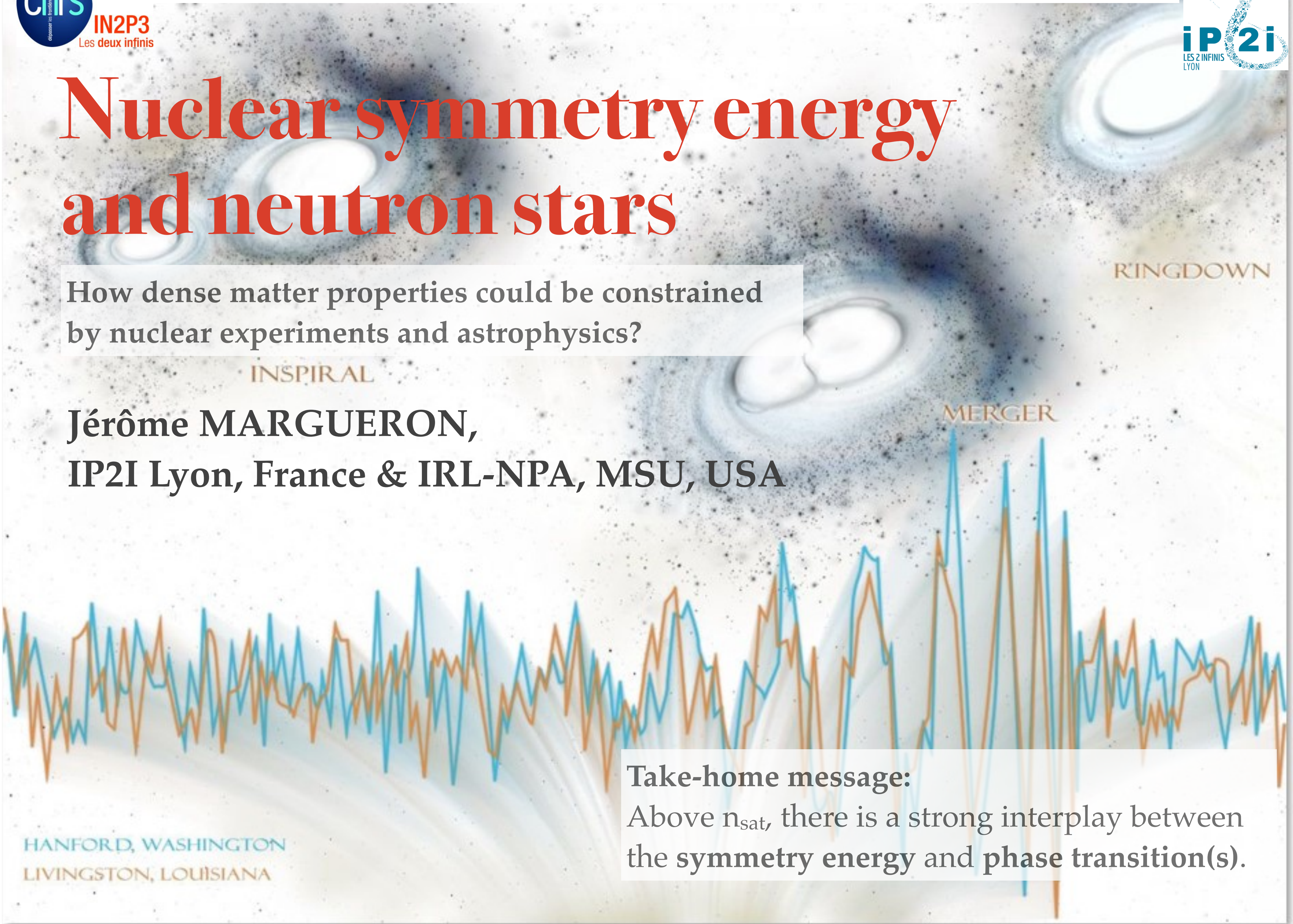
Colloque GANIL 2023, Soustons, Sept. 2023

Nuclear symmetry energy and neutron stars

How dense matter properties could be constrained by nuclear experiments and astrophysics?

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



Take-home message:
Above n_{sat}, there is a strong interplay between the **symmetry energy** and **phase transition(s)**.

Compact stars and the early universe

The present understanding of the **early universe** (million years after the Big Bang) is challenged by the recent observations of the JWST.

Compact stars (Black Holes and Neutron Stars) are expected to be massively formed in the early universe, since massive stars are expected to be more numerous than nowadays.

The **formation rate of early compact stars** will be measured by the **third generation of GW interferometers** (Einstein Telescope and Cosmic Explorer are expected to operate after 2035). It will provide **complementary information** to the JWST.

The understanding of GW from neutron stars require an **accurate modelling** of their properties.

This accurate modelling can be **calibrated** based on the neutron stars observed in **our galaxy** and from **nuclear physics facilities**.

We therefore have about **10 years in front of us** to realise this goal.

→ **How nuclear physics could be employed to better understand neutron star properties?**

Nuclear physics and astrophysics in the same boat!

In order to employ nuclear physics and astrophysics for accurate modelling of neutron stars, we need a **common language**, which annihilate possible misunderstanding.

Exemple:

→ Symmetry energy → Equation of state

We may also massively employ **bayesian statistics** to estimate accurately the connection between **hypotheses** and **uncertainties** in the modelling (ex: **null hypothesis**).

The nuclear symmetry energy in NS/finite nuclei

[Somasundaram, Drischler, Tews, JM, Phys. Rev. C 103, 045803 (2022)]

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

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

Other authors label it as J_0

In asymmetric matter:
(Taylor expansion in δ)

$$e_{\rm tot}(n,\delta) \approx e_{\rm SM}(n) + e_{\rm sym,2}(n)\delta^2 + e_{\rm sym,4}(n)\delta^4 + \dots$$

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

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

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

Be careful: may not be satisfied at all densities.

The nuclear empirical parameters

Definitions:
(Taylor expansion
in density)

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

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

with

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

The coefficients of this Taylor expansion are the nuclear empirical parameters (NEP).

NEP provide an efficient representation of nuclear physics knowledge and lack of knowledge (**uncertainties**).

NEP could be employed to estimate the global neutron star properties (meta-model) compatible with nuclear physics knowledge —> possible null hypothesis.

The nuclear equation of state

The **nuclear empirical parameters** (NEP) capture the properties of the EoS around n_{sat}:

Less known NEP

Unknown NEP

$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots$$

$$e_{sym} = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$

with $\delta = (n_n - n_p)/(n_n + n_p)$ and $x = (n - n_{sat})/(3n_{sat})$

Various nuclear modeling (Skyrme, Gogny, RMF, …).

Semi-agnostic approach (Meta-model):

$$e(n,\delta) = t(n,\delta) + v(n,\delta)$$

Kinetic energy (Fermi gas)

Potential energy

$$v(n,\delta) = \sum_{\alpha=0}^{N} \left(v_\alpha^{\text{is}} + \delta^2 v_\alpha^{\text{iv}}\right) \frac{x^\alpha}{\alpha!} u(x),$$

Directly related to NEP

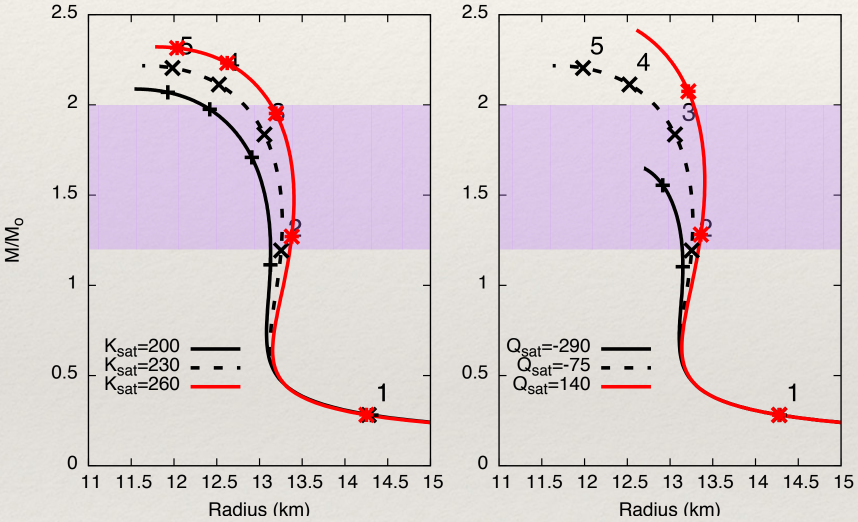
[JM, Casali, Gulminelli, PRC 2018]

We can combine together **nuclear** (neutrons and protons) with **lepton** (electrons and muons) composents to produce an **equation of state** for dense matter,
injected in the **general relativity static** equations (TOV),
producing **global properties of neutron stars**: masses, radii, tidal deformabilities,…

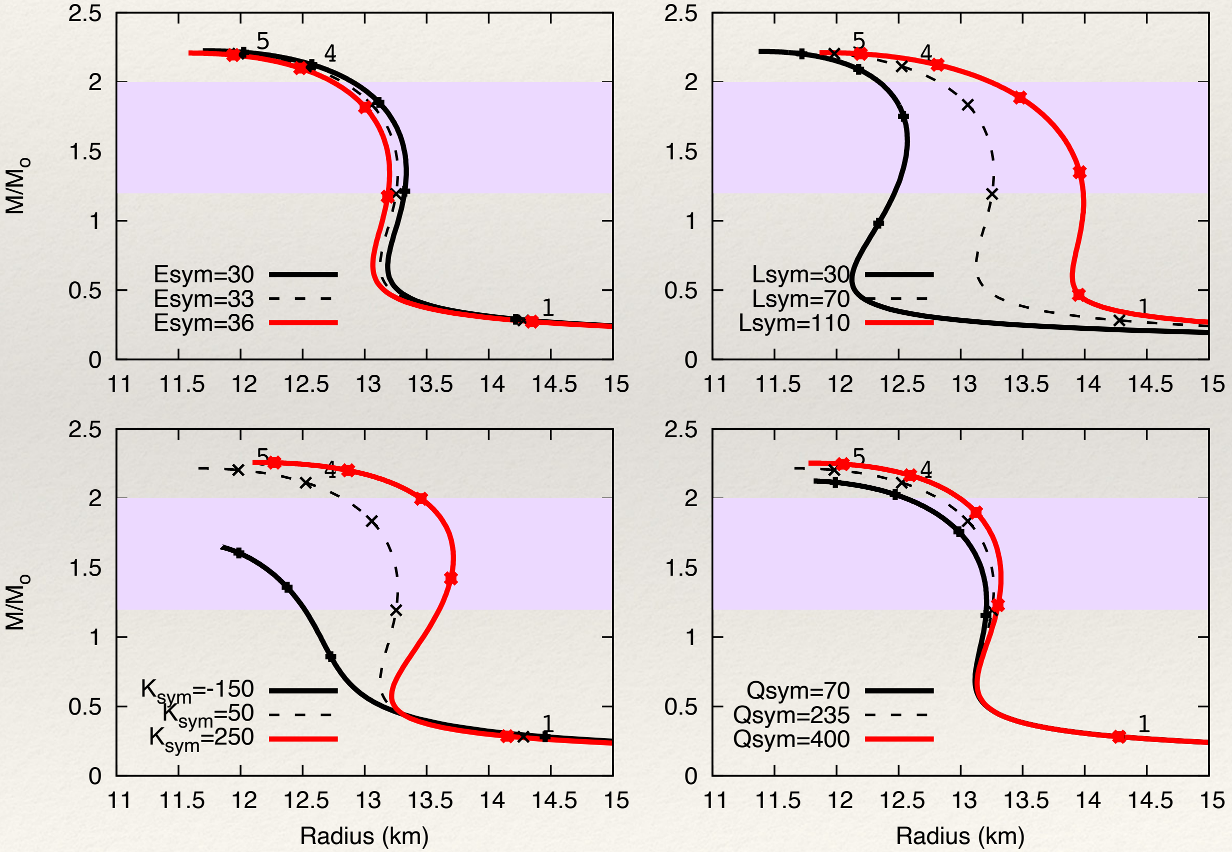
Sensitivity analysis: (M,R) <—> NEP

We vary the empirical parameters are analyse their influence on the MR relation for neutron stars:

Parameters for $e_{\rm sat}$:



Parameters for $e_{\rm sym}$:



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

[JM, Casali, Gulminelli, PRC 2018]

The nuclear equation of state

The **nuclear empirical parameters** (NEP) capture the properties of the EoS around n_{sat}:

Less known NEP

Unknown NEP

$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots$$

$$e_{sym} = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$

with $\delta = (n_n - n_p)/(n_n + n_p)$ and $x = (n - n_{sat})/(3n_{sat})$

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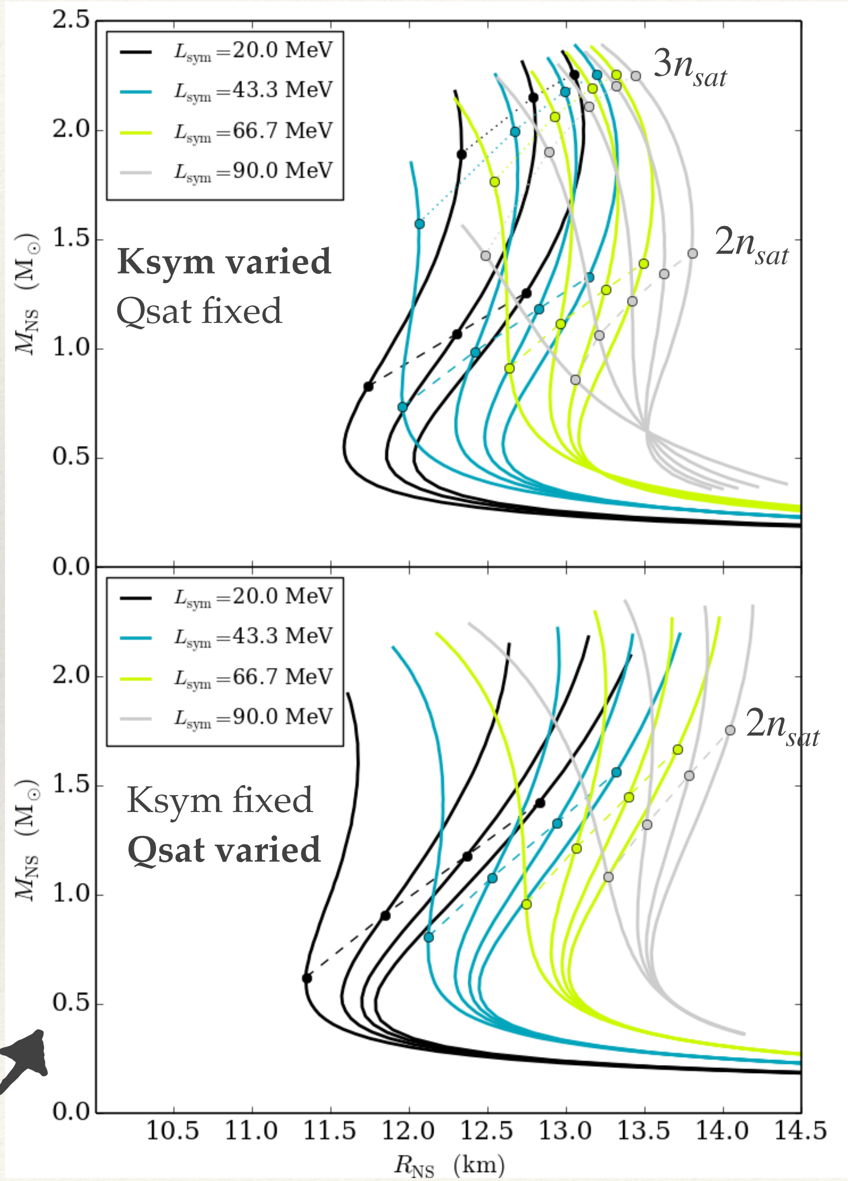
Directly
related to NEP

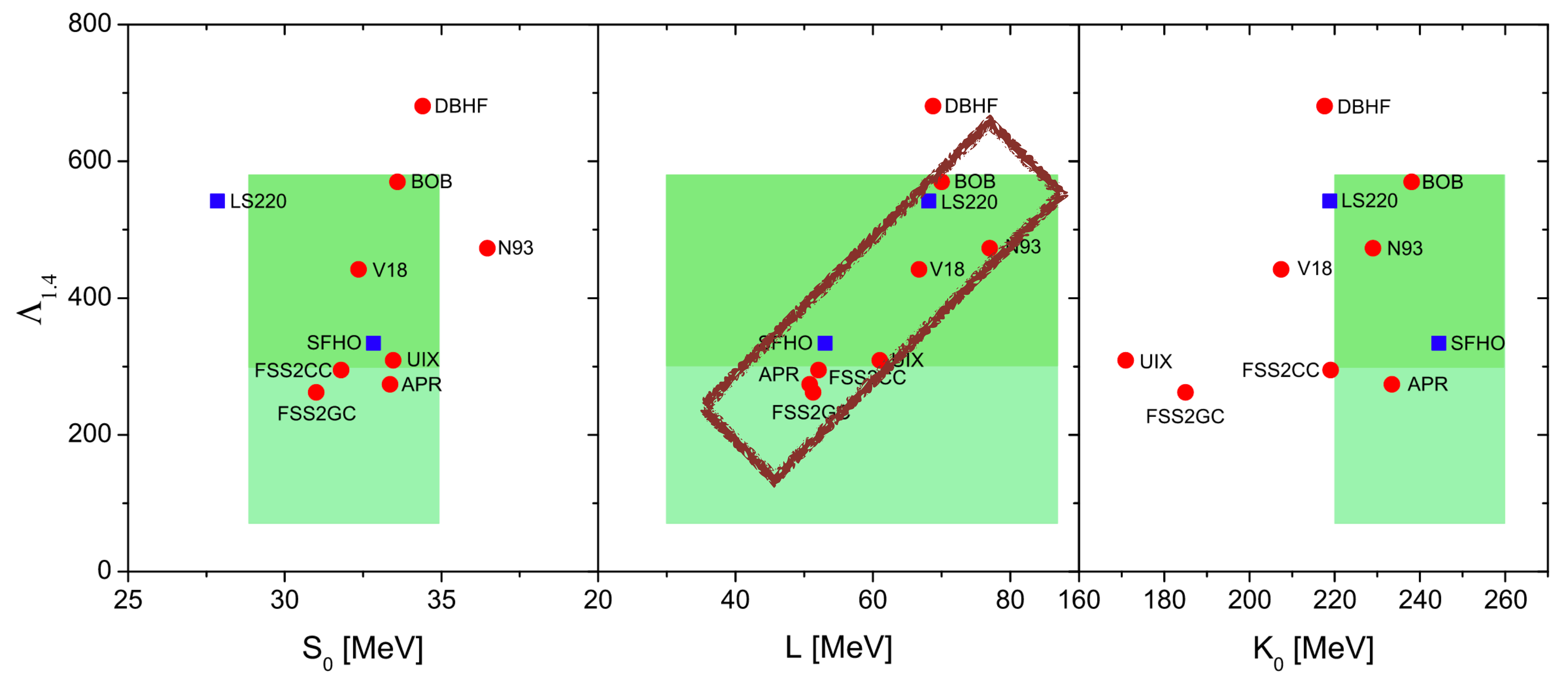
[JM, Casali, Gulminelli, PRC 2018]

[Baillot d'Étivaux+, ApJ 2019]



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, e.g., the correlation is maybe present for L?

