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Instituto Tecnológico da Aeronáutica (ITA)
Brasil

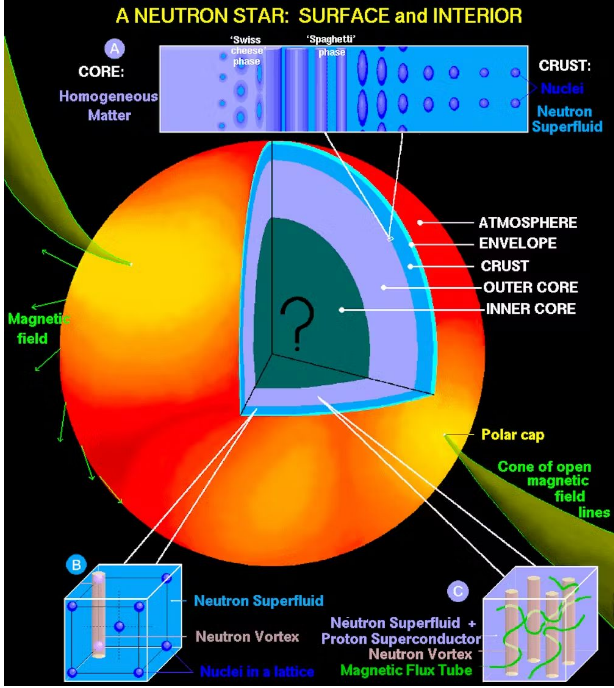
Compact Stars in the QCD phase diagram (CSQCD) - Barcelona

Masquerading Hybrid Stars with Dark Matter: Early Quark Matter Onset and Exotic Configurations

Biesdorf, C., Schaffner-Bielich, J., & Tolos, L. (2025). Phys. Rev. D, 111(8), 083038.

May 21th

- What are the Neutron Star-like objects really made of?
  - Neutrons?
  - Hyperons?
  - Maybe there are also deconfined quarks?
  - And what about Dark Matter?



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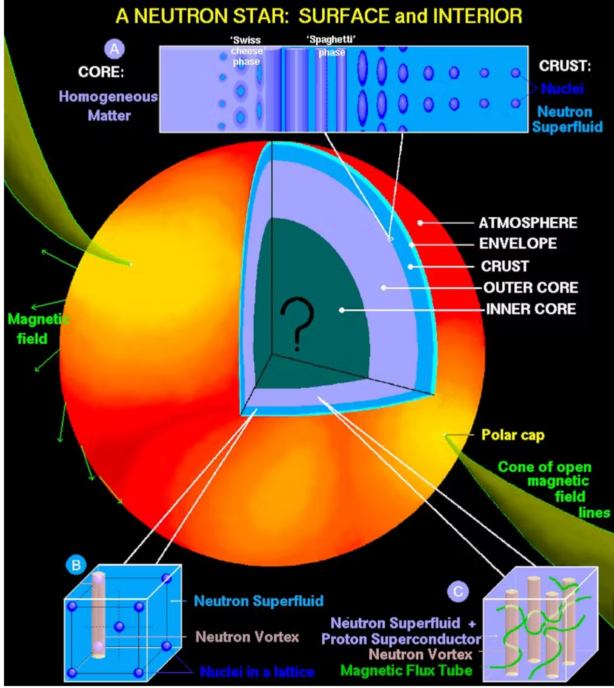

Can DM trigger the appearance of deconfined Quark Matter in Neutron Star-like objects?

Normal Matter (or Ordinary Matter)

Hybrid stars?

According to asymptotic freedom, the quarks may deconfine at very high energies or *very high densities*.

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  - $2.004M_{\odot} < \mathbf{M} < 2.142M_{\odot}$
  - $11.61\ km < \mathbf{R} < 13.77\ km$ [Salmi et al 2024 ApJ 974 294]

  or
  - $2.01M_{\odot} < \mathbf{M} < 2.15M_{\odot}$
  - $11.79\ km < \mathbf{R} < 13.09\ km$ [Dittmann et al 2024 ApJ 974 295]

  ⇒ 2-3× nuclear saturation density
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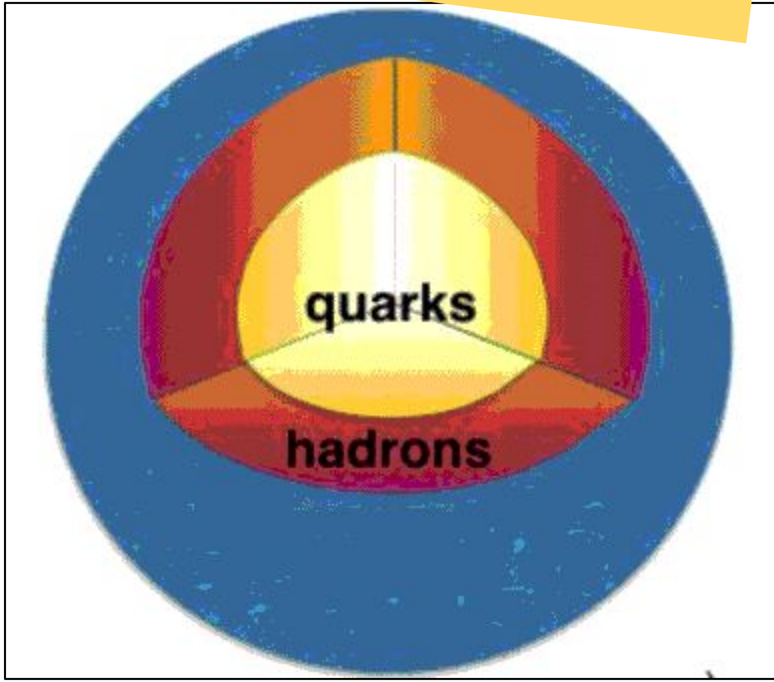

Normal Matter

Hadronic matter: Relativistic Mean Field QHD Model

$$
\begin{aligned}
\mathcal{L}_{NLWM} = & \sum_B \overline{\psi}_B[\gamma_\mu(i\partial^\mu - g_{B\omega}\omega^\mu - g_{B\rho}\frac{\vec{\tau}_B}{2}\vec{\rho}^\mu \\
& - g_{B\phi}\phi^\mu) - m_B^*]\psi_B + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma \\
& - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3!}\kappa\sigma^3 - \frac{1}{4!}\lambda\sigma^4 \\
& - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} \\
& + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu + \Lambda_v g_{N\omega}^2 g_{N\rho}^2 \omega_\mu\omega^\mu\vec{\rho}_\mu\vec{\rho}^\mu \\
& - \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu
\end{aligned}
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For more details see [Biesdorf et al. Braz. J. Phys. 53, 137 (2023)]

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$$

Model	NL3*$\omega\rho$	Constraints
n_0 (fm^{-3})	0.150	0.148 – 0.170
E/A (MeV)	16.3	15.8 – 16.5
K (MeV)	258	220 – 260
M^*/M	0.59	0.6 – 0.8
E_{sym} (MeV)	30.7	28.6 – 34.4
L (MeV)	42	36 – 86.8

➔ The phenomenological constraints are taken from [Dutra et al. Phys. Rev. C 90, 055203 (2014)] and [Dutra et al. Phys. Rev. C 93, 025806 (2016)].

➔ This parametrization also reproduces maximum star masses **above 2 M☉**, even when hyperons are included.

For more details see [Biesdorf et al. Braz. J. Phys. 53, 137 (2023)]

Normal Matter

Quark matter: Modified MIT Bag Model

$$\mathcal{L}_{MIT} = \sum_q \Big\{ \overline{\psi}_q \Big[\gamma^\mu (i\partial_\mu - g_{qqV} V_\mu) - m_q \Big] \psi_q + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} b_4 (g_{uuV}^2 V_\mu V^\mu)^2 - B \Big\} \Theta(\overline{\psi}_q \psi_q) - \frac{1}{2} \overline{\psi}_q \psi_q \delta_S$$

More details can be found in [Lopes et al 2021 Phys. Scr. 96 065303] and [Lopes et al 2021 Phys. Scr. 96 065302]

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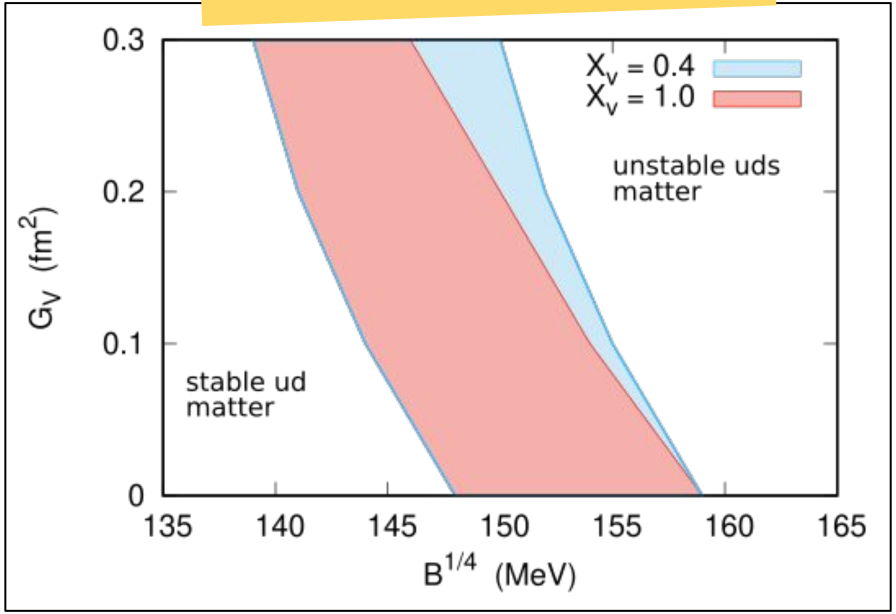

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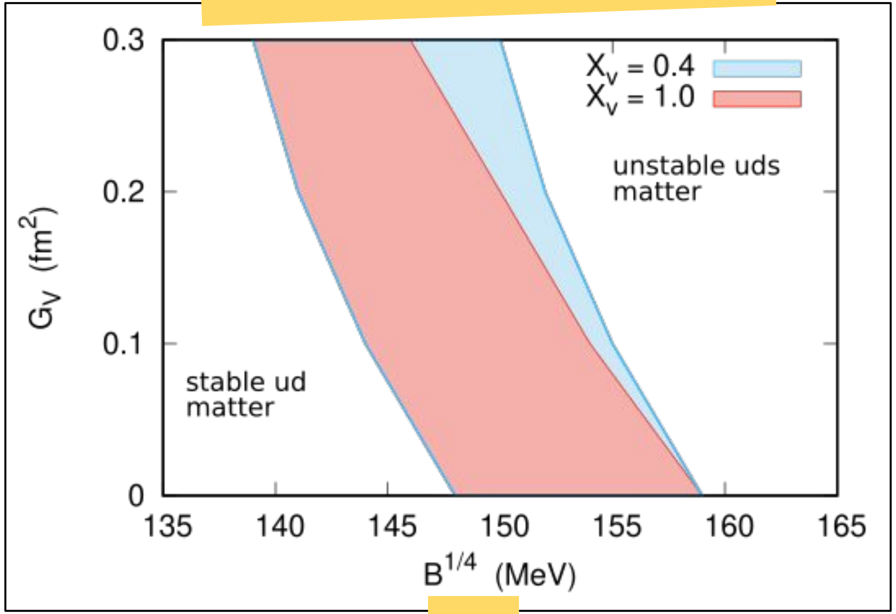


