Generating ultra-compact hybrid stars with bosonic dark matter

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with Sarah Louisa Pitz and Jürgen Schaffner-Bielich

(manuscript in preparation)

Goethe University, Frankfurt

17–21 Aug 2026
Helsinki, Finland

Strong and Electro-Weak Matter 2026

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

CRC-TR 211 Strong-interaction matter under extreme conditions

Alexander von HUMBOLDT STIFTUNG

Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Motivation

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Can dark matter make a neutron star ultracompact?

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Can dark matter make a neutron star ultracompact?

Can we find an observable signature of DM inside a NS?

Neutron Star

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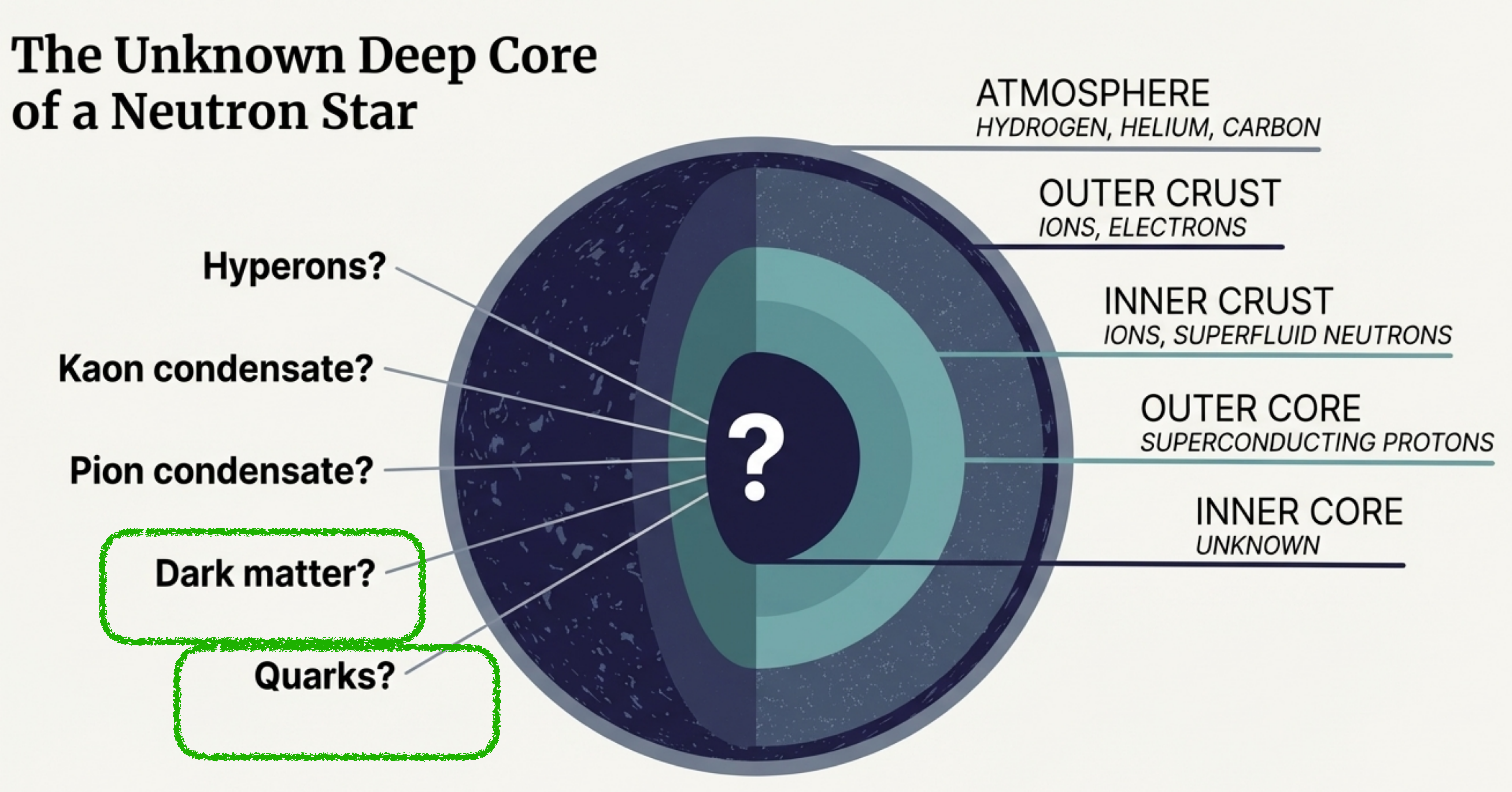


Mass: $M \approx 2\ M_\odot$

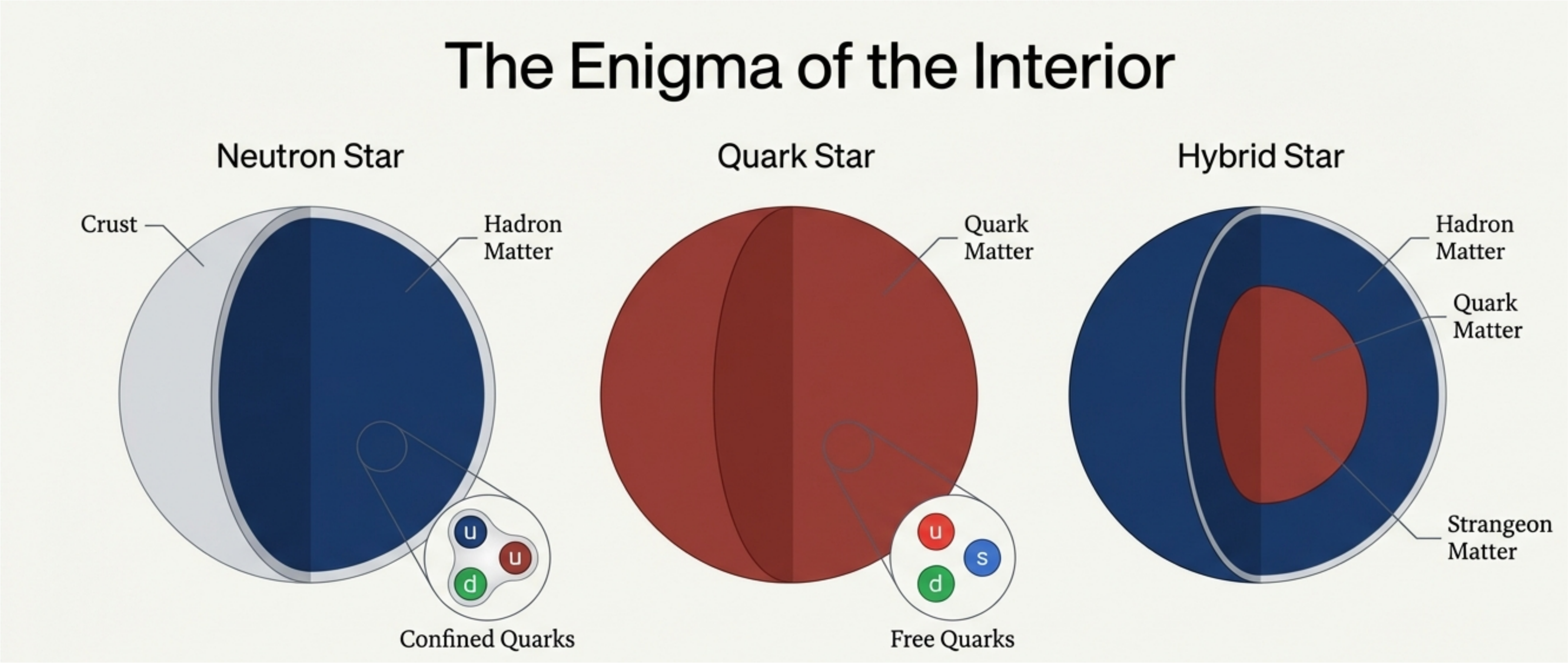
P. Demorest, *et al.* Nature 467, 1081–1083 (2010

Radius: $R \approx 10 - 13km$

(NICER)

L. Mauviard et al., APJ. 995, 60 (2025)
D. Choudhury et al., APJ Lett. 971, L20 (2024).

Neutron Star



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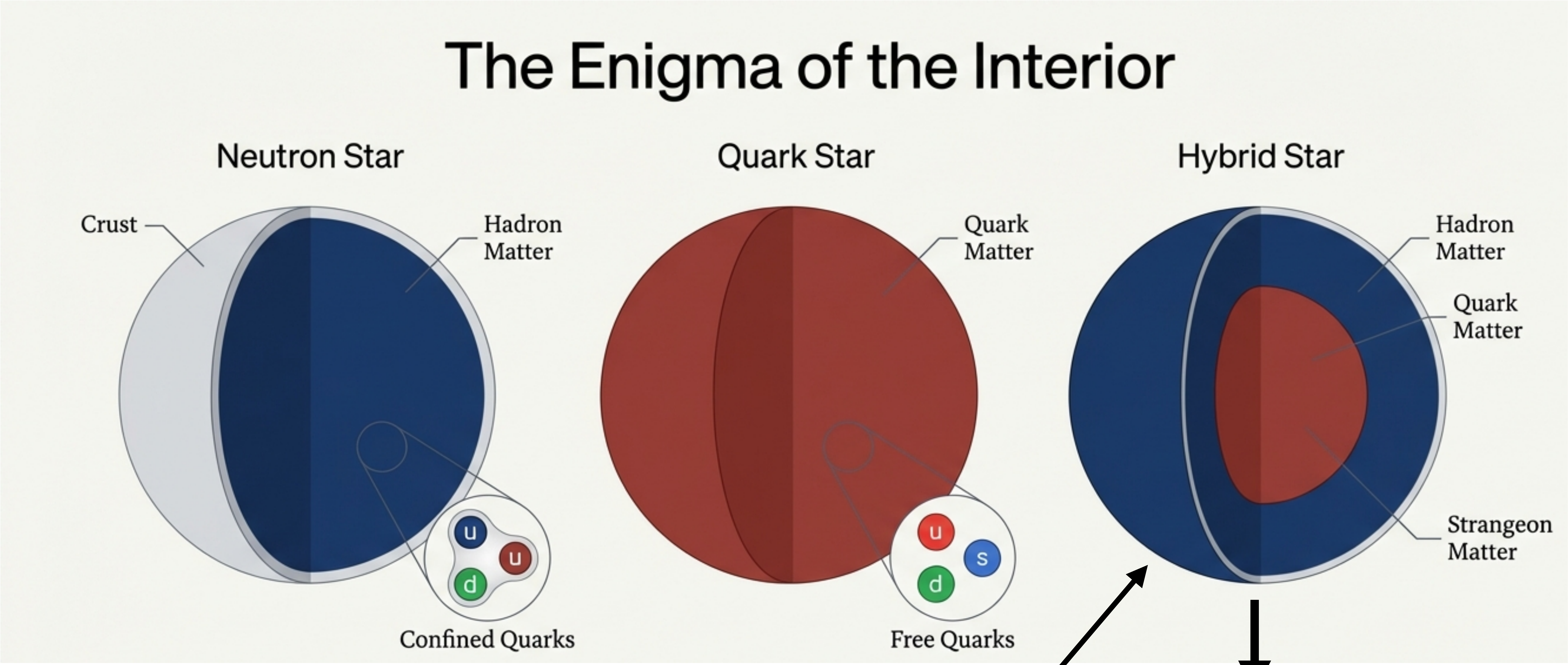

This Talk

Normal Matter

+

Dark Matter

Normal Matter EoS

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Normal Matter

Hadronic

- Piecewise polytopes
- EoS2 ($\Gamma = 4.021$)

$$\varepsilon = \frac{1}{\Gamma - 1} p + \left(\mu_0 n_0 - \frac{\Gamma}{\Gamma - 1} p_0 \right) \left(\frac{p}{p_0} \right)^{1/\Gamma}$$

[Kurkela, Fraga, Schaffner-Bielich & Vuorinen, APJ (2014)]

- **Outer crust**: BPS
- **Inner crust**: Negele-Vautherin
- **Neutron matter**: chiral-EFT

[Baym, Pethick & Sutherland APJ, 1971]
[Negele, Vautherin, Nuc.Phys.A (1973)]
[Hebeler, Lattimer, Pethick & Schwenk, APJ (2013)]

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+

Quark

- constant speed of sound (CSS)
- c_{QM} = 0.7 - 1.0

$$\varepsilon(p) = \begin{cases} \varepsilon_{HM}(p) & p < p_t \\ \varepsilon_{HM}(p_t) + \Delta\varepsilon + c_{QM}^{-2}(p - p_t) & p > p_t \end{cases}$$

M. G. Alford, S. Han, and M. Prakash, PRD 88, 083013 (2013)

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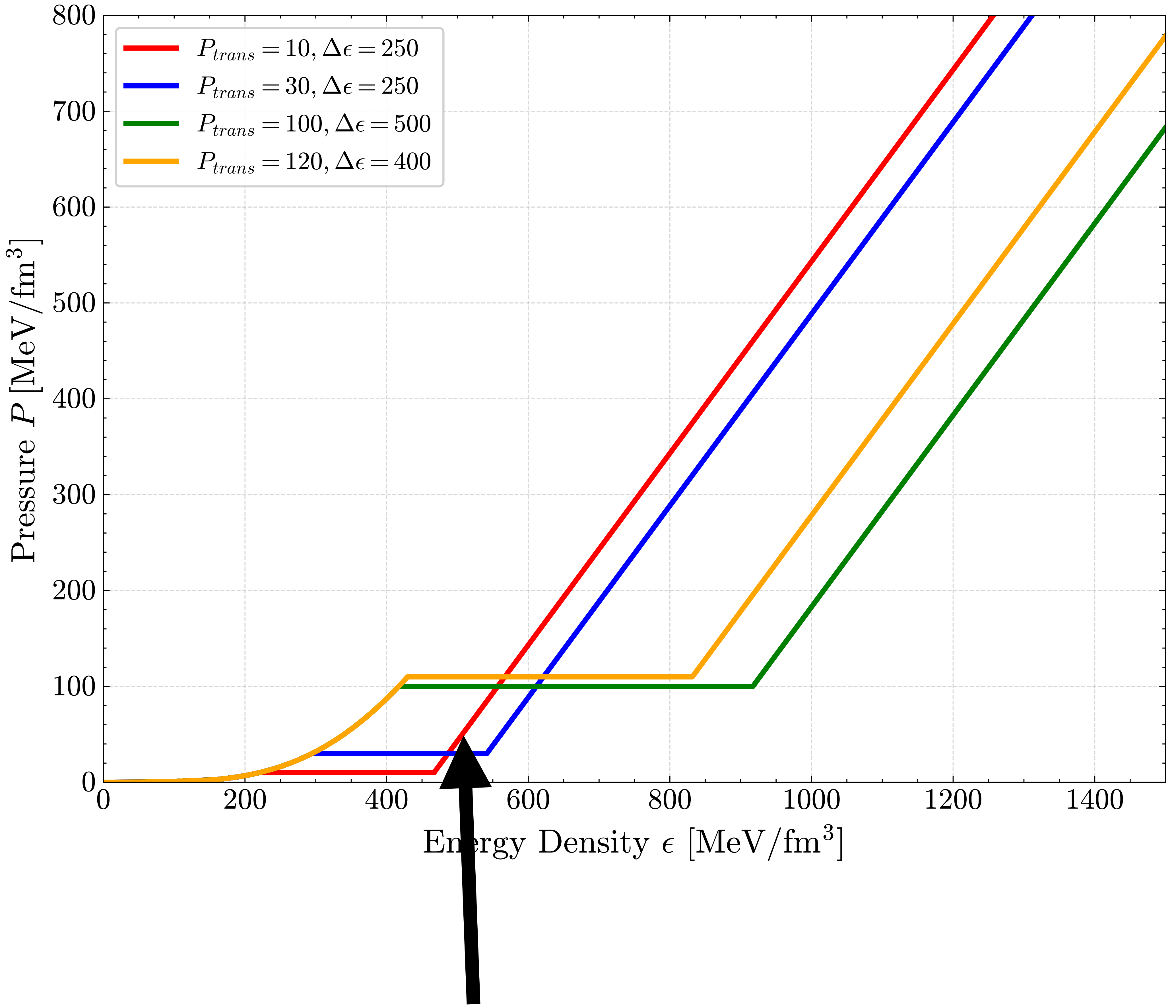
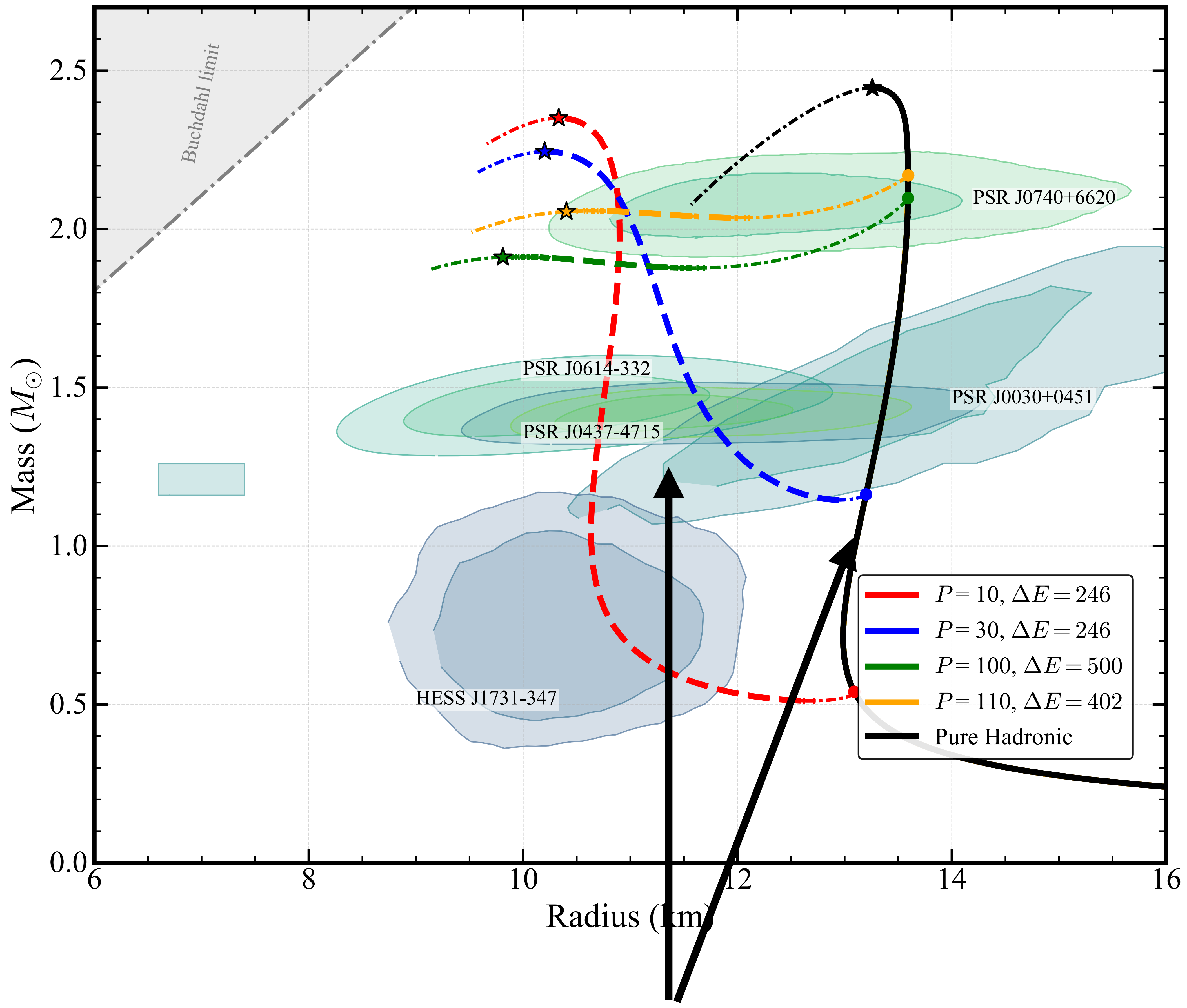
Hadronic → Quark matter
P_t = 10 – 120 MeV/fm³
$\Delta\varepsilon$ = 250 – 500 MeV/fm³
c_{QM} = 0.7 - 1.0

pQCD consistent: $w = 1$ for $c_s^2 = 0.7$
marginal $w \approx 0.14$ for stiff low-P_t cases

Oleg Komoltsev, Aleksi Kurkela *PRL* 128 (2022) 20, 202701

Normal Matter MR





strong first-order

phase transition

Twin Stars

Two stable branches

Two distinct stable stellar configurations- **same mass** but **different radii**.

