Role of the Delta Meson on the Equation of State and dUrca Cooling of Neutron Stars

Luigi Scurto, Helena Pais, Marco Antonelli and Francesca Gulminelli

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Astronomy & Astrophysics

Role of the δ meson in the equation of state and direct Urca cooling of neutron stars

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ABSTRACT

Context. The direct Urca (dUrca) process is a key mechanism driving rapid neutrino cooling in neutron stars. Its baryon density activation threshold is determined by the microscopic model for nuclear matter. Nuclear interactions shape the dUrca threshold, and it is essential to understand this for interpreting the thermal evolution of neutron stars, in particular in light of recent studies of exceptionally cold objects.

Aims. We investigated the impact of incorporating the scalar-isovector δ meson into the neutron star equation of state. This alters the internal proton fraction and consequently affects the dUrca cooling threshold. Proton superfluidity is known to suppress dUrca rates, and we therefore also examined the interplay between the nuclear interaction mediated by the δ meson and the ${}^1S_0$ proton-pairing gap.

Methods. We performed a Bayesian analysis using models built within a relativistic mean-field approximation that incorporated constraints from astrophysical observations, nuclear experiments, and known results of ab initio calculations of pure neutron matter. We then imposed a constraint on the dUrca threshold based on studies of fast-cooling neutron stars.

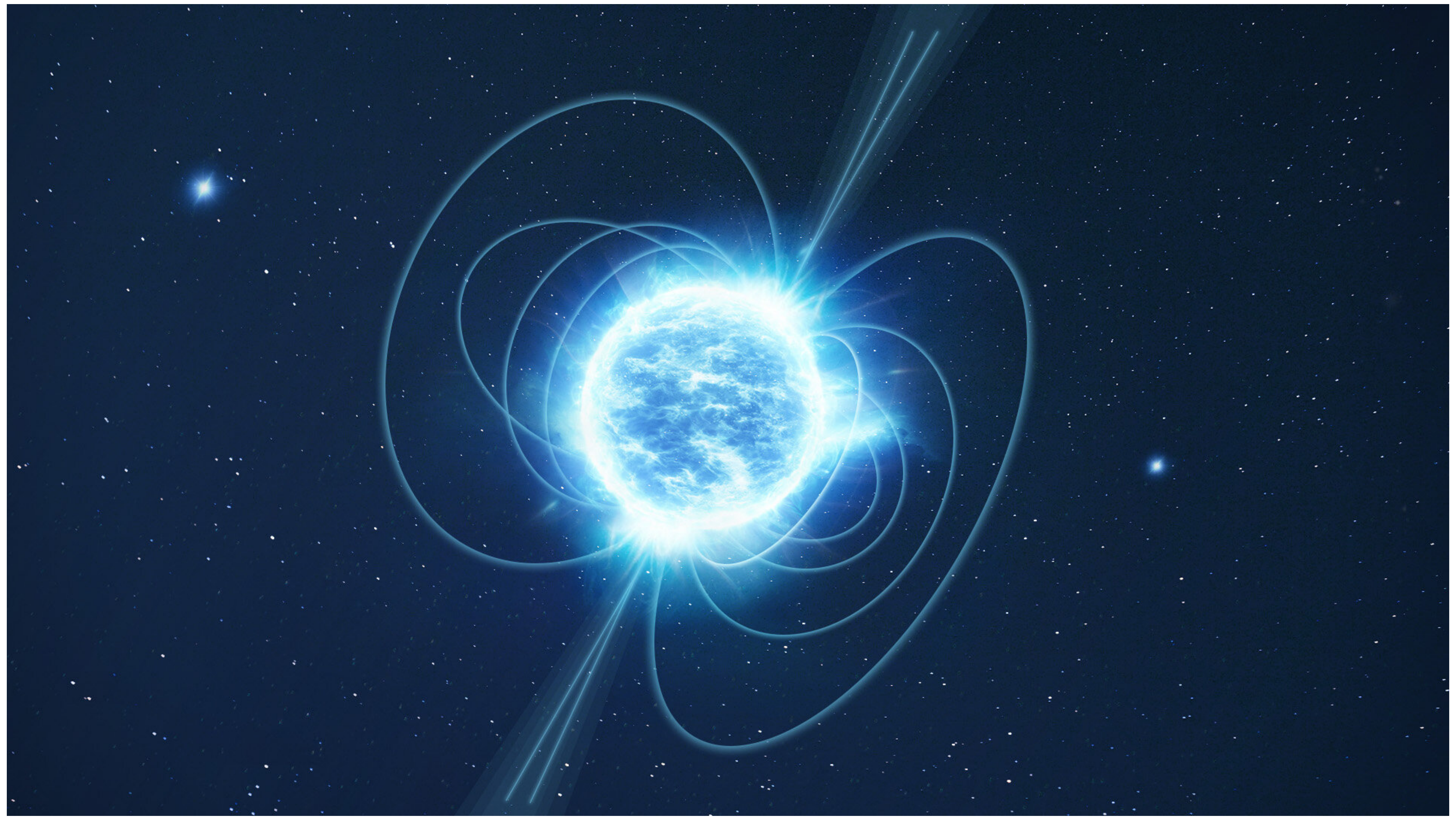
Results. The inclusion of the δ meson expands the range of possible internal compositions and directly influences the stellar mass required for the central density to reach the dUrca threshold. Furthermore, we find that the observation of relatively young and cold neutron stars provides insights into the ${}^1S_0$ proton superfluidity in the core of neutron stars.

Introduction

Neutron Stars

Neutron Stars

Compact objects of extreme interest in the multi messenger era of astrophysics



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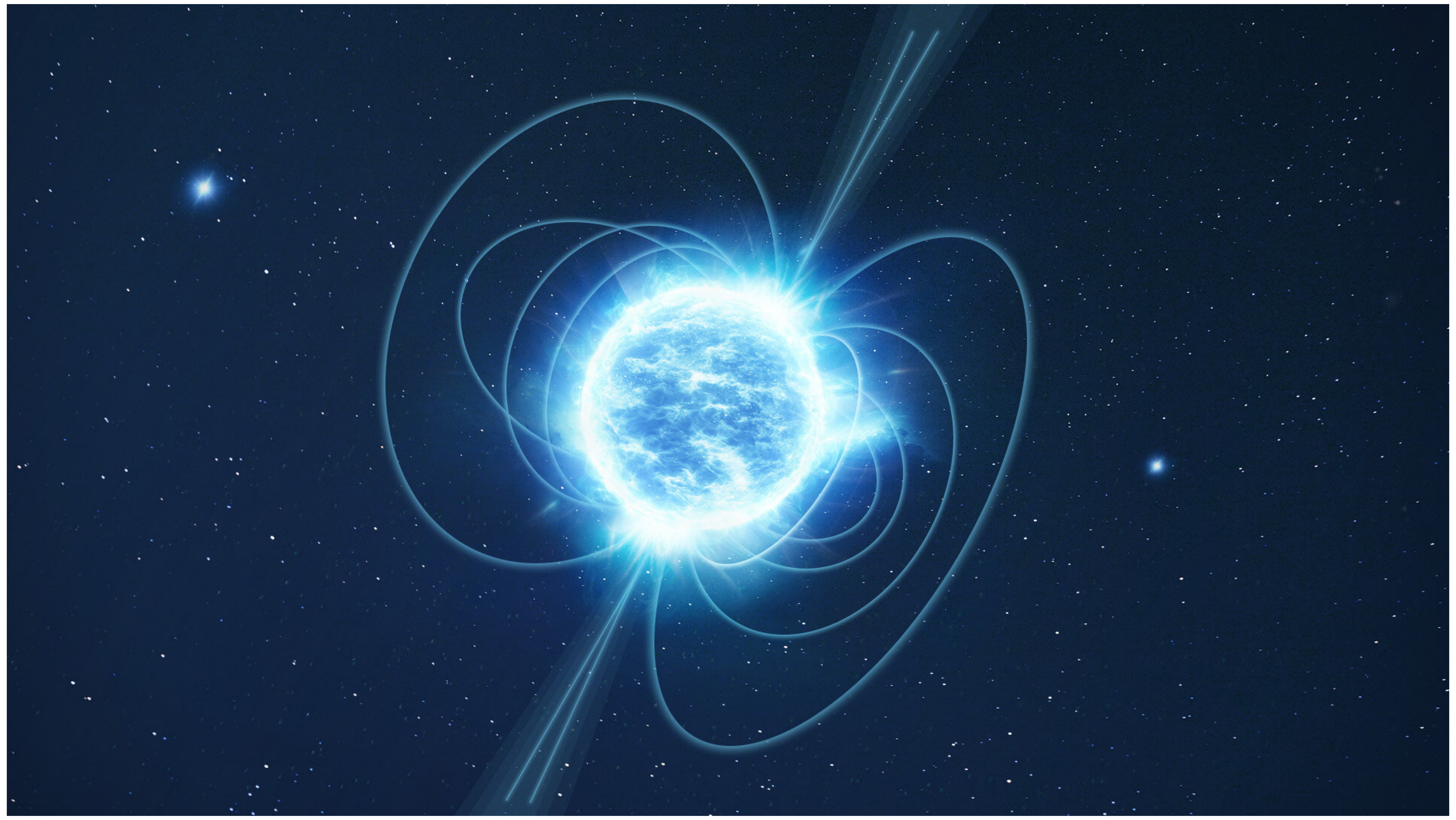

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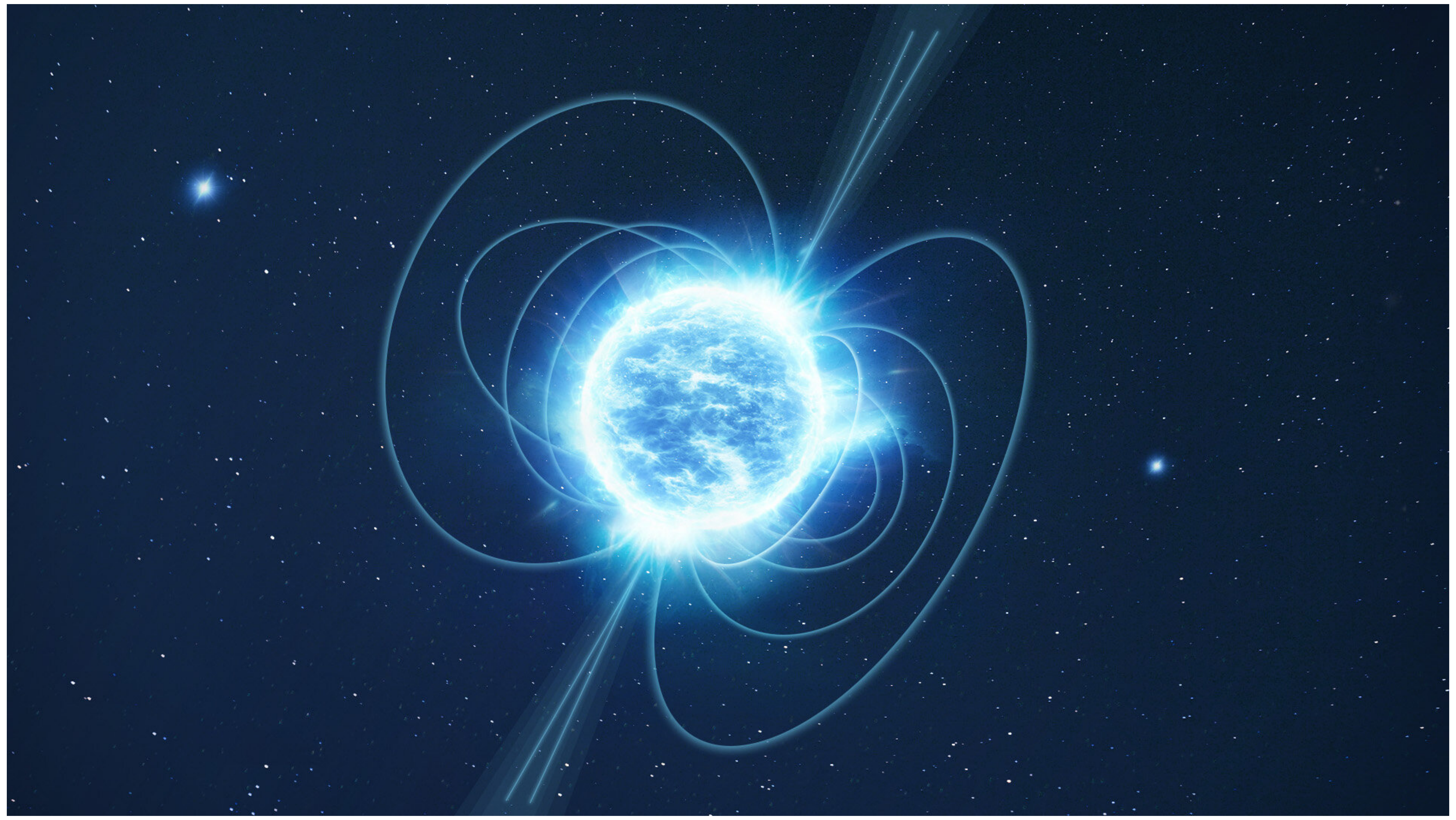

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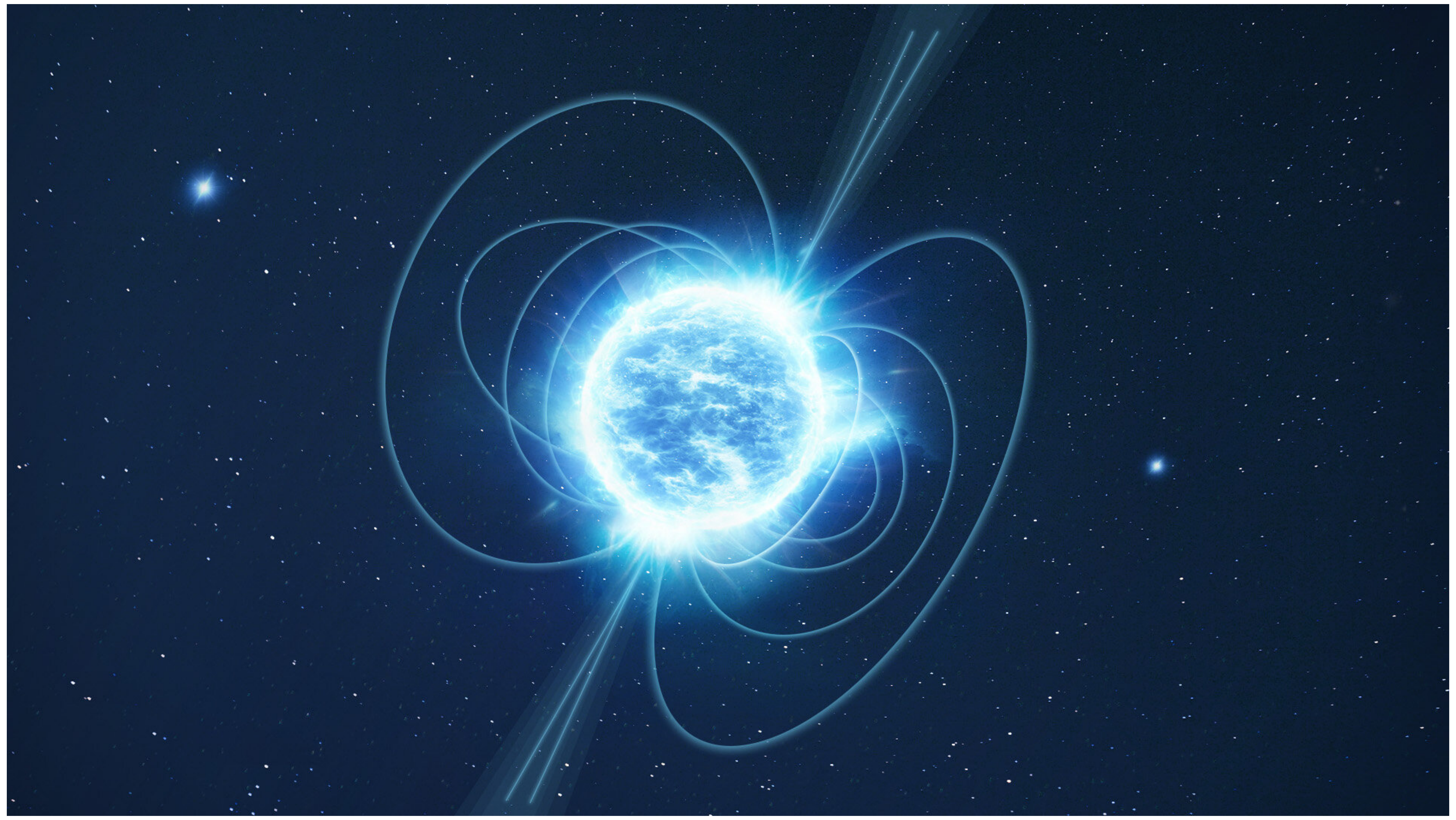

