The Equation of State for the Hadronic Inner Core of Neutron Stars

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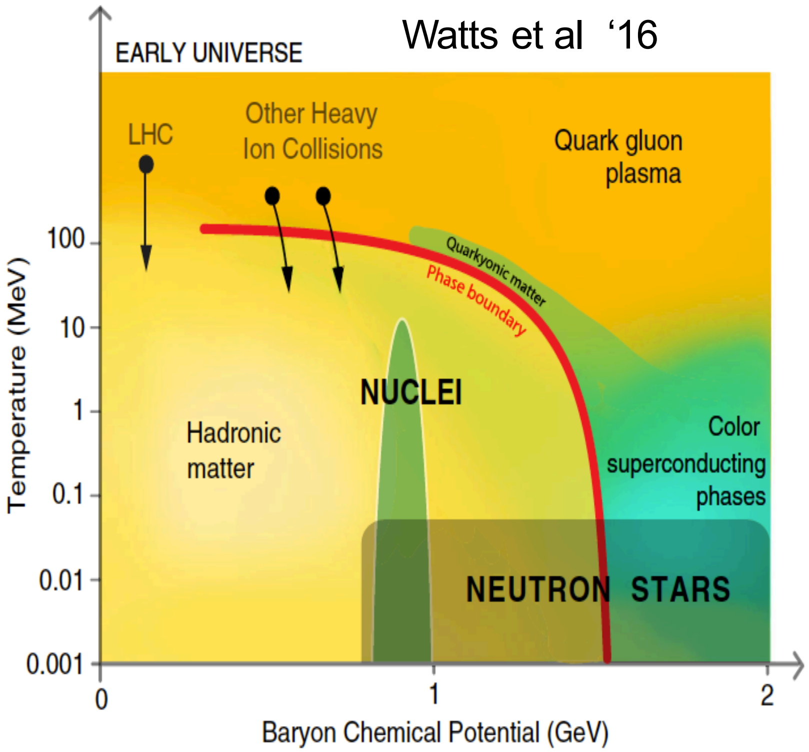
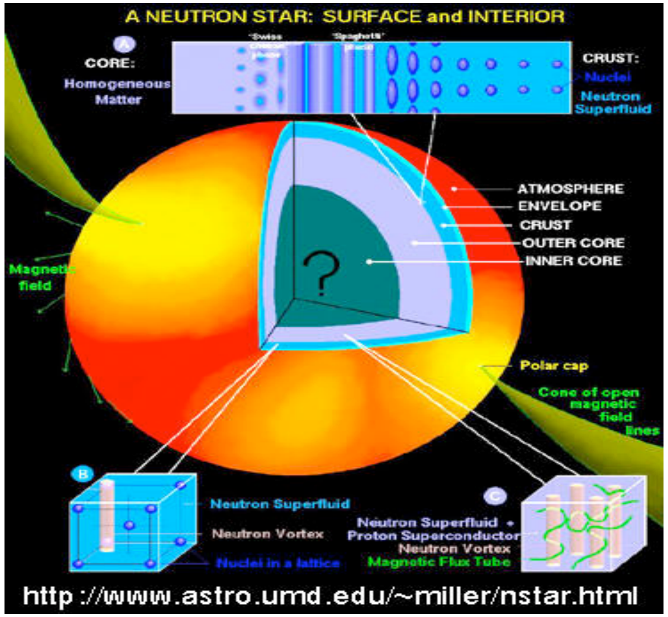
Fire and ice: Hot QCD meets cold and dense matter
Saariselka, Finland, 3-7 April 2018

Neutron Stars: A Cosmic Laboratory for Matter under Extreme Conditions


Watts et al ‘16

Outline

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



http ://www.astro.umd.edu/~miller/nstar.html

Astrophys.J. 834 (2017) no.1, 3
Publ. Astron. Soc. Austral. 34 e065
arXiv: 1804.00334 [astro-ph.HE]

Motivation

Mass

- > 2000 pulsars known

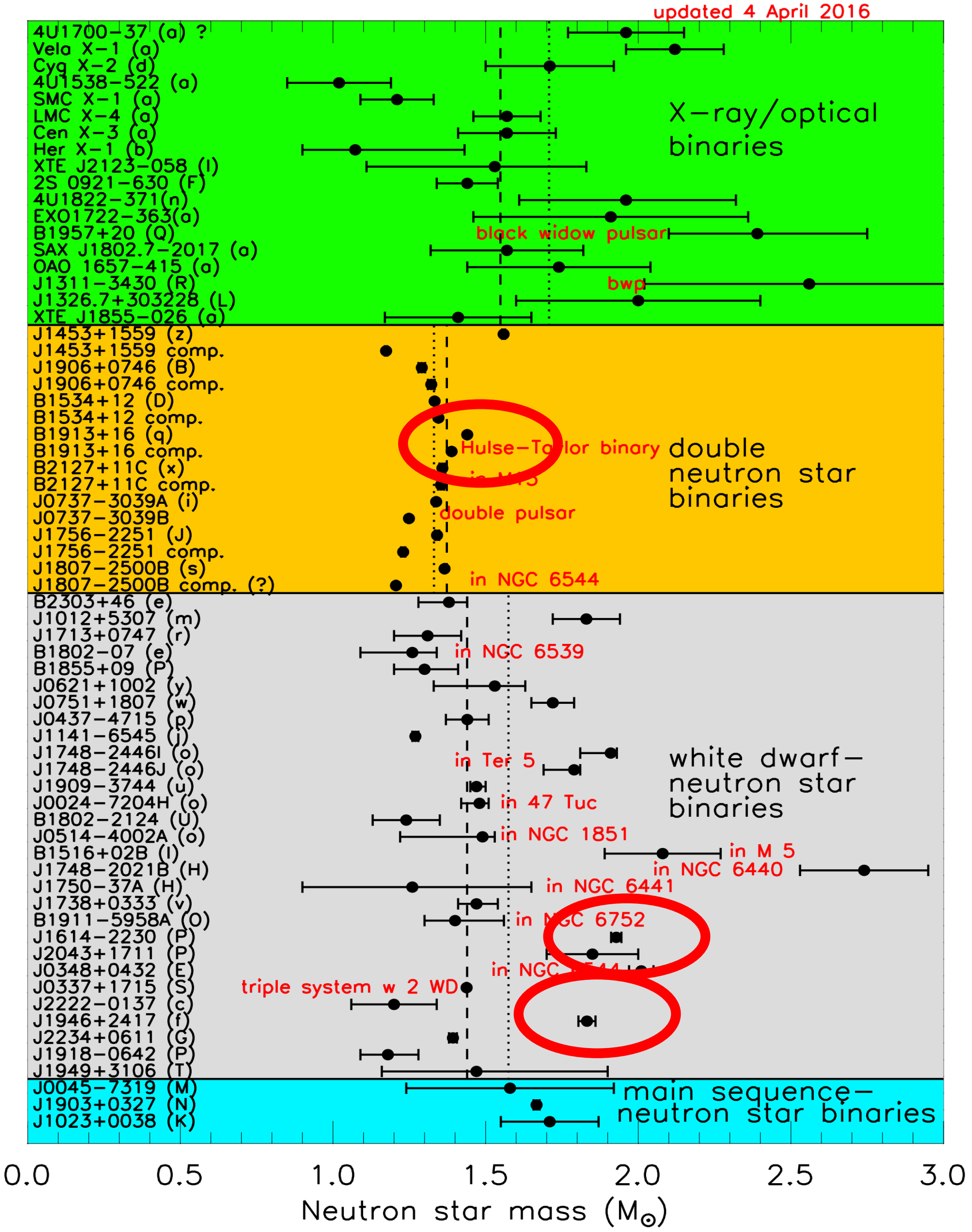
- best determined masses:
Hulse-Taylor pulsar
$M=1.4414 \pm 0.0002\,M_\odot$
Hulse-Taylor Nobel Prize 1994

- PSR J1614-2230[1]
$M=(1.97 \pm 0.04)\,M_\odot$;
PSR J0348+0432[2]
$M=(2.01 \pm 0.04)\,M_\odot$

[1] Demorest et al '10;

