DM Bound State Formation in the Sun

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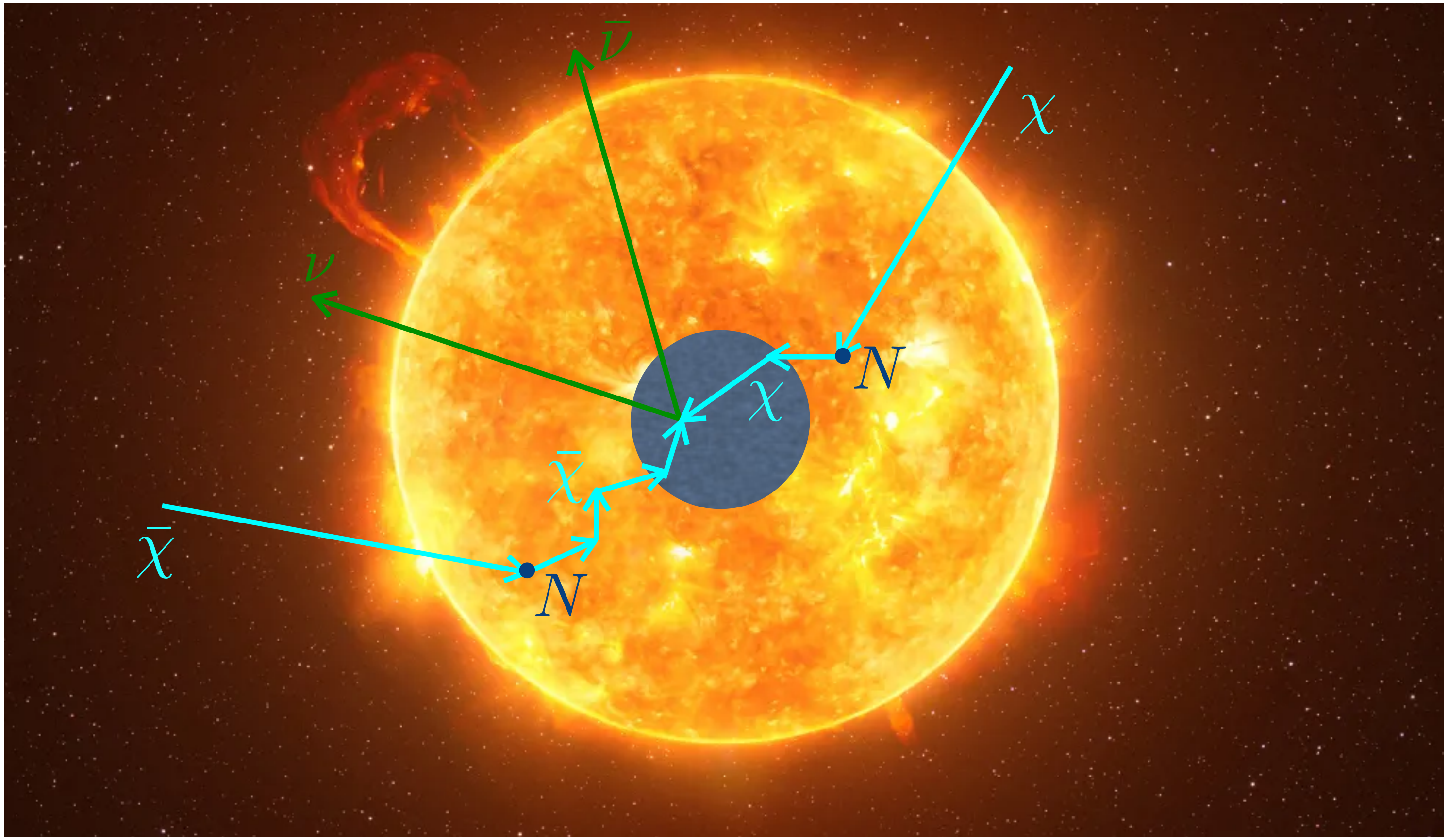
DM capture in the Sun

Press, Spergel 85'

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

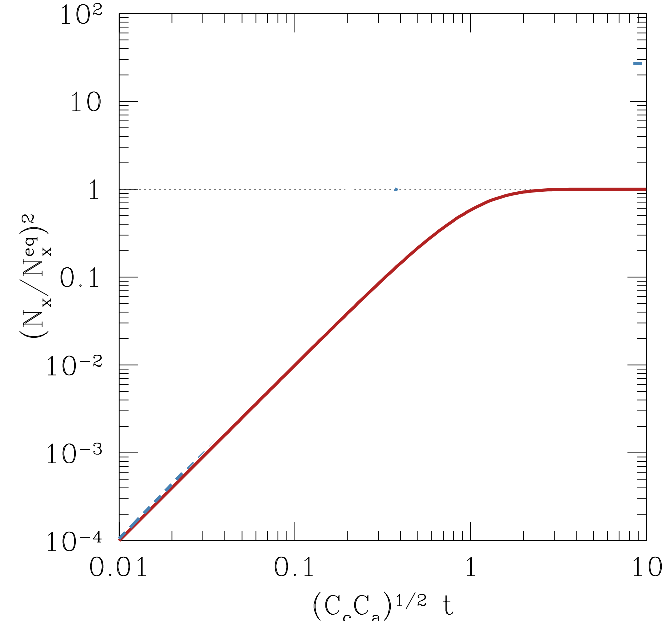


DM capture in the Sun: equilibrium between capture and annihilation

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

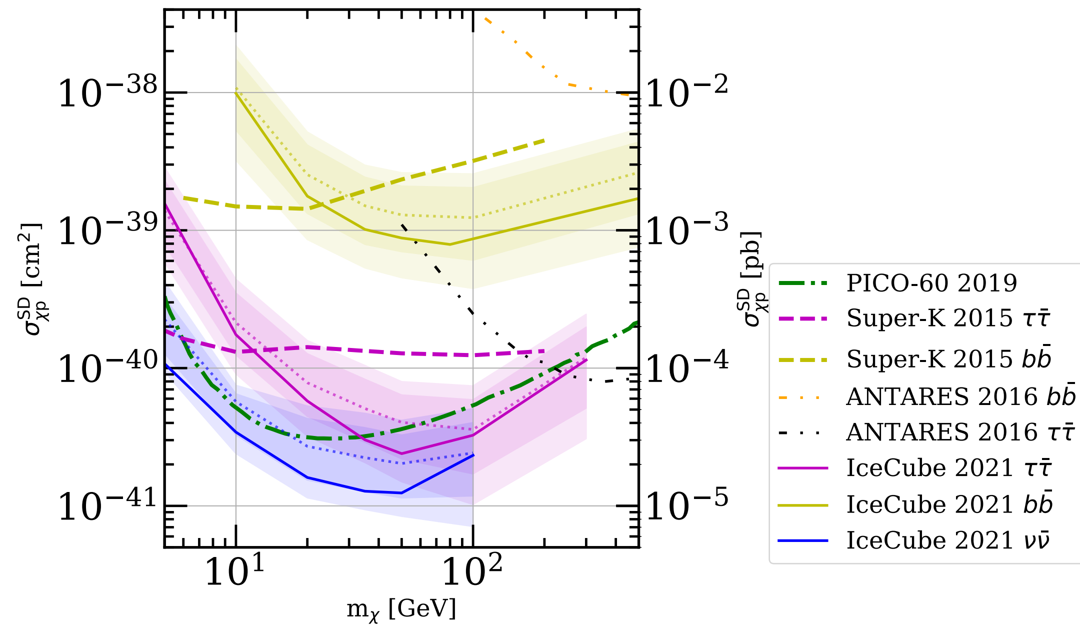
$\Rightarrow$ annihilation equilibrates the capture $N_\chi = \sqrt{C_\star / A}$

