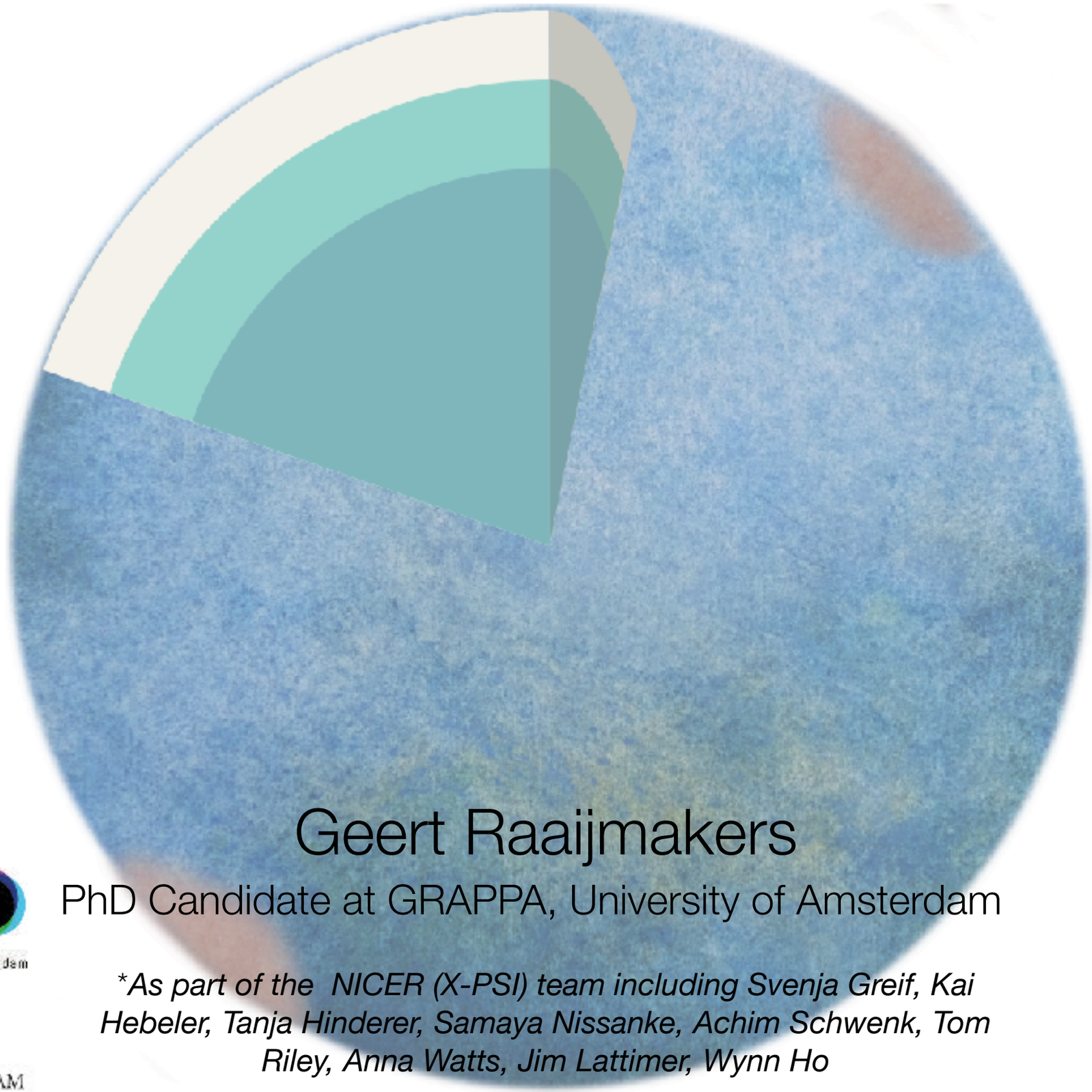
Equation of state constraints from *NICER* and multimessenger observations*



Geert Raaijmakers

PhD Candidate at GRAPPA, University of Amsterdam

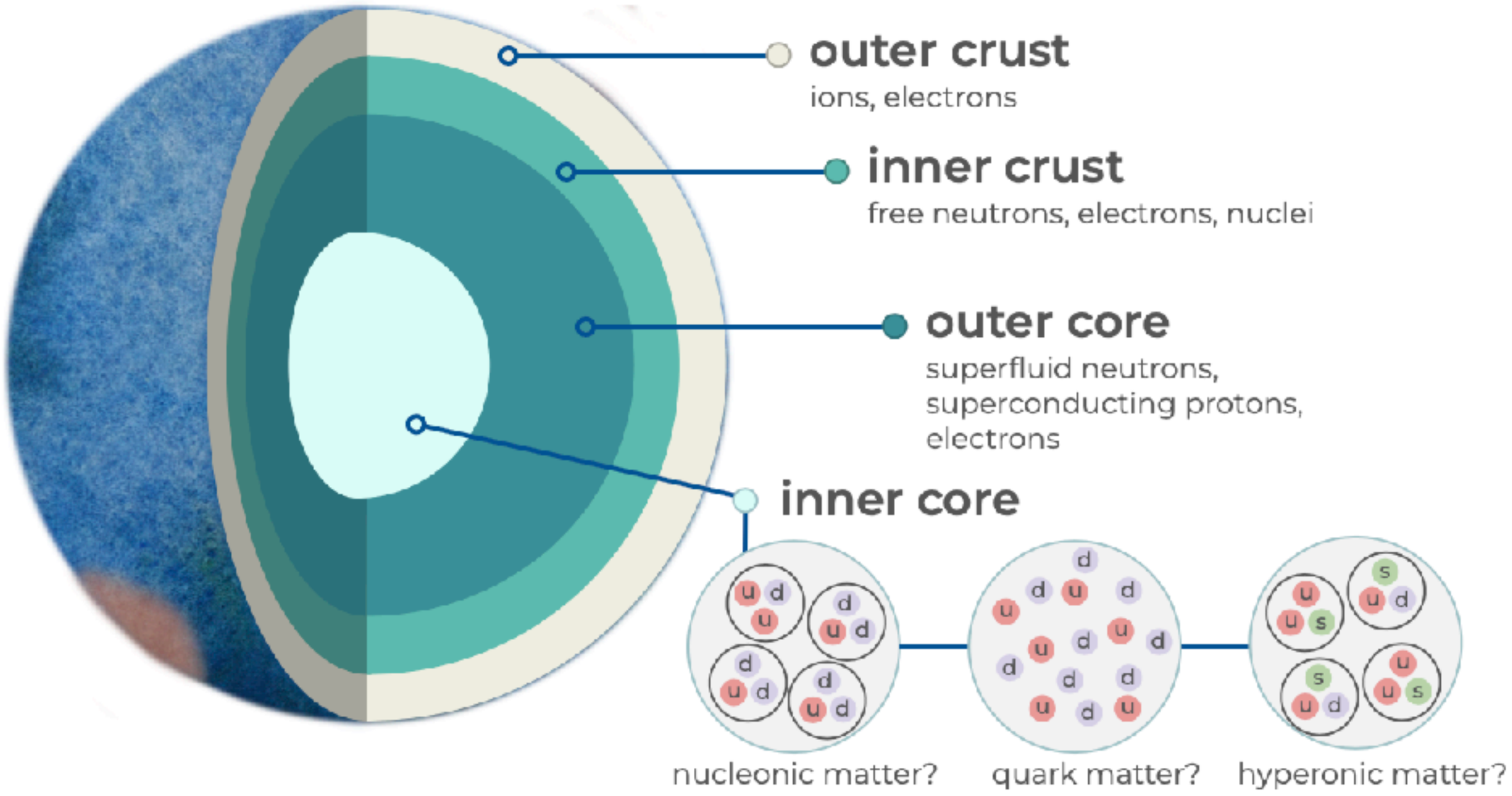
**As part of the NICER (X-PSI) team including Svenja Greif, Kai Hebeler, Tanja Hinderer, Samaya Nissanke, Achim Schwenk, Tom Riley, Anna Watts, Jim Lattimer, Wynn Ho*

GRAPPA

GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

Neutron stars as dense matter probes



QCD phase diagram

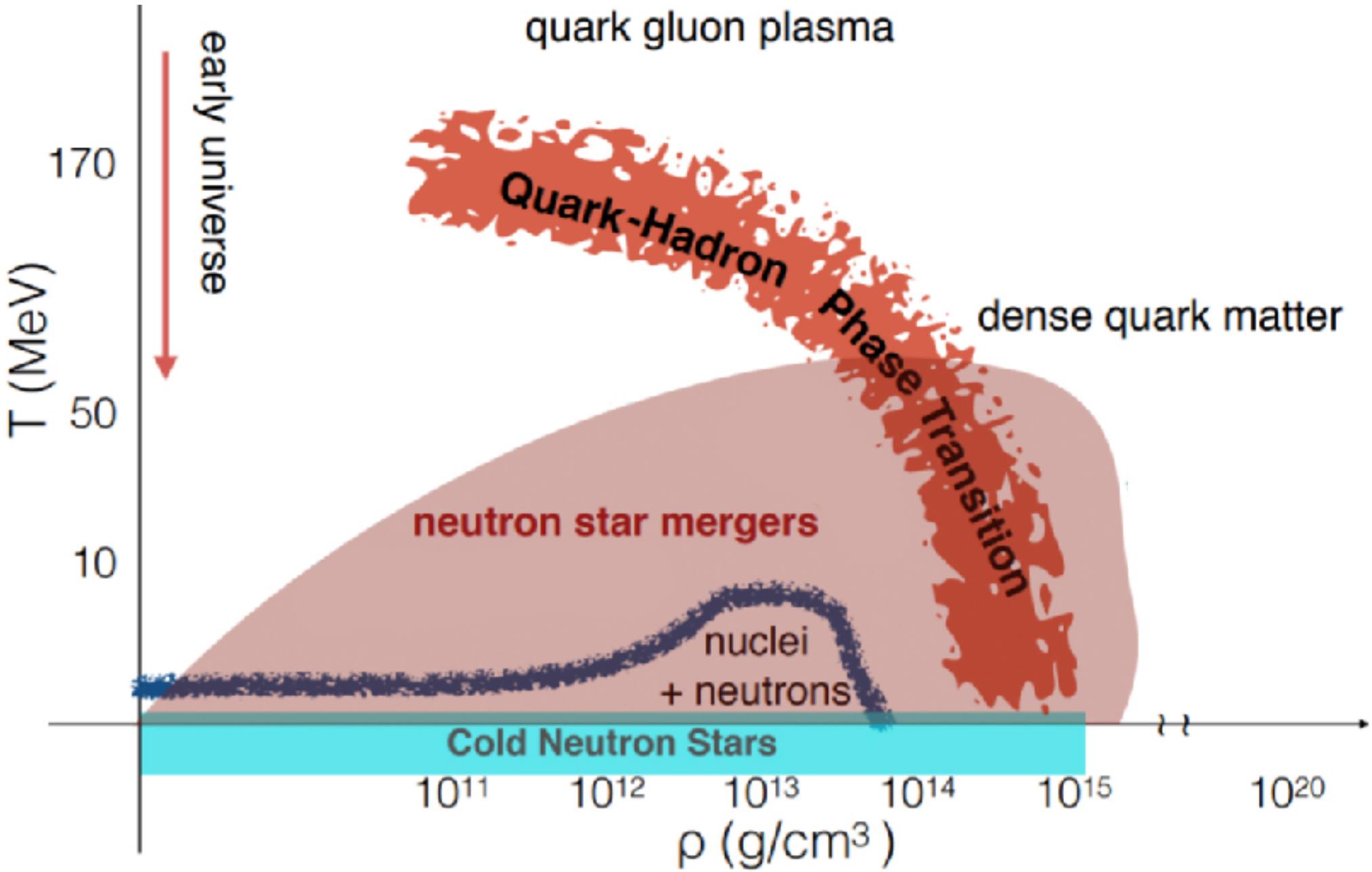
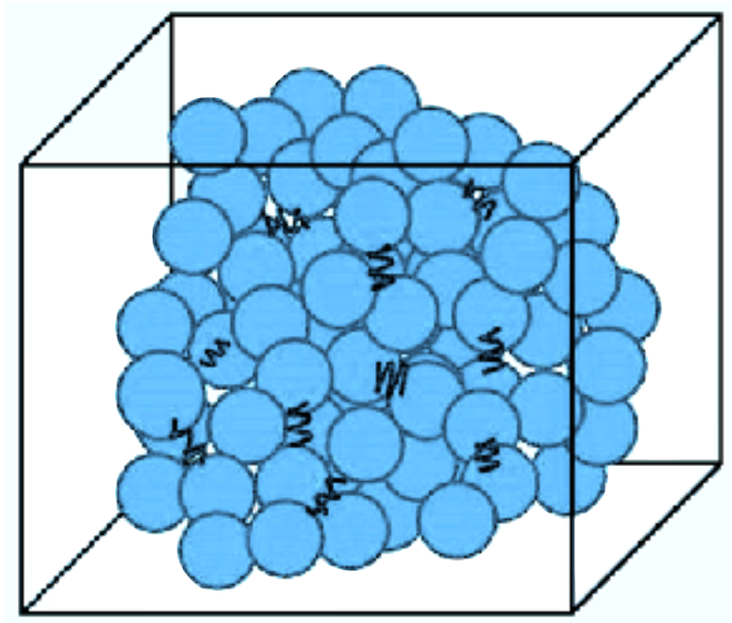


