Image: Olena Shmahalo for NANOGrav

Constraining the Mass-Radius Relations of Non-Standard Neutron Stars

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Content

- Motivation to study Dark Matter in Neutron Stars
- Normal and Dark Matter Equation of State
- Two-fluid formalism and Stability Analysis
- Pure Dark Matter Stars
- Total Mass and Visible Radius
- Two-fluid Tidal Deformability
- Summary

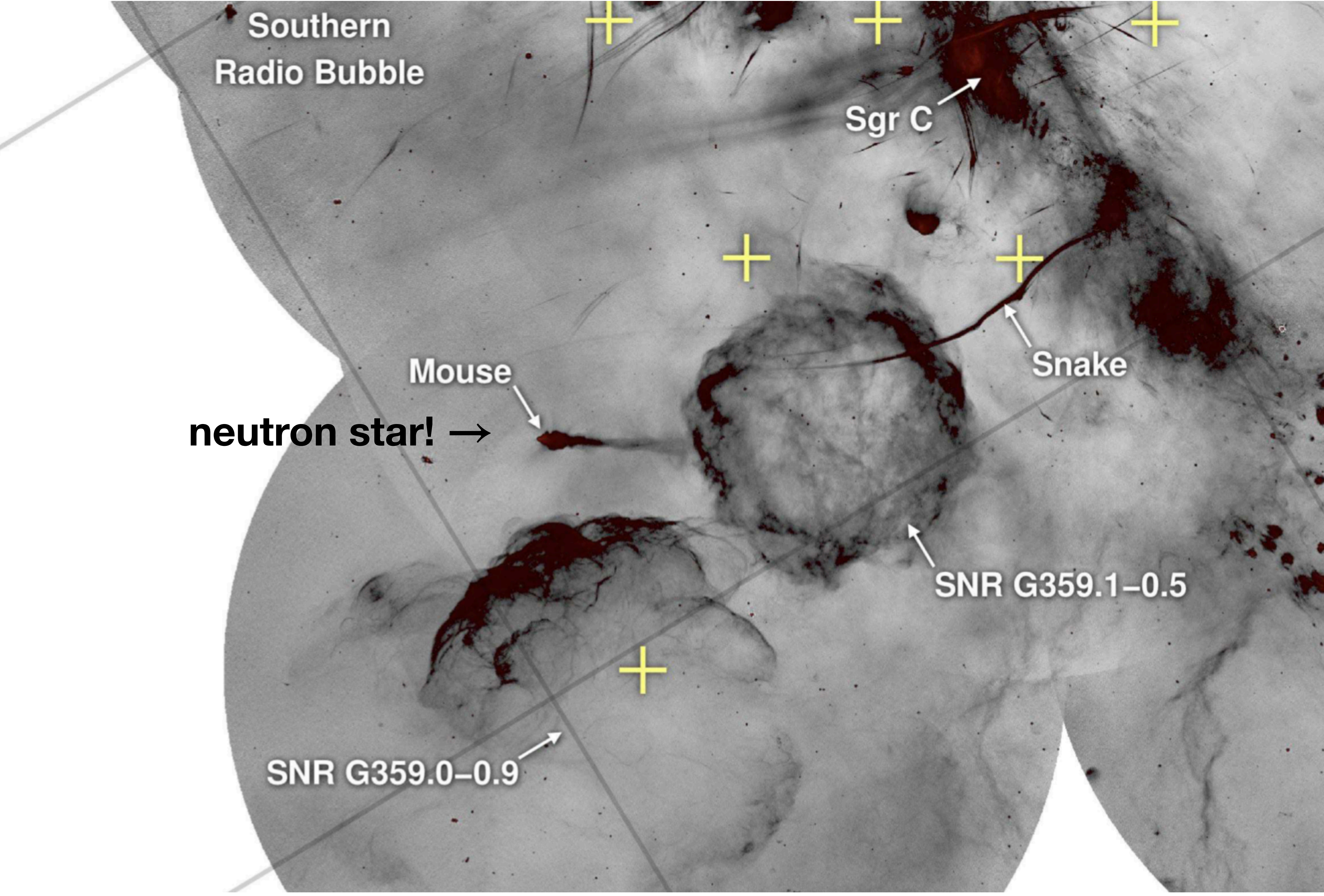

Image: MeerKAT 1.28 GHz Galactic Center

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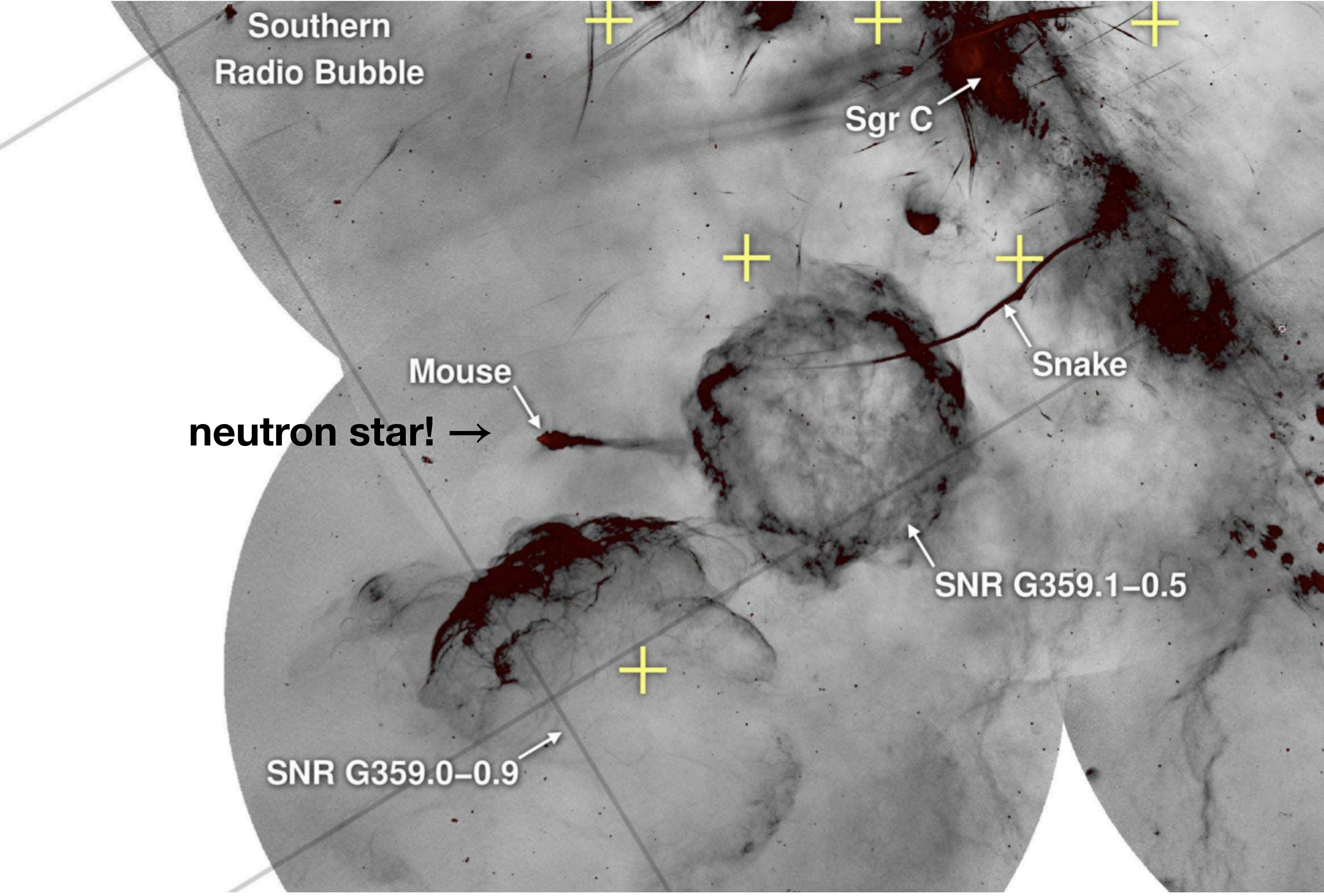

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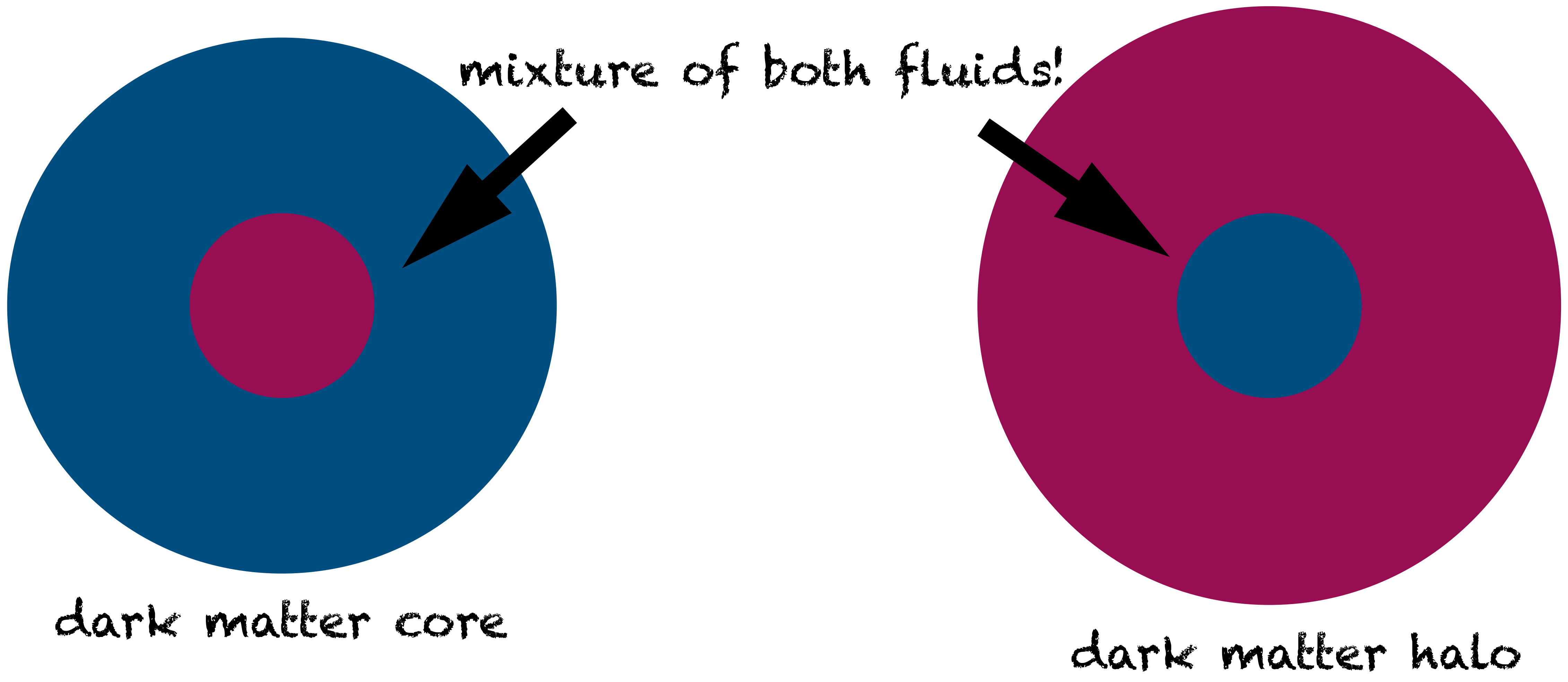


