Strange magnetars admixed with fermionic dark matter

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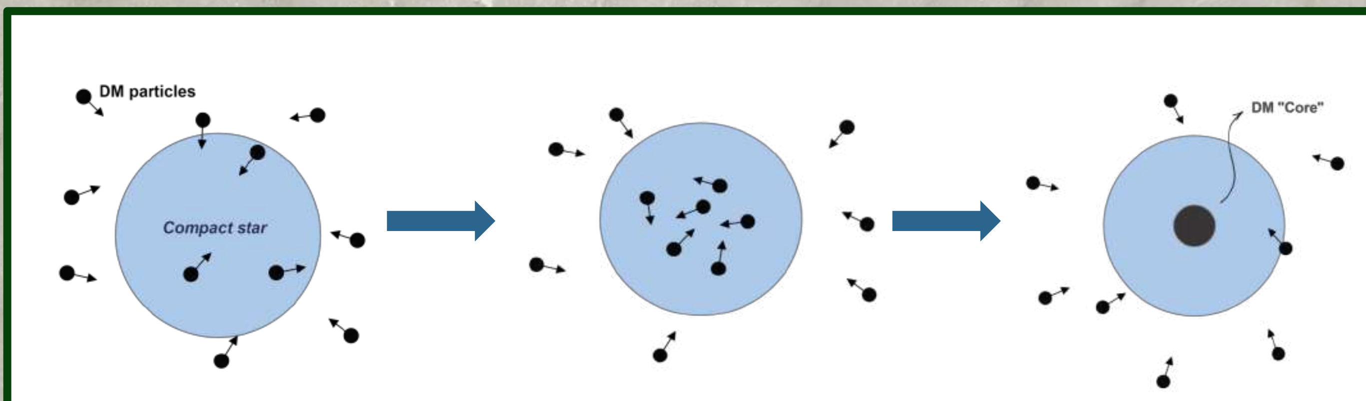
Cold dark matter & compact stars

★ DM is hard to probe, so one needs extreme gravitational interactions.

★ In principle, DM particles could collide with neutrons and other components of NS, loose energy, be gravitationally trapped, and accumulate in their cores.



[Kouvaris et al (2008)]

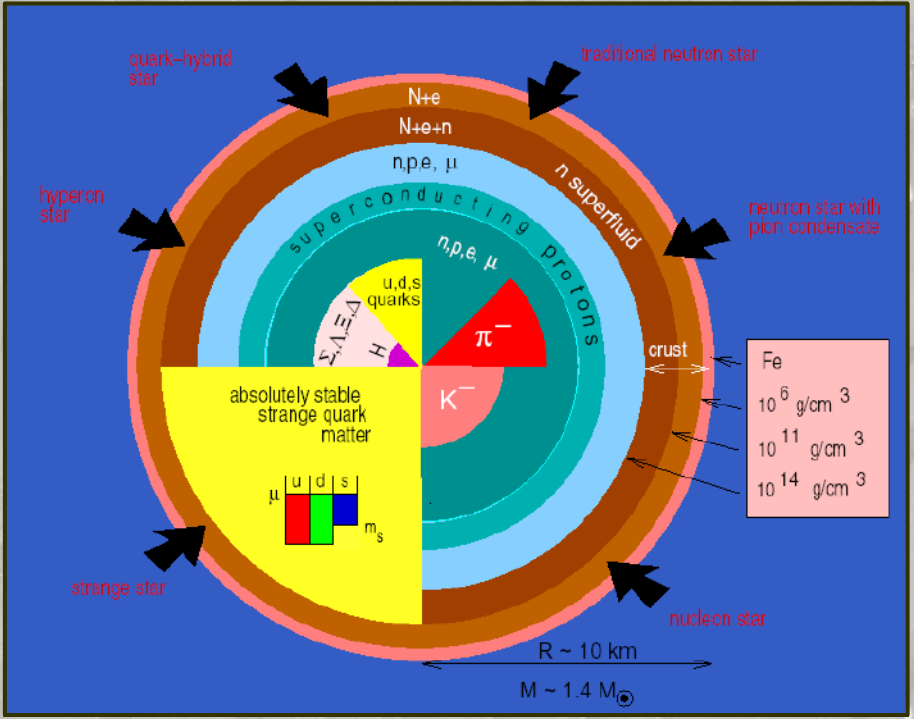
★ NB: nucleon interactions (not ideal Fermi gas) + momentum dependence of the hadronic form factors -> significant suppression of DM capture rate in NS [Bell et al (2021)].

★ For high enough central densities, one expects to find either hybrid stars, i.e., neutron stars with a quark matter core, or even more exotic objects, such as quark stars.

★ If quark stars are to be found in the universe, they have most likely accumulated some amount of dark matter over the course of their lives.

★ What is the effect of the presence of cold fermionic DM on:

- ➡ the structure of quark stars (mass, radius, etc) ?
- ➡ their stability w.r.t. radial oscillations ?
- ➡ quark magnetars with very high magnetic fields ?

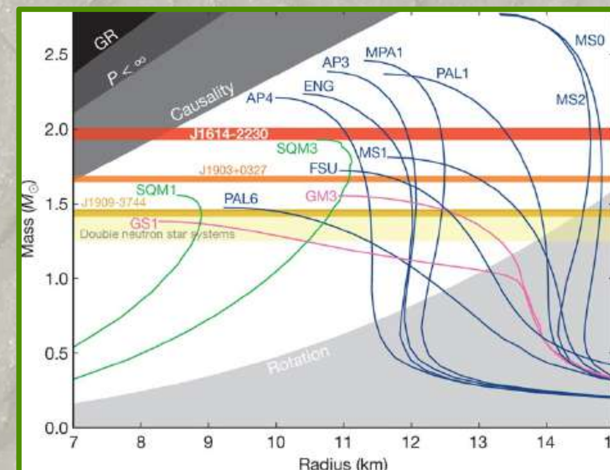


[F. Weber, 2000]

★ Which ingredients do we need?

- ➡ Equations of state for cold DM and cold QM.
- ➡ Stellar structure from TOV equations for two-fluid stars.

pressure(T,μ,B,etc) + TOV



[Demorest et al (2010)]

- ➡ Stability equations & behavior of fundamental frequency.
- ➡ Incorporation of large magnetic fields in the EoS for QM.

[ESO]

Equations of state

Self-interacting CDM

[Narain, Schaffner-Bielich & Mishustin (2006); Mukhopadhyay & Schaffner-Bielich (2016)]

★ Fermi gas + two-body self-repulsion between fermions

★ Useful dimensionless quantities: $z = k_F / m_D$; $y = m_D / m_I$

★ m_I : interaction mass scale

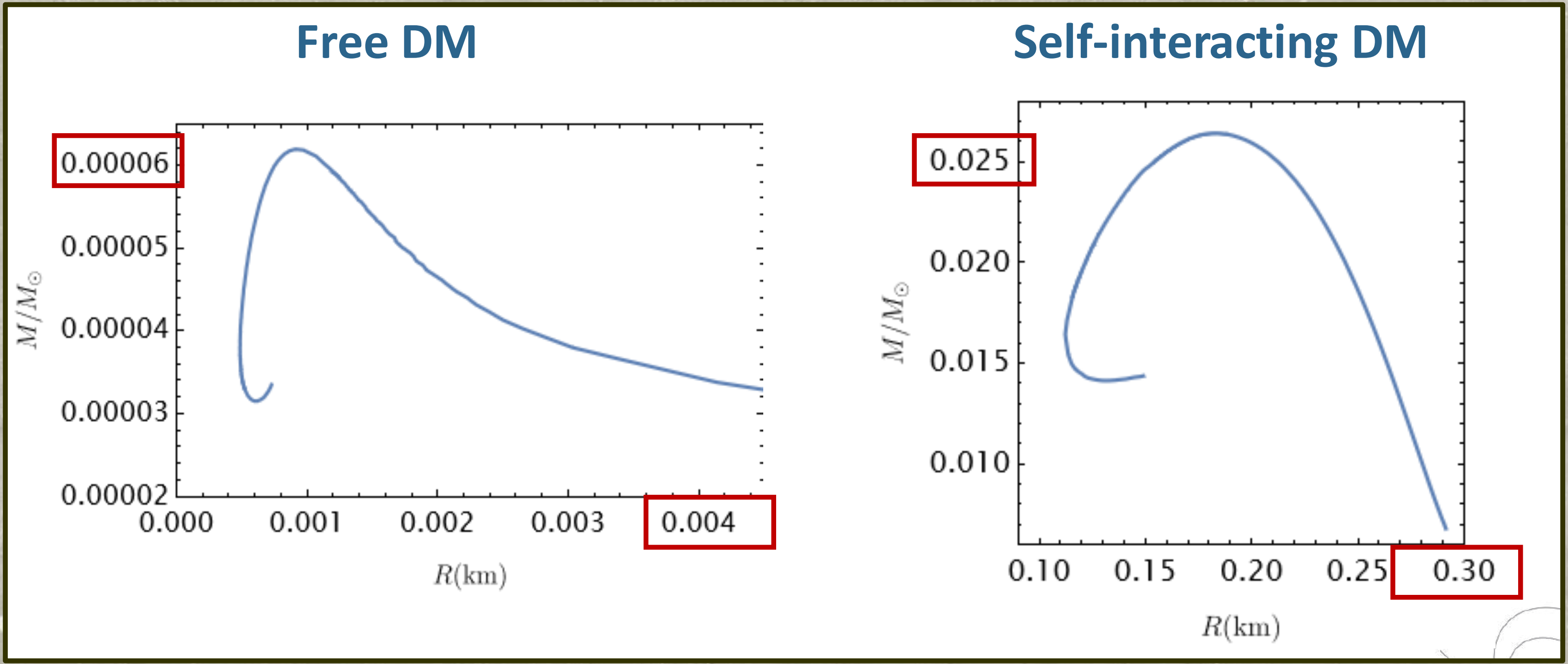
★ m_D = 1, 10, 50, 100, 200, 500 GeV (dark fermion mass)

