Chiral density wave in neutron stars?

PRD 111, 034010 (2025) with Andreas Schmitt

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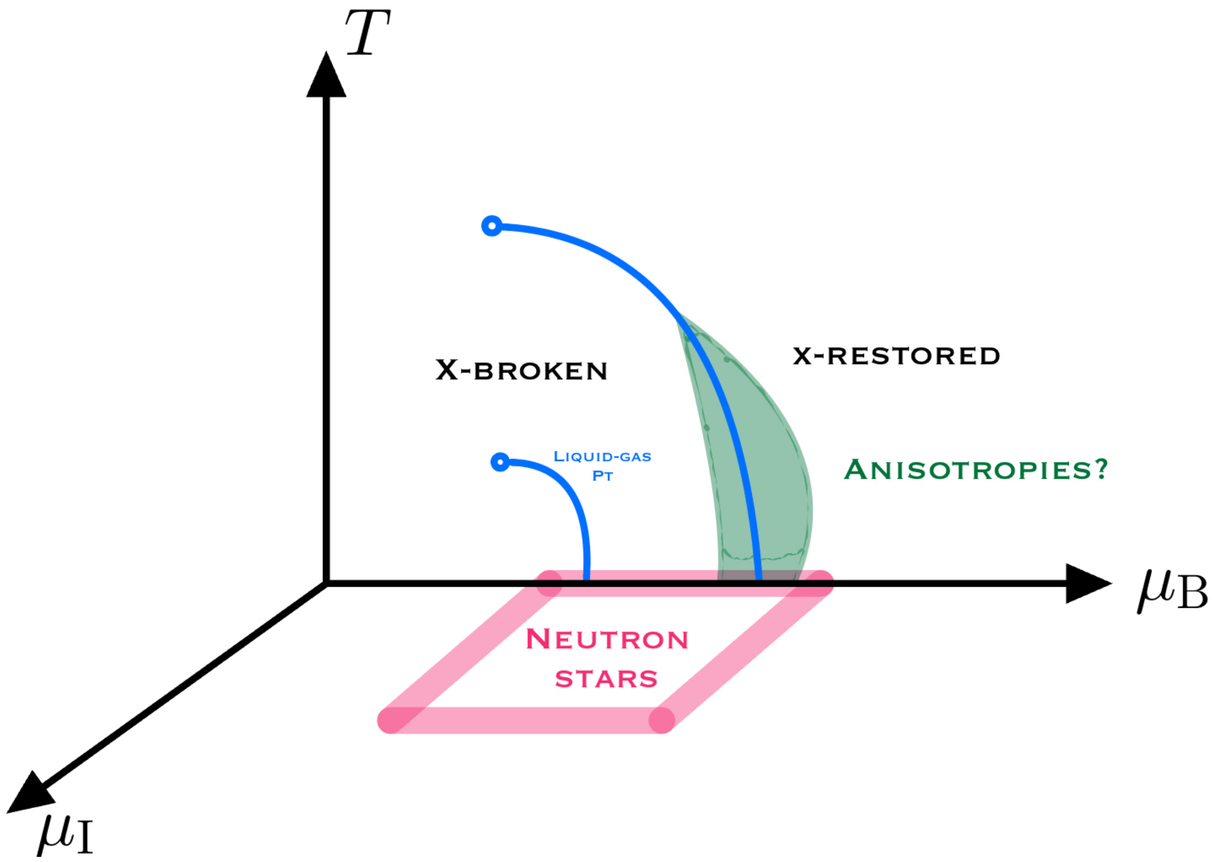
What we are interested in

- Vicinity of chiral phase transition → possible anisotropies [Buballa, Carignano '14 / Demircik, Jokela, Jarvinen, Piispa '24]
- Introduce μ_I, electric charge neutrality, β-equilibrium → neutron star matter

Question: can we have an anisotropic phase present inside a neutron star?