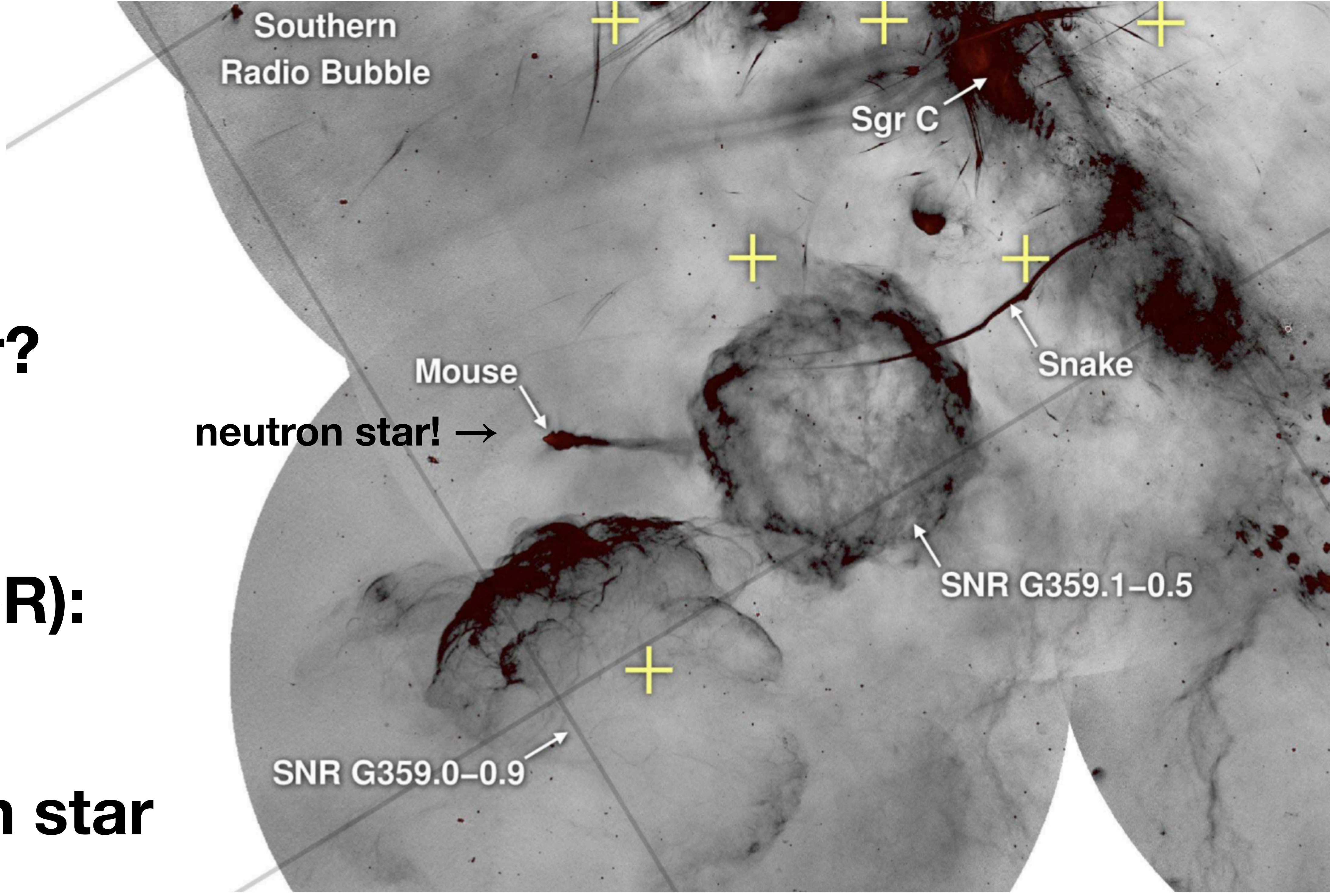
Motivation

- (How) can we detect dark matter inside a neutron star?

- Astrophysical Observations:

  e.g. NICER (Neutron star Interior Composition ExploreR):

  - outside solution is Schwarzschild solution
  - mass-radius prior is within ordinary matter neutron star predictions



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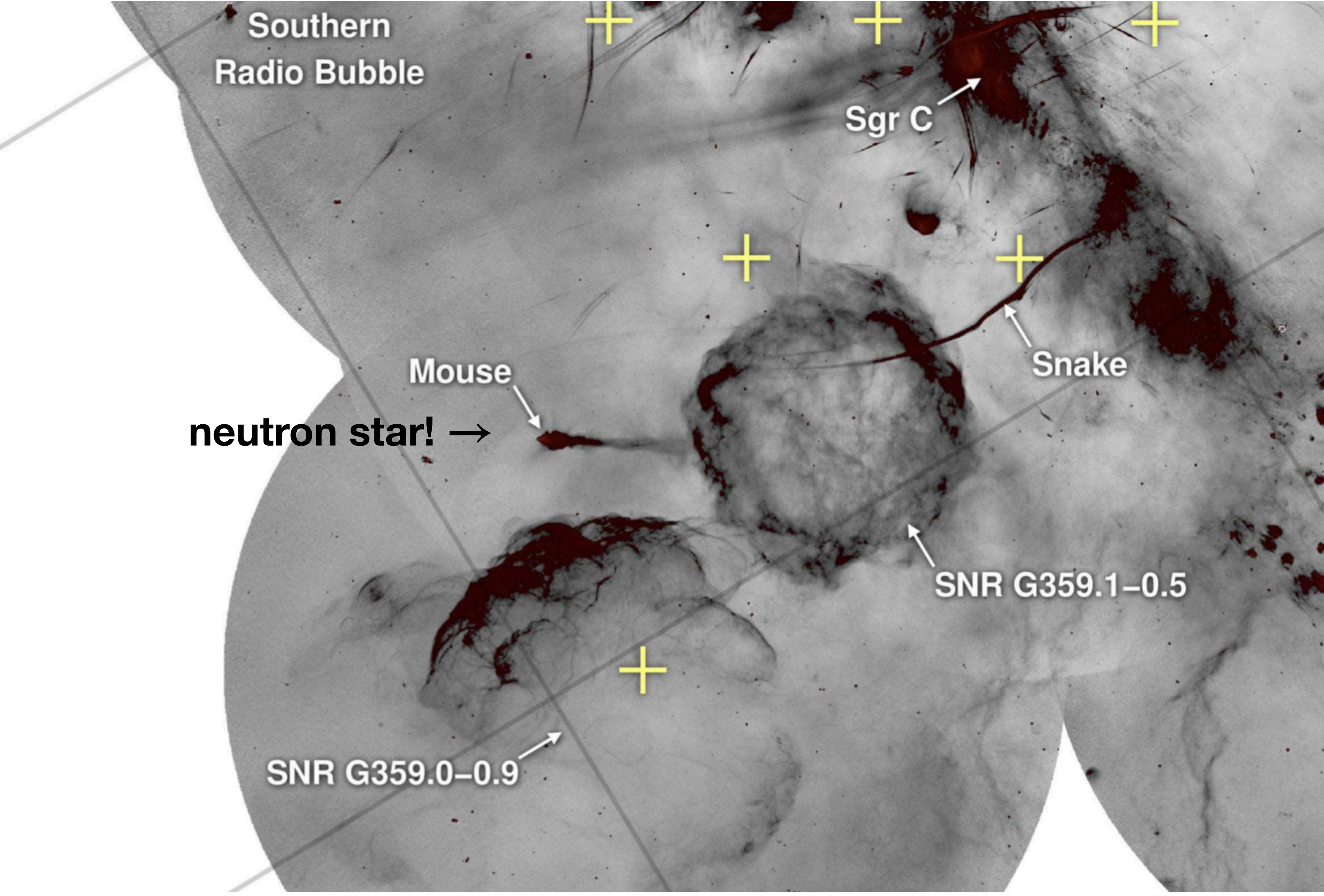
Motivation



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- **Goal:** use most general sample of model-agnostic equations of state that populate the whole allowed space and evolve them under the influence of dark matter

