# The Equation of State and Cooling of Hyperonic Neutron Stars







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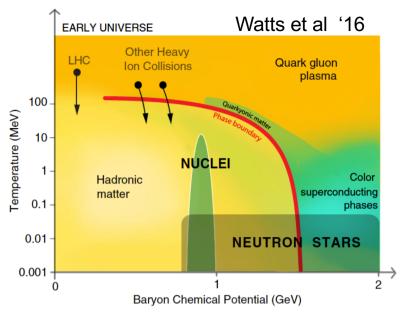
3rd EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC

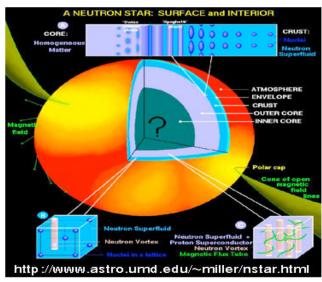
2-6 December 2019 University of Wroclaw

# Neutron Stars: A Cosmic Laboratory for Matter under Extreme Conditions

## **Outline**

- Motivation
- Nucleonic EoS
- Inclusion of Hyperons
- Cooling of Neutron Stars
- Summary





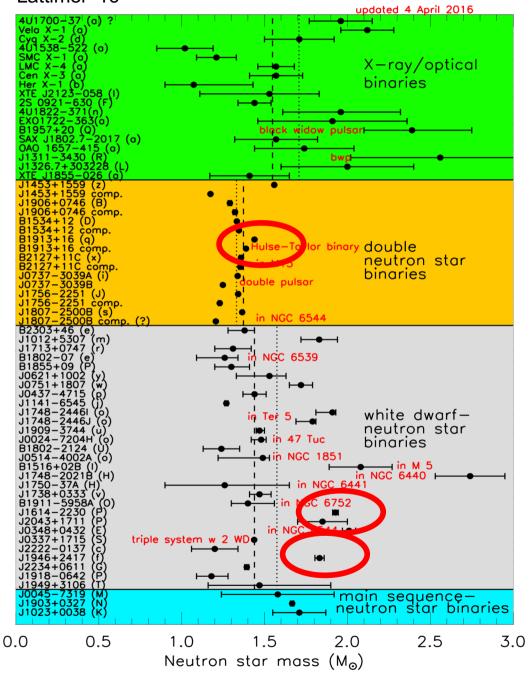
LT, Centelles, Ramos, Astrophys. J. 834 (2017) 3 LT, Centelles, Ramos, Publ. Astron. Soc. Austral. 34 (2017) e065 Negreiros, LT, Centelles, Ramos, Dexheimer, Astrophys. J. 863 (2018) 104

# **Motivation**

# **Mass**

- > 2000 pulsars known
- best determined masses: Hulse-Taylor pulsar M=1.4414  $\pm$  0.0002 M $_{\odot}$  Hulse-Taylor Nobel Prize 1994
- PSR J1614-2230¹ M=(1.97  $\pm$  0.04) M $_{\odot}$ ; PSR J0348+0432² M=(2.01  $\pm$  0.04) M $_{\odot}$ ; MSP J0740+6620³ M=(2.14 + 0.1- 0.09) M $_{\odot}$ ¹Demorest et al '10; ²Antoniadis et al '13; ³Cromartie et al '19

#### Lattimer '16



# Radius (?)

analysis of X-ray spectra emitted by neutron star (NS) atmosphere:

- RP-MSP: rotation-powered radio millisecond pulsars
- BNS: bursting NSs
- QXT: quiescent thermal emission of accreting NSs

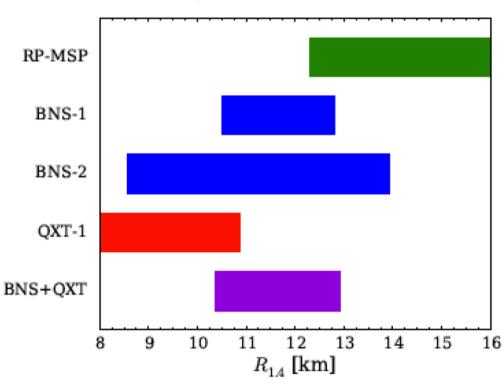
theory + pulsar observations:

R<sub>1.4M</sub>~11-13 Km

Lattimer and Prakash '16

#### Fortin et al '15:

- > RP-MSP: Bodganov '13
- > BNS-1: Nattila et al '16
- > BNS-2: Guver & Ozel '13
- ➤ QXT-1: Guillot & Rutledge '14
- ➤ BNS+QXT: Steiner et al '13



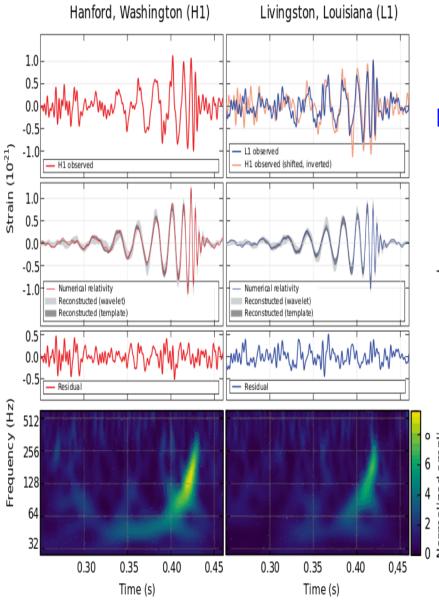
#### Some conclusions:

- ✓ marginally consistent analyses, favored R ≤ 13 Km (?)
- ✓ X-ray telescopes (NICER, eXTP) with precision for M-R of ~5%
- ✓ what about GW170817?

adapted from Fortin's talk

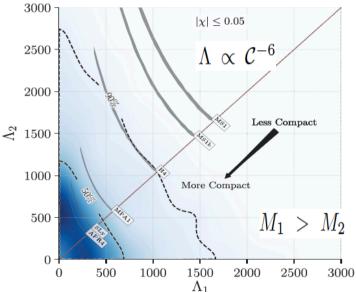
@ NewCompstar Annual Meeting '16;
Fortin, Zdunik, Haensel and Beiger '15

#### **GW170817**



Abbot et al. (LIGO-VIRGO) '17

	Low-spin prior ( $\chi \le 0.05$ )	High-spin prior $(\chi \le 0.89)$
Binary inclination $\theta_{JN}$	$146^{+25}_{-27}$ deg	152 <sup>+21</sup> <sub>-27</sub> deg
Binary inclination $\theta_{JN}$ using EM distance constraint [108]	$151^{+15}_{-11}$ deg	$153^{+15}_{-11}$ deg
Detector-frame chirp mass Mdet	$1.1975^{+0.0001}_{-0.0001} \ \mathrm{M}_{\odot}$	$1.1976^{+0.0004}_{-0.0002} \ \mathrm{M}_{\odot}$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} \mathrm{M}_{\odot}$	$1.186^{+0.001}_{-0.001} \mathrm{M}_{\odot}$
Primary mass $m_1$	(1.36, 1.60) M <sub>☉</sub>	$(1.36, 1.89) \text{ M}_{\odot}$
Secondary mass $m_2$	$(1.16, 1.36) \mathrm{M}_{\odot}$	$(1.00, 1.36) \text{ M}_{\odot}$
Total mass m	$2.73^{+0.04}_{-0.01} \text{ M}_{\odot}$	$2.77^{+0.22}_{-0.05} \text{ M}_{\odot}$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin $\chi_1$	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin $\chi_2$	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	$300^{+500}_{-190}(\text{symmetric})/300^{+420}_{-230}(\text{HPD})$	(0, 630)



$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

tidal deformability

$$k_2 = \frac{3}{2}\lambda R^{-5}$$

$$\Lambda = \frac{2k_2}{3C^5}; C = \frac{M}{R}$$

dimensionless tidal deformability

using tidal deformability sets constraints on  $M_{max} \lesssim 2.2 M_{\odot}$ 

Margalit and Metzger '17, Rezzolla, Most and Weih '18,...

9-10 Km  $\lesssim R_{1.4\text{M}\odot} \lesssim 13$  Km

Annala et al '18, Kumar et al '18, Abbott et al '18, Fattoyev et al '18, Most et al '18, Lim et al '18, Raithel et al '18, Burgio et al '18, Tews et al '18, De et al '18, Abbott et al '18, Malik et al '18, ...

# **Cooling**

Neutrino emission processes:

Fast neutrino reactions:
 direct URCA process
 only in inner core and have density

thresholds

$$n \to p + e^- + \bar{\nu}_e \; ; \; p + e^- \to n + \nu_e$$
  
 $Y \to (Y, N) + e^- + \bar{\nu}_e$ 

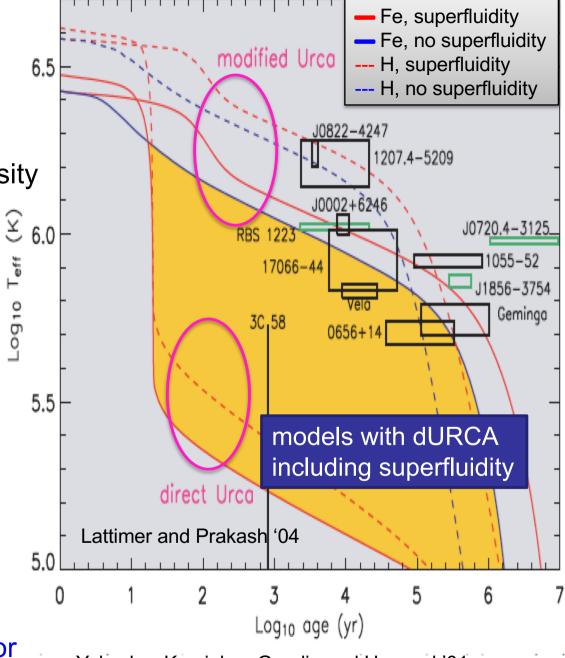
 Slow neutrino reactions: modified URCA process & NN bremsstrahlung everywhere in core, particularly in outer core (low-mass stars)

