Constraining the nuclear equation of state through neutron star observations

Svenja Kim Greif

Hirschegg, January 14, 2020
Nuclear equation of state and neutron stars

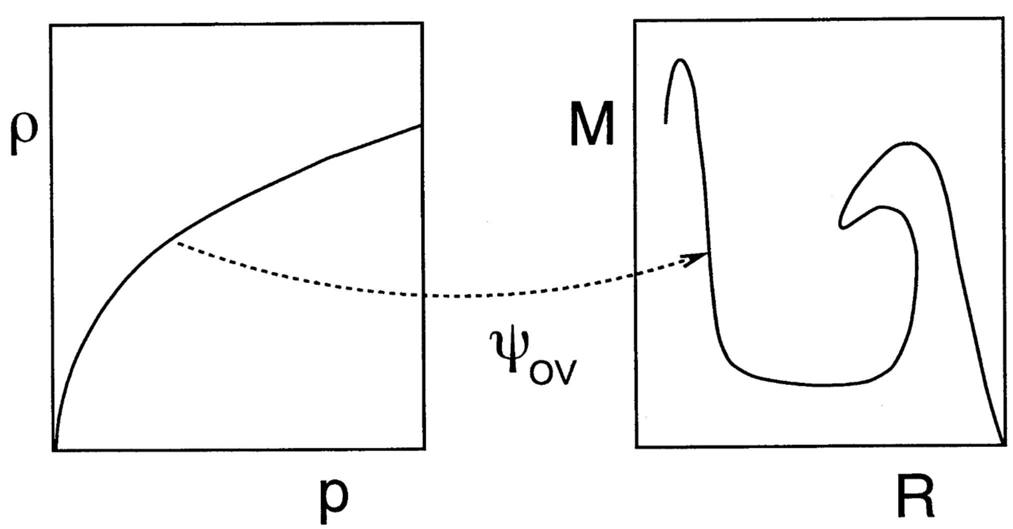
International Workshop XLVIII on Gross Properties of Nuclei and Nuclear Excitations
Hirschegg, Kleinwalsertal, Austria, January 12 - 18, 2020

Outline

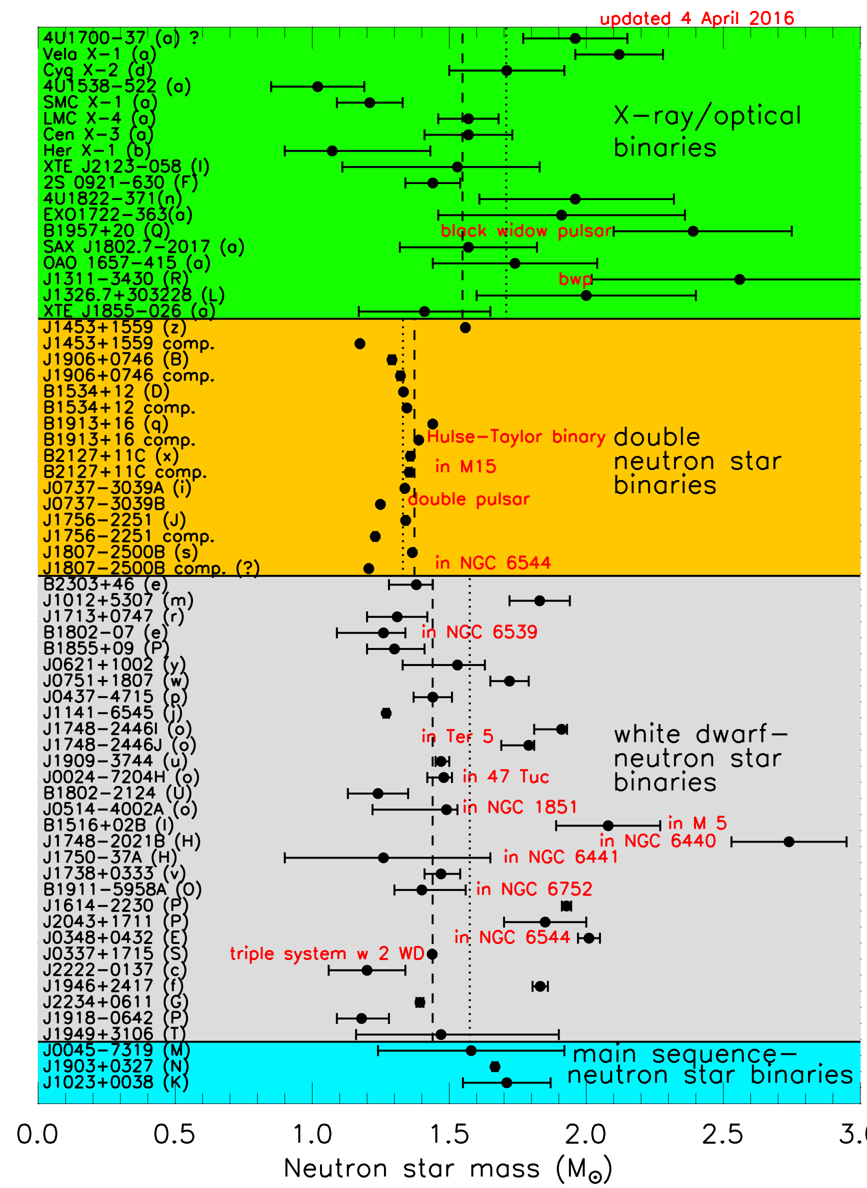
- Motivation
- Equation of state constraints
- Equation of state and neutron star structure
- Mass-radius determination from NICER
- The double pulsar's moment of inertia
- Era of multi-messenger astronomy
- Key messages

Motivation
Neutron stars as unique laboratories

- Equation of state (EOS) of dense matter beyond nuclear saturation density $\rho_{\rm sat} = 2.8 \times 10^{14}\,{\rm g\,cm^{-3}}$ is poorly understood
- Unique relation between EOS and mass-radius



Lindblom, ApJ 398, 569 (1992)



Lattimer & Prakash, PRL 94, 111101 (2005)
https://stellarcollapse.org/nsmasses (2020-01-09)

- Precise mass measurements from pulsar observations are available
- Radius determination is now studied

Equation of state constraints
… from astrophysical observations

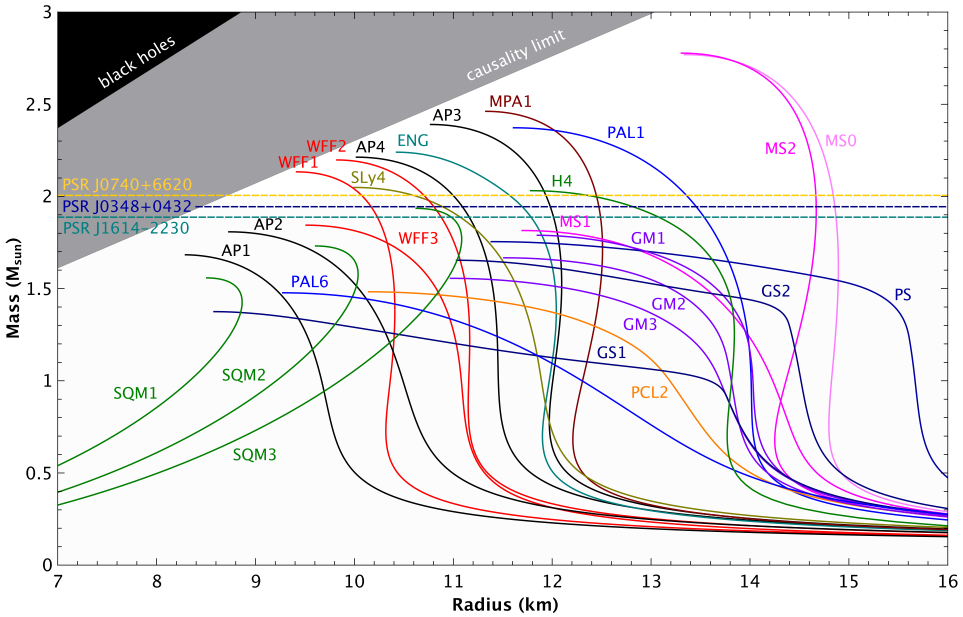


Image credit: N. Wex
https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html (2020-01-09)

- Significant constraints from massive neutron stars, e.g. PSR J0348-0432 and PSR J0740+6620 with masses $2.01^{+0.04}_{-0.04}\,M_\odot$ and $2.14^{+0.10}_{-0.09}\,M_\odot$
  Antoniadis *et al*., Science 340, 6131 (2013); Cromartie *et al*., NatAs, in press (2019)
- Each constructed EOS is required to reproduce the heaviest observed neutron star

- First joint mass-radius measurement from NICER of PSR J0030+0451
  Riley et al., ApJL 887, L21 (2019); Miller *et al*., ApJL 887, L24 (2019)
- Gravitational wave astronomy: direct detection of binary neutron star mergers
  LVC, PRL 119, 161101 (2017); LVC, arXiv:2001.01761 (2020)
- Ongoing measurement of the moment of inertia of PSR J0737-3039A

$M = 1.34^{+0.15}_{-0.16}\,M_\odot$

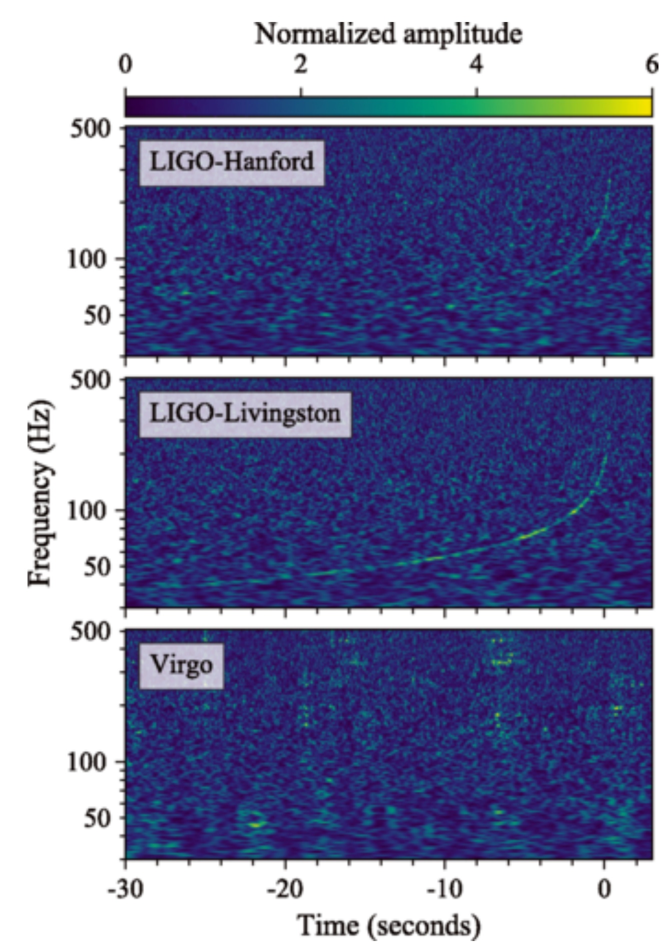
$R = 12.71^{+1.14}_{-1.19}\,\mathrm{km}$

Riley et al. (2019)

$M = 1.44^{+0.15}_{-0.14}\,M_\odot$

$R = 13.02^{+1.24}_{-1.06}\,\mathrm{km}$

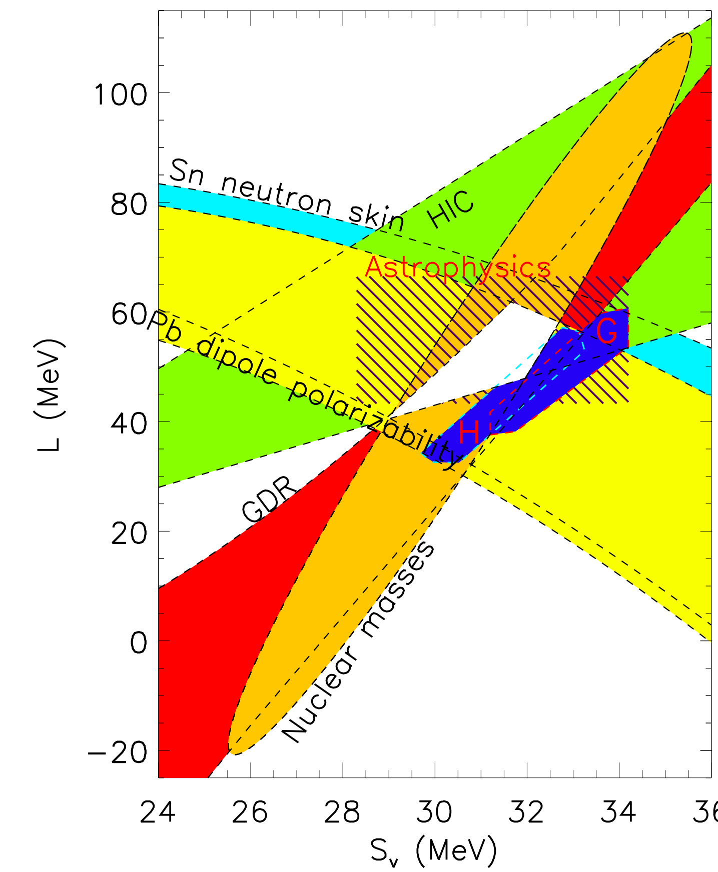
Miller et al. (2019)



