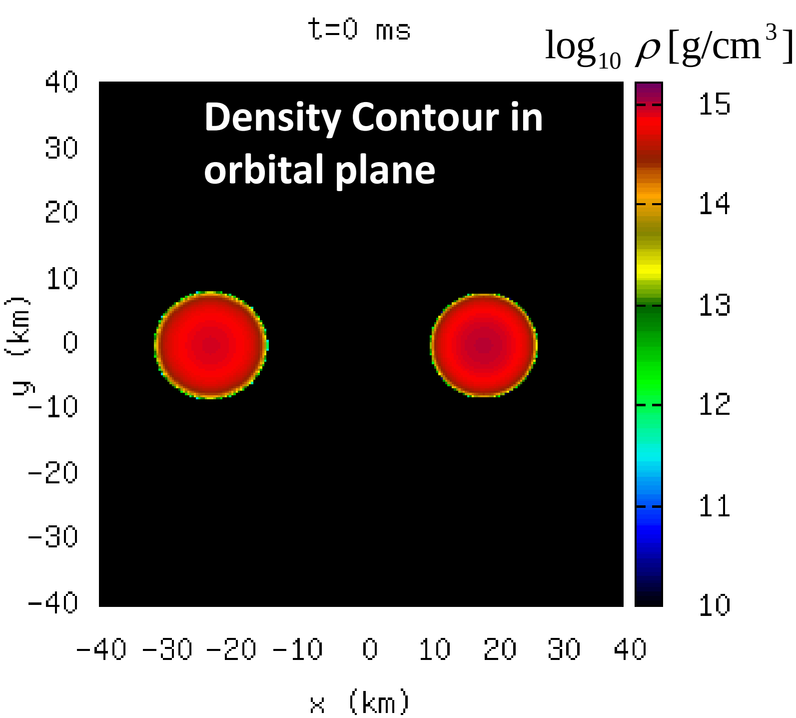
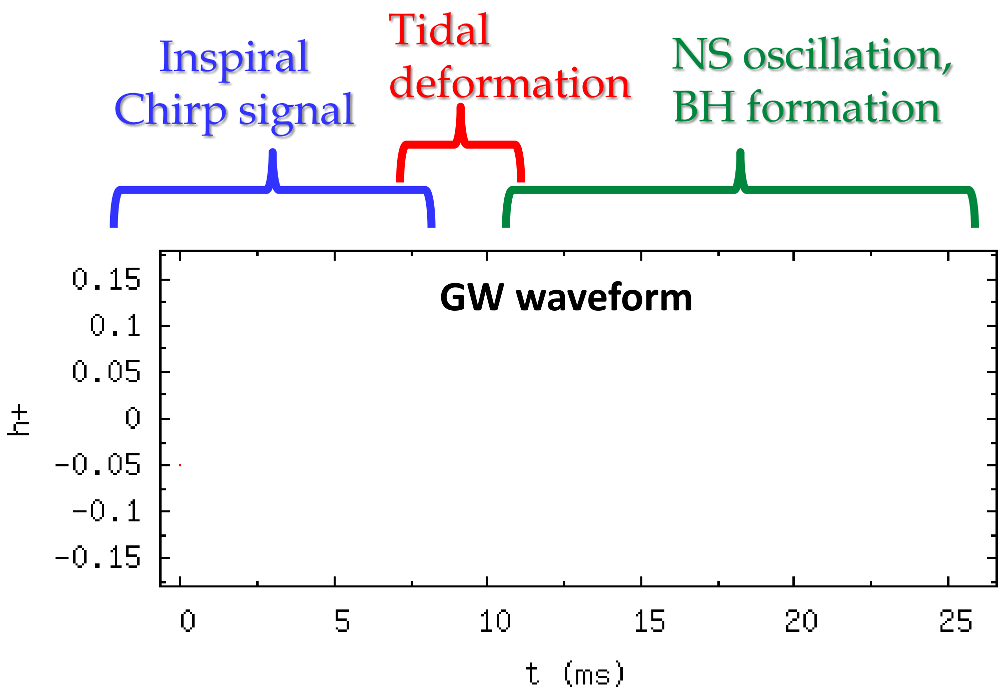


A Numerical Relativity Modelling of GW (from GW170817)

NS(1.2Msolar)-NS(1.5Msolar) binary (APR EOS)





Sekiguchi et al, 2011; Hotokezaka et al. 2013

- Point particle approx.
- Information of orbits, **NS mass**, etc.

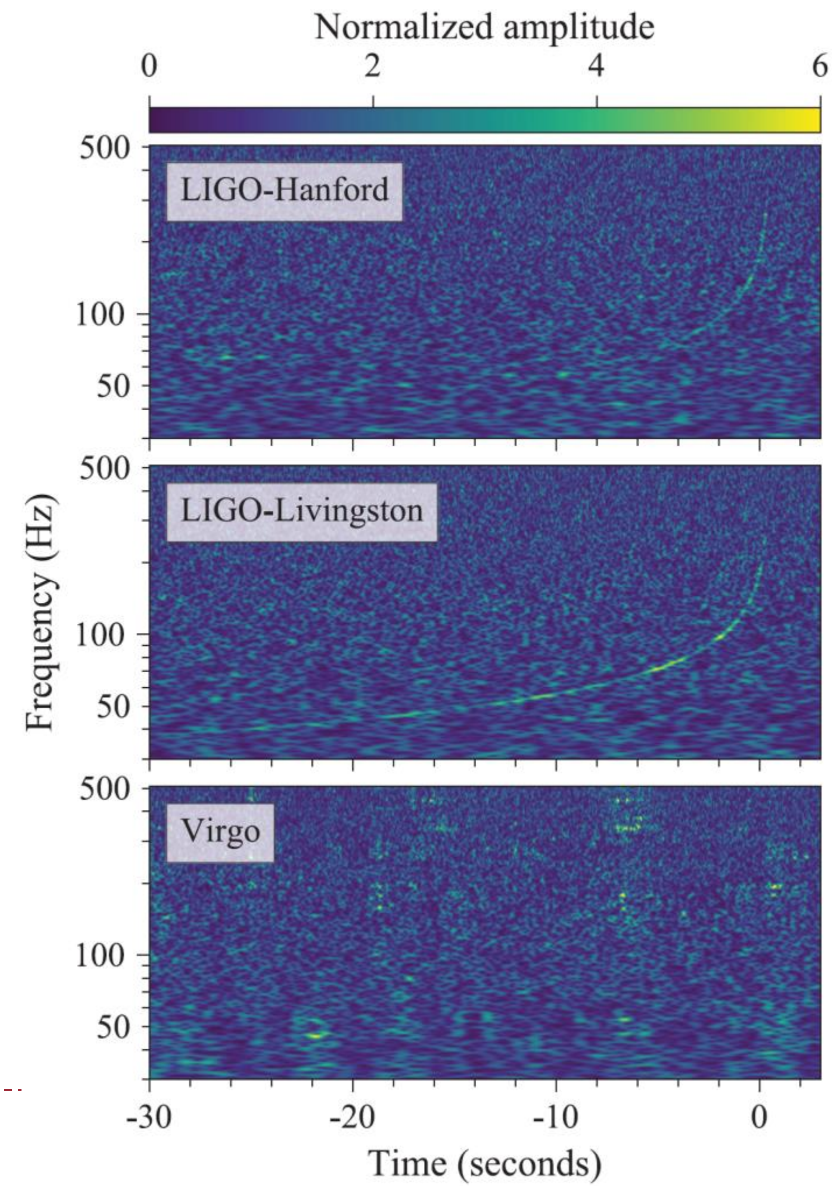
- Finite size effects appear
- **tidal deformability**
- **radius**

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

Inspiral chirp signal provide mass and orbit parameters (90% C.L.)

- GW170817: S/N = 32.4
- under a reasonable assumption that NS is not spinning rapidly
  - In this talk, we only consider this low spin case

Primary mass m_1	$1.36–1.60\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$
Using NGC 4993 location	$\lesssim 28°$



Abbott et al. PRL 119, 161101 (2017)

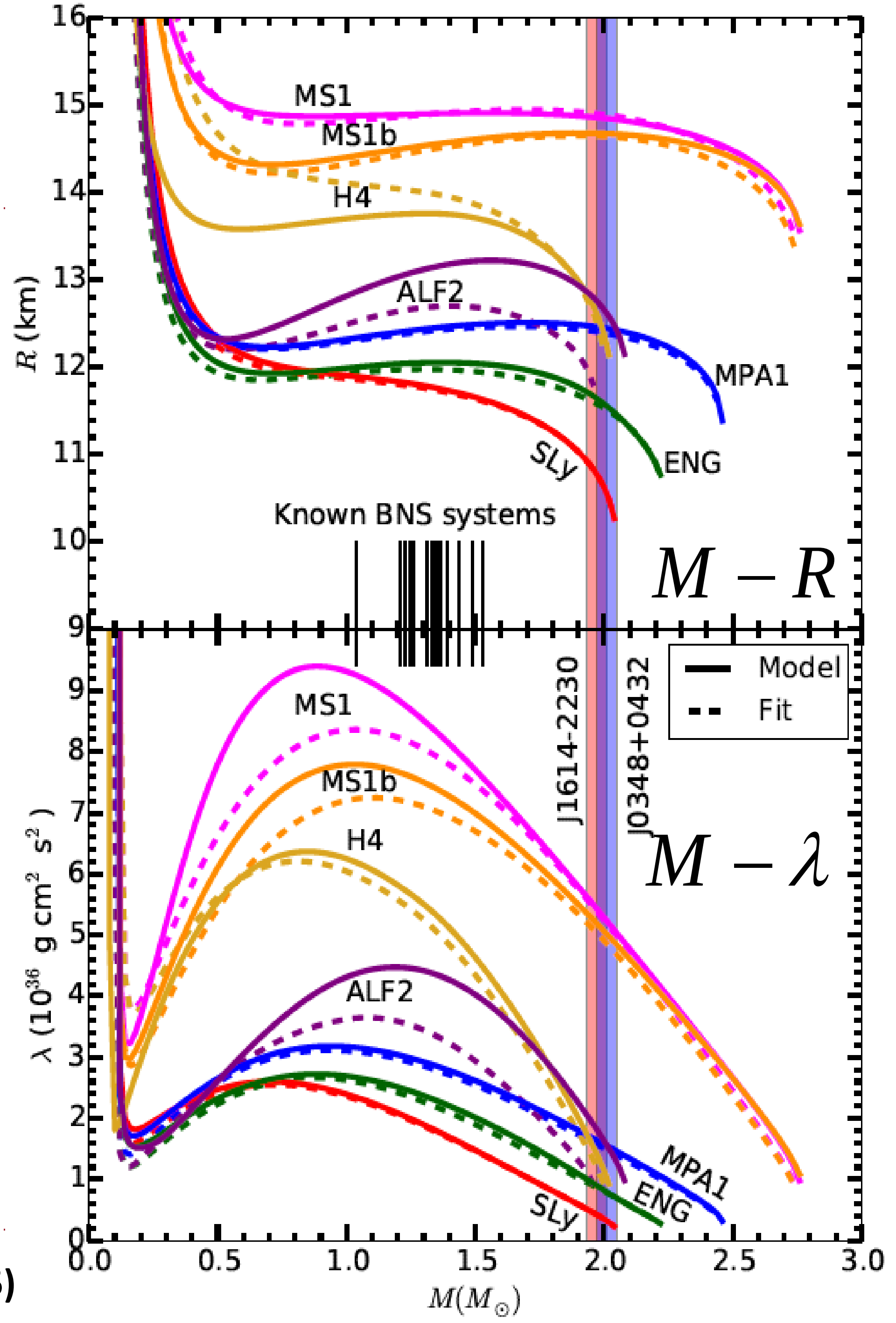
Tidal deformability

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

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

  - Stiffer NS EOS ⇒ larger NS radius ⇒ larger tidal deformability ⇒ more significant deviation of GW from point-particle GW
  - We use non-dimensional version Λ

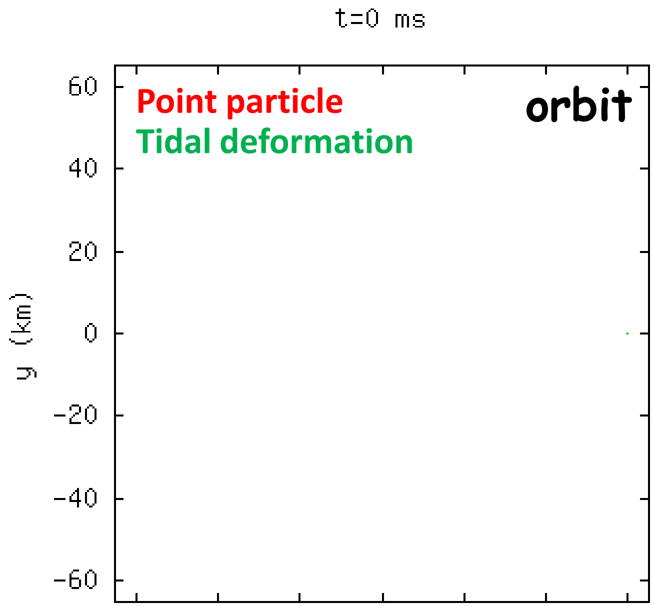
$$\boldsymbol{\lambda = \frac{C}{G}\Lambda R^5 \qquad C = \frac{GM}{c^2 R}}$$



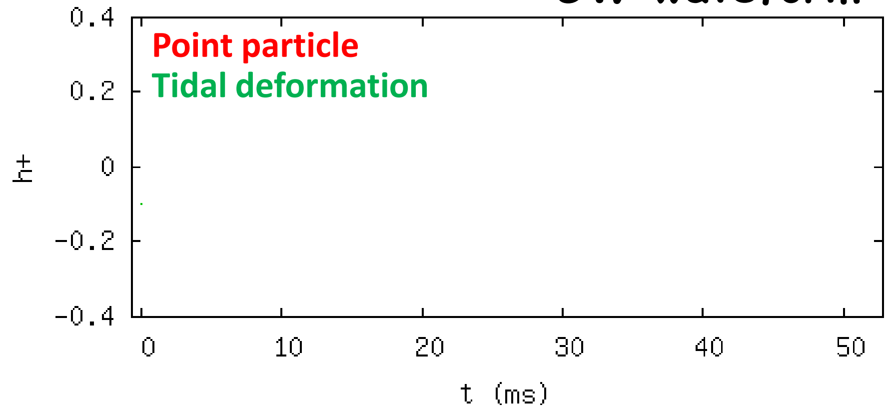
Lackey & Wade (2015)