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

asymmetric DM case:

no more annihilation but still possibility of an observable flux

→ from DM bound state formation

→ allows to emit a flux without destroying the DM particles

→ more DM accumulation and enhanced emitted flux

First step: Capture and thermalization of DM within a DM core

DM capture on nucleons: linear grow of N_χ

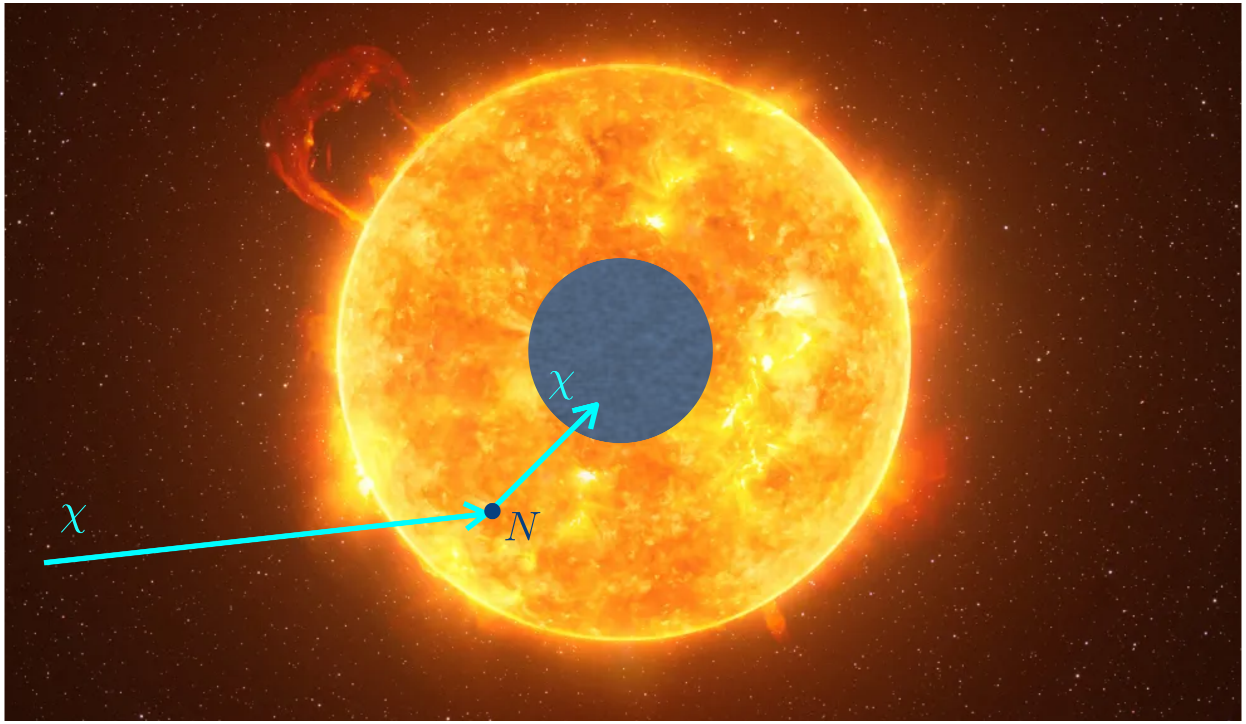
$$\frac{dN_\chi}{dt} = C_\star$$

Press, Spergel 85'

Garani, Palomares-Ruiz 17'

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

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



$$\text{for } m_\chi = 3\,\mathrm{GeV} \;:\; \frac{r_{th}}{r_\odot} \sim 10\%$$

$$\text{for } m_\chi = 300\,\mathrm{GeV} \;:\; \frac{r_{th}}{r_\odot} \sim 1\%$$

$$n_\chi(r,t) = N_\chi(t)\,\frac{e^{-m_\chi \phi(r)/T}}{\int_0^{R_\odot} e^{-m_\chi \phi(r)/T}\, 4\pi r^2\, \mathrm{d}r}$$

