Dark matter Admixed Neutron Stars

Shafayat Shawqi[1]*, Sharon Morsink[1]

Neutron Rich Matter on Heaven and Earth

June 28, 2023

[1]University of Alberta

DM Admixed NSs

- Dark Matter can accumulate in stars (the Sun, white dwarfs and neutron stars)

- Significant amounts (few percent of NS total mass) of DM can exist in stable equilibrium configurations of neutron stars

- Lead to observable effects through GW (tidal deformability) and EM (X-ray) radiation

Dark matter Accumulation

- Accretion from DM galactic halo

$$M_{\text{accretion}} \sim 10^{-16} \left(\frac{\rho_\chi}{\text{GeV/cm}^3}\right)\left(\frac{\sigma_{\chi n}}{10^{-45}\ \text{cm}^2}\right)\left(\frac{t}{10^8\ \text{yrs}}\right) M_\odot$$

  - mostly considered too inefficient for observable effects

    (Goldman & Nussinov 1989), (Kouvaris 2007), (Kouvaris & Tinyakov 2010, 2011), (Nelson et al. 2019), etc.

- Produced from SM species and trapped within NS ($\sim 0.01\ M_\odot$)
  - Due to high core densities (Mckeen et al. 2018), (Baym et al. 2018), (Motta et al. 2018a, 2018b)
  - Due to high temperatures in progenitor supernovae or proto-NS (Nelson et al. 2019), (Reddy & Zhou 2022), (Collier et al. 2022)

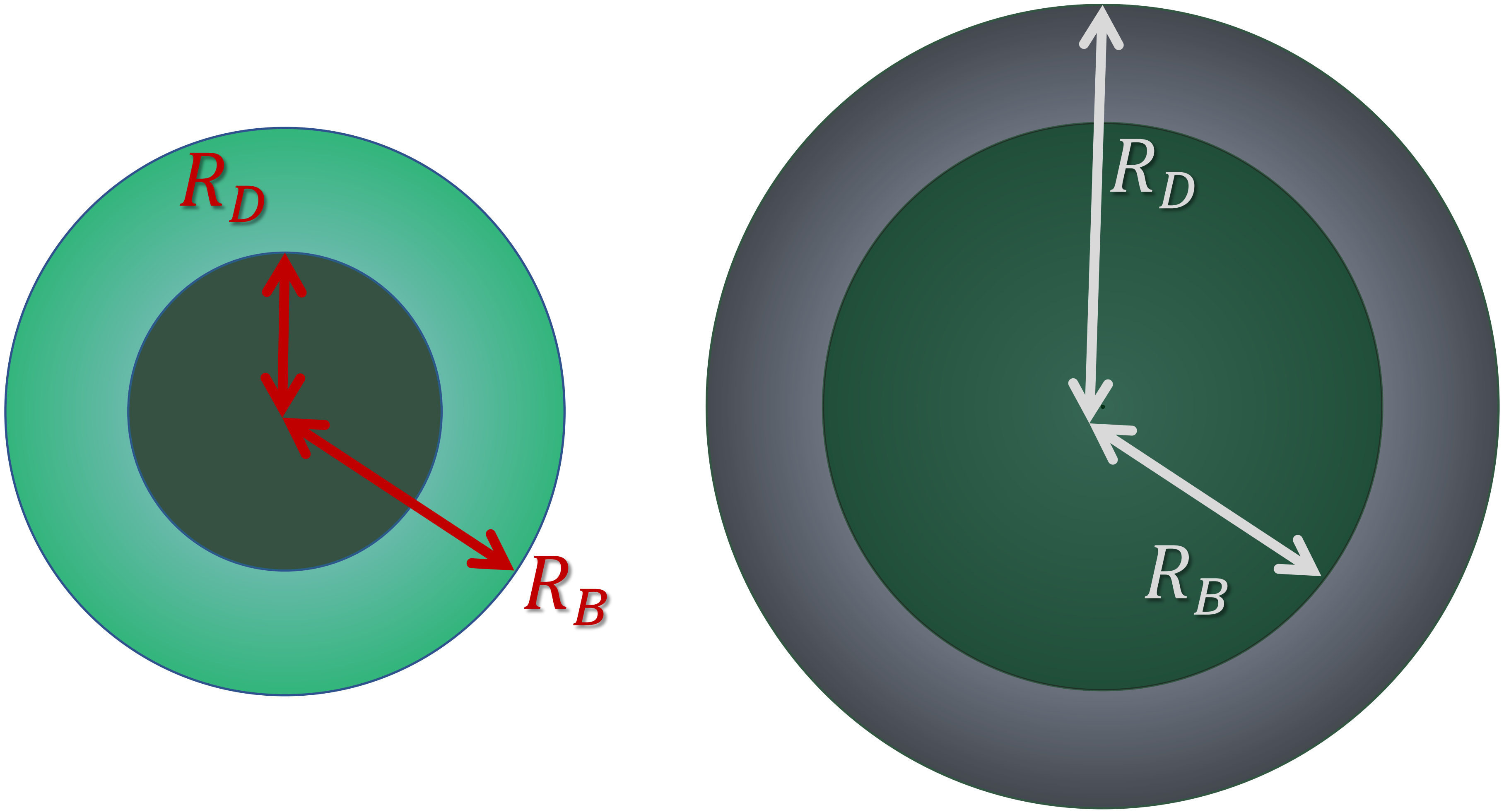
Dark matter Accumulation

- Mergers with dark compact objects
  - self-interacting DM can form dark stars ($\sim 0.1\ M_\odot$)

(Kouvaris & Nielsen 2015, Collier et al. 2022)

Rest of the talk – Assume DM exists in NSs in equilibrium configurations and explore observable effects.

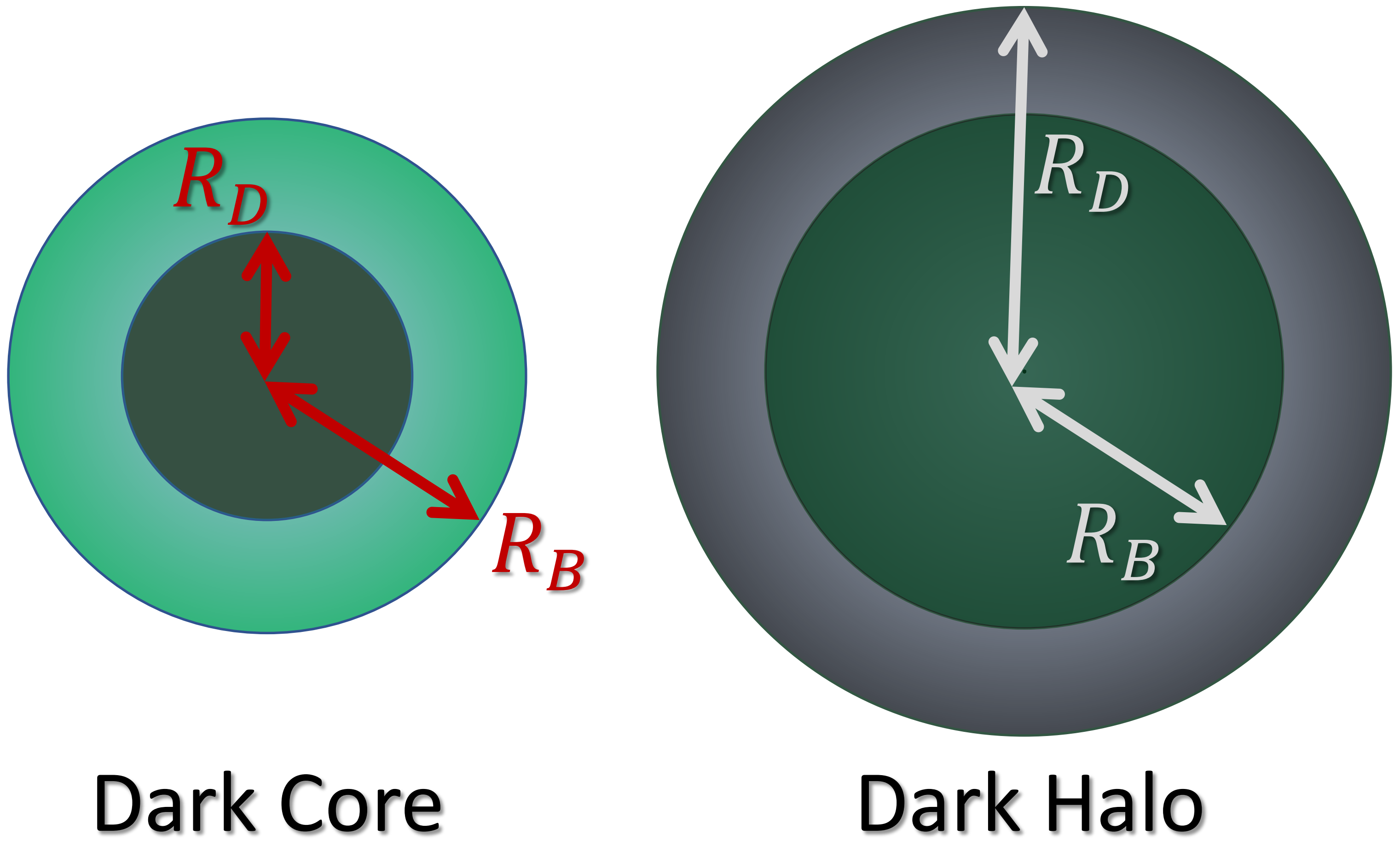
Dark Core or Halo



Dark Core

Dark Halo

Dark Core or Halo



Depending on

i. DM particle mass (m_χ)

ii. self-interaction strength (y)

iii. DM mass fraction in the star (f_χ)

DANS Model Generation

- Single fluid description
  - Compute equation of state with SM couplings between DM and baryonic matter (Panotopoulos & Lopes 2017), (Quddus et al 2020), (Das et al. 2019), (Das et al. 2021), (Lopes et al. 2022)

- Two-fluid description (Sandin & Ciarcelluti 2009), (Ciarcelluti & Sandin 2011), (Miao et al. 2022), (Shakeri et al. 2022a, 2022b), (Collier et al. 2022), (Rutherford et al. 2023)
  - No SM couplings between DM and baryonic matter
  - Only gravitational interaction between the two

Our method of choice since it is more relevant for NICER X-ray observations!

Two-Fluid TOV equations

Energy-momentum of each fluid is conserved separately

$$G_{\mu\nu} = 8\pi\left(T_{\mu\nu,B} + T_{\mu\nu,D}\right)$$

$$\frac{dP_B}{dr} = -\frac{(\epsilon_B+P_B)\left(M+4\pi r^3 P\right)}{r(r-2M)} \qquad \frac{dM_B}{dr} = 4\pi r^2 \epsilon_B$$

$$\frac{dP_D}{dr} = -\frac{(\epsilon_D+P_D)\left(M+4\pi r^3 P\right)}{r(r-2M)} \qquad \frac{dM_D}{dr} = 4\pi r^2 \epsilon_D$$

$$(M = M_B + M_D, P = P_B + P_D, \epsilon = \epsilon_B + \epsilon_D)$$

4 coupled equations with 6 unknowns. Need 2 EOSs relating pressure and energy density of each fluid.

Equation of State

- Baryonic EOS – NL3$\omega\rho$L55
  - choosing stiff EOS just to easily illustrate effects of DM in MR profile
- DM EOS
  - bosonic (requires repulsive self-interaction)
    - without self-interaction collapses to a black hole at the centre of the NS
  - fermionic (no self-interaction required due to degeneracy pressure)
    - we choose to include self-interaction to explore effects

Dark Matter EOS

$$\epsilon_D = \epsilon_{D,\text{kin}} + m_\chi n_D + \frac{n_D^2}{m_I^2}$$

Assume ideal Fermi gas at zero temperature (Nelson et al. 2019)

$$\epsilon_{D,\text{kin}} = \frac{1}{\pi^2}\int_0^{k_F} dk\, k^2 \left(\sqrt{k^2 + m_\chi^2} - m_\chi\right)$$

$$P_D = -\epsilon_D + \frac{\mu_D}{\sqrt{g_{tt}}} n_D \qquad \frac{\mu_D}{\sqrt{g_{tt}}} = \frac{\partial \epsilon_D}{\partial n_D} \qquad n_D = \frac{k_F^3}{3\pi^2}$$

