

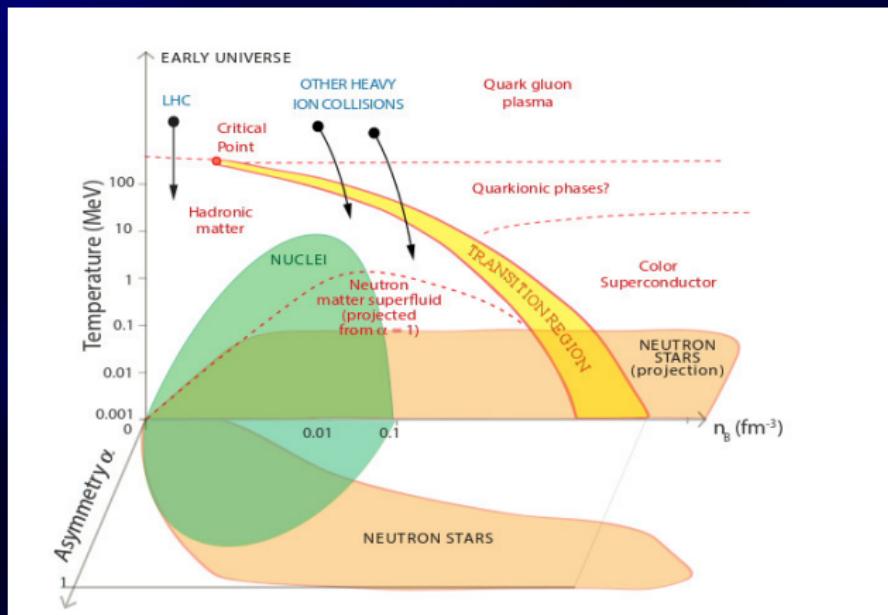
Constraining the equation of state for dense matter through thermal emission of neutron stars

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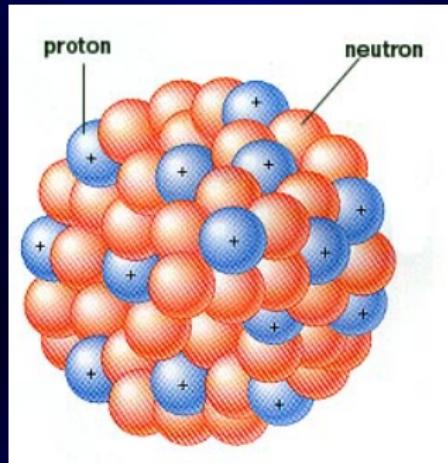
The best laboratory for very high densities :

- Hadronic matter at very high density / Assymetric matter
- Phase transition ?



Hadronic matter, anyway !

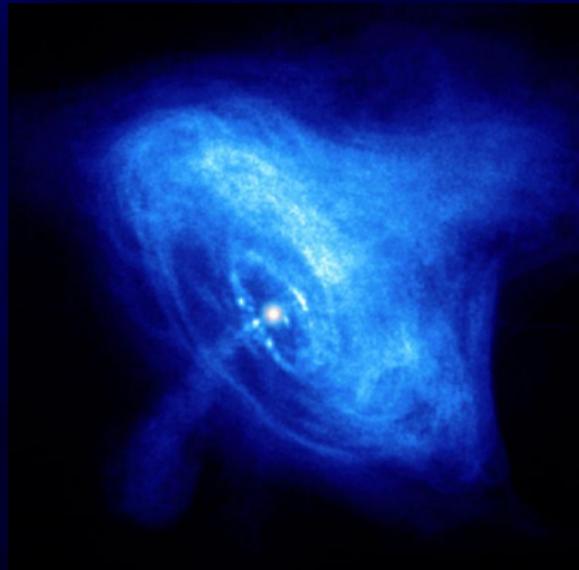
Comparision between two "isotopes" :



$$\simeq 10^{-15} \text{ m}$$

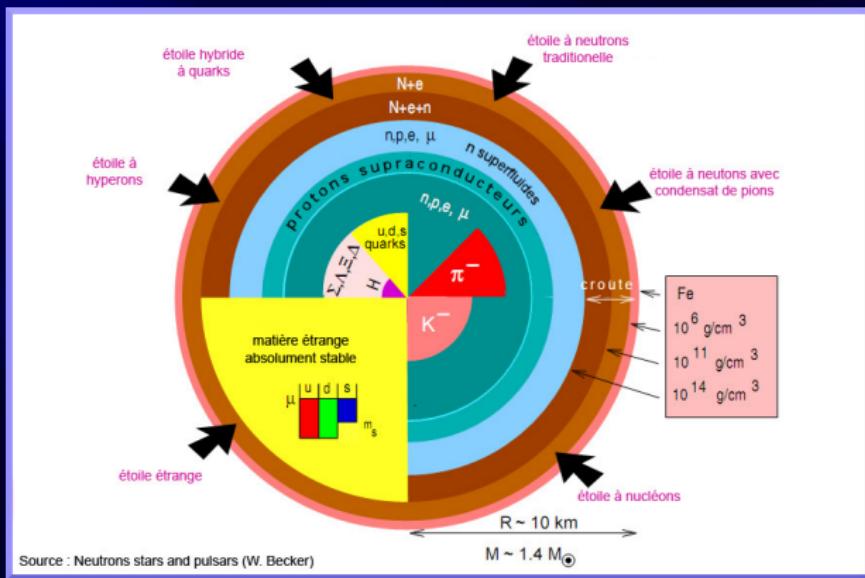


$$\simeq 10^3 \text{ m}$$



Neutron stars structure :

- Very high densities ($1.4M_{\odot}$, $R \sim 10\text{ km} \rightarrow n \sim 10^{14}\text{ g.cm}^{-3}$).
- totally degenerated fermion gaz (nucleons ? hyperons ? mesons ? quarks ? ...)