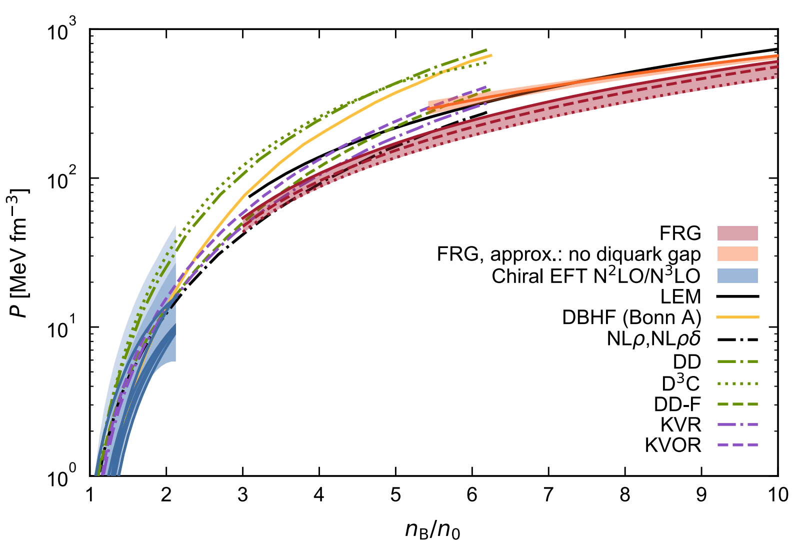
LVC, PRL 119, 161101 (2017)

Equation of state constraints
… from nuclear experiments and pQCD

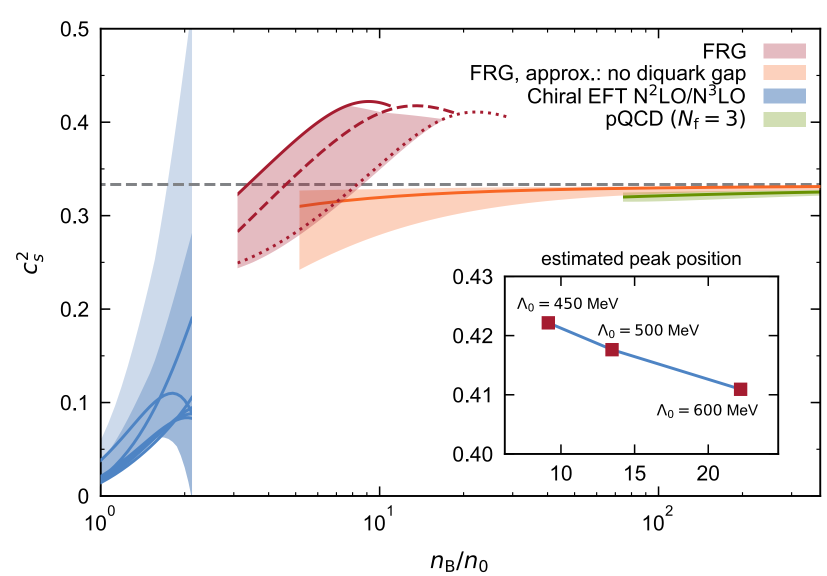
- Radius of typical neutron stars is correlated with EOS properties around ρ_{sat}
- Pressure around ρ_{sat} is correlated with symmetry parameters S_{v} and L
- Constraints from functional renormalization group for symmetric matter are available
- pQCD imposes constraints for the speed of sound at very large densities, e.g. $\gg \rho_{c,\ \mathrm{neutron\ star}}$



Lattimer & Lim, ApJ 771, 51 (2013)



Leonhardt, PhD thesis, TU Darmstadt (2019)



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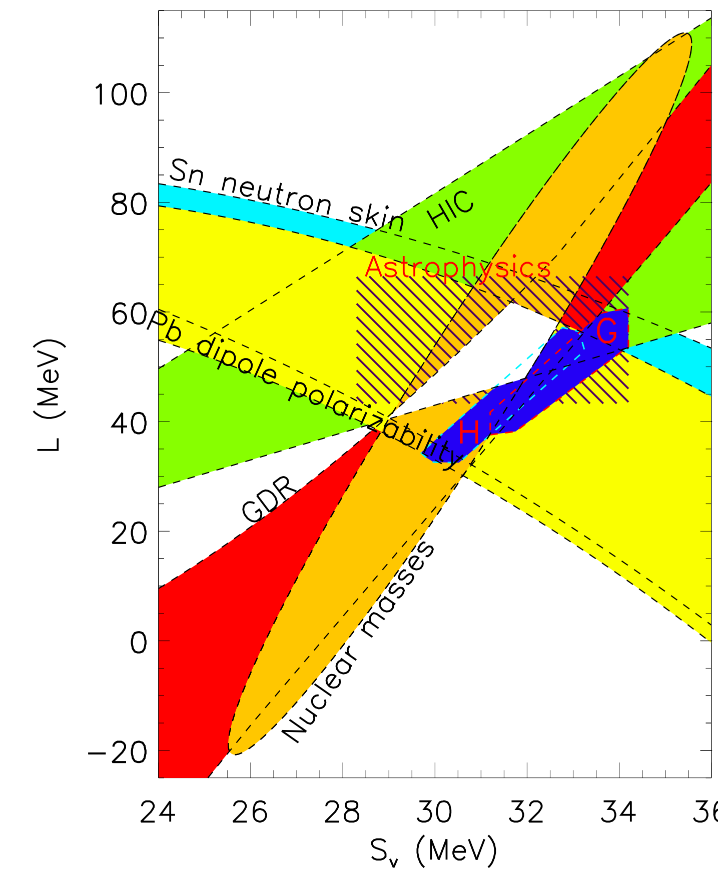
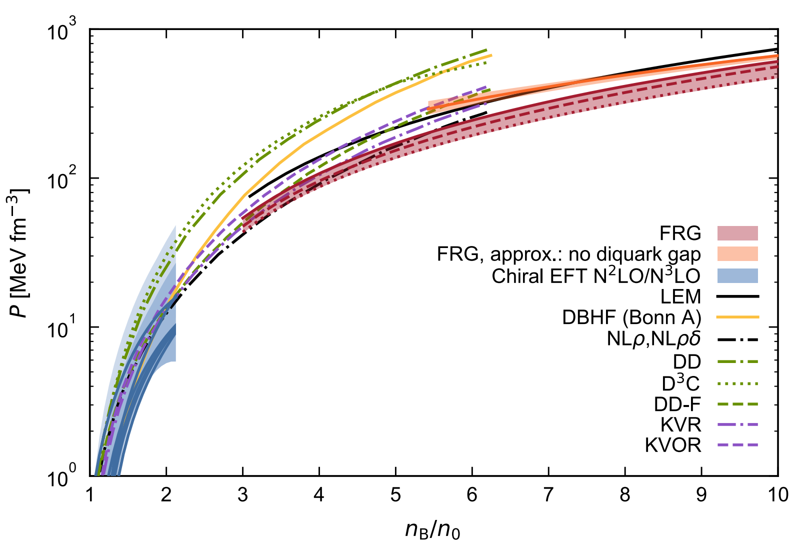


Lattimer & Lim, ApJ 771, 51 (2013)

Yeunhwan's talk
Thursday morning



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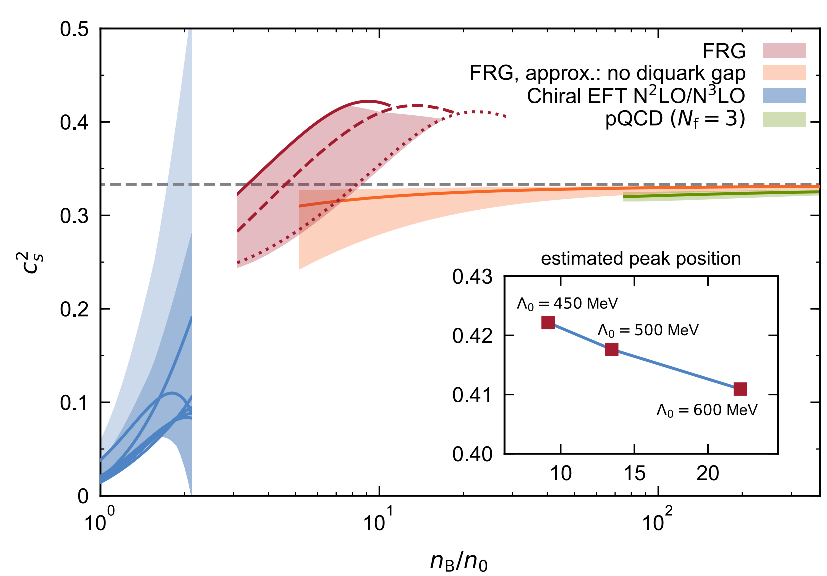
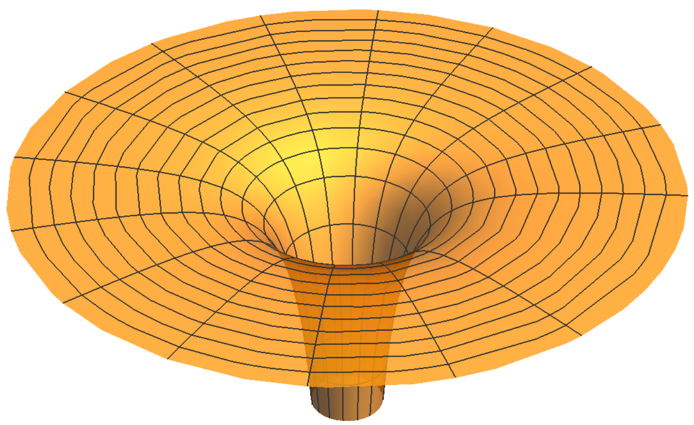


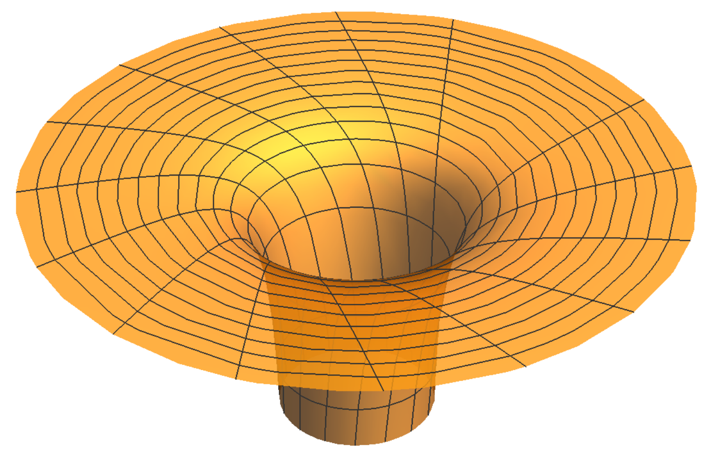
Leonhardt, PhD thesis, TU Darmstadt (2019)

Marc's talk
Next session

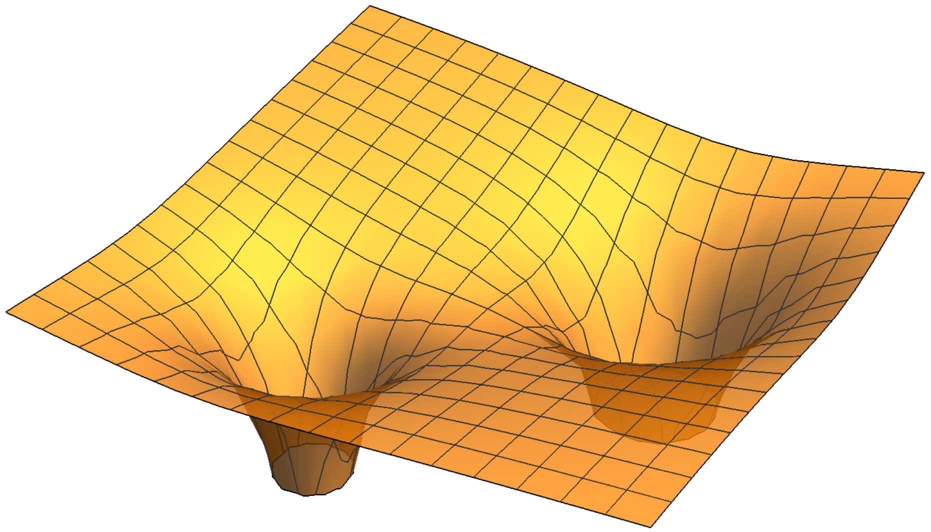
Equation of state and neutron star structure
Slow rotation approximation



Non-rotating neutron stars
Mass M
Radius R



Slowly rotating neutron stars
Moment of inertia I



Interaction with a companion
Tidal deformability λ

See Soumi's talk from Monday

Chirp mass $\mathscr{M}$

$$\mathscr{M} = \frac{(M_1 M_2)^{\frac{3}{5}}}{(M_1 + M_2)^{\frac{1}{5}}}$$

Binary tidal deformability $\tilde{\Lambda}$

$$\tilde{\Lambda} = \frac{16}{13} \frac{(M_1 + 12 M_2)\, M_1^4 \bar{\lambda}_1 + (1 \leftrightarrow 2)}{(M_1 + M_2)^5}$$

Hartle, ApJ 150, 1005 (1967)
Hartle & Thorne, ApJ 153, 807 (1968)
Hinderer, ApJ 677, 1216 (2008)
Lindblom & Indik, PRD 89, 064003 (2014)

