COOLING OF SMALL AND MASSIVE HYPERONIC STARS

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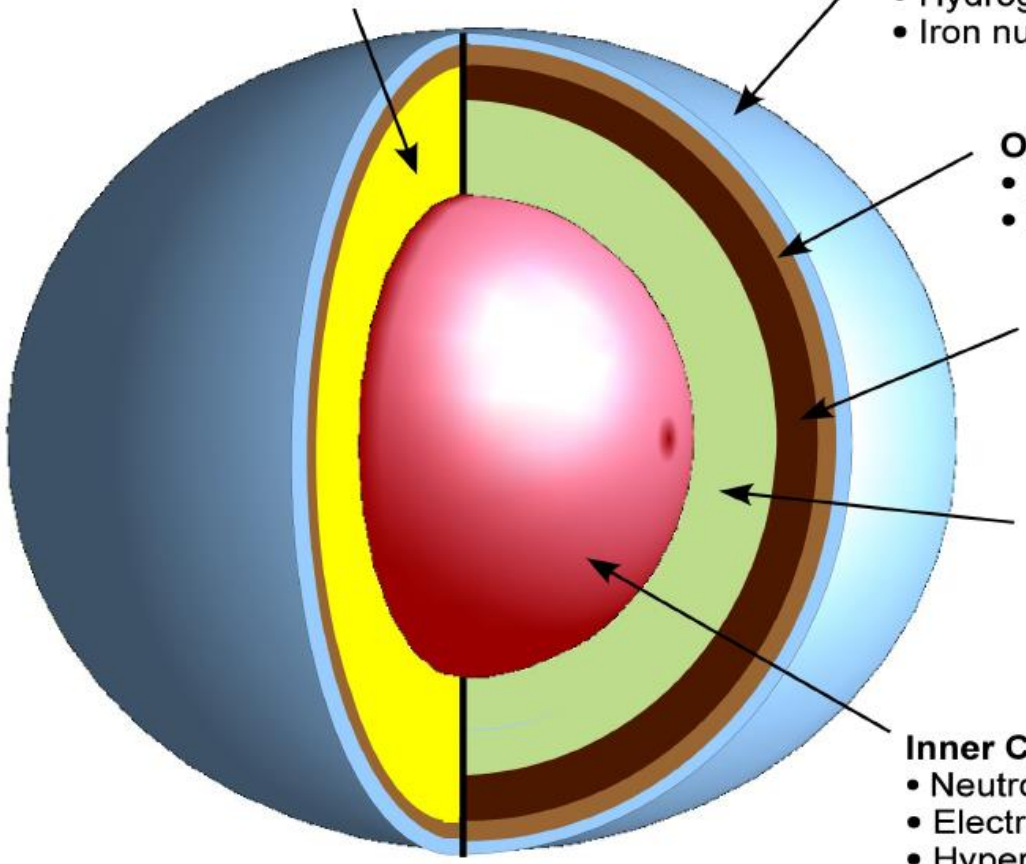
NEUTRON STARS



Color-superconducting strange quark matter

Surface
- Hydrogen/He
- Iron nuclei

Outer Crust
- Ions
- Electron gas

Inner Crust
- Heavy ions
- Relativistic electron gas
- Superfluid neutrons

Outer Core
- Neutrons, protons
- Electrons, muons
- Superconducting protons

Inner Core
- Neutrons, protons
- Electrons, muons
- Hyperons (Σ, Λ, Σ)
- Boson condensates (π, K)
- Deconfined (u,d,s) quarks/quark matter

