Dark matter in compact stars and galactic structure

Joseph Bramante
Queen's University
McDonald Institute
Perimeter Institute

N3AS Seminar June 27

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Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

PERIMETER INSTITUTE

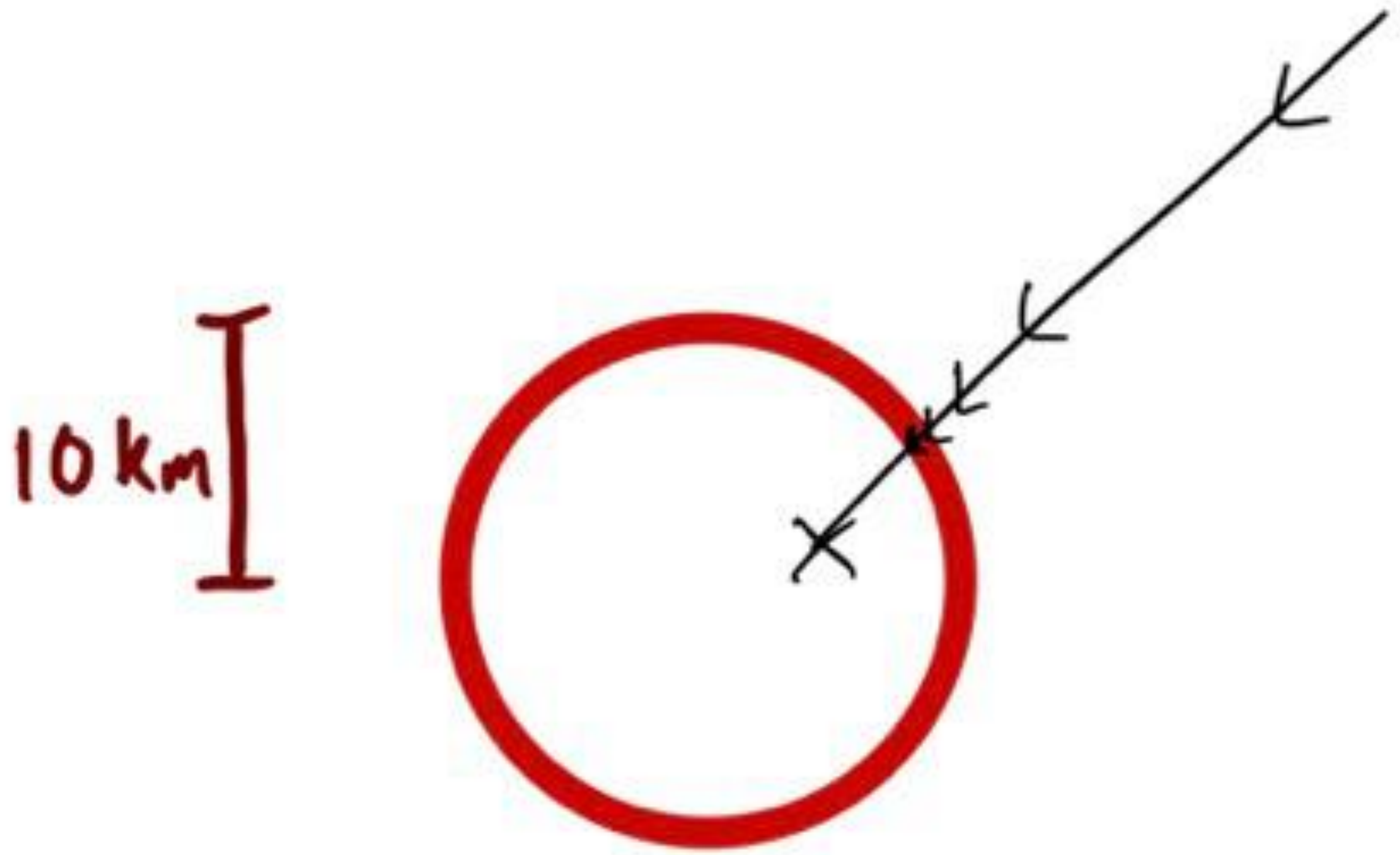
Dark matter in compact stars and galactic structure

- ***Dark matter heating neutron stars through either infall or annihilation***
- Asymmetric dark matter causing neutron stars to implode
  - Connections to missing pulsars (FRBs)
- White dwarf explosions from asymmetric dark matter / composites
  - Connections to type Ia supernovae, galactic structure

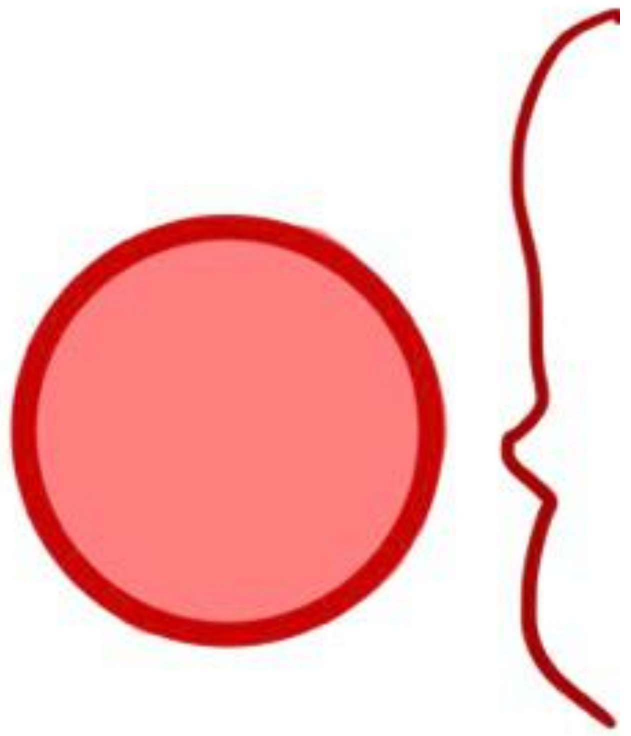
Neutron stars: nature's dark matter accelerators

➤ 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

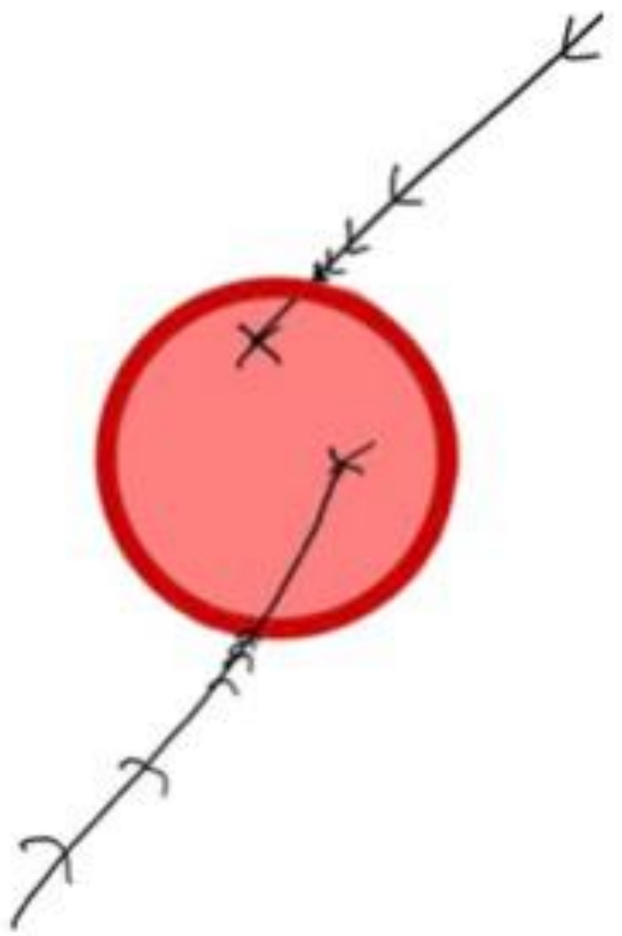
to scatter once with neutron per crossing

$$\sigma_n = \frac{R_{NS}^2}{N_n} \sim 10^{-45}\ \mathrm{cm}^2$$

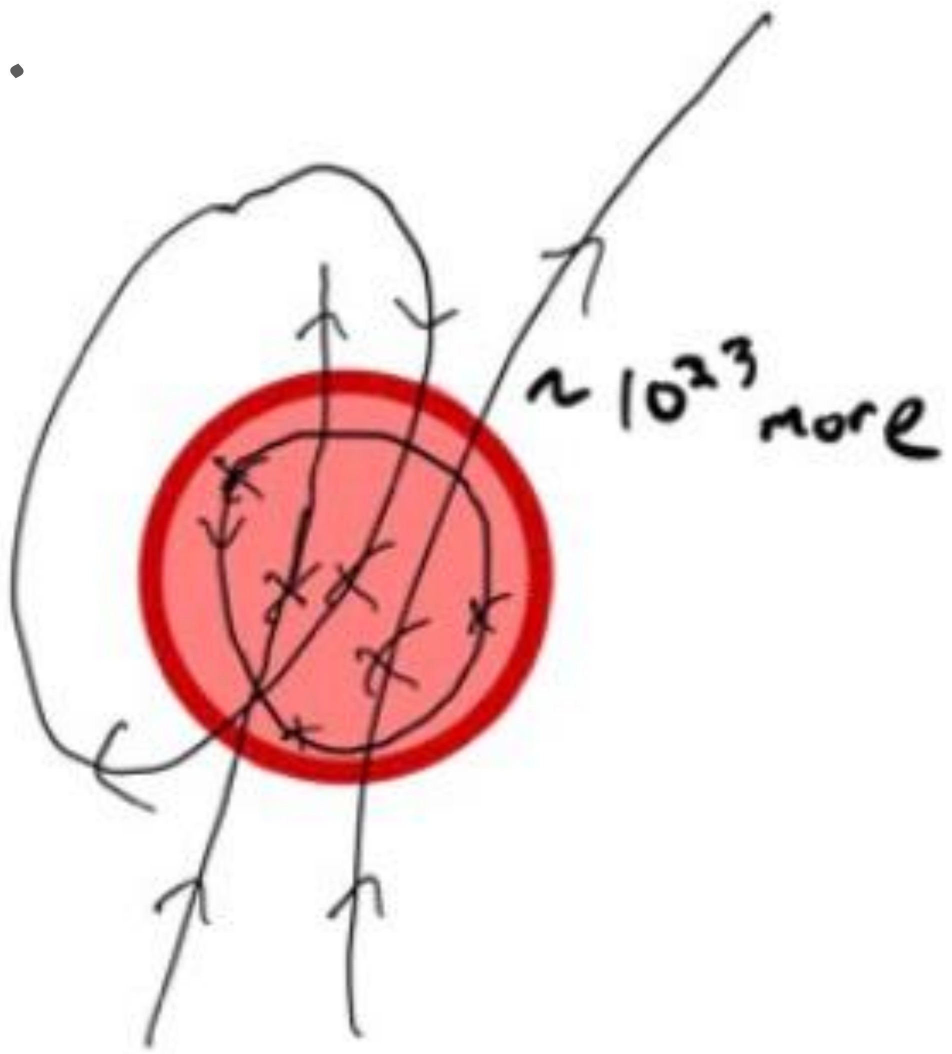
Dark matter kinetic and annihilation heating of neutron stars

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)

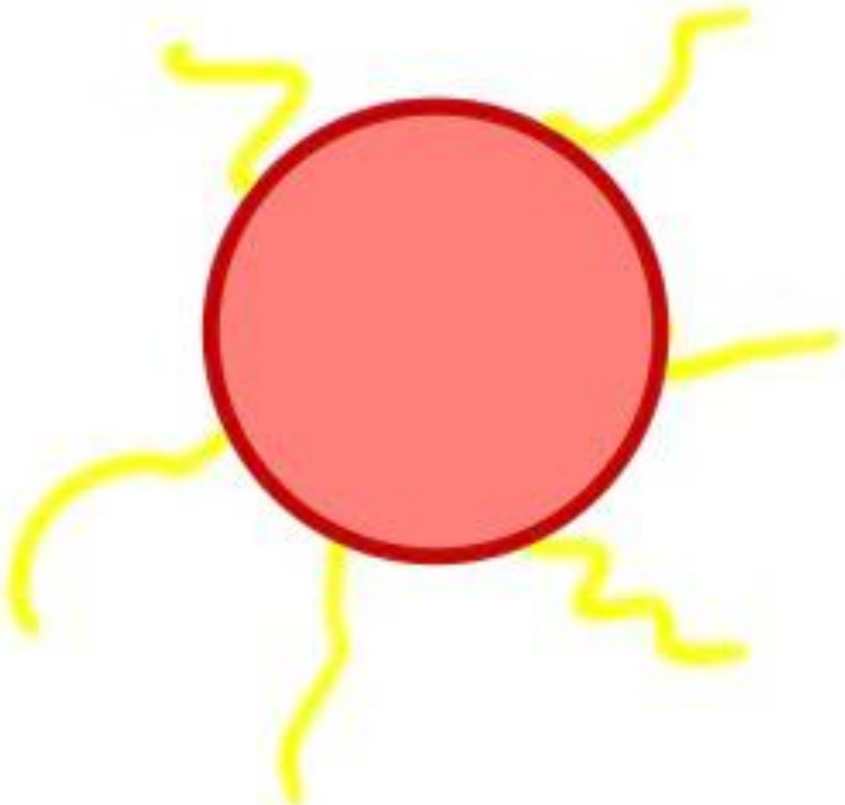
1.



2.



3. *T~1750 / 2500 K, for NS near Earth*



Dark matter kinetic and annihilation heating of neutron stars

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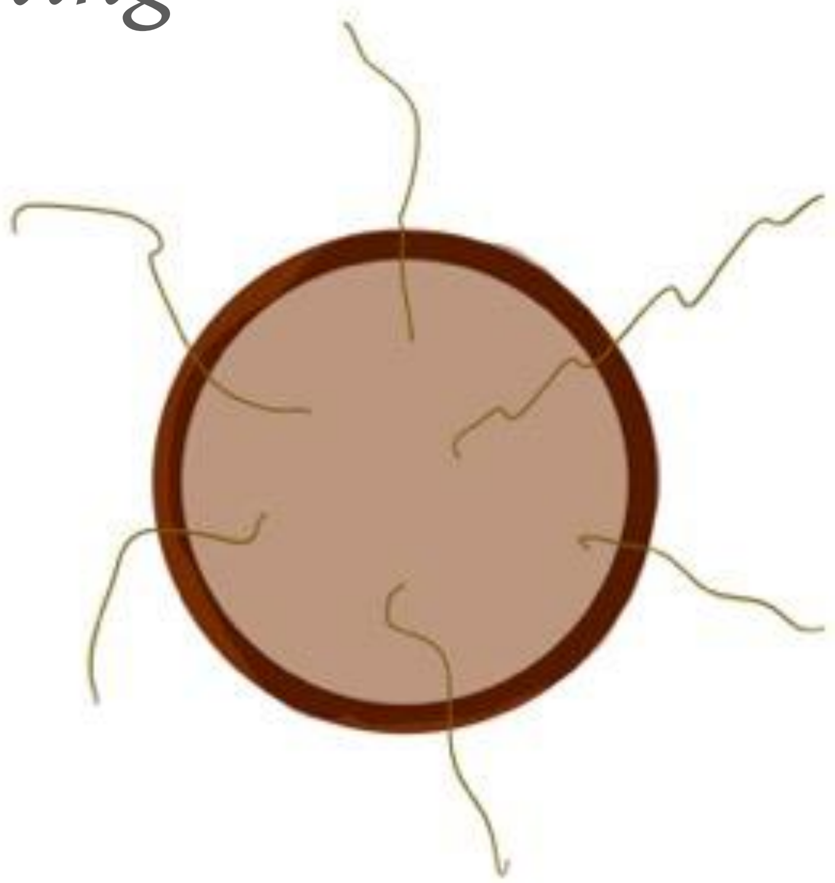
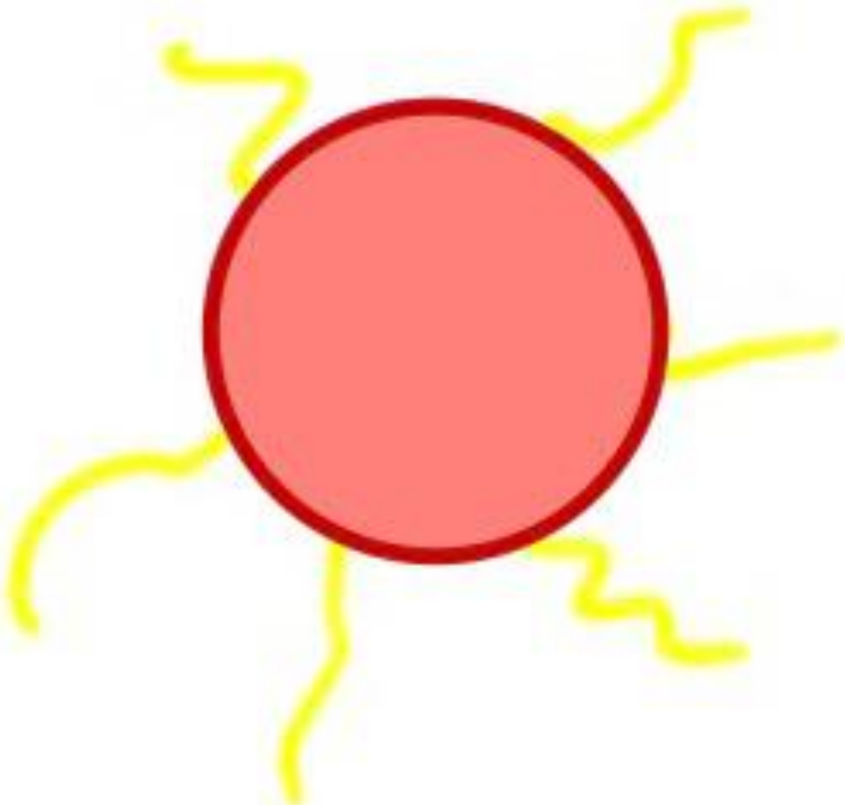
0. Compare to NS without DM heating

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



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

3. T~1750 / 2500 K, for NS near Earth



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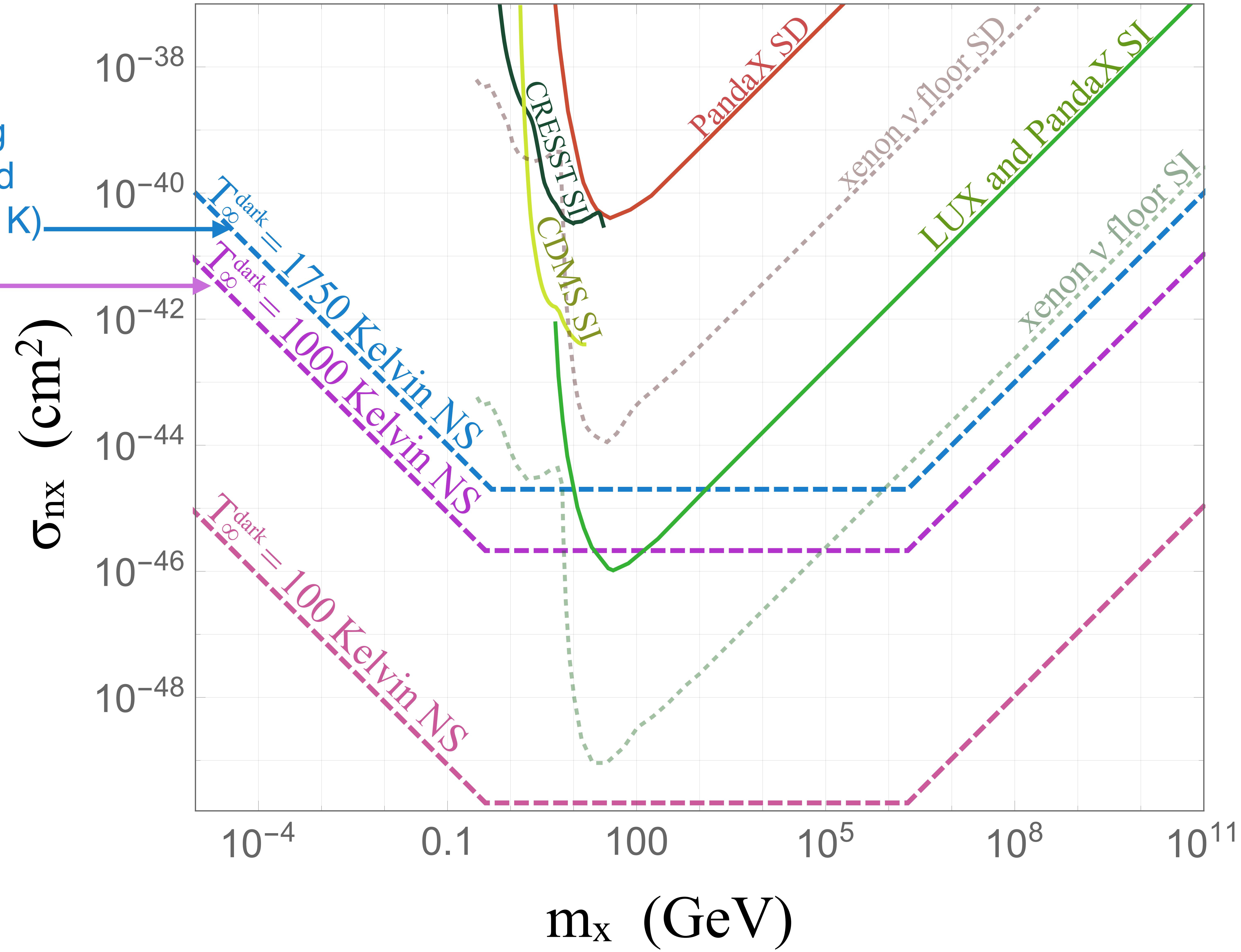
Neutron Star Dark Matter Heating Sensitivity

Baryakhtar, JB, Li, Linden, Raj 2017

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

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



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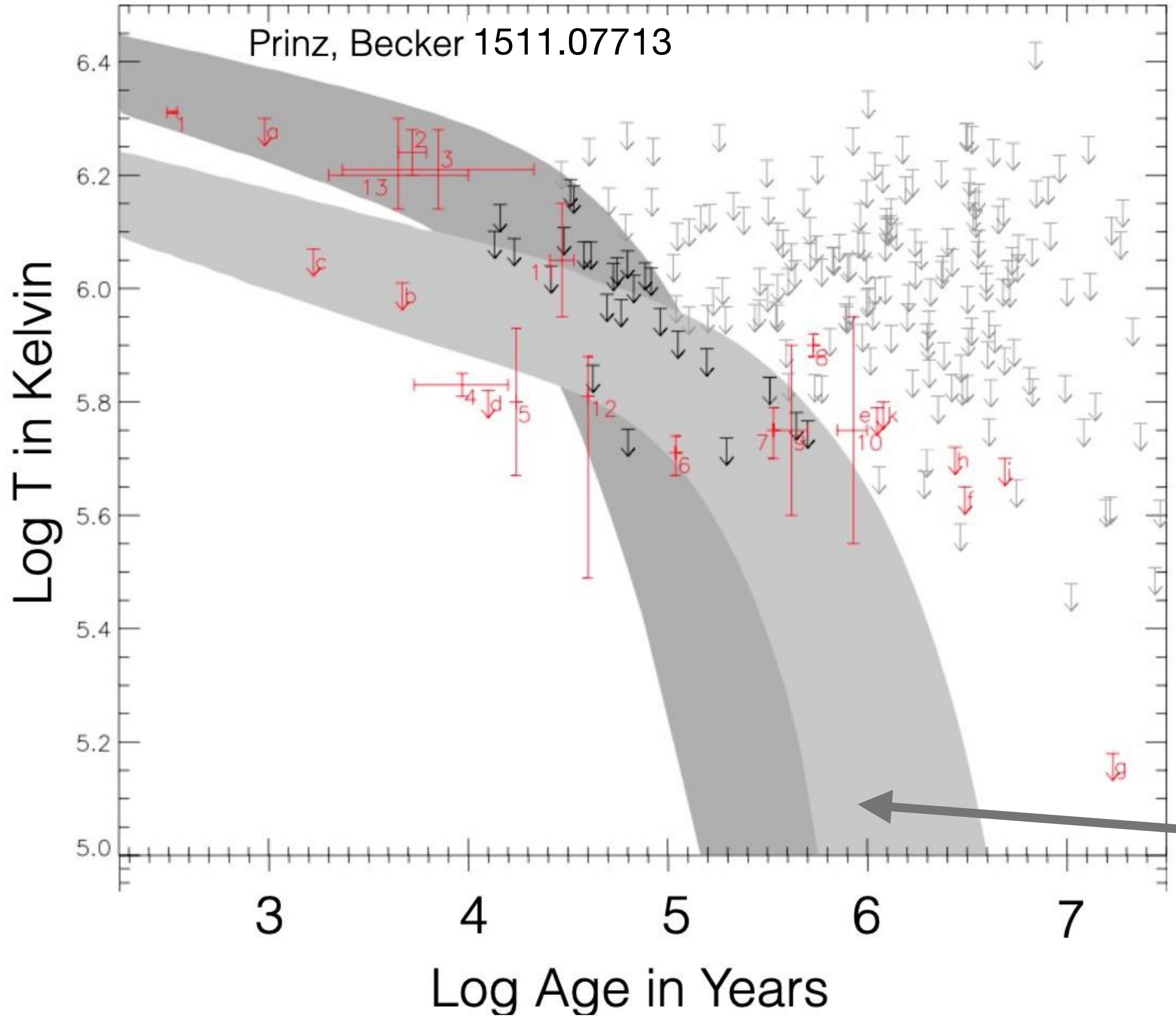
Neutron stars, broad reach for particle dark matter

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 (more…)
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
Dasgupta, Gupta, Ray 2019
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



-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

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

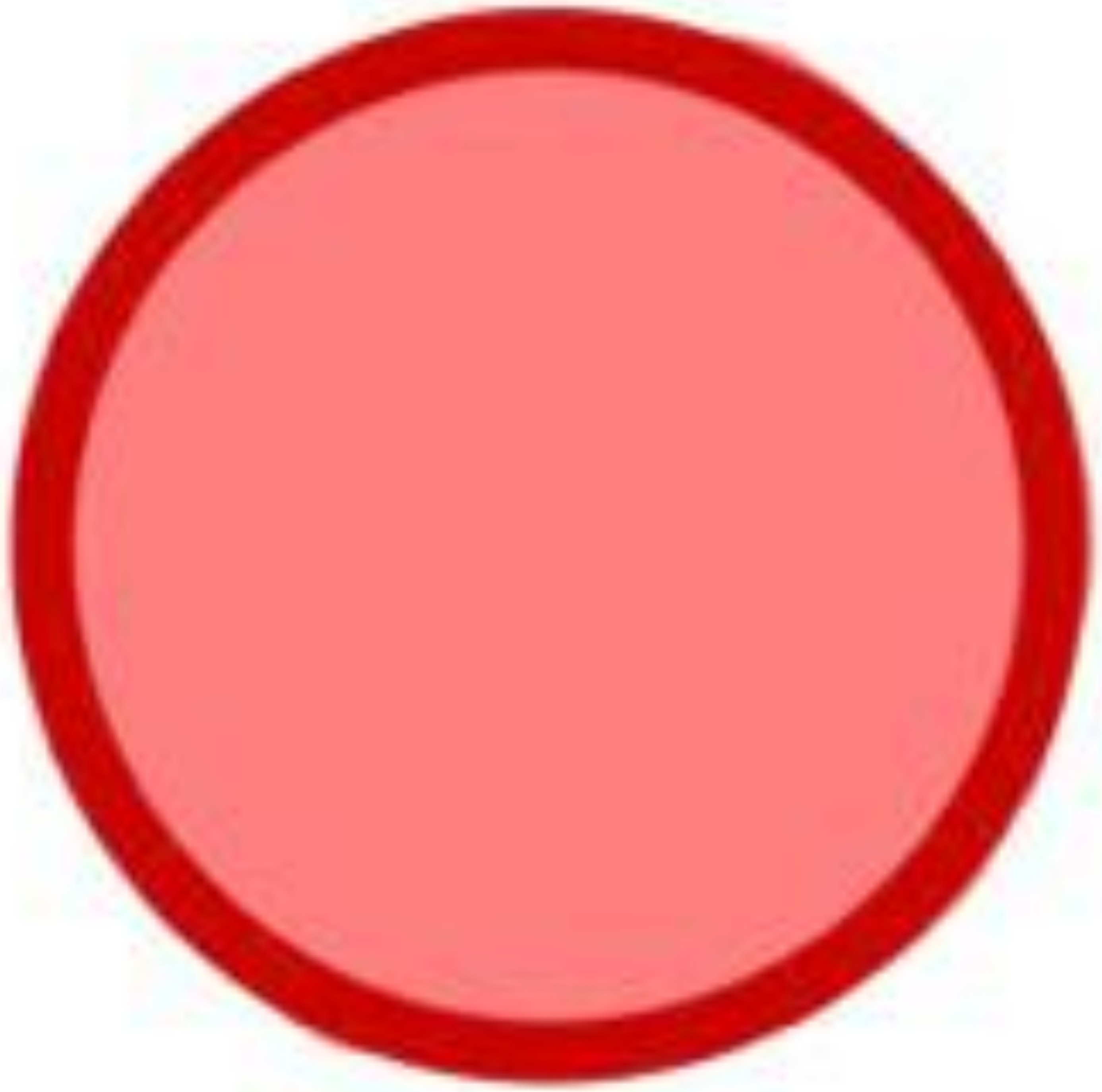
Coldest Known Neutron Star

PSR J2144–3933

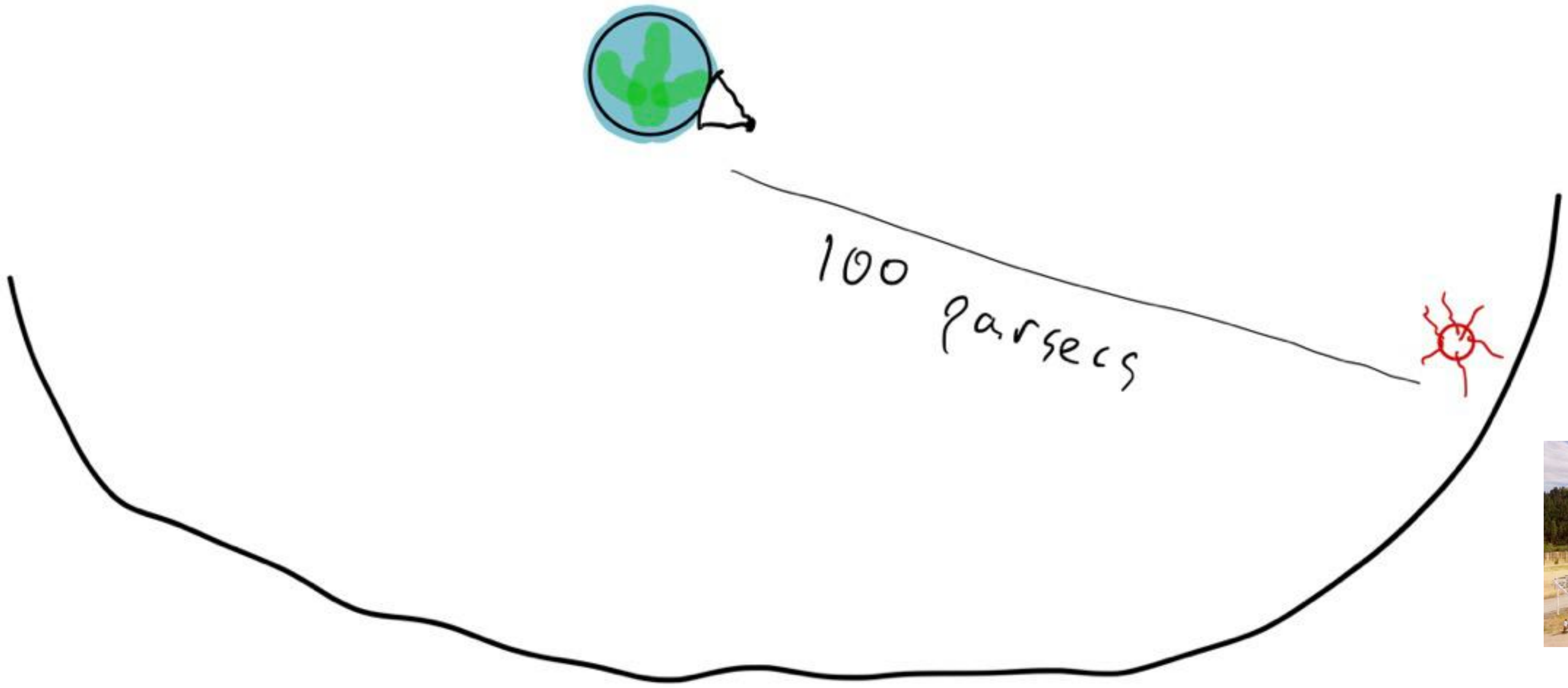
Coldest known neutron star, nearby, deep imaged by HST, observed no emission setting a bound (Guillot et al, 1901.07998)

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

This isn't cold enough to set a bound on local non-subhalo DM, since 0.3 GeV/cm^3 maximally heats NS to ~1750-2500 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

Radio observations of nearby pulsars

-YMW16 dispersion measure distances

	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

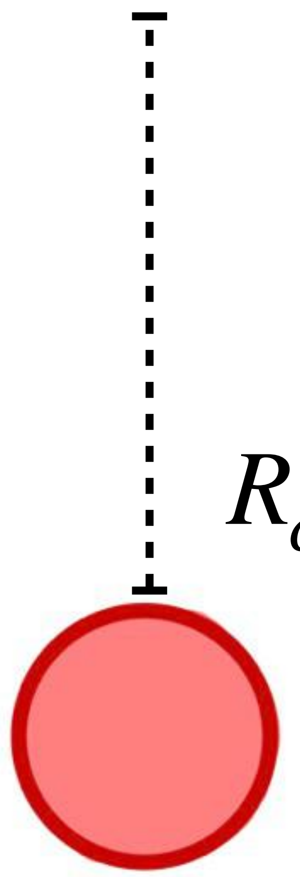
for recent JWST estimates see Garani et al. 2205.05048

Accretion onto NSs, generalized

JB, Kavanagh, Raj 2109.04582

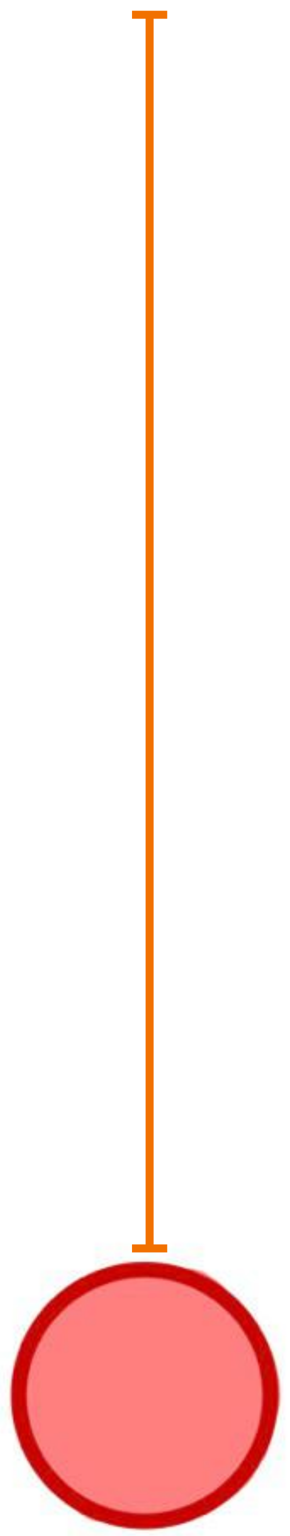
- Radius for DM accretion onto NS depends on size of DM subhalo, and whether accretion is collisionless or collisional