★ $y = 0.1$ (weak DM); $y = 10^3$ (strong DM)

★ Pressure:

$$\frac{p_{\rm DM}}{m_{\rm D}^4} = \frac{1}{24\pi^2}\left[(2z^3 - 3z)\sqrt{1+z^2} + 3\sinh^{-1}(z)\right] + \left(\frac{1}{3\pi^2}\right)^2 y^2 z^6$$

Effects from DM self-interaction

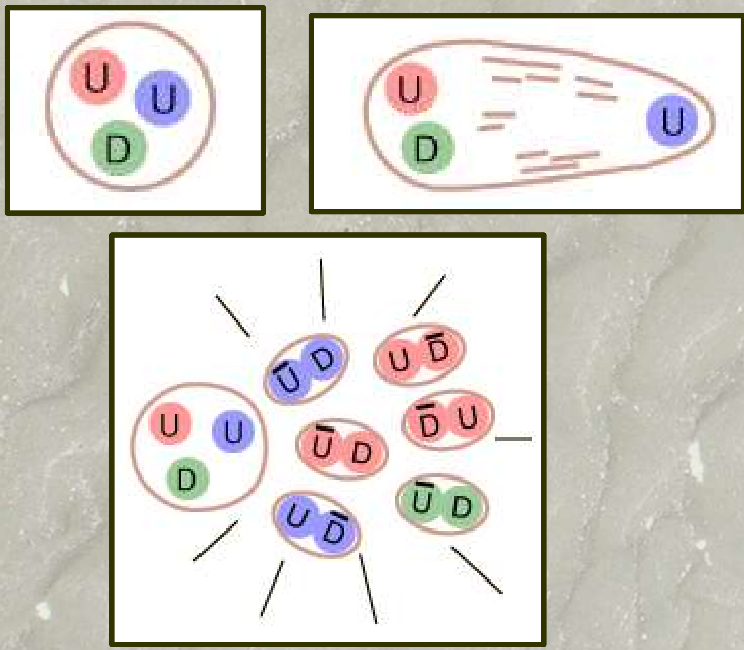


[Ferreira & ESF (in prep.)]

★ Self-interacting case corresponds to <u>much</u> larger masses and radii.

Cold QM

★ MIT bag model, perhaps the most popular approach to QM in NS.



Asymptotic freedom + confinement in the simplest and crudest fashion: bubbles (bags) of perturbative vacuum in a confining medium.
+ eventual corrections ~ α_s

- Asymptotic freedom: free quarks and gluons inside color singlet bags

- Confinement: vector current vanishes on the boundary

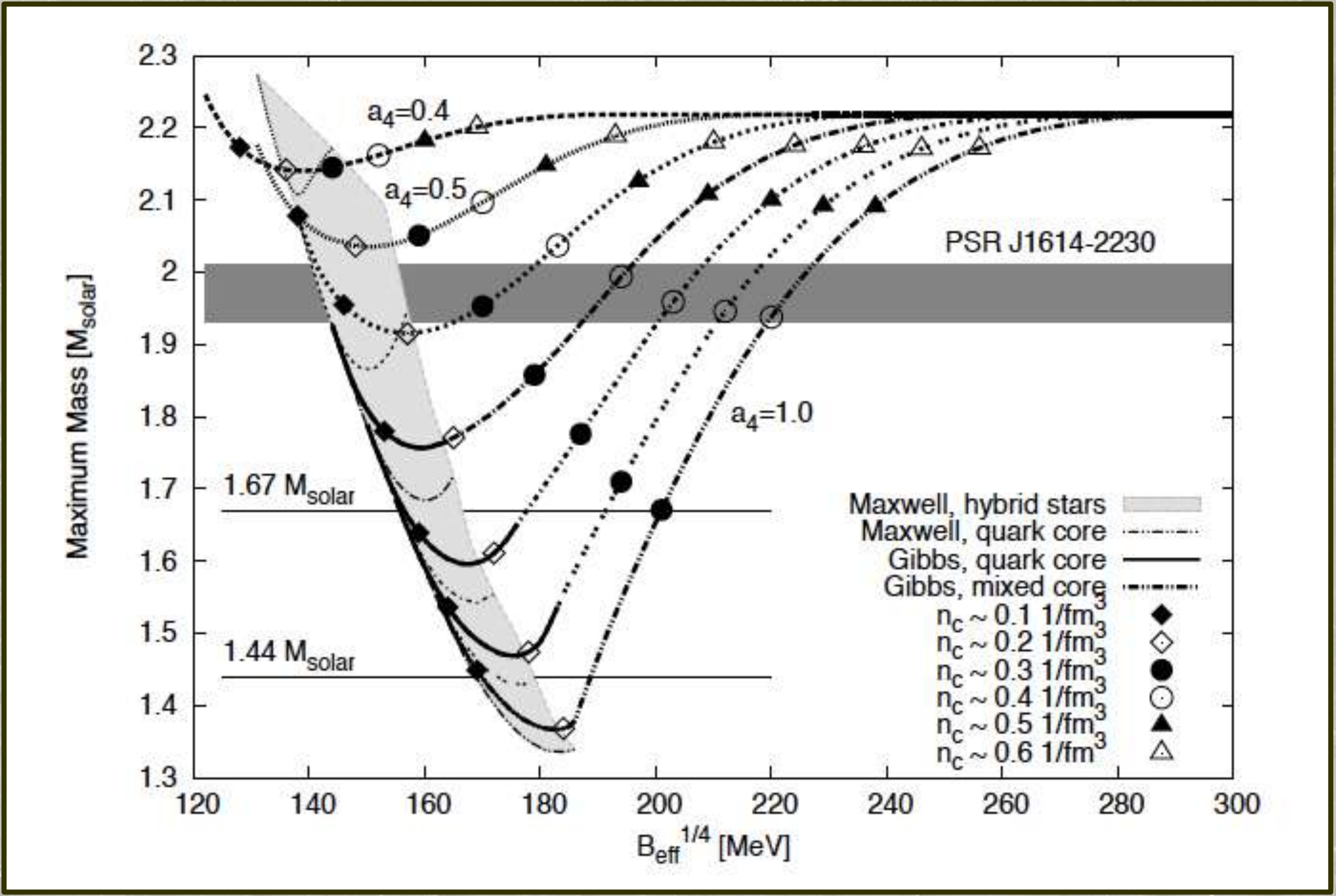
★ $B = (145\text{MeV})^4 \approx 57\text{MeV/fm}^3$ is the bag constant chosen to surpass the two-solar mass limit.

★ Pressure:

$$p_{\mathrm{QM}} = \frac{3\mu_q^4}{4\pi^2} - B$$

(μ_q : quark chemical potential)

Dependence on the choice of the bag constant



[Weissenborn, Sagert, Pagliara, Hempel, Schaffner-Bielich (2011)]

Stellar structure of one-fluid stars

★ From the TOV equations

[Einstein's GR field equations + spherical symmetry + hydrostatic equilibrium]

$$\frac{dp}{dr} = -\frac{G\mathcal{M}(r)\epsilon(r)}{r^2\left[1-\frac{2G\mathcal{M}(r)}{r}\right]}\left[1+\frac{p(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{\mathcal{M}(r)}\right]$$

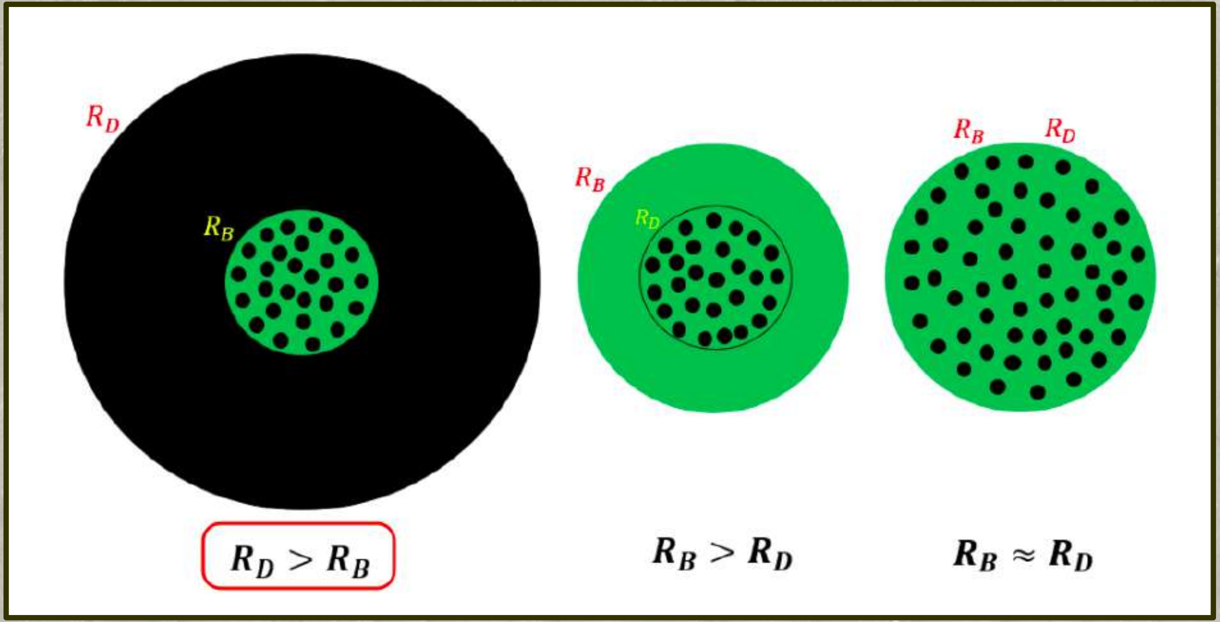
$$\frac{d\mathcal{M}}{dr} = 4\pi r^2\epsilon(r) \;\; ; \quad \mathcal{M}(R) = M$$

m_D	$M_{max}(M_\odot)$	R_{min}	**Compact Star**
100 GeV	10^{-4}	1 m	neutralino star (cold DM)
1 GeV	1	10 km	neutron star
1 GeV/0.5 MeV	1	10^3 km	white dwarf
10 keV	10^{10}	10^{11} km	sterile neutrino star
1 keV	10^{12}	10^{13} km	axino star (warm DM)
1 eV	10^{18}	10^{19} km	neutrino star
10^{-2} eV	10^{22}	10^{23} km	gravitino star

