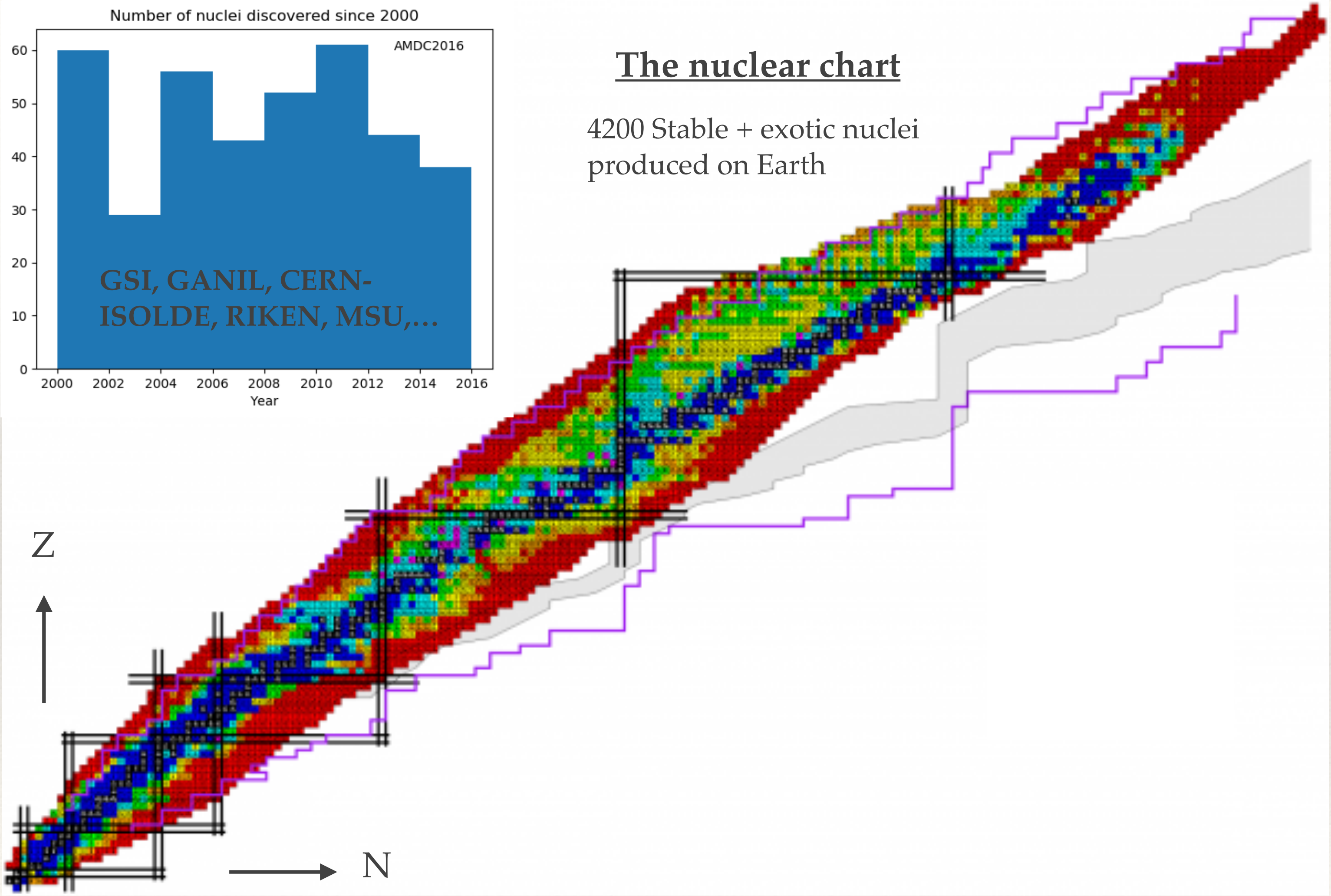
*Gravity seminar, University of Southampton, December 2020*

# Impact of recent neutron star observations on the dense matter equation of state

Jérôme Margueron
iP2i Lyon

*Combining together nuclear physics and astro-observations to better understand dense matter properties.*

# Nuclear physics: from nuclei to dense matter



GSI, GANIL, CERN-ISOLDE, RIKEN, MSU,…

**The nuclear chart**

4200 Stable + exotic nuclei produced on Earth

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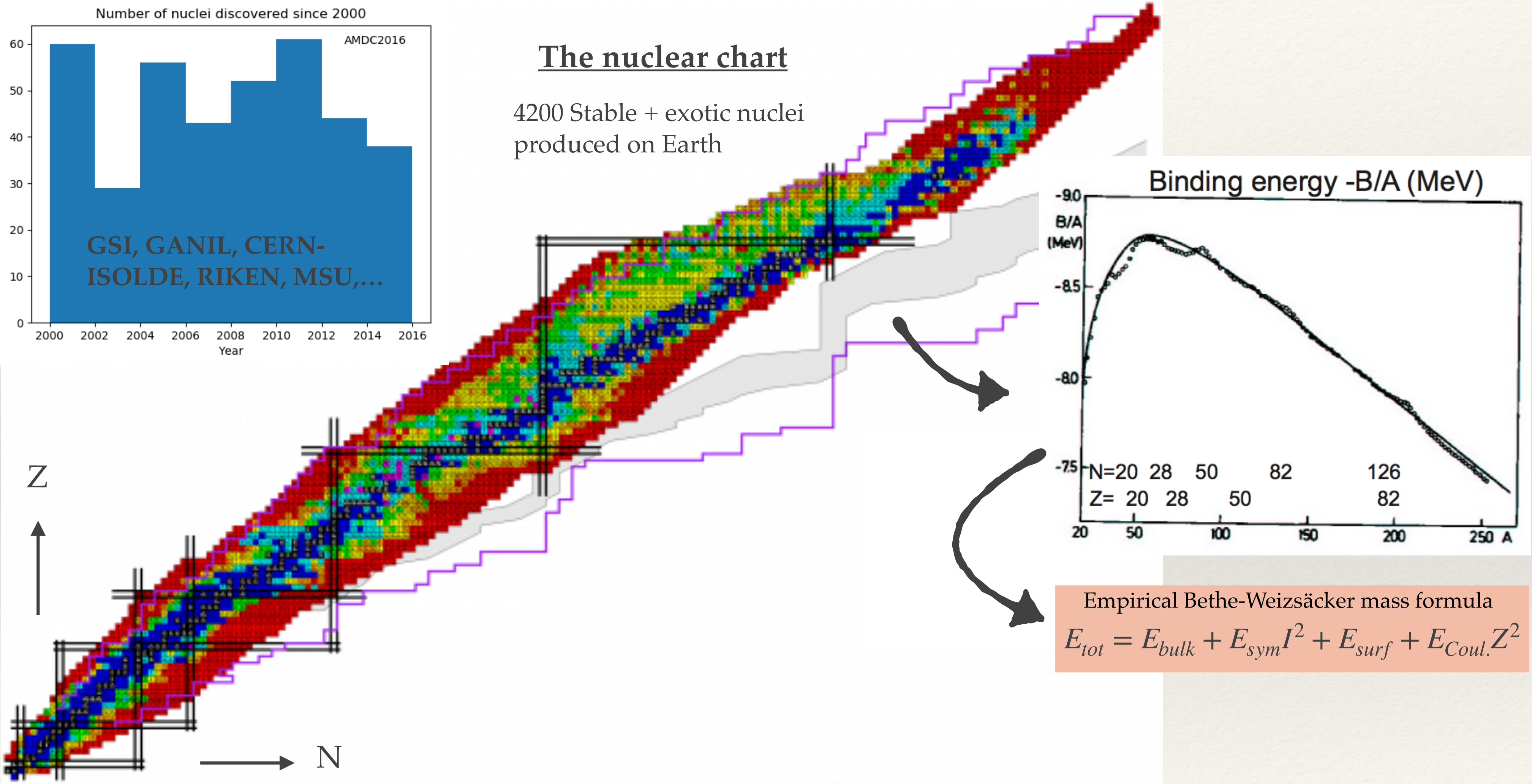

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Empirical Bethe-Weizsäcker mass formula

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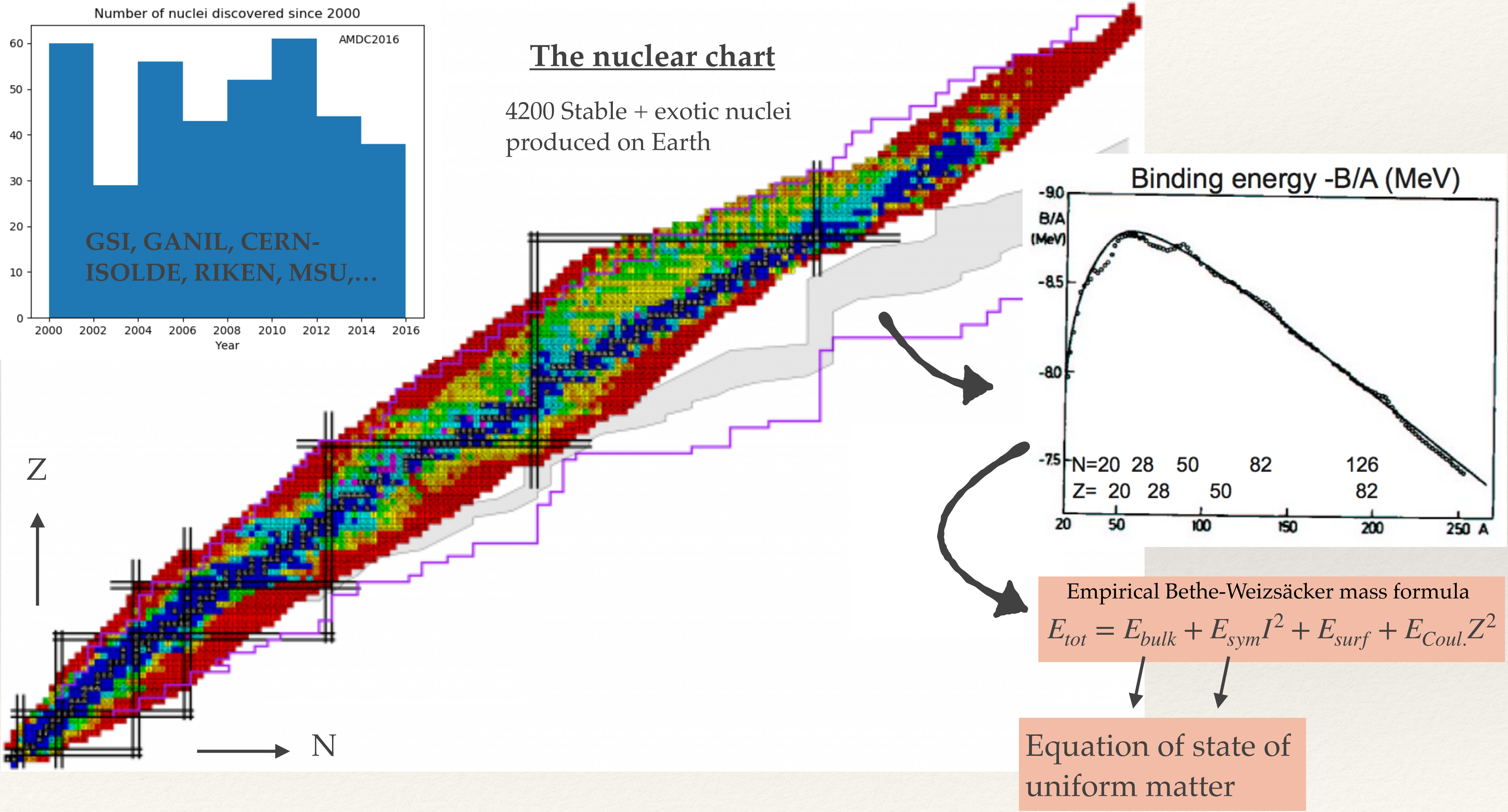

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Equation of state of uniform matter

**Complemented by EDF, EFT, etc…**

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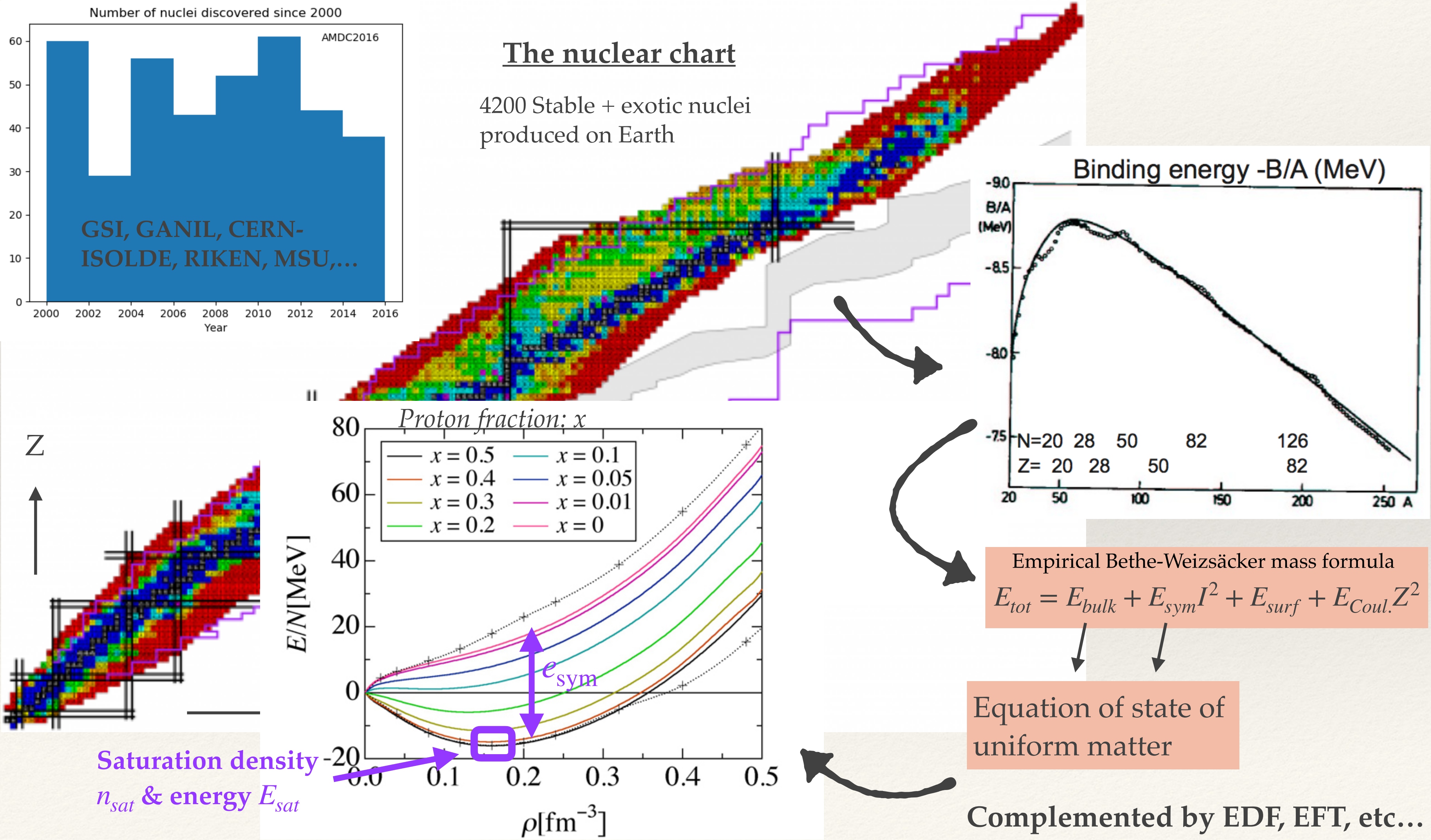

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Equation of state of uniform matter

**Saturation density $n_{sat}$ & energy $E_{sat}$**

**Complemented by EDF, EFT, etc…**

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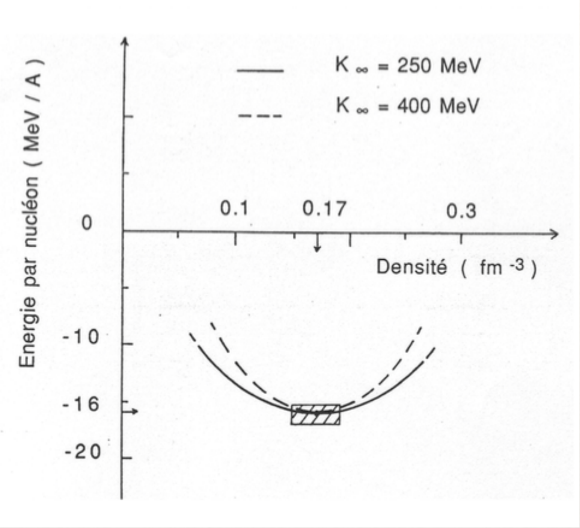
**Density dependence of the energy around $n_{sat}$**



