Constraints on neutron star properties from GW170817

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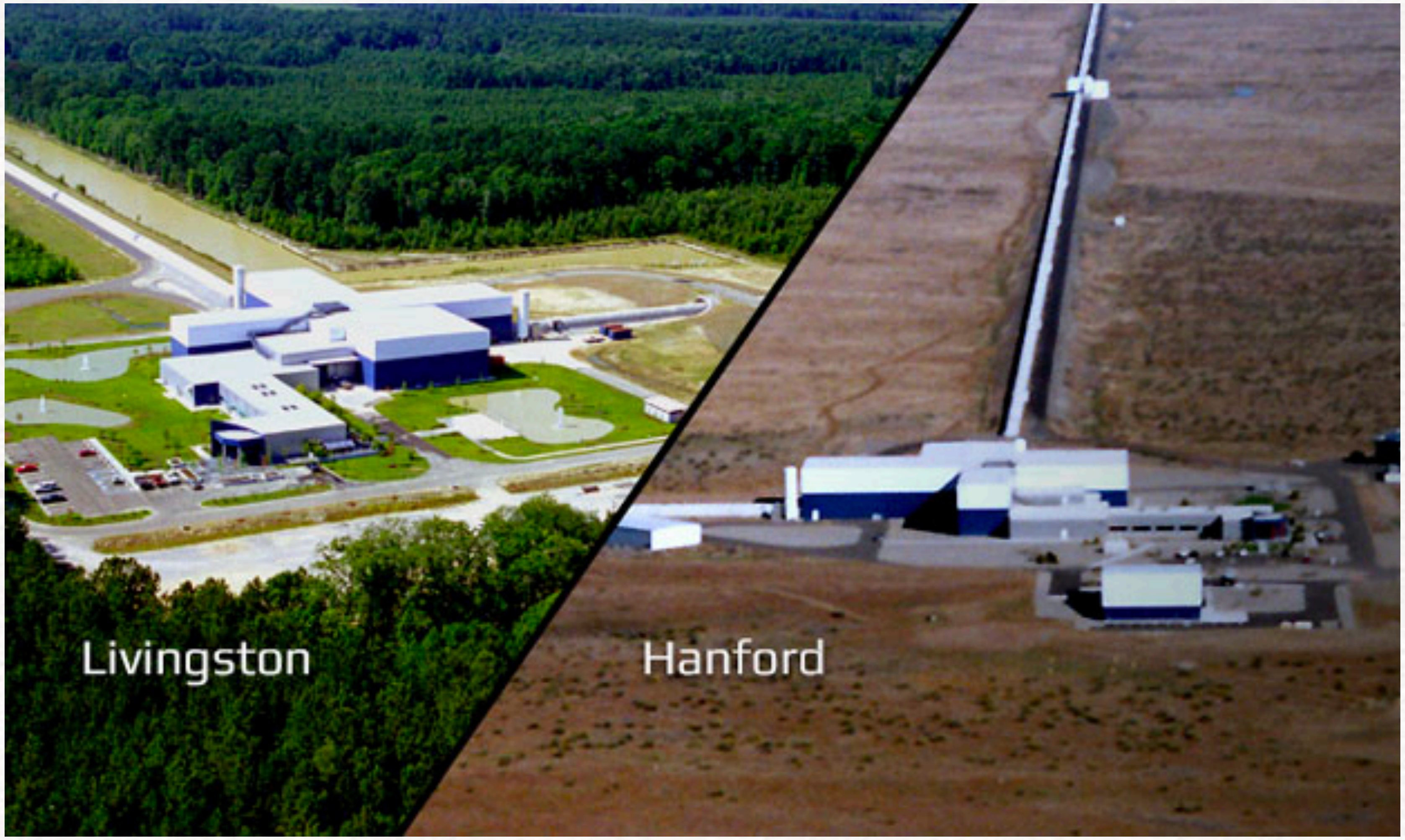
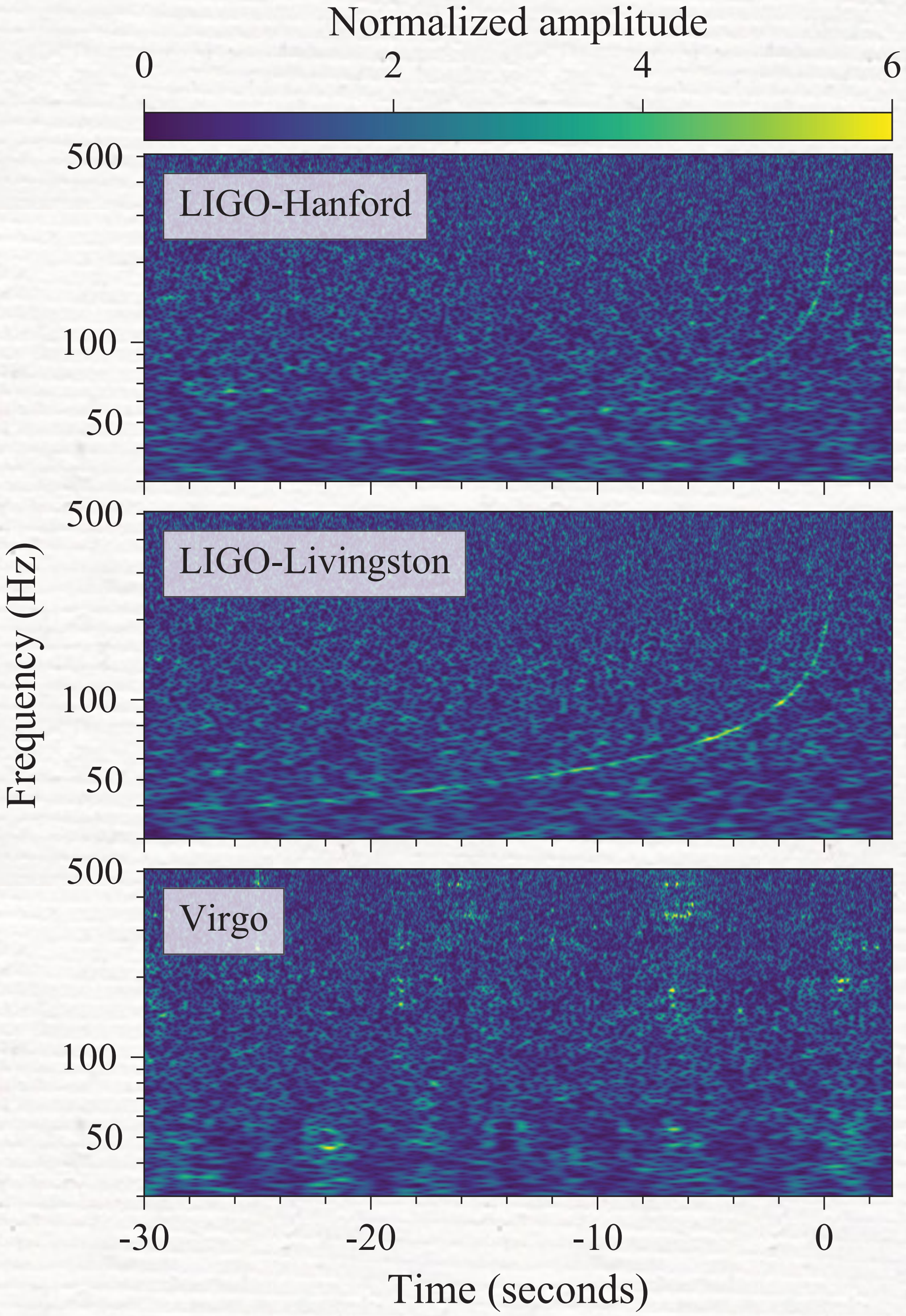
GW170817



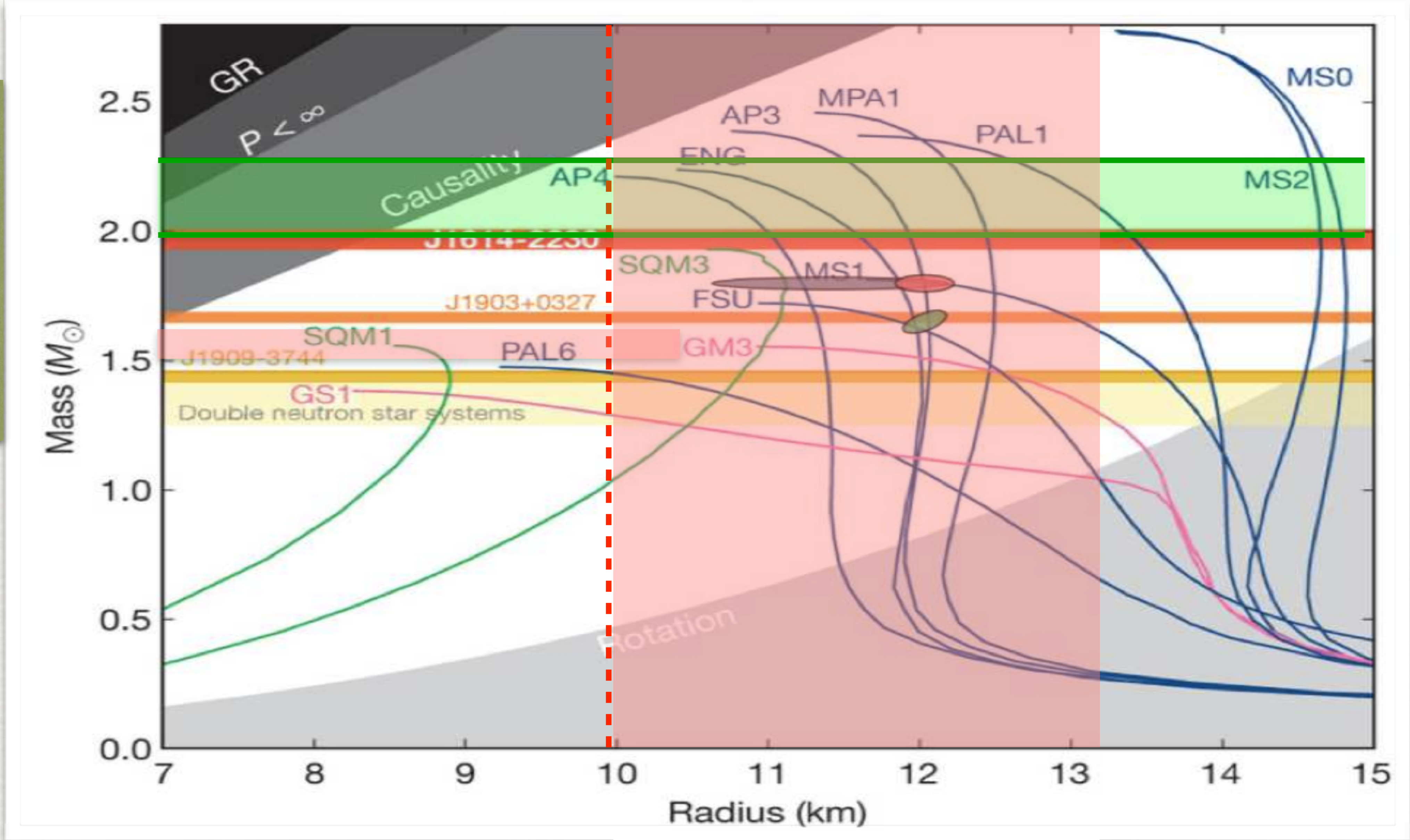
LIGO Lab MIT/Caltech



Abbott et al 2017

Can we translate GW170817 to constraints on the EOS?

maximum mass



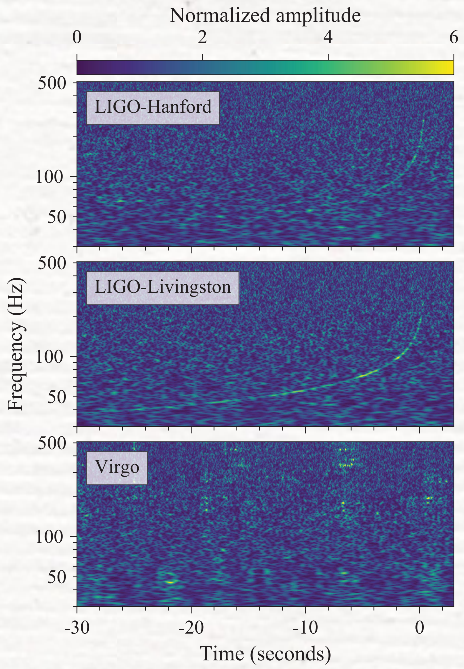
lowest/largest radius

Ingredients to constrain EOS

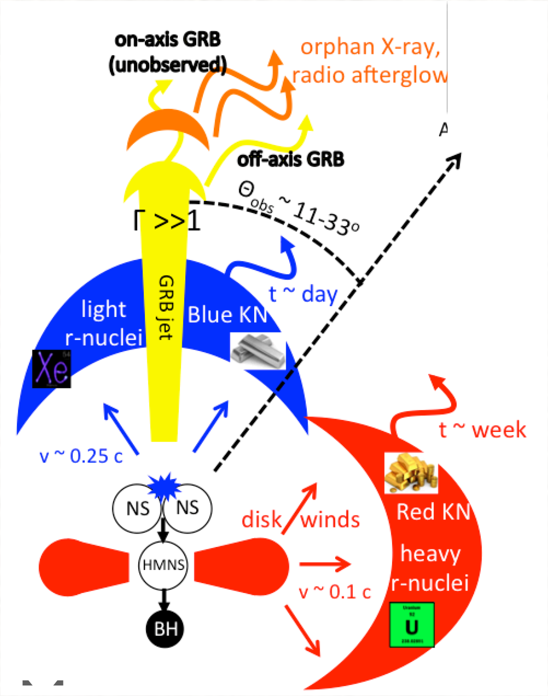
Numerical relativity

Physics modelling

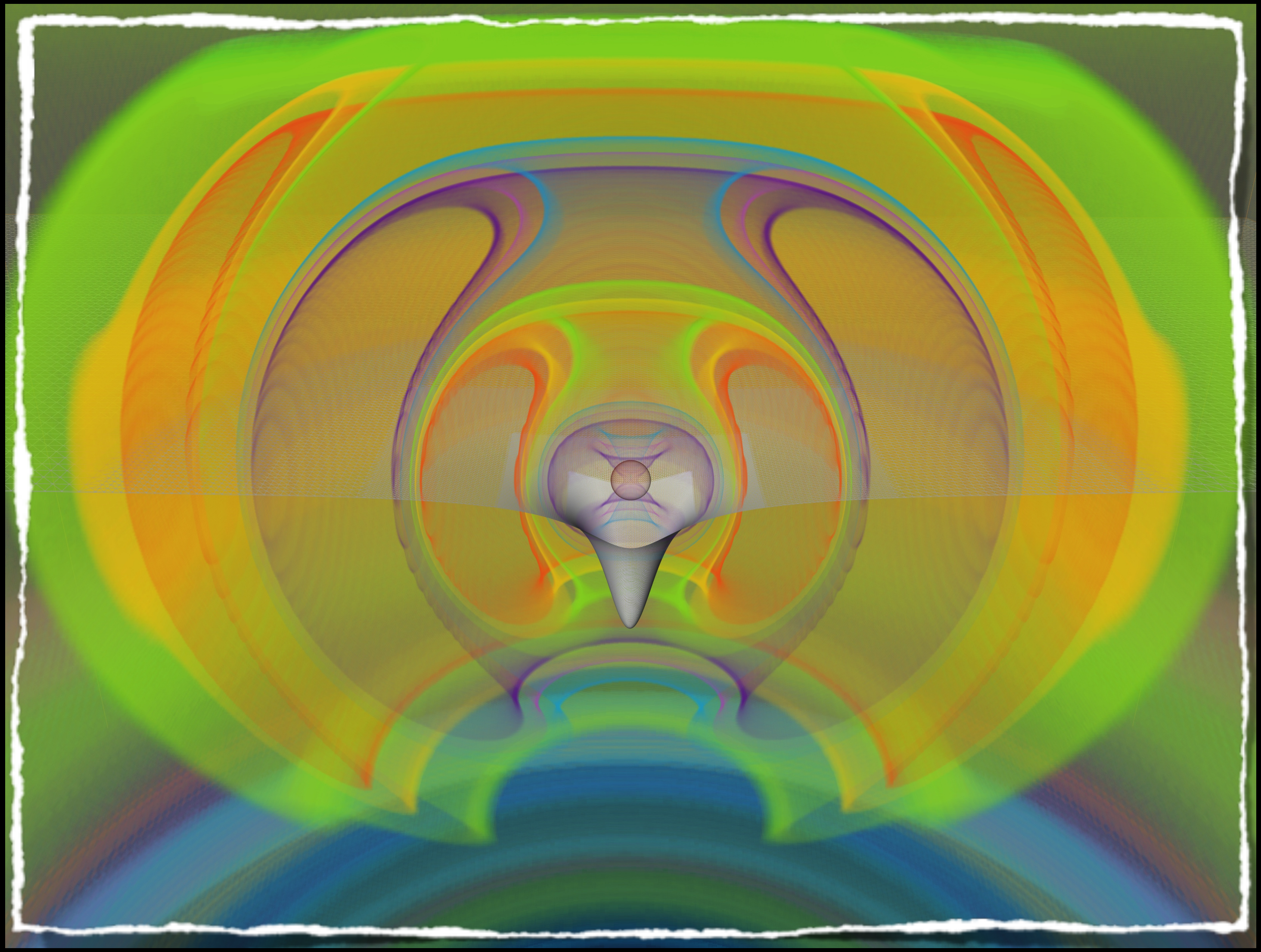
EOS CONSTRAINTS



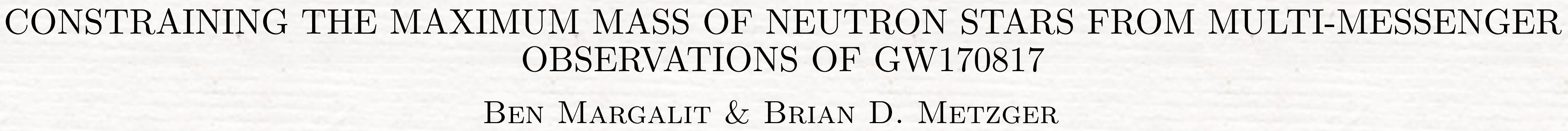
Observation



Maximum mass constraints from GW170817

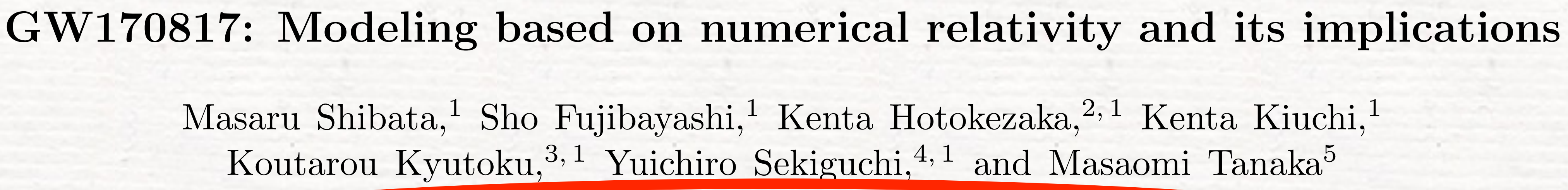


Maximum mass constraints



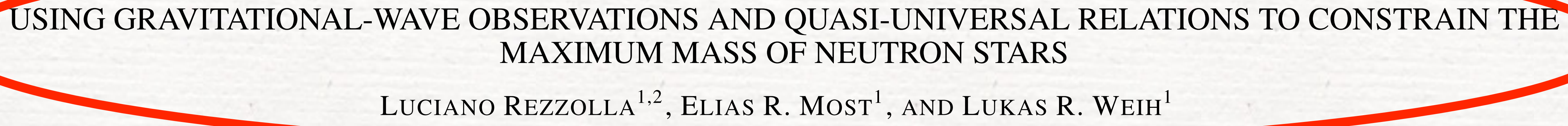
CONSTRAINING THE MAXIMUM MASS OF NEUTRON STARS FROM MULTI-MESSENGER OBSERVATIONS OF GW170817

BEN MARGALIT & BRIAN D. METZGER



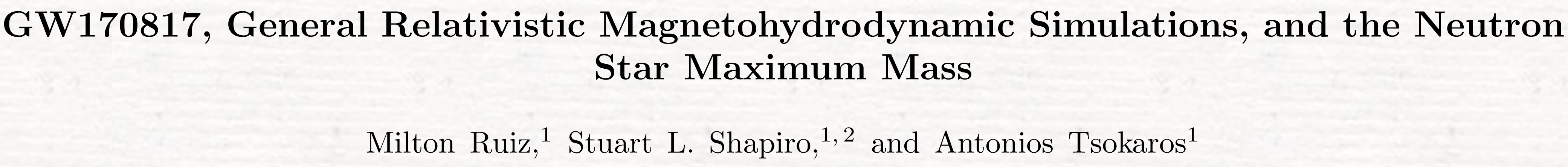
GW170817: Modeling based on numerical relativity and its implications

Masaru Shibata,[1] Sho Fujibayashi,[1] Kenta Hotokezaka,[2,1] Kenta Kiuchi,[1]
Koutarou Kyutoku,[3,1] Yuichiro Sekiguchi,[4,1] and Masaomi Tanaka[5]



USING GRAVITATIONAL-WAVE OBSERVATIONS AND QUASI-UNIVERSAL RELATIONS TO CONSTRAIN THE MAXIMUM MASS OF NEUTRON STARS

LUCIANO REZZOLLA[1,2], ELIAS R. MOST[1], AND LUKAS R. WEIH[1]