$$N + p + e^{-} \rightarrow N + n + \nu_{e}$$

$$N + n \rightarrow N + p + e^{-} + \bar{\nu}_{e}$$

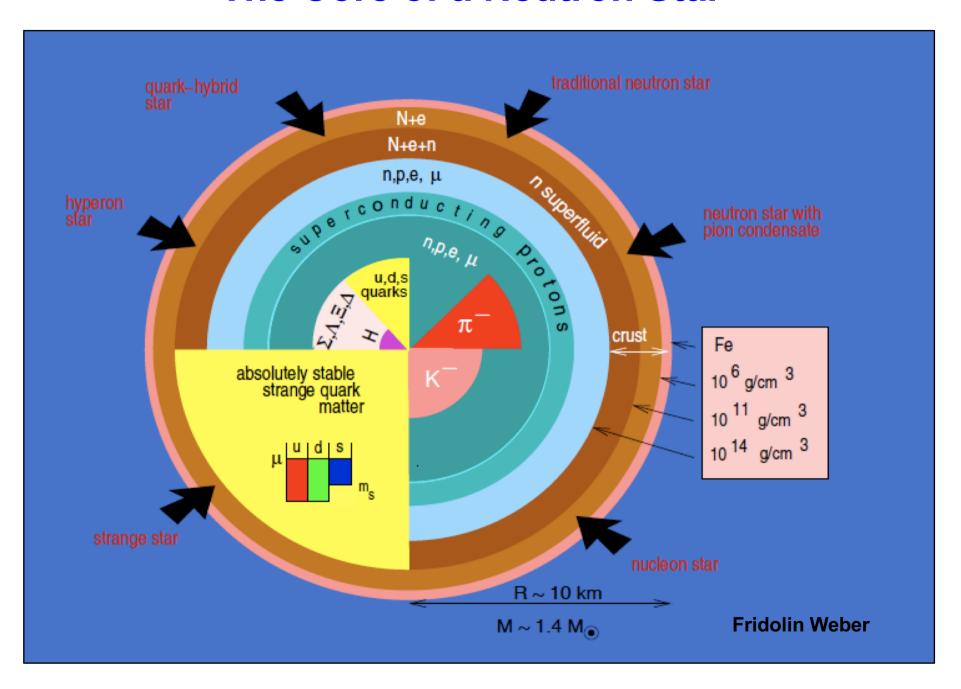
$$N + N \rightarrow \nu\bar{\nu}$$

Superfluidity/superconductivity or magnetic fields affect cooling

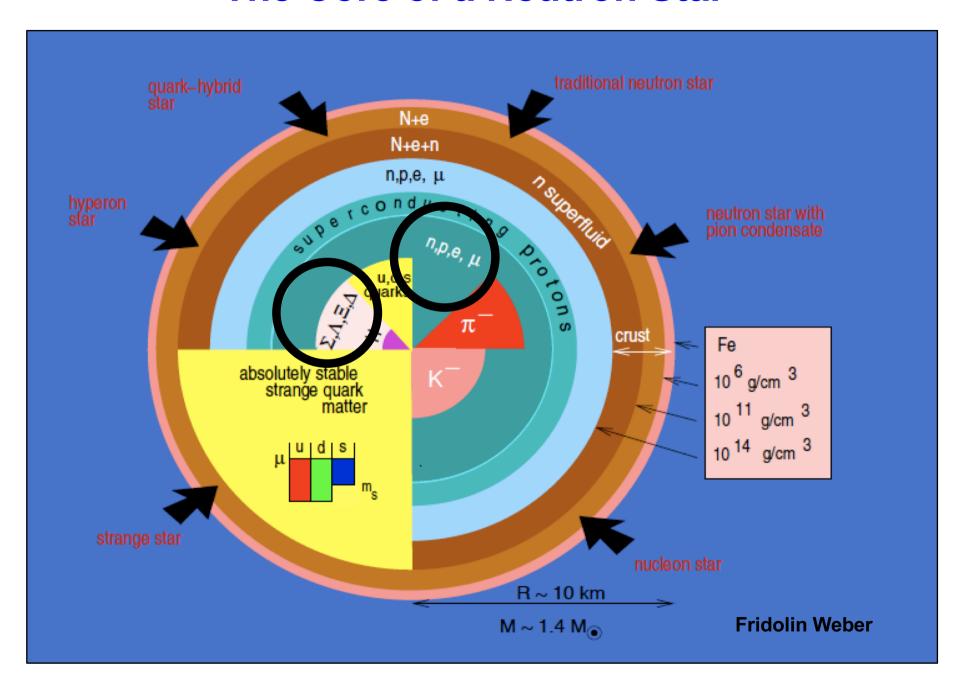


Yakovlev, Kaminker, Gnedin and Haensel '01; Yakovlev and Pethick '04; Potekhin, Pons and Page '15

# The Core of a Neutron Star



# The Core of a Neutron Star



# **Nucleonic EoS**

#### Microscopic ab-initio approaches

Based on solving the many-body problem starting from two- and three-body interactions

- Variational method: APR, CBF,...
- Quantum Montecarlo: AFDMC...
- Coupled cluster expansion
- Diagrammatic: BBG (BHF), SCGF...
- Relativistic DBHF
- RG methods: SRG from  $\chi$ EFT..
- Lattice methods

Advantage: systematic addition of higher-order contributions Disadvantage: applicable up to? (SRG from  $\chi$ EFT ~  $n_0$ )

#### Phenomenological approaches

Based on density-dependent interactions adjusted to nuclear observables and neutron star observations

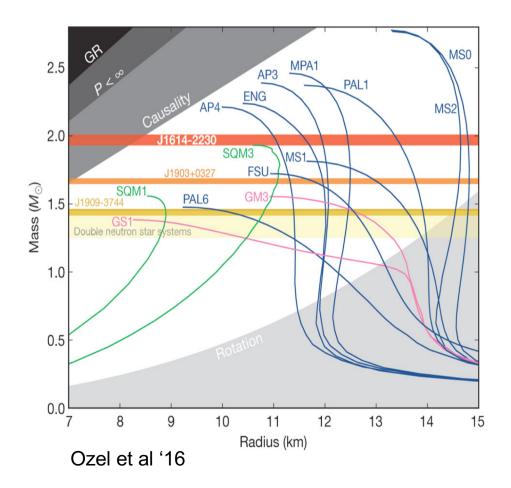
- Non-relativistic EDF: Skyrme...
- Relativistic Mean-Field (RMF) and Relativistic Hartree-Fock (RHF)
- Liquid Drop Model: BPS, BBP,...
- Thomas-Fermi model: Shen
- Statistical Model: HWN,RG,HS...