- Collisionless



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

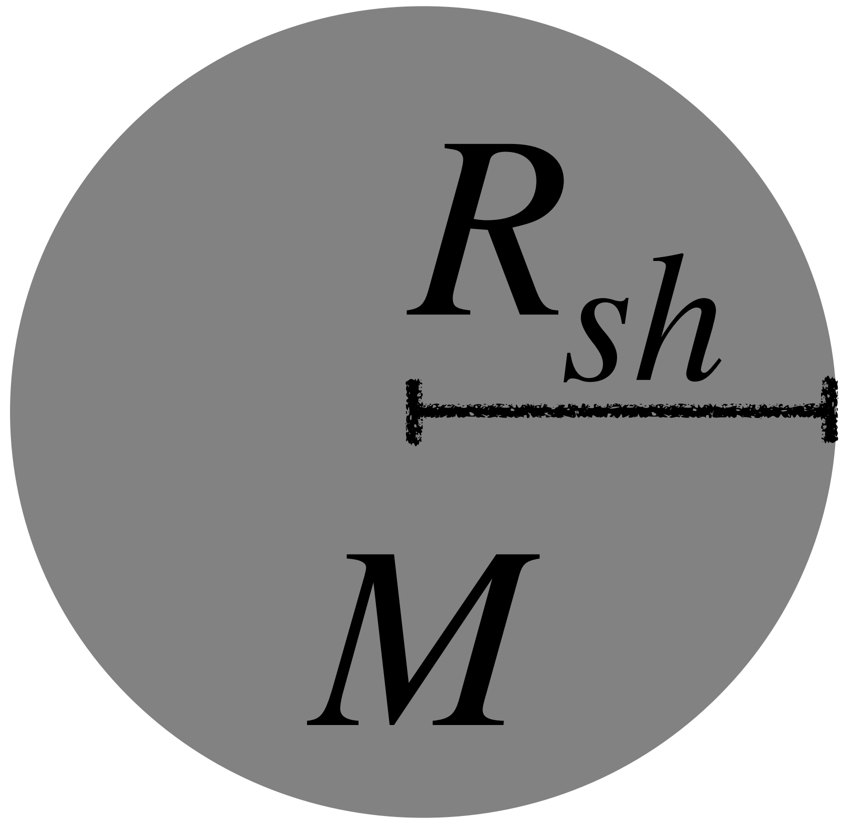
- Collisional/Bondi



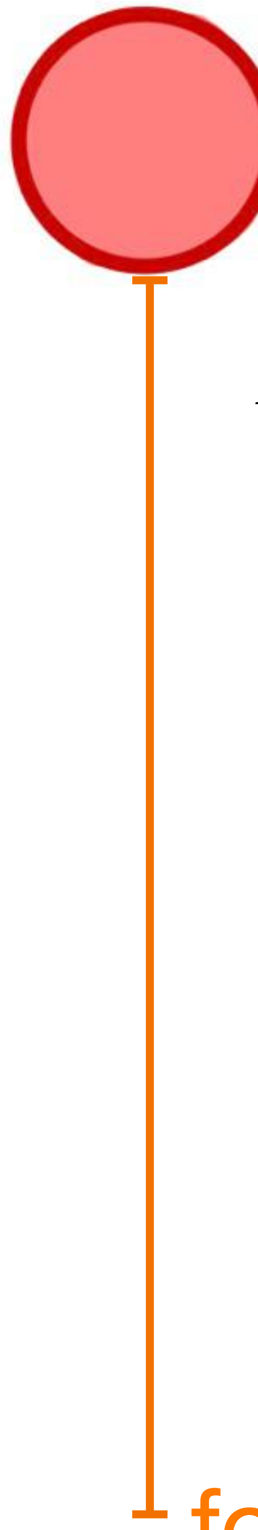
$$R_{co} = \frac{v_{esc}^2}{v_{DM}^2} R_{NS}(1+z)$$

Subhalo DM

- Spherical subhalos, constant density, single mass/radius
- Subhalo DM composes most DM
- Consider both collisionless and collisional

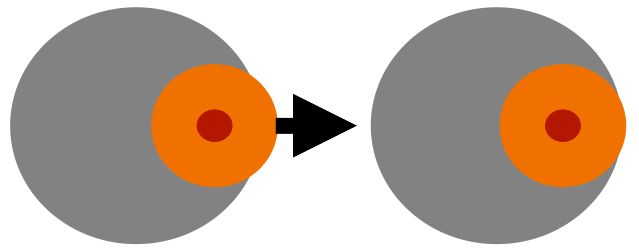


- Future exploration:
- Nontrivial profiles (e.g. NFW, Einasto, boson star)
- Spectrum of subhalo masses

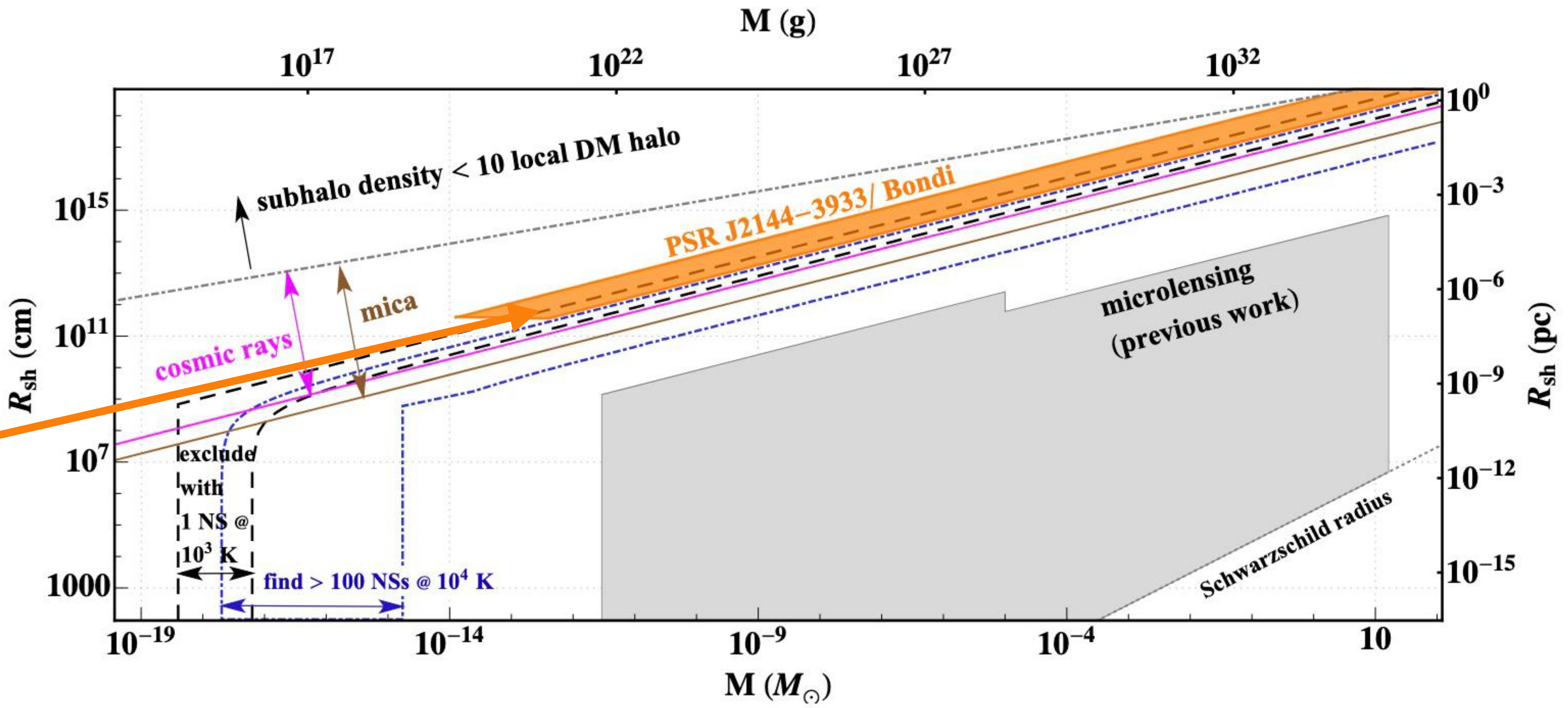


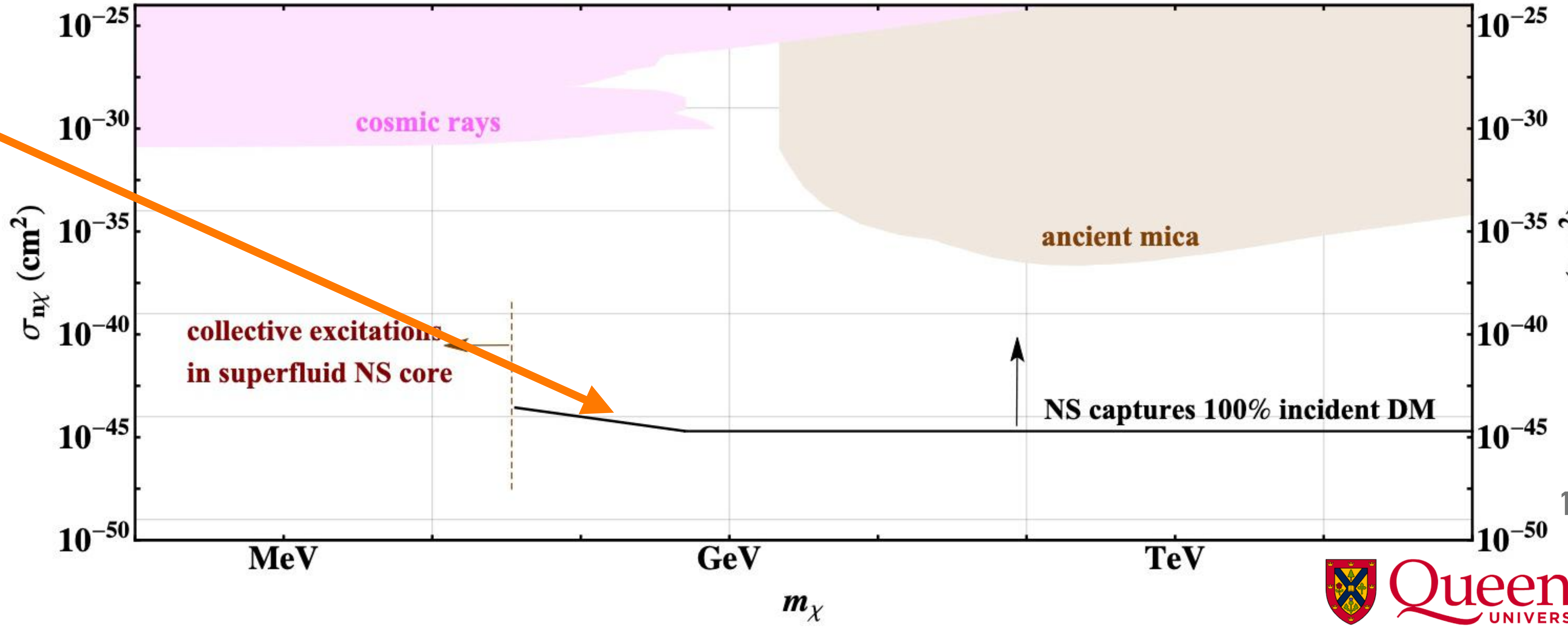
$$R_{co} = \frac{v_{esc}^2}{v_{DM}^2} R_{NS}(1+z)$$

PSR J2144 T < 3 x 10⁴ K
excludes this region
for Bondi accretion



for this DM-nucleon cross-section





JB, Kavanagh, Raj 2109.04582

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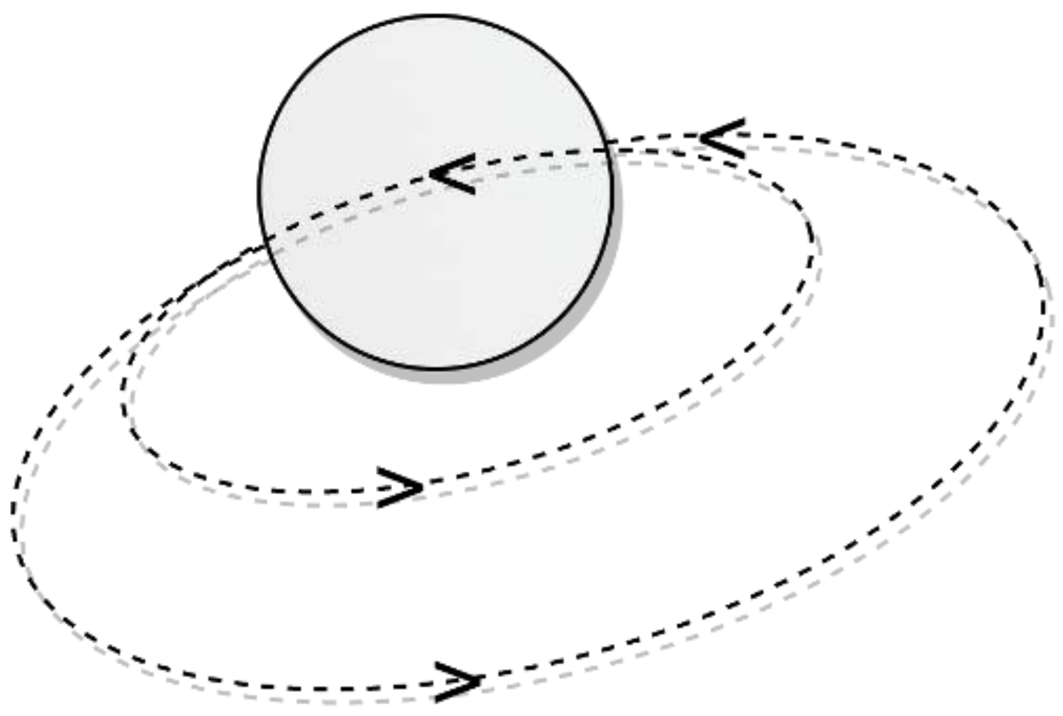
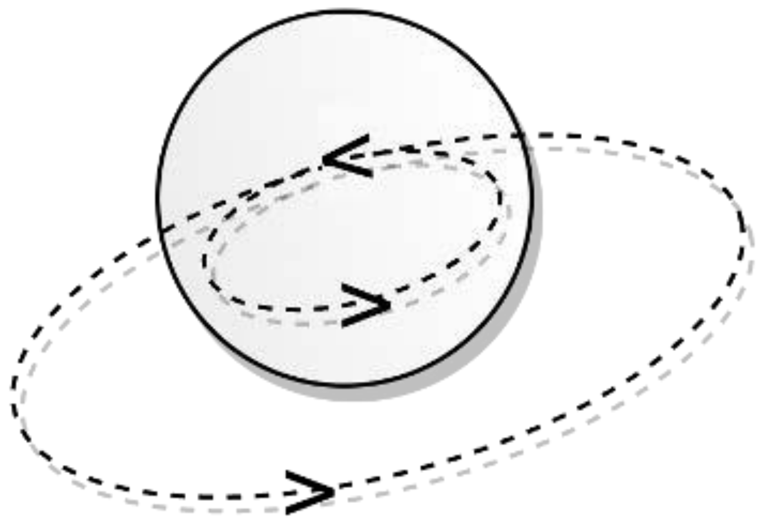
DM thermalizing in compact stars

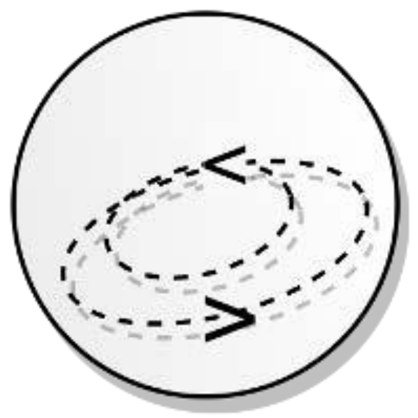


Dark matter is captured, undergoes successive scatters decreasing its orbital radius



Dark matter thermalizes to a radius $R < R_{NS}$, called t_1 thermalization

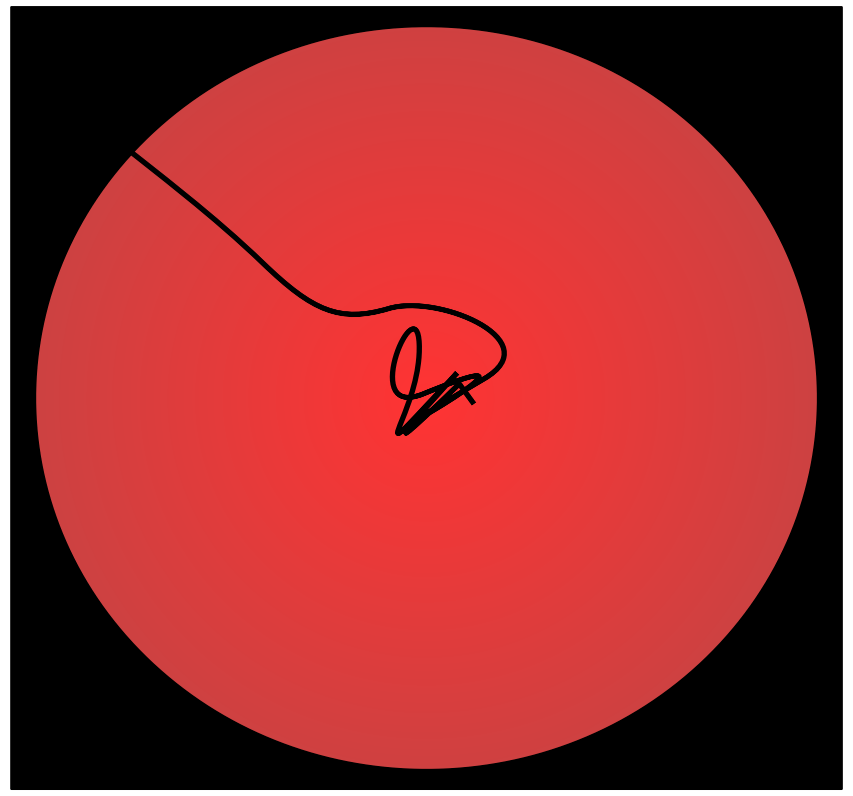
Narayani Tyagi



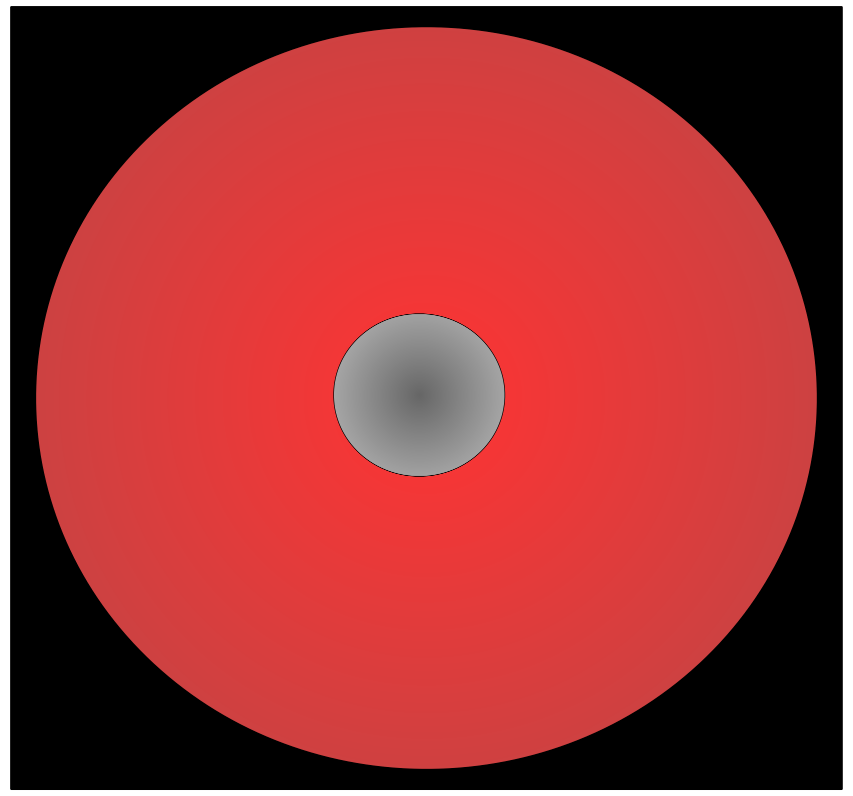
Dark matter continues to thermalize until $T_x = T_{NS}$ after a time called t_2 thermalization

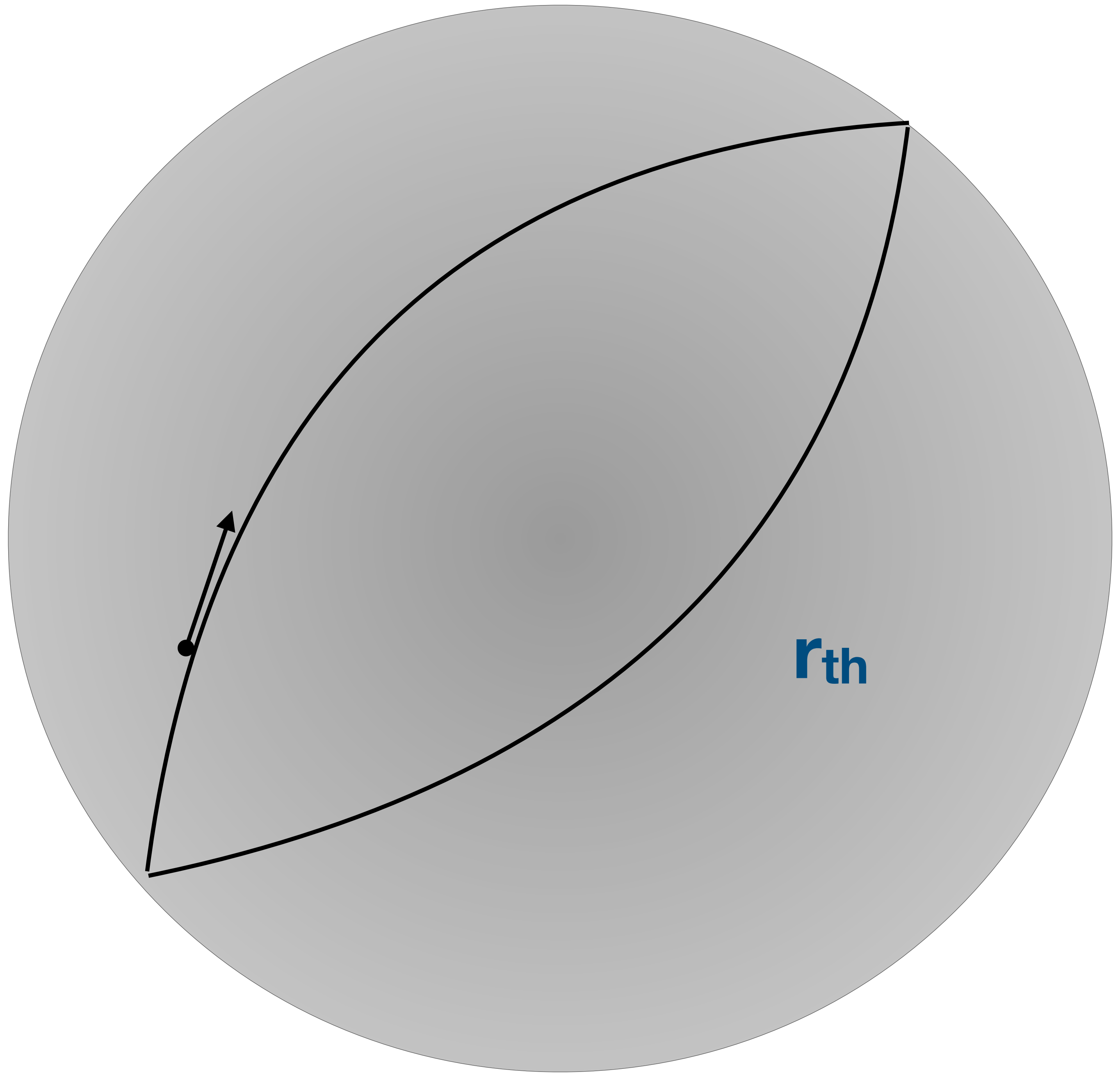
Asymmetric dark matter in compact stars

1. DM captured



2. DM thermalizes





Harmonic oscillator potential

$$k_B T \sim G\rho_{wd} m_x r_{th}^2$$

Thermalization radius

$$r_{th} \sim 1 \text{ millimeter} \sqrt{\frac{\text{PeV}}{m_x}} \sqrt{\frac{T_{ns}}{10^5 \text{ K}}}$$

Asymmetric dark matter in compact stars

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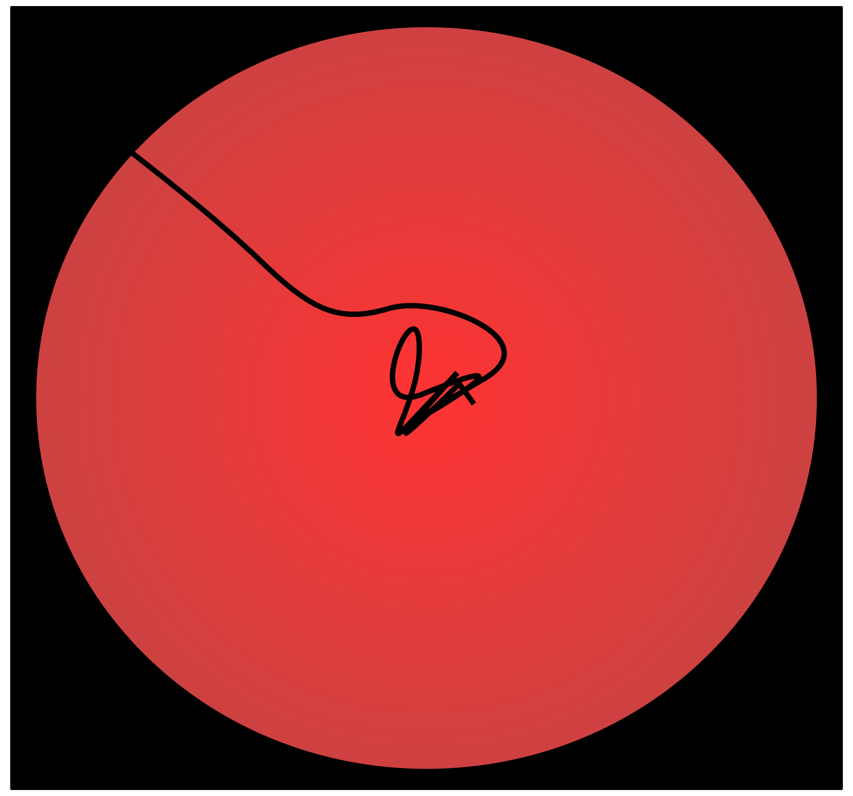

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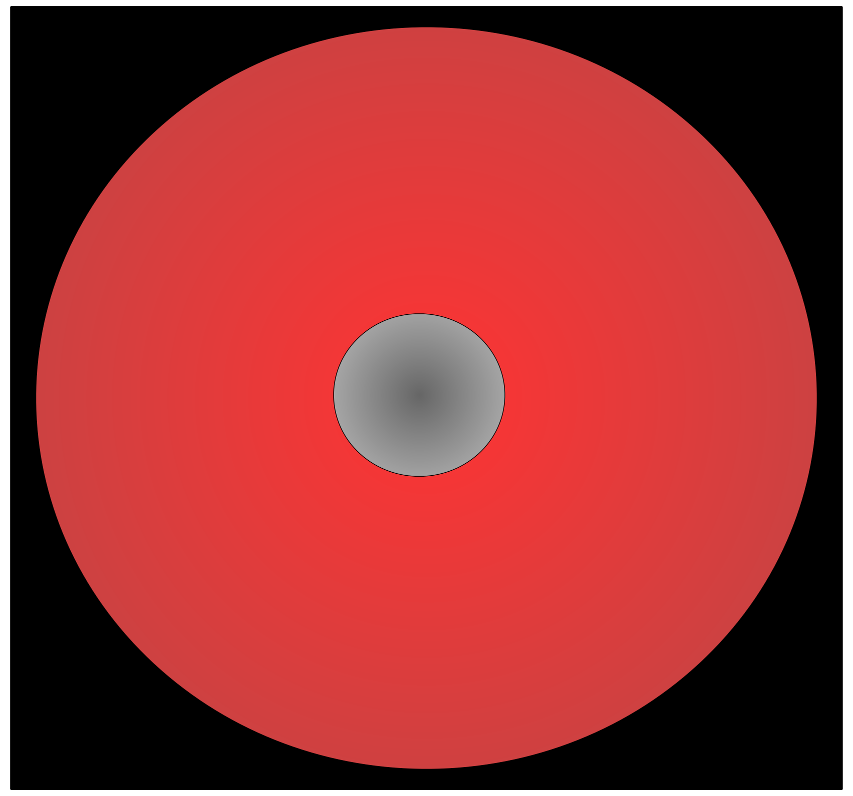
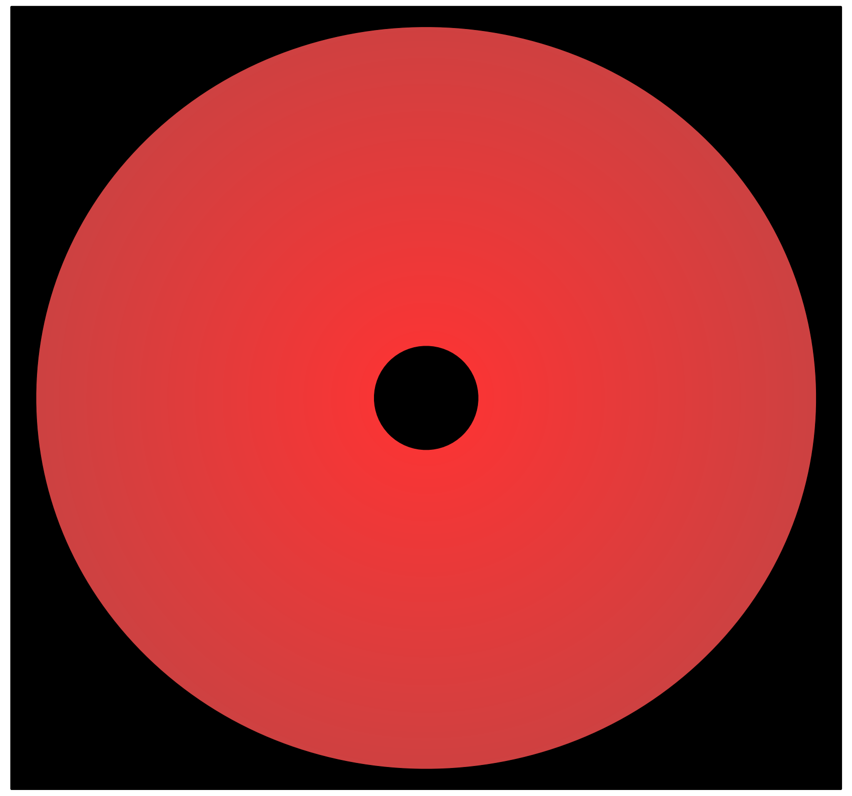


3. DM collapses



DM will collapse to a black hole if it

1. Self-gravitates $\rho_{DM} > \rho_{ns}$

2. Exceeds its own degeneracy pressure

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

(~10^{-12} solar masses for PeV mass DM)

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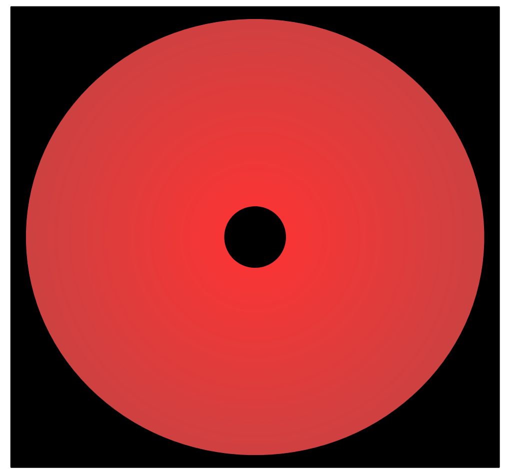
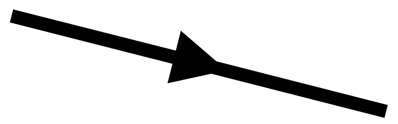


Dark matter that implodes pulsars

X

~GeV mass, asymmetric dark fermions — degeneracy pressure stabilizes up to a solar mass of dark matter.

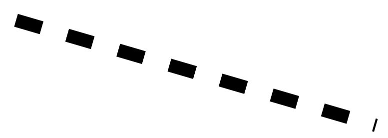


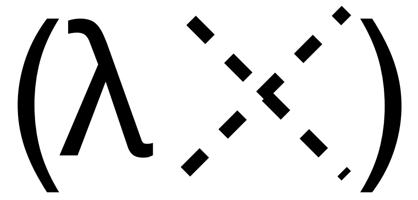
<u>m_X</u>

✓

KeV-PeV

Bosonic dark matter without repulsive self interactions — requires very small effective quartic ($\lambda < 10^{-15}$).





Bosonic DM Constraints
JB, Kumar, et al. 2013

✓

PeV-EeV

Heavy dark matter, fermionic or bosonic — fewer particles required for collapse.