Dark Matter EOS

$$\epsilon_D = \frac{m_\chi^4}{8\pi^2}\left[(2x^3 + x)\sqrt{1+x^2} - \text{arcsinh}(x)\right] + \frac{m_\chi^4 y^2 x^6}{(3\pi^2)^2}$$

kinetic and rest mass

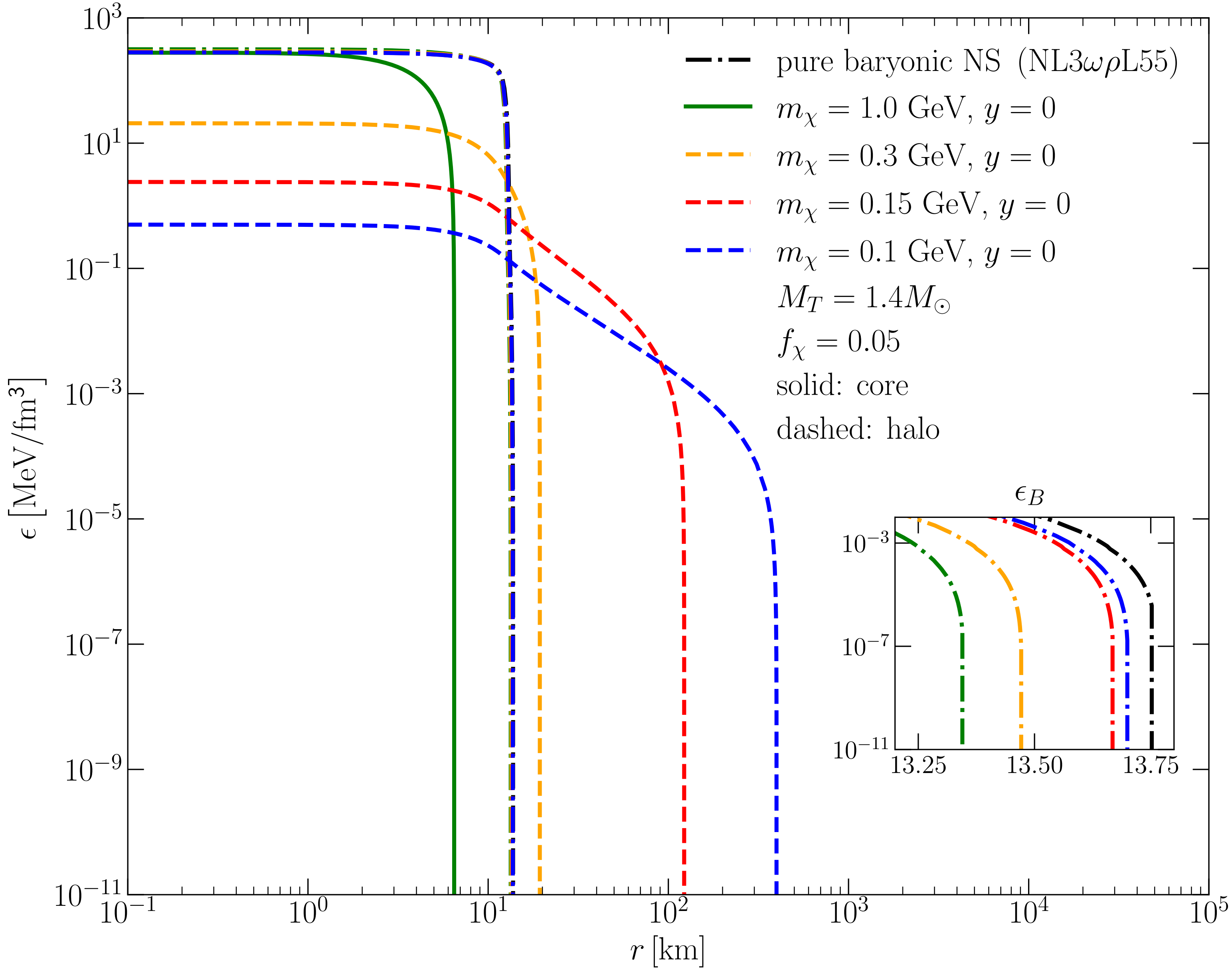
self-interaction

$$P_D = \frac{m_\chi^4}{24\pi^2}\left[(2x^3 - 3x)\sqrt{1+x^2} + 3\,\text{arcsinh}(x)\right] + \frac{m_\chi^4 y^2 x^6}{(3\pi^2)^2}$$

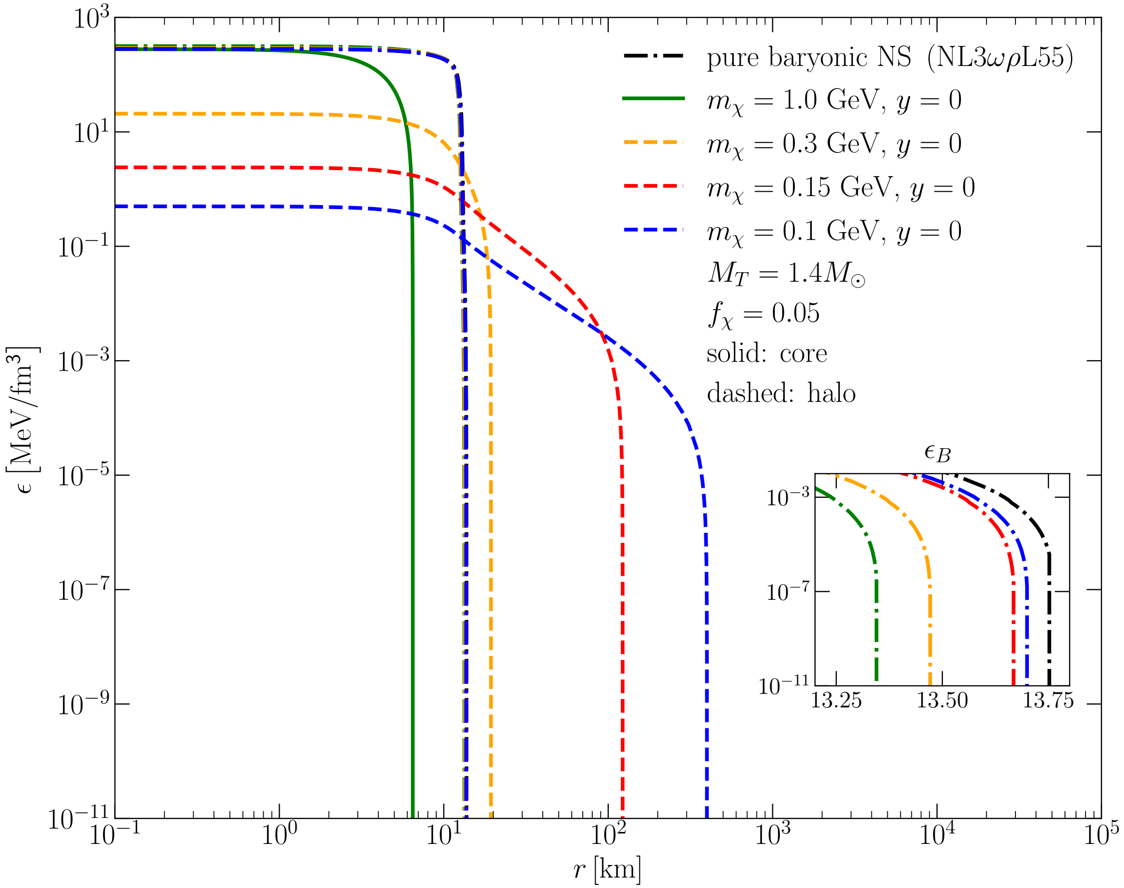
$x = \frac{k_F}{m_\chi}$: relativity parameter

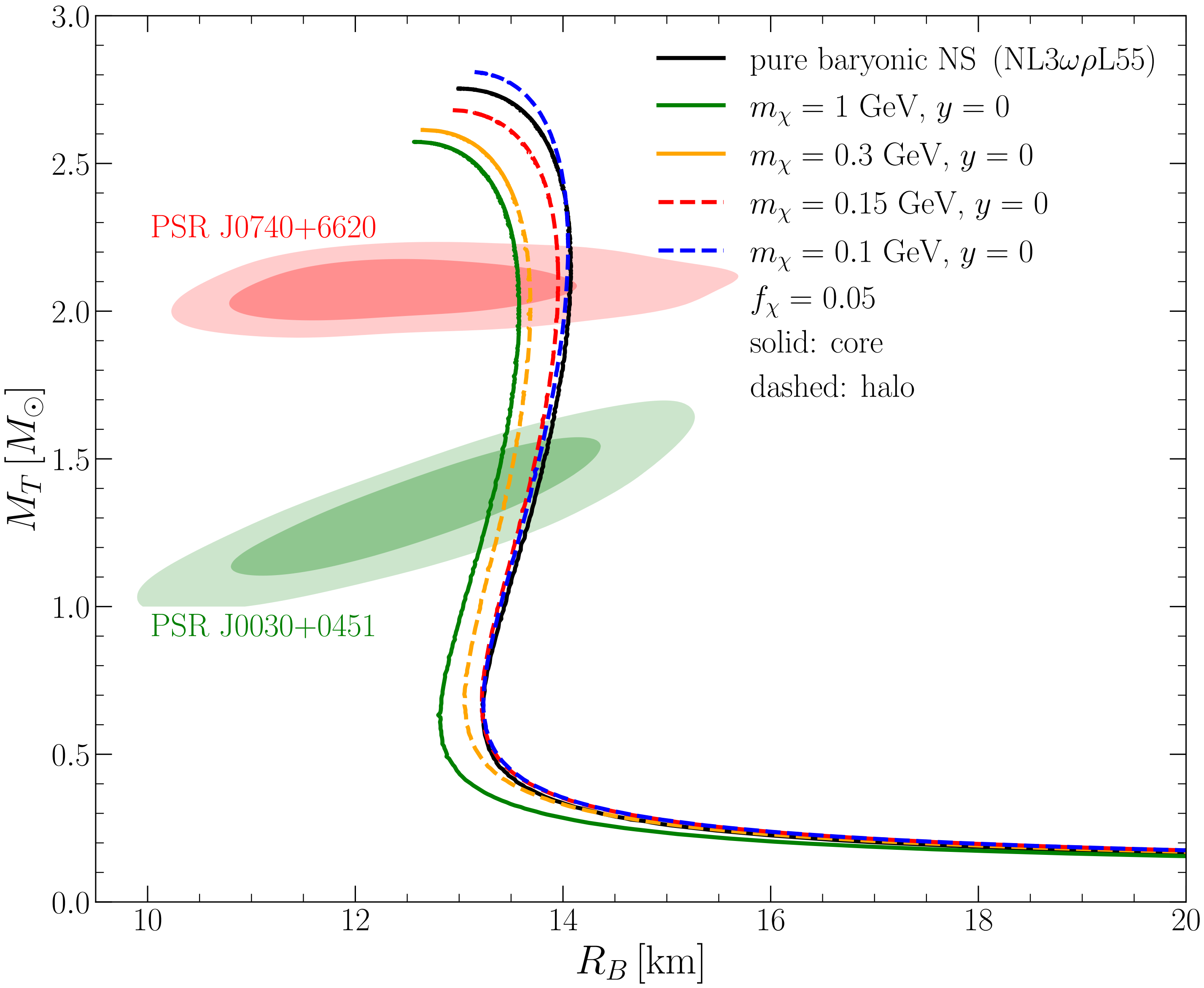
$y = \frac{m_\chi}{m_I}$: self-interaction strength