[Mukhopadhyay & Schaffner-Bielich (2016)]

Quark stars admixed with DM

⋆ Three possible configurations for dark compact stars



[Karkevandi et al. (2021)]

Stellar structure of two-fluid stars

★ Two-fluid TOV equations

[Sandin & Ciarcelluti (2009)]

$$\frac{dp_{\rm QM}}{dr} = -\frac{(p_{\rm QM}+\epsilon_{\rm QM})}{2}\frac{d\nu}{dr}, \qquad \frac{dm_{\rm QM}}{dr} = 4\pi r^2 \epsilon_{\rm QM},$$

$$\frac{dp_{\rm DM}}{dr} = -\frac{(p_{\rm DM}+\epsilon_{\rm DM})}{2}\frac{d\nu}{dr}, \qquad \frac{dm_{\rm DM}}{dr} = 4\pi r^2 \epsilon_{\rm DM},$$

$$\frac{d\nu}{dr} = 2\frac{(m_{\rm QM}+m_{\rm DM}) + 4\pi r^3 (p_{\rm QM}+p_{\rm DM})}{r(r-2(m_{\rm QM}+m_{\rm DM}))},$$

★ Boundary conditions:

- $m_{QM}(r \to 0) = m_{DM}(r \to 0) \to 0$
- $R_{QM} > R_{DM}$: first $p_{DM}(R_{DM}) \to 0$; later $p_{QM}(R_{QM}) \to 0$
- $R_{DM} > R_{QM}$: first $p_{QM}(R_{QM}) \to 0$; later $p_{DM}(R_{DM}) \to 0$

Radial oscillations

[Jiménez & ESF (2022)]

★ $\Delta r/r \equiv \xi$ & Δp are the independent variables ; Γ: adiabatic index

[Gondek et al. (1997)]

★ For two-fluid stars one can write the total Lagrangian variables as $\xi \equiv \xi_{QM} + \xi_{DM}$ and $\Delta p \equiv \Delta p_{QM} + \Delta p_{DM}$

★ Two-fluid radial pulsating equations

$$\frac{d\xi_{\rm QM/DM}}{dr} \equiv -\frac{1}{r}\left(3\xi_{\rm QM/DM} + \frac{\Delta p_{\rm QM}}{\Gamma p}\right) - \frac{dp}{dr}\frac{\xi_{\rm QM/DM}}{(p+\epsilon)} \; ,$$

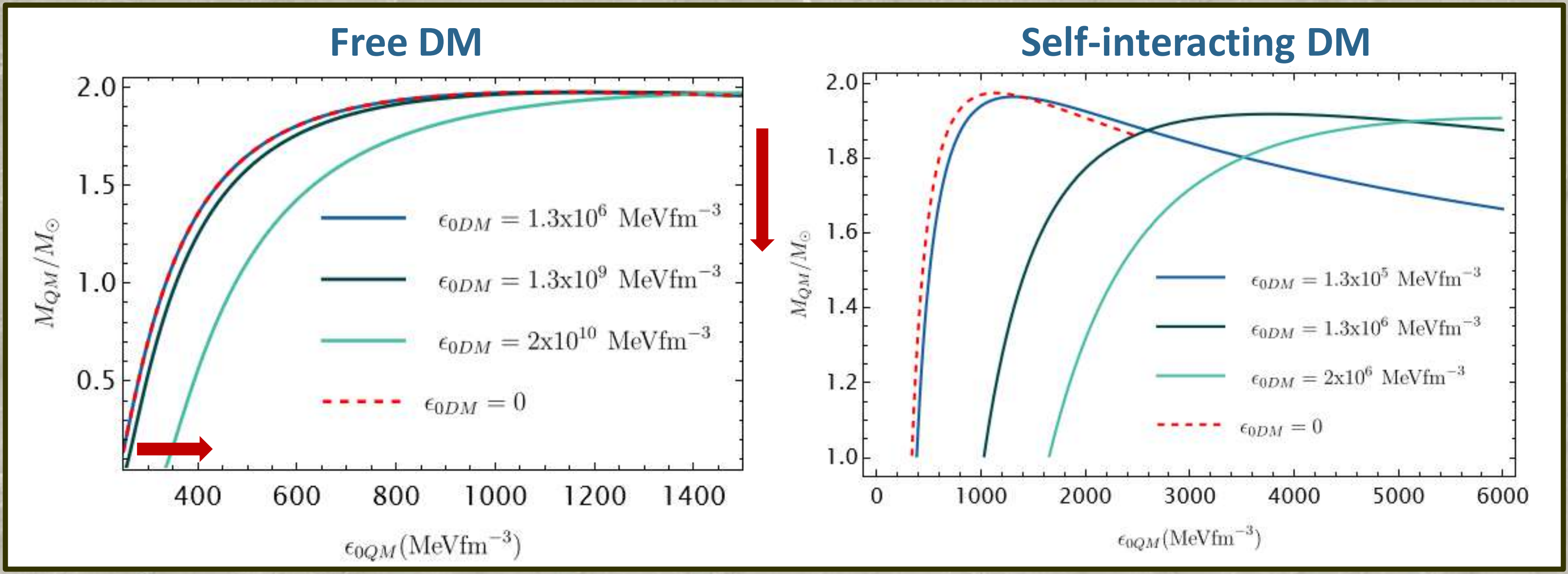
$$\frac{d\Delta p_{\rm QM/DM}}{dr} \equiv \xi_{\rm QM/DM}\left\{\omega^2 e^{\lambda-\nu}(p+\epsilon)r - 4\frac{dp}{dr}\right\} + \xi_{\rm QM/DM}\left\{\left(\frac{dp}{dr}\right)^2 \frac{r}{(p+\epsilon)} - 8\pi e^{\lambda}(p+\epsilon)pr\right\} + \Delta p_{\rm QM/DM}\left\{\frac{dp}{dr}\frac{1}{p+\epsilon} - 4\pi(p+\epsilon)re^{\lambda}\right\}$$

$$\lambda(r) = -\ln(1 - 2(m_{\rm QM}(r) + m_{\rm DM}(r))/r)$$

★ ω: oscillation frequency ; $\lambda(R_{QM}) = -\nu(R_{QM})$ and $\lambda(R_{DM}) = -\nu(R_{DM})$

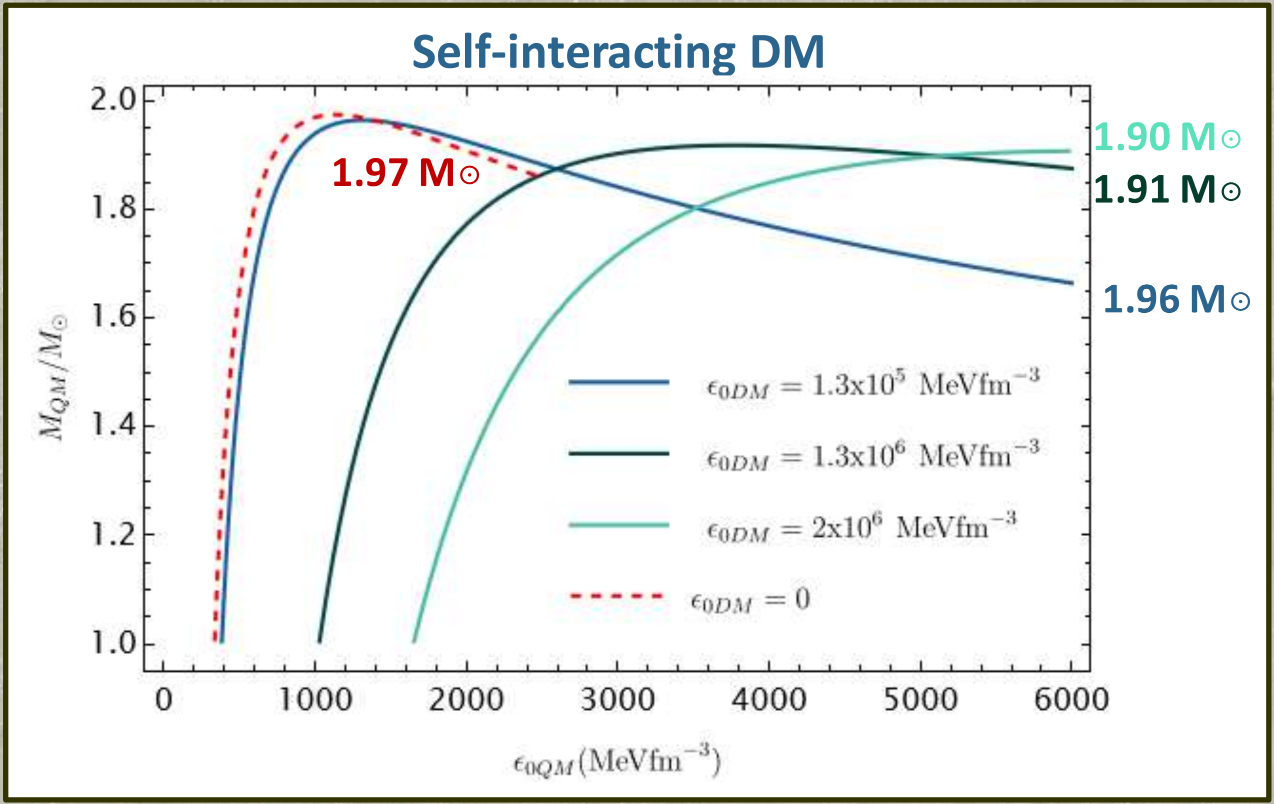
Results for structure and stability

Results for m_D = 100 GeV for illustration: [Ferreira & ESF (2022)]



⋆ The increase in DM central energy density does not change the maximum mass and radius very much, but shifts the curves towards higher central energy densities.