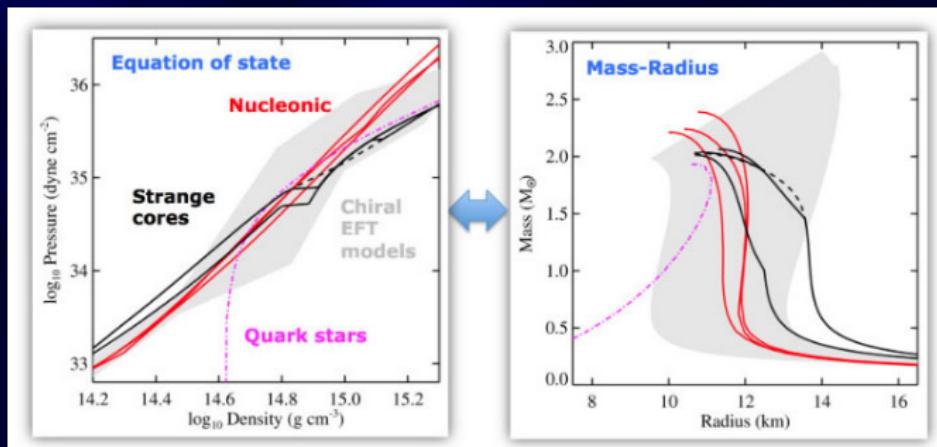
Link between EoS and M-R relation :

T.O.V equations (Tolmann-Oppenheimer-Volkov) :

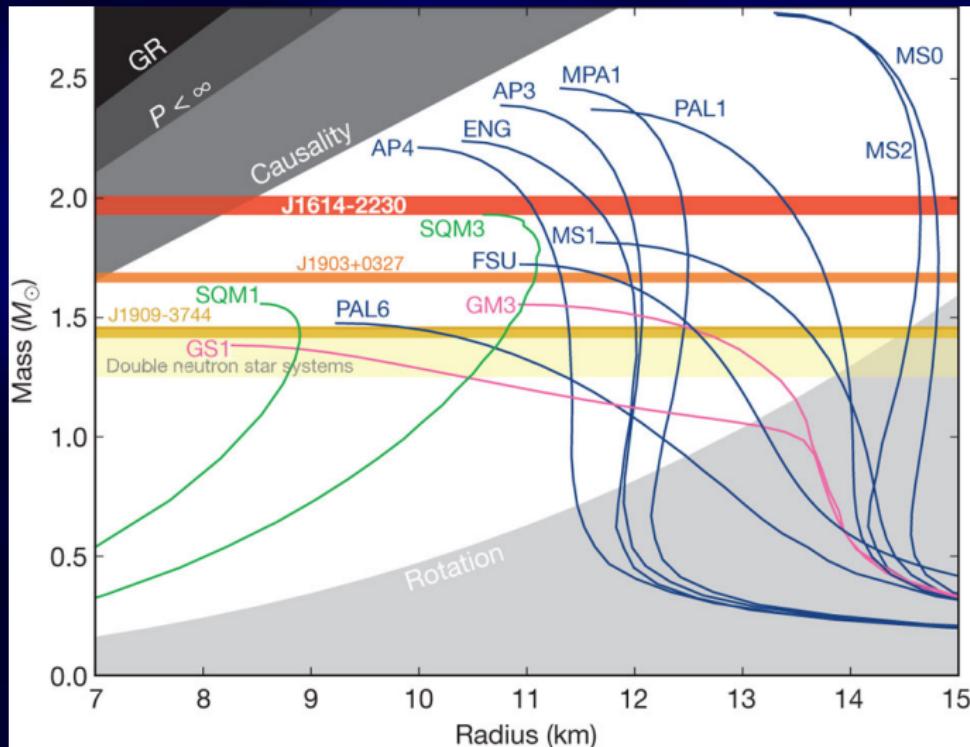
$$\frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r), \quad (1)$$

$$\frac{dP(r)}{dr} = -\frac{G\epsilon(r)m(r)}{r^2} \left(1 + \frac{P(r)}{\epsilon(r)c^2}\right) \left(1 + \frac{4\pi P(r)r^3}{m(r)c^2}\right) \times \left(1 - \frac{r_{sh}}{r} \frac{m(r)}{M}\right)^{-1}. \quad (2)$$

Equation of state : $P(\epsilon) \leftrightarrow$ mass-radius relation.