Advantage: applicable to high densities beyond n<sub>0</sub>
Disadvantage: not systematic

# **Mass-Radius Relation: TOV Equations**

$$\frac{dP}{dr} = -\frac{Gm\epsilon}{c^2r^2} \left(1 + \frac{P}{\epsilon}\right) \left(1 + \frac{4\pi r^3 P}{c^2m}\right) \left(1 - \frac{2Gm}{c^2r}\right)^{-1}$$
 • primary ingredient:  

$$\frac{dm}{dr} = \frac{4\pi r^2 \epsilon}{c^2}$$
 • some constraints:



- some constraints:
- Schwarzschild limit (GR)

 $R \ge 2 \text{ GM/c}^2$ 

- causality limit for EoS

 $R \ge 2.9 \text{ GM/c}^2$ 

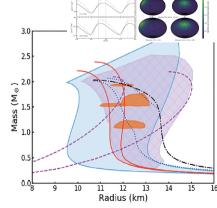
- mass-shedding limit

 $R < (GM/2\pi)^{1/3}/v^{2/3}$ 

Need of simultaneous mass-radius measurements to constrain EoS !!!







Watts et al. (LT) '19

### Phenomenological model based on FSU2 model

Chen and Piekariewicz '12

$$\mathcal{L} = \sum_{b} \mathcal{L}_{b} + \mathcal{L}_{m} + \sum_{l=e,\mu} \mathcal{L}_{l},$$

$$\mathcal{L}_{b} = \bar{\Psi}_{b}(i\gamma_{\mu}\partial^{\mu} - q_{b}\gamma_{\mu}A^{\mu} - m_{b} + g_{\sigma b}\sigma - g_{\omega b}\gamma_{\mu}\omega^{\mu} - g_{\phi b}\gamma_{\mu}\phi^{\mu} - g_{\rho b}\gamma_{\mu}\vec{I}_{b}\vec{\rho}^{\mu})\Psi_{b},$$

$$\mathcal{L}_{l} = \bar{\psi}_{l} \left( i \gamma_{\mu} \partial^{\mu} - q_{l} \gamma_{\mu} A^{\mu} - m_{l} \right) \psi_{l},$$

$$\mathcal{L}_{m} = \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - \frac{1}{2} m_{\sigma}^{2} \sigma^{2} - \frac{\kappa}{3!} (g_{\sigma N} \sigma)^{3} - \frac{\lambda}{4!} (g_{\sigma N} \sigma)^{4} \\
- \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} + \frac{1}{2} m_{\omega}^{2} \omega_{\mu} \omega^{\mu} + \frac{\zeta}{4!} (g_{\omega N} \omega_{\mu} \omega^{\mu})^{4} \\
- \frac{1}{4} \vec{R}^{\mu\nu} \vec{R}_{\mu\nu} + \frac{1}{2} m_{\rho}^{2} \vec{\rho}_{\mu} \vec{\rho}^{\mu} + \Lambda_{\omega} g_{\rho N}^{2} \vec{\rho}_{\mu} \vec{\rho}^{\mu} g_{\omega N}^{2} \omega_{\mu} \omega^{\mu} \\
- \frac{1}{4} P^{\mu\nu} P_{\mu\nu} + \frac{1}{2} m_{\phi}^{2} \phi_{\mu} \phi^{\mu} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}, \tag{2}$$

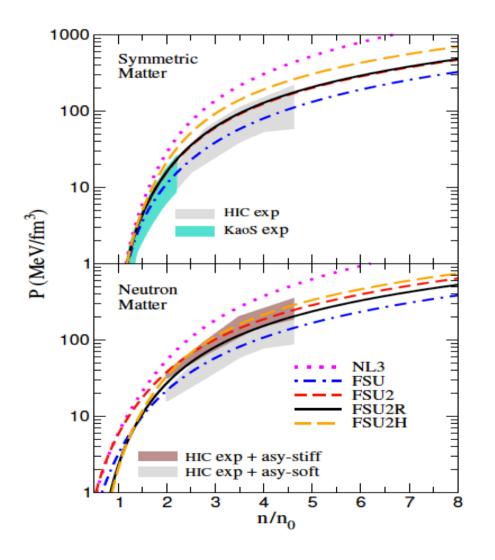
stiffening of EoS at  $n >> n_0$ : small ζ implies stiff EoS at n>>n<sub>0</sub>

modify density dependence of  $E_{svm}$  at 1-2 $n_0$ : small  $\Lambda_w$  implies stiff EoS at ~n<sub>0</sub>

(2)

 $M_{TOV(=max)}$  is governed by the stiffness of the EoS at n>>n<sub>0</sub>

R<sub>1.5M☉</sub> dominated by the density dependence of the EoS at 1-2 n<sub>0</sub>



