DARK MATTER accretion in NEUTRON STARS

Yoann Genolini

A work in collaboration with :
Raghuveer Garani & Thomas Hambye

Based on : **JCAP** (arXiv:**1812.08773**)

SW13 Corsica, May 2018

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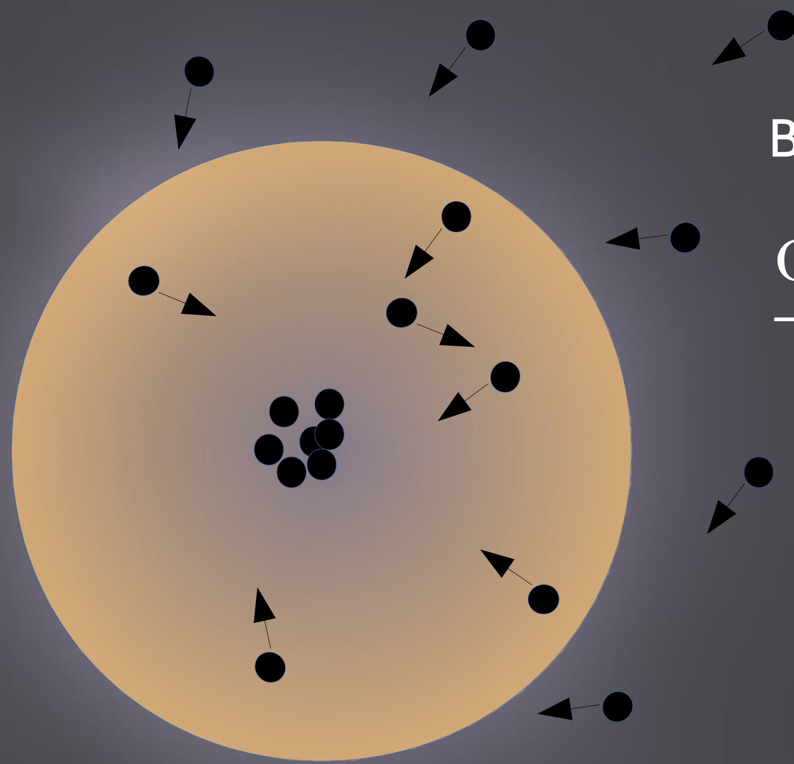
Credit: ESO/L.Calçada

Outline



Symmetric Dark Matter

Boltzmann equation:

$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C_\odot - A_\odot \mathrm{N}_\chi^2 - E_\odot \mathrm{N}_\chi$$

Indirect DM signature!

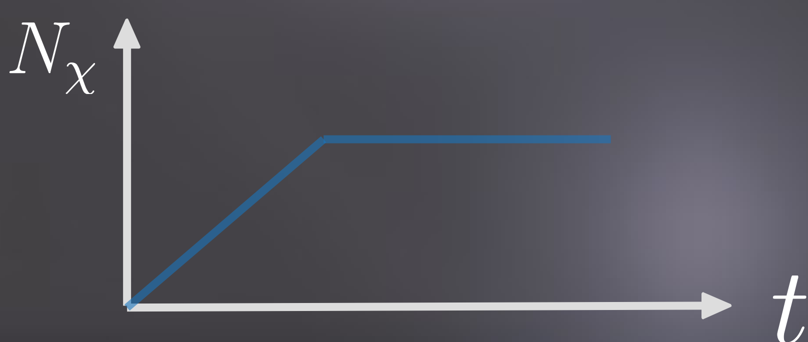
e. g. Solar Neutrino flux: $\frac{d\Phi}{dE_\nu} = \frac{\Gamma_A}{4\pi d_\odot^2} \frac{dN_\nu}{dE_\nu}$

W. H. Press and D. N. Spergel 1985, A. Gould 1987, J. Silk, et al 1985...

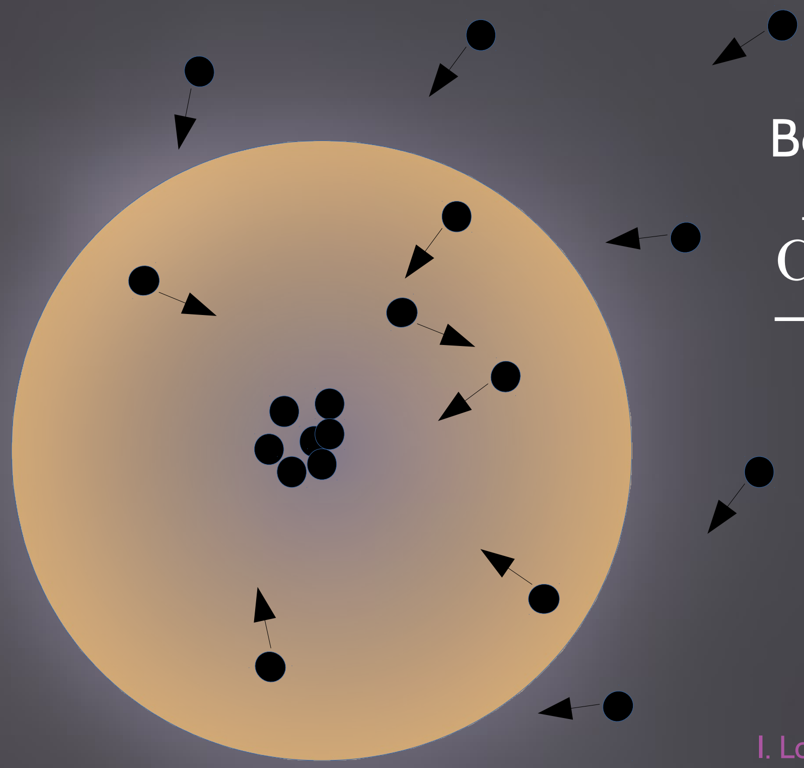
e. g. Reheating NS surface:

$$\frac{dT}{dt} = \frac{-\epsilon_\gamma - \epsilon_\nu + \epsilon_{DM}}{C_V}$$

de Lavallaz, Fairbairn 2010, Kouvaris Tinyakov 2010...,



Extensively studied!



Asymmetric Dark Matter

Boltzmann equation:

$$\frac{\mathrm{dN}_\chi}{\mathrm{dt}} = C_\odot - \cancel{A_\odot \mathrm{N}_\chi^2} - E_\odot \mathrm{N}_\chi$$

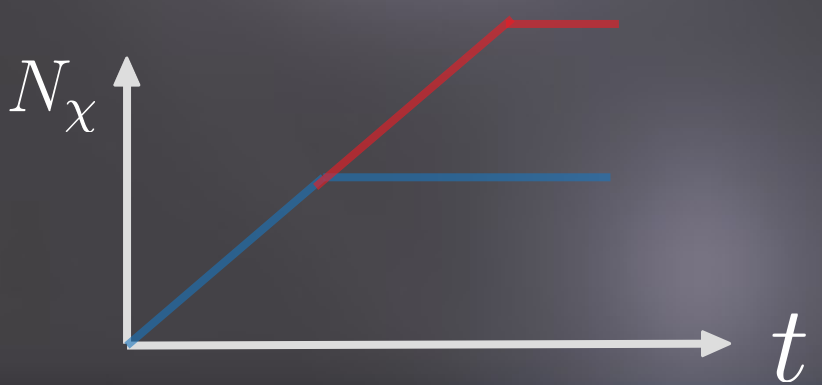
Accumulate more DM particles!

Helioseismology constraints on DM properties:

I. Lopes et al AJ L 2014, A. C. Vincent and P. Scott JCAP 2014, Geytenbeek et al 2018

Black hole formation and collaspe of the star:

Goldman et al. PRD 1989, Kouvaris 2008, Bertone et al PRD 2008, McCullough PRD 2010, Kouvaris and Tinyakov PRD & PRL 2011., McDermott et al 2012, ...,

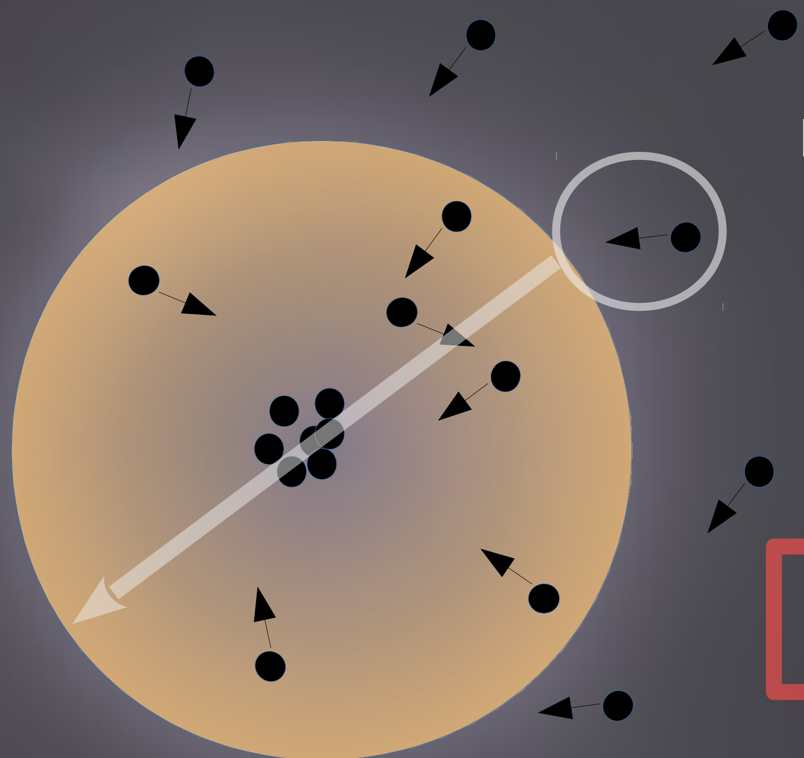


Extensively studied too!...

But accretion rate **never properly computed**

1

Orders of magnitude for capture



Best case scenario for capture: $\sigma_\chi \geqslant \sigma_{\mathrm{geom}}$

$$\sigma^{sun}_{\mathrm{geom}} \approx 1.3 \times 10^{-35}\ \mathrm{cm}^2 \left(\frac{R_\star}{R_\odot}\right)^2 \left(\frac{M_\odot}{M_\star}\right).$$

$$\sigma^{wd}_{\mathrm{geom}} \approx 1.3 \times 10^{-39}\ \mathrm{cm}^2.$$

$$\sigma^{NS}_{\mathrm{geom}} \approx 2 \times 10^{-45}\ \mathrm{cm}^2.$$

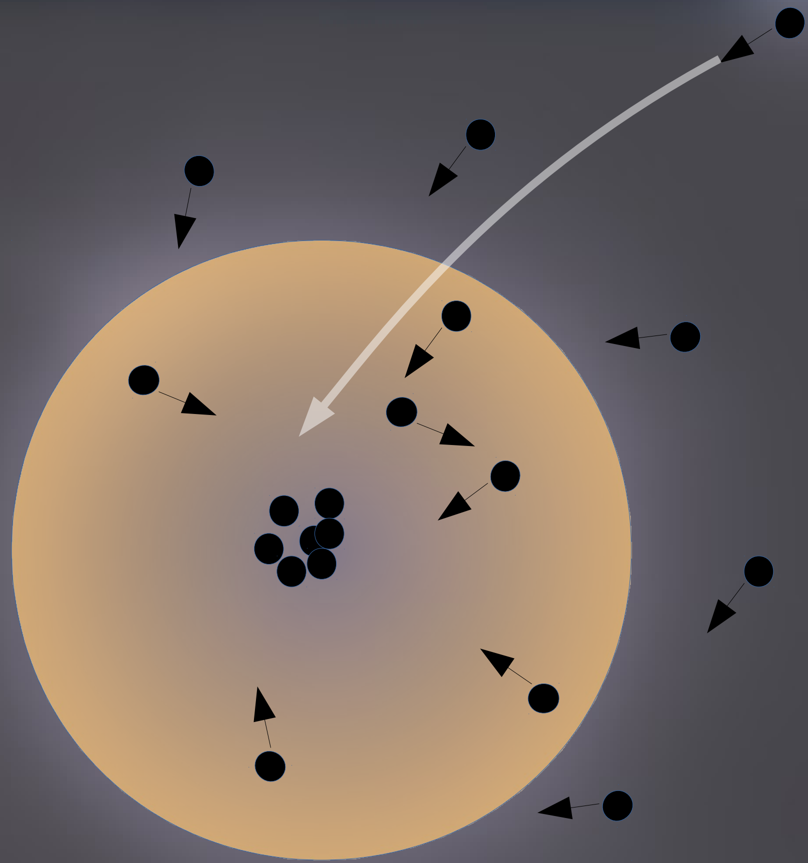
Geometrical cross-section:

$$\sigma_{\mathrm{geom}}\ n_b R_\star \approx 1$$

The capture rate is proportional to the interaction probability:

$$C_\odot \propto \frac{\sigma_\chi}{\sigma_{\mathrm{geom}}}.$$

1



Orders of magnitude for **capture**

The capture rate is proportional to:

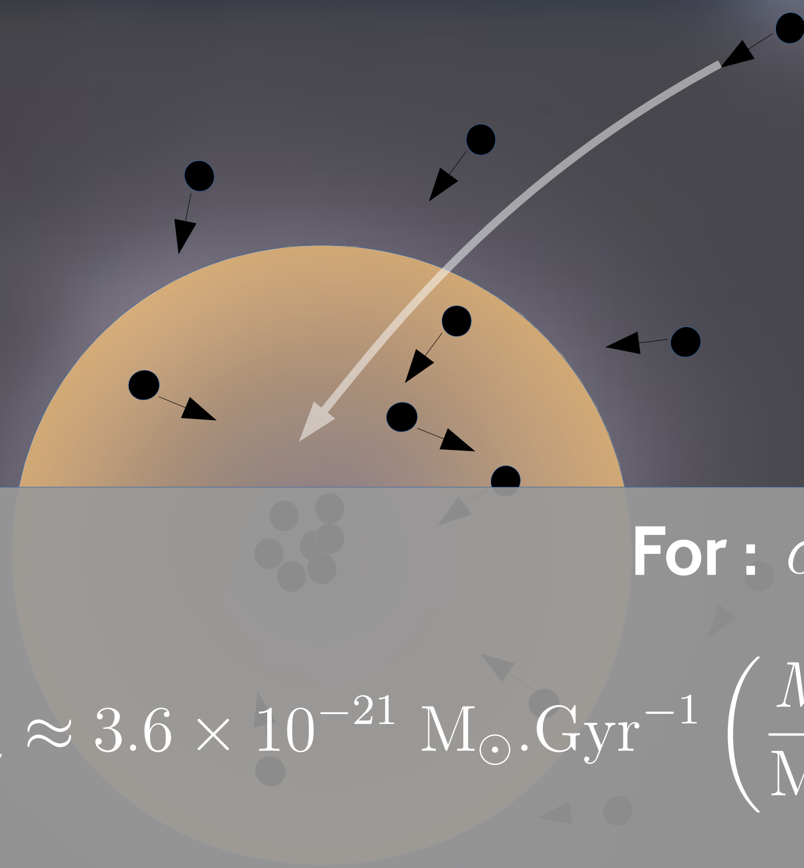
$$C_\star \sim \pi b^2 \times v_\infty \, \rho_{DM} \times \frac{\sigma_\chi}{\sigma_{\rm geom}}.$$

Gravitational cross-section:

$$\pi b^2 = \pi \left(1 + \frac{2GM}{R_\star v_\infty^2} \right) R_\star^2$$

1

Orders of magnitude for capture



The capture rate is proportional to:

$$C_\star \sim \pi b^2 \times v_\infty \, \rho_{DM} \times \frac{\sigma_\chi}{\sigma_{\rm geom}}.$$

For : $\sigma_\chi \leq \sigma_{\rm geom}$:

$$C_{sun} \approx 3.6 \times 10^{-21} \ \mathrm{M_\odot.Gyr^{-1}} \left(\frac{M_\star}{\mathrm{M_\odot}}\right)^2 \left(\frac{\sigma_\chi}{\sigma^{NS}_{\rm geom}} \cdot \frac{\rho_{DM}}{0.3 \ \mathrm{GeV.cm^{-3}}} \cdot \frac{R_\odot}{R_\star}\right)$$

$$C_{wd} \approx 3.6 \times 10^{-19} \ \mathrm{M_\odot.Gyr^{-1}}$$

Gravitational cross-section :

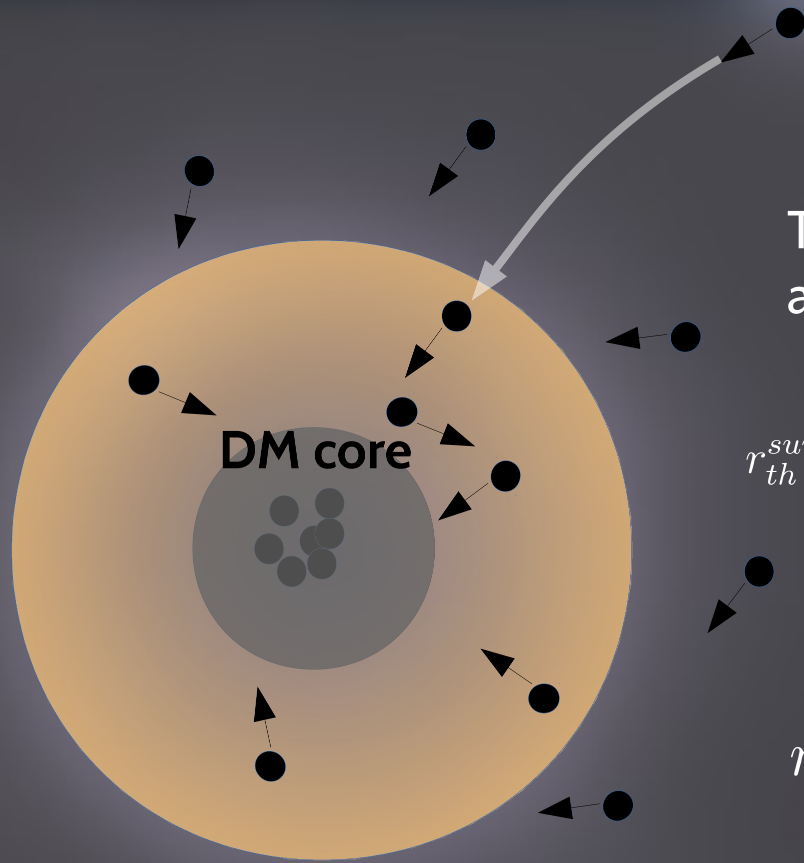
$$C_{NS} \approx 5.7 \times 10^{-16} \ \mathrm{M_\odot.Gyr^{-1}}$$

$$\pi b^2 = \pi \left(1 + \frac{2GM}{R_\star v_\infty^2}\right) R_\star^2$$

Compact objects accrete DM more efficiently !

