

Neutron Star Searches for Clumpy Dark Matter

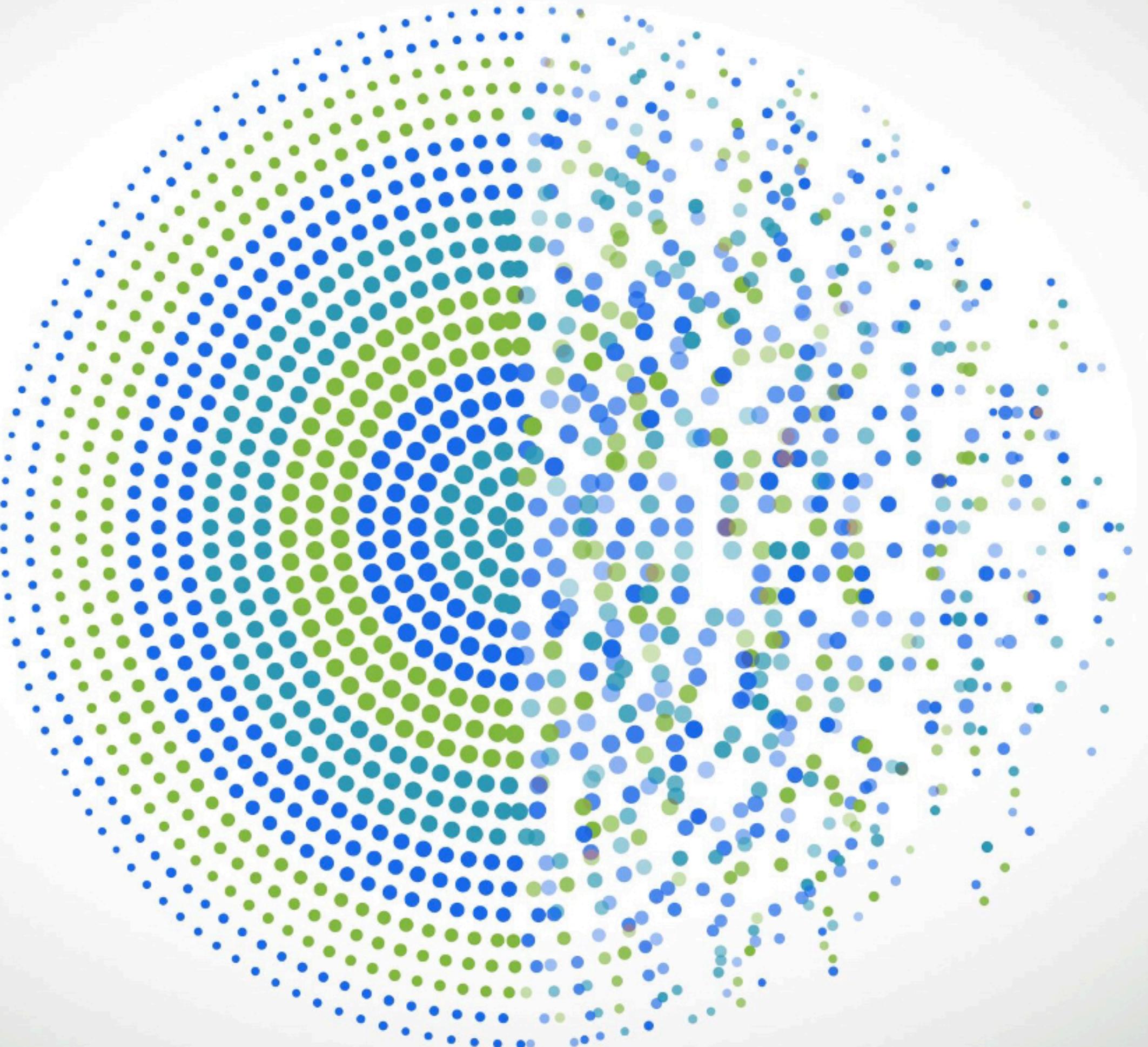
Mega DM Workshop, Mainz 2022

Joseph Bramante

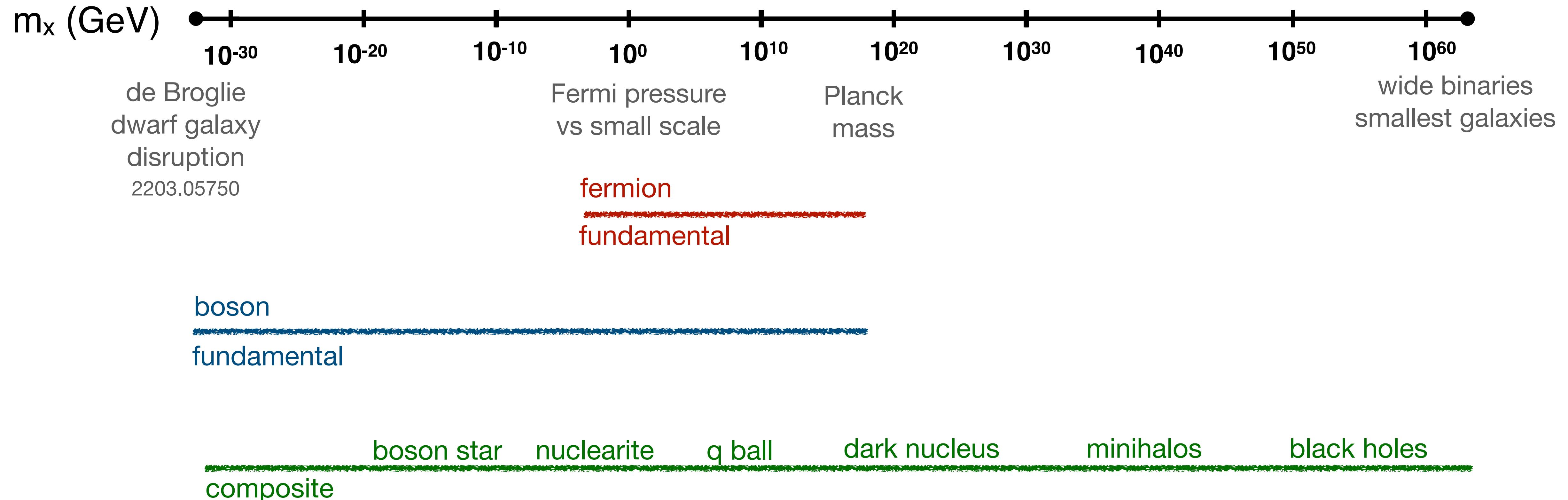
Queen's University

McDonald Institute

Perimeter Institute



What's up with dark matter over here?

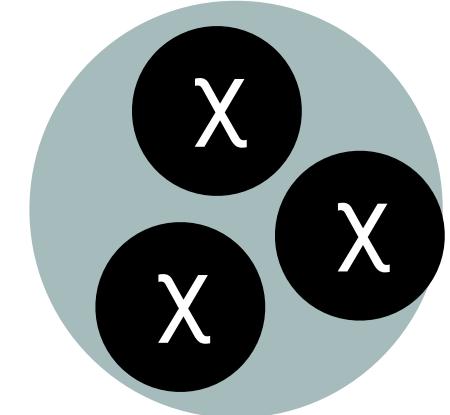
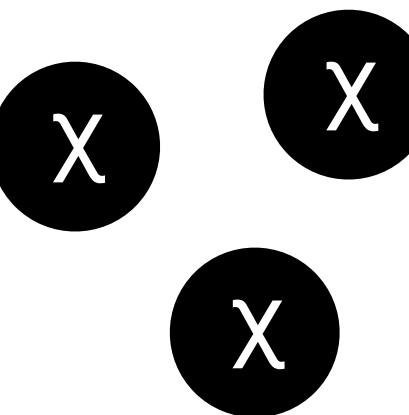


Models

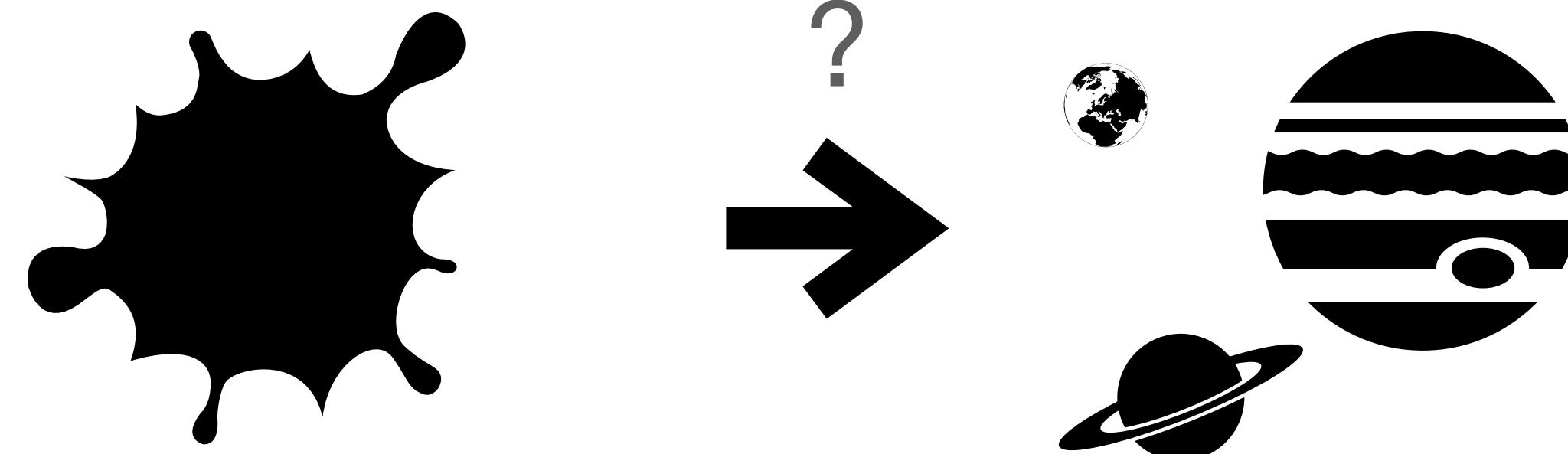
$$-\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 + \bar{X}(i\gamma^\mu\partial_\mu - m_X)X + g_X\bar{X}\varphi X - \frac{1}{2}m_\varphi^2\varphi^2 + g_n\bar{n}\varphi n + \mathcal{L}_{SM},$$

Nice to have a model:

- Early matter domination
- Boson stars
- Dissipative dark sector
- Boson stars
- Q ball
- Dark BBN



On the other hand: What is the Lagrangian / cosmology for planets?



- Planet formation still has open questions (pebble accretion).
- Naive to ask multi-state models to have simple analytic solutions like single-field DM models, which were often selected for convenience.

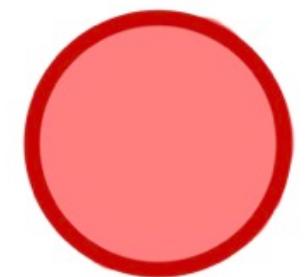
Subhalo DM; clumps, dark stars, big composites

from e.g. early matter domination, dissipation, DM BBN

Searches

- Gravitational microlensing
- Pulsar timing
- Gravitational waves (mergers)
- Molecular gas cloud heating
- Stellar collisions (optically thick clump)
- Neutron stars, minerals, cosmic rays
for subhalo DM-nucleon detection

this talk



DM halo

subhalo

$\sigma_{nx} ?$

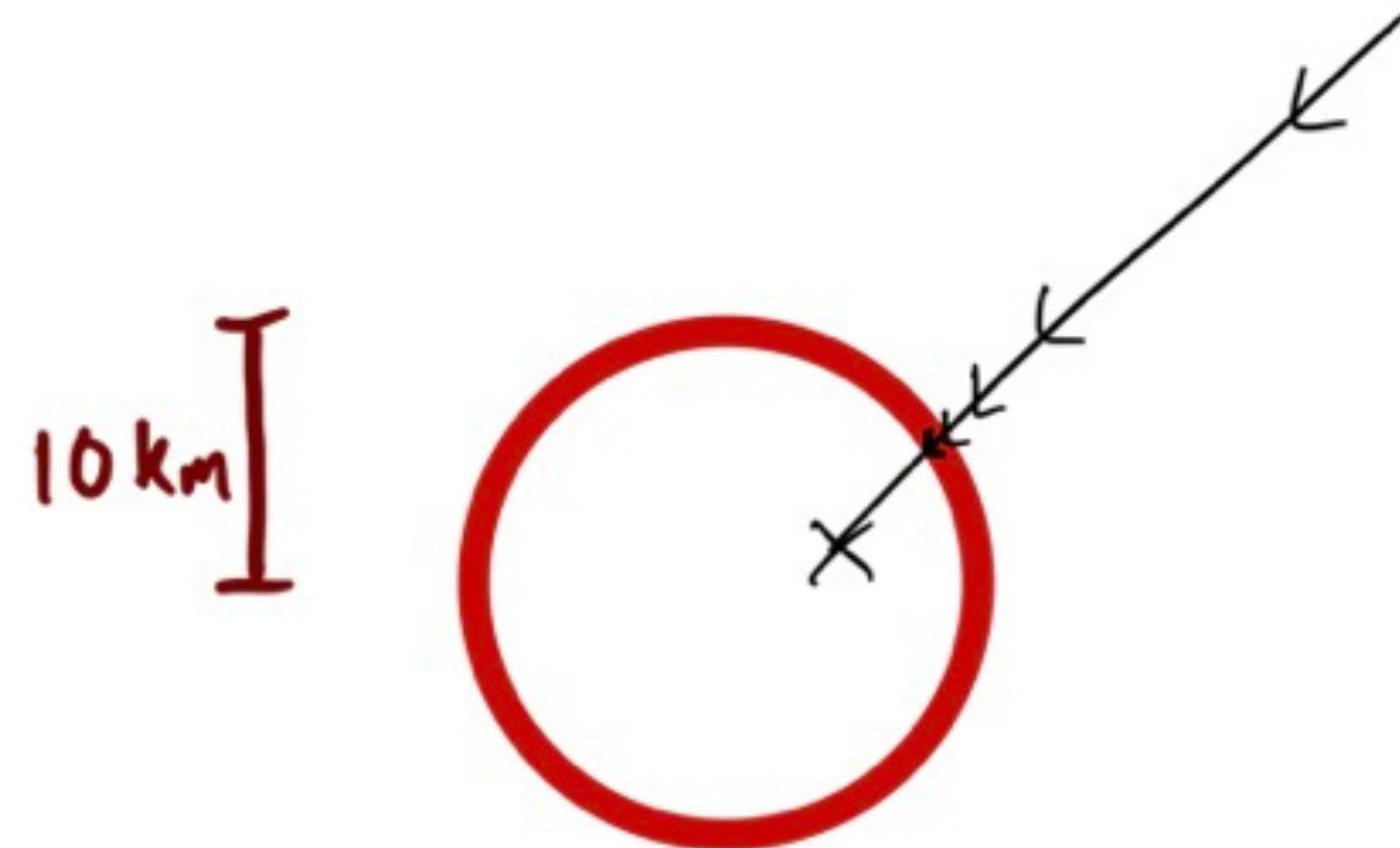
Neutron stars: nature's dark matter accelerators

- Neutron stars accelerate dark matter to beyond freezeout speeds

$$v_{esc} = \sqrt{\frac{2GM}{R}} \sim 0.7c$$

- Dense, accept a large DM flux

- fiducial mass of $\sim 10^{57}$ GeV
- neutrons:protons:electrons $\sim 10:1:1$
- flux of ~ 100 grams of DM/second



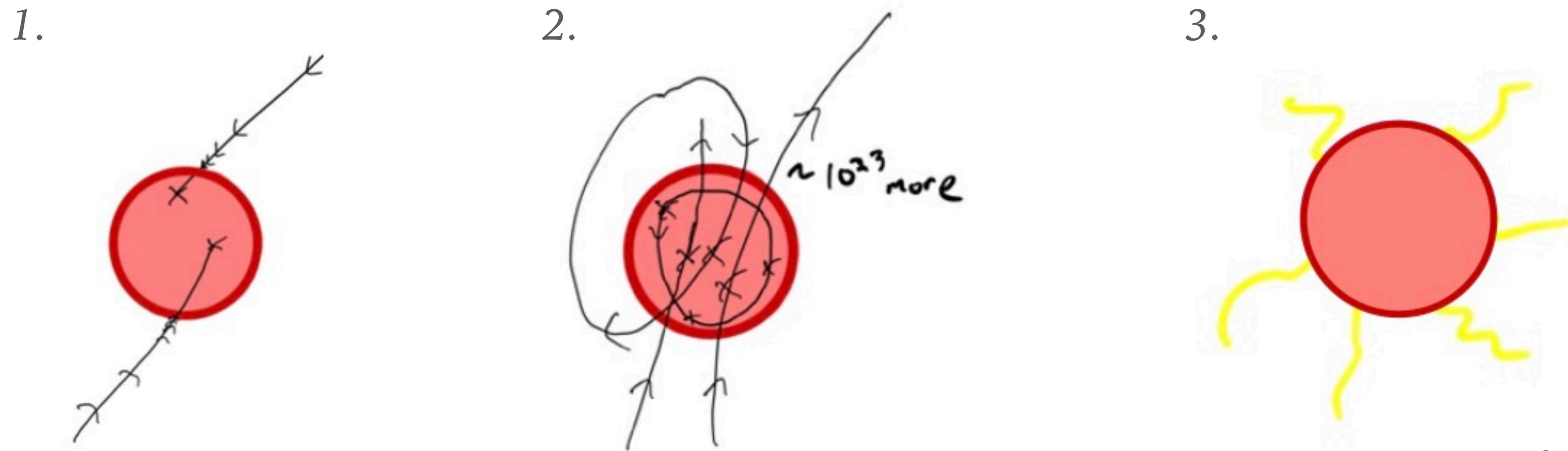
Neutron stars: broad reach for particle dark matter

1. EFT, Spin-Dependent, Spin-Independent, Strongly Interacting, Electroweakino, Inelastic
Kouvaris 2007
Bertone, Fairbairn 2007
JB Delgado, Martin 2017
Baryakhtar, JB, Li, Linden, Raj 2017
Raj, Tanedo, Yu 2017
Acevedo, JB, Leane, Raj 2019
Bell, Busoni, Robles 2019
2. Leptophilic dark matter
Joglekar, Raj, Tanedo, Yu 2019
Chen, Lin 2018
Jin, Gao 2018
3. Self-interacting dark matter
Hamaguchi, Nagata, Yanagi 2019
Garani, Genolini, Hambye 2018
Keung, Marfatia, Tseng 2020
Bai, Berger, Korwar, Orlofsky 2020
Camargo, Queiroz, Sturani 2019
Bell, Busoni, Robles 2020
4. Heavy DM, baryon and lepton annihilating DM, compressed WIMPs, co-annihilating DM
Garani, Heeck 2019
Goldman, Nussinov 1989
Kouvaris, Tinyakov 2011
McDermott, Yu, Zurek 2011
JB, Fukushima, Kumar 2013
Bell, Melatos, Petraki 2013
Bertoni, Nelson, Reddy 2014
JB, Linden 2014
JB, Elahi 2015
5. Winos, Higgsinos, Precision Capture, Pasta Capture
6. Muonphilic
7. Asymmetric (converts NSs into black holes)

(more...)

Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to $\sim 0.7c$ by neutron star
2. DM deposits kinetic energy by scattering and re-scattering in the neutron star
(may also annihilate in the NS)
3. Heats NS to 1750 K if all DM captured, 2500 K with annihilation (for 0.4 GeV/cm³)



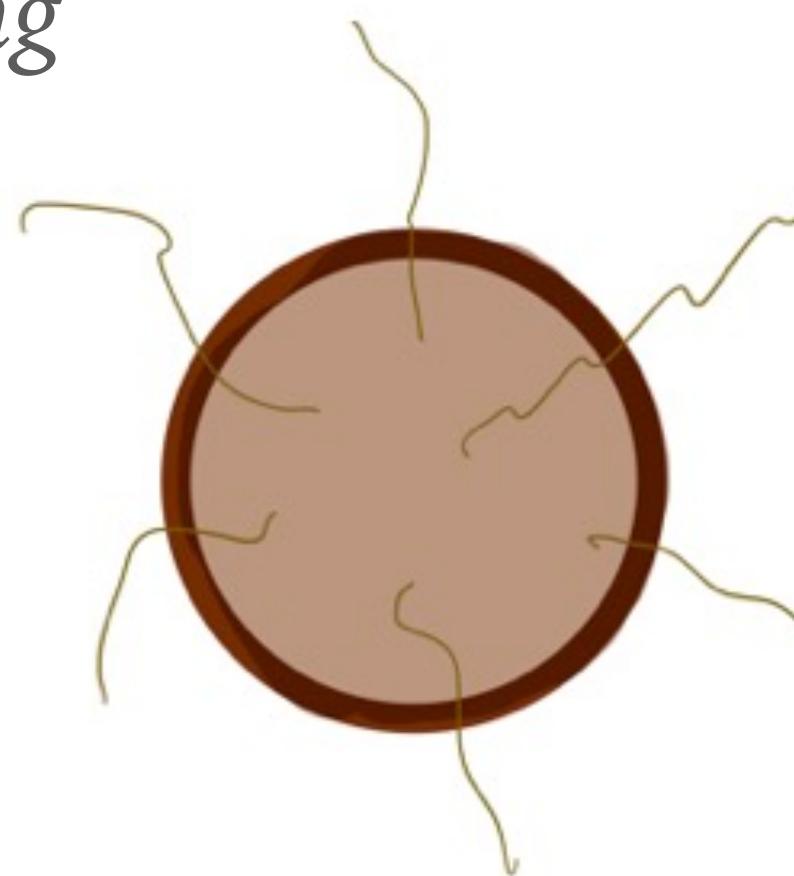
$T \sim 1750 / 2500 \text{ K}$, for NS near Earth

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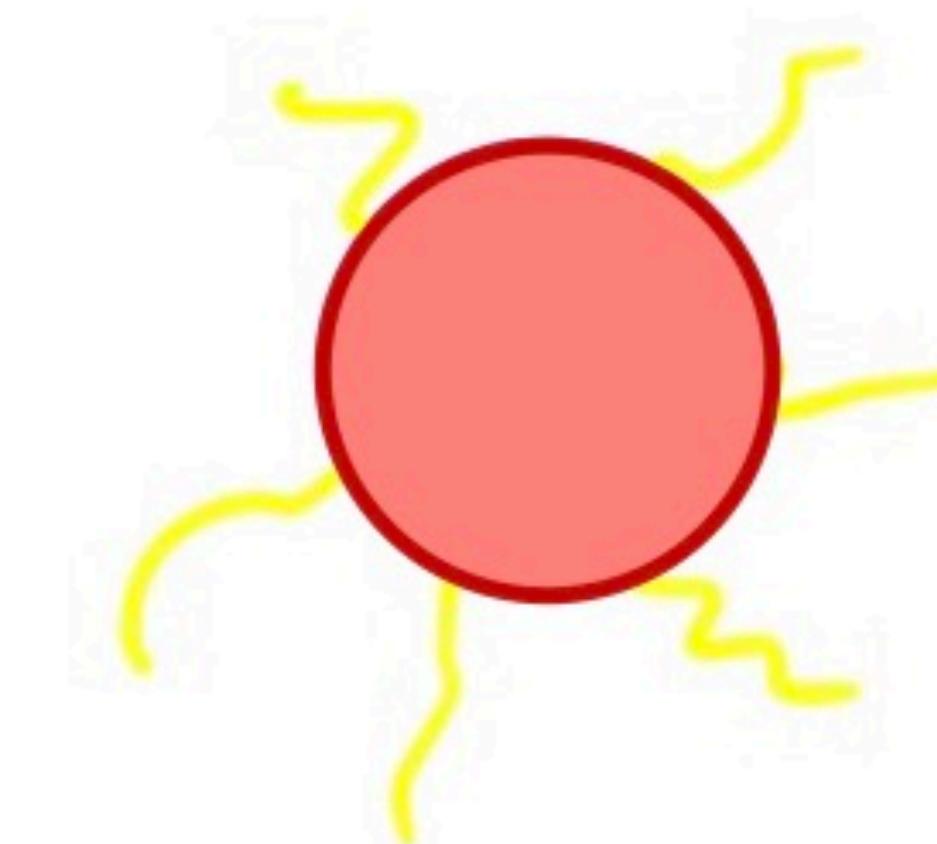
0. Compare to NS without DM heating

$$T_{eff}^\infty \sim 100 \text{ K} \left(\frac{\text{Gyr}}{t} \right)^{1/2}$$



e.g. Yakovlev Pethick astro-ph/0402143
Page Lattimer et al. astro-ph/0403657

3.

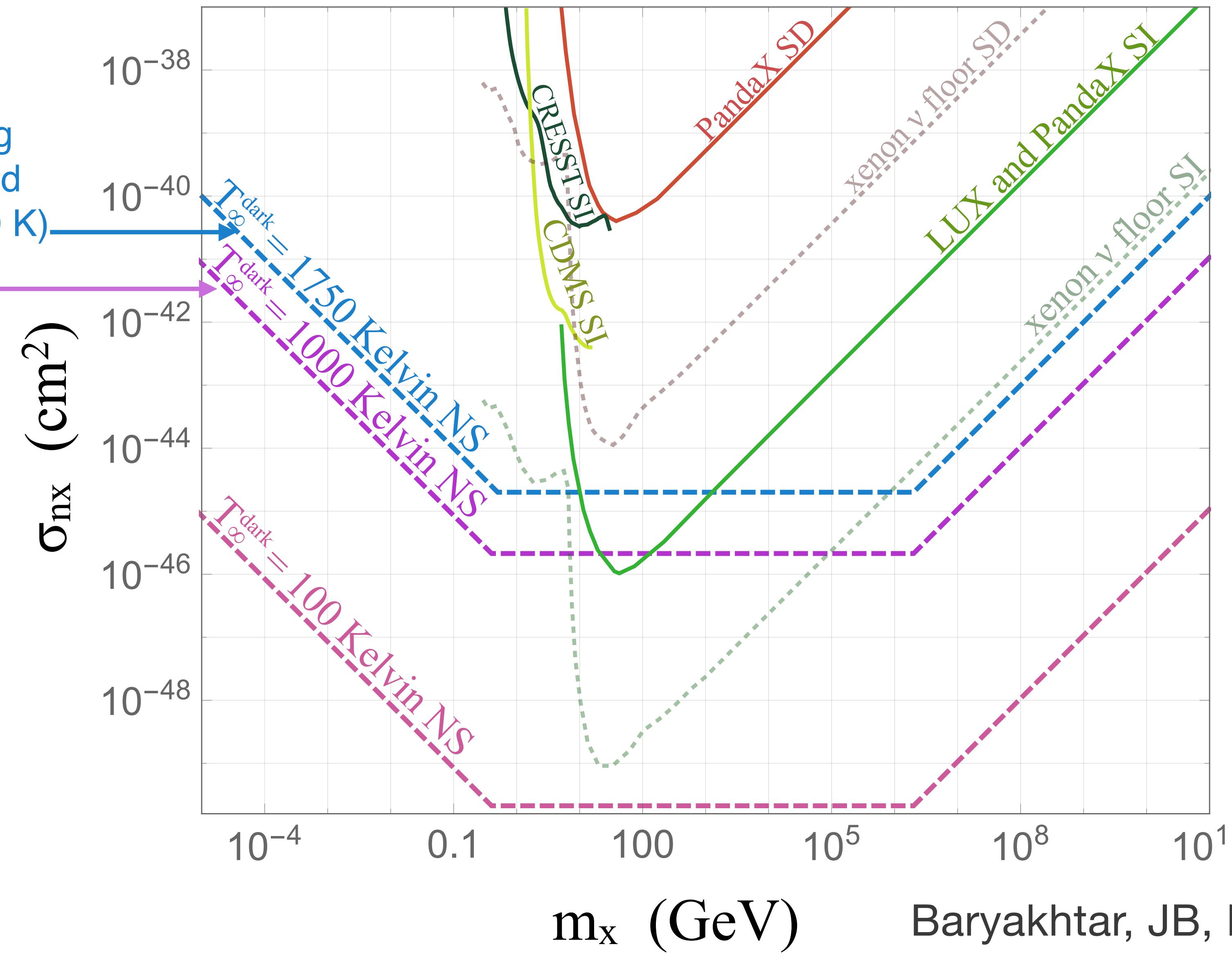


$T \sim 1750 / 2500 \text{ K}$, for NS near Earth

Neutron Star Dark Matter Heating Sensitivity

all incoming
DM captured
(ann. $T \sim 2500$ K)

10% incoming
DM captured
(ann. $T \sim 1400$ K)



Looking for WIMPs with 30+ meter telescopes

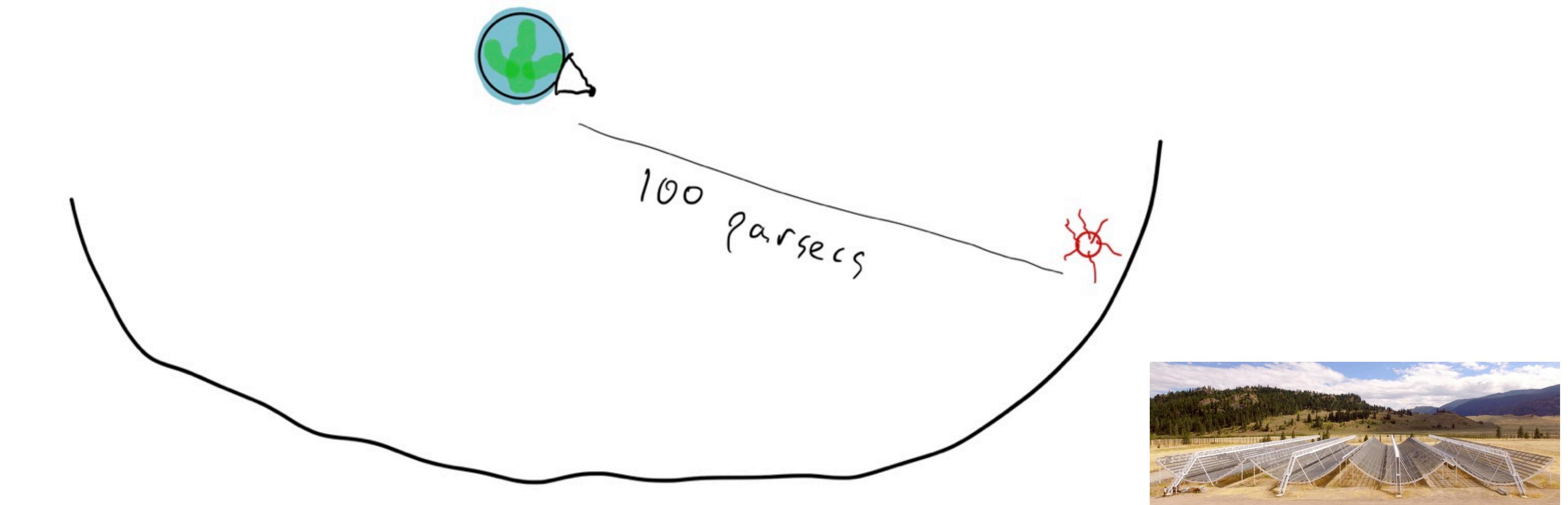
ELT 2 σ sensitivity estimates

annihilation of WIMPs, Higgsinos

$$t \sim 3 \times 10^6 \text{ sec} \left(\frac{d}{100 \text{ pc}} \right)^4 \quad (\text{Y band})$$

kinetic only

$$t \sim 10^6 \text{ sec} \left(\frac{d}{30 \text{ pc}} \right)^4 \quad (\text{K band})$$



Radio observations of nearby pulsars

d (pc)	period (s)
J1057-5226	90
J0736-6304	4.86
J0834-60	0.38
J0711-6830	0.005
J0749-68	0.91
J0924-5814	0.71

-YMW16 dispersion measure distances

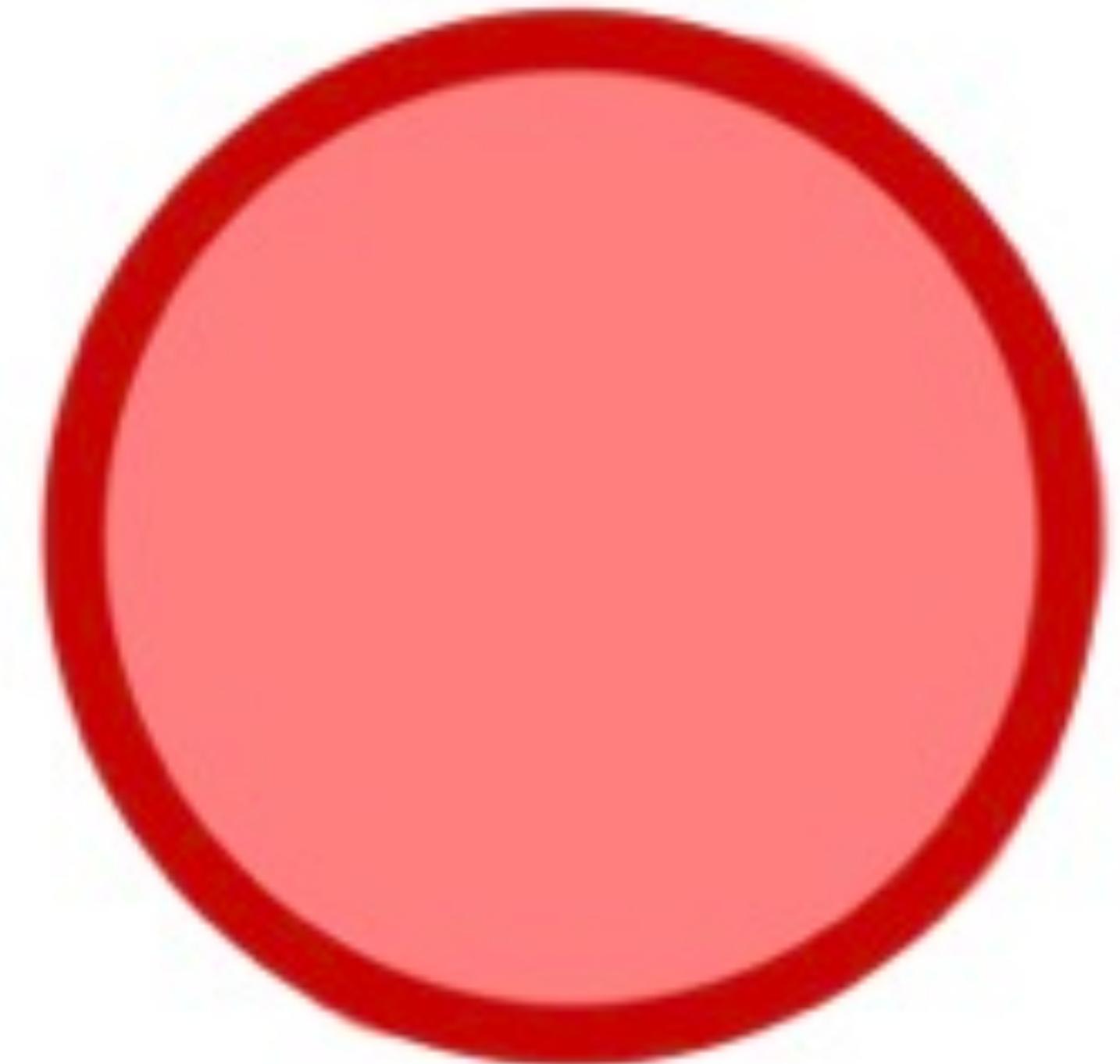
Coldest Known Neutron Star

PSR J2144–3933

Coldest known neutron star, nearby, deep imaged by HST, observed no emission setting a bound (Guillot et al 2019)

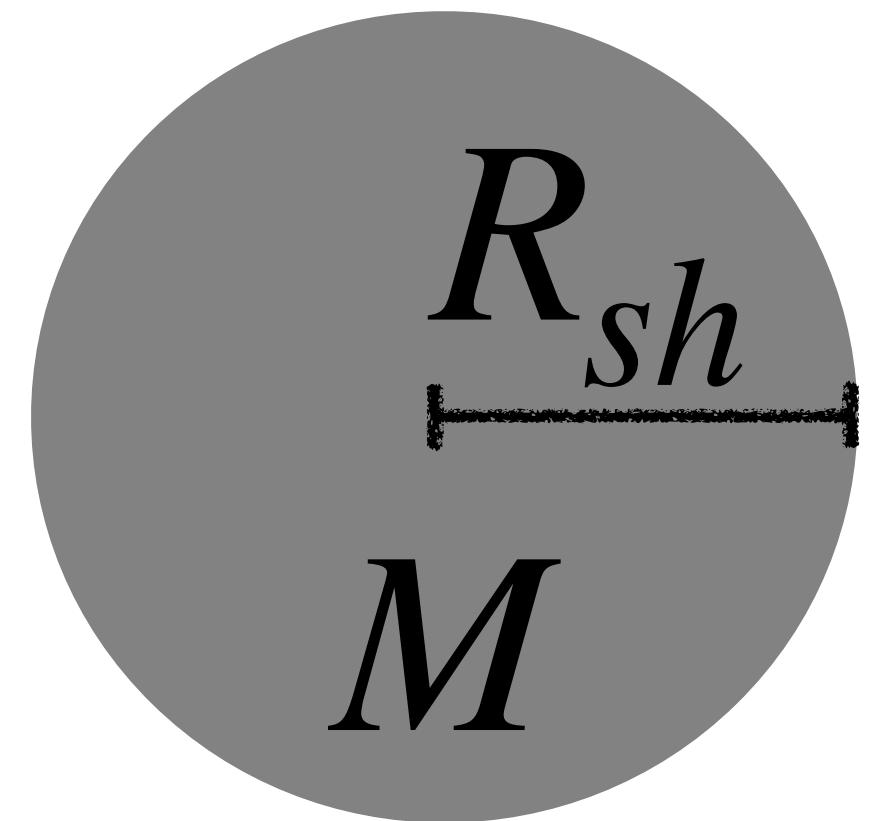
$$T_S < 3 \times 10^4 \text{ K}$$

This isn't cold enough to set a bound on local non-subhalo DM, since 0.3 GeV/cm^3 maximally heats NS to $\sim 1750\text{--}2300 \text{ K}$



