Dark Matter Effects on the Properties of Hybrid and Twin Stars

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Astrophysics > High Energy Astrophysical Phenomena

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Influence of Dark Matter on Hybrid and Twin Stars

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We investigate the impact of dark matter (DM) on both hybrid and twin stars within a two-fluid framework, where DM and normal matter interact only through gravity. A self-interacting fermionic DM model is considered, while for nucleonic and quark matter we employ the relativistic mean-field model and the constant sound-speed parametrization, respectively. Our results show that DM significantly influences the formation of hybrid and twin stars, depending on the transition pressure and the discontinuity in energy density at a fixed sound speed. The presence of DM reduces the number of twin or hybrid stars compared to the case without DM, and this effect directly depends on the DM mass and fraction. We further find that the formation of DM-core or DM-halo configurations is mainly governed by DM parameters, whereas the realization of twin or hybrid star scenarios is primarily controlled by quark parameters. Using the $2M_\odot$ constraint, we demonstrate that the parameter space for twin stars can be further restricted in both DM-core and DM-halo scenarios.

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With improved version in this talk

Sarah Poster (yesterday)

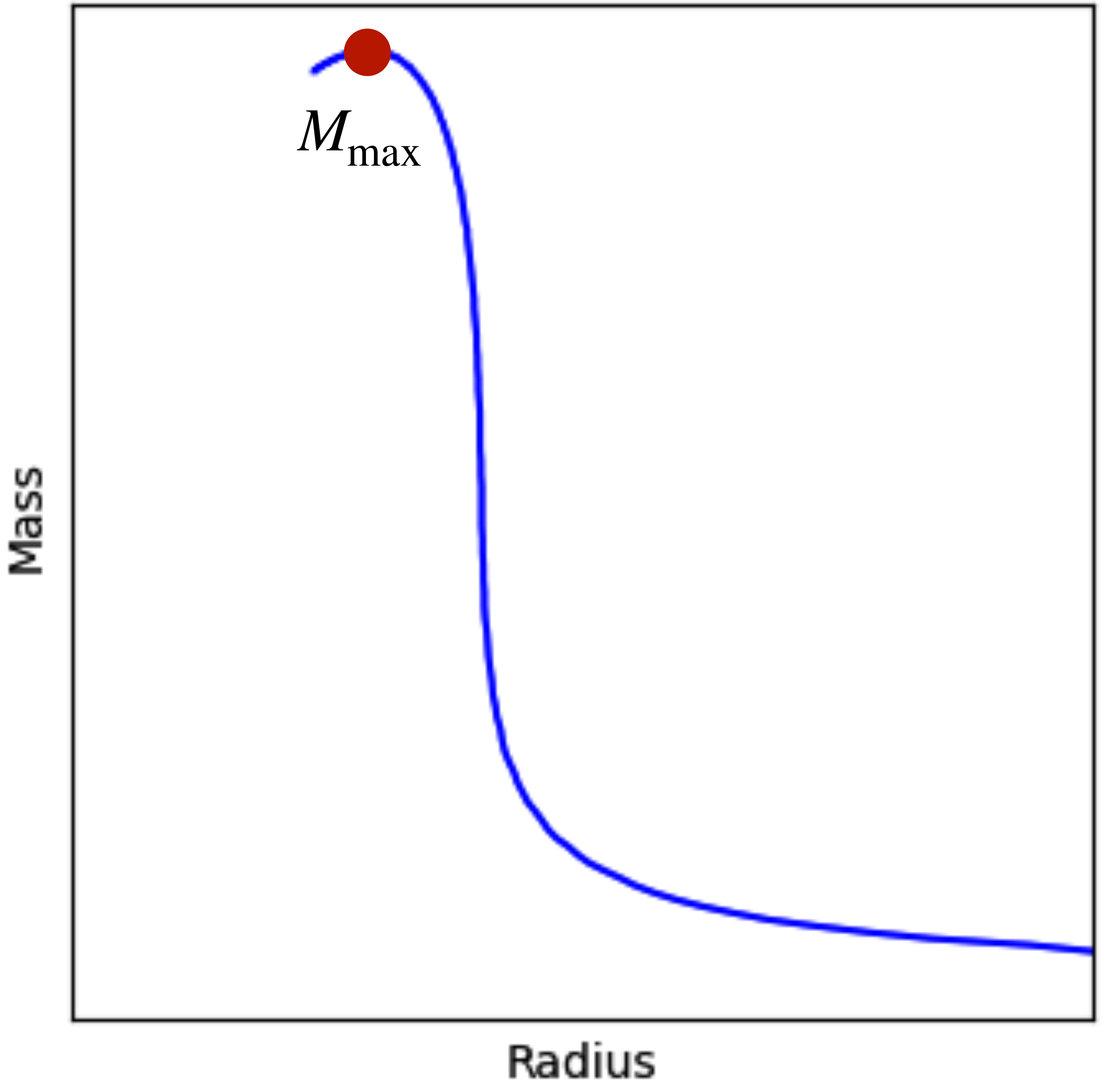
Motivation

- A strong first-order deconfinement transition in neutron stars cores is allowed by current data, but not yet confirmed observationally → What would be its cleanest signature?"
- Hybrid stars/Twin stars are the cleanest signature of a strong first-order transition.
- Neutron stars are natural dark matter (DM) detectors → immense gravity captures and accumulates DM over Gyr timescales.
- DM-admixed hybrid/twin stars probe both sectors simultaneously: the QCD transition AND the dark sector"
- How can we disentangle DM admixture from the nucleon-quark phase transition?"

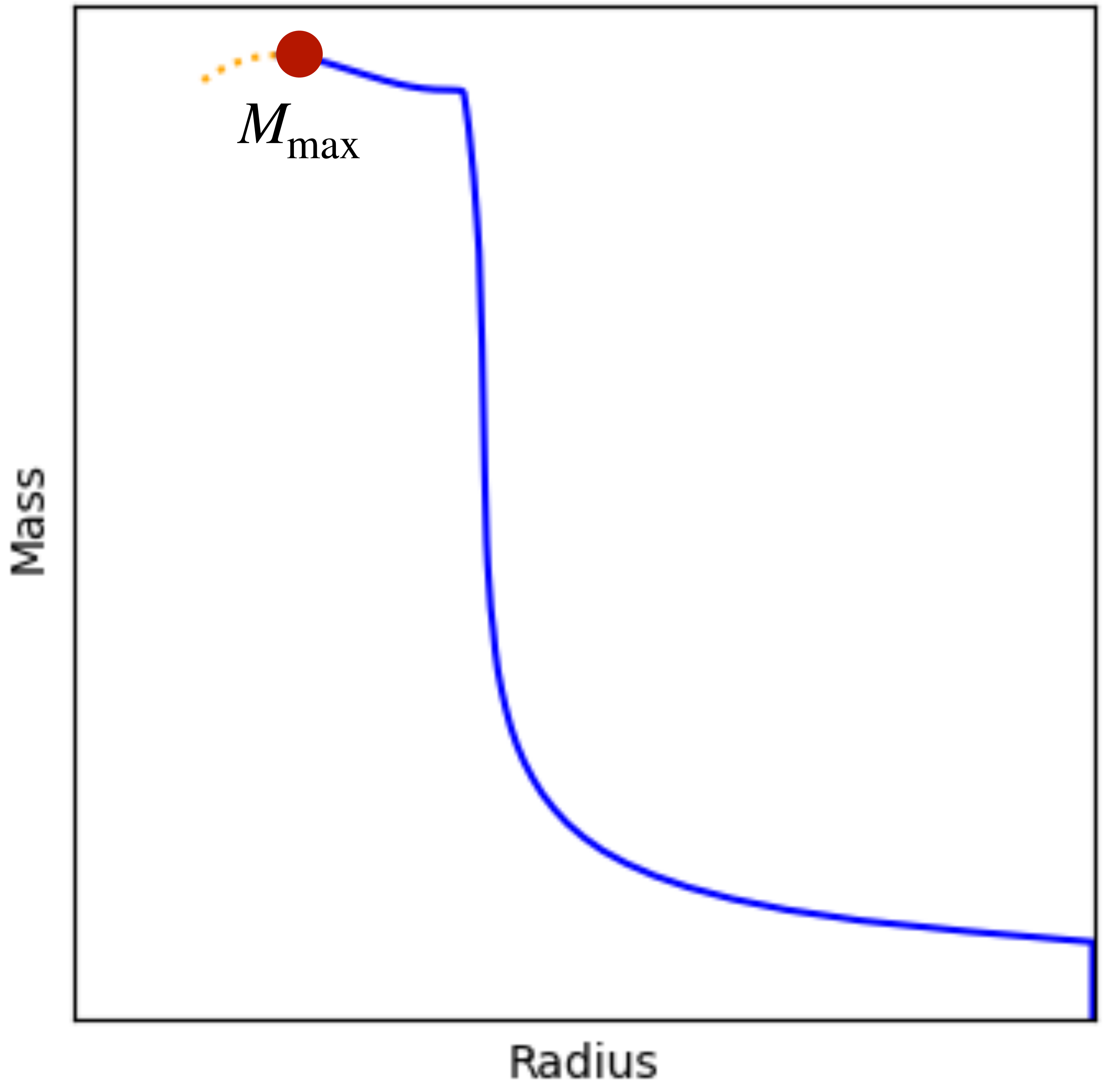
Goldman and Nussinov PRD 40, 3221 (1989), Bertone and Fairbairn PRD 77, 043515 (2008)

Difference between three species

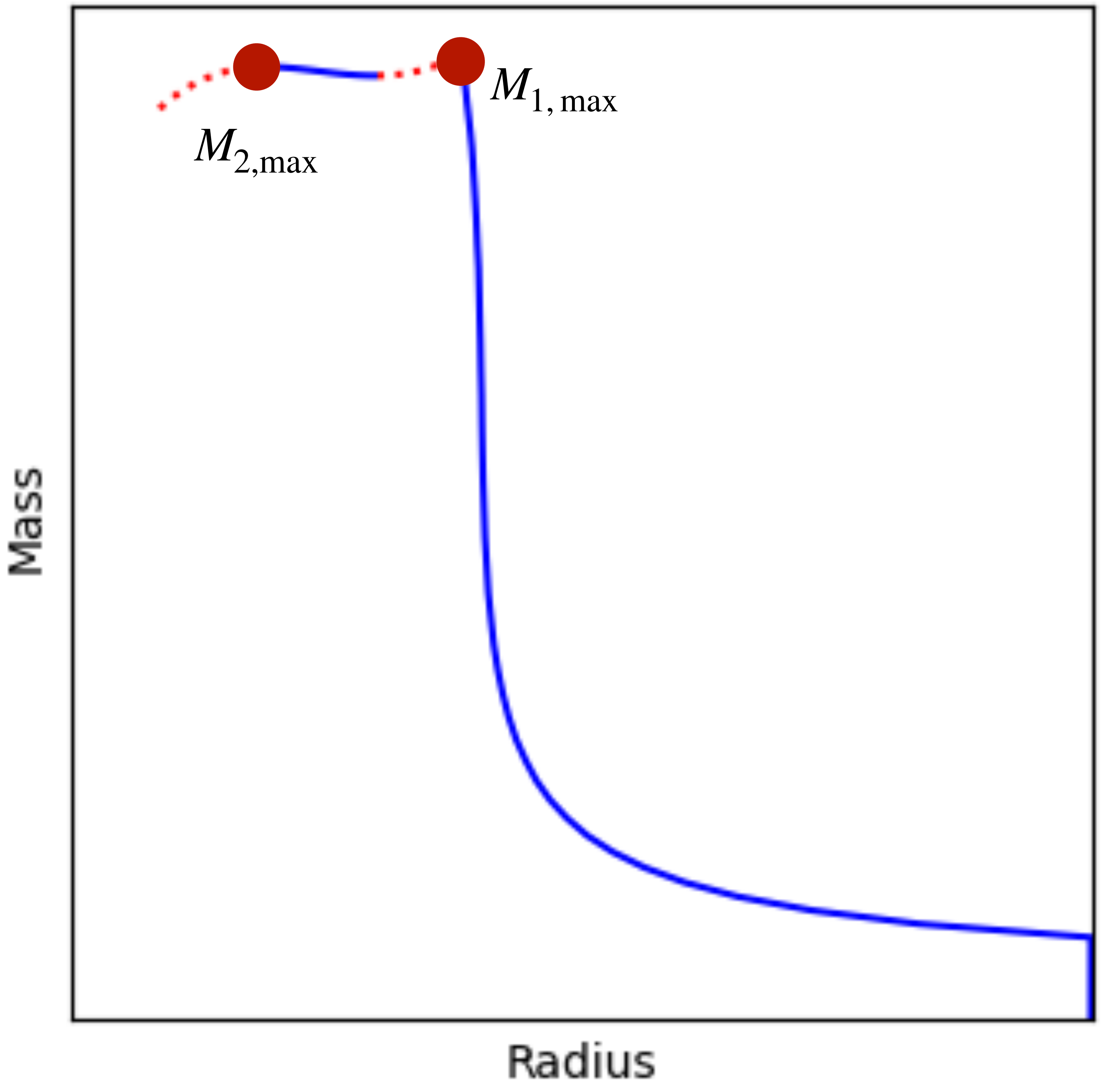
Neutron Stars (NSs)



Hybrid Stars (HSs)



Twin Stars (TSs)