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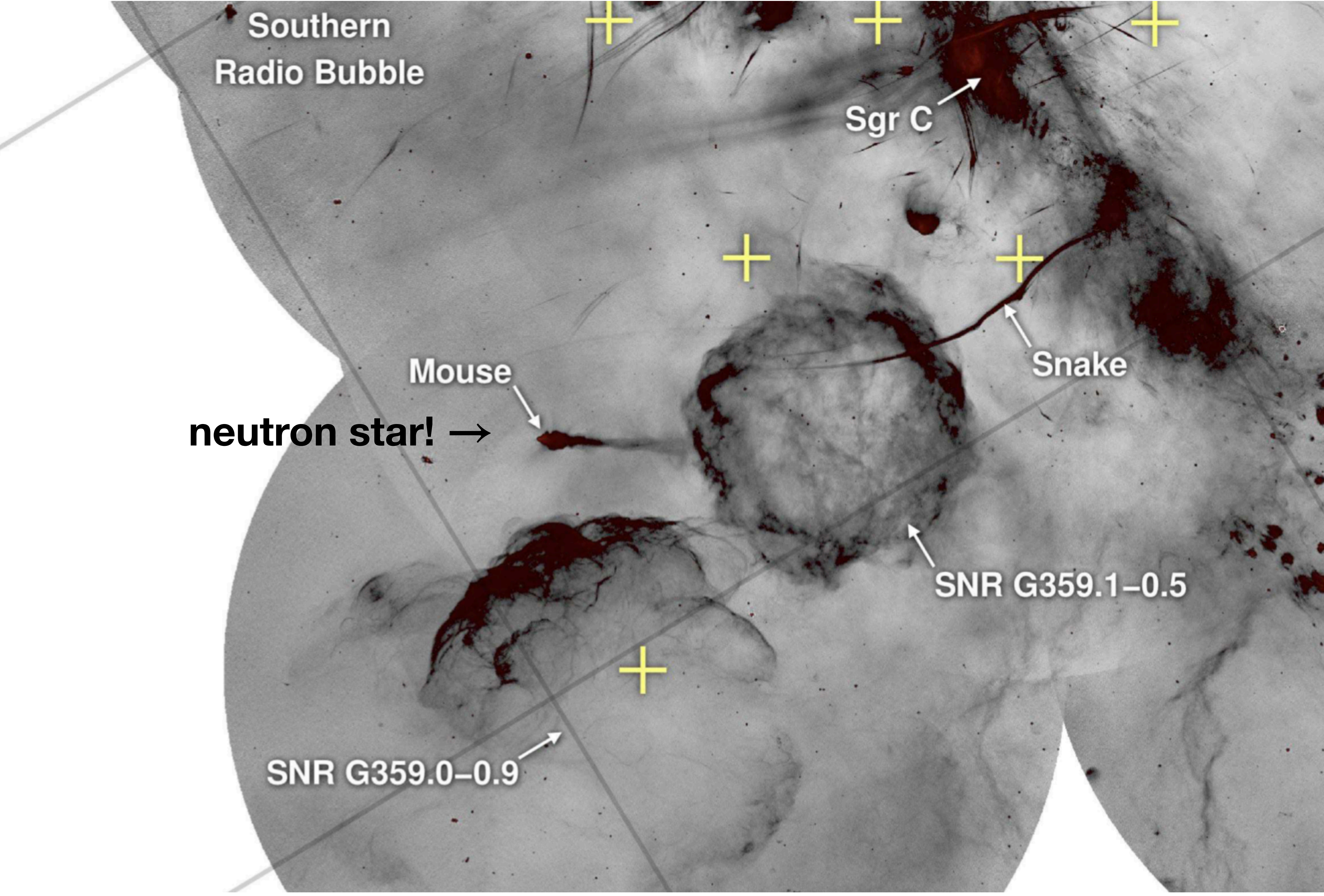

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- **Goal:** use most general sample of model-agnostic equations of state that populate the whole allowed space and evolve them under the influence of dark matter
    - make robust predictions on how dark matter changes observables without any model assumptions on ordinary matter equation of state
    - break degeneracy between additional dark matter and differences in the normal matter equation of state

Equation of State of Ordinary Matter (OM)

Gorda, Komoltsev, Kurkela & Sunde, Astrophys.J. 1002 (2026)

more information:
Oleg Komoltsevs talk

- **Use the most generic model-agnostic equation of state (eos):**
  - **Constrained Gaussian-process-bridge Prior**

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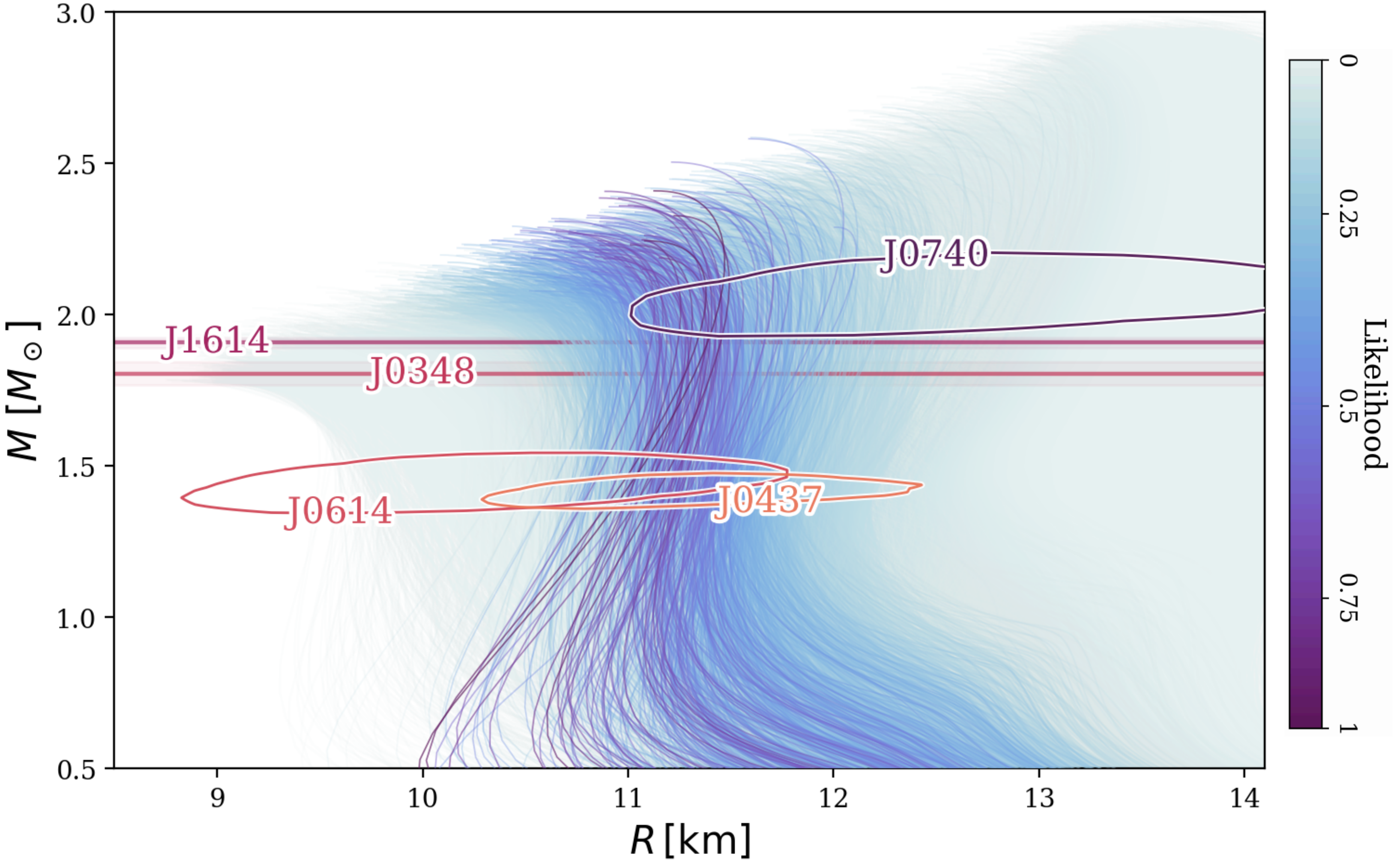


starting point:

mass-radius curves without any dark matter

Equation of State of Dark Matter (DM)

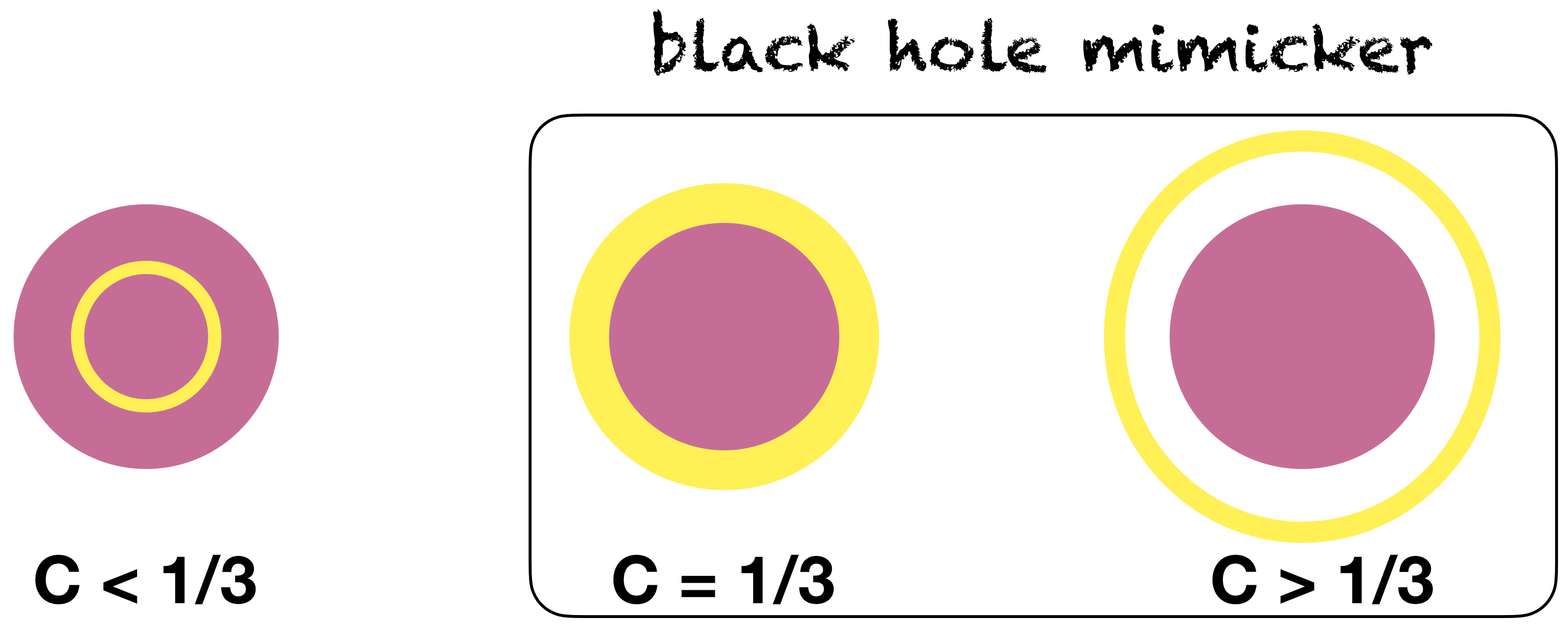
More information and new results:

Ishfaq Rathers talk at 15:30!

