Neutron star searches for subhalo dark matter

CERN Korea BSM Workshop 2022

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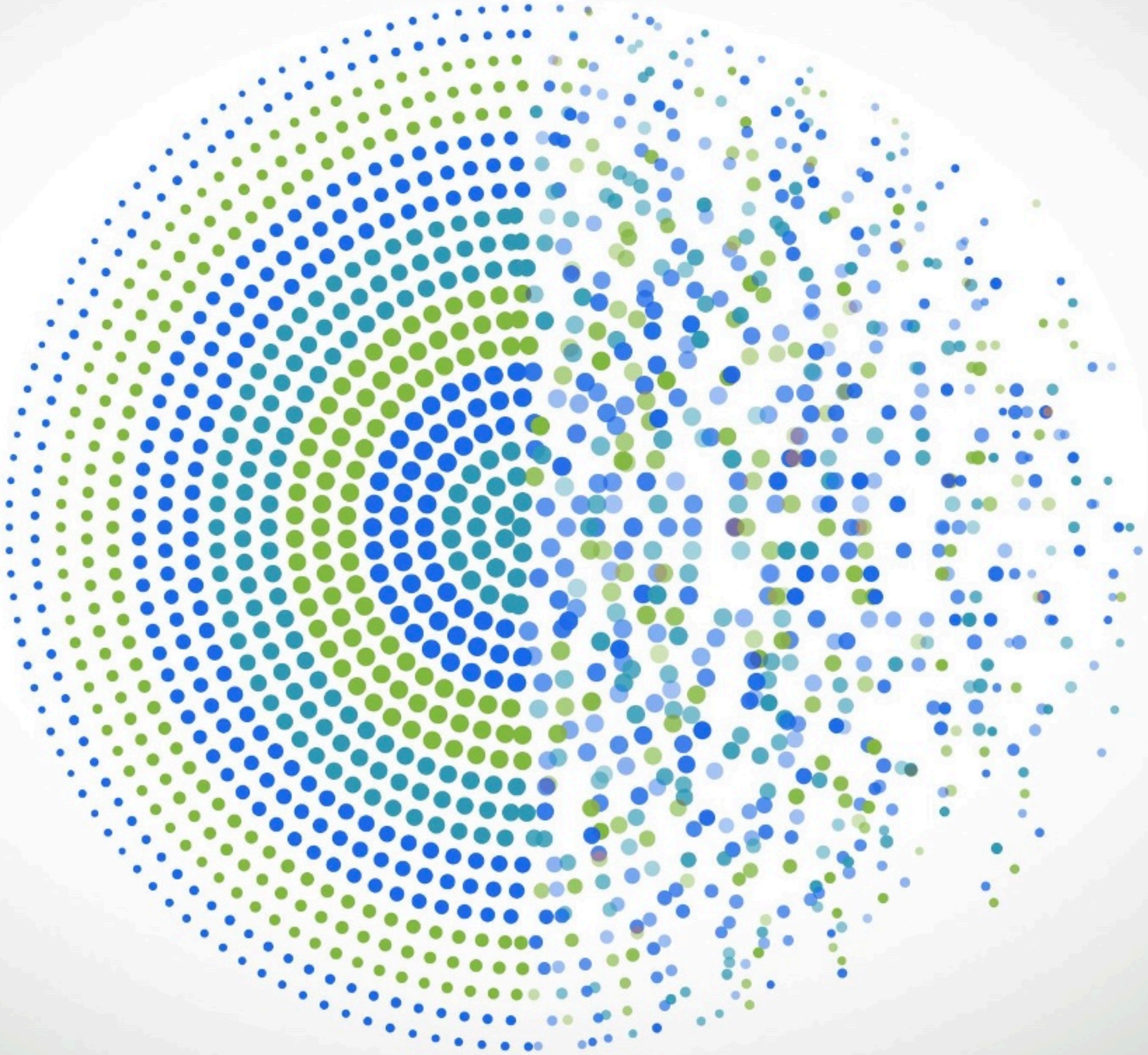
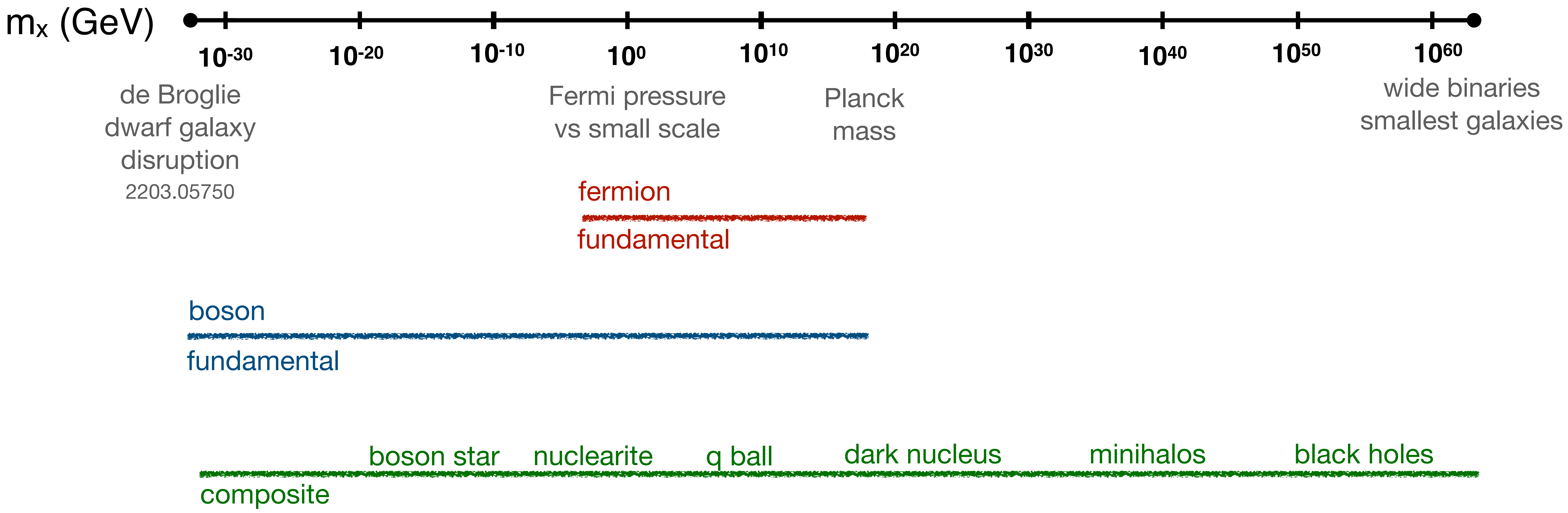


JB, Kavanagh, Raj 2109.04582, PRL

Acevedo, JB, Leane, Raj 1911.06344, JCAP
Baryakhtar, JB, Li, Linden, Raj 1704.01577, PRL

The high mass dark matter frontier



m_x (GeV)

10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

de Broglie
dwarf galaxy
disruption
2203.05750

Fermi pressure
vs small scale

Planck
mass

wide binaries
smallest galaxies

fermion
fundamental

boson
fundamental

boson star nuclearite q ball dark nucleus minihalos black holes
composite

Models

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

Good to have a model

- Early matter domination

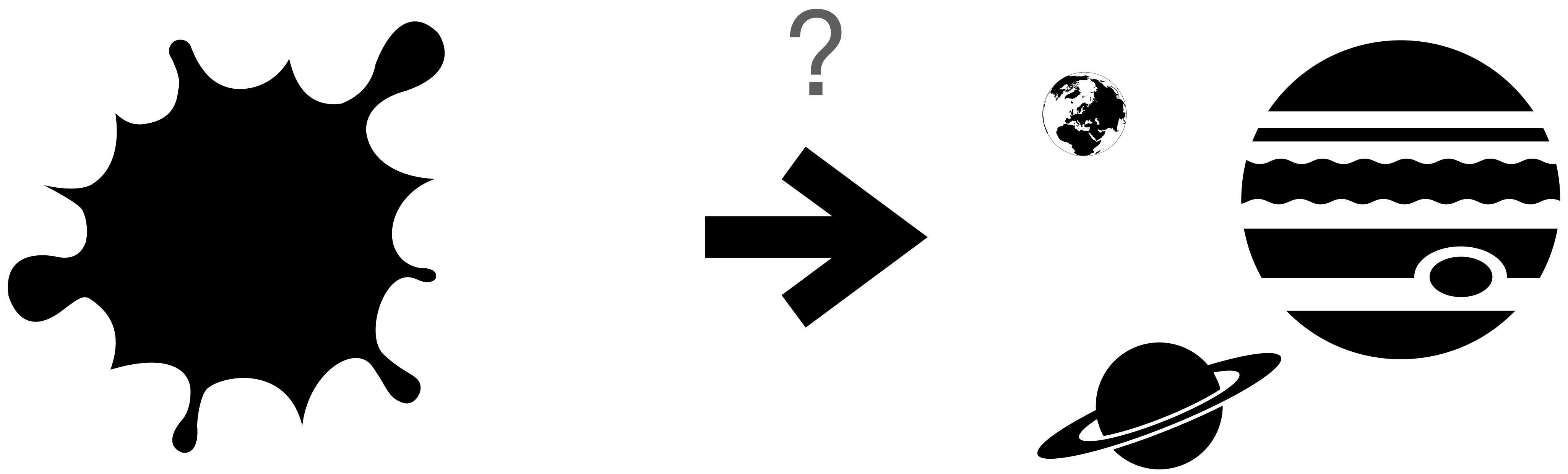
e.g. Erickcek Sigurdson 2011

- Dissipative dark sector

e.g. Fan, Katz, Randall, Reece 2013,
Buckley DiFranzo 2017,
Chang, Egana-Ugrinovic, Essig, Kouvaris 2018

- Dark BBN/Q Ball

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



- Planet formation still has open questions (pebble accretion).
- Multi/bound-state models often don't have simple analytic solutions like single-field DM models.

Subhalo DM; clumps, dark stars, big composites

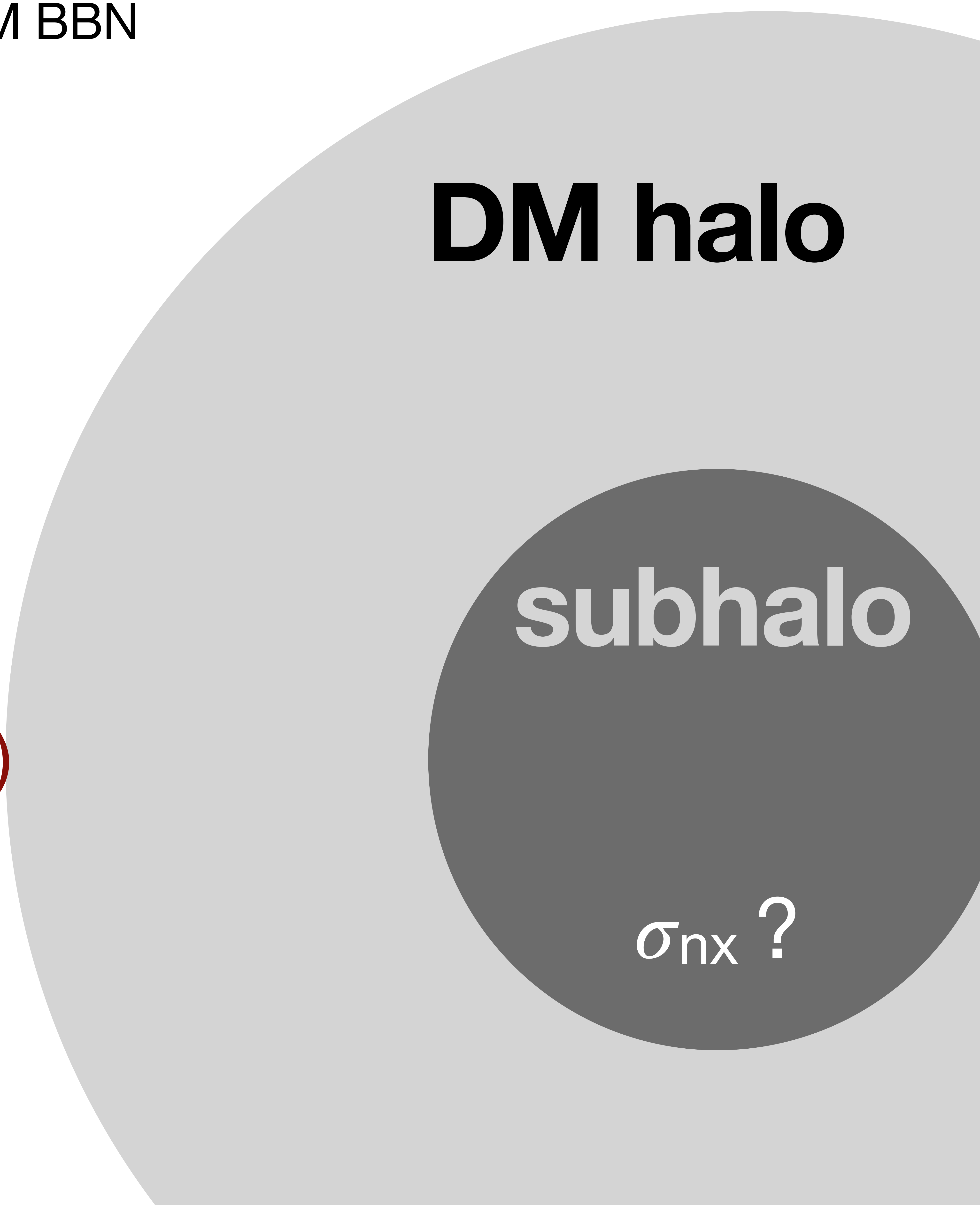
from e.g. early matter domination, dissipation, DM BBN

Searches

- Gravitational microlensing
- Pulsar timing
- Gravitational waves (mergers)
- Molecular gas cloud heating
- Stellar collisions (optically thick clump)

this talk

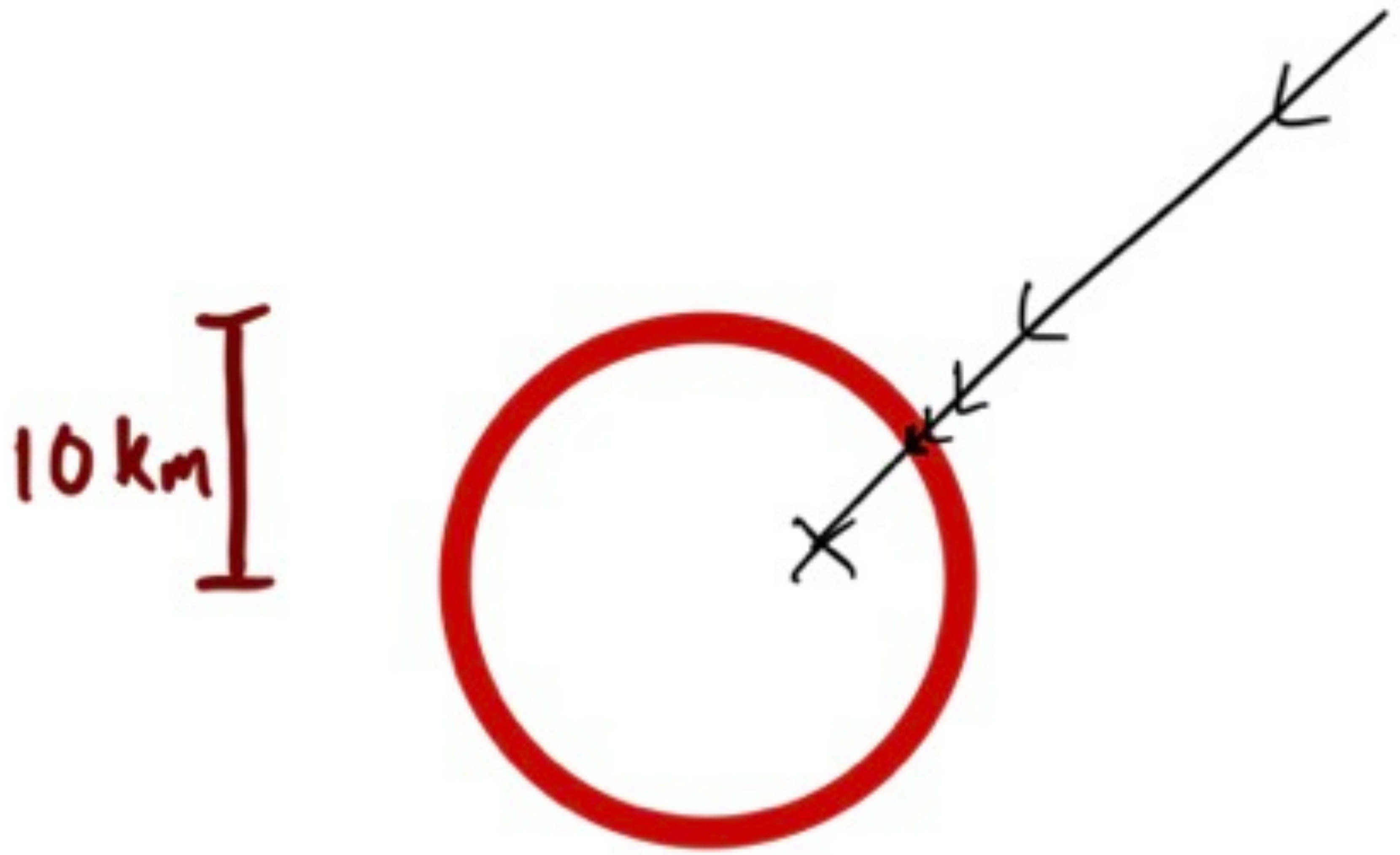
- **Neutron stars**, minerals, cosmic rays
  for subhalo DM-nucleon detection



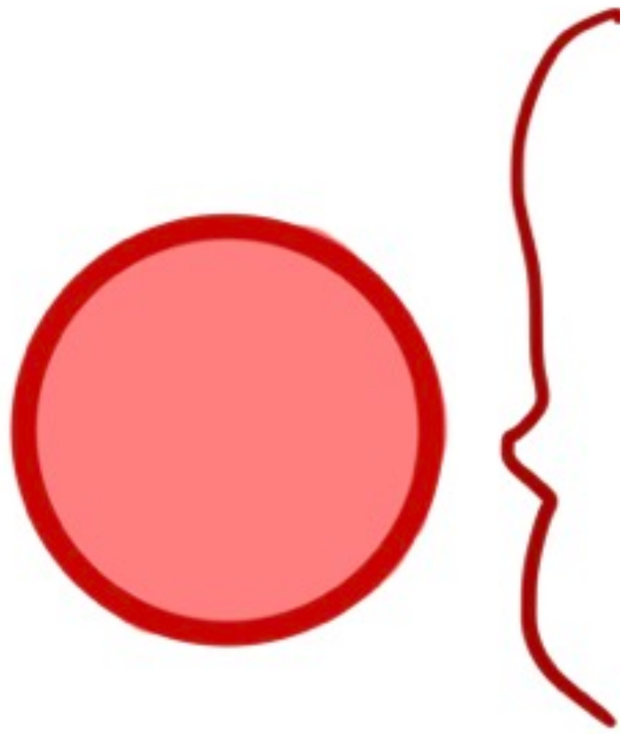
Neutron stars: nature's dark matter accelerators

- ➤ Neutron stars accelerate dark matter to beyond freezeout speeds

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



- ➤ Dense, accept a large DM flux

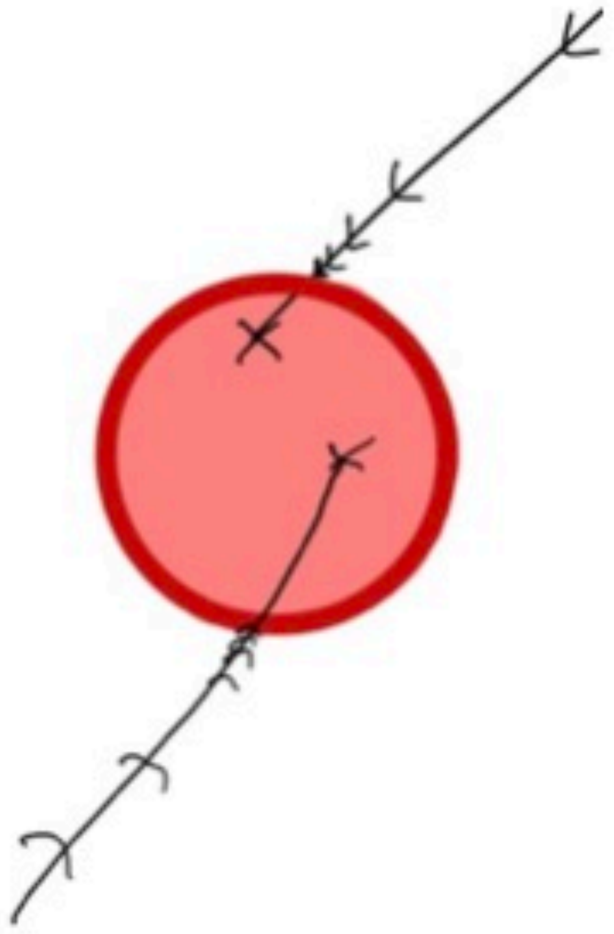


- fiducial mass of $\sim 10^{57}$ GeV
- neutrons:protons:electrons $\sim$10:1:1
- flux of $\sim$100 grams of DM/second

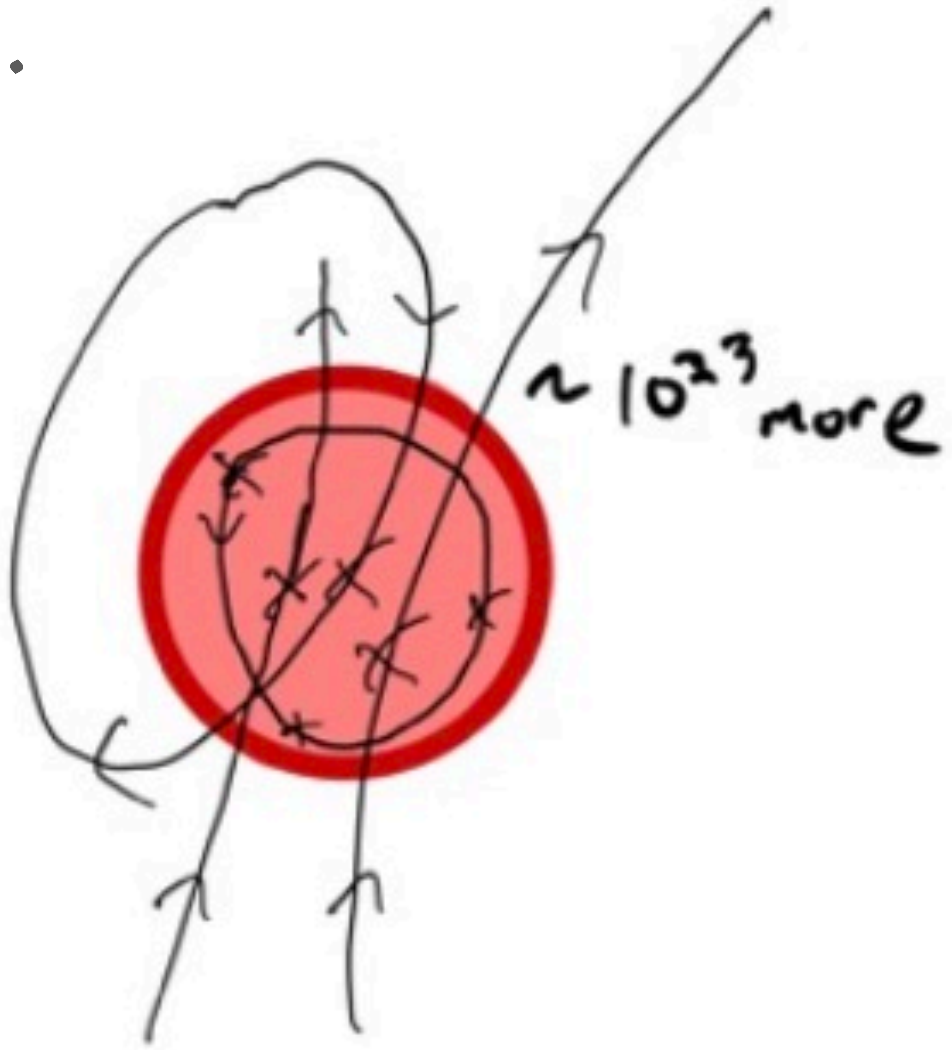
Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to ~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 (0.4 GeV/cm^3 DM)