[2] Antoniadis et al '13

Lattimer '16



Radius

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

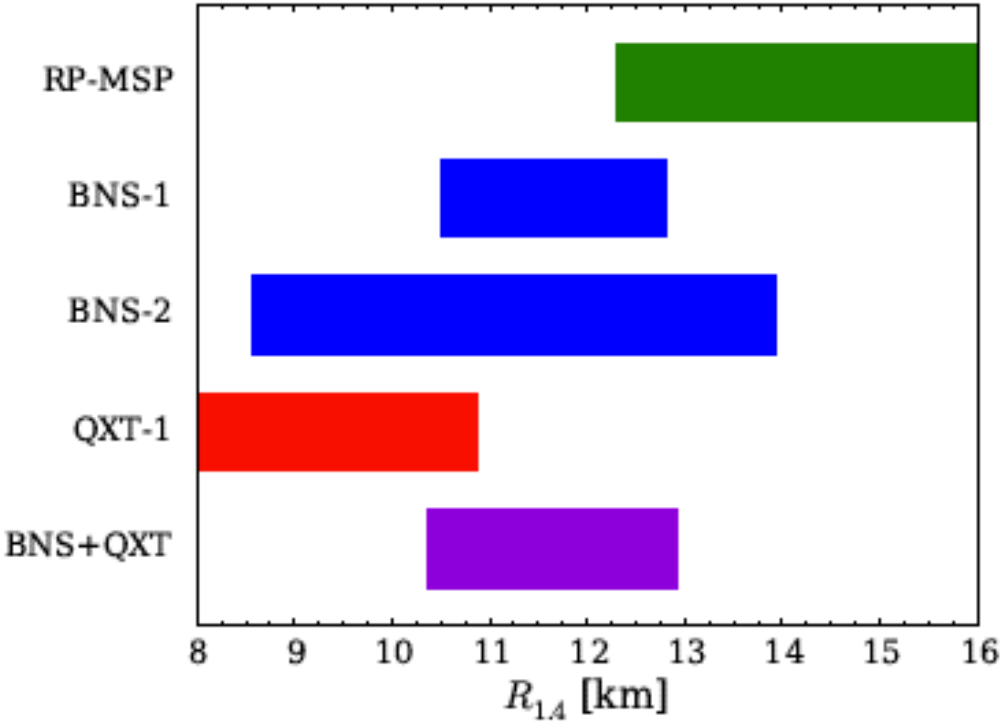
- RP-MSP: X-ray emission from radio millisecond pulsars
- BNS: X-burst from accreting NSs
- QXT: quiescent thermal emission of accreting NSs

theory + pulsar observations:
$R_{1.4M_\odot}$~11-13 Km Lattimer and Prakash '16

EoSs constraint from GW170817
(M_{max} and $\Lambda_{1.4M_\odot}$) Most et al '18
$12 < R_{1.4M_\odot}/\mathrm{Km} < 13.45$

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 (?)
- ✓ future X-ray telescopes (NICER, eXTP) with precision for M-R of ~ 5%
- ✓ GW signals from NS mergers with precision for R of ~1 km
  Bauswein and Janka '12; Lackey and Wade '15

Cooling

Neutrino emission processes:

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

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

$$Y \rightarrow (Y,N) + e^- + \bar{\nu}_e$$

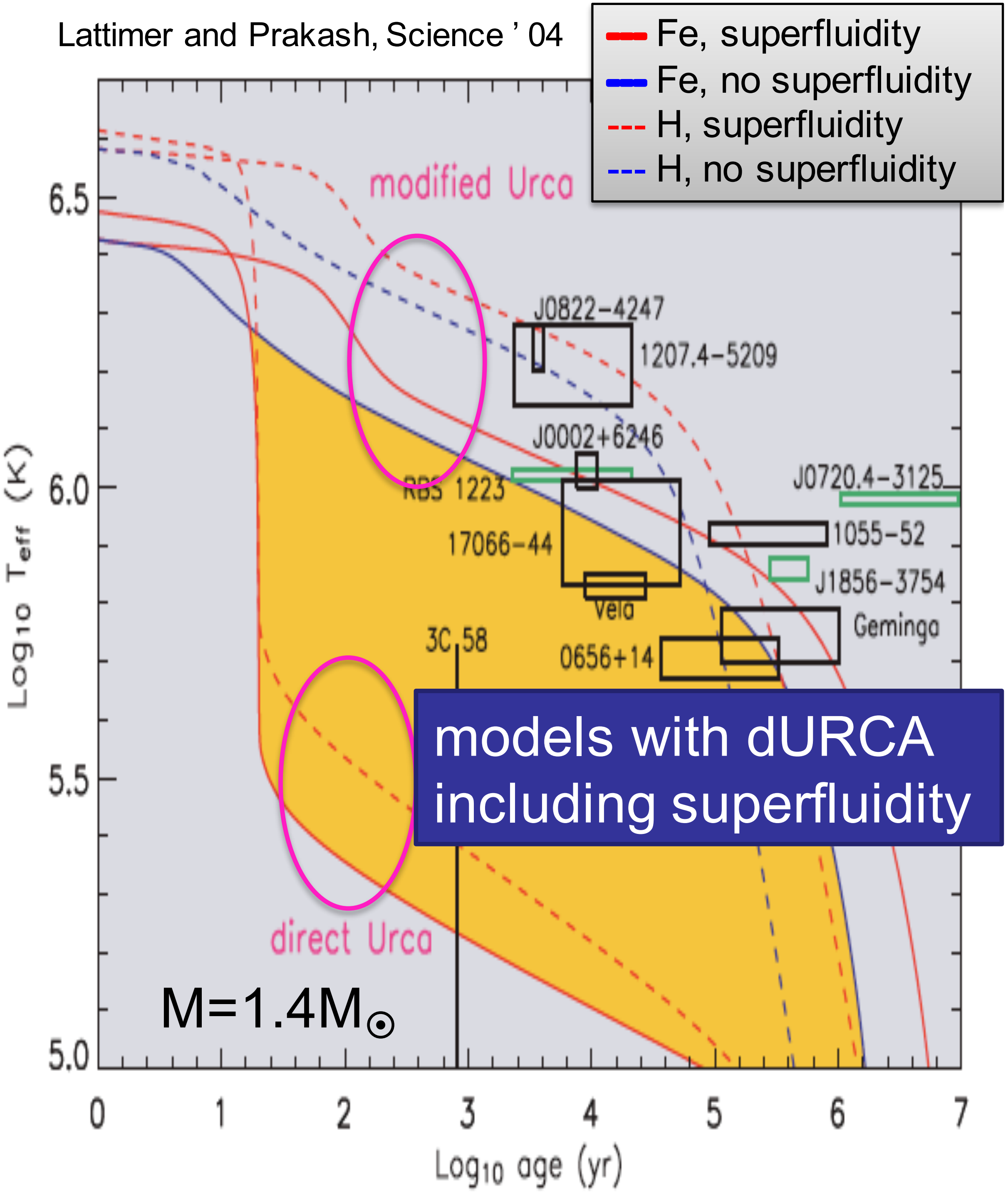
- Slow neutrino reactions:
modified URCA process & NN bremsstrahlung
everywhere in core, particularly in outer core (low-mass stars)

$$N + p + e^- \rightarrow N + n + \nu_e$$

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

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

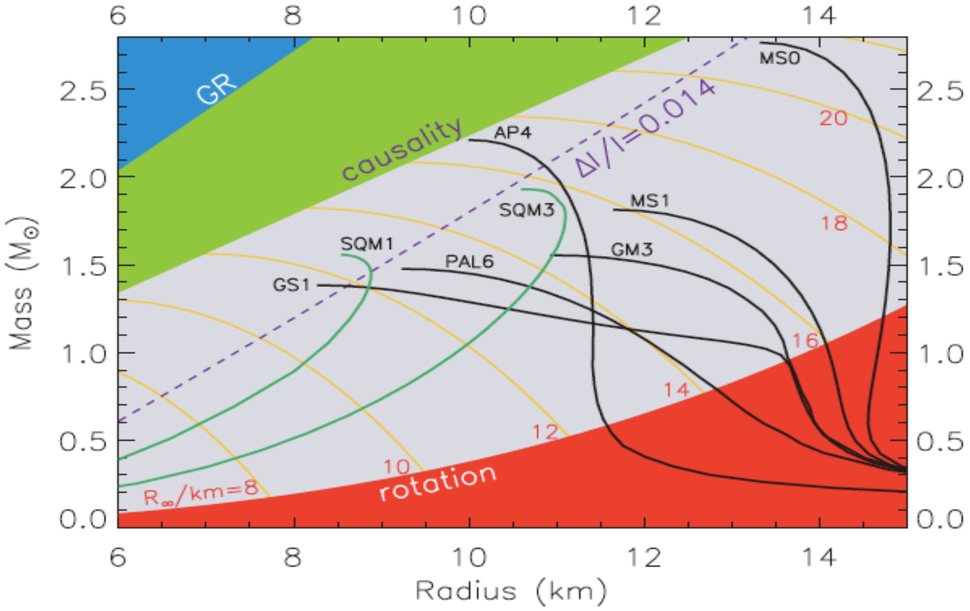
Lattimer and Prakash, Science ' 04



models with dURCA including superfluidity

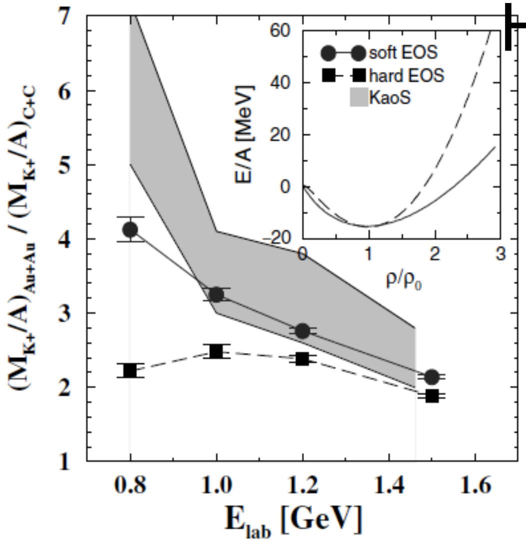
$M = 1.4 M_\odot$

Some Constraints for Neutron Star EoS

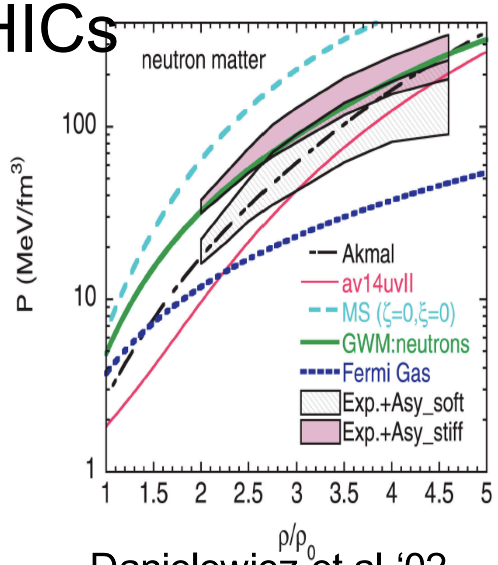


Lattimer and Prakash ’04

HICs



Fuchs et al ‘01



Danielewicz et al ‘02

- **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

- **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: APS, CBF,..*
- *Montecarlo: VMC, DMC..*
- *Diagrammatic: BBG (BHF), SCGF*
- *RG methods: SRG from χEFT*
- *DBHF*