Chiral Density Wave

- Strongly coupled regime → use phenomenological model [Drews, Weise '15 / Fraga, Mata, Pitsinigkos, Schmitt '22]

$$\mathscr{L} = \bar{\psi}\left(i\gamma^\mu\partial_\mu + \gamma^0\hat{\mu}\right)\psi + \quad \text{Nucleons}$$

$$\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\pi_a\partial^\mu\pi^a - U(\sigma,\pi^a) + \frac{1}{2}\left(m_\omega^2\ \omega_\mu\omega^\mu\ +\ m_\rho^2\ \rho_\mu^3\rho_3^\mu\right) + \frac{d_\omega}{4}\left(\omega_\mu\omega^\mu\right)^2 + \frac{d_\rho}{4}\left(\rho_\mu^3\rho_3^\mu\right)^2 + \frac{d_{\omega\rho}}{2}\omega_\mu\omega^\mu\rho_\nu^3\rho_3^\nu + \ldots \quad \text{Mesons}$$

$$-\bar{\psi}\left[g_\sigma(\sigma + i\gamma^5\pi) + \gamma^\mu(g_\omega\omega_\mu + g_\rho\rho_\mu)\right]\psi \quad \text{Interactions} \quad + \text{Free electrons, muons}$$

- Mean-field approximation: neglect meson fluctuations (we work at $T = 0$)
- Chiral density wave (CDW): anisotropic chiral condensate, here

$$\langle\sigma\rangle = \phi\cos(2\vec{q}\cdot\vec{x}), \quad \langle\pi^0\rangle = \phi\sin(2\vec{q}\cdot\vec{x})$$ [Nickel '09 / Dautry, Nyman '79 / Heinz, Giacosa, Rischke '15]

- Keep nucleonic Dirac sea contribution [Pitsinigkos, Schmitt '23]

Parameter Fit

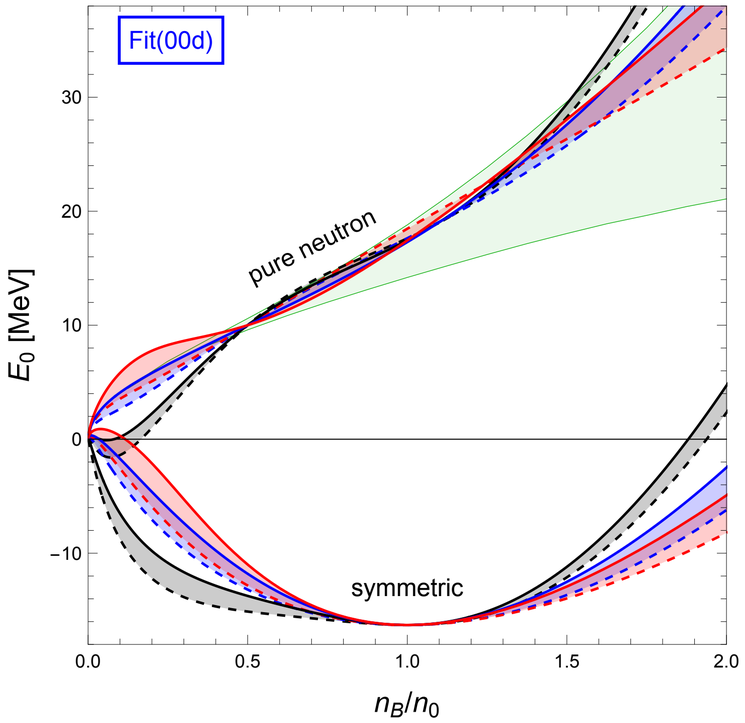
Phenomenological Model → fit model parameters to experimental data:

1. Vacuum
2. Saturation (isospin-symmetric)
3. Pure neutron matter

[Tews, Carlson, Gandolfi, Reddy '18 / Alford, Brodie, Haber, Tews '22]