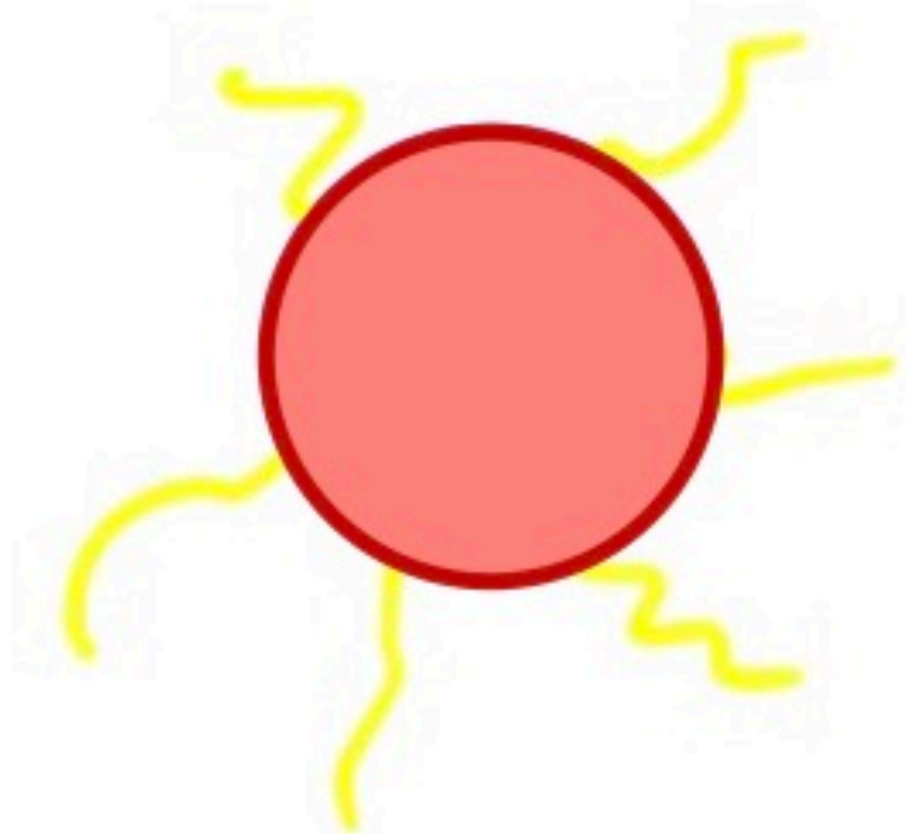
1.



2.



3.



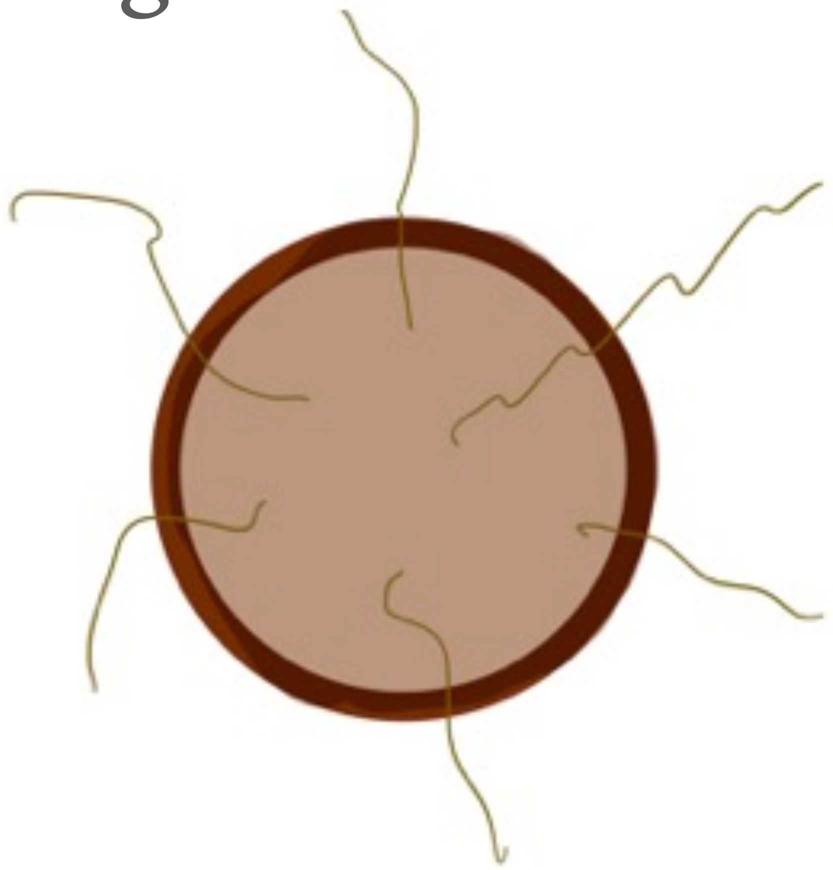
T~1750 / 2500 K, for NS near Earth

Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to ∼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 (0.4 GeV/cm^3 DM)

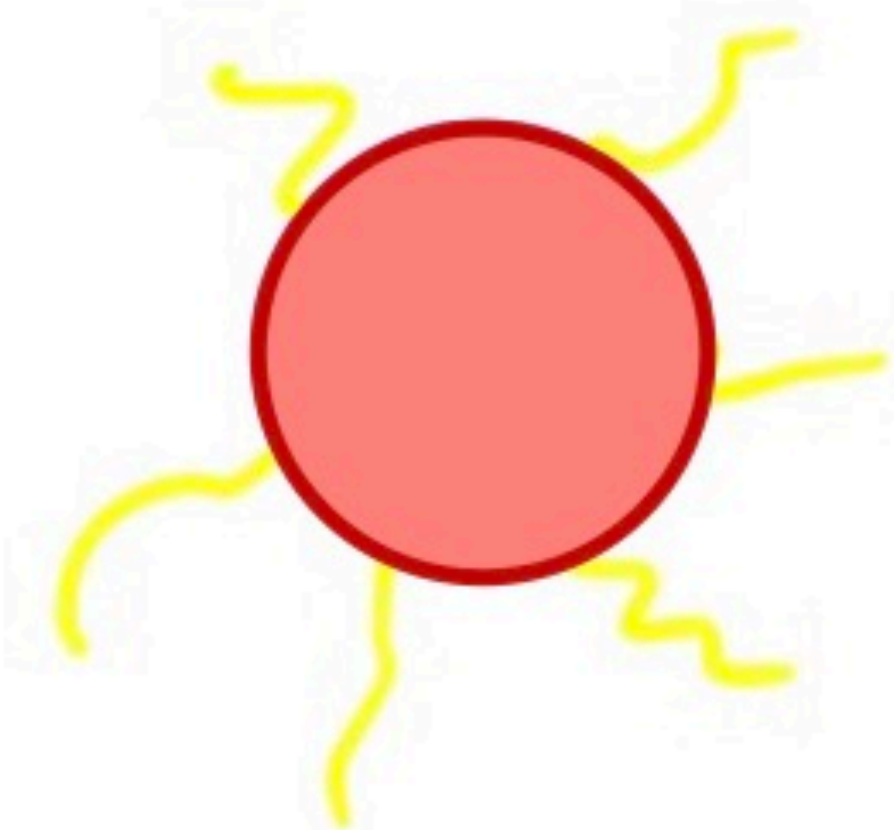
0. Compare to NS without DM heating

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



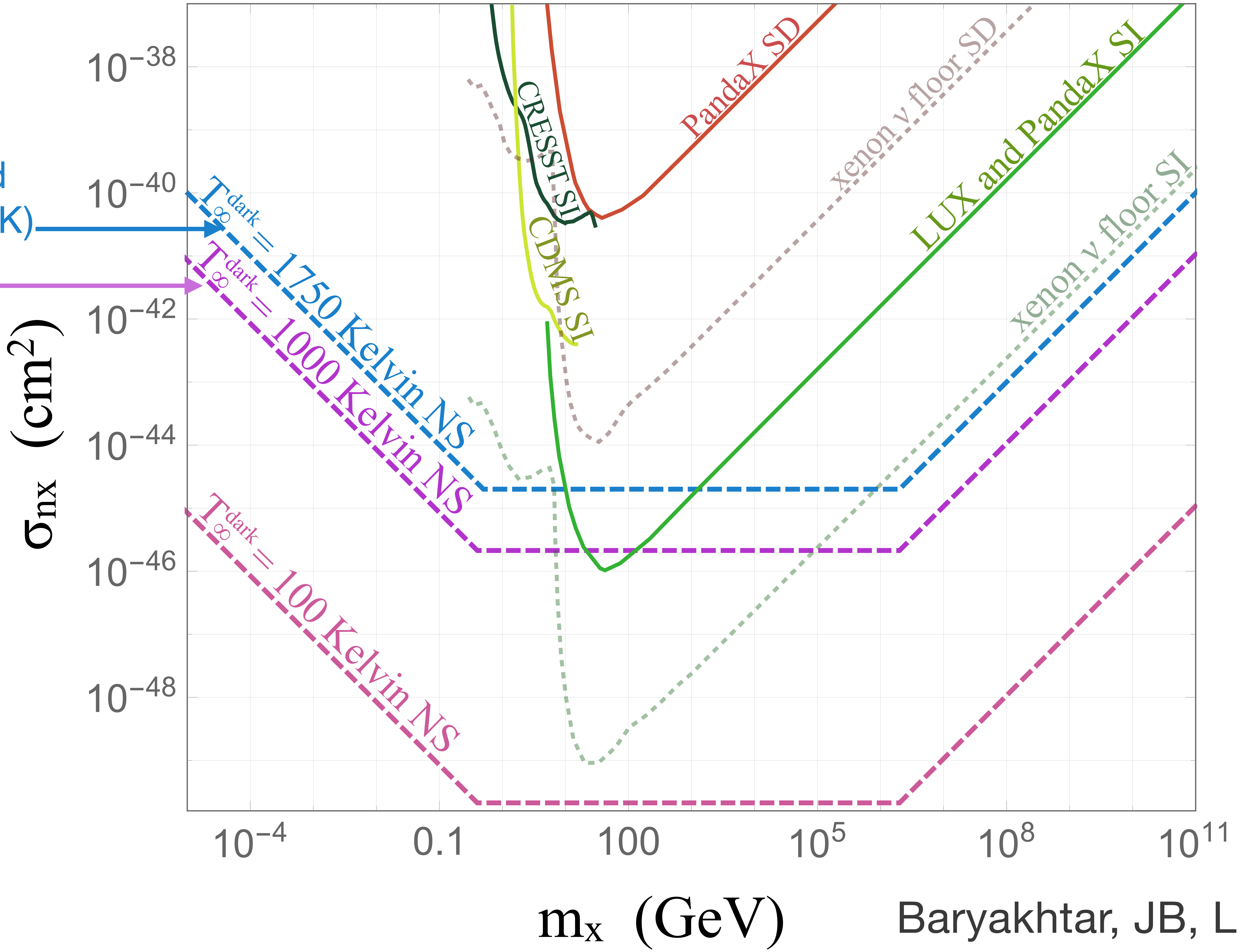
e.g. Yakovlev Pethick astro-ph/0402143
Page Lattimer et al. astro-ph/0403657

3.



T∼1750 / 2500 K, for NS near Earth

Neutron Star Dark Matter Heating Sensitivity



all incoming
DM captured
(ann. T~2500 K)

10% incoming
DM captured
(ann. T~1400 K)

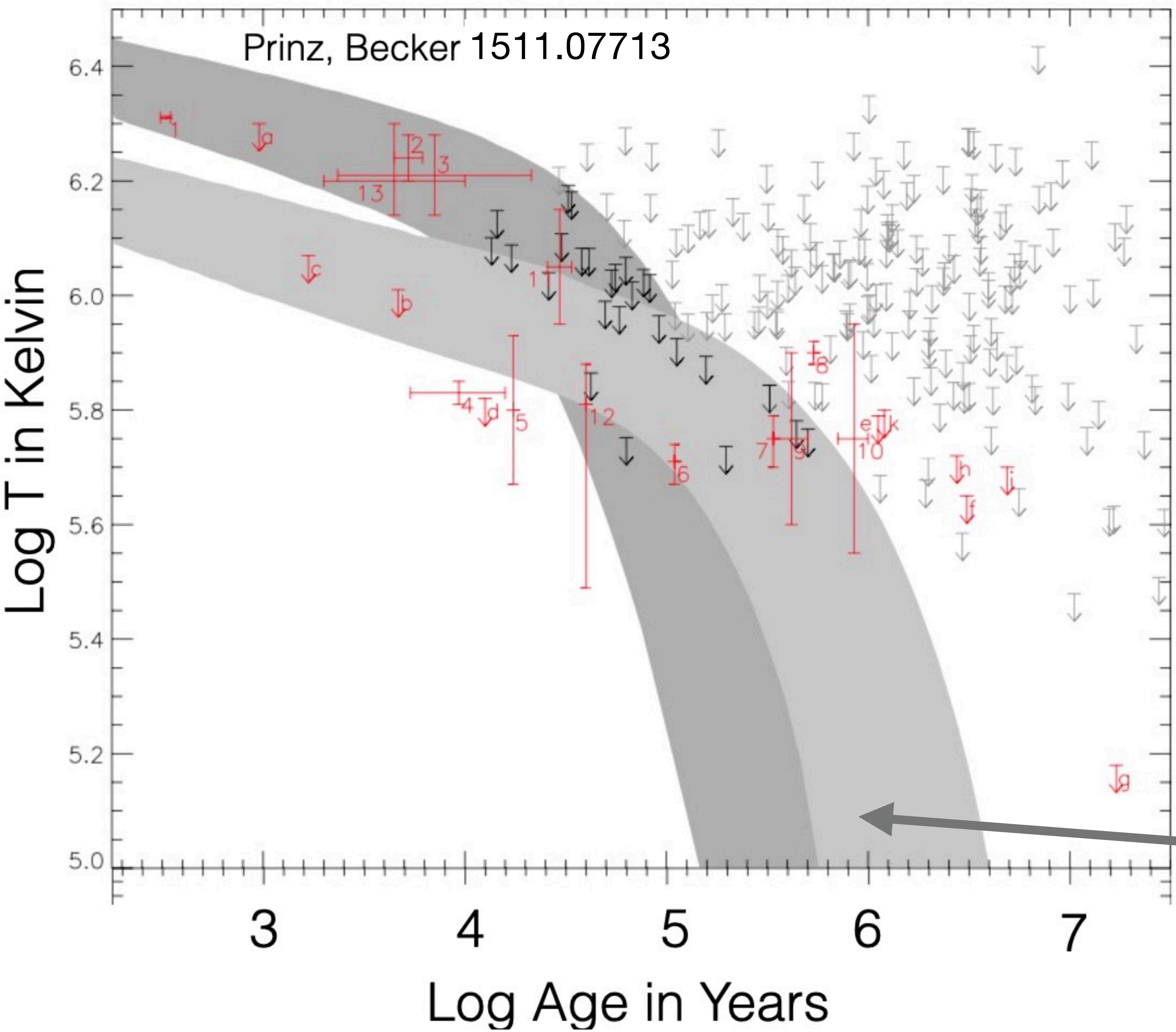
Baryakhtar, JB, Li, Linden, Raj 2017

Neutron stars, broad reach for particle dark matter

1. EFT, Spin-Dependent, Spin-Independent, Strongly Interacting, Electroweakino, Inelastic
2. Leptophilic dark matter
3. Self-interacting dark matter
4. Heavy DM, baryon and lepton annihilating DM, compressed WIMPs, co-annihilating DM
5. Winos, Higgsinos, Precision Capture, Pasta Capture
6. Muonphilic
7. Asymmetric (converts NSs into black holes)

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
Joglekar, Raj, Tanedo, Yu 2019
Chen, Lin 2018
Kopp, Laha, Opferkuch, Shepherd 2018
Jin, Gao 2018
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
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

(more…)



-At early times, NS cooling depends on neutrino emission and crust opacity, along with magnetic heating effects

-At late times, NSs are isothermal, photon emission dominated

-Early temperature discrepancies disappear after ~10 Myr,

Yakovlev & Pethick astro-ph/0402143

Page, Lattimer et al. astro-ph/0403657

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

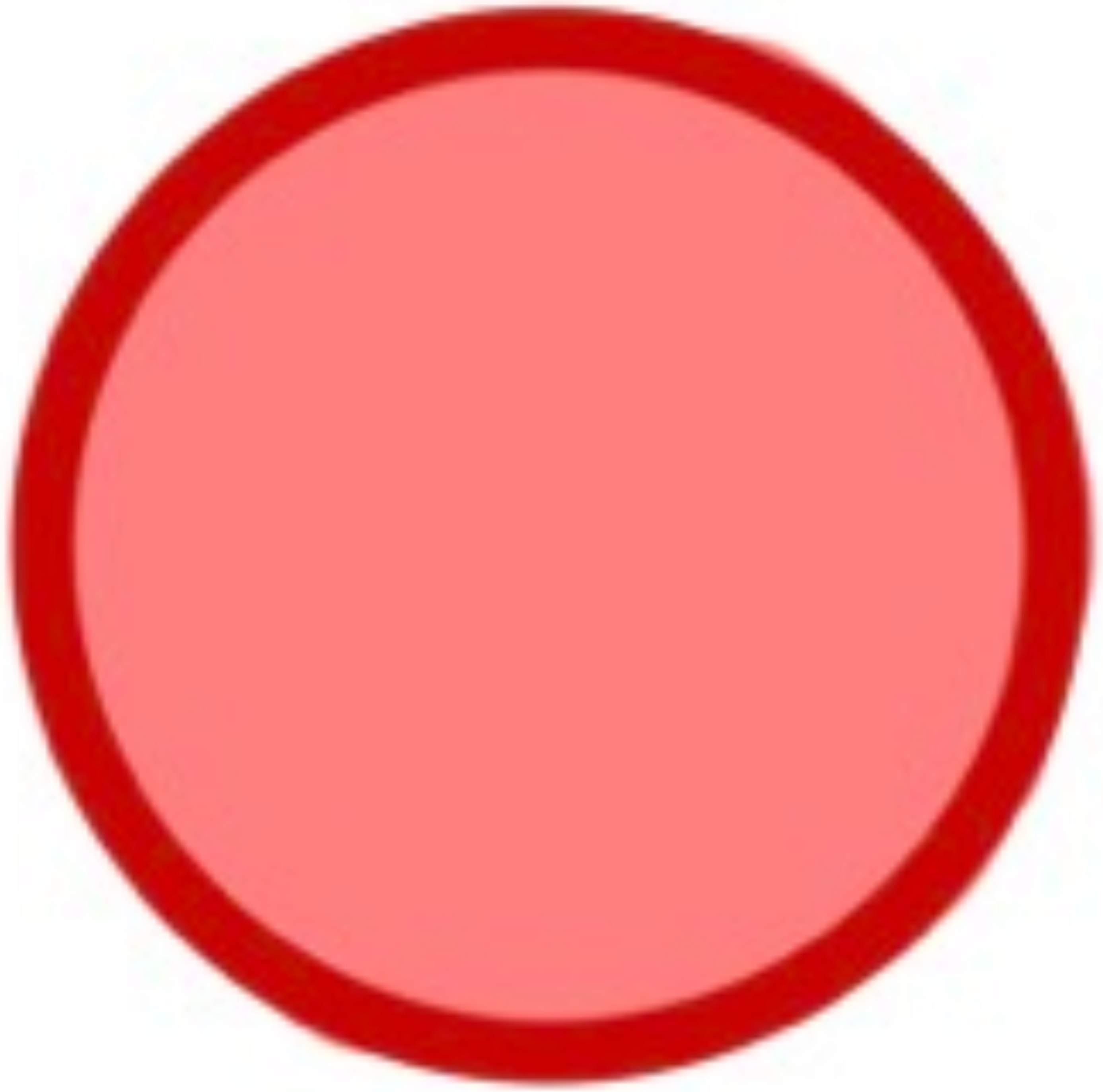
Coldest Known Neutron Star

PSR J2144–3933

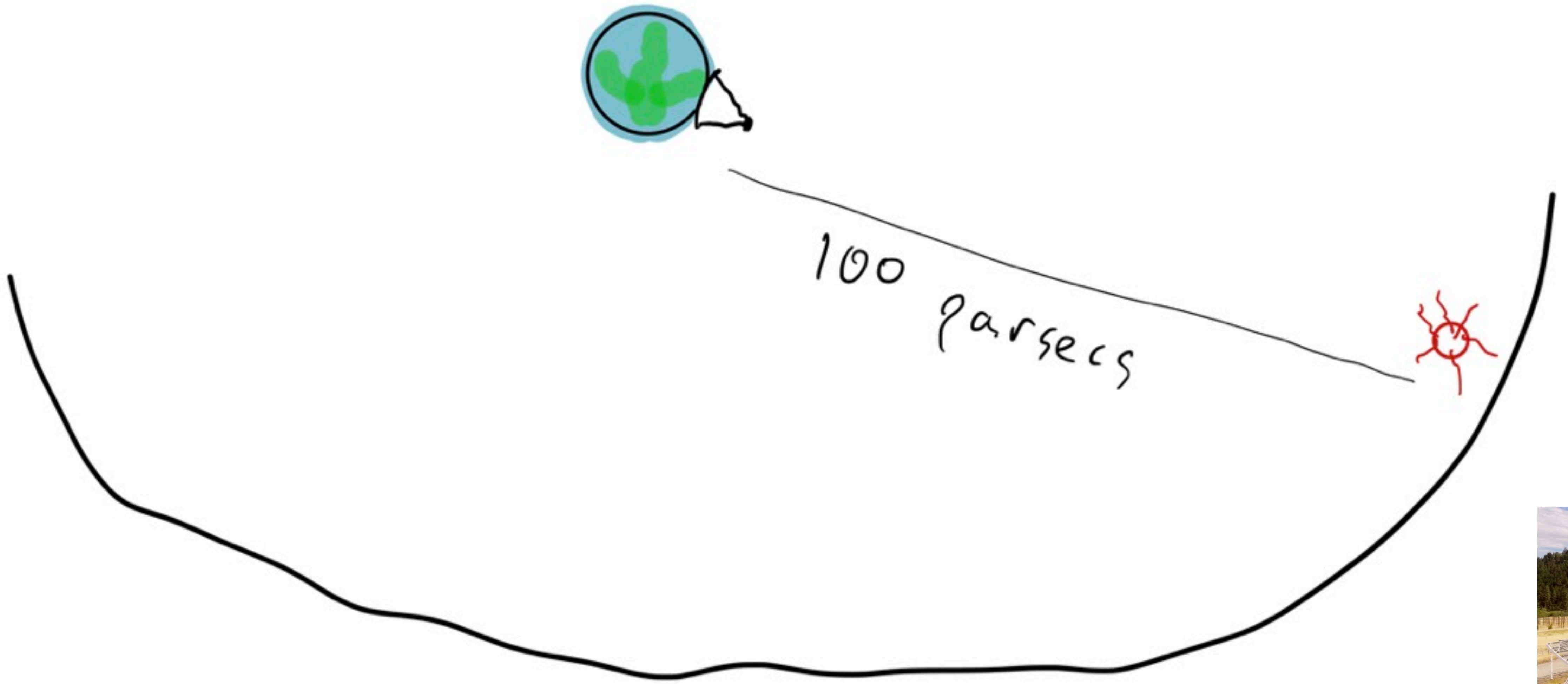
Coldest known neutron star, nearby, deep imaged by HST, observed no emission setting a bound (Guillot et al, 1901.07998)