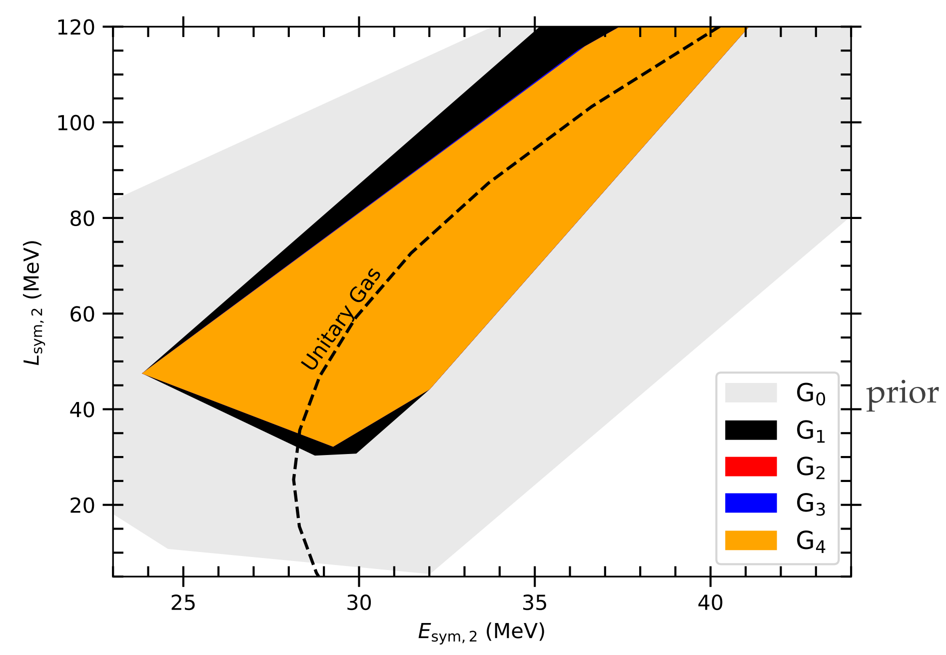
—> we have done a slightly different analysis.

Low-energy nuclear physics and neutron stars

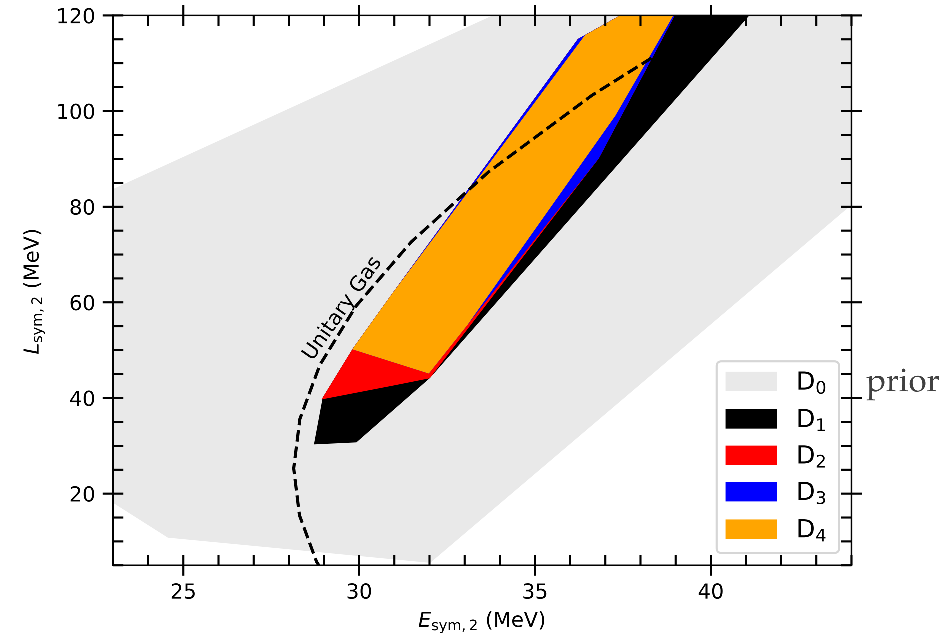
To what extent present low-energy nuclear data constrain NS properties?

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:



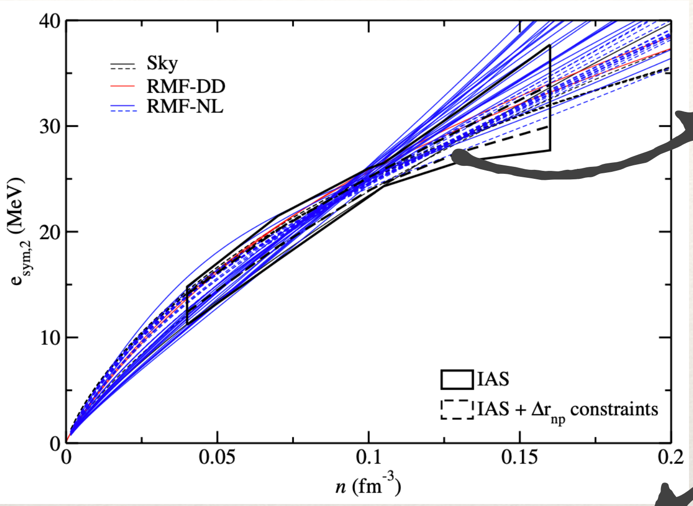
Detailed assessment where $N = Z$ and $N \neq Z$ nuclei are treated equally:



Tighter correlation

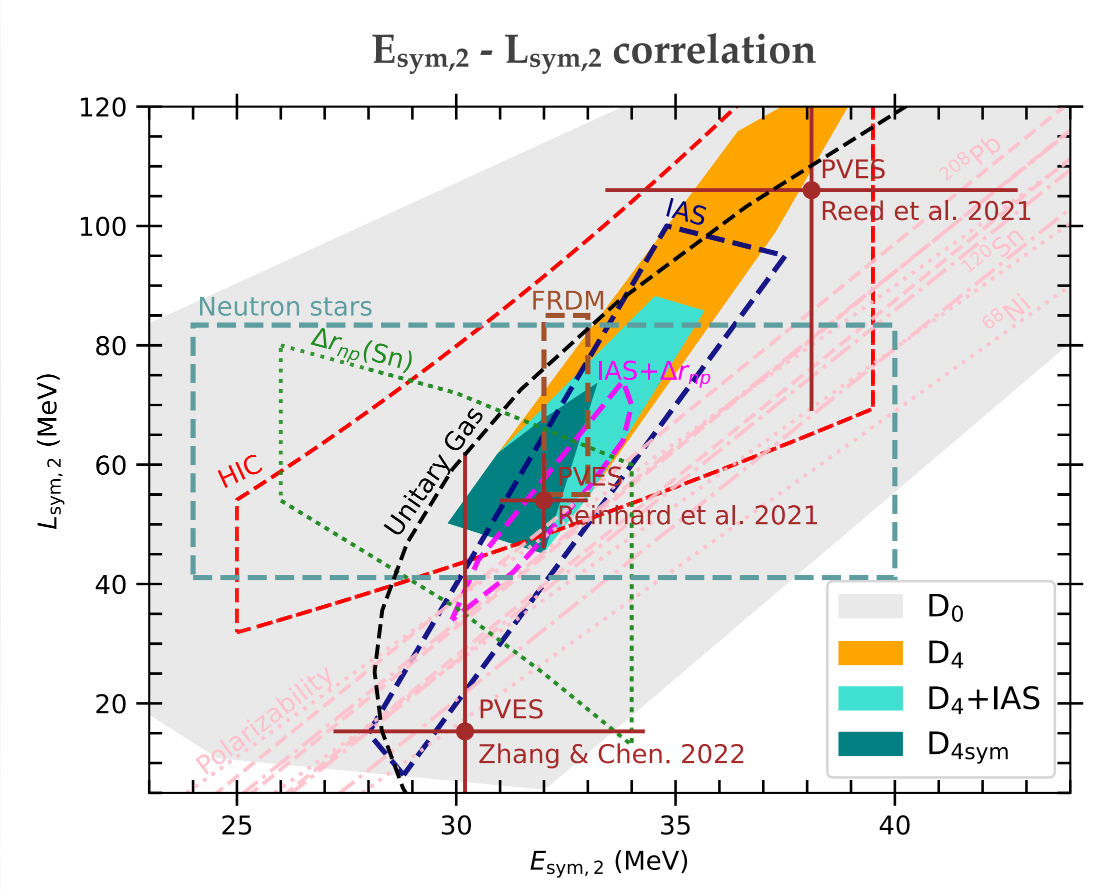
Carlson, Dutra, Lourenço, JM, PRC 107 (2023)

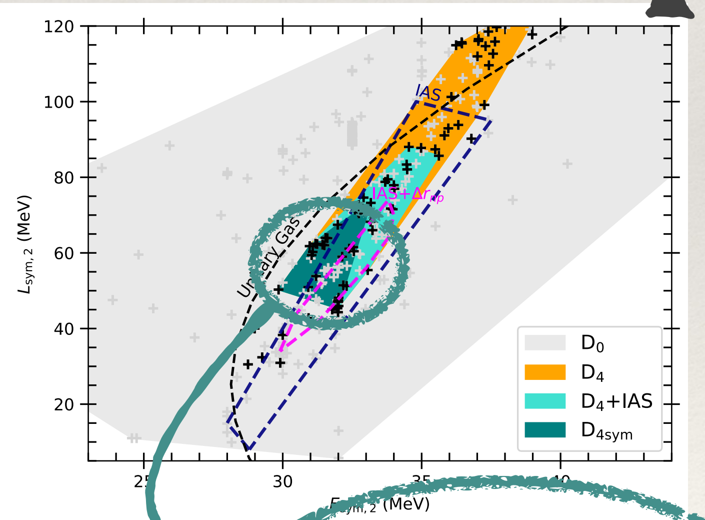
Low-energy nuclear physics and the symmetry energy



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

They filter our models (D4 —> D4sym).



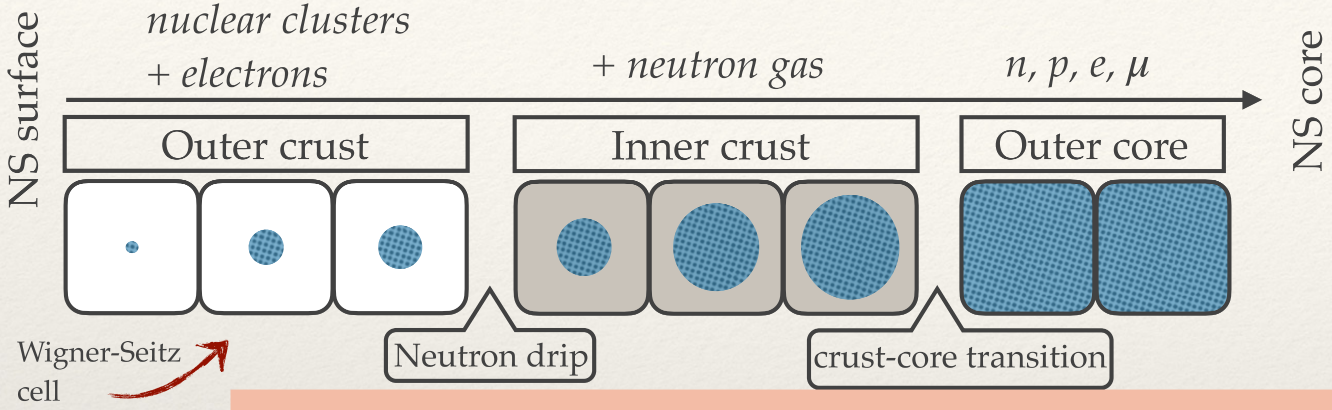


$$E_{sym,2} = 31.7 \pm 0.7 \text{ MeV}$$
$$L_{sym,2} = 58.1 \pm 9.0 \text{ MeV.}$$

Carlson, Dutra, Lourenço, JM, PRC 107 (2023)

Links with neutron star observables

Inhomogeneous matter (crust of NS)



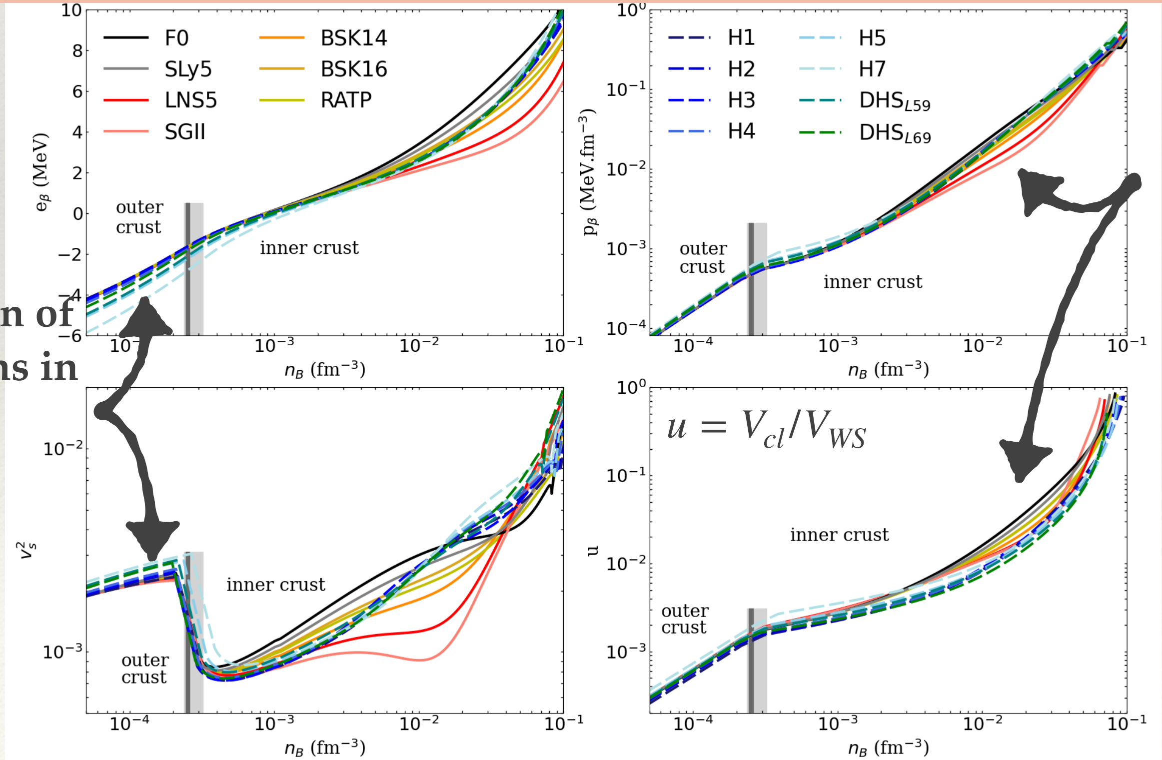
Compressible liquid-drop model based on Skyrme and χEFT functionals.