Advantage: systematic addition of higher-order contributions

Disadvantage: applicable up to ~1-2n_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*

Advantage: applicable to high densities beyond n_0

Disadvantage: not systematic

Phenomenological model based on FSU2 model

Chen and Piekariewicz '12

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

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

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

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

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_w implies stiff EoS at n_0

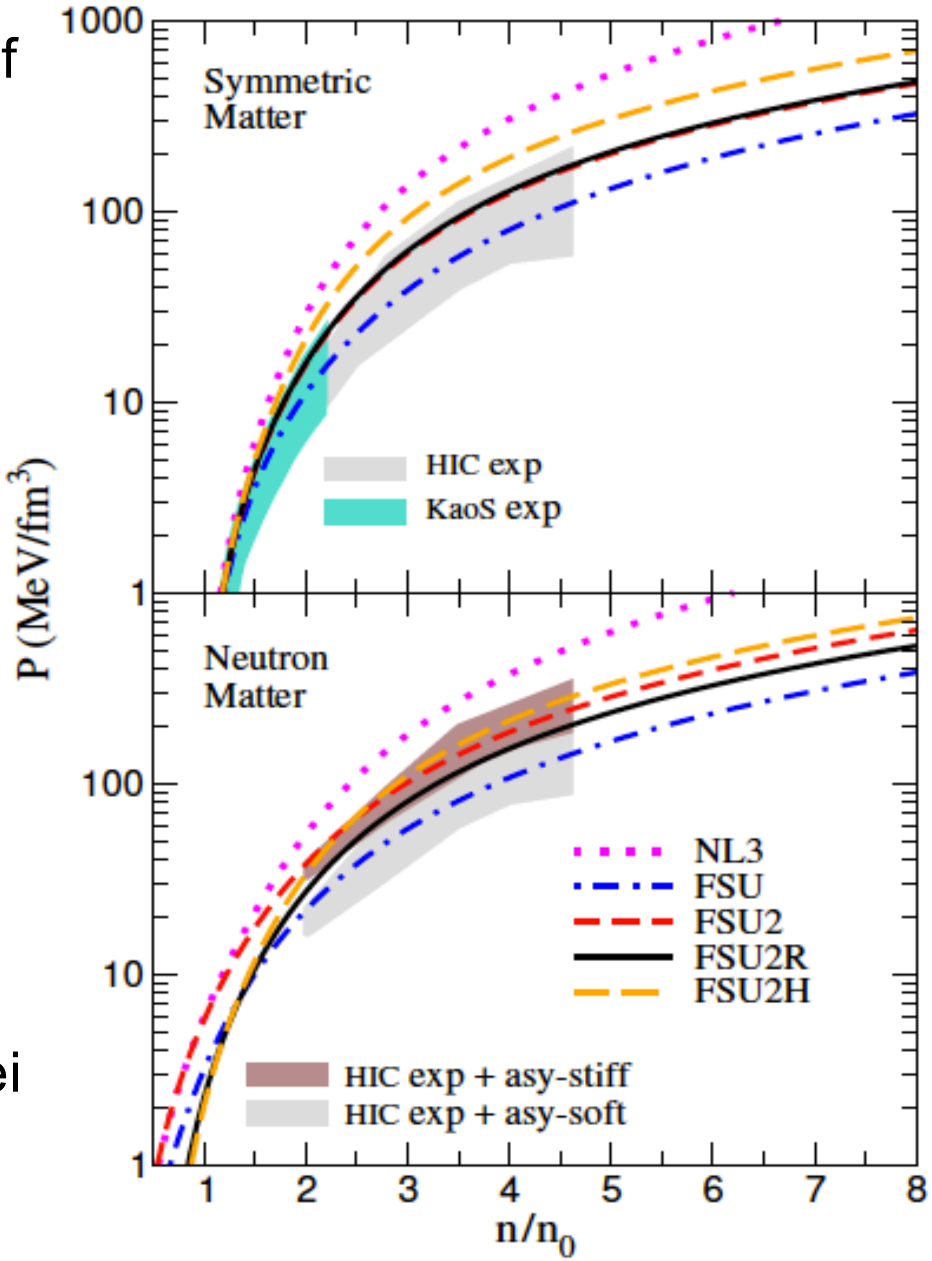
small ζ implies stiff EoS at $n \gg n_0$
small Λ_w implies stiff EoS at n_0

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

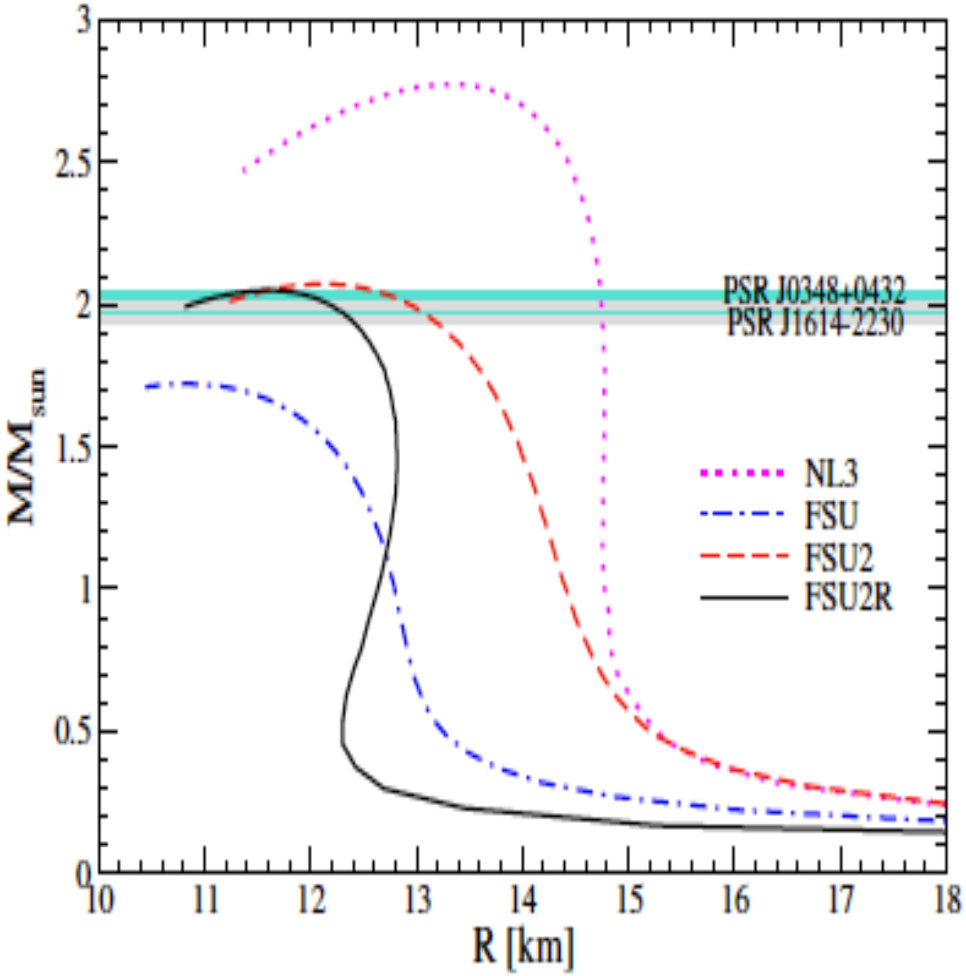
FSU2 ($\zeta= 0.0256$; $\Lambda_w= 0.000823$):
- first best-fit model to $2M_\odot$
- intermediate EoS between NL3 and FSU

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



M_{max} is governed by the stiffness of the EoS at $n >> n_0$
(small ζ → stiff EoS @ $n >> n_0$ → large M_{max})

