« MaNiTou Summer School on Gravitational Waves », July 3-8 2023, Nice

GW and nuclear physics: Neutron stars and the search for the dense matter equation of state

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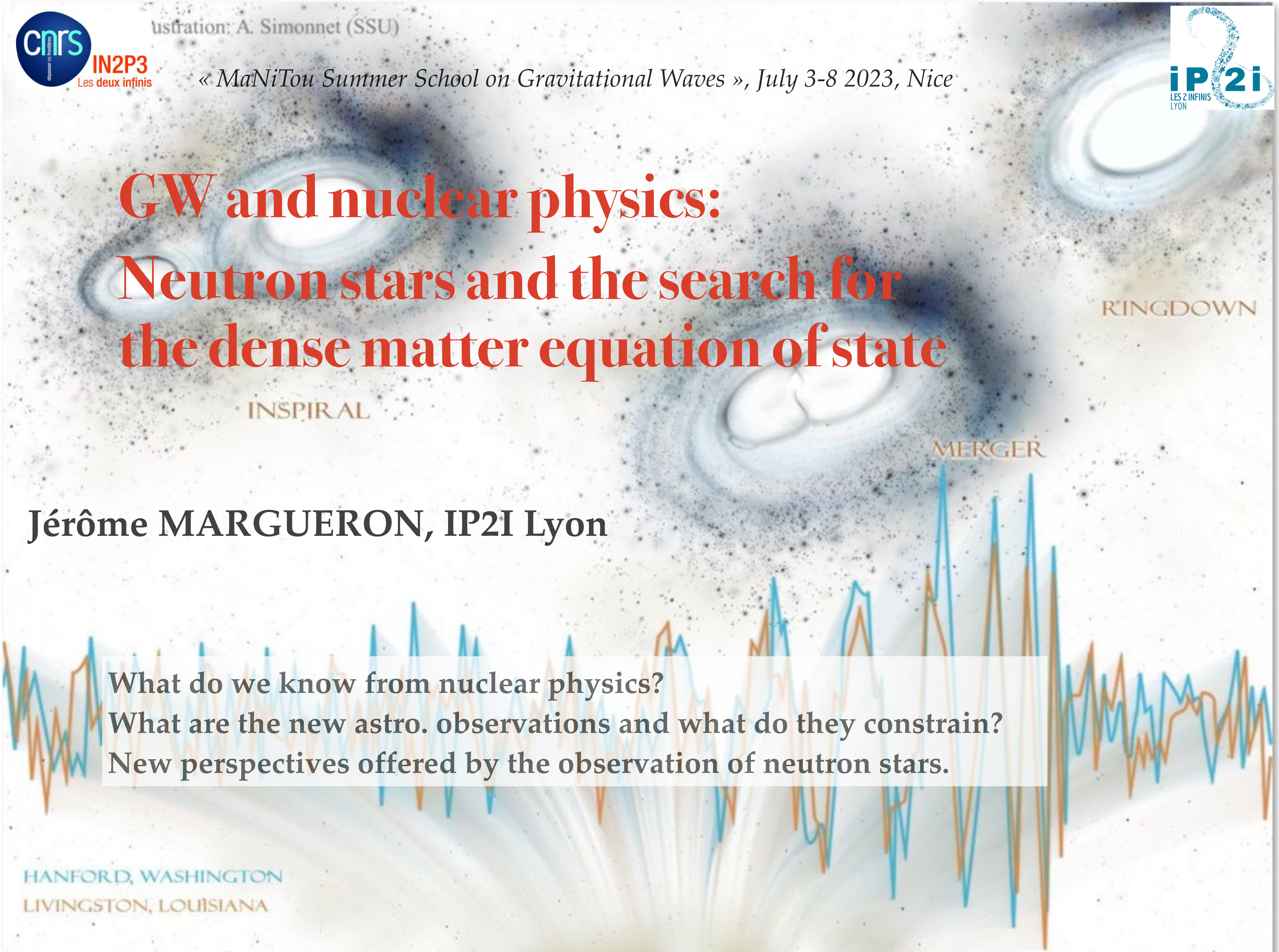


What do we know from nuclear physics?
What are the new astro. observations and what do they constrain?
New perspectives offered by the observation of neutron stars.

What is a neutron star?

Conjectured 1934 **(Baade & Zwickly)**

Discovered 1967 **(Bell & Hewish)**

Known ~ 3300

Expected ~10^8 (in our galaxy)

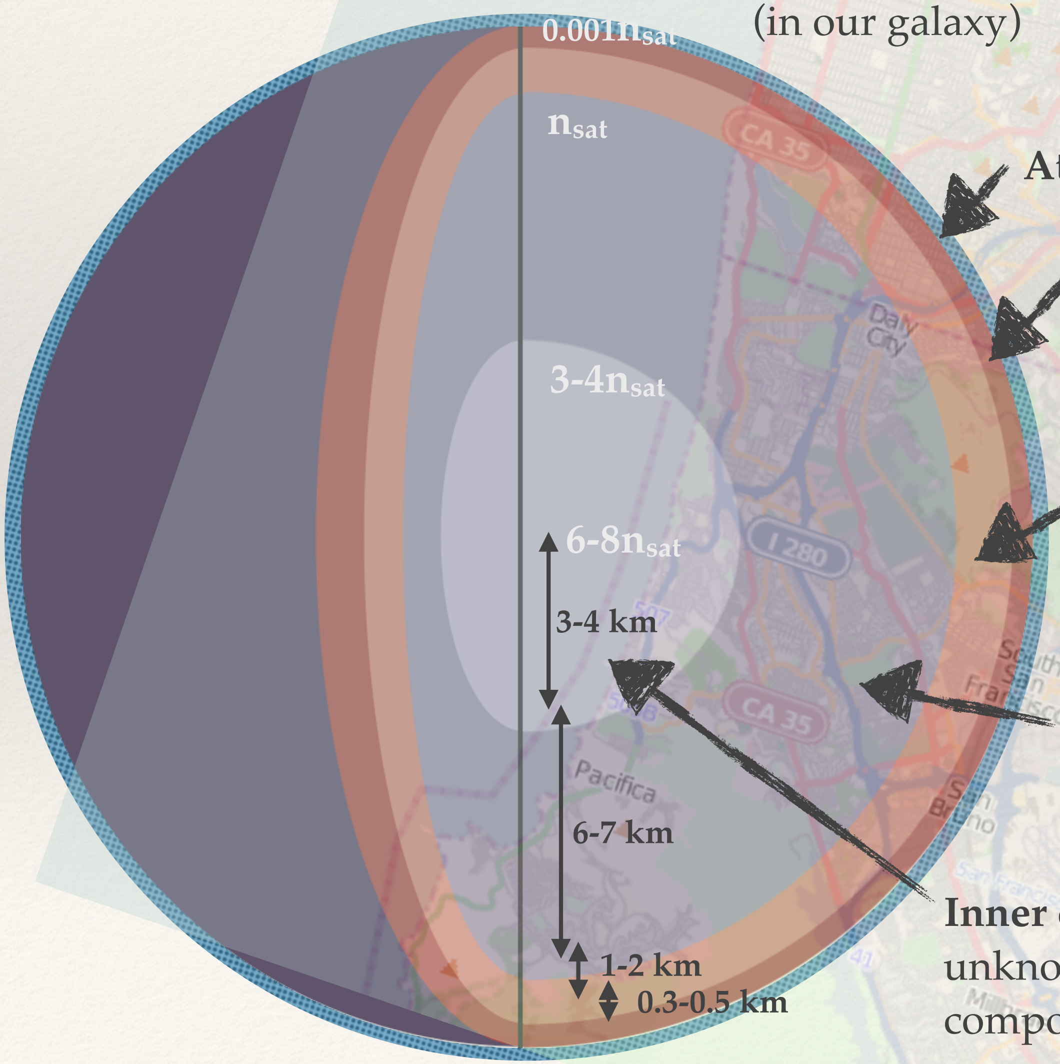
Radius ≈ 10 – 14km

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+electrons

Inner crust: nuclear clusters+electrons+ neutron gas

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

Inner core: unknown composition

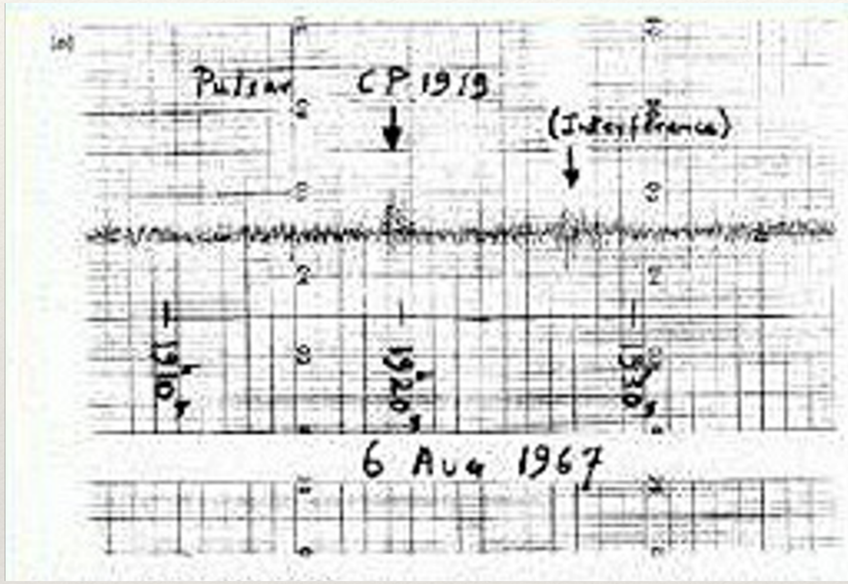
The understanding of NS is mainly due to our knowledge in nuclear physics and in general relativity.

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

NS **mass** mostly provides information about the **core**, the crust contribution is small (1%).

The discovery of Pulsars

In 1967, Jocelyn Bell and Anthony Hewish discovered the first Pulsars (in radio-wave).

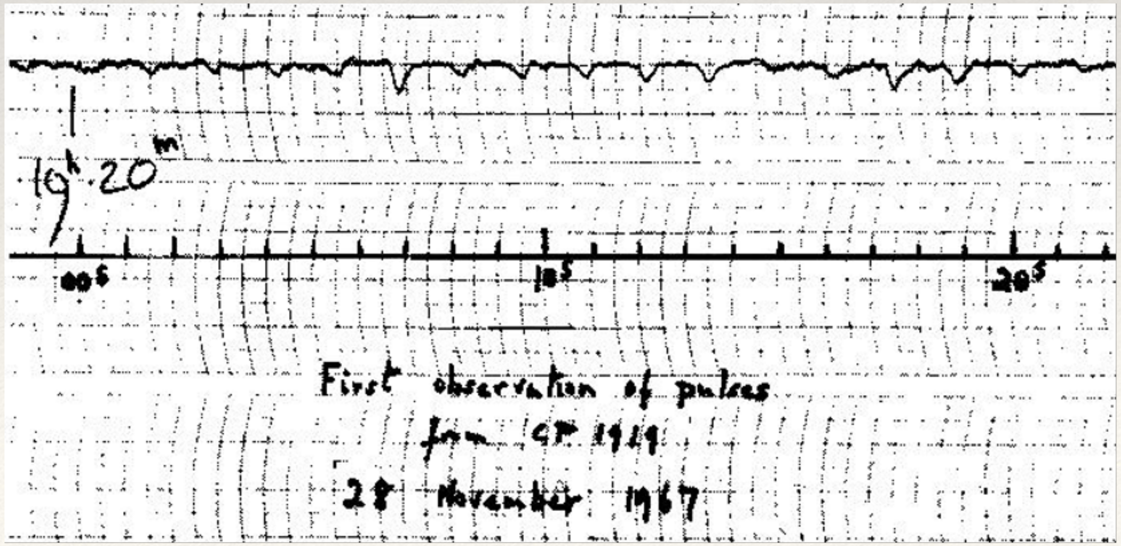


Jocelyn Bell and Anthony Hewish

The signal repeated every days with 4 minutes delay.

—> extra-terrestrial origin !

With a better resolution of the signal (T=1.37 s):



The No'Bell price…

In 1974, Anthony Hewish received the Nobel price for the discovery of pulsars, but not Jocelyne Bell.

Prix No'Bell

QUI A DÉCOUVERT les pulsars, en quelle année, et qu'est-ce qu'un pulsar ? Réponses : Jocelyn Bell, en 1967, une étoile minuscule qui, au lieu de briller de façon continue, tourne très rapidement sur elle-même et agit comme un phare, dont la lumière nous éclaire à intervalles réguliers. L'autrice Elisabeth Bouchaud s'est penchée sur le cas de cette astrophysicienne.

Et quel cas ! Irlandaise, femme, quakeresse, elle a prouvé l'existence de ces étoiles alors qu'elle était encore doctorante à Cambridge. Une découverte majeure que s'est appropriée son directeur de thèse, ce qui lui a permis de décrocher le prix Nobel, en 1974.

La jeune Clémentine Lebocey incarne cette chercheuse. L'euphorie puis l'impuissance face à une telle démonstration de malveillance, elle nous les fait bien sentir. Elle donne la réplique à deux comédien(ne)s. Et joue la carte pédago. On n'est jamais perdu. Jocelyn Bell aurait pu être dévorée par l'amertume. Non, avec l'humour désabusé des personnes à qui on a constamment mis des bâtons dans les roues, elle relativise, ironise. Au fil des années, elle a récolté une kyrielle de prix fameux, dont le Prix de physique fondamentale, en 2018. Sa dotation de 3 millions de dollars, elle en a fait don à une association venant en aide aux étudiants diplômés en physique issus de minorités. Plutôt rare.

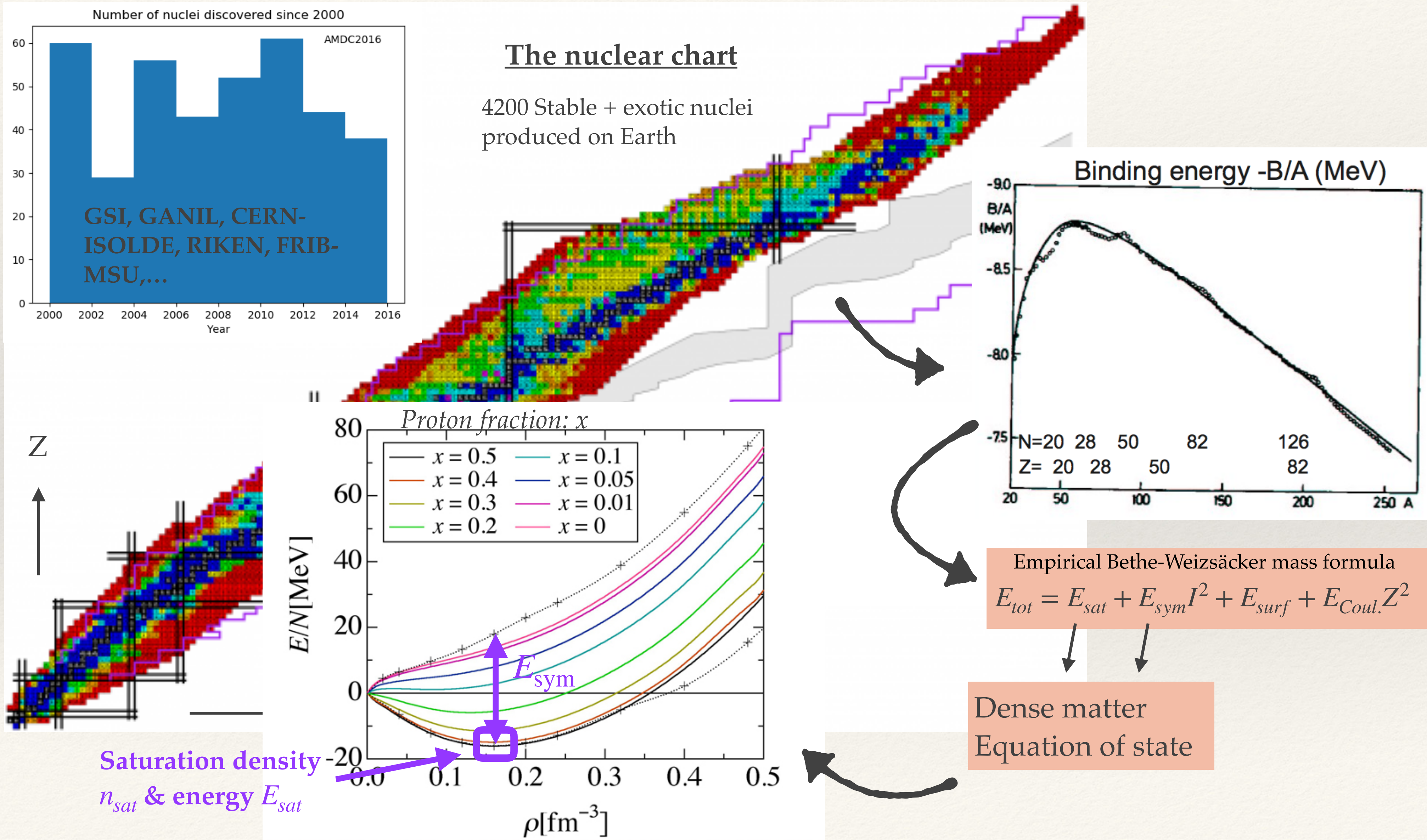
M. P.