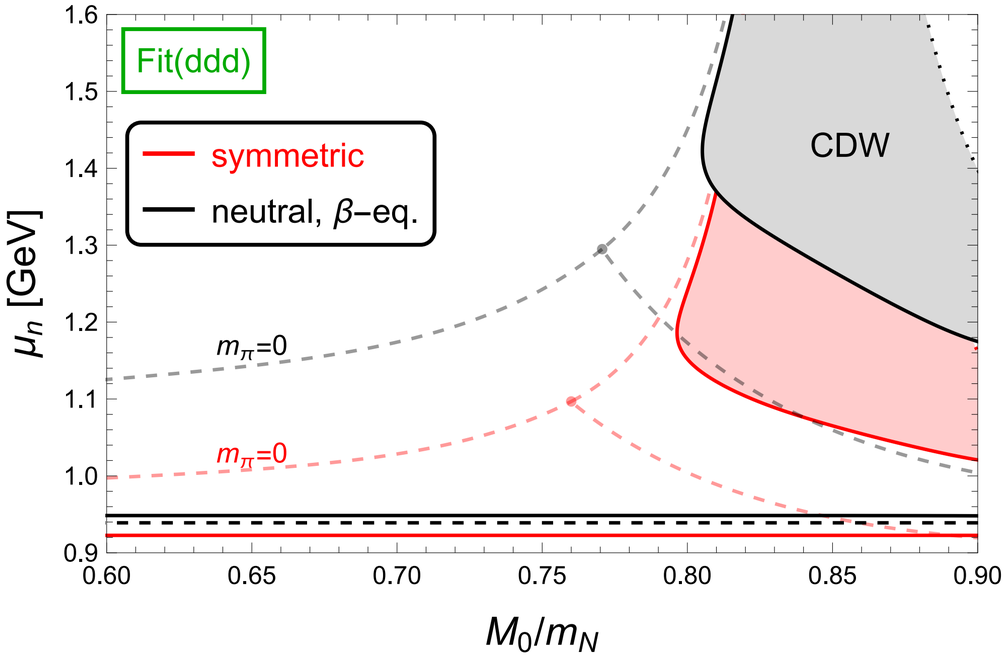
Two distinct fits: Fit(00d) and Fit(ddd)

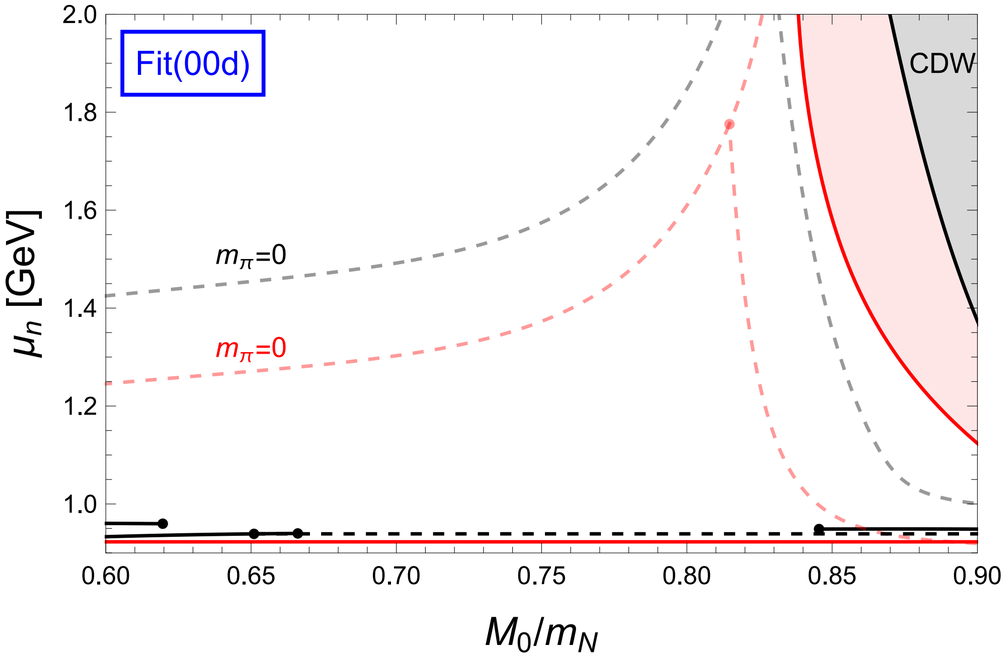
… from $\frac{d_\omega}{4}\left(\omega_\mu\omega^\mu\right)^2 + \frac{d_\rho}{4}\left(\rho_\mu^3\rho_3^\mu\right)^2 + \frac{d_{\omega\rho}}{2}\omega_\mu\omega^\mu\rho_\nu^3\rho_3^\nu$



Extremise w.r.t $\phi, q, \langle\omega_0\rangle, \langle\rho_0^3\rangle, \mu_n, \mu_e$: find thermodynamically stable solutions