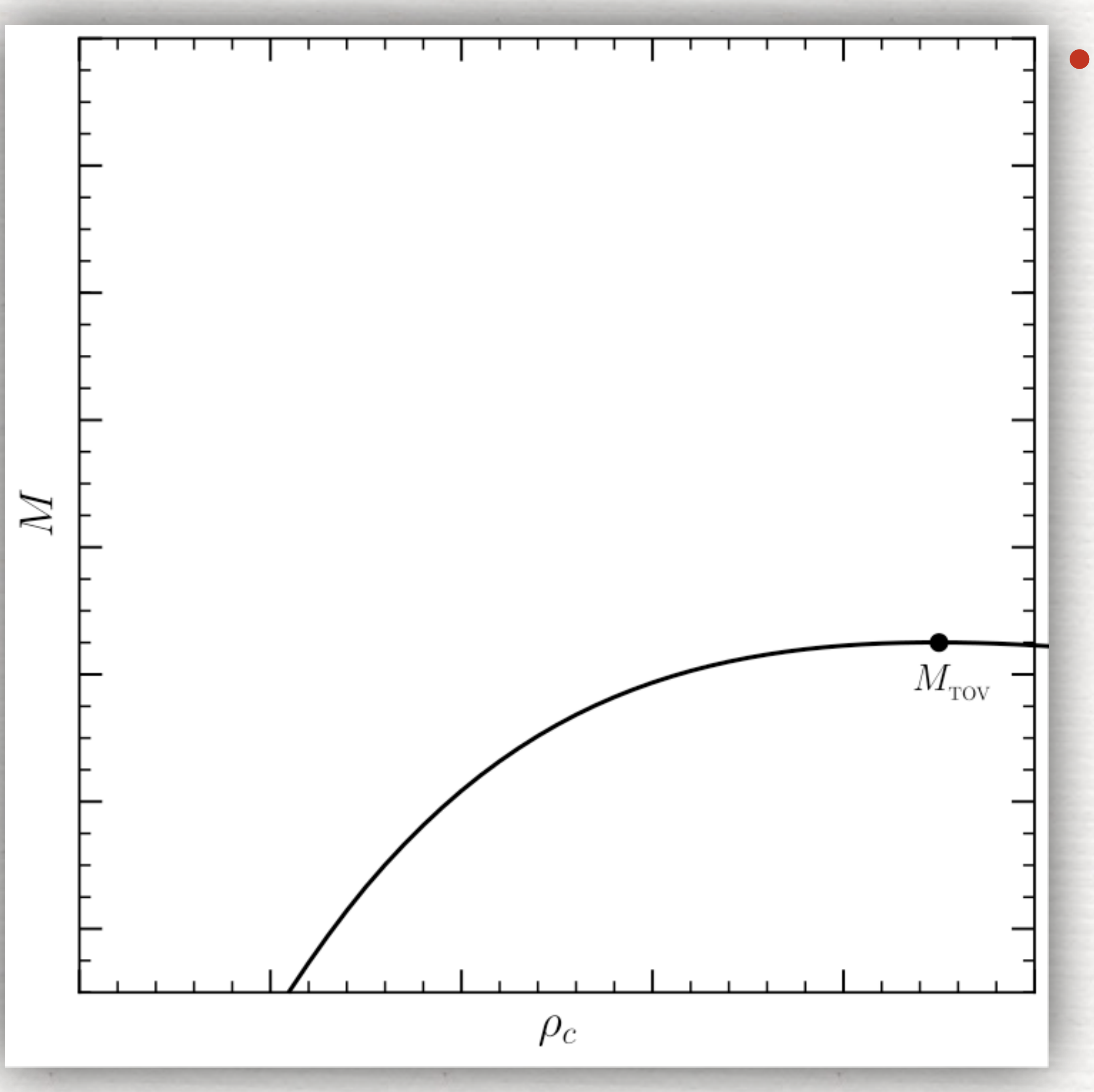


GW170817, General Relativistic Magnetohydrodynamic Simulations, and the Neutron Star Maximum Mass

Milton Ruiz,[1] Stuart L. Shapiro,[1,2] and Antonios Tsokaros[1]

The outcome of GW170817

- The product of GW170817 was likely a hypermassive star, i.e. a differentially rotating object with initial **gravitational** mass $M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$



- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$

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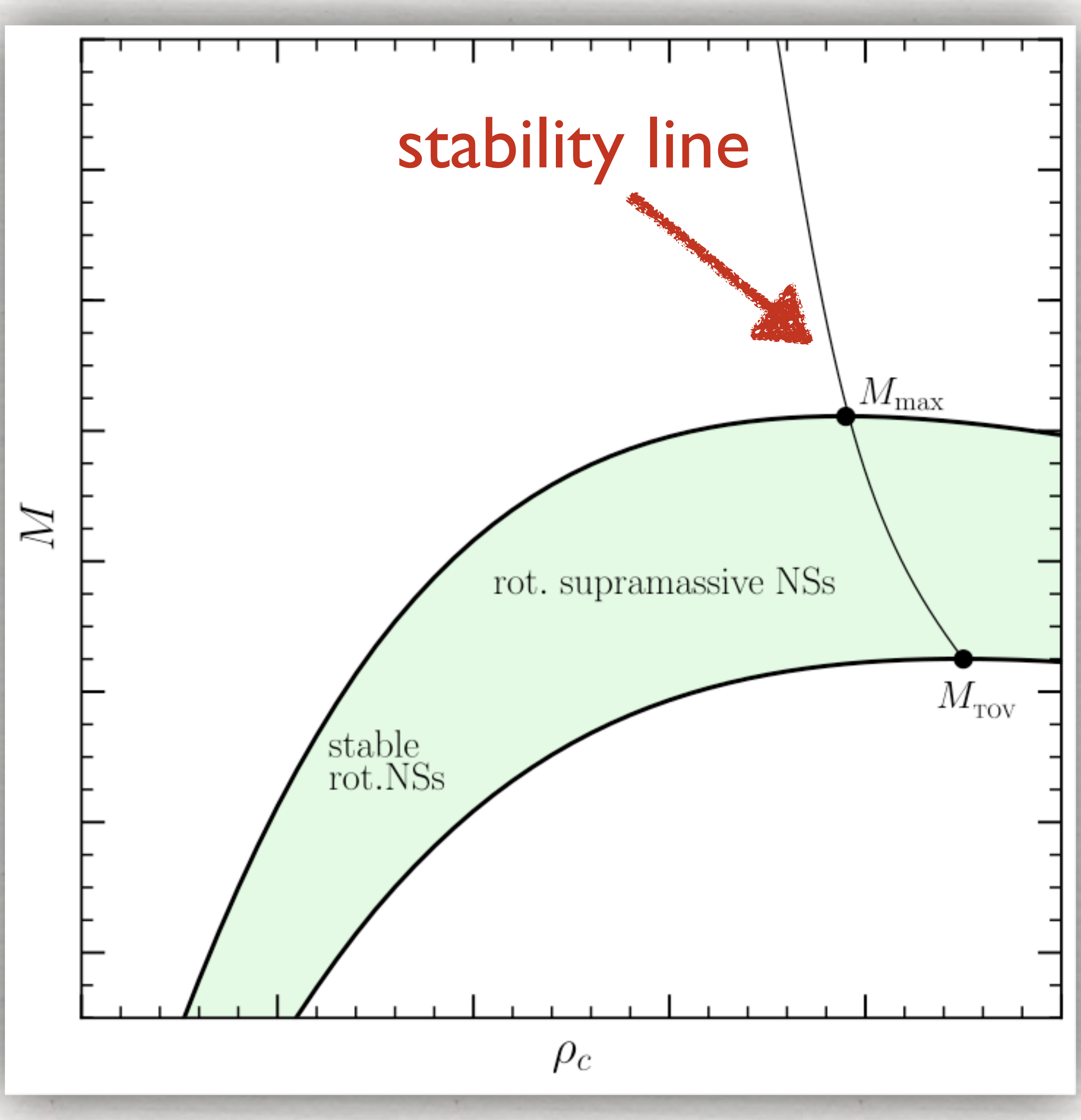

- Sequences of equilibrium models of **nonrotating** stars will have a maximum mass: $M_{\rm TOV}$
- This is true also for **uniformly** rotating stars at mass shedding limit: $M_{\rm max}$
- $M_{\rm max}$ simple and **quasi-universal** function of $M_{\rm TOV}$ (Breu & Rezzolla 2016)

$$M_{\rm max} = \left(1.20^{+0.02}_{-0.05}\right) M_{\rm TOV}$$

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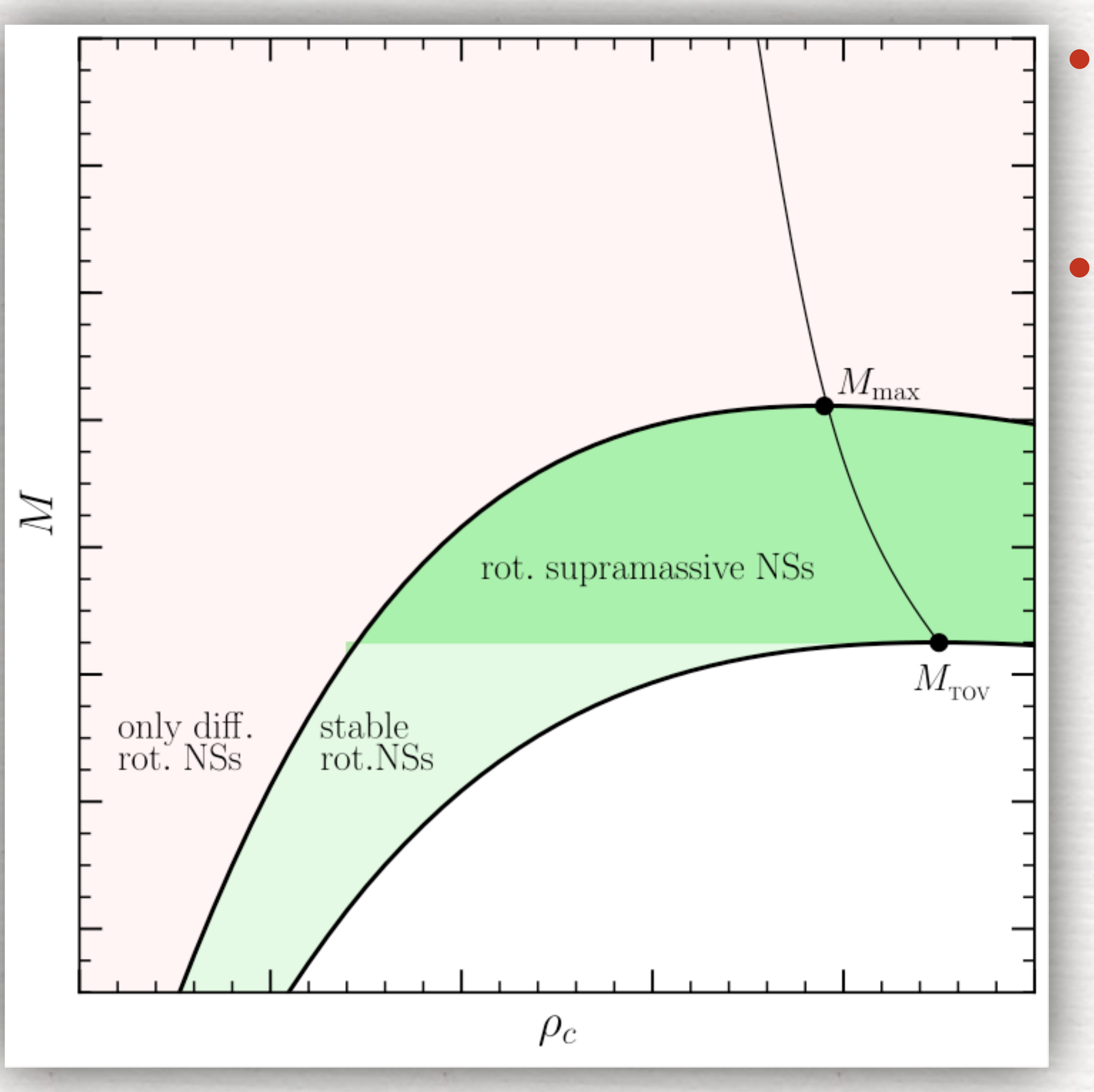

- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.

The outcome of GW170817

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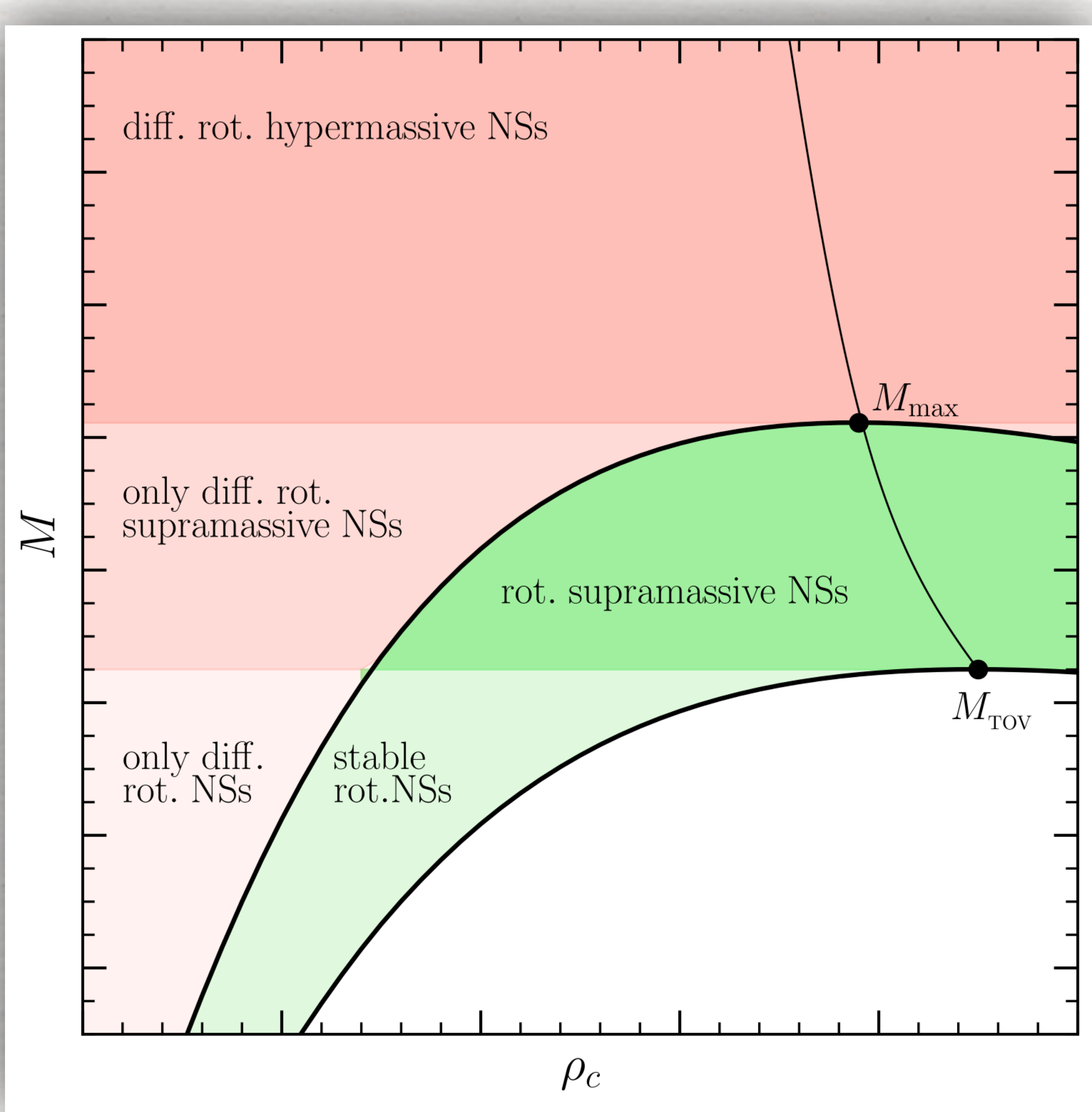


- **Green** region is for **uniformly** rotating equilibrium models.
- **Salmon** region is for **differentially** rotating equilibrium models.
- **Supramassive** stars have

$$M > M_{\rm TOV}$$

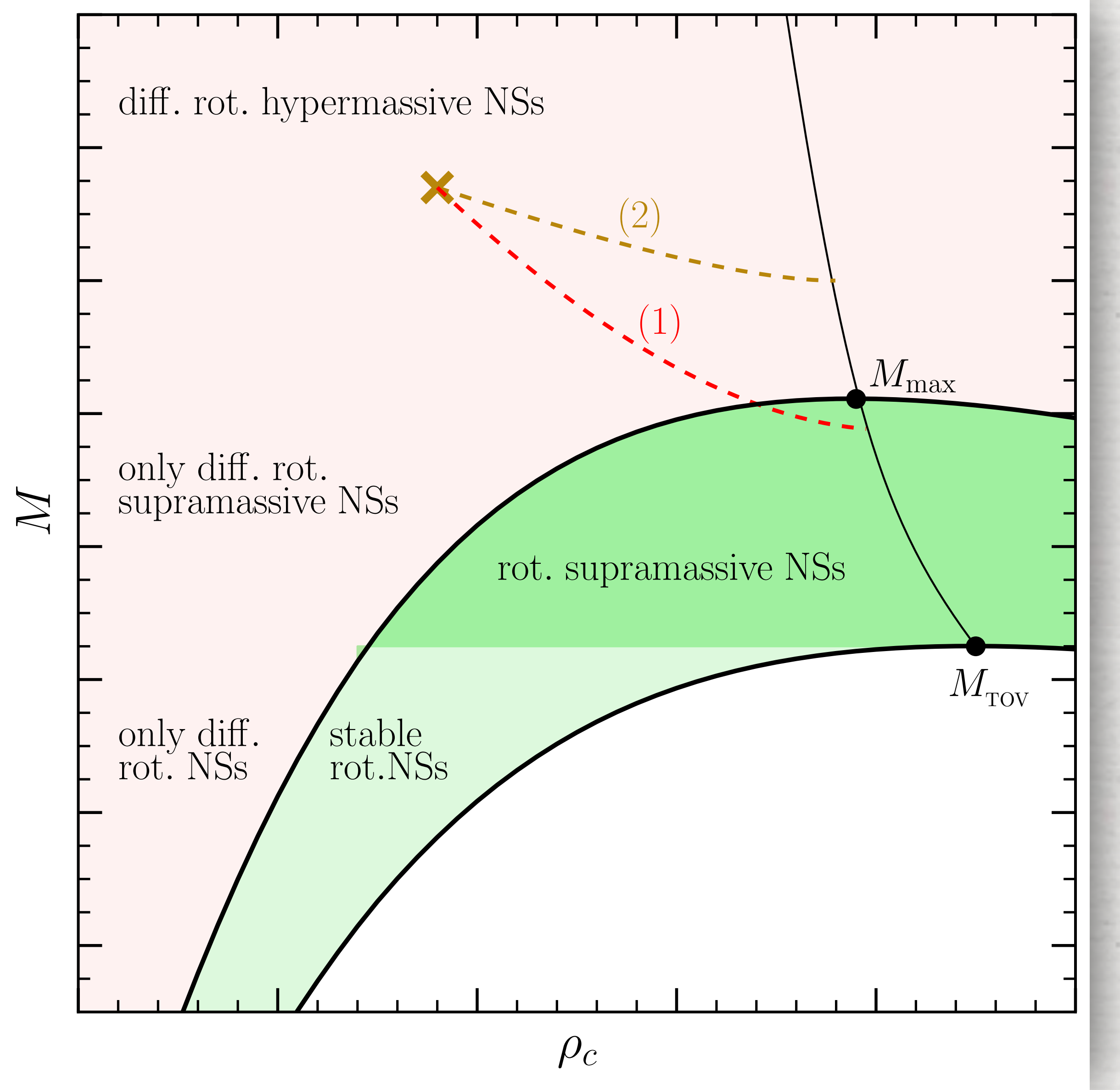
- **Hypermassive** stars have

$$M > M_{\rm max}$$

The outcome of GW170817

- Merger product in GW170817 could have followed two possible tracks in diagram: **fast (2)** and **slow (1)**

- It rapidly produced a BH when still **differentially** rotating **(2)**
- It lost differential rotation leading to a **uniformly** rotating core **(1)**.
- **(1)** is more likely because of large ejected mass (long lived).
- Final mass is near $M_{\rm max}$ and we know this is universal!