Dependence on m_χ

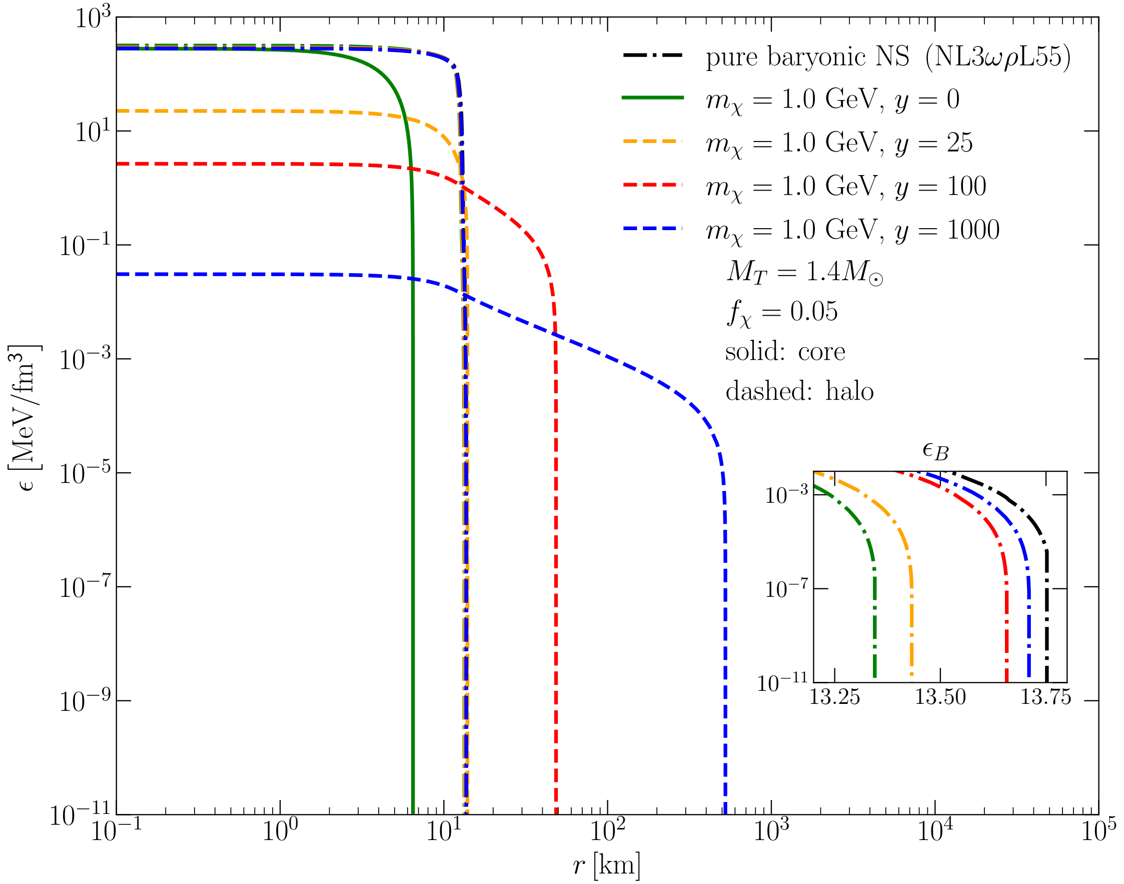


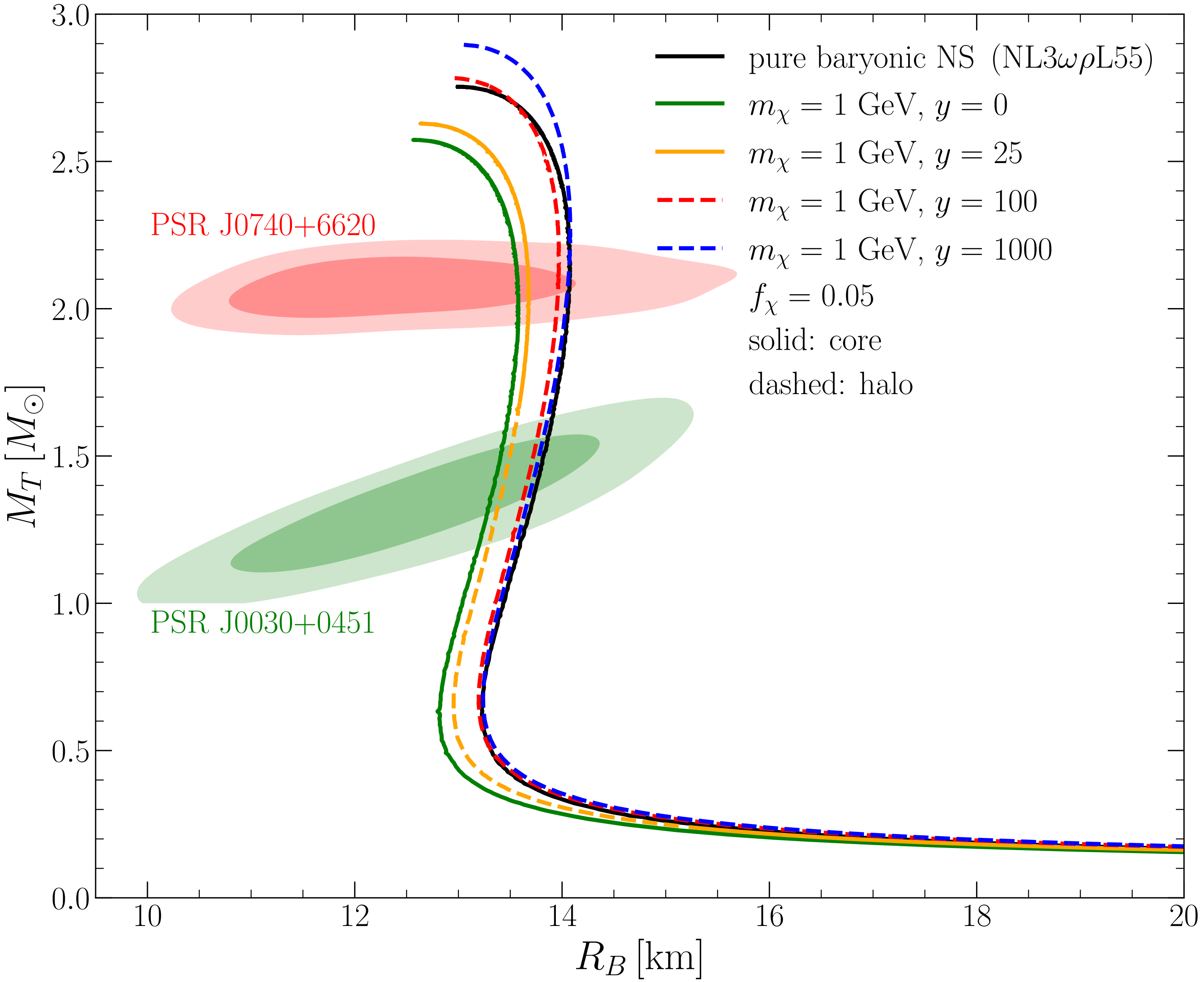
Dependence on m_χ





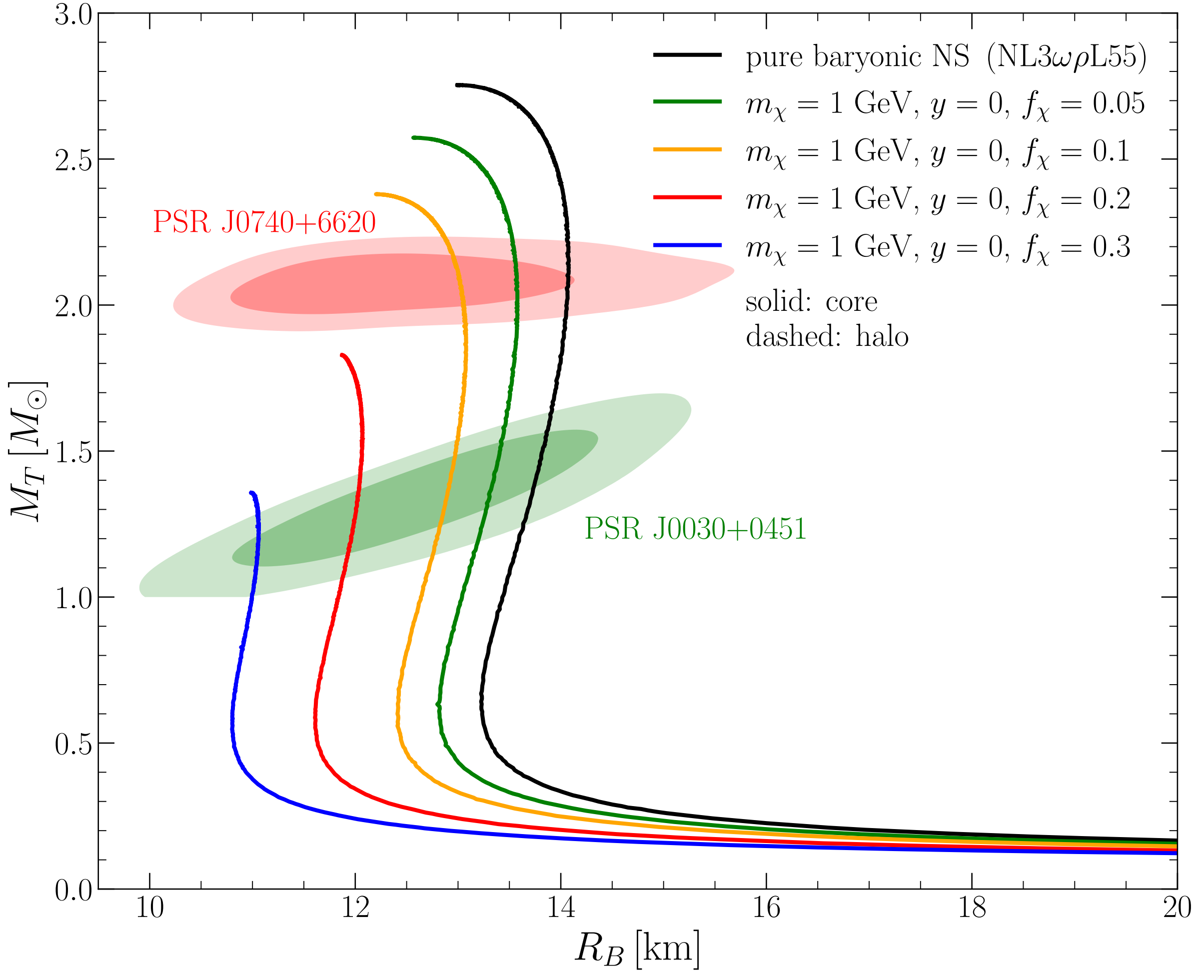
Dependence on y



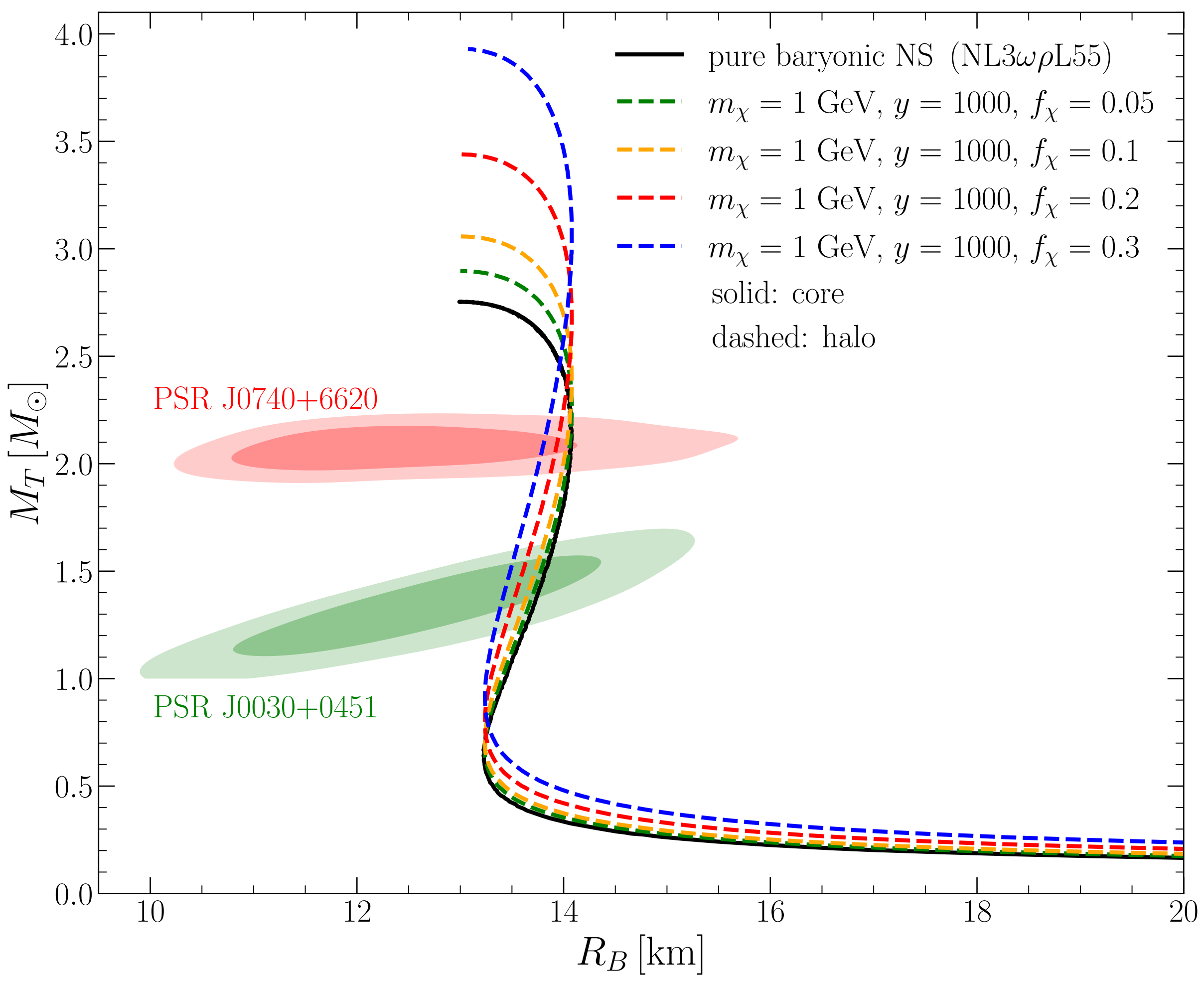


Dependence on f_χ

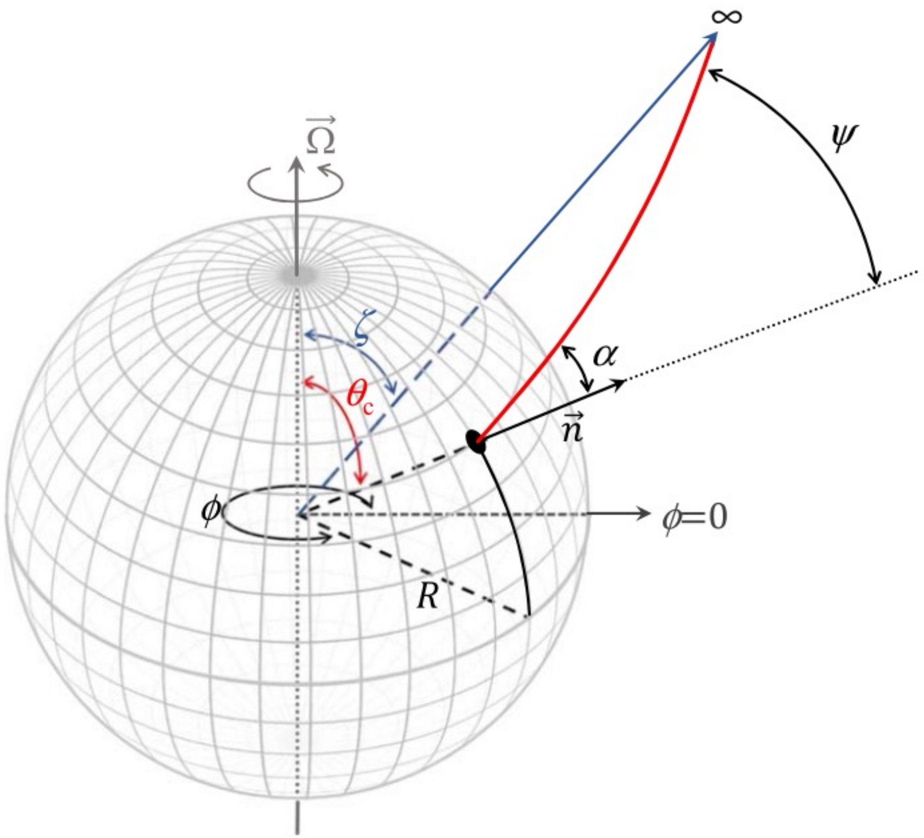
Cores



Halos



Gravitational Self-Lensing



Credit: Bogdanov et al. 2022

$$\cos\psi = \cos\zeta\cos\theta_c + \sin\zeta\sin\theta_c\cos\phi$$

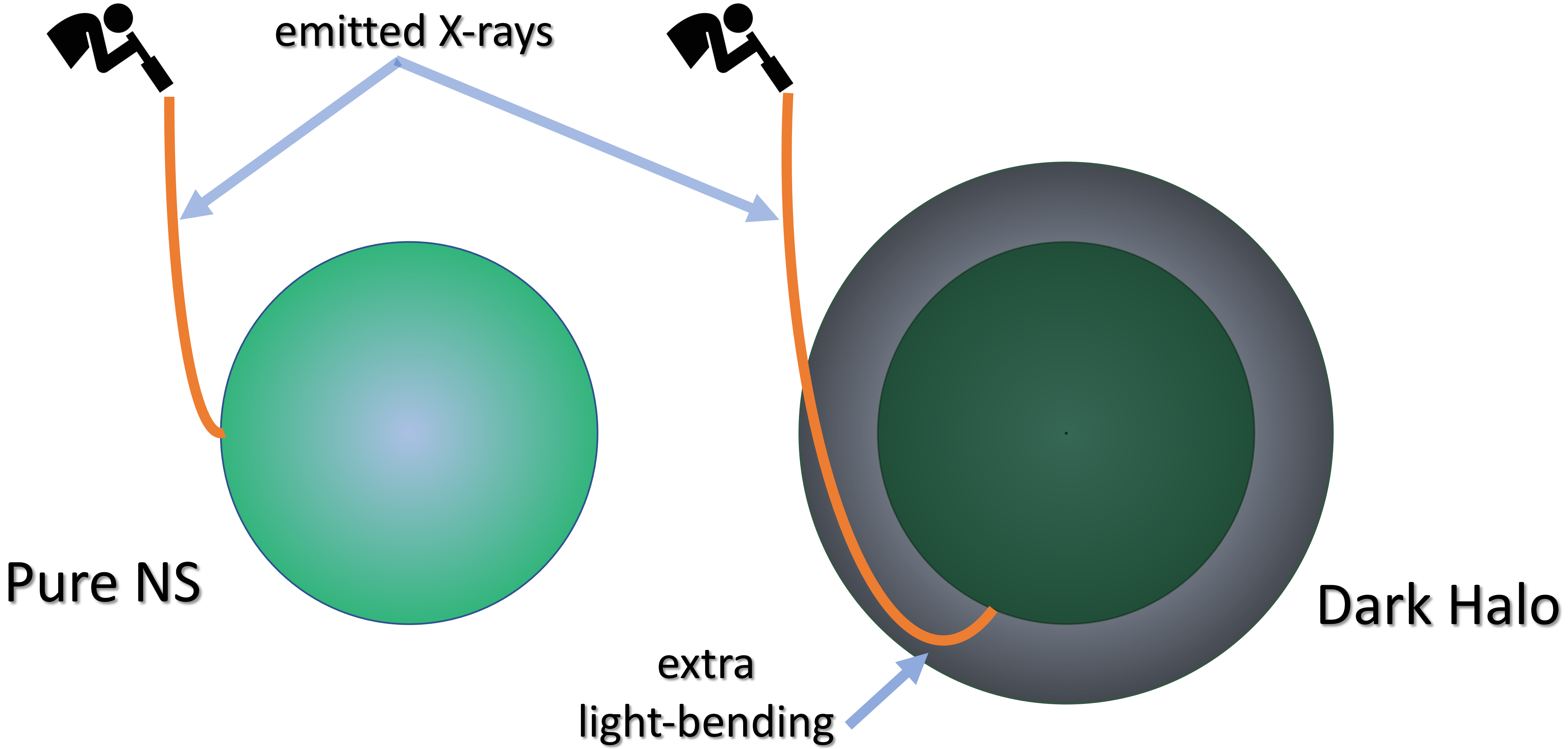
