Neutron Star Radii from Laboratory Experiments

W. Trautmann
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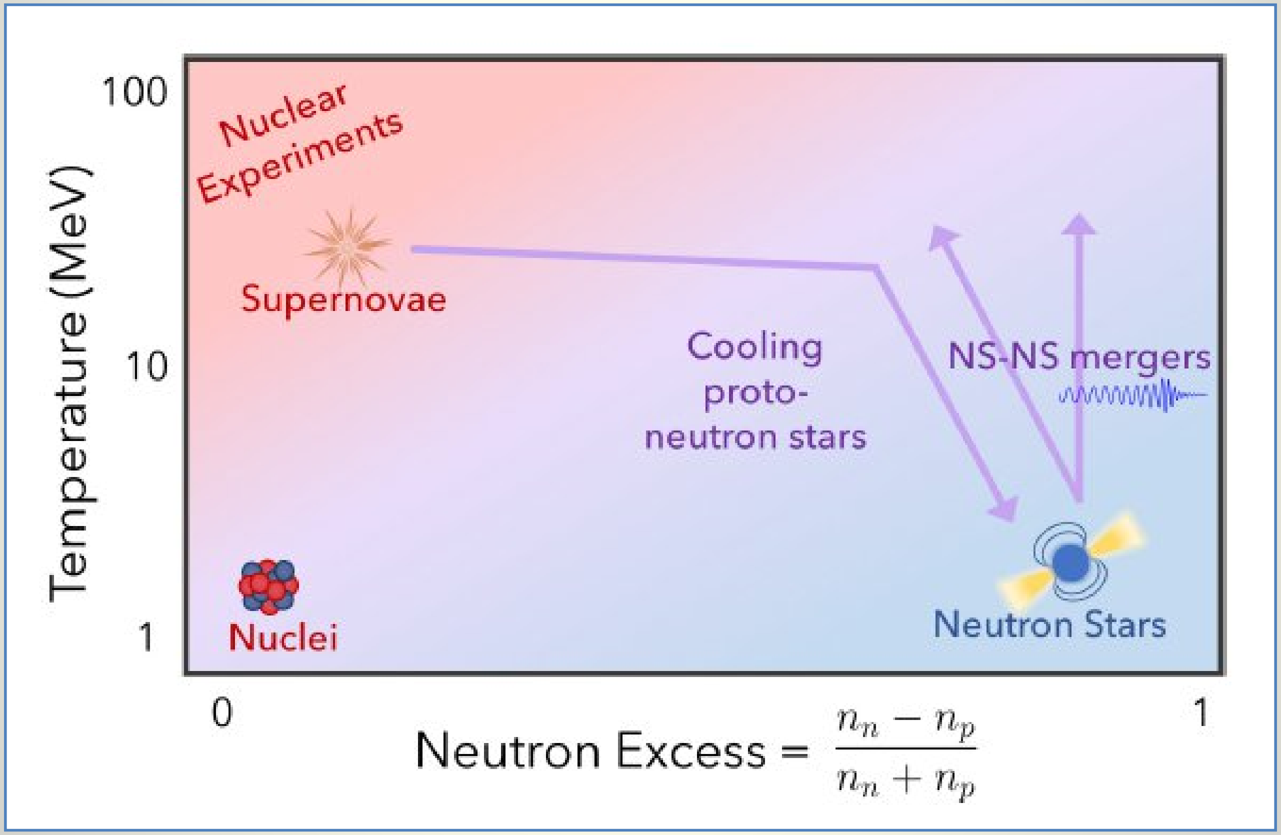


EMMI Workshop:

Collective phenomena and the equation-of-state of dense baryonic matter

GSI Darmstadt, November 10-13, 2025

Neutron Star Radii from Laboratory Experiments

Fig. 1 in Cozma/Trautmann, IJMPE 34, 2530001 (2025)

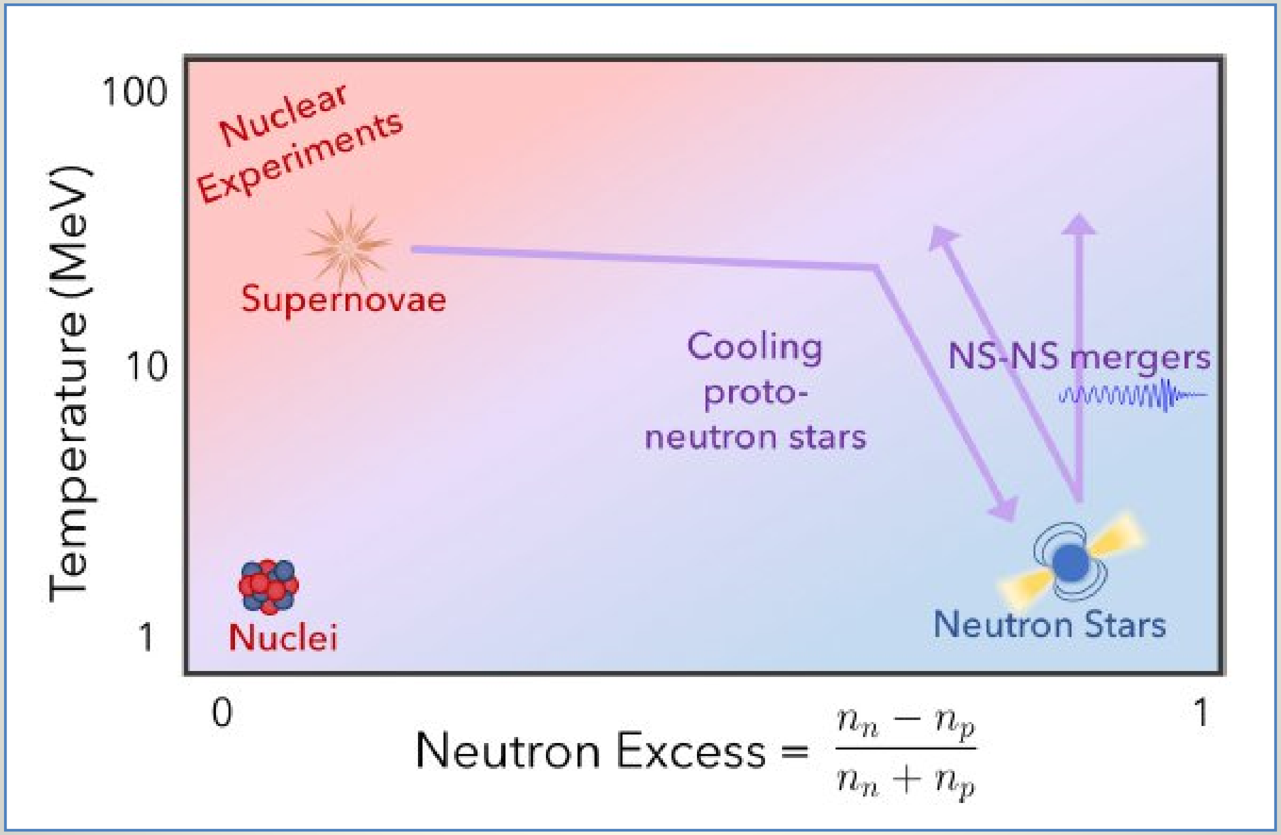
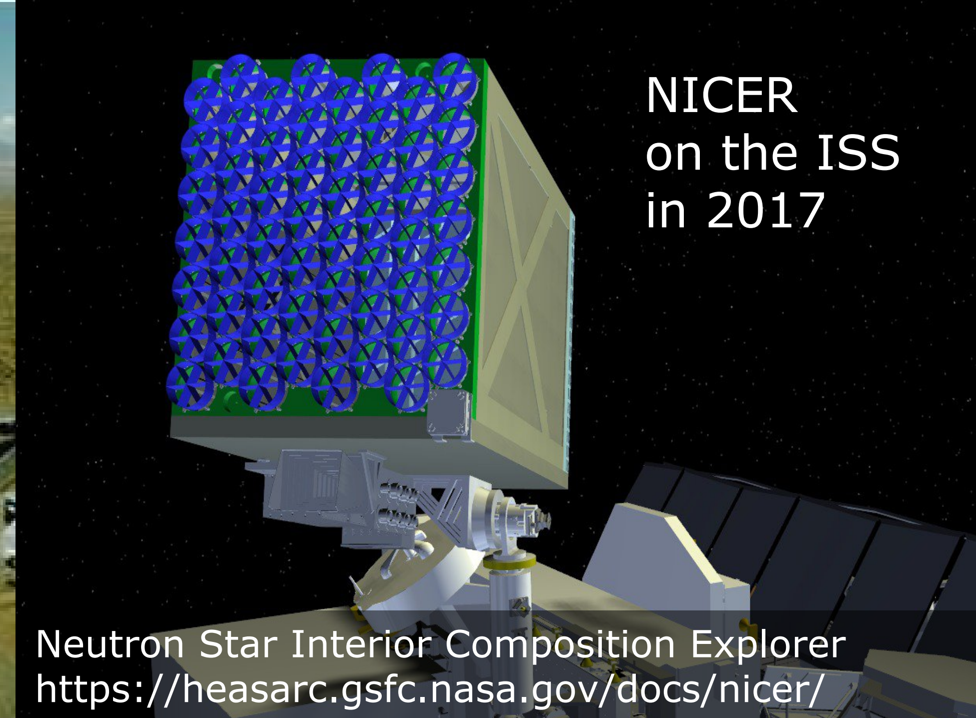
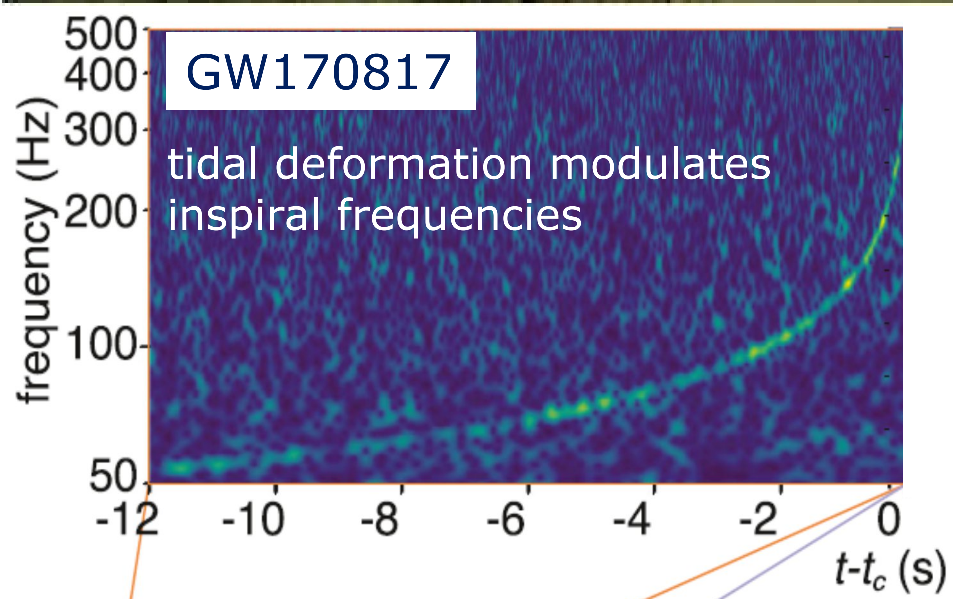


figure taken from Raithel, Özel and Psaltis, ApJ 875:12 (2019)