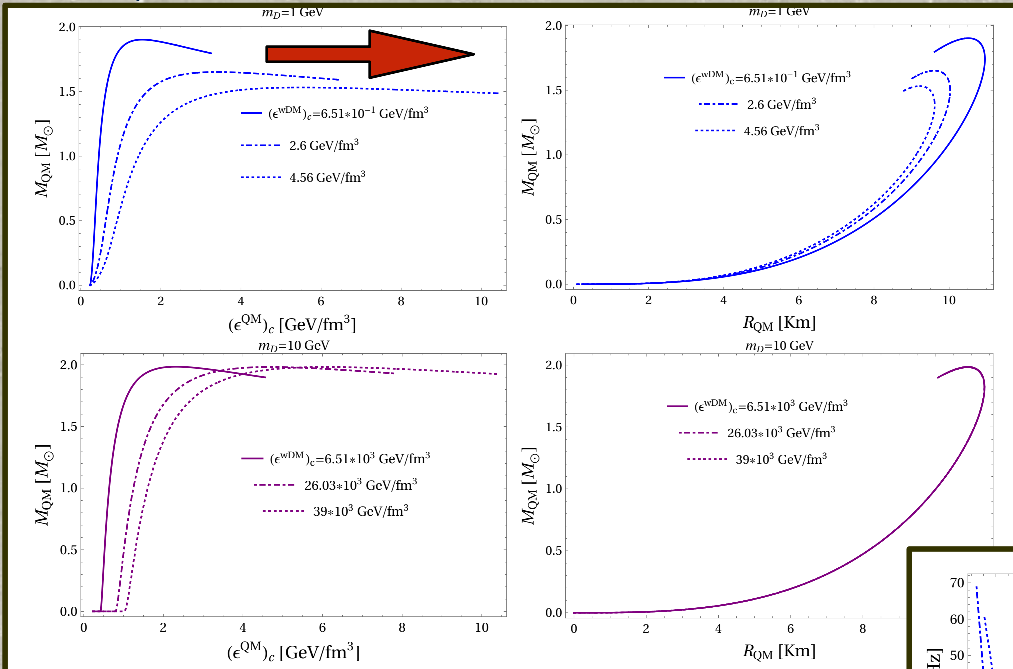
⋆ The range of stable configurations occurs at higher central energy densities.



⋆ Slight decrease of maximum mass with the increase of DM central energy density.

Results for different values of m_D - structure and stability of quark stars admixed with DM

[Jiménez & ESF (2022)]

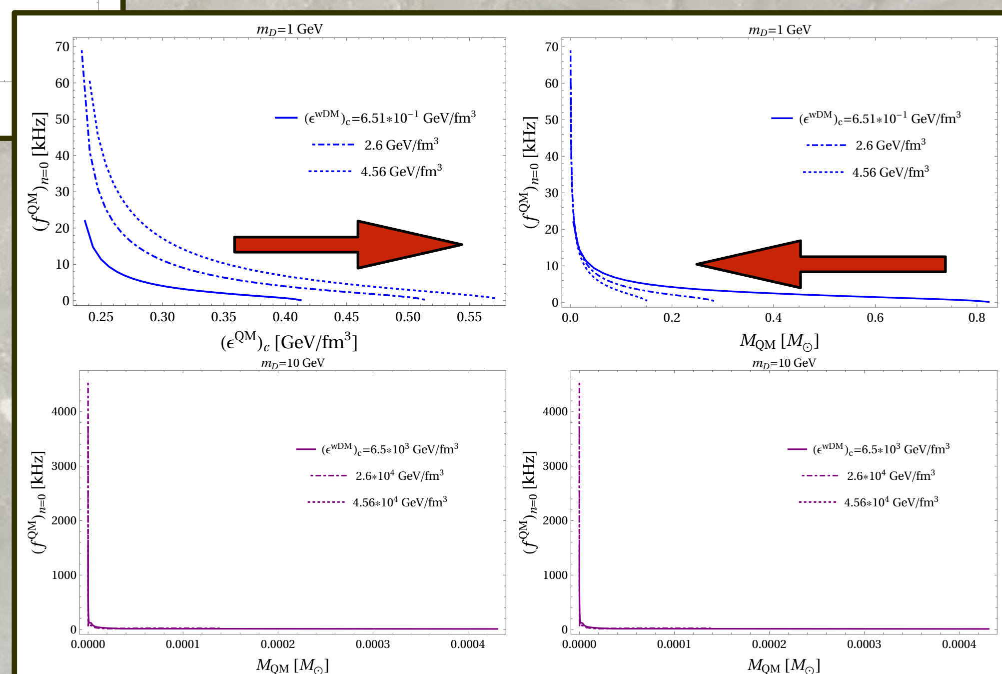


wDM: $y = 0.1$; $m_D = 1, 10$ GeV

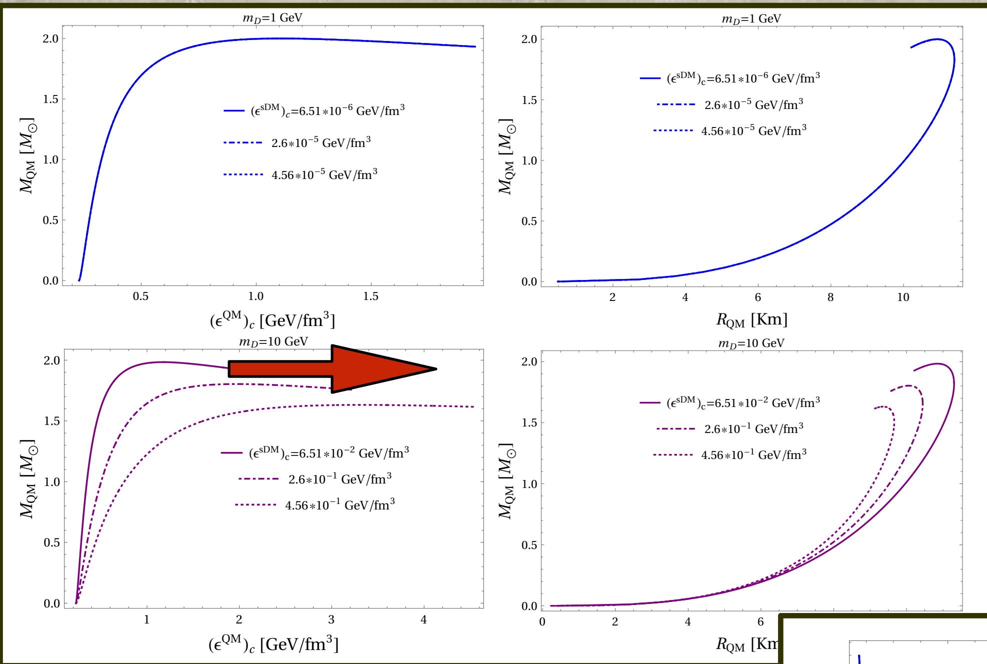
★ Mass-radius visible modifications only for small m_D.

★ Higher QM energy densities to compensate for the extra gravitational pull from DM.

★ Stability window of ultra-light quark stars (surrounded by DM): 10^{-18}-10^{-4} $M_\odot$, depending on m_D -> dark strange "planets" and strangelets.



sDM: $y = 10^3$; m_D = 1, 10 GeV

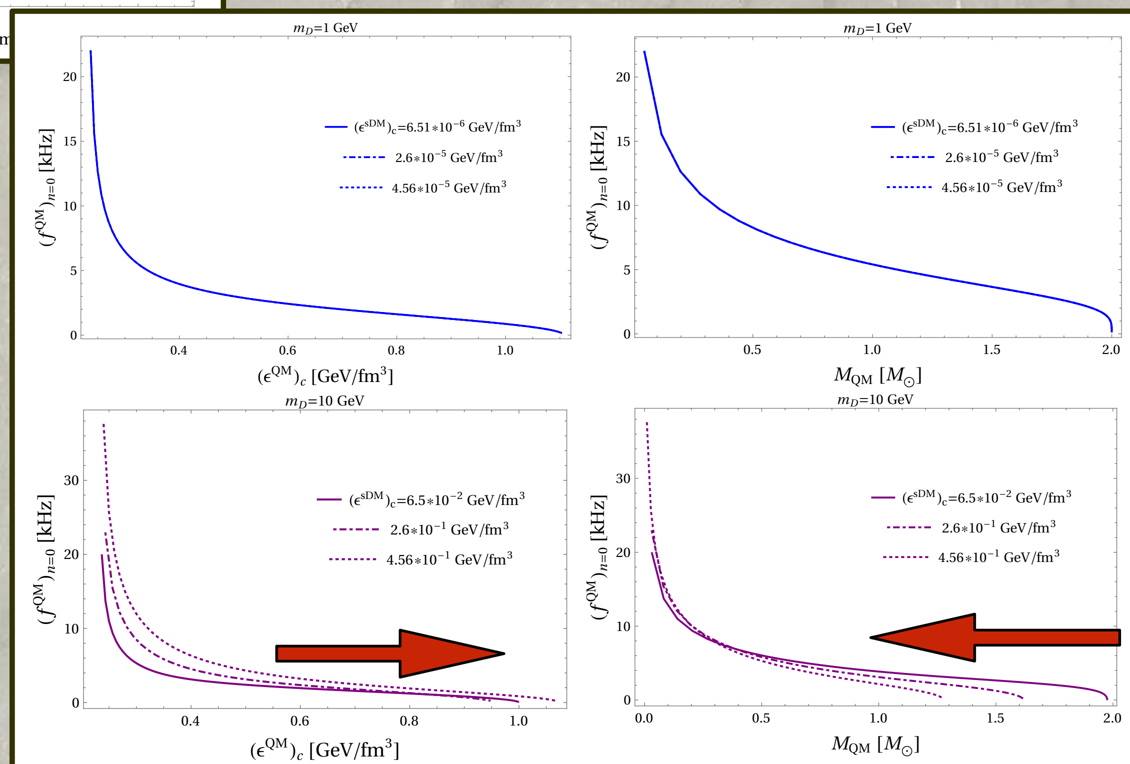


★ As for wDM, in most of the cases M, R and central energy densities of the QM core are not appreciably affected.