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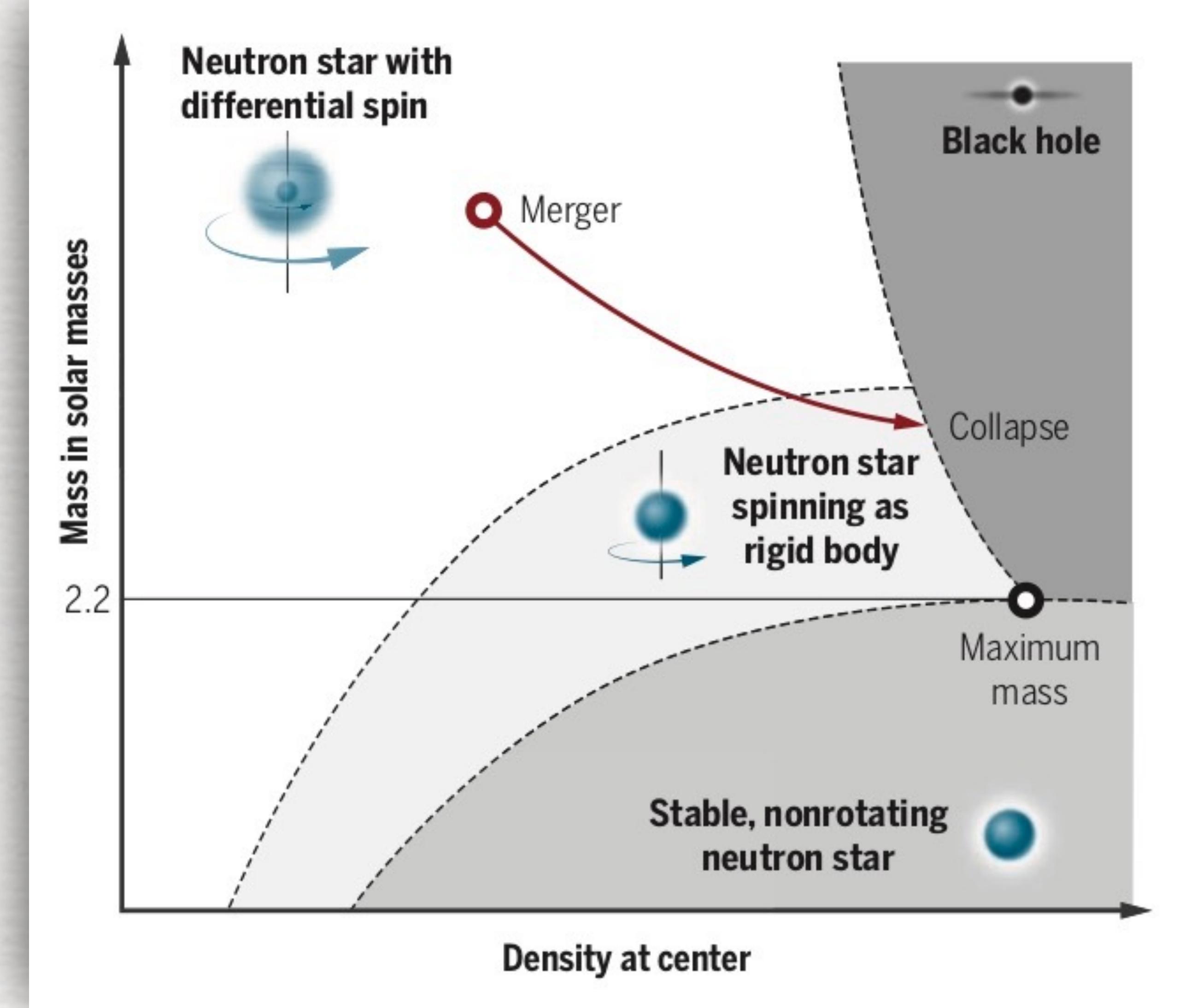


Cho, Bicknell, Science 2018

Maximum mass constraint

- The merger product of GW170817 was initially **differentially** rotating but collapsed as **uniformly** rotating object.

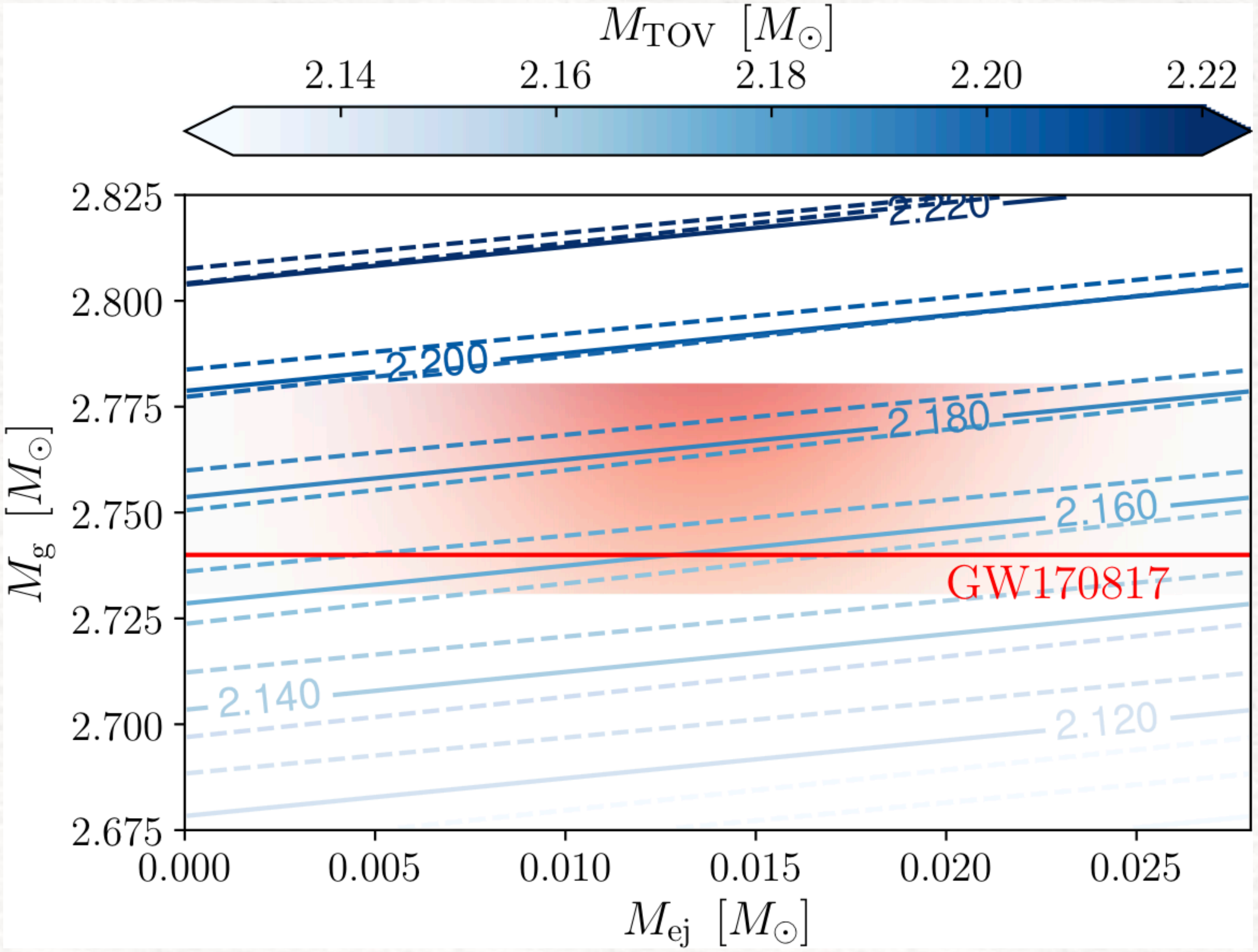
- HMNS core has about 95% **gravitational** mass of

$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

- Ejected **rest mass** deduced from kilonova emission

$$M_{\rm ej}^{\rm blue} = 0.014^{+0.010}_{-0.010}\, M_\odot$$

- Use **universal relations** and account errors to obtain



Rezzolla, ERM, LW (ApJL 2018)

pulsar timing

$$2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$$

universal relations and GW170817; similar estimates by other groups

Overview of different results

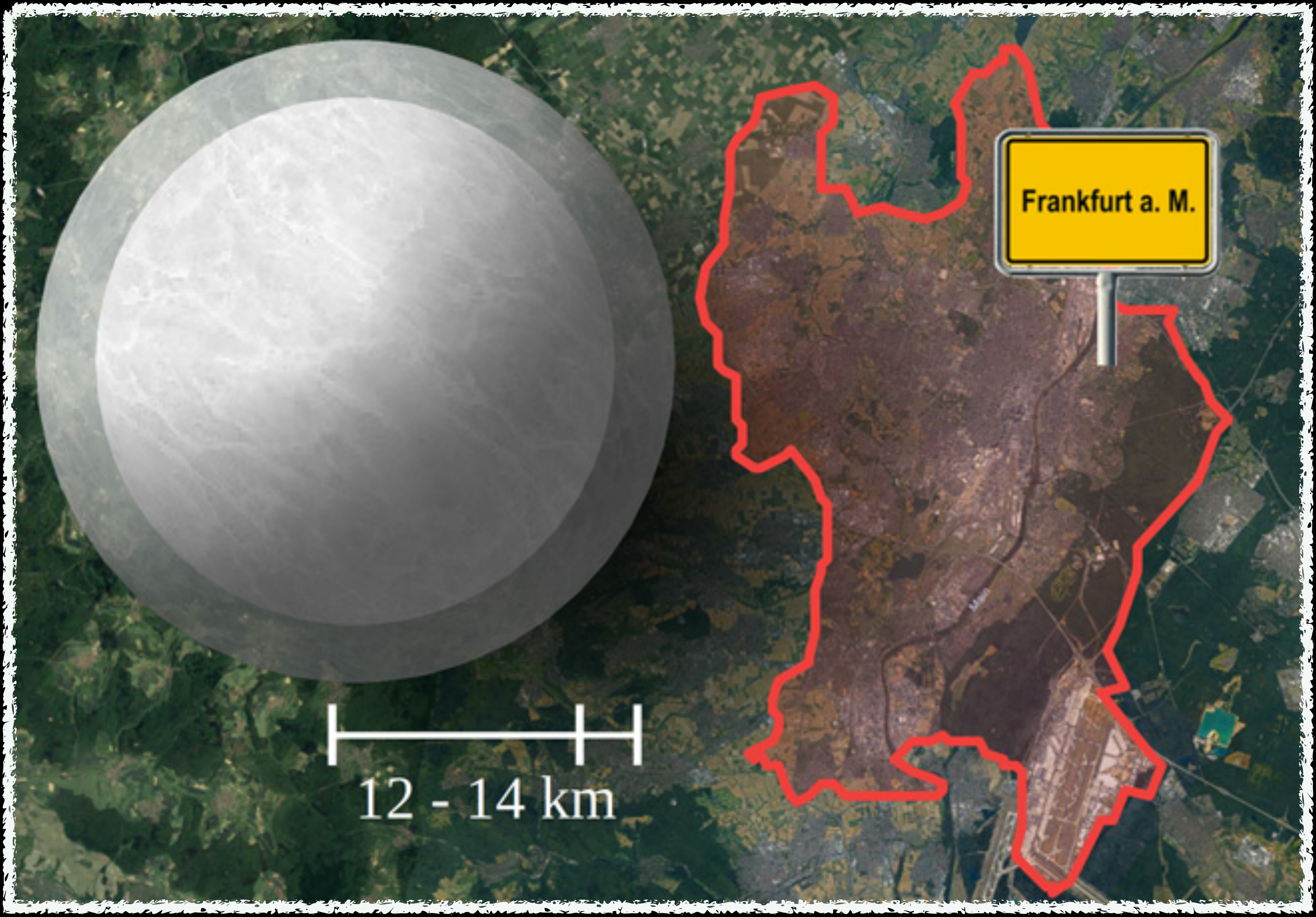
MARGALIT+	Baysian analysis + threshold mass	$< 2.17\ M_{sun}$
SHIBATA+	numerical simulations	$< 2.25\ M_{sun}$
REZZOLLA, ERM,LW	universal relations	$< 2.16\ M_{sun}$
RUIZ+	Ruffini-Treves mass limit	$< 2.17\ M_{sun}$

Note: All groups use input from kilonova modelling

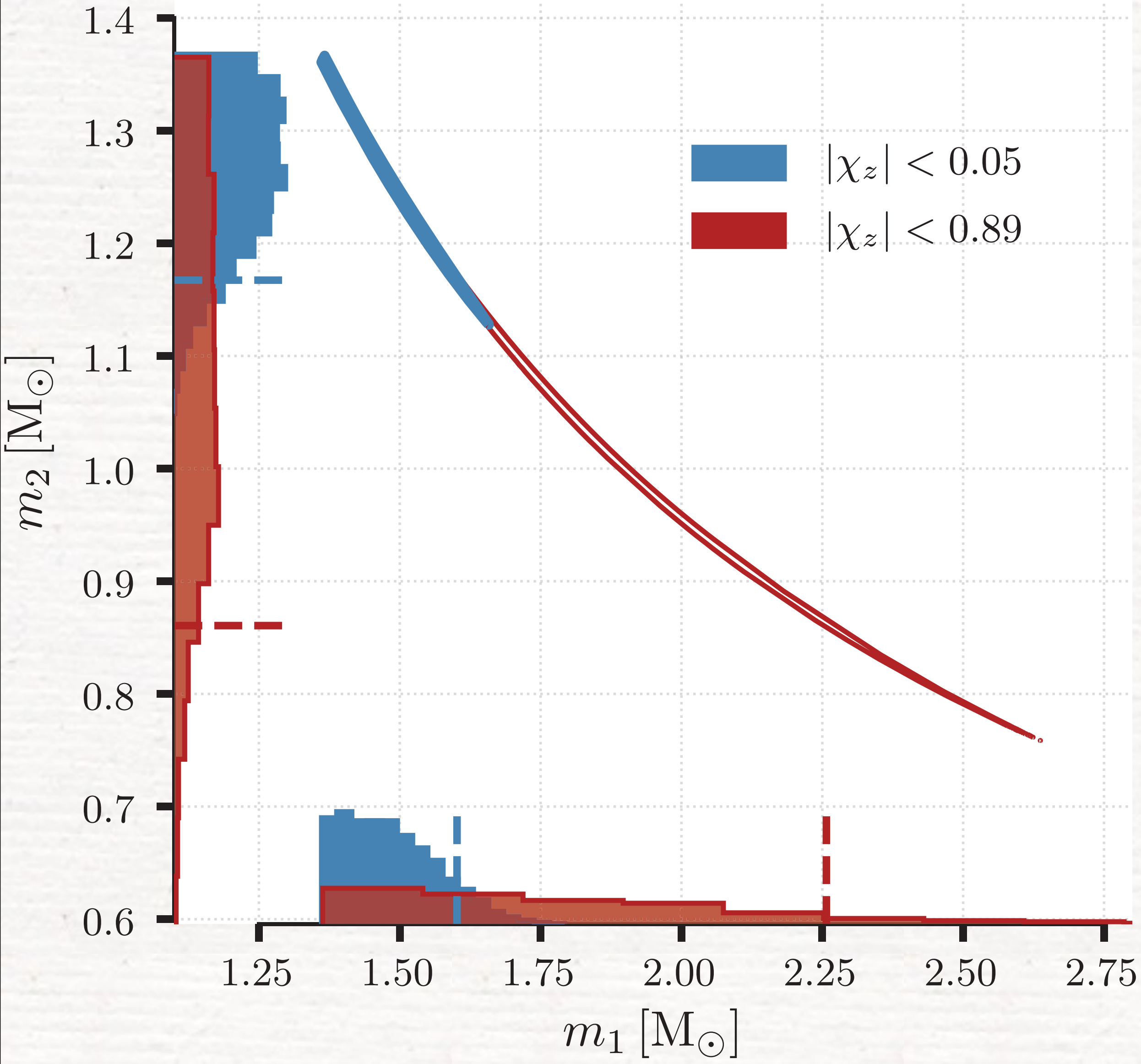
Bottom line:
$M_{max} \sim 2.2\ M_{sun}$

Radius constraints from GW170817:

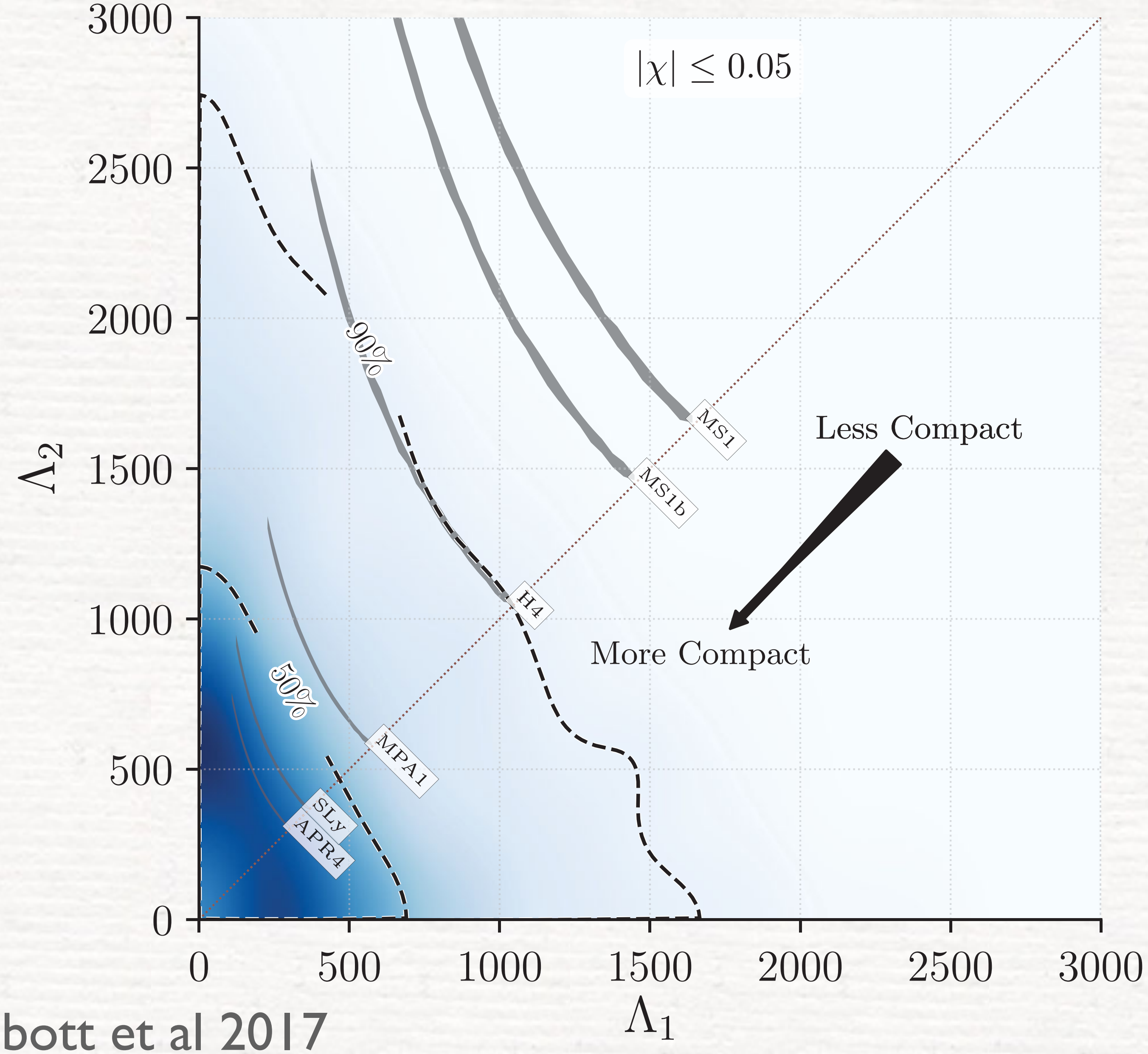
A Frankfurt perspective



GW170817: What do we know?



$$\tilde{\Lambda}_{1.4} < 800$$



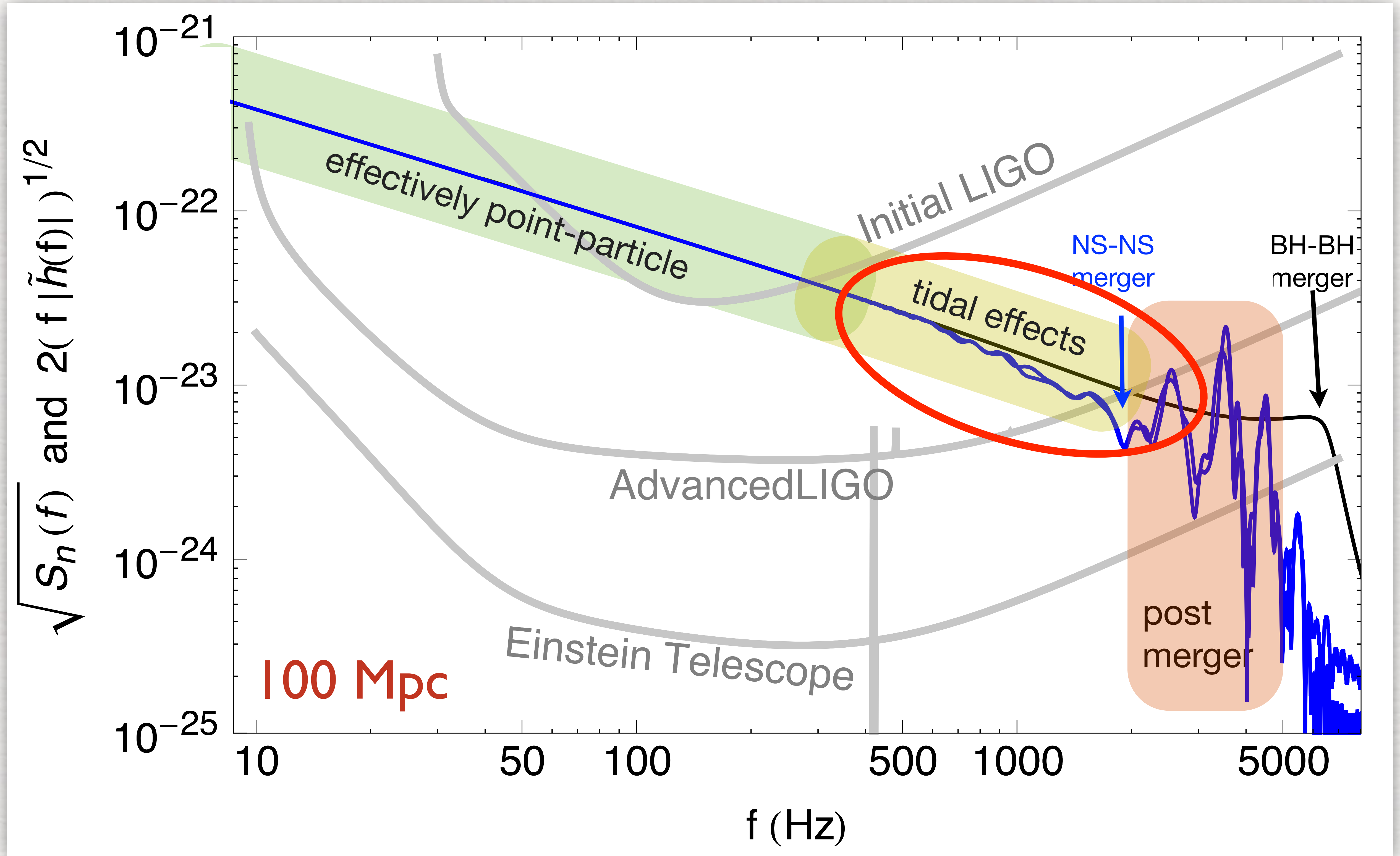
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