Credit: ESO/L.Calçada

2



Thermalisation of DM

Through succesive collisions, DM losse energy and accumulate in the star center.

$$r_{th}^{sun} = 0.15\ \mathrm{R}_\odot \left(\frac{T_{core}}{10^7\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2} \left(\frac{10^2\ \mathrm{g.cm}^{-3}}{\rho_{core}}\right)^{1/2} .$$

$$r_{th}^{wd} = 80\ \mathrm{km} \left(\frac{T_{core}}{10^5\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2} .$$

Thermal radius r_{th} of the core:

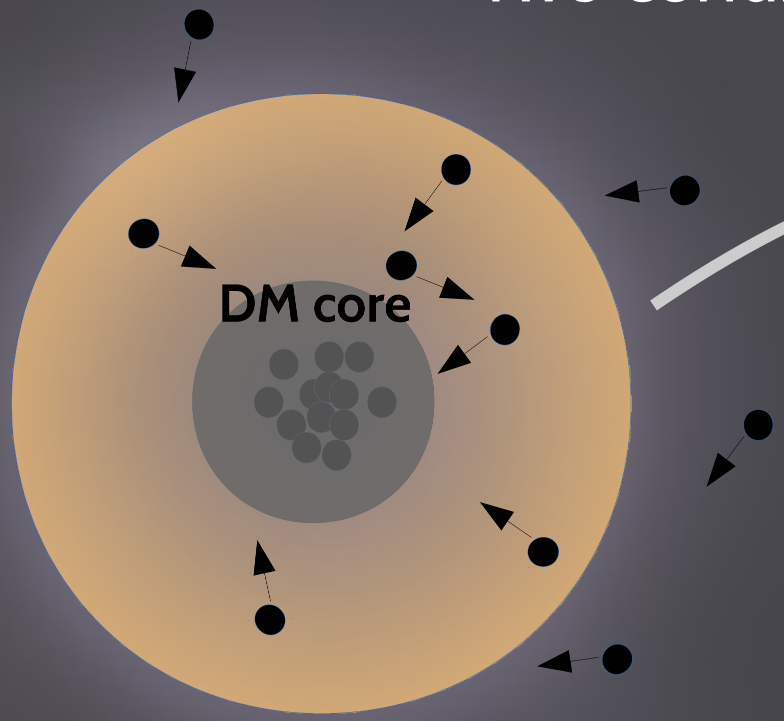
$$\frac{3}{2} k_b T_{core} = \frac{G M_\star(r_{th})\, m_\chi}{r_{th}}$$

$$r_{th}^{NS} = 4.3\ \mathrm{m} \left(\frac{T_{core}}{10^5\mathrm{K}}\right)^{1/2} \left(\frac{1\mathrm{GeV}}{m_\chi}\right)^{1/2} .$$

Small DM core!

3

Two conditions to collapse into a Black Hole



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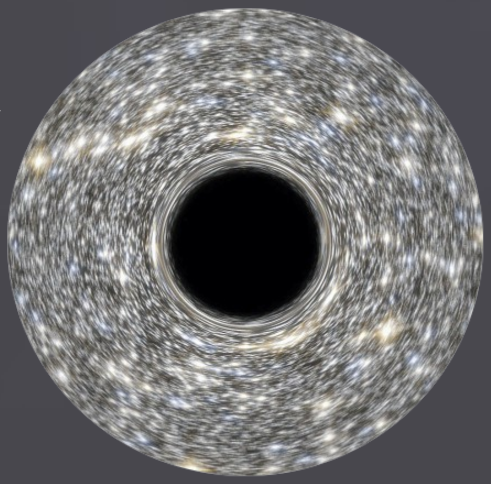


3 Two conditions to collapse into a Black Hole :

1- Self gravitation

$$\rho_{DM} \gtrsim \rho_{core}$$

Assuming DM particles thermalize:

$$\frac{M_\chi}{\frac{4}{3}\pi r_{th}^3} \gtrsim \rho_{core}$$

Critical number for DM to self gravitate:

$$N_{self} \simeq 4.8 \times 10^{41} \left(\frac{100\mathrm{GeV}}{m_\chi}\right)^{5/2} \left(\frac{T_{core}}{10^5\,\mathrm{K}}\right)^{3/2} .$$

2- Chandrasekhar limit

$$E_{tot} = -\frac{G N_\chi m_\chi^2}{R} + E_k .$$

When bosons become relativistic:

$$E_k = \frac{3}{2} k_b T_{core} \rightarrow \frac{1}{R} .$$

Critical number for gravity to dominate against kinetic energy:

$$N_{Cha}^{boson} \simeq 1.5 \times 10^{34} \left(\frac{100\mathrm{GeV}}{m_\chi}\right)^2 .$$

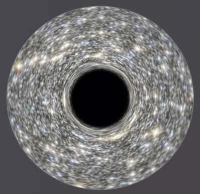
DM constraints from black hole formation

For a given σ_χ and m_χ

1– Compute the **total number of DM particles accreted.**

2– Assume DM particles have **thermalized.**

3– Compare with **black hole formation condition s.**

Accretion time τ_{acc} to  ?

DM constraints from black hole formation

Constraints on σ_χ for m_χ

1– Compute the **total number of DM particles accreted.**

2– Assume DM particles have **thermalized.**

3– Compare with **black hole formation conditions.**

Observation of old NS in **DM-rich environment**.

PSR J0437-4715
PSR J2124-3358

$$\tau_{old}^{NS} = 10\,\mathrm{Gyr}$$

DM constraints from black hole formation

Constraints on σ_χ

New formalism for the capture rate !

1- Compute the **total number of DM particles accreted.**

New treatment for thermalization !

2- Assume DM particles have **thermalized.**

3- Compare with **black hole formation conditions.**

Observation of old NS in **DM-rich environment**.

$$\tau_{old}^{NS} = 10\,\mathrm{Gyr}$$

II- New formalism for capture

Capture rate formalism:

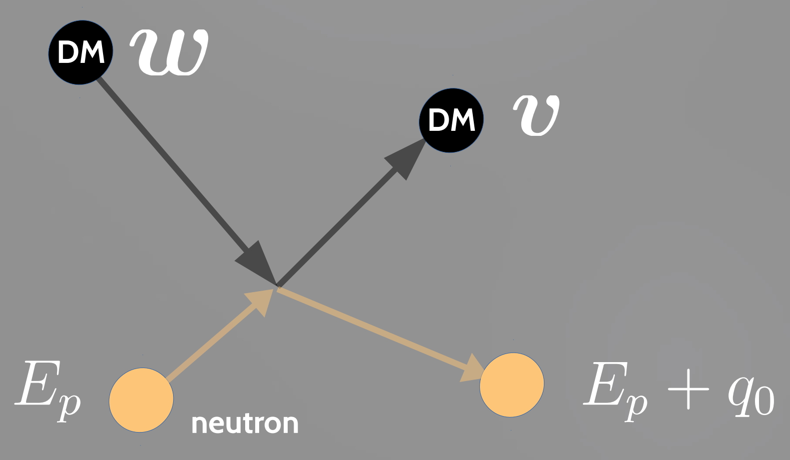
$$C_\star^{\rm w} = \int_0^{R_\star} 4\pi r^2 {\rm d}r \int_0^\infty {\rm d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\star}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_i^-(w \to v)\, {\rm d}v$$

A. Gould 1987

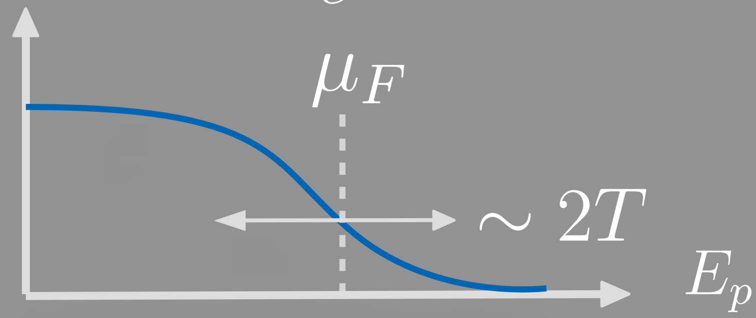
$$R(w \to v) = \int n(r) \frac{{\rm d}\sigma}{{\rm d}v} |\boldsymbol{w} - \boldsymbol{u}| f_p(E_p, r)(1 - f_{p'}(E_p + q_0, r)){\rm d}^3\boldsymbol{u}$$

Garami, YG, Hambye, 2018

Scattering on a degenerate Fermi gaz



$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$



Credit: ESO/L.Calçada

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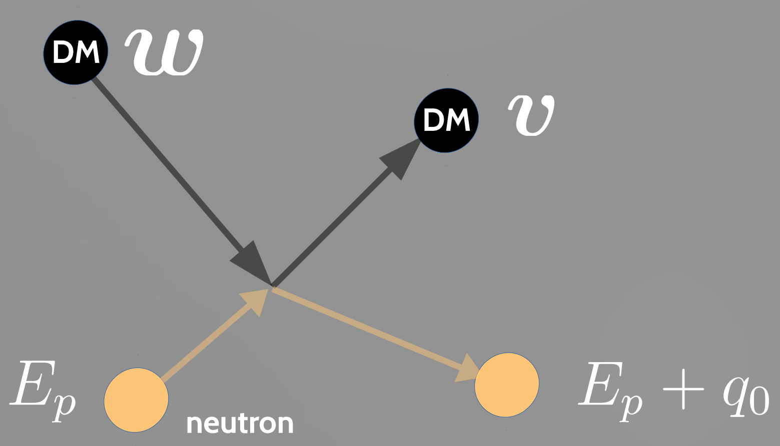
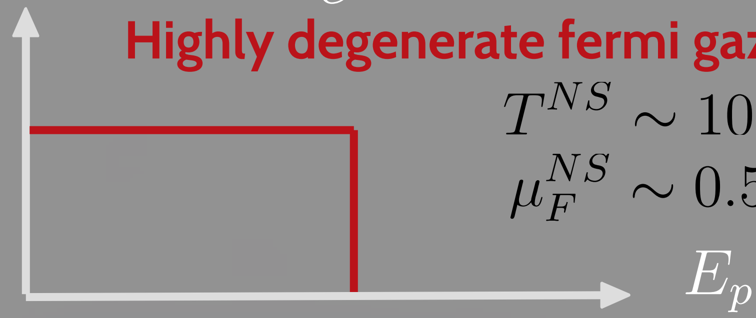


$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$

Highly degenerate fermi gaz !



$$T^{NS} \sim 10^{-8}\,\mathrm{GeV}$$
$$\mu_F^{NS} \sim 0.5\,\mathrm{GeV}$$

Capture rate formalism:

$$C_\star^{\rm w} = \int_0^{R_\star} 4\pi r^2 {\rm d}r \int_0^\infty {\rm d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\star}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_i^-(w \to v)\,{\rm d}v$$

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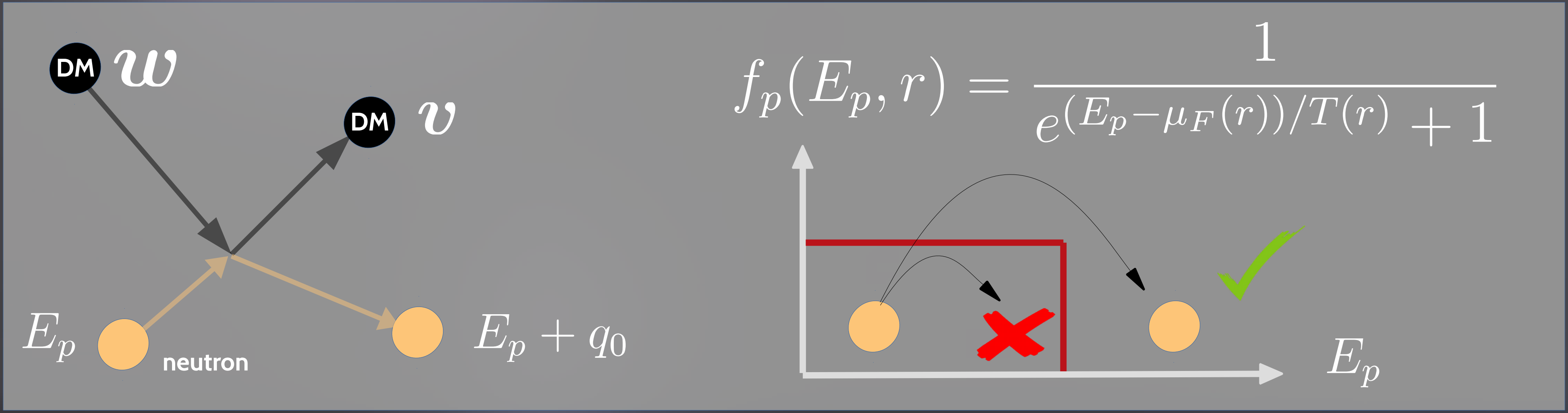