Soft EOS（Smaller NS radius）

Effect of tidal deformation is not prominent

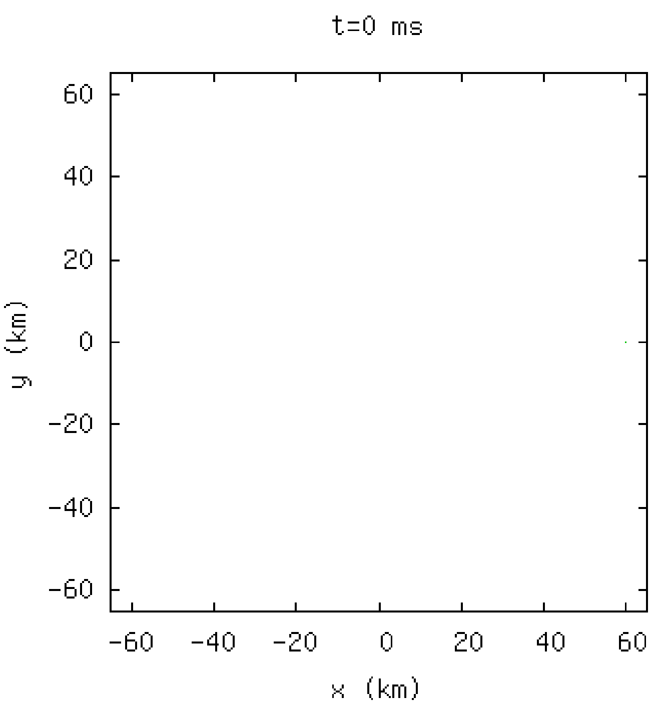


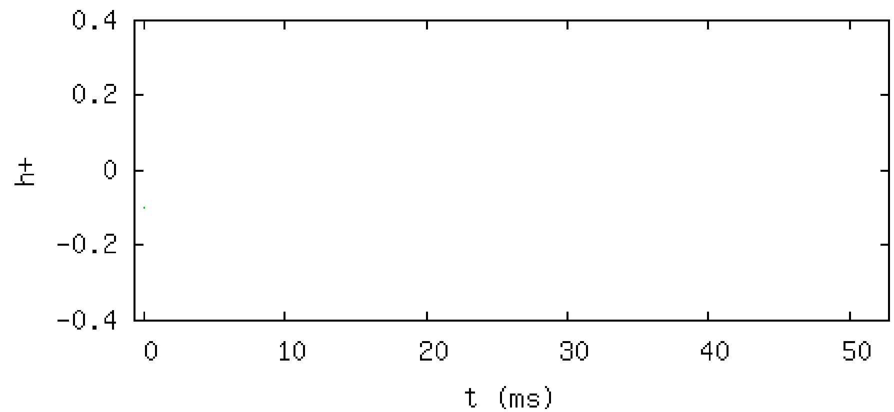
GW waveform



Stiff EOS（larger NS radius）

Deviation from point particle approximation can be clearly seen





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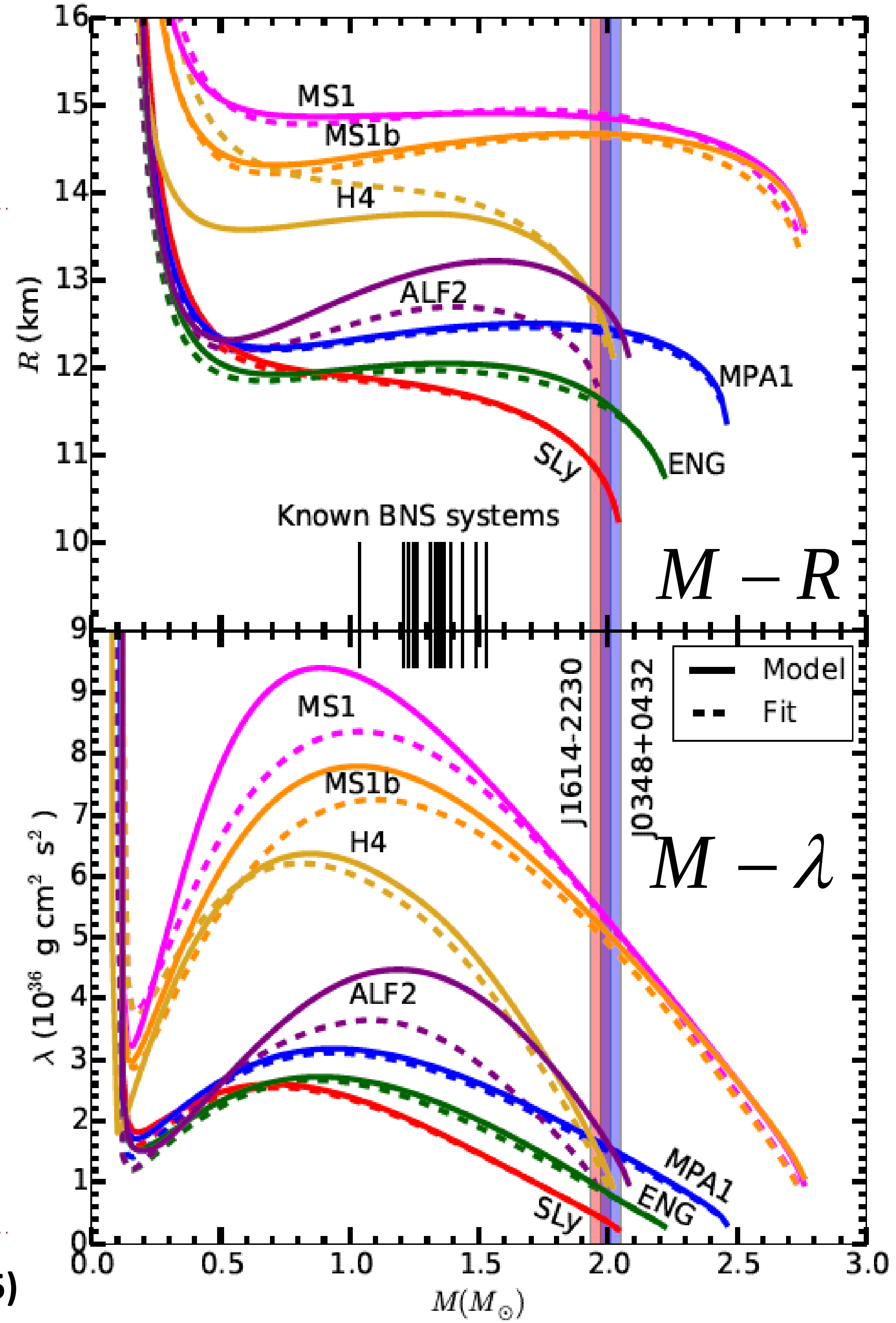
  - We use non-dimensional version Λ

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

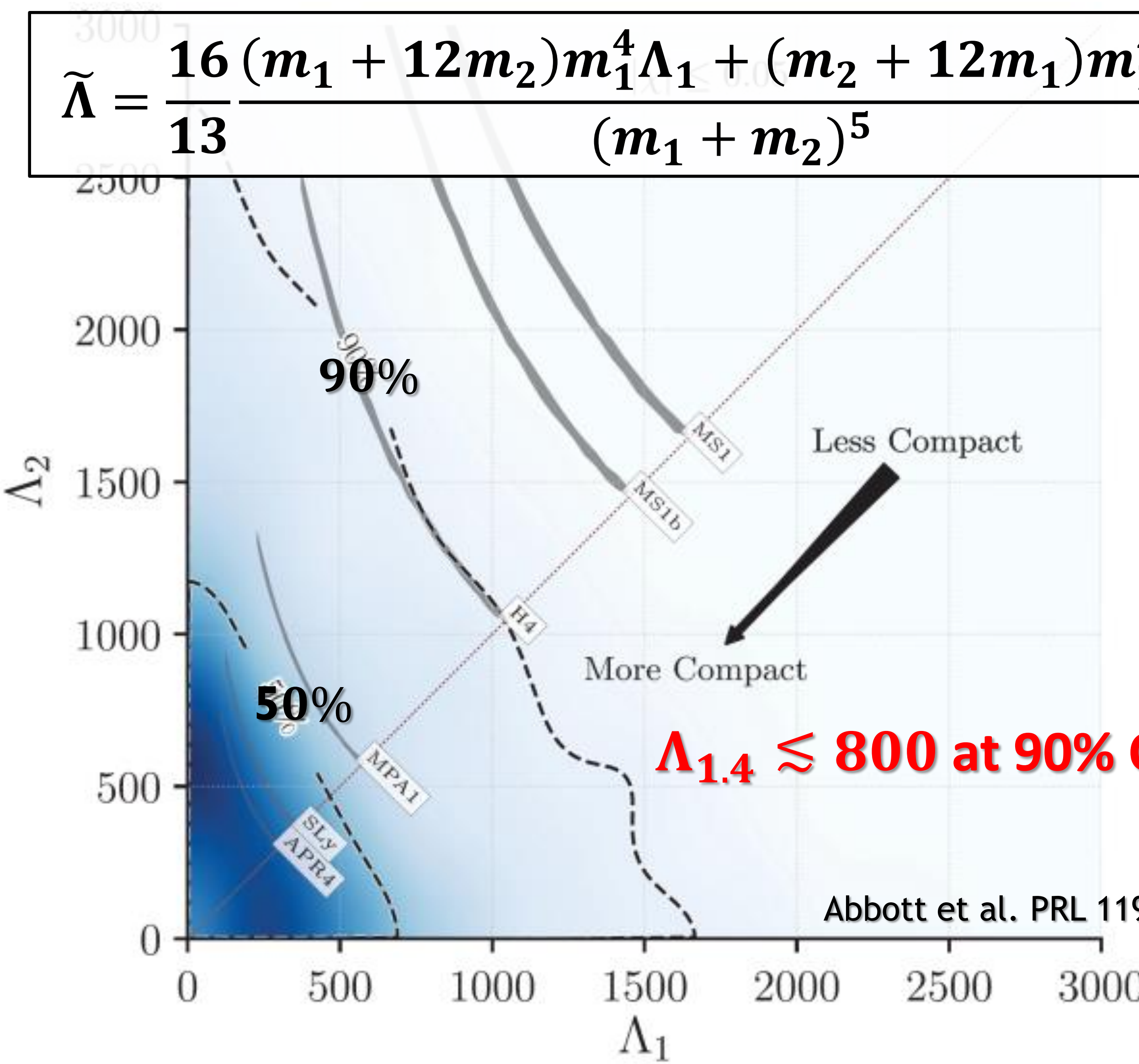
- Upper limit on tidal deformability **$\Lambda_{1.4} \lesssim 800$ at 90% C.L. by GW170817**



Lackey & Wade (2015)

Extraction of Tidal deformability

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



$\Lambda_{1.4} \lesssim 800$ at 90% C.L.

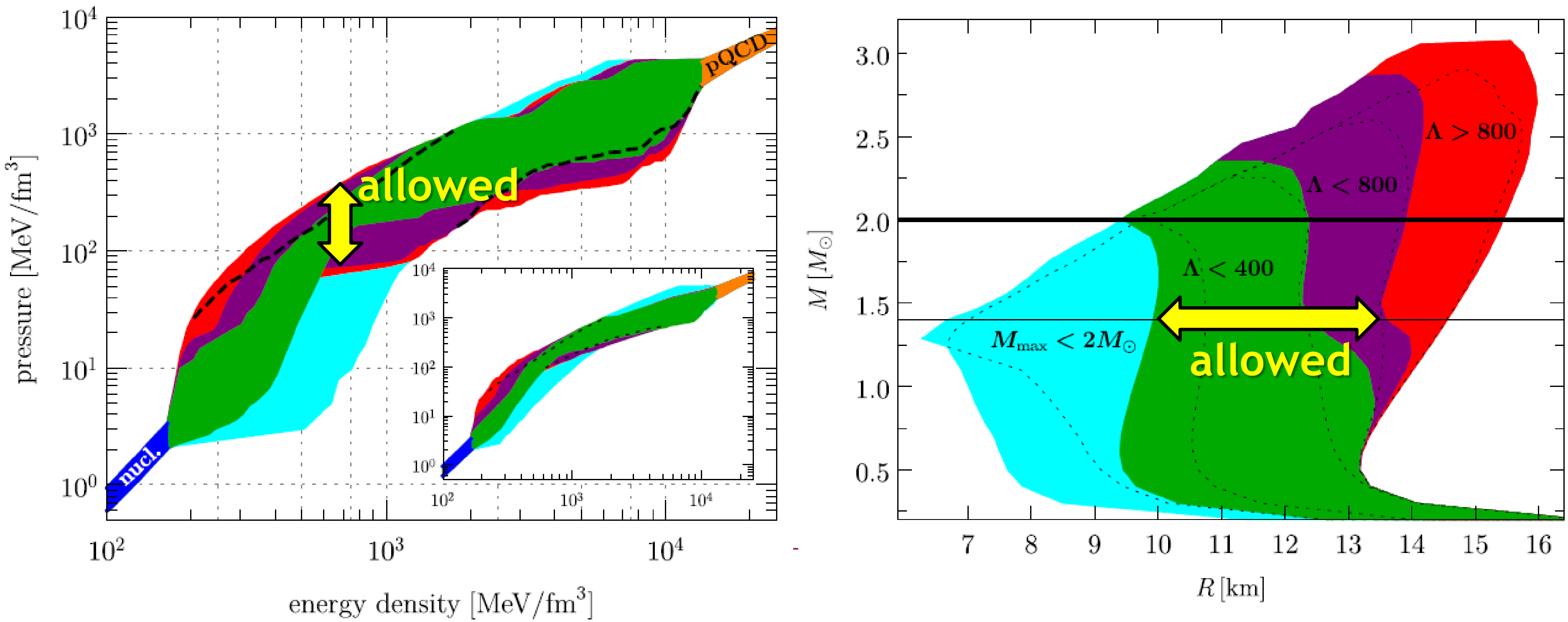
Abbott et al. PRL 119, 161101 (2017)

A lot of studies after GW170817 PRL paper

- Extraction of Λ from GW data (extraction studies)
  - Abbott et al. (2018a,b)
    - 1805.11579 : Updated analysis by LIGO-Virgo, Analysis using GW data only
    - 1805.11581 : Analysis with EOS modelling as in other studies listed below
  - De et al. (2018) 1804.08583
    - Analysis combining GW data with constraints from nuclear experiments
- Interpretation of the extracted Λ (interpretation studies)
  - Annala et al. (2018) PRL 120, 172703
    - Based on chiral EFT + perturbative QCD
      - Hebeler et al. (2013) ApJ 773, 11; Kurkela et al. (2014) ApJ 789, 127
  - Tews et al. (2018) 1804.02783
    - Based on chiral EFT + perturbative QCD
      - Tews et al. (2018) 1801.01923
  - Fattoyev et al. (2018) PRL 120, 172702
    - Combining GW with PREX (symmetry energy) exp. and a small set of EOS family
  - Most et al. (2018) 1803.00549, and more