★ As we increase m_D, the fundamental frequency is strongly affected.

★ Increasing DM central densities, the maximum QM central densities are increased by a factor of ~20 in some cases.

★ Results very sensitive to m_D.



Effects from high magnetic fields

[Ferreira & ESF (2022)]

Soft gamma repeater (SGR) in 1979
(Mazets et al., 1979 [7])
(Cline et al, 1980 [8])

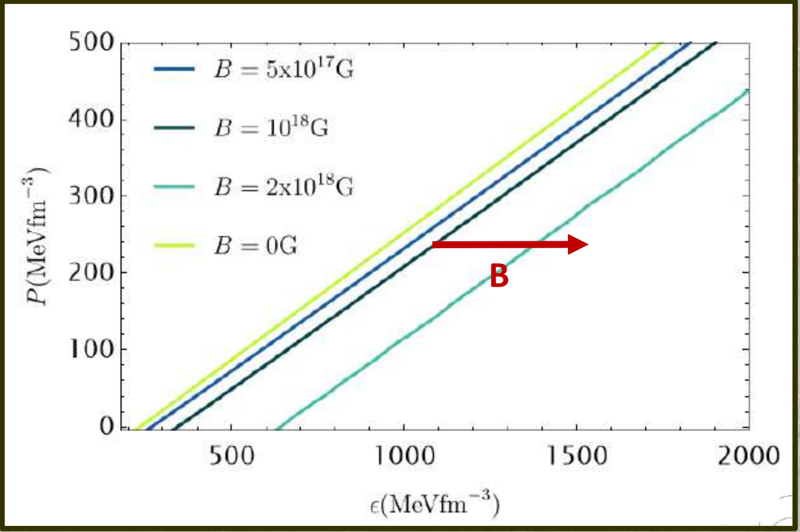
Anomalous X-ray pulsar (AXP)
(Mereghetti & Stella, 1995 [9])

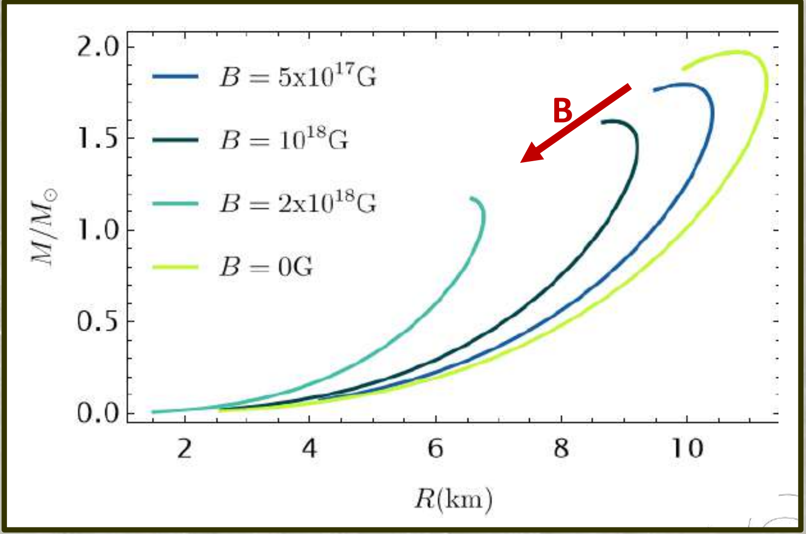
→ **Magnetars surface magnetic fields of the order of 10^{14} G - 10^{15} G.**

★ Magnetic fields inside magnetars may reach values B ~ 10^{18} G.

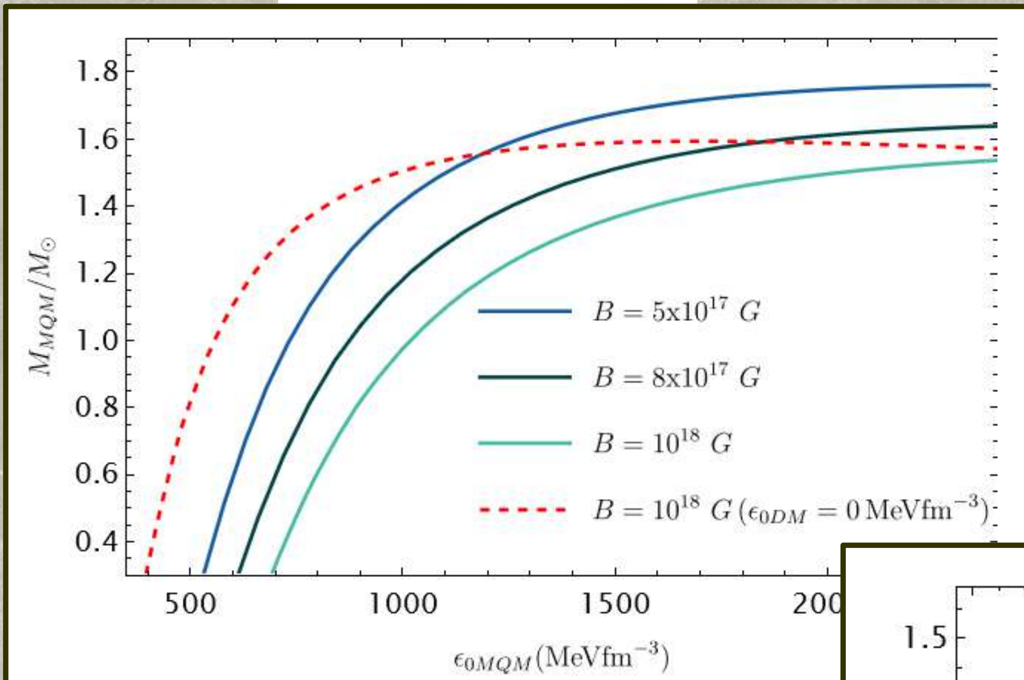
[Cardall, Prakash & Lattimer (2001)]

★ For quark magnetars:





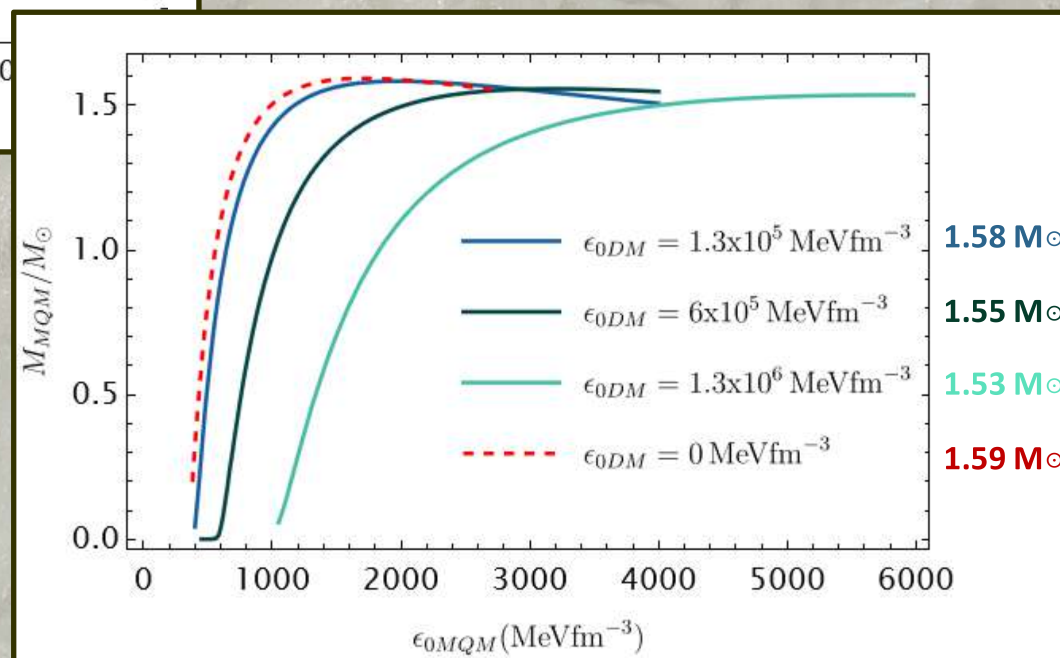
$\epsilon_{0DM} = 6\text{x}10^5\ \text{MeVfm}^{-3}$