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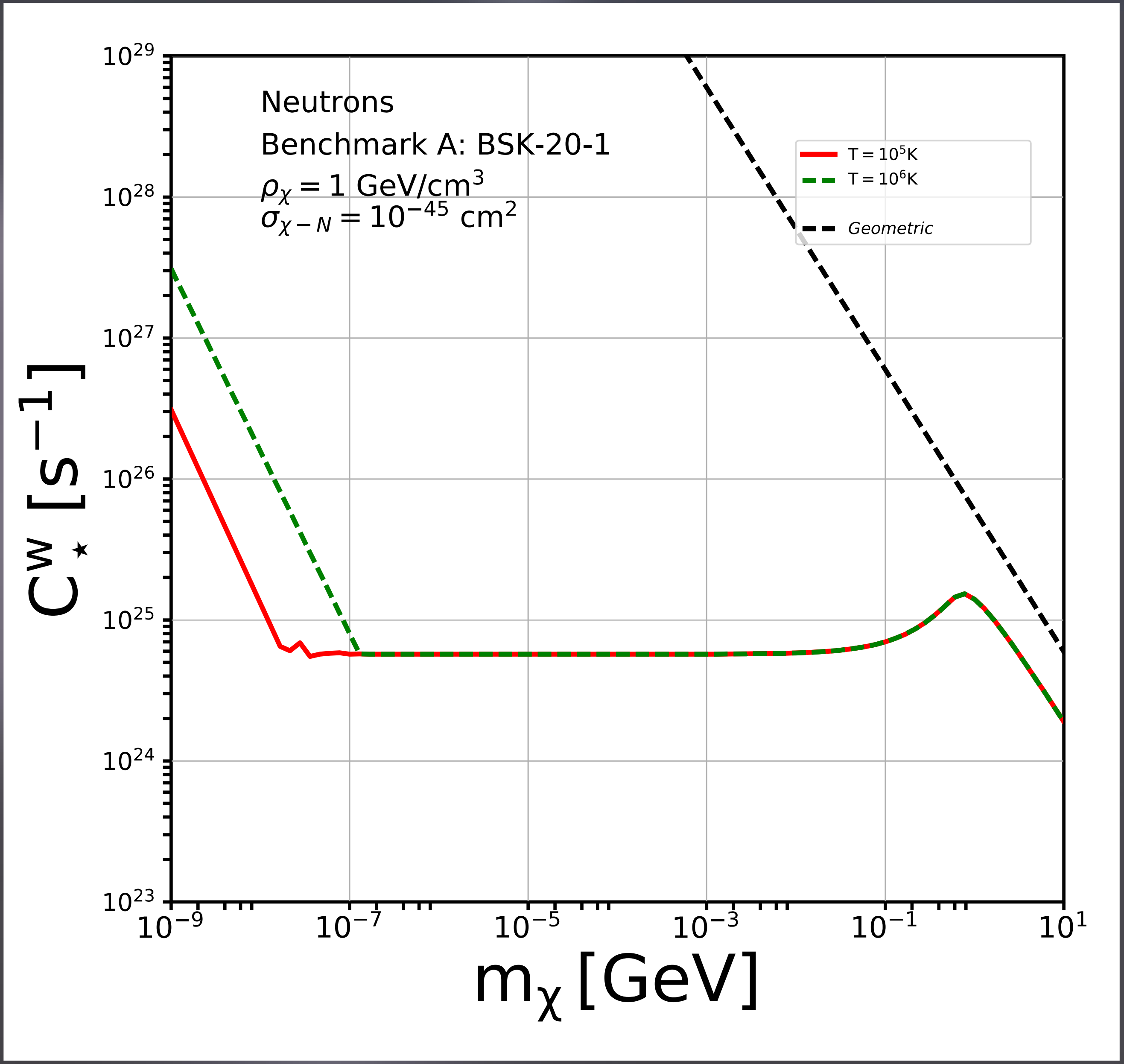
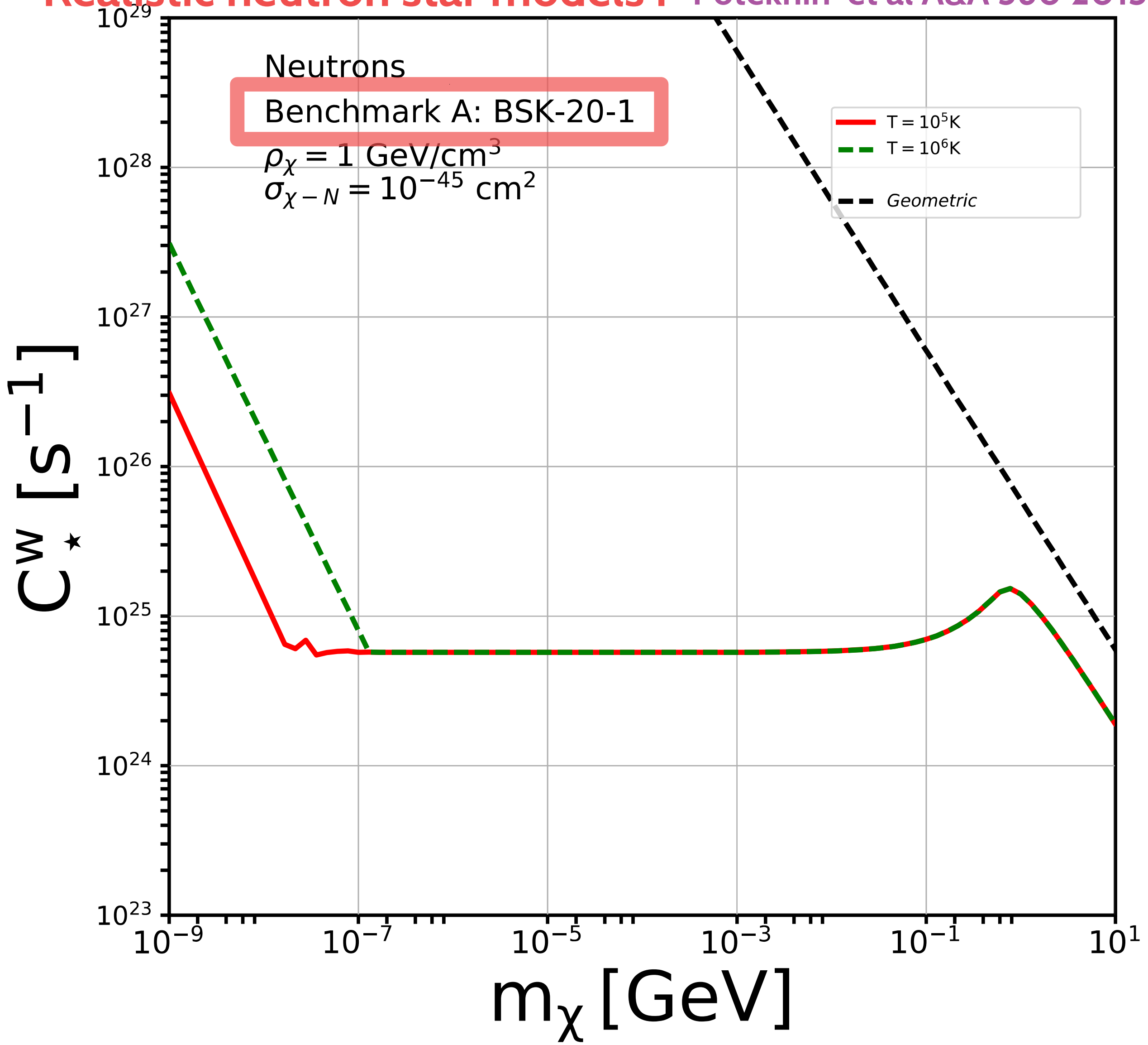
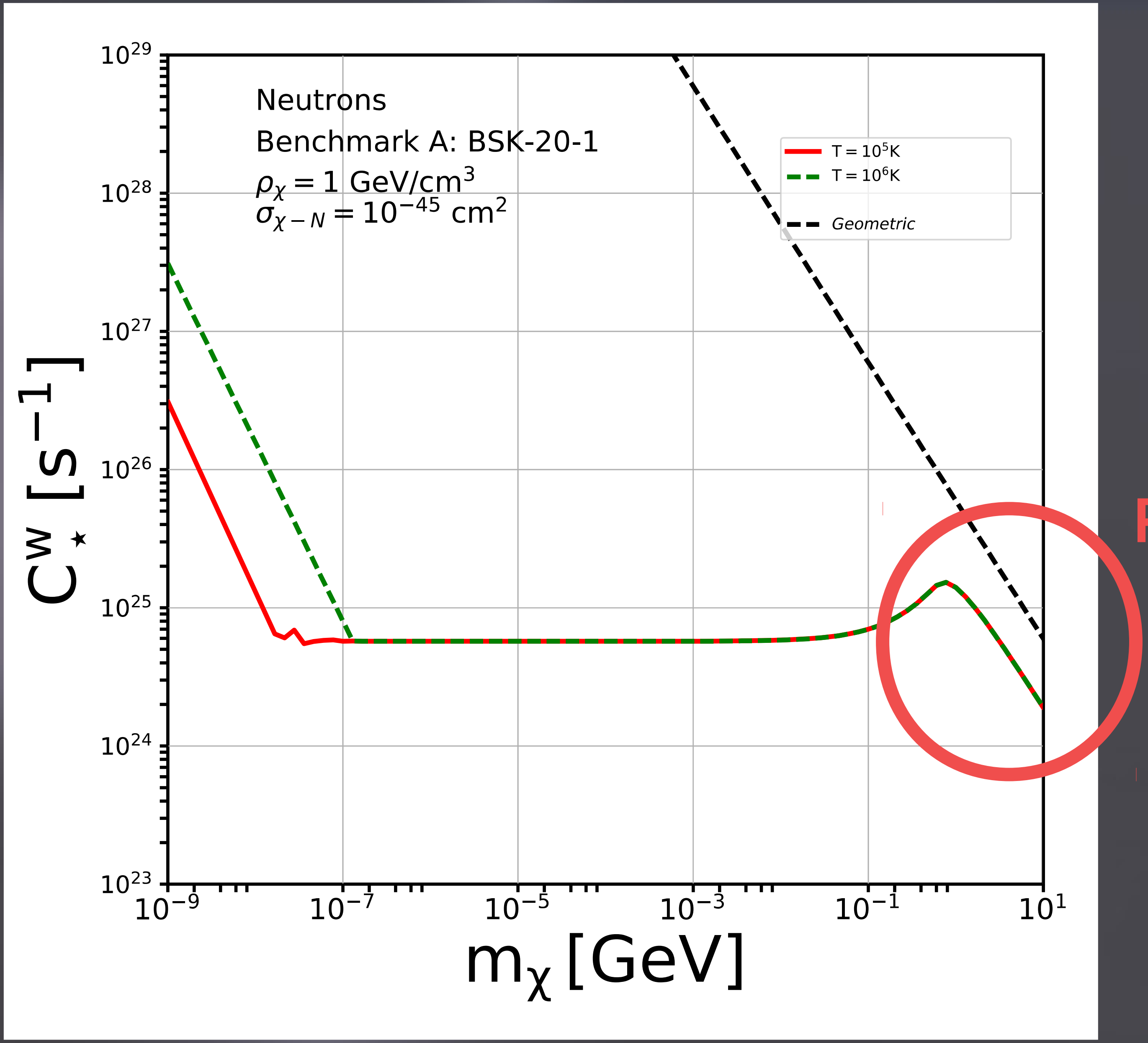

Neutrons
Benchmark A: BSK-20-1
$\rho_\chi = 1$ GeV/cm^3
$\sigma_{\chi-N} = 10^{-45}$ cm^2
T = 10^5K
T = 10^6K
Geometric
$C_\star^w$ [s^{-1}]
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}

Realistic neutron star models : Potekhin et al A&A 560 2013

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Geometric
$C_\star^w$ [s^{-1}]
m_χ [GeV]
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
Regime I

Capture rate formalism:

$$C_\star^{\mathrm{w}} = \int_0^{R_\star} 4\pi r^2 \mathrm{d}r \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\star}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_i^-(w \to v)\, \mathrm{d}v$$

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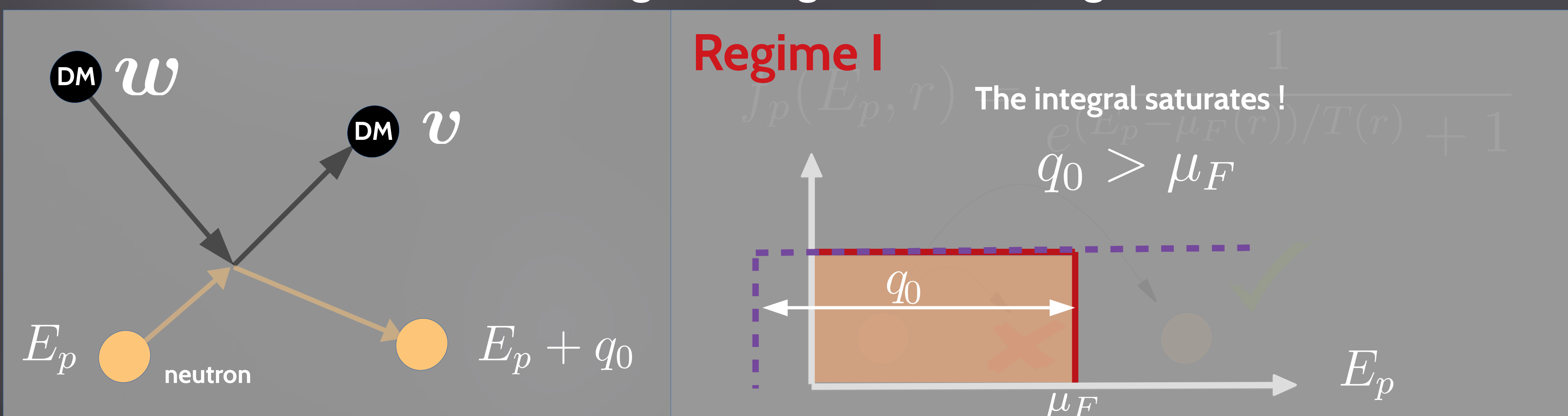

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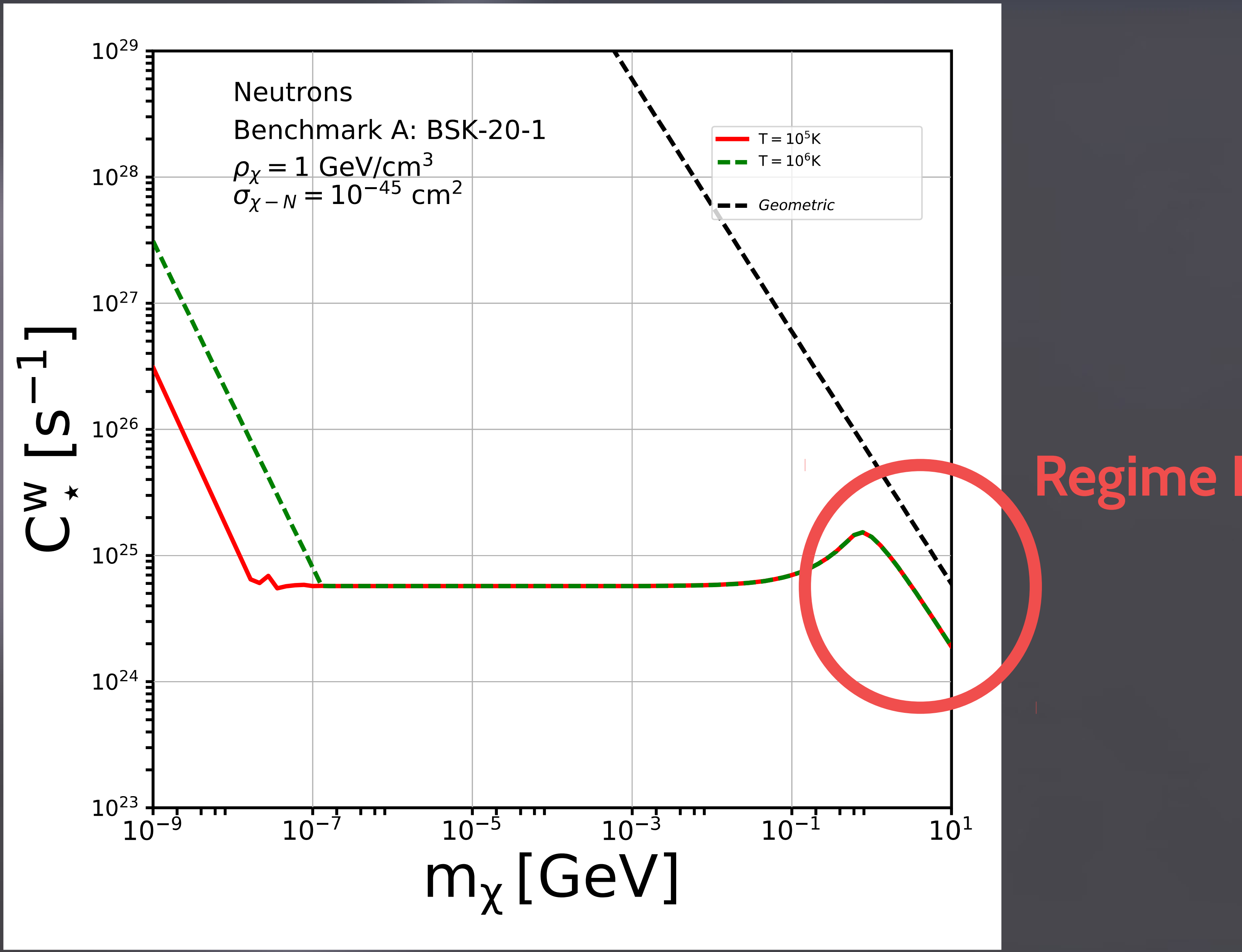
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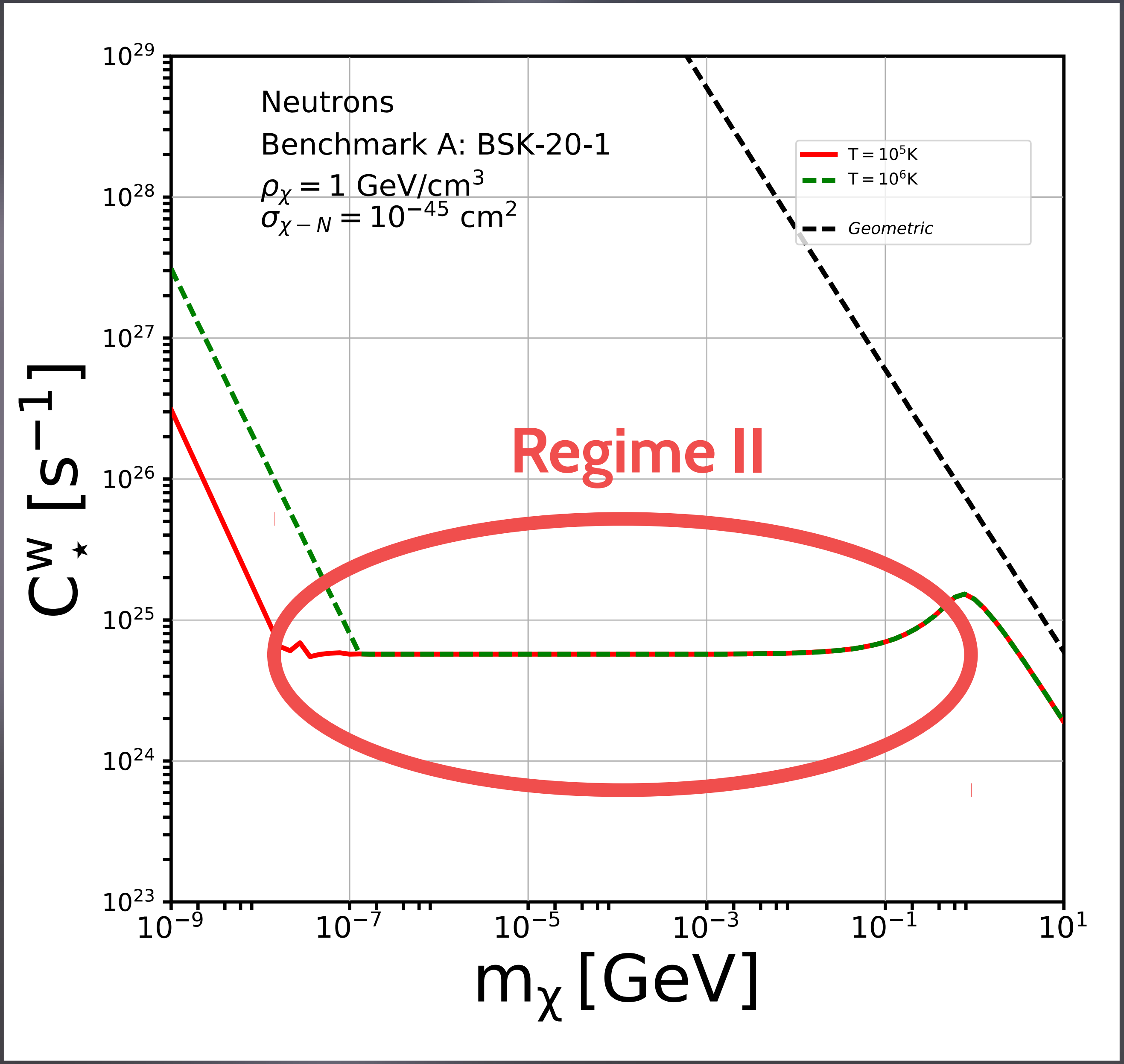
Geometric
$C^w_\star$ [s^{-1}]
m_χ [GeV]
Regime I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Benchmark A: BSK-20-1
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T = 10^5K
T = 10^6K
Geometric
Regime II
$C_\star^w$ [s^{-1}]
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
10^{-7}
10^{-5}
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10^{-1}
10^{1}

