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# Neutron Star Constraints on Neutron Dark Decays

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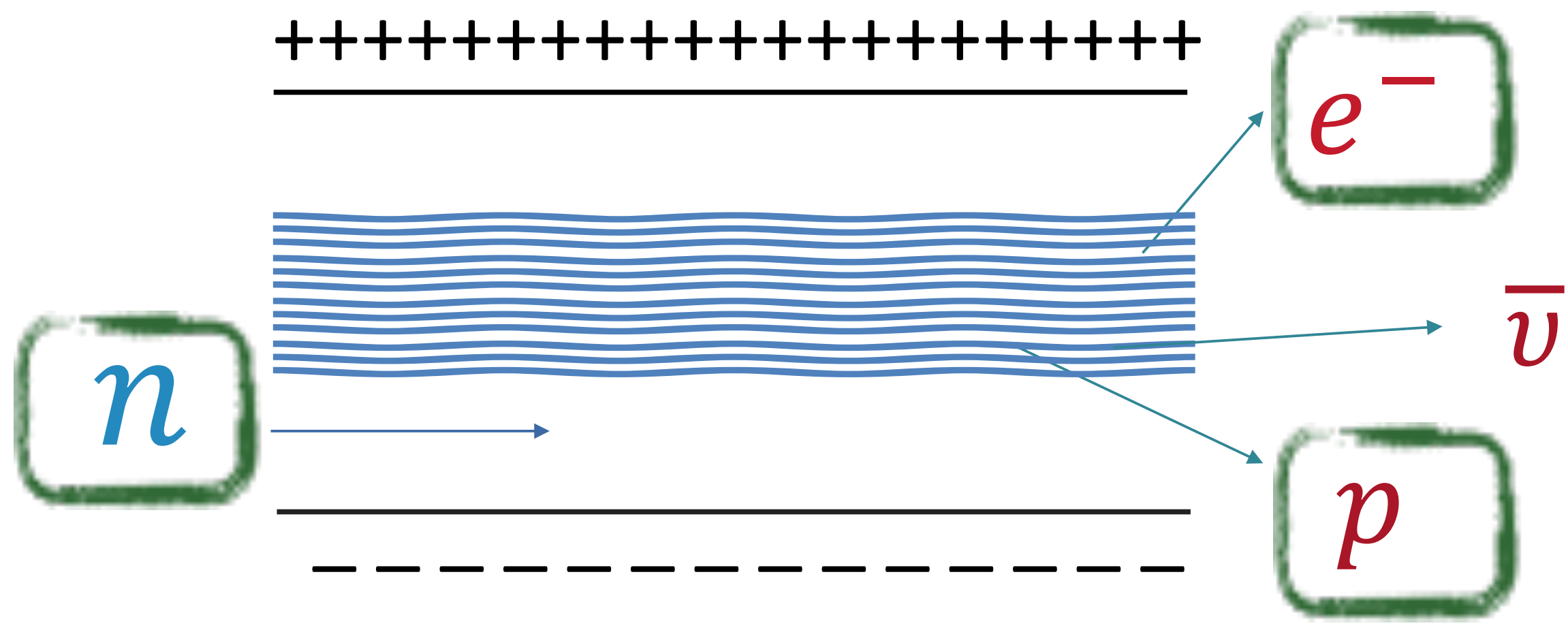
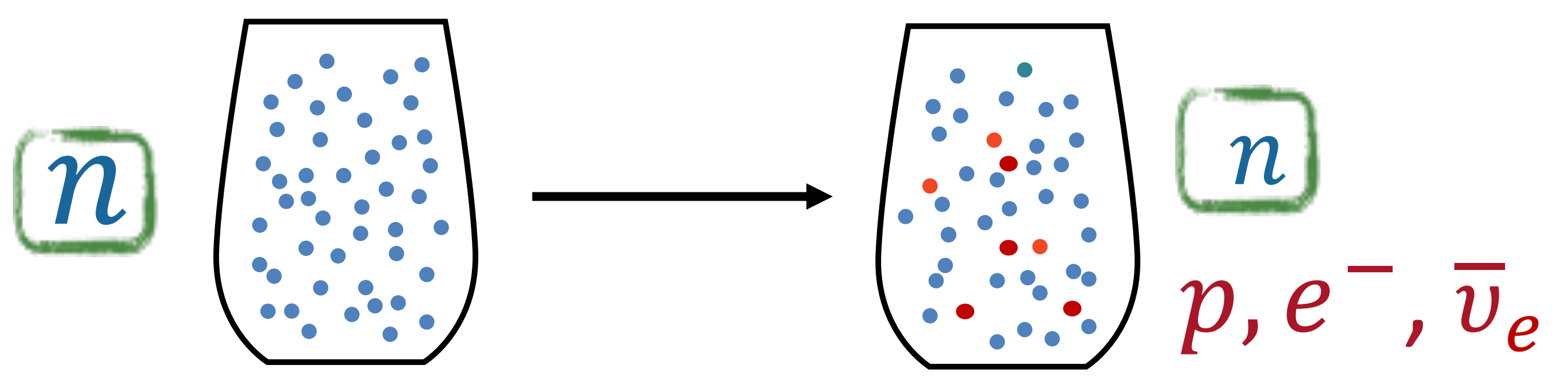
## Motivation: the neutron lifetime puzzle