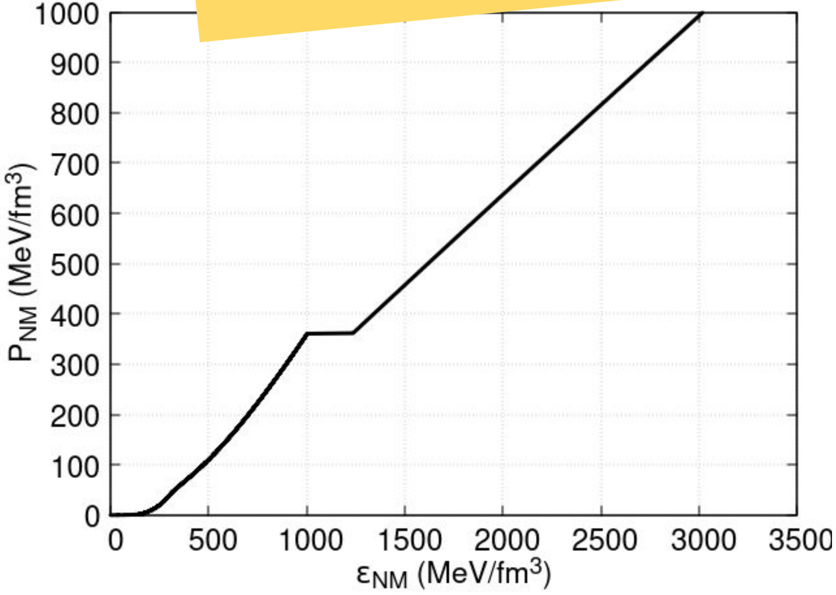
Here we use:

$$B^{1/4} = 155 \text{ MeV} \quad G_V = (g_{uuV}/m_V)^2 = 1.0 \text{ fm}^2 \quad b_4 = 1.2$$

$$X_V = g_{ssV}/g_{uuV} = g_{ssV}/g_{ddV} = 0.4$$

Normal Matter

Hybrid EoS



P_0 (MeV/fm^3)	μ_0 (MeV)	ϵ_H (MeV/fm^3)	ϵ_Q (MeV/fm^3)
361	1698	1003	1280

Normal Matter

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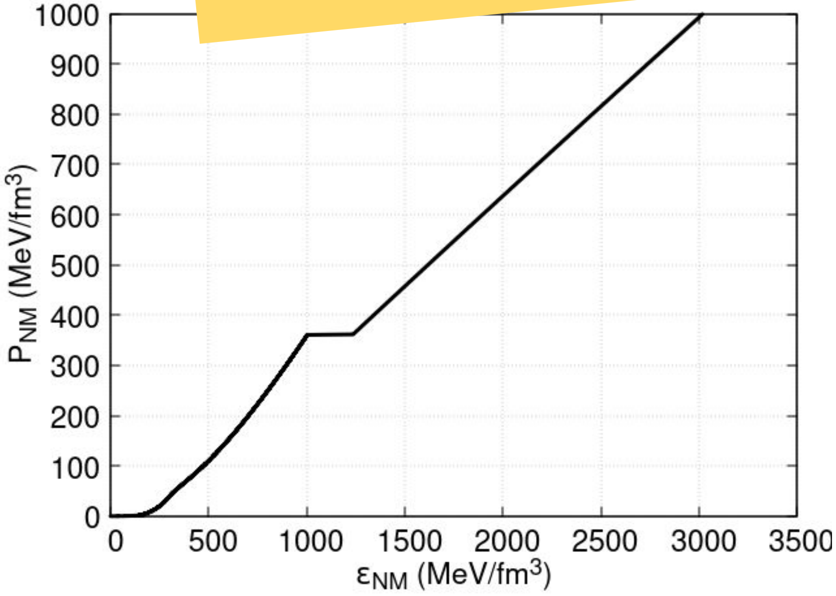

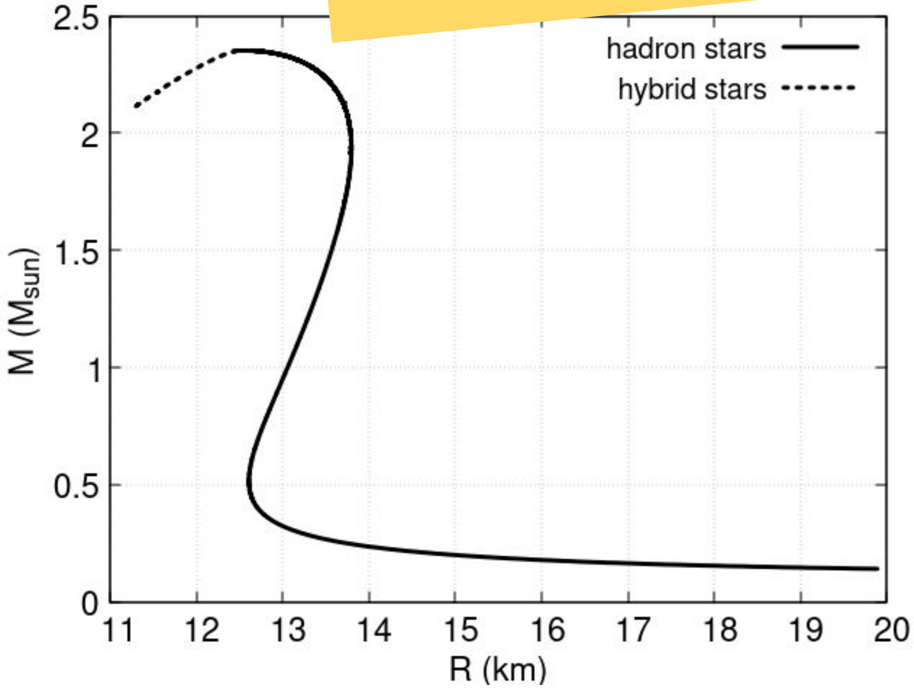

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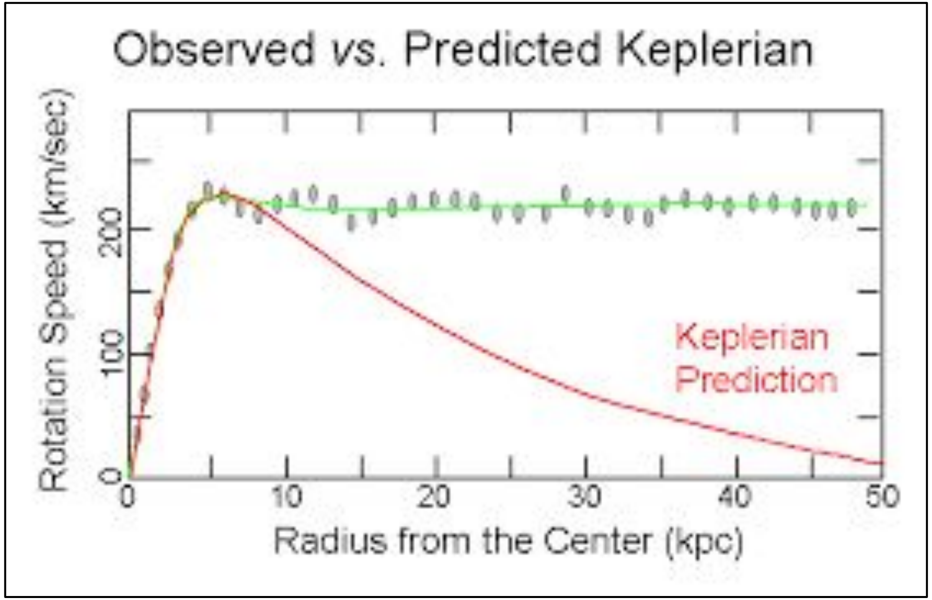
Dark Matter

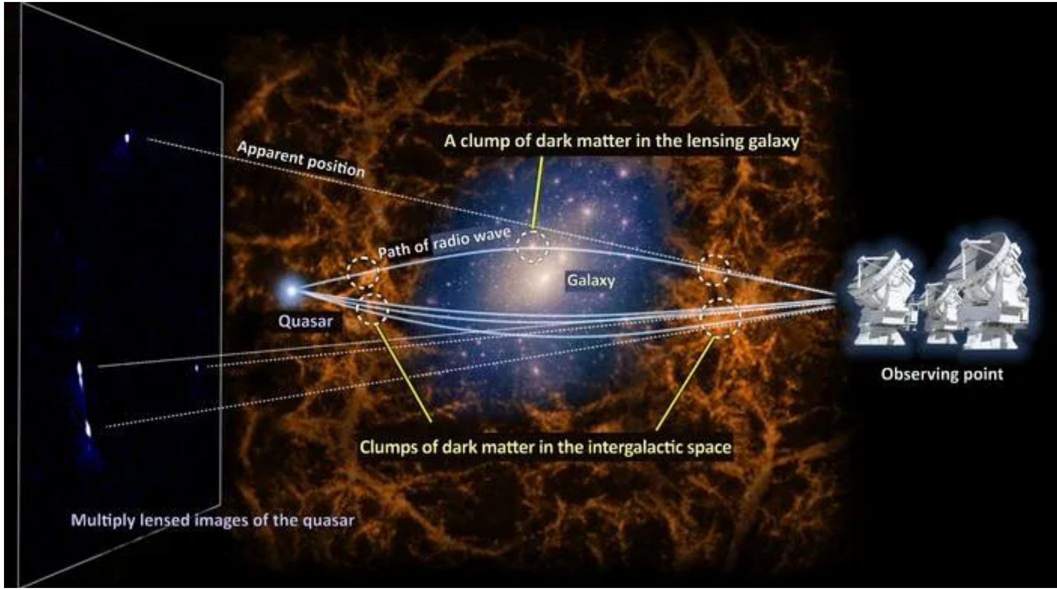
Something is out there - Dark Matter?

- ➢ ***Galaxy rotation curves***: Stars in spiral galaxies rotate too fast for the amount of visible matter present.



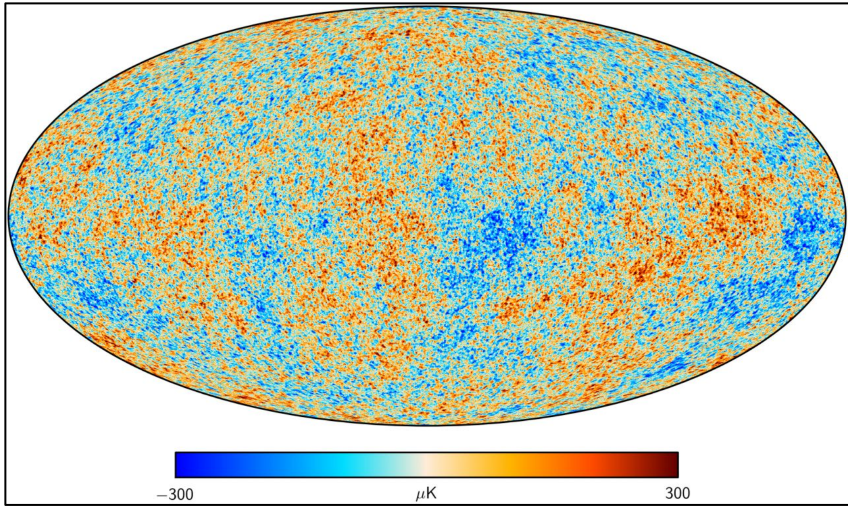
Something is out there - Dark Matter?

- ➢ *__Gravitational lensing__*: Light bends more than visible matter allows.



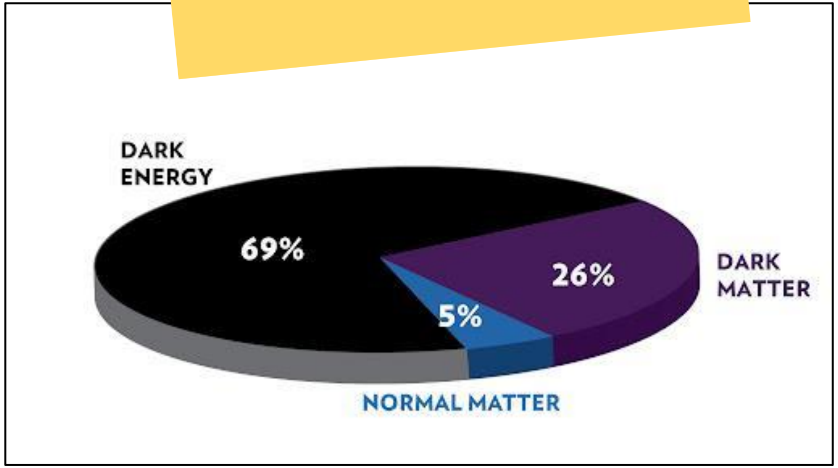
Something is out there - Dark Matter?

➢ ***<u>Cosmic Microwave Background (CMB)</u>*: tiny temperature fluctuations reveal how much matter - visible and invisible - was present in the early universe.**



The observed pattern of these fluctuations cannot be explained without dark matter.

Dark Matter



- *Invisible but powerful*: DM shapes galaxies through gravity alone.
- *Still a mystery*: No direct detection yet - only indirect clues.
- *Neutron stars as DM traps*: Their extreme density boosts DM capture, potentially altering internal structure.

How does dark matter reshape the structure of hybrid stars?

Dark Matter

- ***Symmetric DM***: equal amounts of DM and anti-DM annihilate until freeze-out, leaving a relic density that matches observations. (WIMPs, axions, sterile neutrinos...)

- ***Mirror DM***: hidden mirror copy of the Standard Model - restores the parity problem

- ***Asymmetric DM***: particle-antiparticle asymmetry - like the asymmetry that produced more matter than antimatter in the visible universe.

- etc

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Dark matter

$$\epsilon'_{DM} = \frac{1}{8\pi^2}\left[(2z^3+z)(1+z^2)^{1/2} - \sinh^{-1}(z)\right] + \left(\frac{1}{3\pi^2}\right)^2 y^2 z^6,$$

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$$n'_{DM} = \frac{n_{DM}}{m_D^3} = \frac{z^3}{3\pi^2},$$

where $\epsilon'_{DM} = \frac{\epsilon'_{DM}}{m_D^4}$ and $P'_{DM} = \frac{P_{DM}}{m_D}$

A non-annihilating self interacting asymmetric Dark Matter

z is the dimensionless Fermi momentum

$y = \frac{m_D}{m_I}$ is the interaction strength, with m_I being the energy scale of the interaction between fermions

More details can be found in [Narain et al. Phys. Rev. D 74, 063003 (2006).]