Radius ~ 10 to 14 km, Mass ~ 1 to 2 M_{sun}

$N \sim 10^{57}$ baryons

$M \sim 1\text{–}2\ M_{sun}$

$R \sim 10\text{-}15$ km

$T \sim 10^{6\ \ldots\ 11}$ K

Weber, Hamil, Mimura and Negreiros (2011) state

- N
- R

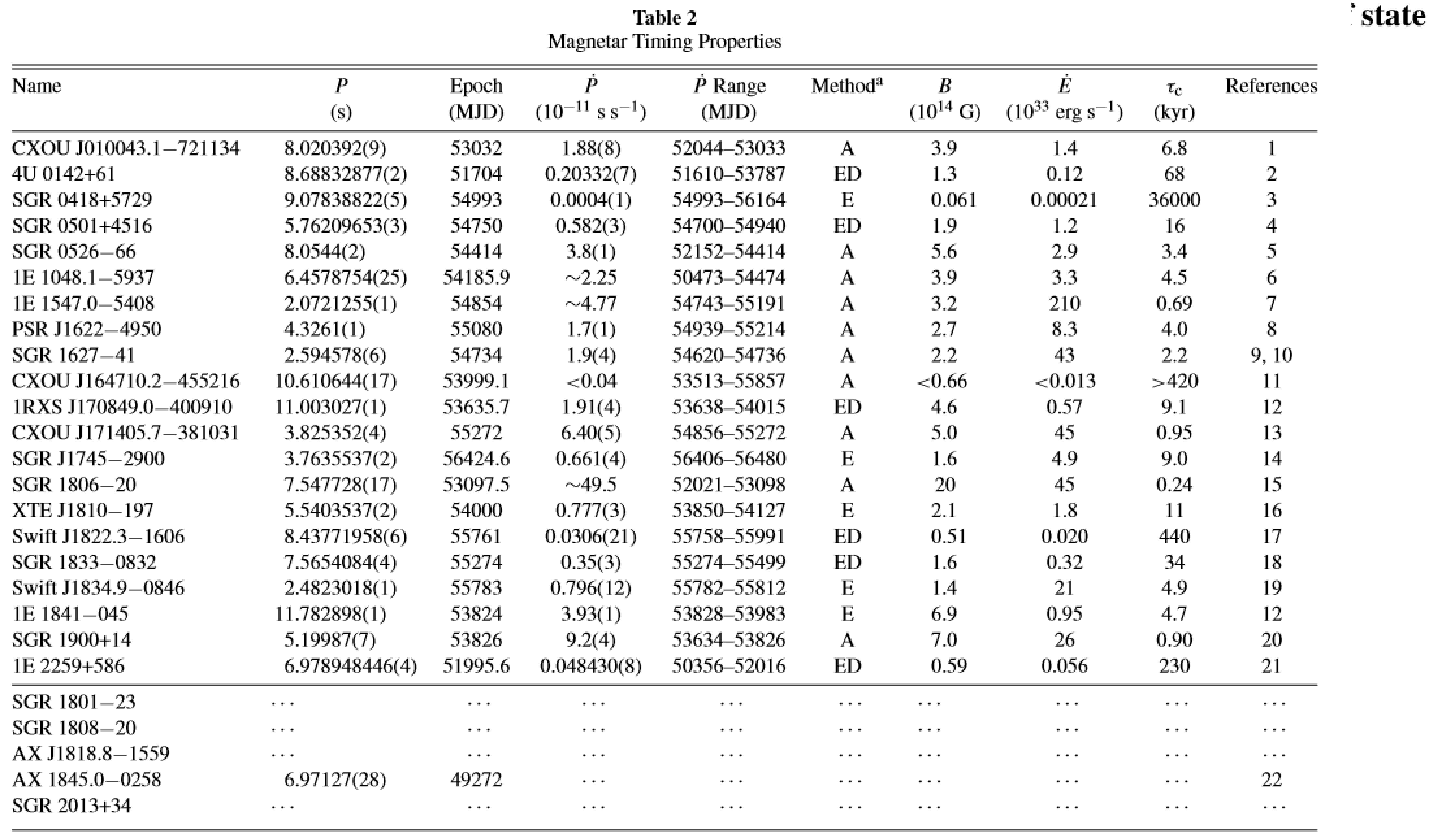


Table 2
Magnetar Timing Properties

Name	P (s)	Epoch (MJD)	$\dot{P}$ (10^{-11} s s^{-1})	$\dot{P}$ Range (MJD)	Method[a]	B (10^{14} G)	$\dot{E}$ (10^{33} erg s^{-1})	τ_c (kyr)	References
CXOU J010043.1−721134	8.020392(9)	53032	1.88(8)	52044–53033	A	3.9	1.4	6.8	1
4U 0142+61	8.68832877(2)	51704	0.20332(7)	51610–53787	ED	1.3	0.12	68	2
SGR 0418+5729	9.07838822(5)	54993	0.0004(1)	54993–56164	E	0.061	0.00021	36000	3
SGR 0501+4516	5.76209653(3)	54750	0.582(3)	54700–54940	ED	1.9	1.2	16	4
SGR 0526−66	8.0544(2)	54414	3.8(1)	52152–54414	A	5.6	2.9	3.4	5
1E 1048.1−5937	6.4578754(25)	54185.9	~2.25	50473–54474	A	3.9	3.3	4.5	6
1E 1547.0−5408	2.0721255(1)	54854	~4.77	54743–55191	A	3.2	210	0.69	7
PSR J1622−4950	4.3261(1)	55080	1.7(1)	54939–55214	A	2.7	8.3	4.0	8
SGR 1627−41	2.594578(6)	54734	1.9(4)	54620–54736	A	2.2	43	2.2	9, 10
CXOU J164710.2−455216	10.610644(17)	53999.1	<0.04	53513–55857	A	<0.66	<0.013	>420	11
1RXS J170849.0−400910	11.003027(1)	53635.7	1.91(4)	53638–54015	ED	4.6	0.57	9.1	12
CXOU J171405.7−381031	3.825352(4)	55272	6.40(5)	54856–55272	A	5.0	45	0.95	13
SGR J1745−2900	3.7635537(2)	56424.6	0.661(4)	56406–56480	E	1.6	4.9	9.0	14
SGR 1806−20	7.547728(17)	53097.5	~49.5	52021–53098	A	20	45	0.24	15
XTE J1810−197	5.5403537(2)	54000	0.777(3)	53850–54127	E	2.1	1.8	11	16
Swift J1822.3−1606	8.43771958(6)	55761	0.0306(21)	55758–55991	ED	0.51	0.020	440	17
SGR 1833−0832	7.5654084(4)	55274	0.35(3)	55274–55499	ED	1.6	0.32	34	18
Swift J1834.9−0846	2.4823018(1)	55783	0.796(12)	55782–55812	E	1.4	21	4.9	19
1E 1841−045	11.782898(1)	53824	3.93(1)	53828–53983	E	6.9	0.95	4.7	12
SGR 1900+14	5.19987(7)	53826	9.2(4)	53634–53826	A	7.0	26	0.90	20
1E 2259+586	6.978948446(4)	51995.6	0.048430(8)	50356–52016	ED	0.59	0.056	230	21
SGR 1801−23	…	…	…	…	…	…	…	…	…
SGR 1808−20	…	…	…	…	…	…	…	…	…
AX J1818.8−1559	…	…	…	…	…	…	…	…	…
AX 1845.0−0258	6.97127(28)	49272	…	…	…	…	…	…	22
SGR 2013+34	…	…	…	…	…	…	…	…	…

- Nuclear r
- Hypernuc
- HIC flow

B

B

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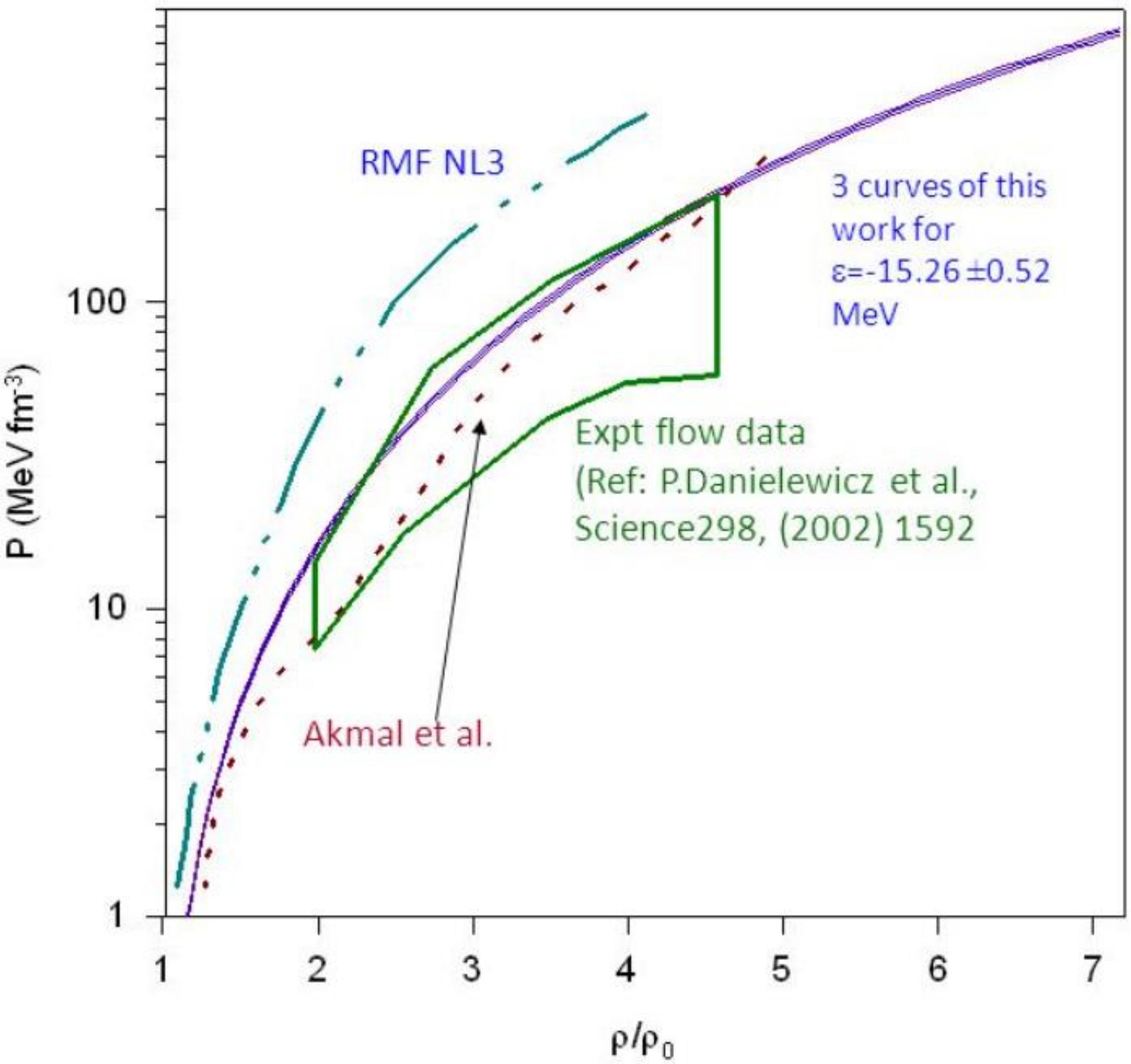
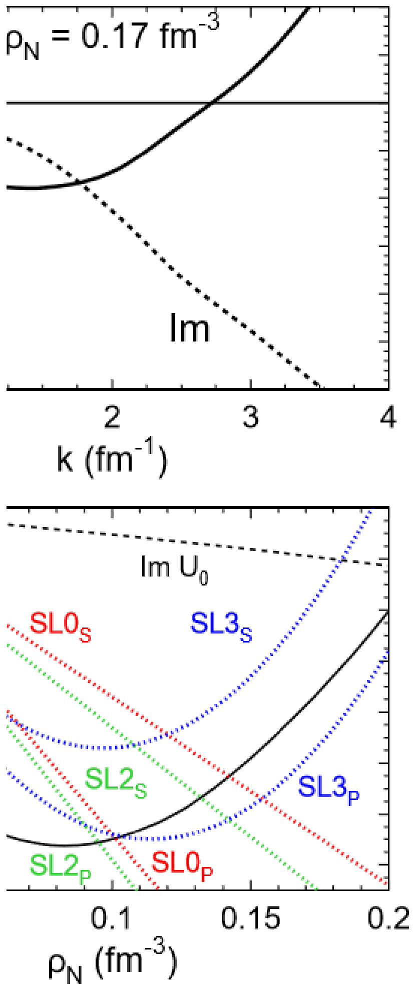