$$M_1 = 1.36 - 1.60 M_\odot$$

$$M_2 = 1.17 - 1.36 M_\odot$$

Abbott et al 2017

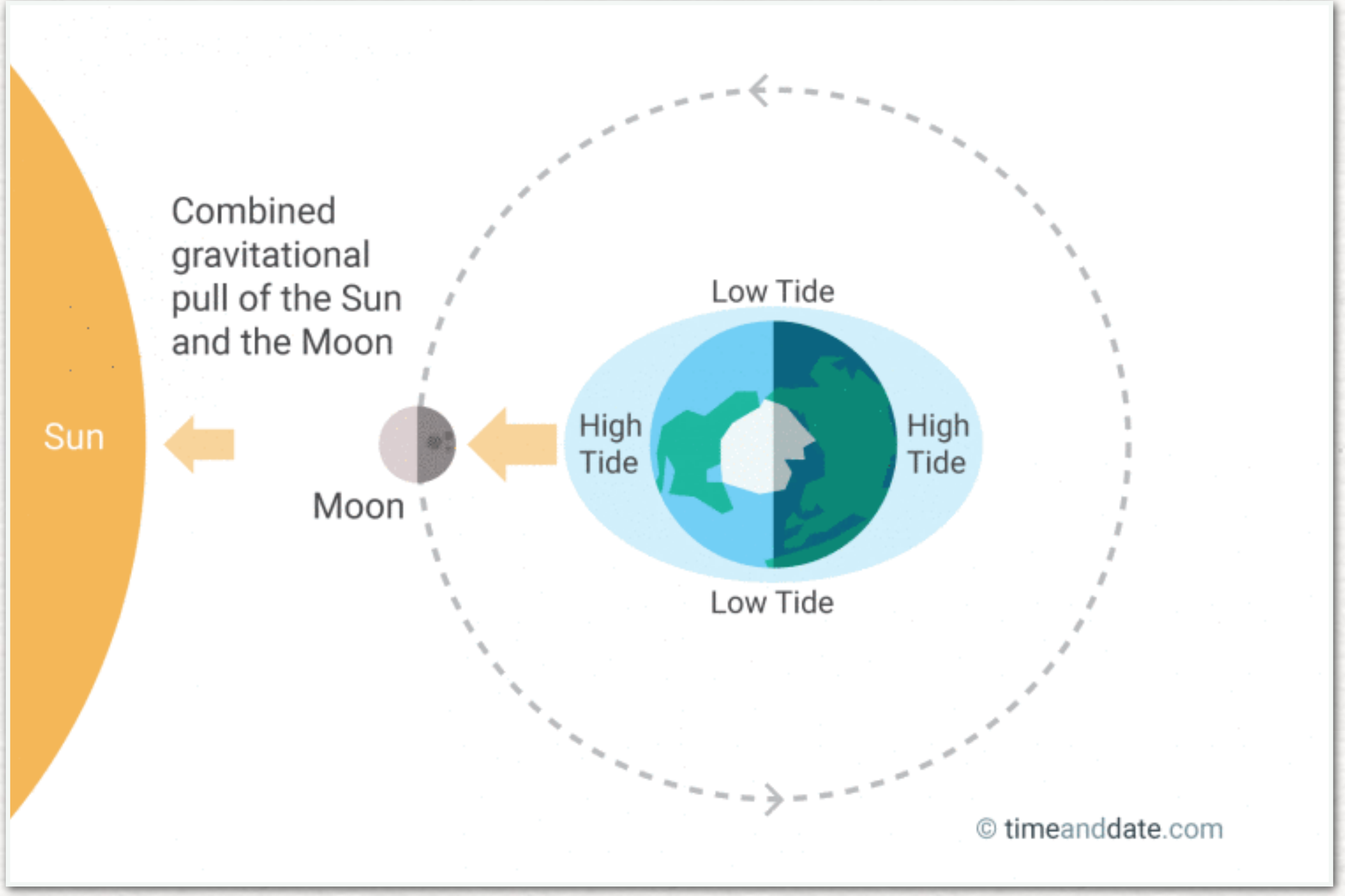
How is BH-BH different from NS-NS?



Read et al. (2013)

How is BH-BH different from NS-NS?

Neutron stars in binary are tidally deformed by companion



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Q : quadrupole moment

$$U = G\frac{M}{r} + \boxed{G\frac{Q}{r^3}}P_2(\cos\theta)$$

What is the quadrupole moment?

$$GQ = 2\kappa_2 R^5 \frac{GM'}{b^3}$$

Tidal field of companion star

Tidal Love number

$$\Lambda = \frac{2}{3}\kappa_2 \left(\frac{Rc^2}{GM}\right)^5$$

Tidal deformability of the isolated neutron star

EOS

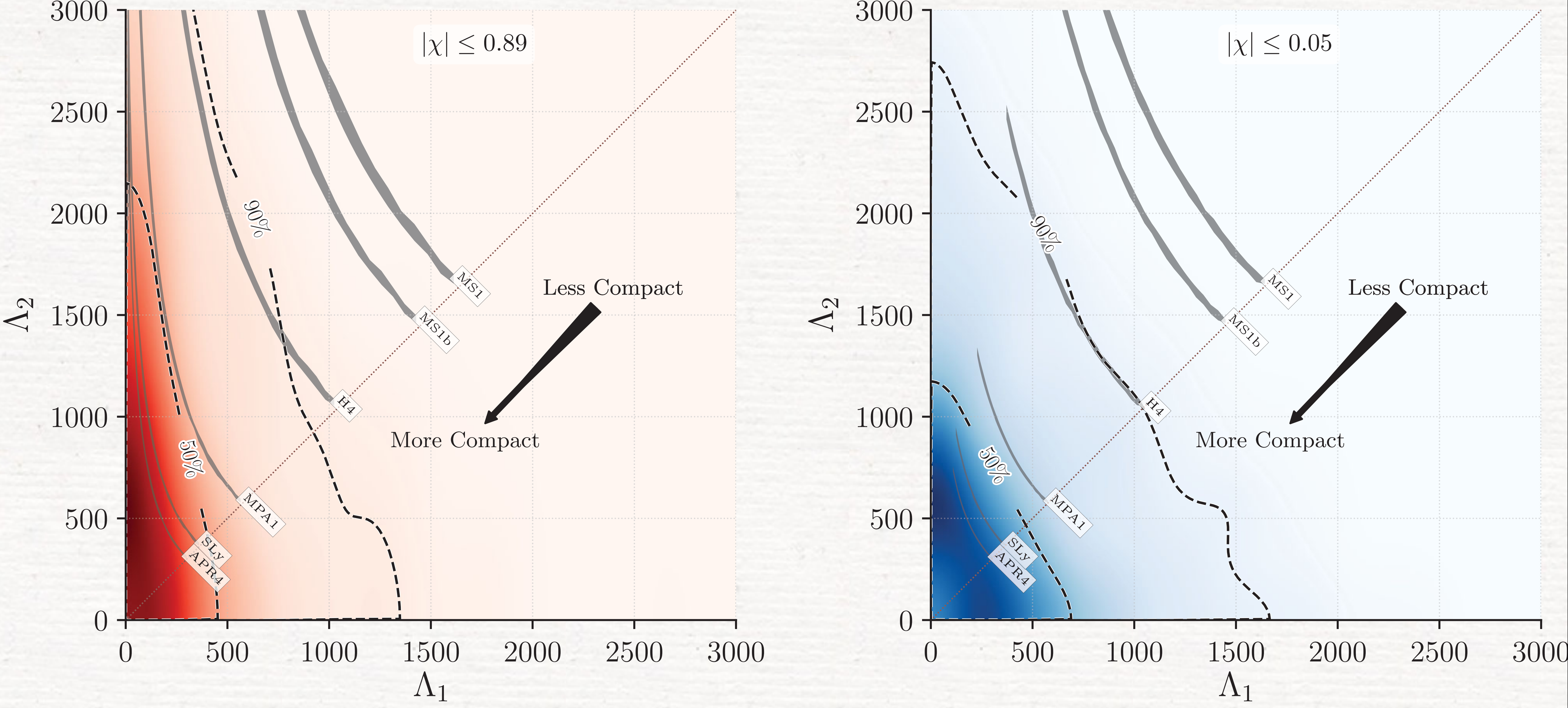
Imprint on gravitational wave:

$$\tilde{h}_{\mathrm{GW}}(f) = \mathscr{A}_{\mathrm{SPA}}(f) \exp i\psi_{\mathrm{SPA}}(f)$$

$$\psi_{\mathrm{SPA}} \sim \ldots - \frac{39}{2}\nu^{-2}\tilde{\Lambda}\left(\pi \mathscr{M} f\right)^{10/3}$$

Mass weighted average

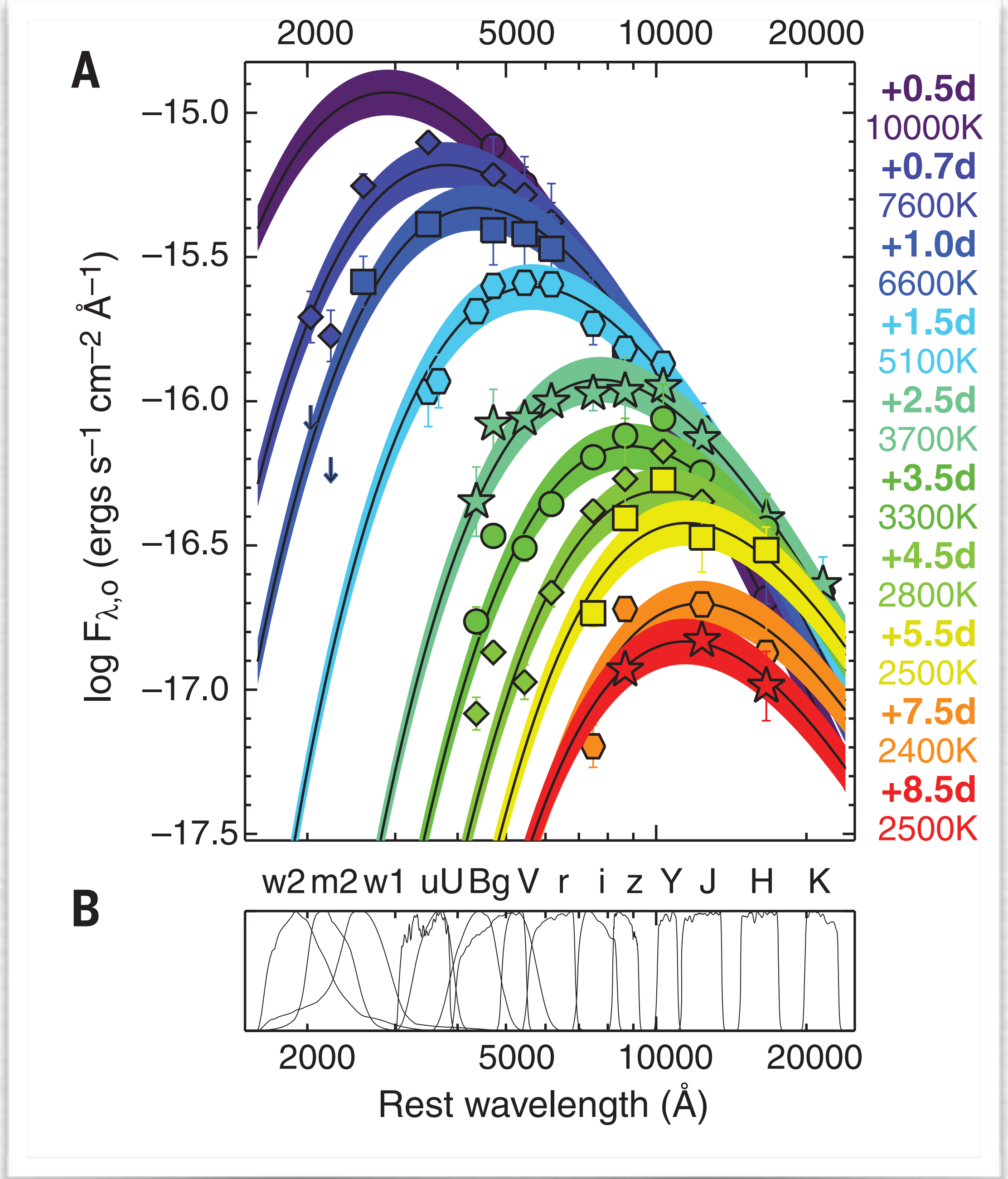
GW170817: What do we know?

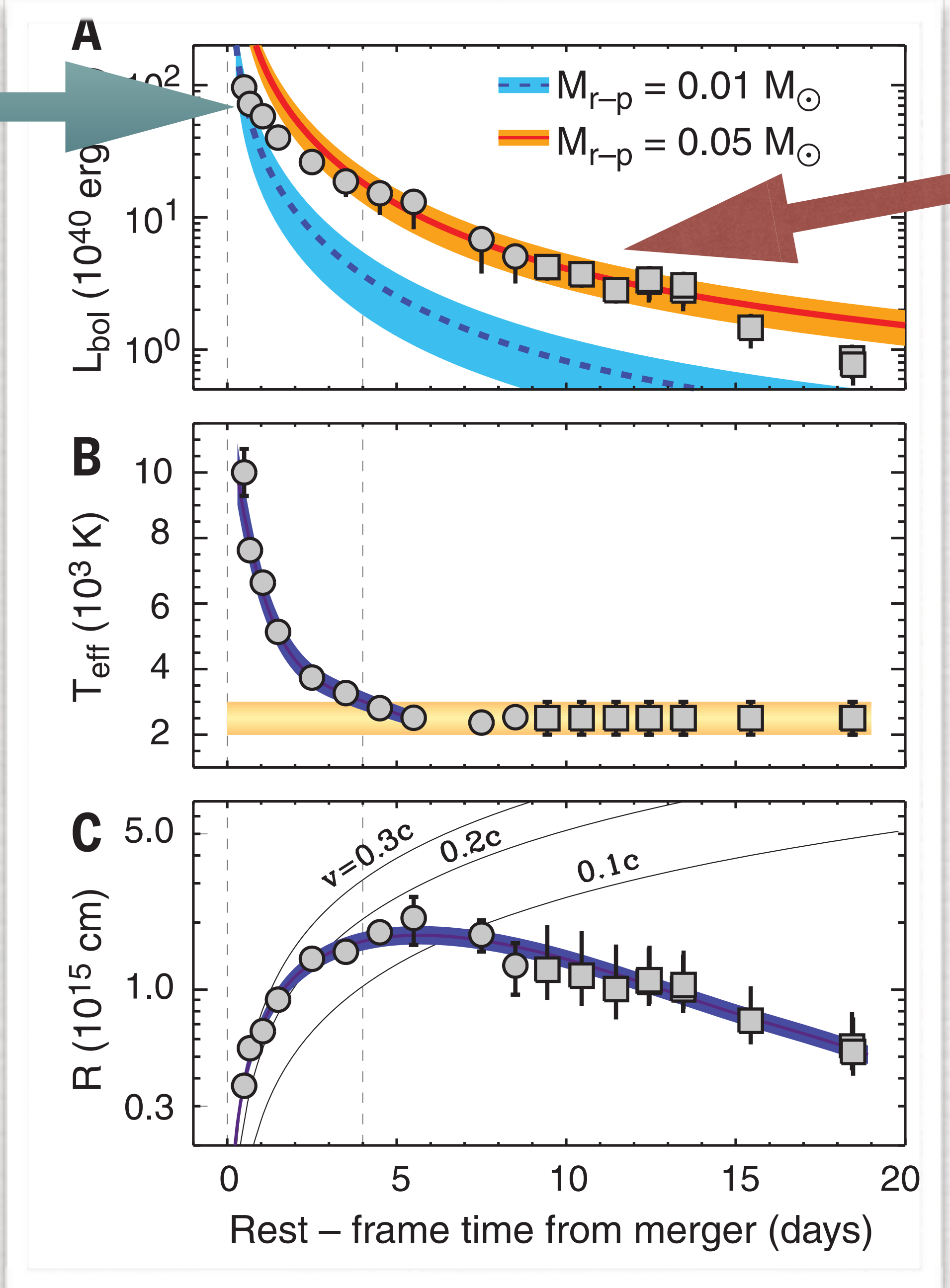


Abbott et al 2017

Light curves

Observations consistent with two component model





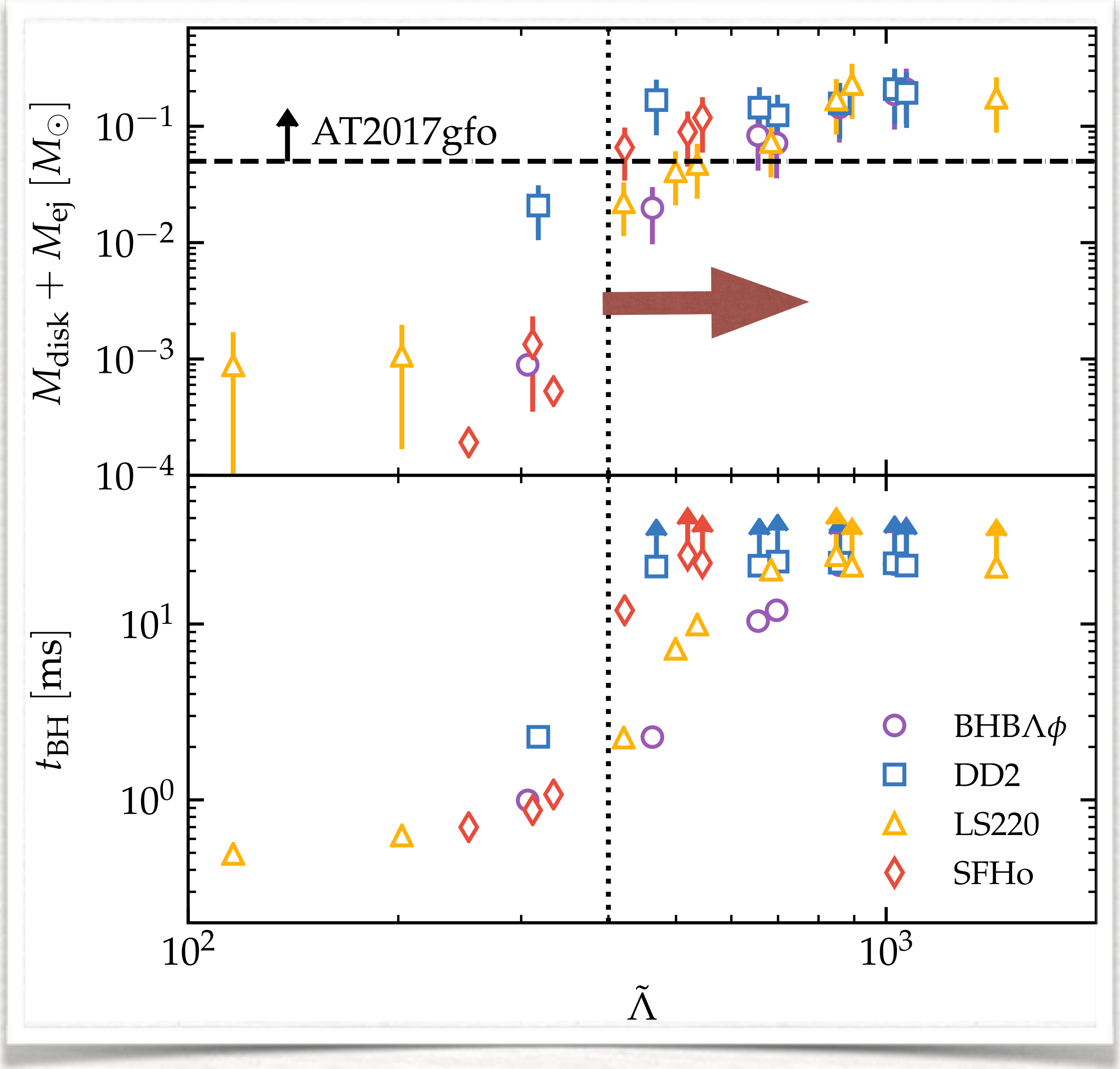
Drout et al 2017

Kilonova constraints on the tidal deformability

- Consistency with kilonova modelling (mass ejection) requires lower limit on tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A + M_B)^5} + (A \leftrightarrow B)\right],$$