- **self-interacting bosonic, scalar dark matter field ϕ**

  Pitz & Schaffner-Bielich, PRD (2025) and Pitz & Schaffner-Bielich, PRD (2023)

- **two parameters: dark matter mass and stiffness of equation of state**
- **stiffness controlled via:** $V = \frac{\lambda}{2^{n/2}} \left(\phi\phi^*\right)^{n/2}$ **– higher *n* = stiffer eos**
- **resulting eos:** $\varepsilon = \frac{n+2}{n-2} p + p^{n/2}$
- $n \geq 40$ **generates compact stars with** $C = M/R \geq 1/3$**! (= neutron stars with a light ring)**



Two-fluid formalism

- **only gravitational coupling → alters Tolman-Oppenheimer-Volkoff equations:**

$$\frac{dp_i}{dr} = -\left(p_i + \varepsilon_i\right)\frac{d\nu}{dr}, \quad \frac{dm_i}{dr} = 4\pi r^2 \varepsilon_i \quad \text{with} \quad \frac{d\nu}{dr} = \frac{(m_i + m_j) + 4\pi r^3 (p_i + p_j)}{r(r - 2(m_i + m_j))} \quad i,j = \{OM, DM\}$$

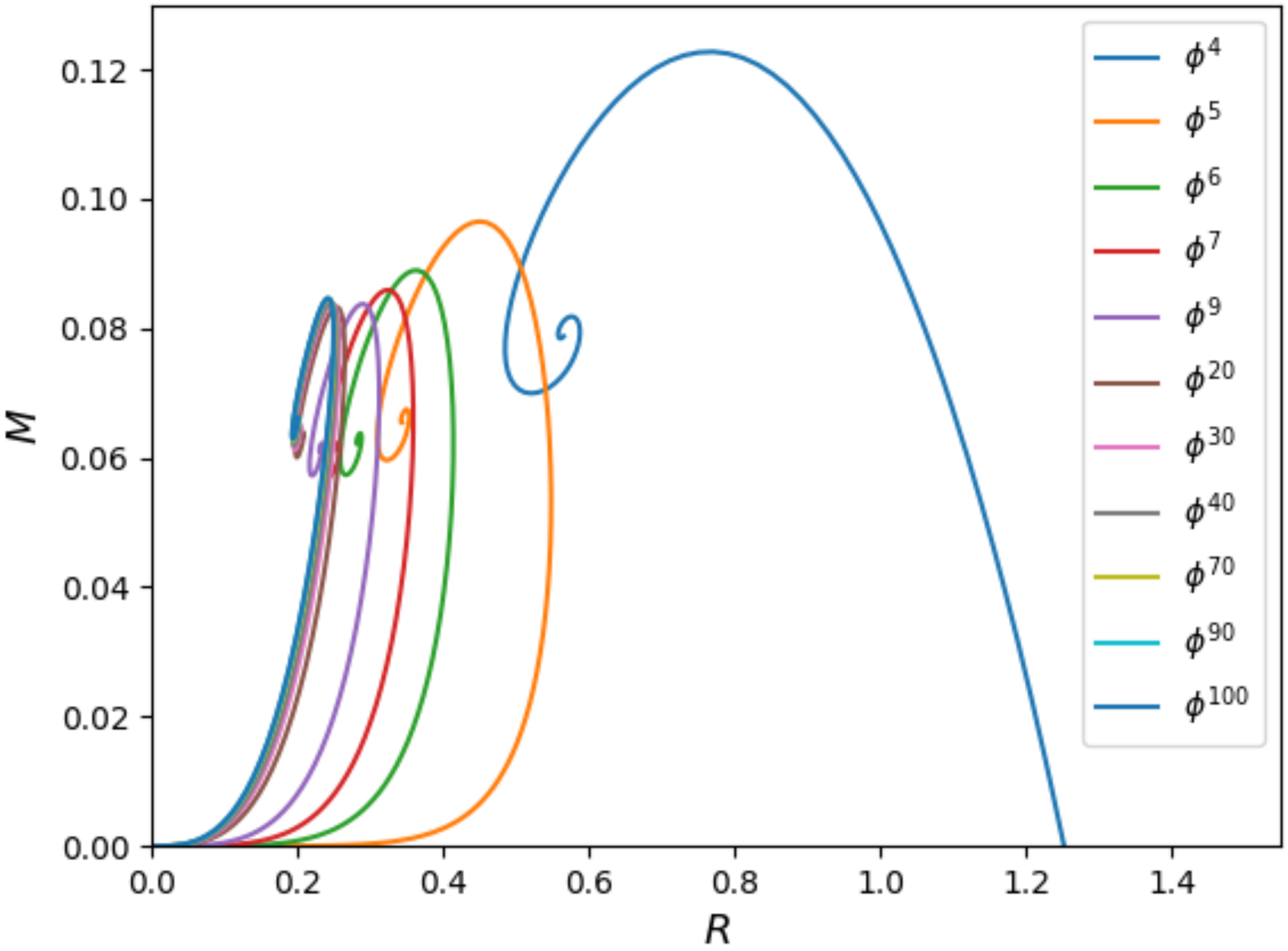
- **stability analysis:** Hippert et al. PRD (2023)

$$\begin{pmatrix} \delta N_{OM} \\ \delta N_{DM} \end{pmatrix} = \begin{pmatrix} \delta N_{OM}/\partial\varepsilon^c_{OM} & \delta N_{OM}/\partial\varepsilon^c_{DM} \\ \delta N_{DM}/\partial\varepsilon^c_{OM} & \delta N_{DM}/\partial\varepsilon^c_{DM} \end{pmatrix} \begin{pmatrix} \delta\varepsilon^c_{OM} \\ \delta\varepsilon^c_{DM} \end{pmatrix} = 0$$ **where N_i = total particle numbers &**

stable stars: both eigenvalues positive

Pure Dark Matter Stars (Boson Stars) - only one fluid

Pitz & Schaffner-Bielich, PRD (2023)



dimensionless Mass (M) and Radius (R)