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

Uncertainty estimation by comparing χEFTwith Skyrme models:

Large dispersion of χEFT predictions in the outer crust.

Uncertainties in finite nuclei properties.



Large dispersion of Skyrme models in the inner crust.

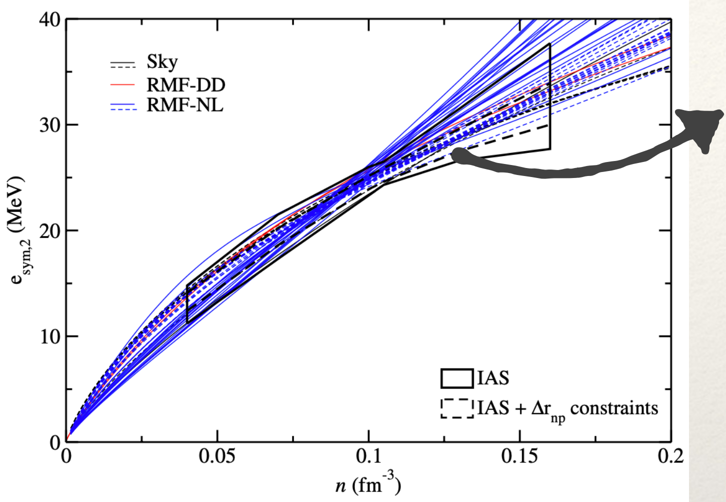
Uncertainties in neutron matter.

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



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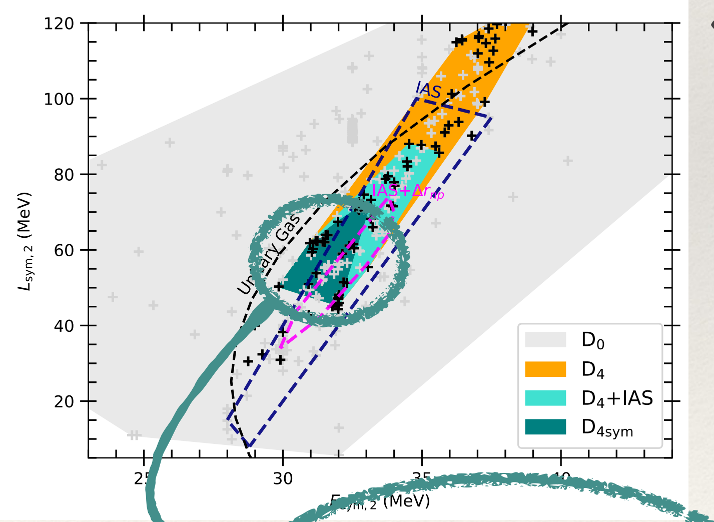
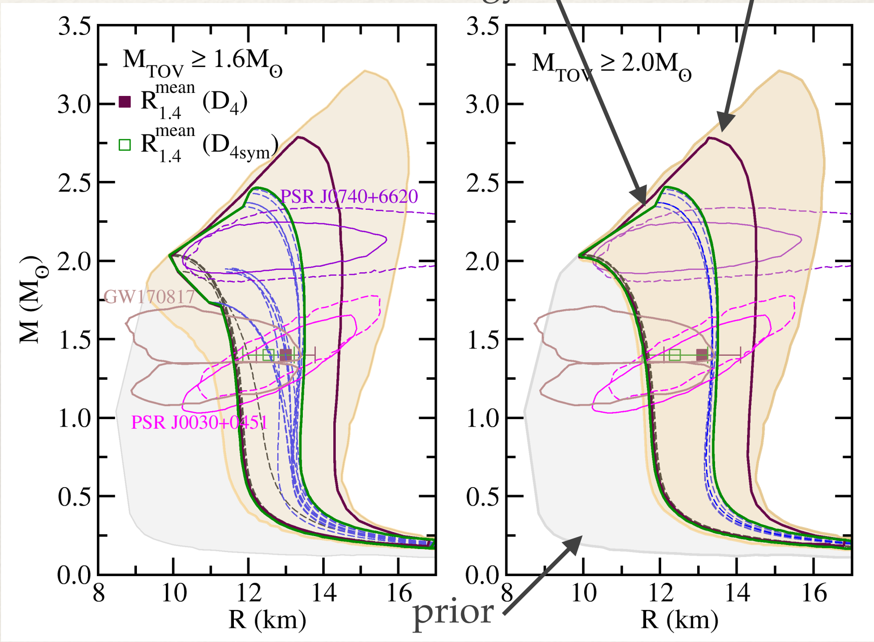


Stiffest EoS are removed.

Symmetry energy

Low-energy nuclear physics



$$E_{sym,2} = 31.7 \pm 0.7 \text{ MeV}$$
$$L_{sym,2} = 58.1 \pm 9.0 \text{ MeV.}$$

A better determination of low-energy nuclear properties may not improve predictions for neutron star global properties. —> the largest source of uncertainties is the **density dependence of the EoS:** symmetry energy, phase transition(s).

HIC are needed!

Carlson, Dutra, Lourenço, JM, PRC 107 (2023)

Thermal emission from qLMXB

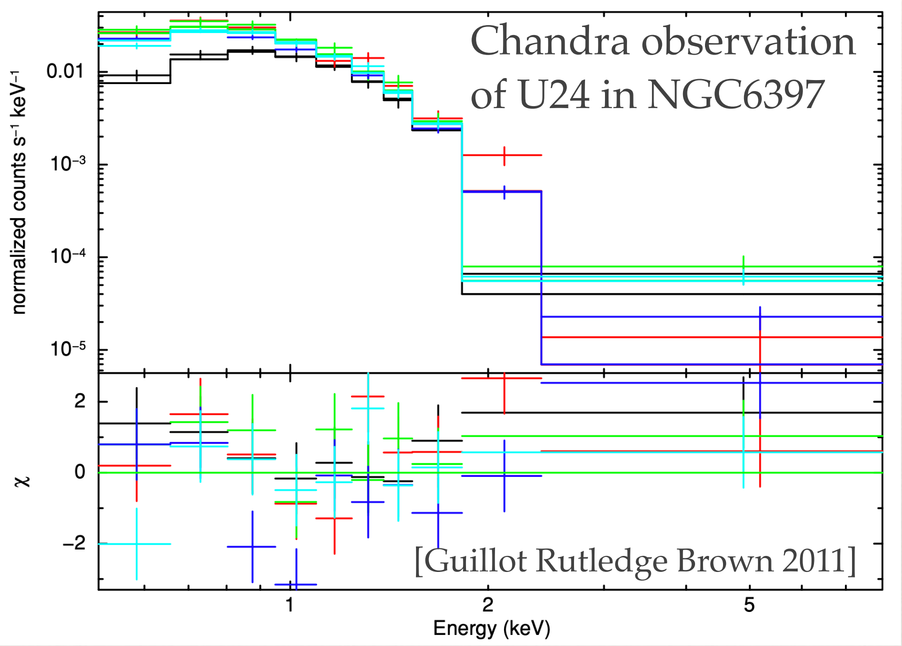
quiescent Low Mass X-ray binaries

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

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

-> get information on M and R

[Rutledge et al. 1999]



Chandra observation of U24 in NGC6397

[Guillot Rutledge Brown 2011]

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

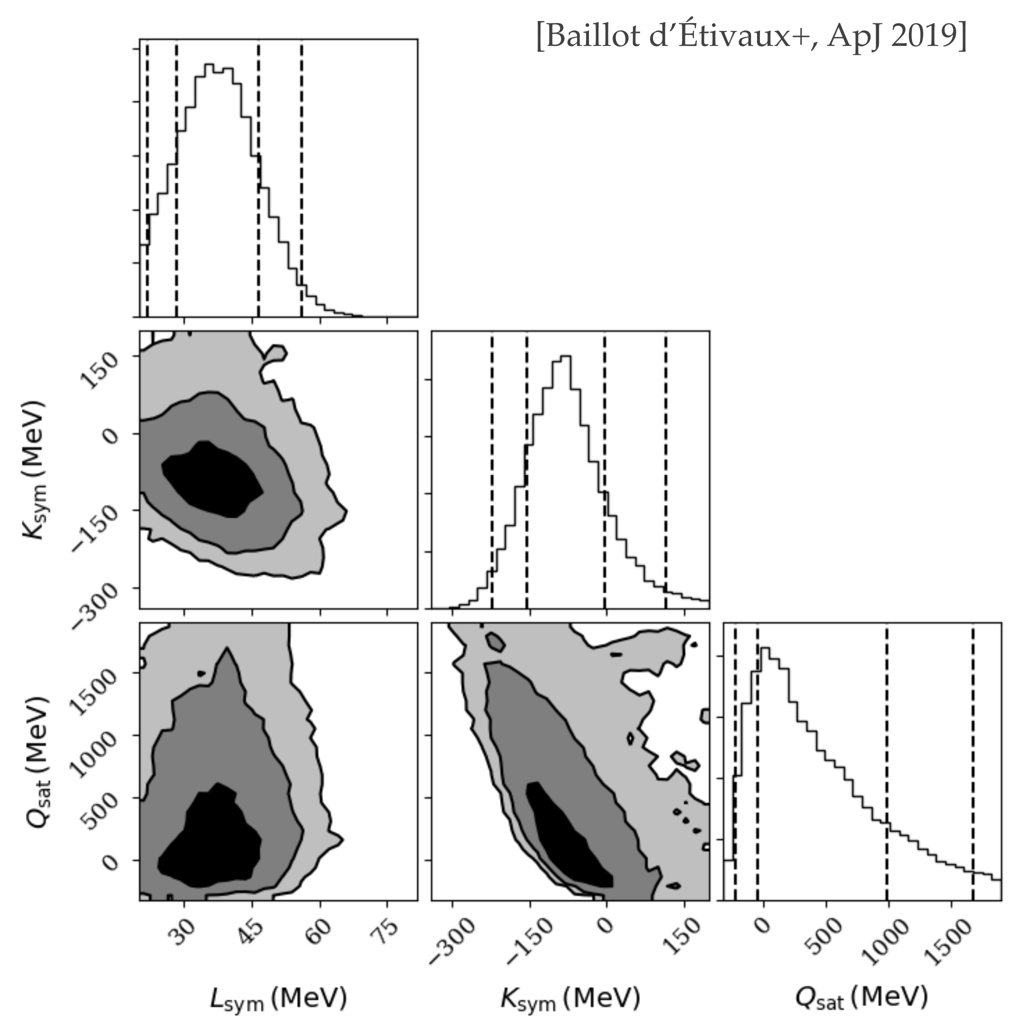
- constant flux, purely H atmosphere,
- Low magnetic fields —> almost pure thermal components,
- In globular clusters —> accurate distances.

Globular Cluster host	R.A.[a] (J2000)	Decl.[a] (J2000)	XMM Exp. time (ks)	Chandra Exp. time (ks)	S/N	Group[b]	Distances *Dist #1* (kpc)	Distances [8] *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 DRII 2018

Confronting the thermal emission from qLMXB with nuclear EoS



Bayesian analysis with prior:
Lsym = 50 ± 10 MeV
Ksym [-400:200] MeV
Qsat [-1300:1900] MeV

MCMC Posteriors:
Lsym = 38 ± 10 MeV
Ksym = −91 ± 80 MeV
Qsat = 350 ± 500 MeV

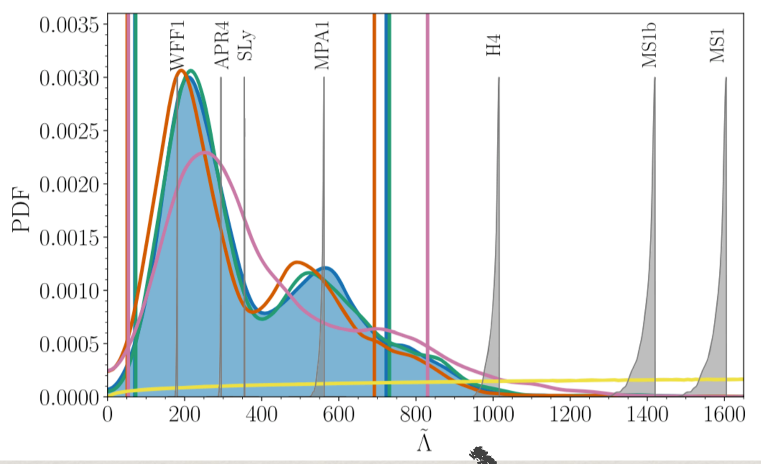
First extraction of Ksym and Qsat from data.

An analysis of BE, neutron skin and GMR concludes [Sagawa 2019]:
Lsym = 53.5 +- 15 MeV (FRDM),
Lsym = 42 +- 15 MeV (n skin)
Ksym = −120 ± 80 MeV

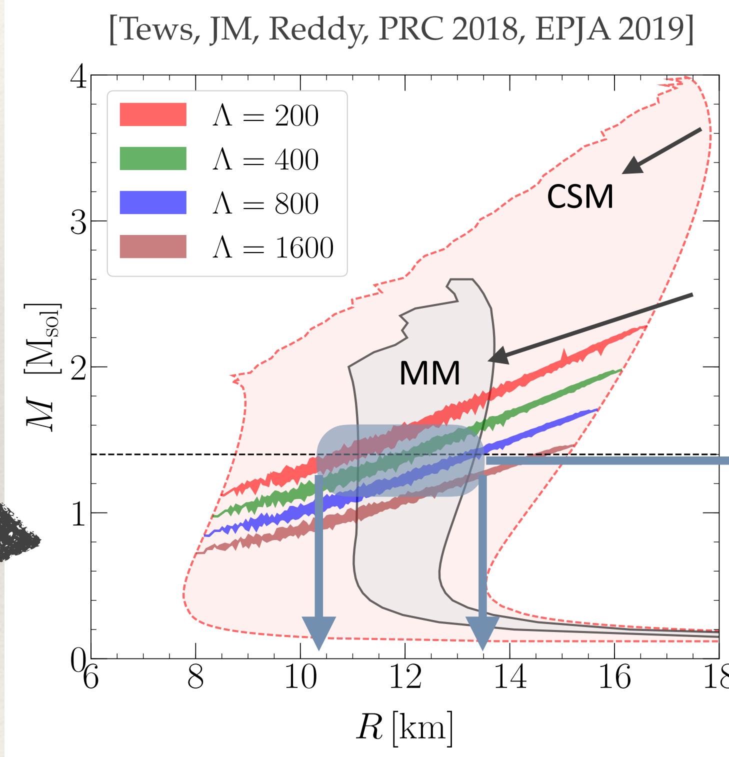
BNS GW [astro] <=> EoS [nuclear]

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]

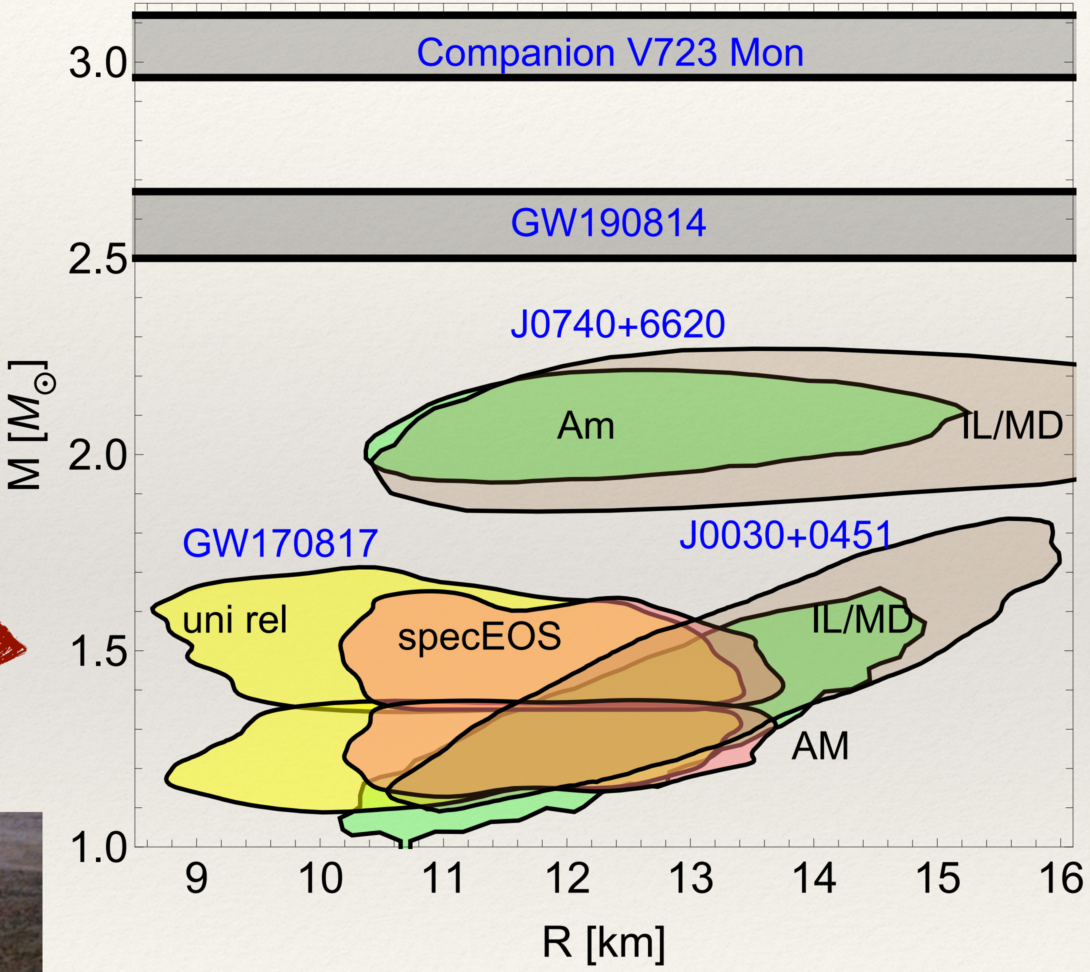
Meta-Model
(nucleonic)
[JM+ 2018]