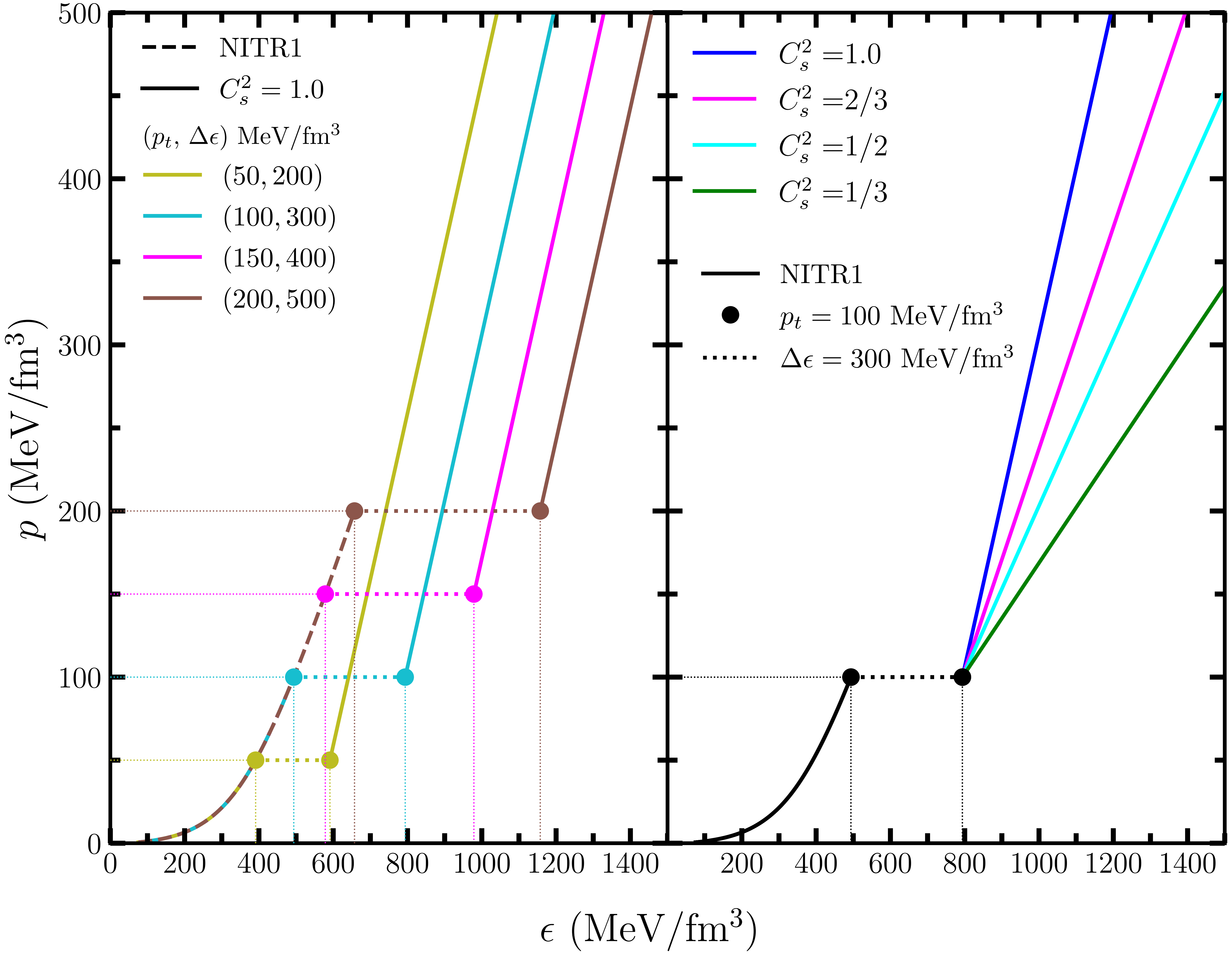
Constant Sound Speed (CSS) Model

$$\epsilon(p) = \begin{cases} \epsilon_{\rm NITR1}(p) & \text{for } p < p_t\,, \\ \epsilon_{\rm NITR1}(p_t) + \Delta\epsilon + ((p-p_t)/C_s^2) & \text{for } p > p_t\,, \end{cases}$$

$p_t \rightarrow$ **transition pressure,** $\Delta\epsilon \rightarrow$ **energy density discontinuity**

- CSS model is a simple parametrisation to describe quark matter inside the NSs.
- It assumes the speed of sound is constant in the high-density phase, $C_s^2 = dp/d\varepsilon =$ const.
- The model is useful to study phase transitions inside the NSs.

Alford et al. PRD 88, 083013 (2013)

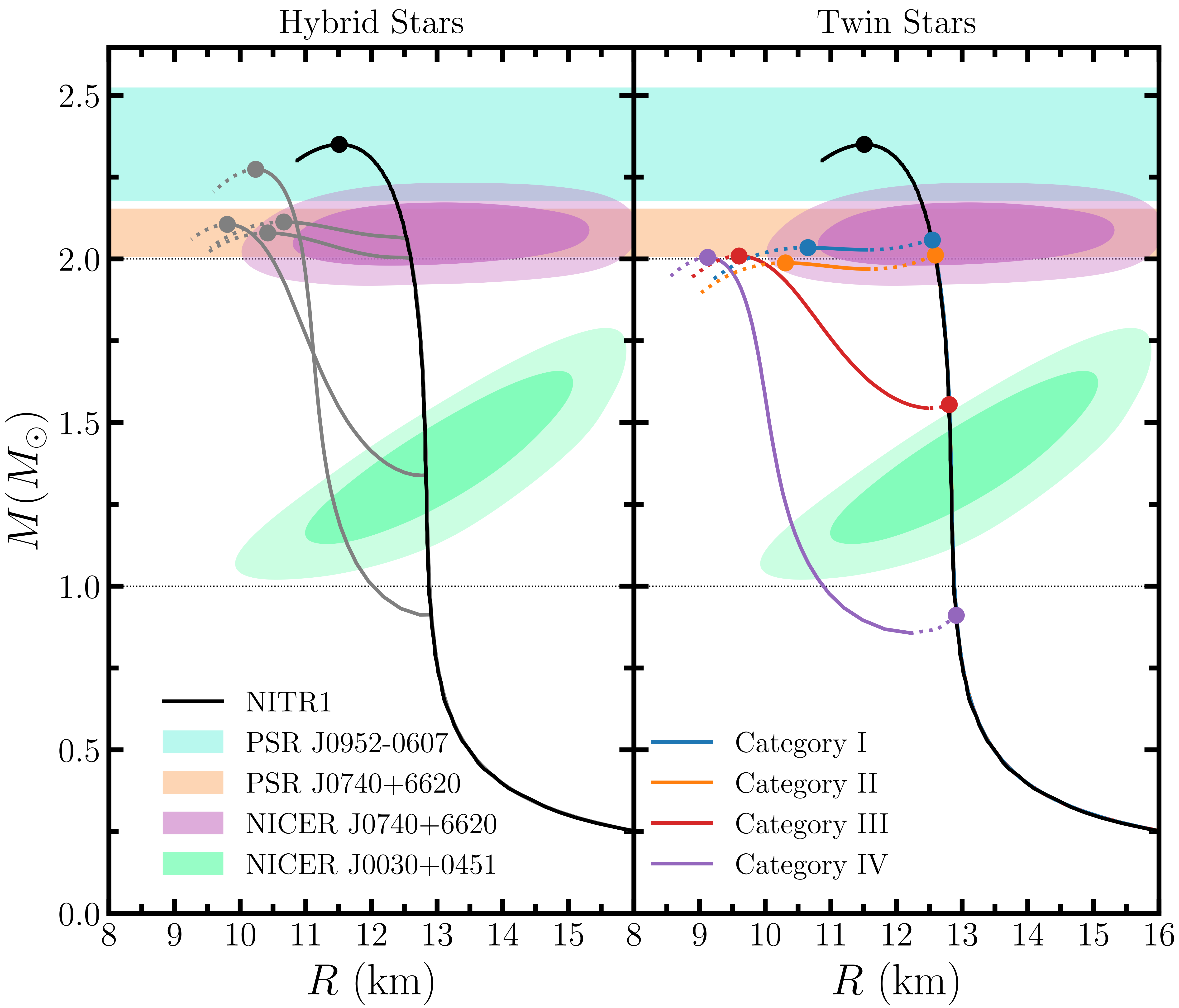


Classification of Twin Stars

The classification is based on the maximum mass values $M_{1,\,\max}$ and $M_{2,\,\max}$ as follow (Based on different pulsar constraints)

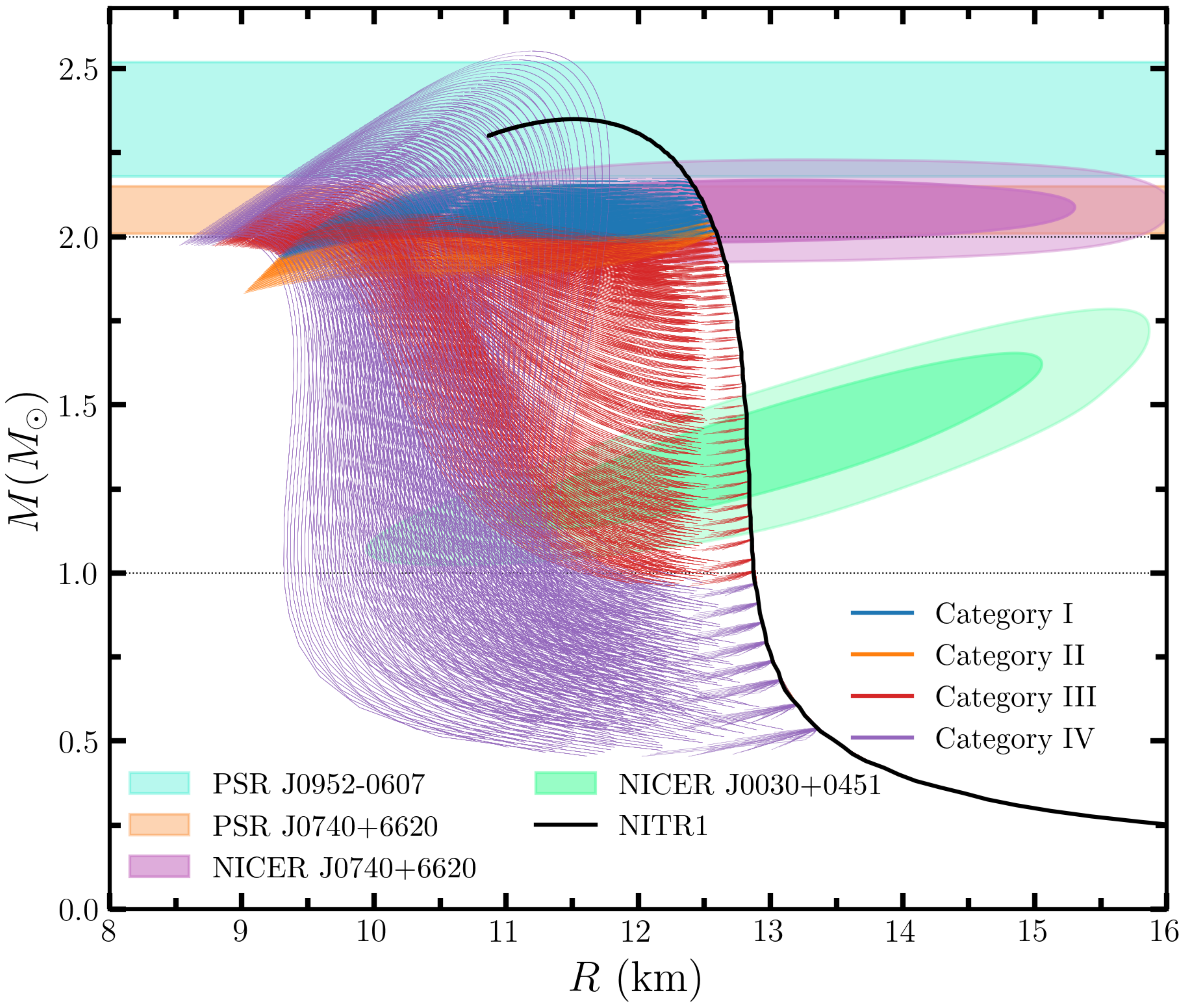
- **Category I:** $M_{1,\,\max} > 2.0$ and $M_{2,\,\max} > 2.0$
- **Category II:** $M_{1,\,\max} \geq 2.0$ and $M_{2,\,\max} < 2.0$
- **Category III:** $1.0 \leq M_{1,\,\max} \leq 2.0$ and $M_{2,\,\max} \geq 2.0$
- **Category IV:** $M_{1,\,\max} \leq 1.0$ and $M_{2,\,\max} \geq 2.0$

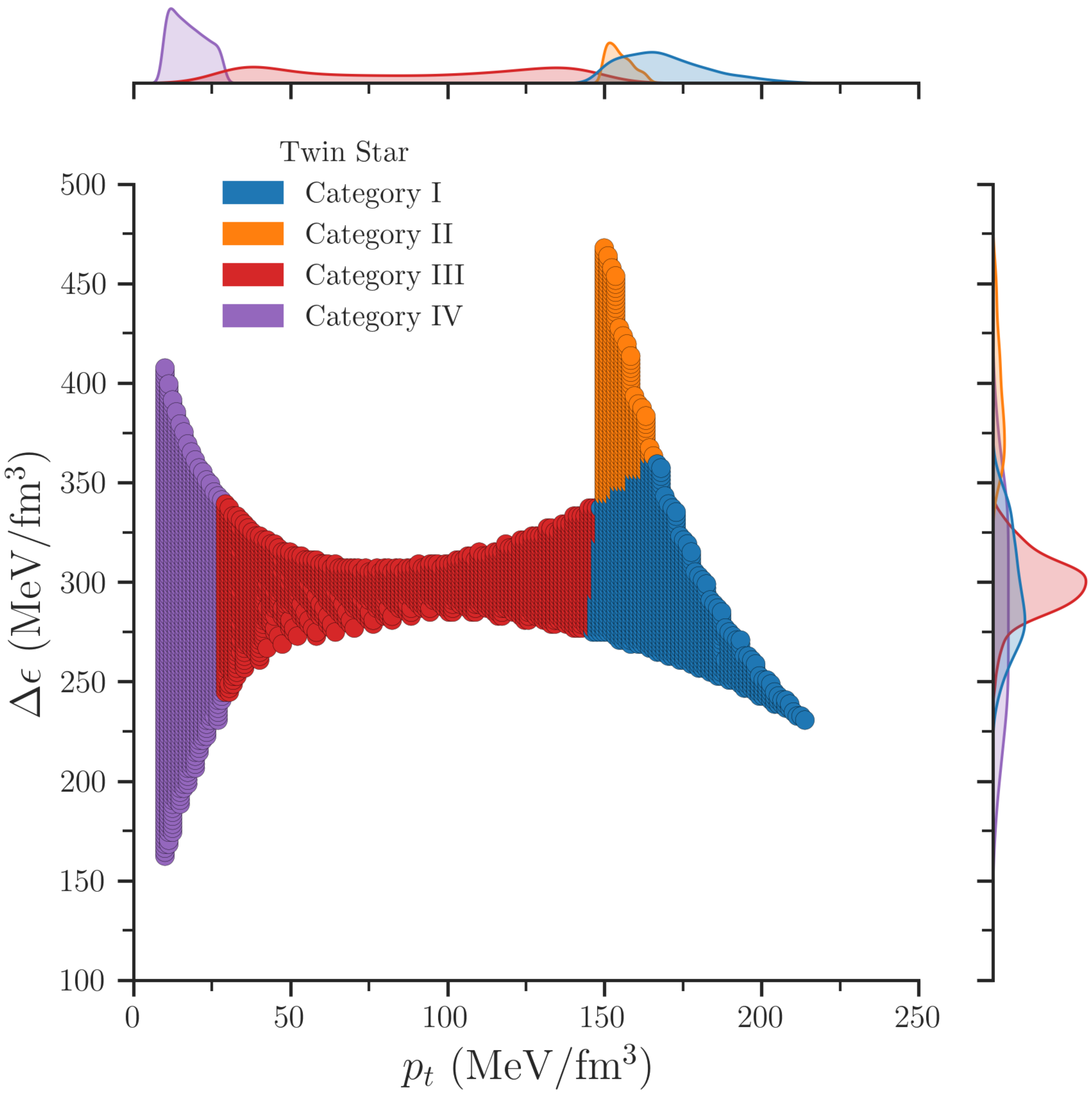
Christian et al. EPJA 54, 28 (2018)



