

The Equation of State for Nucleonic and Hyperonic Neutron Stars

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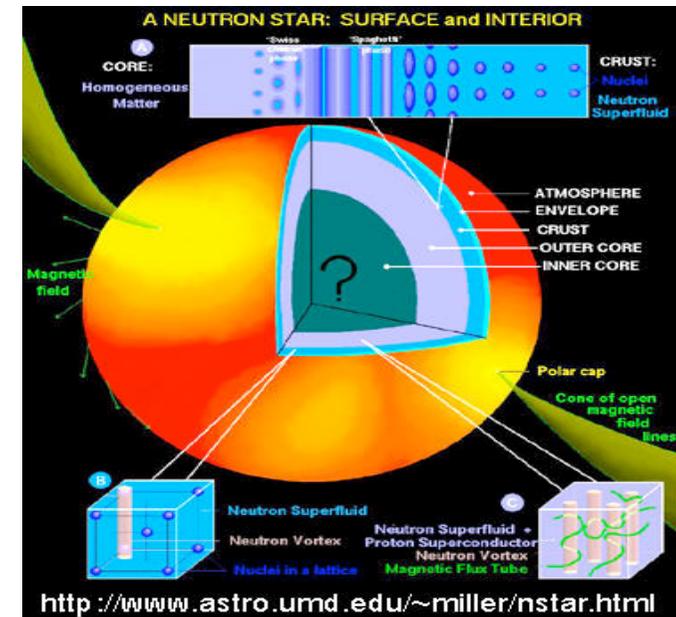
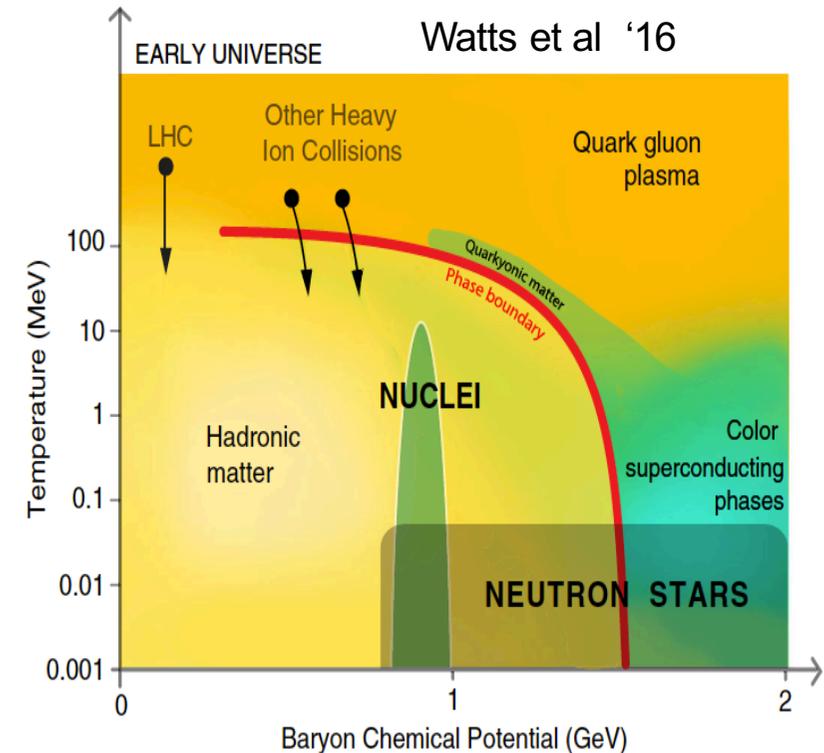


Neutron Stars: A Cosmic Laboratory for Matter under Extreme Conditions

Outline

- Motivation
- FSU2R and FSU2H models
- Hyperons
- Cooling
- Summary

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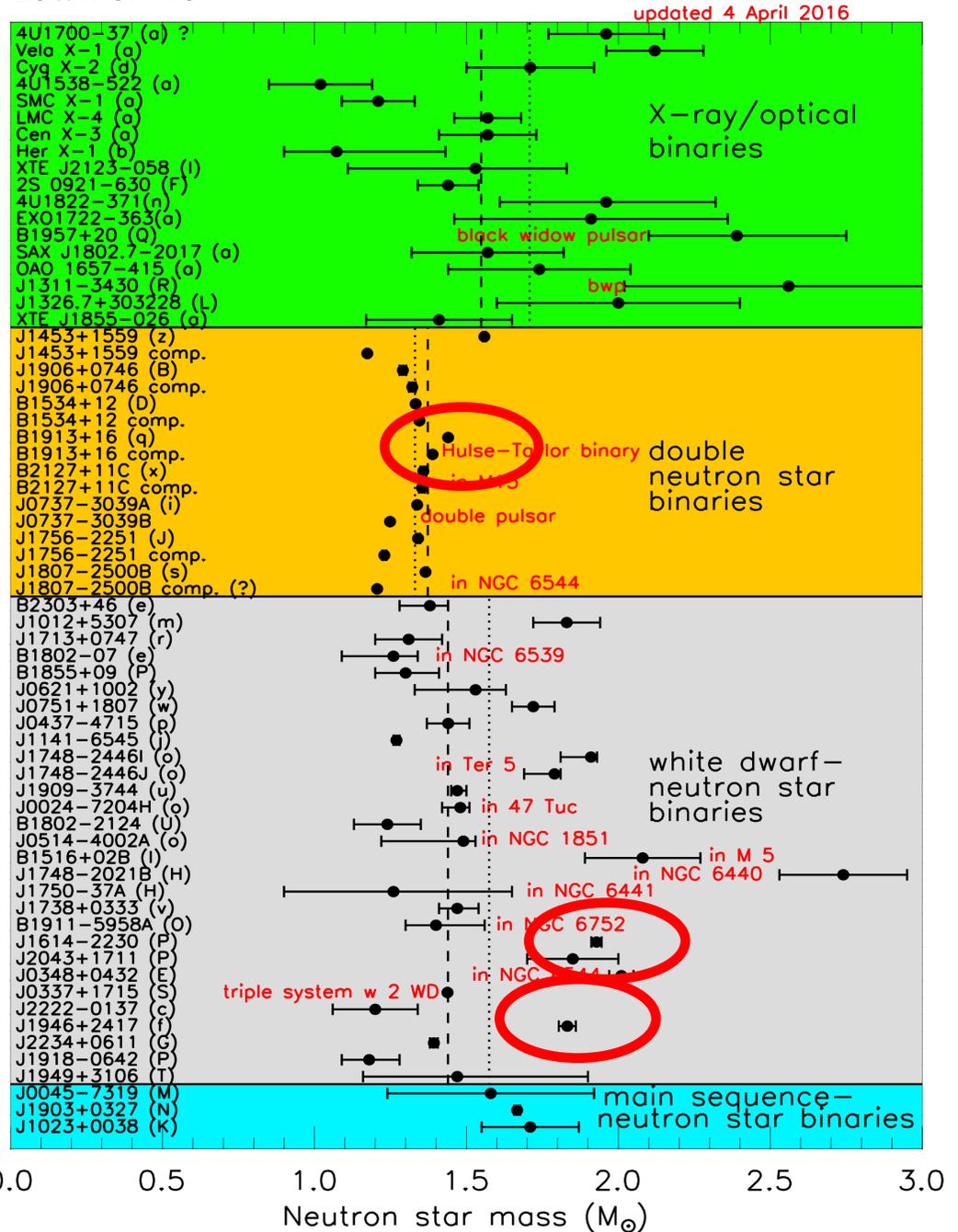


Motivation

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
 $M = (2.01 \pm 0.04) M_{\odot}$
¹Demorest et al '10;
²Antoniadis et al '13

Lattimer '16



Radius

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

- RP-MSP: X-ray emission from radio millisecond pulsars
- BNS: X-burst from accreting NSs
- QXT: quiescent thermal emission of accreting NSs

theory + pulsar observations:

$R_{1.4M_{\odot}} \sim 11-13$ Km Lattimer and Prakash '16

EoSs constraint by GW170817

(M_{\max} and $\Lambda_{1.4M_{\odot}}$) Most et al '18

$12 < R_{1.4M_{\odot}}/\text{Km} < 13.45$

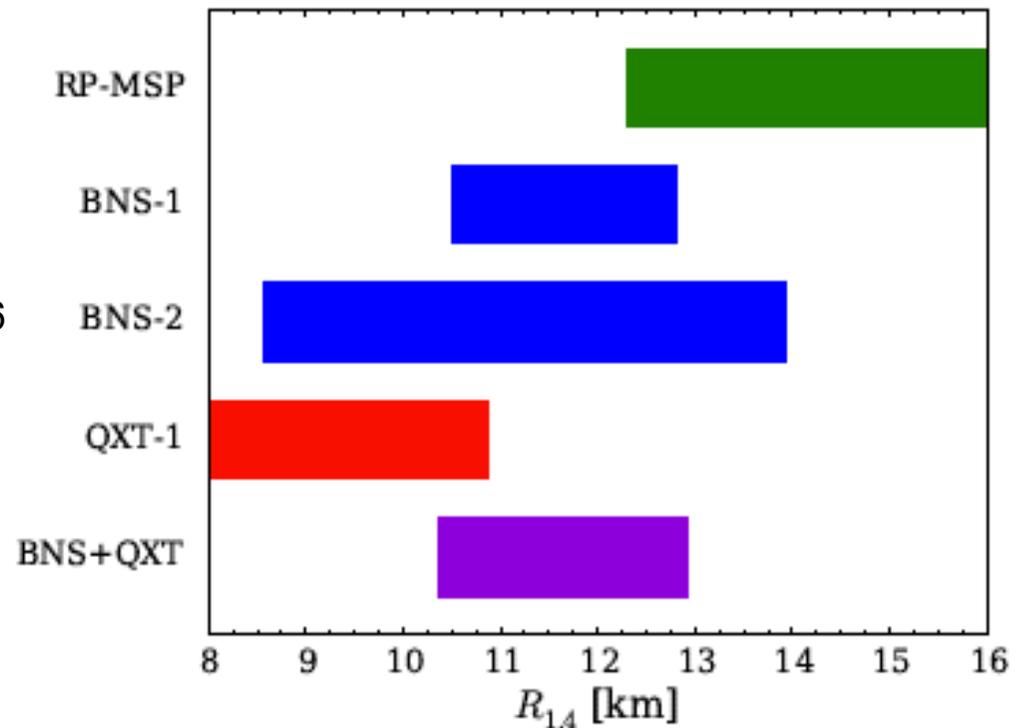
Some conclusions:

- ✓ marginally consistent analyses, favored $R \lesssim 13$ Km (?)
- ✓ future X-ray telescopes (NICER, eXTP) with precision for M-R of $\sim 5\%$
- ✓ GW signals from NS mergers with precision for R of ~ 1 km

Bauswein and Janka '12; Lackey and Wade '15

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



Cooling

Neutrino emission processes:

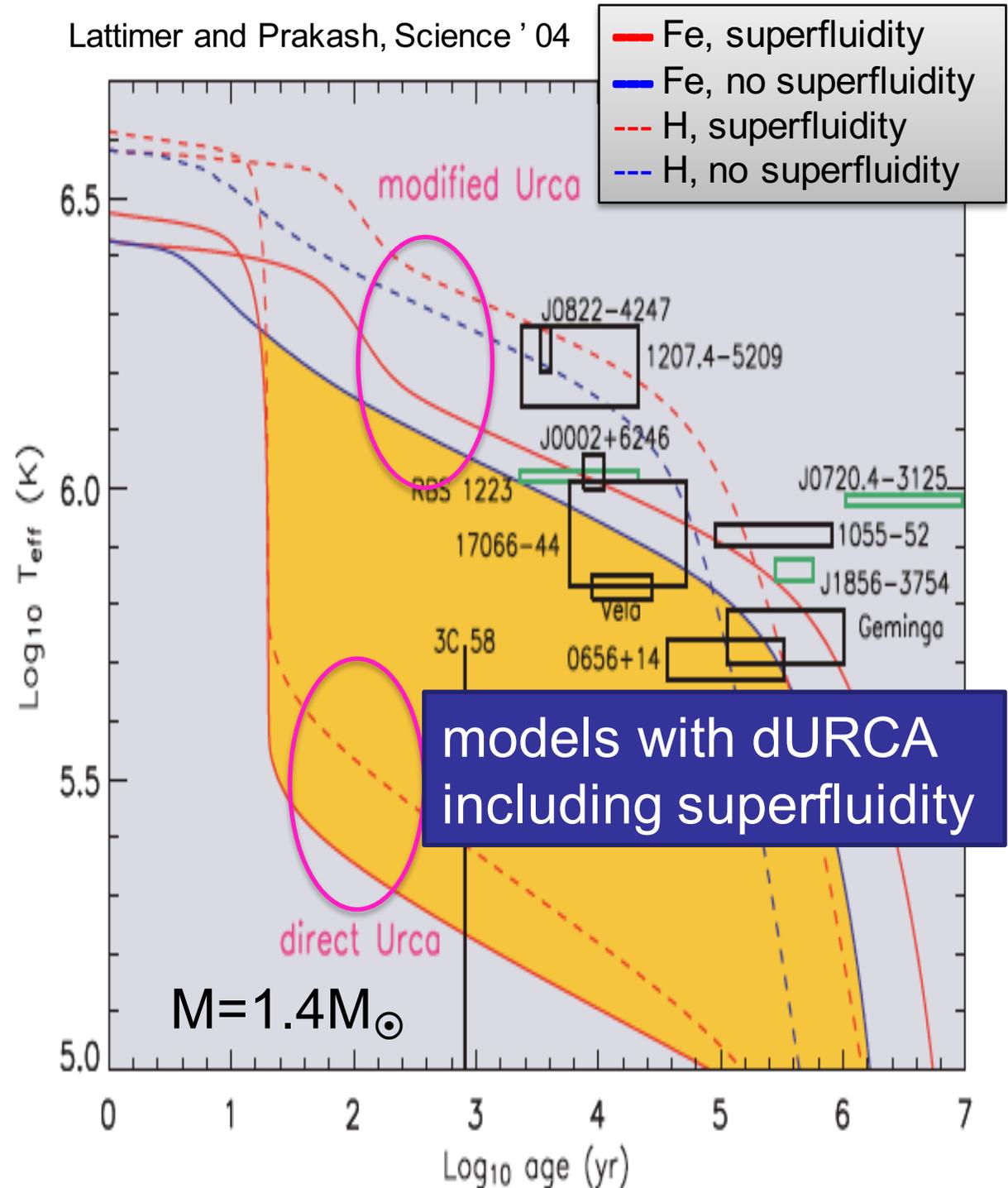
- **Fast** neutrino reactions:
direct URCA process
only in inner core and have
density thresholds



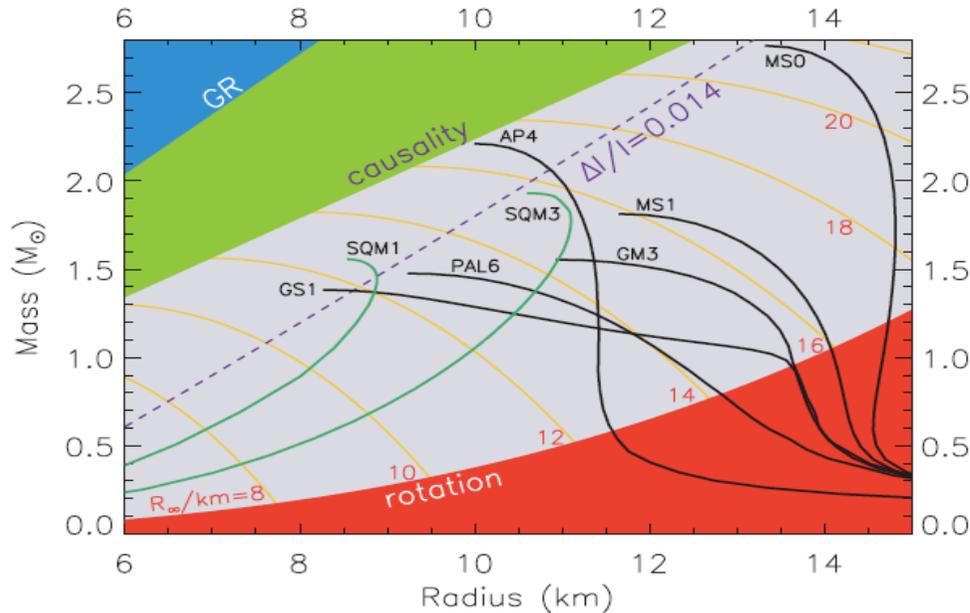
- **Slow** neutrino reactions:
modified URCA process &
NN bremsstrahlung
everywhere in core,
particularly in outer core (low-
mass stars)



Lattimer and Prakash, Science '04



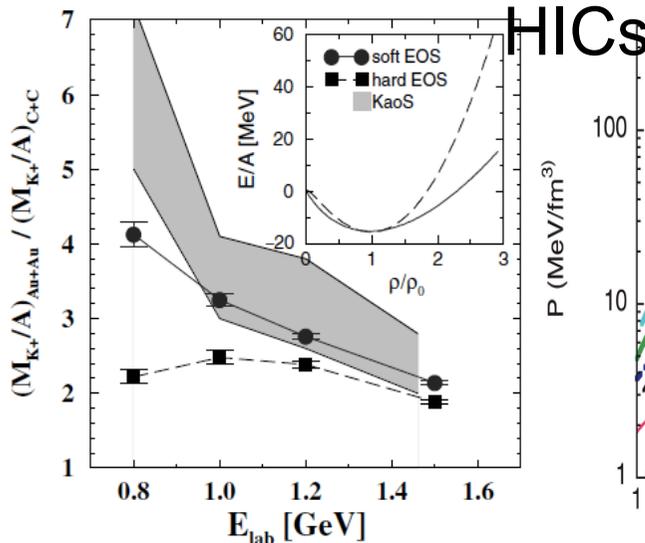
Some Constraints for Neutron Star EoS



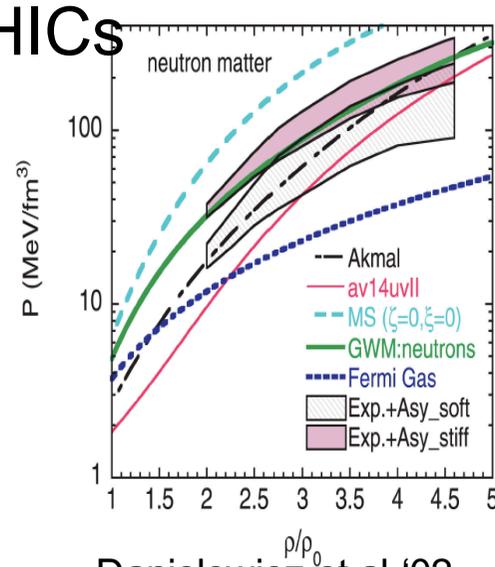
Lattimer and Prakash '04

- **astrophysical observations:**
 $2M_{\odot}$, $R \lesssim 13$ km (?)...

