DM Bound State Formation in the Sun

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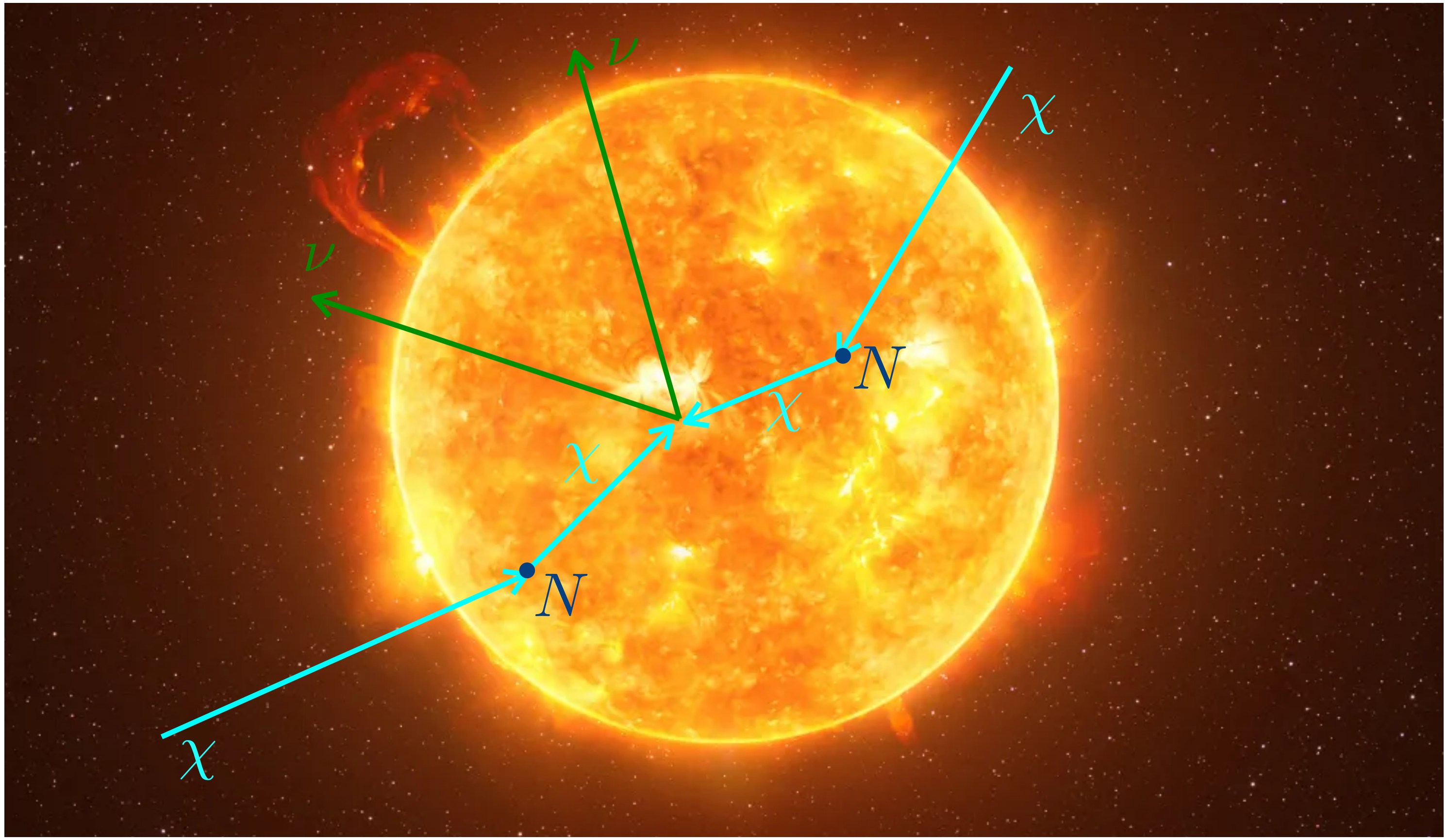
DM capture in the Sun

capture of DM by the Sun through DM-nucleon scatterings, followed by DM annihilation ⇒ flux of primary or secondary neutrinos: observable on earth