- Two methods of determining the neutron lifetime:
  - "Beam" measures beta-decay width



$$P_{\text{decay}}(t) = 1 - \exp(-t/\tau_n^{\text{beam}})$$

  - "Bottle" measures total decay width



$$P_{\text{survival}}(t) = \exp(-t/\tau_n^{\text{bottle}})$$

- Beam-bottle discrepancy currently at 4σ:

| | |
|---|---|
| $\tau_n^{\text{beam}} = 888.0 \pm 2.0\ \text{s}$ | $\tau_n^{\text{bottle}} = 879.6 \pm 0.6\ \text{s}$ |
| [J. Byrne and P. G. Dawber, Europhys. Lett. 33, 187 (1996)]<br>[A. T. Yue *et al*, Phys. Rev. Lett. 111, 222501 (2013)] | [W. Mampe, *et al*, JETP Lett. 57, 82 (1993)]<br>[A. Serebrov *et al*, Phys. Lett. B 605, 72 (2005)]<br>[A. Pichlmaier, *et al*, Phys. Lett. B693, 221 (2010)]<br>[A. Steyerl et al,Phys. Rev. C 85, 065503 (2012)]<br>[A. Pichlmaier, *et al*, Phys. Lett. B693, 221 (2010)] |

## A solution: neutron dark decays

- Dark decays $n \to X_1 X_2$ ... make up 1.3% of the total width
- Subject to kinematic constraints:
  - Kinematically allowed if $\sum_i m_{X_i} < m_n$
  - $^9$Be satable: $\sum_i m_{X_i} > 937.90$ MeV
- Model I: dark neutrons carrying unit baryon number B=1

[Fornal and Grinstein, PRL 120, (2018) 191801]

