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Axion effects in the stability of hybrid stars

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SEDES SAPIENTIÆ
1960

Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

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FAPERGS

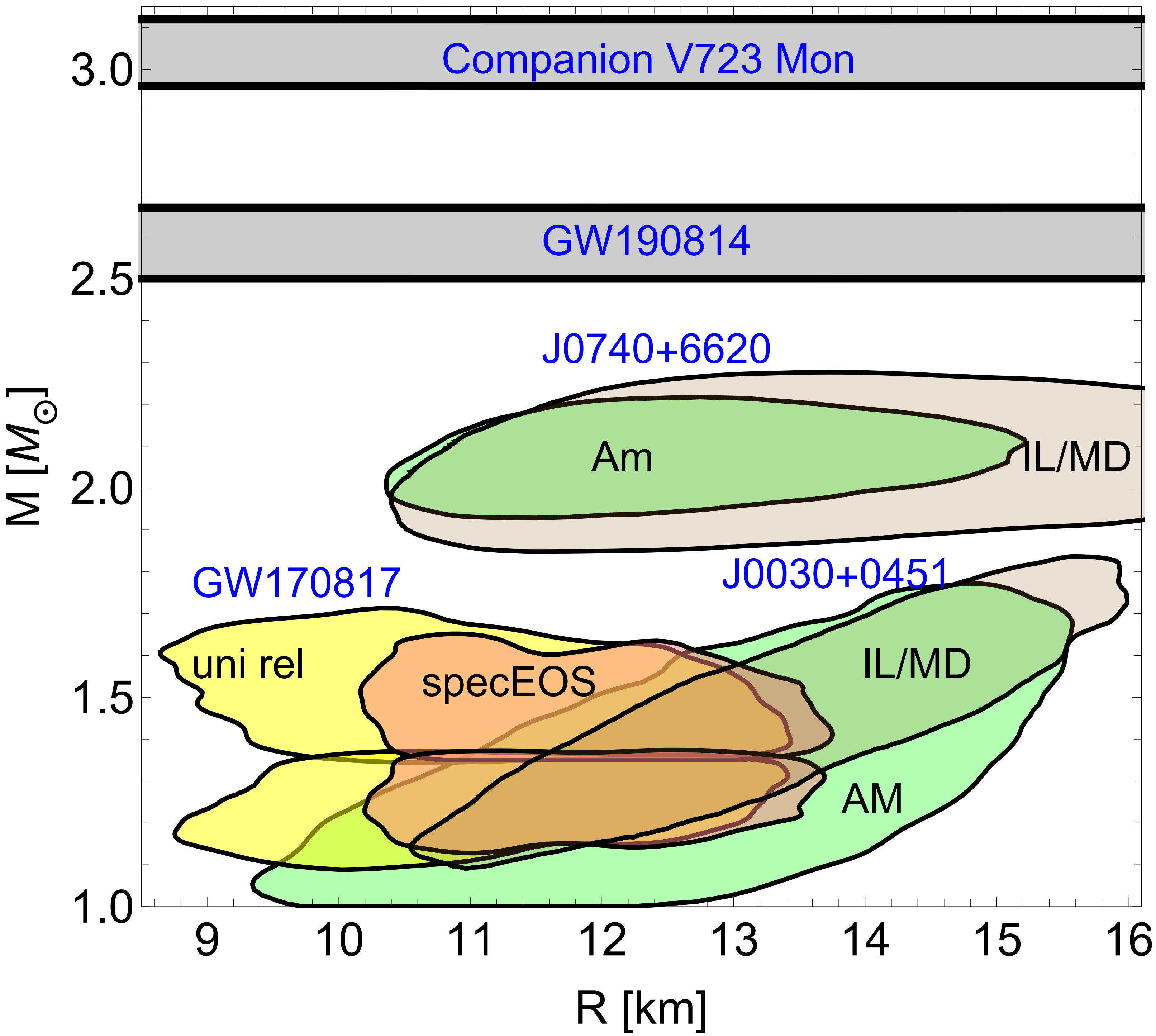
Outline

- Motivation
- Strong charge-parity (CP) violating effects through axion fields
- **QCD** axion + NJL model
- Axion effects on the stability of hybrid stars
- Numerical Results
- Conclusions and perspectives

Motivation: Dark matter (DM)

- There is Dark Matter
- Evidence coming from different observation scales
- It's remarkable that measurements on very different scales all indicate a consistent picture of a Universe containing DM
- DM is one of the few experimentally driven indications for physics beyond the Standard Model
- Questions: Mass? Spin? Couplings? Stable?
- Probes of DM? Indirect detection? Collider searches? Self-interactions? Direct detection?

Motivation



Observational constraints on the neutron star mass-radius plane from LIGO/Virgo and NICER data.

H. Tan, T.Dore, V.Dexheimer, J.Noronha-Hostler, and N. Yunes, Phys. Rev. D 105, 023018 (2022).

Strong charge-parity (CP) violating effects through axion fields

Within the regime of strong interaction instanton contributions can lead to CP violation

In this kind of scenario, where gauge field configurations have nontrivial topologies, the QCD Lagrangian density generally contains an extra θ-term

$$\mathcal{L}_\theta = \frac{\theta g^2}{32\pi^2}\mathcal{F}\bar{\mathcal{F}}$$

g is the coupling for the strong interaction and $\mathcal{F}$ and $\bar{\mathcal{F}}$ are the gluonic field strength tensor

The real parameter θ defines the choice of vacuum from infinite possibilities (and if theory is CP symmetric or not)

Strong charge-parity (CP) violating effects through axion fields

Experimental studies on pseudoscalar mass ratios, electrical dipole moments as well as Lattice QCD calculations conclude that θ is very close to 0 in nature

A simple and elegant way to explain why θ should be so small or null is giving θ a dynamical character, elevating it to a field, the axion, such as to have a vanishing vacuum expectation value.

R. D. Peccei and H. R. Quinn, CP Conservation in the Presence of Instantons, Phys. Rev. Lett. 38, 1440 (1977).

The axion field a is the canonically normalized dynamical θ, $\theta(x) = a(x)/f_a$, where f_a is the axion decay constant.