$$\psi = \int_R^\infty \frac{dr}{r^2}\left[\frac{1}{b^2} - \frac{1}{r^2}\left(1 - \frac{R_S}{r}\right)\right]^{-1/2}$$

$$b = \frac{R\sin\alpha}{\sqrt{1-\frac{R_S}{R}}}$$

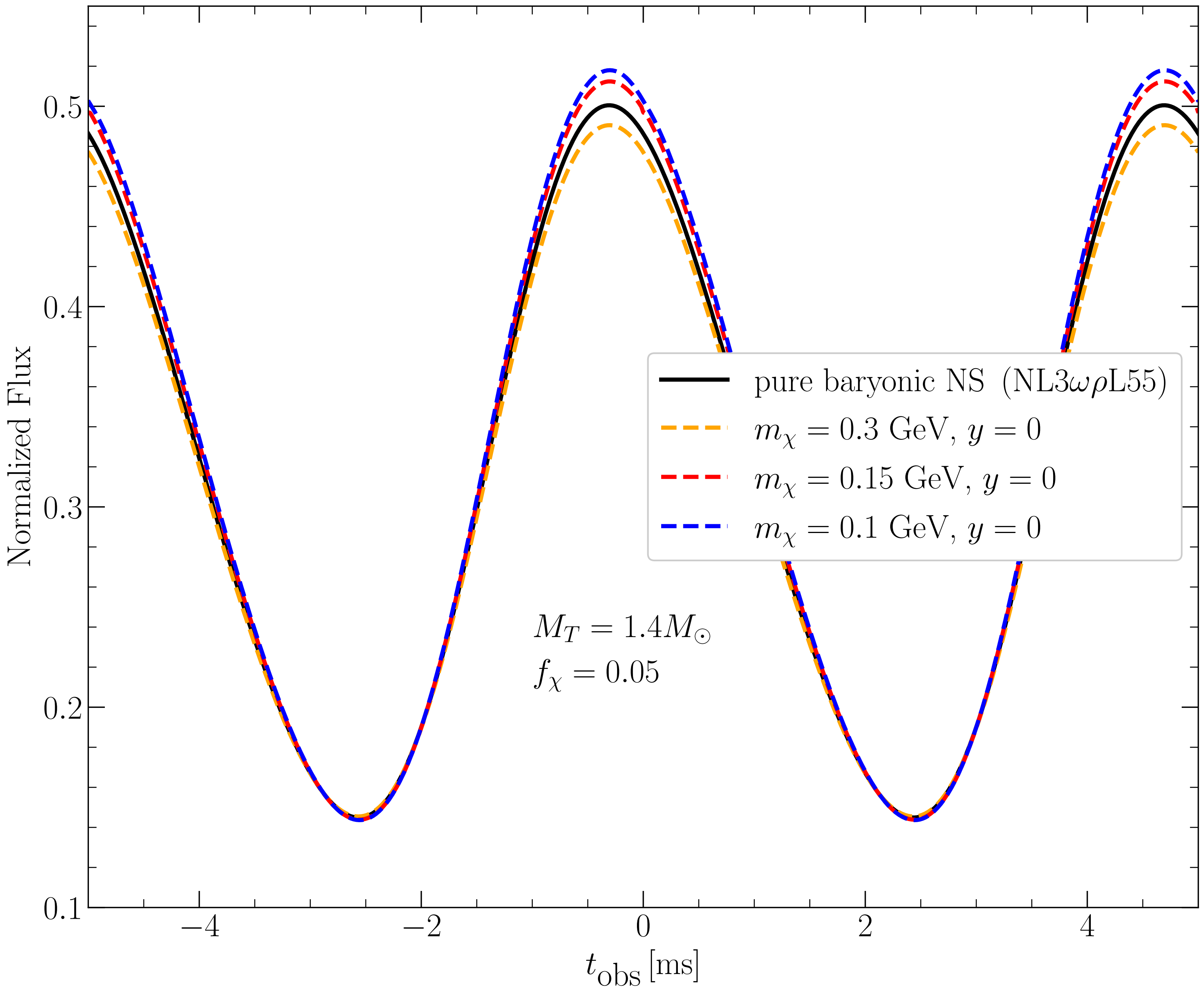
$$F = \delta^5 g_{tt}(R_B)\cos(\alpha)\frac{d\cos(\alpha)}{d\cos(\psi)}$$

This can be used to calculate pulse profiles (flux vs time plots)

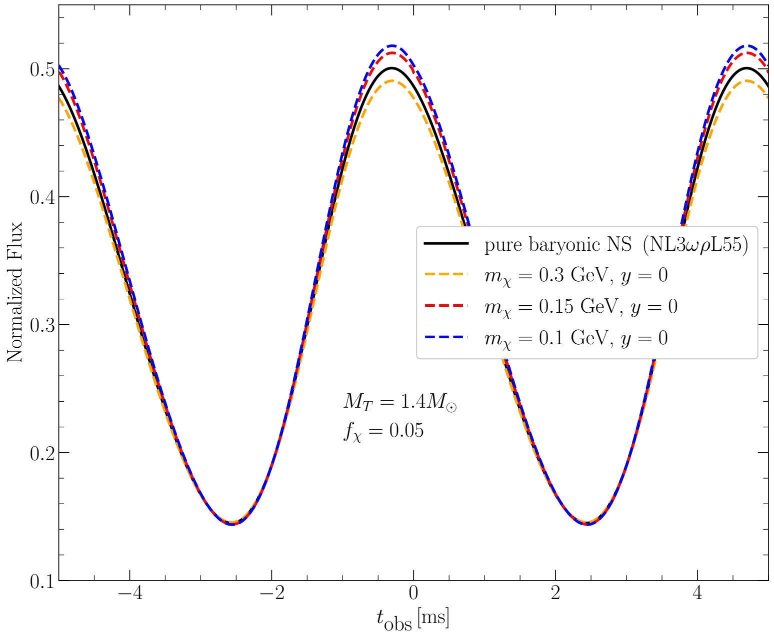
Gravitational Self-Lensing due to Dark Halo