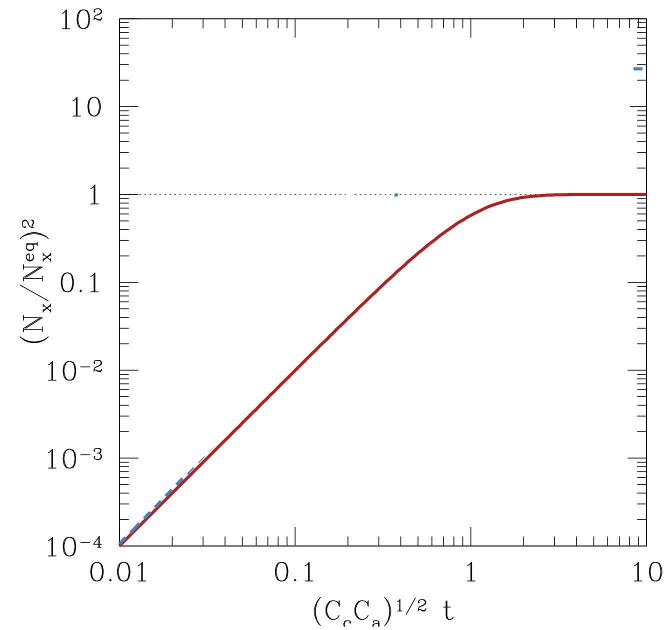


DM capture in the Sun: equilibrium between capture and annihilation

$\Rightarrow$ $$\frac{dN_\chi}{dt} = C_\star - AN_\chi^2$$

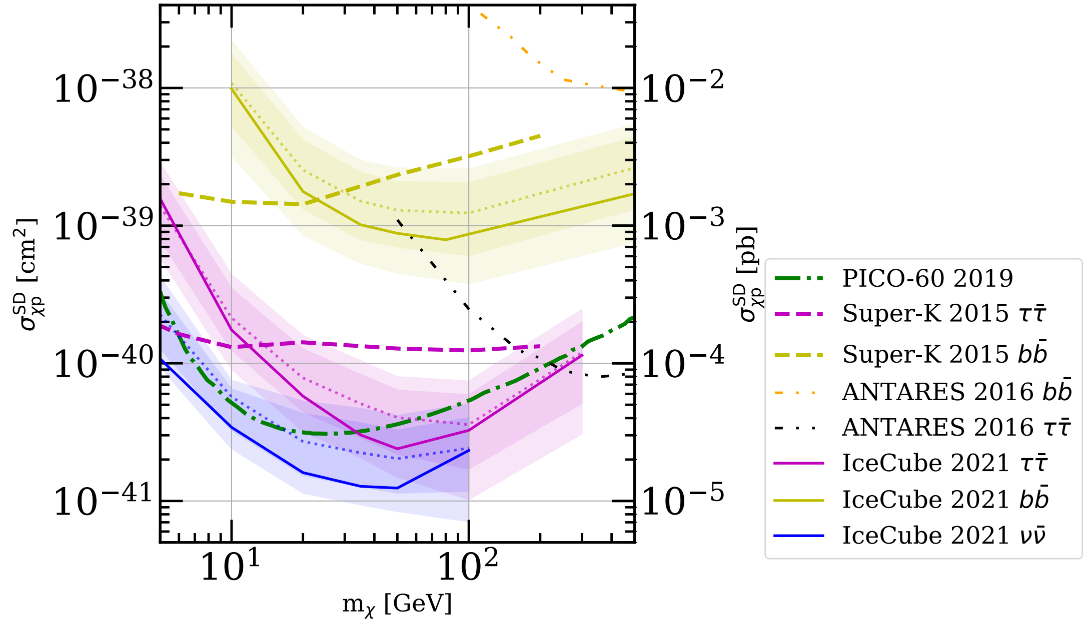
$\Rightarrow$ annihilation equilibrates the capture $N_\chi = \sqrt{C_\star/A}$

neutrino flux $f_\nu \propto C_\star$



$\Rightarrow$ upper bound on DM-nucleon elastic cross section from DM capture in the Sun

(spin-dependent)



applies to the symmetric DM case because requires annihilation

limited accumulation of DM due to the annihilation

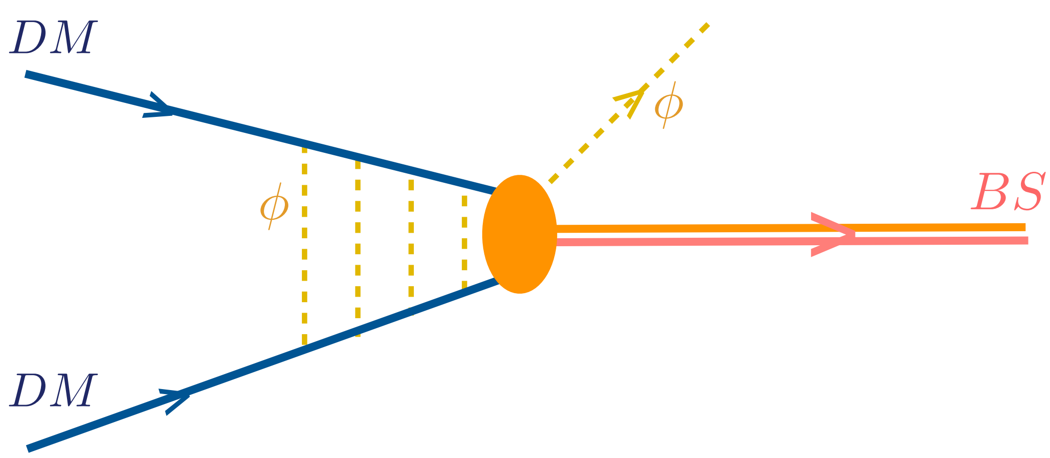
A possibility to probe capture of asymmetric DM in the Sun with large DM accumulation:

Dark matter bound state formation in the Sun

2 DM particles undergoing an attractive force can form a bound state

→ for instance from a Yukawa interaction with a light scalar ϕ

→ BSF proceeds from the emission of this light scalar



→ allow to emit an observable flux even for the asymmetric DM case!

→ without destroying the DM particles!

→ allowing more accumulation of DM particles in the Sun

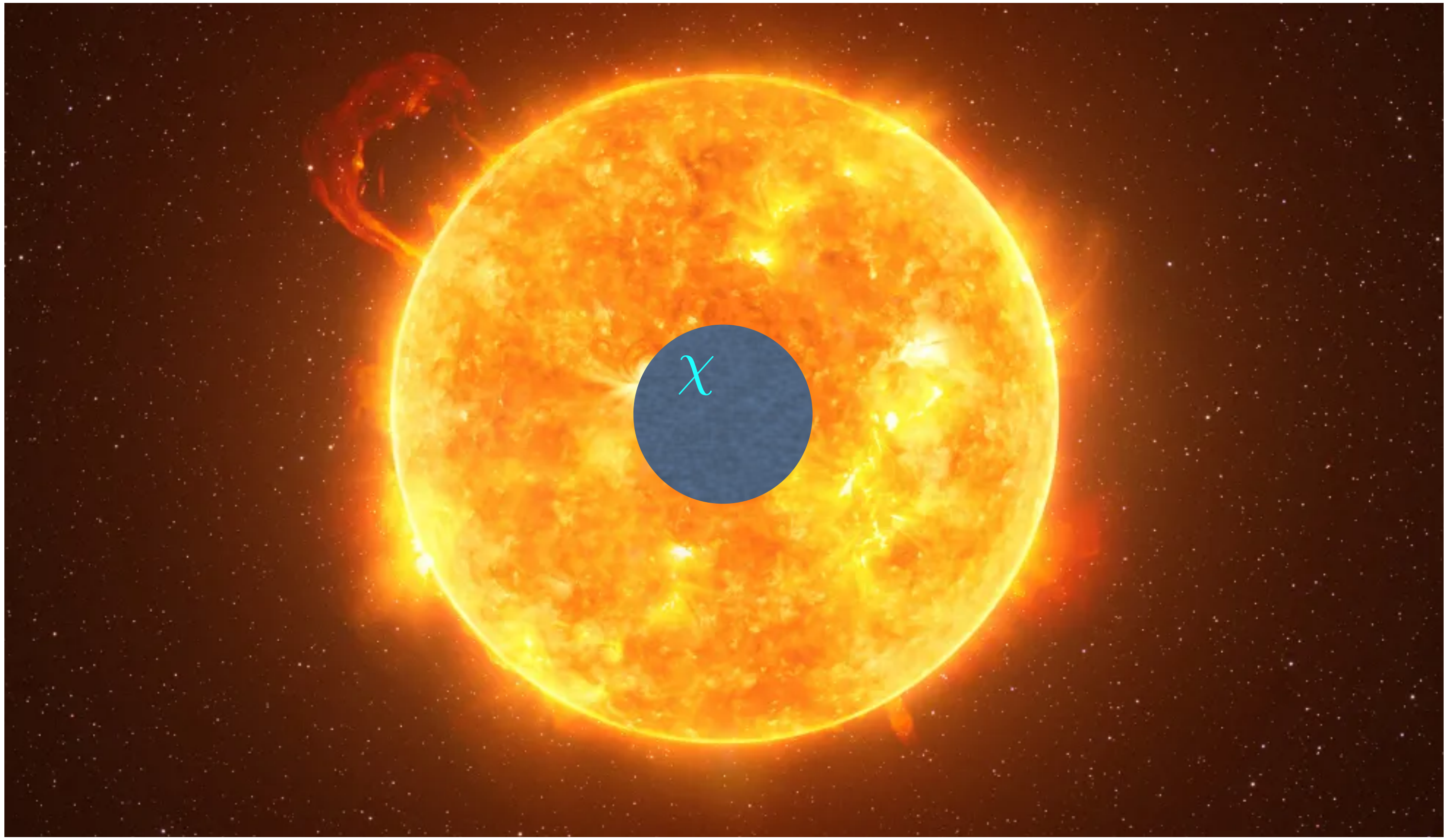
→ leading to enhancement of the emitted flux