Compressible liquid-drop: $B(\rho) \approx B(\rho_0) + \frac{1}{2} K_\infty \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2$

**Incompressibility**

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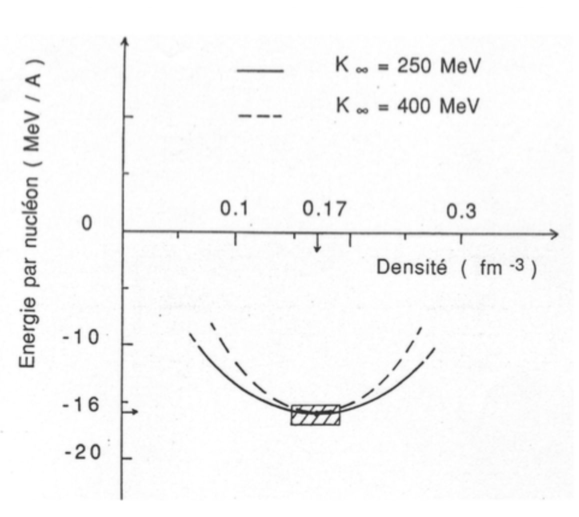

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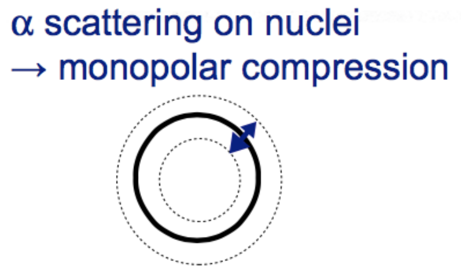
**Incompressibility**

**How incompressibility is measured?**


α scattering on nuclei
→ monopolar compression

Measured in different nuclei

Extracted

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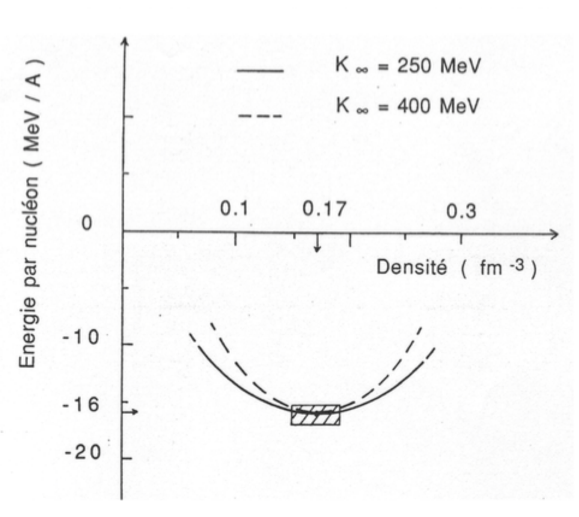

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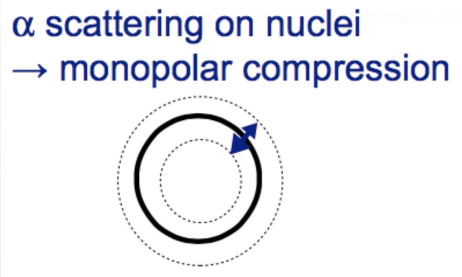
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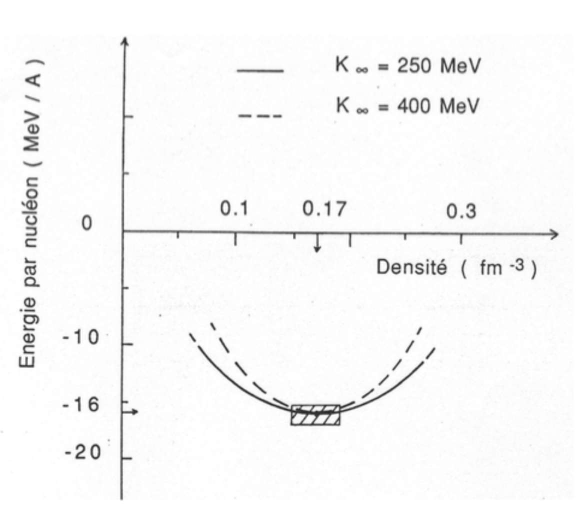

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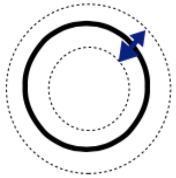

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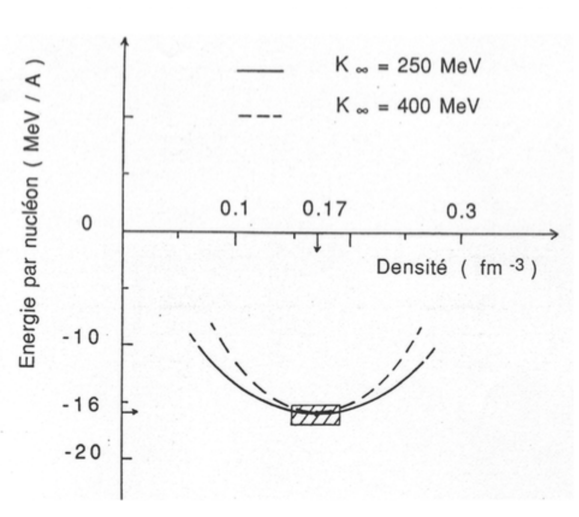

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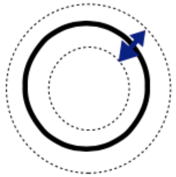

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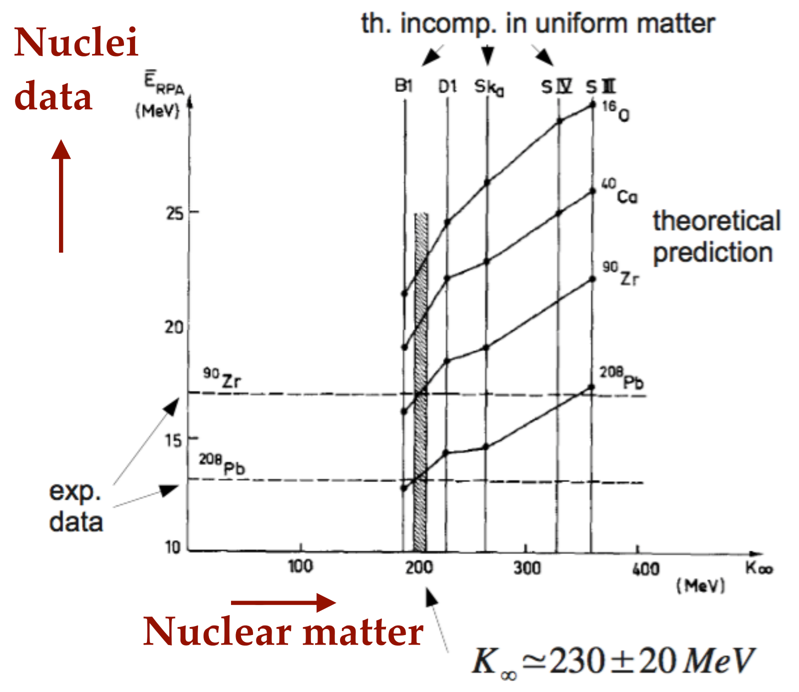

$K_\infty \simeq 230 \pm 20\ MeV$

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

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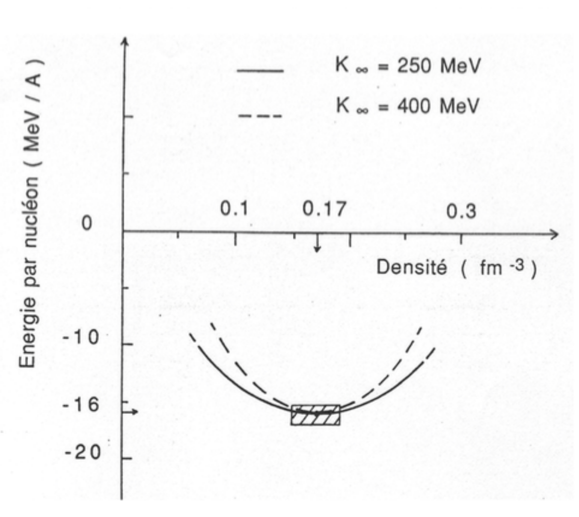

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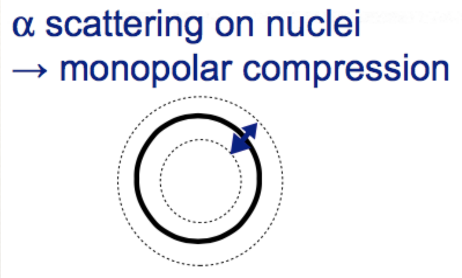
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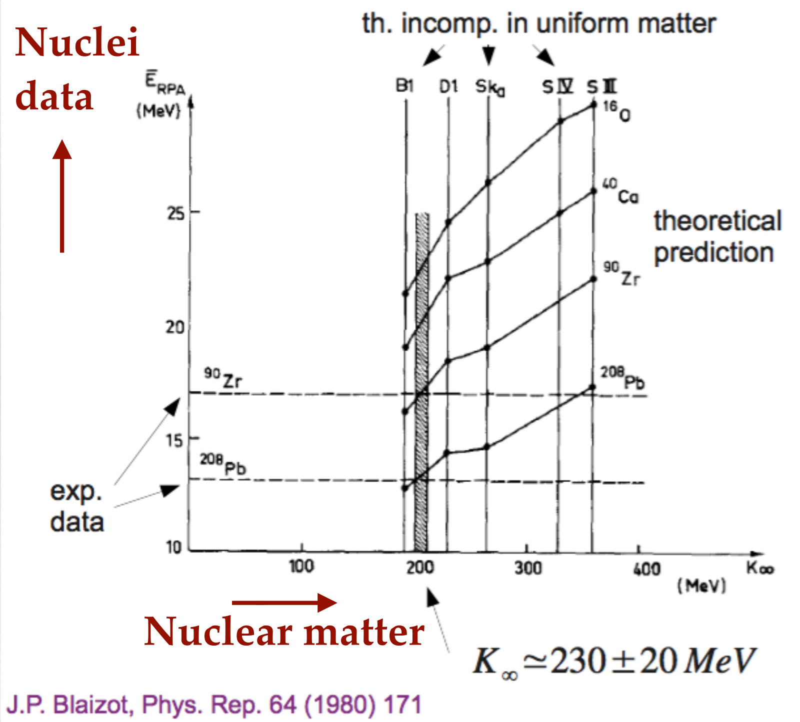

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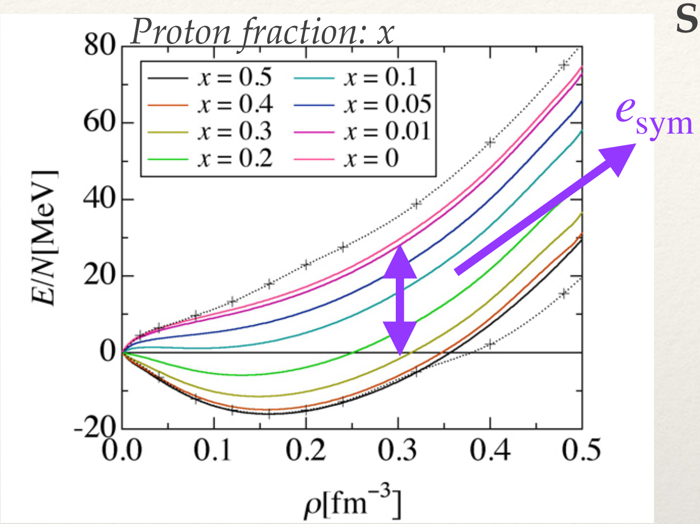
**Model dependence?**

[Khan, JM, Vidaña PRL 2012]

# Nuclear physics: towards neutron stars



**Symmetry energy**

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Difference between PNM and SNM

[Ex: Somasundaram+ arXiv:2009.04737]

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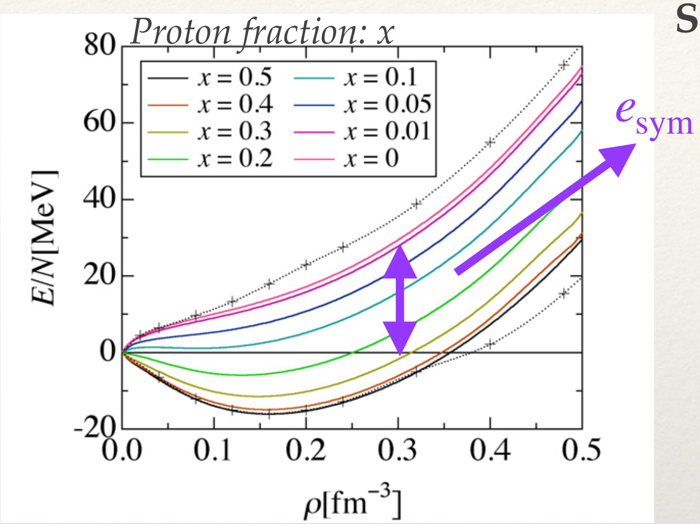

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Major impact on the **beta equilibrium** in neutron stars

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

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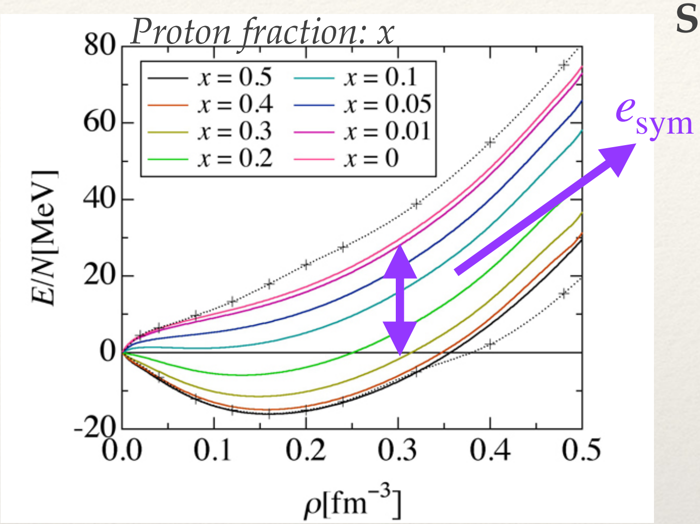

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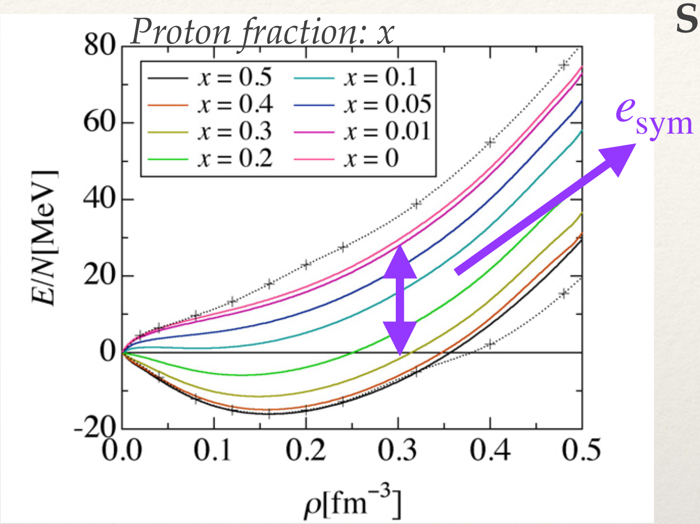