Twin Stars Scenarios

$\Delta\epsilon = [100, 500, N]$ MeV/fm^3, $C_s^2 = 1$
$p_t = [10, 300, N]$ MeV/fm^3 with N = 200





Fermionic Dark Matter Model

Self-interacting Fermionic Lagrangian of DM

$$\mathcal{L}_{\rm DM} = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu},$$

Energy density and pressure are

$$\varepsilon_\chi = \frac{m_\chi^4}{8\pi^2}\left[x\sqrt{1+x^2}(2x^2+1) - \mathrm{arsinh}(x)\right] + \delta,$$

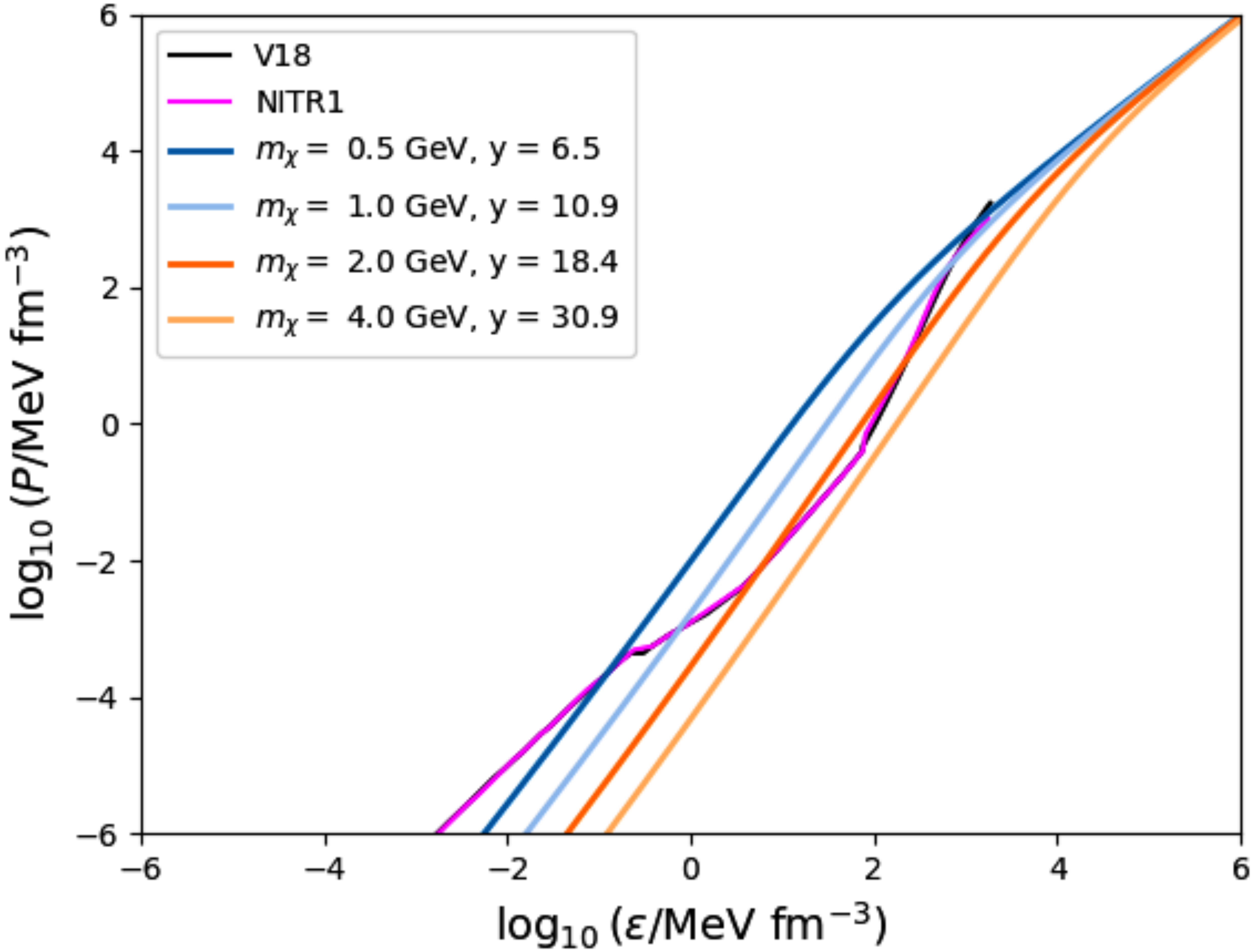
$$p_\chi = \frac{m_\chi^4}{8\pi^2}\left[x\sqrt{1+x^2}(2x^2/3-1) + \mathrm{arsinh}(x)\right] + \delta,$$

$$x = \frac{k_\chi}{m_\chi} = \frac{(3\pi^2 n_\chi)^{1/3}}{m_\chi} \qquad \delta = \left(\frac{y n_\chi}{m_\chi}\right)^2 y \equiv g_\chi m_\chi/(\sqrt{2}m_\phi)$$

Born approximation gives

$$\frac{\sigma_\chi}{m_\chi} = \frac{y^4}{\pi m_\chi^3}, \qquad y \approx 10.94 m_1^{3/4}$$

$$\sigma_\chi/m_\chi = 1\ \mathrm{cm}^2/\mathrm{g} = 4560/\mathrm{GeV}^3,$$



Liu et al. PRD 110, 023024 (2024)

Hydrostatic Equilibrium

Two-fluid TOV equations (for two noninteracting fluids) in the same metric are

$$\frac{d\nu}{dr} = \frac{m + 4\pi r^3 p}{r(r-2m)},$$

$$\frac{dp_i}{dr} = -(p_i + \varepsilon_i)\frac{d\nu}{dr},$$

$$\frac{dm_i}{dr} = 4\pi r^2 \varepsilon_i,\ i = N, \chi$$

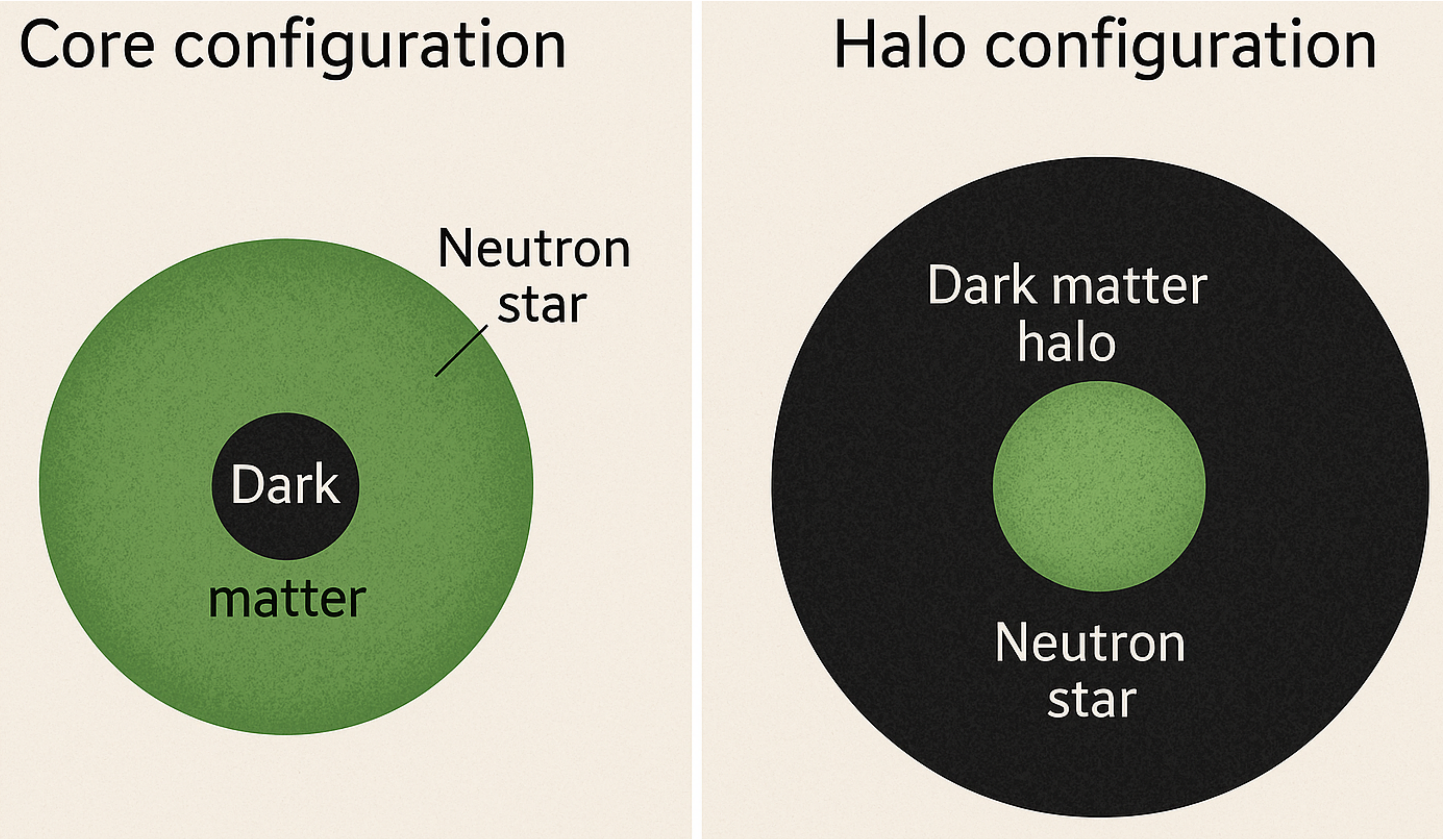
$M = M_N(R_N) + M_\chi(R_\chi)$

$R = \max(R_N, R_\chi)$

DM-core ($R_\chi < R_N$)

DM-halo ($R_\chi > R_N$)

DM fraction, $f_\chi = \dfrac{M_\chi}{M}$



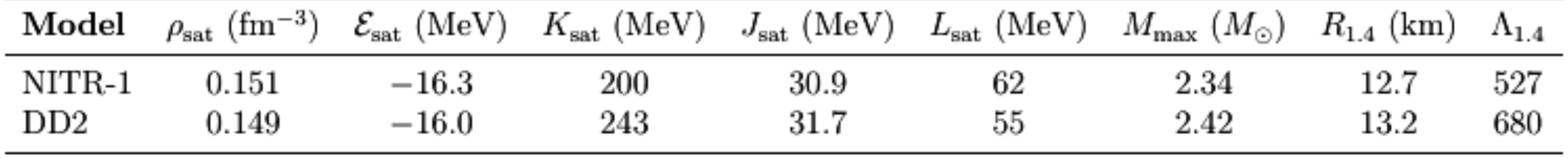
Liu et al. PRD 110, 023024 (2024)

Parameter Space for DHSs/DTSs

- Two Nucleonic Models NITR-1 and DD2
- $p_t = [10,300,100]$ MeV/fm³ (covers sub to supra-saturation transition ranges)
- $\Delta\epsilon = [100,500,100]$ MeV/fm³ (from weak to strong first-order transition)
- $C_s^2 = [1.0,0.8,0.6]$ (up to causal limit 1.0)
- $m_\chi = [0.5,1.0]$ GeV (for core and halo scenarios)
- $f_\chi = [0.1,0.2,0.3]$ (higher fractions are poorly constrained)