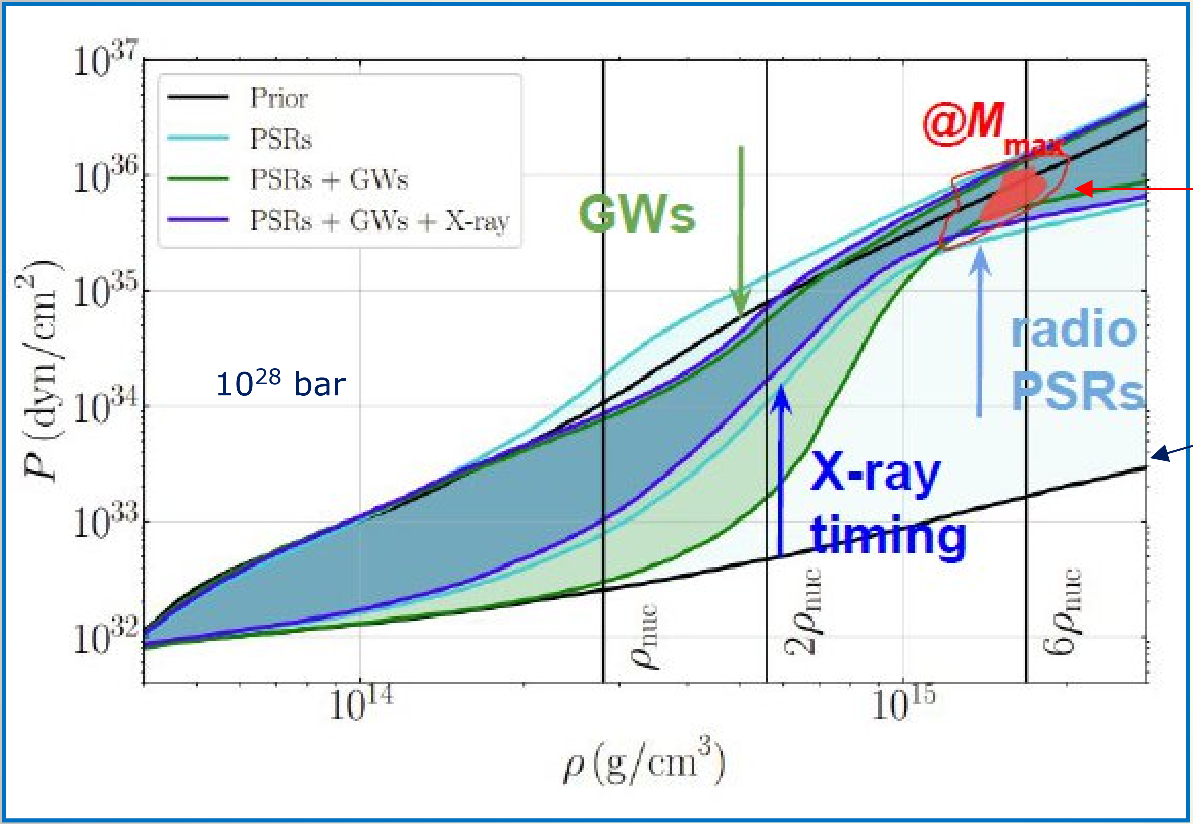
"Finite-temperature Extension for Cold Neutron Star Equations of State"





B.P. Abbott et al., LIGO and Virgo Collab.
The Astrophys. J. Letters, 848:L12 (2017)

Reed Essick at NuSym22 in Catania



Legred+, PRD 104, 063003 (2021)

50%/90% contours

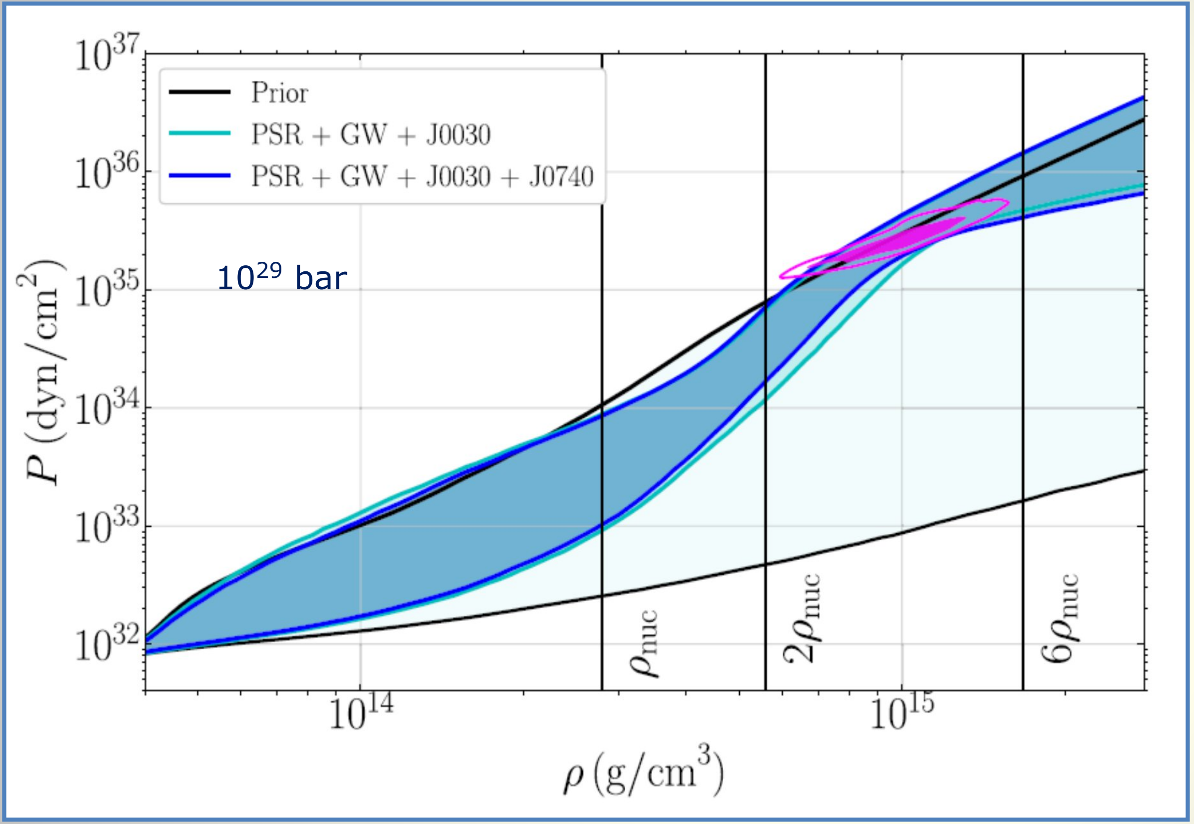
90% shadings

model-agnostic prior

red contours give pressure and density
in the center of a maximum-mass neutron star

Nuclear Equation of State well known at high density

Fig. 2 in IJMPE 34



Legred+, PRD 104, 063003 (2021)

50%/90% contours
90% shadings

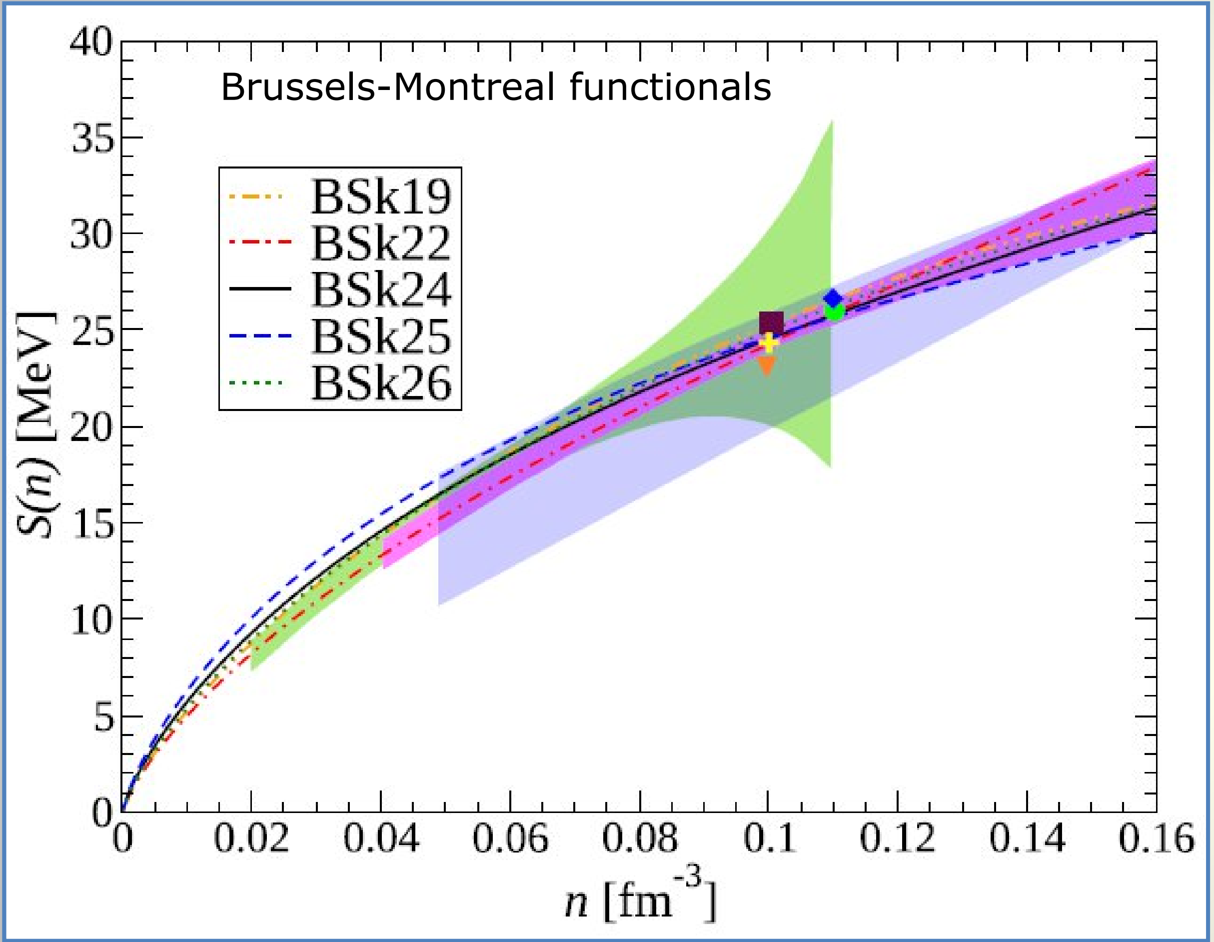
model-agnostic prior

$R_{1.4}$ = 12.6 ± 1.1 km (90%)

magenta contours give the 50% and 90% level of the central pressure-density posterior for **PSR J0740 + 6620** inferred from all available data
(PSR J0740 + 6620: **2.08 ± 0.08 M_O**, R = 12.8 $^{+1.5}_{-1.0}$ km (Dittmann+ 2024), 1.14 kpc)