Capture and thermalization of DM within a DM core

DM capture on nucleons: linear grow of N_χ

$$\frac{dN_\chi}{dt} = C_\star$$

captured DM particles interact with nucleons and thermalize with them forming a thermalized core in the center of the Sun: $E_\chi^{cin} \sim \frac{3}{2} T_{sun}$



BSF catches up the capture on nucleons

$$\frac{dN_\chi}{dt} = C_\star - A_{bsf} N_\chi^2 \Rightarrow$$ equilibrium between BSF and capture on nucleons

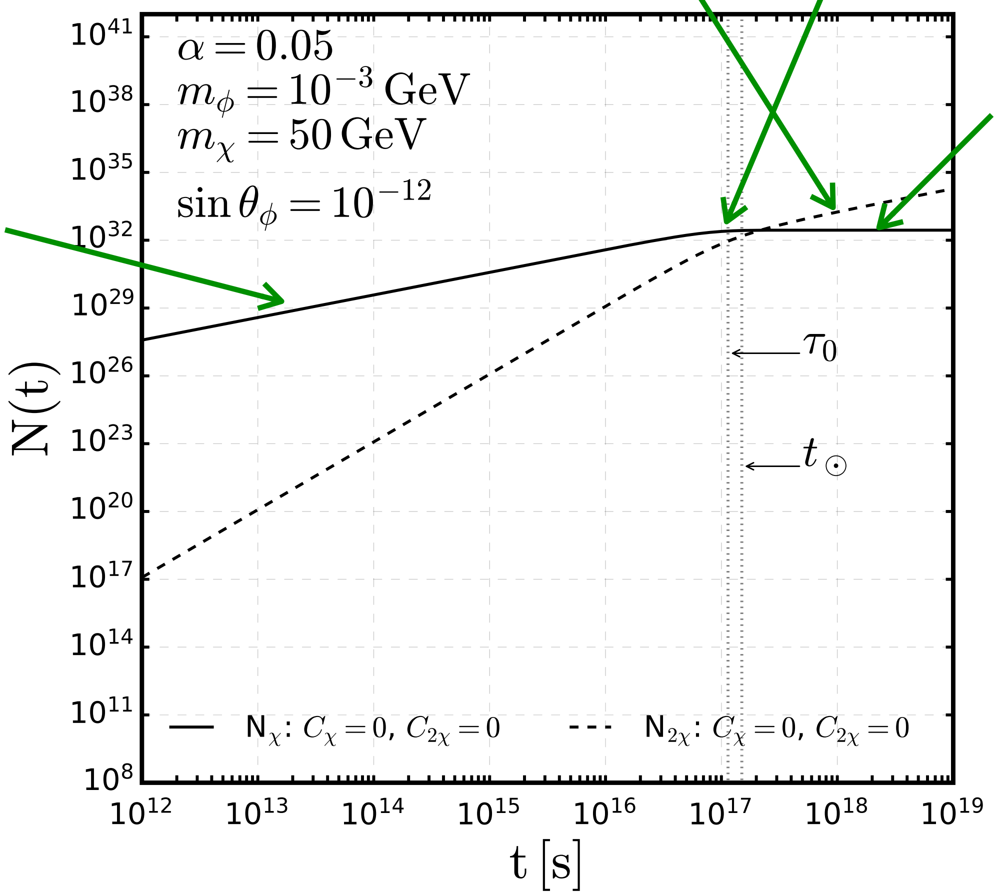
$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2 \Rightarrow$$ BS number do not stop to grow

BSF catching up the capture

linear grow from capture on nucleons

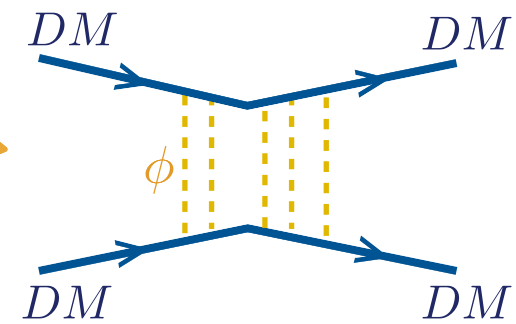
equilibrium between BSF and capture on nucleons

$$t_{equil} \equiv \tau_0 \simeq (C_\star A_{bsf})^{-1/2}$$



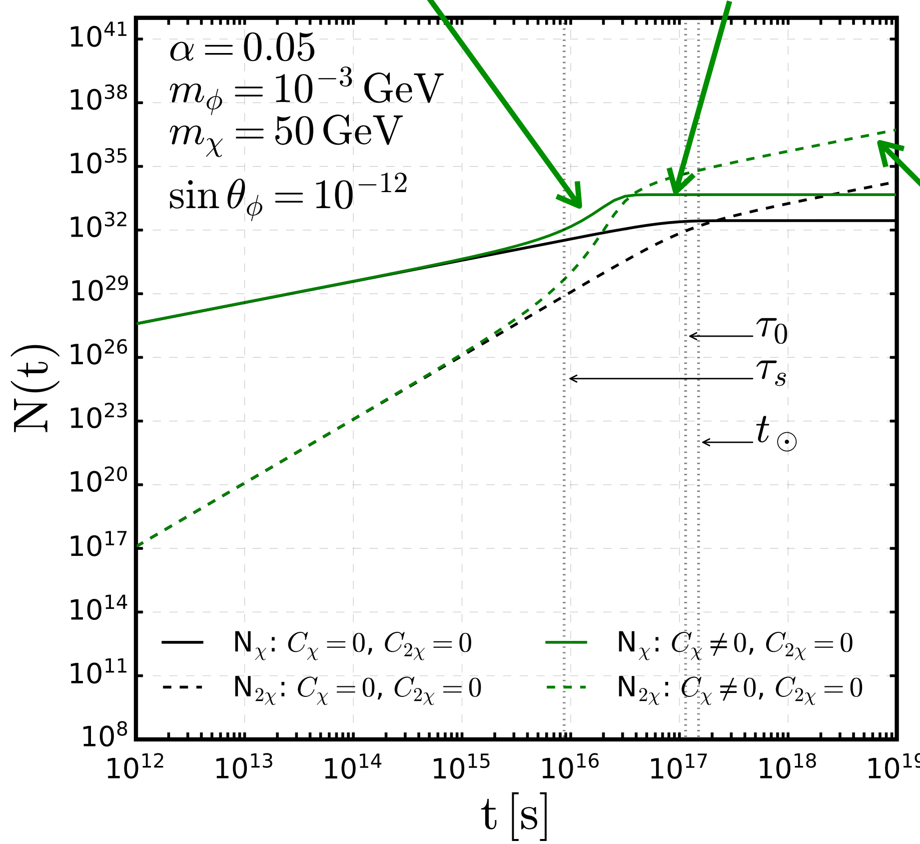
DM capture from DM self-interactions: capture on DM