An interpretation of $\Lambda_{1.4} < 800$

- Interpretation with an EOS model
  - $n < 1.1 n_s$: Chiral EFT Hebeler et al. (2013) ApJ 773, 11
  - $\mu_B > 2.6$ GeV : NNLO pQCD by Kurkela et al. (2014) PRD 81
  - intermediate: A parametrized (piecewise polytrope) EOS with causality constraint
- $10 \lesssim R_{1.4} \lesssim 13.6$ km and $\Lambda_{1.4} \gtrsim 120$ for $M_{\max} > 2M_\odot$



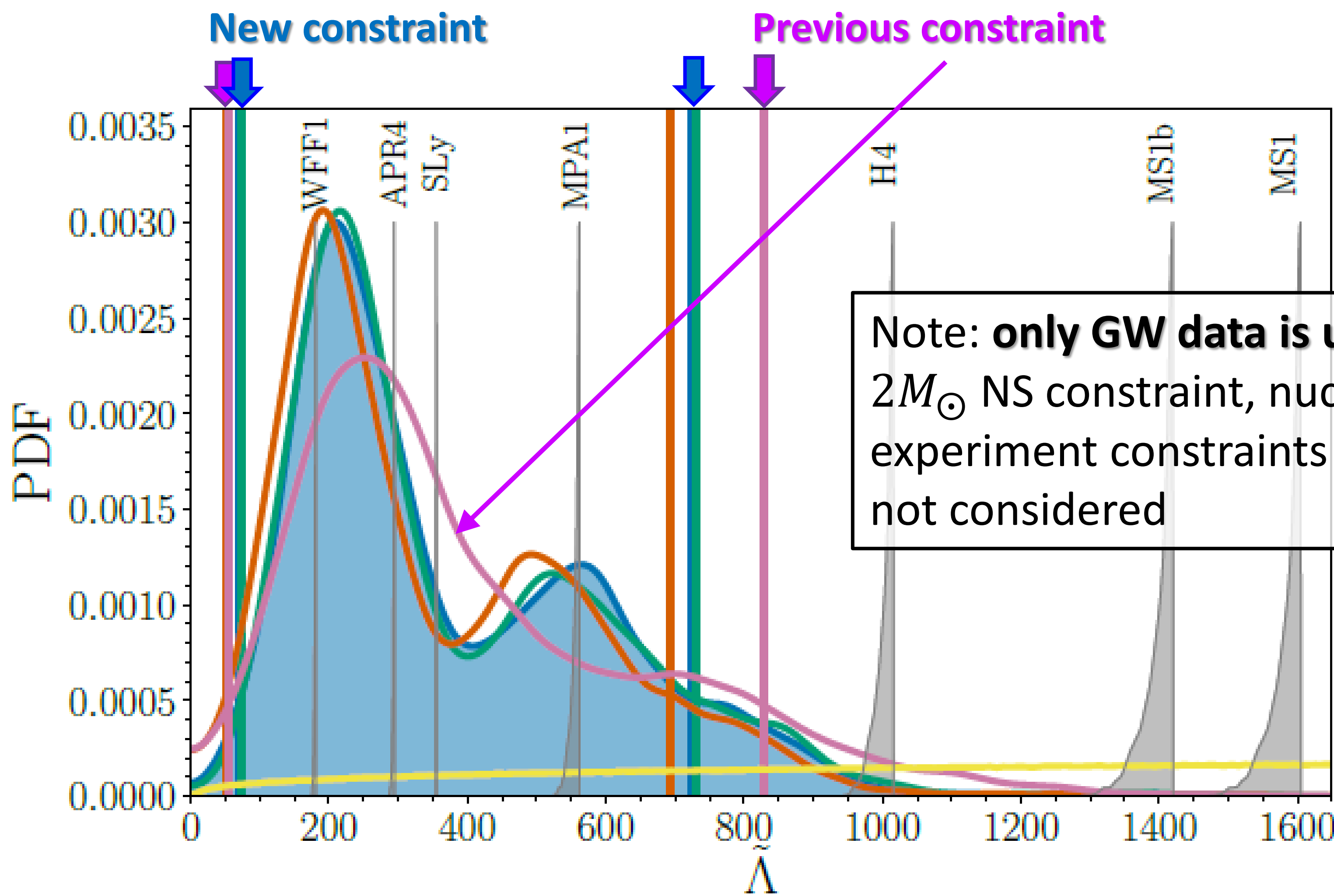
A summary of NS structure constraint

- Extraction of Λ from GW data
  - Abbott et al. (2018a,b) will be reviewed later
  - De et al. (2018) : GW data with constraints from nuclear experiments
    - $\tilde{\Lambda} = 310^{+679}_{-234}$, $R_{1.4} = 11.5^{+2.3}_{-2.2} \pm 0.2$ km (3 mass priors considered)
- Interpretation of the extracted Λ
  - Annala et al. (2018) : chiral EFT (up to 1.1ns) + perturbative QCD
    - $120 \lesssim \Lambda_{1.4} \lesssim 800$, $10 \lesssim R_{1.4} \lesssim 13.6$ km
  - Tews et al. (2018) : chiral EFT (up to 2ns !!) + perturbative QCD
    - $80 \lesssim \Lambda_{1.4} \lesssim 570$ (upper limit from EOS model, not from GW data)
  - Fattoyev et al. (2018) : GW data with PREX data and small EOS familiy
    - $400 \lesssim \Lambda \lesssim 800$, $12 \lesssim R_{1.4} \lesssim 13.6$ km (lower limit from $R^{208}_{\rm skin} \gtrsim 0.15$fm)
  - See also, Most et al. (2018) and more

Updated data analysis by LIGO-Virgo

- Extraction of Λ from GW data : Abbott et al. (2018a,b)
  - 1805.11579 : Updated analysis by LIGO-Virgo, using GW data only
  - 1805.11581 : Analysis with EOS modelling
- Wider frequency range : 30-2048 Hz to 23-2048 Hz
  - 1500 additional GW cycles obtained
- Analysis using sky location from electro-magnetic observations
- Waveforms calibrated by numerical relativity (NR) simulations are used in parameter estimation
  - Tidal effects start to appear in 5PN order
  - 5PN point particle corrections will be necessary
    - 2017 PRL paper : 3.5 PN point particle + Tidal corrections
    - 2018 new paper : NR calibrated, include higher order corrections

New constraint $\tilde{\Lambda} = 300^{+420}_{-230}$ 90% highest posterior density interval

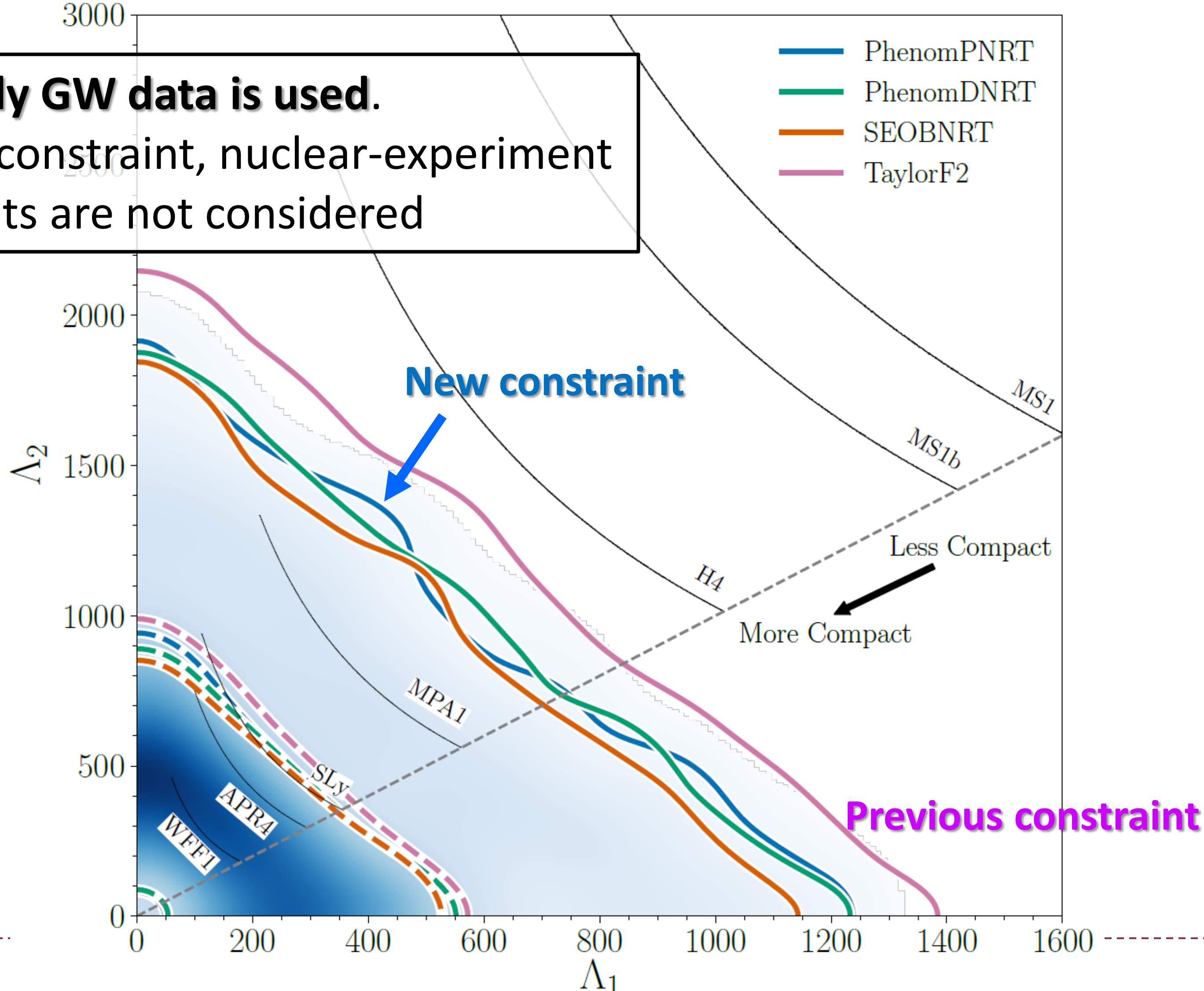


Note: **only GW data is used**. $2M_{\odot}$ NS constraint, nuclear-experiment constraints are not considered

Abbott et al. (2018) 1805.11579

New constraint in $\Lambda_1 - \Lambda_2$ plane

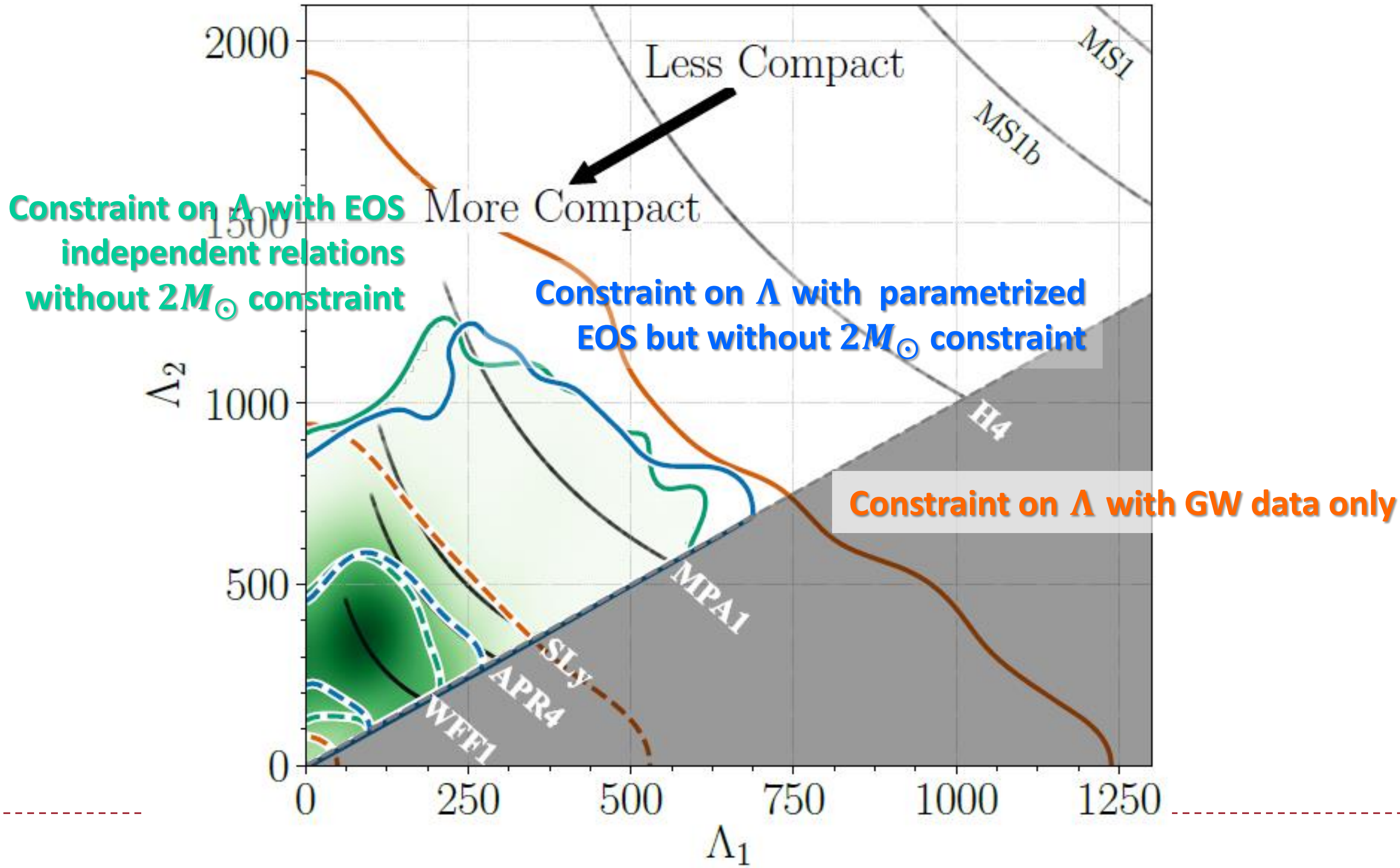
Note: **only GW data is used**.
$2M_\odot$ NS constraint, nuclear-experiment constraints are not considered