- **atomic nuclei:** nuclear ground-state energies, sizes of nuclear charge distributions and ^{208}Pb neutron skin thickness



Fuchs et al '01



Danielewicz et al '02

- **heavy-ion collisions (HICs):**
particle multiplicities and elliptic flow

FSU2R and FSU2H models

Approaches to the nuclear EoS

Microscopic ab-initio approaches

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

- *Variational: APR, CBF,..*
- *Montecarlo: VMC, DMC..*
- *Diagrammatic: BBG (BHF), SCGF..*
- *RG methods: SRG from χ EFT..*
- *DBHF*

Advantage: systematic addition of higher-order contributions

Disadvantage: applicable up to?
(*SRG from χ EFT $\sim n_0$*)

Phenomenological approaches

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

- *Liquid Drop Model: BPS, BBP,..*
- *Thomas-Fermi: Shen*
- *Hartree-Fock: RMF, RHF, QMC..*
- *Statistical Model: HWN, RG, HS..*

Advantage: applicable to high densities beyond n_0

Disadvantage: not systematic

Phenomenological model based on FSU2 model

Chen and Piekariwicz '12

$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_{l=e,\mu} \mathcal{L}_l,$$

$$\mathcal{L}_b = \bar{\Psi}_b (i\gamma_\mu \partial^\mu - q_b \gamma_\mu A^\mu - m_b + g_{\sigma b} \sigma - g_{\omega b} \gamma_\mu \omega^\mu - g_{\phi b} \gamma_\mu \phi^\mu - g_{\rho b} \gamma_\mu \vec{I}_b \vec{\rho}^\mu) \Psi_b,$$

$$\mathcal{L}_l = \bar{\psi}_l (i\gamma_\mu \partial^\mu - q_l \gamma_\mu A^\mu - m_l) \psi_l,$$

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

stiffening of EoS
at $n \gg n_0$:
small ζ implies
stiff EoS at $n \gg n_0$

modify density
dependence of
 E_{sym} at $1-2n_0$:
small Λ_ω implies
stiff EoS at n_0

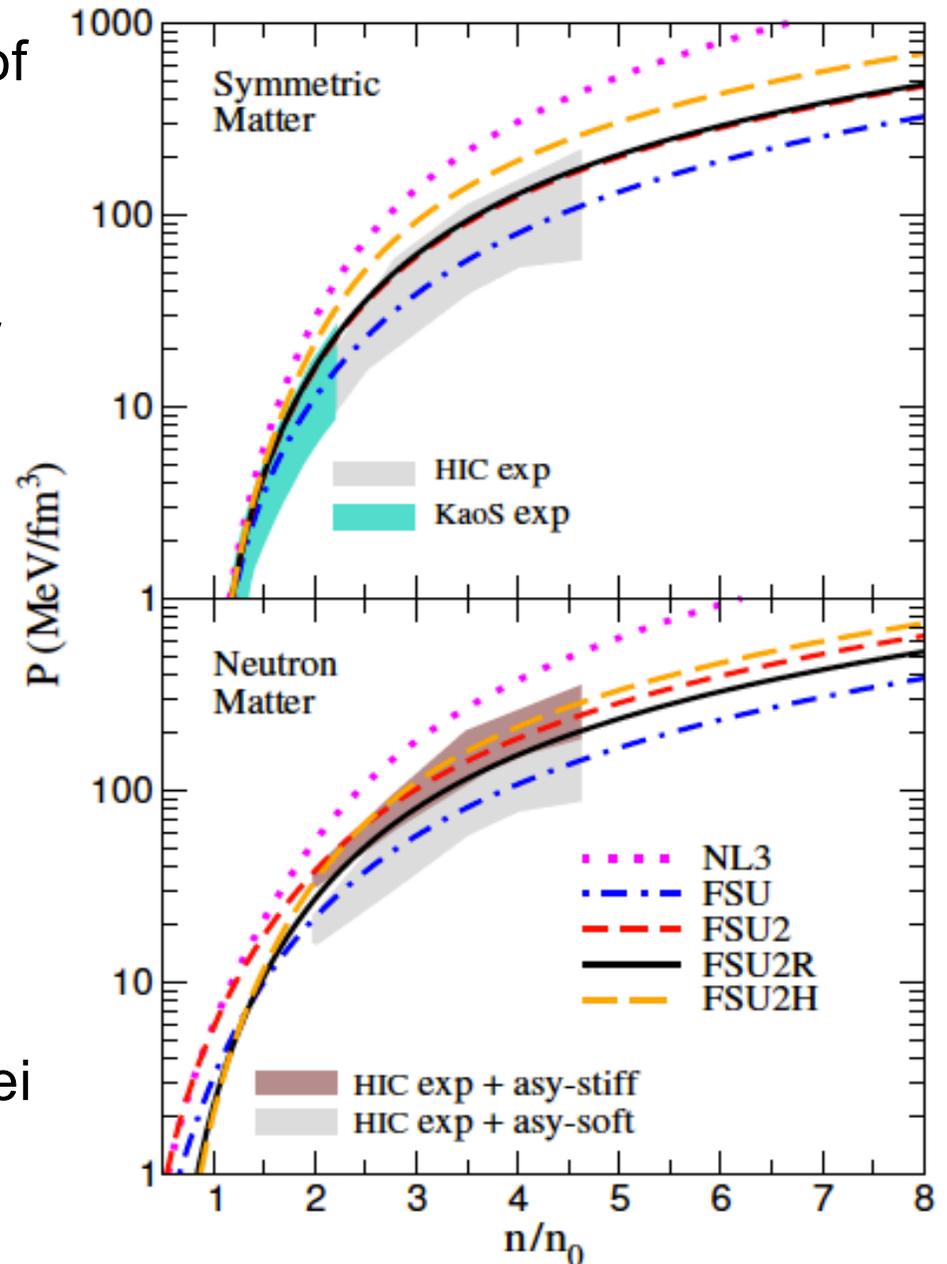
small ζ implies stiff EoS at $n \gg n_0$
 small Λ_w implies stiff EoS at n_0

NL3 ($\zeta = \Lambda_w = 0$): reproduces properties of atomic nuclei but not HICs

FSU ($\zeta = 0.06$; $\Lambda_w = 0.03$): reproduces properties of atomic nuclei while softer than NL3

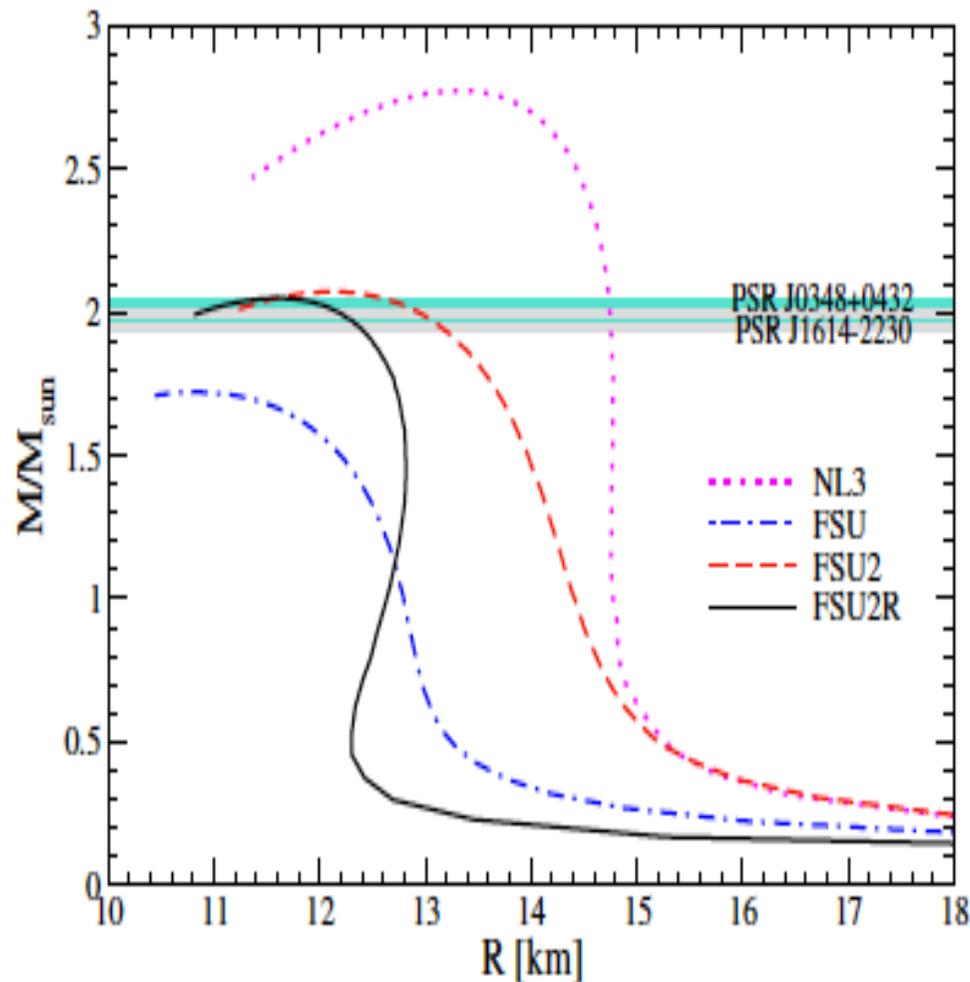
FSU2 ($\zeta = 0.0256$; $\Lambda_w = 0.000823$):
 - one of the first best-fit model to $2M_\odot$
 - intermediate EoS between NL3 and FSU

FSU2R ($\zeta = 0.024$; $\Lambda_w = 0.45$):
 - has FSU2 saturation properties and $E_{\text{sym}}(n=0.1\text{fm}^{-3})$ while fitting $2M_\odot$
 - reproduces properties of atomic nuclei and HICs



M_{\max} is governed by the stiffness of the EoS at $n \gg n_0$
(small $\zeta \rightarrow$ stiff EoS @ $n \gg n_0 \rightarrow$ large M_{\max})

$R_{1.5M_{\odot}}$ dominated by the density dependence of the EoS at $1-2 n_0$
(large $\Lambda_w \rightarrow$ soft EoS @ $1-2 n_0 \rightarrow$ small R)



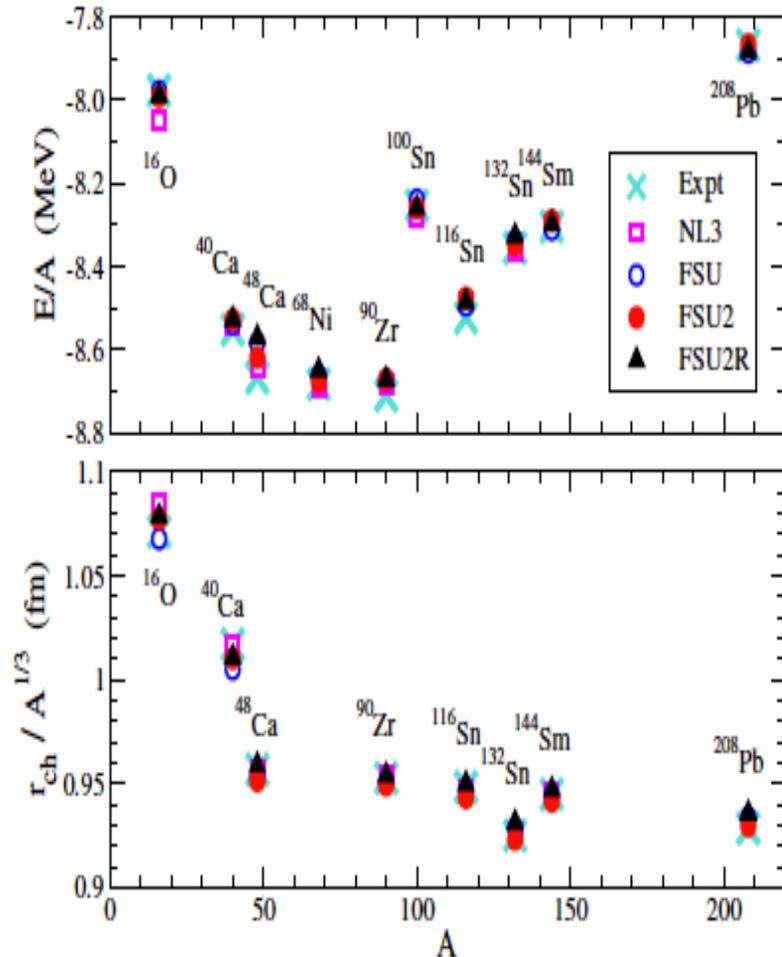
FSU2R ($\zeta = 0.024$; $\Lambda_w = 0.45$):