solution of the TOV equations

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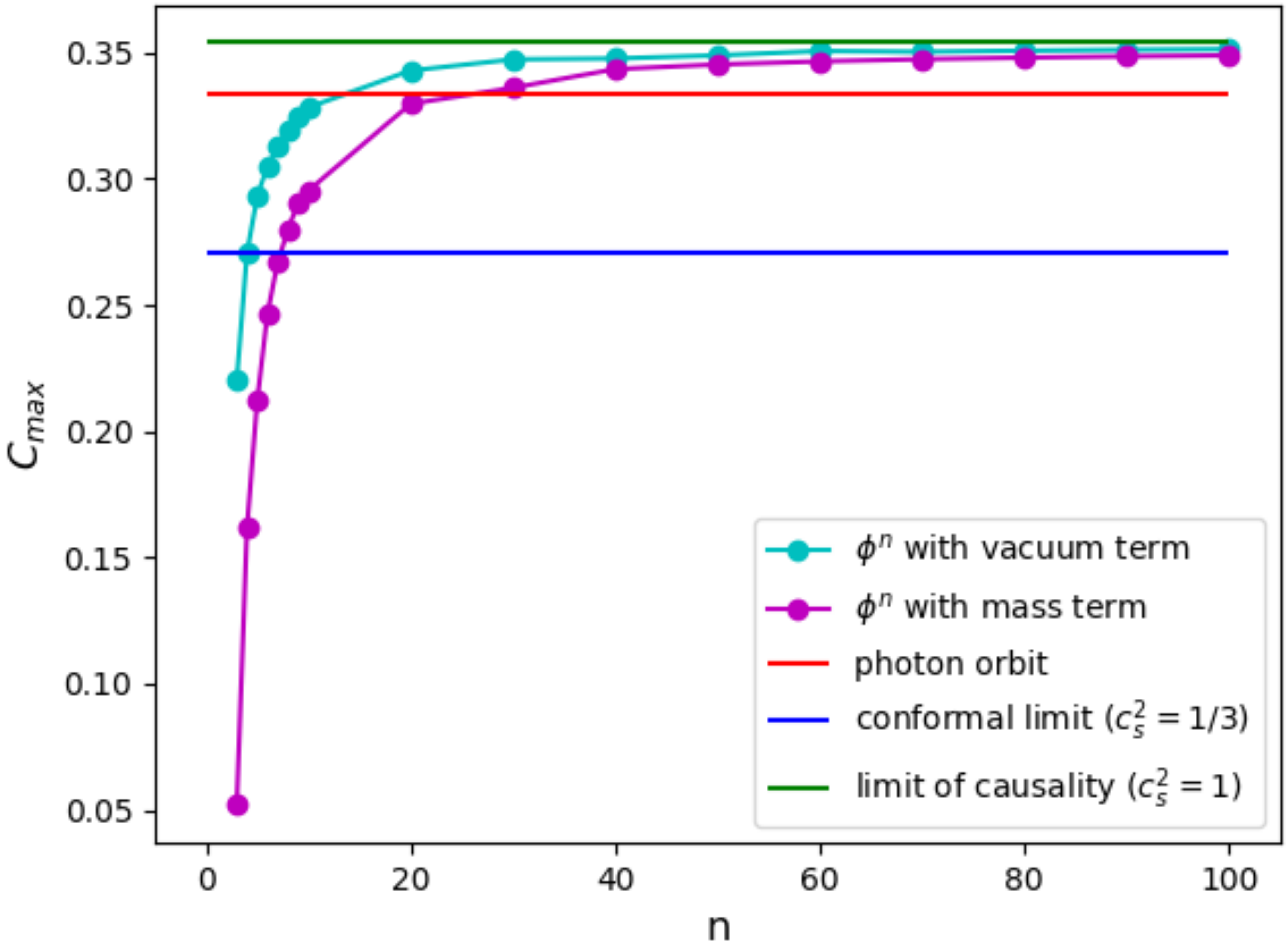
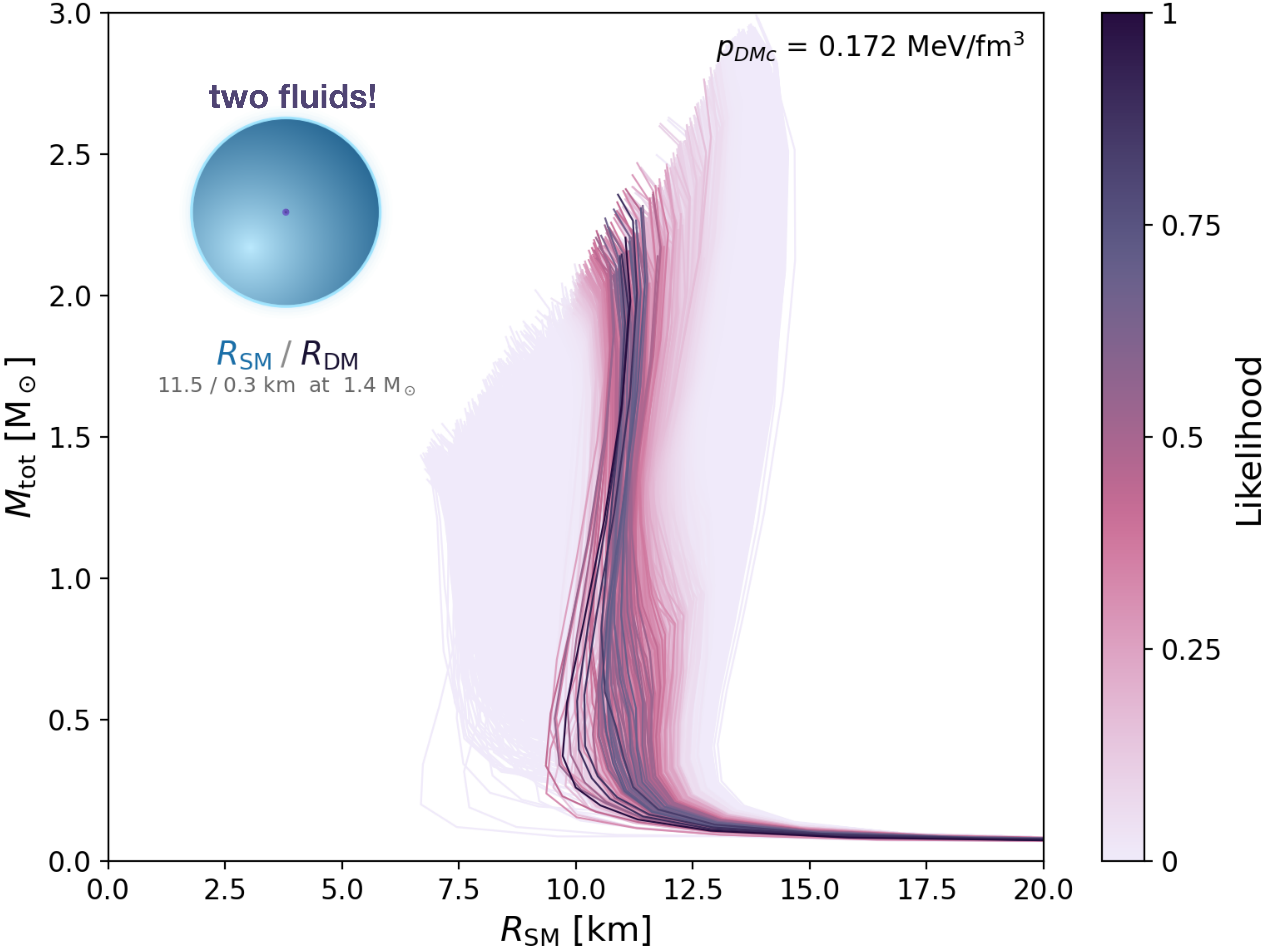


Compactness increases with stiffness of eos

(here $\phi^4 \ldots \phi^{100}$)

Results - Total Mass and Visible Radius (preliminary)



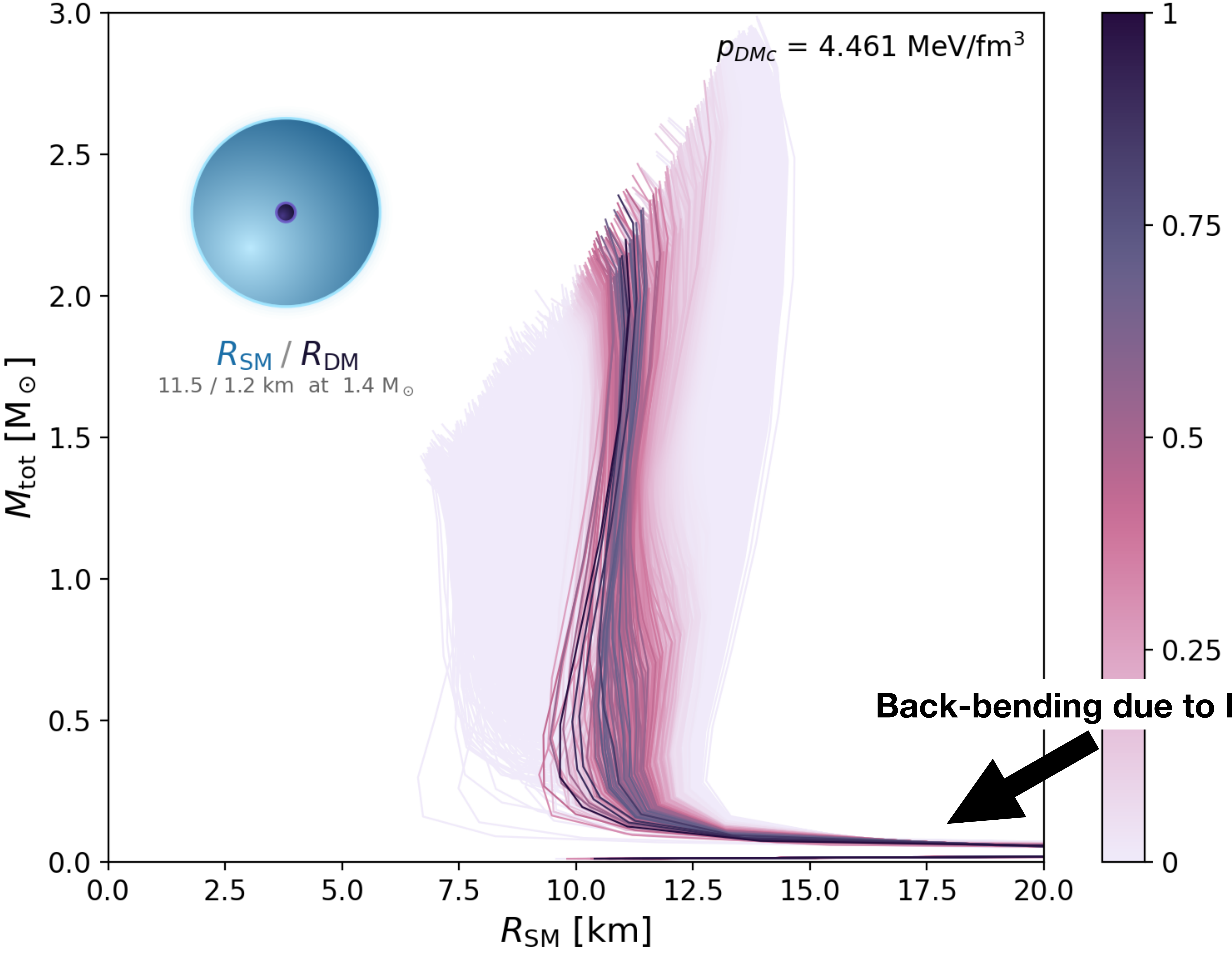
- parameters:

  $n = 40$ and $m_b = 300$ MeV

- only stable stars plotted
- all curves have same DM pressure
- likelihood contains:

  J0740, J0614, J1614, J0348 and J0437 (NICER and radio observations) & GW170817

Results - Total Mass and Visible Radius



Back-bending due to DM impact starts!