Total GRID size = 180000

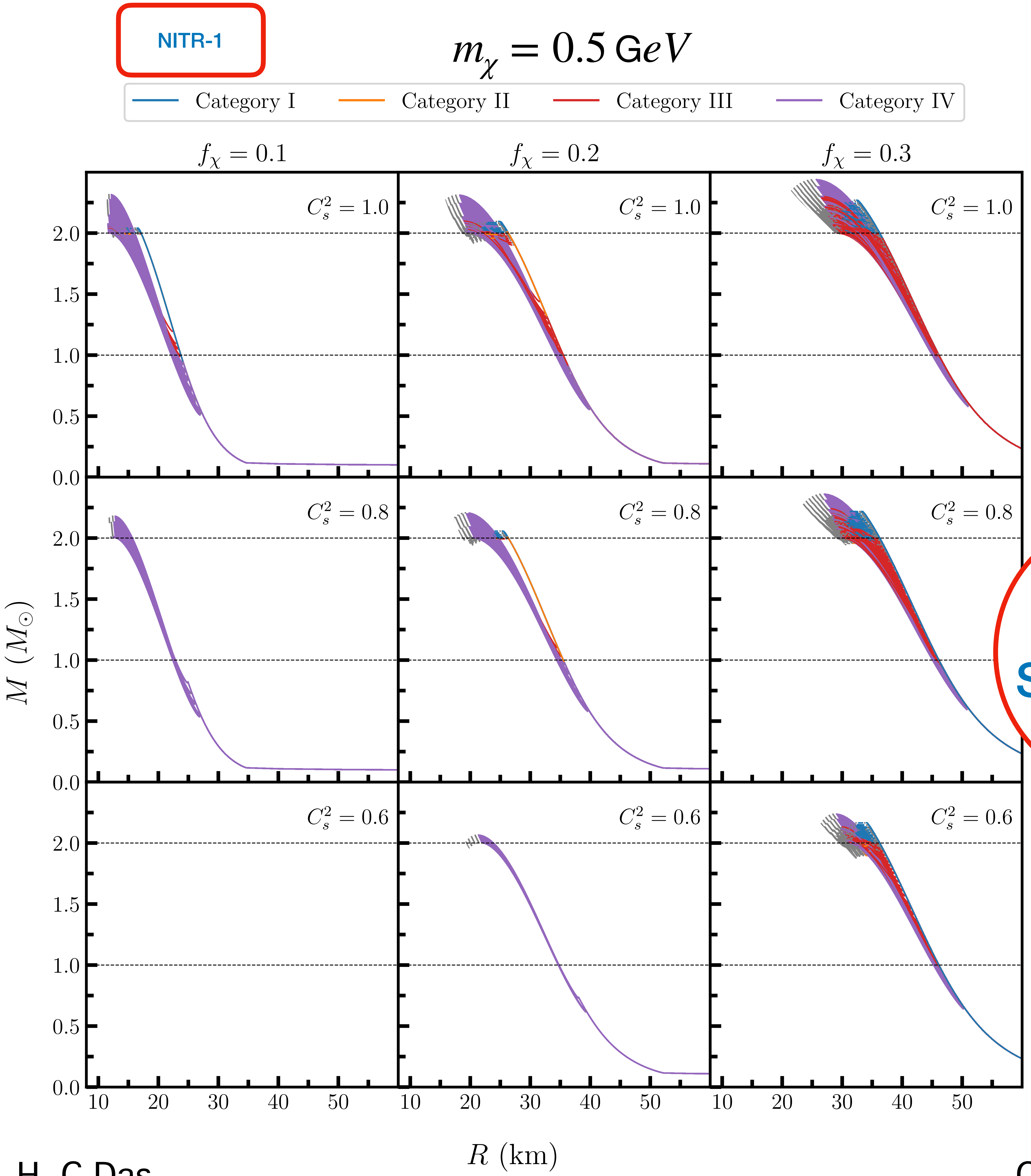
Properties of NMPs and NSs



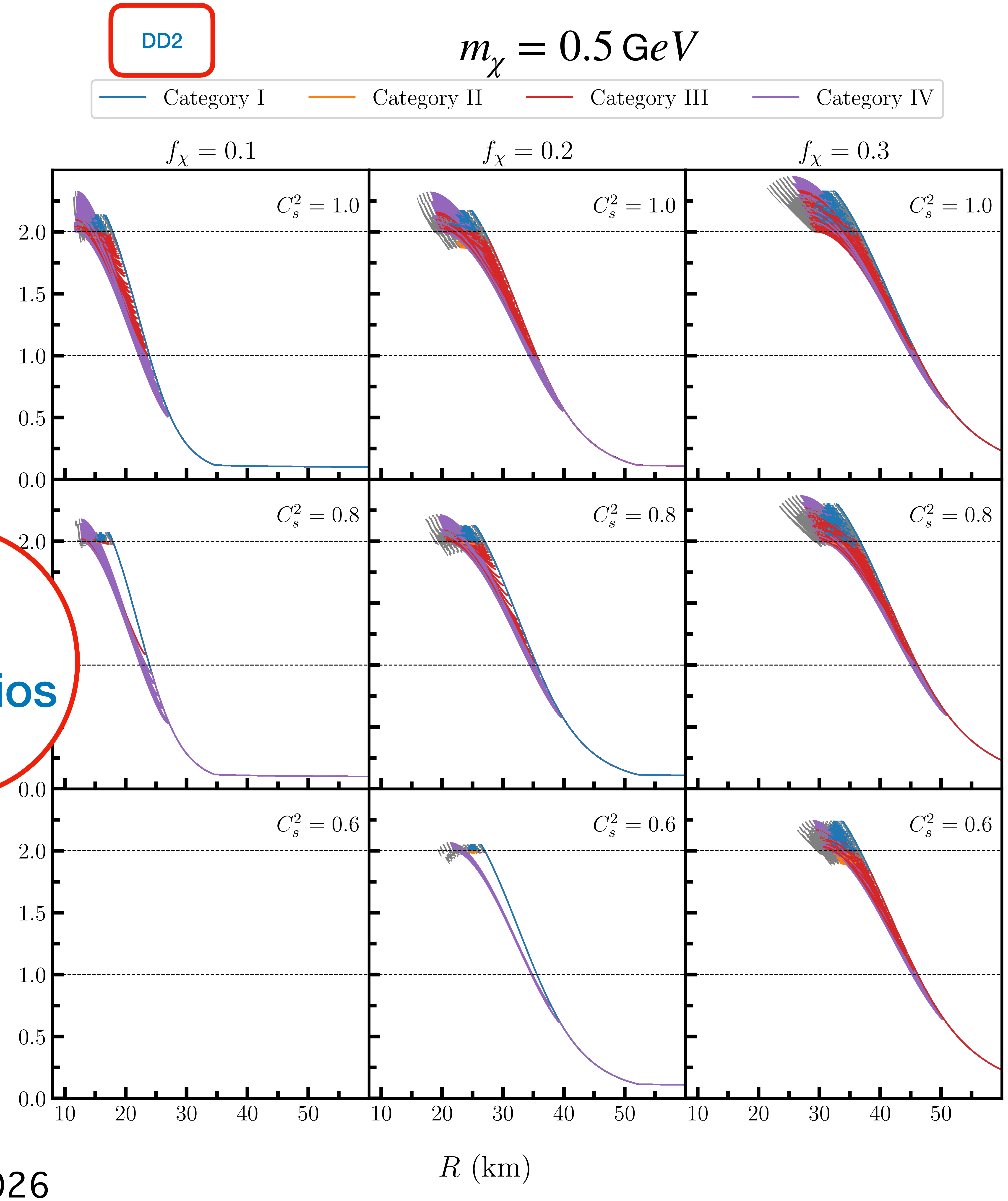
Model	$\rho_{\rm sat}$ (fm^{-3})	$\mathcal{E}_{\rm sat}$ (MeV)	$K_{\rm sat}$ (MeV)	$J_{\rm sat}$ (MeV)	$L_{\rm sat}$ (MeV)	$M_{\rm max}$ ($M_\odot$)	$R_{1.4}$ (km)	$\Lambda_{1.4}$
NITR-1	0.151	-16.3	200	30.9	62	2.34	12.7	527
DD2	0.149	-16.0	243	31.7	55	2.42	13.2	680

Dark Matter Effects on TSs

NITR-1



DD2



Halo Scenarios

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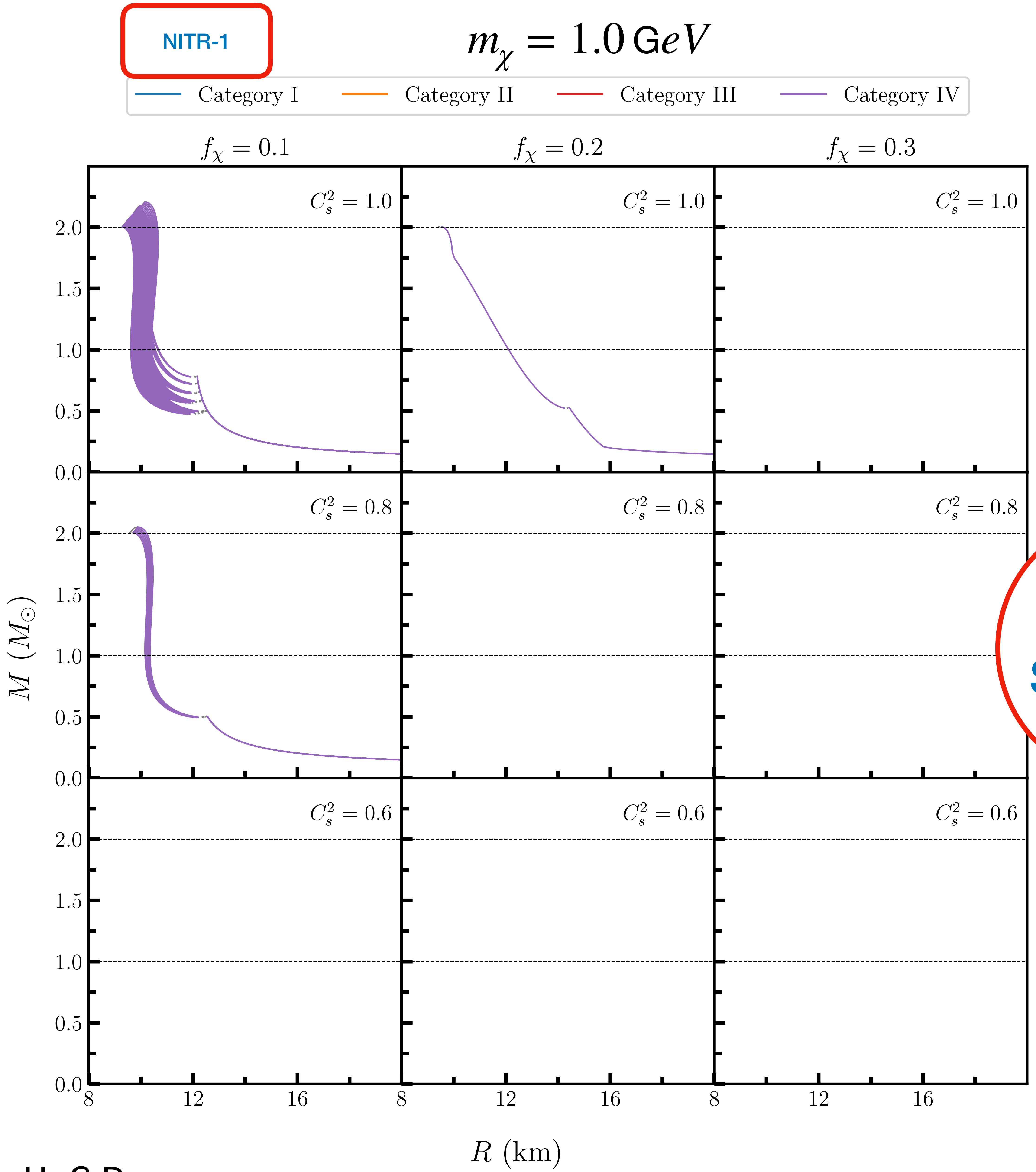
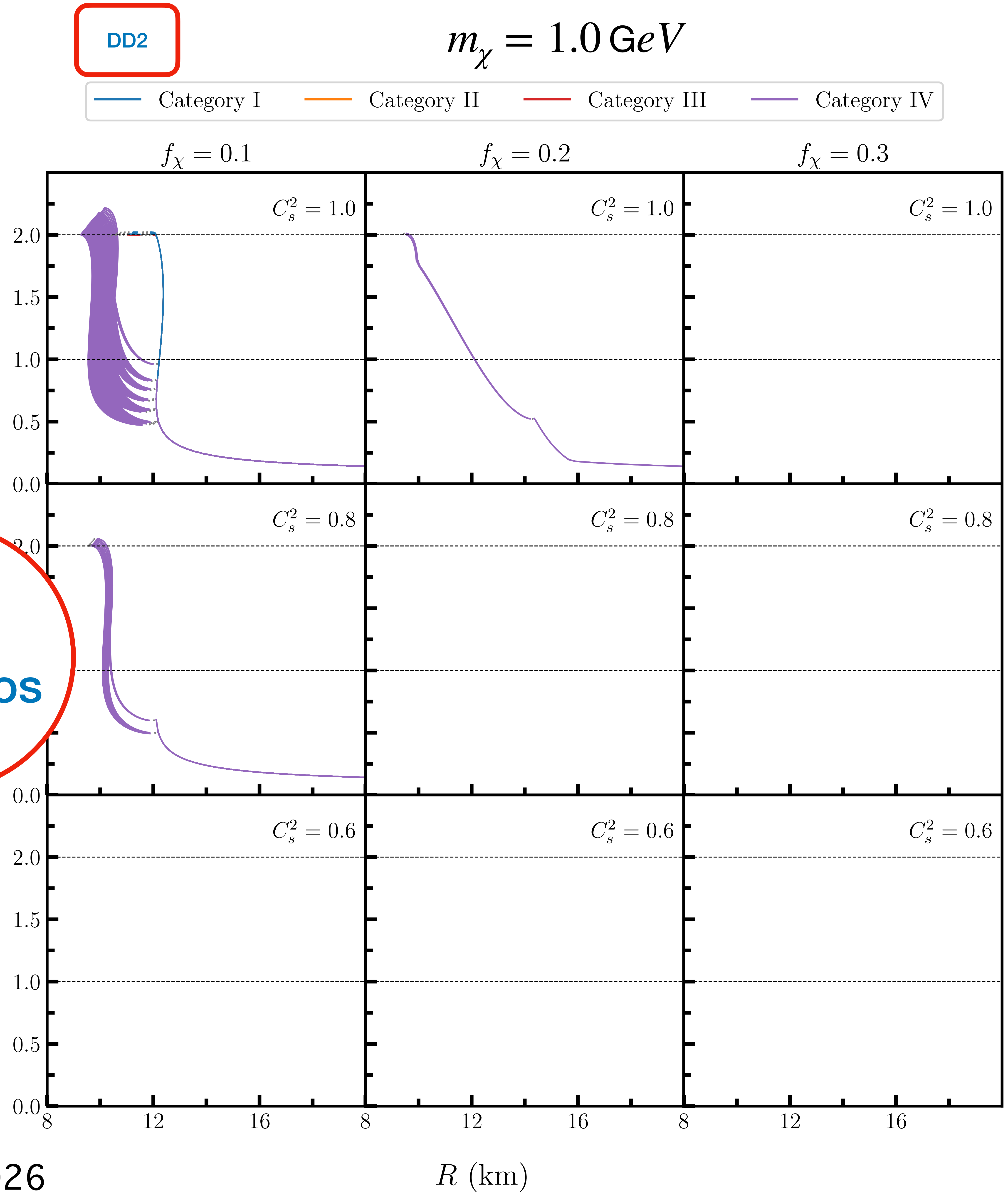
CSQCD 2026