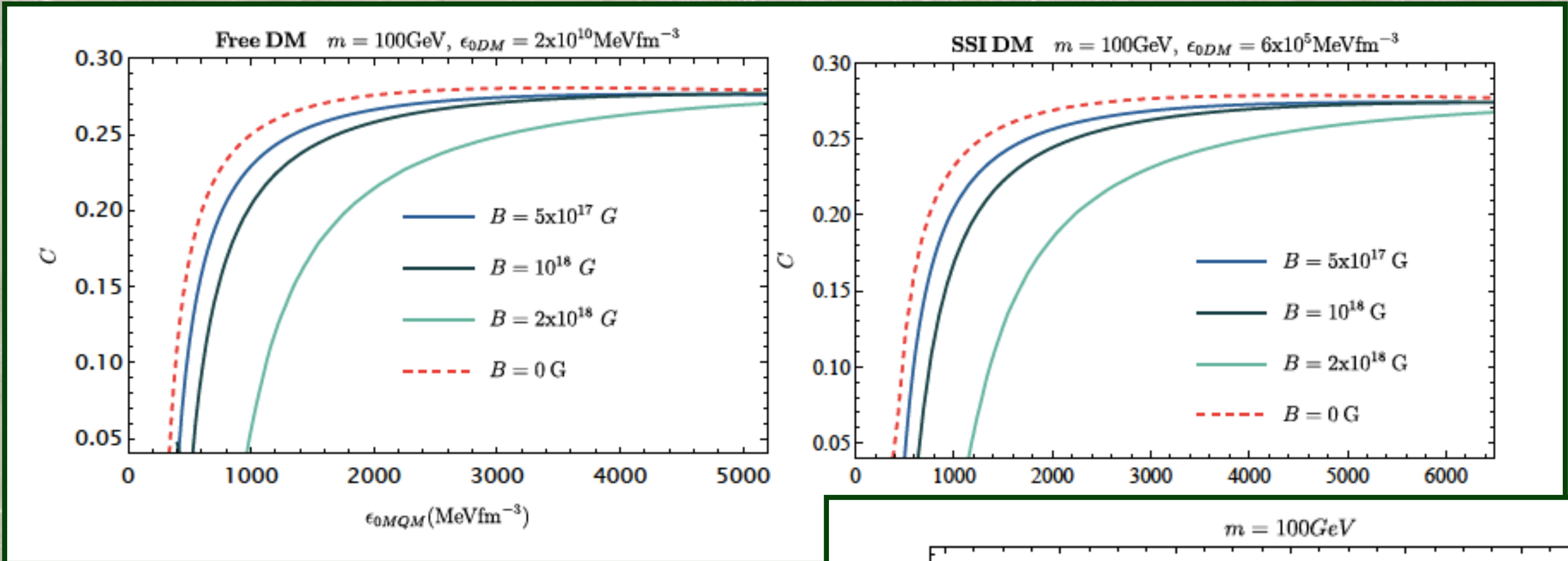
★ Magnetic fields tend to "pull" in the same direction as DM: larger central energy densities, smaller masses.

★ NB: red curves have no DM.

★ There was no concern in producing $2M_\odot$ stars here (which is possible).

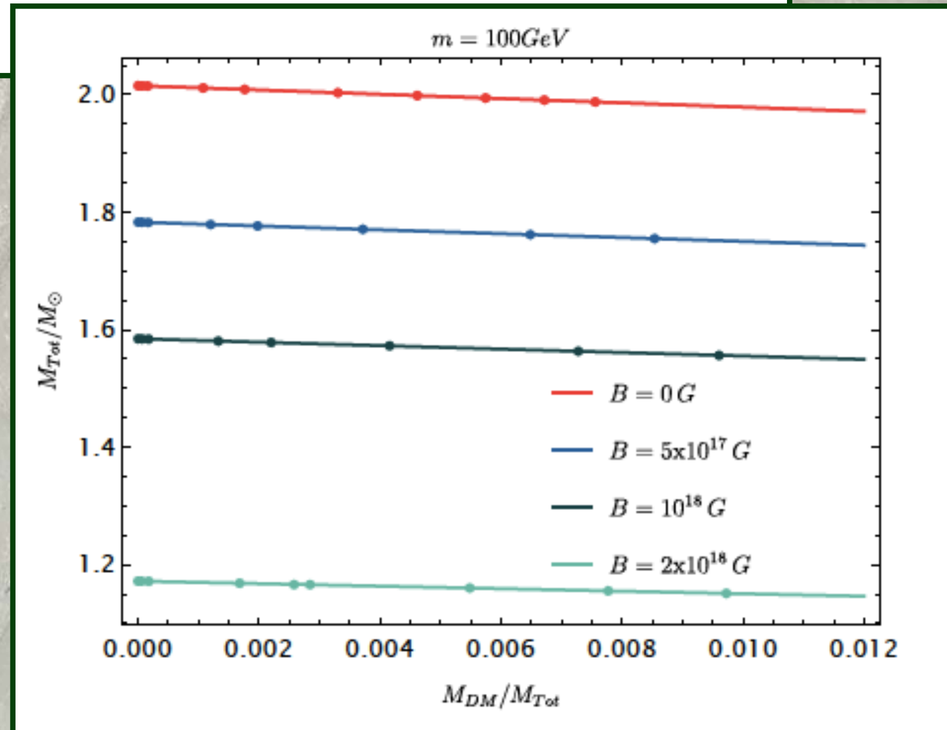


⋆ Compactness:



⋆ Decrease in total mass as a function of the fraction of DM for different values of B:

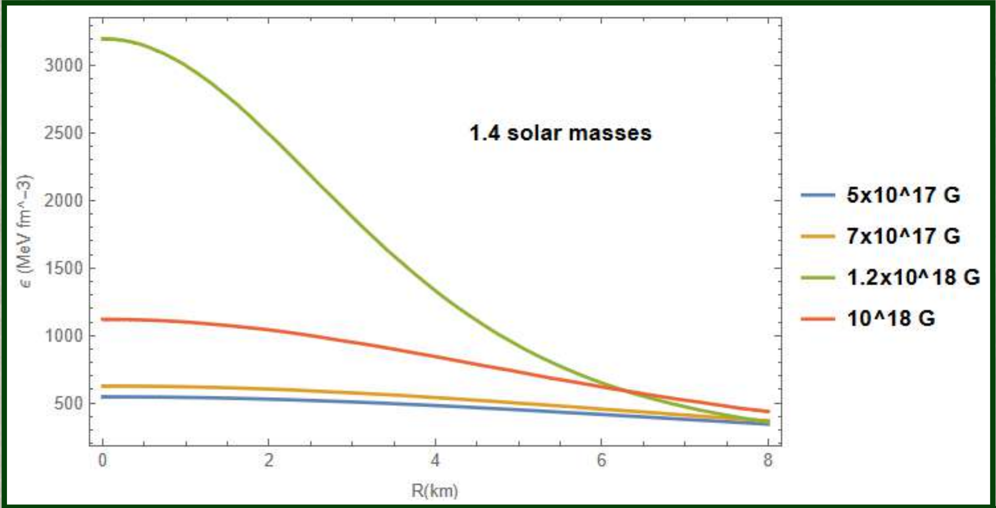
B (G)	Slope of the linear fit (α)
0	-3.6
5×10^{17} G	-3.2
1×10^{18} G	-2.9
2×10^{18} G	-2.1



Other observables - preliminary

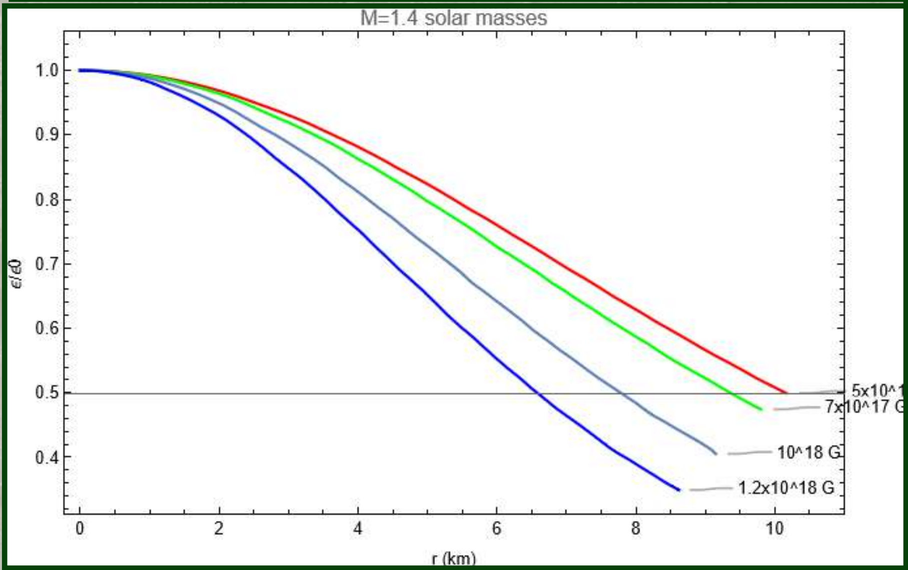
[Ferreira, ESF & Jiménez (in prep.)]

★ Radial profiles (no DM):

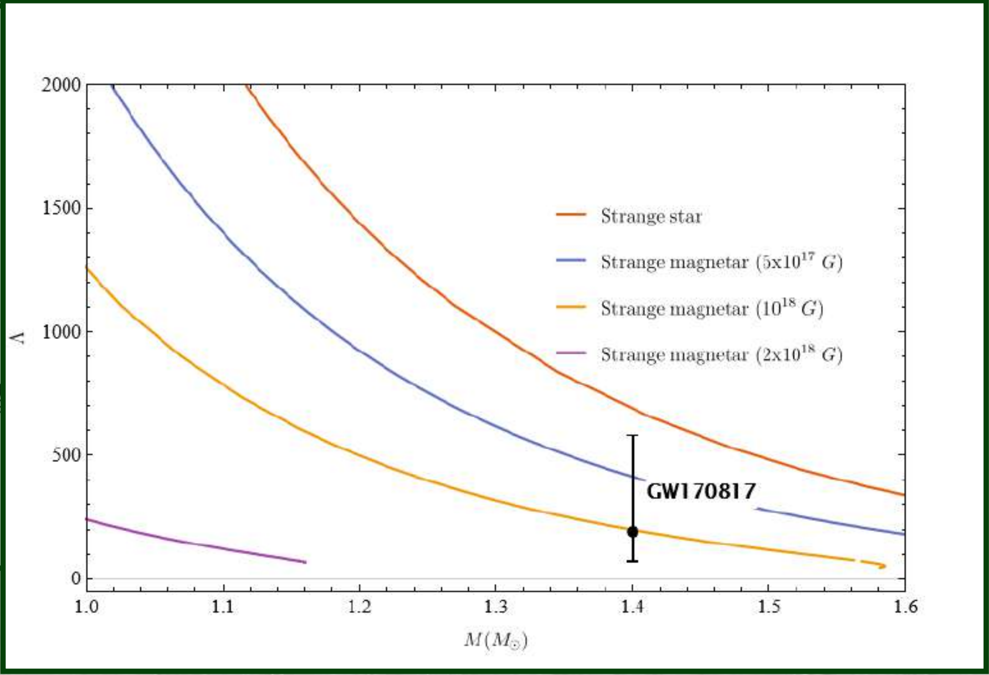


★ Magnetic fields tend to increase the central energy density.