DM starts to dominate: convergence to pure Boson star MR curve

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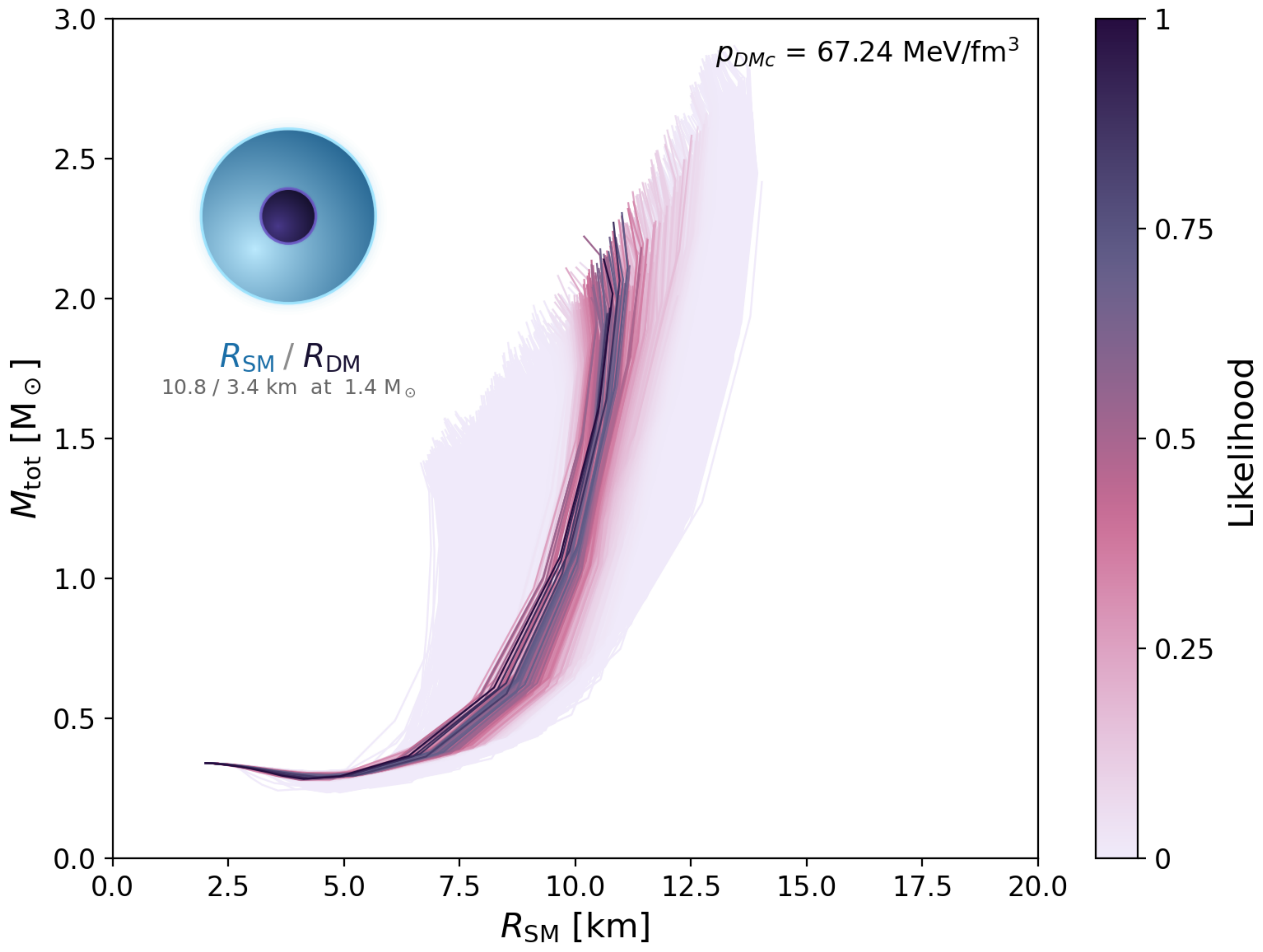