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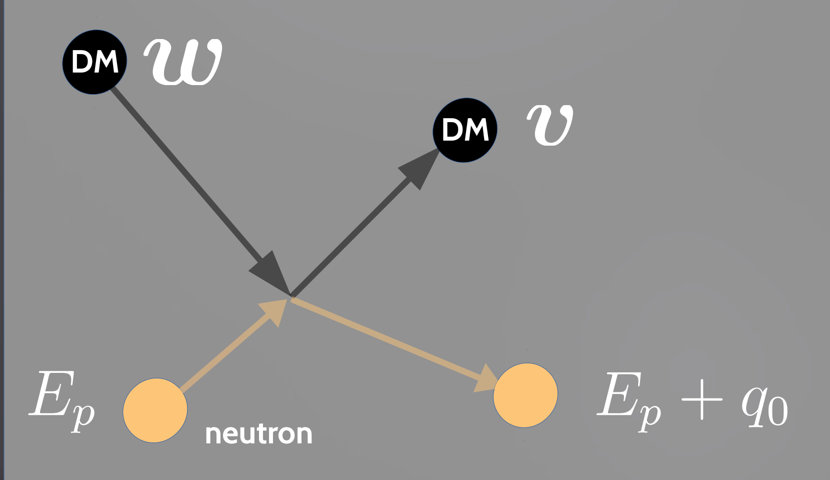
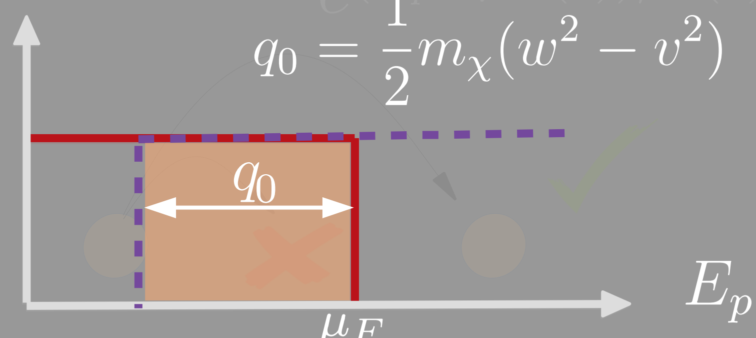


Regime II

$$f_p(E_p, r) = \frac{1}{e^{(E_p - \mu_F(r))/T(r)} + 1}$$

The integral is proportional to :

$$q_0 = \frac{1}{2} m_\chi (w^2 - v^2)$$



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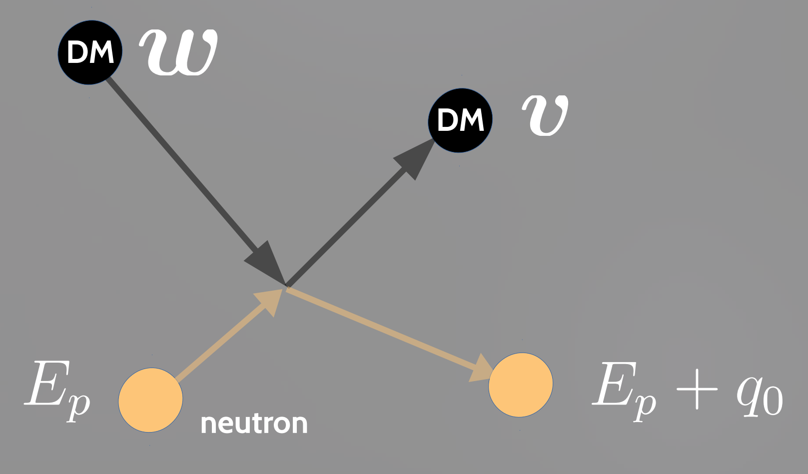

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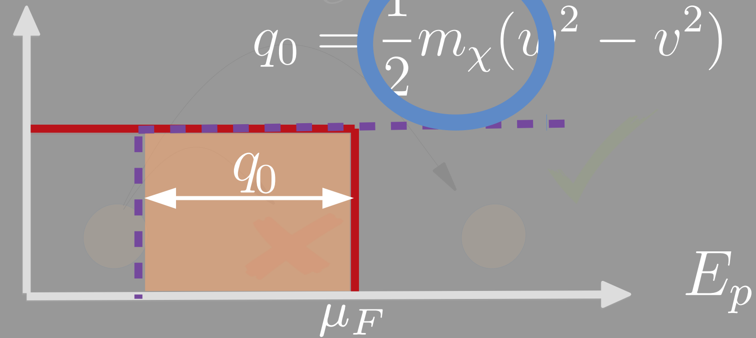

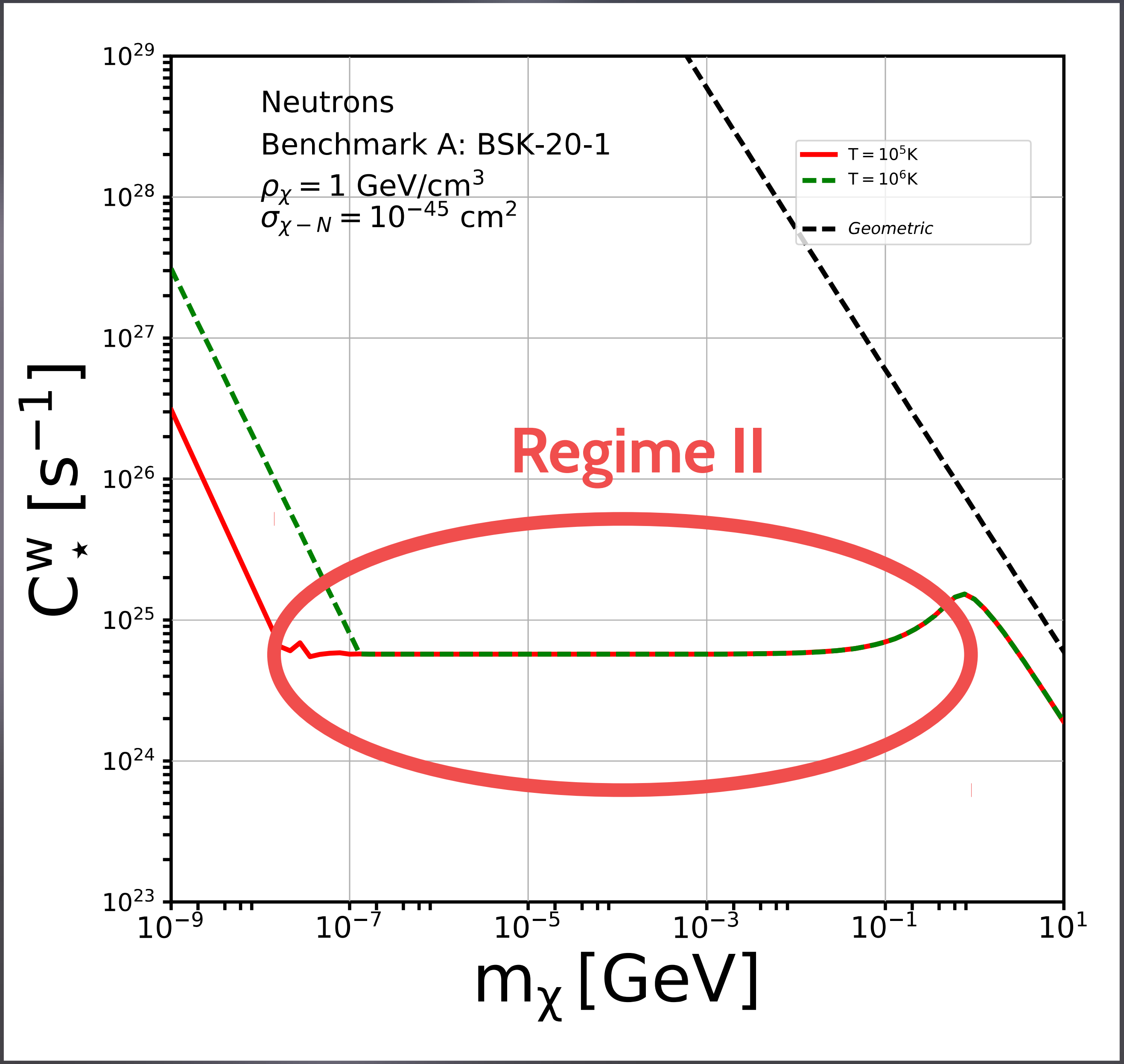
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m_χ [GeV]
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10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
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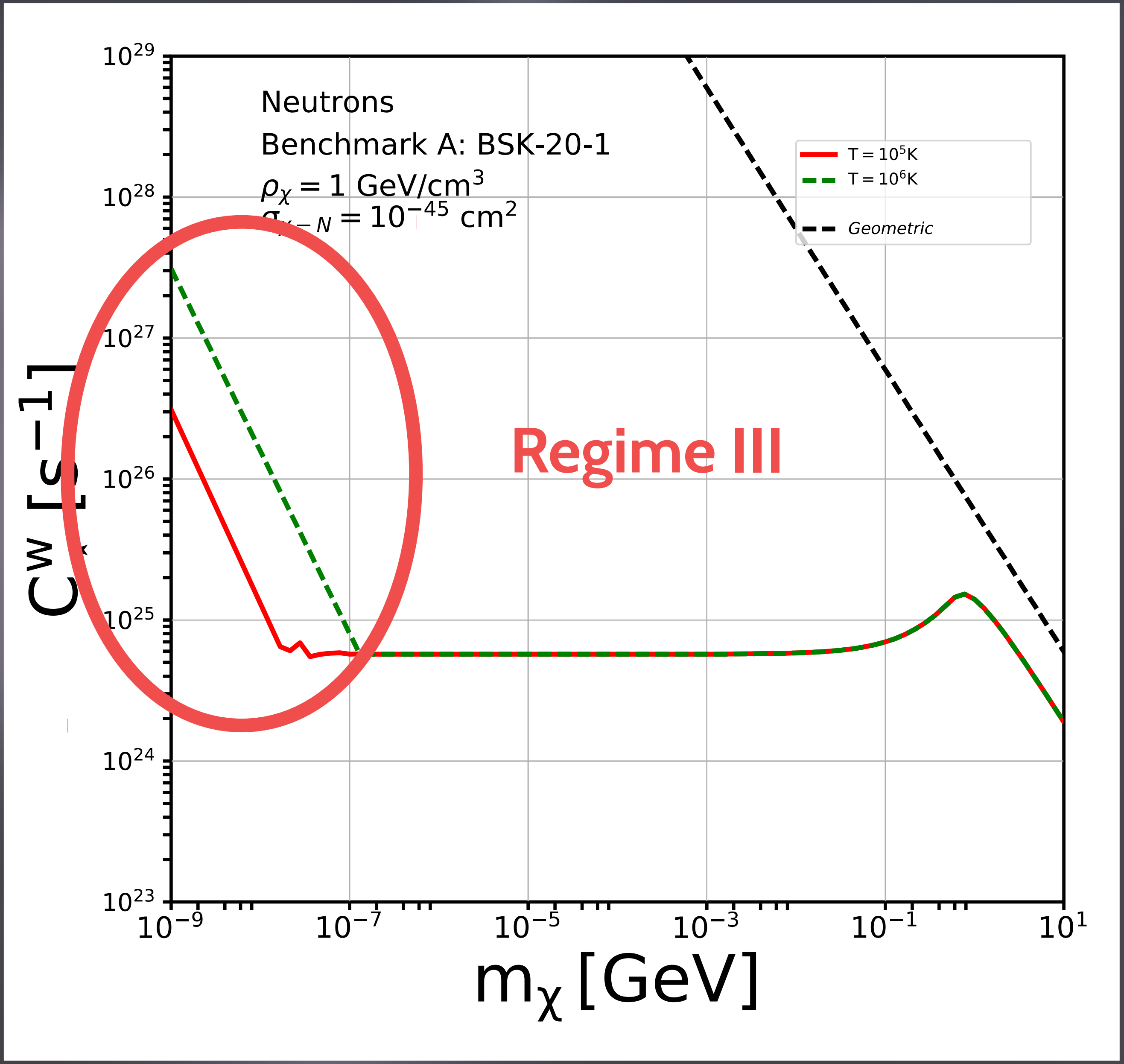
10^{-1}
10^{1}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T = 10^{6}K
Geometric
Regime III
C^w_χ [s^{-1}]
m_χ [GeV]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^{-9}
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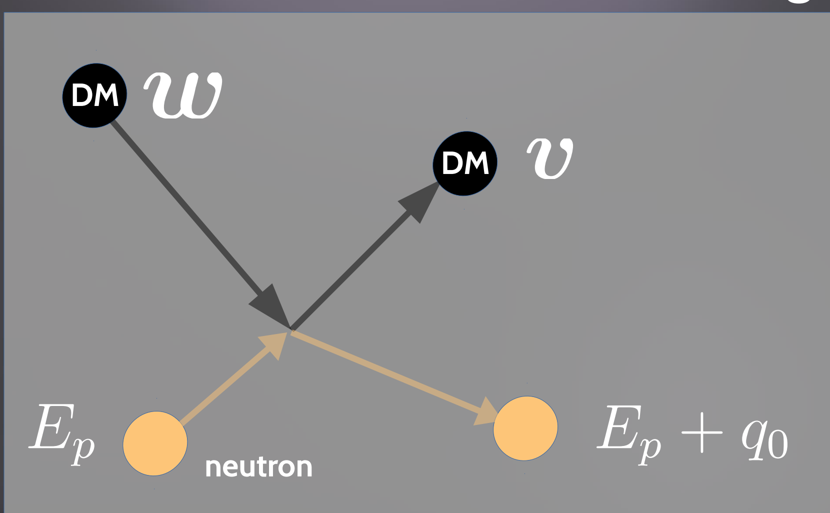

