

# Nuclear symmetry energy and neutron stars

Could dense matter properties be constrained  
by nuclear experiments and astrophysics?

Jérôme MARGUERON,  
IP2I Lyon, France & IRL-NPA, MSU, USA

Take-home message:

Above  $n_{\text{sat}}$ , there is a strong interplay between symmetry energy  
and phase transition.



# The nuclear symmetry energy in NS/finite nuclei

[Somasundaram et al., Phys. Rev. C 103, 045803 (2022)]

**Definition:**  $e_{\text{sym}}(n) = e_{\text{NM}}(n) - e_{\text{SM}}(n)$

It is the cost in energy to convert SM into NM.

Other authors label it as  $S(n)$

Remark: it has a density dependence.

Its value at  $n_{\text{sat}}$  is also call the symmetry energy:  $E_{\text{sym}} = e_{\text{sym}}(n = n_{\text{sat}})$

Other authors label it as  $J_0$

In asymmetric matter:  
(Taylor expansion in  $\delta$ )  $e_{\text{tot}}(n, \delta) \approx e_{\text{SM}}(n) + e_{\text{sym},2}(n)\delta^2 + e_{\text{sym},4}(n)\delta^4 + \dots$

Quadratic dependence of the symmetry energy:  $e_{\text{sym},2}(n) = \frac{1}{2} \frac{\partial^2 e_{\text{tot}}(n, \delta)}{\partial \delta^2}$

Remark:  $e_{\text{sym},2}$  is the quantity which is measured by **nuclear experiments**.

If  $e_{\text{sym},4} \ll e_{\text{sym},2}$ , then:  $e_{\text{sym}} \approx e_{\text{sym},2}$



Be careful: may not be satisfied at all densities.



---

# Empirical parameters

---

**Definitions:**

(Taylor expansion  
in density)

$$e_{\text{sym}}(n) = E_{\text{sym}} + L_{\text{sym}}x + \frac{1}{2}K_{\text{sym}}x^2 + \dots$$

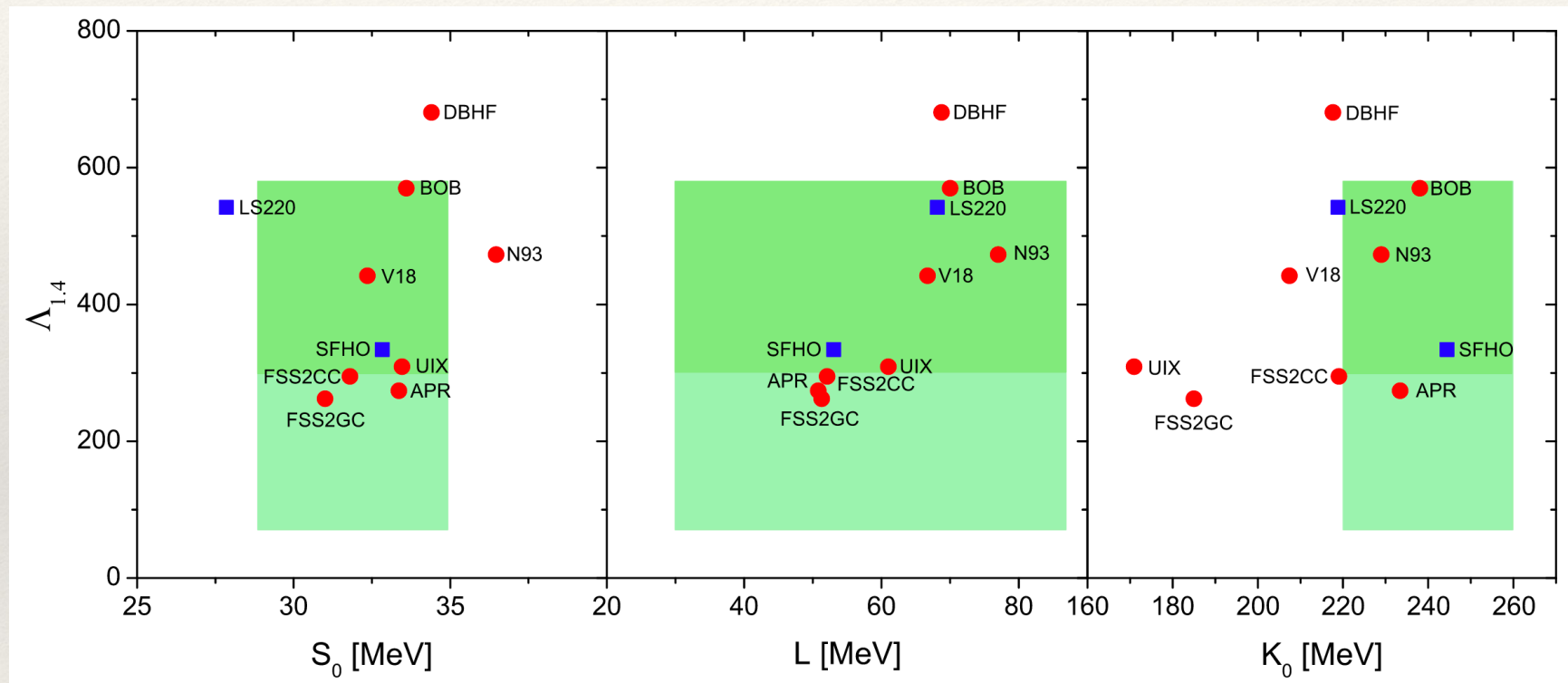
with

$$x = (n - n_{\text{sat}})/(3n_{\text{sat}})$$

$$e_{\text{sym},2}(n) = E_{\text{sym},2} + L_{\text{sym},2}x + \frac{1}{2}K_{\text{sym},2}x^2 + \dots$$

# Are nuclear matter properties correlated with neutron star observables?

Wei, Lu, Burgio, Li, Schulze, EPJA 56, 63 (2020)



The authors concluded that there is no correlations at all.

This conclusion is maybe too strong. —> we have done a slightly different analysis.

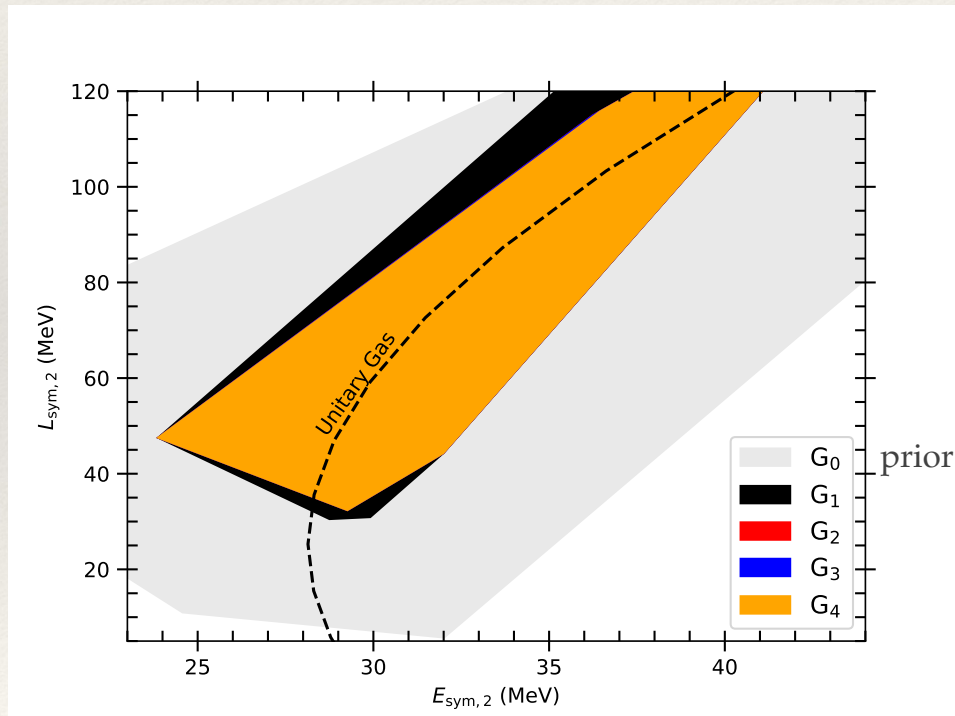


# Low-energy nuclear physics and neutron stars

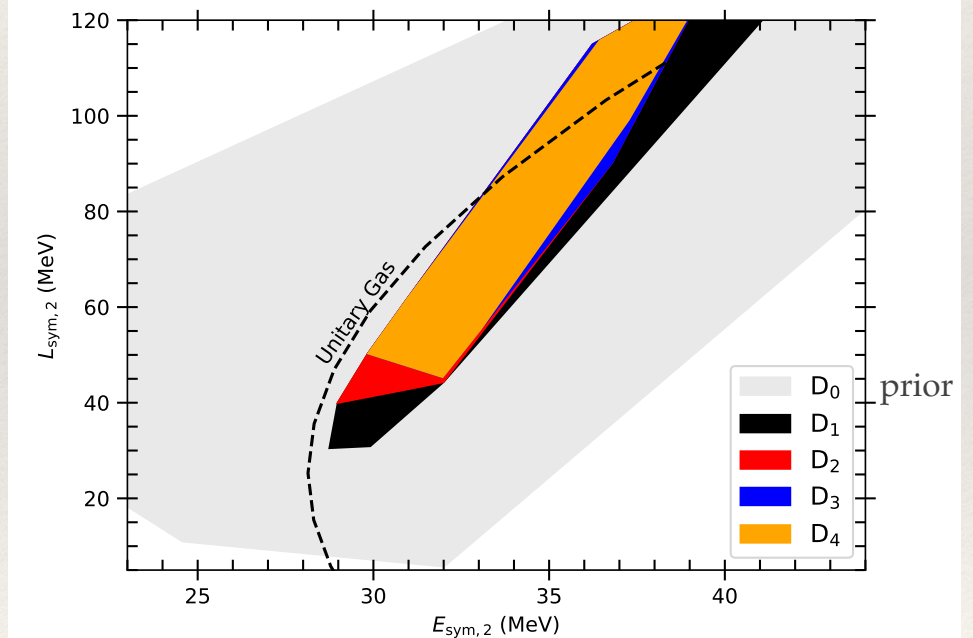
To what extent present low-energy nuclear data constrain NS properties?

We assess the capacity of **415** relativistic and non-relativistic phenomenological models to reproduce low-energy nuclear properties of spherical nuclei (binding energies, charge radii, ISGMR).

Global assessment of all nuclei:

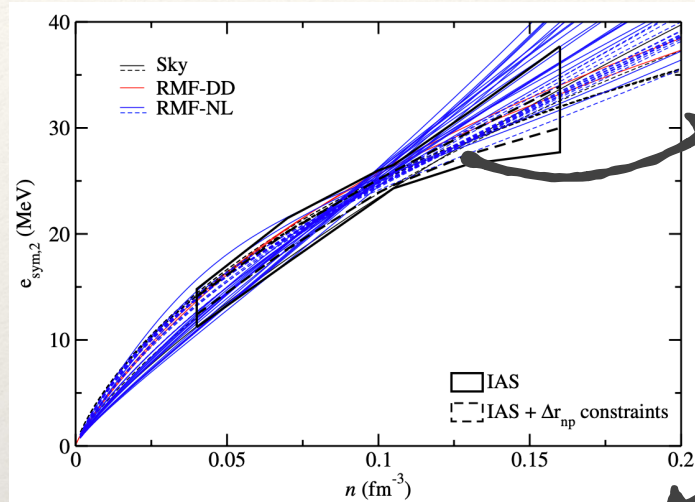


Detailed assessment where  $N = Z$  and  $N \neq Z$  nuclei are treated equally:



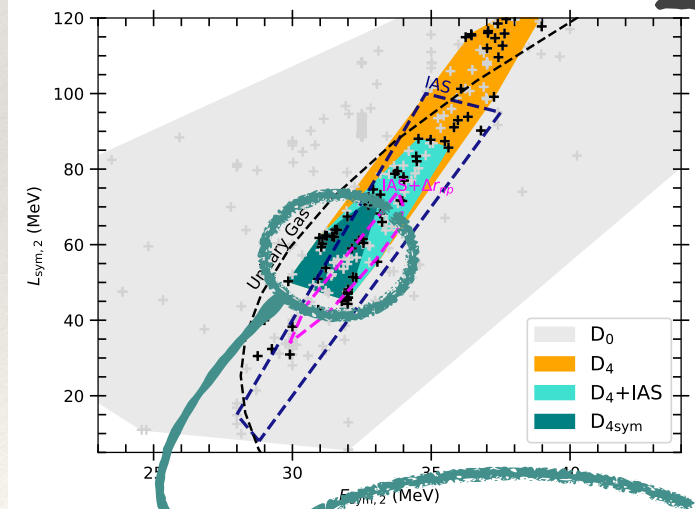
Tighter correlation

# Low-energy nuclear physics and the symmetry energy



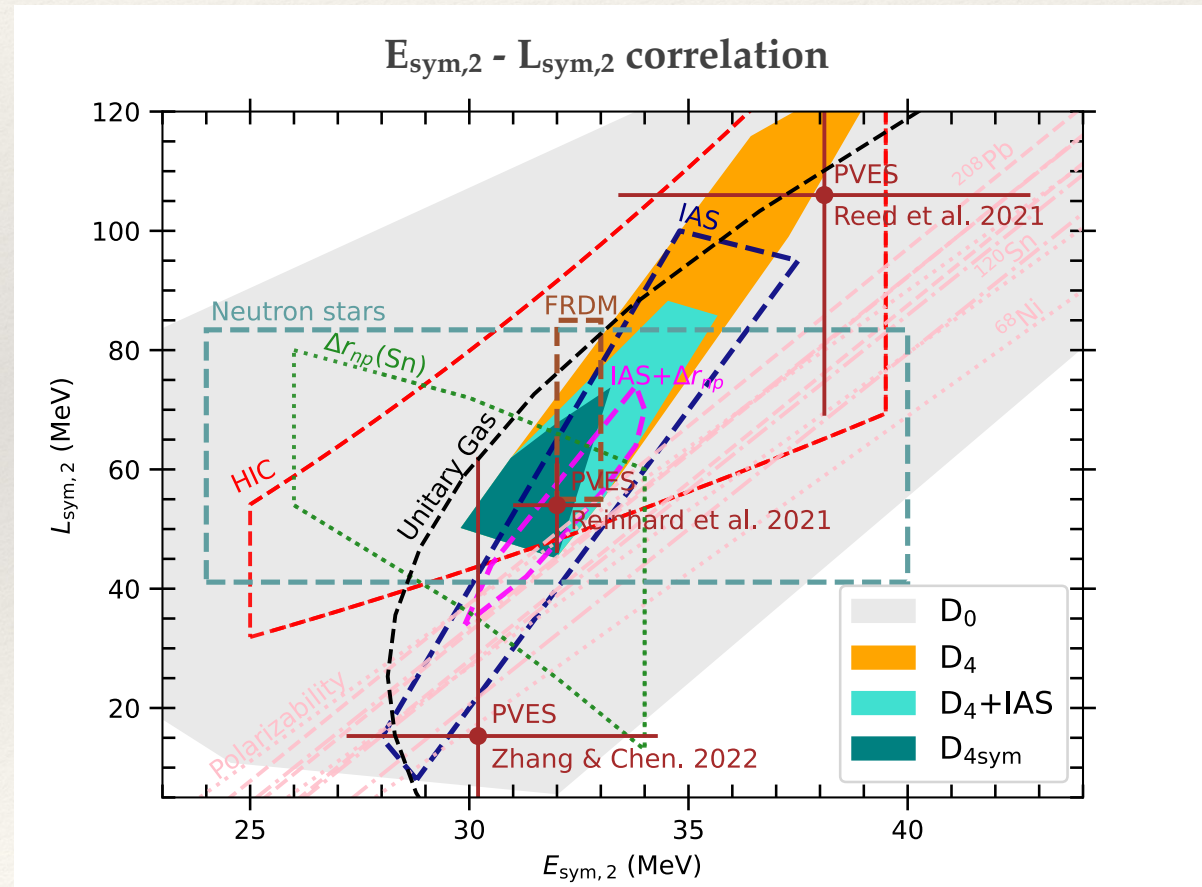
Contour suggested from the analysis of IAS + neutron skin radius by Danielewicz & Lee 2013.