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

GW170817:
→ $70 \leq \Lambda \leq 720$ **(90% CL)**

New data from GW + NICER X-ray observatory

Tan, Dore, Dexheimer+, PRD 105, 023018 (2022)



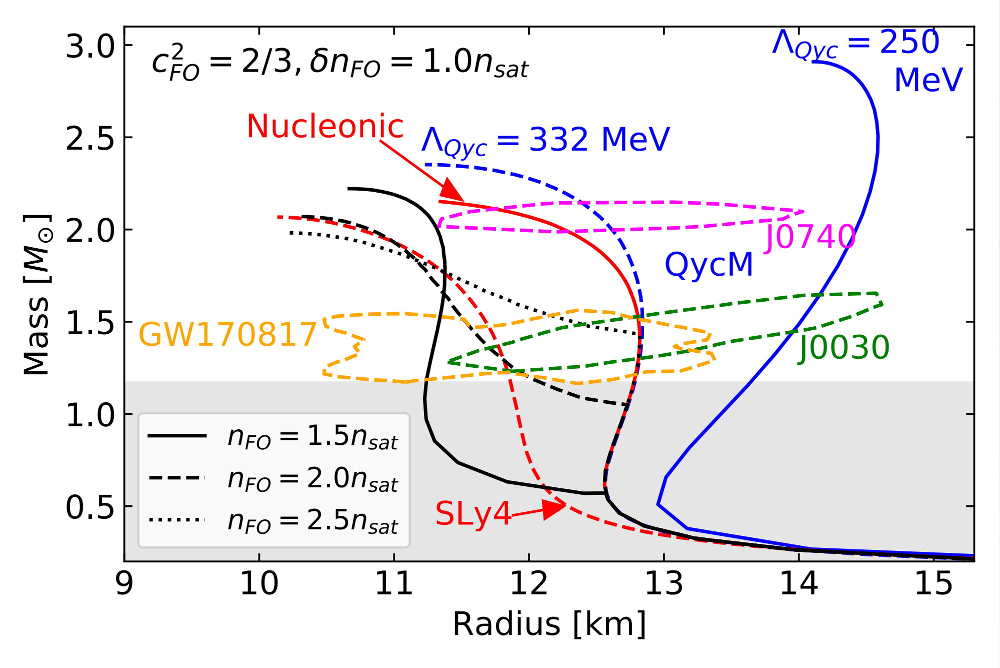
Phase transition(s) at high density

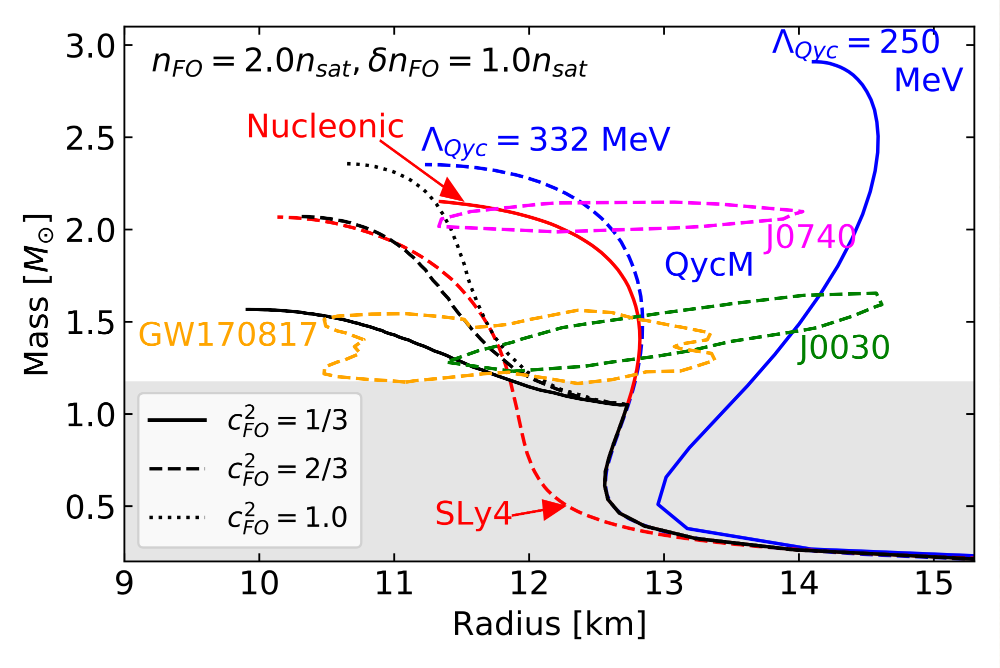
Phase transition(s) in NS

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: It produces smaller neutron stars!

Phase transition(s) in NS

Data:
GW170817 and NICER (J0030 + J0740).

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

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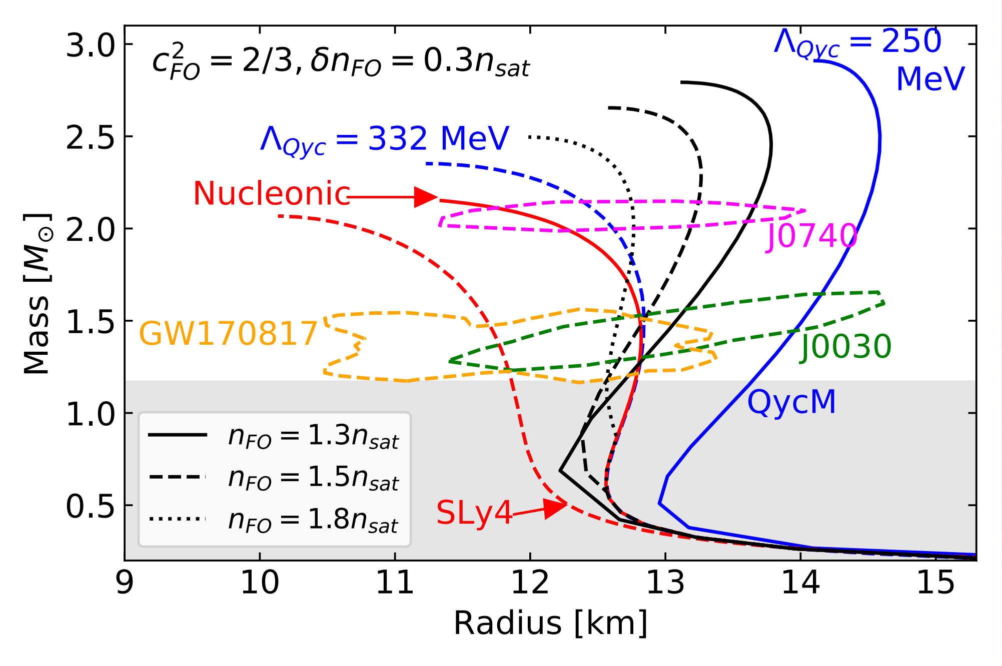
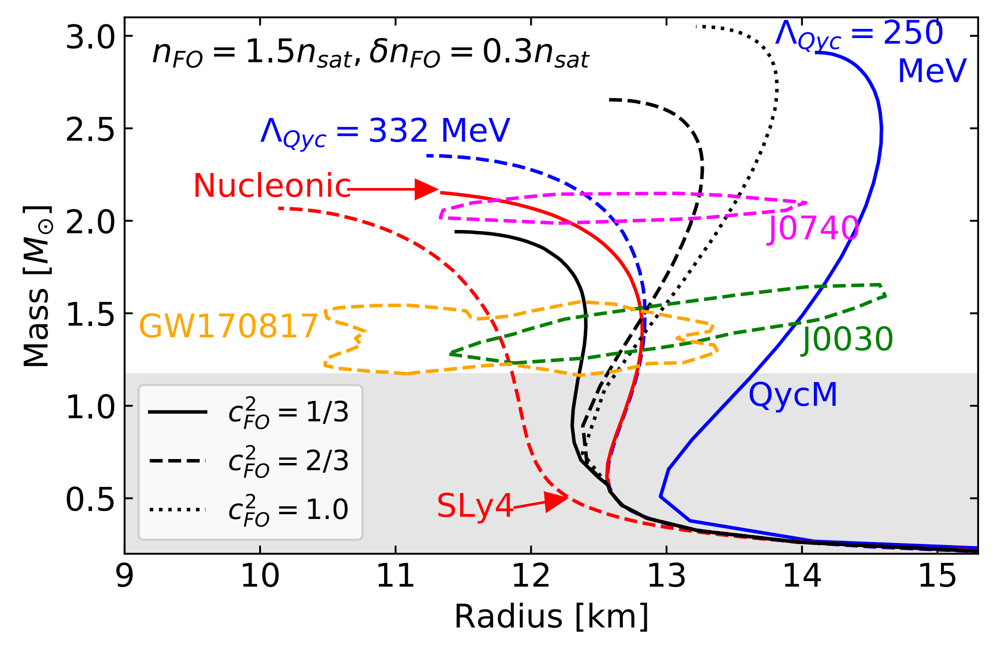
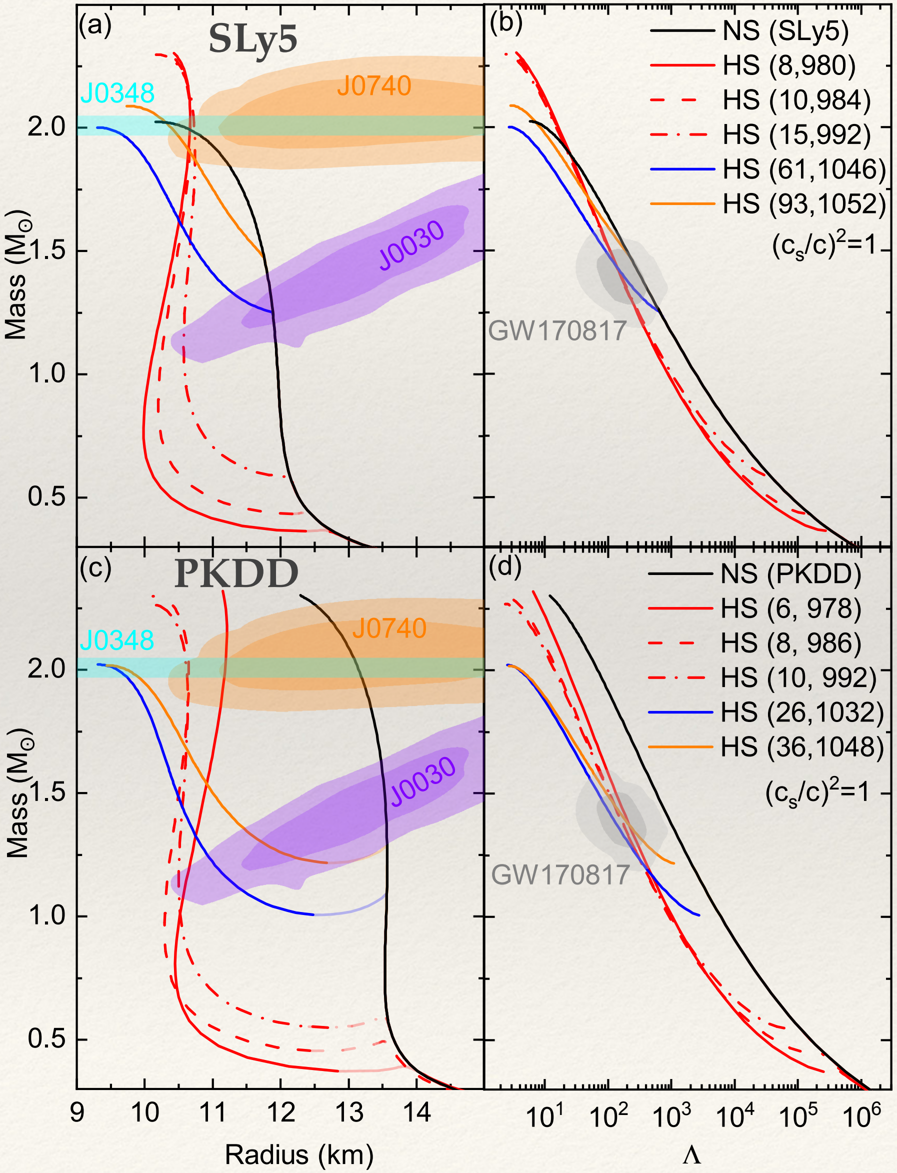




unless the FOPT occurs at low density —> masquerade Qyc and produce bigger stars.

Are GW170817 and NICER compatible?

Guven+, arXiv:2303.18133, PRC 2023



Two nuclear EoSs:
SLy5 (iso-soft, $L_{\mathrm{sym}} \approx 50$ MeV),
PKDD (iso-stiff, $L_{\mathrm{sym}} \approx 80$ MeV).

+ First order phase transition:

3 parameters:

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

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:

3 parameters:

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

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

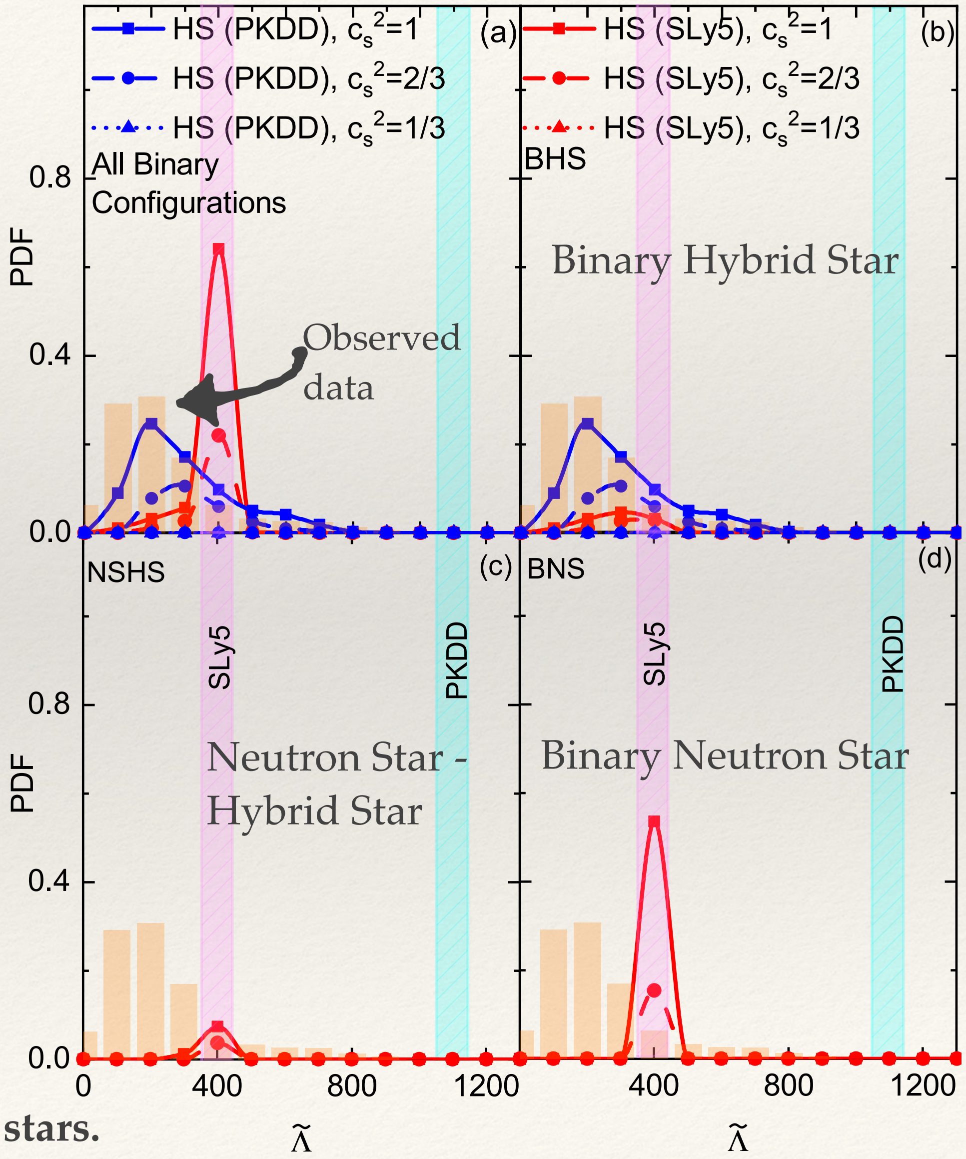
Binary Hybrid Star: the 2 stars have a quark core (with phase transition),

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	**0.28**	0.00	0.00
	PKDD	1	**0.65**	0.00	0.00

Bayesian analysis



GW170817 was most probably the merger of 2 hybrid stars.

