Workshop on the Giant Monopole Resonance, Orsay, Nov. 2020

How thermal emission from neutron stars can constrain the unknown parameter Ksym?

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

In collaboration with
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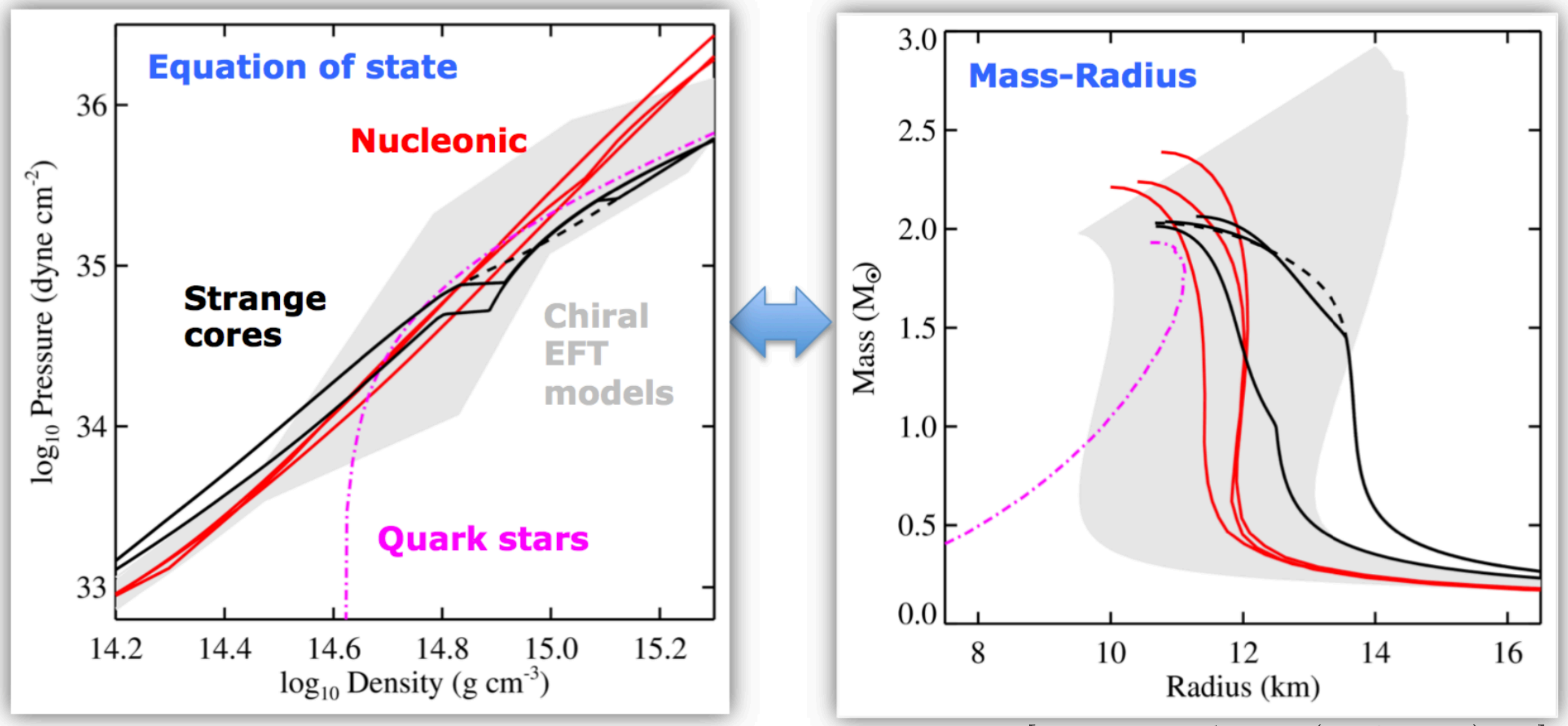
EoS [nuclear] <=> (M,R) [astro]

Tolmann-Oppenheimer-Volkov (TOV) GR equations

P(n)