They filter our models (D4  $\rightarrow$  D4sym).



$$E_{\text{sym},2} = 31.7 \pm 0.7 \text{ MeV}$$

$$L_{\text{sym},2} = 58.1 \pm 9.0 \text{ MeV}$$



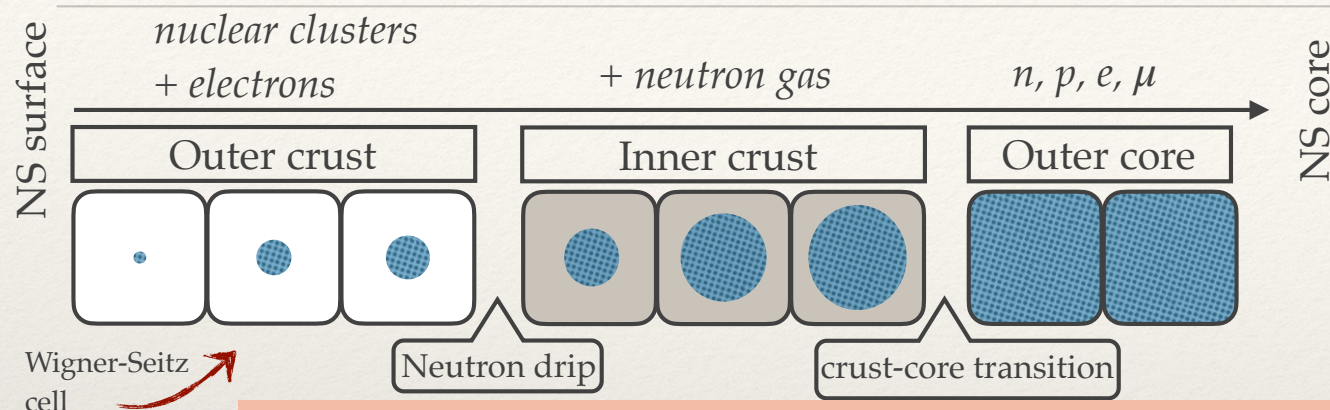


---

# Links with neutron star observables

---

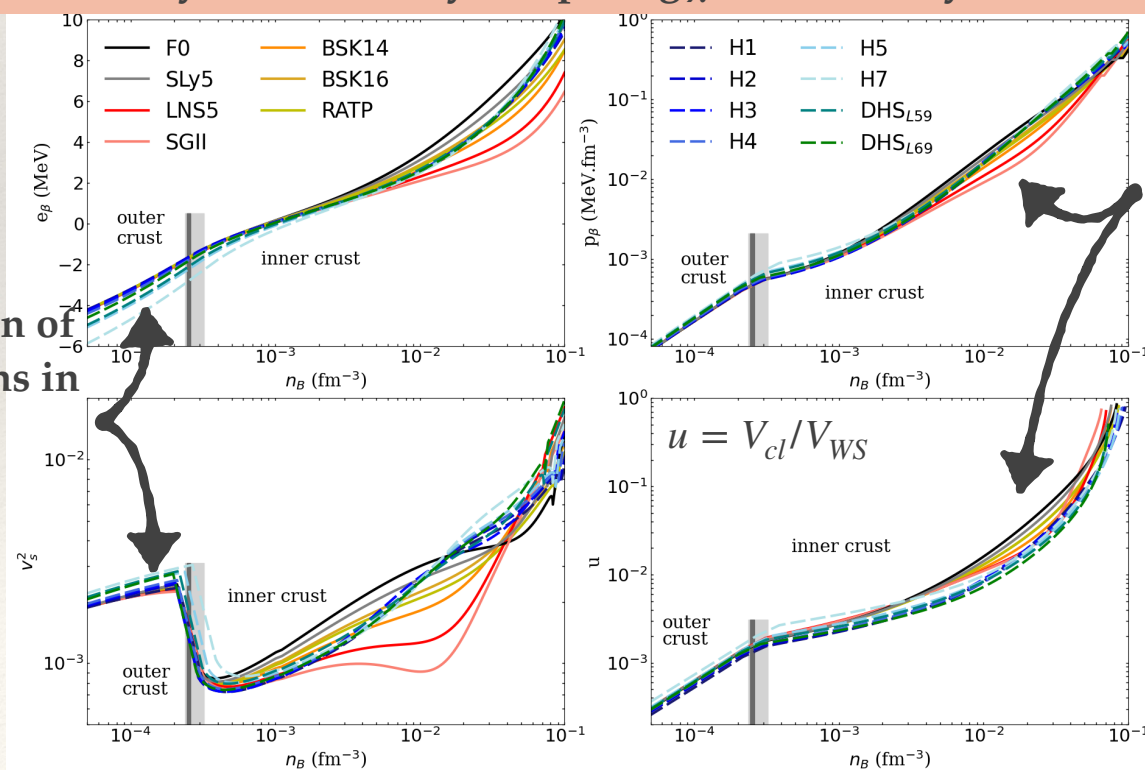
# Inhomogeneous matter (crust of NS)



Compressible liquid-drop model based on Skyrme and  $\chi$ EFT functionals.

[Grams+, FBS 2021, PRC 2022, EPJA 2022]

Uncertainty estimation by comparing  $\chi$ EFT with Skyrme models:



Large dispersion of  $\chi$ EFT predictions in the outer crust.

Uncertainties in finite nuclei properties.

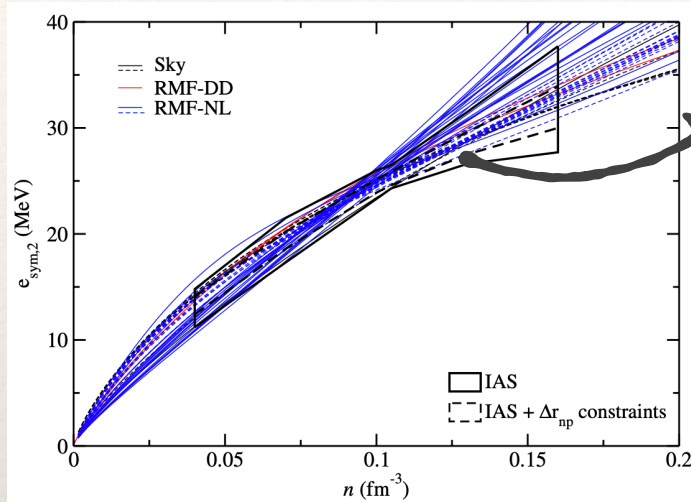
Large dispersion of Skyrme models in the inner crust. Uncertainties in neutron matter.

Nuclear masses play an important role on the outer crust. Neutron matter plays an important role in the inner crust.

Symmetry energy is instrumental for the understanding of the inner crust properties.

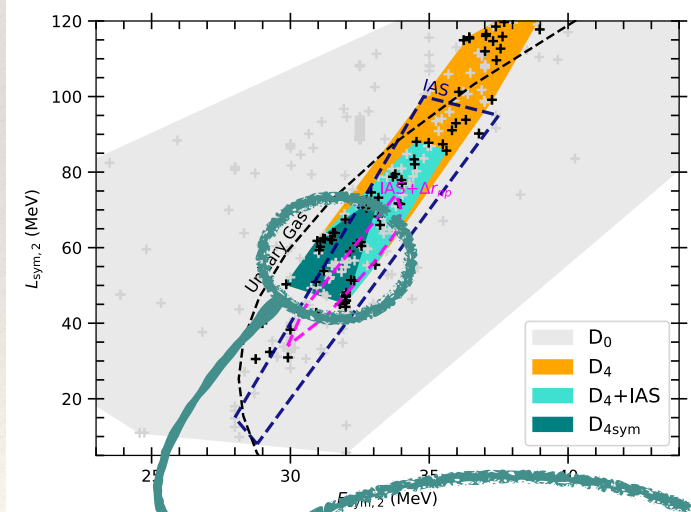


# Low-energy nuclear physics and the symmetry energy



Contour suggested from the analysis of IAS + neutron skin radius by Danielewicz & Lee 2013.

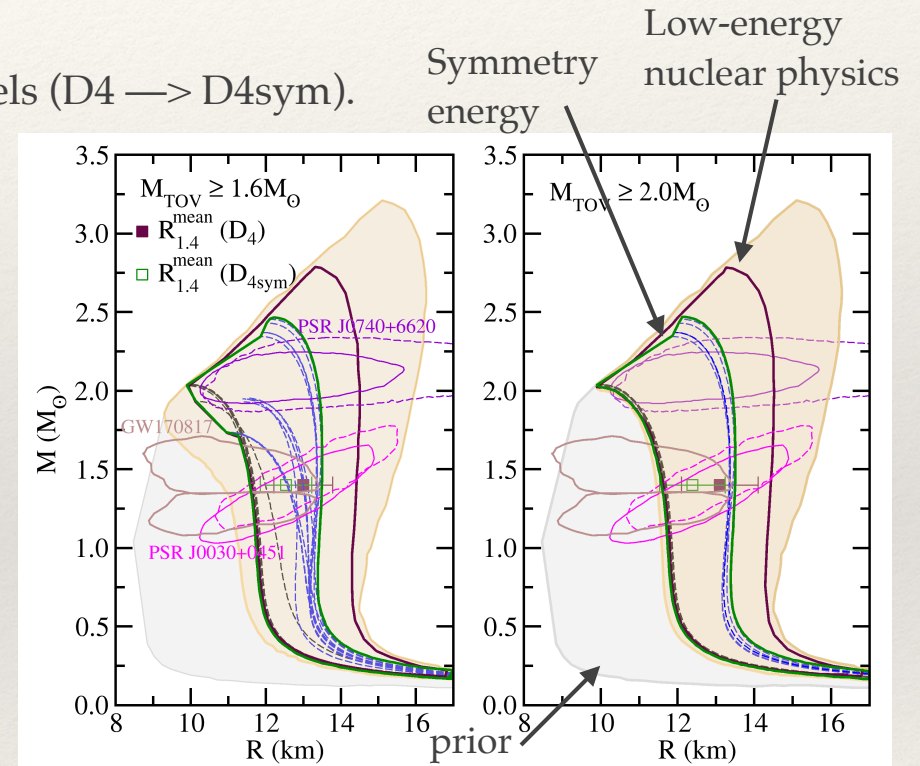
They filter our models ( $D4 \rightarrow D4_{\text{sym}}$ ).



$$E_{\text{sym},2} = 31.7 \pm 0.7 \text{ MeV}$$

$$L_{\text{sym},2} = 58.1 \pm 9.0 \text{ MeV}$$

Stiffest EoS are removed.



A better determination of low-energy nuclear properties may not improve predictions for neutron star global properties.

$\rightarrow$  the largest source of uncertainties is the **density dependence of the EoS** (symmetry energy, phase transitions).

HIC are needed! Carlson, Dutra, Lourenço, JM, PRC 107 (2023)

# Thermal emission from qLMXB

## quiescent Low Mass X-ray binaries

Black body like emission:  $F \propto T^4(R_{\text{inf}}/D)^2$

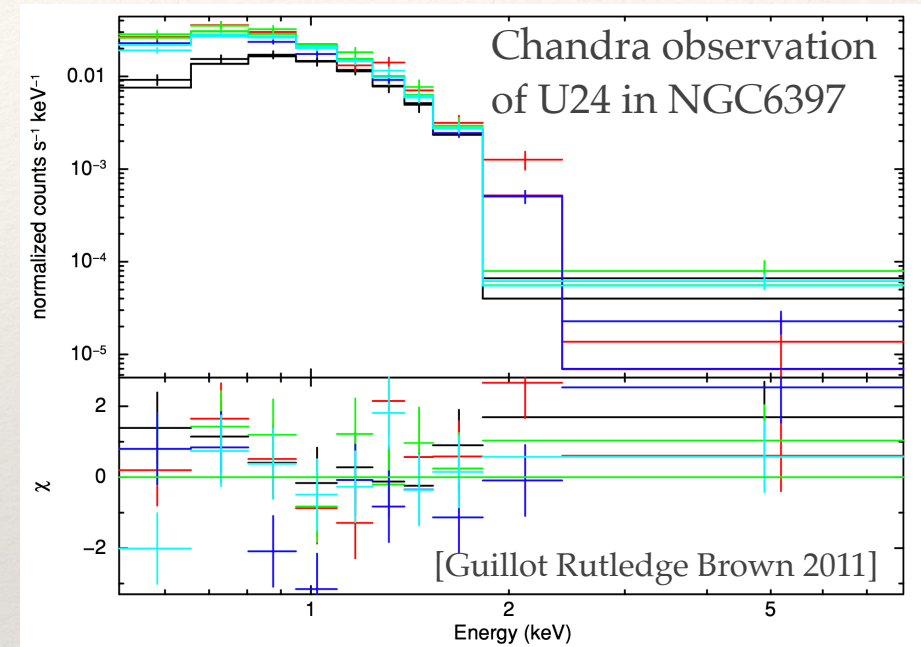
with  $R_{\text{inf}} = R/\sqrt{1 - 2GM/(Rc^2)}$

-> get information on M and R

[Rutledge et al. 1999]

7 sources (**quiescent Low Mass X-ray binaries**) in globular clusters:

- constant flux, purely H atmosphere,
- Low magnetic fields —> almost pure thermal components,
- In globular clusters —> accurate distances.



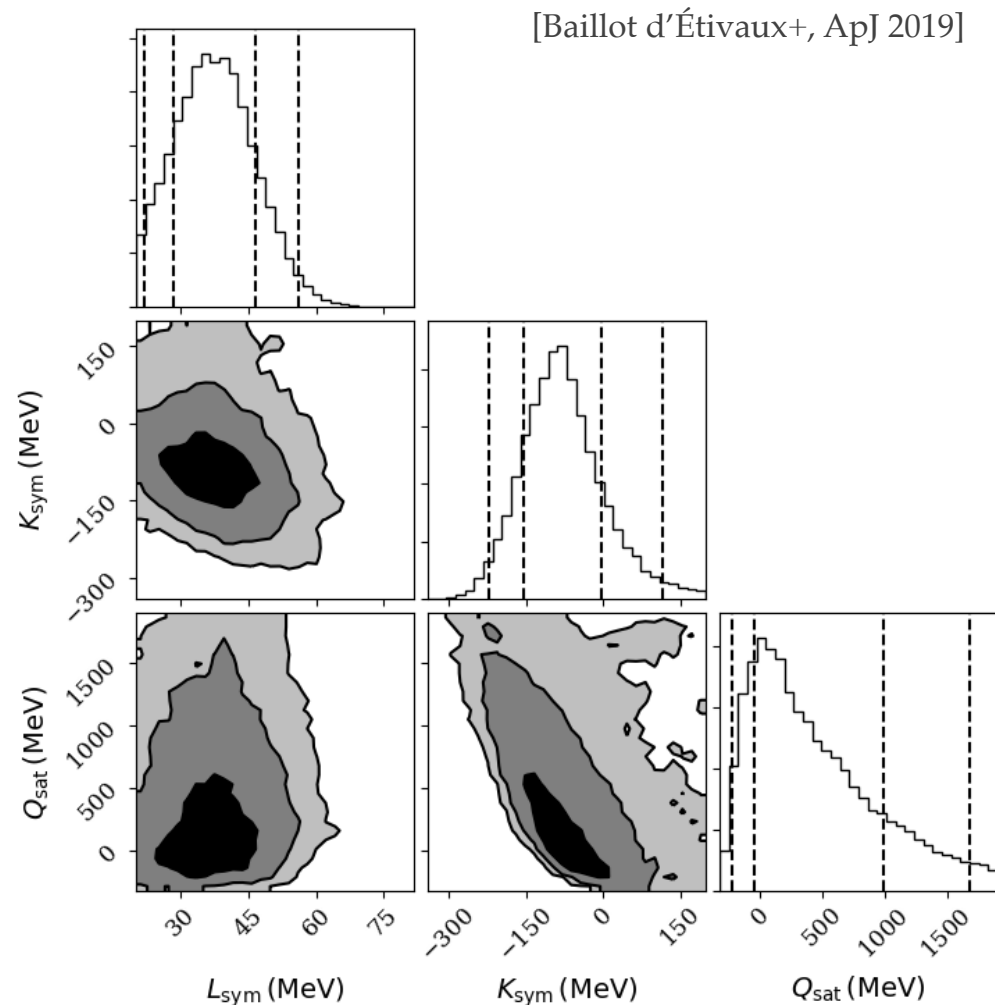
Globular	R.A. <sup>a</sup>	Decl. <sup>a</sup>	XMM Exp.	Chandra Exp.	S/N	Group <sup>b</sup>	Distances	Distances [8]
Cluster host	(J2000)	(J2000)	time (ks)	time (ks)			Dist #1 (kpc)	Dist #2 (kpc)
47Tuc (X-7)	00:24:03.53	-72:04:52.2	0	181	122	A,A'	4.53 ± 0.08 [1]	4.50 ± 0.06
M28	18:24:32.84	-24:52:08.4	0	327	113	A,A'	5.5 ± 0.3 [2,3]	5.50 ± 0.13
NGC 6397	17:40:41.50	-53:40:04.6	0	340	82	A,A'	2.51 ± 0.07 [4]	2.30 ± 0.05
ω Cen	13:26:19.78	-47:29:10.9	36	291	49	B,B'	4.59 ± 0.08 [5]	5.20 ± 0.09
M13	16:41:43.75	+36:27:57.7	29	55	36	B,A'	7.1 ± 0.62 [6]	7.10 ± 0.10
M30	21:40:22.16	-23:10:45.9	0	49	32	B,B'	8.2 ± 0.62 [6]	8.10 ± 0.12
NGC 6304	17:14:32.96	-29:27:48.1	0	97	28	B,B'	6.22 ± 0.26 [7]	5.90 ± 0.14

Recent  
publications

GAIA  
DR11 2018



# Confronting the thermal emission from qLMXB with nuclear EoS



## Bayesian analysis with prior:

$$L_{\text{sym}} = 50 \pm 10 \text{ MeV}$$

$$K_{\text{sym}} [-400:200] \text{ MeV}$$

$$Q_{\text{sat}} [-1300:1900] \text{ MeV}$$

## MCMC Posteriors:

$$L_{\text{sym}} = 38 \pm 10 \text{ MeV}$$

$$K_{\text{sym}} = -91 \pm 80 \text{ MeV}$$

$$Q_{\text{sat}} = 350 \pm 500 \text{ MeV}$$

First extraction of  $K_{\text{sym}}$  and  $Q_{\text{sat}}$  from data.