$$\phi(r) \;=\; \int_0^r G M_\odot(r')/r'^2\, \mathrm{d}r'$$

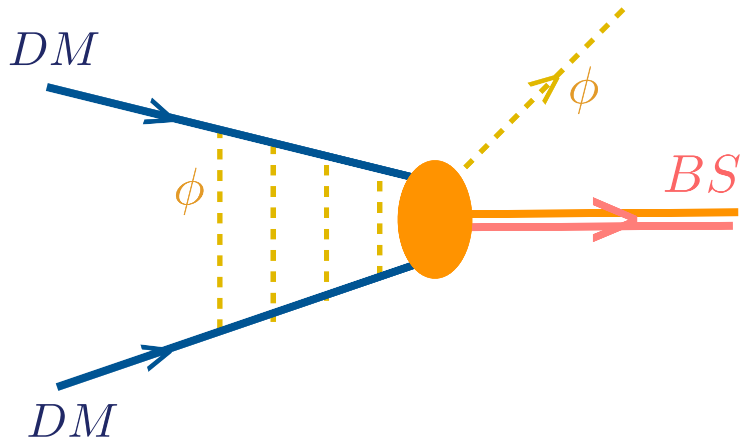
isothermal profile

2nd step: Dark matter bound state formation in the Sun catching up

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



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

2nd step: Dark matter bound state formation in the Sun catching up

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

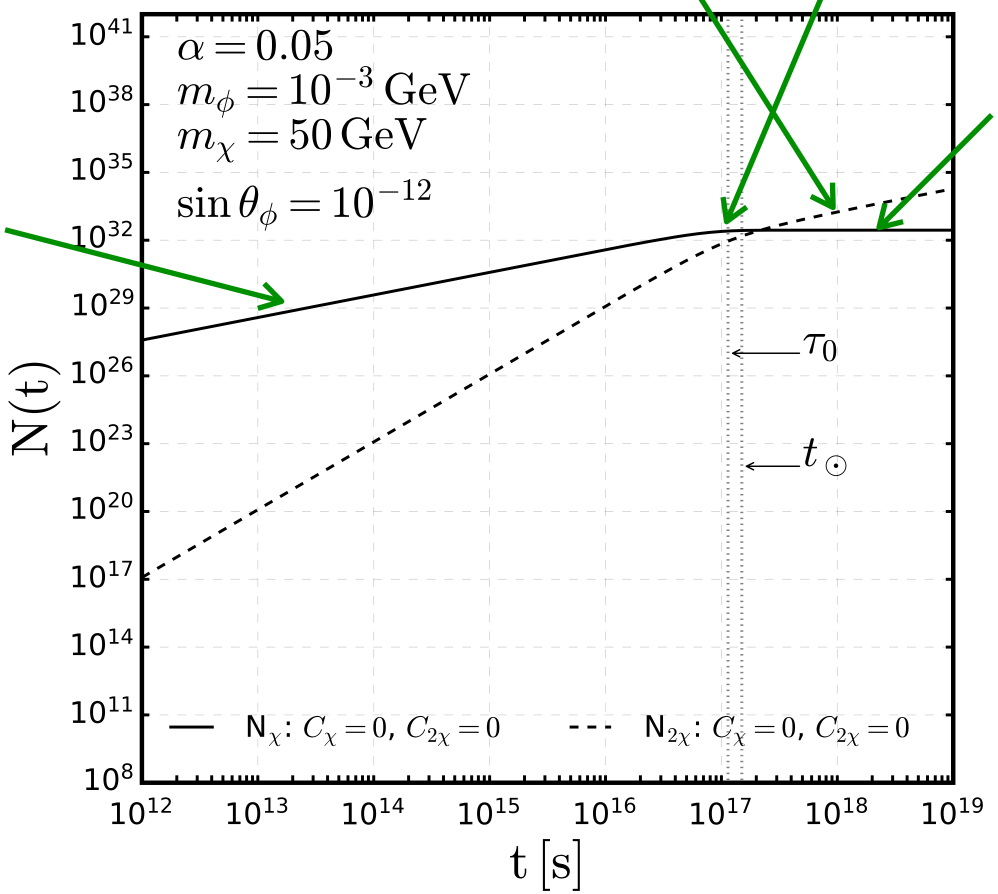
$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$ $\Rightarrow$ BS number do not stop to grow

BSF catching up the capture

linear grow from capture on nucleons

equilibrium between BSF and capture on nucleons

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



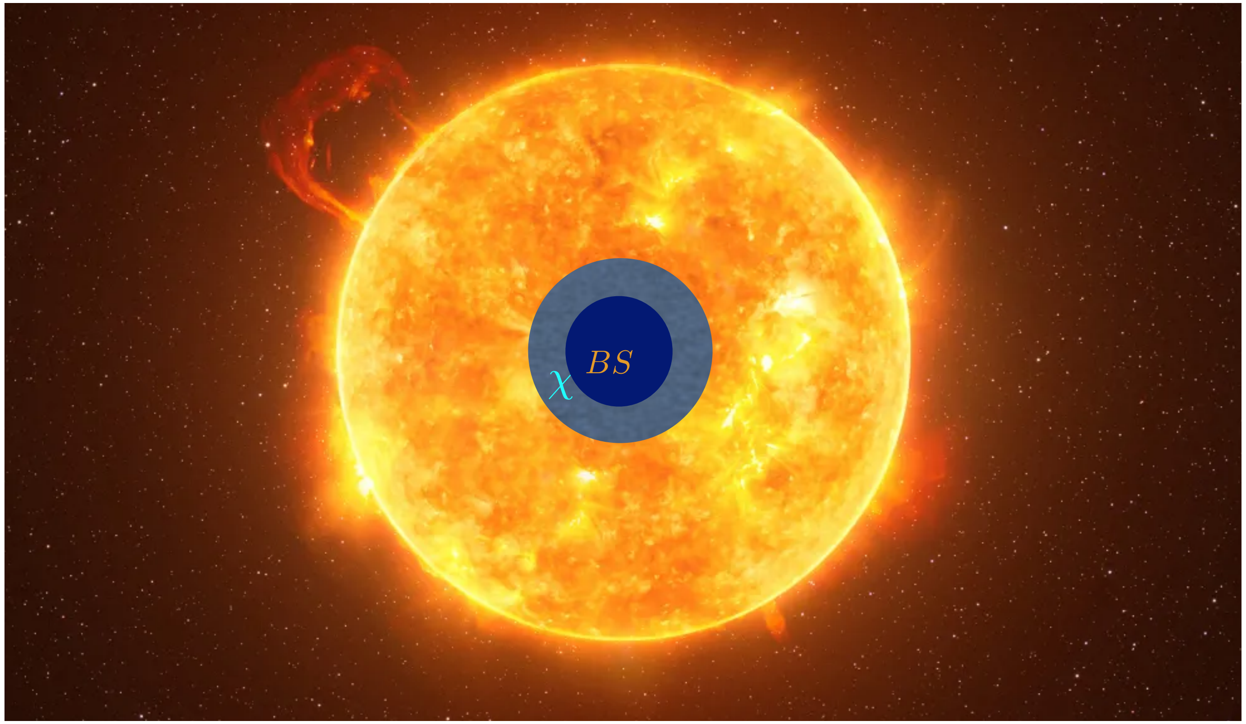
2nd step:Thermal radius for BS

once formed the BS particles thermalize with nucleons

within thermal sphere whose radius is

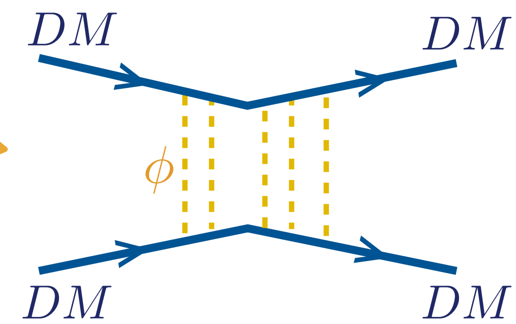
$$\frac{2}{3}\pi G r_{th}^2 \rho_{sun} n m_\chi \sim \frac{3}{2} T_\odot \Rightarrow r_{\rm th} = \left(\frac{9T_\odot}{4\pi G \rho_\odot n m_\chi}\right)^{\frac{1}{2}} = 0.03 R_\odot \left(\frac{T_\odot}{2.2\,\mathrm{keV}} \frac{150\,\frac{\mathrm{g}}{\mathrm{cm}^3}}{\rho_\odot} \frac{10\,\mathrm{GeV}}{n\,m_\chi}\right)^{\frac{1}{2}},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