● A la Reine-Blanche, à Paris, jusqu'au 5/2.

The contribution of Jocelyn Bell to the discovery of pulsars is huge.
She would probably have deserved to receive also the Nobel price.

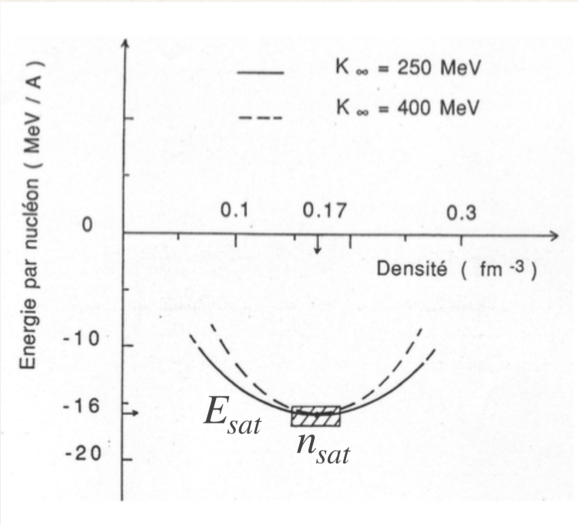
What we know about neutron stars from nuclear physics (with little input from astro. observations):

Dense matter from nuclear physics: Esat and Esym



Contraints from the nuclear breathing mode

Density dependence of the energy around n_{sat}

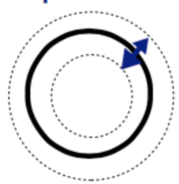


Compressible liquid-drop: $$e(n) \approx e(n_{\rm sat}) + \frac{1}{2} K_{\rm sat} x^2 + \ldots \text{ with } x = (n - n_{\rm sat})/(3n_{\rm sat}).$$

Incompressibility

How is incompressibility measured?

α scattering on nuclei
→ monopolar compression



Measured in different nuclei

Extracted

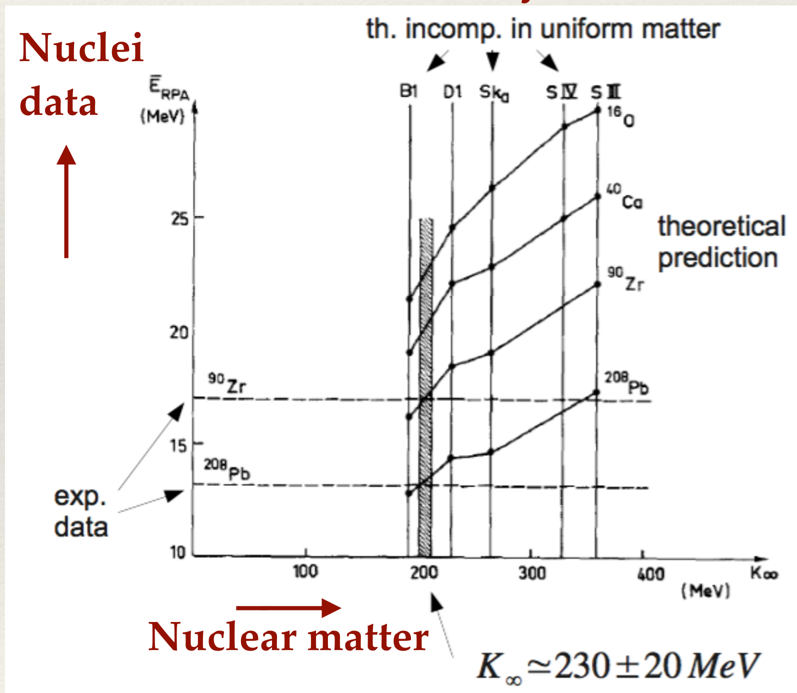
vibration frequency: $$\hbar\omega = \hbar\sqrt{\frac{K_A}{mr_0^2}} A^{-1/3}$$

$$K_A = K_{\rm sat} + K_s A^{-1/3} + K_{sym}\left(\frac{N-Z}{N+Z}\right)^2 + K_{coul}\frac{Z^2}{A^{4/3}}$$

Uniform matter

Finite size effects

Correlation analysis



J.P. Blaizot, Phys. Rep. 64 (1980) 171

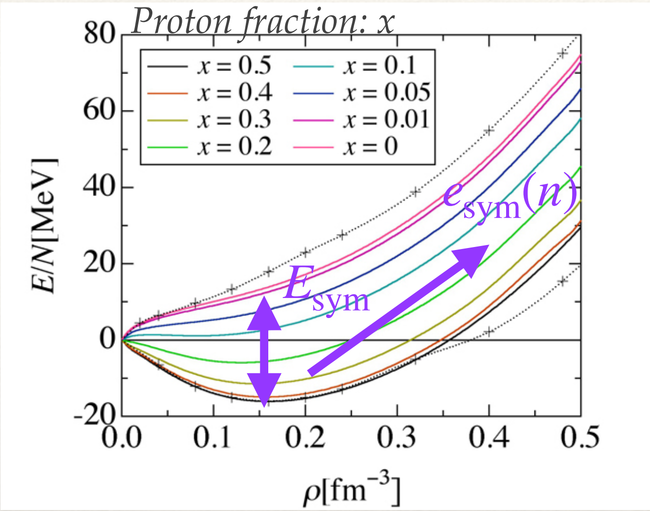
Model dependence?

[Khan, JM, Vidaña PRL 2012, PRC 2013]

[Grams+ PRC 2022]

Isovector channel: symmetry energy

Empirical Bethe-Weizsäcker mass formula: $E_{tot} = E_{bulk} + E_{sym} I^2 + E_{surf} + E_{Coul.} Z^2$



Density dependence of the symmetry energy:

$$e_{\rm sym}(n) = e(n,\delta=1) - e(n,\delta=0) = e_{\rm sym,2} + \dots$$

with $e_{\rm sym,2}(n) = \frac{1}{2}\frac{\partial^2 e(n,\delta)}{\partial \delta^2}|_{\delta=0}$

Difference between NM and SM.

[Ex: Somasundaram+ PRC 2021]

In terms of empirical parameters: $e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$

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

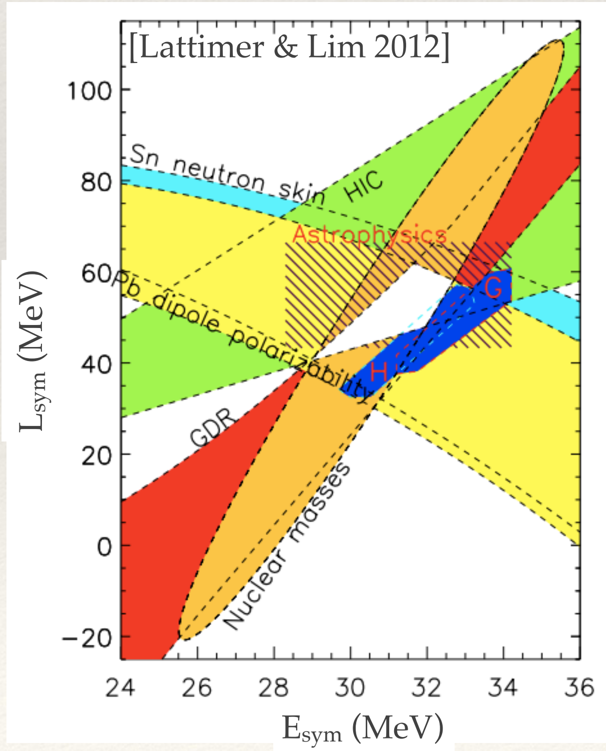
Slope of the symmetry energy (density dependence):

$$L_{sym} = \frac{\partial e_{\rm sym}(x)}{\partial x} = 3n_{\rm sat}\frac{\partial e_{\rm sym}(n)}{\partial n} .$$

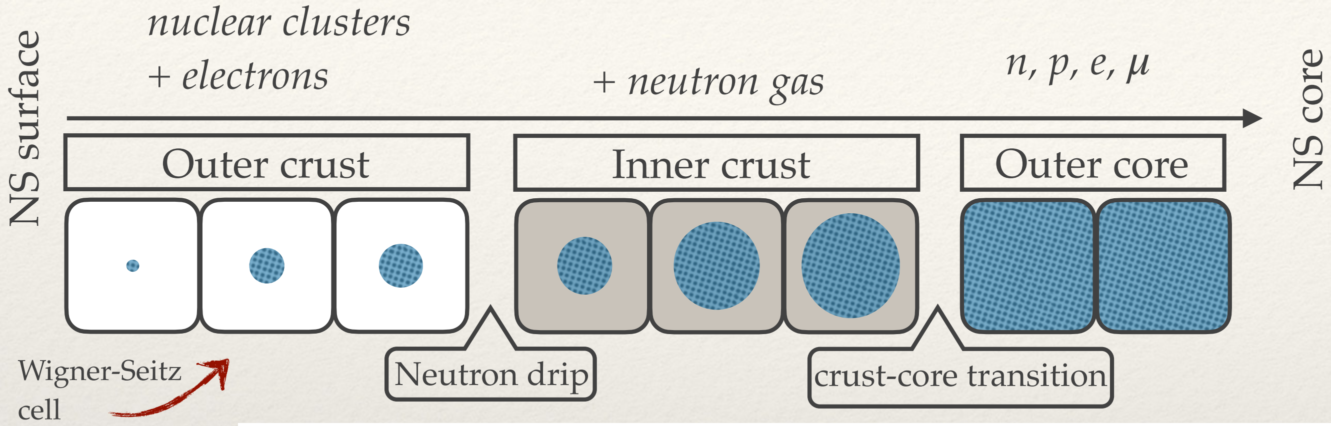
Major impact on the **beta equilibrium** in neutron stars

$\mu_e = \mu_n - \mu_p = 4(1-2x)e_{sym}(n)$

The composition of dense matter is largely determined by the symmetry energy.

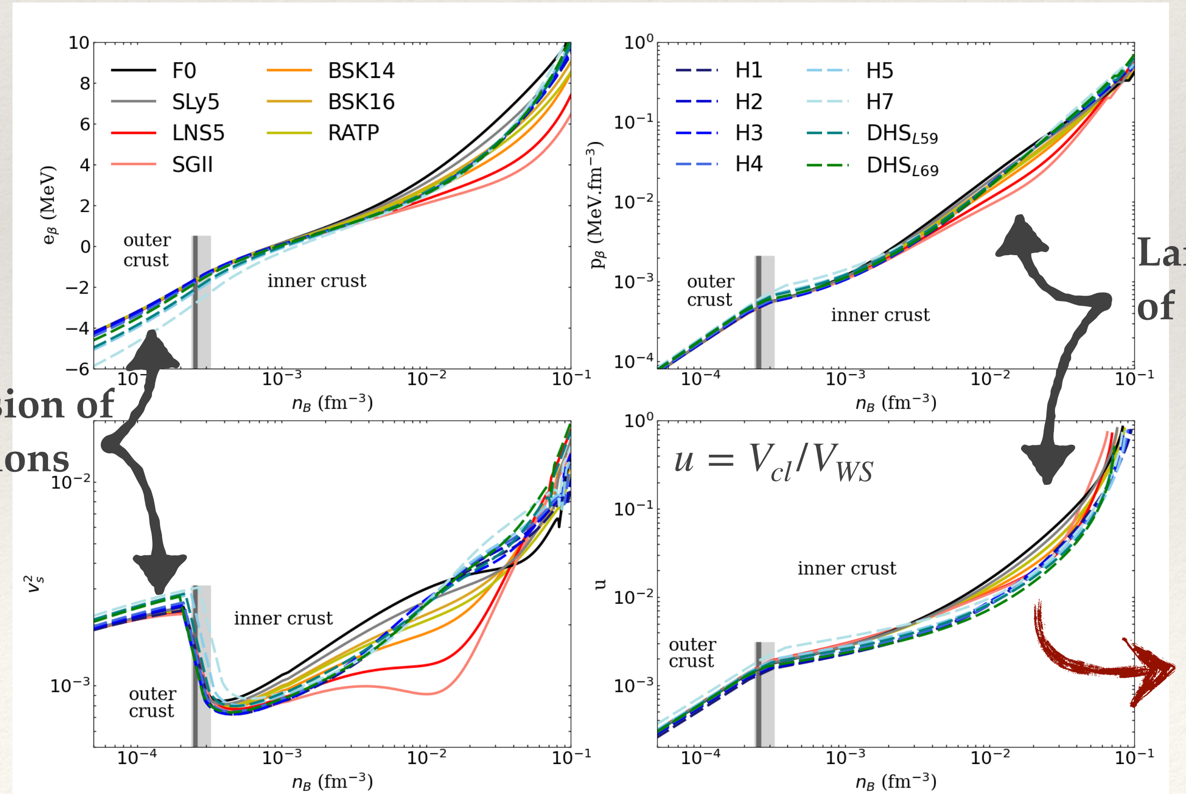


Modeling inhomogeneous matter (crust)



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

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

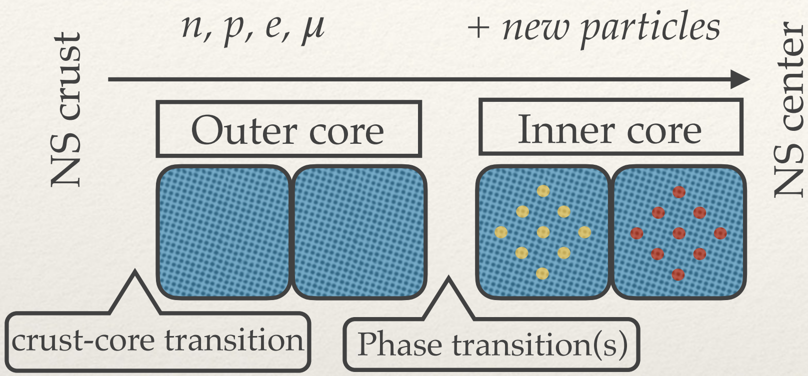


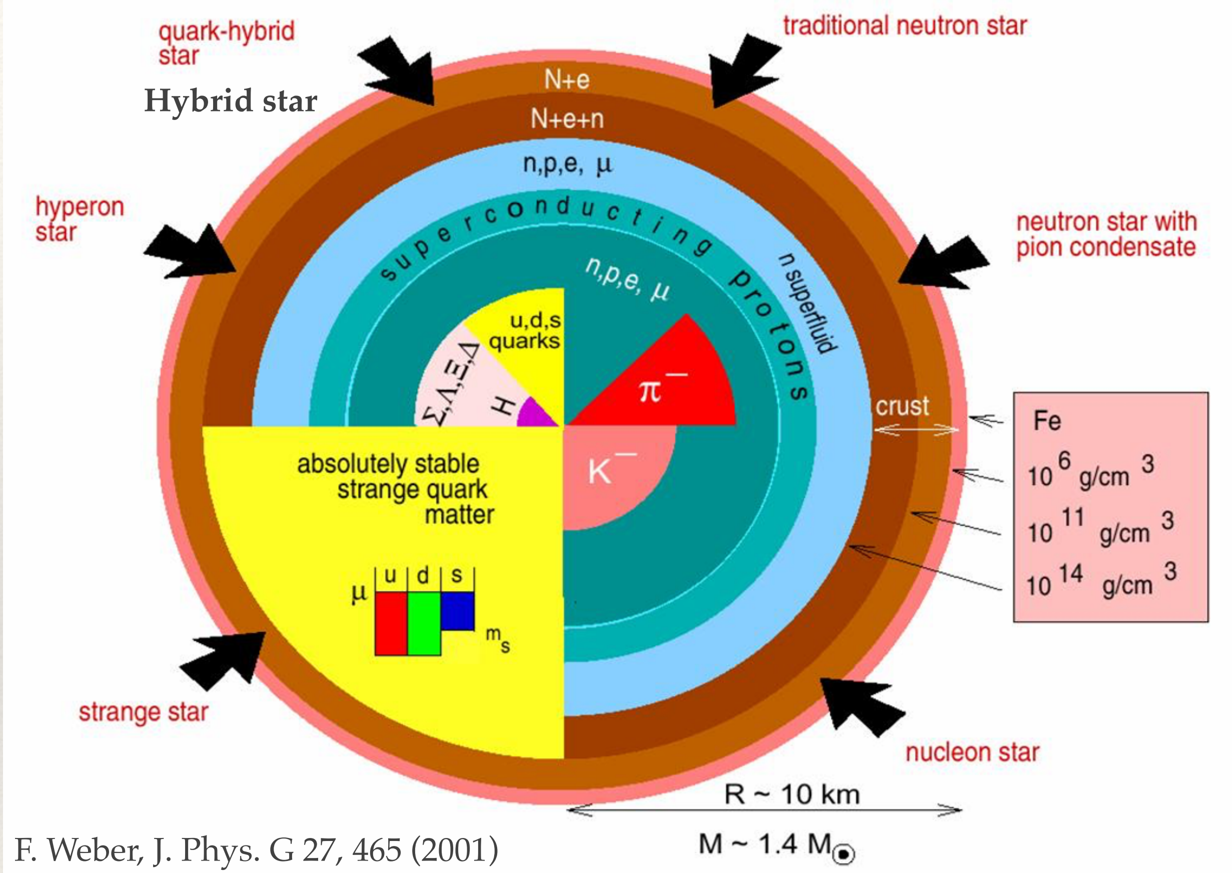
Large dispersion of Skyrme models

Large dispersion of χEFT predictions

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

Modeling homogeneous matter (core)





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

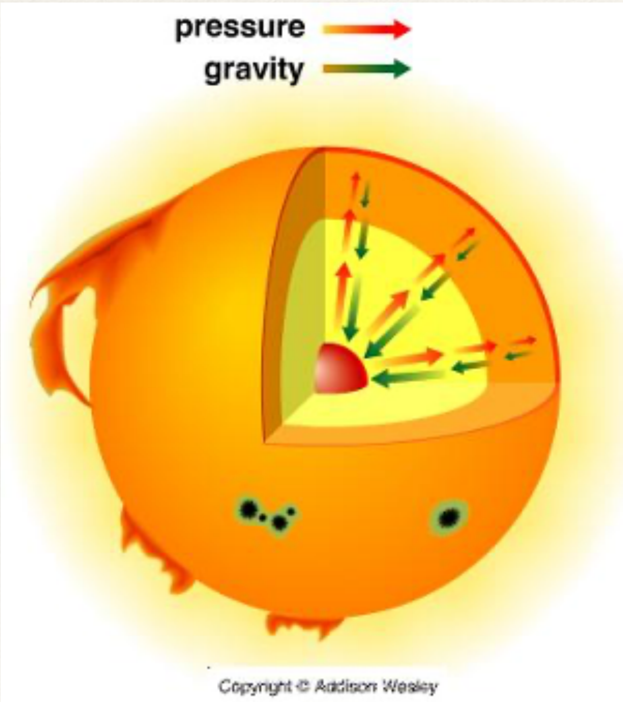
- Is there a phase transition?
- If yes, only one or several?
- What is the composition of the new phases?
- Which impact they have on the equation of state?