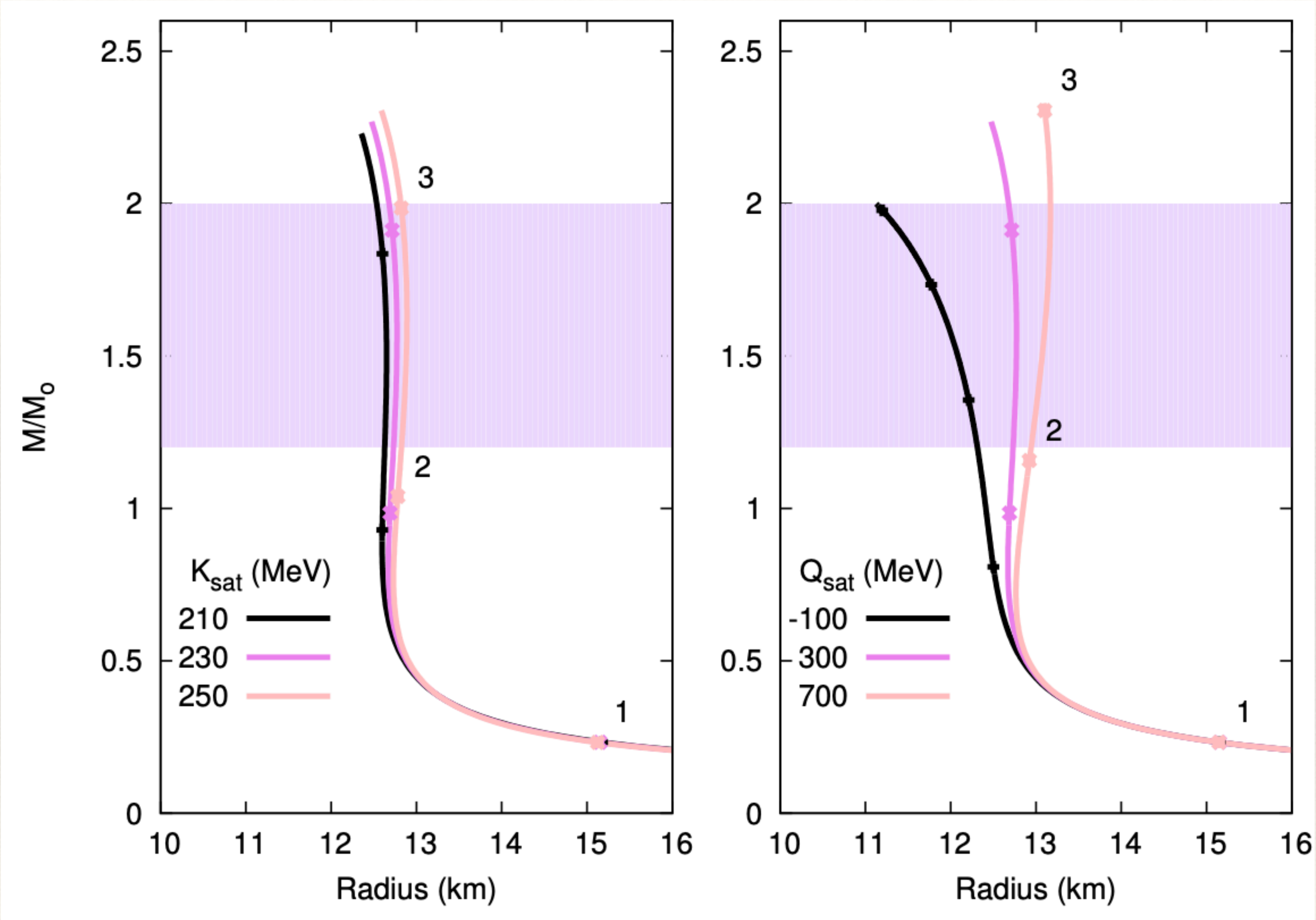
(M,R)(n_c)



