Halo-independent bounds on Inelastic Dark Matter

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Based on: *JCAP 11 (2023) 077* & *JCAP 03 (2023) 011*

in collaboration with: S. Scopel and S. Kang

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Institute for Basic Science (IBS)

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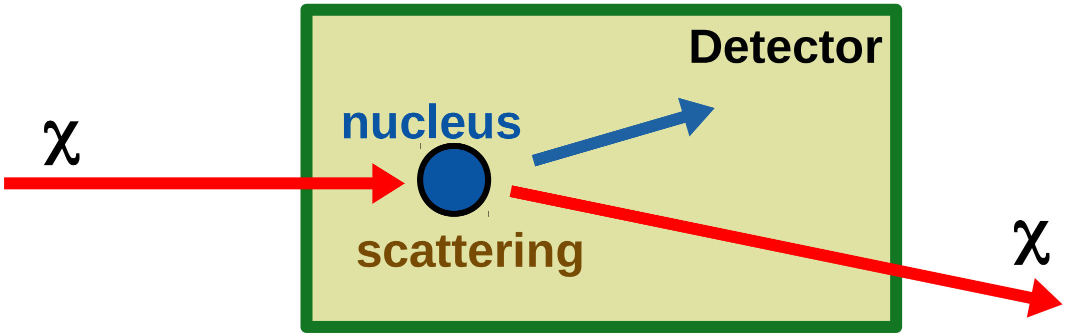
WIMP dark matter searches

- Cold Dark Matter (CDM): provides ~25% of the energy density of the Universe;
  evidences are only through gravitational effects

- Weakly Interacting Massive Particles (WIMPs): one of the most popular candidates for CDM
  [mass in GeV – TeV range]

- ***Direct Detection (DD):*** A popular technique to search for WIMPs
  - mainly based on scatterings of local WIMPs off nuclear targets in terrestrial detectors and the observation of the corresponding nuclear recoil signal



- Non-detection of any new signal in DD experiments

  ⇨ upper-limit on the WIMP-nucleon coupling that drives the WIMP-nucleus scattering

Uncertainties in the signal prediction

- Two classes of major uncertainties in the signal prediction:
  - Nature of the WIMP-nucleus interaction
  - WIMP speed distribution in the local halo that determines the incoming WIMP flux

- WIMP-nucleus interaction:

common choice: **standard spin-independent (SI)** or **spin-dependent (SD)** interaction

- WIMP speed distribution in the local halo:

common choice: a Maxwell-Boltzmann speed distribution w.r.t. the Galactic reference frame
(and boosted to the Lab frame)
Standard Halo Model (SHM)

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WIMP speed distribution: Halo-independent approach

$\boldsymbol{f}(u)$ ⇨ WIMP speed distribution in the local halo

$$\int_0^{u_{max}} f(u)\, du = 1$$

u = WIMP speed in the halo (w.r.t. Solar frame)

$\boldsymbol{u_{max}}$ = Galactic escape speed (w.r.t. Solar frame)
≃ 800 km/s

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- MB distribution (based on Isothermal Model) provides a zero-order approximation to *f(u)*
- Numerical simulations of Galaxy formation can only tell us about the statistical average properties of halos
- Merger events can add sizeable non-thermal components in *f(u)*
- Growing number of observed dwarf galaxies suggests that our halo is not perfectly thermalized

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- **<u>Halo–independent approach</u>**:

➢ **Constraint on the WIMP interaction indpendent of the WIMP speed distribution in the halo**

$\boldsymbol{f}(u) \Rightarrow$ any possible WIMP speed distribution

Halo-independent approach using Direct Detection

- Direct Detection (DD) experiments are sensitive only for a WIMP speed $u > u_{\mathrm{th}}$