Effect of Neutron Star Conditions



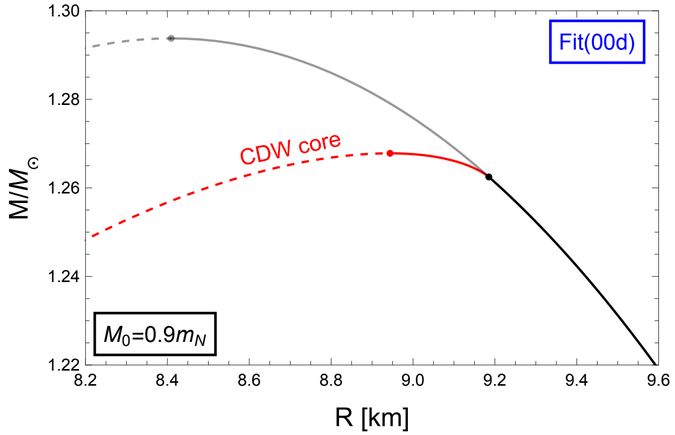


M_0: nucleon mass at saturation $\in (0.7m_N, 0.8m_N)$

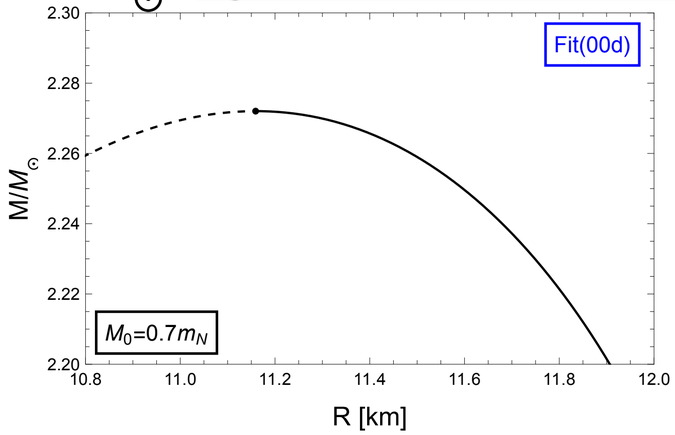
Neutron star conditions → CDW less preferred compared to isospin symmetric matter

Constructing Neutron Stars

Stable CDW core



$M > 2M_\odot$ (agree with observations)



Combine with TOV equations

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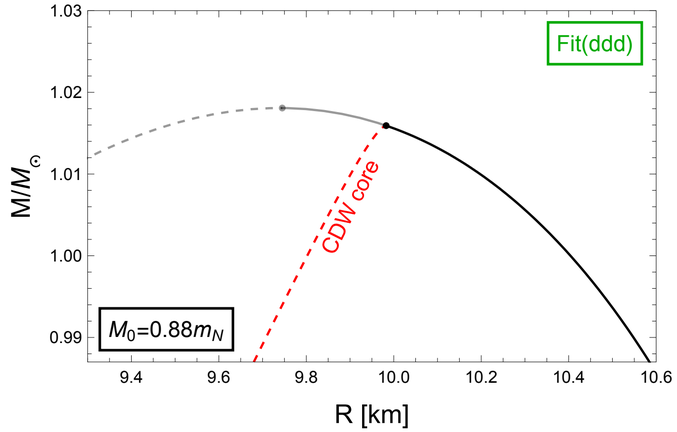
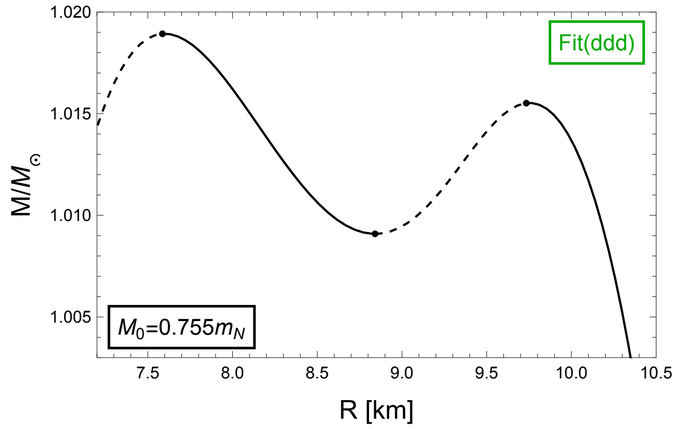
Mass-Radius curves of stable neutron stars