Nuclear Equation of State well known below saturation density

Fig. 3 in IJMPE 34



Perot+, PRC 100, 035801 (2019)

shadings:

isospin diffusion
Tsang+ PRL (2009)

isobaric analog states and neutron skin
Danielewicz and Lee NPA (2014)

electric dipole polarizability in ^{208}Pb
Zhang and Chen PRC (2014)

data symbols:

giant resonances
binding energies,
separation energies,
radii

five data point at known density:
χ^2-analysis: $E_{sym}(0.10\ \rho_0)=24.8\pm0.5$ MeV

Symmetric matter EoS from collective flows

Fig. 4 in IJMPE 34

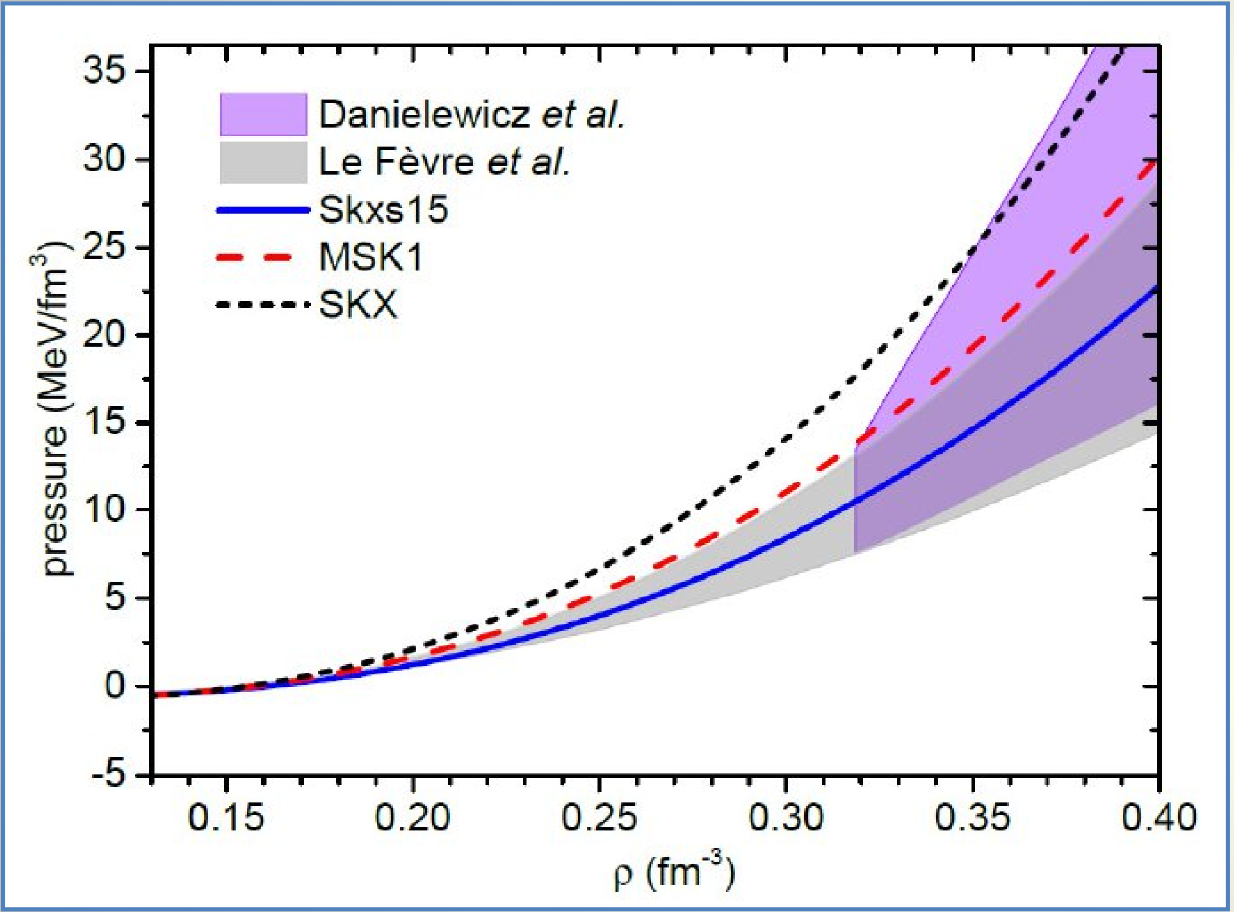


figure from
Yongjia Wang+, PLB 778, 207 (2018)

Danielewicz+
Science (2002)

Le Fèvre+
NPA 945 (2016)
K_0 = 190 ± 30 MeV
(FOPI data)

Yongjia Wang+
K_0 = 220 ± 40 MeV
(FOPI data)

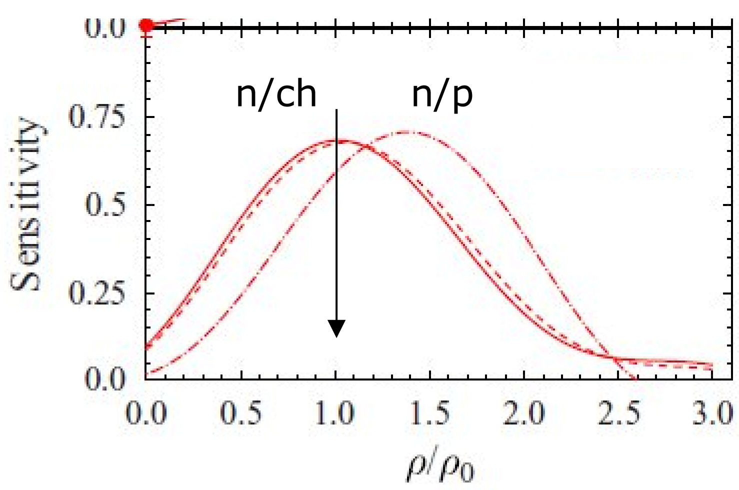
M.N. Harakeh at EuNPC 2025: K_0 = 230 MeV
"Isoscalar electric giant resonances: Compression modes and nuclear incompressibility"

ASY-EOS: neutron vs charged-particle elliptic-flow ratios

studied reaction
^{197}Au + ^{197}Au @ 400 A MeV

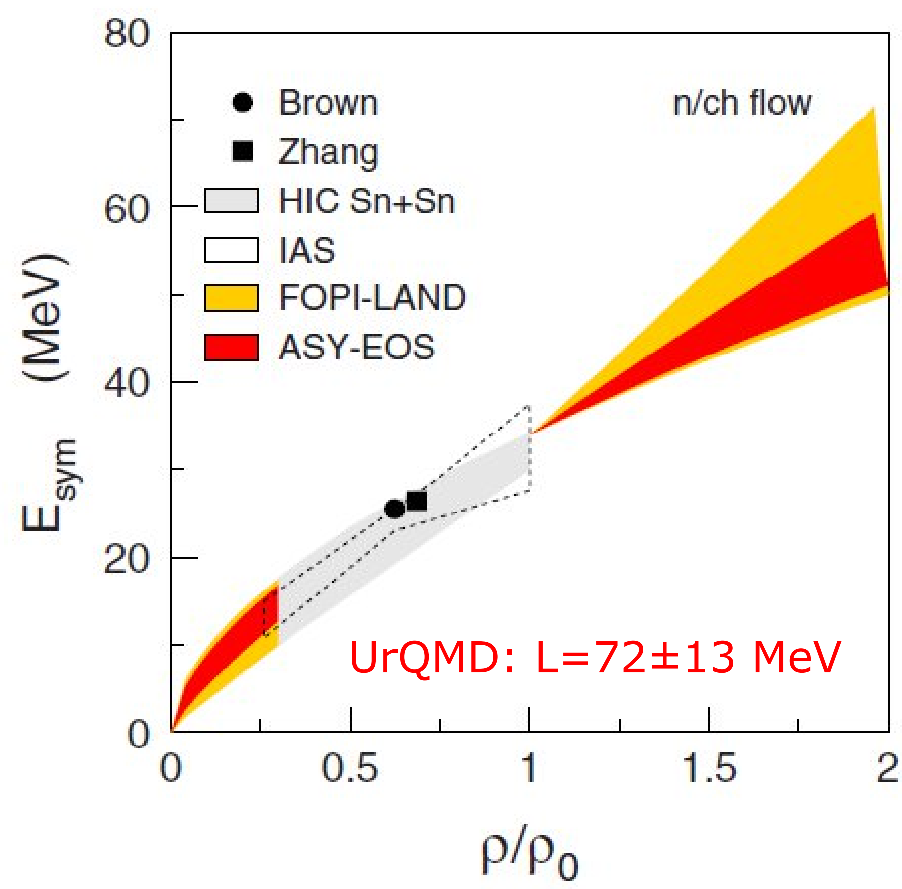
P. Russotto+ PRC 94, 034608 (2016)

sensitivity to density (TüQMD)



density probed extends to 2.5 ρ_0
maximum near saturation density

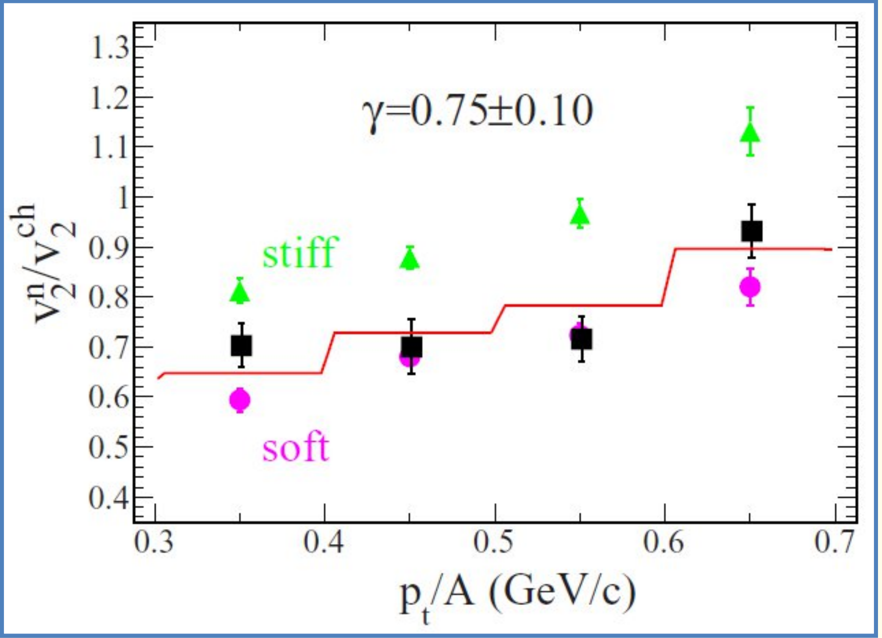
Fig. 8 in IJMPE 34

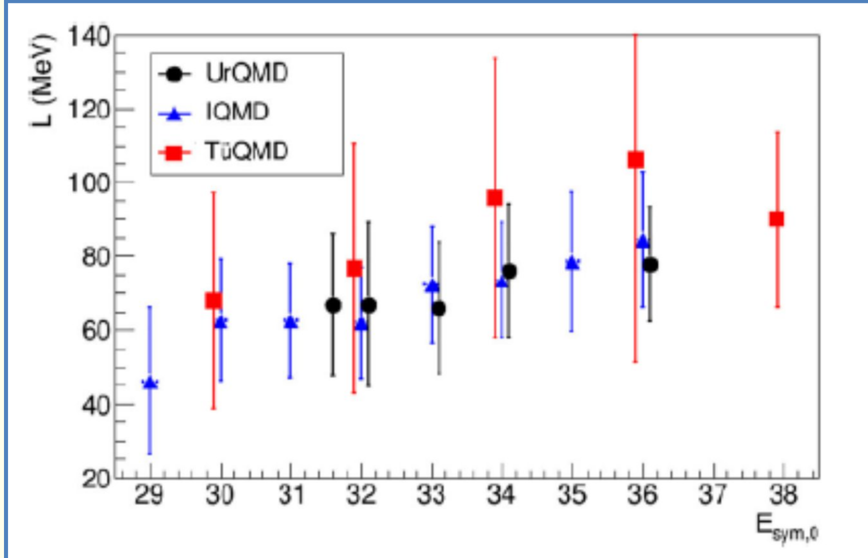


$E_{sym}(\rho_0)$ = 34 MeV => L= 72±13 MeV
$E_{sym}(\rho_0)$ = 31 MeV => L= 63±11 MeV