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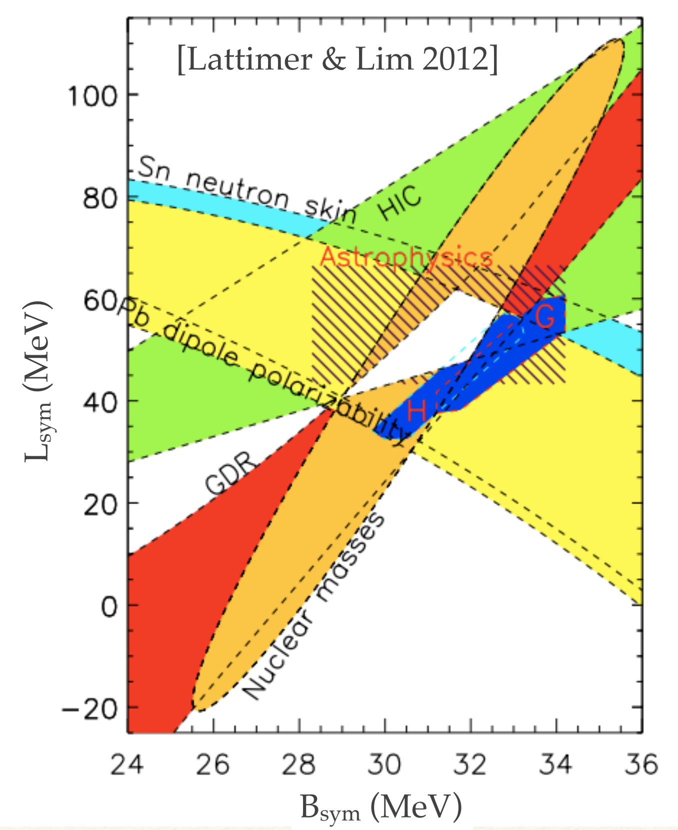
**Slope of the symmetry energy (density dependence):**

$$L_{sym} = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho}$$



# Nuclear Empirical Parameters (NEP)

**Energy in asymmetric matter:**

$$\frac{E}{A}(n,\delta) \approx e_{\mathrm{sat}}(n) + e_{\mathrm{sym},2}(n)\delta^2 + e_{\mathrm{sym},4}(n)\delta^4 + \ldots$$

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

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

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Small uncertainties

Large uncertainties

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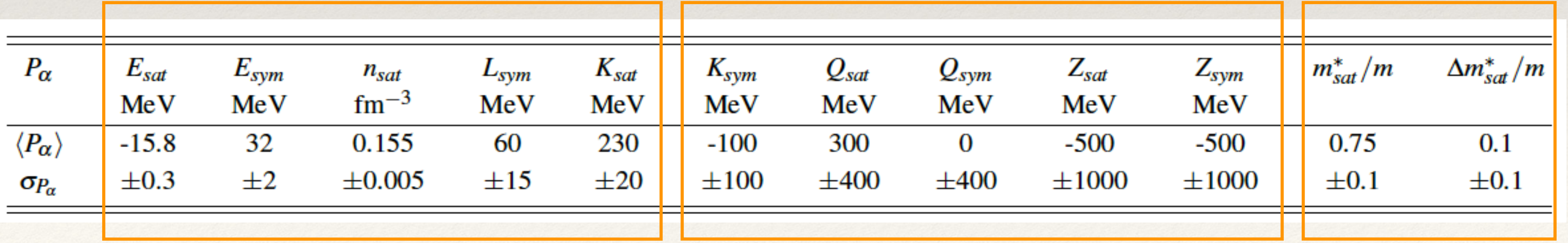


| $P_\alpha$ | $E_{sat}$ MeV | $E_{sym}$ MeV | $n_{sat}$ fm$^{-3}$ | $L_{sym}$ MeV | $K_{sat}$ MeV | $K_{sym}$ MeV | $Q_{sat}$ MeV | $Q_{sym}$ MeV | $Z_{sat}$ MeV | $Z_{sym}$ MeV | $m^*_{sat}/m$ | $\Delta m^*_{sat}/m$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\langle P_\alpha \rangle$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

[JM, Casali, Gulminelli, PRC 2018]

Small impact at T=0

⚠ There are correlations among these parameters

# Impact of high order NEP on correlations

[JM, Gulminelli PRC 2019]

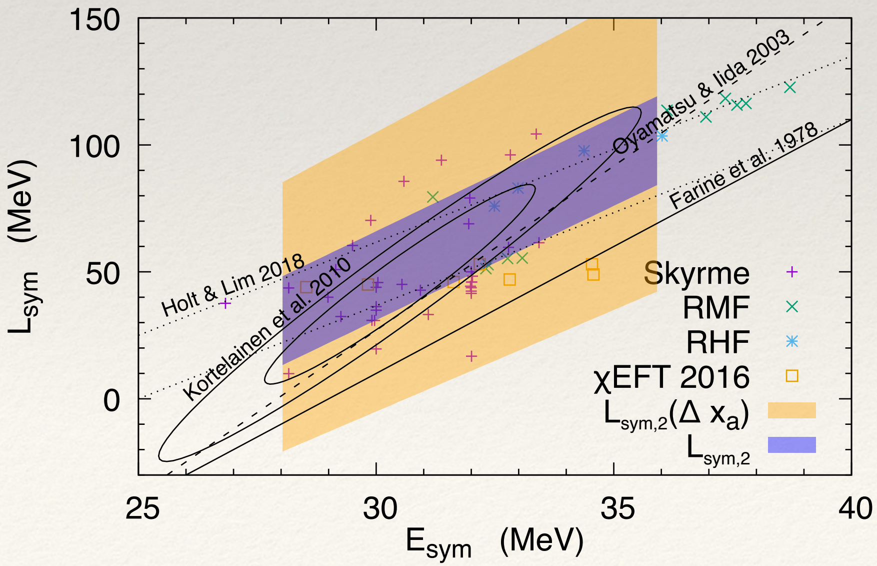
**Nuclear exp.**

$$E_{sym}^a = E_{sym}(n_a \approx 0.1 fm^{-3}) = 24.1 \pm 0.8 \text{ MeV}$$

[Colò, Garg, Sagawa, EPJA 2014
Trippa, Colò, Vigezzi, PRC 2008]

$$\boxed{L_{sym,i} = \beta_{EL} E_{sym} + \alpha_{EL,i}}$$

where $\alpha_{EL,4} = -x_a^{-1} E_{sym} + \frac{x_a}{2} K_{sym} + \frac{x_a^2}{6} Q_{sym} - \frac{x_a^3}{24} Z_{sym} + \dots$

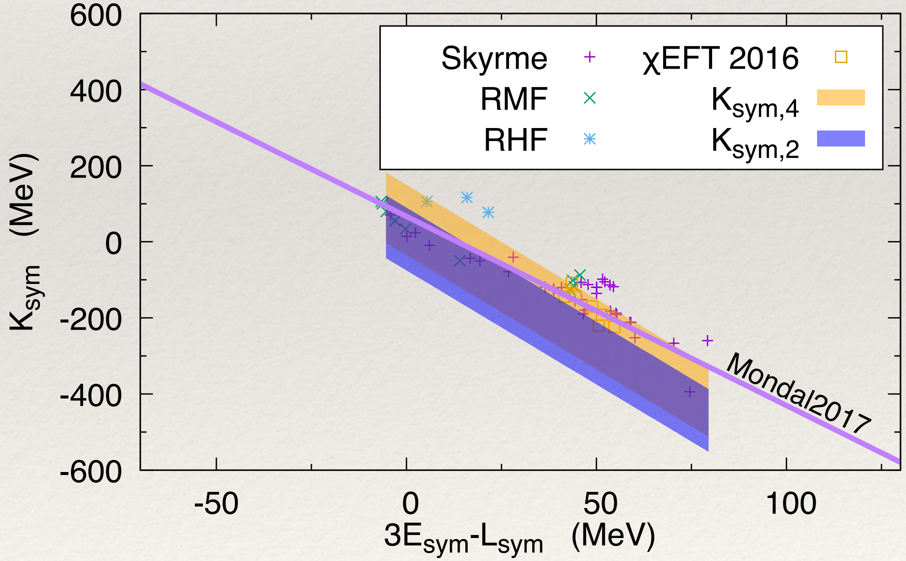


$$e_{NM}(n=0) = 0 \text{ MeV}$$

~~Undetermined reason~~

$$\boxed{K_{sym} = \beta(3E_{sym} - L_{sym}) + \alpha}$$

[Mondal+ PRC 2017]



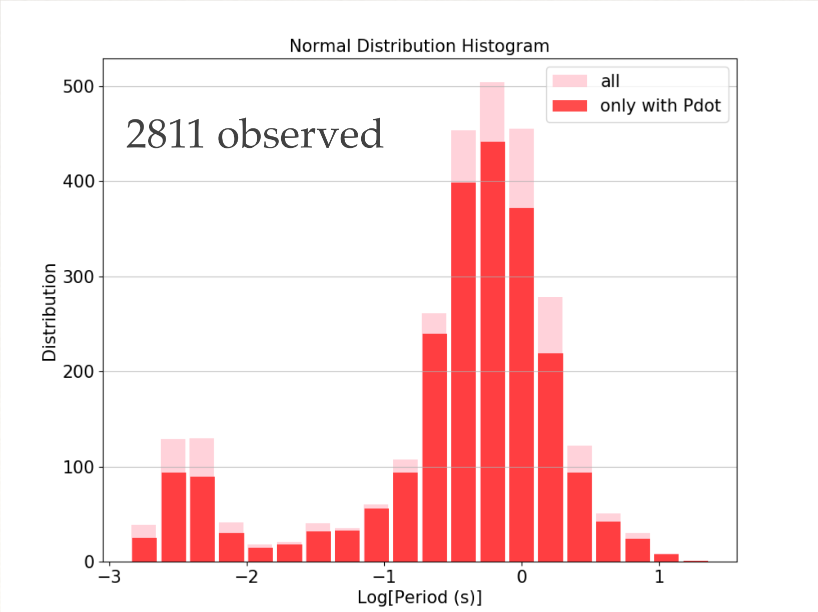
# What is a neutron star?

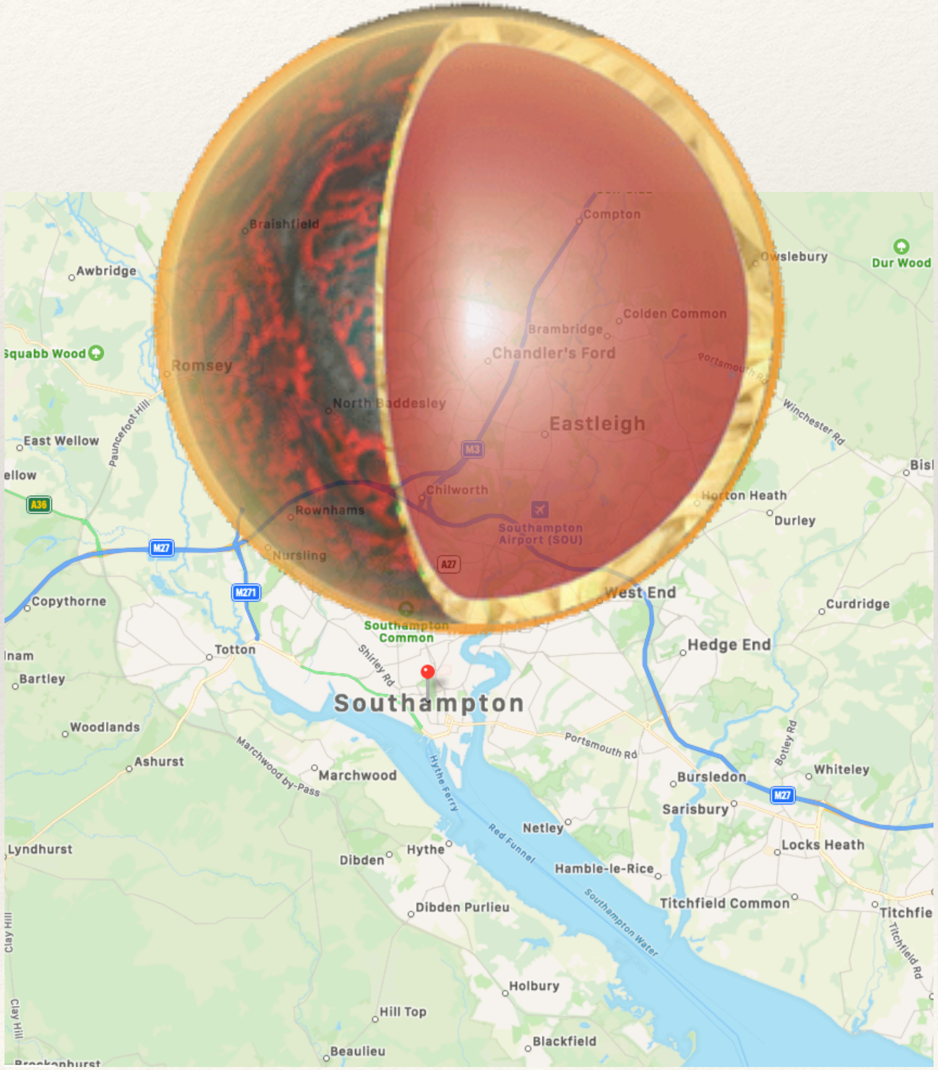
**Main properties:**

M # 1 - 2 $\mathrm{M}_o$ Average density # $10^{15}$ g cm$^{-3}$

R # 10 - 14 km B # $10^{12}$ - $10^{16}$ G

- Aftermath of a core-collapse supernovae,
- Isolated or in binary,
- Could be a pulsar: from radio to/or $\gamma$-rays,
- X-ray emission from accretion disk,
- Fast spinning.





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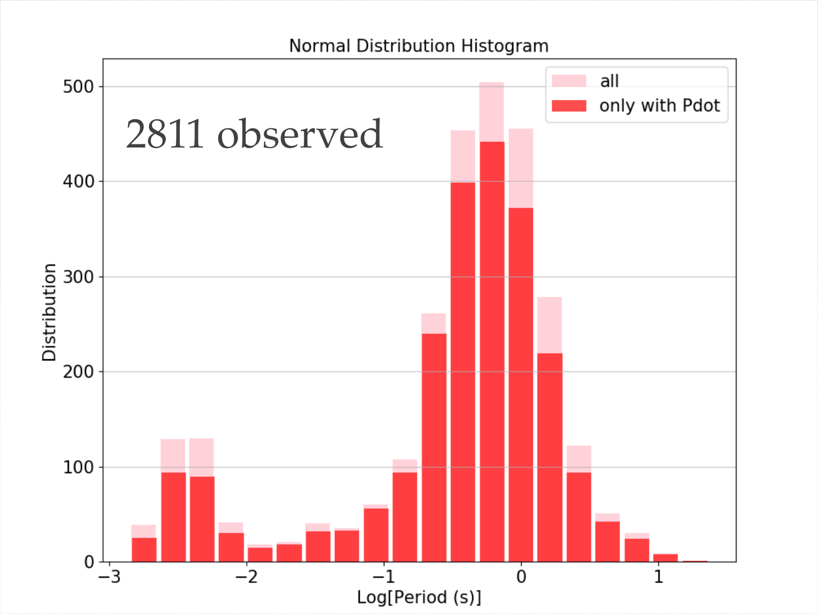
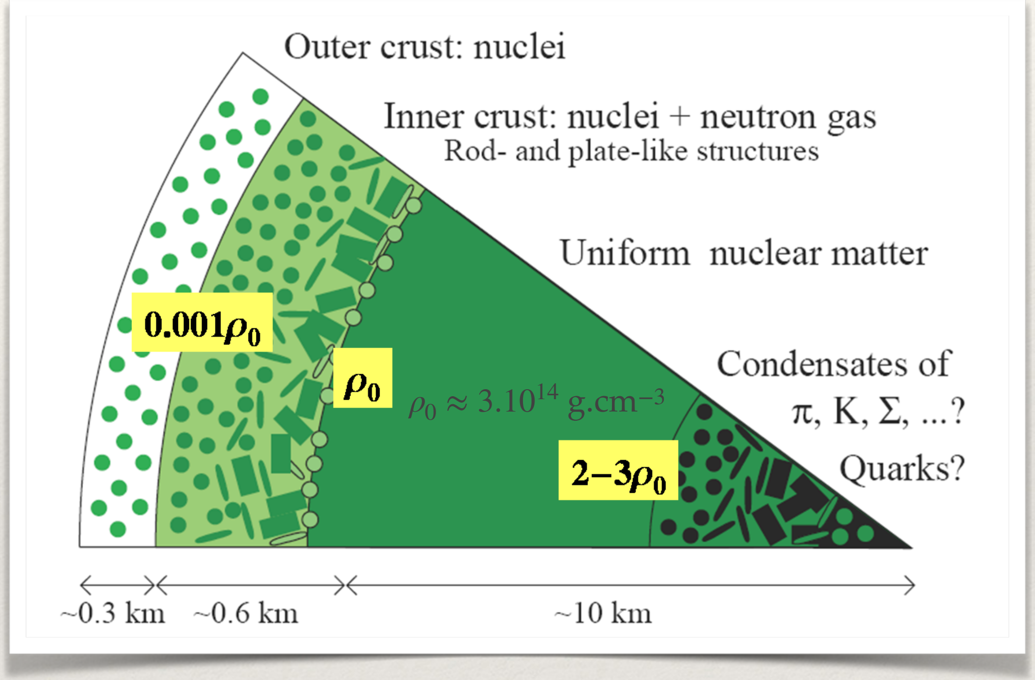