The interaction Lagrangian density can now be written as

$$\mathcal{L}_a = \frac{g^2}{32\pi^2}\frac{a}{f_a}\mathcal{F}\bar{\mathcal{F}}$$

QCD Axion + SU(2) NJL model

NJL model has been extensively used in the similar context of spontaneous CP violation, θ effects on the QCD phase transition

Effect of the chiral phase transition on axion mass and self-coupling, Zhen-Yan Lu and M. Ruggieri, Phys. Rev. D 100, 014013 (2019)

$$\mathcal{L}_a = \frac{g^2}{32\pi^2}\frac{a}{f_a}\mathcal{F}\bar{\mathcal{F}}$$

This equation can be effectively represented as an interaction of the QCD axion field a with the quarks by performing a chiral rotation of the quark fields by the angle a/f_a,

$$\mathcal{L}_a = 8G_2\left[e^{i\frac{a}{f_a}}\det(\psi_R\psi_L) + e^{-i\frac{a}{f_a}}\det(\psi_L\psi_R)\right]$$

where ψ_L and ψ_R are the left- and right-handed components of the quark wave function ψ and G_2 is a coupling constant.

QCD Axion + SU(2) NJL model

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_0)\psi + \mathcal{L}_q + \mathcal{L}_a$$

$$\mathcal{L}_q = G_1\left[(\bar{\psi}\psi)^2 + (\bar{\psi}\tau_k i\gamma_5\psi)^2\right]$$

The thermodynamic potential for the QCD axion within the NJL model in mean field approximation, is given by

$$\begin{aligned}\Omega \;&=\; \Omega_q + G_1(\eta^2+\sigma^2) - G_2(\eta^2-\sigma^2)\cos\frac{a}{f_a} \\ &\quad -2G_2\sigma\eta\sin\frac{a}{f_a}\end{aligned}$$

$G_1 = (1-c)G_s$ and $G_2 = c\,G_s$

where the quark contribution Ω_q is given by

$$\Omega_q = -8N_c\int\frac{d^3p}{(2\pi)^3}\left[\frac{E_p}{2} + T\ln\left(1+e^{-E_p/T}\right)\right]$$

A. Bandyopadhyay, R.L.S. Farias, B.Lopes and R.O. Ramos, Phys. Rev. D 100, 076021 (2019)

QCD Axion + SU(2) NJL model

Effective thermodynamic potential for the QCD axion in a hot medium and within NJL model is then given by

$$\Omega_T(a,T) = \Omega\left[\sigma_0(a,T), \eta_0(a,T), a, T\right]$$

In the present work the axion is treated as a background field!

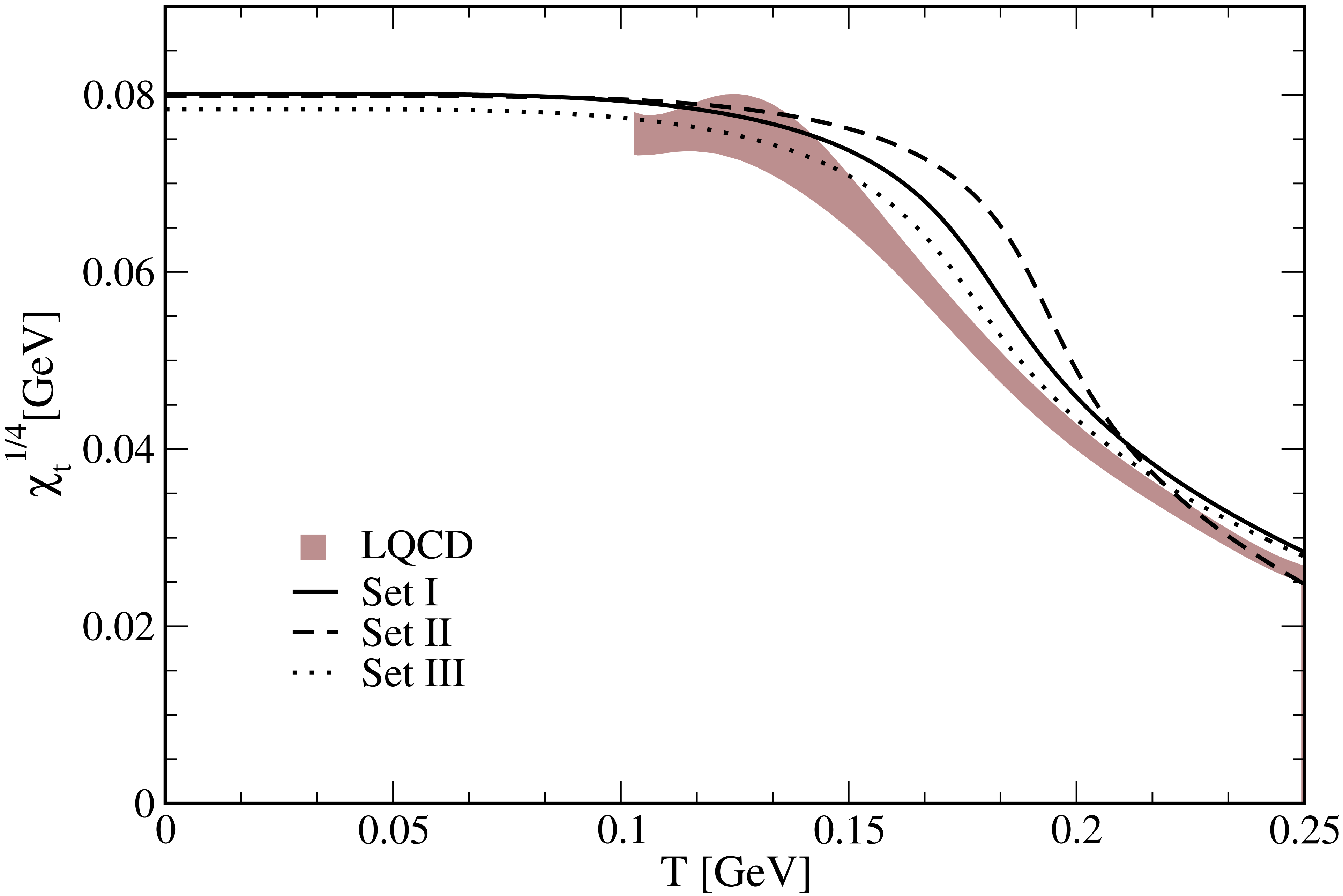
$$m_a^2 = \left.\frac{d^2\Omega_T(a,T)}{da^2}\right|_{a=0} = \frac{\chi_{\rm top}}{f_a^2}$$

where $\chi_{\rm top}$ is the topological susceptibility

$$\lambda_a = \left.\frac{d^4\Omega_T(a,T)}{da^4}\right|_{a=0}$$

A. Bandyopadhyay, R.L.S. Farias, B.Lopes and R.O. Ramos, Phys. Rev. D 100, 076021 (2019)

QCD Axion + SU(2) NJL model



A. Bandyopadhyay, R.L.S. Farias, B.Lopes and R.O. Ramos, Phys. Rev. D 100, 076021 (2019)

QCD Axion + NJL model at finite density?