ASY-EOS: data and transport-model analysis

Fig. 7 in IJMPE 34





P. Russotto et al., Riv. Nuovo Cimento 46, 1 (2023)

stiff γ = 1.5
soft γ = 0.5

dependence on transport model ?
dependence on S_0 ?

parametrization used in UrQMD analysis:

$$E_{\mathrm{sym}} = E_{\mathrm{sym}}^{\mathrm{pot}} + E_{\mathrm{sym}}^{\mathrm{kin}} = 22\ \mathrm{MeV}(\rho/\rho_0)^{\gamma} + 12\ \mathrm{MeV}(\rho/\rho_0)^{2/3}$$

$E_{sym}(\rho_0)$-12 MeV

Huth et al., Nature 606 (2022): χEFT prior + HIC + astro

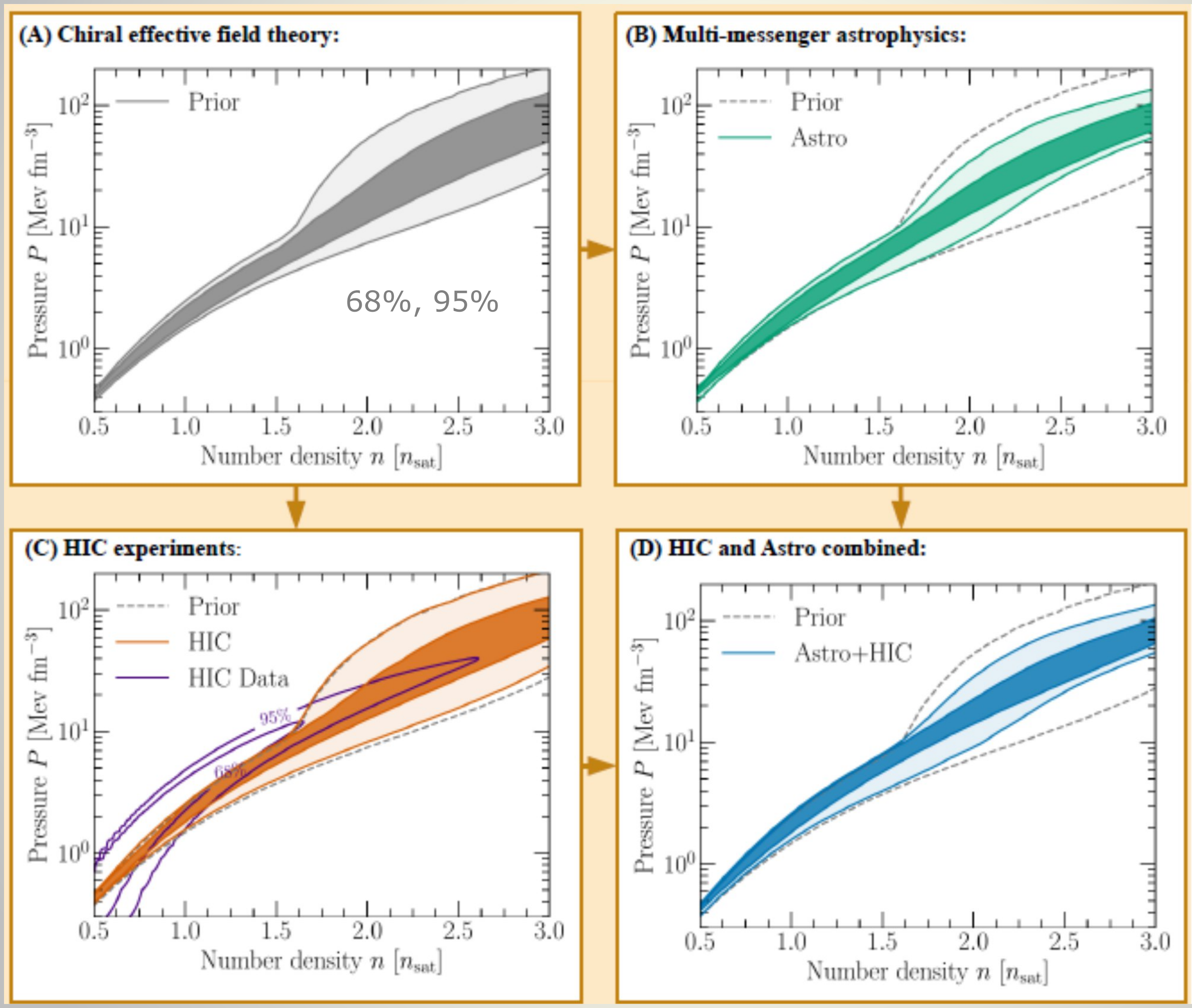


Fig. 1
neutron star matter

contours at 68% and 95% credibility

prior:
χEFT up to 1.5 ρ_0
c_s extension
$M_{max} \geq 1.9\ M_{sun}$

astro:
GW170817
+kilonova
GW190425
NICER 2 stars
XMM-Newton
$M_{max} \leq 2.17\ M_{sun}$

HIC:
PNM: ASY-EOS
SNM: FOPI, AGS

Prior in Huth et al.