$M_{\max} = 2.05 M_{\odot}$,
 $R_{1.5M_{\odot}} = 12.8 \text{ Km}$

fulfilling atomic nuclei
properties and HICs data

Implications for atomic nuclei

Energies and charge radii

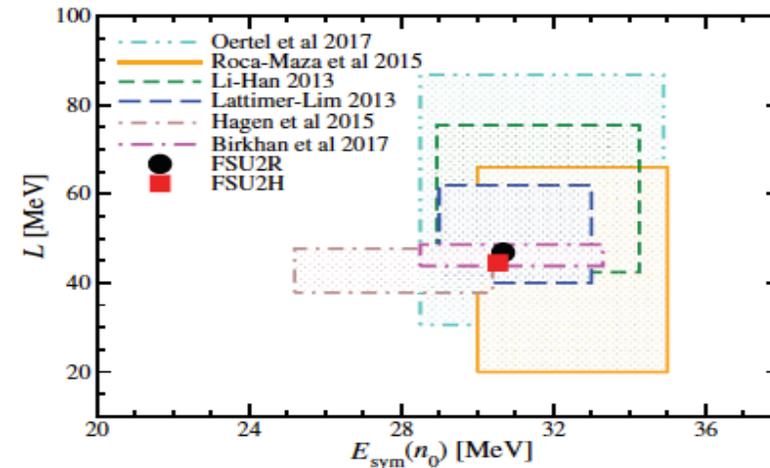


The differences between FSU2R and the experimental energies and charge radii are at the level of 1% or smaller

Symmetry energy and slope

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

$$L = 3n_0 \left(\frac{\partial E_{sym}(n)}{\partial n} \right)_{n_0}$$



Excellent agreement with recent empirical and theoretical constraints

^{208}Pb neutron skin thickness

$$\Delta r_{np} = 0.15 \text{ fm}$$

$$\Delta r_{np} = 0.302 \pm 0.177 \text{ fm} \quad \text{Horowitz et al '12}$$

$$\Delta r_{np} = 0.15 \pm 0.03 \text{ fm} \quad \text{Tarbert et al (MAMI) '14}$$

$$0.13 \lesssim \Delta r_{np} \lesssim 0.19 \text{ fm} \quad \text{Roca-Maza et al '15}$$

Fairly compatible within errors

Hyperons

Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	d ds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	d ss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

Scarce experimental information:

- data from 40 single and 3 double Λ hypernuclei
- few YN scattering data (~ 50 points) due to difficulties in preparing hyperon beams and no hyperon targets available

Chatterjee and Vidana '16

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 $< 2M_{\odot}$**

Solution?

- stiffer YN and YY interactions
- hyperonic 3-body forces
- push of Y onset by Δ or meson condensates
- quark matter below Y onset

Hypernuclear observables

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

Hyperons soften EoS:

M_{\max} gets reduced by $\sim 15\%$

($M_{\max} < 2 M_{\odot}$ for FSU2R)

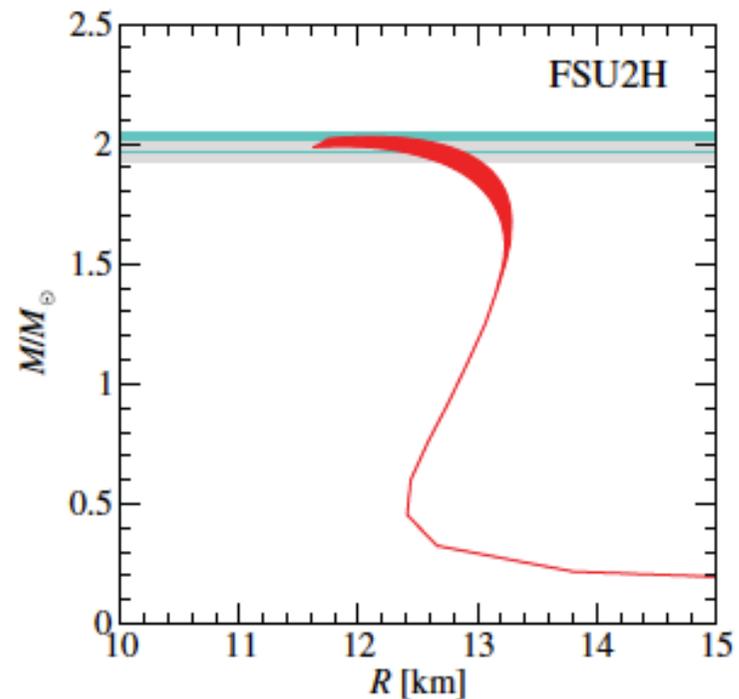
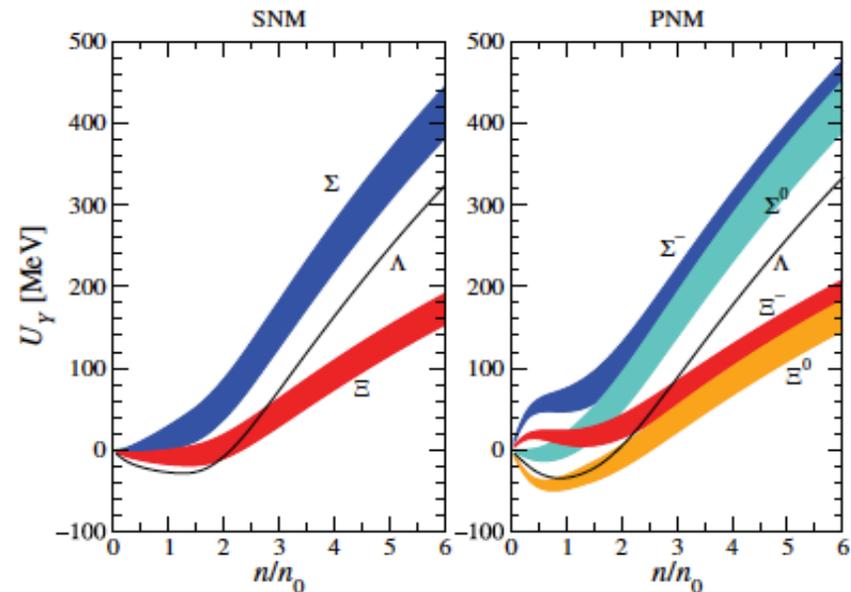
while R insensitive