$$\frac{dN_\chi}{dt} = C_\star - A_{bsf} N_\chi^2 + C_\chi N_\chi$$



exponential increase of N_χ

quick equilibrium with BSF

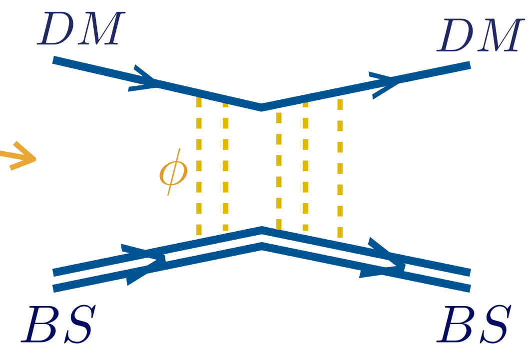


BS number do not stop to grow

$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$

DM capture from DM self-interactions: capture on BS

$$\frac{dN_\chi}{dt} = C_\star - A_{bsf} N_\chi^2 + C_\chi N_\chi + C_{2\chi} N_{2\chi}$$

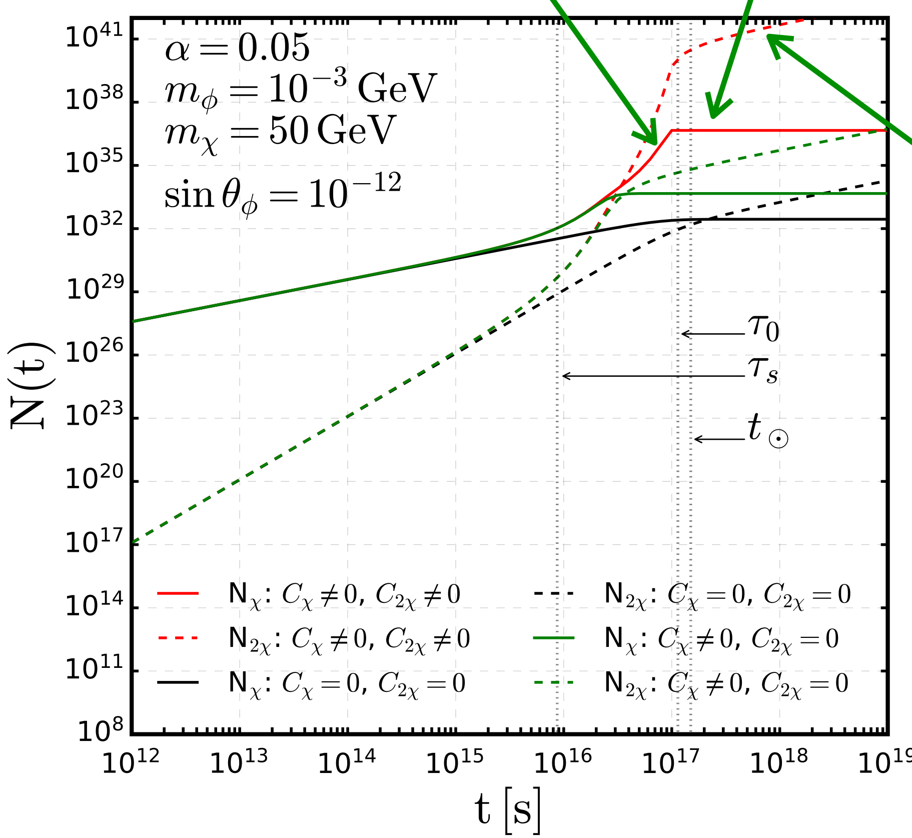


$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$

$$\frac{\mathrm{d}^2 N_\chi}{\mathrm{d}^2 t} = \left(-2A_{\rm bsf} N_\chi + C_\chi\right) \frac{\mathrm{d}N_\chi}{\mathrm{d}t} + \frac{1}{2} C_{2\chi} A_{\rm bsf} N_\chi^2$$