χEFT -> 1.5 ρ_0

stability $c_s > 0$
causality $c_s < c$
segments
with $c_s = 0$

$M_{max} \geq 1.9\ M_{sun}$

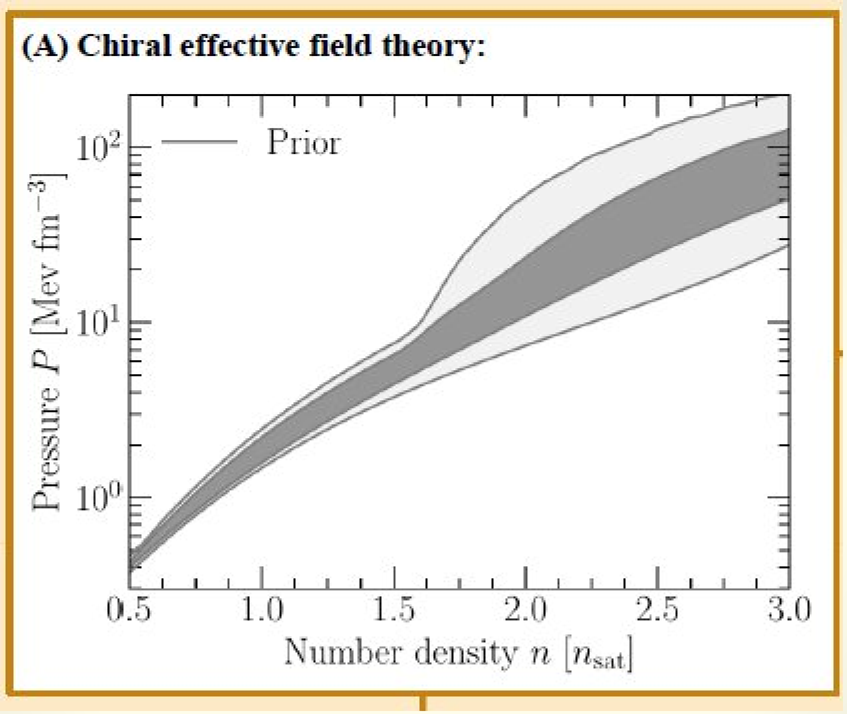


Fig. 1
neutron star matter

contours at 68% and 95% credibility

Prior + HIC

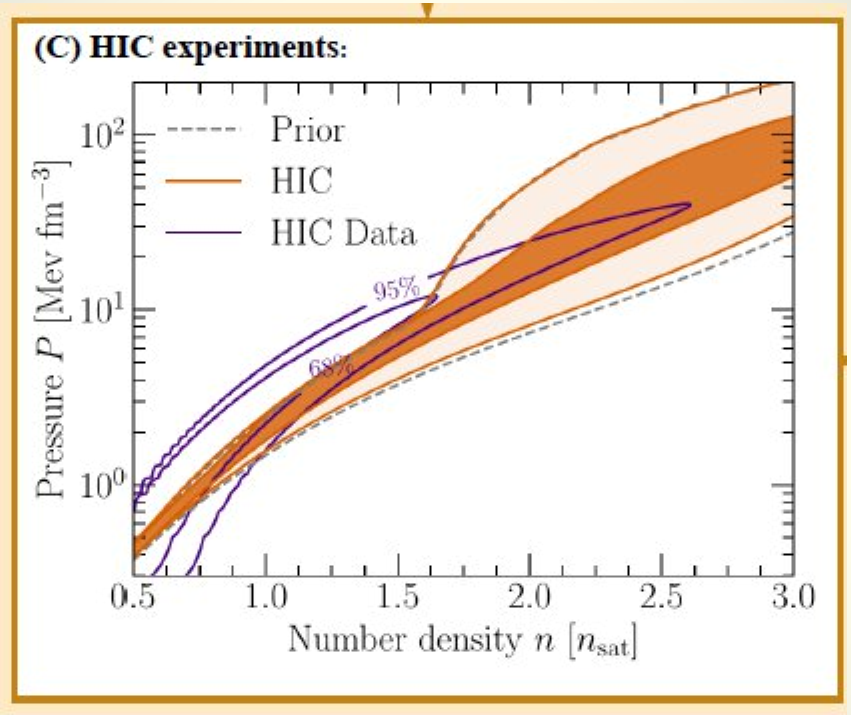


Fig. 1
neutron star matter

contours at 68% and 95% credibility

Prior + HIC + astro

Fig. 11 in IJMPE 34

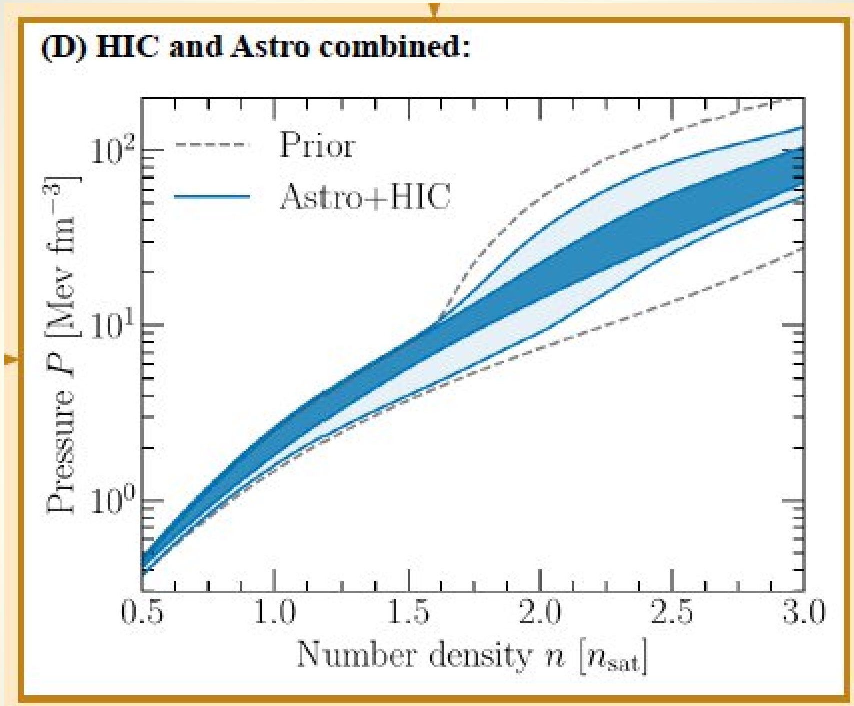


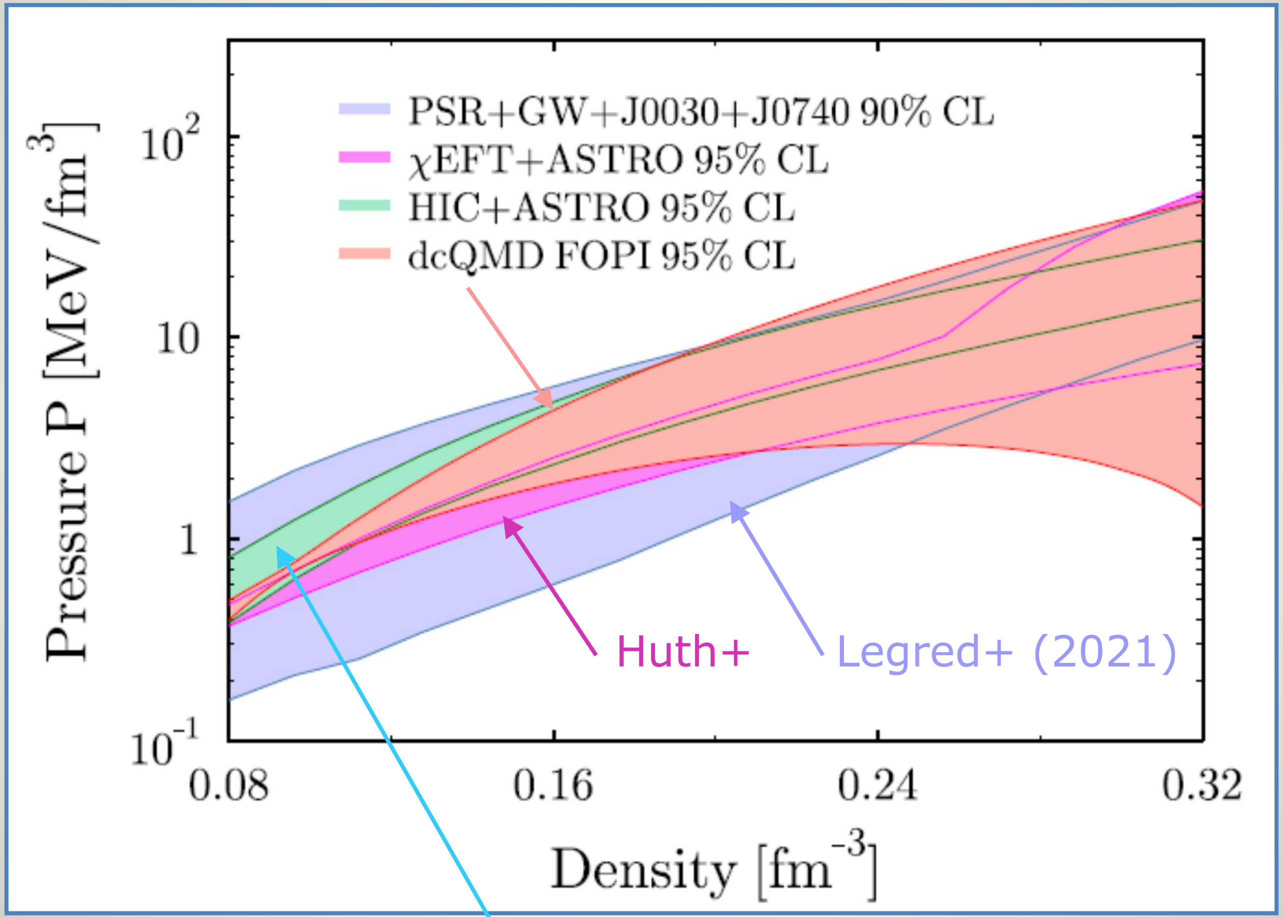
Fig. 1
neutron star matter

contours at 68% and 95% credibility

Physics Today June 2022:
Measurements of heavy-ion collisions predict properties of neutron stars that are consistent with those informed by astrophysical observations.

Nuclear Equation of State: inconsistencies near saturation

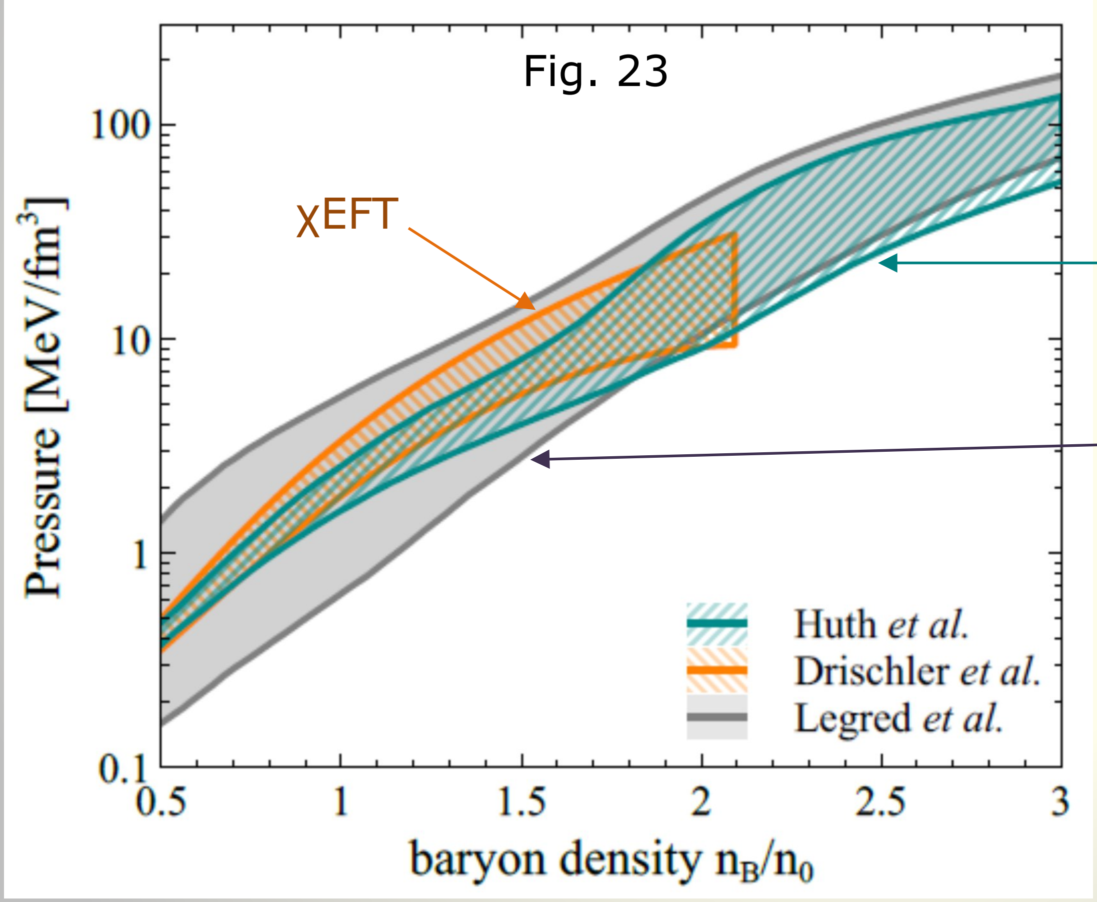
Fig. 10 in IJMPE 34   M.D. Cozma, PRC 110, 064911 (2024)



C.Y. Tsang+, Nature Astronomy 8, 328 (2024).

INT Workshop, Seattle, December 2022

review paper:
Sorensen et al., PPNP 134 (2024) 104080

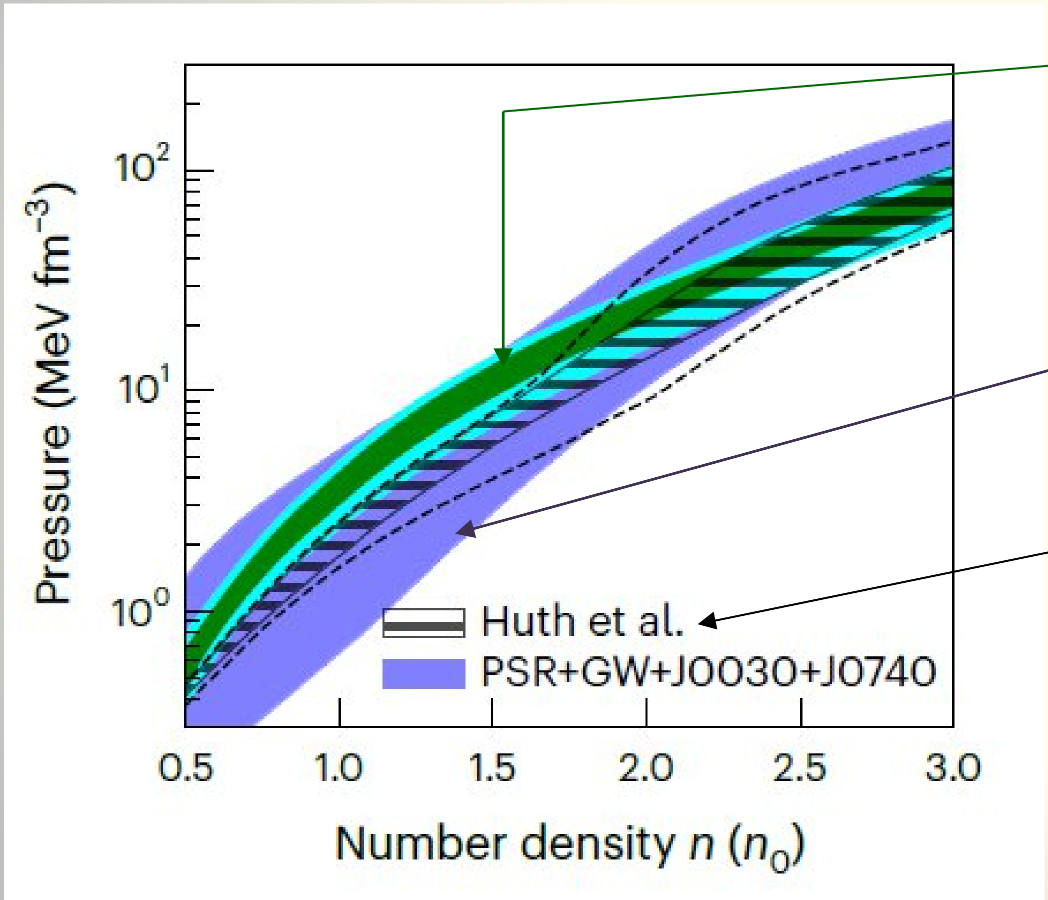


Huth, Pang et al., Nature 606
prior from χEFT up to 1.5 ρ_0
posterior (95%) from HIC
and astro
$R_{1.4}$ = **12.0** ± 0.8 km (95%)