Dark Matter Effects on TSs

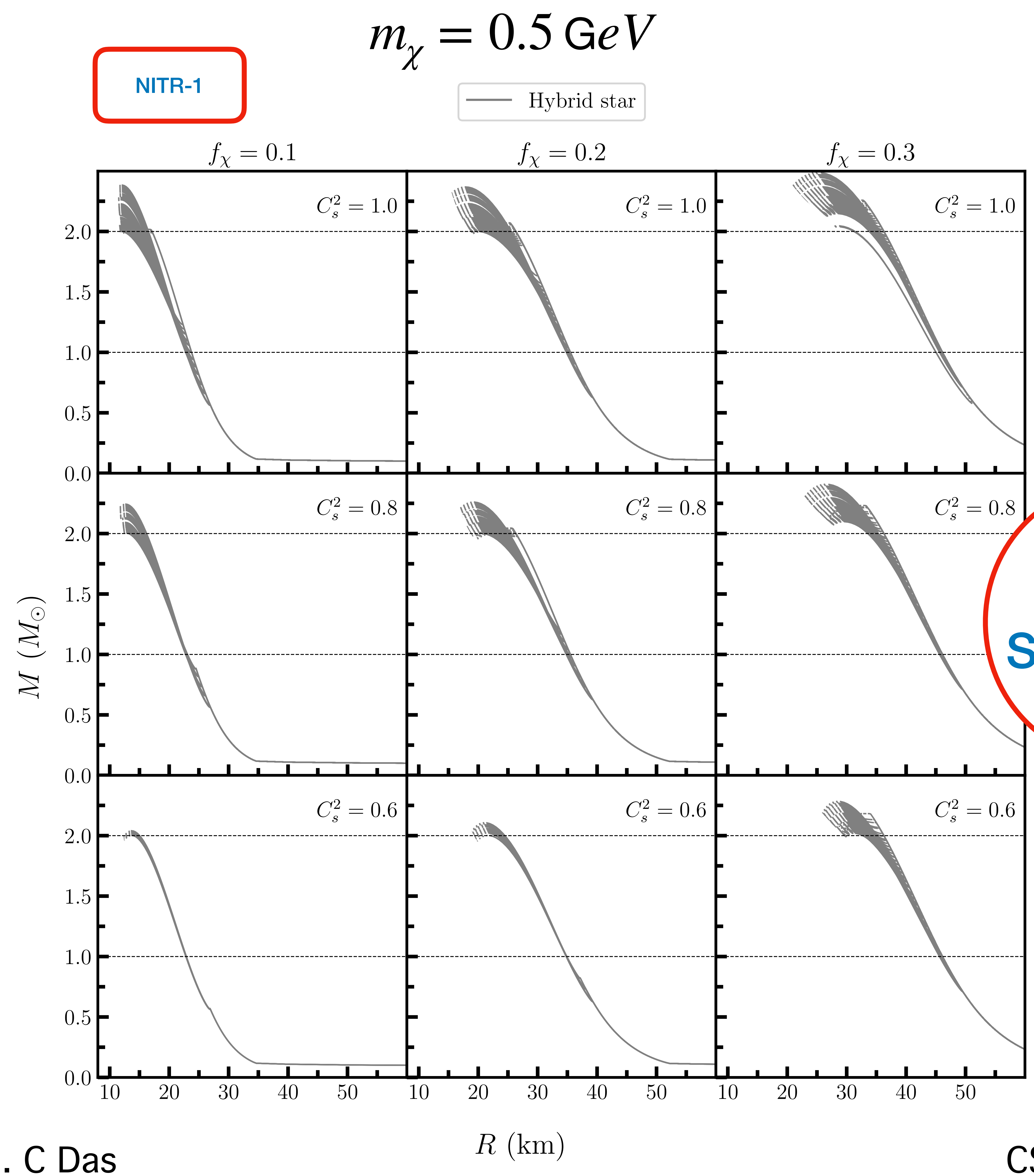


Core Scenarios



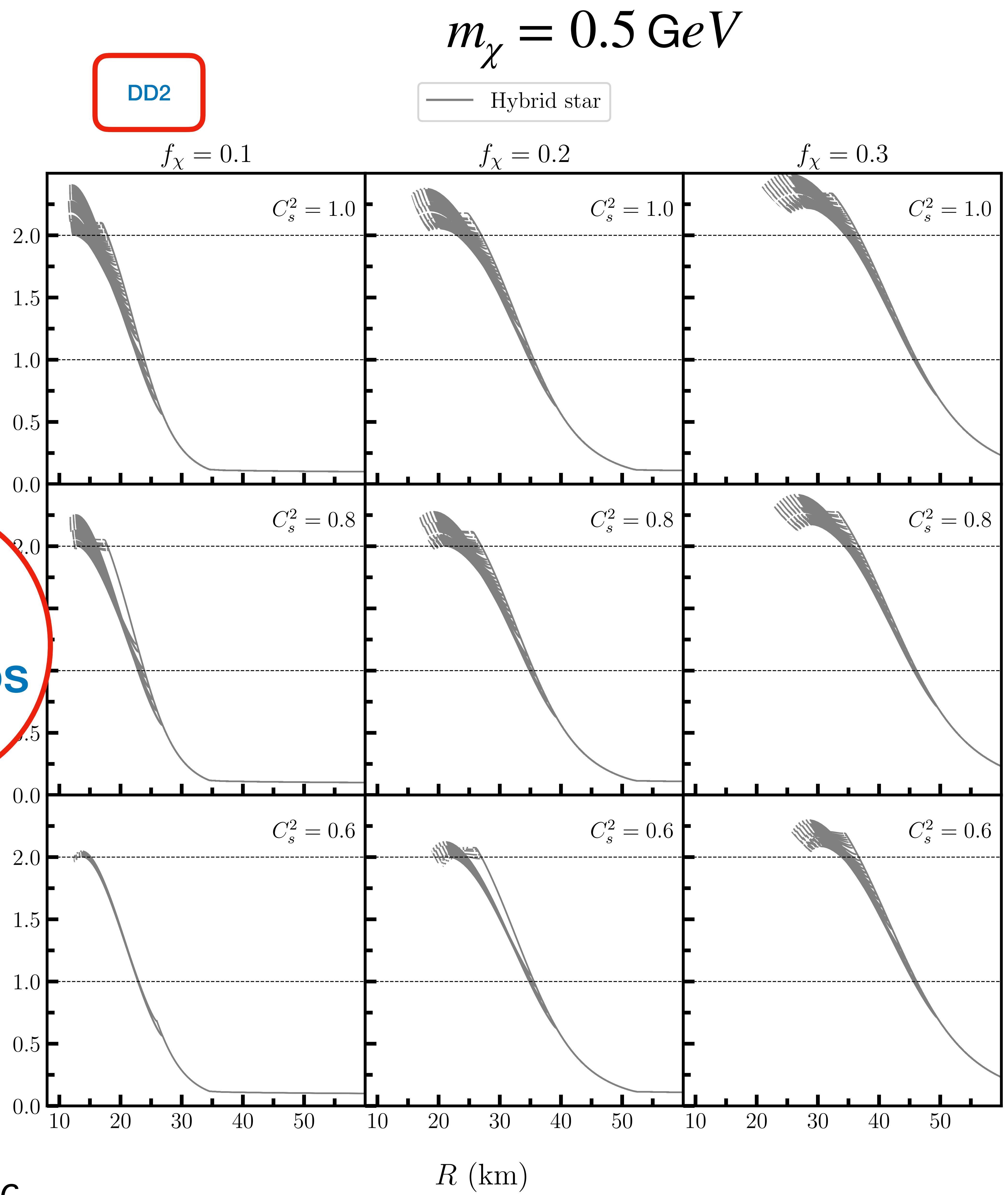
Dark Matter Effects on HSs

NITR-1

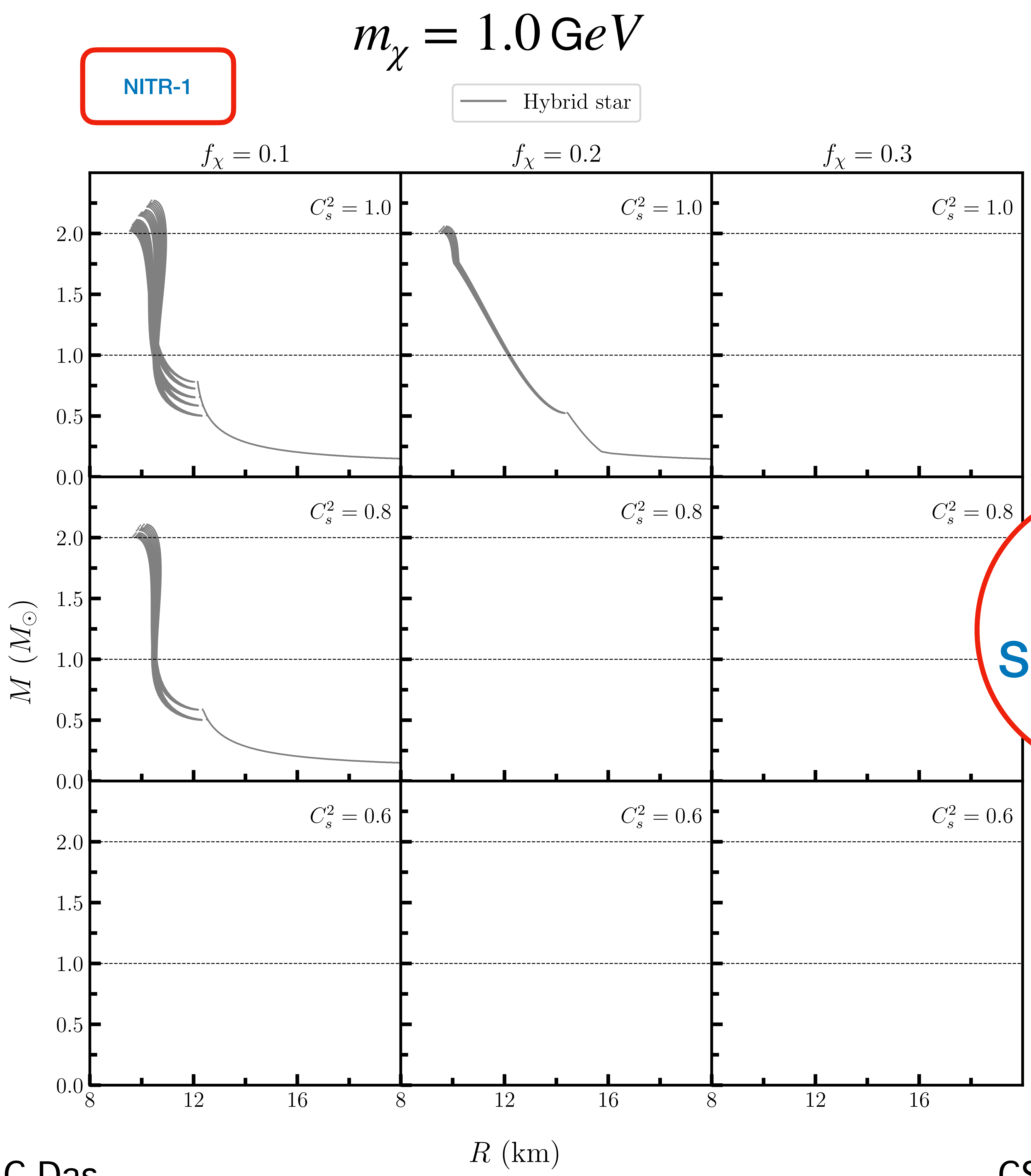


Halo Scenarios

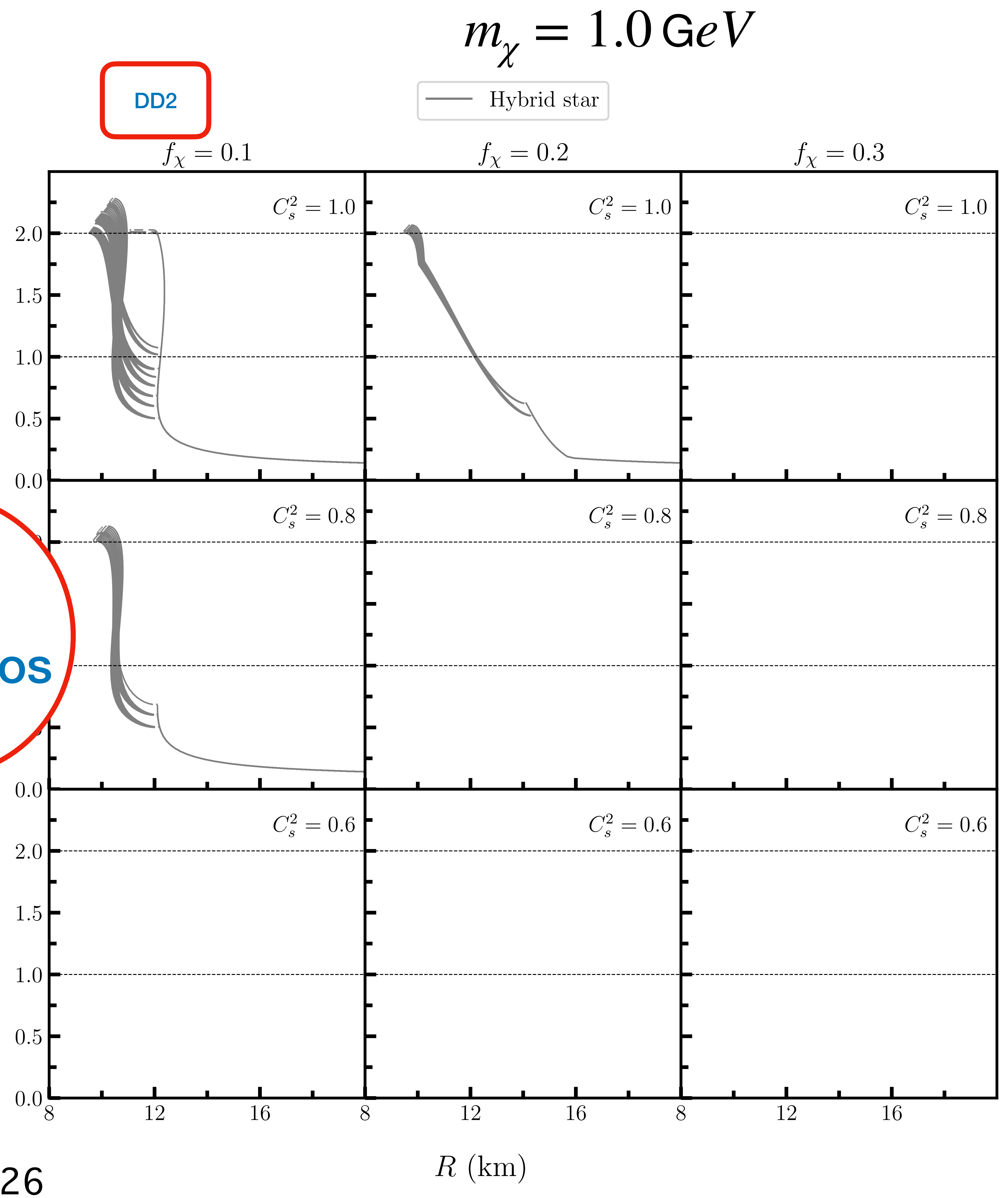
DD2



Dark Matter Effects on HSs



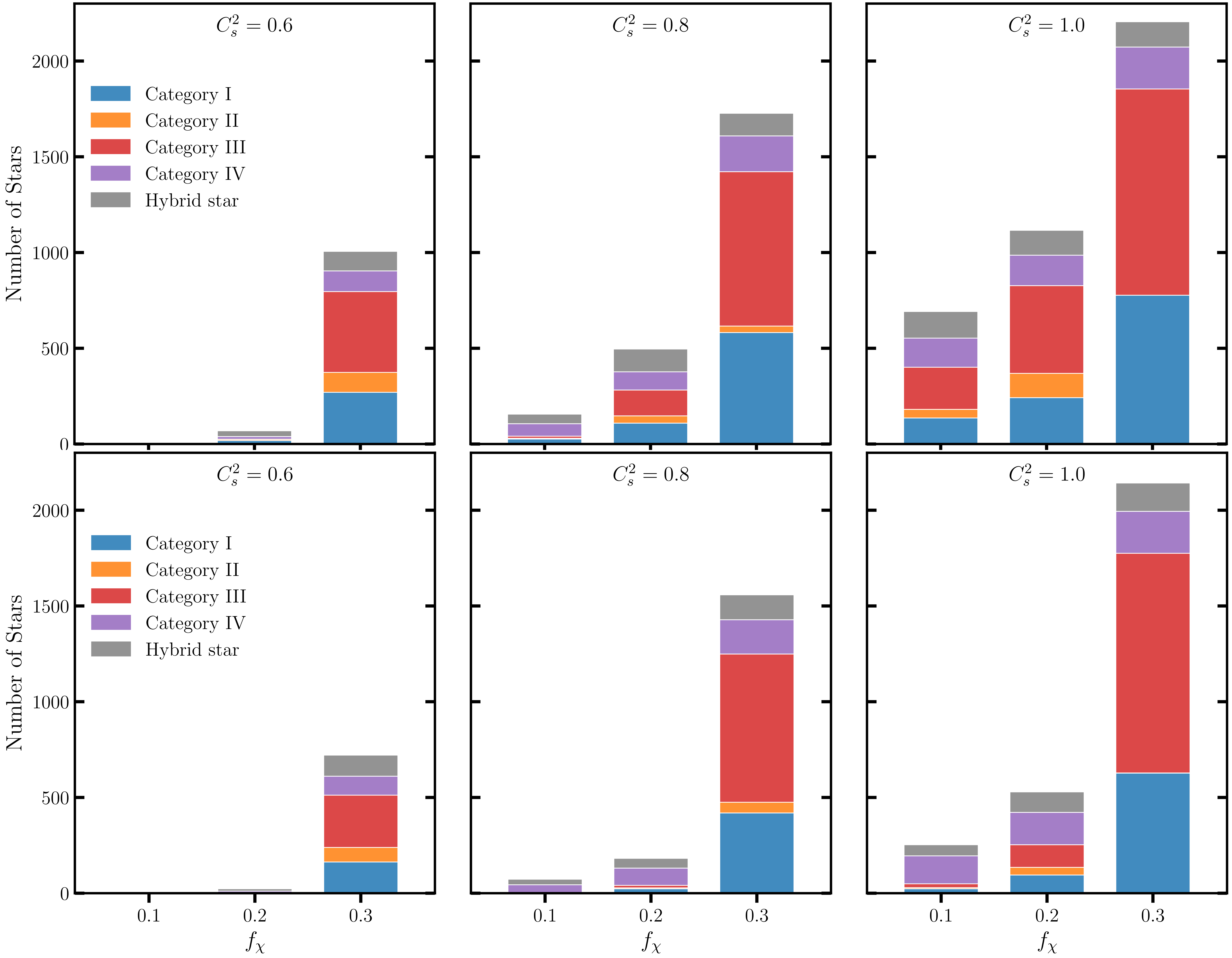
Core Scenarios



Number of Species

DD2