An analysis of BE, neutron skin and GMR concludes [Sagawa 2019]:

$$L_{\text{sym}} = 53.5 \pm 15 \text{ MeV (FRDM),}$$

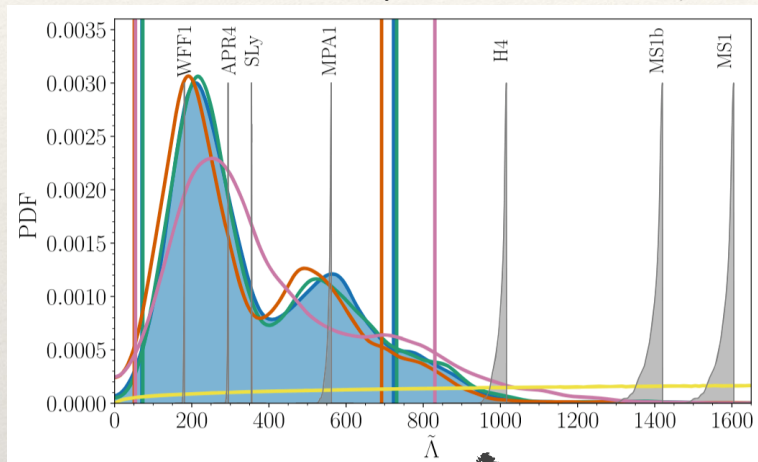
$$L_{\text{sym}} = 42 \pm 15 \text{ MeV (n skin)}$$

$$K_{\text{sym}} = -120 \pm 80 \text{ MeV}$$

# BNS GW [astro] $\Leftrightarrow$ EoS [nuclear]

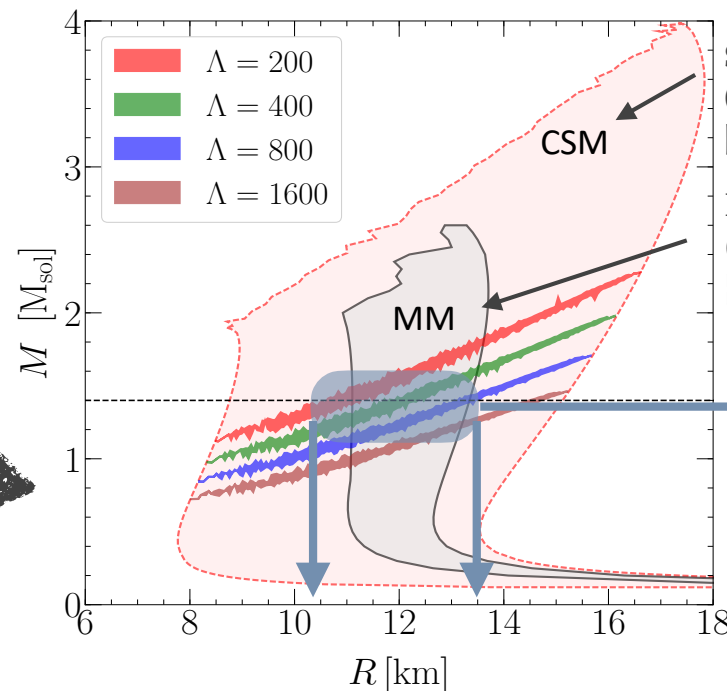
## Analysis of GW170817 waveform:

LVC, Phys. Rev. X 9, 011001 (2019)



The tidal deformability  $\tilde{\Lambda}$  is a measure of the compactness of the star:

[Tews, JM, Reddy, PRC 2018, EPJA 2019]



**Sound-speed Model**  
(phases transitions)  
[Tews+ 2018]

**Meta-Model**  
(nucleonic)  
[JM+ 2018]

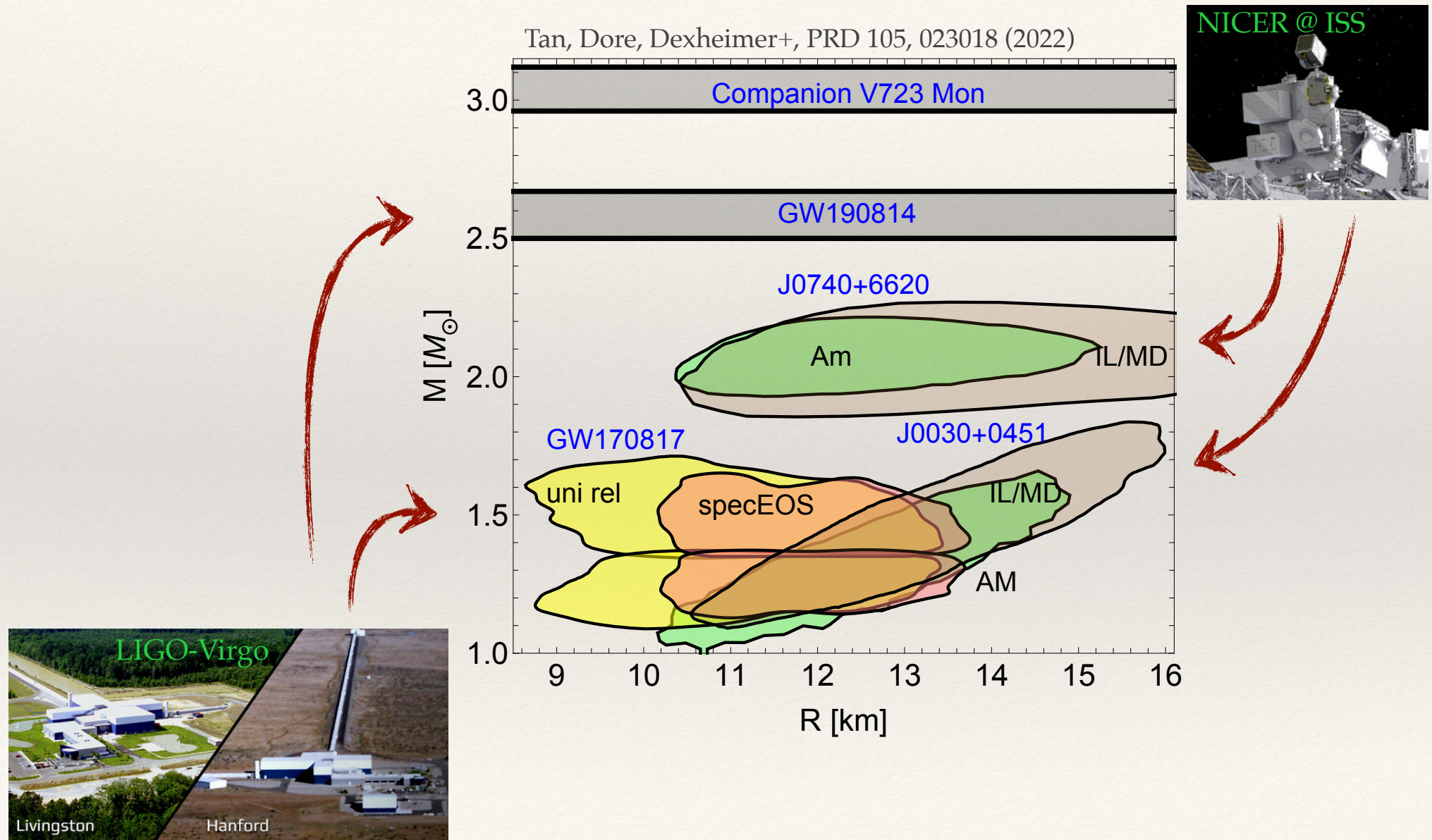
The present measure is compatible with the hypothesis of nucleonic matter but also of matter with phase transition.

**GW170817:**

$\rightarrow 70 \leq \Lambda \leq 720$  (90% CL)



# New data from GW + NICER X-ray observatory





---

# Phase transition(s) at high density

---



# Phase transition(s) in NS

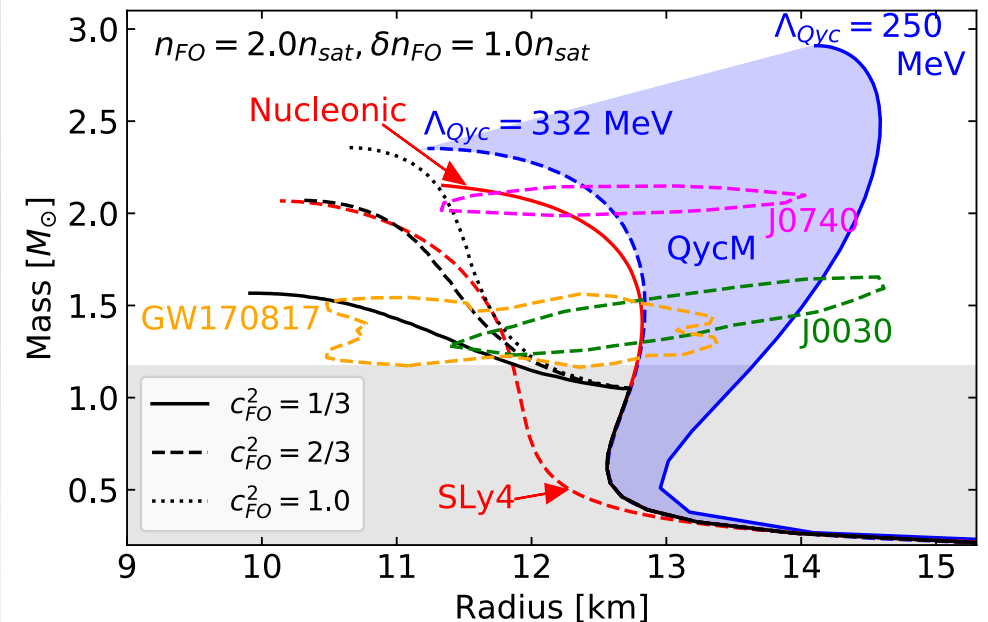
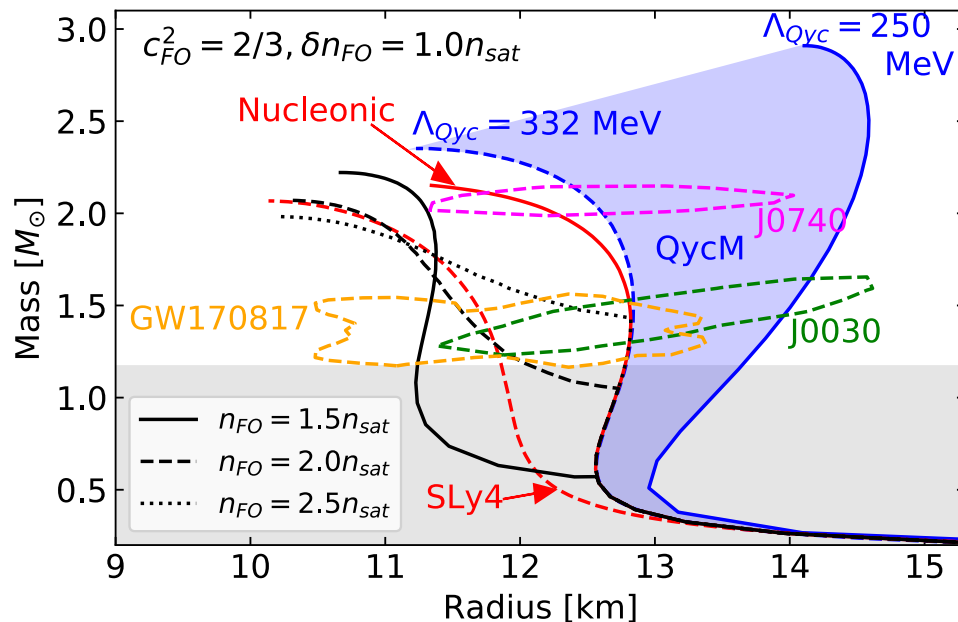
Data:

GW170817 and NICER (J0030 + J0740).

EoS modelings:

- SLy4 (often used in GW papers).
- First order phase transition to exotic matter.
- Cross-over quarkyonic matter (McLerran & Reddy PRL 2020, JM+ PRC 2022).

[Somasundaram, JM, EPL 138 (2022)]



—>First order phase transition softens the EoS: hybrid stars are smaller!