Legred+, PRD 104 (2021)
agnostic prior with astro
$R_{1.4}$ = **12.6** ± 1.1 km (90%)

Drischler+, PRC 103 (2021)
χEFT with correlated
truncation errors

Tsang+, Nature Astronomy 8, 328 (2024)



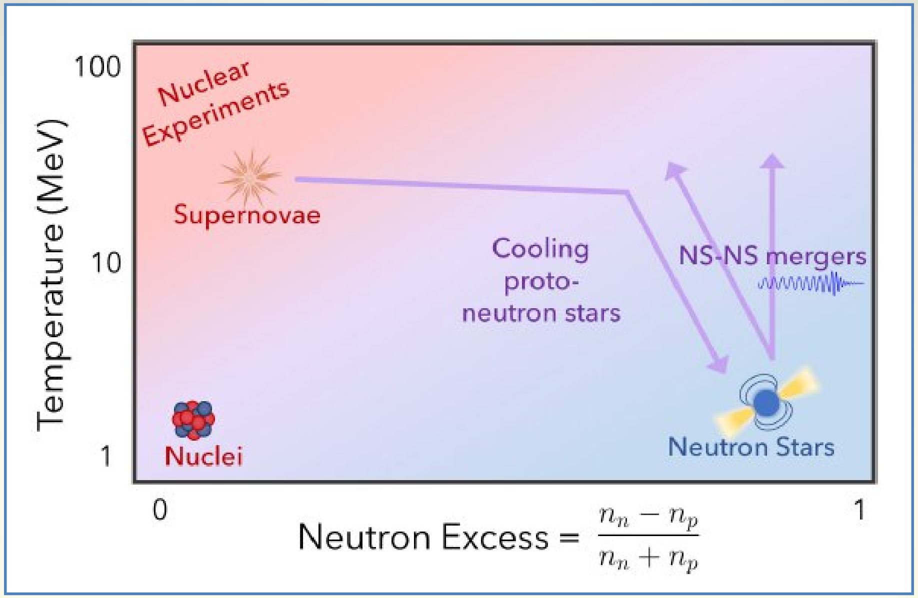
Tsang, Tsang, Lynch et al., Nat Astron. (2024) posterior (68%, 95%) from (mainly) HIC and astro
$R_{1.4}$ = **12.9** ± 0.5 km (68%)

Legred+, PRD 104 (2021) agnostic prior with astro
$R_{1.4}$ = **12.6** ± 1.1 km (68%)

Huth, Pang et al., Nature 606 prior from χEFT up to 1.5 ρ_0 posterior (95%) from HIC and astro
$R_{1.4}$ = **12.0** ± 0.8 km (95%)

the prior makes the difference

Conclusion at this point



precise value for $E_{sym}(\rho)$ at 2/3 ρ_0 from nuclear structure

EoS of neutron-star matter at high density well constrained by astro

inconsistencies at 1 – 2 ρ_0 depending on the chosen prior

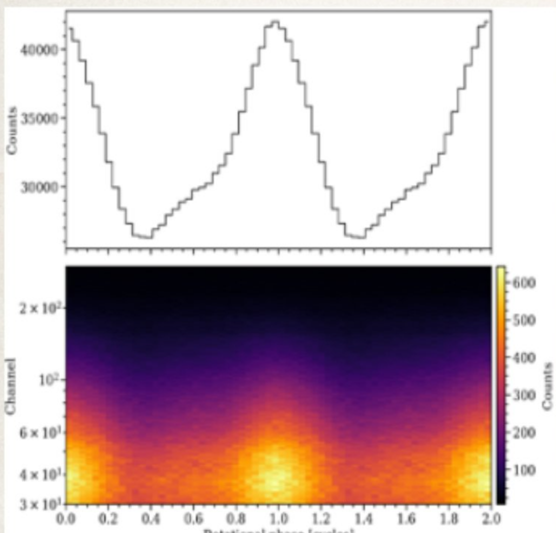
need improvements of
knowledge of $E_{sym}(\rho_0)$ and consistency of transport-model predictions

Choudhury+, Astrophys. J. Lett. 971, L20 (2024)

The new results from PSR J0437–4715 were long awaited…Why did it take so long ?

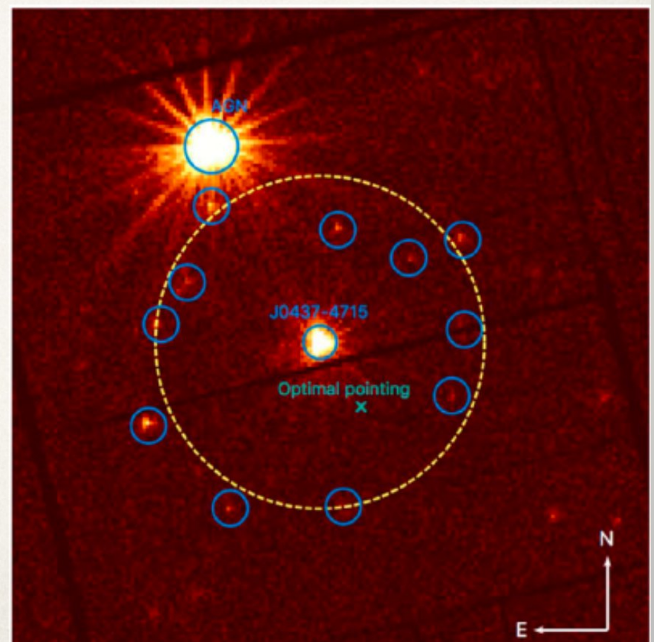
Advantages:

- Precise priors *(Reardon et. al. 2024)* :
  - Mass = 1.418 ± 0.044 Msun
  - Inclination = 137.506 ± 0.016 deg.
  - Distance = 156.98 ± 0.16 pc
- Nearest and brightest: High S/N
- Long observations: Msec of NICER data



Disadvantages:

- Neighbour bright source
- Offset pointing :
  - Different instrument response



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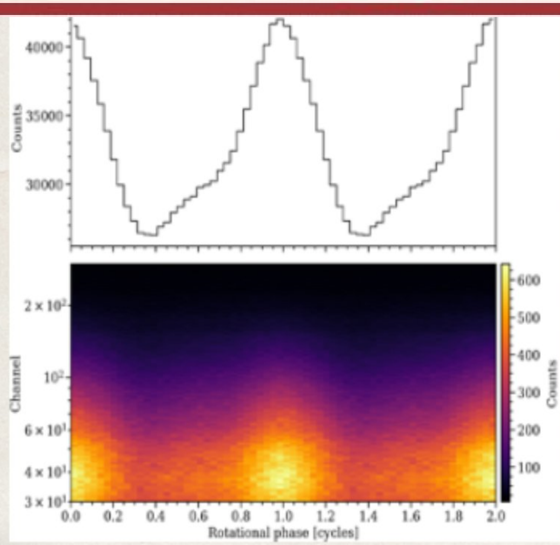
  - Distance = 156.98 ± 0.16 pc

Radius: $11.36^{+0.95}_{-0.63}$ km (68% CI) a



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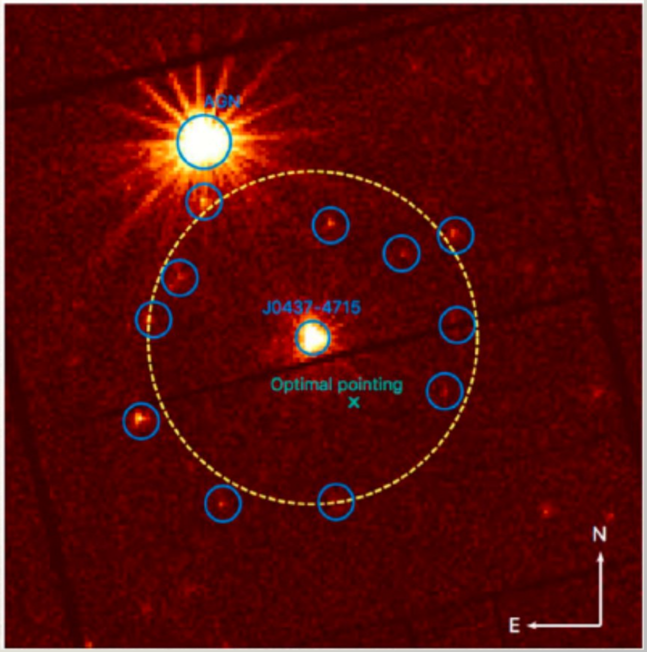
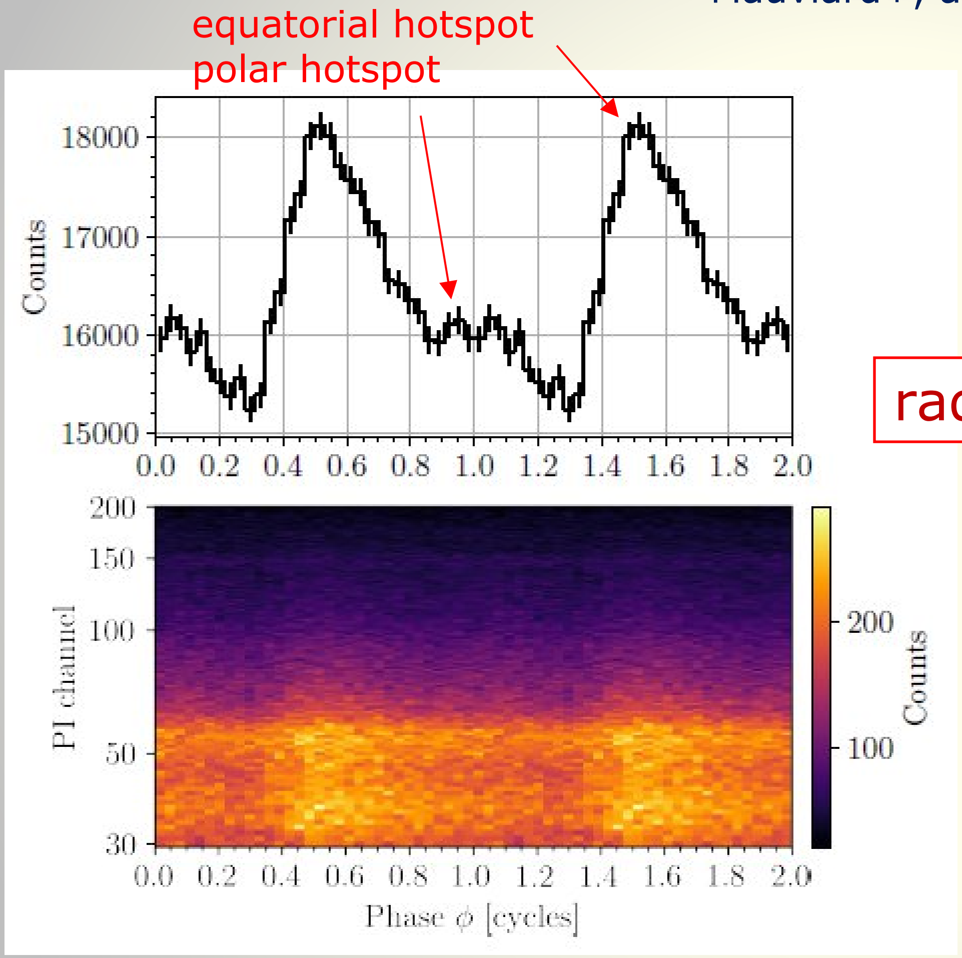