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



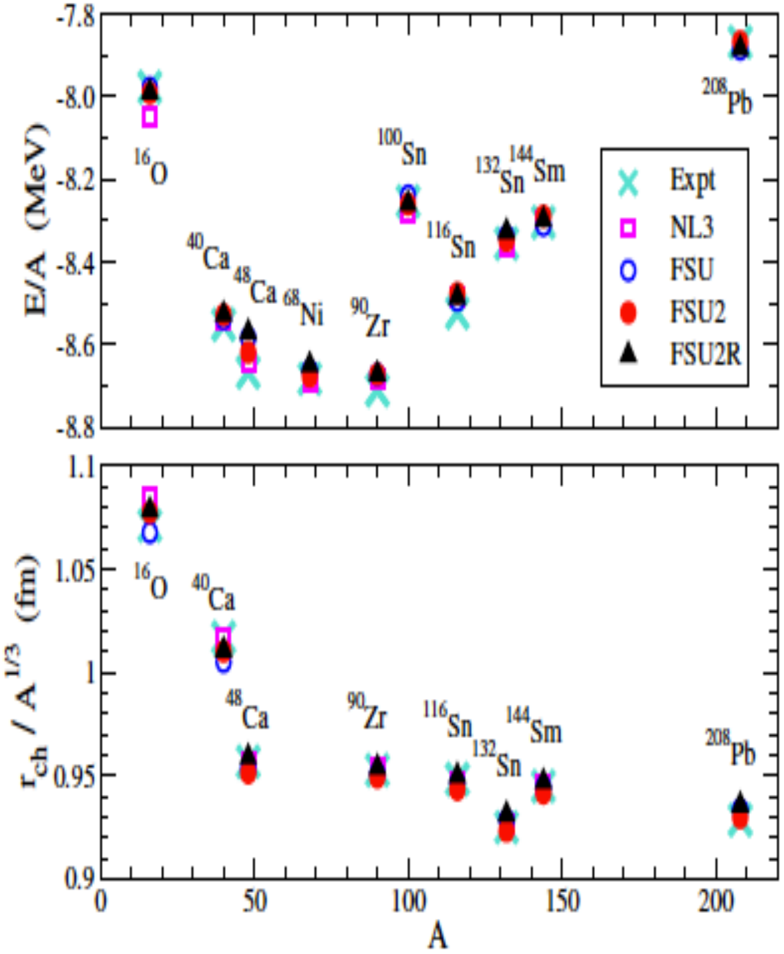
FSU2R (ζ= 0.024; Λ_w= 0.45):

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

fulfilling atomic nuclei properties and HICs data

Implications for atomic nuclei

Energies and charge radii

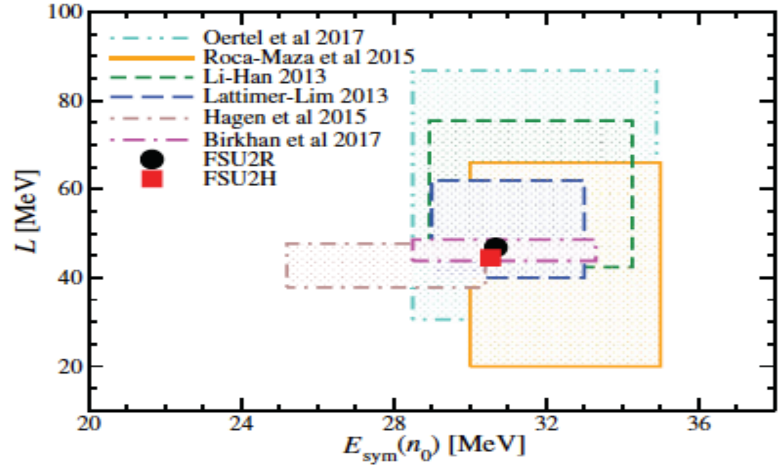


The differences between FSU2R and the experimental energies and charge radii are at the level of 1% or smaller

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

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

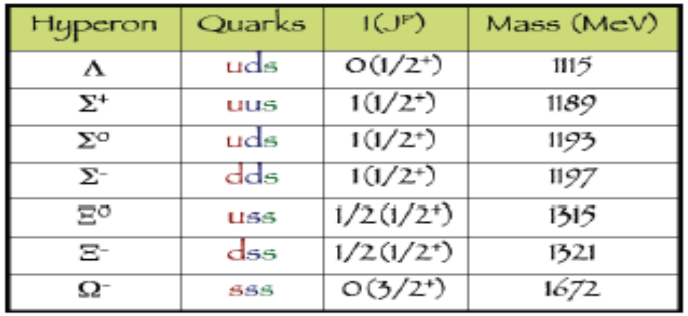
$\Delta r_{np} = 0.302 \pm 0.177$ fm Horowitz et al '12

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

$0.13 \lesssim \Delta r_{np} \lesssim 0.19$ fm 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^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	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

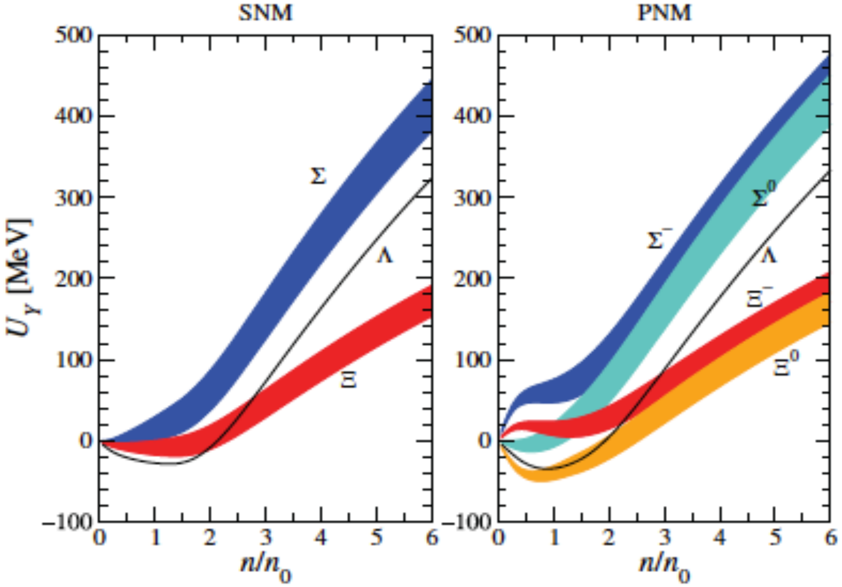
Hyperons soften EoS:
M_{max} gets reduced by ~15%
(M_{max}< 2 $M_\odot$ for FSU2R)
while R insensitive

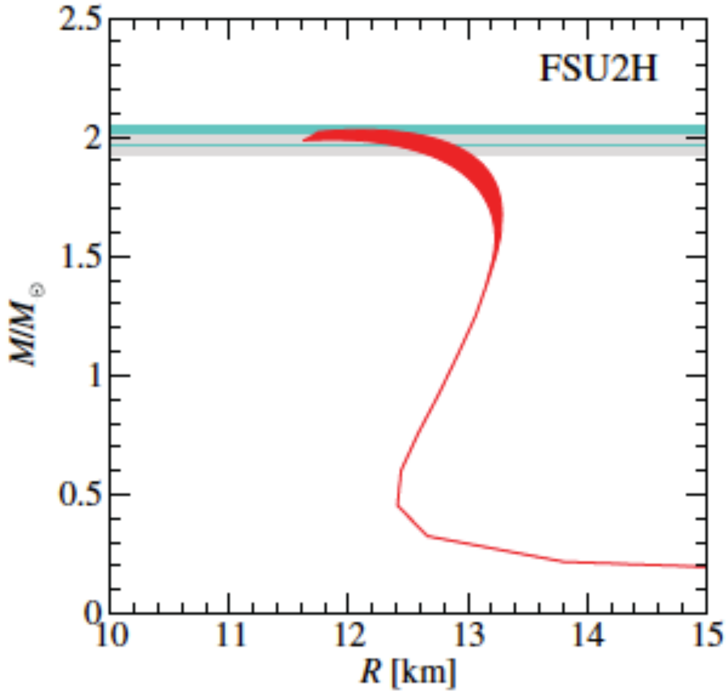
We tense FSU2 to make EoS stiffer
FSU2H (ζ= 0.008; Λ_w= 0.45),
compatible with atomic nuclei and
HiCs for neutron matter

	FSU2H
npeμ	
M_{max}	2.38$M_\odot$
$R_{1.4M\odot}$	13.2 Km
npeμY	
M_{max}	2.02$M_\odot$
$R_{1.4M\odot}$	13.2 Km