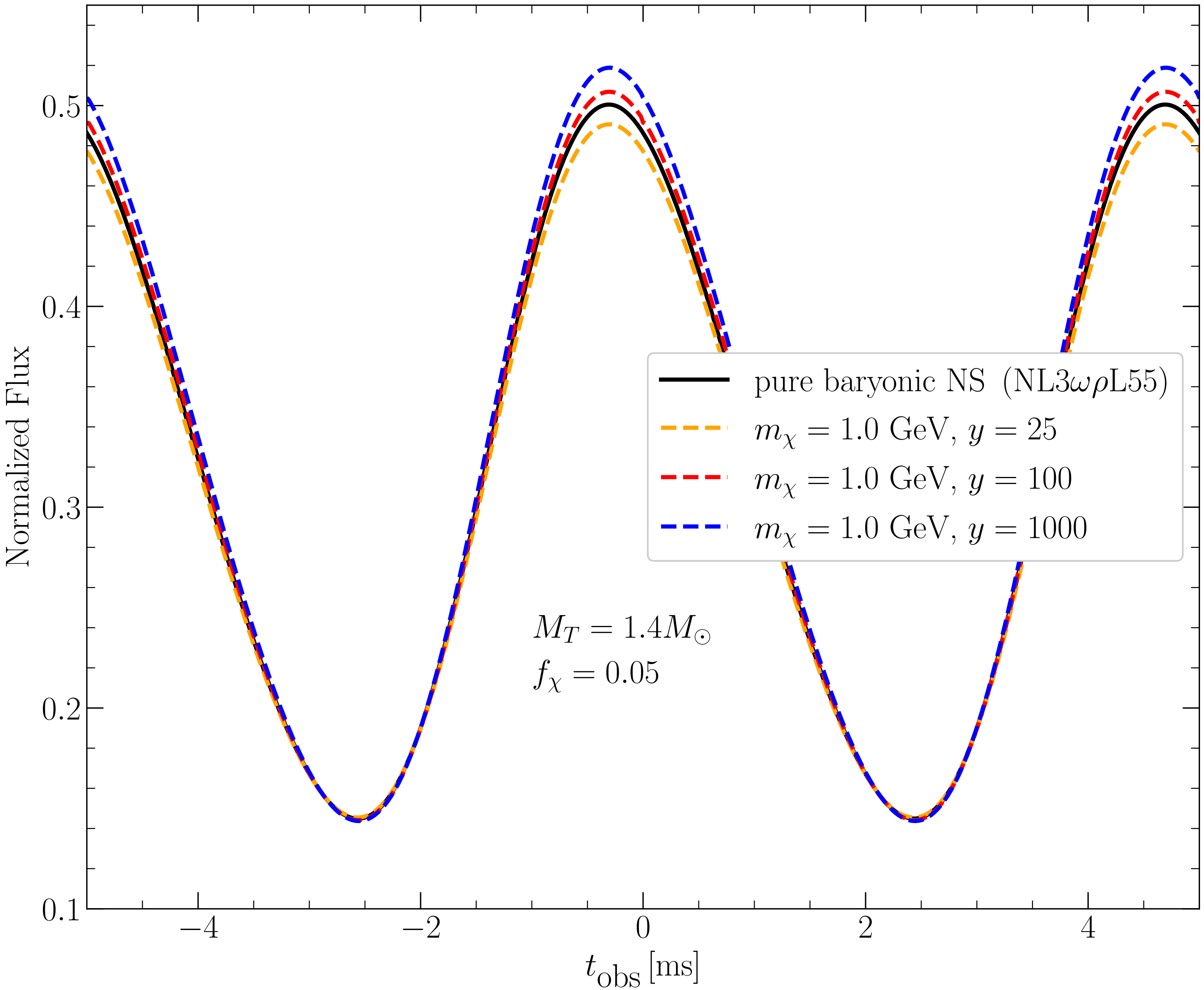


Flux from NS with Dark Halo

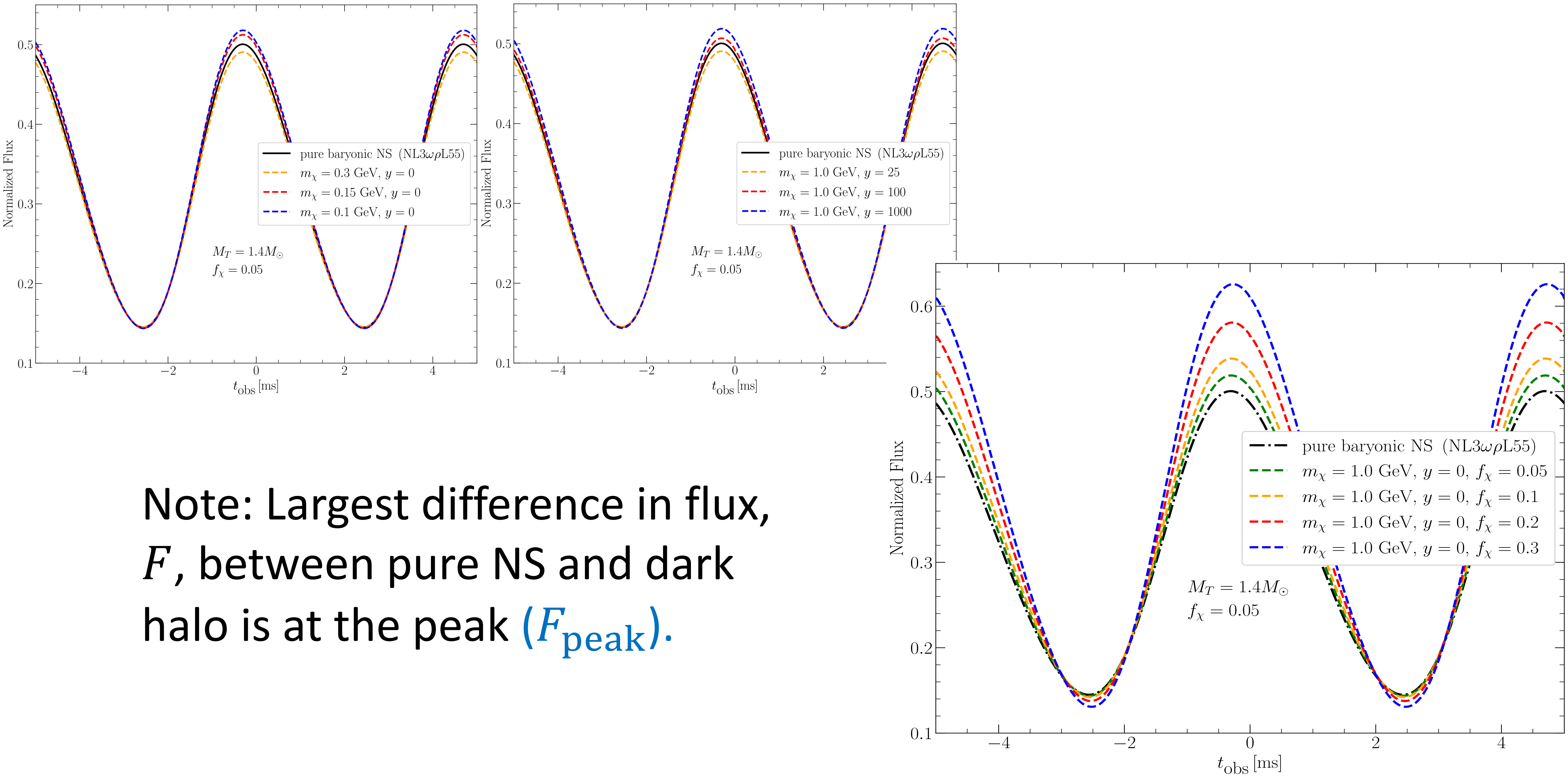


Flux from NS with Dark Halo



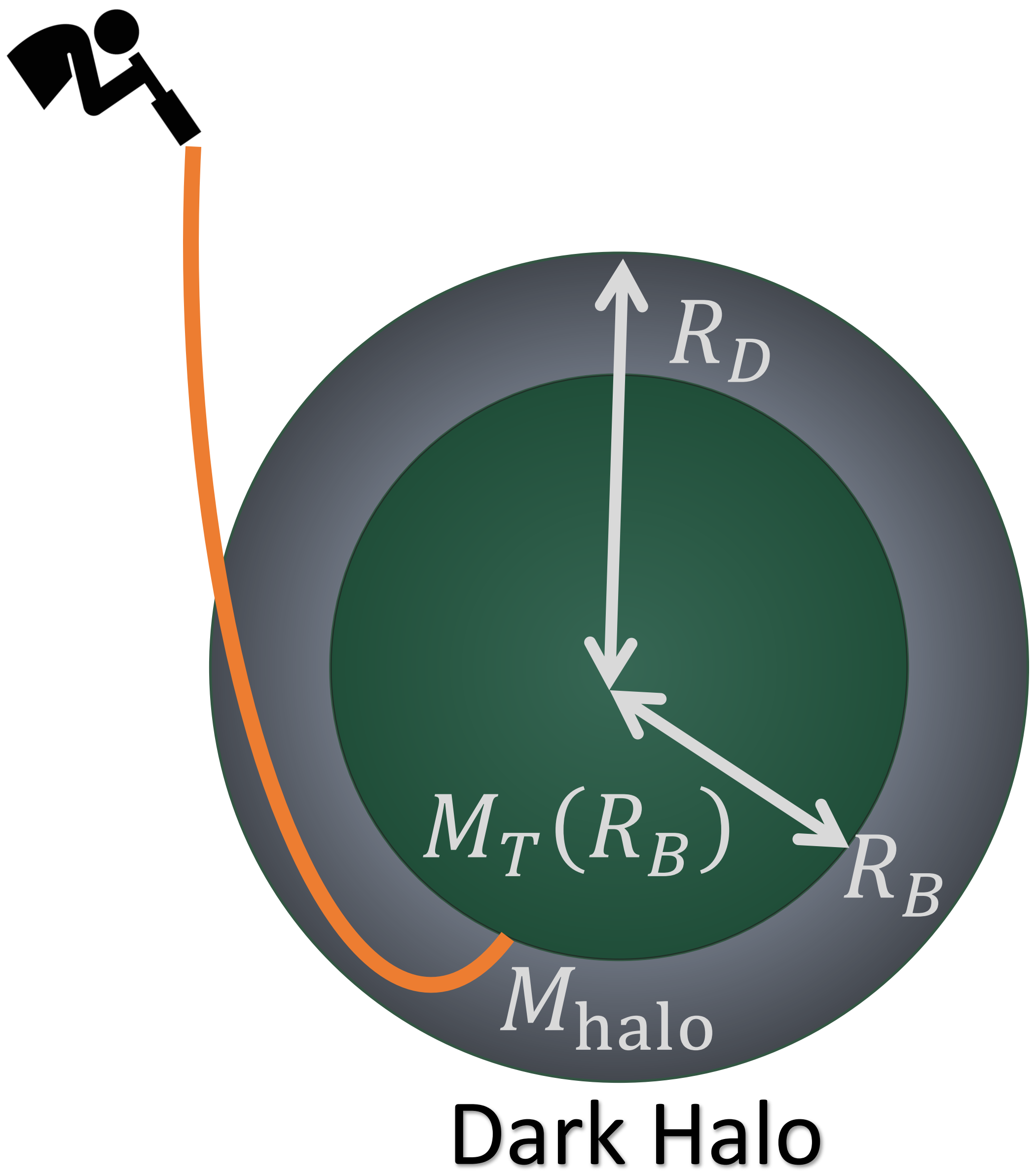


Flux from NS with Dark Halo



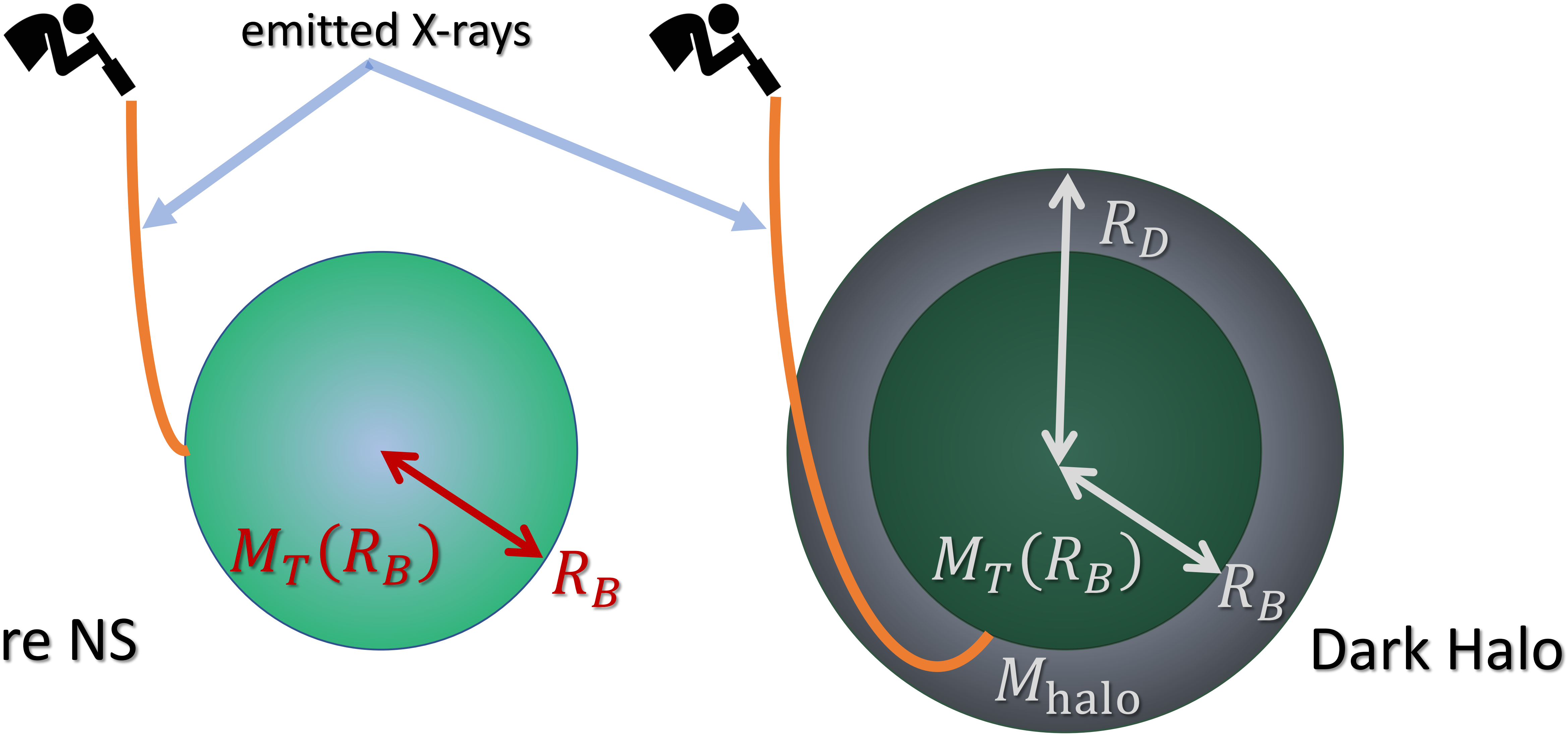
Note: Largest difference in flux, F, between pure NS and dark halo is at the peak (F_{peak}).

NS Mass-Radius Measurements



- Mass measurements through radio observations measures $M_T = M_T(R_B) + M_{\text{halo}}$
- NICER measures $M_T(R_B)$
  - Since light is emitted from R_B and most of light bending occurs near R_B due to strongest gravitational potential

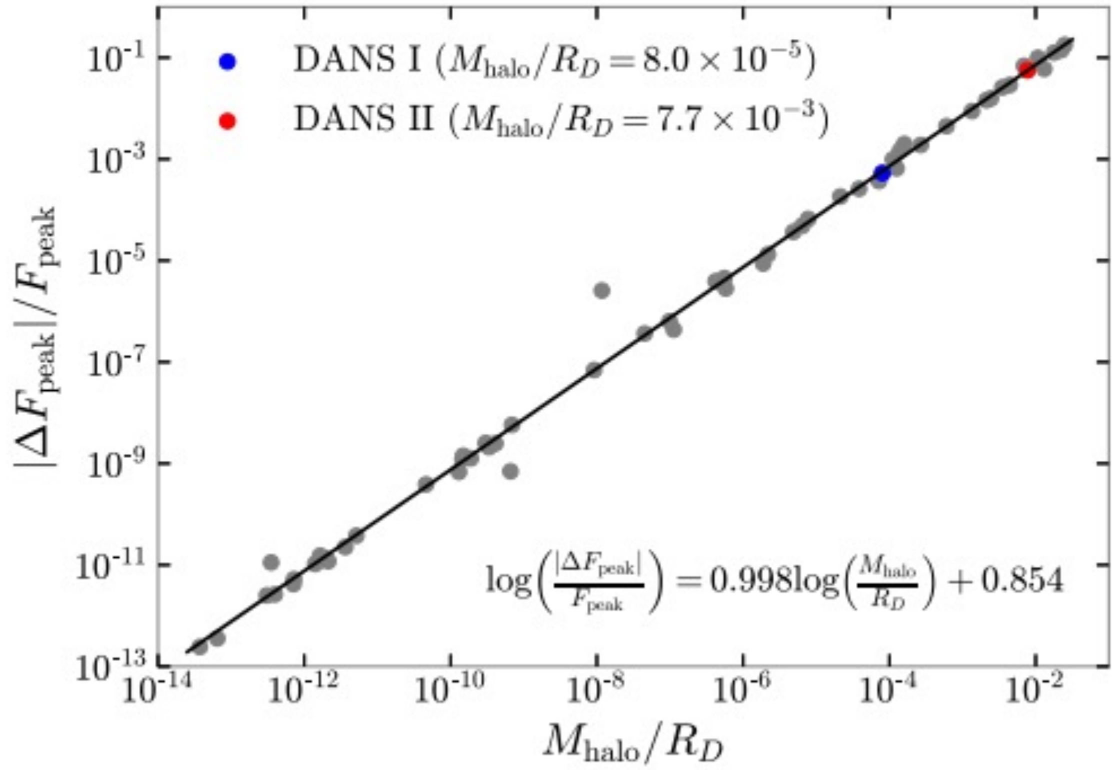
Approximate ΔF_{peak}



Approximate ΔF_{peak}

- Try to approximate the pulse profile of a NS with dark halo by that of a pure NS of mass $M_T(R_B)$.

$$\log\left(\frac{|\Delta F_{\text{peak}}|}{F_{\text{peak}}}\right) = 0.998\log\left(\frac{M_{\text{halo}}}{R_D}\right) + 0.854$$ (Miao et al. 2022)



For sufficiently small $\left(\frac{M_{\text{halo}}}{R_D}\right)$, ΔF_{peak} is small.