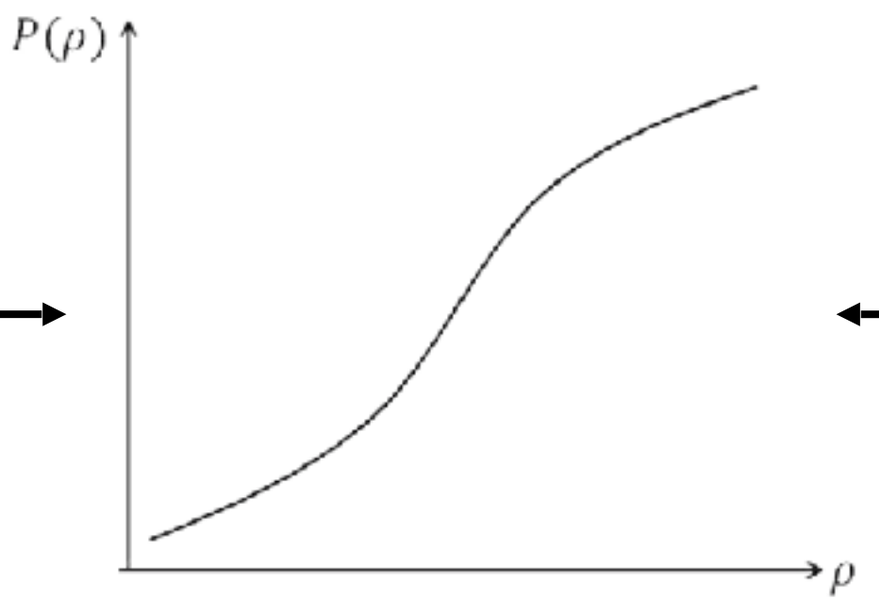
Image credit: S. Reddy

From nuclear physics to astrophysics

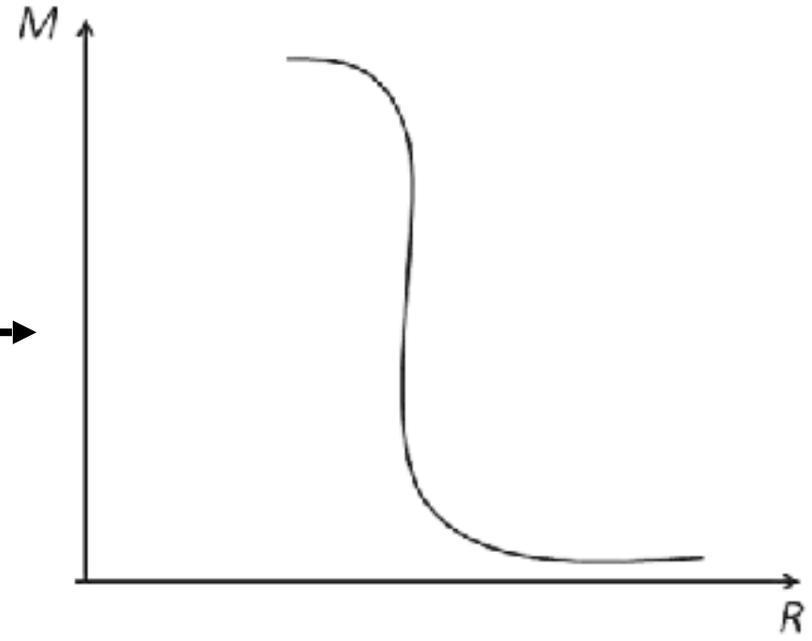
I. Dense Matter Physics

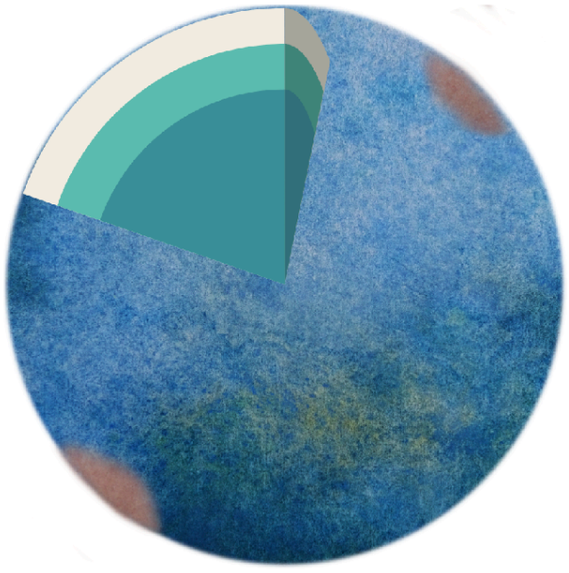


II. Equation of State



III. Mass and Radius





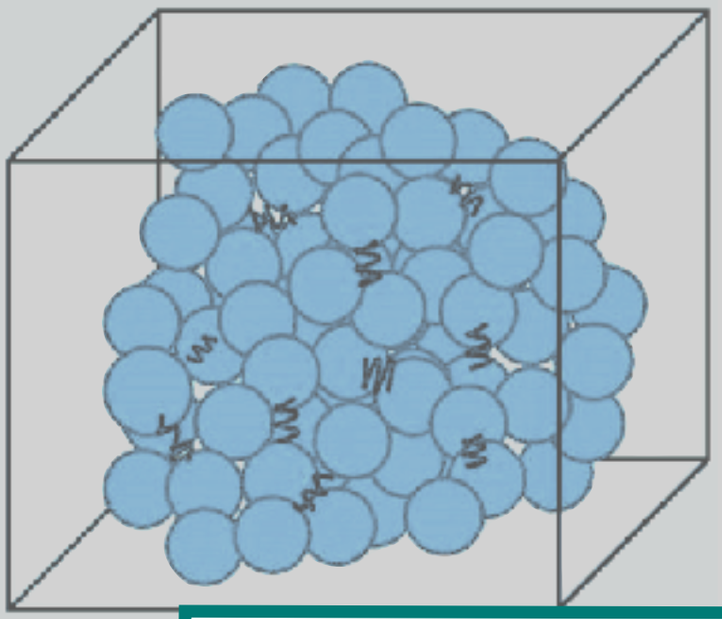
V. Neutron Star

IV. Observables

***See also talk by Serena Vinciguerra**

From nuclear physics to astrophysics

I. Dense Matter Physics



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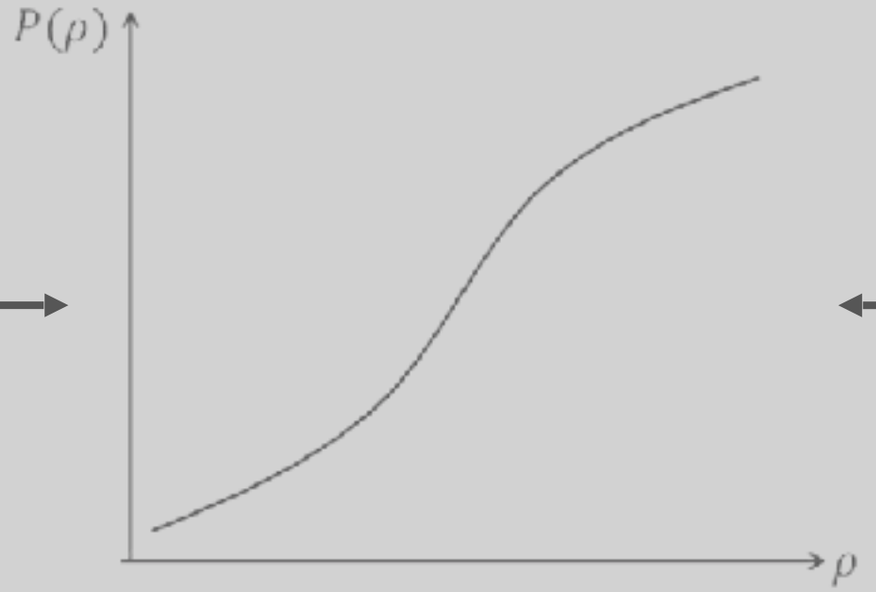

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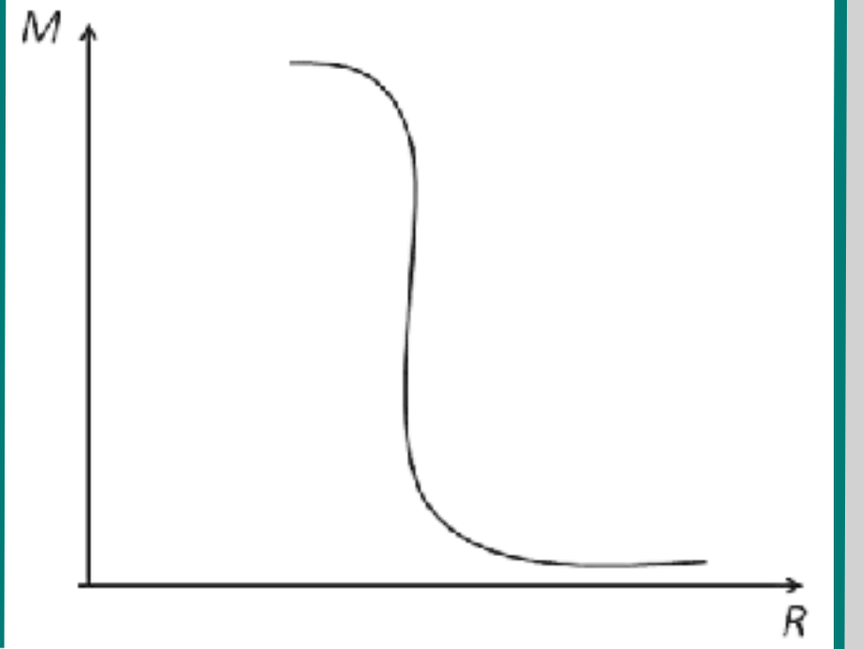
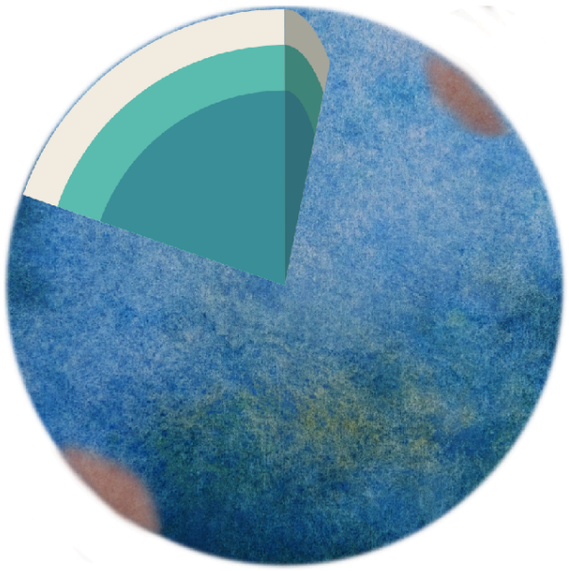


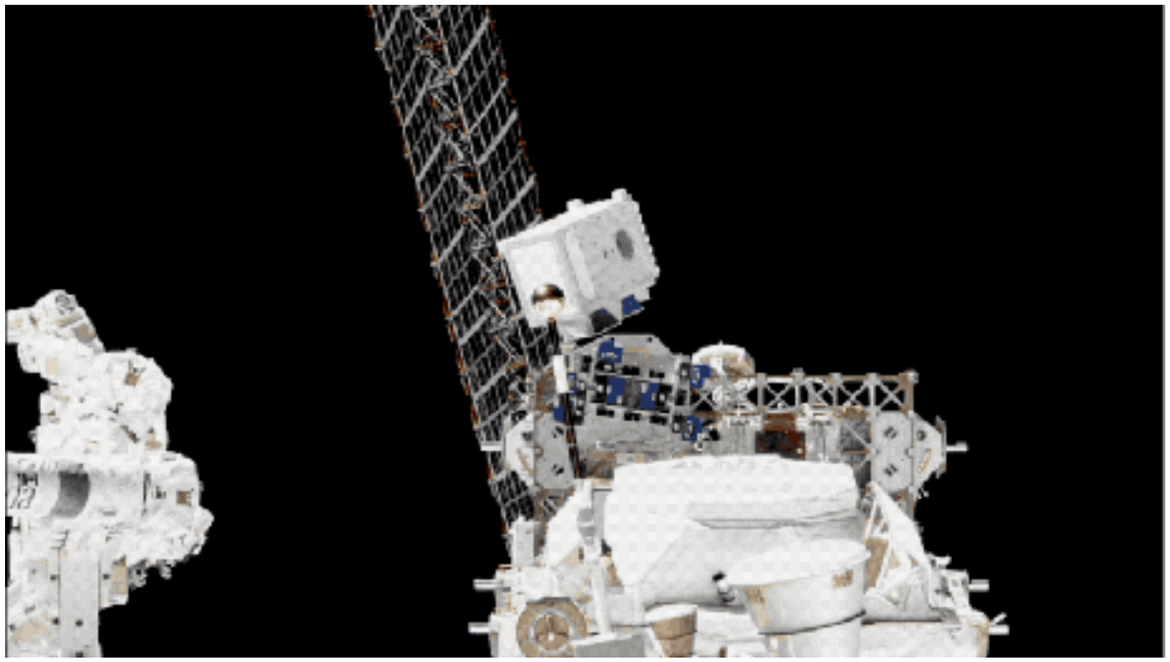


V. Neutron Star

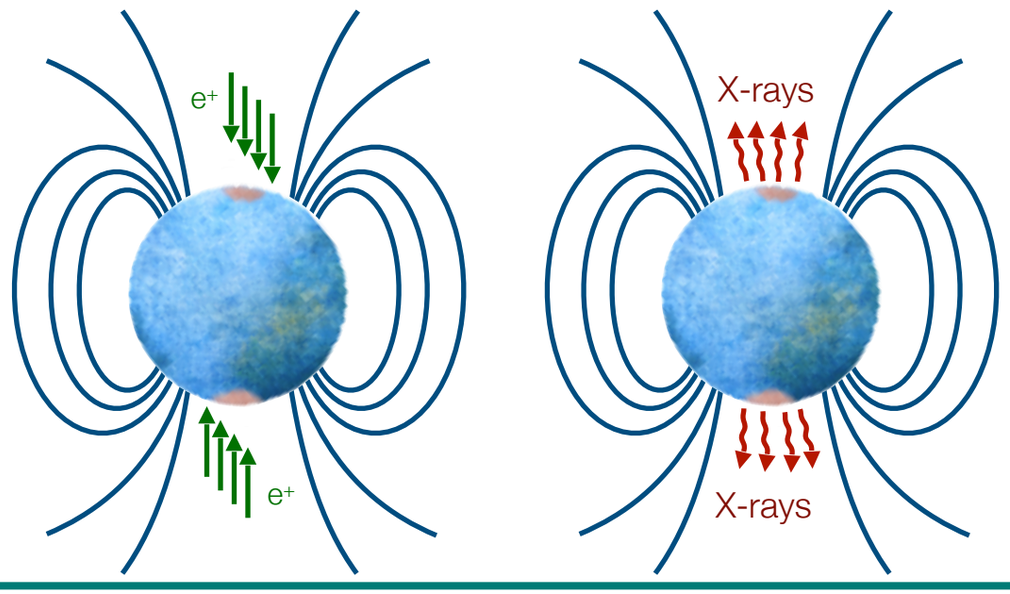
IV. Observables

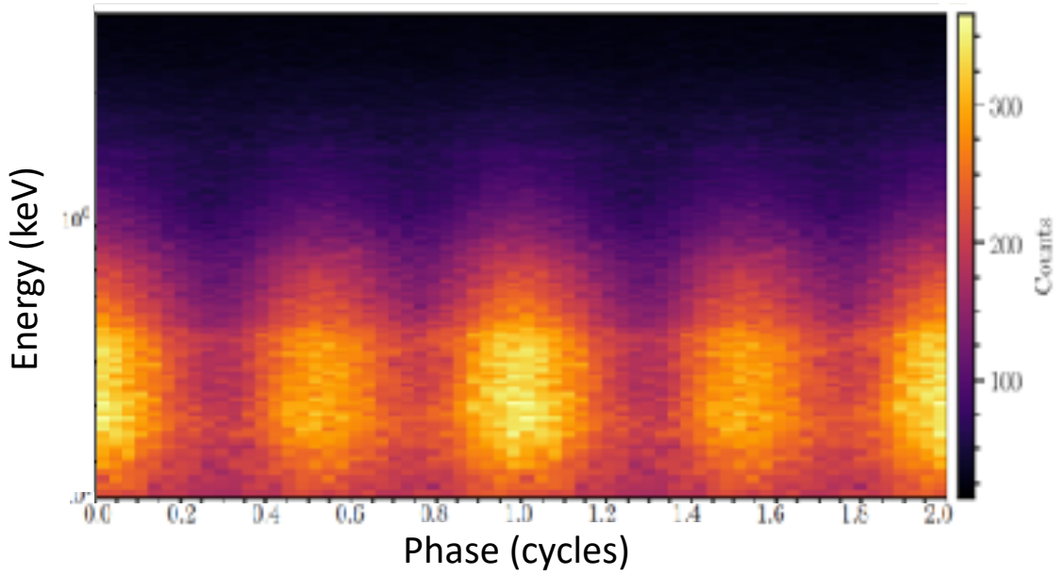
Neutron star **I**nterior **C**omposition **E**xplore**R**

- NASA mission launched in 2017
- Installed on board of the ISS
- Measuring both energy and time of arrival in 0.2 - 12 keV band



- Rotation-powered millisecond pulsars





Pulse profile modeling

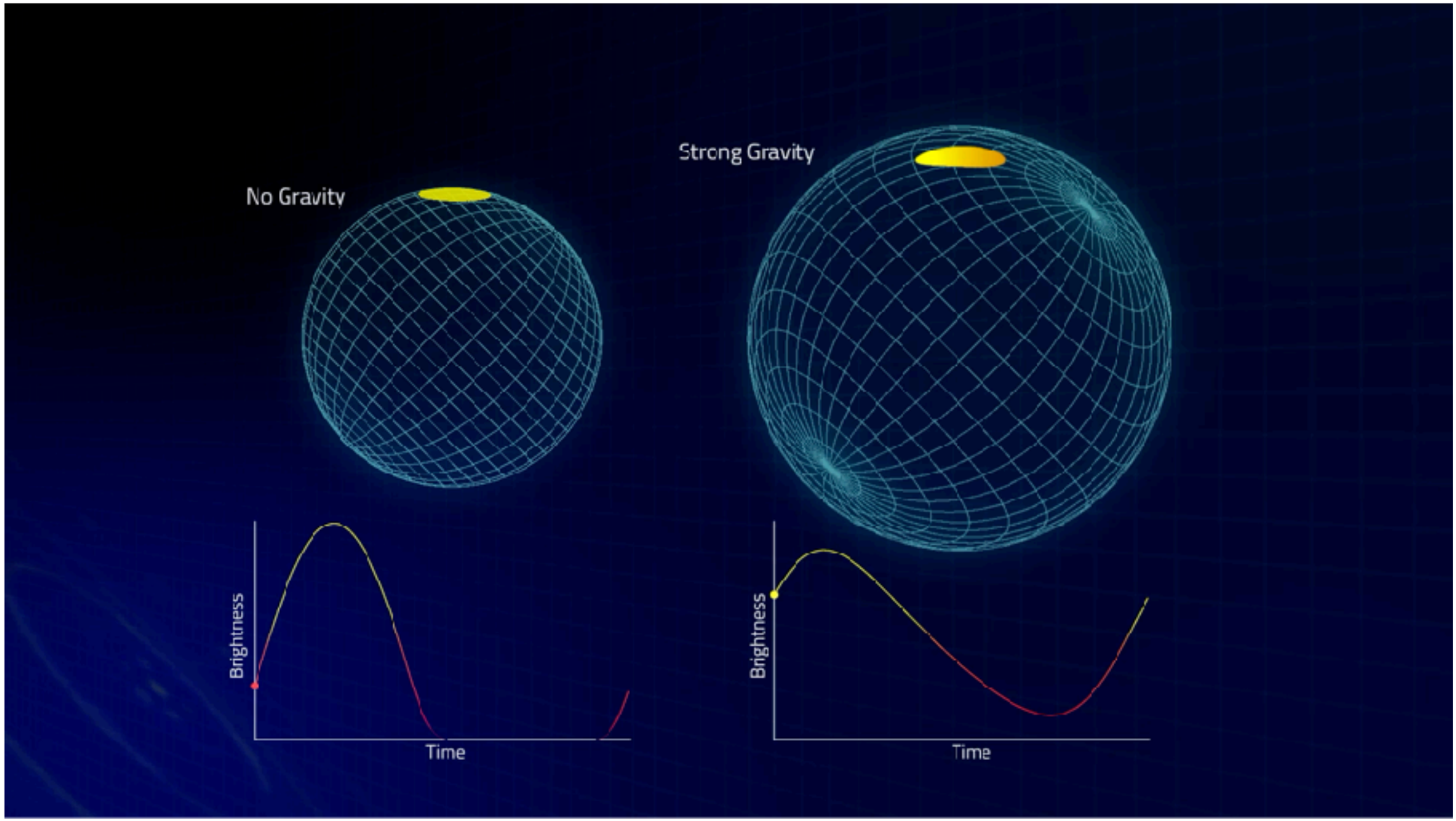


Image credit: Morsink/Moir/Arzoumanian/NASA

Mass-Radius measurements from NICER

PSR J0740+6620:

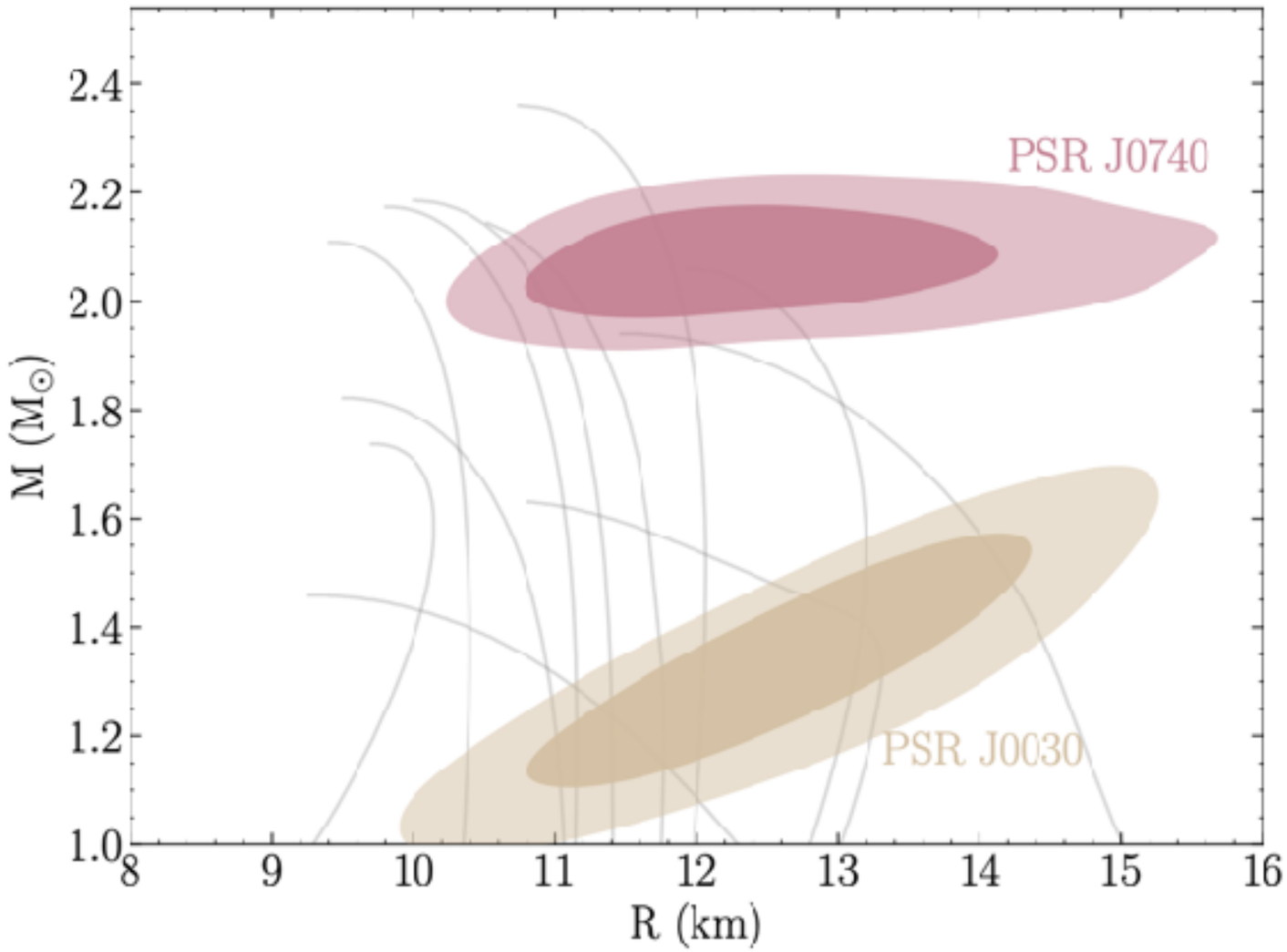
Radius = $12.39^{+1.30}_{-0.98}$

Mass = $2.072^{+0.067}_{-0.066}$

PSR J0030+0451:

Radius = $12.71^{+1.14}_{-1.19}$

Mass = $1.34^{+0.15}_{-0.16}$



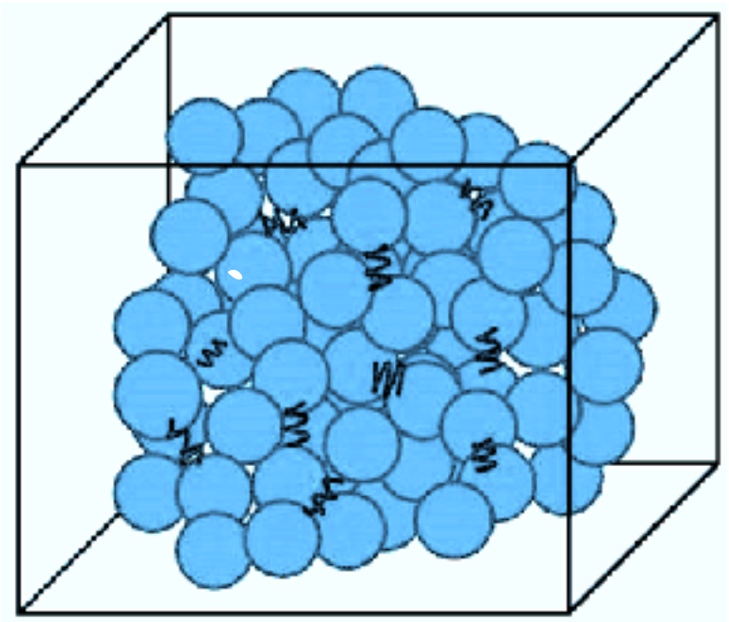
Riley et al. (2019), ApJL, 1912.05702 &
Riley et al. (2021), ApJL, 2105.06980

https://github.com/xpsi-group/xpsi

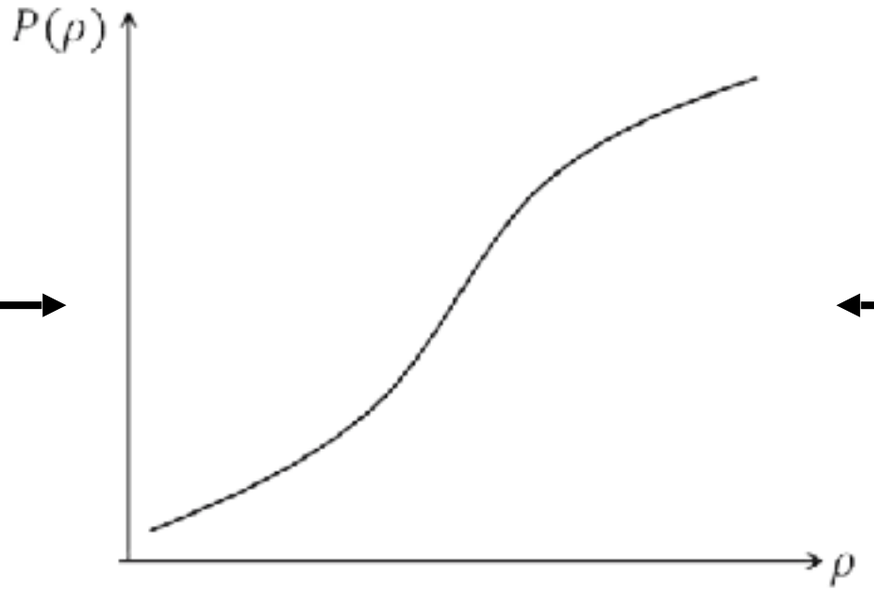
See also Miller et al. (2019) & Miller et al. (2021)