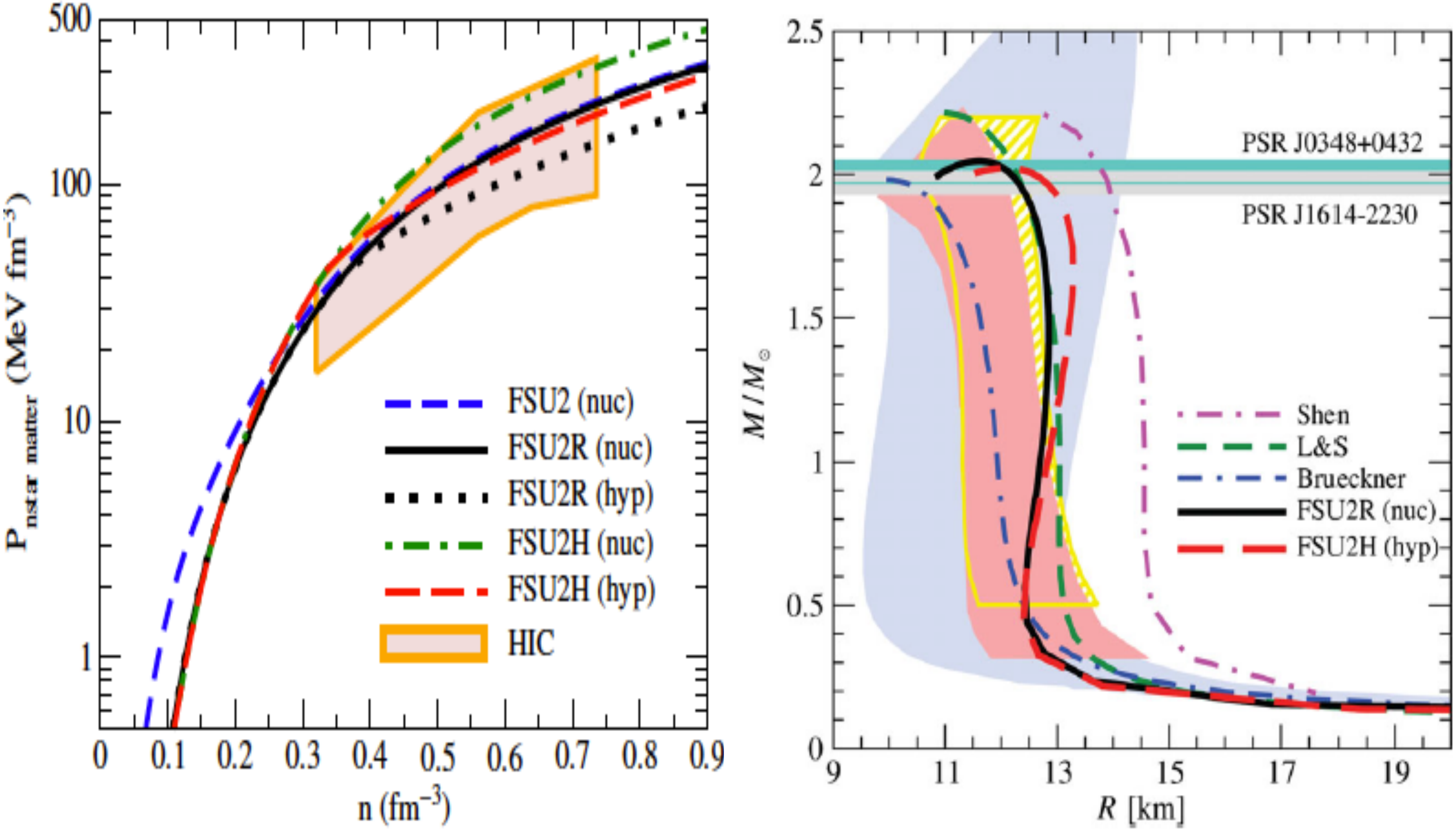
Hypernuclear observables

Hashimoto and Tamura ‘06; Gal et al. ’16



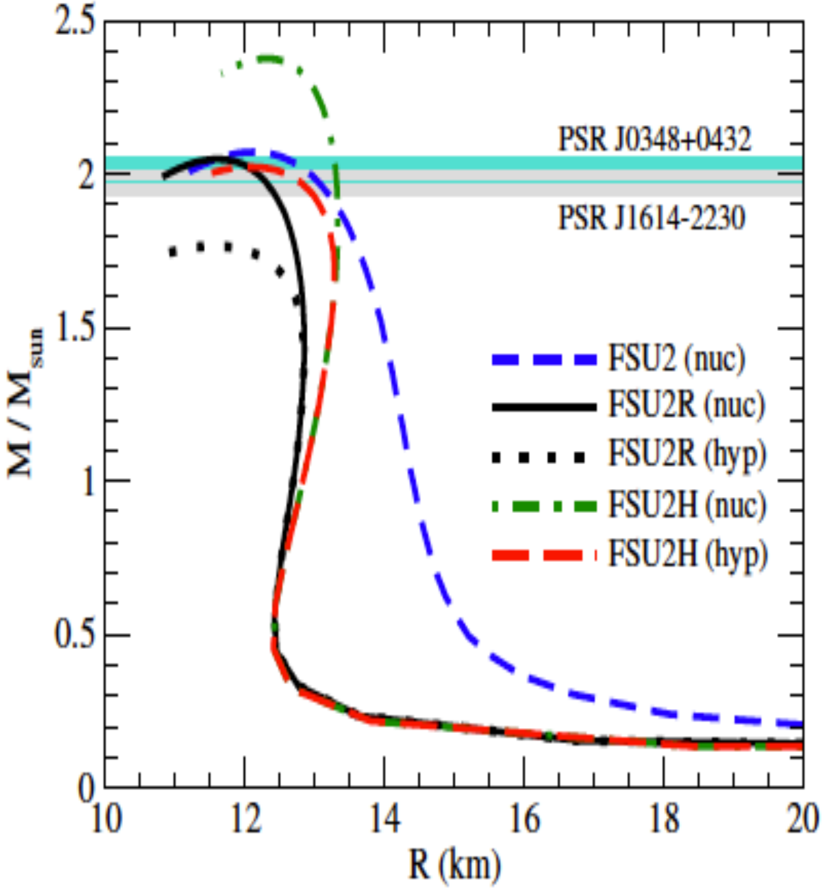


Summarizing…



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

Cooling



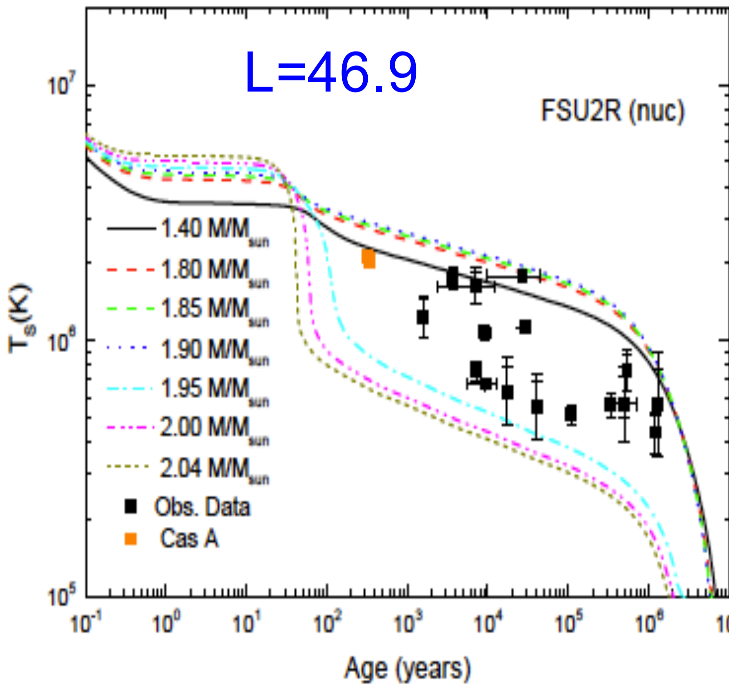
Models	FSU2	FSU2R	FSU2H
n_0 (fm^{-3})	0.1505	0.1505	0.1505
E/A (MeV)	-16.28	-16.28	-16.28
K (MeV)	238.0	238.0	238.0
$E_{\rm sym}(n_0)$ (MeV)	37.6	30.7	30.5
L (MeV)	112.8	46.9	44.5

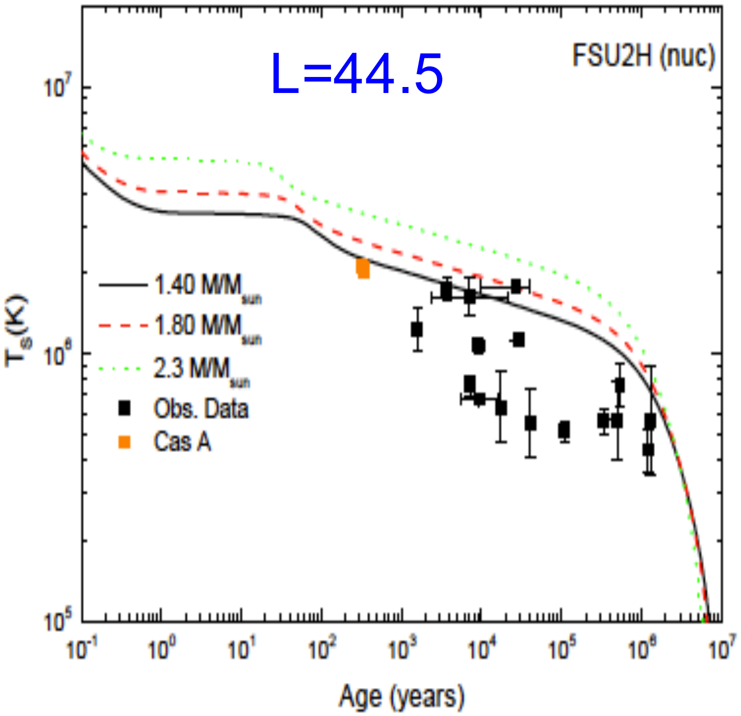
DU:

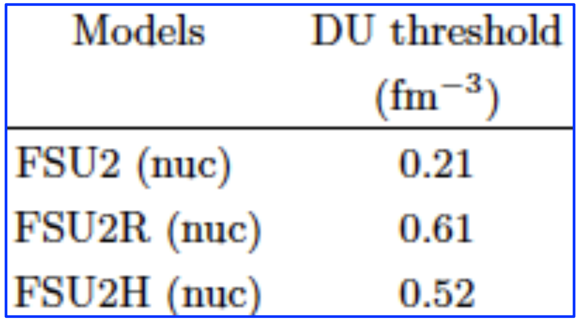
$$n \rightarrow p + e^- + \bar{\nu},$$
$$\Lambda \rightarrow p + e^- + \bar{\nu},$$
$$\Sigma^- \rightarrow n + e^- + \bar{\nu},$$
$$\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu},$$
$$\Sigma^- \rightarrow \Sigma^0 + e^- + \bar{\nu},$$
$$\Xi^- \rightarrow \Lambda + e^- + \bar{\nu},$$
$$\Xi^- \rightarrow \Sigma^0 + e^- + \bar{\nu},$$
$$\Xi^0 \rightarrow \Sigma^+ + e^- + \bar{\nu},$$
$$\Xi^- \rightarrow \Xi^0 + e^- + \bar{\nu}.$$

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)	0.52	—	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~1.4 M_{sun}):
soft/stiff nuclear
symmetry implies
slow/fast cooling







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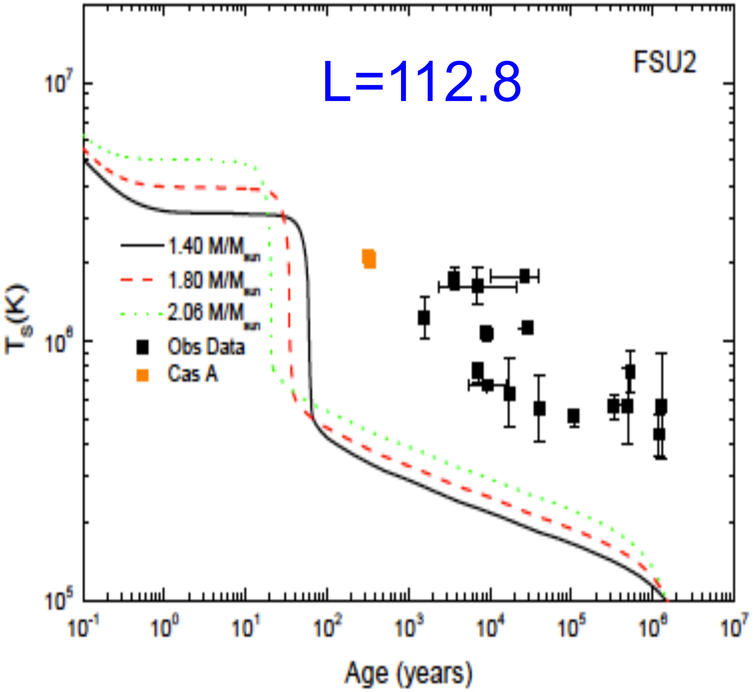
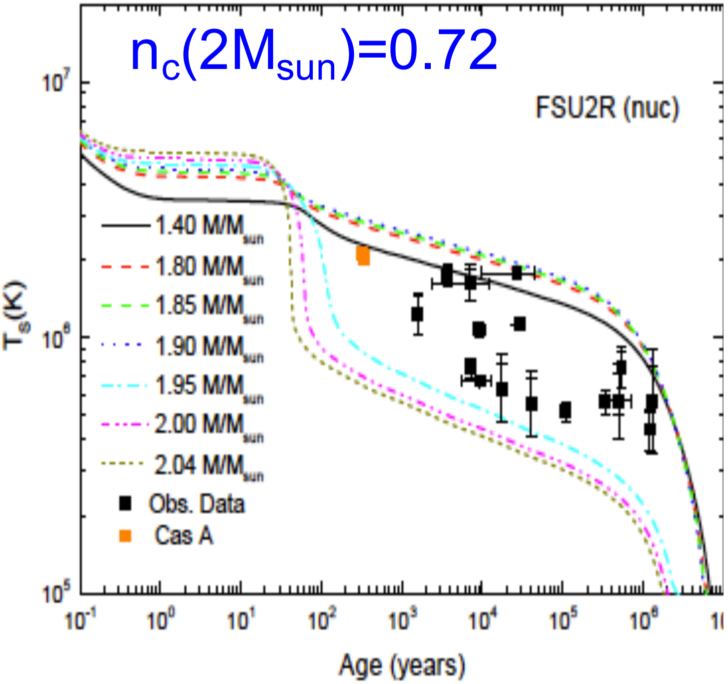
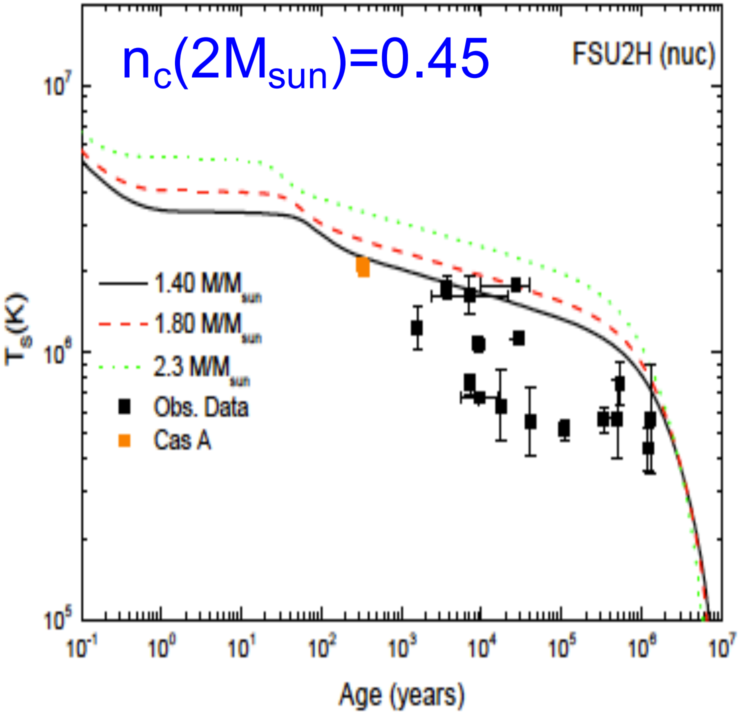
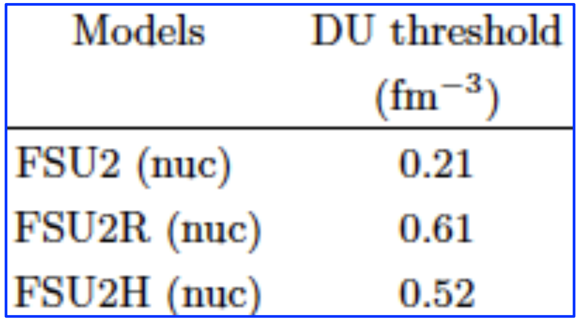


Low-mass stars
($M \sim 1.4\ M_{sun}$):
soft/stiff nuclear
symmetry implies
slow/fast cooling