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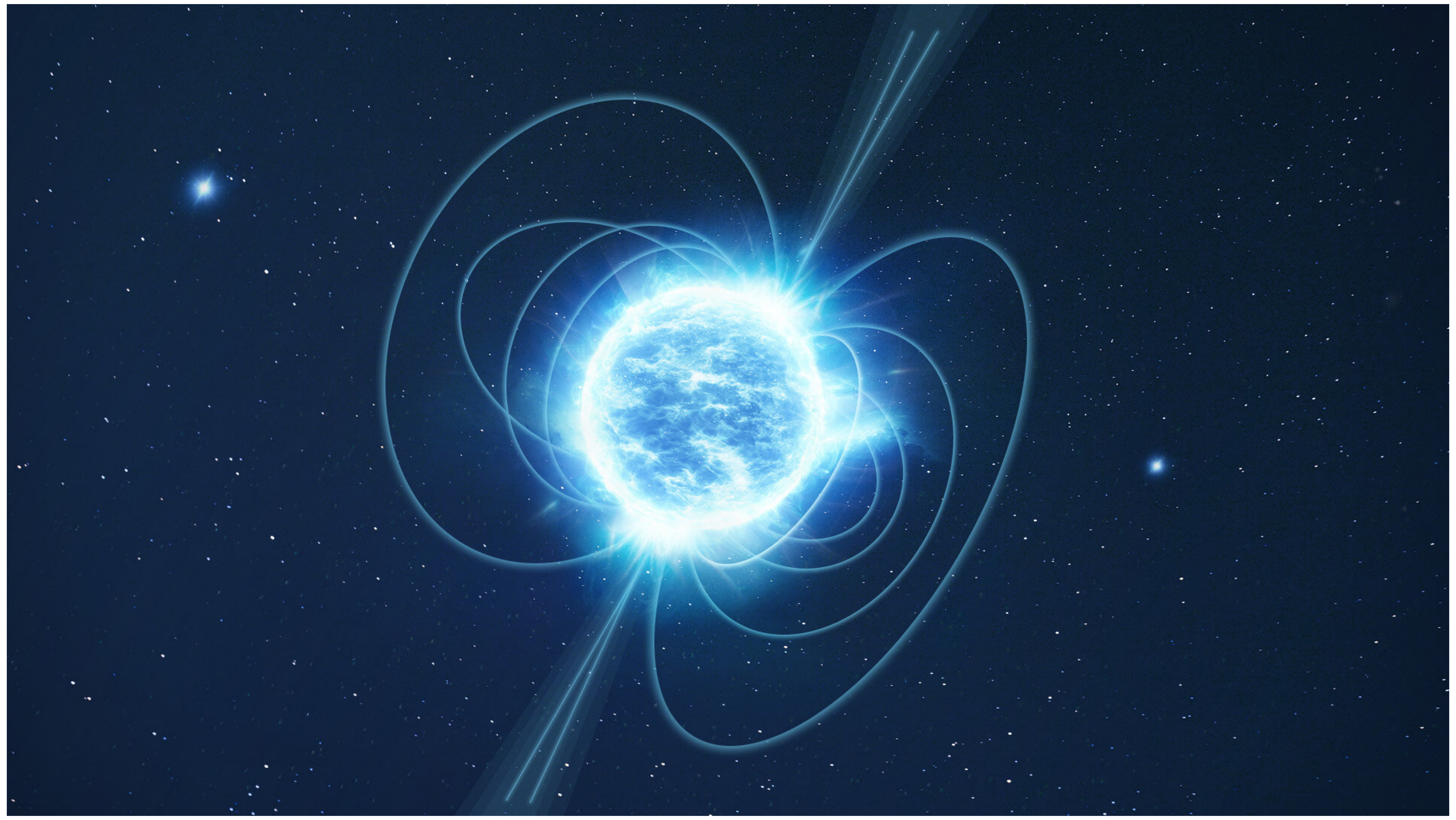

- Magnetic Fields up to $\approx 10^{15}G$ on the surface,
- Central densities up to several times ρ_0 ,
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Their interior composition is still very poorly constrained !

The interior of a Neutron Star

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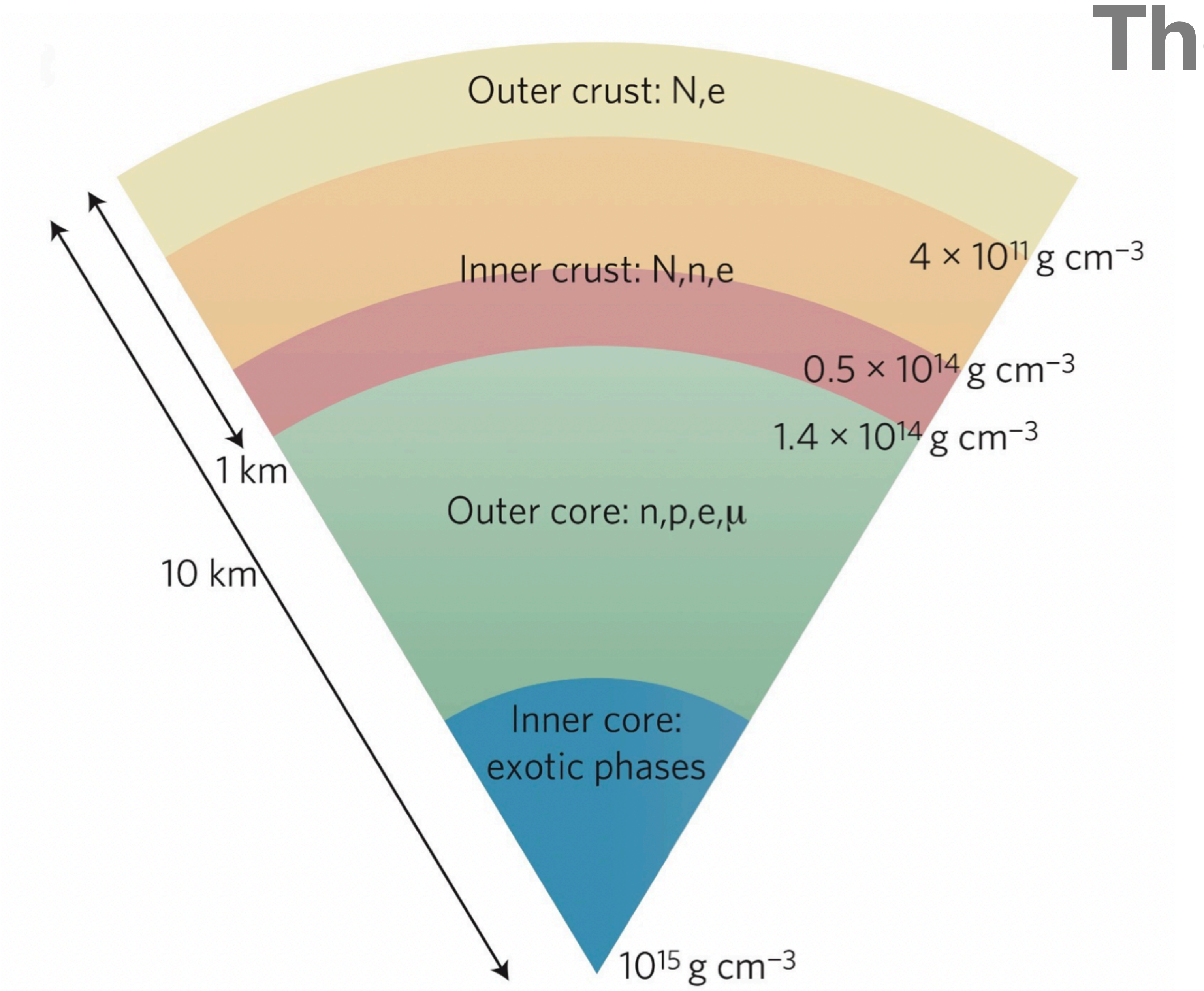

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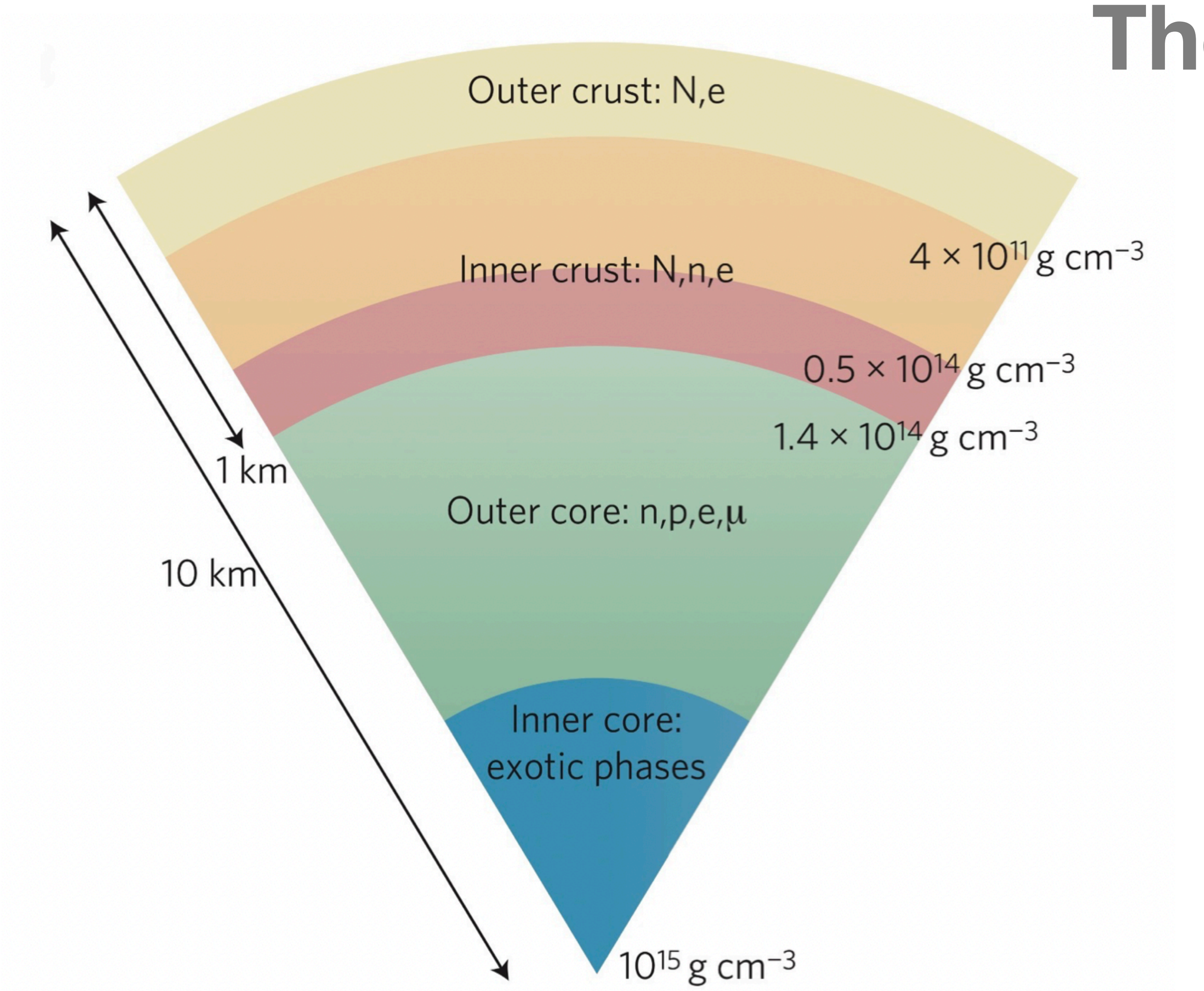
The interior of a NS is considered to be divided into 3 main layers

The interior of a Neutron Star



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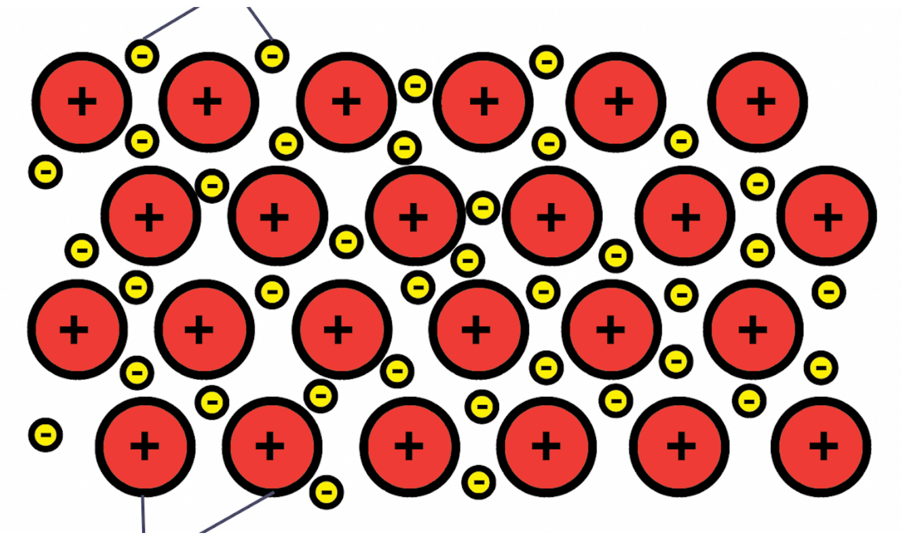