e-Print: arXiv:1611.03661 [nucl-th] | PDF



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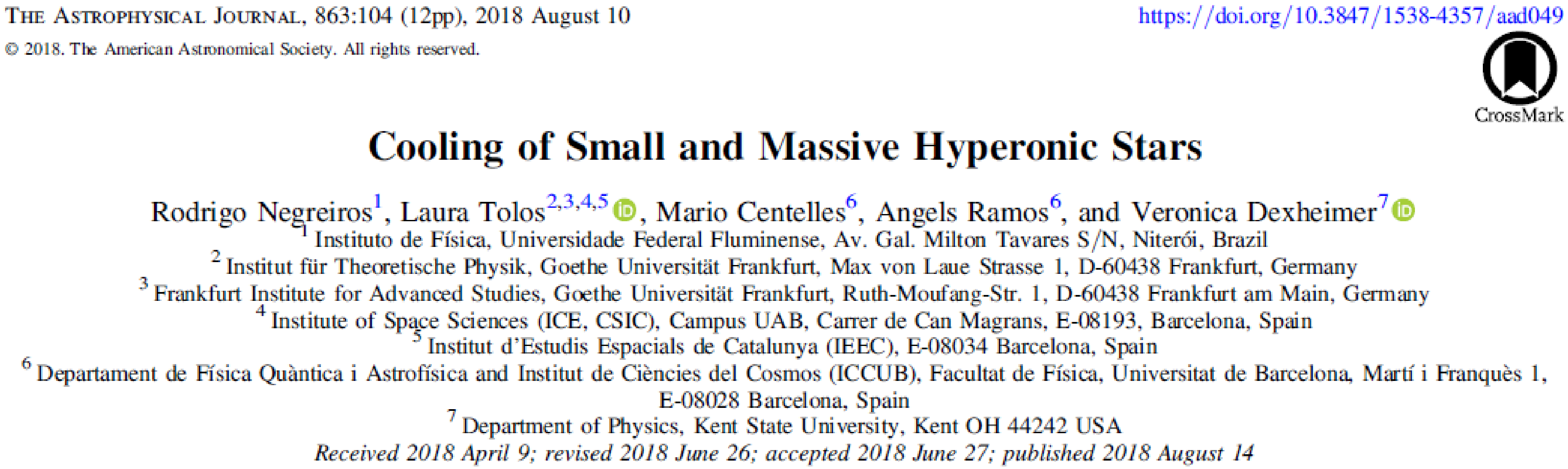
GOALS

- Reconcile microscopic and macroscopic properties.
- Of particular interest is to obtain an EoS that satisfy the observed neutron star high mass as well as small radii.
- For this we need an EoS with softer symmetry energy.
- We also seek a microscopic description that agrees with observed neutron stars thermal data.



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Cooling of Small and Massive Hyperonic Stars

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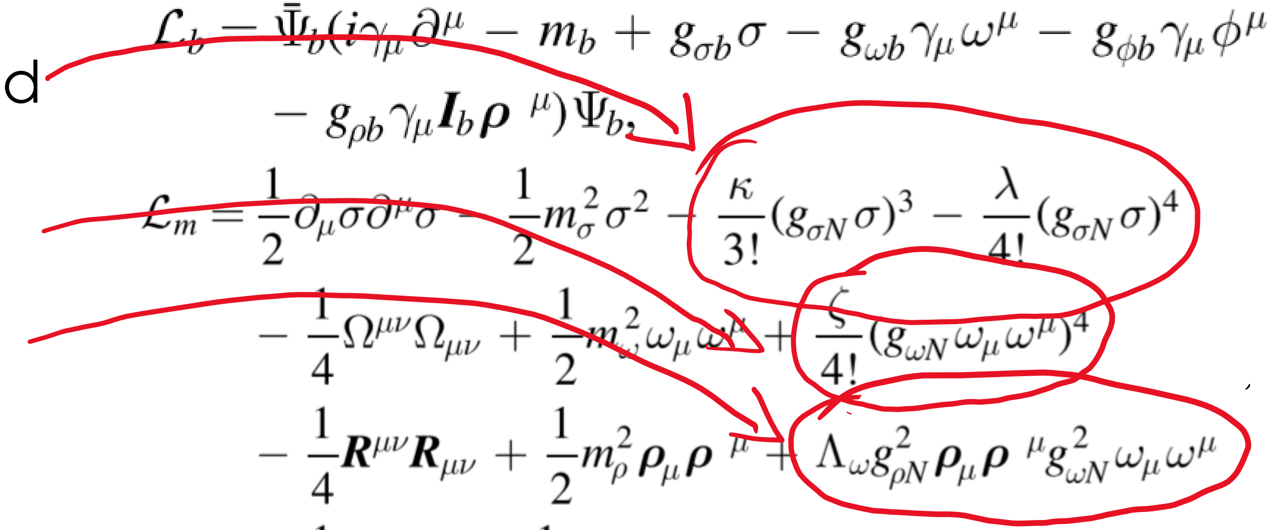
MICROSCOPIC MODEL

- Scalar and vector self-interaction as well as a mixed quartic vector interaction..
- Softening of the symmetric EoS around saturation.
- Softening of the EoS at high densities.
- Modification of density dependence of symmetry energy.



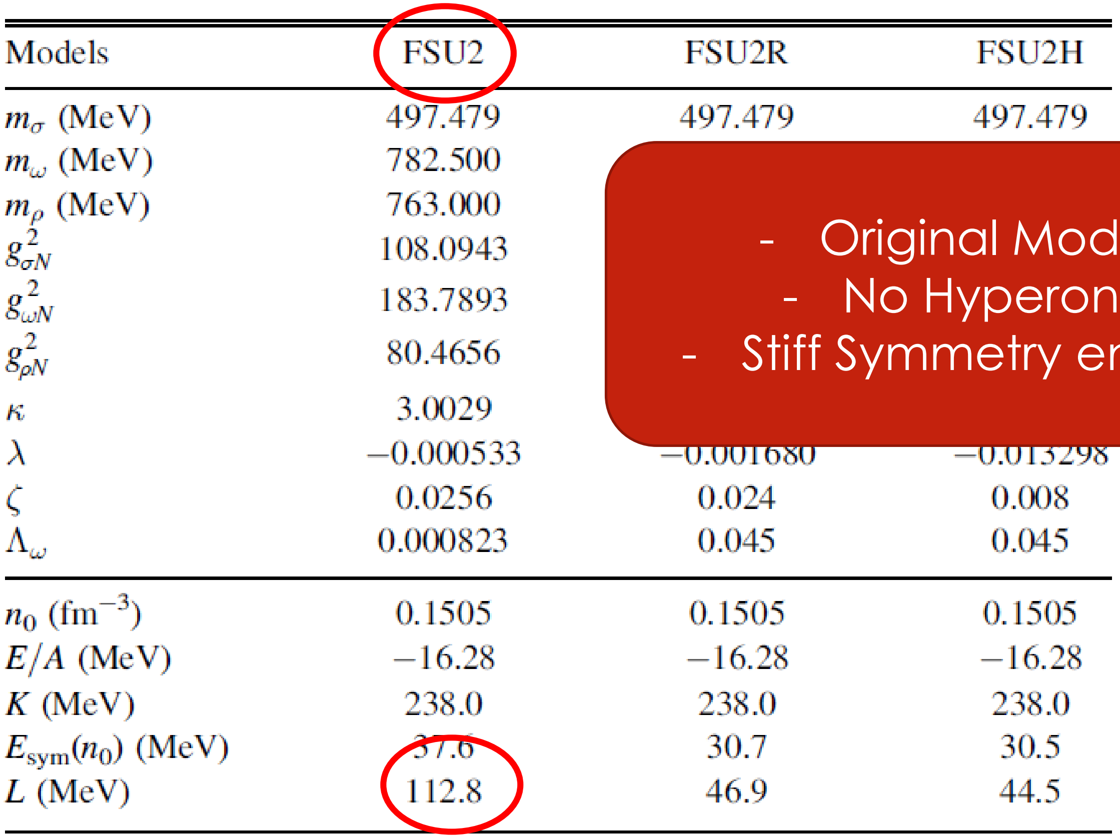
$$\mathcal{L} = \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_{l=e,\mu} \mathcal{L}_l,$$