How new data will help to answer these questions?

Links between nuclear physics and observation of neutron stars:

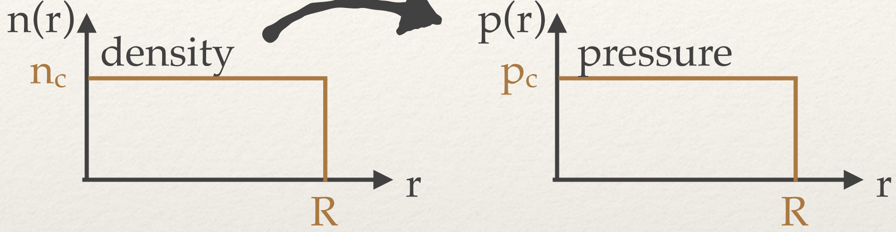
Stars and the equation of state…

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

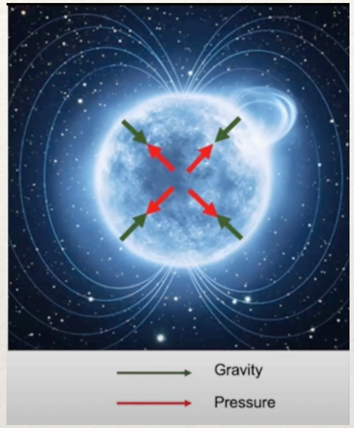


This is the case of all celestial objects. Only **different pressures** create **different objects**.

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).

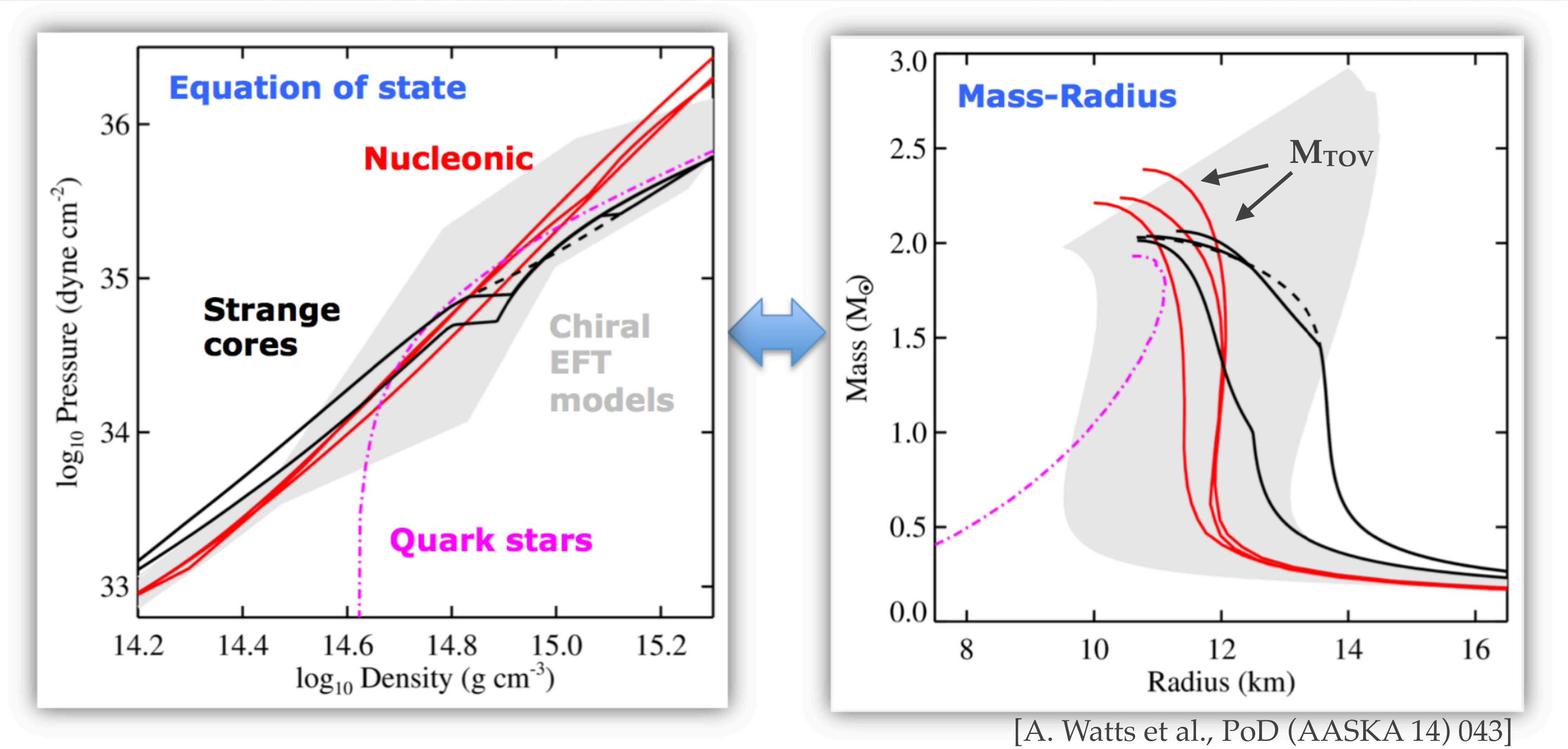
Internal pressure originates from the **Pauli exclusion** between fermions (electrons, nucleons, quarks, …) + **interaction (quantum mechanics)**.

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

Known and unknown from nuclear physics

Energy in asymmetric matter: $e(n,\delta) \approx e_{\rm sat}(n) + e_{{\rm sym},2}(n)\delta^2 + e_{{\rm sym},4}(n)\delta^4 + \ldots$

with $\delta = (n_n - n_p)/(n_n + n_p)$

where the isoscalar and isovector terms are expressed as a Taylor expansion in x:

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

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

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

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

Small uncertainties | Large uncertainties | Some uncertainties

P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m^*_{sat}/m	$\Delta m^*_{sat}/m$
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75	0.1
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

Small impact at T=0

⚠ These parameters are correlated among each other.

[JM, Casali, Gulminelli, PRC 2018]

A semi-agnostic approach for the nuclear EoS

[Baillot d'Étivaux+, ApJ 2019]

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

Less known NEP — Unknown NEP

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

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

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):

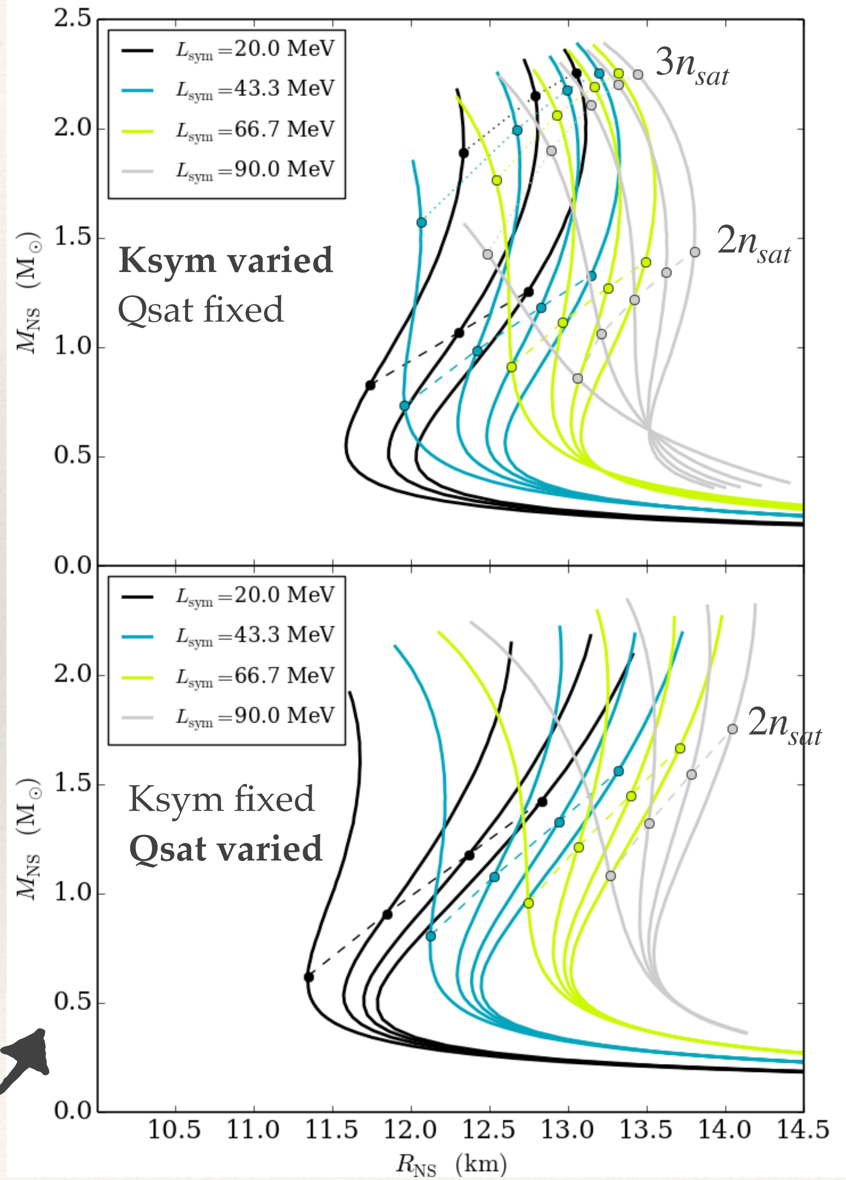
$$e(n,\delta) = t(n,\delta) + v(n,\delta)$$

Kinetic energy (Fermi gas)

Potential energy

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

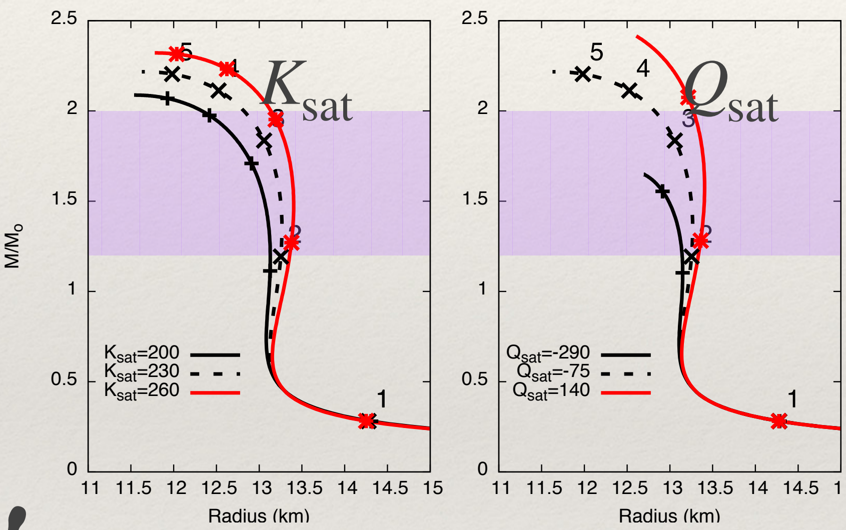
Directly related to NEP



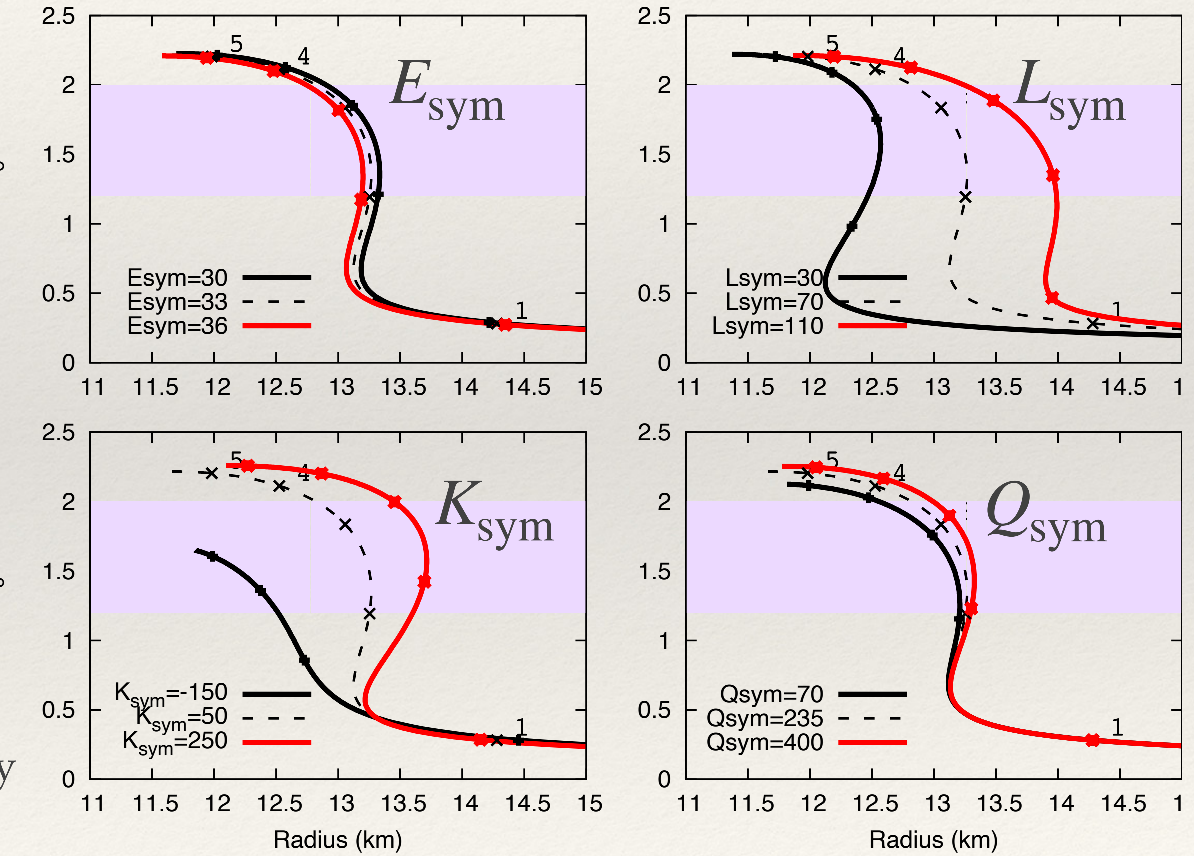
From nuclear physics to neutron star observations

Nuclear Empirical Parameters (NEP) are varied independently in the nuclear meta-model.
-> they influence the NS mass-radius relation (astro. observations). [JM, Casali, Gulminelli, PRC 2018]

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



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



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

A better determination of nuclear properties may not improve the predictions for neutron star.