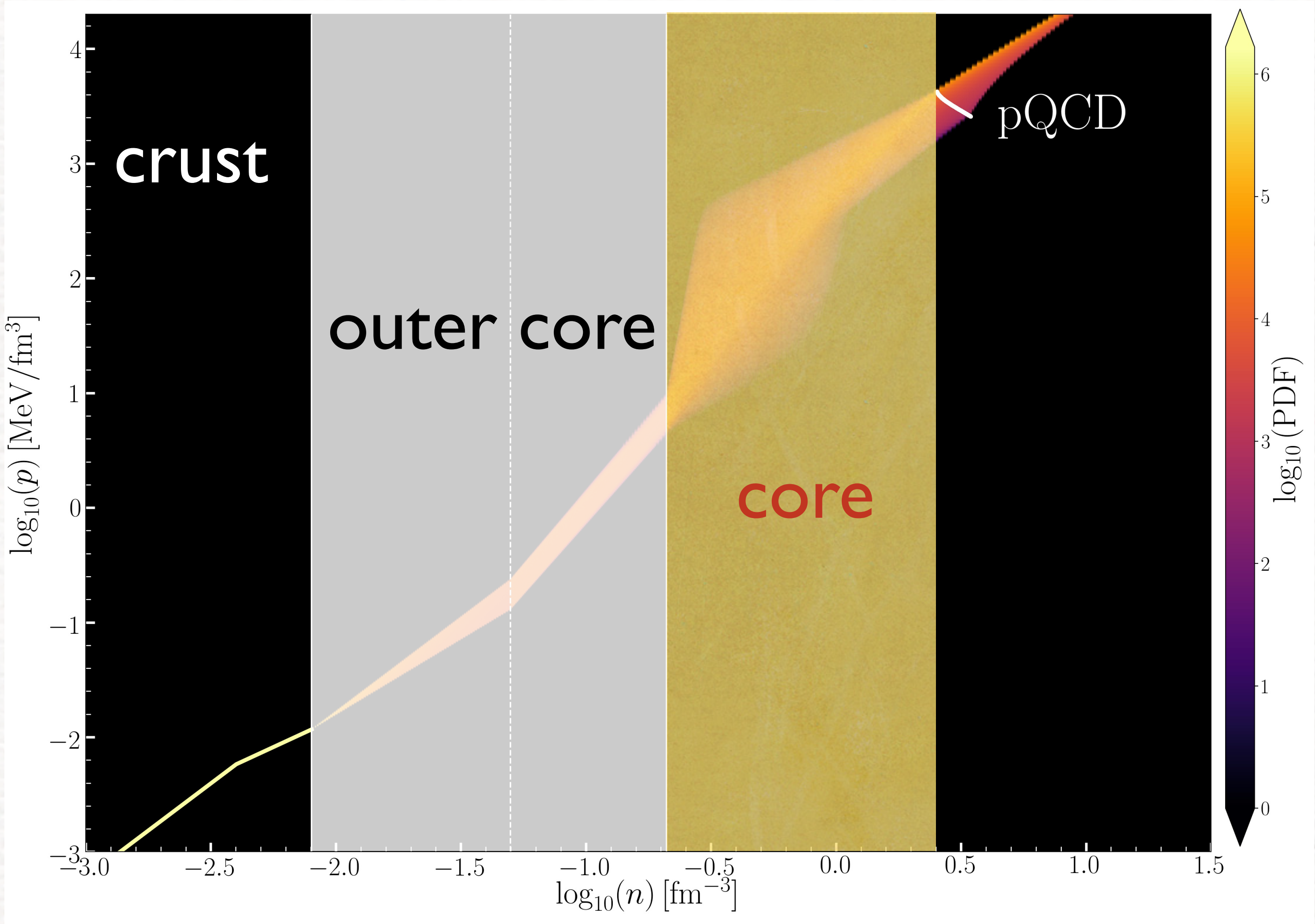
Errors unclear
Might be as low as ~200
(Coughlin+ 2018)



Radice et al 2018

Limits on radii and deformabilities

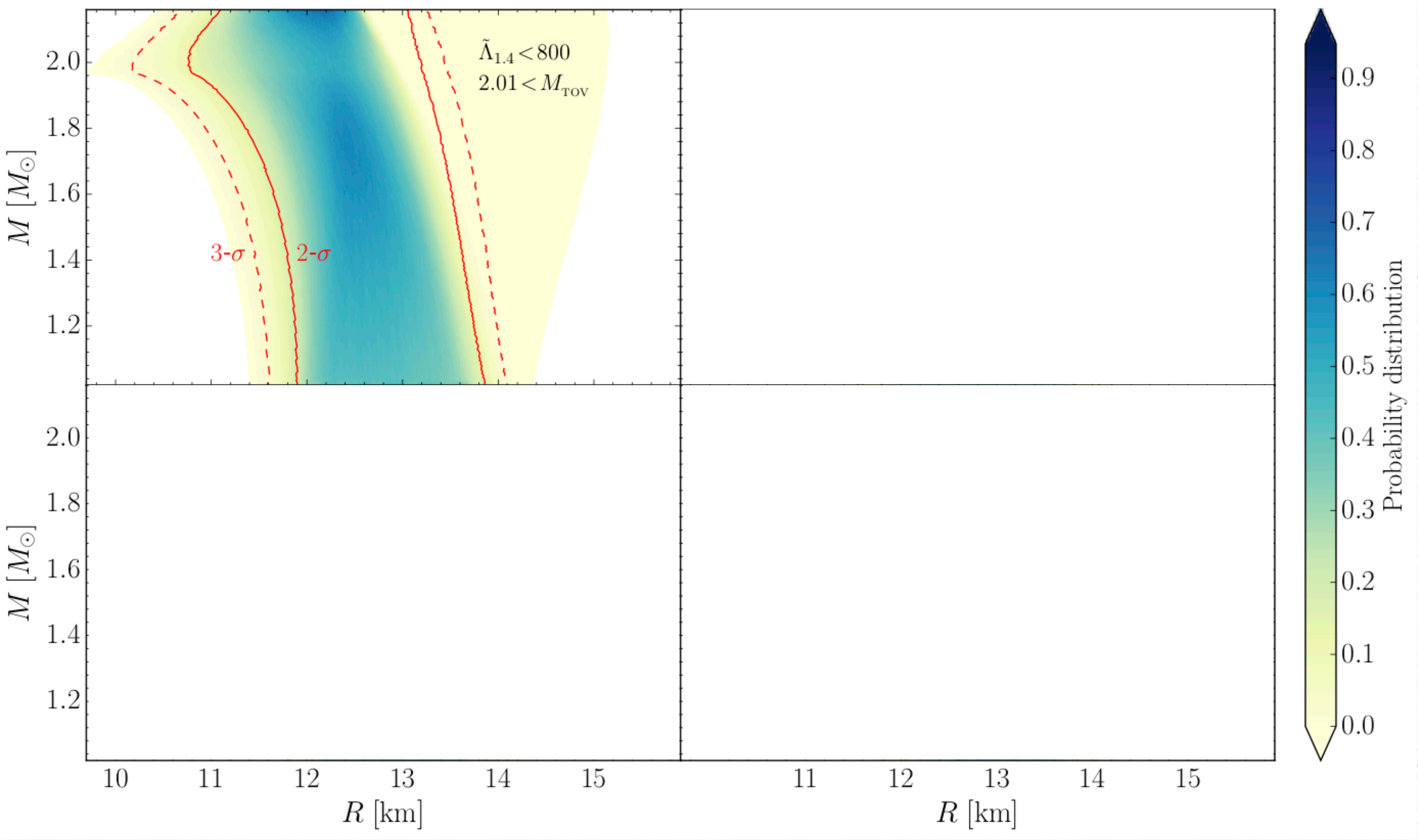
- Constraining NS radii of neutron stars is an effort with thousands of papers published over the last 40 years.
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?
- Ignorance can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on **low** and **high** densities.



Mass-radius relations

- We have produced **10^6 EOSs** with about **10^9 stellar models.**

- Can impose differential constraints from the **maximum mass** and from the **tidal deformability** from **GW170817**



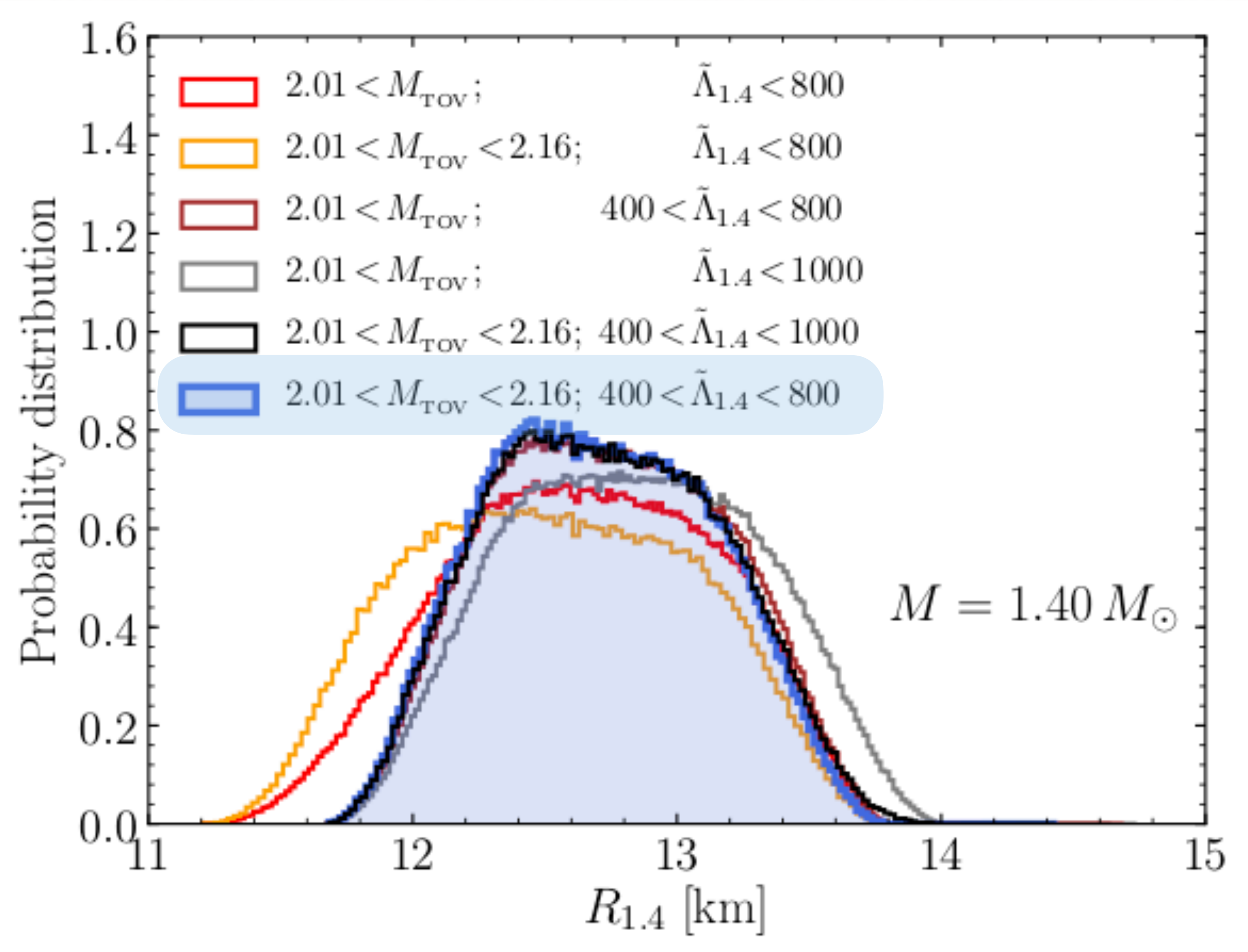
ERM, LW, Rezzolla, Schaffner-Bielich(PRL 2018)

one-dimensional cuts

- Closer look at a mass of $M = 1.40\,M_\odot$
- Can play with different constraints on maximum mass and tidal deformability.
- Overall distribution is very robust

$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$

$$\bar{R}_{1.4} = 12.45\,\mathrm{km}$$



ERM, LW, Rezzolla, Schaffner-Bielich(PRL 2018)

Constraining tidal deformability

- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

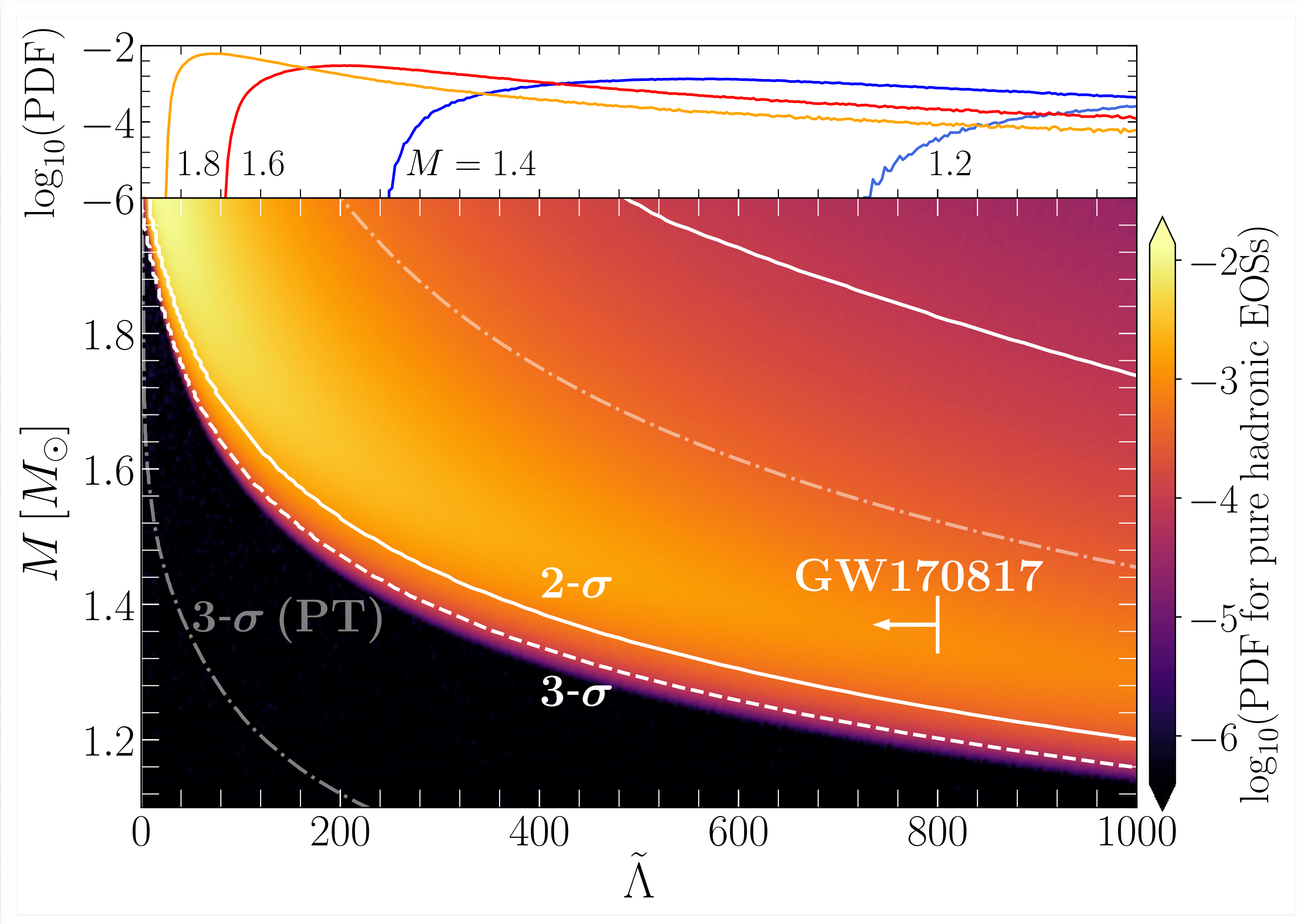
ERM, LW, Rezzolla, Schaffner-Bielich(PRL 2018)

- LIGO has already set upper limit:

$$\tilde{\Lambda}_{1.4} \lesssim 800$$

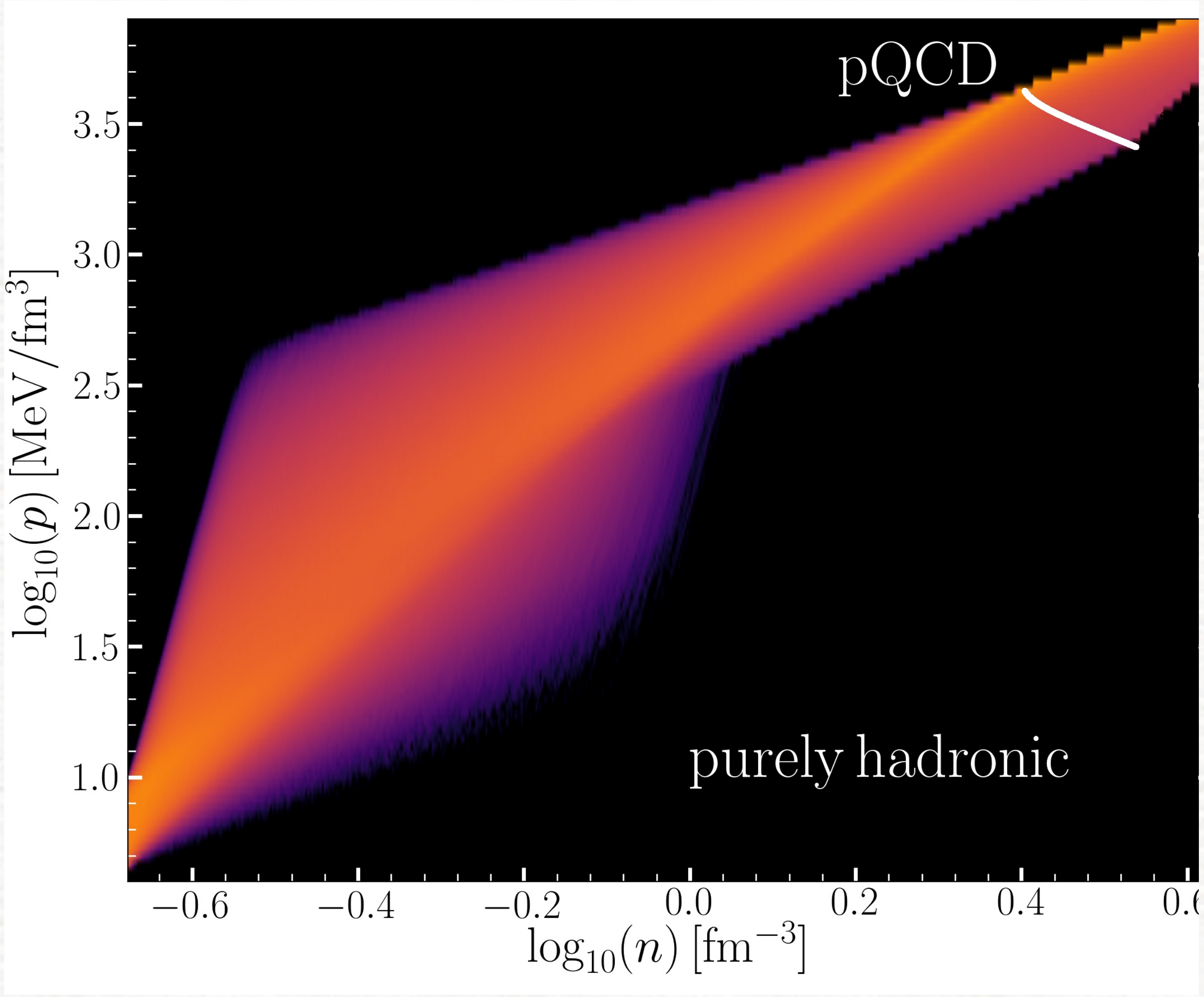
- Our sample naturally sets a lower limit:

$$\tilde{\Lambda}_{1.4} > 375$$



What about phase transitions?

- All EOSs so far are purely hadronic; a conservative but probably **reasonable** assumption.
- What about the possibility of **phase transitions**?
- These are not trivial but not too difficult to model.