Equation of state and neutron star structure
Piecewise polytropic expansion

- Nuclear density regime: knowledge of nuclear physics
  - BPS crust EOS up to $\sim \rho_{\rm sat}/2$
  - Chiral effective field theory interactions up to $\sim \rho_{\rm sat}$
- Direct parametrization: piecewise polytropic expansion $P(\rho) = K\rho^{\Gamma}$
  Read, Lackey, Owen, Friedman, PRD 79, 124032 (2009)
- Large parameter space constrained by general constraints: causality ($c_s < c$) and heaviest neutron star ($M_{\rm max} \geq 1.97\, M_{\odot}$, 1σ lower limit)
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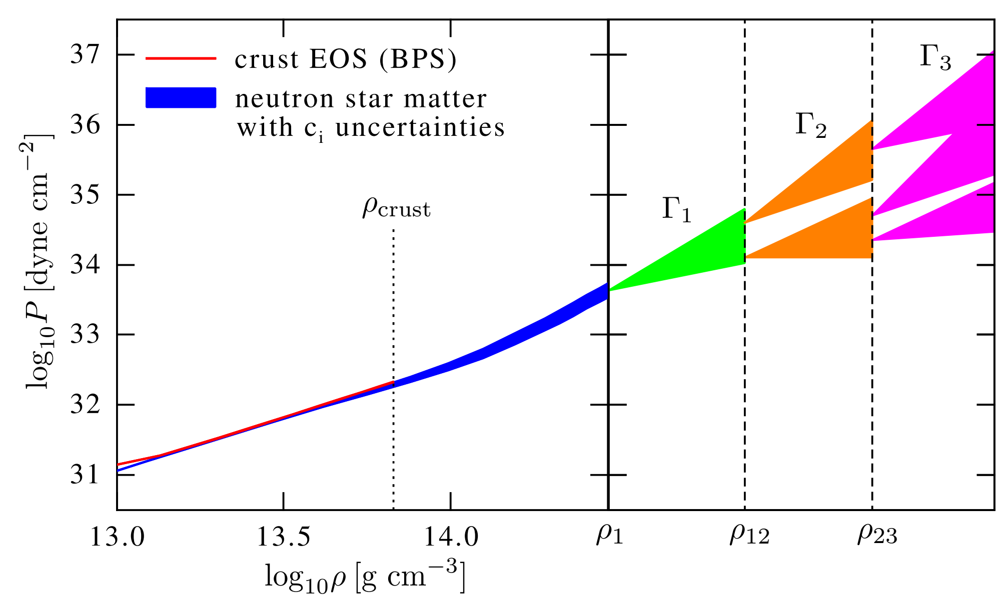

Hebeler, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)

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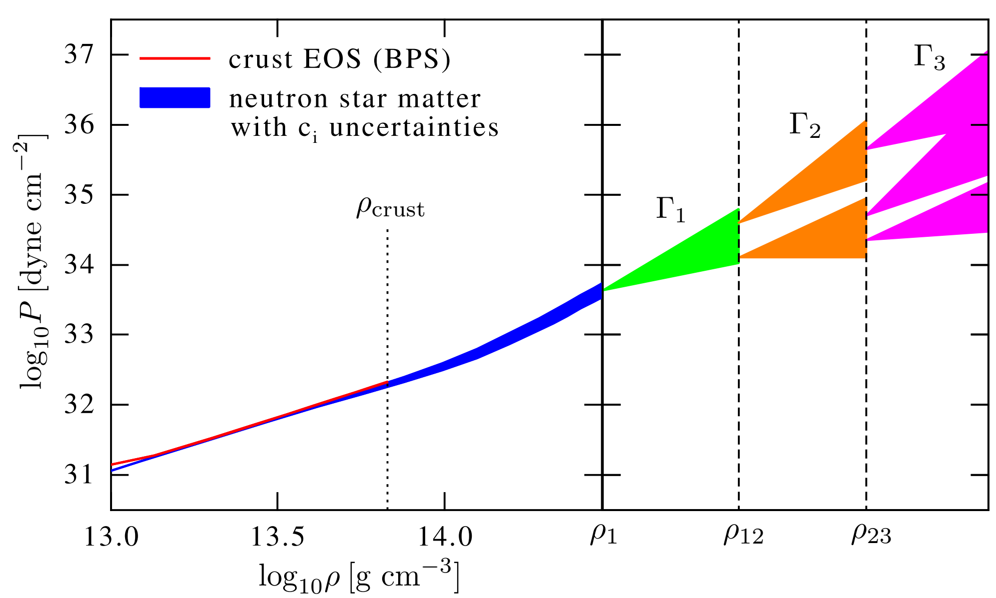


Hebeler, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)

- Speed of sound: $c_s^2 = \dfrac{dP}{d\epsilon}$
- Piecewise polytropic parametrisation causes discontinuities in c_s^2

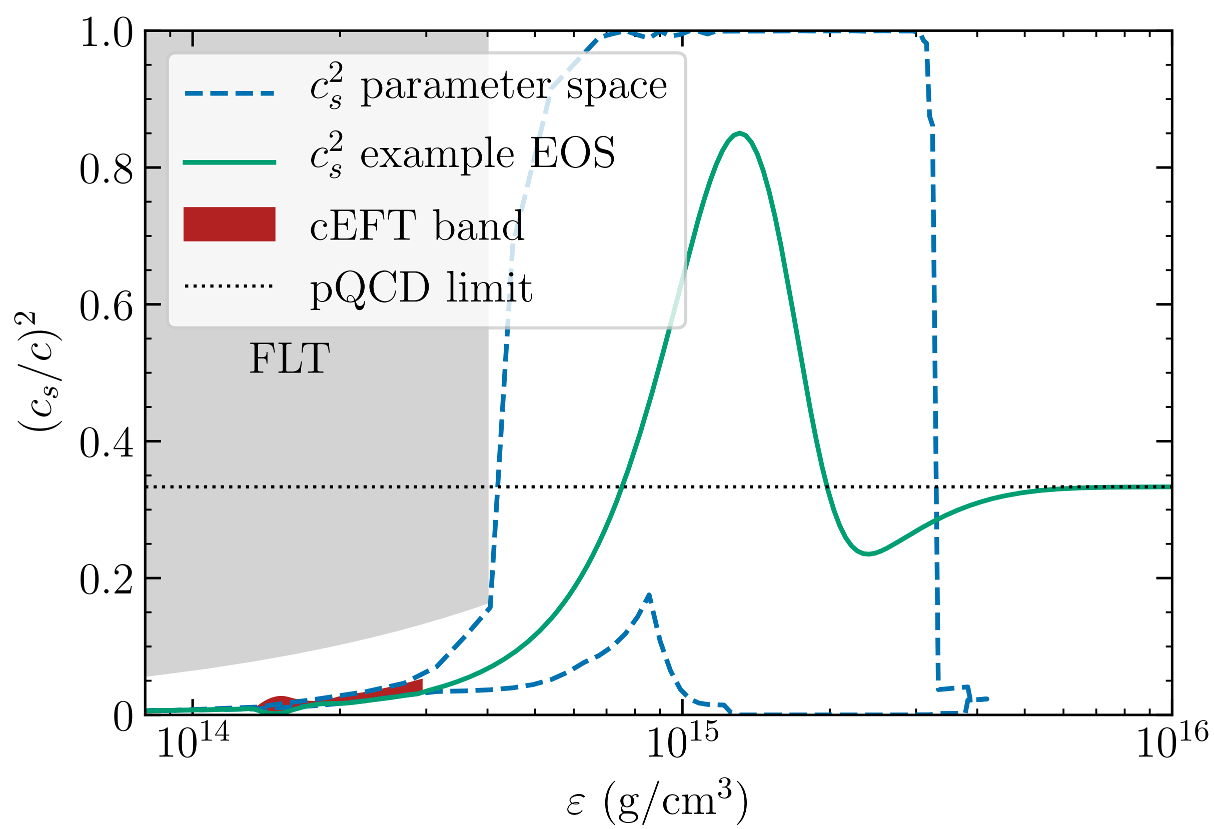
→ **Idea: parametrize c_s^2 and infer the EOS**

Equation of state and neutron star structure
New speed of sound parametrization

- Physically motivated parametrization of the speed of sound c_s
  - Approach pQCD constraint $c_s^2 \rightarrow 1/3$ from below
    Kurkela, Romatschke, Vuorinen, PRD 81, 105021 (2010)
  - Exceed conformal limit for intermediate densities
    Bedaque & Steiner, PRL 114, 031103 (2015)
  - Constraints at nuclear densities from Fermi liquid theory
  - Continuous matching to chiral EFT band
- Parameters are varied to explore full parameter space

$$c_s^2(\epsilon) = a_1 e^{-\frac{1}{2}\frac{(\epsilon - a_2)^2}{a_3^2}} + a_6 + \frac{\frac{1}{3} - a_6}{1 + e^{-a_5(\epsilon - a_4)}}$$

$$P(\epsilon) = \int_{\epsilon_0}^{\epsilon} d\epsilon' \; c_s^2(\epsilon')$$

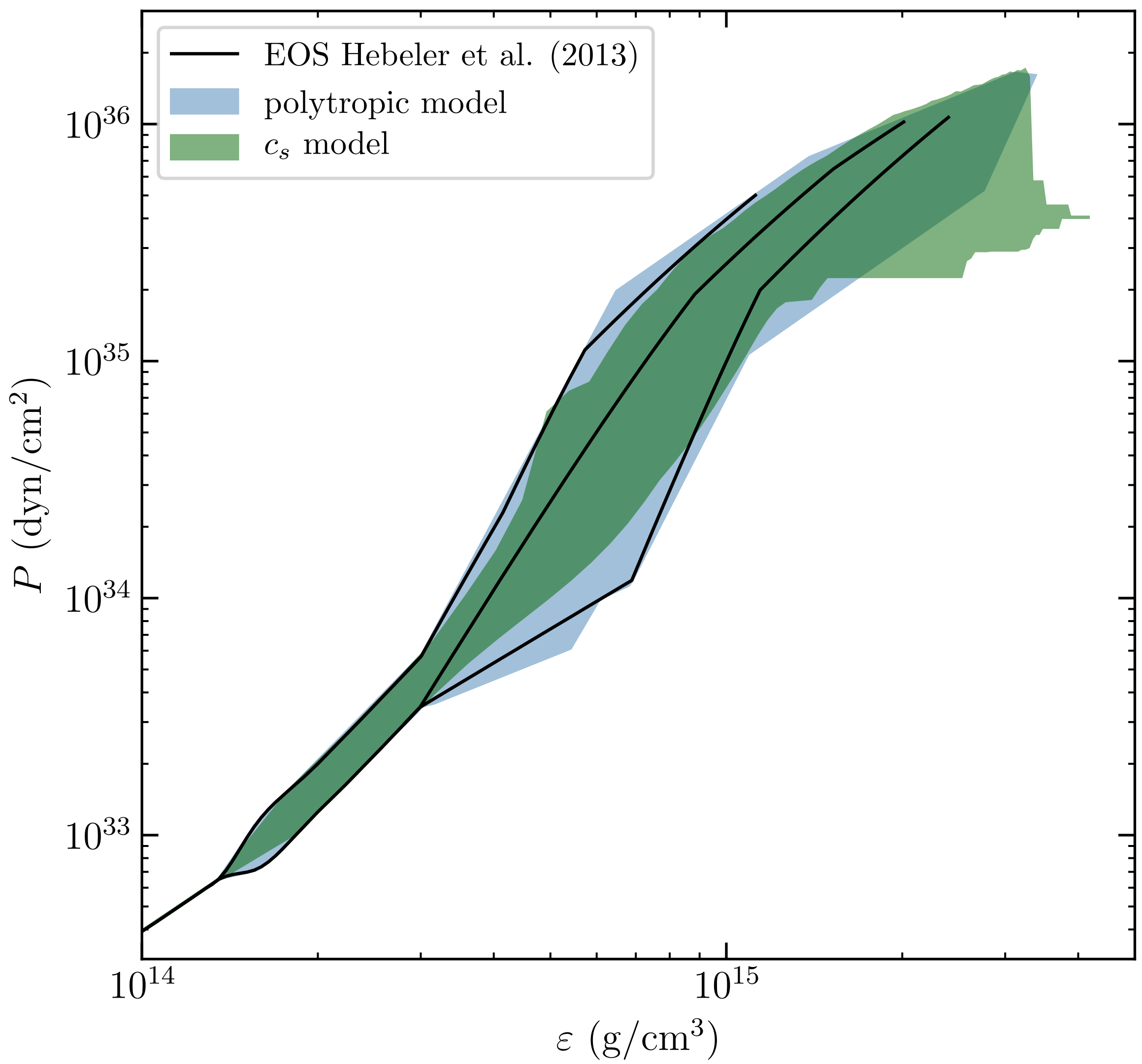


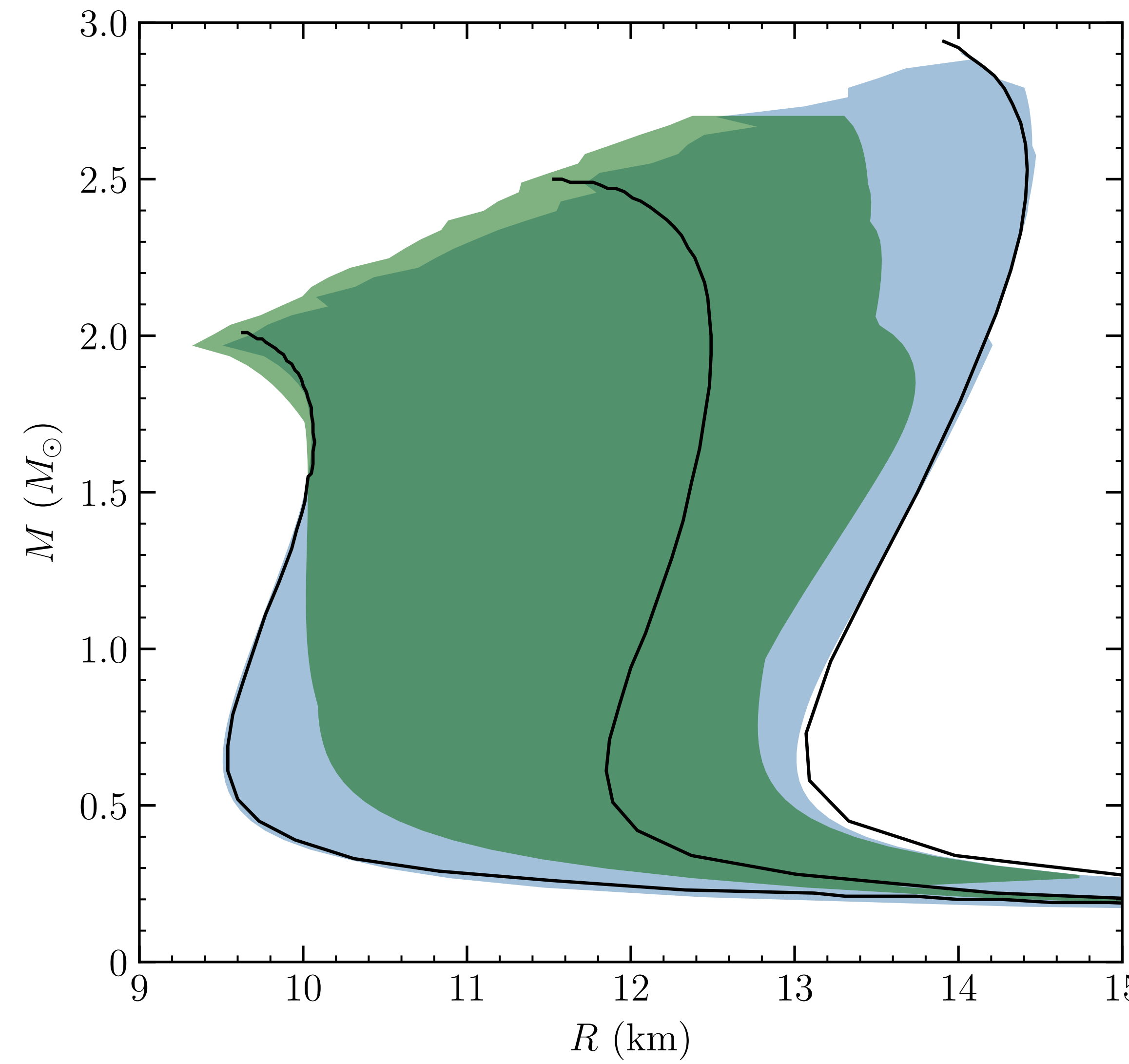
SKG, Raaijmakers, Hebeler, Schwenk, Watts, MNRAS 485, 5363 (2019)