$m_\chi = 0.5$ **GeV**

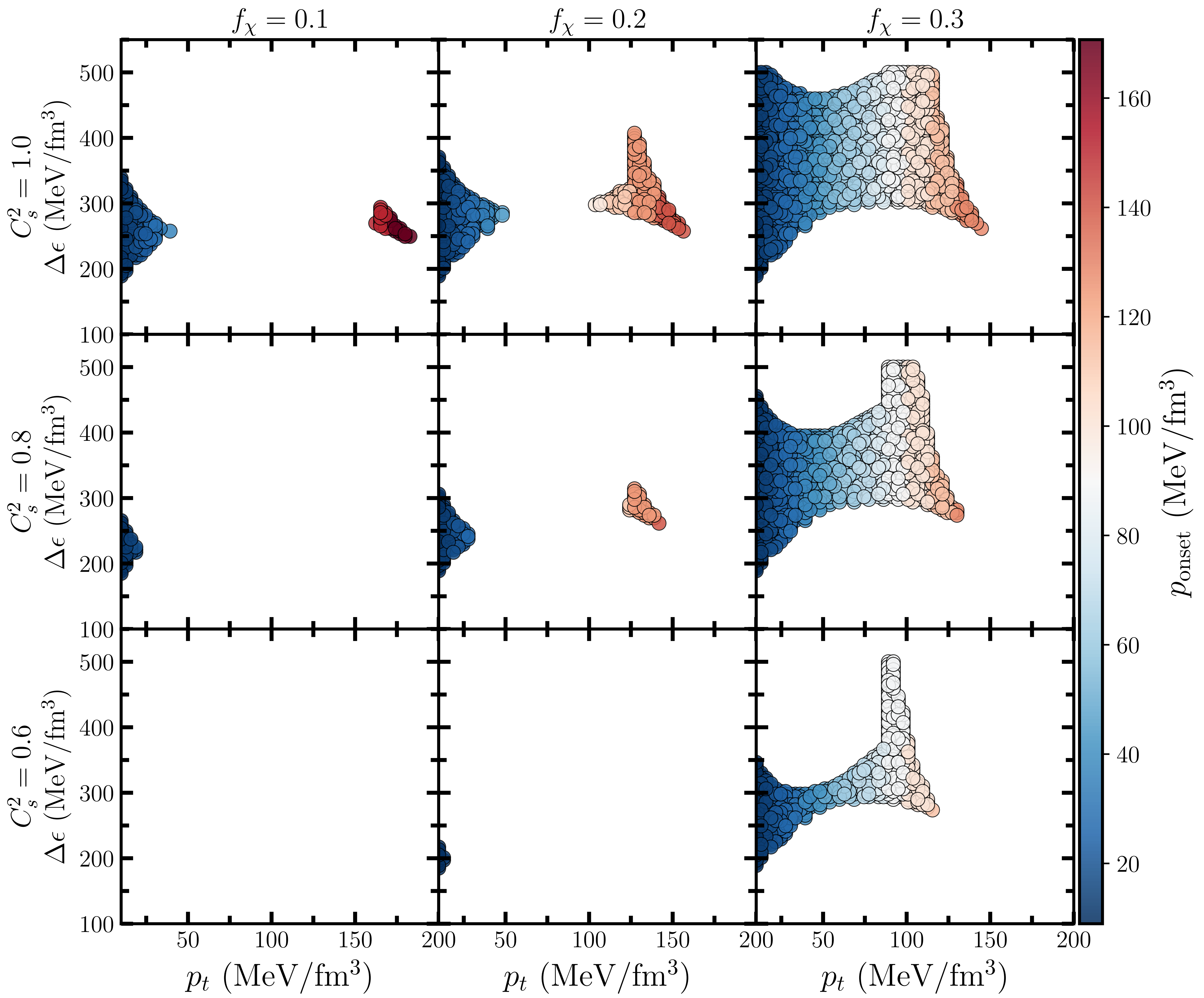
NITR1
$m_\chi = 0.5$ **GeV**



Dark Matter Effects on $p_{\rm onset}$

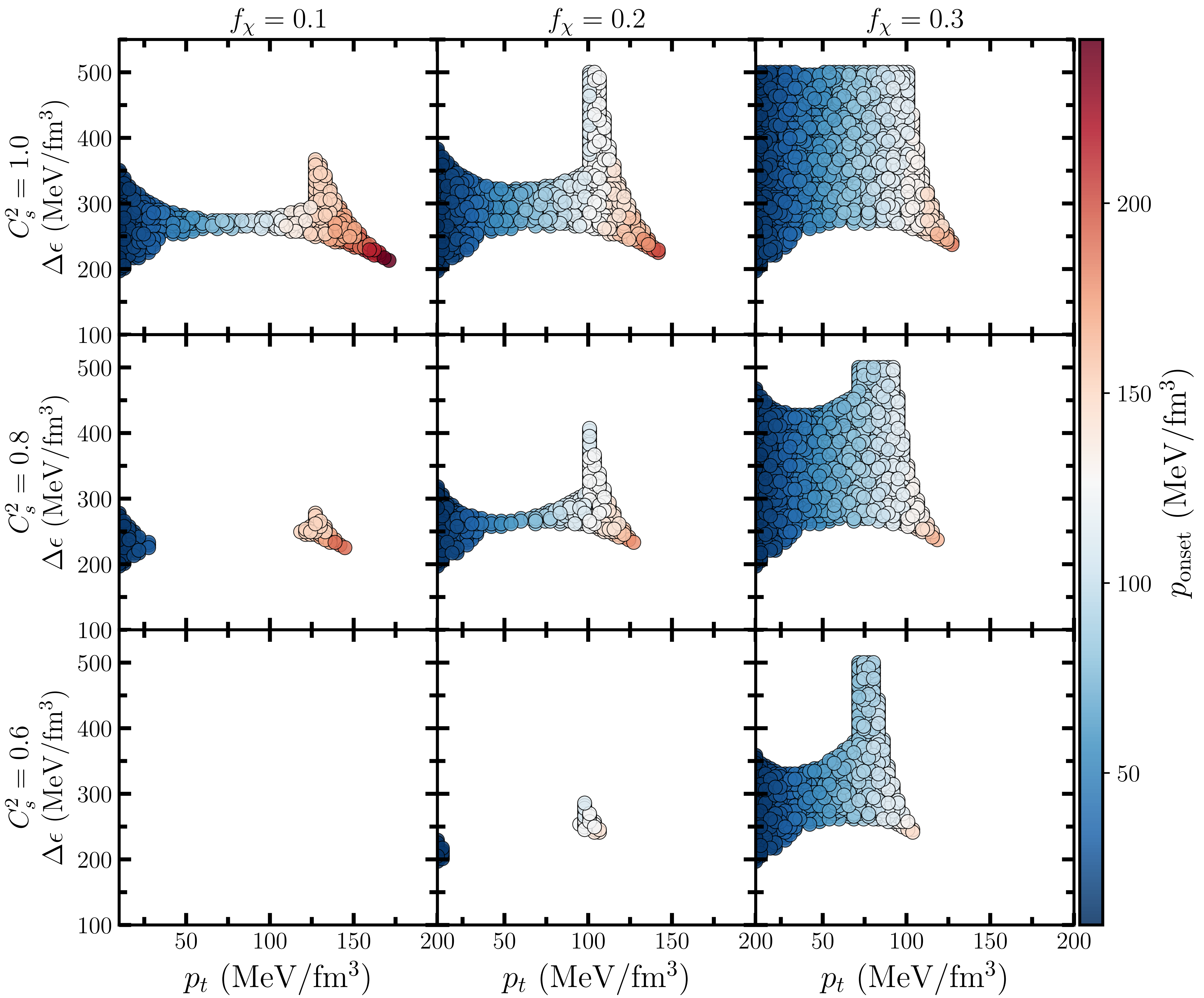
NITR-1

$m_\chi = 0.5\,\mathrm{GeV}$



DD2

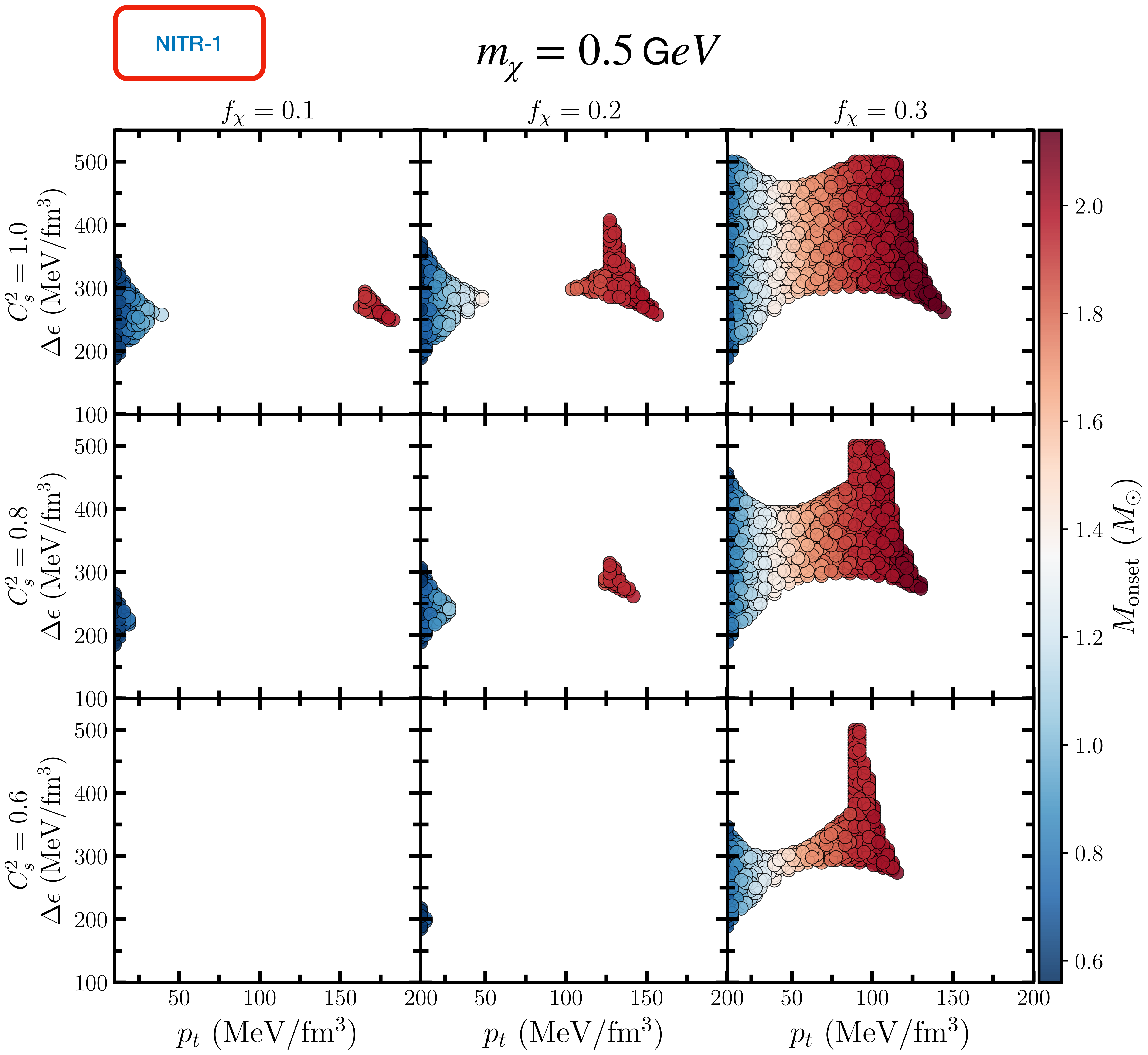
$m_\chi = 0.5\,\mathrm{GeV}$

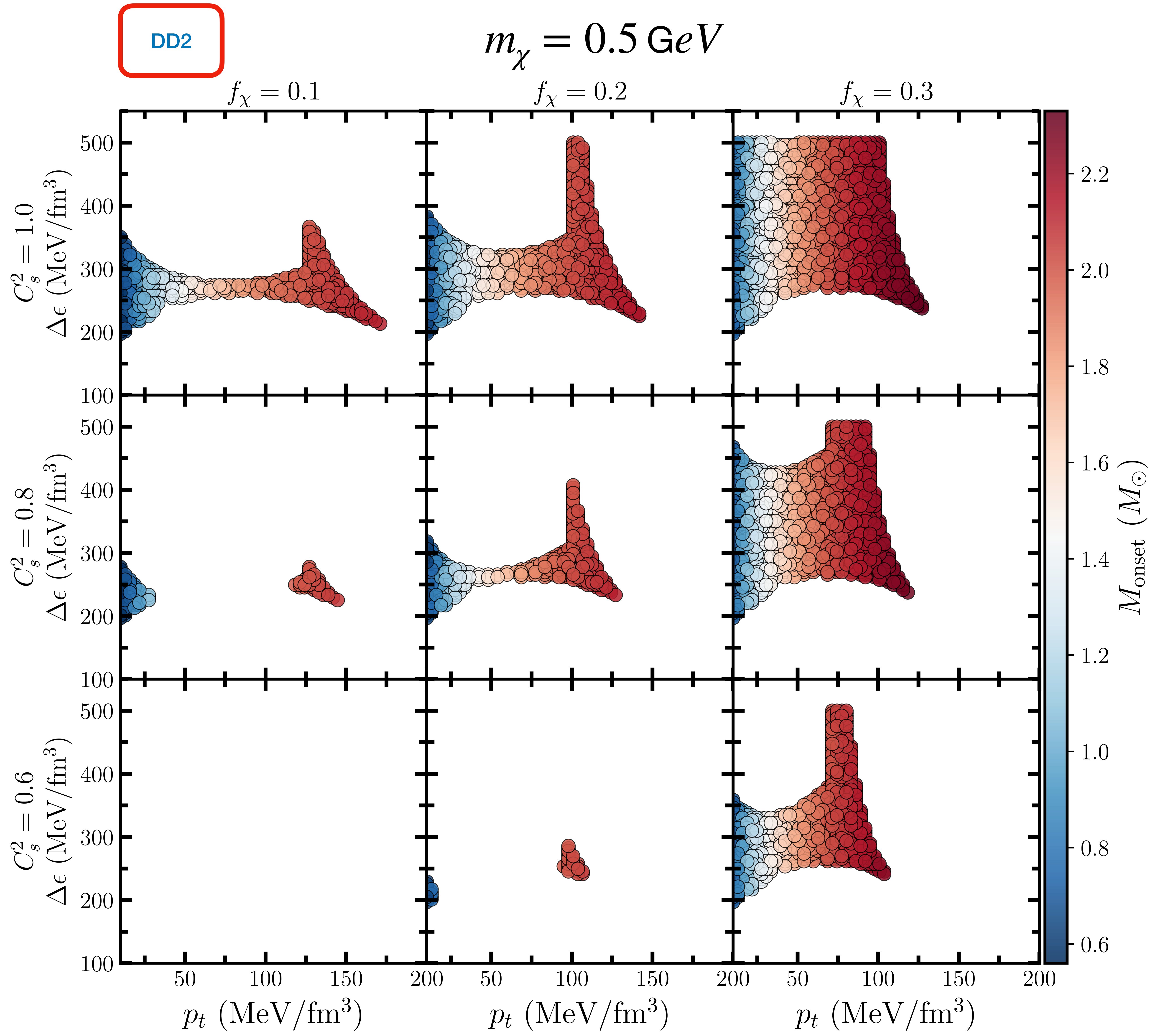


Dark Matter Effects on p_{onset}

- More DM → higher p_{onset} → quark matter is pushed to larger densities regardless of EOS or C_s^2 .
- NITR1 gap at low f_χ → soft nuclear matter cannot sustain twin configurations without sufficient DM pressure support
- Gap fills with increasing f_χ → DM is actively stabilizing otherwise forbidden configurations
- Same trend in both NITR1 and DD2 → this is a DM effect, not a nuclear model dependent.

