The 8th Huada school on QCD @ CCNU, Wuhan, China

Foundations of GW from BNS merger

with application to nuclear/hadron physics

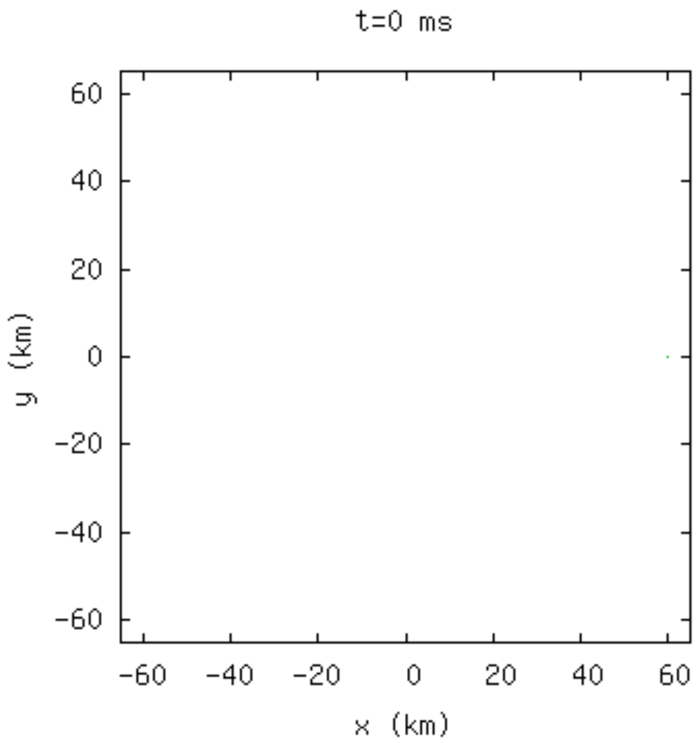
Yuichiro Sekiguchi (Toho University)

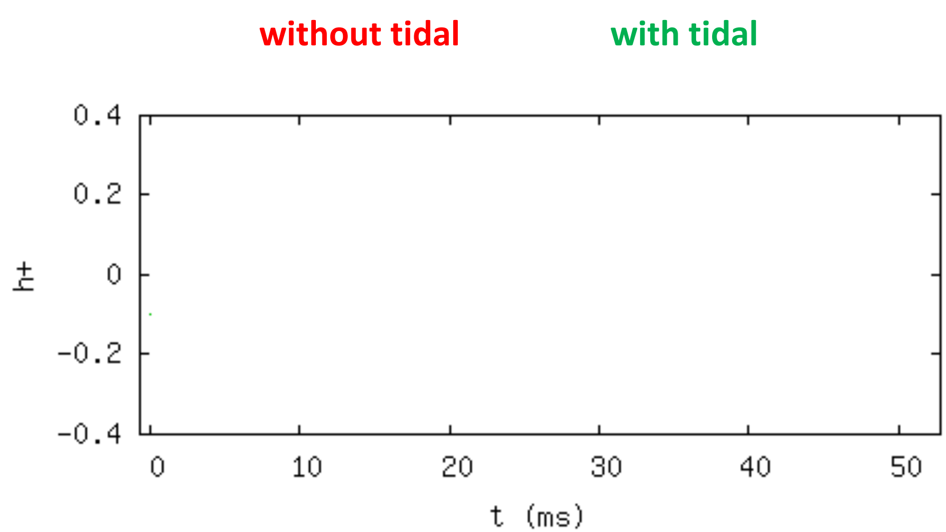
Contents

- Aim : Introduce physics of GW from NS-NS in a pedagogical viewpoint
- Lecture 1: Linearized theory
  - GW propagation, TT gauge, polarization of GW (+, and × modes)
  - GW production, quadrupole formula
- Lecture 2: GW from binary system in circular orbit
  - the (point-particle) chirp signal, tidal deformability
  - Post-Newtonian GW
- Lecture 3: Achievement in GW170817
  - Extraction of tidal deformability and its interpretation
  - Current constraint on EOS (combining with EM signals)
- Lecture 4: Future prospects
  - higher density regions, proving hadron-quark transition
  - Numerical Relativity

Summary of the previous lectures

- We can simultaneously extract information of both mass and tidal deformability, Λ, from GW from NS-NS, with which we can constrain the EOS of NS matter
  - Leading order of Tidal-deformability is 5PN
- The correction in G^n or $(v/c)^{2n}$ is called n-th order PN correction

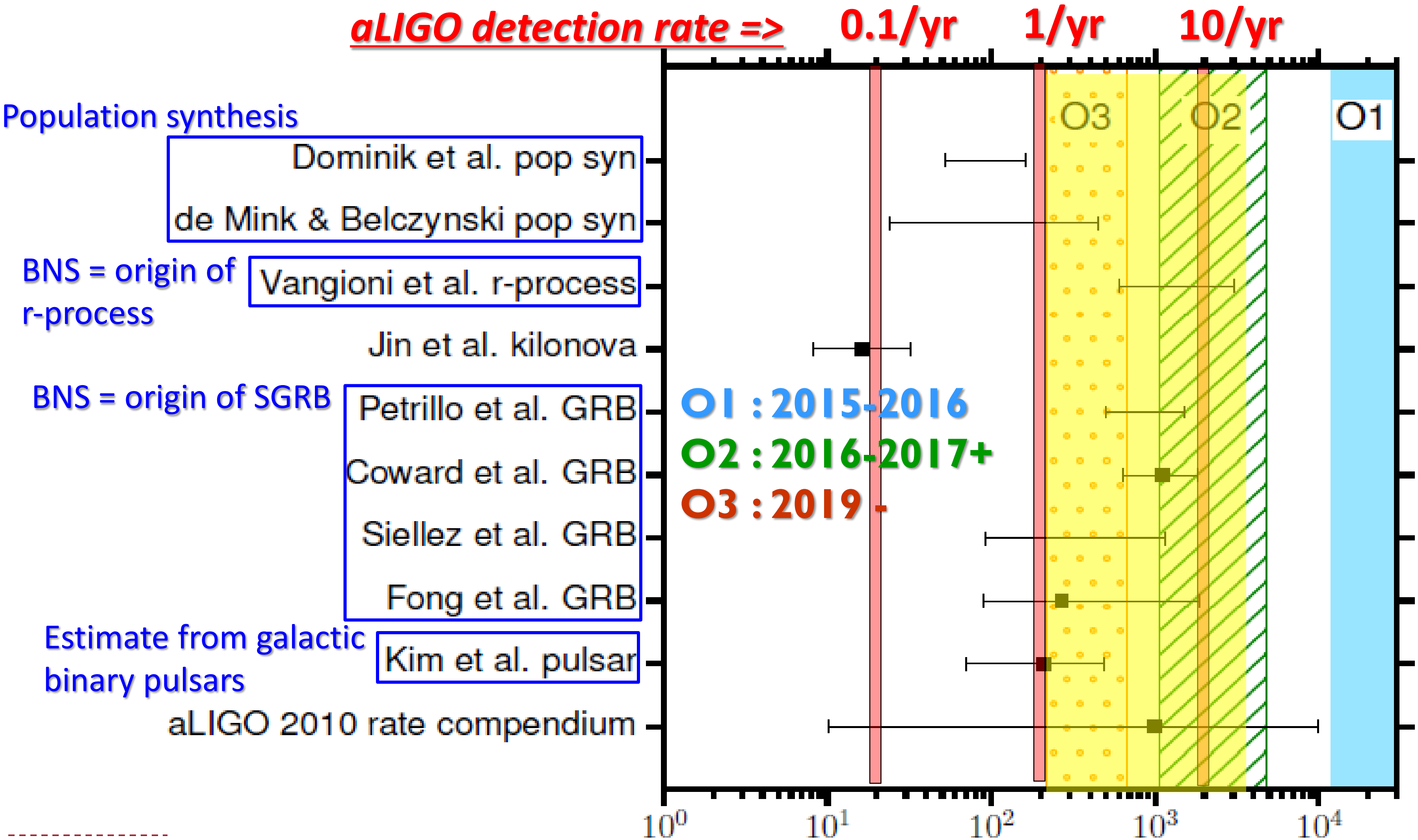




Lecture 3: GW170817

LIGO-Virgo Collaboration GWTC-1 paper

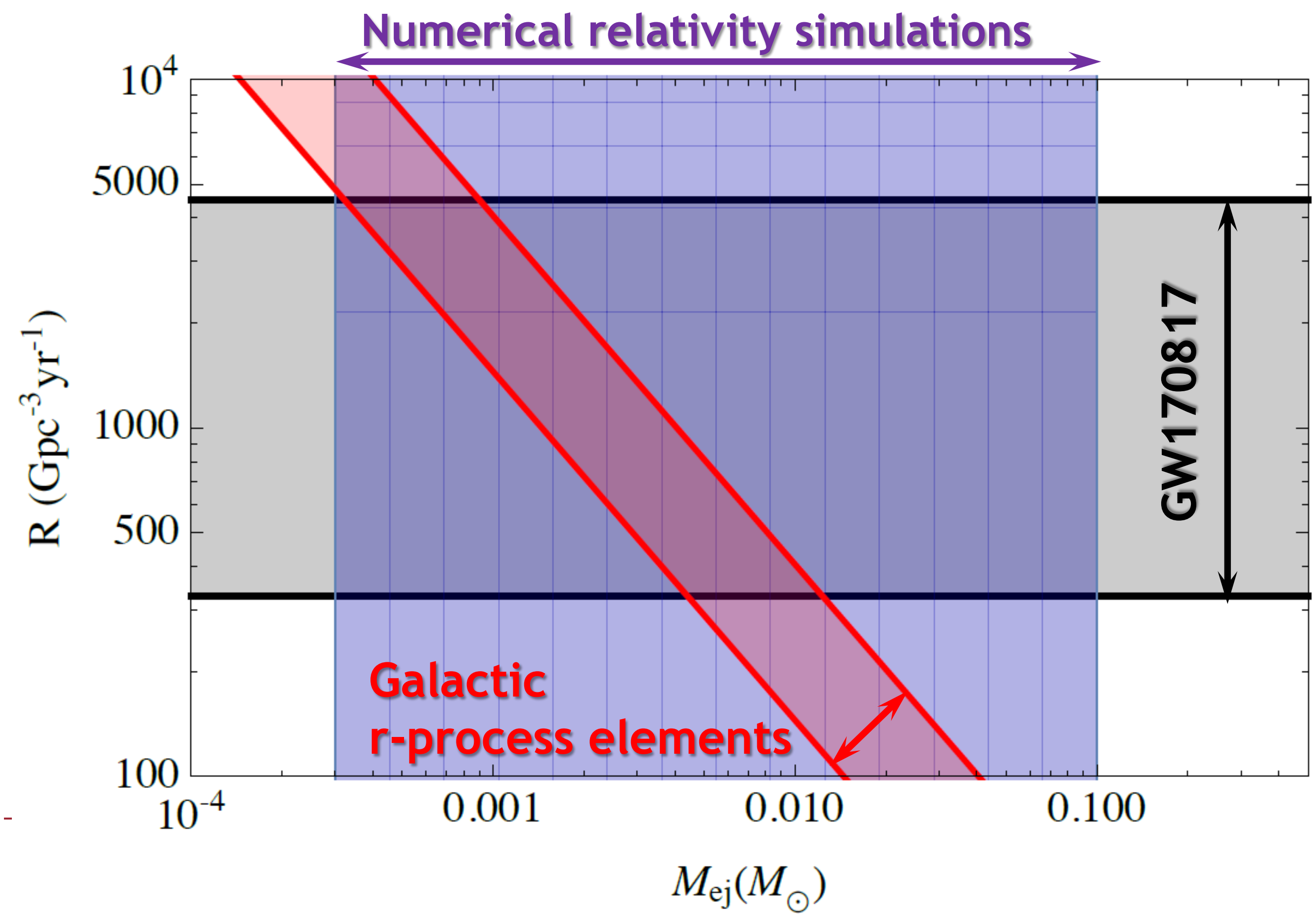
NS-NS merger event rate : **110-3840 $Gpc^{-3}yr^{-1}$**



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)



NS-NS(BH) candidates : S190425a and S190426c

- We have two additional candidates of GW from compact binary mergers including NS

- S190425a
  - probability (from mass estimation) being NS-NS : 0.999
  - $D \approx 160^{+40}_{-40}$ Mpc

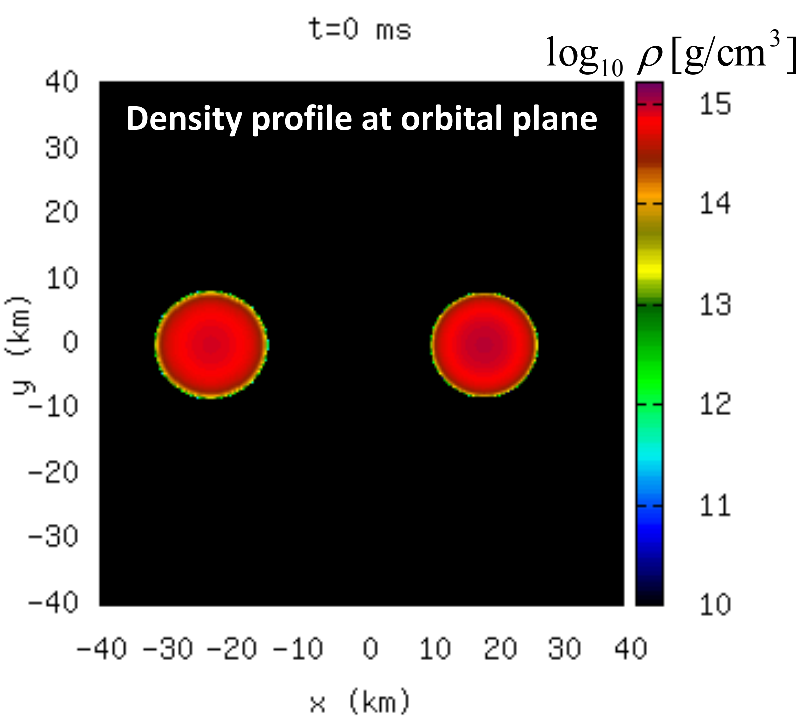
- S190426c
  - probability being
    NS-NS : 0.493, NS-BH($> 5M_\odot$) : 0.129, NS-(NS or low mass BH) : 0.237 ,
    unknown terrestrial : 0.140
  - $D \approx 420^{+130}_{-130}$ Mpc

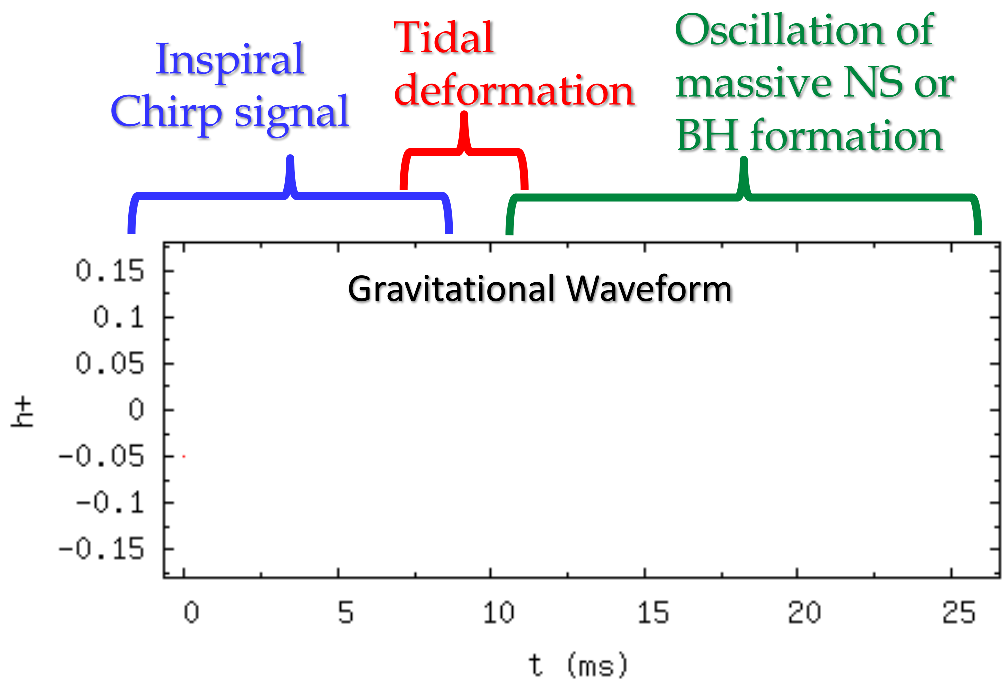
$\Rightarrow$ suggest that the event rate may be relatively high as $\sim$ 10/yr

Sekiguchi et al, 2011; Hotokezaka et al. 2013

Gravitational waves from NS merger

Numerical relativity simulation modelling GW170817





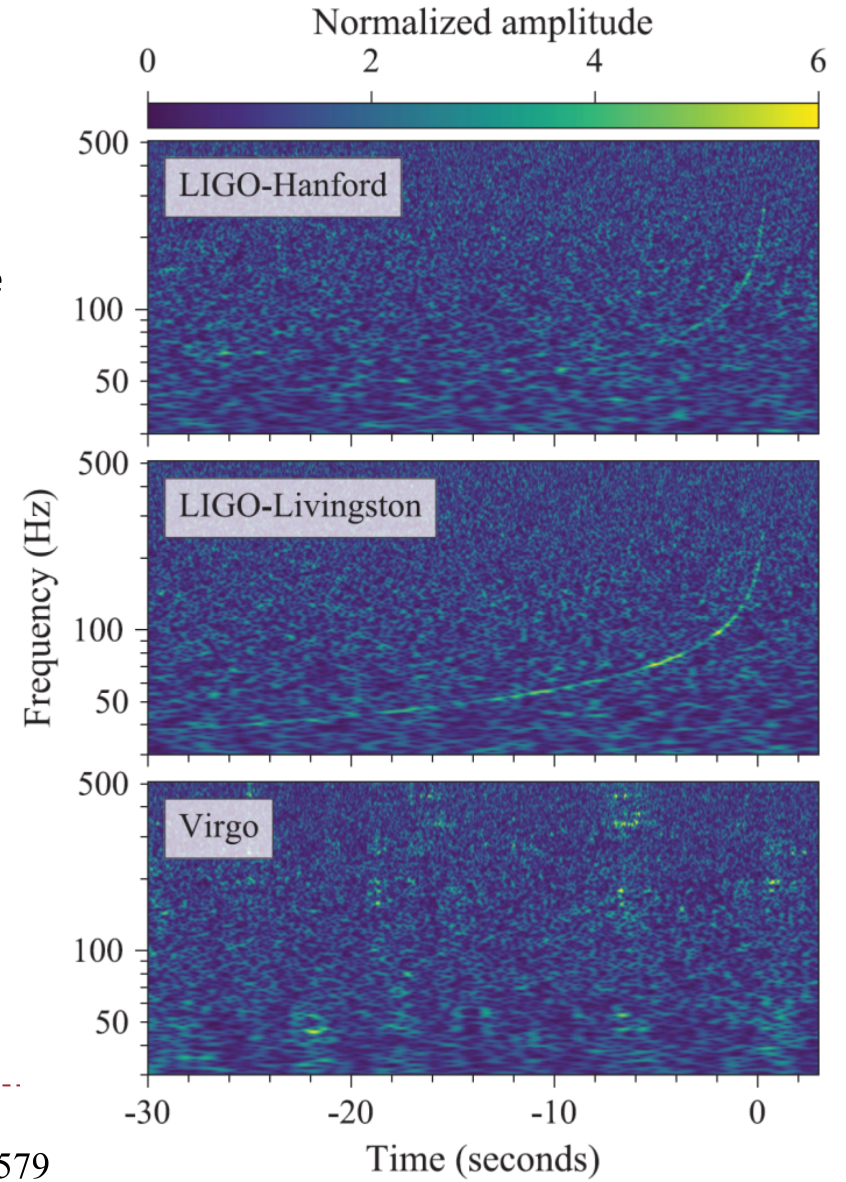
- point particle approx.
- information of binary parameter (**NS mass**, etc)