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

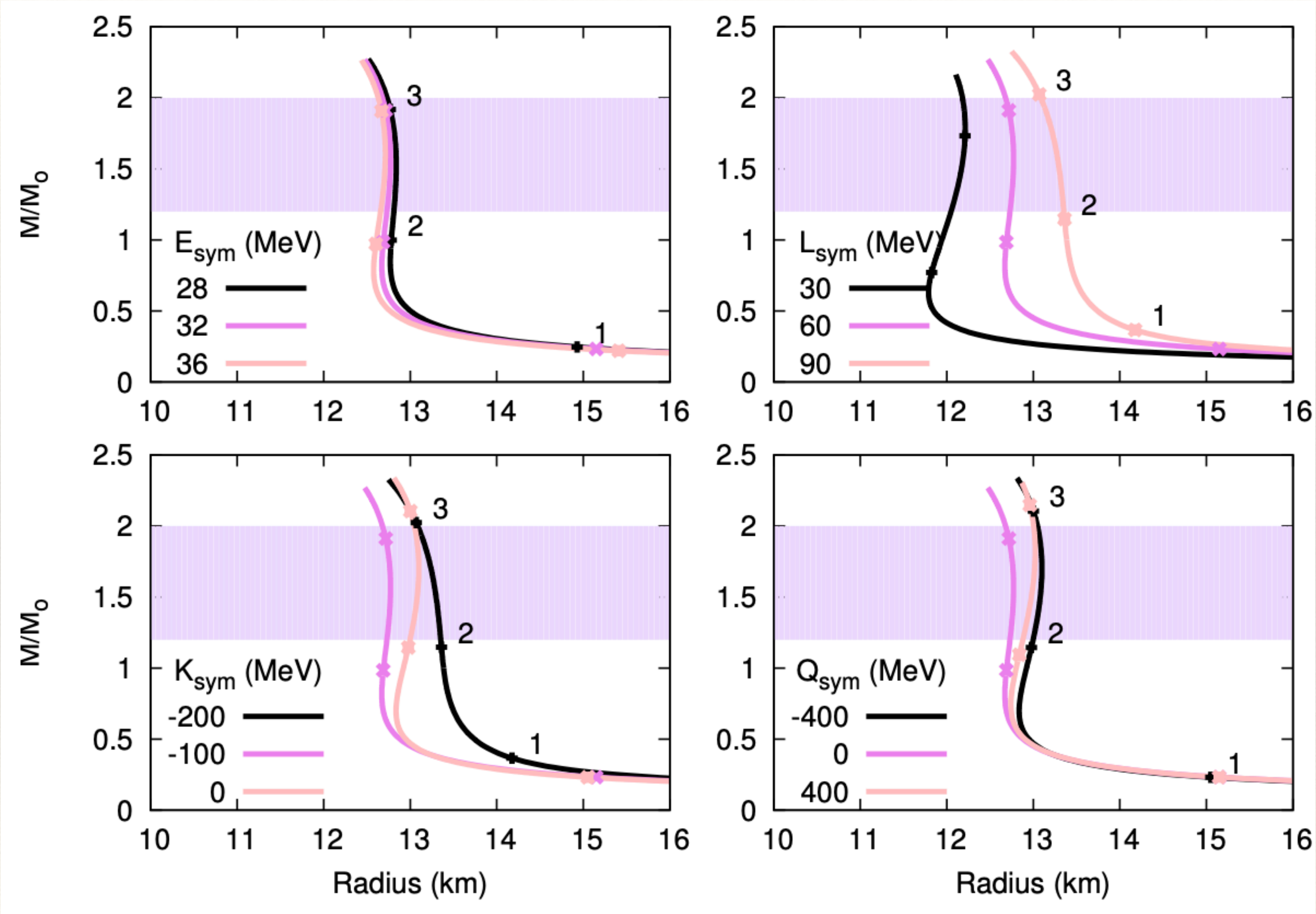
Reverse engineering,
Bayesian statistics

M-R: impacts of the isoscalar NEP



JM, Casali, Gulminelli, PRC 2018

M-R: impacts of the isovector NEP



JM, Casali, Gulminelli, PRC 2018

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**

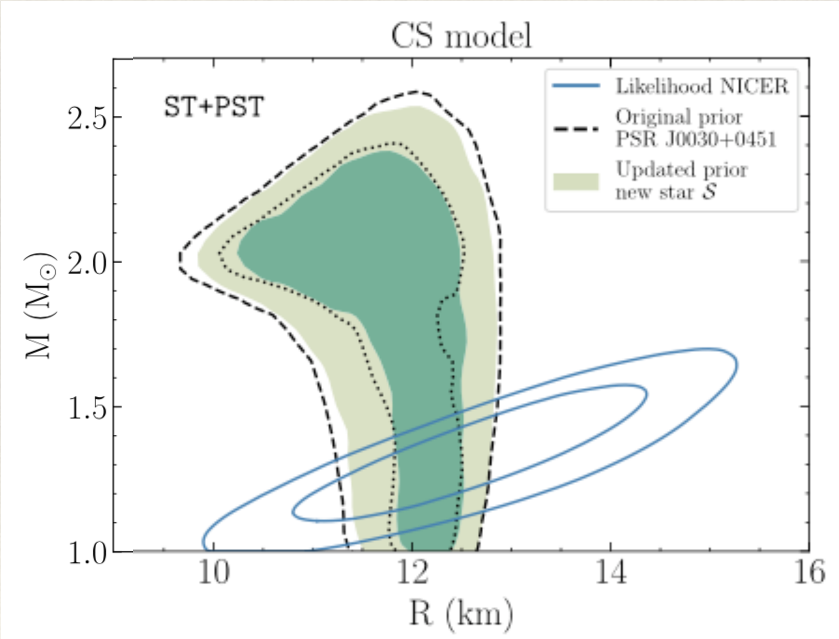
  [Poutanen 2013, Ozel 2016, Nattila 2017]
- **Gravitational waves** from binary NS mergers