Abbott et al. (2018) 1805.11579

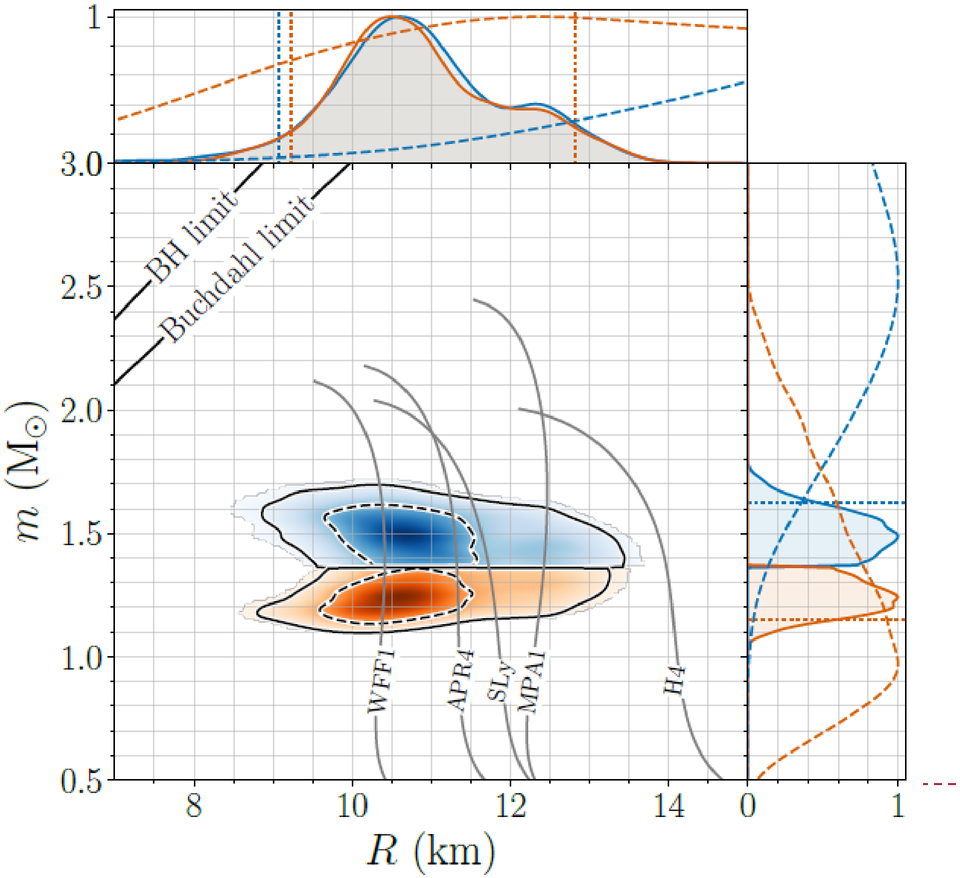
Updated analysis **using EOS model**

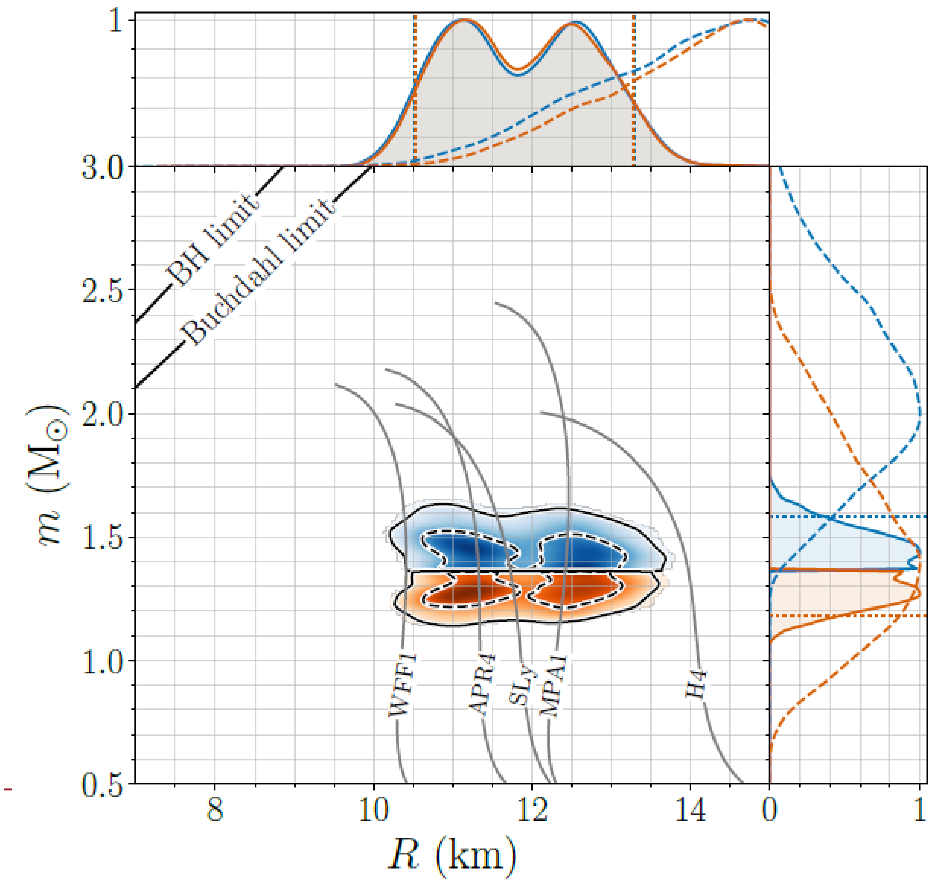
- extracted Λ without the $2M_{\odot}$ constraint (blue curve)



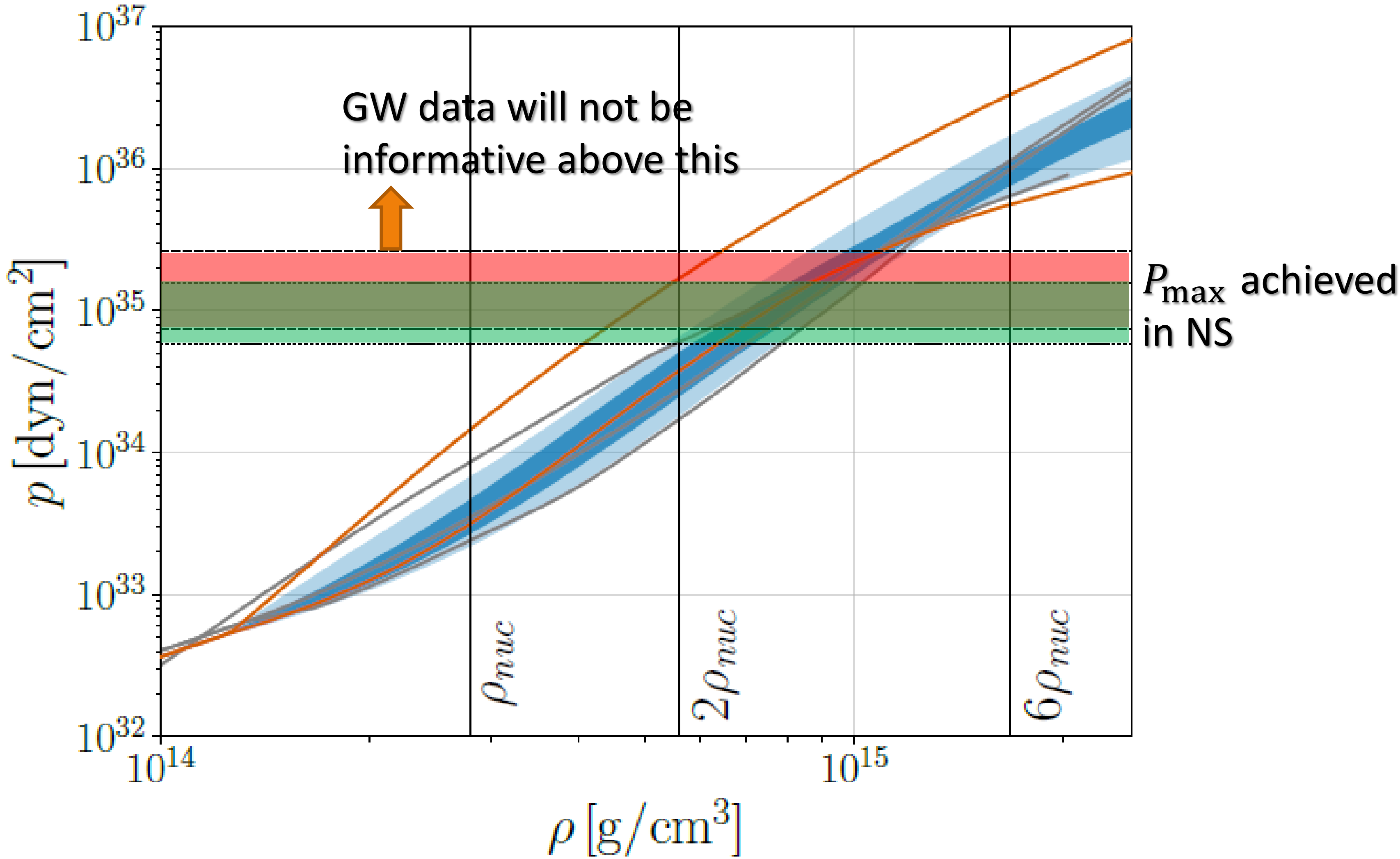
Updated analysis **using EOS model**

- 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





Constraint on NS EOS



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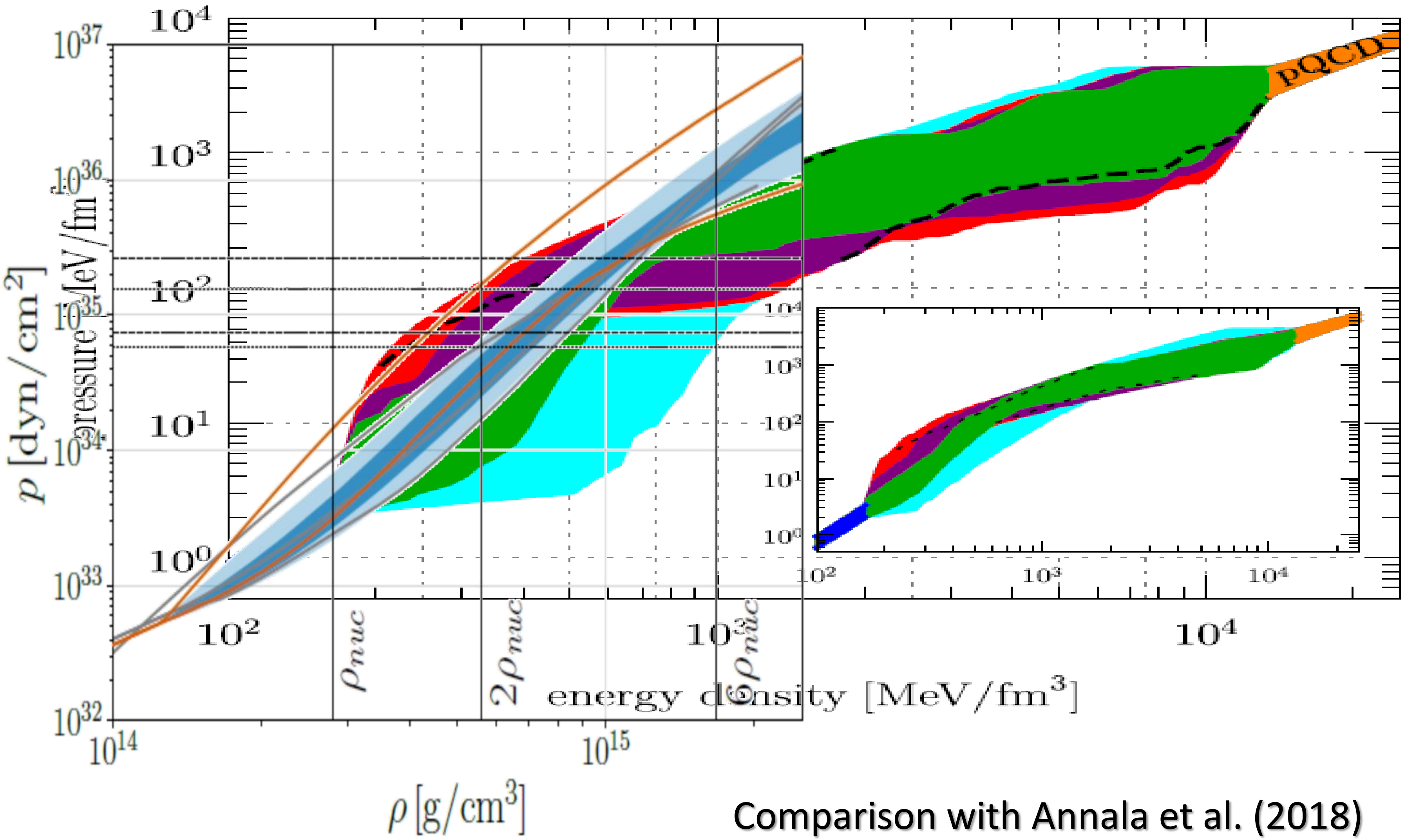
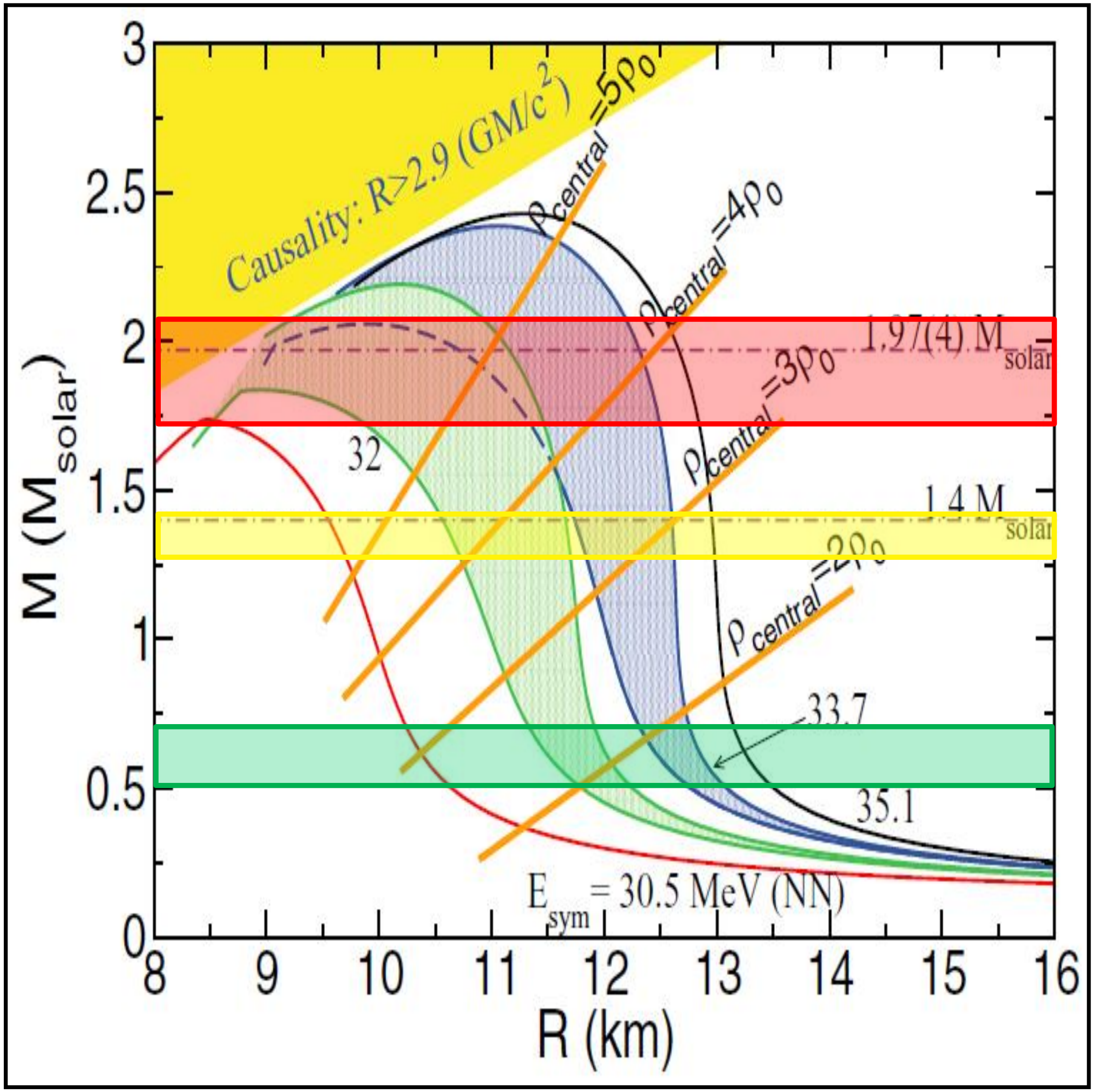