We tense FSU2 to make EoS stiffer

FSU2H ($\zeta = 0.008$; $\Lambda_w = 0.45$),

compatible with atomic nuclei and

HiCs for neutron matter



FSU2H

$n_{pe\mu}$

$M_{\max} \quad 2.38 M_{\odot}$

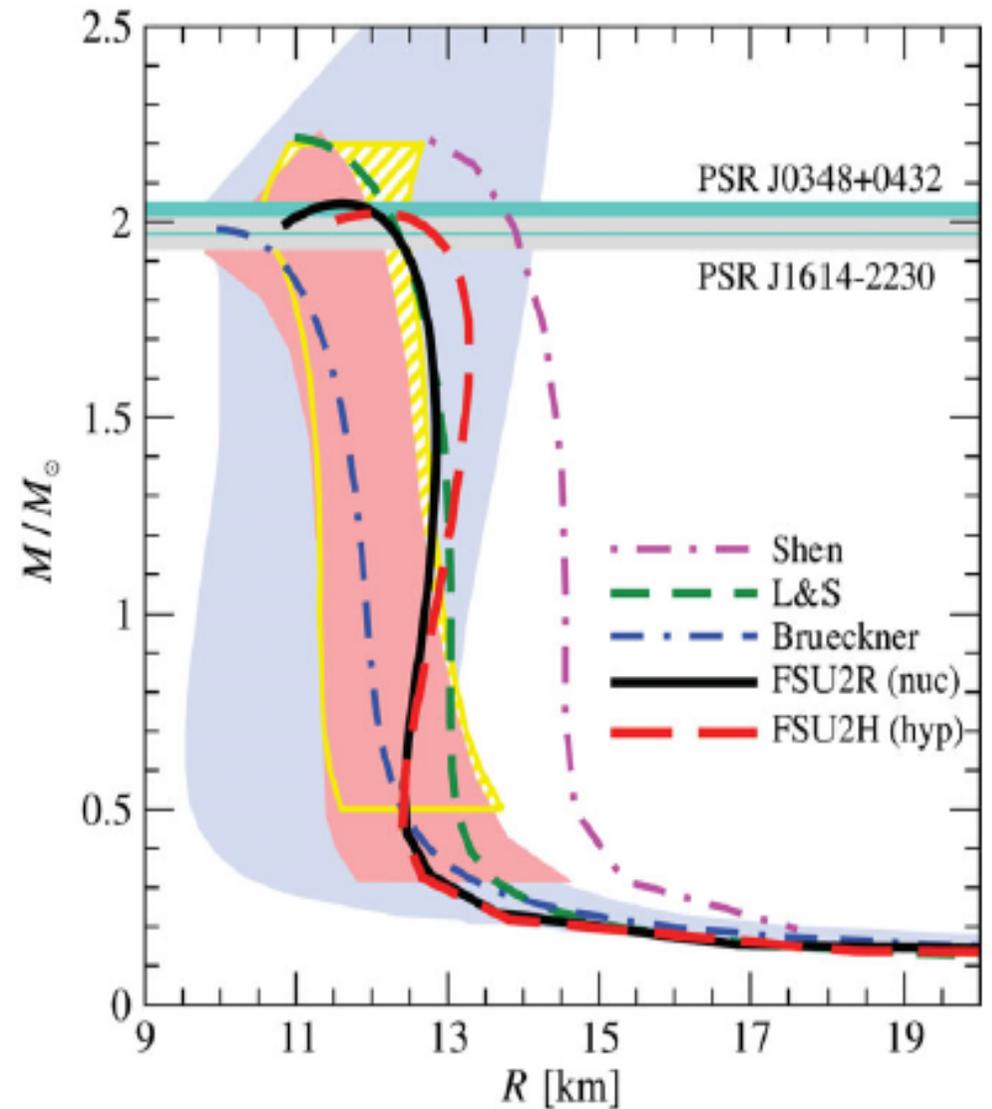
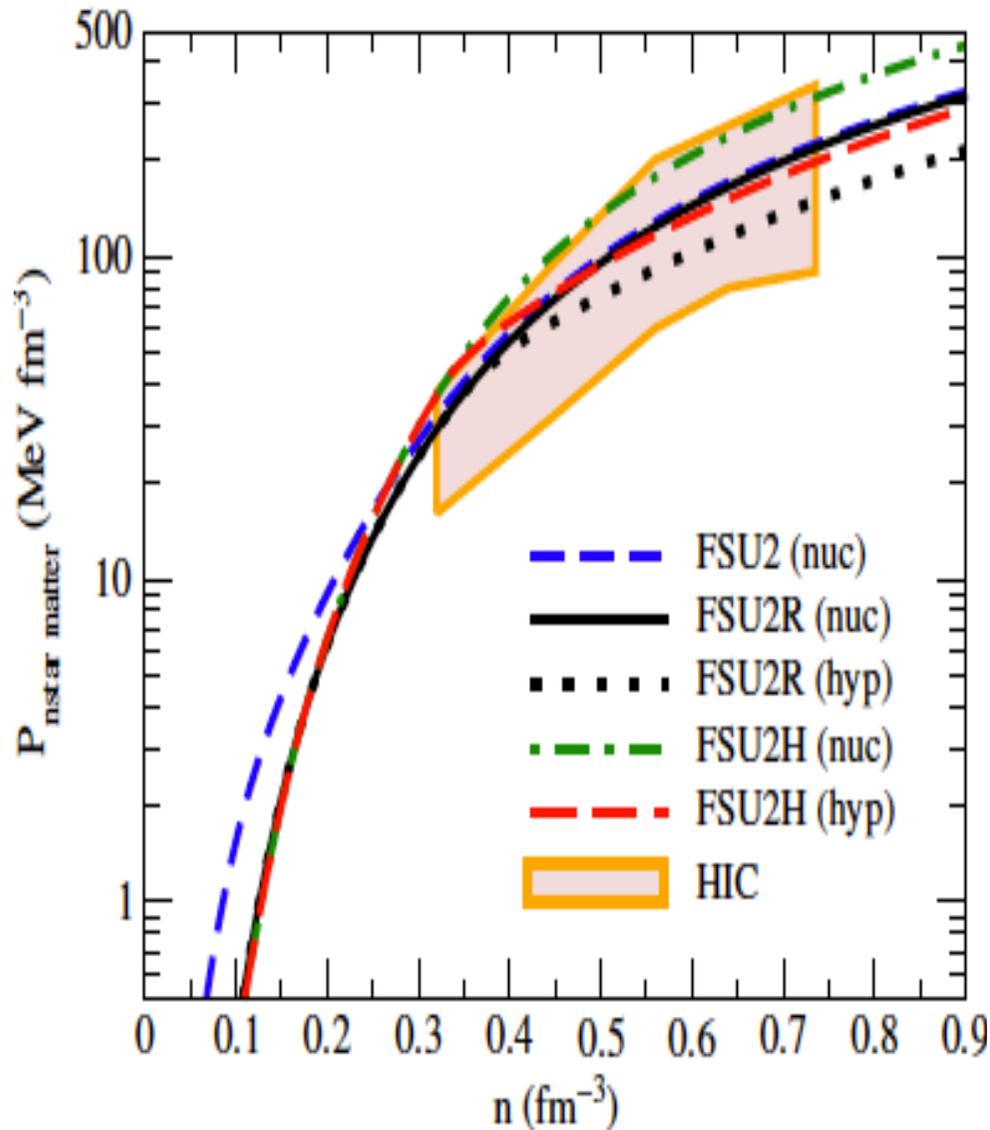
$R_{1.4 M_{\odot}} \quad 13.2 \text{ Km}$

$n_{pe\mu Y}$

$M_{\max} \quad 2.02 M_{\odot}$

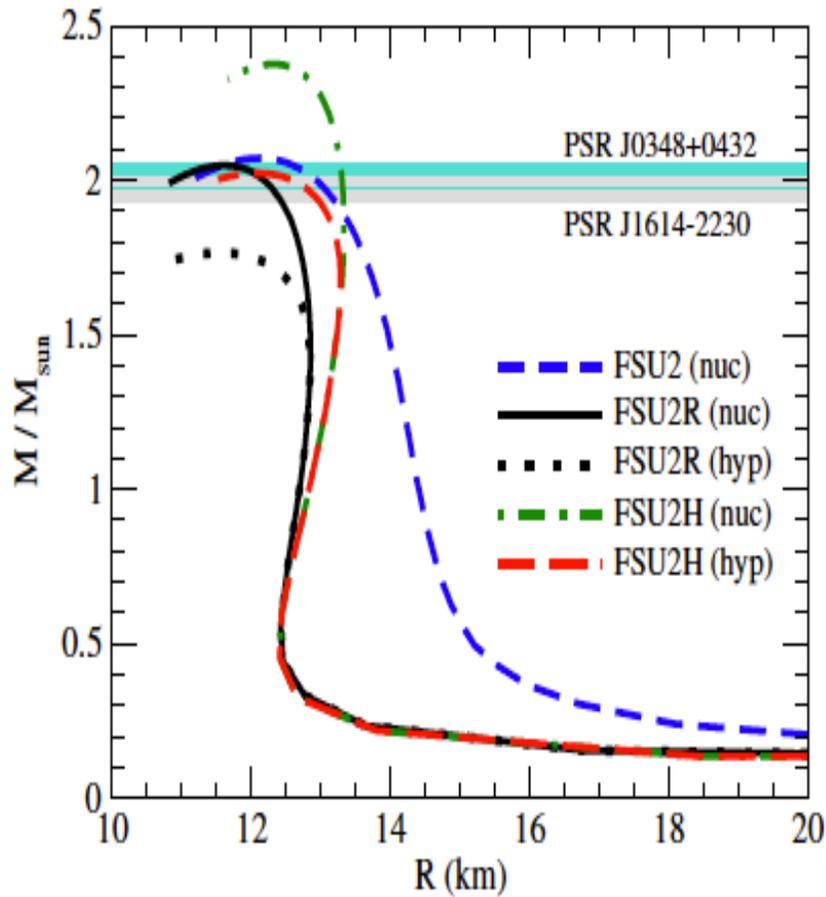
$R_{1.4 M_{\odot}} \quad 13.2 \text{ Km}$

Summarizing...



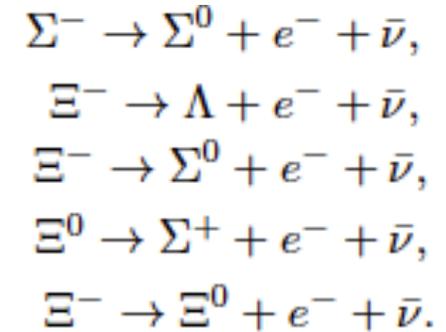
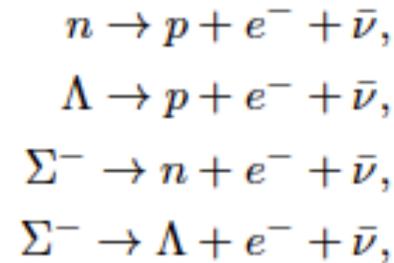
EoS for the nucleonic and hyperonic inner core that satisfies $2M_{\text{sun}}$ observations and determinations of $R \lesssim 13$ Km, while fulfilling saturation properties of nuclear matter and finite nuclei as well as constraints from HiCs