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

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

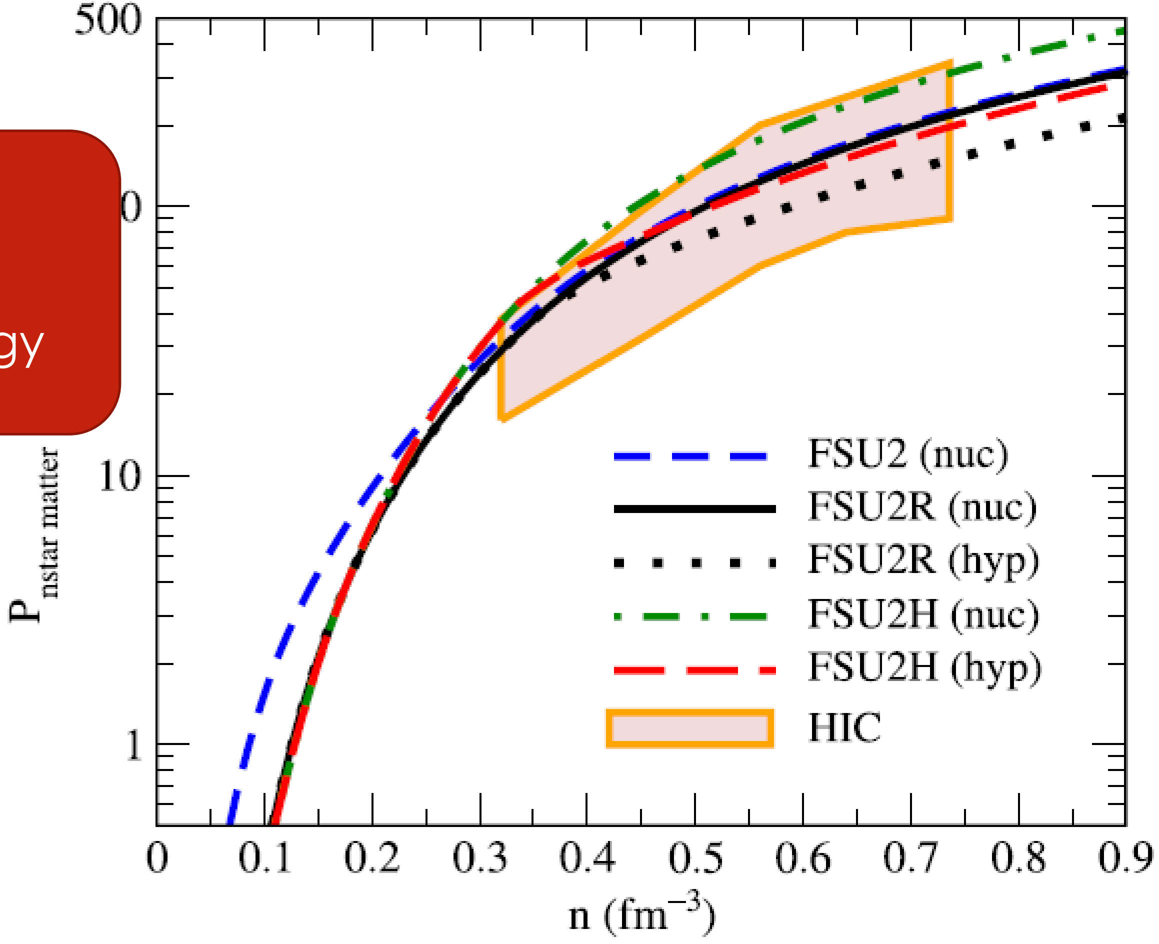
$$\mathcal{L}_l = \bar\psi_l(i\gamma_\mu\partial^\mu - m_l)\psi_l,$$

MICROSCOPIC MODEL

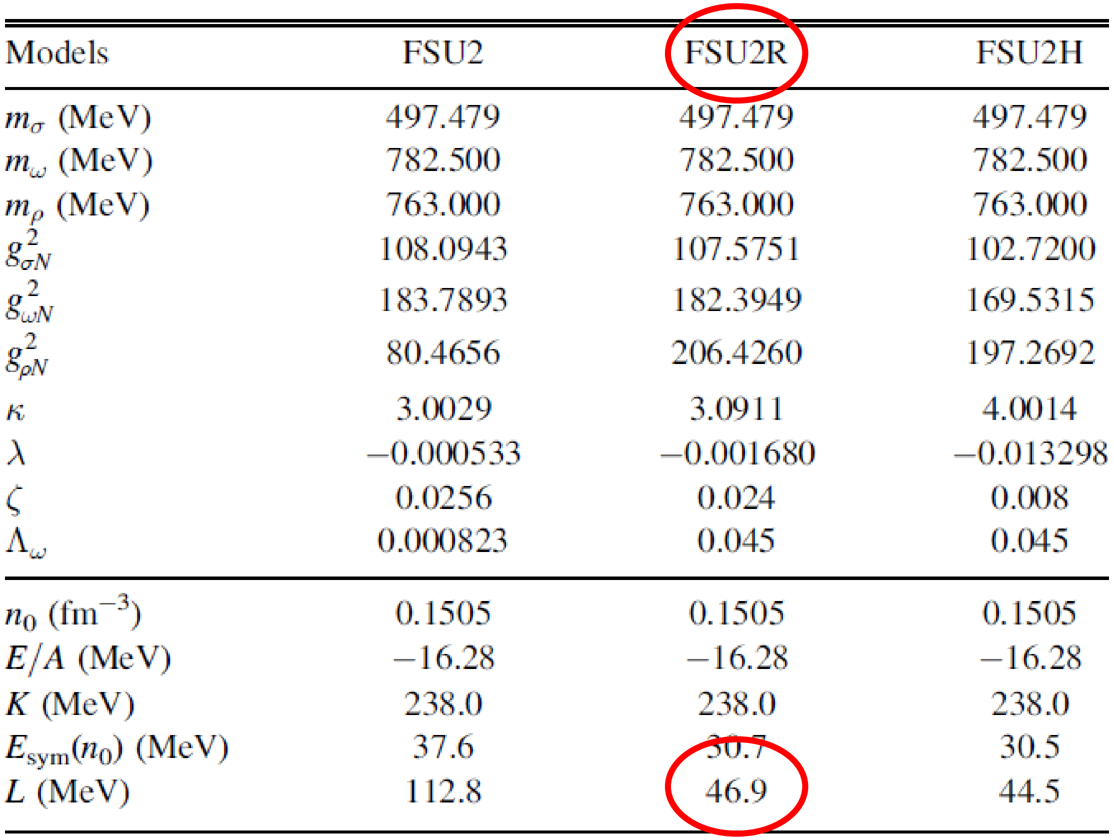


Models	FSU2	FSU2R	FSU2H
m_σ (MeV)	497.479	497.479	497.479
m_ω (MeV)	782.500	[illegible]	[illegible]
m_ρ (MeV)	763.000	[illegible]	[illegible]
$g^2_{\sigma N}$	108.0943	[illegible]	[illegible]
$g^2_{\omega N}$	183.7893	[illegible]	[illegible]
$g^2_{\rho N}$	80.4656	[illegible]	[illegible]
κ	3.0029	[illegible]	[illegible]
λ	−0.000533	−0.001680	−0.013298
ζ	0.0256	0.024	0.008
Λ_ω	0.000823	0.045	0.045
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
$E_{\mathrm{sym}}(n_0)$ (MeV)	37.6	30.7	30.5
L (MeV)	112.8	46.9	44.5