QCD axion + SU(3) NJL model

- Axions effects in NJL via an effective 't Hooft determinant interaction

- SU(3) NJL model + CP violating effects through axion fields, can be expressed in the form:

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_0\right)\psi$$
$$+G_s\sum_{b=0}^{8}\left[\left(\bar{\psi}\lambda^b\psi\right)^2 + \left(\bar{\psi}i\gamma_5\lambda^b\psi\right)^2\right] - G_V\left(\bar{\psi}\gamma^{\mu}\psi\right)^2$$
$$-K\left\{e^{i\frac{a}{fa}}\det\left[\bar{\psi}\left(1+\gamma^5\right)\psi\right] + e^{-i\frac{a}{fa}}\det\left[\bar{\psi}\left(1-\gamma^5\right)\psi\right]\right\}$$

The last term represents the axion contribution, i.e., the interaction between the axion field a and the quarks, with strength K, through a chiral rotation by the angle a/fa.

QCD axion + SU(3) NJL model

Conditions such as electric charge neutrality and β-equilibrium need to be satisfied:

$$\mu_u = \frac{\mu_B}{3} - \frac{2}{3}\mu_e,$$

$$\mu_d = \mu_s = \frac{\mu_B}{3} + \frac{1}{3}\mu_e,$$

$$\frac{2}{3}n_u - \frac{1}{3}(n_d + n_s) - n_e = 0$$

For such a system, the thermodynamic potential at $T = 0$ and finite quark chemical potential reads

$$\Omega = \Omega_q + 2G_s \sum_{i=u,d,s} \left(\sigma_i^2 + \eta_i^2\right) + 4K \left(\sigma_u\sigma_d\sigma_s \cos\frac{a}{f_a} + \eta_u\eta_d\eta_s \sin\frac{a}{f_a}\right) - 4K \left[\cos\frac{a}{f_a}\left(\eta_u\eta_d\sigma_s + \eta_u\eta_s\sigma_d + \eta_d\eta_s\sigma_u\right) + \sin\frac{a}{f_a}\left(\sigma_u\sigma_d\eta_s + \sigma_u\sigma_s\eta_d + \sigma_d\sigma_s\eta_u\right)\right] - G_V n^2$$

QCD axion + SU(3) NJL model

$\sigma_i = -\langle\bar{\psi}_i\psi_i\rangle$ and $\eta_i = \langle\bar{\psi}_i i\gamma_5\psi_i\rangle$ are the scalar and pseudoscalar quark condensates and $n = \langle\psi^\dagger\psi\rangle$ is the total quark number density

$$\Omega_q = -2N_c \sum_{i=u,d,s}\left[\int_\Lambda \frac{d^3p}{(2\pi)^3} E_p^i + \int_{p_F^i} \frac{d^3p}{(2\pi)^3} \left(\tilde{\mu}_i - E_p^i\right)\right]$$

$$E_p^i = \sqrt{p^2 + {M^i}^2} \text{ with } M^i = \sqrt{{M_s^i}^2 + {M_{ps}^i}^2}$$

$$\begin{aligned} M_s^i &= m_0^i + 4G_s\sigma_i + 2K\left[\cos\frac{a}{f_a}(\sigma_j\sigma_k - \eta_j\eta_k)\right. \\ &\quad \left. - \sin\frac{a}{f_a}(\sigma_j\eta_k + \eta_j\sigma_k)\right], \\ M_{ps}^i &= 4G_s\eta_i - 2K\left[\cos\frac{a}{f_a}(\sigma_j\eta_k + \eta_j\sigma_k)\right. \\ &\quad \left. - \sin\frac{a}{f_a}(\eta_j\eta_k - \sigma_j\sigma_k)\right] \end{aligned}$$

$$\tilde{\mu} = \mu - 2G_V n$$

$$p_F^i = \sqrt{\tilde{\mu}^2 - (M^i)^2}\;\theta(\tilde{\mu}^2 - (M^i)^2)$$

Axion effects on the stability of hybrid stars

Physical values for the condensates σ_i, η_i, and n:

$$\frac{\partial\Omega}{\partial\sigma_i} = \frac{\partial\Omega}{\partial\eta_i} = \frac{\partial\Omega}{\partial n} = 0$$

With those physical values we obtain $\Omega = \Omega(a,\mu)$

$$\Omega_N = \Omega(a,\mu) - \Omega(a,0)$$

$$p = -\Omega_N + \frac{\mu_e^4}{12\pi^2},$$

$$\epsilon = \Omega_N + \sum_{i=u,d,s} \mu_i n_i + \frac{\mu_e^4}{4\pi^2},$$

$$n_B = \frac{1}{3}\sum_{i=u,d,s} n_i = \frac{1}{3\pi^2}\left({p_F^u}^3 + {p_F^d}^3 + {p_F^s}^3\right)$$

Axion effects on the stability of hybrid stars

- Finding an EoS describing stable pure quark matter can be a challenging task, and the problem is **aggravated** with the introduction of a vector interaction!

- **For this reason, one needs to consider a hadronic crust together with the quark matter core.**

- In this work, we will present results for the $\mathrm{NL3}_{\omega\rho}$ and $\mathrm{CMF}_{\omega\rho,\omega^4}$ models

- the $\mathrm{NL3}_{\omega\rho}$ is a nucleonic model that contains the fewest ingredients that allow hadronic matter to be in agreement with nuclear and astrophysical observations, with the $\omega\rho$ referring to a mixed vector-isovector interaction.
- Chiral Mean Field $\mathrm{CMF}_{\omega\rho,\omega^4}$ model accounts for chiral symmetry restoration, while also being in agreement with nuclear and astrophysical observations.