## Neutron star composition:

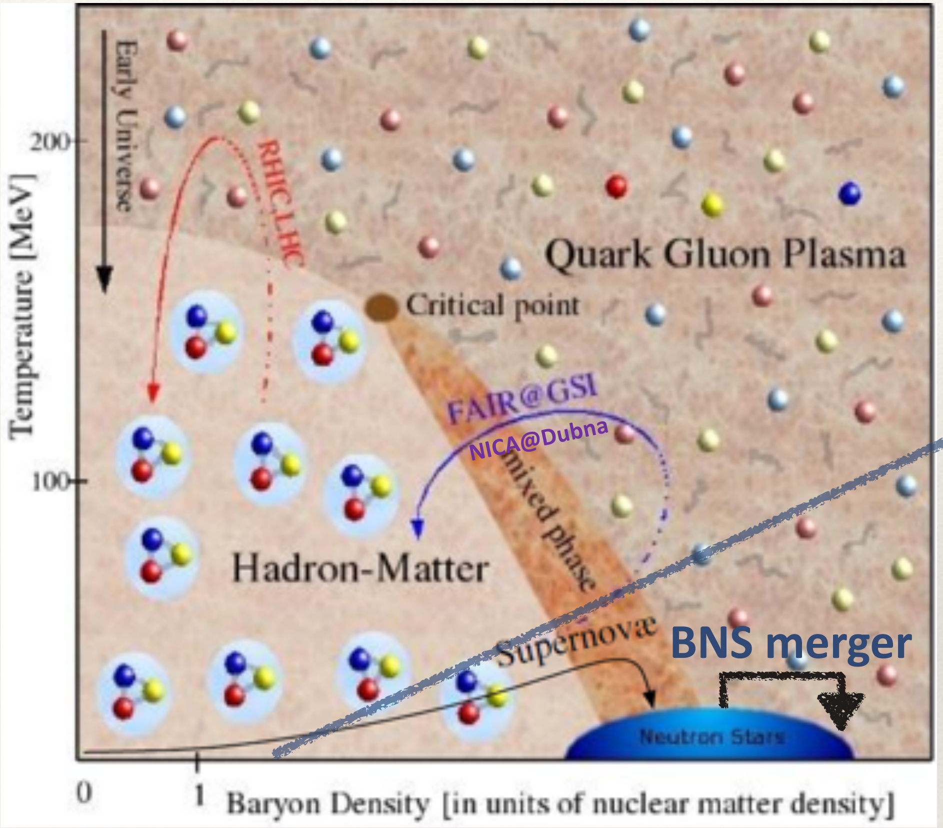


Requires the knowledge of dense matter equation of state.

**-> Two main questions for nuclear physicists:**

- How accurate is the nuclear physics knowledge?
- Is there a phase transition to hyperon matter or quark matter at high density?

# Probing extreme matter physics with GW

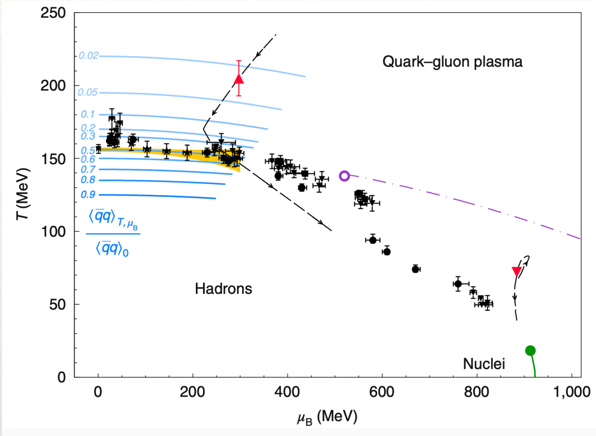


*Particle and nuclear accelerators*

*Astrophysical observations*

*Neutron stars, supernovae, kilonovae…*

**Heavy Ion collision**



[Hades, Nature phys. 2019]

**Probe limits of extreme matter**

**Questions to be answered:**

What is the **nuclear interaction** in dense, isospin asymmetric matter, hot?

Which **new particles** appear at supra-saturation densities?

At which density occurs the **deconfinement** from hadrons to Quarks-Gluons Plasma (QGP)?

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

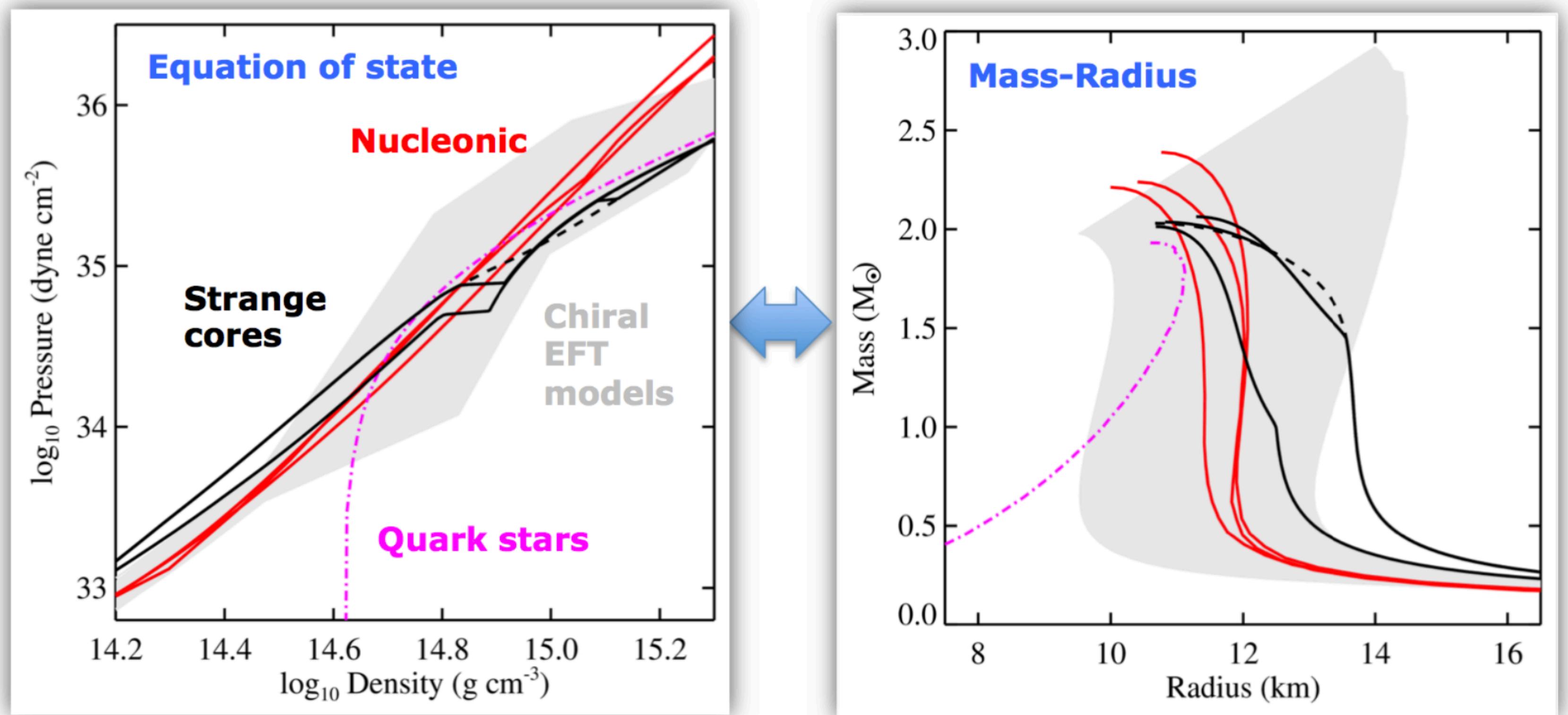
Are BNS the main astrophysical site for the **r-process**?

# EoS [nuclear] <=> (M,R) [astro]

**Tolmann-Oppenheimer-Volkov (TOV) GR equations**

P(n)

(M,R)($n_c$)



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

Reverse engineering,
Bayesian statistics

# A semi-agnostic approach for the nuclear EoS

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

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

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

**Semi-agnostic approach (Meta-model):**

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

Potential energy

Kinetic energy
(Fermi gas)

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

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Directly
related to NEP

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

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

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

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

**Semi-agnostic approach (Meta-model):**

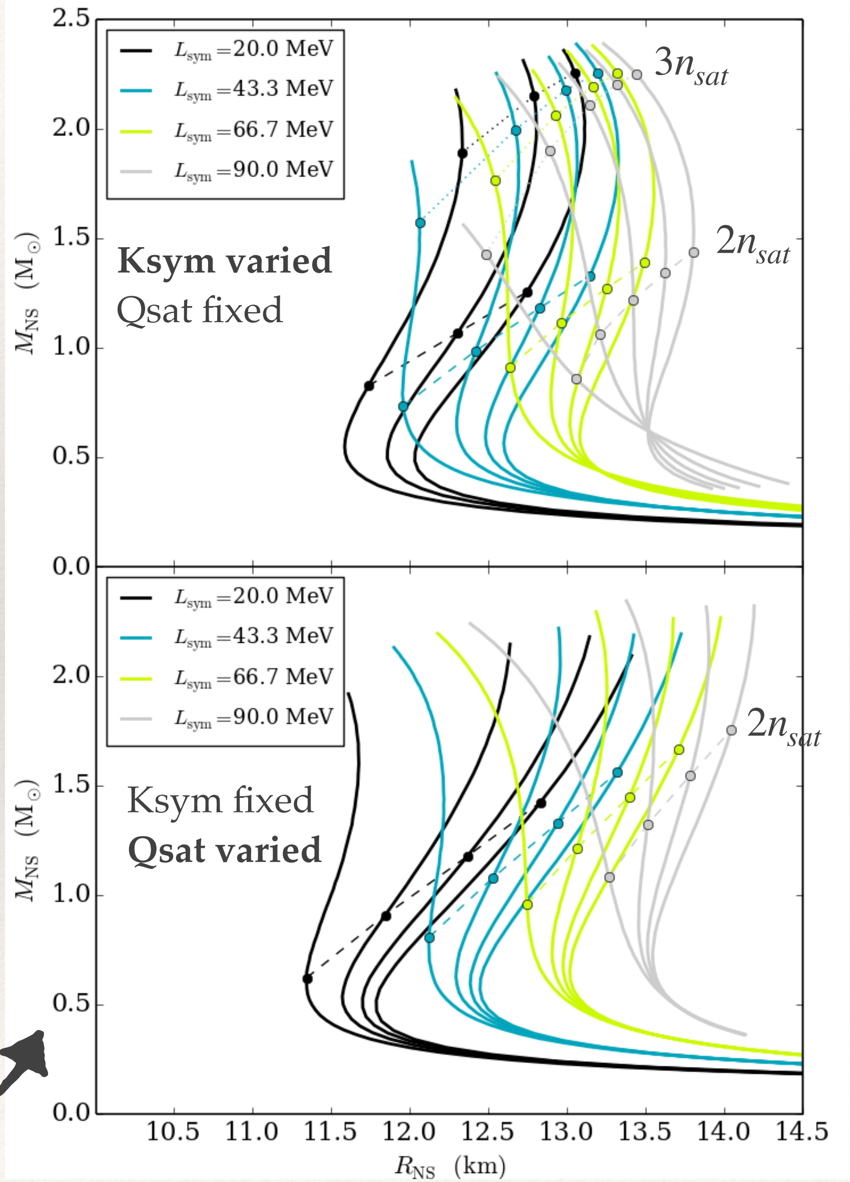
$$e(n,\delta) = t(n,\delta) + v(n,\delta)$$

Potential energy

Kinetic energy
(Fermi gas)

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

Directly
related to NEP



# Neutron stars masses

NS masses estimation: $M \in [1.17 : 2]M_\odot$

**Minimum masses:**
$1.174(4)M_\odot$ [Ozel & Freire 2016]

**Maximum masses:**

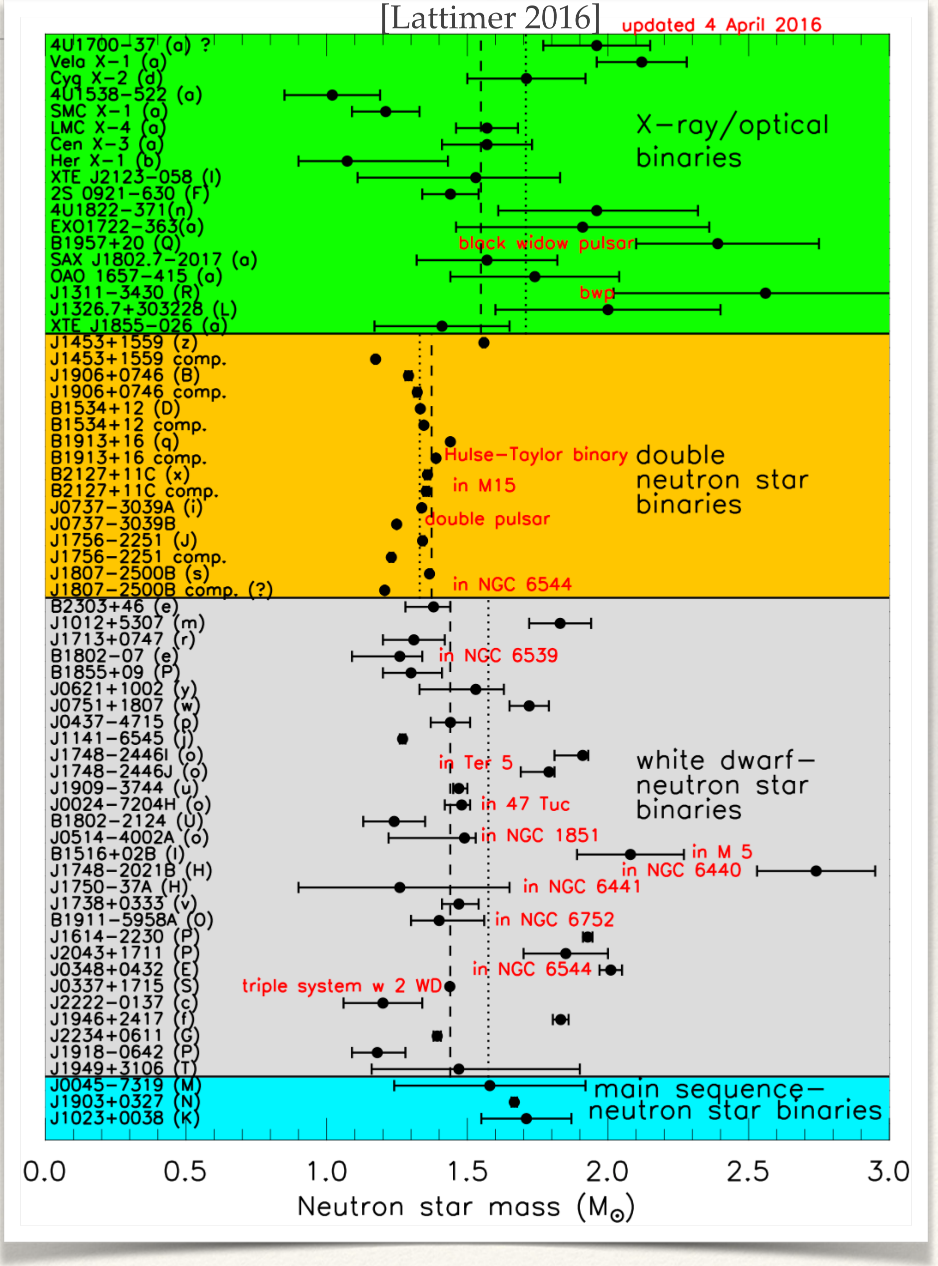
- PSR J1614-2230: $M = 1.908(16)M_\odot$

  [Arzoumanian et al. 2018, first Demorest et al.]