enhanced exponential increase of N_χ

saturation of the geometric rate



BS number does not stop to grow

$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$

Thermal radius for DM and for BS and geometric rates

once captured/formed the DM/BS particles thermalize with nucleons

→ orbits within thermal spheres whose radius are

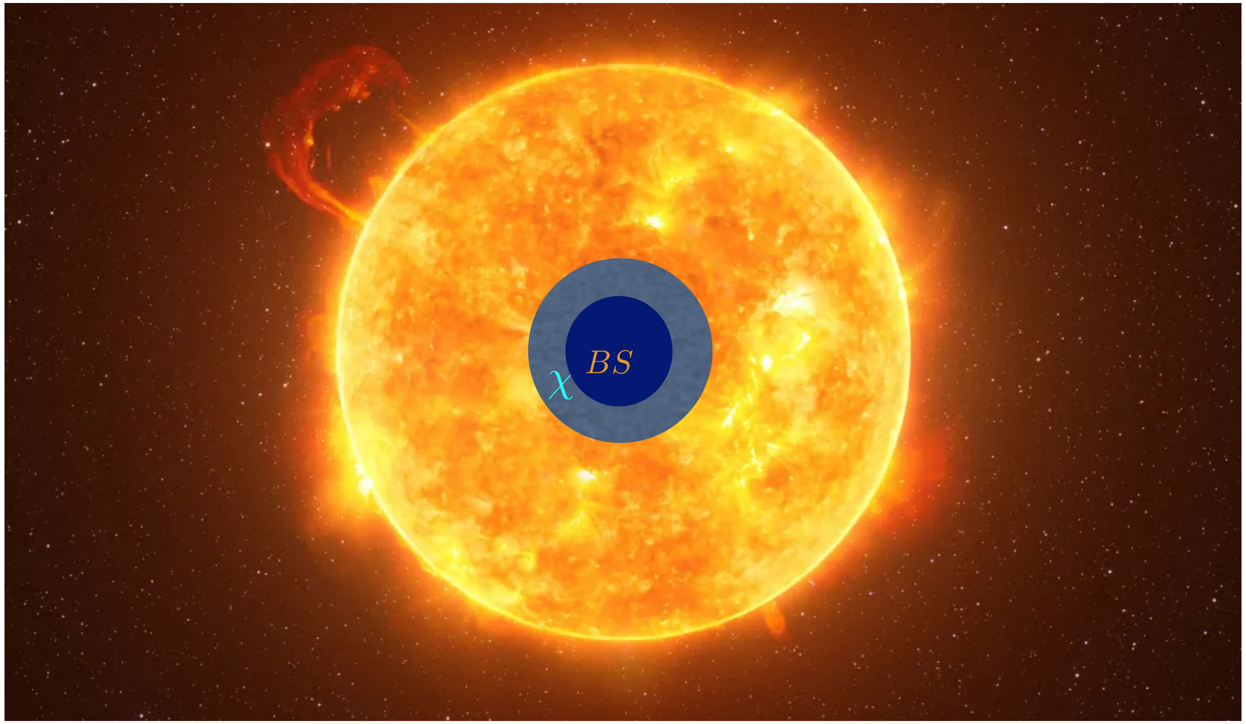
Press, Spergel 85'

Garani, Palomares-Ruiz 17'

$$\frac{2}{3}\pi G r_{th}^2 \rho_{sun} n m_\chi \sim \frac{3}{2} T_{sun} \Rightarrow r_{\rm th} = \left(\frac{9T_\odot}{4\pi G \rho_\odot n m_\chi}\right)^{\frac{1}{2}} = 0.03 R_\odot \left(\frac{T_\odot}{2.2\,{\rm keV}} \frac{150\,\frac{\rm g}{\rm cm^3}}{\rho_\odot} \frac{10\,{\rm GeV}}{n\, m_\chi}\right)^{\frac{1}{2}},$$

$n = 1 \leftarrow \chi$

$n = 2 \leftarrow BS$



capture geometric rate on nucleons: $C_\star^g = \frac{\rho_\chi}{m_\chi} \pi R_\odot^2 \bar{v} \simeq 6 \times 10^{28}\,{\rm s}^{-1} \left(\frac{\rho_\chi}{0.3\,{\rm GeV/cm^3}} \cdot \frac{10\,{\rm GeV}}{m_\chi}\right)$ never saturates

capture geometric rate on DM: $C_\chi^g = 5 \times 10^{25}\,{\rm s}^{-1} \left(\frac{10\,{\rm GeV}}{m_\chi}\right)^2$ never saturates

capture geometric rate on BS: $C_{2\chi}^g \approx 2.6 \times 10^{25}\,{\rm s}^{-1} \left(\frac{10\,{\rm GeV}}{m_\chi}\right)^2$ can saturate

Flux of scalar mediators once the geometric rate is saturated

$$\frac{dN_\chi}{dt} = C_\star - A_{bsf} N_\chi^2 + C_{2\chi} N_{2\chi} = C_\star + C_{2\chi}^g - A_{bsf} N_\chi^2 \simeq 0$$

$$\Rightarrow N_{\chi,\mathrm{eq}} \simeq \left(\frac{C_\star + C_{2\chi}^g}{A_{\mathrm{bsf}}} \right)^{1/2}$$

$\Rightarrow$ number of ϕ emitted per second: $\Gamma(t) = \frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{\mathrm{bsf}} N_{\chi,\mathrm{eq}}^2 \simeq \frac{C_\star + C_{2\chi}^g}{2}$

Capture on nucleon, BSF, capture on DM and capture on BS rates

capture on nucleon rate:

$$C_\star \approx \sum_i \int_0^{R_\odot} 4\pi r^2 n_i(r)\mathrm{d}r \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \times u_\chi \, \omega^2(r) f_\odot(u_\chi) \int_{E_R^{min}}^{E_R^{max}} \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \mathrm{d}E_R$$

here we assume for definiteness that DM-nucleon scattering proceeds through mixing of ϕ with the SM scalar

BSF rate: binding energy: $E_{\rm bind} \simeq \frac{m_\chi \alpha^2}{4} - \alpha m_\phi$: must be larger than m_ϕ

$$\sigma_{\rm BSF} v \simeq \frac{256\pi^2\alpha^5}{5e^4 m_\chi^2 v_{\rm rel}} \qquad A_{\rm bsf} = \frac{\int n_\chi^2 \sigma_{\rm BSF} v \, dV}{\left(\int n_\chi dV\right)^2} \qquad n_\chi(r,t) = N_\chi(t) \frac{e^{-m_\chi \phi(r)/T}}{\int_0^{R_\odot} e^{-m_\chi\phi(r)/T} 4\pi r^2 \, \mathrm{d}r}$$

Wise, Zhang 14'

Yukawa potential between 2 identical particle is attractive $V(r) = -\frac{\alpha}{r} e^{-m_\phi r}$

capture on DM rate:

Gould 92',…

$$C_\chi = \int_0^{r_{th}^\chi} \mathrm{d}r 4\pi r^2 n_\chi(r) \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) u_\chi \, f_\odot(u_\chi) \, w^2 \int_{\cos\theta_{\rm min}}^{\cos\theta_{\rm max}} \frac{\mathrm{d}\sigma_{\chi-\chi}}{\mathrm{d}\cos\theta} \mathrm{d}\cos\theta$$

integrating only on kinematical cases which allow capture in one scattering

calculated in semi-classical approximation with partial wave expansion…

Chu, Garani, Garcia-Cely, TH 24'

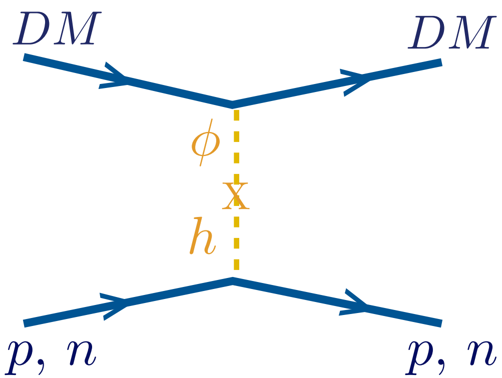
capture on BS rate:

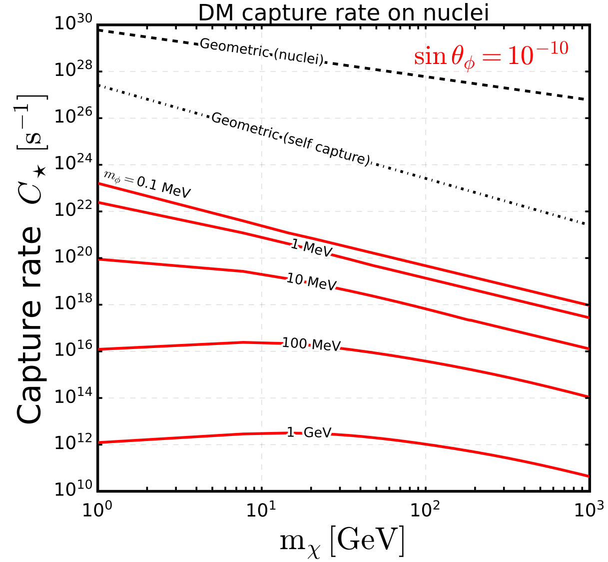
$$C_{2\chi} = \int_0^{r_{th}^{2\chi}} \mathrm{d}r 4\pi r^2 n_{2\chi}(r) \int_0^\infty \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) u_\chi \, f_\odot(u_\chi) \, \omega^2 \int_{\cos\theta_{\rm min}}^{\cos\theta_{\rm max}} \frac{\mathrm{d}\sigma_{2\chi-\chi}}{\mathrm{d}\cos\theta} F_\chi^2\left(\frac{E_r}{Q_\chi}\right) \mathrm{d}\cos\theta$$

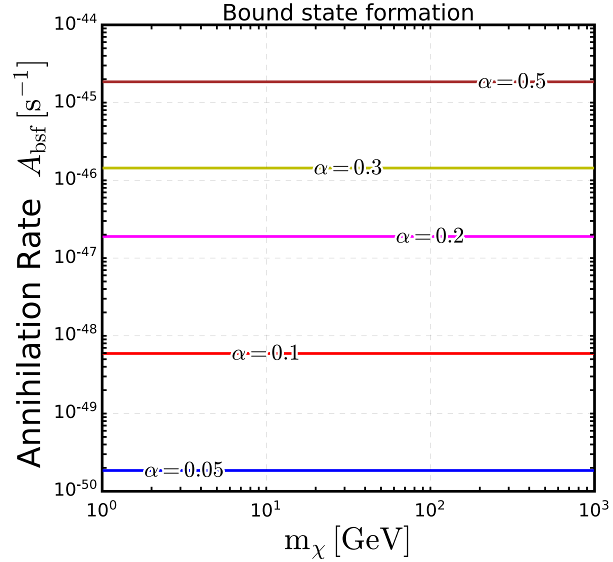
↑ form factor

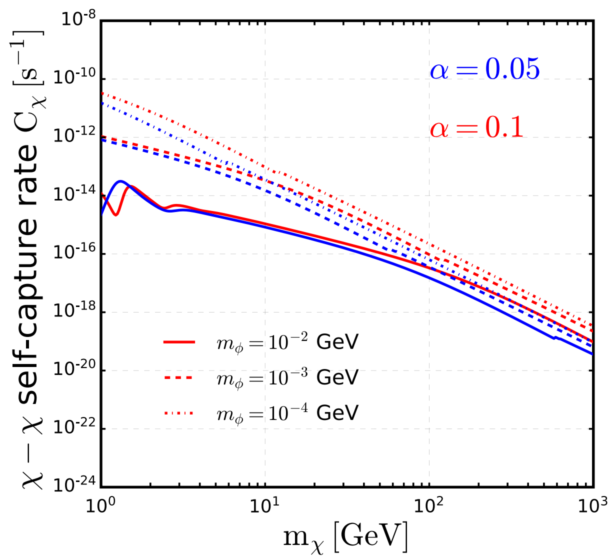
Chu, Garani, Garcia-Cely, TH 24'

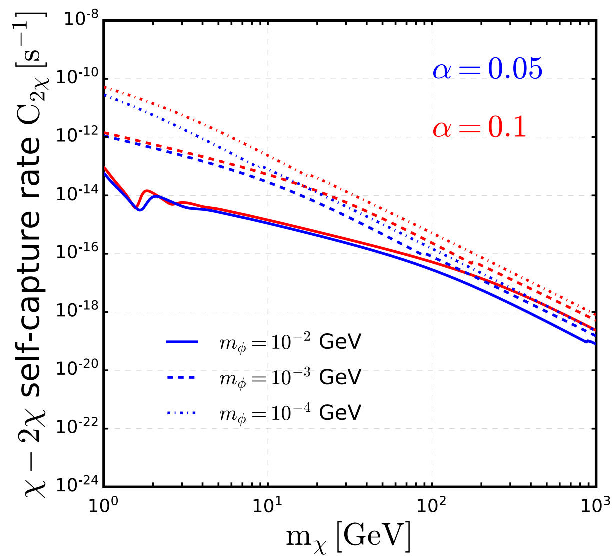
Capture on nucleon, BSF, capture on DM and capture on BS rates