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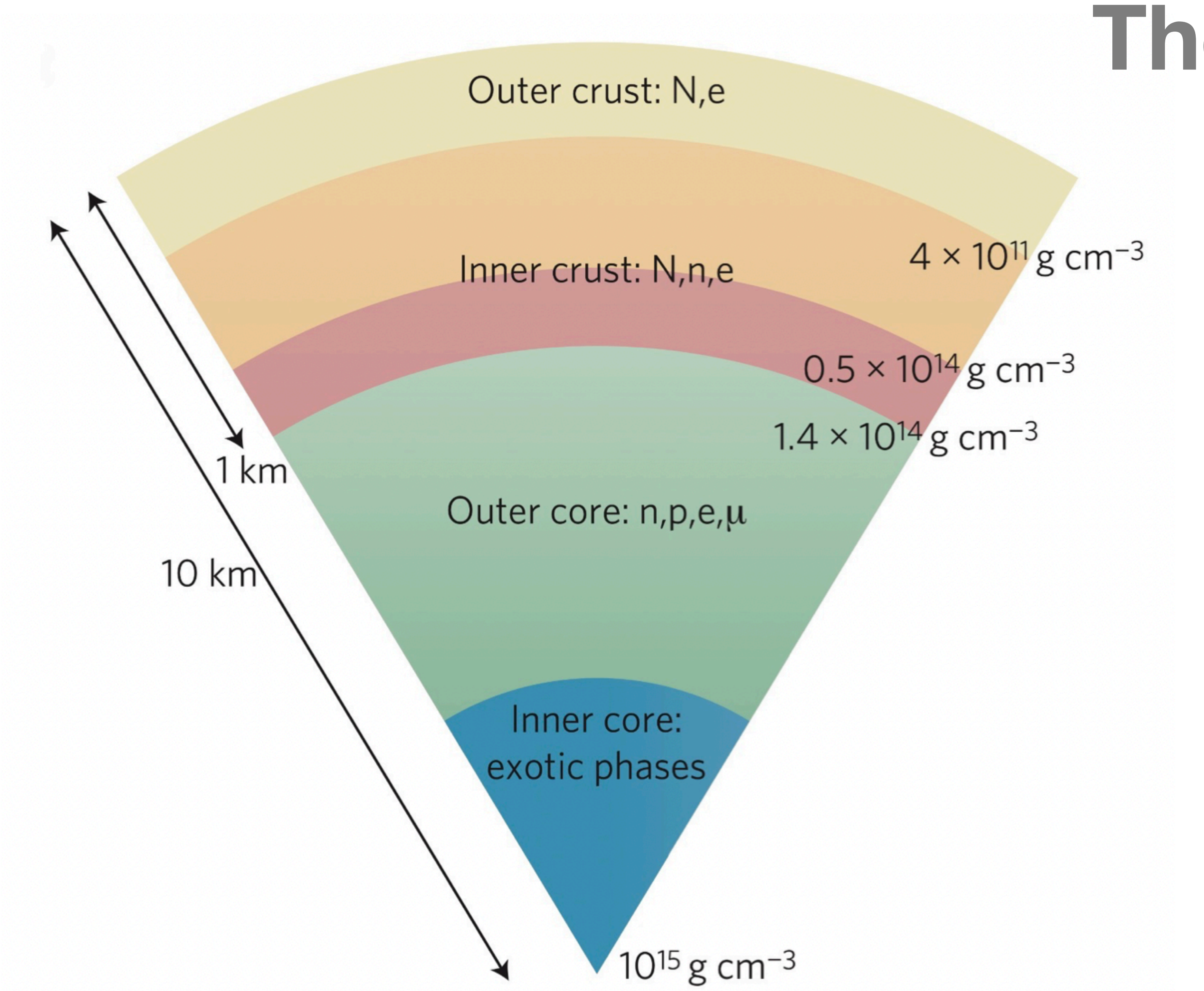

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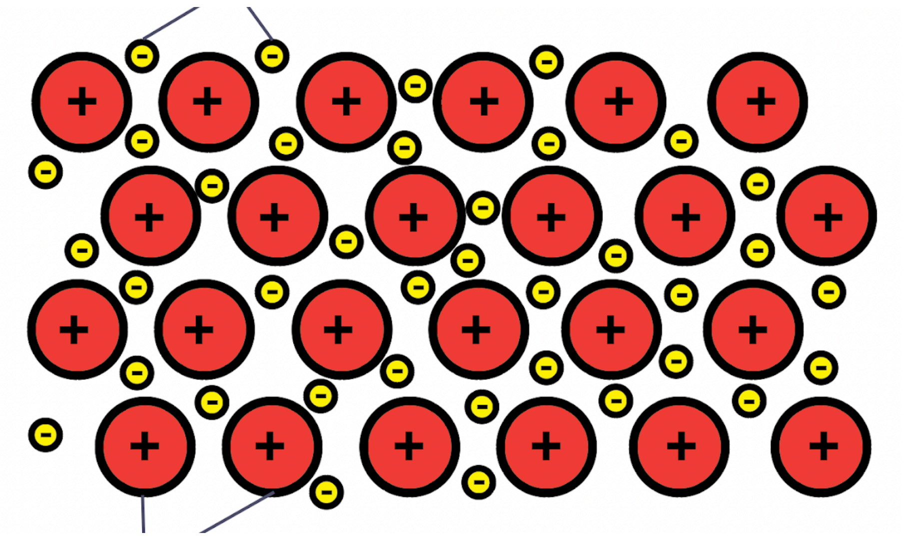

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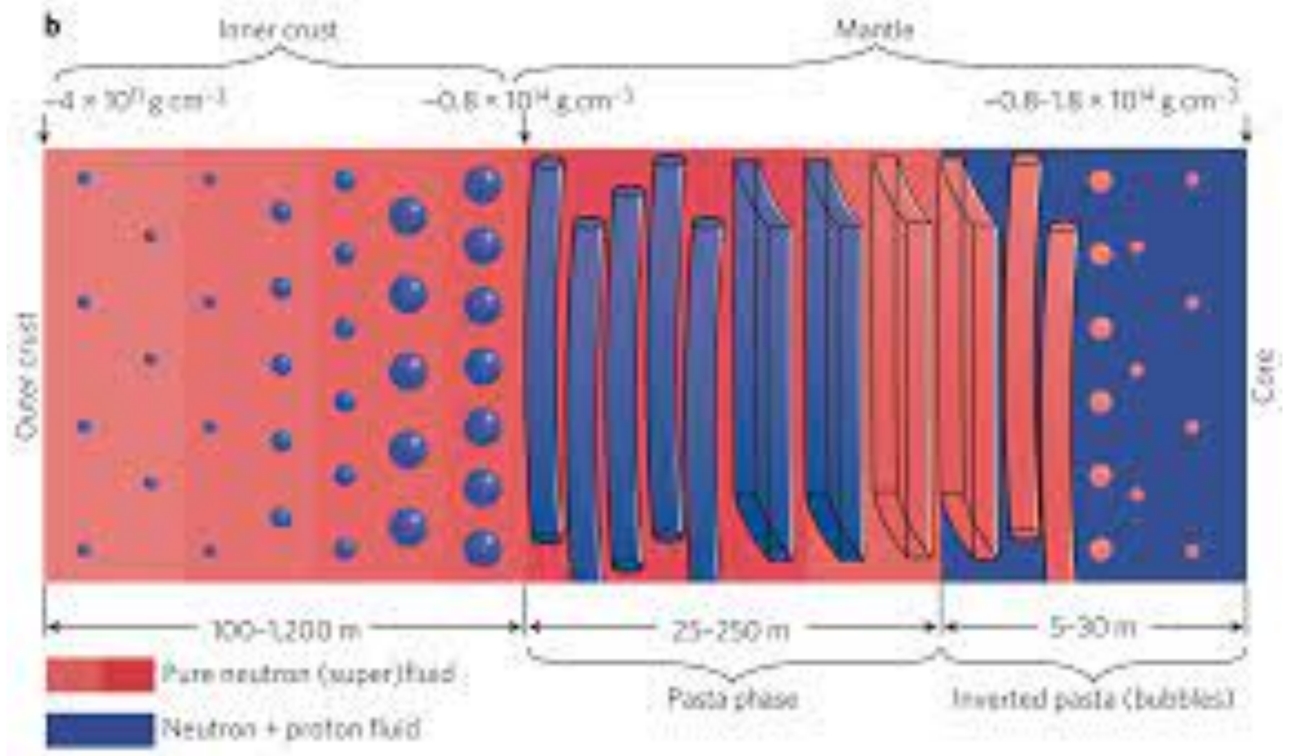

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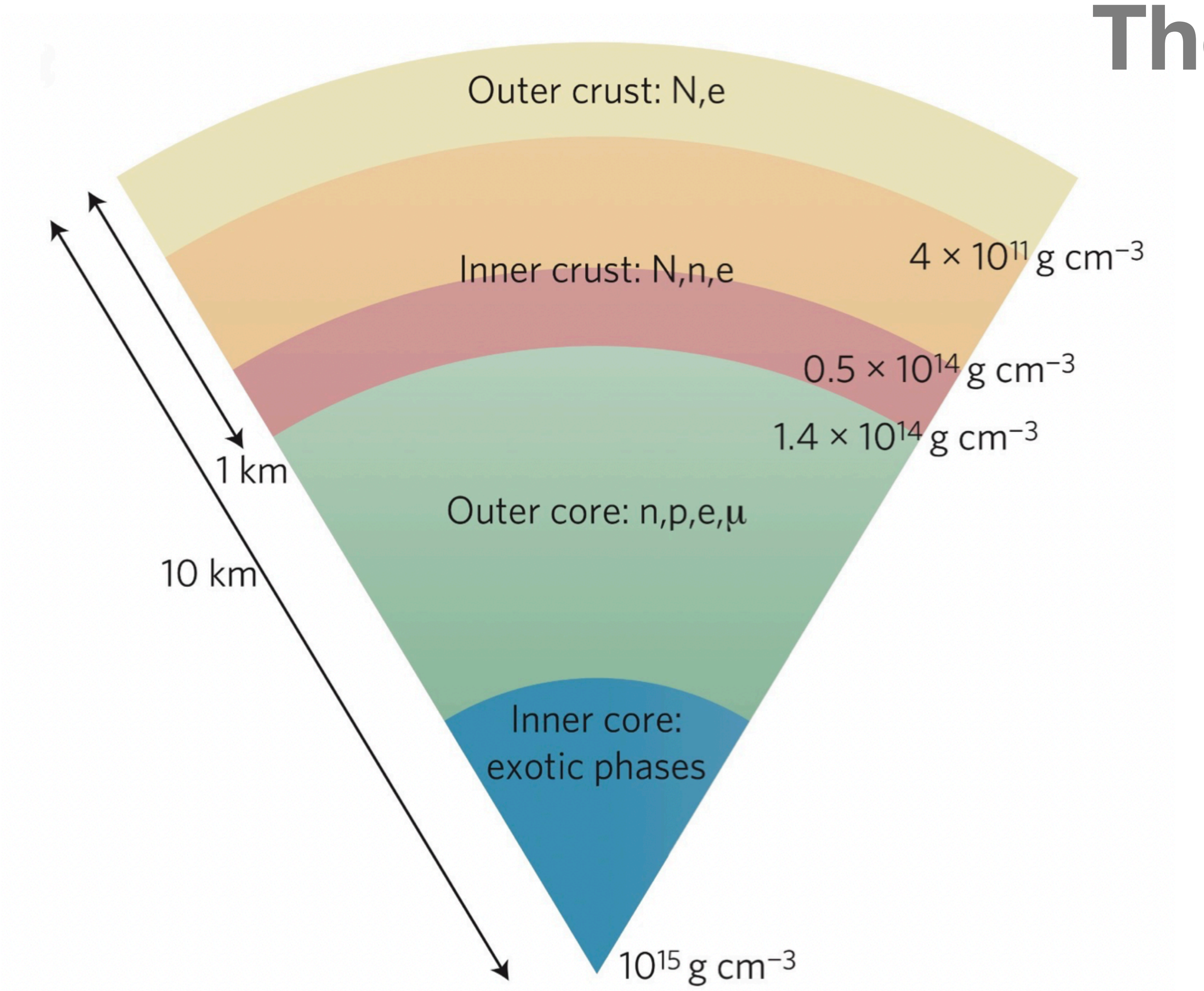

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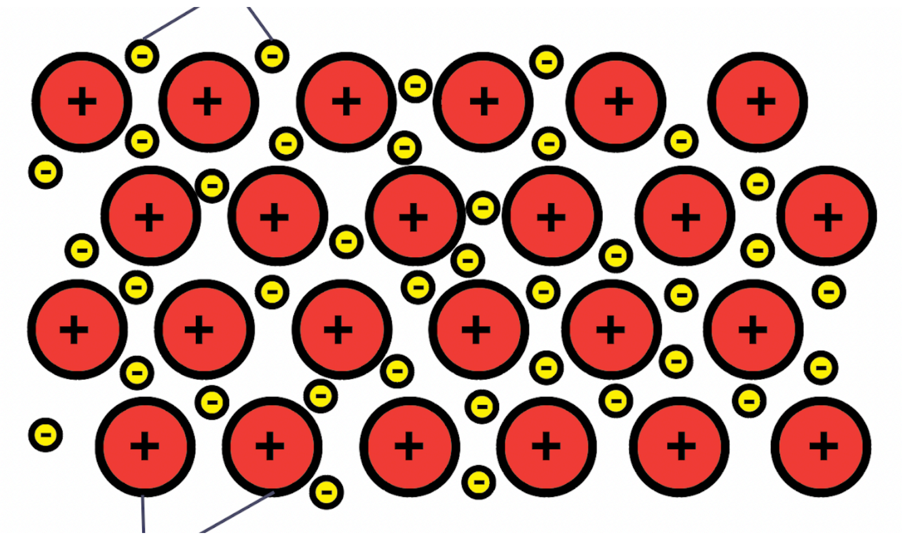
- Outer Crust
- Inner Crust
- Core



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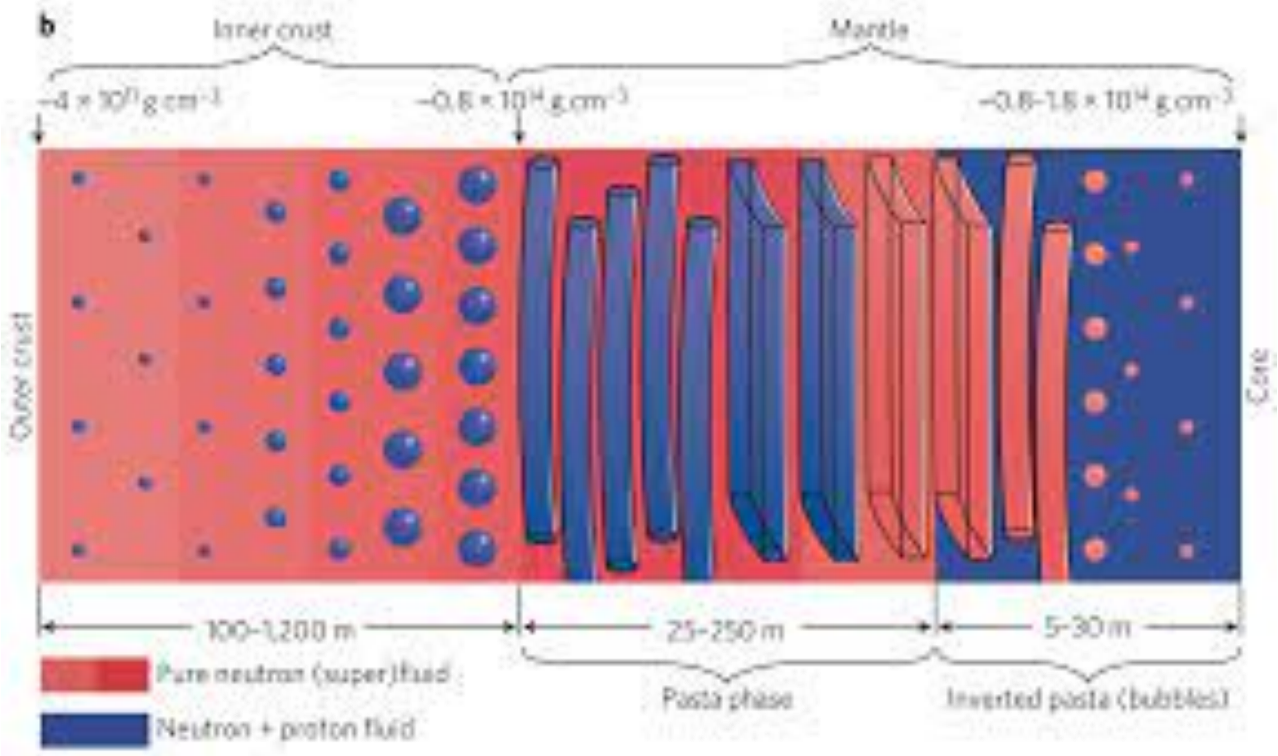