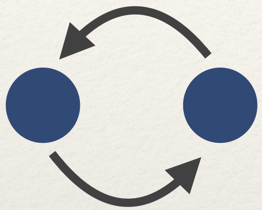
—> the largest source of uncertainties is the **density dependence of the EoS** (Symmetry energy, phase transitions).

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

Recent advances in astro. observation which really impact neutron star equation of state:

From gravitational waves…

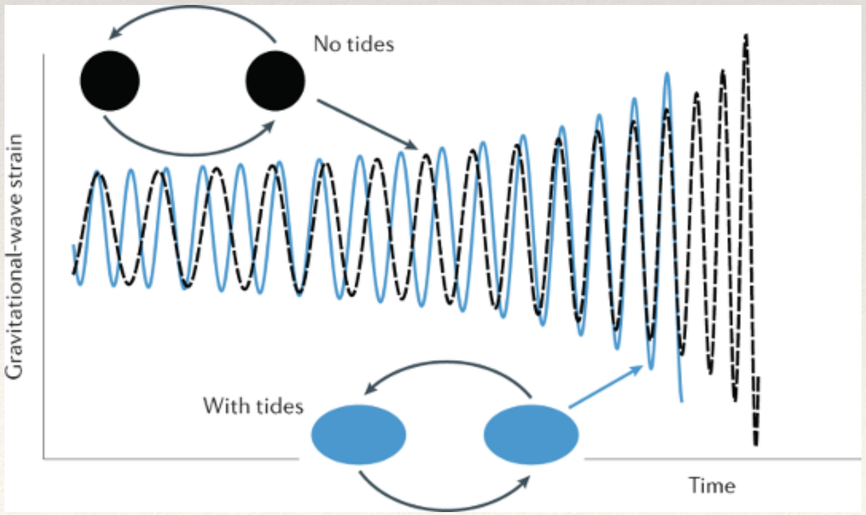
Binary neutron stars: Produce gravitational waves with frequency # distance between NS.



If the radius is small, the BNS will reach high frequencies.
If the radius is large, the BNS will be limited in the maximum frequency.

The first observation of the merger of a BNS in 2017 (**GW170817**) didn't observed the last orbit (due to the noise back-ground).

But there is another way to estimate the compactness of NS: the **tidal deformability**.



$$\Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3} k_2 \frac{R^5}{m^5} = \frac{2}{3} k_2 C^{-5}$$

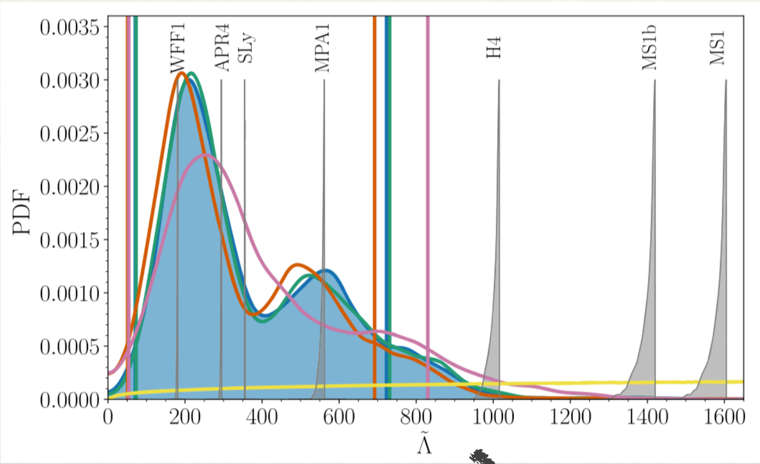
k_2 is the Love number and C the compactness.
Λ quantifies how easy it is to deform the star. It distorts the GW signal, and can therefore be measured from the observation.

Yunes et al., Nature Rev. Phys. 4 (2022).

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

Analysis of GW170817 waveform:

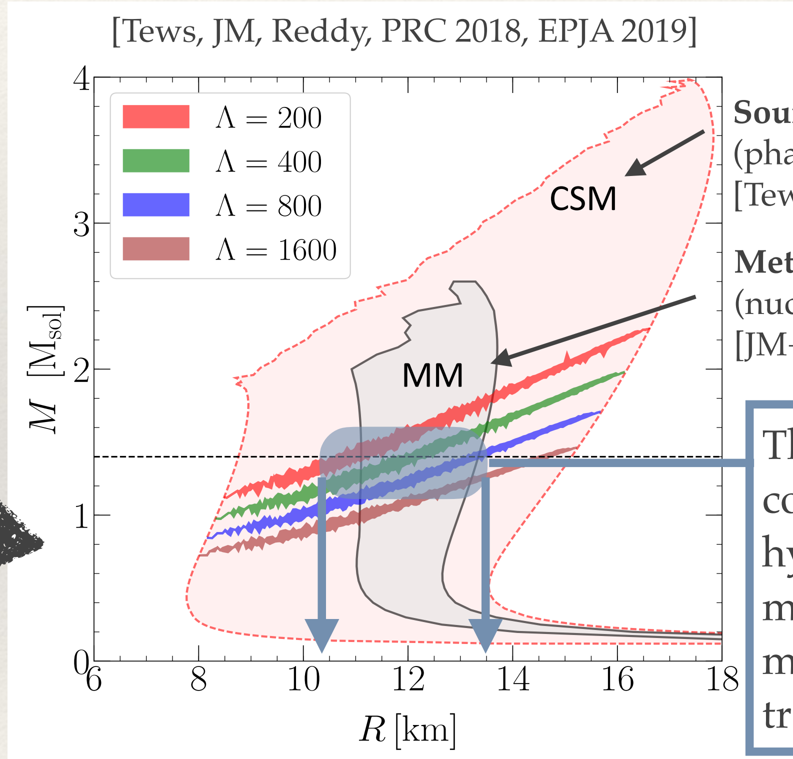
LVC, Phys. Rev. X 9, 011001 (2019)



GW170817:

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

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



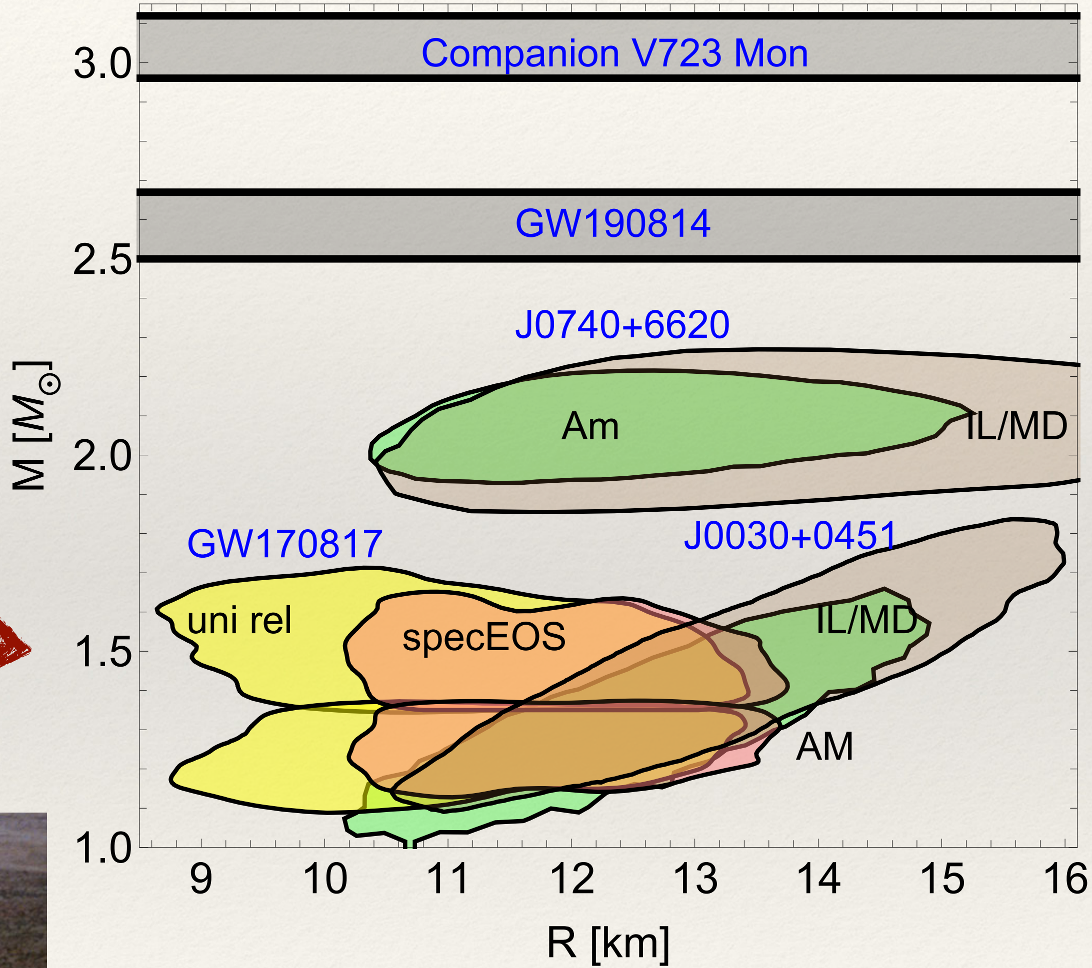
Sound-speed Model
(phases transitions)
[Tews+ 2018]

Meta-Model
(nucleonic)
[JM+ 2018]

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

New data from GW + NICER X-ray observatory

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

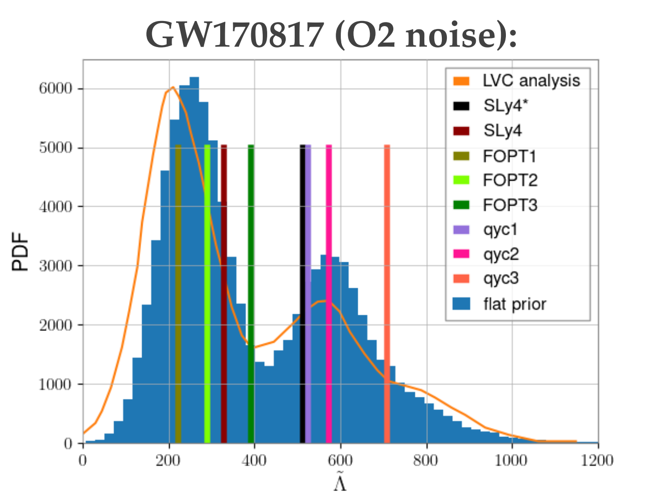


What shall we expect from future detections of GW?

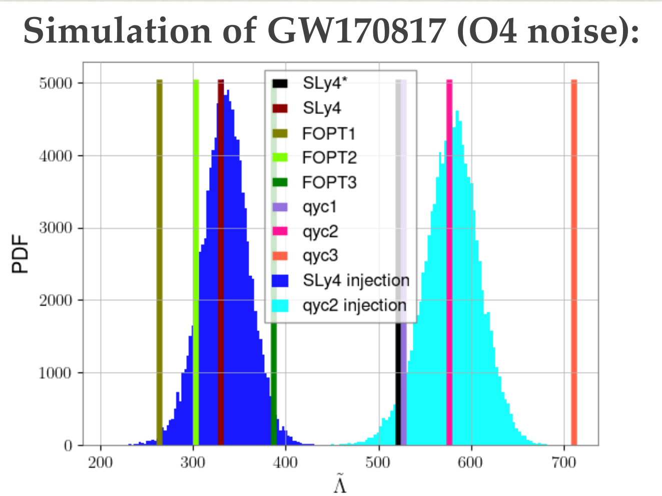
Coupechoux et al., PRD 107 (2023).

On May, 26th, O4 have started for 18 months.

How GW170817 was measured:

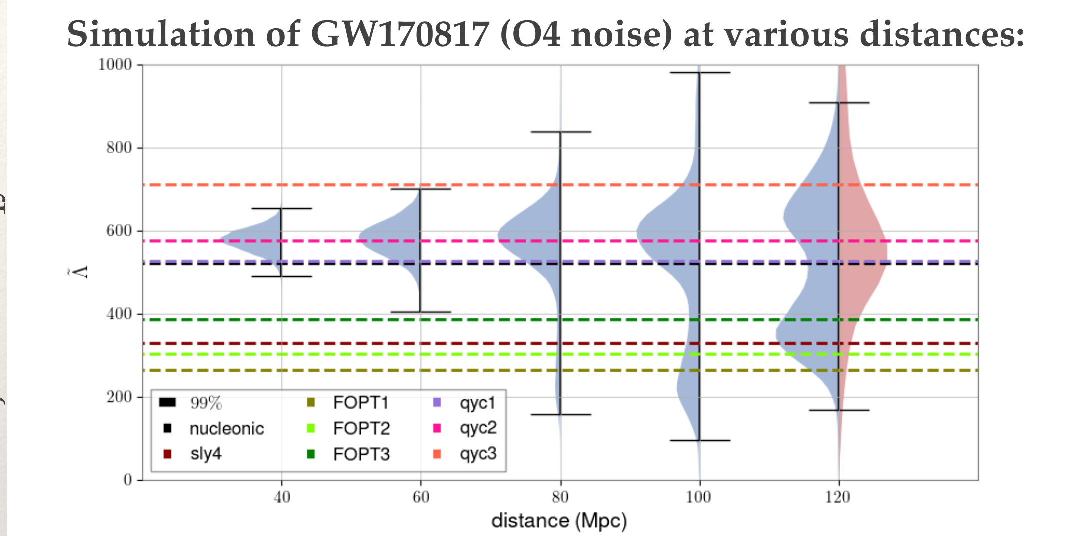


How it will be measured now:

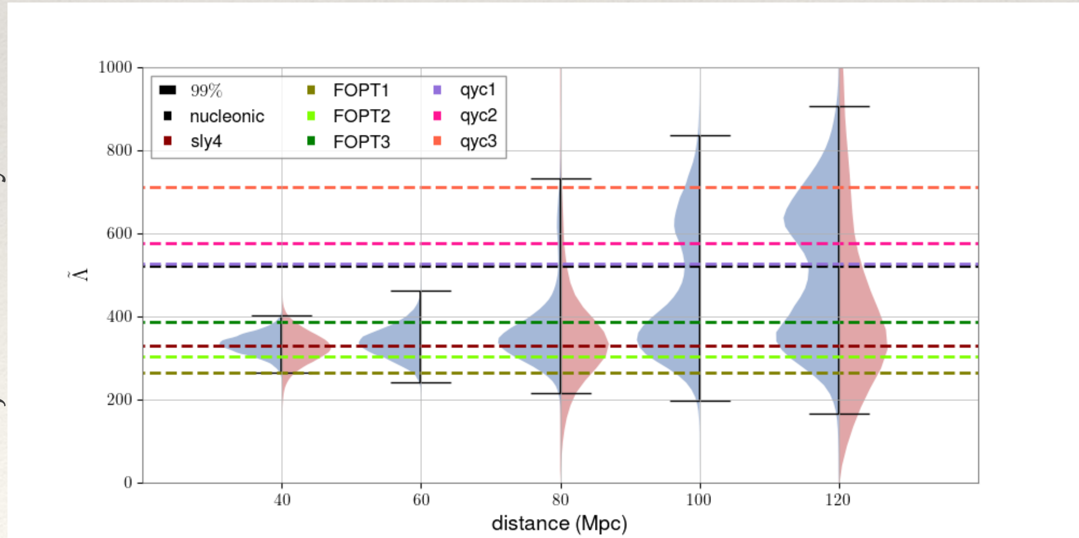


How all events will be measured:

Injection of qyc2



Injection of SLy4



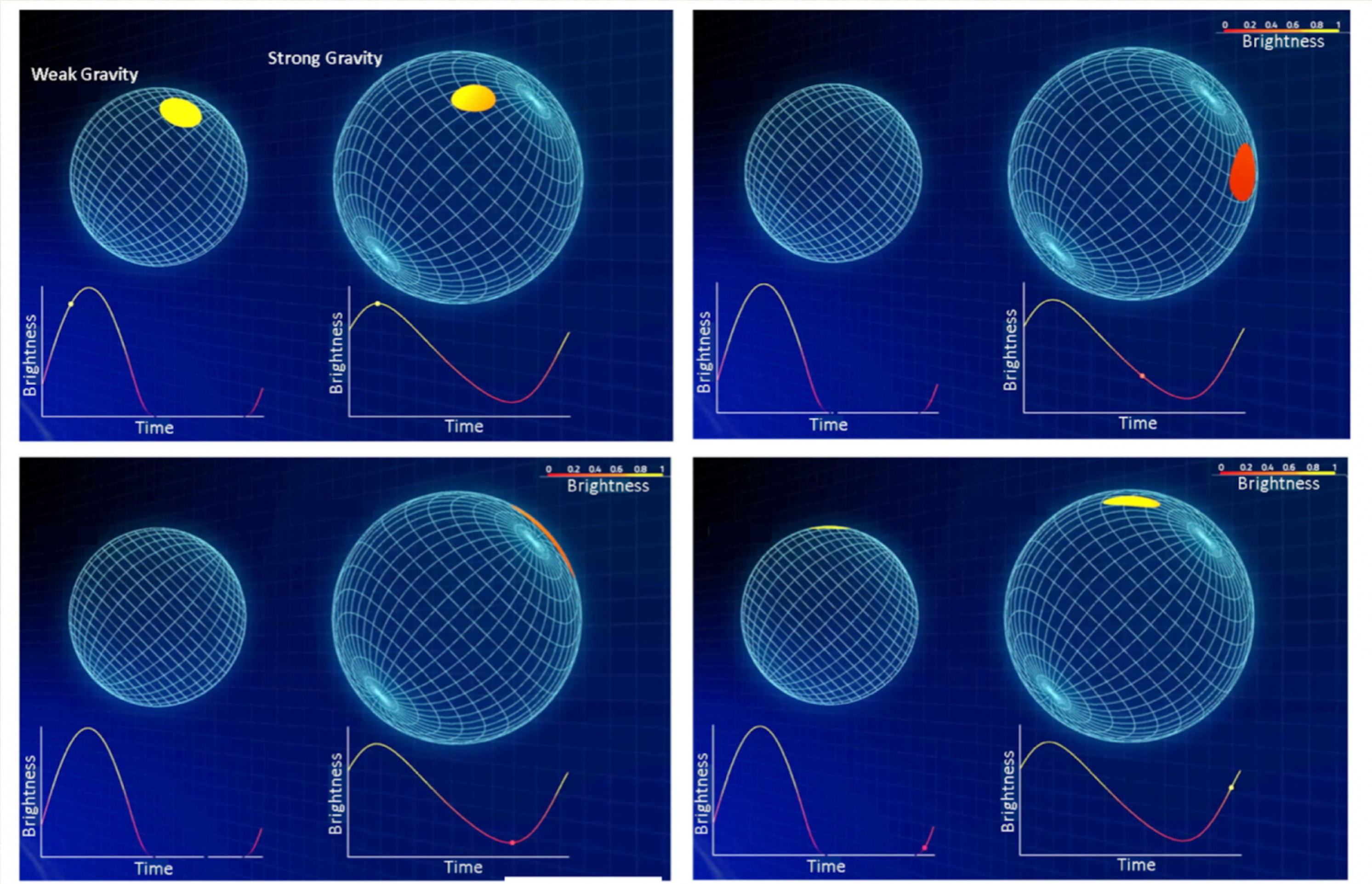
—> an event similar to GW170817 with D<100 Mpc will bring new information.