Comparison with Annala et al. (2018)

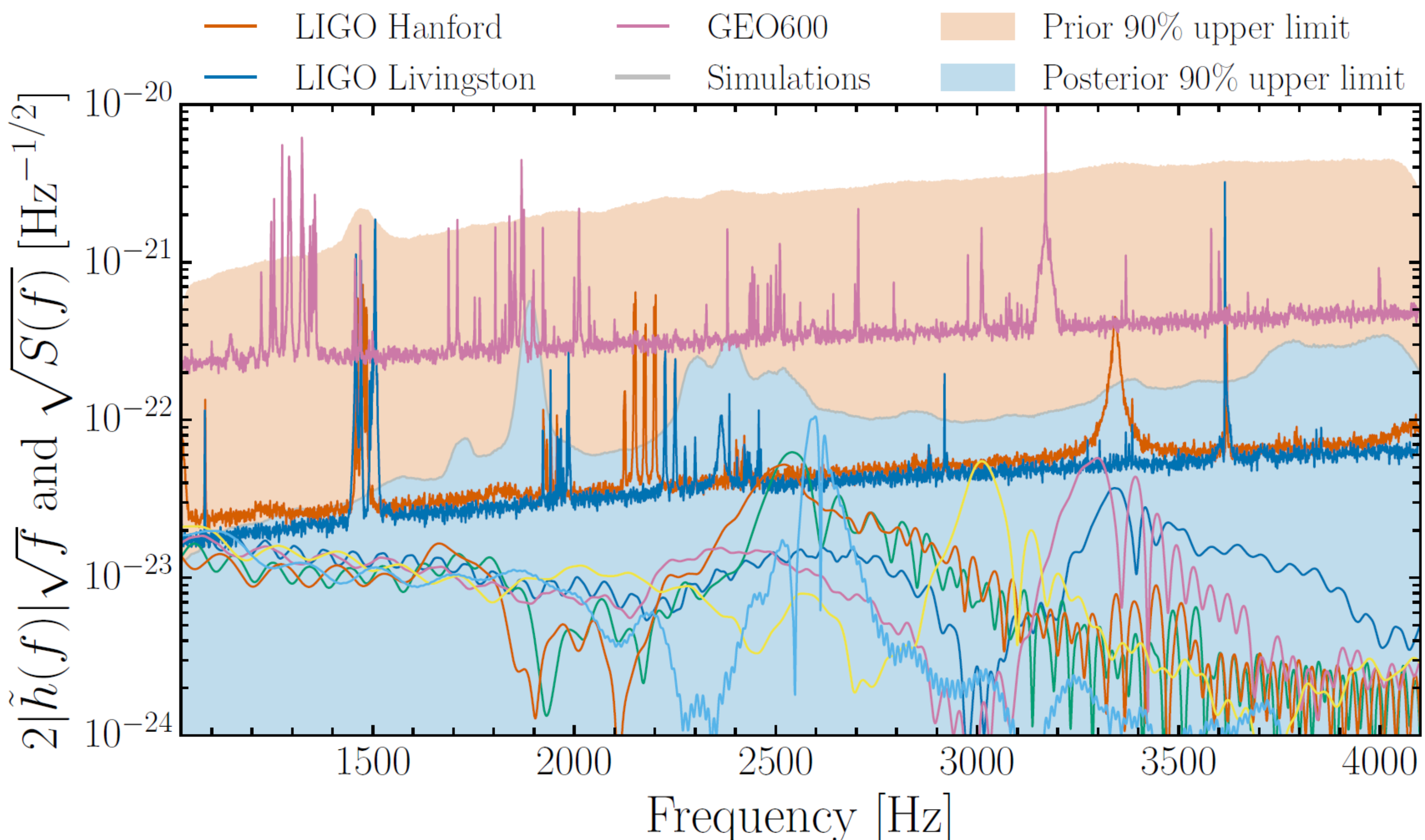
Massive NS is necessary to explore high density region

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

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

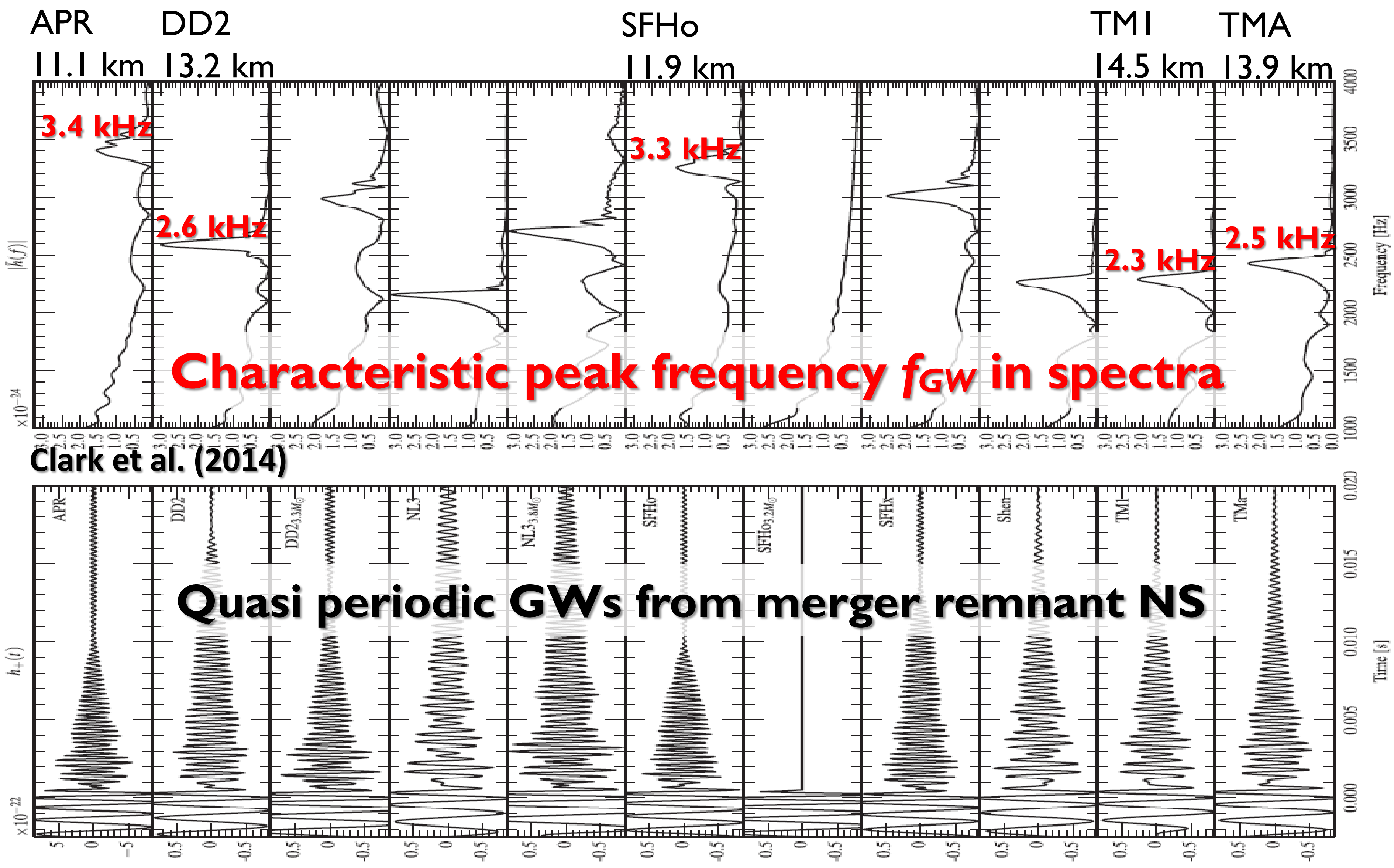


No GW from merger remnant detected



Abbott et al. (2018) 1805.11579

GW spectra and characteristic peak f_{GW}



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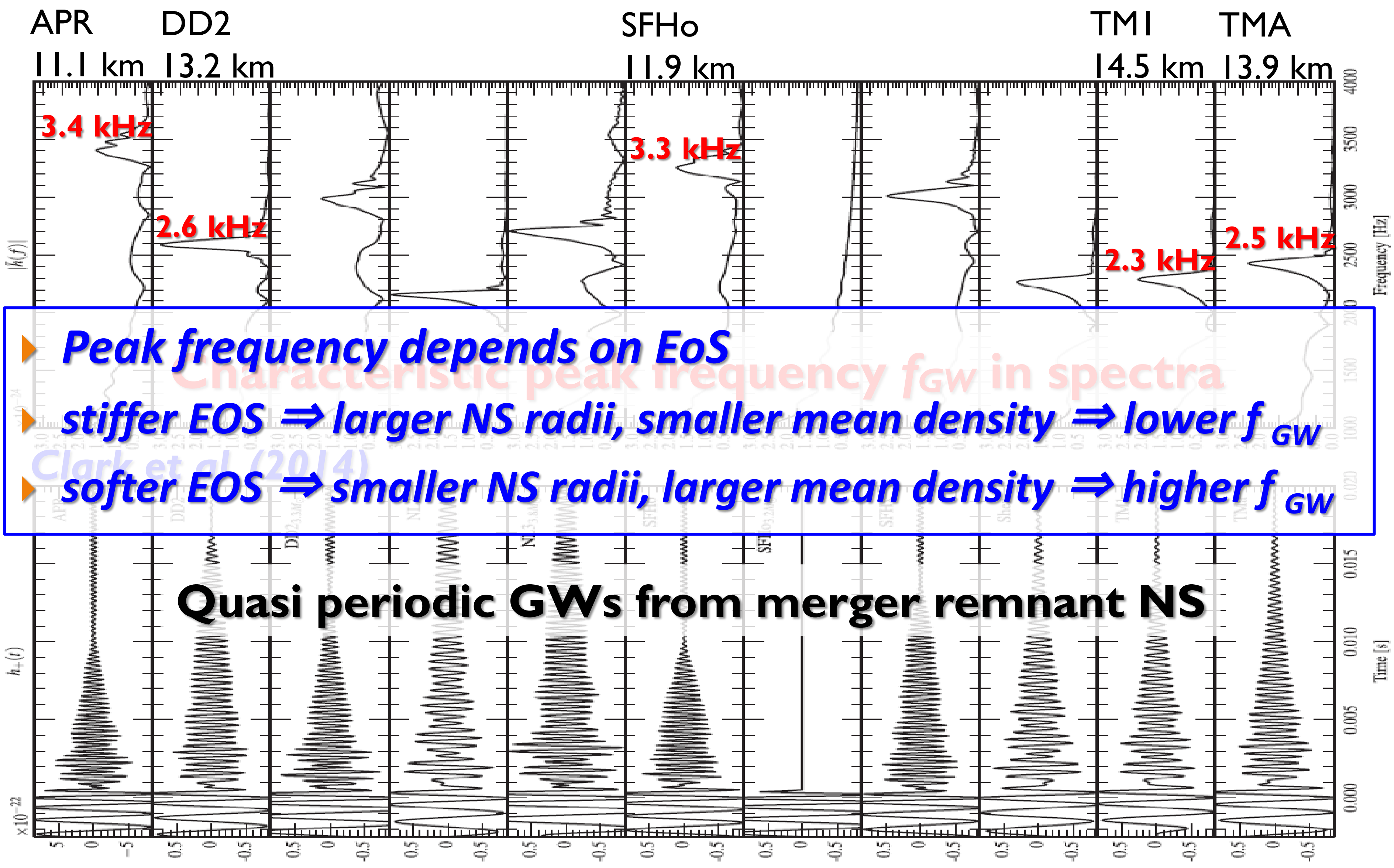


- ***Peak frequency depends on EoS***
- ***stiffer EOS ⇒ larger NS radii, smaller mean density ⇒ lower f_{GW}***
- ***softer EOS ⇒ smaller NS radii, larger mean density ⇒ higher f_{GW}***

Constraint on $M_{\max}$ from merger modelling and observations of EM counterpart

- **Condition 1 : BH should not be directly formed :**

$$M_{\rm crit} \gtrsim 2.74 M_\odot$$

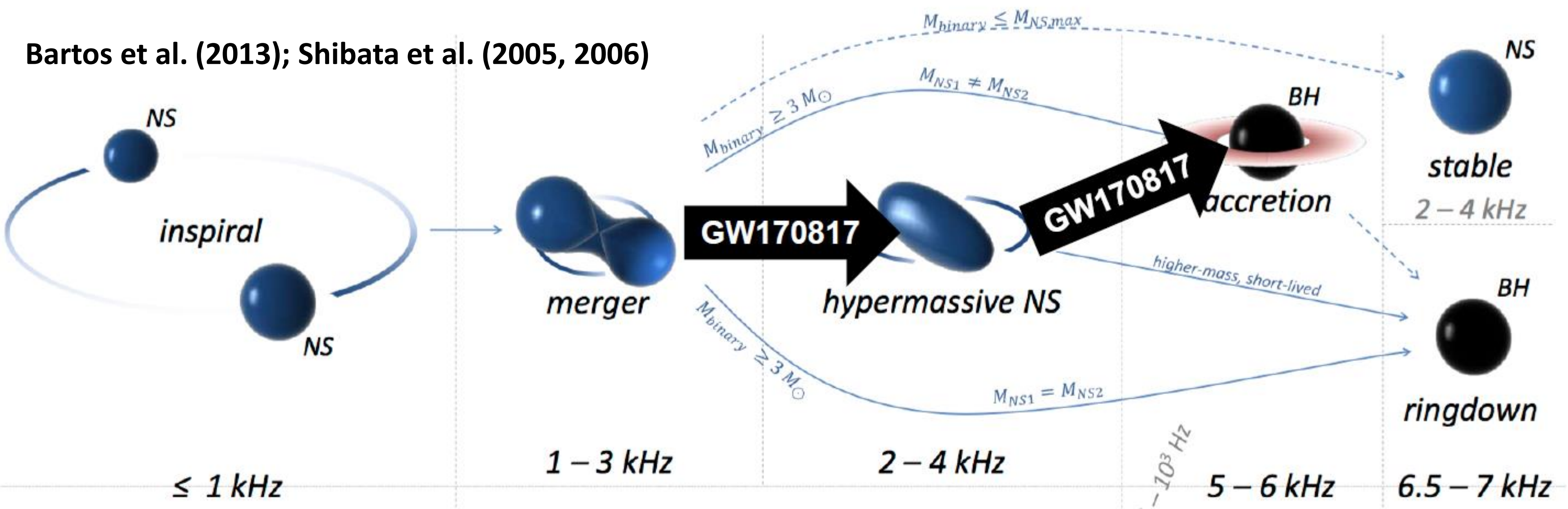
  - To small mass ejection and observed kilonova cannot be explained