$T_S < 3 \times 10^4$ 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 ~1750-2300 K



Looking for WIMPs with 30+ meter telescopes



ELT 2σ sensitivity estimates

annihilation of WIMPs, Higgsinos

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

kinetic only

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

Baryakhtar, JB, Li, Linden, Raj 1704.01577

for recent JWST estimates see Garani et al. 2205.05048

Radio observations of nearby pulsars

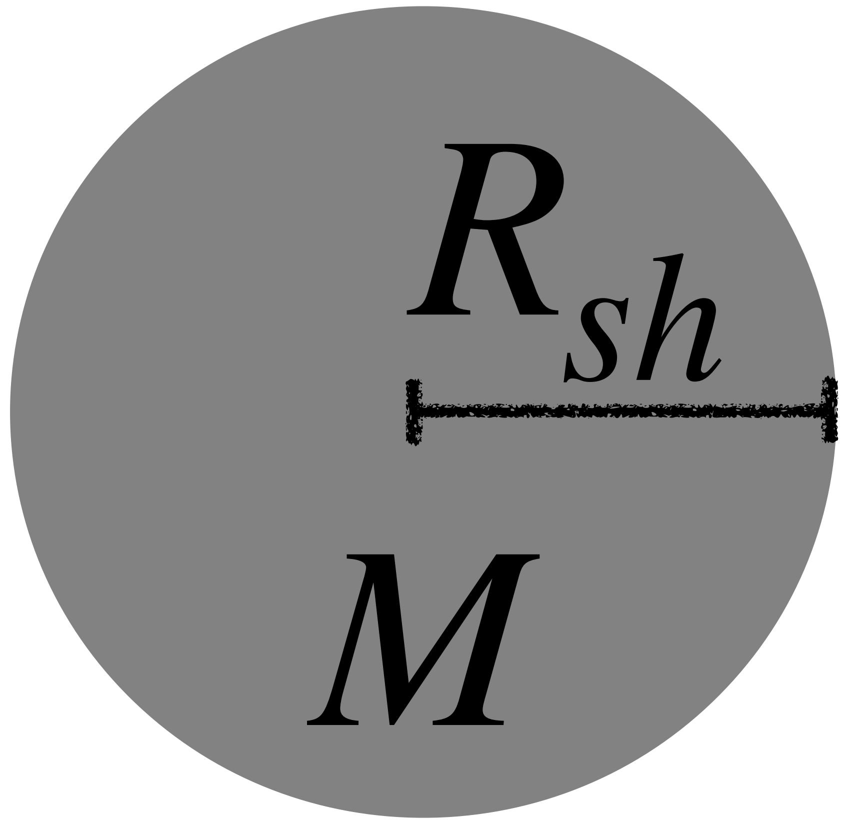
	d (pc)	period (s)
J1057-5226	90	0.19
J0736-6304	95	4.86
J0834-60	100	0.38
J0711-6830	110	0.005
J0749-68	110	0.91
J0924-5814	110	0.71

-YMW16 dispersion measure distances

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

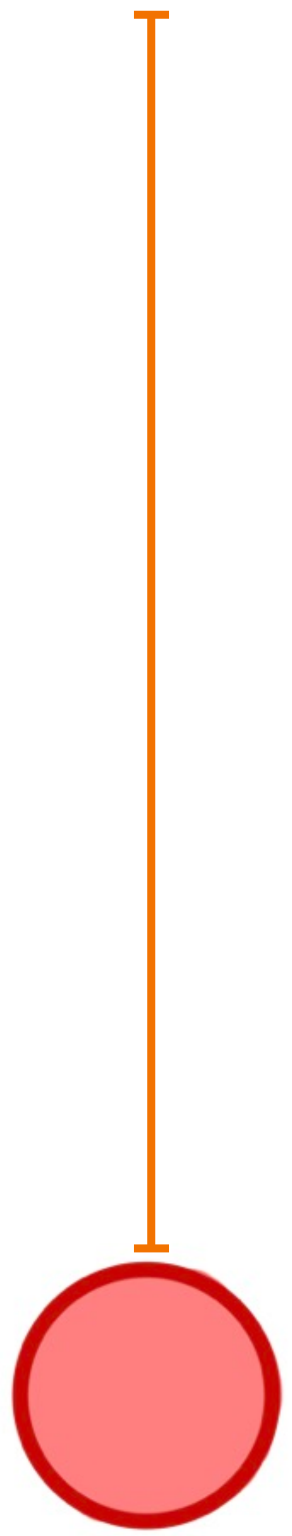


Accretion onto NSs, generalized

JB, Kavanagh, Raj 2109.04582

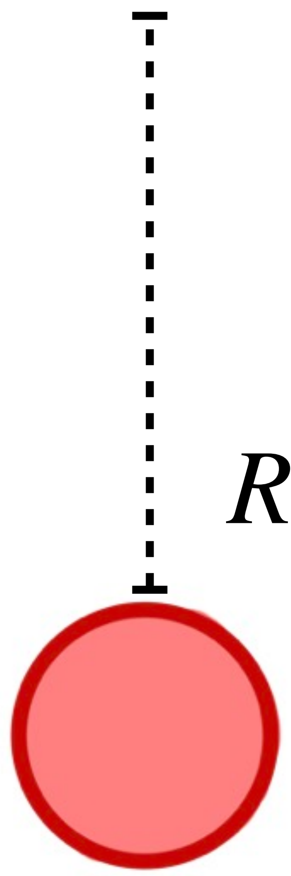
- Radius for DM accretion onto NS depends on size of DM subhalo, and whether accretion is collisionless or collisional

- Collisional/Bondi



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

- Collisionless



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

Accretion II: size of subhalo

JB, Kavanagh, Raj 2109.04582

- Consistency requirements for both accretion regimes

- Collisionless

$R_{NS}+R_{SH}$=closest approach

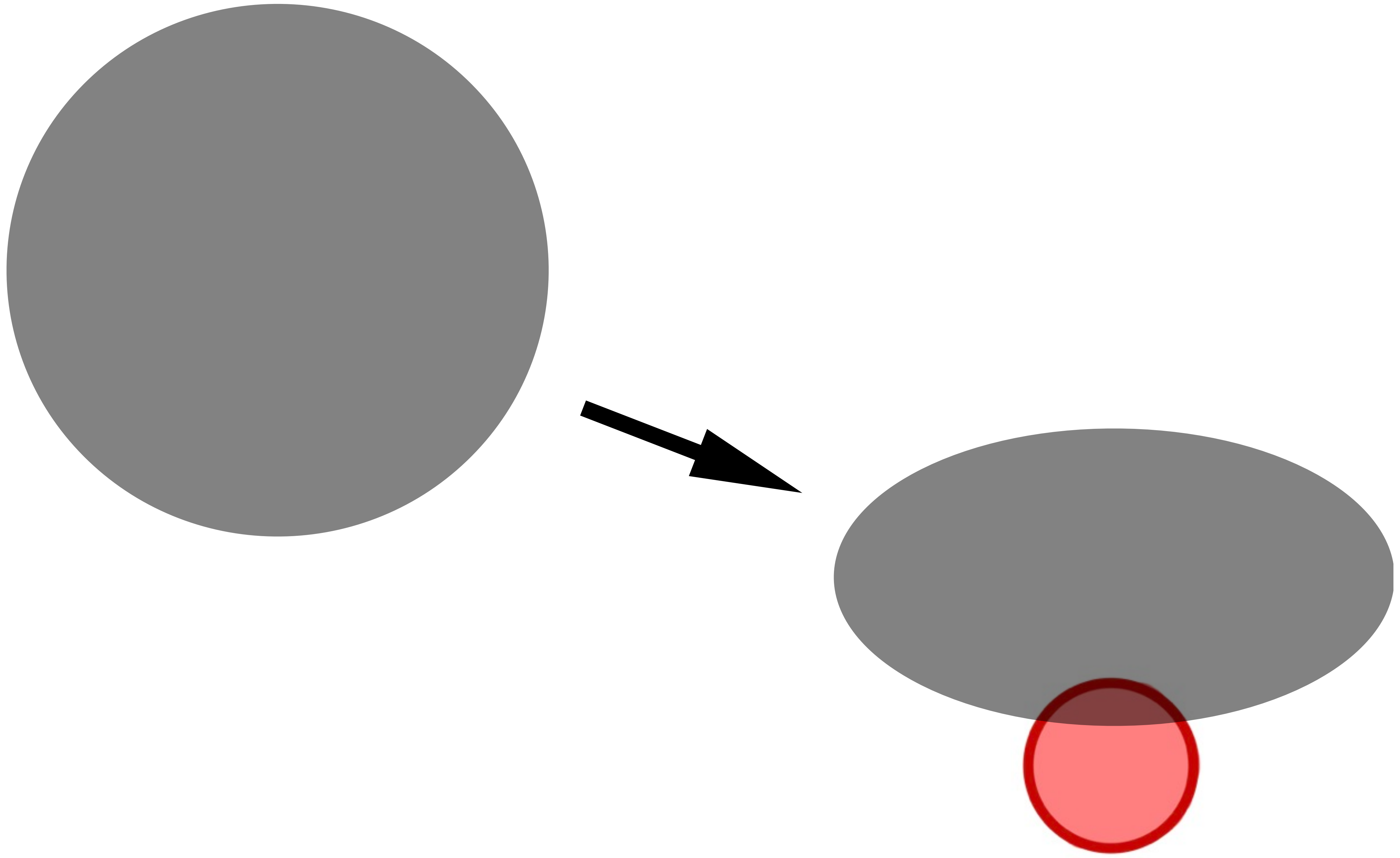
- Collisional/Bondi

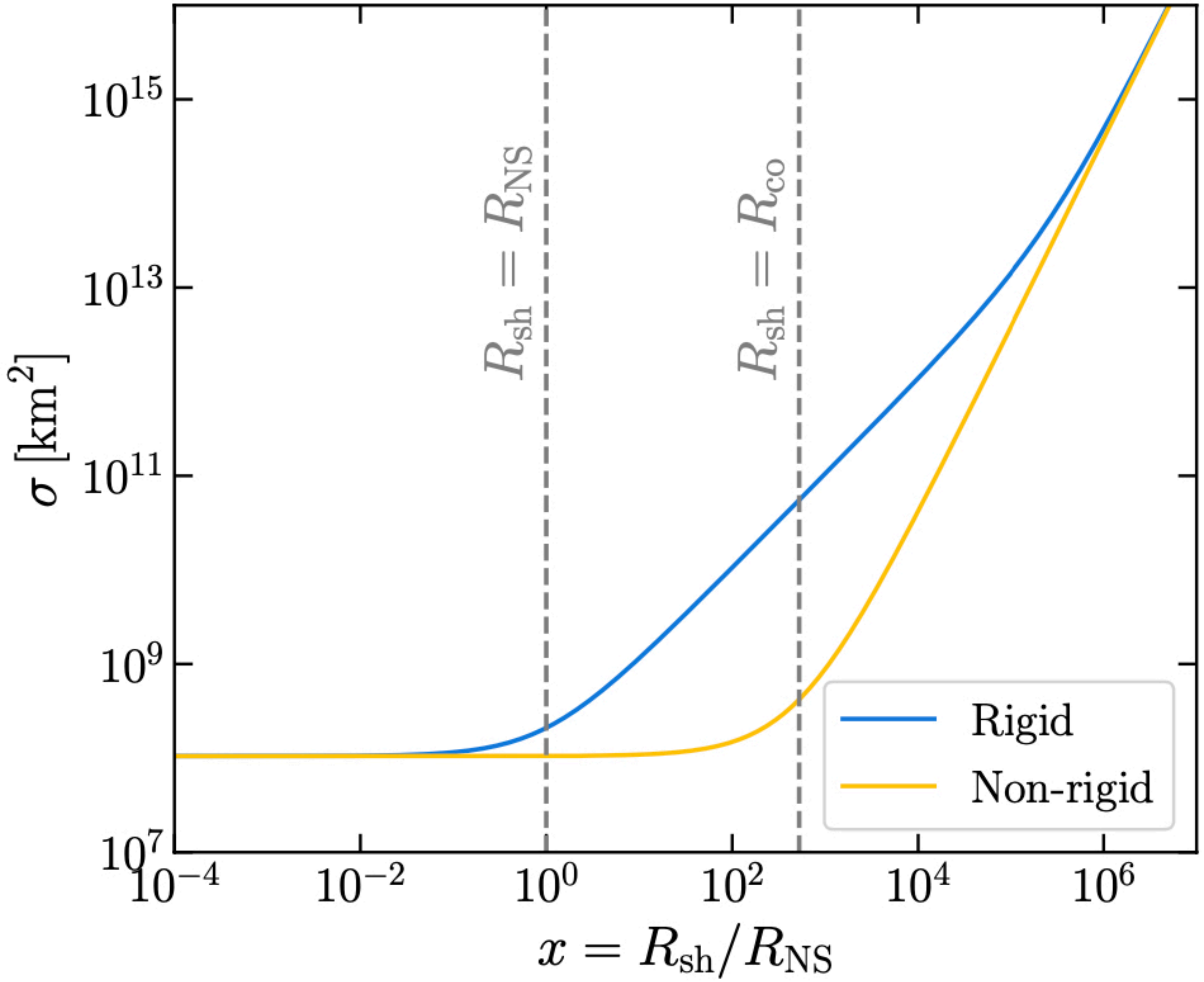
$R_{CO} < R_{SH}$

Accretion III: rigidity

JB, Kavanagh, Raj 2109.04582

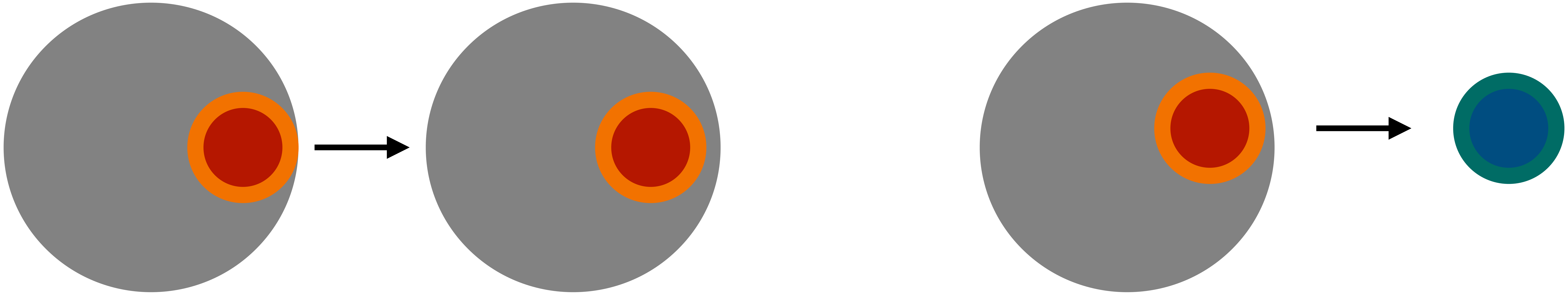
- In what follows we assume deformable subhalos





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

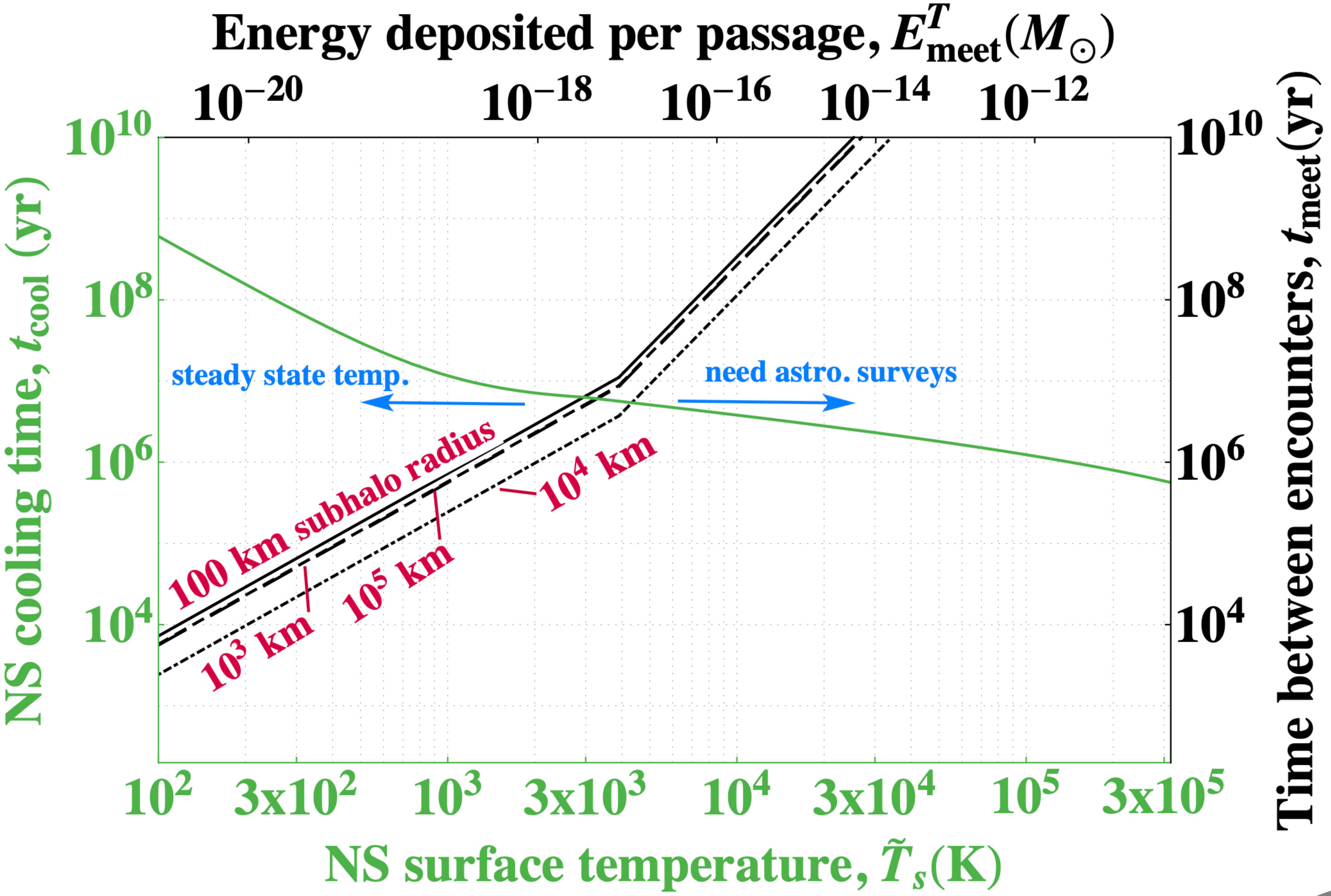


$$\left(\frac{\widetilde{T}_{\rm hot}}{10^4\ {\rm K}}\right)^2 = \left(\frac{\widetilde{T}_{\rm cold}}{10^4\ {\rm K}}\right)^2 + \frac{E_{\rm meet}}{6.2\times10^{-18}\ M_\odot}$$