See Ingo's talk from Monday

Tews, Carlson, Gandolfi, Reddy, ApJ 860, 149 (2018)

EOS and MR space



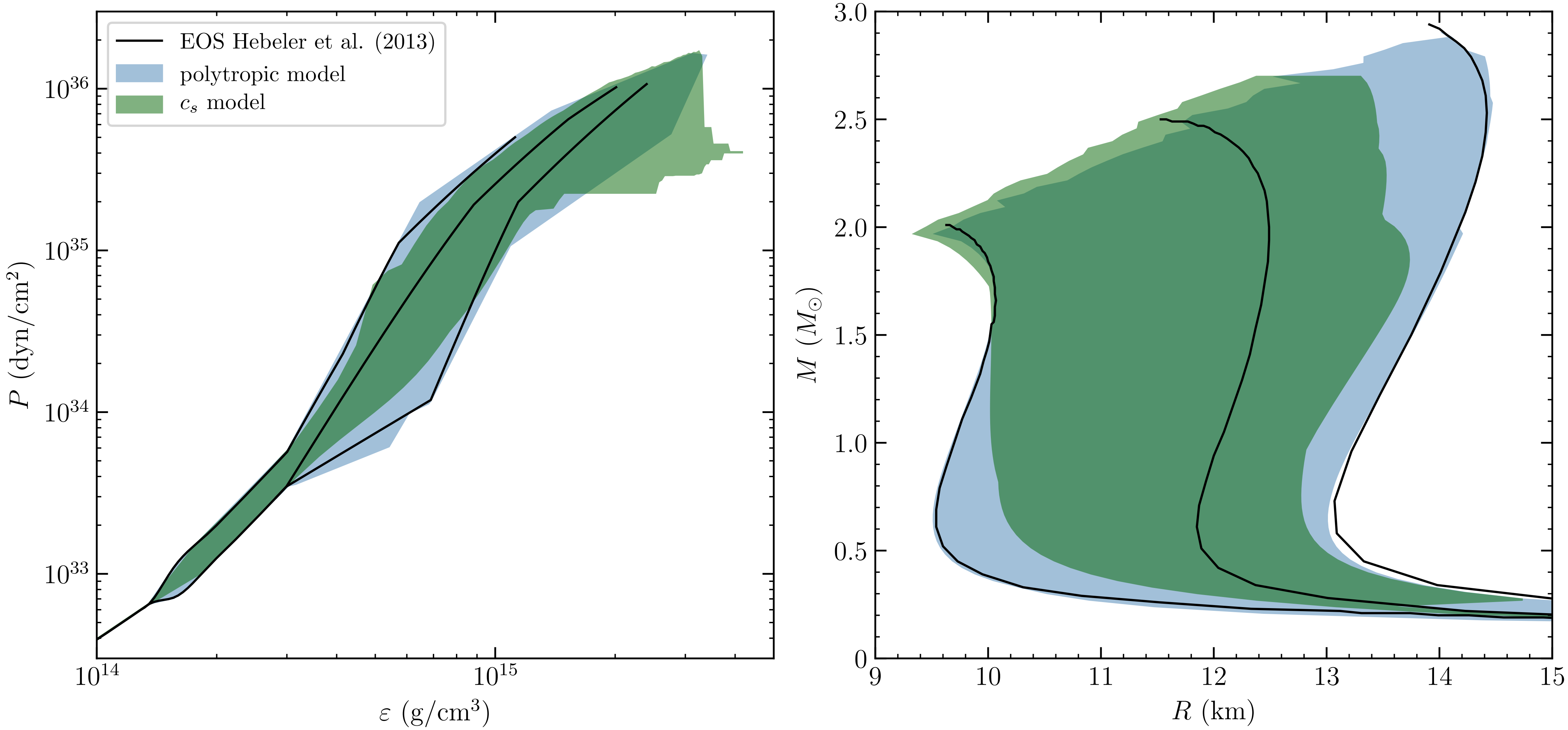


SKG, Raaijmakers, Hebeler, Schwenk, Watts, MNRAS 485, 5363 (2019)

$R^{\mathrm{PP}}_{1.4\,M_\odot} = 9.97 - 13.65\,\mathrm{km}$

$R^{\mathrm{CS}}_{1.4\,M_\odot} = 10.04 - 13.32\,\mathrm{km}$

EOS and MR space



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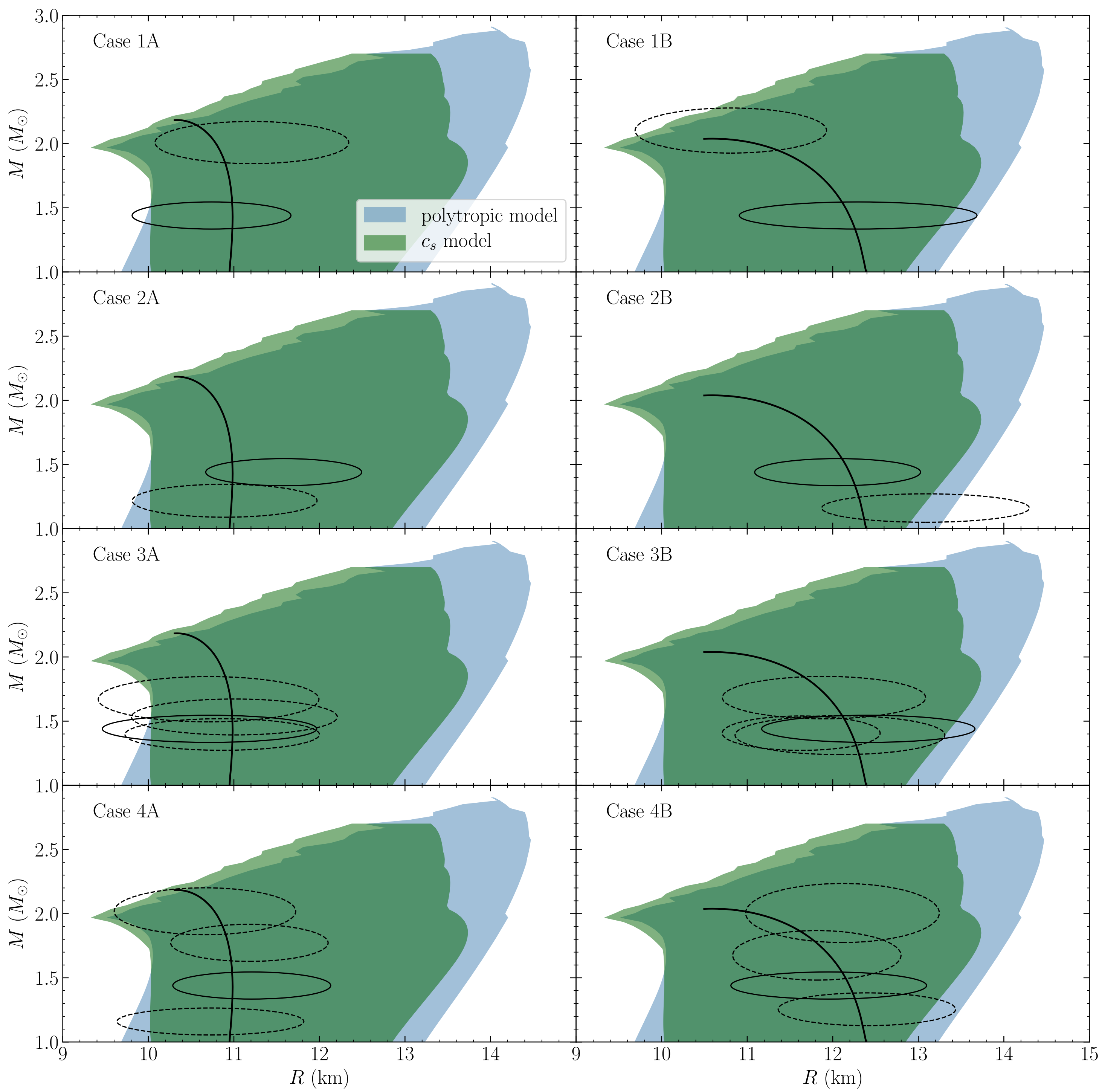
→ **How do observations constrain this further?**

Mass-radius determination from NICER



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- Analysis framework for simultaneous mass-radius measurements based on NICER's primary science targets
- Results of both parametrizations are compatible
- Posterior distribution from Bayesian analysis

Geert's talk
Wednesday morning

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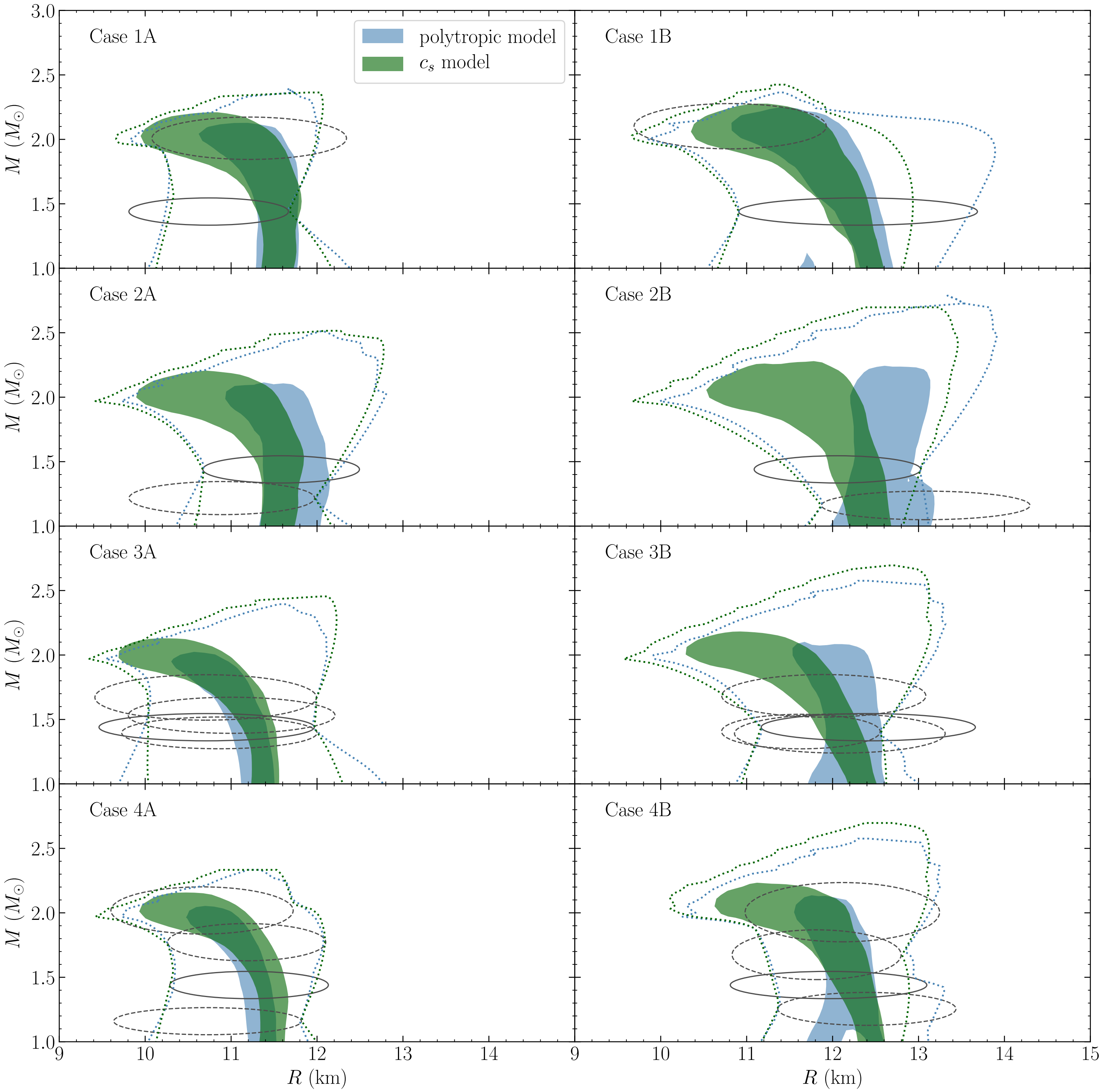