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


$n_c(2M_{sun})=0.72$


$n_c(2M_{sun})=0.45$



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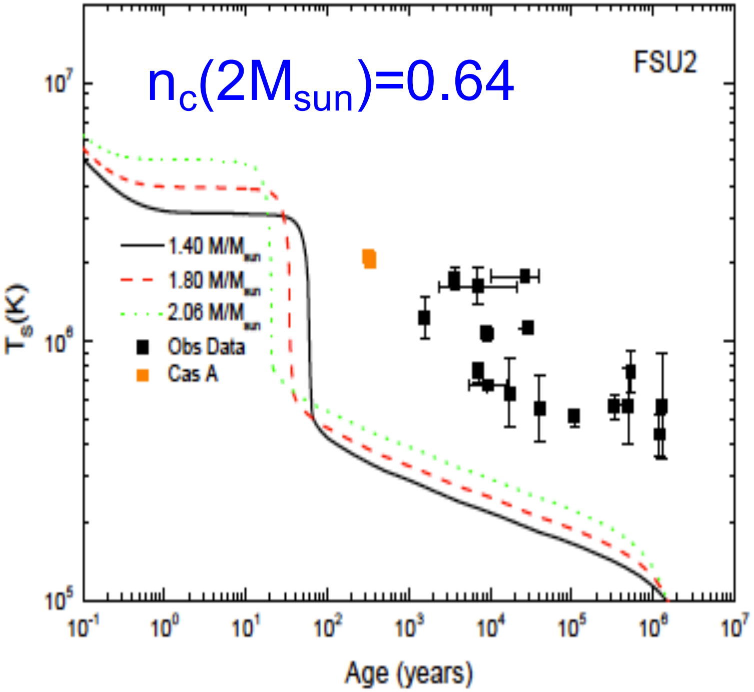
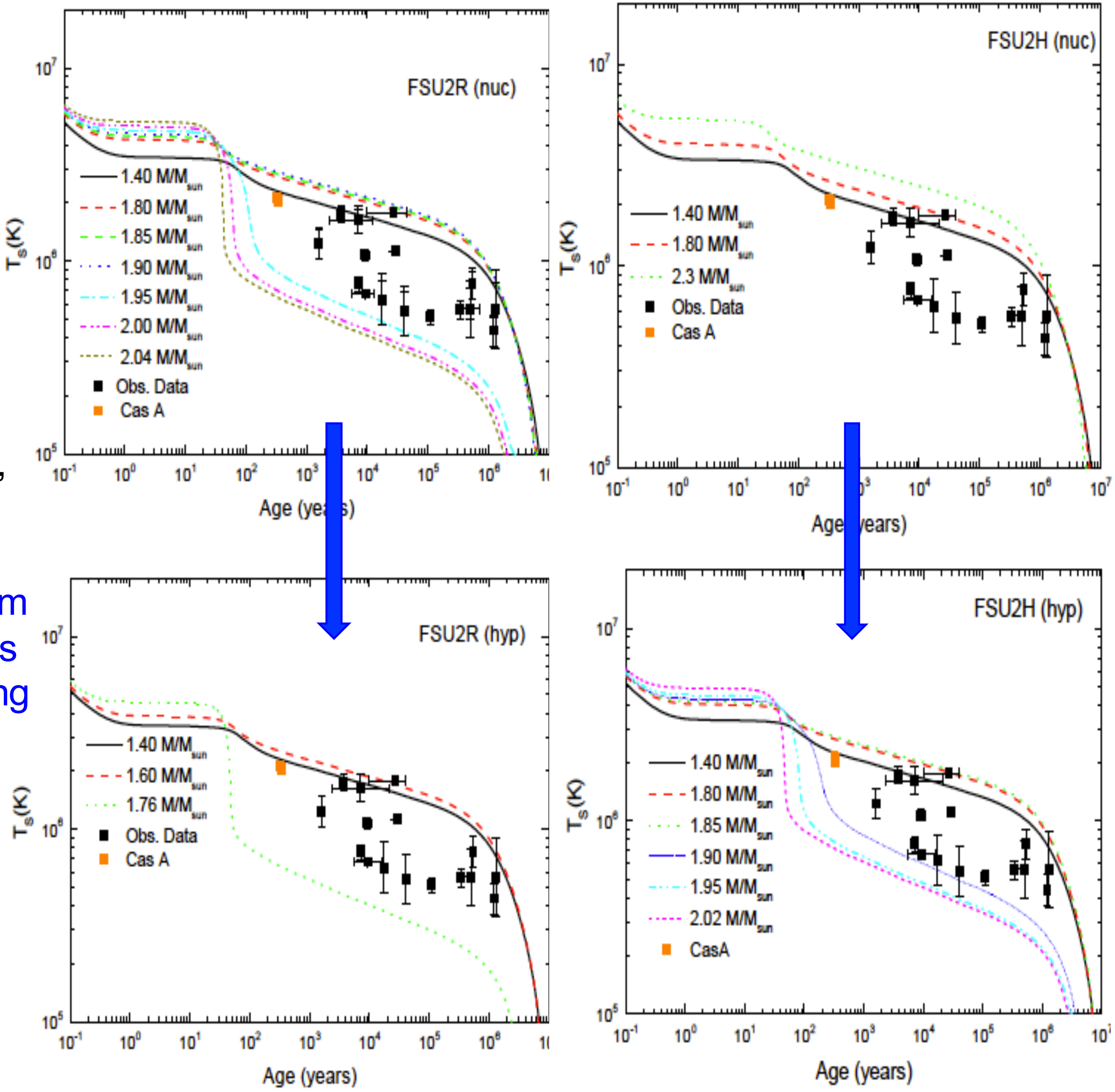

$n_c(2M_{sun})=0.64$

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

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

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

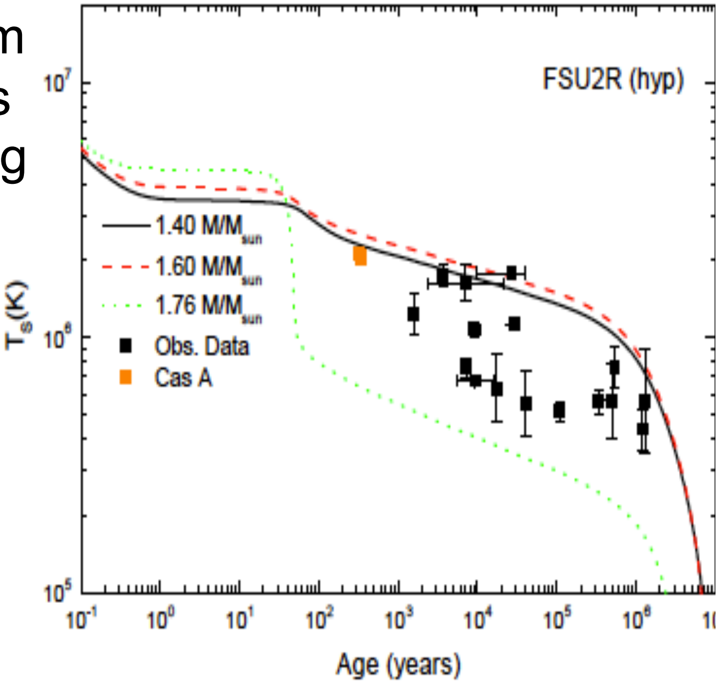


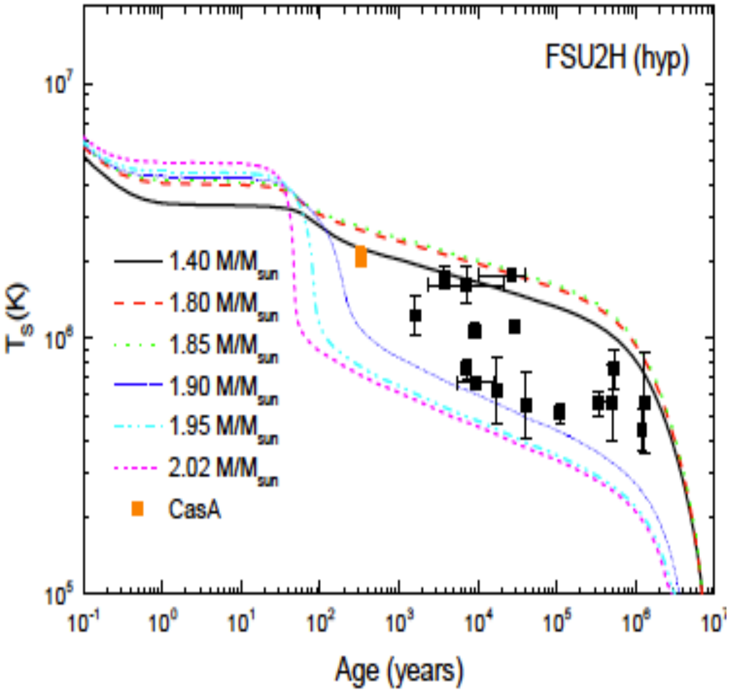
Low-mass stars
(M~1.4 M_{sun}):
soft/stiff nuclear symmetry implies slow/fast cooling

