Constraining the nuclear equation of state from nuclear physics and neutron star observations

EMMI Physics Day 2019
GSI Darmstadt

Svenja Kim Greif

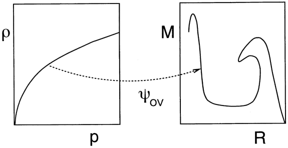
Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation
- Equation of state constraints
- Equation of state and neutron star structure
- First insights into the NICER results
- The double pulsar's moment of inertia
- Era of multi-messenger astronomy
- Key messages

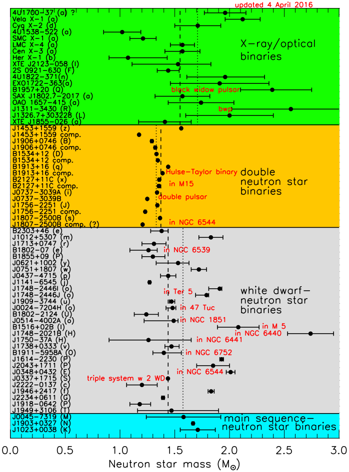
Motivation
Neutron stars as unique laboratories

- equation of state (EOS) of dense matter for densities beyond $\rho_{\rm sat} = 2.8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$ is poorly understood
- unique relation between EOS and mass-radius (MR)



Lindblom, APJ 398, 569 (1992)

- precise measurements from pulsar observations are available
- radius determination is now studied



Lattimer & Prakash, PRL 94, 111101 (2005)
https://stellarcollapse.org/nsmasses (2019-11-13)

Equation of state constraints
. . . from astrophysical observations

TECHNISCHE UNIVERSITÄT DARMSTADT

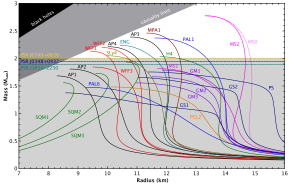
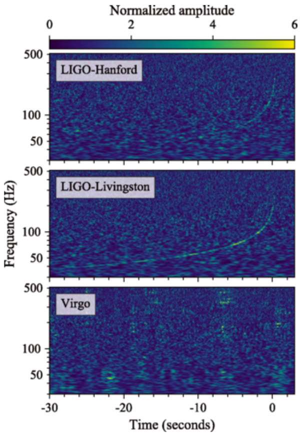


image credit: N. Wex

`https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html` (2019-10-16)

- significant constraints from the heaviest neutron star PSR J0348 + 0432
  Antoniadis *et al.*, Science 340, 6131 (2013)
- each constructed EOS is required to reproduce neutron stars of at least 1.97 $M_\odot$
- gravitational wave astronomy: direct detection from a binary neutron star merger
  LVC, PRL 119, 161101 (2017)
- analysis of GW170817 provides ranges for chirp mass and binary tidal deformability



LVC, PRL 119, 161101 (2017)

Equation of state constraints
… from astrophysical observations

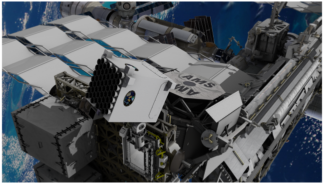


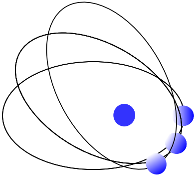
image credit: NASA/Conceptual Image Lab/Walt Feimer
`https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=20266` (2019-10-16)

- NICER (Neutron star Interior Composition ExploreR) using pulse-profile observations
  Arzoumanian *et al.*, PROC SPIE 9144, 914420 (2014)
- light-curve modeling and inference of neutron star properties using prior information provides posterior distribution for masses, radii, and the EOS

- ongoing measurement of the moment of inertia of PSR J0737 − 3039A
  Lyne *et al.*, Science 303, 1153 (2004)
- additional contribution to periastron advance $\dot{\omega}$ due to spin-orbit interaction

$$\dot{\omega} = \dot{\omega}_{1\mathrm{pN}} + \dot{\omega}_{2\mathrm{pN}} + \dot{\omega}_{\mathrm{SO}}$$