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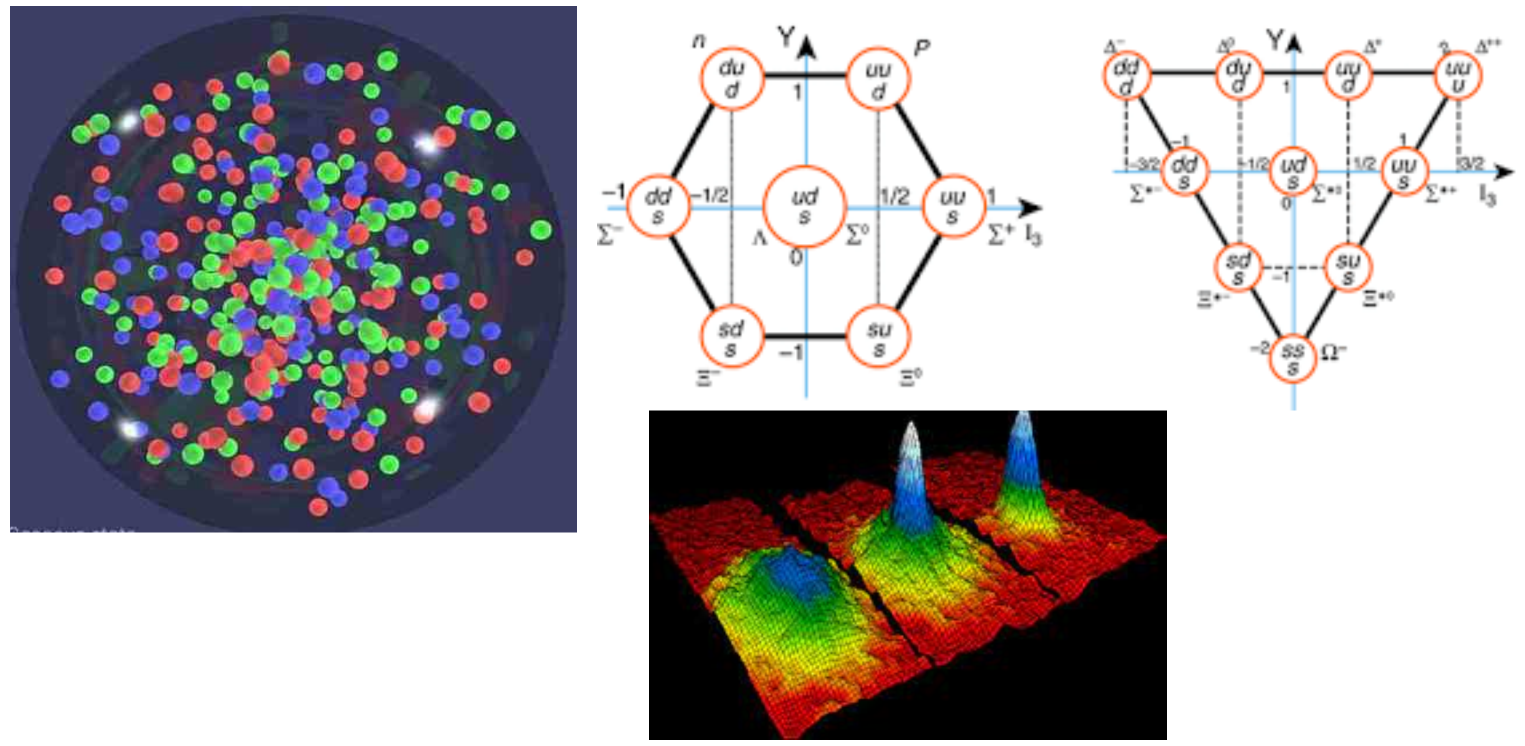

Credits:E.A.Cornell et al., H. Lenske & M. Dhar, F.Cain

Framework

Relativistic Mean Field Approximation

In our work we use two different Relativistic Mean Field (RMF) models in order to describe stellar matter (npem). In this approximation, the interaction between nucleons is mediated by mesons.

$$\mathscr{L} = \sum_{i=p,n} \mathscr{L}_i + \mathscr{L}_l + \mathscr{L}_\sigma + \mathscr{L}_\omega + \mathscr{L}_\rho$$

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Nucleons

$$\mathscr{L}_i = \bar{\psi}_i \left[\gamma_\mu i \partial^\mu - g_\omega V^\mu - \frac{g_\rho}{2} \tau \cdot \mathbf{b}^\mu - M^* \right] \psi_i$$

$$M^* = M - g_\sigma \phi$$

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Leptons

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Mesons

$$\mathscr{L}_\sigma = \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m_\sigma^2\phi^2\right)$$

$$\mathscr{L}_\rho = -\frac{1}{4}\mathbf{B}_{\mu\nu}\cdot\mathbf{B}^{\mu\nu} + \frac{1}{2}m_\rho^2\mathbf{b}_\mu\cdot\mathbf{b}^\mu$$

$$\mathscr{L}_\omega = -\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2 V_\mu V^\mu$$

The mesons are then replaced with their ground state expectation value

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Nucleons · **Leptons** · **Mesons**

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Nucleon-Meson couplings

Inclusion of the delta meson

In the work, we introduce an additional interaction channel via the scalar isovector meson delta

$$\mathscr{L} = \sum_{i=p,n} \mathscr{L}_i + \mathscr{L}_l + \mathscr{L}_\sigma + \mathscr{L}_\omega + \mathscr{L}_\rho + \mathscr{L}_\delta$$

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$$\mathscr{L}_\delta = \frac{1}{2} \left(\partial_\mu \boldsymbol{\delta} \cdot \partial^\mu \boldsymbol{\delta} - m_\delta^2 \boldsymbol{\delta} \cdot \boldsymbol{\delta} \right)$$

$$M_n^* = M - g_\sigma \phi + \frac{g_\delta}{2} \delta_3 \qquad M_p^* = M - g_\sigma \phi - \frac{g_\delta}{2} \delta_3$$

The main effect of the delta is to create a difference between the Dirac masses of protons and neutrons

Nucleon-Meson Couplings

In our study we consider the couplings being a function of the baryonic density

$$g_i = a_i + b_i e^{-c_i x}$$

with $x = \rho/\rho_0$

A modified version of the GDFM functional

P. Gogelein, E.N.E. van Dalen, C. Fuchs and H. Muther, Phys. Rev. C 77, 025802 (2008)

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We have two sets of models

Set A	Set B
σ, ω, ρ	$\sigma, \omega, \rho, \delta$
9 parameters	12 parameters

Constraints for the Bayesian Inference

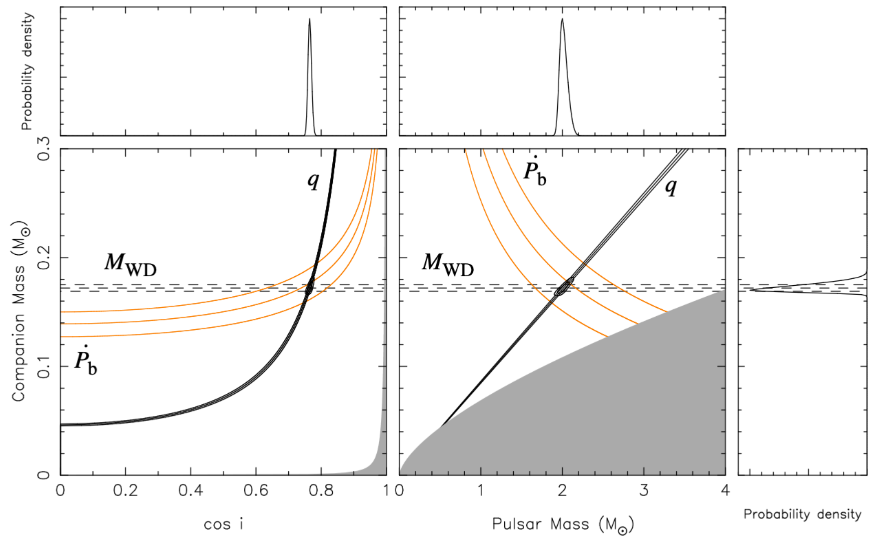
Astrophysical Constraints

Nuclear Constraints

Constraints for the Bayesian Inference

Astrophysical Constraints

PSR J0348+0432 maximum mass constraint



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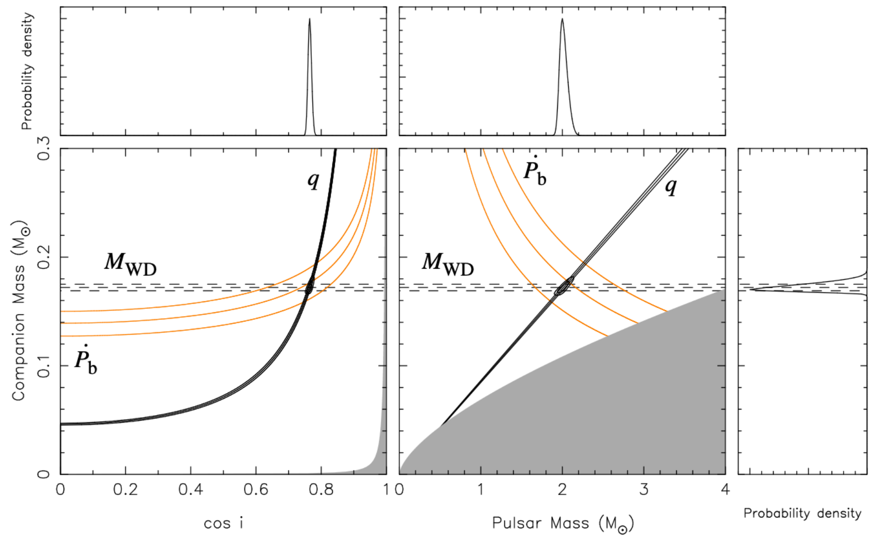

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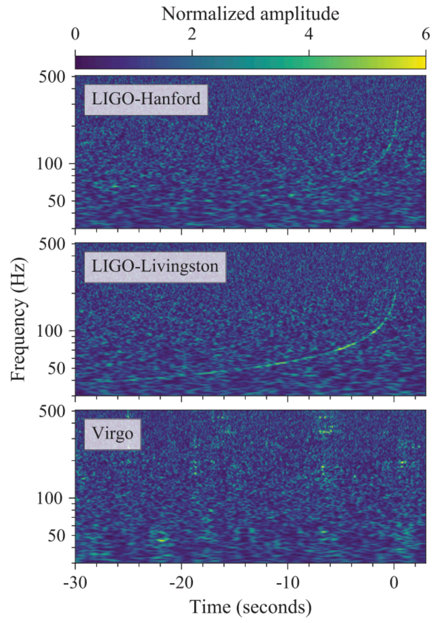
GW170817 constraint of the tidal deformability



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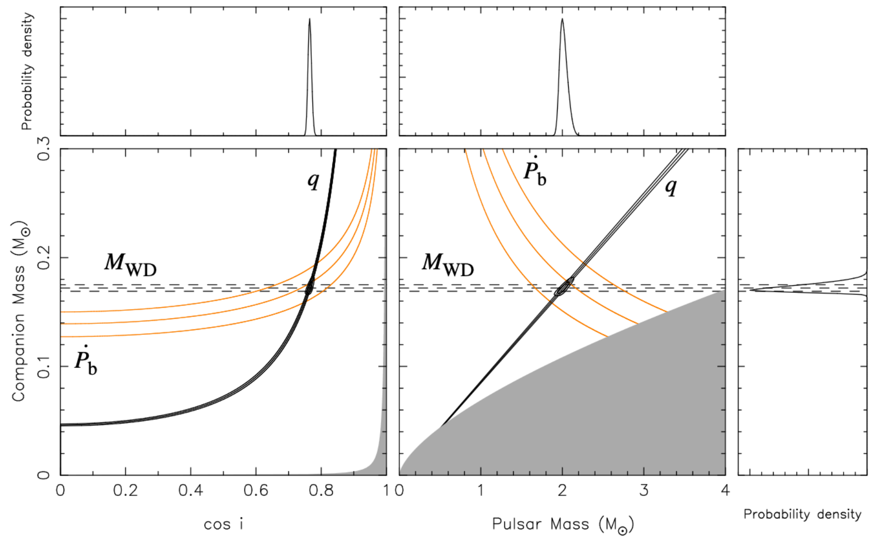

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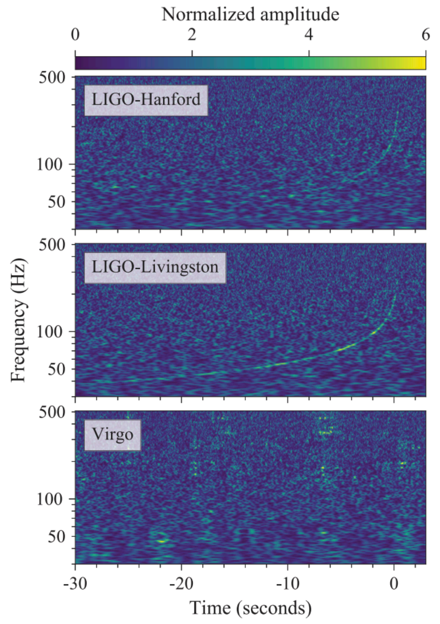

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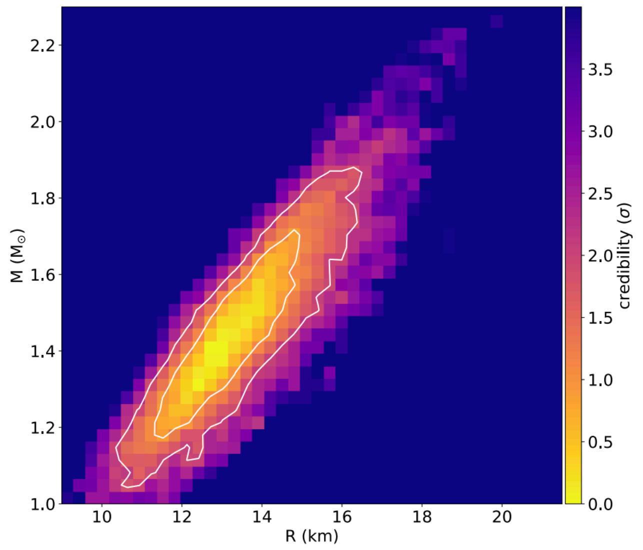
NICER constraints of the radius



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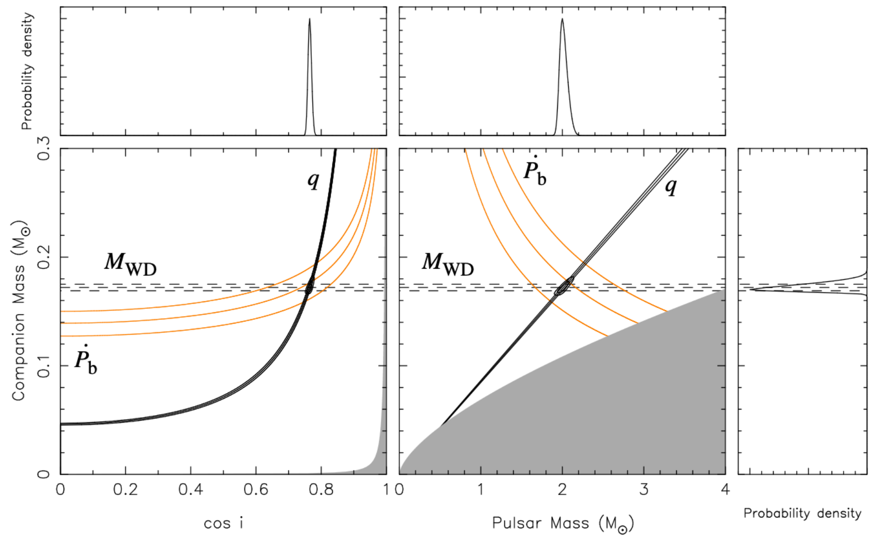