- 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

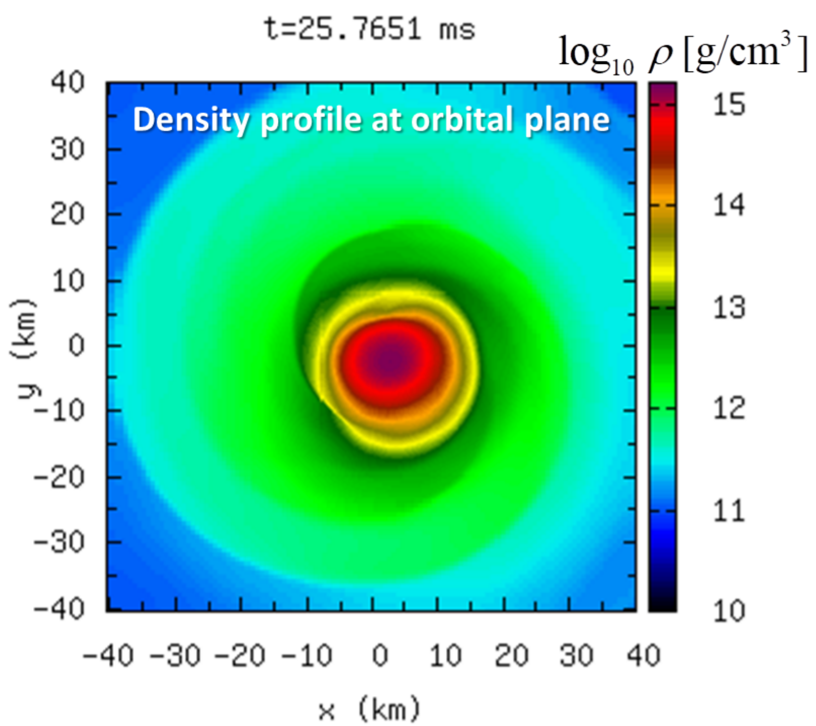
- S/N = 33.0 (signal to noise ratio)
  - Assumption/setup of data analysis :
    - NS is not rotating rapidly like BH
    - Using the EM counterpart SSS17a/AT2017gfo for the source localization
    - Using distance indicated by the red-shift of the host galaxy NGC 4993
- Chirp mass : $\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.186^{+0.001}_{-0.001} M_\odot$
  - 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) : $1.27^{+0.09}_{-0.09} M_\odot$**
- Luminosity distance to the source : 40^{+10}_{-10} Mpc

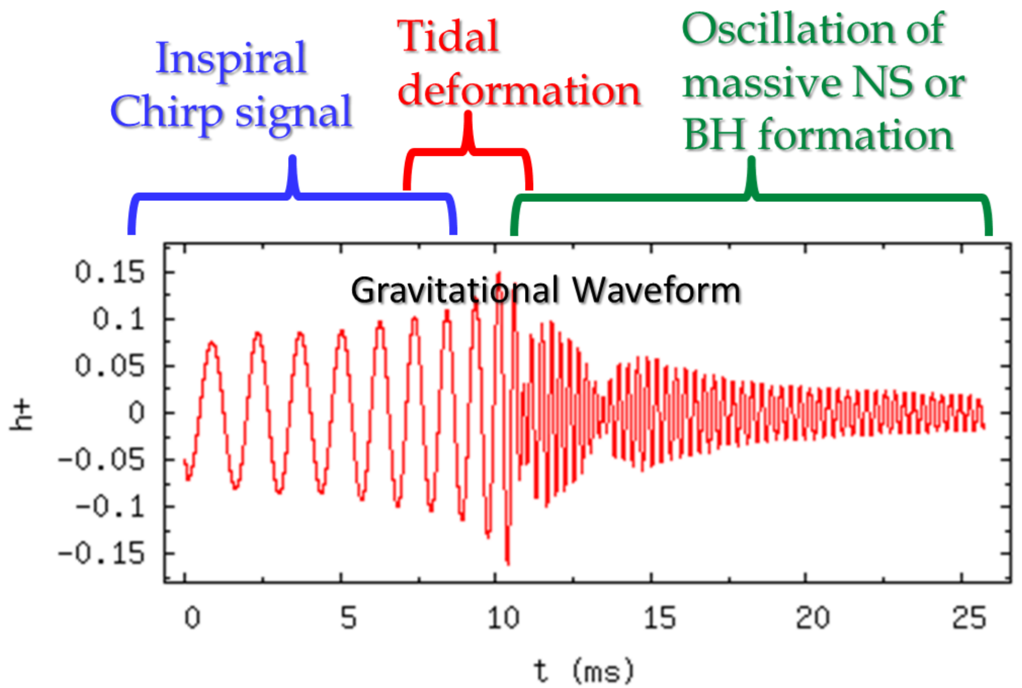


- LIGO-Virgo Collaboration GWTC-1 paper
  See also Abbott et al. PRL 119, 161101 (2017); arXiv:1805.11579

Tidal deformation and NS EOS

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**

Tidal deformability

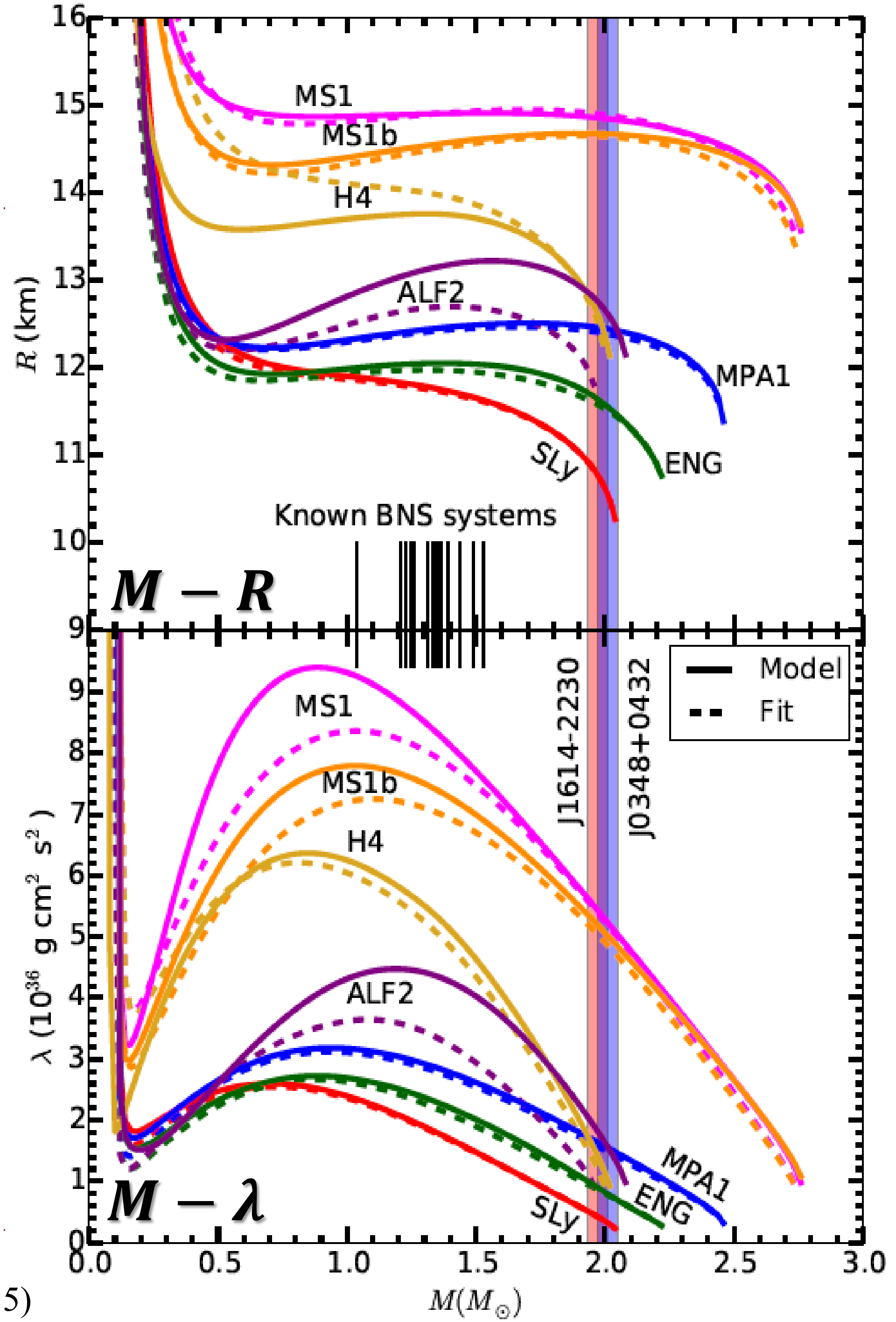
- Tidal Love number : λ
  - Response of quadrupole moment Q_{ij} to external tidal field E_{ij}

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

  - 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)

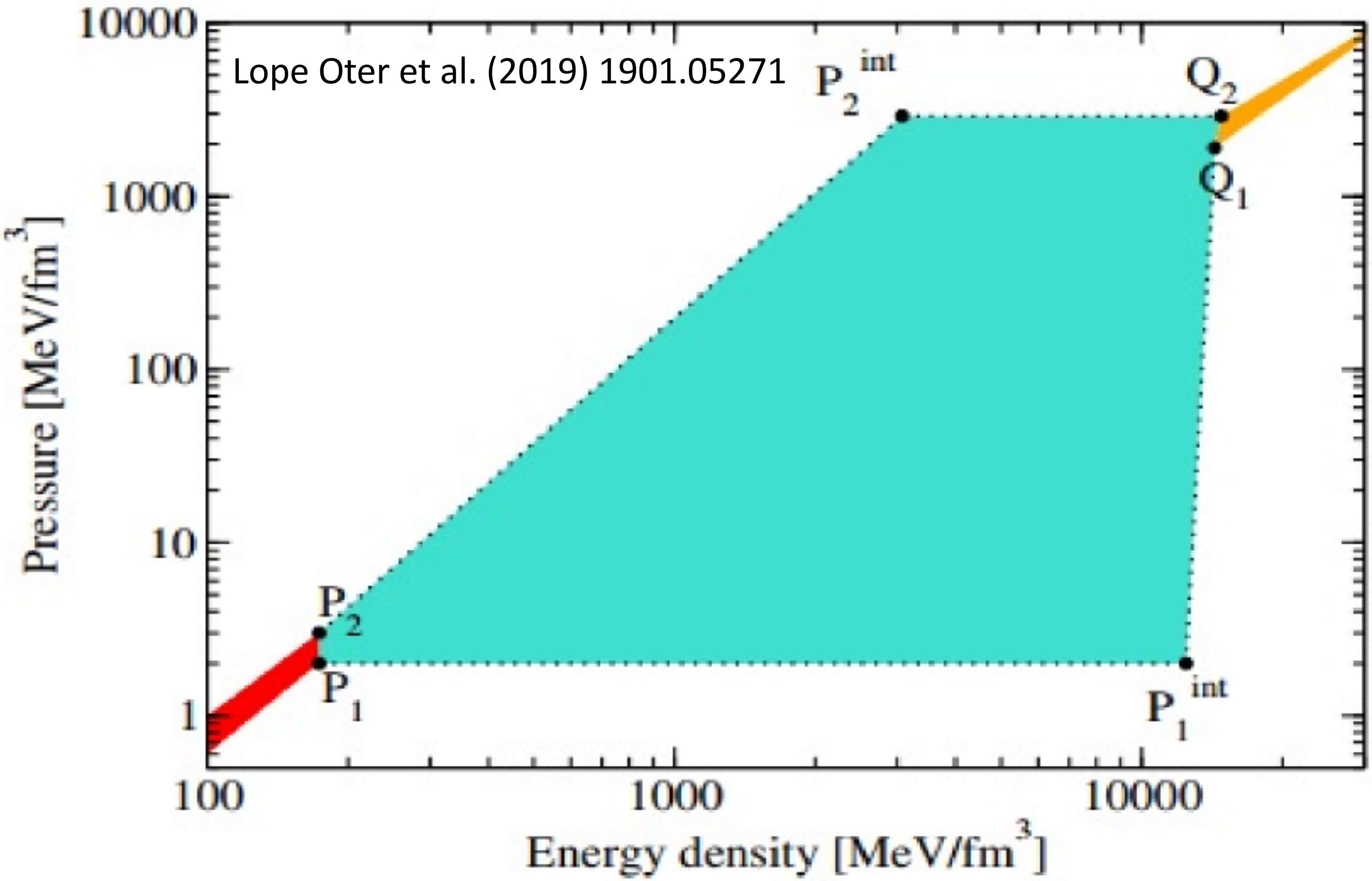
$$\tilde{\Lambda} < 800 \;\Rightarrow\; \Lambda_{1.4} \lesssim 800$$

- The analysis uses 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
- are NOT taken into account

Annala et al. PRL 120, 172703 (2018)

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

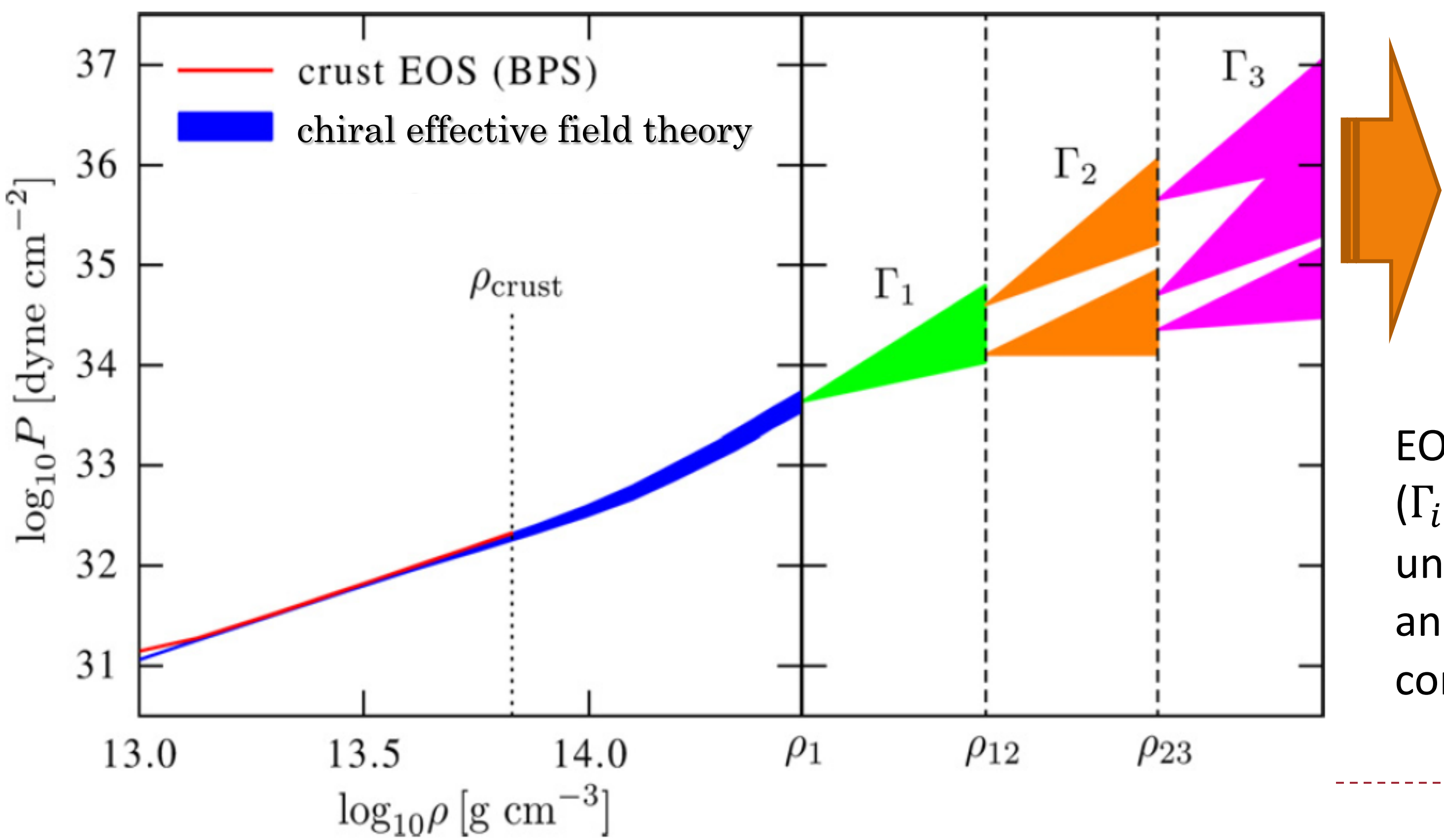
- $\Lambda_{1.4} \lesssim 800$ **: in terms of NS radius** $10 \lesssim R_{1.4M_\odot} \lesssim 13.5$ **km for EOS**
  - connect to the NNLO pQCD (Kurkela et al. 2010) and chiral EFT (Hebeler et al. 2013)



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 EOS**
  - connect to the NNLO pQCD (Kurkela et al. 2010) and chiral EFT (Hebeler et al. 2013)
  - causality $c_s < c$ and $M_{\mathrm{EOS,max}} > 2M_\odot$ constraints in the intermediate region