- All the crust EoS's utilized in this work are available in the CompOSE repository (https://compose.obspm.fr)

B.Lopes, R.L.S. Farias, V. Dexheimer, A. Bandyopadhyay and R.O.Ramos, e-Print: 2206.01631 [hep-ph]

Mass-radius relation

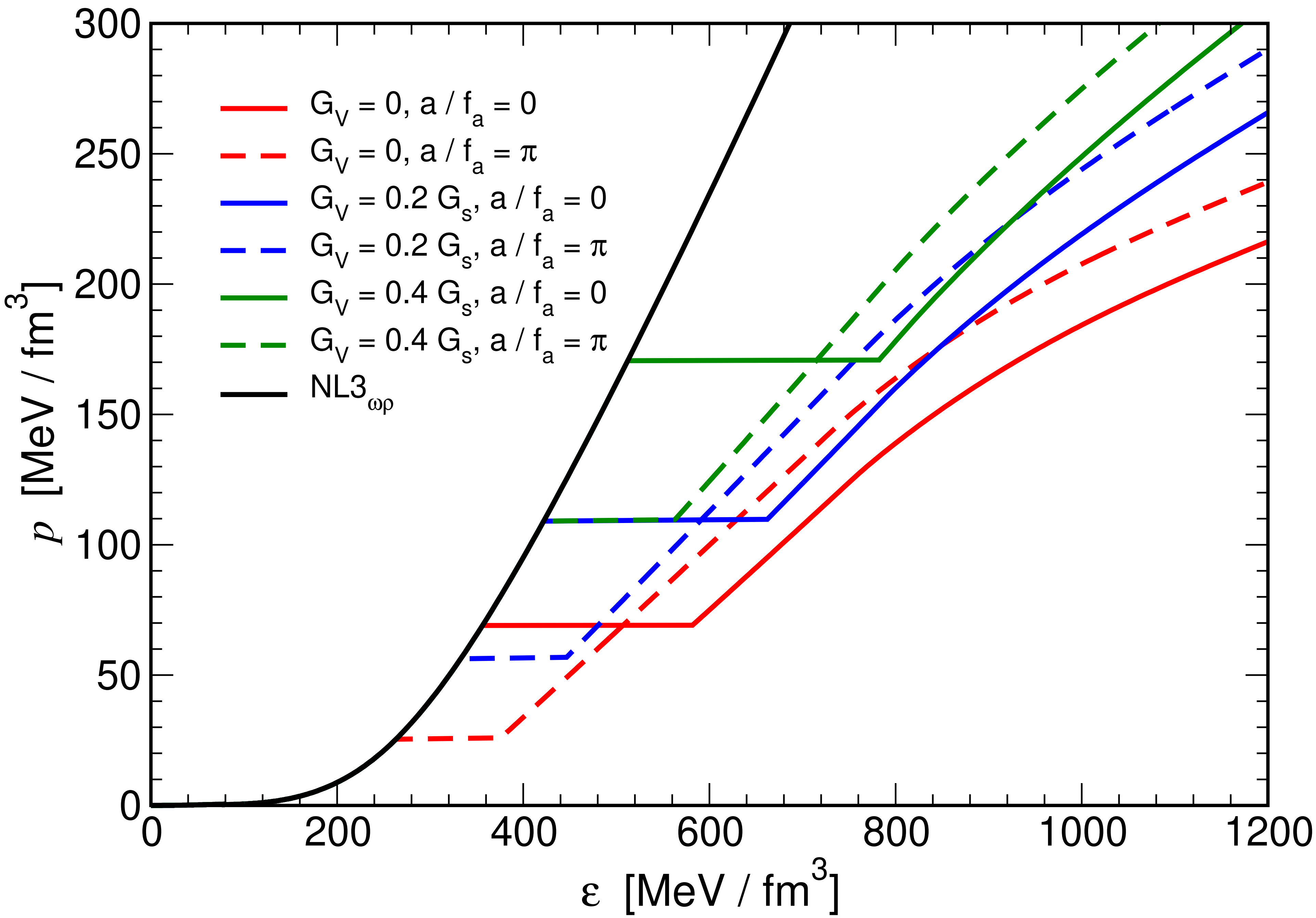
The mass-radius relation for the stars is obtained solving the Tolman-Oppenheimer-Volkoff (TOV) equations:

$$\frac{dp(r)}{dr} = -\frac{G\epsilon(r)m(r)}{c^2r^2}\left(1+\frac{p(r)}{\epsilon(r)}\right)\left(1+\frac{4\pi r^3 p(r)}{m(r)c^2}\right)\left(1-\frac{2Gm(r)}{c^2 r}\right)^{-1}$$

$$\frac{dm(r)}{dr} = \frac{4\pi r^2}{c^2}\epsilon(r)$$

Parameters of SU(3) NJL model: $\Lambda = 631.4$ MeV, $G_s = 1.835/\Lambda^2$, $K = 9.29/\Lambda^5$, $m_0^{u,d} = 5.5$ MeV, and $m_0^s = 135.7$ MeV

Numerical Results



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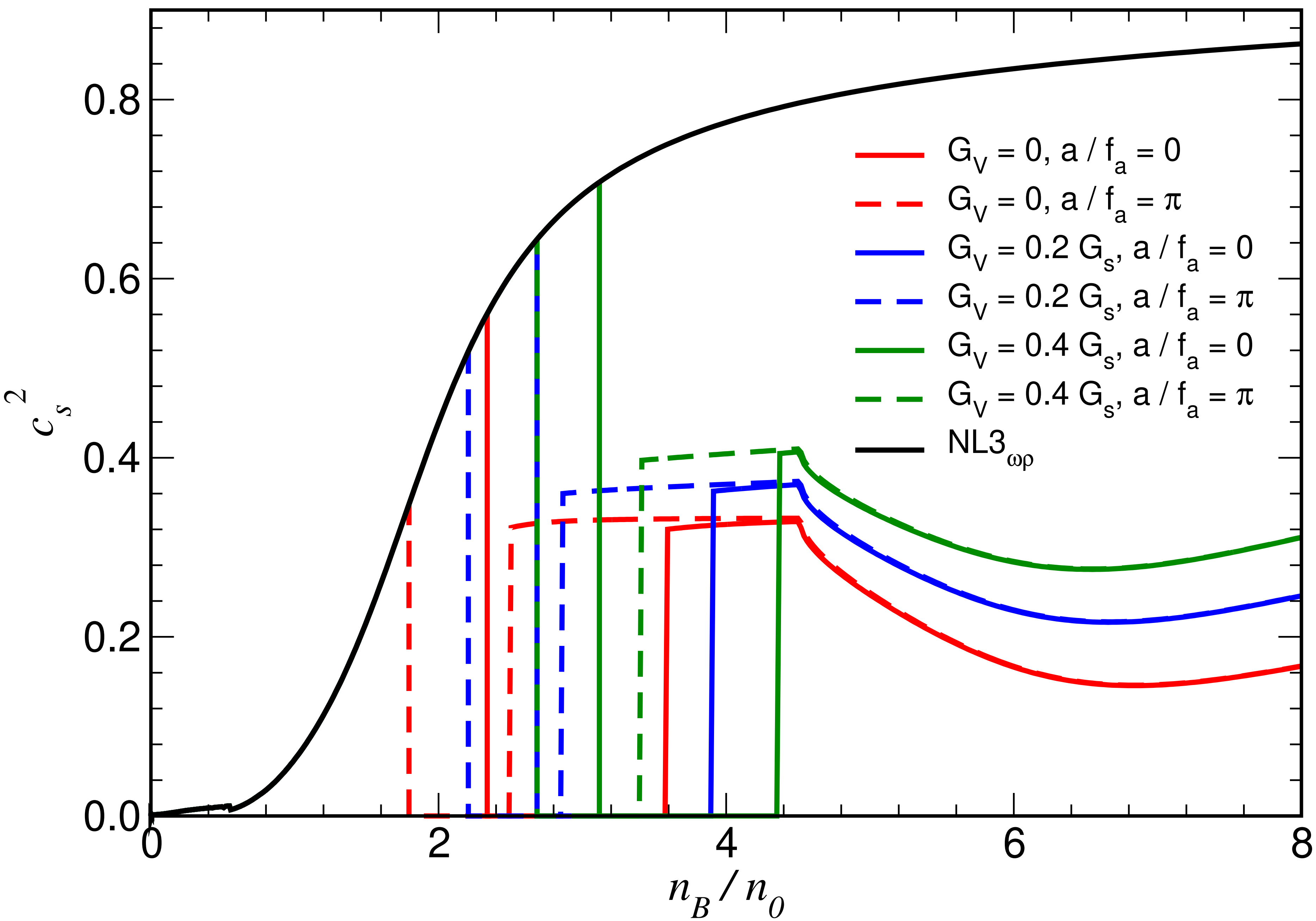