Largest difference in F between pure NS and dark halo is at the peak flux F_{peak}

Relate F_{peak} to $g_{tt}(R_B)$

$$ds^2 = -g_{tt}(r)dt^2 + g_{rr}(r)dr^2 + r^2 d\theta^2 + r^2 \sin^2(\theta) d\phi^2$$

$$F = \delta^5 g_{tt}(R_B)\cos(\alpha)\frac{d\cos(\alpha)}{d\cos(\psi)} \sim g_{tt}^2(R_B) \text{ (at peak)} \sim (1+z)^{-4} \text{ (bolometric)}$$

$$\frac{|\Delta F_{\mathrm{peak}}|}{F_{\mathrm{peak}}} \sim \frac{2|\Delta g_{tt}(R_B)|}{g_{tt}(R_B)}$$

- Energy dependent flux will depend on a different power of $g_{tt}(R_B)$
  - Even if M_{halo}/R_D relation does not hold, $\Delta g_{tt}(R_B)$ can be used to set maximum ΔF_{peak}

- Both M_{halo}/R_D and $g_{tt}(R_B)$ can be indicators towards if ΔF_{peak} is small

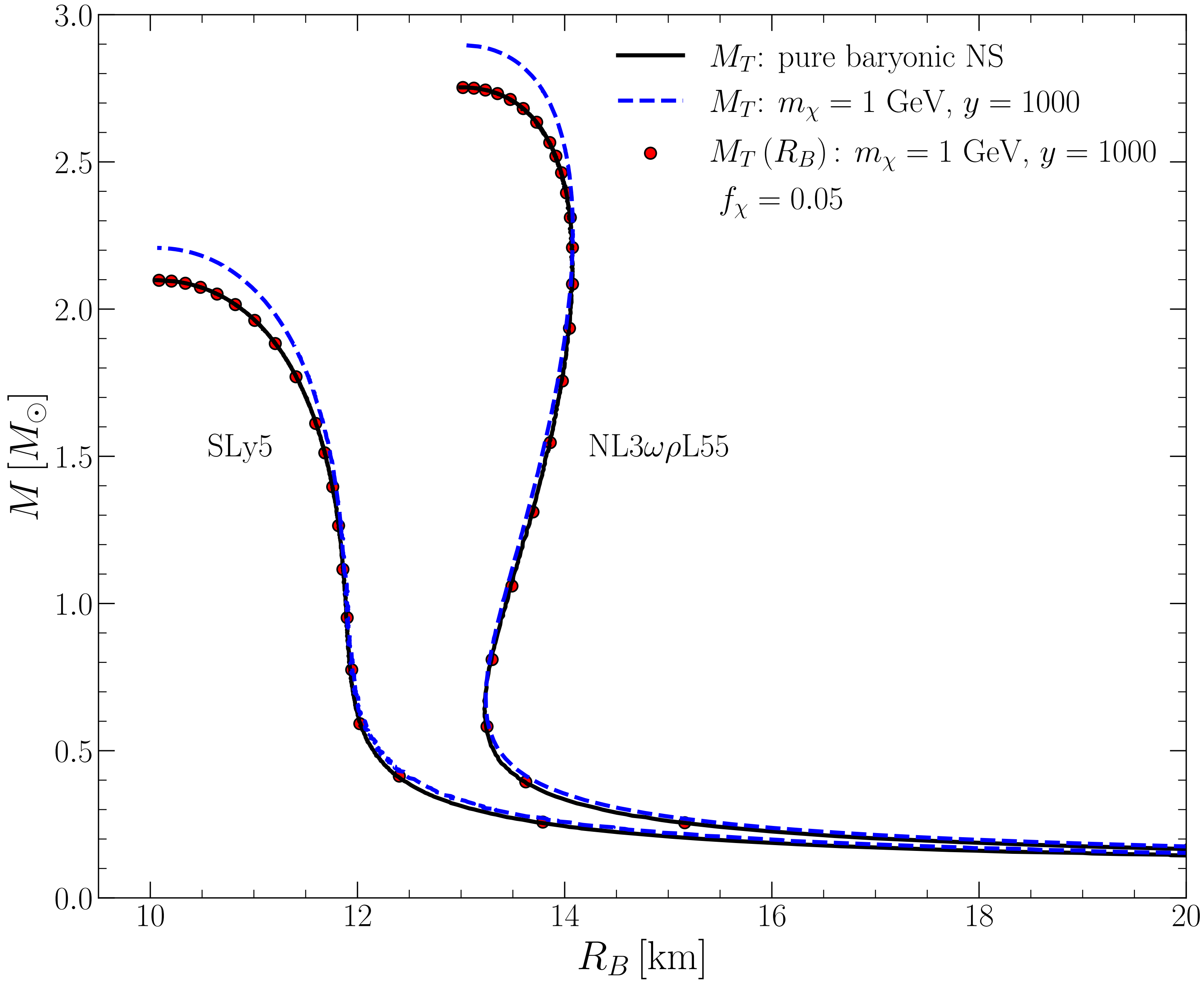
Can we use current NICER results to constrain Dark Halos?

- Current NICER results assume no DM exists in the NSs
- If ΔF_{peak} (or M_{halo}/R_D or $g_{tt}(R_B)$) is large, a NICER reanalysis is required to constrain DM properties
  - Current $M_T(R_B)$ and R_B measurements significantly differ from that of NS with dark halo
- If ΔF_{peak} is sufficiently small, we can use current NICER results to analyse the validity of baryonic EOSs and constrain f_χ in the NS

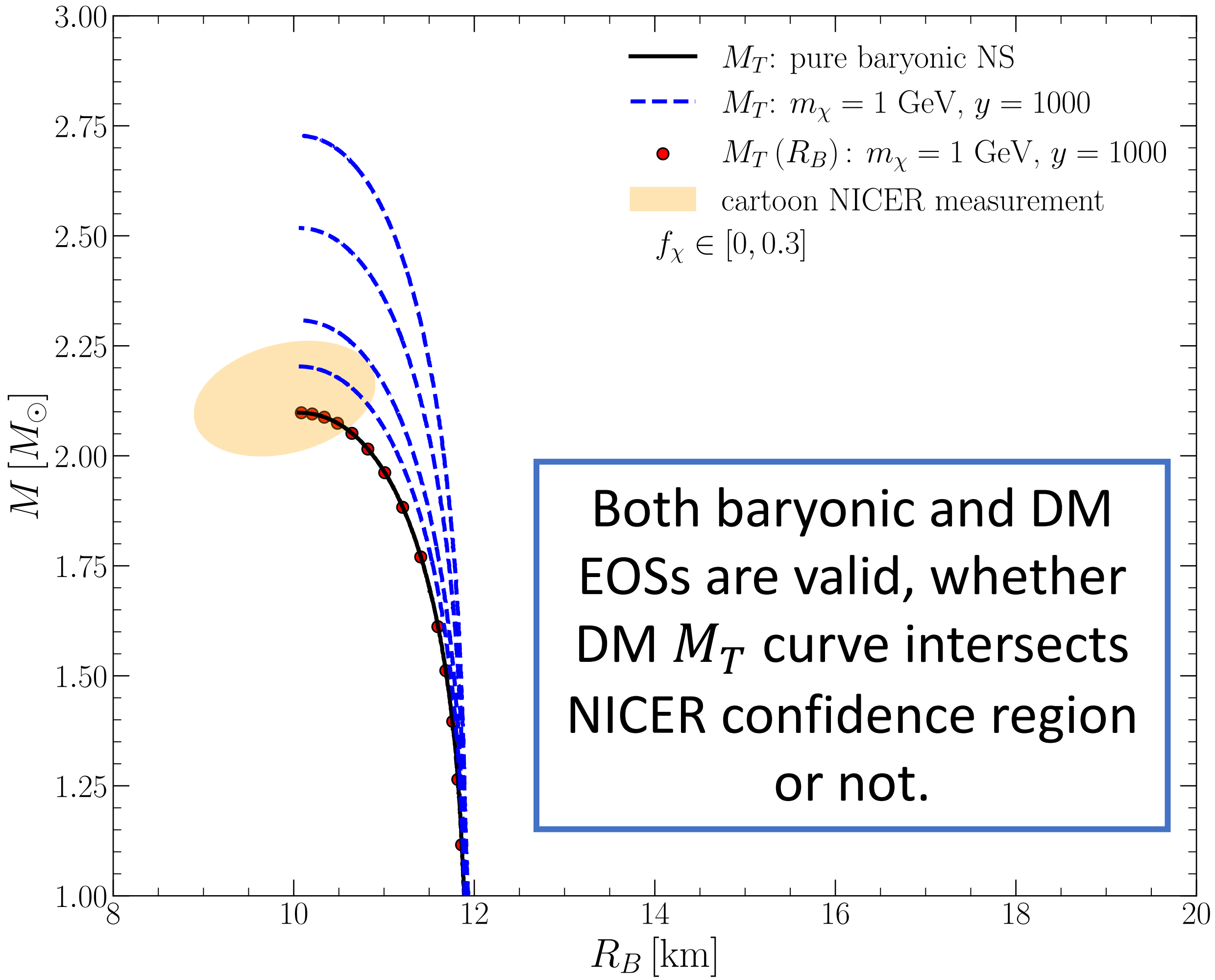
Effects on Baryonic EOS constraints

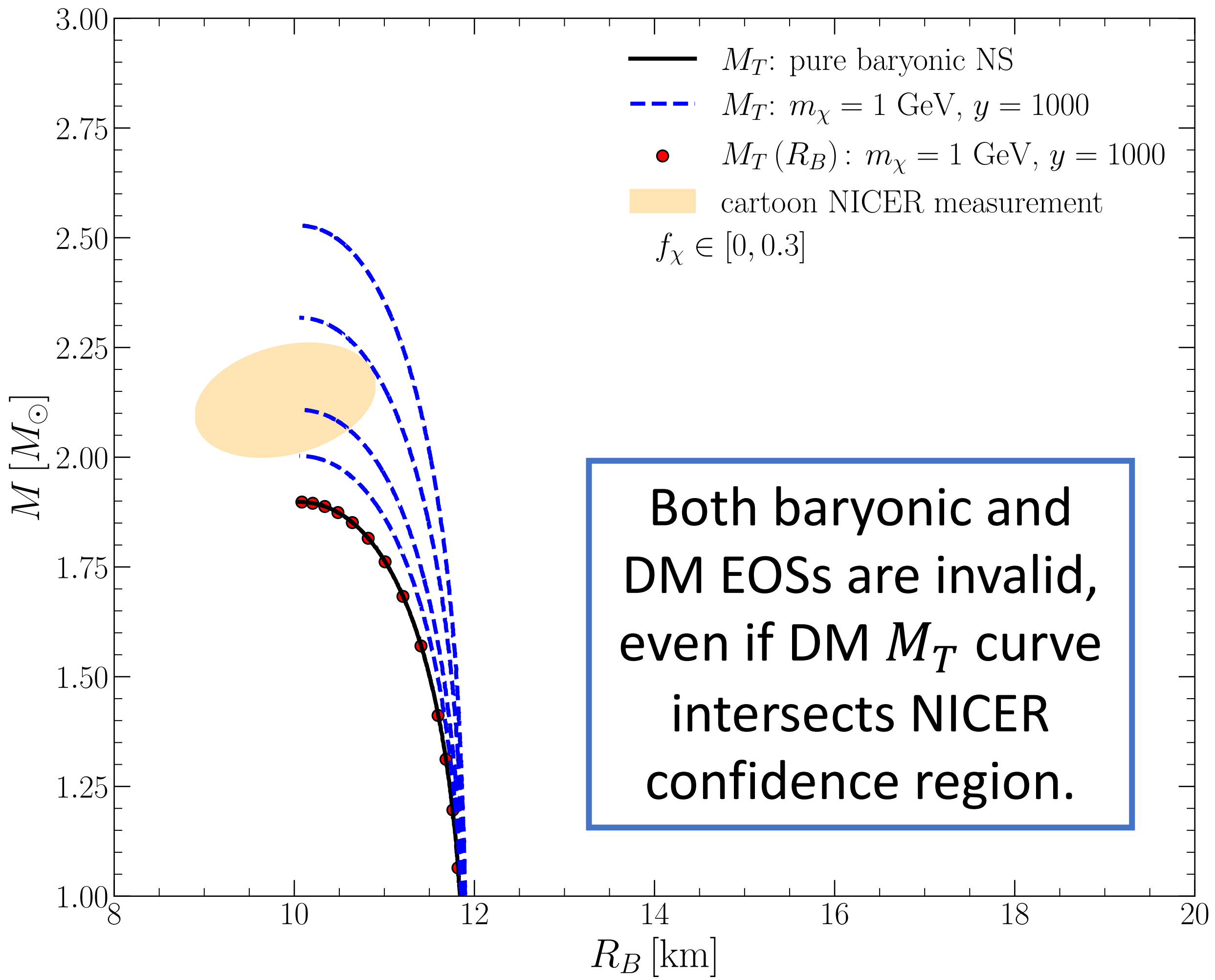
- We find that
  $M_T(R_B) \approx M_{T,\mathrm{pure}}$
  for large parameter space of dark halo cases

- In these cases, we can analyse whether baryonic EOSs are valid if a dark halo exists