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

Neutron stars cooling and heating

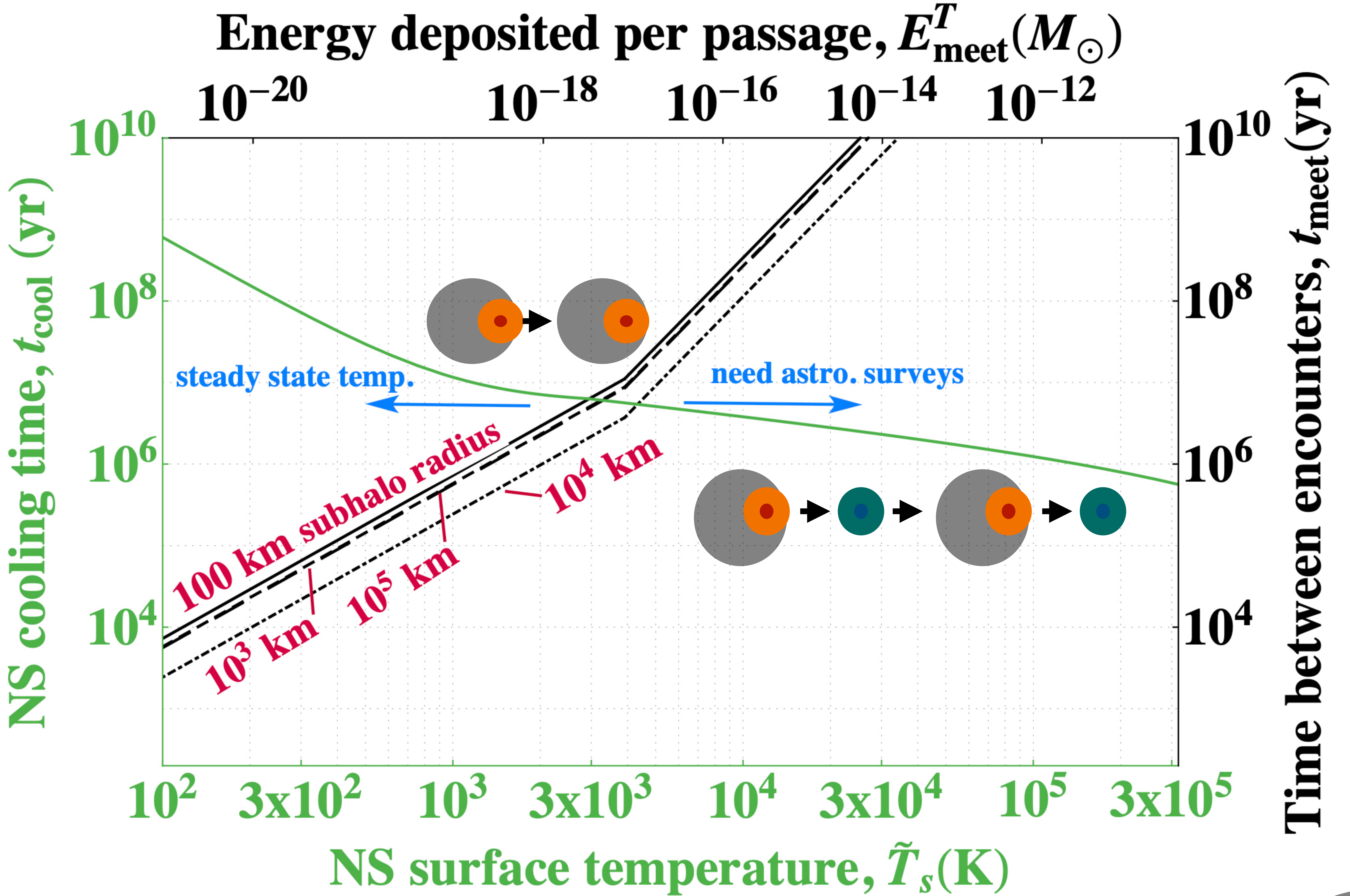
cooling



heating

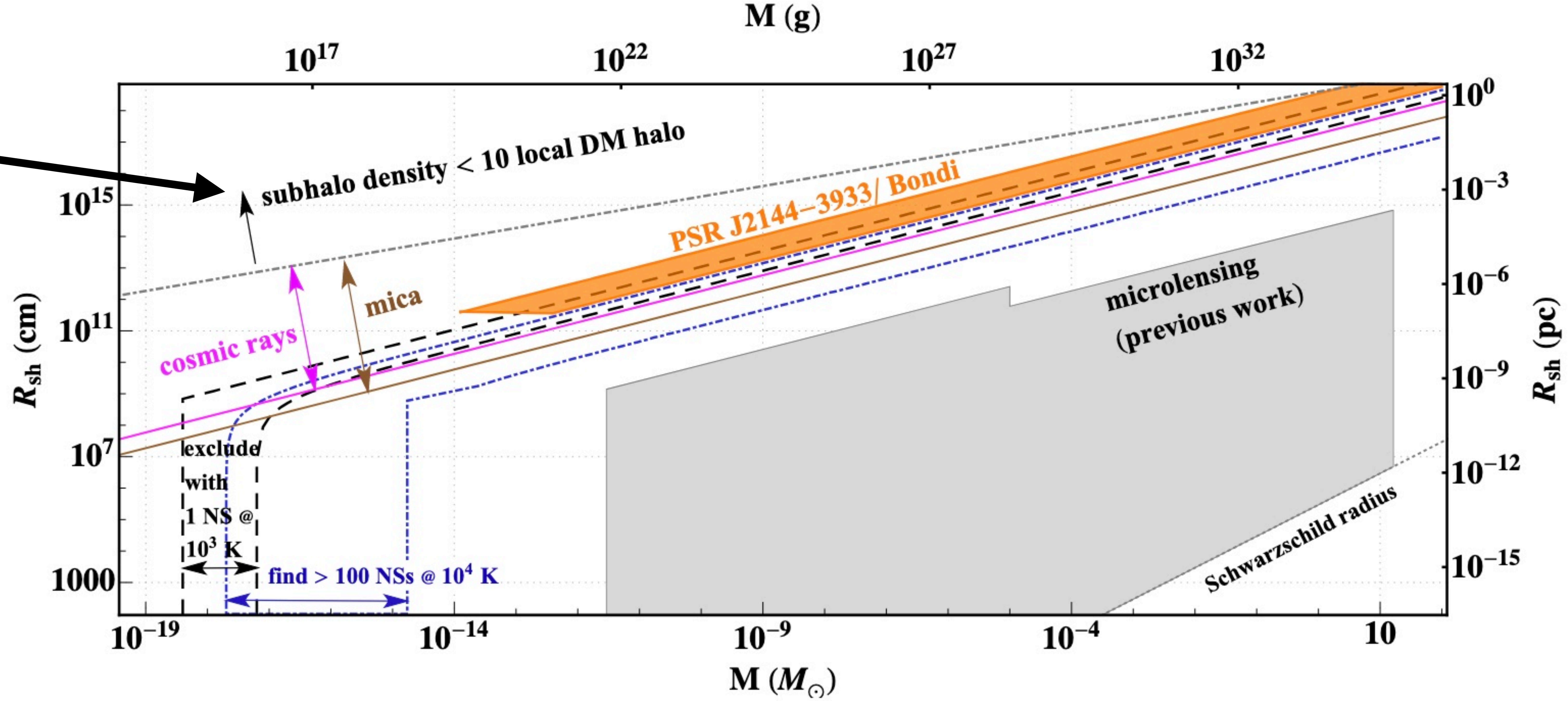
Neutron stars cooling and heating

cooling

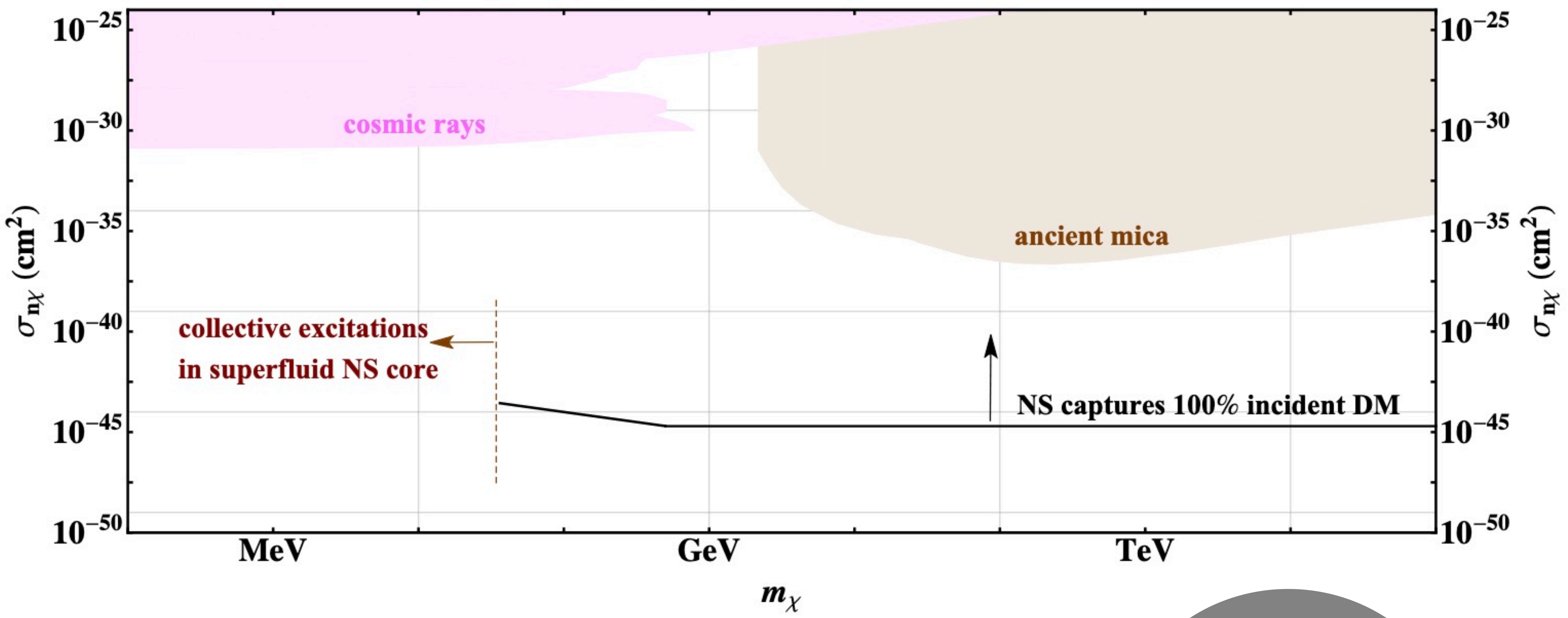


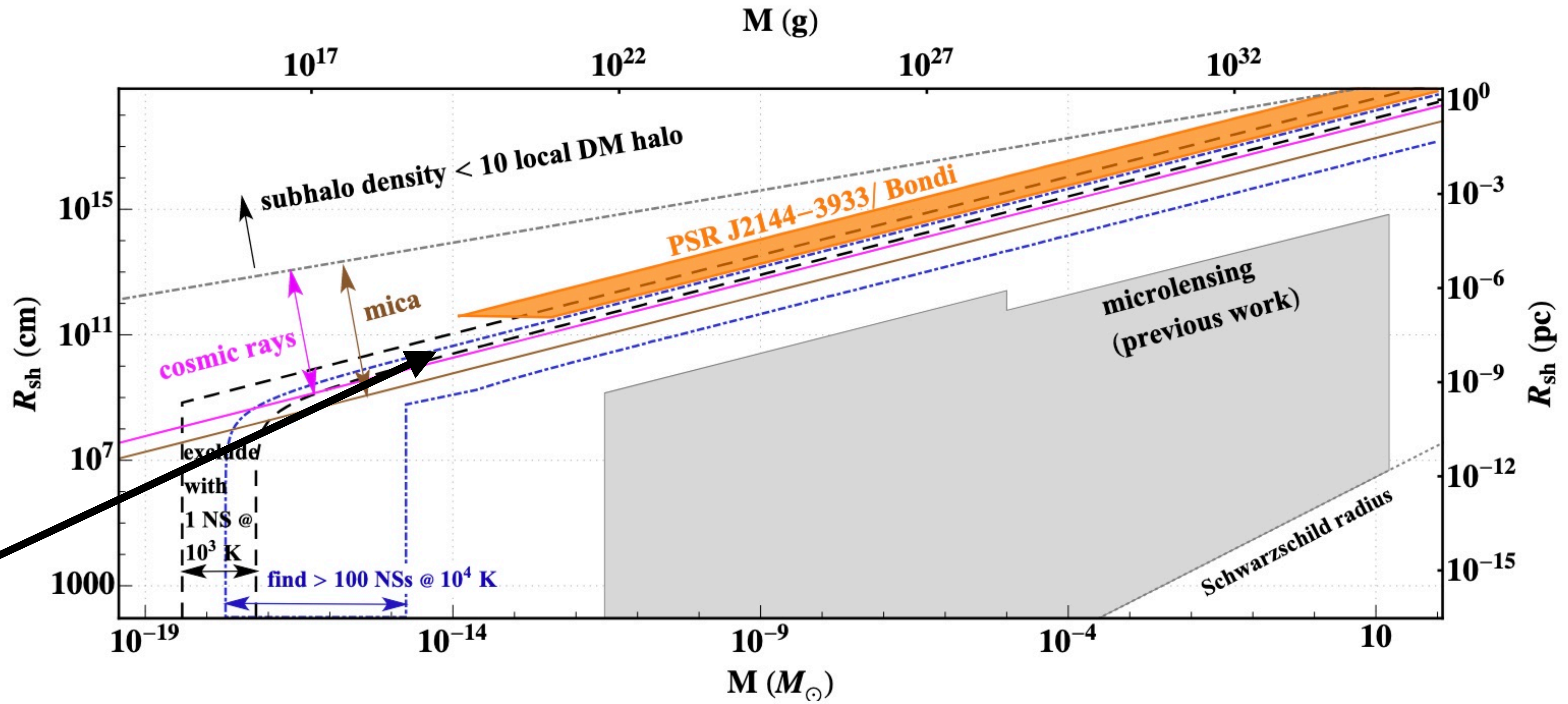
heating

subhalo density < halo density



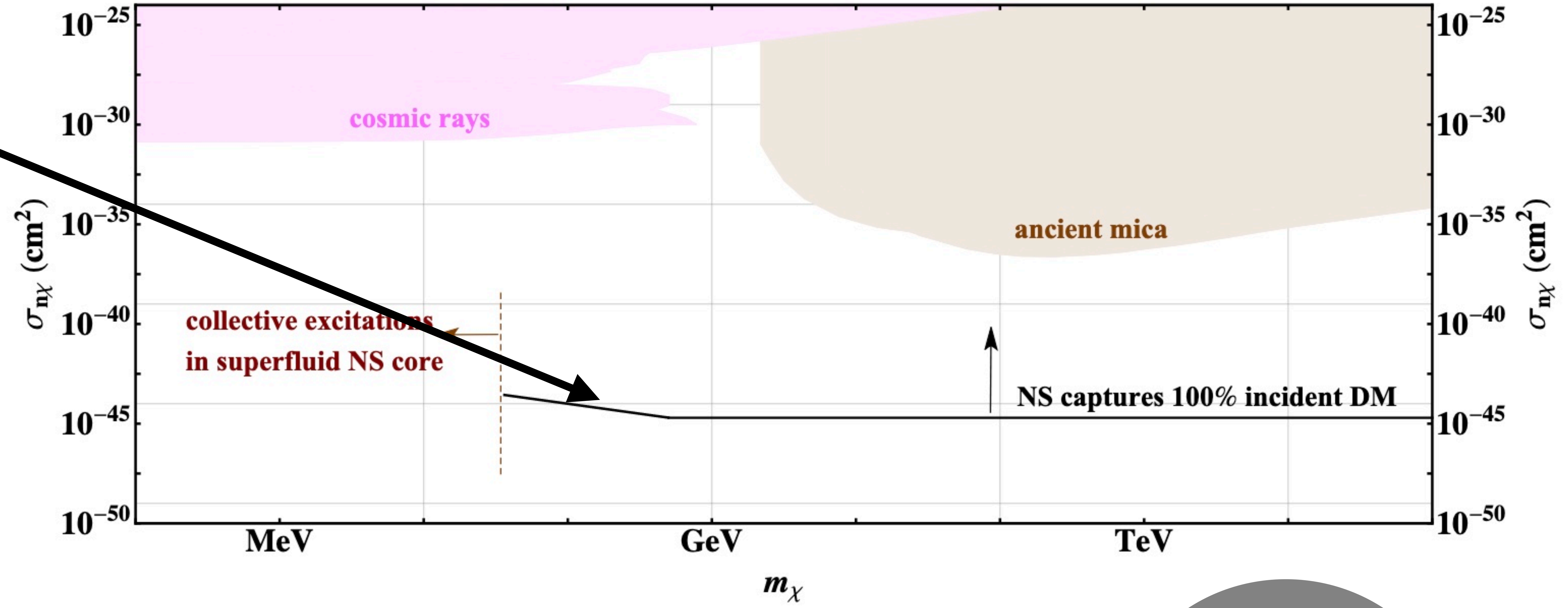
These bounds assume all DM is in subhalos





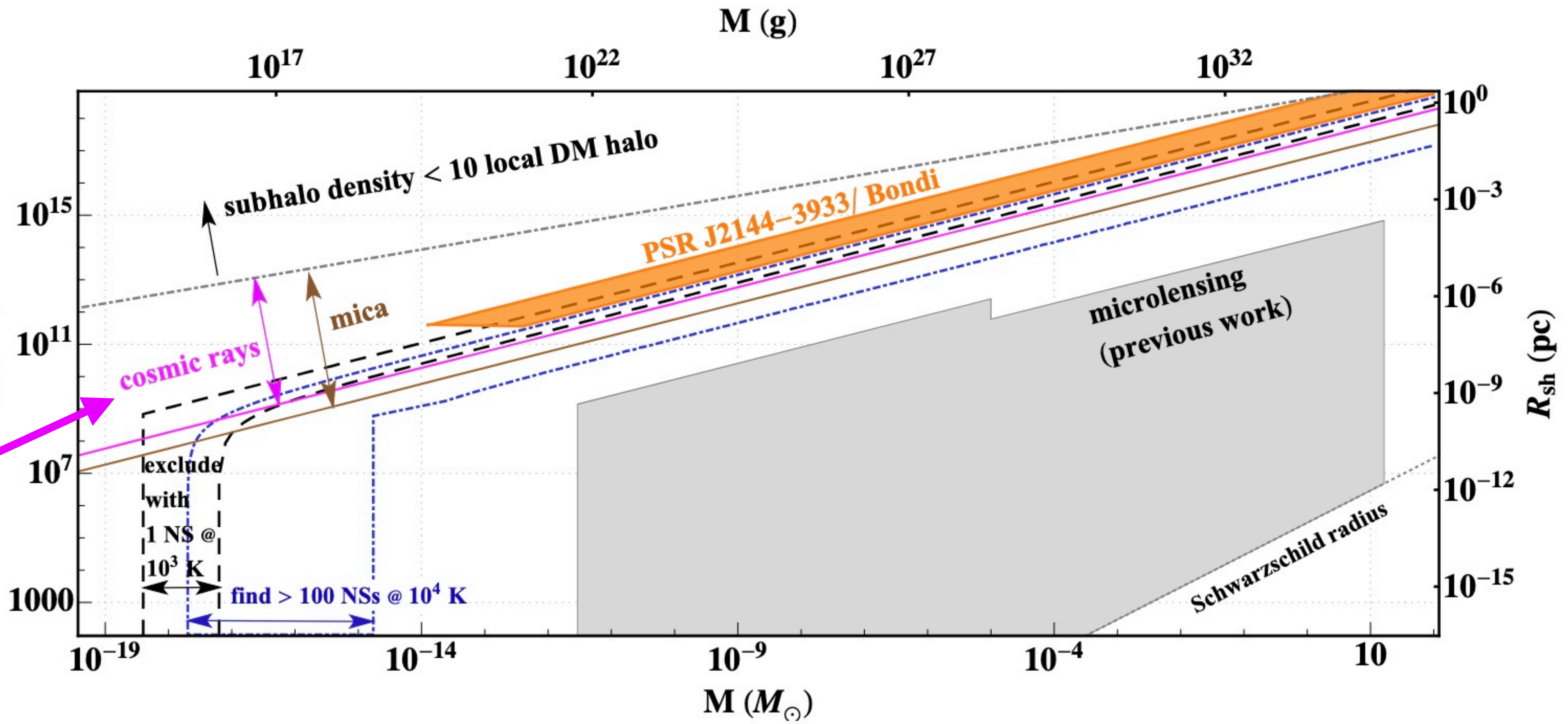
All sensitivity curves in this plot

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



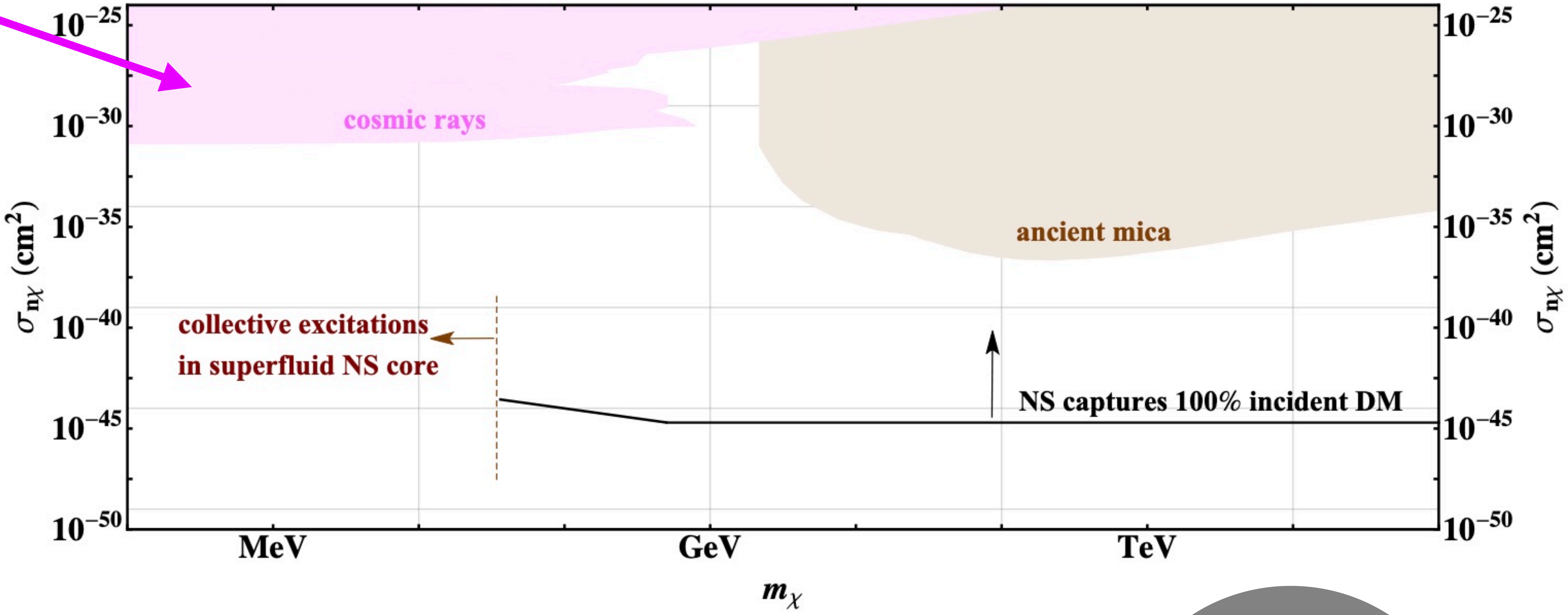
Cosmic rays will boost dark matter in subhalos so long as the interaction rate matches CR-diffuse DM interactions over ~8 kpc interaction lengths