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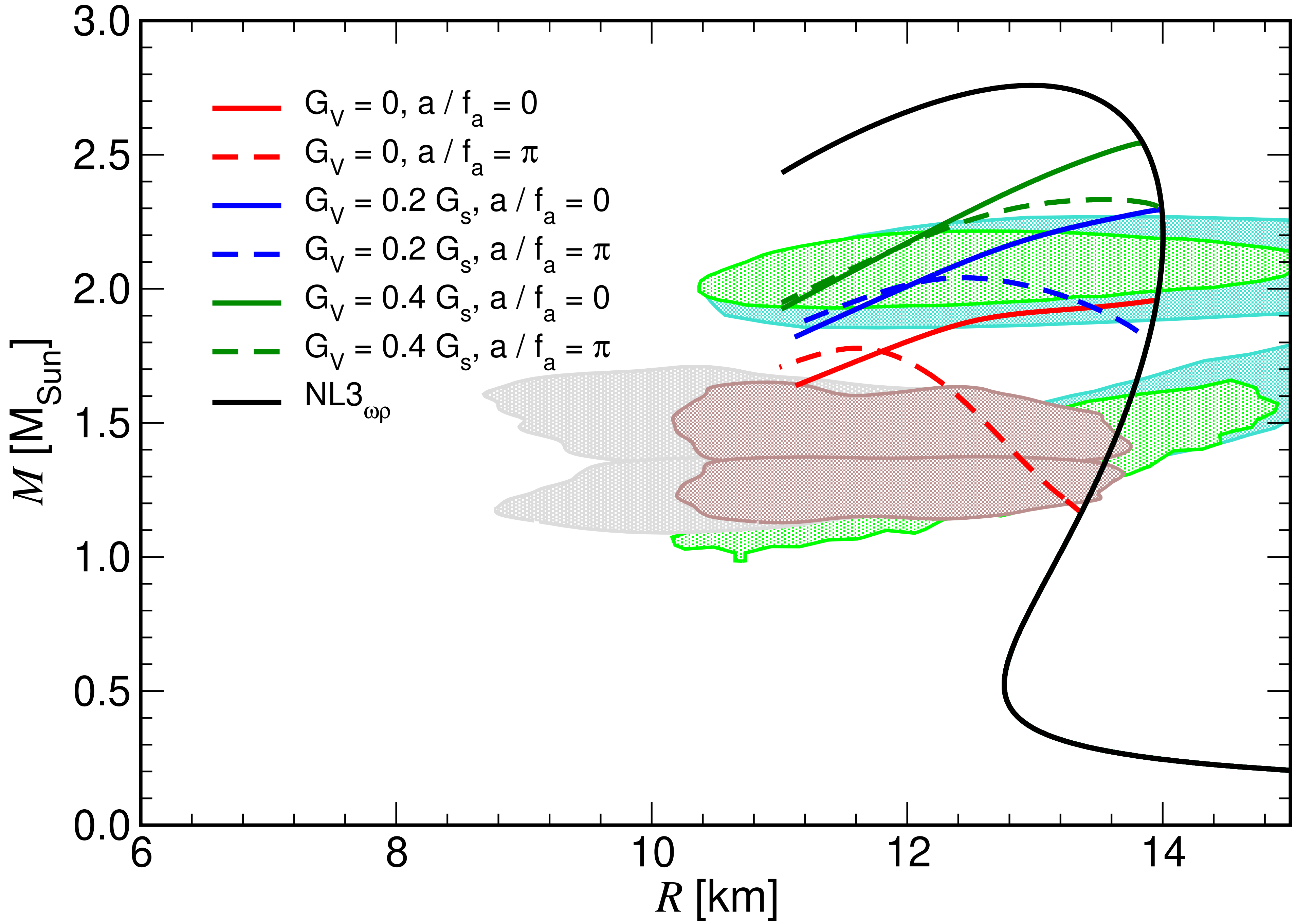