Dark Matter EoS

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Dark Matter

- Self-interacting Bosonic DM (ϕ^n)
- Complex scalar fields in sub-GeV mass range.

$$\varepsilon = \varepsilon_0 \left(\frac{p}{\varepsilon_0}\right)^{2/n} + \frac{n+2}{n-2}\, p$$

m_b = 300 MeV, n = 40 (stiff)
m_b = 1000 MeV, n = 4 (soft)

Pitz and Schaffner-Bielich PRD 108, 103043 (2023)
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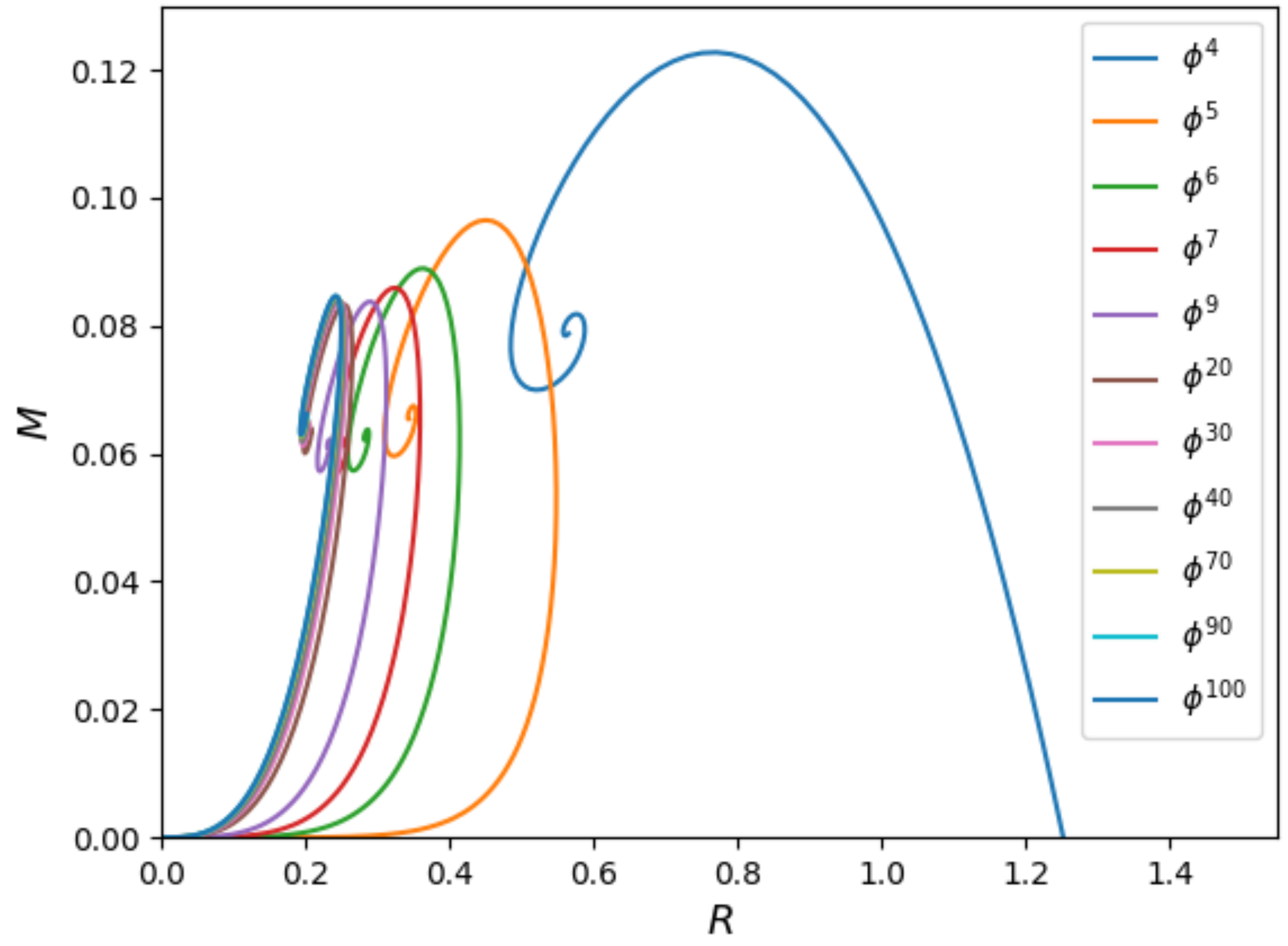

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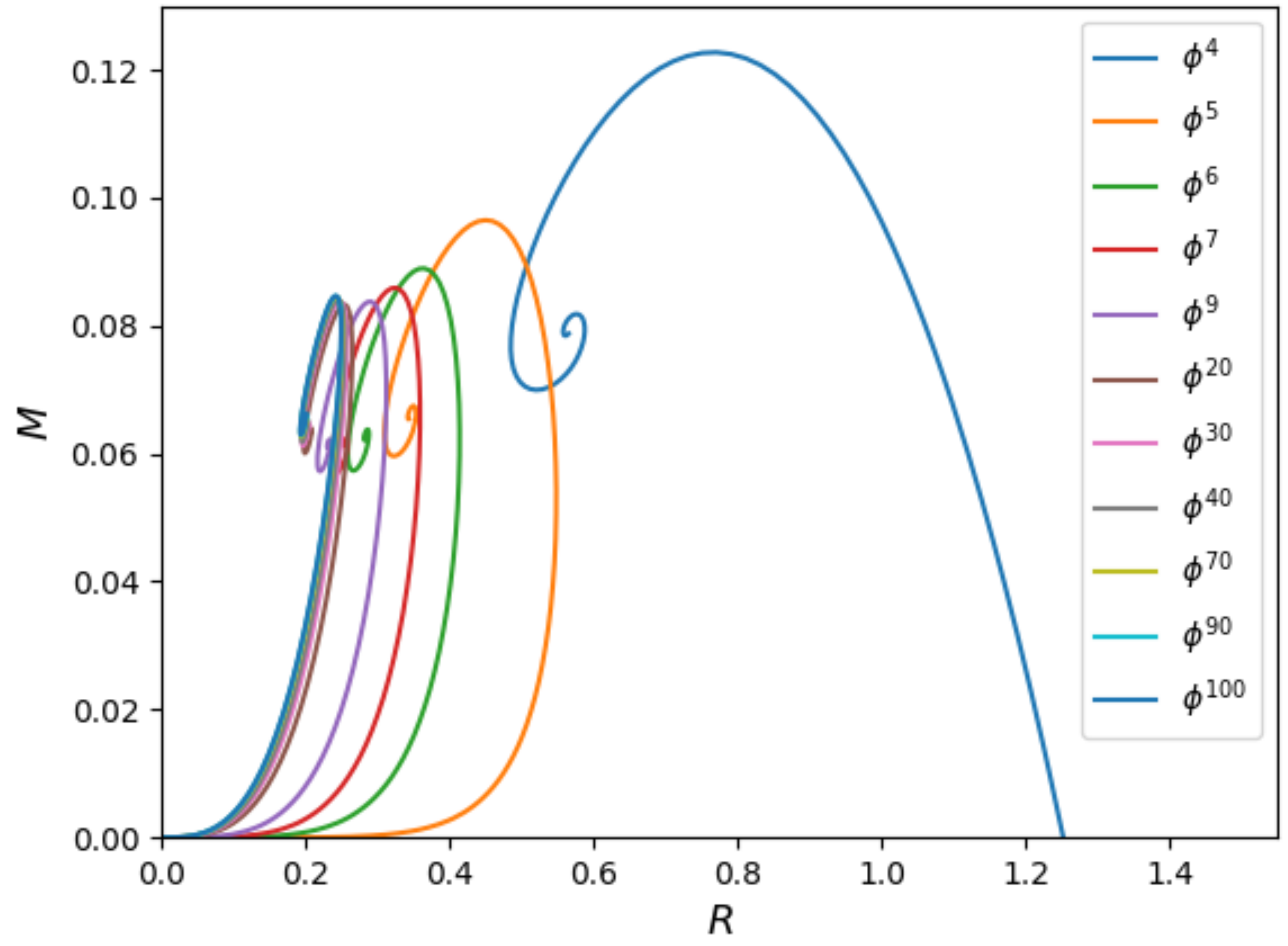

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Dark Matter

$R_{DM} > R_{NM}$

Dark Matter

$R_{DM} < R_{NM}$

Two-Fluid analysis

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- Ordinary/Normal matter (NM/OM) and dark matter (DM) as two fluids.
- Coupled only gravitationally.
- Two-fluid TOV equations

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Astropart.Phys. 32 (2009) 278-284

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$$\frac{dM_{NM}}{dr} = 4\pi r^2 \rho_{NM} \qquad \frac{dp_{NM}}{dr} = -\frac{(\rho_{NM} + p_{NM})(M_{NM} + M_{DM} + 4\pi r^3[p_{NM} + p_{DM}])}{r^2\left(1 - \frac{2(M_{NM} + M_{DM})}{r}\right)}$$

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A complex stability analysis [Hippert et al. PRD 107 (2023)]

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

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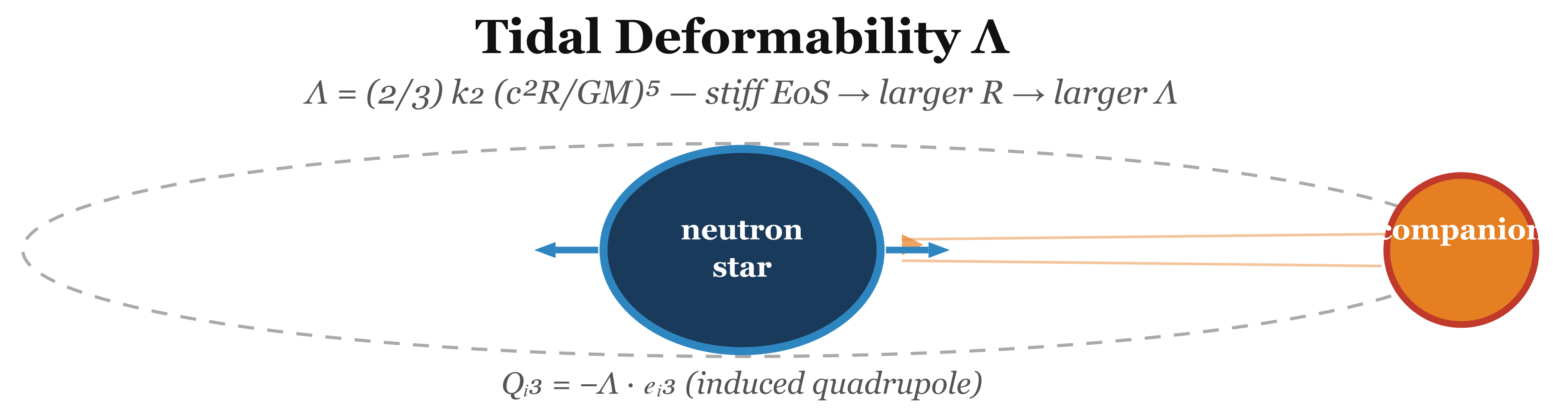


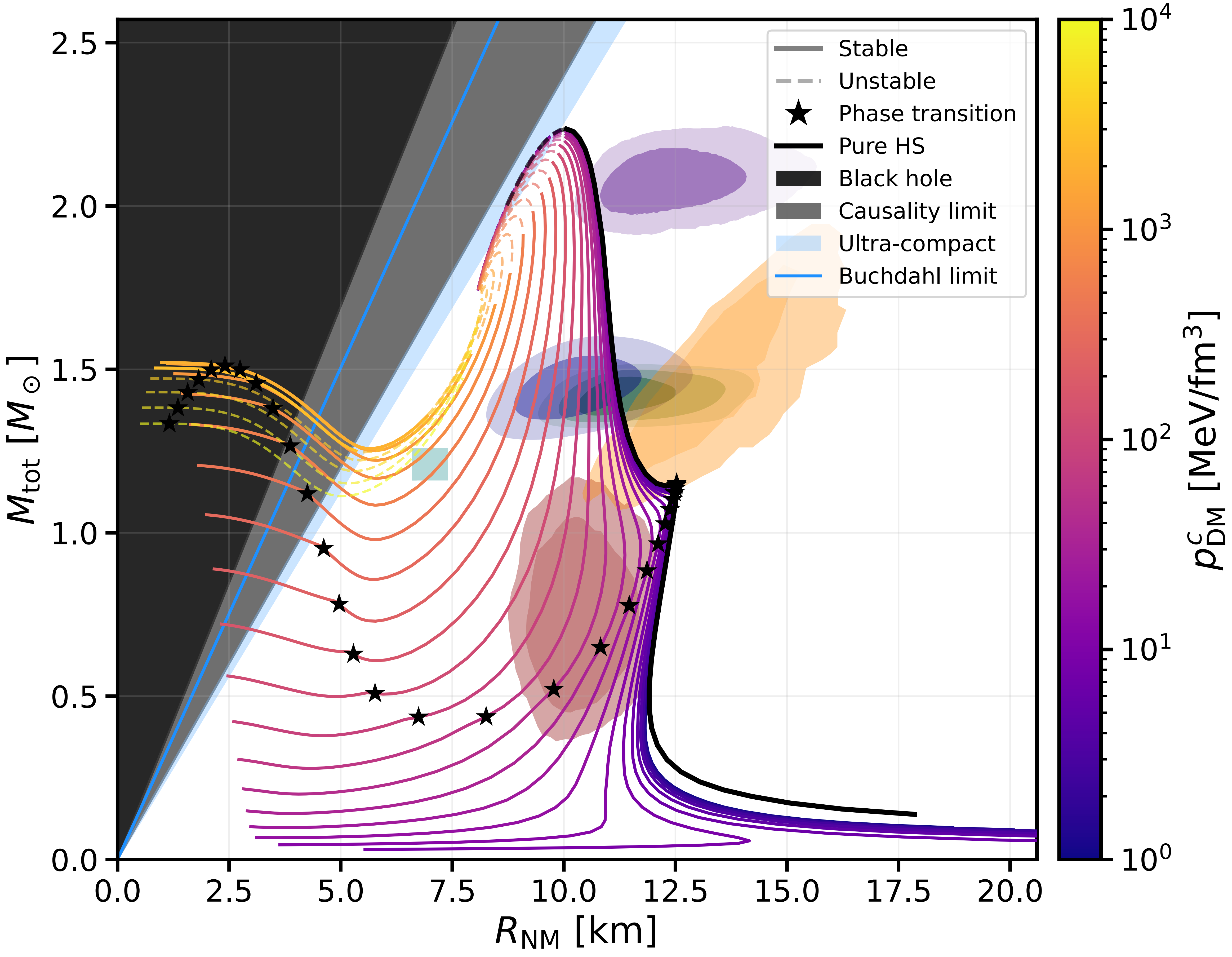
Tells us how squishy a NS is

MR with NM radius

$m_b = 300$ MeV, $n = 40$

= stable   = unstable

$P_t = 30 MeV/fm^3$ $\Delta\varepsilon = 250 MeV/fm^3$



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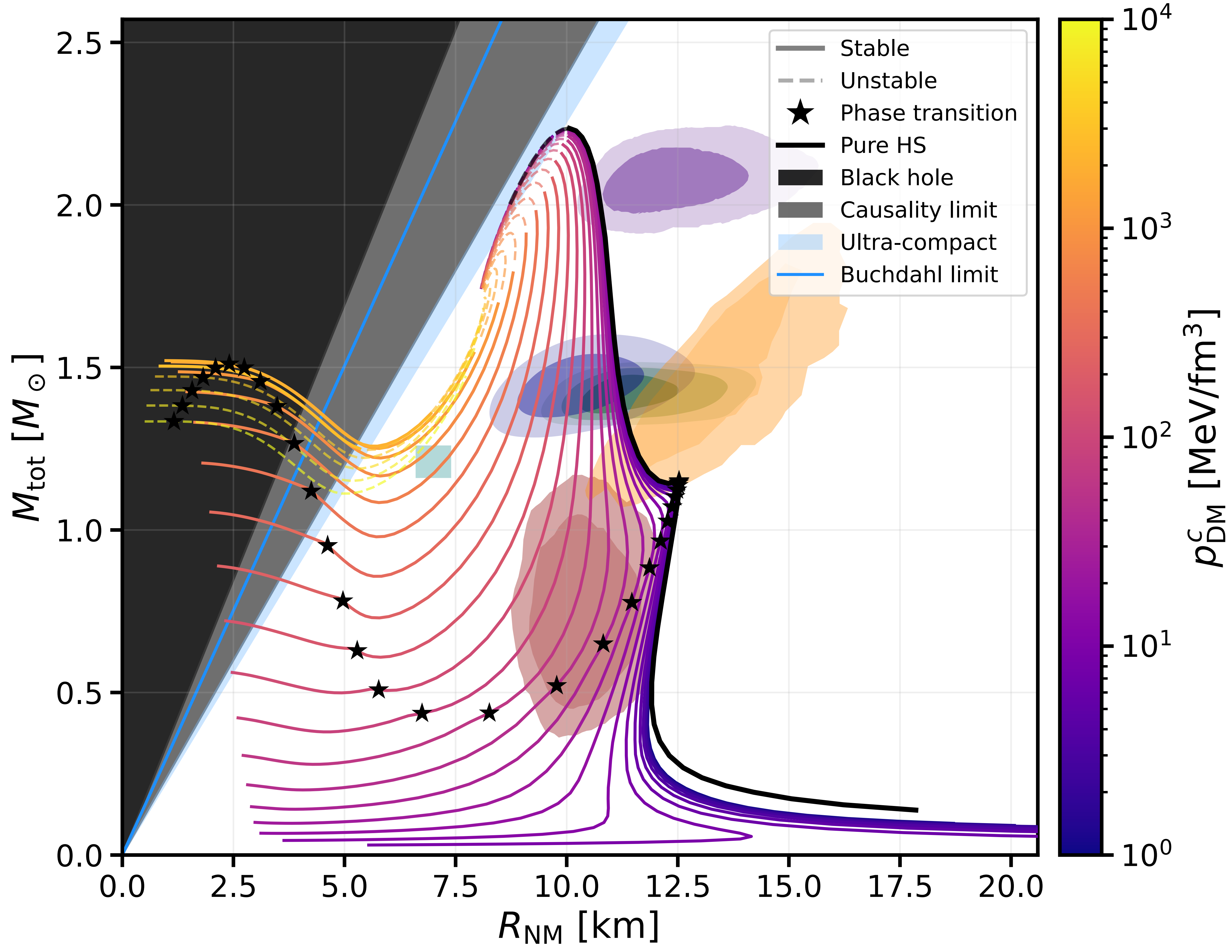

Phase transition creates a local minimum in the MR sequence

classical twin stars

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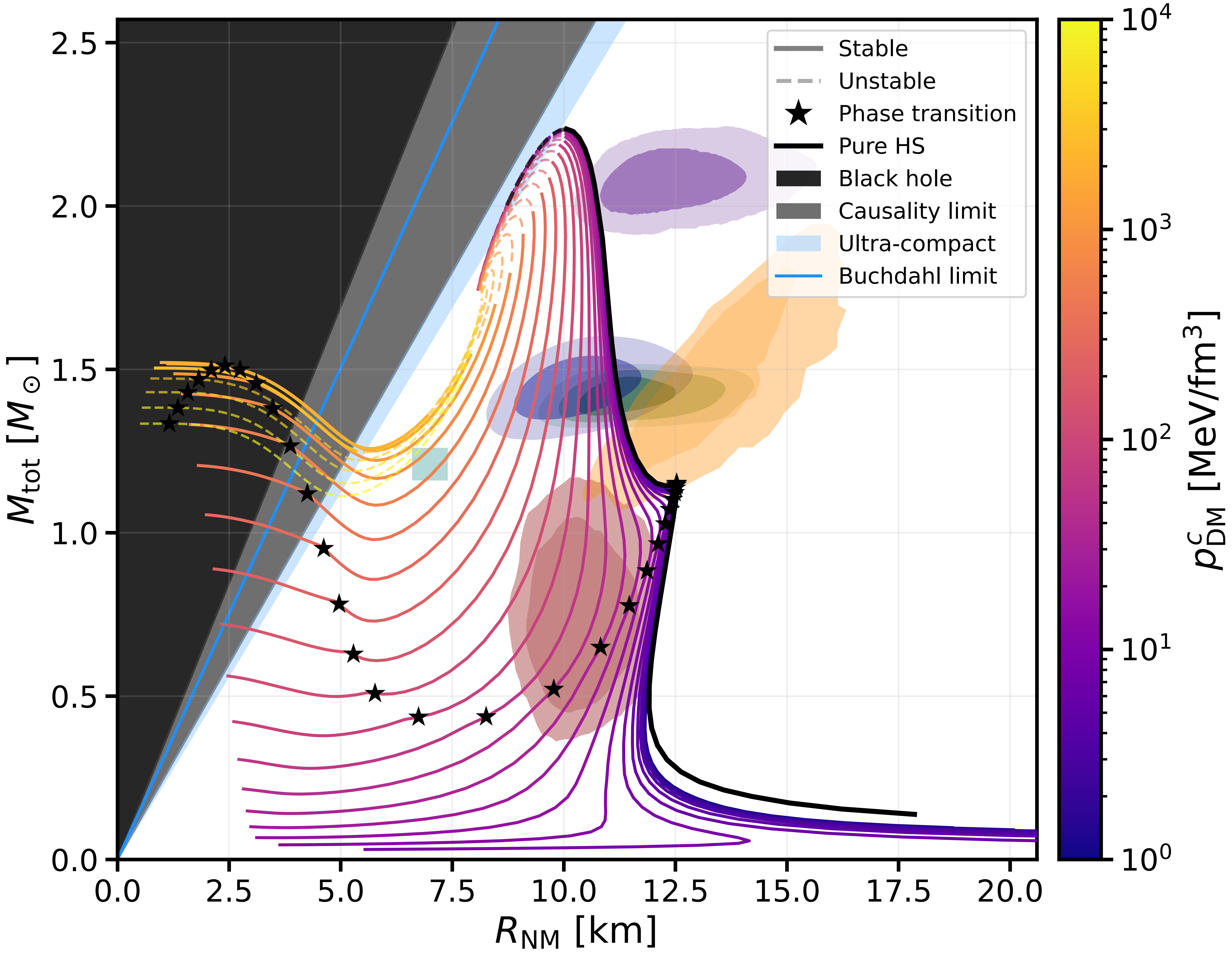

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Increasing p^c_{DM}

DM masks the twin-star gap in MR but does not destroy twins

Ultimate twin stars?

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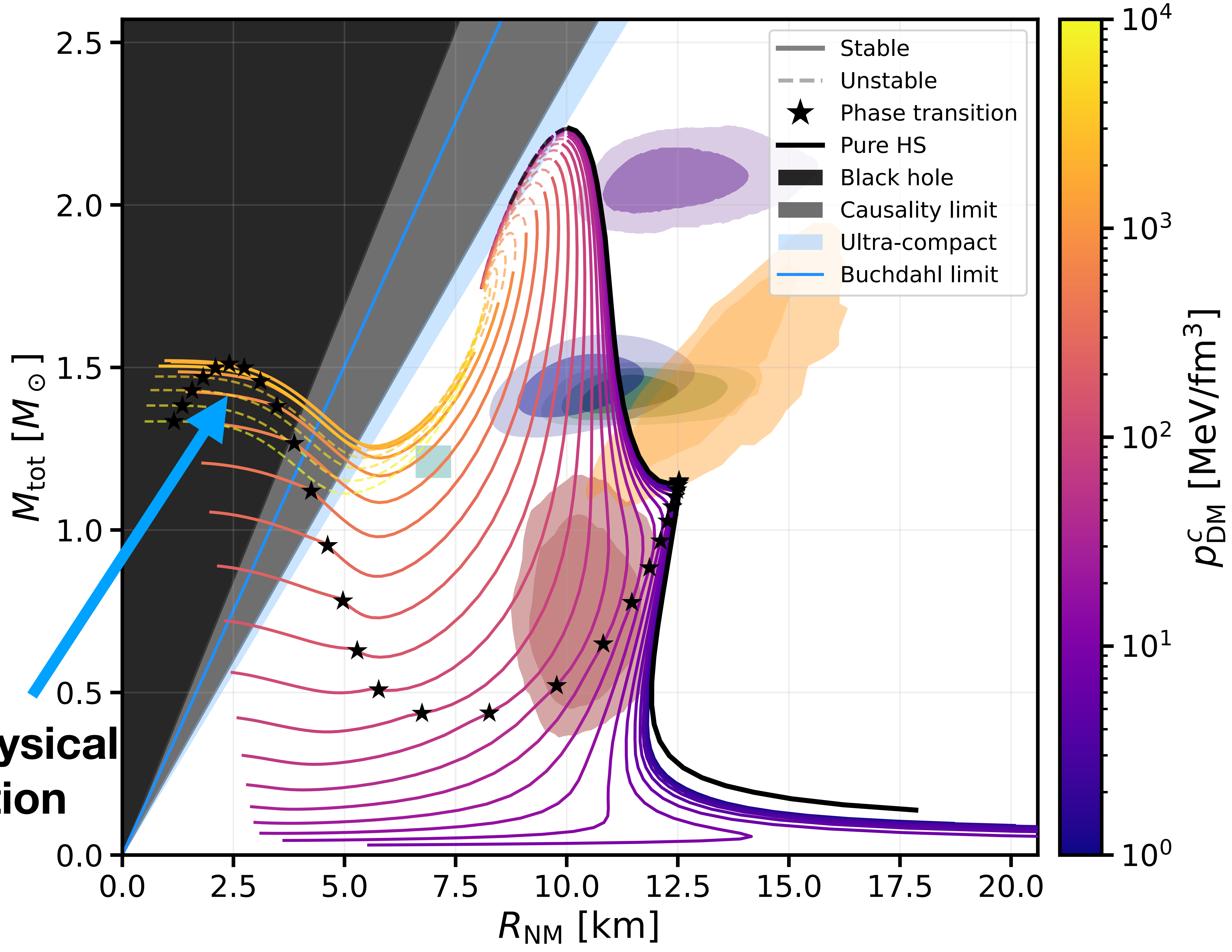