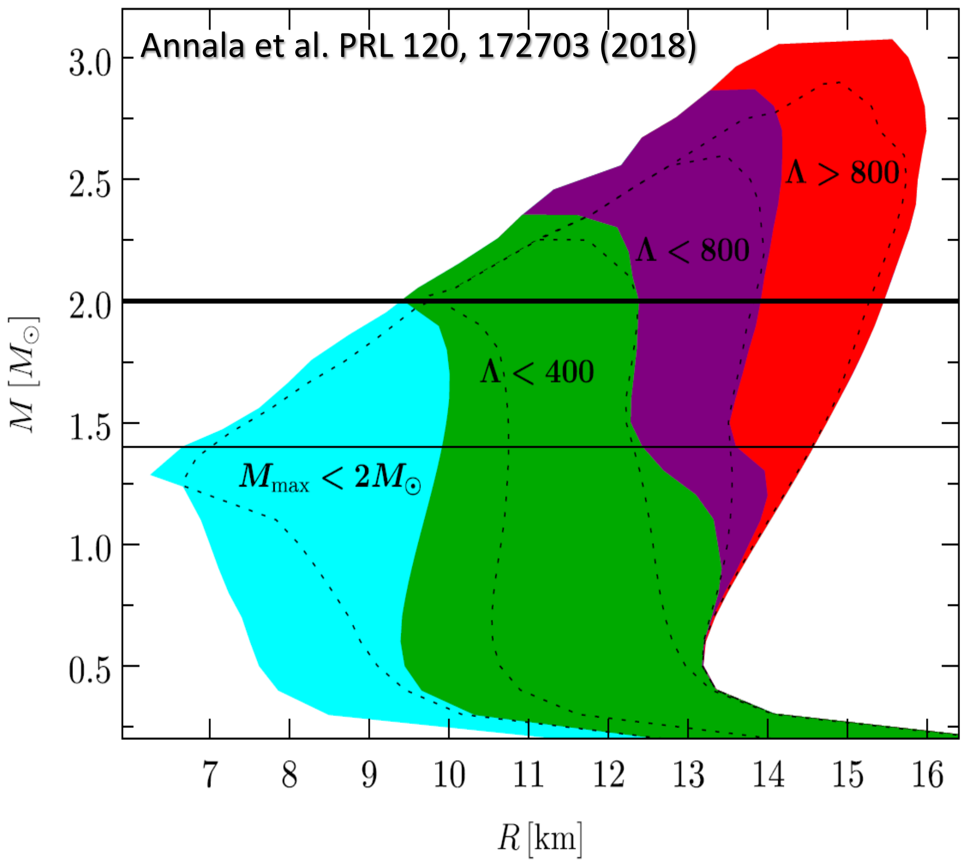


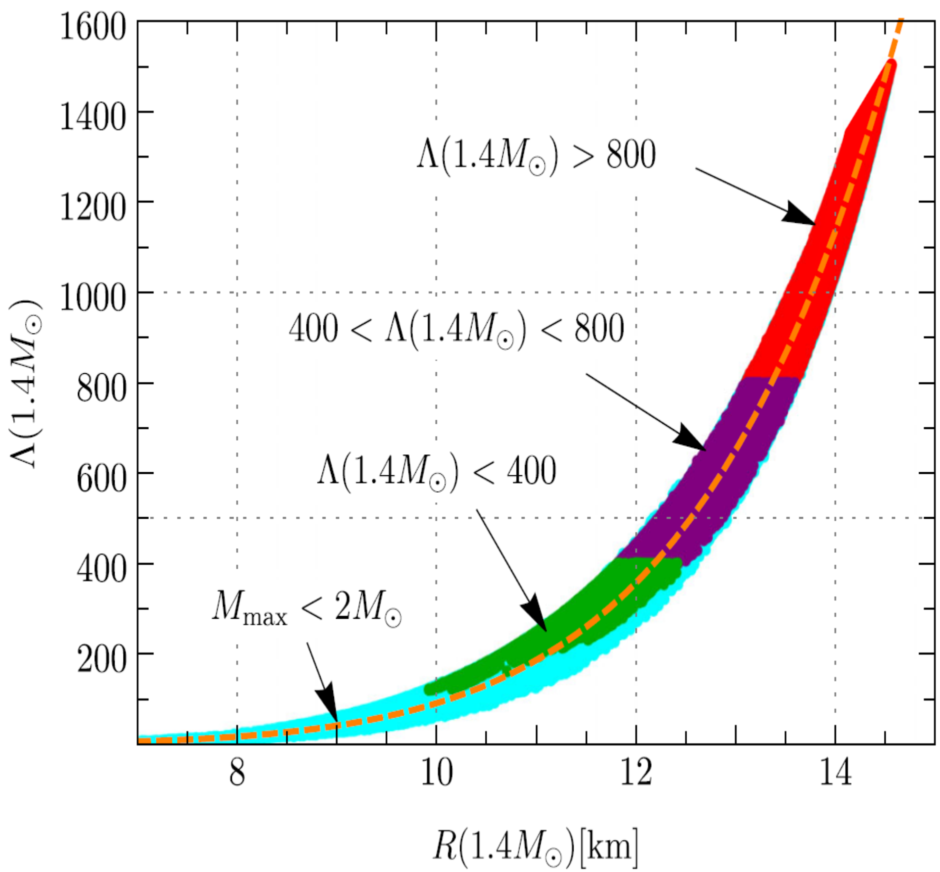
Asymptotically matches pQCD

EOS parameters $(\Gamma_i, \rho_{ij}, \cdots)$ are set under the causality and $M_{\mathrm{EOS,max}}$ constraints

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

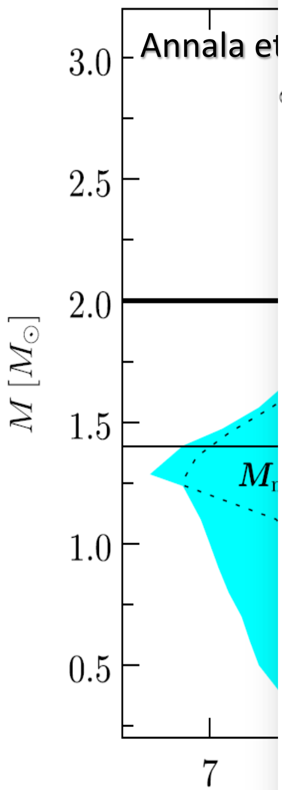
- **$\Lambda_{1.4} \lesssim 800$: in terms of NS radius $10 \lesssim R_{1.4M_\odot} \lesssim 13.5$ km for EOS**
  - connect to the NNLO pQCD (Kurkela et al. 2010) and chiral EFT (Hebeler et al. 2013)
  - causality $c_s < c$ and $M_{\rm EOS,max} > 2M_\odot$ constraints in the intermediate region

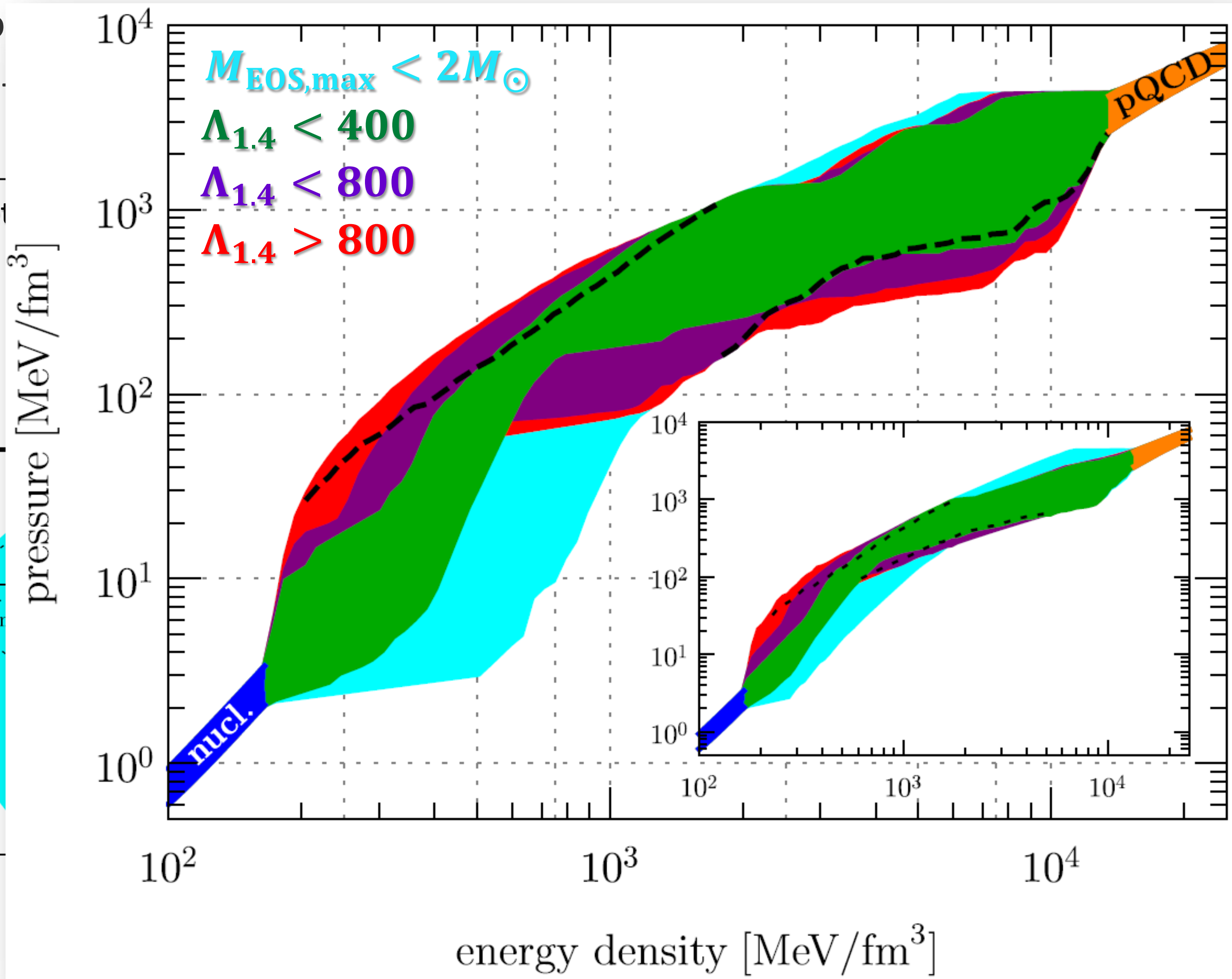


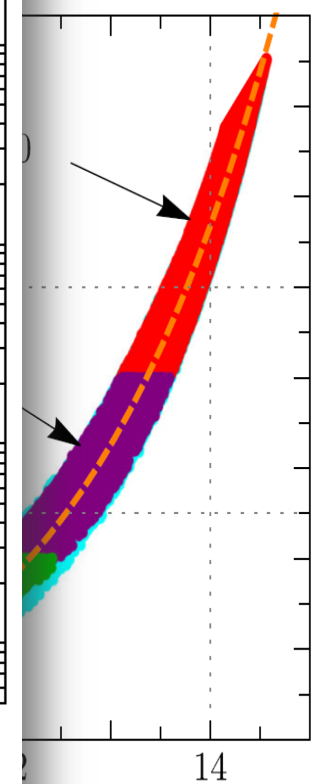


Impact of $\tilde{\Lambda} < 800$ on NS radius & EOS

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







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

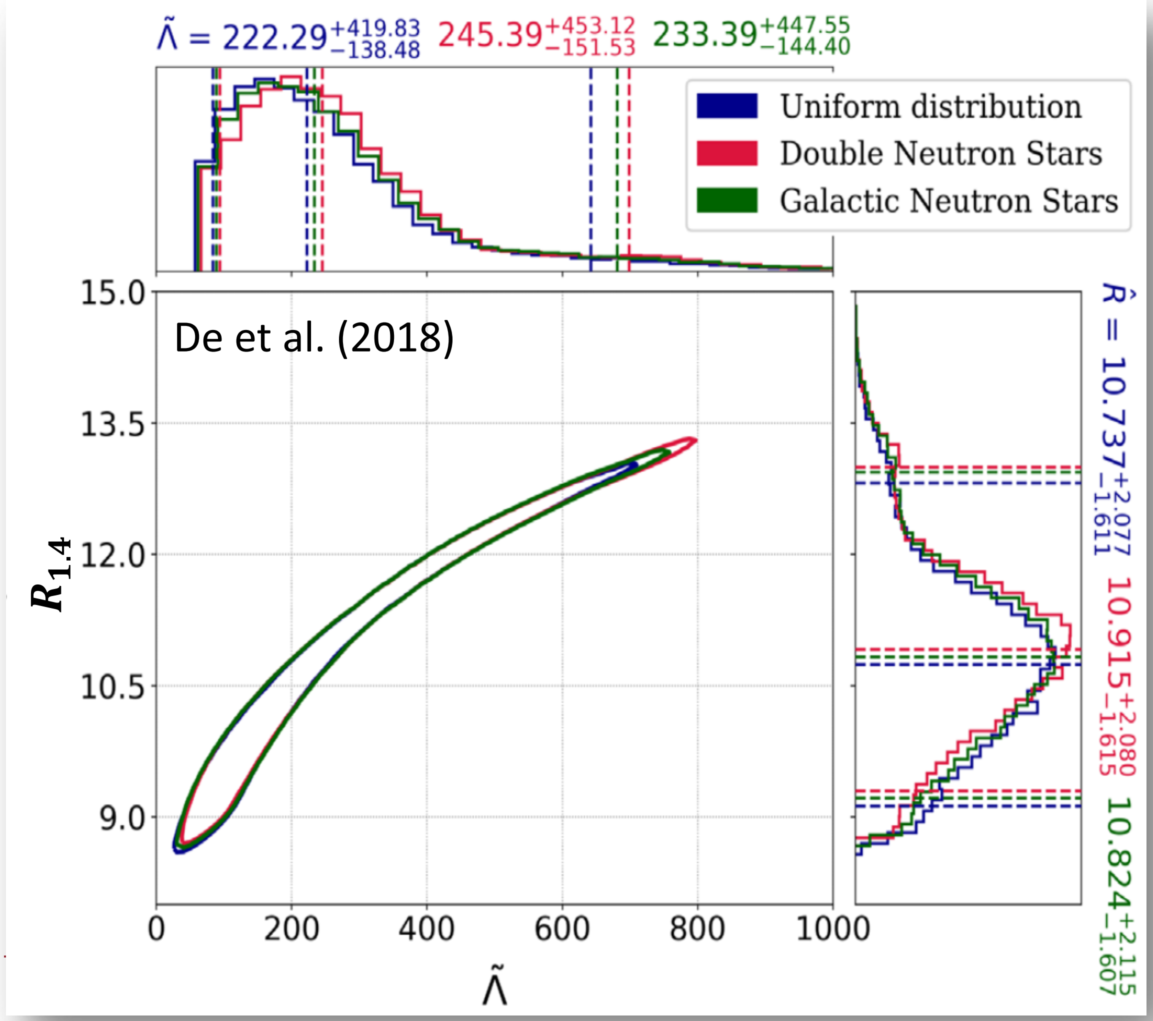
- Almost all studies assume some phenomenological EOS model as in Annala et al. (2018)
  - Annala et al. (2018) : chiral EFT (up to 1.1ns) + pQCD
    - $120 \lesssim \Lambda_{1.4} \lesssim 800$, $10 \lesssim R_{1.4} \lesssim 13.6$ km
  - Tews et al. (2018) : chiral EFT (up to 2ns !!)
    - $80 \lesssim \Lambda_{1.4} \lesssim 570$ (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 ⇒ larger NS radius
  - Malik et al. (2018) : using nuclear data (symmetry energy, incompressibility)
    - $12 \lesssim R_{1.4} \lesssim 14$ km
  - and many other studies

Importance of the other constraints

- <u>GW data analysis</u> (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

$\tilde{\Lambda} \sim 100 - 400$

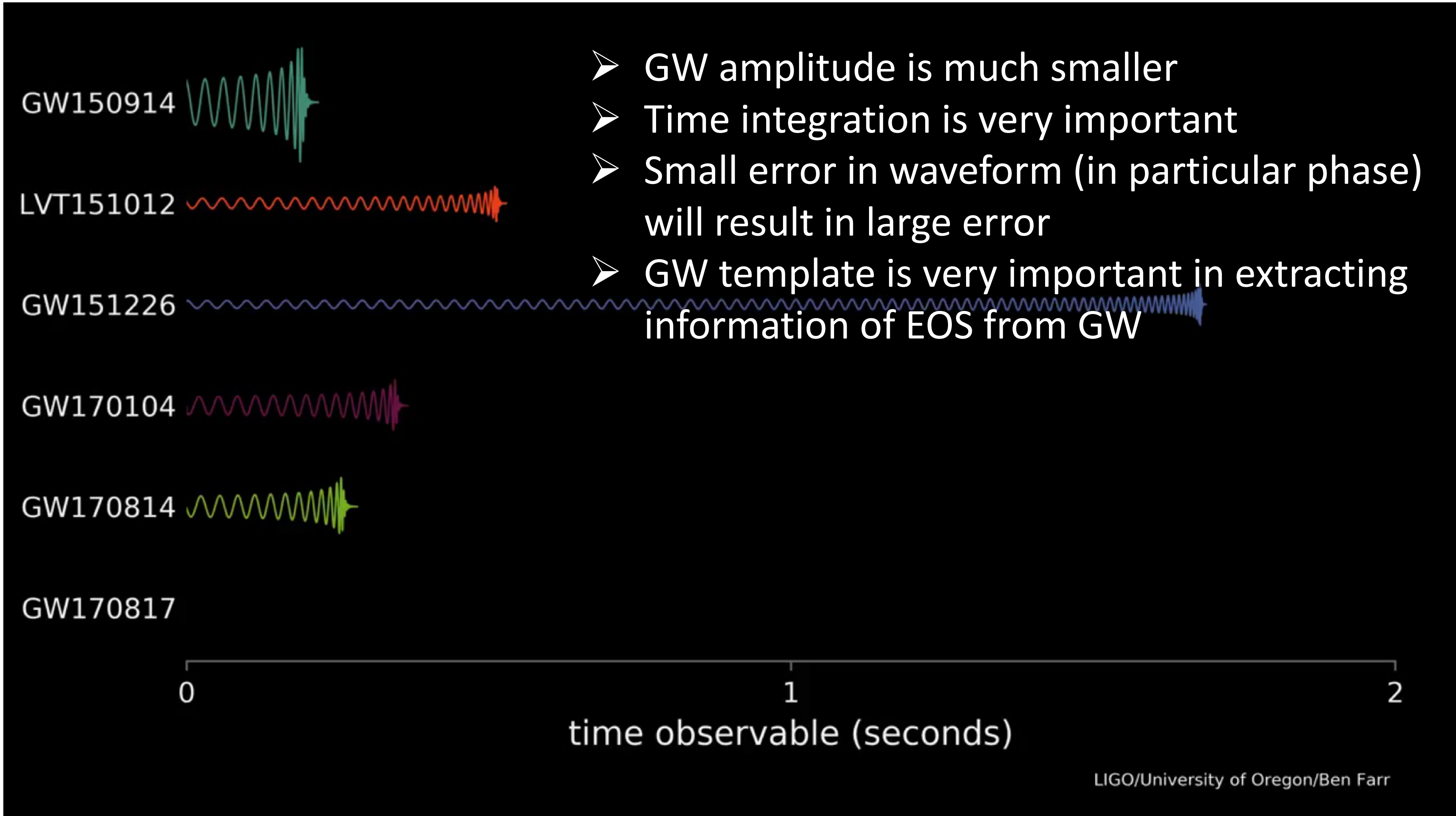
$R_{1.4} \sim 10 - 12$ km



De et al. PRL 121, 091102 (2018)