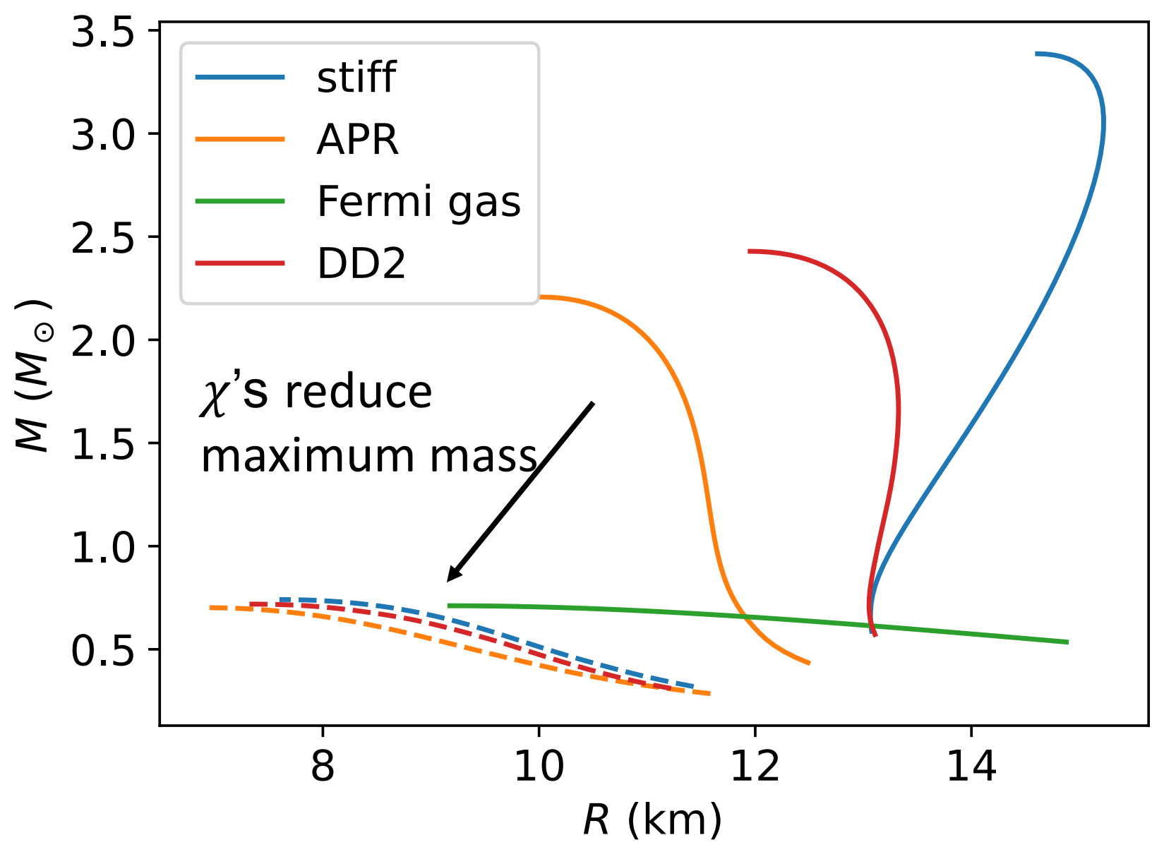
  - Either visible $n \to \chi\,\gamma$ , or invisible $n \to \chi\,\phi$ , ...
  - $\chi$ stable thus DM candidate if $m_\chi > m_p + m_e \approx 938.87$ MeV
  - LANL searched for $\gamma$, ruled out $\chi$ as DM candidate, or $n \to \chi\,\gamma$ as a complete resolution if $\chi$ is stable [Z Tang *et al PRL* **2018**, *121]*
- **Model II: dark quarks $n \to \chi_i \chi_j \chi_k$ ...**

[*D Zhou*, *Universe* 9 (2023) 11, 484]

  - They are fermions each carrying baryon number 1/3
  - Can be identical or distinct with $N_f$ species

## Neutron stars (NSs) and dark neutrons

- **NSs yield model-independent bounds on dark neutrons**
  - Non-interacting $\chi$'s dominate NS, their Fermi gas equation of state (EOS) only support $\sim 0.8 M_\odot$ stars