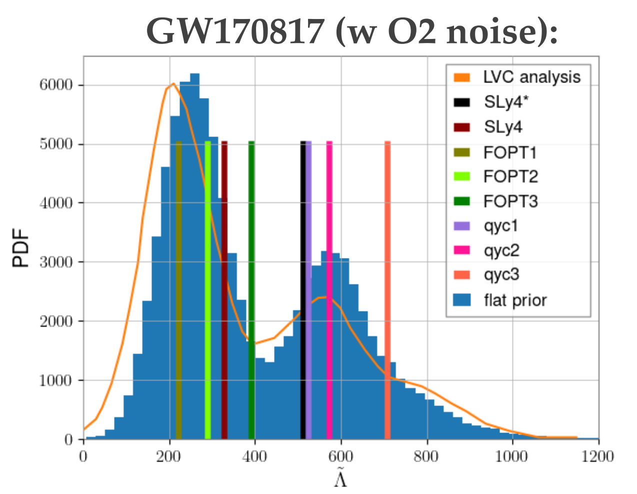
Expectations from O4 observations

Future GW detections (O4)

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

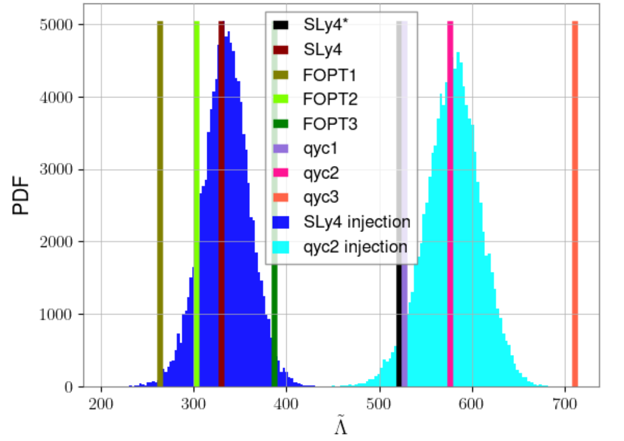
J.-F. Coupechoux et al., PRD 107, 124006 (2023)

How GW170817 was measured:


GW170817 (w O2 noise):

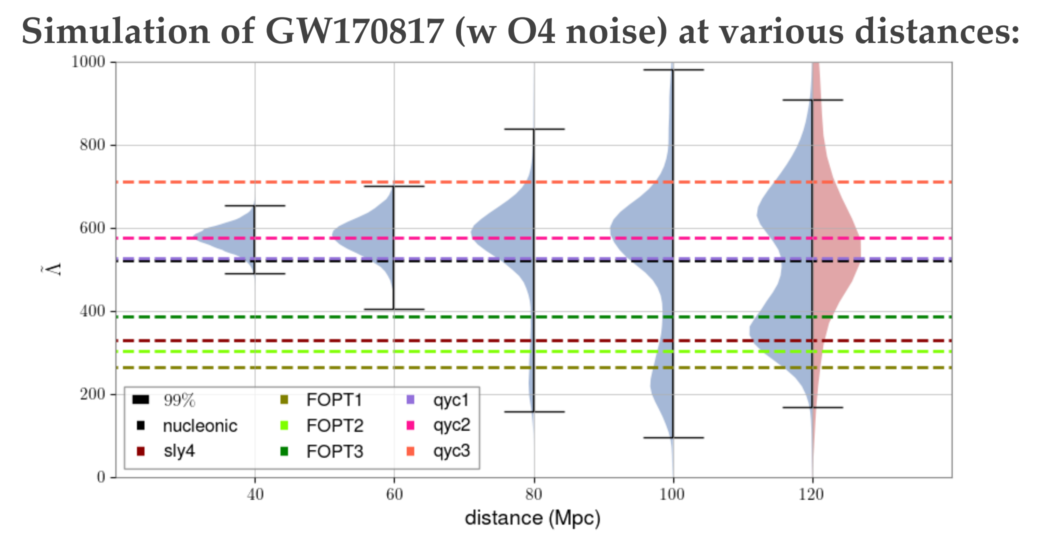
How it will be measured nowadays:

Simulation of GW170817 (w O4 noise):

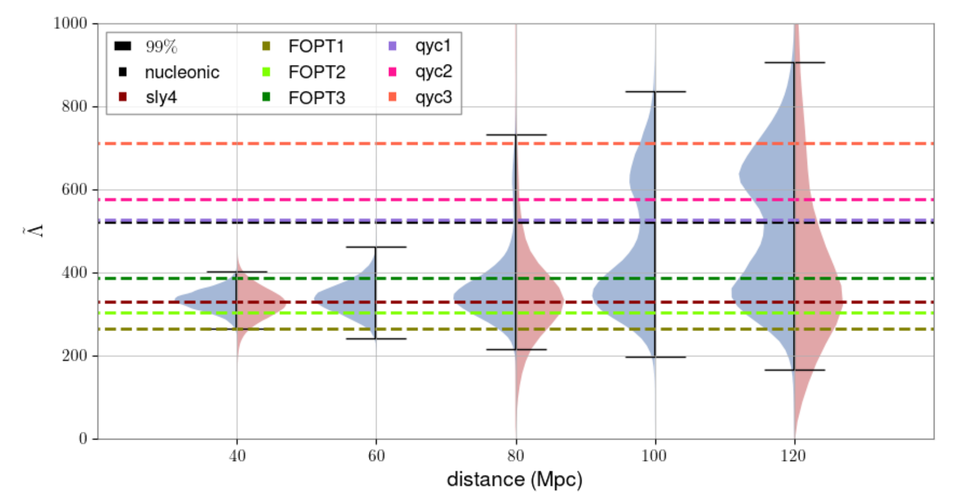


How all events will be measured:

Injection of qyc2


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

Injection of SLy4



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

Conclusions

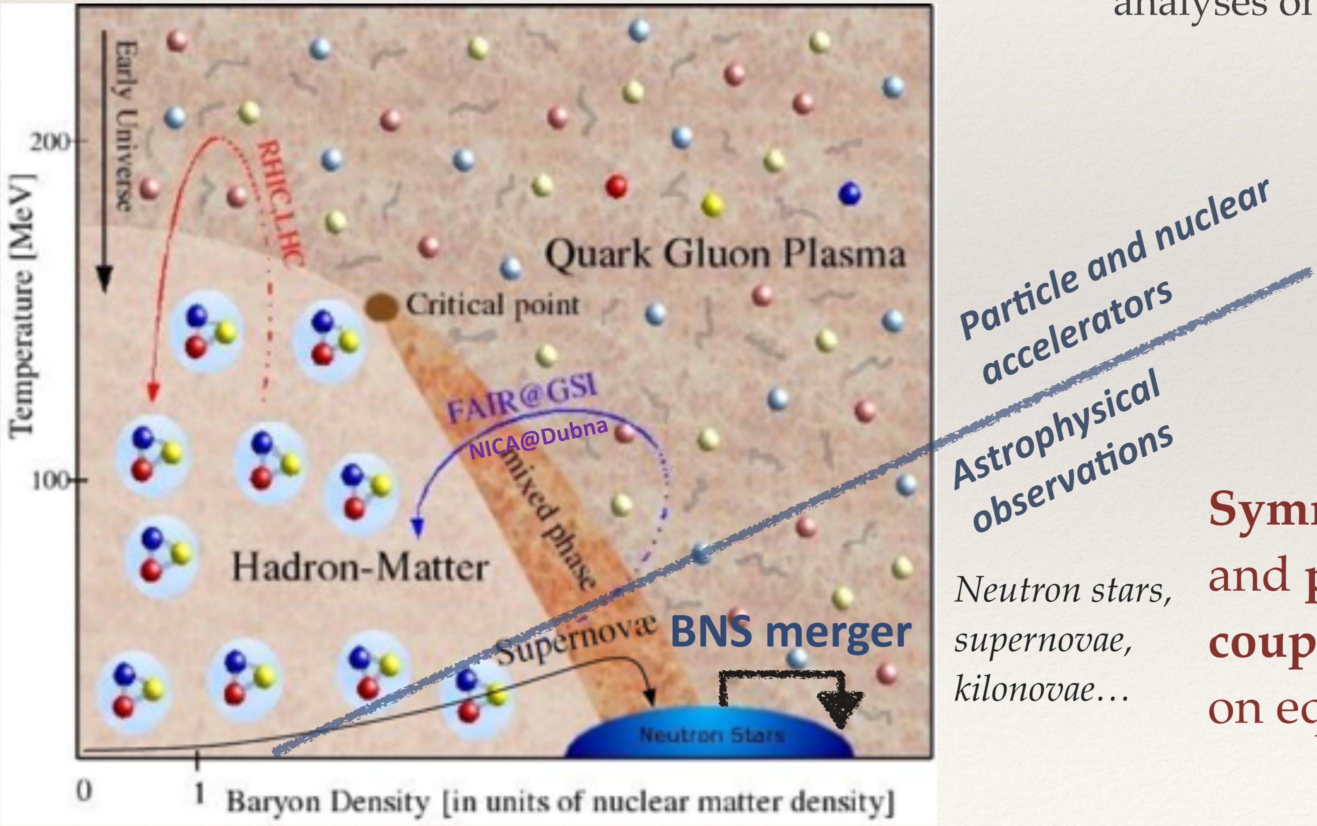
From nuclear physics: ← **Complementarity** → **From astrophysics:**

From nuclear physics:

- Better determination of the density dependence of the EoS (Heavy ion collisions, collective motion).
- Better or new measurements of L_{sym}, K_{sym}, Q_{sat}.

From astrophysics:

- 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…

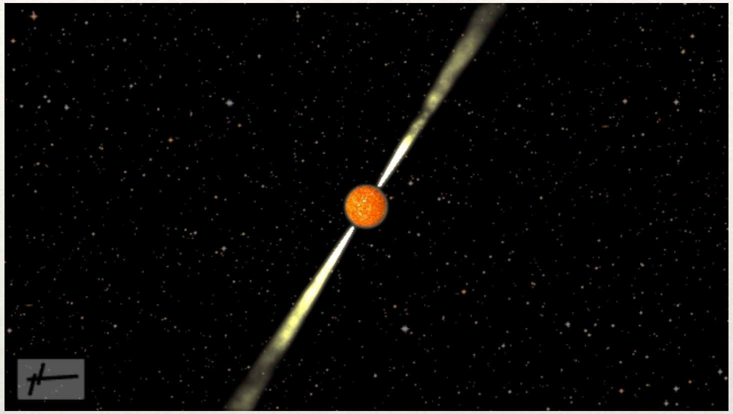
Future new data from nuclear physics and from astrophysics are highly expected.

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.

New IRL Nuclear Physics and Nuclear astrophysics (NPA)

@FRIB, MSU

Four **research topics** in nuclear physics:

1. Nuclear **structure** and **reactions** from stability to rare isotopes,
2. Nuclear **astrophysics** from nuclear reactions in the cosmos to extreme matter equation of state
3. Nuclear **theory** from finite systems to uniform matter,
4. **Instrumental** developments of common interest at GANIL and FRIB.

In 2023:

- July 18th: Official inauguration of the IRL at MSU (with R. Pain and M. Grasso).
- September: Start of the IRL for 5 years with JM (director) and Oscar Naviliat-Cuncic (co-director).
- December 11-13th: kickoff meeting at MSU. Please connect us if you want to participate.

In 2024 and after:

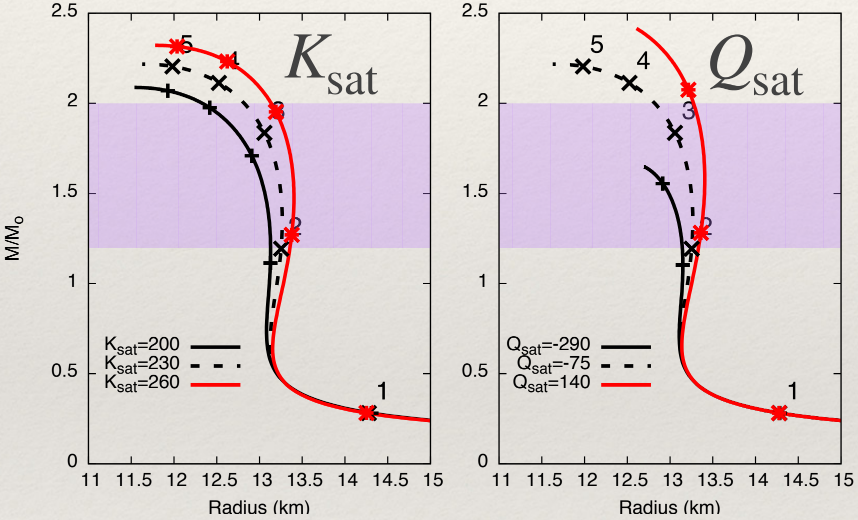
- Host long term visits (sabbatical).
- Organise workshops on focussed questions (suggested by the community) and linked with RESANET in France.

Backup slides

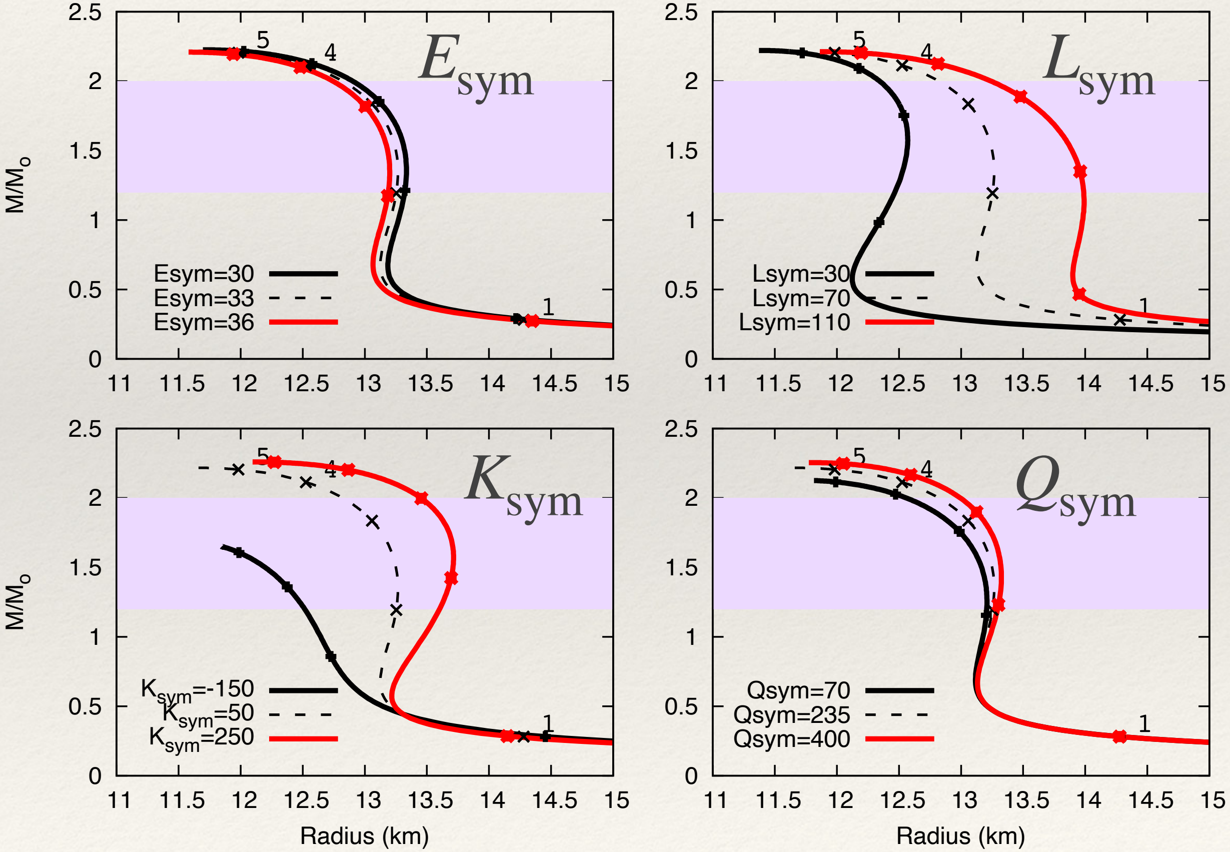
Sensitivity analysis: (M,R) <=> NEP

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

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



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

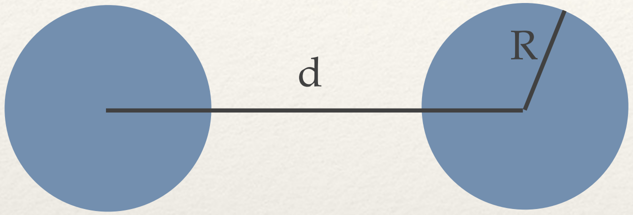


The largest source of uncertainties are from Q_{sat}, L_{sym} and K_{sym}.