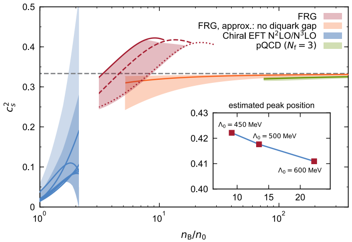
Kramer & Wex, Class. Quant. Grav. 26, 073001 (2009)



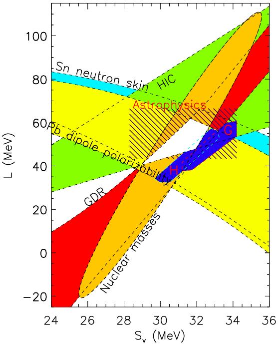
Equation of state constraints
... from nuclear experiments and pqCD

TECHNISCHE UNIVERSITÄT DARMSTADT

- 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 (FRG) for symmetric matter are available



Leonhardt, PhD Thesis, TUD (2019)



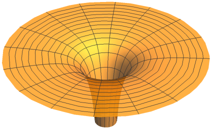
Lattimer & Lim, APJ 771, 51 (2013)

Equation of state and neutron star structure
Slow rotation approximation

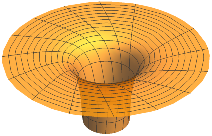
Hartle, APJ 150, 1005 (1967)
Hartle & Thorne, APJ 153, 807 (1968)
Hinderer, APJ 677, 1216 (2008)
Lindblom & Indik, PRD 89, 064003 (2014)

TECHNISCHE UNIVERSITÄT DARMSTADT

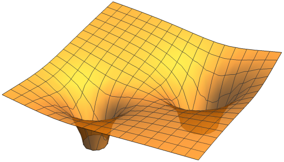
- non-rotating neutron stars
  mass M, radius R



- slowly rotating neutron stars
  moment of inertia I



- tidal interaction with a companion
  dimensionless tidal deformability $\bar{\lambda}$



Equation of state and neutron star structure
Piecewise polytropic expansion

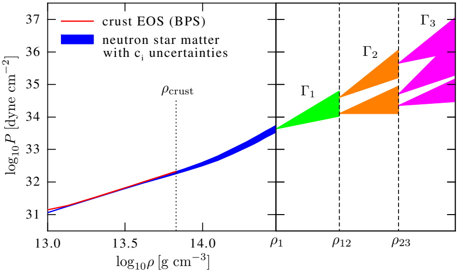
- nuclear density regime: knowledge of nuclear physics
  - BPS crust EOS up to $\sim \rho_{\text{sat}}/2$
  - Chiral effective field theory interactions up to $\sim \rho_{\text{sat}}$
- direct parametrization: piecewise polytropic expansion

$$P(\rho) = K\rho^{\Gamma}$$

Read, Lackey, Owen, Friedman, PRD 79, 124032 (2009)

- large parameter space constrained by general constraints: causality ($c_s < c$) and heaviest neutron star ($M_{\text{max}} \geq 1.97\, M_{\odot}$, 1σ lower limit)

Antoniadis *et al.*, Science 340, 6131 (2013)



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

Equation of state and neutron star structure
Piecewise polytropic expansion

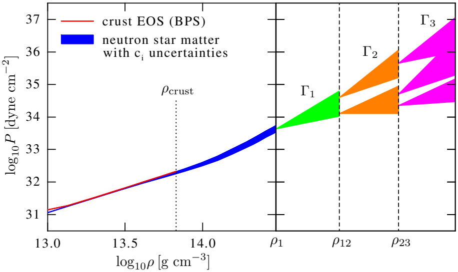
- nuclear density regime: knowledge of nuclear physics
  - BPS crust EOS up to $\sim \rho_{\text{sat}}/2$
  - Chiral effective field theory interactions up to $\sim \rho_{\text{sat}}$
- direct parametrization: piecewise polytropic expansion

$$P(\rho) = K\rho^{\Gamma}$$

Read, Lackey, Owen, Friedman, PRD 79, 124032 (2009)

- large parameter space constrained by general constraints: causality ($c_s < c$) and heaviest neutron star ($M_{\text{max}} \geq 1.97\, M_{\odot}$, 1σ lower limit)

Antoniadis *et al.*, Science 340, 6131 (2013)