not a physical violation

Phase transition creates a local minimum in the MR sequence

classical twin stars

Increasing p^c_{DM}

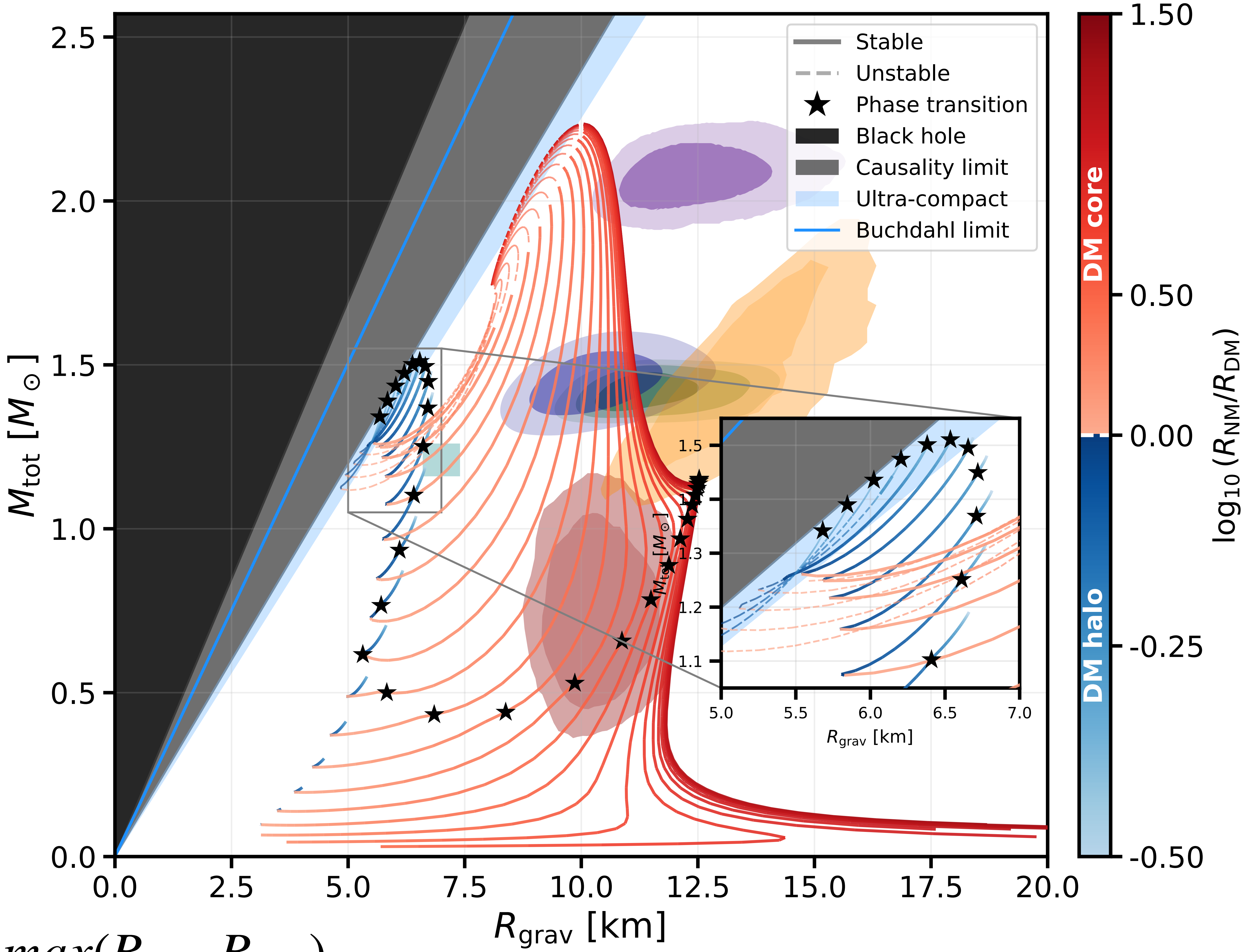
DM masks the twin-star gap in MR but does not destroy twins

Ultimate twin stars?

R_{NM} : where $P_{NM} \rightarrow 0$ what NICER sees in X-ray timing

MR with grav. radius

$m_b = 300$ MeV, $n = 40$ ▬▬ = stable ▬ ▬ ▬ = unstable



$$R_{grav} = max(R_{NM}, R_{DM})$$

sets compactness $C = M/R_{grav}$ what gravity "feels"

MR with grav. radius

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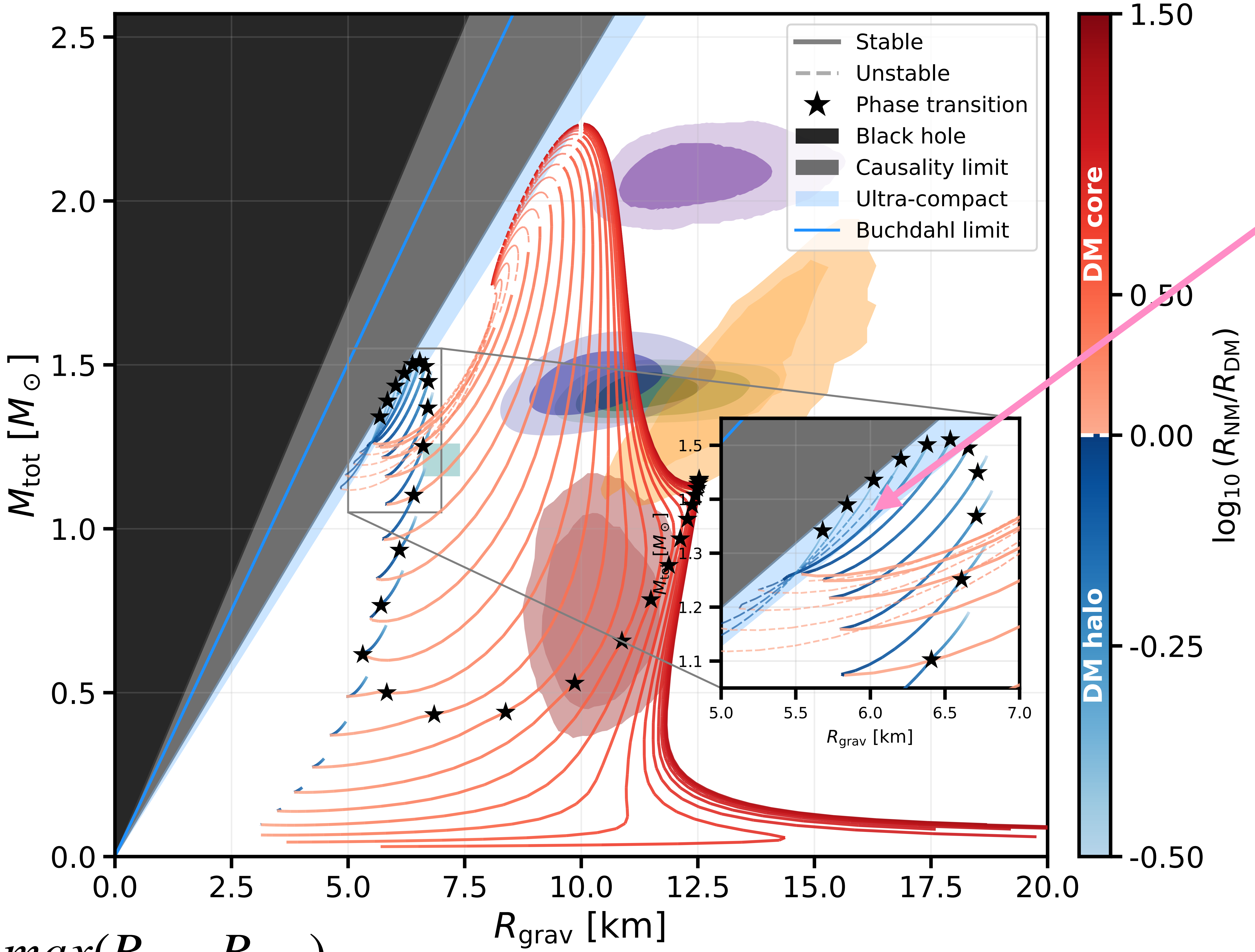
$m_b = 300$ MeV, $n = 40$ — = stable - - - = unstable



UCOs — Ultra Compact Objects

$C = M/R > 1/3$

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MR with grav. radius

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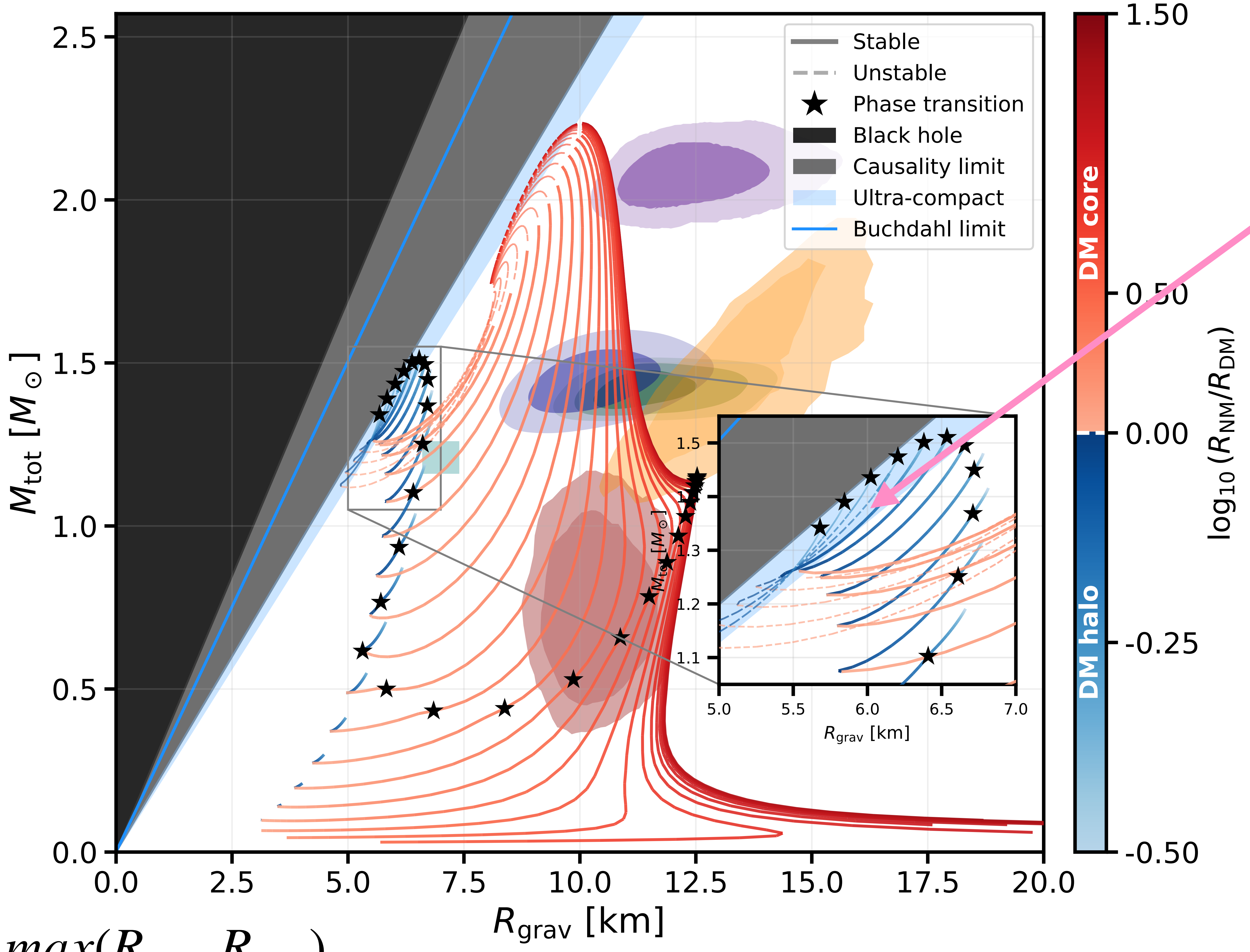


UCOs — Ultra Compact Objects

$C = M/R > 1/3$

- **Possess photon spheres at R = 3M**
- **Distinct light-echo from the photon orbit**
- **Echoes due to GW trapping between NS surface and light ring**

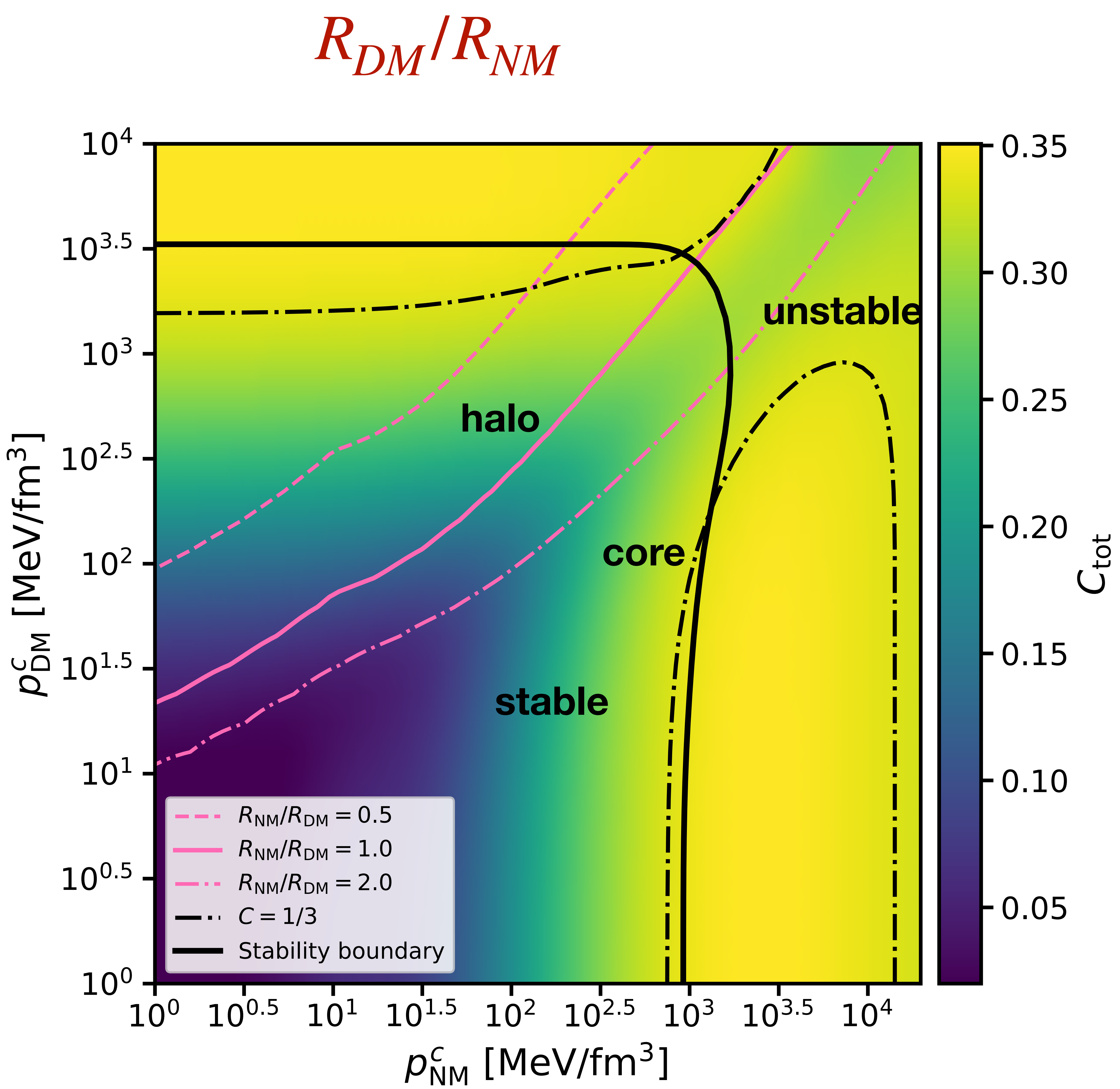
UCO signature

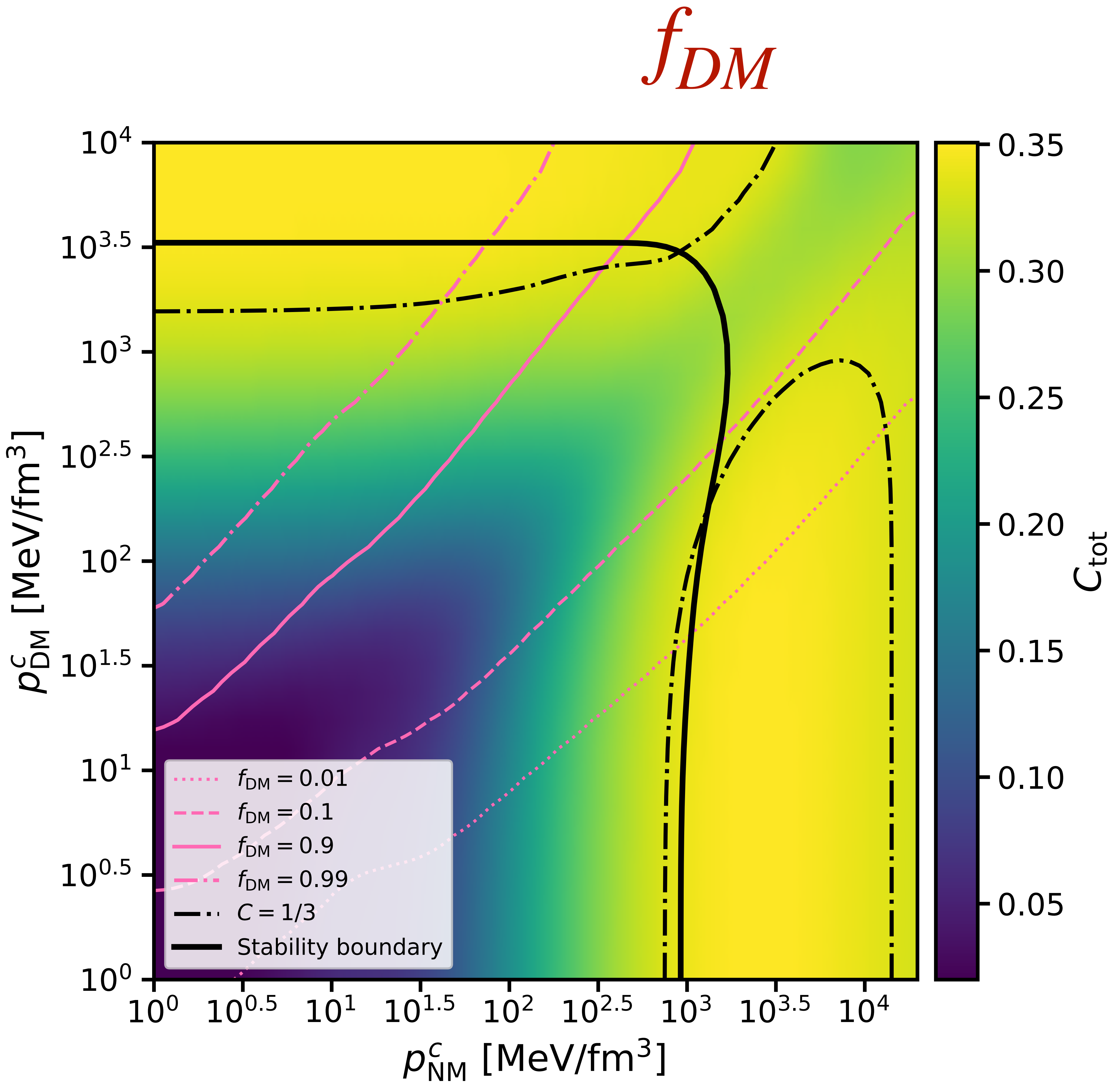
$R_{grav} = max(R_{NM}, R_{DM})$

sets compactness $C = M/R_{grav}$ what gravity "feels"

V. Cardoso *et al.* Phys. Rev. D 90, 044069 (2014), Pitz and Schaffner-Bielich PRD 111, 043050 (2025)

UCOs

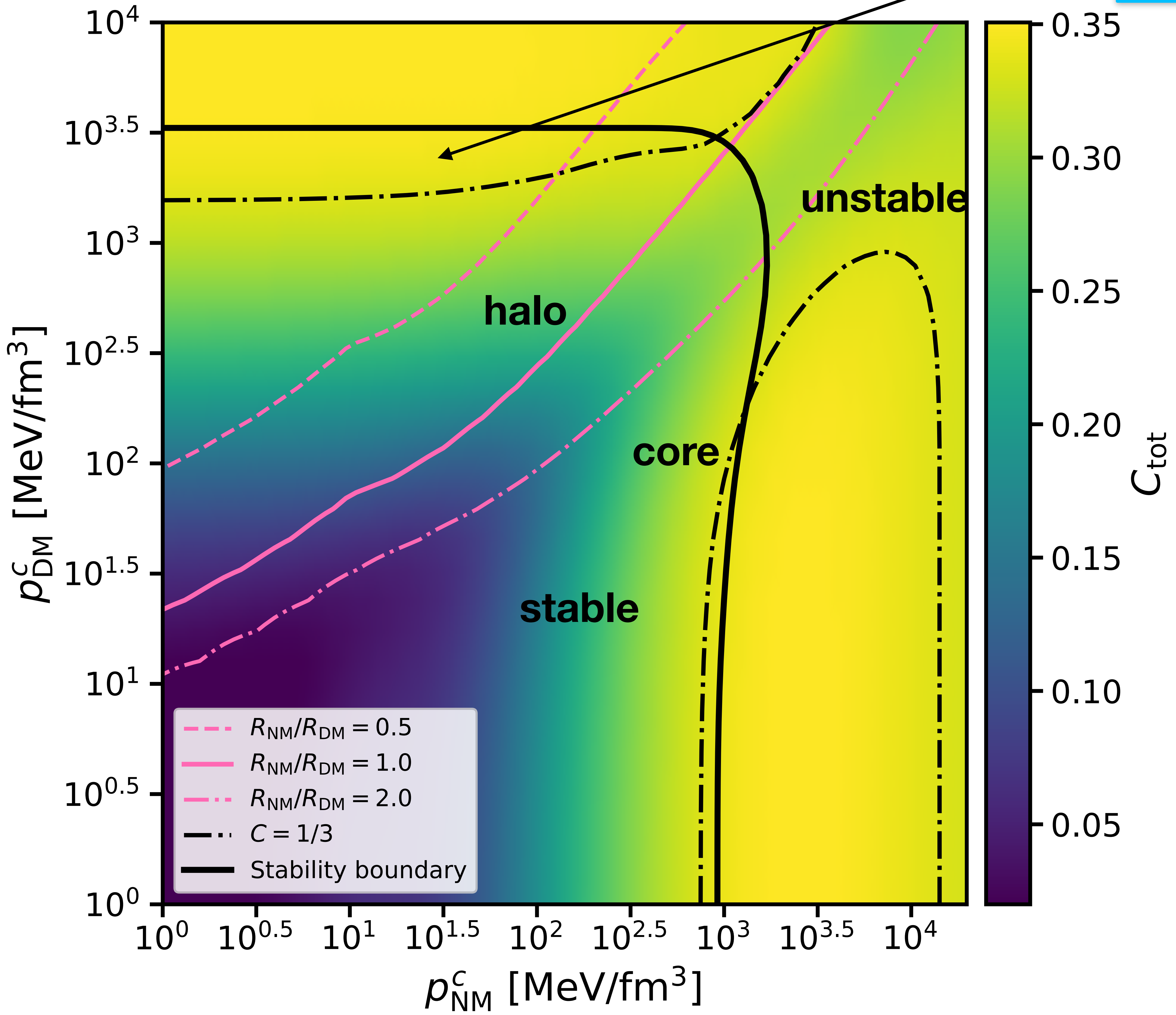

R_{DM}/R_{NM}
unstable
halo
core
stable
$R_{NM}/R_{DM} = 0.5$
$R_{NM}/R_{DM} = 1.0$
$R_{NM}/R_{DM} = 2.0$
$C = 1/3$
Stability boundary
p^c_{DM} [MeV/fm^3]
p^c_{NM} [MeV/fm^3]
C_{tot}


f_{DM}
$f_{DM} = 0.01$
$f_{DM} = 0.1$
$f_{DM} = 0.9$
$f_{DM} = 0.99$
$C = 1/3$
Stability boundary
p^c_{DM} [MeV/fm^3]
p^c_{NM} [MeV/fm^3]
C_{tot}