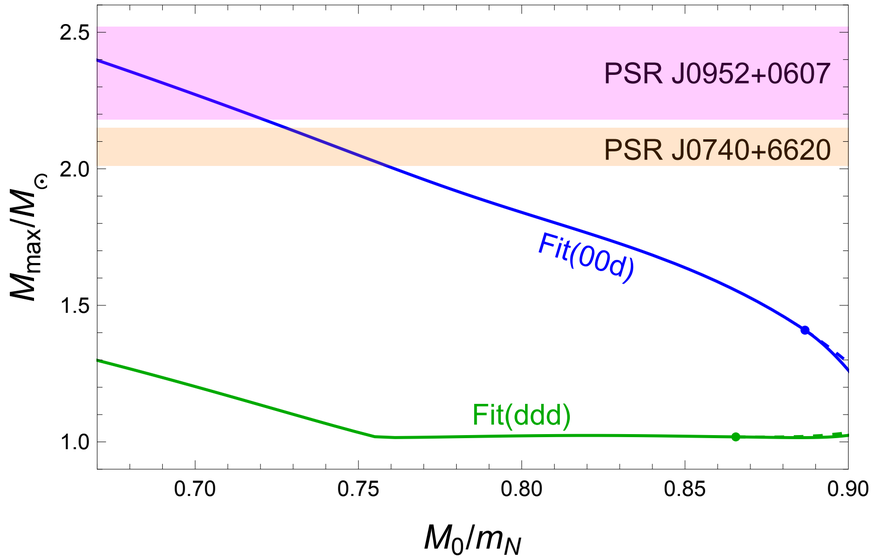
Unstable CDW core



Twin star construction



Realistic CDW Stars?



Compare with observations

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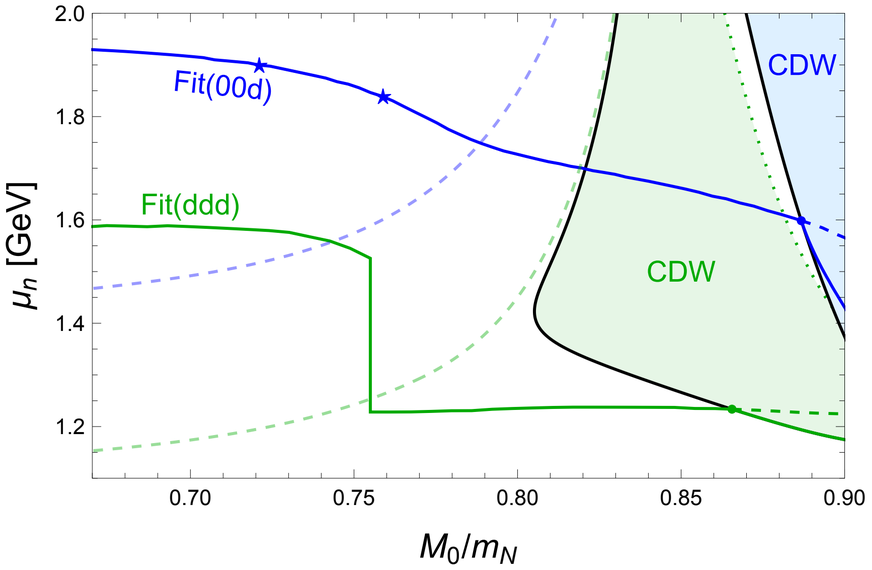
Fit(00d) can create massive enough stars (without CDW), Fit(ddd) cannot



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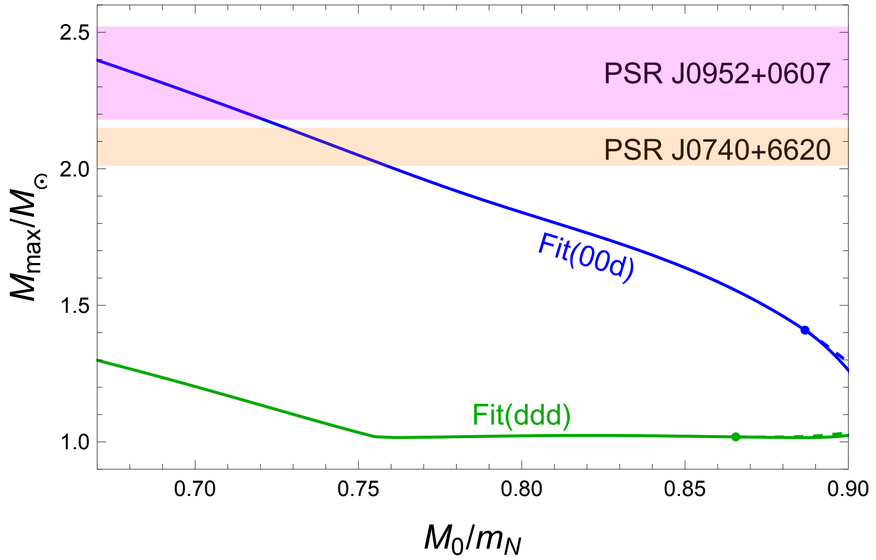