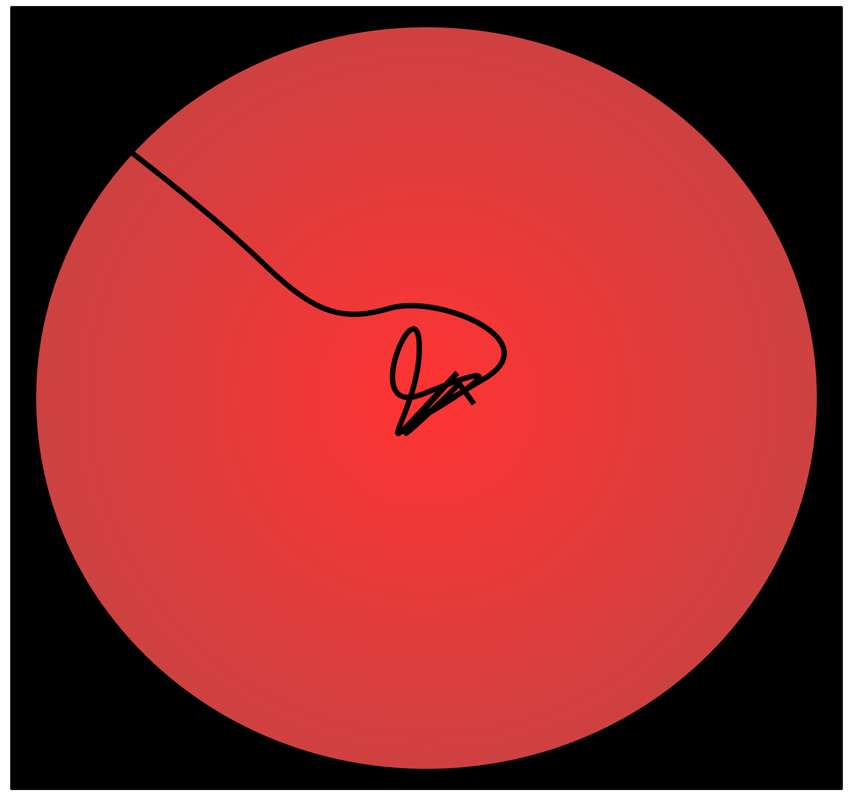
$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

$$M_{crit}^{bos} \simeq \sqrt{\lambda} M_{pl}^3/m_X^2$$

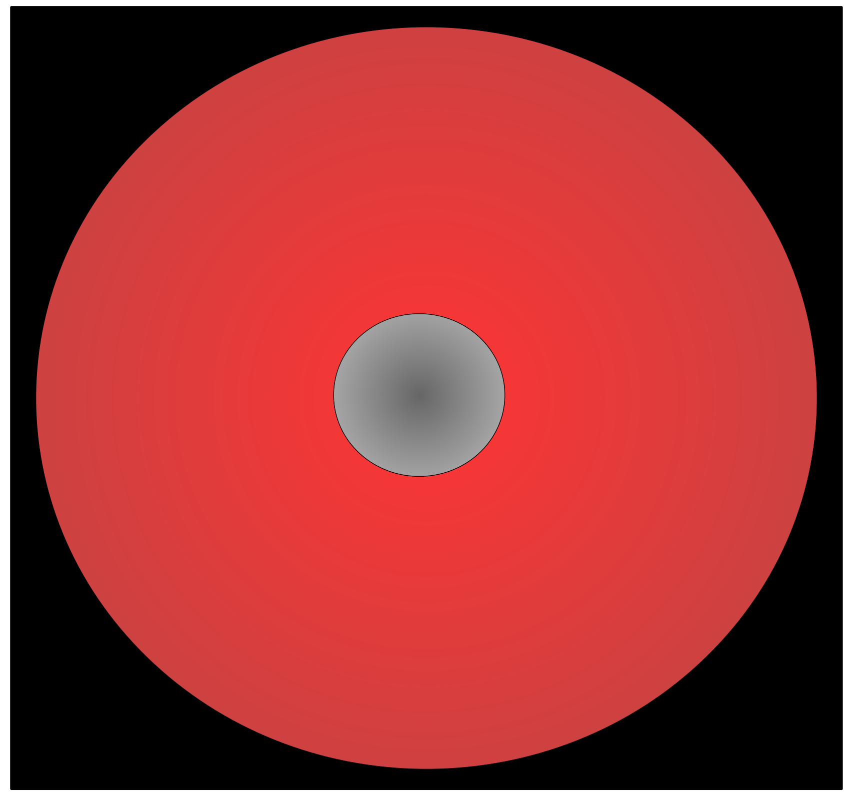
~10^{-12} solar masses

Asymmetric dark matter in compact stars

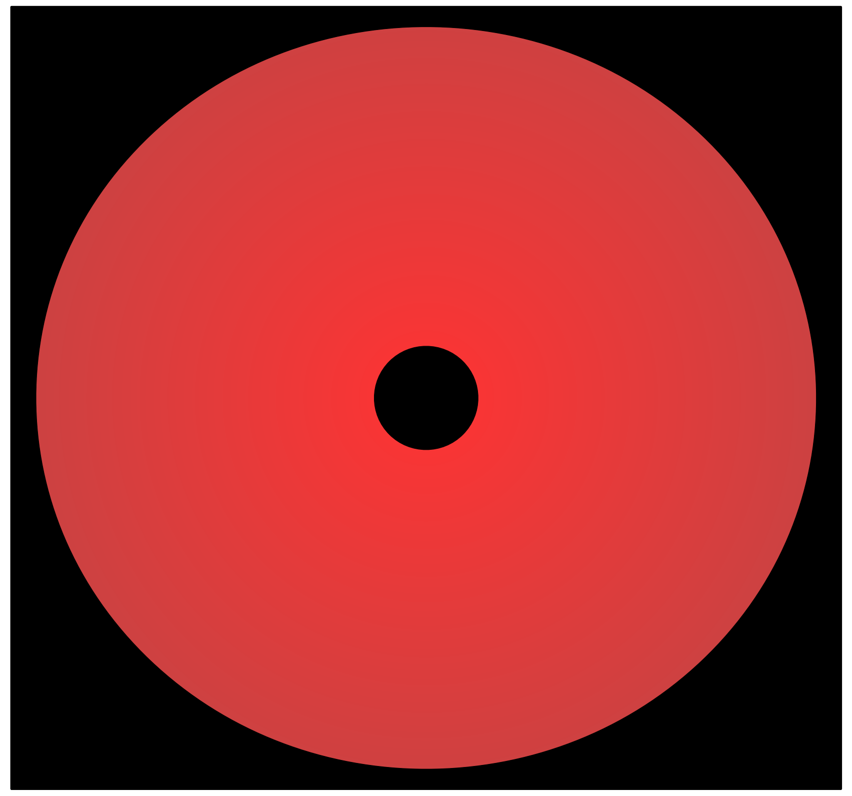
1. DM captured



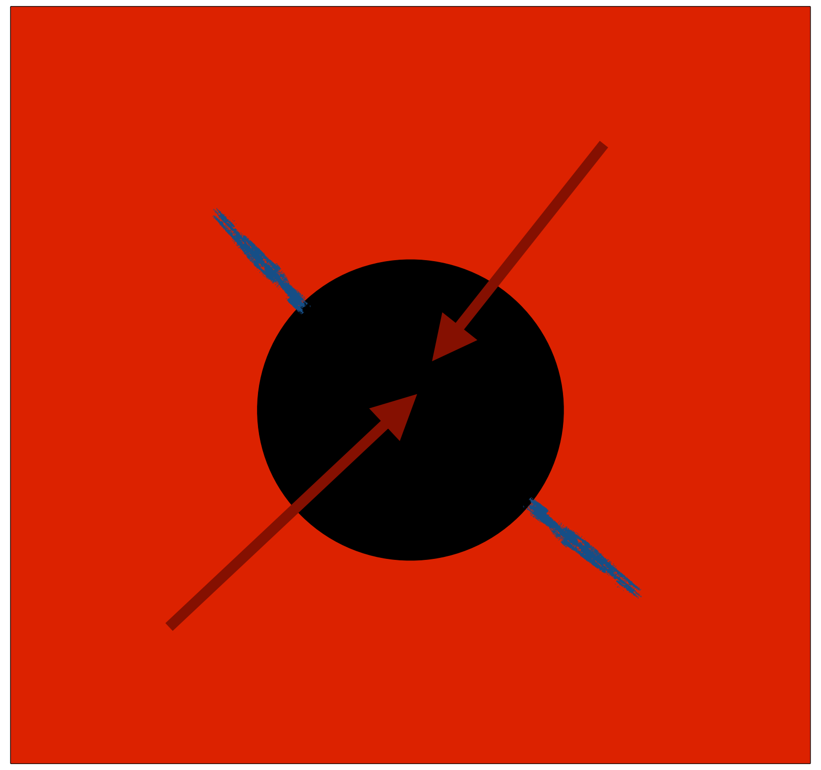
2. DM thermalizes



3. DM collapses



4. BH consumes neutron star



$$\frac{dM_{bh}}{dt} \approx \frac{4\pi\rho_{ns}(GM_{bh})^2}{v_s^3} - \frac{1}{15360\pi(GM_{bh})^2}$$

Asymmetric dark matter in compact stars

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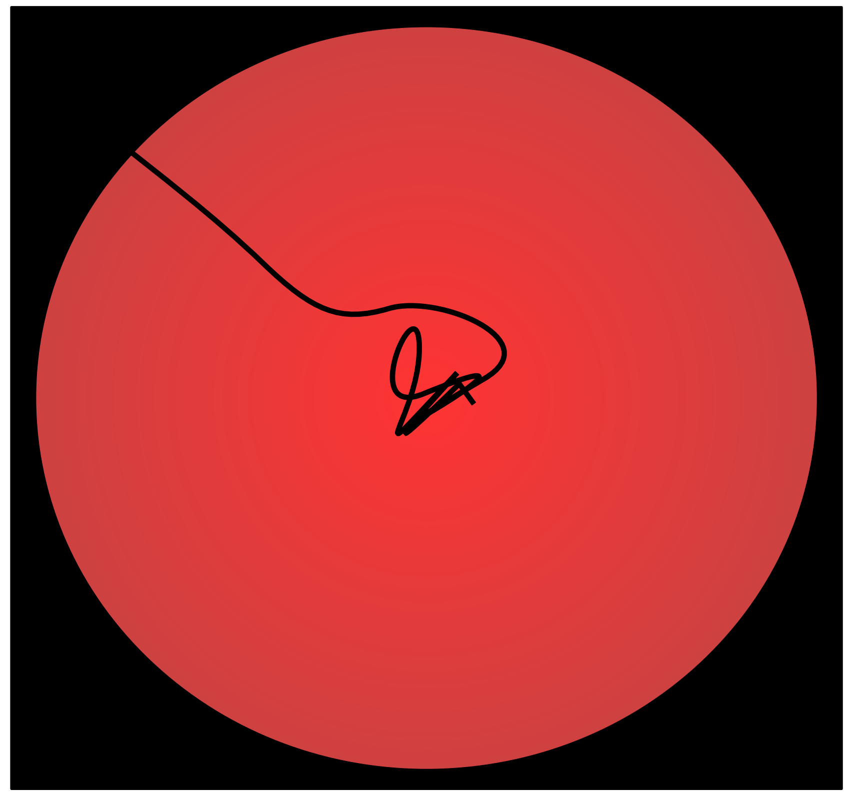

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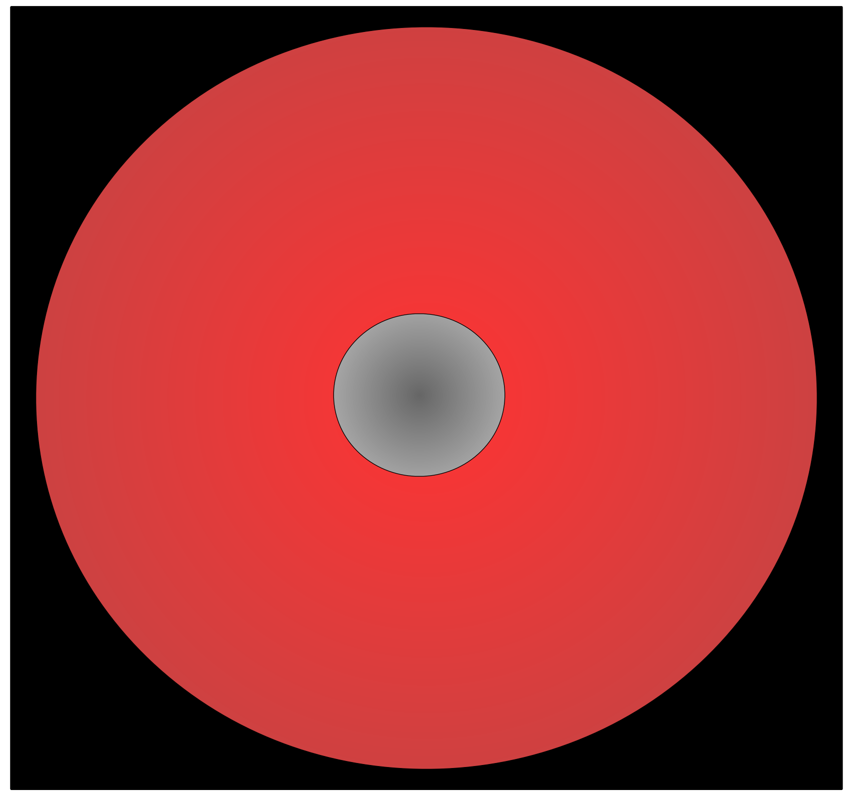

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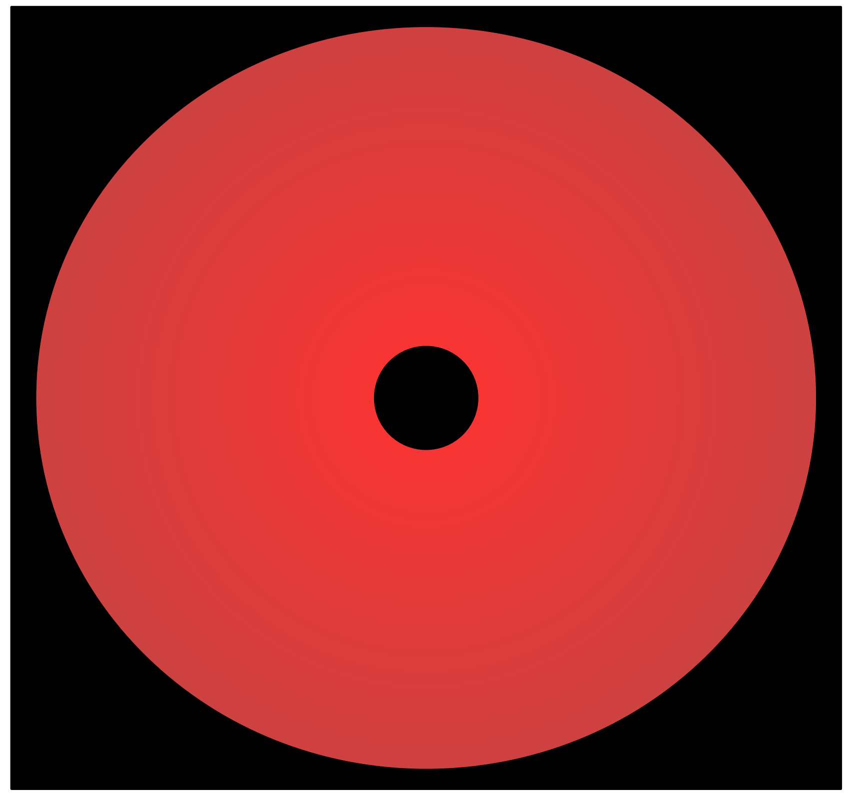

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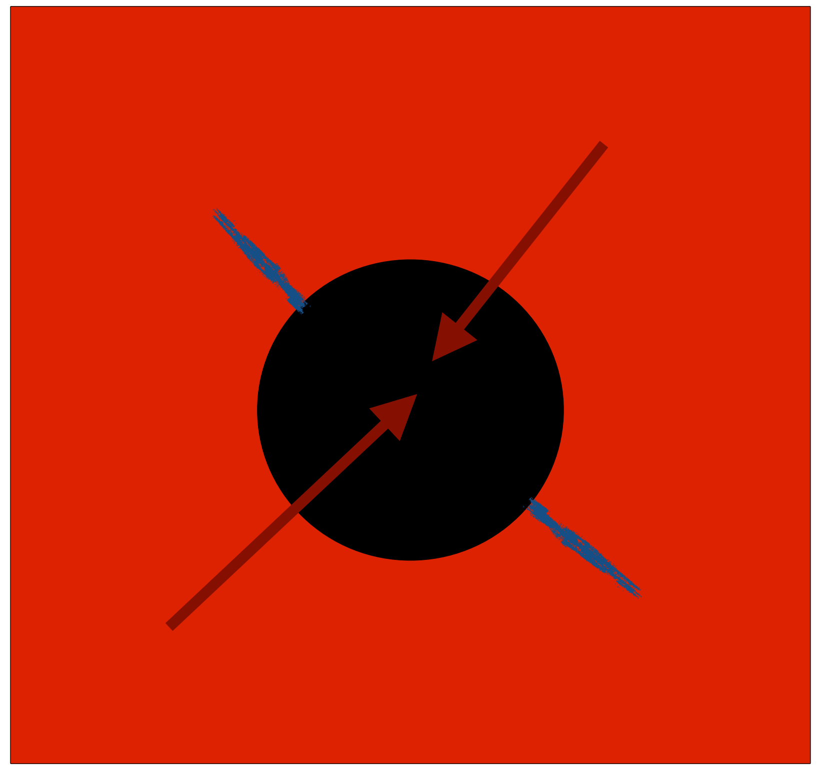
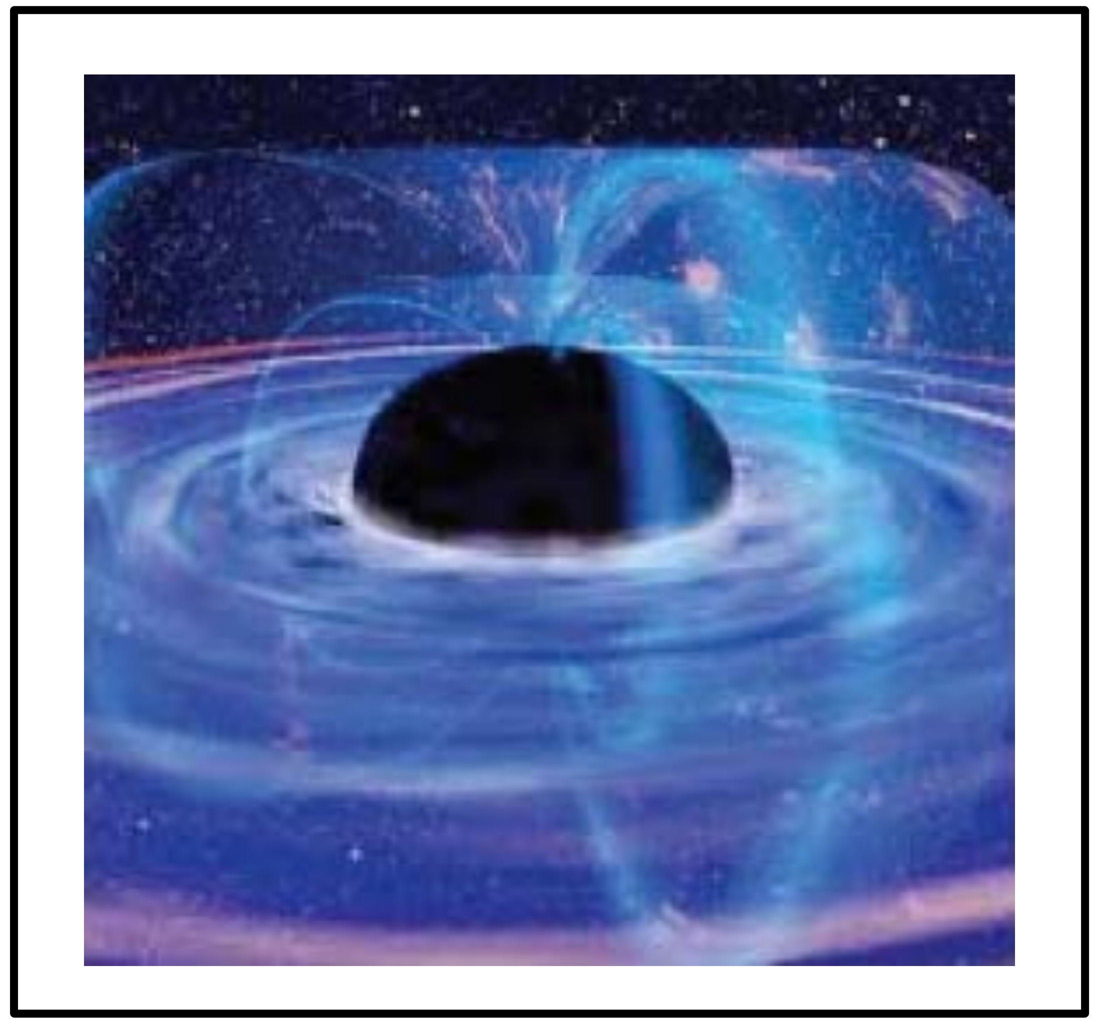
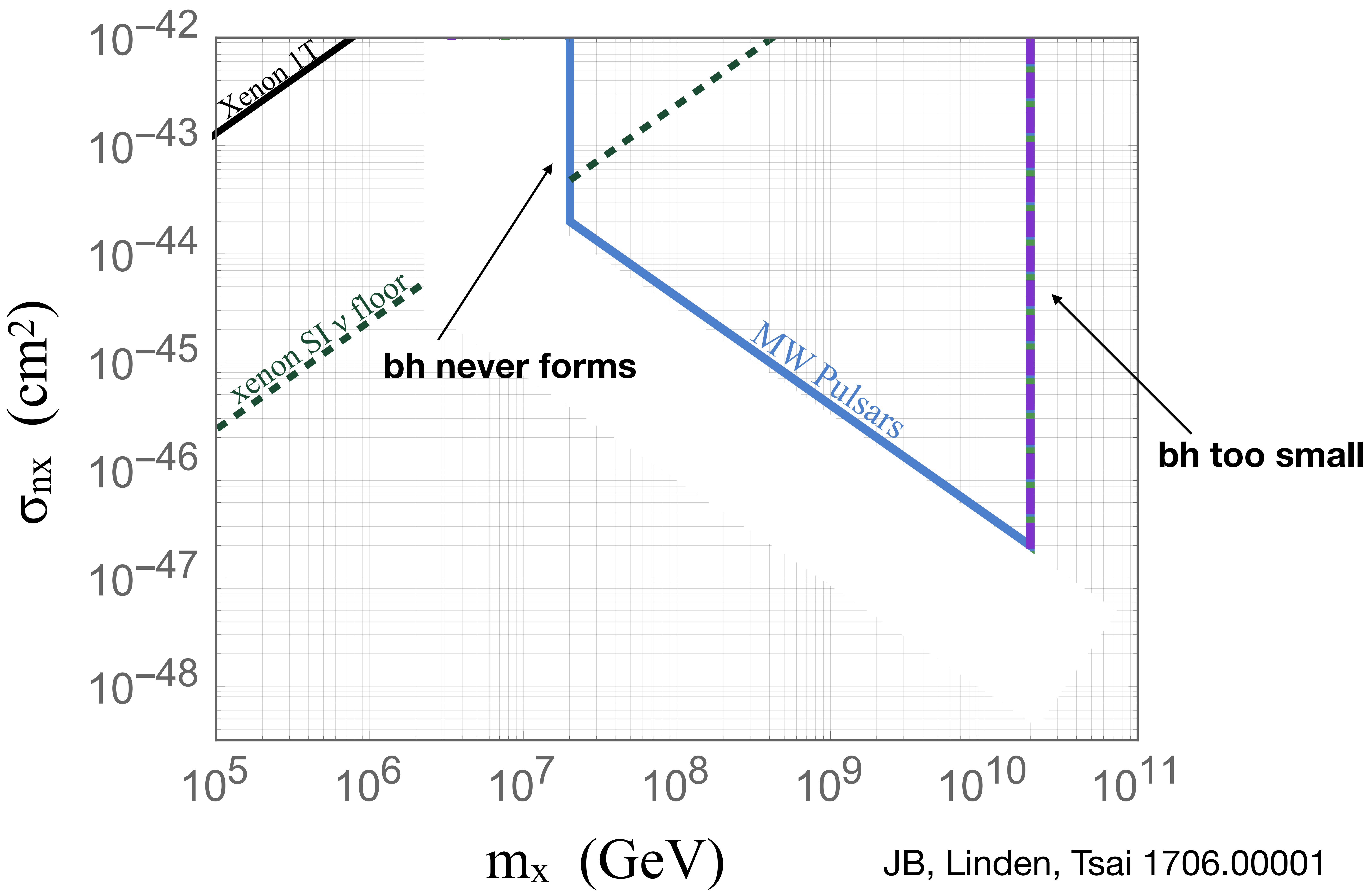


5. Form solar mass BH



$$\frac{dM_{bh}}{dt} \approx \frac{4\pi \rho_{ns} (GM_{bh})^2}{v_s^3} - \frac{1}{15360\pi (GM_{bh})^2}$$

Using an old pulsar in the Milky Way, the best bound so far…



JB, Linden, Tsai 1706.00001

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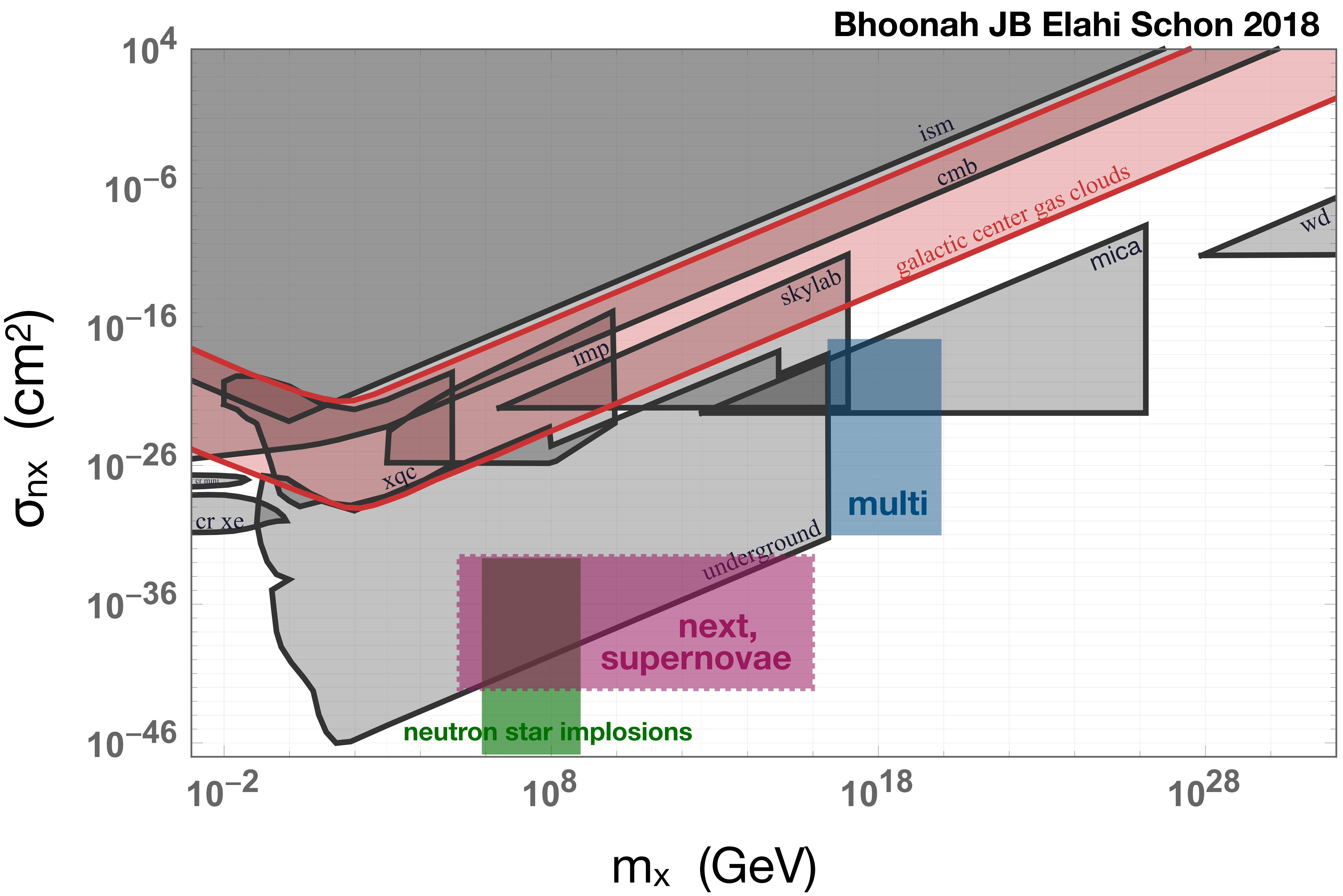

Bhoonah JB Elahi Schon 2018
10^{4}
10^{-6}
10^{-16}
10^{-26}
10^{-36}
10^{-46}
σ_{nx} (cm^2)
10^{-2}
10^{8}
10^{18}
10^{28}
m_x (GeV)
ism
cmb
galactic center gas clouds
wd
mica
skylab
imp
xqc
cr xe
multi
underground
next, supernovae
neutron star implosions

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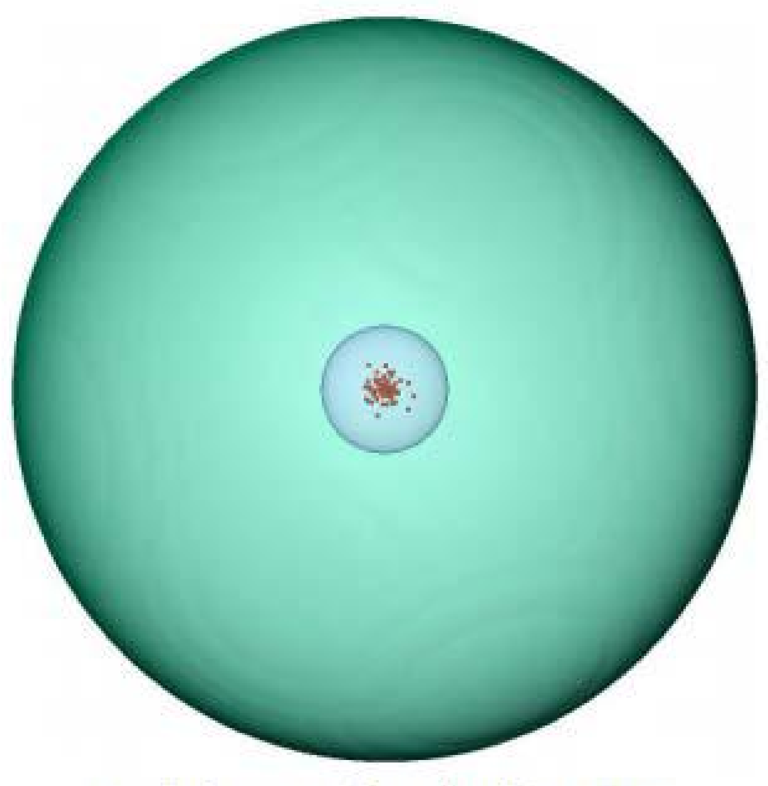
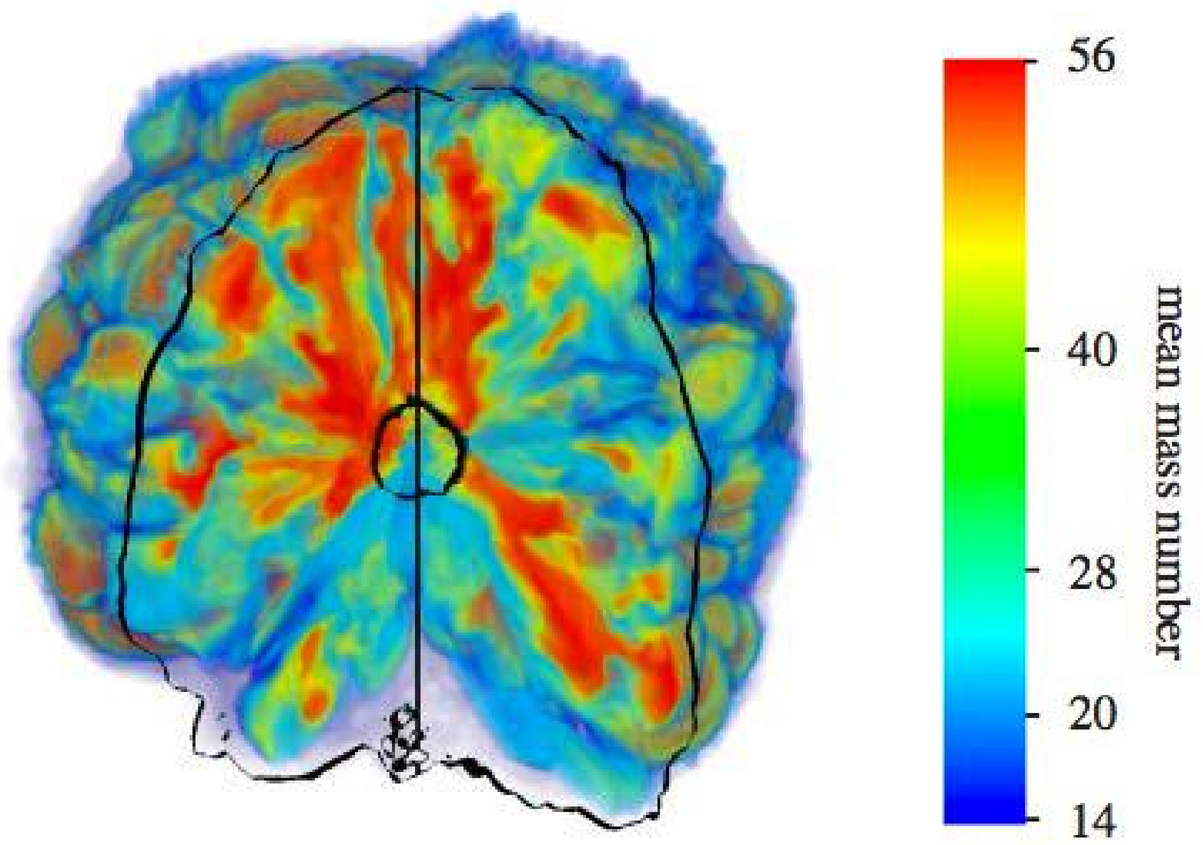
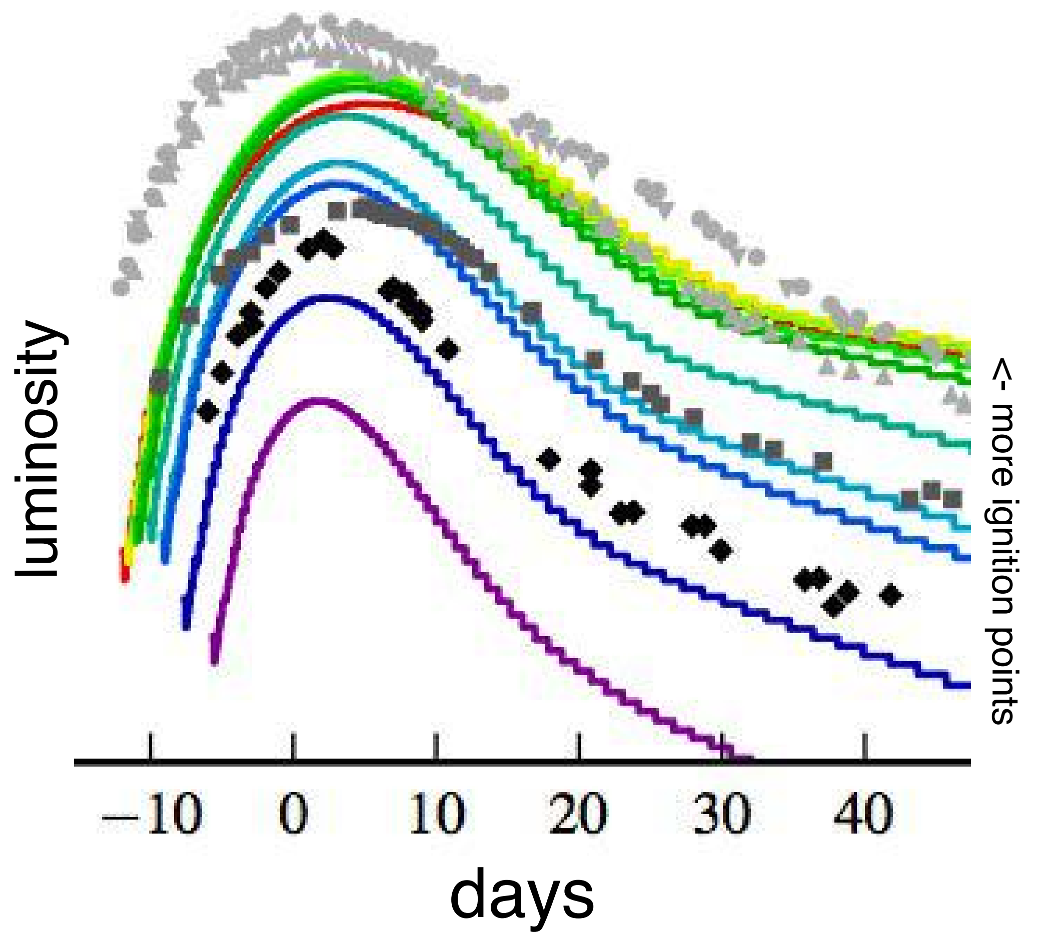


ignition



nuclei fuse (^{56}Ni)



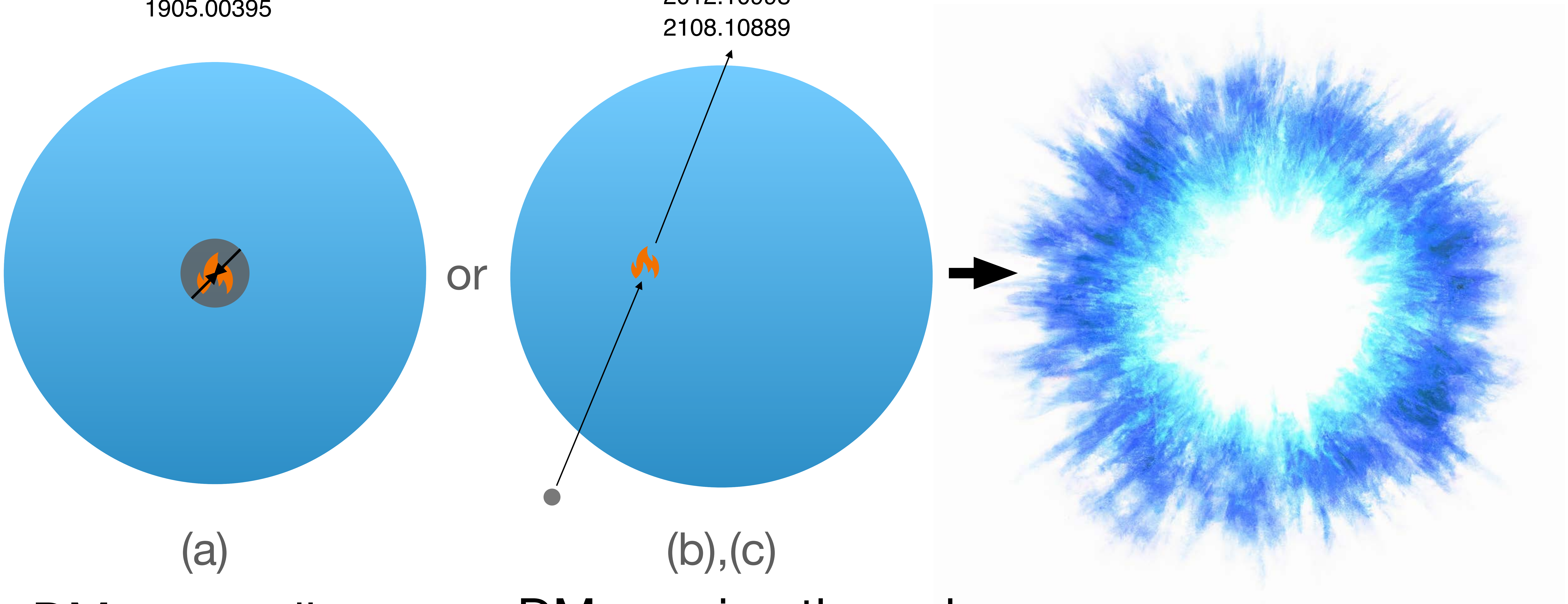
nuclei decay

(figures from 1308.3257)

Type Ia supernovae erupt when a portion of white dwarf becomes heated, igniting a thermonuclear flame-front that sweeps through the star, followed by an explosion.