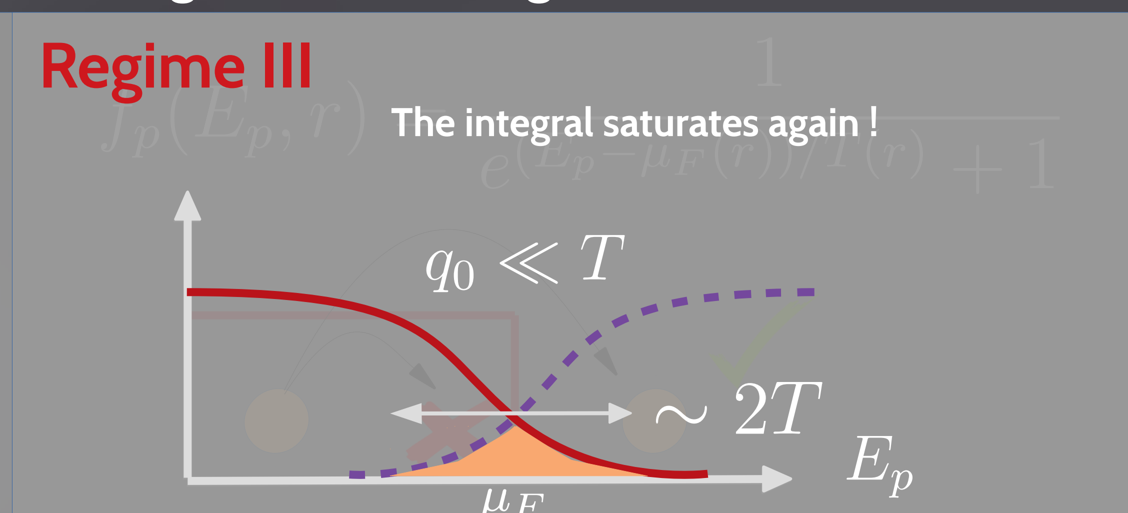

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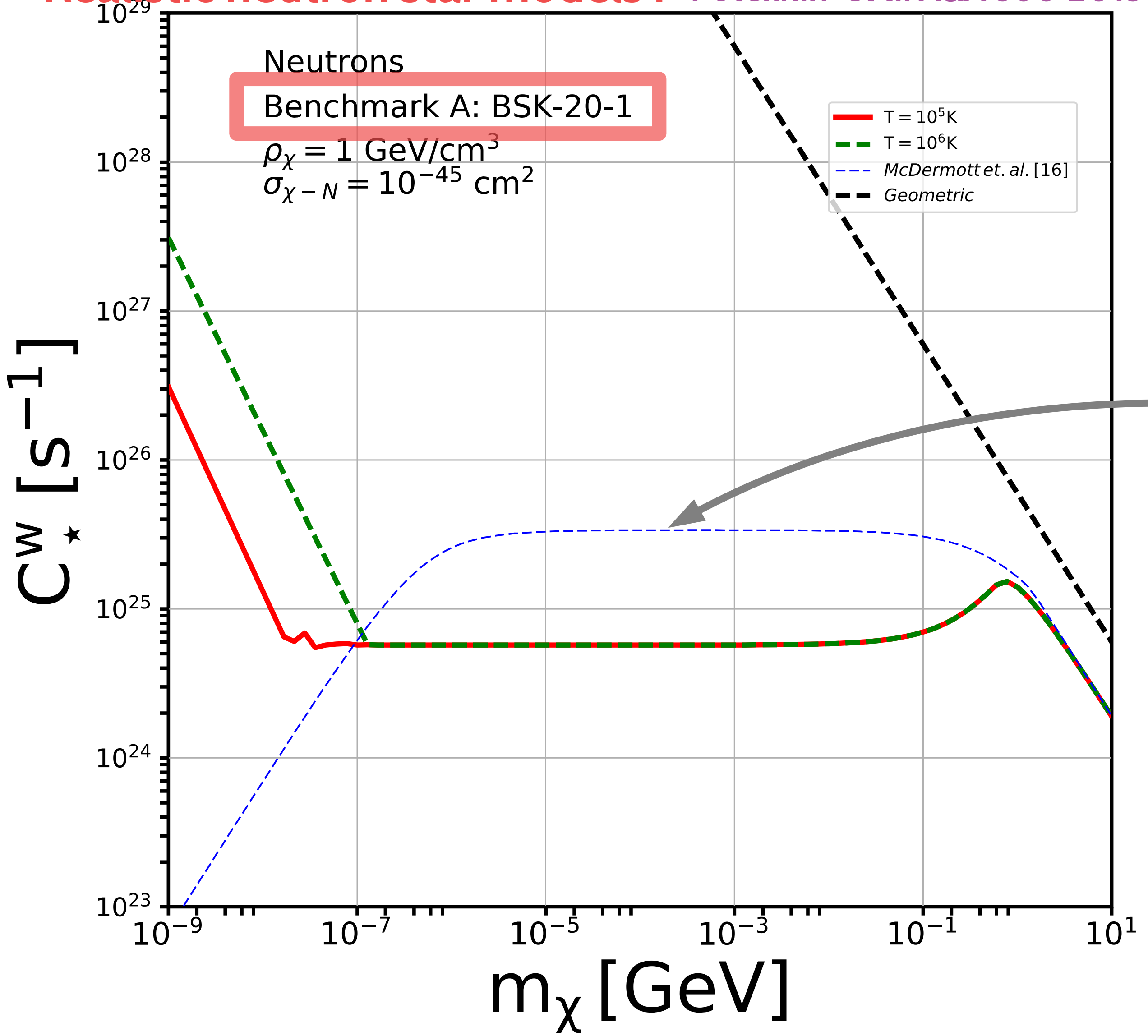
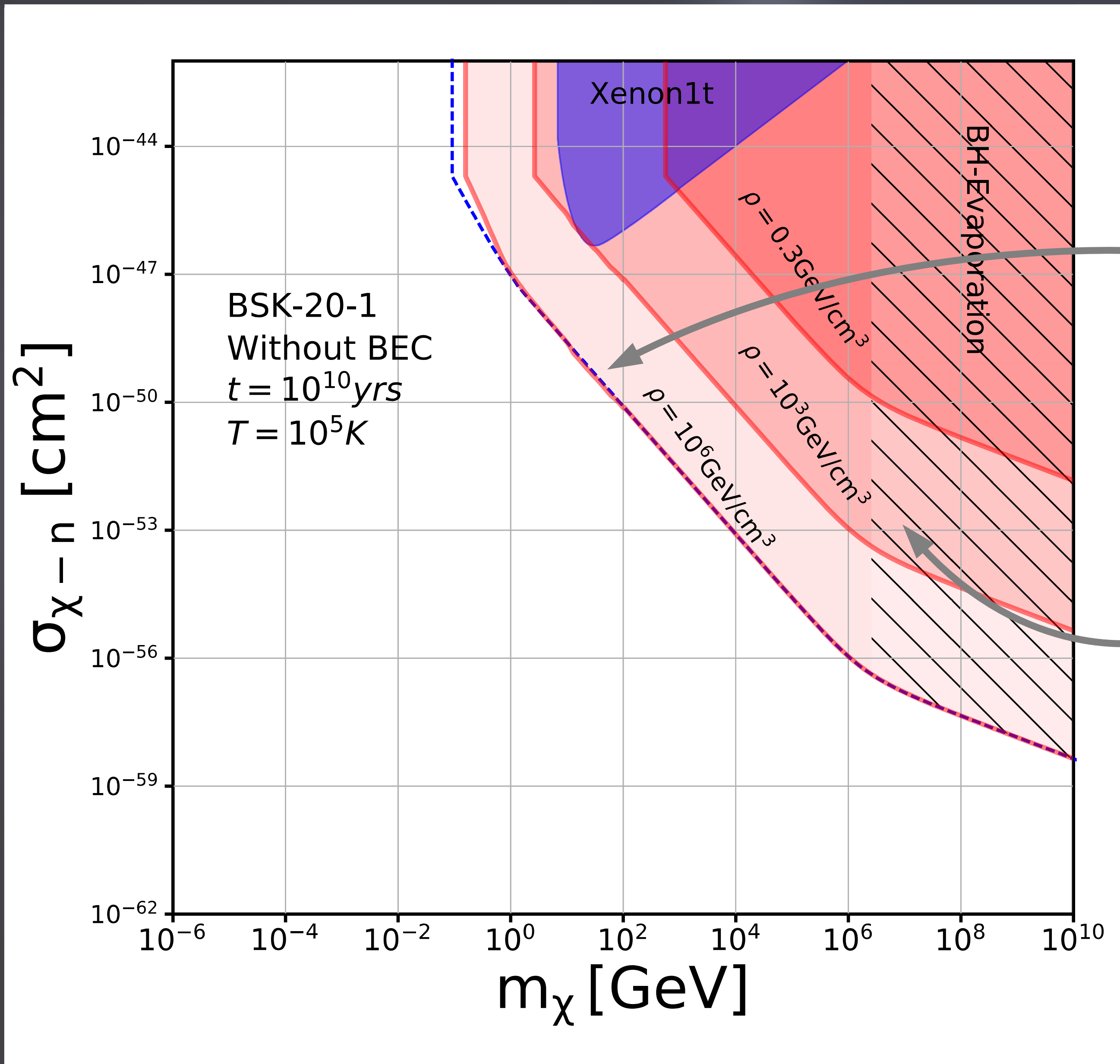
Realistic neutron star models : Potekhin et al A&A 560 2013



Using heuristic argument

McDermott et al 2012



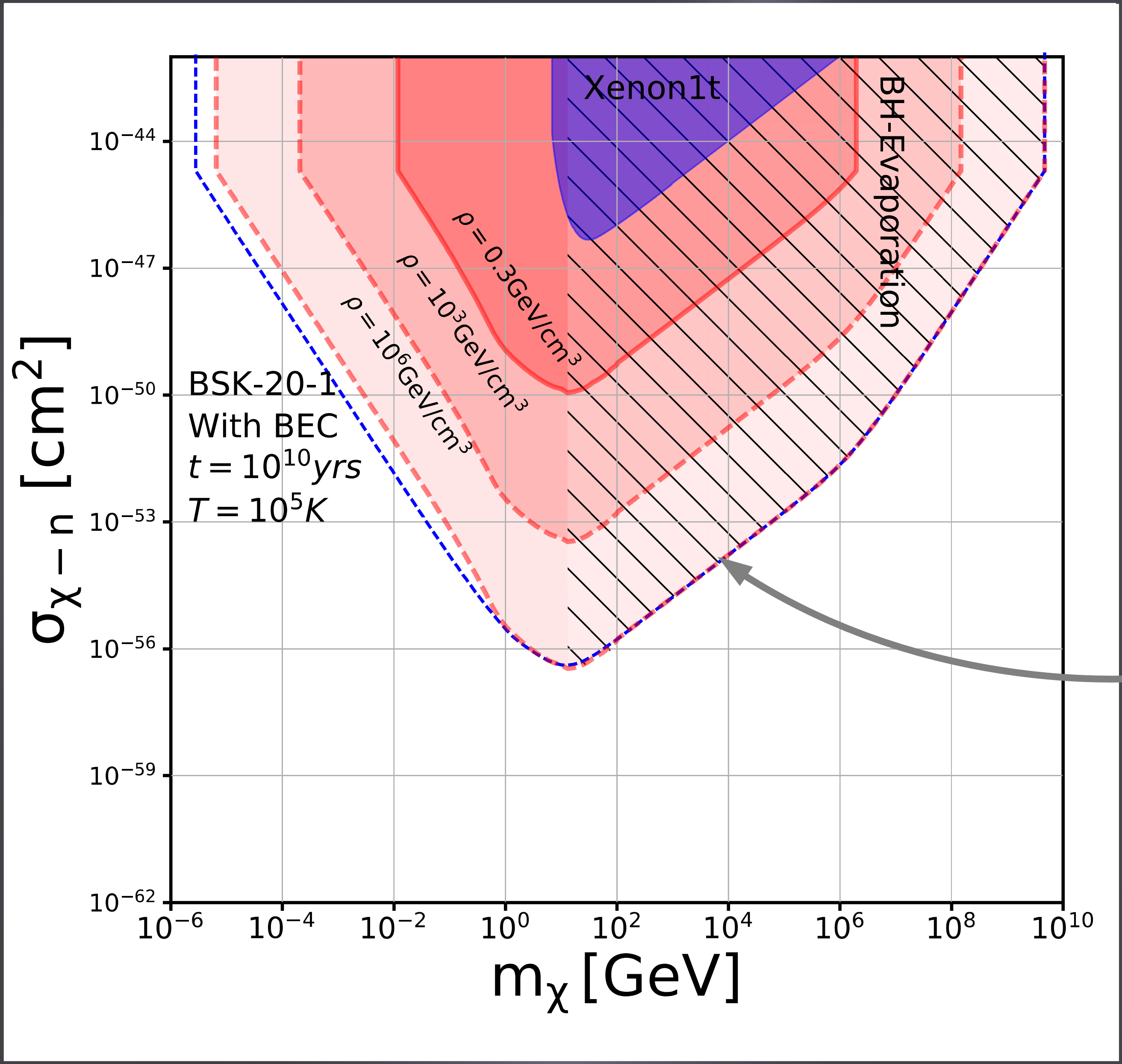
Novel DM constraints

Self-gravitaion condition

$$C_\star^W \times \tau_{old}^{NS} = N_{self}$$

BH evaporates too fast

Confirmation of previous results using heuristic arguments



Novel DM constraints

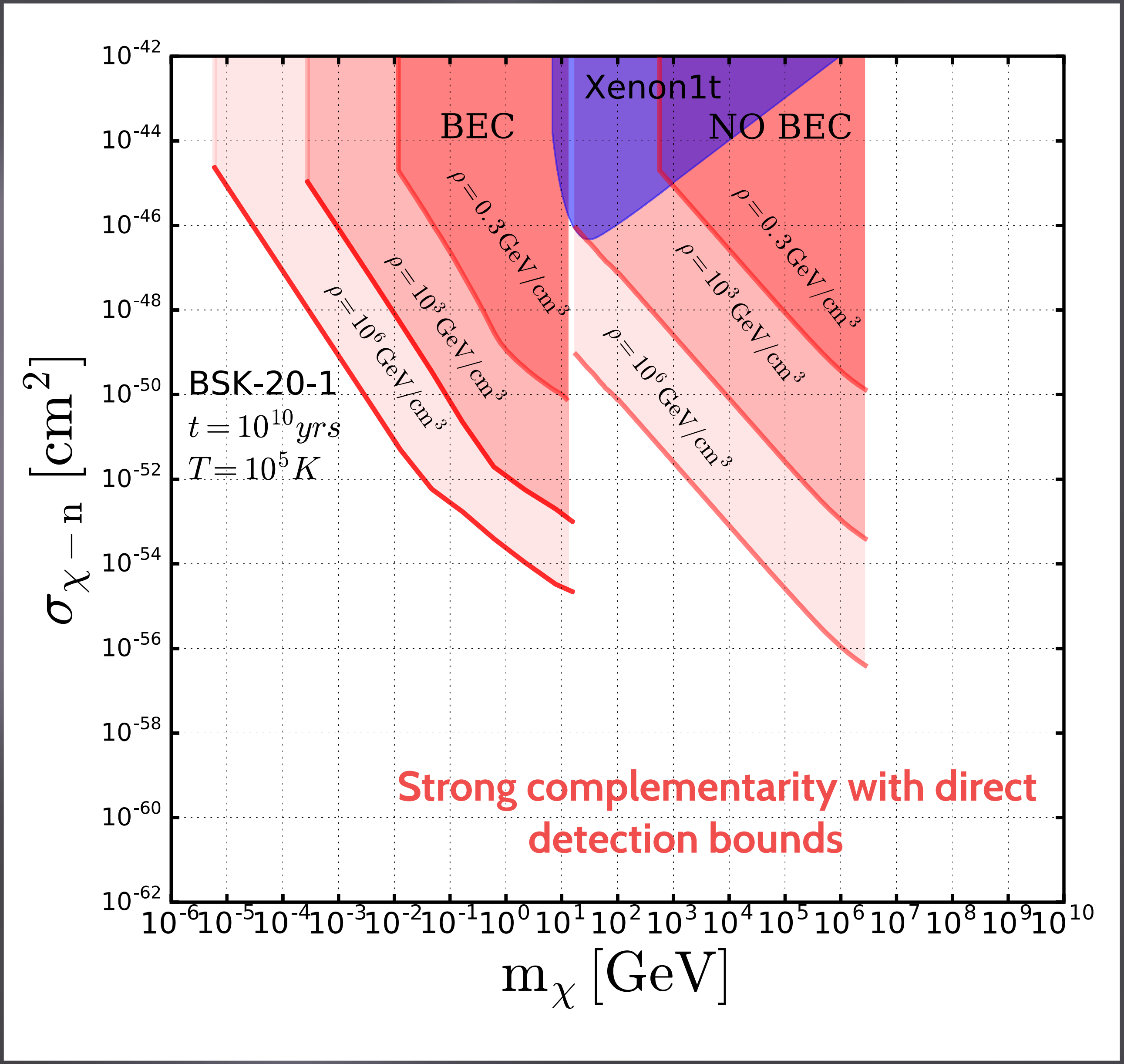
Bose Einstein Condensate

$$N_{self}^{BEC} \ll N_{Chan}^{boson}$$

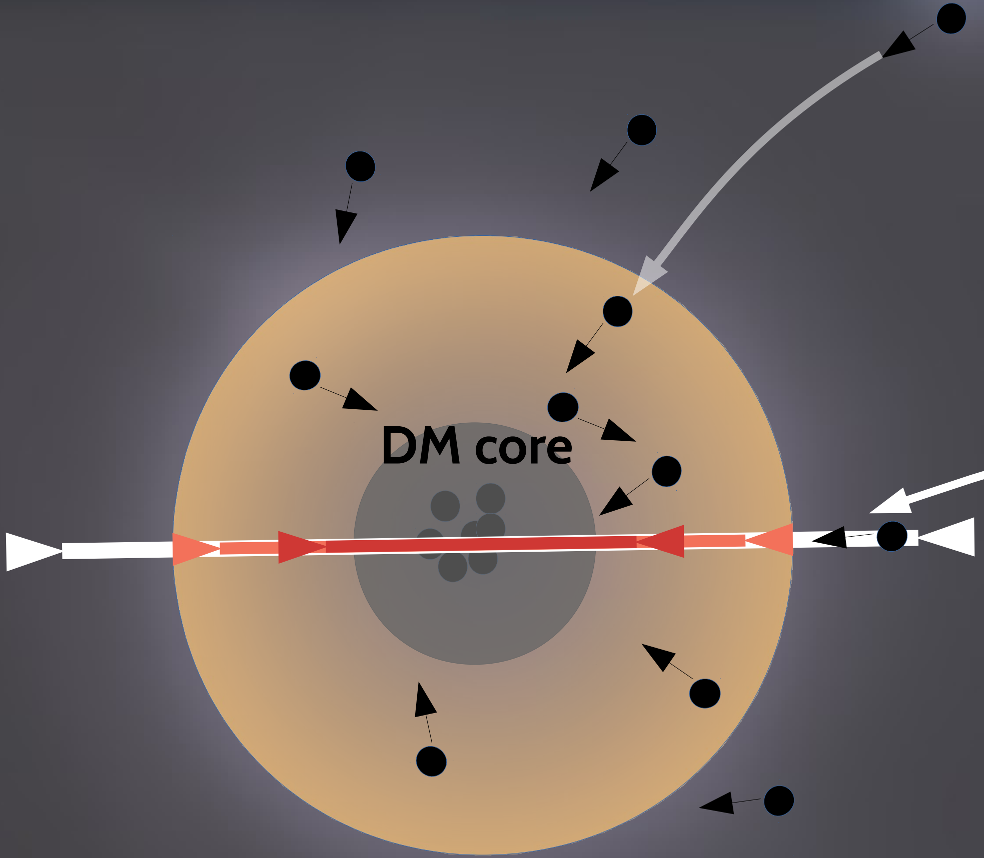
NEW limiting condition

$$C_\star^W \times \tau_{old}^{NS} = N_{Chan}^{boson}$$

Confirmation of previous results using heuristic arguments


Xenon1t
BEC
NO BEC
$\rho = 0.3\,\mathrm{GeV/cm^3}$
$\rho = 10^3\,\mathrm{GeV/cm^3}$
$\rho = 10^6\,\mathrm{GeV/cm^3}$
BSK-20-1
$t = 10^{10} yrs$
$T = 10^5 K$
Strong complementarity with direct detection bounds
$\sigma_{\chi-\mathrm{n}}\ [\mathrm{cm}^2]$
$\mathrm{m}_\chi\ [\mathrm{GeV}]$

III- Revisiting Dark Matter thermalisation



Thermalisation time of DM

Through successive collisions, DM losses energy and accumulates in the star center.