$$r_{th}^{2\chi} = r_{th}^{\chi}/\sqrt{2}$$



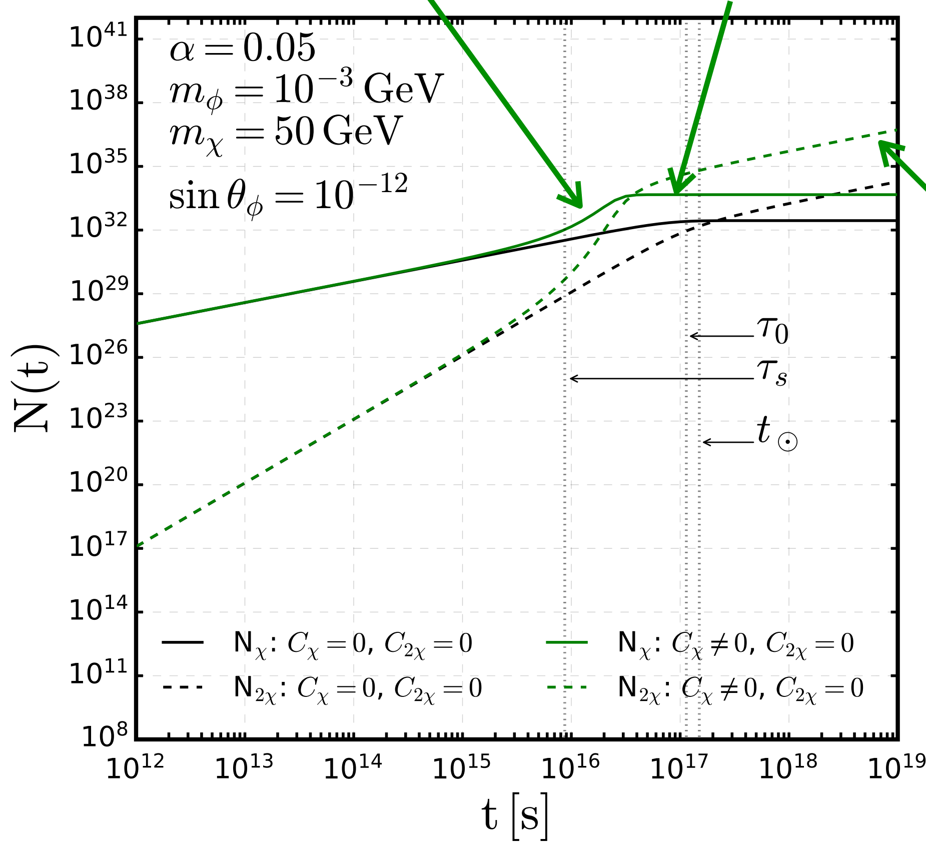
3rd step: DM capture from DM self-interactions: capture on DM

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



exponential increase of N_χ

quick equilibrium with BSF



BS number do not stop to grow

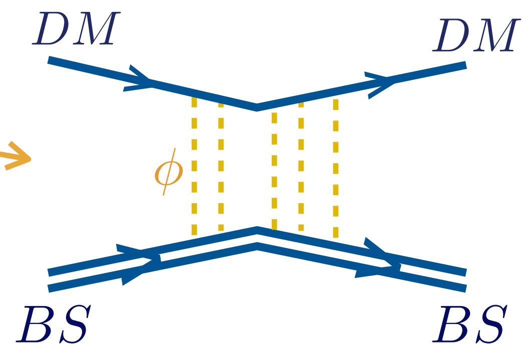
$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$

4th step: DM capture from DM self-interactions: capture on BS

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

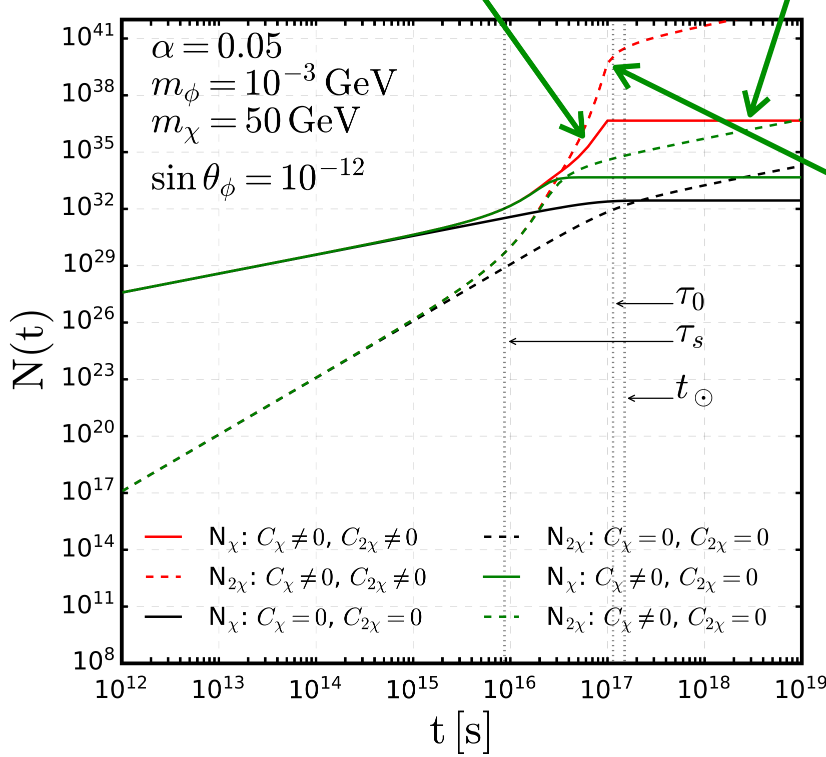
$$\frac{dN_{2\chi}}{dt} = \frac{1}{2} A_{bsf} N_\chi^2$$