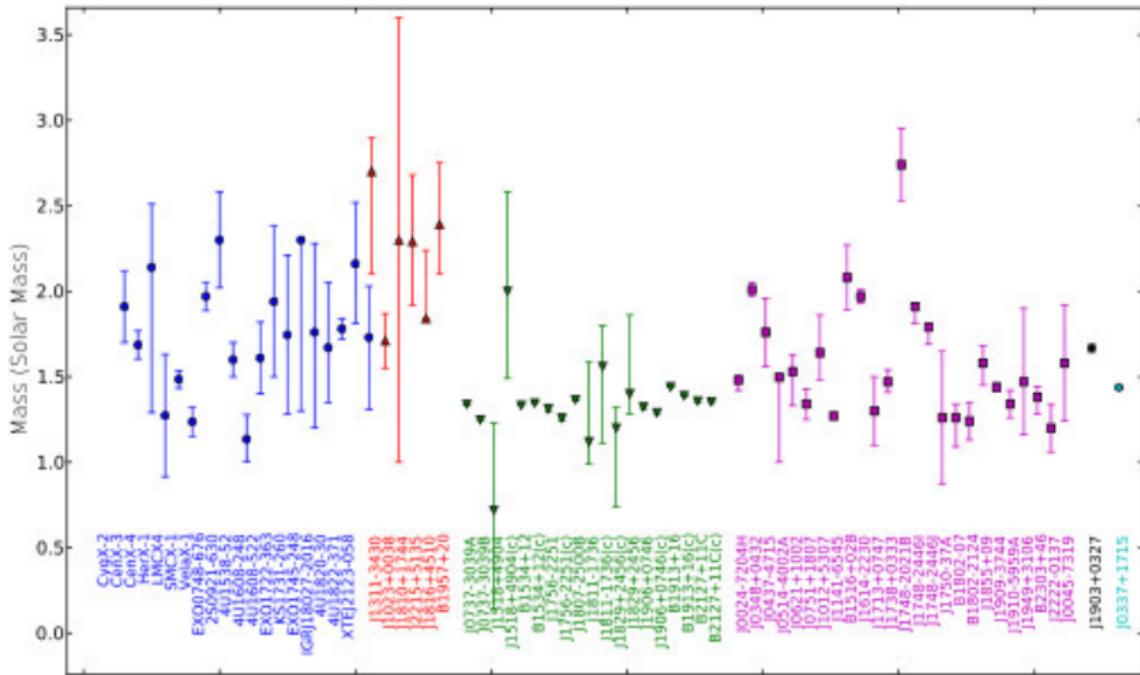


Various equations of state vs. observations :



(Demorest et. al. 2010)

Masses distribution of NS :



Radii distribution of NS :

$$R \in [0; +\infty] \text{ km.}$$

Radii distribution of NS :

More seriously,
 $R \in [5; 30]$ km.

Constraining nuclear equation of state from thermal radiation of neutron stars :

- Developpement of pulsar X-ray astronomy → strong limits on the equation of state at high density (Özel et al 2010 , Steiner et al 2010).
- Tool : Thermal radiation from the surface of neutron stars.
- Developpement of atmosphere models (Heinke et al 2006).
- Applying Bayesian analysis for several qLMXBs (Guillot et al 2013, Lattimer & Steiner 2014, Heinke et al 2014, Özel et al 2015, Bogdanov 2016).

The equation of state (EoS) for neutron stars interior :

Various kinds of EoS :

- Purely nucleonic \rightarrow no phase transition, **smooth EoS** with n, y_e, T .
- Phase transition :
 - hadronic matter : onset of hyperons, pion condensate ...
 - pure quark stars (absolutely stable strange matter) ?
 - hybrid stars (QGP/color superconductivity in the core) ?

Motivation for choosing **pure nucleonic matter** :

- smooth EoS
- extrapolation of nuclear physics knowledge (and uncertainties) towards high densities and low Y_p .
- **Define M-R boundaries for smooth EoS.**

The EoS model based on empirical parameters :

Definition of the empirical parameters :

$$\epsilon(n, \delta) = \epsilon_{IS} + \delta^2 \epsilon_{IV} \quad (3)$$

$$\epsilon_{IS} = E_{sat} + \frac{1}{2} K_{sat} x^2 + \frac{1}{3!} Q_{sat} x^3 + \frac{1}{4!} Z_{sat} x^4 + o(x^5) \quad (4)$$

$$\epsilon_{IV} = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \frac{1}{3!} Q_{sym} x^3 + \frac{1}{4!} Z_{sym} x^4 + o(x^5) \quad (5)$$