1505.07464
1904.11993
1905.00395

1505.04444
1911.08883
2012.10998
2108.10889



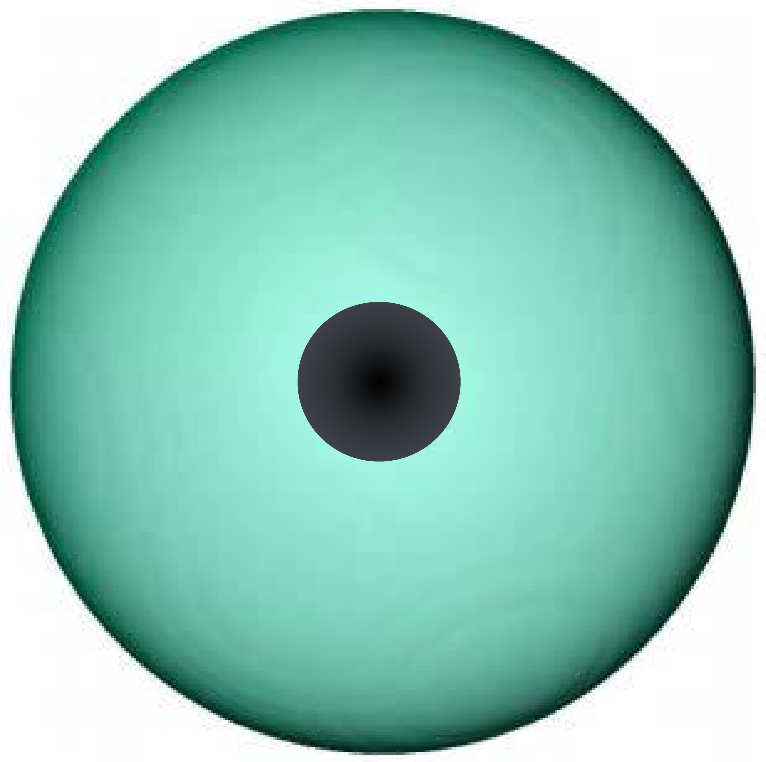
(a)
DM core collapse

(b),(c)
DM passing through
(scatter, internal potential)

Two primary methods to explode WDs with dark matter.

Heavy Dark Matter Ignition of Type Ia Supernovae

In order to ignite a carbon-oxygen white dwarf, the dark matter must be **heavy** so that it thermalizes inside a small volume within the white dwarf, and collects to the point of collapse within ~10^{10} years.



DM collects to the point of self-gravitation.

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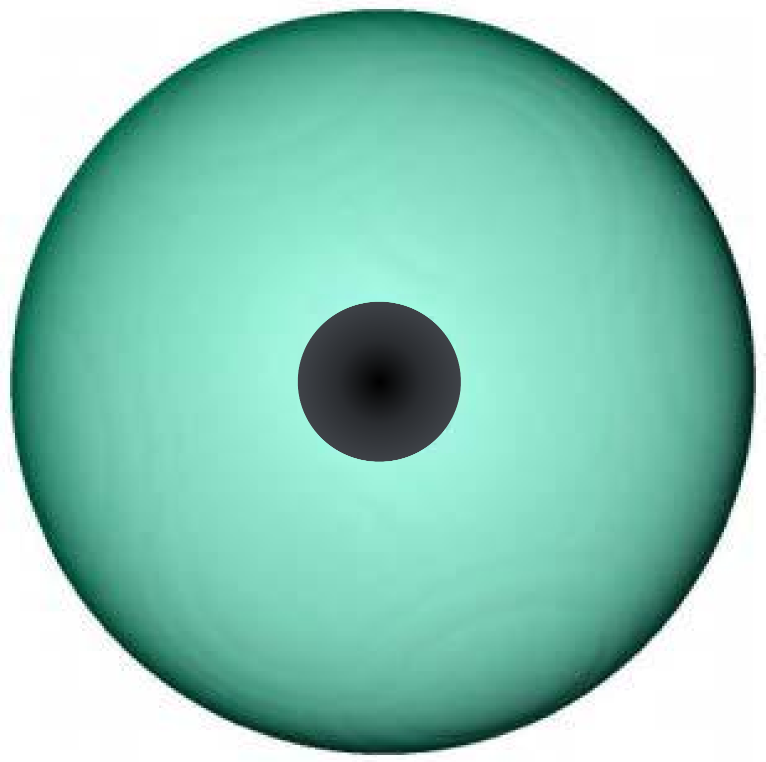


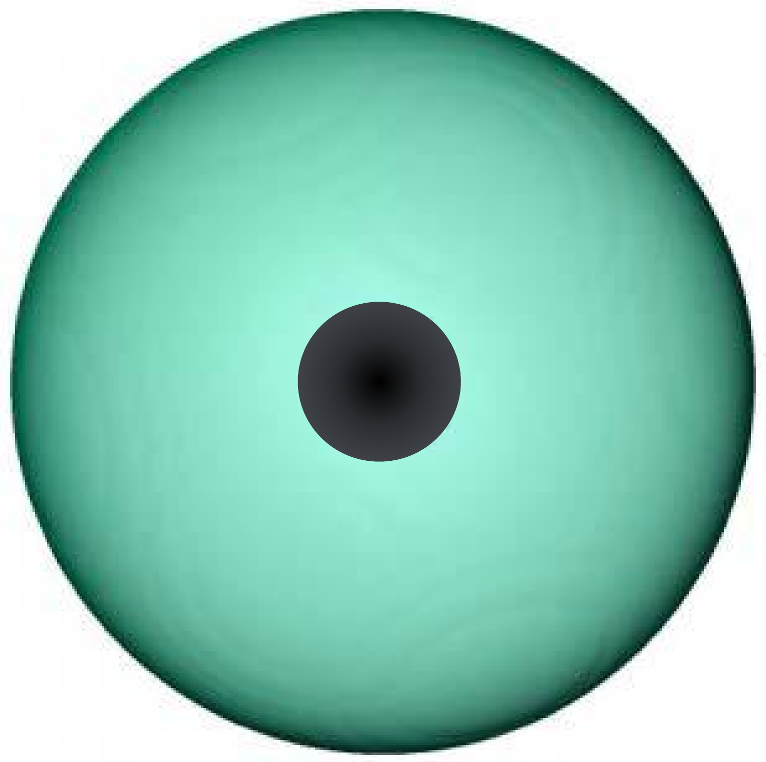
DM collects to the point of self-gravitation.

Harmonic Oscillator potential

$$k_B T \sim G \rho_{wd} m_x r_{th}^2$$

Heavy Dark Matter Ignition of Type Ia Supernovae

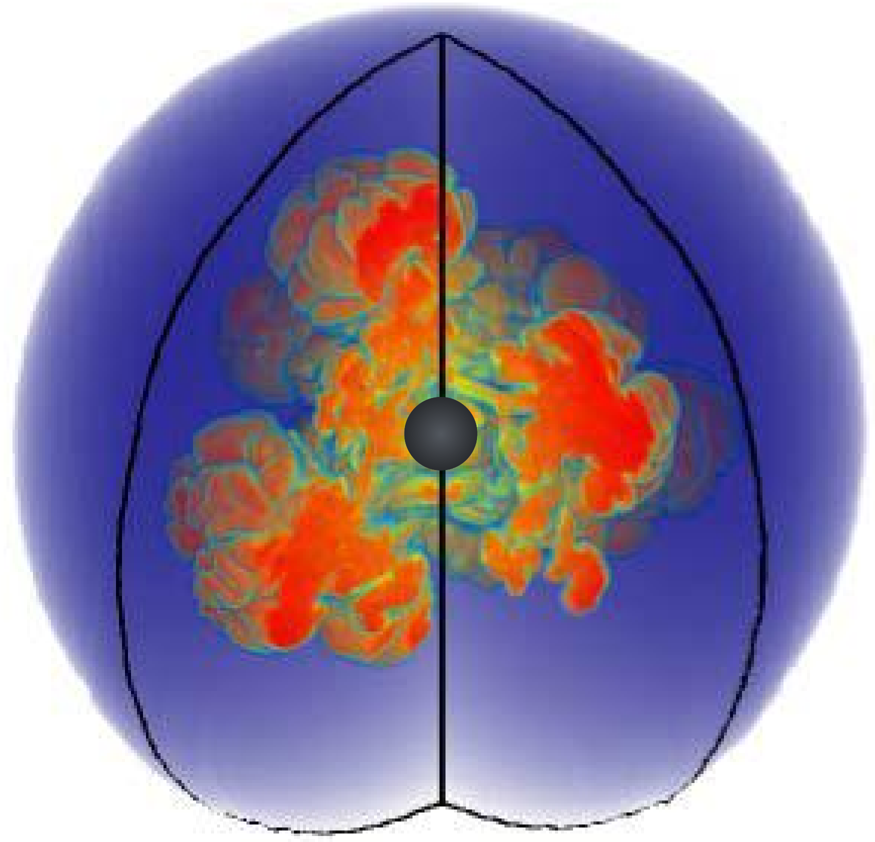
In order to ignite a carbon-oxygen white dwarf, the dark matter must be **heavy** so that it thermalizes inside a small volume within the white dwarf, and collects to the point of collapse within ~10^{10} years.



DM collects to the point of self-gravitation.

Harmonic Oscillator potential

$$k_B T \sim G \rho_{wd} m_x r_{th}^2$$



DM collapses, shedding gravitational potential energy through **scattering**, igniting a SNIa.

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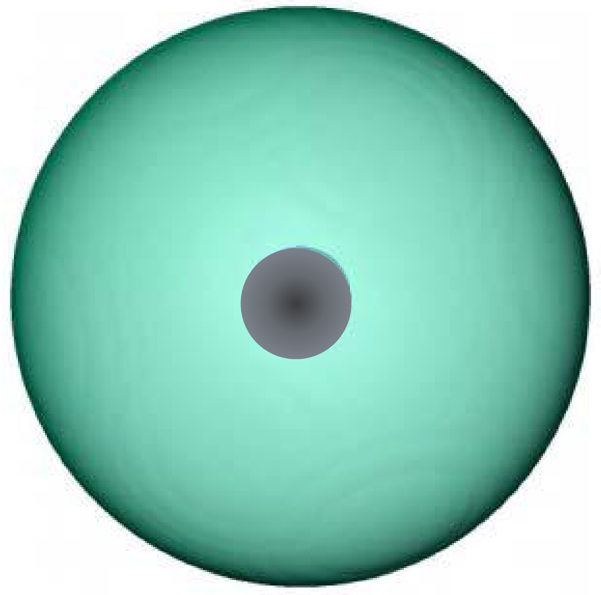
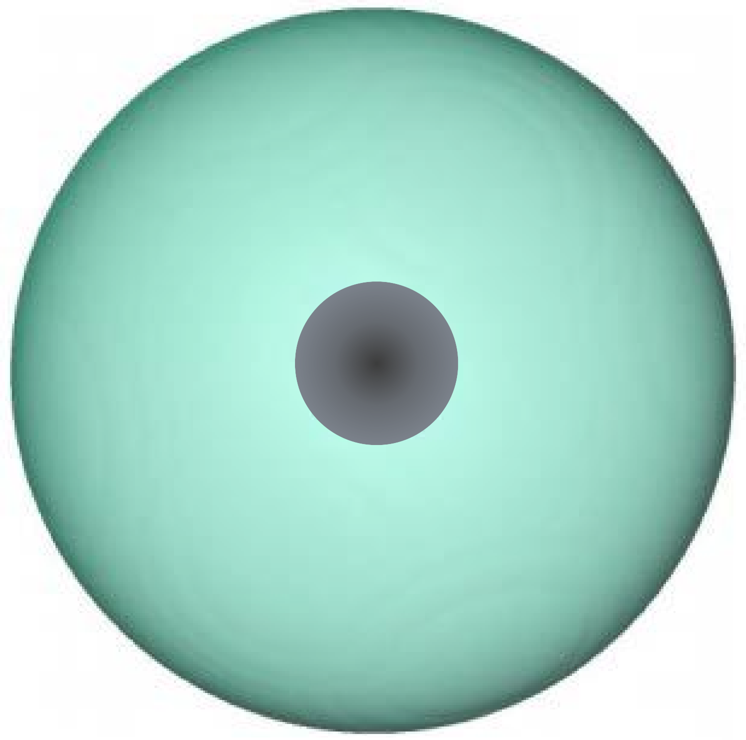


more massive WD,
DM collapses sooner



less massive WD,
DM collapses later

A more massive white dwarf is denser, so dark matter collects into a smaller ball, and collapses sooner.

Altogether, this shortens the time for dark matter collapse in more massive white dwarfs.

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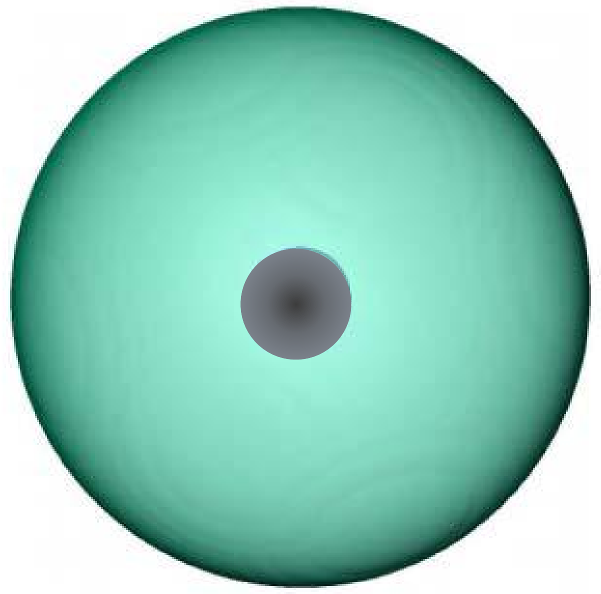
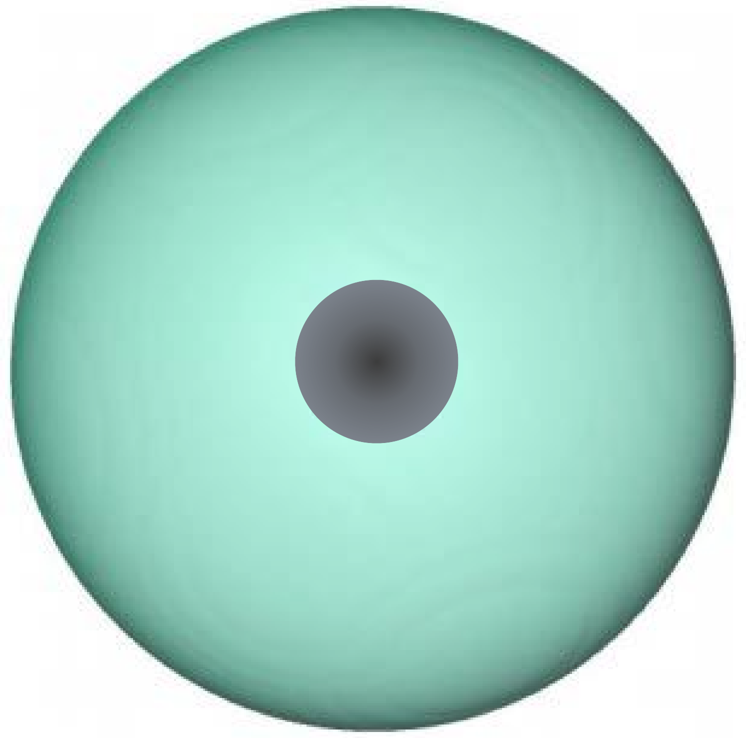
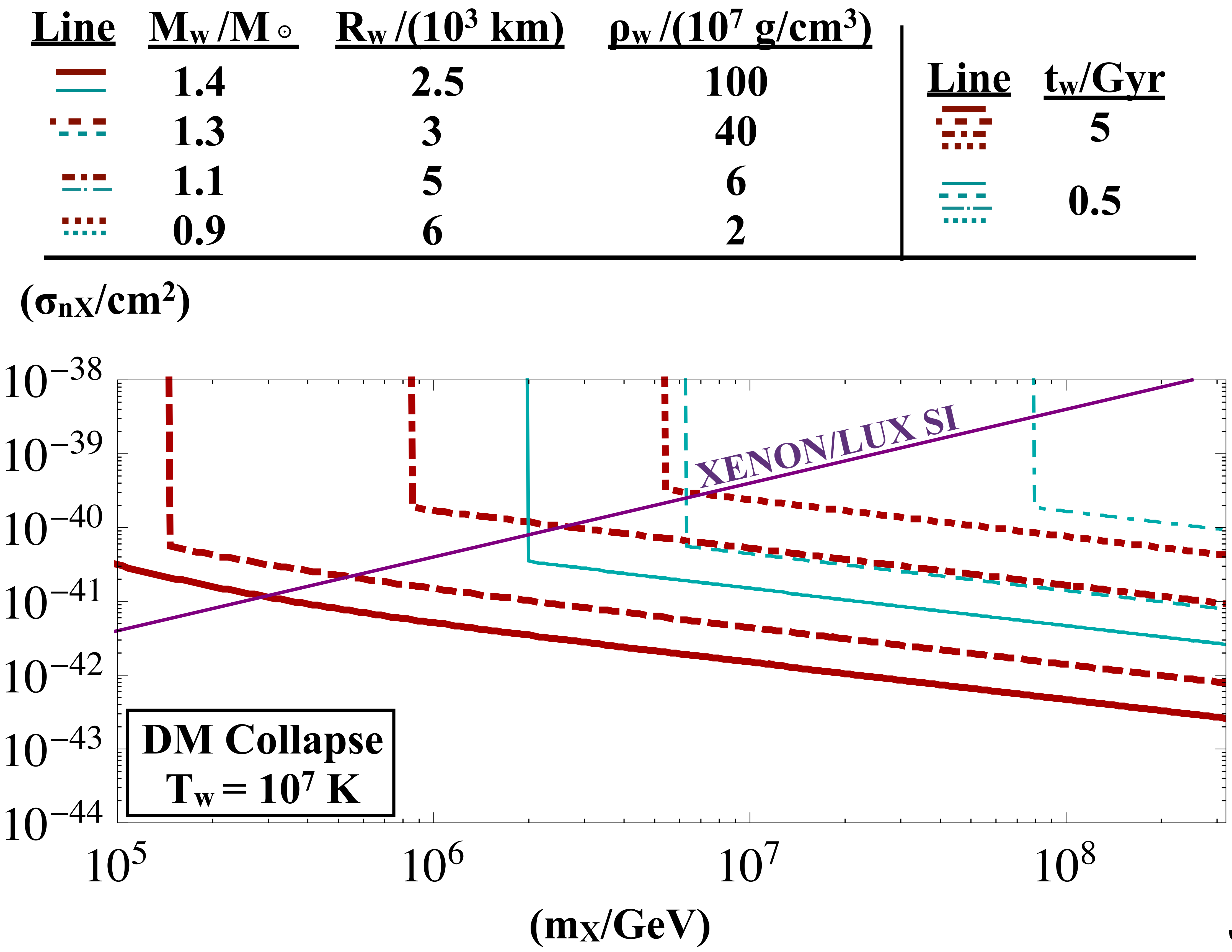


DM collapses sooner

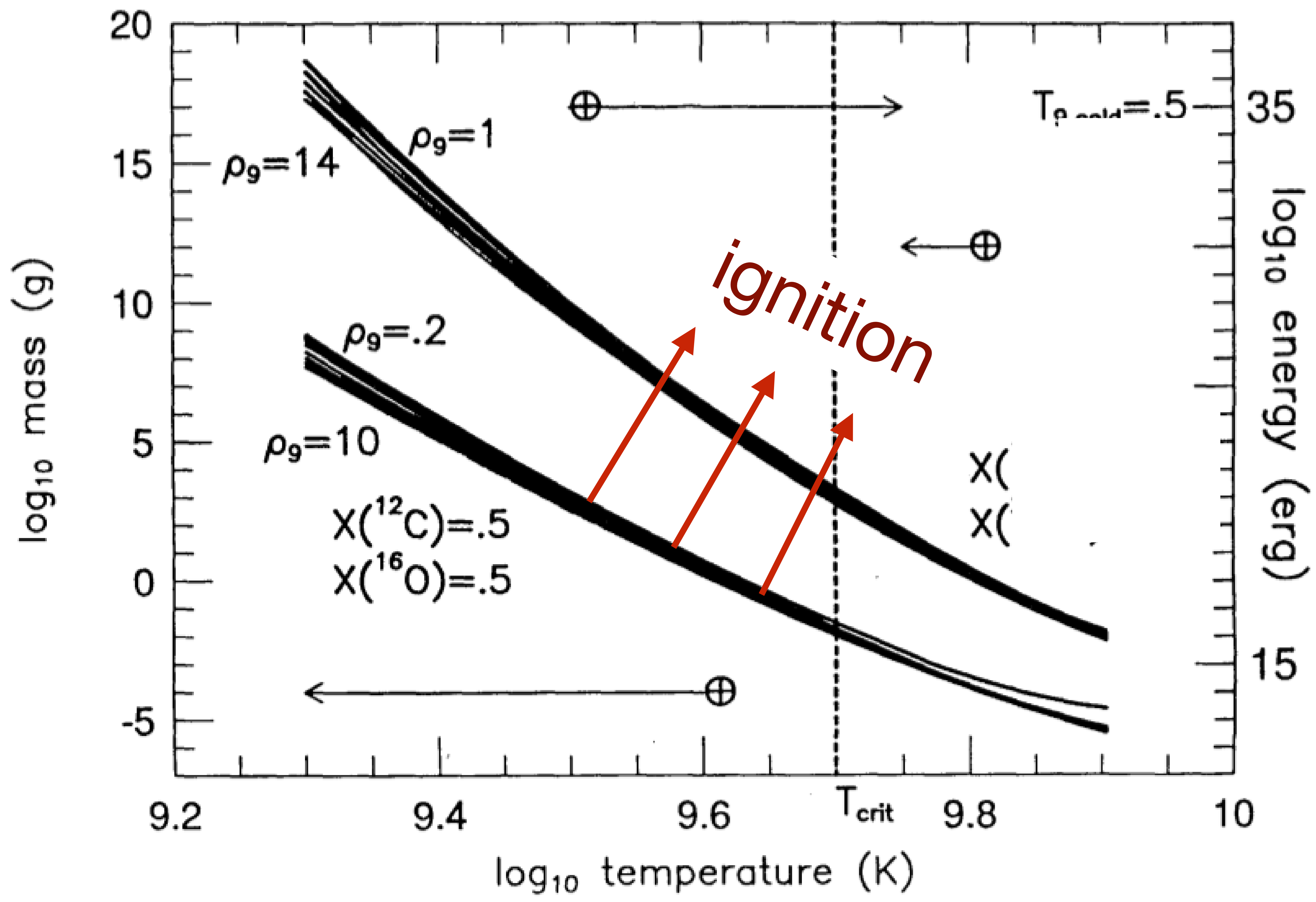


DM collapses later



JB 1505.01764

As it collapses to its minimum energy state, dark matter will shed gravitational potential energy.



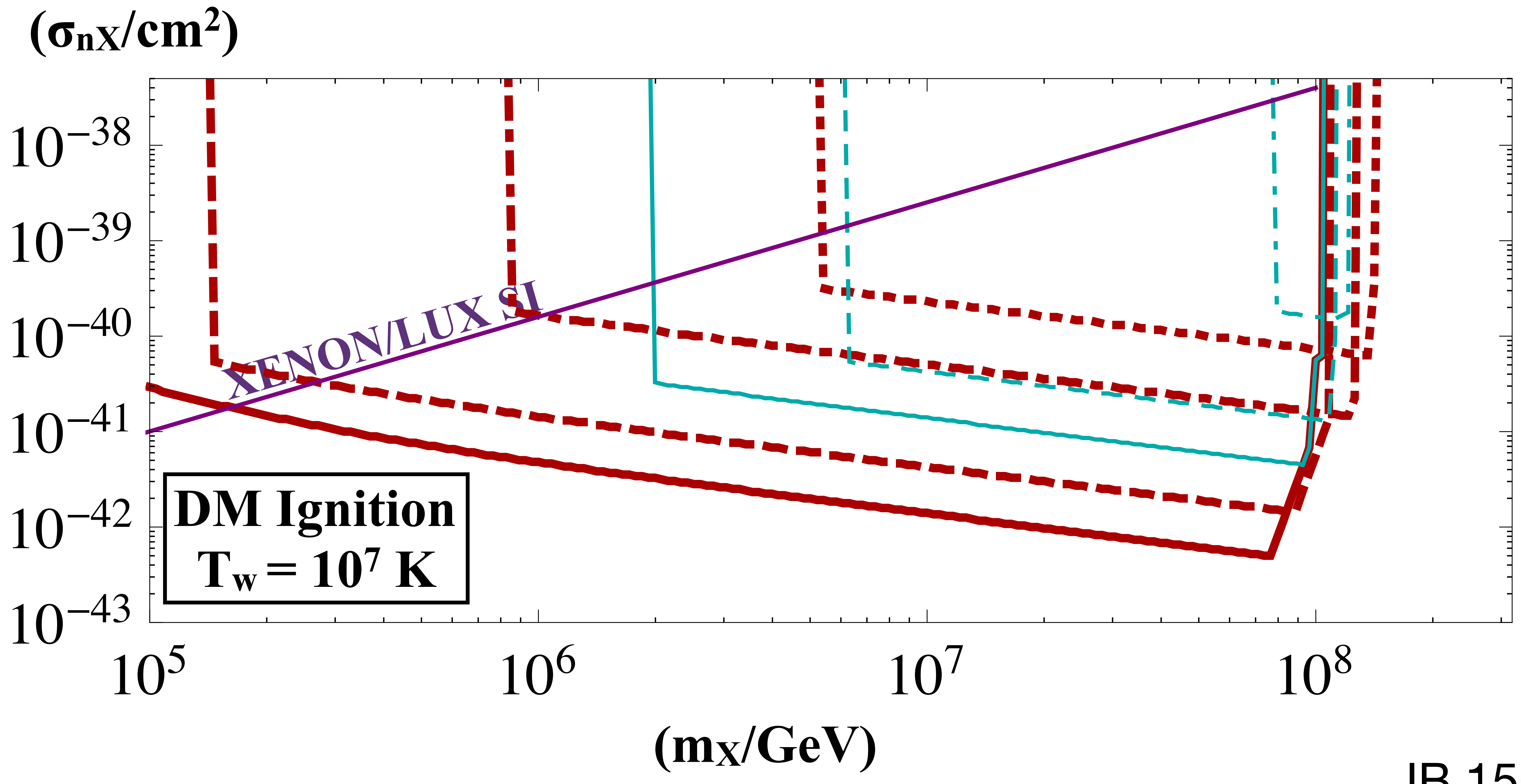
Timmes & Woosley 1992

For ignition to occur, at a given temperature, the speed of nuclear burning across a fixed region must exceed the white dwarf's electron conduction diffusion rate.

The limiting factor for heavy DM-induced-ignition of white dwarfs is the mass of the DM particle. Heavier DM collapses after fewer particles have collected, and fewer collapsing particles transfer less heat.

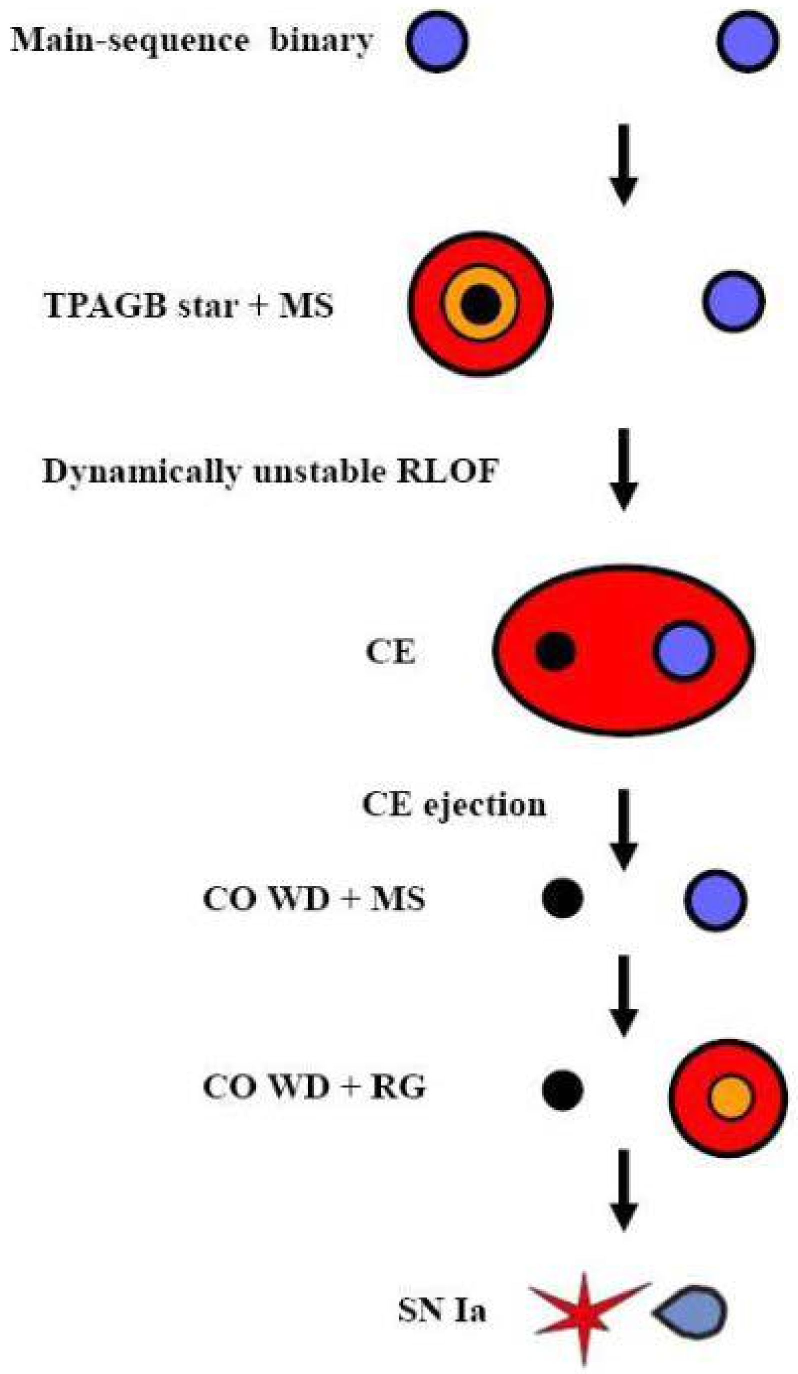
Line	$M_w/M_\odot$	$R_w/(10^3$ km$)$	$\rho_w/(10^7$ g/cm$^3)$
	1.4	2.5	100
	1.3	3	40
	1.1	5	6
	0.9	6	2

Line	t_w/Gyr
	5
	0.5

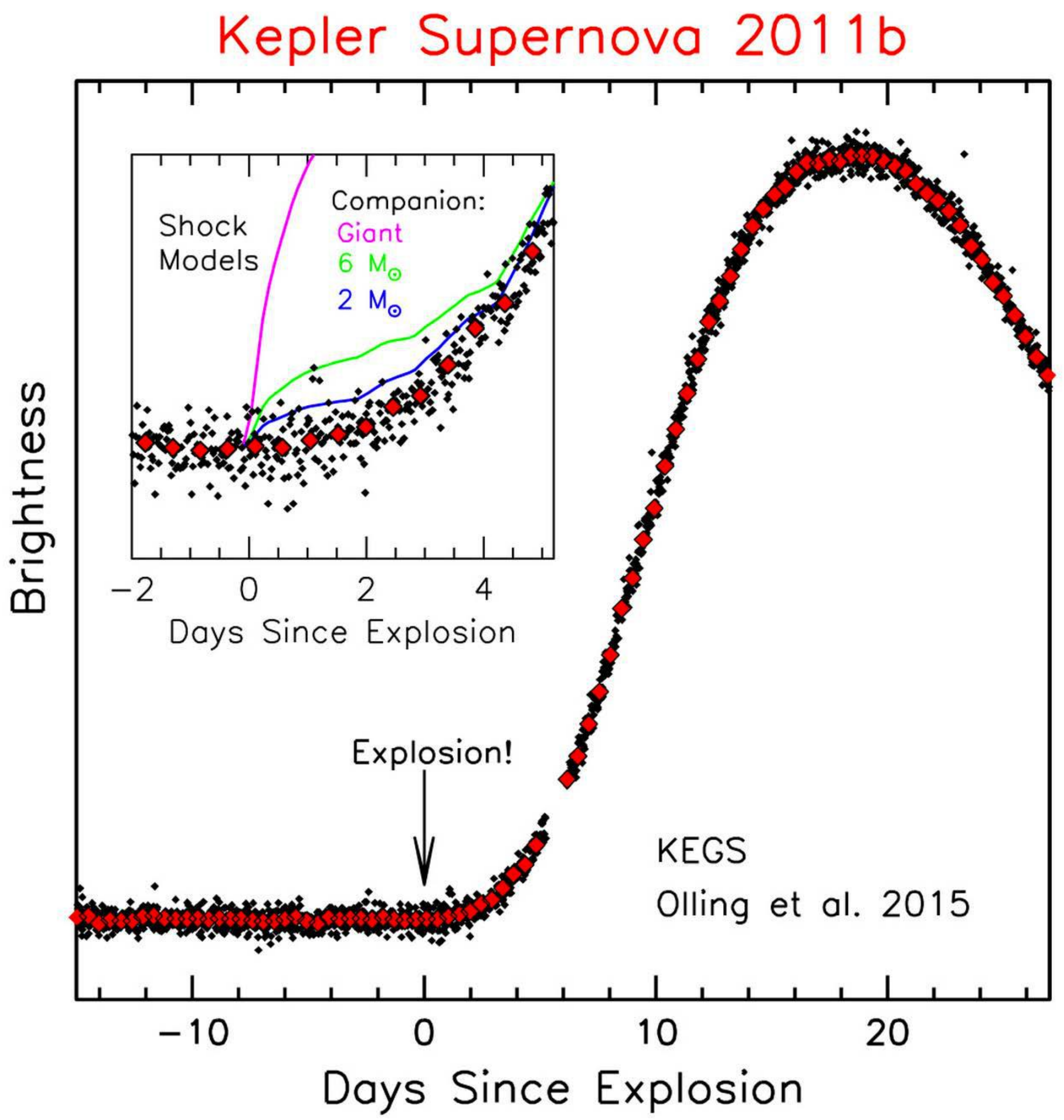


JB 1505.01764

It is not clear what ignites type Ia supernovae. Candidates include binary accretion to criticality (a.k.a. Chandrasekhar mass), and white dwarfs merging.