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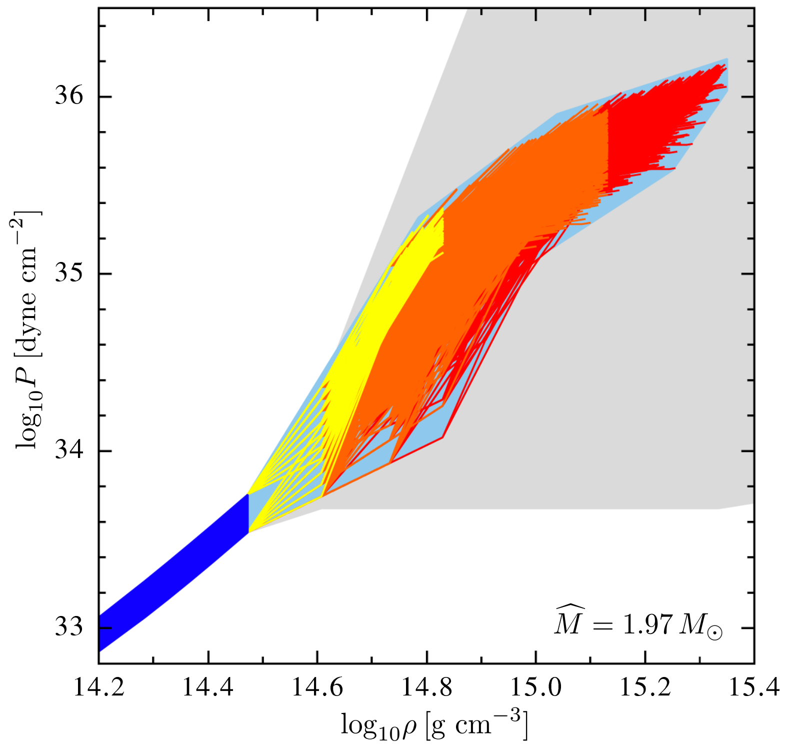
Geert's talk
Wednesday morning

- Underlying EOS is not recovered in each case
- Results are sensitive to the prior and the parametrization

Mass-radius determination from NICER
Prior information



Hebeler, Lattimer, Pethick, Schwenk, ApJ 773, 11 (2013)

- Matching to chiral EFT band causes bimodal structure

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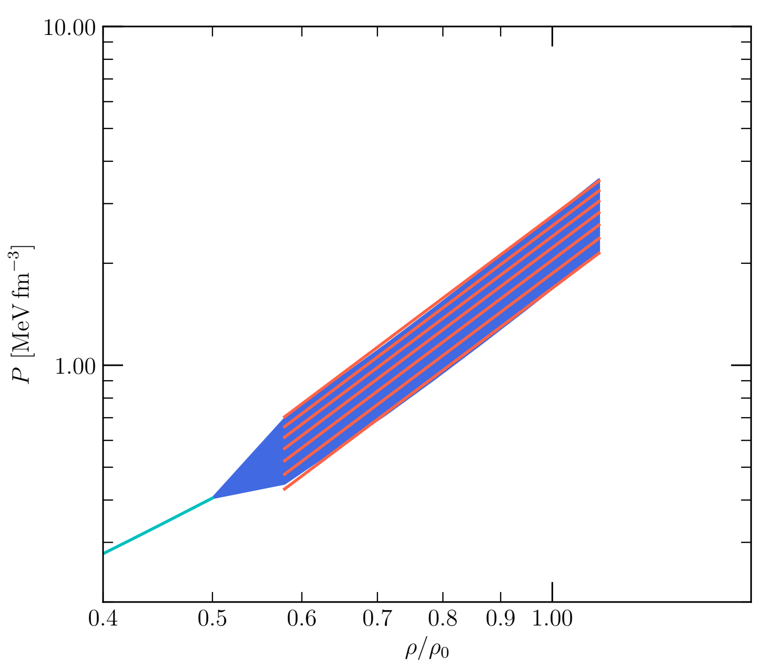
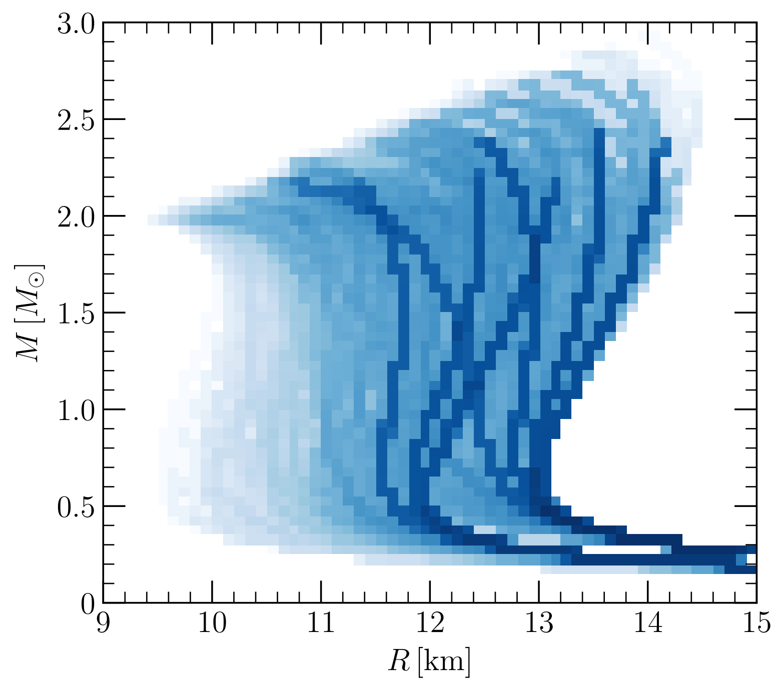
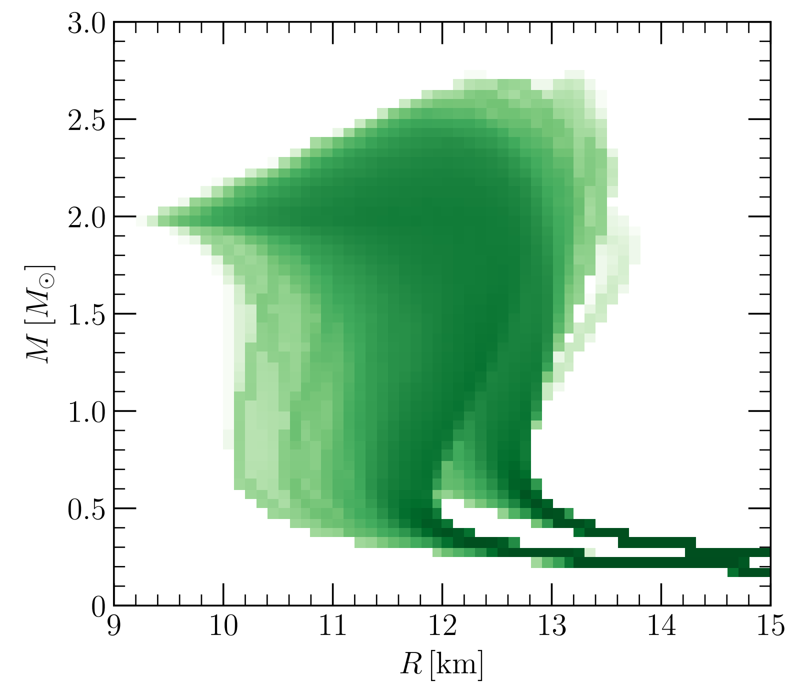
- Parametrize the EOS inside the chiral EFT band by a polytropic EOS for both models PP and CS

  Raaijmakers, Riley, Watts, SKG, *et al*., ApJL 887, L22 (2019)







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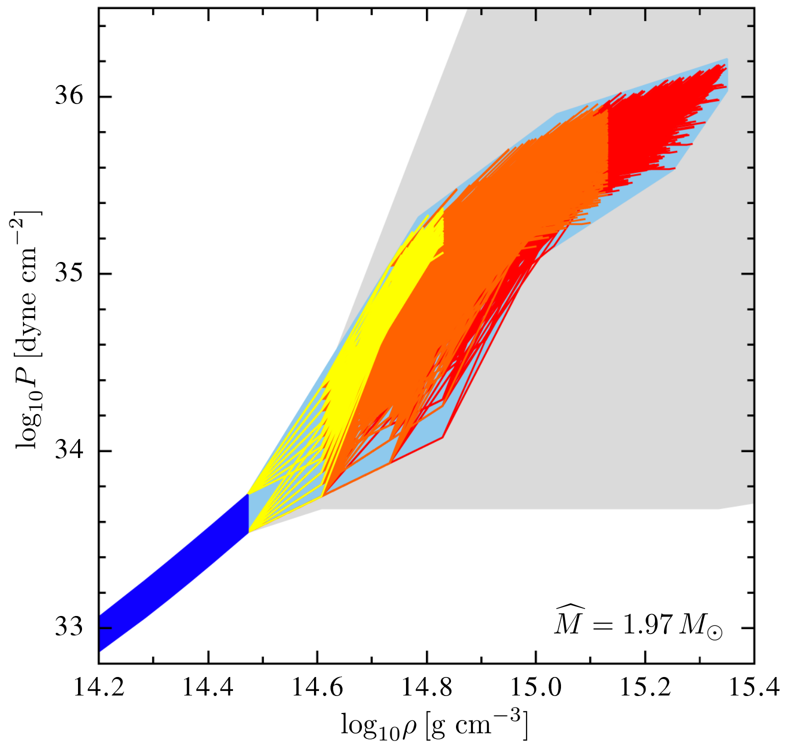

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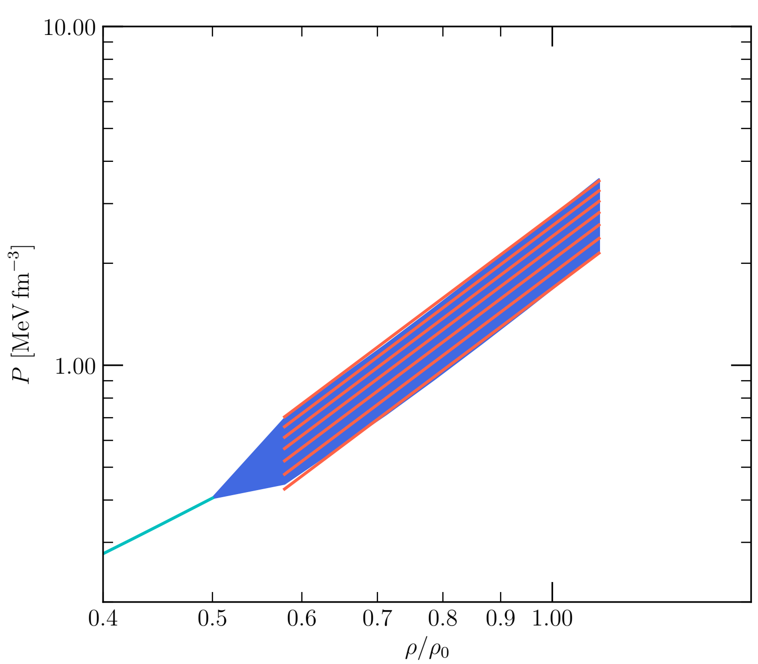
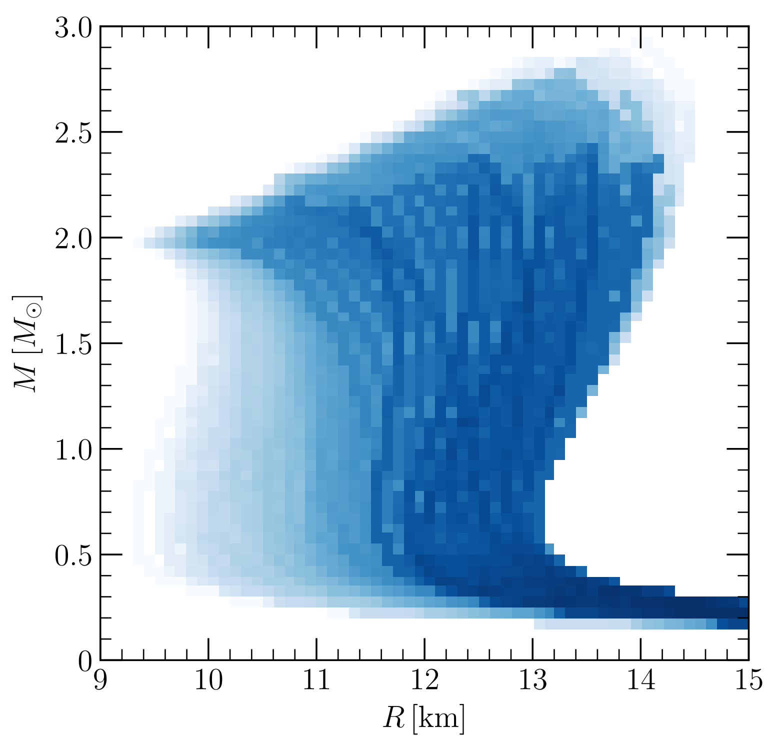
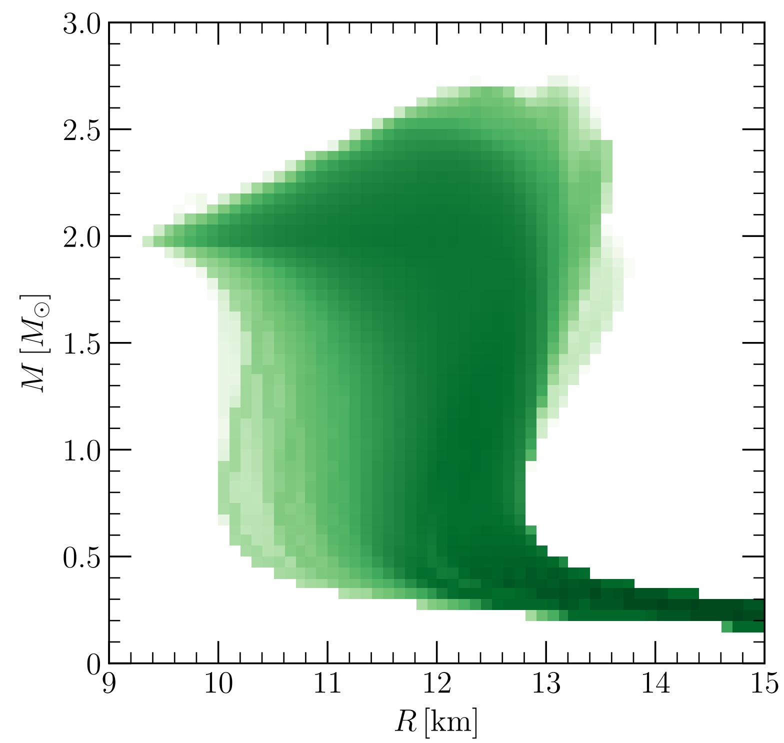
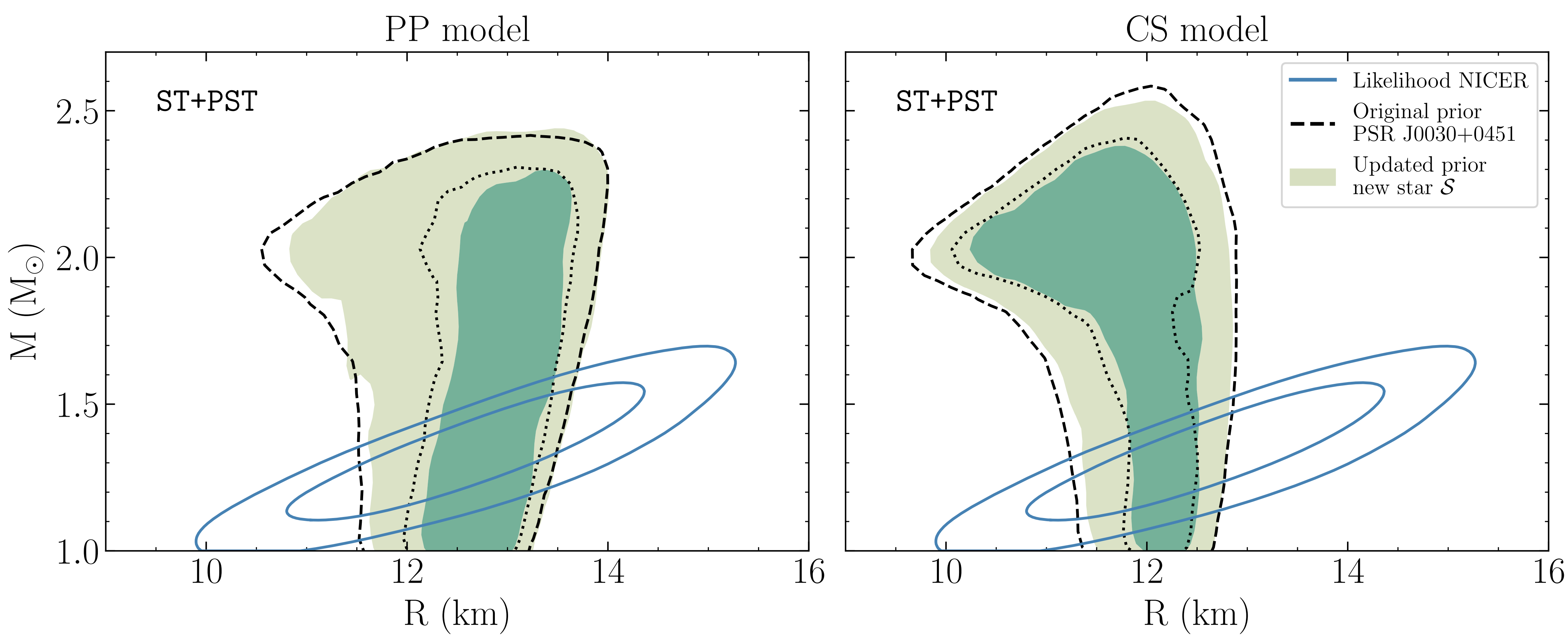