Subhalo DM

- Spherical subhalos, constant density, single mass/radius
 - Subhalo DM composes most DM
 - Consider both collisionless and collisional
-
- Future exploration:
 - Nontrivial profiles (e.g. NFW, Einasto, boson star)
 - Spectrum of subhalo masses



Accretion onto NSs, generalized

JB, Kavanagh, Raj 2109.04582

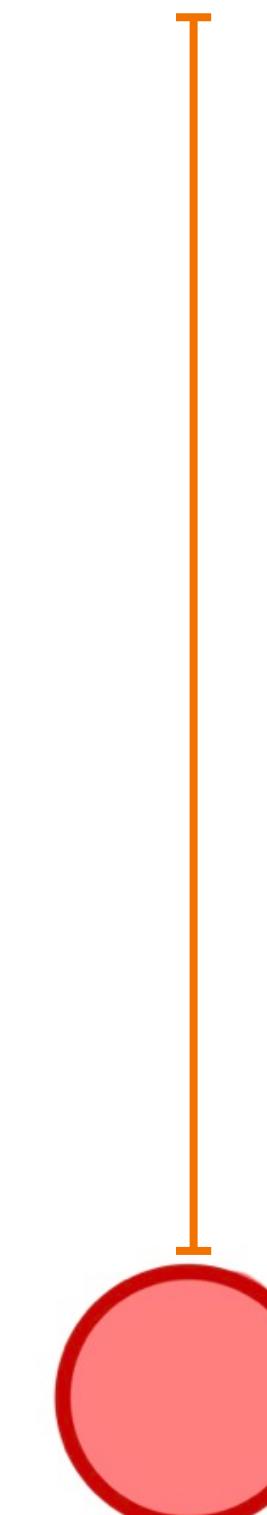
- Radius for DM accretion onto NS depends on size of DM subhalo, and whether accretion is collisionless or collisional

- Collisionless



$$R_{co} = \frac{v_{esc}}{v_{DM}} R_{NS}(1 + z)$$

- Collisional/Bondi

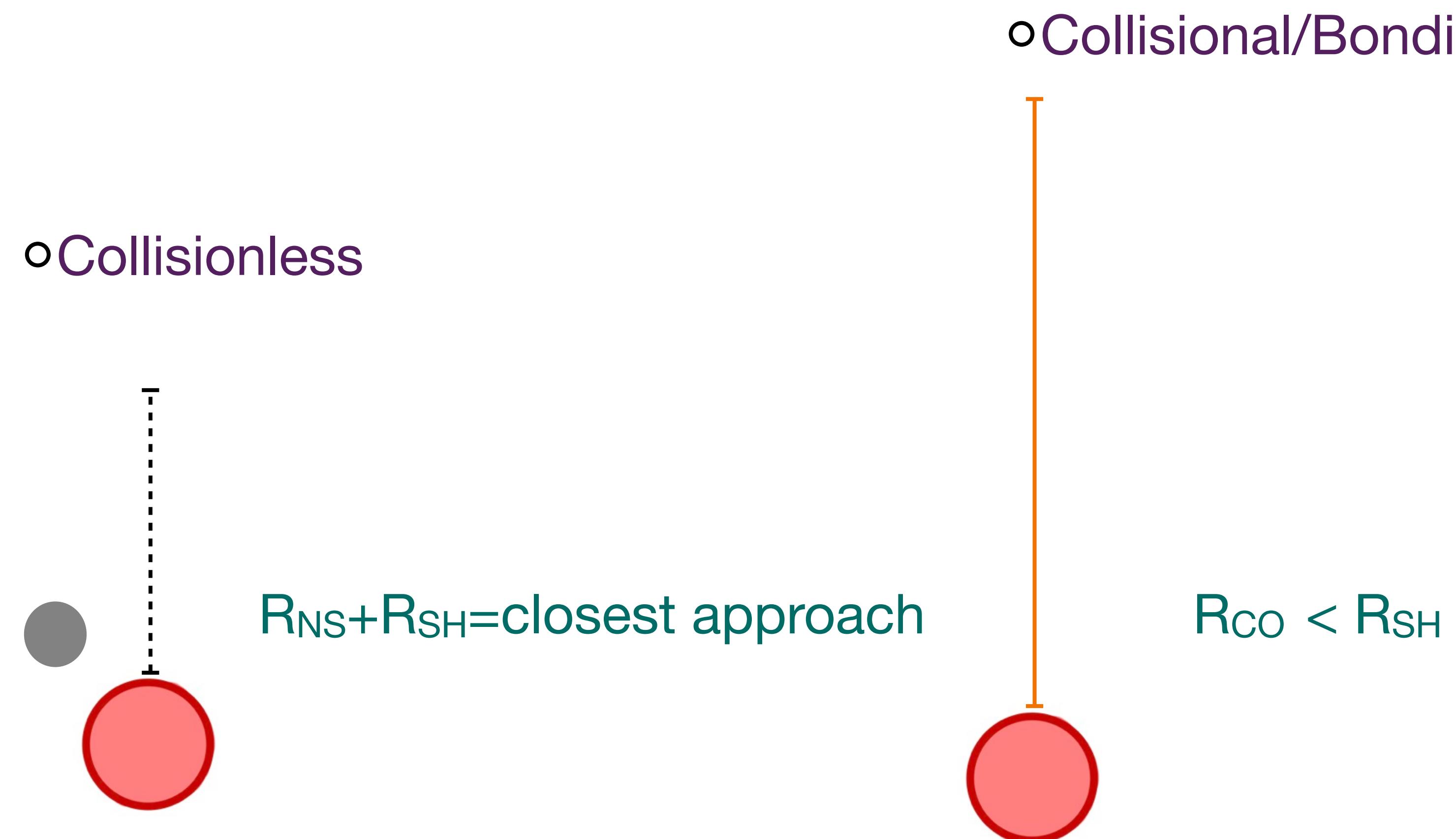


$$R_{co} = \frac{v_{esc}^2}{v_{DM}^2} R_{NS}(1 + z)$$

Accretion: size of subhalo

JB, Kavanagh, Raj 2109.04582

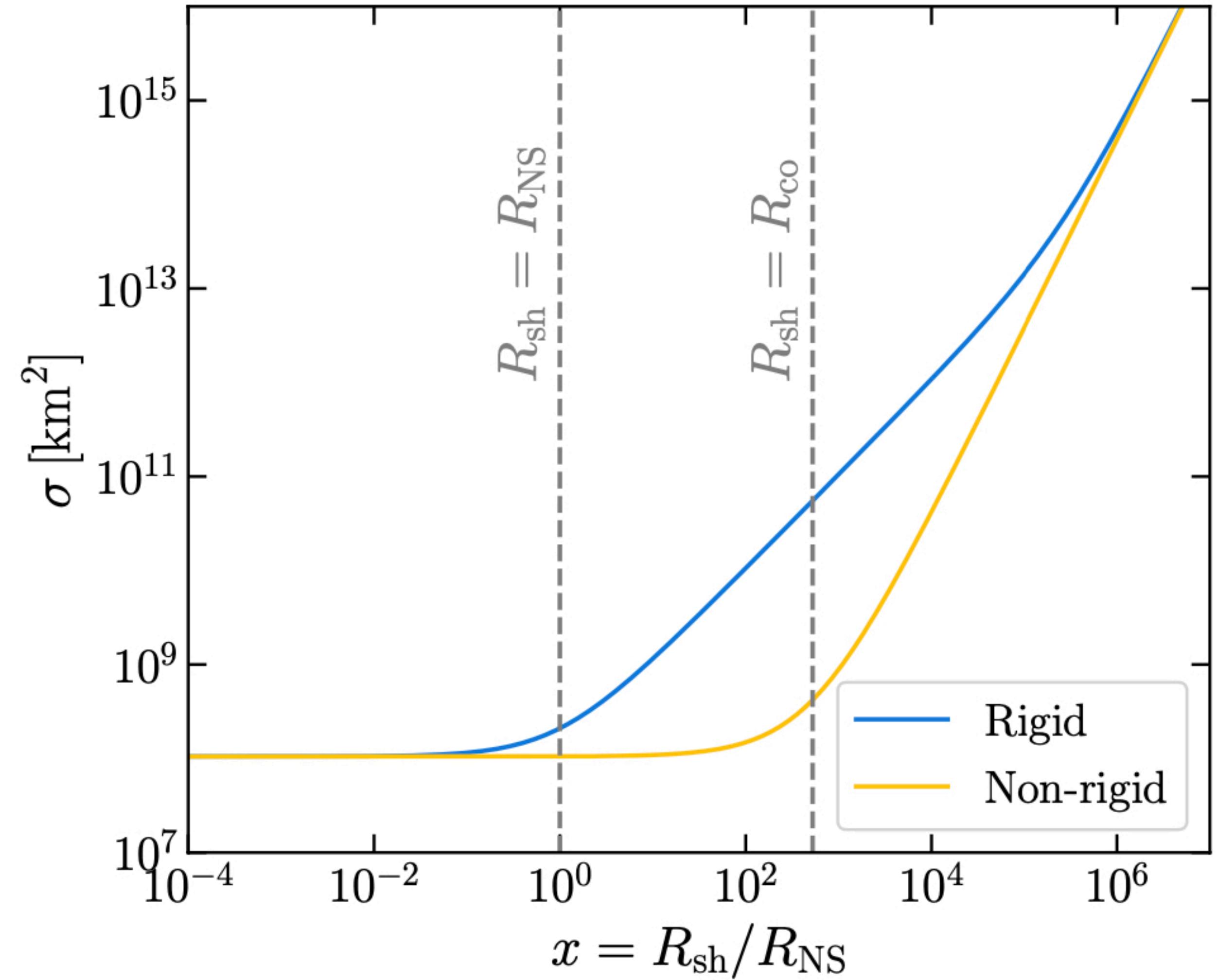
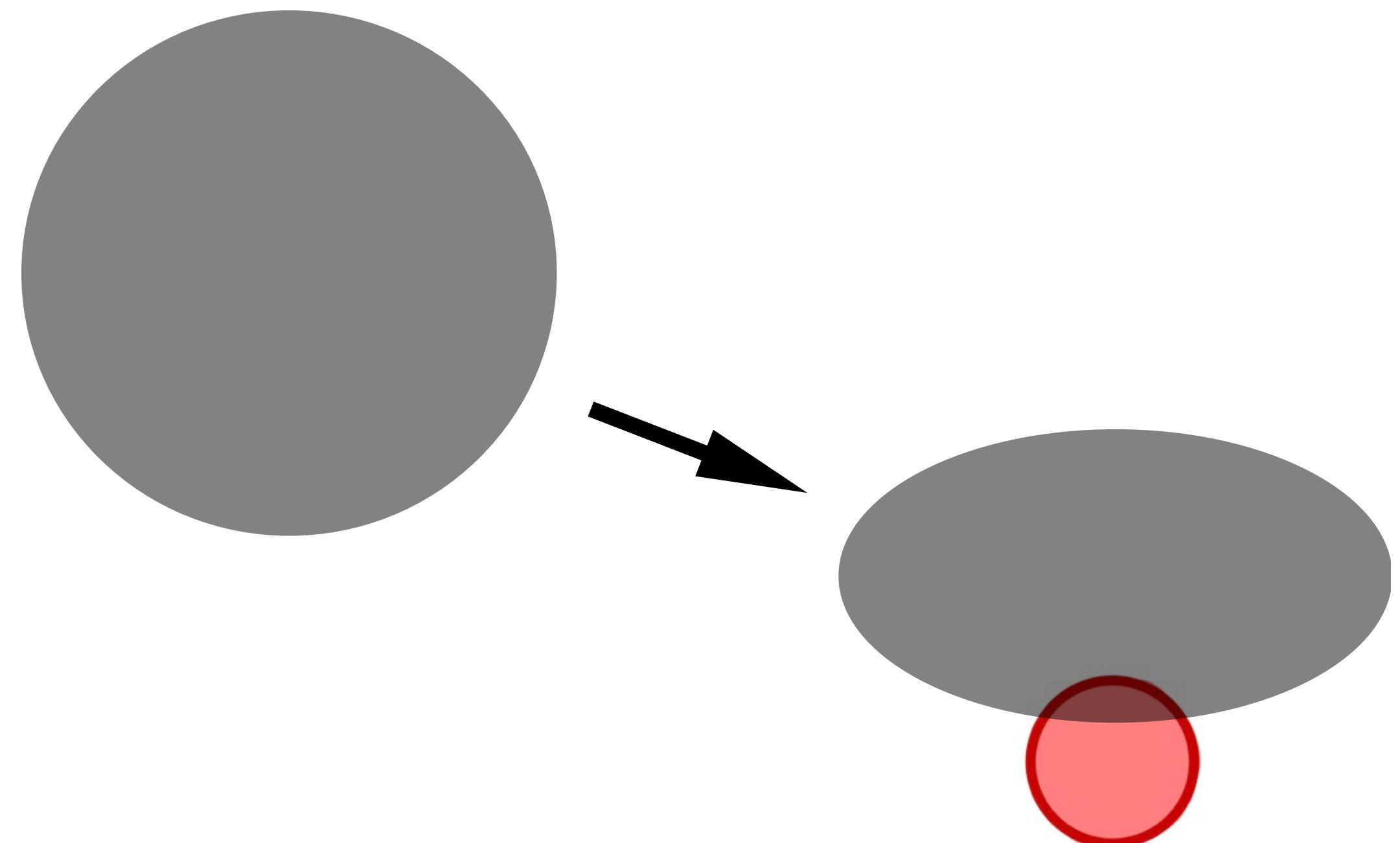
- Consistency requirements for both accretion regimes



Accretion III: rigidity

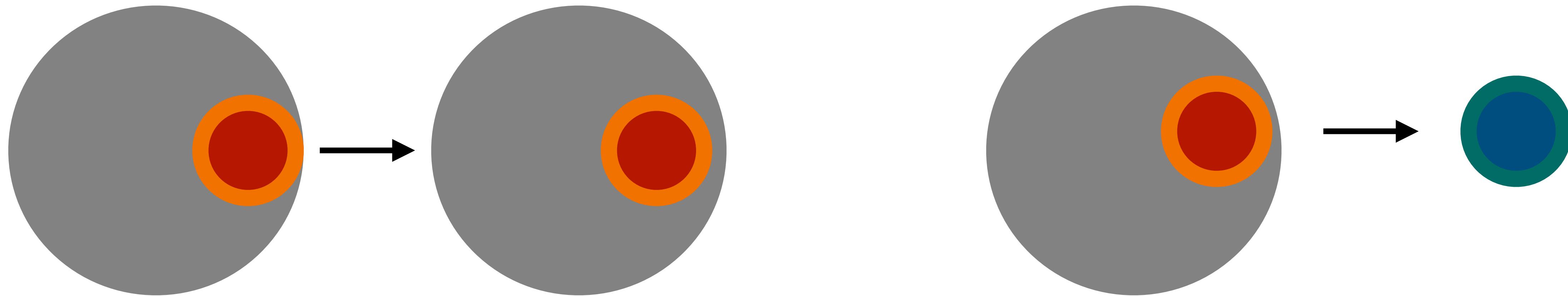
JB, Kavanagh, Raj 2109.04582

- In what follows we assume deformable subhalos



Neutron stars either sporadically flash heated or multi-subhalo steady-state heated

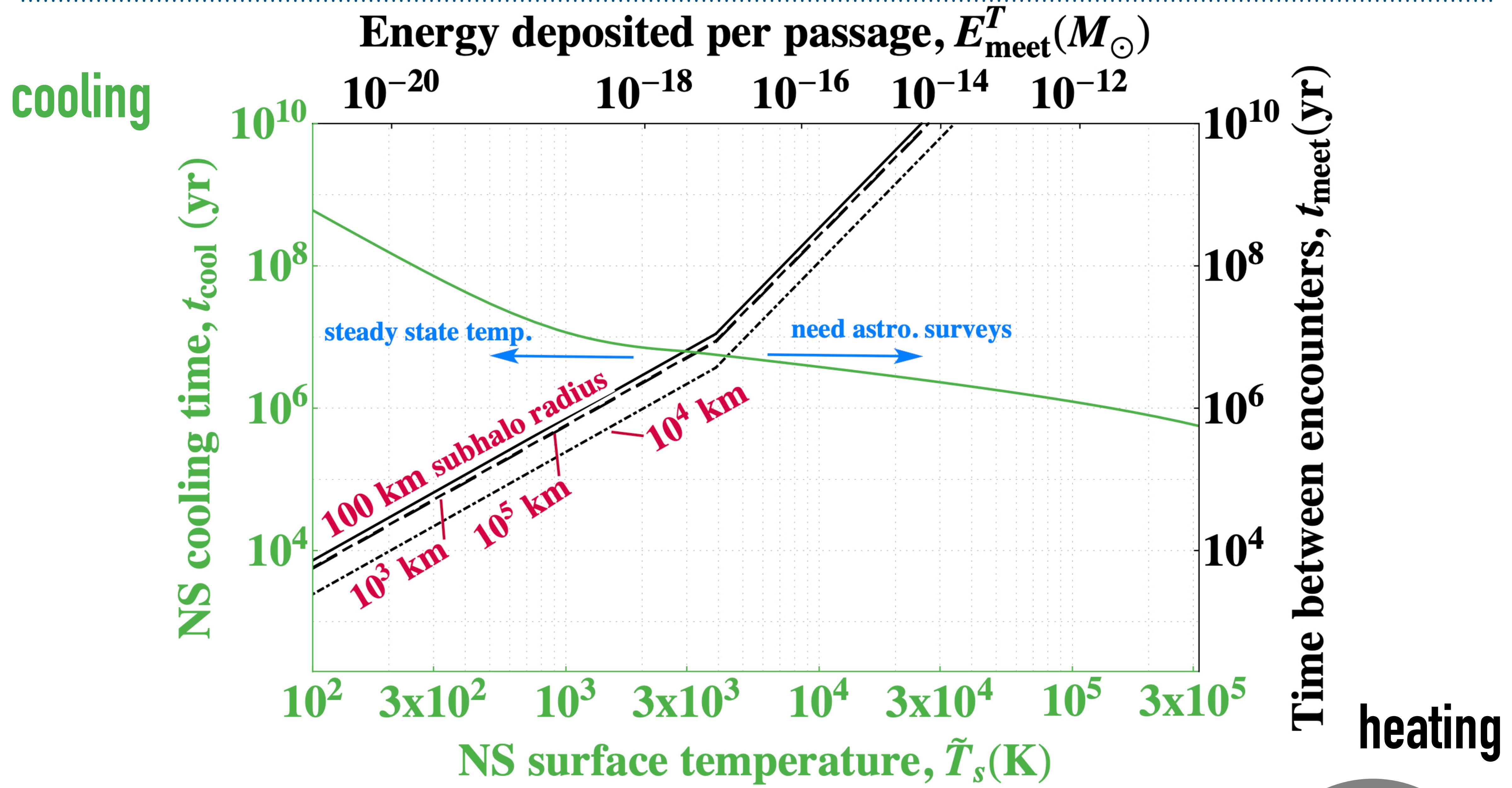
- Neutron stars heated to higher temperatures as they pass by/through dense DM subhalos