From nuclear physics to astrophysics

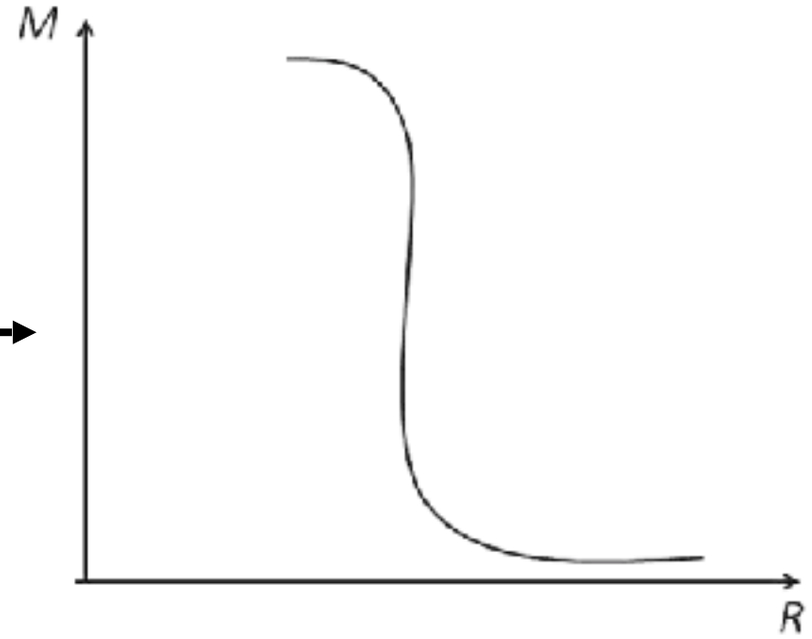
I. Dense Matter Physics

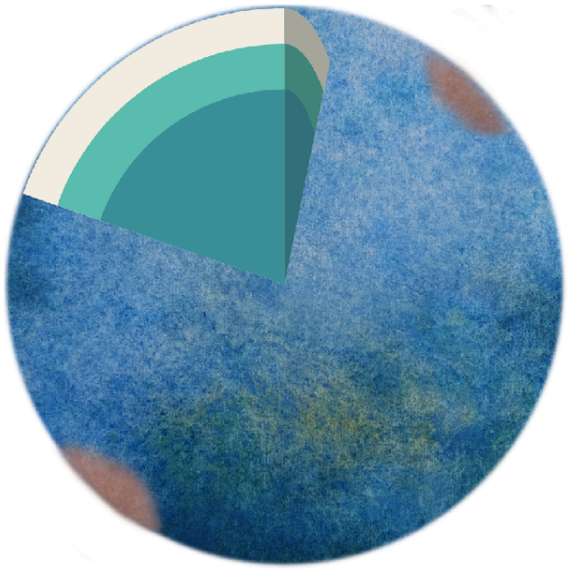


II. Equation of State



III. Mass and Radius



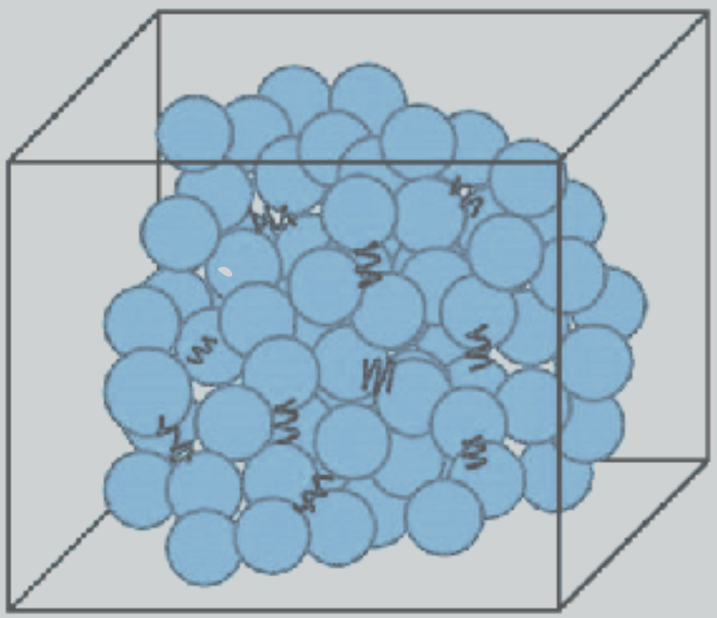


V. Neutron Star

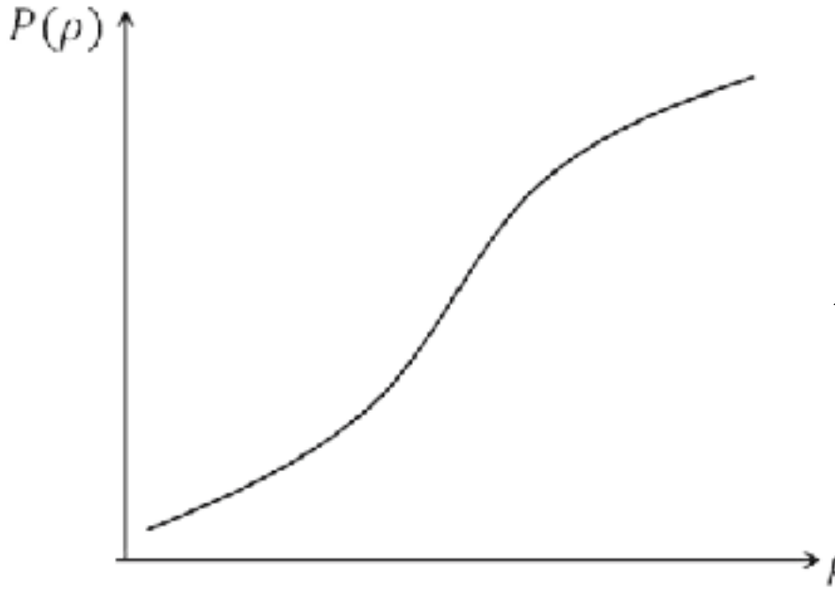
IV. Observables

From nuclear physics to astrophysics

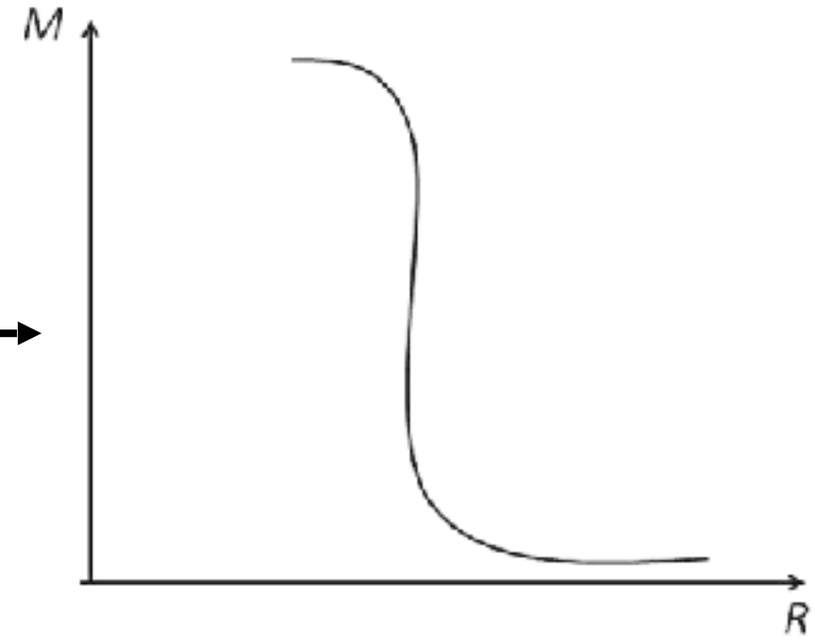
I. Dense Matter Physics

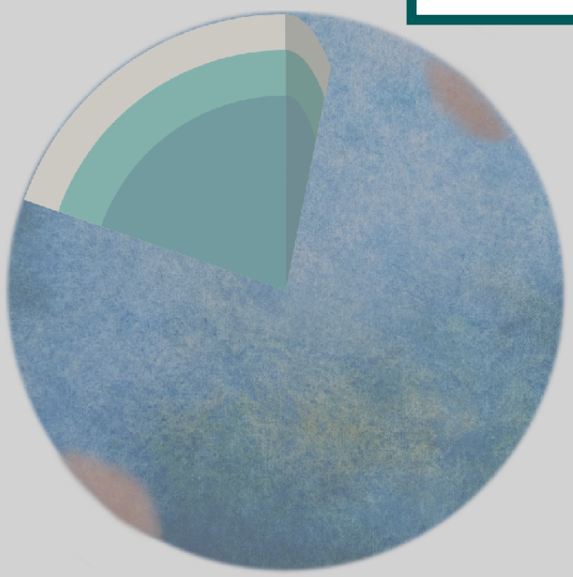


II. Equation of State



III. Mass and Radius





V. Neutron Star

IV. Observables

Theoretical equation of state models

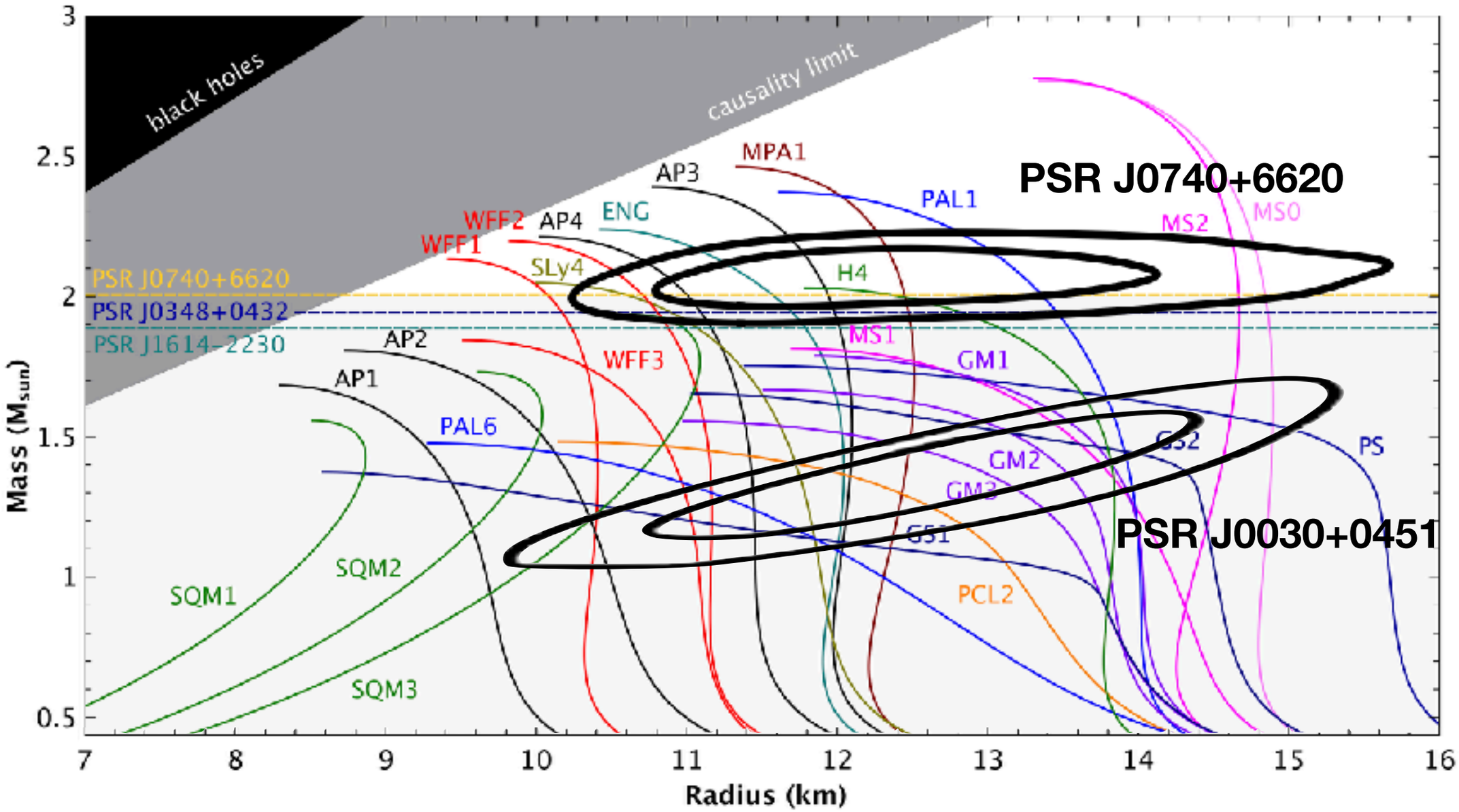


Image credit: Norbert Wax

Theoretical equation of state models

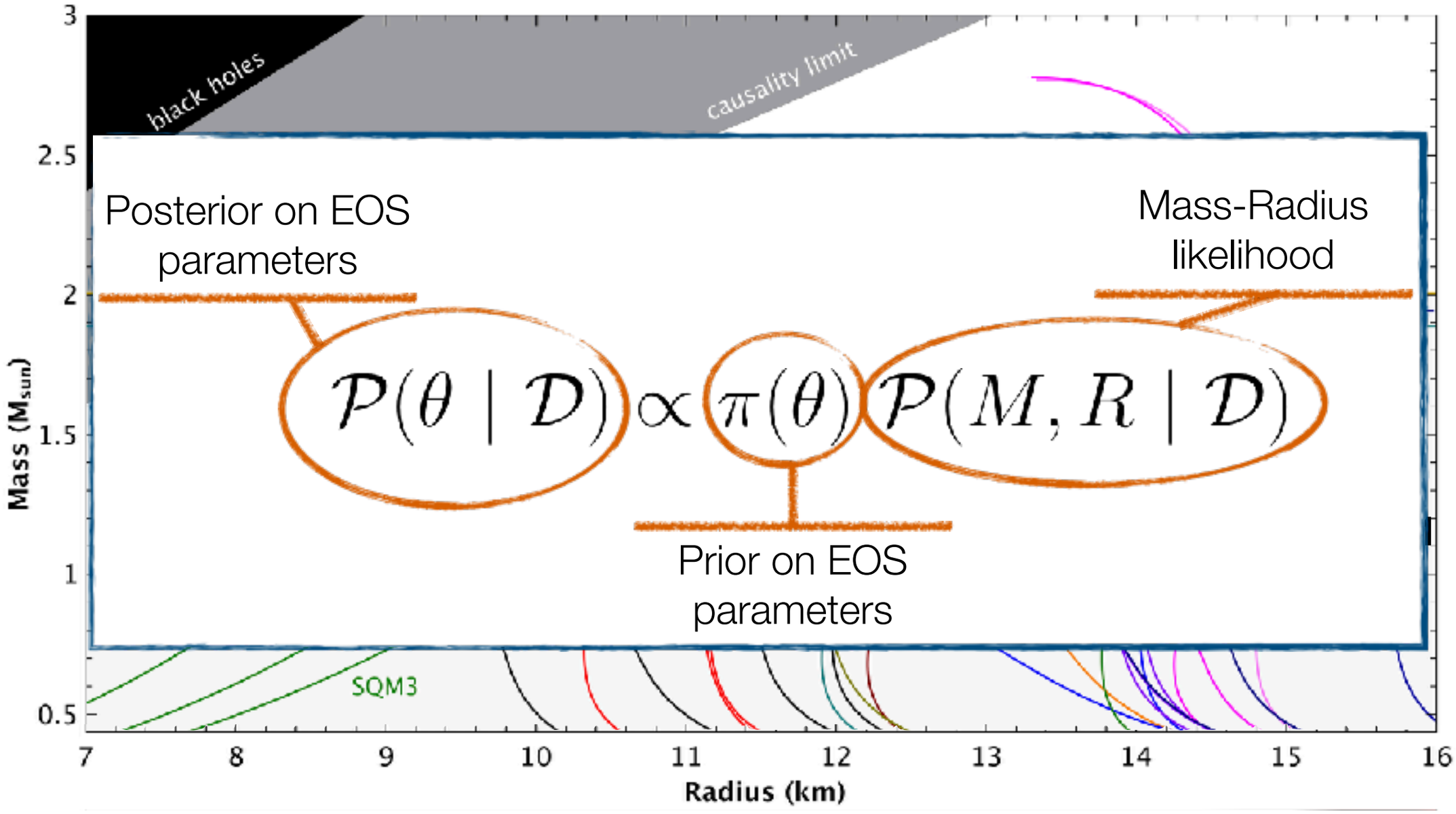
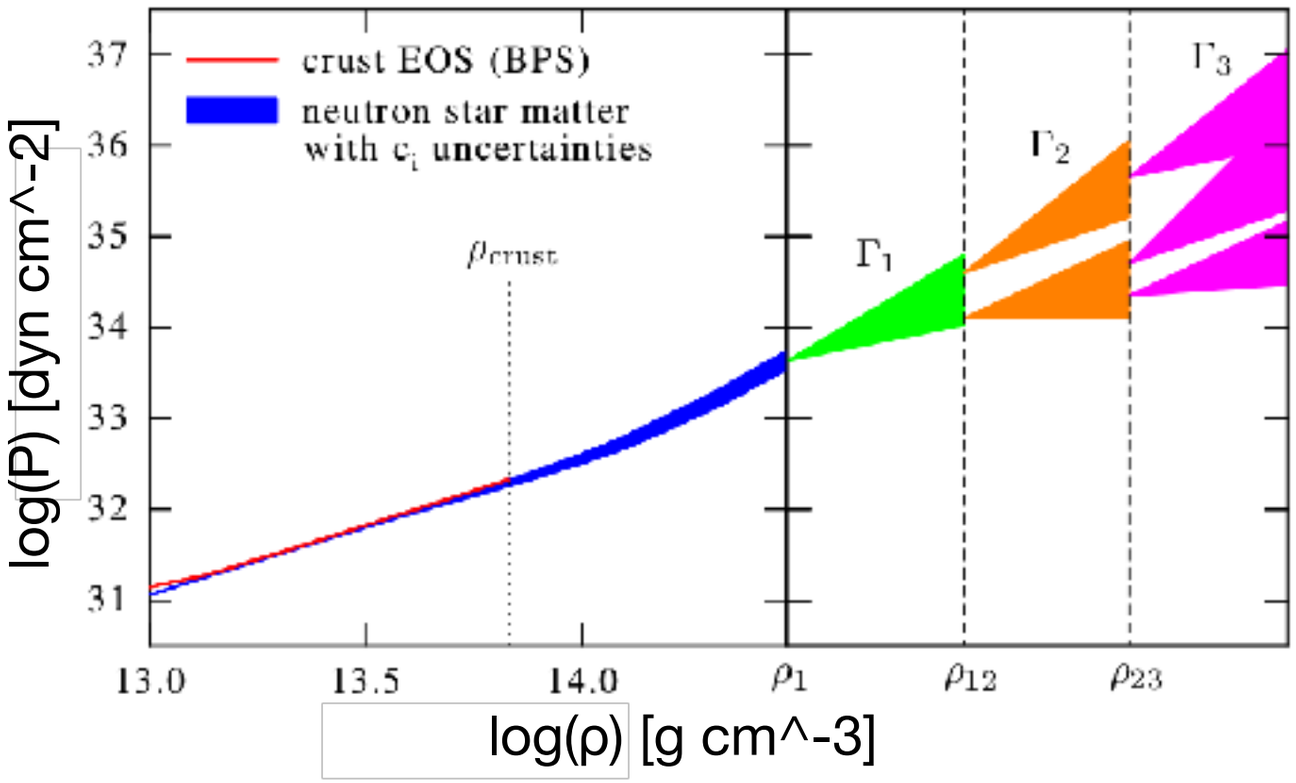


Image credit: Norbert Wax

EOS parameterizations

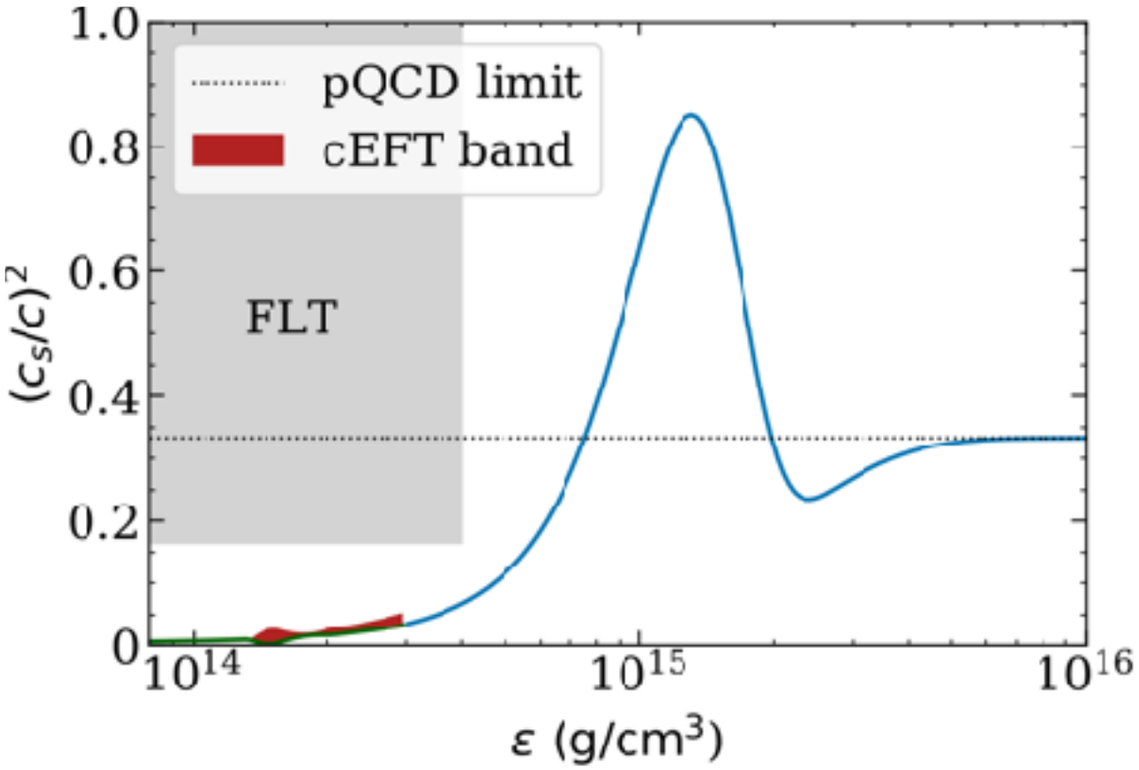
Piecewise polytropic model

Read et al. (2009), Hebeler et al. (2013)



Speed of sound model

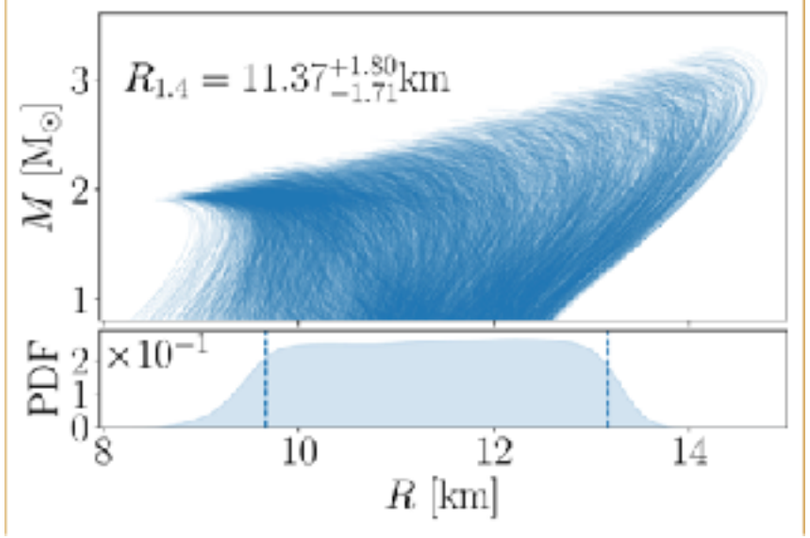
based on Bedaque & Steiner (2015)
see also Tews et al. (2018)



- Matched to low density EOS calculations around saturation density (cEFT)