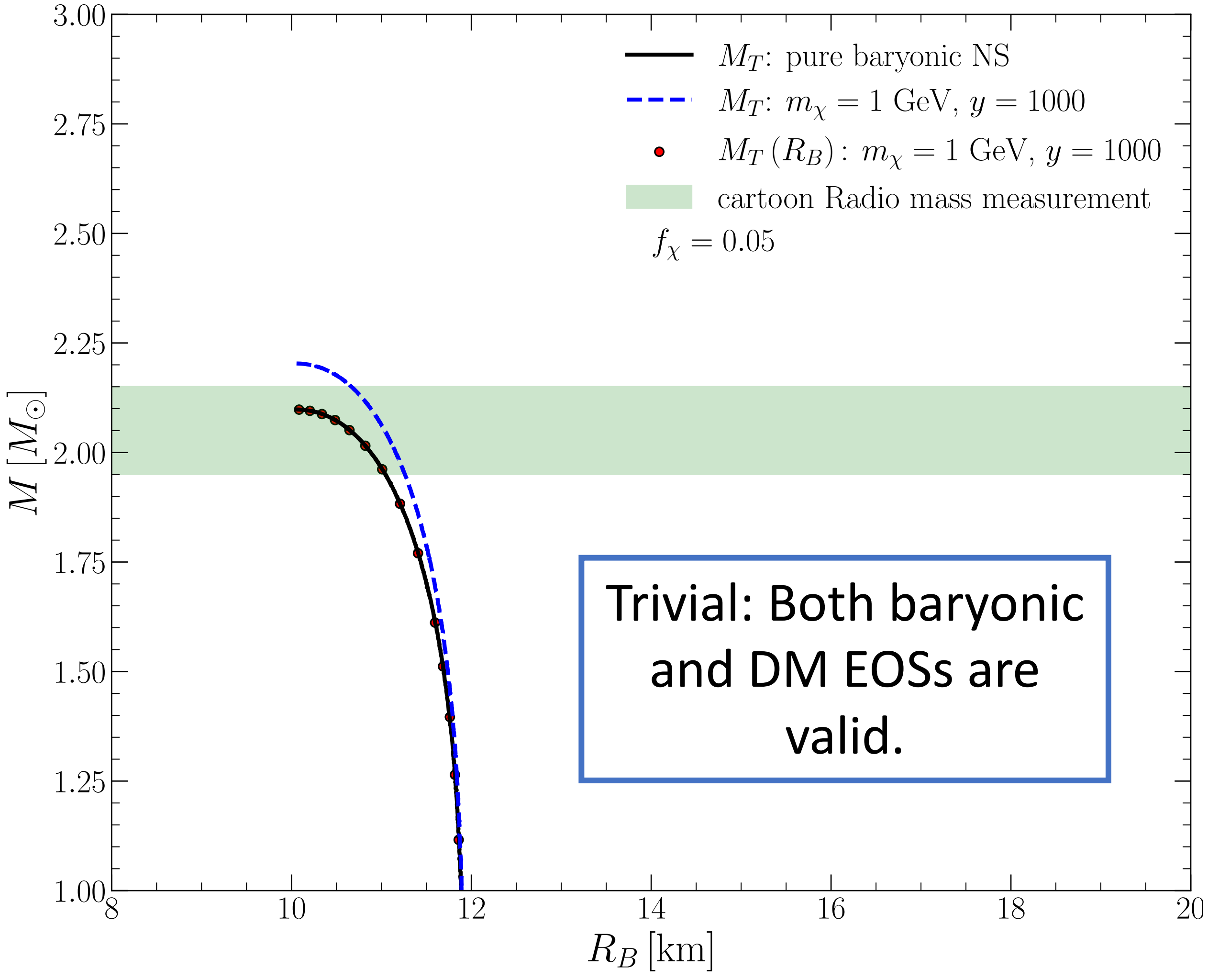


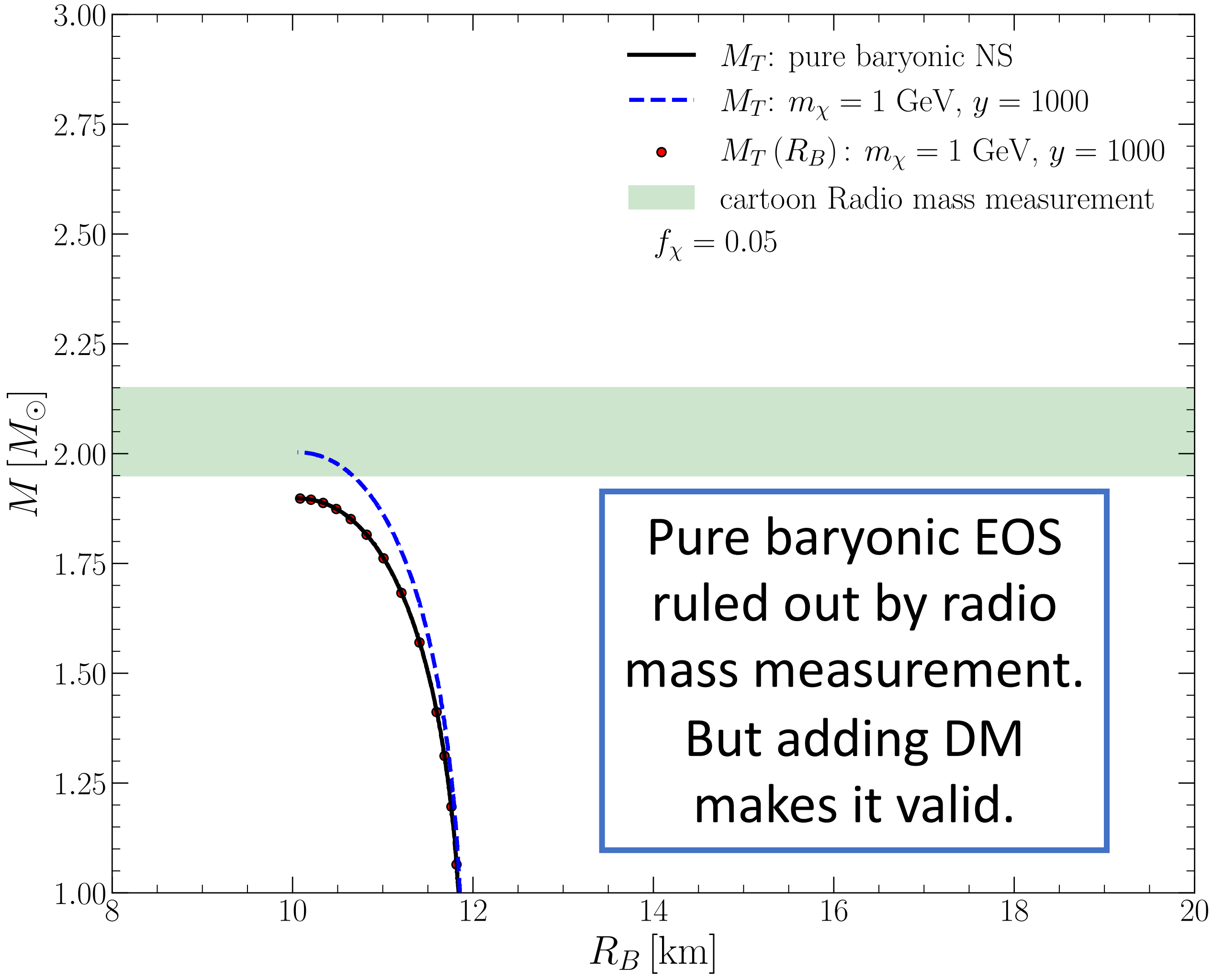
Case 1: No radio mass measurement. Only NICER measurement available.



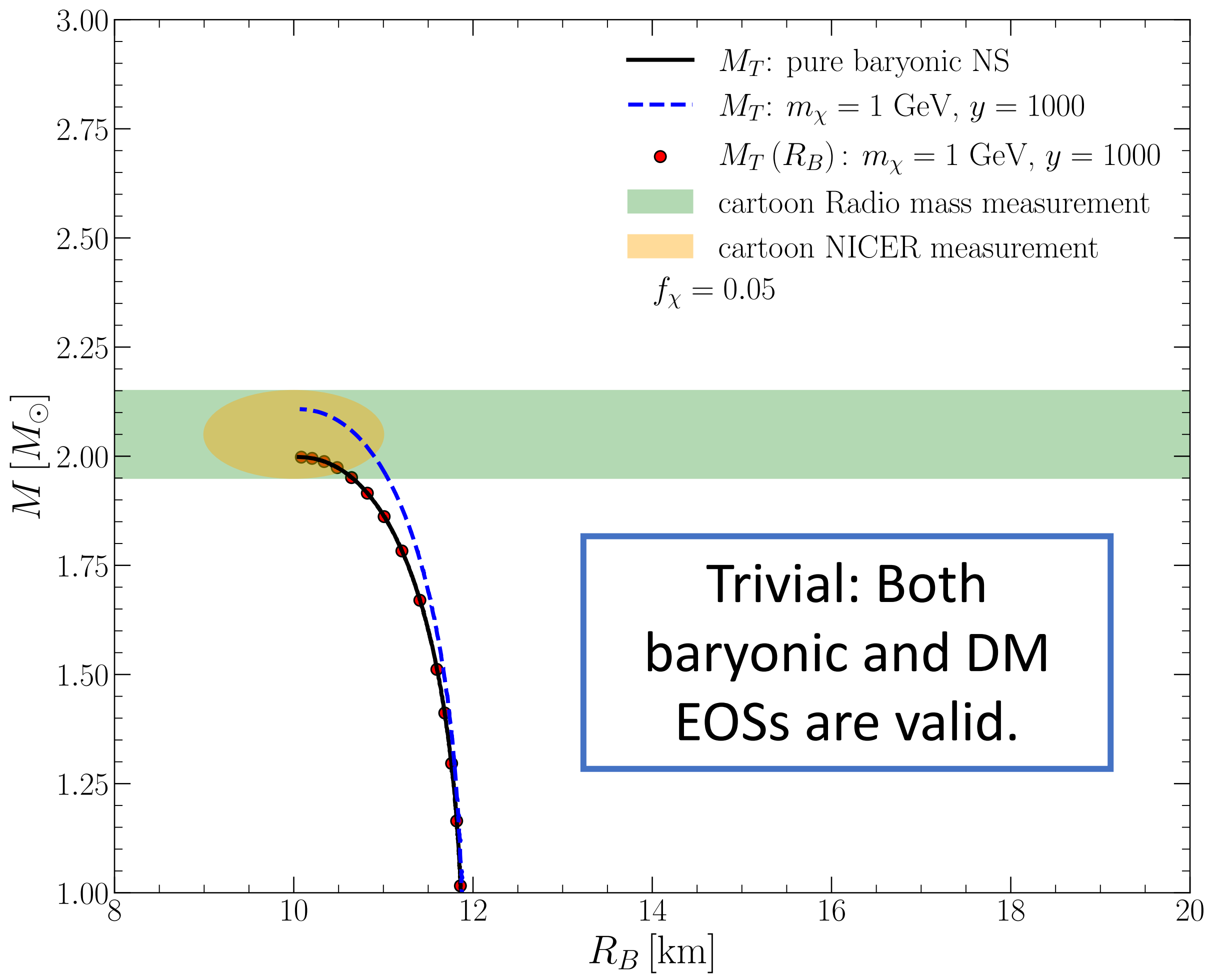


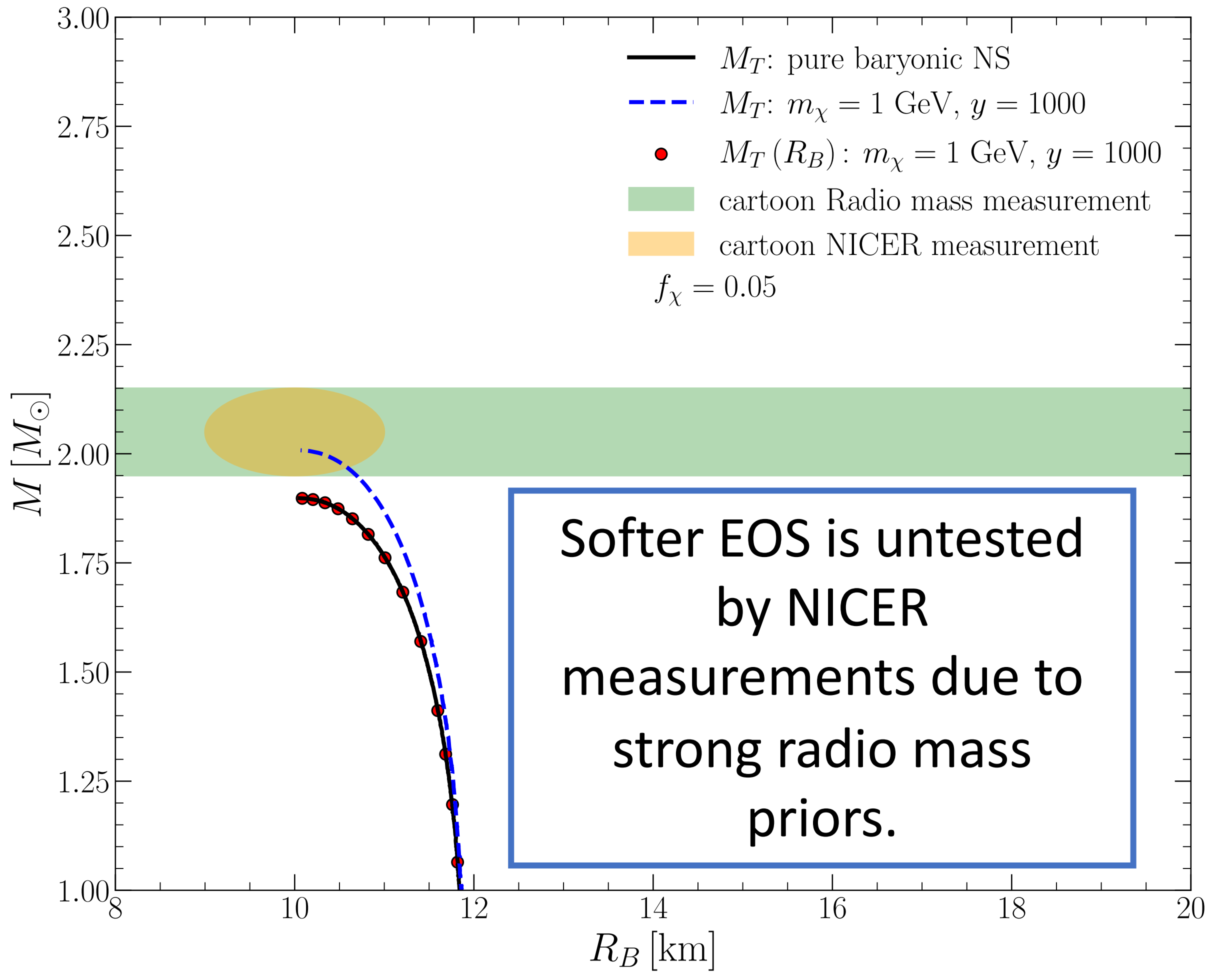
Case 2: Only radio mass measurement available. No NICER measurement.