# Phase transition(s) in NS

Data:

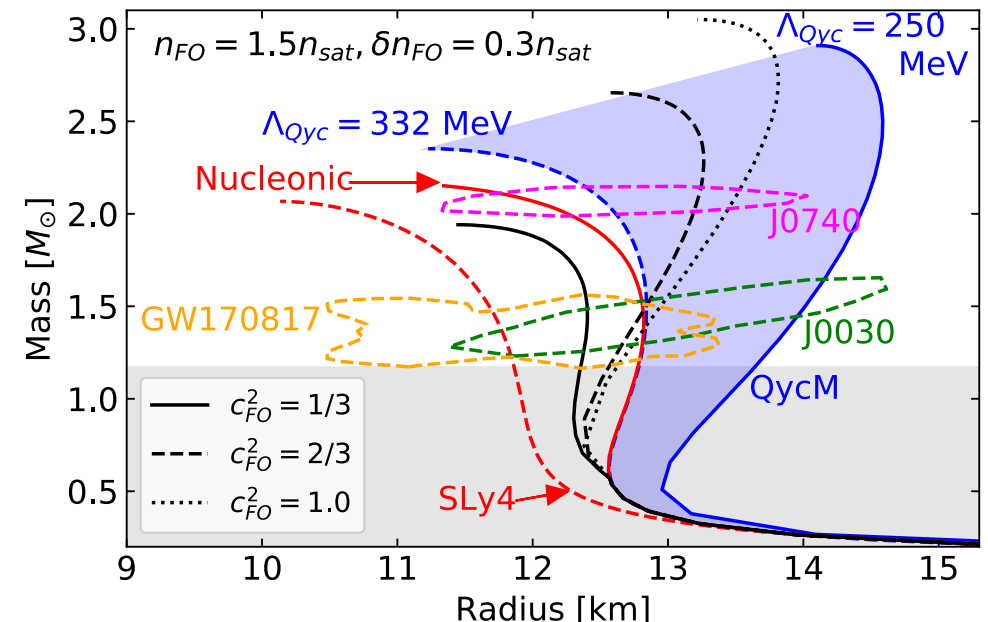
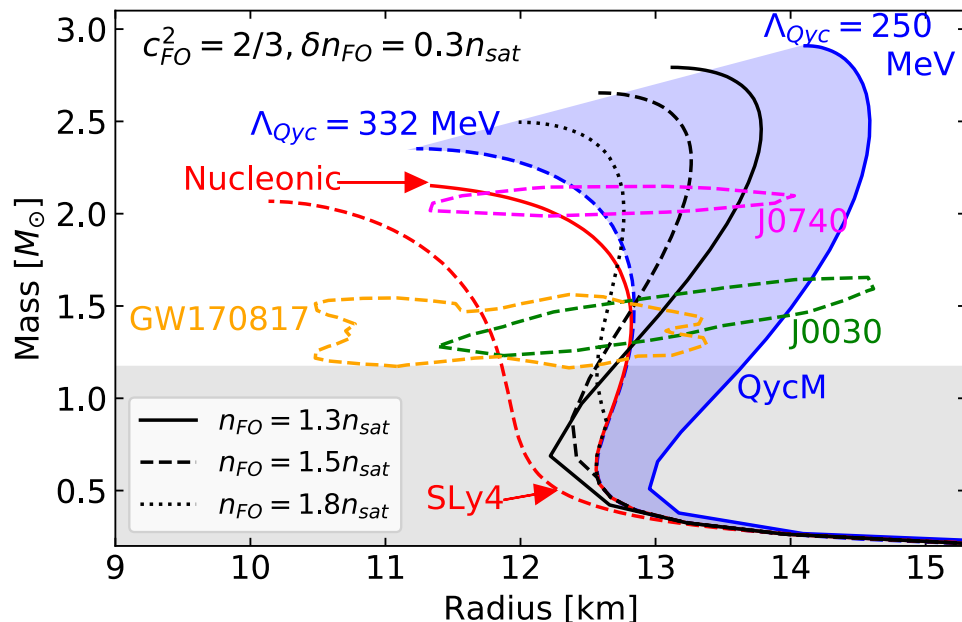
GW170817 and NICER (J0030 + J0740).

EoS modelings:

- SLy4 (often used in GW papers).
- First order phase transition to exotic matter.
- Cross-over quarkyonic matter (McLerran & Reddy PRL 2020, JM+ PRC 2022).



[Somasundaram, JM, EPL 138 (2022)]

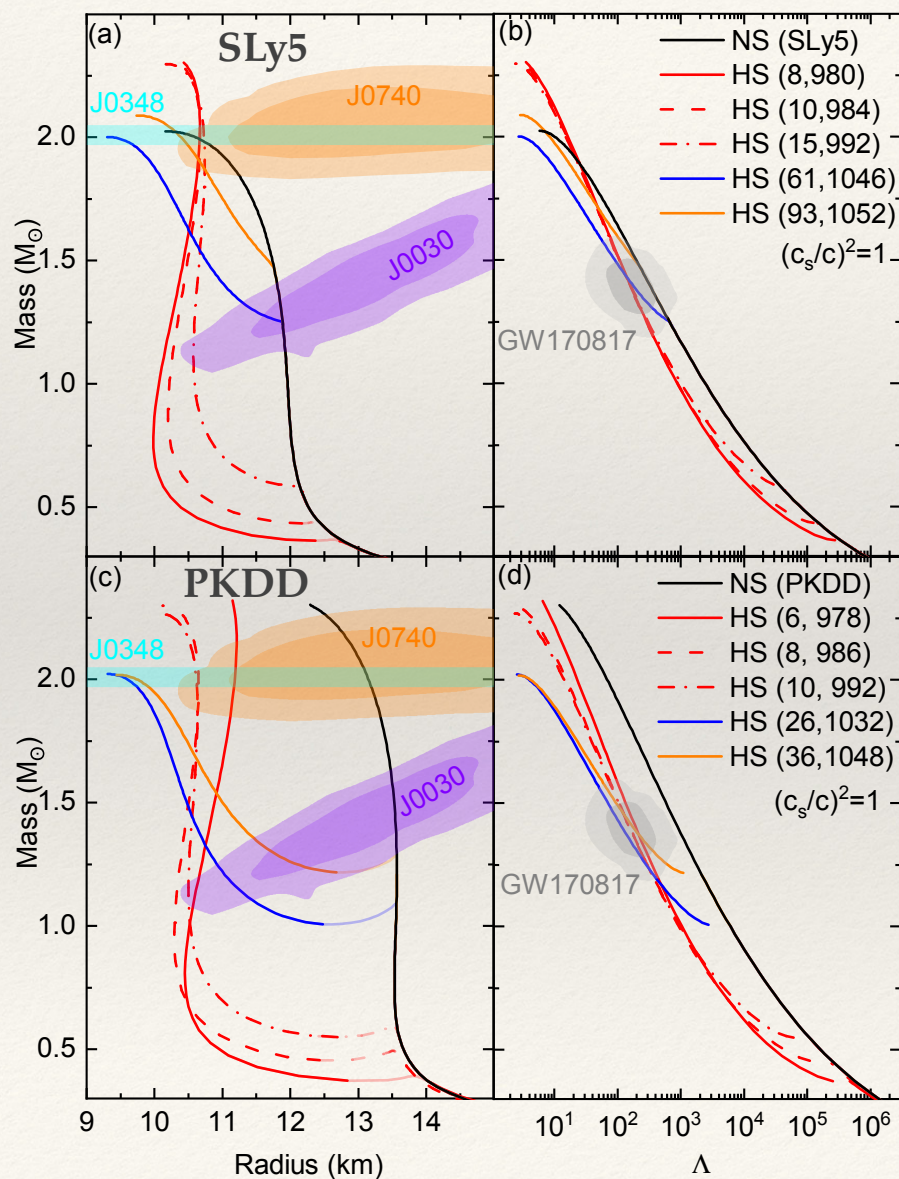


unless the FOPT occurs at low density → masquerade Qyc and produce bigger stars.



# Are GW170817 and NICER compatible?

Guven+, arXiv:2303.18133, PRC 2023



Two nuclear EoSs:

**SLy5** (iso-soft,  $L_{\text{sym}} \approx 50$  MeV),

**PKDD** (iso-stiff,  $L_{\text{sym}} \approx 80$  MeV).

+ First order phase transition:

$$\varepsilon(p) = \begin{cases} \varepsilon_{\text{NM}}(p) & p < p_{\text{PT}} \\ \varepsilon_{\text{NM}}(p_{\text{PT}}) + \Delta\varepsilon_{\text{PT}} + (p - p_{\text{PT}})/\alpha & p \geq p_{\text{PT}} \end{cases}$$

3 parameters:  $p_{\text{PT}}$ ,  $\Delta\varepsilon_{\text{PT}}$ ,  $\alpha$

GW170817 prefers soft EOS.

NICER prefers stiff EOS.



Future detections of GW will help to understand better this tension.



# Nature of GW170817?

Guven+, arXiv:2303.18133

Two nuclear EoSs: SLy5 (iso-soft), PKDD (iso-stiff).

+ First order phase transition:

$$\varepsilon(p) = \begin{cases} \varepsilon_{\text{NM}}(p) & p < p_{\text{PT}} \\ \varepsilon_{\text{NM}}(p_{\text{PT}}) + \Delta\varepsilon_{\text{PT}} + (p - p_{\text{PT}})/\alpha & p \geq p_{\text{PT}} \end{cases}$$

**3 parameters:**  $p_{\text{PT}}$ ,  $\Delta\varepsilon_{\text{PT}}$ ,  $\alpha$

**Binary Neutron Star:** the 2 stars are nucleonic  
(no phase transition),

**Binary Hybrid Star:** the 2 stars have a quark core  
(with phase transition),

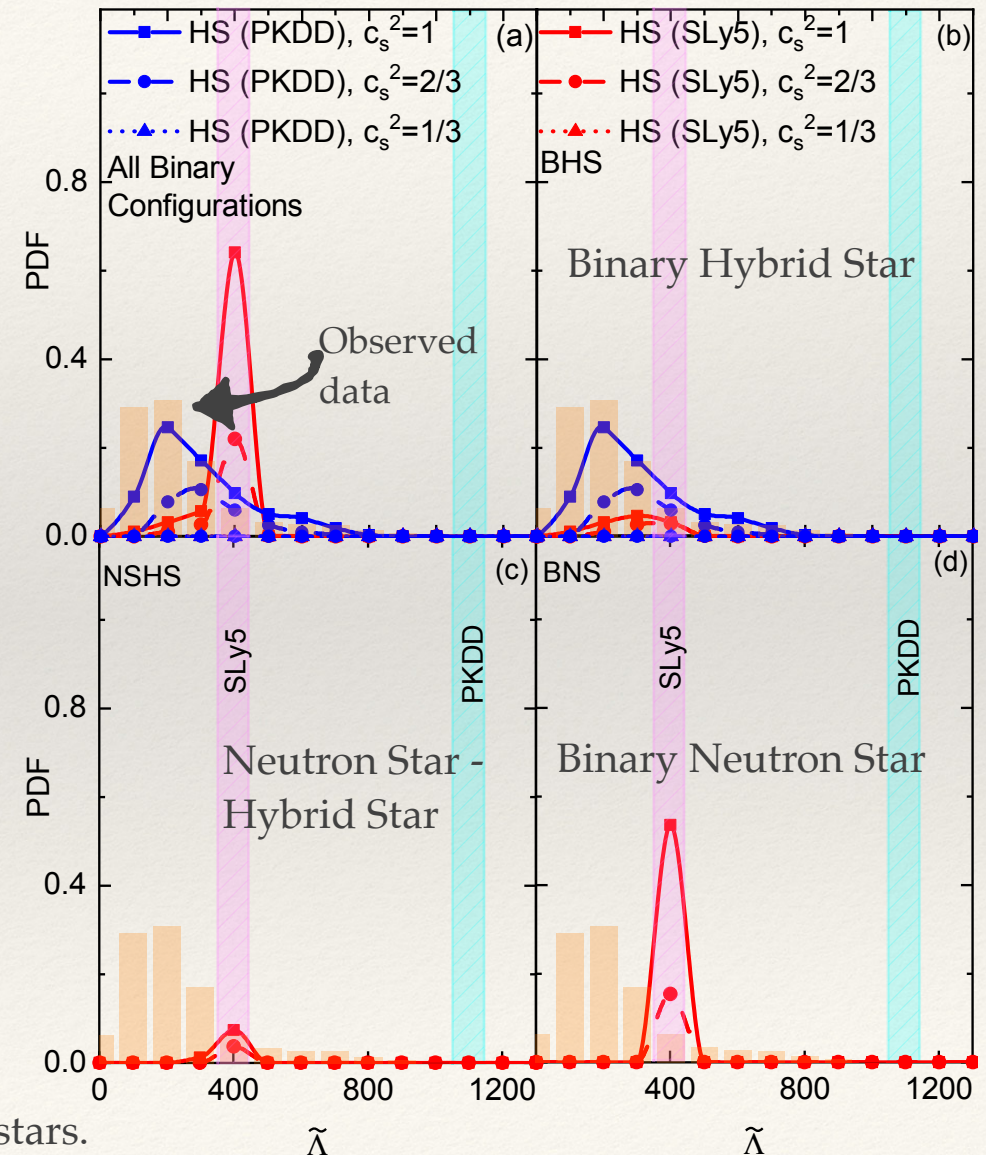
**Neutron Star - Hybrid Star:** 1 NS + 1 star with quark core.

Overlap between data and model predictions:

	EOS	$c_s^2$	BHS	NSHS	BNS
asy-soft	SLy5	1/3	0.00	0.00	0.00
	SLy5	2/3	0.07	0.04	0.07
	SLy5	1	0.12	0.08	0.06
asy-stiff	PKDD	1/3	0.00	0.00	0.00
	PKDD	2/3	<b>0.28</b>	0.00	0.00
	PKDD	1	<b>0.65</b>	0.00	0.00

GW170817 was most probably the merger of 2 hybrid stars.

## Bayesian analysis



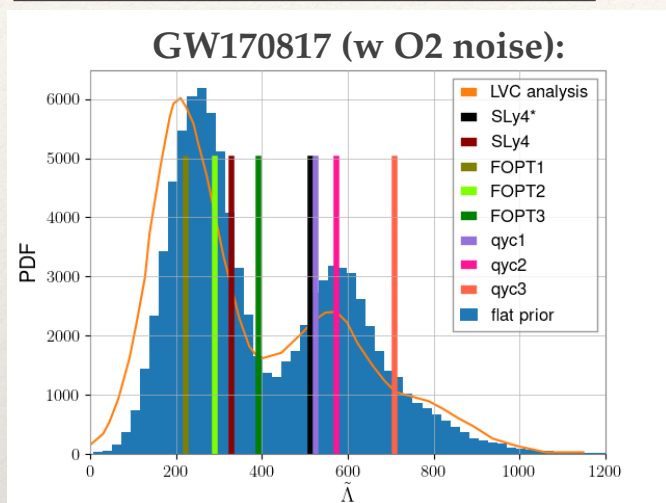


# Future GW detections (O4)

O4 has started for 18 months (beg. May 2023).

J.-F. Coupechoux et al., PRD 107, 124006 (2023)

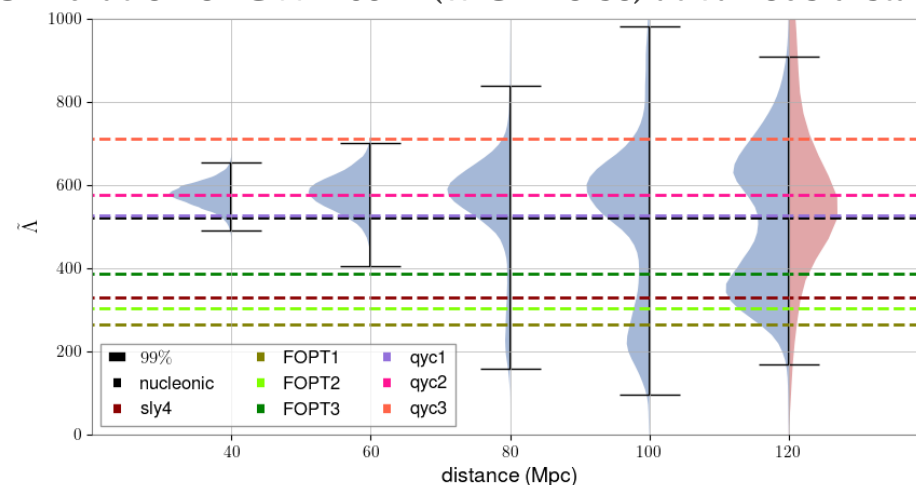
How GW170817 was measured:



How all events will be measured:

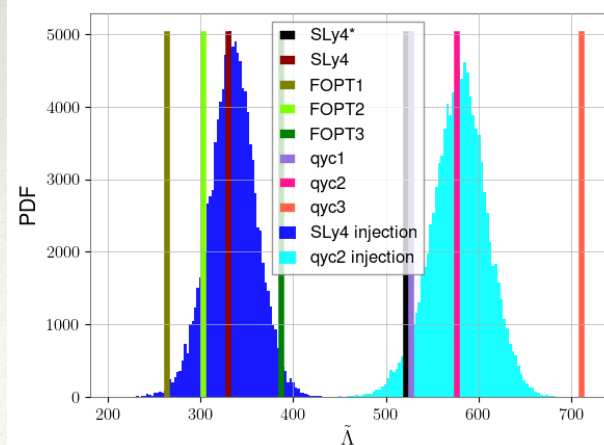
**Simulation of GW170817 (w O4 noise) at various distances:**