Importance of GW template

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



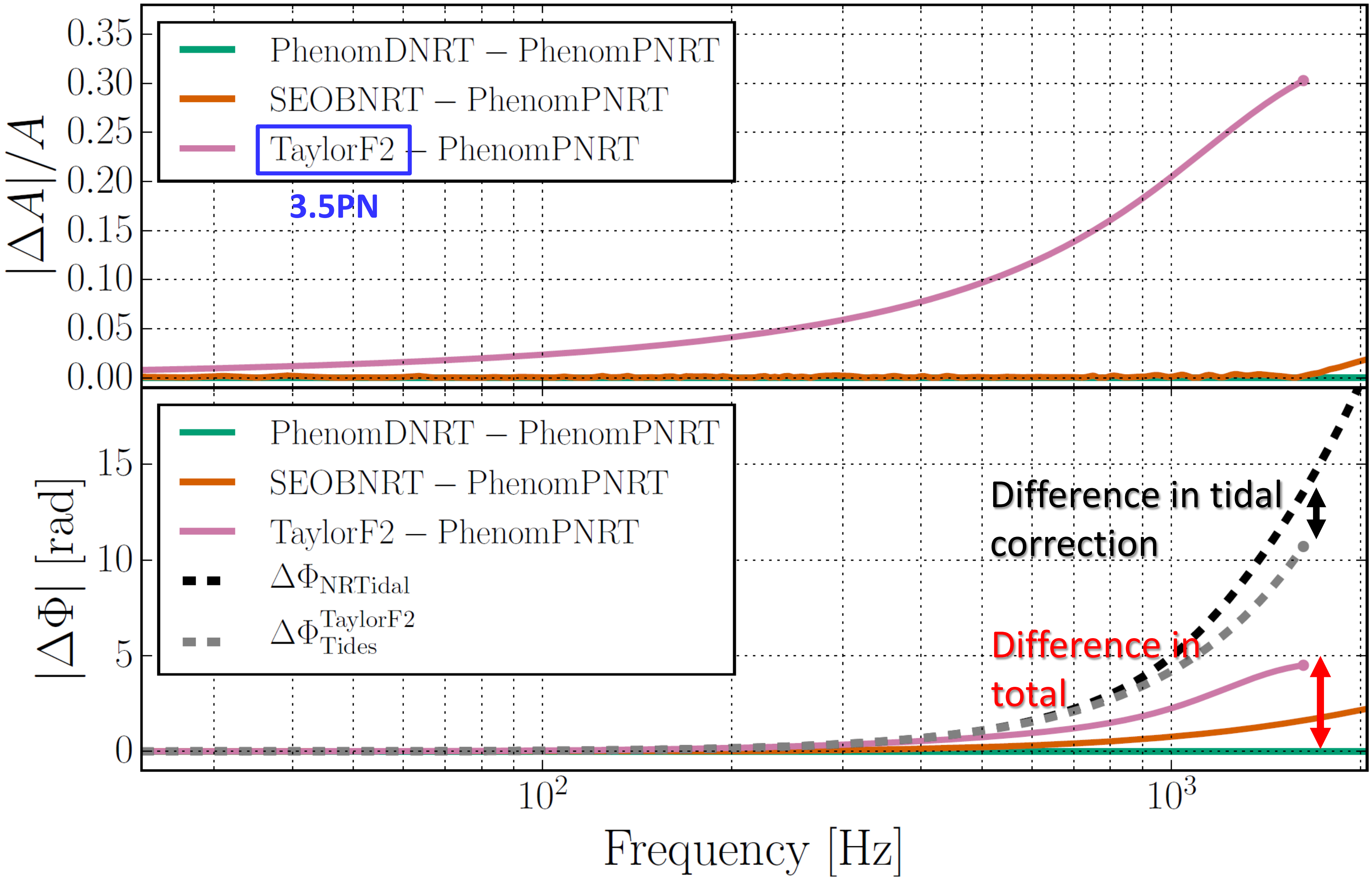
- GW amplitude is much smaller
- Time integration is very important
- Small error in waveform (in particular phase) will result in large error
- GW template is very important in extracting information of EOS from GW

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 (and actually seems to be overestimated) :
      - 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

Abbott et al. arXiv:1805.11579

Comparison of NR and PN (TaylorF2) waveform



Abbott et al. PRL 121, 161101 (2018)

Update analysis with NR waveform (1)

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

Editors' Suggestion

GW170817: Measurements of Neutron Star Radii and Equation of State

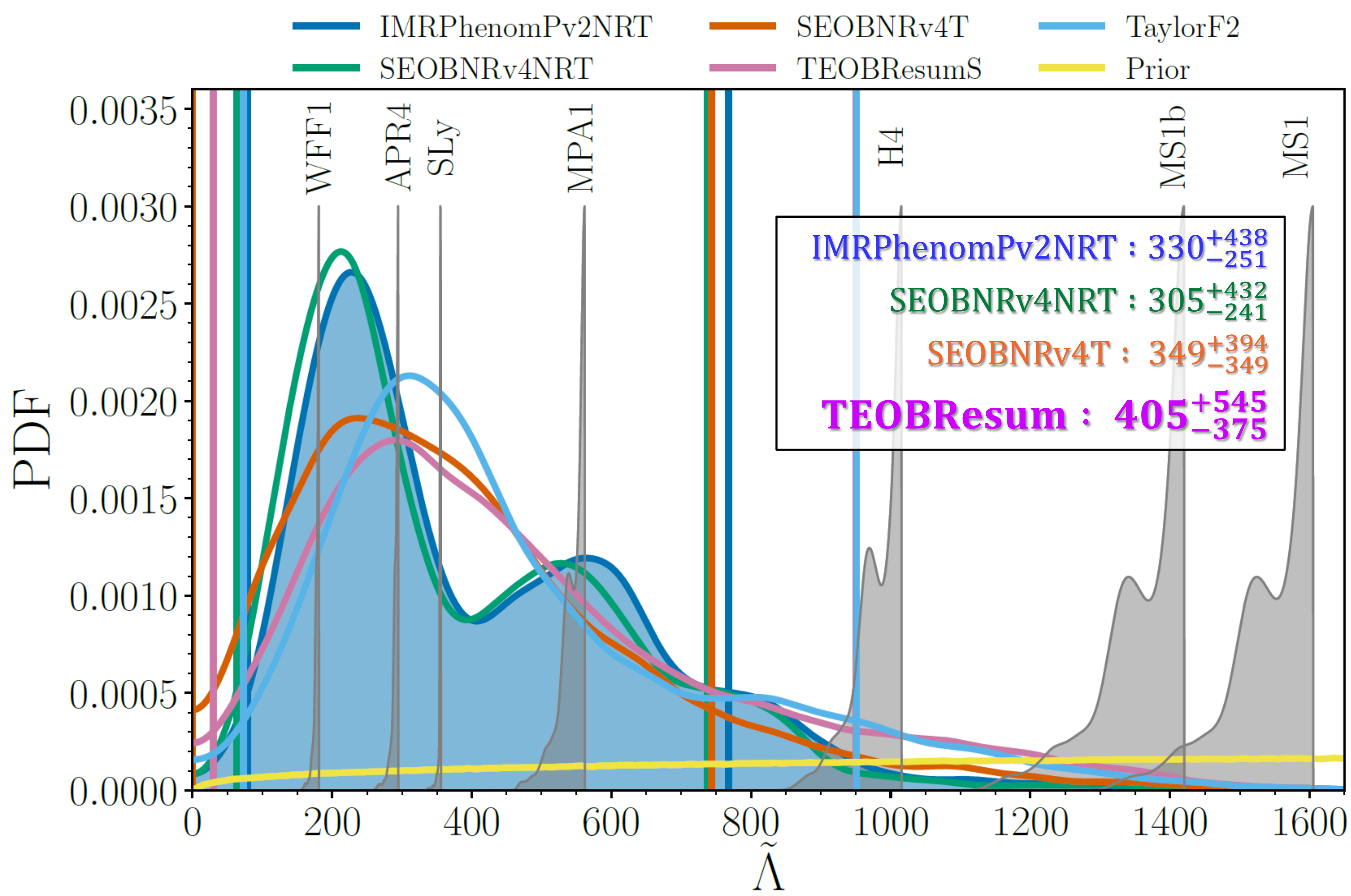
B. P. Abbott *et al.**
(The LIGO Scientific Collaboration and the Virgo Collaboration)

(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

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

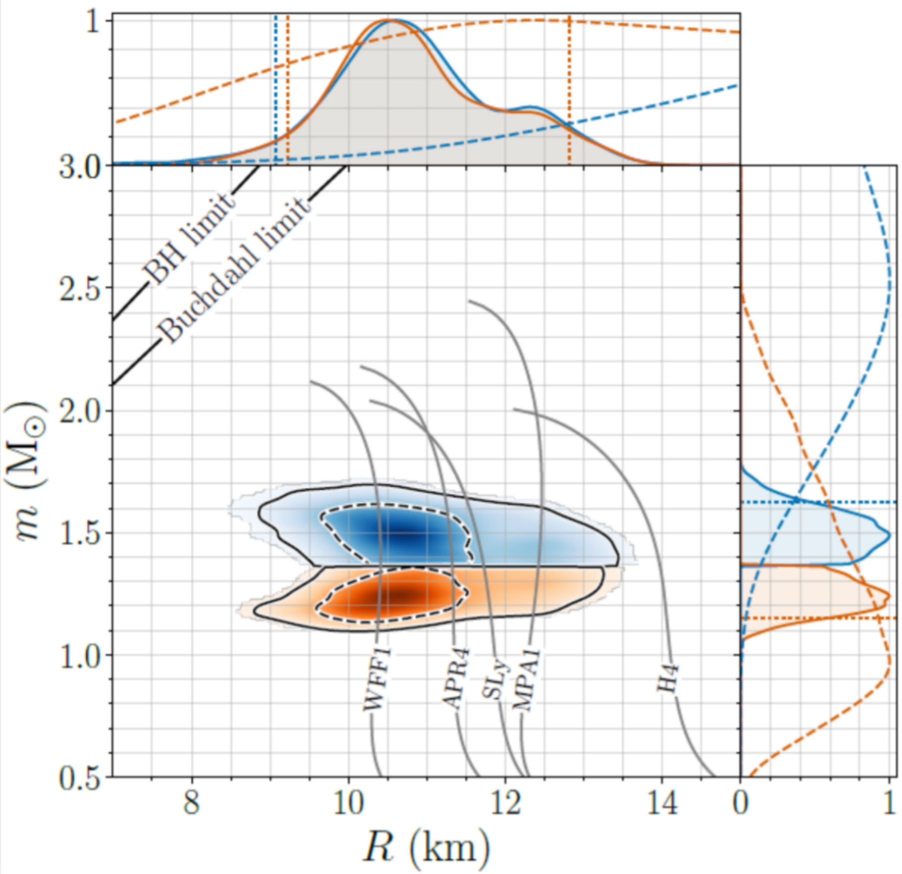
Update analysis with NR waveform (2)



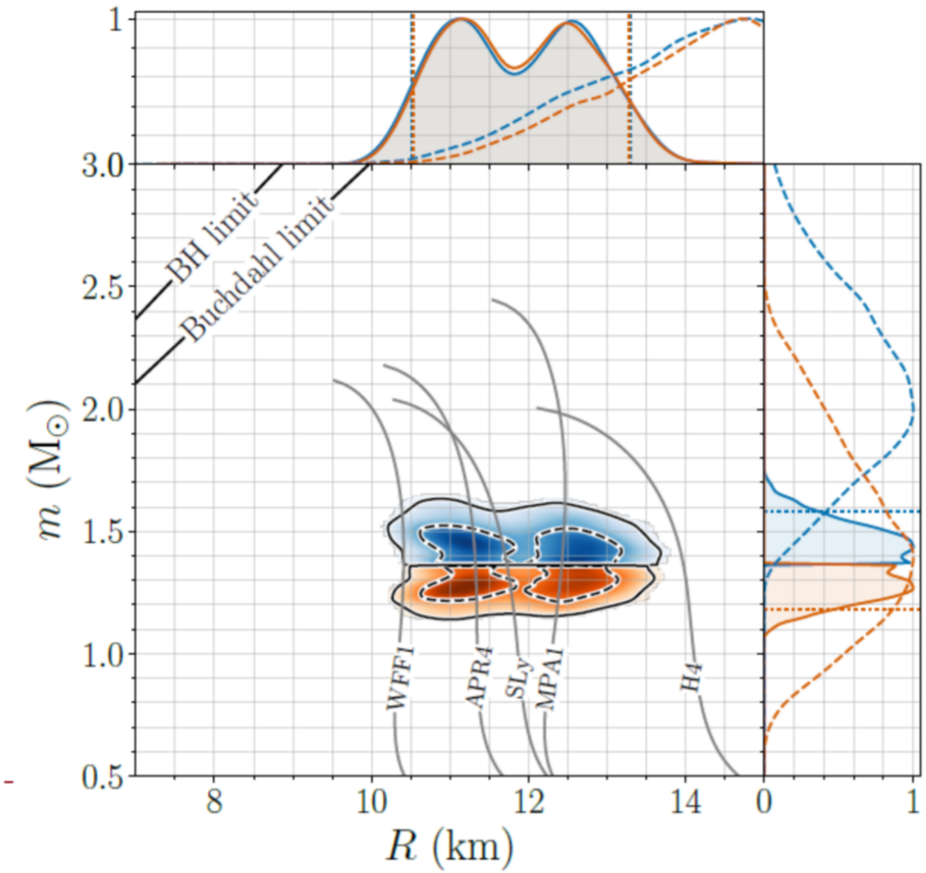
Abbott et al. PRL 121, 161101 (2018)

Update analysis with NR waveform (3)

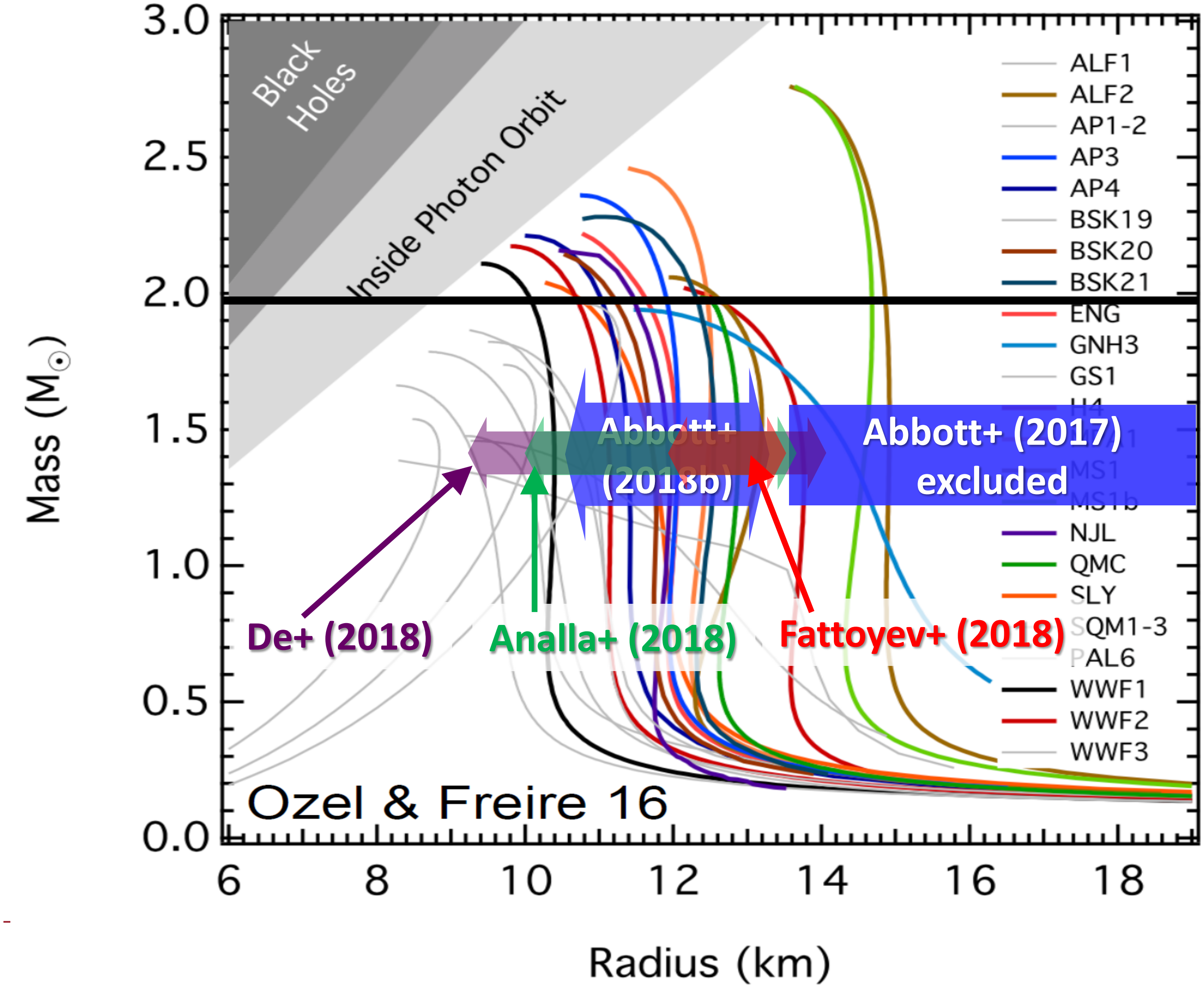
- Analysis without $2M_\odot$ constraint
  - $R_1 = 10.8^{+2.0}_{-1.7}$ km
  - $R_2 = 10.7^{+2.1}_{-1.5}$ km