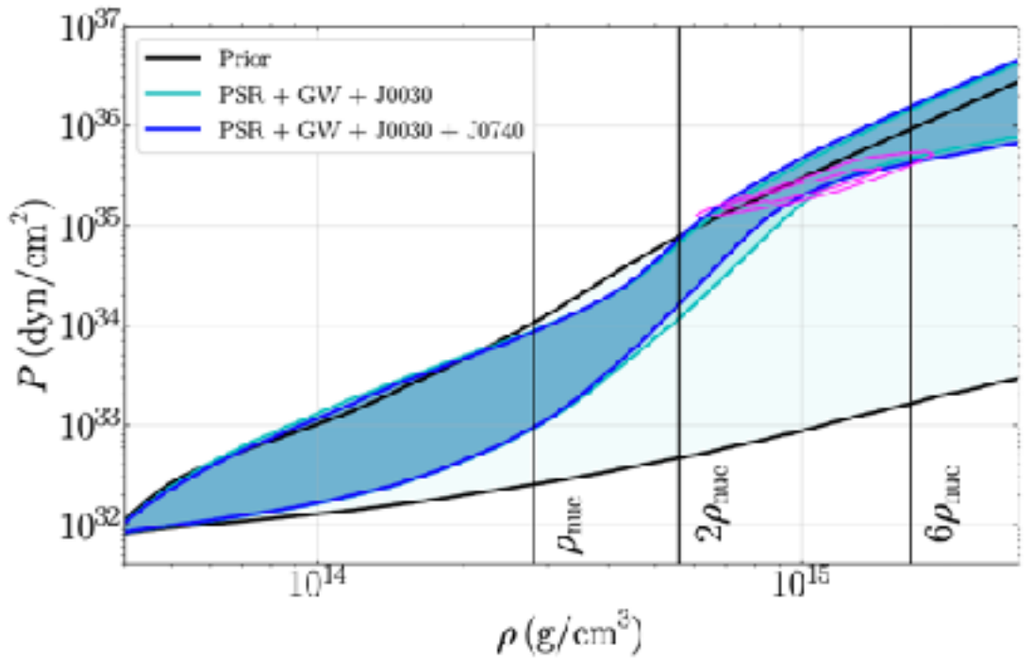
EOS parameterizations

(A) Chiral effective field theory:
EOS derived with the chiral EFT framework



- Discrete sampling of precomputed set of EoS

Capano et al. (2020), Dietrich et al. (2020)



- Non-parametric EoS inference

Landry & Essick (2018), Miller et al. (2021), Legred et al. (2021)

log(P) [dyn cm^{-2}]

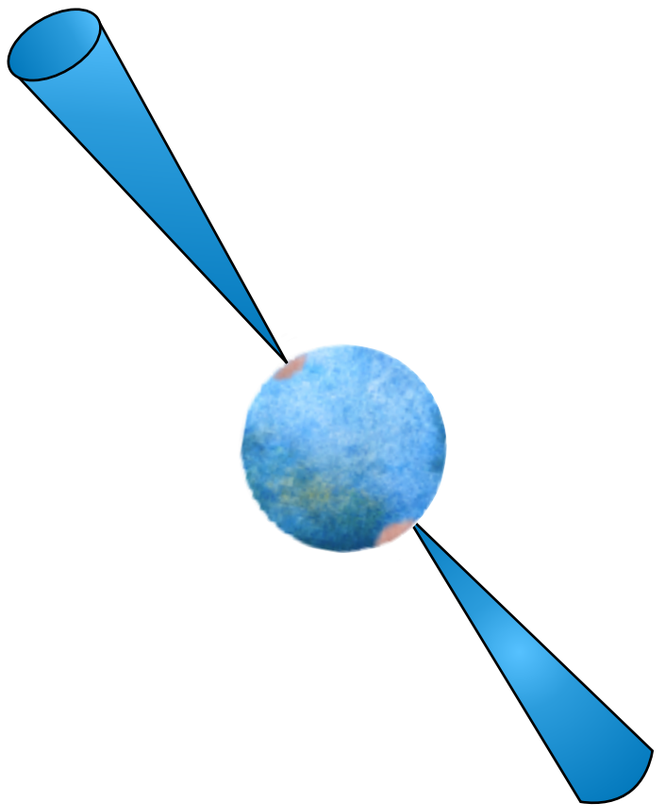
16

Multimessenger Observables

Radio timing

Mass measurement PSR J0740

Fonseca et al. (2021), 2104.00880

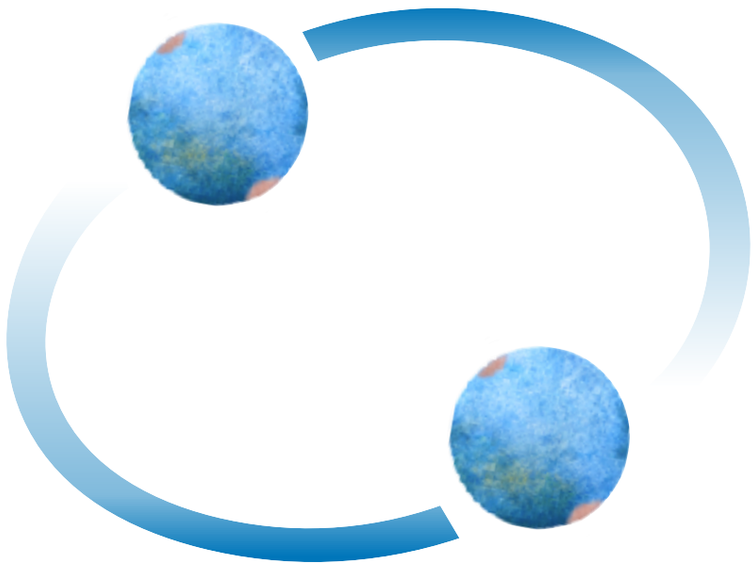


Radio pulsars

Gravitational wave signals

Tidal deformability measurement

GW170817 & GW190425



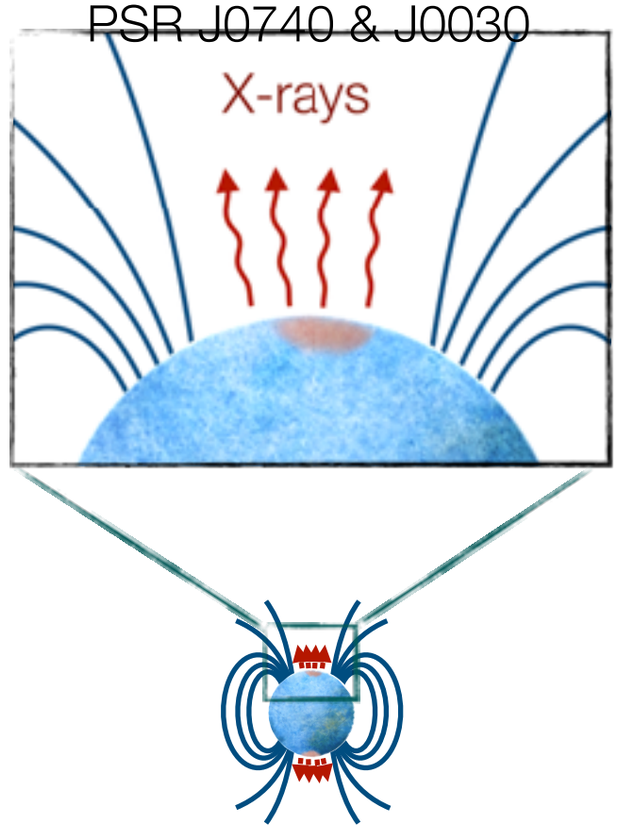
Binary neutron star &

black hole - neutron star mergers

X-ray pulse profile modeling

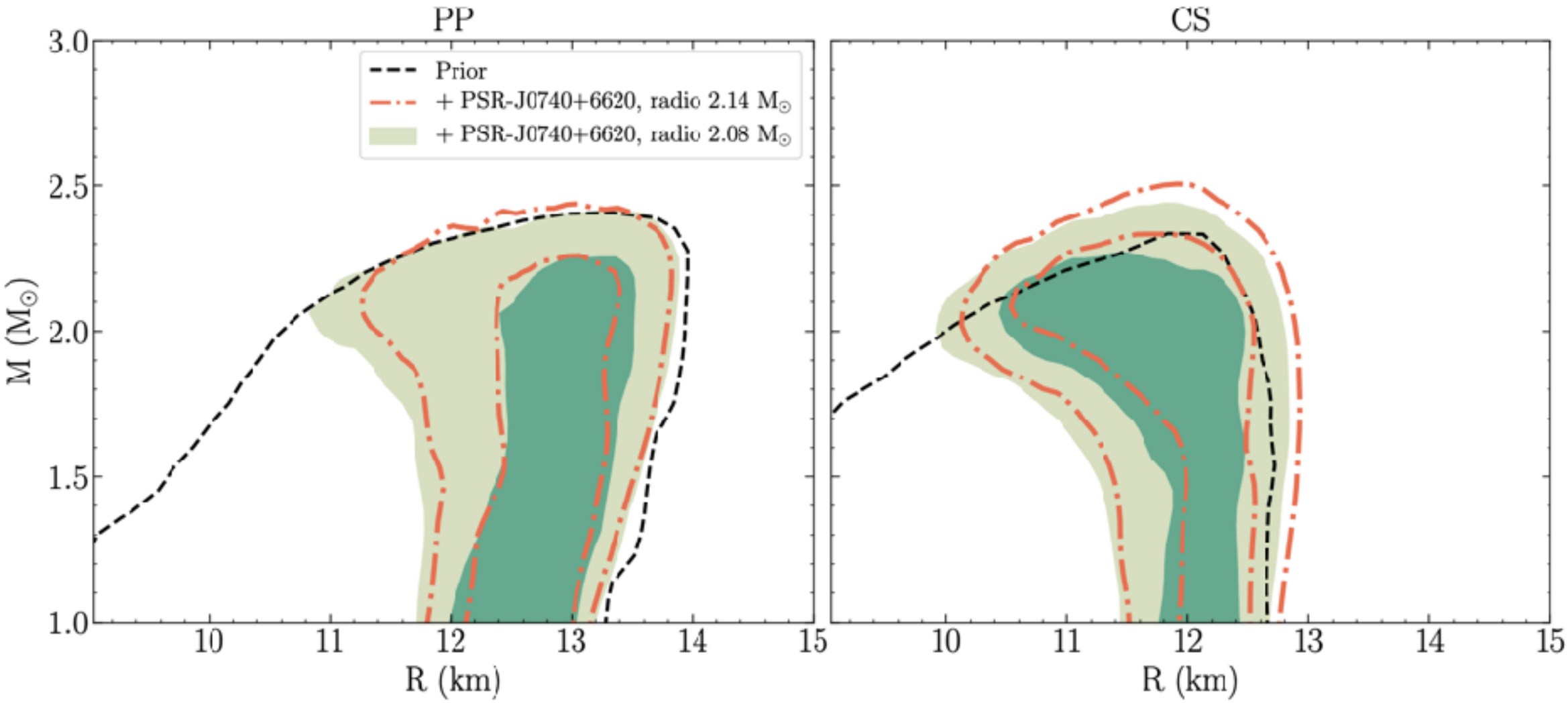
Mass-radius measurement

PSR J0740 & J0030



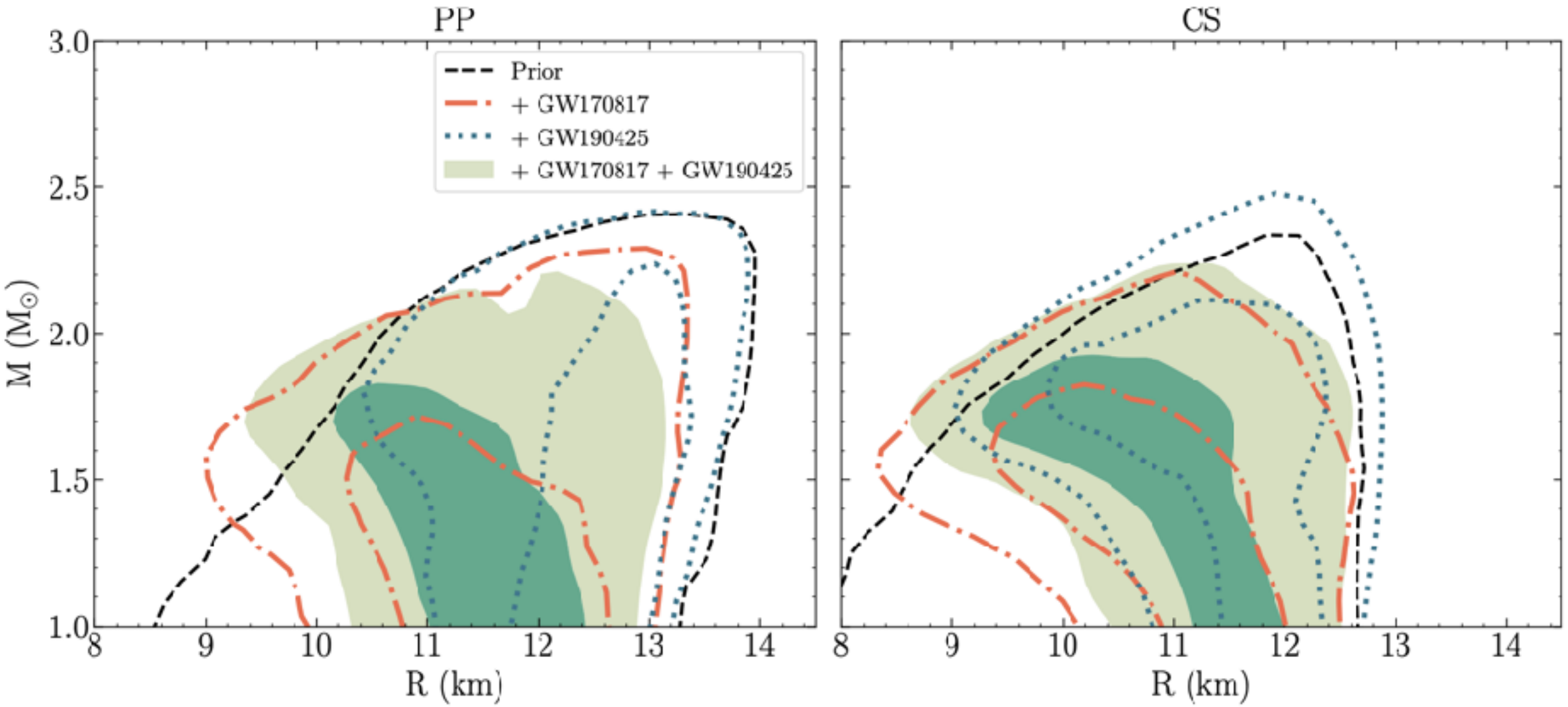
X-ray pulsars

EoS constraints - radio timing



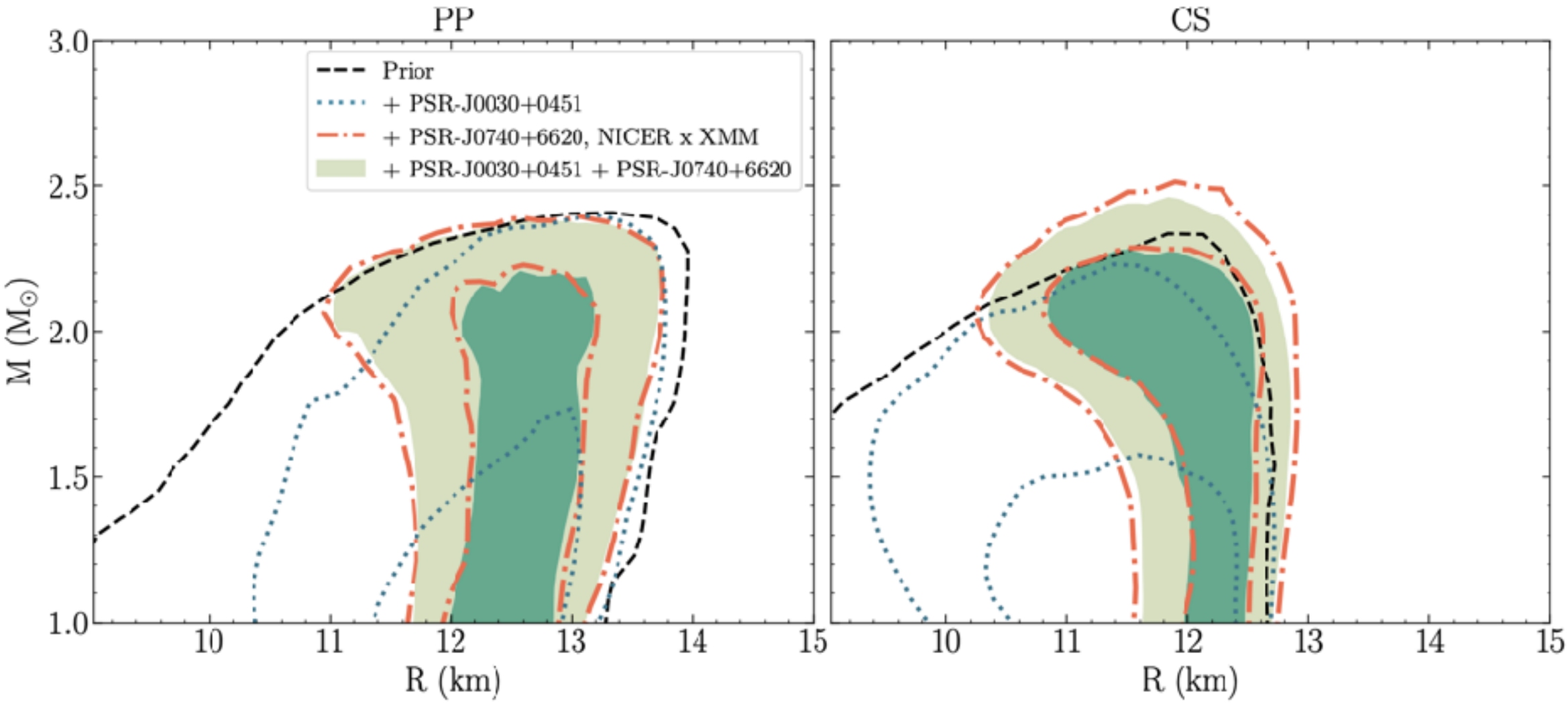
- Updated mass measurement of PSR J0740-6620 (Fonseca et al. 2021)