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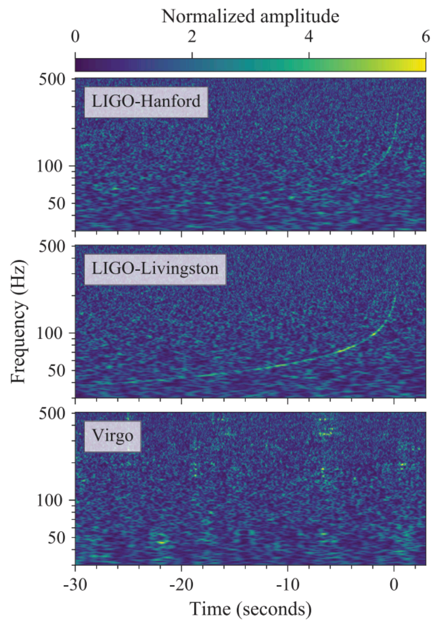

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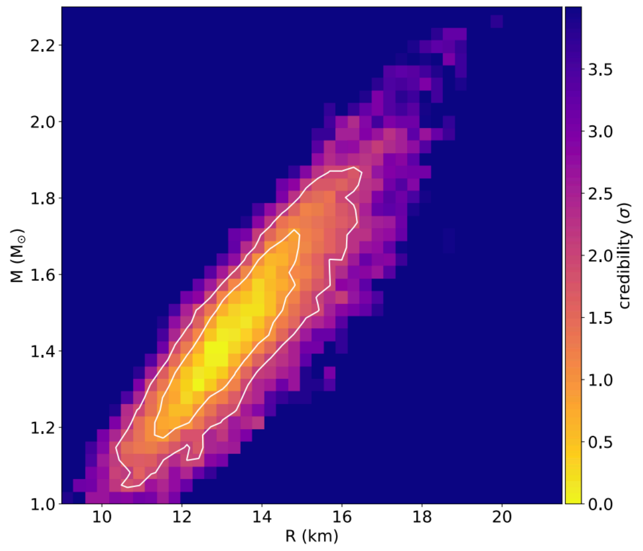

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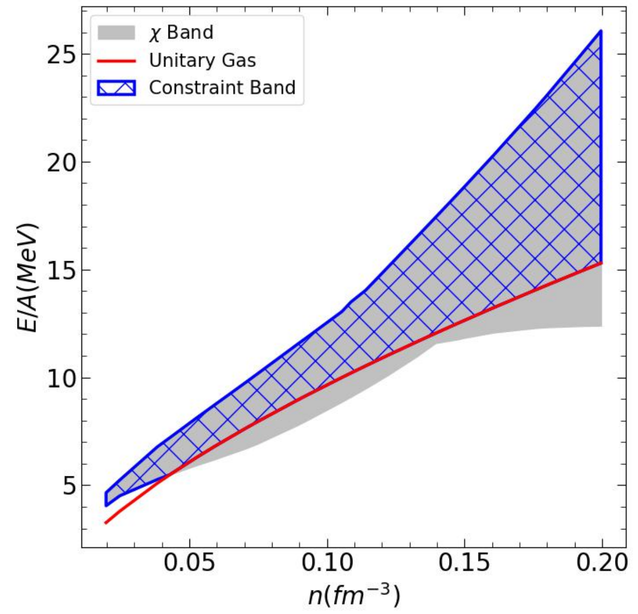
Nuclear Constraints

Chiral EFT constraint on the EoS of PNM



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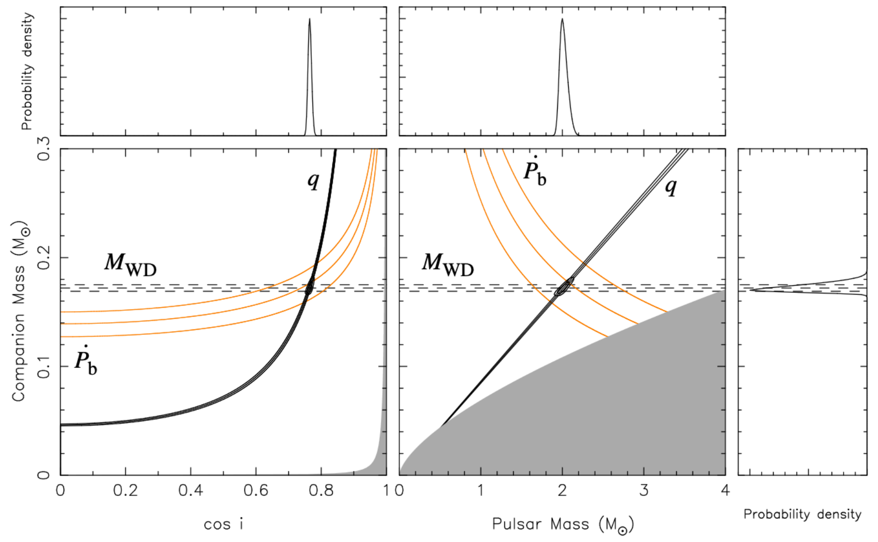

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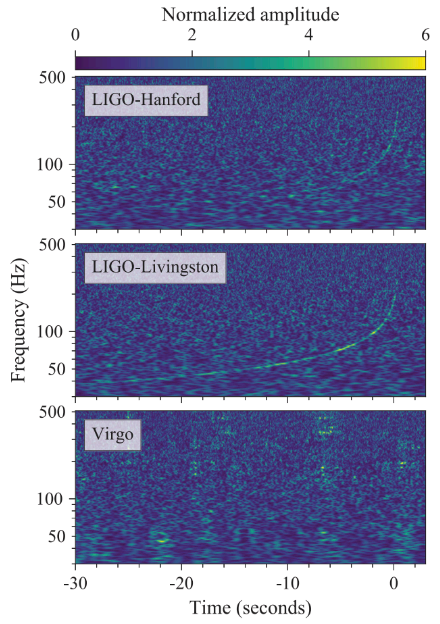

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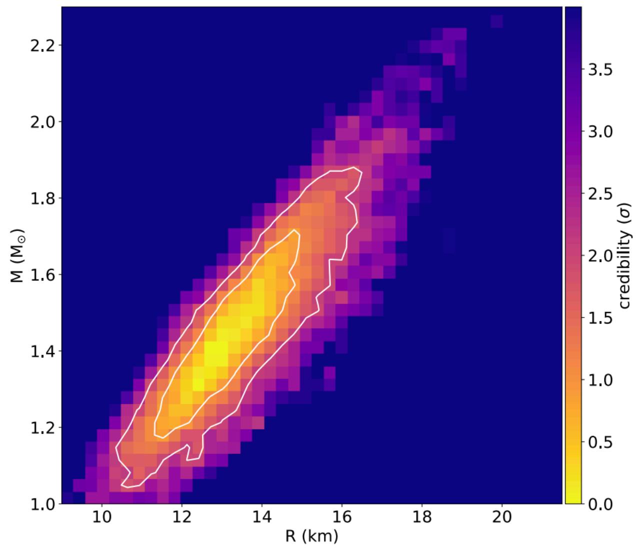

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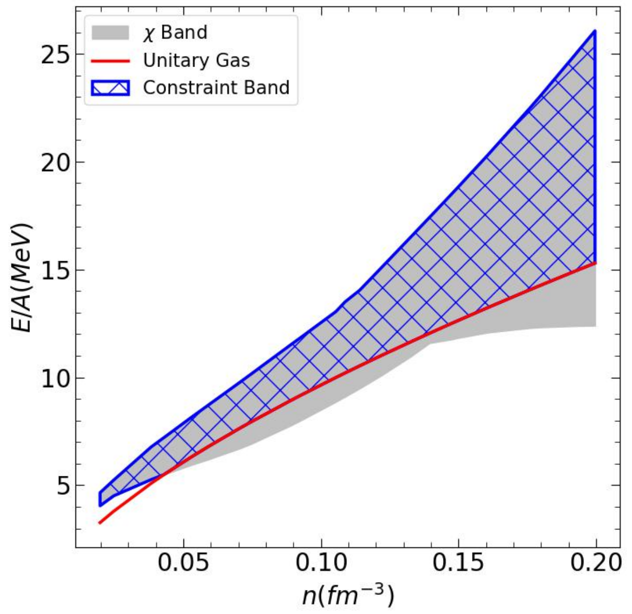

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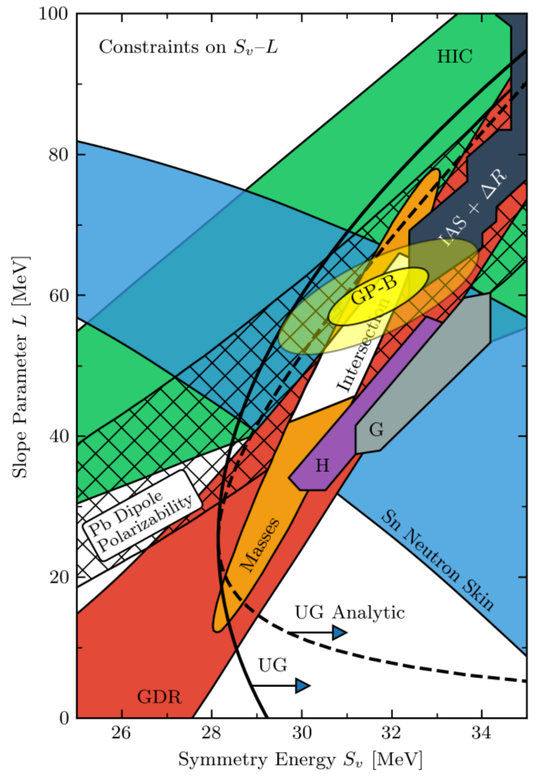
Nuclear experiments constraint on the derivatives of the energy per baryon of symmetric matter at saturation

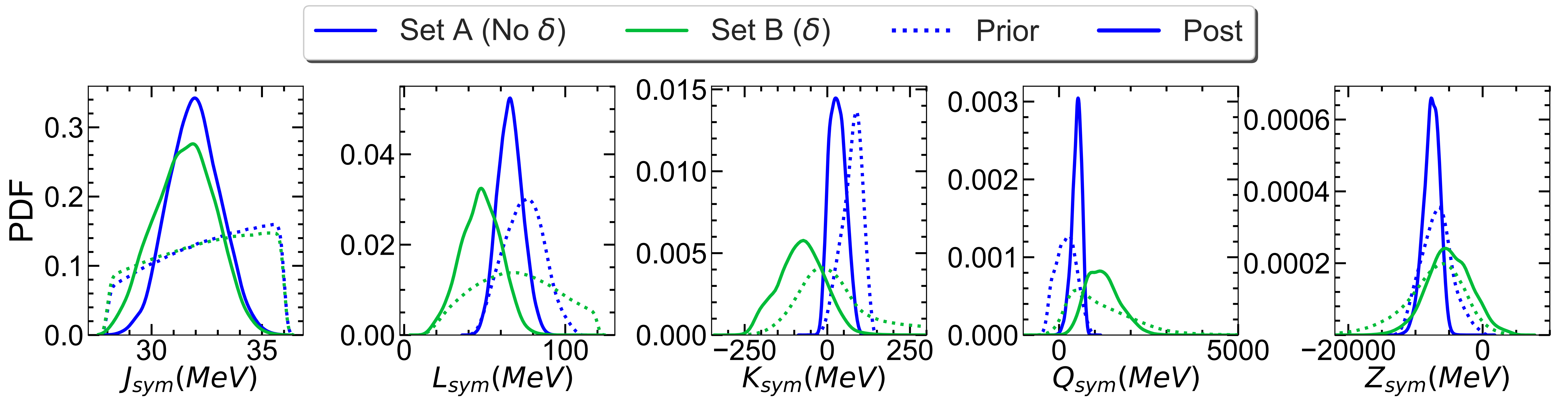


J. Margueron, R. Hoffmann Casali, F. Gulminelli, Phys. Rev. C 97, 025805 (2018)

C. Drischler et al., Phys. Rev. Lett. 125,202702 (2020)

Delta vs No Delta

Effects of delta on the NS composition



→ **Broader distributions and lower values of L and K**

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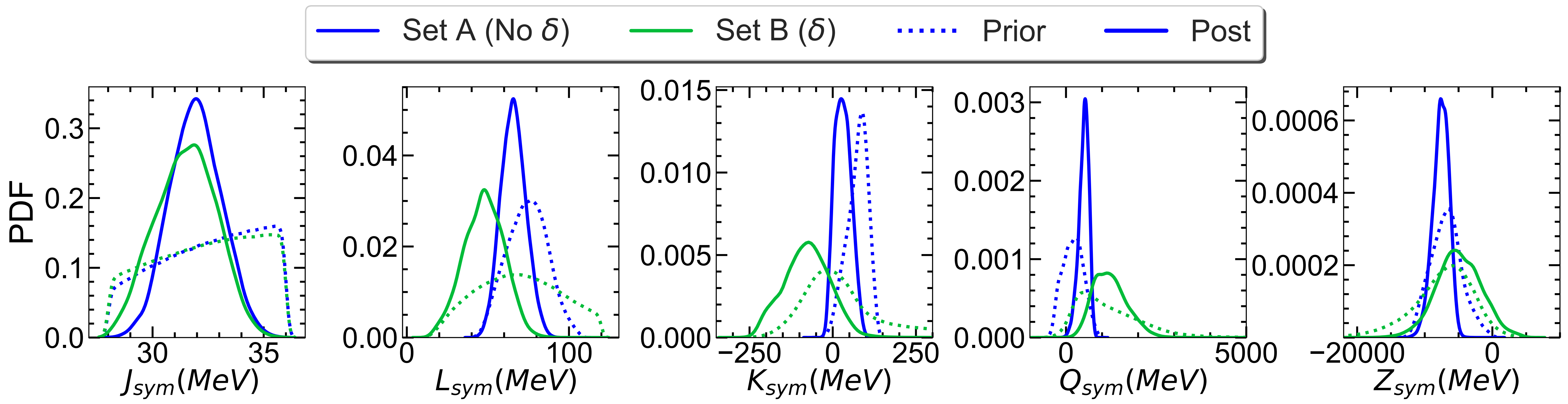