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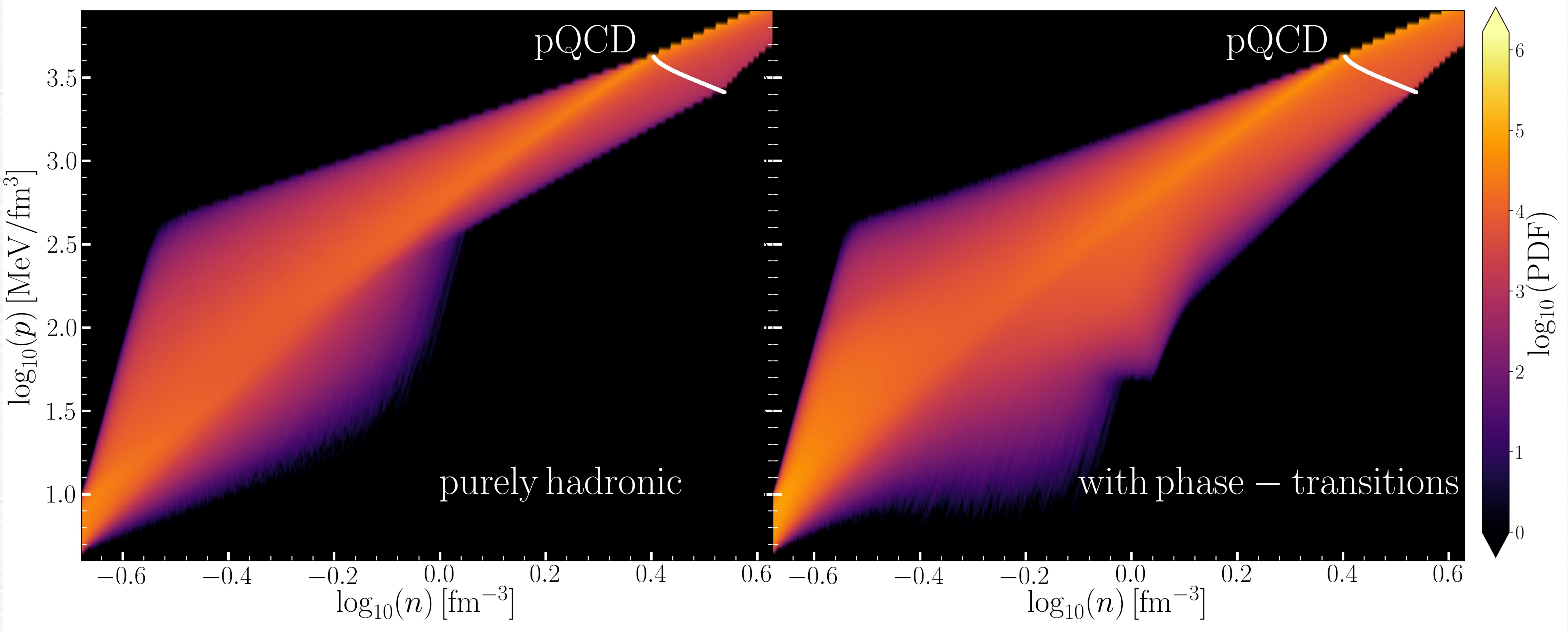
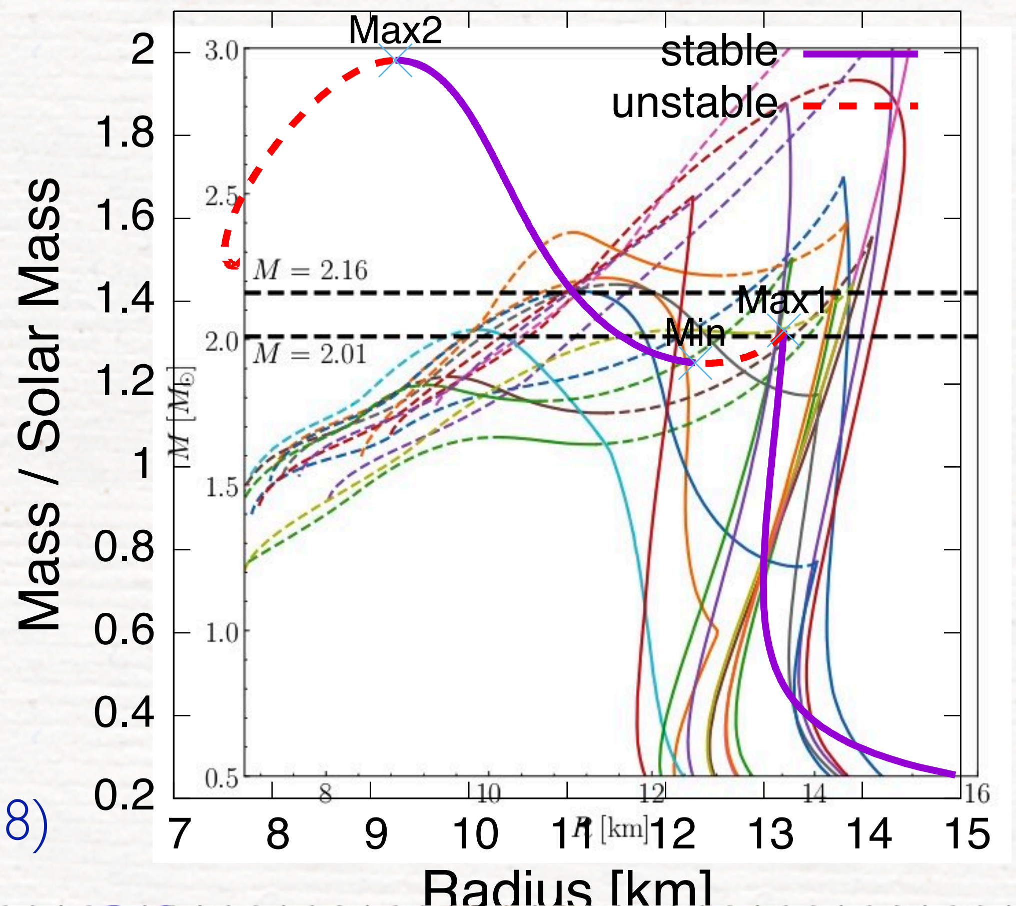


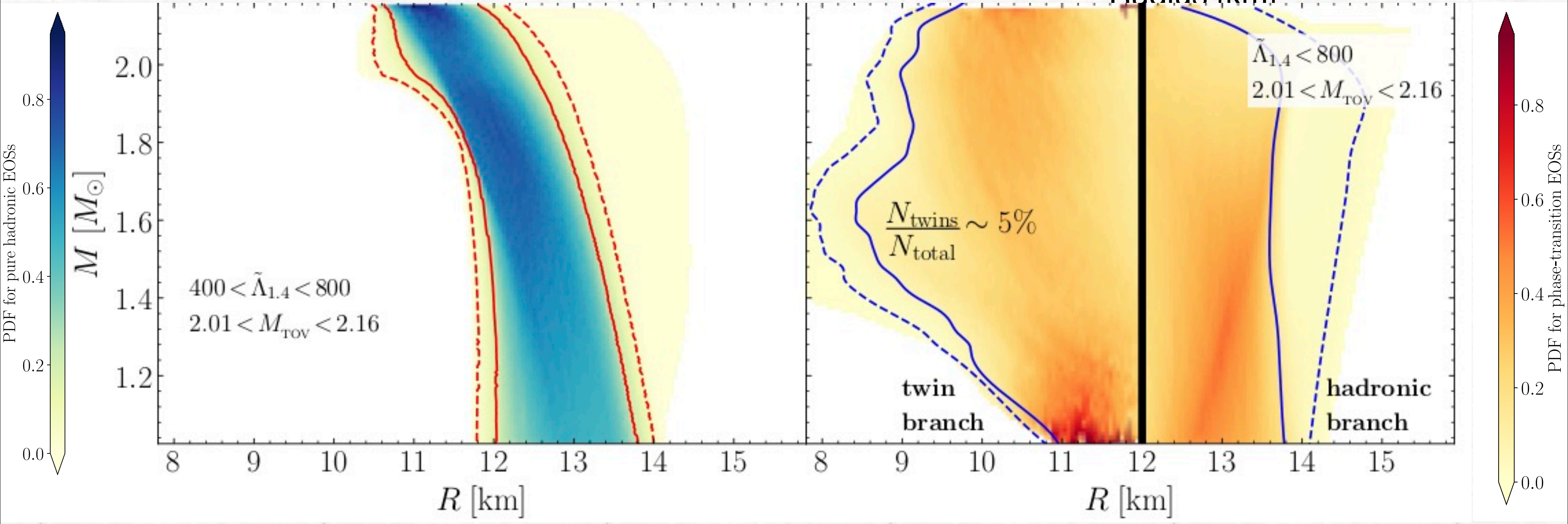
Mass-radius relations

Christian+ (2018)

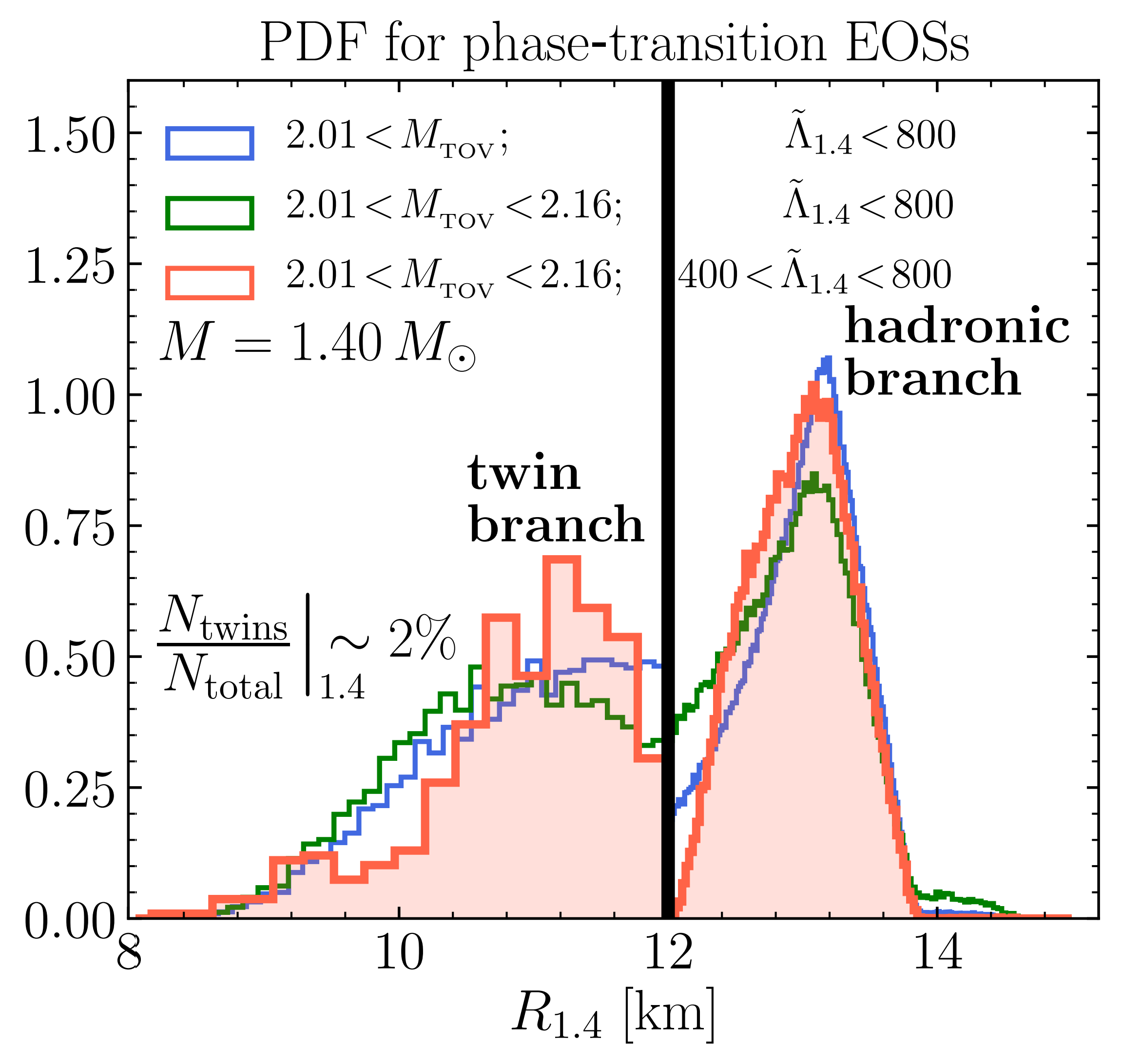
- Presence of a phase transition leads to second stable branch and “**twin-star**” models.

ERM, LW, Rezzolla, Schaffner-Bielich(PRL 2018)





One-dimensional cuts: PTs



Applying all constraints from GW170817:

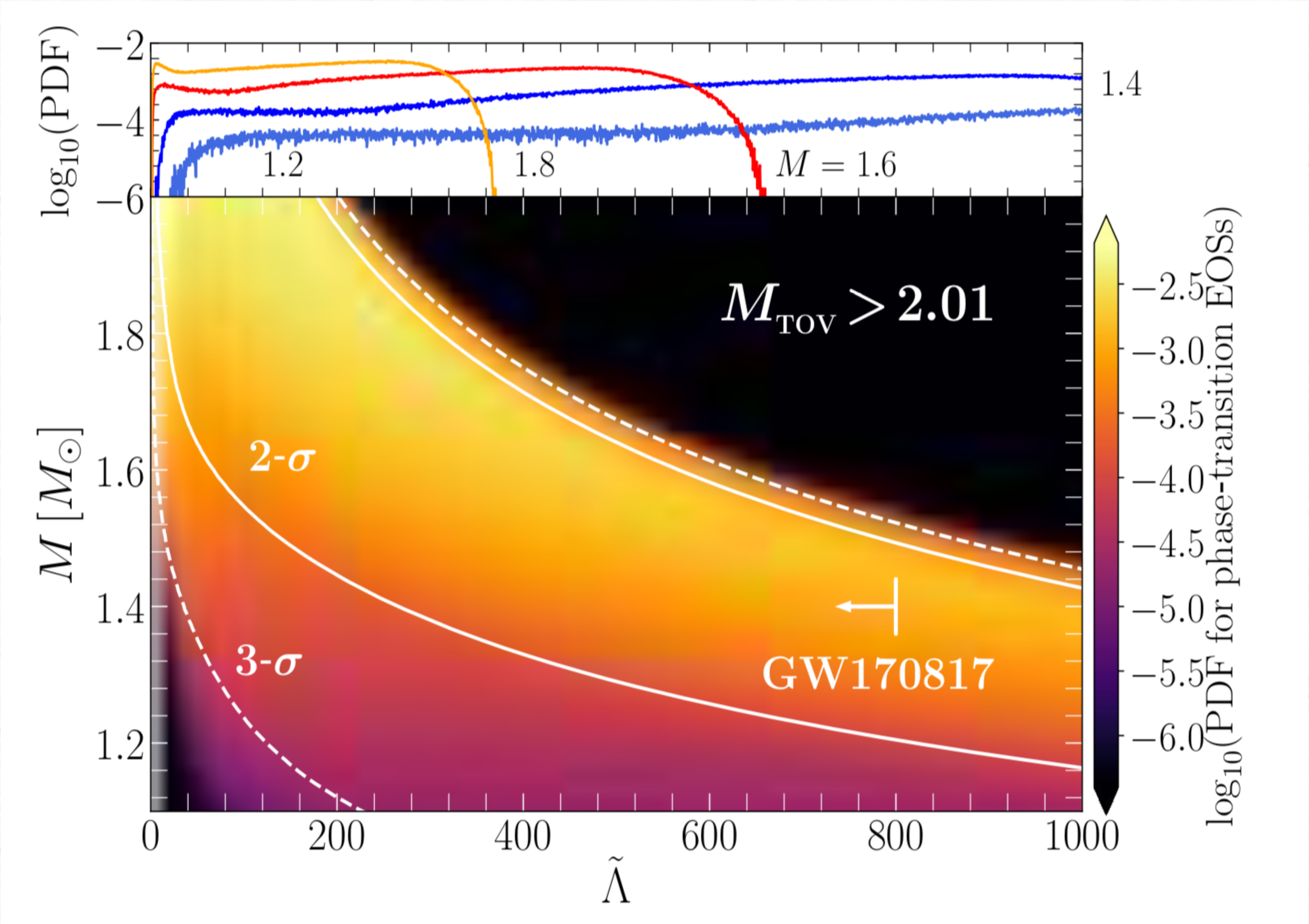
$8.53 < R_{1.4}/\mathrm{km} < 13.74$ $\bar{R}_{1.4} = 13.06\,\mathrm{km}$

phase transitions (with twins)

Constraining tidal deformability: **PT**s

- Can repeat considerations with EOSs having PTs
- Lower limit much weaker: $\tilde{\Lambda}_{1.4} \gtrsim 35$
- Large masses have sharp cut-off on upper limit:

$$\tilde{\Lambda}_{1.7} \lesssim 460$$



GW detection with $\tilde{\Lambda}_{1.7} \sim 700$ would rule out twin stars!

Conclusions from Frankfurt

- ✶**GW170817** provides new limits on **maximum mass** and **radii:**

$$2.01^{+0.04}_{-0.04} \leq M_{\mathrm{TOV}}/M_{\odot} \lesssim 2.16^{+0.17}_{-0.15}$$

$12.00 < R_{1.4}/\mathrm{km} < 13.45$ $\quad \bar{R}_{1.4} = 12.45\,\mathrm{km}$

$8.53 < R_{1.4}/\mathrm{km} < 13.74$ $\quad \bar{R}_{1.4} = 13.06\,\mathrm{km}$

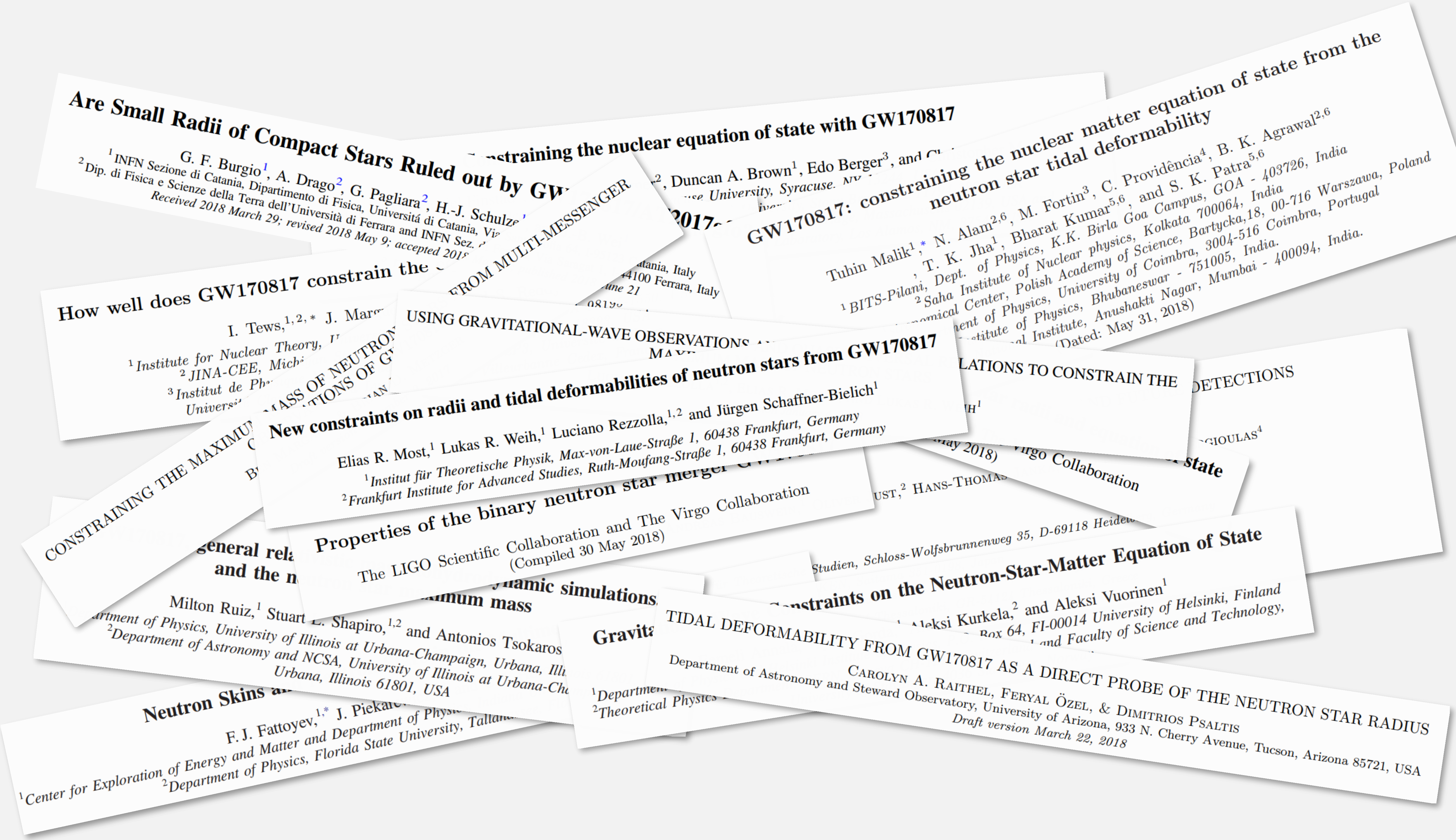
hadronic EOS

phase transitions

$\tilde{\Lambda}_{1.7} \lesssim 460$

Upper limit on deformability can rule out twin stars

A flood of publications



Are Small Radii of Compact Stars Ruled out by GW
G. F. Burgio[1], A. Drago[2], G. Pagliara[2], H.-J. Schulze[1]
[1] INFN Sezione di Catania, Dipartimento di Fisica, Universitá di Catania, Via
[2] Dip. di Fisica e Scienze della Terra dell'Università di Ferrara and INFN Sez.
Received 2018 March 29; revised 2018 May 9; accepted 201
atania, Italy
44100 Ferrara, Italy
une 21

nstraining the nuclear equation of state with GW170817
2, Duncan A. Brown[1], Edo Berger[3], and Ch
use University, Syracuse, NY
2017

GW170817: constraining the nuclear matter equation of state from the neutron star tidal deformability
Tuhin Malik[1,*], N. Alam[2,6], M. Fortin[3], C. Providência[4], B. K. Agrawal[2,6]
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stitute of Physics, Bhubaneswar - 751005, India.
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(Dated: May 31, 2018)

How well does GW170817 constrain the
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[1] Institute for Nuclear Theory, U
[2] JINA-CEE, Mich
[3] Institut de Ph
Universi

FROM MULTI-MESSENGER

CONSTRAINING THE MAXIMUM MASS OF NEUTRON
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USING GRAVITATIONAL-WAVE OBSERVATIONS A
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New constraints on radii and tidal deformabilities of neutron stars from GW170817
Elias R. Most,[1] Lukas R. Weih,[1] Luciano Rezzolla,[1,2] and Jürgen Schaffner-Bielich[1]
[1] *Institut für Theoretische Physik, Max-von-Laue-Straße 1, 60438 Frankfurt, Germany*
[2] *Frankfurt Institute for Advanced Studies, Ruth-Moufang-Straße 1, 60438 Frankfurt, Germany*

Properties of the binary neutron star merger GW17
The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled 30 May 2018)

general rela
and the n
ynamic simulations
ximum mass
Milton Ruiz,[1] Stuart L. Shapiro,[1,2] and Antonios Tsokaros
rtment of Physics, University of Illinois at Urbana-Champaign, Urbana, Illi
[2] *Department of Astronomy and NCSA, University of Illinois at Urbana-Cha*
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Neutron Skins a
F. J. Fattoyev,[1,*] J. Piekare
[1] *Center for Exploration of Energy and Matter and Department of Phys*
[2] *Department of Physics, Florida State University, Tallah*

DETECTIONS
GIOULAS[4]
state
Virgo Collaboration
UST,[2] HANS-THOMA
Studien, Schloss-Wolfsbrunnenweg 35, D-69118 Heide

onstraints on the Neutron-Star-Matter Equation of State
Aleksi Kurkela,[2] and Aleksi Vuorinen[1]
Box 64, FI-00014 University of Helsinki, Finland
and Faculty of Science and Technology,

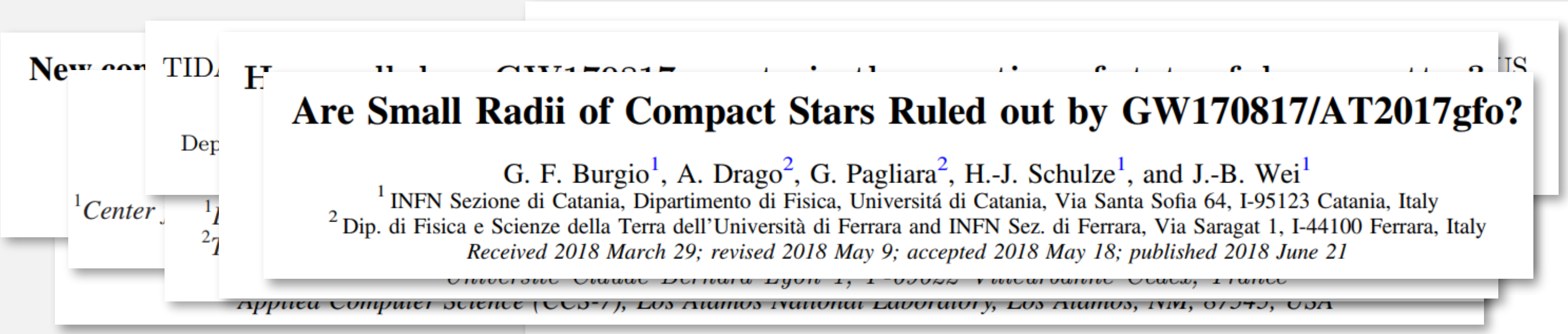
Gravita
[1] *Departme*
[2] *Theoretical Physics*

TIDAL DEFORMABILITY FROM GW170817 AS A DIRECT PROBE OF THE NEUTRON STAR RADIUS
CAROLYN A. RAITHEL, FERYAL ÖZEL, & DIMITRIOS PSALTIS
Department of Astronomy and Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, Arizona 85721, USA
Draft version March 22, 2018

Methods

Statistical

$\tilde{\Lambda} < 800$



Are Small Radii of Compact Stars Ruled out by GW170817/AT2017gfo?