NICER: Neutron star Interior Cosmic explorER

NICER measures the radius of NS with high precision.

How it comes?

Some pulsars have hot spots located at their surface.
When the hot spot goes farther from us, its color if red-shifted (doppler effect). When it goes closer to us, it is blue-shifted.



NICER : an accurate mesure of the neutron star radius

The amplitude of the color shift (**doppler-shift**) depends on the speed of the hot spot (v).

The hot spot is located at the surface of the pulsar (radius R).

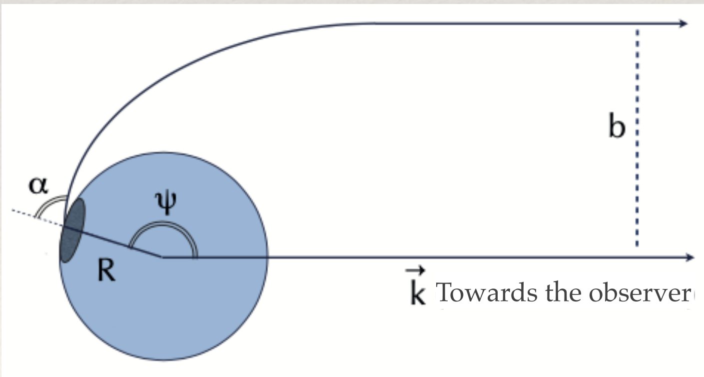
We know the rotation frequency (f).

Since $v = R \times 2\pi f$

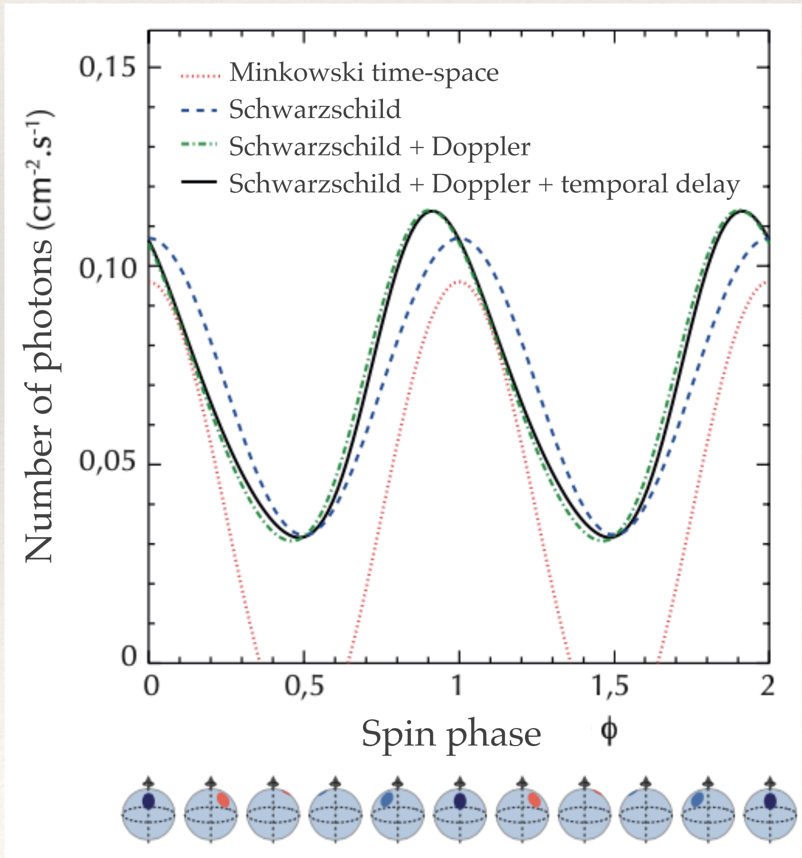
Knowing v and f, one can deduce R (+ general relativity effects)

In addition :

The trajectory of the photons is curved by strong gravity (**temporal delay**).



From v, f and C, one could deduce R and M.

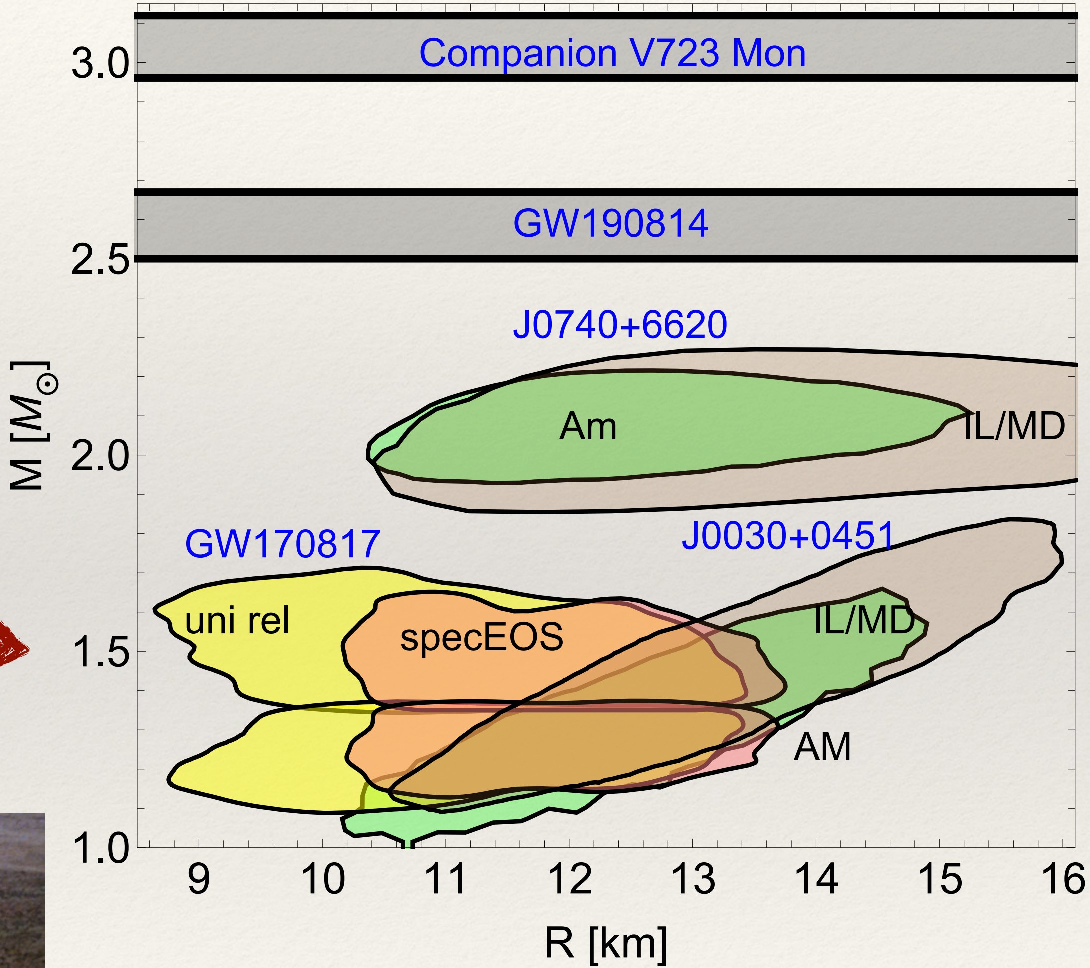


—> The hot spot is always visible!!

This effect is proportional to the space-time curvature, and so to the compactness of the star : $C = M/R$

NICER X-ray observatory + GW

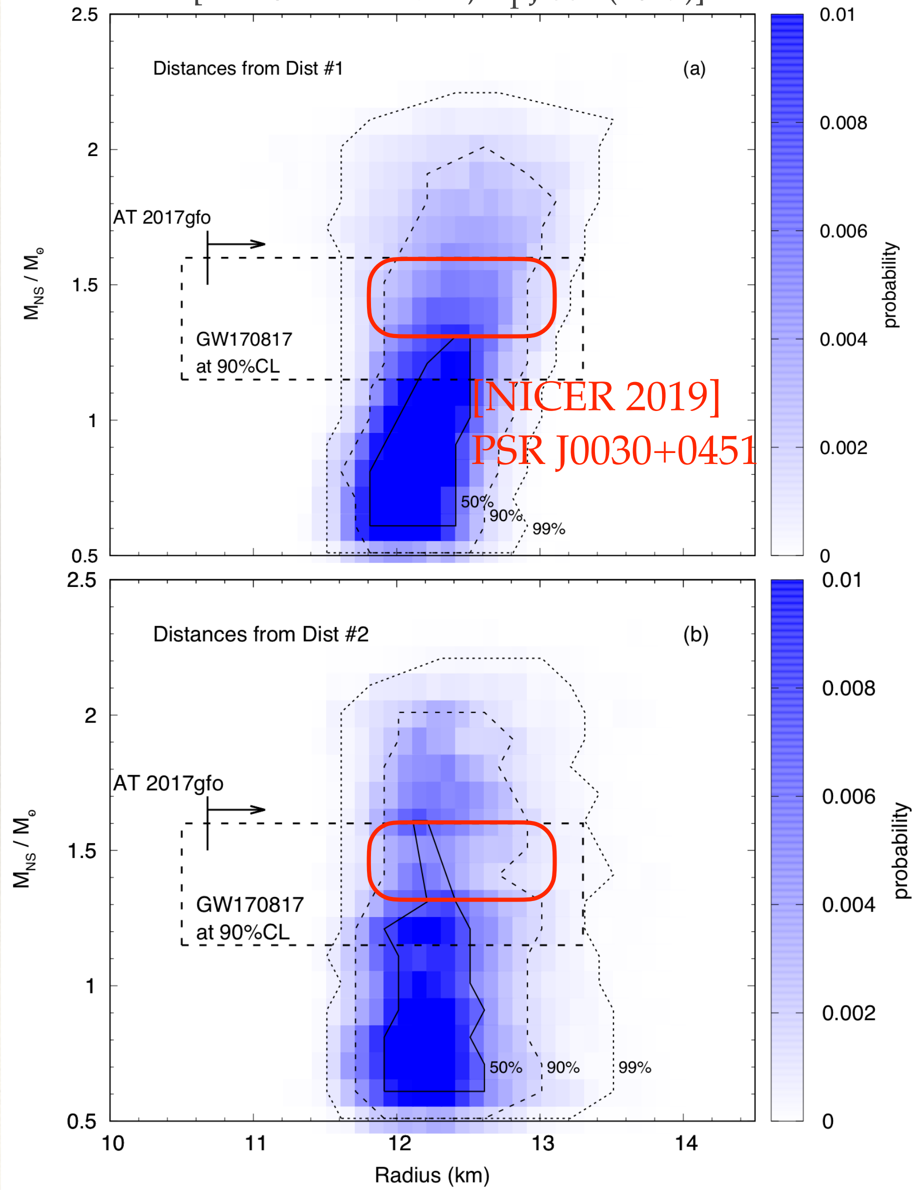
Tan, Dore, Dexheimer+, PRD 105, 023018 (2022)



From the thermal emission from qLMXB

quiescent Low Mass X-ray binaries

[Baillot d'Étivaux+, ApJ 887 (2019)]



Black body like emission:

$$F \propto T^4 (R_{obs}/D)^2 \quad \text{and} \quad R_{obs} = R_{NS}/(1 + M/R)$$

Rutledge+ ApJ 577 (2002)
Guillot+ ApJ 732 (2011), ApJ 738 (2011), ApJ 772 (2013), ApJL 796 (2014)
Özel RPP 76 (2013)
Steiner+, ApJL 765 (2013), MNRAS 476 (2018)
Heinke+ MNRAS (2014)
Lattimer+ ApJ 784 (2014)
Bogdanov+ ApJ 831 (2016)
Baillot d'Étivaux ApJ 887 (2019), …

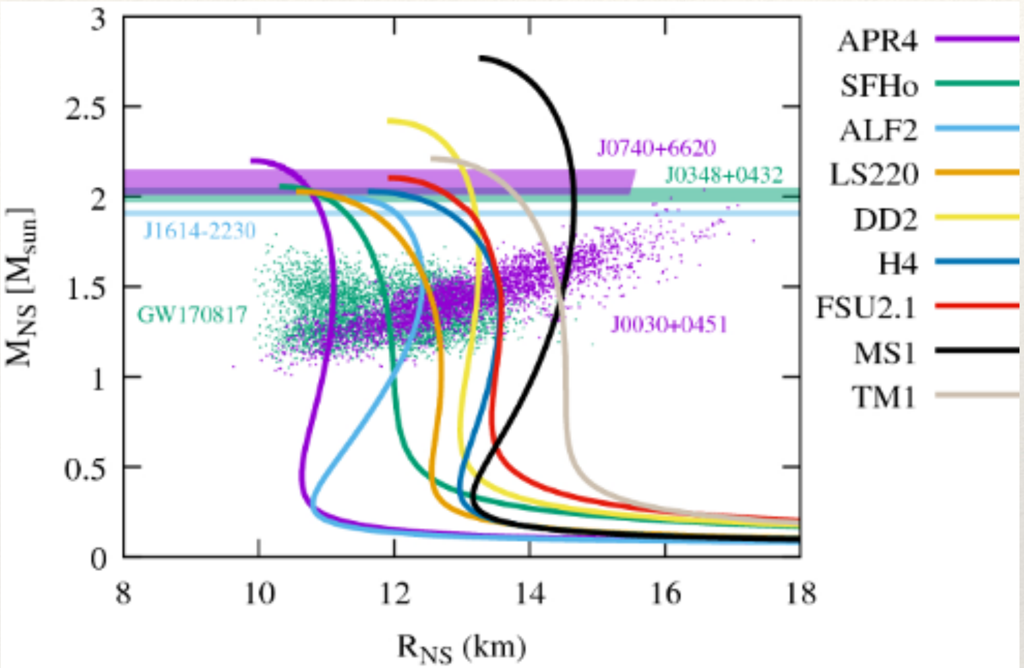
—> Bayesian analysis considering 7 sources in globular clusters, where the EoS is directly injected into the data analysis (first time).

Average radius (12-13km) preferred.

—> These results are consistent with GW and NICER data.

Modeling the dense matter equation of state

The dense matter equation of state



Kyutoku et al., Living Rev. Rel 24 (2021)

- What is the symmetry energy around saturation density?
  -> fix the composition of matter.
- What is the composition of dense matter?
  - Ordinary neutron, proton, electron and muon degrees of freedom?
  - Or new dof such as hyperons or quarks?

  -> determine the radius of massive NS.

Microscopic description of dense matter

There is no microscopic theory for dense matter, only models. *Why?*

QCD is the theory for **strong force**.
It describes the interaction between quarks and it has a special property: **asymptotic freedom**.
-> it is perturbative at high density, non-perturbative at **low energy**.

