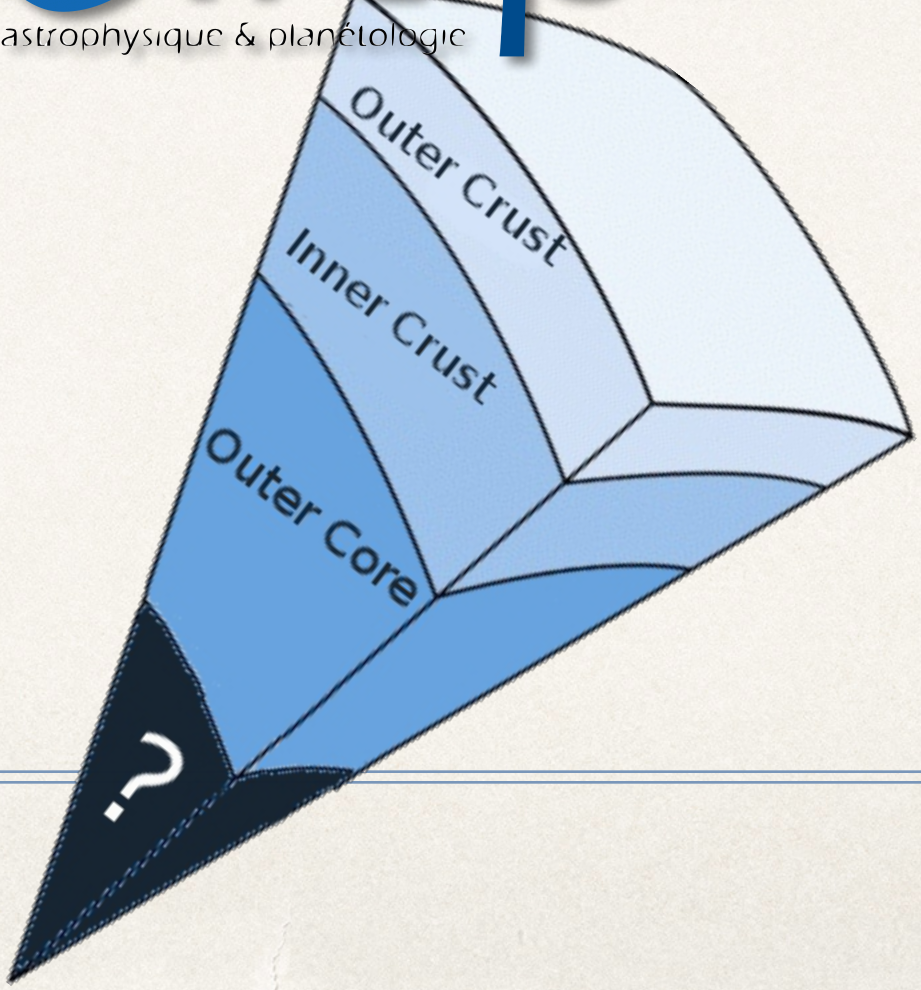
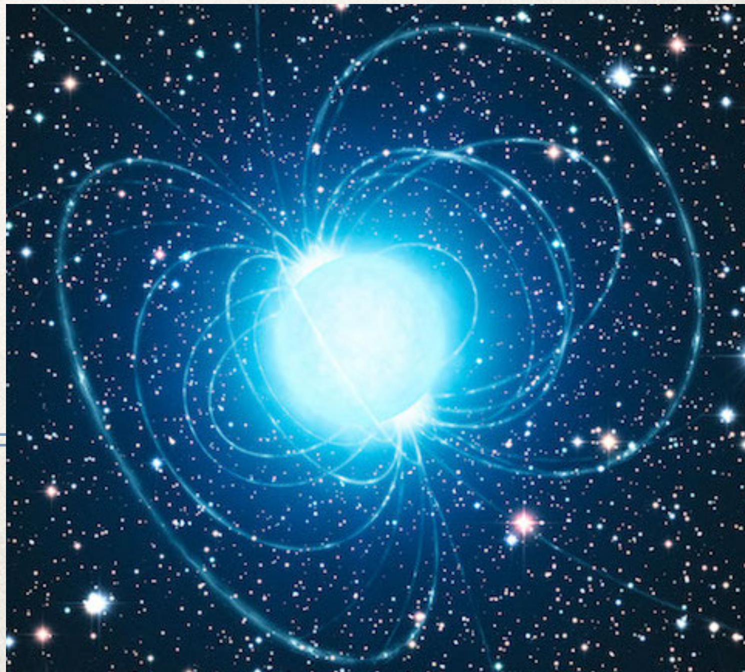
GW and EM observations of neutron stars to constrain dense matter

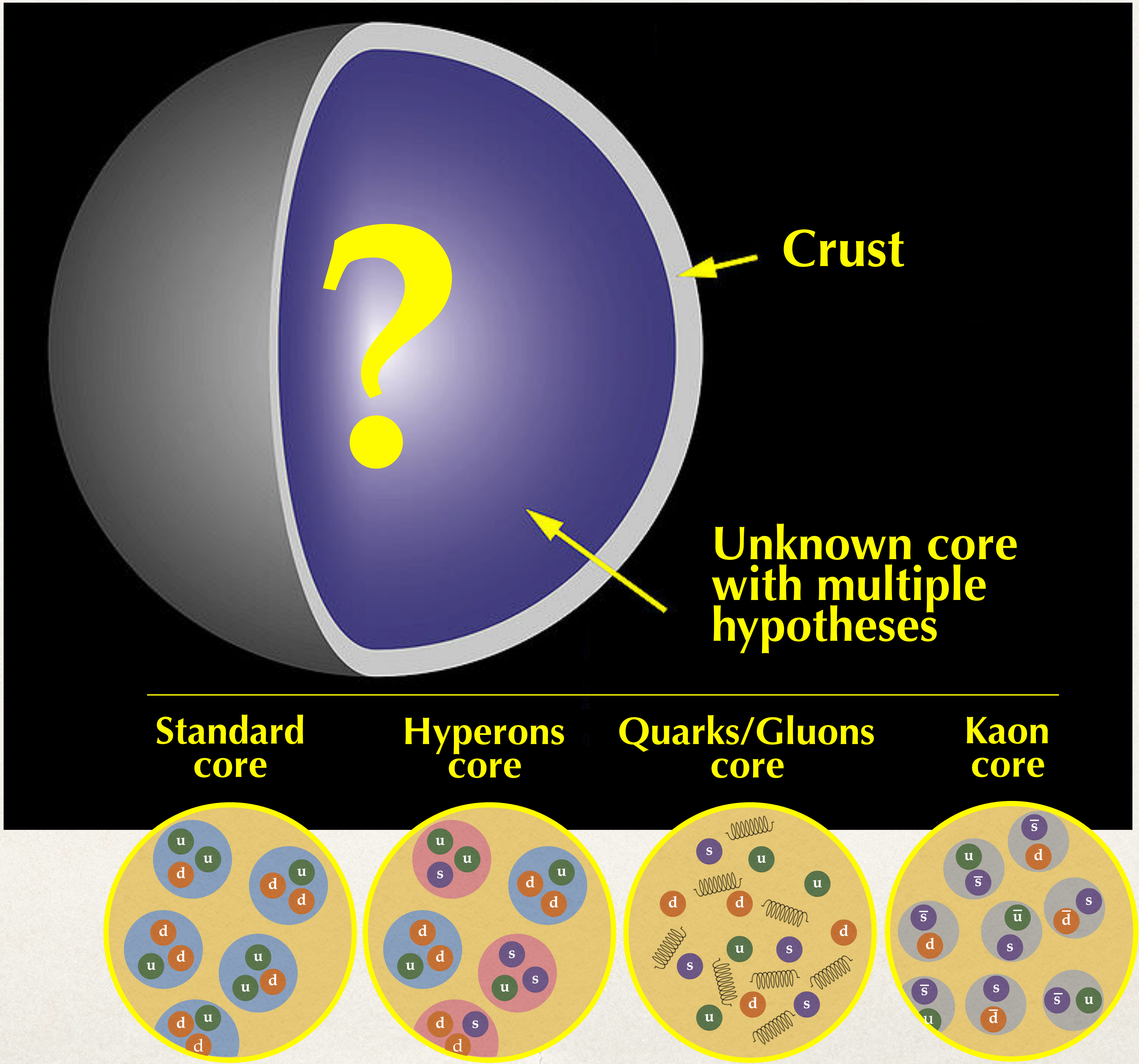
Sebastien Guillot

Institut de Recherche en Astrophysique et Planétologie

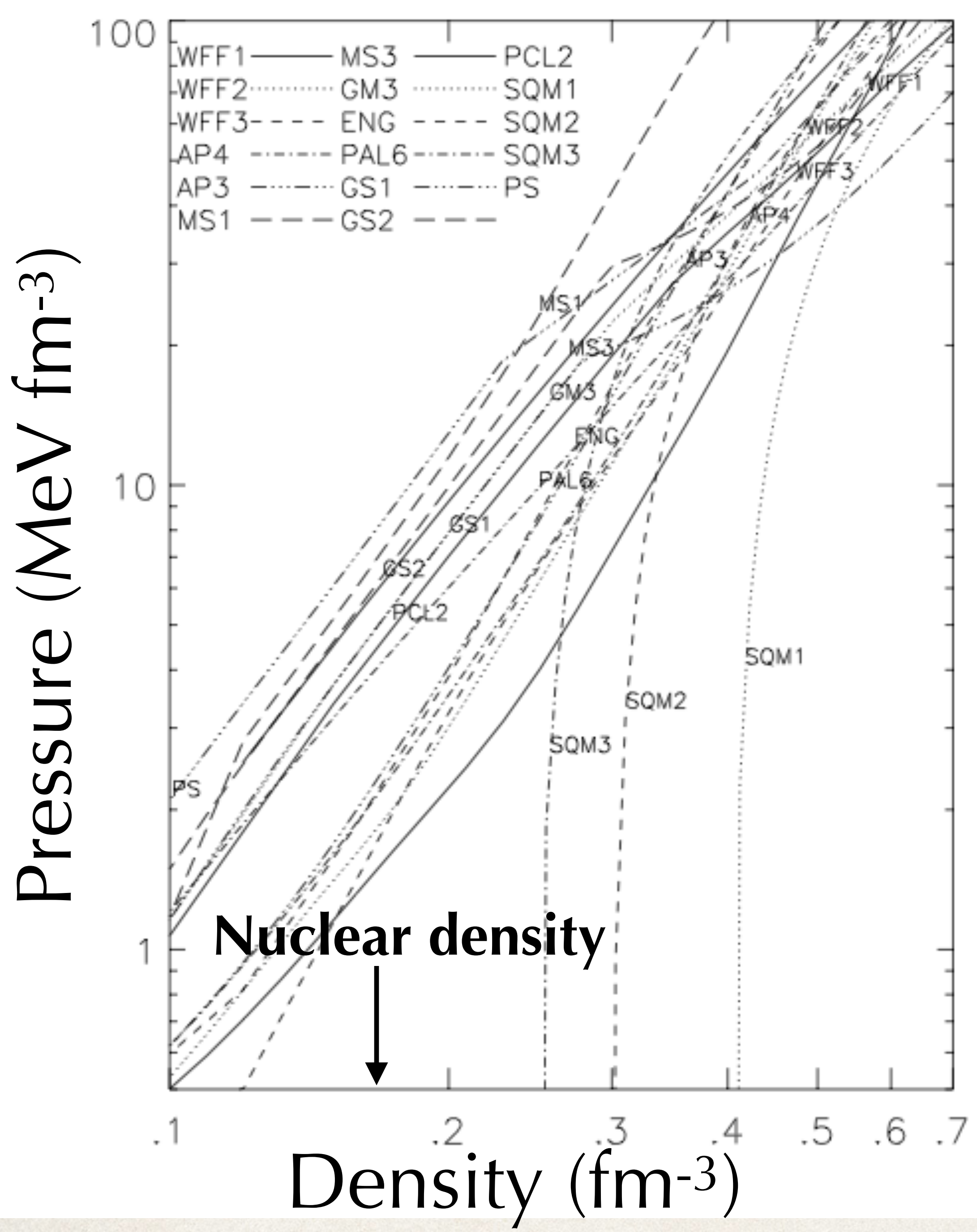




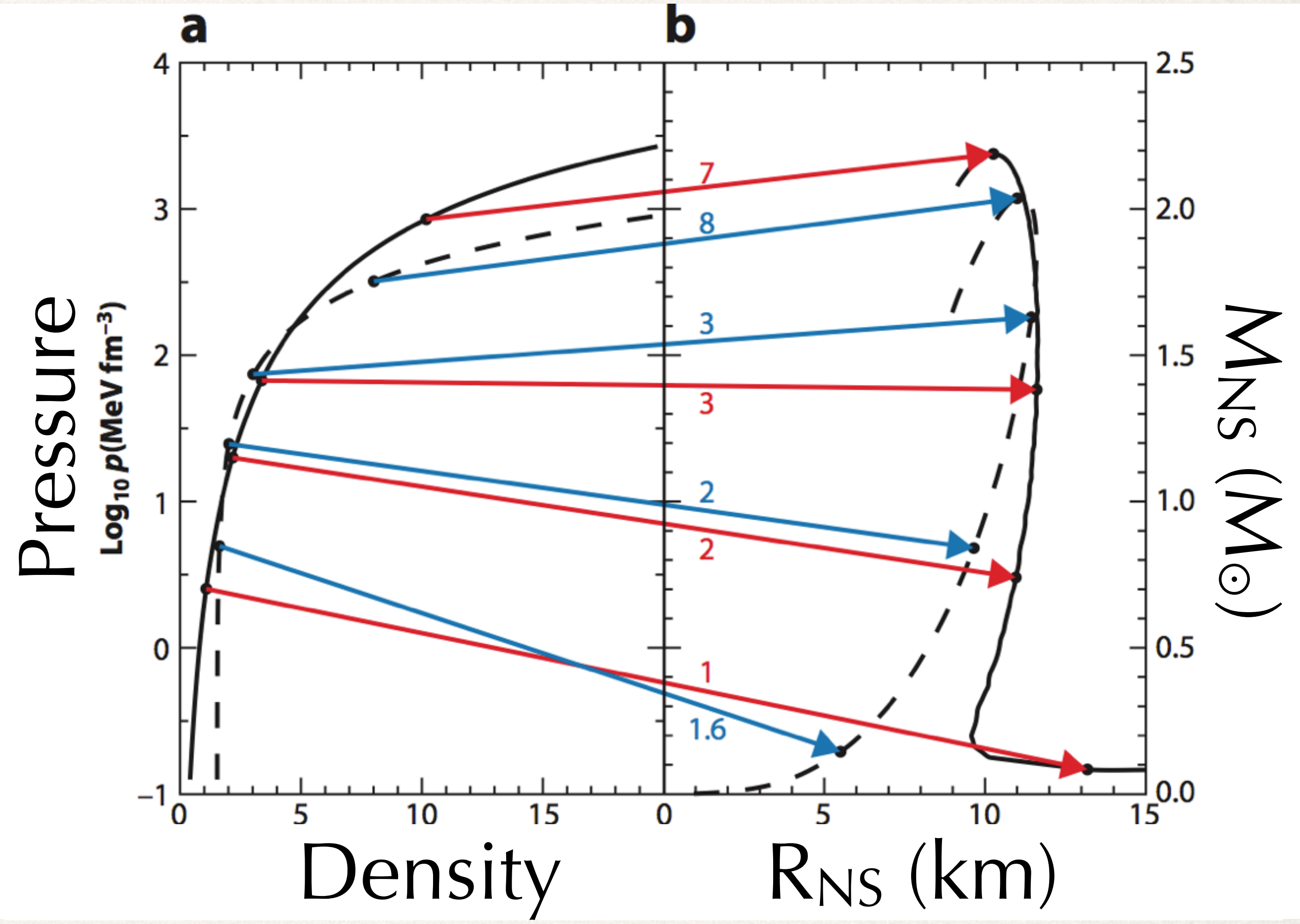
Prologue: The internal structure of neutron stars is still unknown and numerous theories are proposed, with important implications for (astro)physics.



Prologue: Understanding dense matter requires determining the equation of state beyond nuclear density.



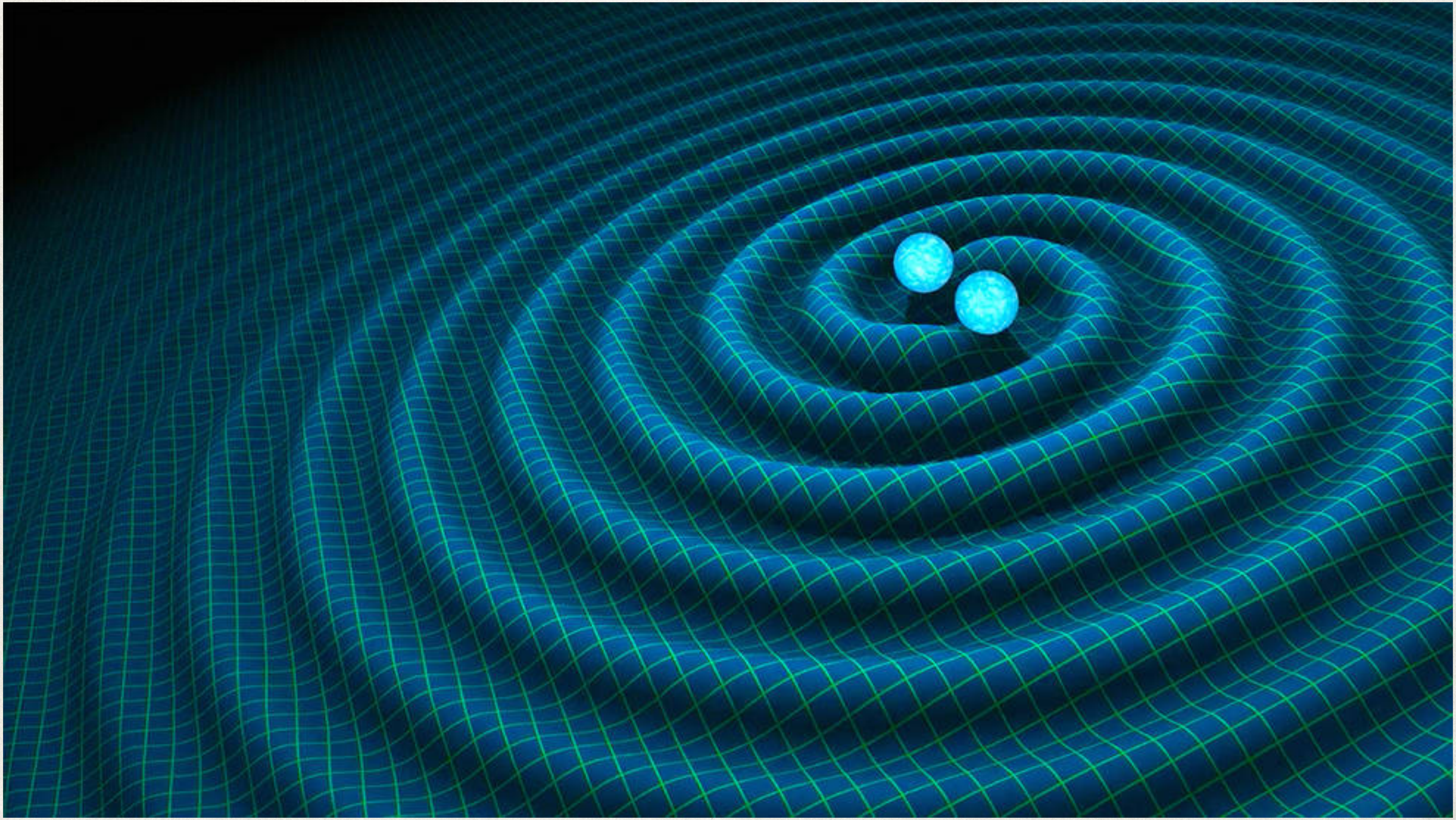
Lattimer and Prakash 2001



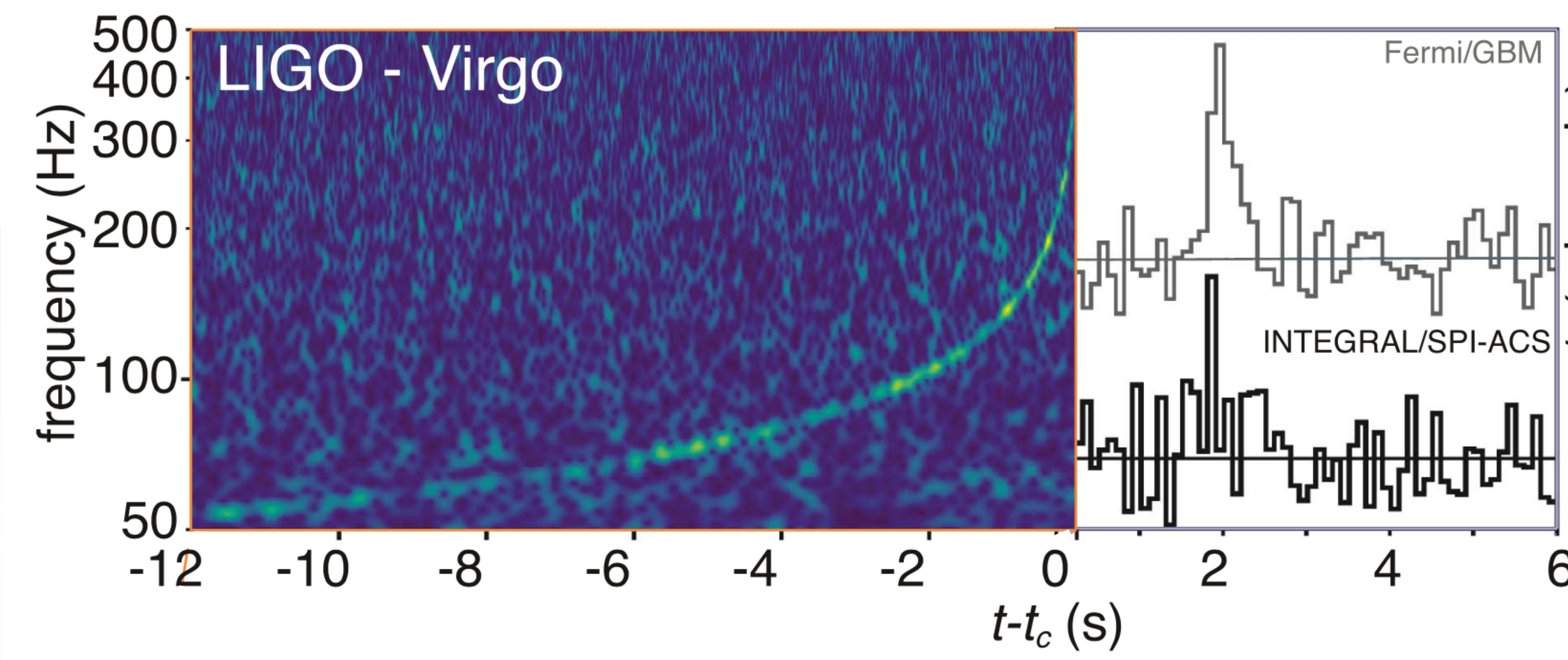
Macro properties of neutron stars:

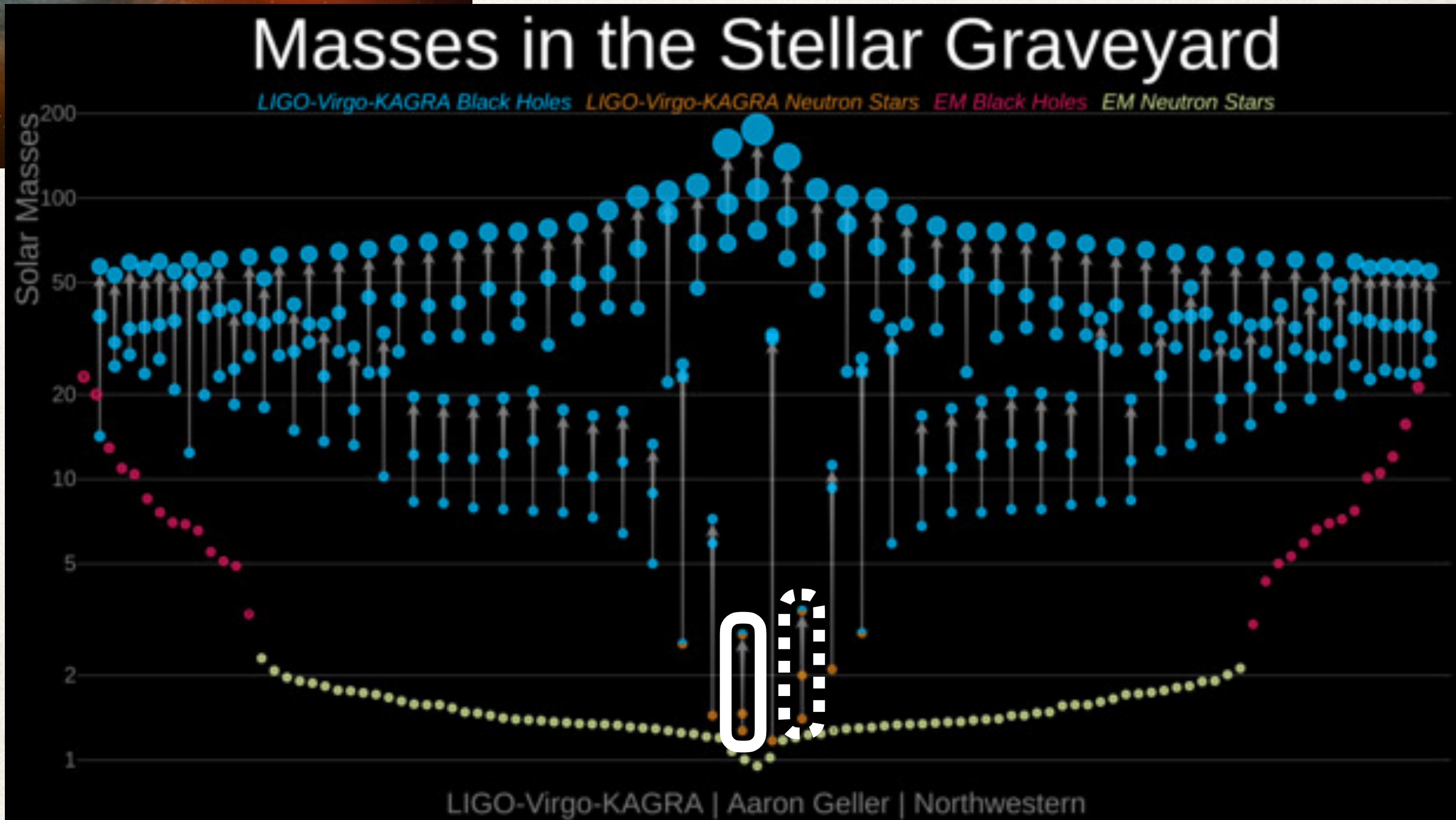
M_{NS}, R_{NS}, Λ_{NS}, I_{NS}

GW observations of neutron stars to constrain dense matter



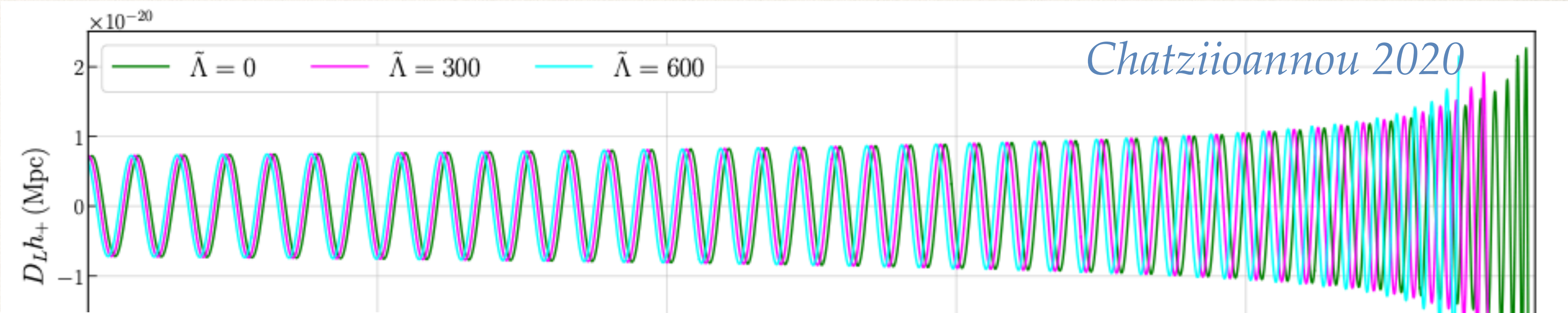
GW 170817



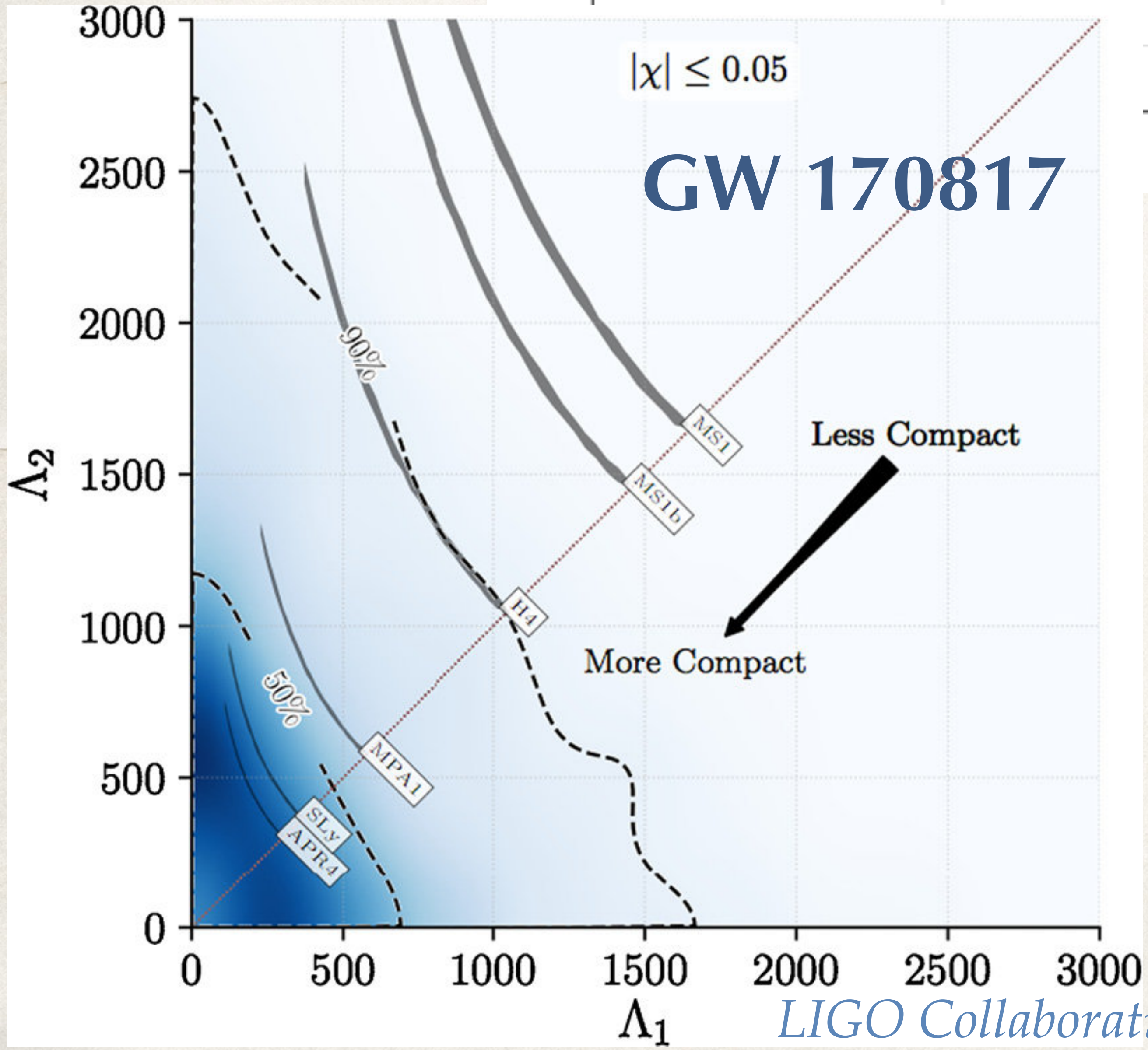


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

In addition to the masses, the gravitational wave signals hides information about the tidal deformability (and therefore on the neutron star radii).



Chatziioannou 2020

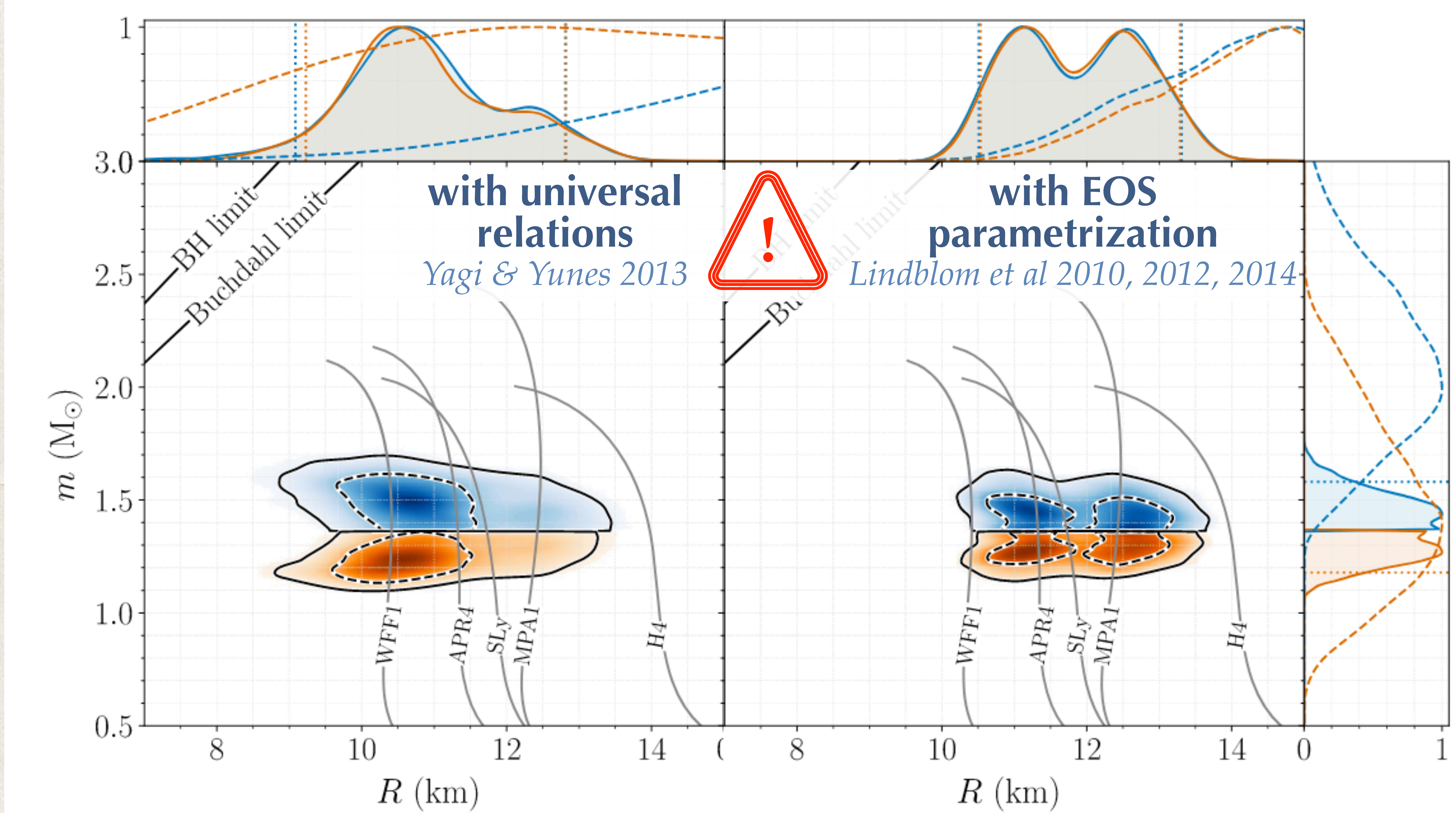


GW 170817

LIGO Collaboration 2018

The pre-merger frequency increases faster for large $\tilde{\Lambda}$

In addition to the masses, the gravitational wave signals hides information about the tidal deformability (and therefore on the neutron star radii).