- **Condition 2 : merger remnant should not be too long-lived :**

$$M_{\rm max,sph} + \Delta M_{\rm rot,rig} \lesssim 2.74 M_\odot$$

  - If long-lived, activities associated with this monster magnetar (merger remnant is strongly magnetized) should have been observed

Bartos et al. (2013); Shibata et al. (2005, 2006)



Constraint on $M_{\max}$ from merger modelling and observations of EM counterpart

- **Critical mass of BH formation**

$$M_{\mathrm{crit}} = M_{\mathrm{max,sph}} + \Delta M_{\mathrm{rot,rig}} + \Delta M_{\mathrm{rot,diff}} + \Delta M_{\mathrm{therm}}$$

  - $M_{\mathrm{max,sph}}$: maximum mass of cold spherical NS
  - $\Delta M_{\mathrm{rot,rig}}$: effect of rigid rotation
  - $\Delta M_{\mathrm{rot,diff}}$: effect of differential rotation
  - $\Delta M_{\mathrm{therm}}$: thermal contribution

- **Condition 1 : BH should not be directly formed :**

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Constraint on $M_{\max}$ from merger modelling and observations of EM counterpart

- **Condition 1 : BH should not be directly formed :**

$$M_{\rm crit} \gtrsim 2.74 M_\odot$$

  - Constraint on NS radius (compactness) or maximum mass
  - $R_{1.6} \gtrsim 10.68^{+0.15}_{-0.04}$ km (Bauswein et al. 2017)
  - $M_{max,sph} \gtrsim 2.1 M_\odot$ (Shibata et al. 2017)

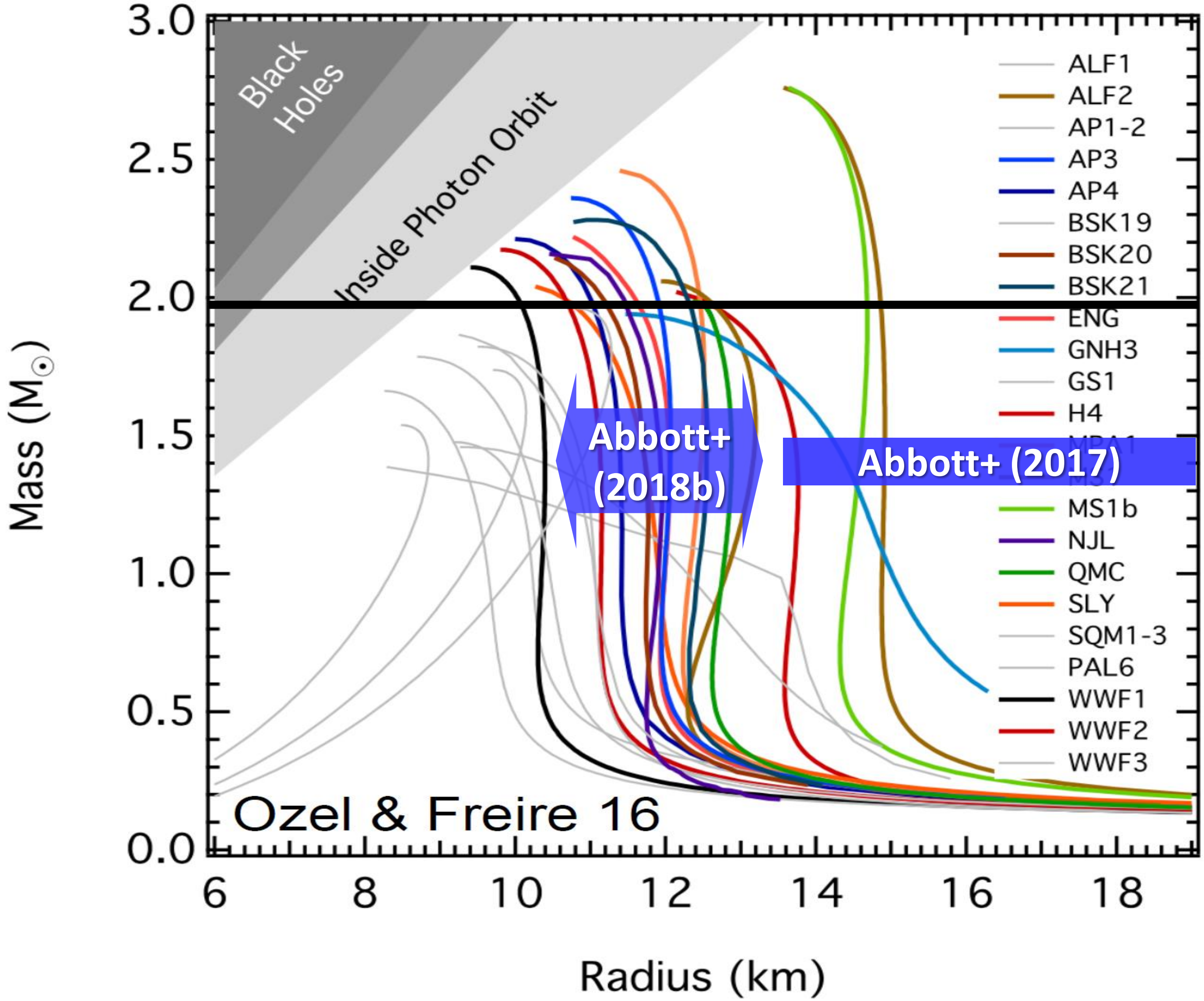
- **Condition 2 : merger remnant should not be too long-lived :**

$$M_{\rm max,sph} + \Delta M_{\rm rot,rig} \lesssim 2.74 M_\odot$$

  - Constraint on $M_{max,sph}$
  - $M_{max,sph} \lesssim 2.17 M_\odot$ (Margalit & Metzger 2017)
  - $M_{max,sph} \lesssim 2.25 M_\odot$ (Shibata et al. 2017)
  - $M_{max,sph} \lesssim 2.16^{+0.17}_{-0.15} M_\odot$ (Rezzolla et al. 2018)

see also Shibata et al. 2017)

Summary on NS structure constraint



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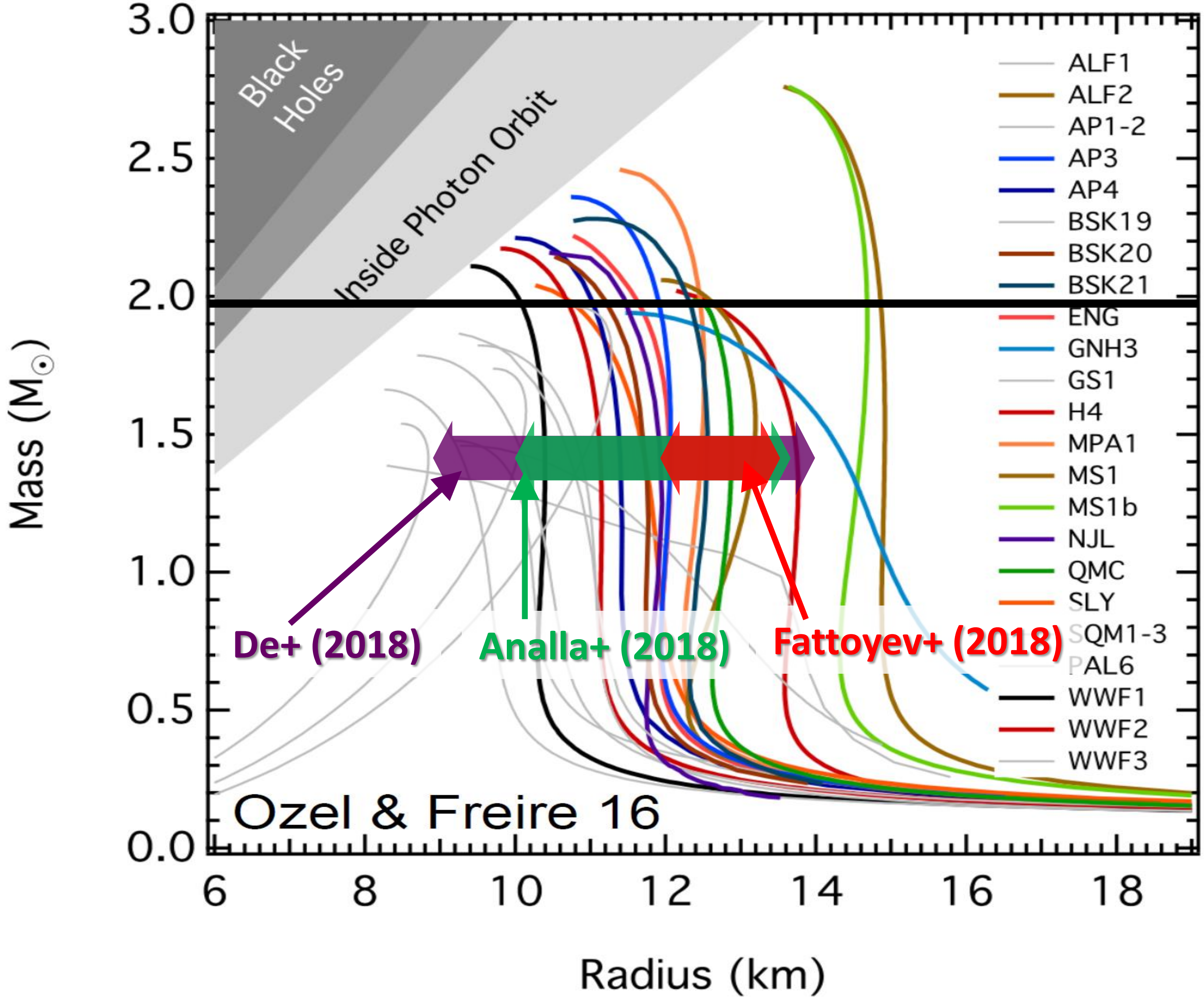

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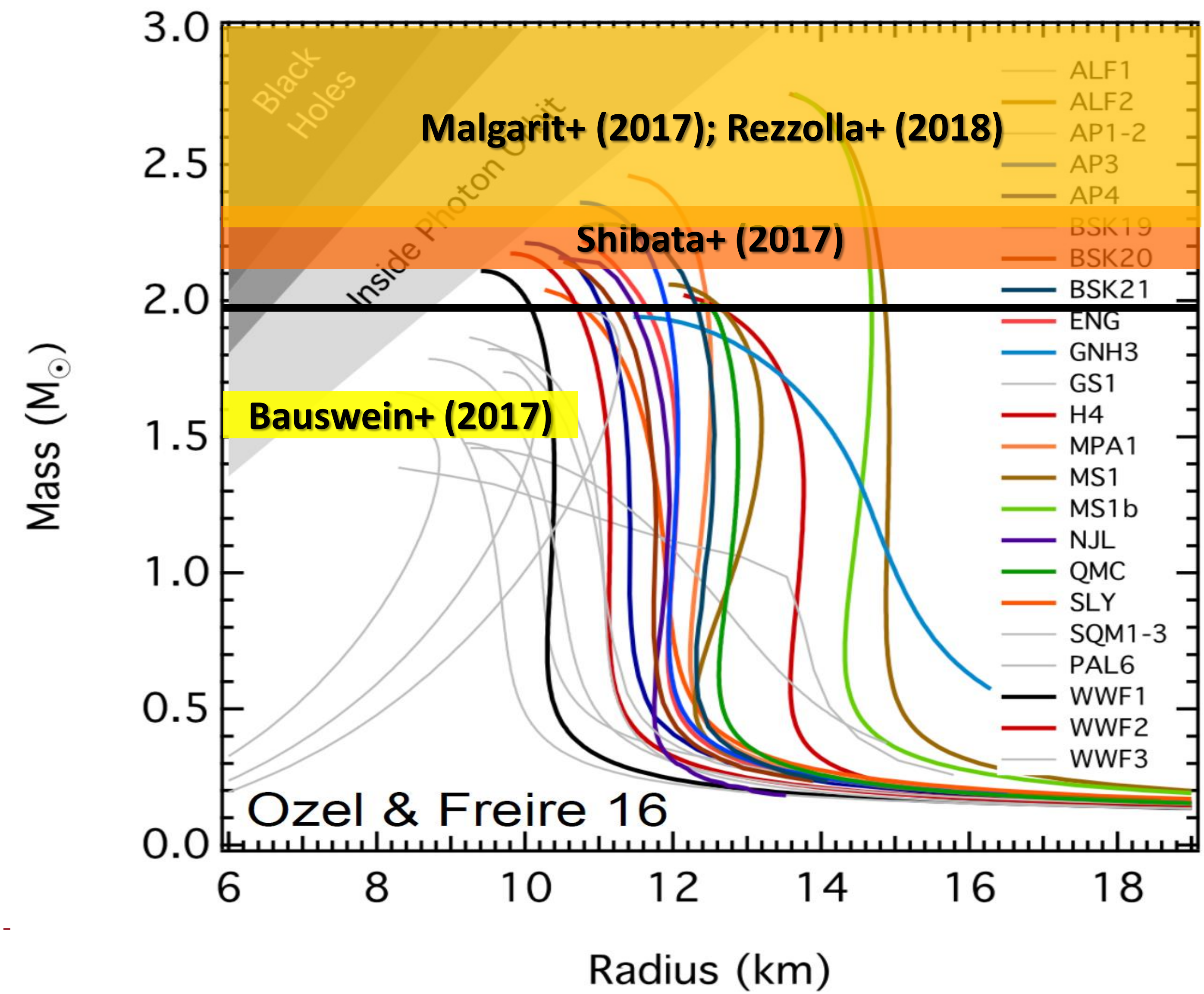