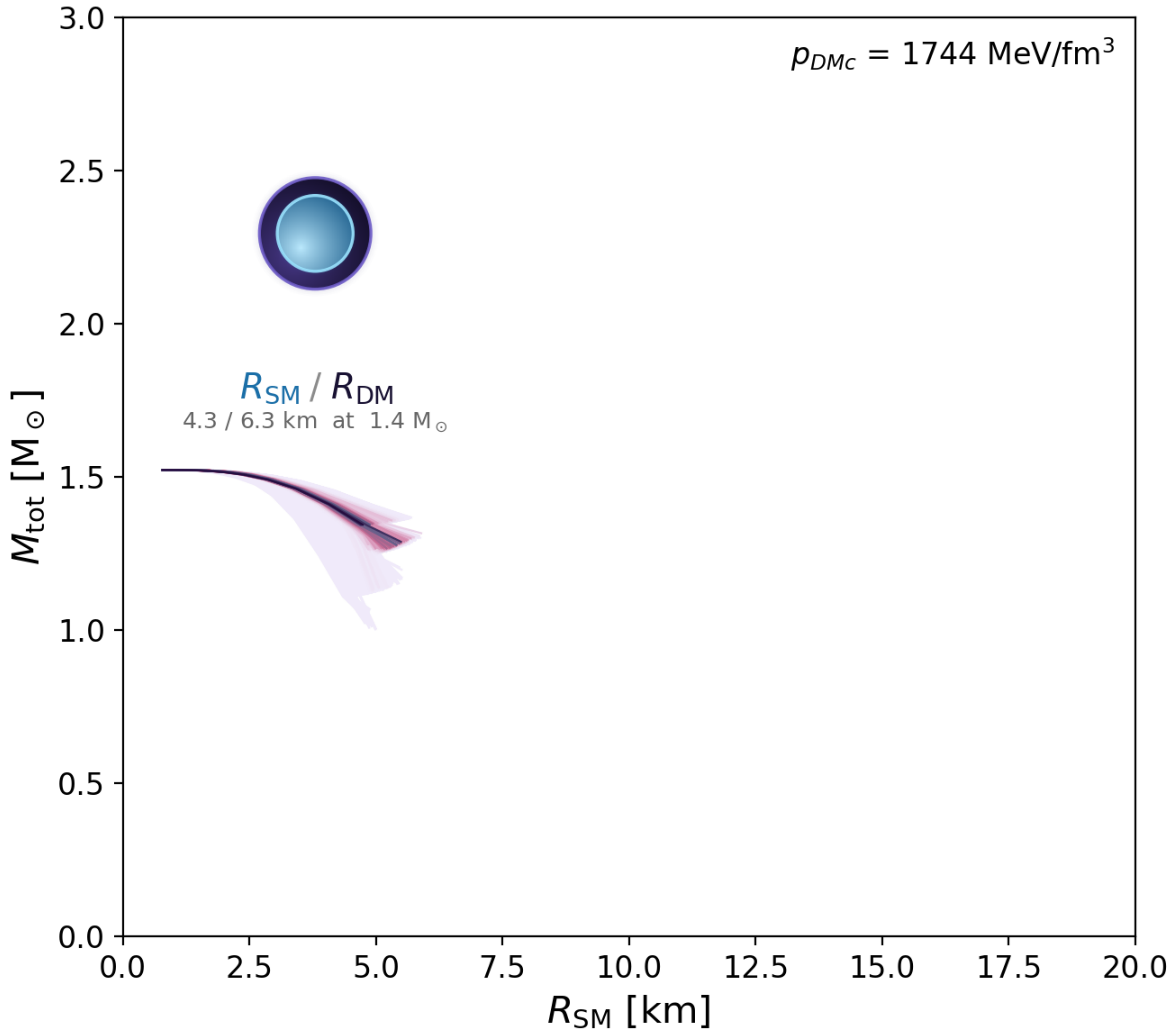

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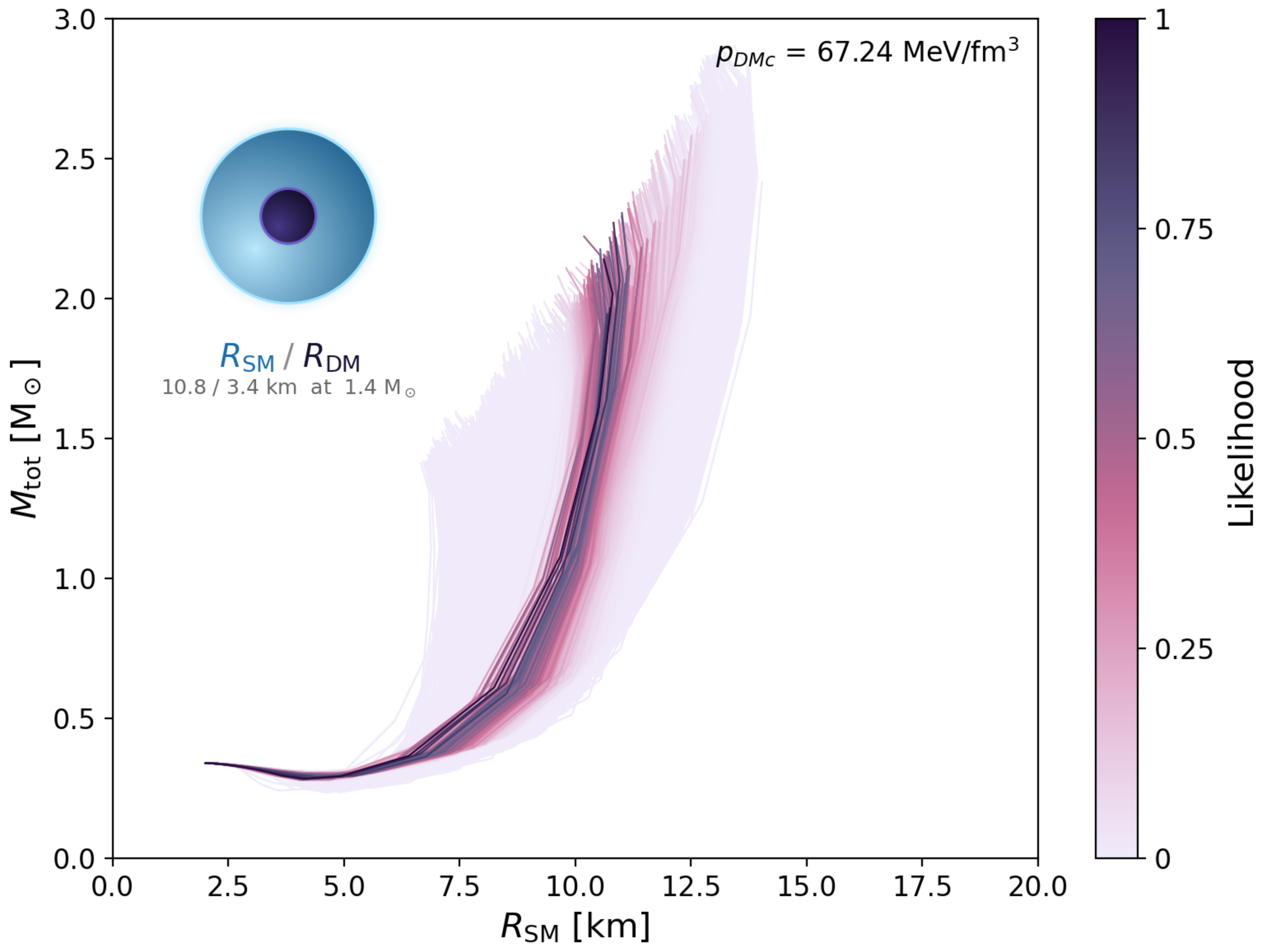
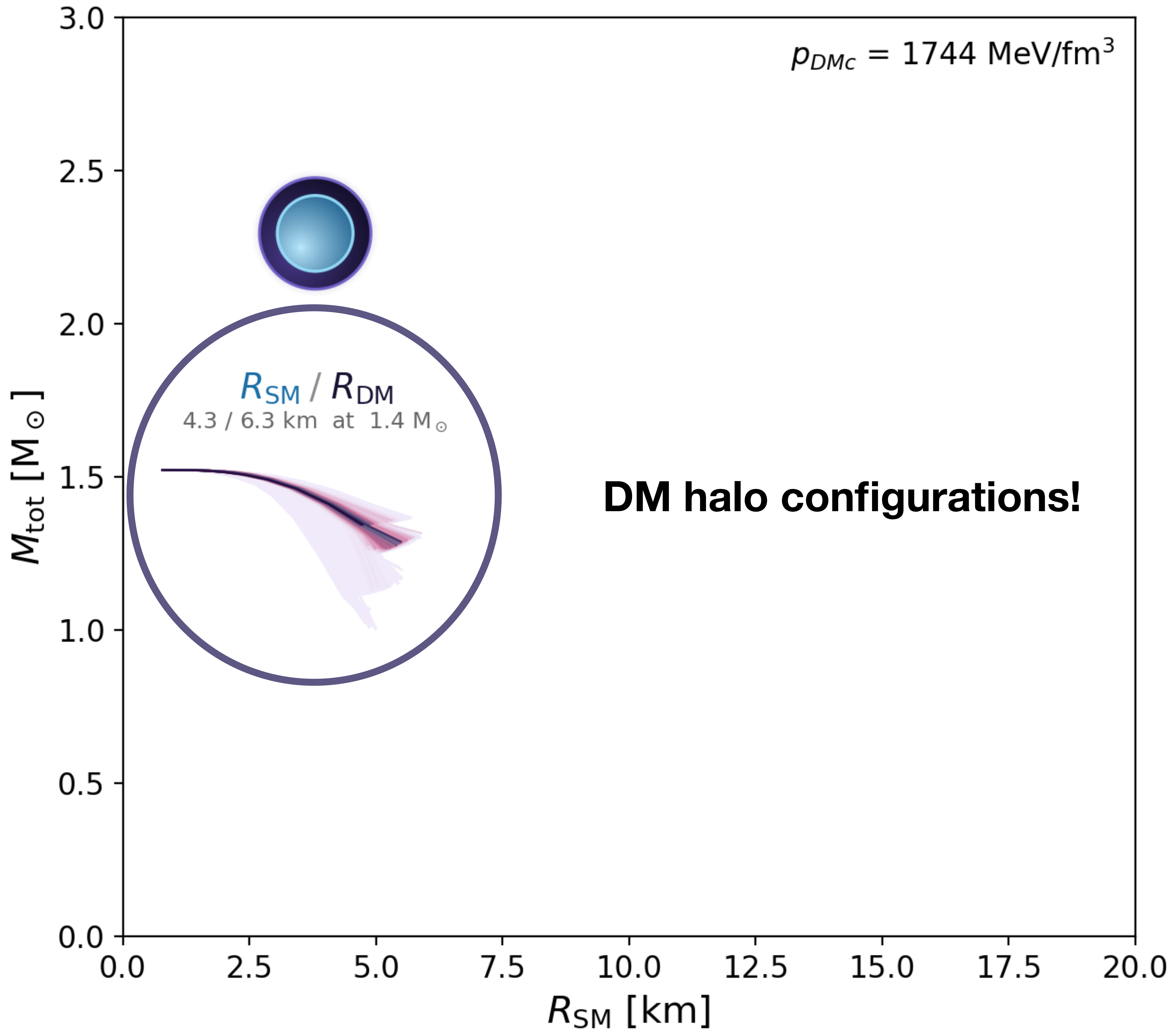
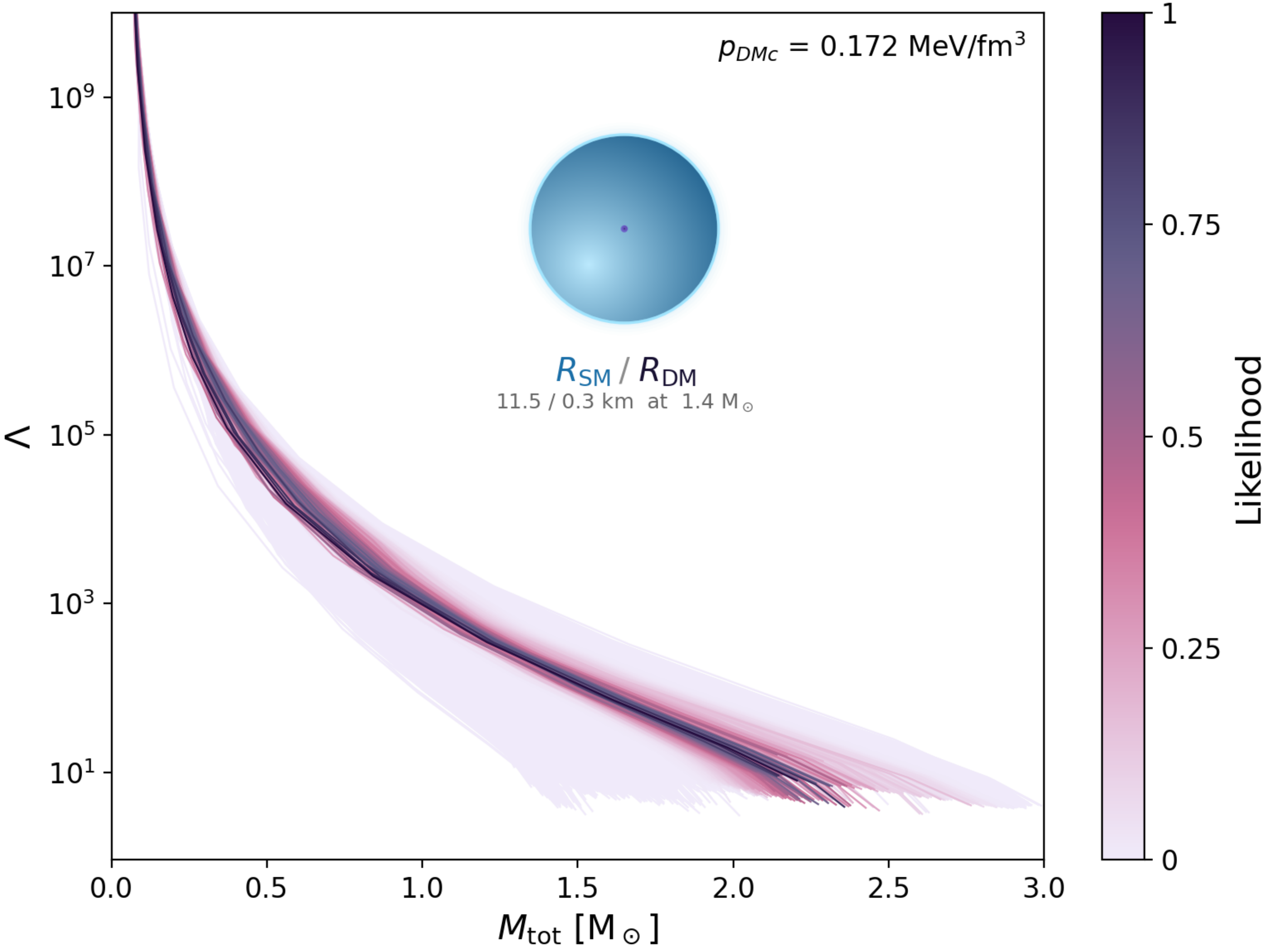




DM halo configurations!

Results - Two-fluid Tidal Deformability (preliminary)



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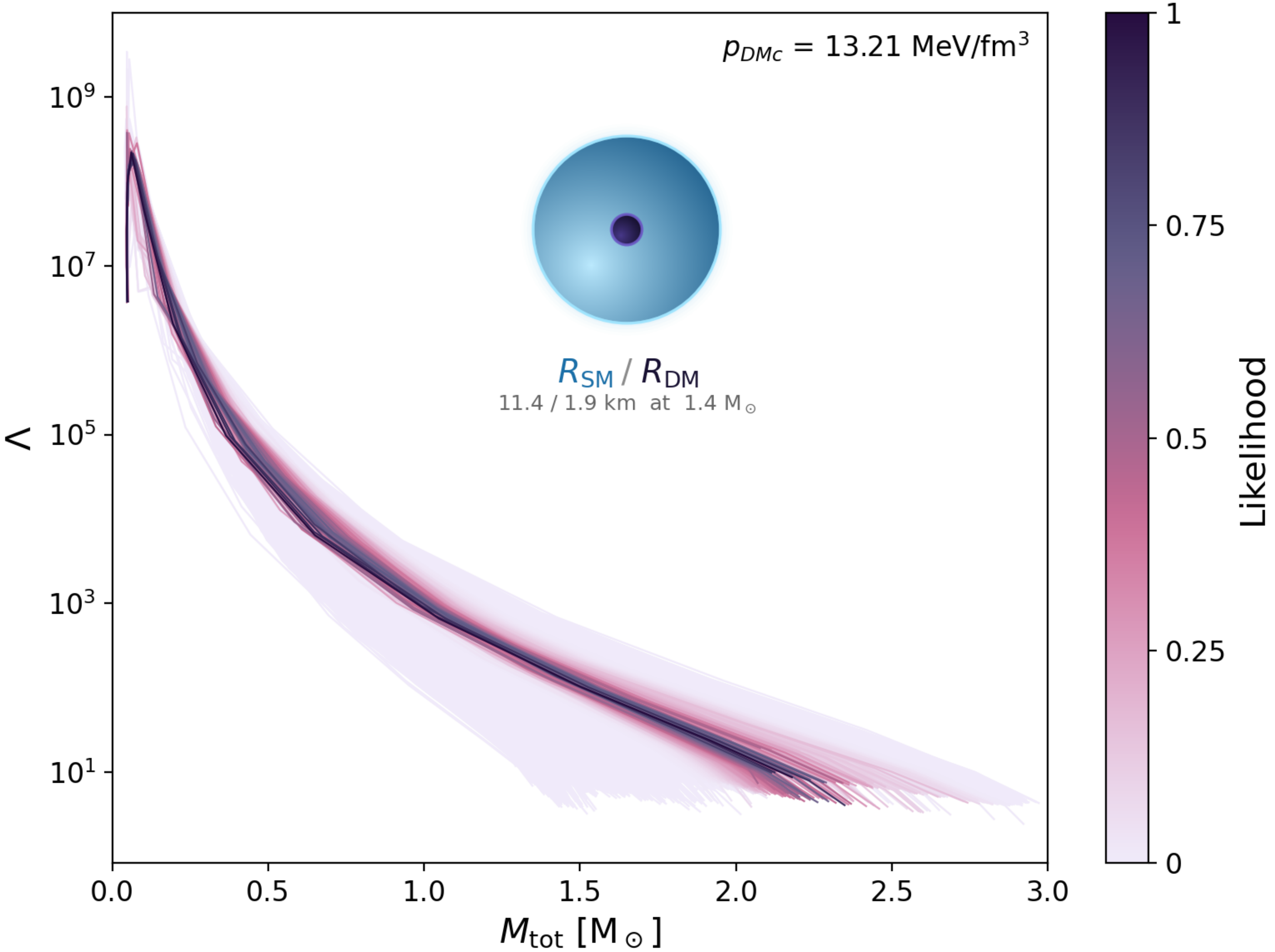