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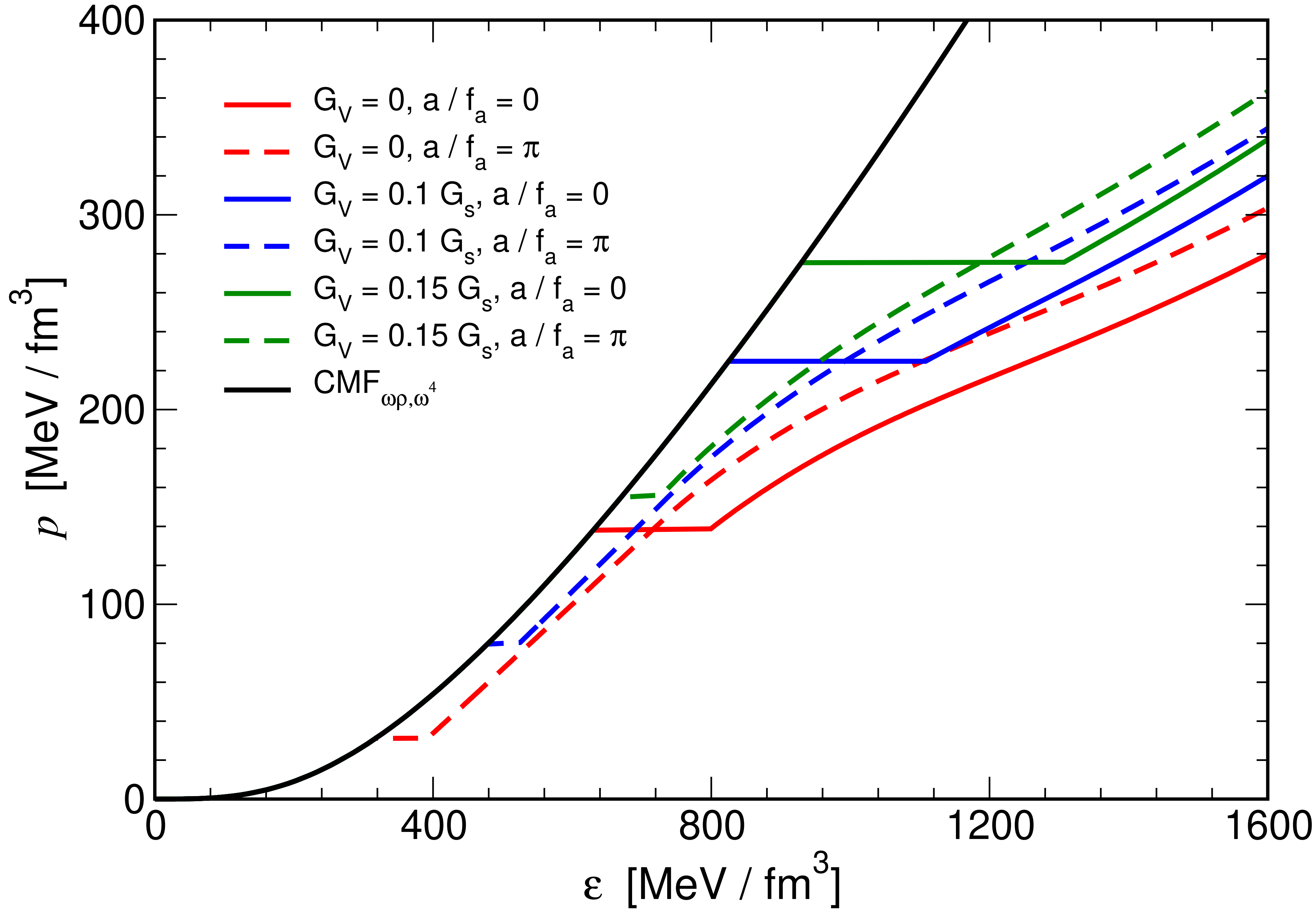

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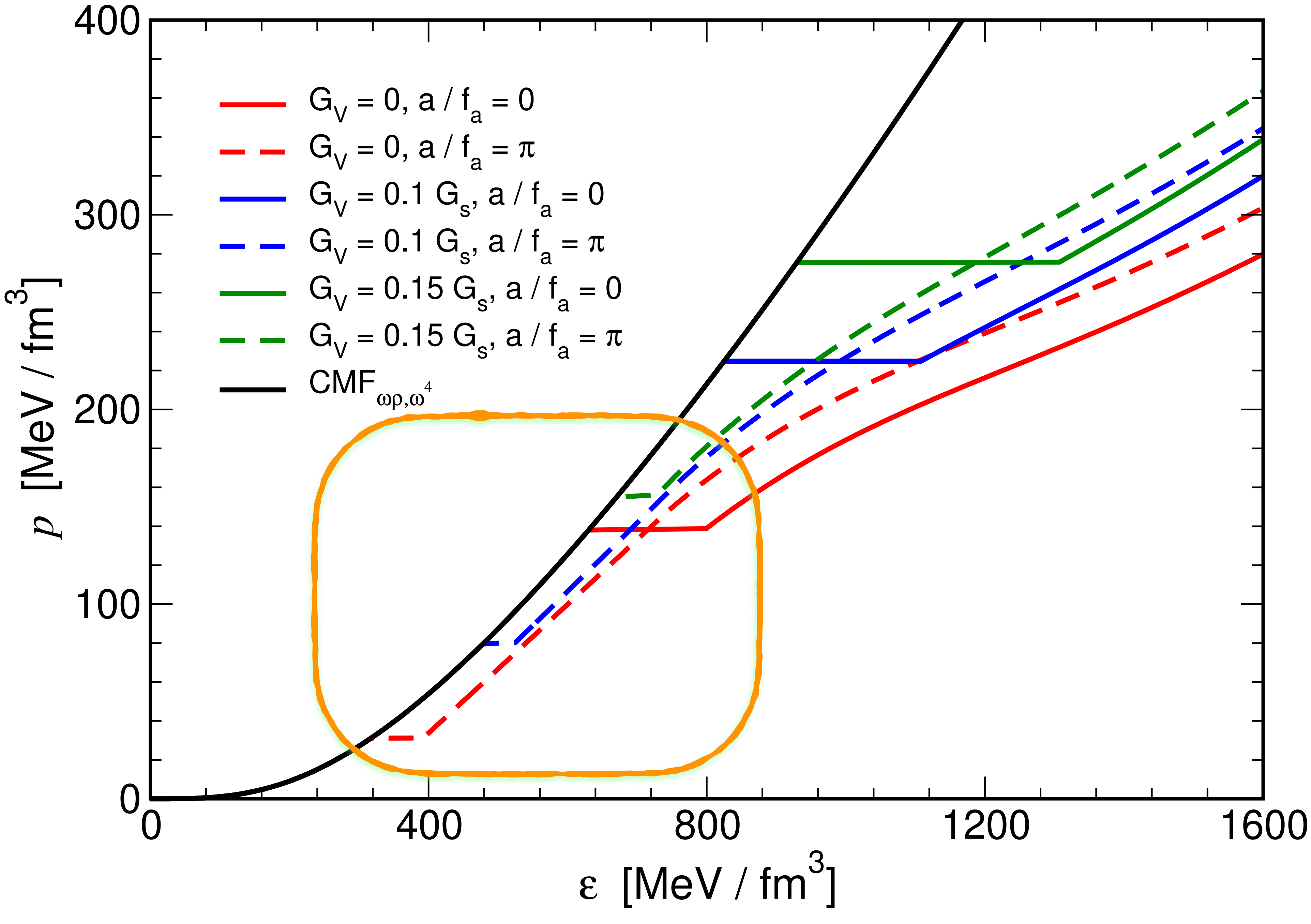