Dark matter

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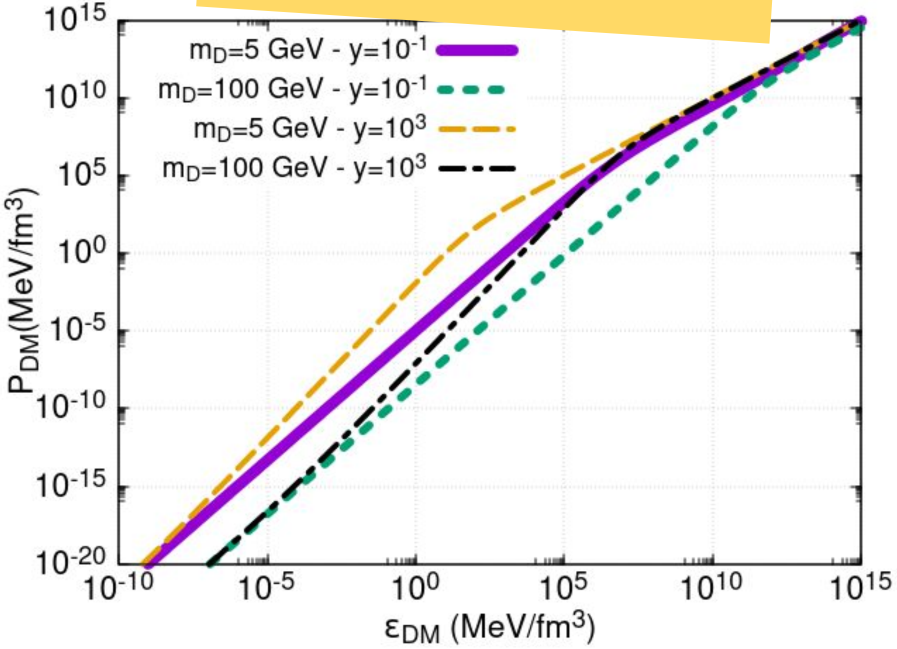

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Two-Fluids TOVs

If the fluids only interact gravitationally:

$$\boxed{\nabla_\mu T^{\mu\nu}_{NM} = 0} \qquad \boxed{\nabla_\mu T^{\mu\nu}_{DM} = 0}$$

For a static, spherically symmetric perfect fluid:

Two-Fluids TOVs

$$\frac{dp'_{NM}}{dr} = -(p'_{NM} + \epsilon'_{NM})\frac{d\nu}{dr}$$

$$\frac{dm_{NM}}{dr} = 4\pi r^2 \epsilon'_{NM}$$

$$\frac{dp'_{DM}}{dr} = -(p'_{DM} + \epsilon'_{DM})\frac{d\nu}{dr}$$

$$\frac{dm_{DM}}{dr} = 4\pi r^2 \epsilon'_{DM}$$

$$\boxed{\frac{d\nu}{dr} = \frac{(m_{NM} + m_{DM}) + 4\pi r^3 (p'_{NM} + p'_{DM})}{r(r - 2(m_{NM} + m_{DM}))}}$$

Stability of Two-Fluid Stars

$$\frac{dN_i'}{dr} = 4\pi \frac{n_i'}{\sqrt{1 - 2(m_{NM} + m_{DM})/r}} r^2$$

Stability of Two-Fluid Stars

$$\begin{pmatrix} \delta N_{NM} \\ \delta N_{DM} \end{pmatrix} = \begin{pmatrix} \partial N_{NM}/\partial \epsilon_c^{NM} & \partial N_{NM}/\partial \epsilon_c^{DM} \\ \partial N_{DM}/\partial \epsilon_c^{NM} & \partial N_{DM}/\partial \epsilon_c^{DM} \end{pmatrix} \begin{pmatrix} \delta \epsilon_c^{NM} \\ \delta \epsilon_c^{DM} \end{pmatrix} = 0$$

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$$\boxed{\kappa_A > 0 \qquad \text{and} \qquad \kappa_B > 0}$$

- Stability requires both NM and DM components to resist collapse.
- The system is stable if both eigenvalues $\boldsymbol{\kappa}_A>0$ and $\boldsymbol{\kappa}_B>0$.
- This generalizes the classic single-fluid condition $\partial M/\partial \mathcal{E}_C > 0$.

[Hippert et al. Phys. Rev. D 107, 115028 (2023)]

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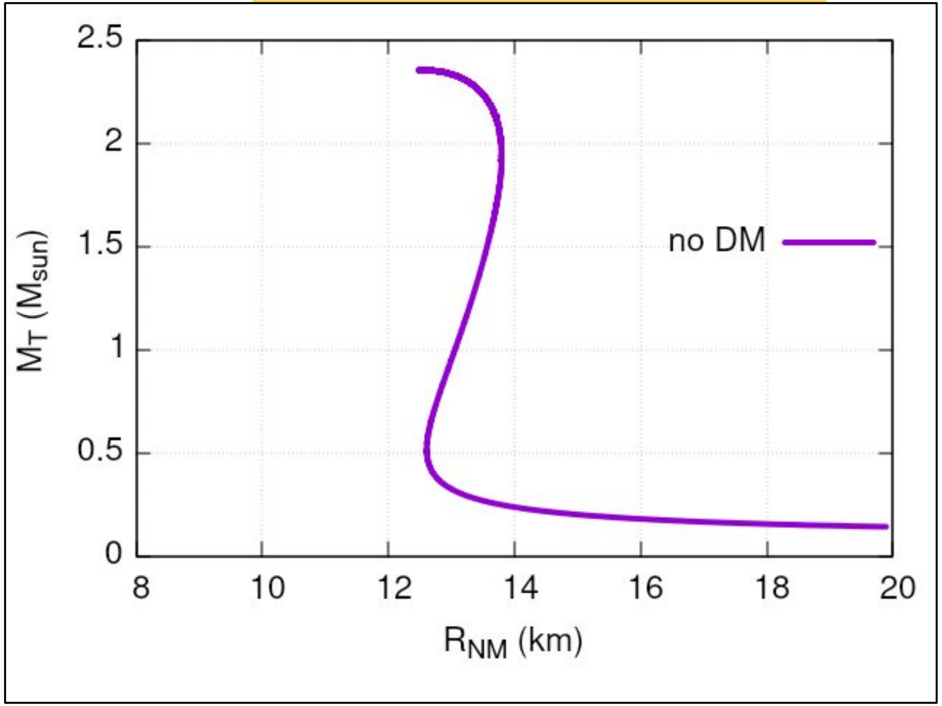
It is equivalent to the analysis through radial oscillations, according to [Kumar et al. Phys. Rev. D 112, 063030 (2025)]

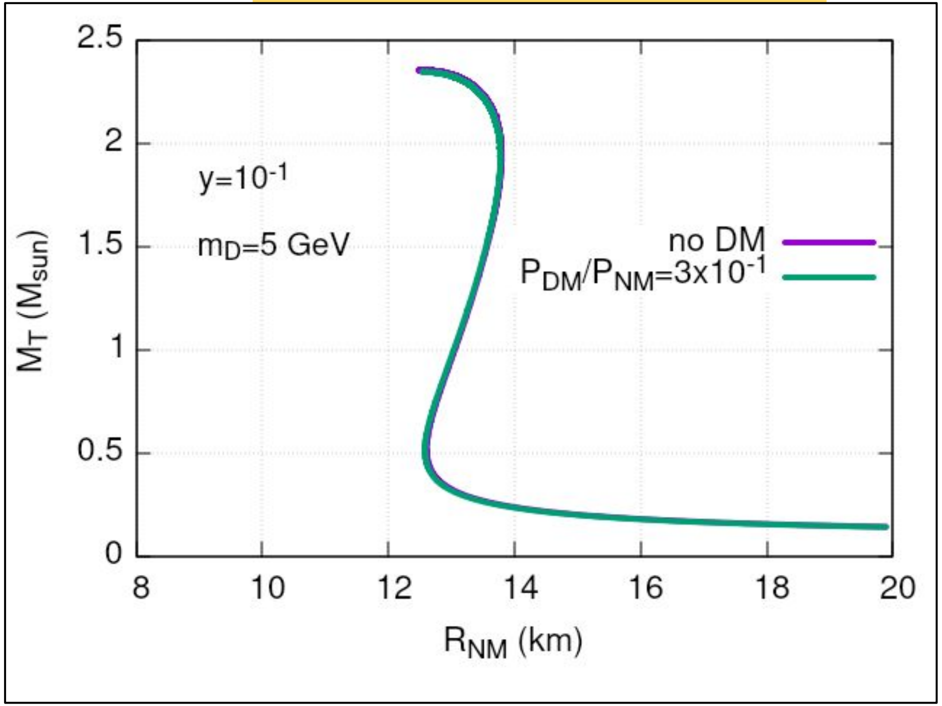
[Hippert et al. Phys. Rev. D 107, 115028 (2023)]

Dark Matter Admixed Hybrid Stars



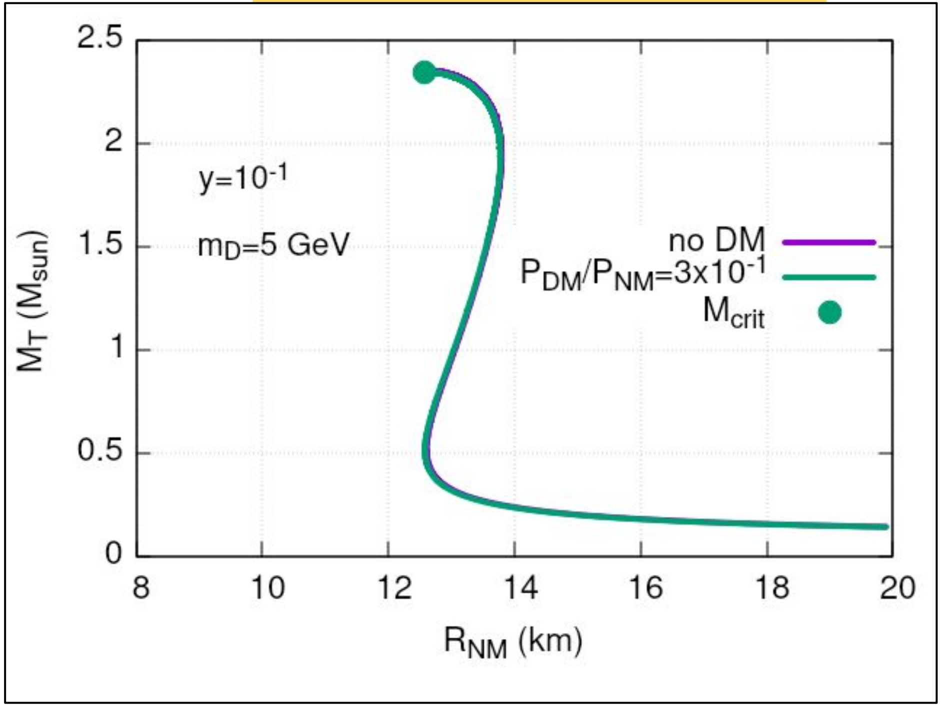
No DM ⇒ no dynamically stable hybrid star

Dark Matter Admixed Hybrid Stars



And what about now?