EoS constraints - Gravitational waves



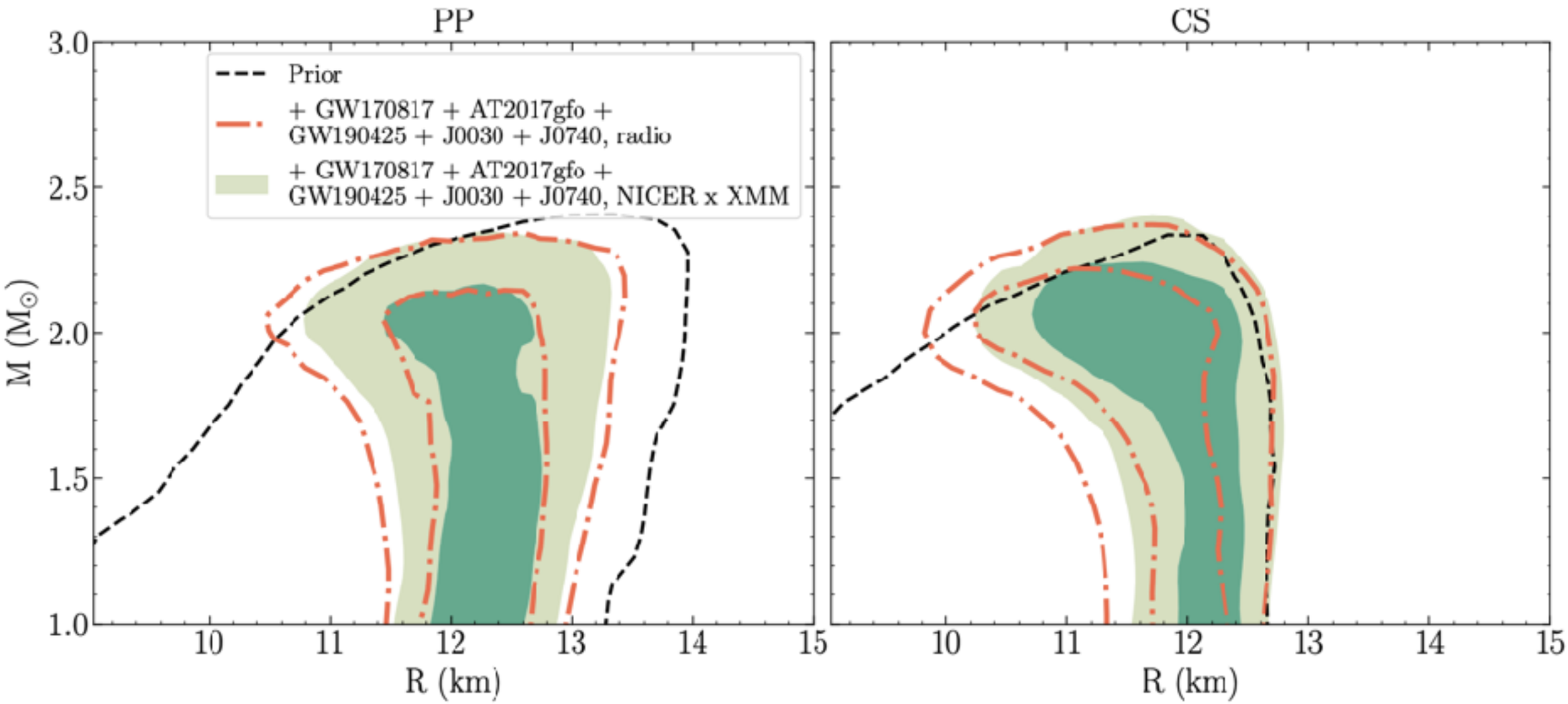
- Binary neutron star mergers GW170817 and GW190425

EoS constraints - Pulse profile modeling



- NICER x XMM measurement PSR J0740+6620 and NICER measurement PSR J0030+0451

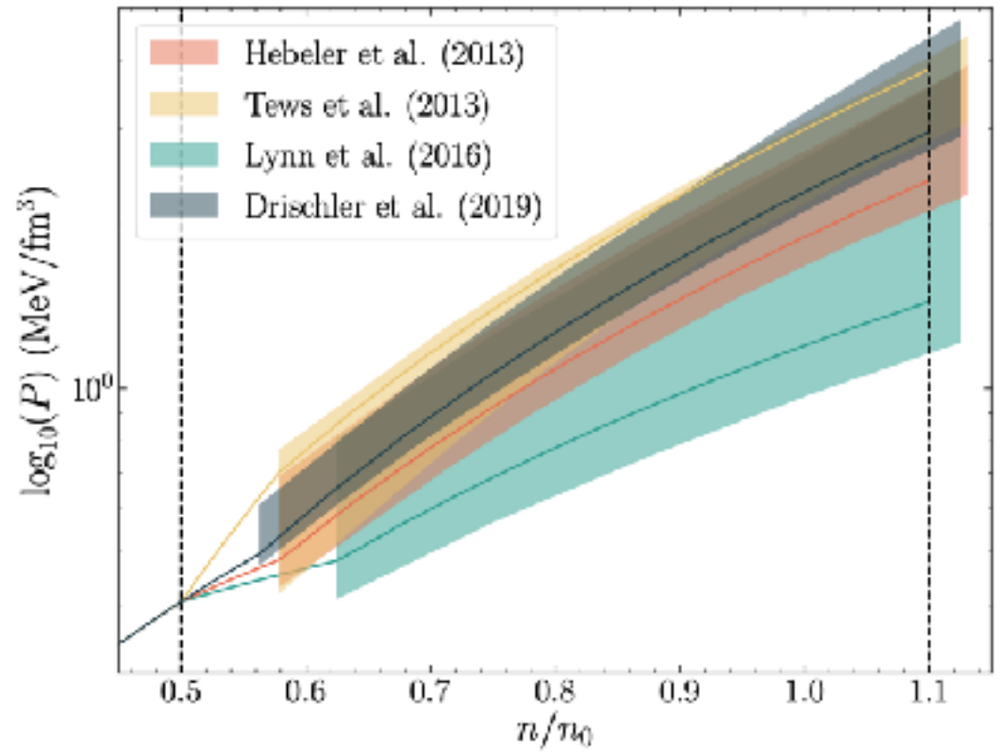
EoS constraints - Multimessenger contributions

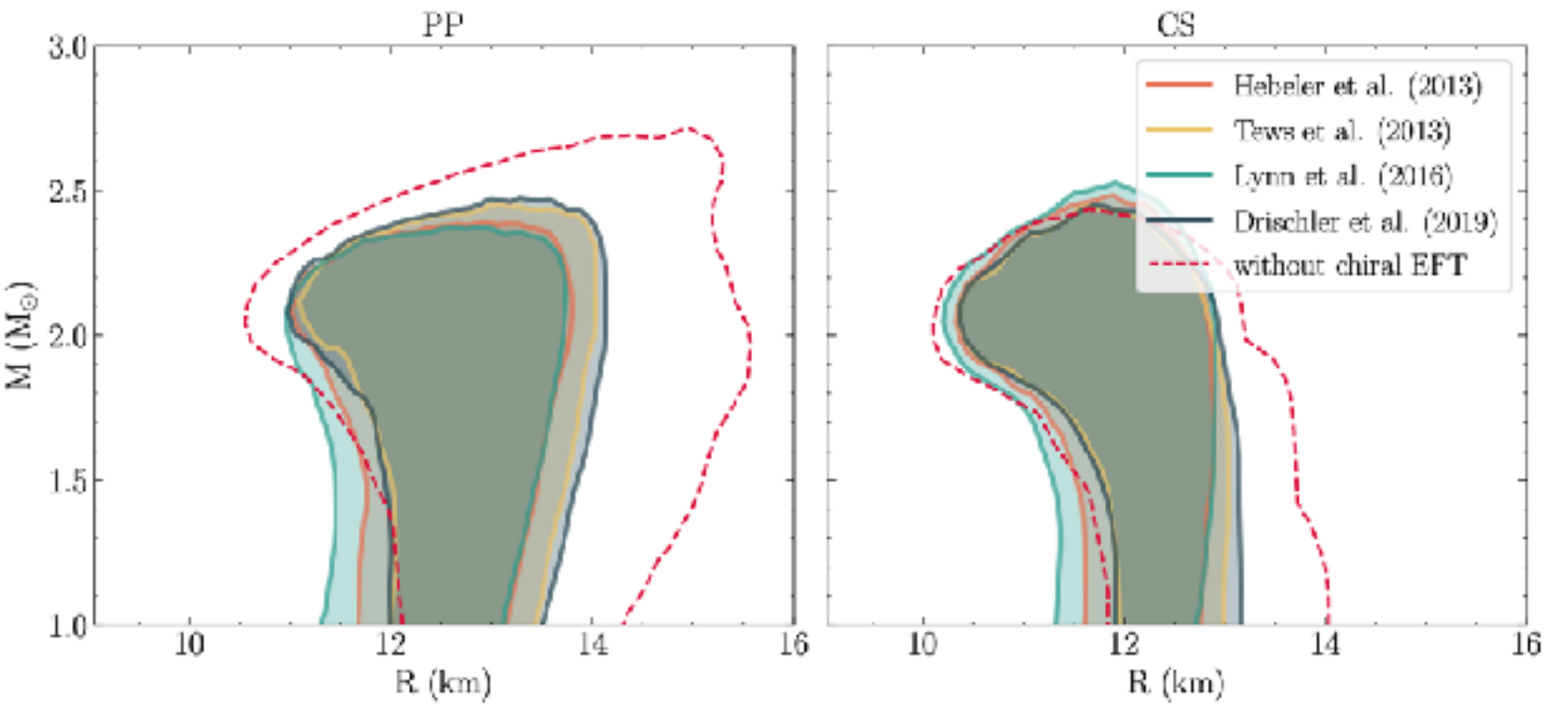


- Combining all previously known observables shows impact of PSR J0740+6620

Impact of low-density EoS calculations

- 4 neutron star matter calculations at low density using chiral EFT
- Approximated with single polytrope up to $1.1n_0$

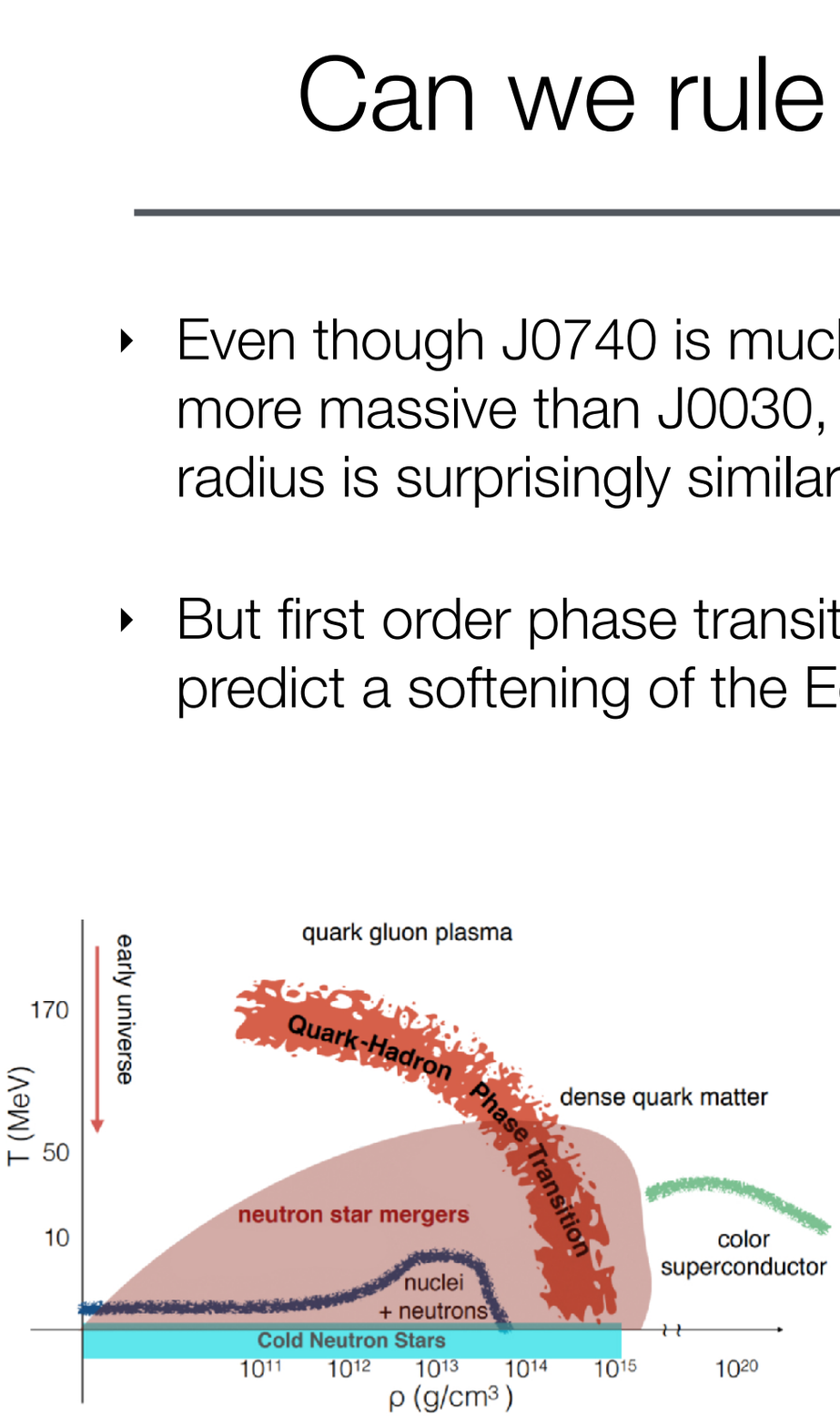


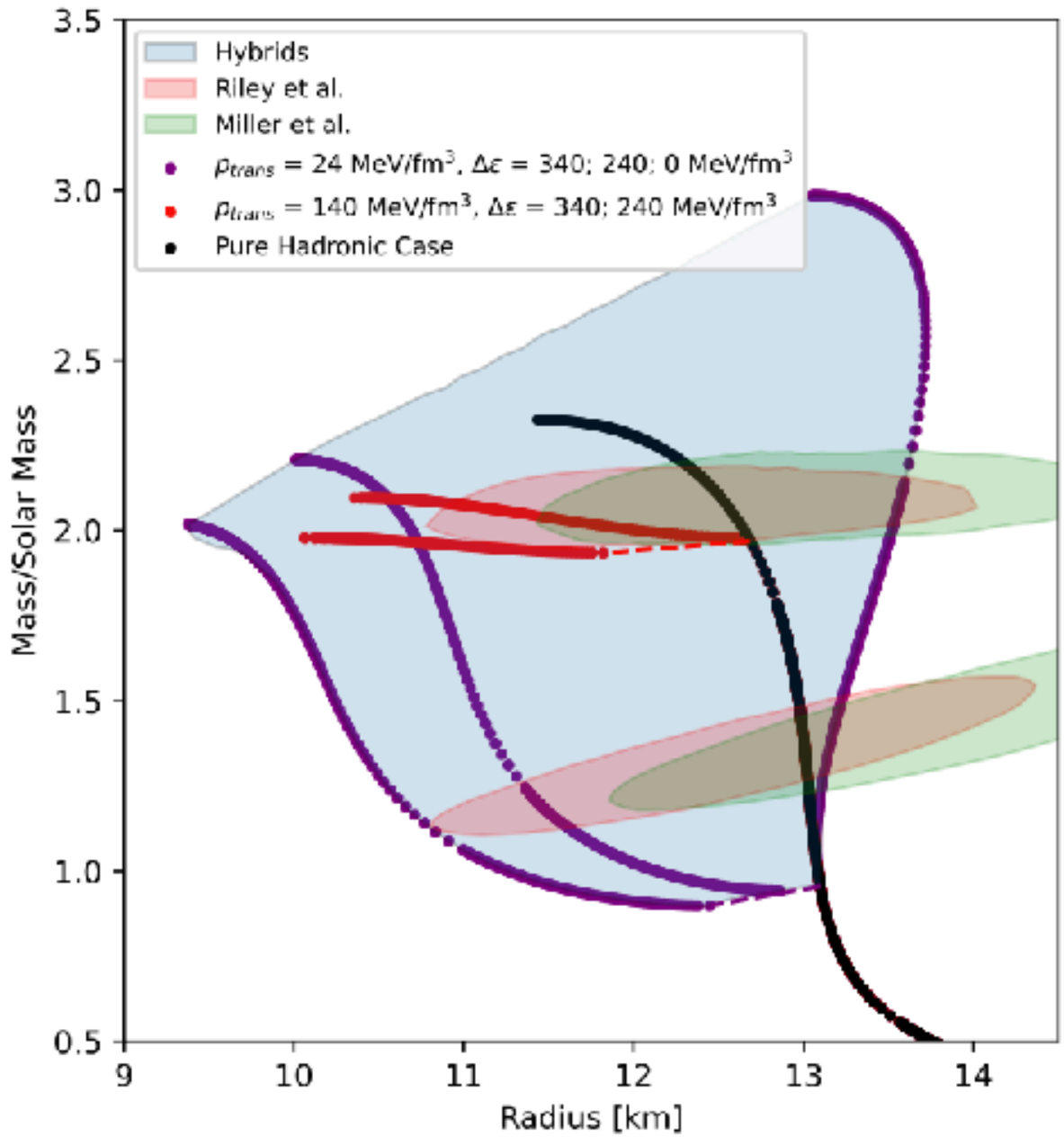


- Uncertainties of the order of 0.5 km

Can we rule out a phase transition?