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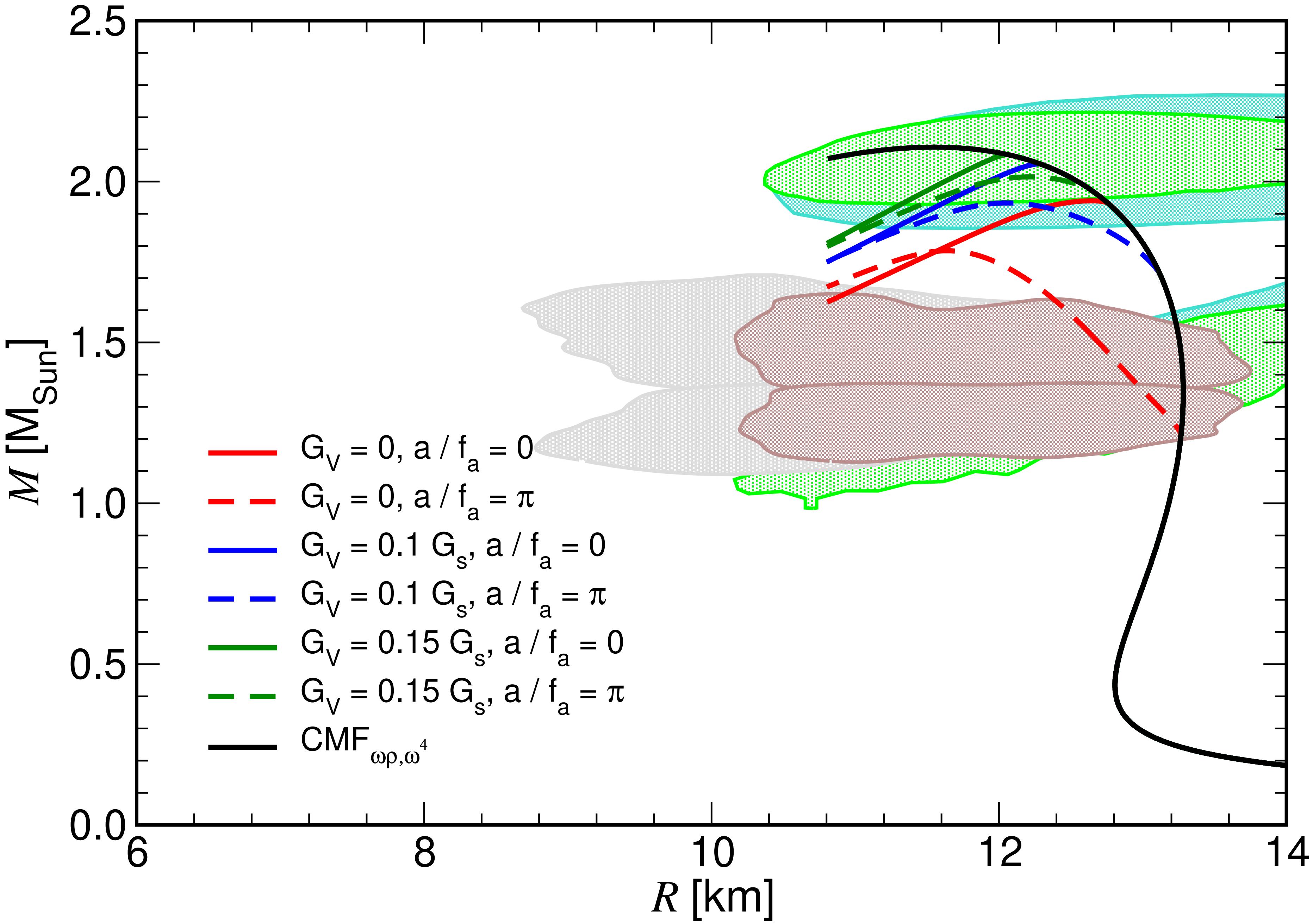

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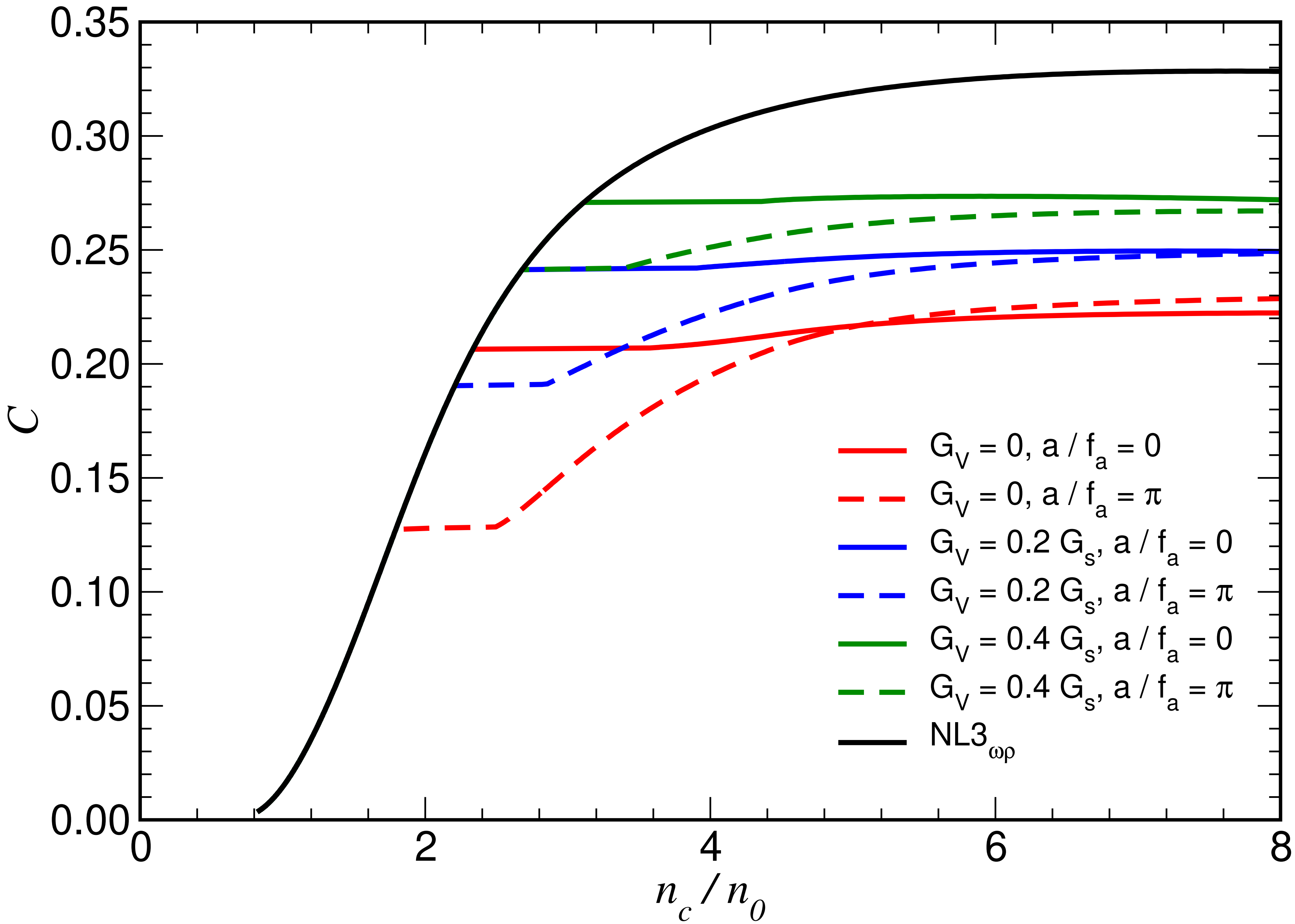
Numerical Results