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

- speed of sound: $c_s^2 = \frac{dP}{d\epsilon}$
- parametrization causes discontinuities in c_s^2

Equation of state and neutron star structure
Piecewise polytropic expansion

TECHNISCHE UNIVERSITÄT DARMSTADT

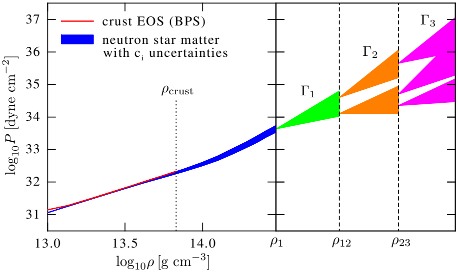
- nuclear density regime: knowledge of nuclear physics
  - BPS crust EOS up to $\sim \rho_{sat}/2$
  - Chiral effective field theory interactions up to $\sim \rho_{sat}$
- direct parametrization: piecewise polytropic expansion

$$P(\rho) = K\rho^{\Gamma}$$

Read, Lackey, Owen, Friedman, PRD 79, 124032 (2009)

- large parameter space constrained by general constraints: causality ($c_s < c$) and heaviest neutron star ($M_{max} \geq 1.97\, M_{\odot}$, 1σ lower limit)

Antoniadis *et al.*, Science 340, 6131 (2013)

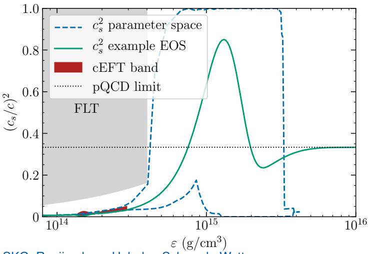


Hebeler, Lattimer, Pethick, Schwenk, APJ 773, 11 (2013)

- speed of sound: $c_s^2 = \frac{dP}{d\epsilon}$
- parametrization causes discontinuities in c_s^2

idea: parametrize the speed of sound

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



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

- obtain the EOS via integration

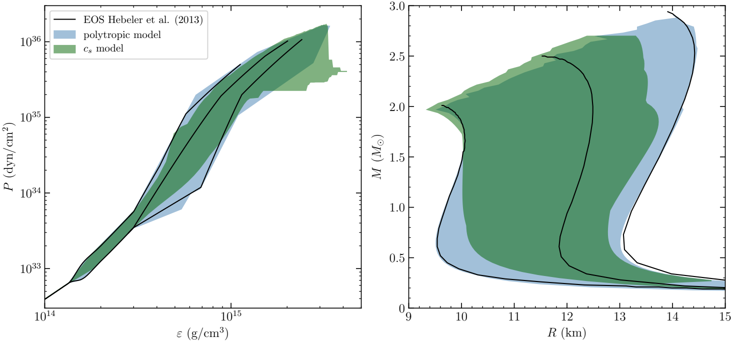
$$P(\epsilon) = \int_{\epsilon_0}^{\epsilon} \mathrm{d}\epsilon' \, c_s^2(\epsilon')$$

- physically motivated parametrization of the speed of sound c_s
  - approach pQCD constraint $c_s^2 \to 1/3$ 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

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

- parameters are varied to explore full parameter space

First insights into the NICER results
EOS and MR space



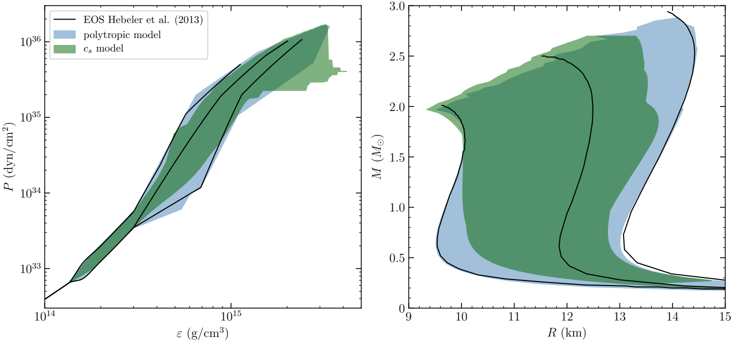
SKG, Raaijmakers, Hebeler, Schwenk, Watts, MNRAS 485, 5363 (2019)