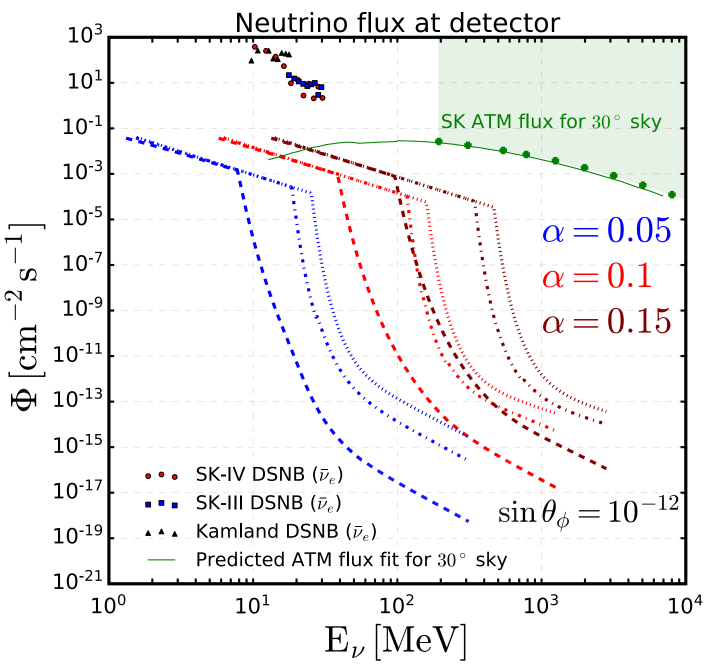


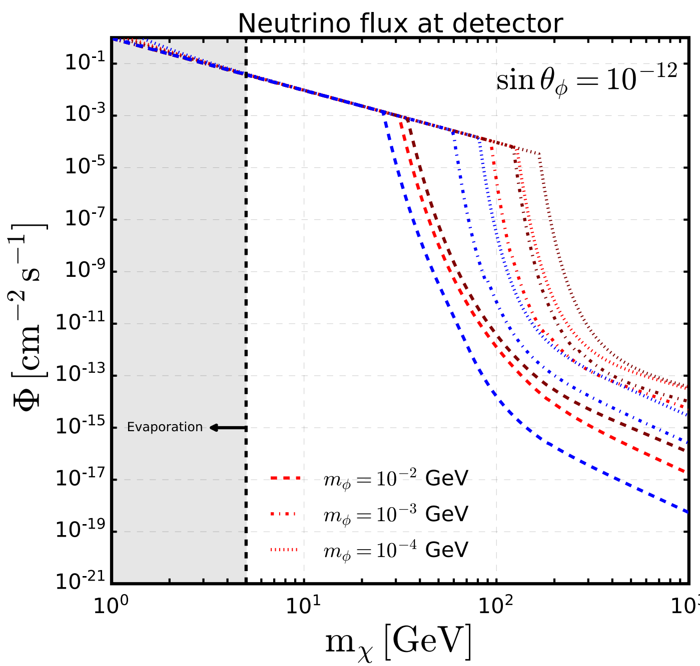
Flux of neutrinos reaching the earth

very few parameters entering in all rates, binding energy and many other constraints

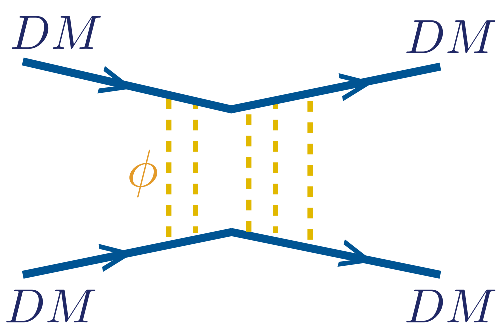
$$m_\chi,\ m_\phi,\ \alpha = \frac{y_\phi^2}{4\pi},\ \sin\theta_\phi$$

here we assume ϕ , once emitted, decays into 2 neutrinos escaping the Sun



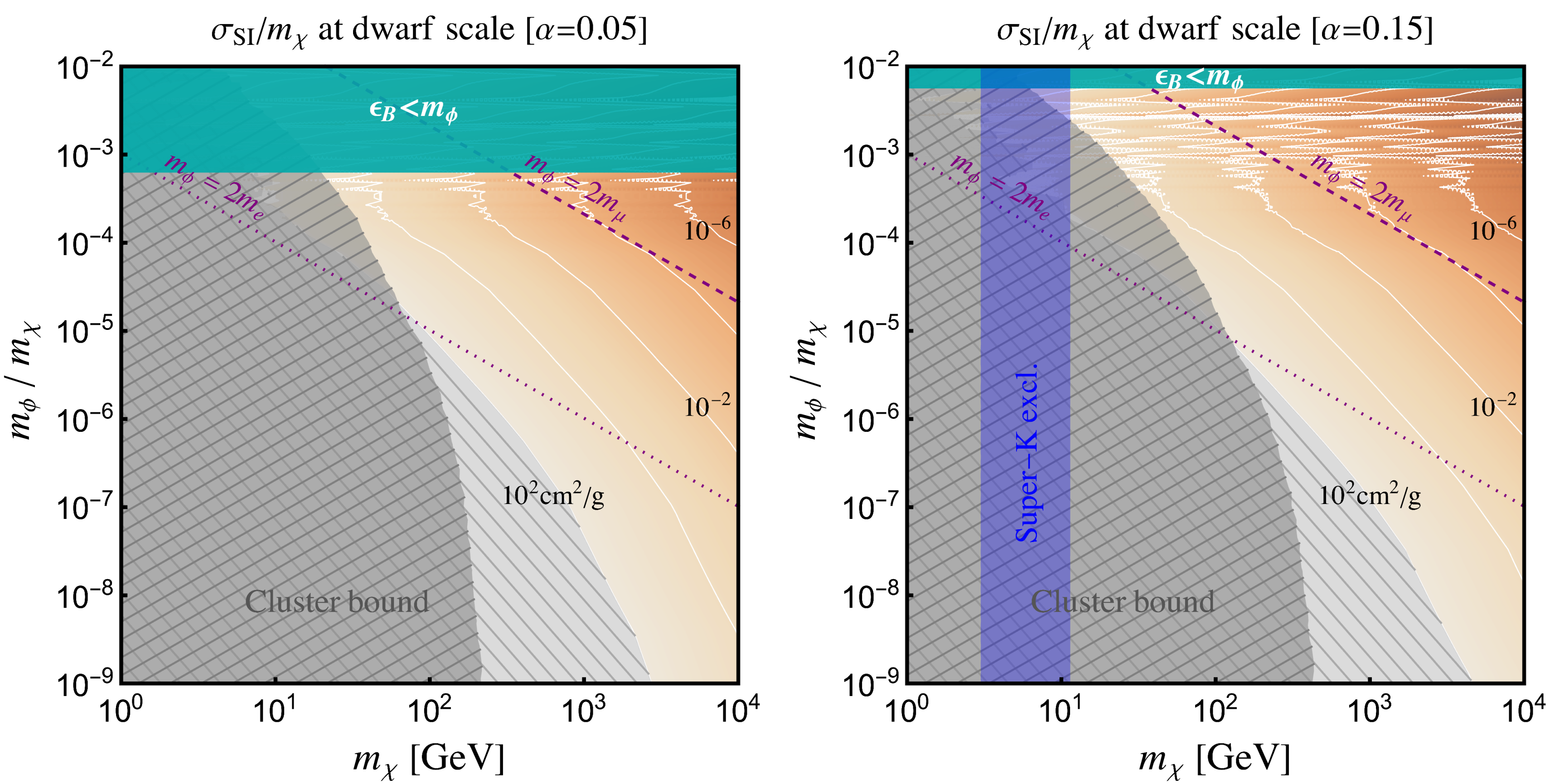


DM self-interactions constraints

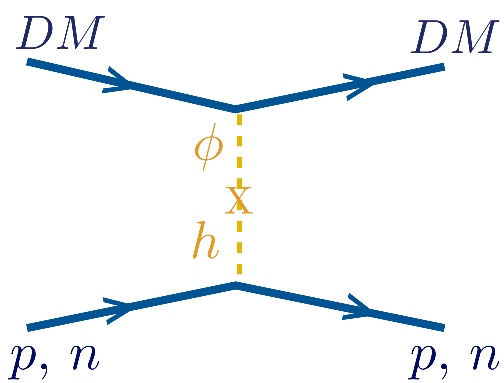


bullet cluster upper bound: $\frac{\sigma_{\rm SI}}{m_\chi} \lesssim 0.5\,{\rm cm}^2/{\rm g}$ $\quad v \sim 1000$ km/sec

small scale anomalies: $0.1\,{\rm cm}^2/{\rm g} \lesssim \frac{\sigma_{SI}}{m_\chi} \lesssim 10^2\,{\rm cm}^2/{\rm g}$ $\quad v \sim 25$ km/sec