1. Twin star structure

Compare with observations

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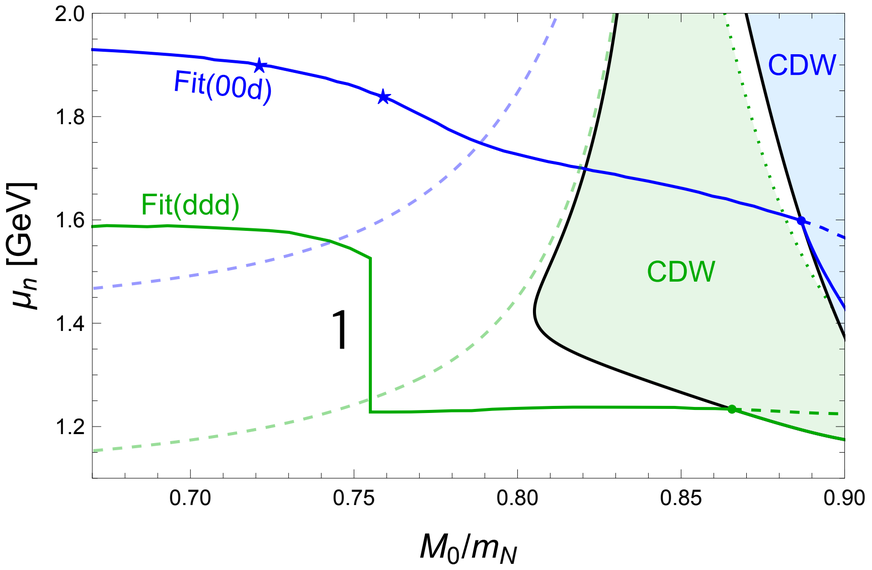

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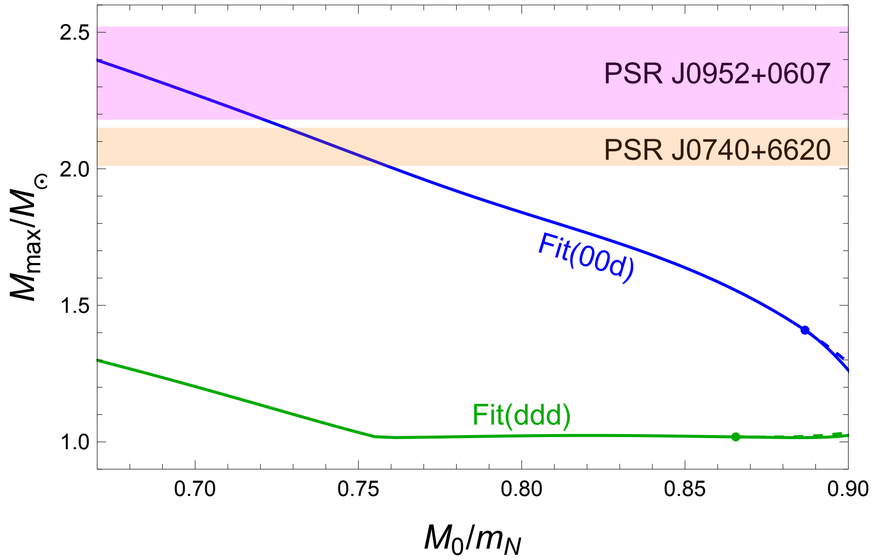