Injection of qyc2

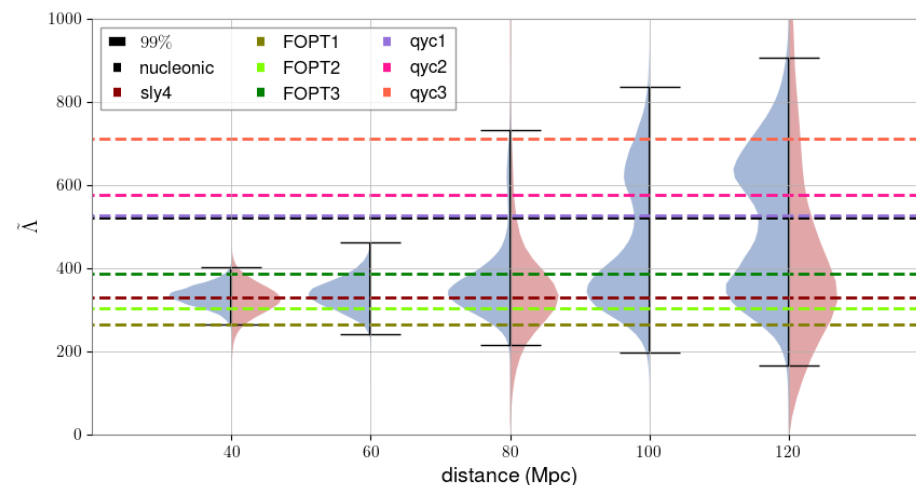


How it will be measured nowadays:

**Simulation of GW170817 (w O4 noise):**



Injection of SLy4

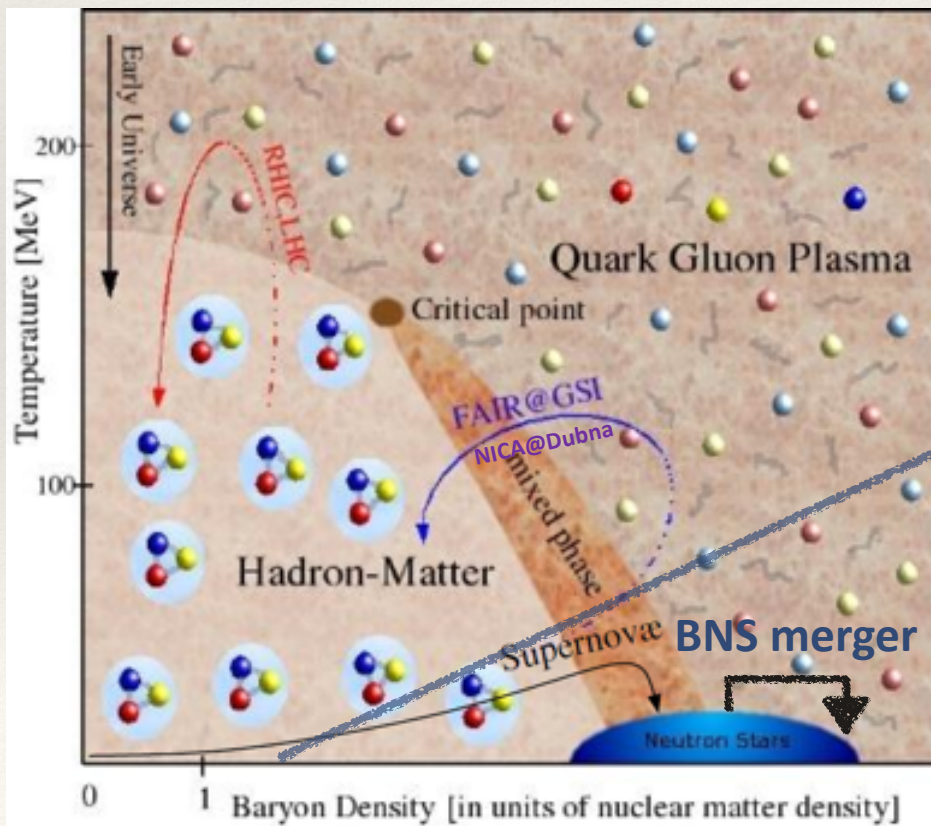


—> an event similar to GW170817 with  $D < 100$  Mpc will bring new information.

# Conclusions

From nuclear physics: ← **Complementarity** → From astrophysics:

- Better determination of the density dependence of the EoS (Heavy ion collisions, collective motion).
- Better or new measurements of  $L_{\text{sym}}$ ,  $K_{\text{sym}}$ ,  $Q_{\text{sat}}$ .
- Future detections by Advanced LIGO and Virgo (O4 and O5): expect several BNS at long distance, not always with electromagnetic counterparts.
- NICER: release of new pulsars or updated analyses on existing results.



Particle and nuclear  
accelerators  
Astrophysical  
observations

Neutron stars,  
supernovae,  
kilonovae...

**Future new data from nuclear physics and from astrophysics are highly expected.**

**Symmetry energy at high density and phase transition(s) are strongly coupled together and shall be treated on equal footing.**



---

# Work in collaboration

---

## France

**IP2I Lyon:** Guy Chanfray, Hubert Hansen, Mohamad Chamseddine (PhD).

**IP2I Lyon Virgo group:** Viola Sordini, Roberto Chierici, Jean-François Coupechoux (Post-doc).

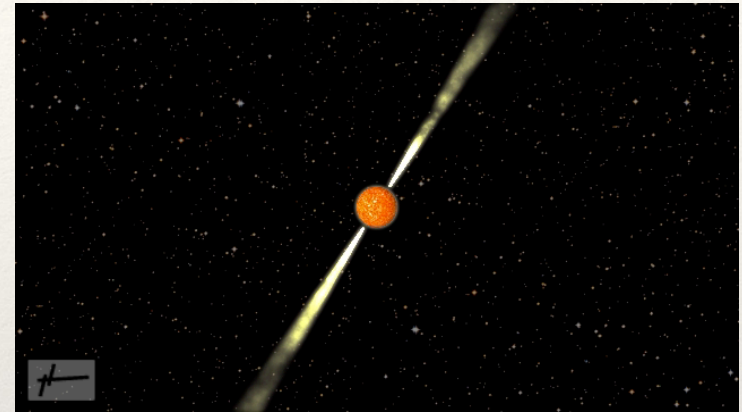
**IJCLab Orsay:** Elias Khan, Nguyen Van Giai.

**GANIL:** Anthea Fantina.

**LPC Caen:** Francesca Gulminelli.

**IRAP Toulouse:** Sébastien Guillot, Natalie Webb.

A lighthouse in the Universe.



## Belgium

**IAA Bruxelles:** Nicolas Chamel, Stephane Goriely, Guilherme Grams (Post-doc).

## Italy

**Milano U.:** Gianluca Colò.

**Biccoca U. (Milano):** Bruno Giacomazzo.

**Ferrara U.:** Alessandro Drago, Giuseppe Pagliara.

**Catania INFN:** Hans-Josef Schulze, Isaac Vidaña.

## USA

**LANL:** Ingo Tews, Rahul Somasundaram (Post-doc).

**INT Seattle:** Sanjay Reddy.

**UTK:** Andrew Steiner, Zidu Lin (Post-doc).

## China

**Lanzhou U.:** Wenhui Long.

**Southwest U. (Chongqing):** Jiajie Li.

## Turkey

**Yildiz TU:** Kutsal Bozkurt, Hasim Güven.

## Brasil

**ITA San Jose dos Campos:** Brett V.

Carlson, Mariana Dutra, Odilon Lourenço.



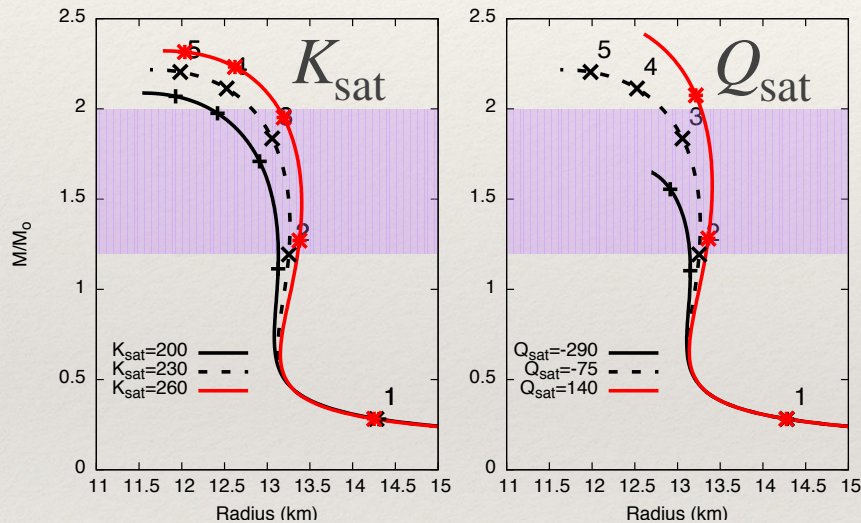
Backup slides



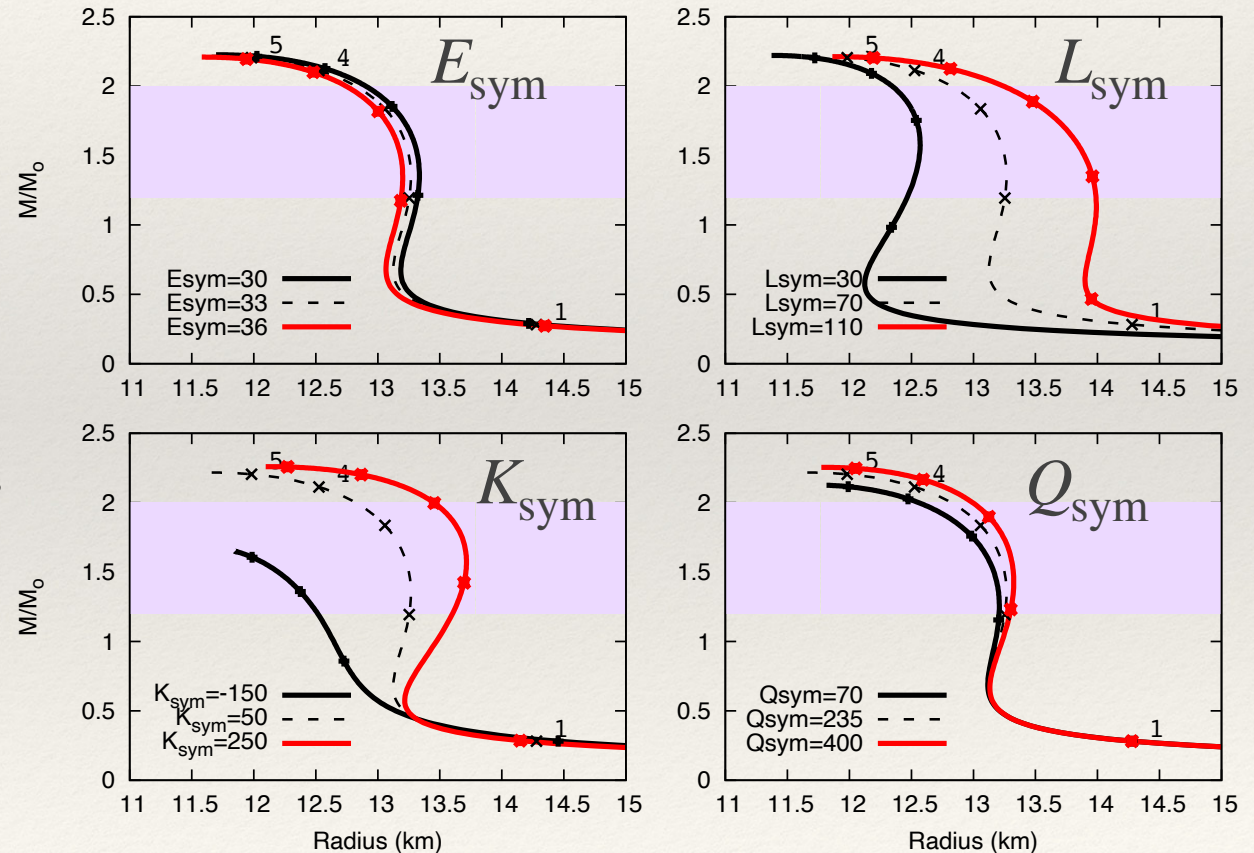
# Sensitivity analysis: $(M,R) \Leftrightarrow \text{NEP}$

Nuclear Empirical Parameters (NEP) are varied independently.  
 -> they influence the NS mass-radius relation.

Parameters for  $e_{\text{sat}}(n)$ :



Parameters for  $e_{\text{sym}}(n)$ :

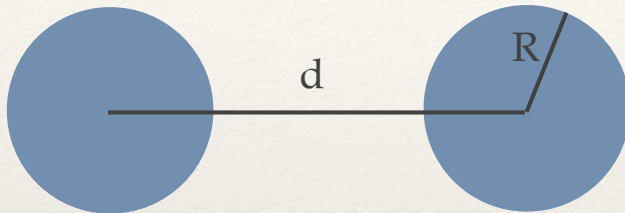


The largest source of uncertainties are from  $Q_{\text{sat}}$ ,  $L_{\text{sym}}$  and  $K_{\text{sym}}$ .



# Phase transition(s) at high density

Geometrical condition for phase transition:



d average distance between nucleons.  
R nucleon size.

If the instability condition is  $d=4R$ : The density is:  $n = \frac{8}{d^3} = \frac{1}{8R^3}$

**What is the nucleon size?** If it is about 0.7 fm ( $=R$ ), then  $n \approx 0.5\text{fm}^{-3} \approx 3n_{\text{sat}}$

—> nucleonic matter could be replaced by quark matter at  $\approx 3n_{\text{sat}}$ .



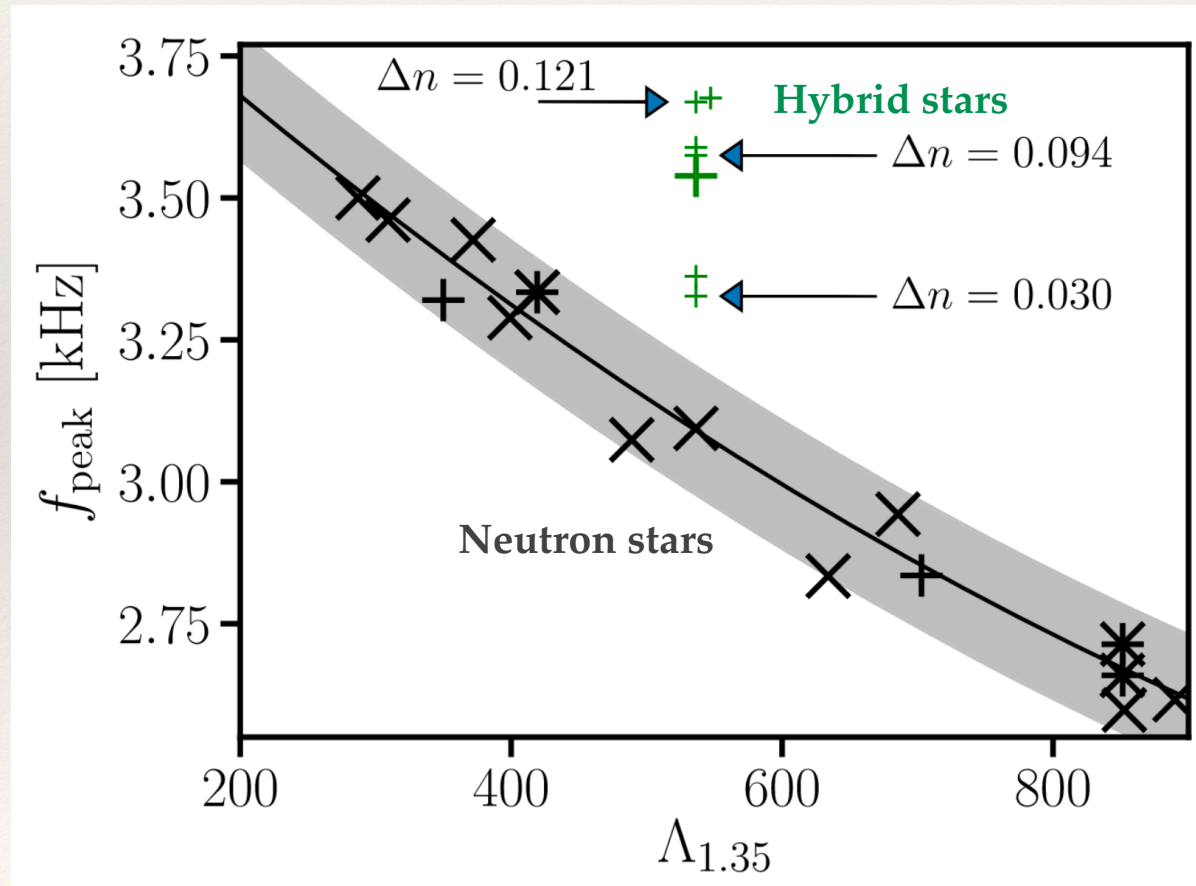
Heavy neutron stars may have a quark core.  
Can it be proven by observations?