Dark Matter Admixed Hybrid Stars



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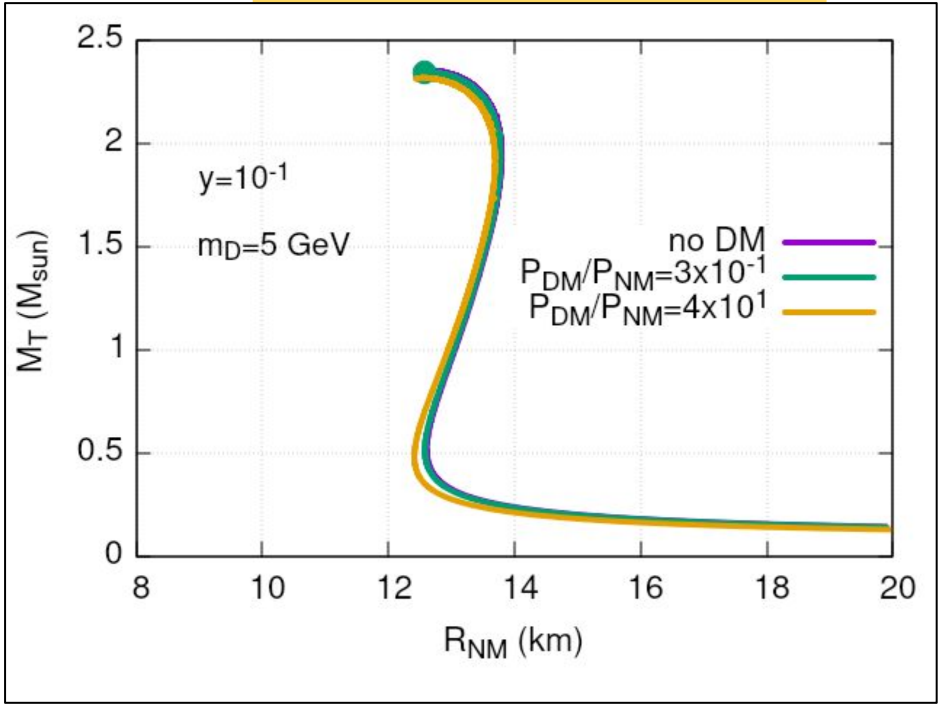

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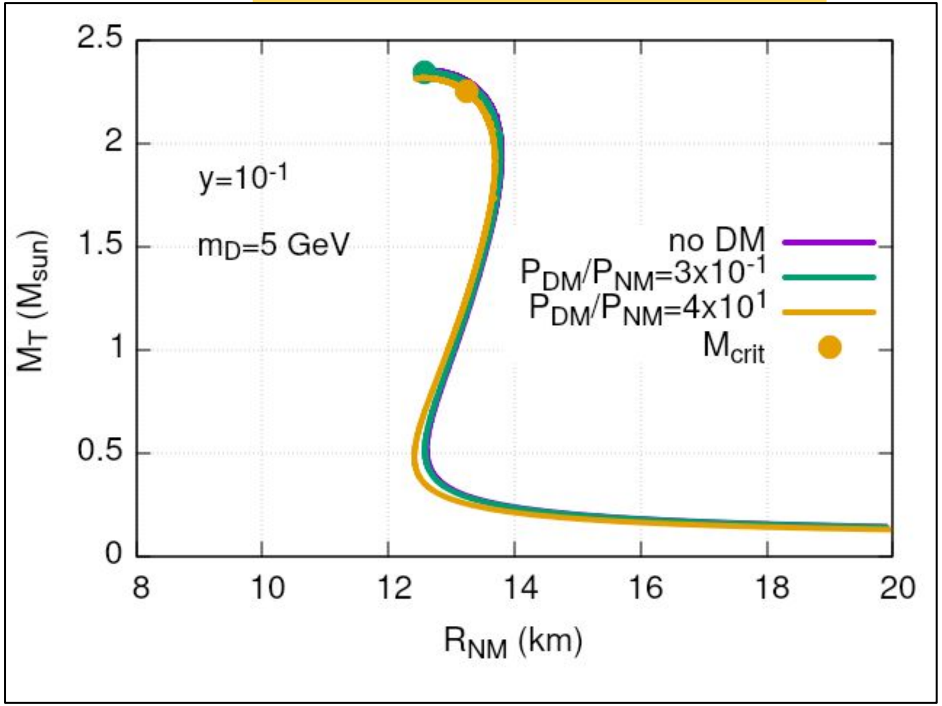

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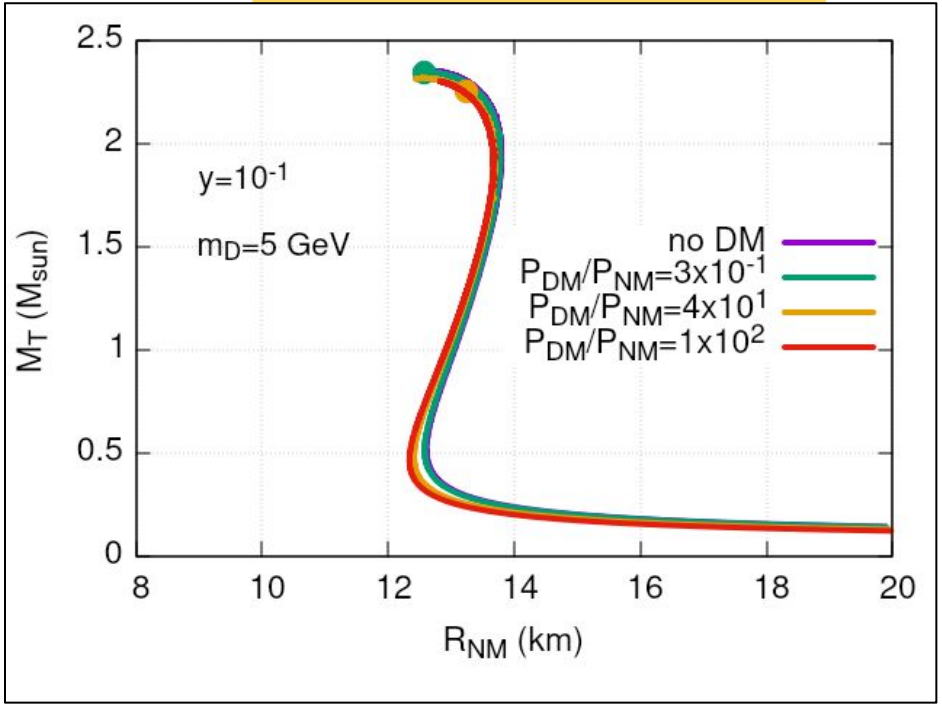

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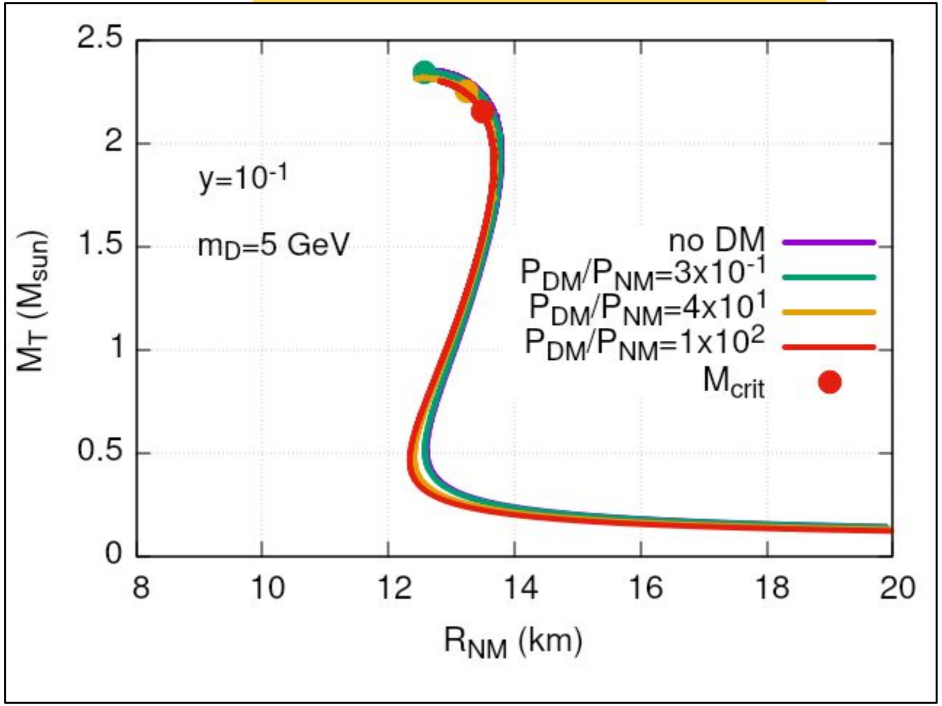

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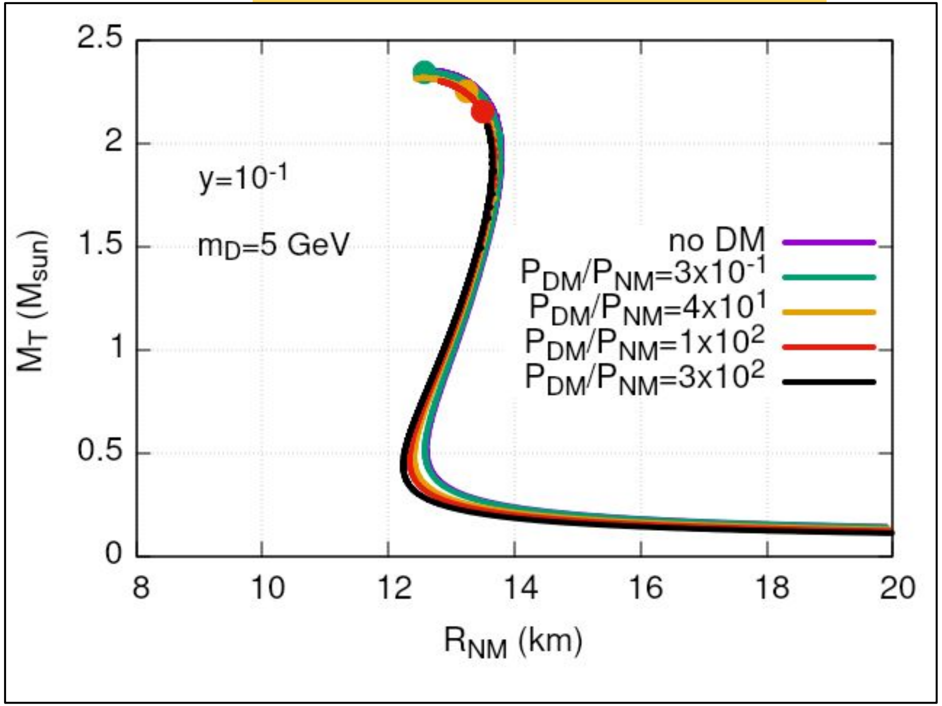

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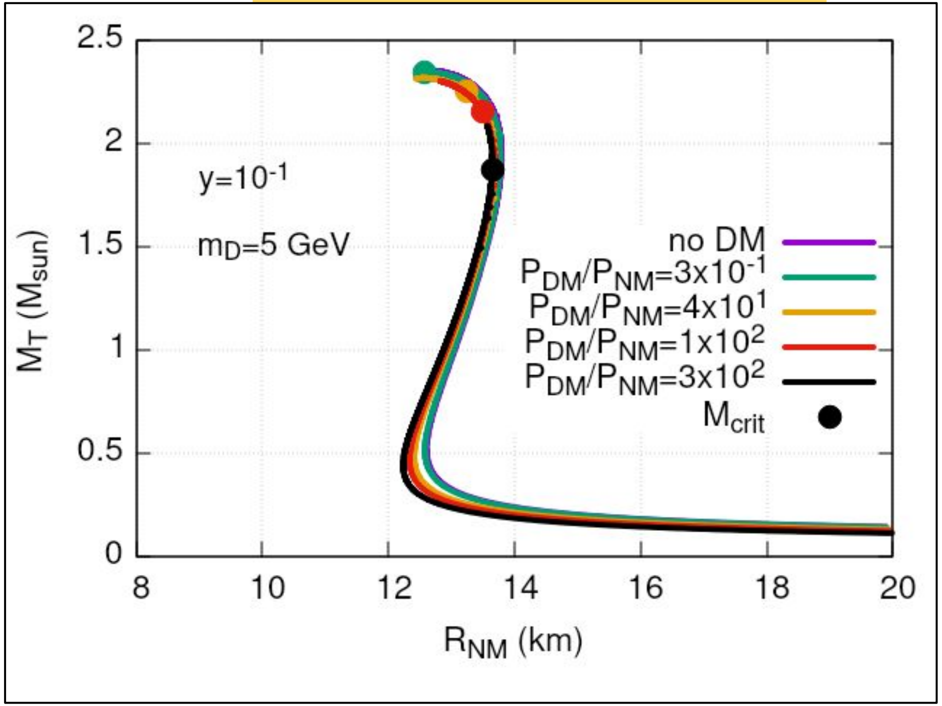