implied shocks not seen



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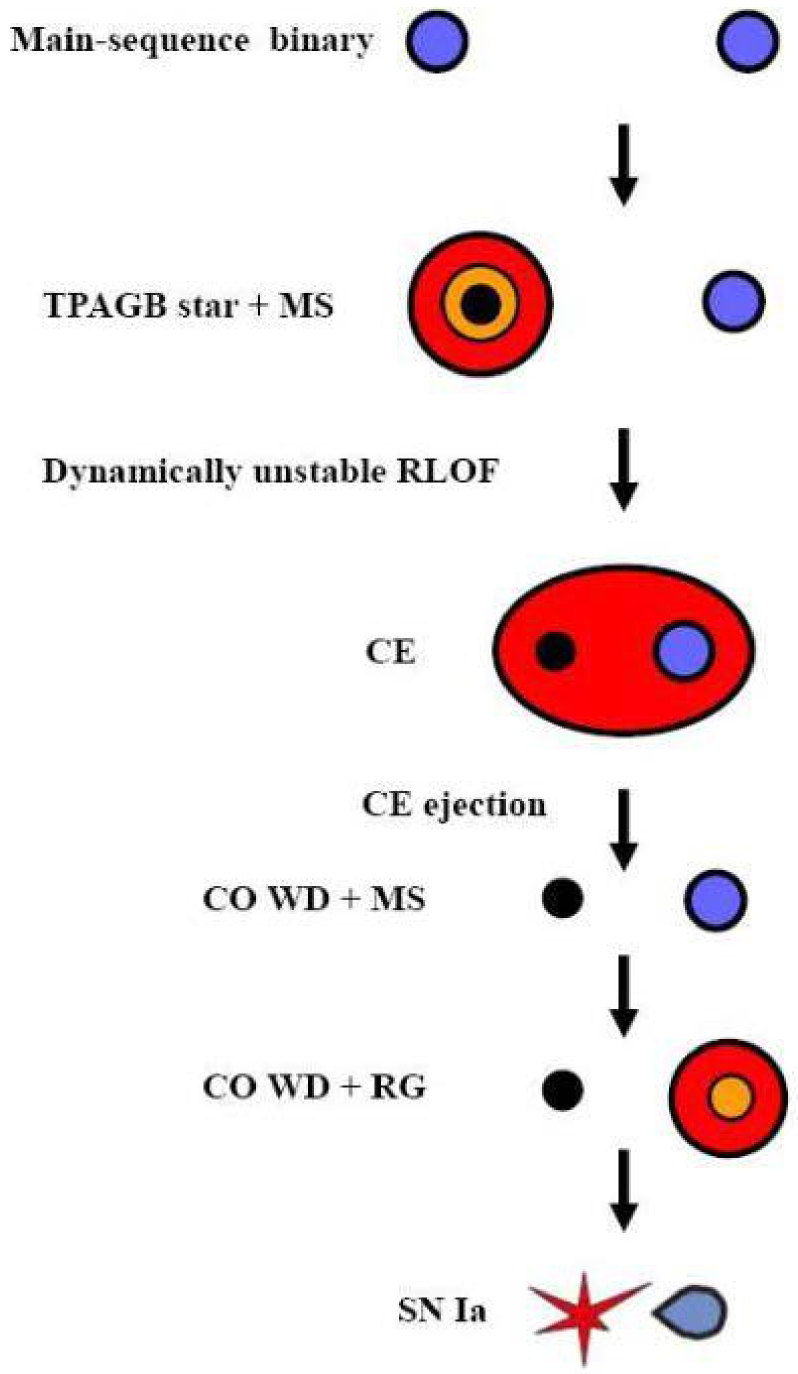
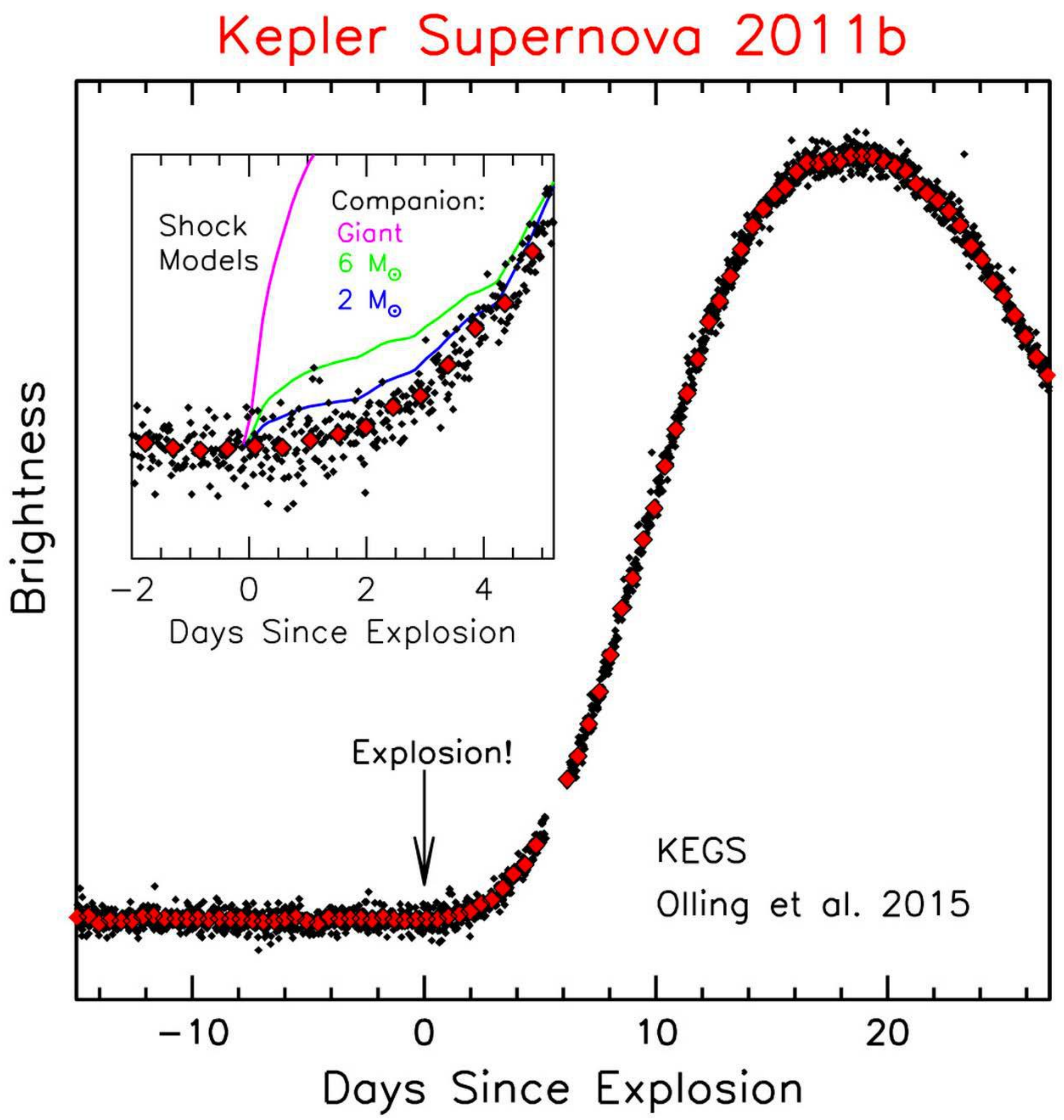


implied shocks not seen



Binary ignition is now disfavored, by a lack of companion star "shocks" in SNIa light curves, along with the non-observation of H or He lines in any type Ia spectra. White dwarf mergers may not match the high rate of type Ia supernovae.

Maoz et al. 1312.0628 (Review), Olling et al. Nature 2015

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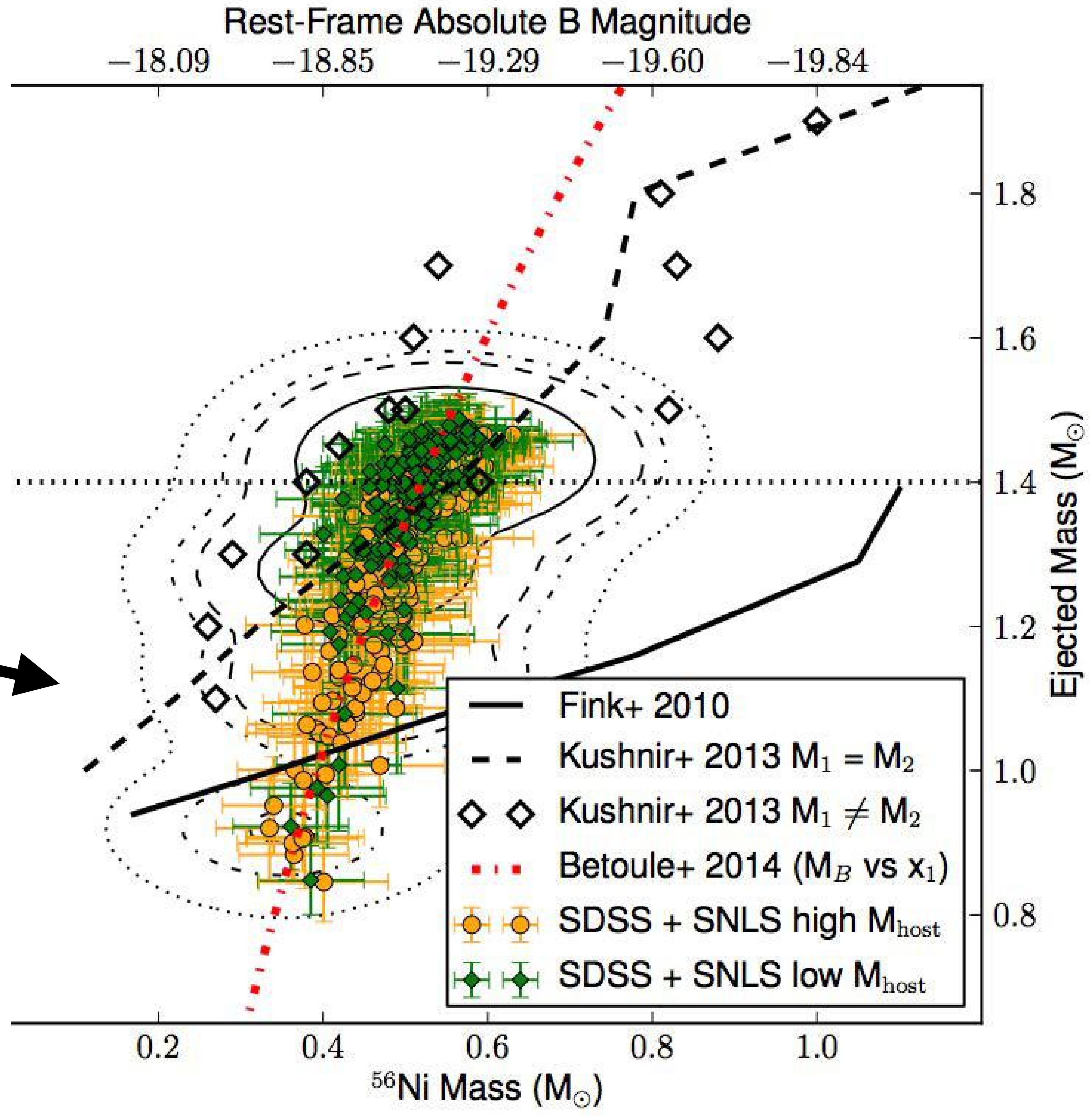
The existence of sub-Chandrasekhar supernovae presents a quandary that binary accretion has trouble accounting for.

Long tail of
sub-Chandrasekhar mass SNIa



1408.6601

$$\frac{M_{\rm ej}}{M_\odot} = (1.322 \pm 0.022) + (0.185 \pm 0.018)x_1, \quad x_1 = [-3, 2]$$

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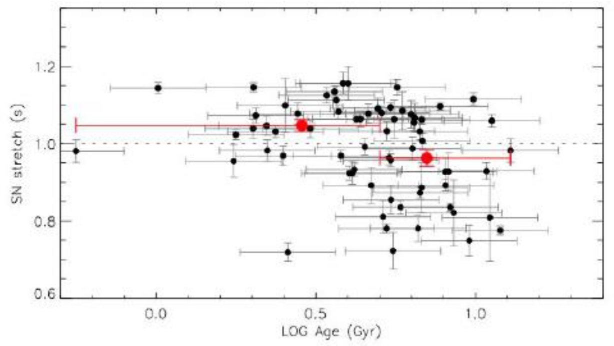
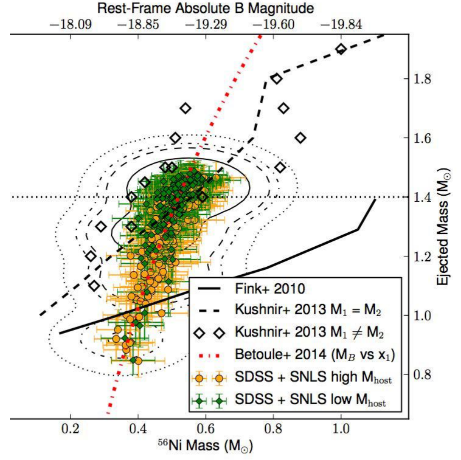


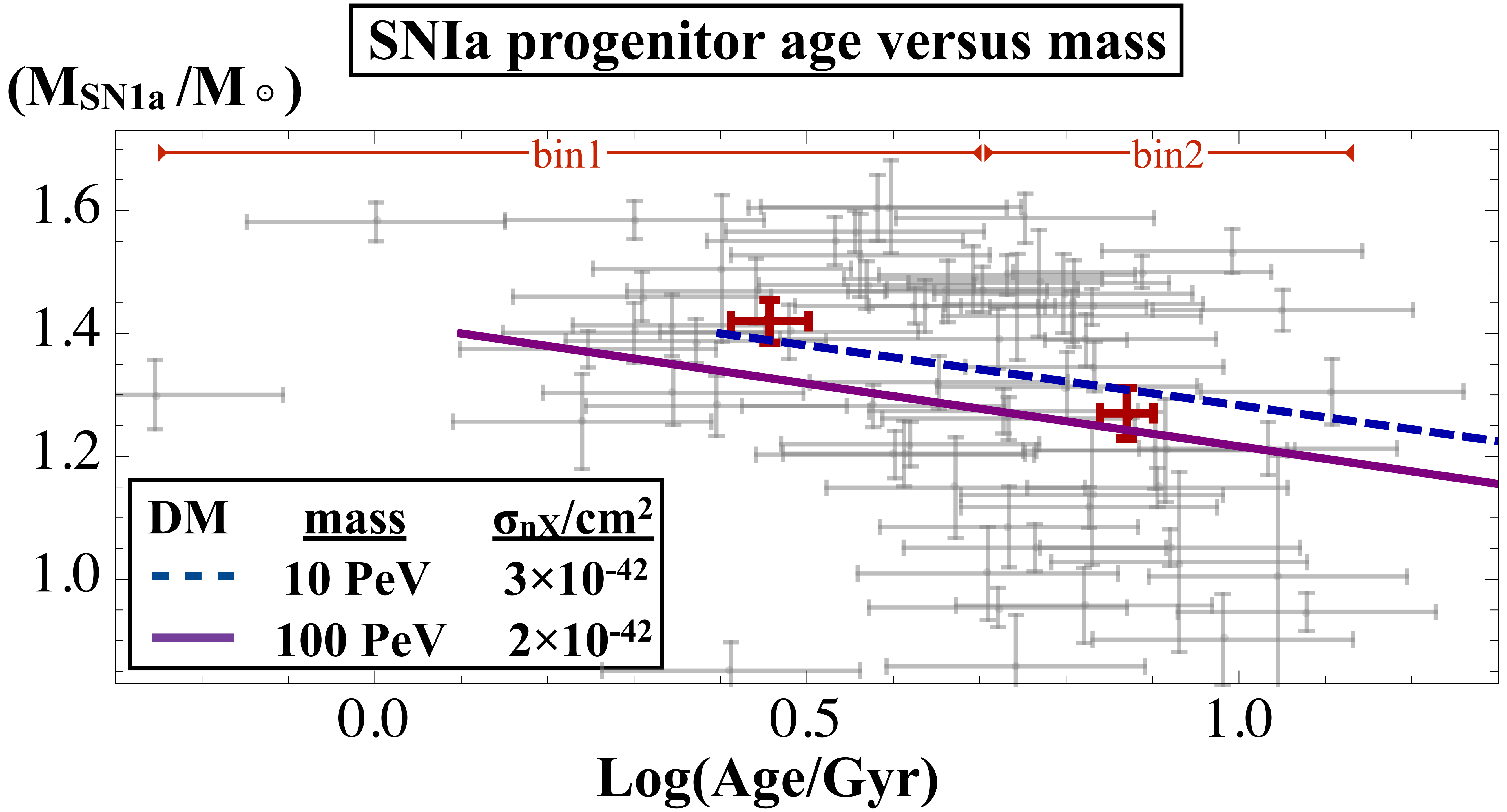
1311.6344



1408.6601

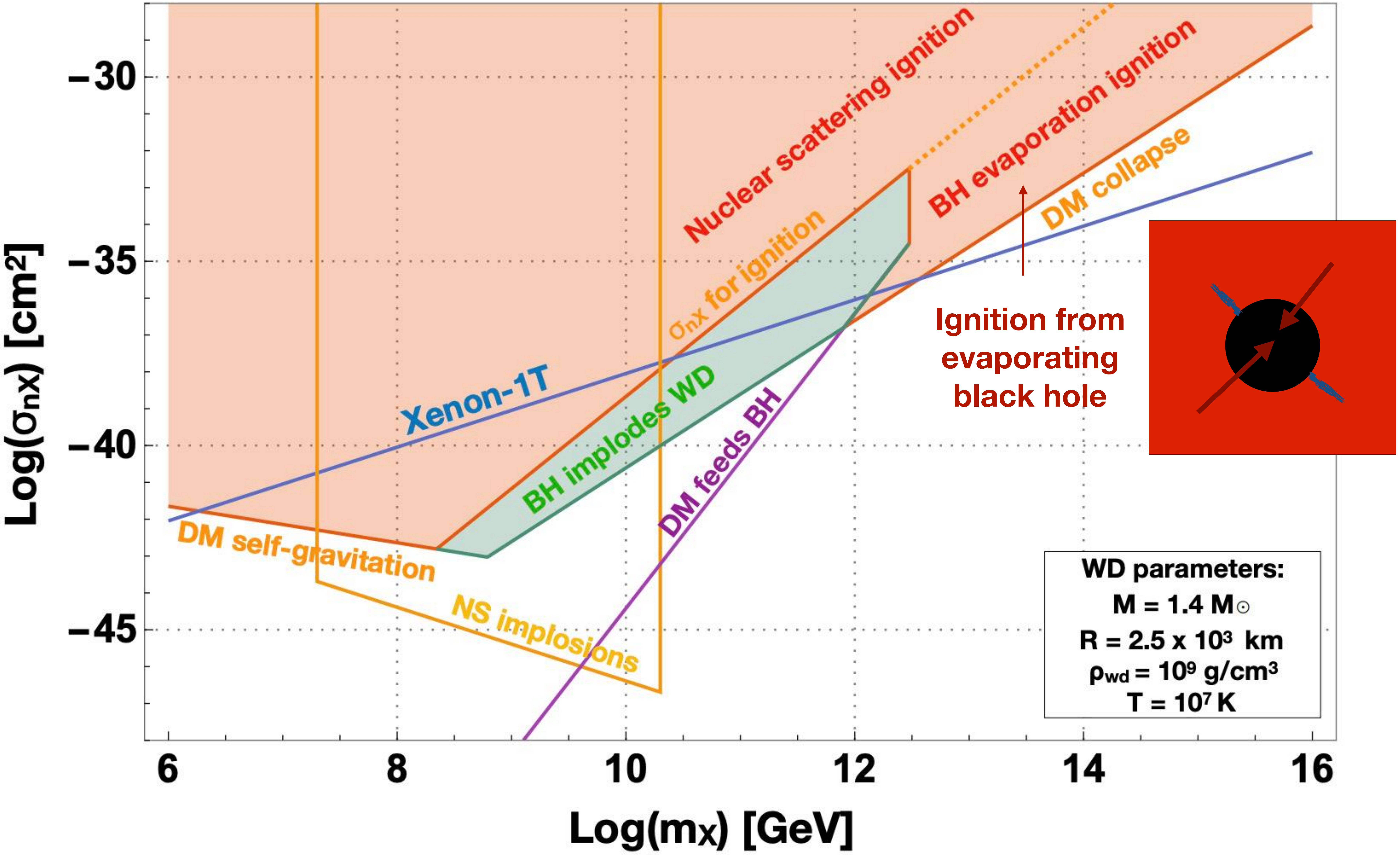
Data on the ages of stars adjacent to type Ia supernovae

Data on the mass of type Ias inferred from luminosity



Interesting trend — more massive WDs explode sooner.

Bounds on dark matter from an old GAIA White Dwarf



Javier Acevedo

Acevedo JB 1904.11993

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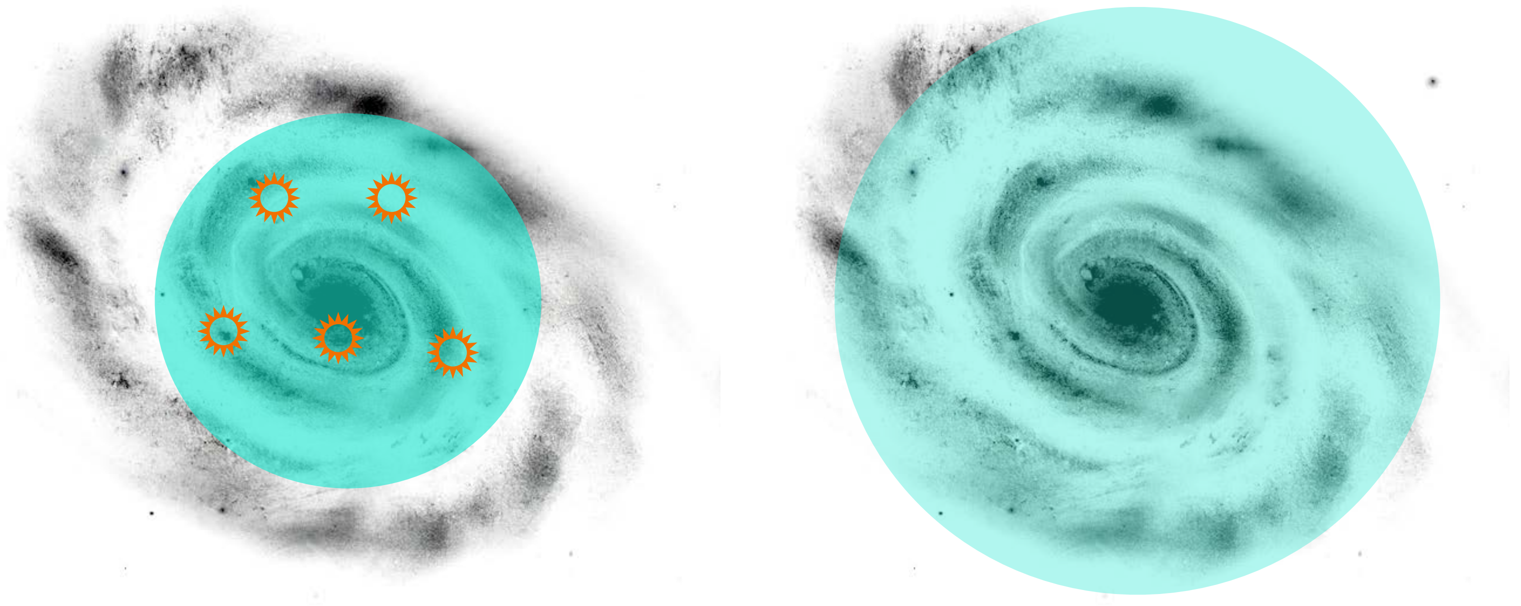
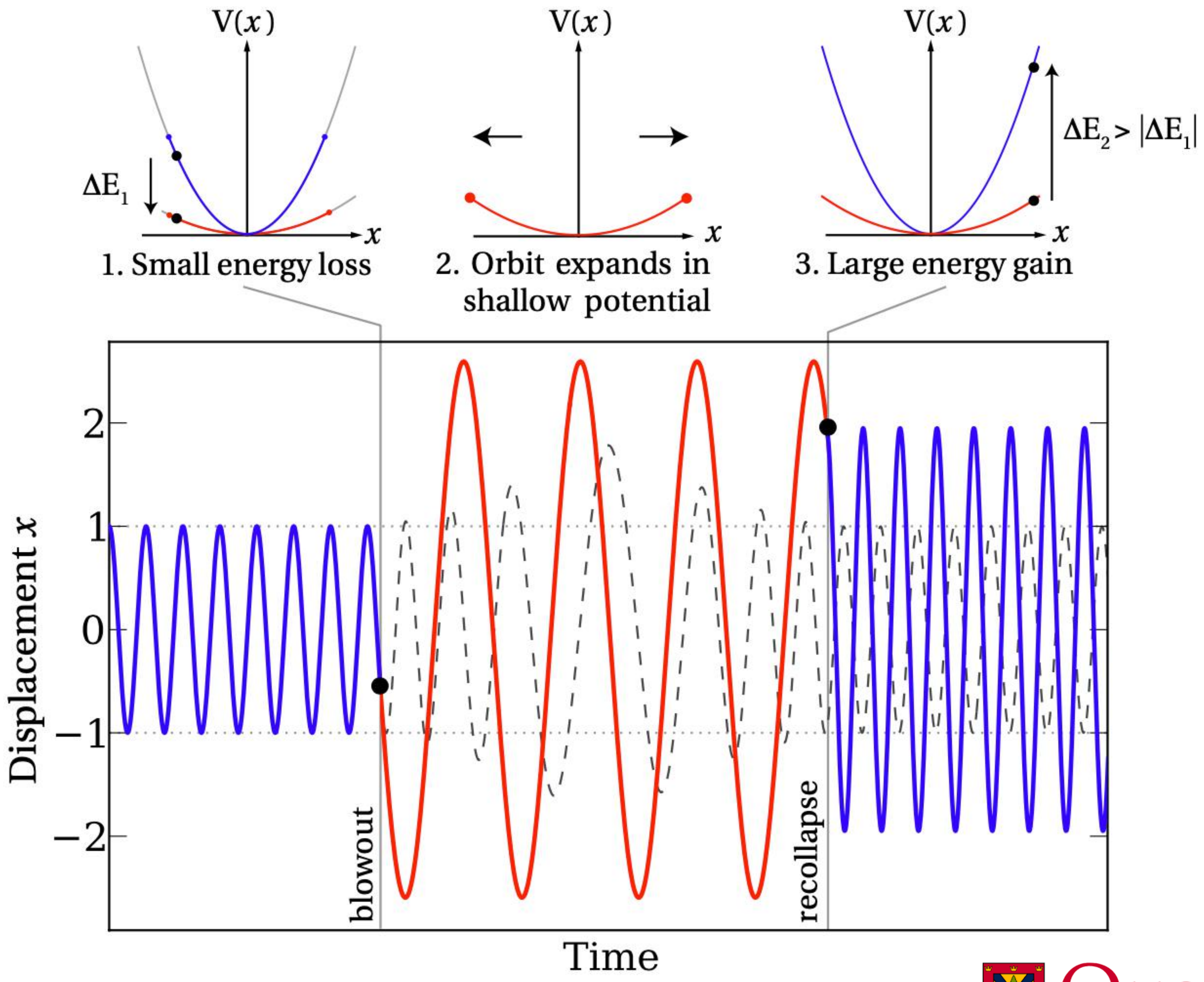
BARYONIC FEEDBACK CREATING HALO PROFILE CORES IN GALAXIES

Pontzen and Governato 1106.0499





- Supernovae in galaxies blowout gas, non-adiabatic shift in gas potential

- Particles at the end of orbital phase end up on wider orbits, leading to a cored dark matter halo profile

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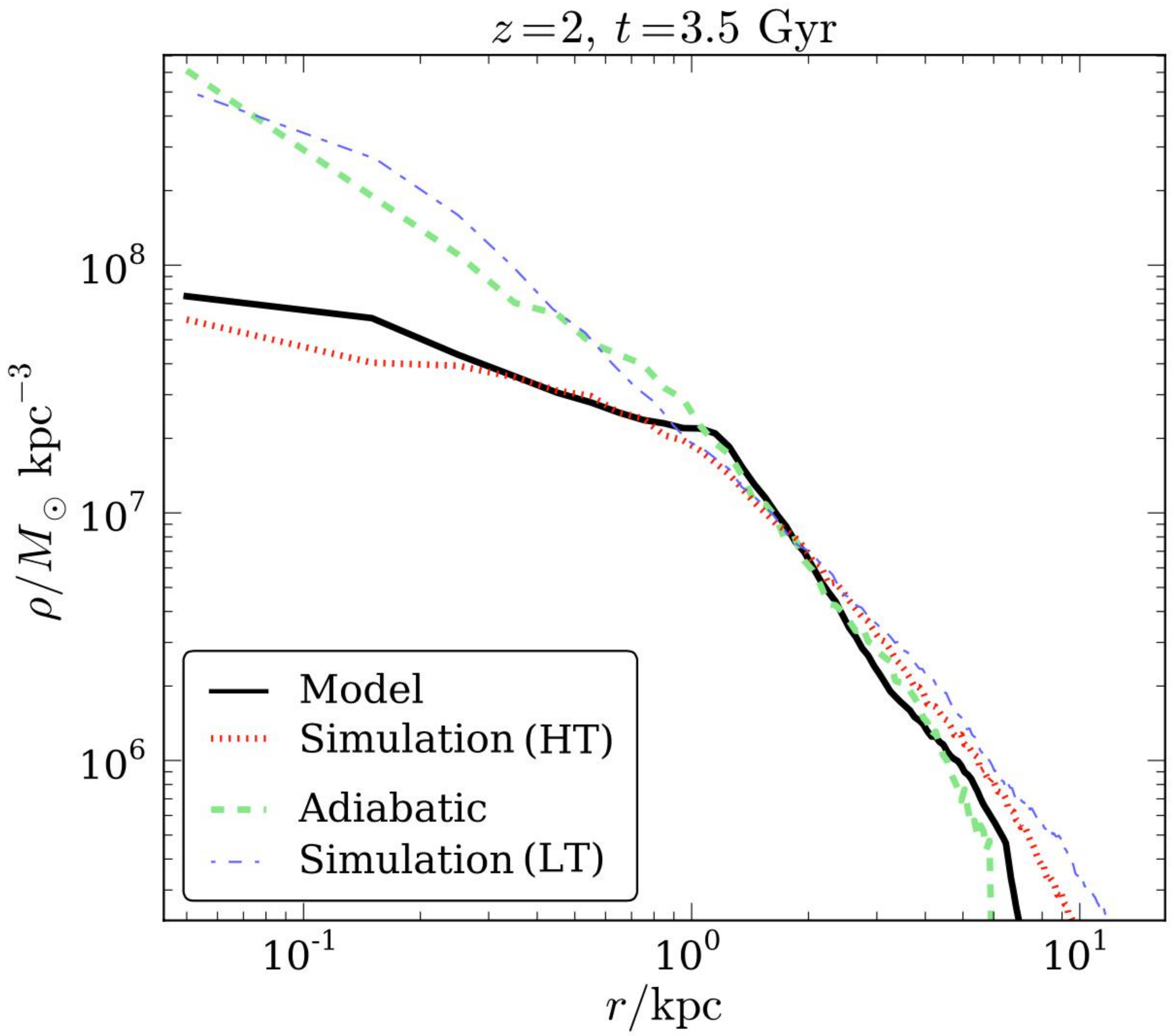
BARYONIC FEEDBACK CREATING HALO PROFILE CORES IN GALAXIES



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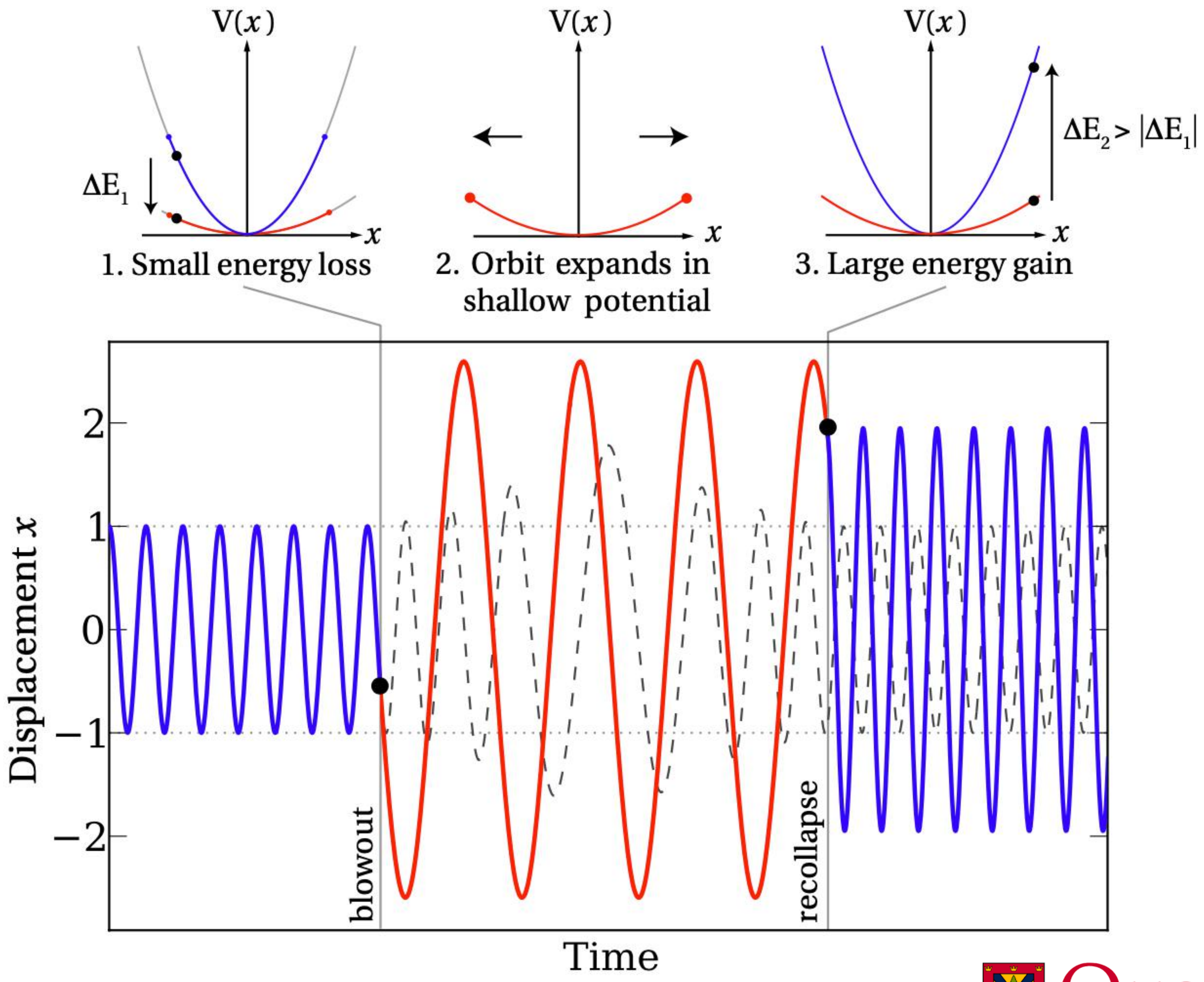

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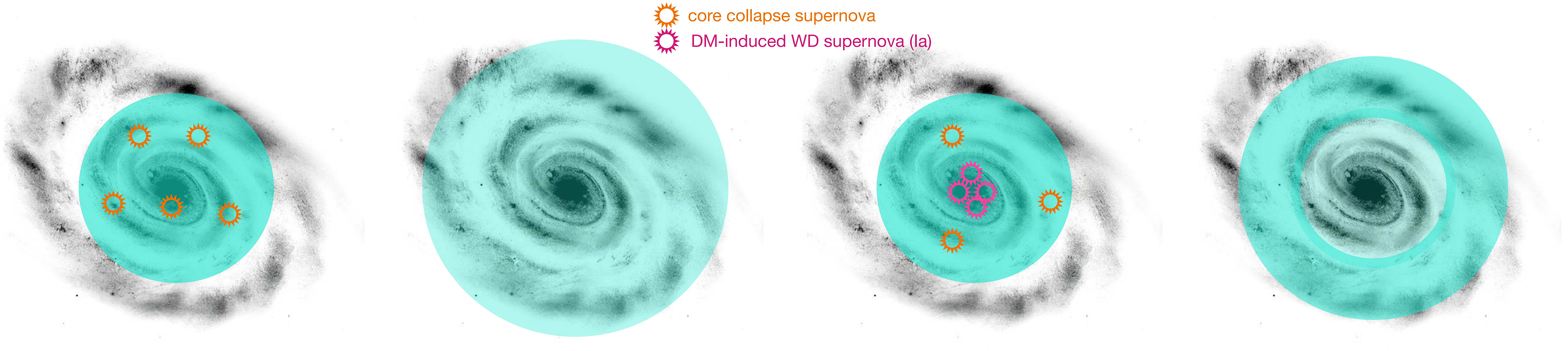
DARK MATTER INDUCED BARYONIC FEEDBACK