- Original Model
- No Hyperons
- Stiff Symmetry energy



MICROSCOPIC MODEL



Models	FSU2	FSU2R	FSU2H
m_σ (MeV)	497.479	497.479	497.479
m_ω (MeV)	782.500	782.500	782.500
m_ρ (MeV)	763.000	763.000	763.000
$g^2_{\sigma N}$	108.0943	107.5751	102.7200
$g^2_{\omega N}$	183.7893	182.3949	169.5315
$g^2_{\rho N}$	80.4656	206.4260	197.2692
κ	3.0029	3.0911	4.0014
λ	−0.000533	−0.001680	−0.013298
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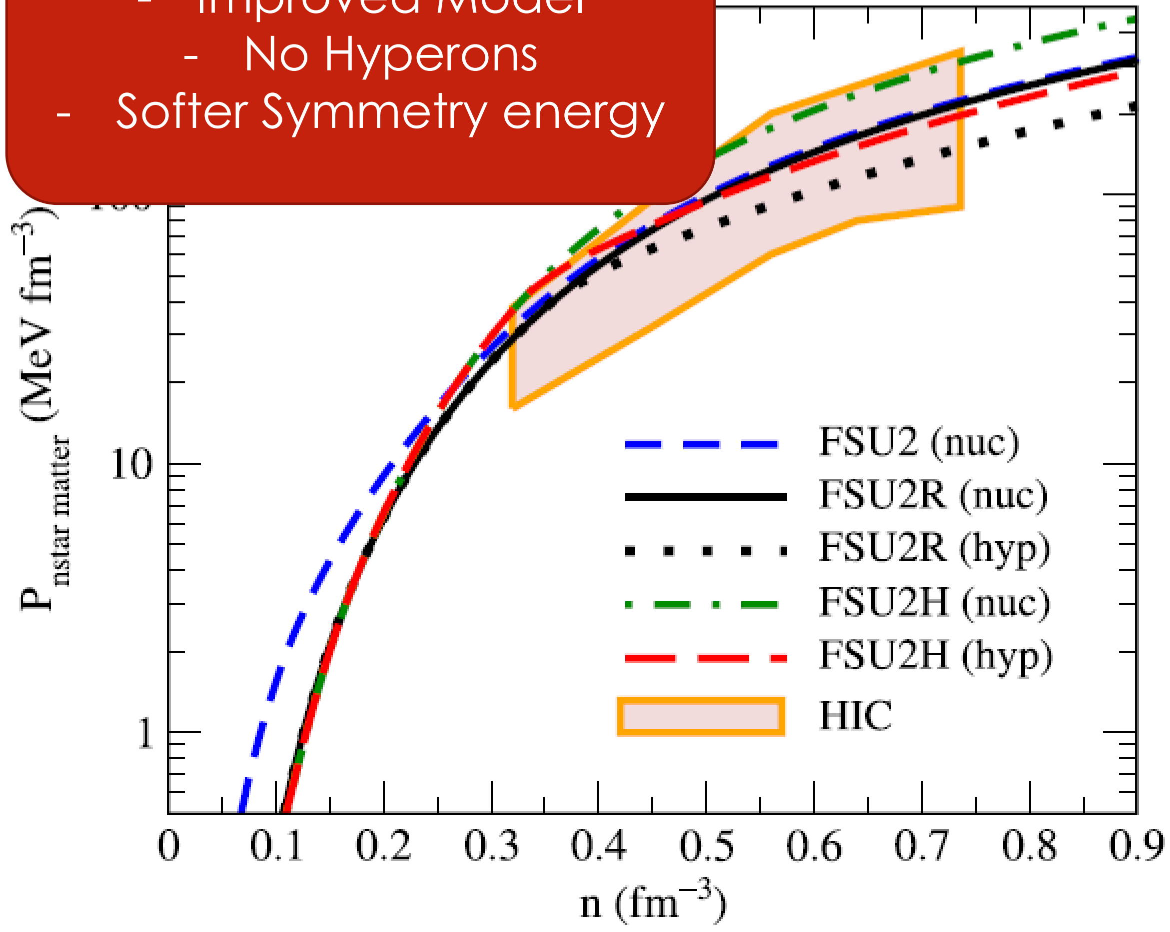
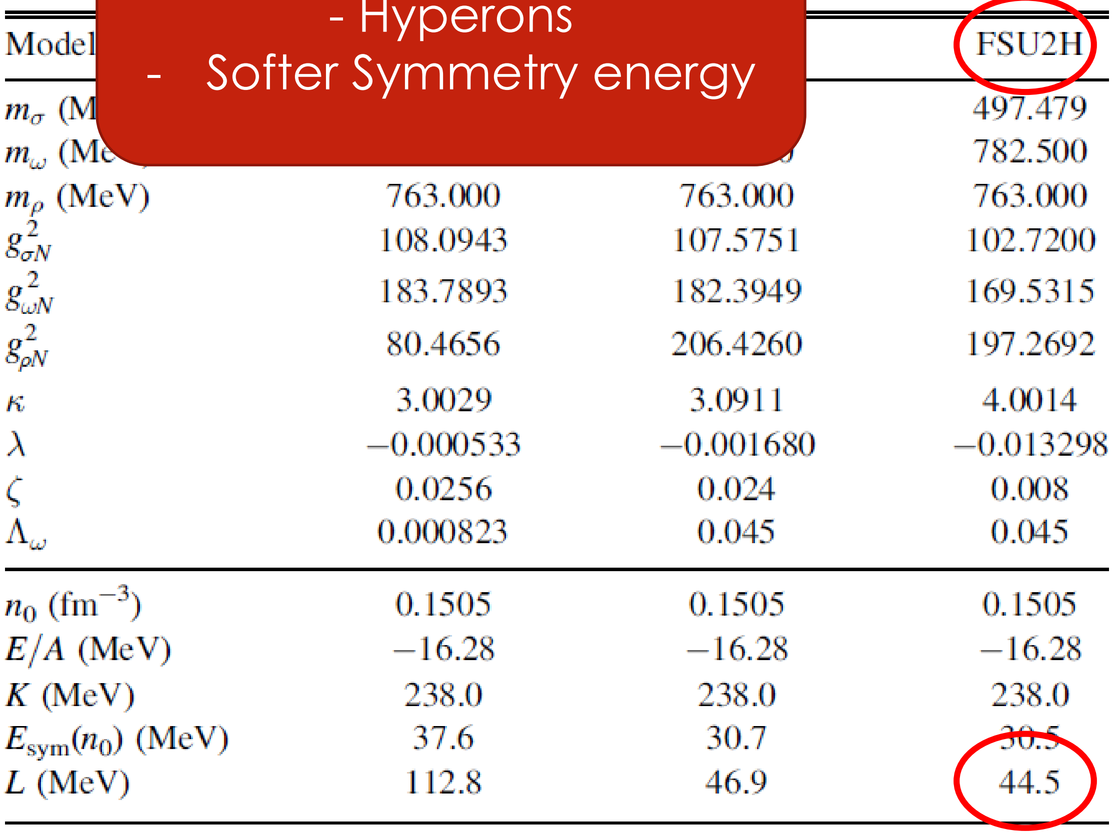
L (MeV)	112.8	46.9	44.5