$\tau_{\mathrm{CR}} > 1$

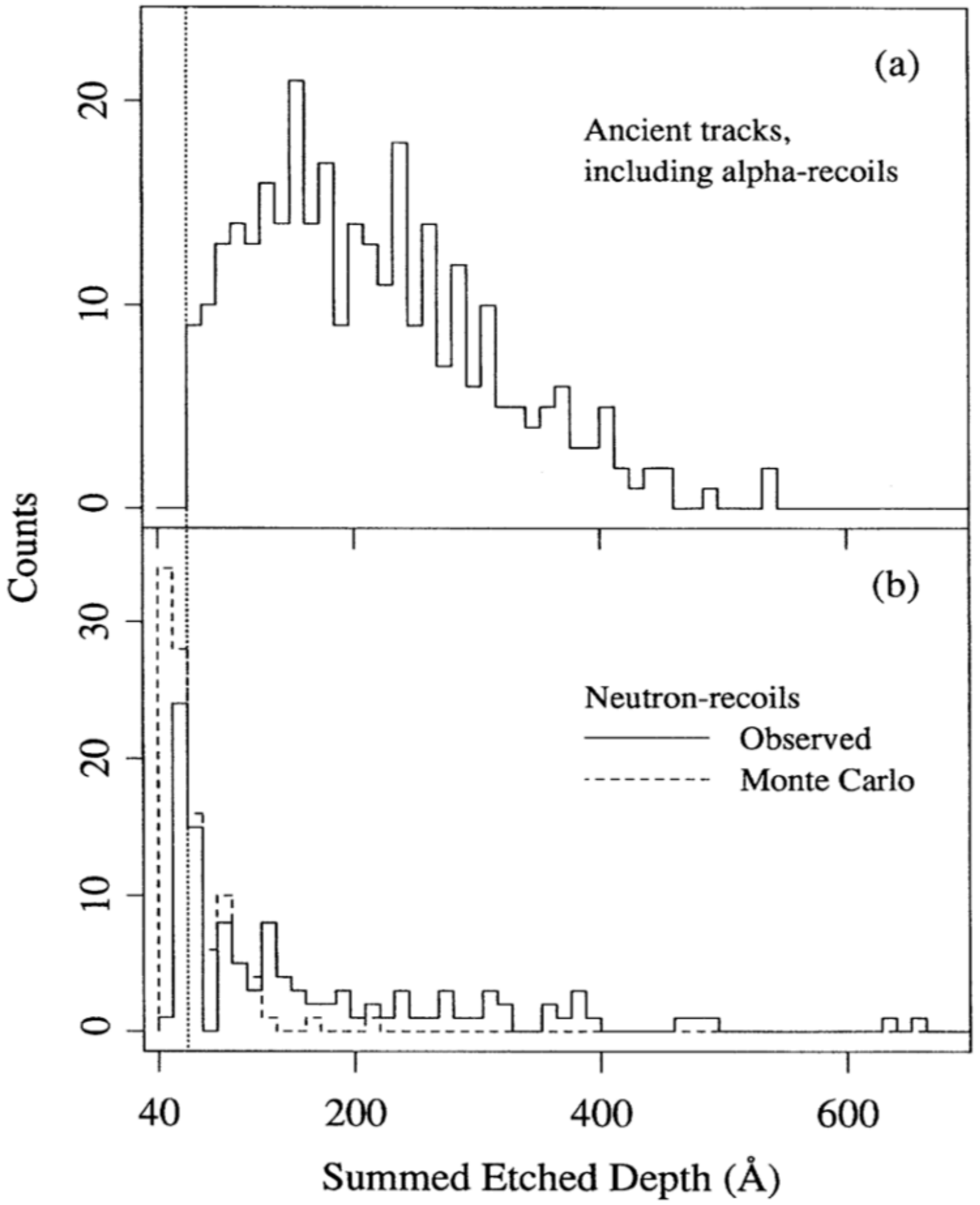


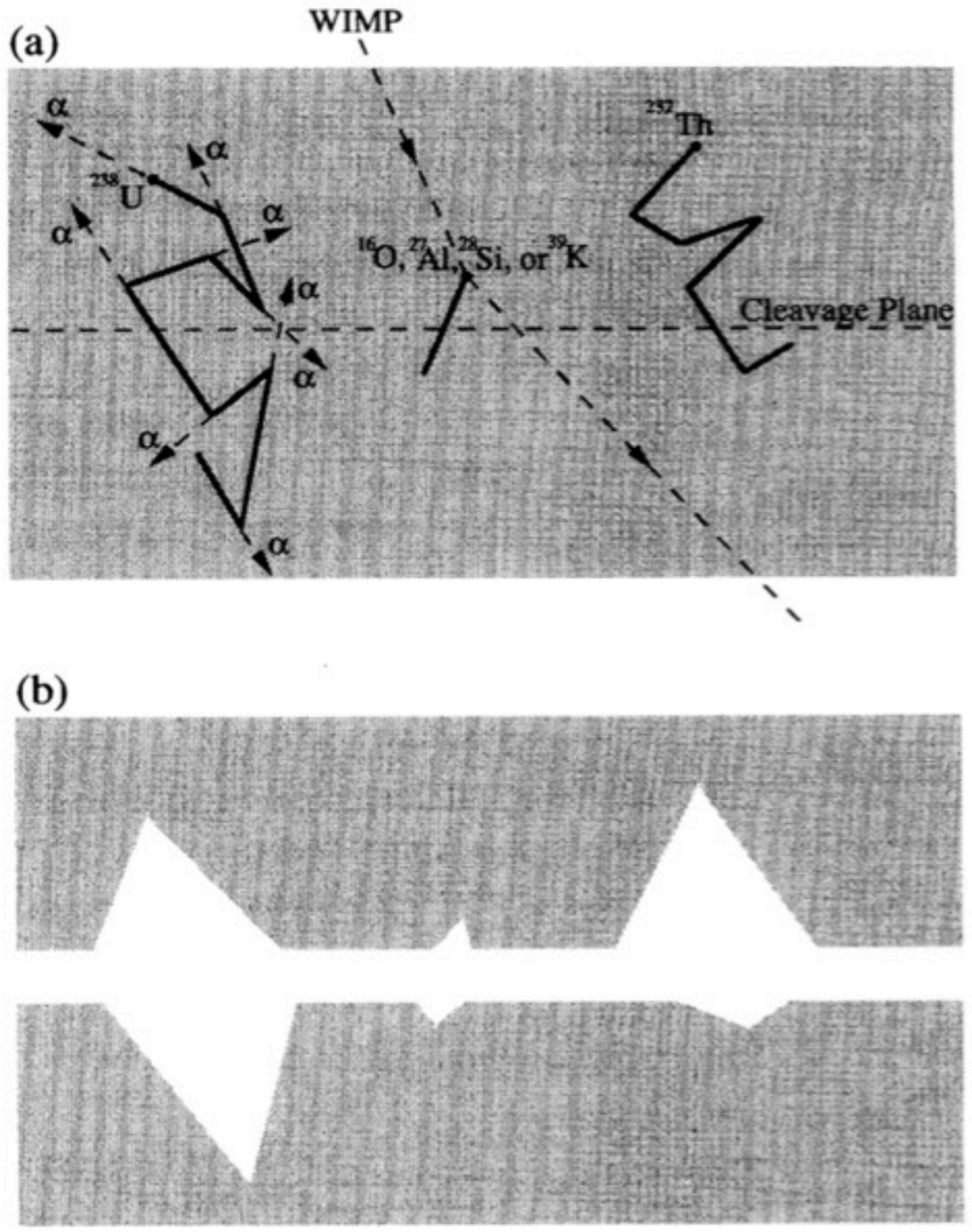
$$\tau_{\mathrm{CR}} = \int_0^{L_{\mathrm{dfs}}} ds\; n_\chi(s)\sigma_{\mathrm{geo}} f_{\mathrm{hit}} = \frac{\rho_\odot}{M}\sigma_{\mathrm{geo}}$$

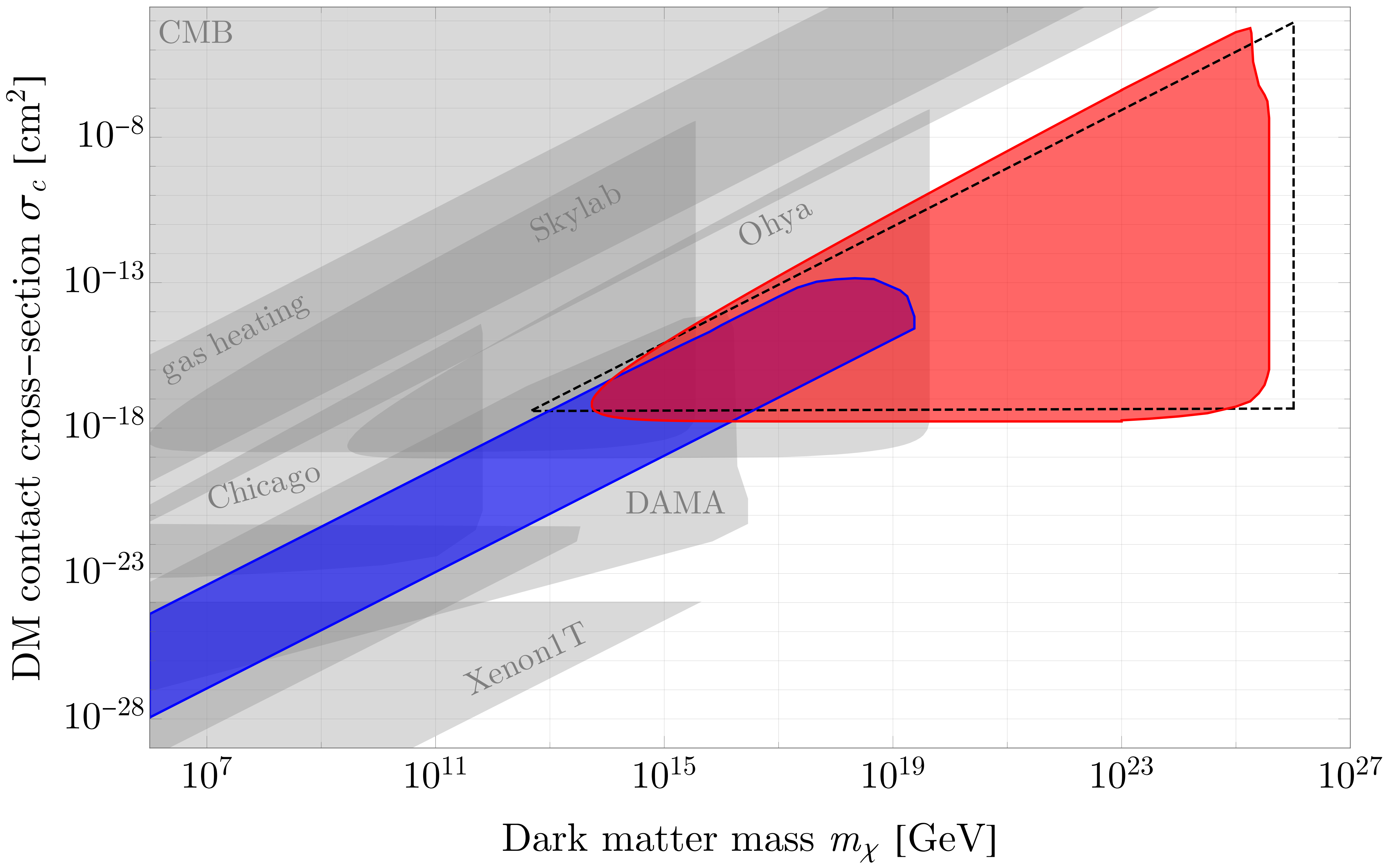
Low-mass DM boosted out of a subhalo yields similar CR-boosted DM bounds



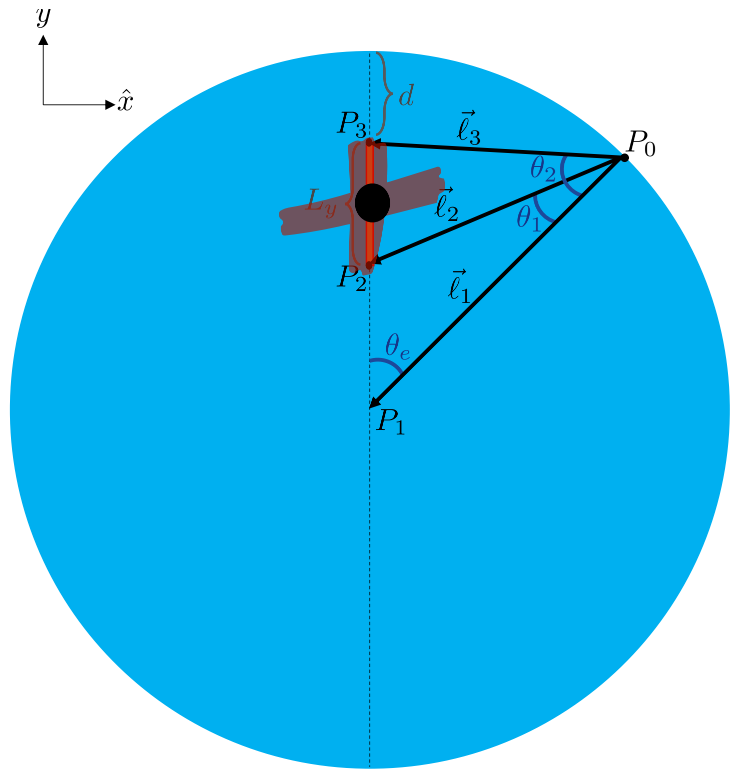
Ancient search for new particles: mica







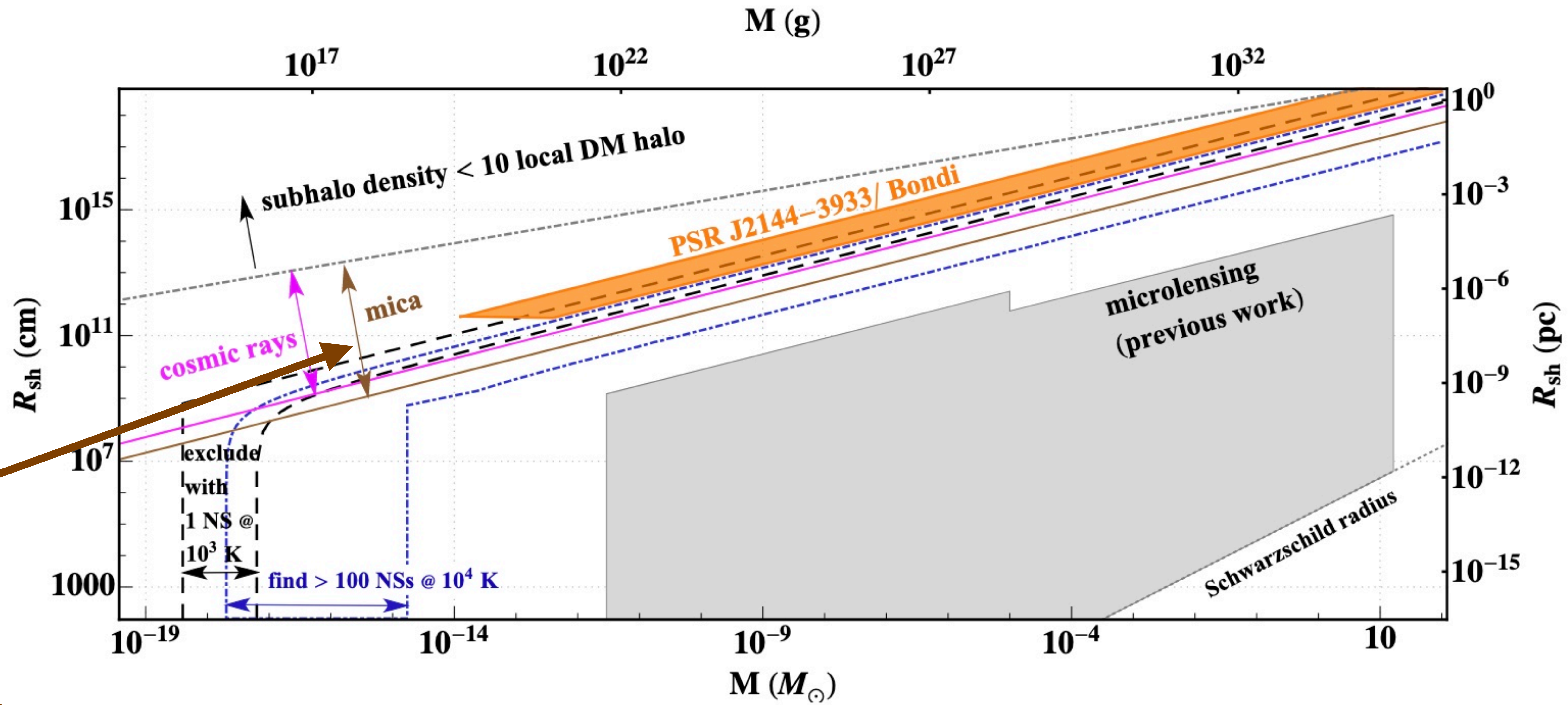
- Calibrated and etched mica samples from Price 1986, Snowden-Ifft 1995

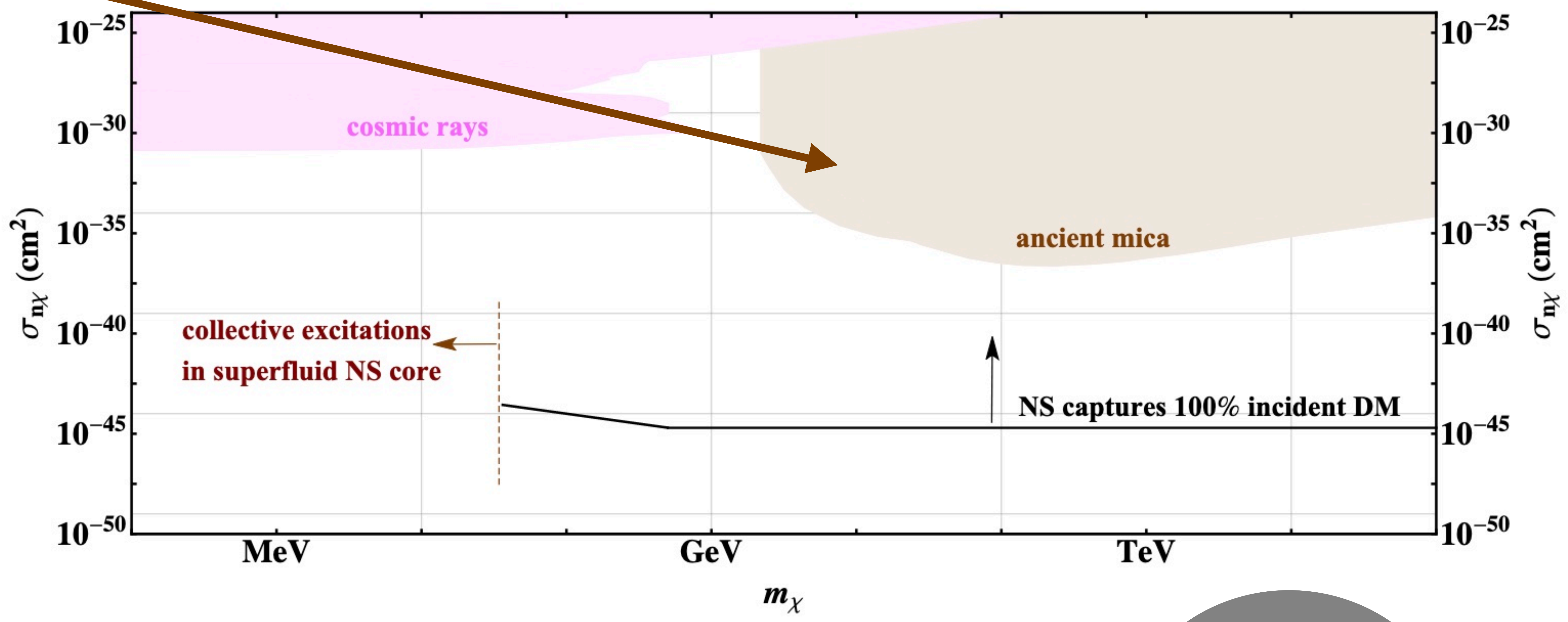


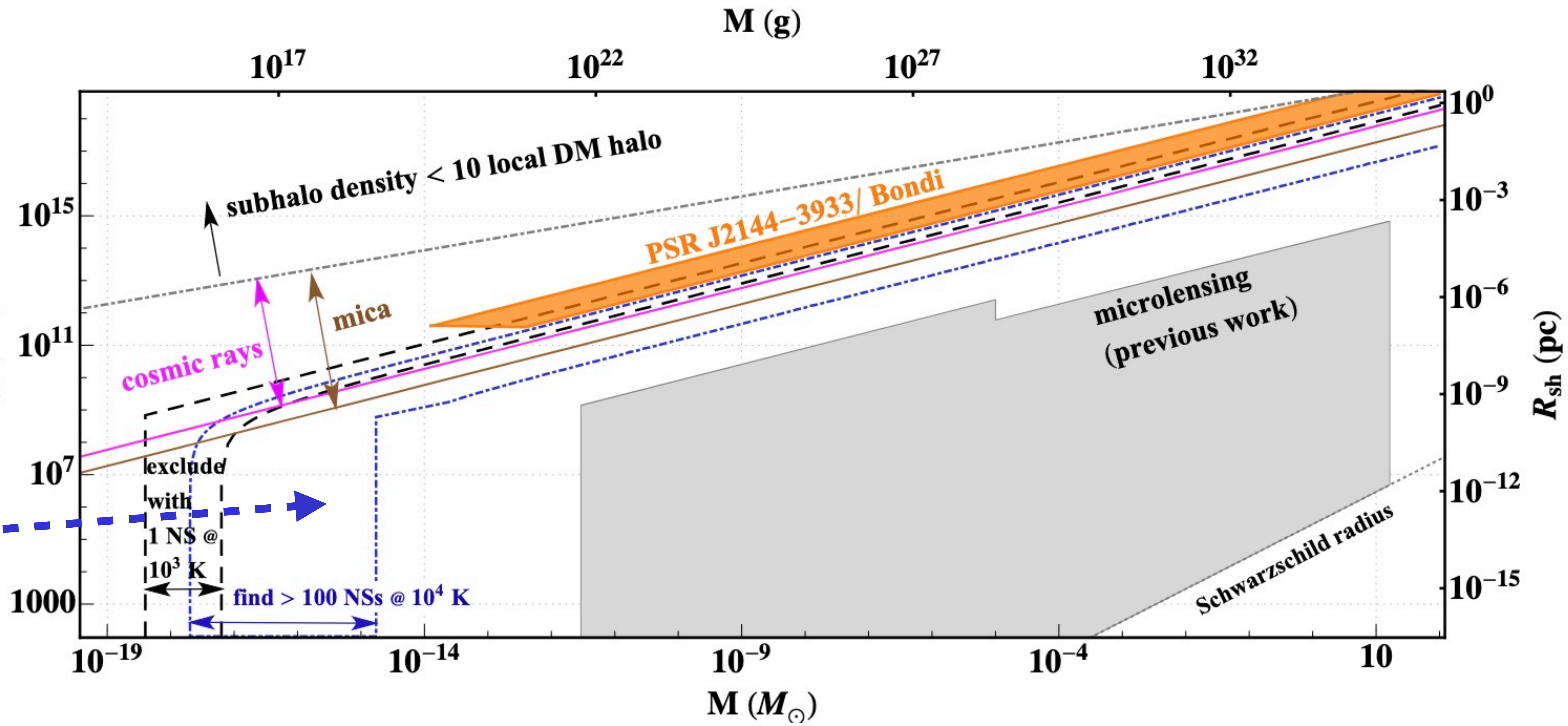
- Reanalyzed mica data using overburden

Acevedo, JB, Goodman 2105.06473
Bhoonah, JB, Courtman Song 2012.13406

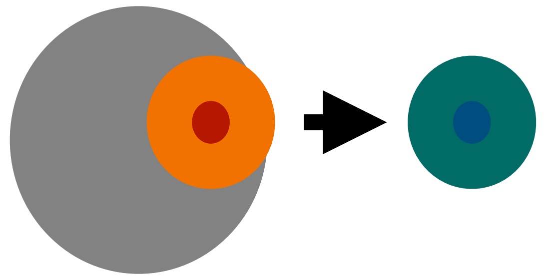
Requiring that subhalos interact
with ancient mica in
500 Myr yields this bound