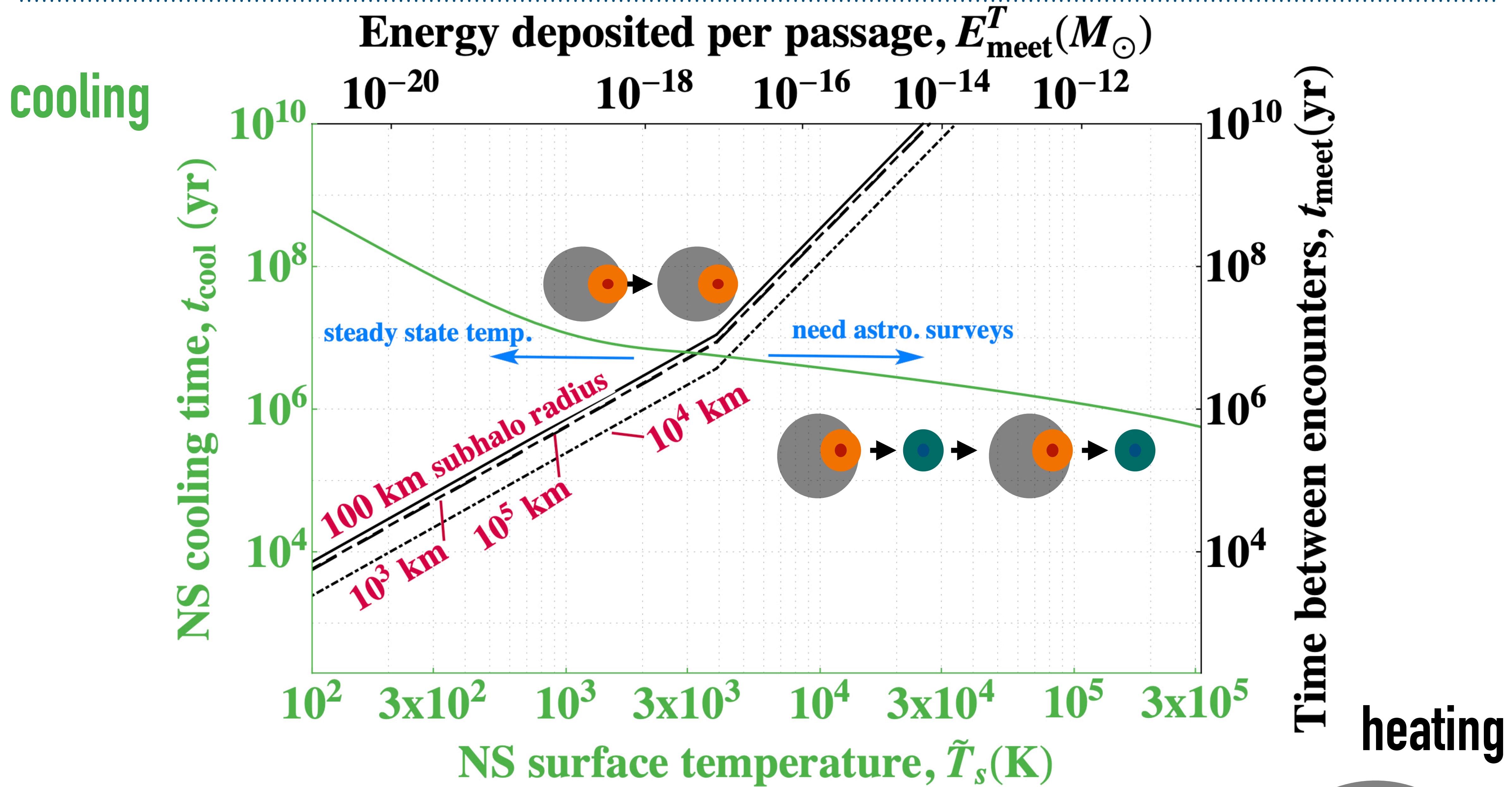
$$\left(\frac{\tilde{T}_{\text{hot}}}{10^4 \text{ K}} \right)^2 = \left(\frac{\tilde{T}_{\text{cold}}}{10^4 \text{ K}} \right)^2 + \frac{E_{\text{meet}}}{6.2 \times 10^{-18} M_{\odot}}$$

$$E_{\text{meet}} = zM \min \left[1, \left(\frac{R_{\text{co}}}{R_{\text{sh}}} \right)^2 \right]$$

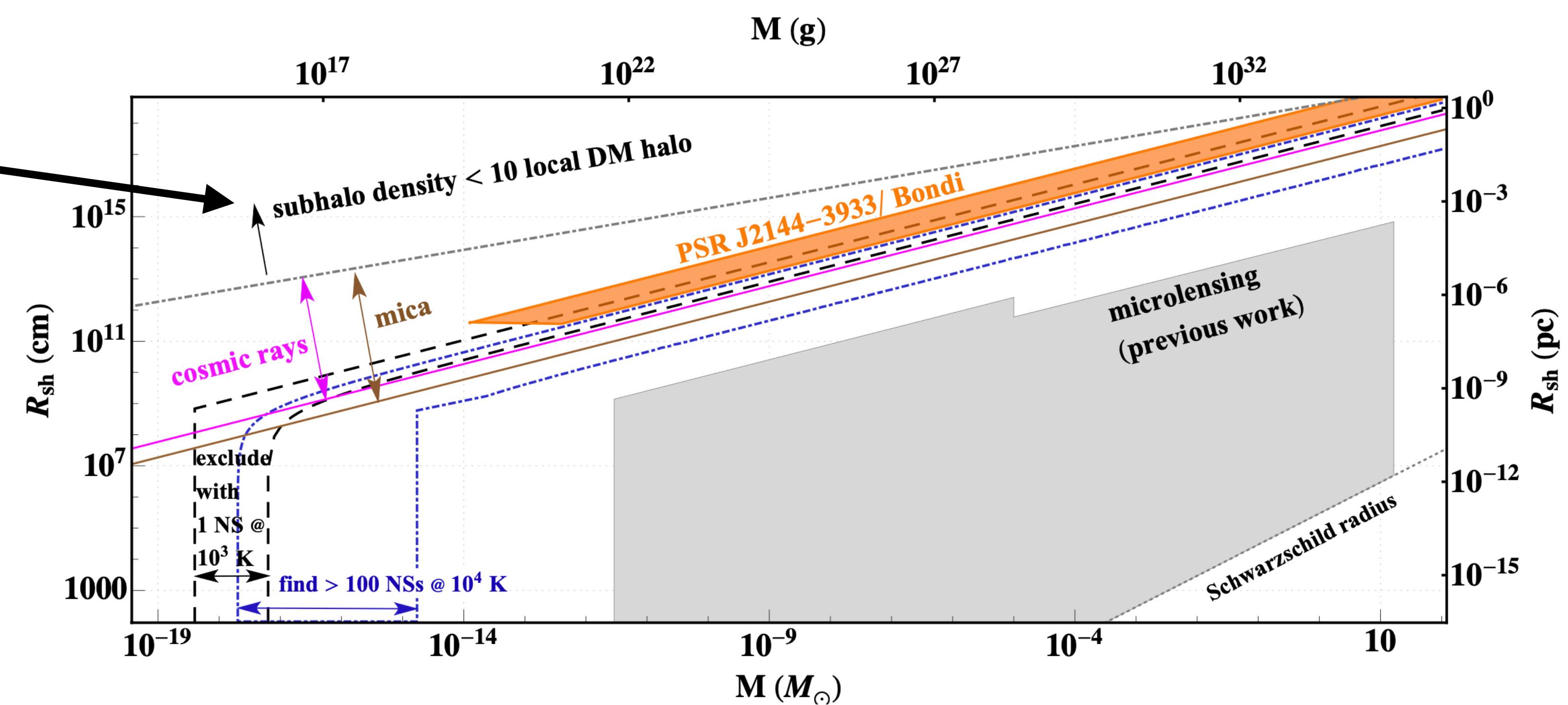
Neutron stars cooling and heating



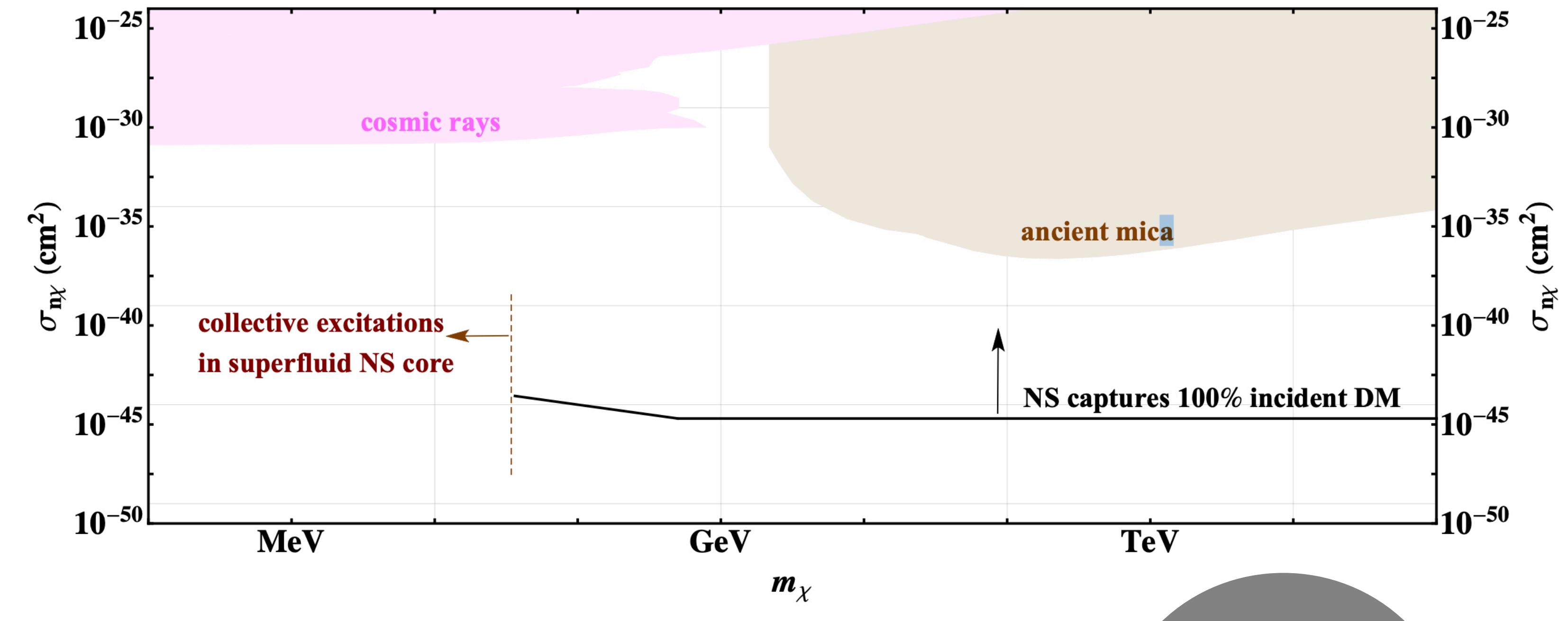
Neutron stars cooling and heating



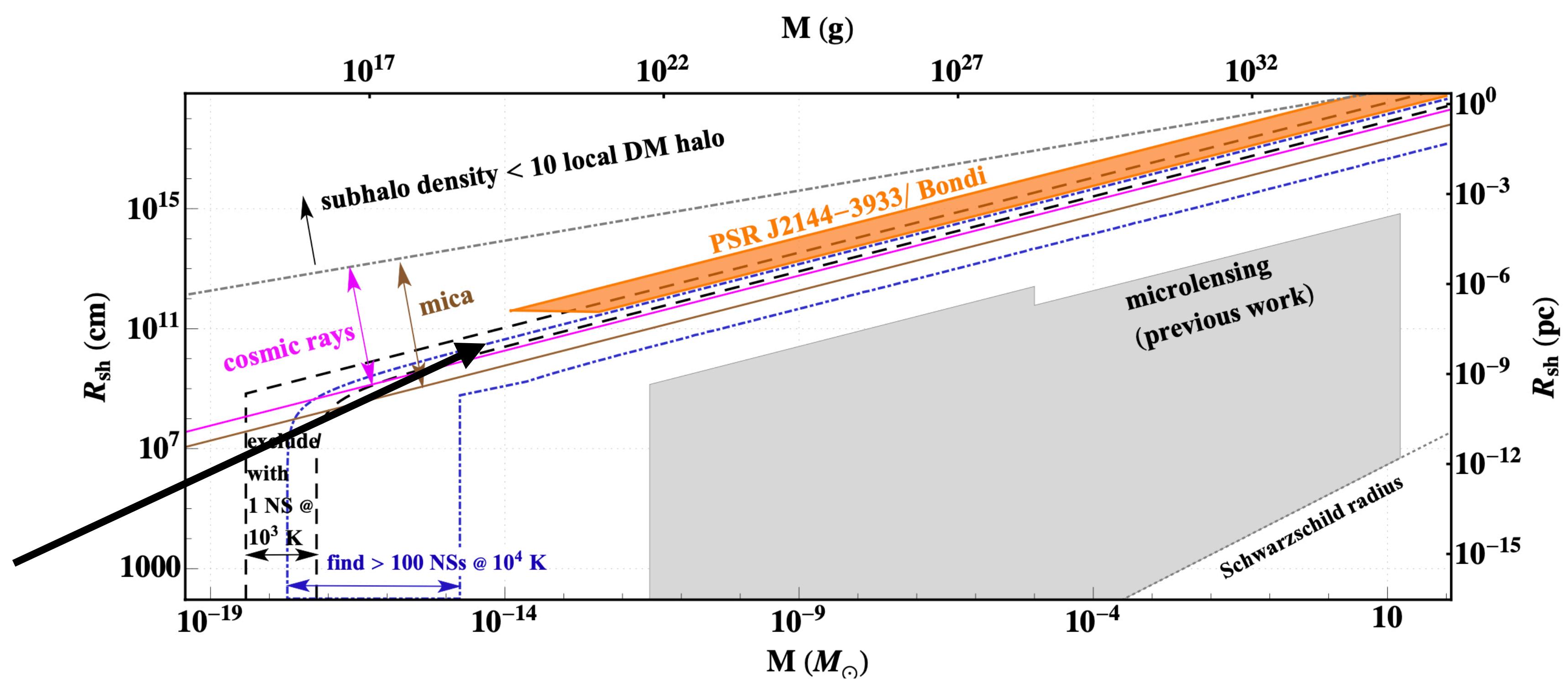
subhalo density < halo density



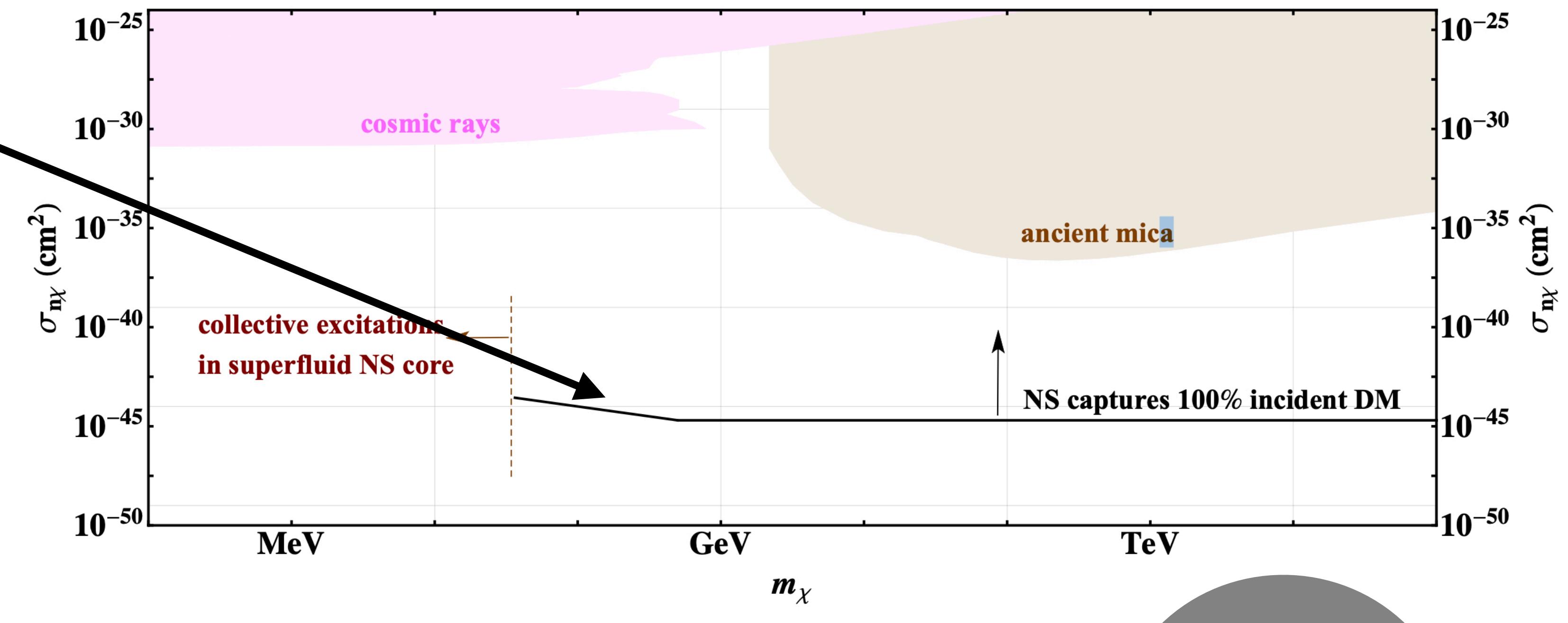
These bounds assume all DM is in subhalos