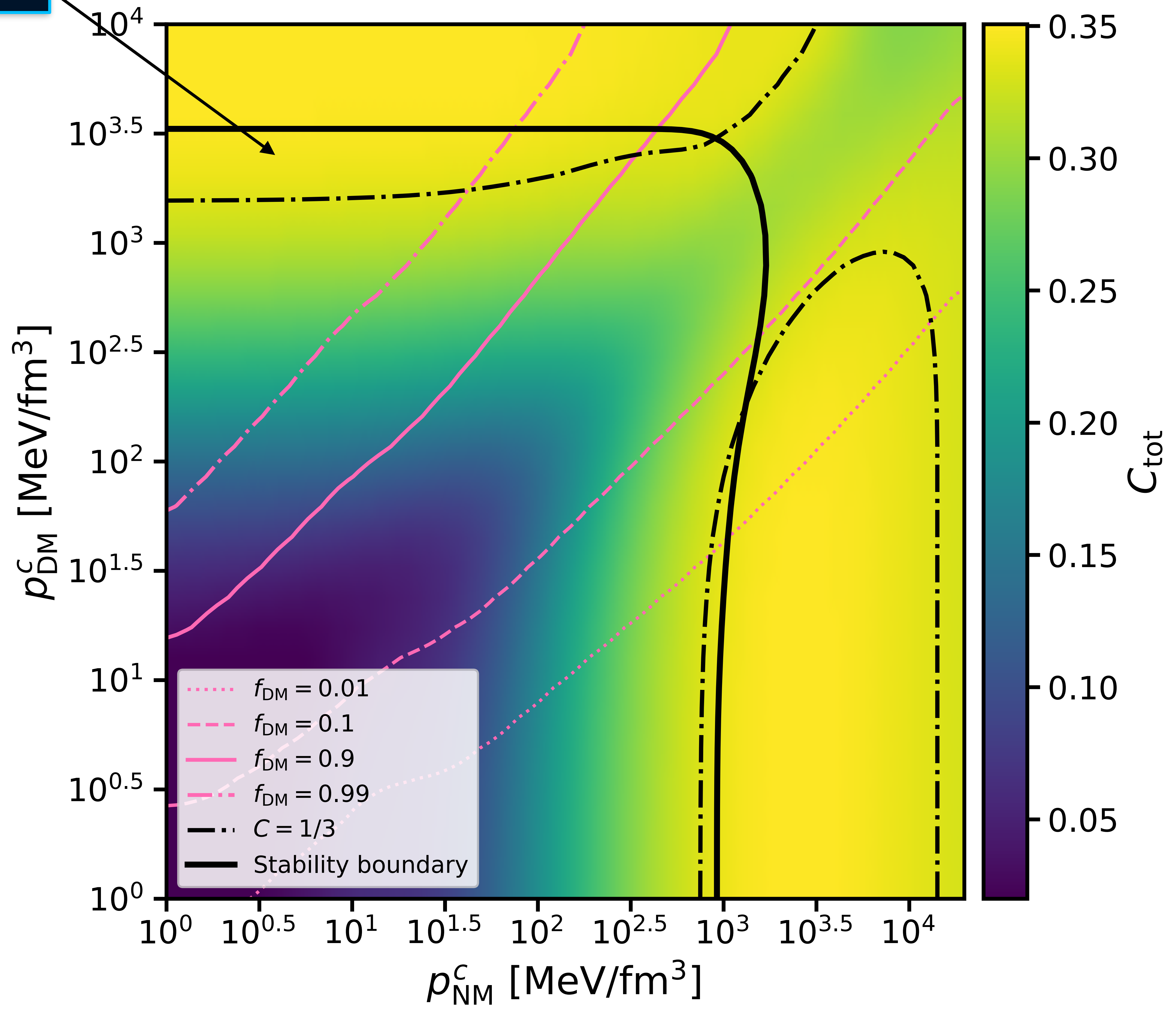
UCOs

DM-HALO UCOs
f_{DM} > 0.9 → C ≥ 1/3

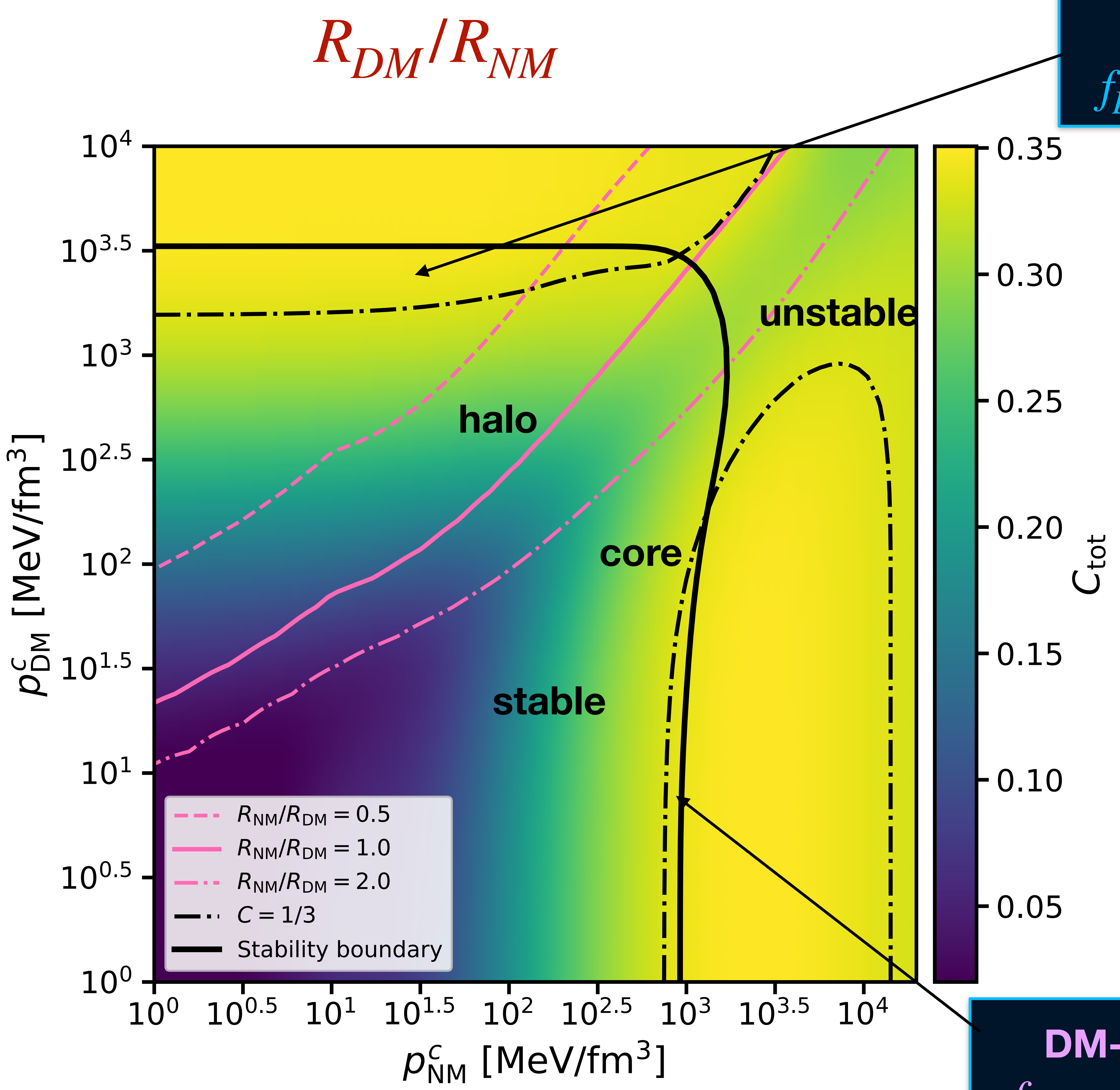
R_{DM}/R_{NM}



(self-gravity) f_{DM}

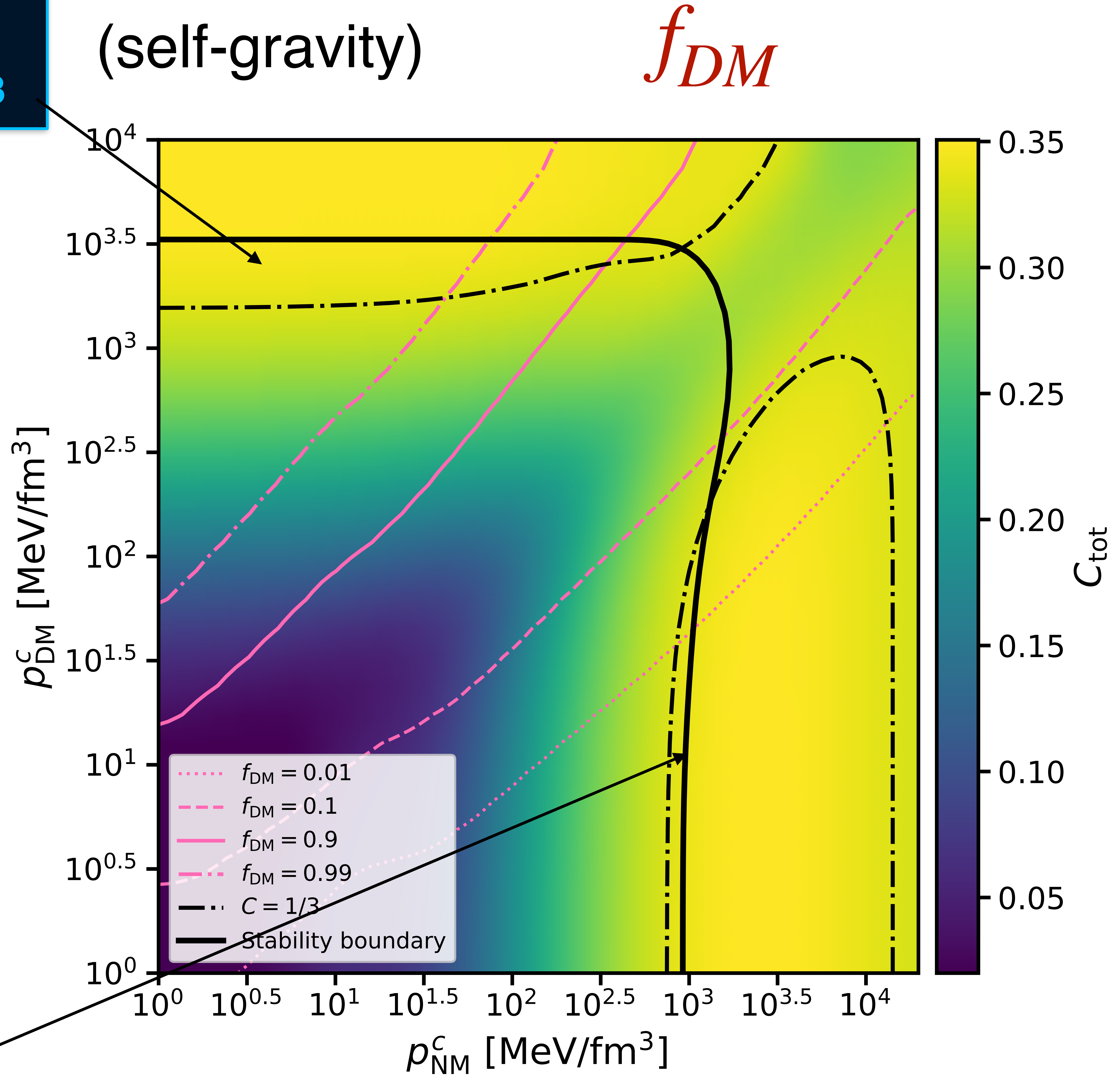


UCOs



DM-HALO UCOs
$f_{DM} > 0.9 \rightarrow C \geq 1/3$

(self-gravity)



DM-CORE UCOs
$f_{DM} < 0.1 \rightarrow C \geq 1/3$

(quark PT)

UCOs

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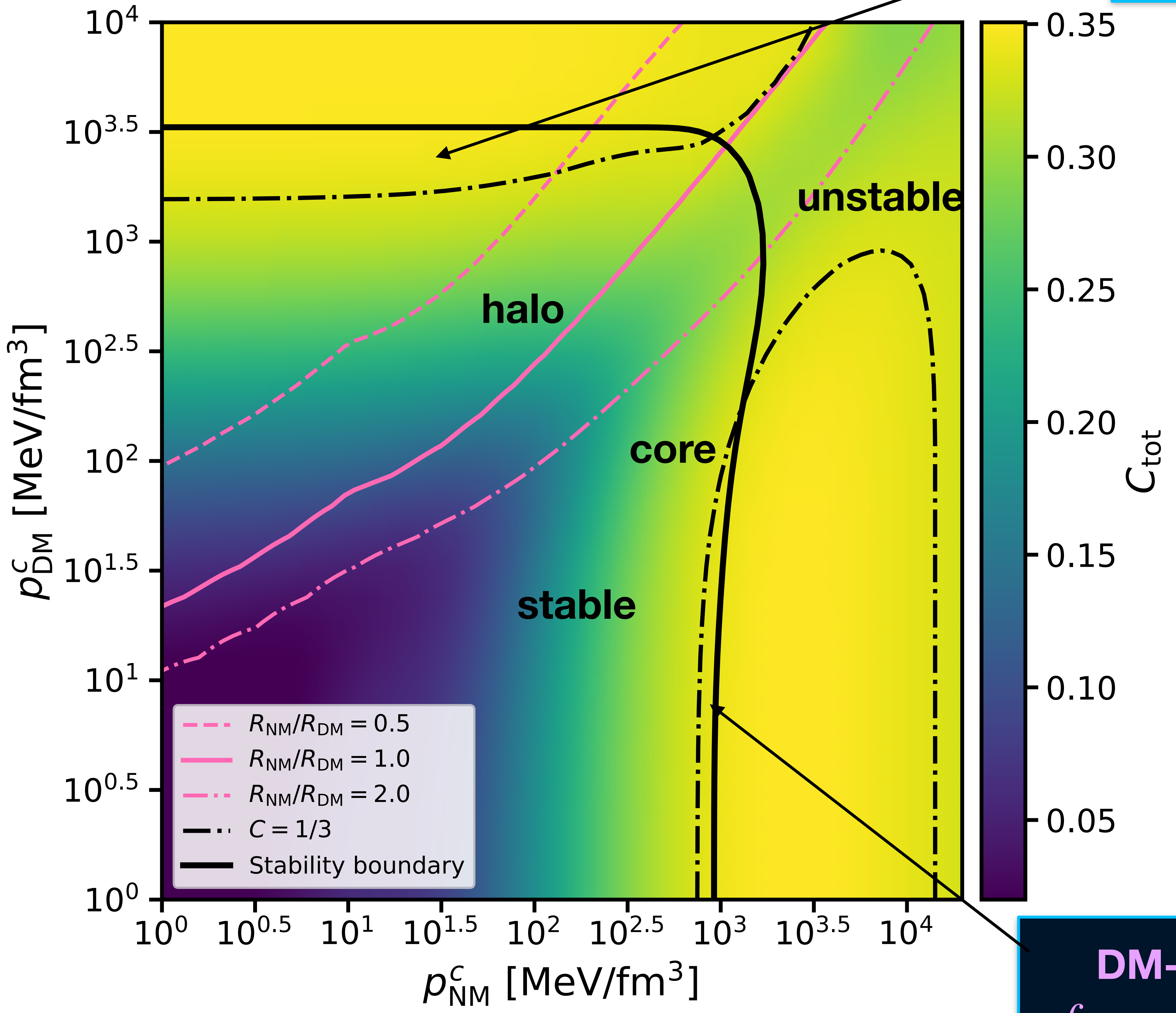
R_{DM}/R_{NM}

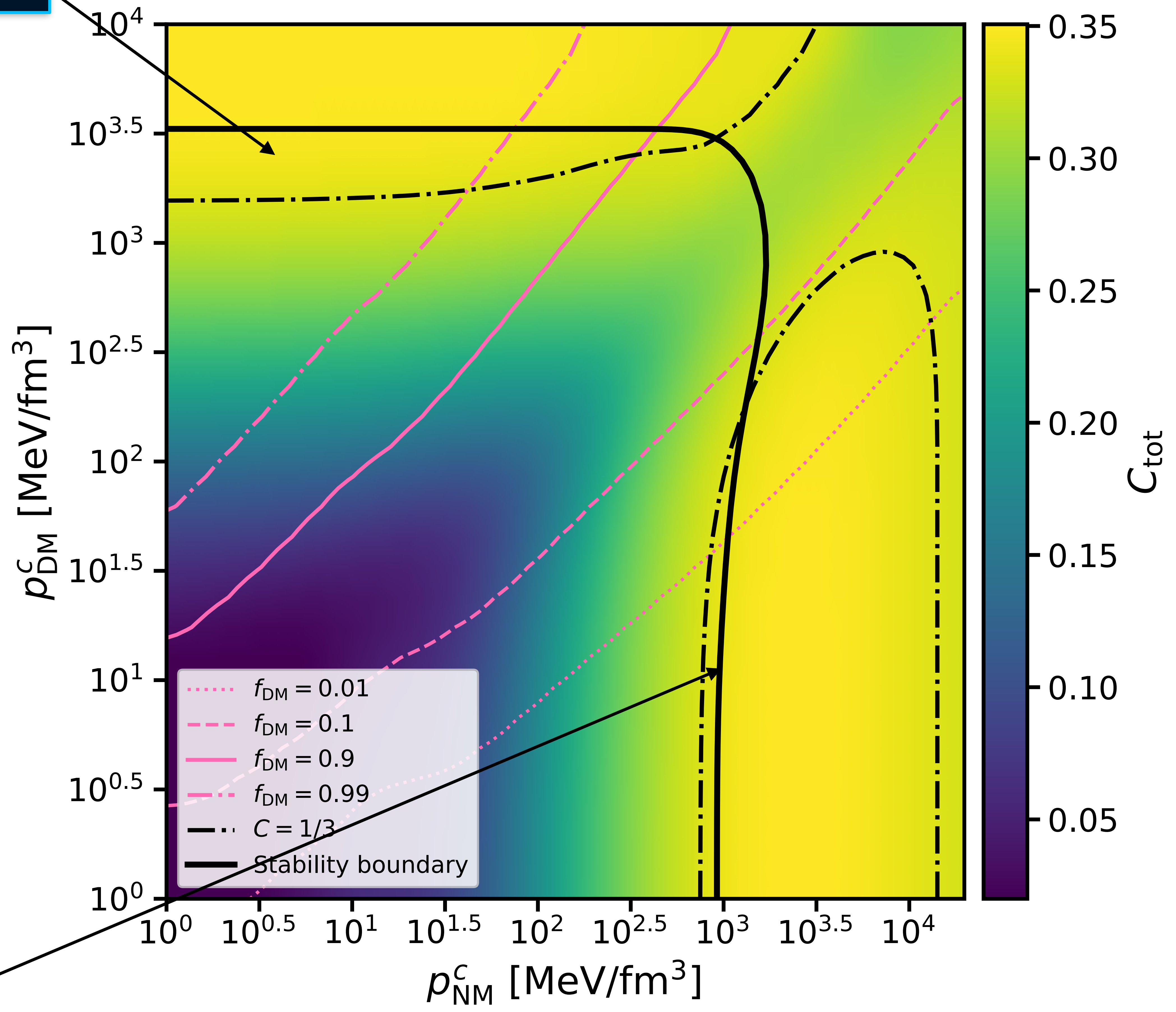
DM-HALO UCOs

f_{DM} **> 0.9 → C ≥ 1/3**

(self-gravity)

f_{DM}





DM-CORE UCOs

f_{DM} **< 0.1 → C ≥ 1/3**

(quark PT)

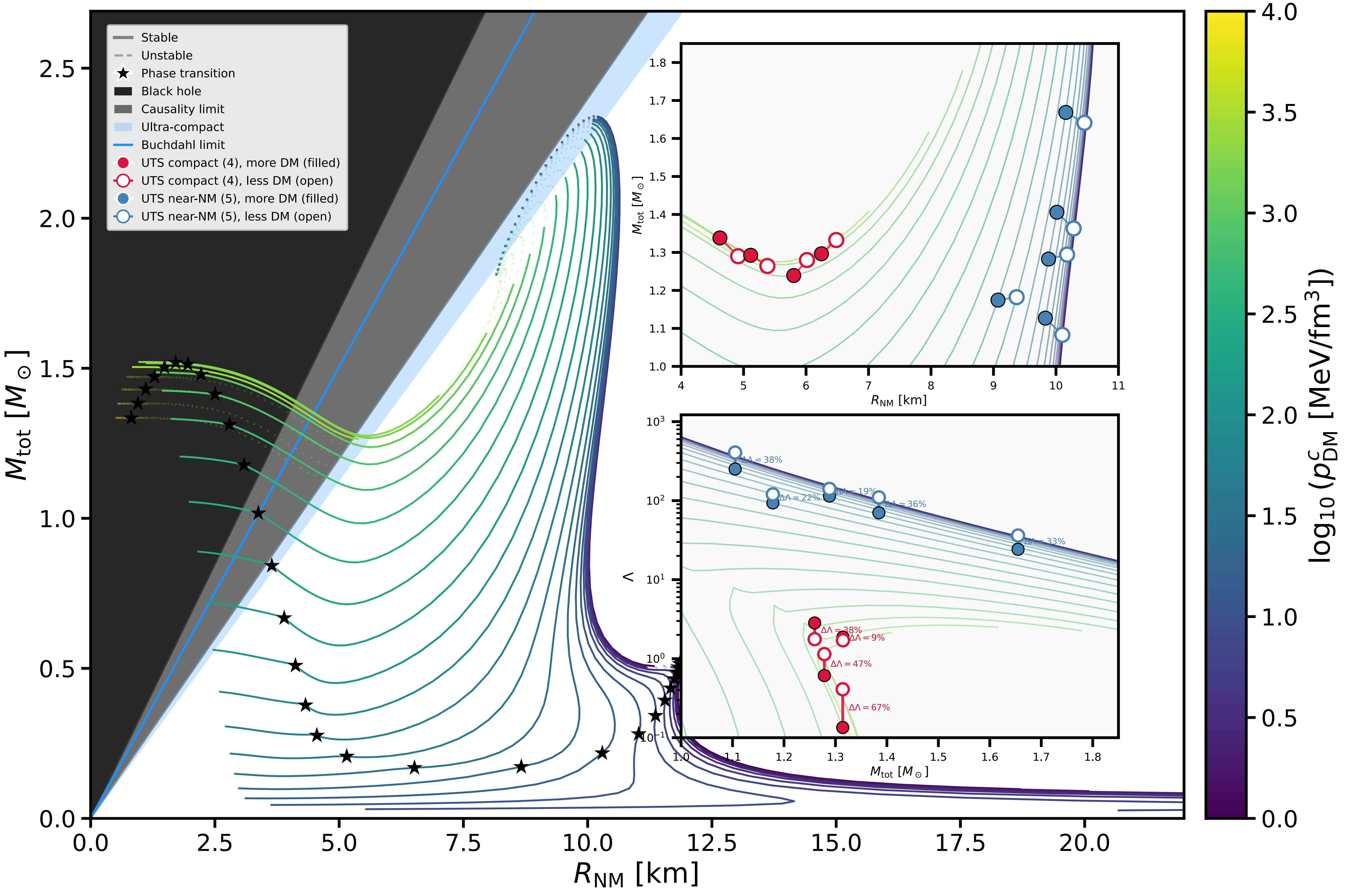
Two independent mechanisms two distinct C≥1/3 islands