- Improved Model
- No Hyperons
- Softer Symmetry energy



MICROSCOPIC MODEL

- Improved Model
- Hyperons
- Softer Symmetry energy



Model			FSU2H
m_σ (M			497.479
m_ω (Me			782.500
m_ρ (MeV)	763.000	763.000	763.000
$g_{\sigma N}^2$	108.0943	107.5751	102.7200
$g_{\omega N}^2$	183.7893	182.3949	169.5315
$g_{\rho N}^2$	80.4656	206.4260	197.2692
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n_0 (fm^{-3})	0.1505	0.1505	0.1505
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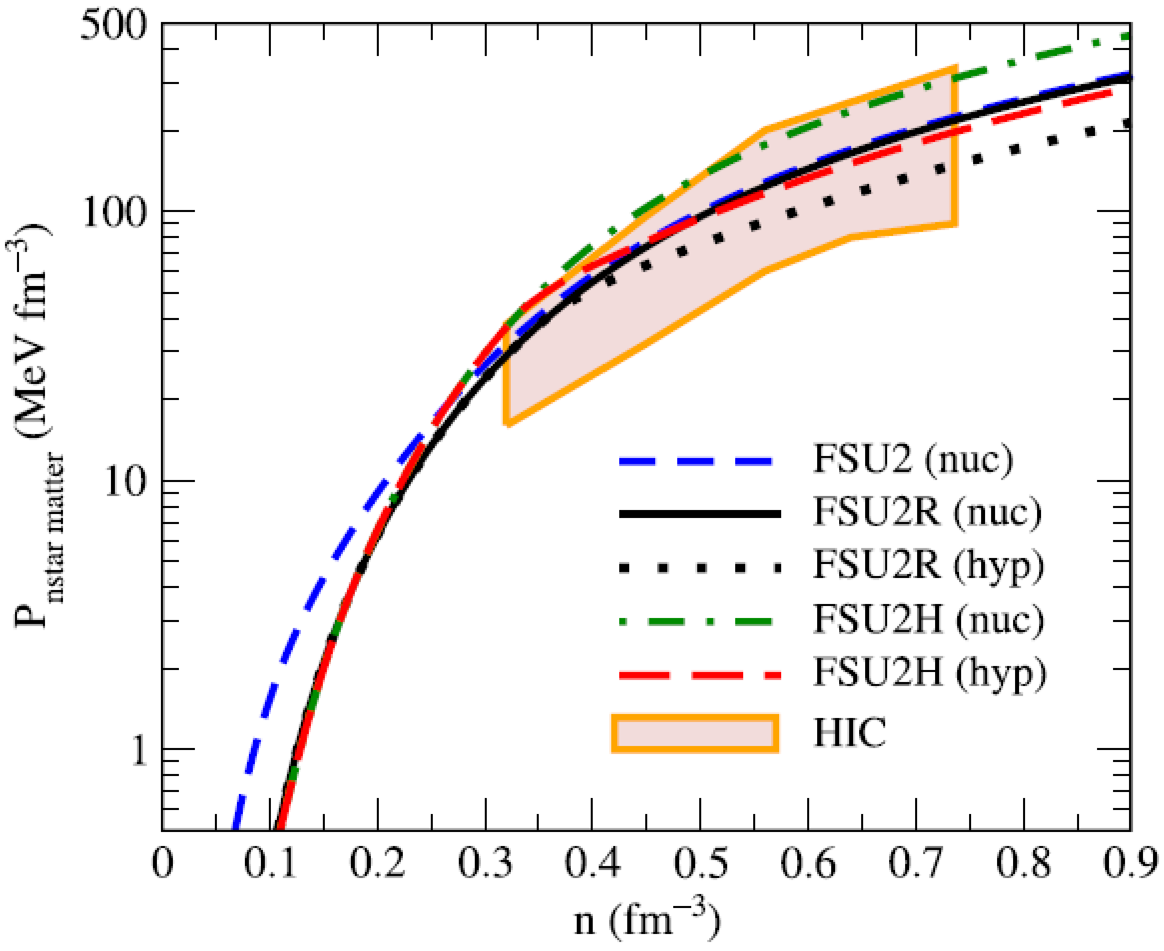
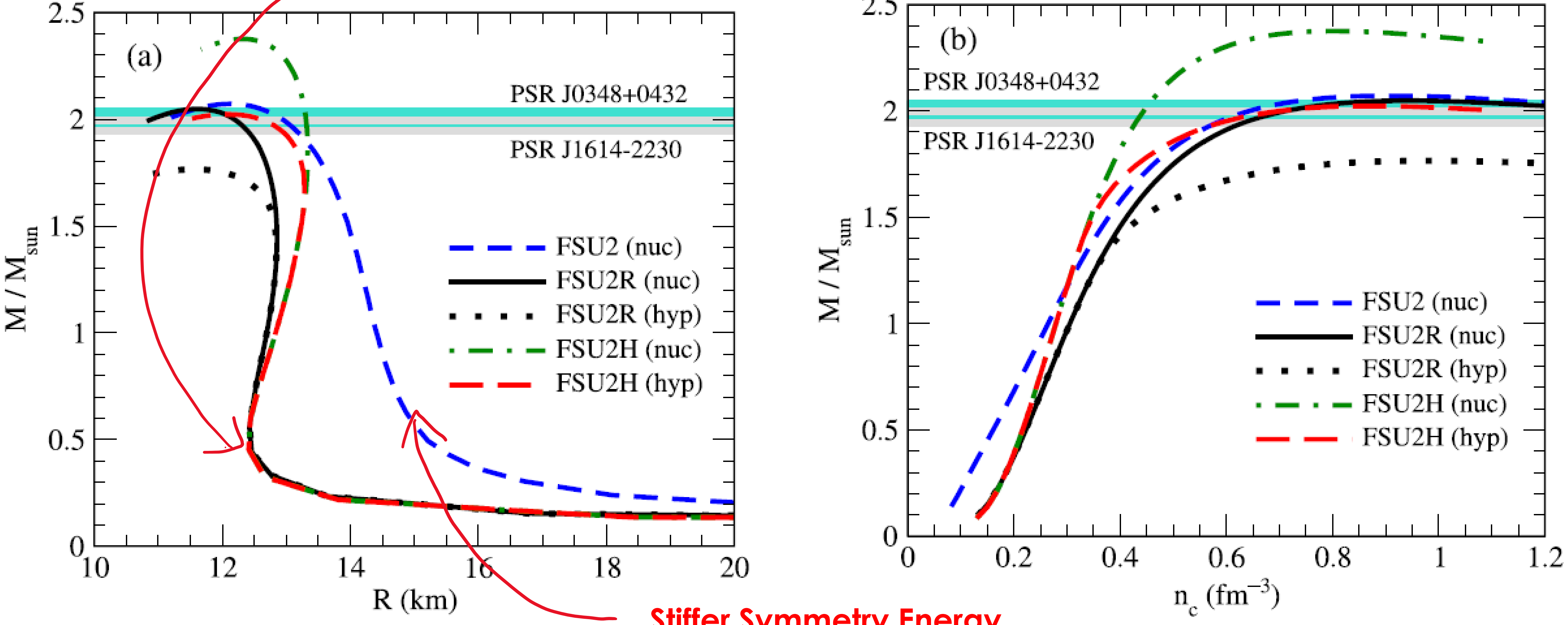