Nuclear physics is low-energy
-> it is then in the **non-perturbative** regime of QCD.

At low energy, QCD has another property: **color confinement**.

Quarks prefer to be color white, then to combine together 3 complementary colors.
-> quarks form neutrons and protons.

The nuclear interaction between neutrons and protons is the **residual of the strong force** (like Van der Waals force in atomic physics).

Bridging from QCD (fundamental theory) to nuclear interaction is difficult.
It is necessary to consider an effective or phenomenological approach.

-> There are **several approaches in nuclear physics** with various links to QCD. No theory, but several models.

Description of dense matter

Microscopic approach

Hamiltonian or Lagrangian

Many-body treatment (Hartree-Fock, quantum Monte-Carlo, …)

Phase(s) transition(s)

Matter at beta-equilibrium

Lepton contribution

EoS in extreme matter

Description of dense matter

Microscopic approach

Hamiltonian or Lagrangian

Many-body treatment (Hartree-Fock, quantum Monte-Carlo, …)

Phase(s) transition(s)

Matter at beta-equilibrium

Lepton contribution

Agnostic approach

Construct the relation p <-> ρ mathematically.

Ignore the interaction.

Ignore the many-body treatment.

May include phase(s) transition(s).

But ignoring the composition of matter.

EoS in extreme matter

Exemple of an agnostic approach

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

Adiabatic index

Pression (dyn cm-2)

Density (g cm-3)

We deduce the energy as

$$e(\rho) = 1 + a + \frac{1}{\Gamma - 1} K\rho^{\Gamma-1}$$

constant

using

$$P(\rho) = \rho^2 \frac{de}{d\rho}$$

Piecewise polytropes:

Above ρ_0, a set of densities is considered: $\rho_0 < \rho_1 < \rho_2 < \ldots$

$$P(\rho) = K_i \rho^{\Gamma_i}$$

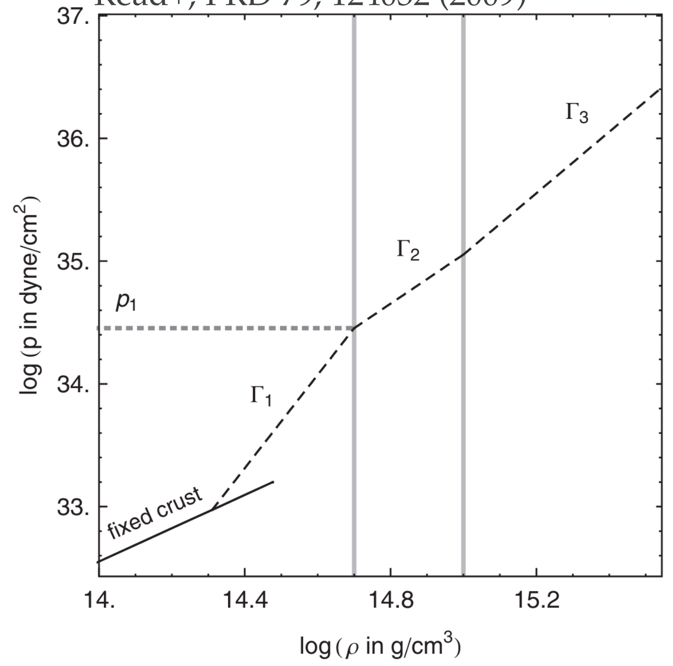
$$e(\rho) = 1 + a_i + \frac{1}{\Gamma_i - 1} K_i \rho^{\Gamma_i - 1}$$

The continuity of P and e at ρ_i is imposed -> fix a_i and K_i.

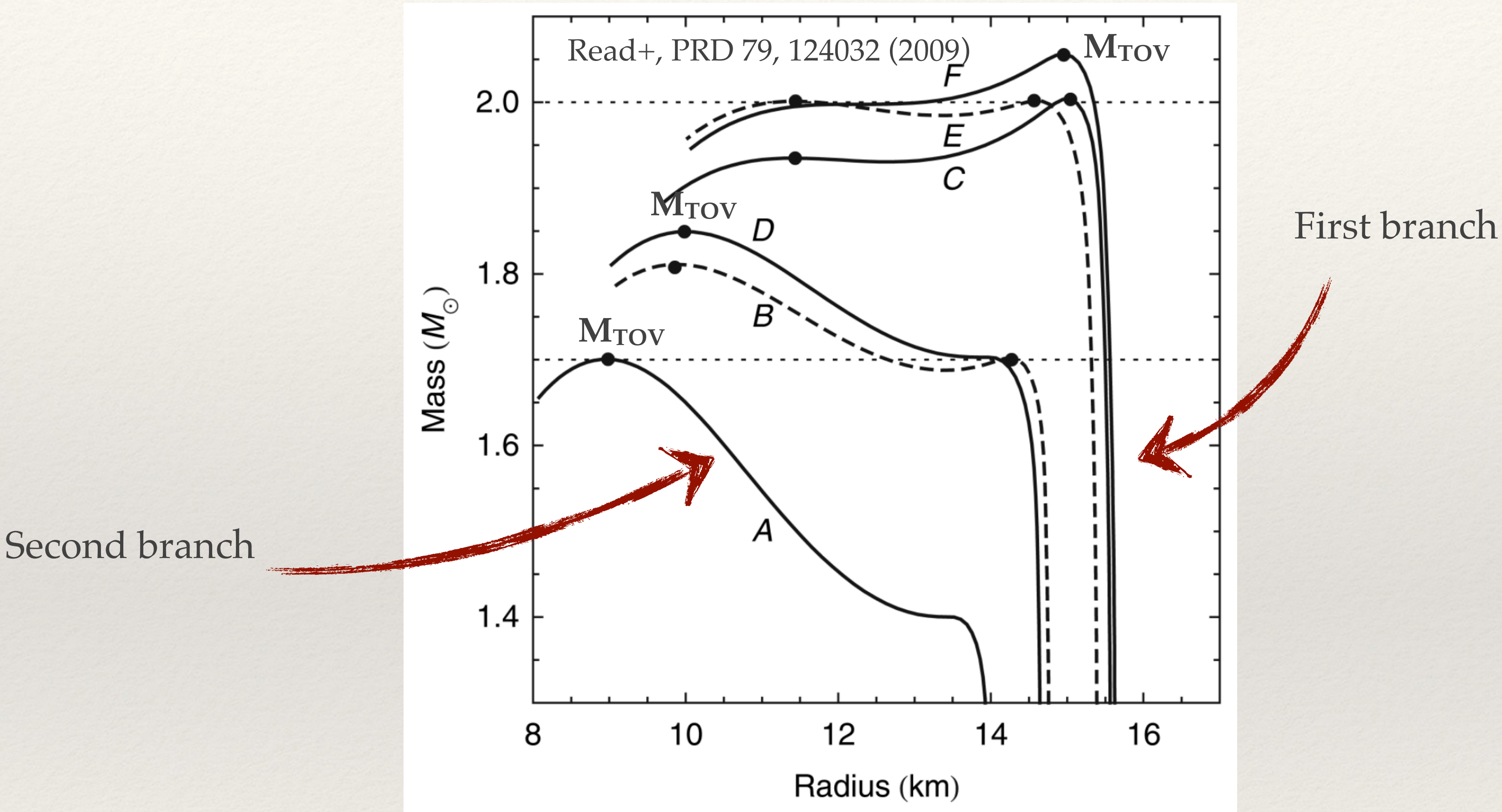
ρ_i and Γ_i are free parameters:

- They can be adjusted to reproduce existing EoS,
- Or they can be tossed randomly in a MCMC exploration.

Read+, PRD 79, 124032 (2009)



MR relations from piecewise polytropes



-> There are maybe 2 branches of neutron stars:
First branch explaining large radii,
Second branch explaining small radii.

This is not specific from piecewise polytopes.
From microscopic understanding, this comes from the onset of a **phase transition** between **nuclear matter** towards an **exotic matter**.

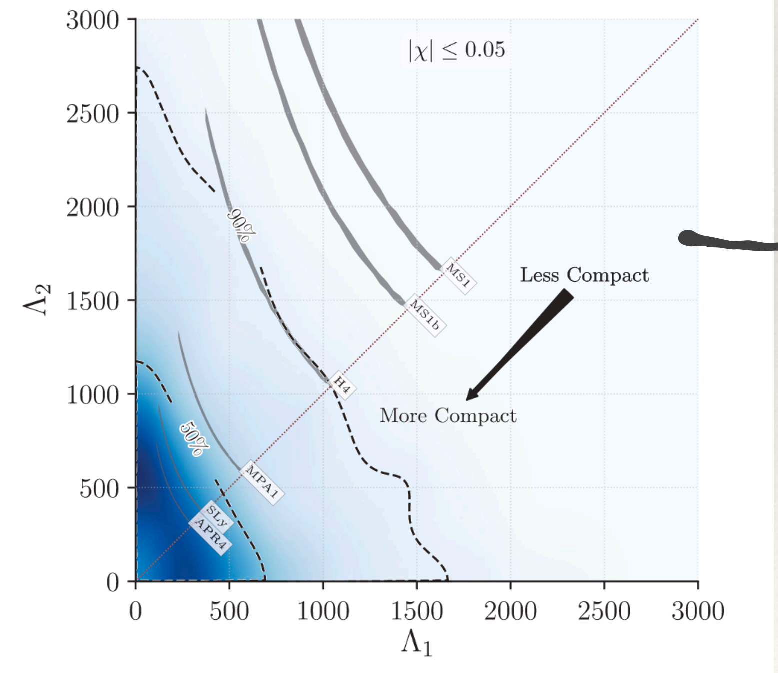
→ Quark matter, or hyperon matter, or …

Agnostic analysis of GW170817

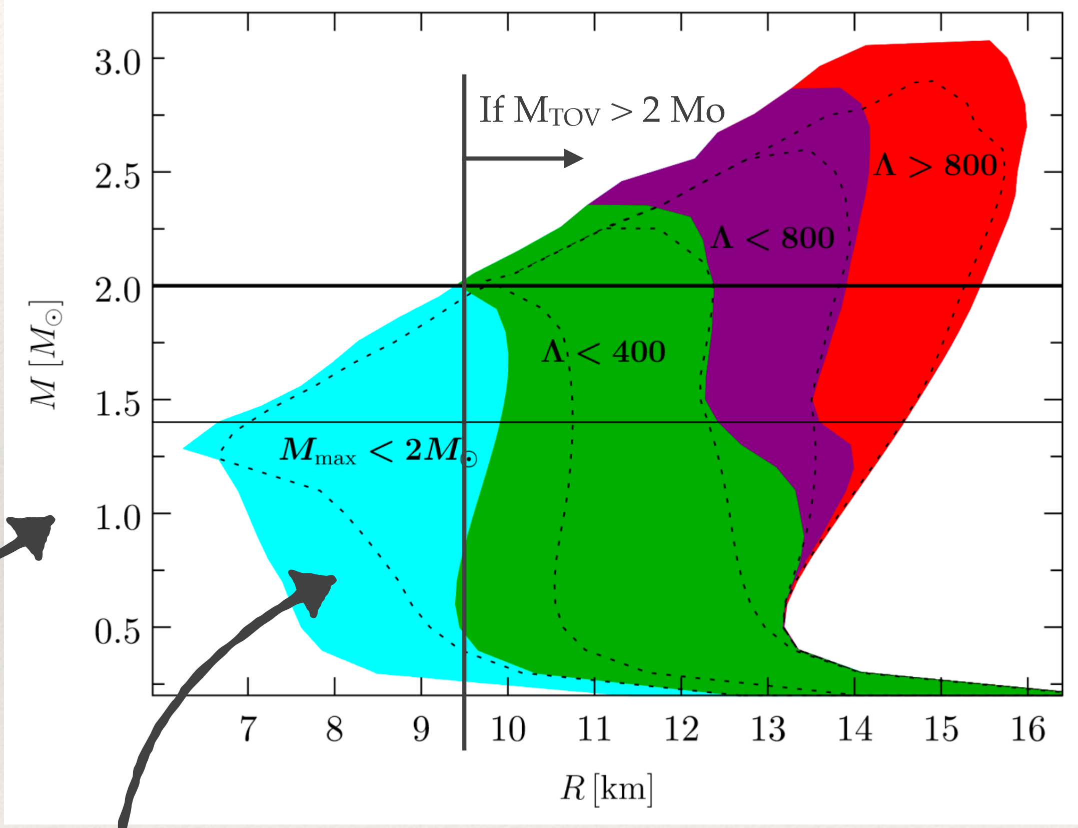
GW170817 detection and analysis in terms of the tidal deformability:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Abbott, LVC Coll. PRL 119, 161101 (2017)



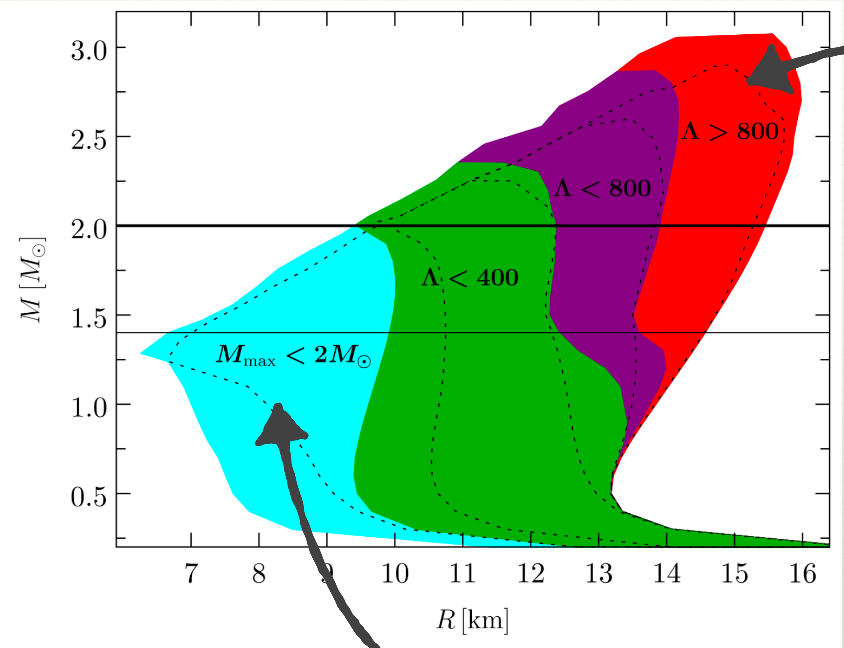
Annala+, PRL 120, 172703 (2018)

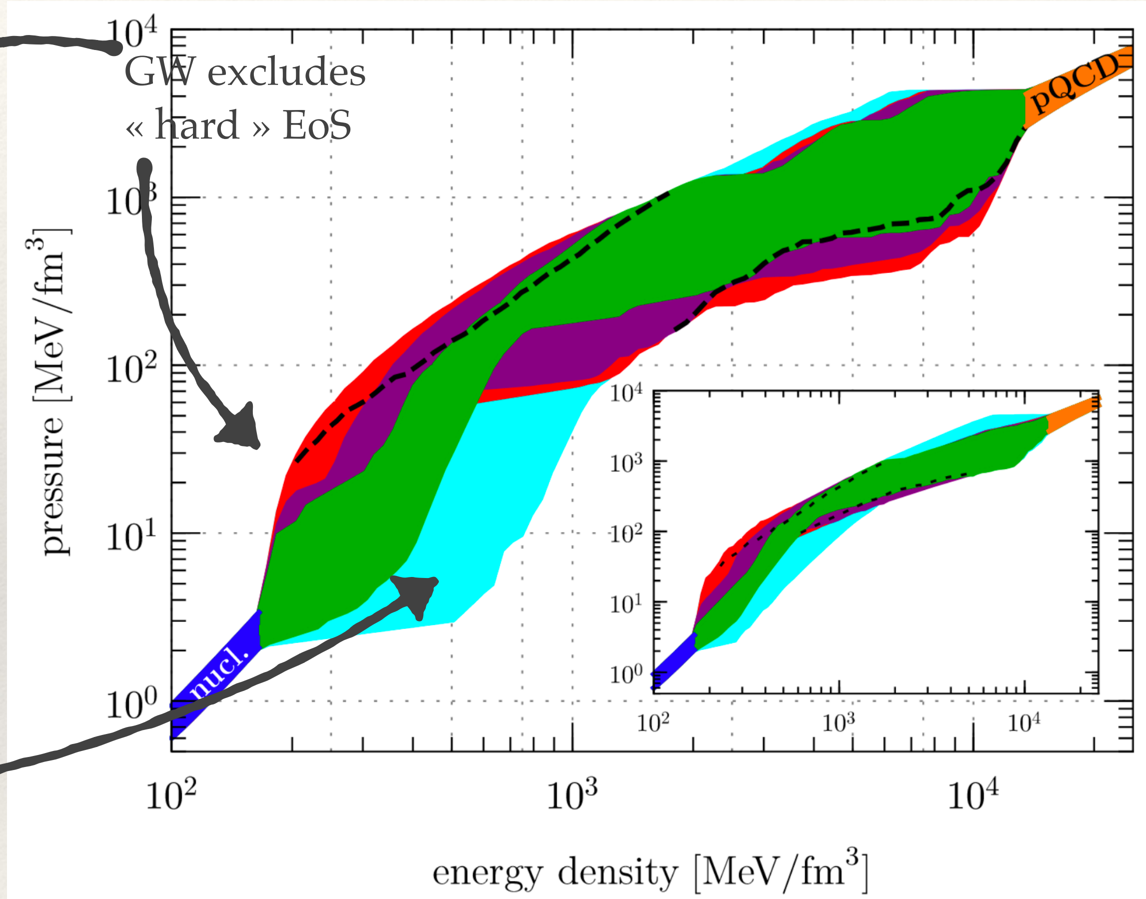


NS with M>2Mo has recently been observed (radio astronomy): -> $M_{TOV} > 2$ Mo

Consequences for extreme matter EoS

Annala+, PRL 120, 172703 (2018)





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 (see talk of S. Antier for more evolved analyses).