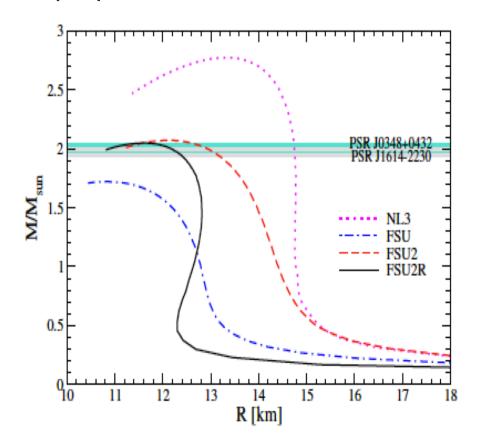
# **Including nucleons..**

**FSU2R** ( $\zeta$ = 0.024;  $\Lambda_{w}$ = 0.45):

 $M_{TOV}$ = 2.05  $M_{\odot}$ ,

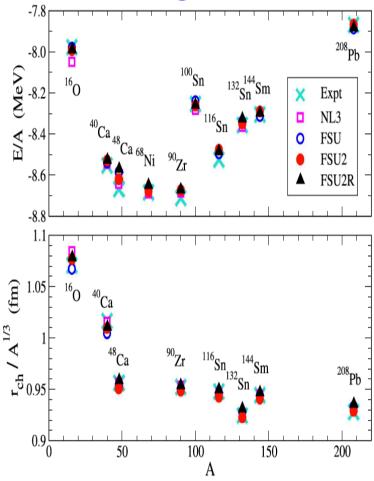
 $R_{1.5M\odot} = 12.8 \text{ Km}$ 

to get 2M<sub>☉</sub> and R ≤13 Km while fulfilling HICs data, nuclear matter properties and finite nuclei



## **Atomic nuclei**

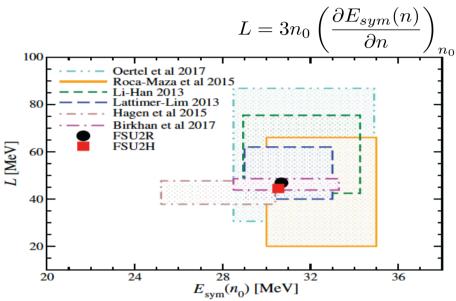
# **Energies** and charge radii



The differences between FSU2R and the experimental energies and charge radii are at the level of 1% or smaller

# Symmetry energy and slope

$$E_{sym} = E/A(n_0, x_p = 0) - E/A(n_0, x_p = 0.5)$$



Excellent agreement with recent empirical and theoretical constraints

#### <sup>208</sup>Pb neutron skin thickness

FSU2R: 
$$\Delta r_{np} = 0.133$$
 fm

$$\Delta r_{np}=0.302\pm0.177~{
m fm}$$
 Horowitz et al '12  $\Delta r_{np}=0.15\pm0.03~{
m fm}$  Tarbert et al (MAMI) '14  $0.13\lesssim\Delta r_{np}\lesssim0.19$  Roca-Maza et al '15

Fairly compatible within errors

# **Inclusion of Hyperons**

# Scarce experimental information:

- data from > 40 single and few double Λ hypernuclei
- few single Ξ-hypernuclei
- no Σ-hypernuclei
- few YN scattering data
   (~50 points) due to
   difficulties in preparing
   hyperon beams and no
   hyperon targets available

Chatterjee and Vidana '16 Vidana '18

The Hyperon Puzzle



The presence of hyperons in neutron stars is energetically probable as density increases. However, it induces a strong softening of the EoS that leads to maximum neutron star masses < 2M<sub>©</sub>

#### Solution?

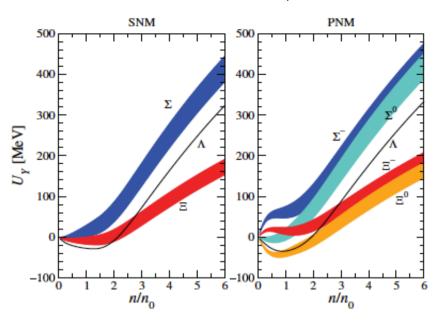
- > stiffer YN and YY interactions
- hyperonic 3-body forces
- $\triangleright$  push of Y onset by  $\triangle$  or meson condensates
- quark matter below Y onset
- > others: modified gravity...

# Hyperons soften EoS: $M_{TOV}$ gets reduced by ~15% $(M_{TOV} < 2 M_{\odot} \text{ for FSU2R})$ while R insensitive

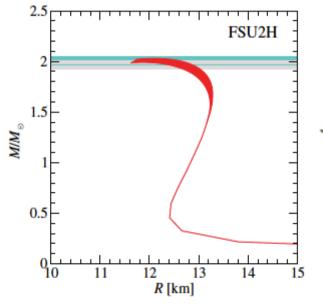
We tense FSU2 to make EoS stiffer: FSU2H ( $\zeta$ = 0.008;  $\Lambda_{\rm w}$ = 0.45), compatible with atomic nuclei and HiCs for neutron matter

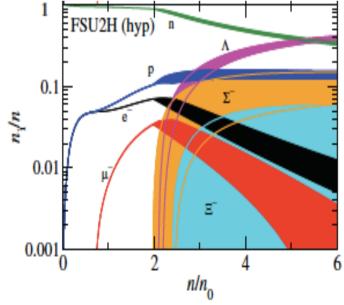
#### Hypernuclear observables

Hashimoto and Tamura '06; Gal et al. '16



	FSU2H
npeµ M <sub>TOV</sub>	2.38M <sub>⊙</sub>
R <sub>1.4M☉</sub>	13.2 Km
npeµY	
$M_{TOV}$	$2.02 M_{\odot}$
R <sub>1.4M⊙</sub>	13.2 Km