after submission

Mauviard+, arXiv:2506.14883 [astro-ph.HE] (2025)



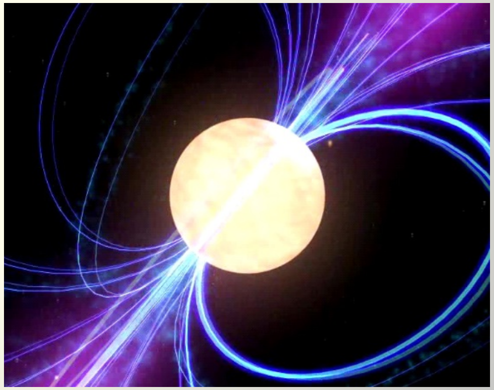
Reduced and phase-folded NICER event data for PSR J0614−3329 duplicated over two rotational cycles for visualization purpose (PI channel gives X-ray energy 0.3 – 2.0 keV).

PSR J0614-3329

distance 540 – 630 pc
mass 1.44 ± 0.07 M_O

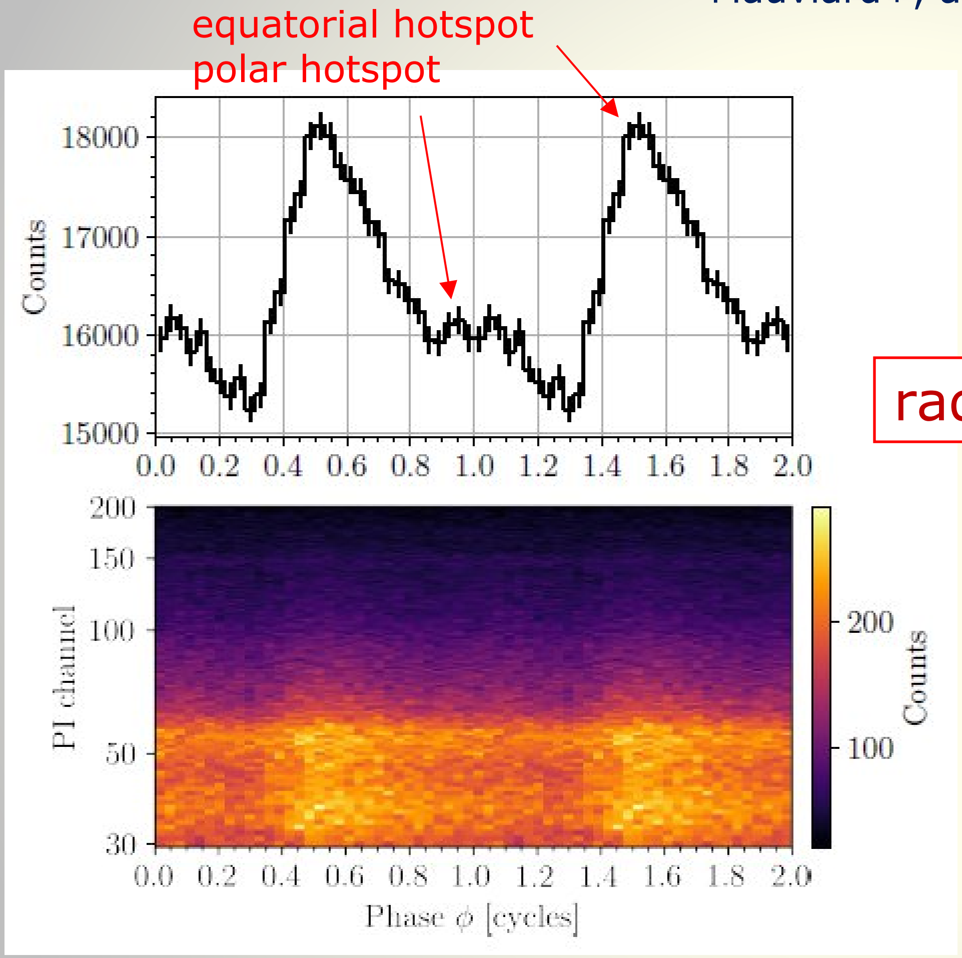
radius 10.29 $^{+1.01}_{-0.86}$ km (68%)

emissions **NOT** as shown here



after submission: from NICER

Mauviard+, arXiv:2506.14883 [astro-ph.HE] (2025)



Reduced and phase-folded NICER event data for PSR J0614−3329 duplicated over two rotational cycles for visualization purpose (PI channel gives X-ray energy 0.3 – 2.0 keV).

PSR J0614-3329

distance 540 – 630 pc
mass 1.44 ± 0.07 M_O

radius 10.29 $^{+1.01}_{-0.86}$ km (68%)

the models:
ST-U: 9.1 ± 0.7 km
ST+PDT 10.2 $^{+1.0}_{-0.9}$ km
PDT-U 10.9 $^{+1.1}_{-1.0}$ km

best model
ST+PDT 10.29 $^{+1.01}_{-0.86}$ km

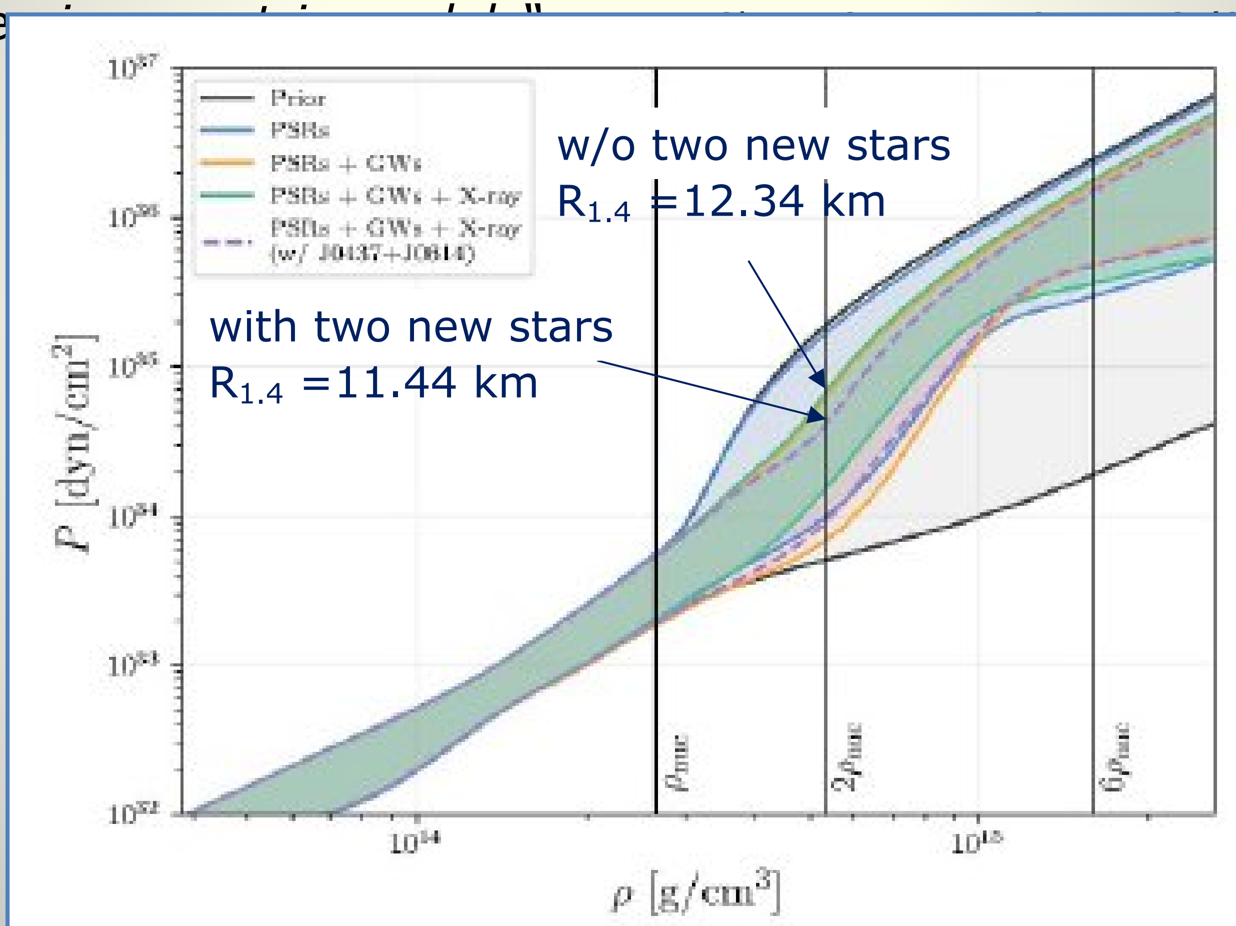
ST Single Temperature
U Unshared
PDT Protruding Double Temperature

published October 17 2025:

Sunny Ng, Isaac Legred, Lami Suleiman, Philippe Landry, Lyla Traylor, Jocelyn Read

"Inferring the neutron star equation of state with nuclear-physics informed se

025) 205008



additional slides

published October 17 2025:

Sunny Ng, Isaac Legred, Lami Suleiman, Philippe Landry, Lyla Traylor, Jocelyn Read

Table 2. A comparison of our reference astrophysical quantities to a range of recent works where the same quantities inferred with a variety of modeling frameworks and observational data. The most massive well-measured PSR J0740 + 6620 is used in all results. Notation follows previous figures when possible; see text for details. Ranges presented follow selected summary statements in the references and may vary in the percentile covered (e.g. 90 or 95).