# GW post-merger signal

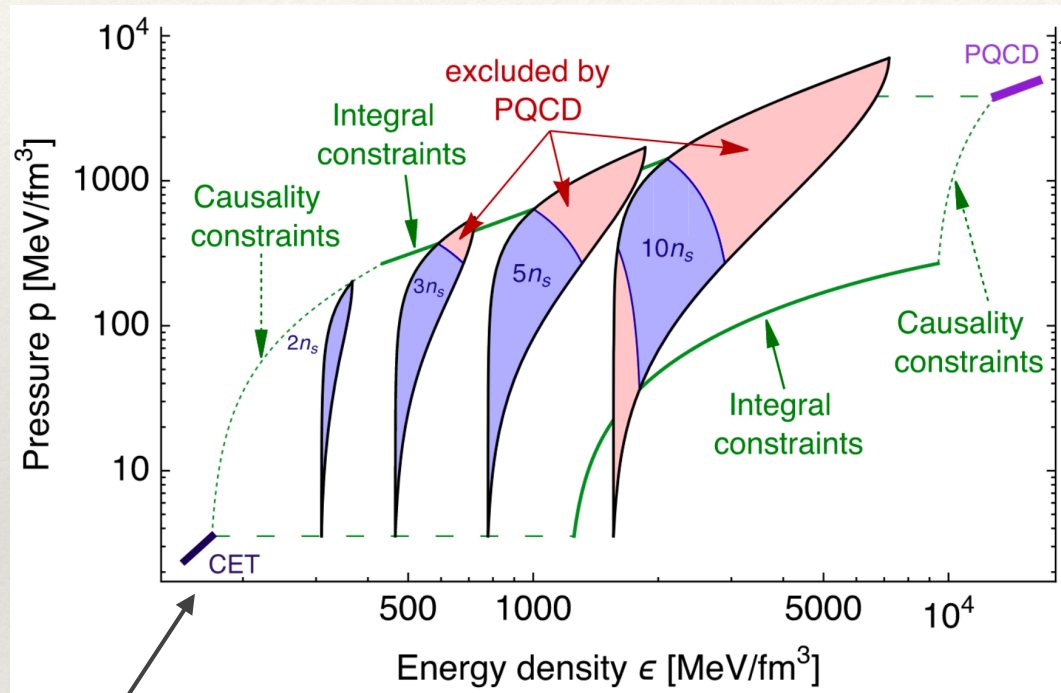
Phase transitions in the hypermassive NS can alter the correlation between the tidal deformability and post-merger oscillations.

Bauswein+ PRL 122 (2019)



# Connection to pQCD at high density

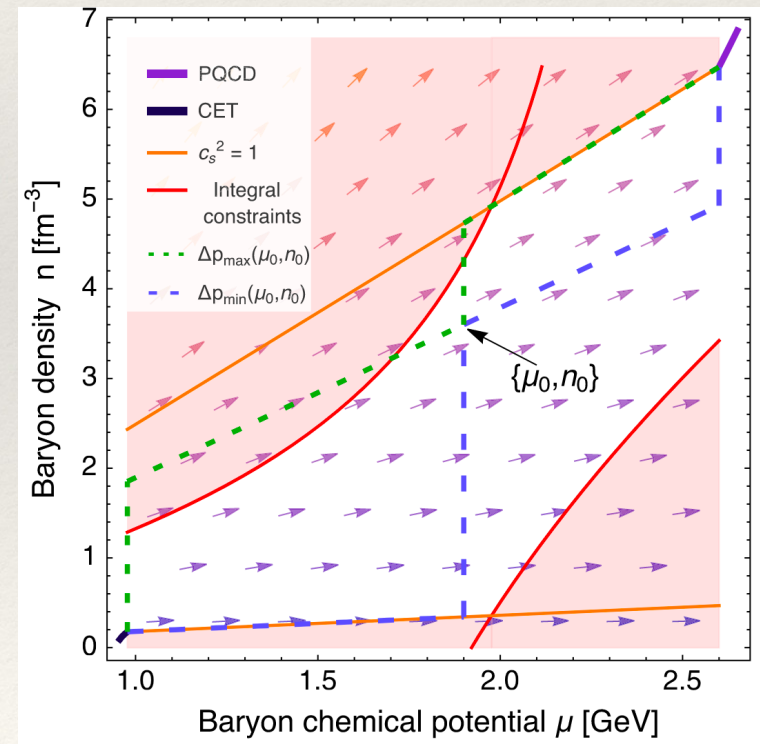
Komoltsev and Kurkela, PRL 128, 202701 (2022)



Constraints  
from chiral EFT

The most general way to connect to pQCD.

	PQCD			Loop scale parameter
	X = 1	X = 2	X = 4	
$\mu$ (GeV)		2.6		
$n$ (1/fm <sup>3</sup> )	6.14	6.47	6.87	
$p$ (MeV/fm <sup>3</sup> )	2334	3823	4284	



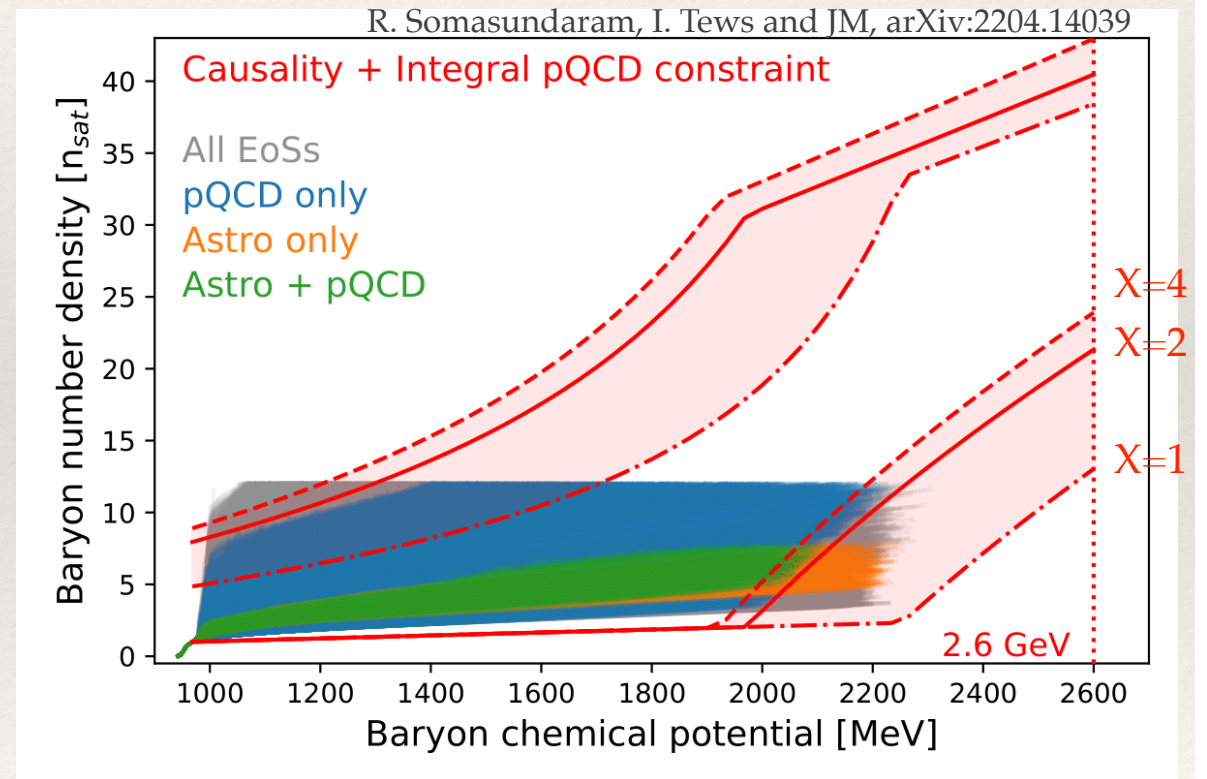
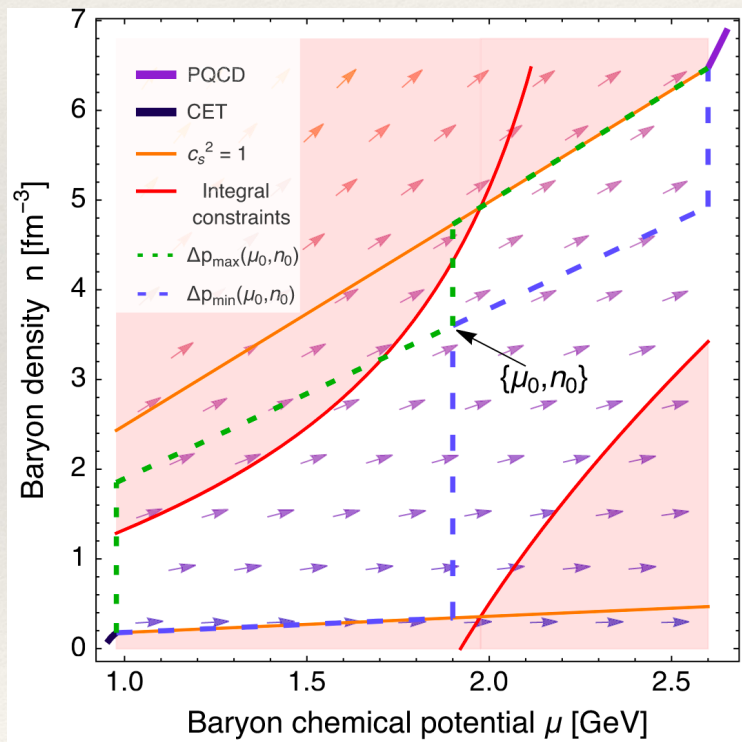


# Connection to pQCD at high density

## Crust EOS

- + sound speed model
- + extrapolation from  $n_{\text{TOV}}$  to pQCD limit (see Komoltsev & Kurkela, PRL 2022).

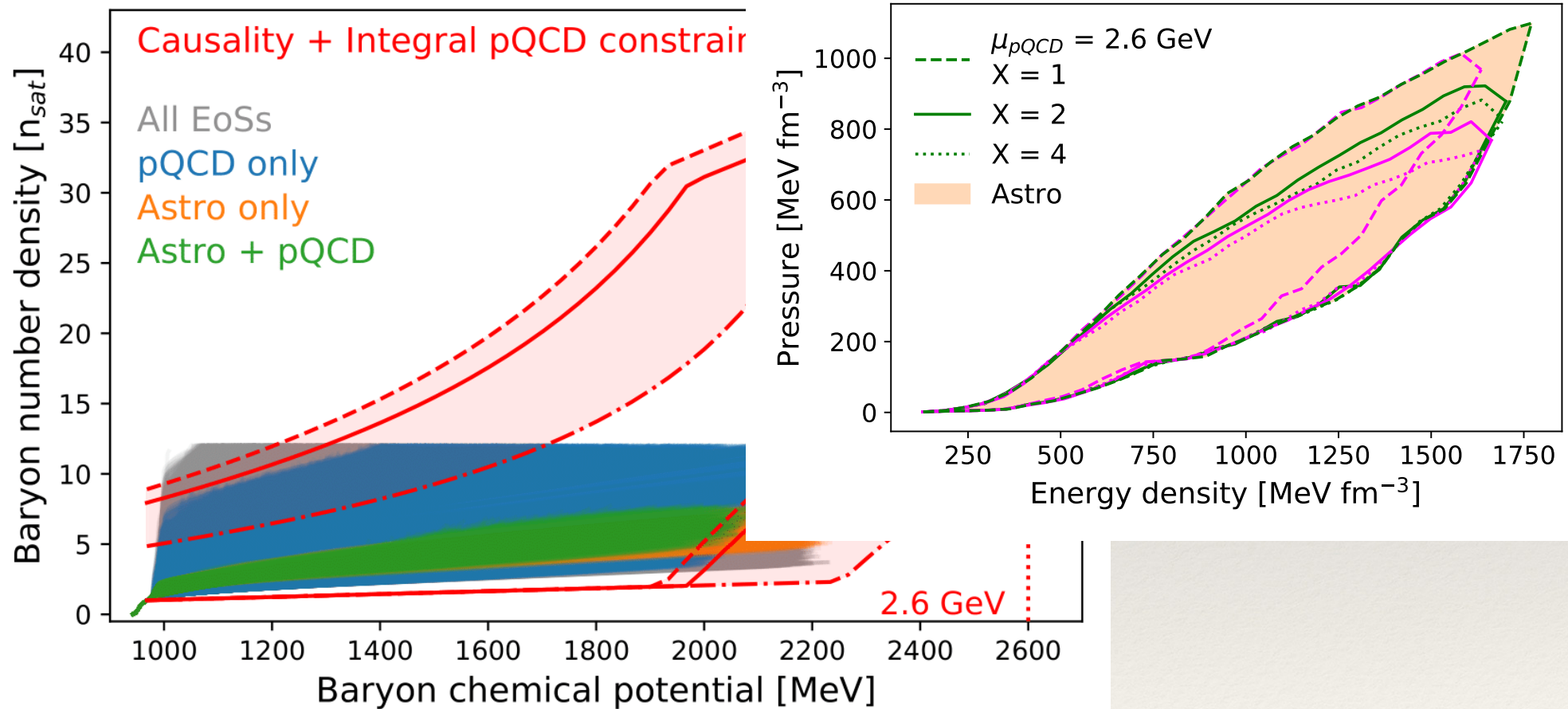
	PQCD		
	$X = 1$	$X = 2$	$X = 4$
$\mu$ (GeV)		2.6	
$n$ (1/fm <sup>3</sup> )	6.14	6.47	6.87
$p$ (MeV/fm <sup>3</sup> )	2334	3823	4284



Constraints from astrophysical observations are still better than pQCD.  
Note opposite conclusions from Gorda, Komoltsev and Kurkela, arXiv:2204.11279.

# Connection to pQCD at high density

R. Somasundaram, I. Tews and JM, arXiv:2204.14039



Constraints from astrophysical observations are still better than pQCD.

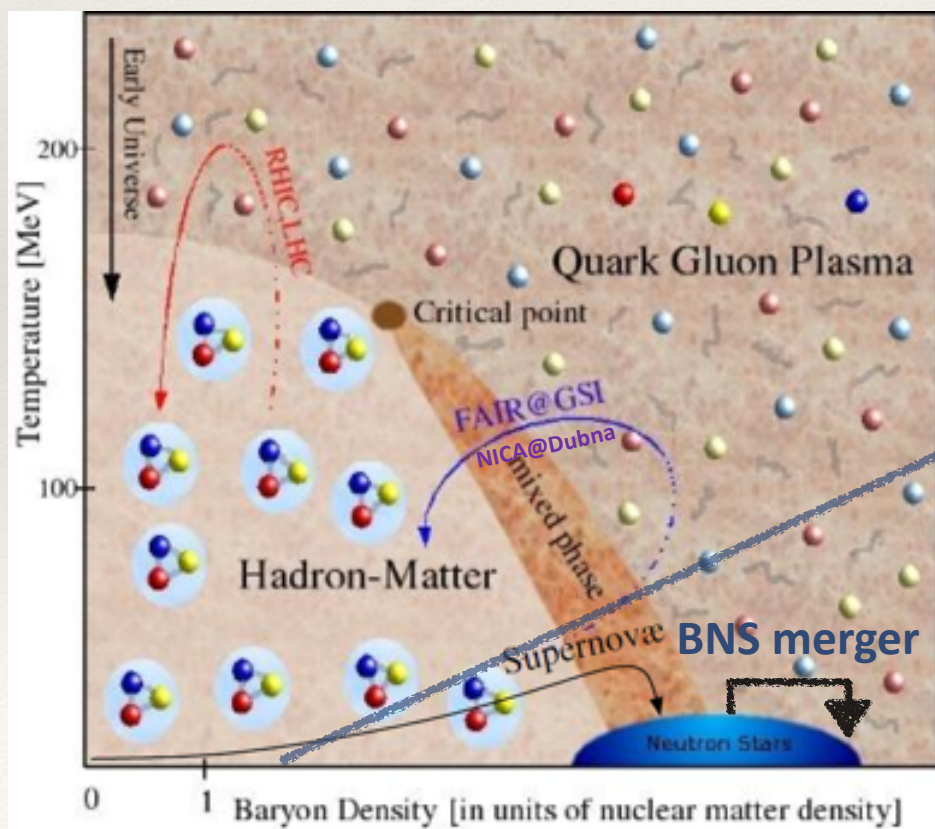
Note opposite conclusions from Gorda, Komoltsev and Kurkela, arXiv:2204.11279.