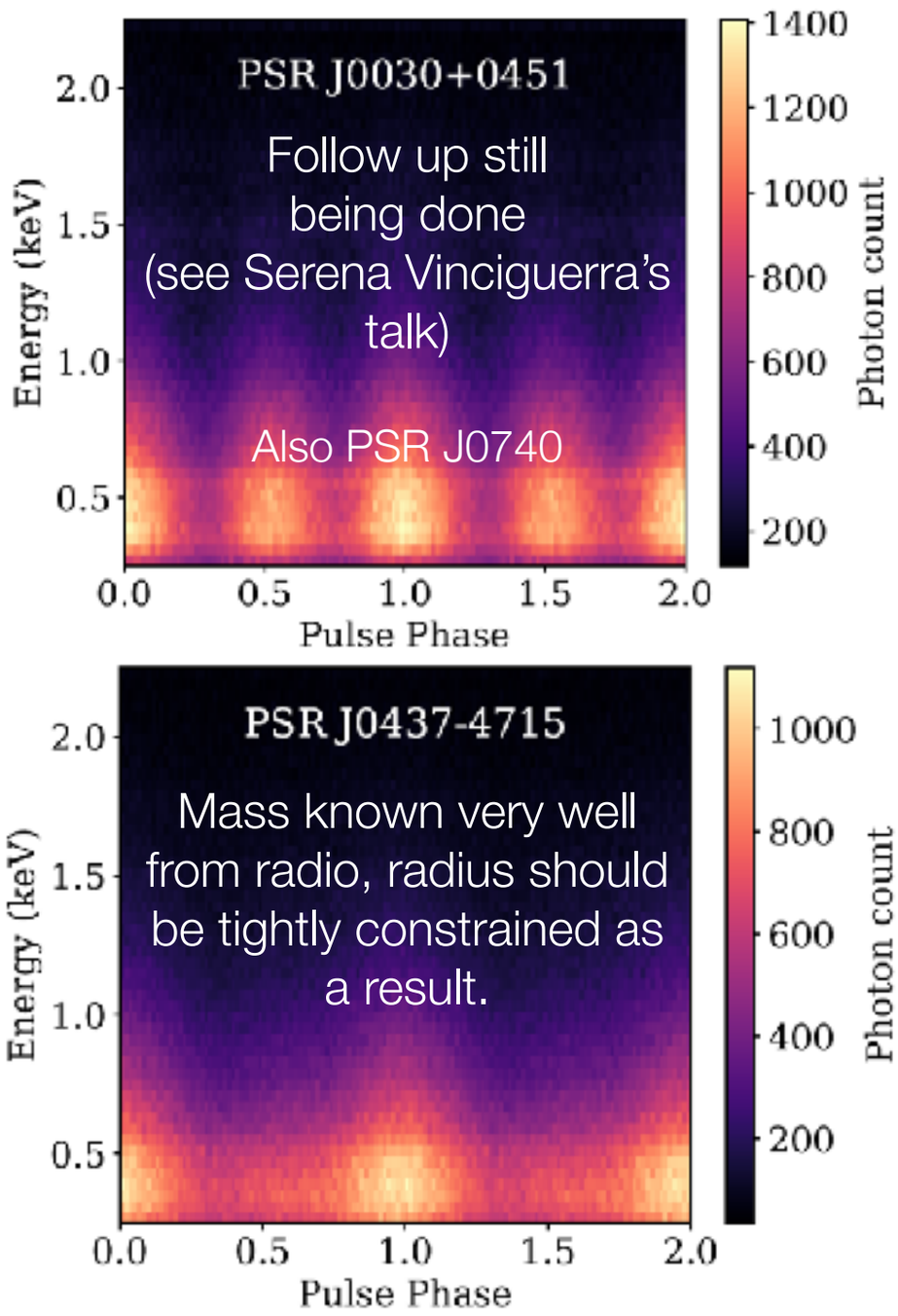
- Even though J0740 is much more massive than J0030, radius is surprisingly similar
- But first order phase transitions predict a softening of the EoS

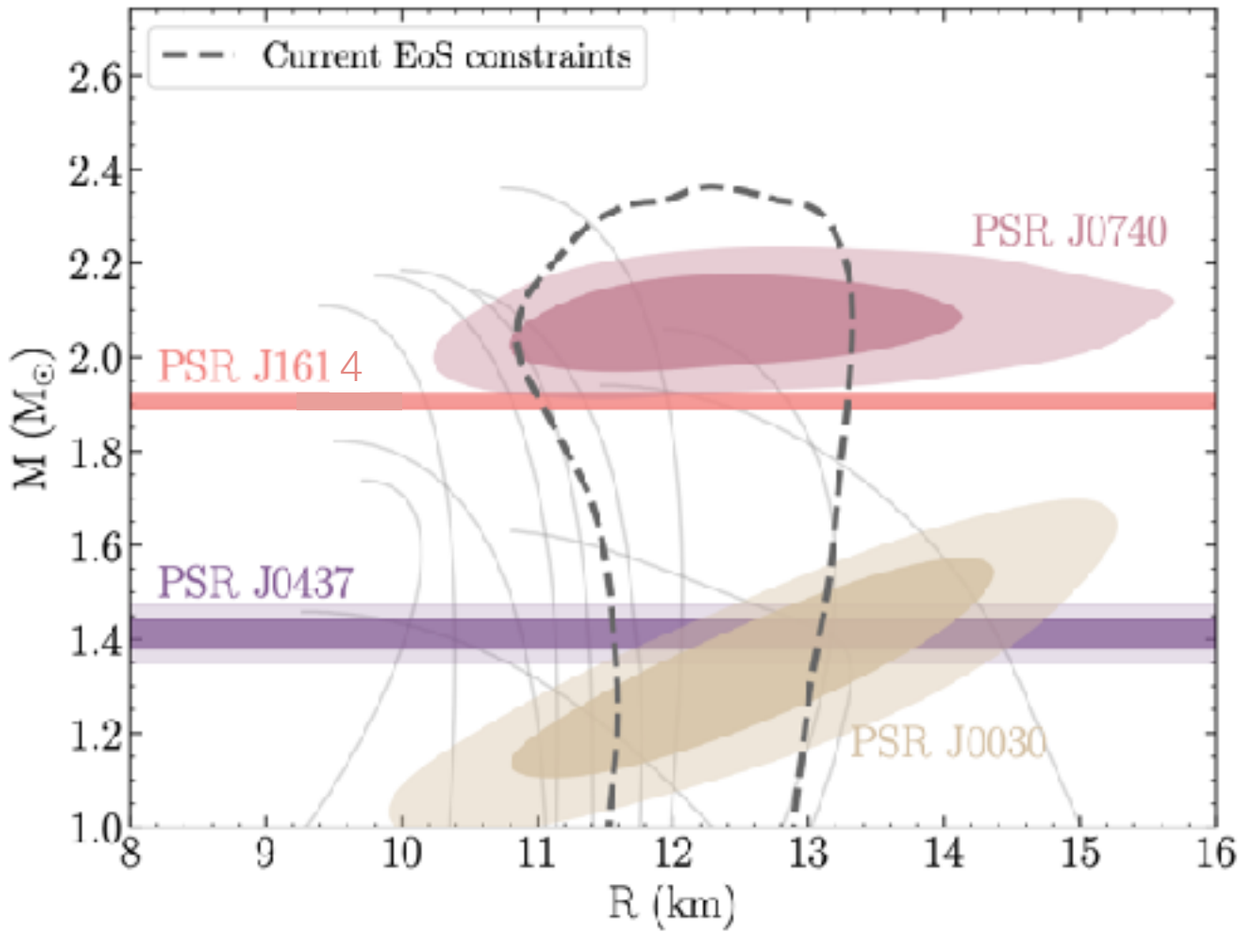




[Christian & Schaffner-Bielich (2021): 2109.04191]

Outlook - other *NICER* sources

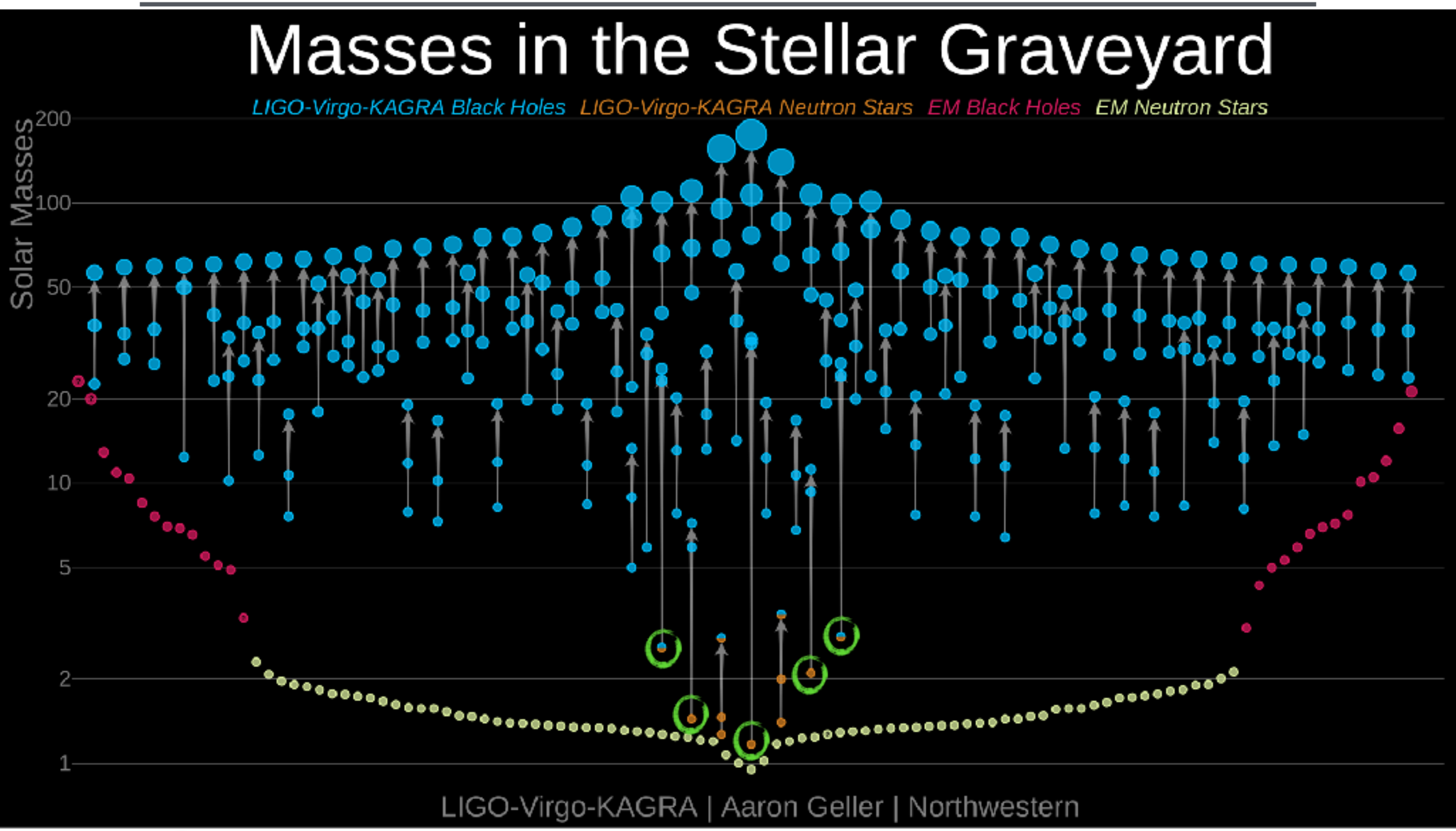




Other possibilities include:

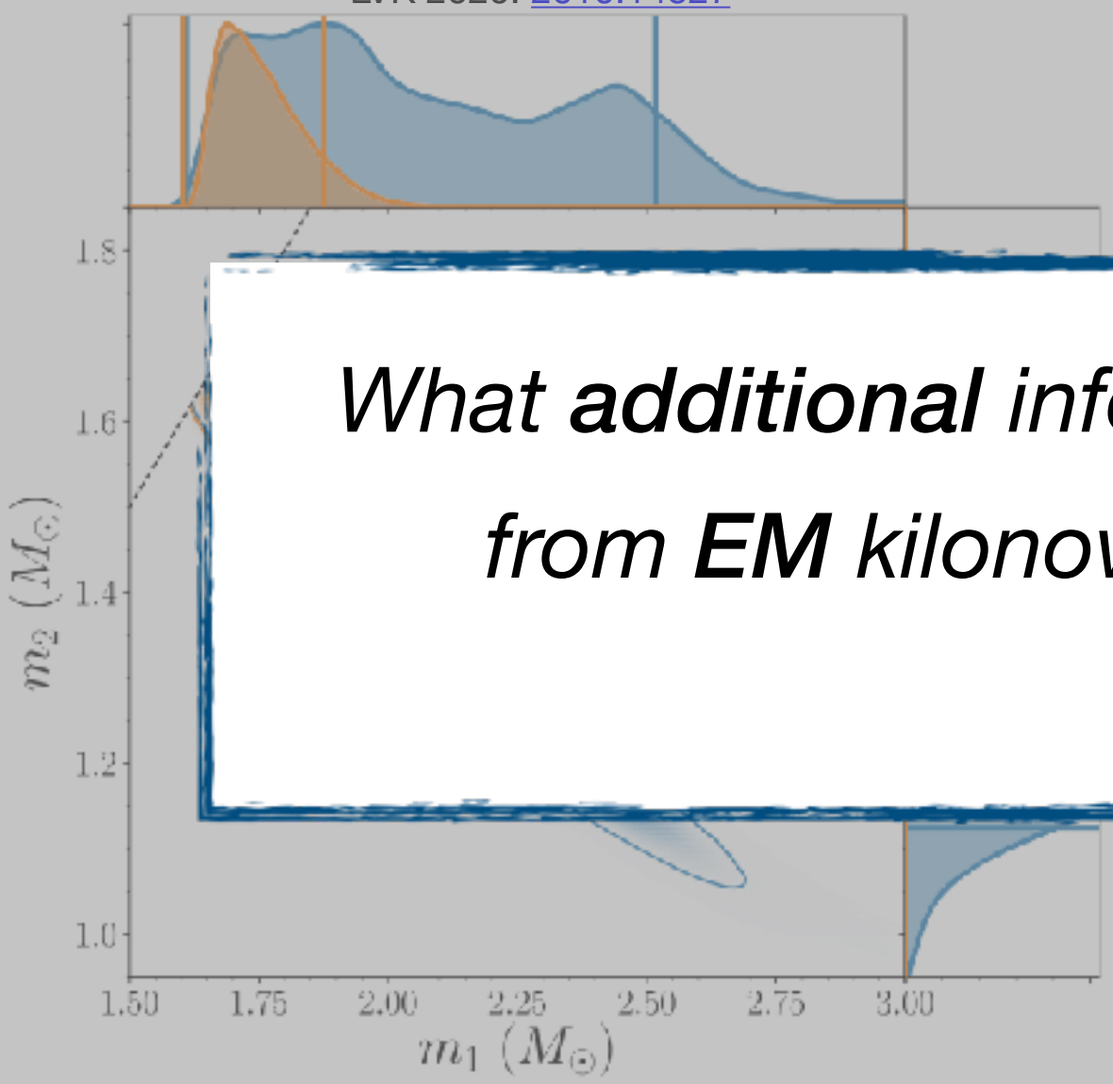
- PSR J1614-2230, a 1.9 solar mass pulsar