Both observable via photon-sphere echo in GW ringdown

Ultimate Twins

Same M, R (NICER blind)

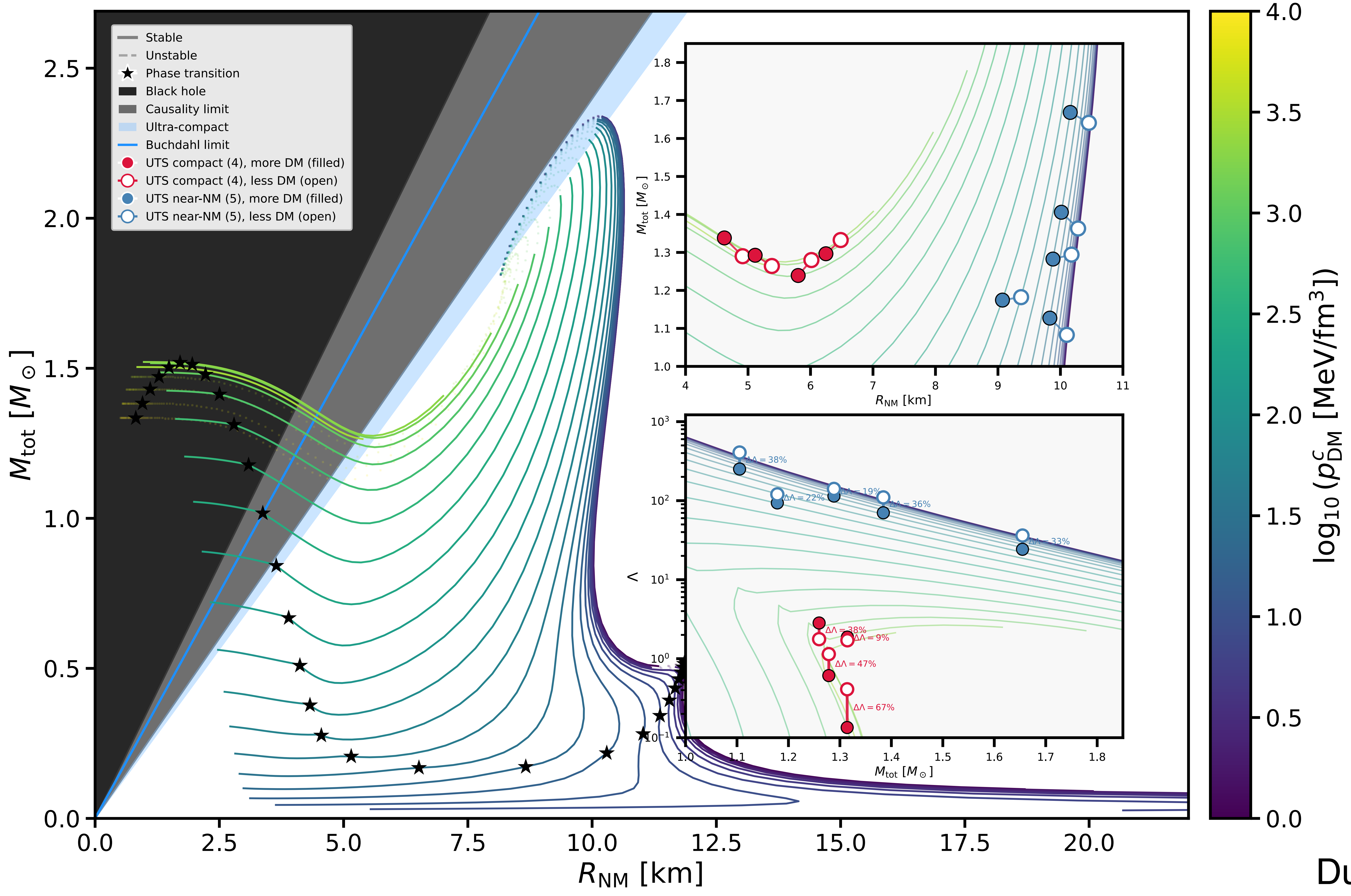
$$\Delta R = 0.1 - 0.3km$$

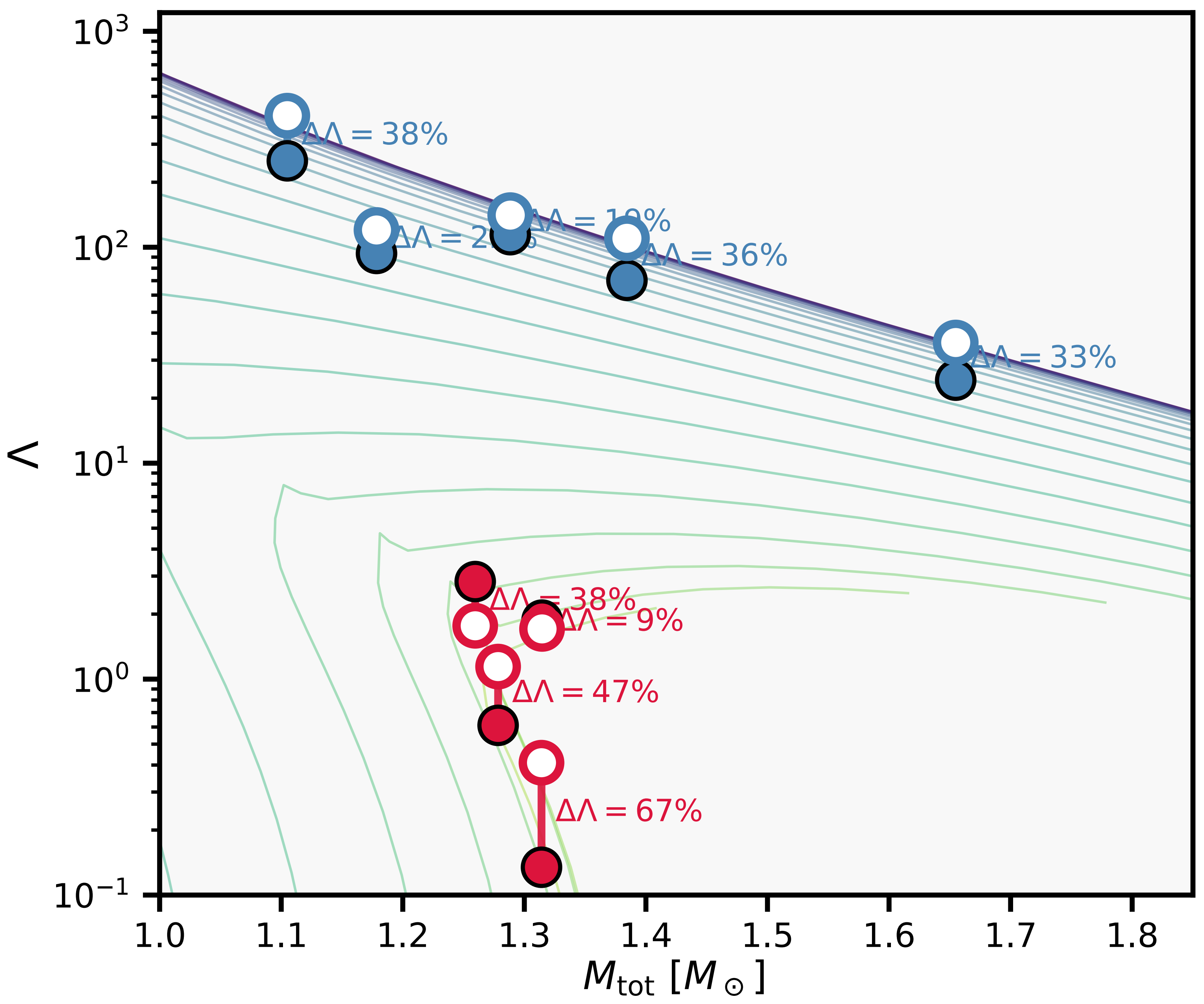


Same M, R (NICER blind)

Different Λ, ΔΛ up to 67% (GW distinguishable)

$\Delta R = 0.1 - 0.3 km$





ΔΛ up to 67% I hidden variable: f_{DM}

Dual of tidal doppelgängers (Raithel & Most 2023)

Summary & Outlook

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Summary

- Two UCO mechanisms: DM-halo (self-gravity) + quark PT
- Photon sphere → BH mimicker, detectable echo
- DM masks the twin-star gap but does not destroy twin — hidden my DM mass.
- Ultimate twins: same (M,R), different Λ up to 67%

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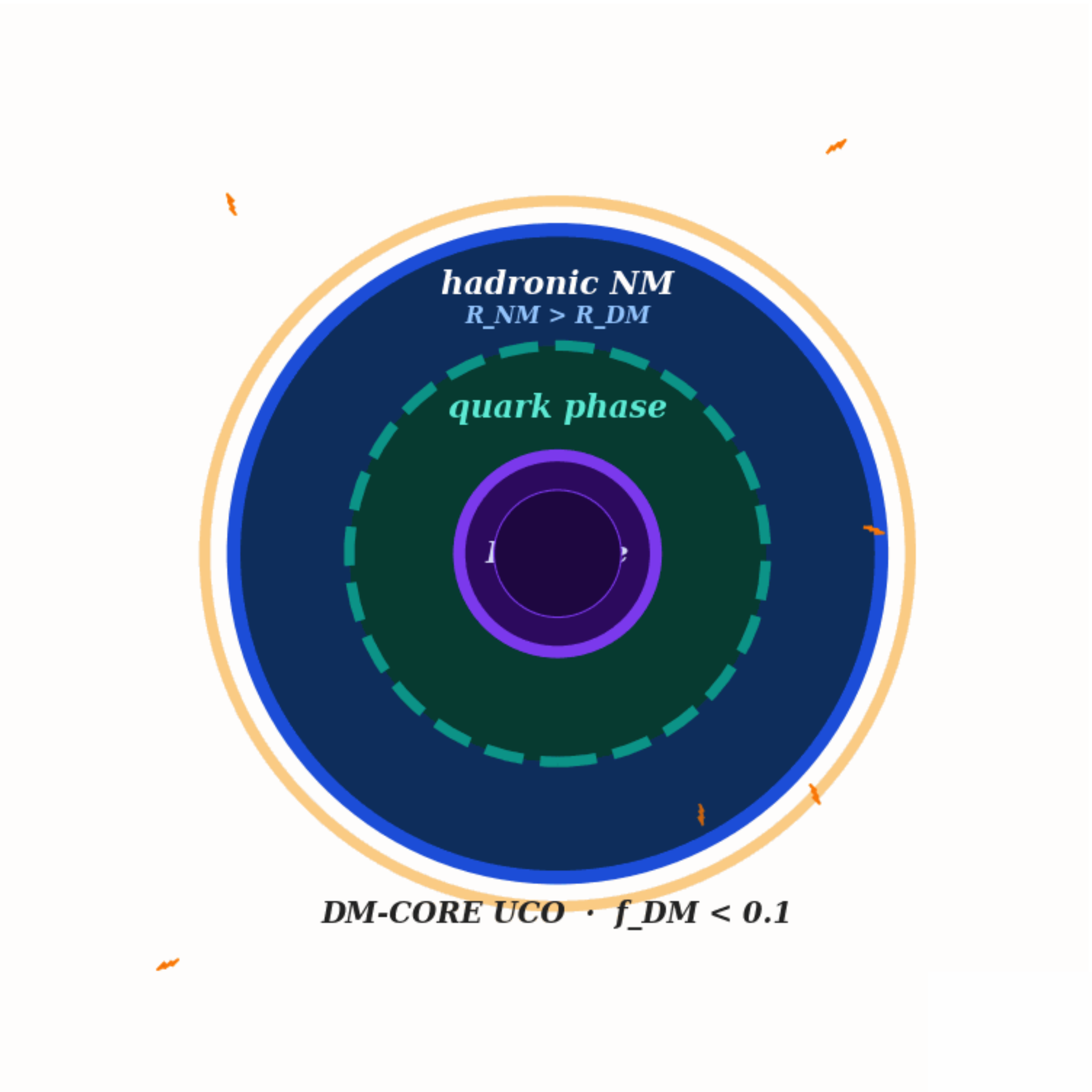
Outlook

- Dynamic stability analysis - Two fluid Radial Perturbations.
- GW Echoes from UCOs.
- Next-gen detectors (ET, CE): ΔΛ~10% resolvable.
- X-ray timing: photon-sphere echo → UCO vs BH mimicker discrimination.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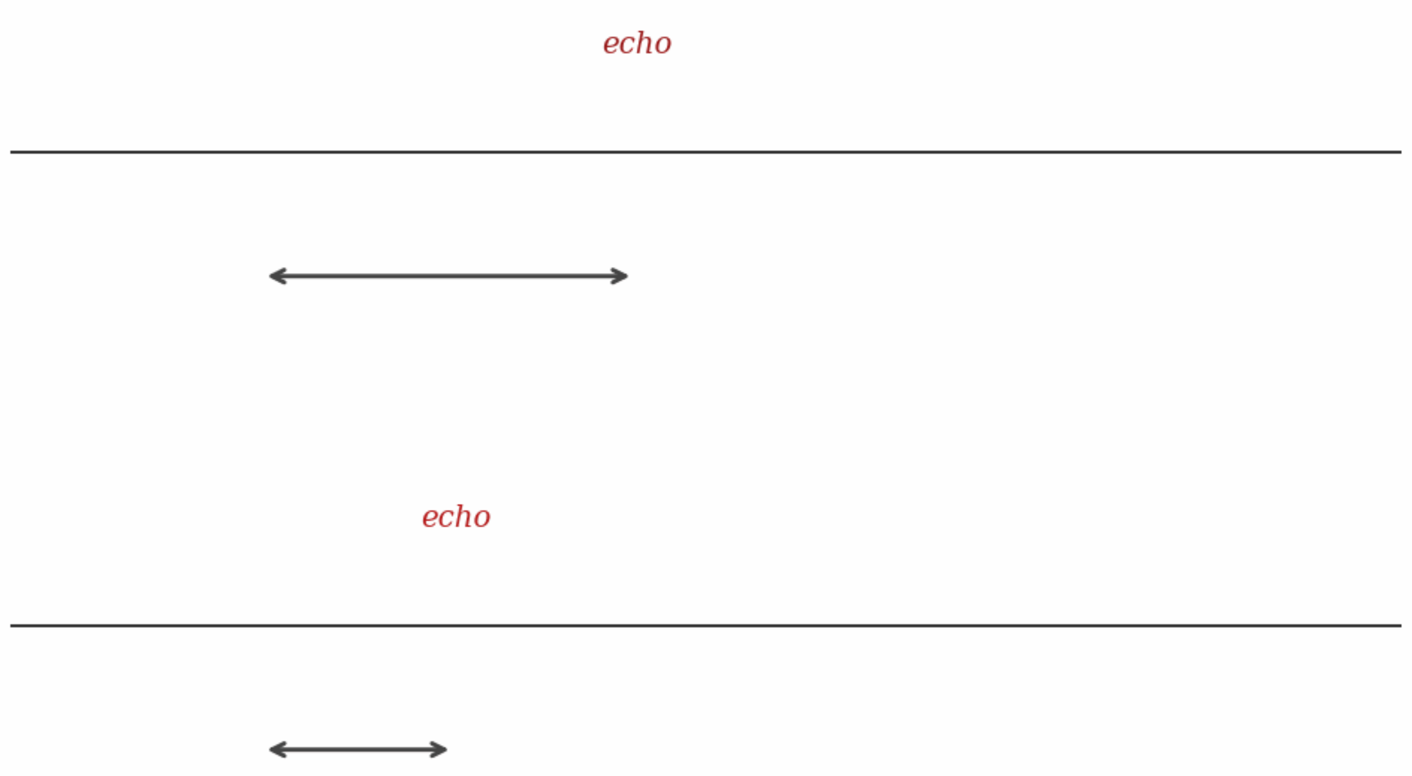
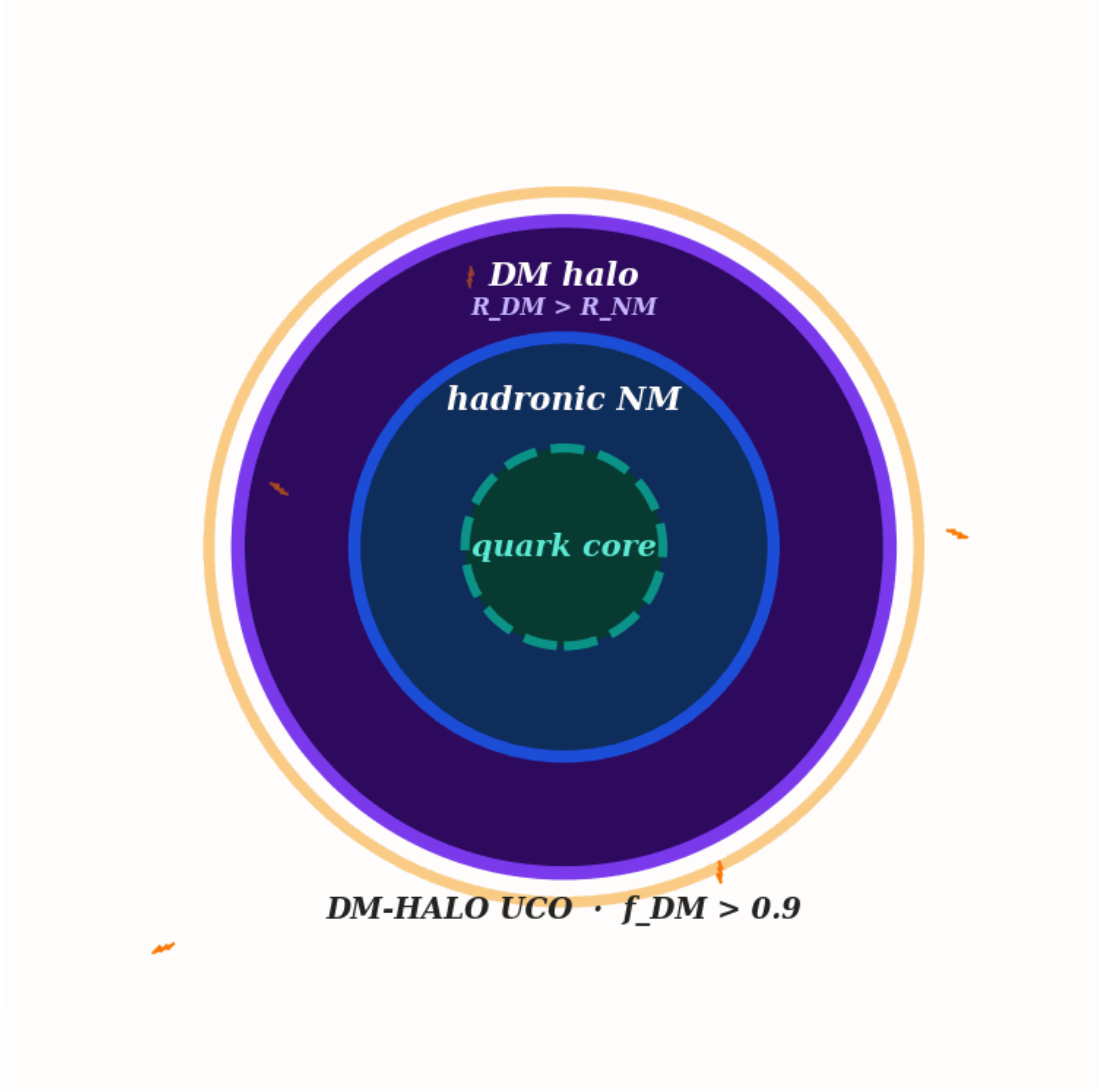
quark phase
DM-CORE UCO · f_DM < 0.1