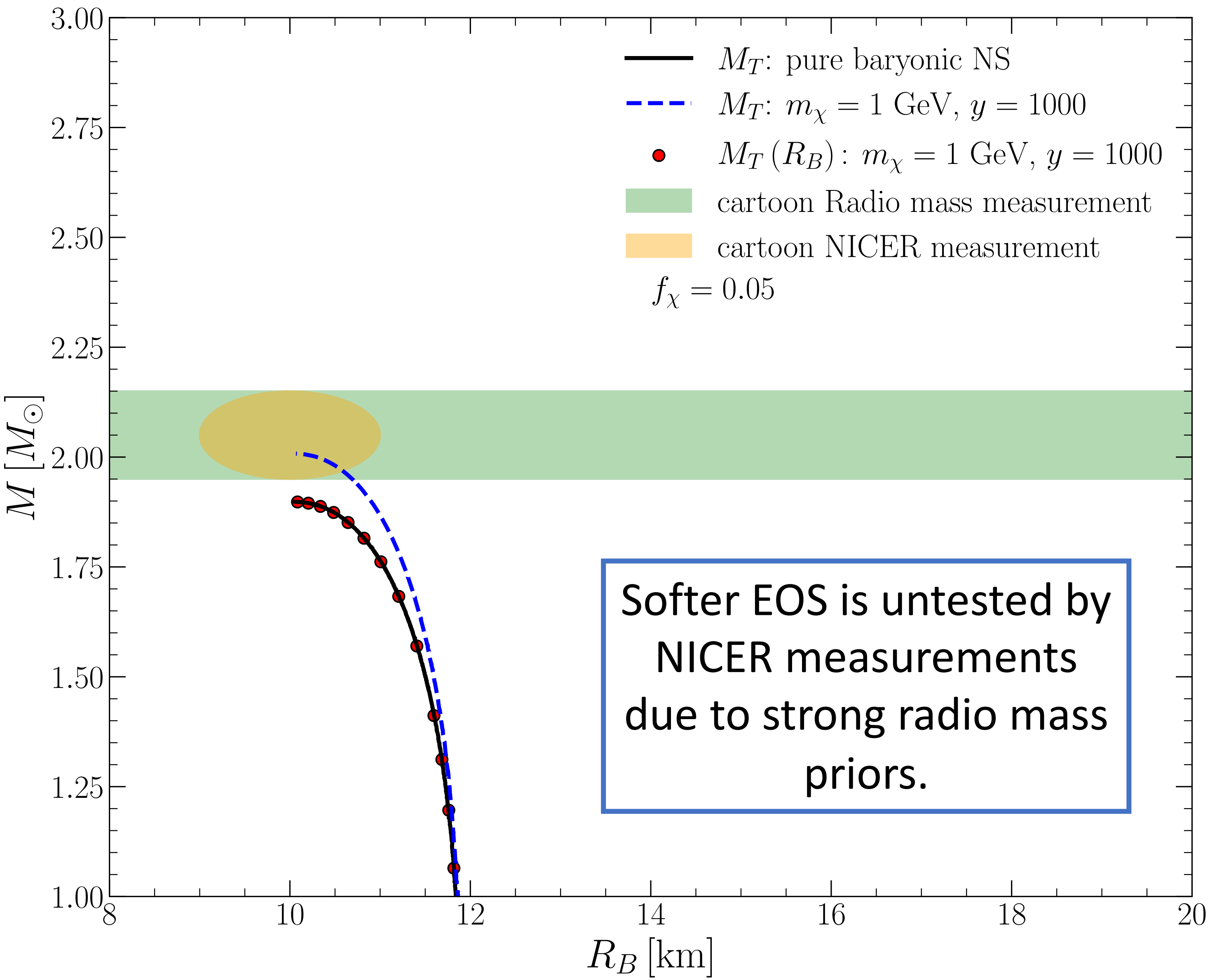
Case 3: Both Radio mass and NICER measurements available.





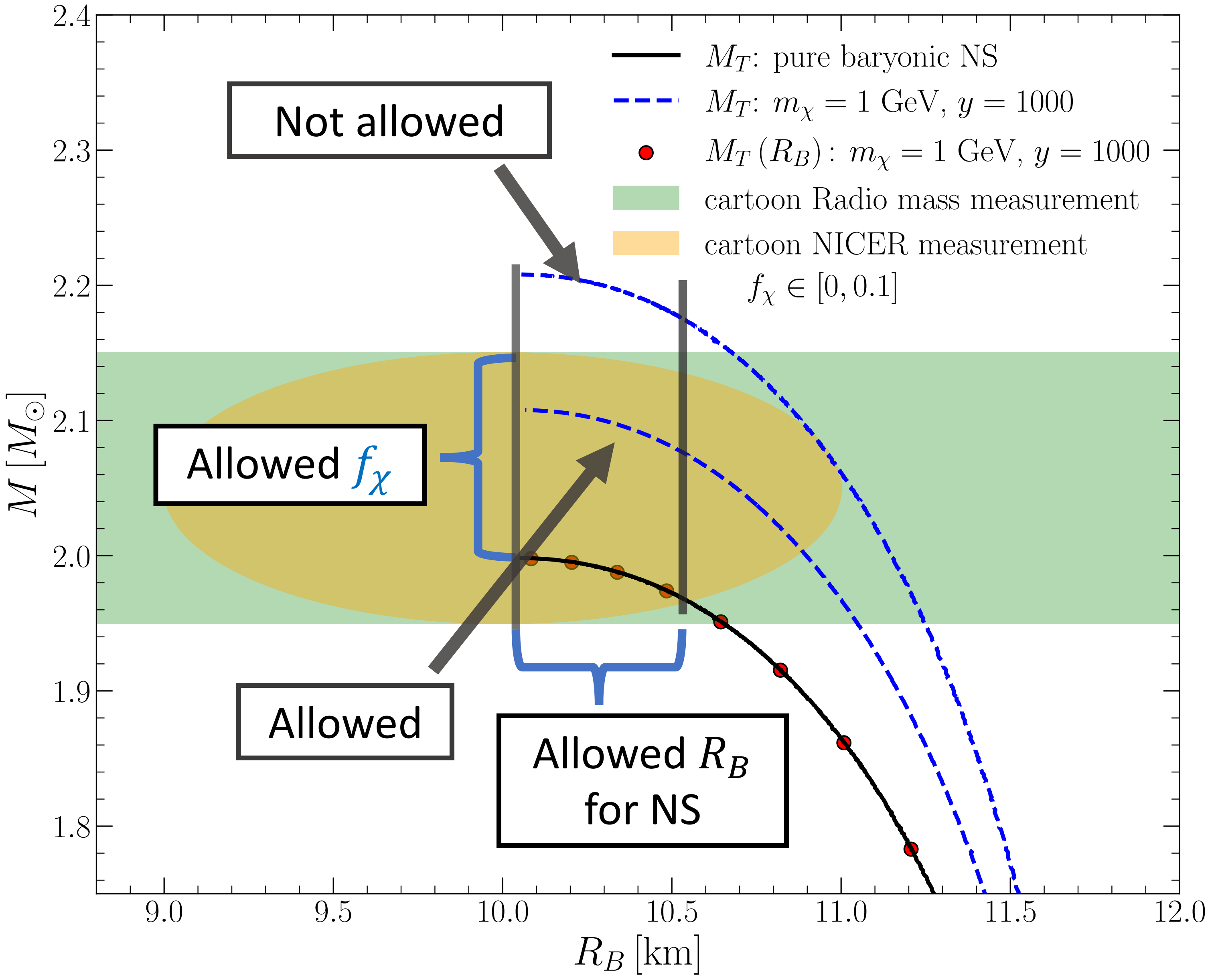
Soft EOSs Untested by NICER

- Assume some maximum $f_\chi \sim 0.05$.
- Reduce NICER mass priors by f_χ.
- Redo NICER analysis to measure new $M_T(R_B)$ and R_B.
- Check which EOSs are valid now.



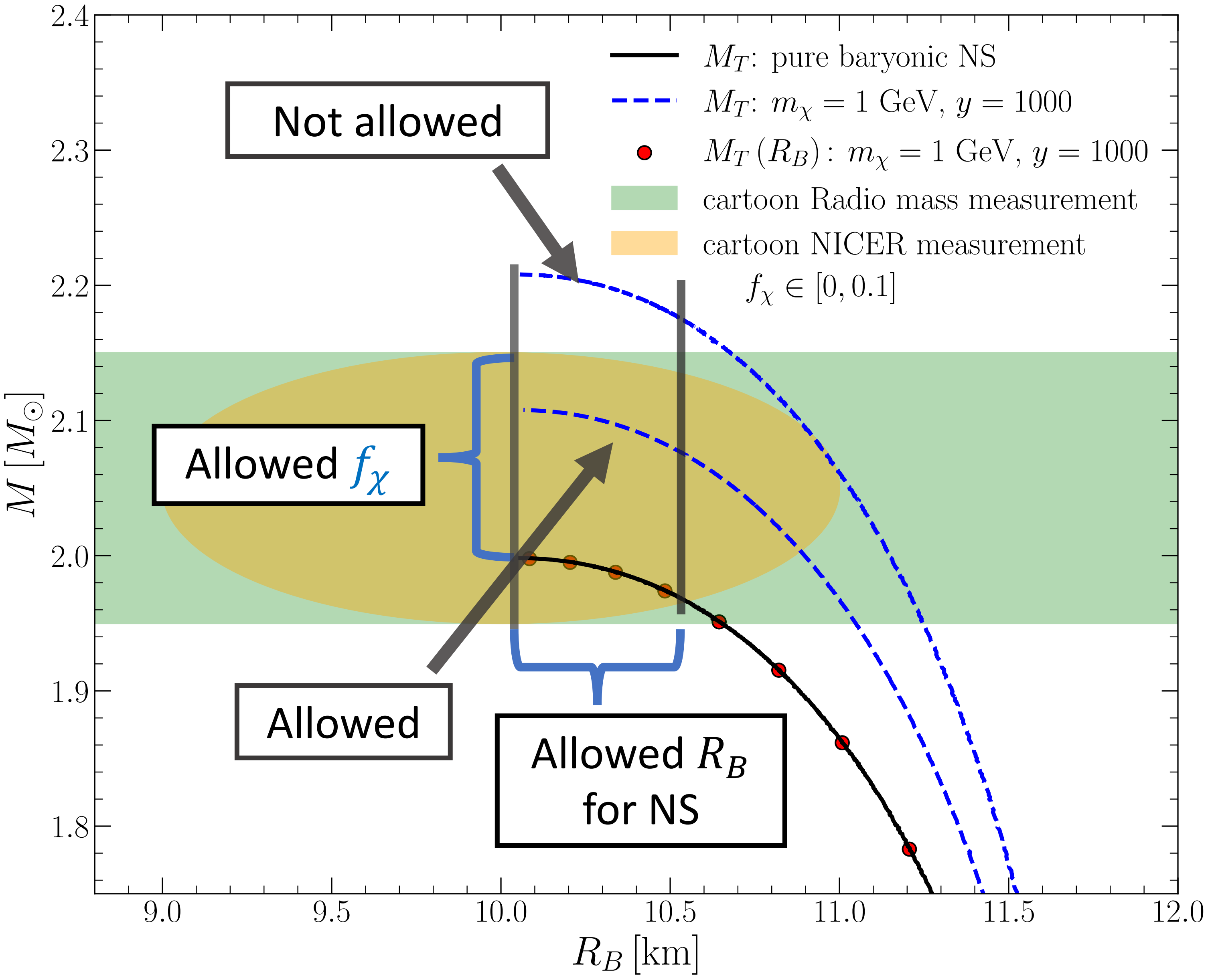
Softer EOS is untested by NICER measurements due to strong radio mass priors.

Constrain f_χ in NS



Constrain f_χ in NS

- Simulate dark halos
- Is ΔF_{peak} small?
- Is $M_T(R_B) \approx M_{T,\text{pure}}$?
- Constrain f_χ based on a particular baryonic EOS and DM m_χ and y.



Conclusions

- Dark matter Admixed NSs can have M-R and X-ray pulse profiles significantly different from pure baryonic NSs
- If $\frac{|\Delta F_{\text{peak}}|}{F_{\text{peak}}}$ for DM halo is large, NICER reanalysis is required to constrain DM properties
- If $\frac{|\Delta F_{\text{peak}}|}{F_{\text{peak}}}$ for DM halo is small, we can use current NICER results to constrain both baryonic EOSs as well as DM fractions for a wide parameter space of DM m_χ and y