All sensitivity curves in this plot

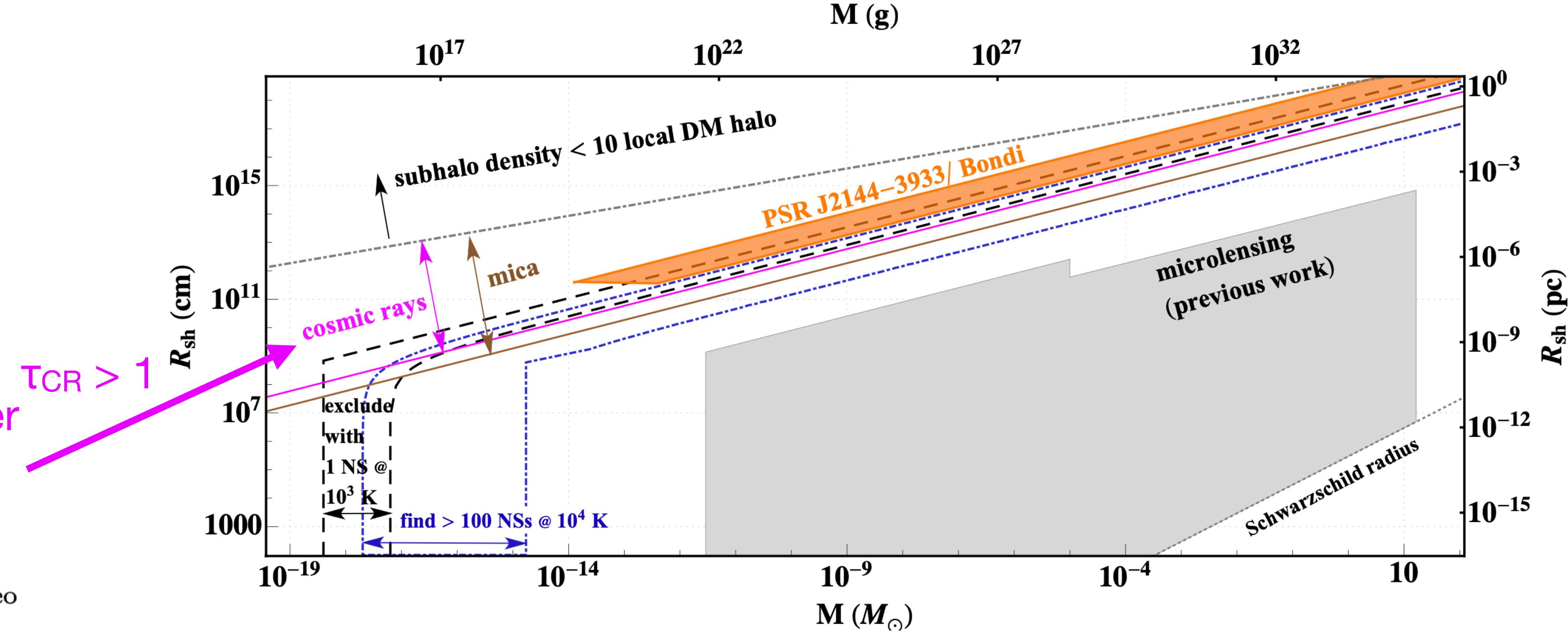


Correspond to the DM-nucleon cross-section sensitivity shown here

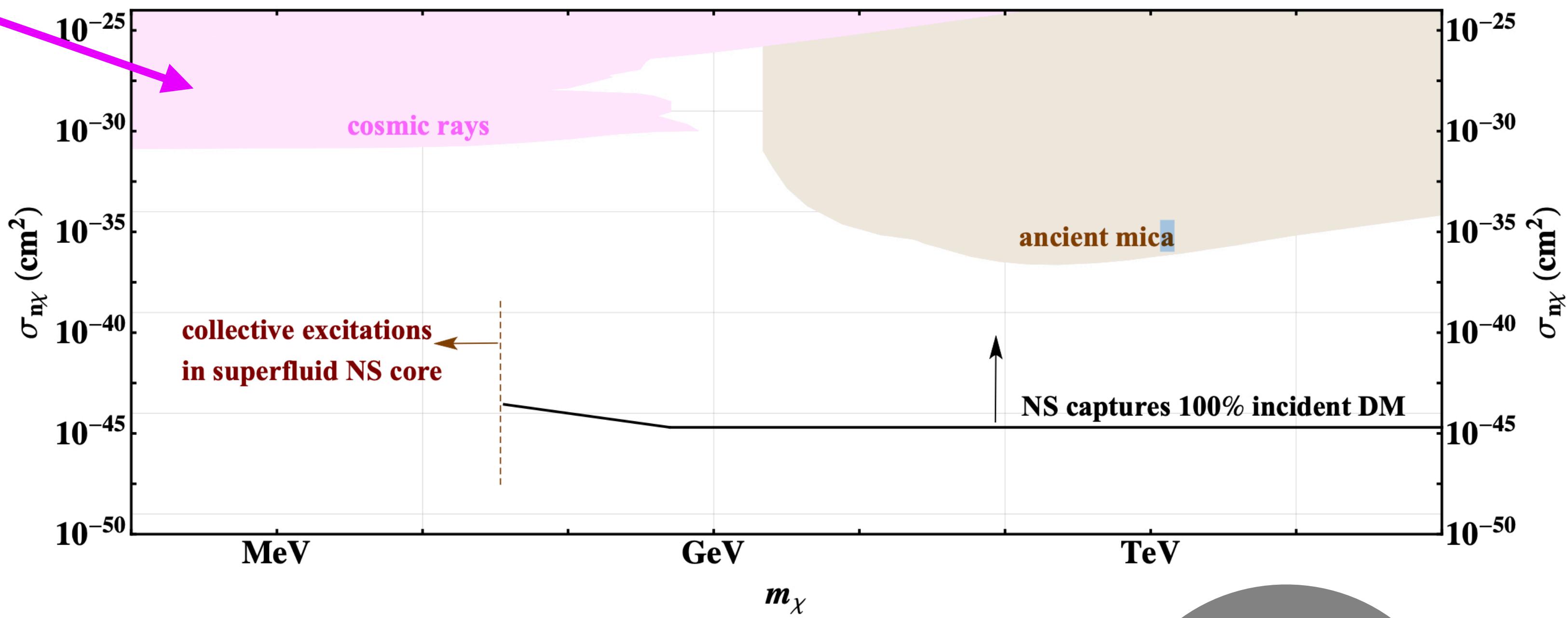


Cosmic rays will boost dark matter in subhalos so long as the interaction rate matches CR-diffuse DM interactions over ~ 8 kpc interaction lengths

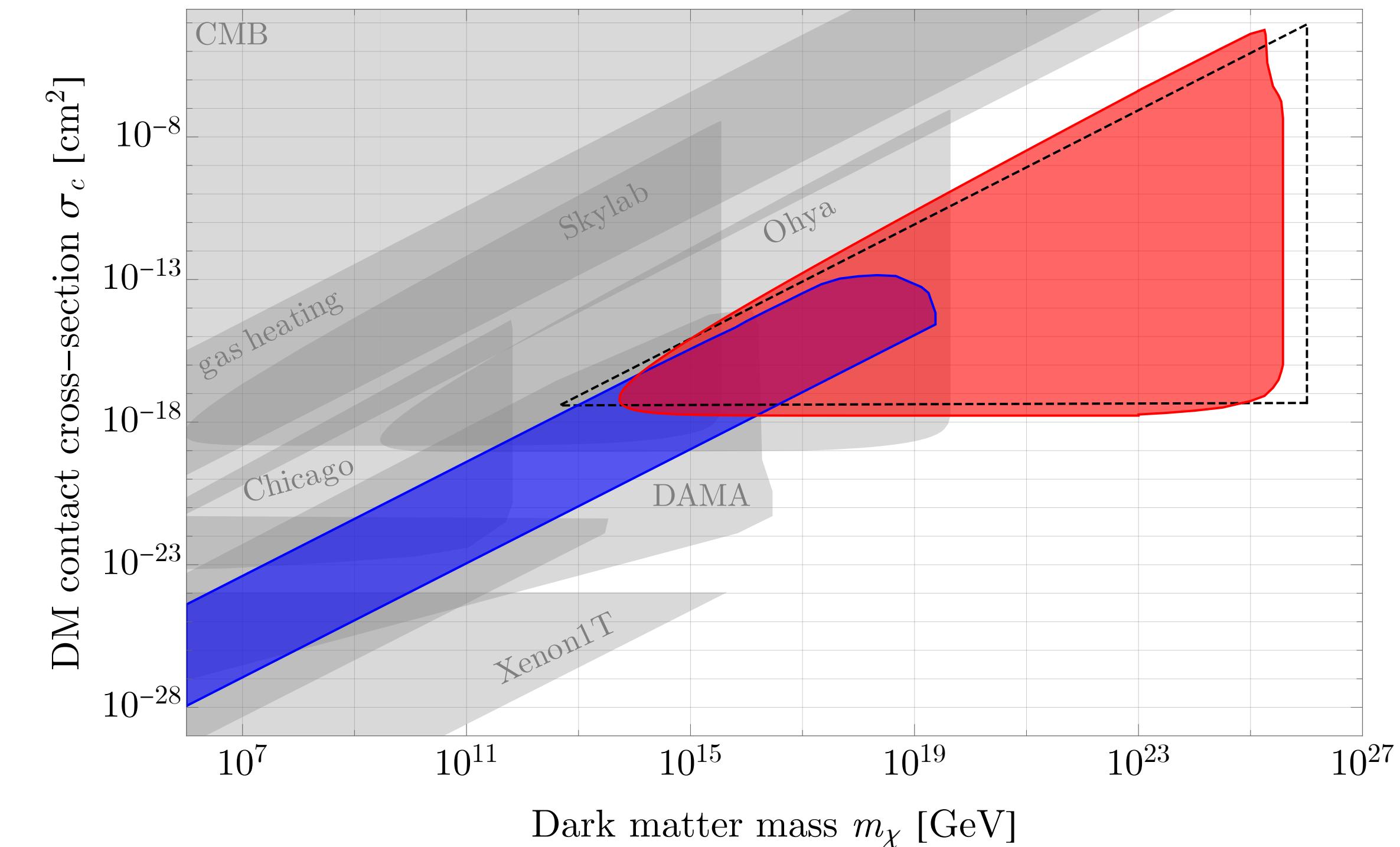
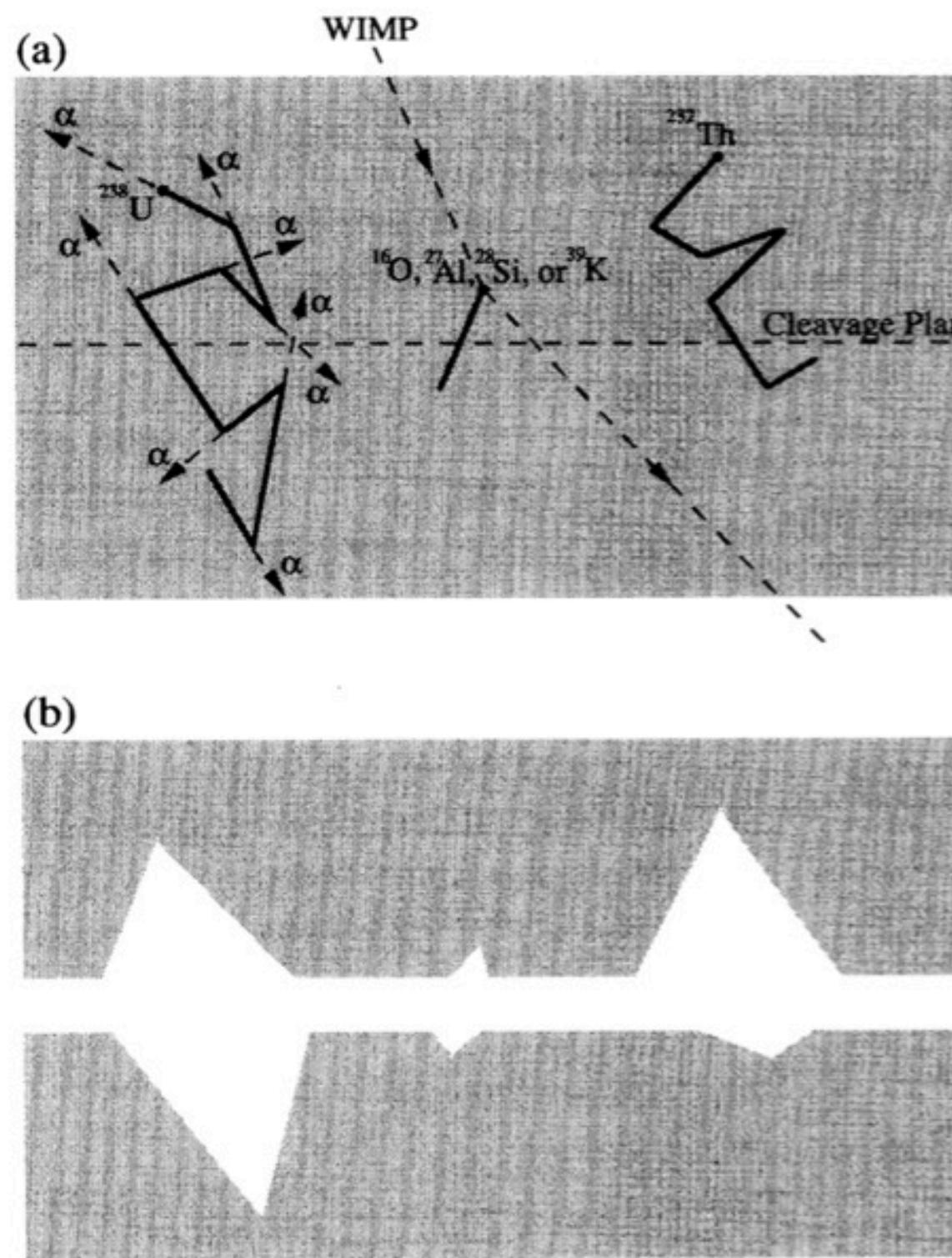
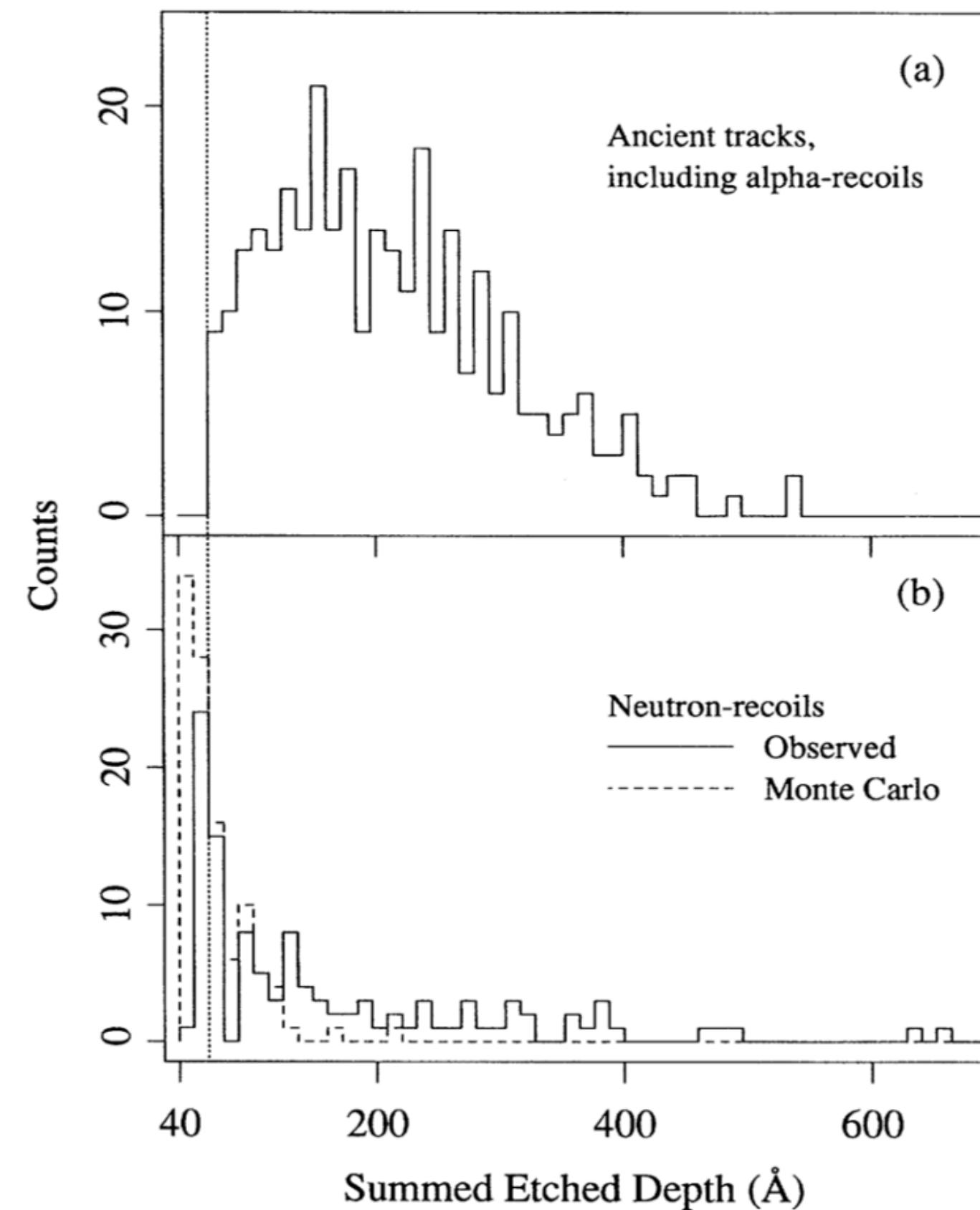
$$\tau_{\text{CR}} = \int_0^{L_{\text{dfs}}} ds n_\chi(s) \sigma_{\text{geo}} f_{\text{hit}} = \frac{\rho_\odot}{M} \sigma_{\text{geo}}$$



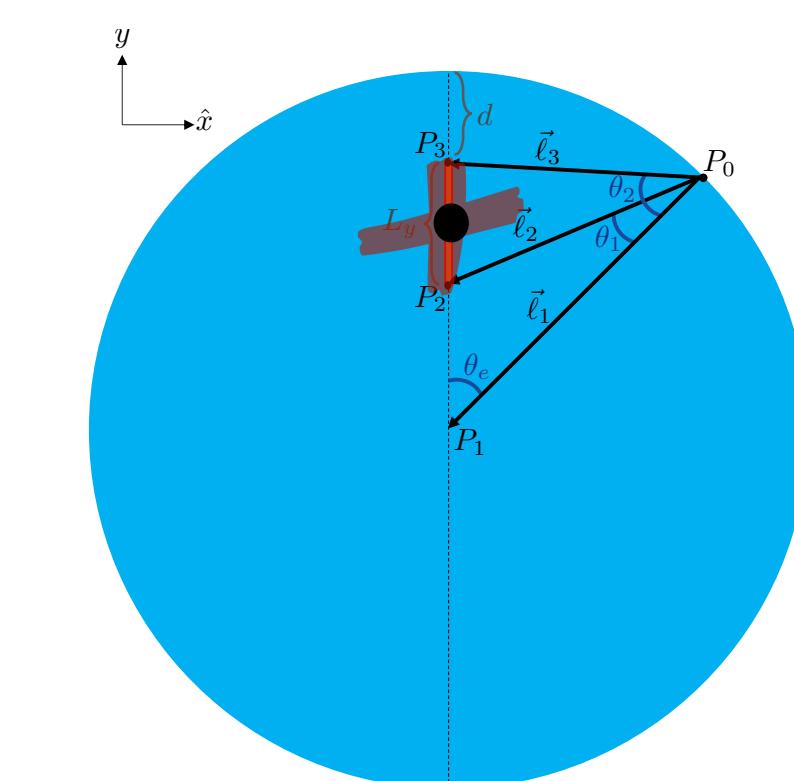
Low-mass DM boosted out of a subhalo yields similar CR-boosted DM bounds