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



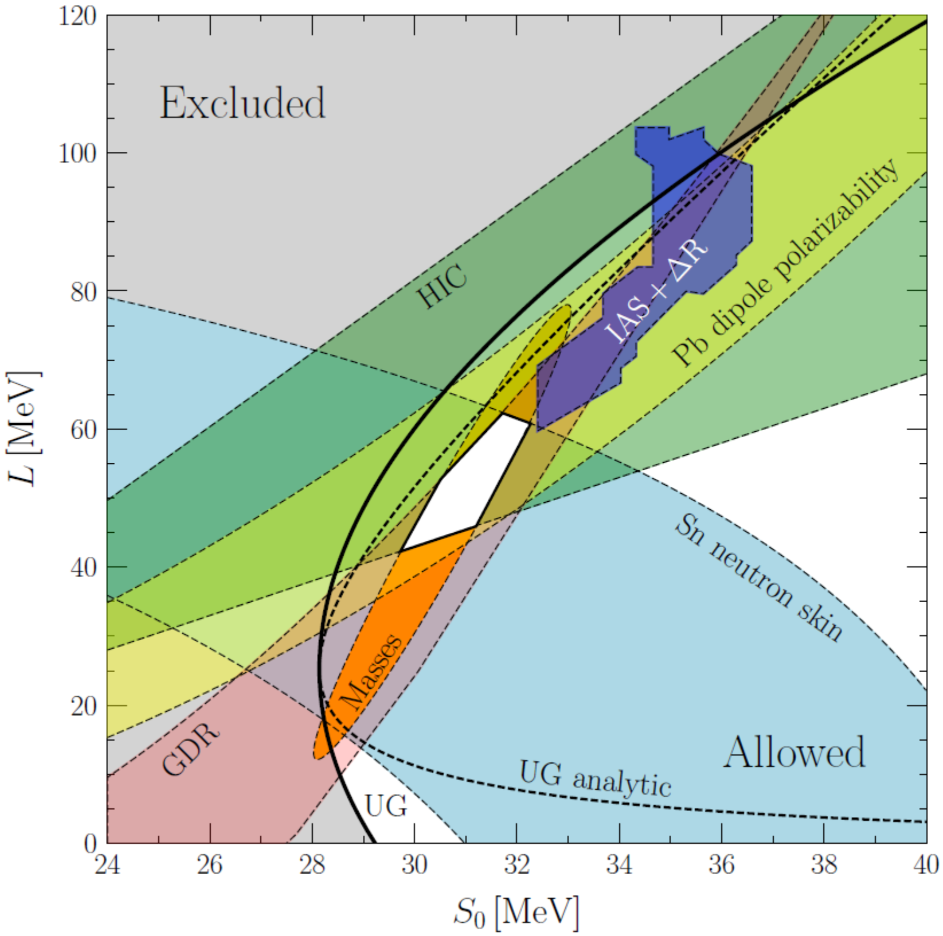
A summary of NS structure constraint

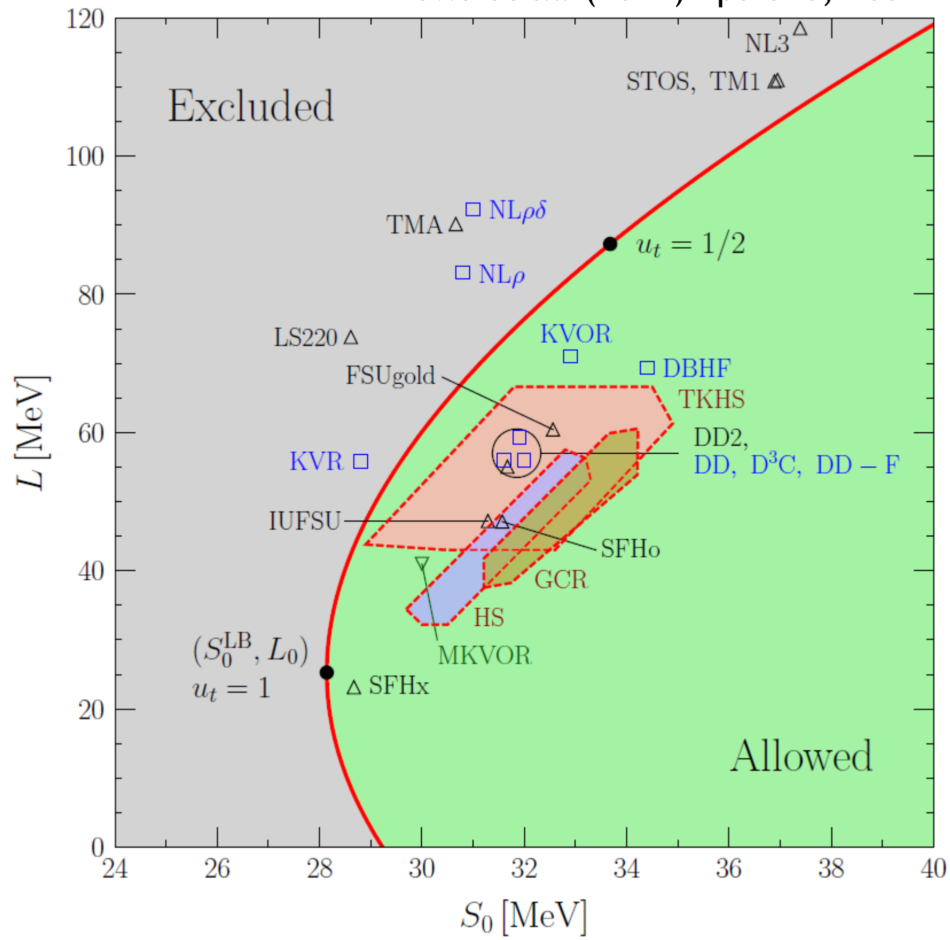


Constraint from nuclear experiments+

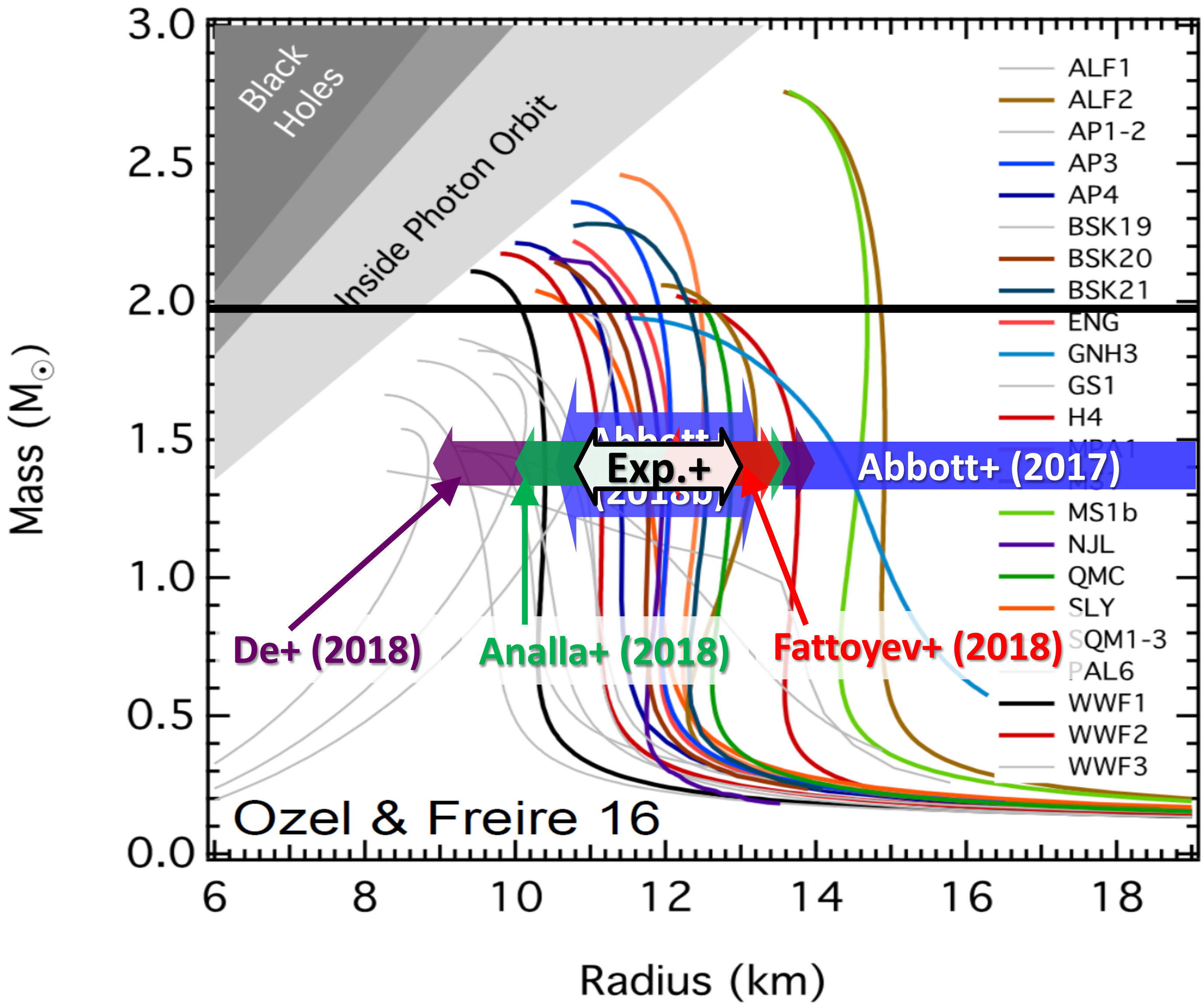
- Symmetry energy constraints from nuclear experiments
  ⇒ NS radius constraint

Tews et al. (2017) ApJ 848, 105



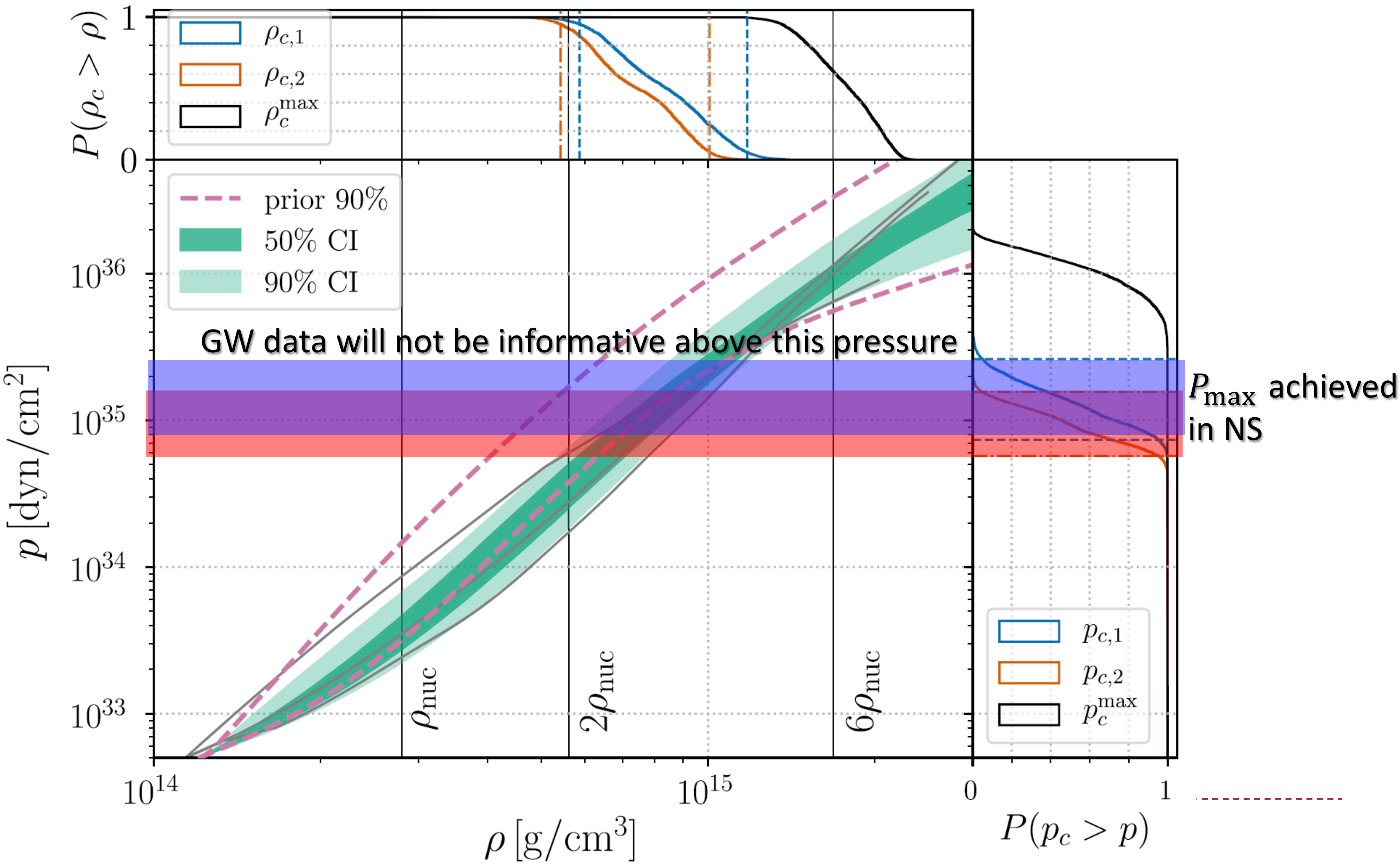


Constraint from nuclear experiments+

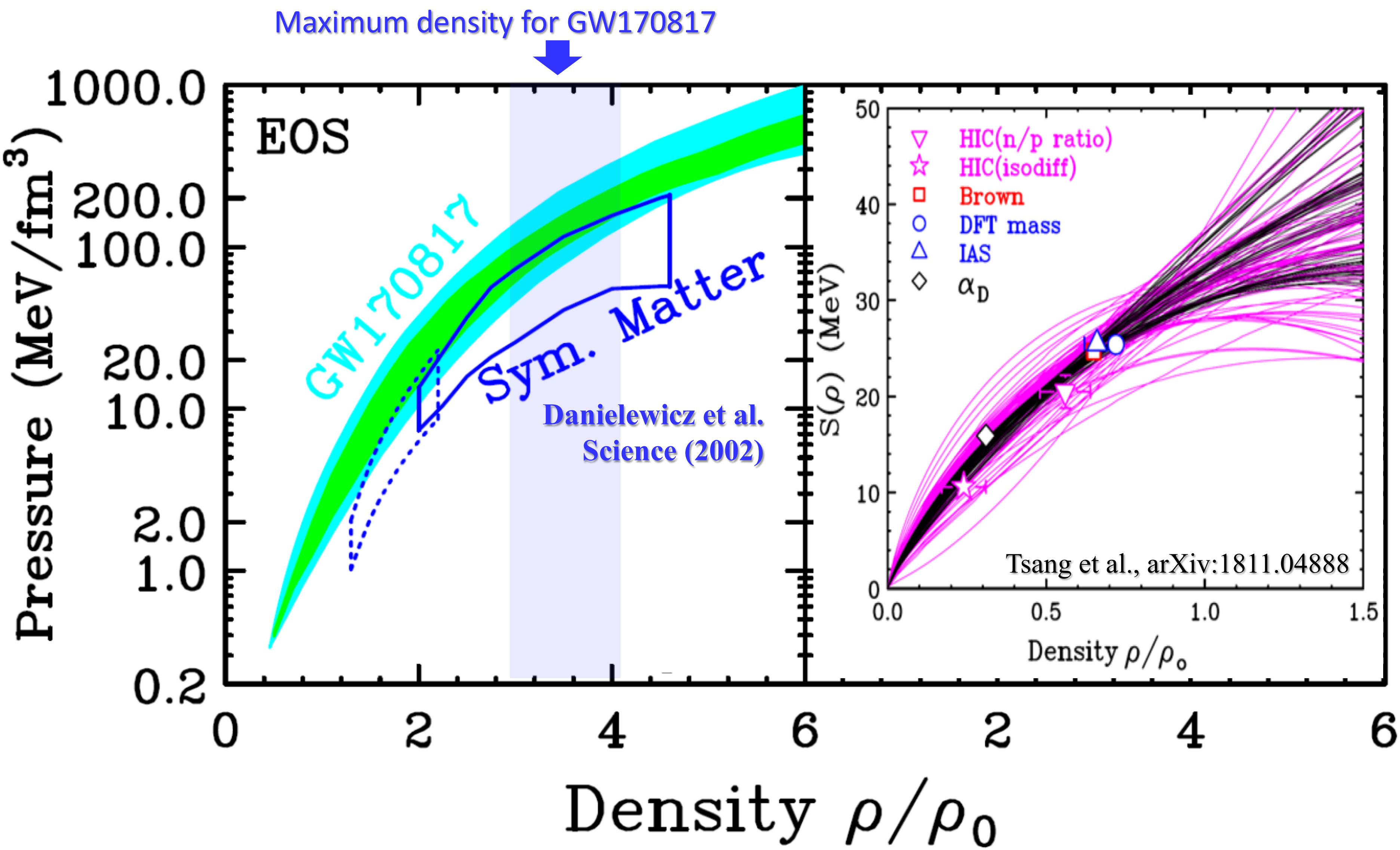


Abbott et al. PRL 121, 161101 (2018)

Constraints on EOS



EOS comparison : GW vs. Heavy Ion Col.

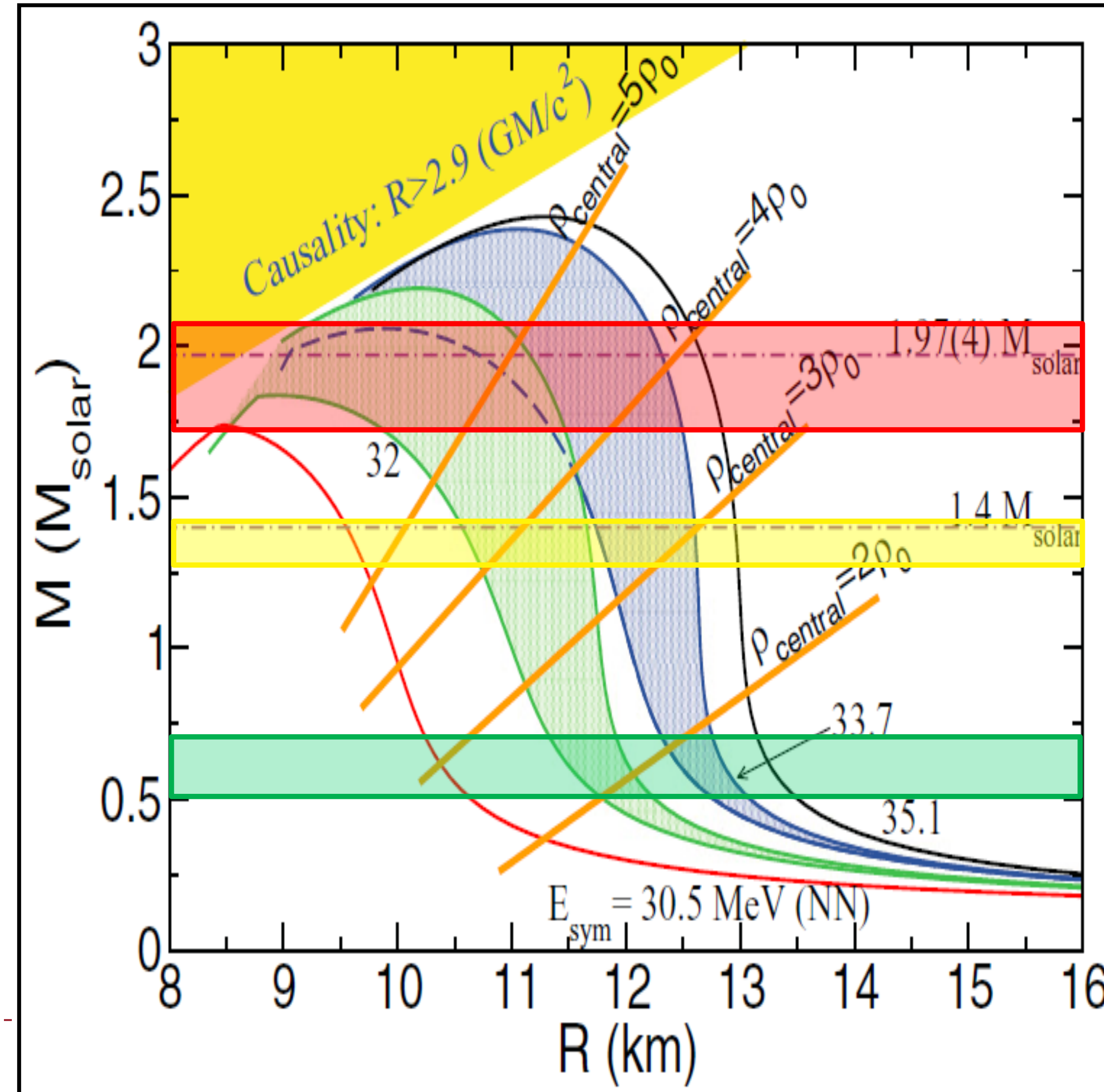


How to explore the higher densities ?