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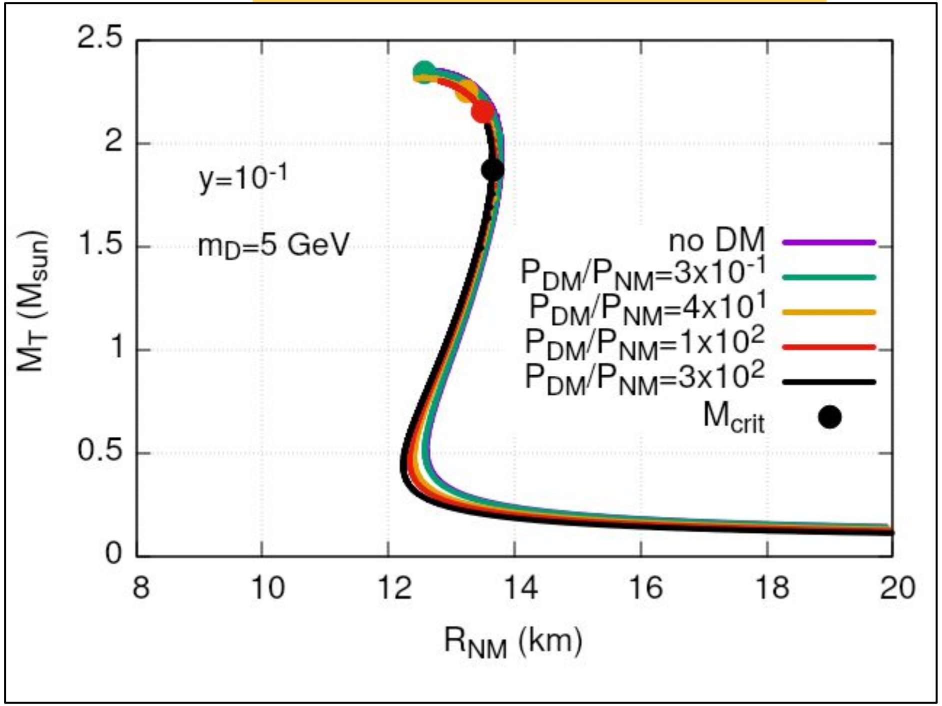
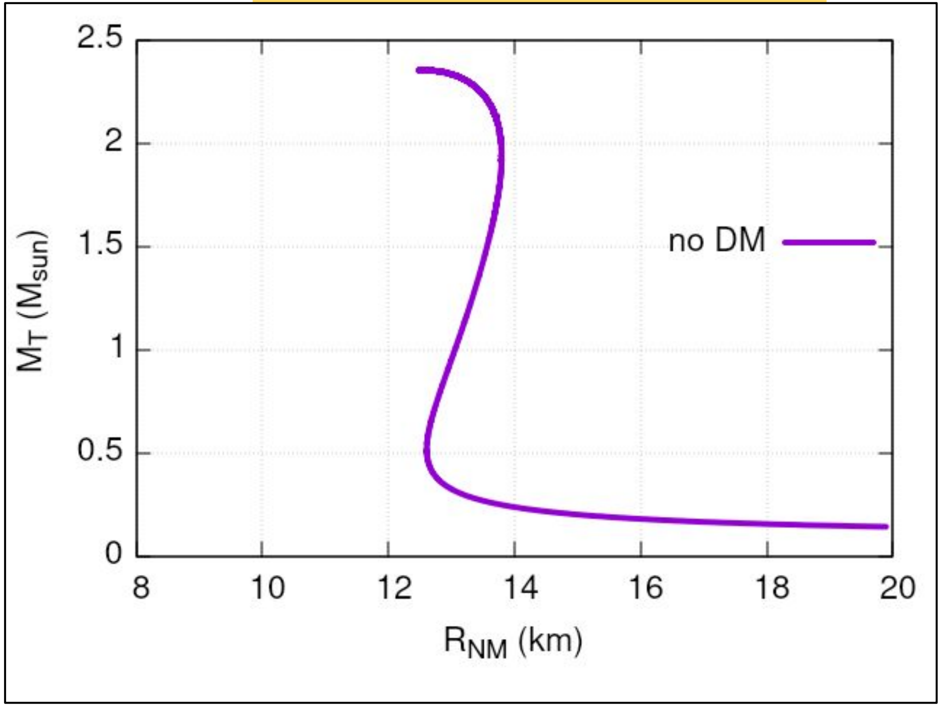


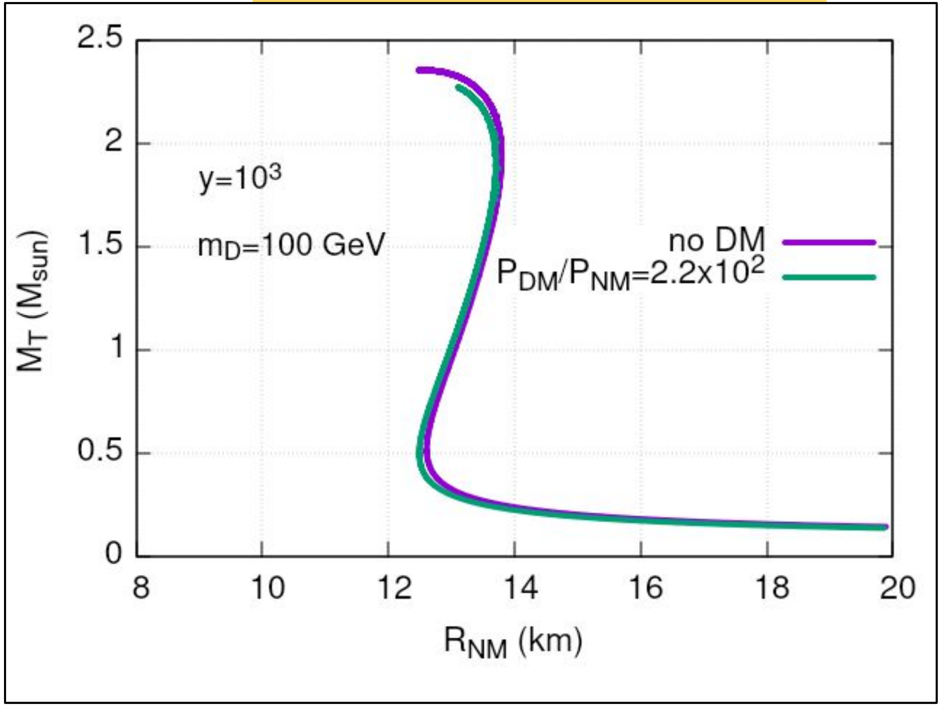
This was for weakly self-interacting DM (y^{-1}) and low DM particle mass (m_D=5 GeV)

What about other y and m_D?

Dark Matter Admixed Hybrid Stars

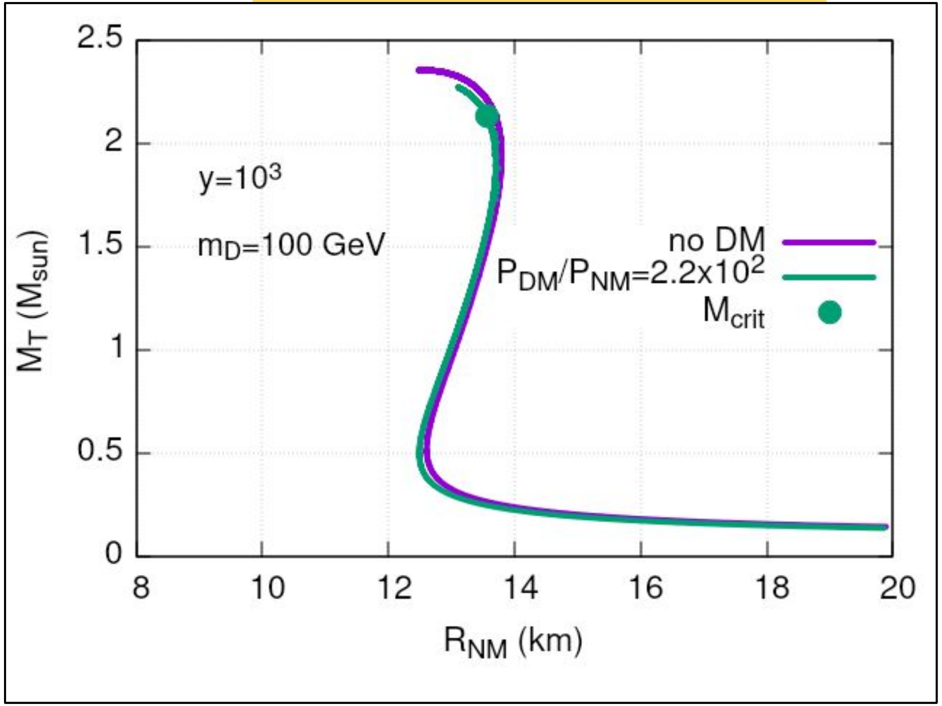


Dark Matter Admixed Hybrid Stars



Now for strongly self-interacting DM (y^3) and high DM particle mass (m_D=100 GeV)

Dark Matter Admixed Hybrid Stars



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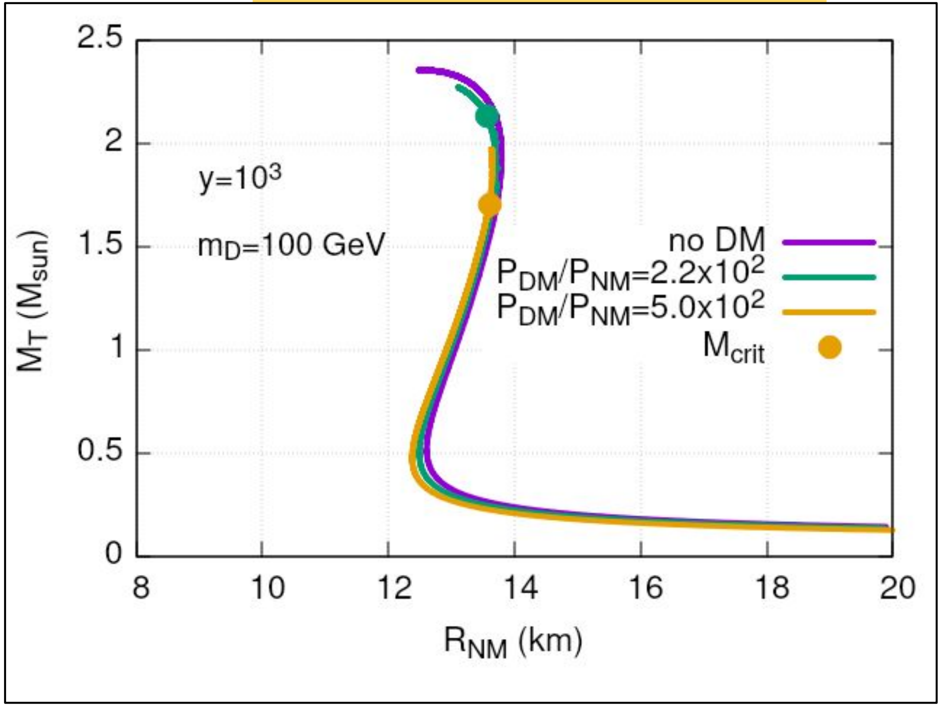

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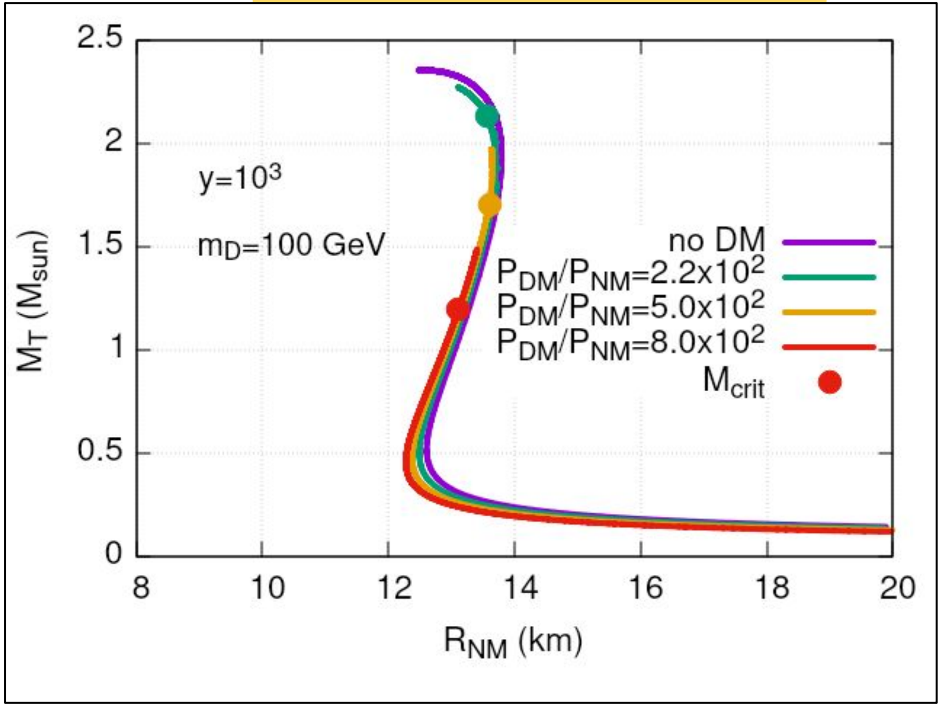