Ancient search for new particles: mica

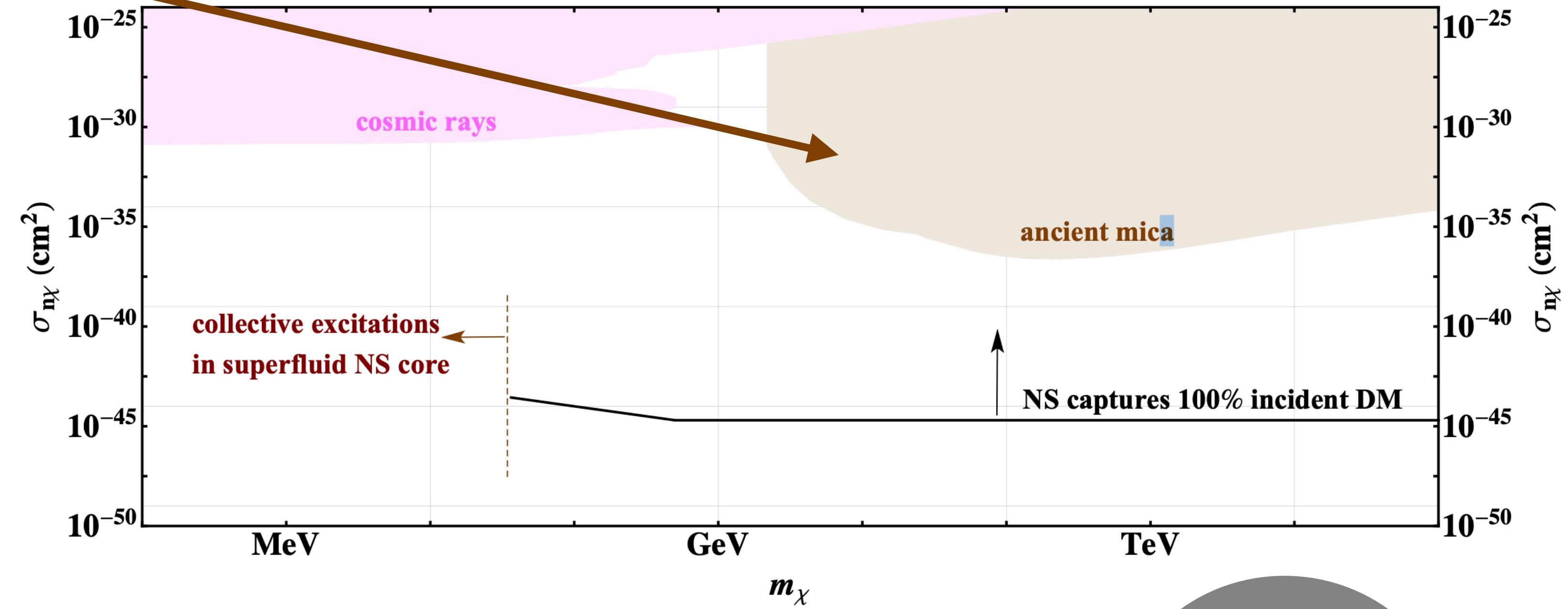
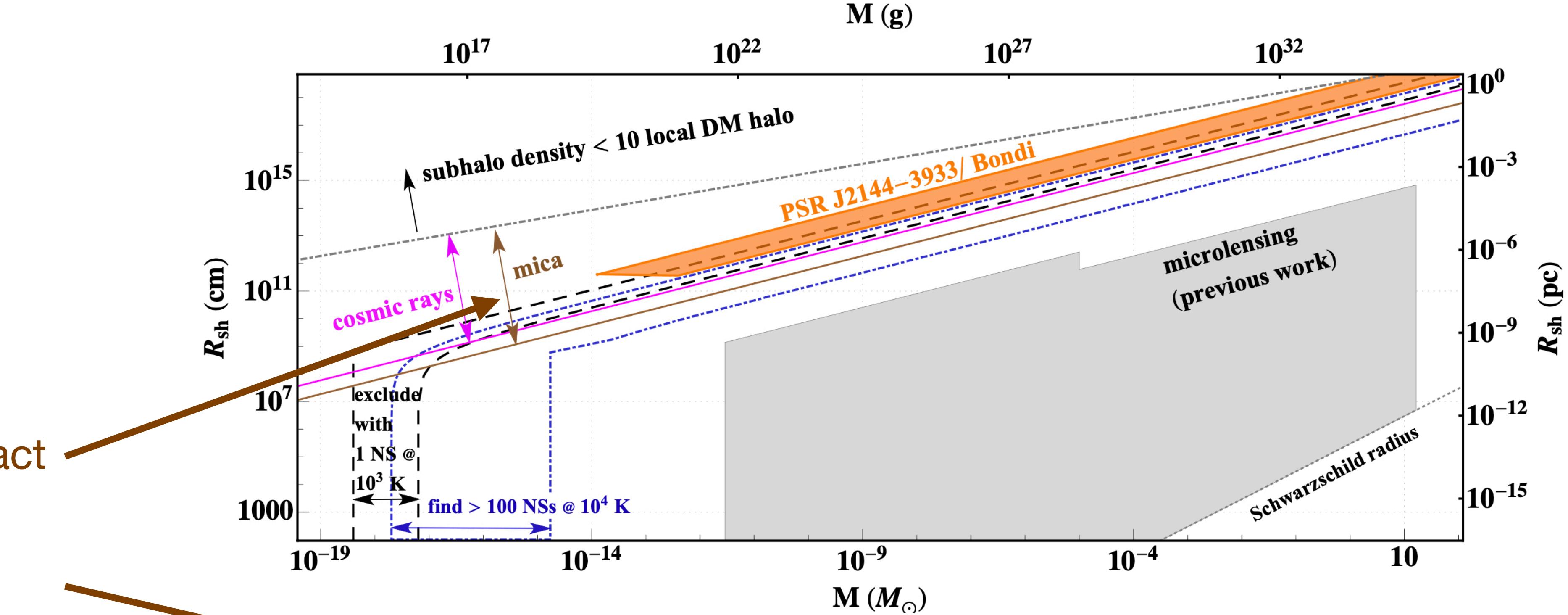


- Calibrated and etched mica samples from Price 1986, Snowden-Ifft 1995

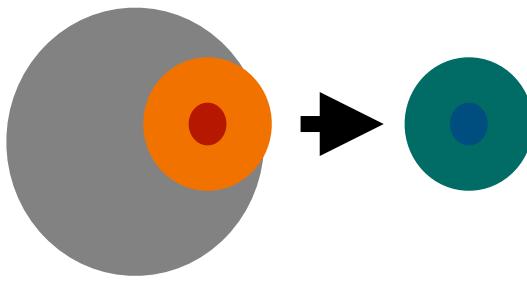


- Reanalyzed mica data using overburden
Acevedo, JB, Goodman 2105.06473
Bhoonah, JB, Courtman Song 2012.13406

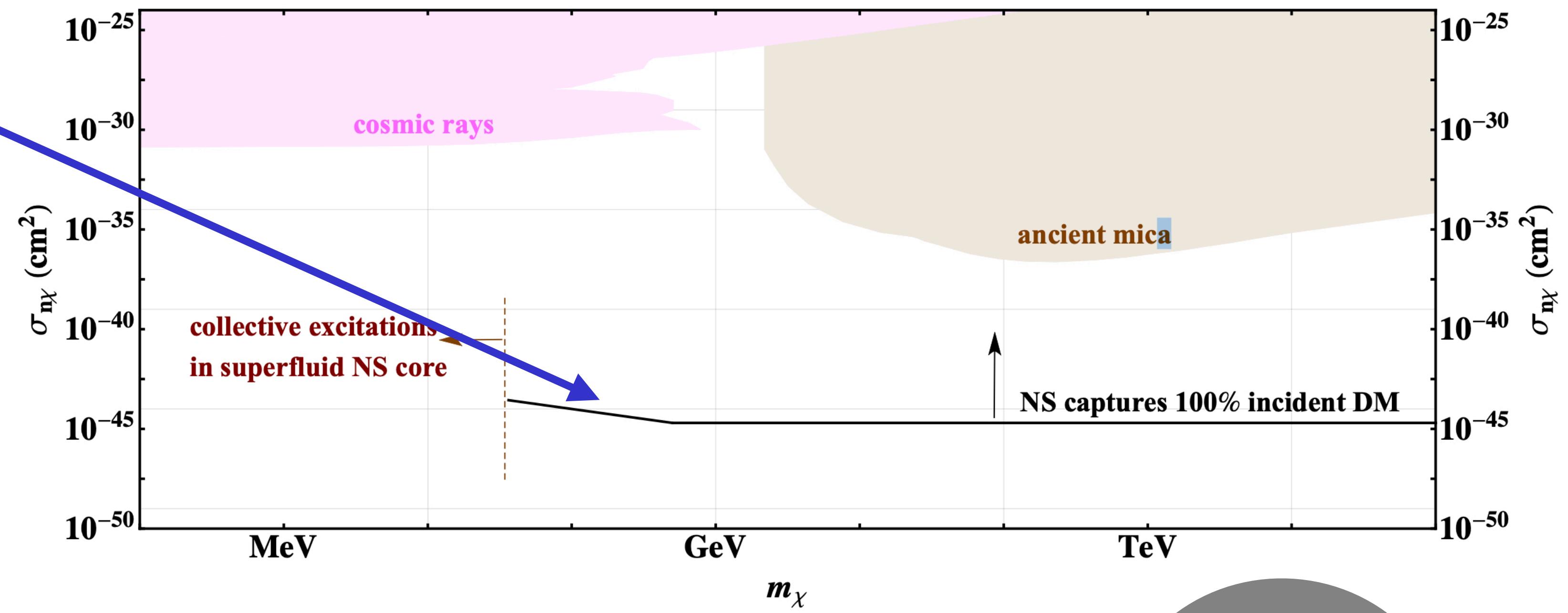
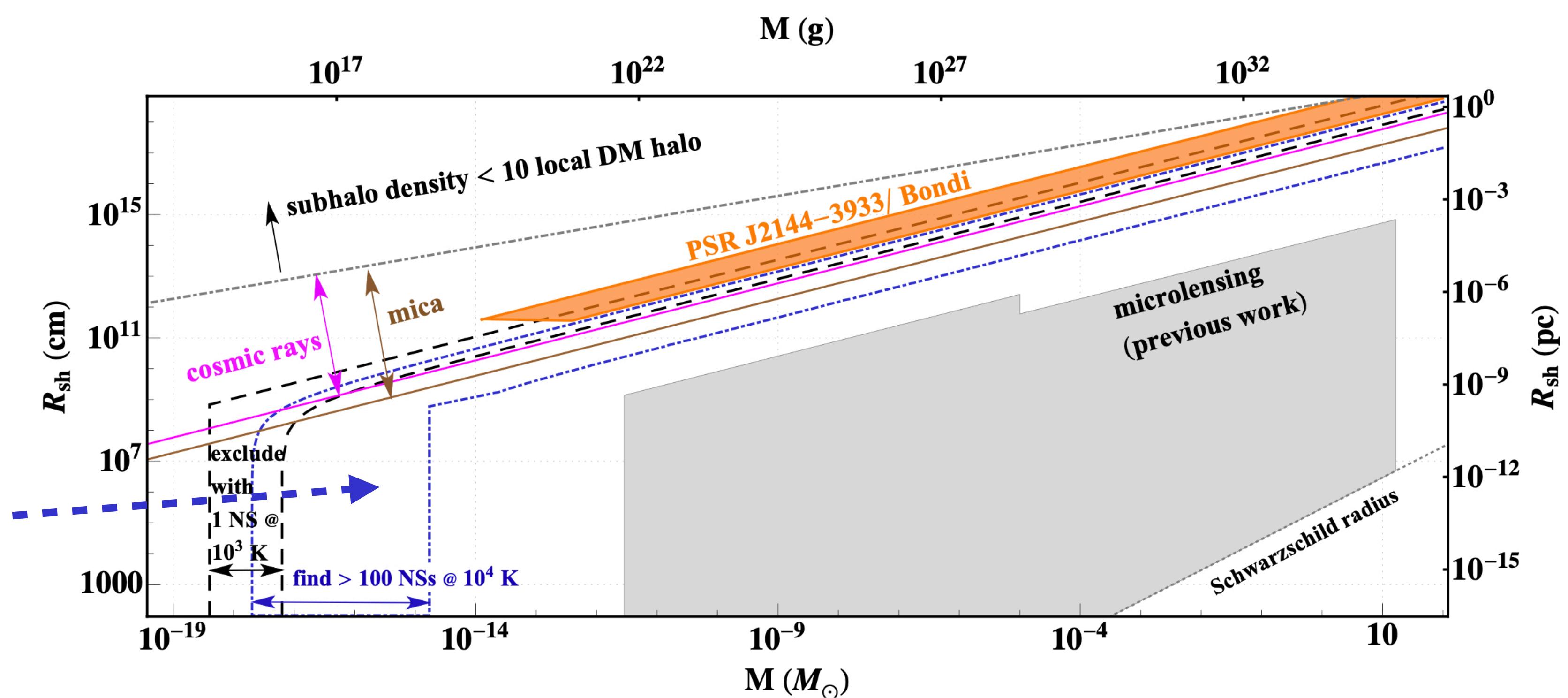
Requiring that subhalos interact
with ancient mica in
500 Myr yields this bound



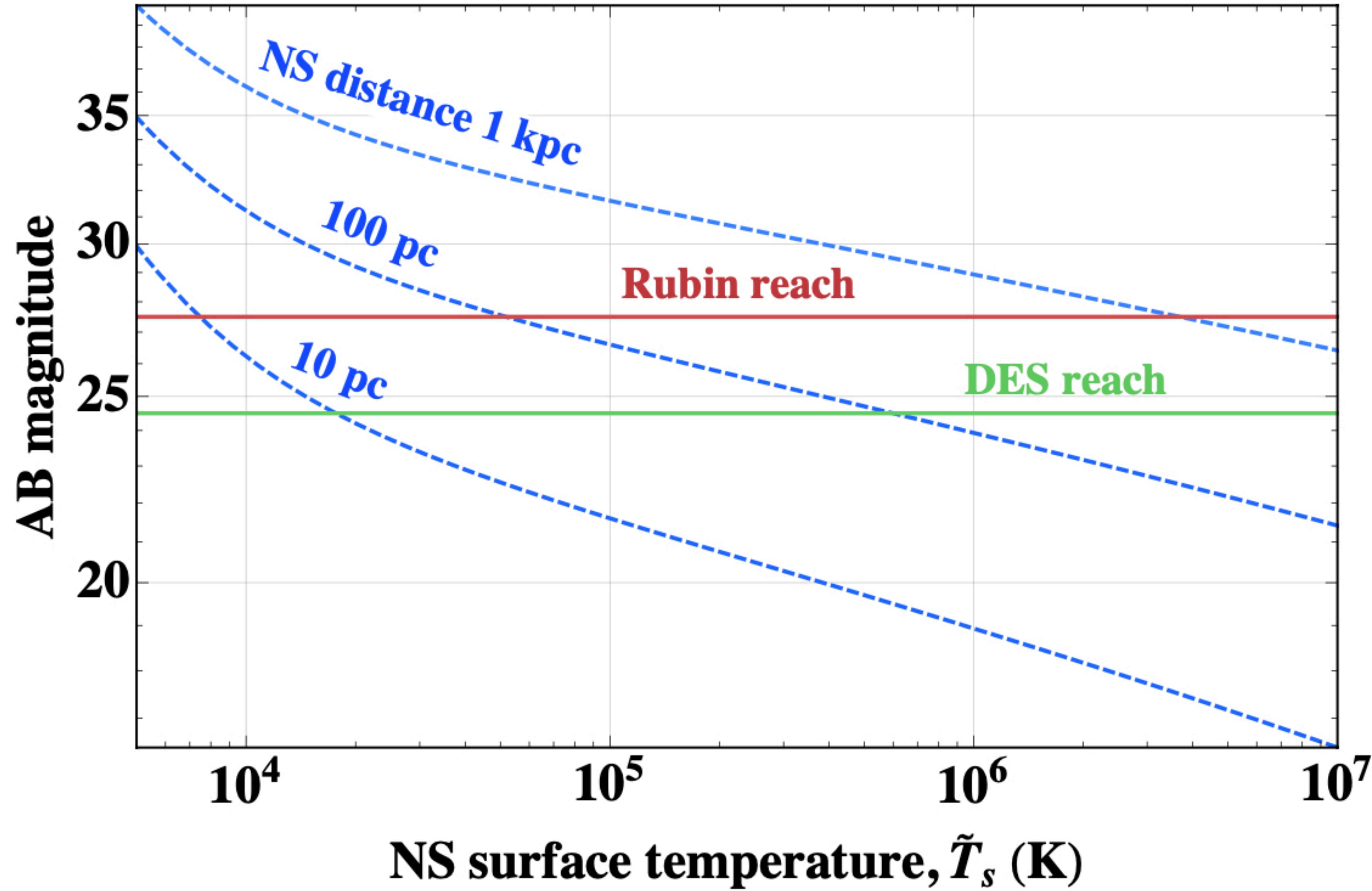
This region predicts a population of 100 NSs within a kpc of Earth heated to 10^4 K (flash-heated)