An, Acevedo, Boukhtouchen, JB, Richardson, Sansom




Yilda Boukhtouchen

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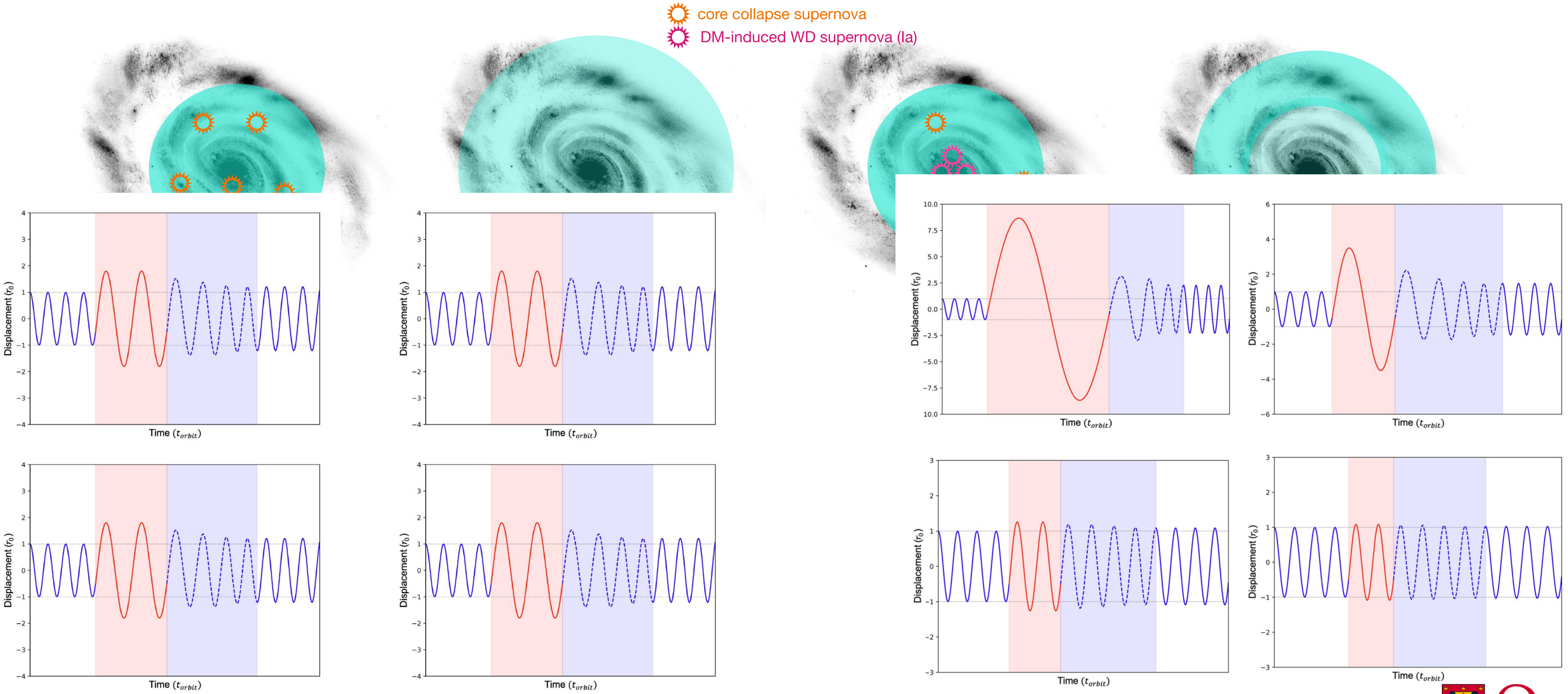
An, Acevedo, Boukhtouchen, JB, Richardson, Sansom



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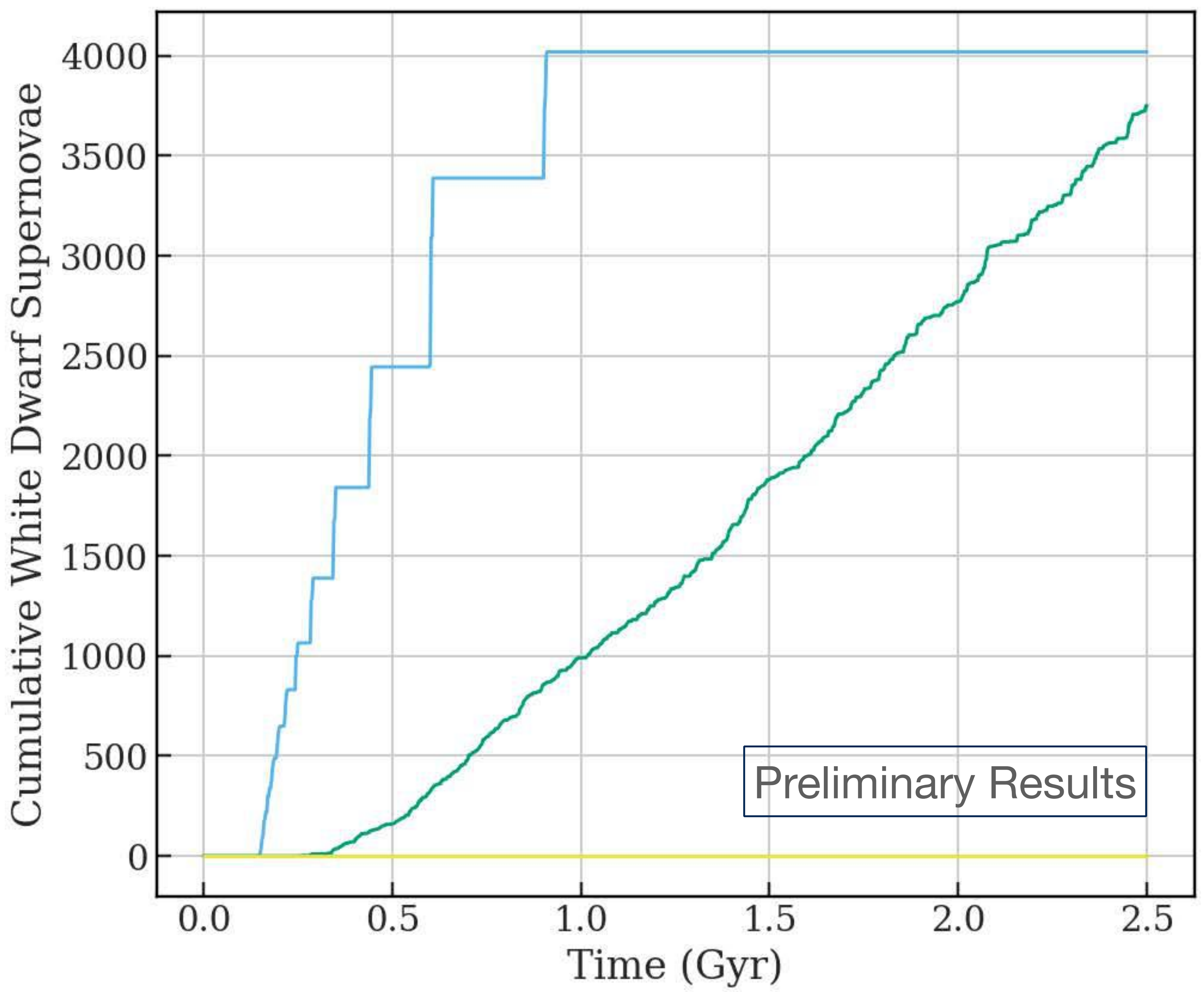
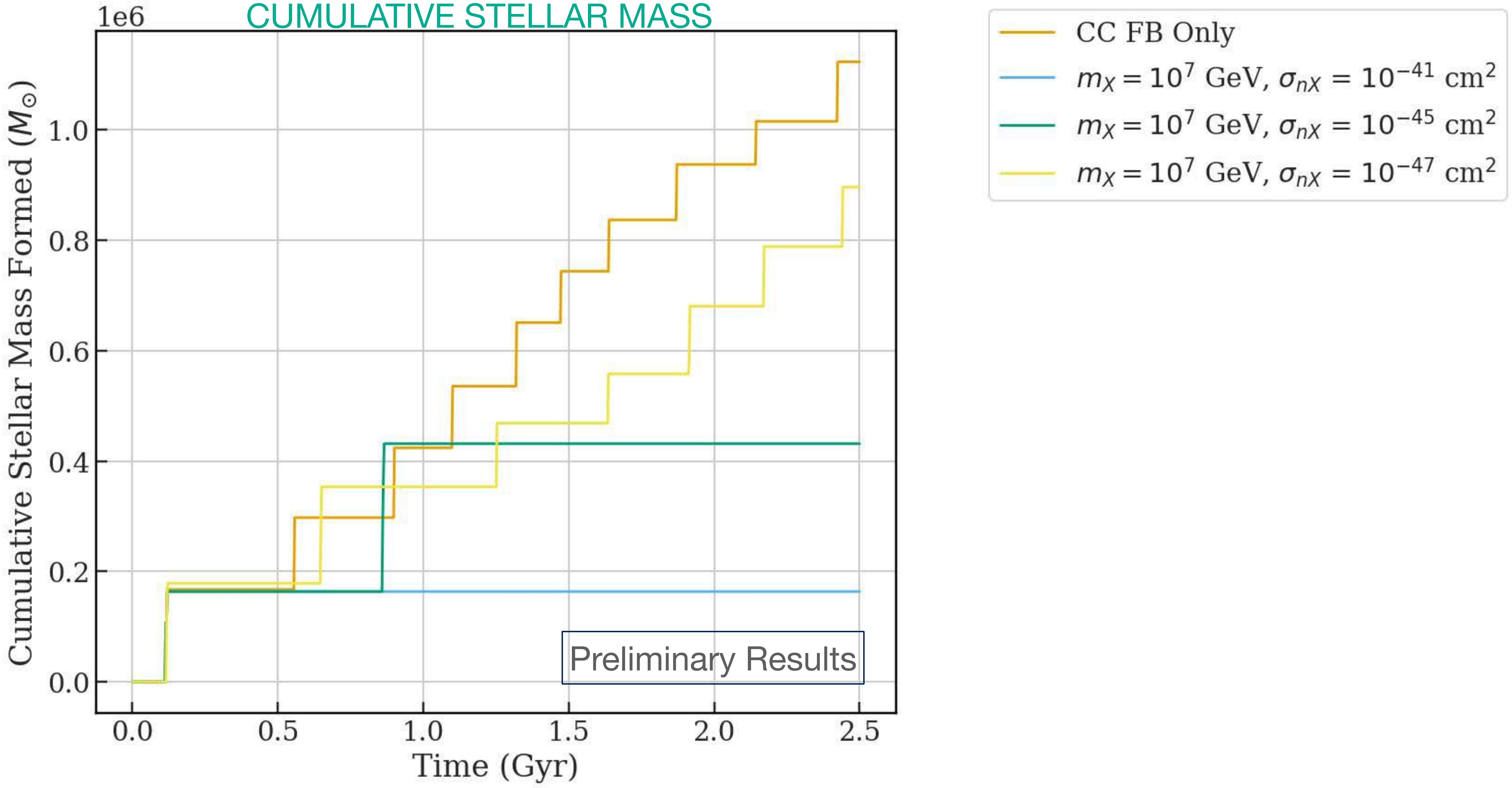
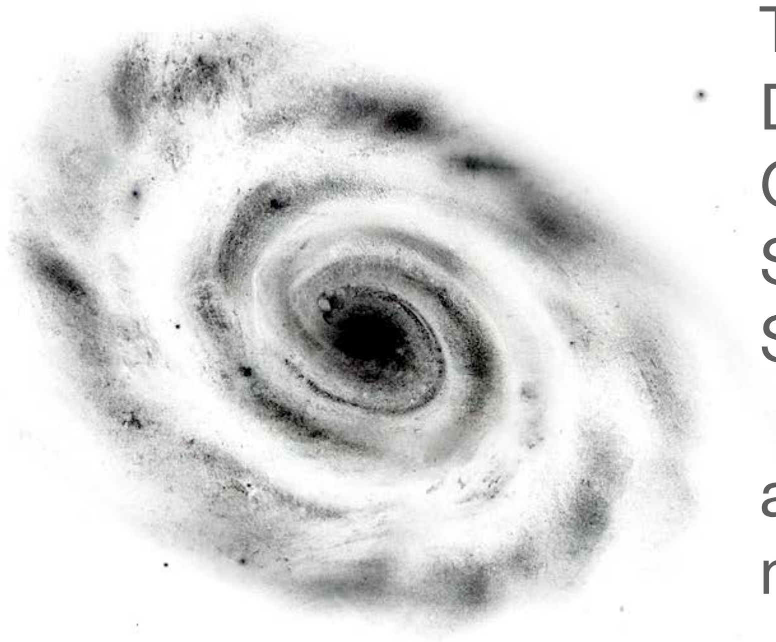
DARK MATTER INDUCED BARYONIC FEEDBACK – SMALL GALAXY RESULTS

WHITE DWARF EXPLOSIONS (Type Ia)



CUMULATIVE STELLAR MASS





Total Galaxy Mass: 1.86 *10^9 Msun
DM mass fraction: 0.9615
Gas mass fraction: 0.0175
Stellar disk mass fraction: 0.0175
Stellar bulge mass fraction: 0.0035

all particles have mass of 3721 M_sun
modified GIZMO codebase

An, Acevedo, Boukhtouchen, JB, Richardson, Sansom

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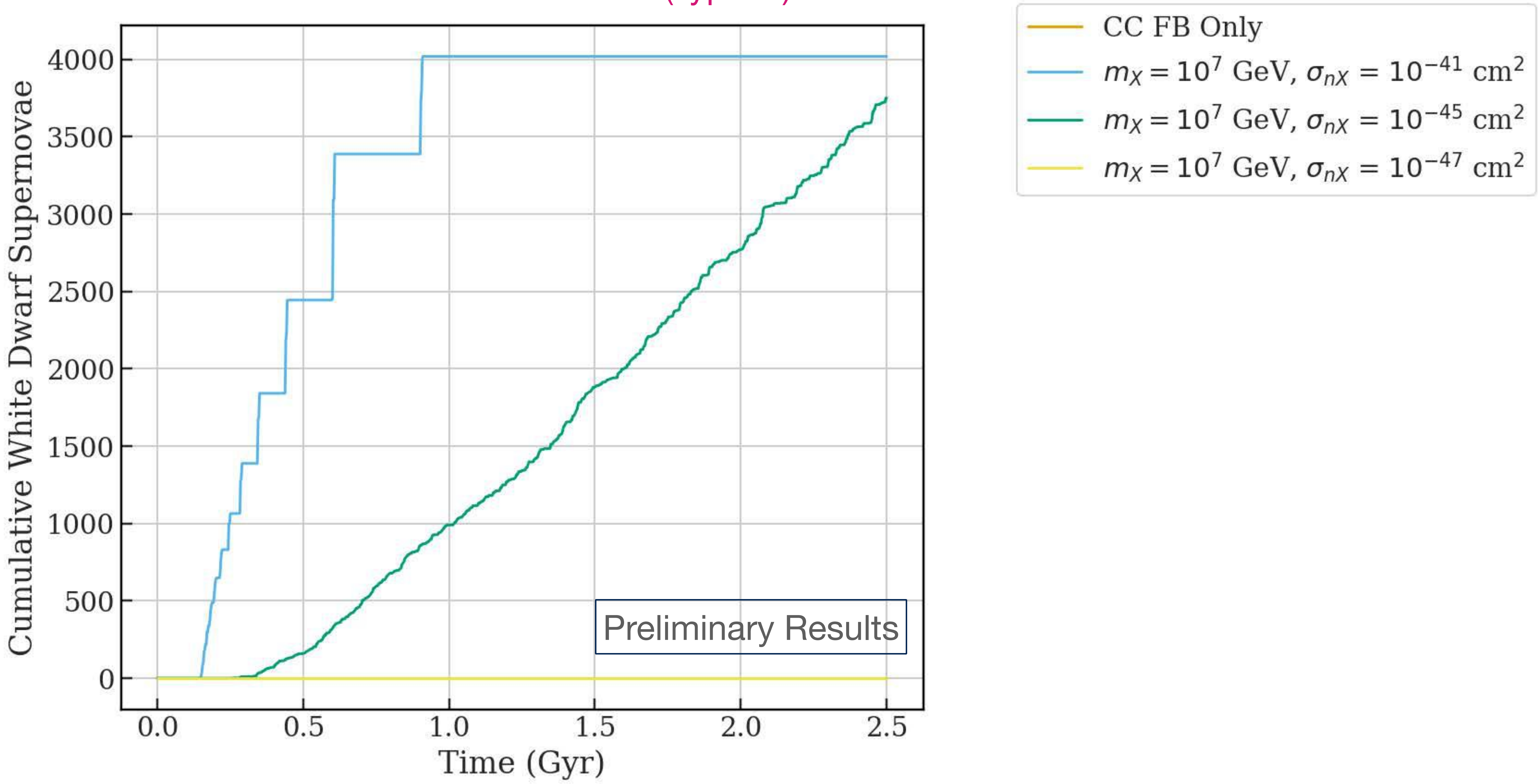

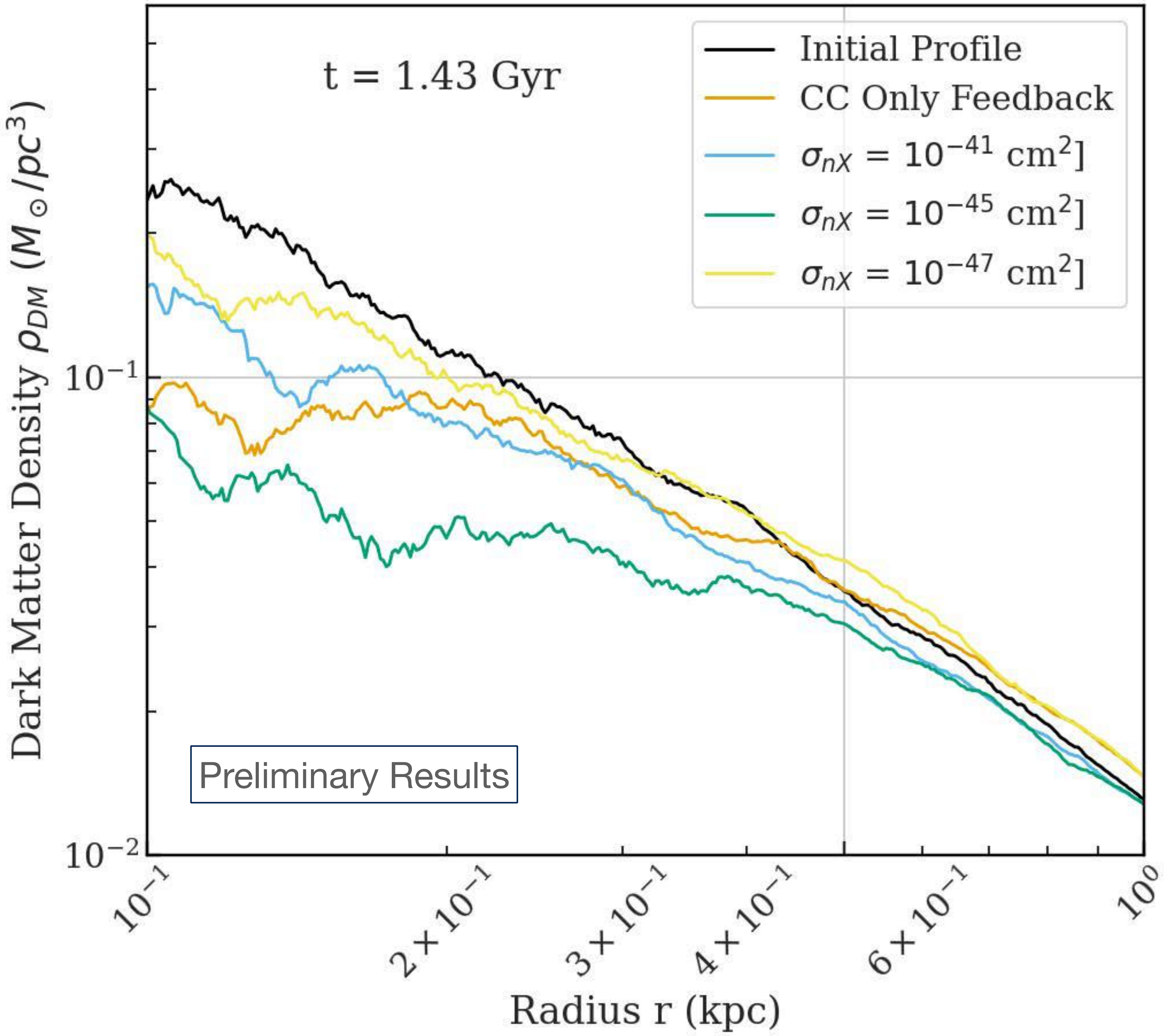

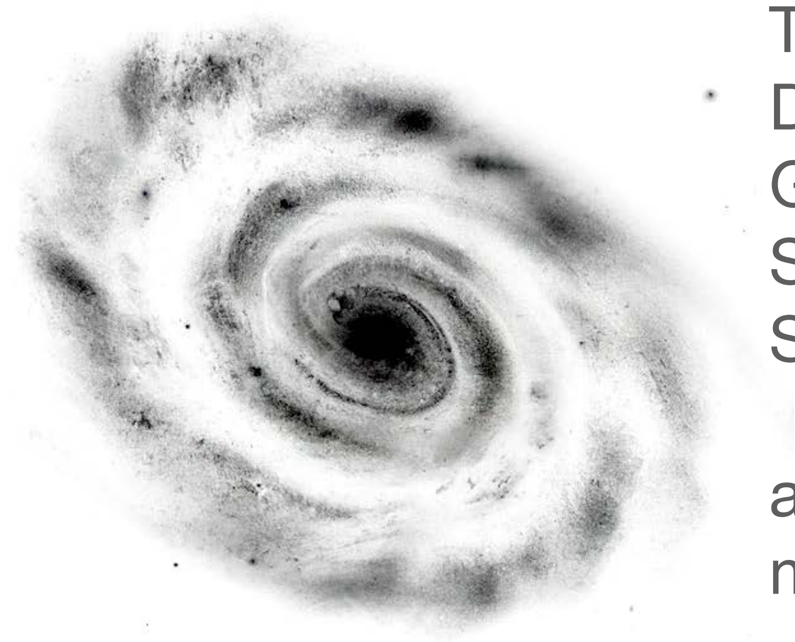

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An, Acevedo, Boukhtouchen, JB, Richardson, Sansom

Dark matter in compact stars and galactic structure

- Dark matter heating neutron stars through either infall or annihilation

- Asymmetric dark matter causing neutron stars to implode
  - Connections to missing pulsars (FRBs)

- White dwarf explosions from asymmetric dark matter / composites
  - Connections to type Ia supernovae, galactic structure

Thanks!

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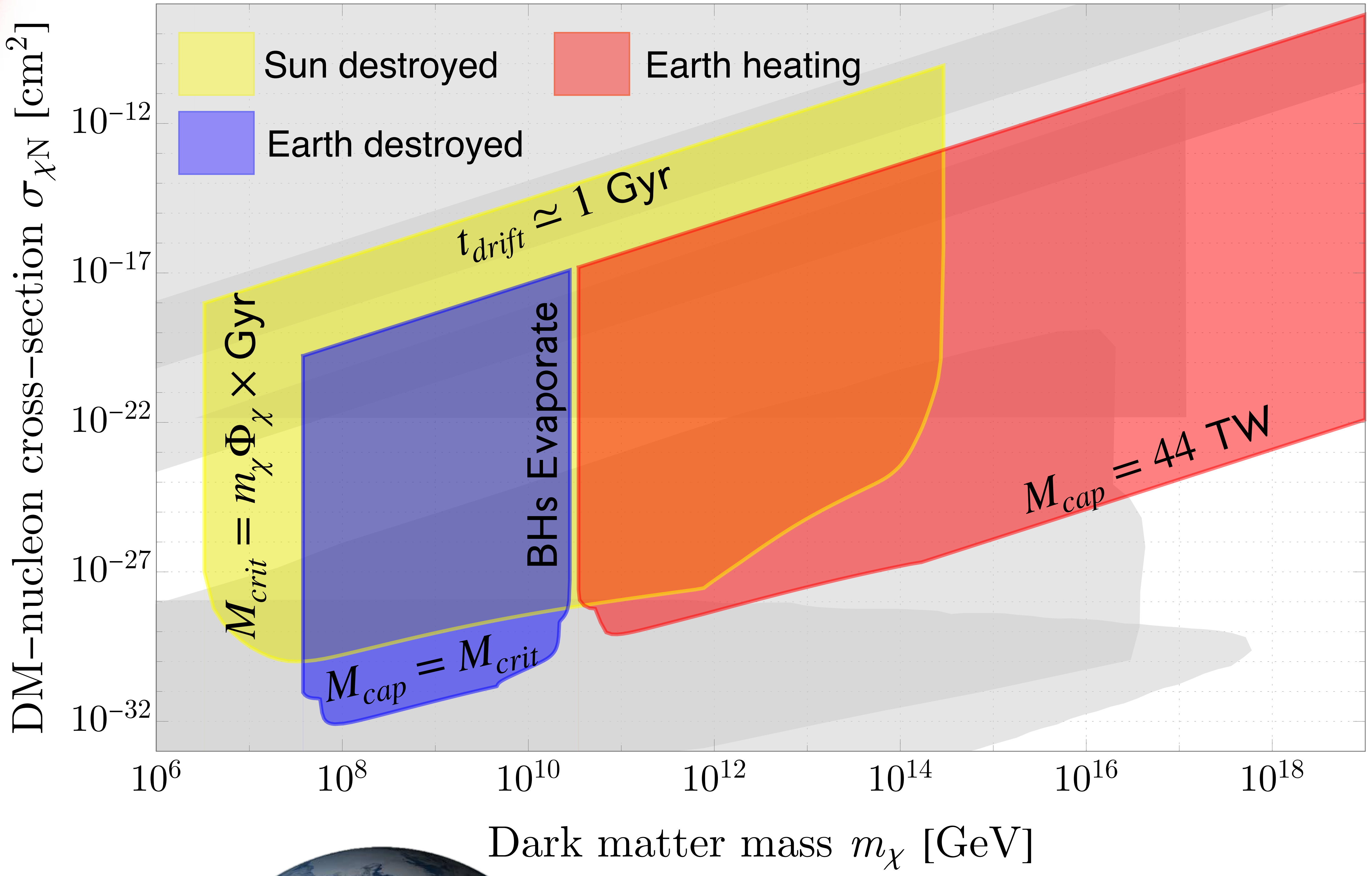
Also BHs from DM in the sun, earth

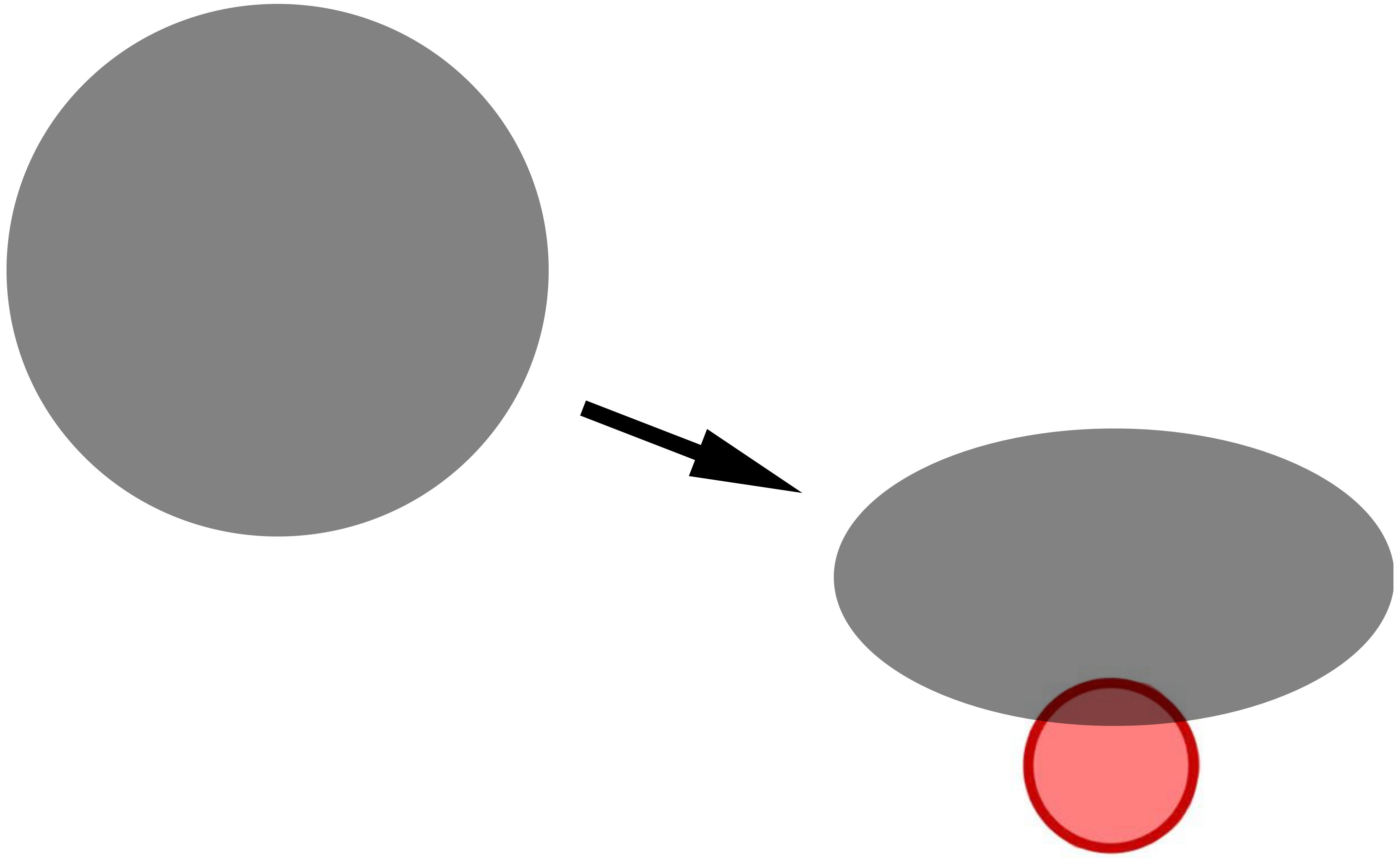


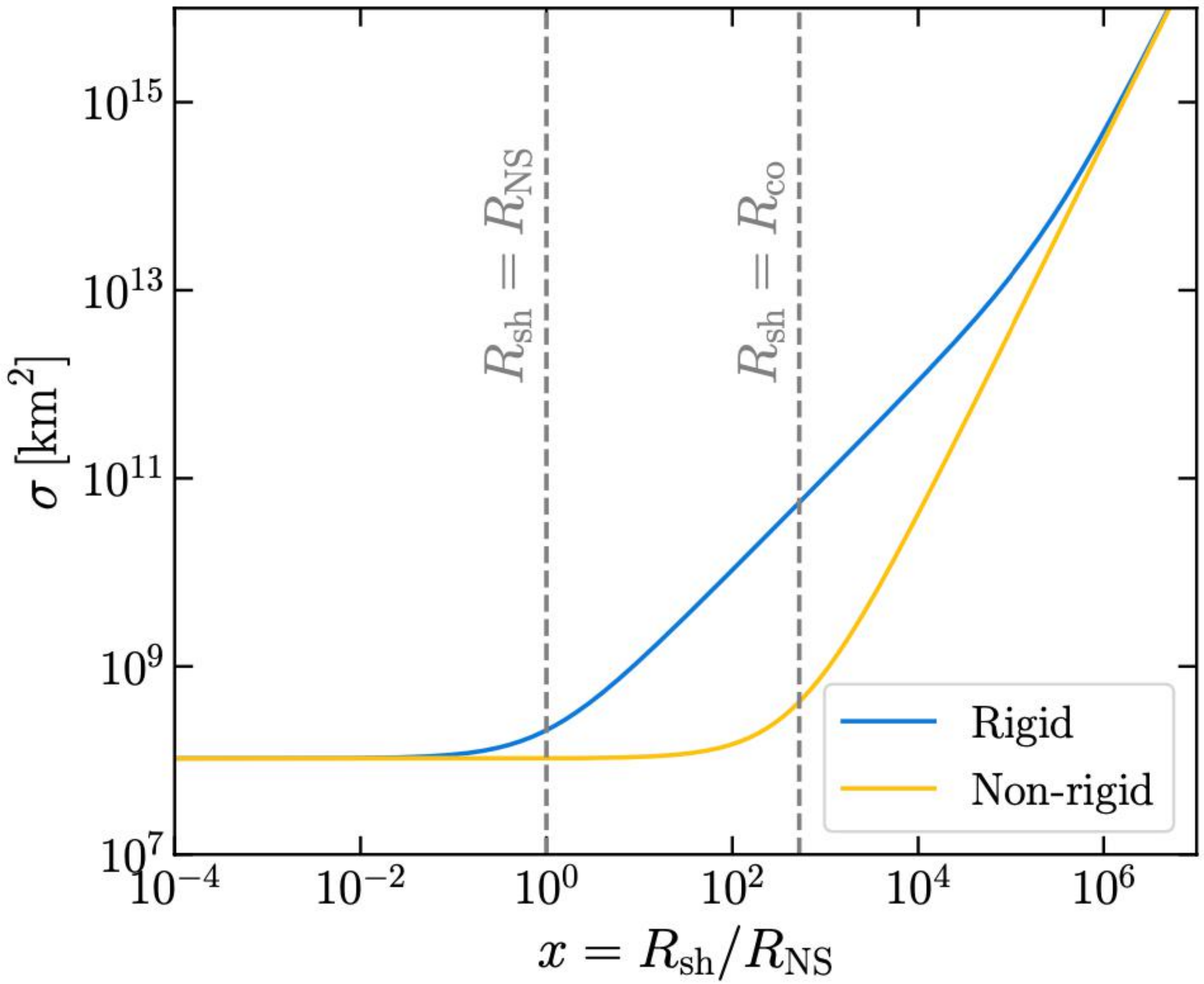
Acevedo, JB, Goodman, Kopp, Opferkuch 2012.09176

Accretion: rigidity

JB, Kavanagh, Raj 2109.04582

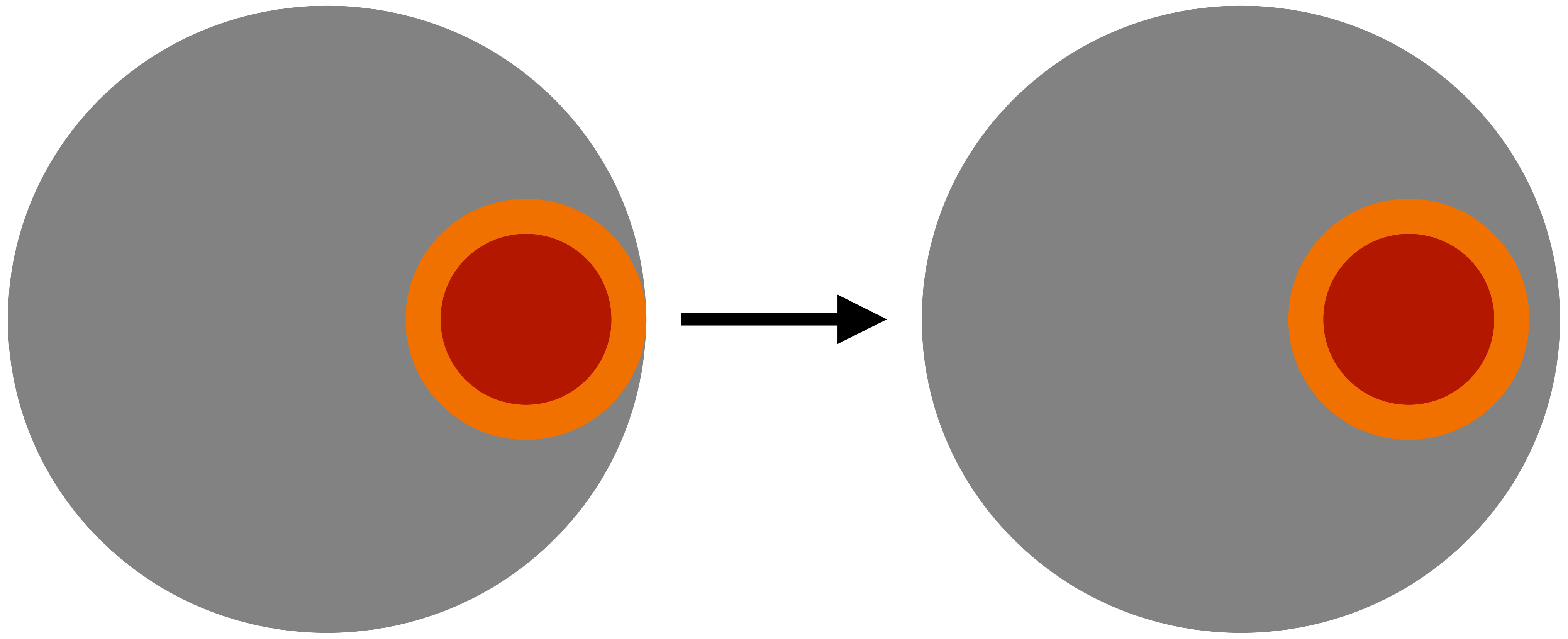
- In what follows we assume deformable subhalos