Cooling



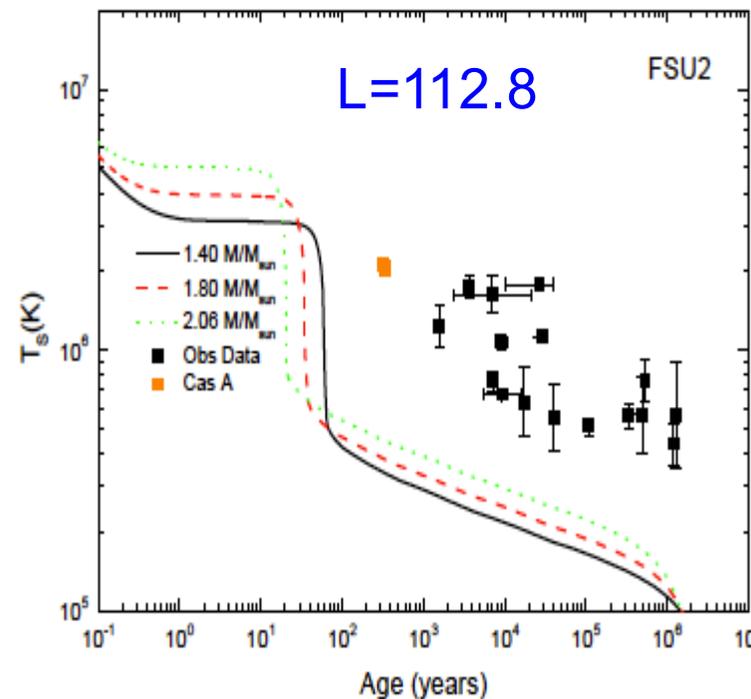
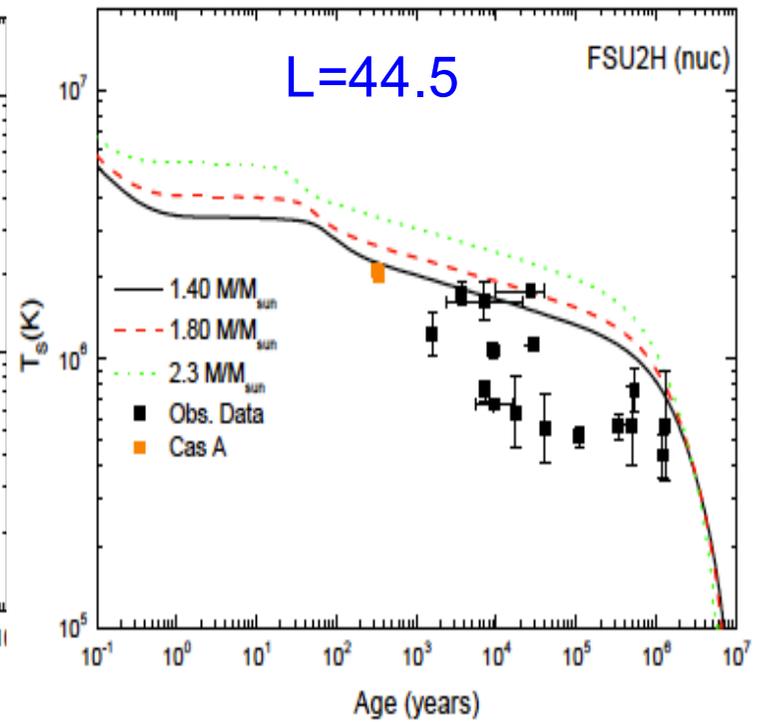
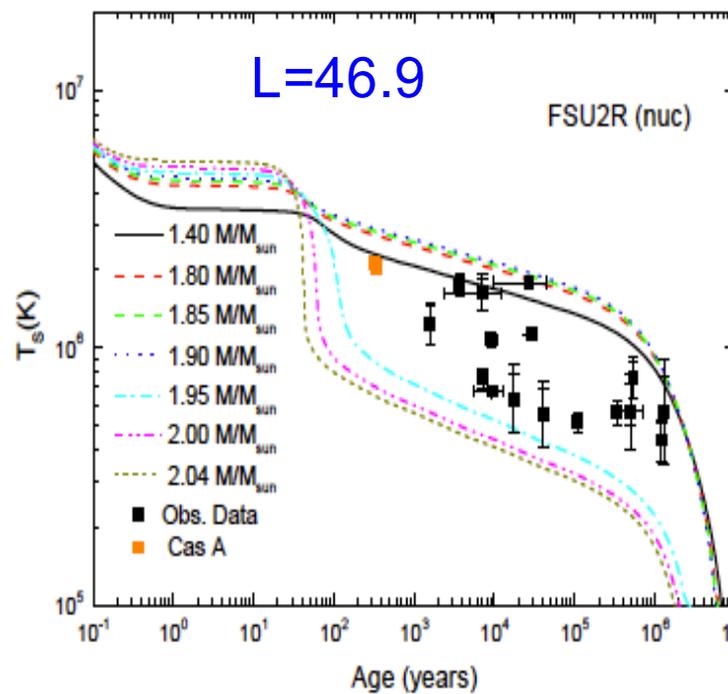
Models	FSU2	FSU2R	FSU2H
n_0 (fm^{-3})	0.1505	0.1505	0.1505
E/A (MeV)	-16.28	-16.28	-16.28
K (MeV)	238.0	238.0	238.0
$E_{\text{sym}}(n_0)$ (MeV)	37.6	30.7	30.5
L (MeV)	112.8	46.9	44.5

DU:



Models	DU threshold (fm^{-3})	hyp DU threshold (fm^{-3})	$1.4M_\odot$ n_c (fm^{-3})	$1.4M_\odot$ cooling	$1.76M_\odot$ n_c (fm^{-3})	$1.76M_\odot$ cooling	$2.0M_\odot$ n_c (fm^{-3})	$2.0M_\odot$ 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

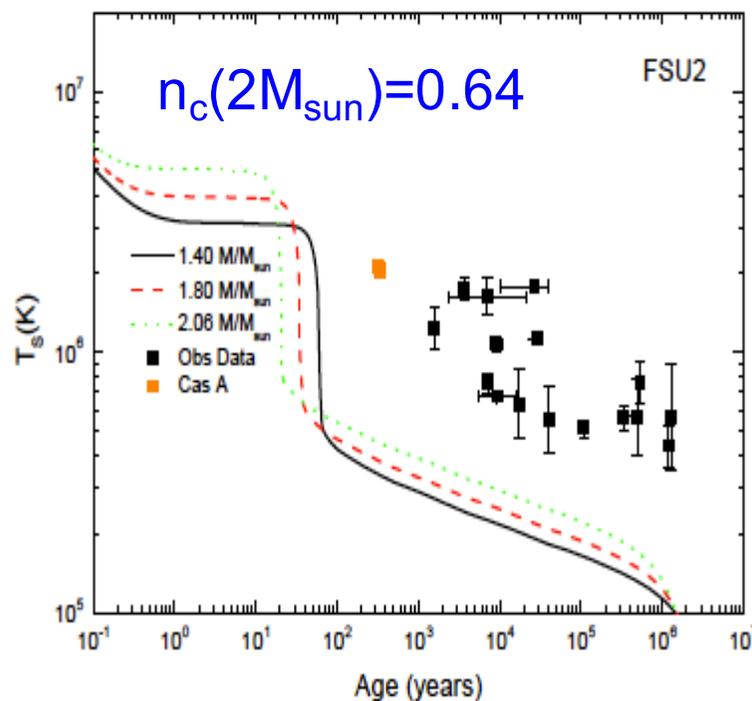
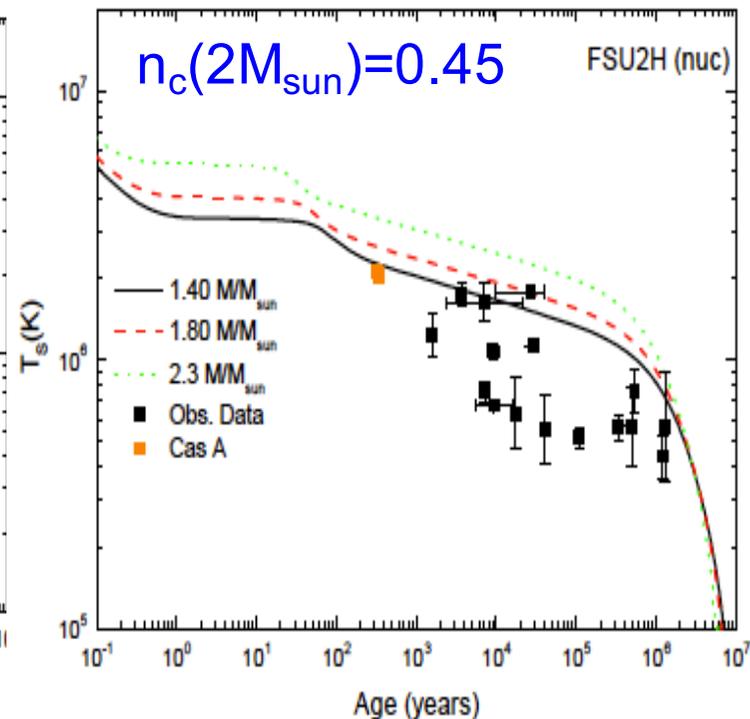
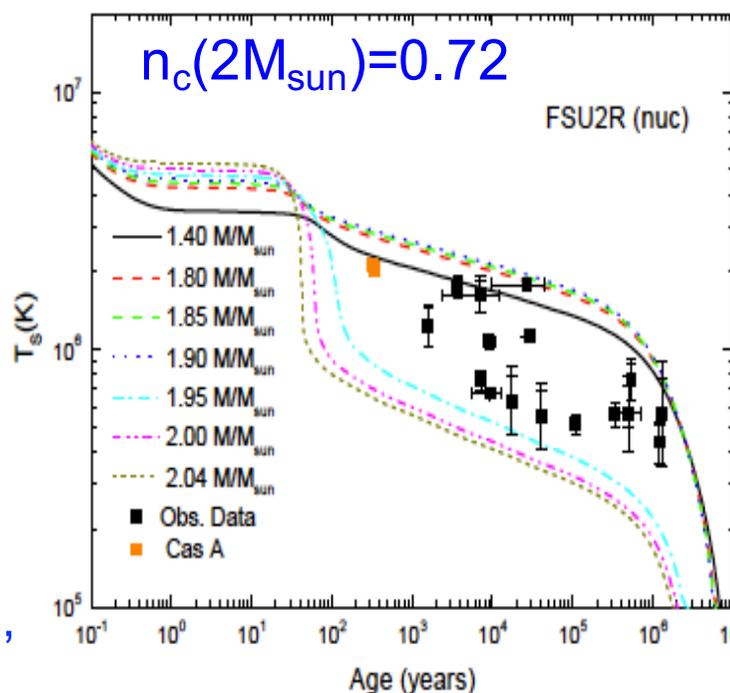
Low-mass stars
 ($M \sim 1.4 M_{\text{sun}}$):
 soft/stiff nuclear
 symmetry implies
 slow/fast cooling