with universal relations

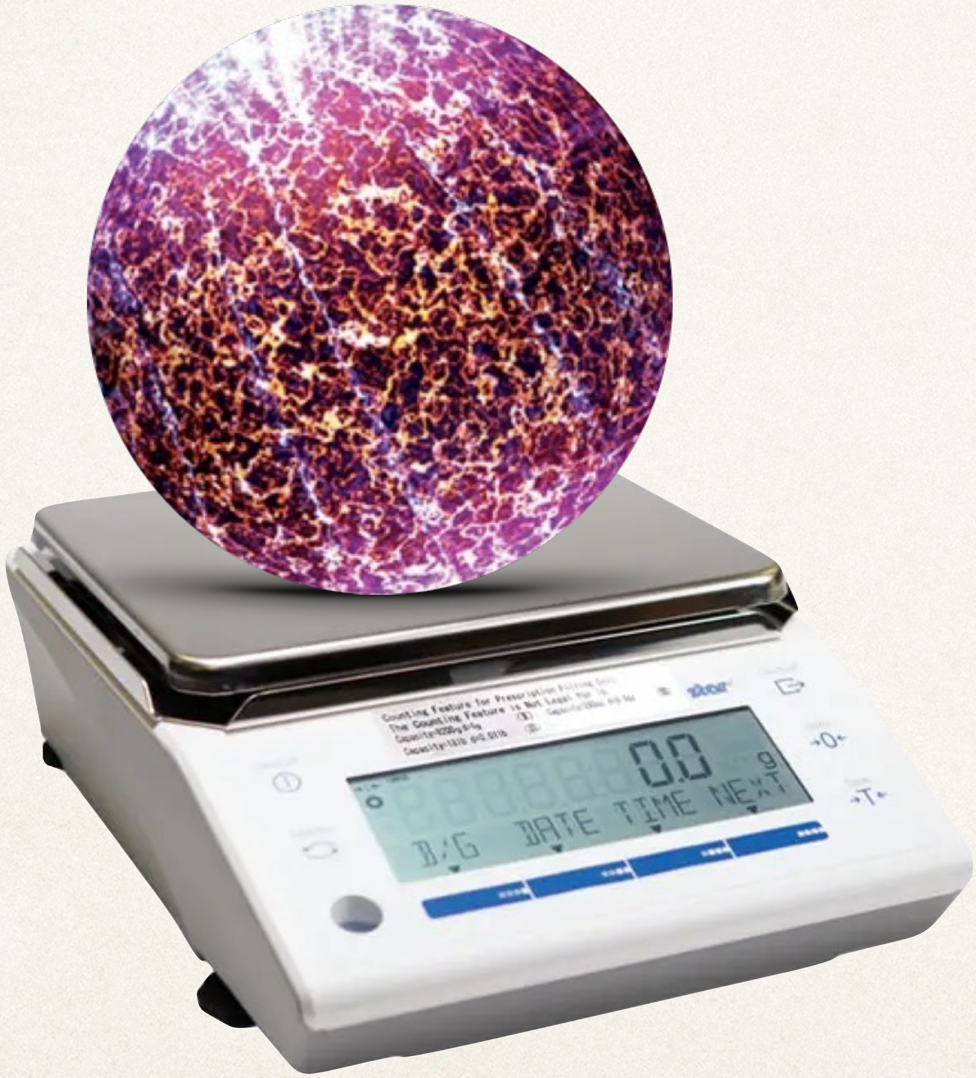
Yagi & Yunes 2013

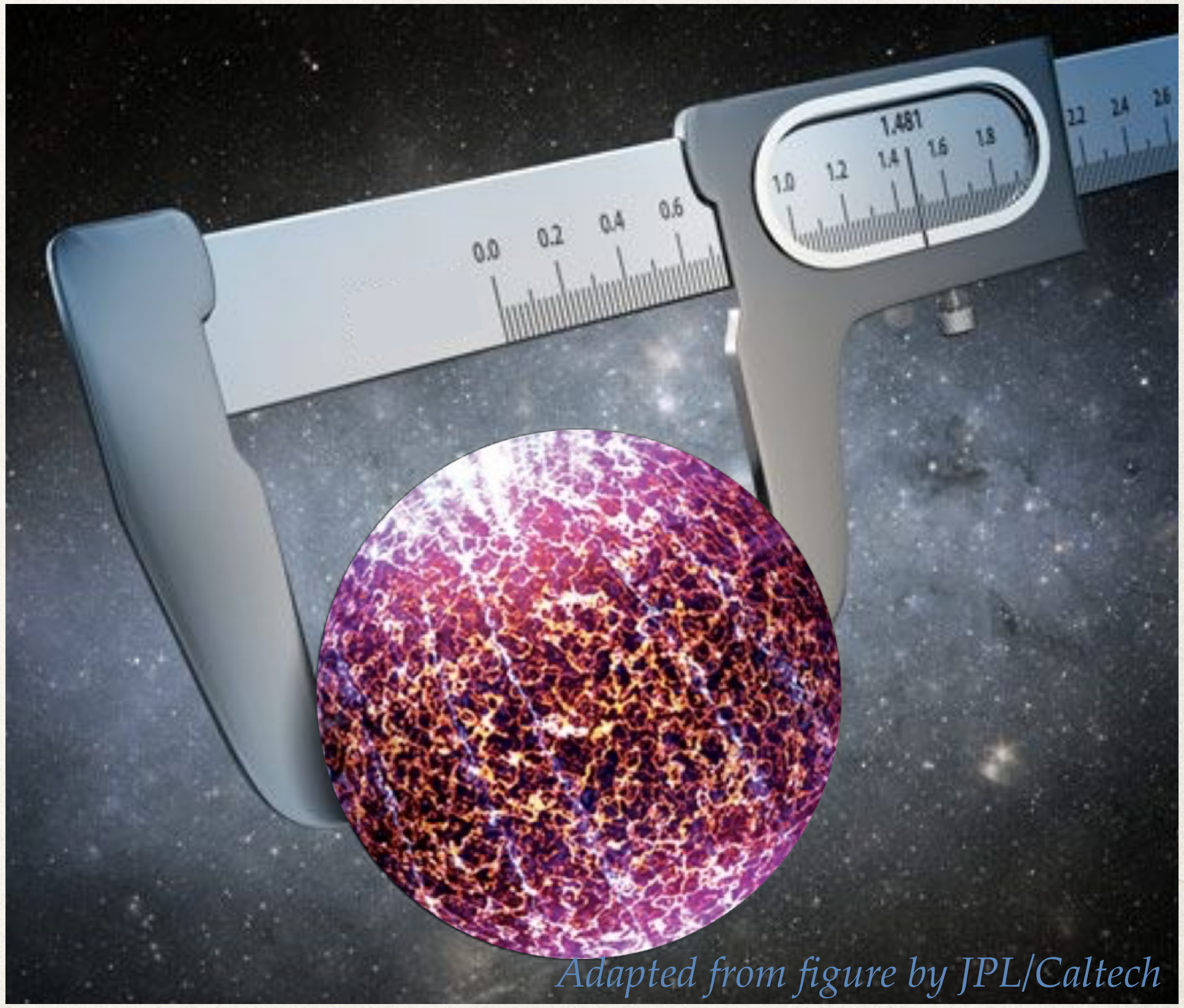
with EOS parametrization

Lindblom et al 2010, 2012, 2014

LIGO Collaboration 2018

EM observations of neutron stars to constrain dense matter



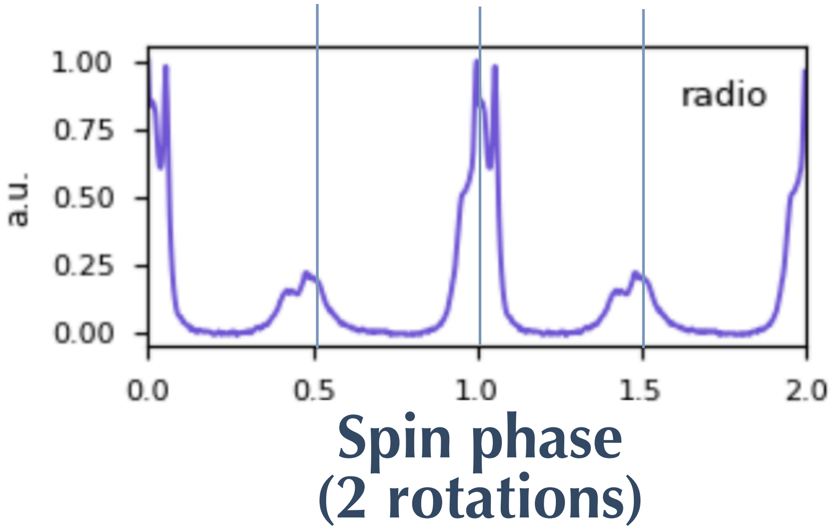


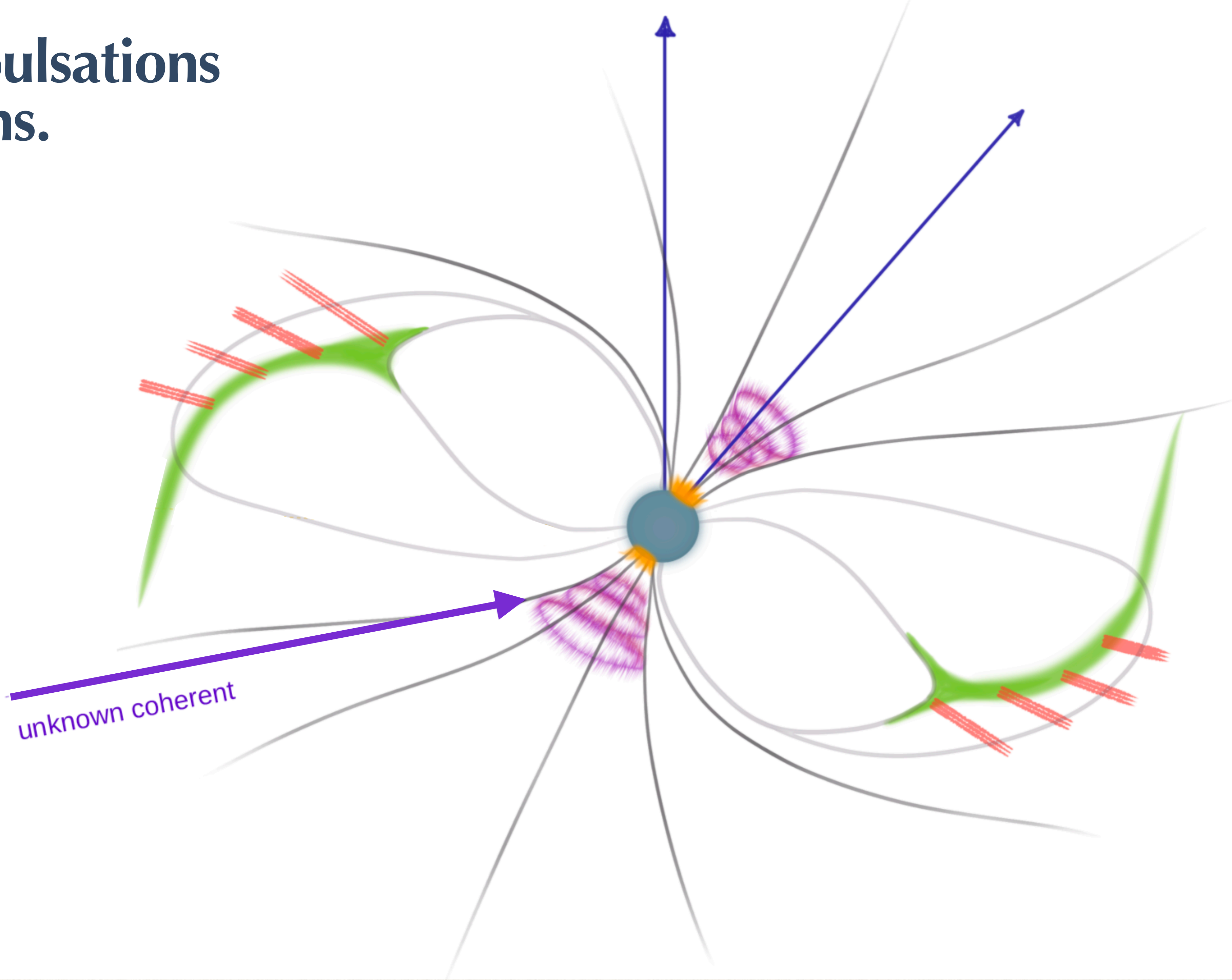
Adapted from figure by JPL/Caltech

Measuring neutron star masses and radii

Radio pulsars (in binary systems) provide the most precise measurements of neutron stars masses.

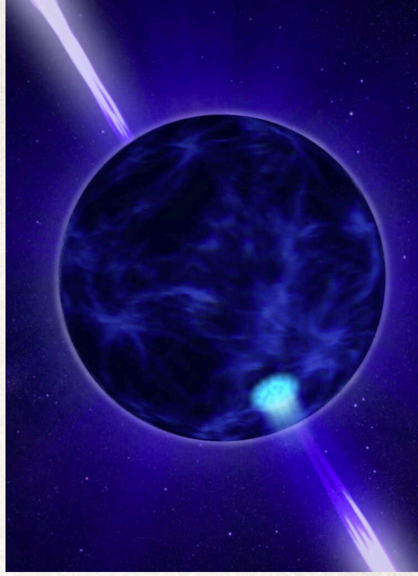
Some pulsars display pulsations at different wavelengths.



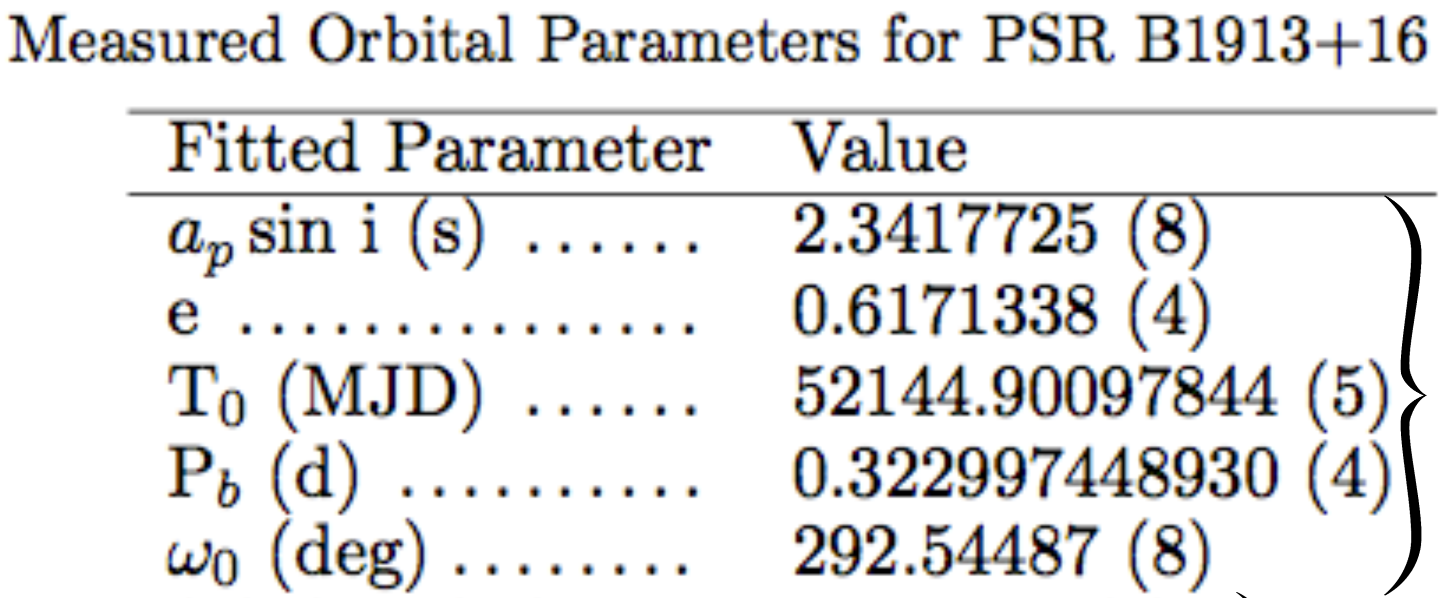


Credits: A. Bilous

Radio timing of pulsars in binary systems permits measurements of orbital parameters.



Monitoring of binary pulsars results in precise determination of Keplerian parameters.

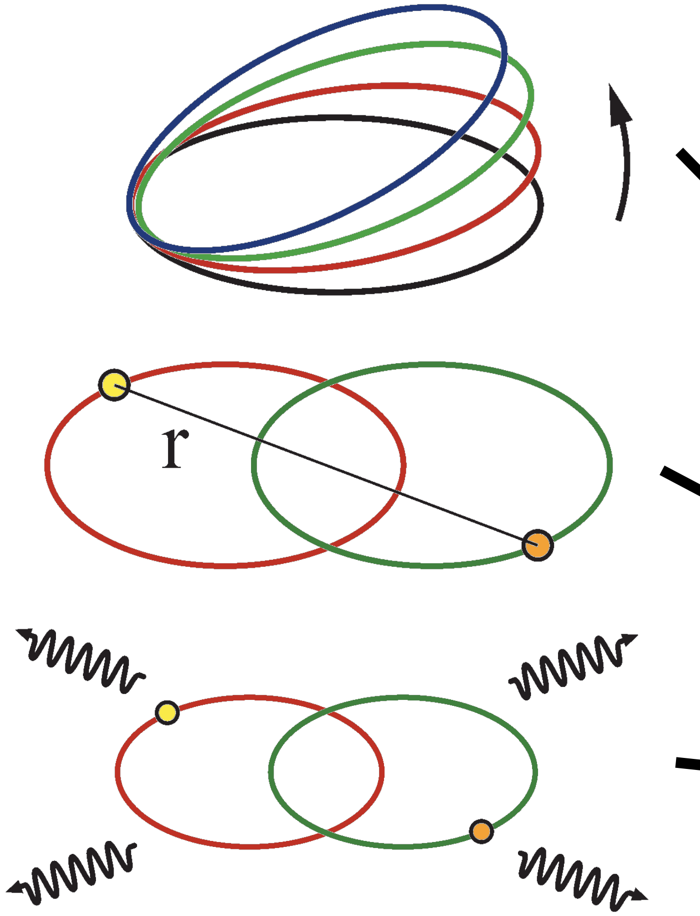


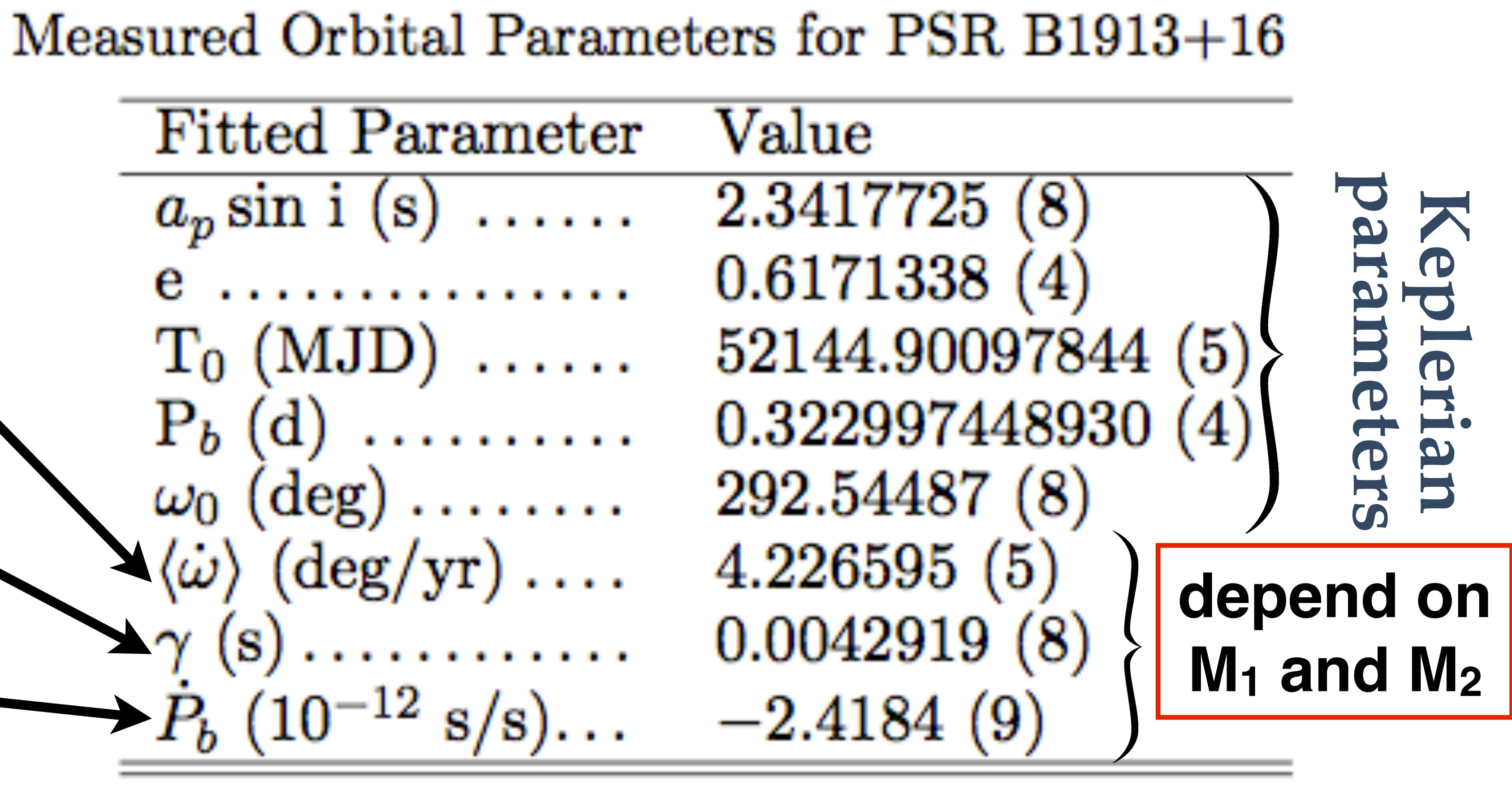
Measured Orbital Parameters for PSR B1913+16

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)

Keplerian parameters

Long term monitoring of binary pulsars results in precise determination of “post-Keplerian” parameters.





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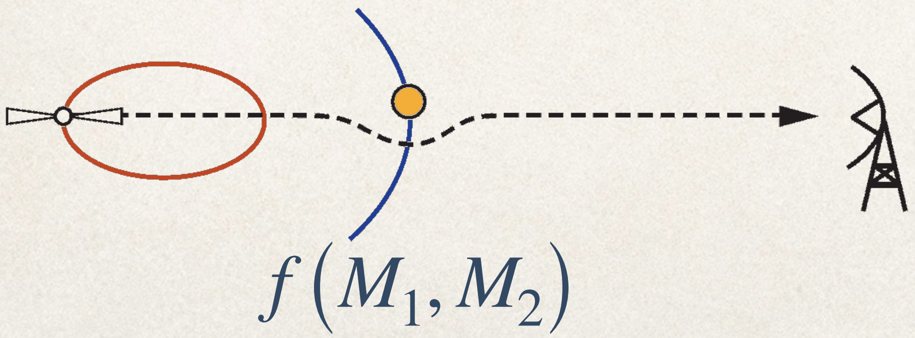
T_0 (MJD) ……	52144.90097844 (5)
P_b (d) ……….	0.322997448930 (4)
ω_0 (deg) ……..	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr) ….	4.226595 (5)
γ (s) ………….	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)…	−2.4184 (9)

Keplerian parameters

depend on M_1 and M_2

+ Shapiro delay

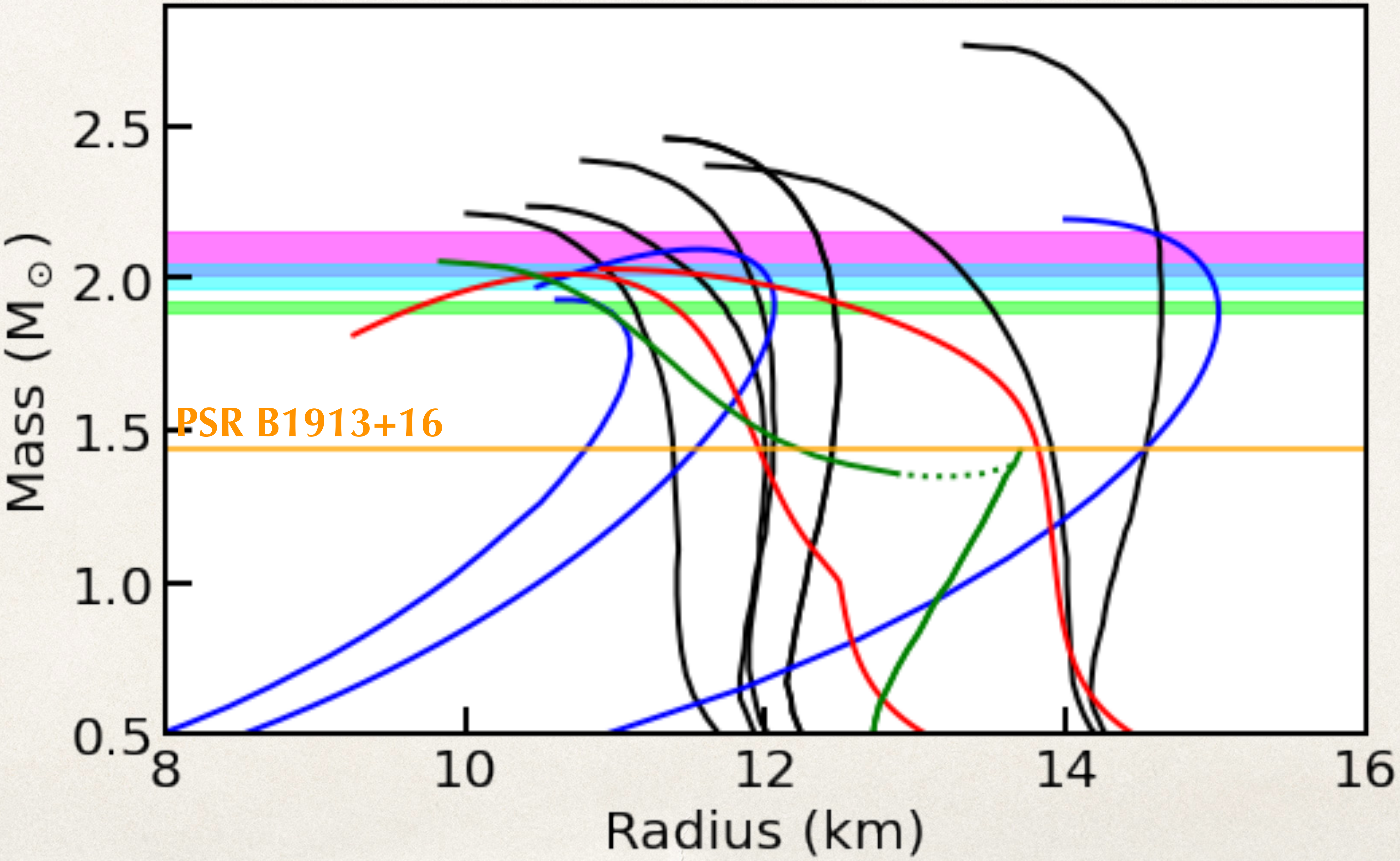


Double-NS system PSR B1913+16
Best M_{NS} measurement
$M_{PSR} = 1.4414 \pm 0.0002\ M_\odot$