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

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

First insights into the NICER results
EOS and MR space

TECHNISCHE UNIVERSITÄT DARMSTADT



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

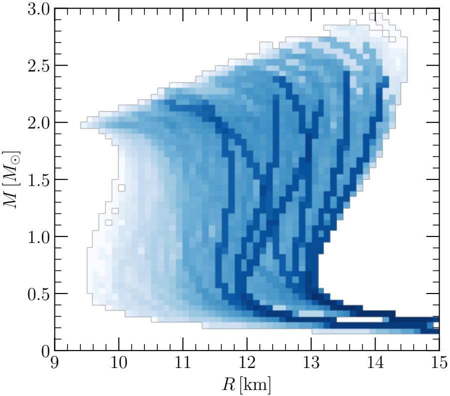
$$R^{\mathrm{PP}}_{1.4\,M_\odot} = 9.97 - 13.65\,\mathrm{km}$$

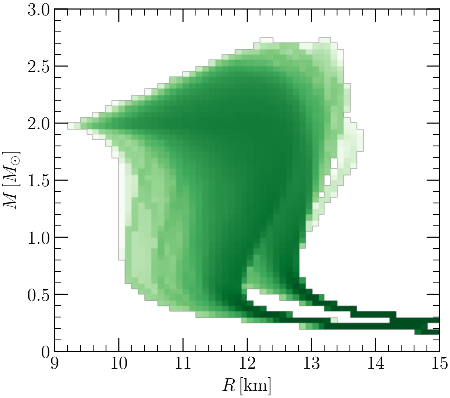
$$R^{\mathrm{CS}}_{1.4\,M_\odot} = 10.04 - 13.32\,\mathrm{km}$$

How do observations constrain this further?

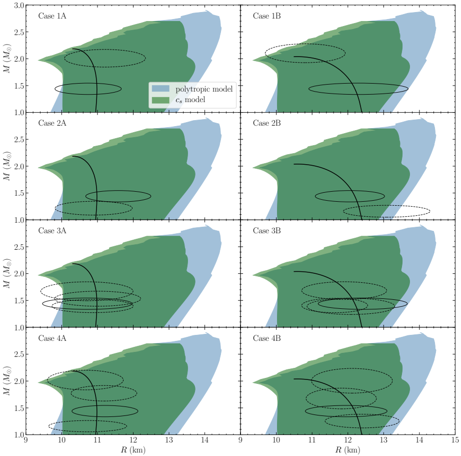
First insights into the NICER results
Prior information

TECHNISCHE UNIVERSITÄT DARMSTADT





First insights into the NICER results
Simultaneous mass-radius measurements

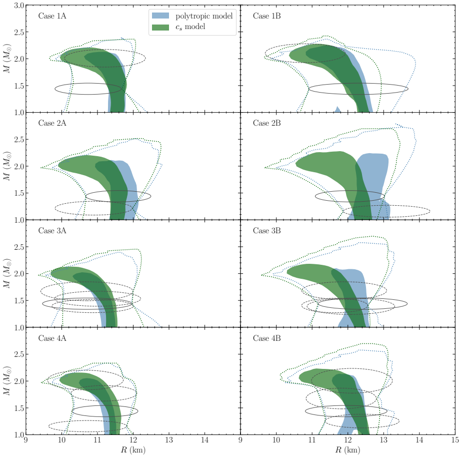


SKG, Raaijmakers, Hebeler, Schwenk, Watts, MNRAS 485, 5363 (2019)

- hypothetical MR measurements based on the primary science targets of the NICER mission
- results of both parametrizations are compatible
- posterior distribution from Bayesian analysis
  - underlying EOS is not recovered in each case
  - results are sensitive to the prior and the parametrization