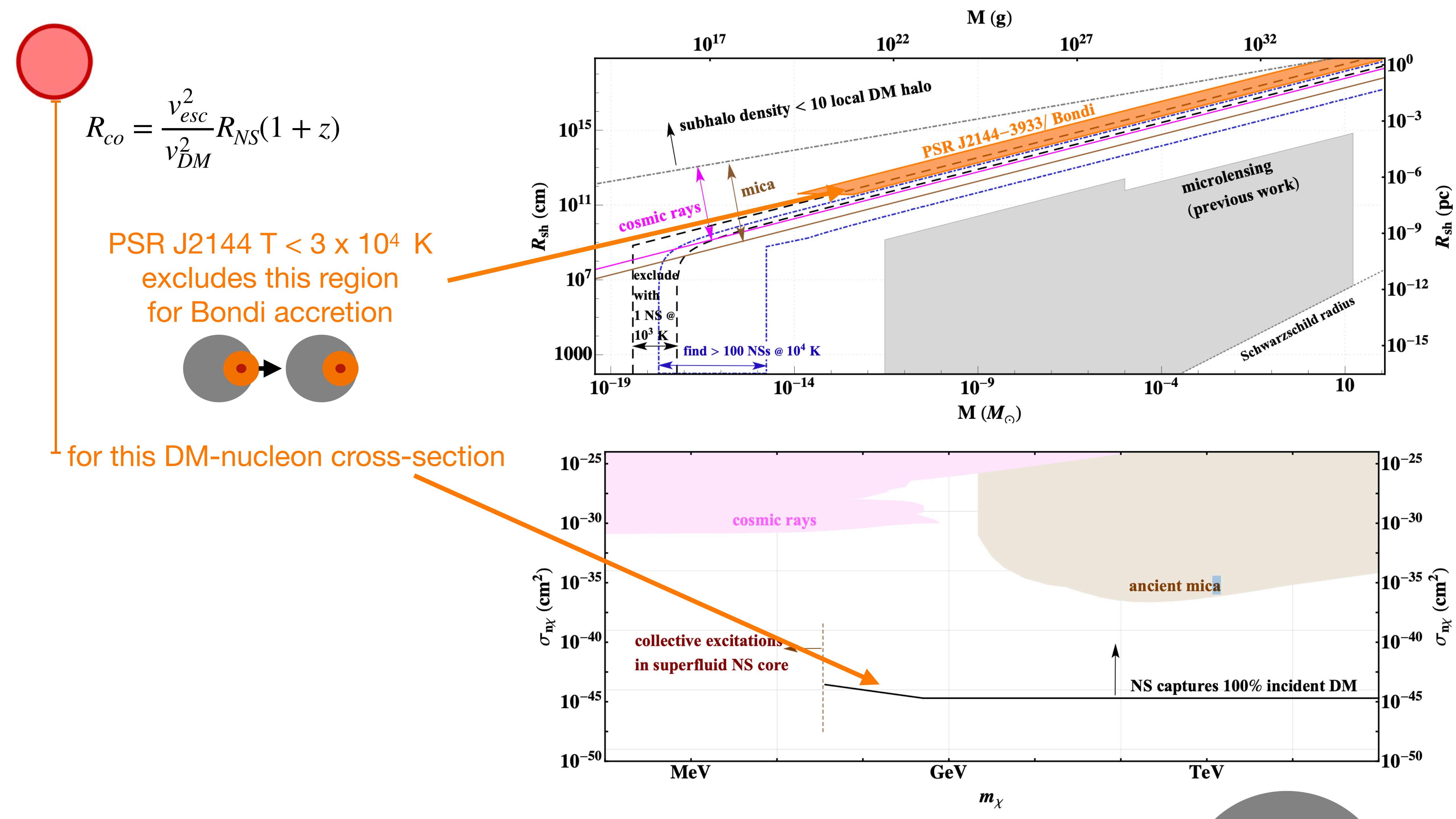


for this DM-nucleon cross-section

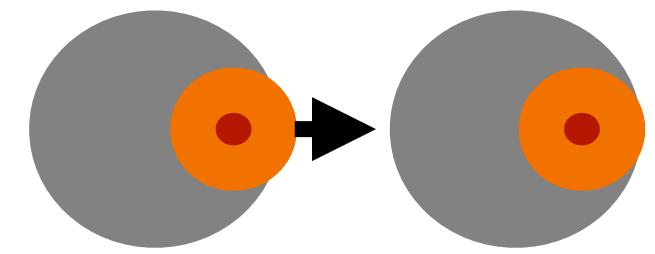


Prospects for future NS surveys finding subhalo heated NSs

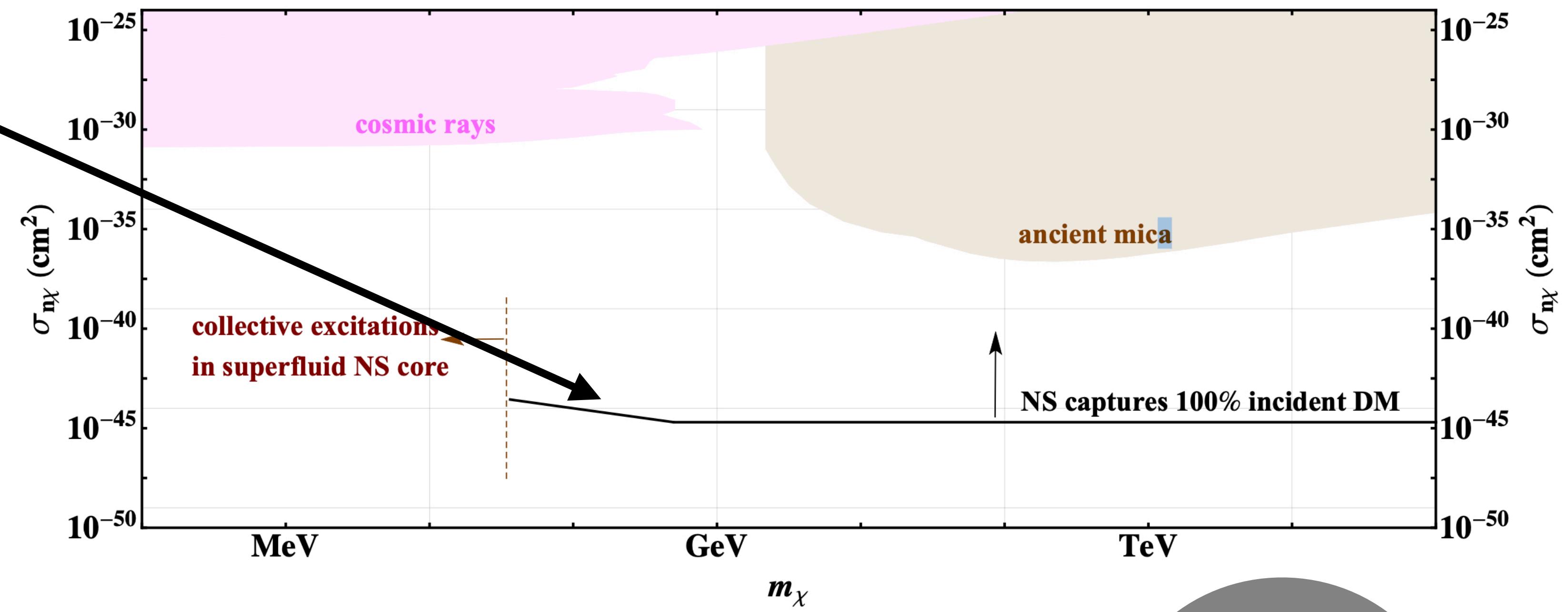
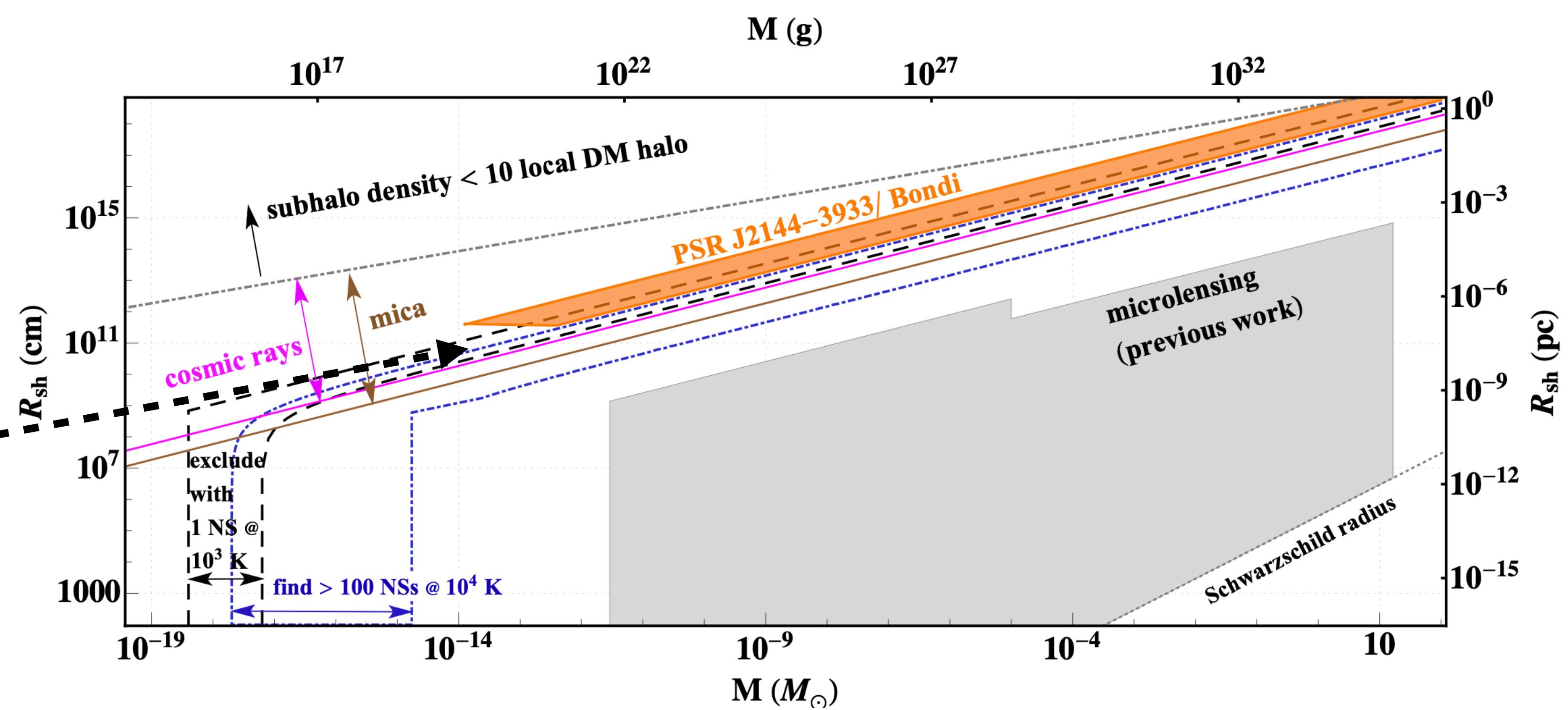




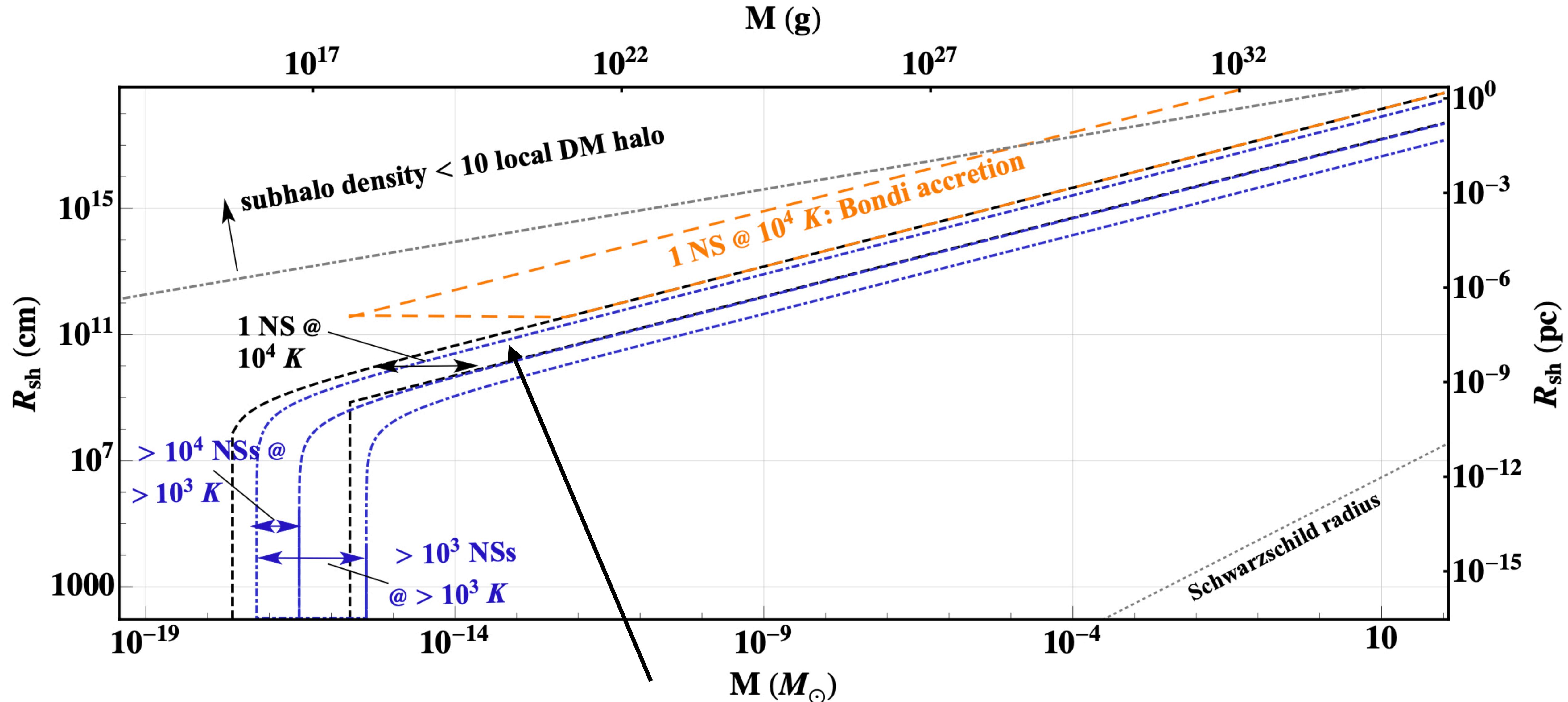
A future NS temp bound of $T < 10^3$ K would cover this region for collisionless accretion



for this DM-nucleon cross-section



More prospects for subhalo DM detection using neutron stars

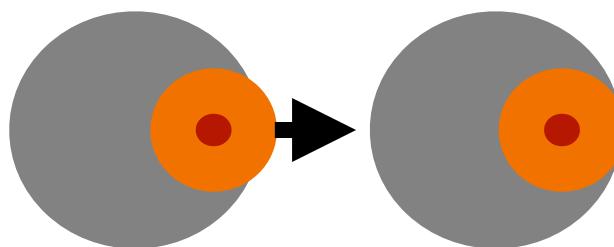
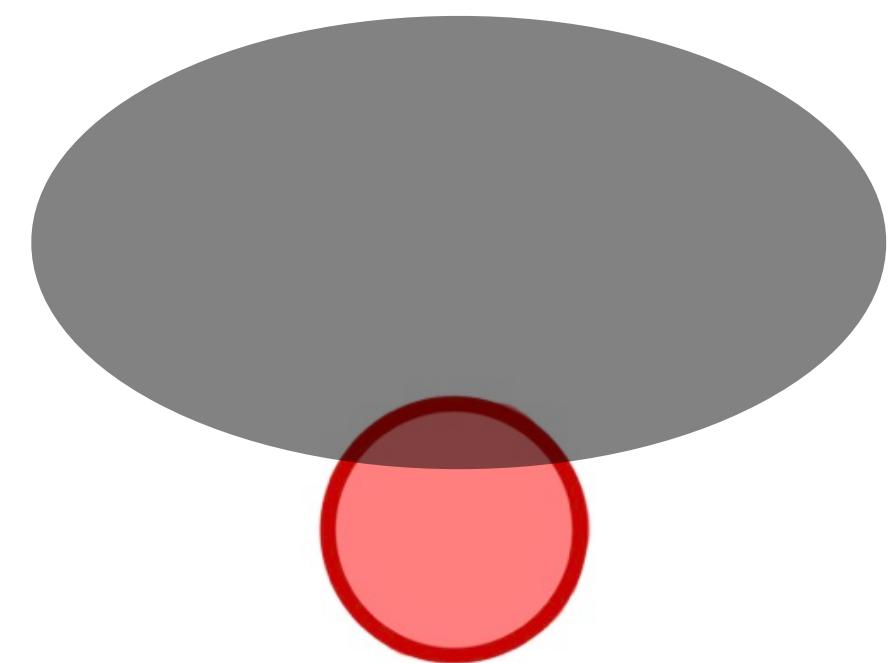
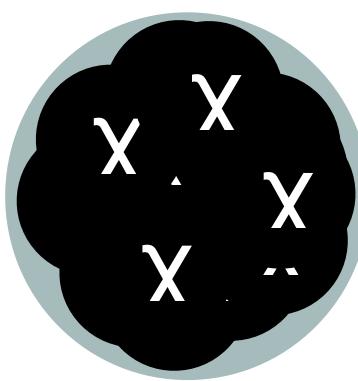


With $\sim 10x$ HST observation time, could perhaps achieve this

Mega DM: Neutron Star Searches for Clumps



- ◆ The origin and composition of high mass DM is novel and often complex
- ◆ Neutron stars can search for DM primarily residing in subhalos
- ◆ Already can place a bound on fluid-like (dissipative) subhalo DM
- ◆ Future prospects for cosmic rays, minerals, NS populations

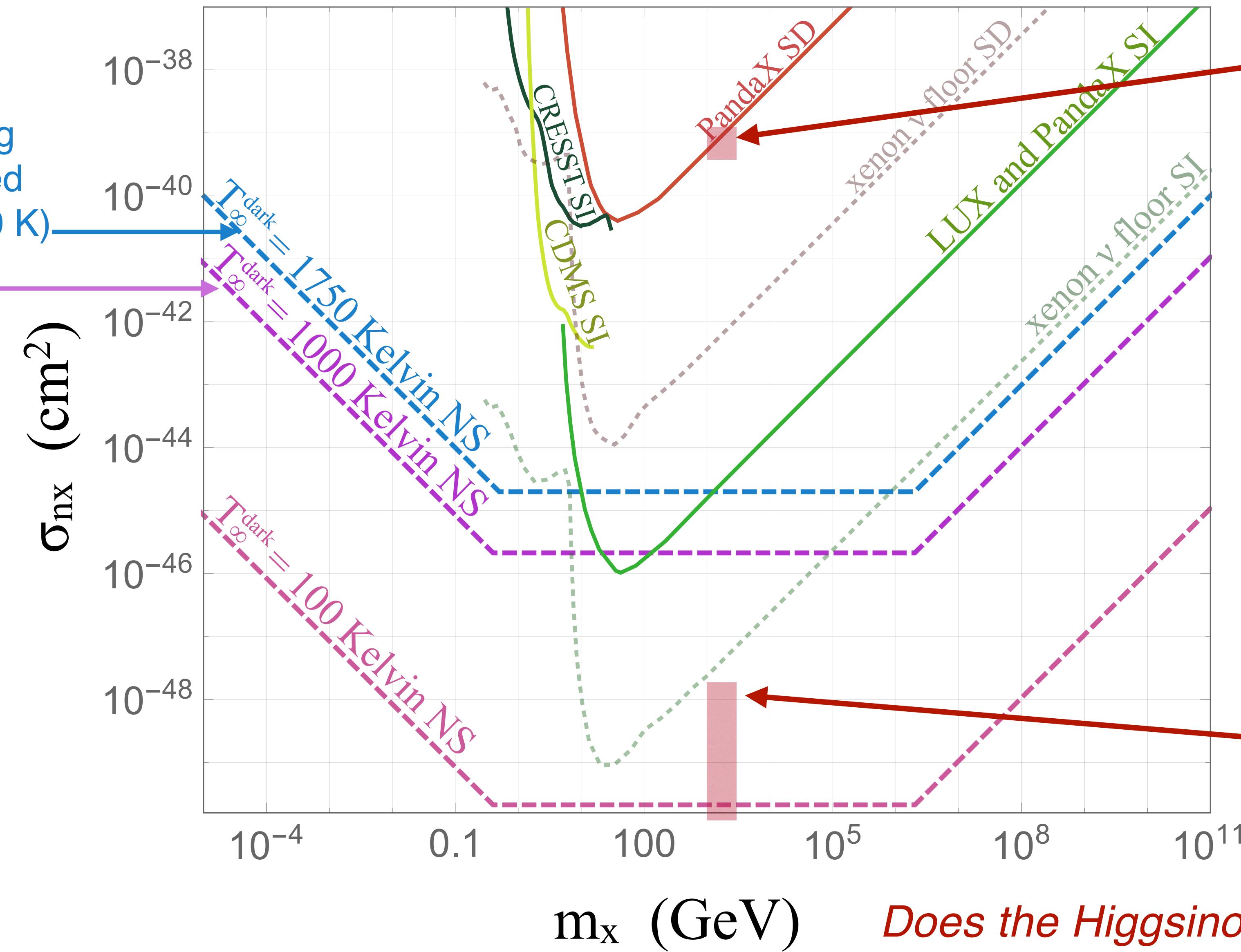


Thanks!