[JM, Casali, Gulminelli, PRC 2018]

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: $n = \dfrac{8}{d^3} = \dfrac{1}{8R^3}$

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

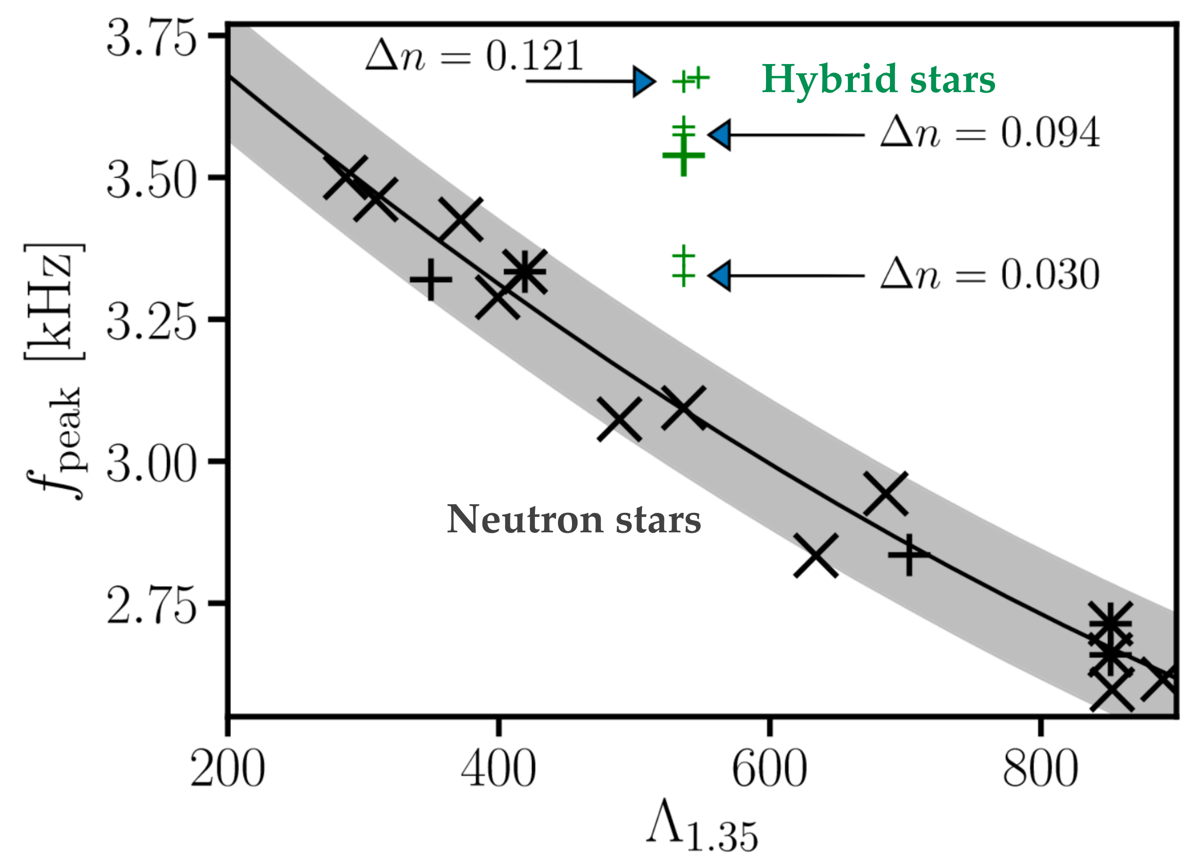
—> nucleonic matter could be replaced by quark matter at $\approx 3n_{\text{sat}}$.

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

GW post-merger signal

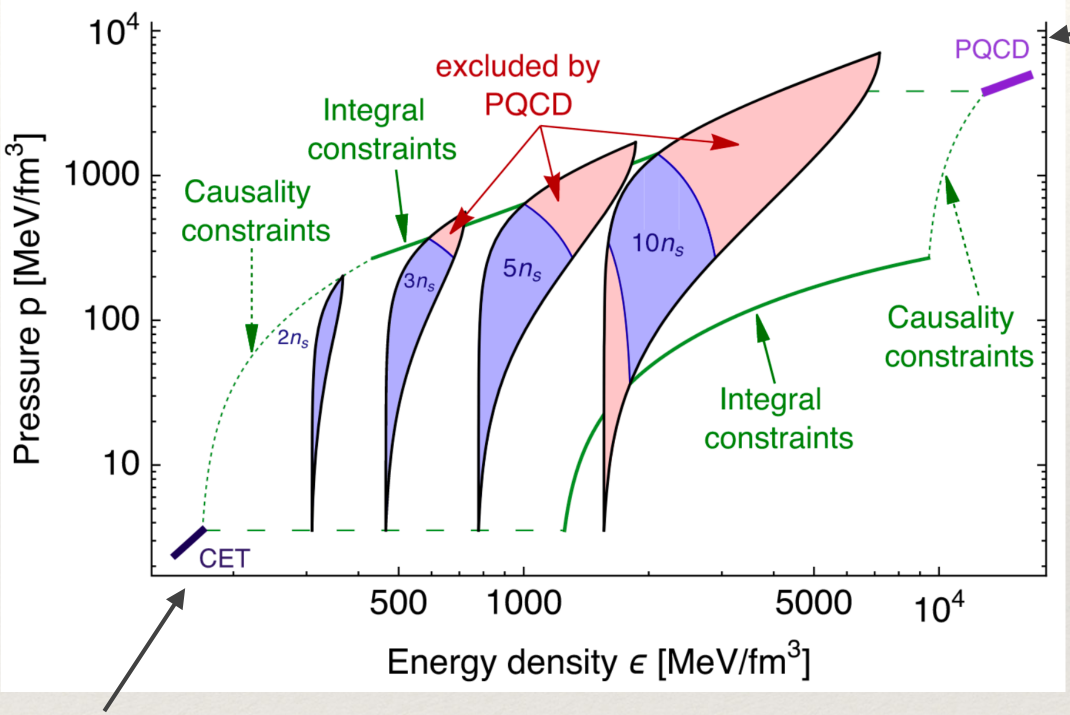
Phase transitions in the hypermassive NS can alter the correlation between the tidal deformability and post-merger oscillations.

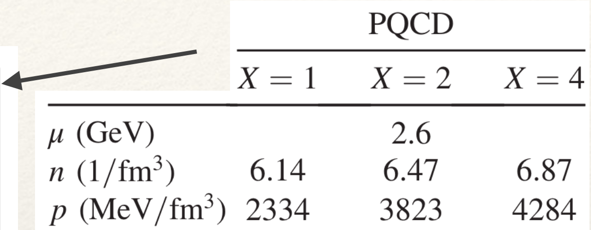
Bauswein+ PRL 122 (2019)



Connection to pQCD at high density

Komoltsev and Kurkela, PRL 128, 202701 (2022)

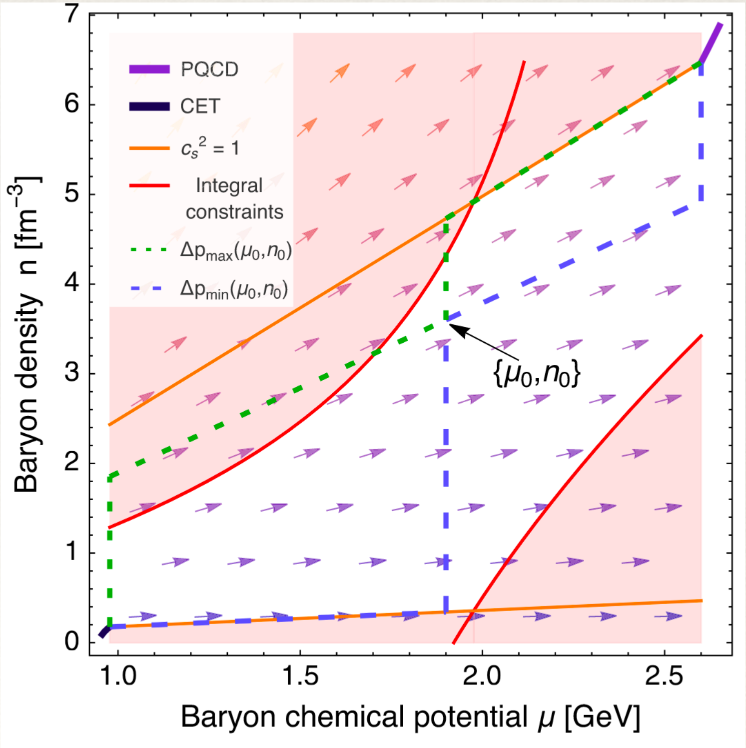




	PQCD		
	$X = 1$	$X = 2$	$X = 4$
μ (GeV)		2.6	
n (1/fm^3)	6.14	6.47	6.87
p (MeV/fm^3)	2334	3823	4284

Loop scale parameter

Constraints
from chiral EFT

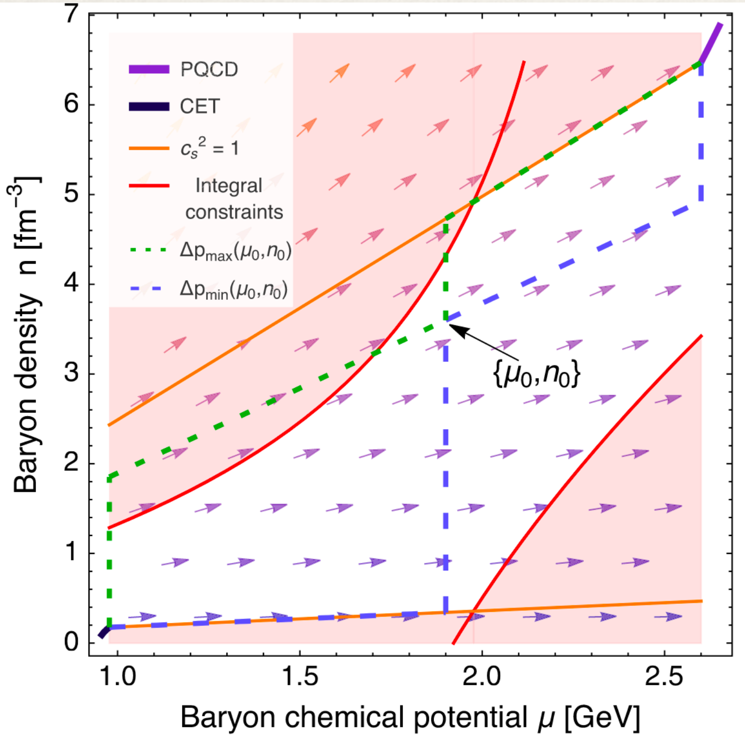


The most general way to connect to pQCD.

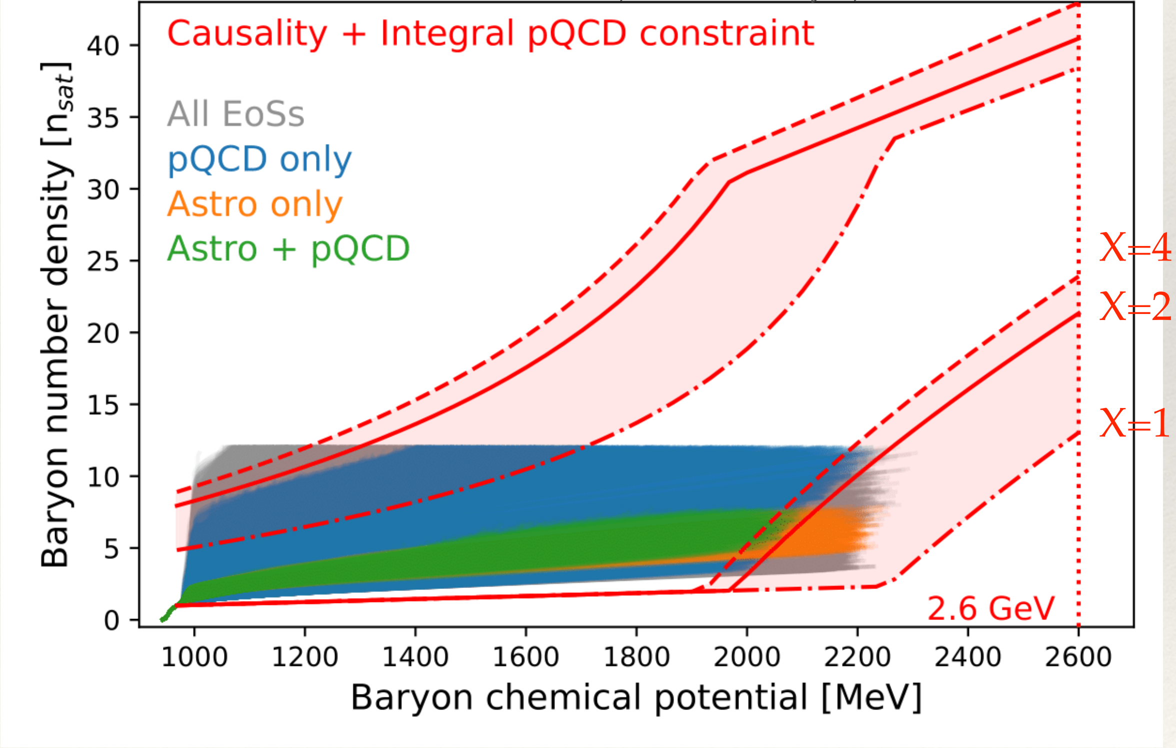
Connection to pQCD at high density

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

	PQCD		
	$X=1$	$X=2$	$X=4$
μ (GeV)		2.6	
n (1/fm^3)	6.14	6.47	6.87
p (MeV/fm^3)	2334	3823	4284



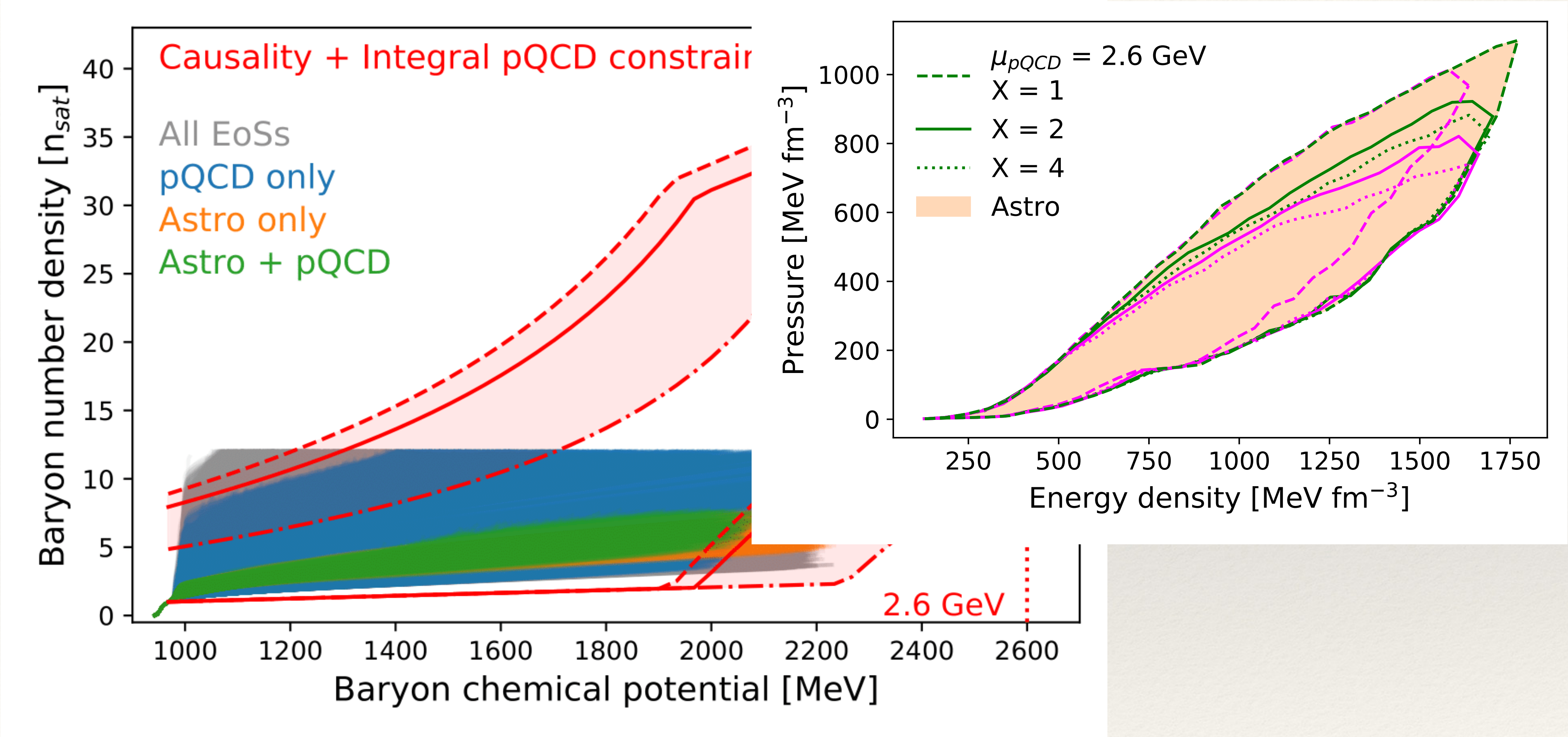
R. Somasundaram, I. Tews and JM, arXiv:2204.14039