Weisberg et al. 2005

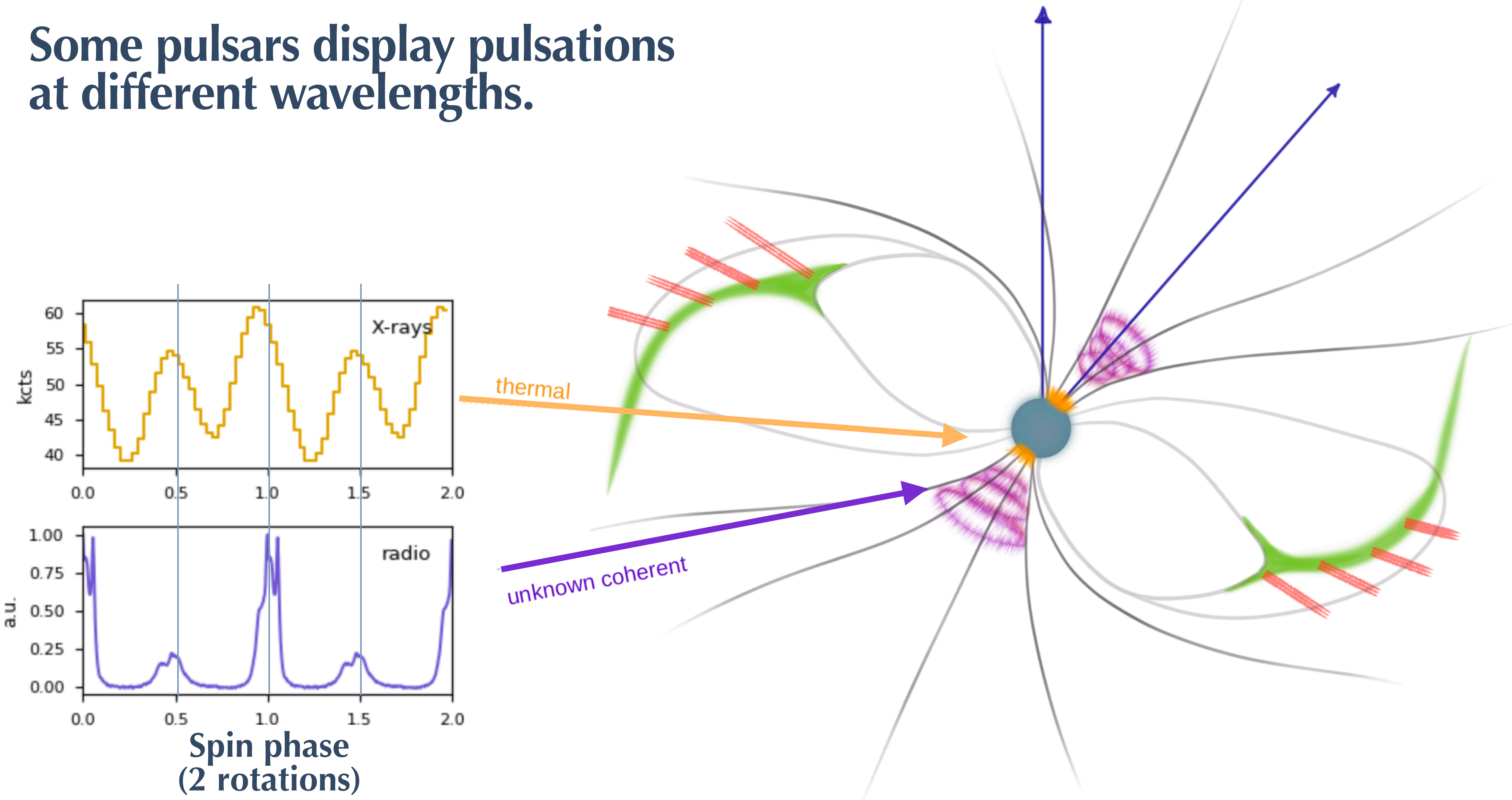
Measurements of the mass M_{NS} exist, but only the highest M_{NS} brings new constraints.

Demorest et al. 2010
Antoniadis et al. 2013
Cromartie et al. 2019



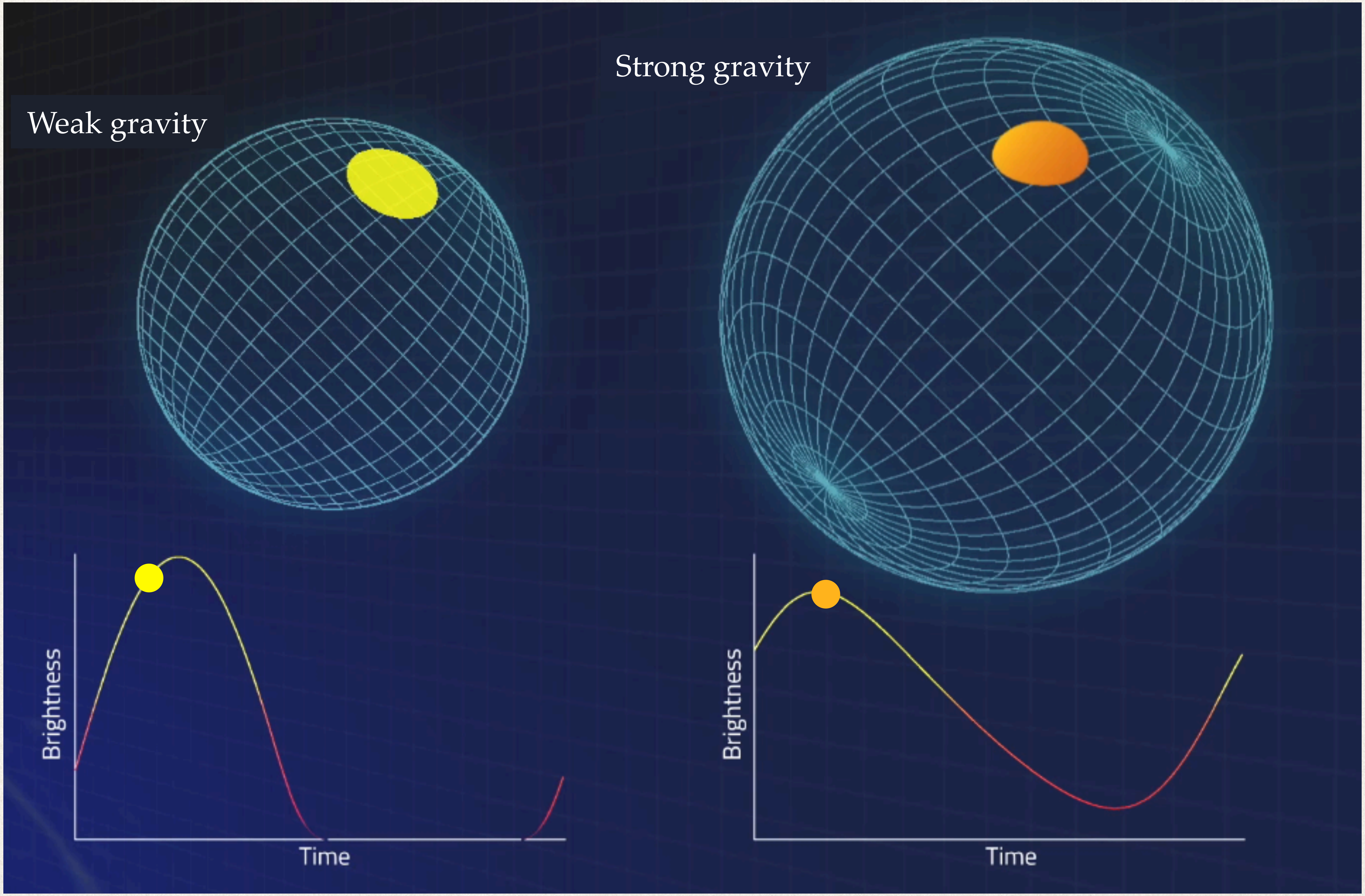
X-ray emitting neutrons stars and X-ray pulsars can provide measurements of neutron stars radii.

Some pulsars display pulsations at different wavelengths.



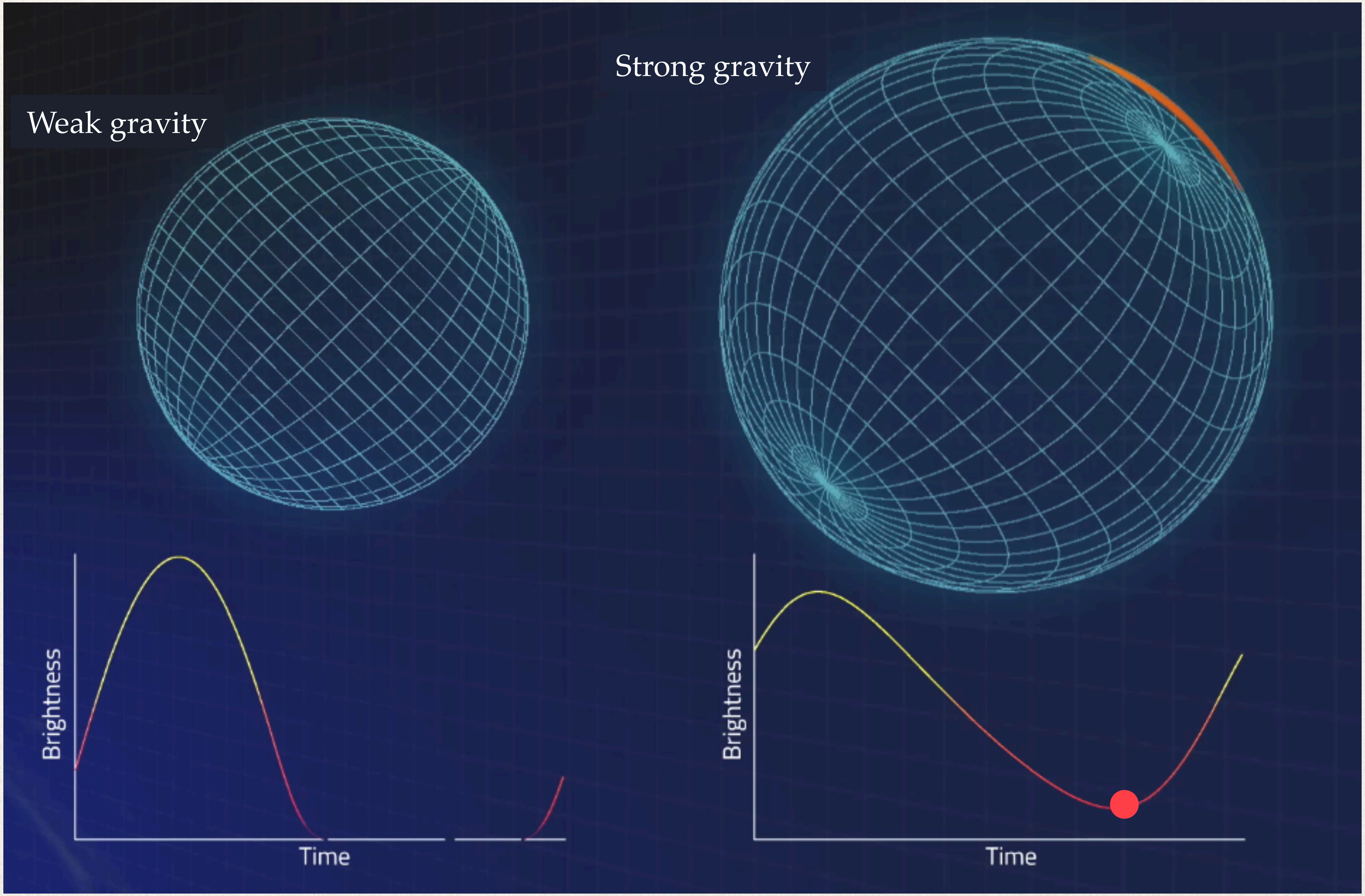
Credits: A. Bilous

Strong gravity permits seeing beyond the hemisphere of the neutron star.



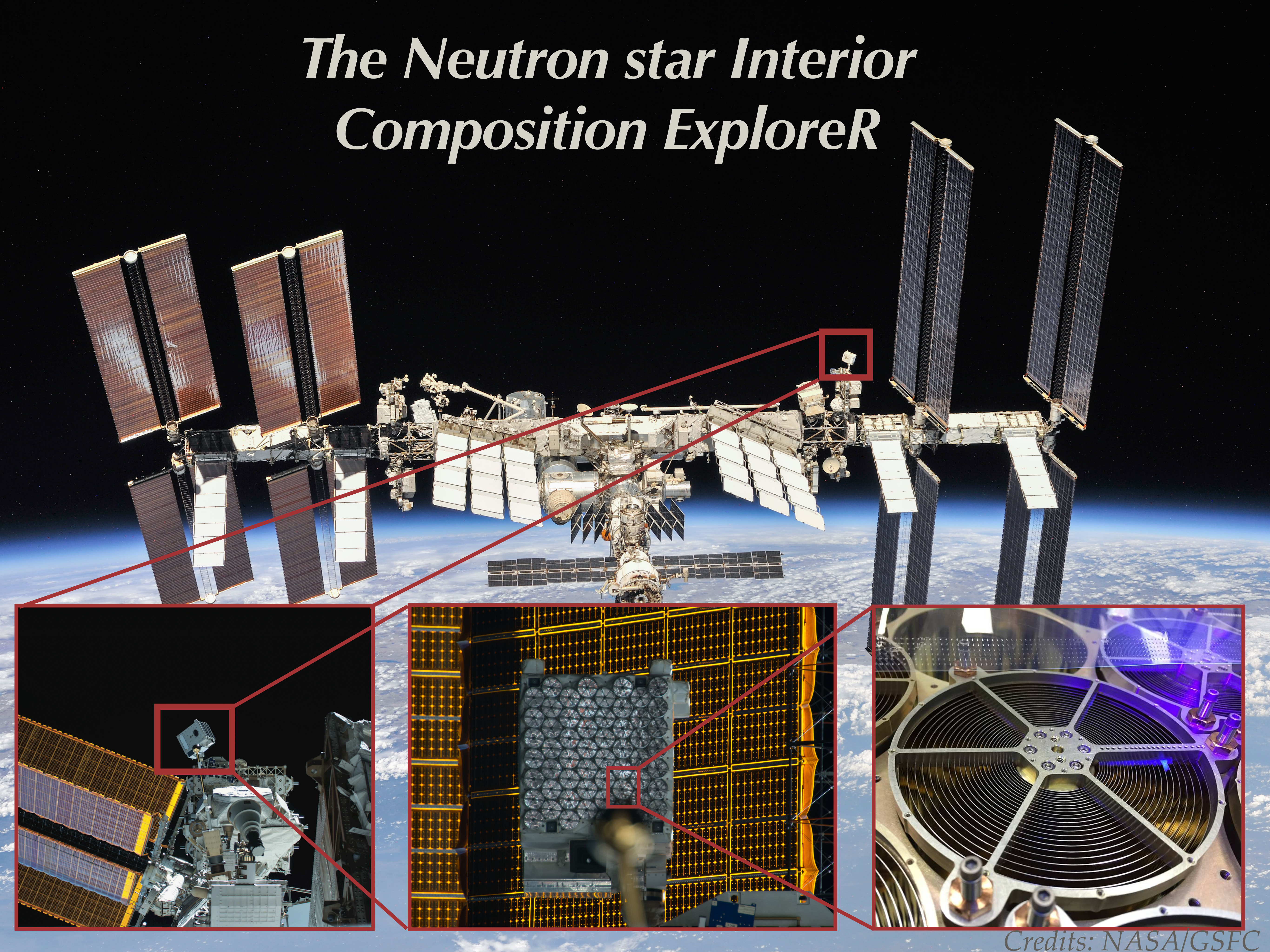
Credits: S. Morsink / NASA

Strong gravity permits seeing beyond the hemisphere of the neutron star.



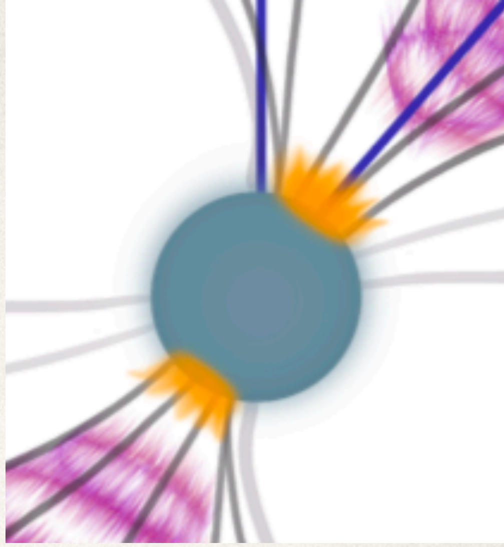
Credits: S. Morsink / NASA

The Neutron star Interior Composition ExploreR



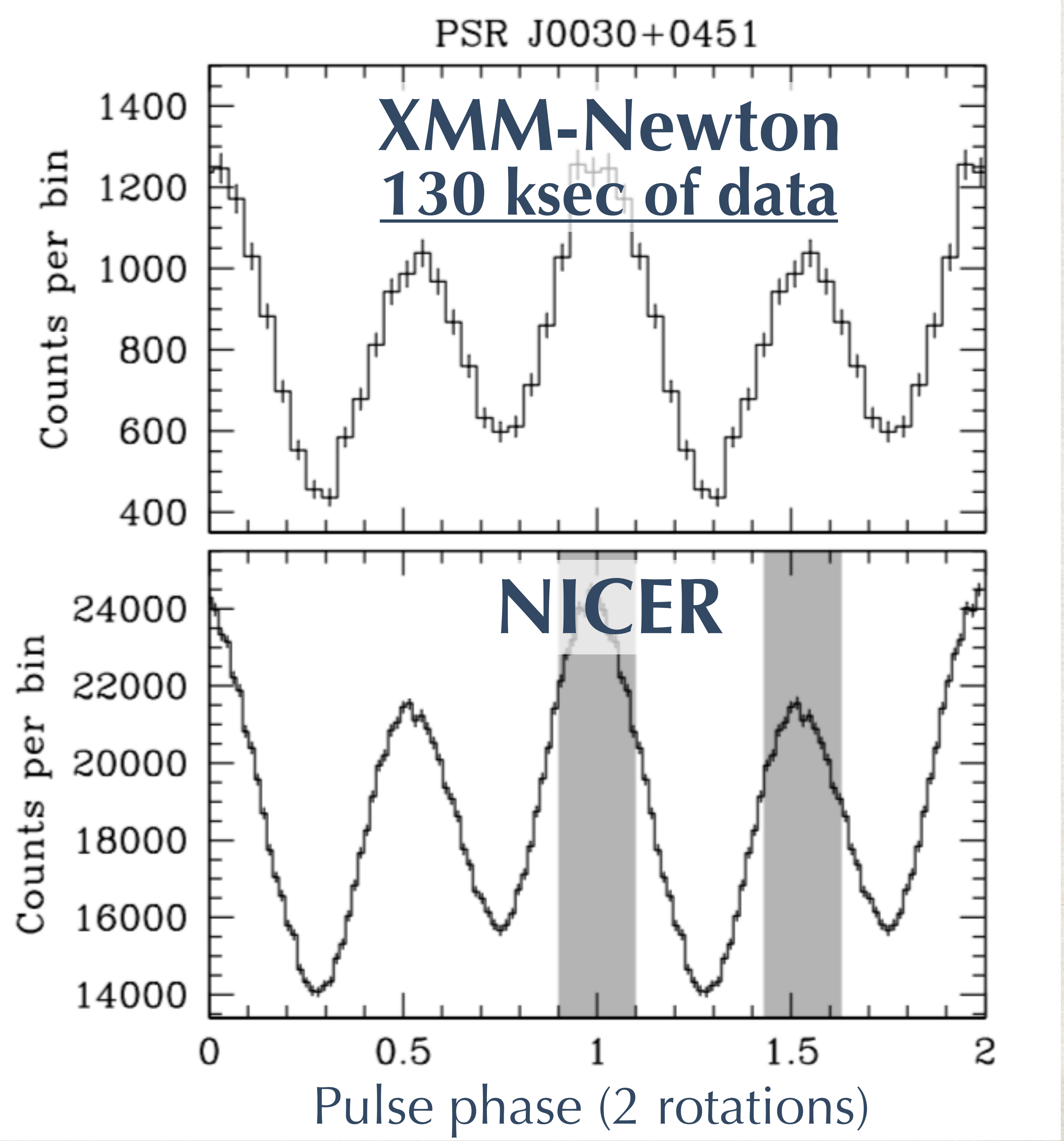
Credits: NASA/GSFC

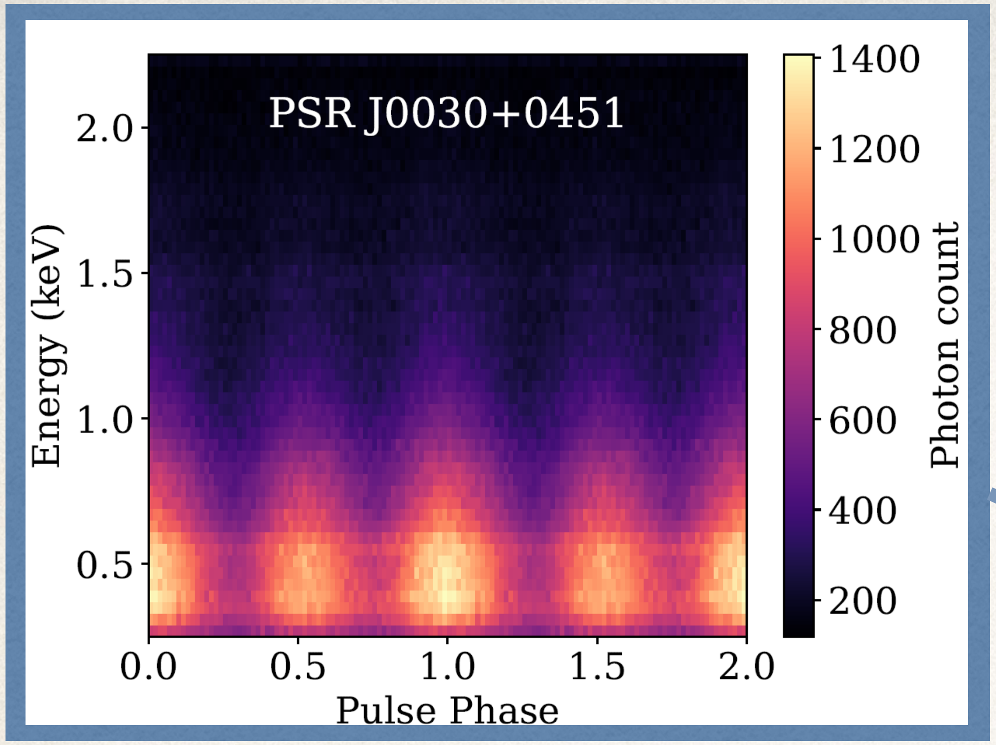
NICER has accumulated weeks of continuous data on several key pulsars to attain unprecedented signal-to-noise data.