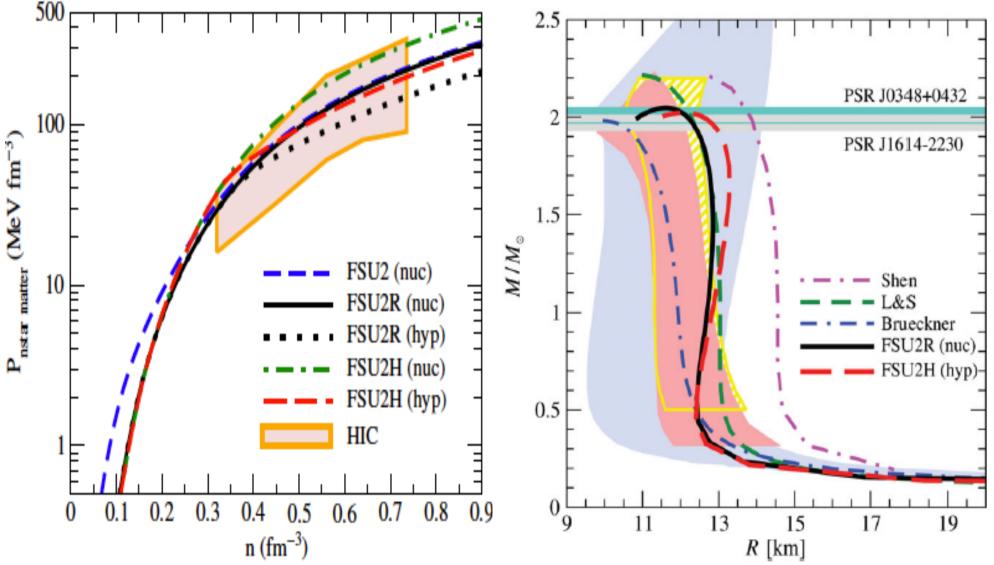






LT, Centelles, Ramos, Astrophys. J. 834 (2017) 3

LT, Centelles, Ramos, Publ. Astron. Soc. Austral. 34 (2017) e065



EoS for the nucleonic and hyperonic inner core that satisfies  $2M_{\odot}$  observations and determinations of R  $\pm 13$  Km, while fulfilling saturation properties of nuclear matter and finite nuclei as well as constraints from HiCs

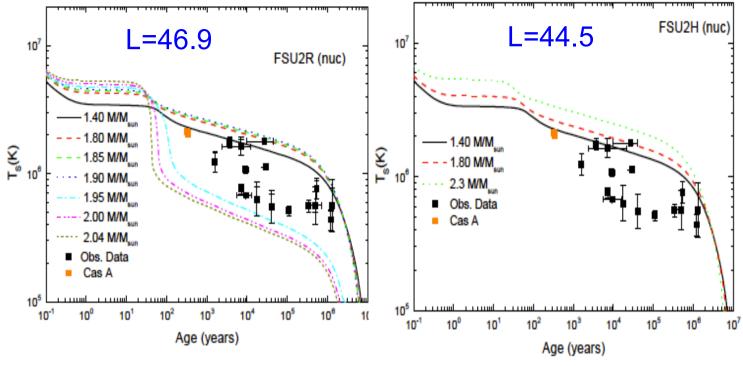
#### PSR J0348+0432 PSR J1614-2230 FSU2 (nuc) - FSU2R (nuc) • • FSU2R (hyp) - FSU2H (nuc) FSU2H (hyp) 0.5 0 10 20 12 14 16 18 R (km)

# **Cooling of Neutron Stars**

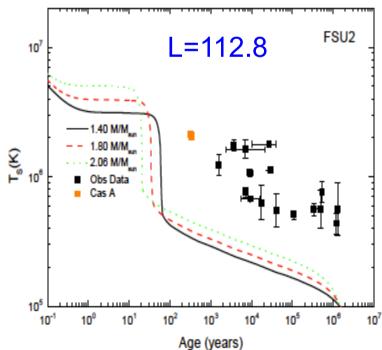
Models	FSU2	FSU2R	FSU2H
$n_0 \; ({\rm fm}^{-3})$	0.1505	0.1505	0.1505
$E/A \; (\mathrm{MeV})$	-16.28	-16.28	-16.28
K  (MeV)	238.0	238.0	238.0
$E_{\text{sym}}(n_0) \text{ (MeV)}$	37.6	30.7	30.5
L  (MeV)	112.8	46.9	44.5

DU:	$\Sigma^-  o \Sigma^0 + e^- + \bar{\nu},$
$n \to p + e^- + \bar{\nu},$	$\Xi^- \rightarrow \Lambda + e^- + \bar{\nu}$ ,
$\Lambda \to p + e^- + \bar{\nu},$	$\Xi^- \to \Sigma^0 + e^- + \bar{\nu}$ ,
$\Sigma^- \to n + e^- + \bar{\nu},$	$\Xi^0 \rightarrow \Sigma^+ + e^- + \bar{\nu}$ ,
$\Sigma^- \to \Lambda + e^- + \bar{\nu},$	$\Xi^- \rightarrow \Xi^0 + e^- + \bar{\nu}$