Massive NS is necessary to explore high density region

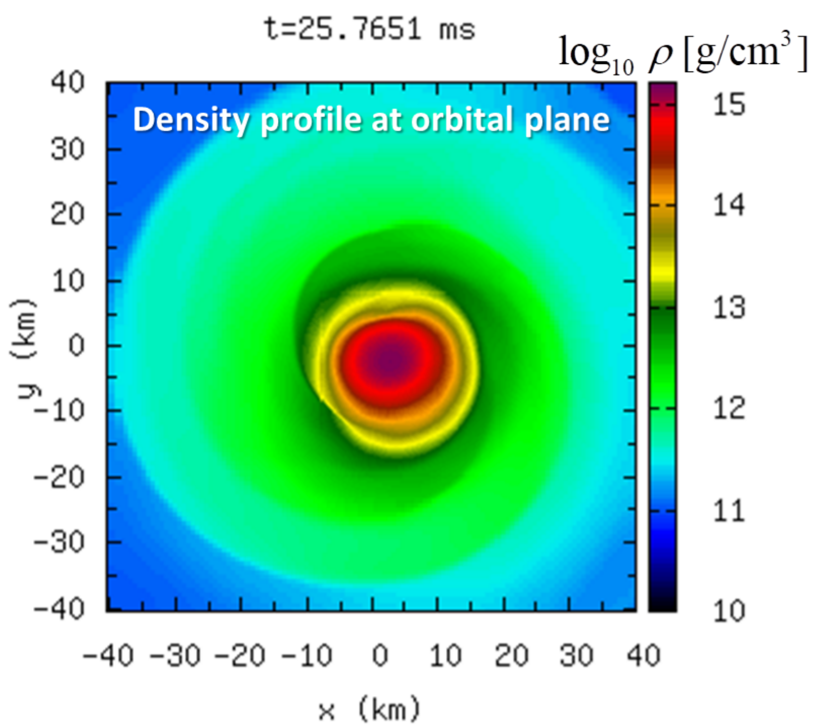
- Supernova core bounce
  - mass：0.5~0.8Msun
  - ρc：a few ρs
- Canonical mass NS
  - mass： 1.35-1.4Msun
  - ρc：several ρs
- Massive NS (> 1.6 Msun)
  - ρc ：> 4ρs
- We need more massive NS to explore high density region
  - **GW from massive NS formed after the merger**
  - **Constraint of $M_{\mathrm{EOS,max}}$ from BH formation after merger**

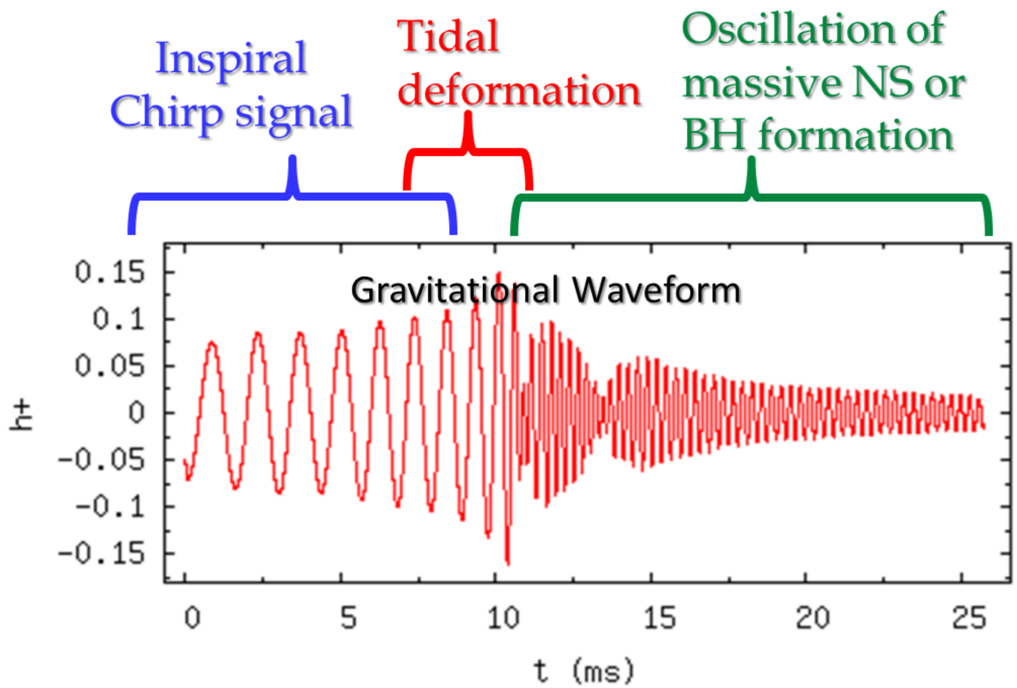
Gandolfi et al. (2012) PRC 85 032801(R)



GW from post-merger phases

Numerical relativity simulation modelling GW170817





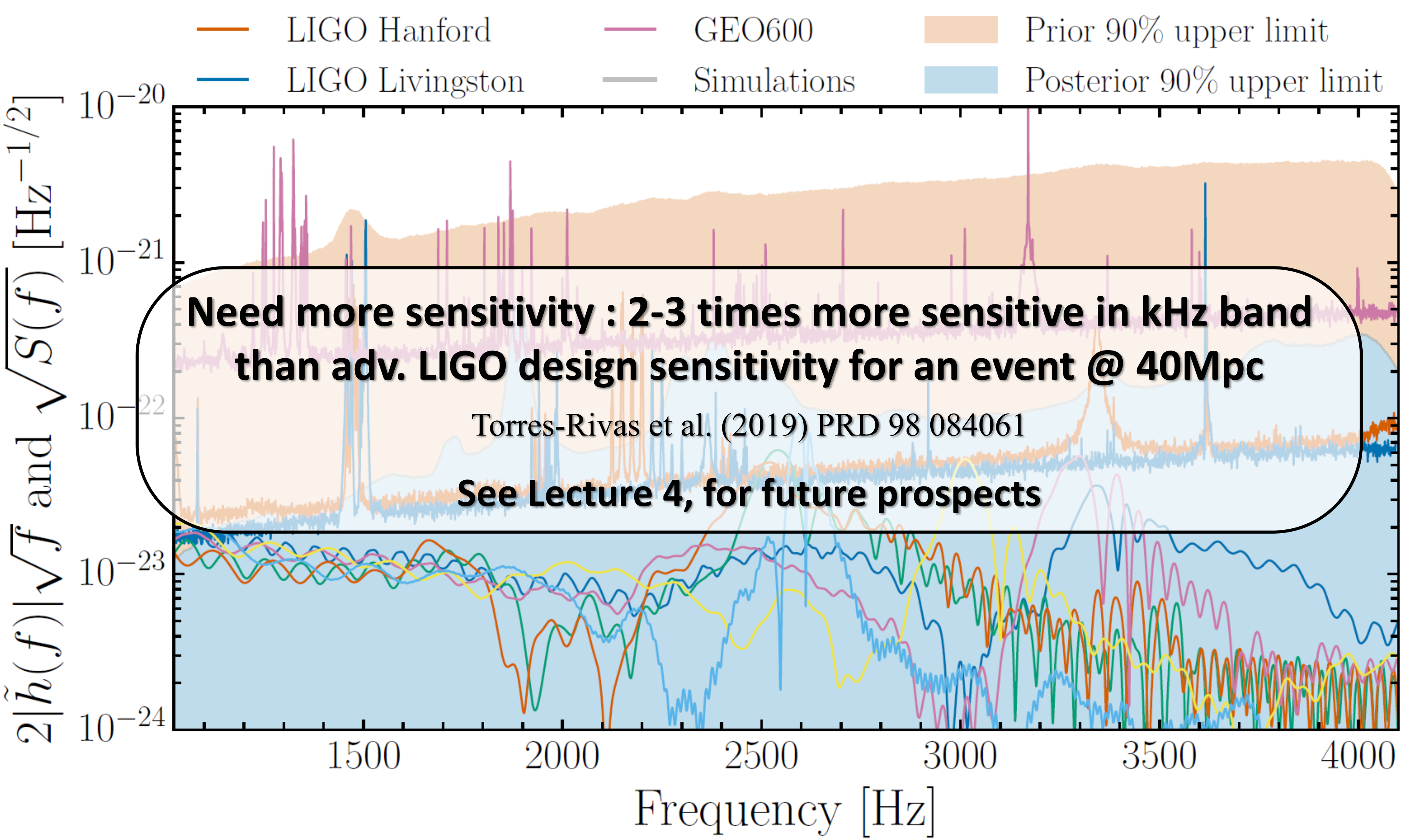
- point particle approx.
- information of binary parameter (**NS mass**, etc)

- 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



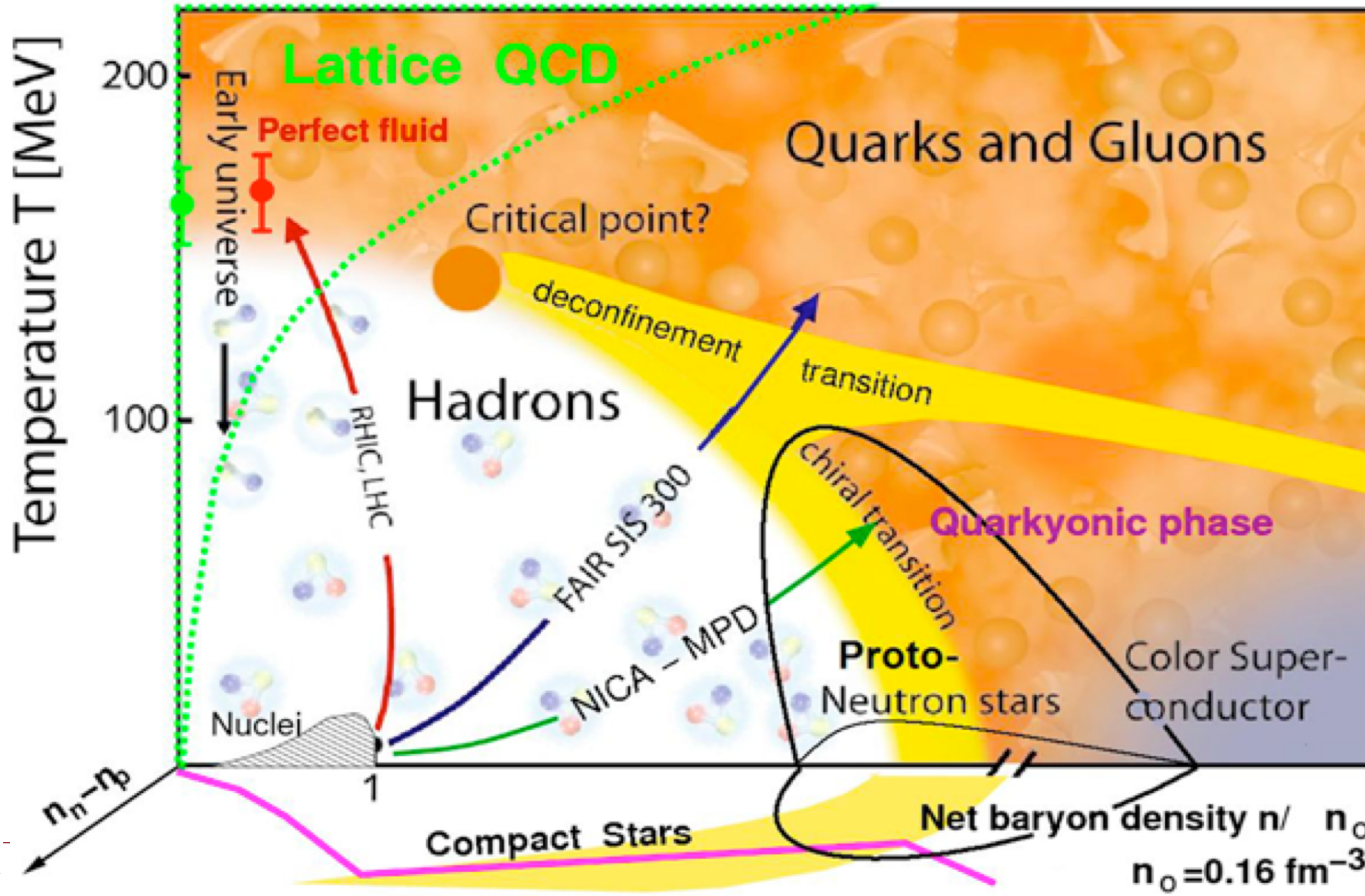
Need more sensitivity : 2-3 times more sensitive in kHz band than adv. LIGO design sensitivity for an event @ 40Mpc

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

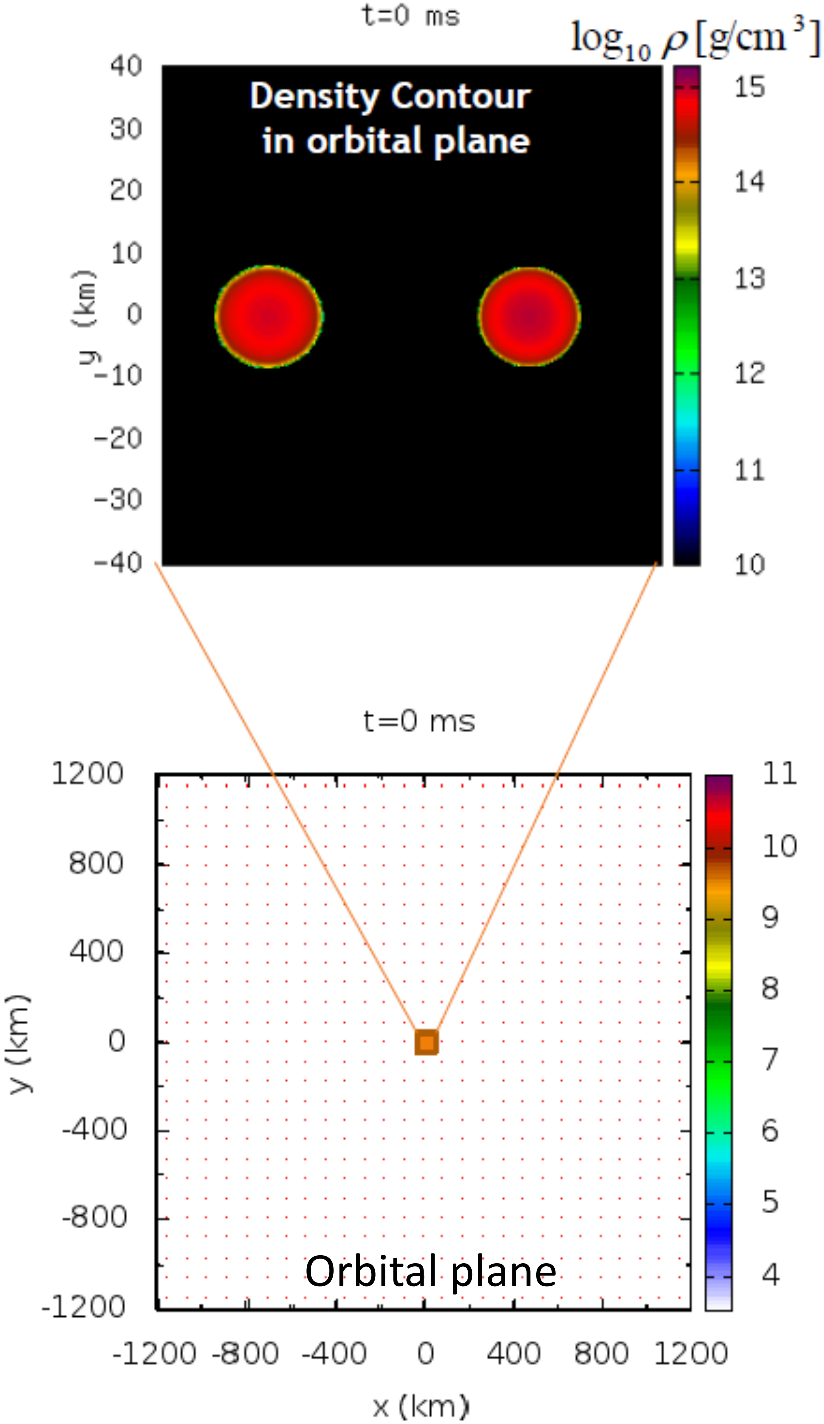
See Lecture 4, for future prospects

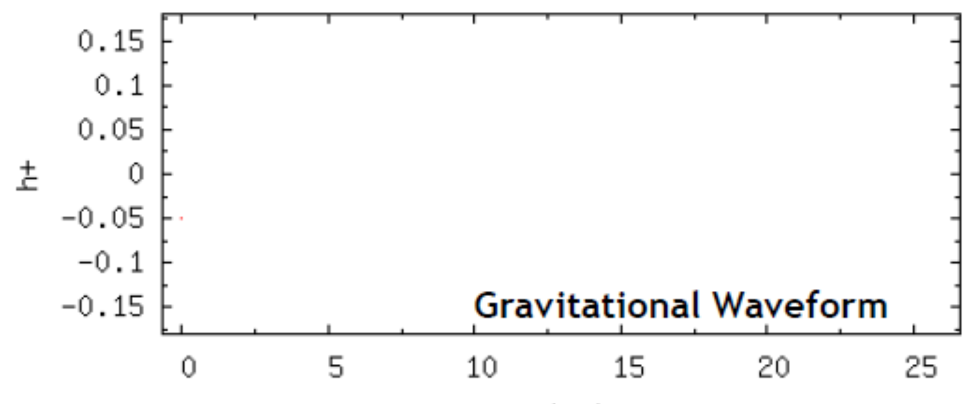
QCD Phase diagram and NS

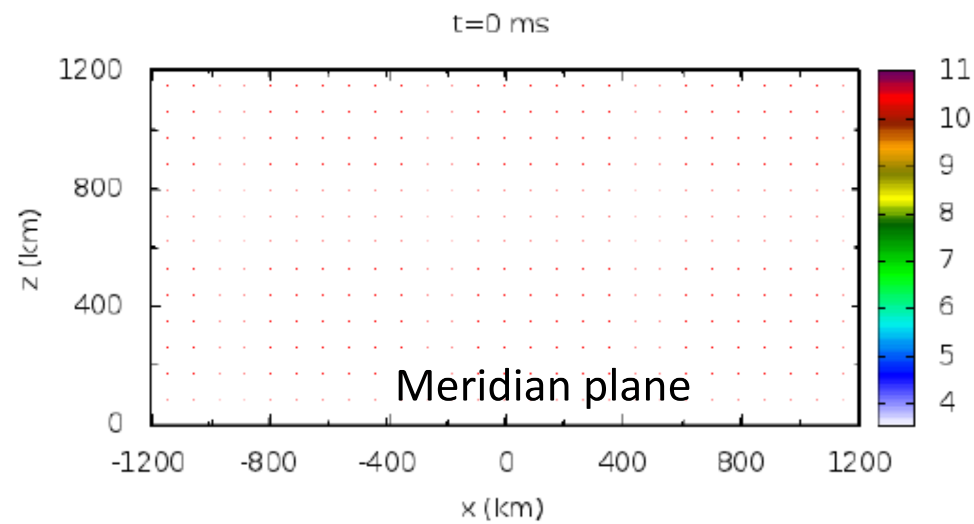
McLerran, Nucl.Phys.Proc.Suppl. 195, 275 (2009)