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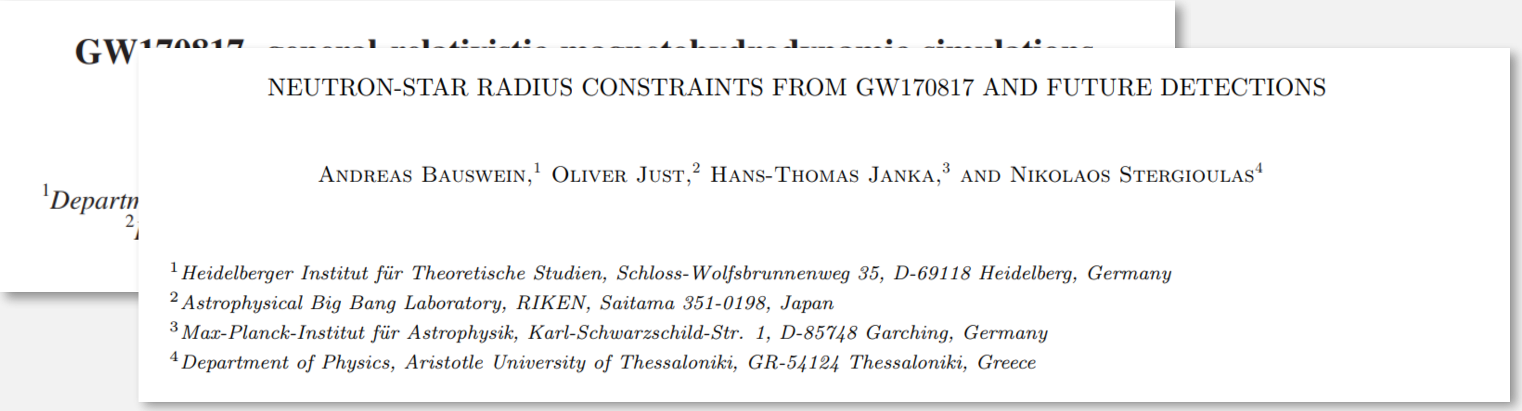
Numerical



NEUTRON-STAR RADIUS CONSTRAINTS FROM GW170817 AND FUTURE DETECTIONS

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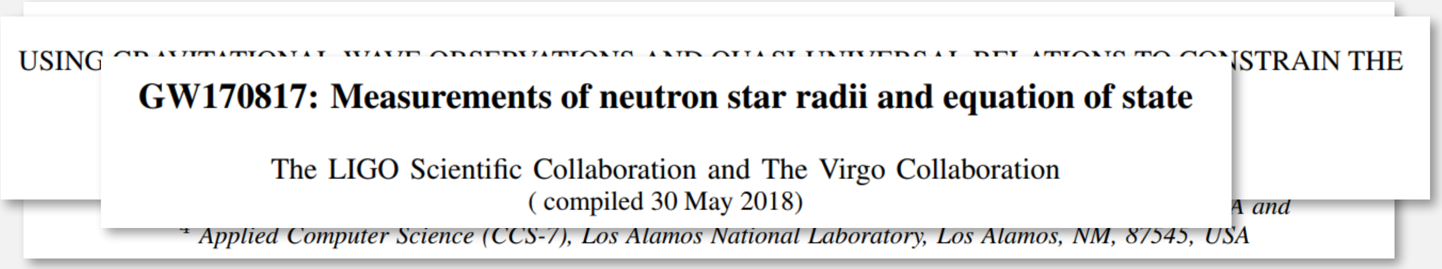
Universal relations



GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration

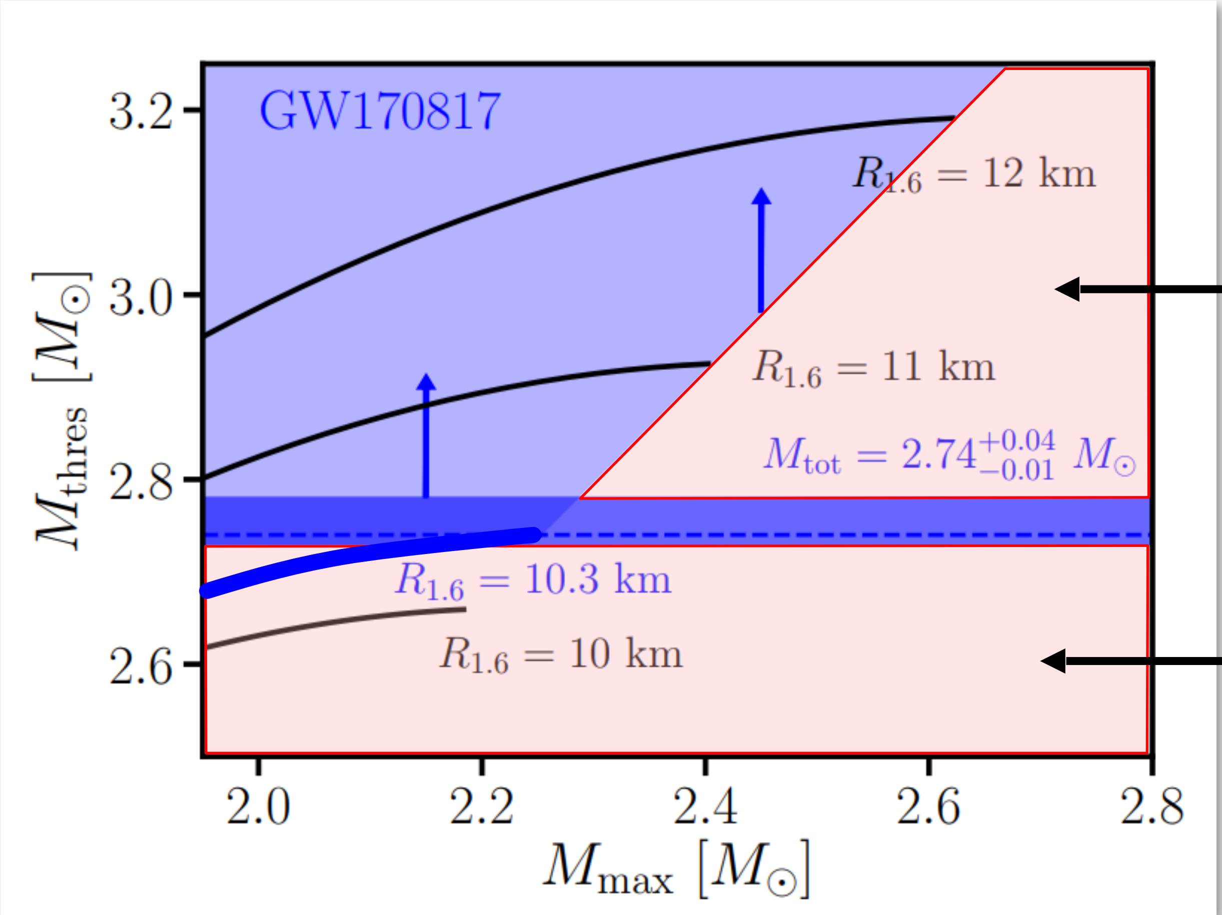
(compiled 30 May 2018)

Comparison to numerical simulations

No prompt collapse → $M_{\rm thres} > M_{\rm tot}^{\rm GW170817} = 2.74^{+0.04}_{-0.01}\ M_\odot$

Comparison with numerical simulations:

$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right)\cdot M_{\rm max}$$

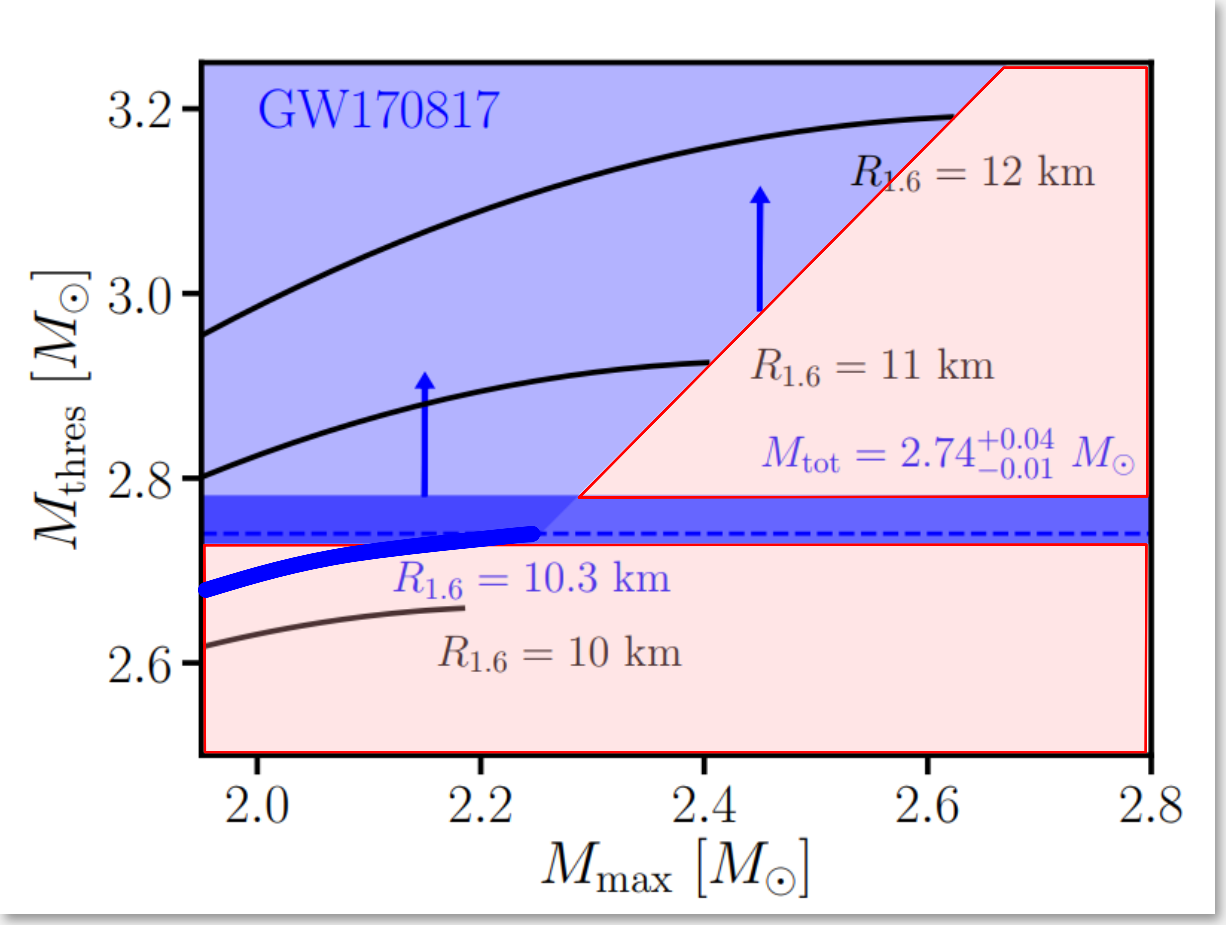


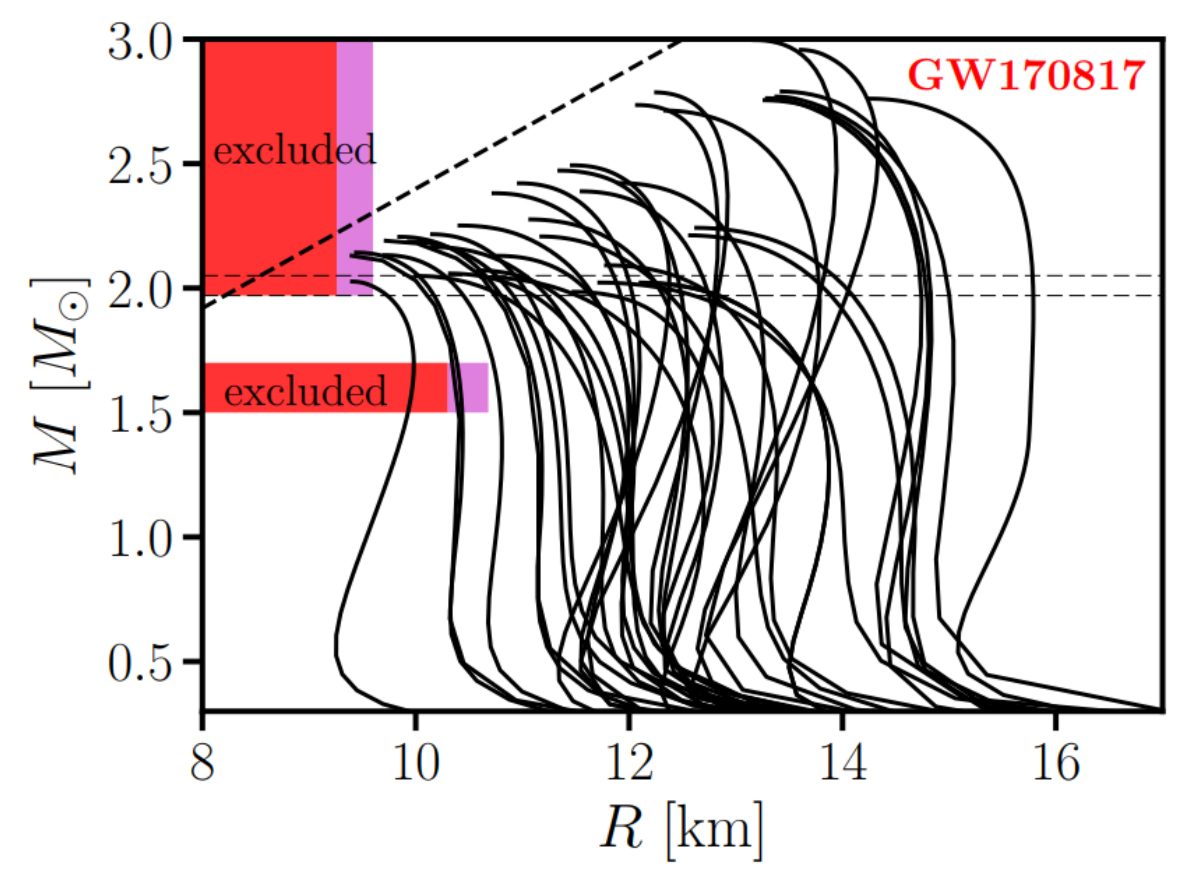
Causailty: $M_{\rm thres} > 1.22 M_{\rm max}$

excluded

Bauswein, Just, Janka, Stergioulas (2017)

Comparison to numerical simulations





Bauswein, Just, Janka, Stergioulas (2017)

Comparison to numerical simulations

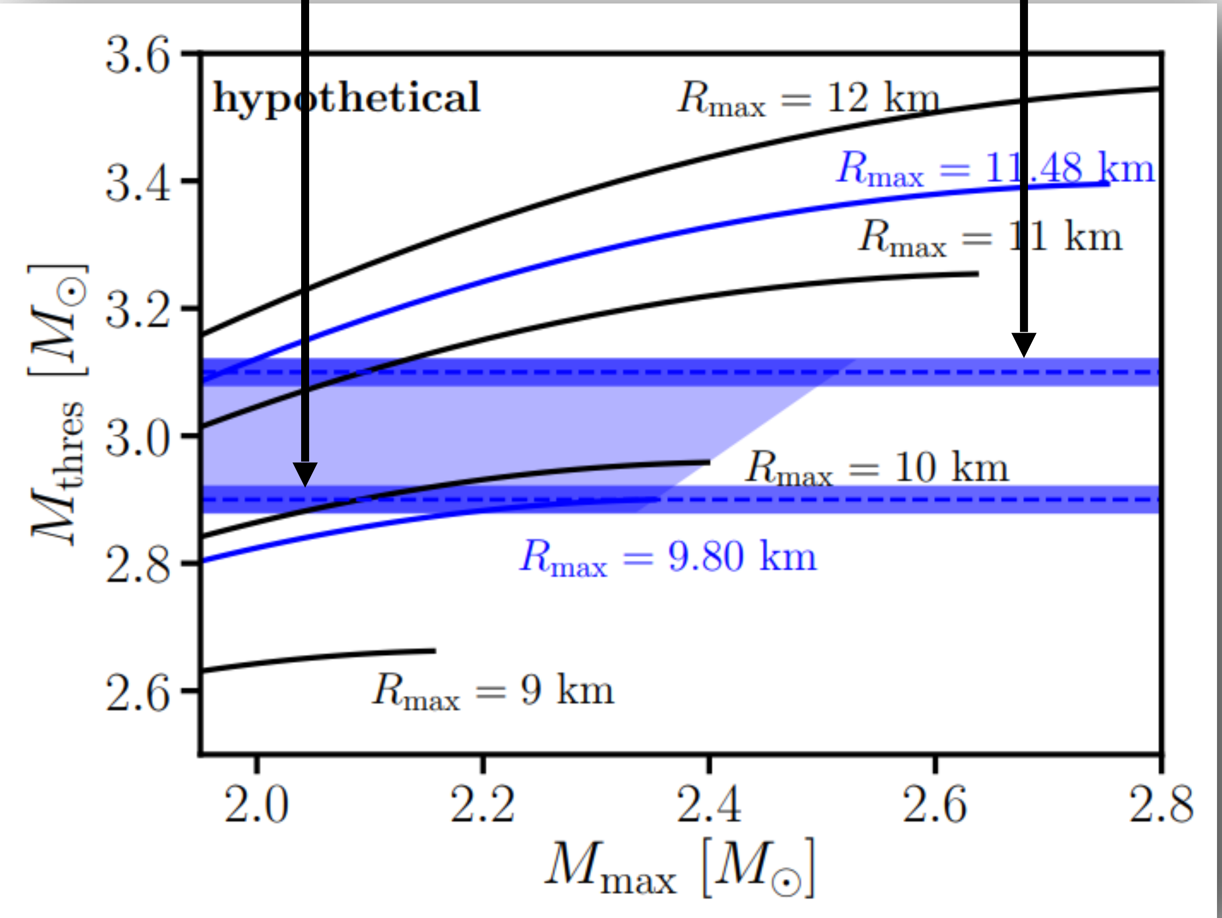
$$M_{\mathrm{thres}} = \left(-3.606 \frac{G M_{\mathrm{max}}}{c^2 R_{1.6}} + 2.38 \right) \cdot M_{\mathrm{max}}$$

1. Only purely hadronic EOSs
2. Not dereived in full GR: error at least 5%

Need more precise equation

3.1M_{tot}, no prompt collapse

2.9M_{tot}, prompt collapse



Bauswein, Just, Janka, Stergioulas (2017)

Universal relations (+ statistics)

STEP 1

- Chirp mass: $\mathscr{M}_{\text{chirp}} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = 1.188 M_\odot$
- Mass ratio: $q = m_1/m_2 = 0.7 - 1$
- Symmetric deformability: $\Lambda_s = (\Lambda_1 + \Lambda_2)/2$
- Asymmetric deformability: $\Lambda_a = (\Lambda_1 - \Lambda_2)/2$
- EOS-independent (universal) relation #1: $\Lambda_a = \Lambda_a(\Lambda_s, q)$
- EOS-independent (universal) relation #2: $\Lambda = \Lambda(C)$ with compactness $C = M/R$