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High-mass stars
($1.8-2 M_{\text{sun}}$):
stiff EoS implies
lower central
densities and, thus,
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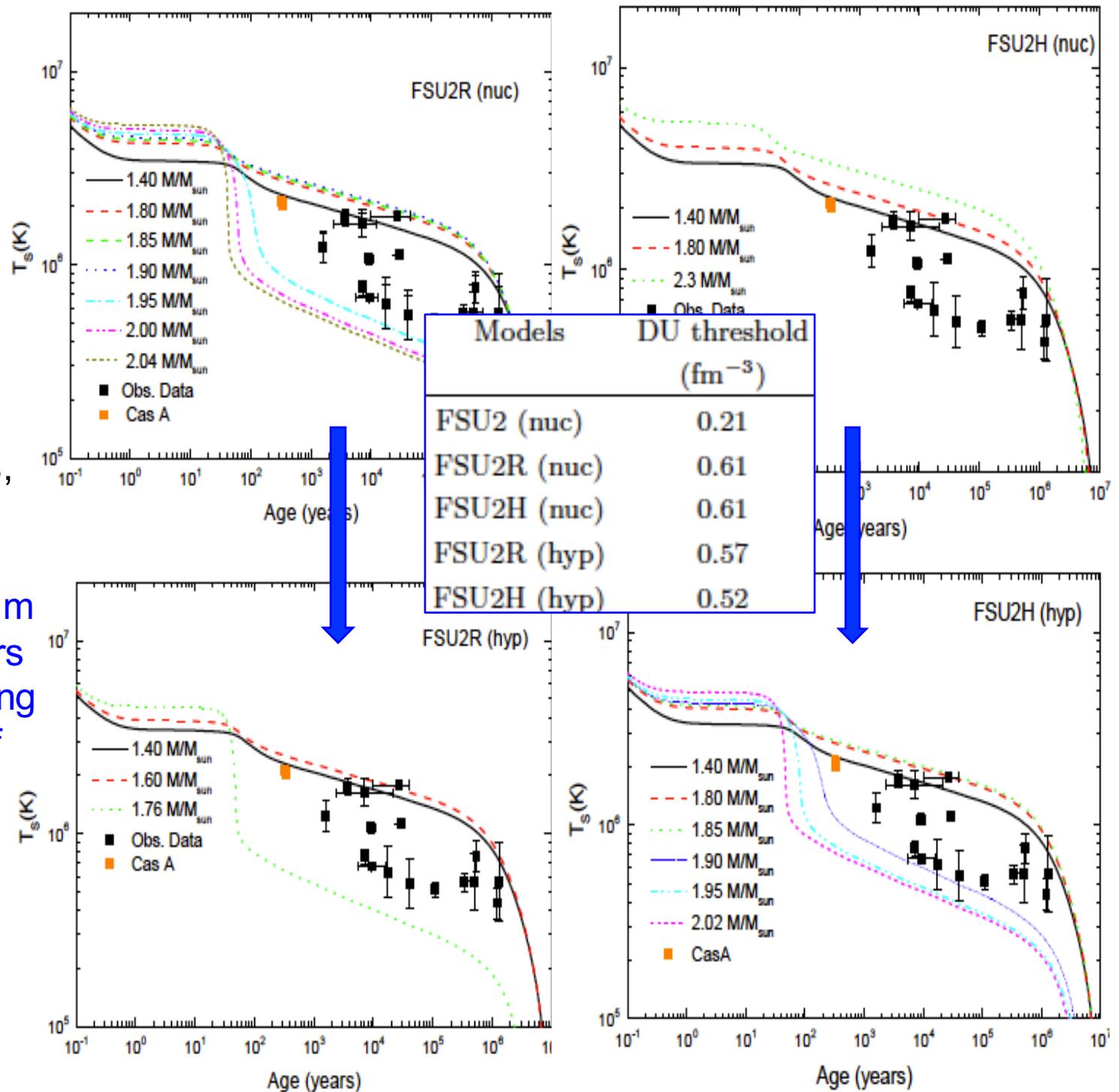


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Hyperons in medium
to heavy mass stars
speed up the cooling
due to reduction of
neutron fraction

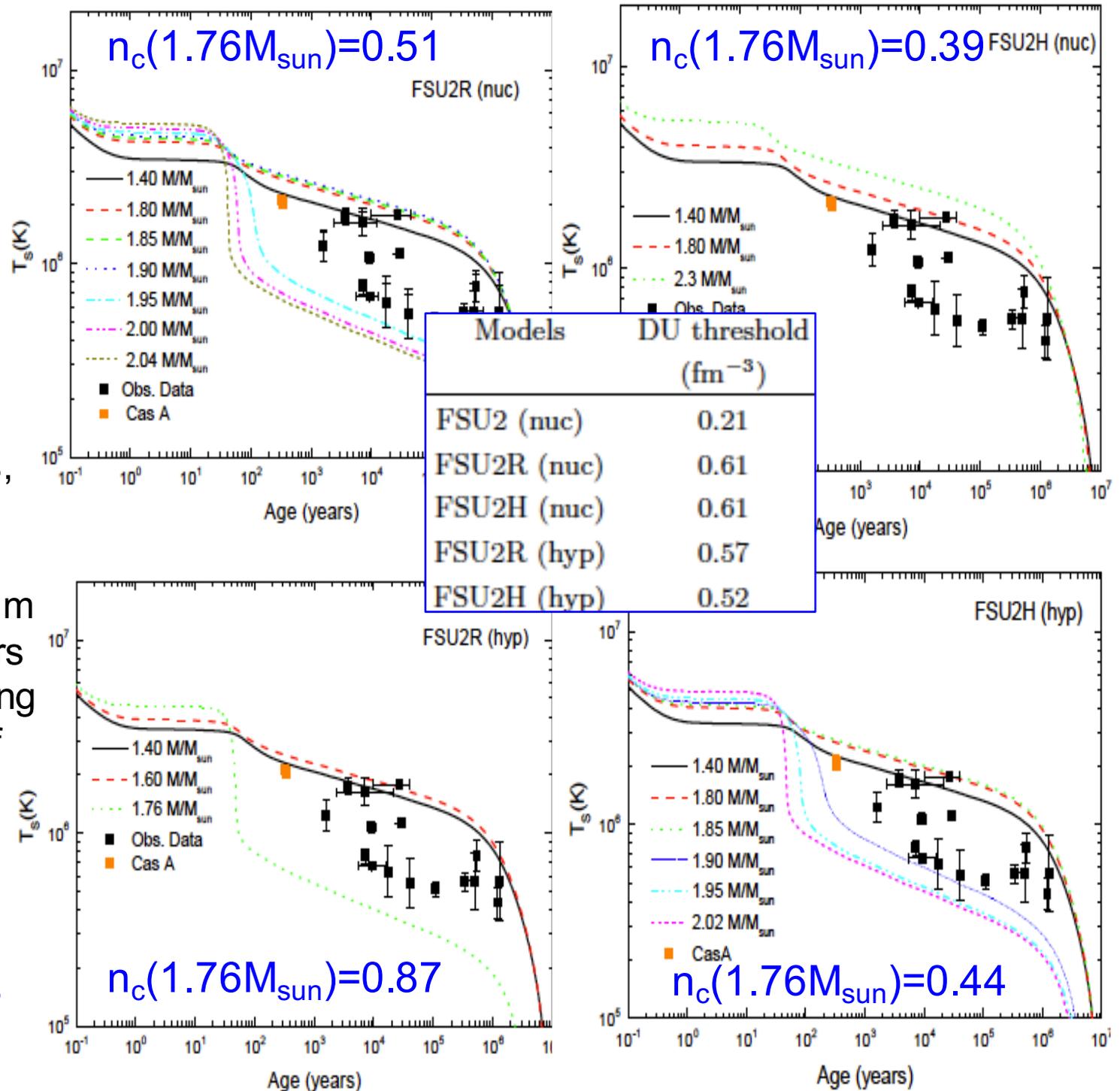


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Softer EoS (larger
densities) with
hyperons activates
cooling

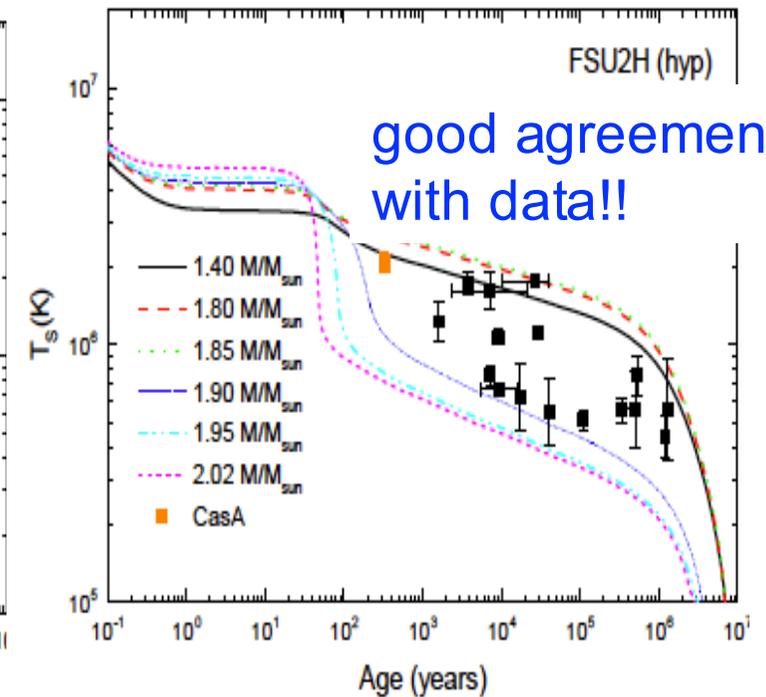
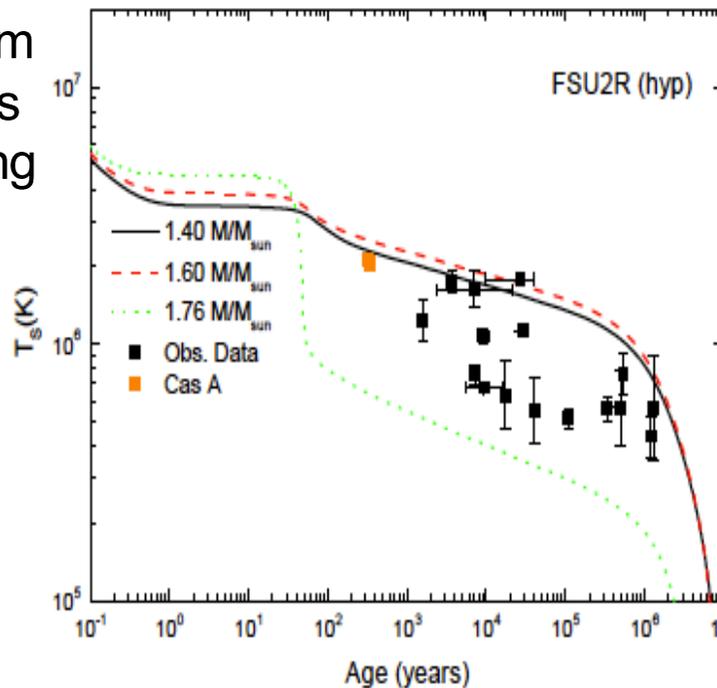
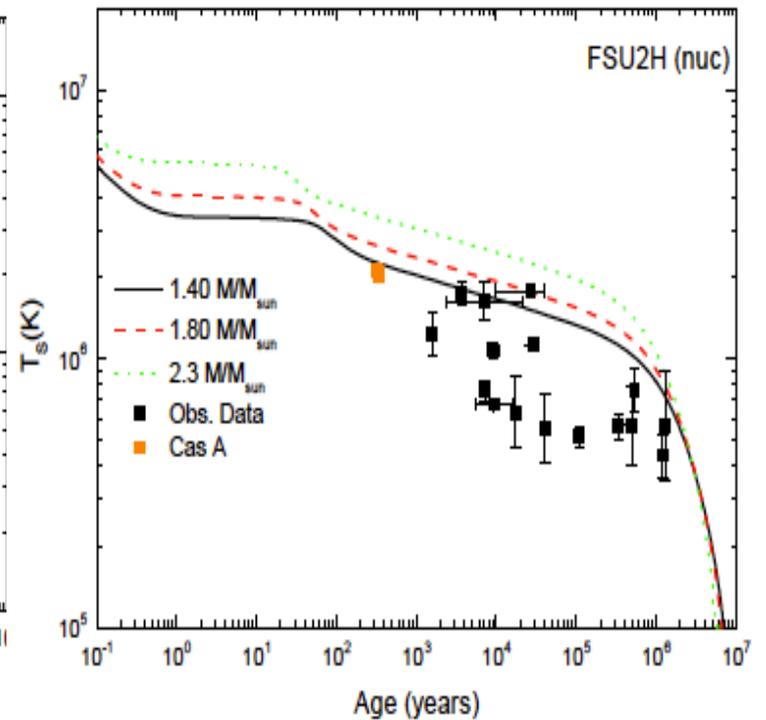
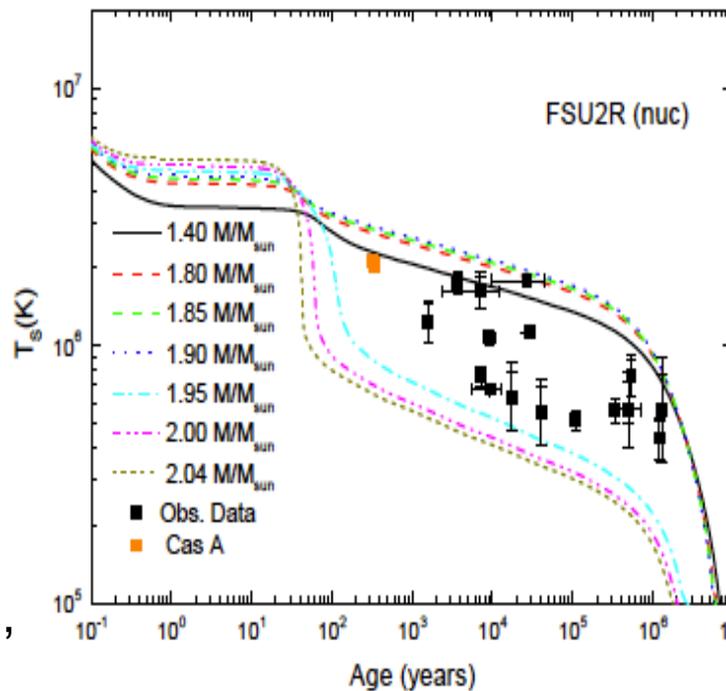