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



enhanced exponential increase of N_χ

saturation of the geometric rate



BS number does not stop to grow

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

Flux of scalar mediators once the geometric rate is saturated

$$\#\text{ of }\phi\text{ emitted/sec} = \#\text{ of BS created/sec} = \frac{\#\text{ of DM captured/sec}}{2} = \frac{\#\text{ of DM crossing the BS core/sec}}{2}$$

$$\Gamma(t) = \frac{dN_{2\chi}}{dt} \simeq \frac{C^g_{2\chi}}{2}$$

capture geometric rate on BS: $C^g_{2\chi} \approx 2.6 \times 10^{25}\,\mathrm{s}^{-1}\left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $\longleftarrow$ can saturate easily

unlike capture rate on DM or on nucleons

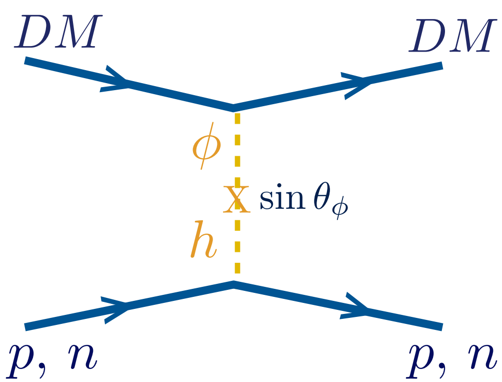
$$\frac{dN_\chi}{dt} = C_\star - A_{bsf}N_\chi^2 + C_{2\chi}N_{2\chi} = C_\star + C^g_{2\chi} - A_{bsf}N_\chi^2 \simeq 0 \quad \Longrightarrow \quad N_{\chi,eq} \simeq \left(\frac{C^g_{2\chi}}{A_{bsf}}\right)^{1/2}$$

Determination of the rates (I)

capture on nucleon rate:

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

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



$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{g_s^2 \cos^2\theta_\phi \sin^2\theta_\phi}{2\pi} \frac{m_N^2 f_N^2}{v_H^2} \frac{m_N}{\omega^2(2m_N E_R + m_\phi^2)^2} F^2\left(\frac{E_R}{Q_0}\right)$$

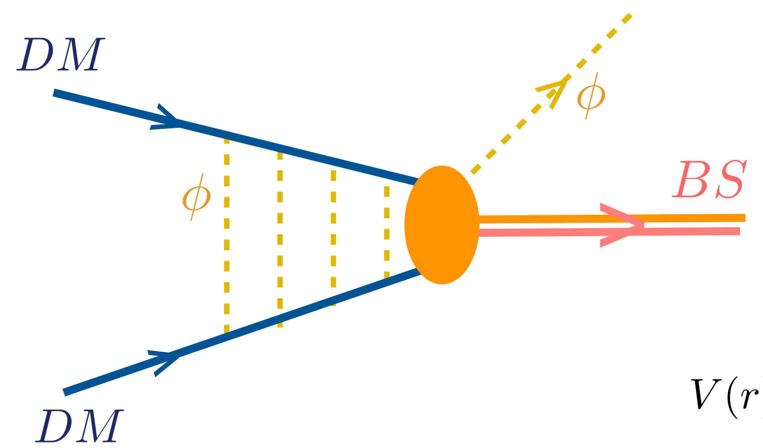
Determination of the rates (2)

BSF rate: $A_{\rm bsf} = \dfrac{\int n_\chi^2\, \sigma_{\rm BSF} v\, dV}{\left(\int n_\chi dV\right)^2}$

$$\sigma_{\rm BSF} v \simeq \frac{256\pi^2\alpha^5}{5e^4 m_\chi^2 v_{\rm rel}}\,;$$

Wise, Zhang 14'

$$\alpha = \frac{y_\phi^2}{4\pi}$$



$$V(r) = -\frac{\alpha}{r}e^{-m_\phi r}$$

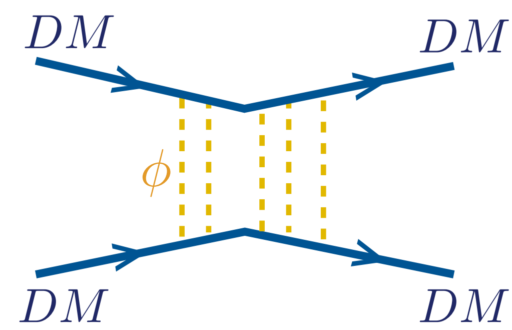
Yukawa potential between 2 identical particle is attractive

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

Determination of the rates (3)

capture on DM rate: DM self-interactions

Gould 92',...



Chu, Garani, Garcia-Cely, TH 24'

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

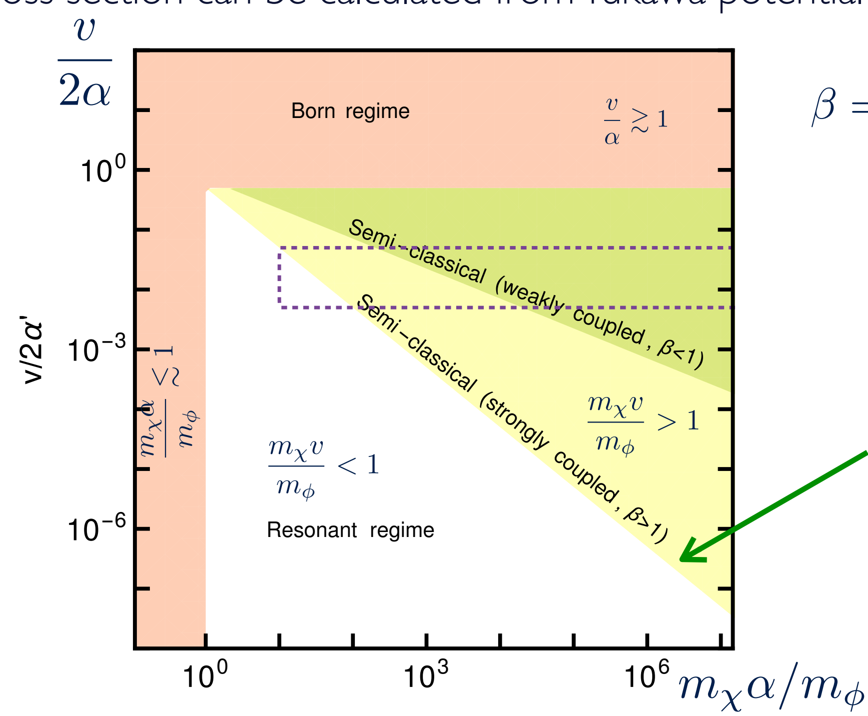
$$n_\chi(r,t) = N_\chi(t)\, \frac{e^{-m_\chi\phi(r)/T}}{\int_0^{R_\odot} e^{-m_\chi\phi(r)/T}\, 4\pi r^2\, \mathrm{d}r}$$

integrating only on kinematical cases which allow capture in one scattering

calculated in semi-classical approximation with partial wave expansion...

range of the Yukawa force $\sim 1/m_\phi$ is much larger than de Broglie wavelength of DM particle $\sim 1/(m_\chi v)$

elastic cross section can be calculated from Yukawa potential in a classical way

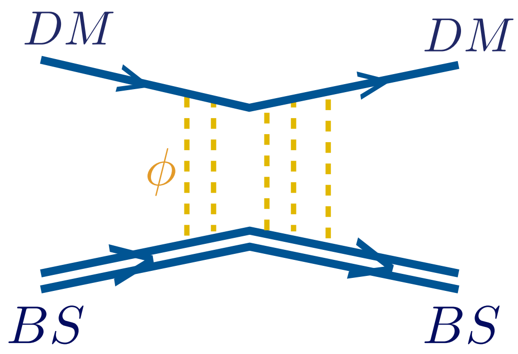


$$\beta = 2m_\phi\alpha/(m_\chi v^2)$$

$$\frac{m_\chi v}{m_\phi} = 1$$

Determination of the rates (4)

capture on BS rate:



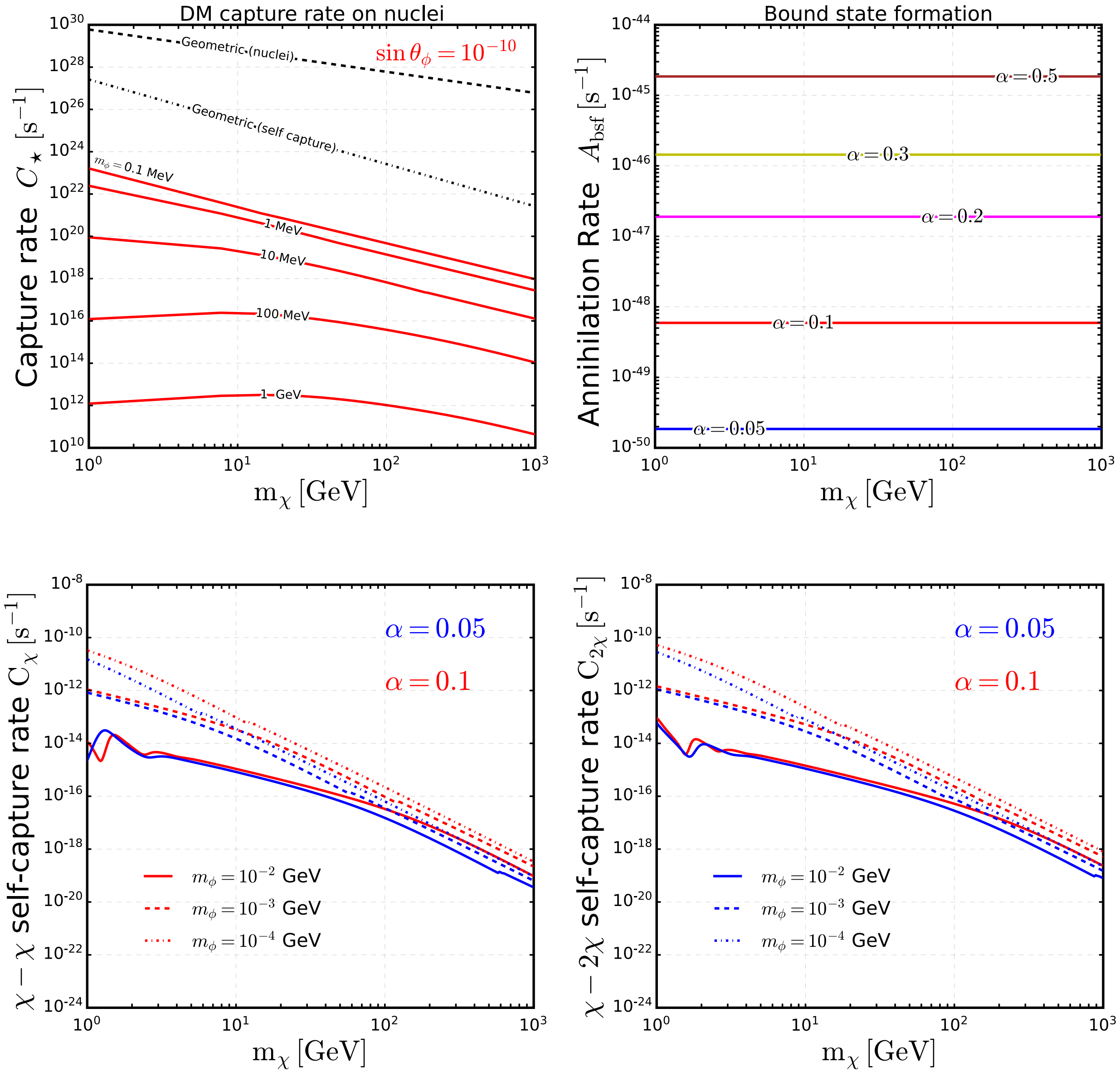
$$C_{2\chi} = \int_0^{r_{th}^{2\chi}} \mathrm{d}r 4\pi r^2 n_{2\chi}(r) \int_0^{\infty} \mathrm{d}u_\chi \left(\frac{\rho_\chi}{m_\chi}\right) u_\chi \, f_\odot(u_\chi)\, \omega^2 \int_{\cos\theta_{\min}}^{\cos\theta_{\max}} \frac{\mathrm{d}\sigma_{2\chi-\chi}}{\mathrm{d}\cos\theta}\, F_\chi^2 \left(\frac{E_r}{Q_\chi}\right)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

form factor

Chu, Garani, Garcia-Cely, TH 24'

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

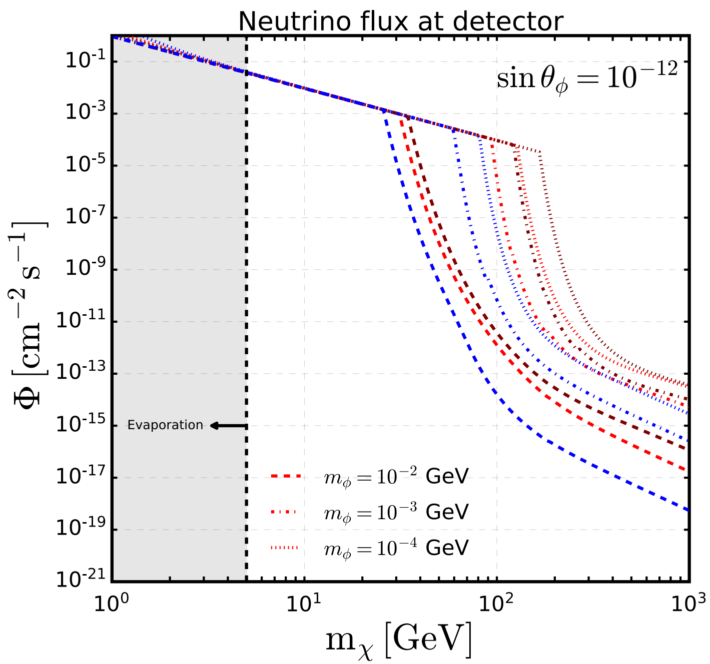
very few parameters entering in all rates and binding energy: $m_\chi,\ m_\phi,\ \alpha = \dfrac{y_\phi^2}{4\pi},\ \sin\theta_\phi$