Constraining the EoS with GW+EM measurements of BHNS mergers



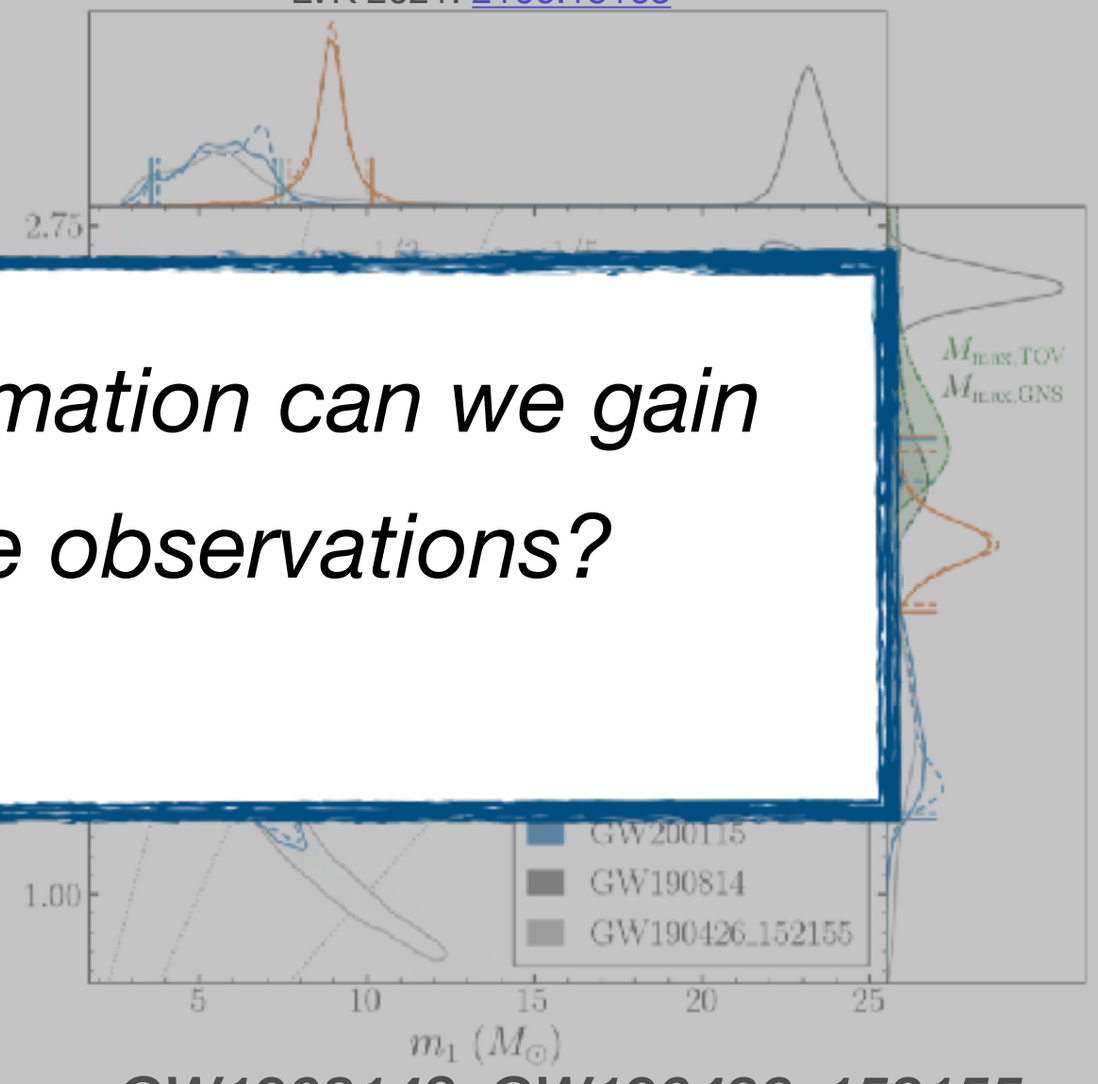
GW detections of BH-NS mergers so far

LVK 2020: 2010.14527



GW190425?

LVK 2021: 2106.15163



GW190814?, GW190426_152155, GW200105, GW200115

*What **additional** information can we gain from **EM** kilonovae observations?*

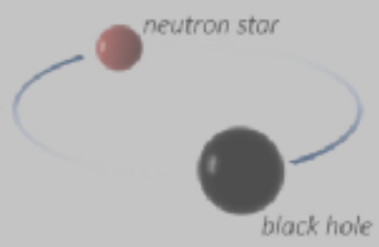
➡ No EM counterparts detected

Binaries to kilonova light curves - end-to-end framework GEMMA*

**Gravitational waves and ElectroMagnetic counterparts Multimessenger Analysis*

Binary properties

$\vec{x} = \{\mathrm{M_{BH}}, \mathrm{M_{NS}}, \chi_{\mathrm{BH}}, \Lambda_{\mathrm{NS}}, \dots\}$



Outflow properties

$\vec{y} = \{\mathrm{M_{dyn}}, \mathrm{M_{wind}}, \mathrm{v_{dyn}}, \mathrm{v_{wind}}, \dots\}$

Fit formulae to numerical simulations

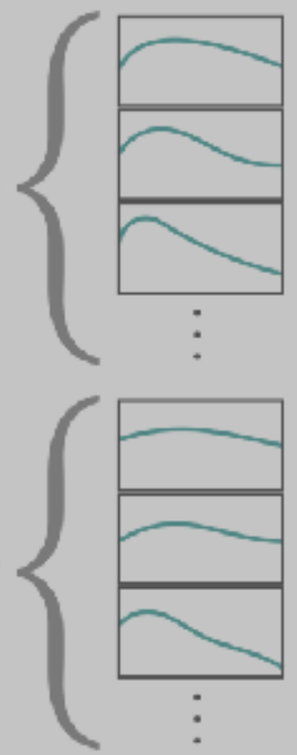
$\vec{x}_1$

$\vdots$

$\vec{y}_{11}$
$\vec{y}_{12}$
$\vec{y}_{13}$
$\vdots$

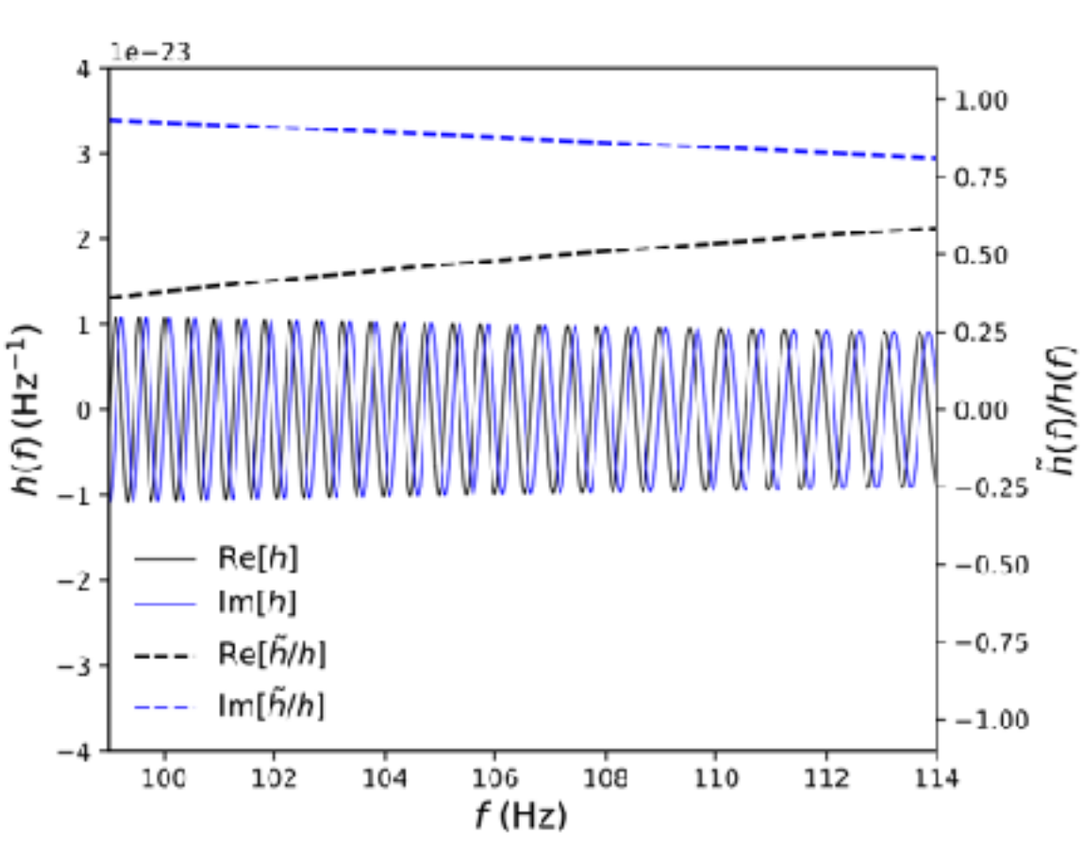
Semi-analytical light curve model

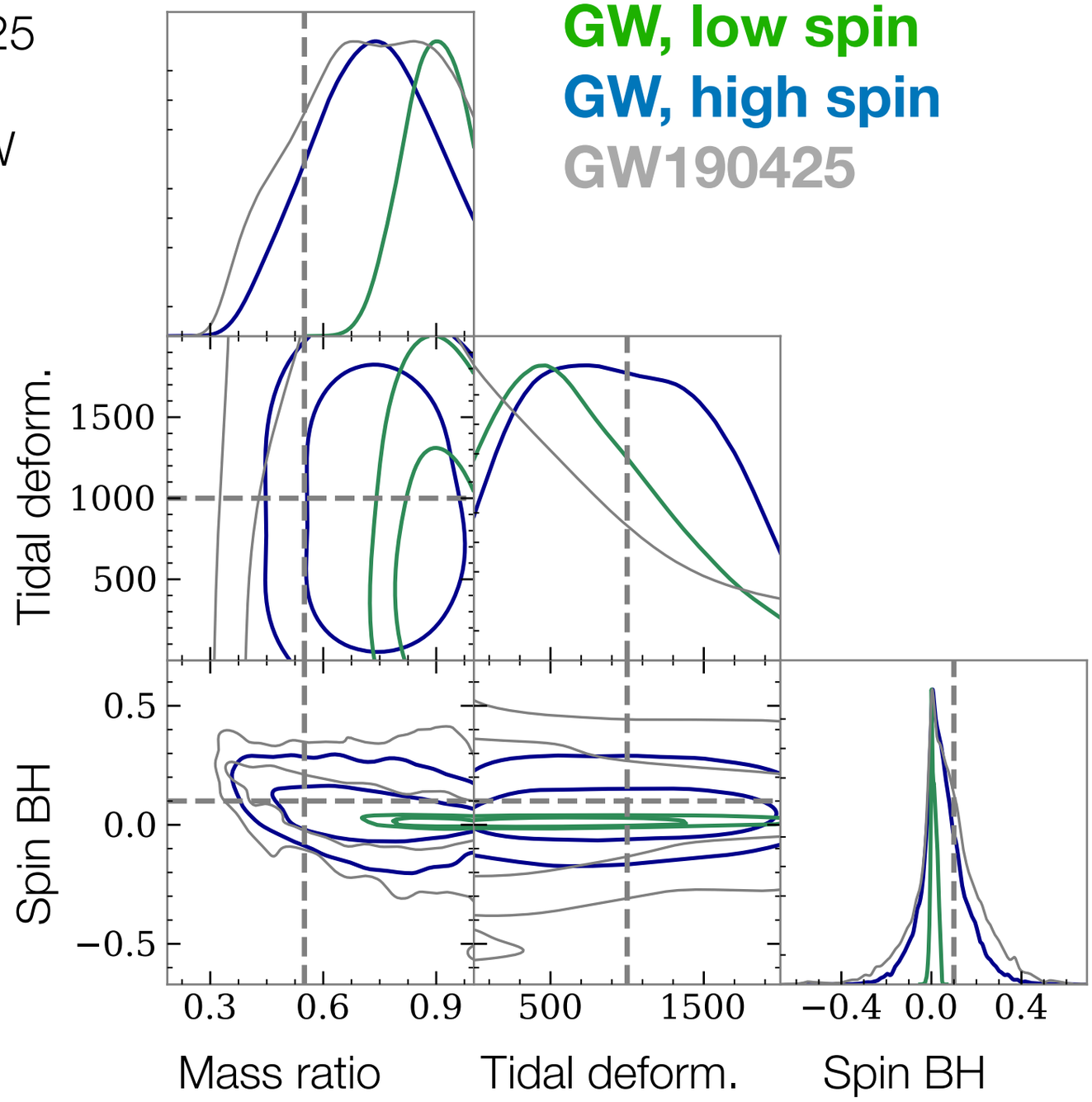
Light curves



Parameter inference on a simulated signal

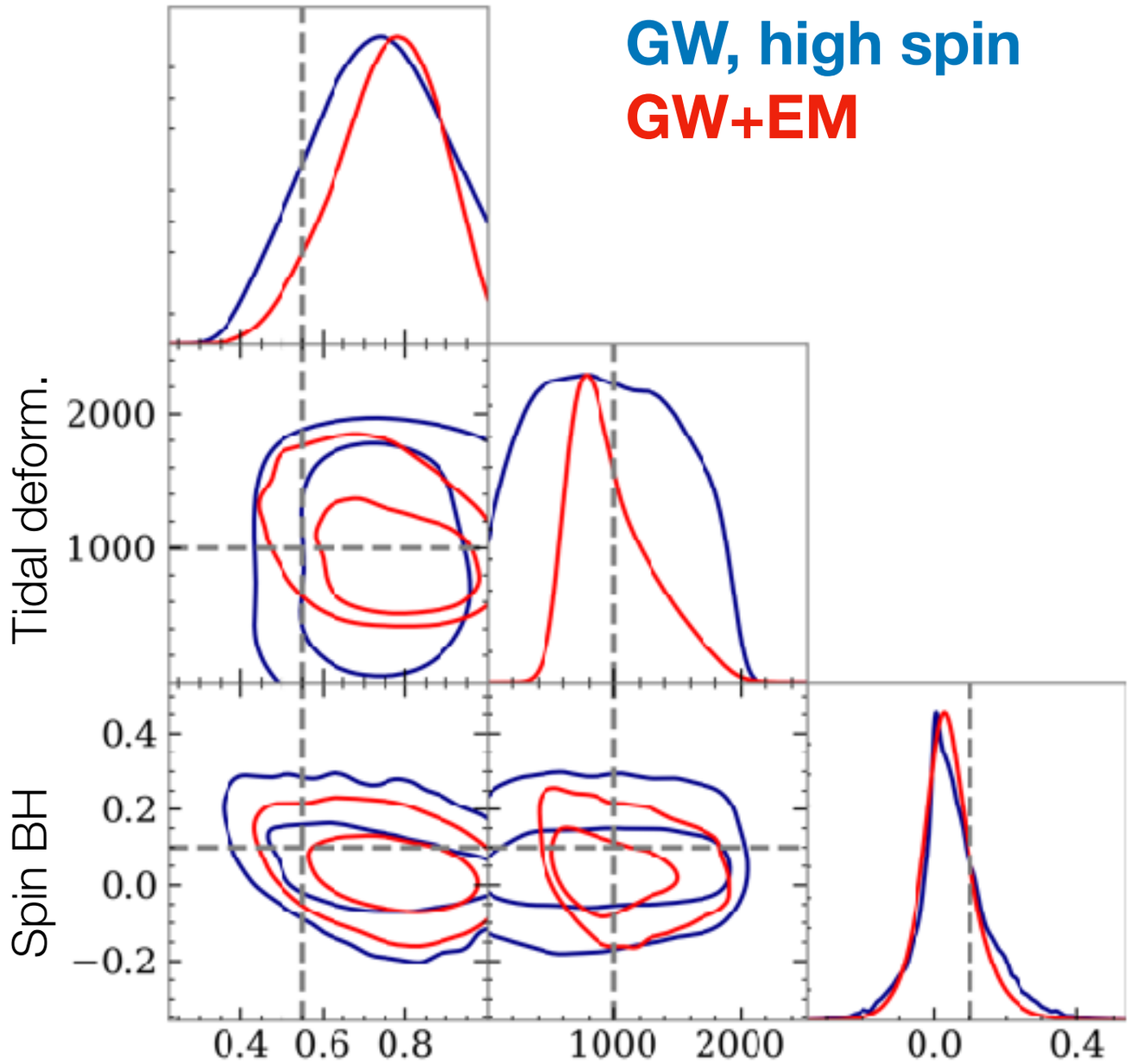
- Simulate a GW signal similar to GW190425
- Using relative binning to speed up the GW analysis [Zackay et al. (2018):]





Parameter inference on a simulated signal

- Simulate optical data in griz-bands
- Largest additional constraints on tidal deformability of the NS -> EoS constraints!



Outlook - summary

- *NICER's* mass-radius estimate of PSR J0740+6620 shows support for EoS that are **stiff**

- In the future missions like **eXTP** and **STROBE-X** will provide tighter/more mass-radius estimates

- Multimessenger GW observations provide an exciting complimentary method
  - Updates to LIGO/Virgo/KAGRA, new follow-up instruments, 3G detectors…