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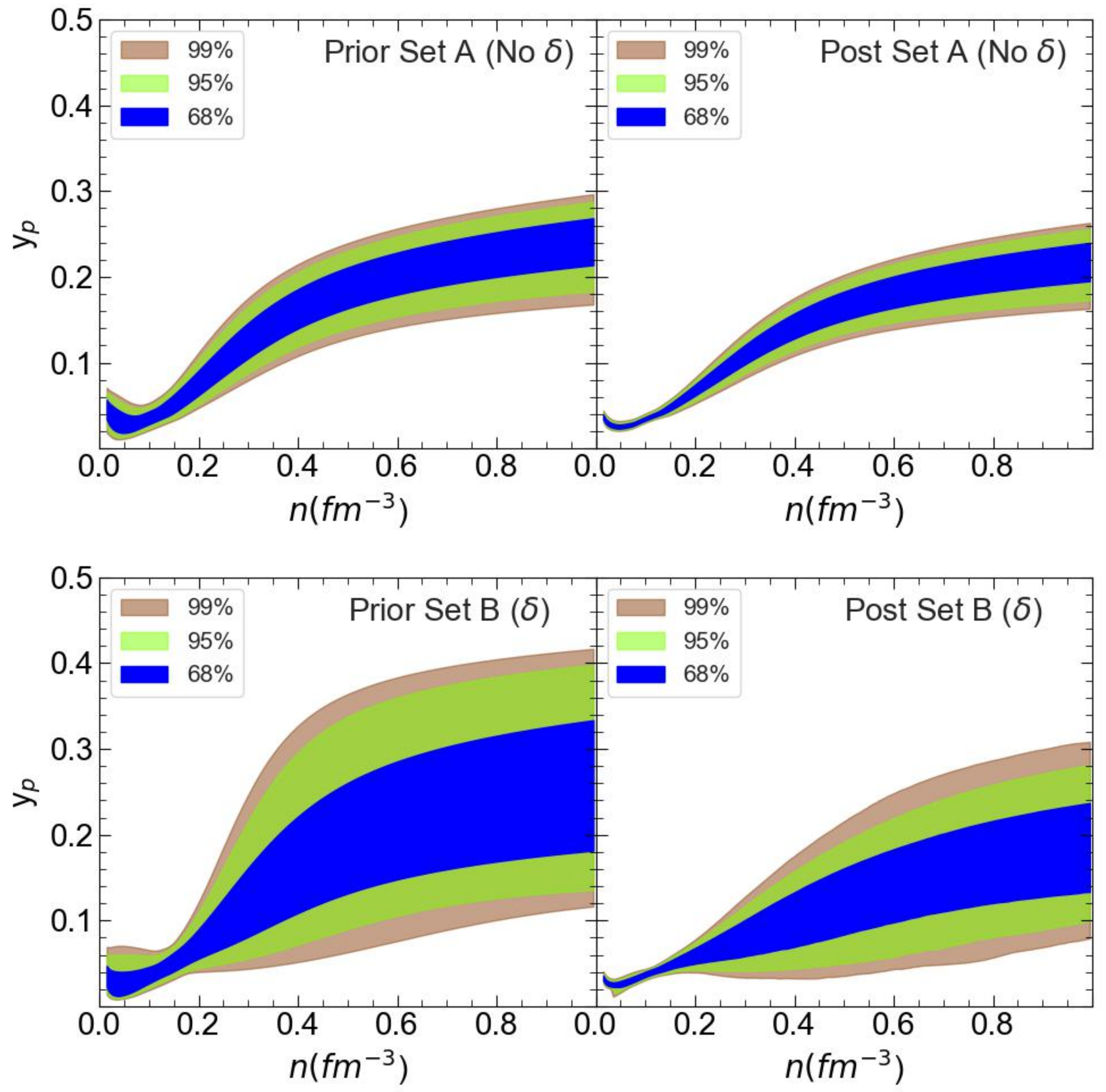
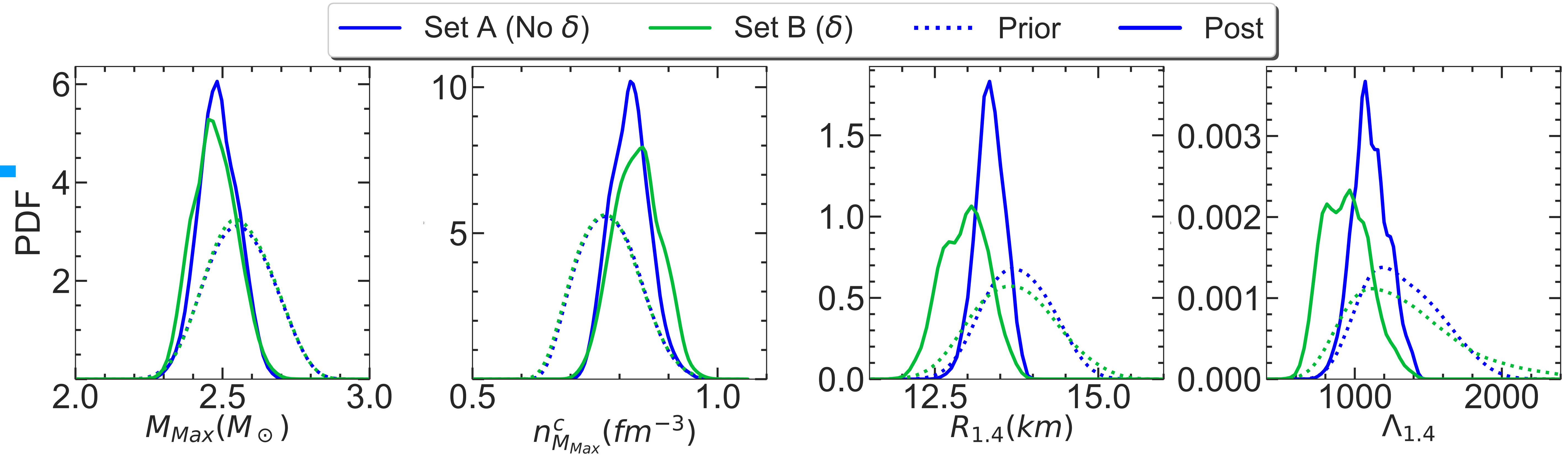


- The inclusion of the delta makes the distribution of the proton fraction broader
- Te behaviour of the proton fraction is smoother compared to the previous study
- The difference in the Dirac mass of protons and neutrons allows for models with very low proton fraction

Effects of delta on the NS observables

The properties of the most massive star are not significantly affected

Strong correlation to the isoscalar sector, weak correlation to the isovectorial sector



Effects of delta on the NS observables

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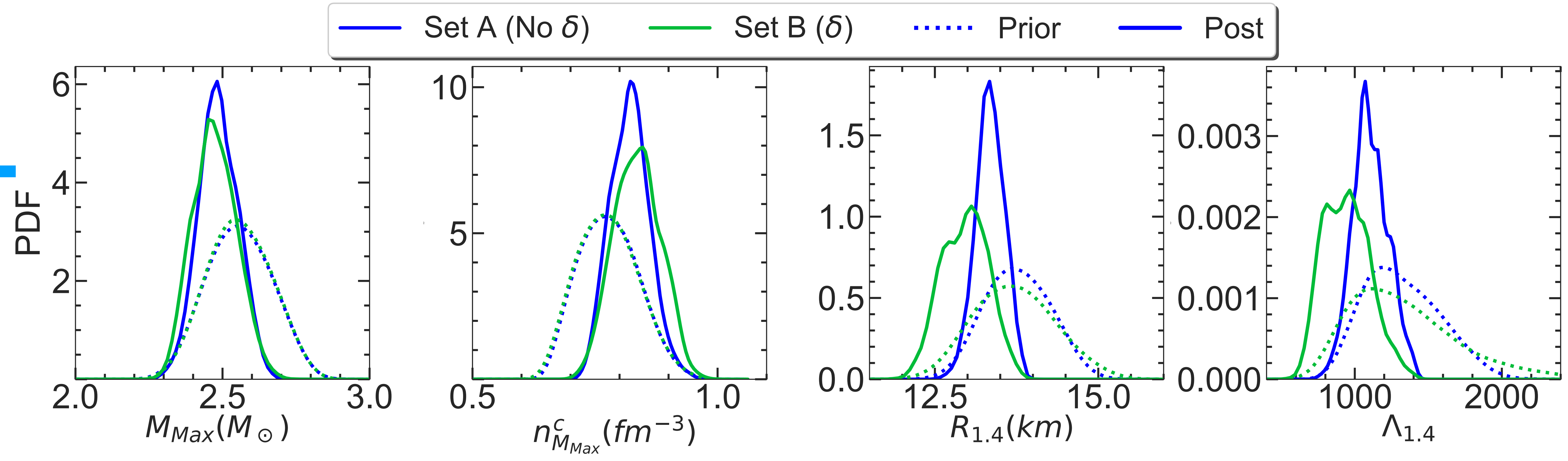
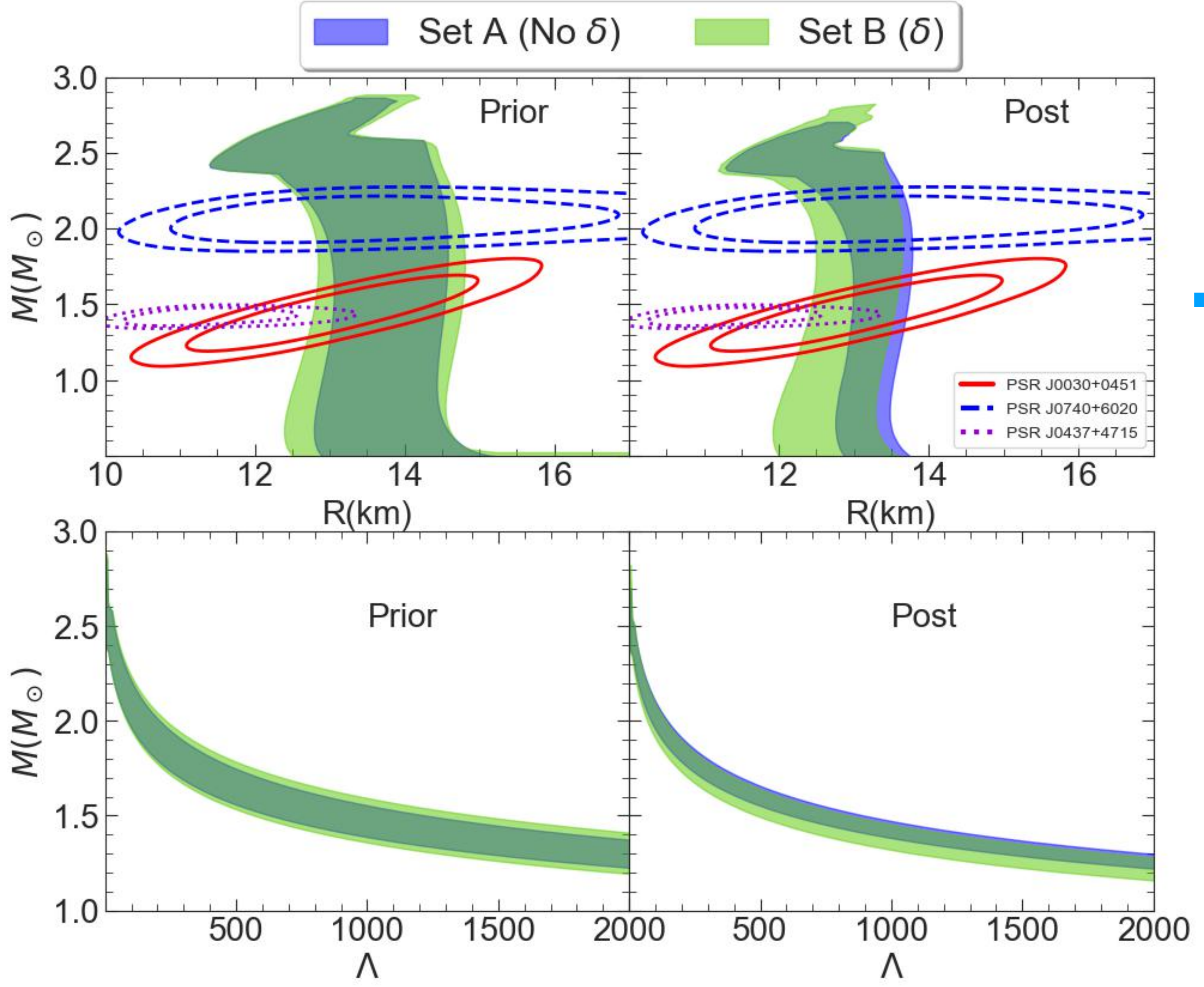




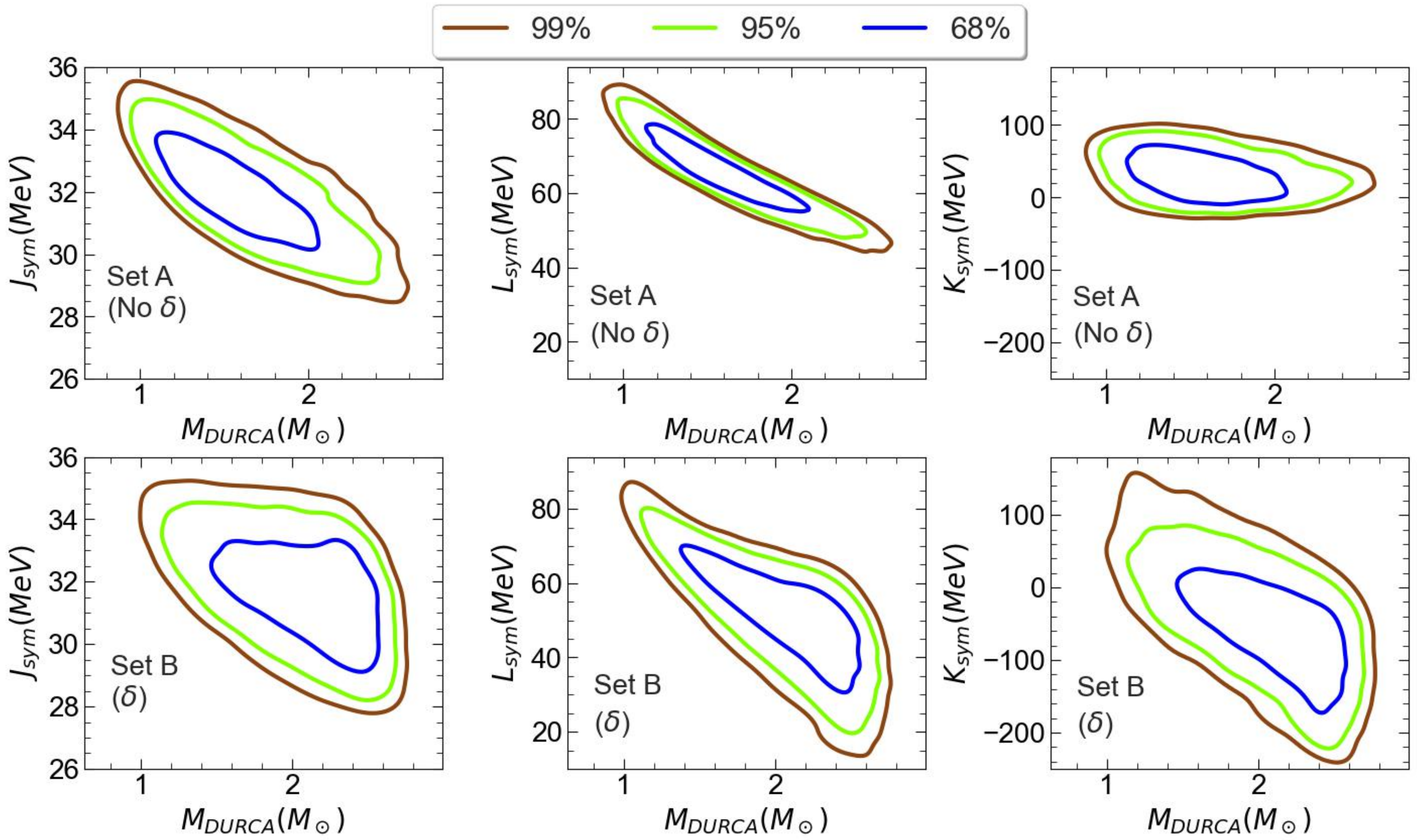
Bigger effect on the radius of intermediate mass stars