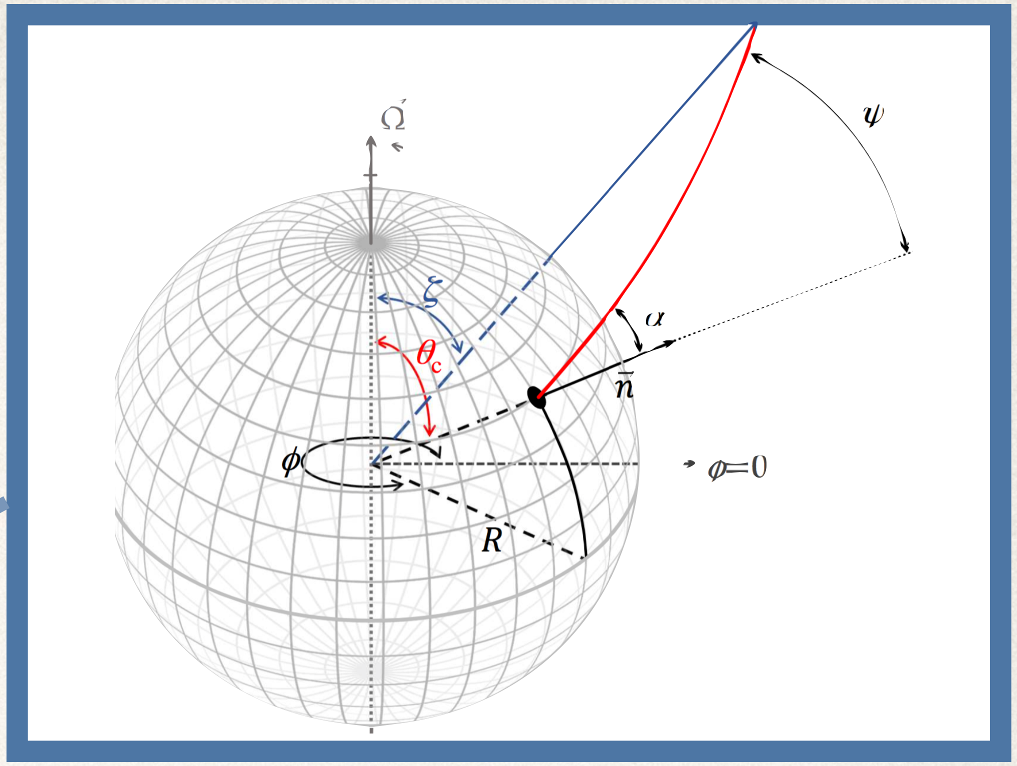


Bogdanov, Guillot et al. (2019a)

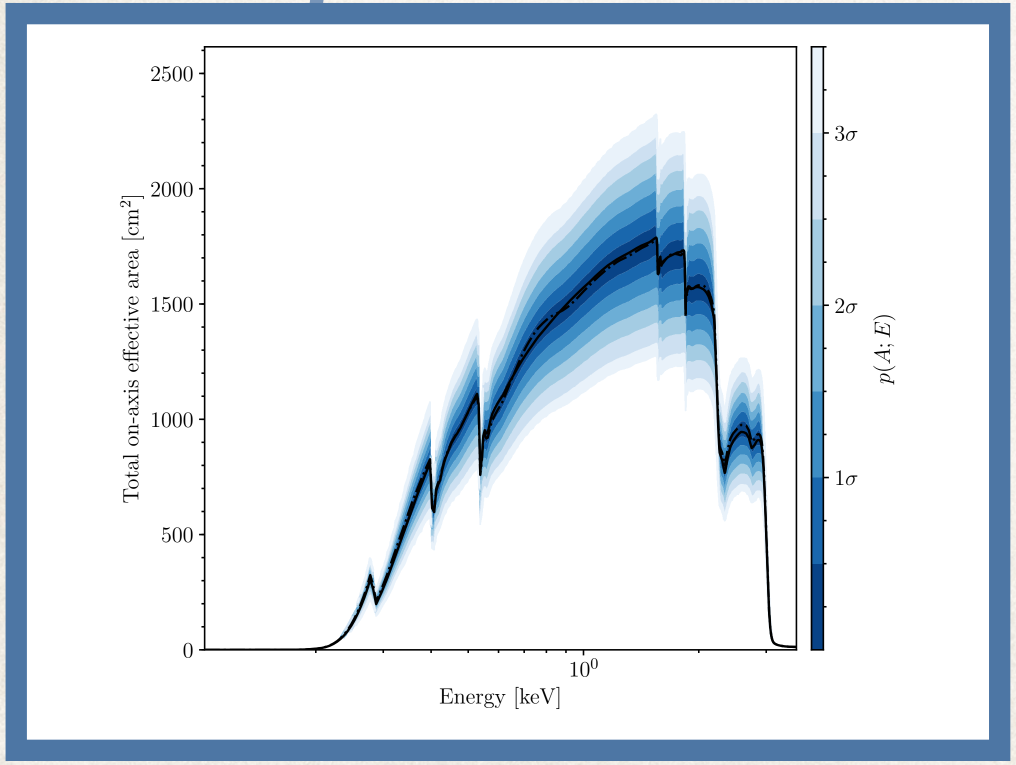
Target	Total observing time	
PSR J0030	**3.6 Msec**	**41 days**
PSR J0740	**2.9 Msec**	**33 days**
PSR J1231	2.9 Msec	33 days
PSR J0437	2.6 Msec	32 days
PSR J2124	1.9 Msec	22 days
PSR J0614	1.1 Msec	12 days
PSR J1614	1.0 Msec	11 days



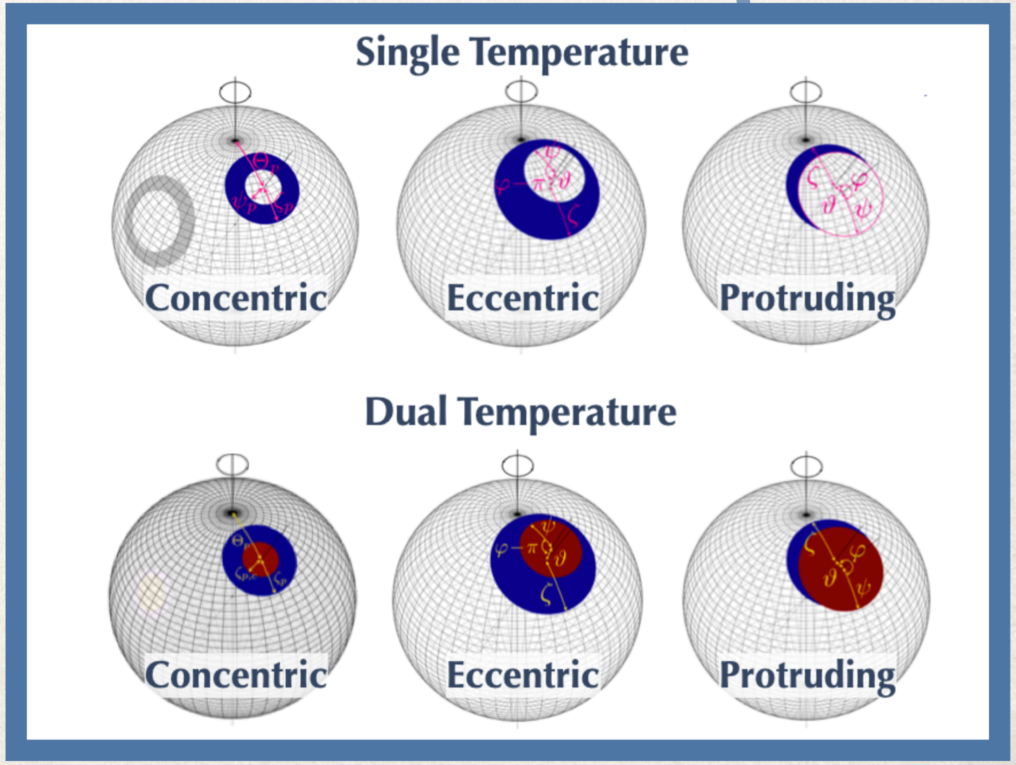




NS properties inference
(Likelihood statistical sampling)

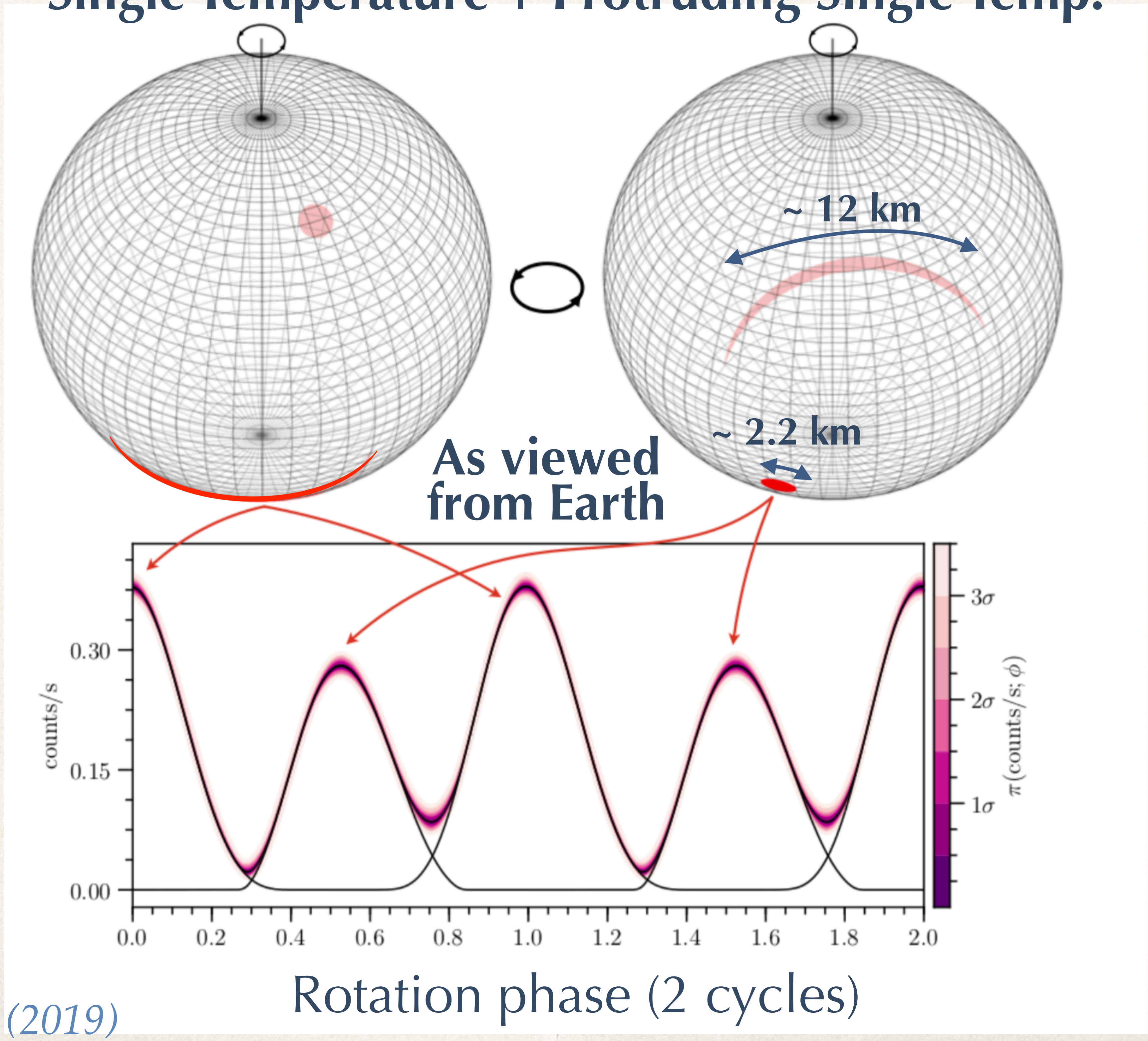


Mass,
Radius,
…



PSR J0030+0451: The preferred model consists in a small circular spot and an elongated crescent.

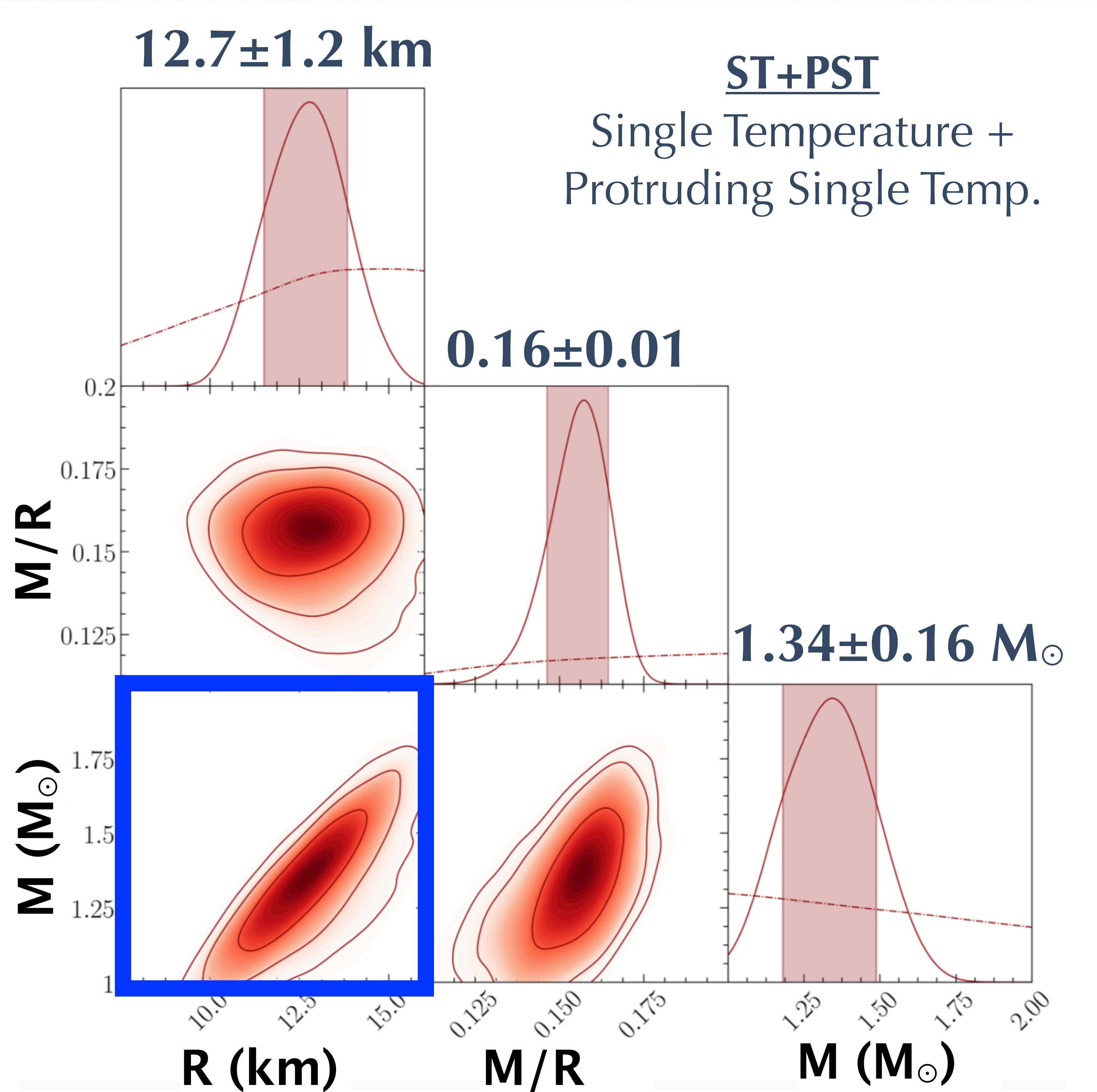
Single Temperature + Protruding Single Temp.



Rotation phase (2 cycles)

Riley, …, SG et al. (2019)

PSR J0030+0451: In addition to the unexpected geometry, we also constrained M_{NS} and R_{NS}.



12.7±1.2 km

0.16±0.01

1.34±0.16 $M_\odot$

ST+PST
Single Temperature +
Protruding Single Temp.

R_{NS} = 12.7 ± 1.2 km

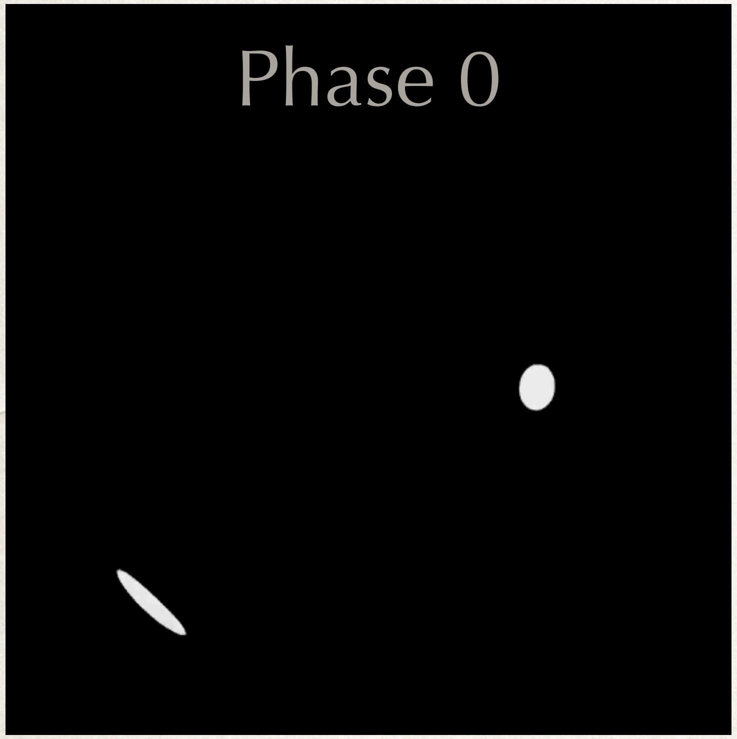
M_{NS} = 1.34 ± 0.16 $M_\odot$

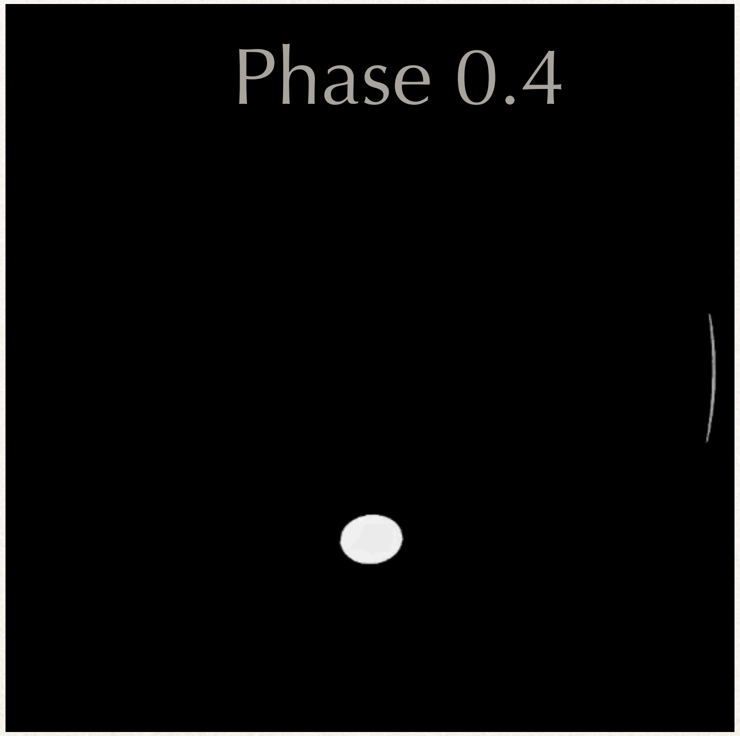
Riley, …, SG et al. (2019)
See also Miller, …, SG et al. (2019)