Sound speed model (CSM)

The sound speed is defined as: $c_s^2 = \frac{dp}{d\rho}$ (At zero temperature and for a single component)

Introducing the energy density (MeV fm^{-3}): $\epsilon = \rho c^2$ and the number density (fm^{-3}): $n = \rho / m_{nuc}$

From thermodynamic: Chemical potential: $\mu = \frac{d\epsilon}{dn}$ and number density: $n = \frac{dp}{d\mu}$

We deduce: $(c_s/c)^2 = \frac{n}{\mu}\frac{d\mu}{dn}$

Similarly to the piecewise polytopes, one can consider a set of densities where the sound speed is given.

Given $n_0 < n_1 < n_2 < \ldots$ with $c_{s,0}^2, c_{s,1}^2, c_{s,2}^2$ well chosen (to reproduce existing model or to explore uncertainties), one can obtain:

$$\mu(n) = \mu_i \left(\frac{n}{n_i}\right)^{c_{s,i}^2} \qquad \epsilon(n) = \epsilon_i + \int \frac{d\epsilon}{dn'} dn' = \epsilon_i + \int \mu(n')dn'$$

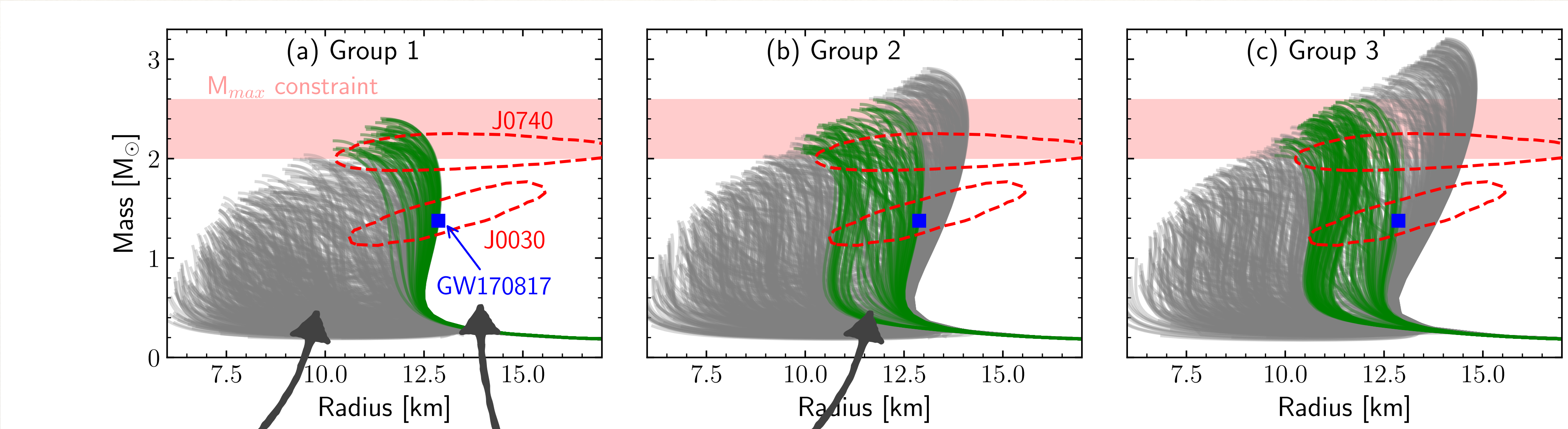
$$p(n) = p_i + \int \frac{dp}{dn'} dn' = p_i + \int \frac{dp}{d\epsilon}\frac{d\epsilon}{dn'} dn' = p_i + c_{s,i}^2 \int \mu(n')dn'$$

Tews+, ApJ 860, 149 (2018)

Sound speed structure from NS observations

Agnostic approach based on the sound speed approach.

[Somasundaram+, arXiv 2022]



Prior

Posterior

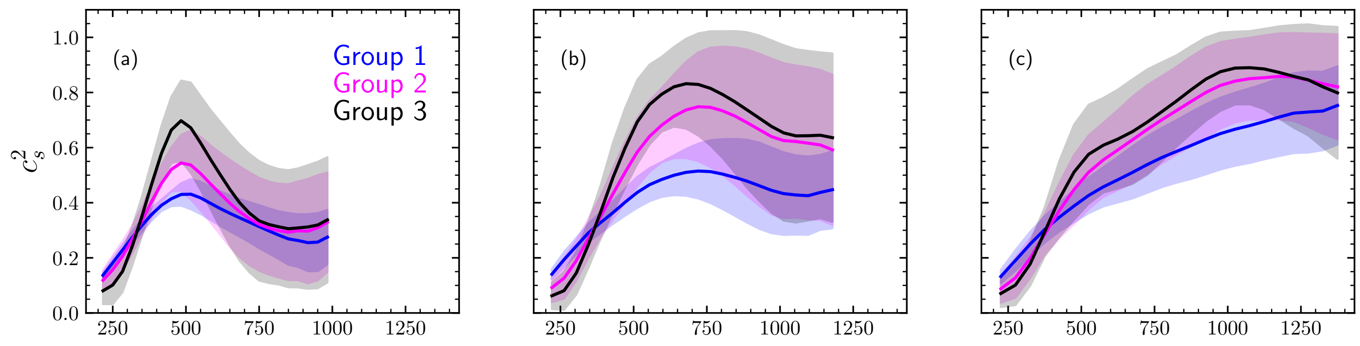
NS observations

The groups reflect the slope of the sound speed:

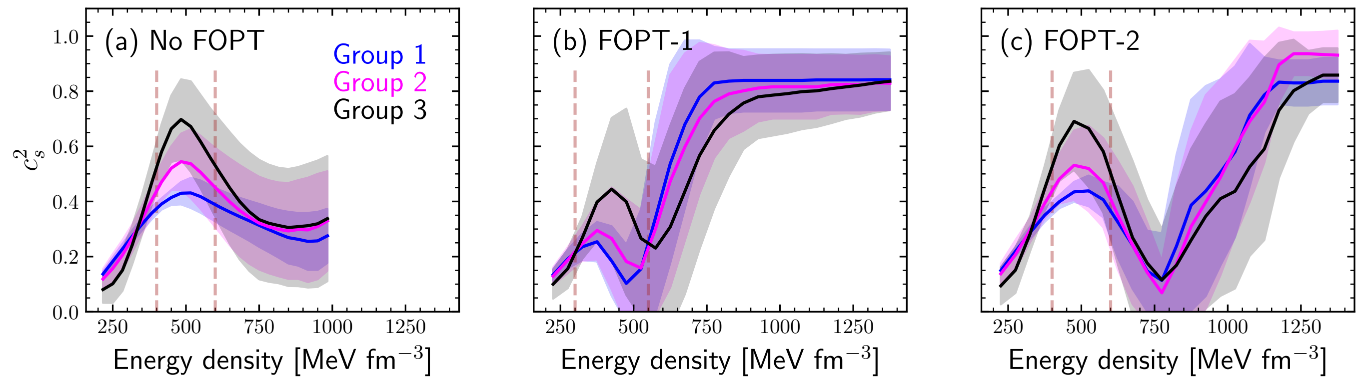
Increasing slope of c_s

Sound speed structure from NS observations

Increasing slope of c_s

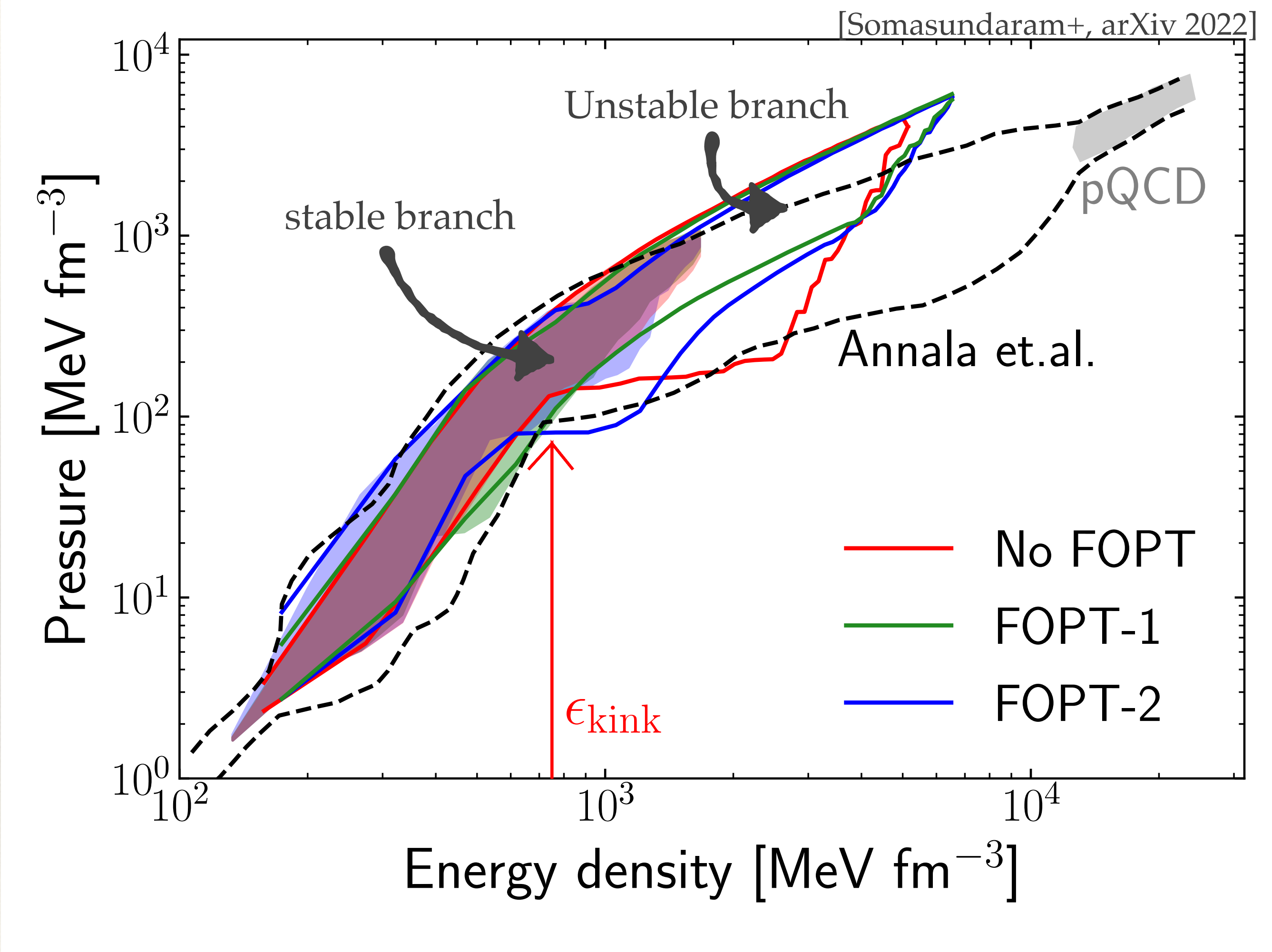


First order phase transition (FOPT) explicitly considered



[Somasundaram+, arXiv 2022]

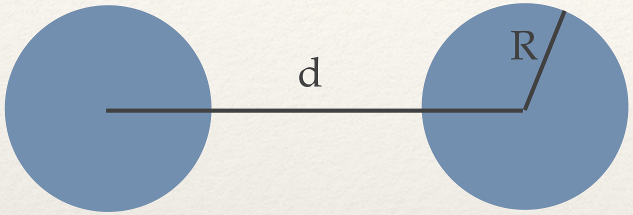
Impact on the EoS



—> astrophysical information to date do not necessarily require a phase transition to exotic (quark) matter.

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 $n \approx 0.5 \text{fm}^{-3} \approx 3n_{sat}$

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

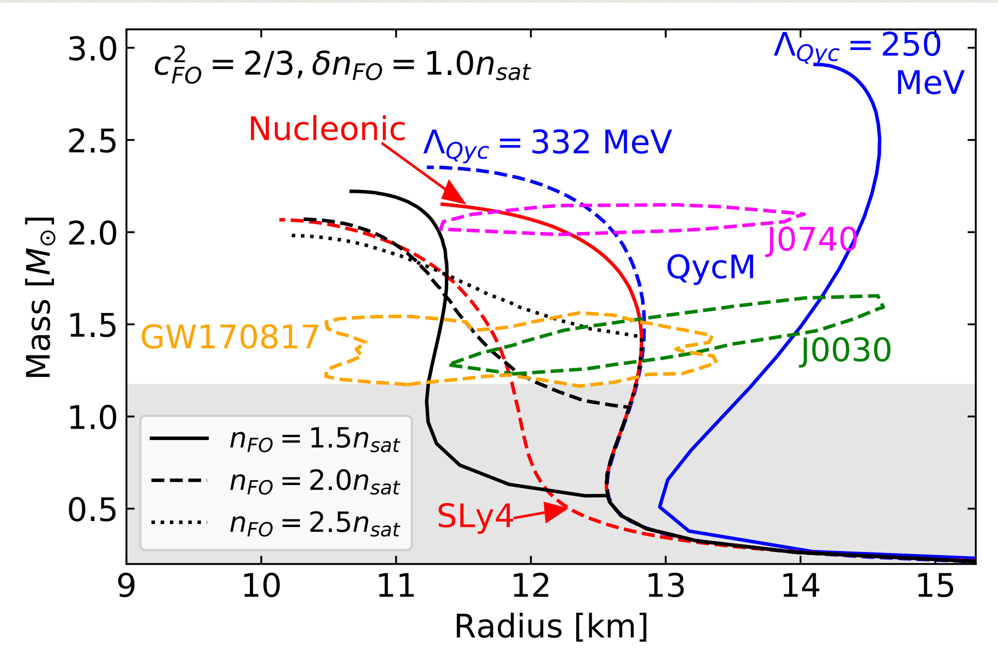
Heavy neutron stars may have a quark core.
Can it be proven by observations?