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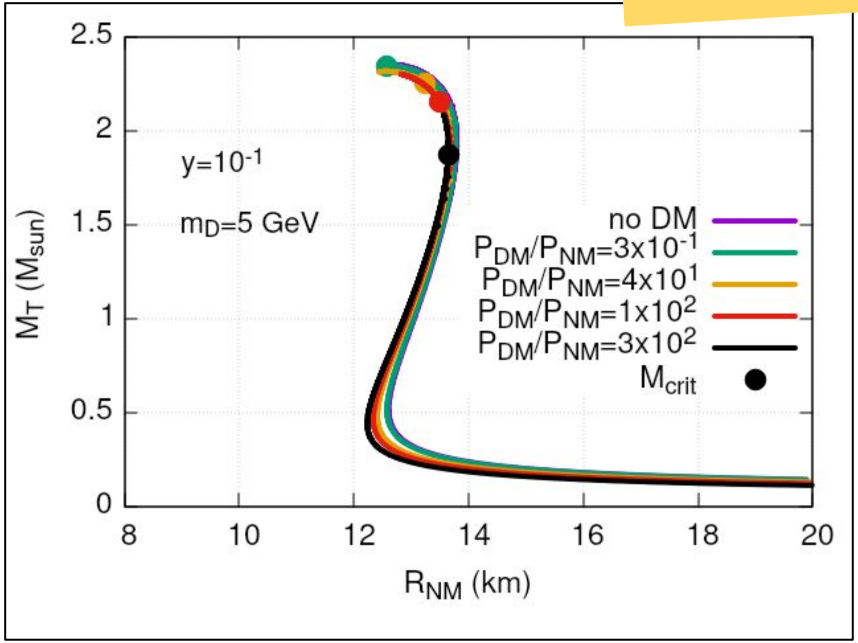
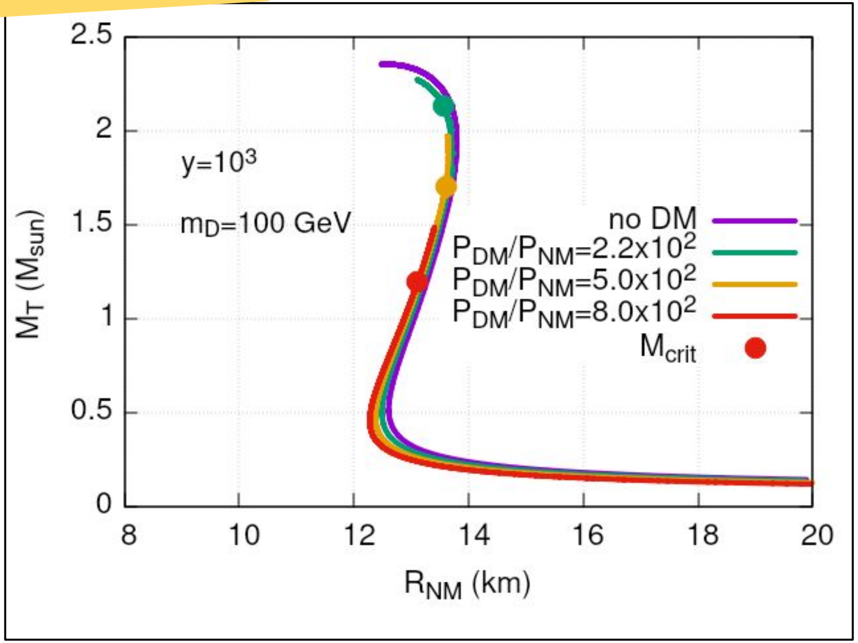
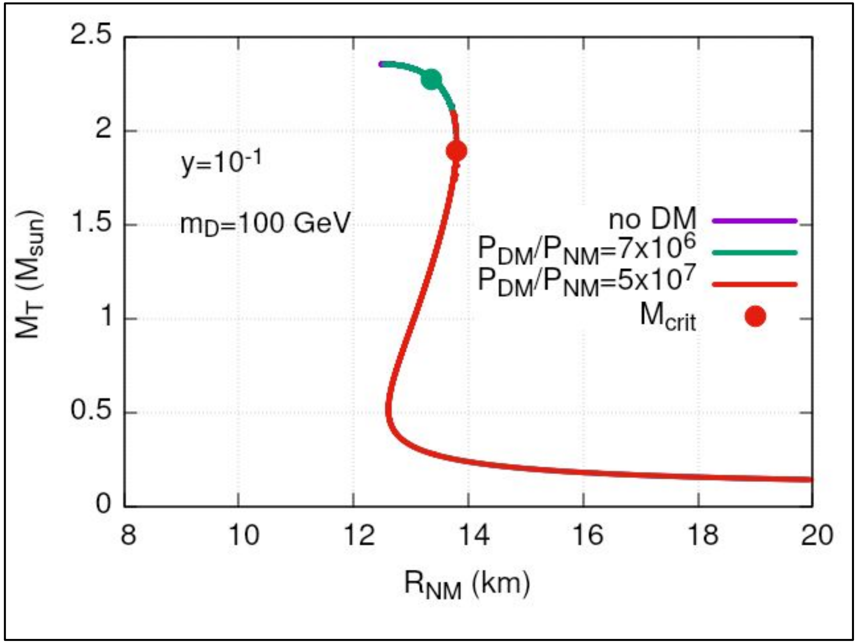




These plots show how DM can quietly reshape the core without changing the star's observable radius

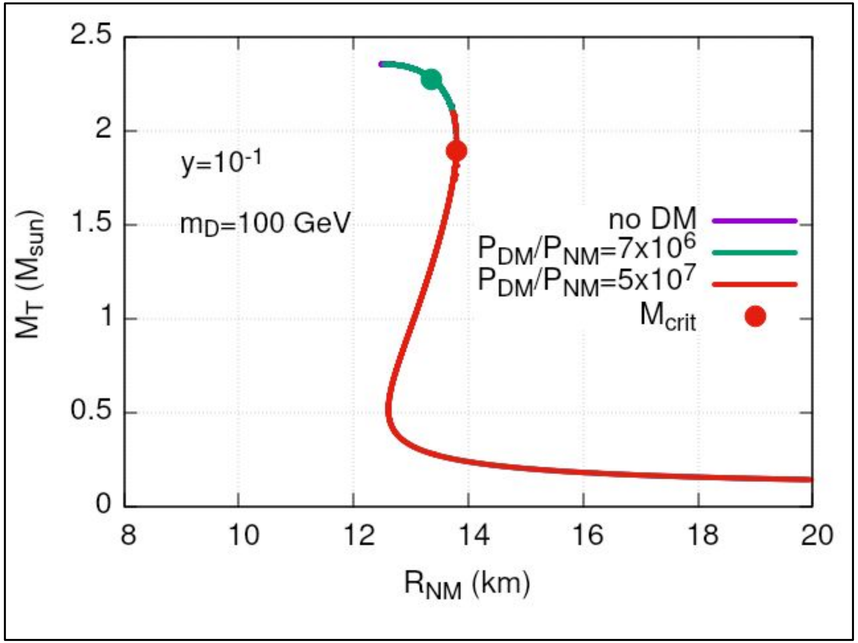
Dark Matter Admixed Hybrid Stars



Lower y ⇒ higher DM pressure fraction needed

Lower m_D ⇒ lower DM pressure fraction needed

Dark Matter Admixed Hybrid Stars

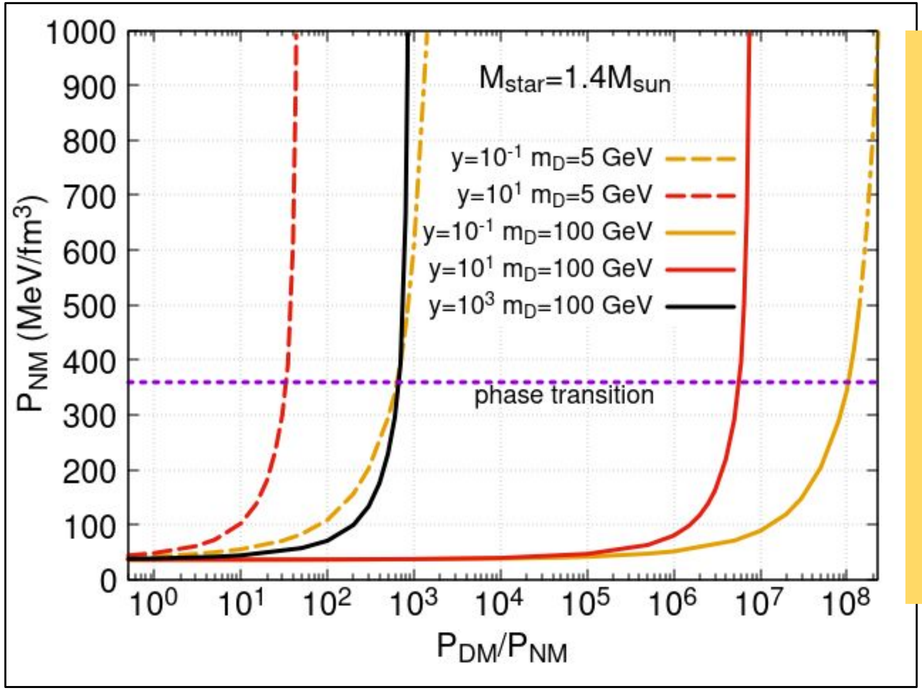


Lower y ⇒ higher DM pressure fraction needed

Lower m_D ⇒ lower DM pressure fraction needed

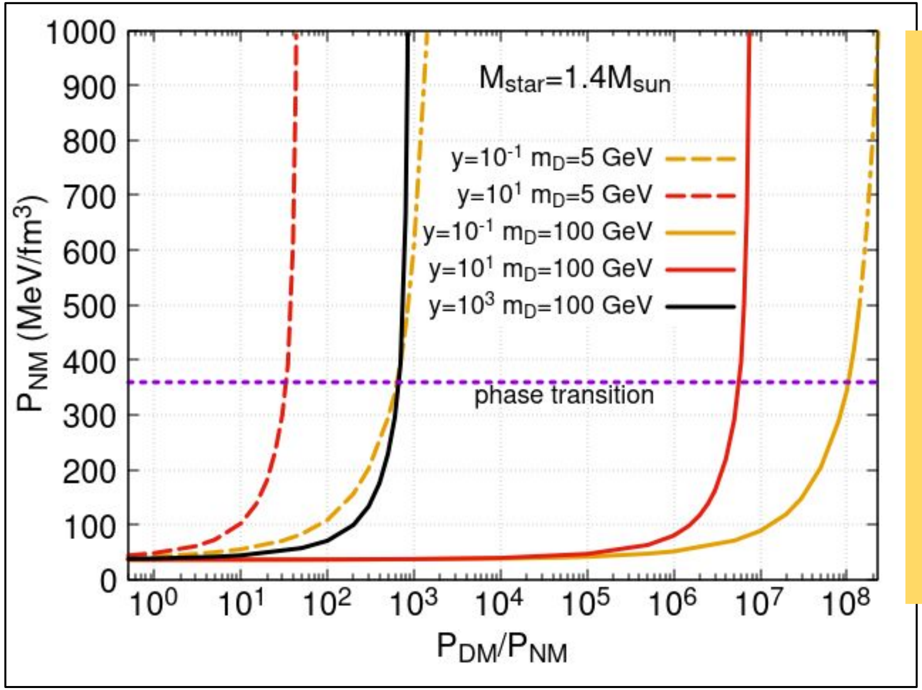
And what about strongly self-interacting DM (y^3) and low DM particle mass (m_D=5 GeV)?