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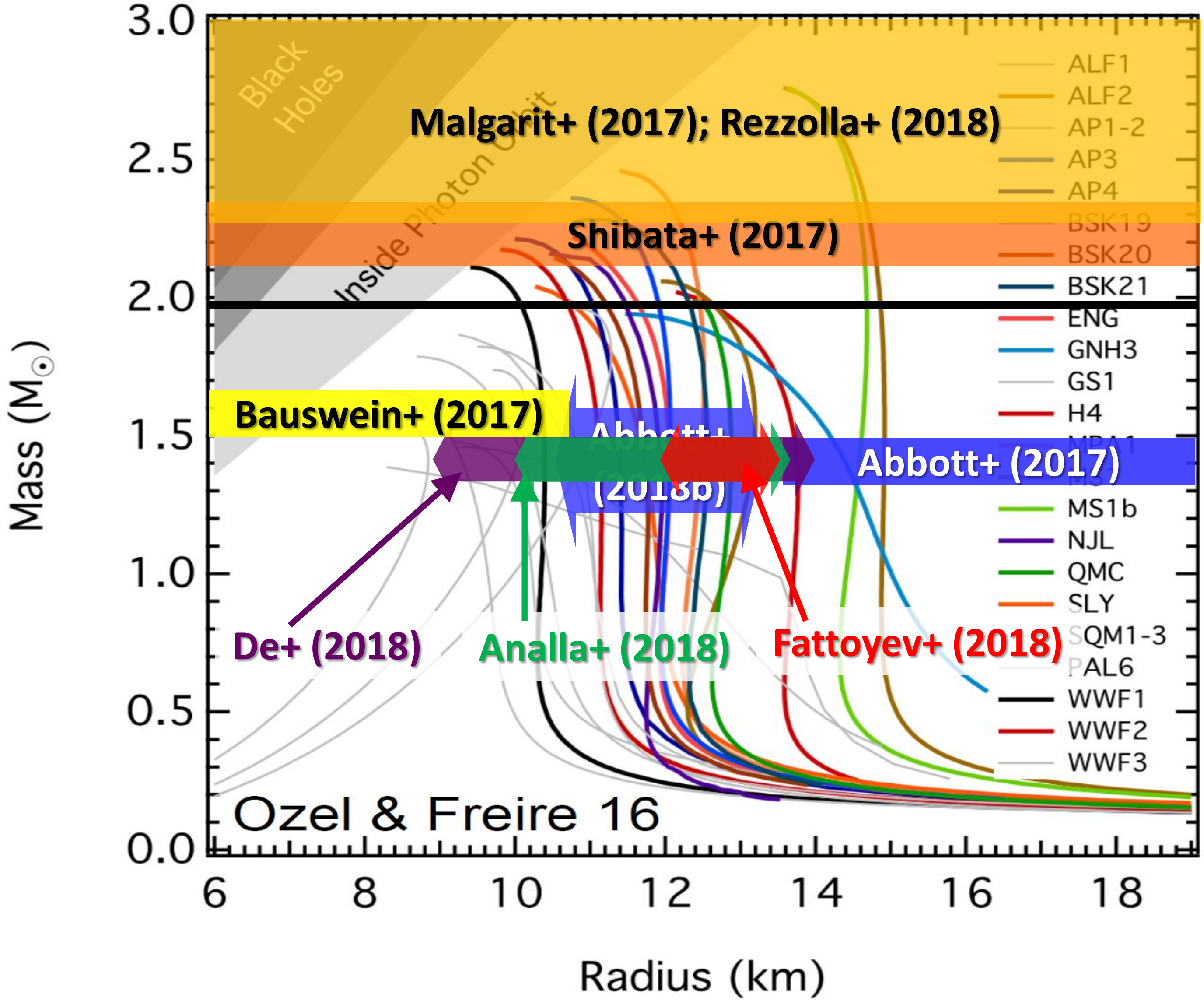
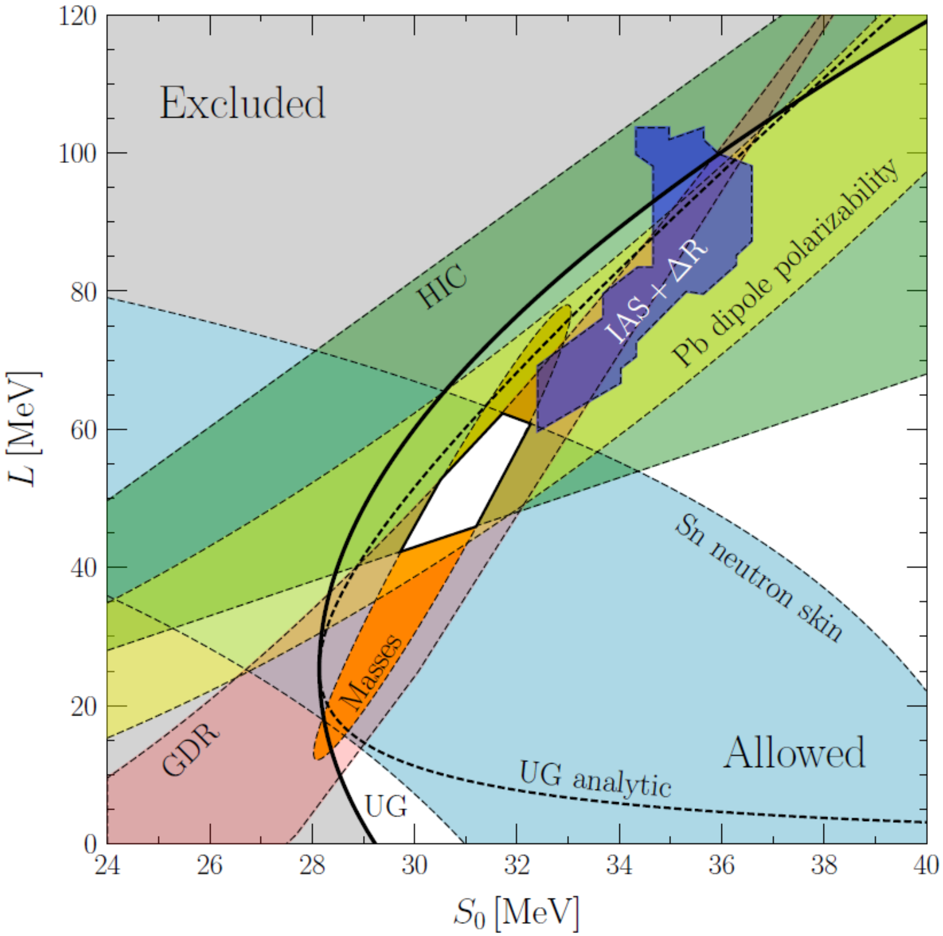
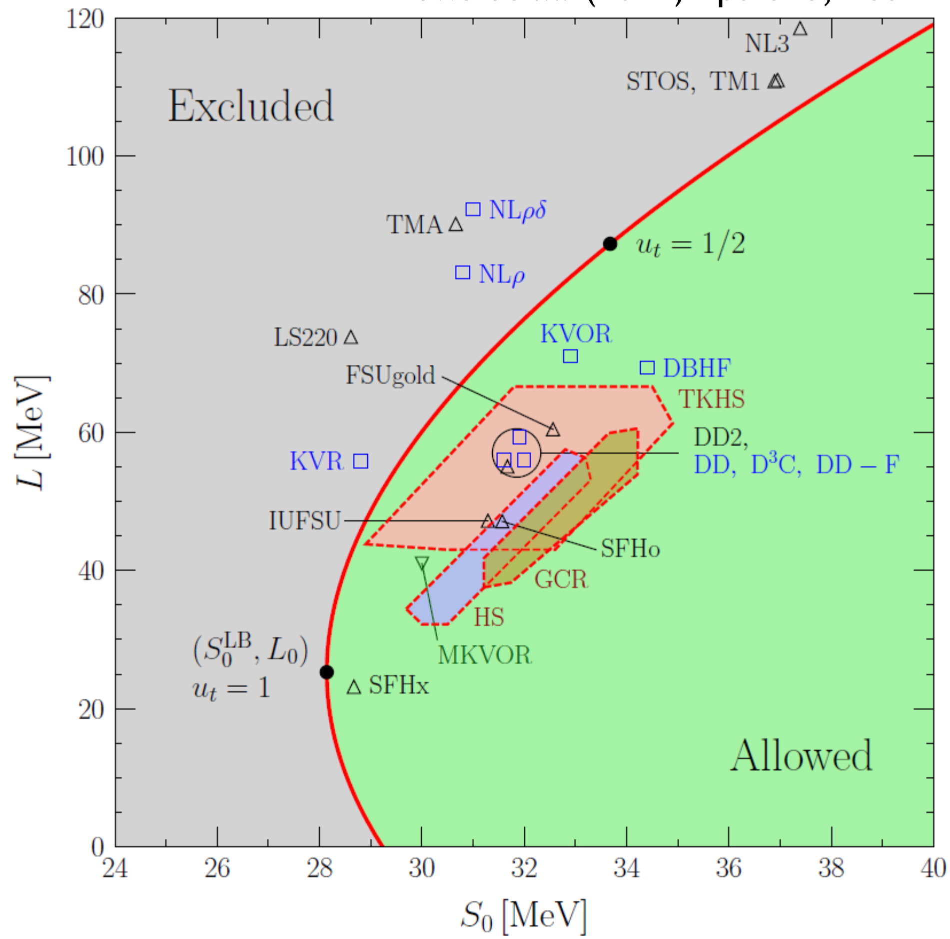