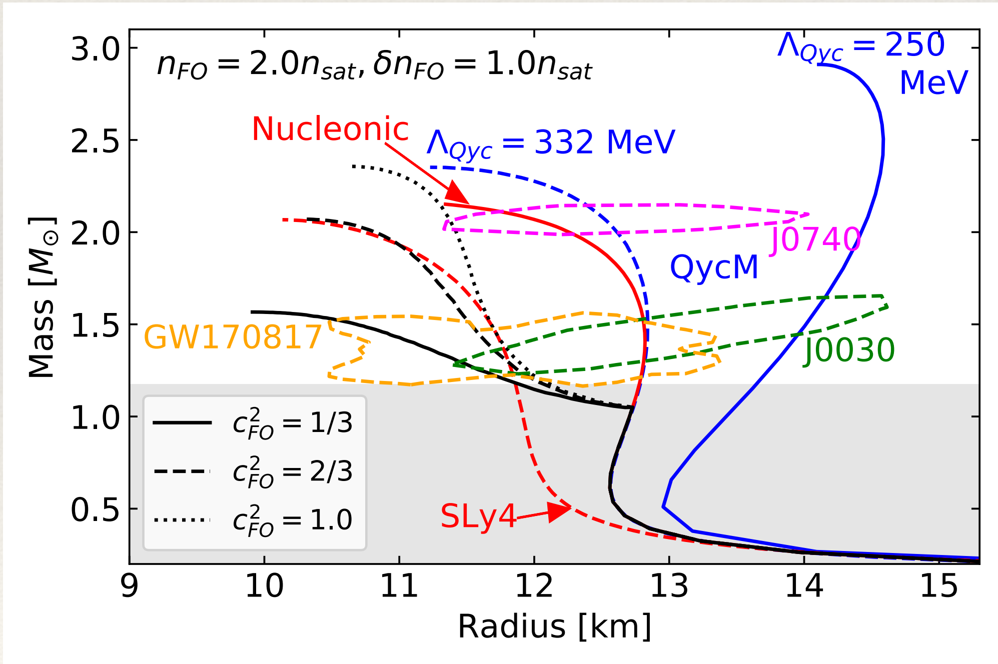
Phase transition(s) in NS

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

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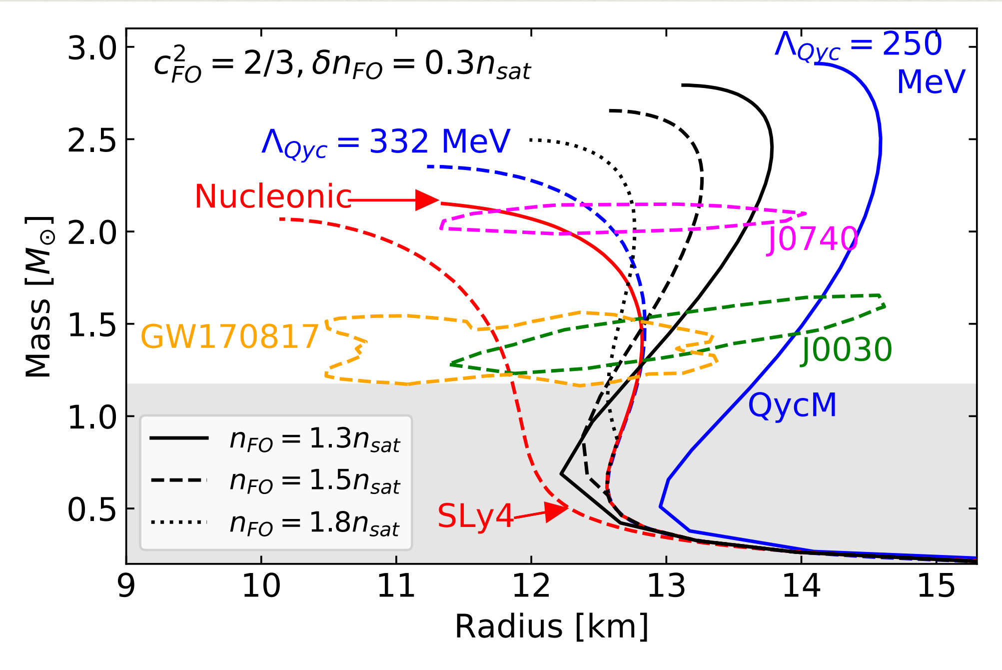
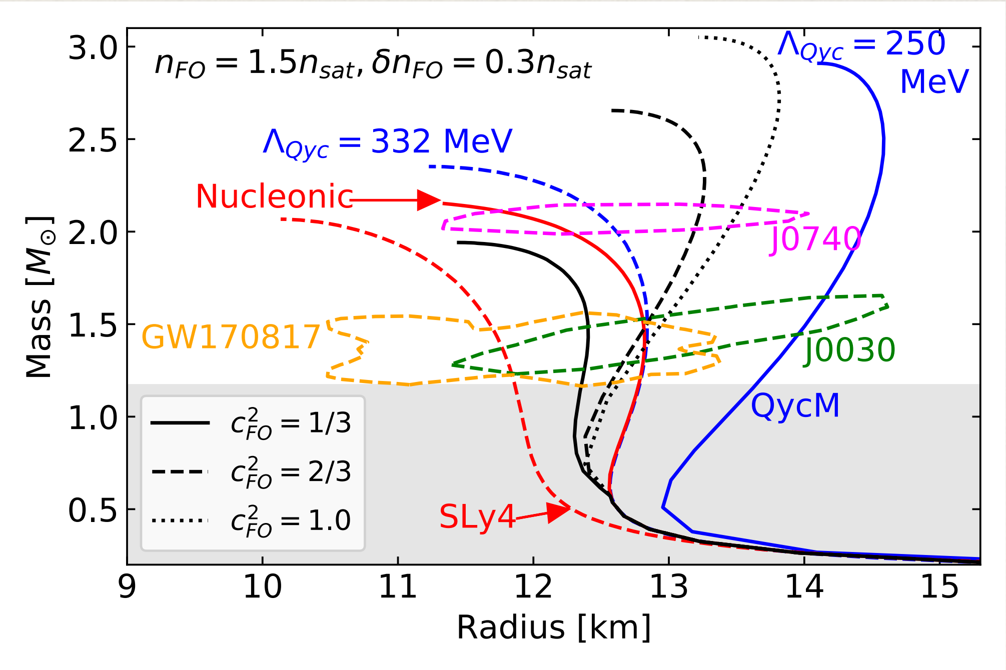




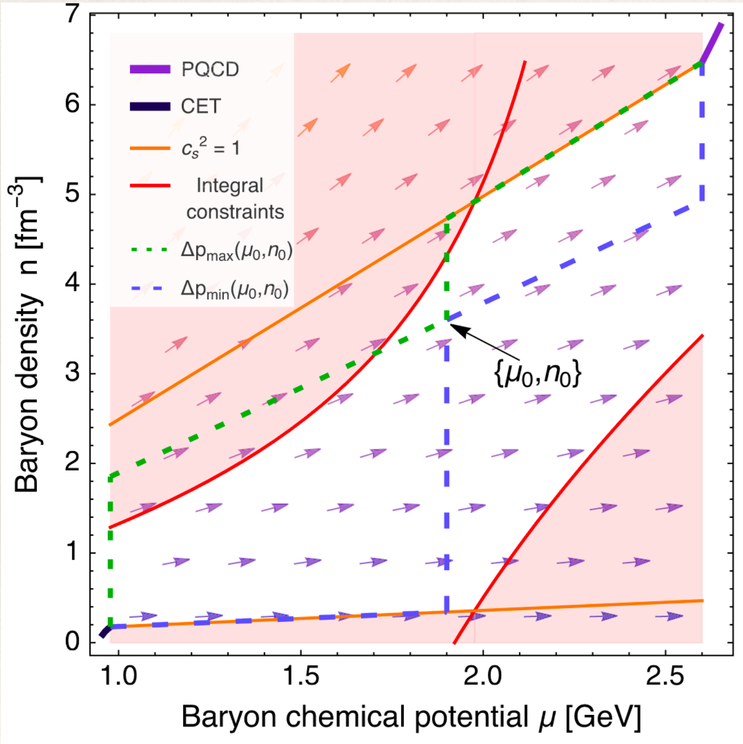
If the FOPT occurs at low density —> masquerade Qyc and produce bigger stars.

Connection to pQCD at high density

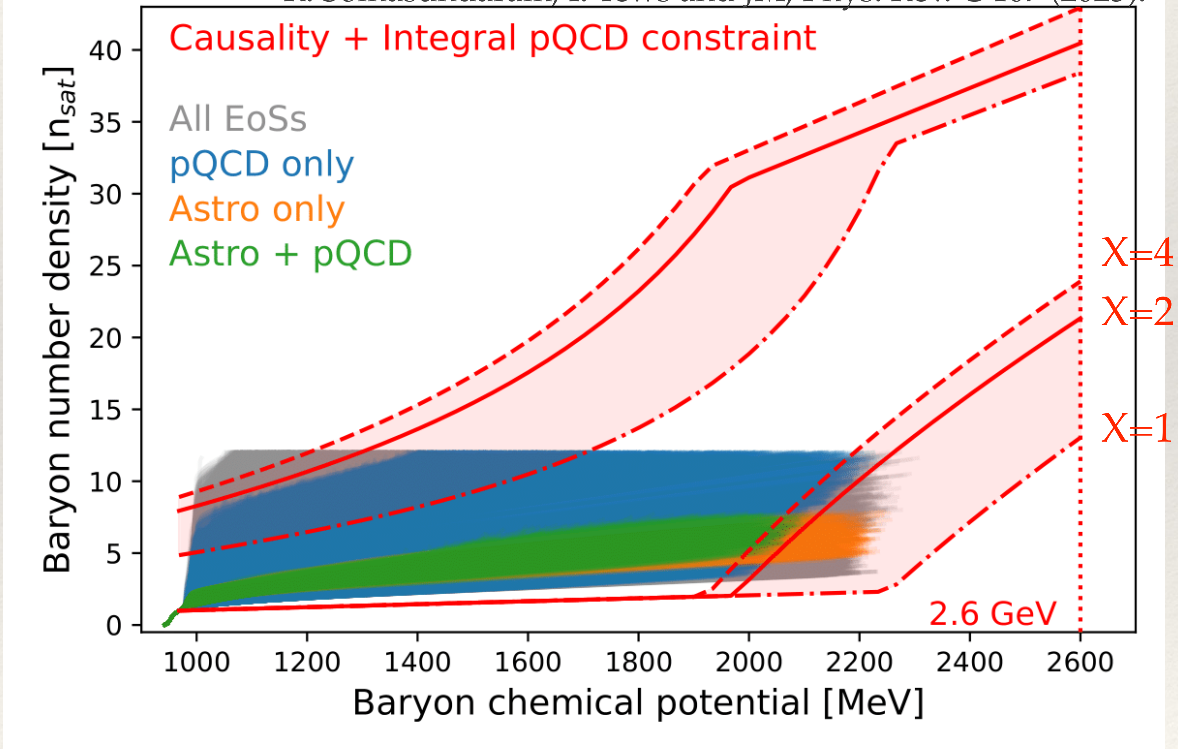
Crust EOS

+ 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, Phys. Rev. C 107 (2023).



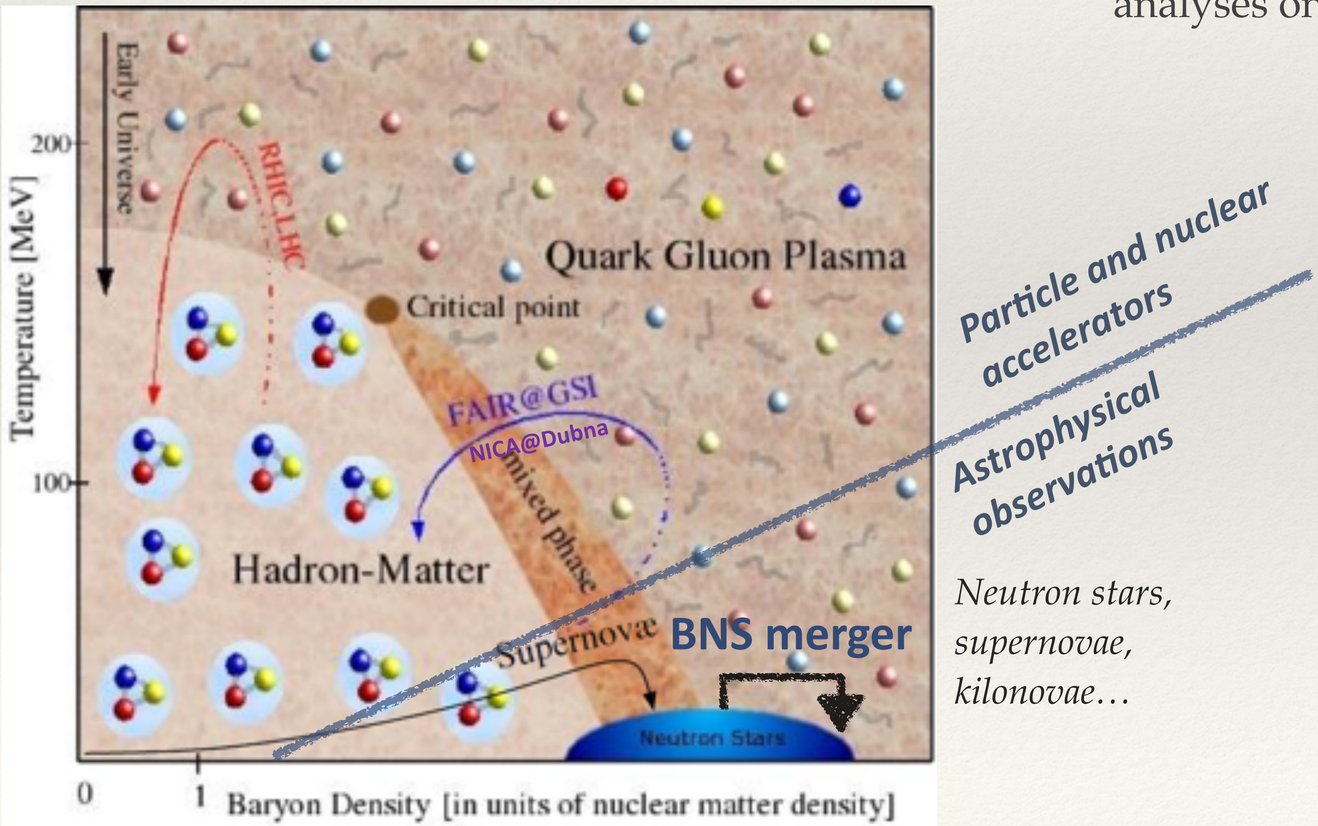
Constraints from astrophysical observations are still better than pQCD.
Note opposite conclusions from Gorda, Komoltsev and Kurkela, arXiv:2204.11279.

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_{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.



Neutron stars, supernovae, kilonovae…

Outlook for the future

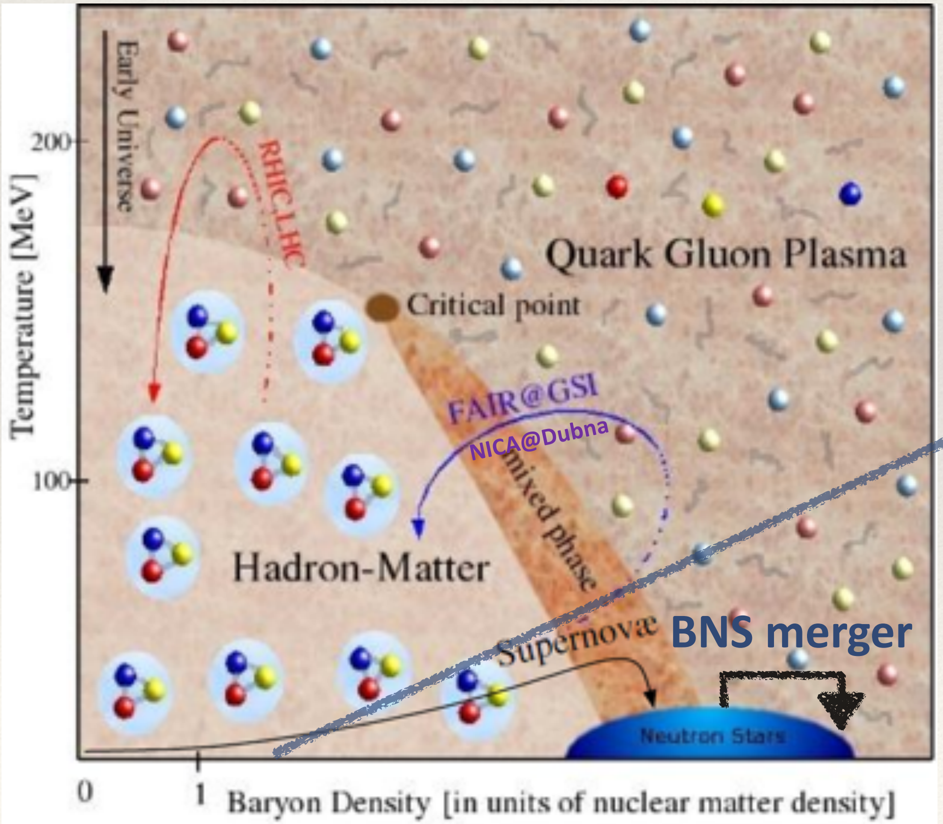
The nuclear physics community is ready for the future new data from nuclear physics and from astrophysics.

Question we want to answer:

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

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

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



Particle and nuclear accelerators

Astrophysical observations

Neutron stars, supernovae, kilonovae…

Future questions:

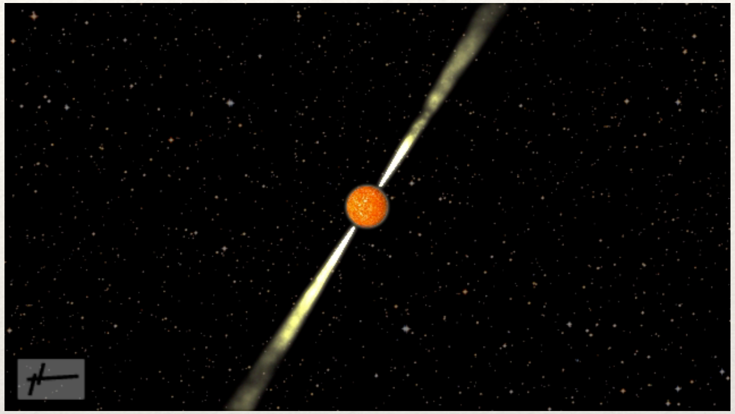
How **neutrinos** propagate? What are the **transport properties** of extreme matter?

Are BNS the main astrophysical site

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
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Milano U.: Gianluca Colò.
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Ferrara U.: Alessandro Drago, Giuseppe Pagliara.
Catania INFN: Hans-Josef Schulze, Isaac Vidaña.

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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.