$$u_{\mathrm{th}} = \sqrt{\frac{m_N}{2\mu_{\chi N}^2}\boxed{E_{\mathrm{th}}}}$$

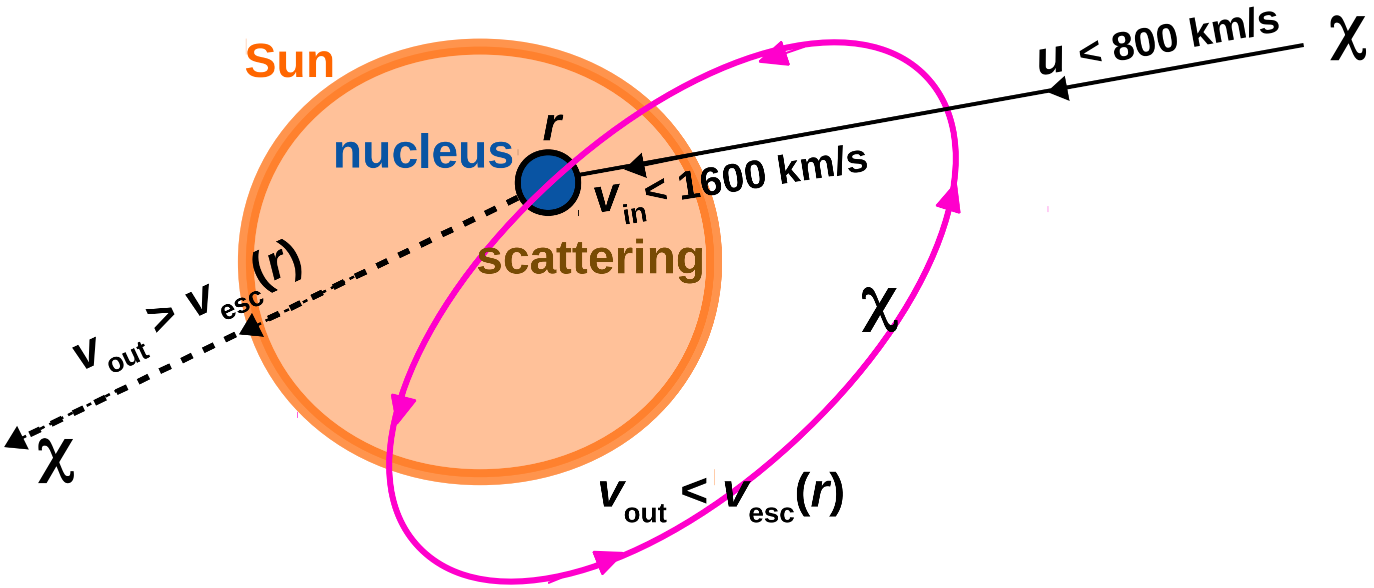
($\mu_{\chi N}$ = WIMP-nucleus reduced mass)

- For a $f(u)$ concentrated below u_{th} the DD sensitivity is zero

- A halo-independent approach is not possible using only DD

Capture of WIMPs in the Sun and the Neutrino Signal

- **Capture of WIMPs in the Sun** is favoured for low (or even vanishing) speeds



$v_{esc}(r)$ = escape speed inside the Sun
= [620 , 1400] km/s
(from solar surface to center)

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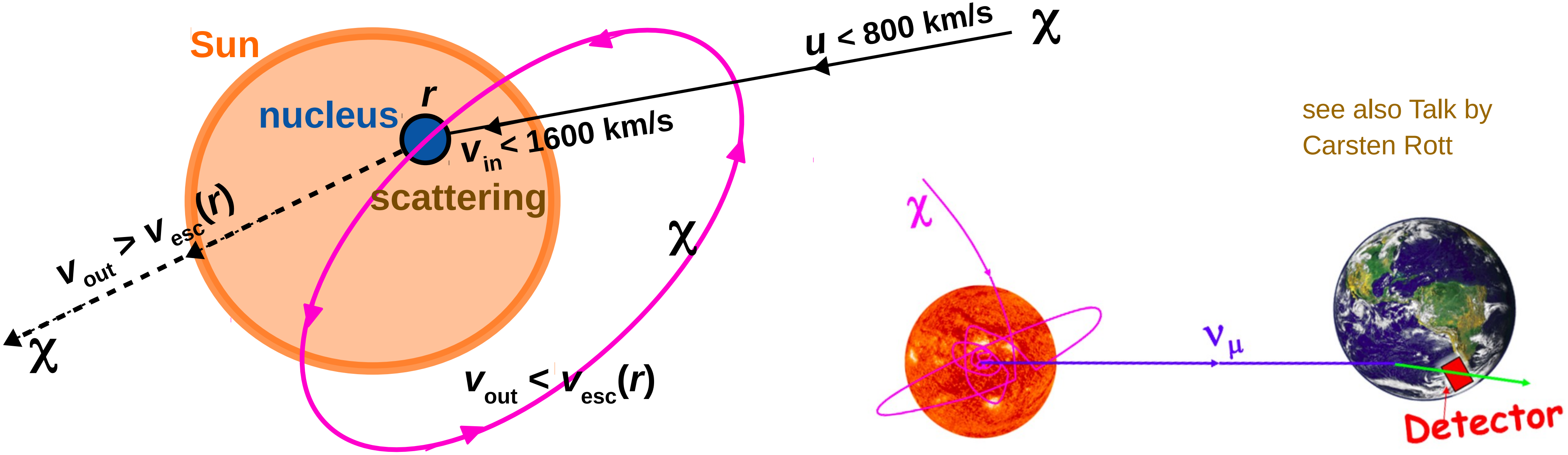