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

  [Miller 2019, Raaijmakers 2019, Bogdanov 2019, Guillot 2019]
- Future: **ATHENA** mission

  [Barcons 2017]

[Raaijmakers 2019 - NICER]



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:

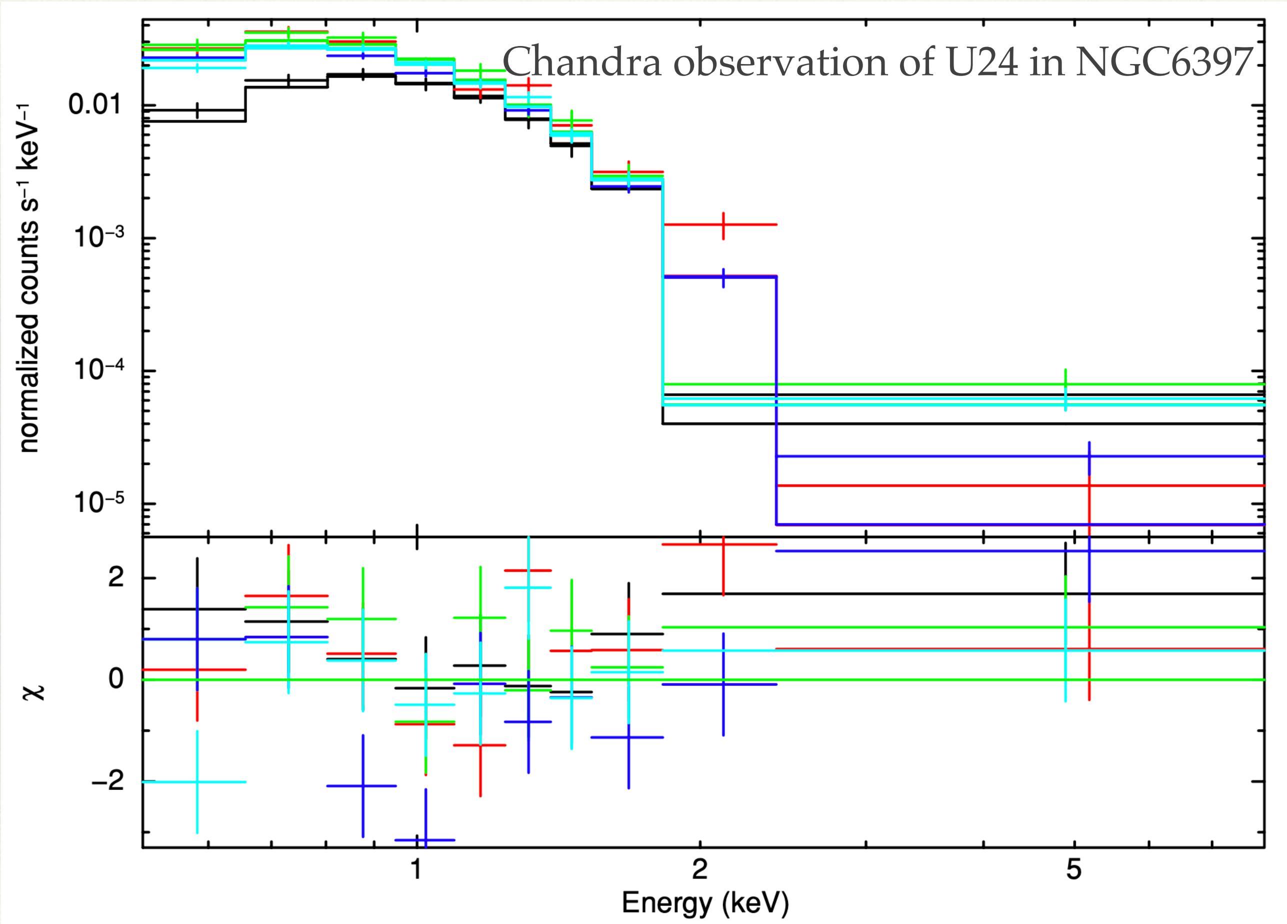
- PSR J1614-2230: $M = 1.908(16)M_\odot$ [Arzoumanian et al. 2018, first Demorest et al.]
- PSR J0348+0432: $M = 2.01(4)M_\odot$ [Antoniadis et al., 2013]
- A few recent observed high mass NS with large error-bars:
  - MSP J0740+6620: $M = 2.14(10)M_\odot$ (Shapiro delay) [Cromartie et al., 2019]
  - PSR J2215+5135: $M = 2.27(15)M_\odot$ (« redback », magnesium lines) [Linares et al. 2018]