Dark Matter Effects on M_{onset}

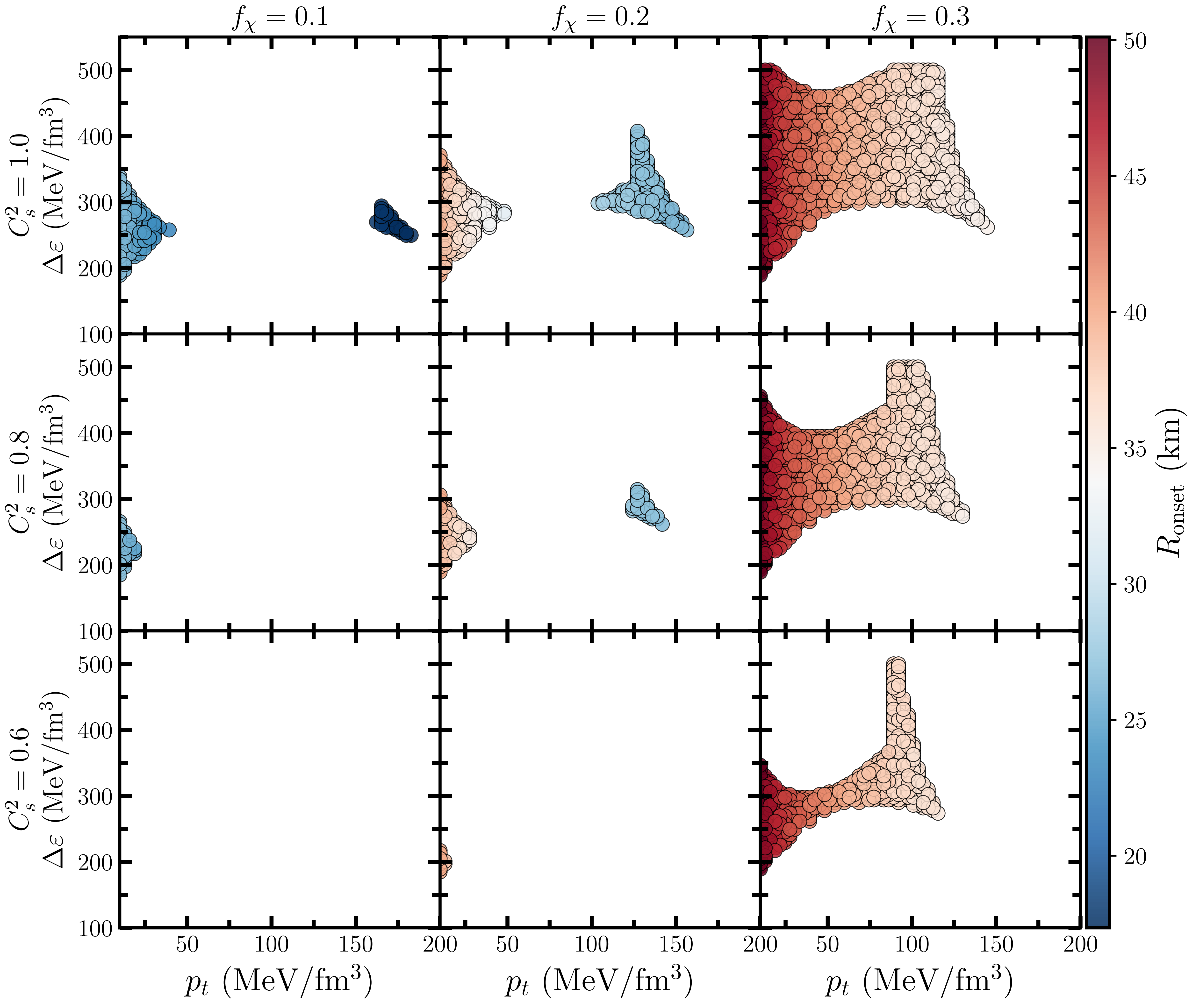




Dark Matter Effects on $R_{\rm onset}$

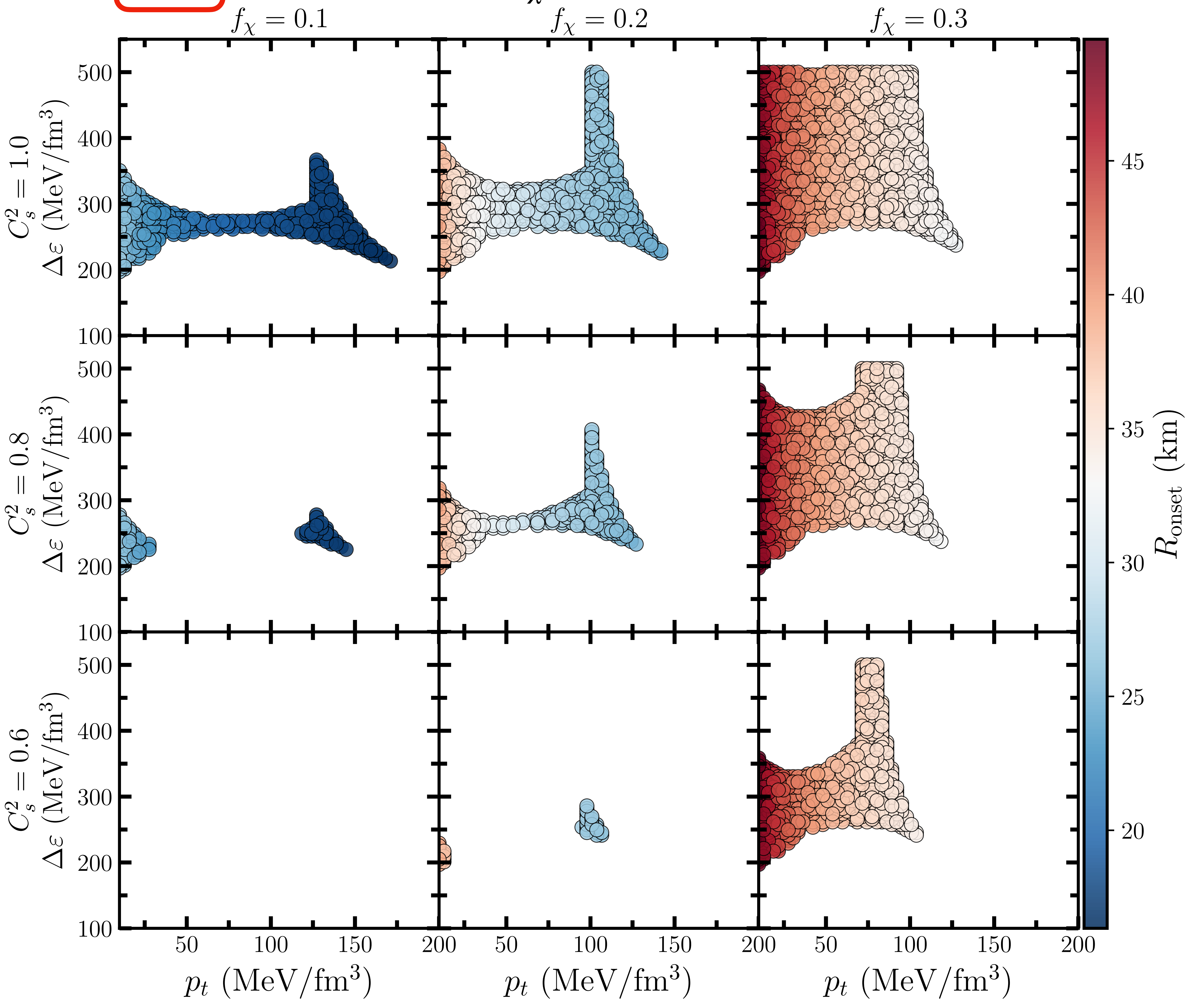
NITR-1

$m_\chi = 0.5\,{\rm GeV}$



DD2

$m_\chi = 0.5\,{\rm GeV}$

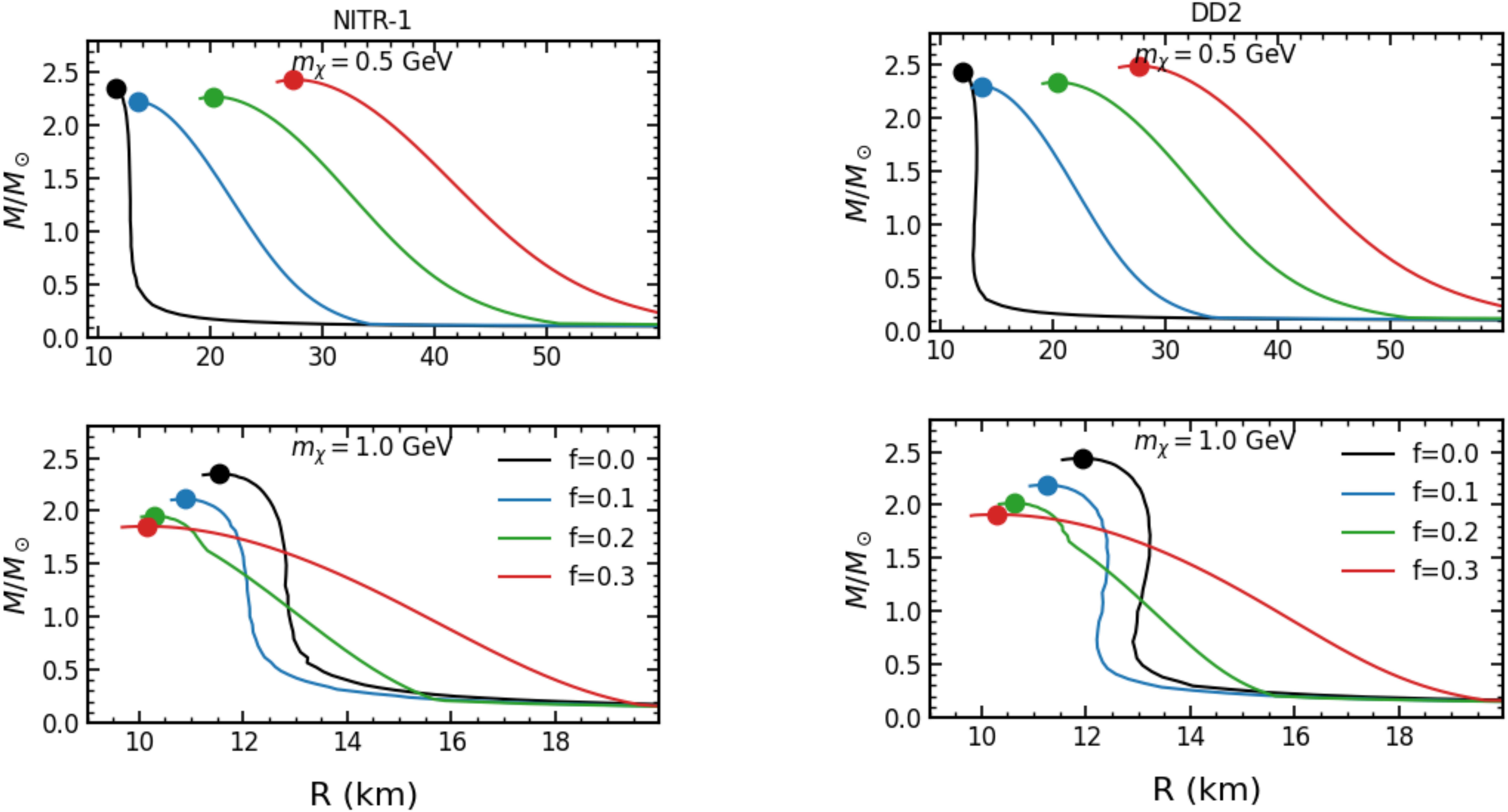


Summary and Outlook

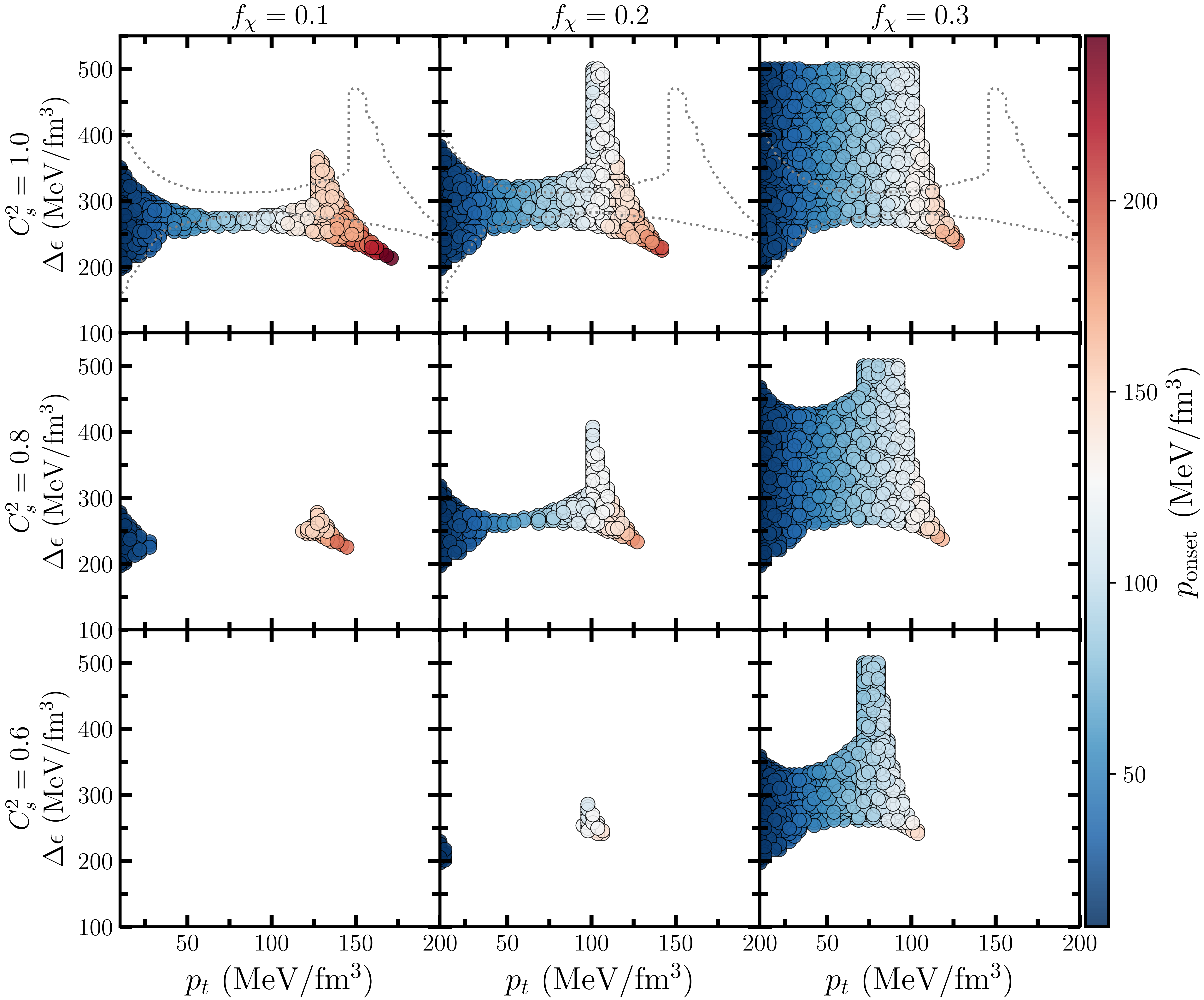
- DM effects on HSs/TSs studied via CSS + two-fluid TOV across large parameter combinations for NITR-1 and DD2.
- CSS parameters $(p_t, \Delta\epsilon, c_s^2)$ set the hybrid/twin configuration; DM mass and fraction switch between core and halo → the two sectors are partially separable.
- DM stabilises hybrid/twin configurations unstable in the pure-baryonic case → expanding the viable parameter space beyond CSS alone.
- DM fraction pushes the nucleon-to-quark transition to higher densities →$p_{\rm onset}$, $M_{\rm onset}$, and $R_{\rm onset}$ all rise with f_χ, potentially hiding quark matter from current observations.
- Bayesian scan underway to quantify the DM-QCD degeneracy and identify observational constraints from pulsar, NICER, and GW data.

T H A N K   Y O U

Halo/Core Scenarios



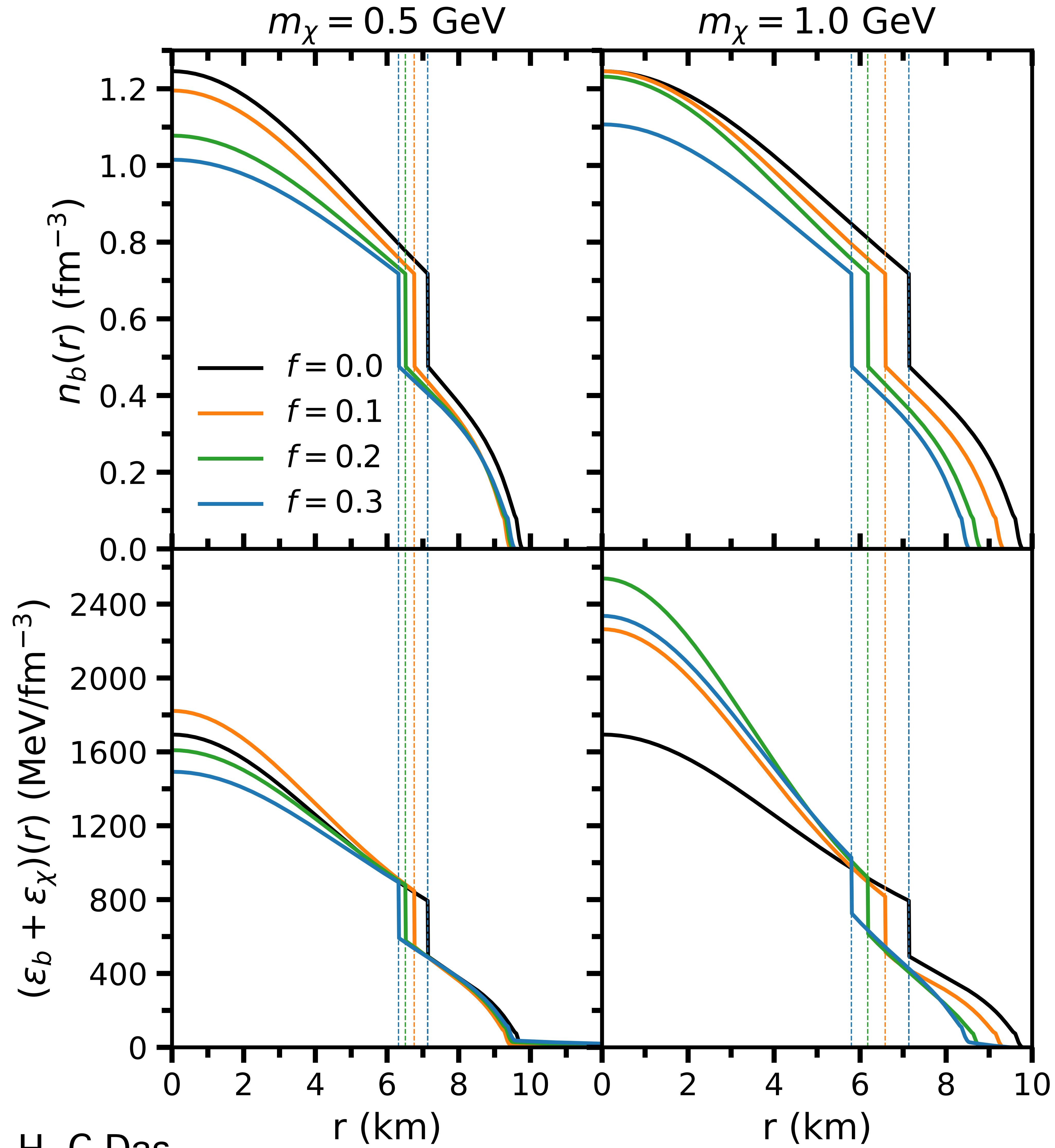
Comparison



$f_\chi = 0.1$
$f_\chi = 0.2$
$f_\chi = 0.3$
$C_s^2 = 1.0$
$C_s^2 = 0.8$
$C_s^2 = 0.6$
$\Delta\epsilon$ (MeV/fm^3)
100
200
300
400
500
50
100
150
200
p_t (MeV/fm^3)
p_{onset} (MeV/fm^3)
50
100
150
200

Density, Energy Density Profiles

Fixed $(p_t, \Delta\epsilon)$ = 100, 300 MeV/fm³



Different $(p_t, \Delta\epsilon)$