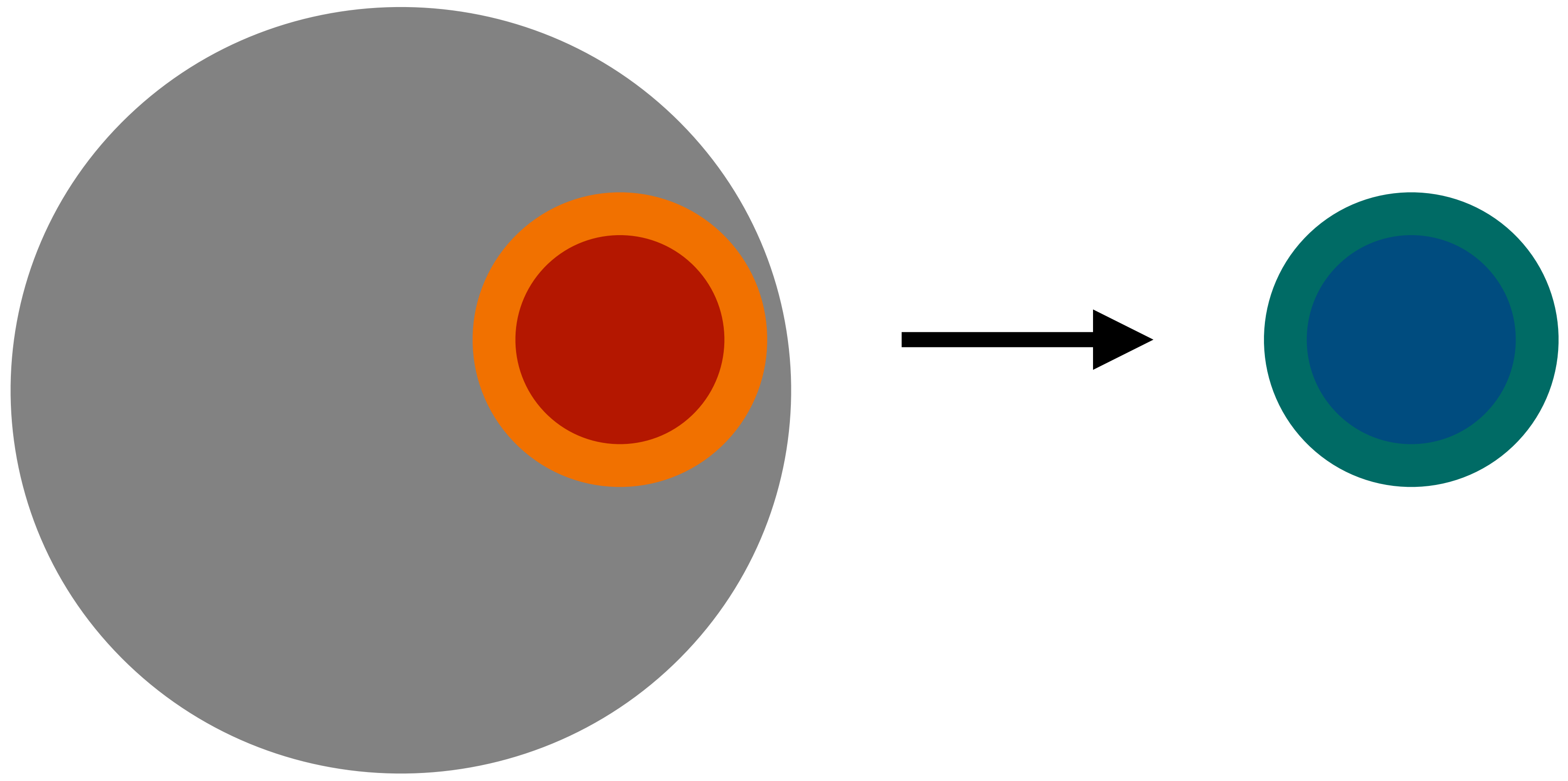




Neutron stars either sporadically flash heated or multi-subhalo steady-state heated

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



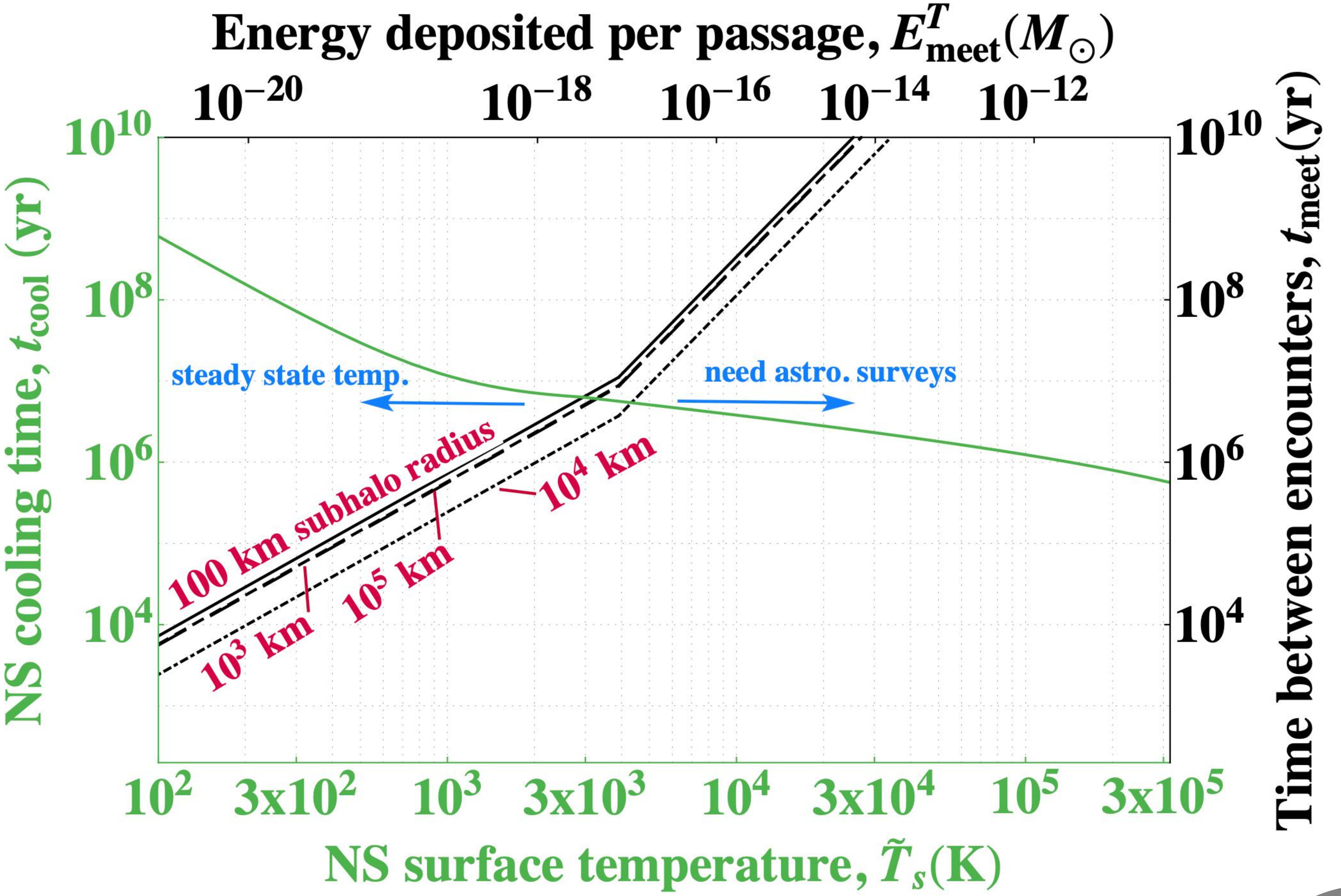


$$\left(\frac{\widetilde{T}_{\text{hot}}}{10^4\ \text{K}}\right)^2 = \left(\frac{\widetilde{T}_{\text{cold}}}{10^4\ \text{K}}\right)^2 + \frac{E_{\text{meet}}}{6.2 \times 10^{-18}\ M_\odot}$$

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

Neutron stars cooling and heating

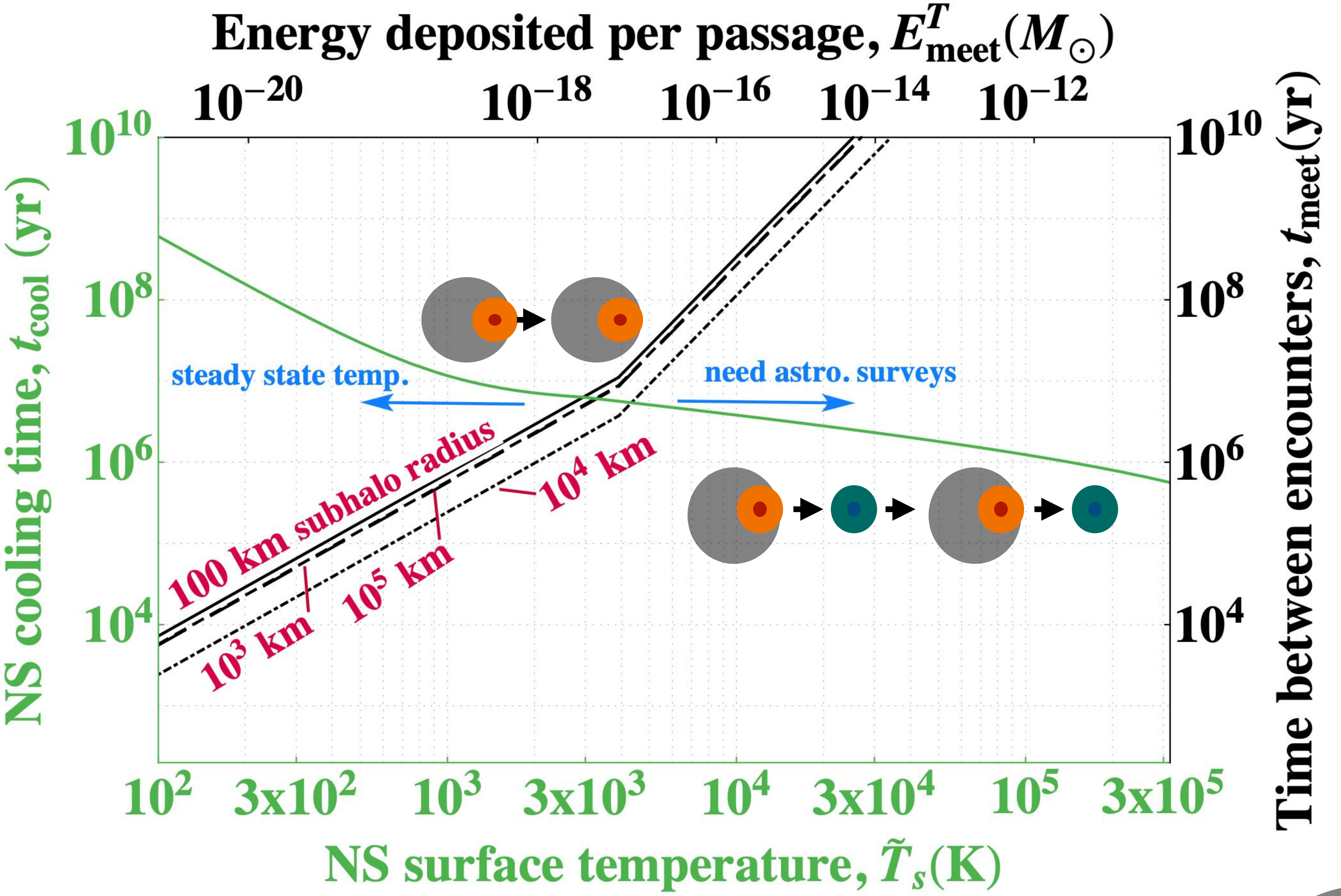
cooling



heating

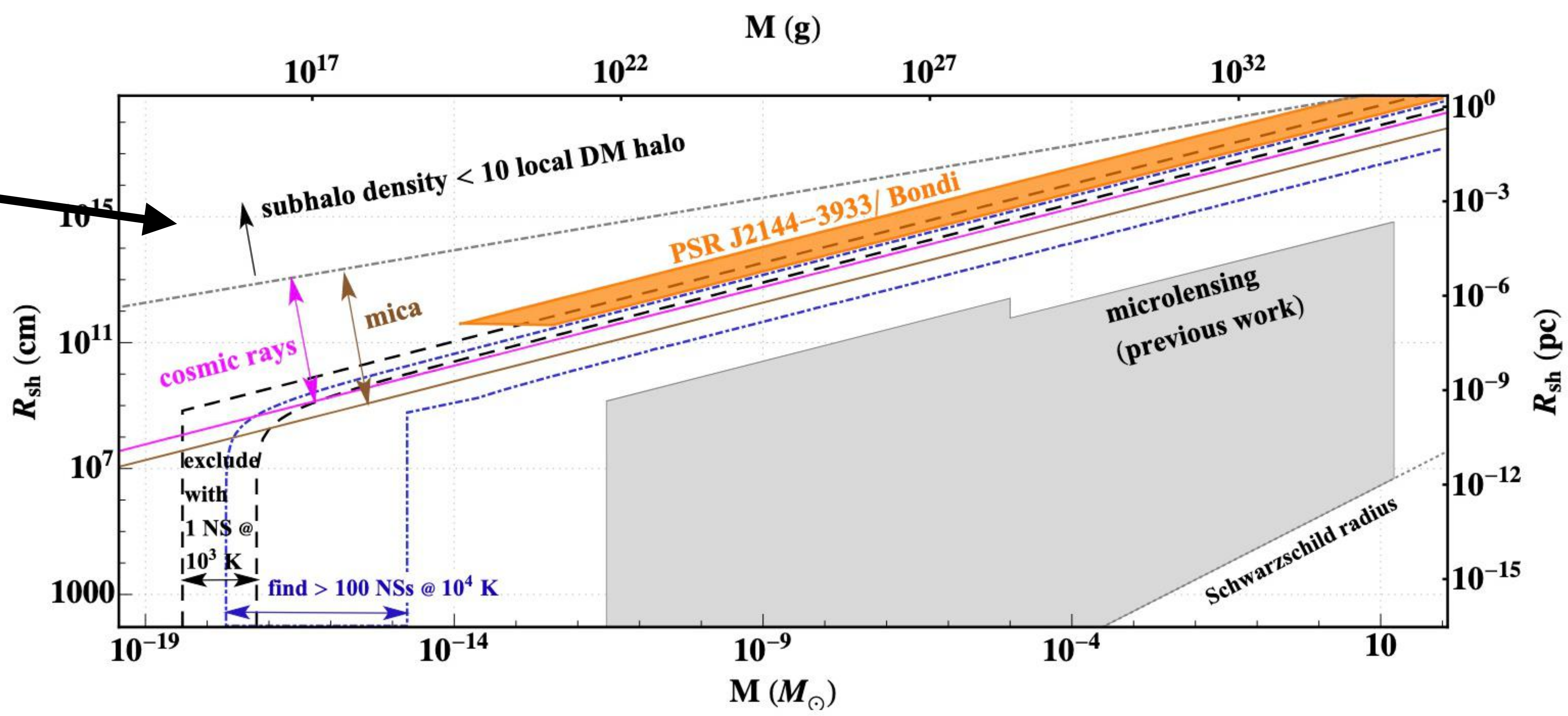
Neutron stars cooling and heating

cooling

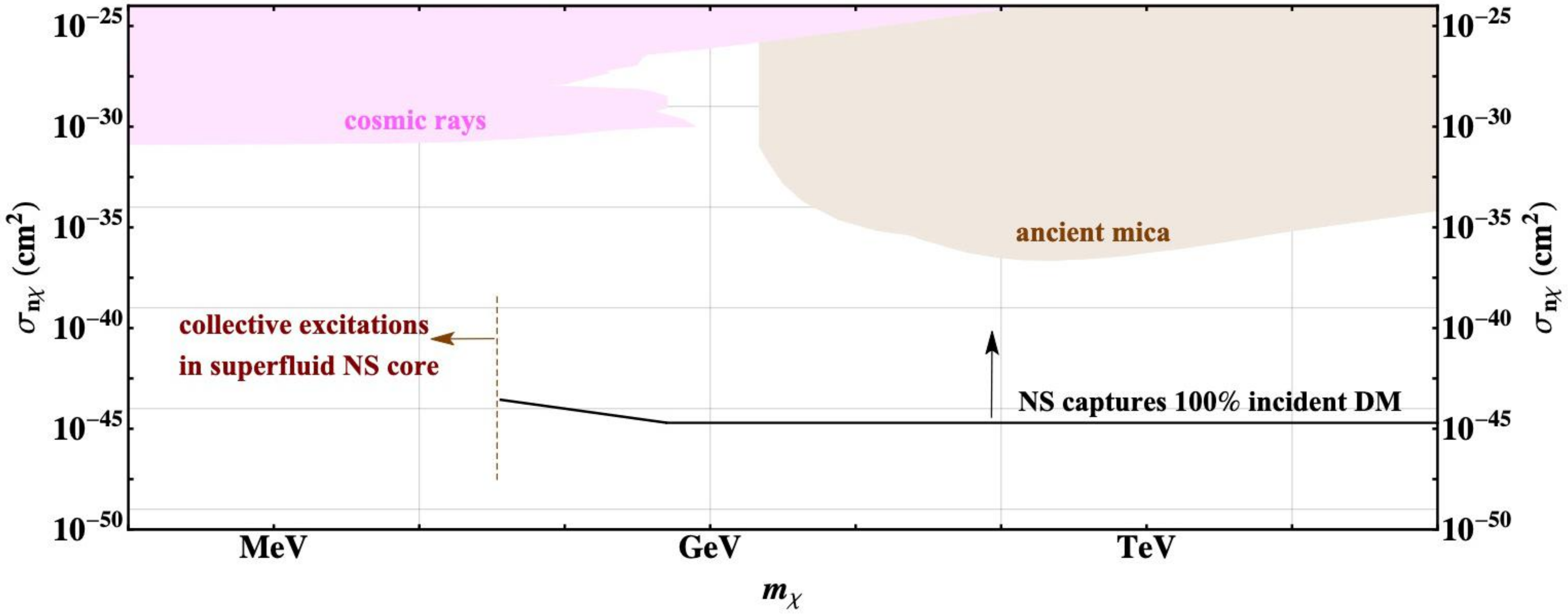


heating

subhalo density < halo density



These bounds assume all DM is in subhalos



JB, Kavanagh, Raj 2109.04582

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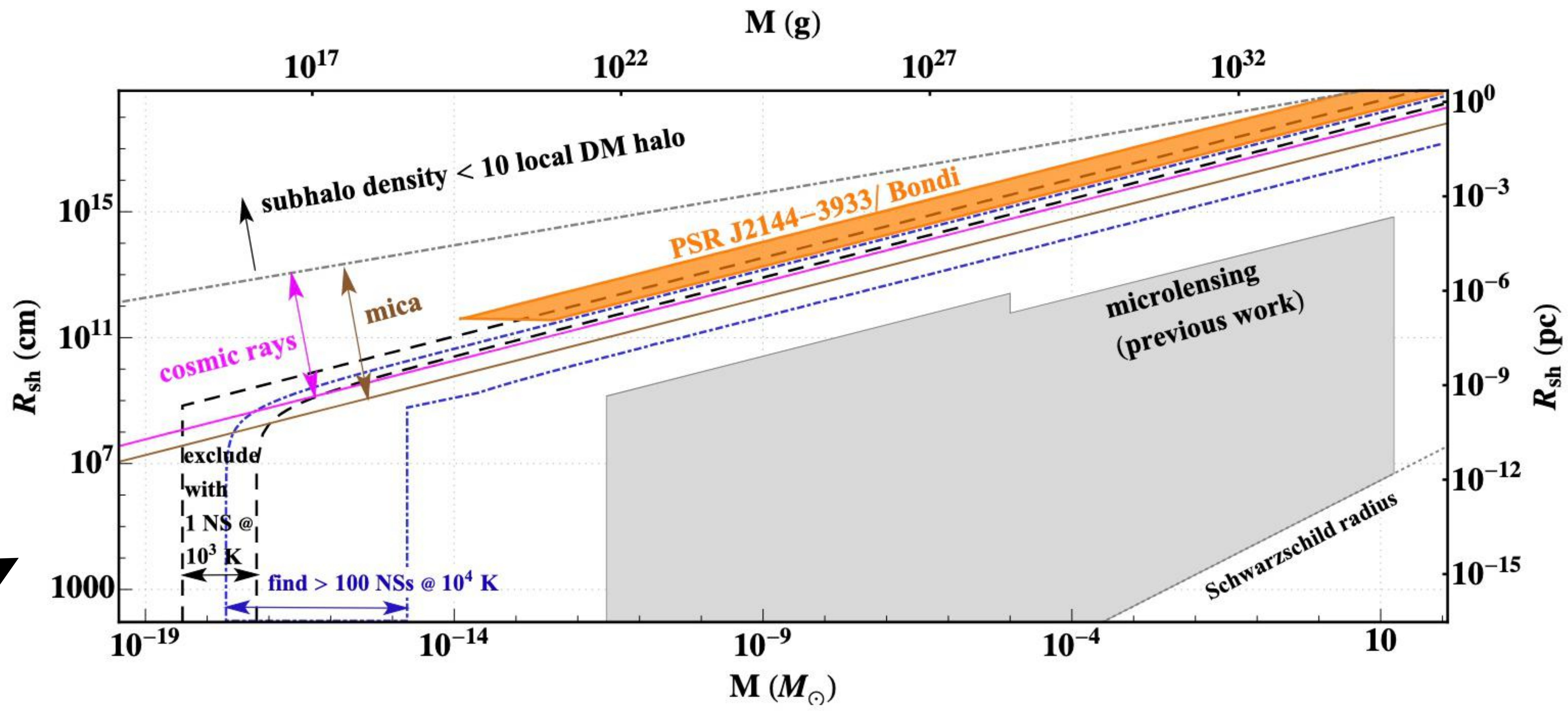
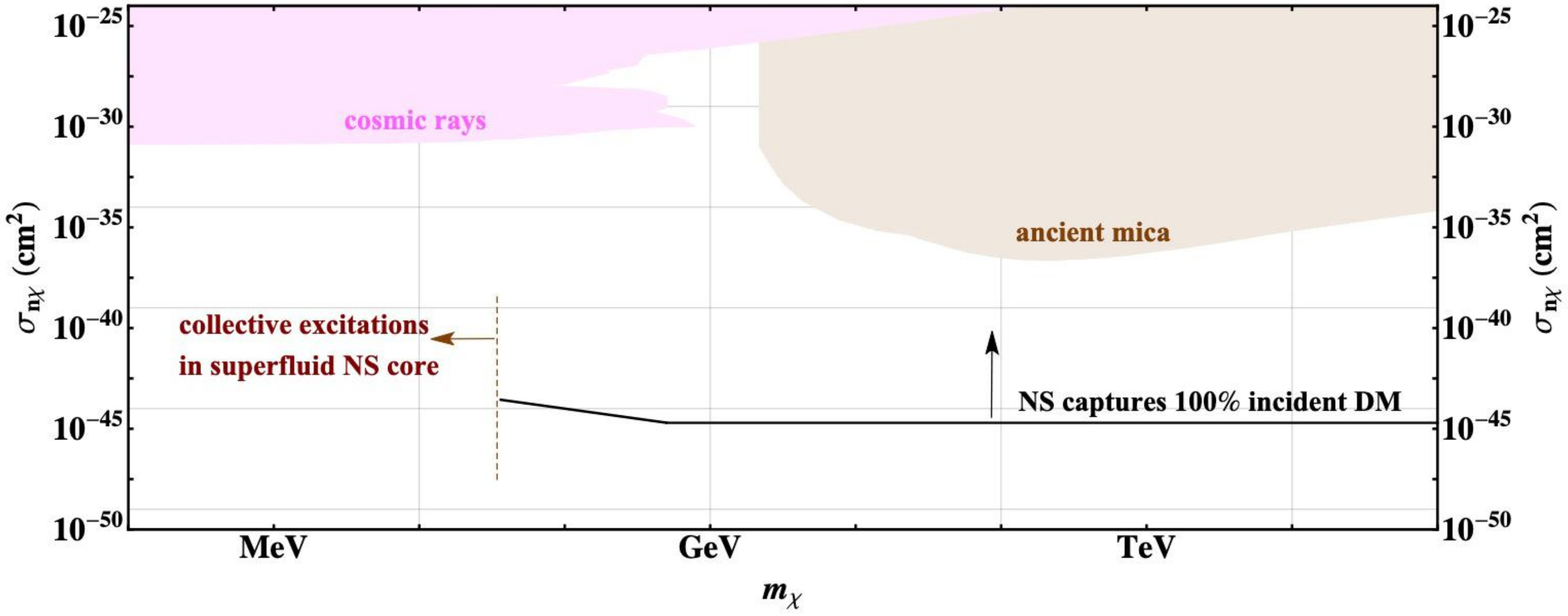
Subhalo mass/radius sensitivity regions in this plot



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



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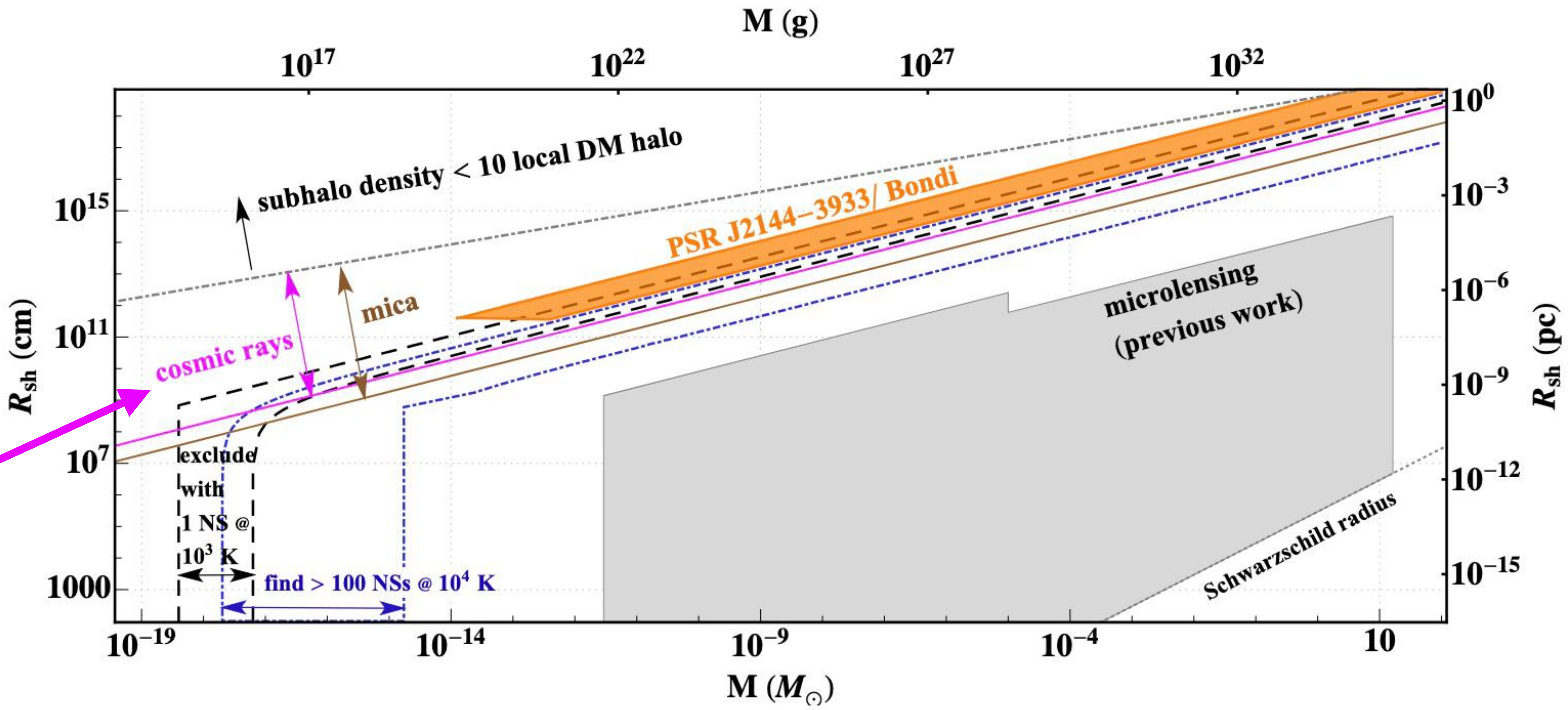
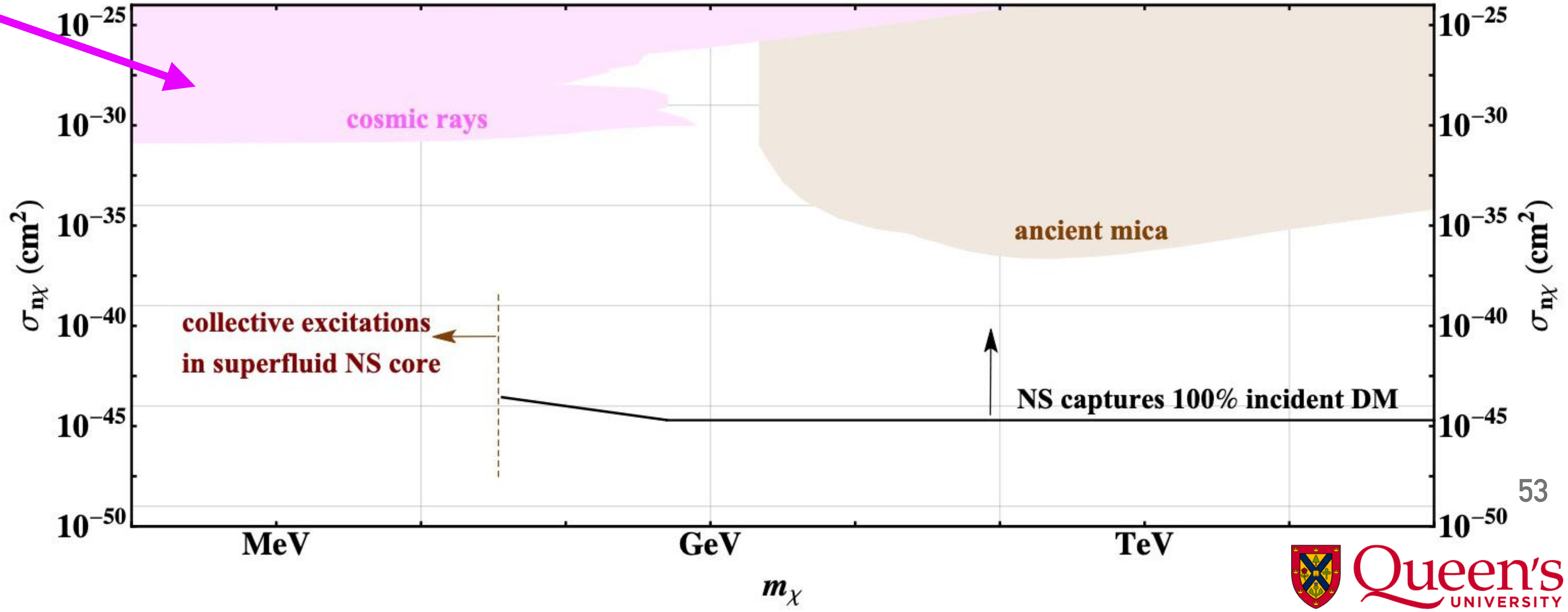
Cosmic rays will boost dark matter in subhalos so long as the interaction rate matches CR-diffuse DM interactions over ~8 kpc interaction lengths