Dark Matter Admixed Hybrid Stars

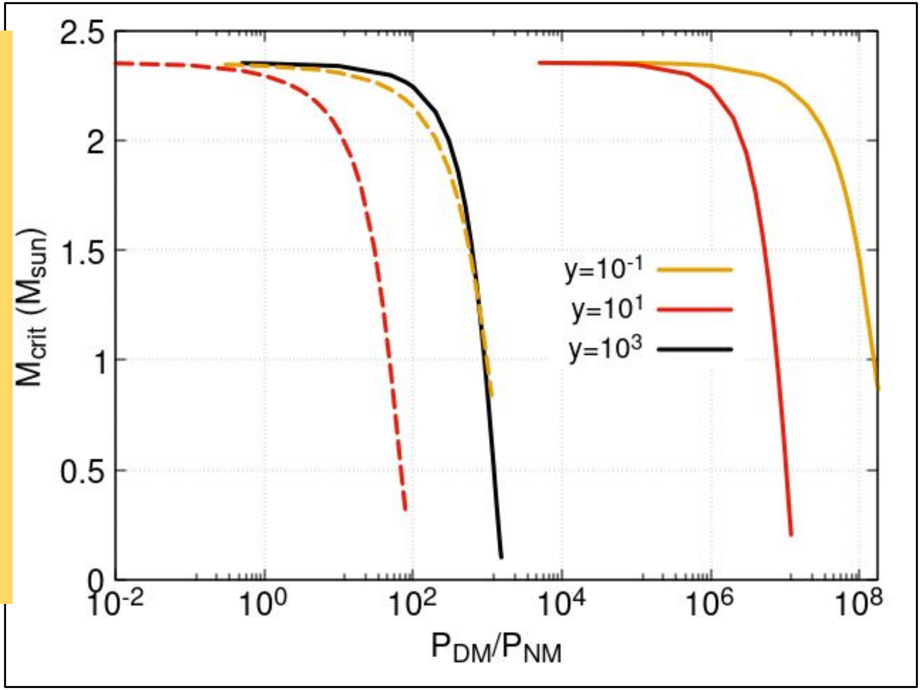


DM increases the central pressure

Dark Matter Admixed Hybrid Stars

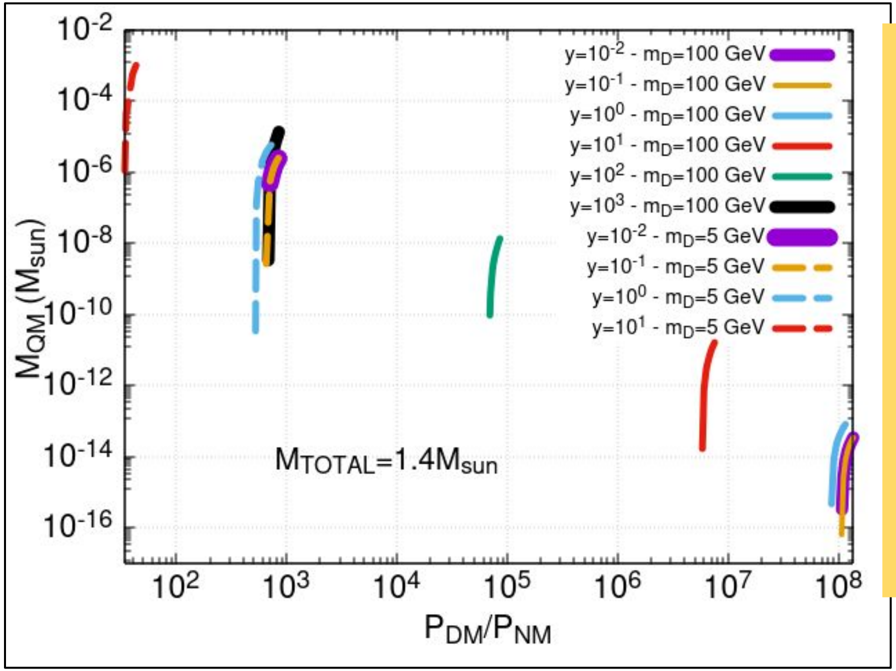


DM increases the central pressure



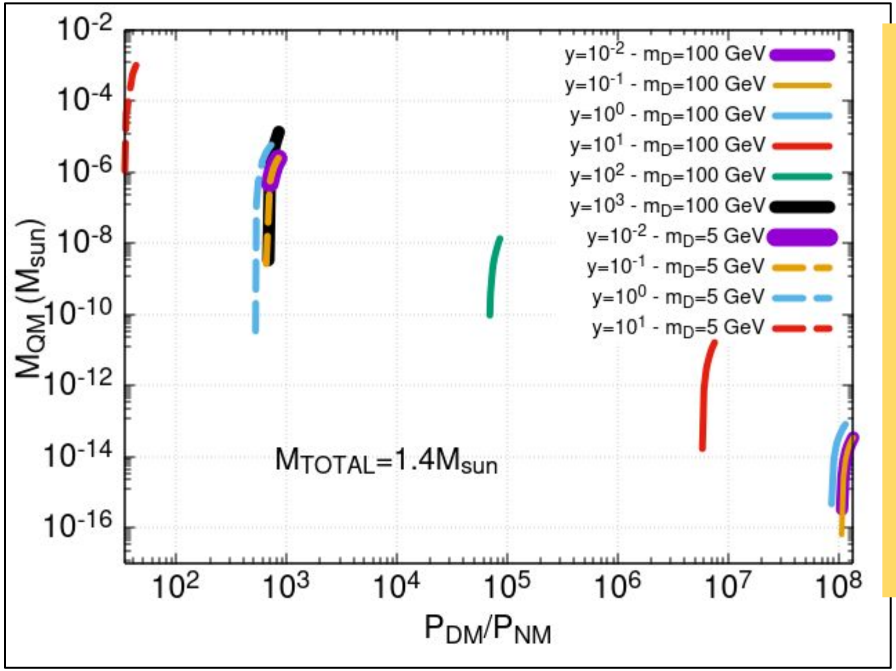
which shifts the onset of quark matter to lower masses

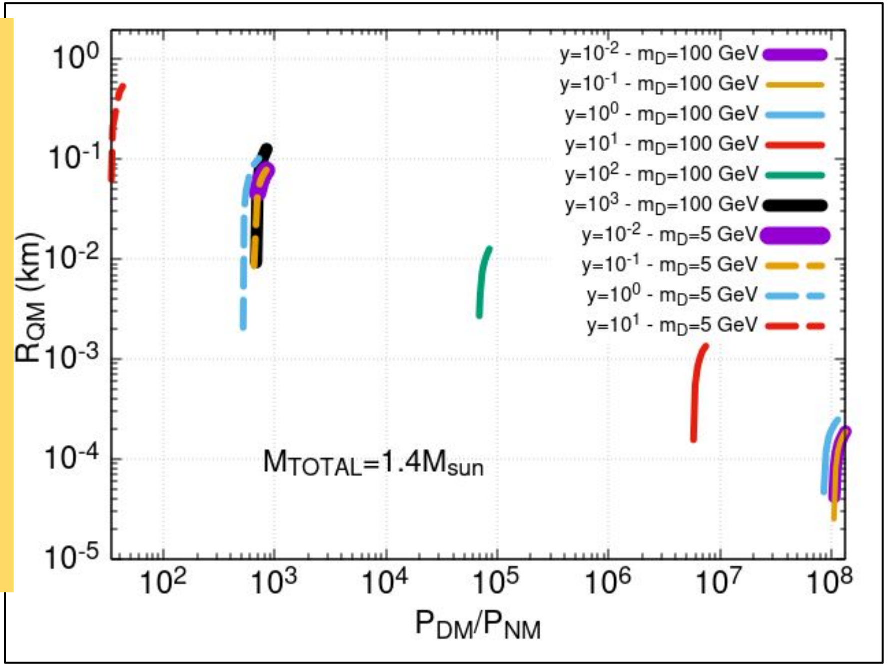
Hadrons, Quarks and Dark Matter in Stars



- For smaller y, higher P_{DM}/P_{NM} are needed ⇒ smaller the contribution to the total mass coming from the quarks
- For smaller m_D, smaller P_{DM}/P_{NM} are needed ⇒ bigger the contribution to the total mass coming from the quarks

Hadrons, Quarks and Dark Matter in Stars

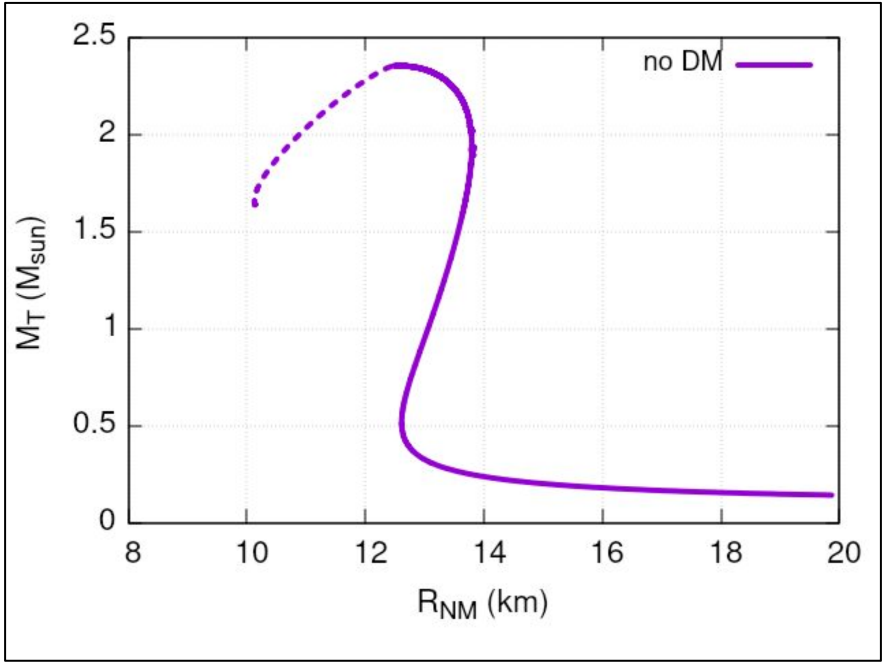




The quantity of QM (and its radius) is small and depends on the DM particle mass and interaction strength.
When quark matter is already present, DM tends to increase its amount—enhancing the quark core.

Dark Matter Admixed Hybrid Stars

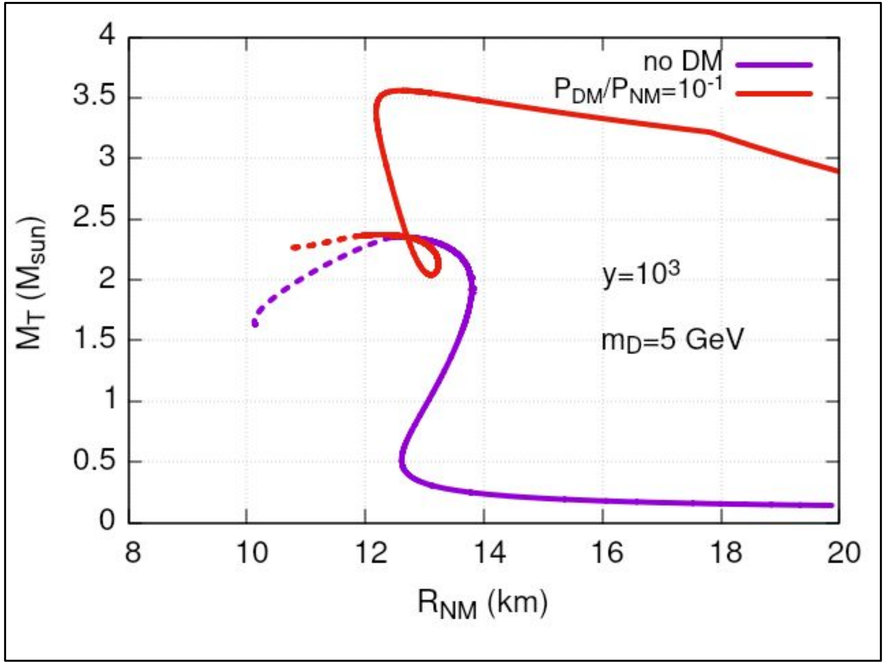
The strongly interacting DM ($y=10^3$) with low particle mass (5 GeV) case.



The dashed line represents dynamically unstable stars

Dark Matter Admixed Hybrid Stars

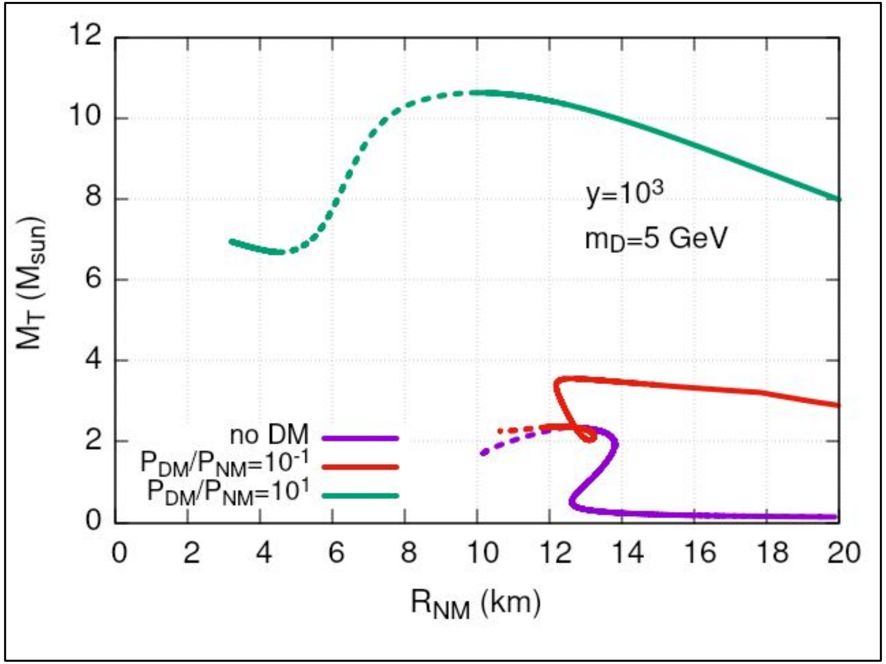
The strongly interacting DM ($y=10^3$) with low particle mass (5 GeV) case.