Thermal emission from qLMXB

Black body like emission: F # $T^4(R_{inf}/D)^2$ [Rutledge et al. 1999]

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

-> get information on M and R



Guillot Rutledge Brown 2011

Thermal emission from qLMXB

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

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

Thermal emission from qLMXB

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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 α, 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 ($M_{\odot}$).

A semi-agnostic approach for the nuclear EoS

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

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

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

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

Semi-agnostic approach (Meta-model):

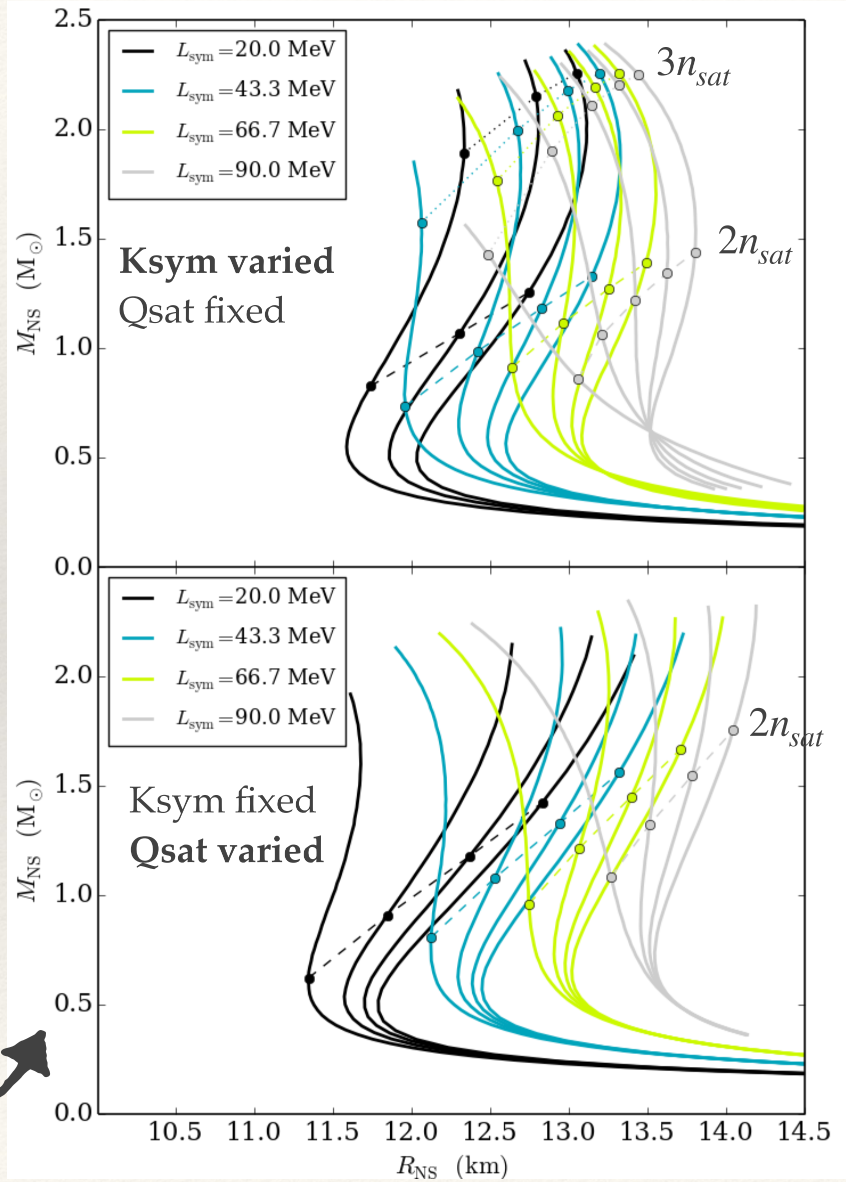
$$e(n,\delta) = t(n,\delta) + v(n,\delta)$$