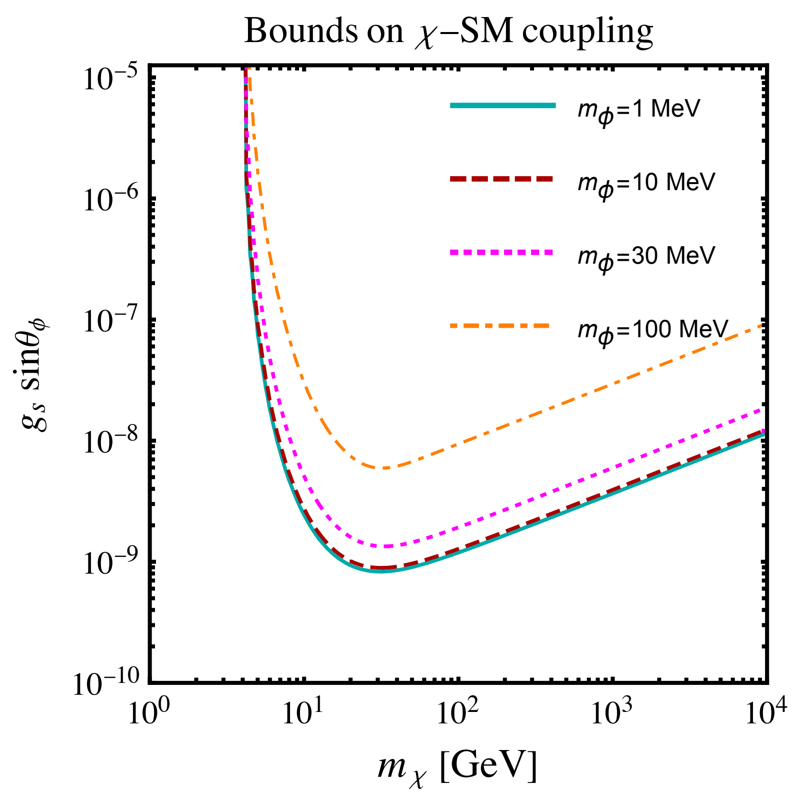
DM direct detection constraints



boosted by light
mediator exchange

BSF also in the galactic center

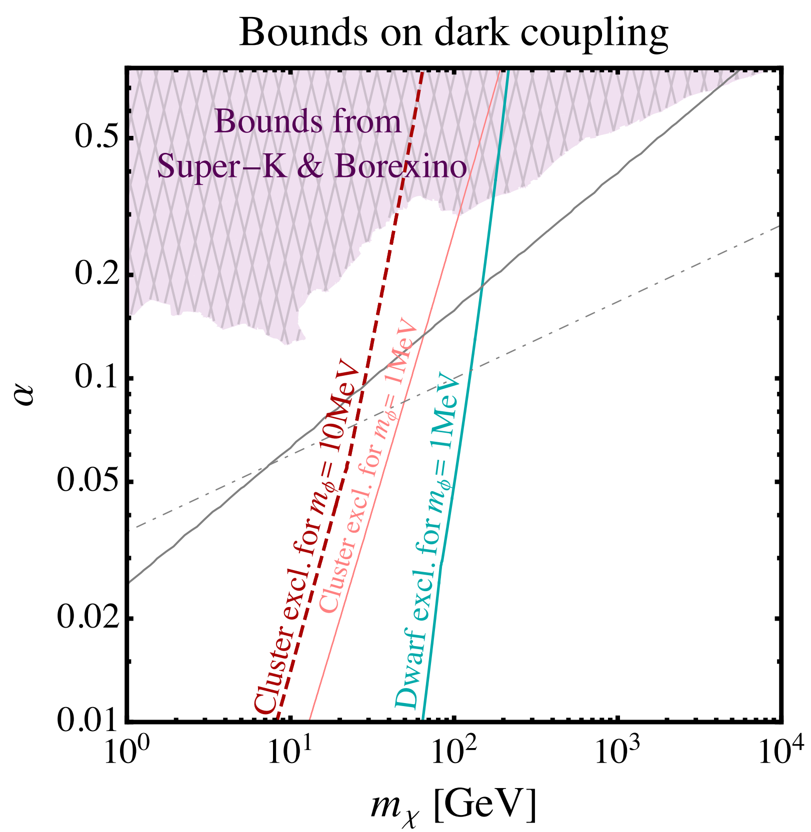
flux of neutrinos from galactic center



DM indirect detection constraints (neutrino flux from galactic center)

if BSF in the Sun ⇒ unavoidable BSF also in the galactic center

↪ flux of neutrinos from galactic center



Example of explicit particle physics model

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_{N_R} + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{1}{2}\left(\partial\phi\right)^2 - g_s\phi\bar{\chi}\chi - \underline{V(\phi, H)}$$

ϕ-h mixing

$$-\mathcal{L}_{N_R} = \underline{Y_\nu \bar{N} L \cdot H} + \frac{m_N}{2}\overline{N^c}N + \underline{Y_\phi \phi \overline{N^c} N} + \text{h.c.}$$

ν-N seesaw mixing

$\phi \to \nu\nu$ decay

Summary

Captured DM could form DM bound states in the center of the Sun

- allow to emit a flux of particles for asymmetric DM and without destroying DM

  ↪ for instance from DM Yukawa interaction with light scalar

- the BS provide additional targets for capturing DM in the Sun from DM self-interact.

  ↪ induced by same Yukawa interact.

  ↪ can allow large exponential increase of DM capture in the Sun

  ↪ exponentially increased flux of emitted particles

- can lead to observable flux of 10 MeV-1 GeV neutrinos
- rich and around the corner associated phenomenology

  ↪ DM direct detection

  DM self-interactions

  DM indirect detection from galactic center