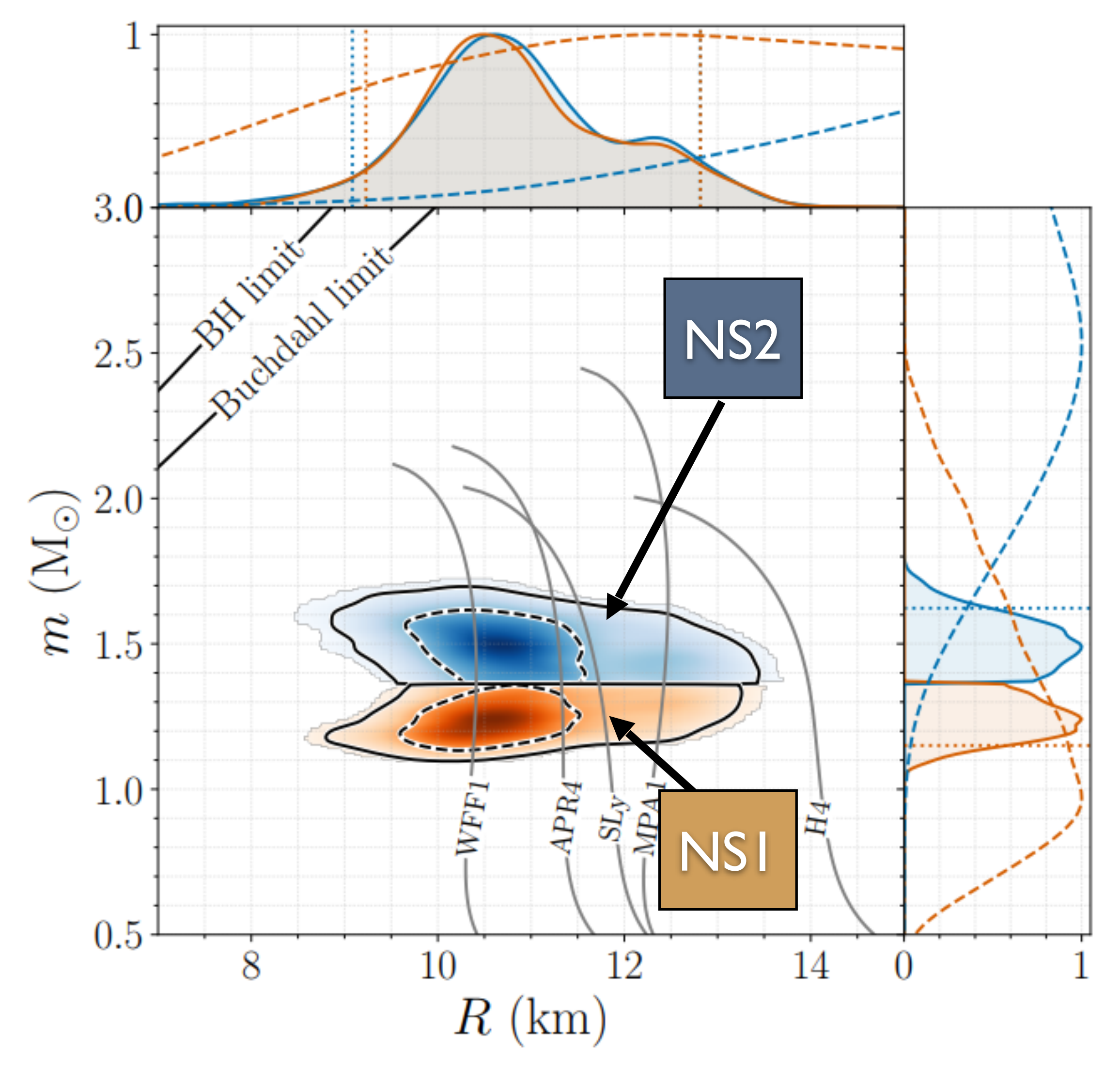
STEP 2

- Sample $\Lambda_s \in [0,5000]$
- Compute $\Lambda_a(\Lambda_s, q)$ to obtain Λ_1 and Λ_2
- Compute $\Lambda_{1,2}$ by inverting $\Lambda_{1,2} = \Lambda_{1,2}(C_{1,2})$

See **Ligo/Virgo (2018) arXiv:1805.1158**

(De, Finstad, Lattimer, Brown, Berger, Biwer arXiv1804.08583)

Universal relations (+ statistics)



Ligo/Virgo (2018) arXiv:1805.1158

NS1: $9.1 < R_1 < 12.8$ (90%)

NS2: $9.2 < R_2 < 12.8$ (90%)

Include $M_{max} > 2.01 M_{sun}$ constraint:

$10.5 < R_1 \sim R_2 \sim R_{1.4} < 13.3$ (90%)

Summary

Statistical

$\boxed{12.0 > R_{1.4} > 13.5}$

(and many others)

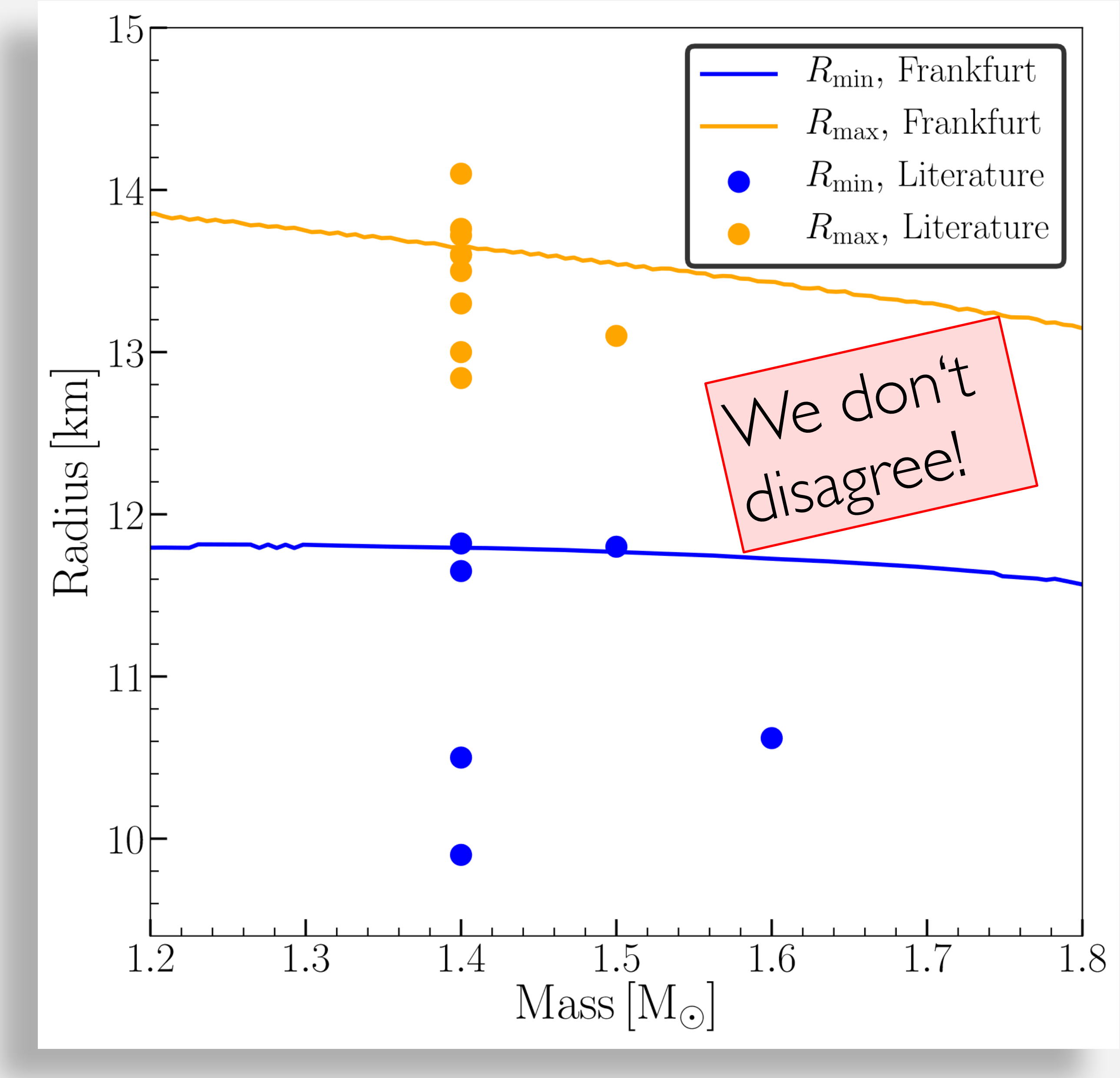
Numerical

$\boxed{10.6 < R_{1.6} \sim R_{1.4}}$

Universal relations

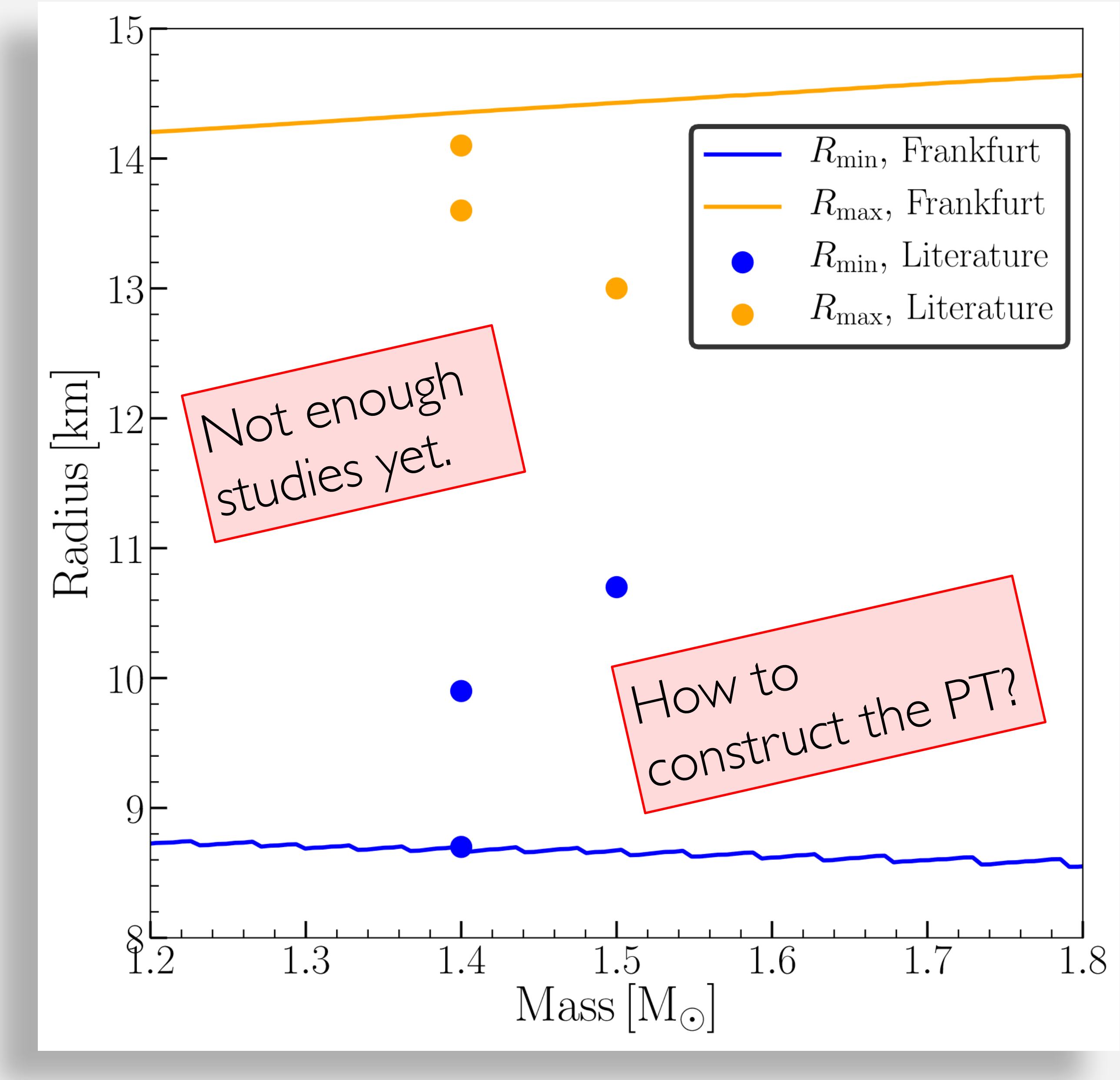
$\boxed{10.5 < R_1 \sim R_2 \sim R_{1.4} < 13.3}$

Summary



We don't disagree!

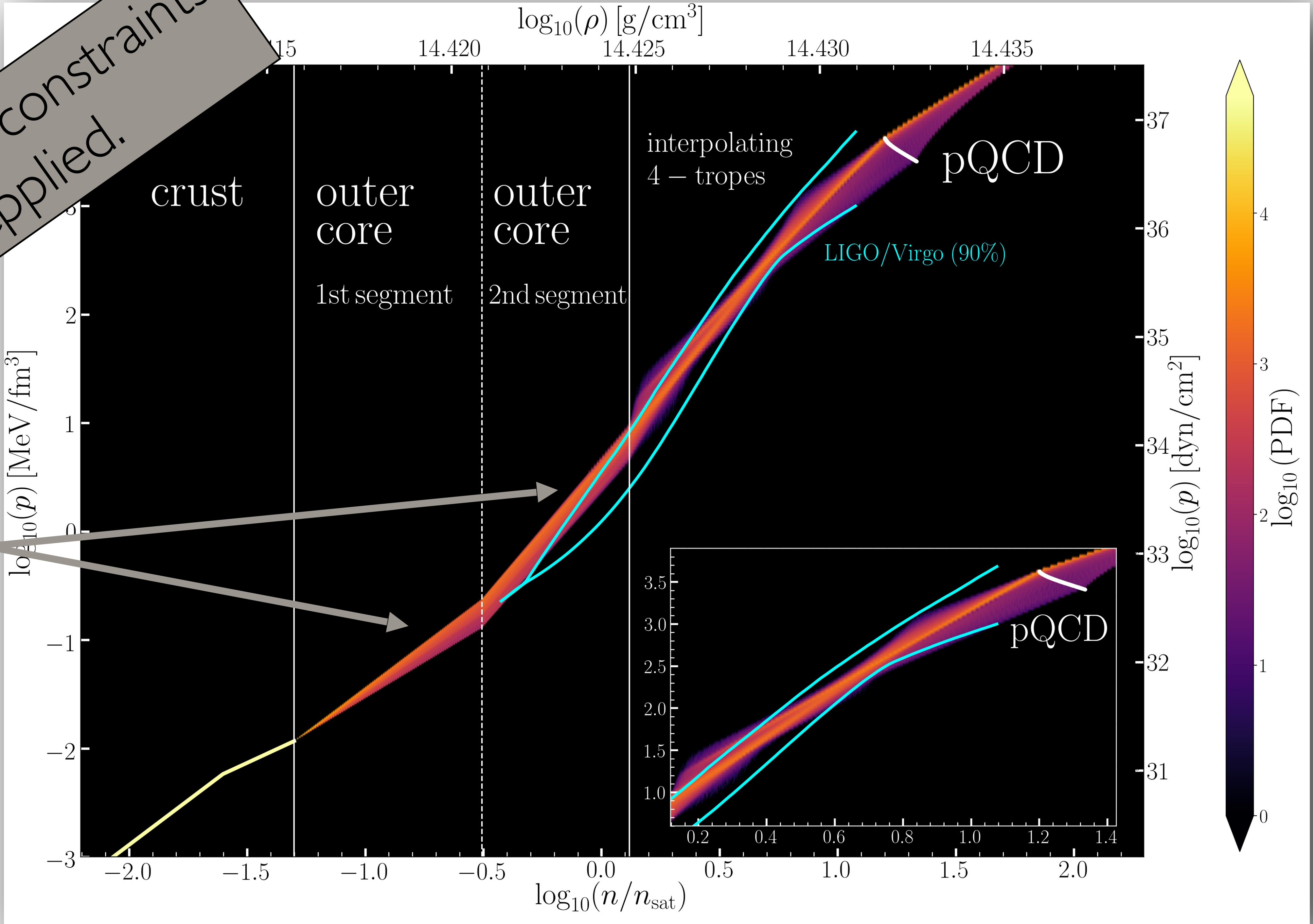
What about phase-transitions?



Not enough studies yet.

How to construct the PT?

So what about the EOS?

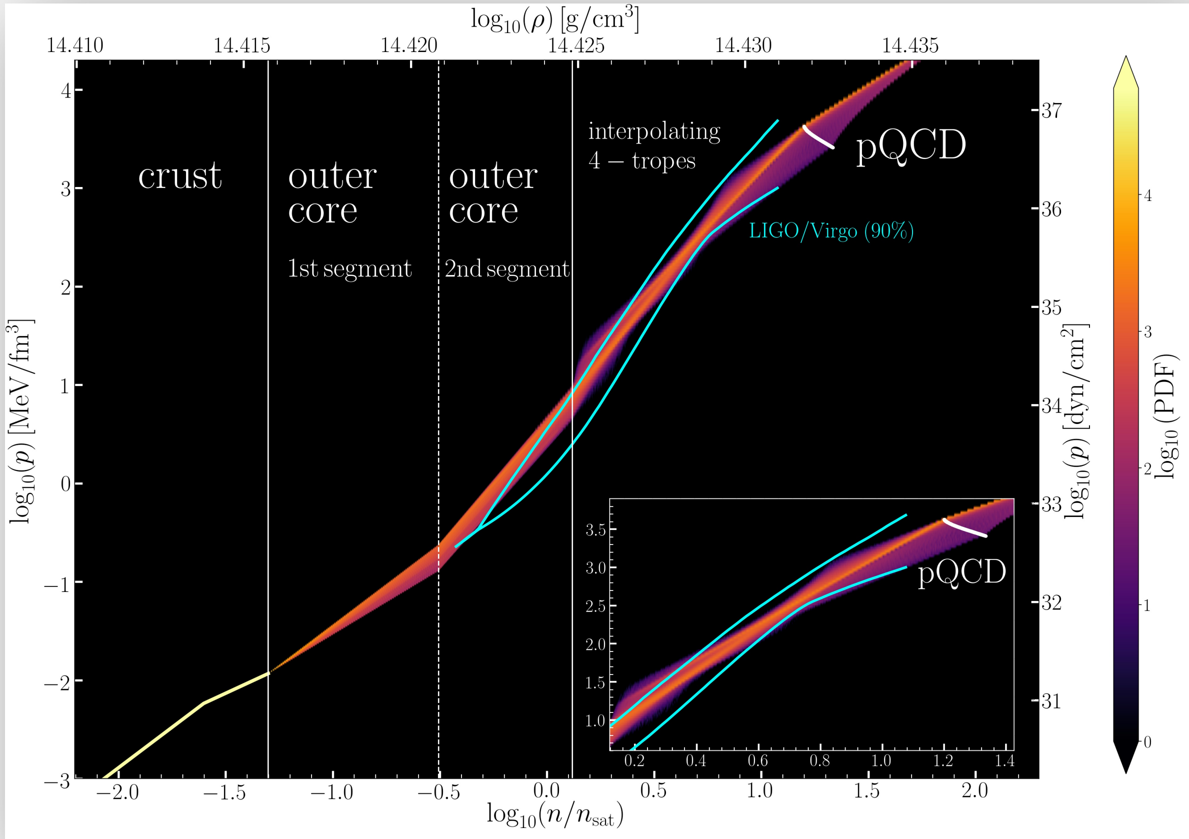


All constraints applied.

Outer core determines radius

Summary

FROM ONLY ONE MULTI-MESSENGER SIGNAL



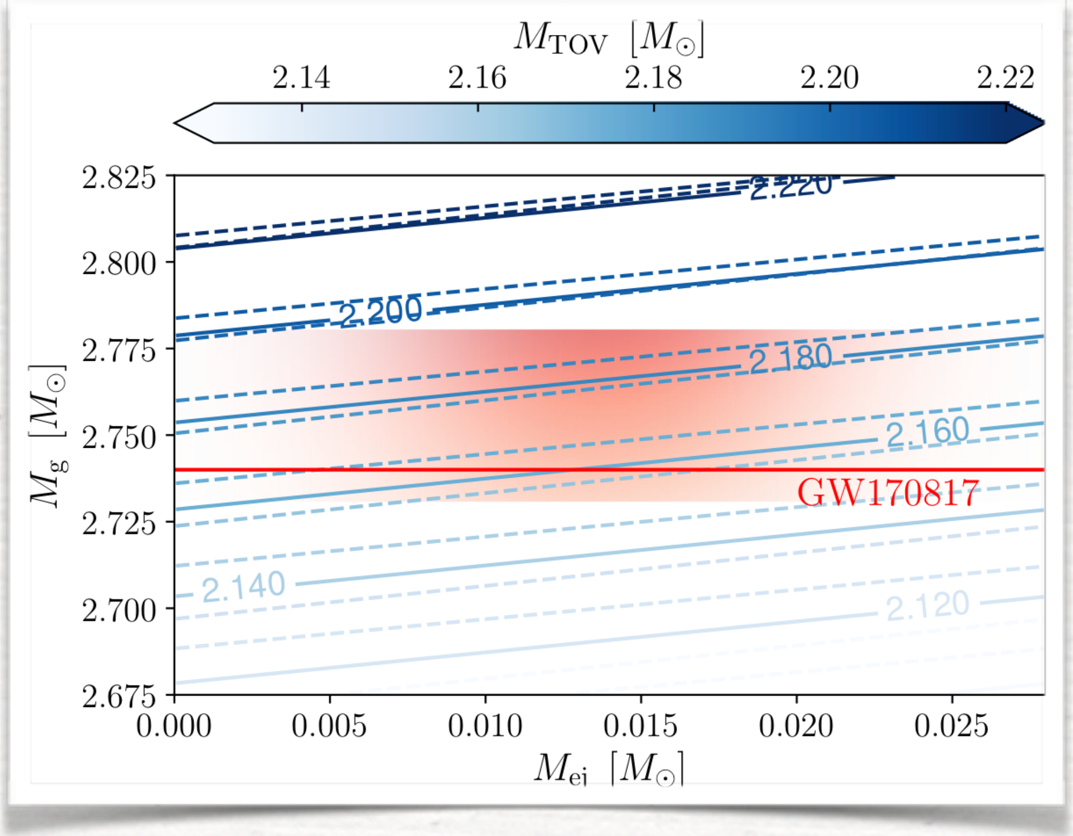
<u>Different approaches yield the same results:</u>

- $M_{max} < 2.2 M_{sun}$
- $10\ (12) > R_{1.4} > (13.5)\ 14$
- No tight limits for EOS with phase transition

BUT: could be destinguished via tidal deformability

<u>To-Do:</u>
How does this compare to constraints from X-ray observations?

Summary



- GW170817 has helped to improve our knowledge of **maximum masses** and **radii** of neutron stars

- Future **multimessenger observations** will help to even more narrow down uncertainties of neutron star properties and will help to unravel the **EOS**

< 50 per year