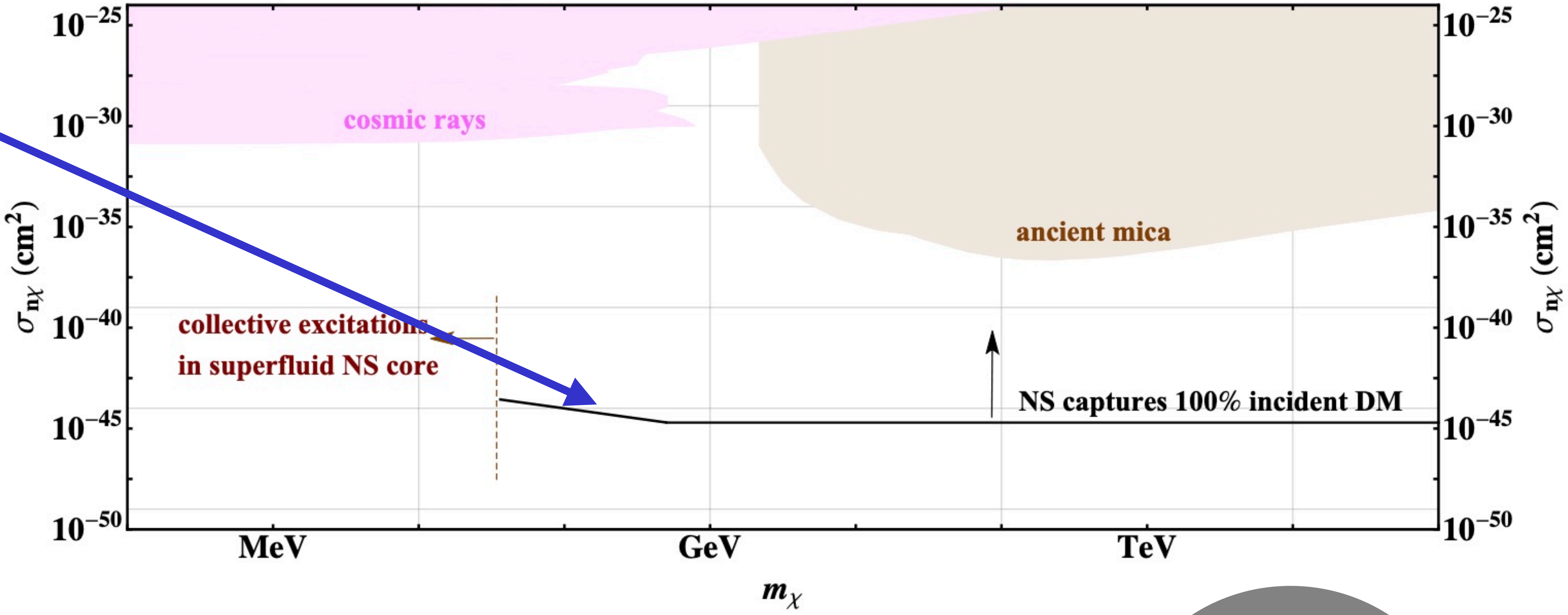




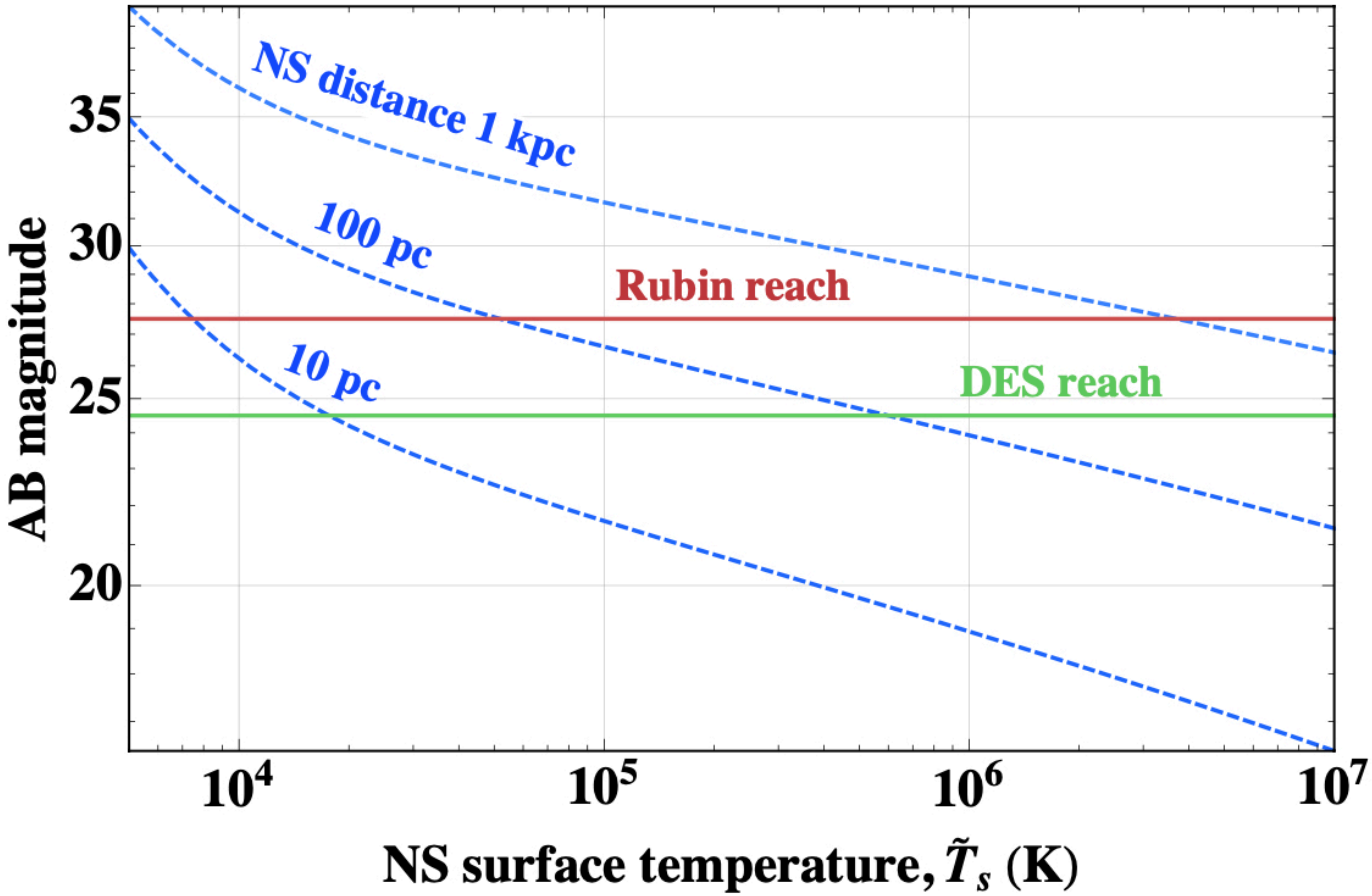
This region predicts a population of 100 NSs within a kpc of Earth heated to 10^4 K (flash-heated)

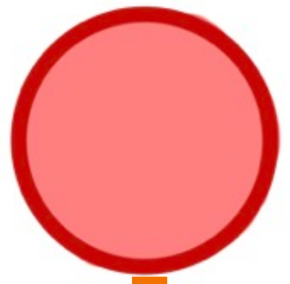


for this DM-nucleon cross-section



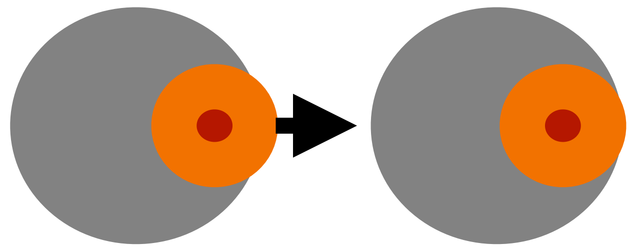
Prospects for future NS surveys finding subhalo heated NSs

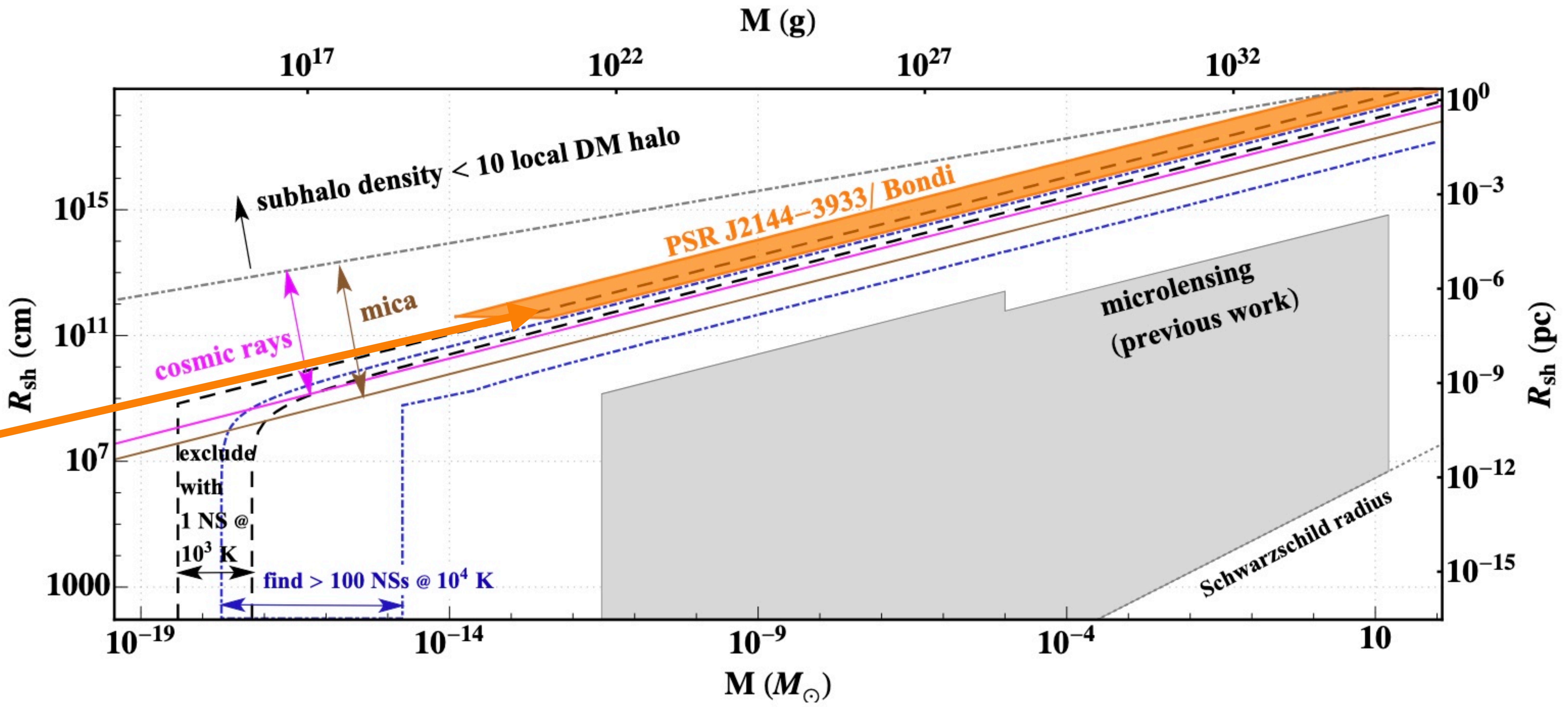




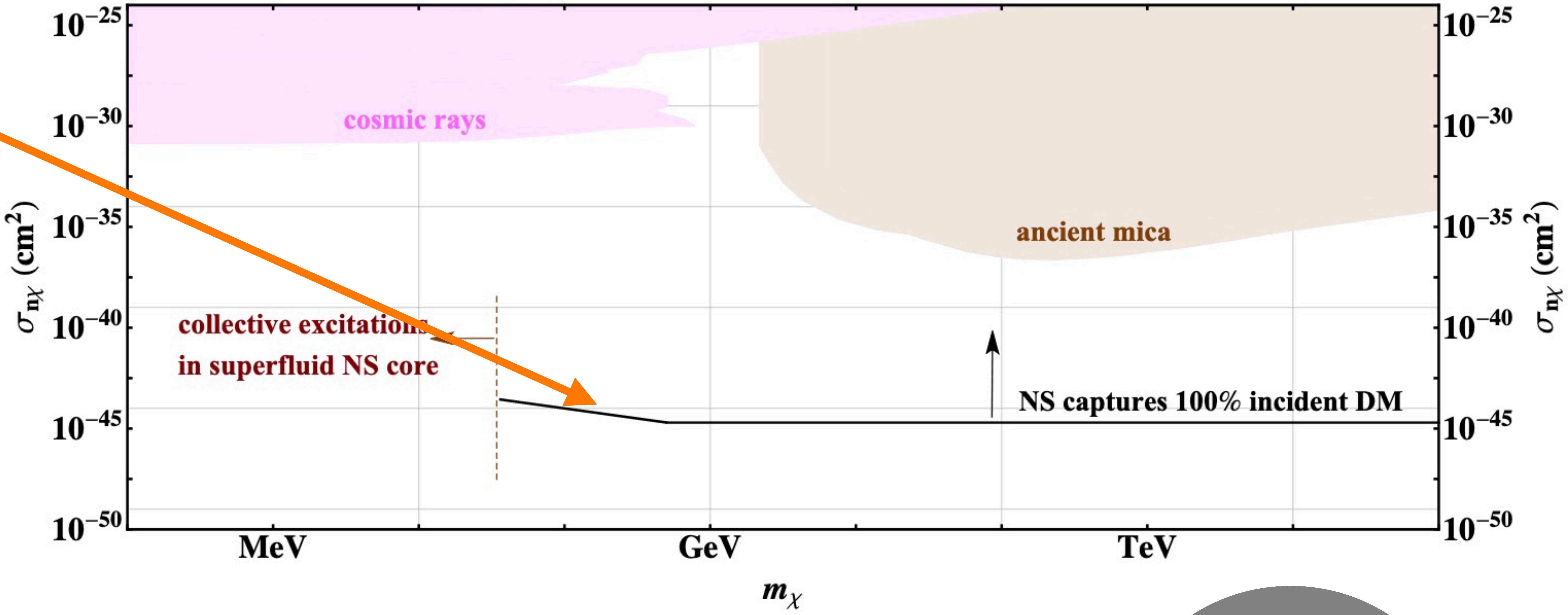
$$R_{co} = \frac{v_{esc}^2}{v_{DM}^2} R_{NS}(1+z)$$

PSR J2144 T < 3 x 10^4 K
excludes this region
for Bondi accretion

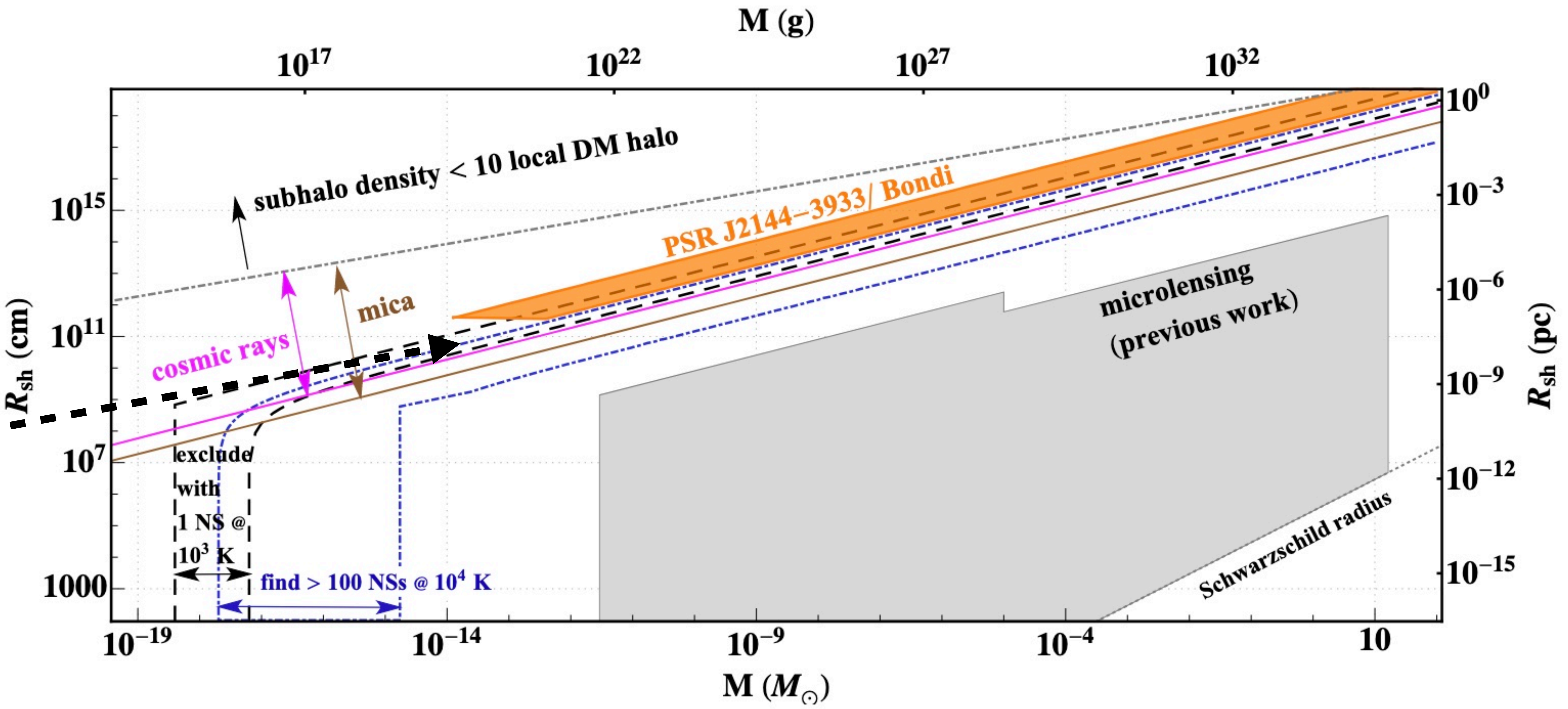


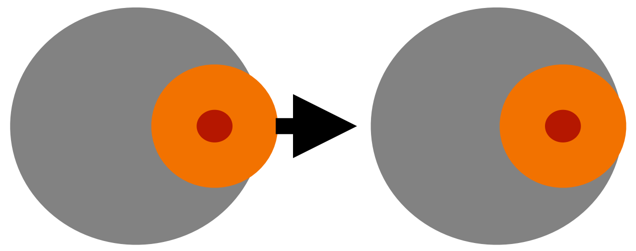


for this DM-nucleon cross-section

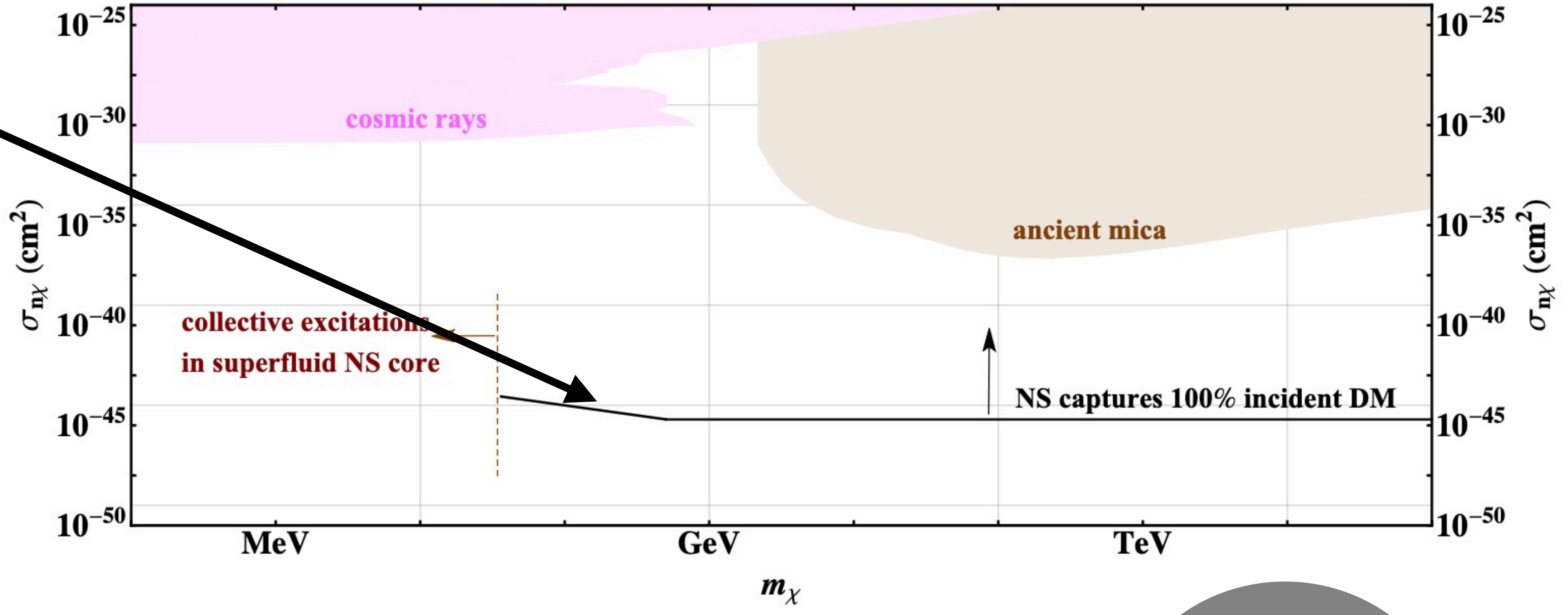


A future NS temp bound of T < 10^3 K would cover this region for collisionless accretion





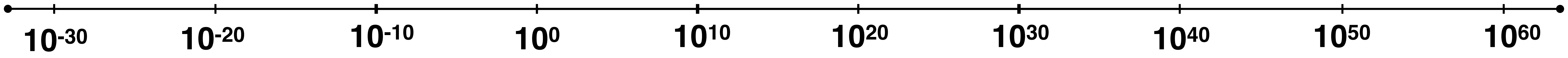
for this DM-nucleon cross-section



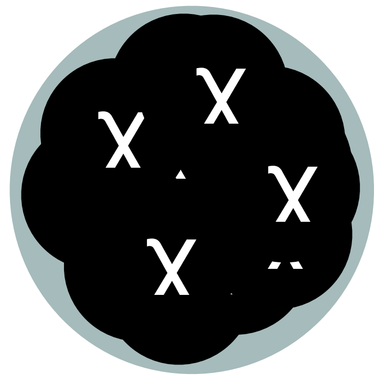
More prospects for subhalo DM detection using neutron stars

With ~10x HST observation time, perhaps could reach this.