see also Talk by
Carsten Rott

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WIMP annihilation in the Sun

$$\chi\chi \rightarrow b\bar{b},\ \tau^+\tau^-,\ W^+W^-,\ \ldots$$

$$\Rightarrow \nu\left(\bar{\nu}\right)$$

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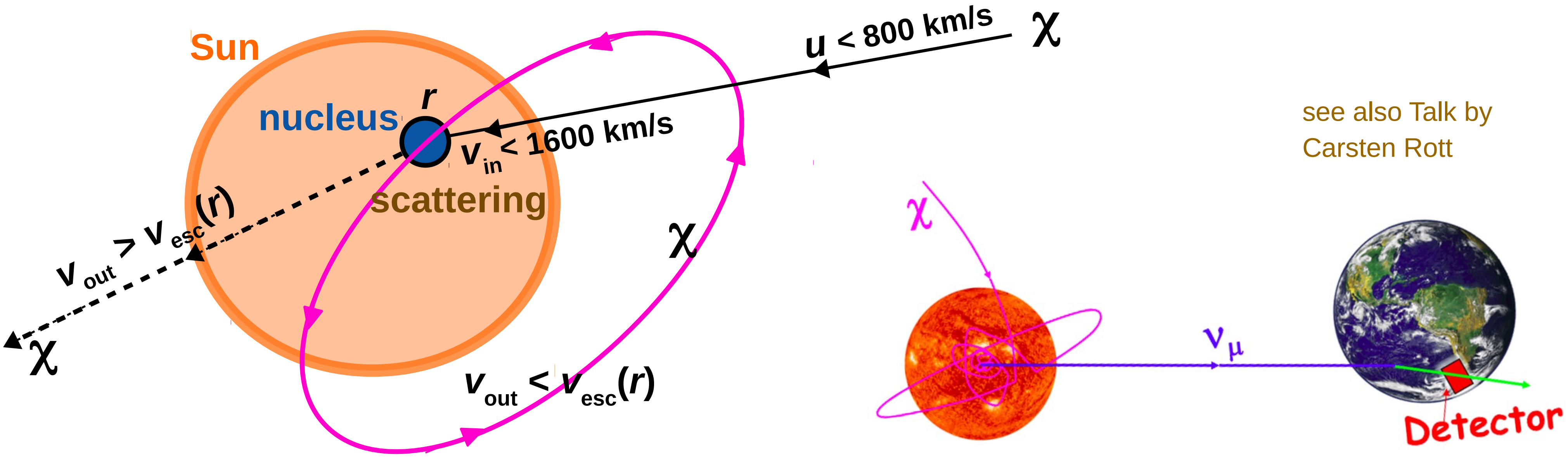