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

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





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

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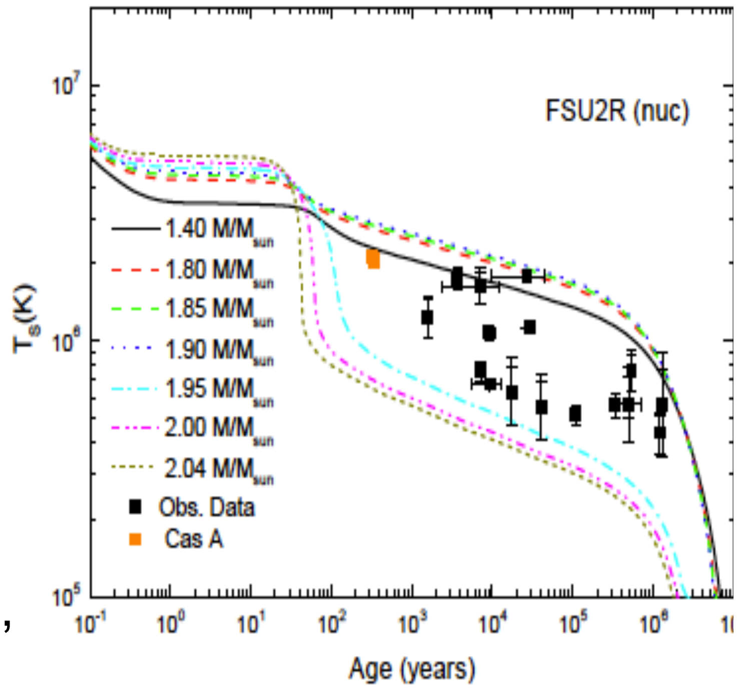
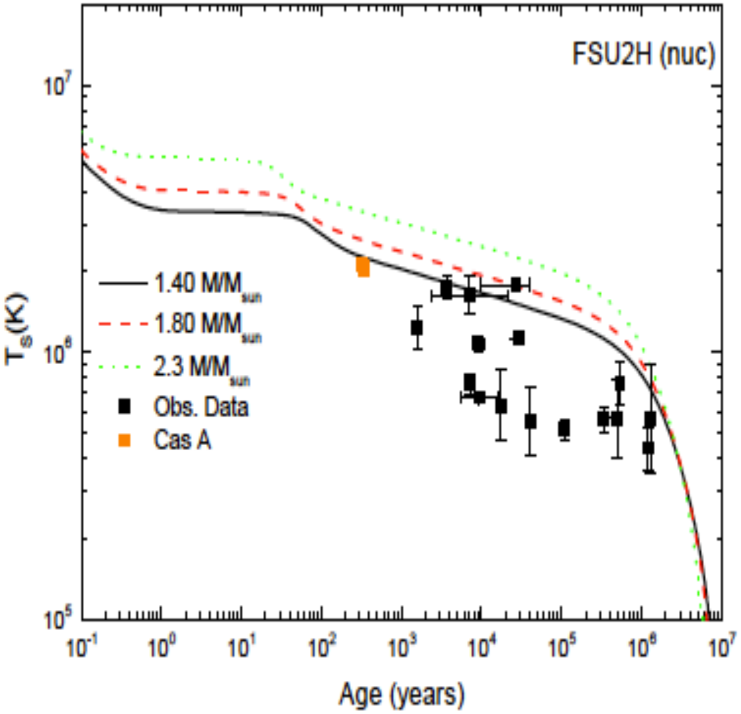
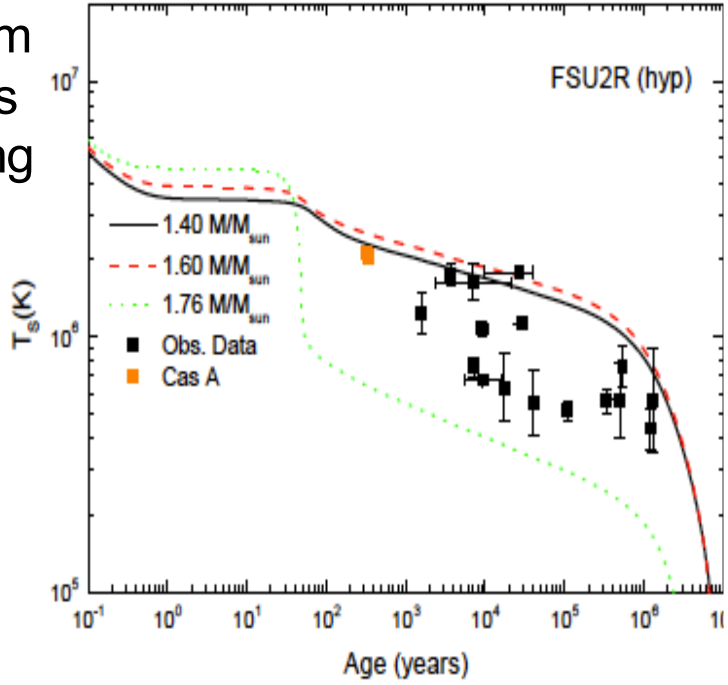
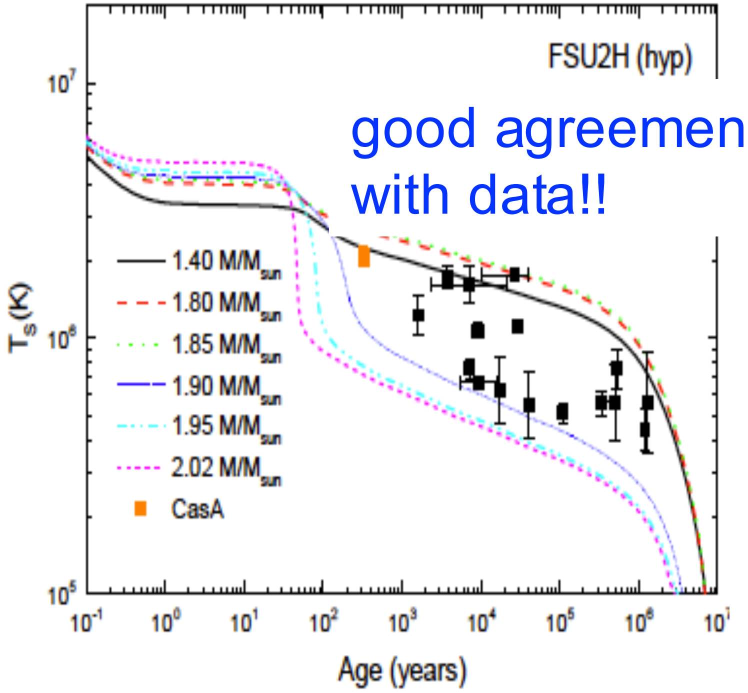




Hyperons in medium to heavy mass stars speed up the cooling due to reduction of neutron fraction

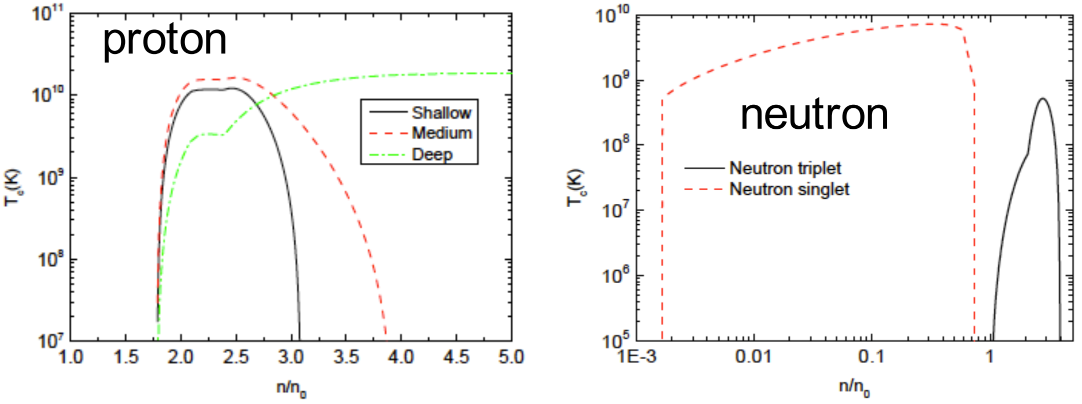
Softer EoS (larger densities) with hyperons activates cooling

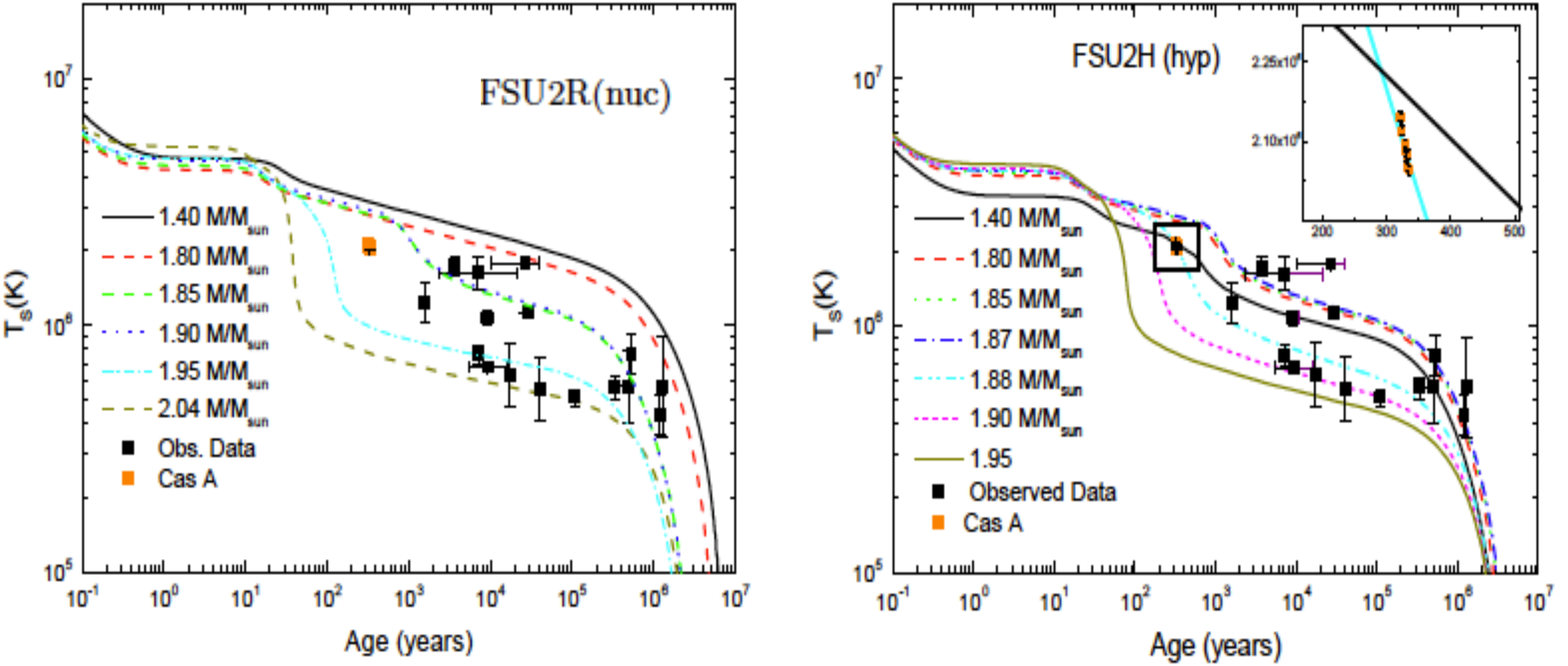




good agreement with data!!

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_{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 parametrization, FSU2R, fulfills $2M_\odot$ with $R \lesssim 13$ Km, while reproducing the energies and charge radii of nuclei, having E_{sym}=30.7 MeV & L=46.9 MeV and producing Δr_{np}=0.15fm

- 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_{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 neutron stars with $M > 1.8\ M_{sun}$

- future directions: cooling with magnetic fields, neutron star mergers,..

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