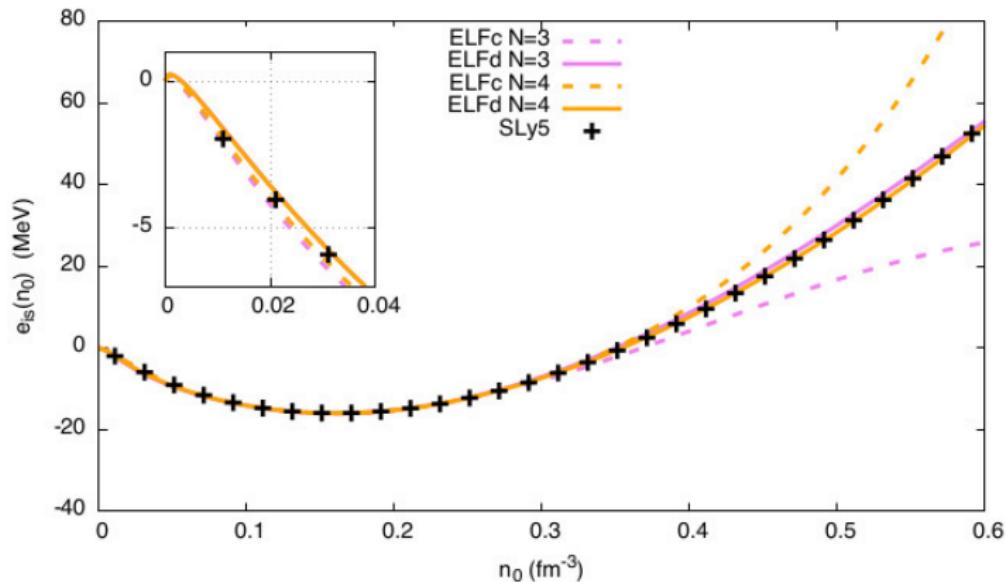
Taylor expansion around n_0 for the energy density :

$$\epsilon(n, \delta) = t(n, \delta) + \sum_{\alpha \geq 0}^N v_\alpha(\delta) \frac{x(n)^\alpha}{\alpha!} u_\alpha^N(x), \quad \delta = \frac{(n_n - n_p)}{n}, \quad x = \frac{(n - n_0)}{3n_0}$$

$$v_\alpha(\delta) = v_{\alpha, IS} + v_{\alpha, IV} \delta^2$$

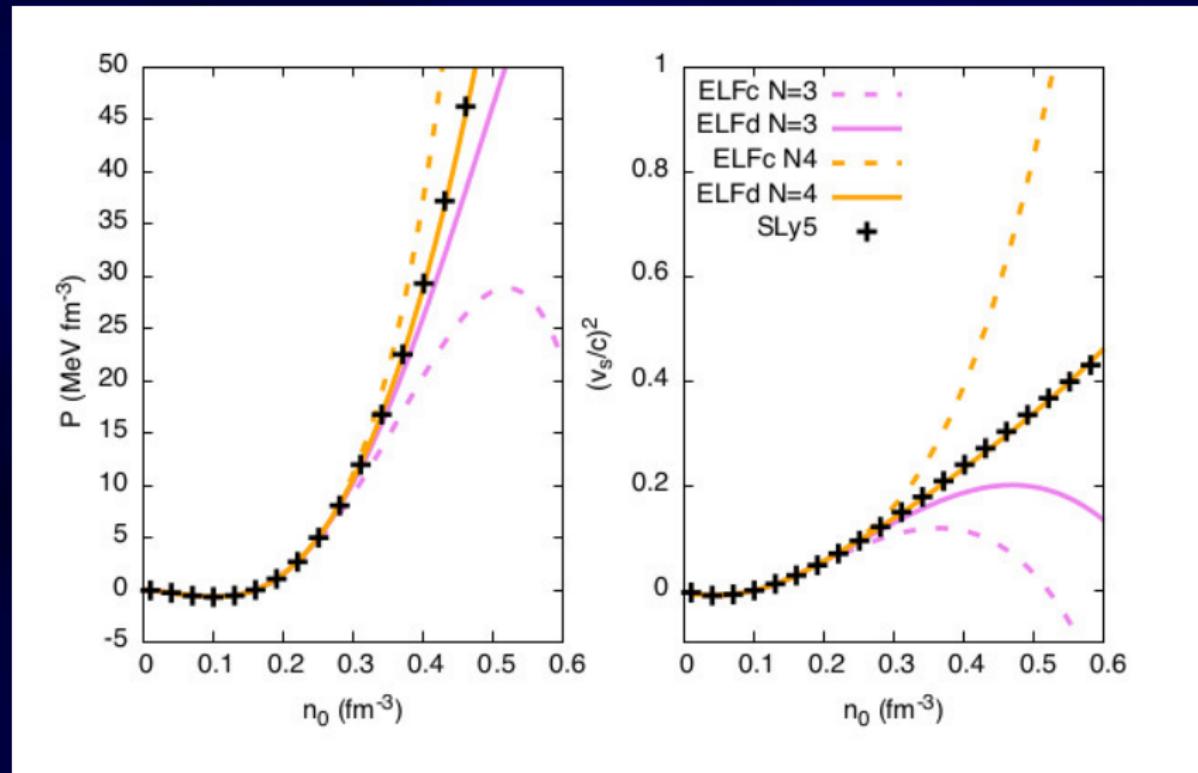
(Margueron, Casali, Gulminelli, in preparation)