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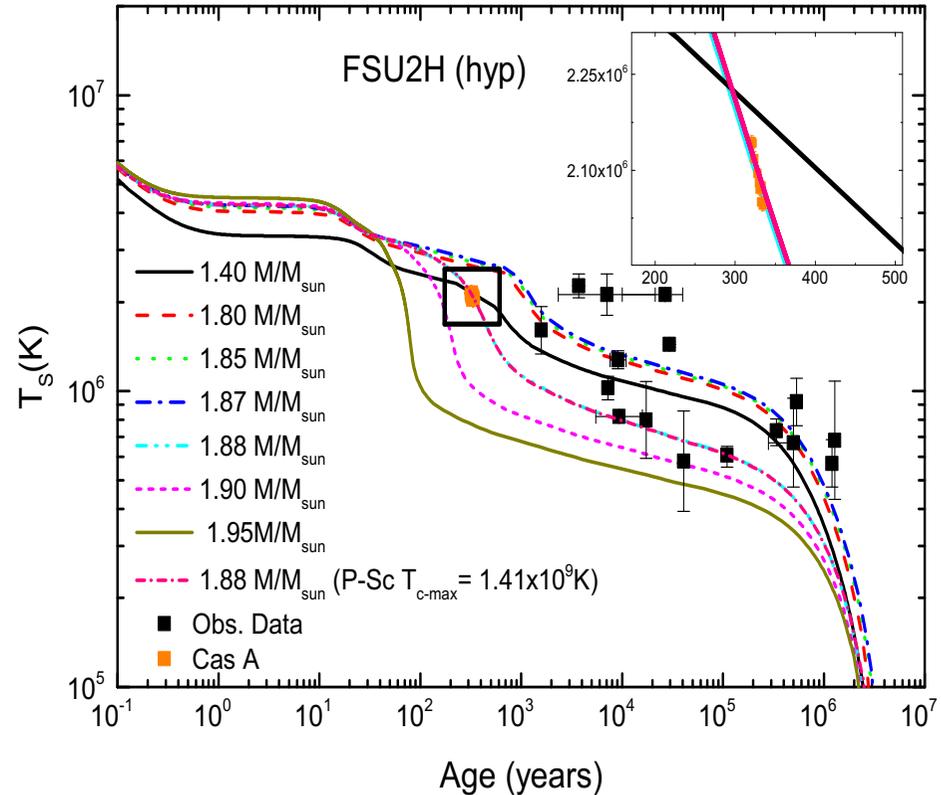
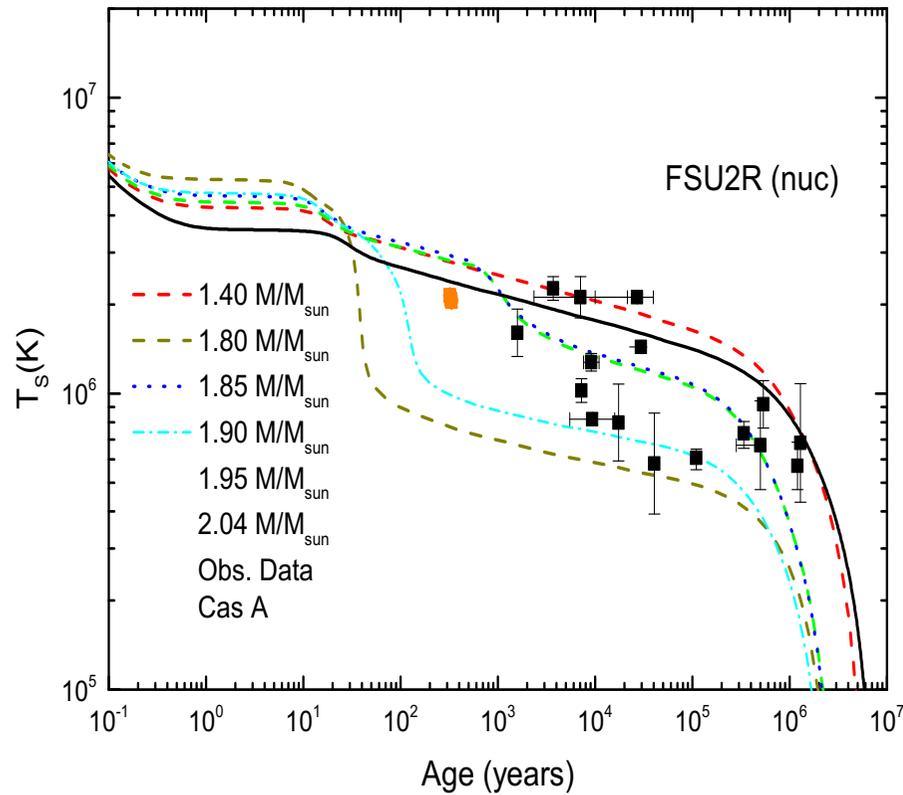
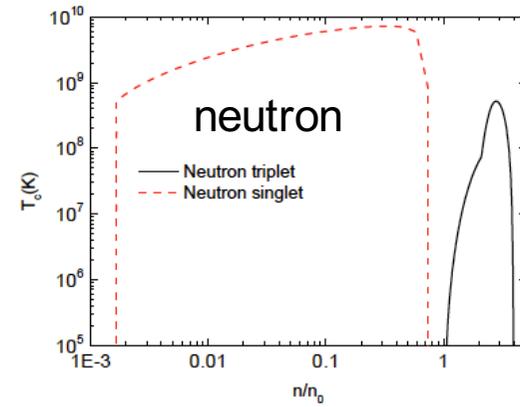
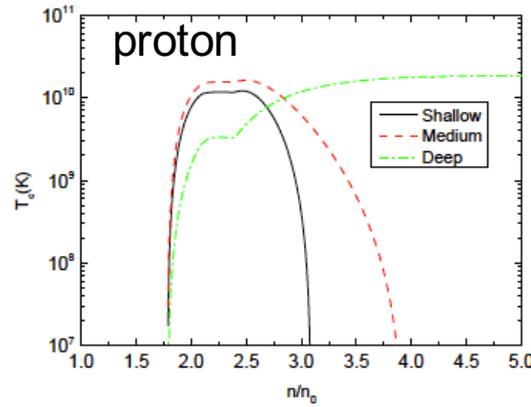
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Softer EoS (larger
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cooling



with
nucleon pairing...



including medium proton pairing improves the agreement with observations, specially Cas A for preferred FSU2H(hyp), but cold stars with $M > 1.8 M_{\text{sun}}$

Summary

We have obtained a **new EoS for the nucleonic and hyperonic inner core of neutron stars** that fulfills $2M_{\odot}$ and $R \lesssim 13$ Km, as well as the saturation properties of nuclear matter, the properties of atomic nuclei together with constraints from HICs:

- a new parameterization, **FSU2R**, fulfills $2M_{\odot}$ with $R \lesssim 13$ Km, while reproducing the **energies and charge radii of nuclei**, with $E_{\text{sym}}=30.7$ MeV & $L=46.9$ MeV and producing $\Delta r_{np}=0.15$ fm
- **hyperons soften EoS** and FSU2R produces $M < 2M_{\odot}$, while R is insensitive: a slight modified parametrization, **FSU2H**, still **compatible with the properties of atomic nuclei** ($E_{\text{sym}}=30.5$ 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 $M > 1.8 M_{\text{sun}}$
- working on cooling with magnetic fields, twin star oscillations, neutron star mergers including phase transition...