Compare with observations

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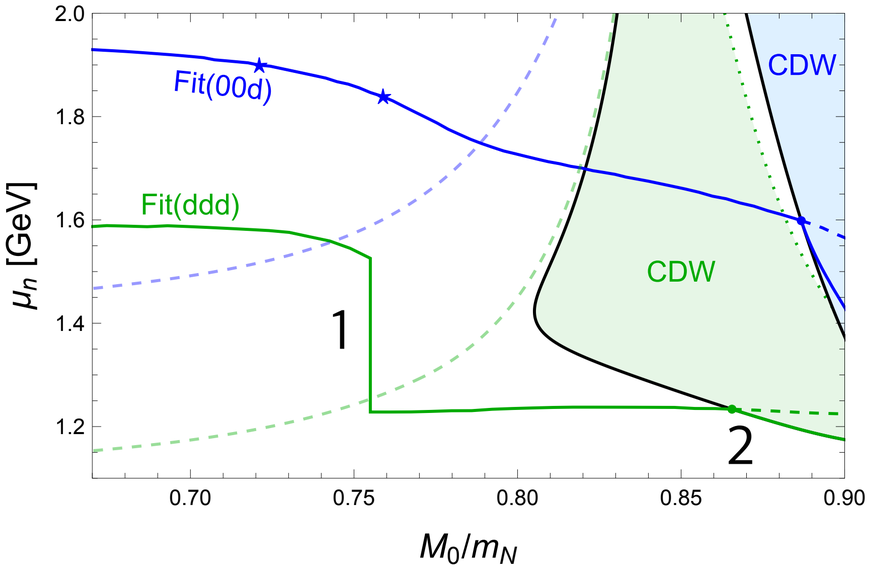
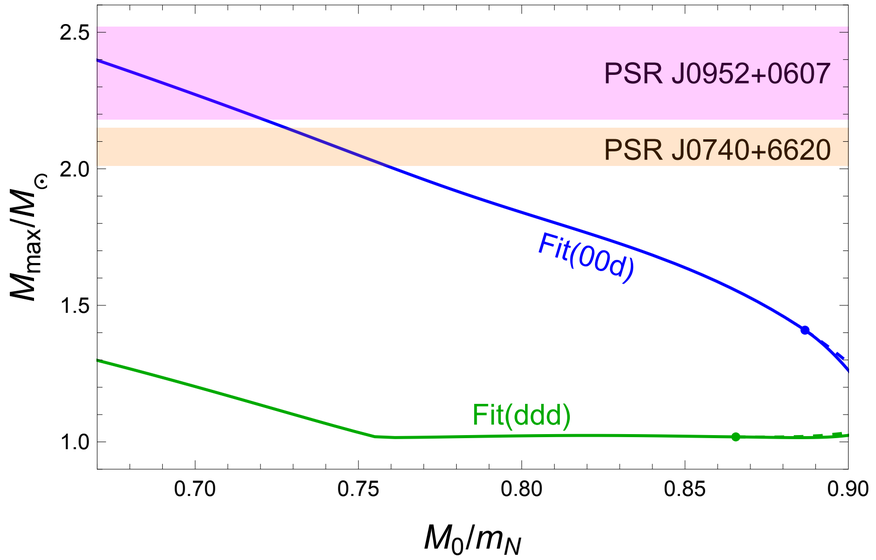
Fit(00d) can create massive enough stars (without CDW), Fit(ddd) cannot

1. Twin star structure
2. Unstable stars with CDW cores



Realistic CDW Stars?



Compare with observations

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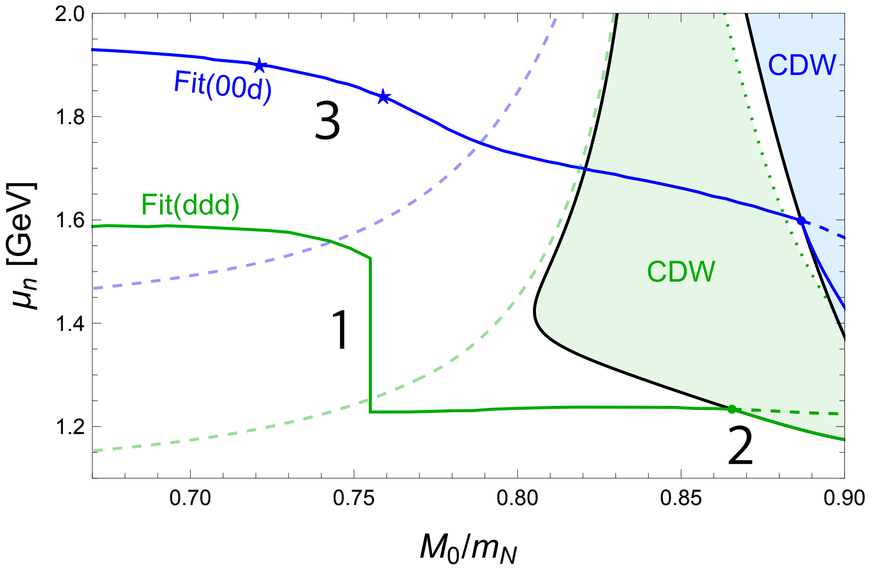
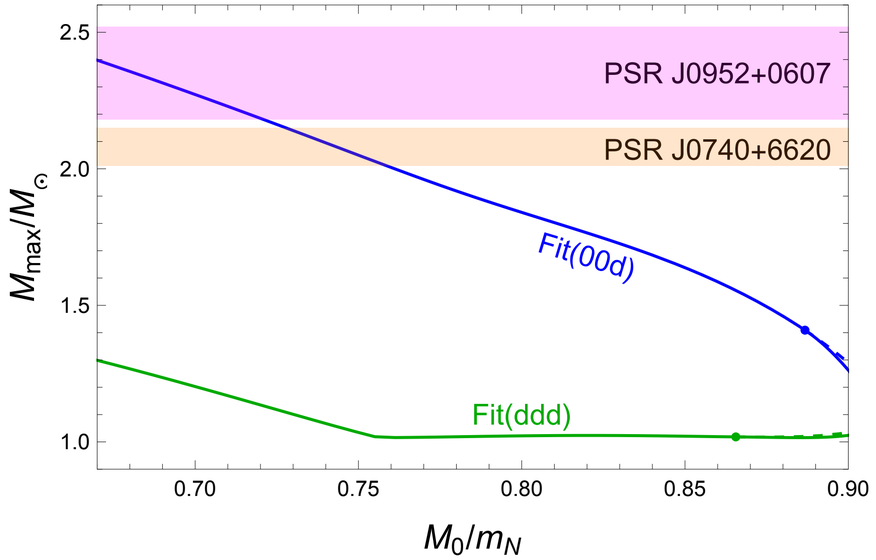
Fit(00d) can create massive enough stars (without CDW), Fit(ddd) cannot