Ability of the EoS to mimic known EoS : example of SLy5



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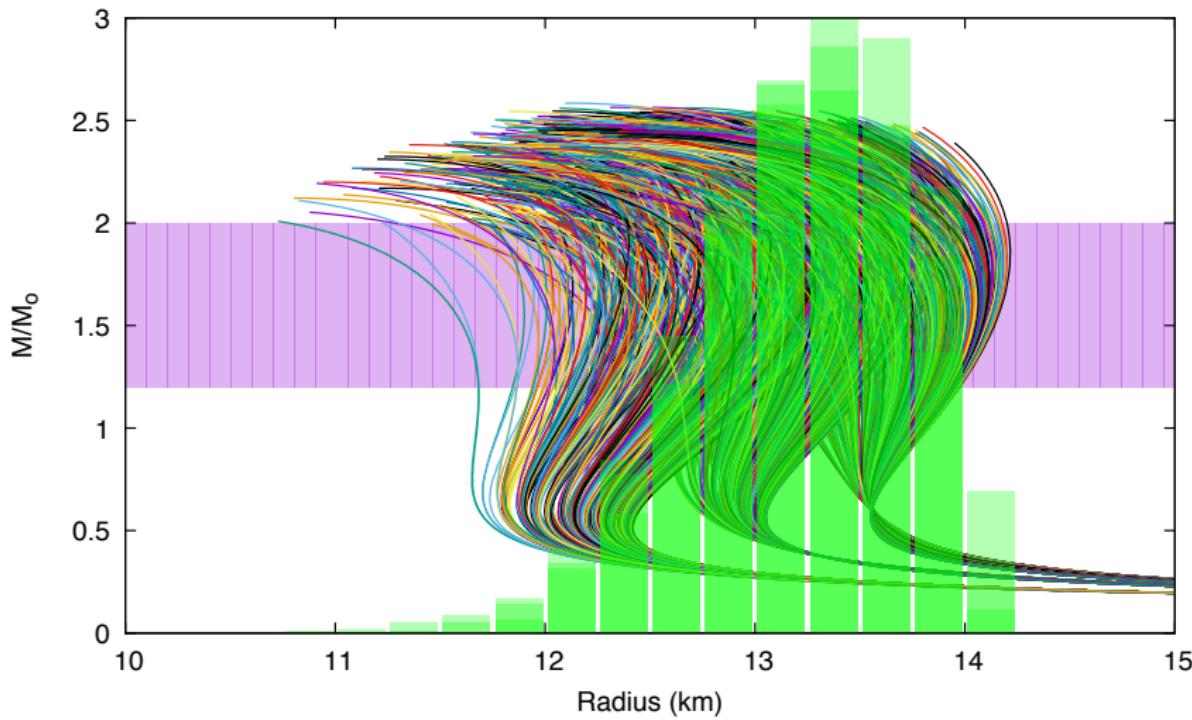
Our present knowledge of the empirical parameters :

Empirical parameters for various effective approaches :

Model (N_α)	der. order	fixed			Explore in small interval		Explore in large interval				
		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
Skyrme (16)	Average	-15.88	30.25	0.1595	47.8	234.2	-129.8	-357.0	377.9	1500.0	-2218.9
	σ	0.15	1.70	0.0011	16.8	10.2	66.0	22.4	110.3	169.3	617.6
Skyrme (35)	Average	-15.87	30.82	0.1596	49.6	237.3	-131.7	-349.0	370.0	1447.6	-2175.1
	σ	0.18	1.54	0.0039	21.6	26.6	89.1	88.5	187.9	510.4	1069.4
RMF (11)	Average	-16.24	35.11	0.1494	90.2	268.0	-4.6	-1.9	271.1	5058.3	-3671.8
	σ	0.06	2.63	0.0025	29.6	33.5	87.7	392.5	357.1	2294.1	1582.3
RHF (4)	Average	-15.97	33.97	0.1540	90.0	248.1	128.2	389.2	523.3	5269.1	-9955.5
	σ	0.08	1.37	0.0035	11.1	11.6	51.1	350.4	236.8	838.4	4155.7
Total (50)	Average	-16.03	33.30	0.1543	76.6	251.1	-2.7	12.7	388.1	3925.0	-5267.5
	σ_{tot}	0.20	2.65	0.0054	29.2	28.6	131.7	431.1	289.4	2269.7	4281.9
	Min	-16.35	26.83	0.1450	9.9	201.0	-393.9	-748.0	-86.2	-903.0	-16916.2
	Max	-15.31	38.71	0.1746	122.7	355.4	213.2	949.8	846.3	9997.3	-4.9

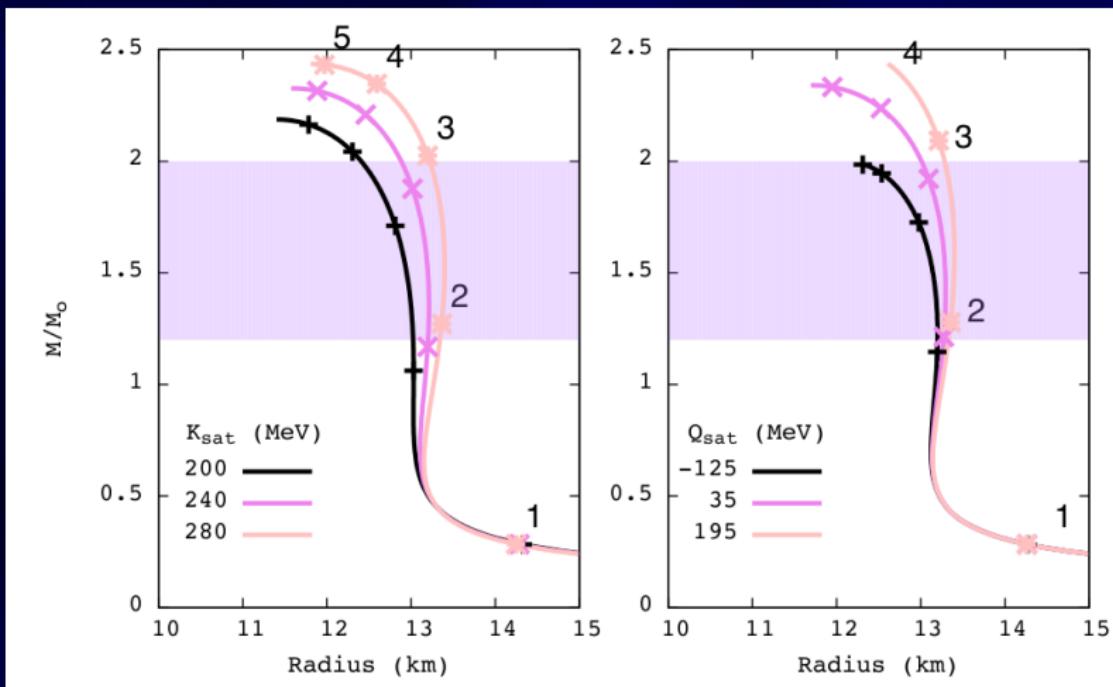
Dependence of M-R on the empirical parameters :