- PSR J0348+0432: $M = 2.01(4)M_\odot$

  [Antoniadis et al., 2013]

- Few observed high mass NS with large error-bars:
  - MSP J0740+6620: $M = 2.14(10)M_\odot$ (Shapiro delay) [Cromartie et al., 2019]
  - PSR J2215+5135: $M = 2.27(15)M_\odot$ (« redback », magnesium lines) [Linares et al. 2018]



[Lattimer 2016]

# Neutron star radii

Radius estimation: $R_{1.4} \in [10 : 14]$ km for a 1.4 $M_\odot$ NS

(my own) **classification:**
**small** radii (10-11 km),
**average** radii (12-13 km),
**large** radii (>14 km).

How to extract a radius?

- **Thermal emission** from qLMXB (quiescient Low-Mass X-ray binaries)

  [Guillot 2013, Ozel 2016, Bogdanov 2016, Steiner 2018]
- **X-ray bursts**

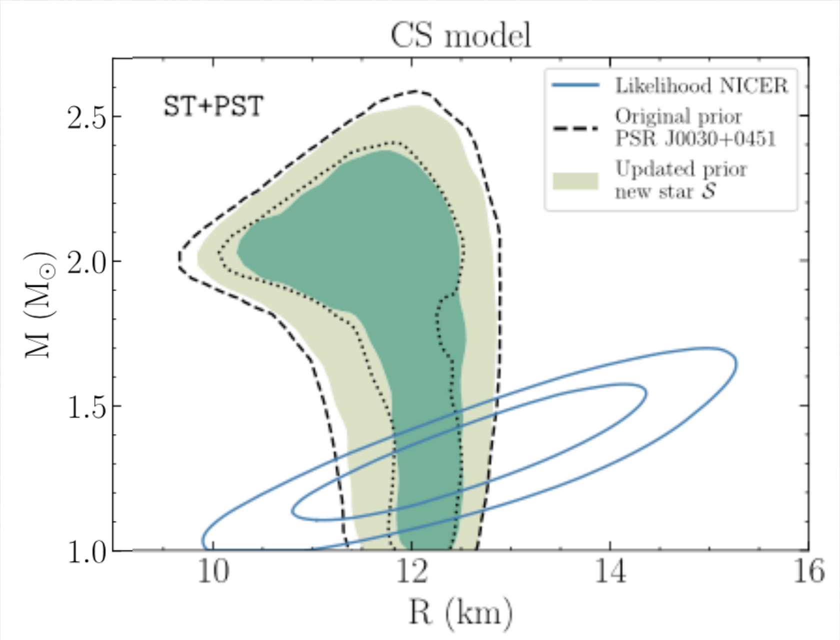
  [Poutanen 2013, Ozel 2016, Nattila 2017]
- **Gravitational waves** from binary NS mergers

  [LVC PRL 2017, Tews PRC 2018, …]
- **NICER** mission

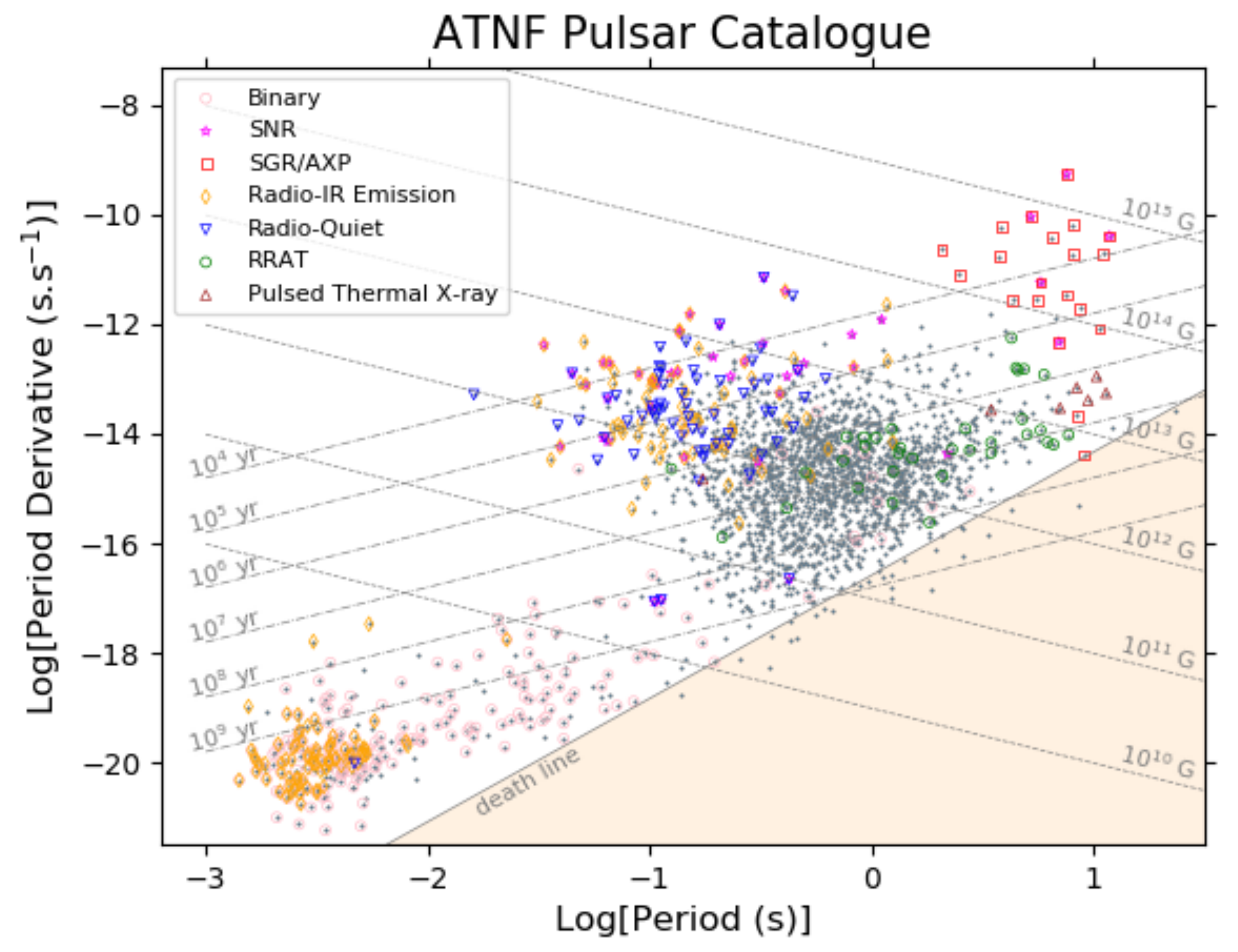
  [Watts 2019 *preliminary results*]
- Future: **ATHENA** mission

  [Barcons 2017]

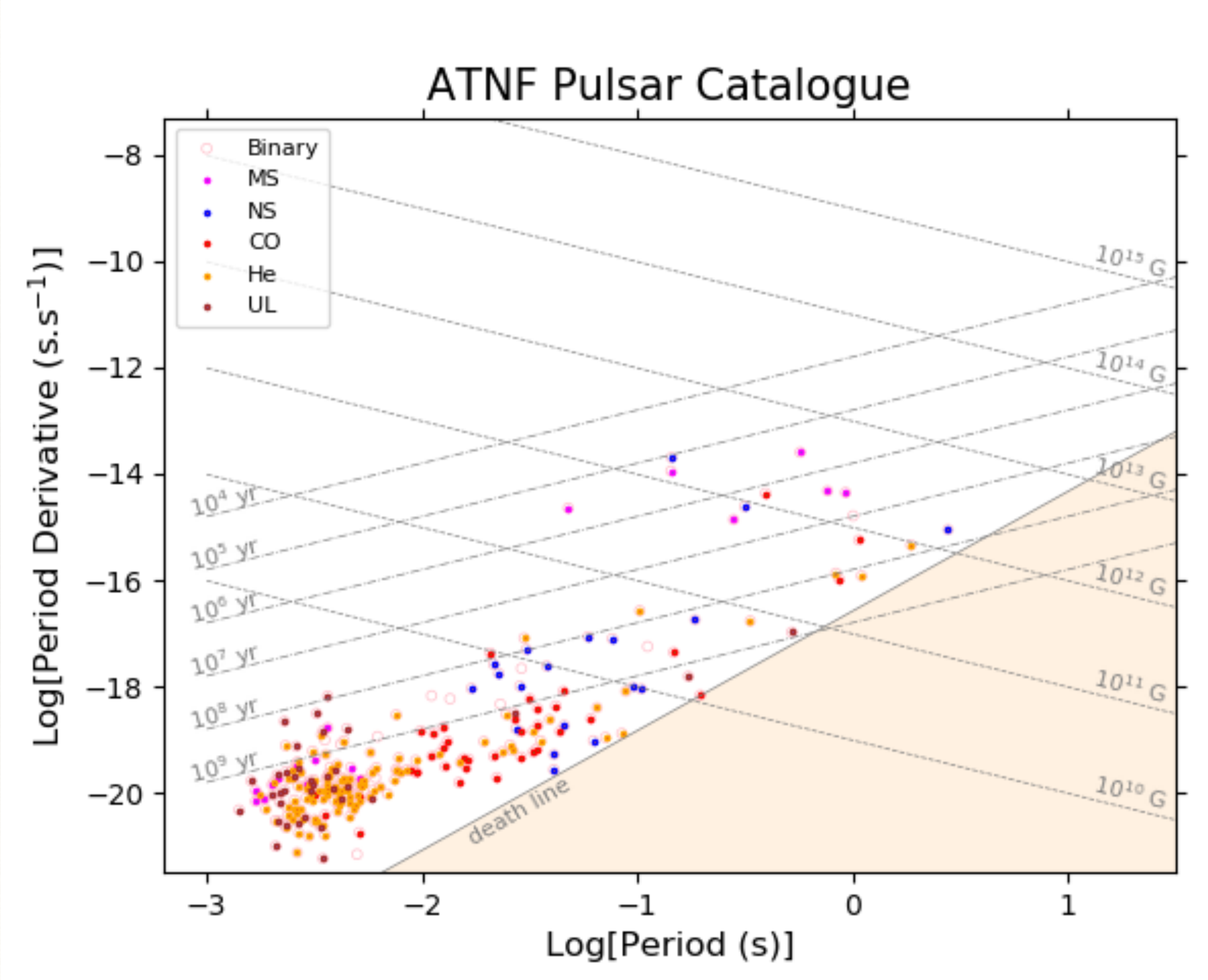
[Raaijmakers 2019 - NICER]



# Neutron star diversity



# Binary (+NS) diversity



# Thermal emission from qLMXB

**quiescent Low Mass X-ray binaries**

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

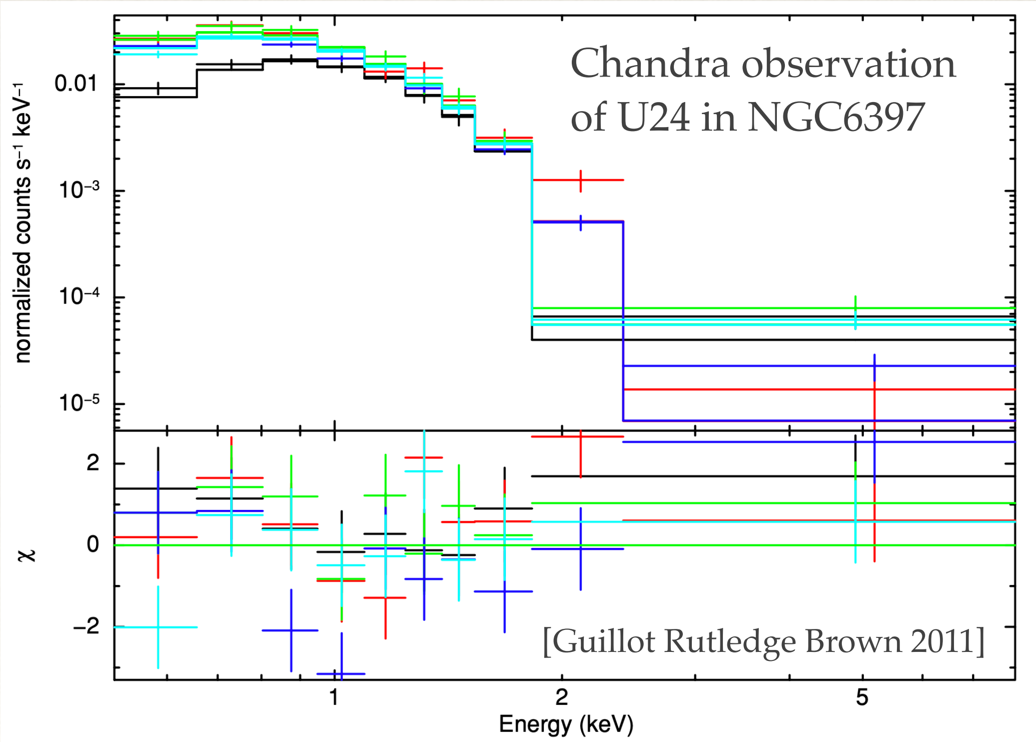
- constant flux, purely H atmosphere,
- Low magnetic fields —> almost pure thermal components,
- In globular clusters —> accurate distances.

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]

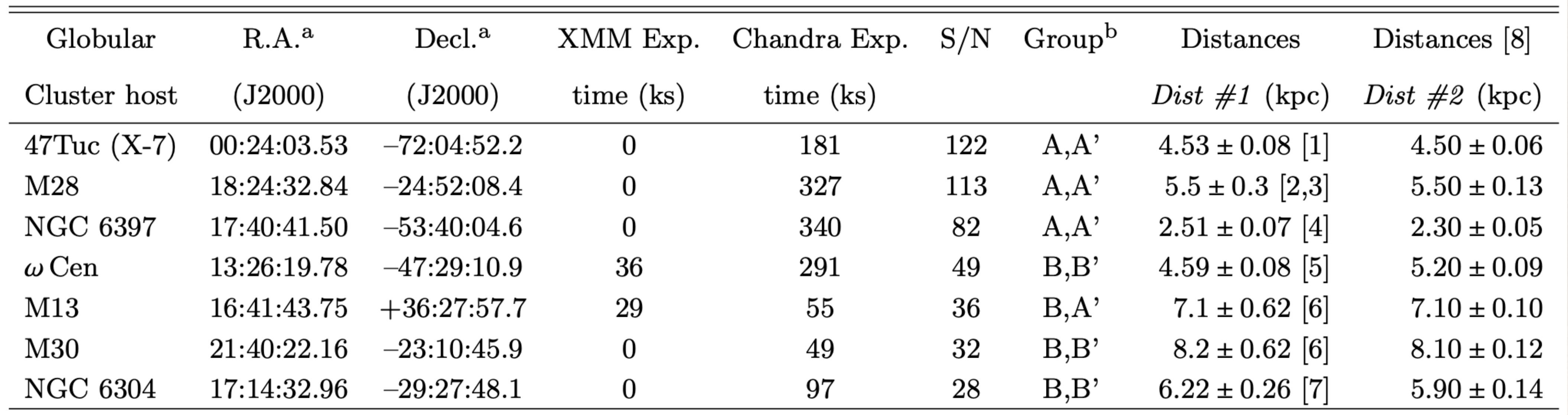
# Thermal emission from qLMXB

## quiescent Low Mass X-ray binaries

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.

[Baillot d'Étivaux+, ApJ 2019]



| Globular | R.A.[a] | Decl.[a] | XMM Exp. | Chandra Exp. | S/N | Group[b] | 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 |
| $\omega$ 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

# Thermal emission from qLMXB

**quiescent Low Mass X-ray binaries**

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.

Modeling of the **X-ray spectra** with Xspec:

- **spectrum model** includes: « pile-up » [Davis 2001, Bogdanov 2016], « TBgas » absorption and « nsatmos » for the atmosphere [Heinke 2006] + « power-law ».
- **parameters**: pile-up parameter $\alpha$, hydrogen column density on the line site $n_{H,22}$ ($10^{22}$ $cm^{-2}$), power-law normalisation, distance to the star D (kpc), surface effective temperature $T_{eff}$ (K), mass of the stars $M$ ($M_{\odot}$).