Potential energy

Kinetic energy (Fermi gas)

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

Directly related to NEP



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

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

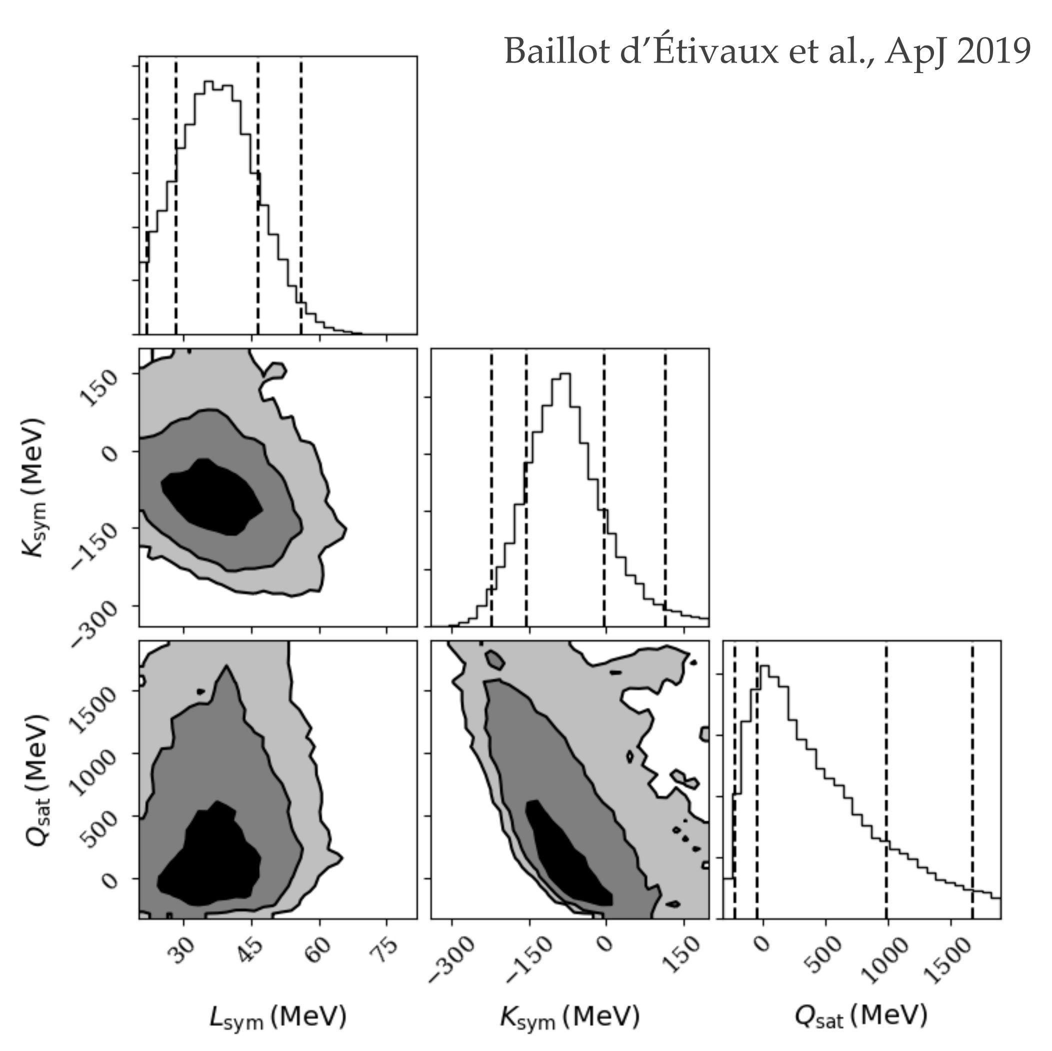
- **Observational** (emission model) parameters: M, D, T, n_H, …
- **Nuclear** EoS parameters: Lsym, Ksym, Qsat, etc…
- Functional relation between M and R through the EoS: $M \rightarrow_{(EoS)} R$.