+ constrains : $0 < v_s^2 < c^2$ and $\epsilon_{IV}(n) > 0$ for $n < 4n_{sat}$



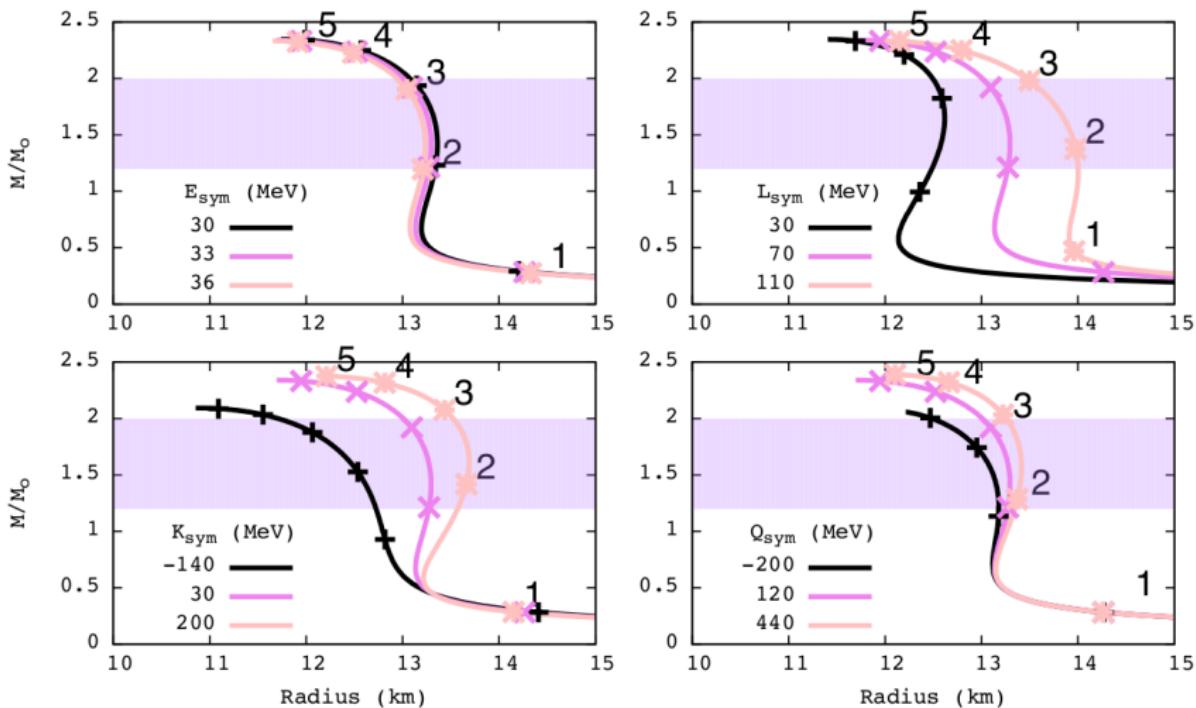
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X-ray observations of neutron stars :