MICRO → MACROSCOPIC PROPERTIES

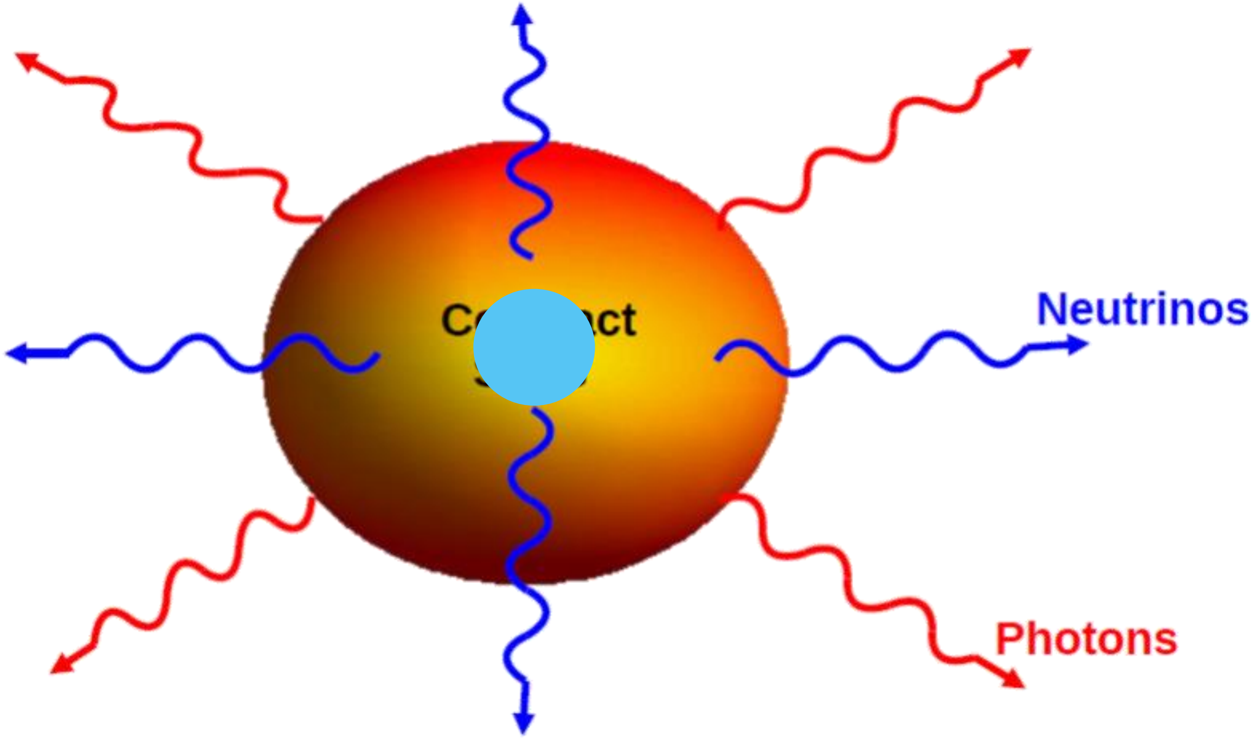


Softer Symmetry Energy

Stiffer Symmetry Energy

THERMAL EVOLUTION

- Thermal evolution is driven by neutrino emissions from the core, and photon emission from the surface.
- Neutrino emissions strongly depend on the core composition.
- Depending on its mass, a neutron star may exhibit fast or slow cooling.



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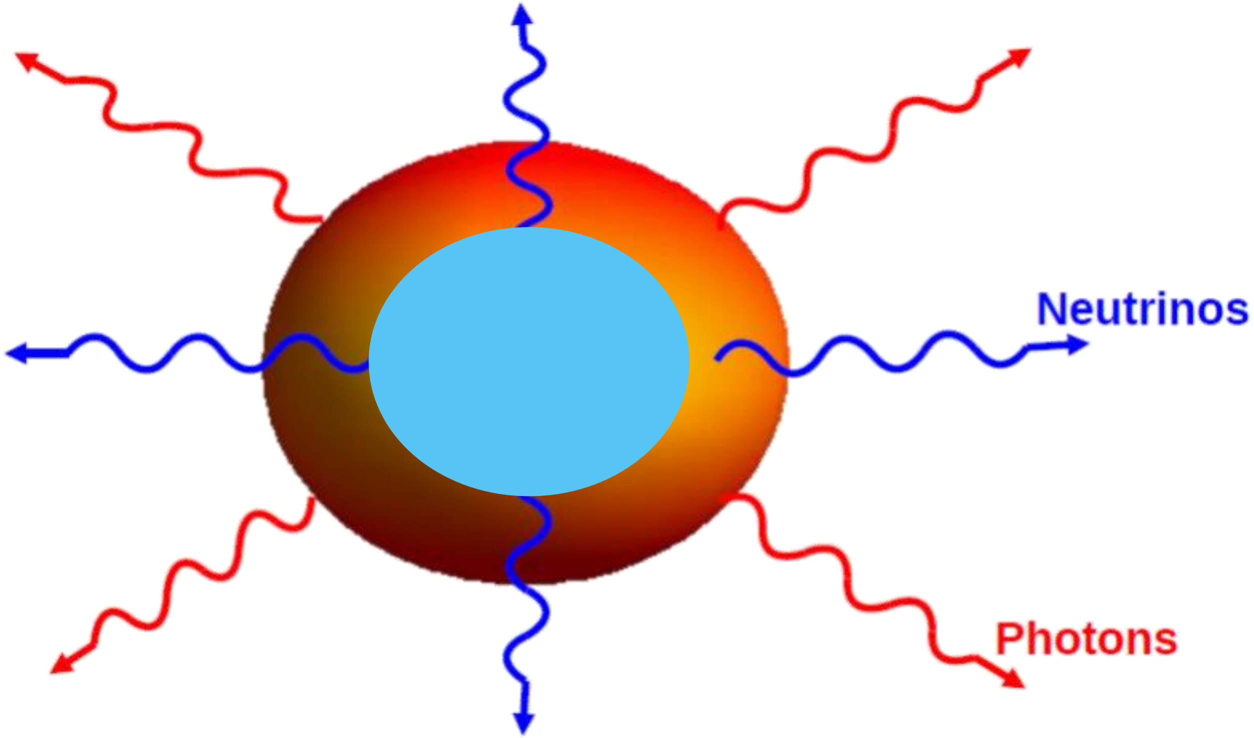
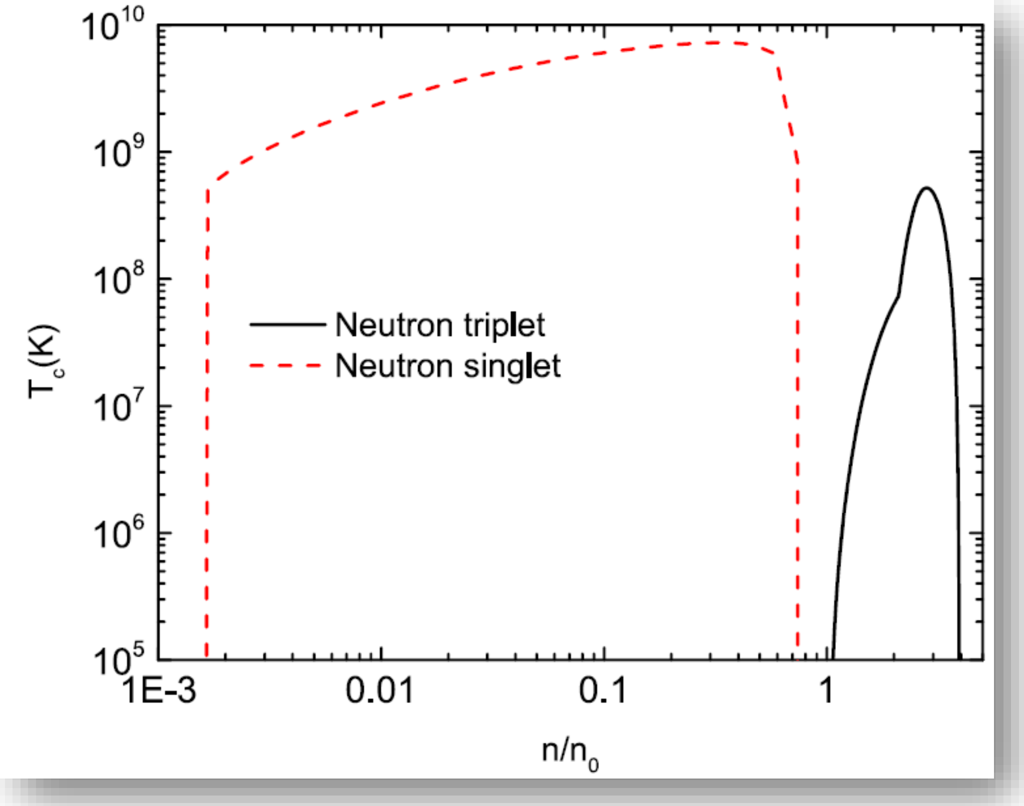
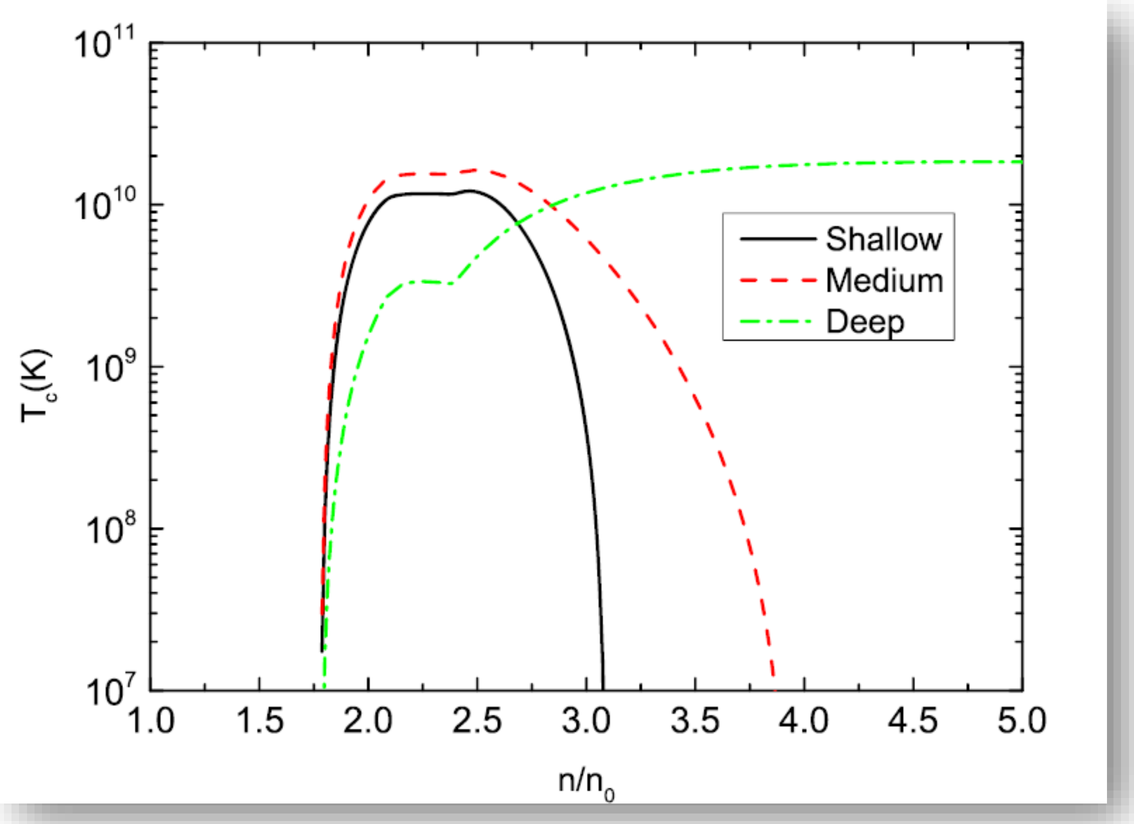
NEUTRON STARS COOL INSIDE OUT!