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

Connection to pQCD at high density

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



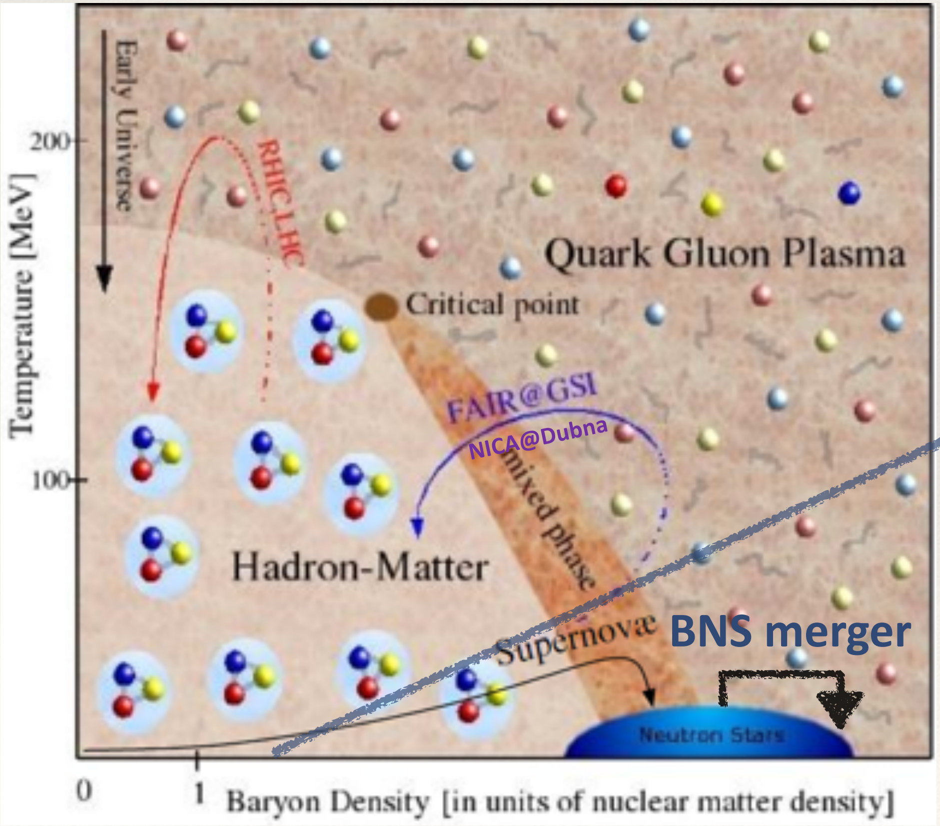
Constraints from astrophysical observations are still better than pQCD.
Note opposite conclusions from Gorda, Komoltsev and Kurkela, arXiv:2204.11279.

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_{sym}, K_{sym}, Q_{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 & Zwickly)**

Discovered 1967 **(Bell & Hewish)**

Known ~ 3300

Expected ~10^8
(in our galaxy)

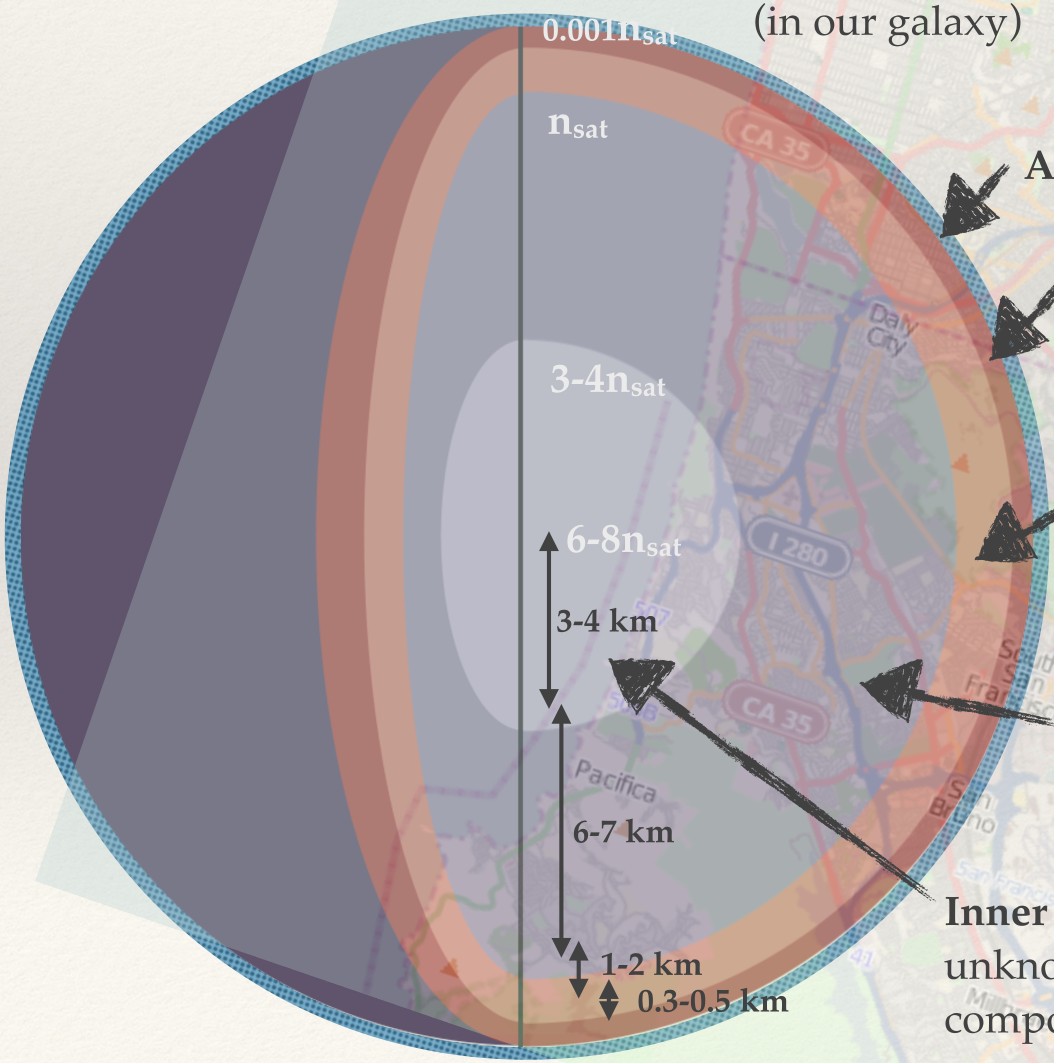
Radius ≈ 10 – 14km

Mass ≈ 1.2 – 2.1$M_\odot$ (observed)

Density ≈ 10^{15} g cm³

Spin ≥ 716 **Hz**

Magnetic field up to ~10^{16} **G**



Atmosphere: H, He

Outer crust: nuclear clusters+electons

Inner crust: nuclear clusters+electrons+ neutron gas

Outer core: uniform nuclear matter (n, p, e, μ)

Inner core: unknown composition

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] <=> NS (M,R) [astro]

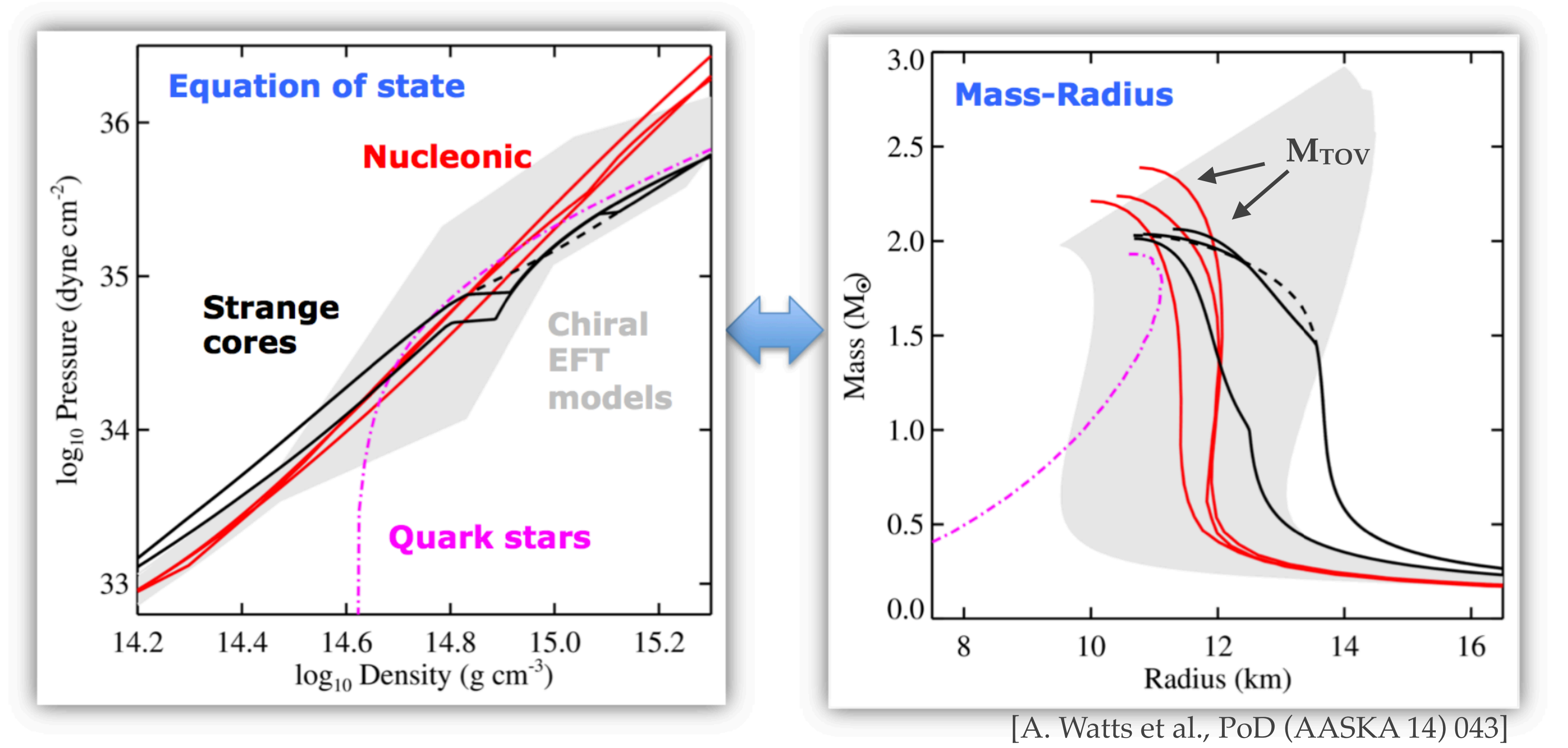
Properties of extreme matter

P(n)

Tolmann-Oppenheimer-Volkov (TOV) GR equations

(M,R)(n_c)

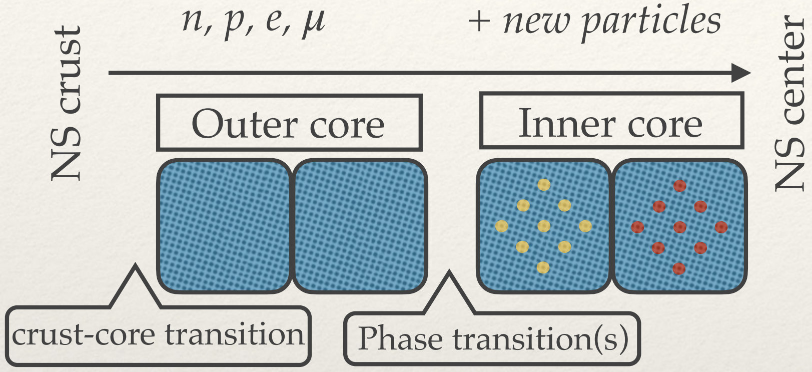
Astrophysical observations



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

Reverse engineering,
Bayesian statistics

Modeling homogeneous matter (core)



NS crust

n, *p*, *e*, *μ*

+ *new particles*

NS center

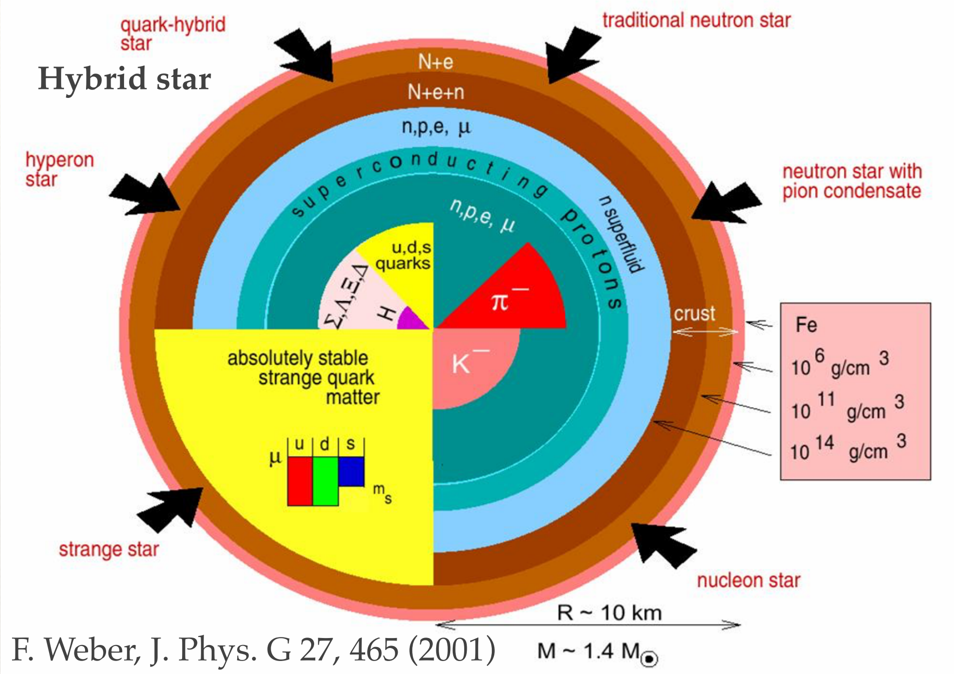
Outer core

Inner core

crust-core transition

Phase transition(s)

- 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?

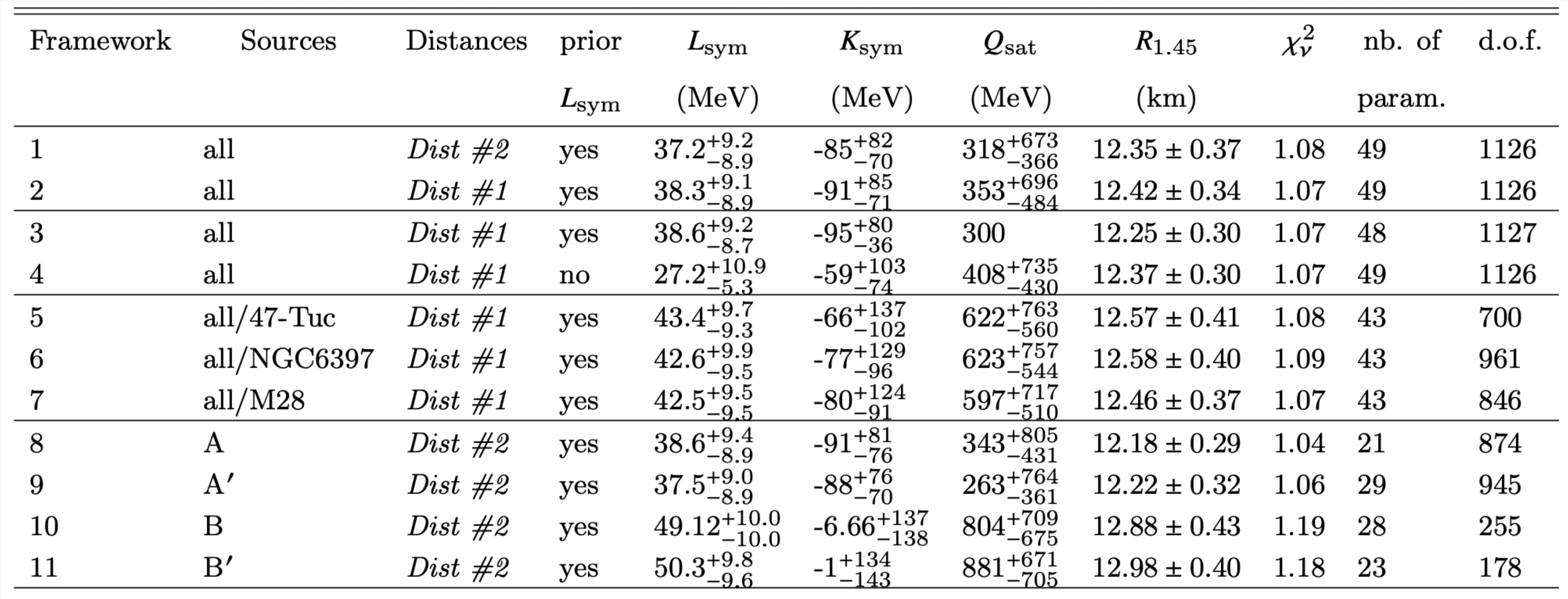


F. Weber, J. Phys. G 27, 465 (2001)

How new data will help to answer these questions?