First insights into the NICER results
Simultaneous mass-radius measurements

TECHNISCHE UNIVERSITÄT DARMSTADT

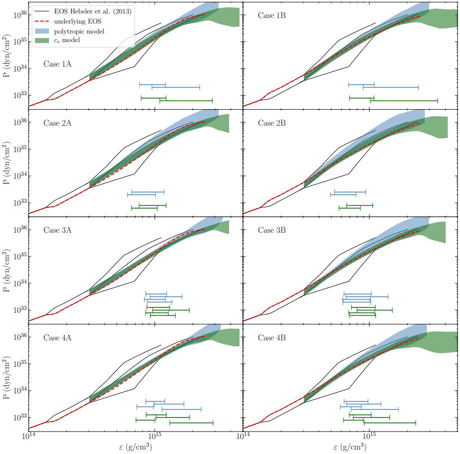


- hypothetical MR measurements based on the primary science targets of the NICER mission
- results of both parametrizations are compatible
- posterior distribution from Bayesian analysis
  - underlying EOS is not recovered in each case
  - results are sensitive to the prior and the parametrization

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

First insights into the NICER results
Simultaneous mass-radius measurements

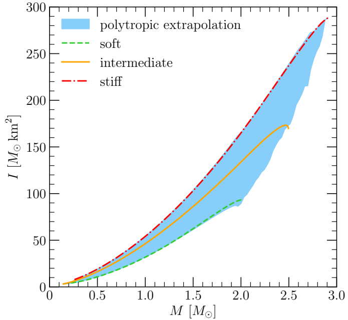
TECHNISCHE UNIVERSITÄT DARMSTADT

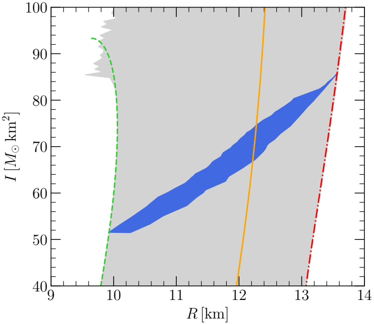


- hypothetical MR measurements based on the primary science targets of the NICER mission
- results of both parametrizations are compatible
- posterior distribution from Bayesian analysis
  - underlying EOS is not recovered in each case
  - results are sensitive to the prior and the parametrization

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

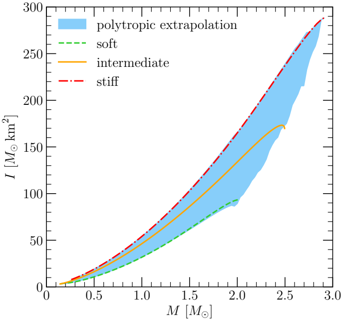
The double pulsar's moment of inertia
Radius constraints from the moment of inertia

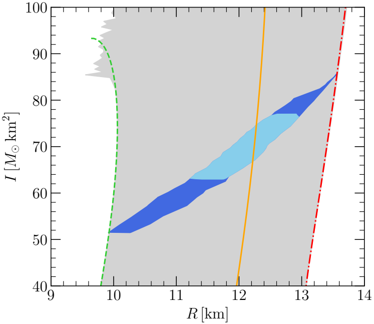




- PSR J0737 − 3039A with $M_A = 1.3381(7)\, M_\odot$
  Burgay *et al.*, Nature 426, 531 (2003)
  Lyne *et al.*, Science 303, 1153 (2004)
- accuracy of $\Delta I = 10\%$ seems feasible
  Lattimer, Schutz, APJ 629, 979 (2005)
- predicted range: $I_A = 51.5 - 86.0\, M_\odot\,\mathrm{km}^2$
- assume a measurement of $I_A = 70 \pm 7\, M_\odot\,\mathrm{km}^2$

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





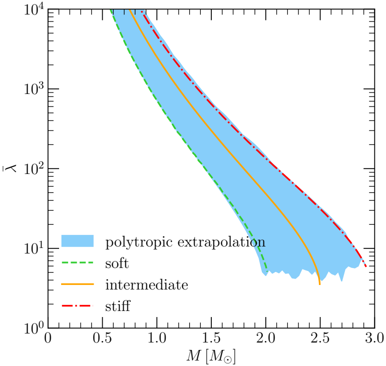
- PSR J0737 − 3039A with
  $M_A = 1.3381(7)\,M_\odot$
  Burgay *et al.*, Nature 426, 531 (2003)
  Lyne *et al.*, Science 303, 1153 (2004)
- accuracy of $\Delta I = 10\%$ seems feasible
  Lattimer, Schutz, APJ 629, 979 (2005)