Constraints from EM signals

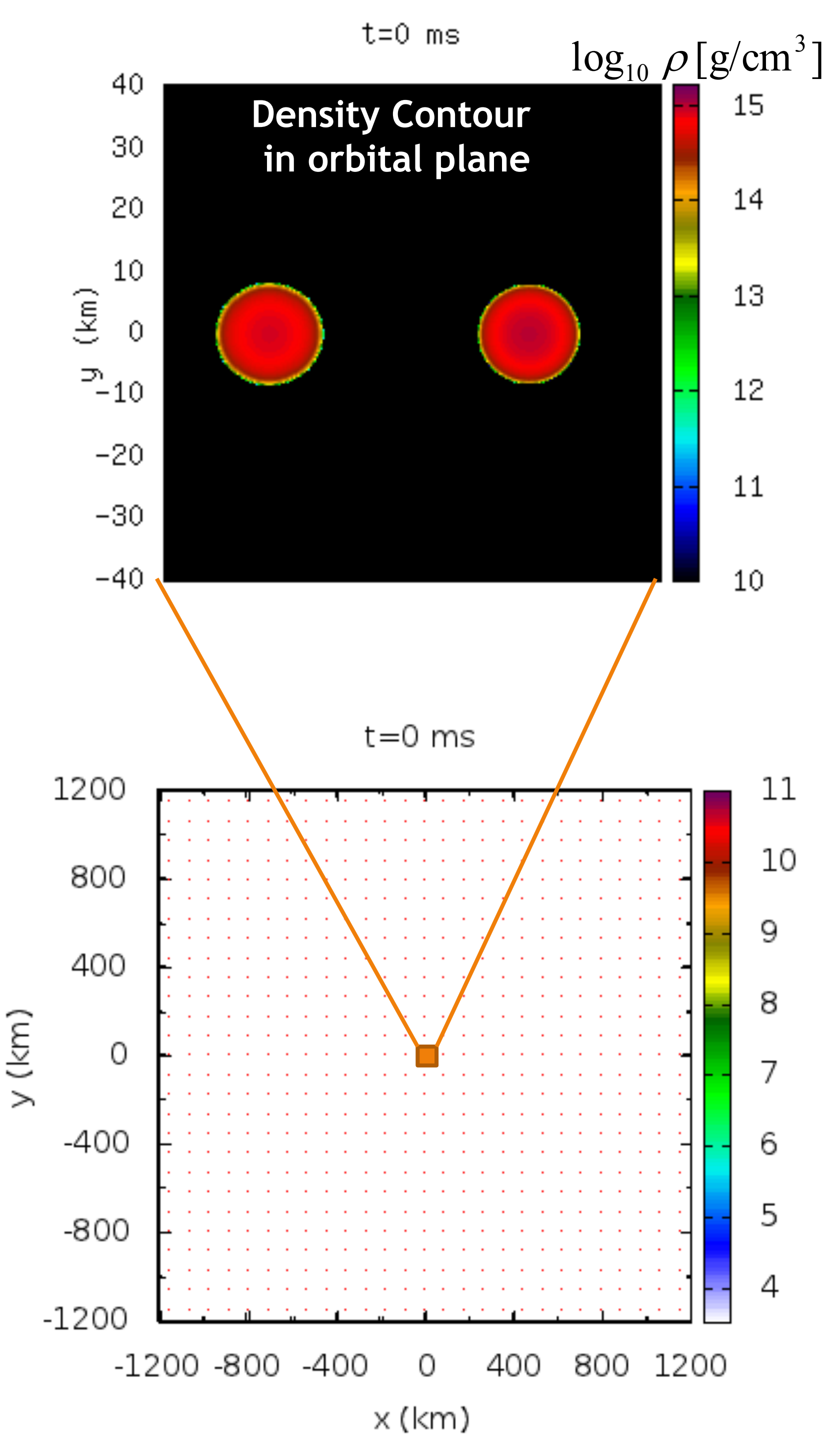


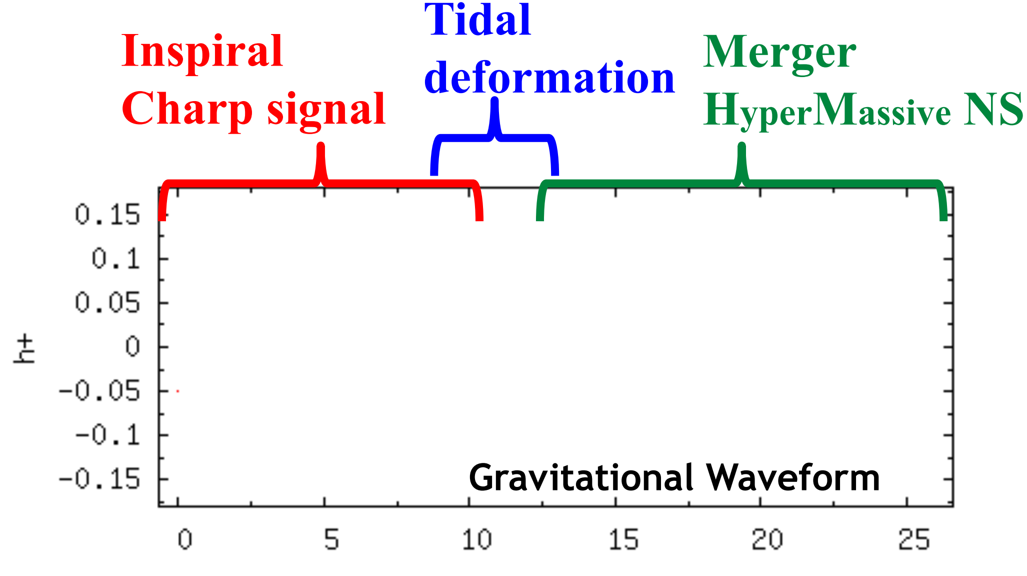


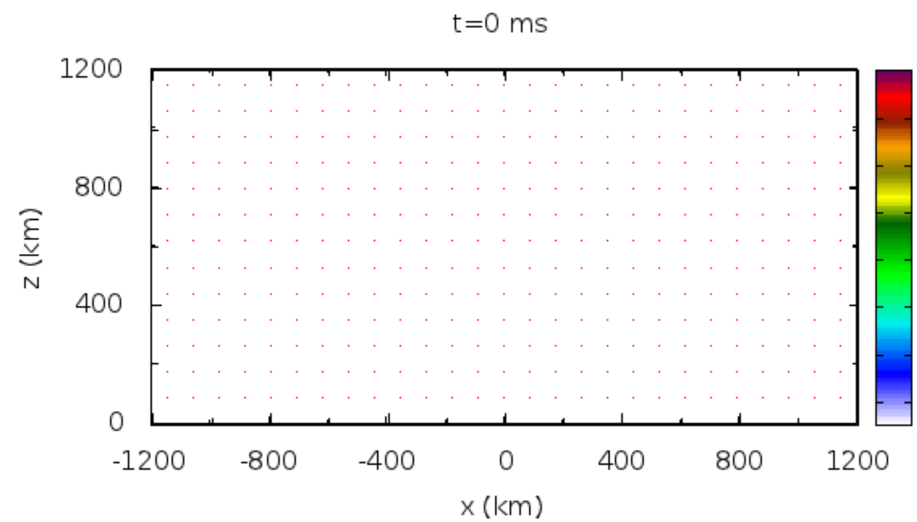


Animation by Hotokezaka

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







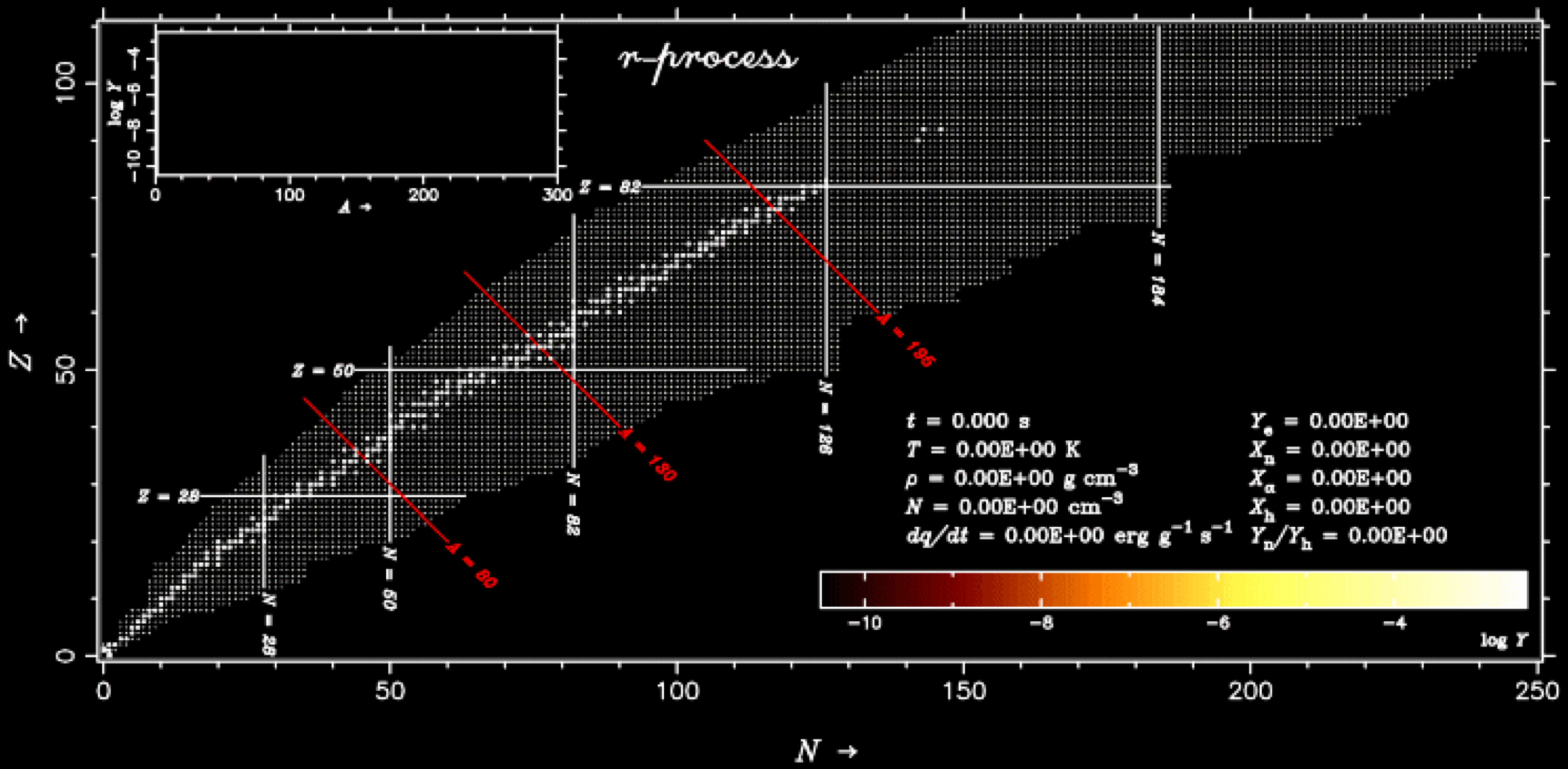
Animation by Hotokezaka

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)

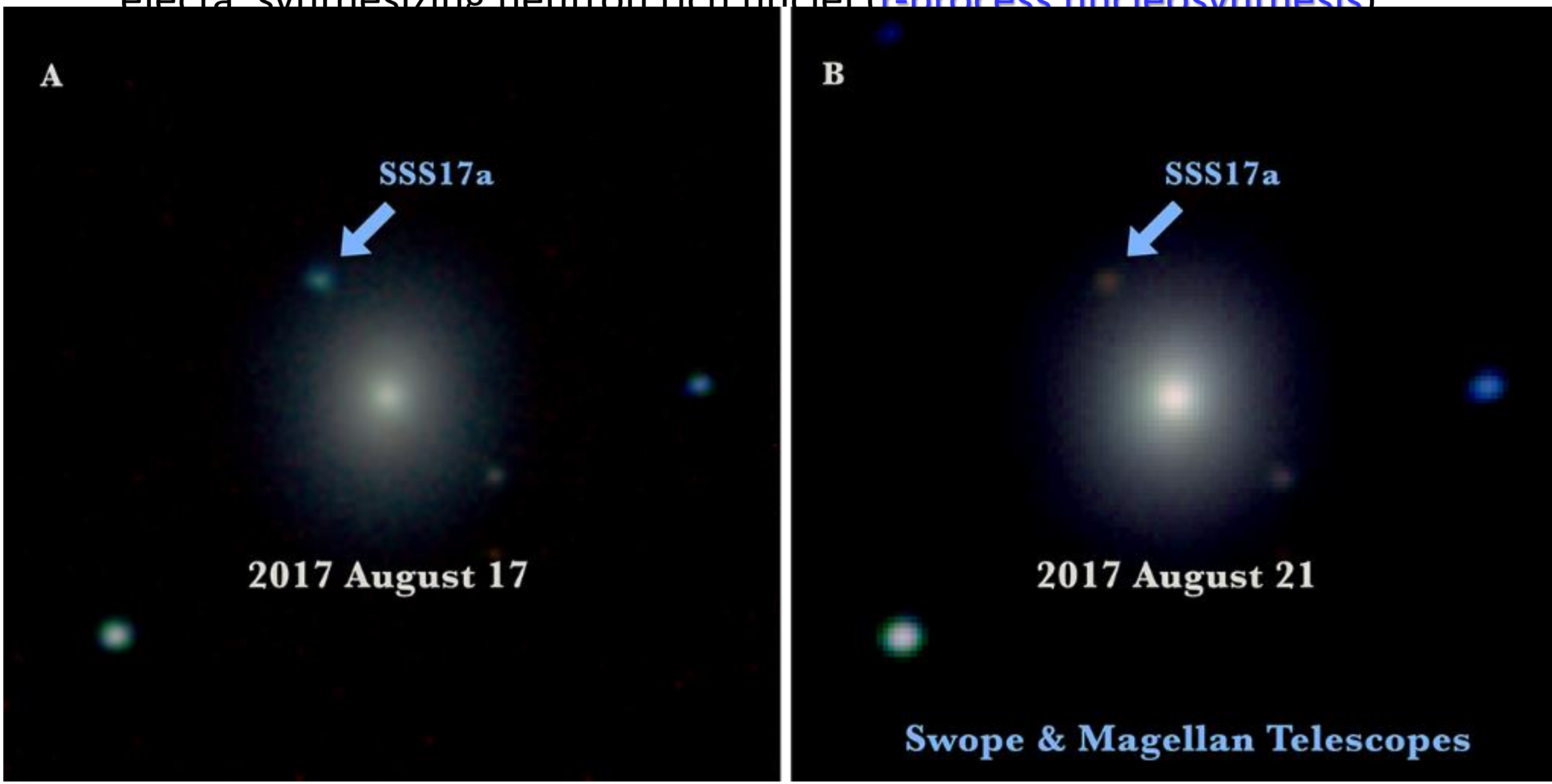
r-process in NS-NS merger ejecta (Y_e = 0.09)



Credit : S. Wanajo

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)
- **Kilonova** : Radioactive decay of r-process nuclei will power the ejecta (by gamma-rays and electrons) to shine in UV, optical, and IR bands (due to the opacity of r-process elements like lanthanides)
  - Luminosity is basically determined by the ejecta mass
  - Ejecta mass depends on the merger dynamics
  - The merger dynamics depends on NS EOS

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**

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

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

Numerical relativity simulation

Constraints from EM observations

$$\boldsymbol{M}_{\mathbf{crit}} = \boldsymbol{M}_{\mathbf{EOS,max}} + \Delta\boldsymbol{M}_{\mathbf{rot,rig}} + \Delta\boldsymbol{M}_{\mathbf{rot,diff}} + \Delta\boldsymbol{M}_{\mathbf{therm}}$$

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

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

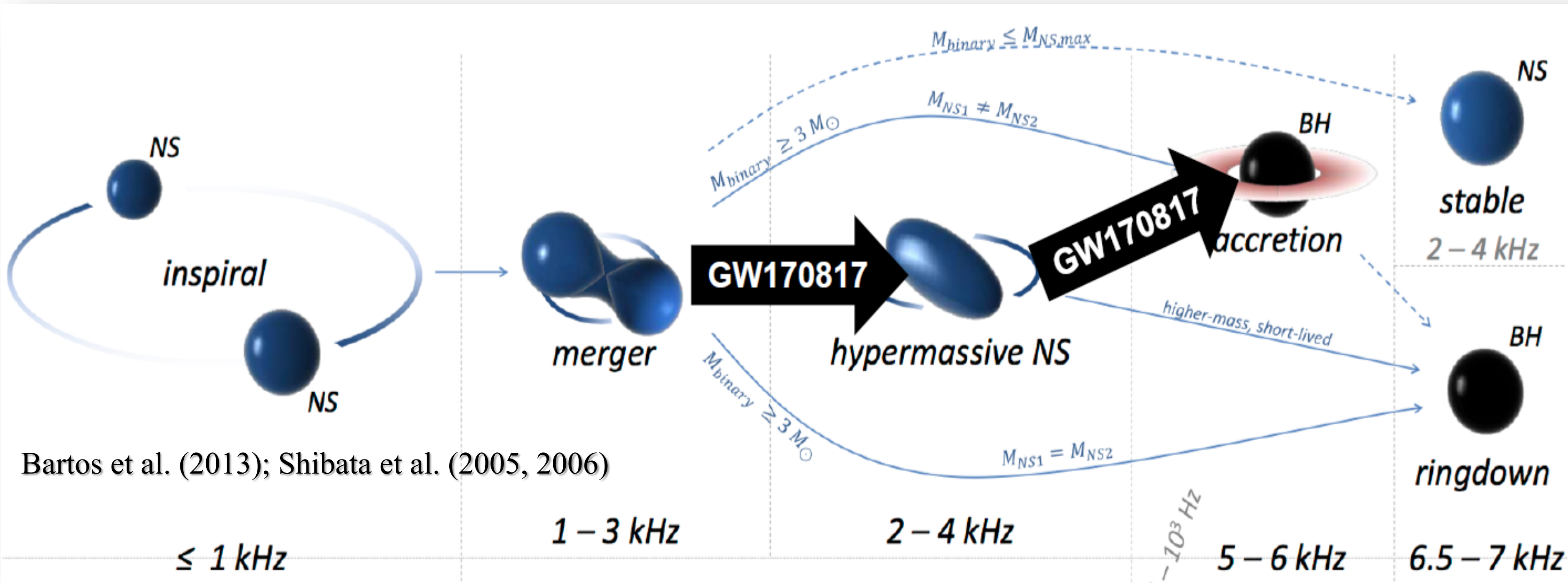
  - too soft EOS or too compact NS is excluded (e.g., Bauswein et al. 2017)
- **Condition 2 : massive NS formed after the merger should not be too long-lived**
  - No signal from long-lived NS (e.g. Sun et al. 2017)

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

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

Constraints from EM observations

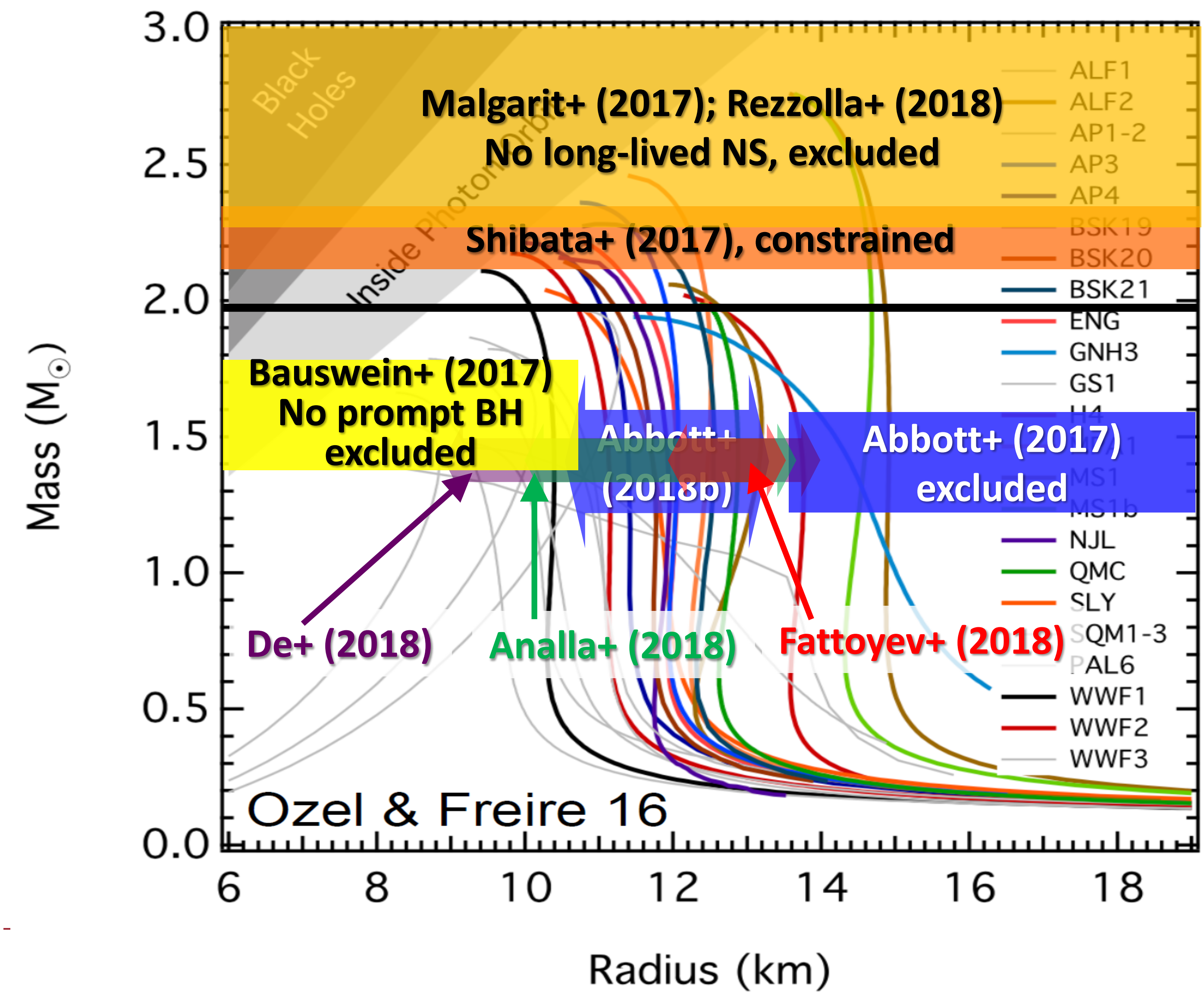
$$M_{\text{crit}} = M_{\text{EOS,max}} + \Delta M_{\text{rot,rig}} + \Delta M_{\text{rot,diff}} + \Delta M_{\text{therm}}$$