$$C = M/R$$



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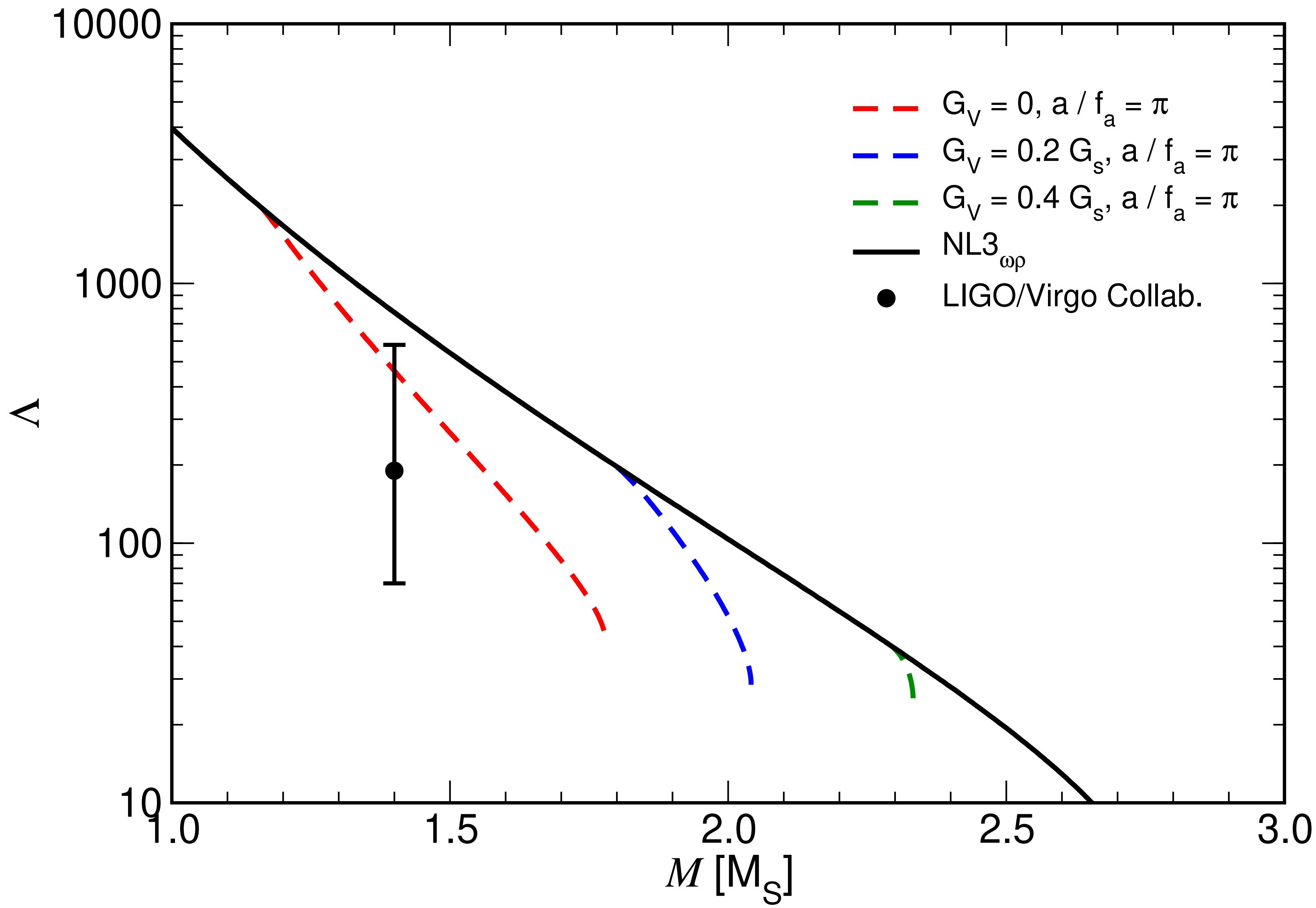
Numerical Results



The vertical bar is the empirical tidal deformability at $M = 1.4 M_{\rm Sun}$ inferred from the Bayesian analysis of the GW170817 data at the 90% confidence level

LIGO Scientific and Virgo Collaborations • B.P. Abbott (LIGO Lab., Caltech) et al. (May 29, 2018), Published in: *Phys.Rev.Lett.* 121 (2018) 16, 161101

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Conclusions

- More specifically, the axion field modifies the quark EoS basically only around the deconfinement phase transition by **weakening** it and **bringing it to lower densities**, thus allowing for a more extended region for stability in the mass-radius diagram

- The axion field thus contributes non-trivially to allow for branches with stable massive hybrid stars, which cannot be achieved by the effects of the vector interaction alone

- Our results show that in the regime of maximum CP violation for the magnitude of the axion field ratio, $a/f_a = \pi$, stable stars with a maximum mass $M > 2$ M_Sun are allowed for $G_V = 0.2 - 0.4\ G_S$

- For higher values of G_V, hybrid stars are more compact

Perspectives

✓ Finite temperature effects on the EoS

✓ Effects of (bosonic) dark matter to the structure of compact stars

Thank you for your attention!

Backup…

QCD axion + NJL model

- Chiral Mean Field $\text{CMF}_{\omega\rho,\omega^4}$ model accounts for chiral symmetry restoration, while also being in agreement with nuclear and astrophysical observations.

- the ω^4 refers to a higher-order vector interaction.

- The complete EoSs also contain separate treatments at very low density to account for the presence of nuclei. The CMF model includes a unified EoS by Gulminelli and Raduta with effective Skyrme interaction of the type SkM proposed by L. Bennour and cluster energy functionals from Danielewicz and Lee.

- The NL3 includes the Baym-Pethick-Sutherland (BPS) EoS and a self-consistent Thomas-Fermi approach with non-spherical pasta phases.

- All the crust EoS's utilized in this work are available in the CompOSE repository.

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