echo
echo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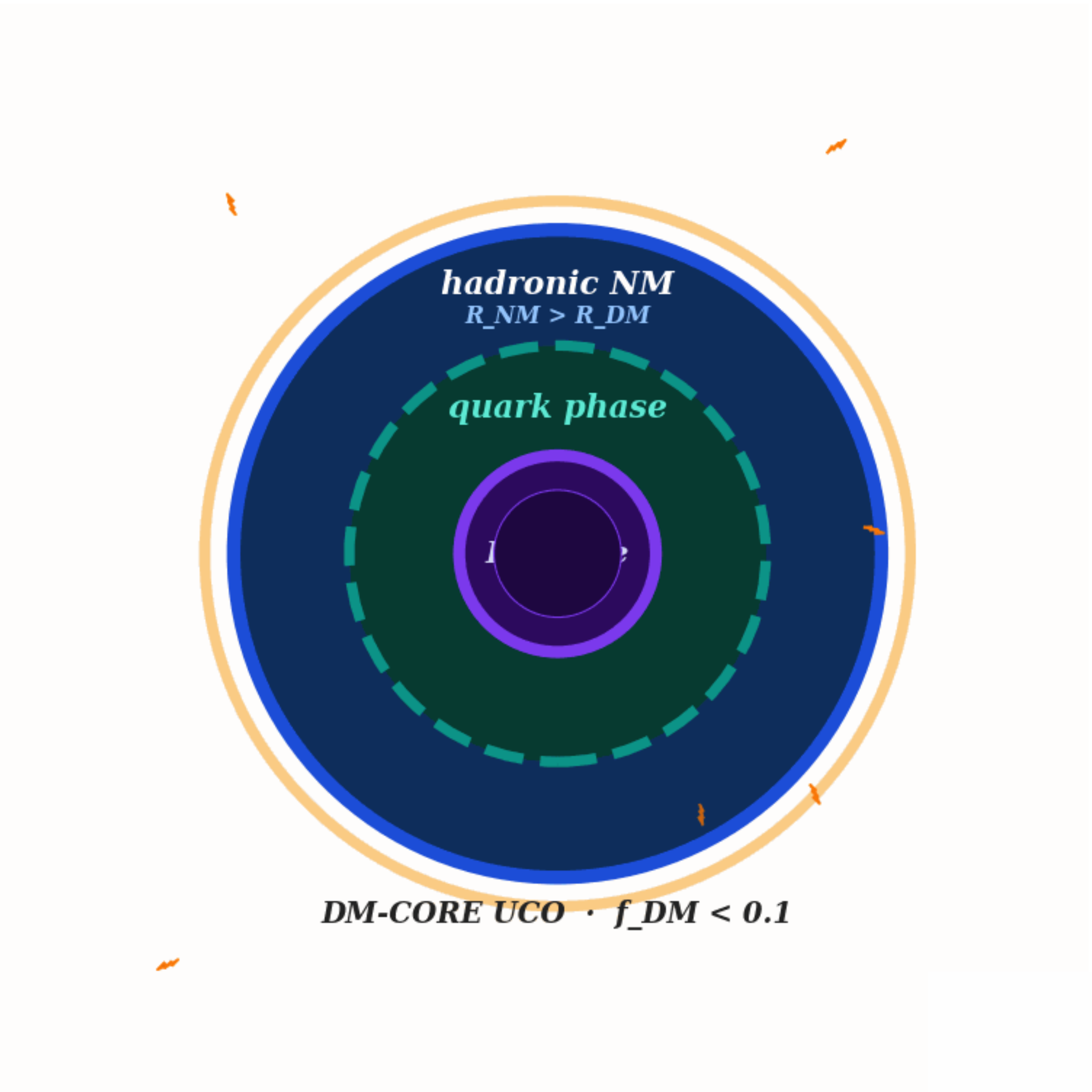
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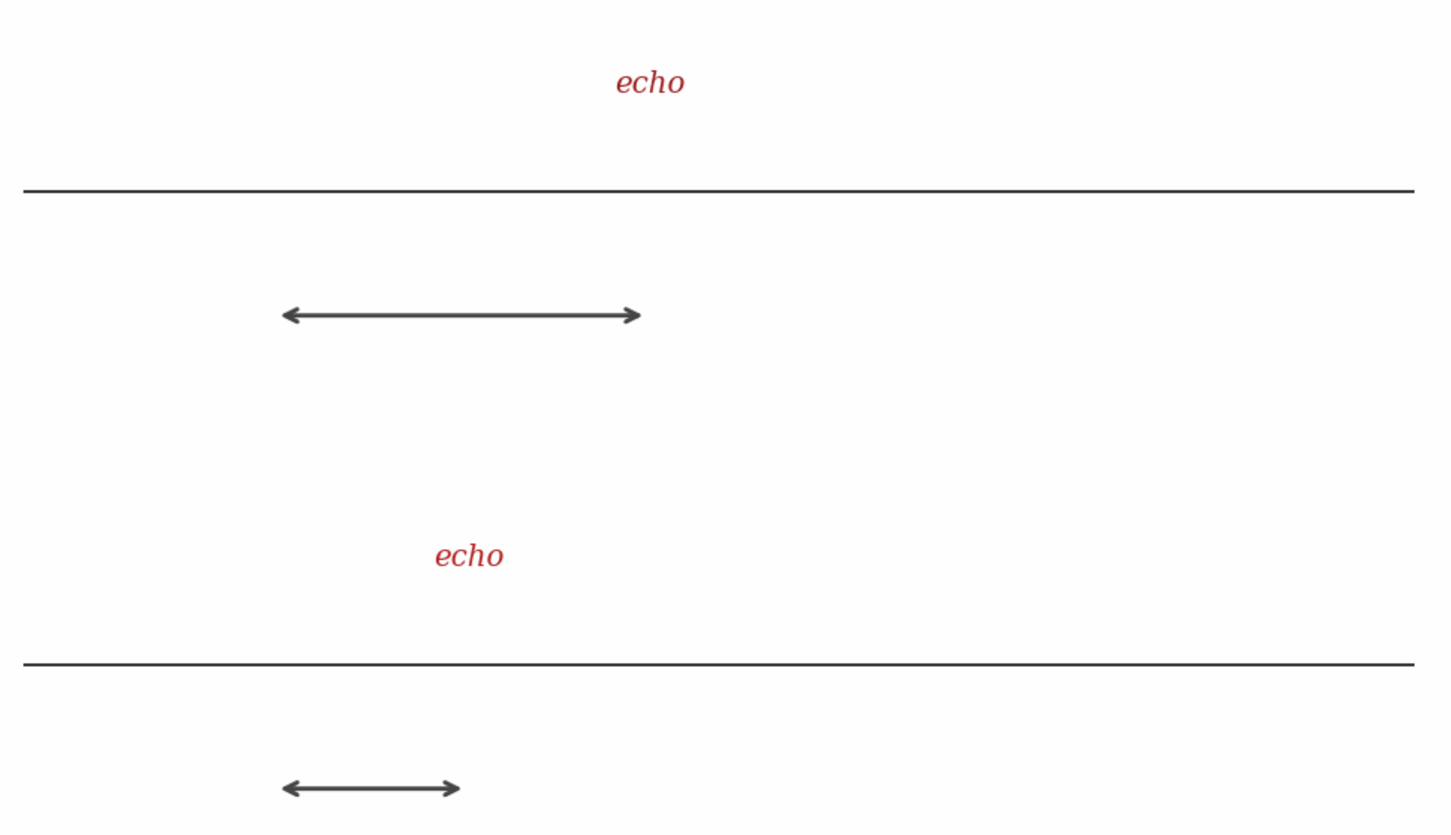
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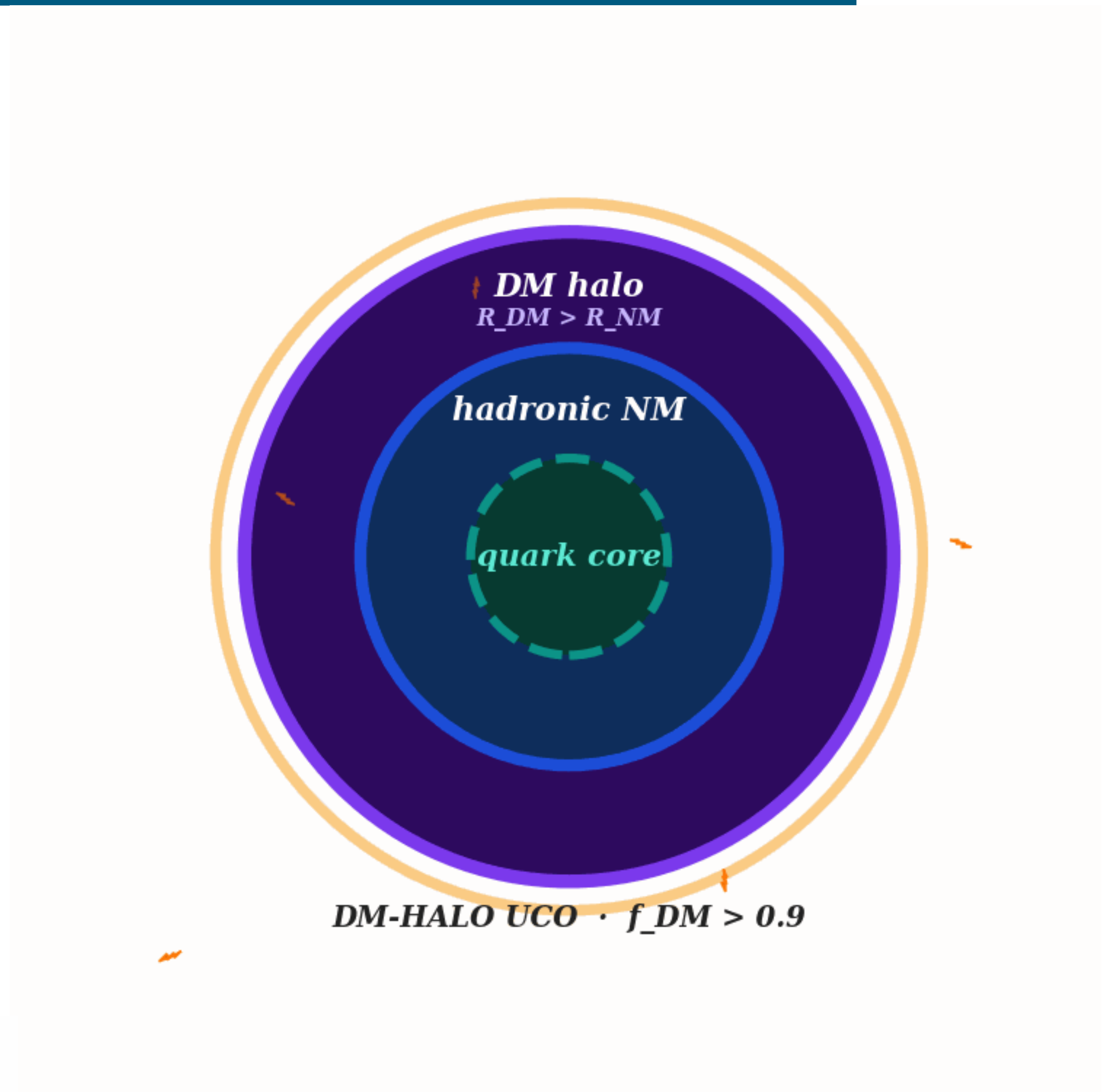
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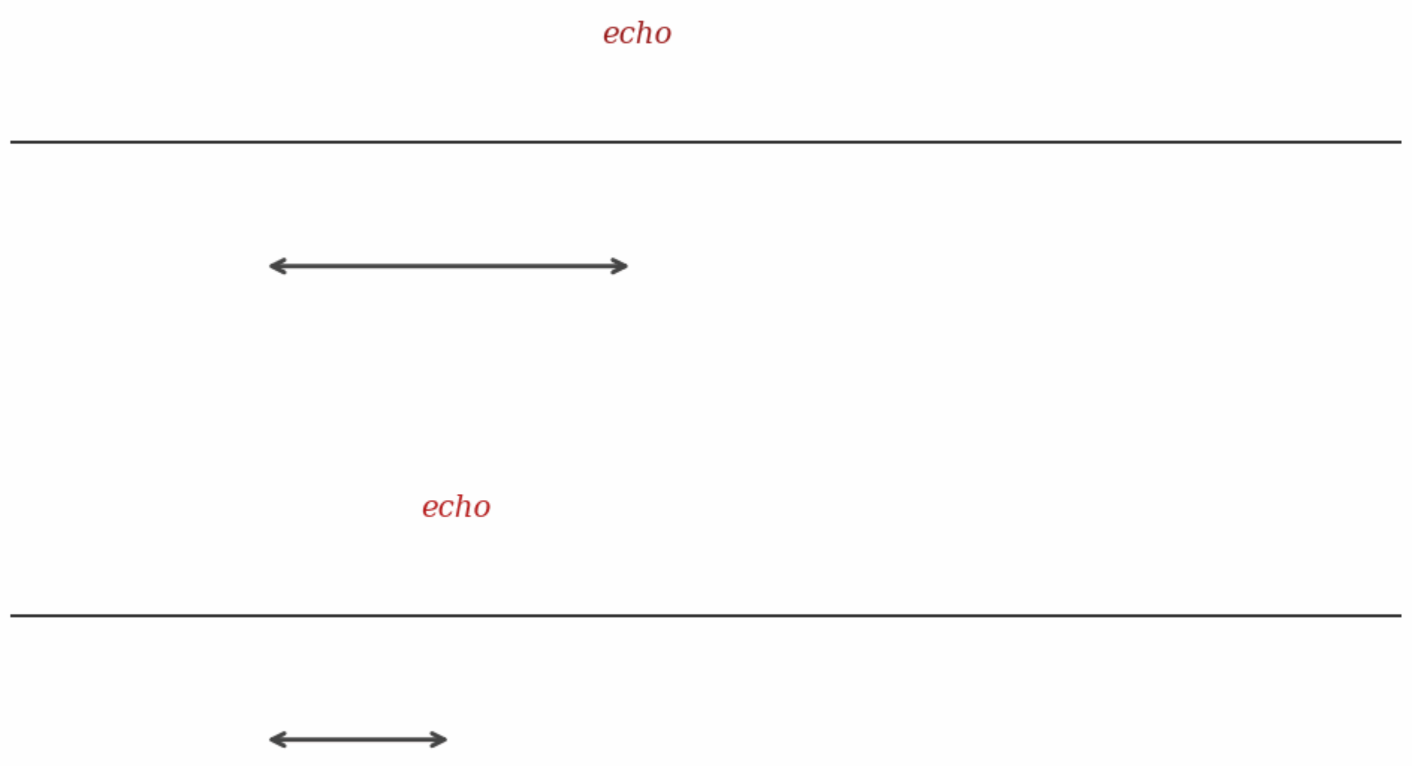
echo
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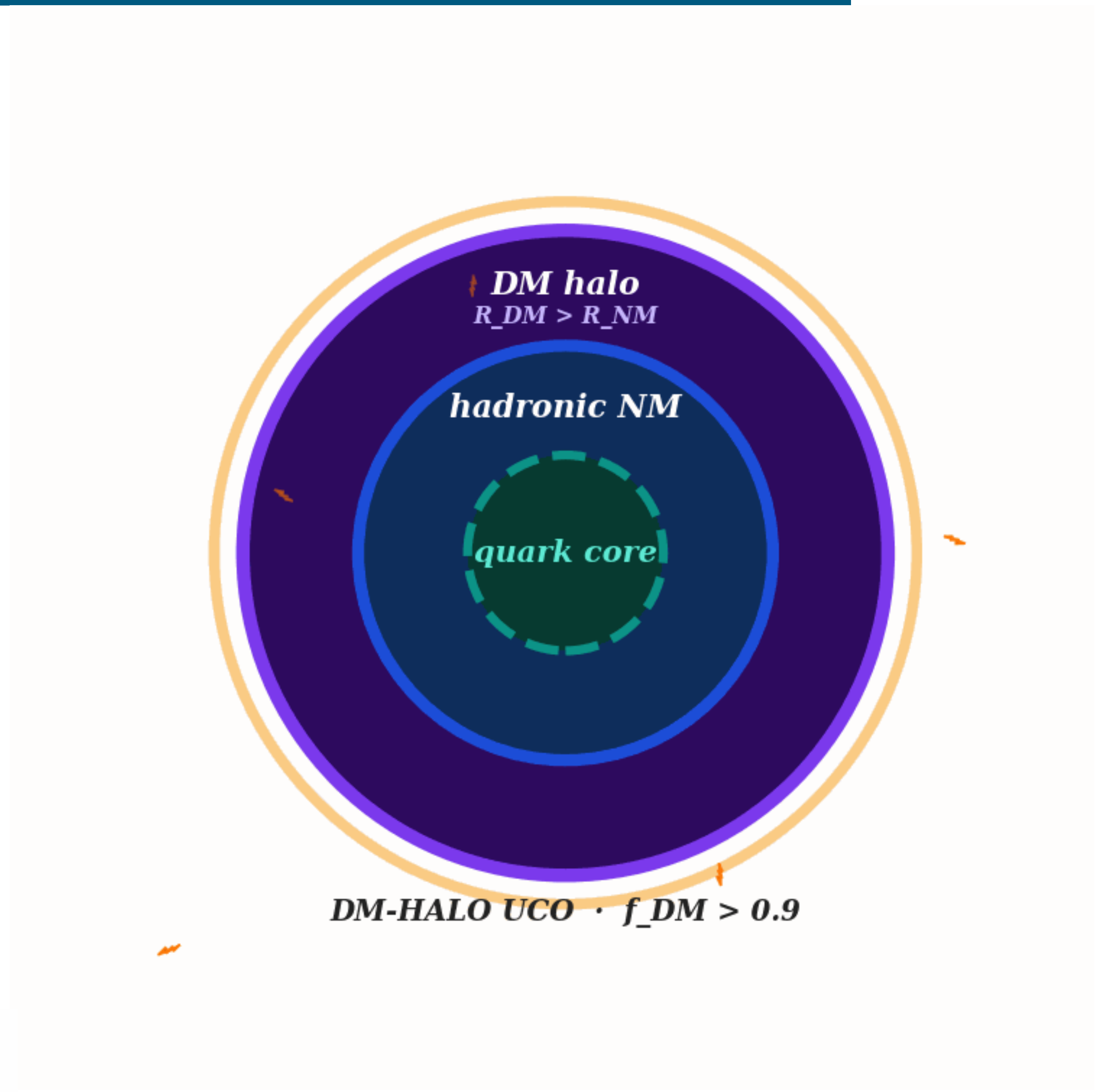
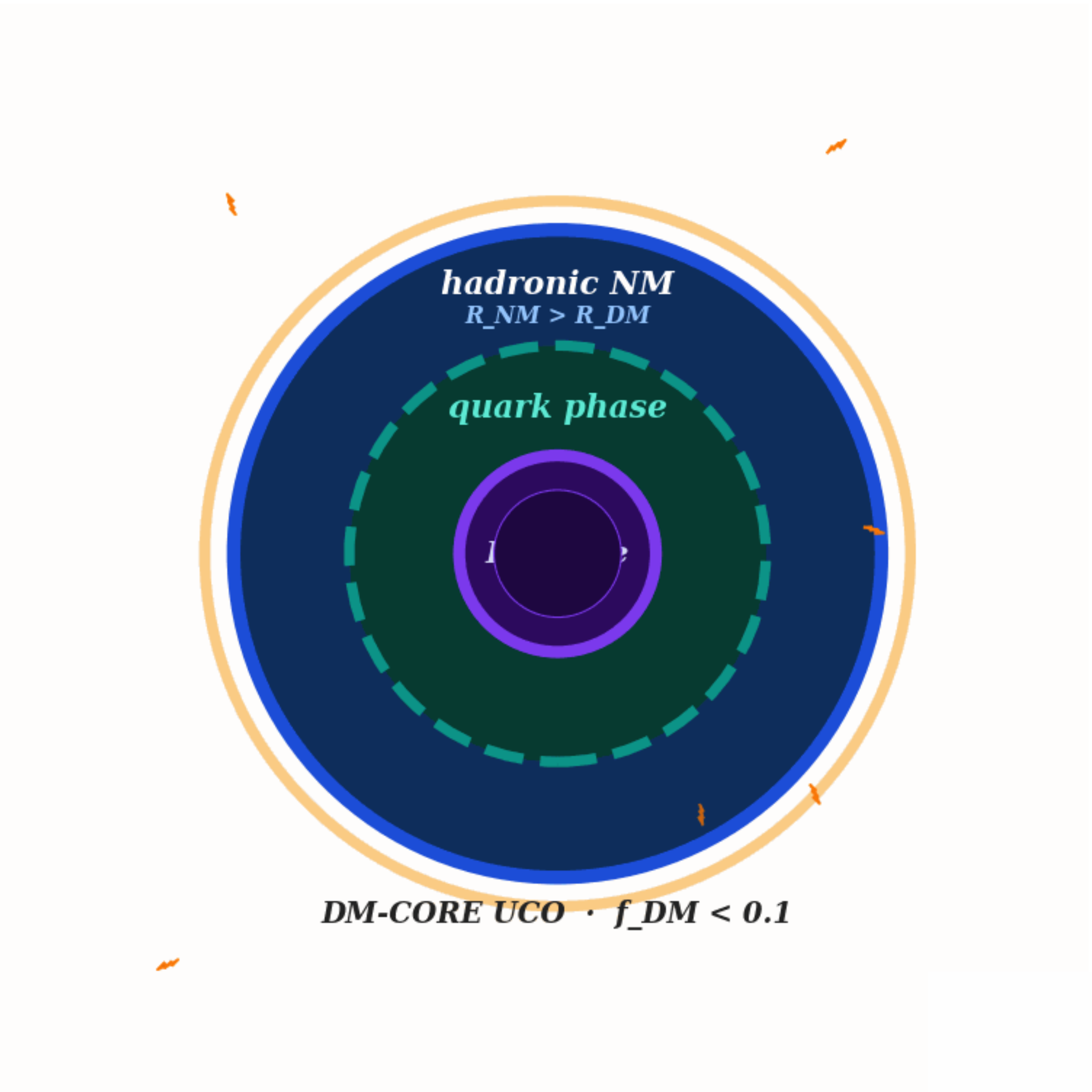