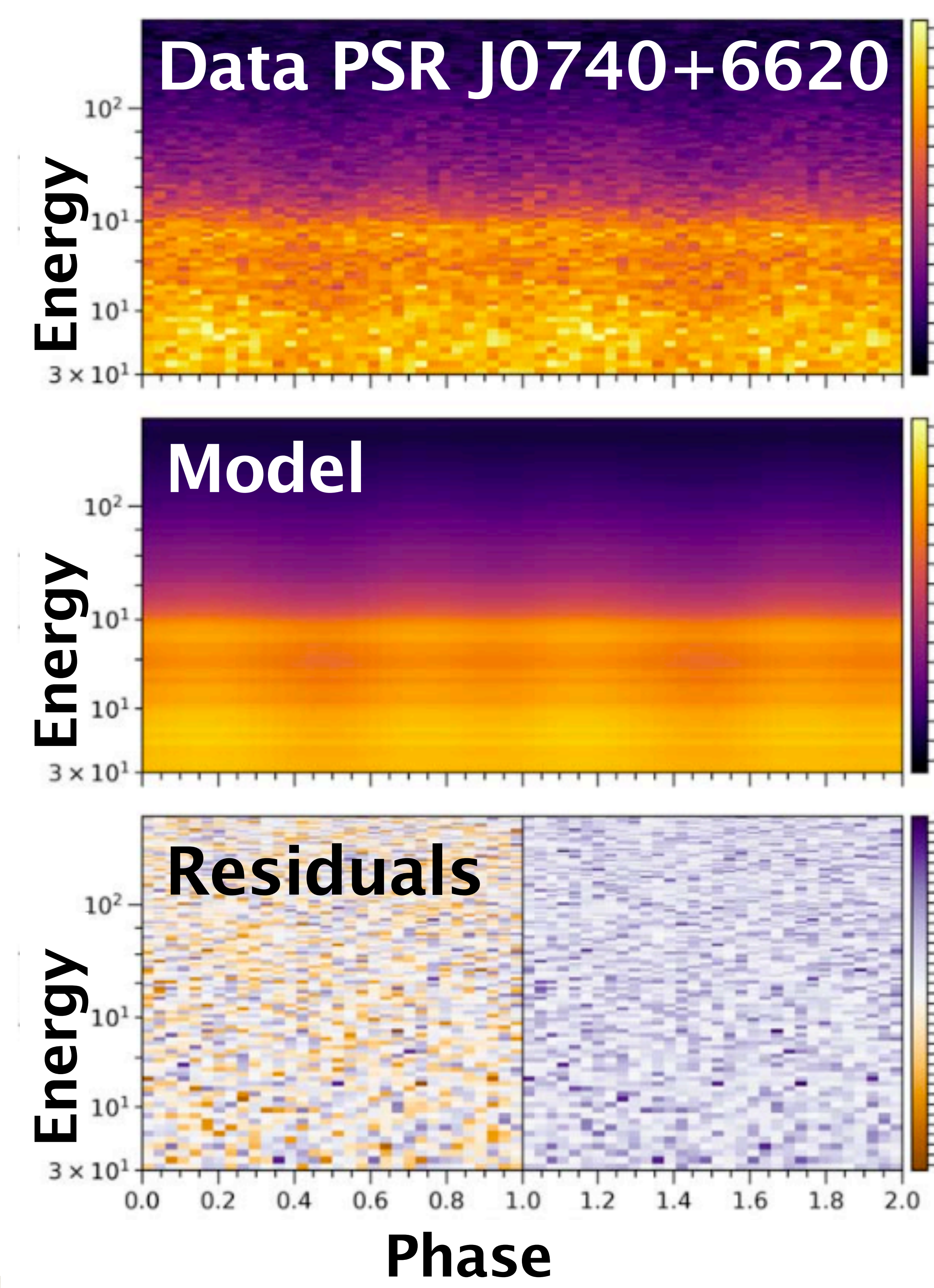
PSR J0740+6620: The simplest model is a good description of the data.

ST+ST

Single Temperature +
Single Temperature





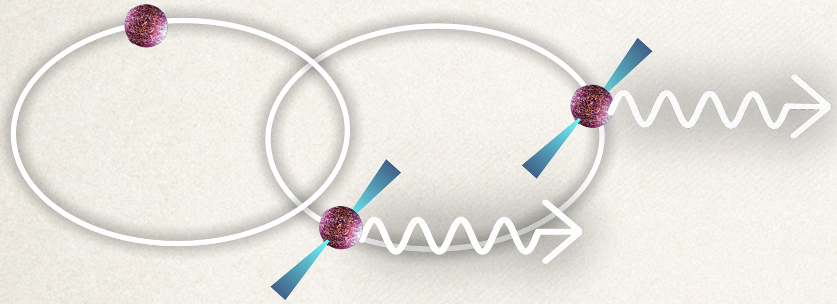


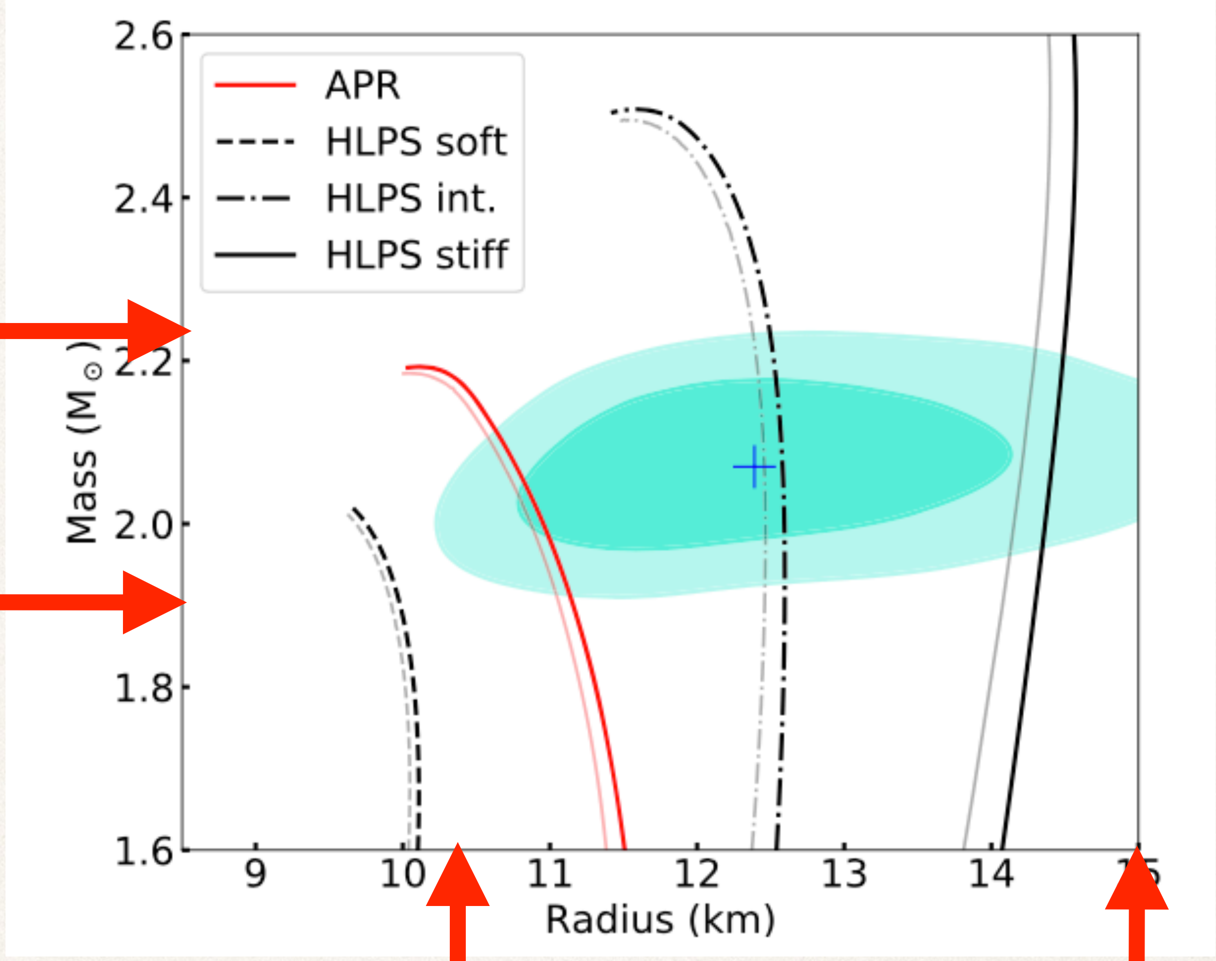
Riley, …, SG et al. (2021)

The M-R constraints from PSR J0740+6620 are useful thanks to its independently measured high mass.

Using mass prior from radio timing observations:

M = 2.07±0.07 Msun



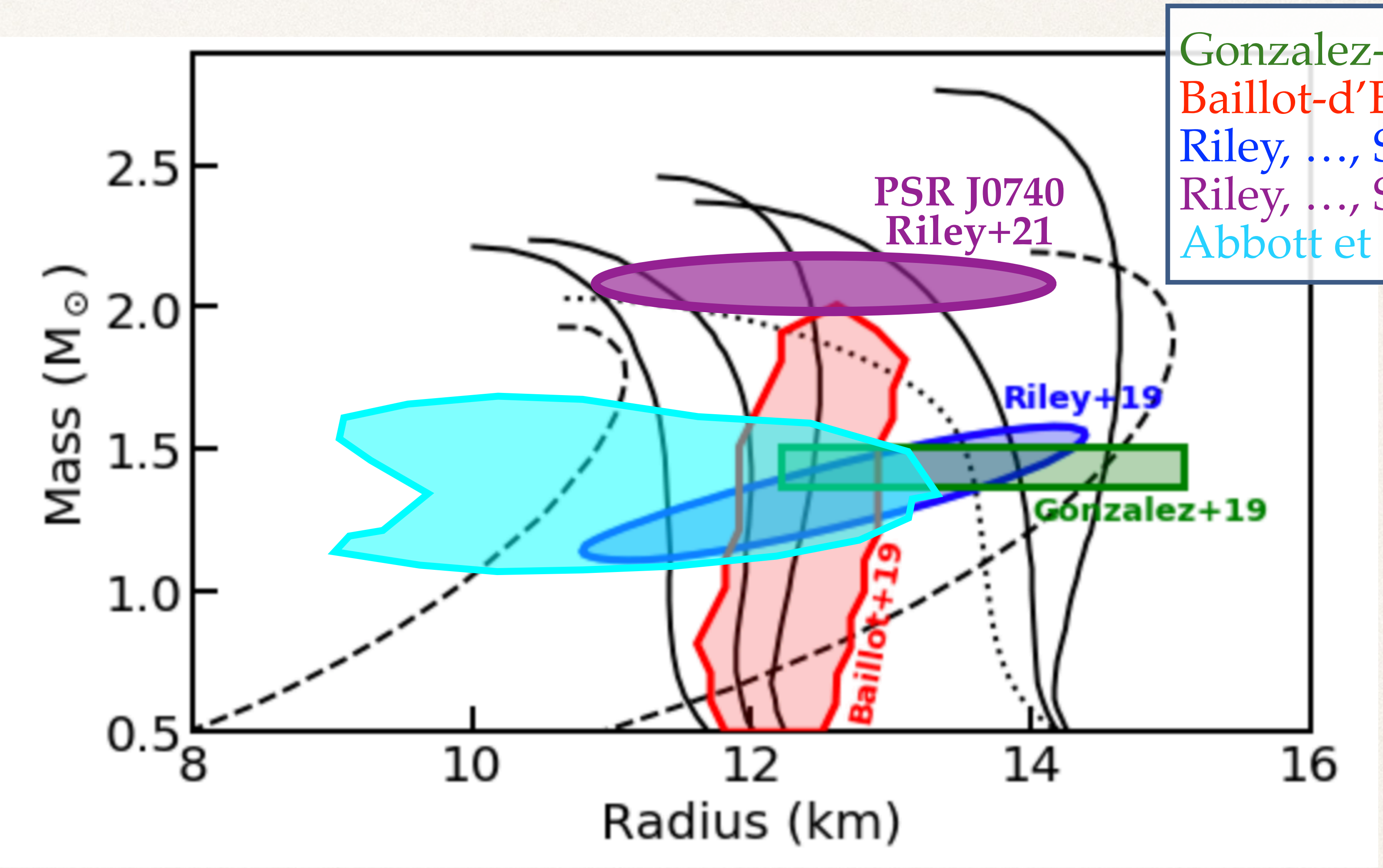


Constraints on radius from NICER+XMM data

R = 12.4 ± 1.3 km

Riley, …, SG et al. (2021)
See also Miller, …, SG et al. (2021)

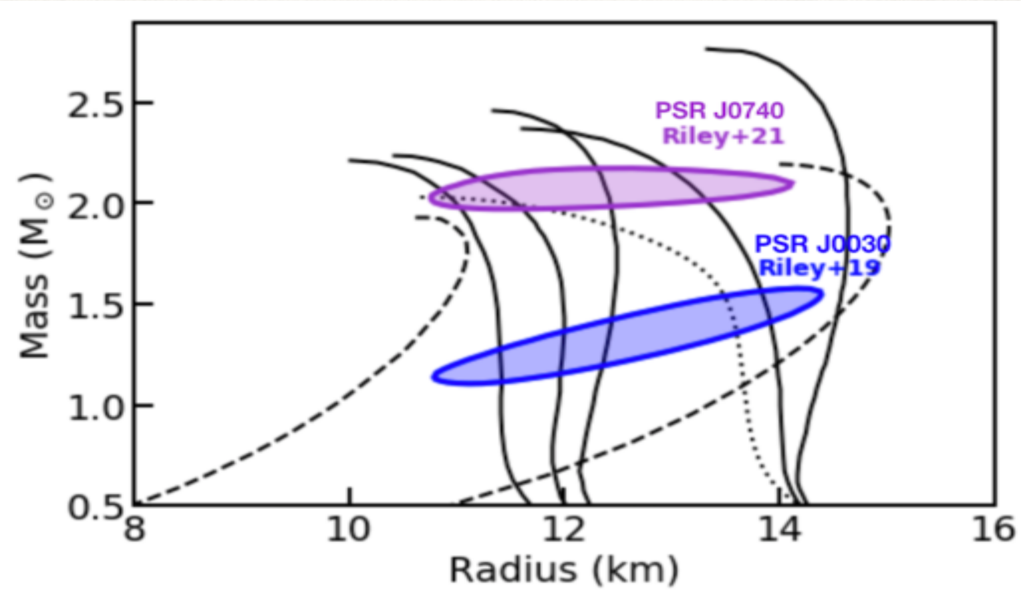
GW and EM observations of neutron stars to constrain dense matter



Gonzalez-Canuilef, SG et al. 2019
Baillot-d'Etivaux, SG et al. 2019
Riley, …, SG et al. 2019
Riley, …, SG et al. 2021
Abbott et al. 2018

Combining GW and EM constraints

The NICER results for these two pulsars bring some additional constraints on equation of state models.



<u>PSR J0030+0451</u> brings little additional information on EoSs parametrization (polytropes)

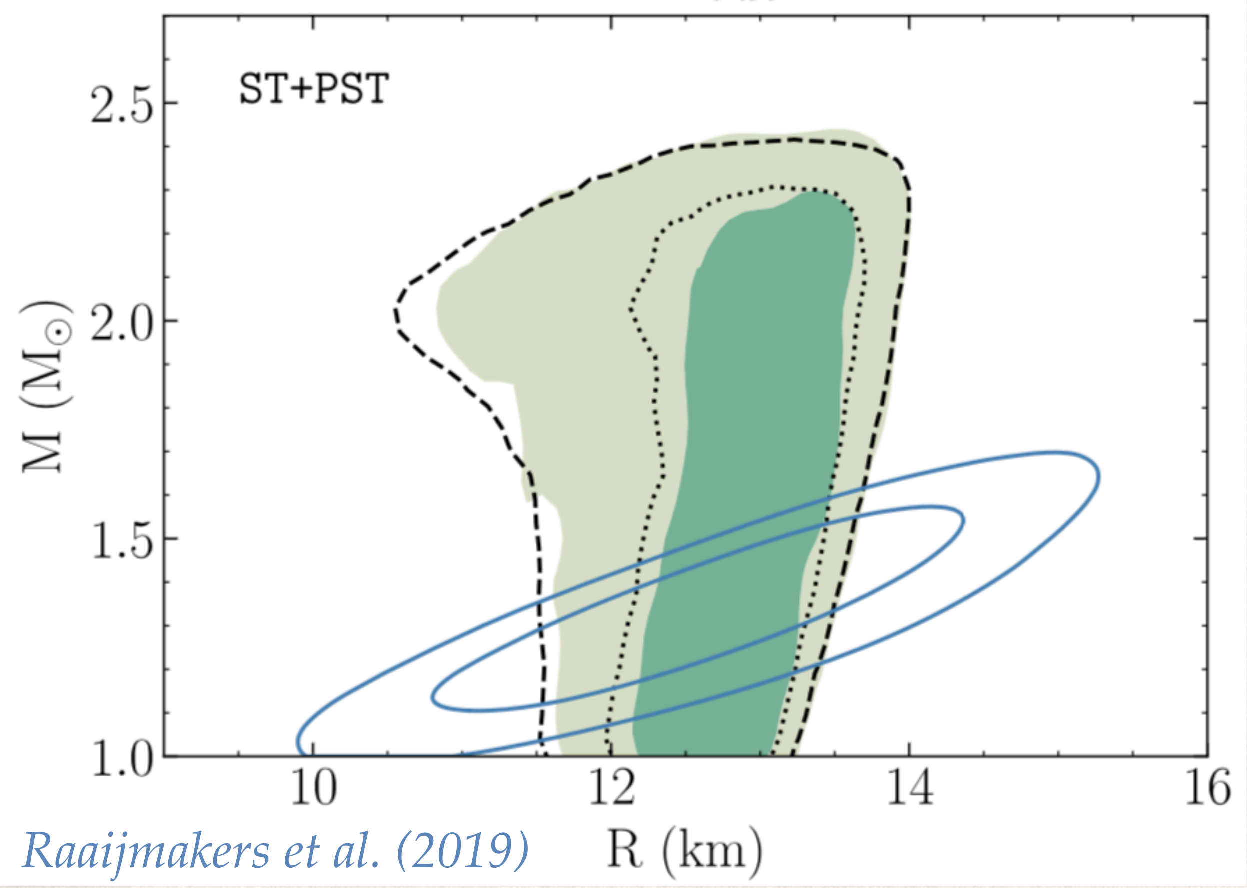
<u>PSR J0740+6620</u> adds some improvement on the EoSs models, thanks to its high mass.