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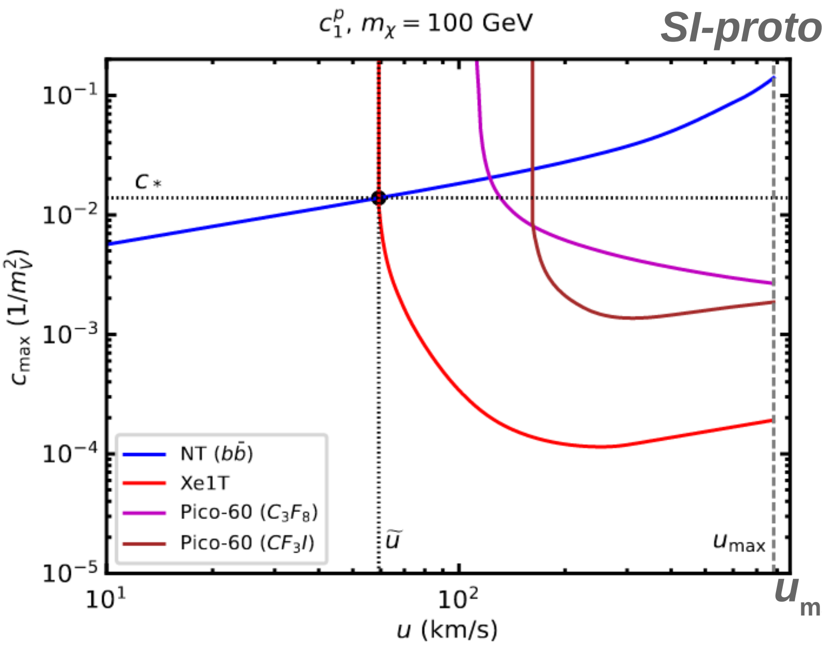
- **A possible solution to the Halo–independent approach:**
  Direct detection (DD) “+” Neutrino Telescope (NT)

[F. Ferrer, A. Ibarra, S. Wild; (JCAP 09 (2015) 052]

Halo-independent approach

SI-proton, m_χ***= 100 GeV***



Limit on coupling

WIMP speed in the halo (km/s)

$u_{\rm max}$

[S. Kang, AK, S. Scopel, (JCAP 03 (2023) 011)]

u_{max} = Galactic escape speed
(w.r.t. Solar frame)
$\simeq$ **800 km/s**

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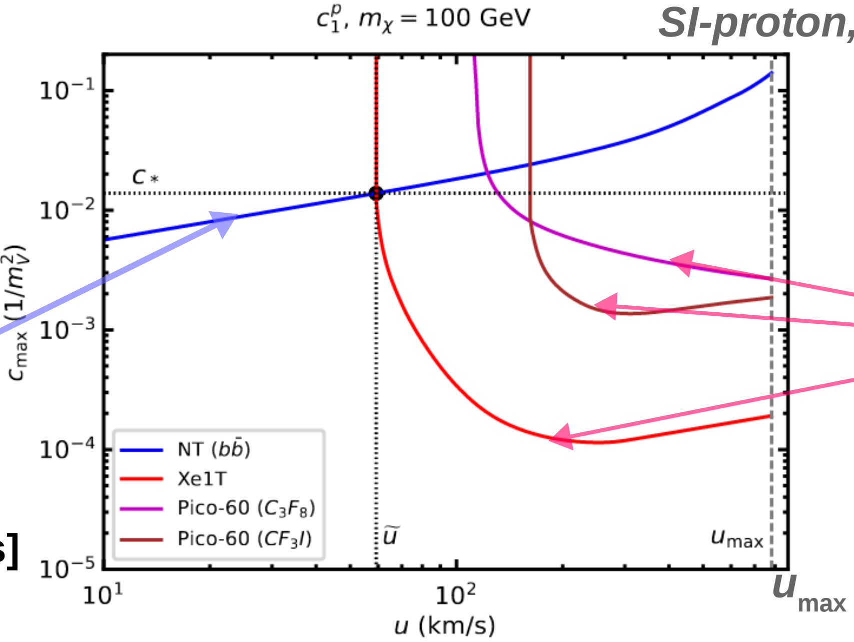

Limit on coupling

WIMP speed in the halo (km/s)

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Neutrino Telescope (NT)

[sensitive to low speed WIMPs]

Direct detection (DD)

[sensitive to high speed WIMPs]