# Outlooks for the future

From nuclear physics: ← **Complementarity** → From astrophysics:

- Better determination of the density dependence of the EoS (Heavy ion collisions, collective motion).
- Better or new measurements of  $L_{\text{sym}}$ ,  $K_{\text{sym}}$ ,  $Q_{\text{sat}}$ .
- Future detections by Advanced LIGO and Virgo (O4 and O5): expect several BNS at long distance, not always with electromagnetic counterparts.
- NICER: release of new pulsars or updated analyses on existing results.



Particle and nuclear  
accelerators  
Astrophysical  
observations

Neutron stars,  
supernovae,  
kilonovae...

## Related questions:

How changes the **nuclear interaction** with temperature?

Which **new particles** appear at supra-saturation densities (phase transition)?

Links between **deconfinement** and **chiral symmetry** restoration?

How **neutrinos** propagate? What are the **transport properties** of extreme matter?

Are BNS the main astrophysical site for the **r-process**?



# Anatomy of a neutron star

Conjectured 1934 (Bade & Zwicky)

Discovered 1967 (Bell & Hewish)

Known  $\sim 3300$

Expected  $\sim 10^8$   
(in our galaxy)

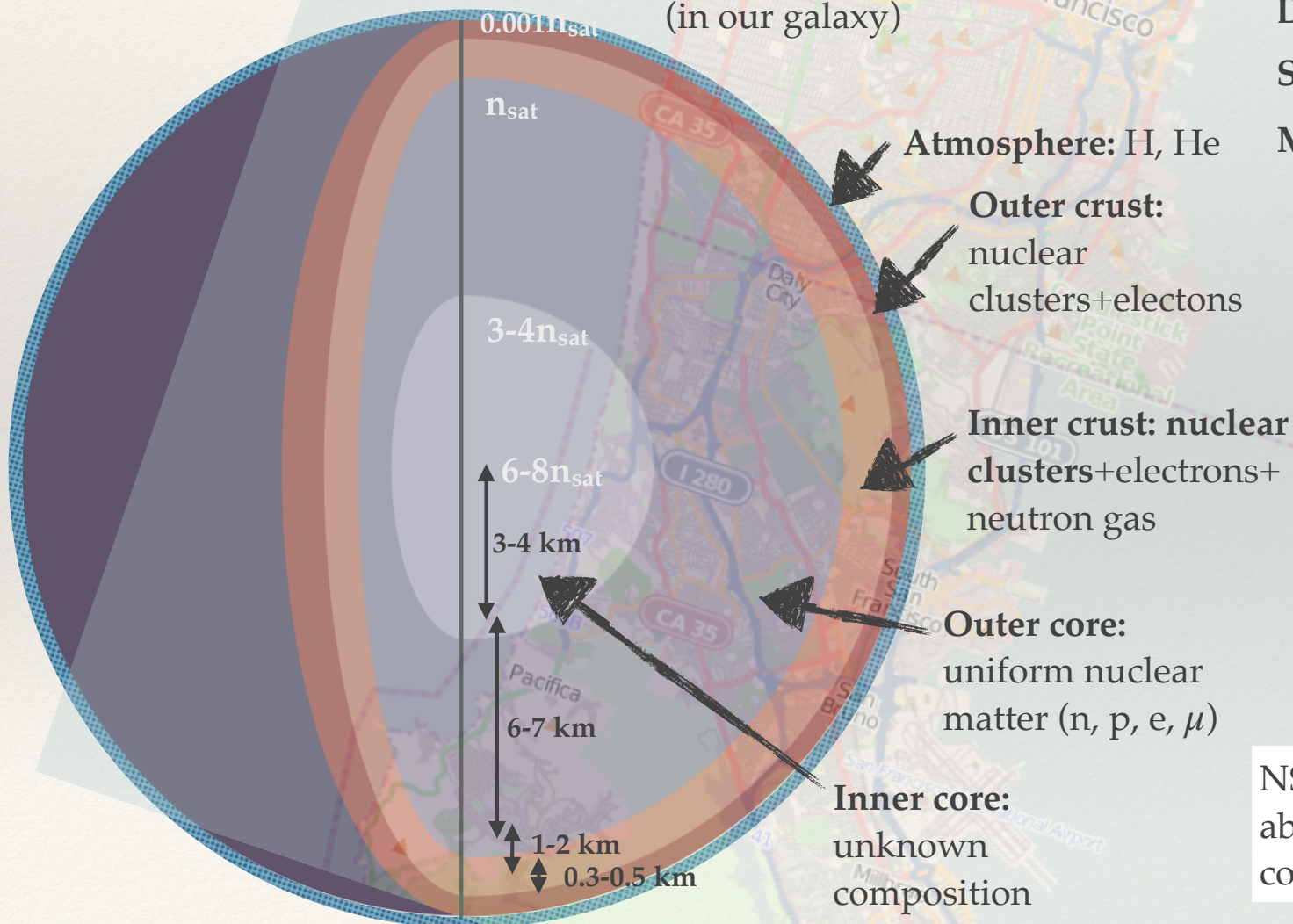
Radius  $\approx 10 - 14 \text{ km}$

Mass  $\approx 1.2 - 2.1 M_{\odot}$  (observed)

Density  $\approx 10^{15} \text{ g cm}^{-3}$

Spin  $\geq 716 \text{ Hz}$

Magnetic field up to  $\sim 10^{16} \text{ G}$



The understanding of NS is mainly due to our knowledge in nuclear physics (+ general relativity).

NS **radius** provides information about the **core**, but there is also a contribution from the crust (10%).

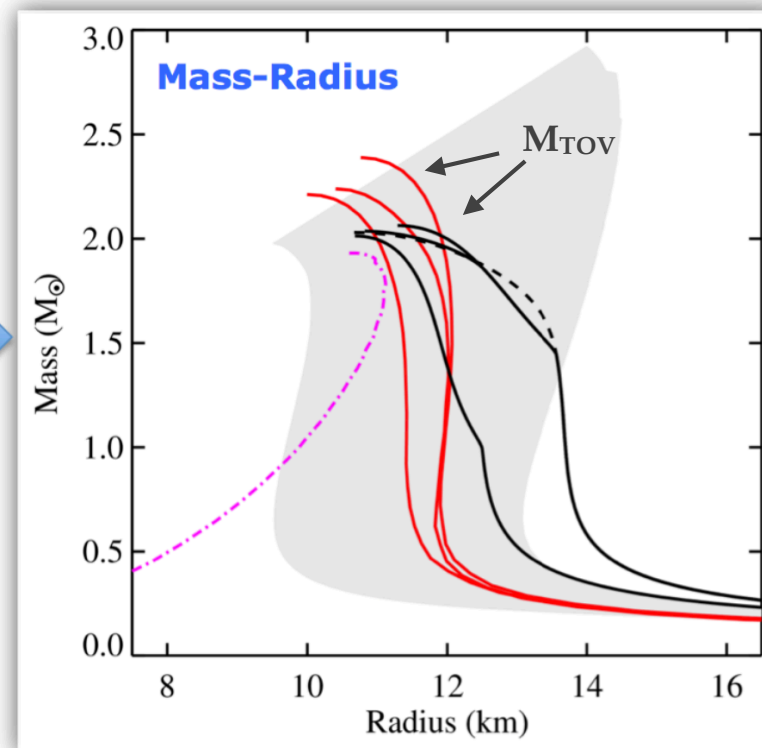
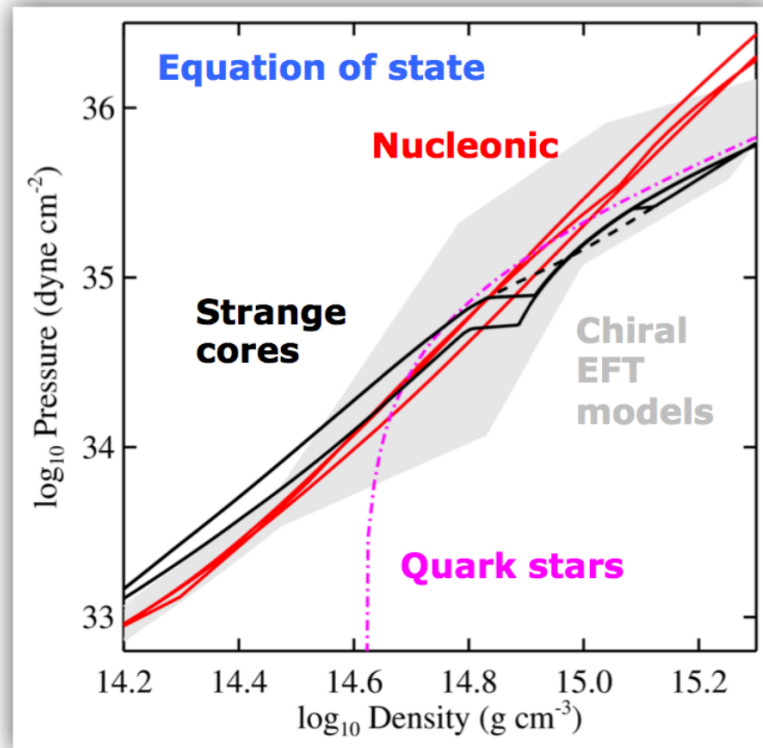


# EoS [nuclear] $\Leftrightarrow$ NS (M,R) [astro]

Properties of  
extreme matter

Tolmann-Oppenheimer-  
Volkov (TOV) GR equations

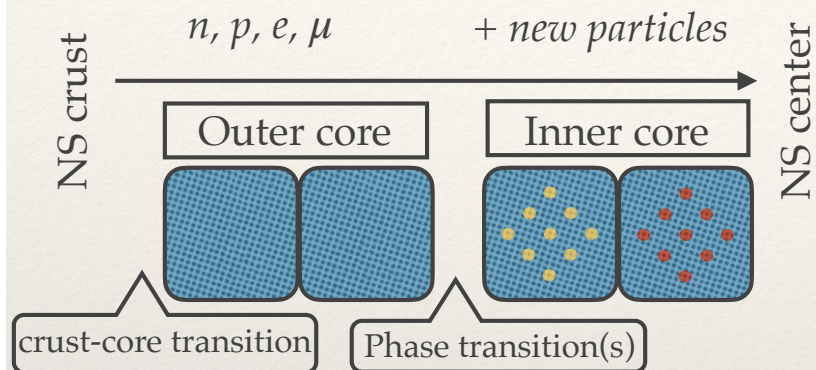
Astrophysical  
observations



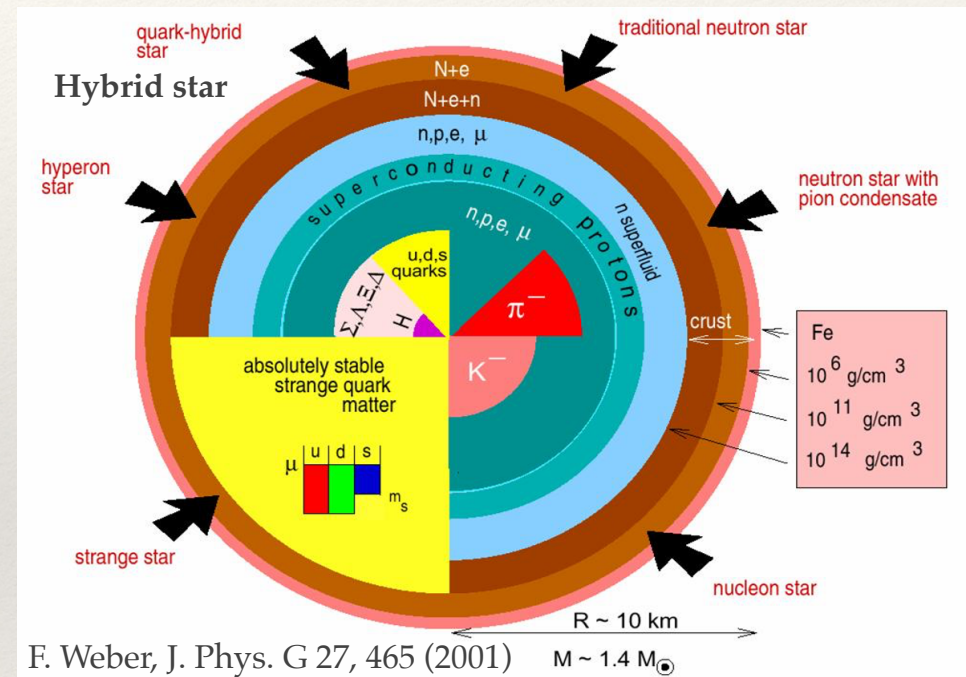
[A. Watts et al., PoD (AASKA 14) 043]

Reverse engineering,  
Bayesian statistics

# Modeling homogeneous matter (core)



- ❖ What is the composition of the outer core?
- ❖ Is there a phase transition in the inner core?
- ❖ If yes, only one or several?
- ❖ What is the composition of the new phases in the inner core?
- ❖ Which impact they have on the equation of state?



How new data will help to answer these questions?