⋯⋯ Nucl. Phys. + GW170817

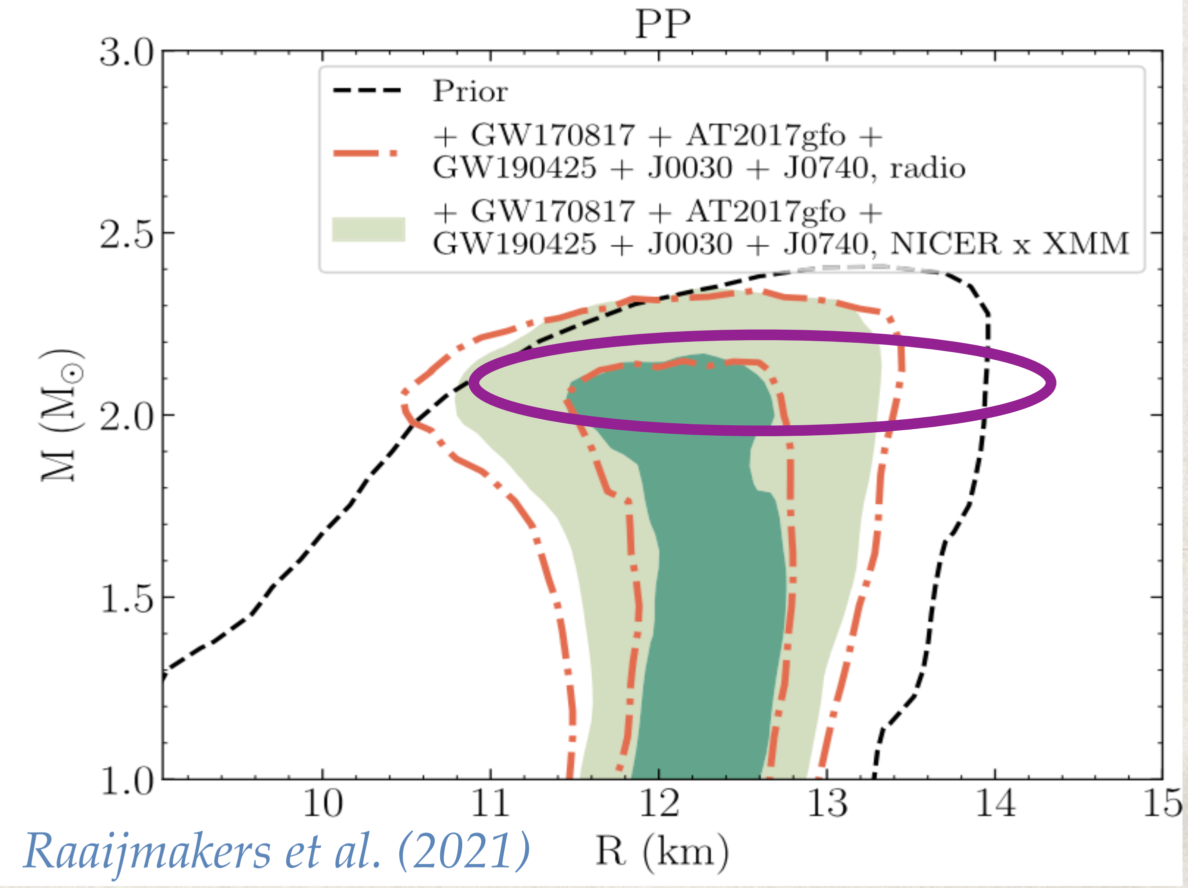
🟩 + PSR J0030

- - - - + mass of PSR J0740

🟩 + PSR J0740



Raaijmakers et al. (2019)



Raaijmakers et al. (2021)

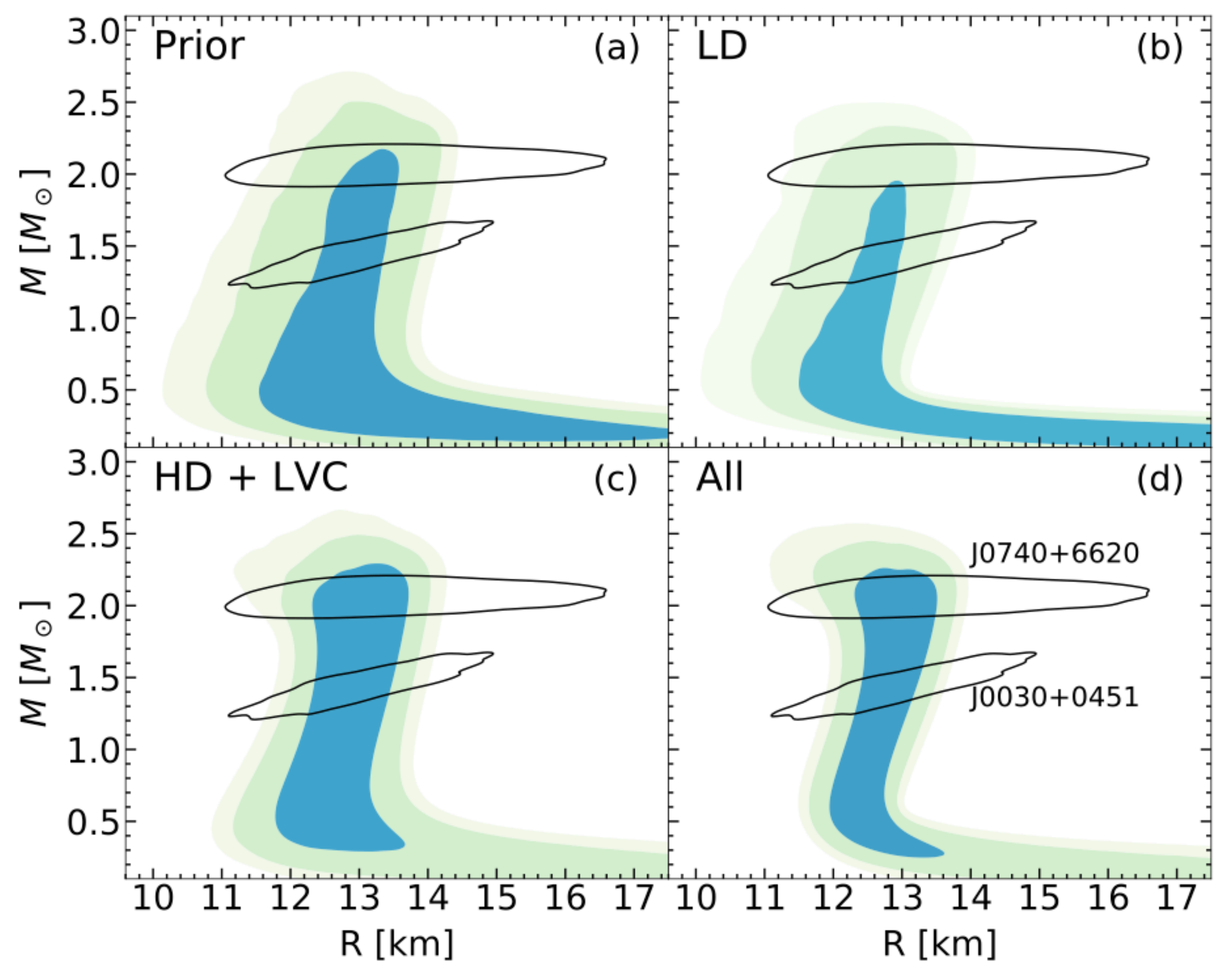
Different approaches use different ways to model the equation of state.

Dinh Thi et al. (2021)

Meta-modelling of the EOS

Margueron et al. (2018)

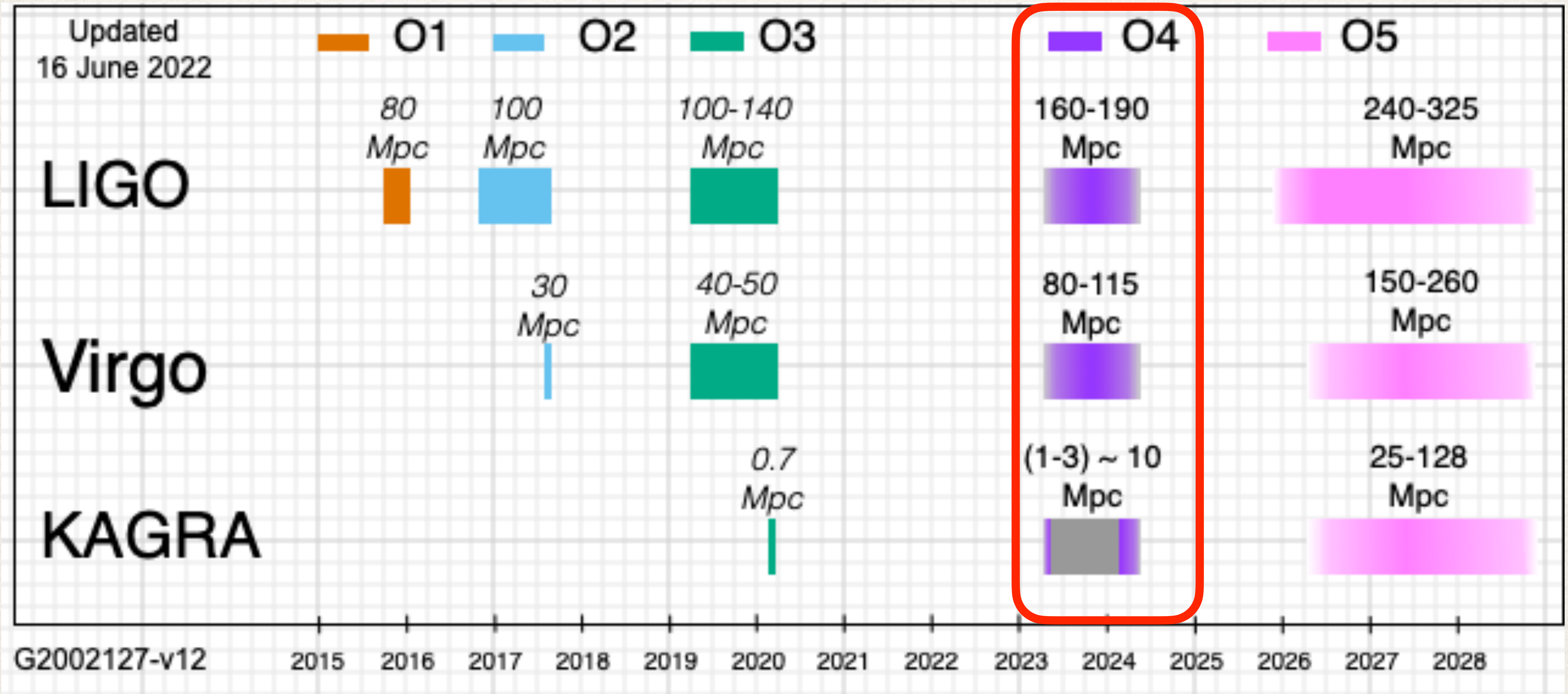
Taylor expansion of the energy density around e_{sat}



Epilogue:

What's the future of astrophysical constraints on the EOS

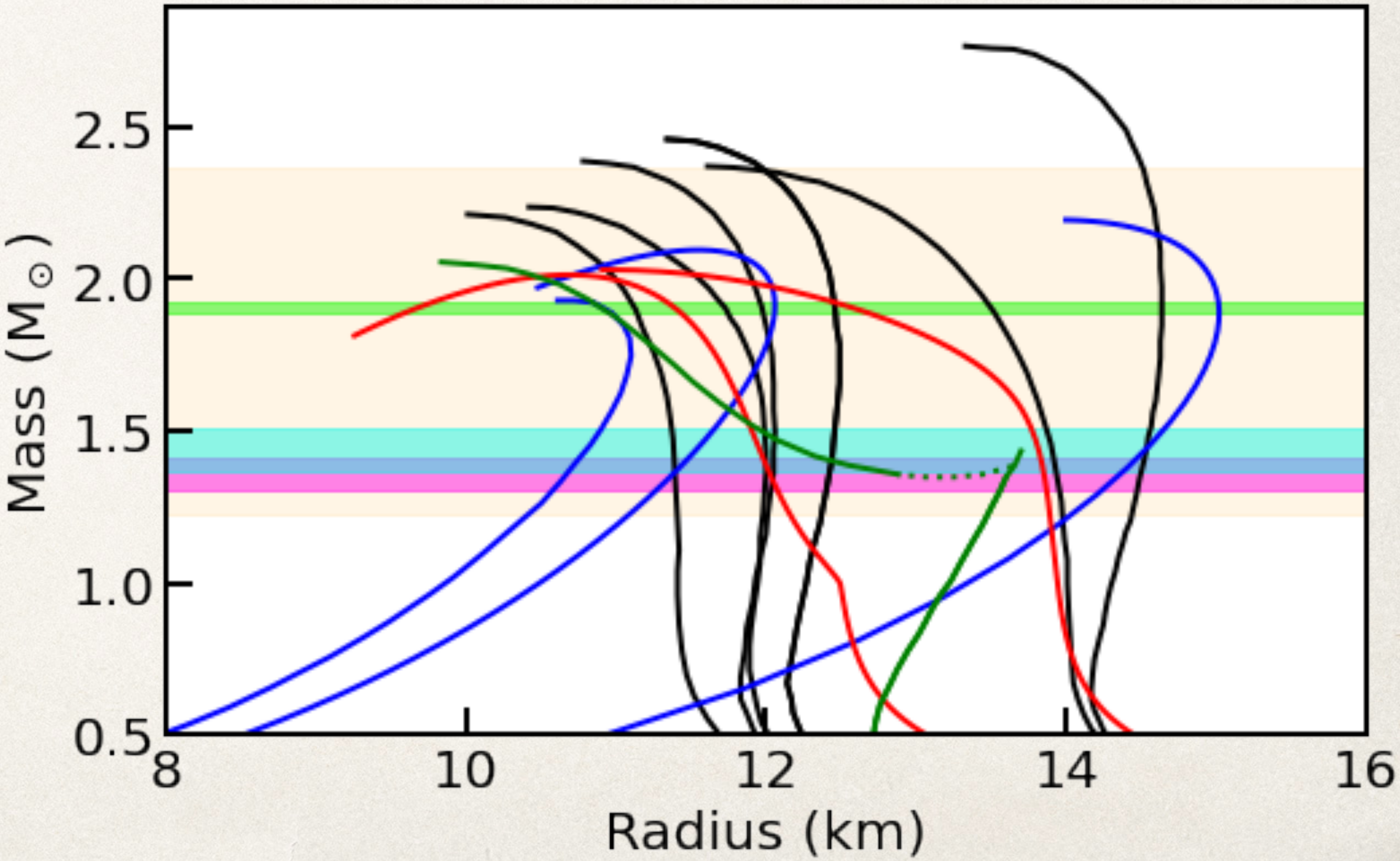
Future LVK runs will detect more NS-NS mergers.



The next generation of GW interferometers will then permit studies with large populations of NS-NS mergers.

There are analyses of NICER pulsars in progress with upcoming M_{NS} and R_{NS} measurements.

Target	Total time
PSR J0030	3.6 Msec
PSR J0740	2.9 Msec
PSR J1231	2.9 Msec
PSR J0437	2.6 Msec
PSR J2124	1.9 Msec
PSR J0614	1.1 Msec
PSR J1614	1.0 Msec



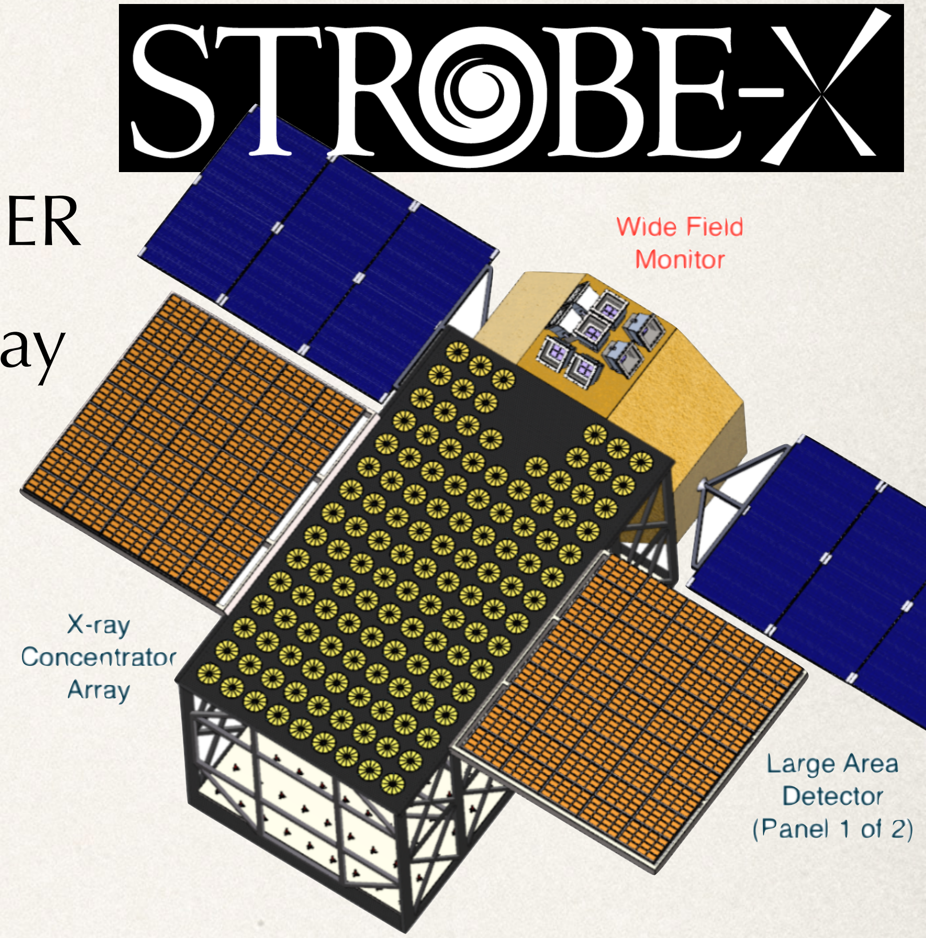
Future X-ray missions will also enable M_{NS} and R_{NS} measurements for a few tens of neutron stars.

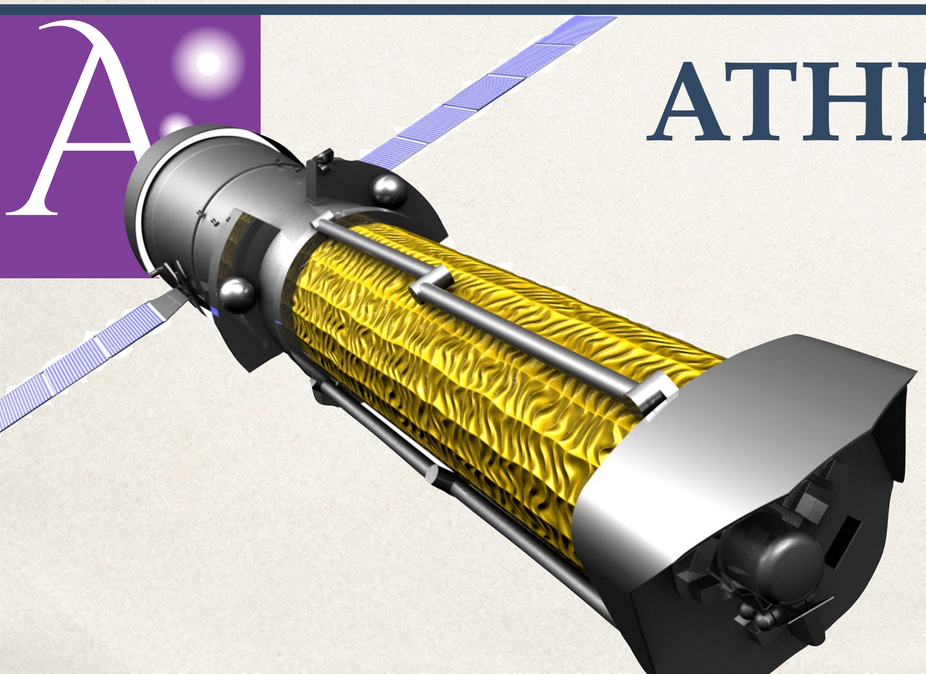
eXTP (~2028)

- Modest imaging capabilities (60″ PSF)
- ~ 4–5 × more sensitive than NICER
- + Hard X-ray instrument

~2030

- ~ 10× NICER
- + Hard X-ray instrument

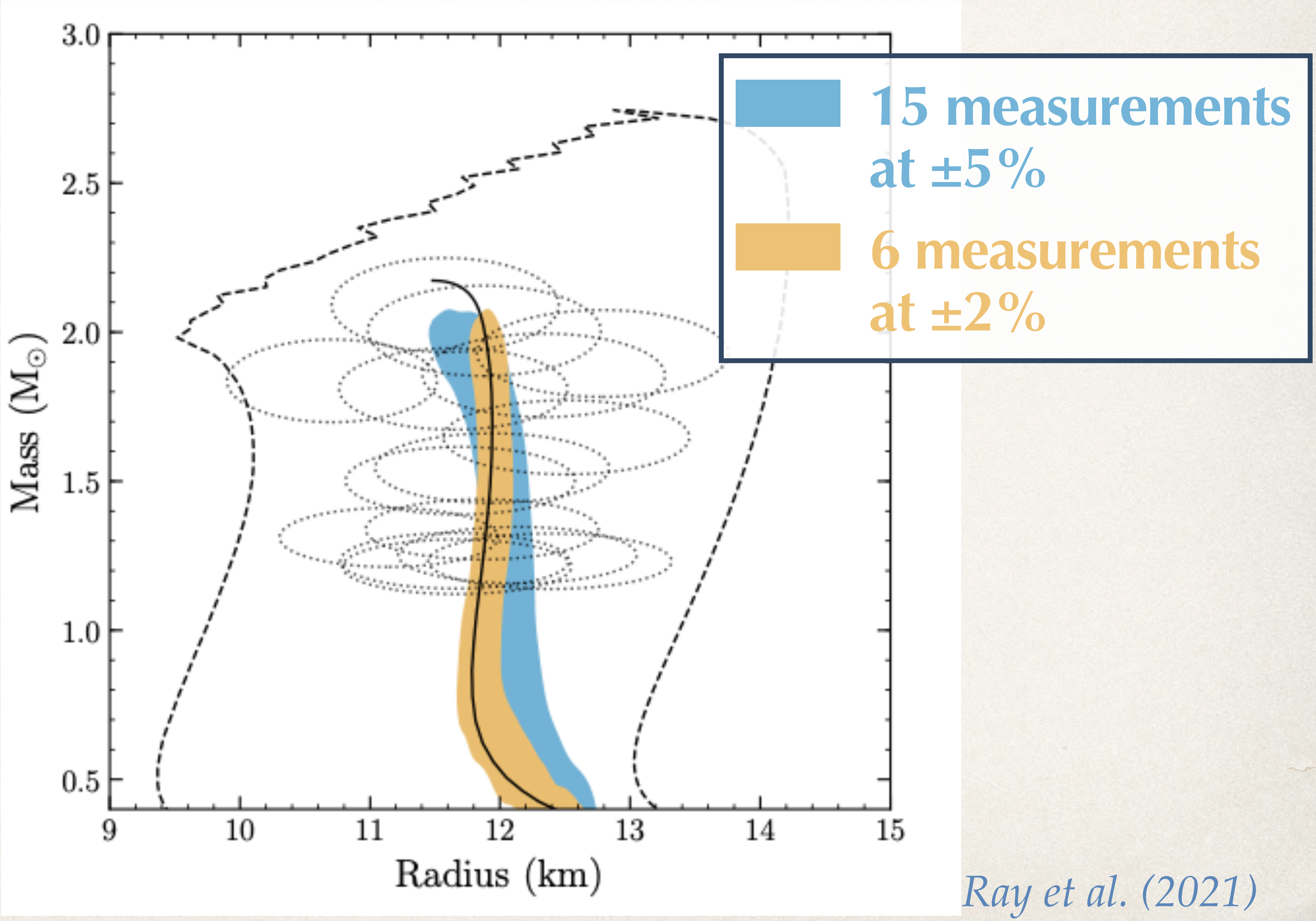




ATHENA ? (~2035)