Confronting the thermal emission from qLMXB with nuclear EoS

Sensitivity analysis



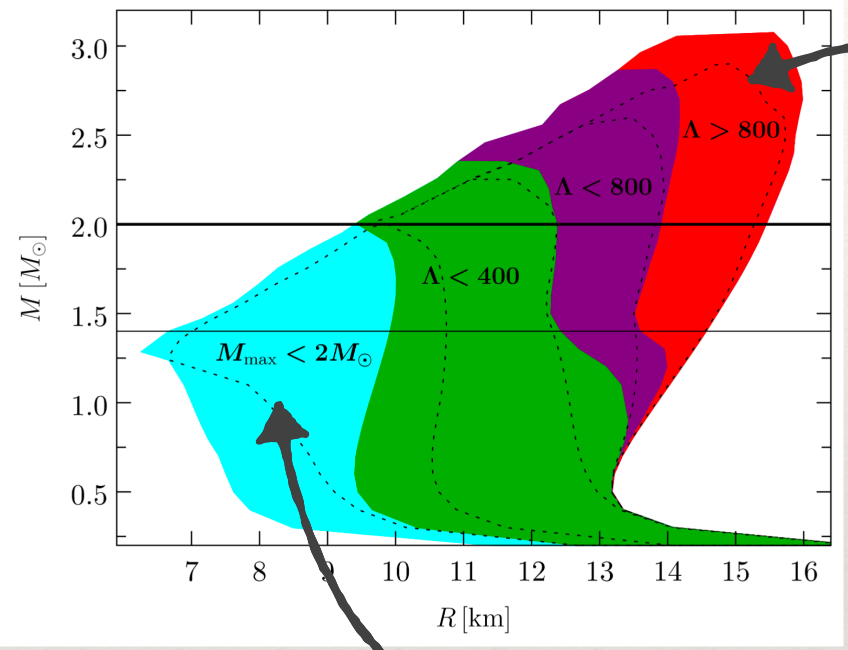
Framework	Sources	Distances	prior L_{sym}	L_{sym} (MeV)	K_{sym} (MeV)	Q_{sat} (MeV)	$R_{1.45}$ (km)	χ^2_ν	nb. of param.	d.o.f.
1	all	*Dist #2*	yes	$37.2^{+9.2}_{-8.9}$	-85^{+82}_{-70}	318^{+673}_{-366}	12.35 ± 0.37	1.08	49	1126
2	all	*Dist #1*	yes	$38.3^{+9.1}_{-8.9}$	-91^{+85}_{-71}	353^{+696}_{-484}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

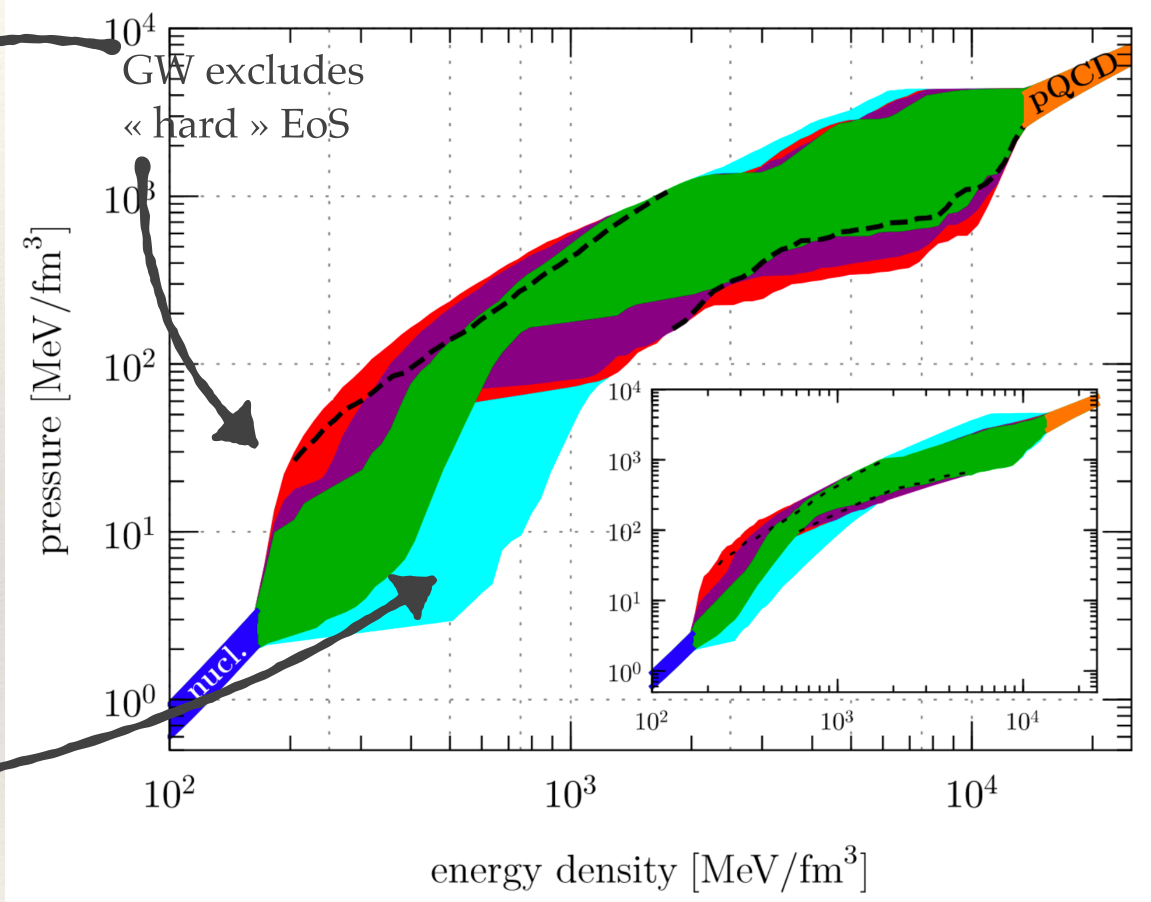
Outlook:
Include phase transition
Confront with other observations

N. Baillot d’Etivaux *et al.*, Astro. J. 887, 1 (2019).

Consequences for extreme matter EoS

Annala+, PRL 120, 172703 (2018)





GW excludes « hard » EoS

Excluded by M_{TOV} limit

« soft » EoS

Radio and GW astronomy bound the EoS.

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

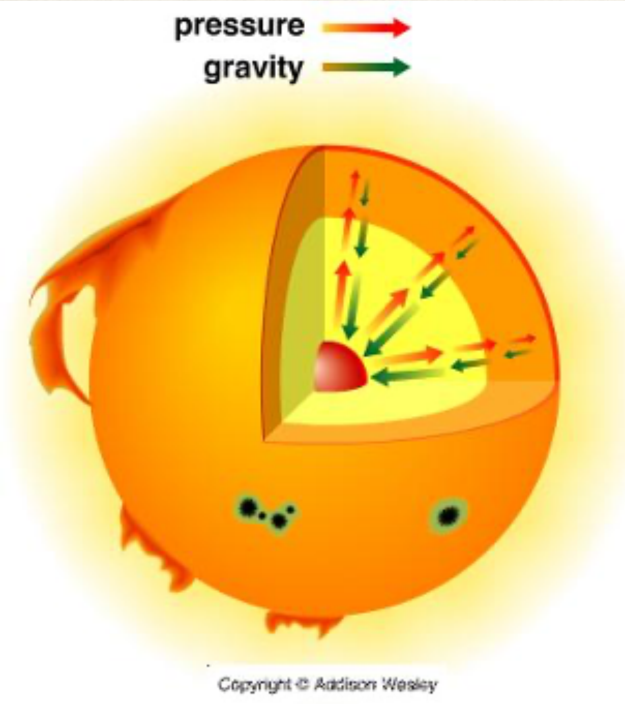
Some basics on stars

	Sun	**Neutron stars**
Central temperature	$15\text{x}10^{6}$ K	$\sim10^{7,8}$ K
Thermal energy	$\sim10^{-3}$ MeV	$\sim10^{-3,-2}$ MeV
Mass-density	$\sim1{,}2$ g cm^{-3}	$\sim10^{15}$ g cm^{-3}
Particle density	0.1,1.0 fm^{-3}	0.1,1.0 fm^{-3}
Fermi momentum		1.0,2.0 fm^{-1}
Fermi energy		~40,200 MeV
	Classical Boltzmann gas.	**Degenerate (=quantum) Fermi gas.**

Radius	700 000 km	10,15 km	
GR parameter $\Xi = \dfrac{R_{sch}}{R}$	$10^{-5,-6}$	0.2,0.3	→ **Relativistic Star**

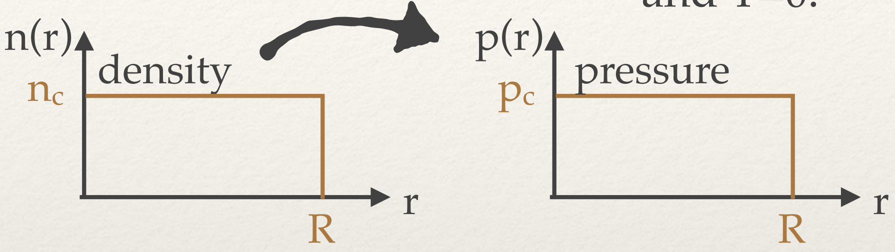
Stars and the equation of state…

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

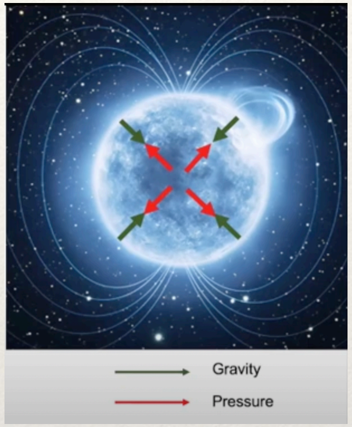


This is the case of all celestial objects. Only **different pressures** create **different objects**.

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



A neutron star



The **radius** R of neutron stars reflects this equilibrium:
- large radii —> large internal pressure,
- small radii —> lower internal pressure.

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

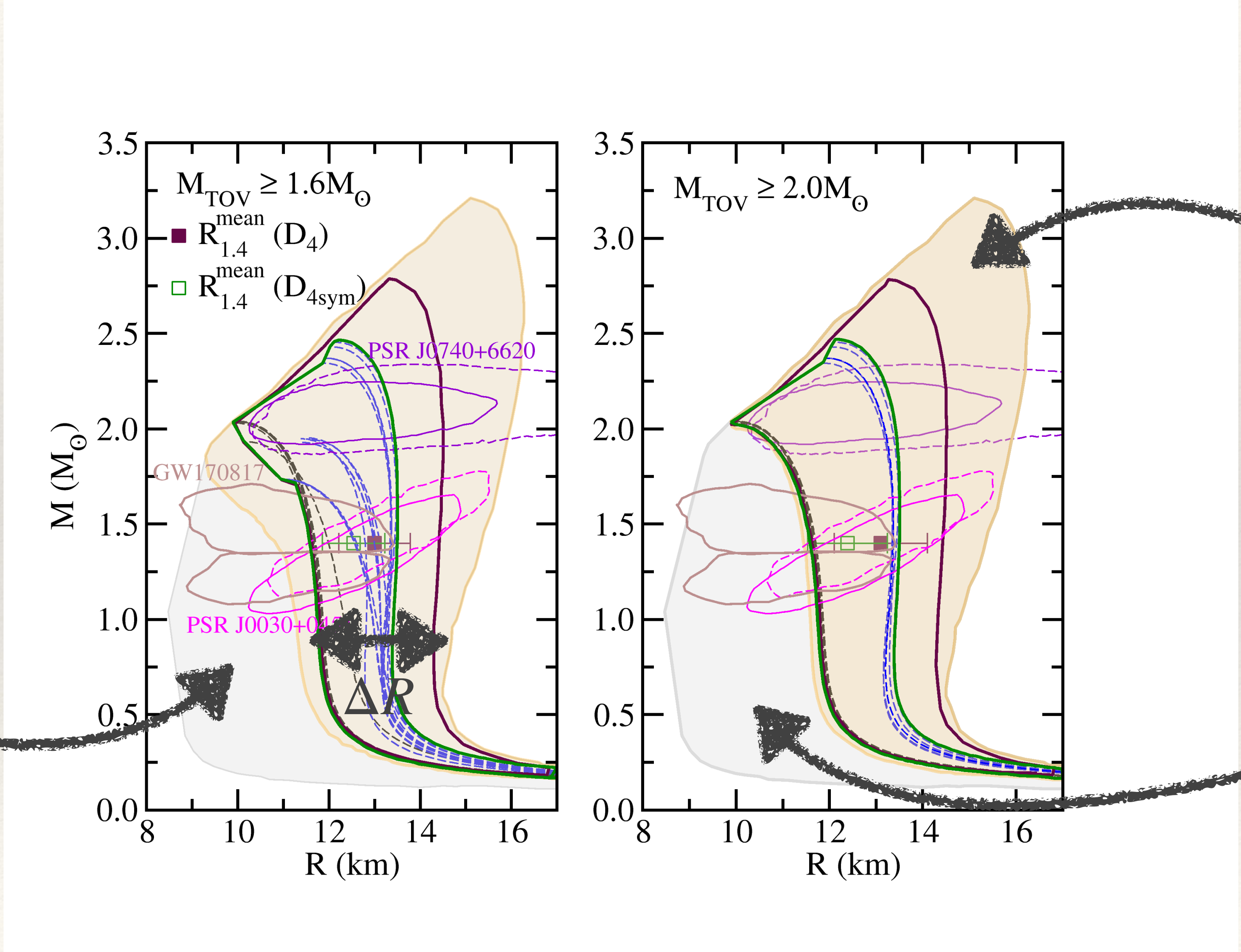
The **mass** and the **radius** define the **density**: $\rho \propto M/R^3$

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

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



Excluded by low energy nuclear physics, in the absence of phase transition in dense matter.

Do not reach 1.6 Mo

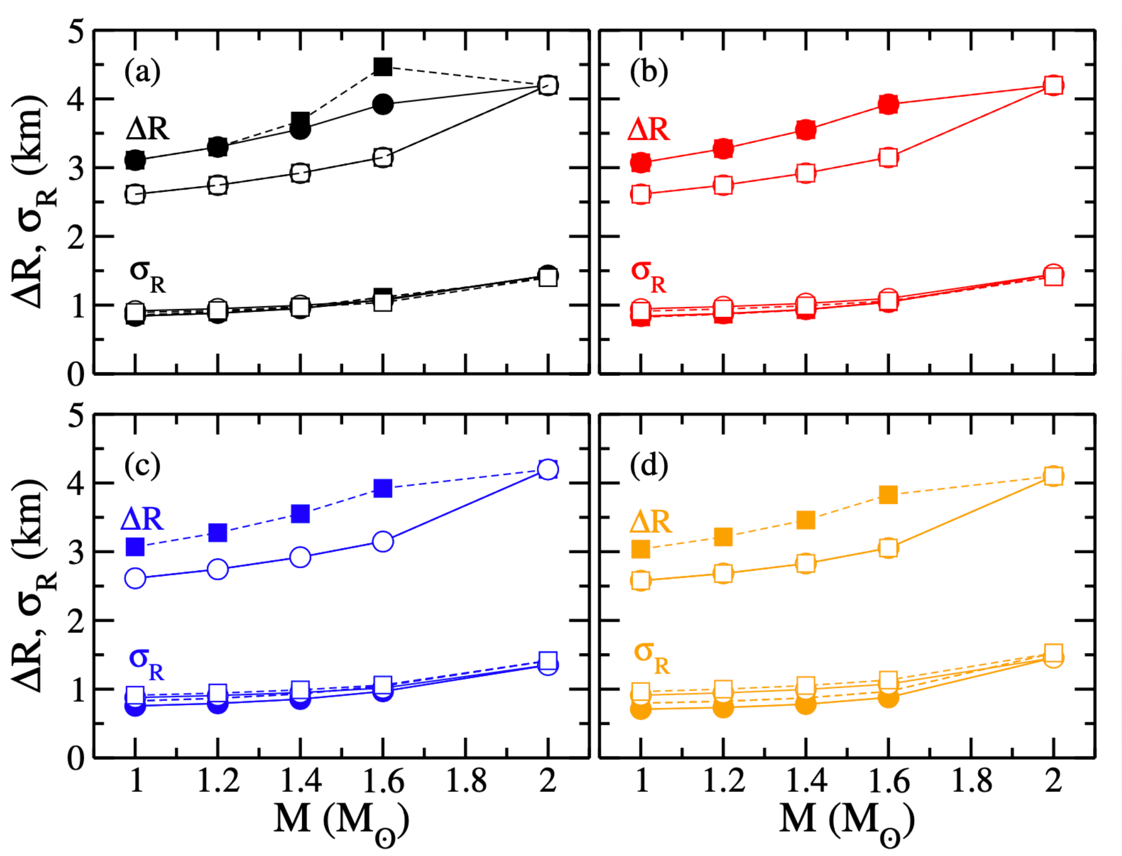
Do not reach 2.0 Mo

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_{sat} while a 1.4Mo NS has 2-3 n_{sat} at its center.

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