—> 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



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

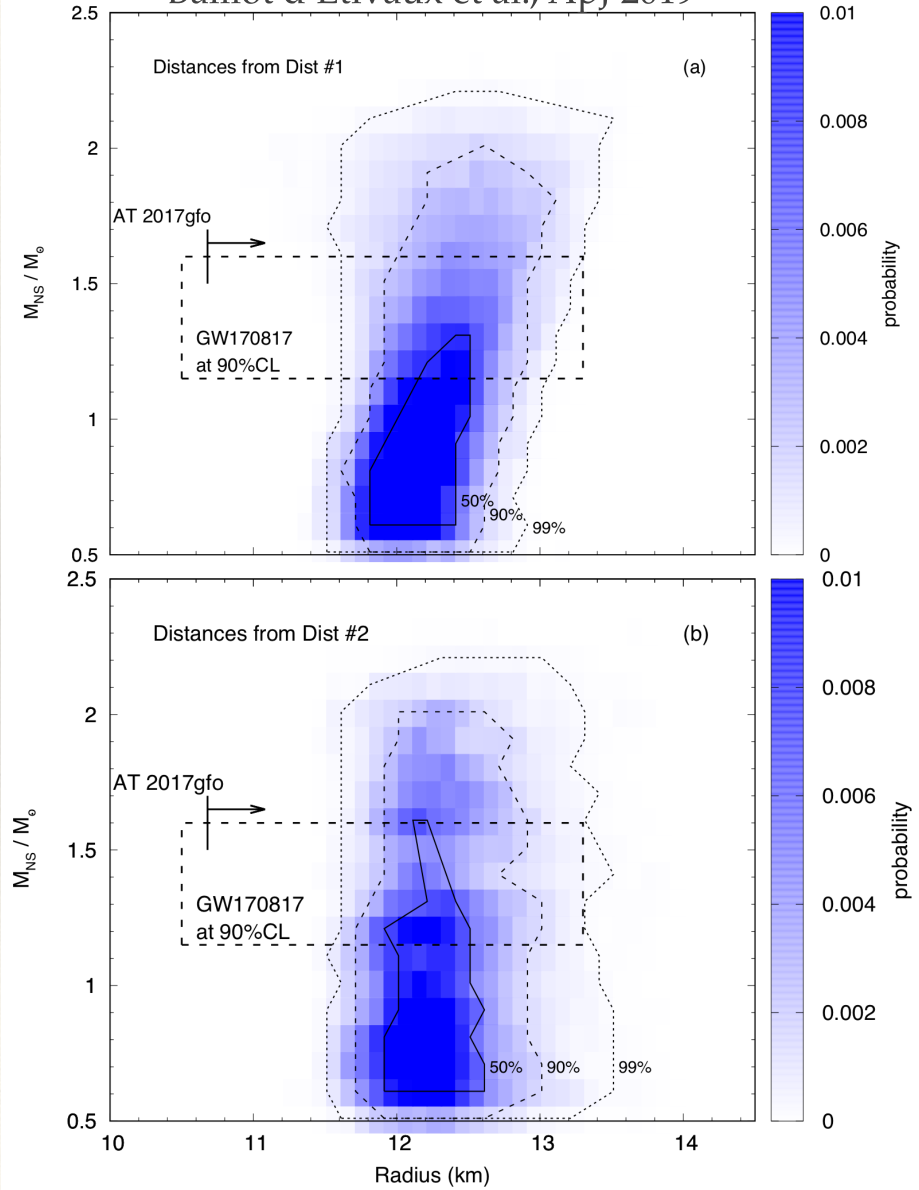
Posteriors:
Lsym = 38 ± 10 MeV
Ksym = −91 ± 80 MeV
Qsat = 350 ± 500 MeV

First extraction of Ksym and Qsat from data.

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

Confronting the thermal emission from qLMXB with nuclear EoS

Baillot d'Étivaux et al., ApJ 2019



—> 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 et al. 2019]
+ $R_{1.4} \approx 11$ km [Güven 2020 in preparation]

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).