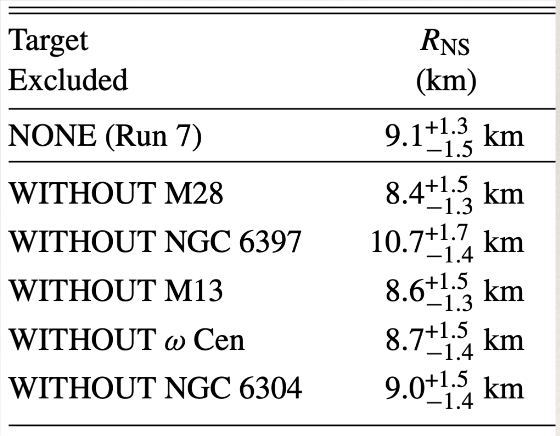
# Thermal emission from qLMXB

**quiescent Low Mass X-ray binaries**

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.

**Exemple**: constant radius model [Guillot 2013]

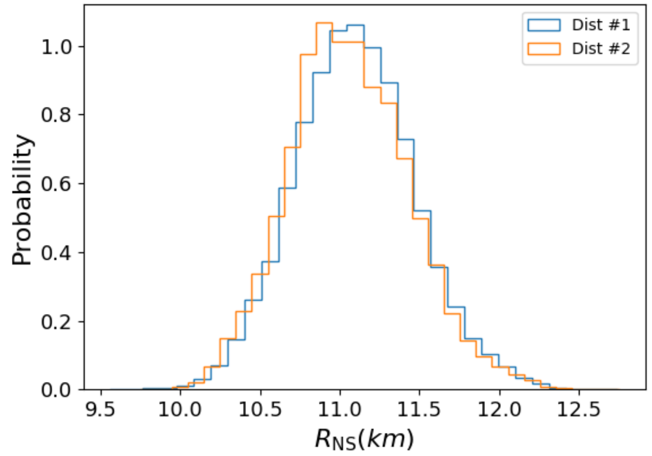


| Target<br>Excluded | $R_{\rm NS}$<br>(km) |
|---|---|
| NONE (Run 7) | $9.1^{+1.3}_{-1.5}$ km |
| WITHOUT M28 | $8.4^{+1.5}_{-1.3}$ km |
| WITHOUT NGC 6397 | $10.7^{+1.7}_{-1.4}$ km |
| WITHOUT M13 | $8.6^{+1.5}_{-1.3}$ km |
| WITHOUT $\omega$ Cen | $8.7^{+1.5}_{-1.4}$ km |
| WITHOUT NGC 6304 | $9.0^{+1.5}_{-1.4}$ km |

—> very **low radii** (8-11 km)

With latest X-ray spectra model and new data :

[Baillot d'Étivaux+, ApJ 2019]



$$R_{NS} \approx 11.0(5) \text{ km}$$

—> *Is it compatible with nuclear physics?*

# So…

Is there a **contradiction** between nuclear physics expectations and observations?

If confirmed, this contradiction may be solved by advocating **phase transition(s)**

—> producing **smaller radii**

But first, we should **cross-check** the observational analysis.

—> employing the meta-model directly **inside** the observational analysis.

# Confronting the thermal emission from qLMXB with nuclear EoS

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.

Simultaneous analysis assuming a **single EoS** for all qLMXB (here the **nuclear meta-model**)

EoS **directly** implemented in the data analysis (***first time!***):

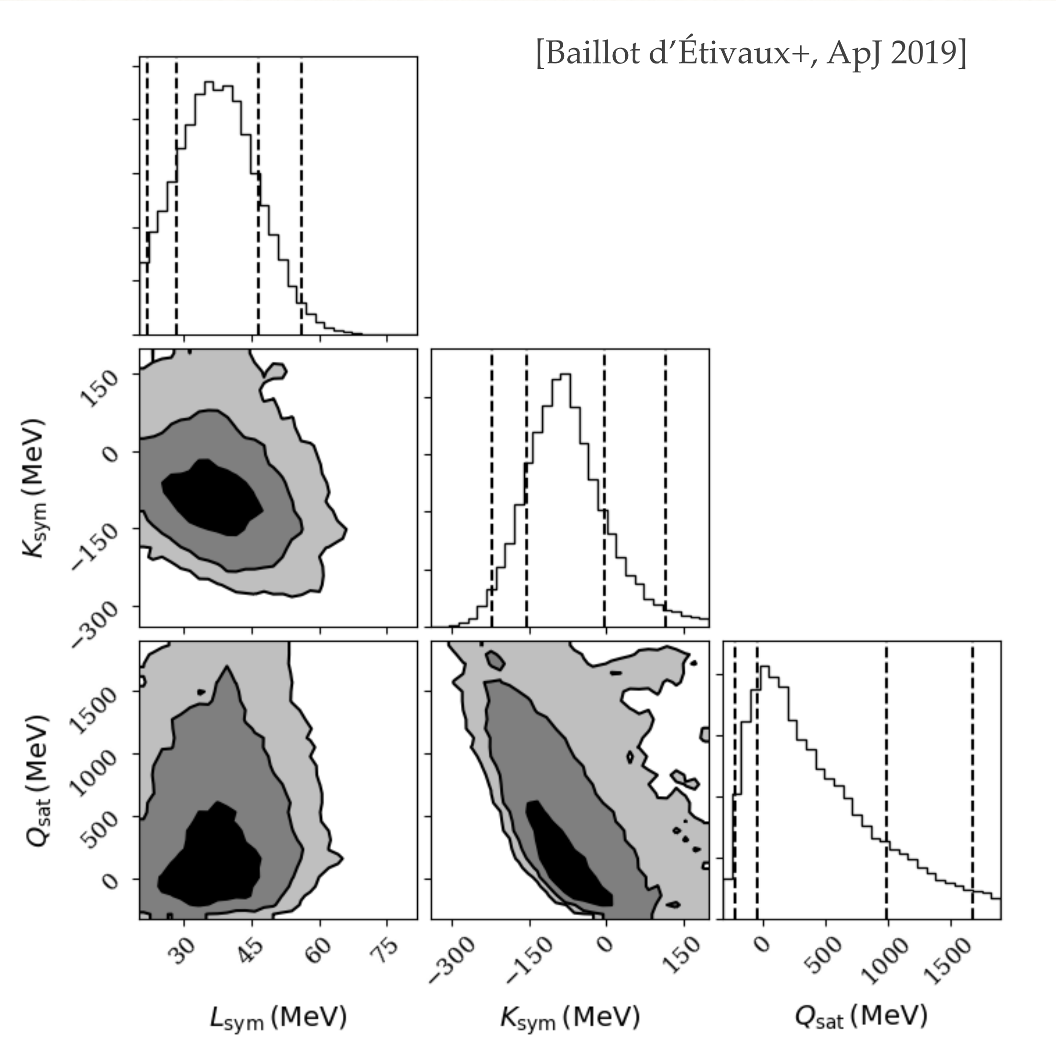
- **Observational** (emission model) parameters: M, D, T, $n_H$, …
- **Nuclear** EoS parameters: Lsym, Ksym, Qsat, etc…
- Functional relation between M and R through the EoS: $M \rightarrow_{(EoS)} R$.

—> Fitting X-ray spectra provides the whole set of **observational + EOS parameters**.
~50 free parameters, ~1000 data

—> use of Bayesian method + MCMC (Markov-Chain Monte Carlo)

- Gaussian prior on the distances (recent publications, Gaia DRII-2018)
- Gaussian prior on the nuclear parameter Lsym (50 ± 10 MeV).

# Confronting the thermal emission from qLMXB with nuclear EoS


[Baillot d'Étivaux+, ApJ 2019]

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

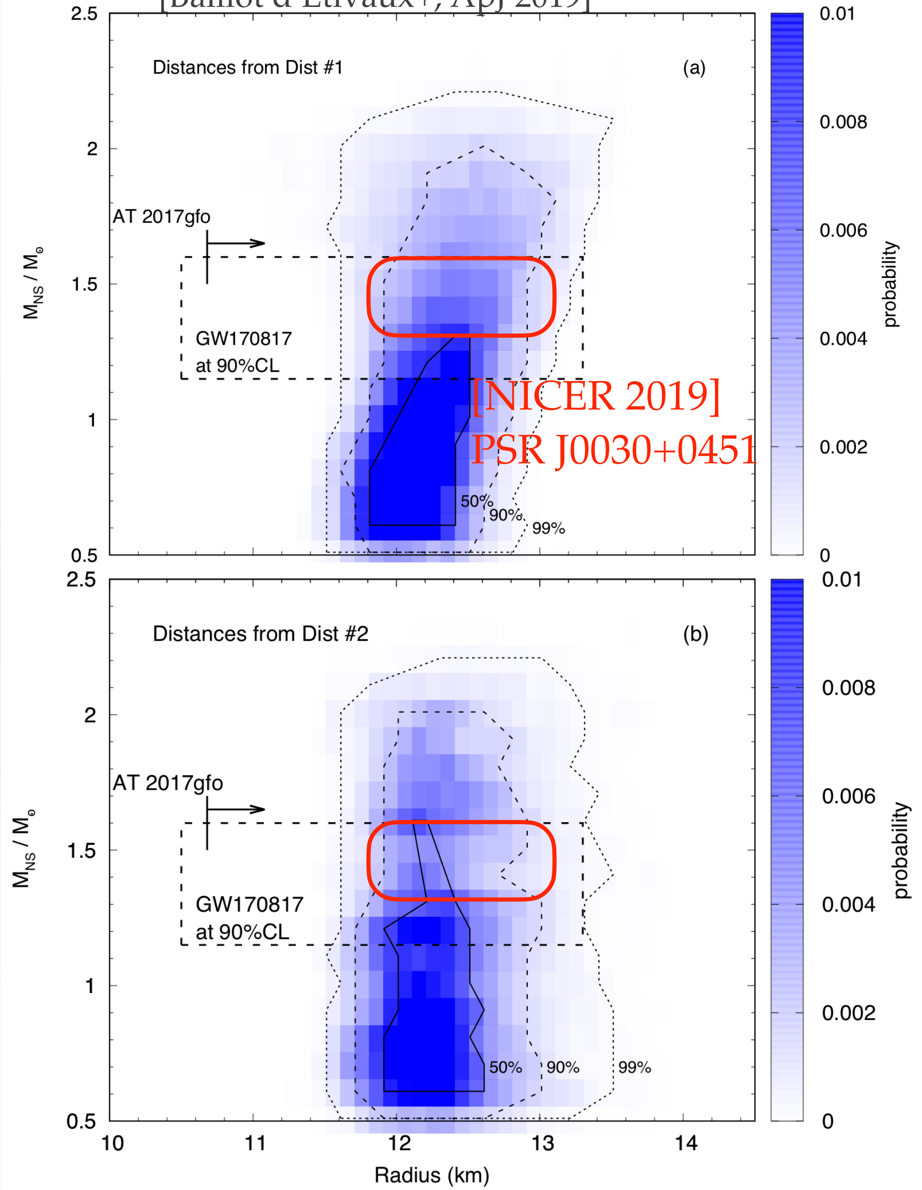
**Posteriors:**
Lsym = 38 ± 10 MeV
Ksym = −91 ± 80 MeV
Qsat = 350 ± 500 MeV

First extraction of Ksym and Qsat from data.

A recent analysis of pygmy GDR concludes:
Ksym = −120 ± 80 MeV [Sagawa 2019]

# Confronting the thermal emission from qLMXB with nuclear EoS

[Baillot d'Étivaux+, ApJ 2019]



[NICER 2019]
PSR J0030+0451

—> The new analysis is compatible with nuclear physics.
(with same chi2 as previous analyses).
**Average radii** preferred.

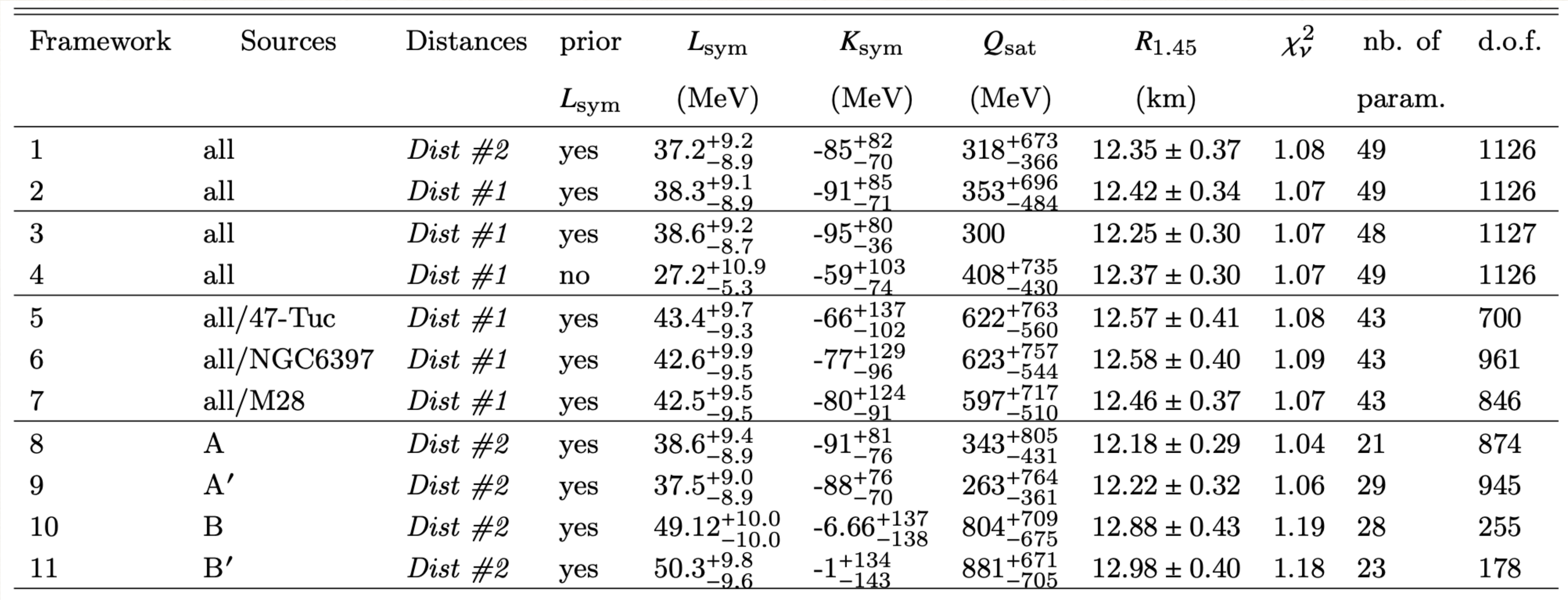
—> The comparison with other approaches (GW170817, AT2017gfo) provides a consistent understanding of the data.