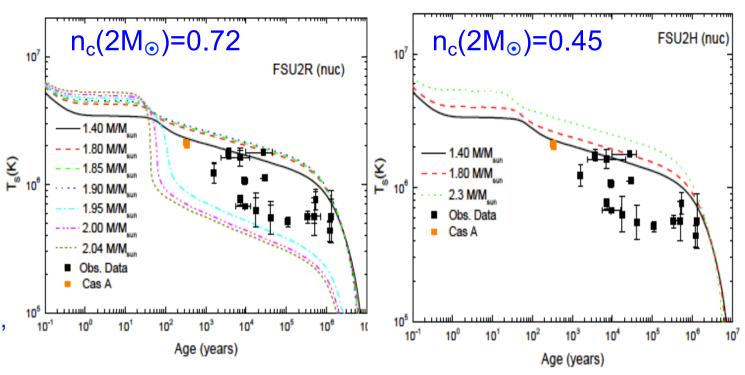
Models	DU threshold	${\rm hyp}~{\rm DU}~{\rm threshold}$	$1.4M_{\odot}$	$1.4M_{\odot}$	$1.76M_{\odot}$	$1.76 M_{\odot}$	$2.0M_{\odot}$	$2.0M_{\odot}$
	$(\mathrm{fm^{-3}})$	$({\rm fm}^{-3})$	$n_c~({\rm fm^{-3}})$	cooling	$n_c~({\rm fm}^{-3})$	cooling	$n_c~({\rm fm}^{-3})$	cooling
FSU2 (nuc)	0.21	_	0.35	fast	0.47	fast	0.64	fast
FSU2R (nuc)	0.61	_	0.39	slow	0.51	slow	0.72	fast
FSU2H (nuc)	0.61	_	0.34	slow	0.39	slow	0.45	slow
FSU2R (hyp)	0.57	0.37	0.40	slow	0.87	fast	_	_
FSU2H (hyp)	0.52	0.34	0.34	slow	0.44	slow	0.71	fast



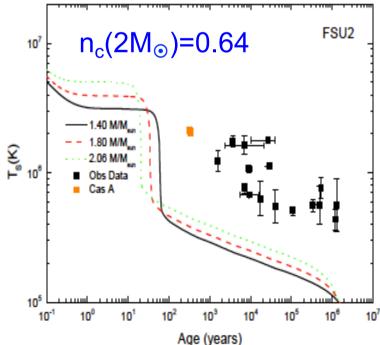
Models	DU threshold	
	$(\mathrm{fm^{-3}})$	
FSU2 (nuc)	0.21	
FSU2R (nuc)	0.61	
FSU2H (nuc)	0.61	



High-mass stars (1.8-2 M<sub>☉</sub>): stiffer EoS implies lower central densities and, thus, slower cooling

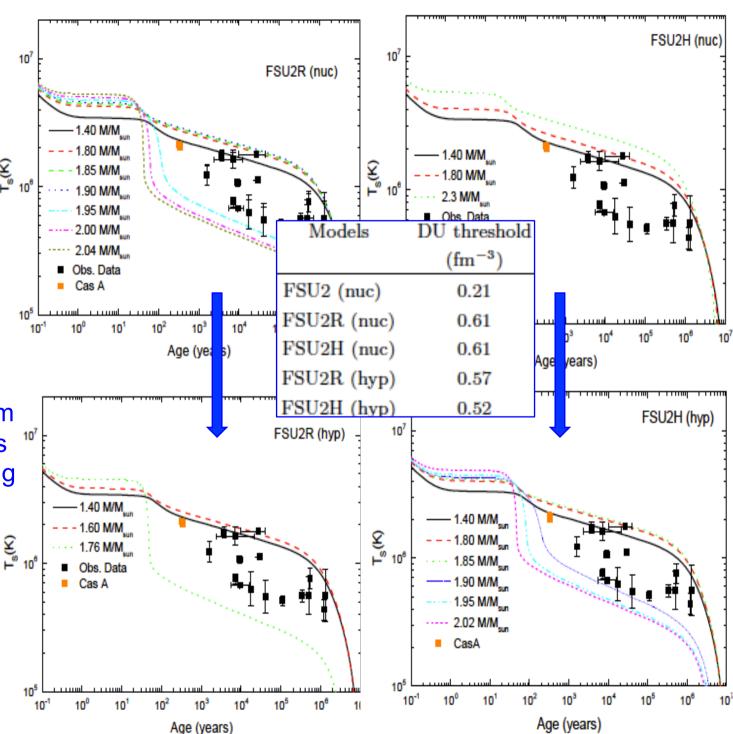


Models	DU threshold	
	$({\rm fm}^{-3})$	
FSU2 (nuc)	0.21	
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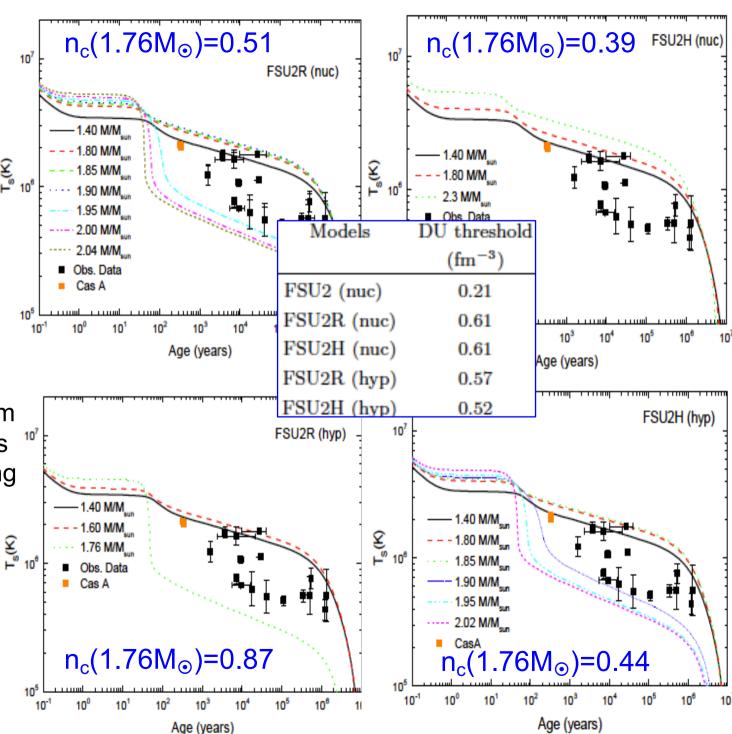
Hyperons in medium to heavy mass stars speed up the cooling due to reduction of neutron fraction