★ Significant effect on the tidal deformability.



★ Tidal deformability:



★ More observables on the way...

Summary and outlook

⋆ We investigated effects of weakly ($y = 0.1$) and strongly ($y = 10^3$) self-interacting DM on the structure of quark stars for dark fermion masses $m_D = 1, 10, 50, 100, 200, 500$ GeV.

⋆ Results are very sensitive to (m_D,y). In most situations, central QM densities are increased by the presence of DM (extra gravitational pull). Other effects are usually modest modifications.

⋆ Strong magnetic fields affect significantly density profiles and tidal deformability. Total mass, radius and compactness not so much.

⋆ Next steps: new observables, quark matter EoS from cold and dense pQCD, hybrid stars, include magnetic field effects on TOV.

Back up slides

Boundary conditions

★ Demanding:

➡ smoothness at the QM or DM stellar center

➡ Vanishing $p_{QM/DM}$ at $R_{QM/DM}$

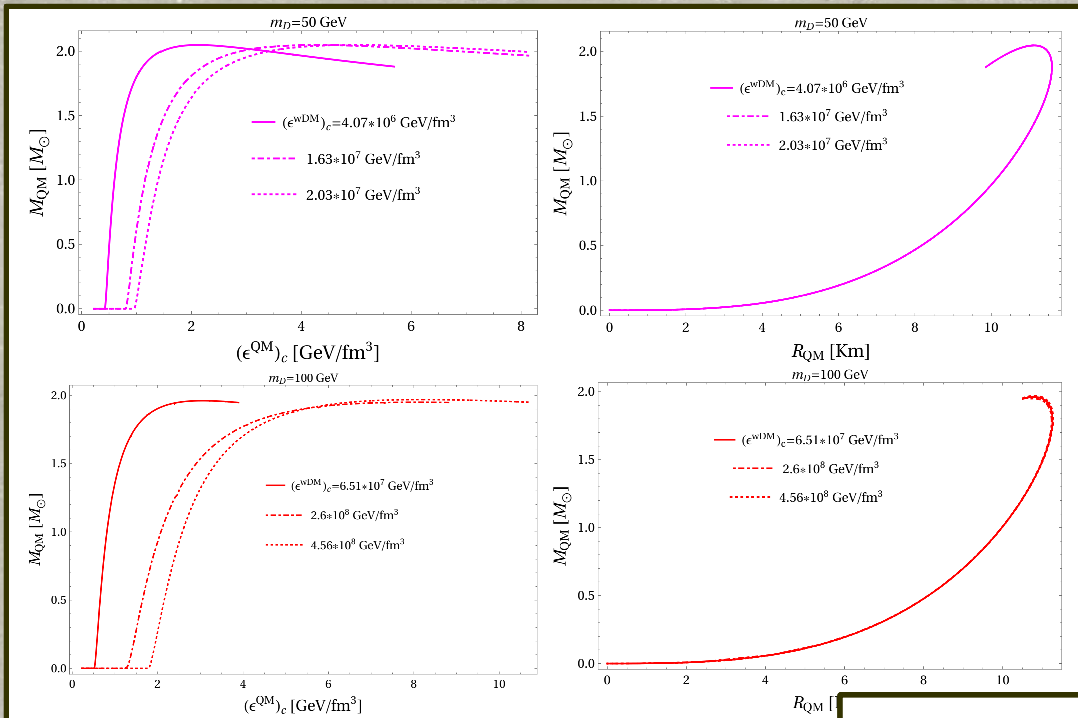
$$\nu(R_{\rm QM}) = \ln\left(1 - \frac{2(M_{\rm QM} + m_{\rm DM}(R_{\rm QM}))}{R_{\rm QM}}\right)$$

$$\nu(R_{\rm DM}) = \ln\left(1 - \frac{2(m_{\rm QM}(R_{\rm DM}) + M_{\rm DM})}{R_{\rm DM}}\right)$$

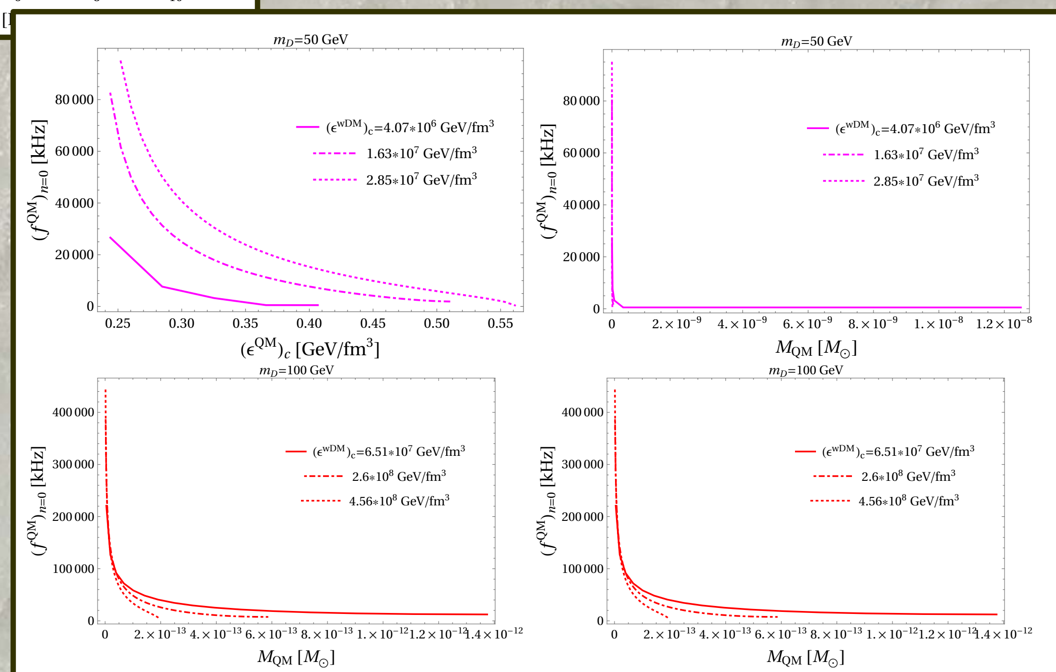
$$(\Delta p_{\rm QM/DM})_{\rm center} \equiv -3(\xi_{\rm QM/DM}\Gamma p_{\rm QM/DM})_{\rm center}$$

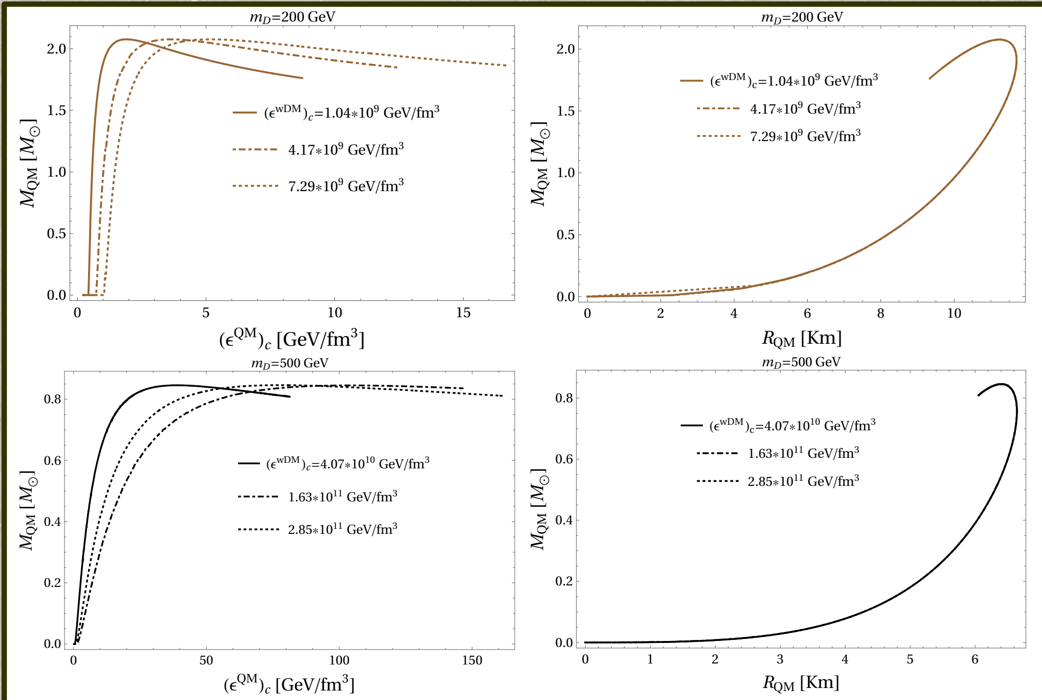
$$(\Delta p_{\rm QM/DM})_{\rm surface} \equiv 0$$

★ We define $\omega^2 \rightarrow \omega^2_{QM/DM}$ if we are dealing with a QM/DM oscillating core in the admixed star.