Constraint from nuclear experiments+

- Symmetry energy constraints from nuclear experiments
  ⇒ NS radius constraint

Tews et al. (2017) ApJ 848, 105

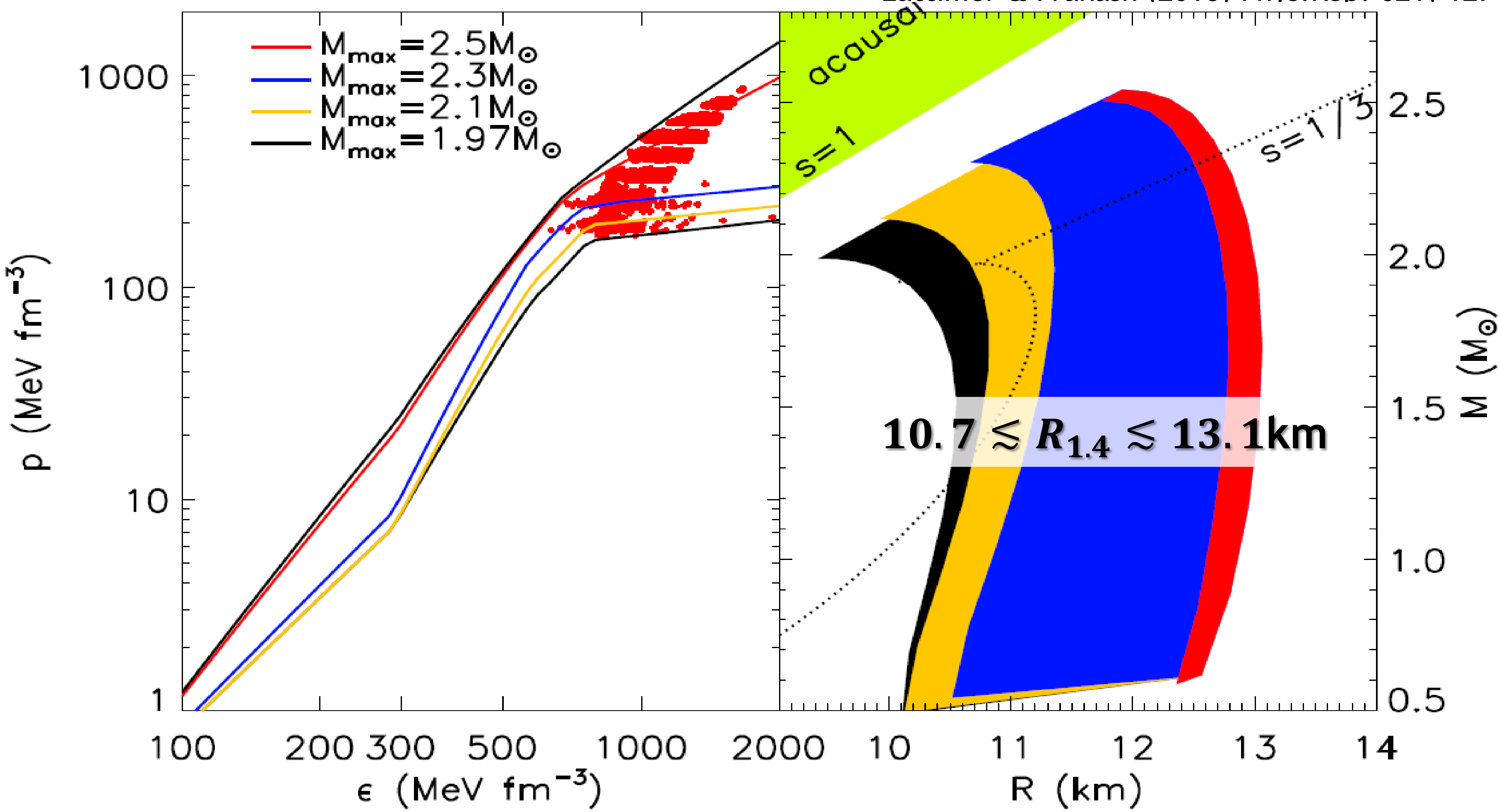




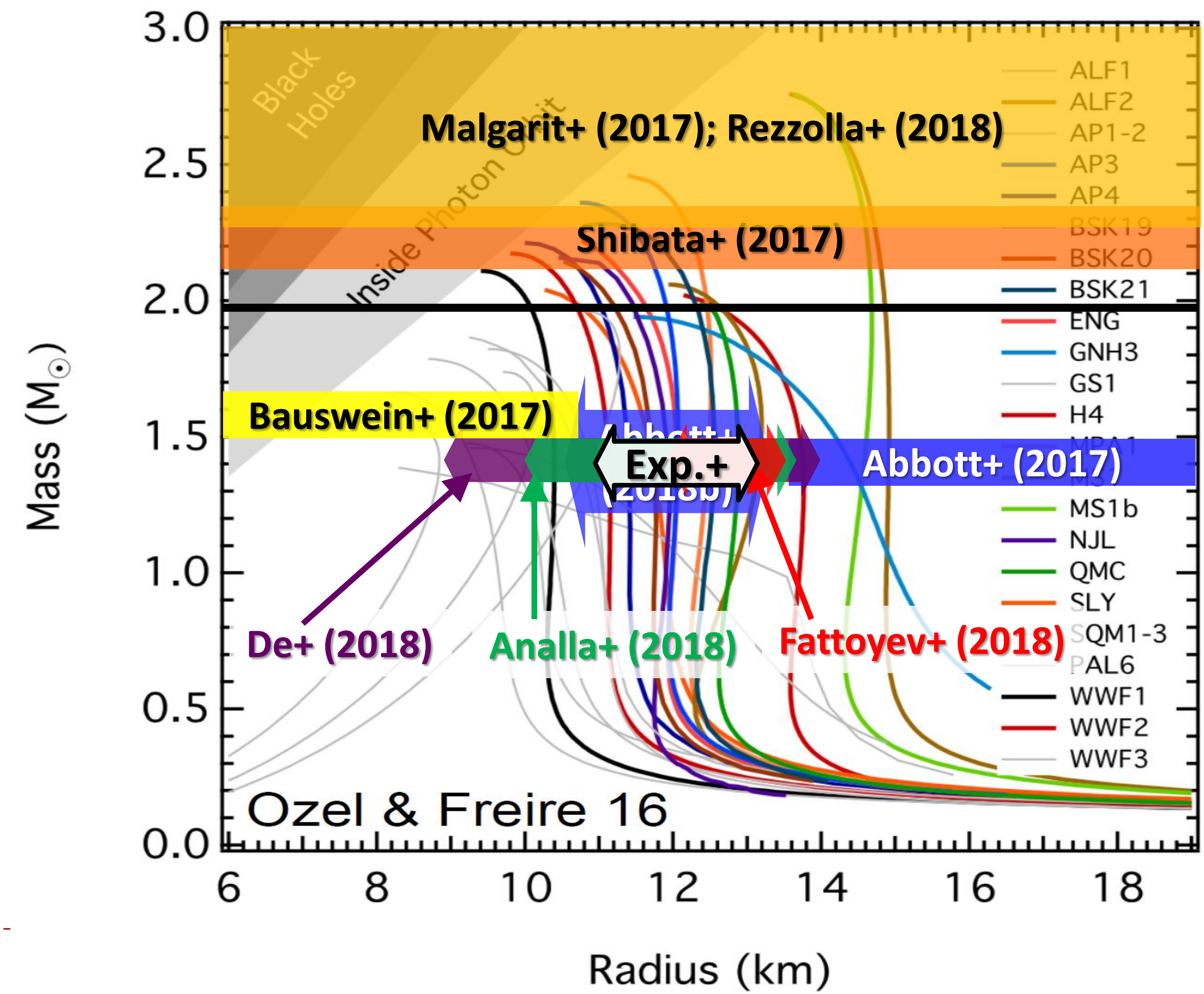
Constraint from nuclear experiments

- Symmetry energy constraints from nuclear experiments
  $\Rightarrow$ NS radius constraint

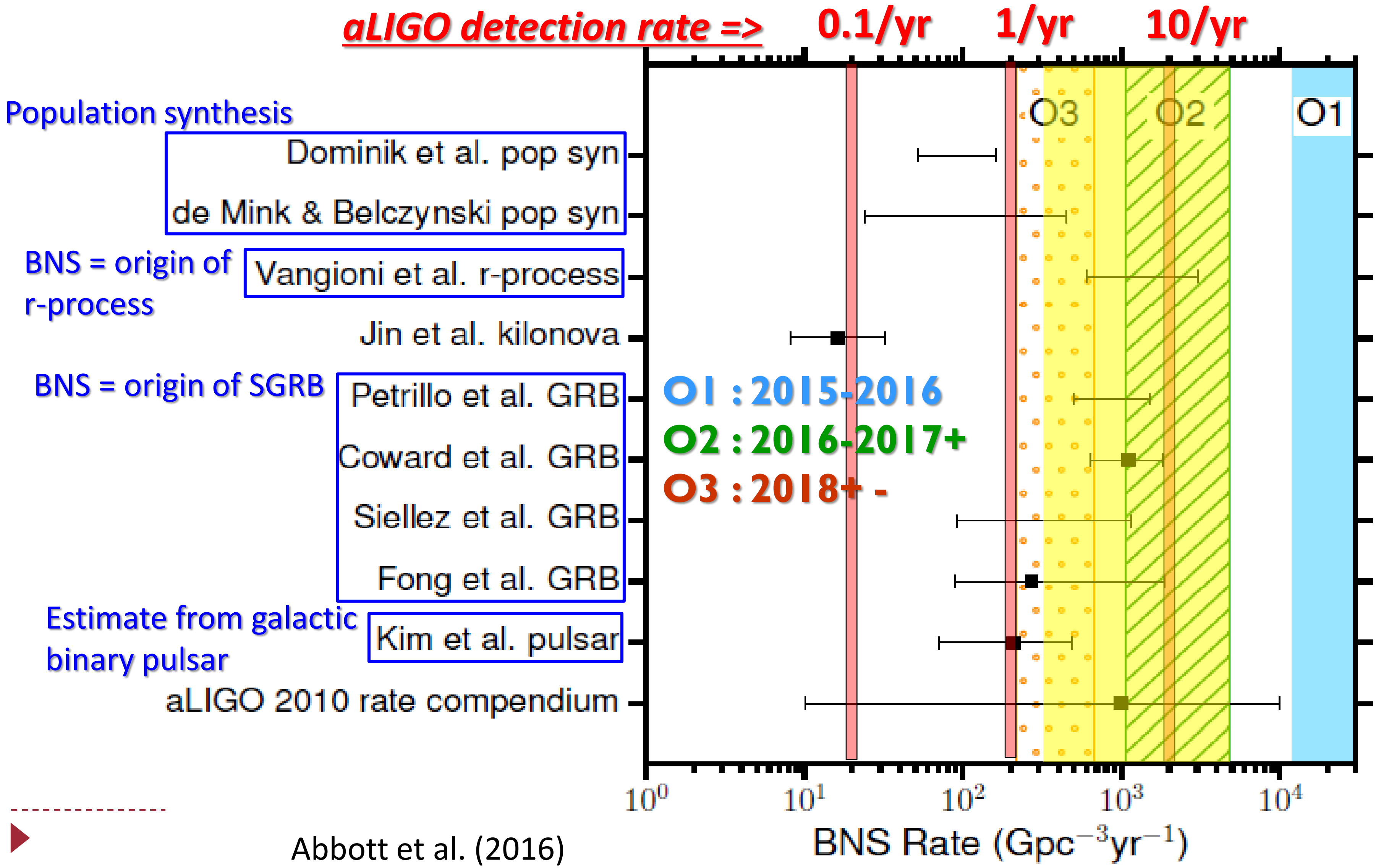
Lattimer & Prakash (2016) Phys.Rep. 621, 127



Summary on NS structure constraint



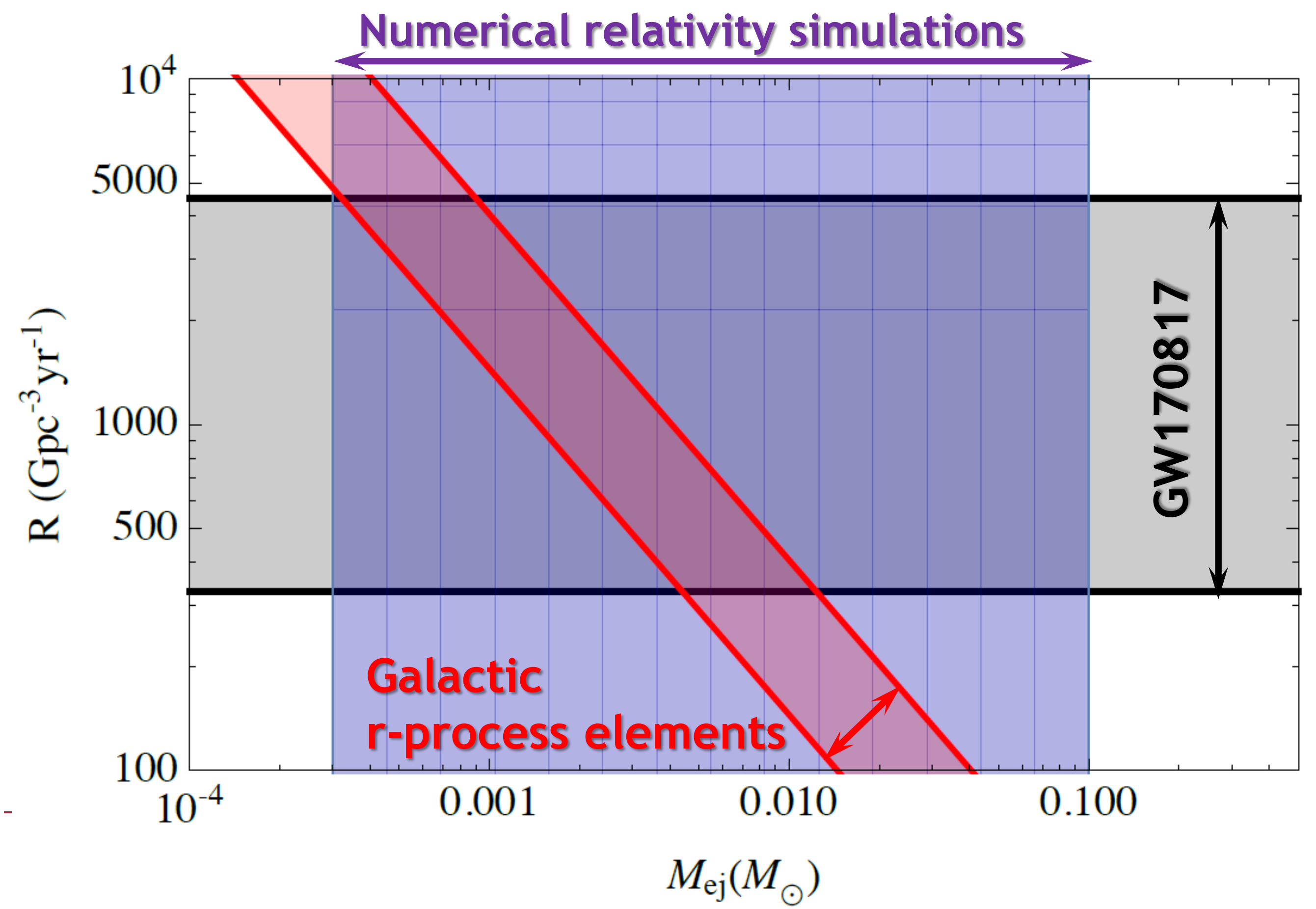
Expected NS-NS merger rate: **320-4740 Gpc^{-3}yr^{-1}**



Abbott et al. (2016)

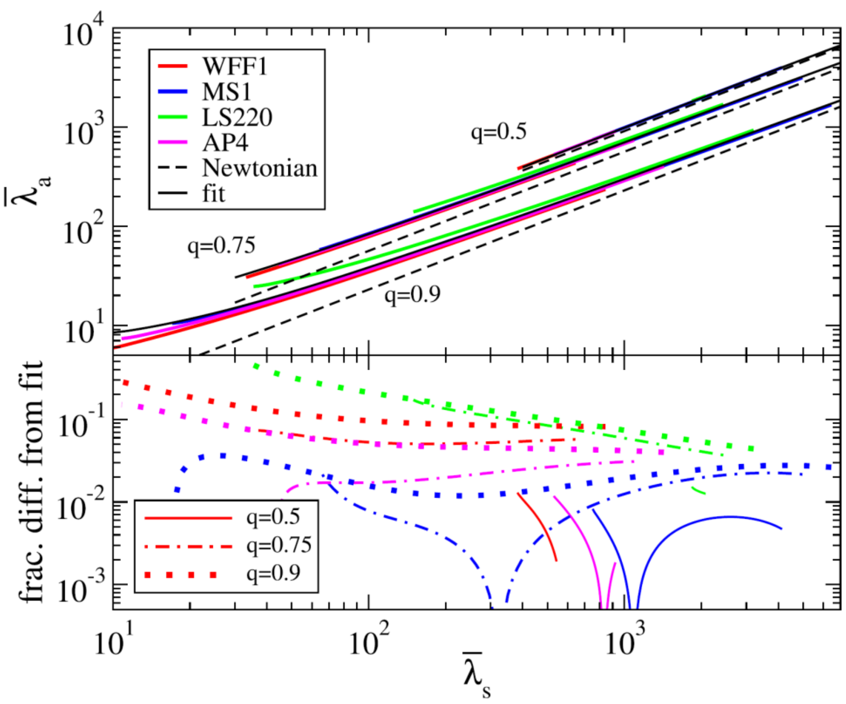
NS-NS merger as origin of r-process nucleosynthesis

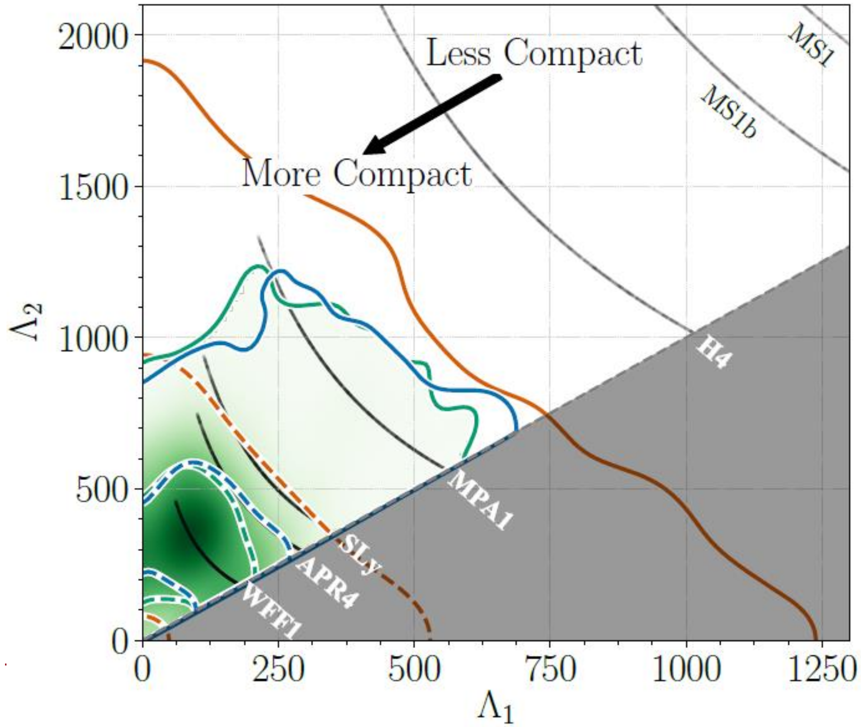
- NS-NS rate from GW170817 : 320-4740 $Gpc^{-3}yr^{-1}$
  - Mej ~ 0.01 Msun is sufficient for NS-NS merger to be the origin of r-process elements ! (Abbott et al. 2017)



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





Annala et al. (2018)
PRL 120, 172703

- Chiral EFT by Hebeler et al. (2013) ApJ 773, 11 for n < 1.1ns and NNLO pQCD by Kurkela et al. (2014) PRD 81, 105021 for mu_B > 2.6GeV (n >~ 40ns), parametrized EOS between them with causality constraint