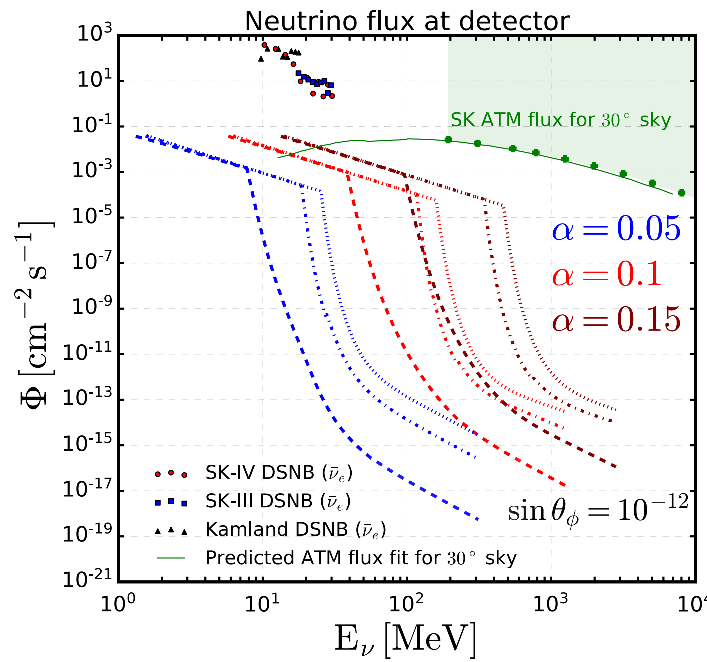


Flux of neutrinos reaching the earth

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

$$E_\nu = \frac{E_{bind}}{2} \simeq \frac{m_\chi \alpha^2}{8} - \frac{\alpha m_\phi}{2}$$





flux of neutrinos from the direction of the Sun, unlike atmospheric neutrinos

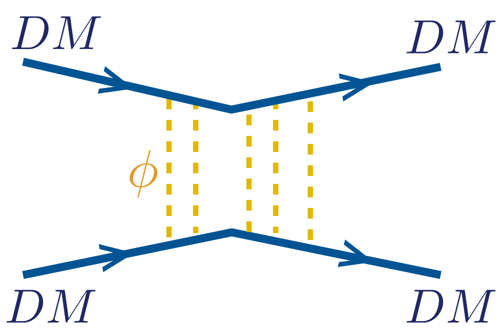
Long list of constraints: a kind of miracle that one can get an observable flux!

the only 4 parameters enter in many relevant quantities and potential extra effects:

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

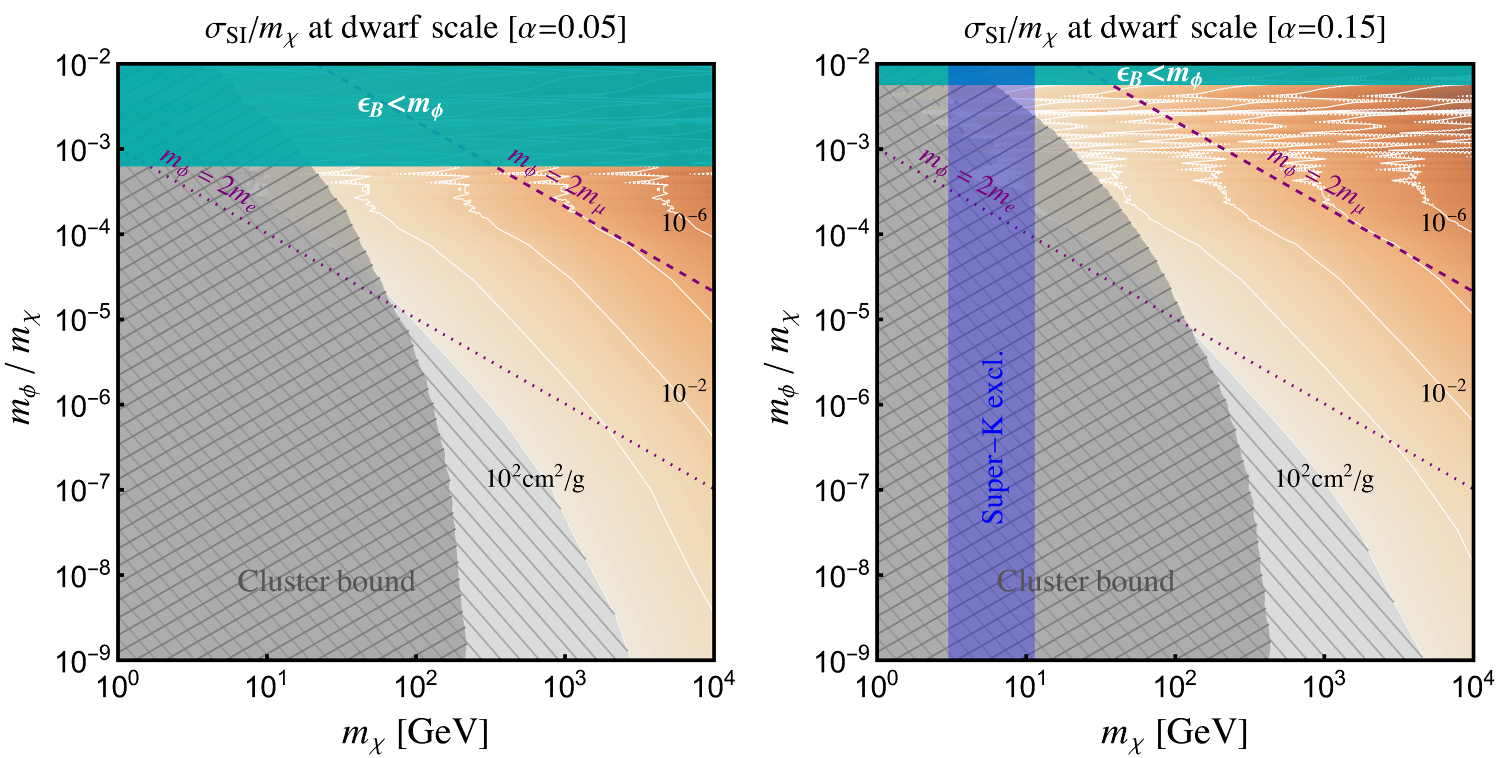
- $C_\star,\, A_{bsf},\, C_\chi,\, C_{2\chi}$ $\quad \sigma_{\rm BSF} v \simeq \frac{256\pi^2\alpha^5}{5e^4 m_\chi^2 v_{\rm rel}}$ very sensitive to α
- binding energy: $E_{\rm bind} \simeq \frac{m_\chi \alpha^2}{4} - \alpha m_\phi$: must be larger than m_ϕ
- recoil velocity of bound state: $v_{rec} = \alpha^2/8$: must be smaller than escape velocity $\longrightarrow \alpha \leq 0.18$
- thermal radius $\propto 1/m_\chi^{1/2}$
- self-capture leading directly to bound state: subleading
- creation of heavier bound state: presumably subleading
- evaporation of DM particles: negligible for $m_\chi \gtrsim 5\,\mathrm{GeV}$
- DM self-interactions
- DM direct detection: same cross section as for capture on nucleons
- DM indirect detection: neutrino flux from BSF in the galactic center
- BBN constraint on ϕ lifetime