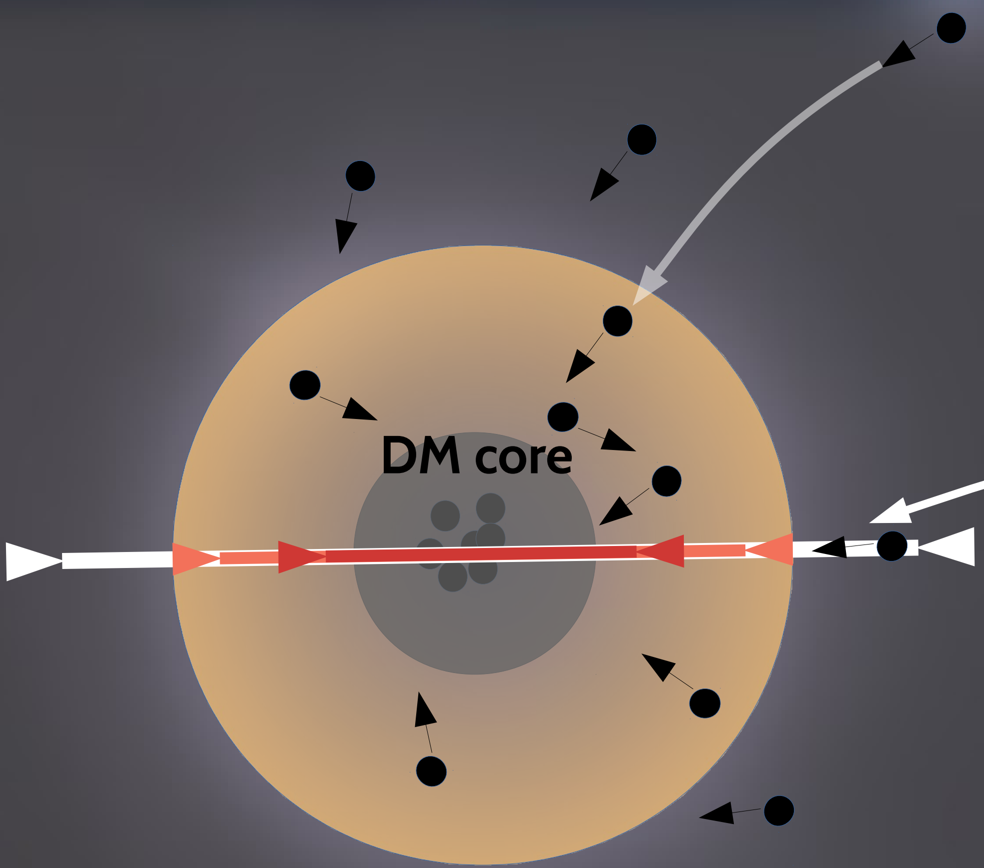
The orbits are shrinking and reach :

$$r_{th}^{NS} = 4.3 \text{ m} \left(\frac{T_{core}}{10^5 \text{K}}\right)^{1/2} \left(\frac{1\text{GeV}}{m_\chi}\right)^{1/2}$$

Differential scattering rate in energy :

$$\frac{d\Gamma}{dE'_k} = \sigma_\chi \frac{m_n^2 m_\chi}{2\pi^2 m_r^2} \sqrt{\frac{E'_k}{E_k}} \left(E_k - E'_k\right)$$

Bertoni et al 2013



Thermalisation time of DM

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The orbits are shrinking and reach :

$$r_{th}^{NS} = 4.3 \text{ m} \left(\frac{T_{core}}{10^5 \text{K}}\right)^{1/2} \left(\frac{1\text{GeV}}{m_\chi}\right)^{1/2}$$

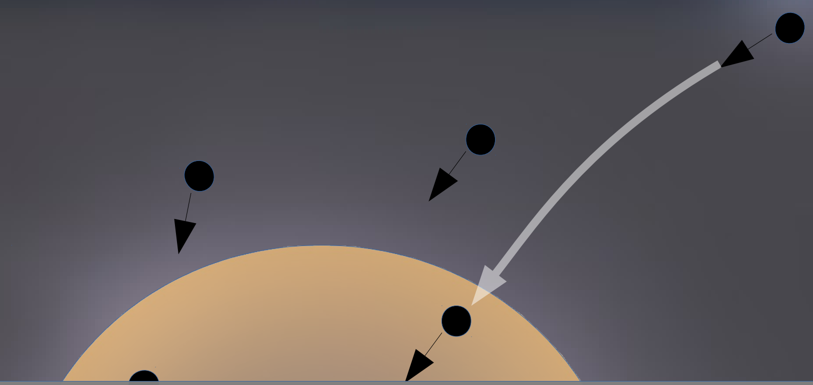
Two **novelties**:

1- Average of the differential energy losses along the orbits.

Differential scattering rate in energy :

$$\frac{d\Gamma}{dE_k'} = \sigma_\chi \frac{m_n^2 m_\chi}{2\pi^2 m_r^2} \sqrt{\frac{E_k'}{E_k}} \left(E_k - E_k'\right)$$

Bertoni et al 2013



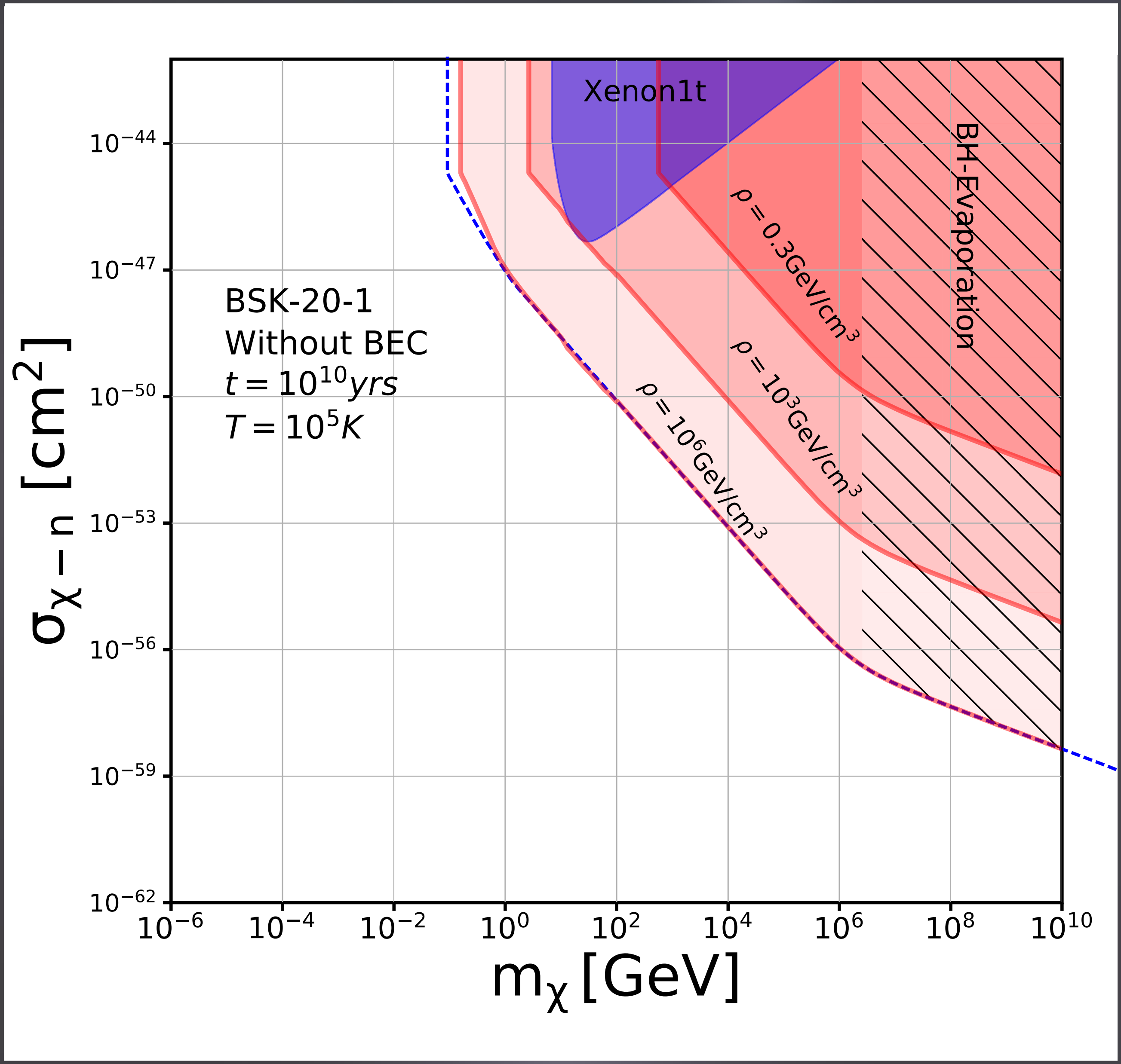
Thermalisation time of DM

Through successive collisions, DM losses energy and accumulates in the star center.

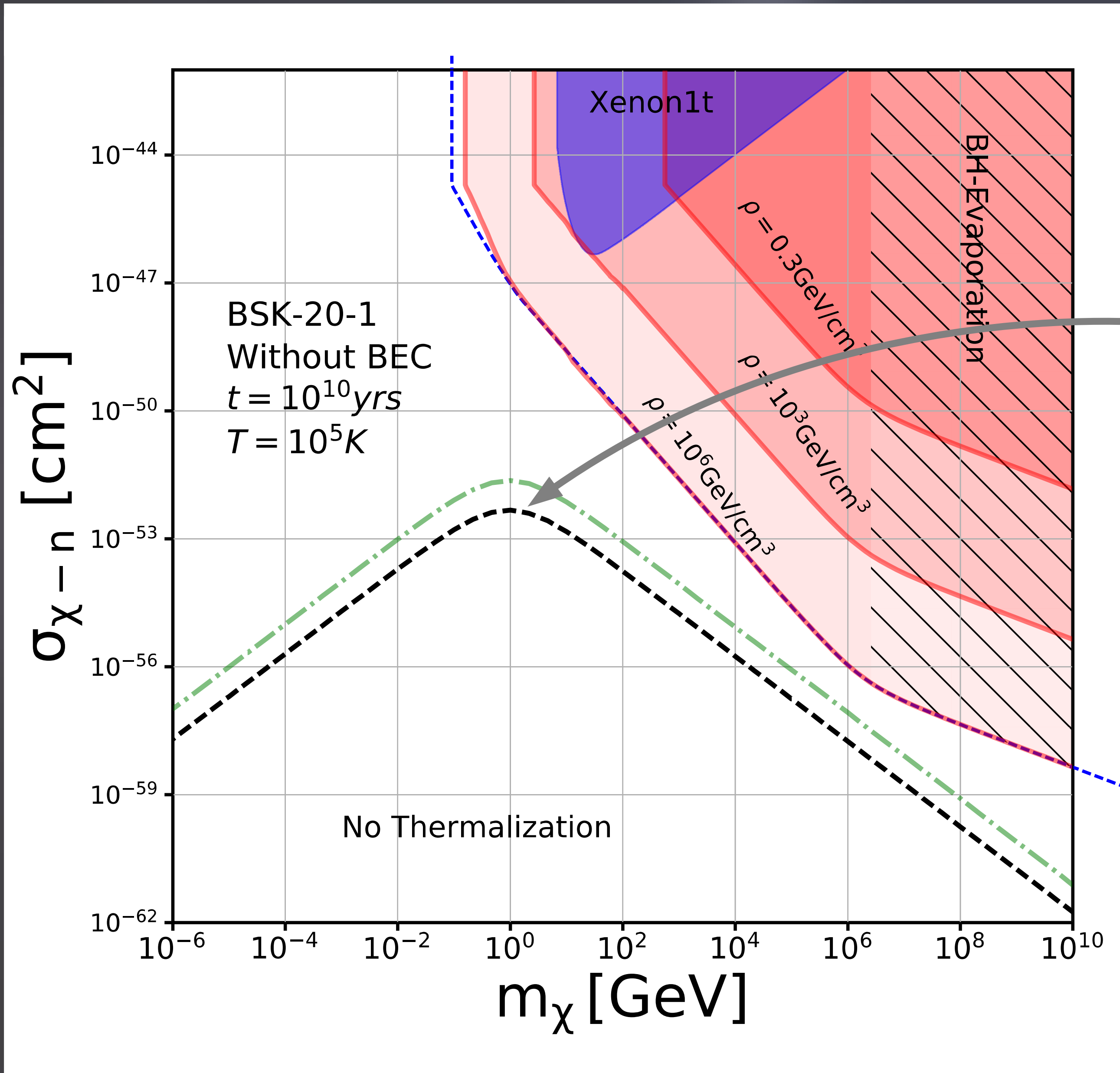
$$t_2 = \int_{E_{\rm surf}}^{E_{\rm th}} \frac{dE}{b_2(E)}\,.$$

$$t_2 \approx \frac{21\pi^2 m_r^2}{\sigma_\chi m_n^2 m_\chi}\frac{1}{E_{th}^2} \approx 10700 \text{ yrs } \frac{\gamma}{(1+\gamma)^2}\left(\frac{10^5\,\mathrm{K}}{T}\right)^2\left(\frac{10^{-45}\mathrm{cm}^2}{\sigma_\chi}\right)$$

For a given time, we define and upper bound below which ***DM particles « do not thermalize »***