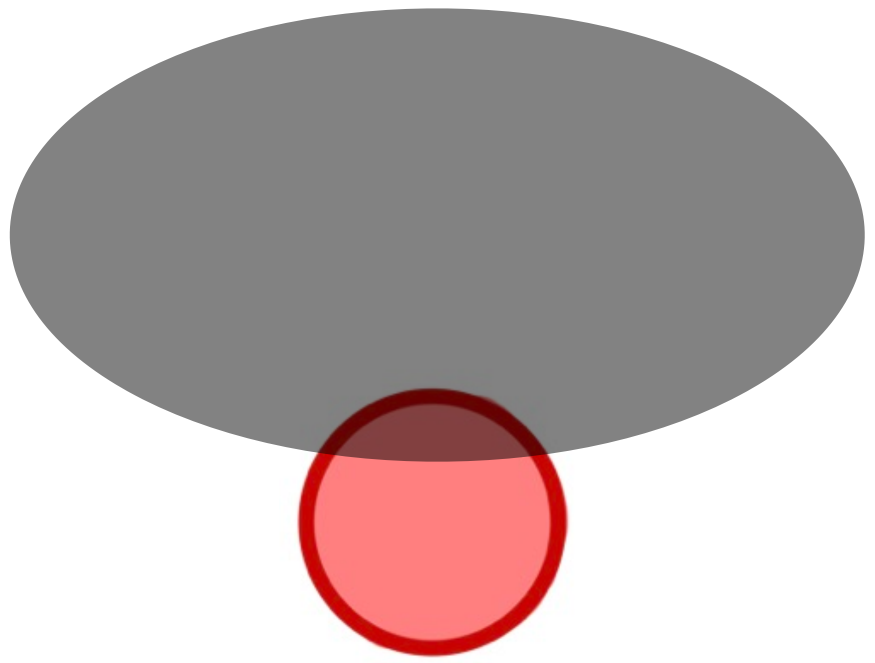
Neutron Star Searches for Subhalos



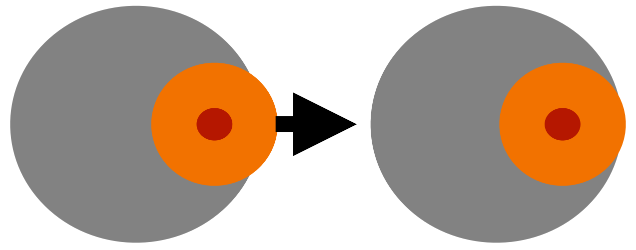
- The origin and composition of high mass DM may be rich



- Neutron stars can search for DM in subhalos (and outside, soon)



- Already can place a strong bound on fluid-like (dissipative) subhalo DM
- Future prospects for cosmic rays, minerals, NS populations

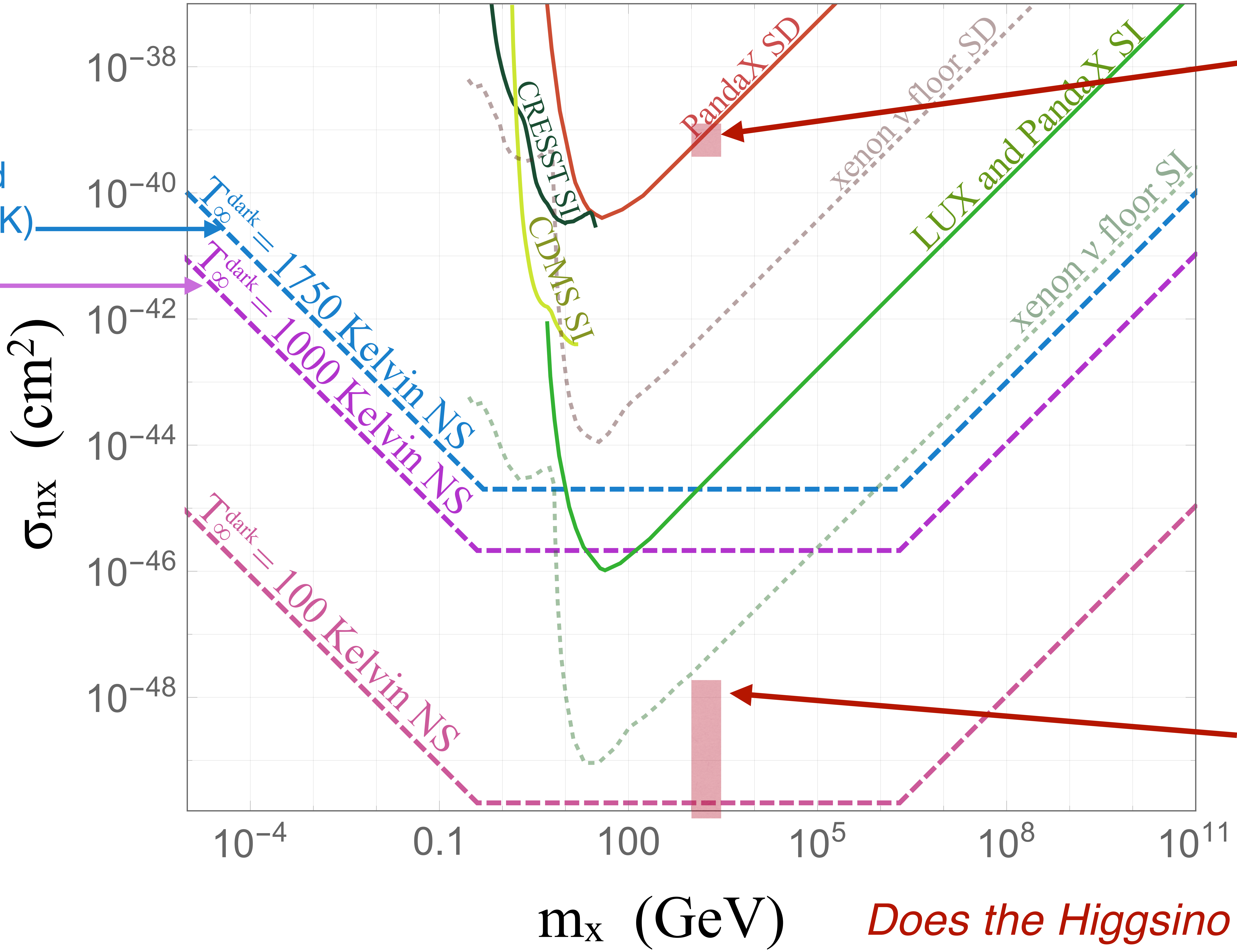


Thanks!

Neutron Star Dark Matter Heating Sensitivity

all incoming DM captured (ann. T~2500 K)

10% incoming DM captured (ann. T~1400 K)

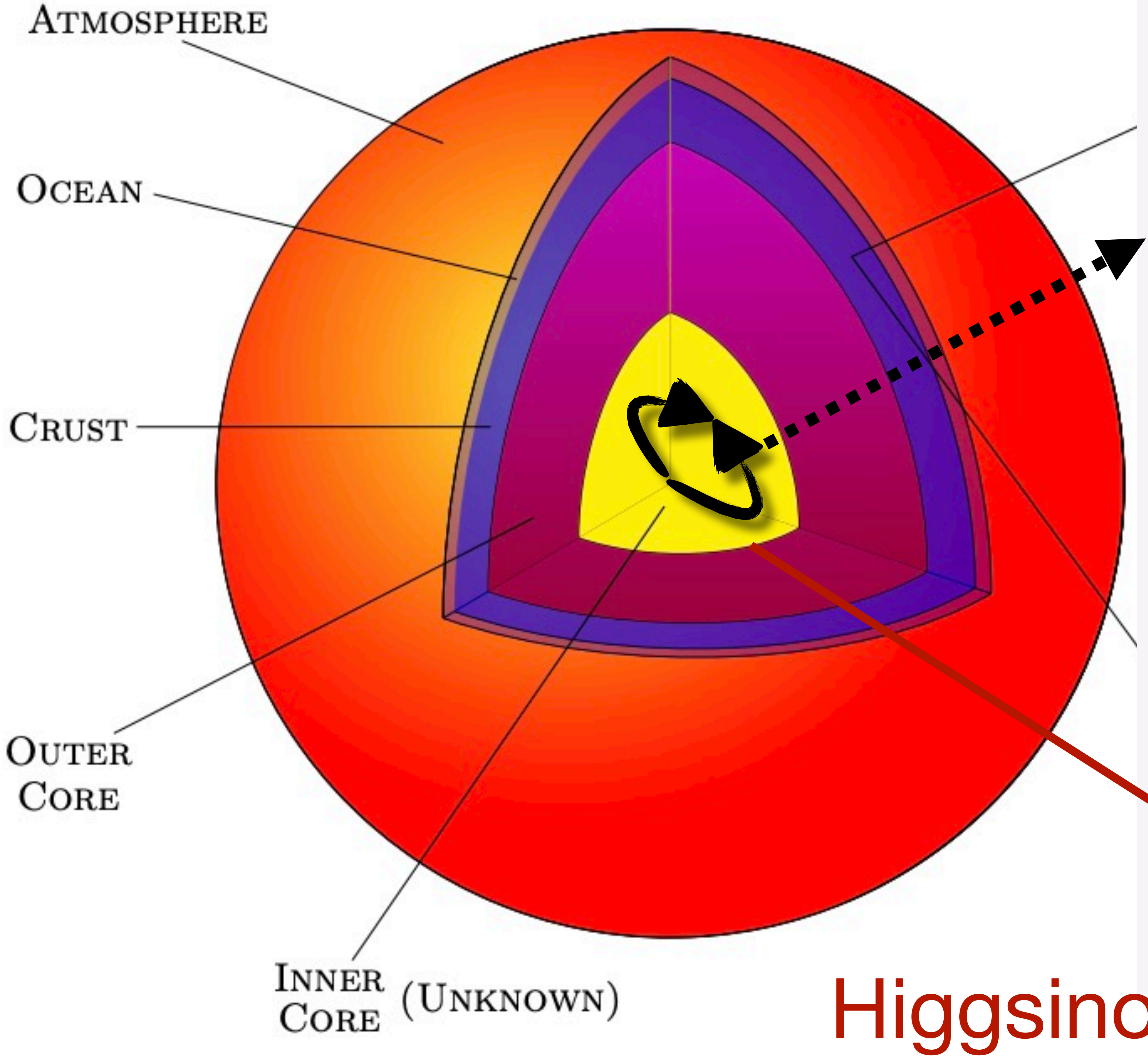


Higgsino DM in a NS, 0.7c

Higgsino DM at 0.001c

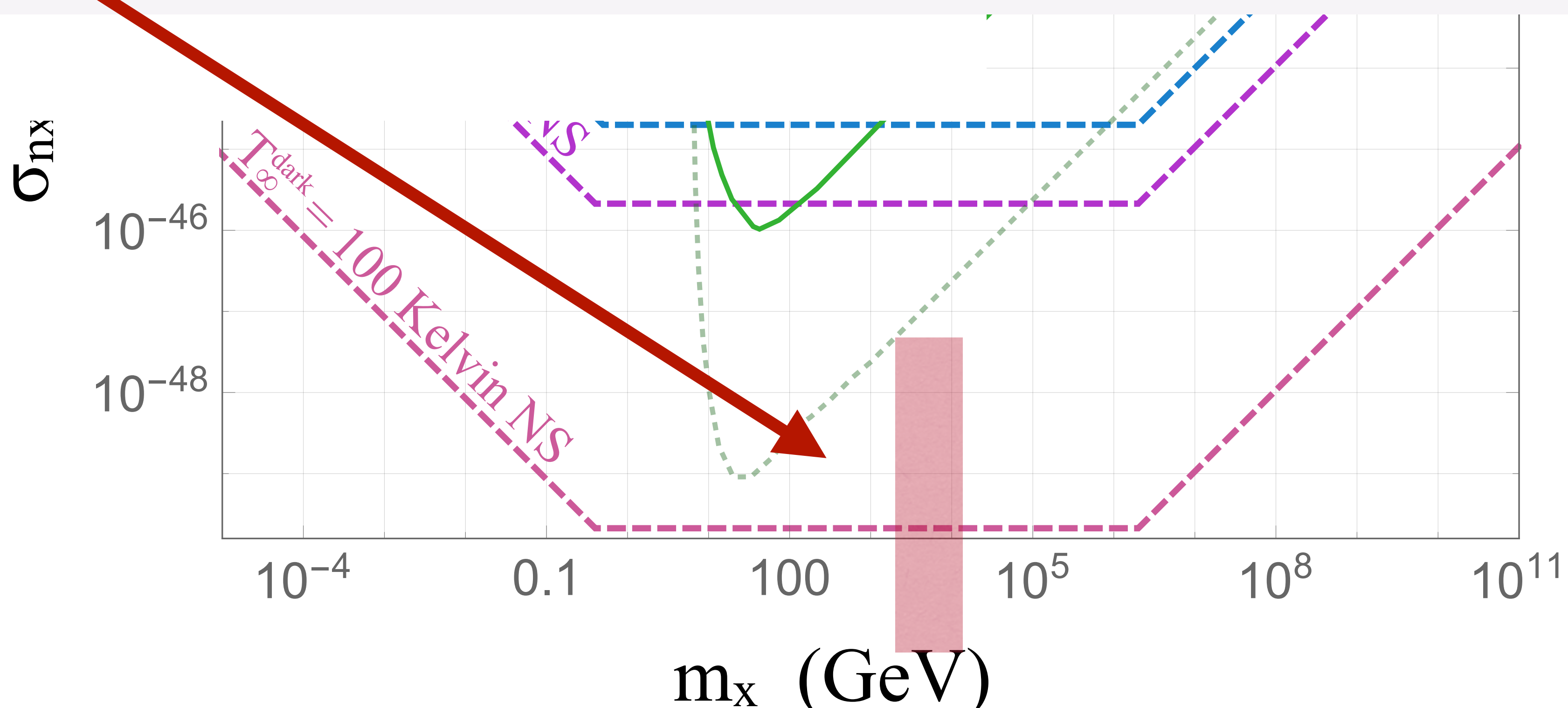
Does the Higgsino annihilate in a NS?

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

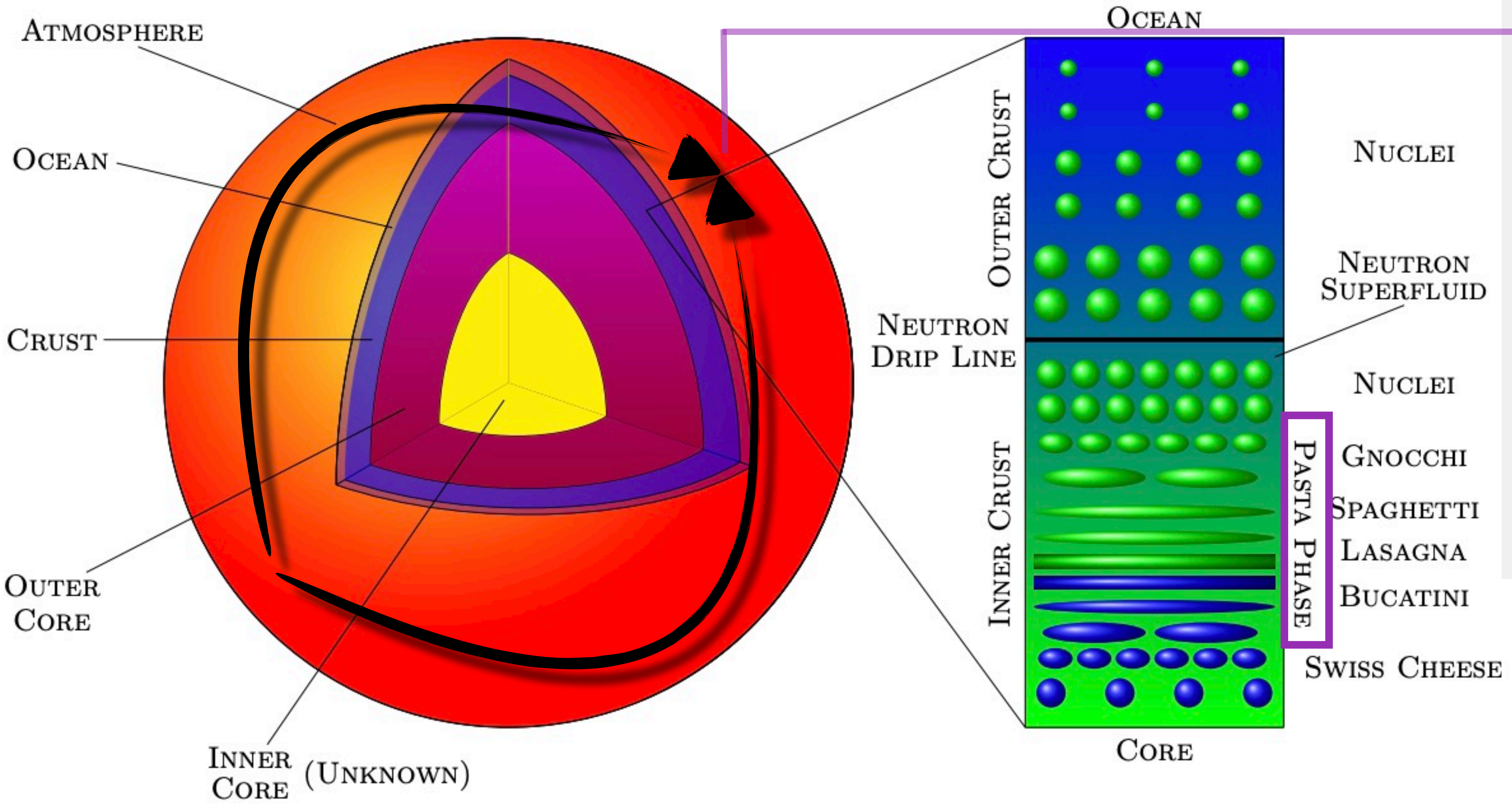


- Standard NS heating calculation uses DM annihilation at low velocities, settling in NS core
- DM-neutron cross-section is unbounded for DM that settles into NS core because of accidental loop-level nucleon coupling cancellation and pdf uncertainties
- The timescale for DM settling in NS core can't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

Higgsino DM at v << c



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



- Solution: annihilation in "pasta" region as limiting case

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

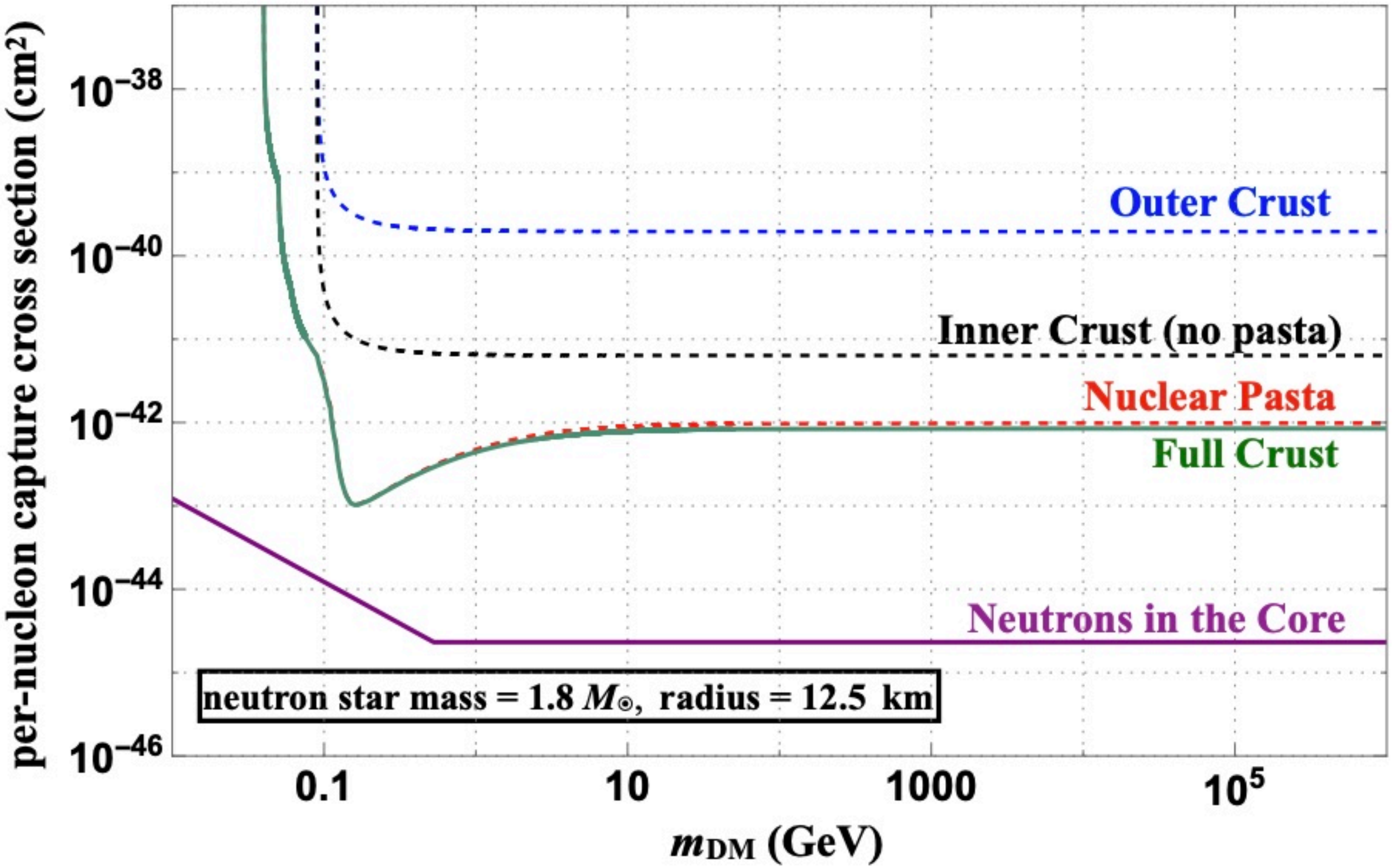
- DM annihilates at ~0.1c much like in the early universe
- keV-PeV mass WIMPs annihilate, for s-wave (l=0), p-wave (l=1), $\langle \sigma_a v \rangle = 3 \times 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}}$, with

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

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

Acevedo, JB, Leane, Raj 1911.06334

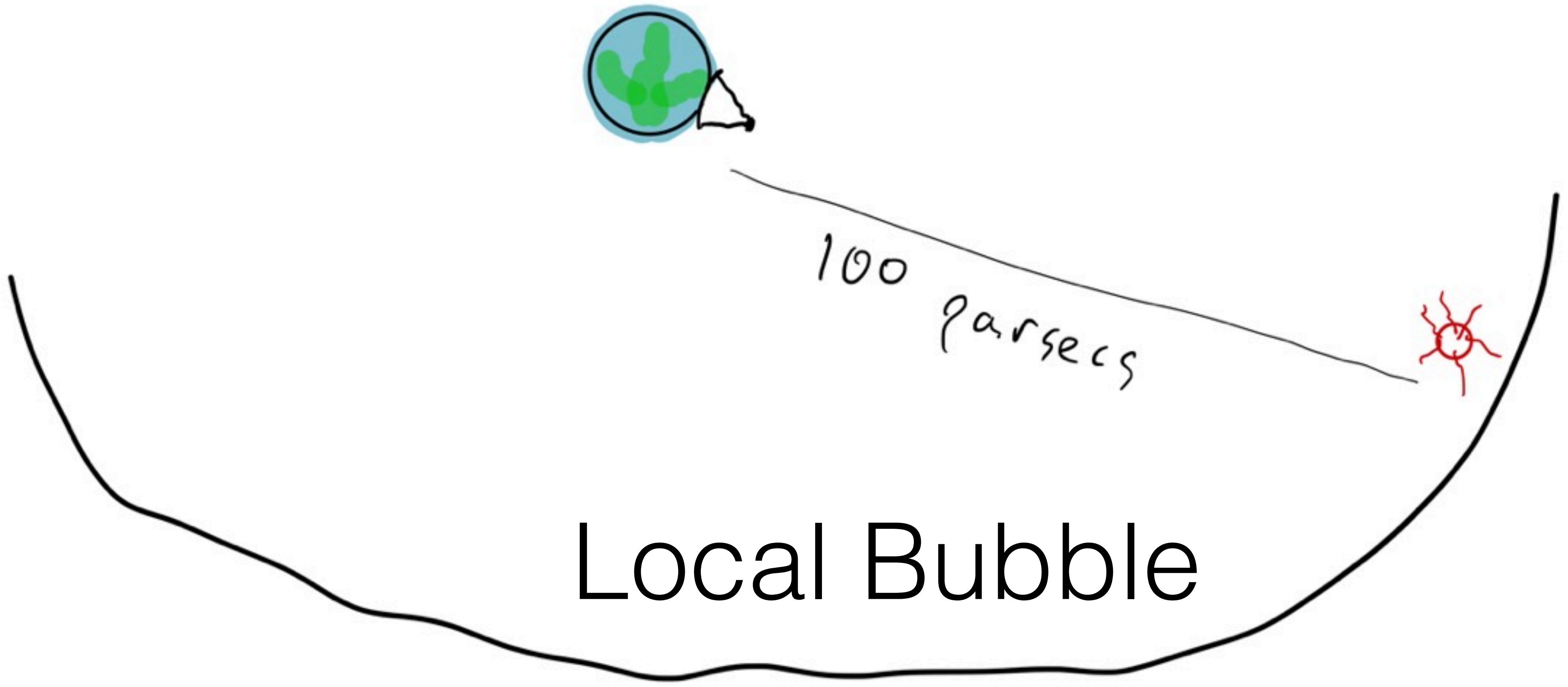
Neutron Star Pasta Cooker: WIMPs in NS Crust