Mass-radius determination from NICER
Inferred mass-radius for PSR J0030+0451



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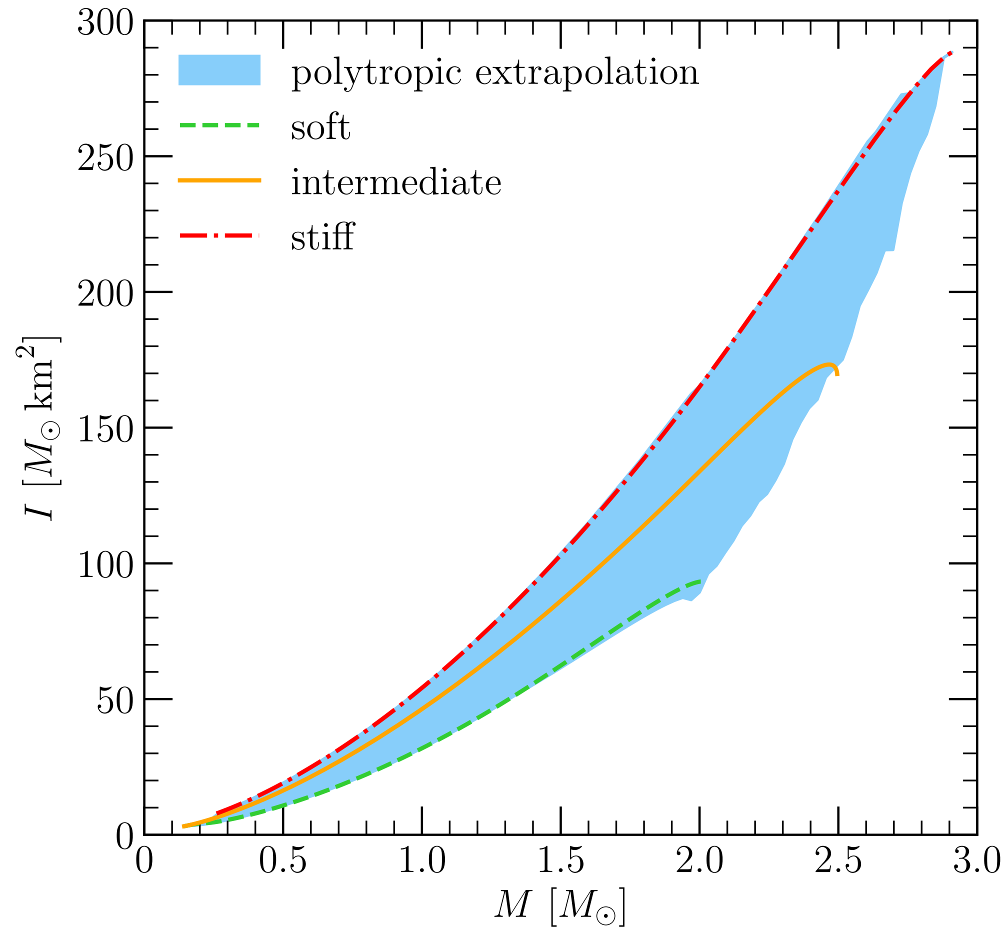
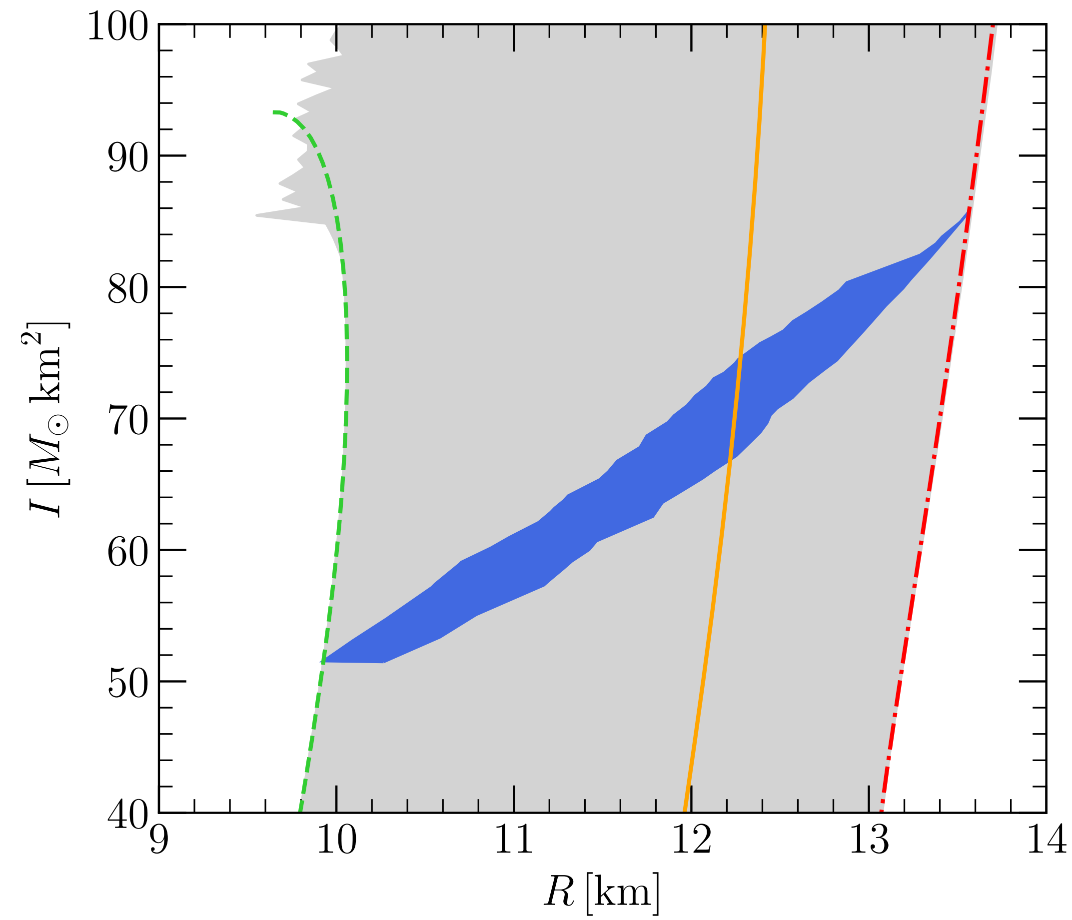
Geert's talk
Wednesday morning

The double pulsar's moment of inertia
Radius constraints from the moment of inertia





- PSR J0737-3039A with $M_\mathrm{A} = 1.3381(7)\,M_\odot$
- Accuracy of $\Delta I = 10\,\%$ seems feasible

- Predicted range: $I_\mathrm{A} = 51.5 - 86.0\,M_\odot\,\mathrm{km}^2$
- Assume a measurement of $I_\mathrm{A} = 70 \pm 7\,M_\odot\,\mathrm{km}^2$

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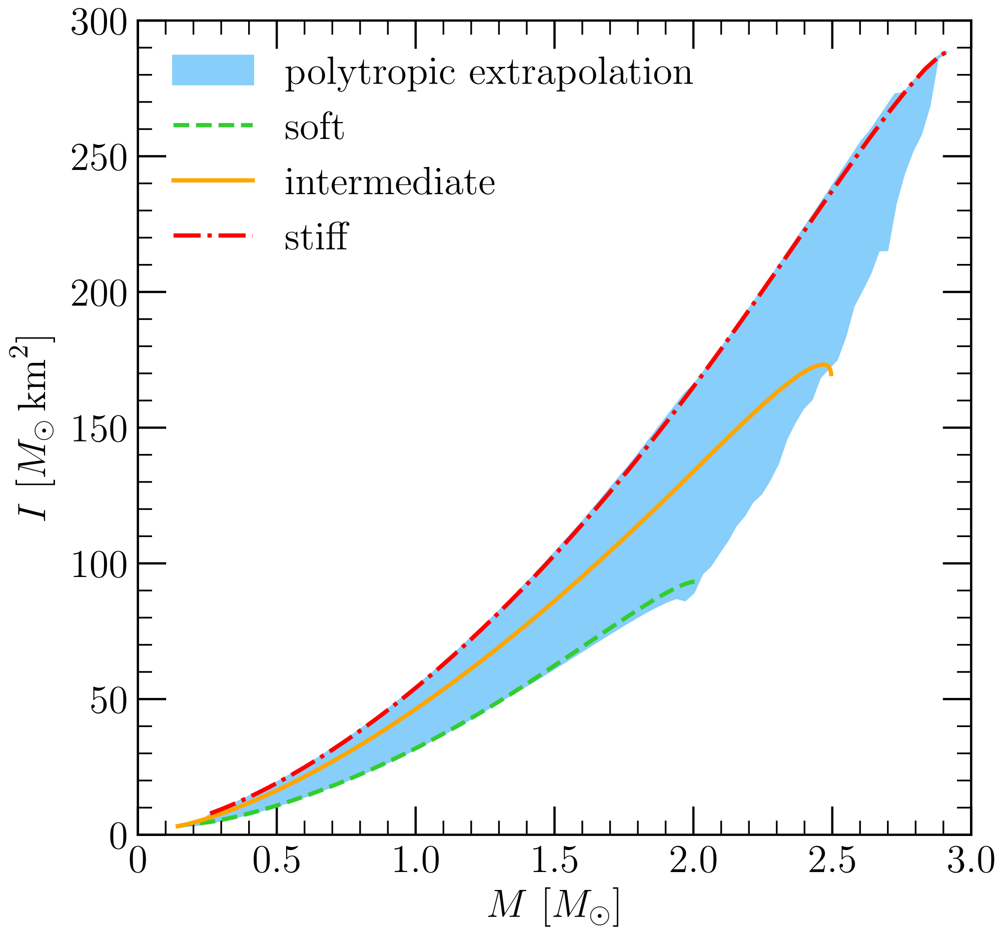