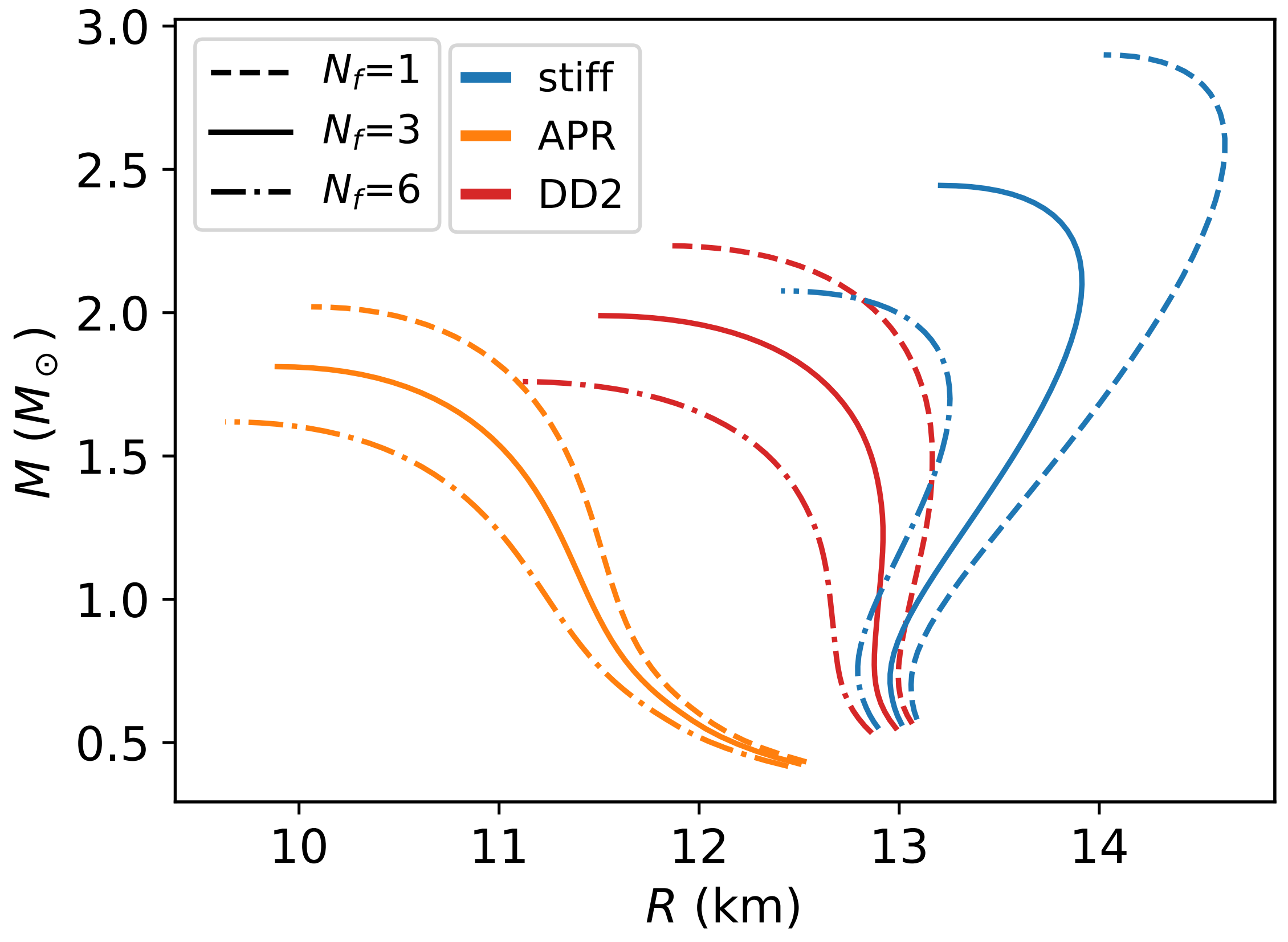


| Sub-model | Constraint |
|---|---|
| non-interacting | excluded |
| mirror neutron | $C_{s,\max} \gtrsim 0.6$ |
| self-interacting | $g/m_V \gtrsim 0.01\ \text{MeV}^{-1}$ |

  - Existence of 2 $M_\odot$ neutron stars requires strong interactions among $\chi$'s
  - **Valid for $n\chi$ mixings much smaller than probed at terrestrial labs**

## Dark quarks I: degenerate masses: $m_\chi \approx m_n/3$

- Up to 6 non-interacting species ($N_{\text{f}} \leq 6$) may be allowed



The sound speed squared of Fermi gas approaches 1/3 faster for lower masses:

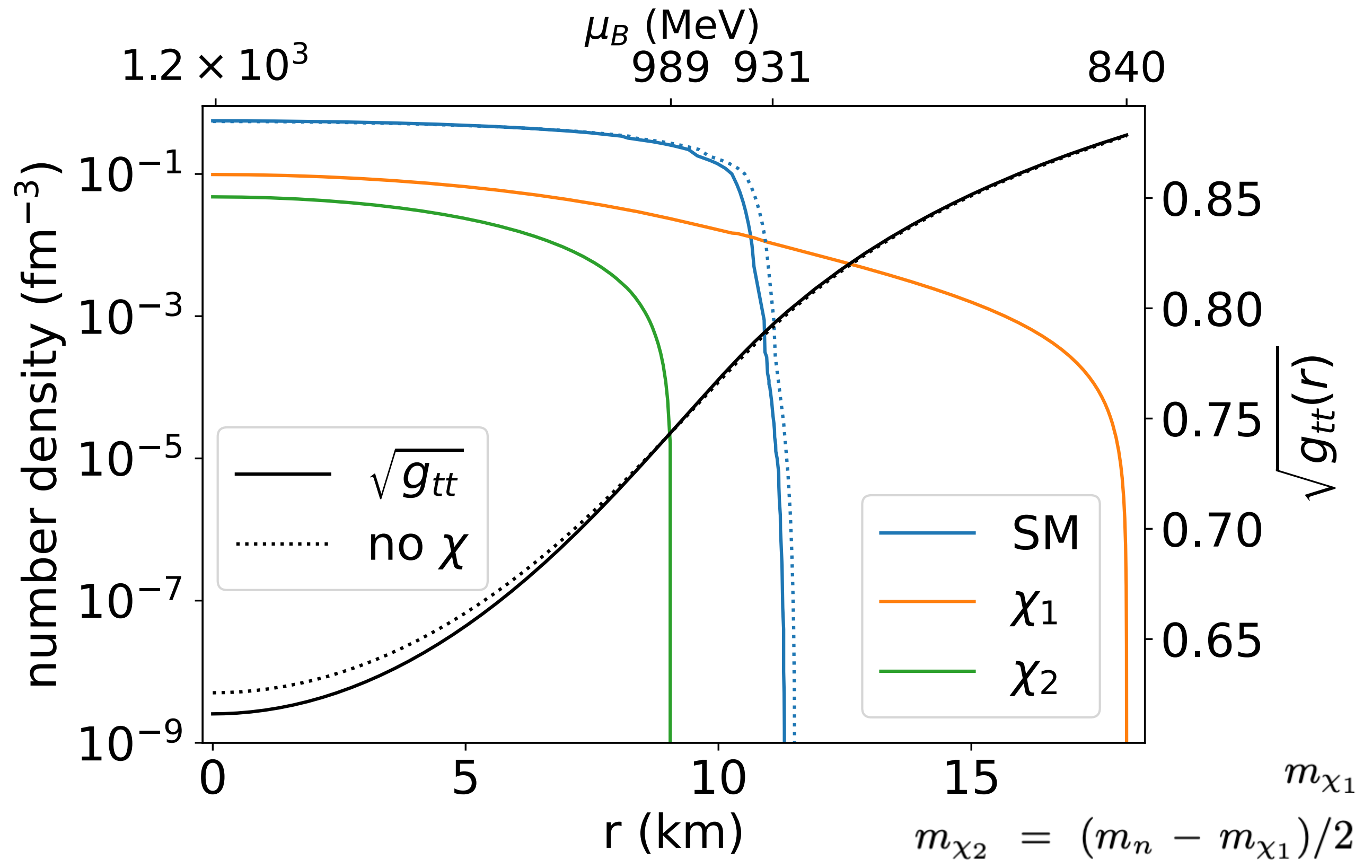
$$C_s = \frac{1}{3}\left[1 + \frac{m^2}{(3\pi^2 n)^{2/3}}\right]^{-1}$$

sufficient to support massive pulsars even in the absence of strong self-repulsions.

## Dark quarks II: light dark quarks and dark halos

- Dark quarks with $m_\chi < m_n/3$ form halos surrounding NSs
  - Nonzero pressure at the surface pushes dark quarks outward
  - In equilibrium sourced by local baryon chemical potentials $\mu_B$; Due to gravity a gradient is established as:

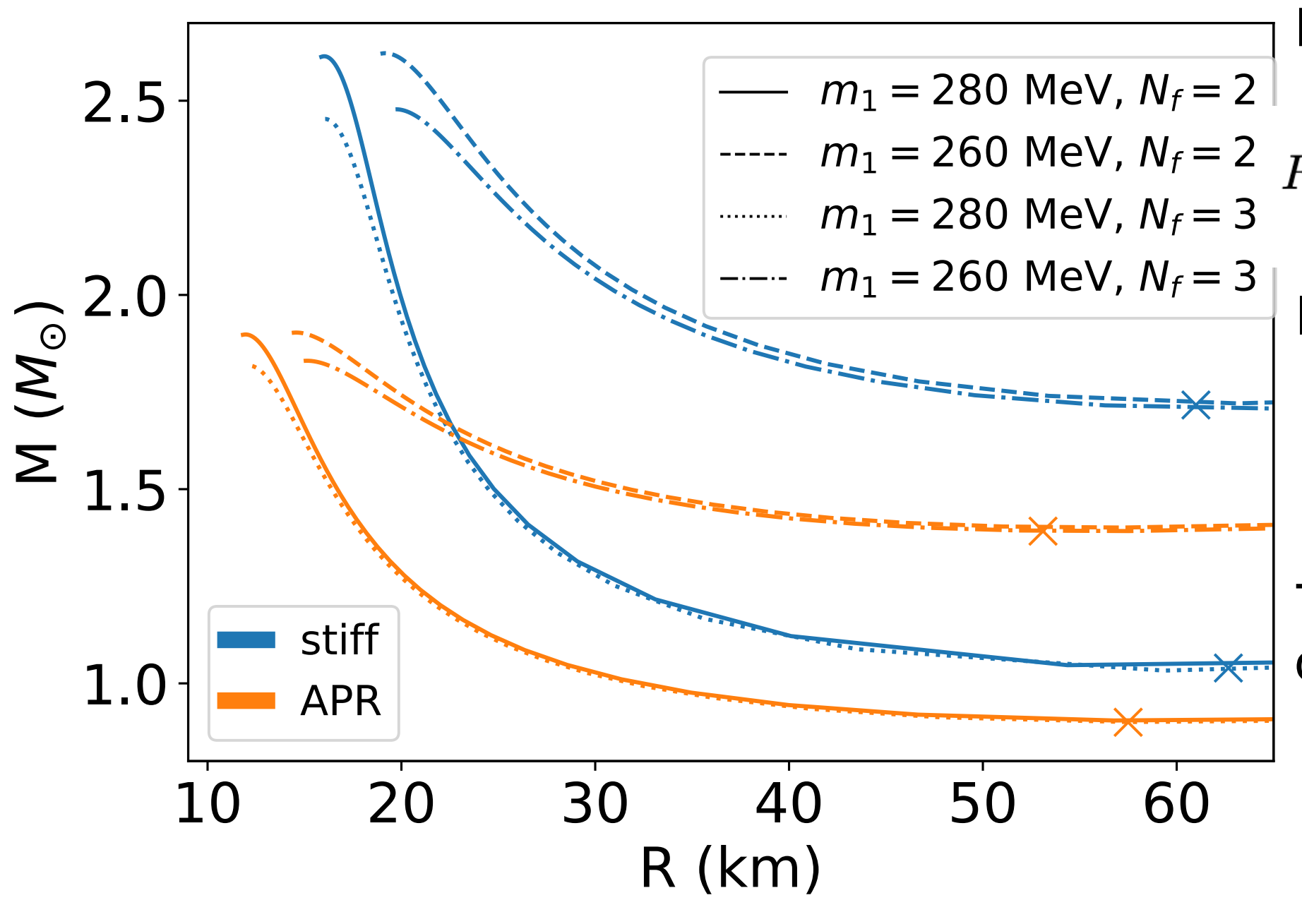
$$\mu_B(r)\ \sqrt{g_{tt}(r)} = \text{constant}$$



$$m_{\chi_1} = 280\ \text{MeV}$$
$$m_{\chi_2} = (m_n - m_{\chi_1})/2 \approx 329\ \text{MeV}.$$

## Light dark quarks and dark halos

- $\chi$'s inside the star reduce maximum NS mass; $\chi$'s in the halo raise minimum NS mass
  - It is energetically favorable to store baryon numbers in the lightest dark quarks, the ground state in vacuum
  - Without strong gravitational fields, low-mass stars may have trouble curb the growth of halos which would eventually become gravitationally unbounded
  - The minimum NS mass thus puts a lower bound on $m_\chi$