—> But more recent GW170817 analyses prefer **lower radii**:

- $R_{1.4} = 11^{+0.9}_{-0.6}$ km [Capano, Tews+ nature 2020]
- $R_{1.4} \approx 11$ km [Güven+ arXiv:2001.10259]

# Confronting the thermal emission from qLMXB with nuclear EoS

**Sensitivity analysis**

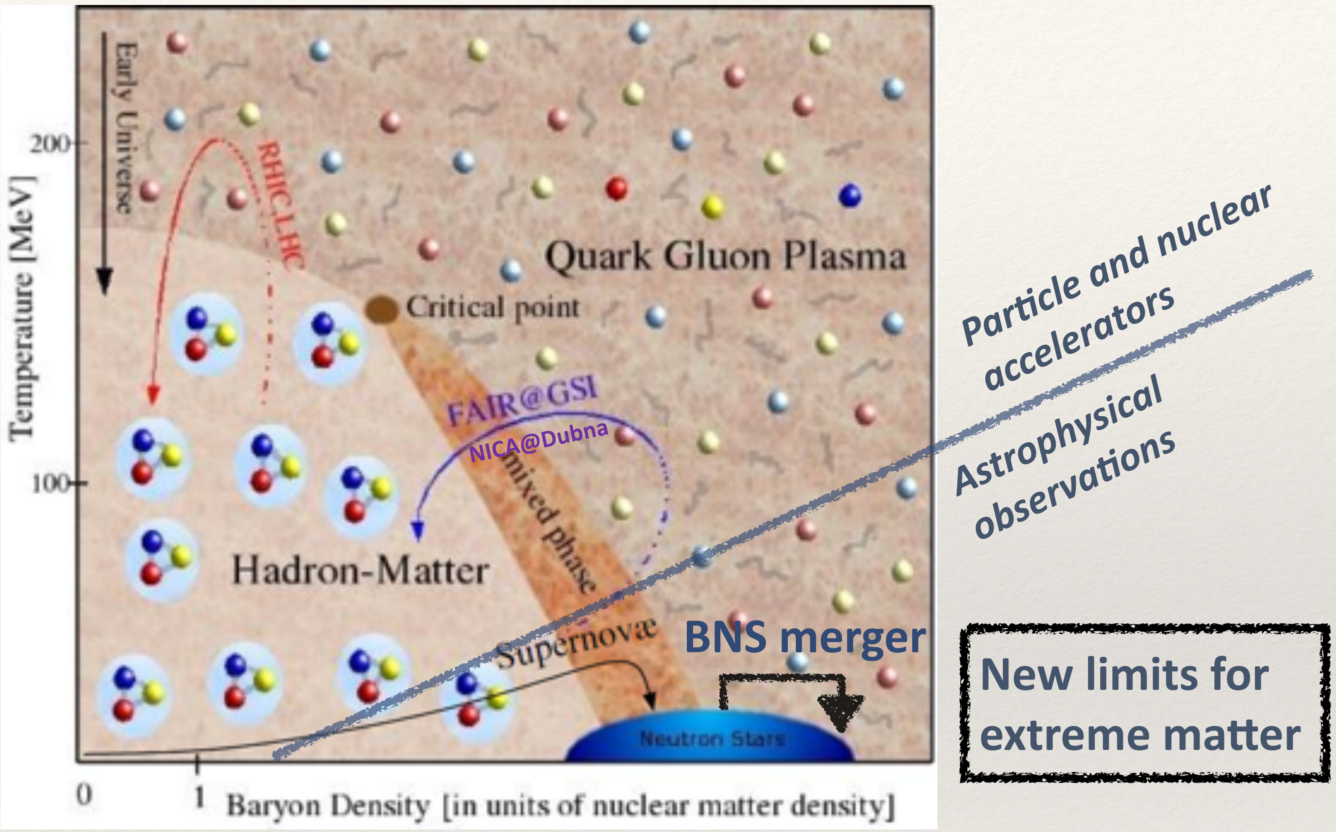


| Framework | Sources | Distances | prior $L_{\rm sym}$ | $L_{\rm sym}$ (MeV) | $K_{\rm sym}$ (MeV) | $Q_{\rm sat}$ (MeV) | $R_{1.45}$ (km) | $\chi^2_\nu$ | nb. of param. | d.o.f. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | all | *Dist #2* | yes | $37.2^{+9.2}_{-8.9}$ | $-85^{+82}_{-70}$ | $318^{+673}_{-366}$ | 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 |

[Baillot d'Étivaux+, ApJ 2019]

**Outlook**:
Include phase transition
Confront with other observations

# Probing extreme matter physics with GW



**New limits for extreme matter**

*Neutron stars,*
*supernovae,*
*kilonovae…*

What is the **nuclear interaction** in dense, isospin asymmetric matter, hot?
Which **new particles** appear at supra-saturation densities?
At which density occurs the **deconfinement** from hadrons to Quarks-Gluons Plasma (QGP)?
How **neutrinos** propagate and what are the **transport properties** of extreme matter?
Are BNS the main astrophysical site for the **r-process**?

# Tidal deformability

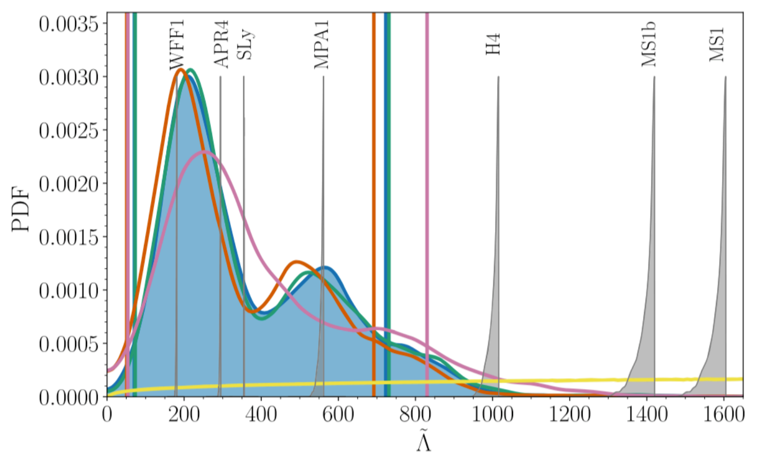
- Tidal field $E_{ij}$ from companion star induces a quadrupole moment $Q_{ij}$ in the NS
- Amount of deformation depends on the stiffness of EOS via the tidal deformability $\Lambda$.

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

Post-Newtonian expansion of the waveform: Tidal effect enters at 5th order.

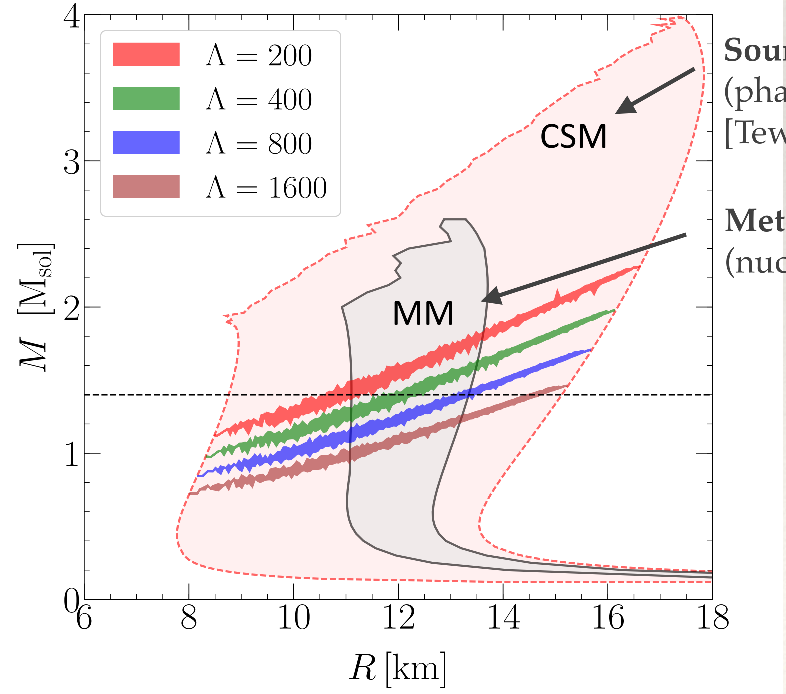
Hinderer+ 2008, Blanchet, Damour

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



**GW170817**
→ 70 ≤ Λ ≤ 720 (90% CL)
→ +E-M 300 ≤ Λ ≤ 800

[Tews, JM, Reddy, EPJA special issue on GW (2019)]

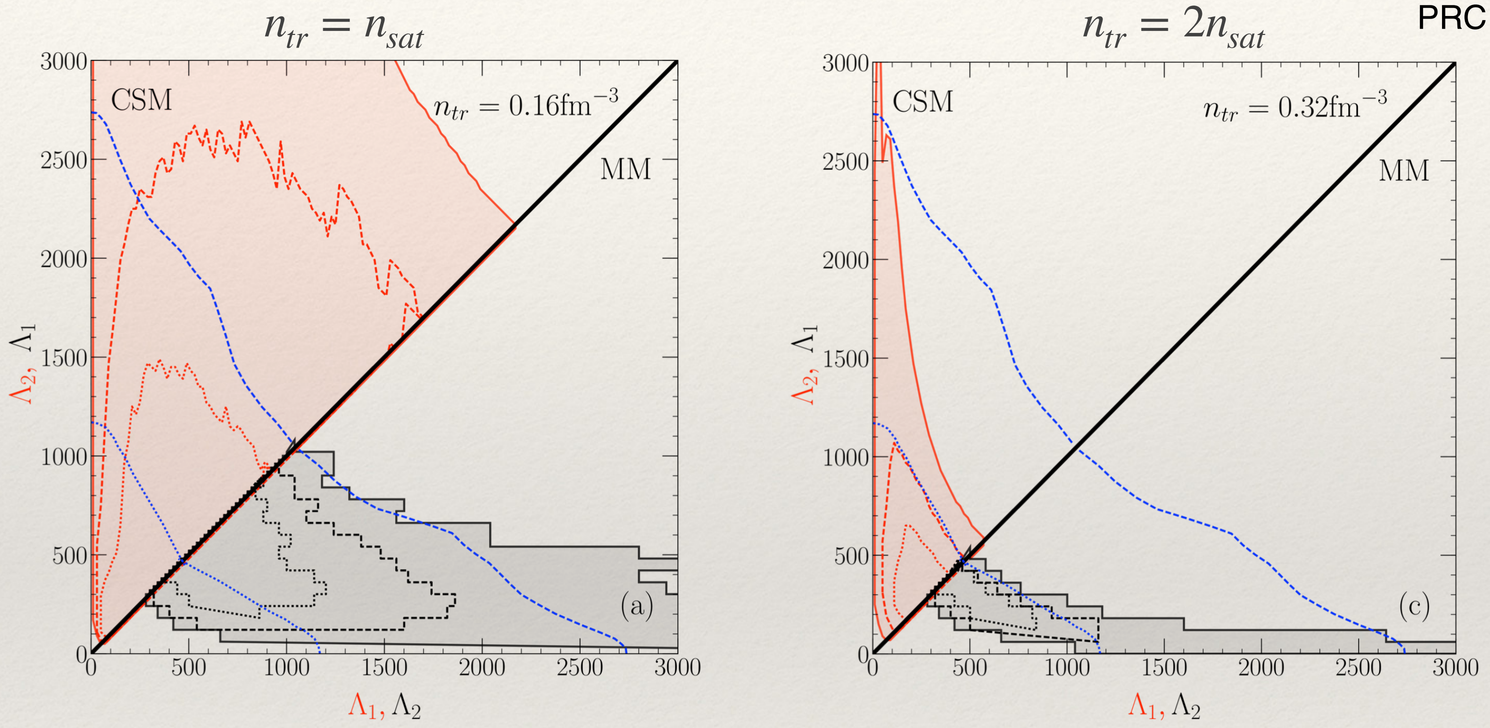


**Sound-speed Model** (phases transitions) [Tews+ 2018]

**Meta-Model** (nucleonic)

# Confront EoS / GW

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



**Required GW accuracy to improve our knowledge:**

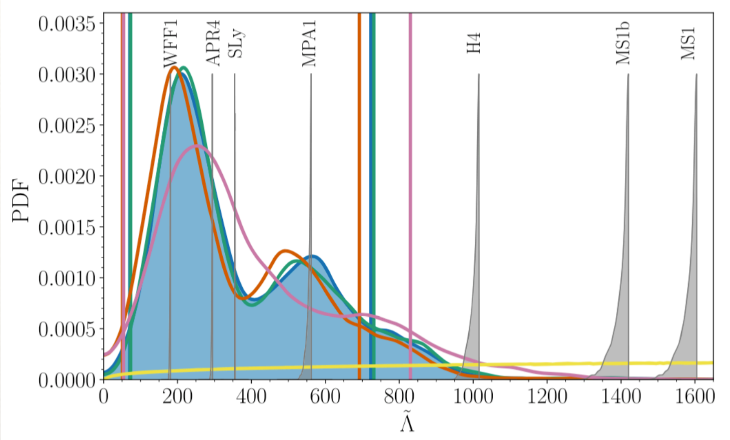
$\Delta\Lambda \approx$ 200-300 → Probe EOS from 1 to $2n_{sat}$

Confirm or rule out nuclear physics

$\Delta\tilde{\Lambda} \approx$ 50-100 → Probe matter composition above $2n_{sat}$

# Using the full structure of the Λ-pdf

LVC, PRX 9 (2019)



**Impact of 2 analyses from raw data:**

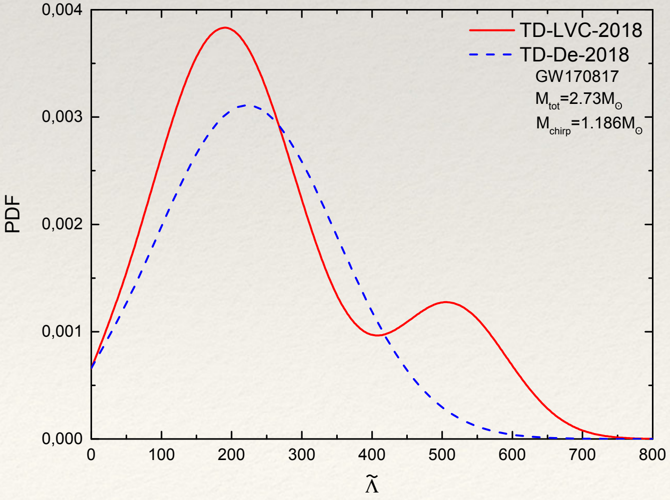
- LVC, PRX 9 (2019)
- De et al., PRL 121 (2019)

—> Bayesian analysis

**Impact of 2 prior sets:**

#1: small ranges defined from global nuclear physics analysis (JM 2018)

#2: large ranges (included non-zero probabilities)



**GW170817**

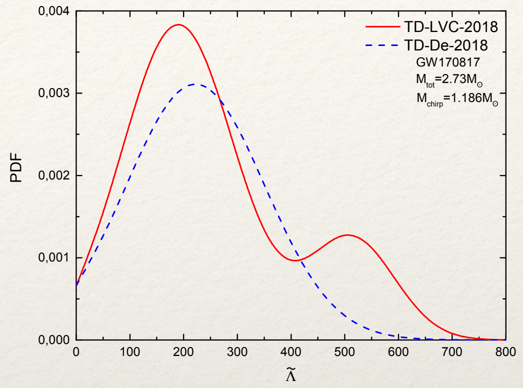
**→ 70 ≤ L ≤ 720 (90% CL)**

**→ 70 ≤ L ≤ 500 (90% CL)**

# Using the full structure of the Λ-pdf

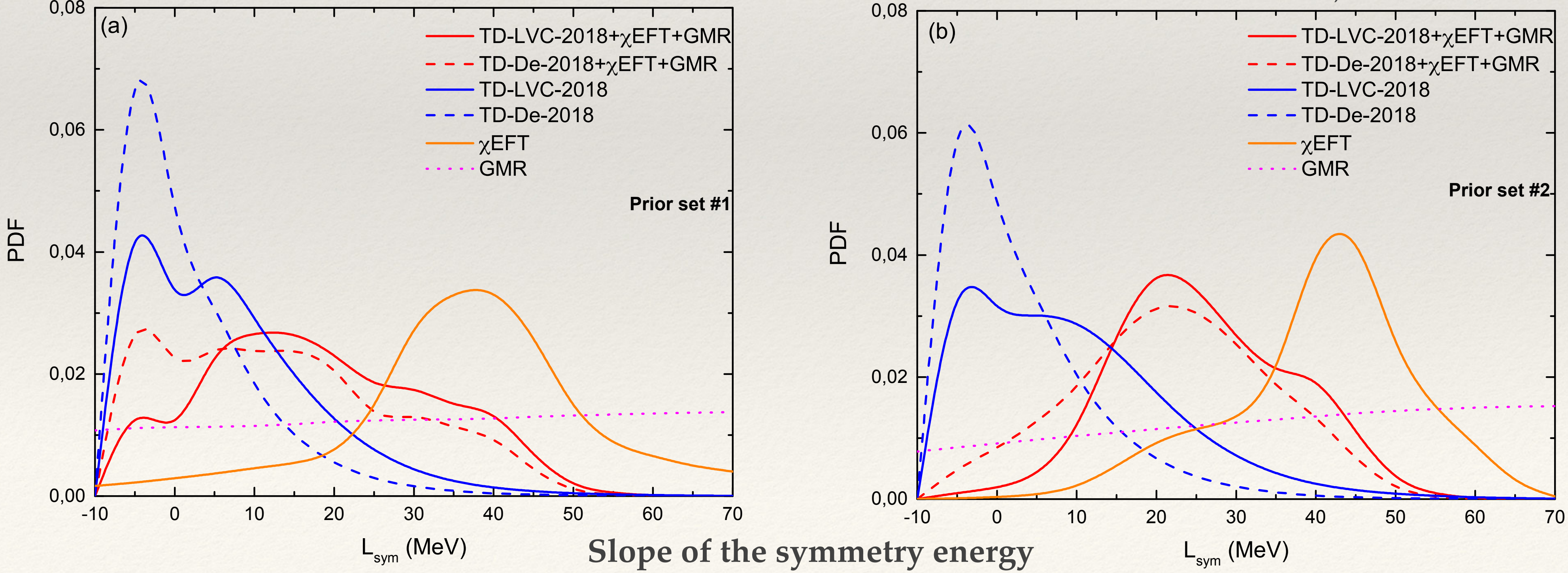
**Impact of 2 analyses from raw data:**
LVC, PRX 9 (2019)
De et al., PRL 121 (2019)