	Model $\lesssim$ to $\sim \rho_{\rm nuc}$	Model $\gtrsim \rho_{\rm nuc}$	Observations	$R_{1.4}$ (km)	$M_{\rm max}$ ($M_\odot$)
This work	MM+χ	GP	GWs + x-ray	$12.34^{+0.70}_{-0.99}$	$2.40^{+0.45}_{-0.32}$
Legred *et al* 2021 [56]	GP	GP	GWs + x-ray	$12.56^{+1.00}_{-1.07}$	$2.21^{+0.31}_{-0.21}$
Altiparmak *et al* 2022 [77]	χ	CS	GWs + x-ray	$12.42^{+0.52}_{-0.99}$	—
Malik *et al*2022 [83]	RMF	RMF	GWs + x-ray + PSR J1810+1714	$12.62^{+0.59}_{-0.55}$	$2.144^{+0.211}_{-0.123}$
Char *et al* 2023 [82]	Relativistic MM	Relativistic MM	GWs	$12.72^{+0.46}_{-0.46}$	—
Fan *et al* 2024 [85]	FFNN/CS/GP	FFNN/CS/GP	GW + x-ray	—	$2.25^{+0.08}_{-0.07}$
Tsang *et al* 2024 [2]	MM	MM	GWs + x-ray	$12.9^{+0.4}_{-0.5}$	—
Koehn *et al* 2025 [1]	MM	CS	GWs + x-ray	$12.26^{+0.80}_{-0.91}$	$2.25^{+0.42}_{-0.22}$
Rutherford *et al* 2024 [87]	PP + χ	PP	GWs + x-ray + J0437	$12.30^{+0.55}_{-1.04}$	$2.15^{+0.20}_{-0.20}$
‘...’	PP + χ	CS	GWs + x-ray + J0437	$12.29^{+0.47}_{-1.03}$	$2.08^{+0.25}_{-0.17}$
Biswas *et al* 2024 [80]	SLy	χ + PP	GWs + x-ray + J0437	$12.34^{+0.43}_{-0.53}$	$2.22^{+0.21}_{-0.19}$
Li *et al* 2025 [84]	CDF	CDF	GWs + x-ray + HESS J1231-1411	$12.47^{+0.48}_{-0.50}$	$2.20^{+0.23}_{-0.17}$
This work	MM+χ	GP	GWs + x-ray + J0437+J0614	$11.44^{+0.98}_{-0.60}$	$2.31^{+0.35}_{-0.23}$
Mauviard *et al* 2025 [30]	PP + χ	PP	GWs + x-ray+J0437+J0614	$12.05^{+0.56}_{-0.79}$	—
‘...’	PP + χ	CS	GWs + x-ray+J0437+J0614	$11.71^{+0.71}_{-0.63}$	—

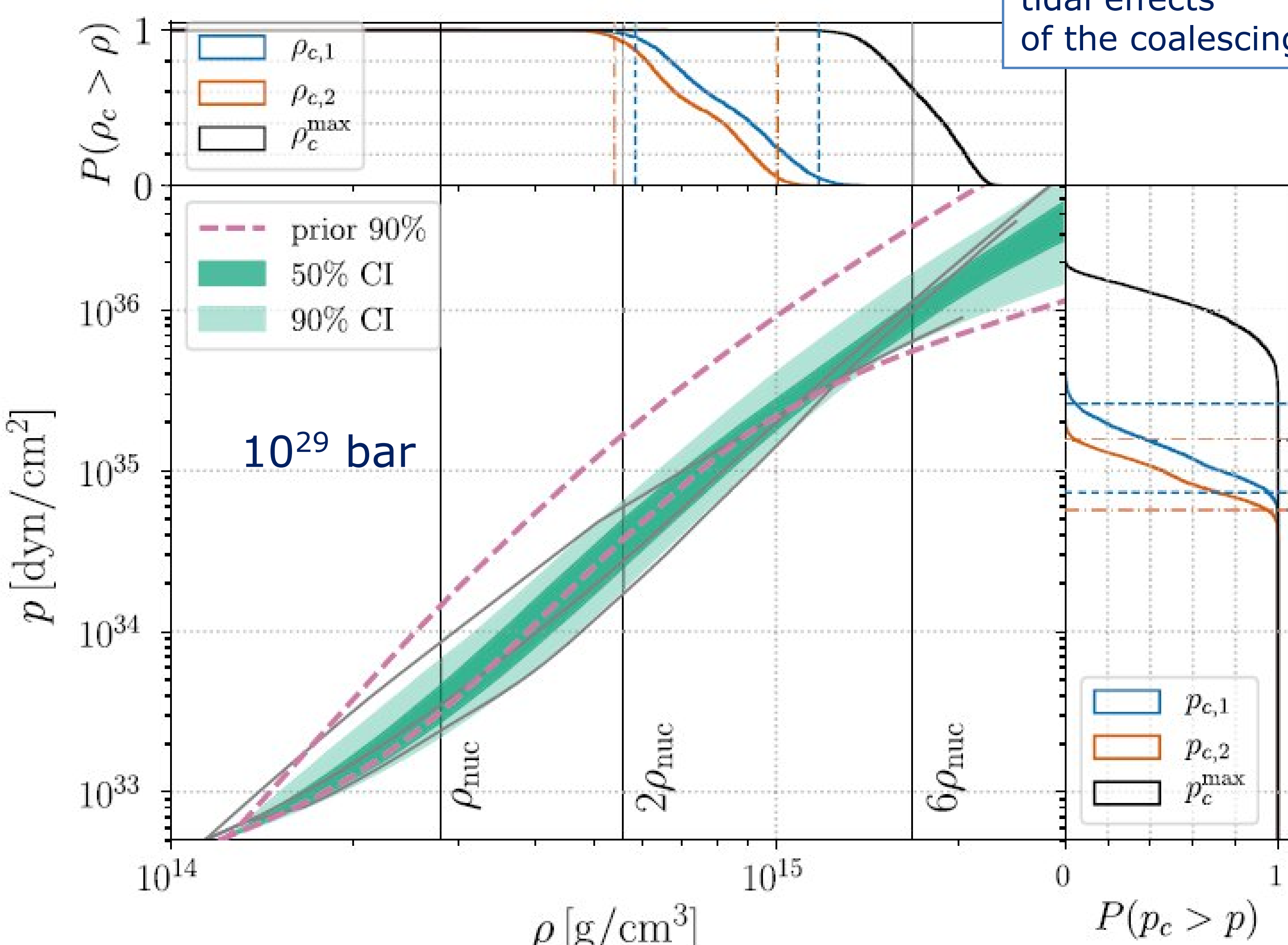
mean value of R1.4: ~12.45 km

mean upper limit of neutron star mass: ~2.2 M_O

Margalit&Metzger (2017) 2.17 M_O ; Rezzolla+ (2018) 2.16 M_O

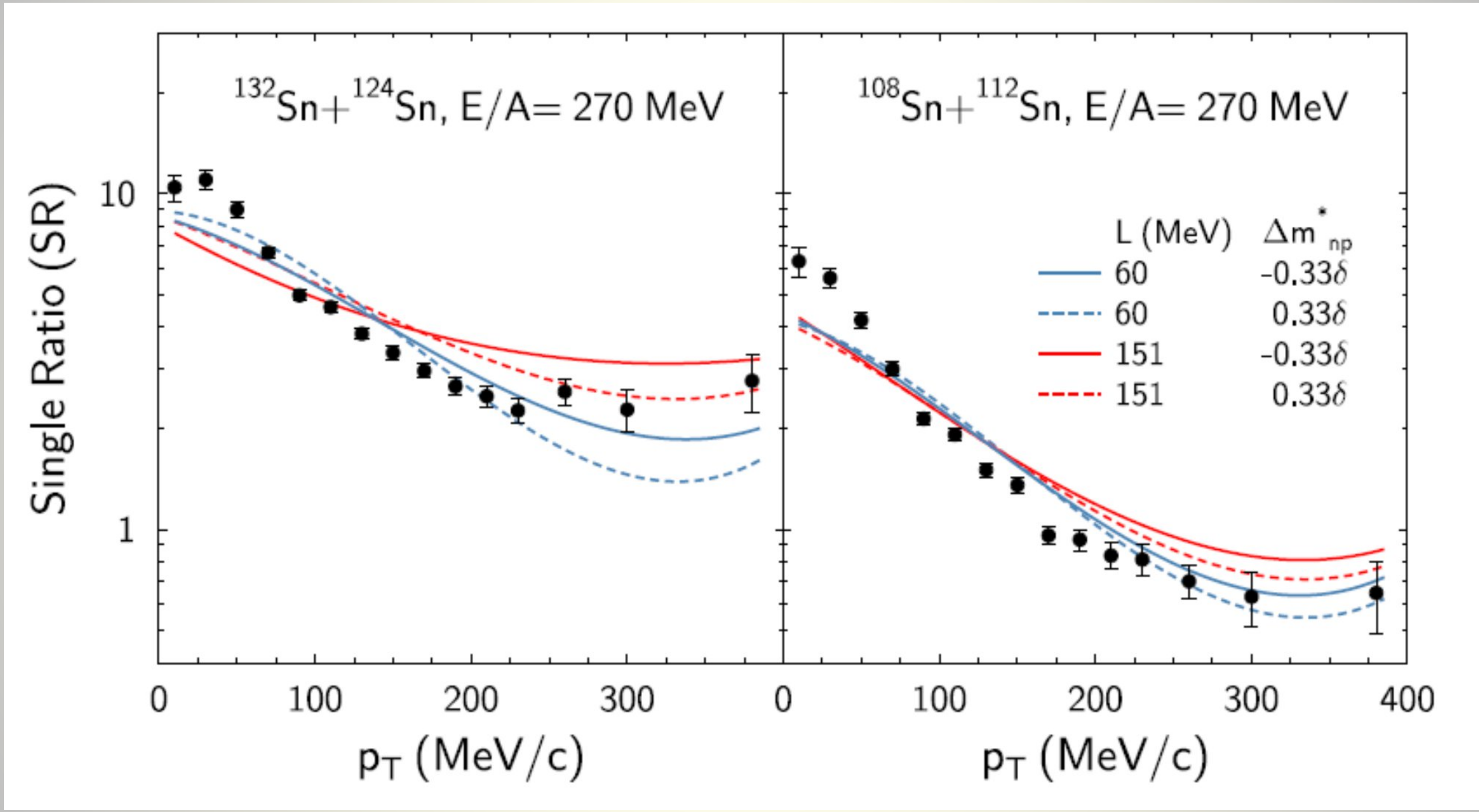
LIGO-Virgo: pressure vs density

GW170817
Abbott et al., PRL (2018)
LIGO & Virgo
tidal effects
of the coalescing bodies



neutron star matter

SϖRIT at RIKEN: Estee+, PRL 126 (2021)



42 ≤ L ≤ 117