$\tau_{CR} > 1$



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

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



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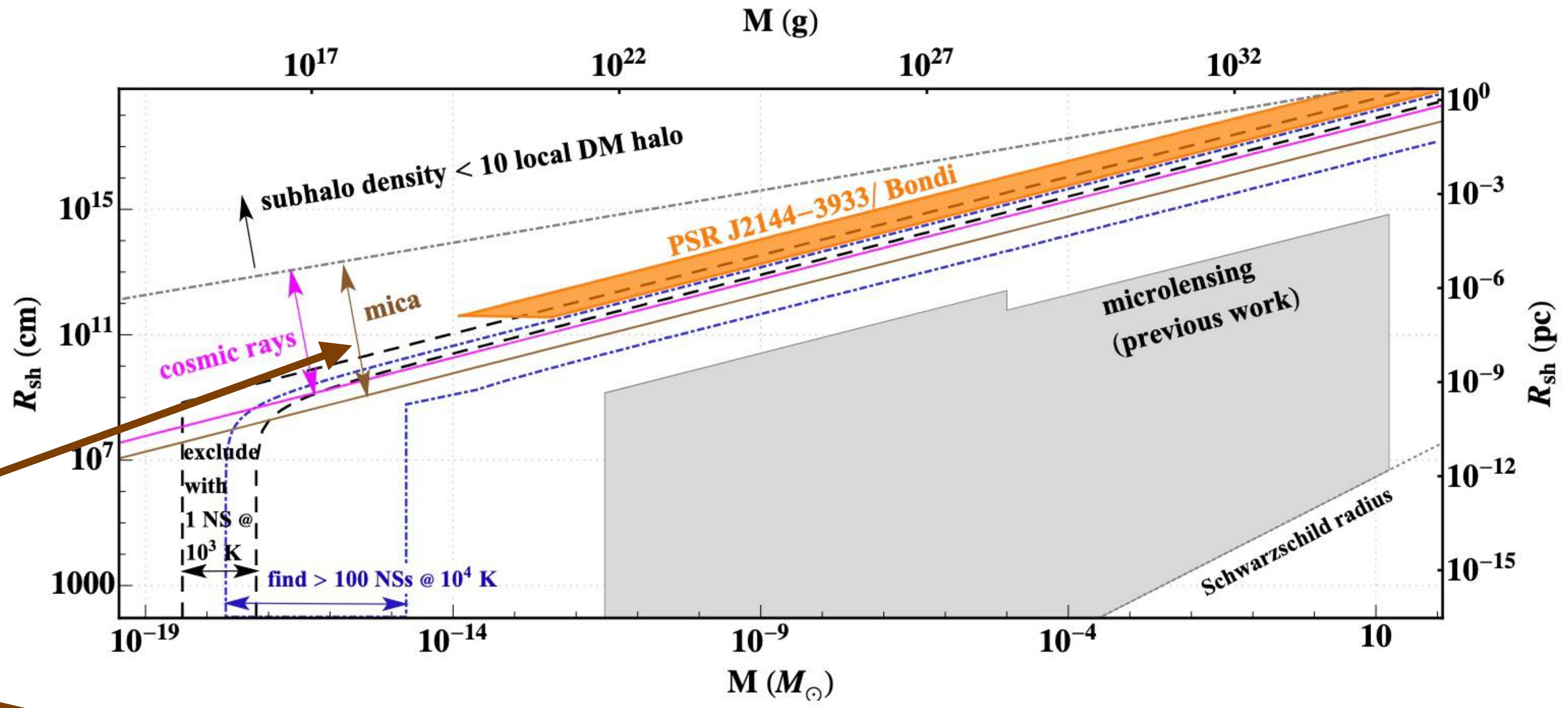
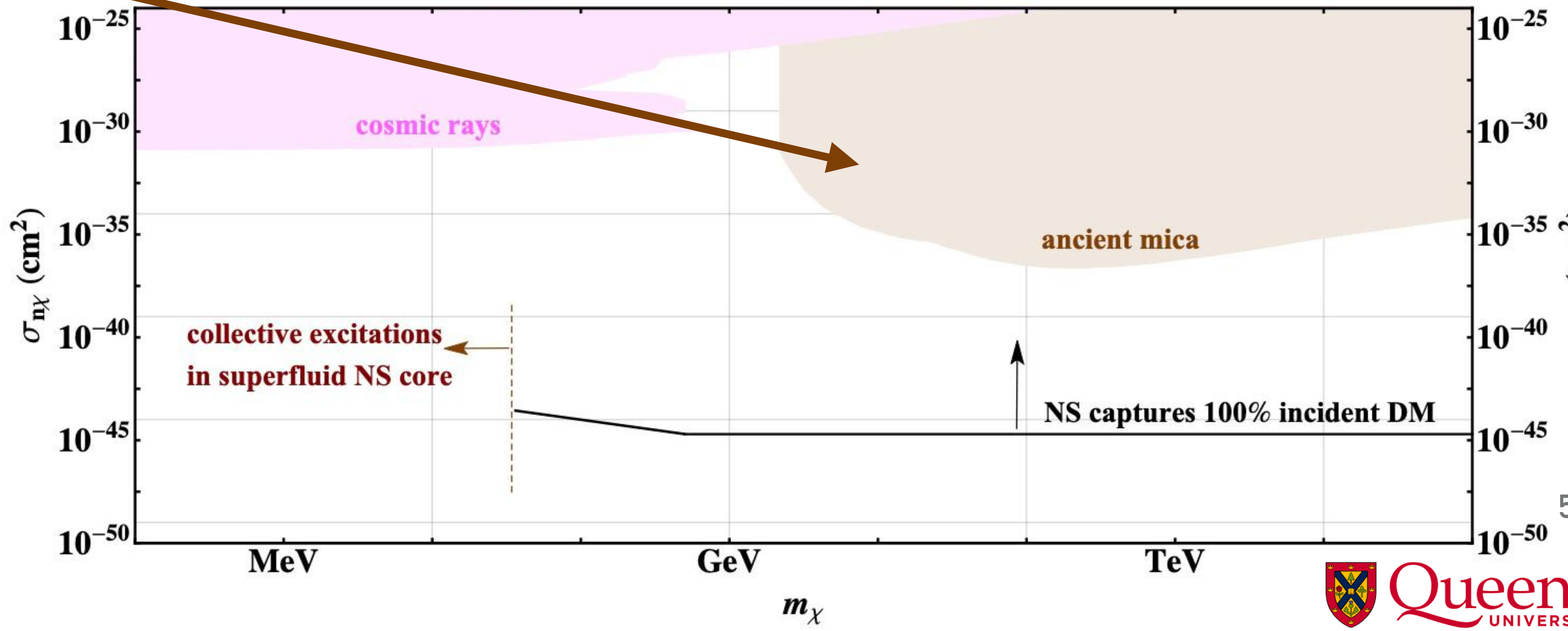
Requiring that subhalos interact with ancient mica in 500 Myr yields this bound





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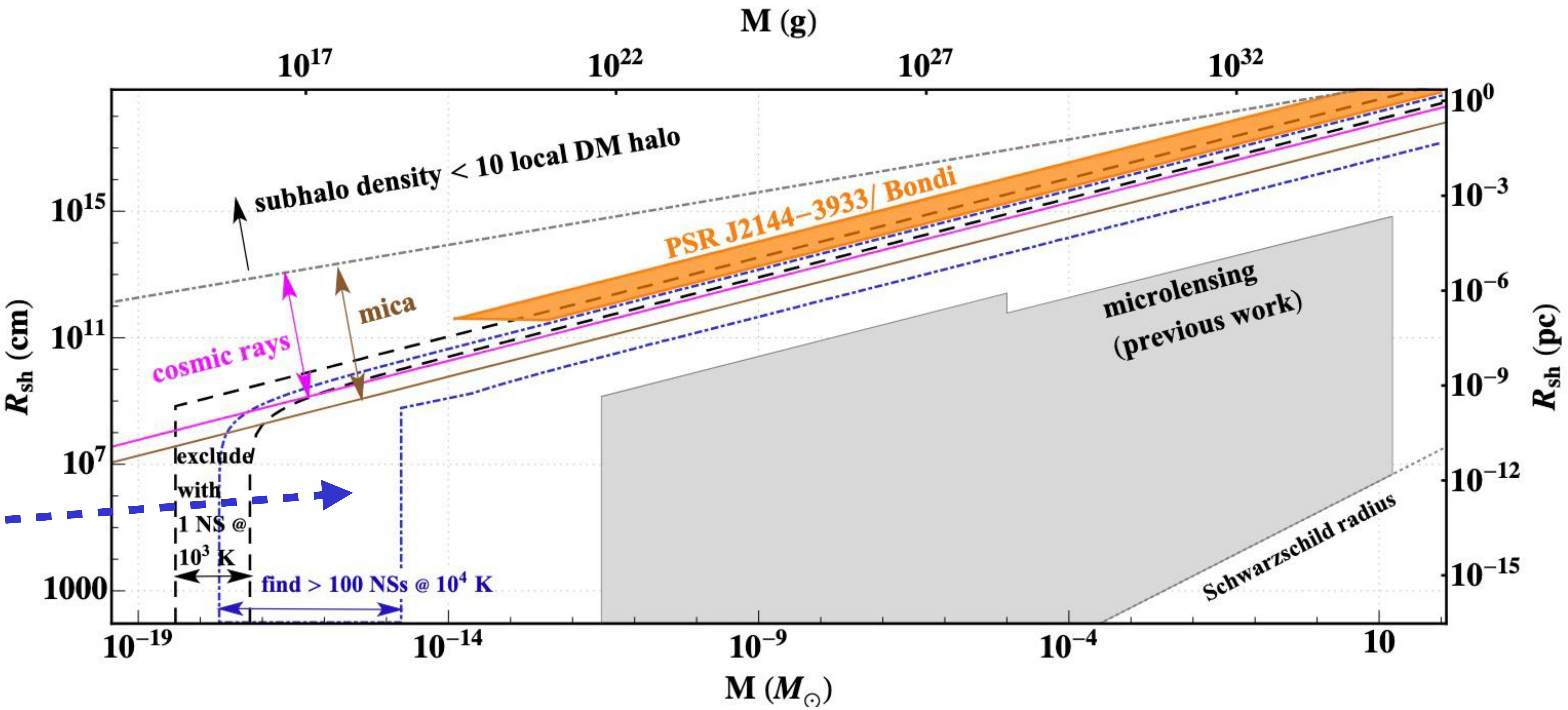
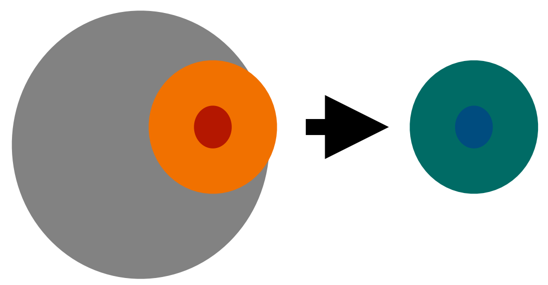
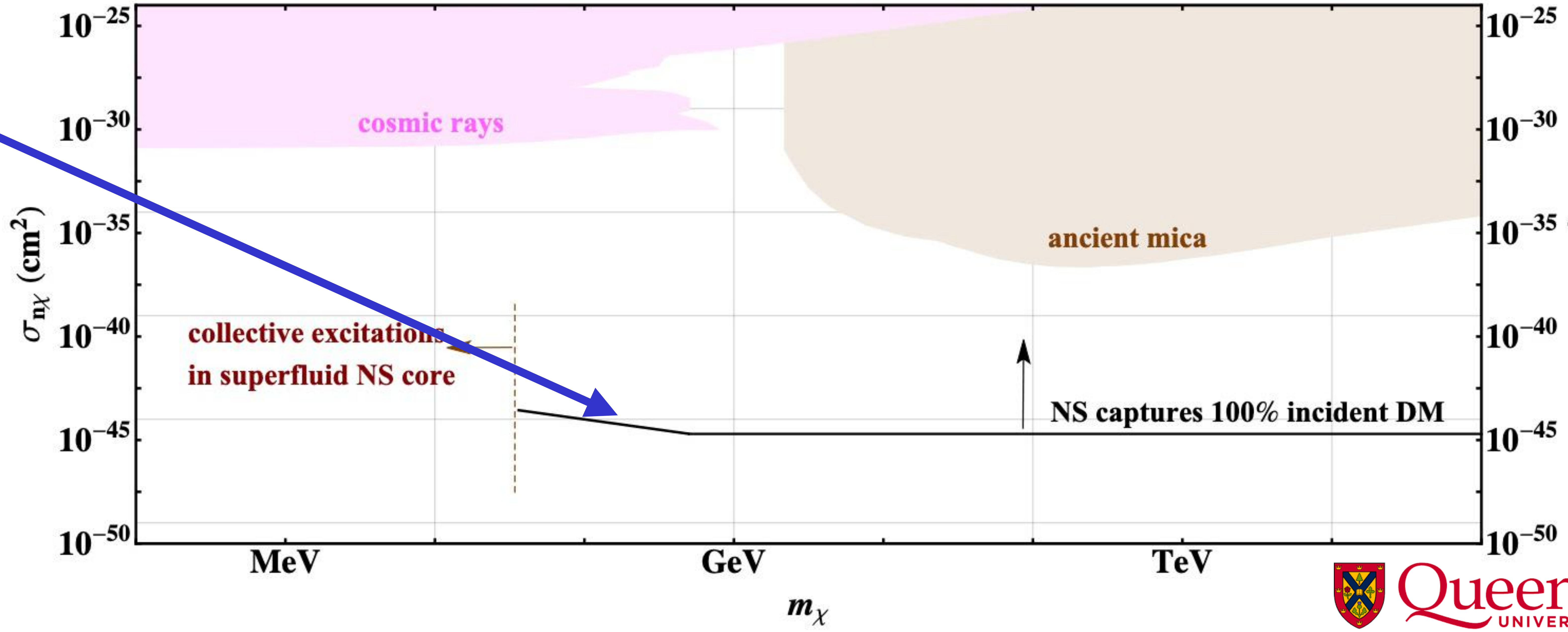
This region predicts a population of 100 NSs within a kpc of Earth heated to 10^4 K (flash-heated)





for this DM-nucleon cross-section



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DETERMINING HOW DARK MATTER HEATS NEUTRON STARS

kinetic only

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

(very sensitive
to escape velocity)

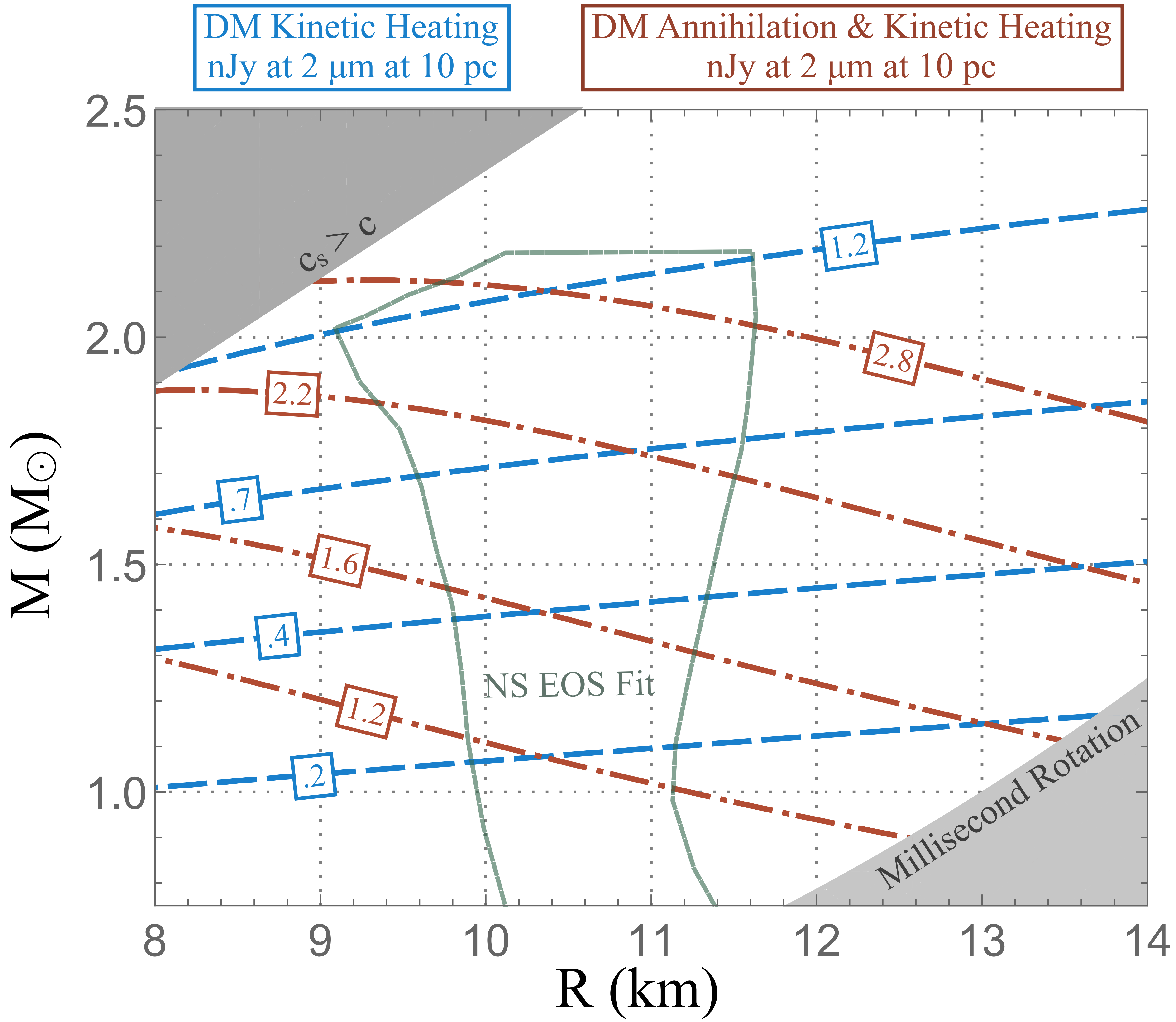
annihilation

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

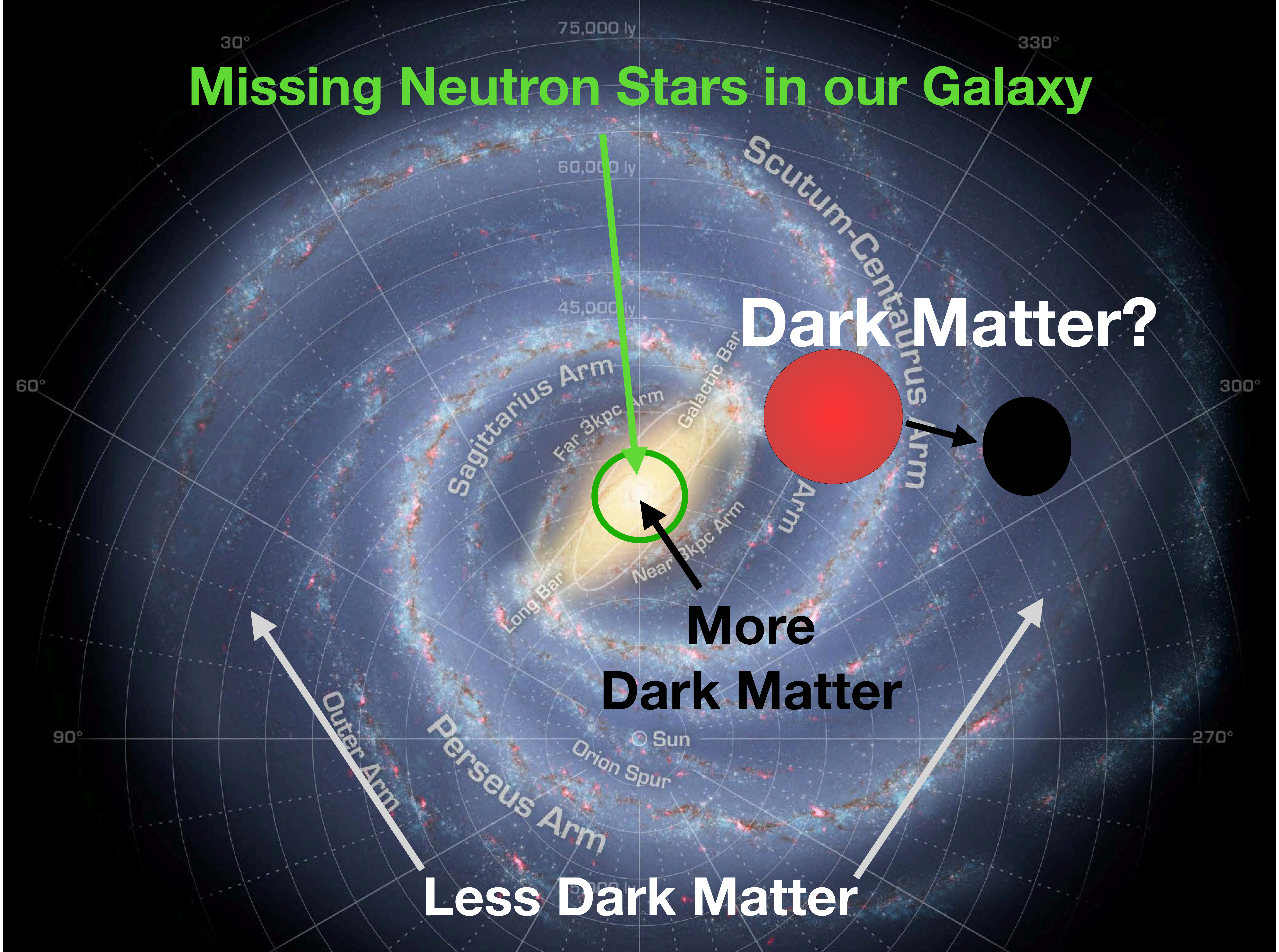
(heating mostly from captured
mass, scales with NS mass)

Test against ISM accretion:

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

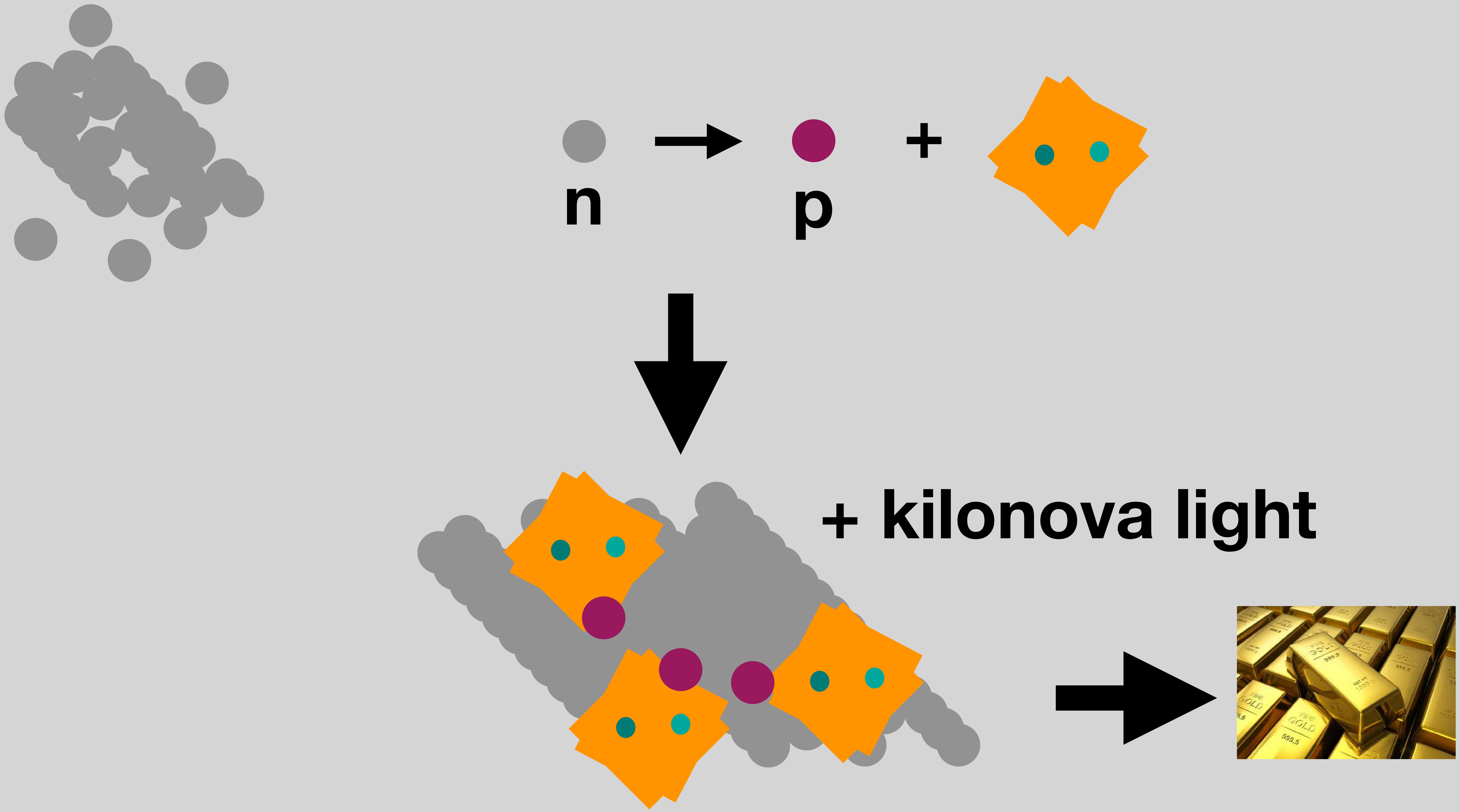


nanoJansky ~ 10^{-30} GeV / (cm^2 s Hz)


Missing Neutron Stars in our Galaxy
Dark Matter?
More
Dark Matter
Less Dark Matter
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

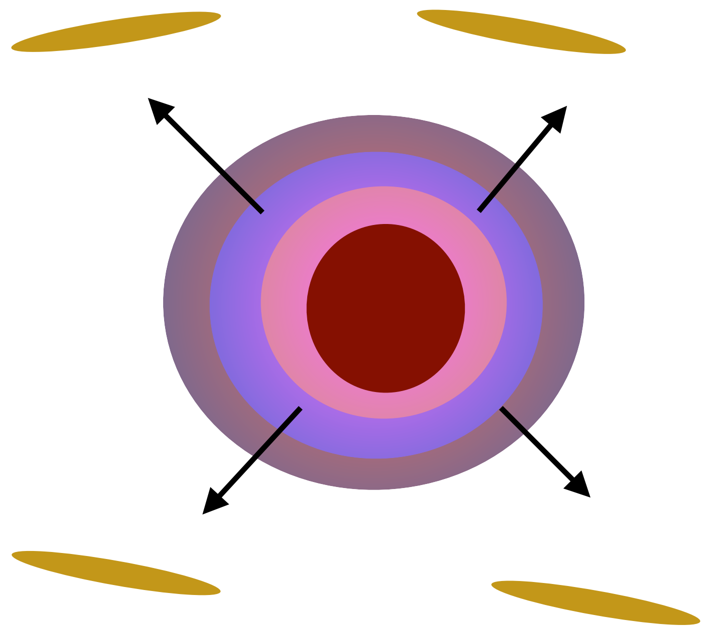
What makes gold? (heavier elements)

Recipe: lots of neutrons, very hot (10^9 K)

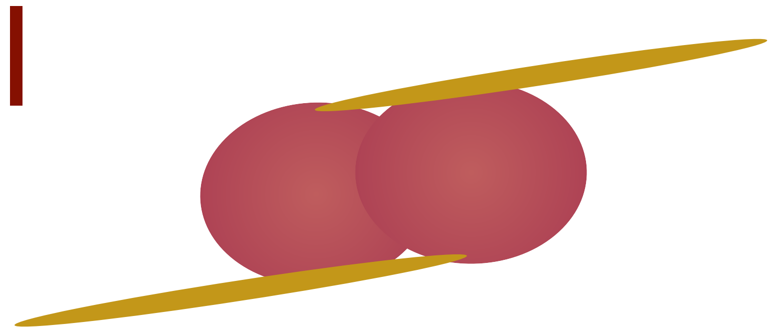


Possible r-process sites — total 10^4 $M_\odot$ produced in Milky Way

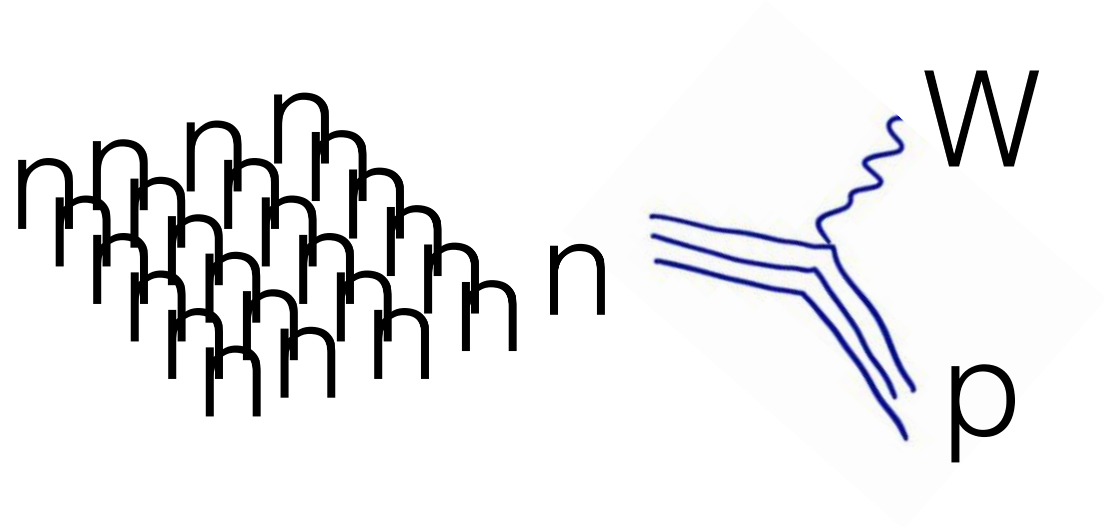
-Neutrons ejected by neutrino wind during core collapse supernovae (frequent, ~1/100 years)



-Merging neutron star binaries, tidal forces expel dense neutron star fluid (rare, ~1/10^4 years)



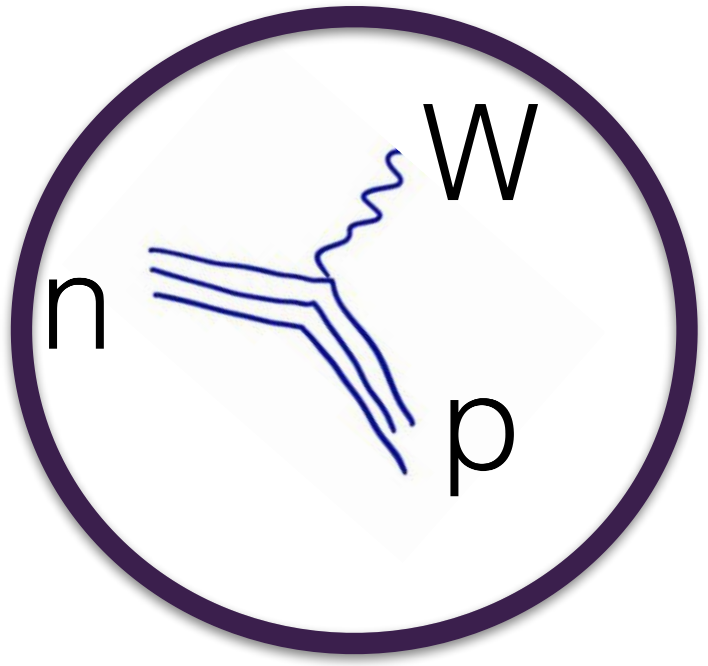
In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.



…

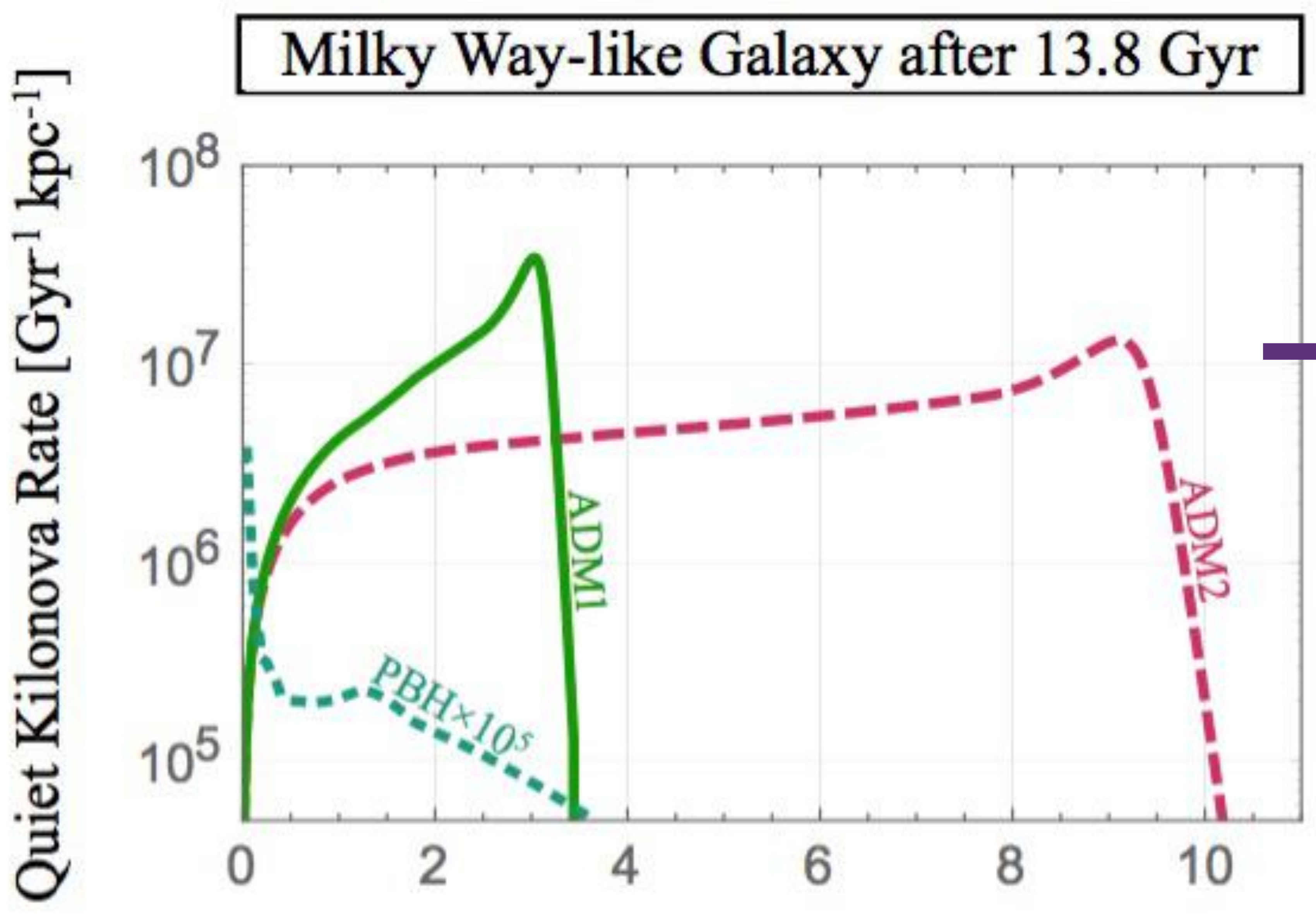
Gold, Uranium,
Europium, Barium…

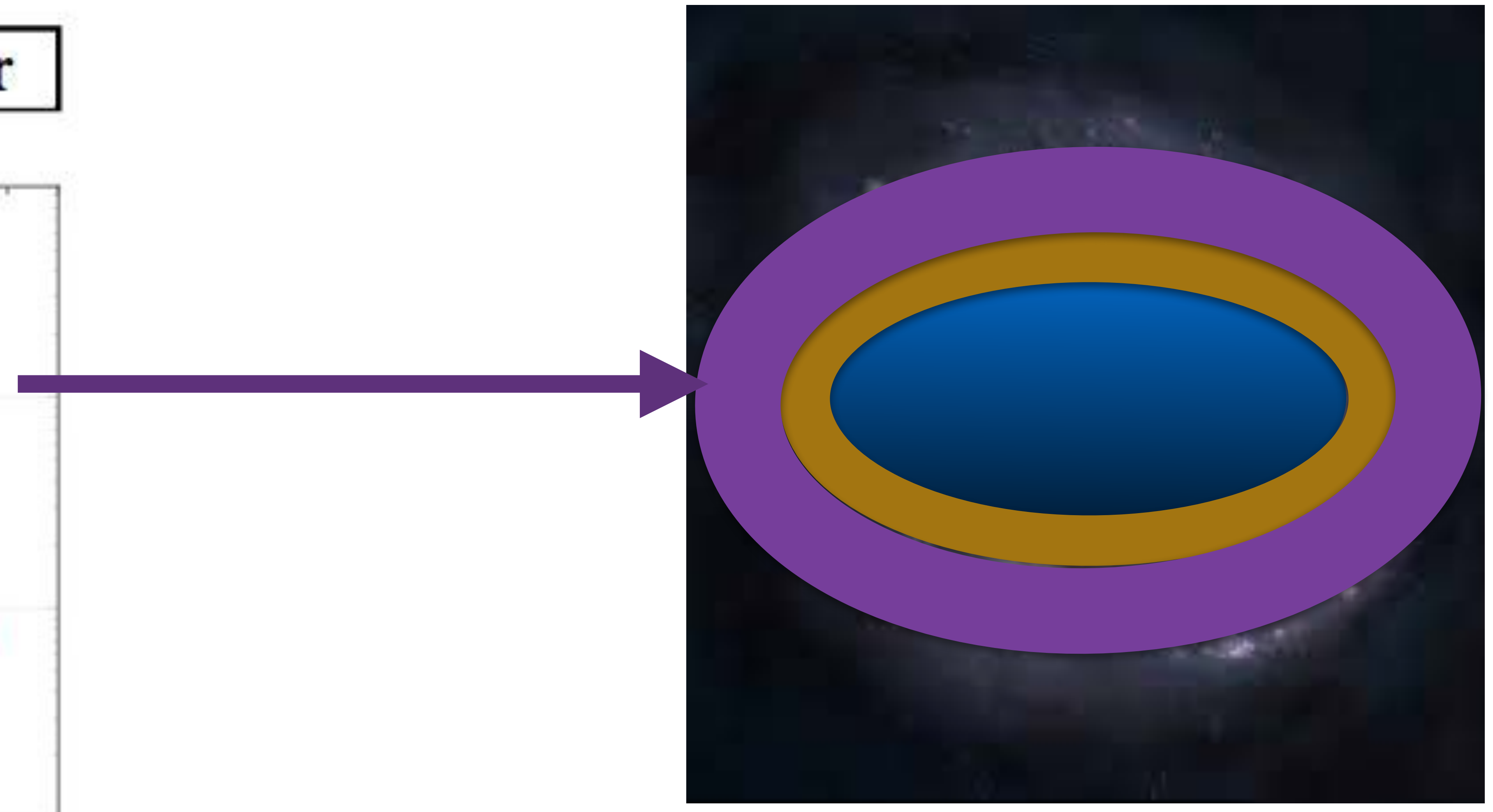
R-process donuts



Gravity Waves
From NS mergers

R-Process Donuts: Standard NS merger kilonovae occur in donut shaped external regions of disc galaxies





Asymmetric Dark Matter Using Kilonovae And NS Mergers