- Good imaging capabilities (5–10″ PSF)
- ~ 5–10 × more sensitive than NICER
- 10 µs time resolution

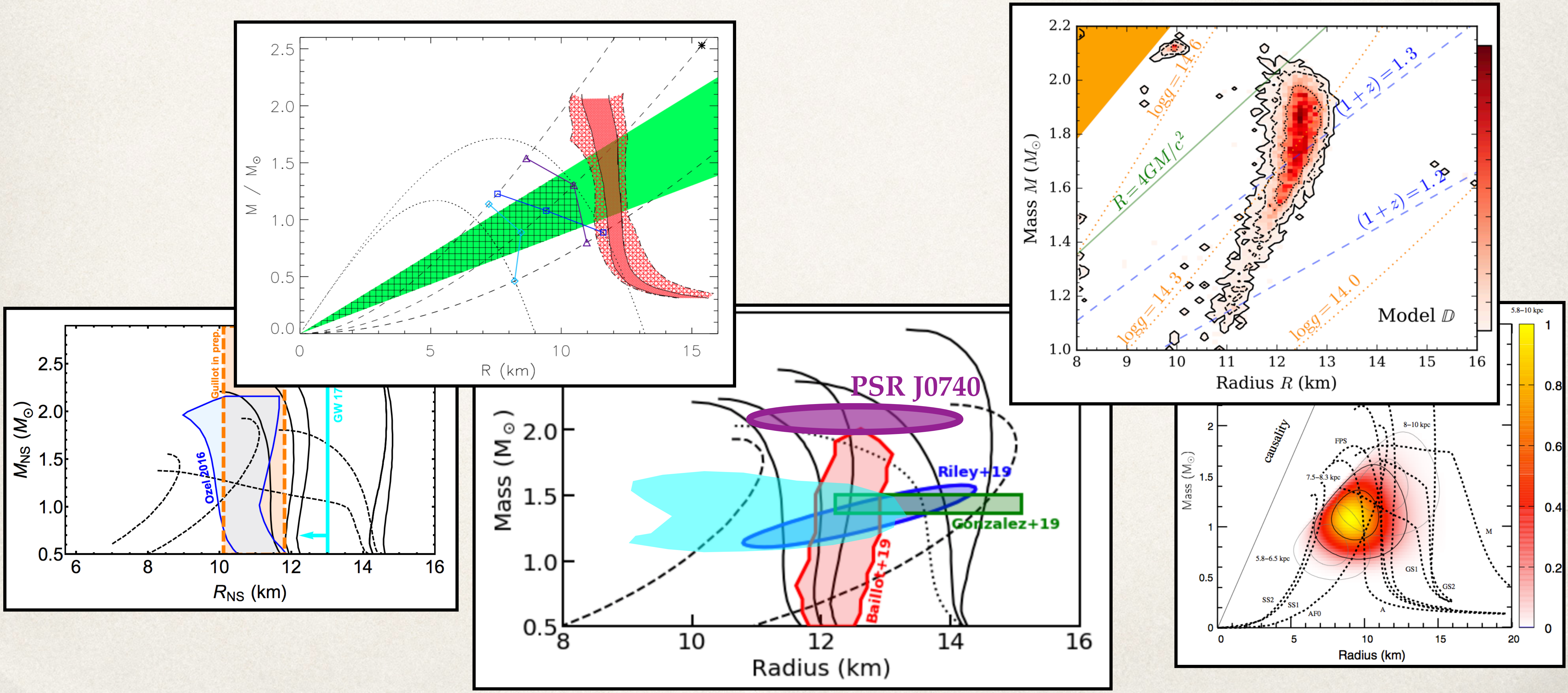
While more measurements will improve the constraints on the EOS, the quality of the measurement is really key.



Ray et al. (2021)

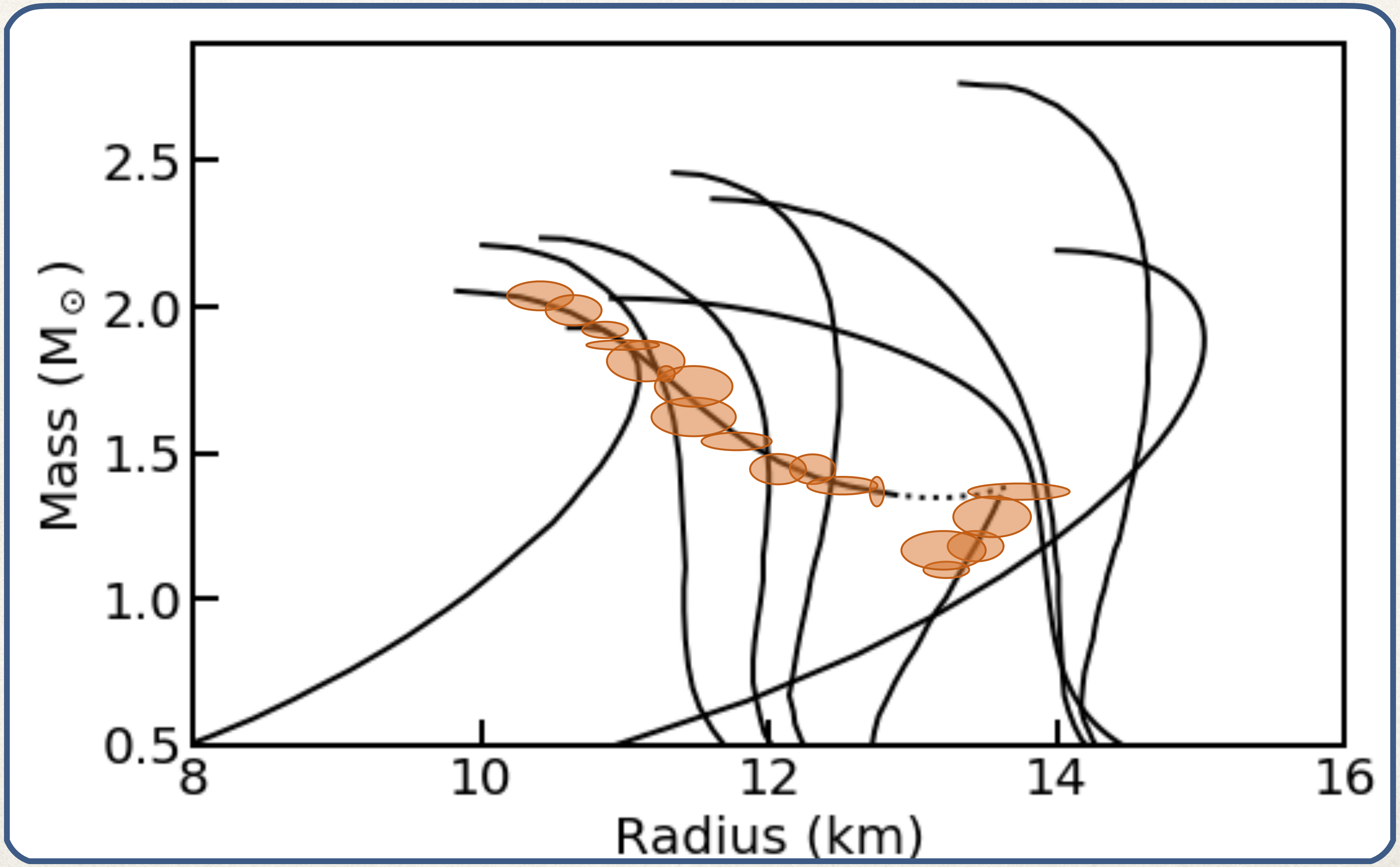
CompARE : An upcoming repository for M_{NS}, R_{NS}, Λ_{NS} measurements.

- **Facilitate the interaction between observers and nuclear physicists / modellers**
- **Offer a uniform/unified repository of M-R or M-Λ constraints from NS and NS-NS mergers**
- **Stay as close as possible to the astrophysical data, free of EOS pre-modelling**
- **Offer easy conversions from the different type of inputs (MCMC samples, posteriors, ...)**
- **In the long term, encourage the observer community to provide their full posteriors**



Conclusion

Many M_{NS}–R_{NS} measurements are necessary to truly constrain the equation of state, and to be sensitive to possible phase transitions.

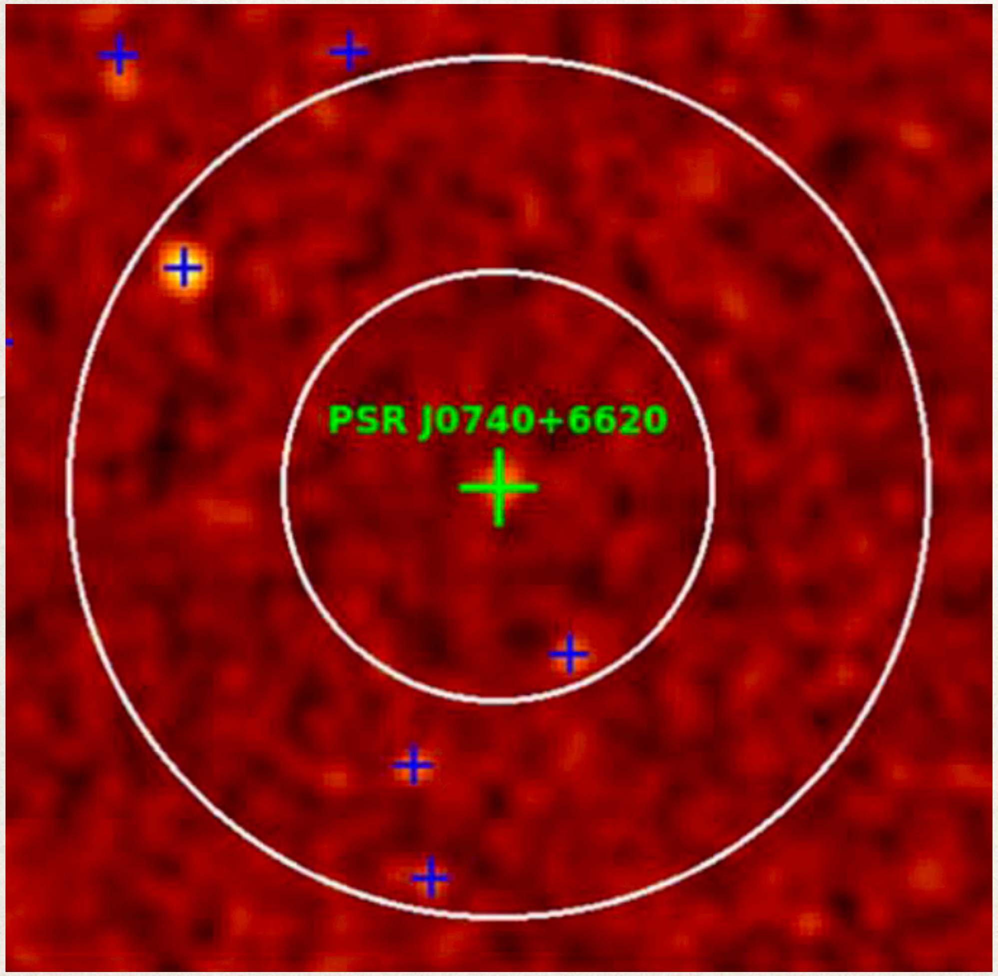


Extra

Constraining the NICER background will be key for robust M–R measurements.

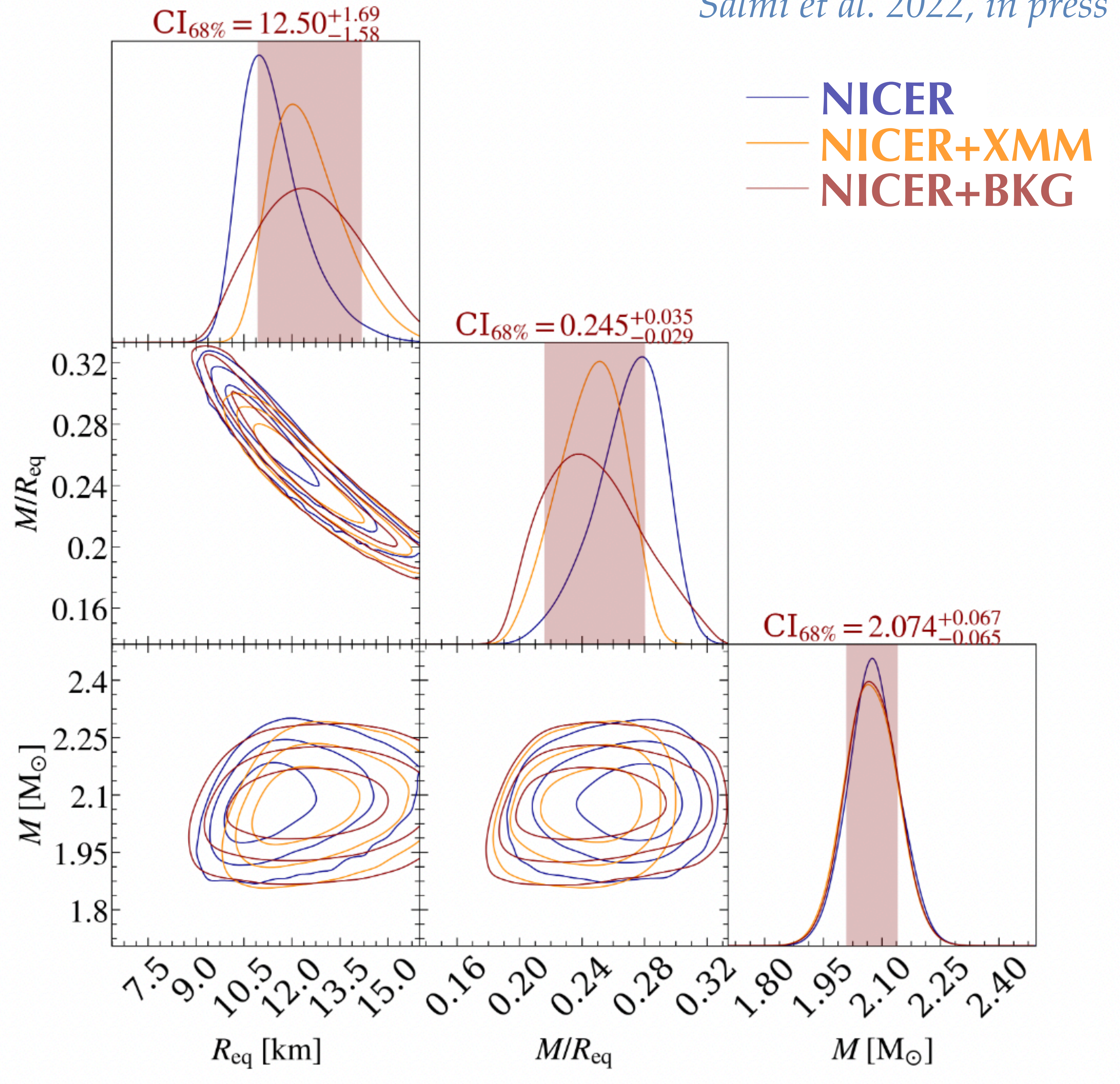
Sources of background:

- Instrumental background
- Particle background
- Cosmic Xray background
- Nearby sources

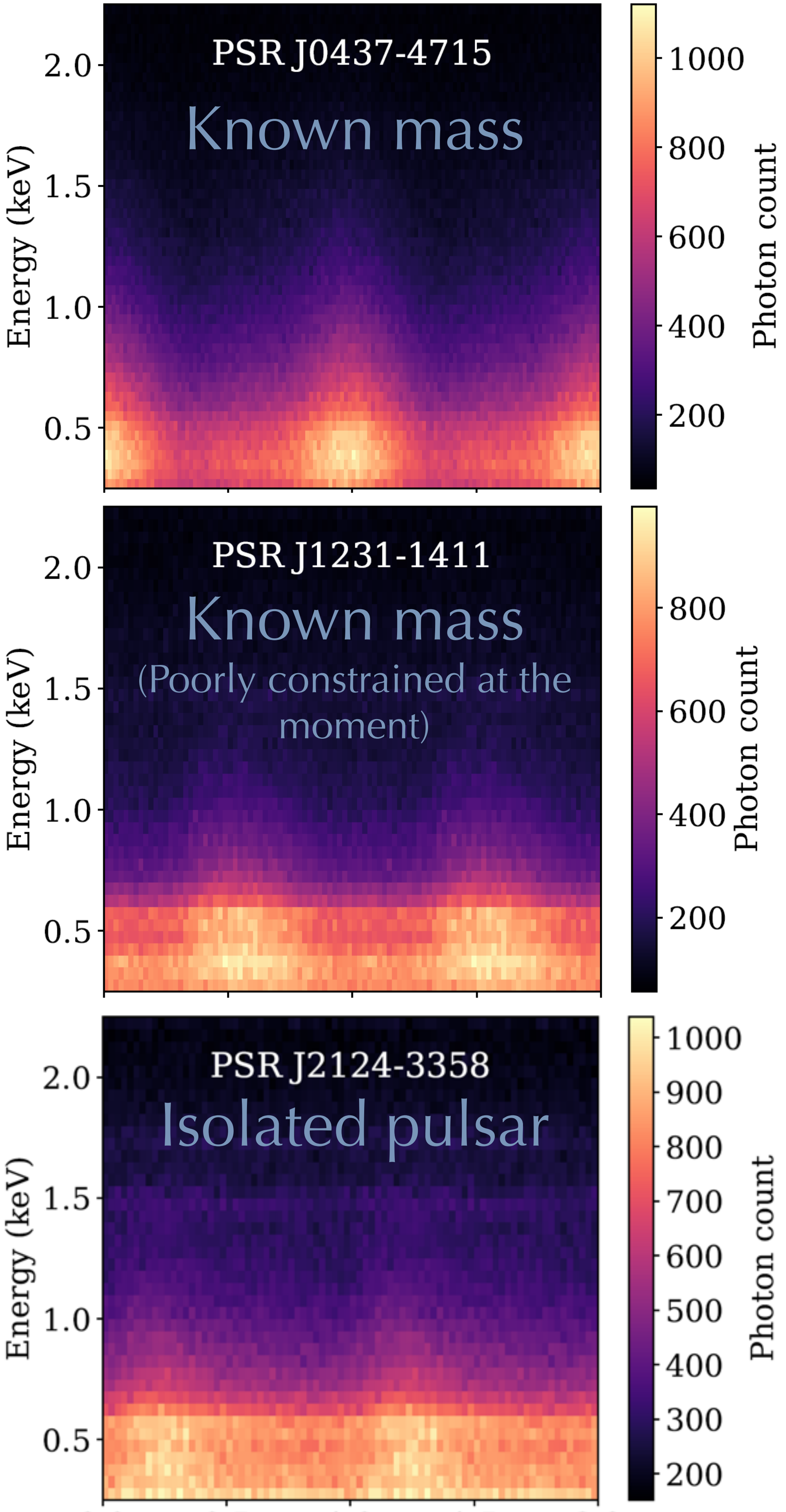


Wolff, SG et al 2021

Salmi et al. 2022, in press



There are still several pulsars observed by NICER to analyse.

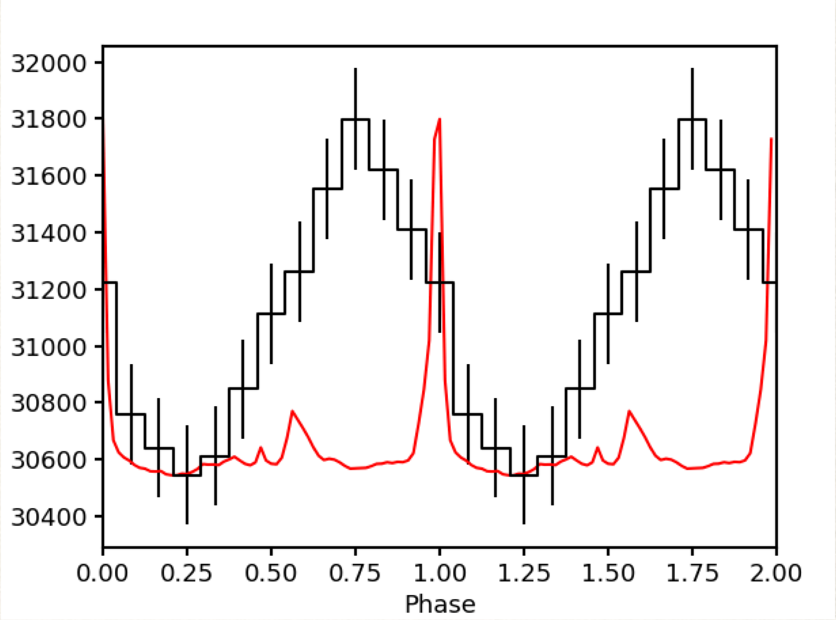


Bogdanov, SG et al. (2019)

PSR J1614-2230

Wolff, SG et al. 2021

Known high mass:
M = 1.908±0.016 Msun



Guillot et al. (2019)