1. Twin star structure
2. Unstable stars with CDW cores
3. Agree with observations



Realistic CDW Stars?



Compare with observations

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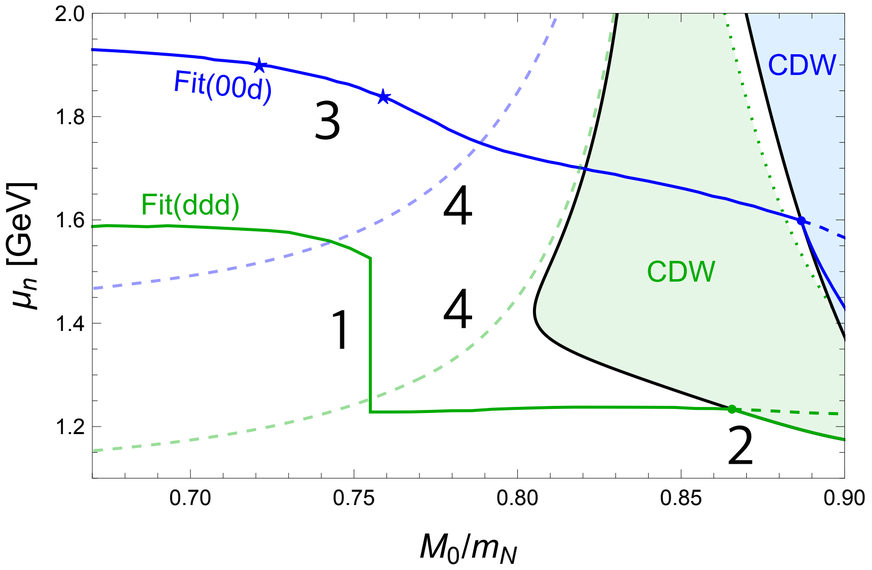
Fit(00d) can create massive enough stars (without CDW), Fit(ddd) cannot

1. Twin star structure
2. Unstable stars with CDW cores
3. Agree with observations
4. Hybrid star criterion



Summary

- Studied CDW ansatz within nucleon–meson model (with Dirac sea), and constructed neutron stars
- Neutron star conditions disfavour the CDW
- Can construct stars with CDW, although they are not massive enough
- Without CDW, can construct hybrid stars that agree with maximum mass observations

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Outlook

- Model dependence: extend to chiral partner model [Fraga, Mata, Schaffner-Bielich ‘23]
- Add magnetic field: enhances the preference of anisotropic phases [Carignano, Ferrer, de la Incera, Paulucci ’15]
- More complicated anisotropic structures [Pisarski, Tsvelik, Valgushev ‘20]
- Strongly coupled calculation: use AdS/CFT correspondence [Kovensky, Poole, Schmitt ’22 / Ecker, Kovensky, OP, Schmitt ’25]

Thank you for your attention!

Grazie mille!