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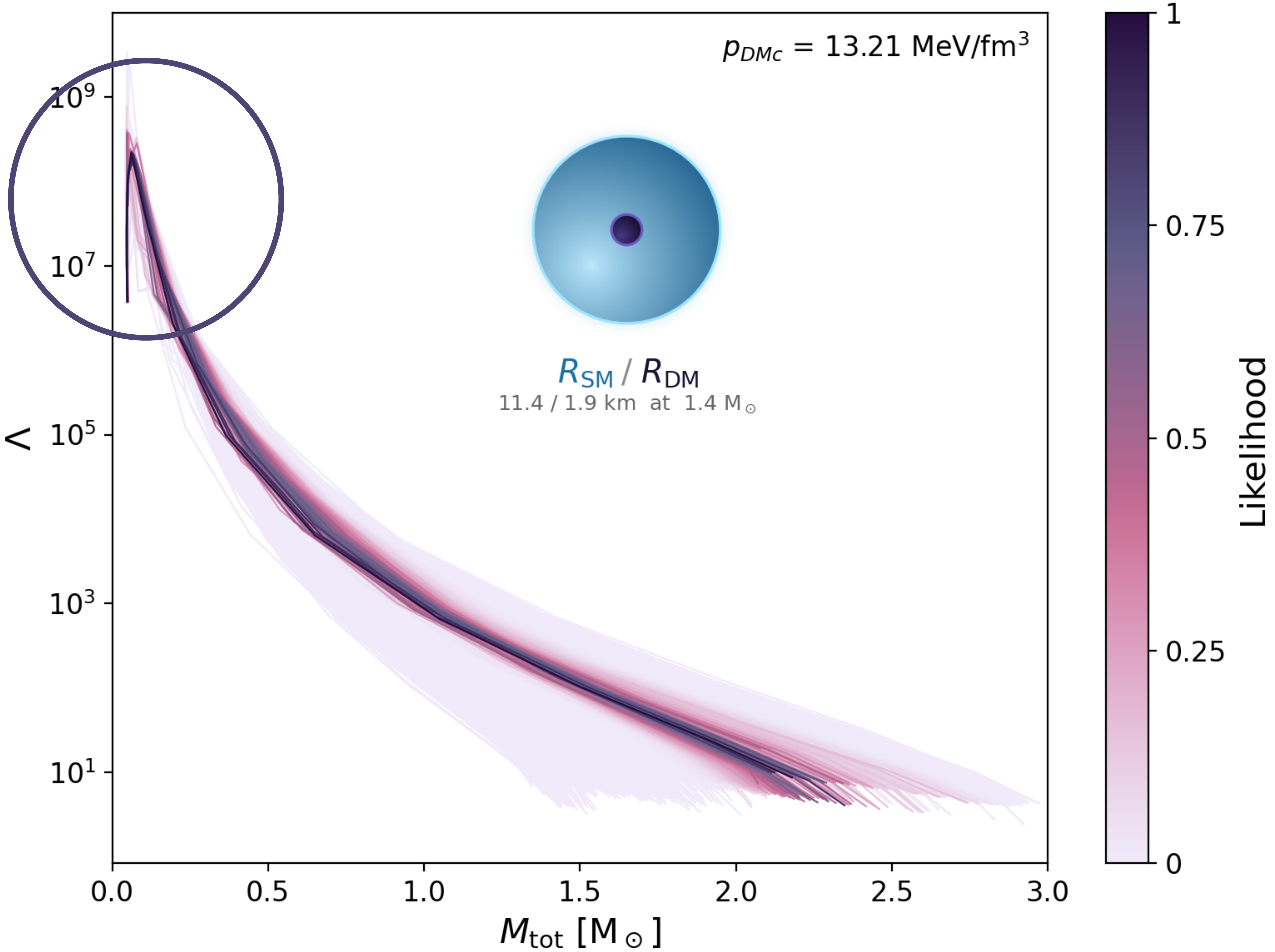
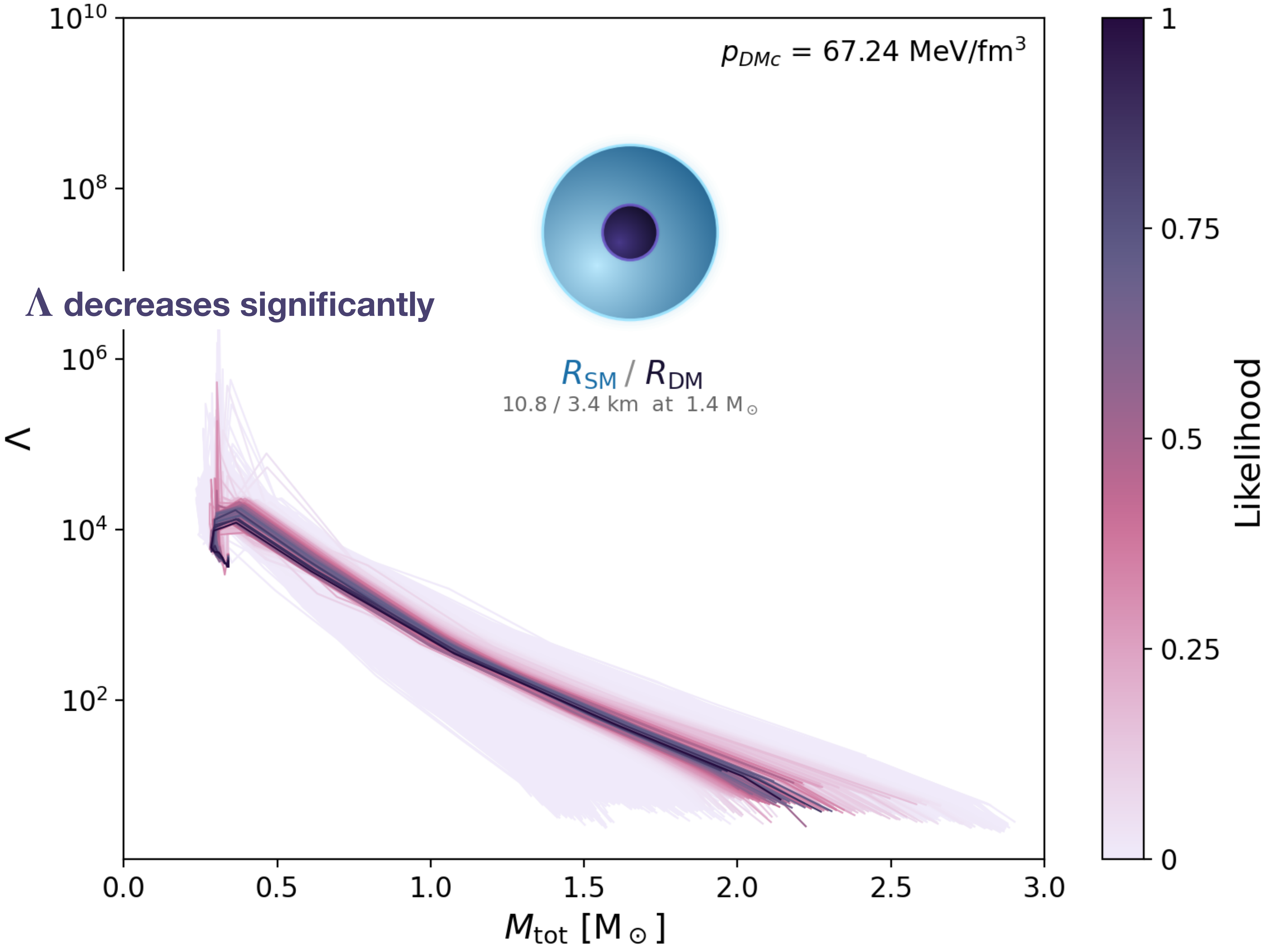


DM impact is growing

back-bending comes from DM taking over (also visible in MR)

Results - Two-fluid Tidal Deformability



Λ decreases significantly

Summary

- General study of dark-matter admixed neutron stars with model-agnostic equations of state
- Evolution of mass-radius and tidal deformability has been studied → presence of DM reduces the radius of neutron stars
  - Stiff DM: higher compactness, soft DM: lower compactness
- Generates stable ultra-compact neutron stars, i.e. neutron stars with light rings!
- Possibility of dark stars that accreted normal matter = tiny neutron star in a DM halo (could be visible with X-ray satellite missions ATHENA (2030s) or eXTP (2027))
  - LIGO O5 run (2029) and future gravitational wave detectors like the Einstein Telescope can probe the existence of these exotic ultracompact objects

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Thank you for your attention!