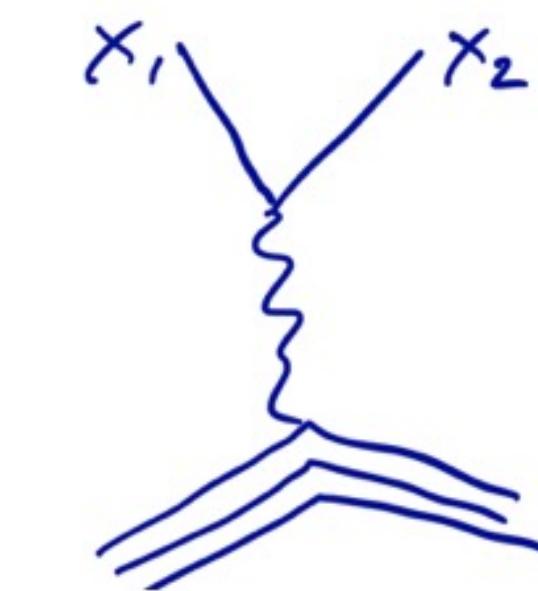
Neutron Star Dark Matter Heating Sensitivity

all incoming
DM captured
(ann. $T \sim 2500$ K)

10% incoming
DM captured
(ann. $T \sim 1400$ K)

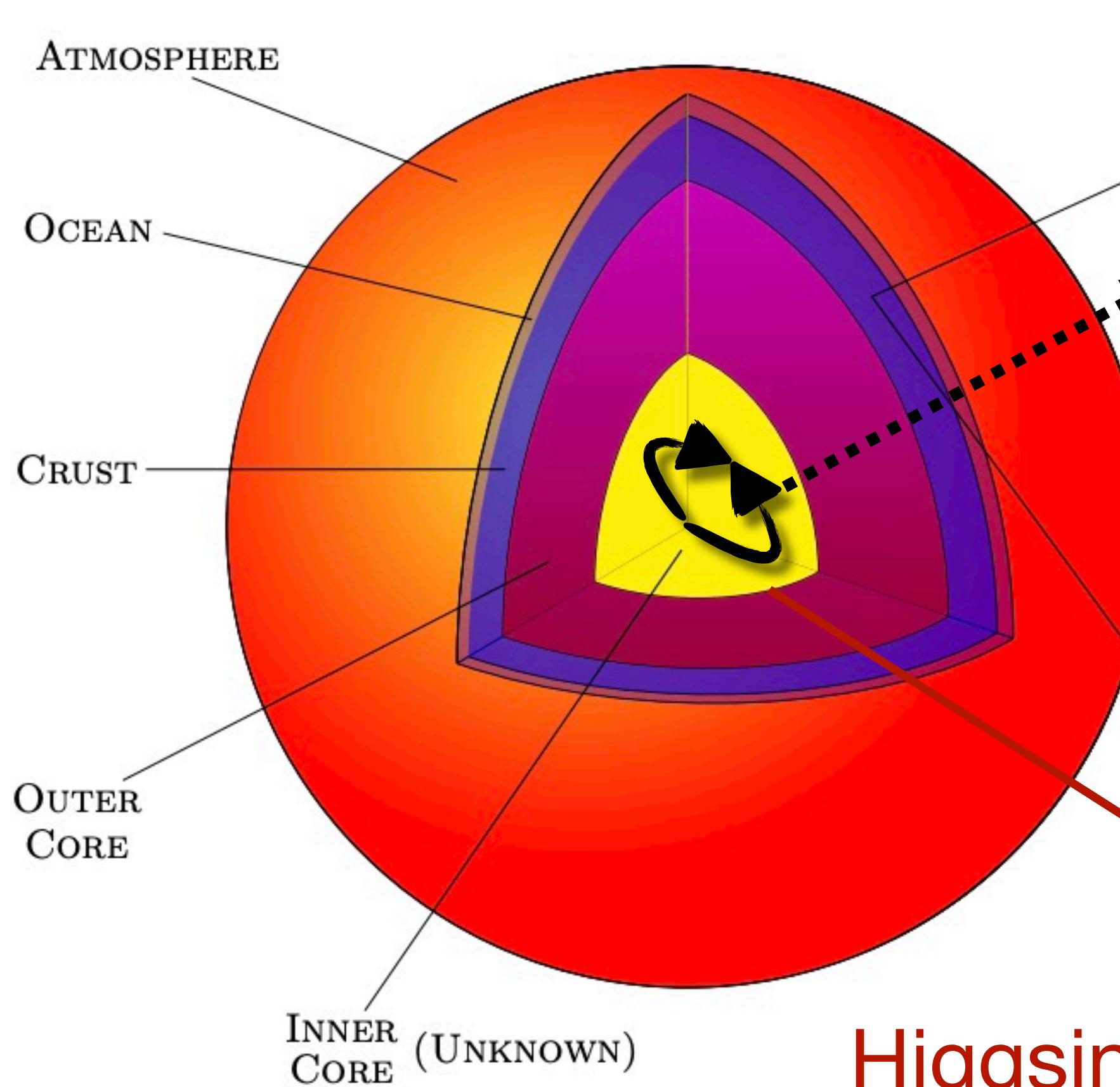


Higgsino DM
in a NS, 0.7c



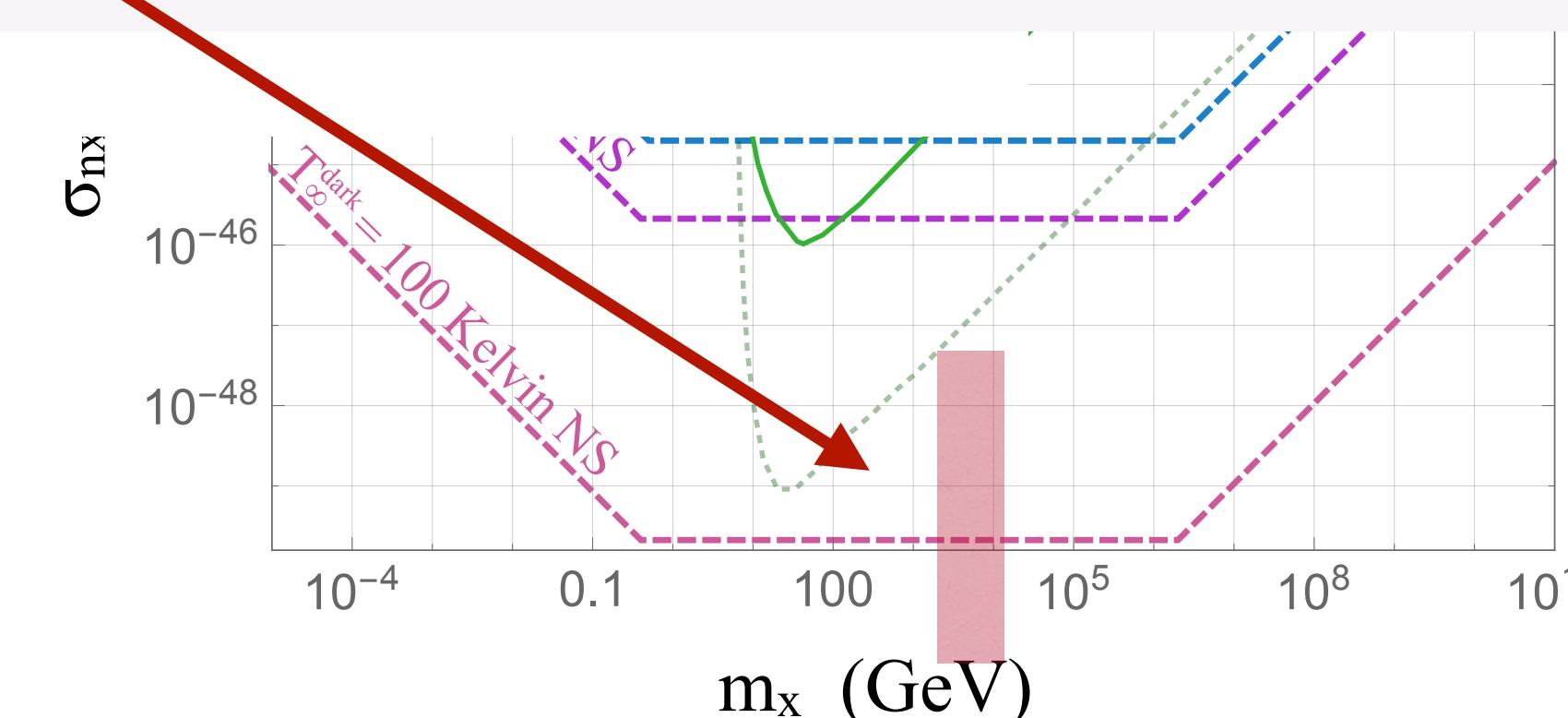
Higgsino DM
at 0.001c

Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS

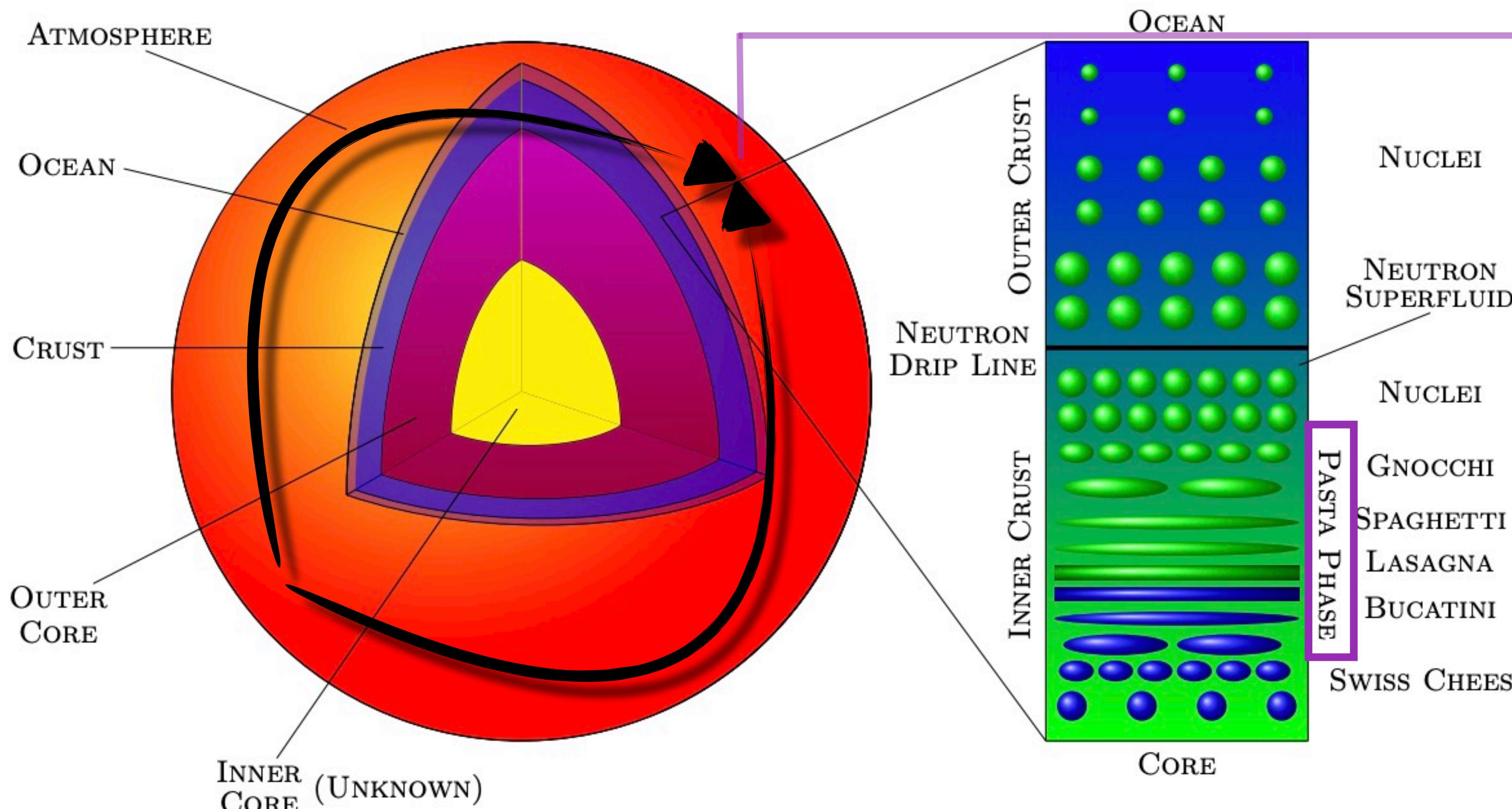


Higgsino DM
at $v \ll c$

- Standard NS heating calculation uses DM annihilation at low velocities, settling in NS core
- DM-neutron cross-section is unbounded for DM that settles into NS core because of accidental loop-level nucleon coupling cancellation and pdf uncertainties
- The timescale for DM settling in NS core can't be computed without ($v \ll c$) cross-section



Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS



→ Solution: annihilation in “pasta” region as limiting case

$$\tau_{eq} \propto R_{ann}^{(3-2\ell)/2}$$

► DM annihilates at $\sim 0.1c$ much like in the early universe

► keV-PeV mass WIMPs annihilate, for s-wave ($l=0$), p-wave ($l=1$),
 $\langle \sigma_a v \rangle = 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$, with

$$\tau_{eq} \lesssim 10^4 \text{ yrs} \left(\frac{m_x}{\text{TeV}} \right)^{1/2}$$

Where τ_{eq} is the time for annihilation-capture equilibrium

DM Mass Unitarity Limit

Griest, Kamionkowski, '87

1. Assume freeze-out abundance set with annihilation

$$\sigma_0 \sim \text{picobarn} = 10^{-36} \text{ cm}^2$$

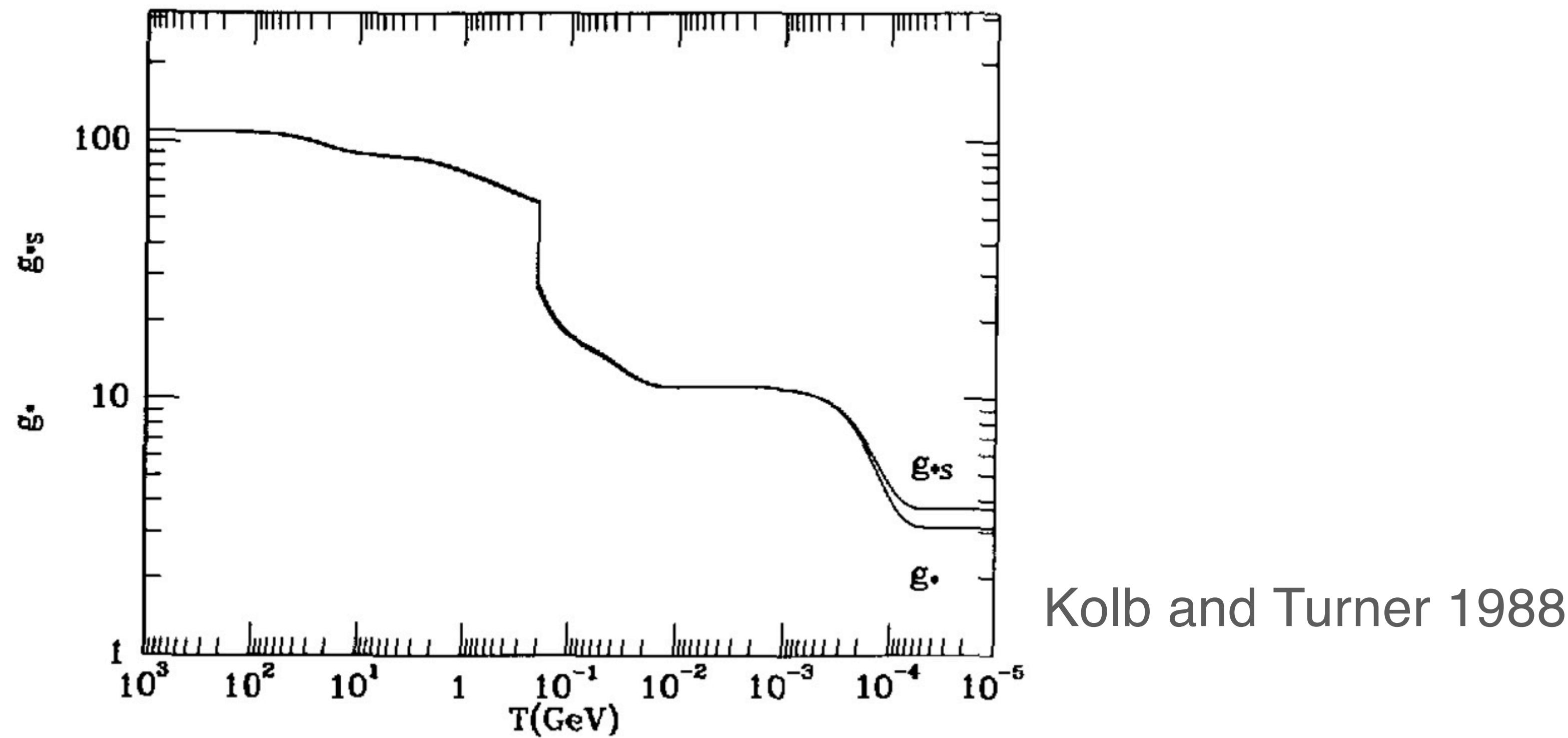
2. Require the annihilation cross-section not exceed a perturbative bound

$$\sigma_0 \lesssim 4\pi/m_{\text{DM}}^2$$

3. Then because this cross-section is a picobarn for thermal freeze-out, the suggestion for frozen out dark matter mass is

$$m_{\text{DM}} \lesssim 100 \text{ TeV}$$

Unitarity mass limit does not apply to most cosmologies.
Example: entropy changes in the early universe



Also: Matter domination, chemical potential,
gravitational production, freeze-in, asymmetric reheating,
direct production from decay, moduli fields, preheating...