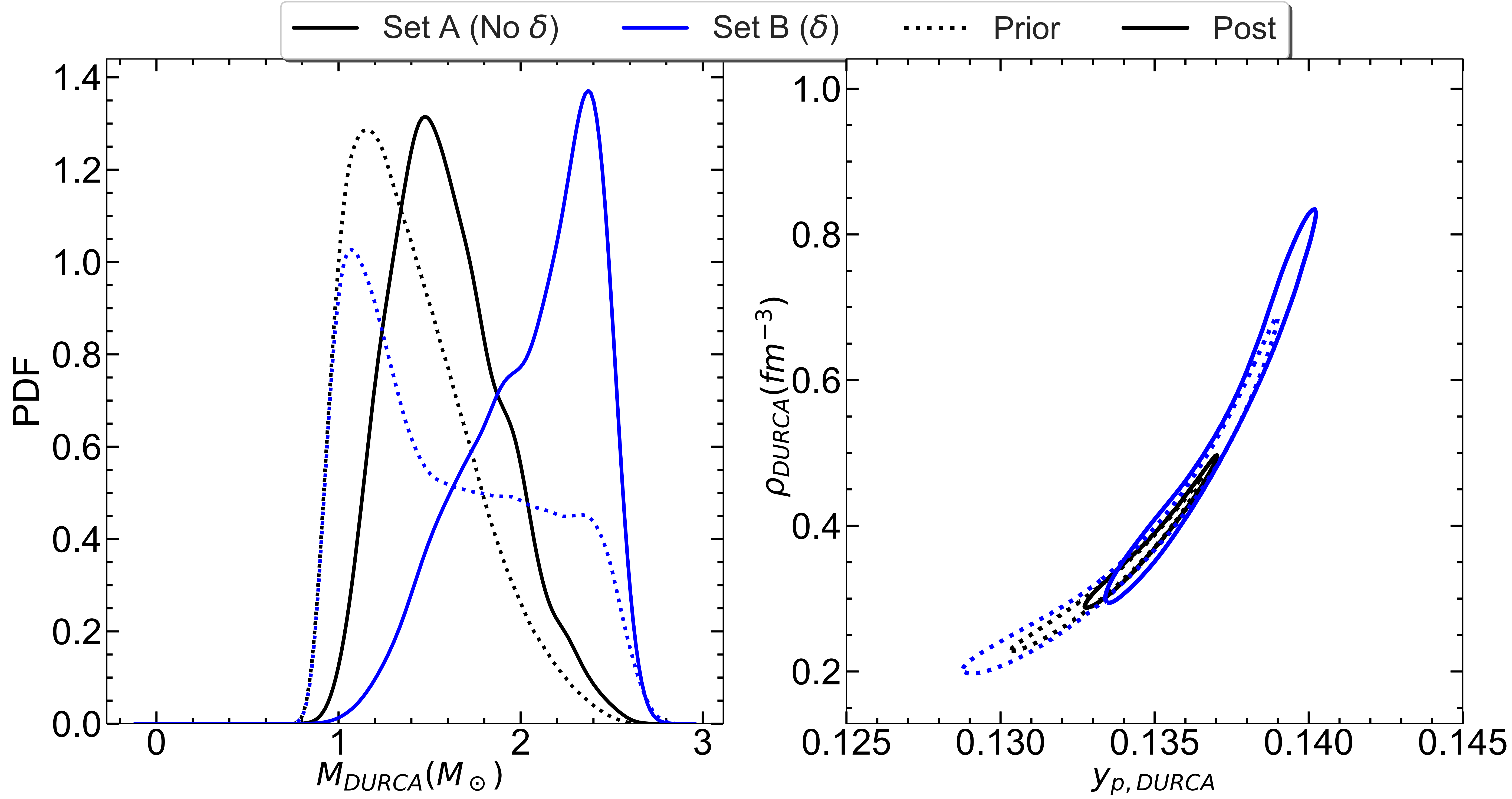
The delta meson allows for lower radii and tidal deformabilities, so that the posterior for Set B is in better agreement with the NICER measurement of the radius of PSR J0437+4715

Neutron Star Cooling

Constraining the dUrca threshold

- The dUrca mass threshold appears to be strongly correlated to the isovectorial NMPs for both sets, thus the inclusion of the delta meson strongly broadens the distribution of the threshold

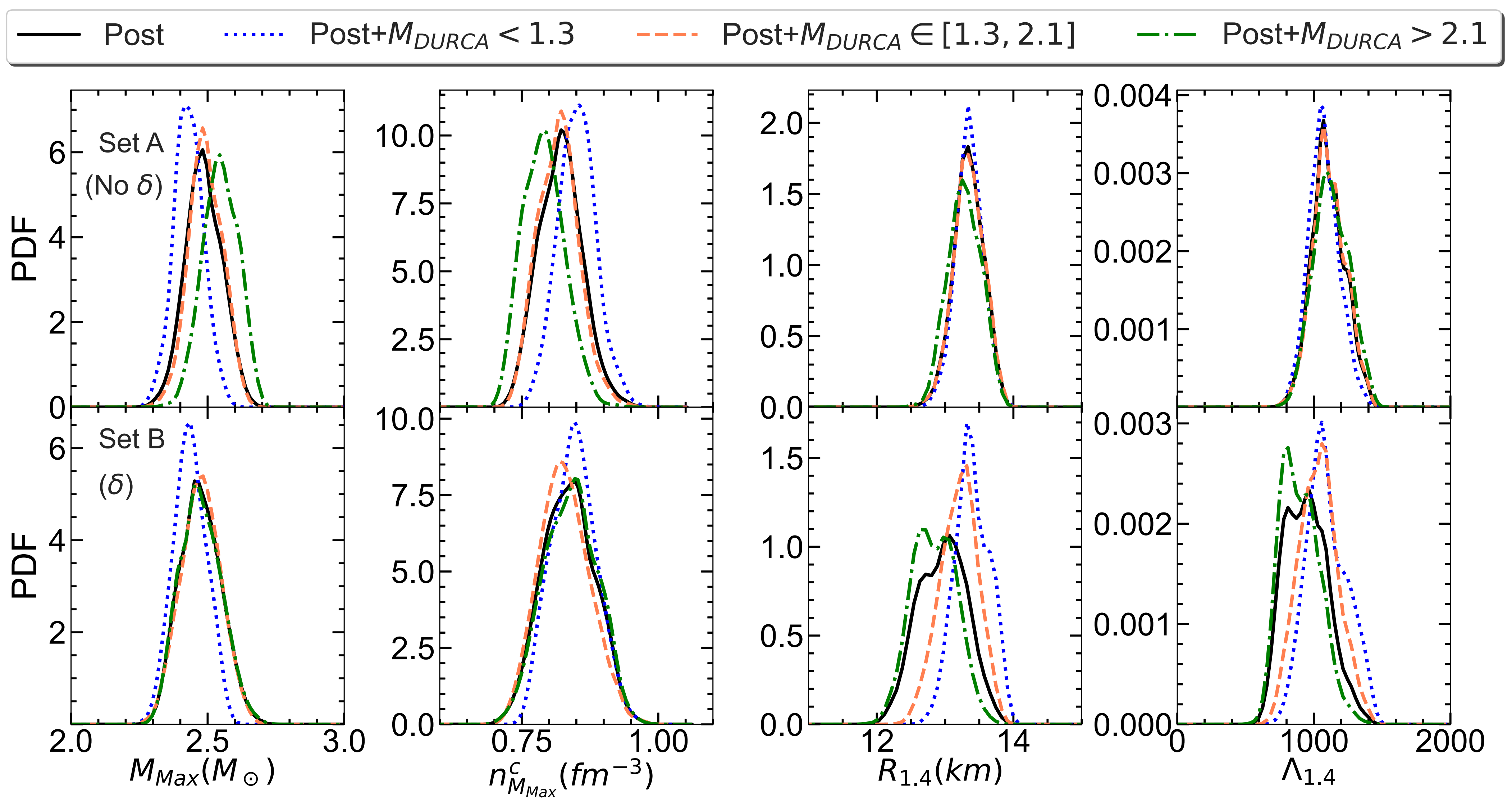




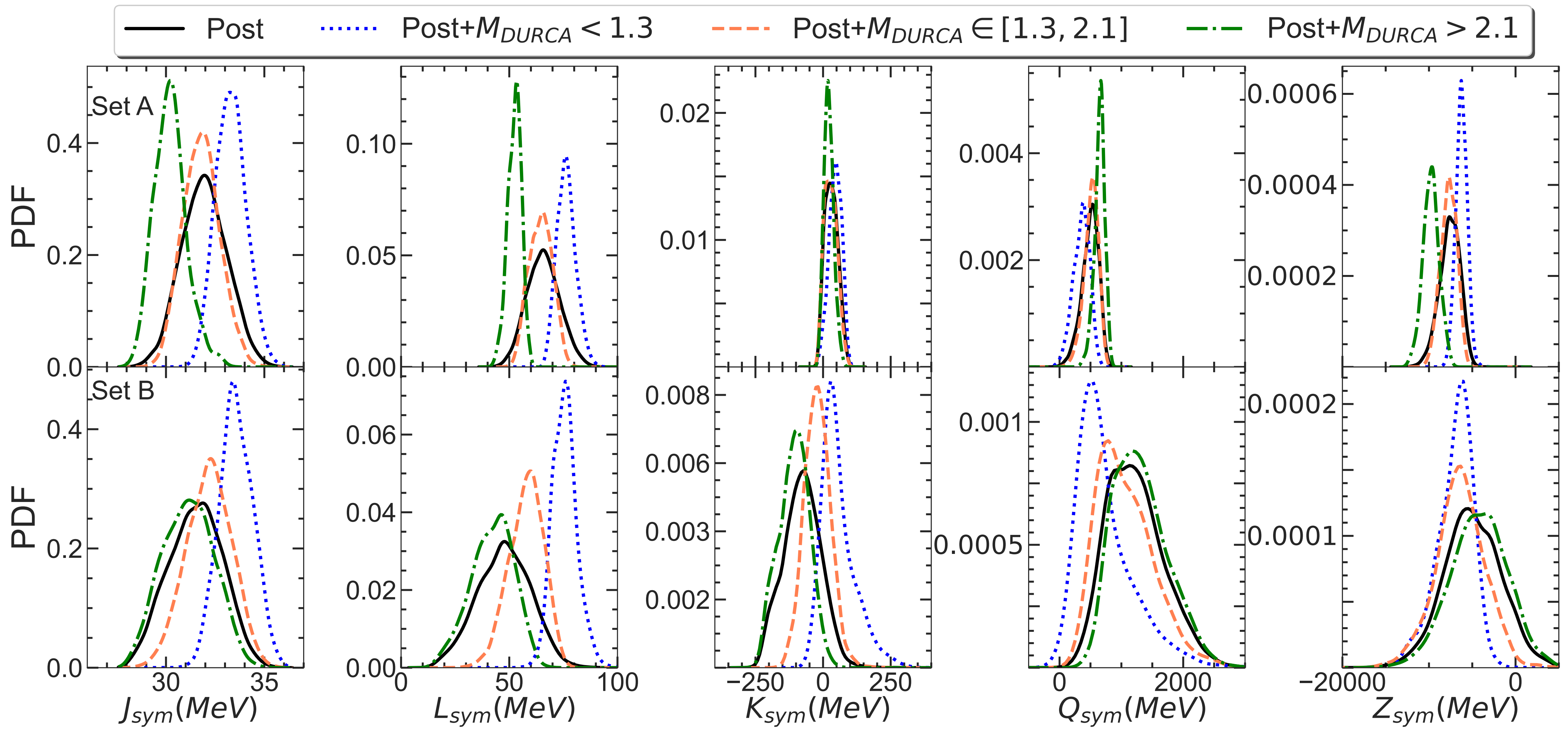
Constraining the dUrca threshold

Following the observation of young cold NSs, we implement an hypothetical constraint on the dUrca threshold, considering three scenarios

- **Always** $M_{DURCA} < 1.3 M_{\odot}$
- **Sometimes** $1.3 M_{\odot} > M_{DURCA} < 2.1 M_{\odot}$
- **Never** $M_{DURCA} > 2.1 M_{\odot}$



The models with a lower value of the radius and the tidal deformability appear to mostly have a higher dUrca threshold



Both sets show a clear correlation between NMPs and threshold

Inclusion of the 1S0 Proton Pairing Gap

We introduce a simplified model for the 1S0 proton pairing gap, give by

$$\Delta(n_p, s_y, s_x) = s_y \Delta_{BCS}(n_p/s_x)$$

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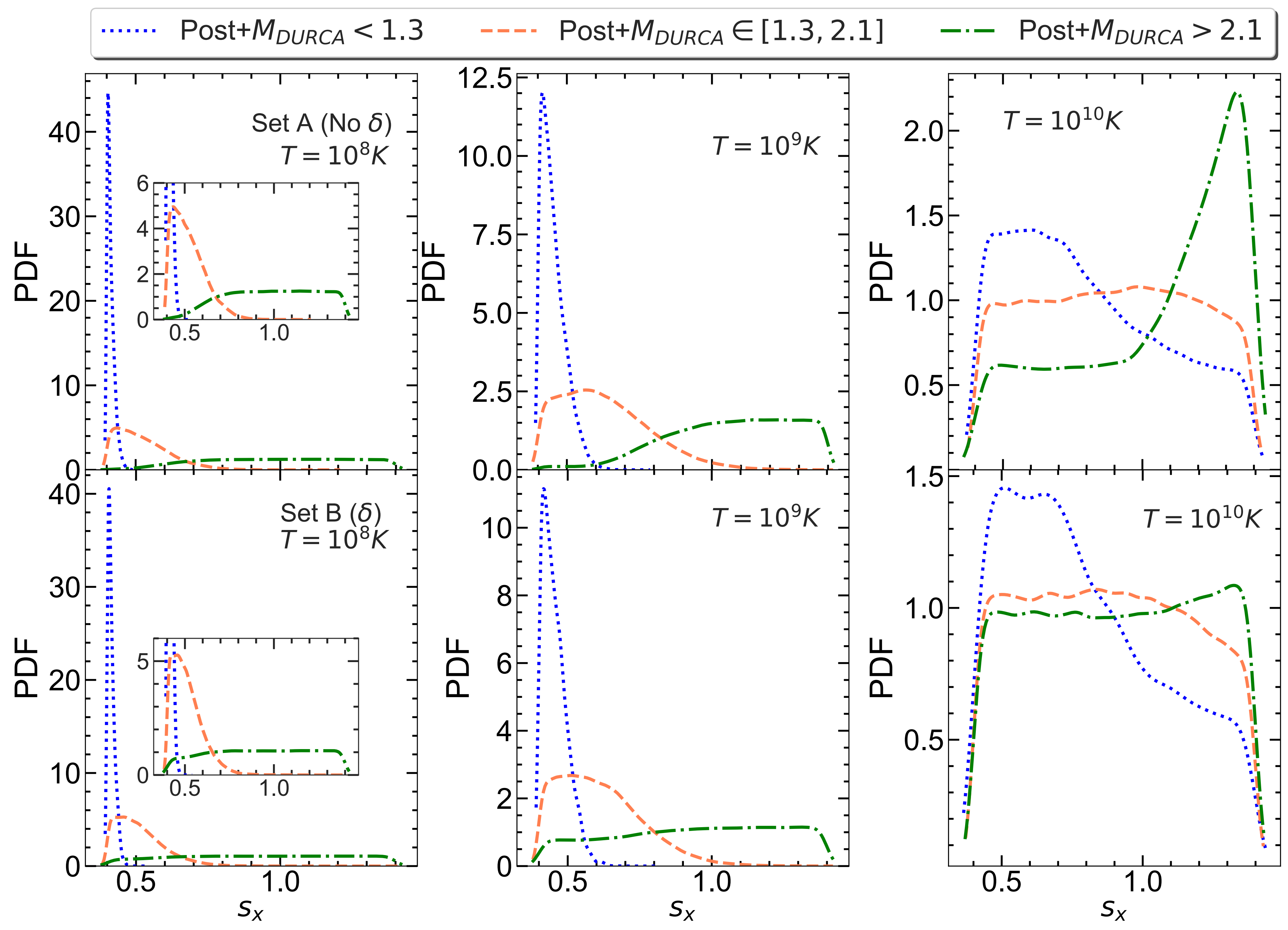
We then try to constraint the scaling parameters using the hypothetical constraint on the dUrca threshold, considering three possible temperatures for the star