Halo radius can be estimated as

$$R_\chi = \frac{2M}{1 - (1 - 2M/R_\star)\,(3m_\chi/m_n)^{-2}}$$

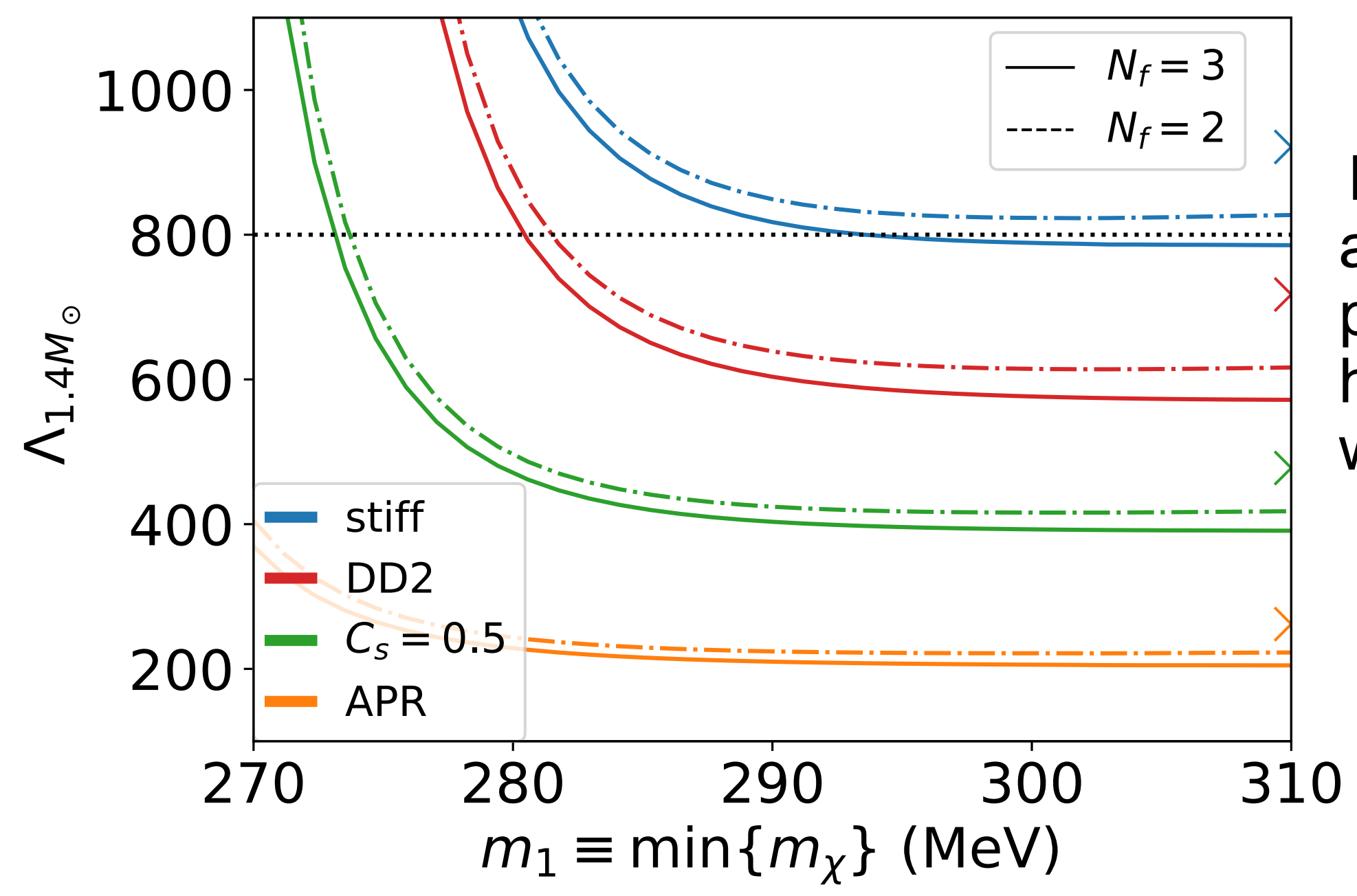
It stays finite if

$$m_\chi \geq \frac{m_n}{3}\sqrt{1 - \frac{2M}{R_\star}}.$$

To get low mass stars $\sim 1.2 M_\odot$, dark quarks must satisfy

$$\boldsymbol{m_\chi \gtrsim 270\ \text{MeV}}$$

- Dark quark halos could also enhance tidal interaction during binary neutron star inspirals



Numerical simulations are required to reliably predict the evolution of halos and gravitational wave observables

GW170817 suggests $\Lambda_{1.4M_\odot} \lesssim 800$, disfavors $m_\chi \lesssim 270$ MeV.

## Conclusions

- Neutron dark decays can populate neutron stars with sizable amounts of dark matter, affecting static properties and leaving observable imprints
- Neutron stars are sensitive to dark decay partial widths much less than can be probe in labs; Studying their evolution and observables could lead to additional bounds on slow processes.

## References

[1] D McKeen, A Nelson, S Reddy, **D Zhou,** PRL 121 (2018) 6, 061802
[2] **D Zhou,** *Universe* 9 (2023) 11, 484

## Acknowledgement

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