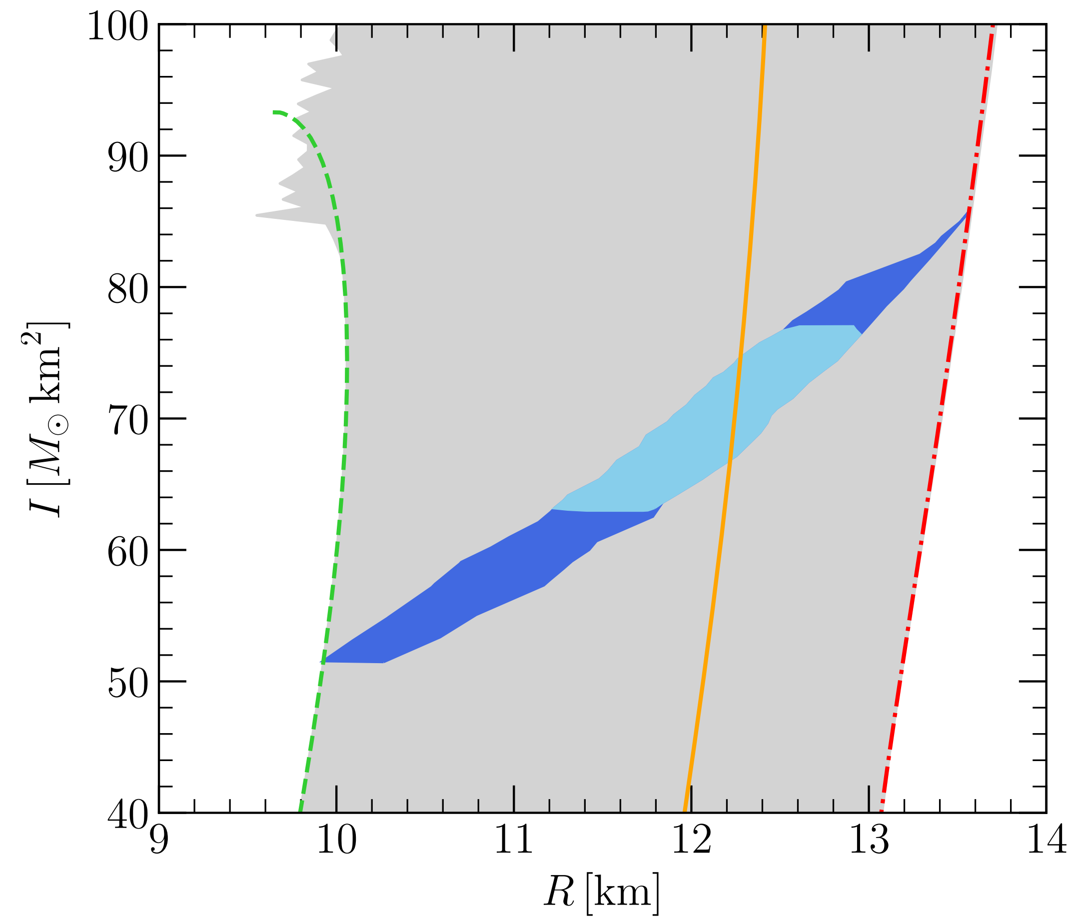

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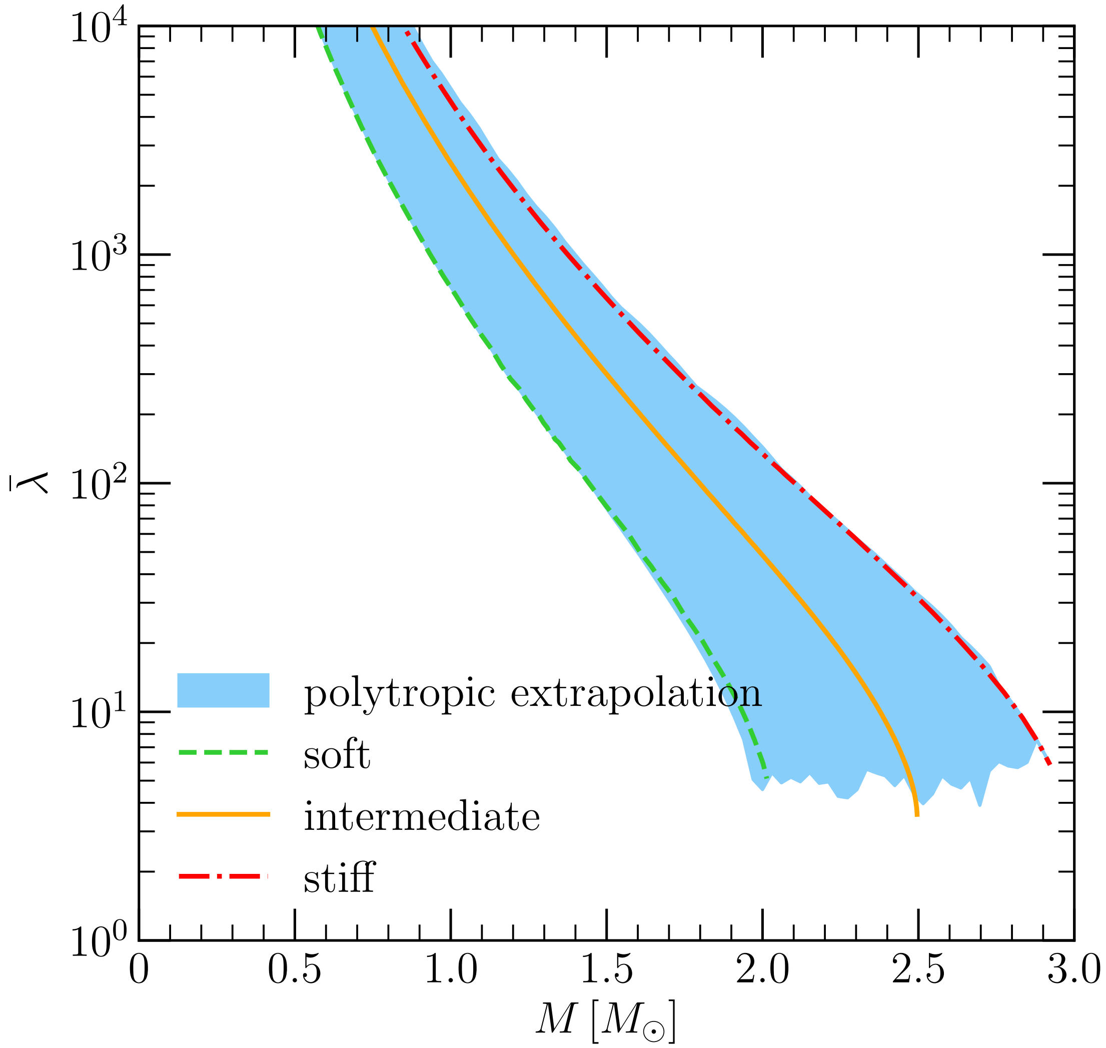
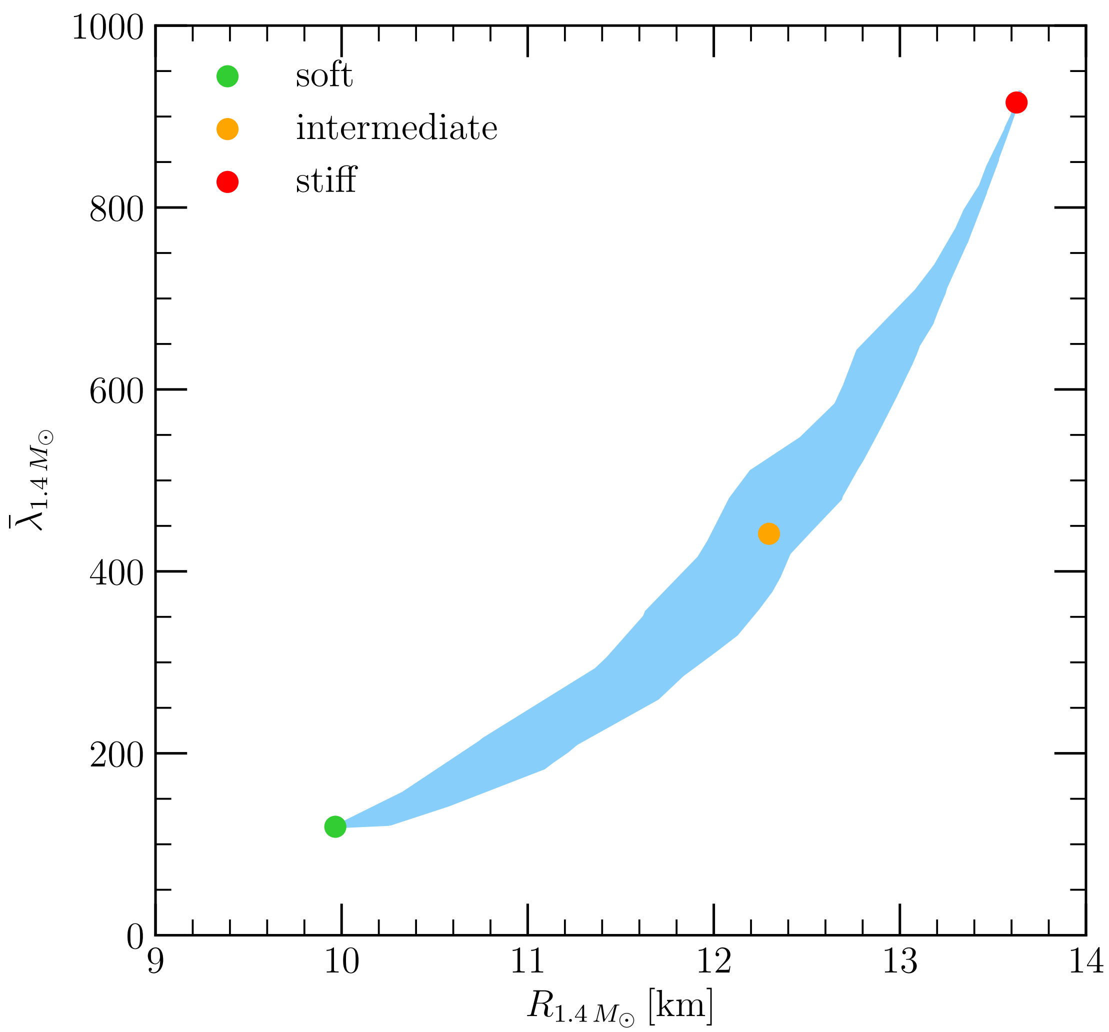
$\Delta I = \pm\,10\,\%$ measurement yields a reduction of 50% in radius uncertainty