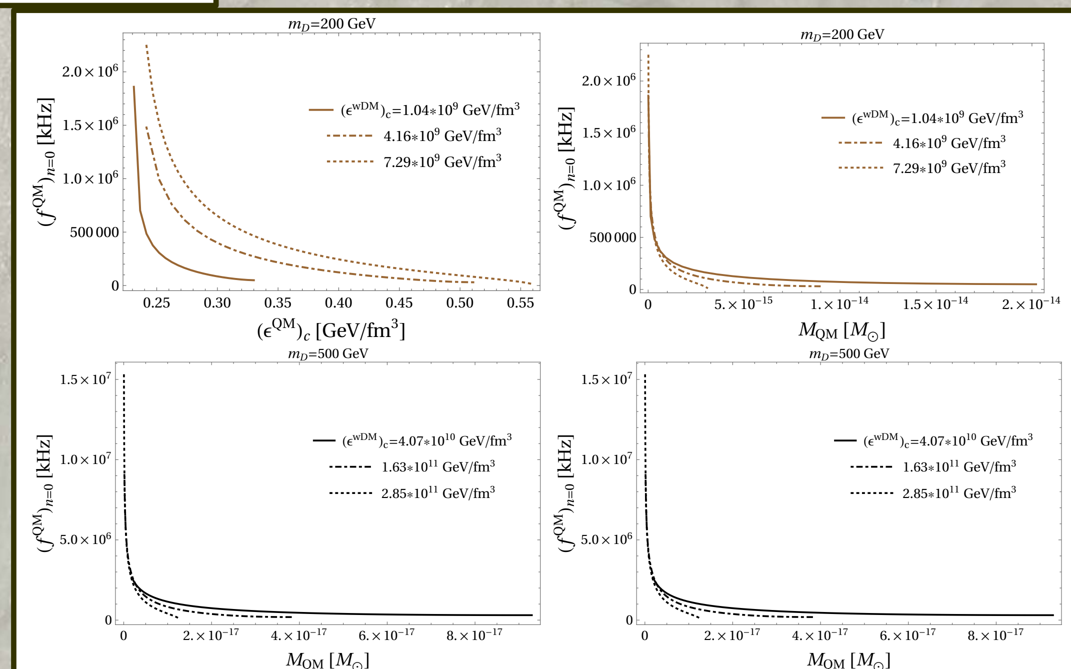


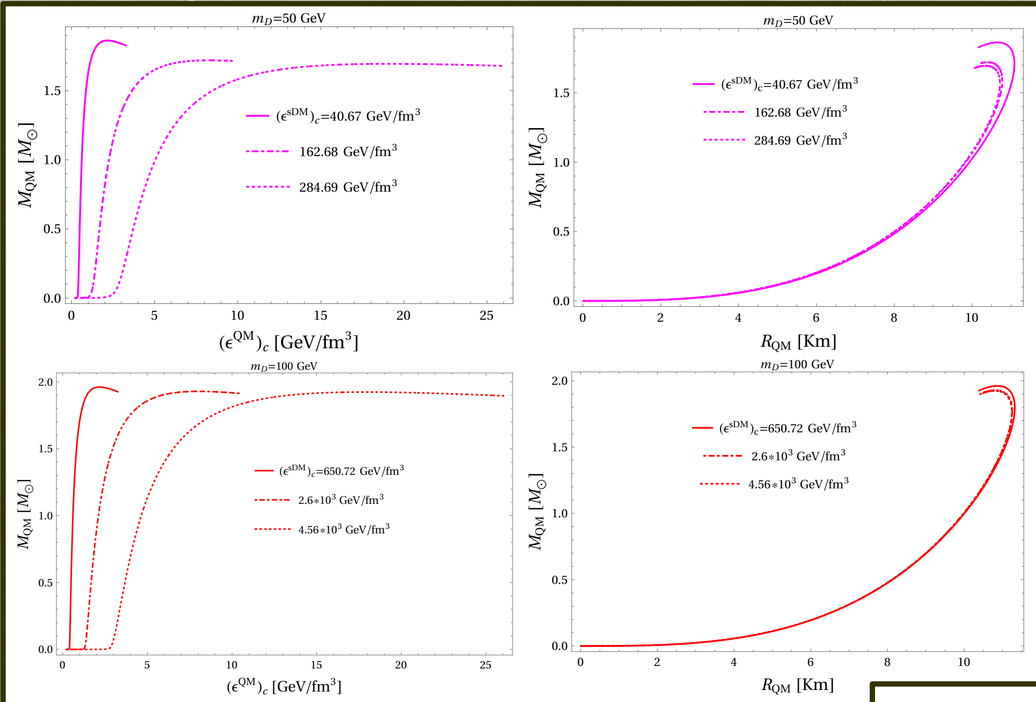
- ★ $y = 0.1$
- ★ $m_D = 50,\ 100$ GeV

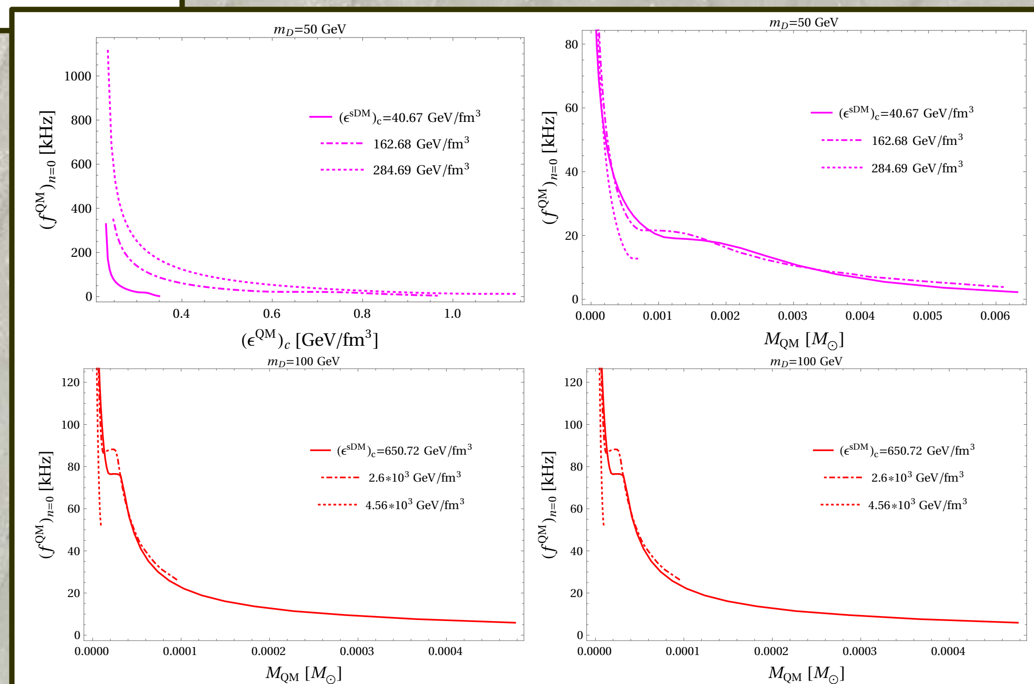




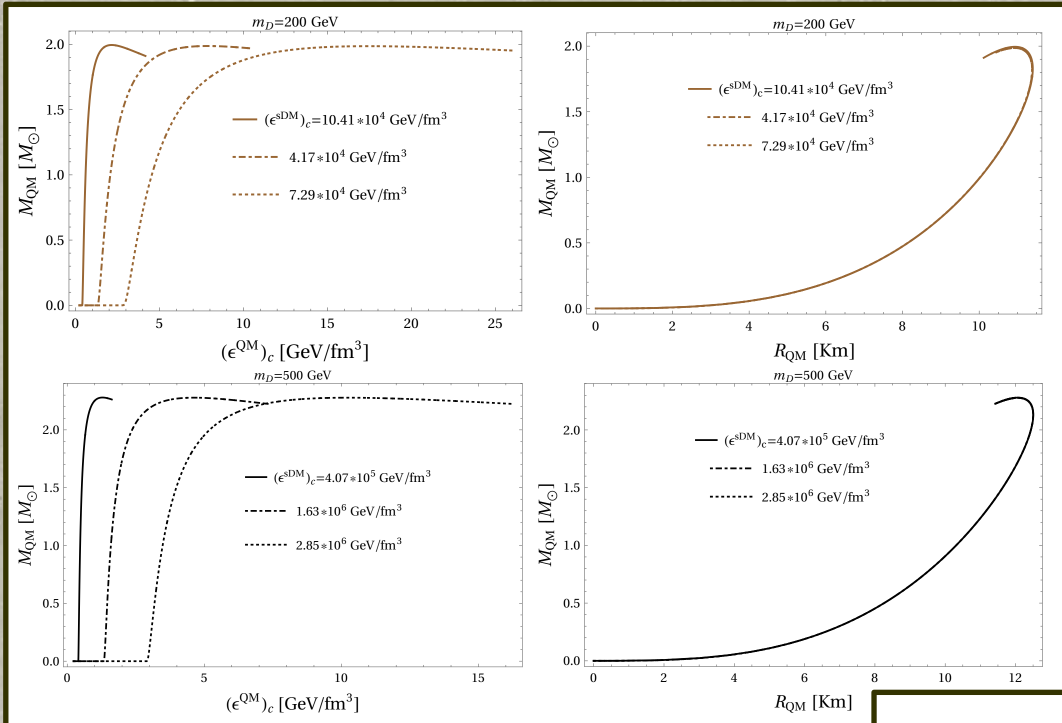
- ★ y = 0.1
- ★ m_D = 200, 500 GeV







- ★ $y = 10^3$
- ★ m_D = 50, 100 GeV



- ★ y = 10^3
- ★ m_D = 200, 500 GeV