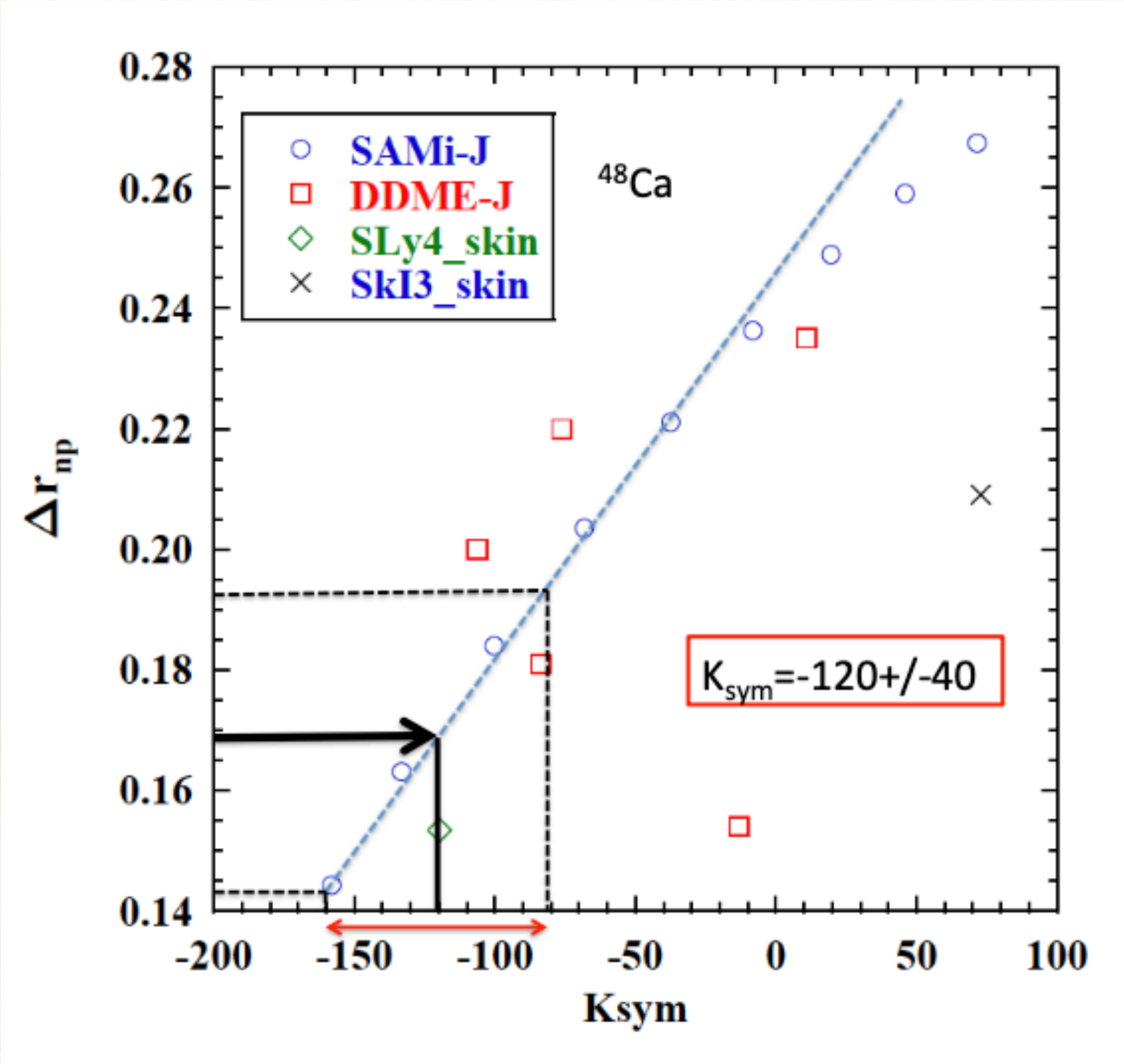
Ksym from nuclear experiments

Sagawa et al, AIP 2127, 020002 (2019)

$E_{ISGMR}(^{208}Pb)$ -> Ksat = 225 +- 20 MeV

FRDM -> Esym = 32.3 +- 0.5 MeV
Lsym = 53.5 +- 15 MeV

Neutron skin (p,p')
-> Lsym = 42 +- 15 MeV
Ksym = -120 +- 40 MeV



But **be careful**: only **Skyrme** models have been considered. **Systematical uncertainties** may still influence these results.

Conclusions

In N. Baillot d'Etivaux *et al.*, Astro. J. 887, 1 (2019):
From thermal emission of qLMXB + using meta modeling -> Ksym = -90 +- 80 MeV
This is the first extraction of Ksym from data, *if you believe (i) GR, (ii) thermal emission model, and (iii) that canonical NS are made of nucleons only*.

From neutron skin + Skyrme models -> Ksym = -120 +- 40 MeV

Be careful of the model dependence of the analysis!! May be stronger than Ksat !!

We need more analyses ! —> discussion