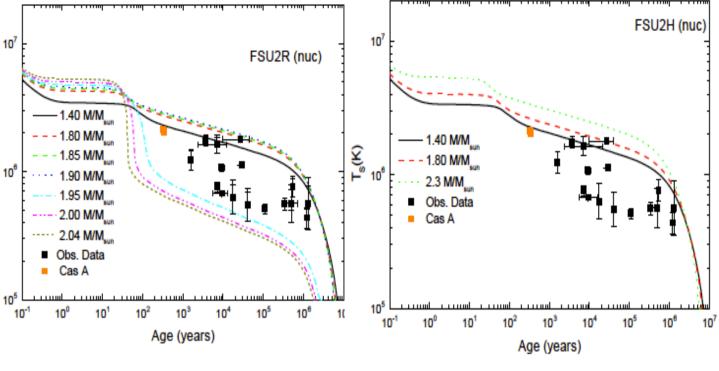
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Softer EoS (larger densities) with hyperons activates cooling

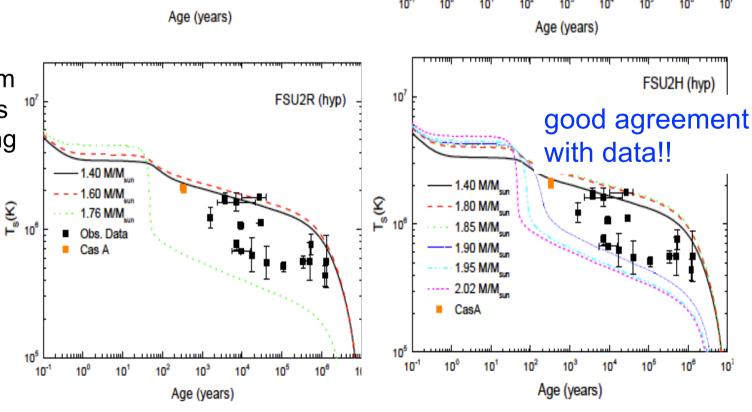


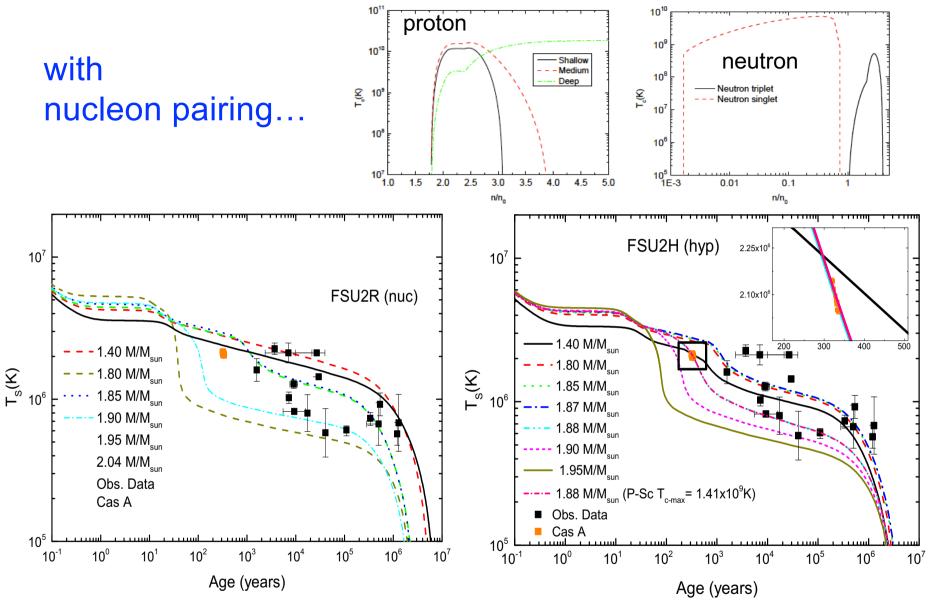
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Hyperons in medium to heavy mass stars speed up the cooling due to reduction of neutron fraction

Softer EoS (larger densities) with hyperons activates cooling





including medium proton pairing improves the agreement with observations, specially Cas A for preferred FSU2H(hyp), but cold stars with M > 1.8  $M_{\odot}$  No magnetic fields have been considered!! Negreiros, LT, Centelles,

Ramos and Dexheimer '18







- We have obtained a new EoS for the nucleonic and hyperonic inner core of neutron stars that fulfills 2M<sub>☉</sub> and R ≾ 13 Km, as well as the saturation properties of nuclear matter, the properties of atomic nuclei and constraints from HICs:
- FSU2R, fulfills 2M<sub>☉</sub> with R  $\stackrel{<}{_{\sim}}$  13 Km, while reproducing the energies and charge radii of nuclei, with E<sub>sym</sub>=30.7 MeV & L=46.9 MeV and  $\Delta r_{np}$ =0.15fm
- hyperons soften EoS and FSU2R produces M<2M<sub>☉</sub>, while R is insensitive: a slight modified parametrization, FSU2H, is still compatible with the properties of atomic nuclei (E<sub>svm</sub>=30.5 MeV & L=44.5 MeV) and HiCs
- Our results suggest that cooling observations are compatible with a soft nuclear symmetry energy and, hence, small radii, but favoring old neutron stars with M > 1.8M<sub>☉</sub>
- Future: cooling with magnetic fields,...