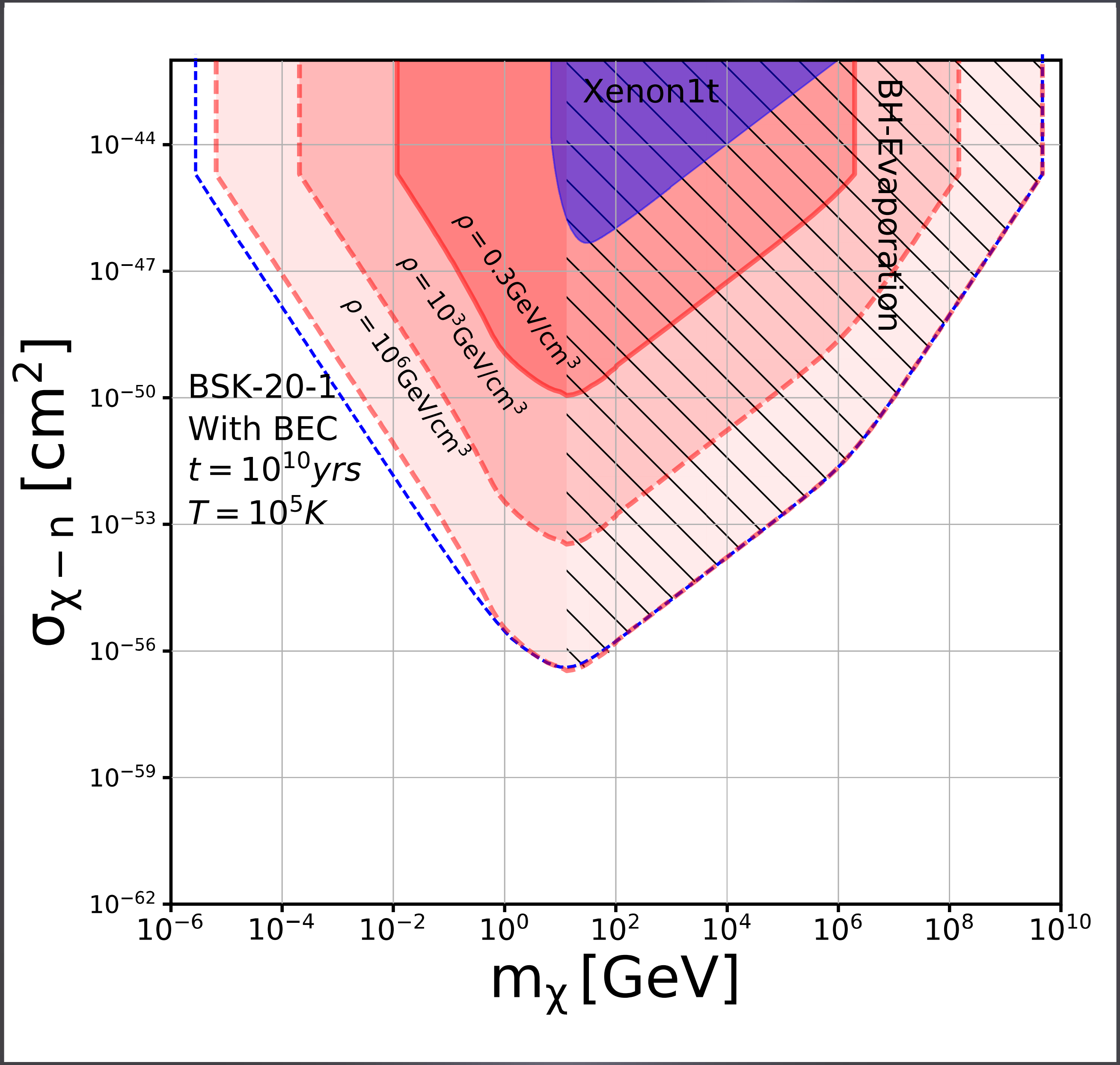


Novel Thermalisation bound

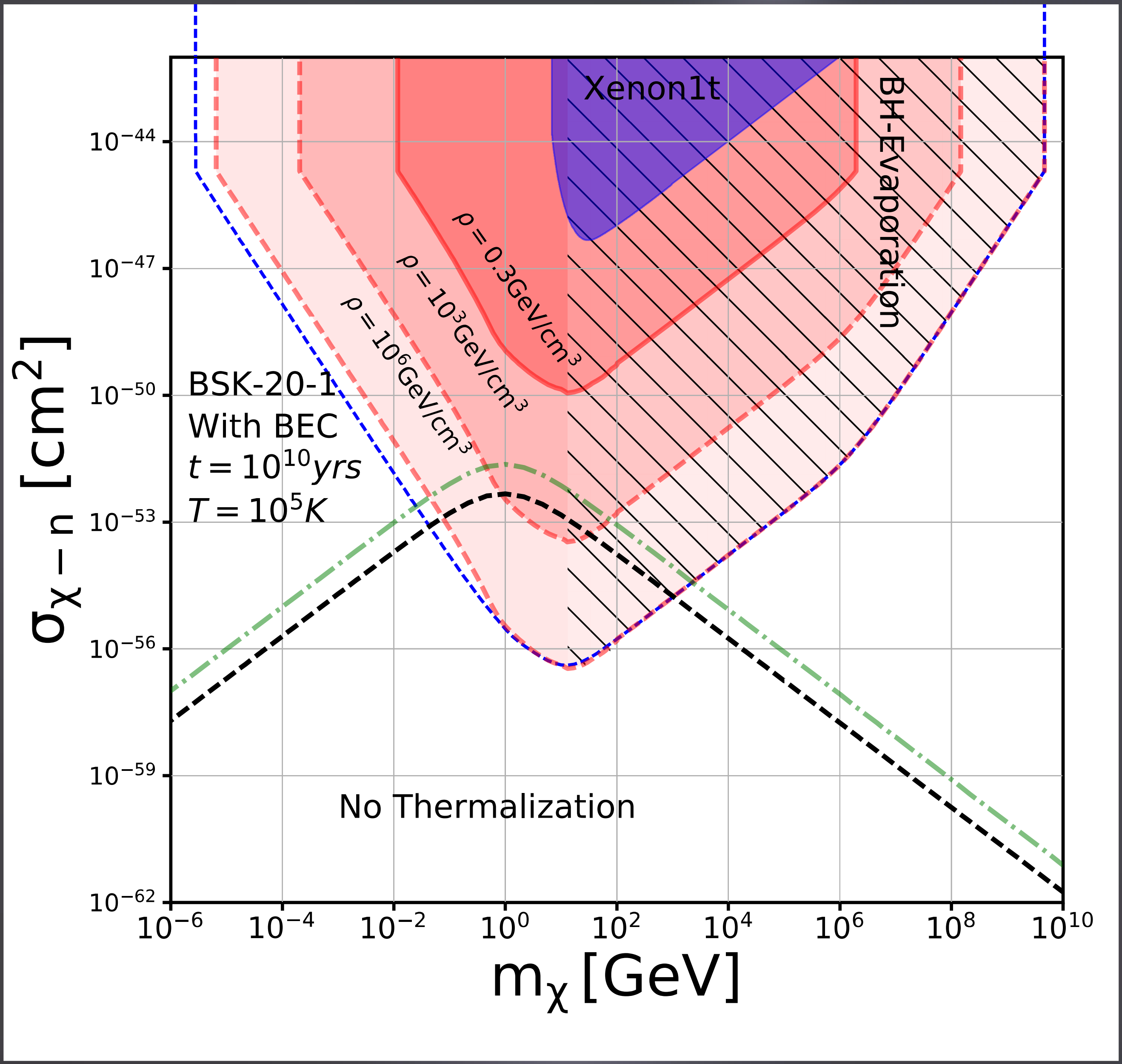


Novel Thermalisation bound

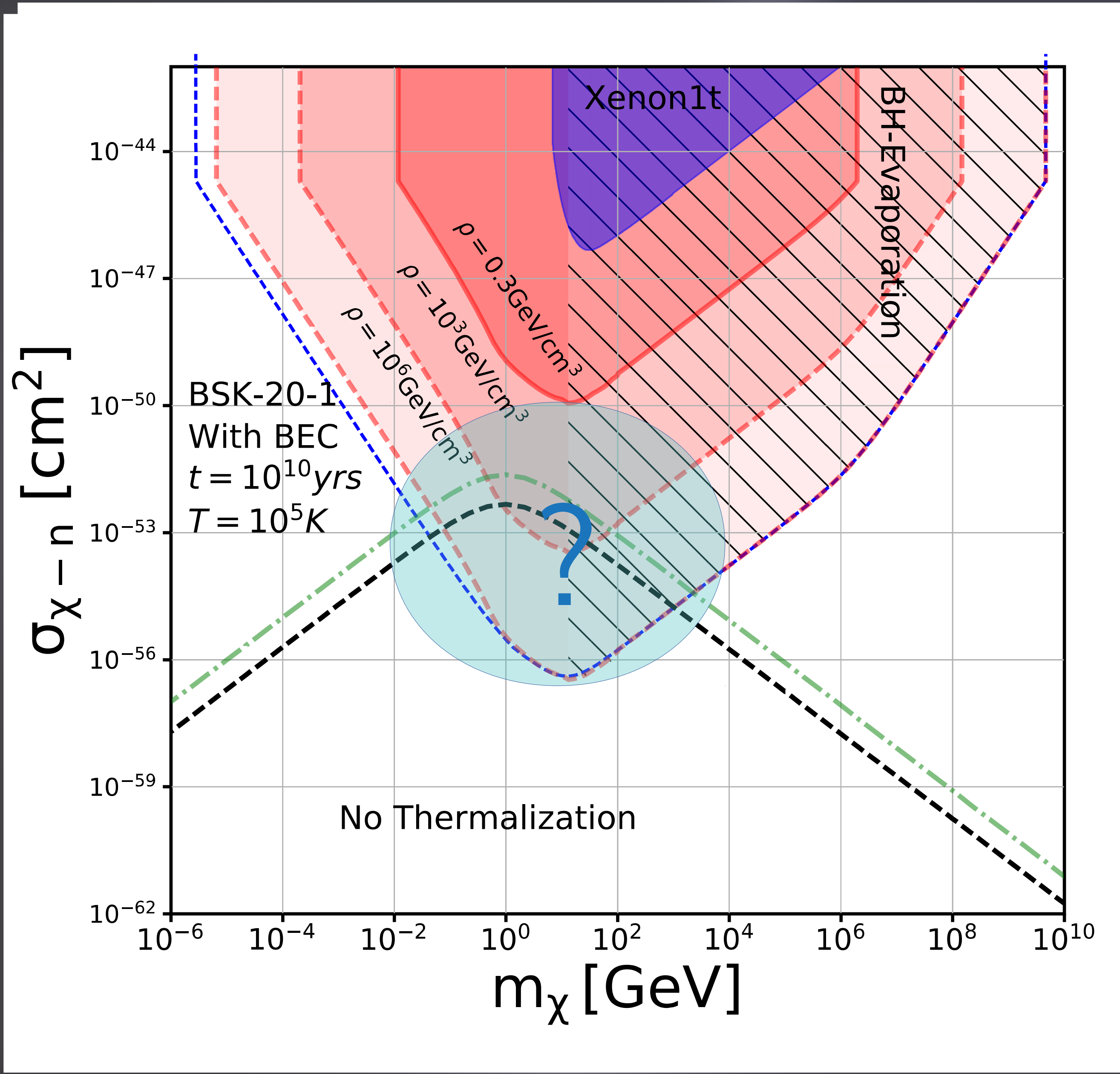
Bertoni et al 2013



Novel Thermalisation bound



Novel Thermalisation bound



Novel Thermalisation bound

The limits do not hold in the « No thermalisation » region

For larger cross-sections, a larger amount of DM is accreted and a sufficient amount of DM might have thermalized

To go beyond..second **novelty**:

2- Solve the time dependent equation of DM **energy distribution**.

$$\frac{\partial f_\chi}{\partial t}(E,t) = \int_E^{+\infty} dE' \frac{d\Gamma}{dE'}(E' \to E) f_\chi(E',t) - \Gamma(E) f_\chi(E,t) + q(E,t)$$

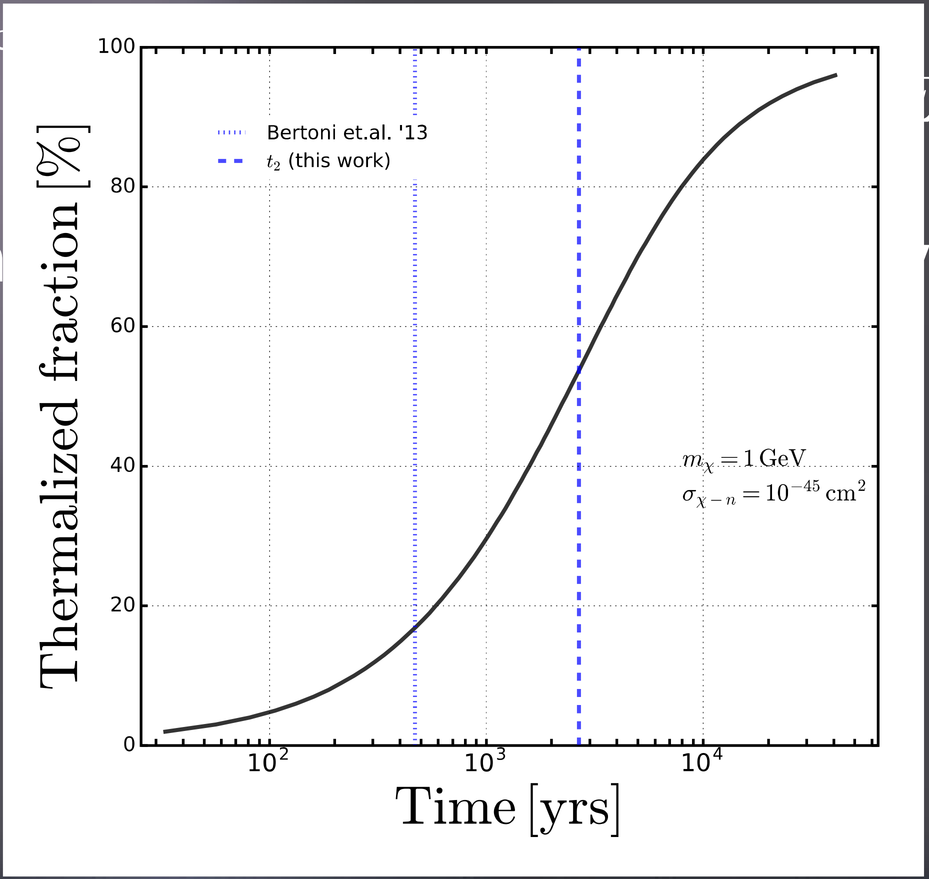
➡ The number of DM particles which have thermalized.

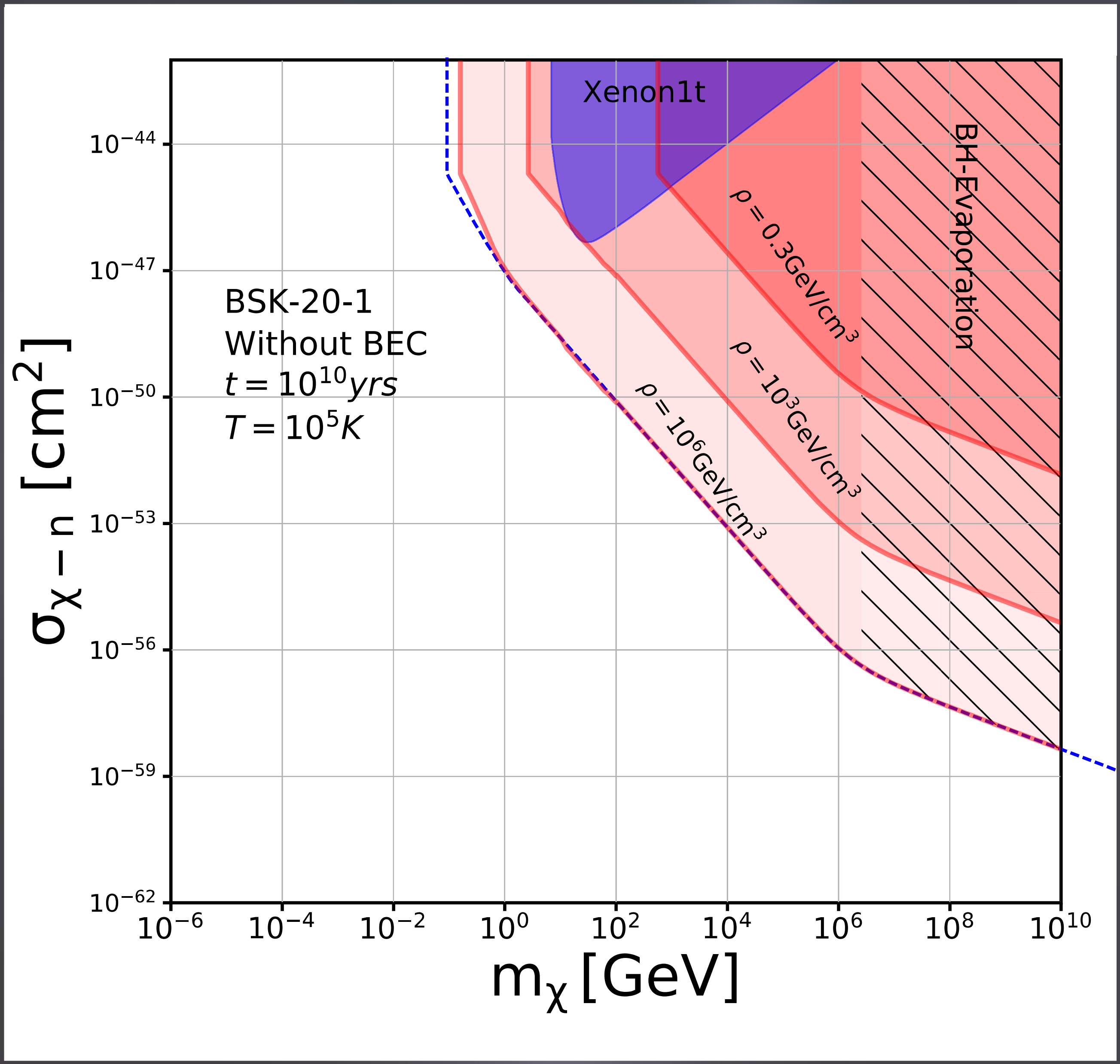
To go beyond..second novelty:

2- Solve the time dependent equation of DM energy distribution.

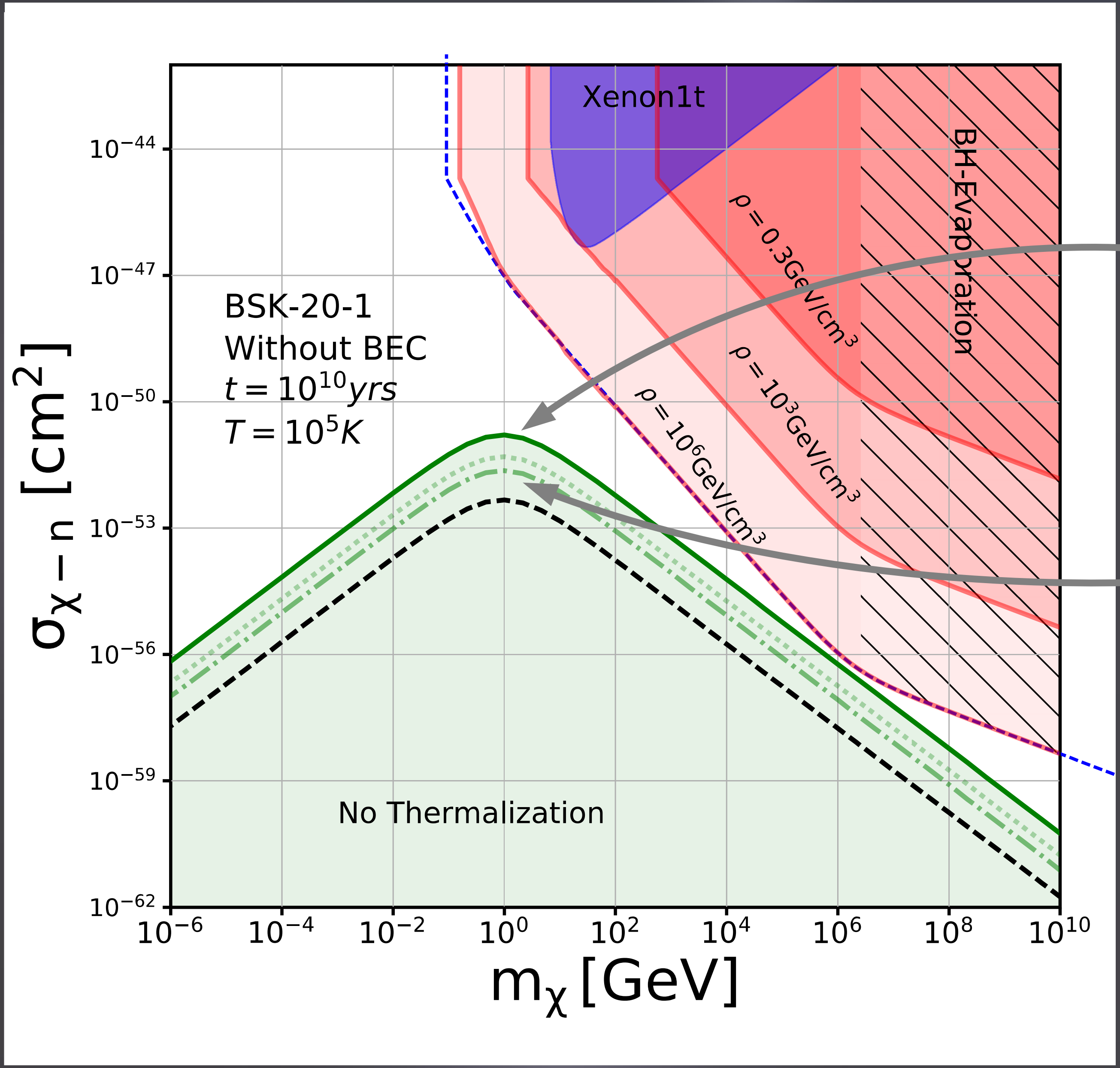
$$\frac{\partial f_\chi}{\partial t}(E,t) = \int_E^{+\infty} \quad \ldots \quad E) f_\chi(E,t) + q(E,t)$$

➡ The num … e thermalized.