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

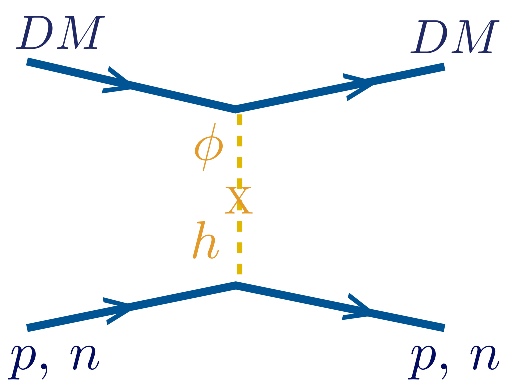
small scale anomalies: $0.1\,{\rm cm}^2/{\rm g} \lesssim \frac{\sigma_{SI}}{m_\chi} \lesssim 10^2\,{\rm cm}^2/{\rm g}$ $\quad v \sim 25$ km/sec



minimal self-interacting DM models with light mediator are in strong tension with the many constraints that apply on them but there are minimal ways out ***TH, Vanderheyden 19'***

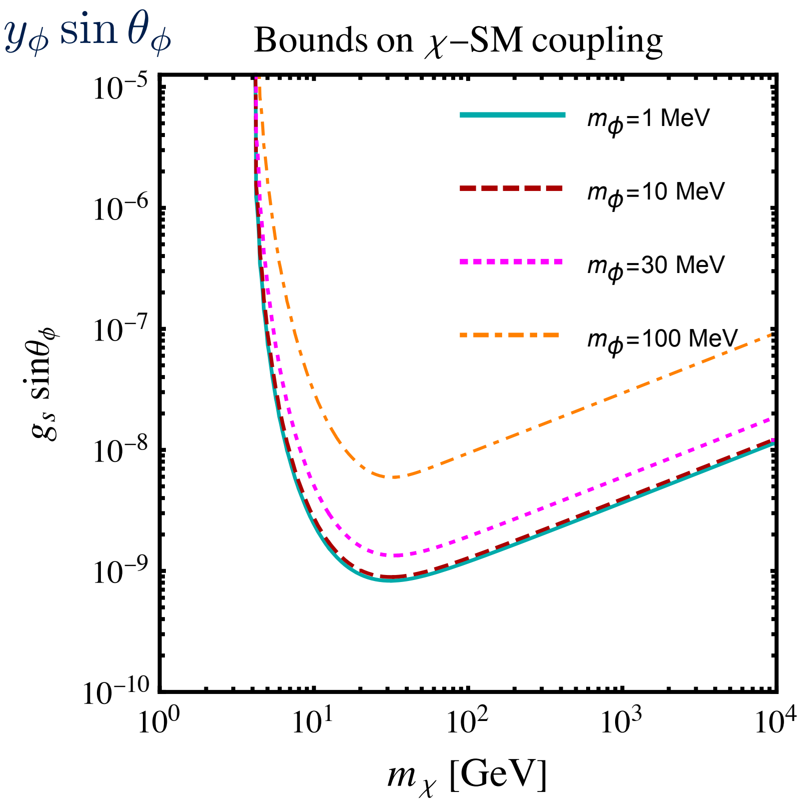
asymmetric self-interacting DM is one of the way to avoid more easily some of the constraints

DM direct detection constraints



boosted by light
mediator exchange

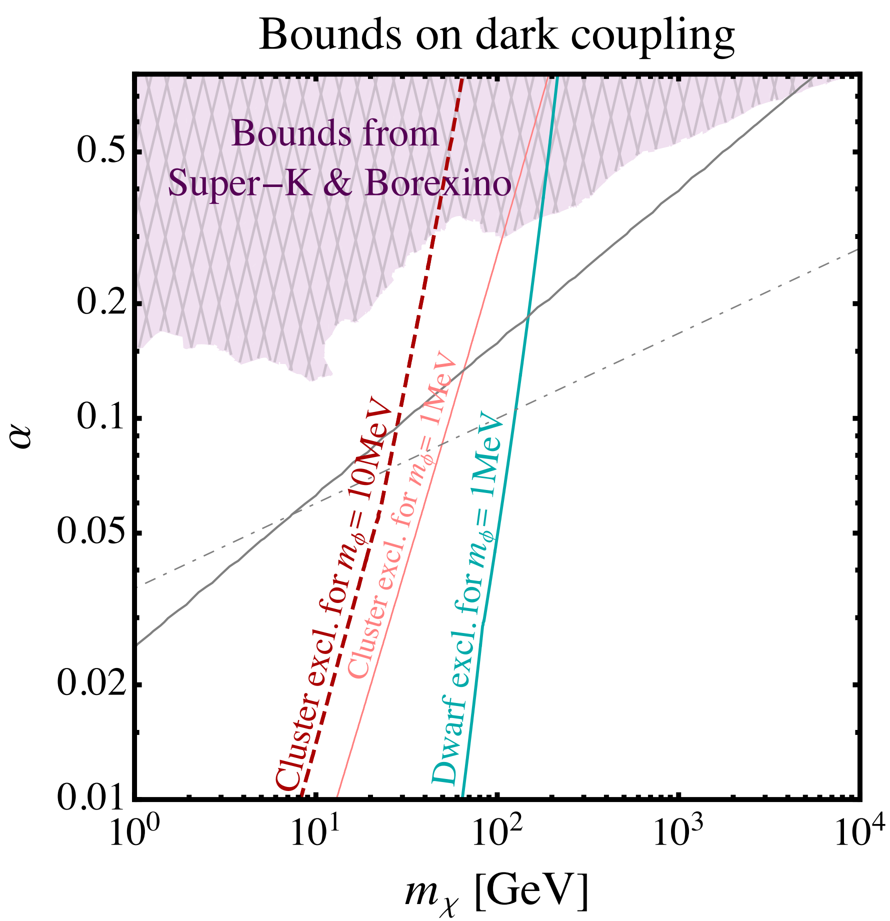
$y_\phi \sin\theta_\phi$



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

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

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

Summary

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

for instance from DM Yukawa interaction with light scalar

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

- 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

Lower bound on scalar mixing for thermalization of DM