# Confronting the thermal emission from qLMXB with nuclear EoS

## Sensitivity analysis

Framework	Sources	Distances	prior	$L_{\text{sym}}$	$K_{\text{sym}}$	$Q_{\text{sat}}$	$R_{1.45}$	$\chi^2_\nu$	nb. of	d.o.f.
			$L_{\text{sym}}$	(MeV)	(MeV)	(MeV)	(km)		param.	
1	all	<i>Dist #2</i>	yes	$37.2^{+9.2}_{-8.9}$	$-85^{+82}_{-70}$	$318^{+673}_{-366}$	$12.35 \pm 0.37$	1.08	49	1126
2	all	<i>Dist #1</i>	yes	$38.3^{+9.1}_{-8.9}$	$-91^{+85}_{-71}$	$353^{+696}_{-484}$	$12.42 \pm 0.34$	1.07	49	1126
3	all	<i>Dist #1</i>	yes	$38.6^{+9.2}_{-8.7}$	$-95^{+80}_{-36}$	300	$12.25 \pm 0.30$	1.07	48	1127
4	all	<i>Dist #1</i>	no	$27.2^{+10.9}_{-5.3}$	$-59^{+103}_{-74}$	$408^{+735}_{-430}$	$12.37 \pm 0.30$	1.07	49	1126
5	all/47-Tuc	<i>Dist #1</i>	yes	$43.4^{+9.7}_{-9.3}$	$-66^{+137}_{-102}$	$622^{+763}_{-560}$	$12.57 \pm 0.41$	1.08	43	700
6	all/NGC6397	<i>Dist #1</i>	yes	$42.6^{+9.9}_{-9.5}$	$-77^{+129}_{-96}$	$623^{+757}_{-544}$	$12.58 \pm 0.40$	1.09	43	961
7	all/M28	<i>Dist #1</i>	yes	$42.5^{+9.5}_{-9.5}$	$-80^{+124}_{-91}$	$597^{+717}_{-510}$	$12.46 \pm 0.37$	1.07	43	846
8	A	<i>Dist #2</i>	yes	$38.6^{+9.4}_{-8.9}$	$-91^{+81}_{-76}$	$343^{+805}_{-431}$	$12.18 \pm 0.29$	1.04	21	874
9	A'	<i>Dist #2</i>	yes	$37.5^{+9.0}_{-8.9}$	$-88^{+76}_{-70}$	$263^{+764}_{-361}$	$12.22 \pm 0.32$	1.06	29	945
10	B	<i>Dist #2</i>	yes	$49.12^{+10.0}_{-10.0}$	$-6.66^{+137}_{-138}$	$804^{+709}_{-675}$	$12.88 \pm 0.43$	1.19	28	255
11	B'	<i>Dist #2</i>	yes	$50.3^{+9.8}_{-9.6}$	$-1^{+134}_{-143}$	$881^{+671}_{-705}$	$12.98 \pm 0.40$	1.18	23	178

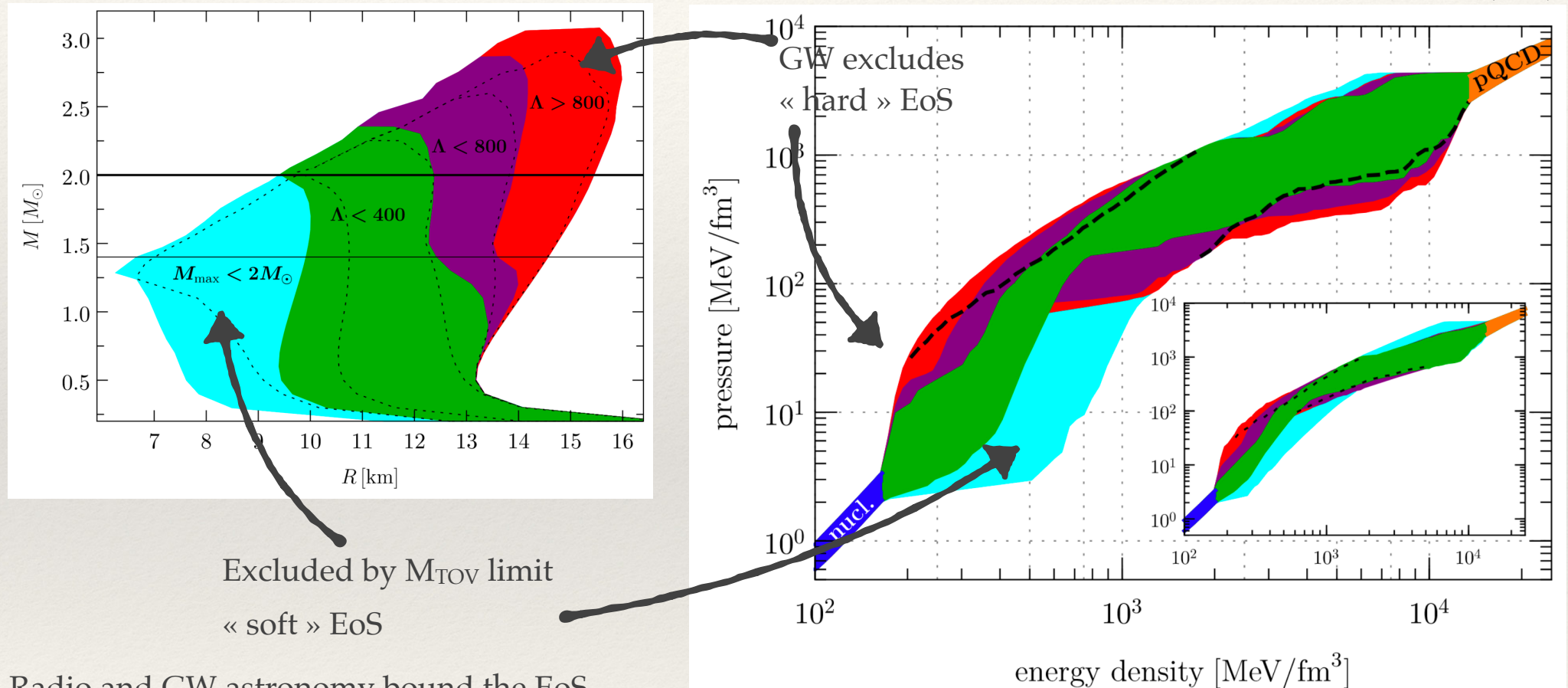
## Outlook:

Include phase transition

Confront with other observations

# Consequences for extreme matter EoS

Annala+, PRL 120, 172703 (2018)



Radio and GW astronomy bound the EoS.

- ➔ More accurate measurement of  $\tilde{\Lambda}$   $\rightarrow$  further reduction of EoS band.
- ➔ Simple illustration of a multi-messenger analysis.



# Some basics on stars

	Sun	Neutron stars
Central temperature	$15 \times 10^6 \text{ K}$	$\sim 10^{7,8} \text{ K}$
Thermal energy	$\sim 10^{-3} \text{ MeV}$	$\sim 10^{-3,-2} \text{ MeV}$
Mass-density	$\sim 1,2 \text{ g cm}^{-3}$	$\sim 10^{15} \text{ g cm}^{-3}$
Particle density	$0.1, 1.0 \text{ fm}^{-3}$	$0.1, 1.0 \text{ fm}^{-3}$
Fermi momentum		$1.0, 2.0 \text{ fm}^{-1}$
Fermi energy		$\sim 40, 200 \text{ MeV}$
	↓	↓
	Classical Boltzmann gas.	Degenerate (=quantum) Fermi gas.

Radius

700 000 km

10, 15 km

GR parameter  $\Xi = \frac{R_{sch}}{R}$

$10^{-5,-6}$

0.2, 0.3

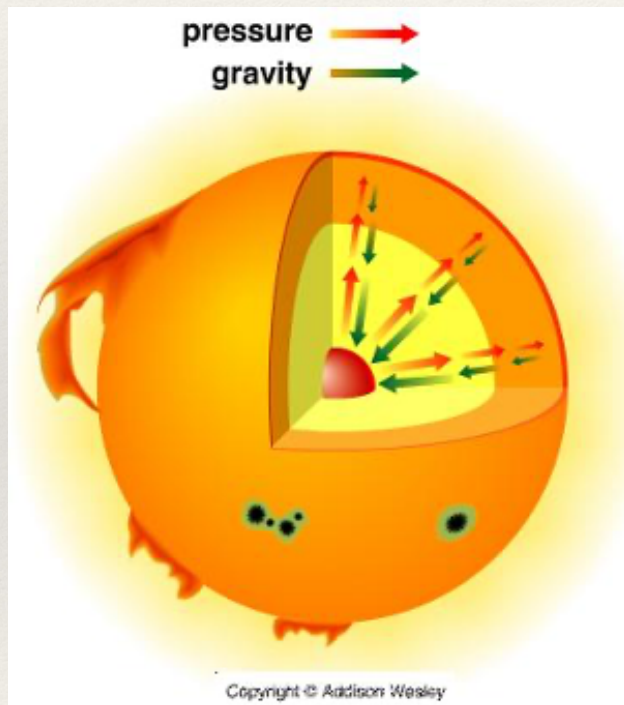


Relativistic Star



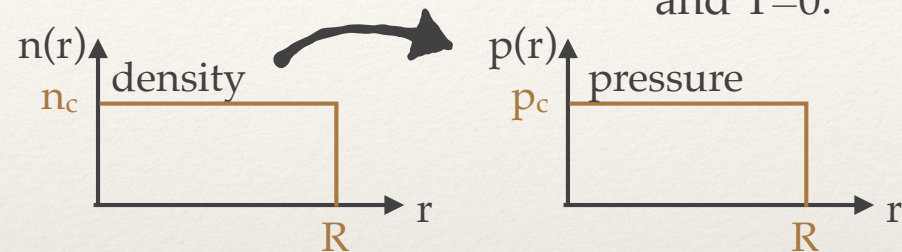
# Stars and the equation of state...

The sun is at equilibrium between **gravity** and internal (radiative) **pressure**.



This is the case of all celestial objects. Only **different pressures** create **different objects**.

**Neutron stars** are also at equilibrium. Assume the density in the star is constant and  $T=0$ :



The **radius**  $R$  of neutron stars reflects this equilibrium:

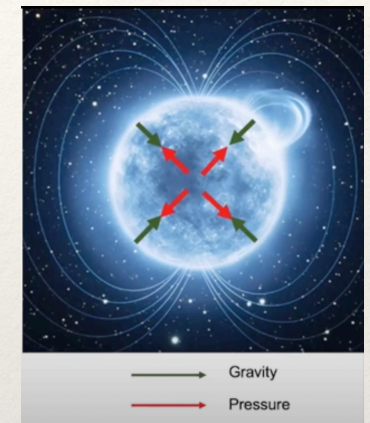
- large radii  $\rightarrow$  large internal pressure,
- small radii  $\rightarrow$  lower internal pressure.

Measuring neutron star **radius** is a way to measure the **internal pressure**.

The **mass** and the **radius** define the **density**:  $\rho \propto M/R^3$

The relation between the internal pressure and the density is called the **equation of state (EoS)**.

A neutron star

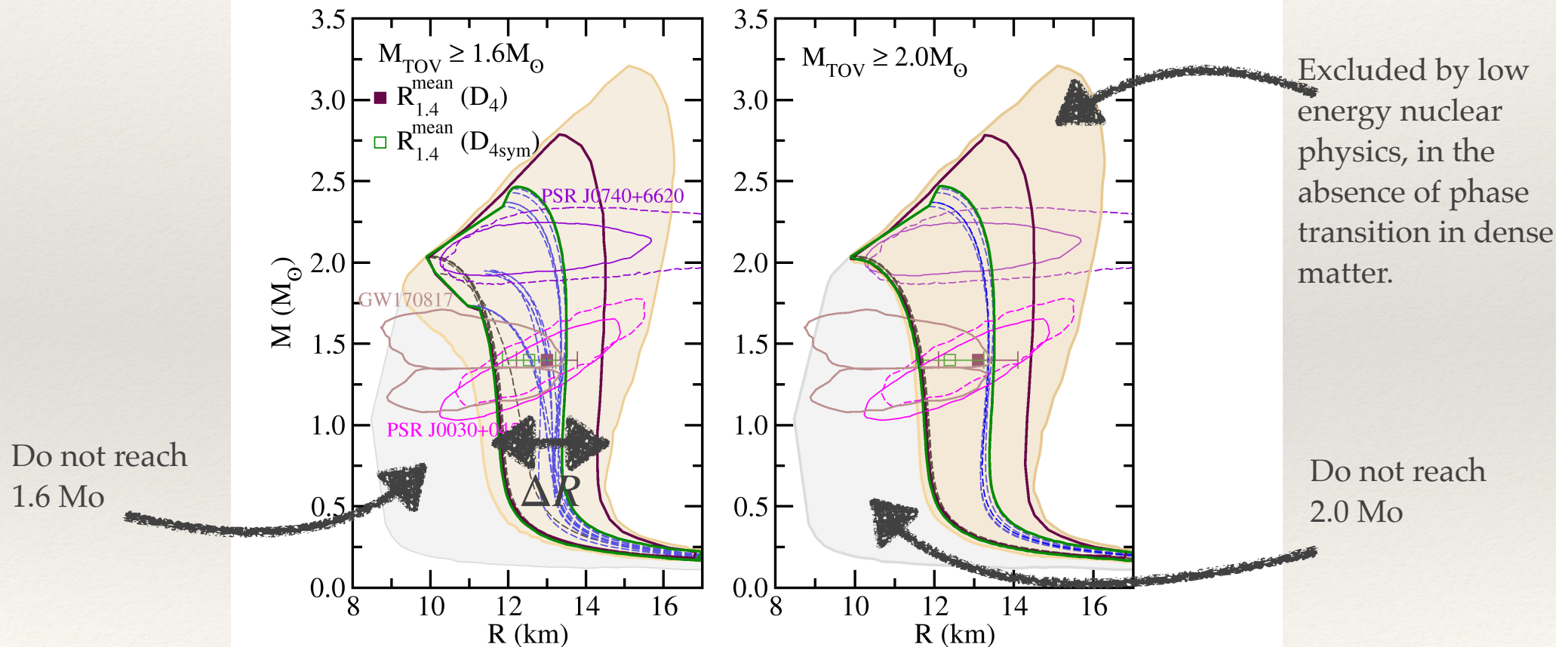


Internal pressure originates from the **Pauli exclusion** between fermions (electrons, nucleons, quarks, ...) + **interaction (quantum mechanics)**.



# Low energy nuclear physics and neutron stars

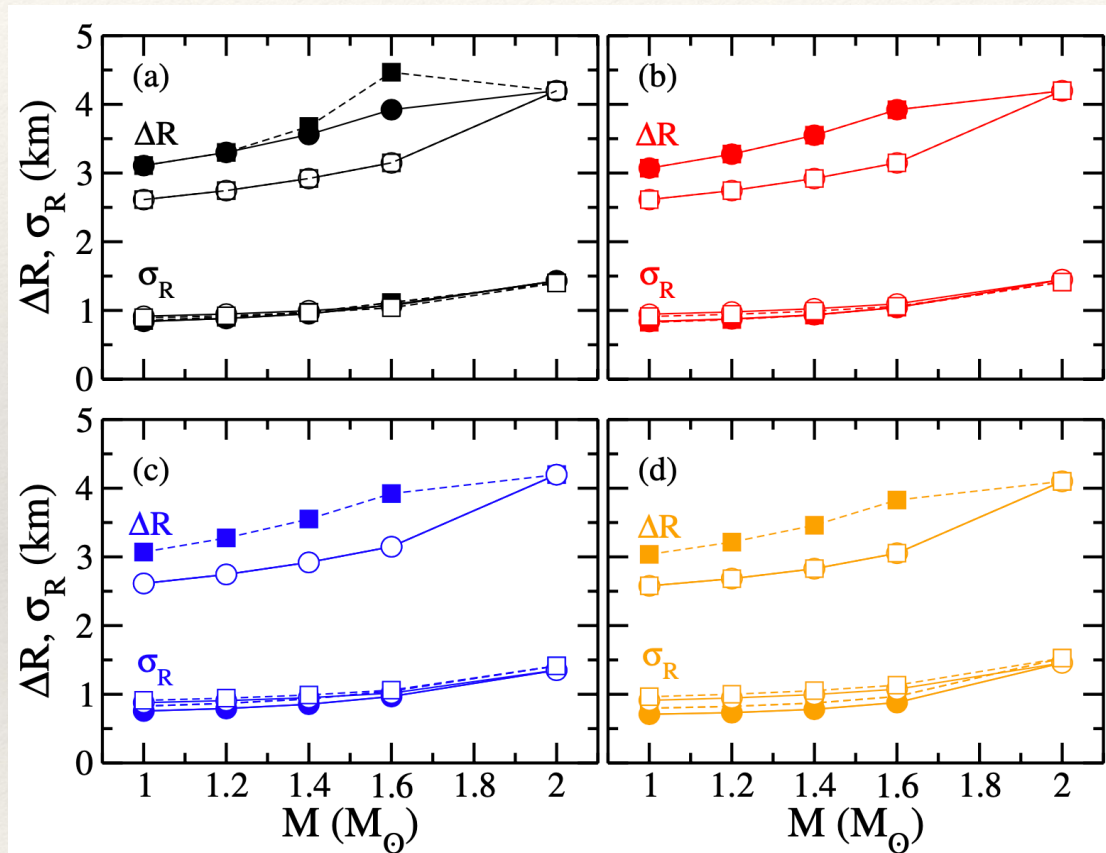
Carlson, Dutra, Lourenço, JM, arXiv: 2209.03257



# Low energy nuclear physics and neutron stars

Carlson, Dutra, Lourenço, JM, arXiv: 2209.03257

Models reproducing nuclear binding energies with large uncertainties.



Models reproducing nuclear binding with small uncertainties.

Models reproducing nuclear binding + charge radius with small uncertainties.

Models reproducing nuclear binding + charge radius + GMR energies with small uncertainties.

Better low energy nuclear properties may not improve predictions for neutron star global properties.  
Reason: nuclei sit around  $n_{\text{sat}}$  while a 1.4 $M_\odot$  NS has 2-3  $n_{\text{sat}}$  at its center.

—> the largest source of uncertainties is the **density dependence of the EoS** (Symmetry energy, phase transitions).