Novel **Thermalisation bound**

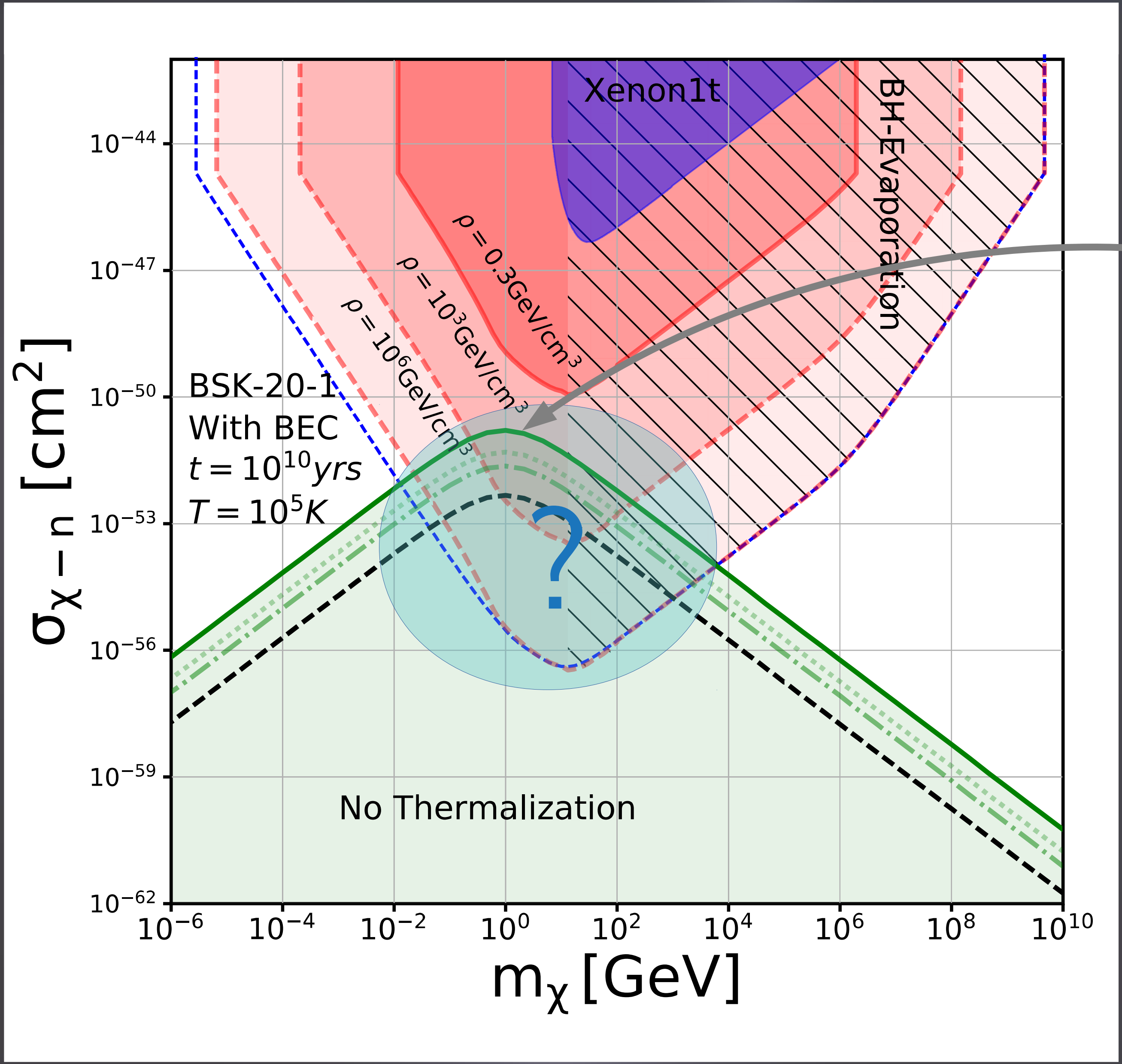


Novel Thermalisation bound

90 % of the particles
In thermal equilibrium

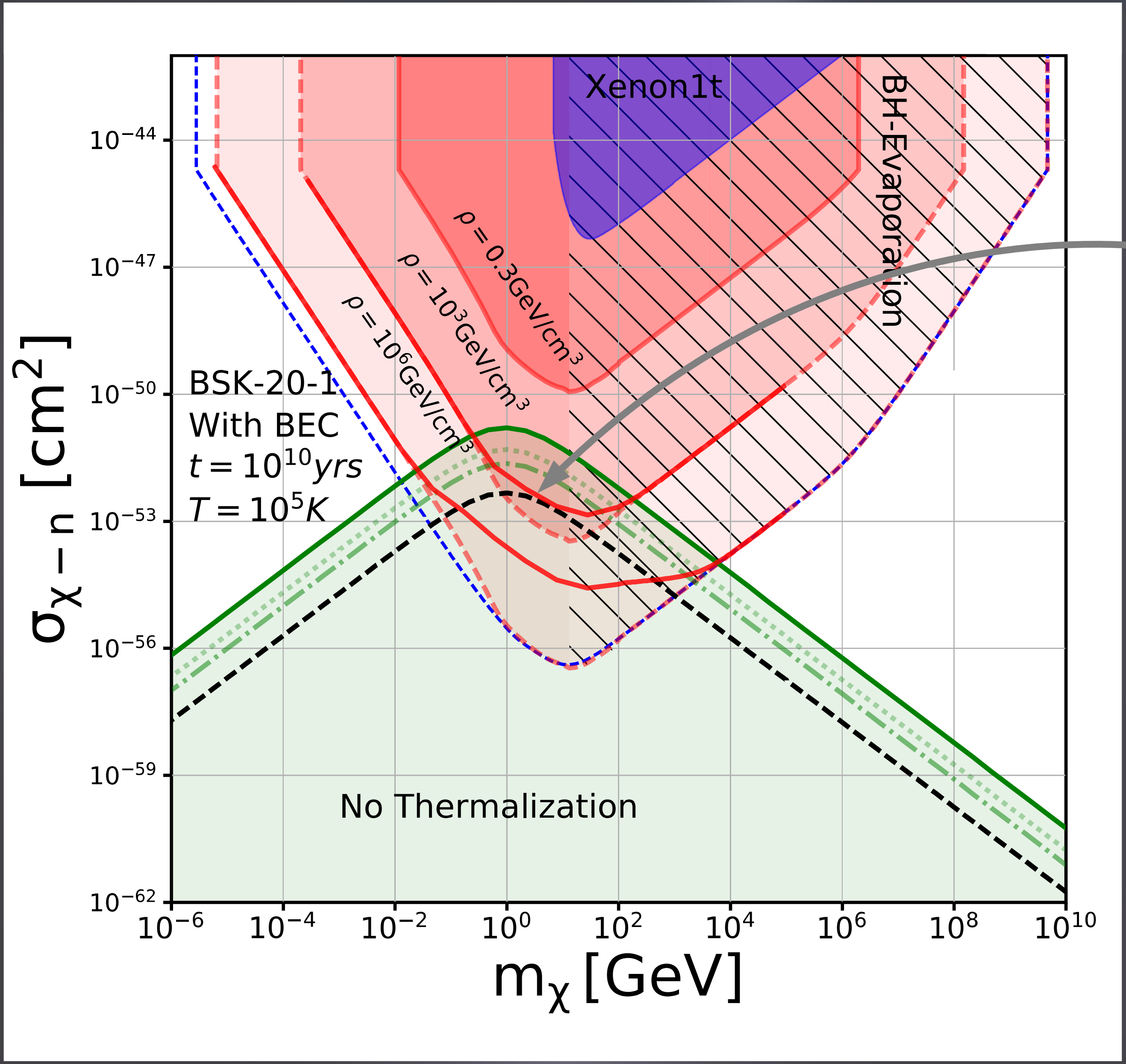
Thermalisation hypothesis OK!

50 % of the particles
In thermal equilibrium



Novel Thermalisation bound

90 % of the particles
In thermal equilibrium



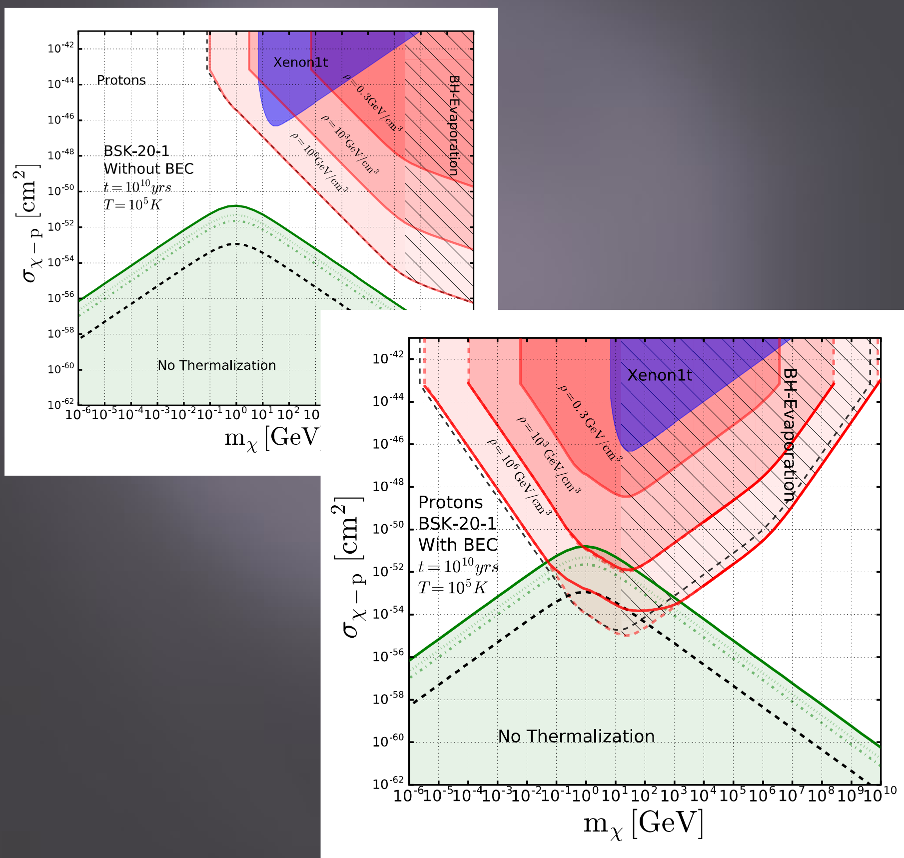
Novel Thermalisation bound

NEW bounds!

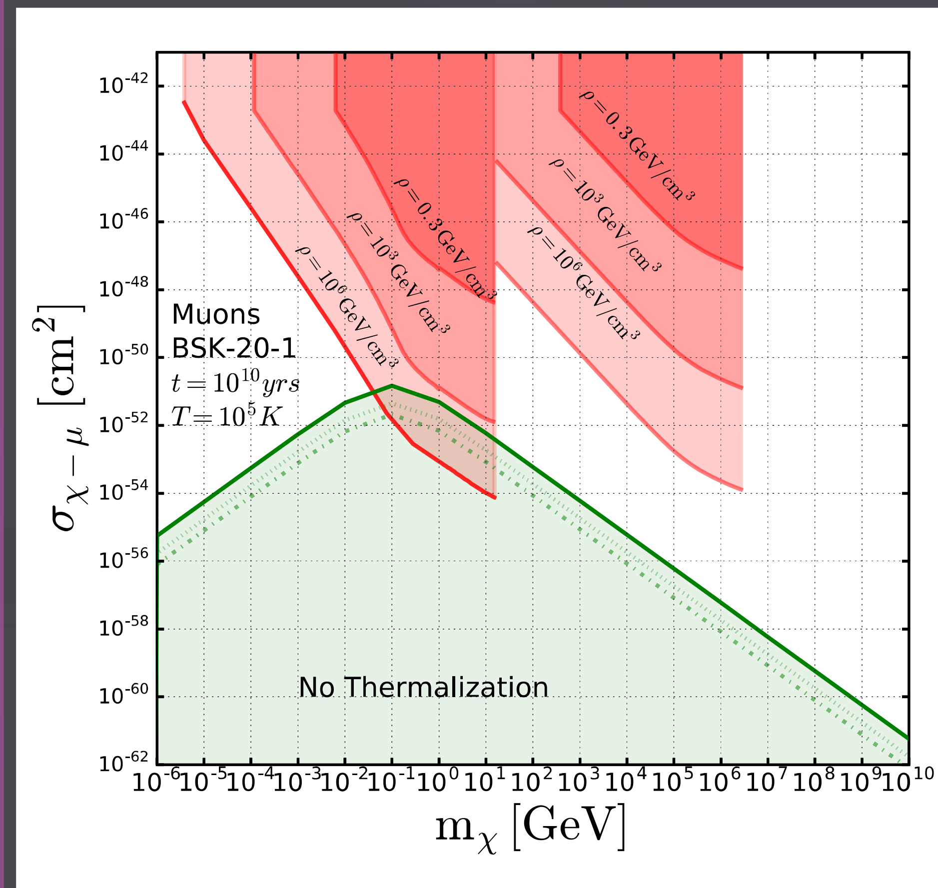
Gain of orders of magnitudes from observations of old NS in dense environement!

IV- More results and conclusion

Consistently with the NS EOS we extend our contraints to the other components ...

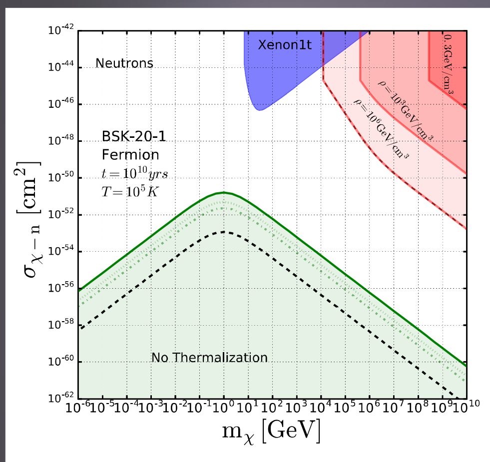


Protons

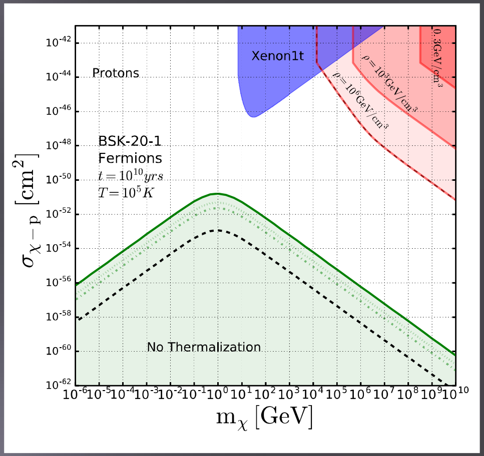


Muons !

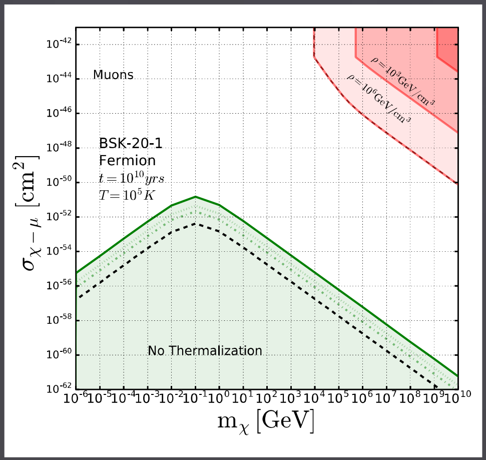
Case of fermionic DM particle



Neutrons



Protons



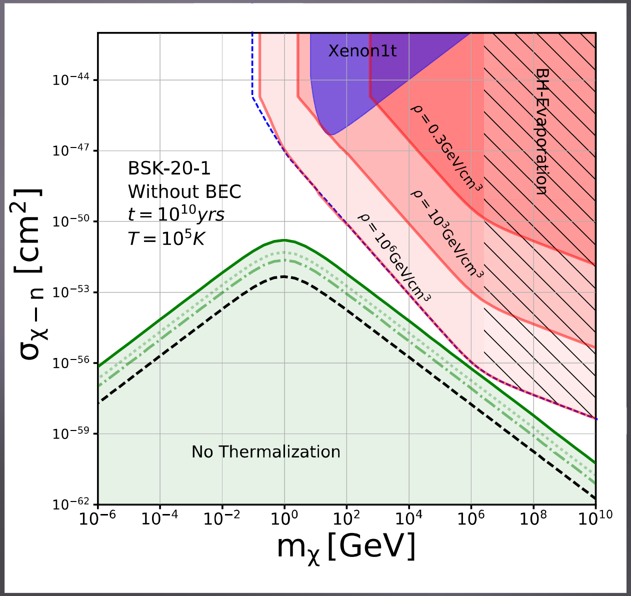
Muons

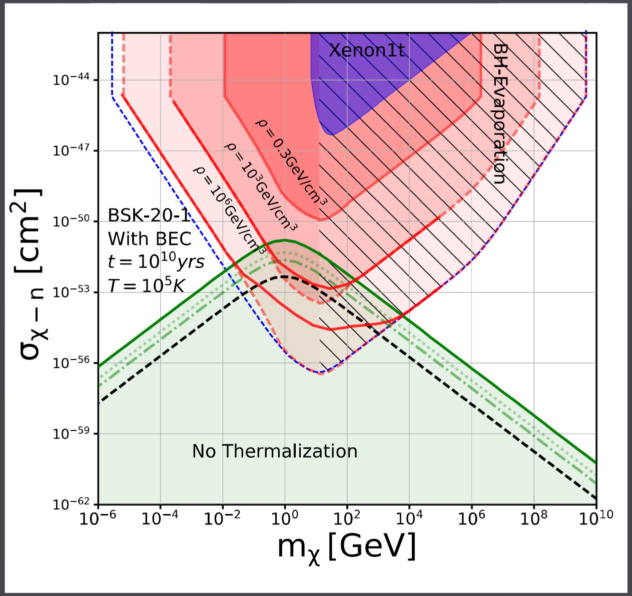
Conclusion & prospects:

-New formalism for capture, let include realistic NS profiles.

-New Dark Matter constraints, (n, p, mu) & improved treatment of thermalization.

-Robust constraints : tested with several EOS still allowed by data





-Could be a leading mecanism for « Light » black hole formation detected by GW ?