DM halo
R_DM > R_NM
hadronic NM
quark core
DM-HALO UCO · f_DM > 0.9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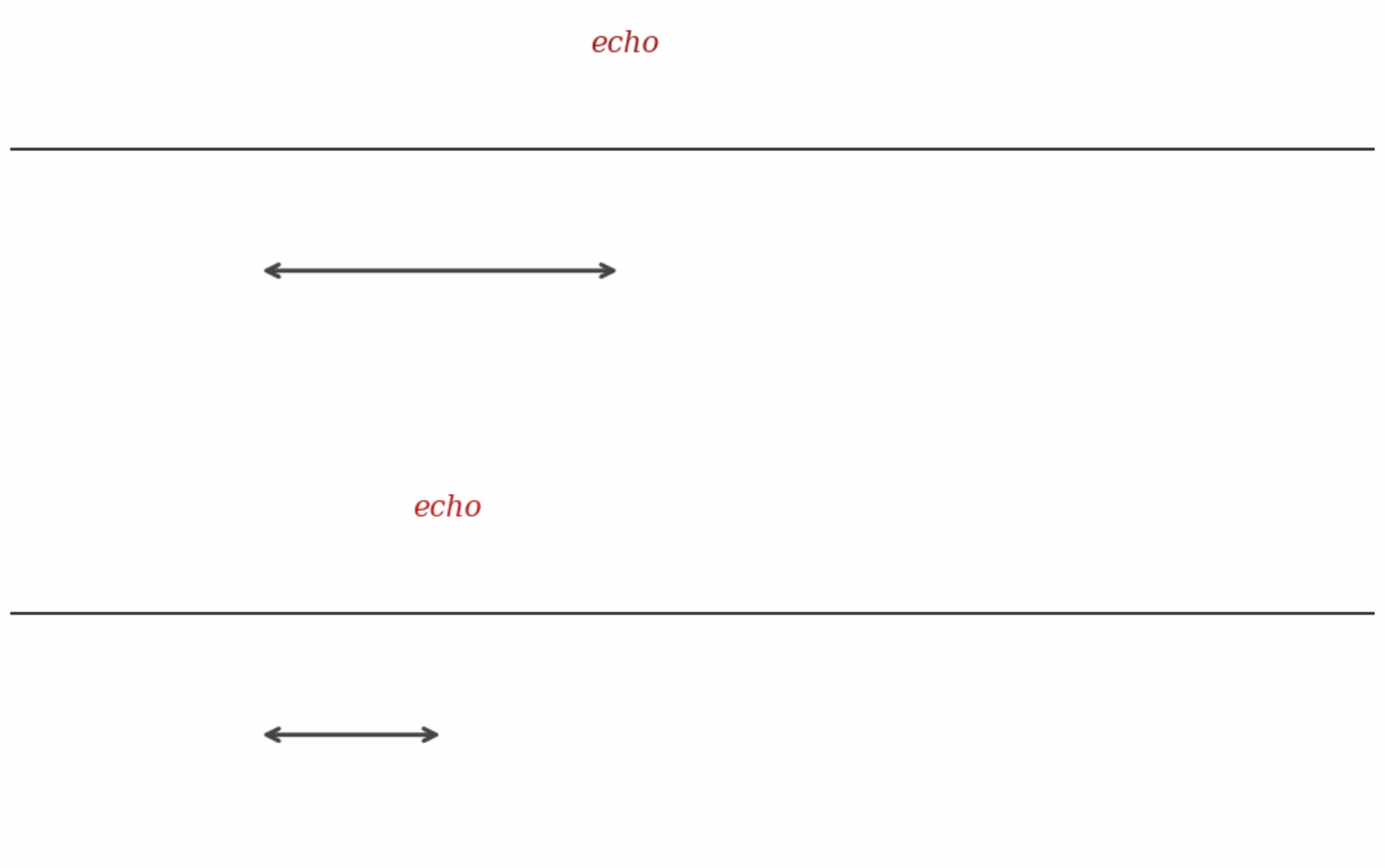
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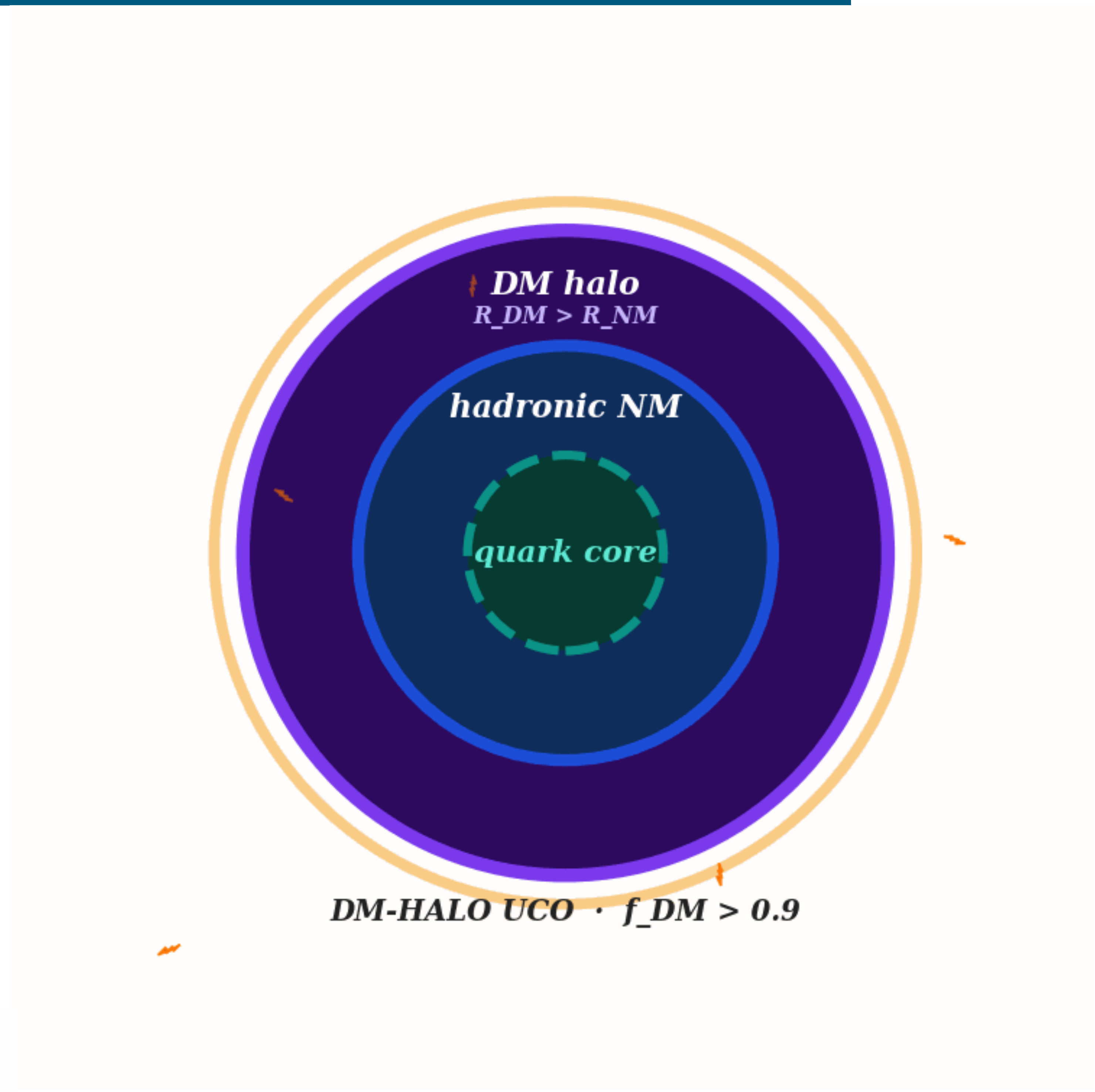
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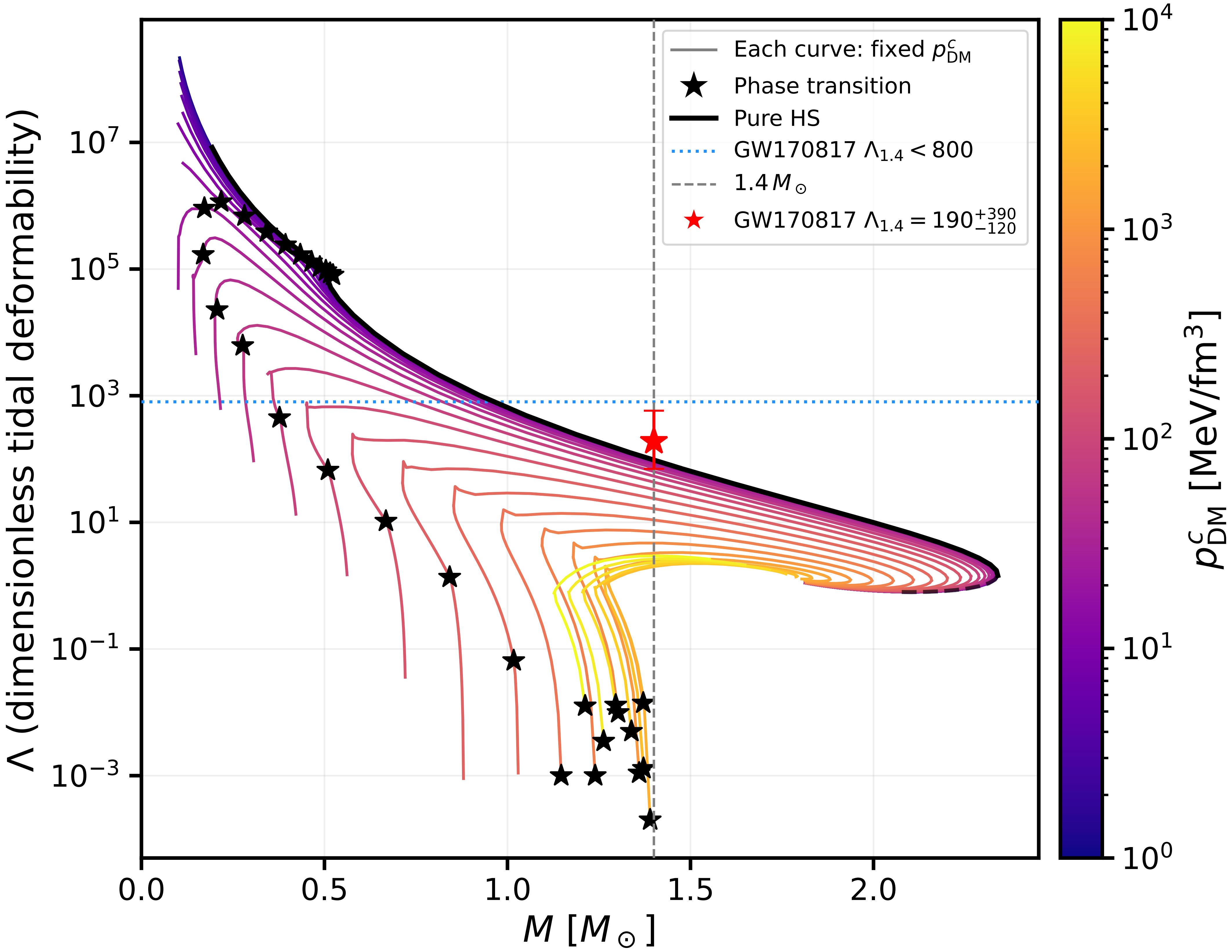
Tidal deformability

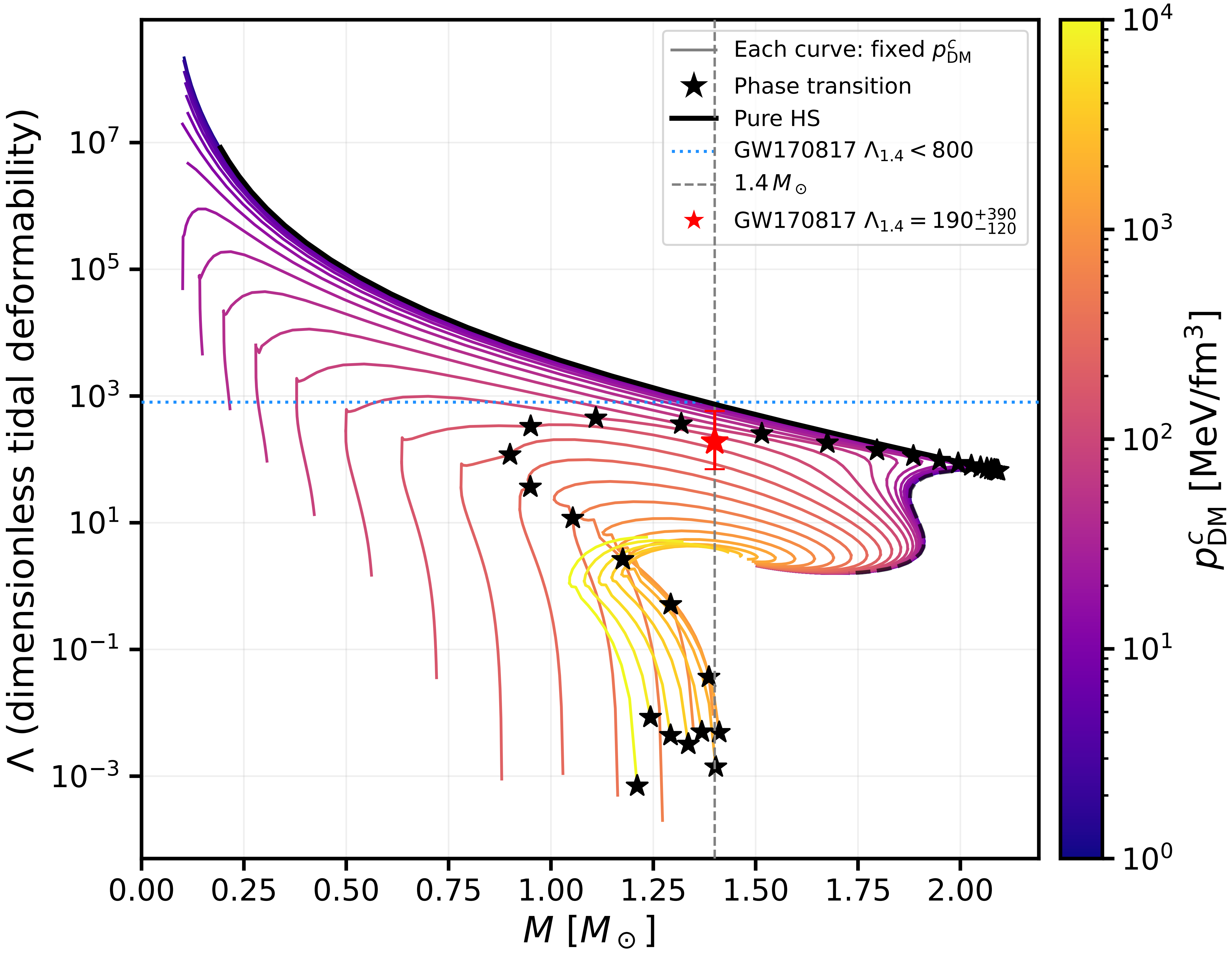
$m_b = 300$ MeV, $n = 40$

= stable   = unstable

$P_t = 30 MeV/fm^3 \quad \Delta\varepsilon = 250 MeV/fm^3$



$P_t = 120 MeV/fm^3 \quad \Delta\varepsilon = 500 MeV/fm^3$



Compatible with GW170817

Twin Stars

Twin Stars

- Two distinct stable stellar configurations- **same mass** but **different radii**.
- Emerge due to a **strong first-order phase transition.**

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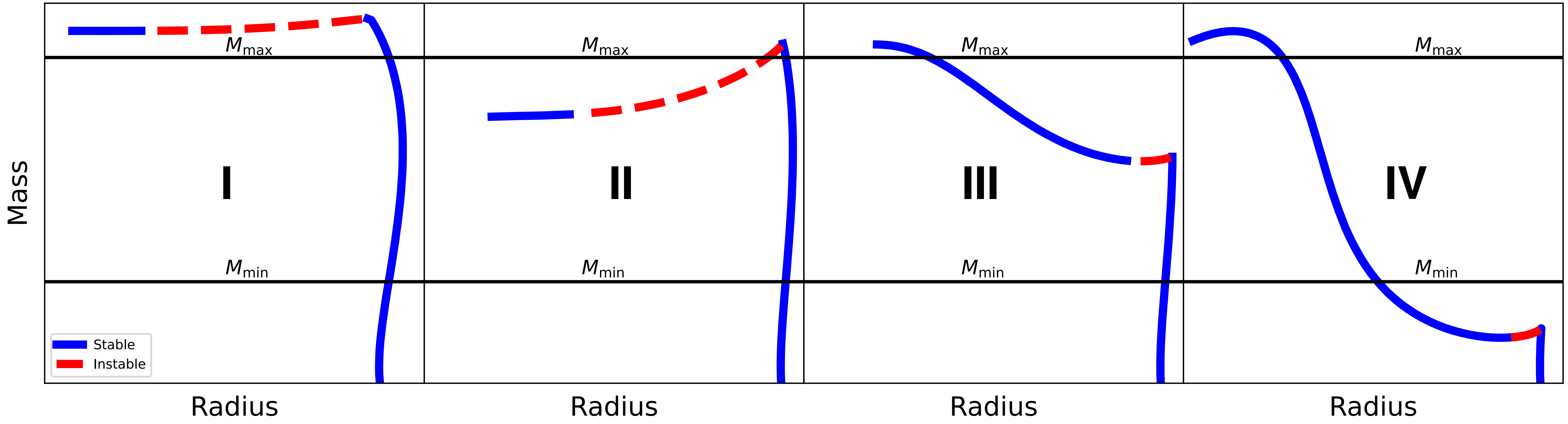

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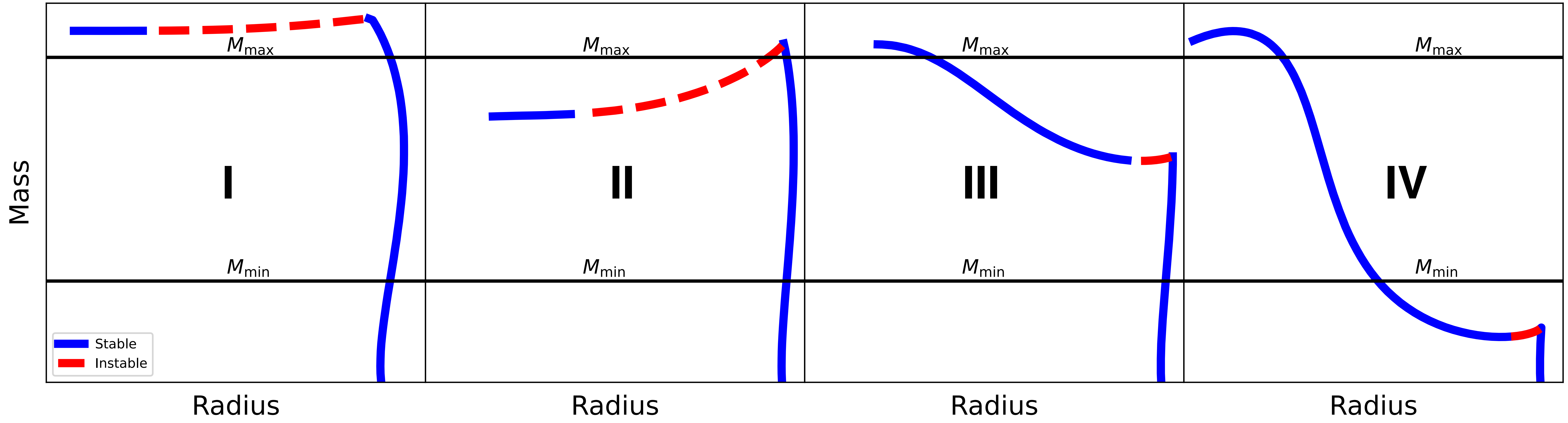

J.E.C, PRD 109, 063035 (2024)

$$M_{max} = 2.0\,M_{\odot}$$

Nature 467, 1081 (2010)
Science 340, 6131 (2013).

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J. G. Martine *et al.*, ApJ 812, 143 (2015)

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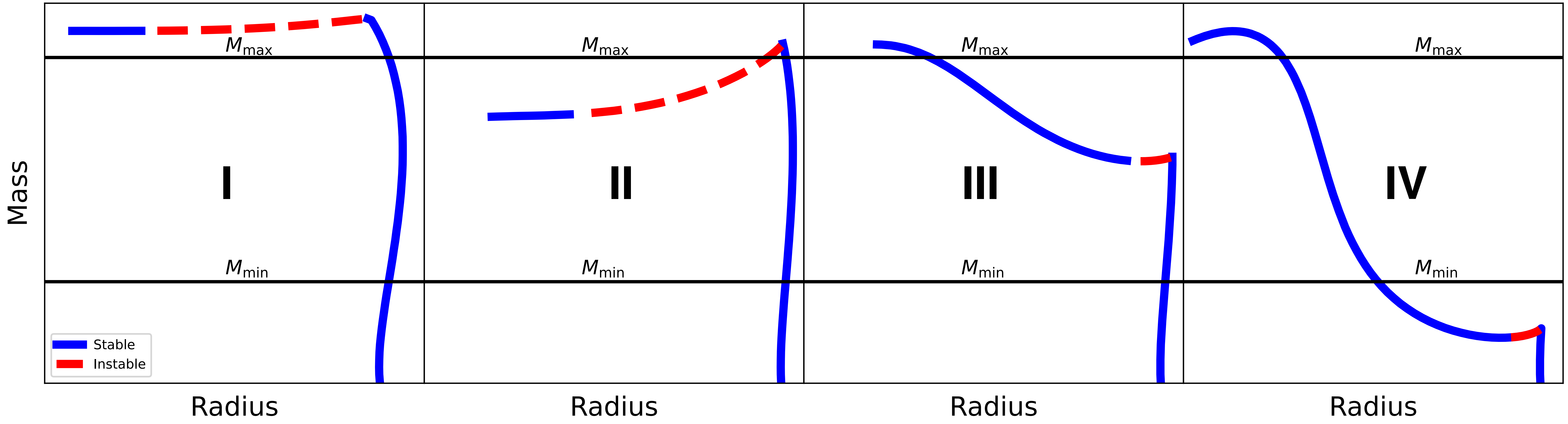

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Seidov Limit

$$\frac{\Delta\epsilon}{\epsilon_{trans}} = \frac{1}{2} + \frac{3}{2}\frac{P_{trans}}{\epsilon_{trans}}$$

minimum energy density jump required at the transition to destabilize the star and allow twin configurations.

Z. F. Seidov, Sov. Astron. 15, 347 (1971).
B. Kämpfer, Phys. Lett. 101B, 366 (1981).

different DM parameters

CRC-TR 211

$m_b = 300$ MeV, $n = 40$

$m_b = 1000$ MeV, $n = 4$

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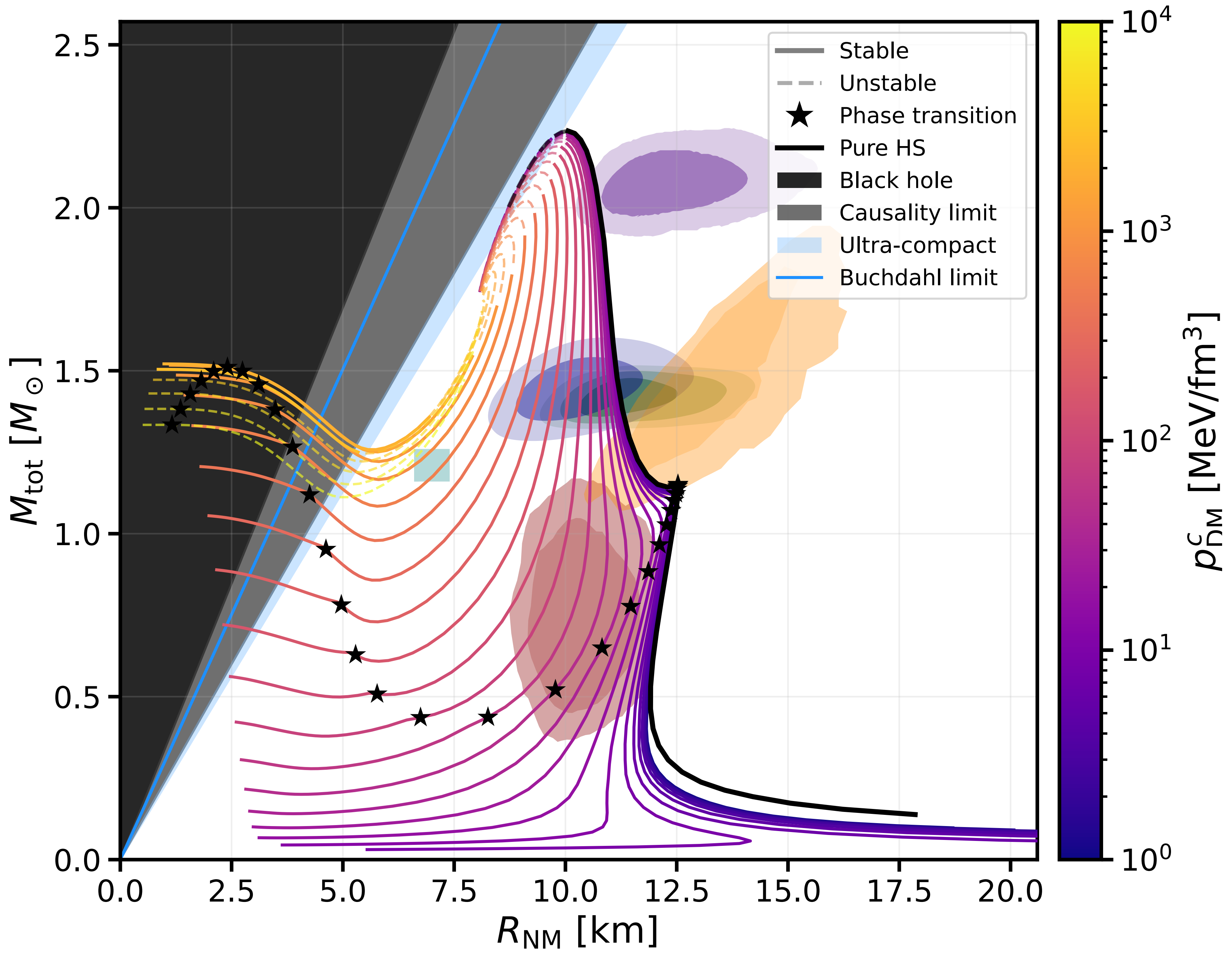