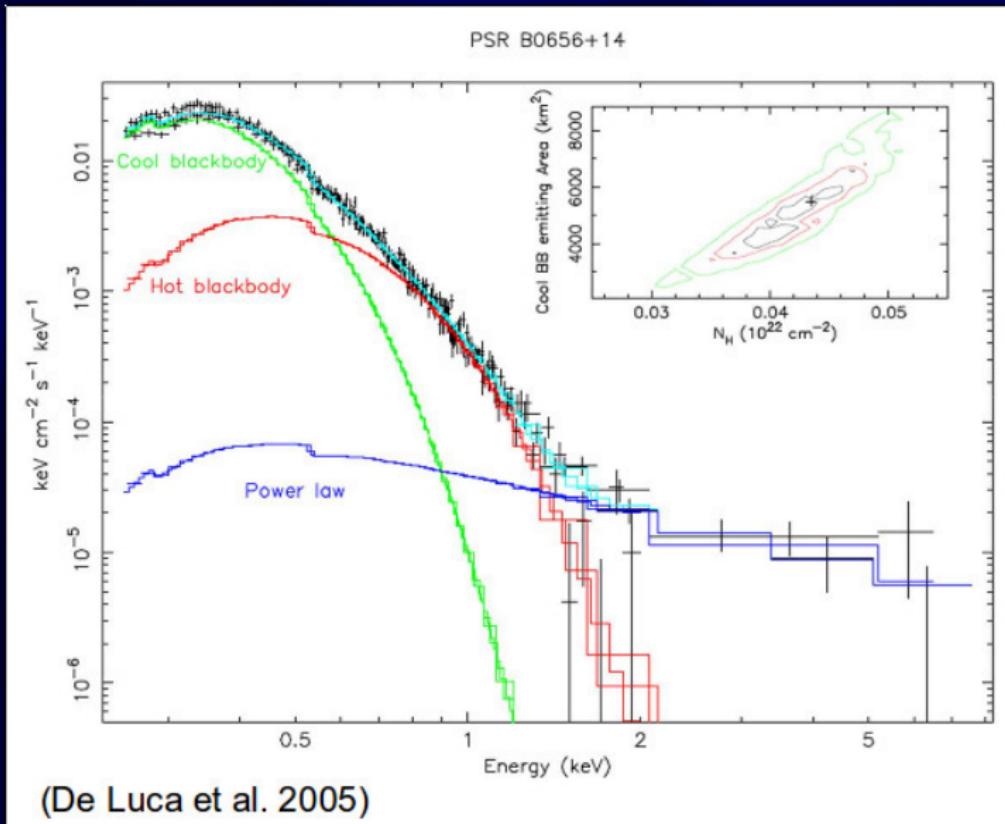


XMM-Newton



Chandra Observatory

Thermal emission of neutron stars :



Observations of thermal emission from NS :

black body like emission :

$$F \propto T^4(R_\infty/D)^2$$

(Rutledge et al. 1999)

- 6 low mass X-ray transients : almost pure thermal components, low magnetic fields, constant flux, atmosphere composition is purely H, in globular clusters (well constrained distances).
- a single EoS → simultaneous analysis.

Sources	Obs.	distance (kpc)	nH ($10^{22} cm^{-2}$)	atm.	pile-up α	Teff (K)
M13	Chandra	7.1 ± 0.4	[0; 1]	H	[0; 1]	[5; 6.5]
M28	Chandra	5.5 ± 0.3	[0; 1]	H	[0; 1]	[5; 6.5]
M30	Chandra	9 ± 0.4	[0; 1]	H	[0; 1]	[5; 6.5]
NGC6304	Chandra	6.22 ± 0.26	[0; 1]	H	[0; 1]	[5; 6.5]
NGC6397	Chandra	2.39 ± 0.13	[0; 1]	H	[0; 1]	[5; 6.5]
ω Cen	Chandra	4.59 ± 0.08	[0; 1]	H	[0; 1]	[5; 6.5]

Modeling the spectra with Xspec :

Spectrum model used :

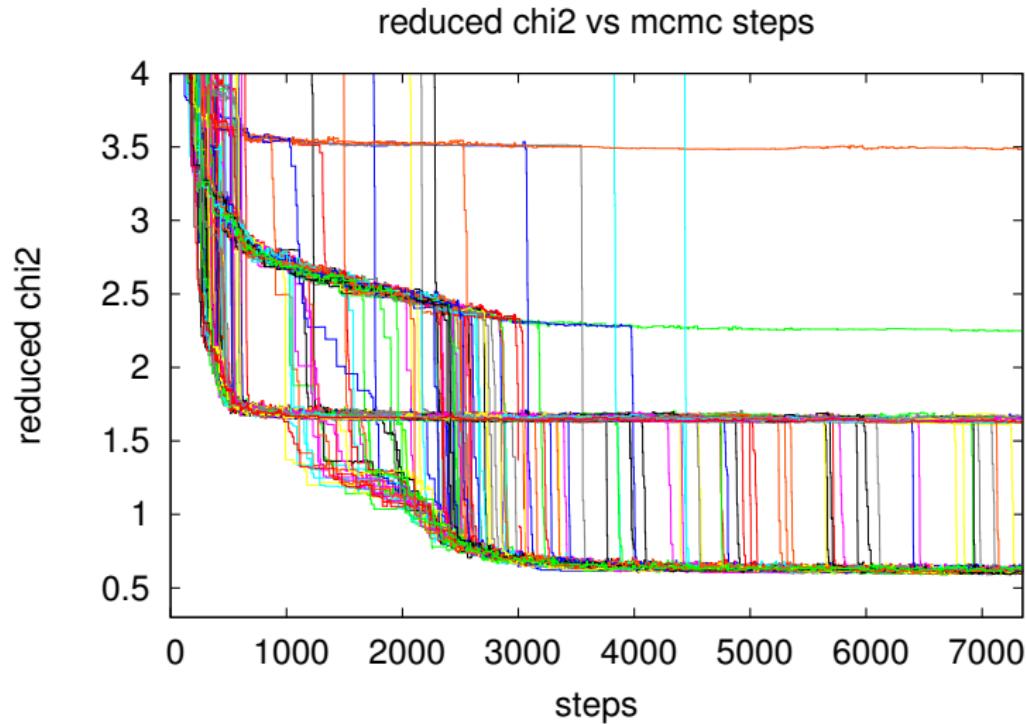
- "pile-up" (Davis 2001, Bogdanov 2016), "phabs" absorbtion and "nsatmos" for the atmosphere (Heinke et al. 2006).
- $E < 2$ keV : only thermal component and no power-law