**Impact of 2 prior sets:**
#1: small ranges defined from global nuclear physics analysis (JM 2018)
#2: large ranges (included non-zero probabilities)



**Marginalization over Lsym**

H. Güven et al., to be submitted

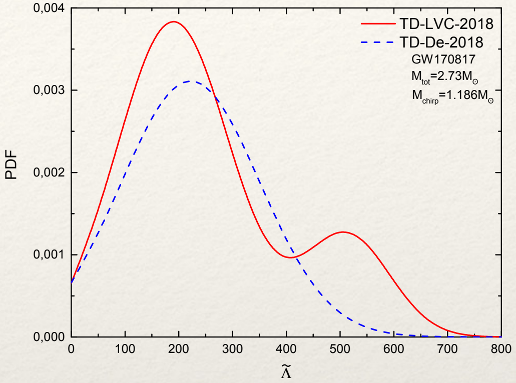


**Slope of the symmetry energy**

# Using the full structure of the Λ-pdf

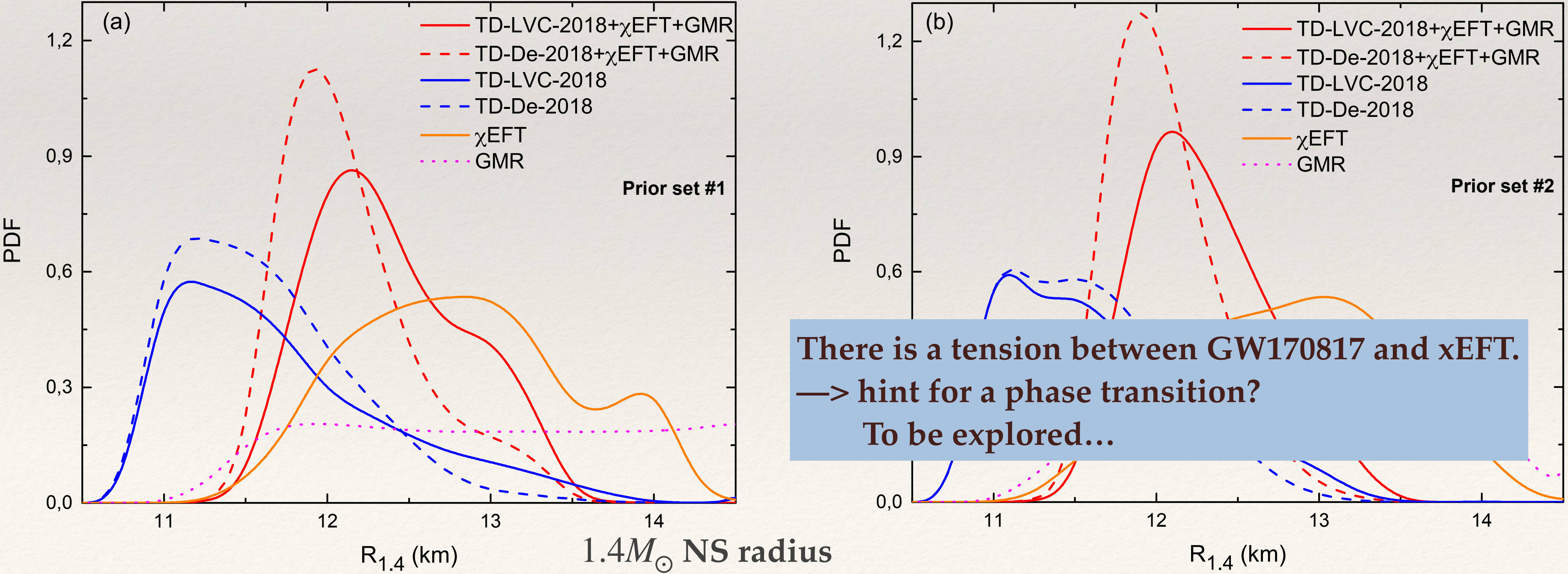
**Impact of 2 analyses from raw data:**
LVC, PRX 9 (2019)
De et al., PRL 121 (2019)

**Impact of 2 prior sets:**
#1: small ranges defined from global nuclear physics analysis (JM 2018)
#2: large ranges (included non-zero probabilities)



## Marginalization over $R_{1.4}$

H. Güven et al., to be submitted



$1.4M_\odot$ **NS radius**

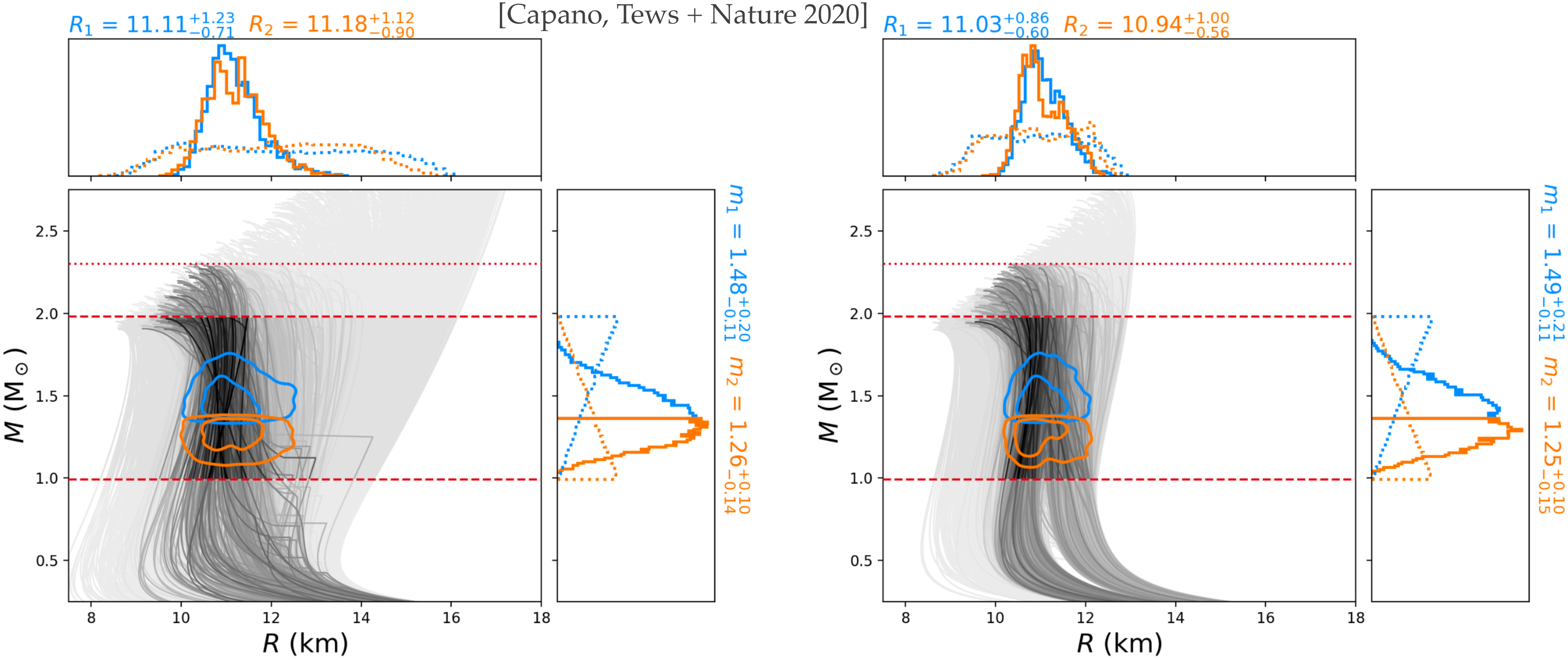
**There is a tension between GW170817 and xEFT.**
**—> hint for a phase transition?**
**To be explored…**

# Stringent constraints on NS radii

Direct comparison of the GW waveforms to the raw data, with EoS modeling + $M_{\text{total}} \leq M_{\text{thresh}} (\approx 2.3 M_\odot)$.

$n_{tr} = n_{sat}$ $n_{tr} = 2n_{sat}$

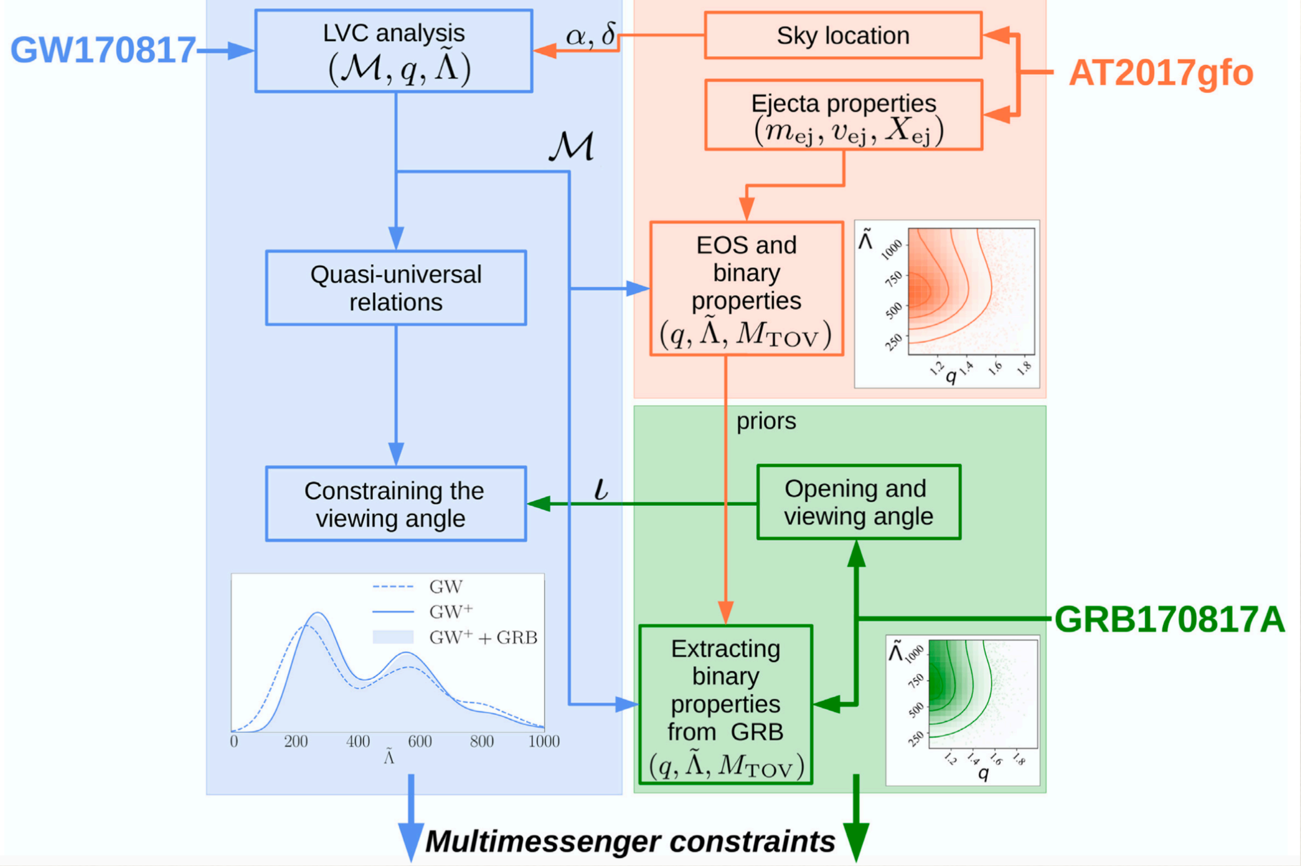
[Capano, Tews + Nature 2020]

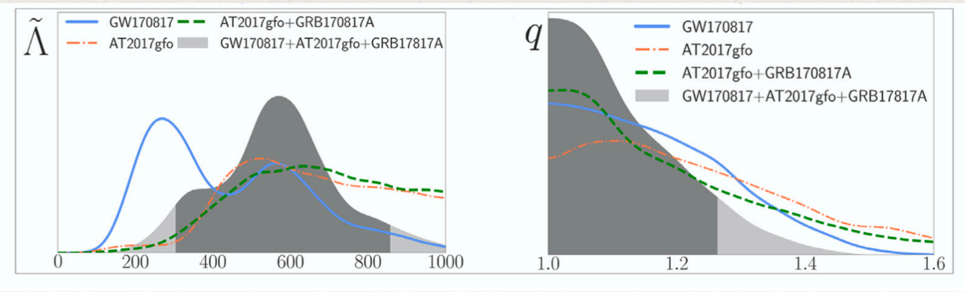


—> **Low NS radii** also seems to be preferred.

# Richness & complexity of multi-messenger analysis

[Coughlin+ MNRAS 2019]





**GW170817**
→ $70 \leq \Lambda \leq 720$ (90% CL)
→ +E-M $300 \leq \Lambda \leq 800$

If confirmed:
—> large radii are preferred.
But yet complex and highly model dependent.

# In summary

**Thermal emission from qLMXB:**

Could predict **low radii**.
Could also be compatible with nuclear physics (**average radii**).

**GW170817 + multi-messenger:**

Requires improved precision for $\tilde{\Lambda}$.
More detailed analyses: tend to prefer **small radii** (~11 km).
Extended GW+EM analysis: prefer **average radii** (12-13 km).

**NICER:**

Data from
PSR J0030+0451: **average radii** seems to be preferred…

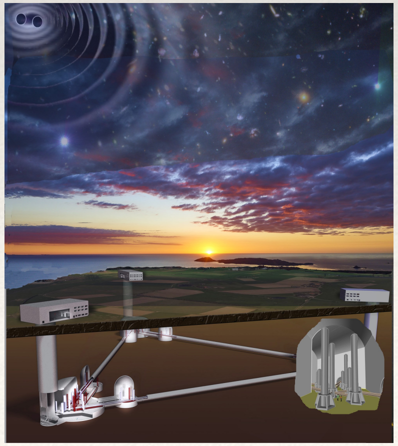
Tension seems to **emerge** between various observational signals.
—> to which extend it signs the existence of a **phase transition**?

# Conclusion and outlook

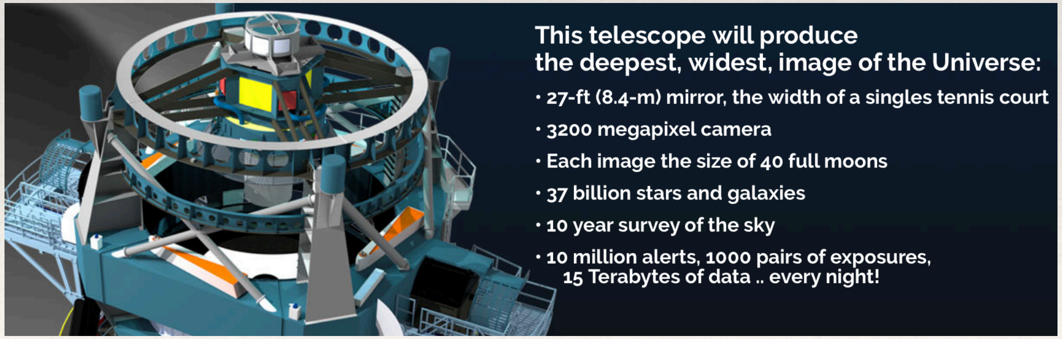
**Multi-messenger observation**: The BNS GW + kilonovae EM signal + GRB (+ neutrinos?).
**Variety of GW sources:** BNS, BH-NS, CCSN, continuous emission, etc…
**(Futur) post-merger GW signal:** investigation of phase transitions.

**Future upgrades and new telescopes (a lot of new data):**
GW interferometers: upgrades of LIGO-Virgo (KAGRA, LIGO India).
E-M follow-up: GRANDMA, ZTF → (future) LSST.
3rd generation (~2030-2040): Cosmic Explorer, Einstein Telescope.
Space interferometer (LISA ~2035): low frequencies (trigger future mergers).

ET



LSST



This telescope will produce
the deepest, widest, image of the Universe:

- 27-ft (8.4-m) mirror, the width of a singles tennis court
- 3200 megapixel camera
- Each image the size of 40 full moons
- 37 billion stars and galaxies
- 10 year survey of the sky
- 10 million alerts, 1000 pairs of exposures, 15 Terabytes of data .. every night!

**Blooming future —> answering fundamental questions about dense matter**