Era of multi-messenger astronomy
Constraints from GW170817

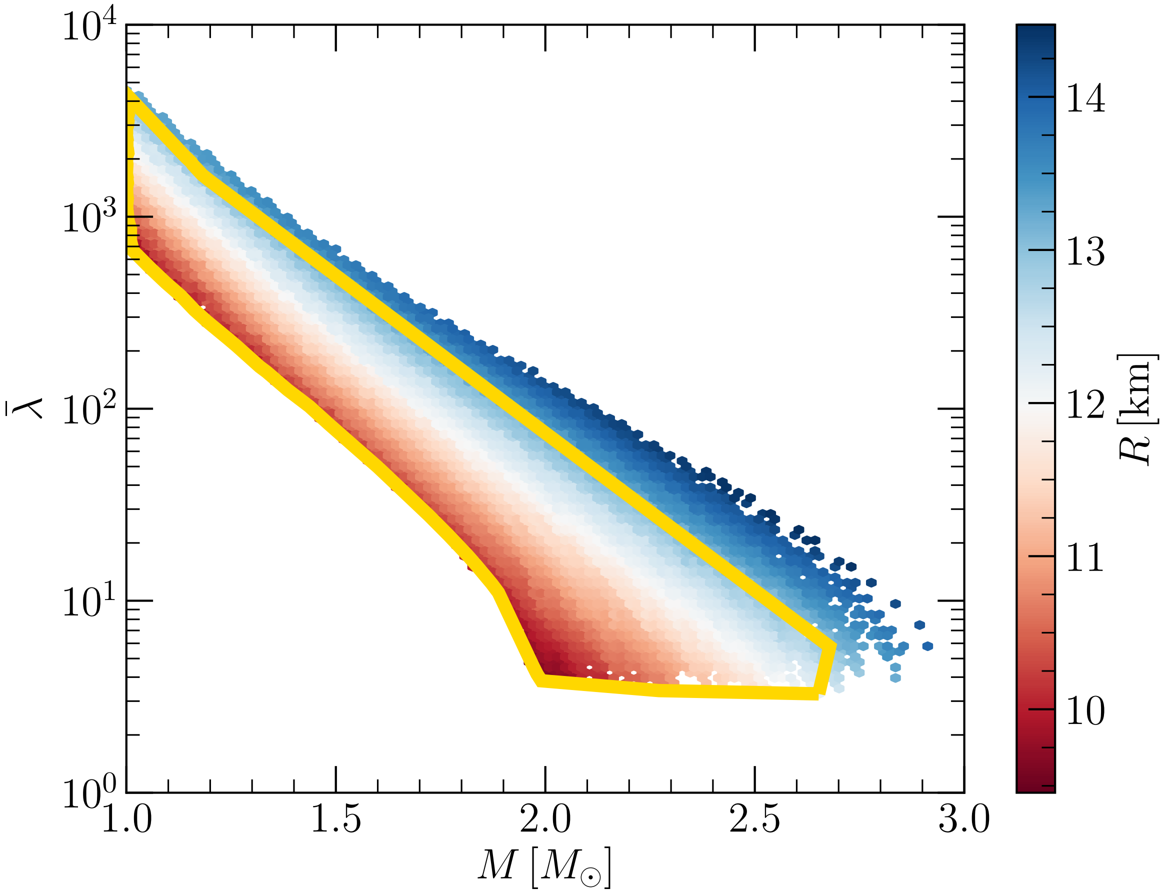


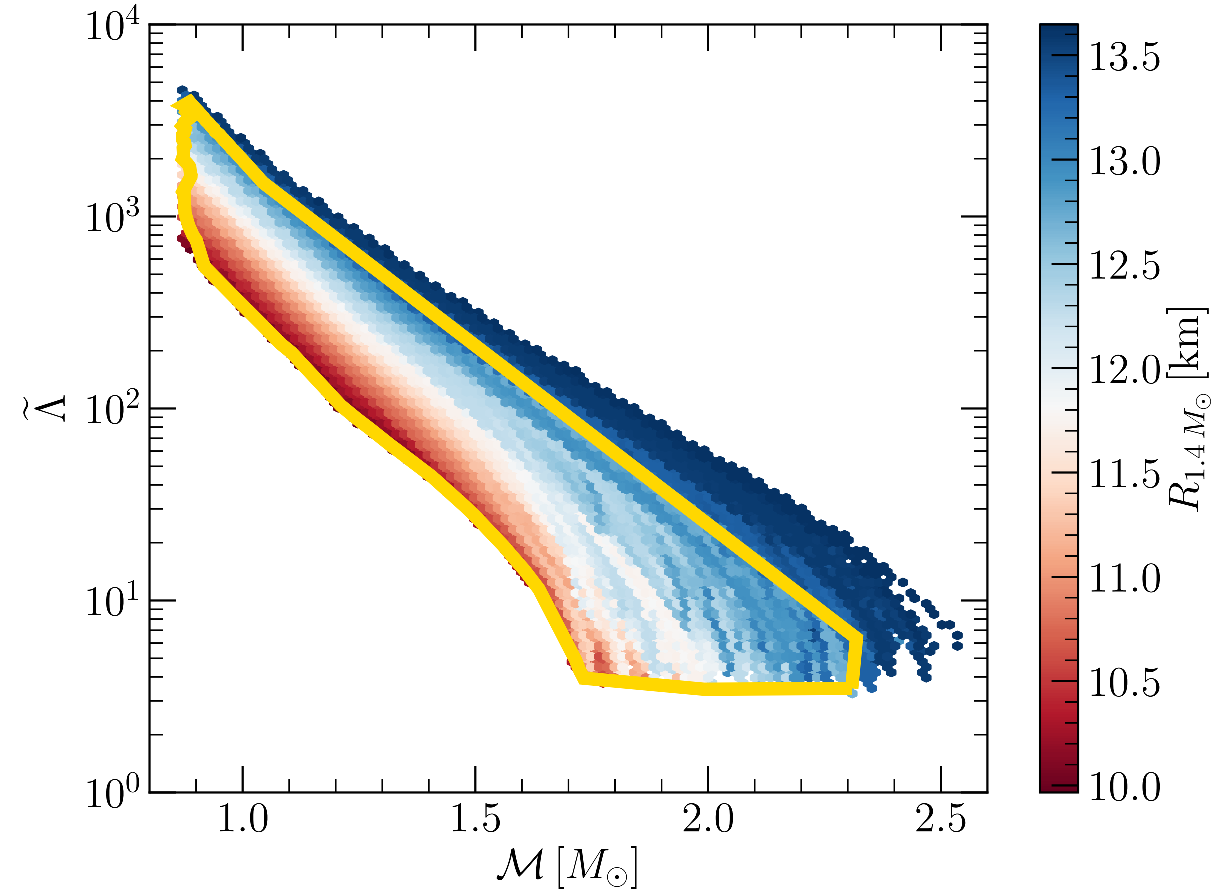


- Predicted range for typical neutron stars: $\bar{\lambda}_{1.4\,M_\odot} \approx 120 - 930$
- LVC: $\bar{\lambda}_{1.4\,M_\odot} = 190^{+390}_{-120}$

LVC, PRL 121, 161101 (2018)

Era of multi-messenger astronomy
Constraints from GW170817





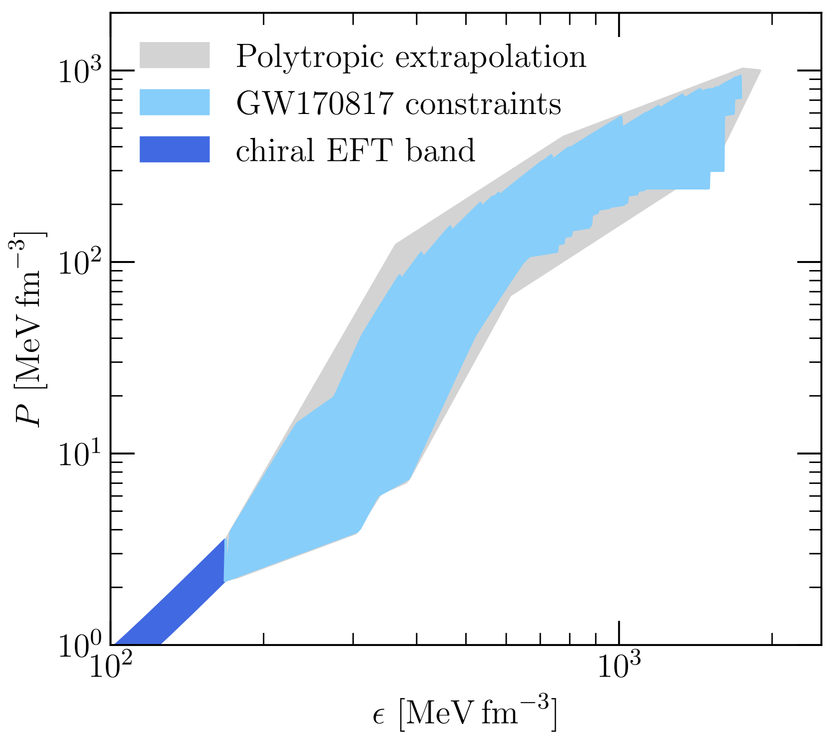
- From GW170817 extracted ranges:
  $\mathscr{M} = 1.186 \pm 0.001\, M_\odot$ and
  $\tilde{\Lambda} = 300^{+500}_{-190}$

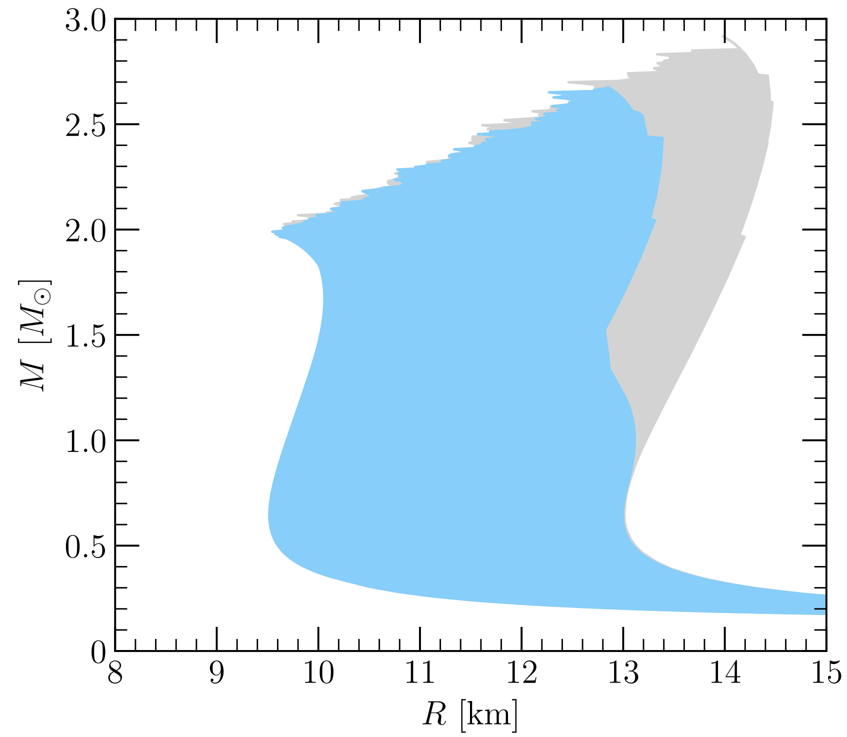
LVC, PRL 119, 161101 (2017)
LVC, PRL 121, 161101 (2018)
LVC, PRX 9, 011001 (2019)

$$R^{\rm PP}_{1.4\,M_\odot} = 9.97 - 12.85\,{\rm km}$$

First GW event provides no strong constraints

Era of multi-messenger astronomy
Inferred constraints for the EOS and radii





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GW170817

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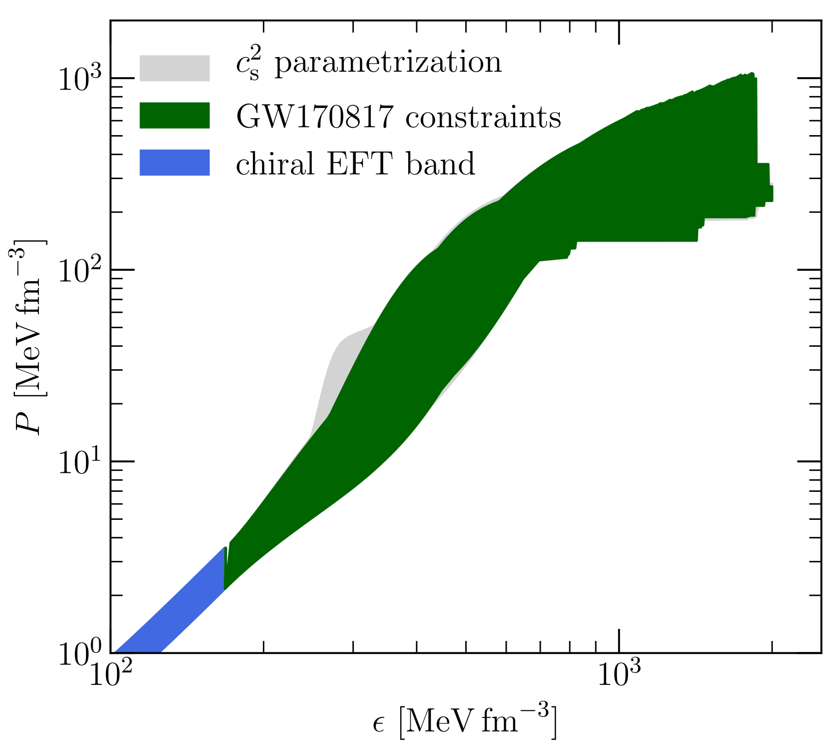

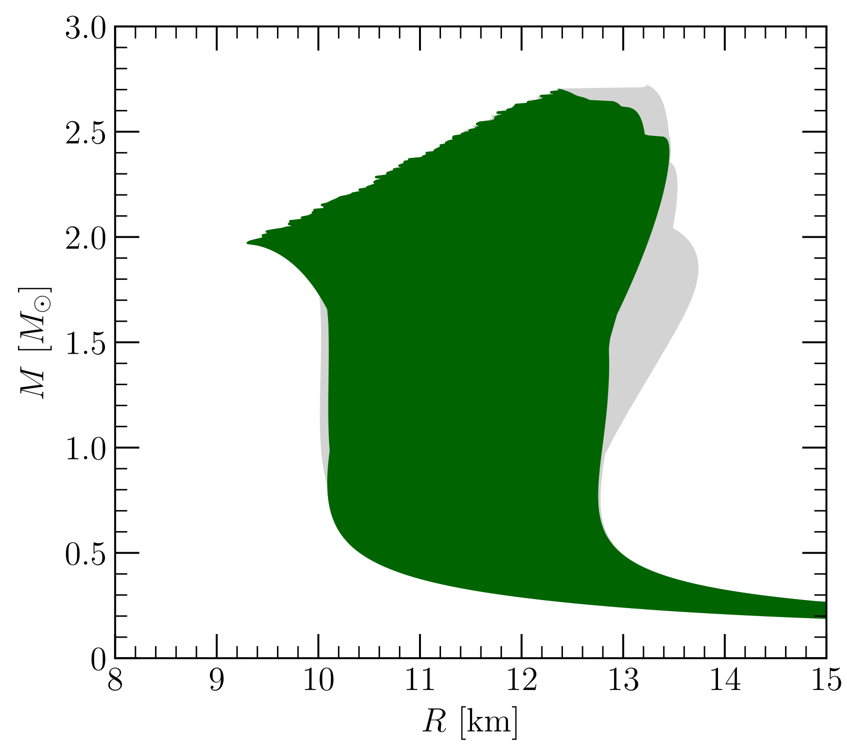

$R^{CS}_{1.4\,M_\odot} = 10.04 - 13.32\,\mathrm{km}$

GW170817

$R^{CS}_{1.4\,M_\odot} = 10.11 - 12.85\,\mathrm{km}$

Key messages

- Parametrization of the EOS using piecewise polytopes and new speed of sound model
- General constraints for the EOS and neutron star structure
  - BPS crust EOS up to $\sim \rho_{\mathrm{sat}}/2$
  - Results based on chiral EFT up to $\sim \rho_{\mathrm{sat}}$
  - Physically motivated constraints (causality and $2\,M_{\odot}$ neutron stars)
- First radius constraints from NICER data (multiple sources existent)
- Future moment of inertia measurement hat the potential to provide strong constraints on neutron star radii and the EOS (only one candidate so far)
- Complementary constraints from multi-messenger astronomy (only two events so far)

Key messages

TECHNISCHE UNIVERSITÄT DARMSTADT

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  - Physically motivated constraints (causality and $2\,M_{\odot}$ neutron stars)
- First radius constraints from NICER data (multiple sources existent)
- Future moment of inertia measurement hat the potential to provide strong constraints on neutron star radii and the EOS (only one candidate so far)
- Complementary constraints from multi-messenger astronomy (only two events so far)

In collaboration with K. Hebeler, J. Lattimer, C. Pethick, G. Raaijmakers, A. Schwenk, and A. Watts

Thank you for your attention!

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