Parameters which are allowed to vary :

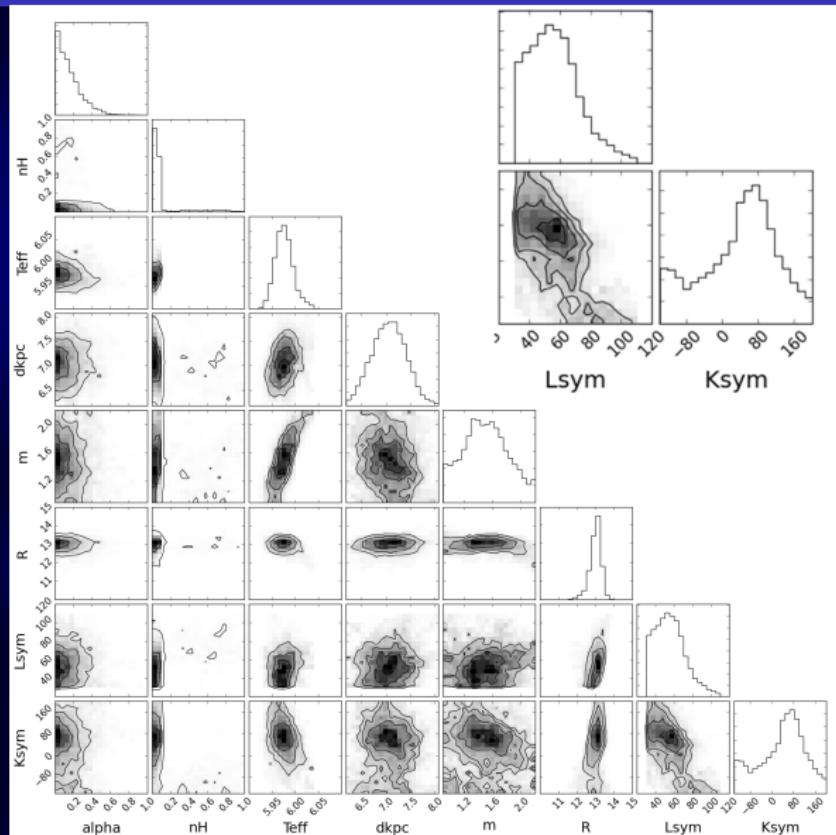
- pile-up alpha
- hydrogen column density on the line of site (nH)
- distance to the stars (dkpc)
- the surface effective temperature (Teff)
- the mass of the stars.
- the nuclear parameters K_{sym} and L_{sym} :

$$\text{EoS}(K_{sym}, L_{sym}, \text{Mass}) \rightarrow \text{Radius}$$

Reproducing the data :

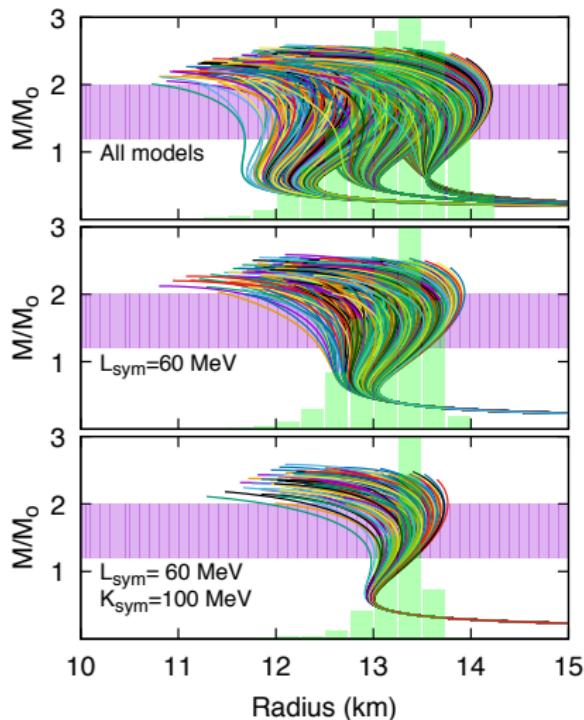


Preliminary results (M13 parameters) :



Conclusion :

- Present knowledge of nuclear physics + smooth EoS $\rightarrow R \simeq 11.5 - 14$ km and $M < 2.5M_{\odot}$
- Main source of uncertainties : L_{sym} and K_{sym} .
- if better knowledge on L_{sym} and K_{sym} : reduce uncertainty $\simeq 1$ km
- measurement of R out of these boundaries \rightarrow non-smooth EoS
→ Phase transition !



Outlooks :

- ➊ Finalizing this study.
- ➋ Extension of present EoS to include **quark matter**.
- ➌ Further analysis of occurrence of a phase transition from X-ray data :
Bayes factor.
- ➍ Waiting for L_{sym} measurement from PREX.
- ➎ Confronting our results with NICER or NS mergers data.



Thank you !