A little bit of DM and the MR digram goes crazy already

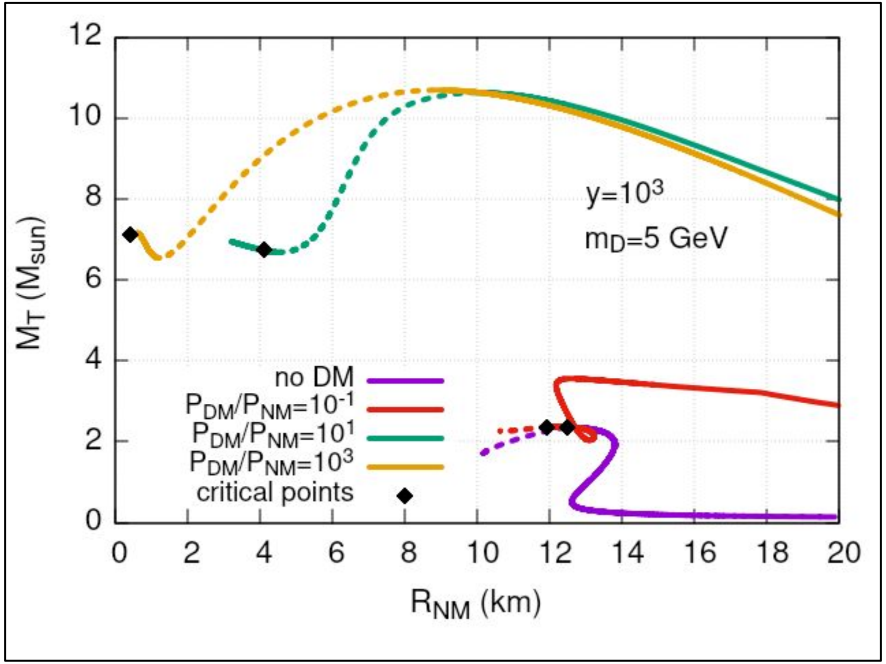
Dark Matter Admixed Hybrid Stars

The strongly interacting DM ($y=10^3$) with low particle mass (5 GeV) case.



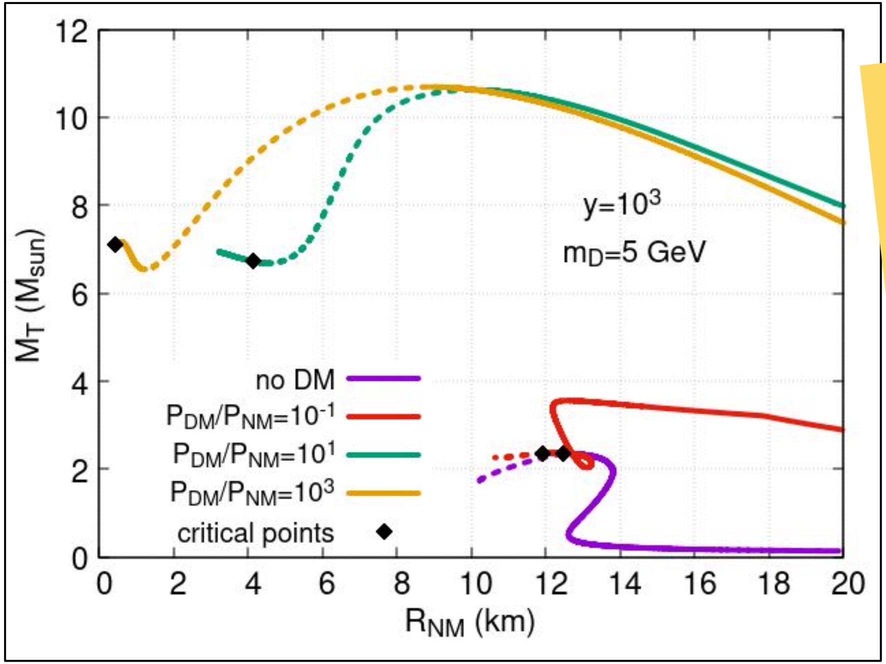
Dark Matter Admixed Hybrid Stars

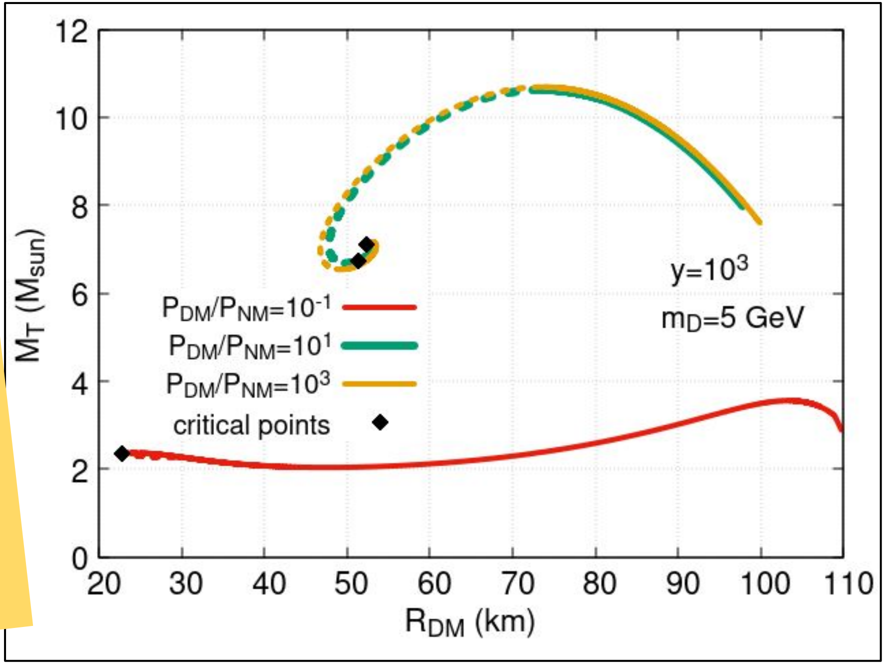
The strongly interacting DM ($y=10^3$) with low particle mass (5 GeV) case.



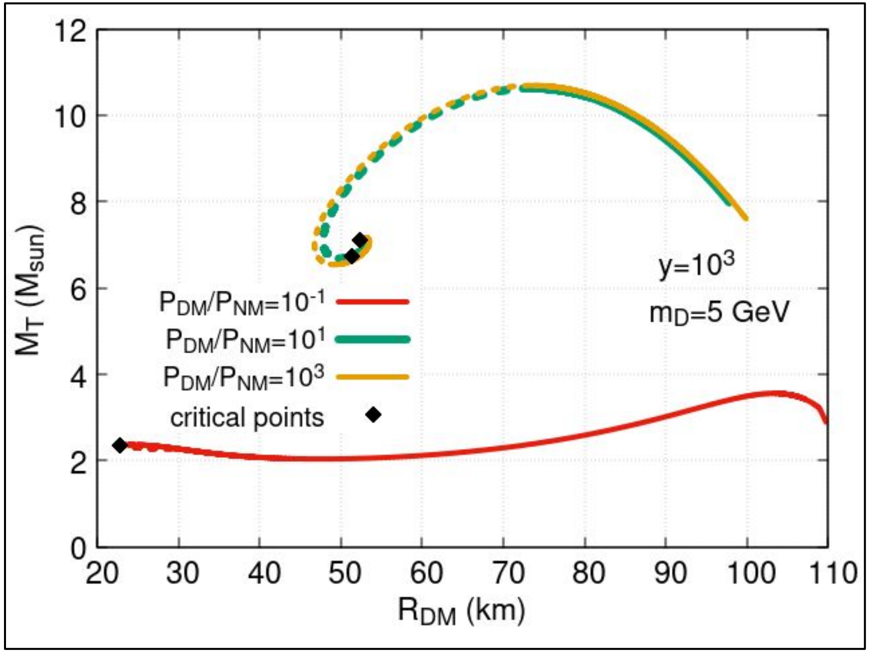
Dark Oysters

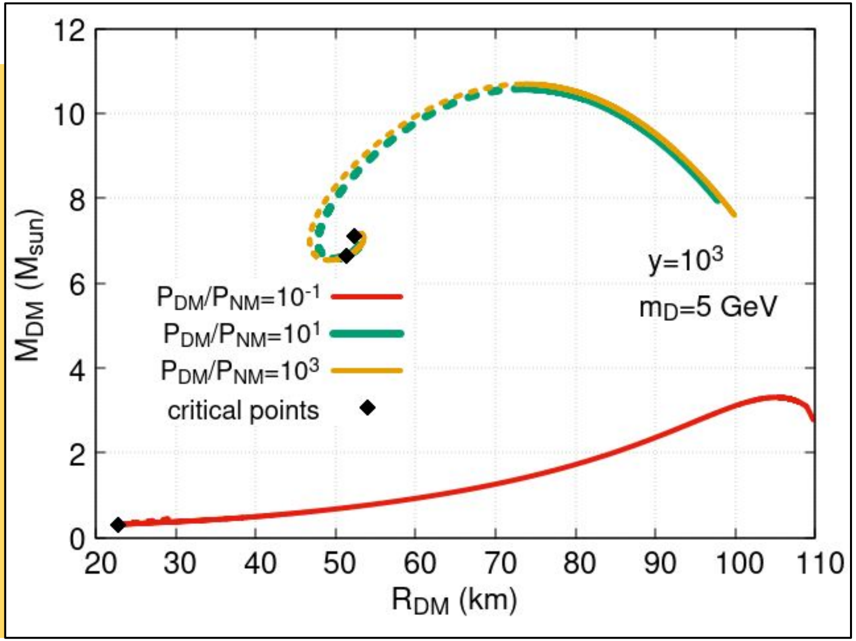
Strongly interacting DM ($y=10^3$) with low particle mass (5 GeV) leads to compact stars with **very small normal matter cores** and **large DM halos**.





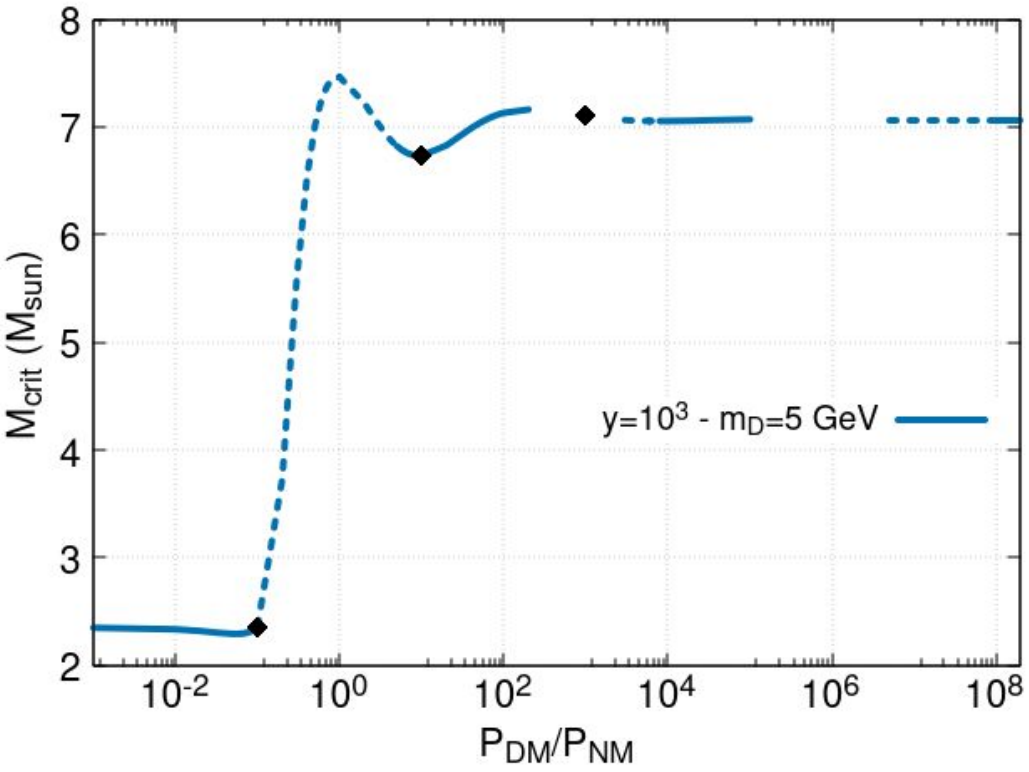
Dark Oysters





The DM does not only dominate quickly the radius of the star, it also dominates the mass

Dark Oysters



- In this case the critical mass increases

Masquerading Hybrid Stars with DM

- **Dark Matter Can Trigger Quark Core Formation**
  - DM raises central pressure, enabling the appearance of quark matter at lower stellar masses.
- **Masquerading Hybrid Stars**
  - DM-admixed stars mimic hadronic ones.
- **Critical Mass Decreases with DM Content**
  - The minimum mass required for a quark core ($M_{(crit)}$) drops as the DM-to-NM pressure ratio increases.
- **DM Properties Shape Star Composition**
  - particle mass & interaction strength shape composition.
  - Low DM particle masses with a strong interaction among those particles can lead to exotic objects called Dark Oysters

DM doesn't just surround neutron stars—it may quietly reshape their cores.

If dark matter can quietly reshape the cores of neutron stars, what else might it be hiding from us?

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