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

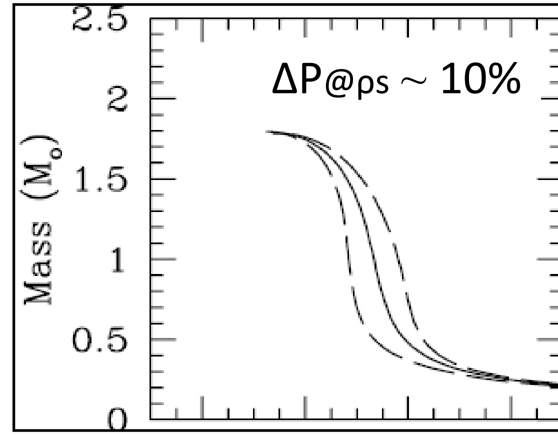
- stiff EOS with $M_{\text{EOS,max}} \gtrsim 2.3 M_\odot$ is excluded
- Margalit & Metzger 2017; Shibata et al. 2017; Rezzolla et al. 2018

Summary of constraint on NS structure using both GW and EM

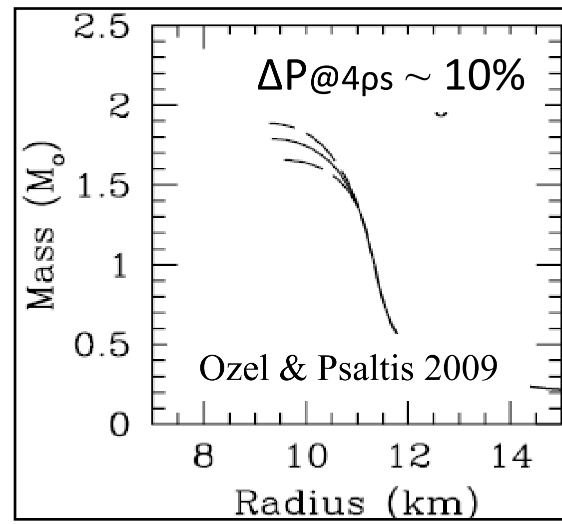


NS mass/radius measurement: GW vs. EM

- **GW : Simultaneous mass and radius measurement**
  - **Inspiral waveform naturally provides the mass** of each NS
  - Degeneracy of M and R in EM observations : additional information (assumption) required
- **GW : contains multiple information**
  - Tidal deformation (radius) : lower (~ρ_s) density
  - Oscillation of NS after the merger : higher density
  - Maximum mass : highest density
- **Simple in a complementary sense (GW obs. rare)**
  - GW : quadrupole formula, no interaction with matter
    - EOS (what we want to know) is only uncertain (**provided GR is correct and GWs are detected**) ⇒could be smoking-gun
  - EM : a number of parameters, models
    - Atmosphere, distance, column density, B-field, fc, …
      (recent debate : Ozel et al., Steiner&Lattimer, Guillot et al.)



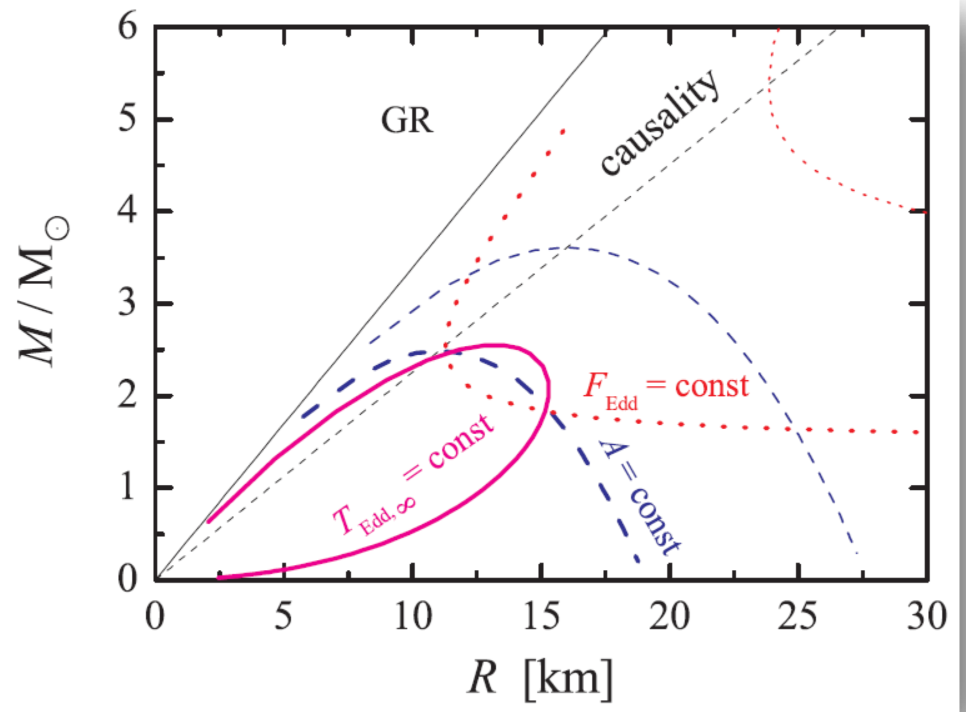
Radius is sensitive to relatively low density parts



Maximum mass depends on most dense parts

Comments on R_{NS} determination by EM

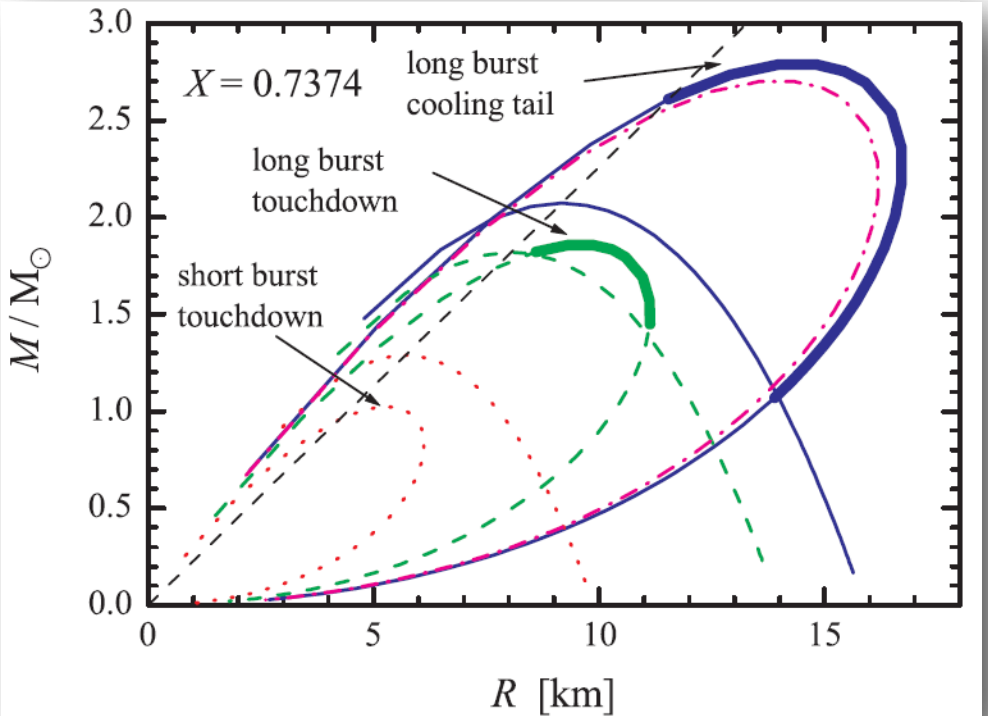
- NS in X-ray binaries sometimes show burst activity
  - Three observables can be obtained in a model dependent manner : *A* (apparent size), F_{Edd} and T_{Edd} (Eddington flux and temperature)
  - Each observables draw a curve in M-R plane
  - If the model is good, these three curves will intersect self-consistently
  - But often they do not
    - In some case, no intersection
  - **After statistical manipulation, intersection point emerges**
    - M and R depends on Authors
- Situation is similar for the other EM observation
  - Observation of quiescent low mass X-ray binaries (qLMXB)



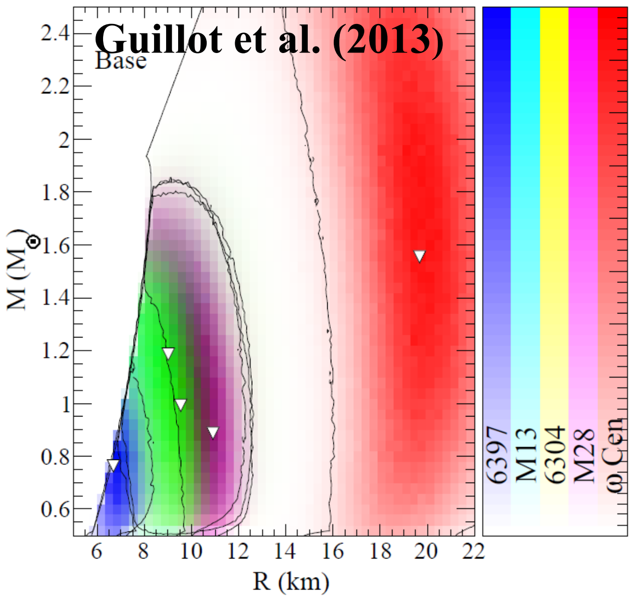
Sulemimanov et al. (2011)

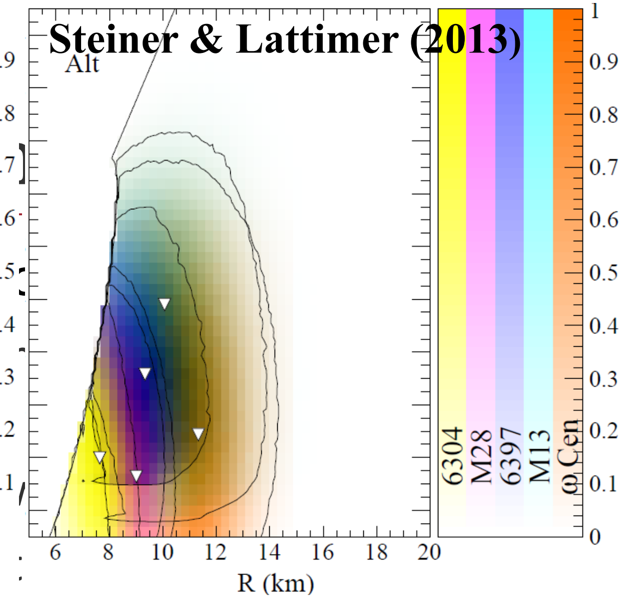
Comments on R_{NS} determination by EM

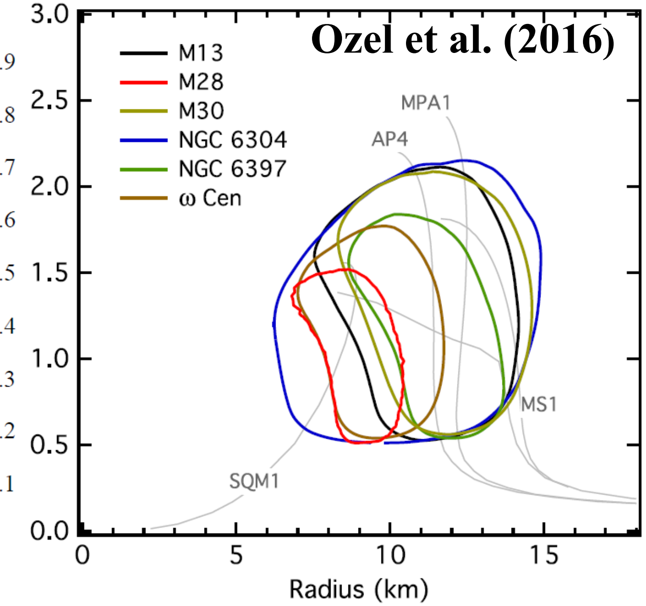
- NS in X-ray binaries sometimes show burst activity
  - Three observables can be obtained in a model dependent manner : *A* (apparent size), F_{Edd} and T_{Edd} (Eddington flux and temperature)
  - Each observables draw a curve in M-R plane
  - If the model is good, these three curves will intersect self-consistently
  - But often they do not
    - In some case, no intersection
  - **After statistical manipulation, intersection point emerges**
    - M and R depends on Authors
- Situation is similar for the other EM observation
  - Observation of quiescent low mass X-ray binaries (qLMXB)



Sulemimanov et al. (2011)

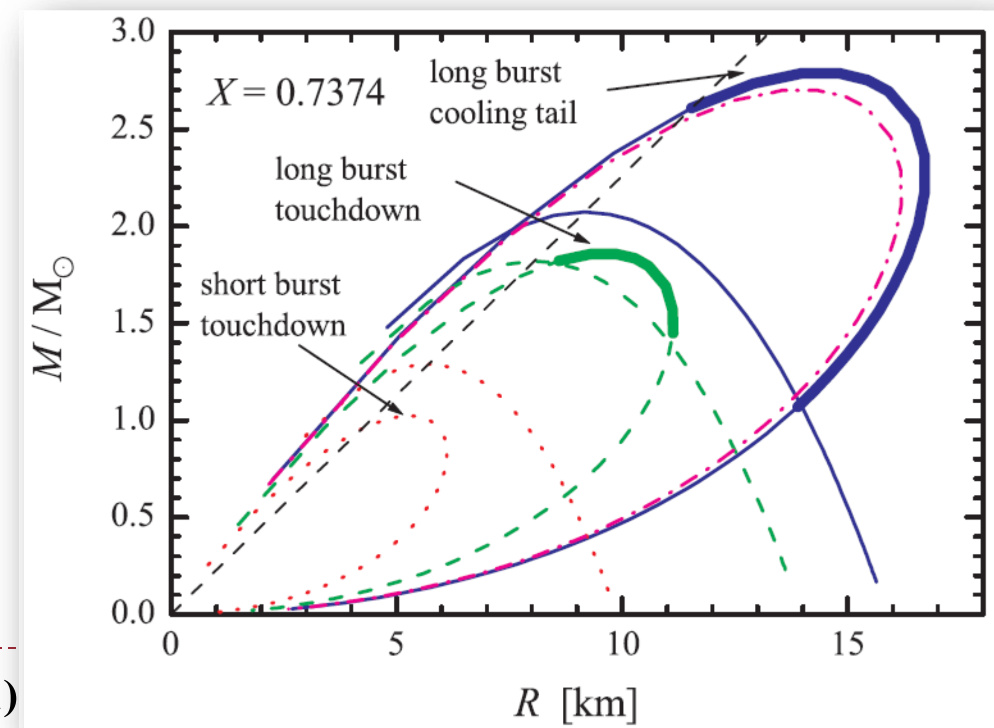






- But often they do not
  - In some case, no intersection
- **After statistical manipulation, intersection point emerges**
  - M and R depends on Authors

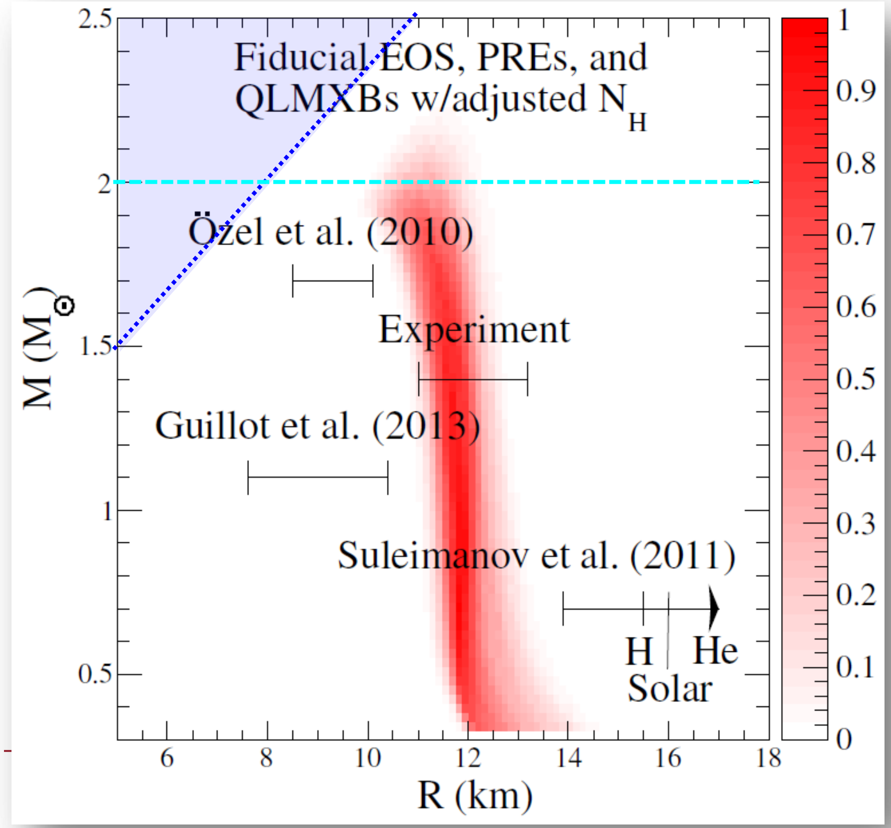
- Situation is similar for the other EM observation
  - Observation of quiescent low mass X-ray binaries (qLMXB)



Sulemimanov et al. (2011)

NS mass/radius measurements by EM

- The measurement of flux and temperature yields an apparent angular size (pseudo-BB) $\frac{R_\infty}{D} = \frac{R}{D}\frac{1}{\sqrt{1-GM/Rc^2}}$ $F \propto T_{\mathrm{eff}}^4 \frac{R_\infty^2}{D^2}$
  - Many uncertainties : redshift, distance, interstellar absorption, atmospheric composition
- Good Targets:
  - Quiescent X-ray binaries in globular clusters
  - Bursting sources with peak flux close to Eddington limit
- Imply rather small radius
  - **If true, maximum mass may not be much greater than 2Msun**



Lattimer & Steiner 2014