Acevedo, JB, Leane, Raj 1911.06334

Possible backgrounds:

Interstellar medium accretion



Local Bubble

-Local bubble around earth has ISM of <0.01 GeV/cm^3

-Majority of ISM appears to be deflected by NS magnetic fields (sub-Bondi accretion)

astro-ph/0305421

Other

— Magneto-thermal heating damps out after a million years

0812.3018

— EOS-dependent rotochemical effects dissipate for t > 7 ms period pulsars

1905.02991

— Standard thermodynamics and NS cooling indicate 100 K after ~Gyr

DETERMINING HOW DARK MATTER HEATS NEUTRON STARS

kinetic only

$$(\gamma - 1)\dot{m}_x$$

(very sensitive
to escape velocity)

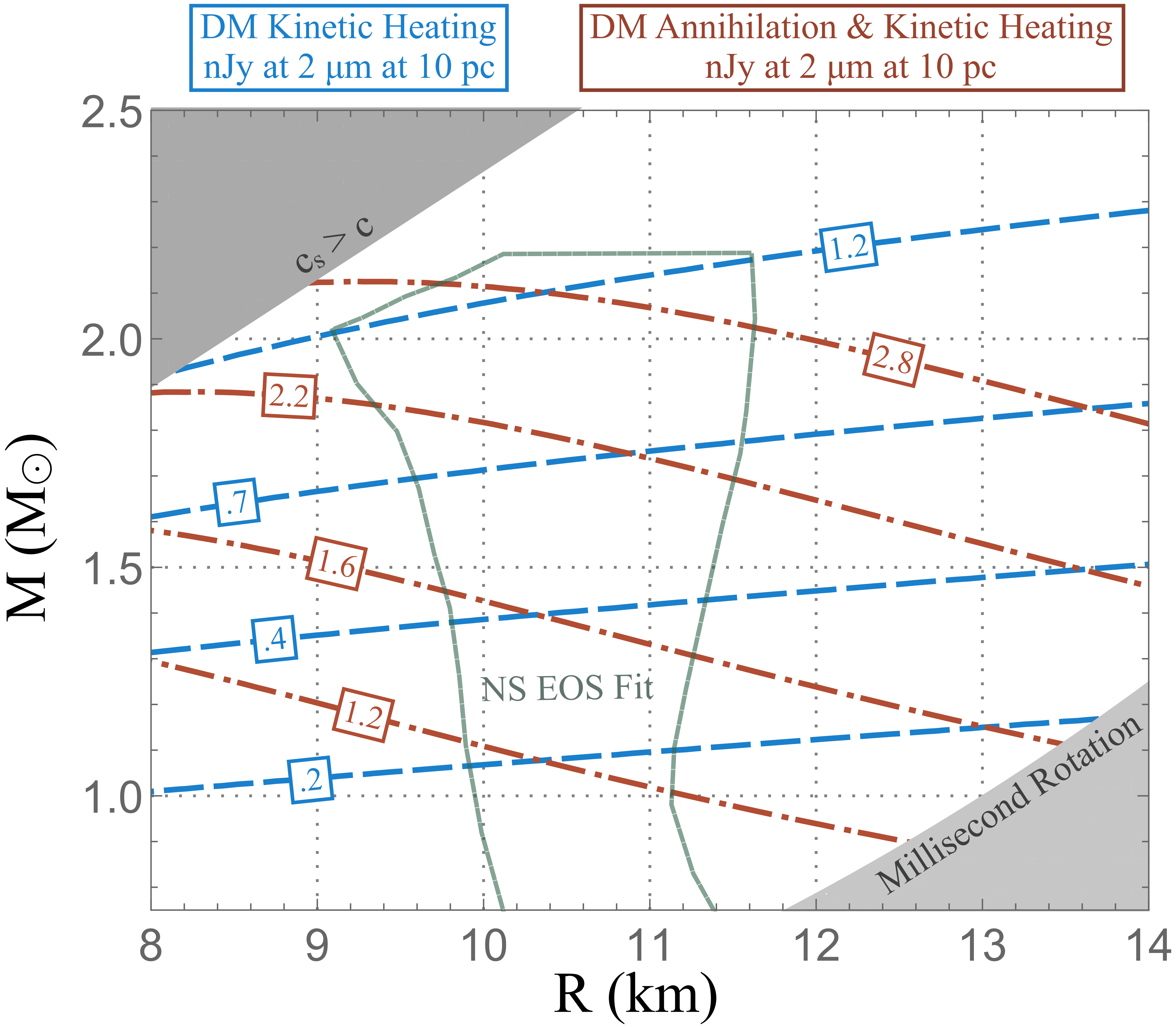
annihilation

$$\gamma \dot{m}_x$$

(heating mostly from captured
mass, scales with NS mass)

Can test against ISM accretion:

$$L_{dm} \propto \frac{1}{v_{dm-ns}} \qquad L_{bar} \propto \frac{1}{v_{bar-ns}}$$



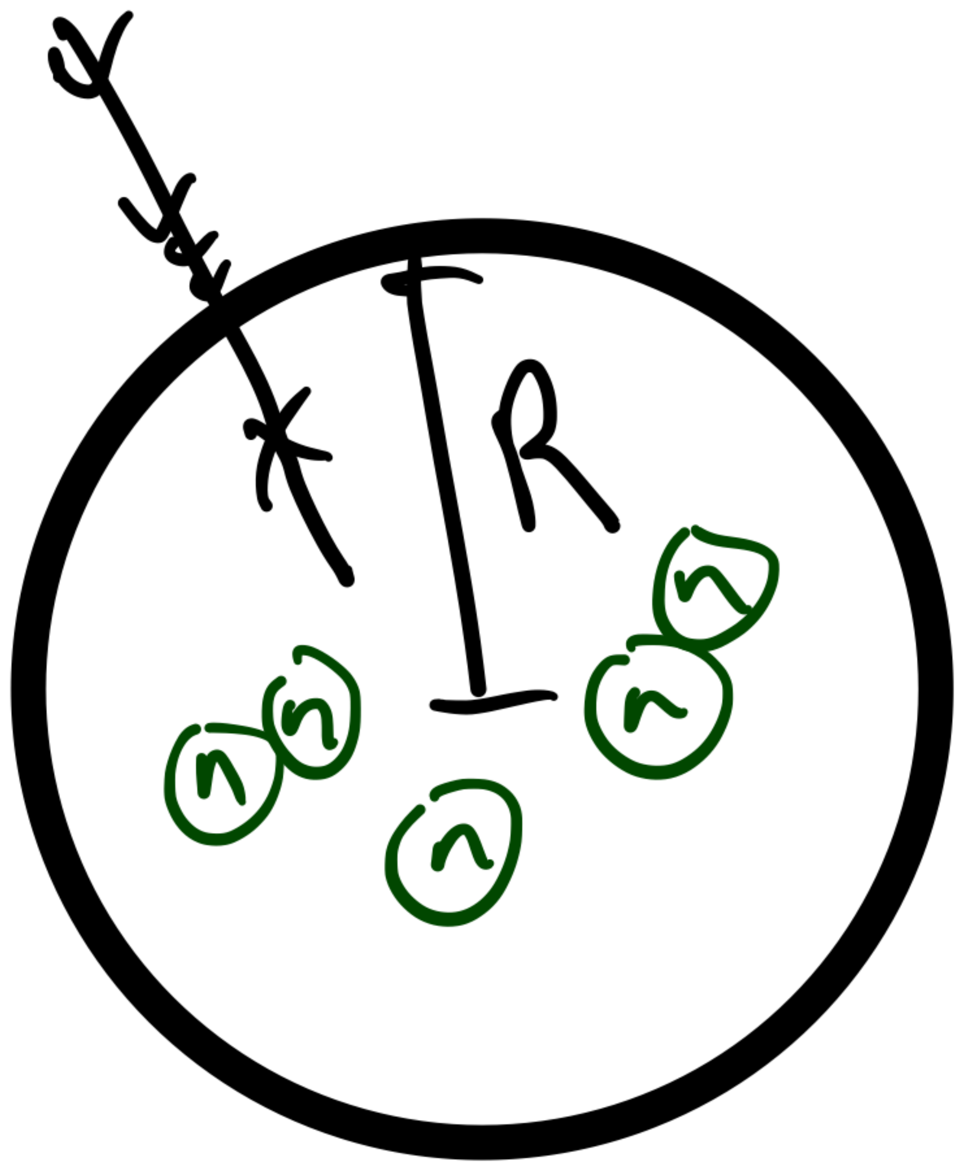
nanoJansky ~ 10^{-30} GeV / (cm^2 s Hz)

DM Capture

Fraction of DM captured:

$$f \equiv \mathrm{Min}\left[1, \frac{\sigma_{nx}}{\sigma_{sat}}\right]$$

- σ_{sat} is the cross-section for all NS transiting DM to be captured



Mean free path $\ell_s = (n\sigma)^{-1}$

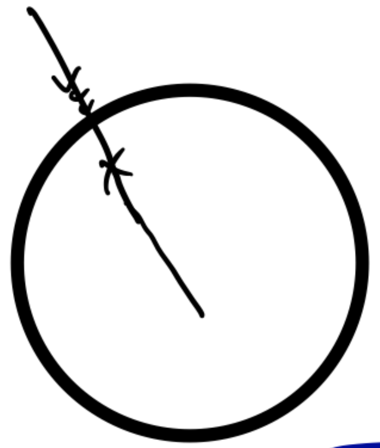
Star opaque to DM if

$$\frac{\pi R^2}{N_n} = \frac{\pi R^2 m_n}{M} > \sigma_{nx}$$

DM Capture - By Mass

DM must lose its halo kinetic energy

$$E_K \sim 10^{-6} m_\chi$$

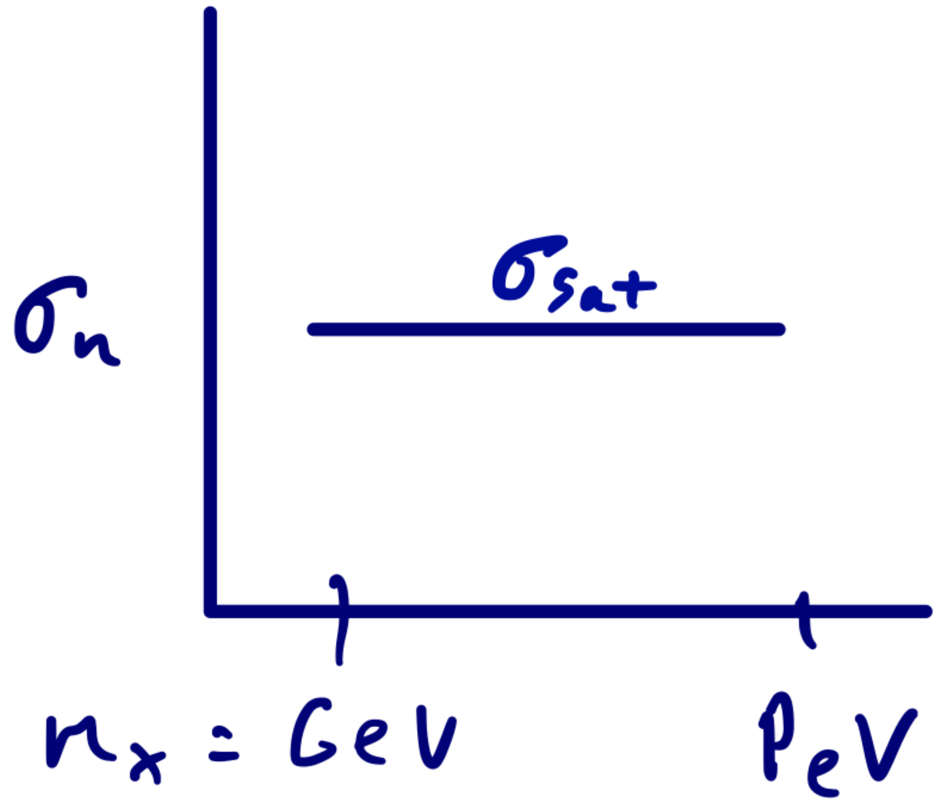


By scattering with the neutron star to become captured

$$\boxed{m_\chi = \text{GeV} - \text{PeV}}$$

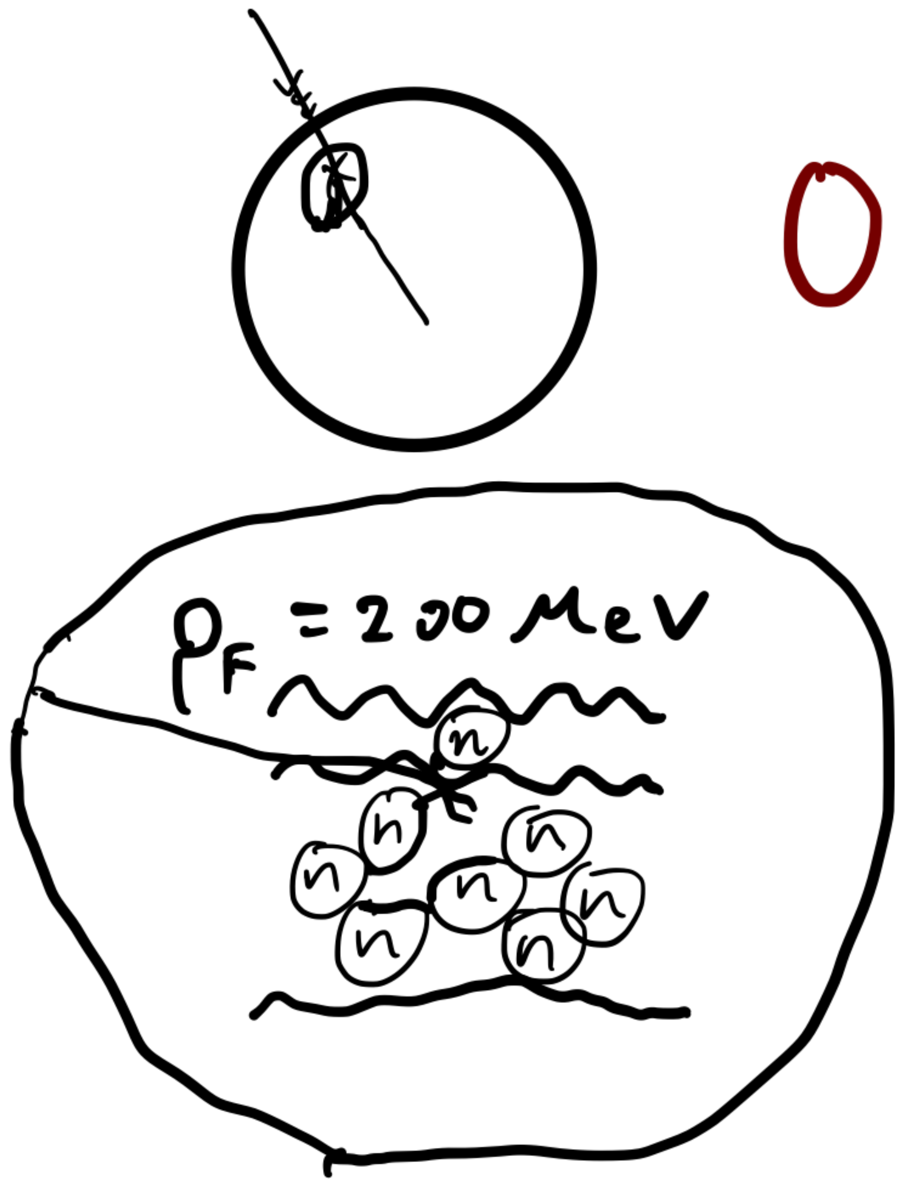
Compare $\frac{1}{2} m_\chi v_\chi^2 \sim 10^{-6} m_\chi$ to energy lost scattering

$$E_R \sim \mu_{N\chi} v_s^2 \sim \text{GeV}$$



$$\boxed{\sigma_{sat} = \pi R^2 m_n / M \sim 2\cdot 10^{-45}\,\text{cm}^2}$$

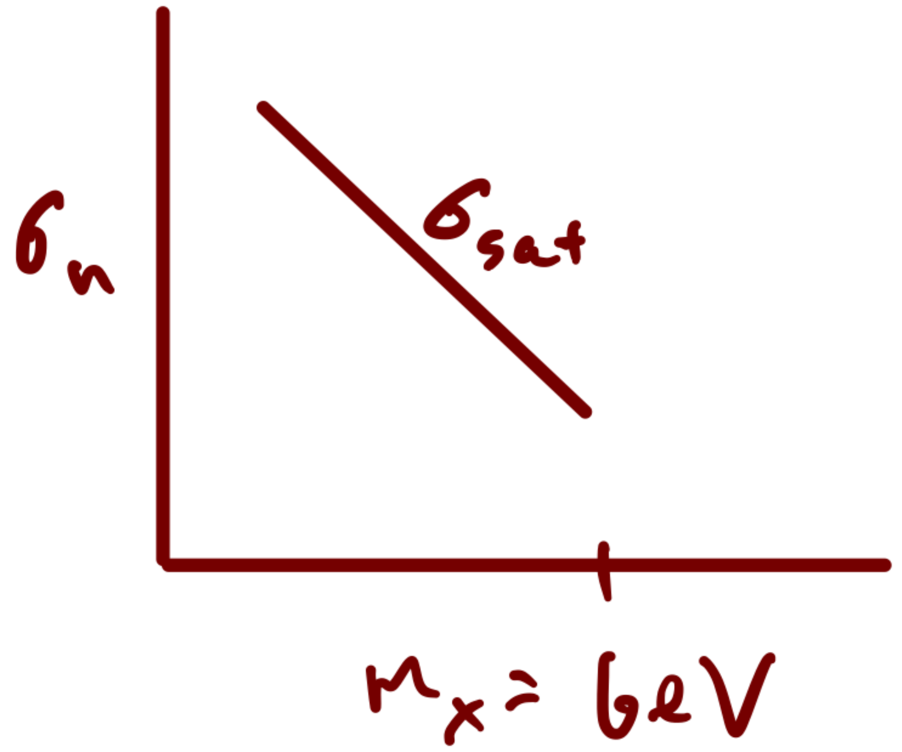
$\boxed{m_\chi < \mathrm{GeV}}$ Pauli Blocking



Only a fraction $\left(\frac{\Delta p}{p_F}\right)$ of neutrons can scatter above Fermi surface

$$\boxed{\Delta p \sim \gamma m_\chi v_s \sim m_\chi}$$

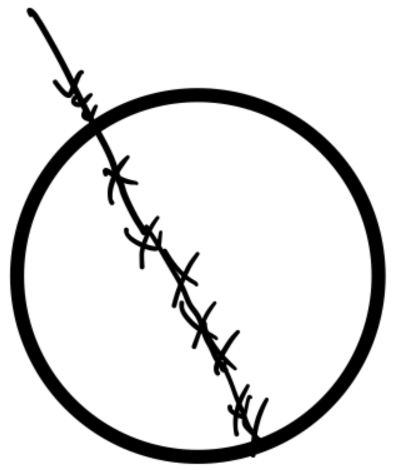
So scattering is suppressed by $\frac{m_\chi}{p_F}$



$$\boxed{\sigma_{sat} = \frac{\pi R^2 m_n}{M} \frac{p_F}{m_\chi} = 2 \cdot 10^{-45}\,\mathrm{cm}^2 \left(\frac{\mathrm{GeV}}{m_\chi}\right)}$$

$\boxed{m_\chi > \text{PeV}}$ Multi-Scatter

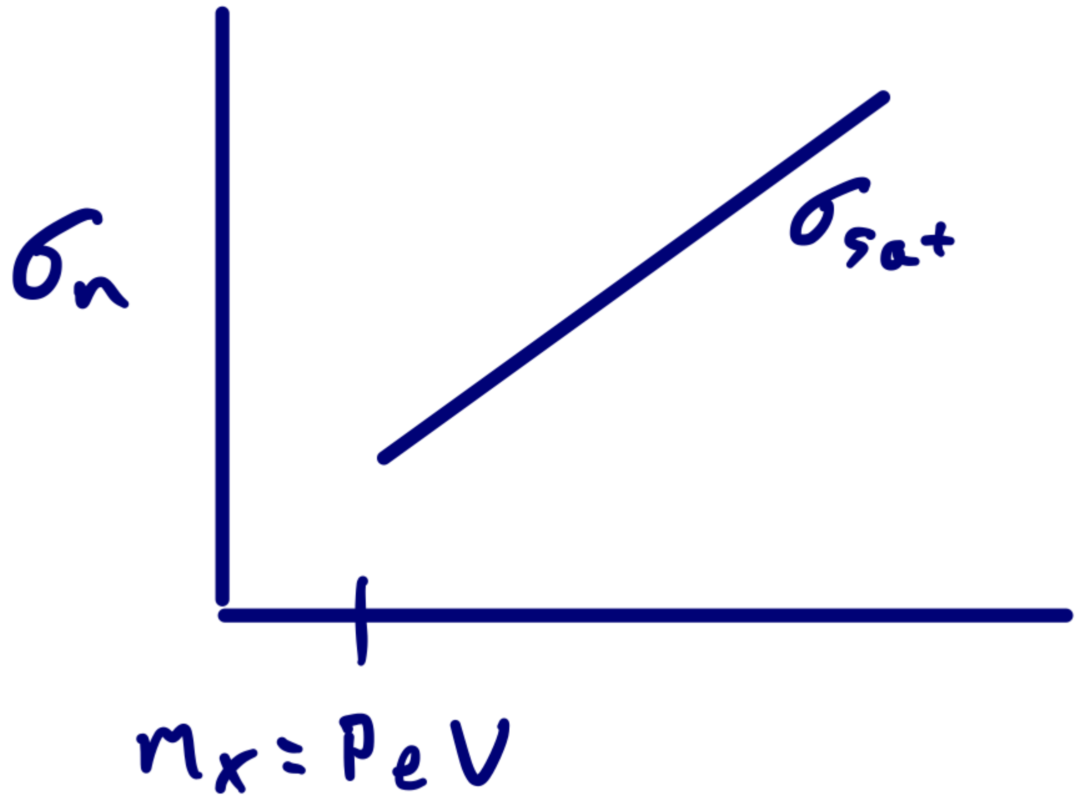
For dark matter masses > PeV, need to scatter multiple times (N) while crossing the star to capture



$$E_k = \frac{1}{2} m_\chi v_\chi^2 < (N) E_R$$

$$N E_R \sim (n_n \sigma_n R) m_n$$

$$\rightarrow \boxed{\sigma_{sat} \propto m_\chi}$$



$$\boxed{\sigma_{sat} = 2 \cdot 10^{-45}\,\text{cm}^2 \left(\frac{m_\chi}{\text{PeV}}\right)}$$