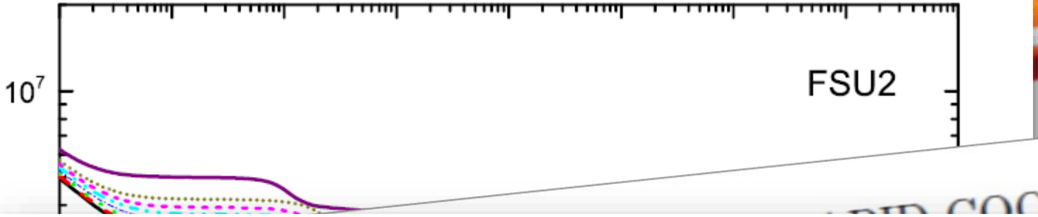
SUPERFLUIDITY

- Both protons and neutrons may form pairs inside the neutron star.
- We consider standard neutron singlet (crust) and triplet (core) pairing.
- For the proton singlet, we explore three possibilities: shallow, médium and deep.

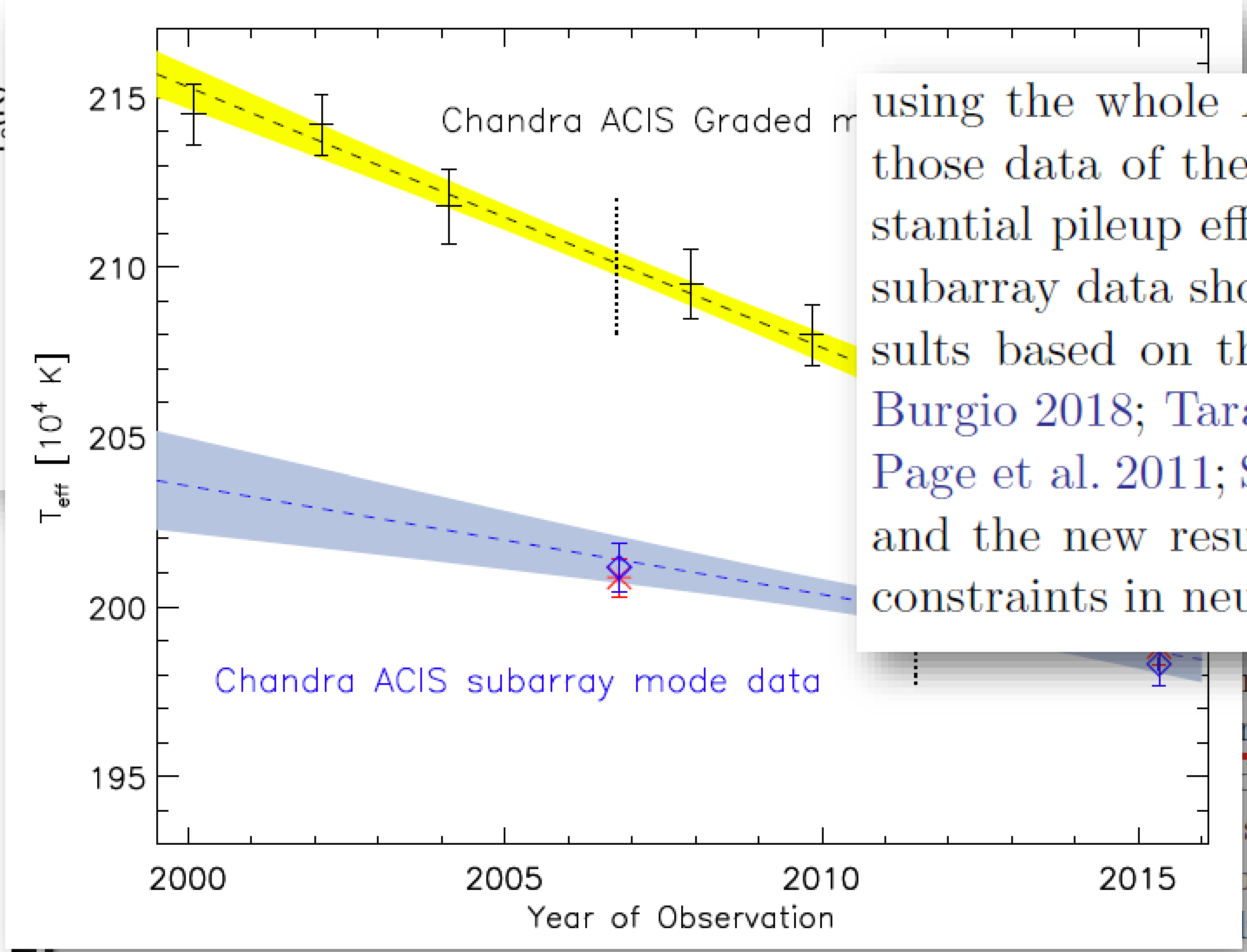




THERM



ID COOLING OF THE CENTRAL COMPACT OBJECT IN CAS A



using the whole ACIS chip in Graded mode. Because those data of the Cas A CCO are impacted by a substantial pileup effect (distorting the spectra), while the subarray data show negligibe pileup, the theoretical results based on those data (e.g., Negreiros et al. 2018; Burgio 2018; Taranto et al. 2016; Grigorian et al. 2016; Page et al. 2011; Shternin et al. 2011) should be revised, and the new result should be used for any theoretical constraints in neutron star cooling models.

r 2006 and 2012 *Chandra* spectra of the CCO did
resent additional observations from 2015 taken in
detect no significant temperature decrease, using
s. Our conservative 3σ upper limits correspond to
osphere model fits with varying or constant values
y revised model for the ACIS filter contaminant
has a strong effect on the fit results, reducing the significance of the previously reported temperature and flux changes. We expect that a further improved contaminant model and longer time coverage can significantly lower the upper

SUMMARY

- We have obtained an equation of state that satisfies the (current) constrains on mass and radii, as well as nuclear and HIC flow data.
- We have found good agreement with thermal properties, without the need to resort to pervasive proton-pairing.
- Our cooling results indicate that thermal data is better described by EoS with softer symmetry energy – smaller radius.
- We thus have more evidence favoring smaller radii (softer symmetry energy).
- Cooling data regarding Cas A may have to be revised.