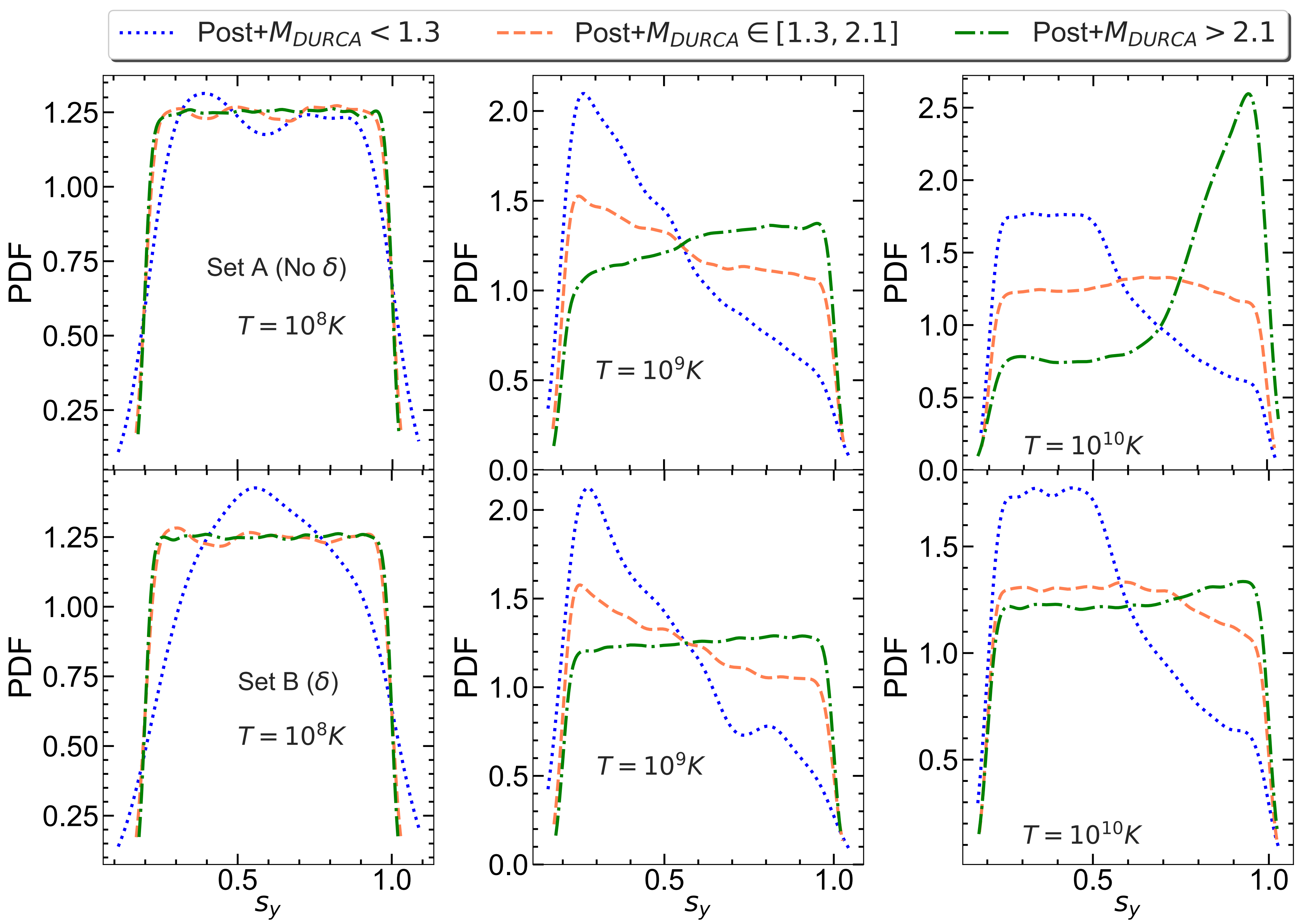
Hot $T = 10^{10} K$

Warm $T = 10^{9} K$

Cold $T = 10^{8} K$

Inclusion of the 1S0 Proton Pairing Gap





- **The s_x scaling parameter is strongly constrained both in the Sometimes and the Always scenario**
- **The s_y scaling parameter isonly weakly constrained by the durra constraint**

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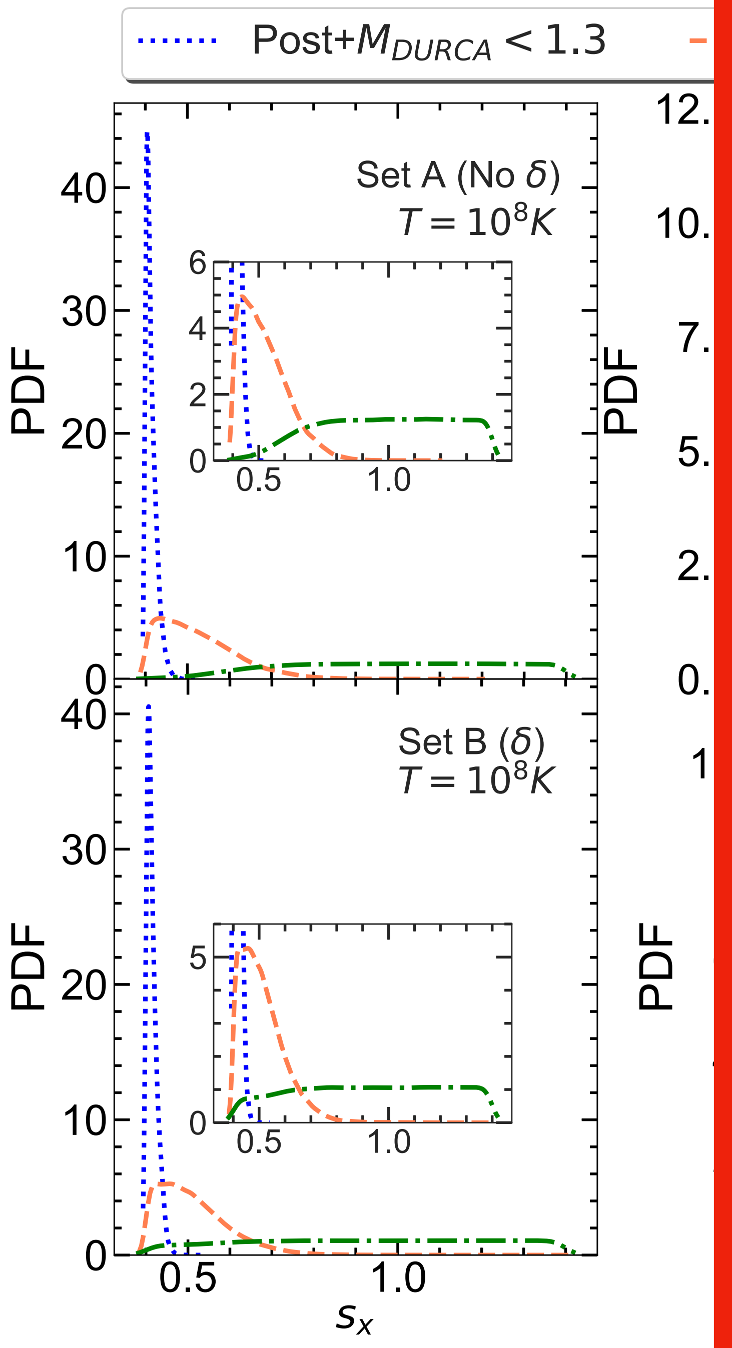

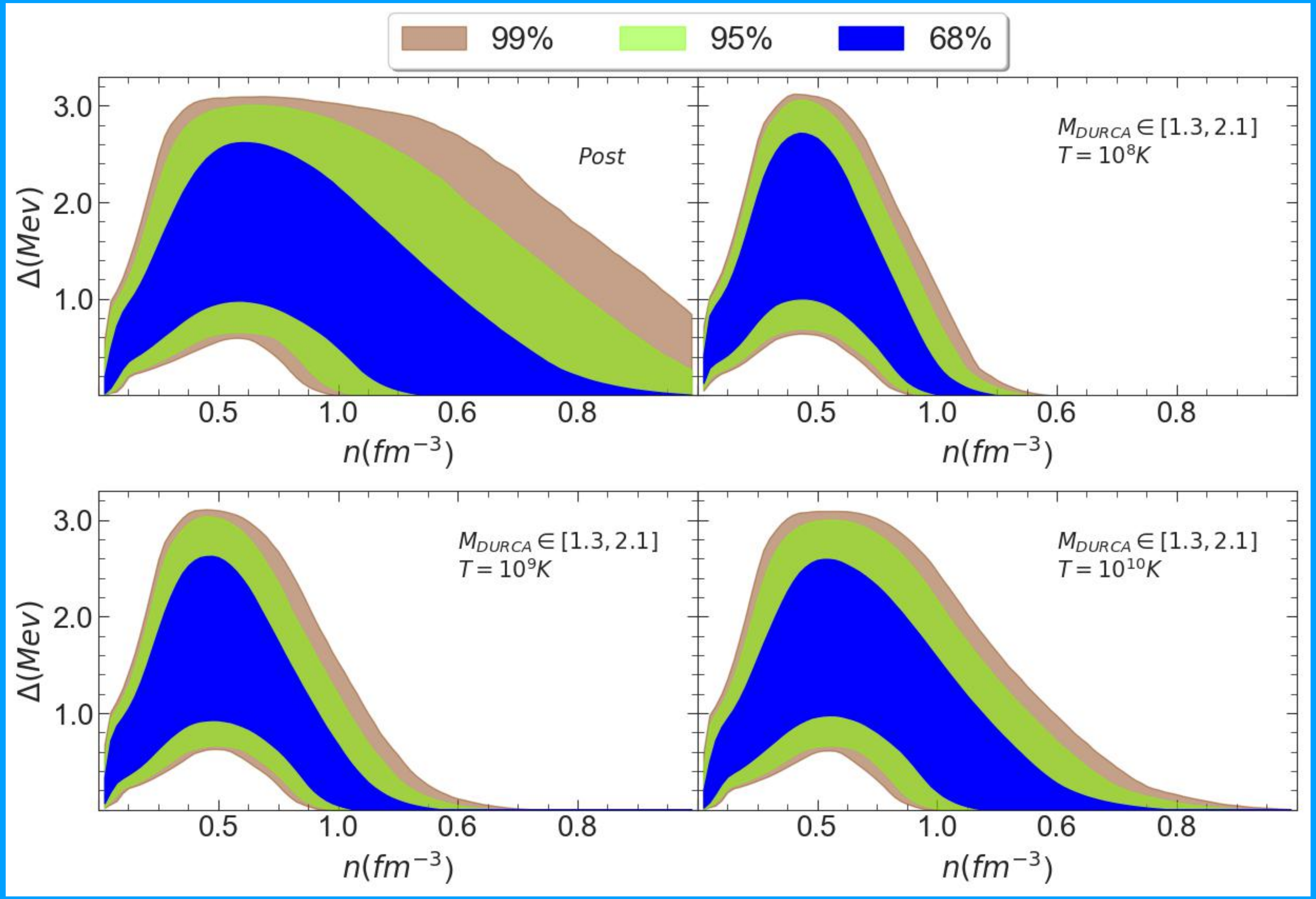

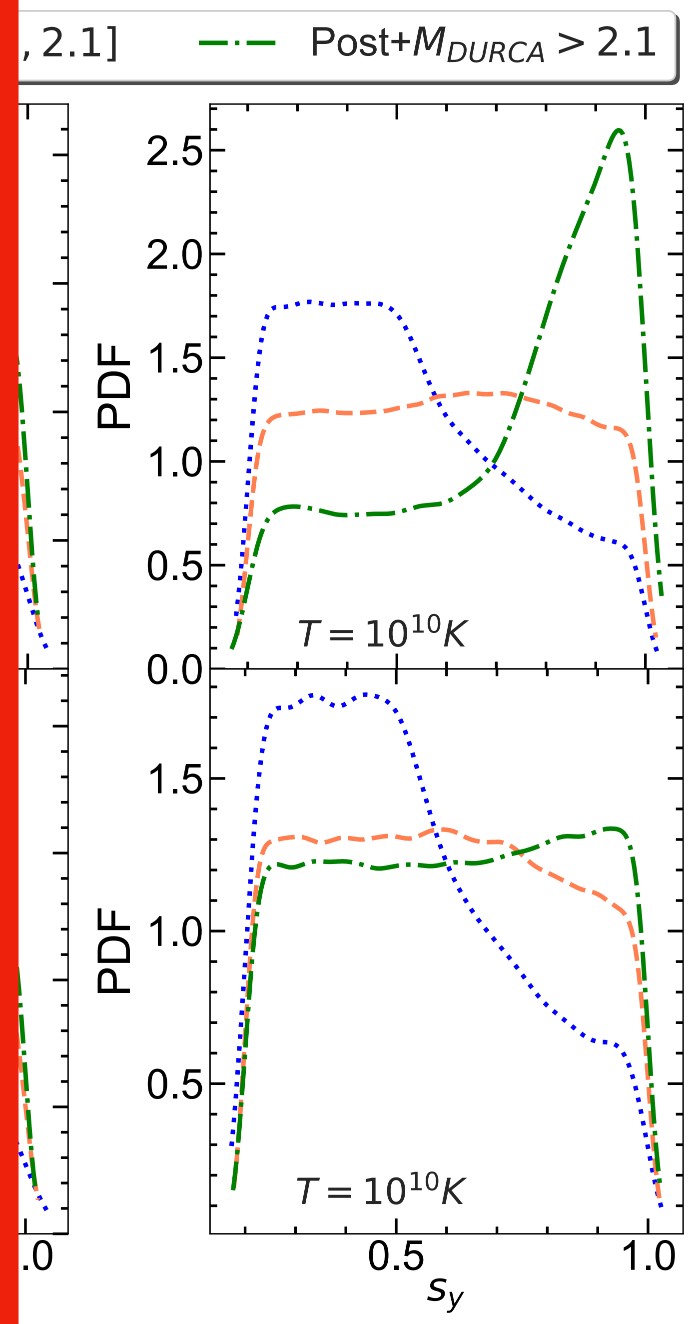

- The s_x scaling pa… …eter isonly weakly both in the Some… …rra constraint

Overall, constraining the dUrca threshold constrains the density range in which the gap is non zero

Conclusions

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- **We observed how the inclusion of the delta meson allows for a broad distribution of many physical quantities, without the need to artificially increase the complexity of the coupling density functional**

- **We introduce an hypothetical constraint on the dUrca threshold and observe that information of the NS's radius could help constraint the dUrca threshold**

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We perform a bayesain analysis to study the EoS of NS within a unified RMF framework, comparing the results obtained with and without the inclusion of the scalar isovector meson delta.

- **We observed how the inclusion of the delta meson allows for a broad distribution of many physical quantities, without the need to artificially increase the complexity of the coupling density functional**
- **We introduce an hypothetical constraint on the dUrca threshold and observe that information of the NS's radius could help constraint the dUrca threshold**
- **We implement a simple model for the proton 1S0 pairing gap in the core and show that the observation of fast cooling NSs could help in constraining the density interval in which the gap is different from zero**

Thank you!