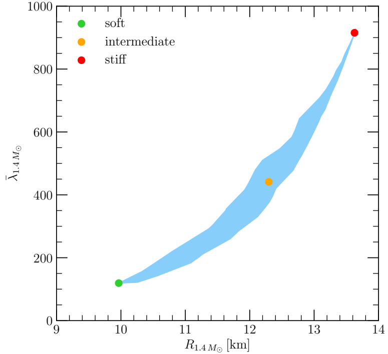
- predicted range:
  $I_A = 51.5 - 86.0\,M_\odot\,\mathrm{km}^2$
- assume a measurement of
  $I_A = 70 \pm 7\,M_\odot\,\mathrm{km}^2$

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

Era of multi-messenger astronomy
Constraints from GW170817

TECHNISCHE UNIVERSITÄT DARMSTADT

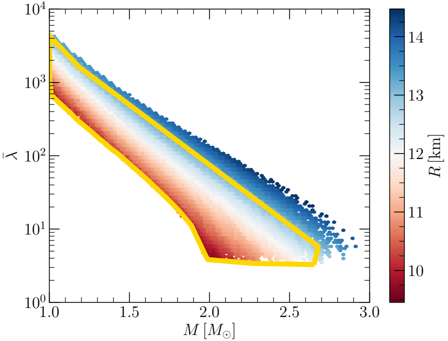


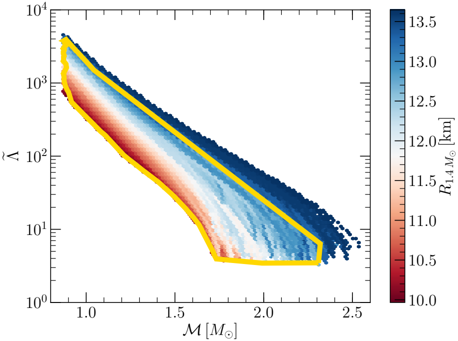


- predicted range for typical neutron stars: $\bar{\lambda}_{1.4\,M_\odot} \approx 120 - 930$
- LVC: $\bar{\lambda}_{1.4\,M_\odot} = 190 \pm^{+390}_{-120}$

  LVC, PRL 121, 161101 (2018)

Era of multi-messenger astronomy
Constraints from GW170817





- from GW170817 extracted ranges: $\mathcal{M} = 1.186 \pm 0.001\, M_\odot$ and $\tilde{\Lambda} = 300^{+500}_{-190}$
  LVC, PRL 119, 161101 (2017)
  LVC, PRL 121, 161101 (2018)
  LVC, PRX 9, 011001 (2019)

- $R_{1.4\,M_\odot} = 12.00 - 13.45\,\text{km}$
  Most *et al.*, PRL 120, 261103 (2018)

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

Key messages

TECHNISCHE UNIVERSITÄT DARMSTADT

- parametrization of the EOS using piecewise polytropes and new speed of sound model
- general constraints for the EOS and neutron star structure
  - BPS crust EOS up to $\rho_{\mathrm{sat}}/2$
  - results based on chiral EFT interactions up to $\sim \rho_{\mathrm{sat}}$
  - physically motivated constraints (causality and 2 $M_\odot$ neutron stars)
- first radius constraints from preliminary NICER data (multiple sources existent)
- future moment of inertia measurement has the potential to provide strong constraints on neutron star radii and the EOS (only one candidate so far)
- complementary constraints from multi-messenger astronomy

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

SFB 1245

Key messages

- parametrization of the EOS using piecewise polytropes and new speed of sound model
- general constraints for the EOS and neutron star structure
  - BPS crust EOS up to $\rho_{\text{sat}}/2$
  - results based on chiral EFT interactions up to $\sim \rho_{\text{sat}}$
  - physically motivated constraints (causality and 2 $M_\odot$ neutron stars)
- first radius constraints from preliminary NICER data (multiple sources existent)
- future moment of inertia measurement has the potential to provide strong constraints on neutron star radii and the EOS (only one candidate so far)
- complementary constraints from multi-messenger astronomy

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

Thank you for your attention!