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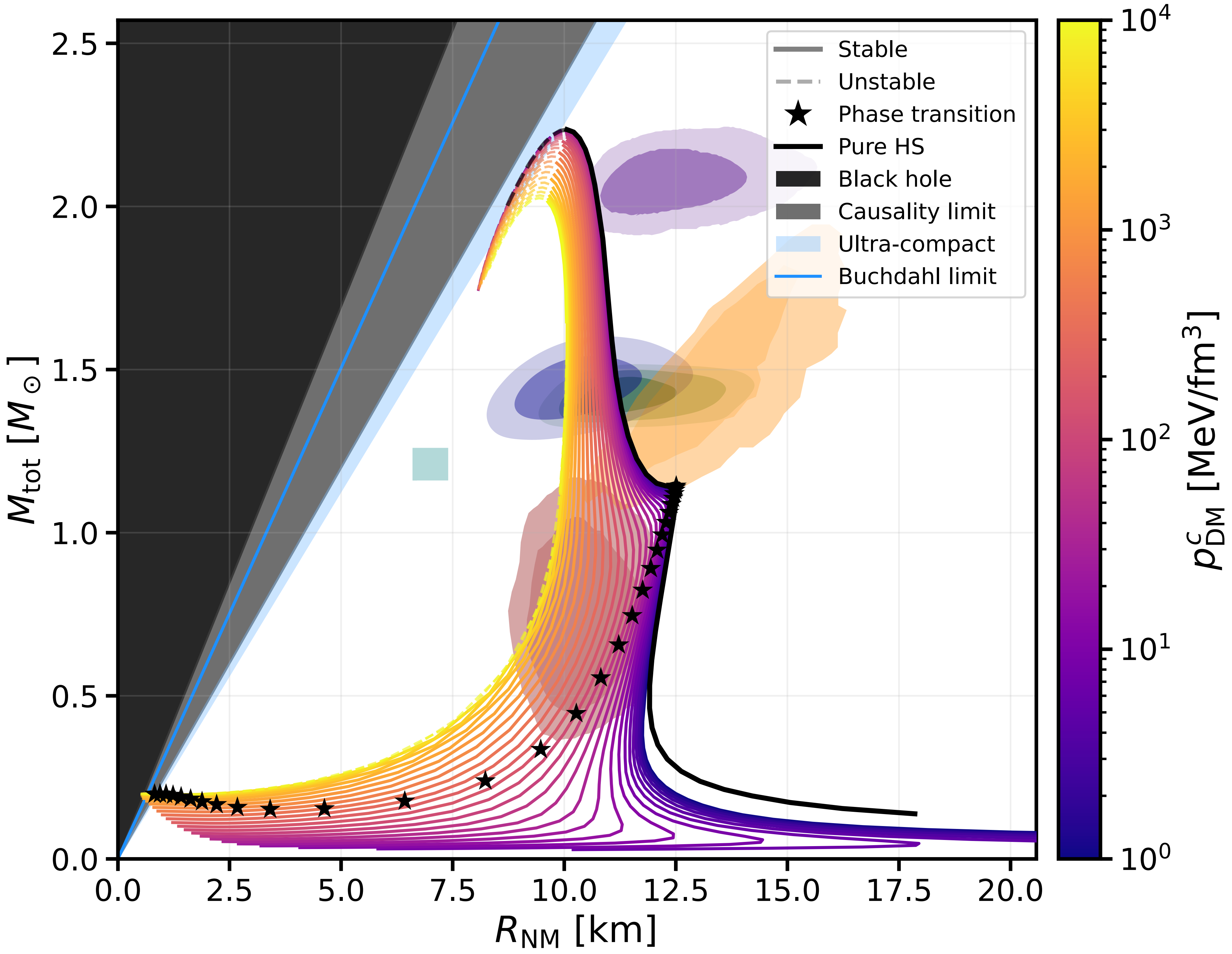

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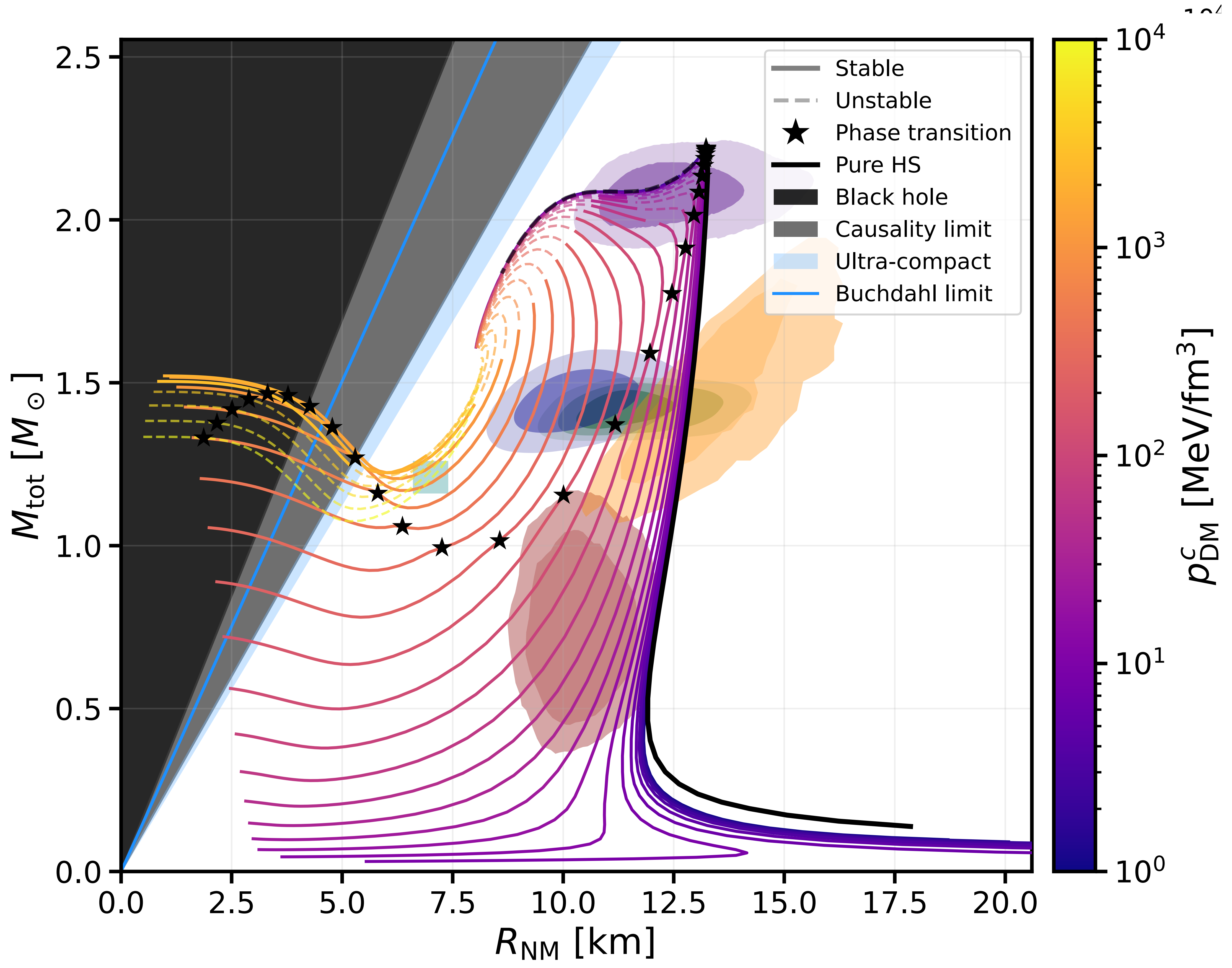

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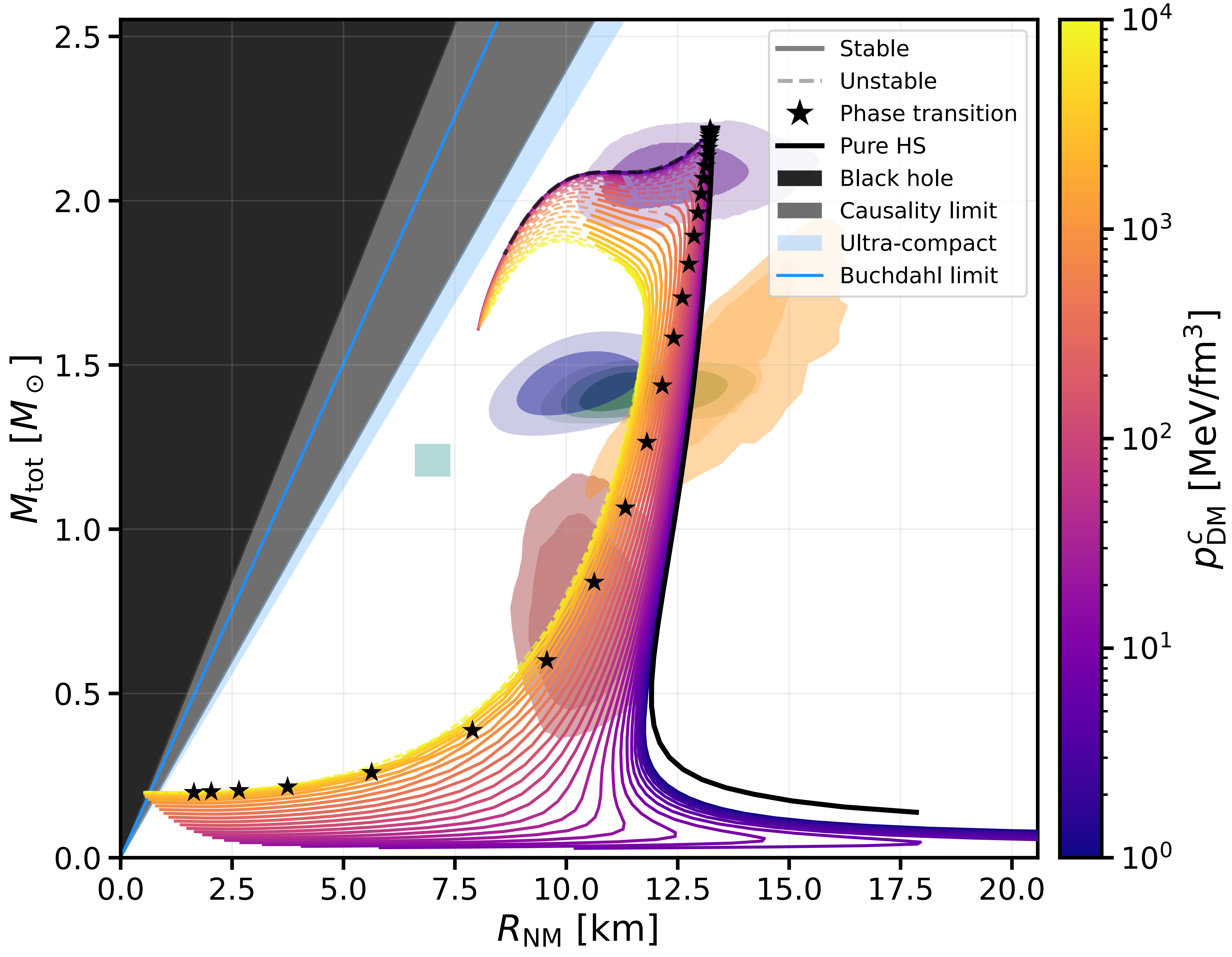
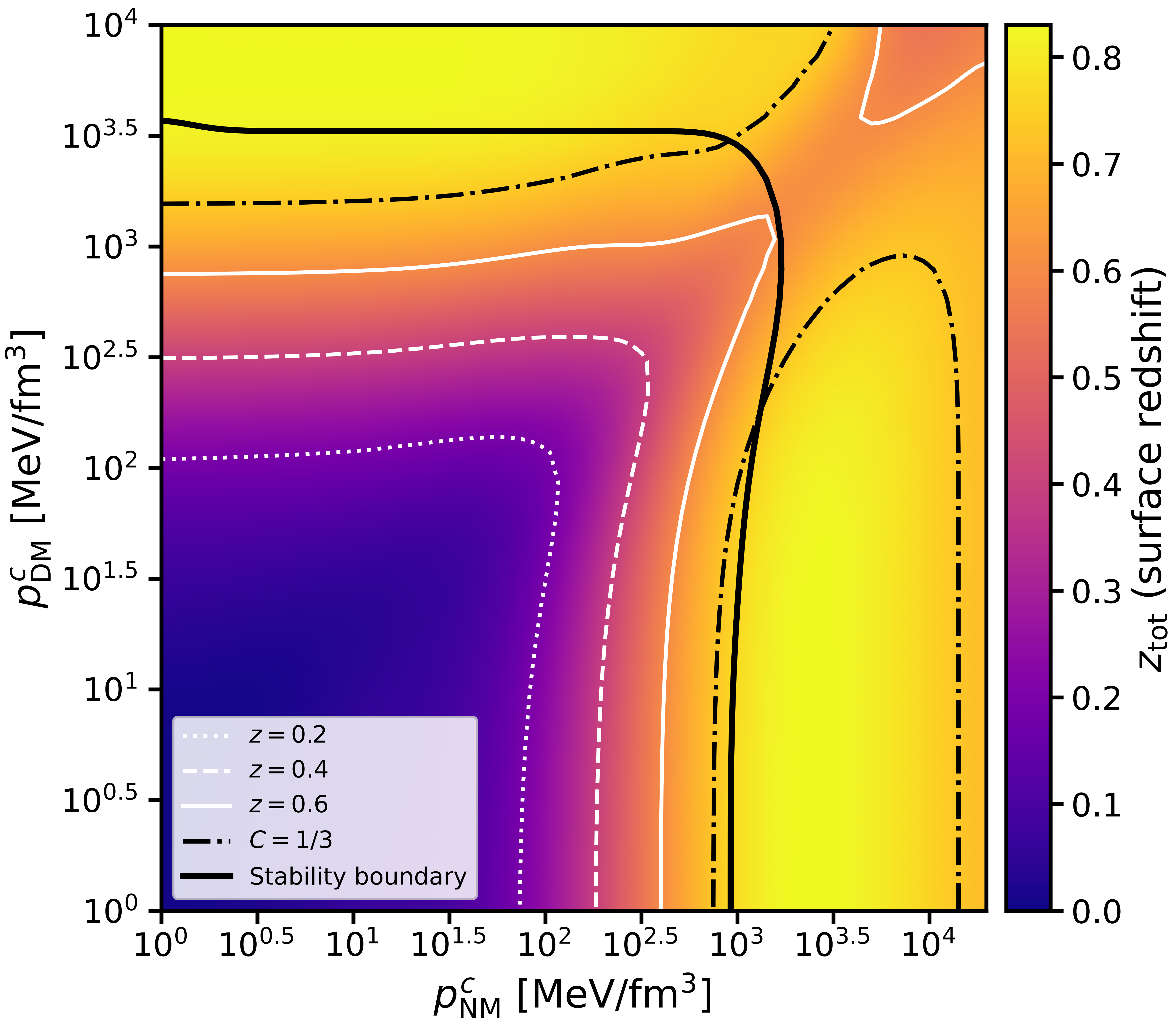


Redshift



- z ~ 0.6–0.8 in UCO region
- z ~ 0.2 for typical NS — factor ~3–4 enhancement.
- Observable via spectral line shifts

NM MR

Hadronic → Quark matter

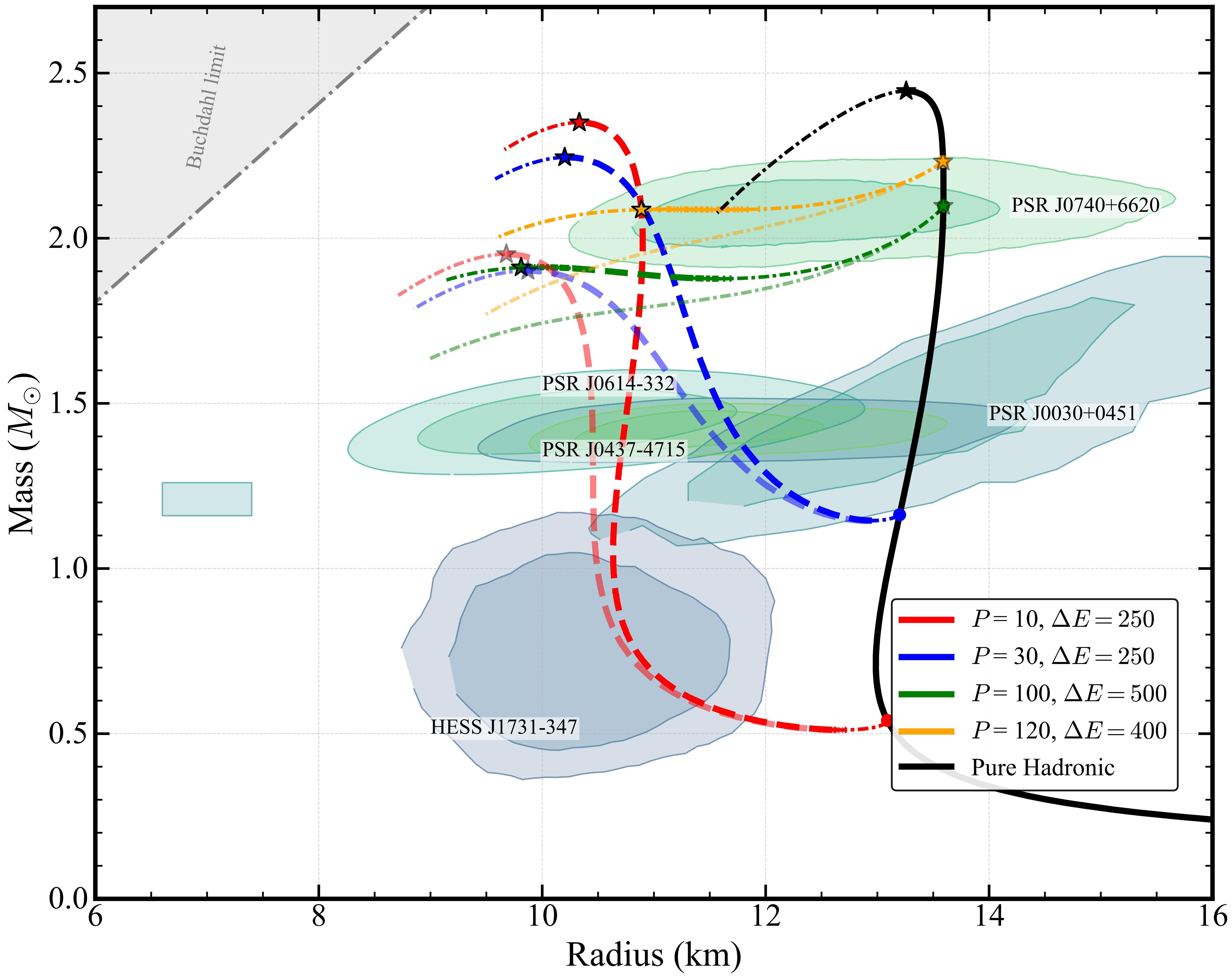
P_t = 10 – 120 MeV/fm³

$\Delta\varepsilon$ = 250 – 500 MeV/fm³

c_{QM} = 0.7 - 1.0

Compatible with pQCD constraints

Oleg Komoltsev, Aleksi Kurkela *PRL*128 (2022) 20, 202701



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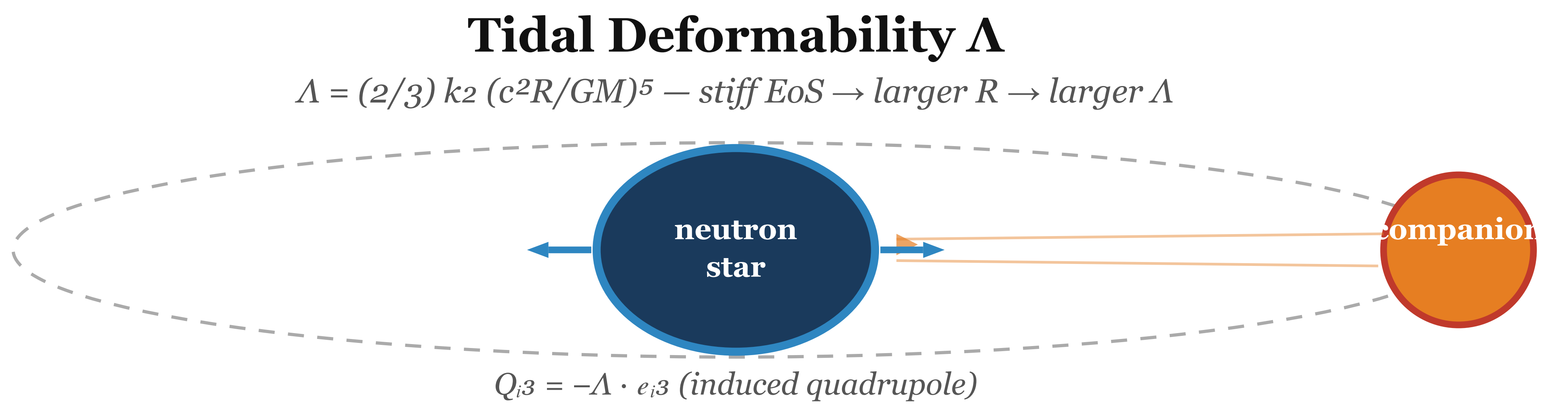
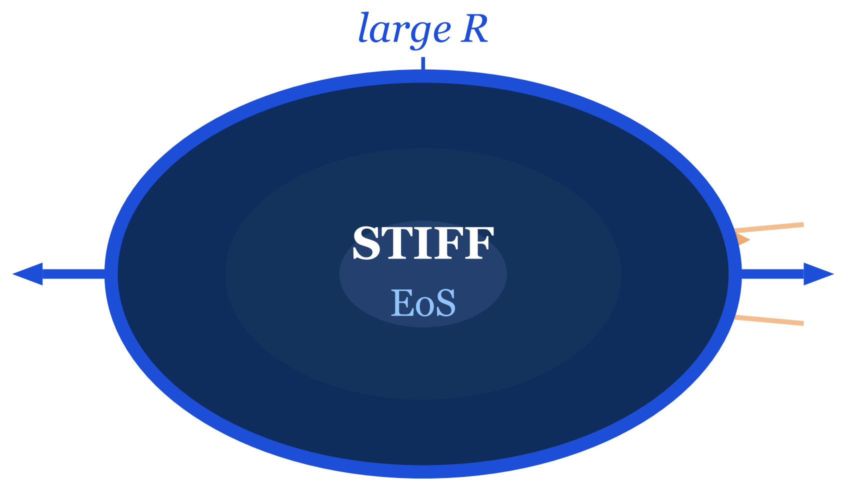
Tidal deformability

$$Q_{ij} = -\lambda_{\rm tid}\mathcal{E}_{ij}$$

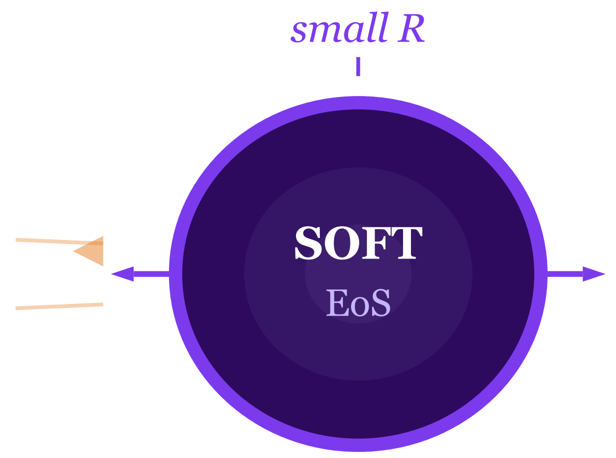


$$k_2 = \frac{8}{5}\beta^5(1-2\beta)^2[2 - y_R + 2\beta(y_R \cdots)]$$
$$\times \{2\beta(6 - 3y_R + 3\beta(5y_R - 8))$$
$$+ 4\beta^3[13 - 11y_R + \beta(3y_R - 2) + 2\beta^2(1 + y_R)]$$
$$+ 3(1-2\beta)^2[2 - y_R + 2\beta(y_R - 1)]\log(1-2\beta)\}^{-1}$$

$$\lambda_{\rm tid} = \frac{2}{3}k_2 R^5$$



Λ ~ 600–800
large quadrupole moment
big because R is large (R^5 dominates)



Λ ~ 100–400
small quadrupole moment
compact star, R^5 suppressed

T. Hinderer, ApJ. 677, 1216 (2008)
S. Postnikov, M. Prakash, and M. Lattimer, PRD 82, 024016 (2010).