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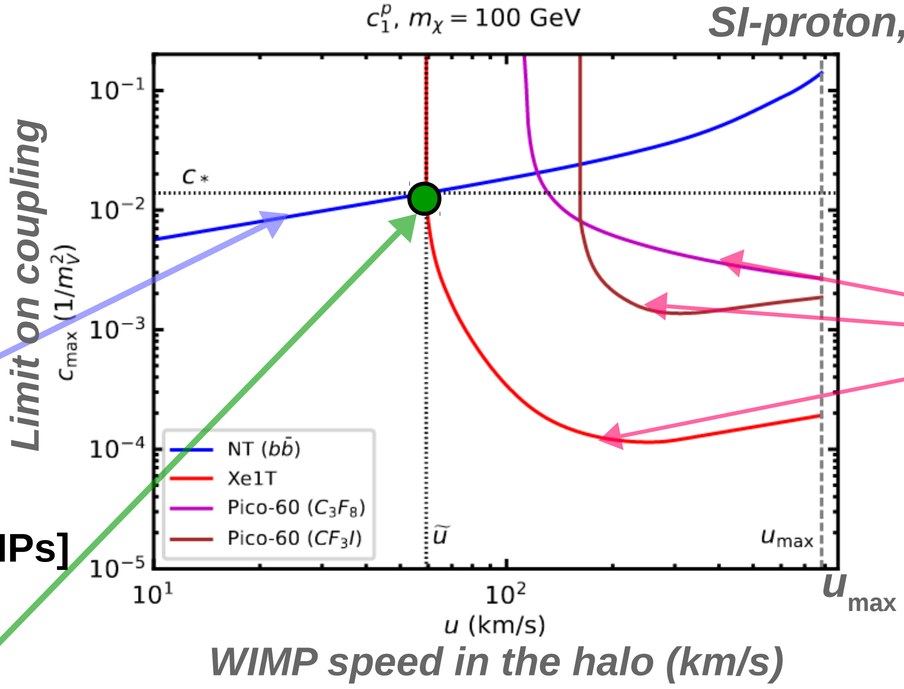

Direct detection (DD)

[sensitive to high speed WIMPs]

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**Halo-independent limit is determined by
the weakest point of the experimental sensitivity**

Halo-independent approach

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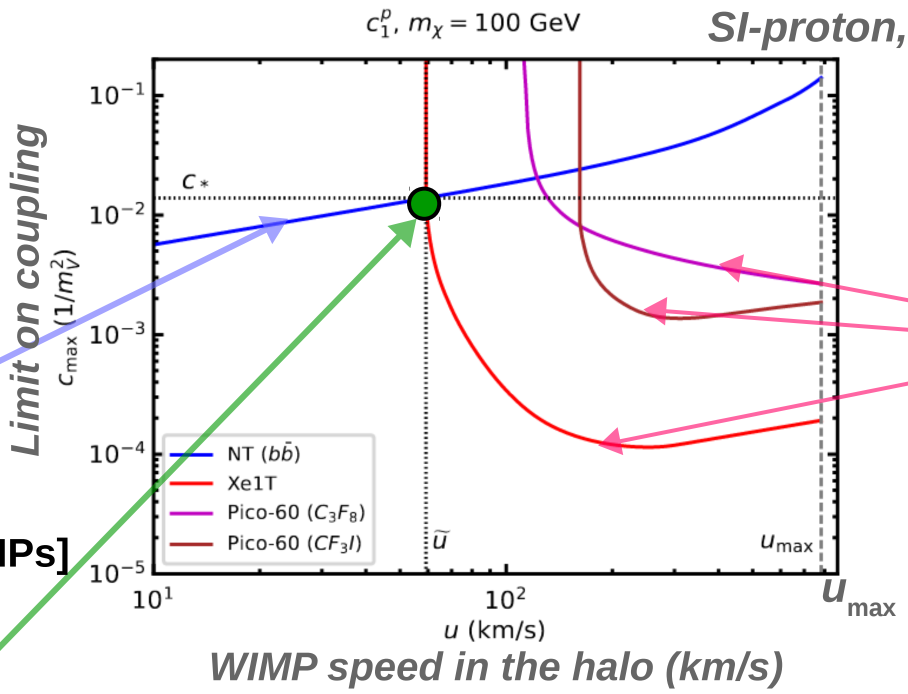

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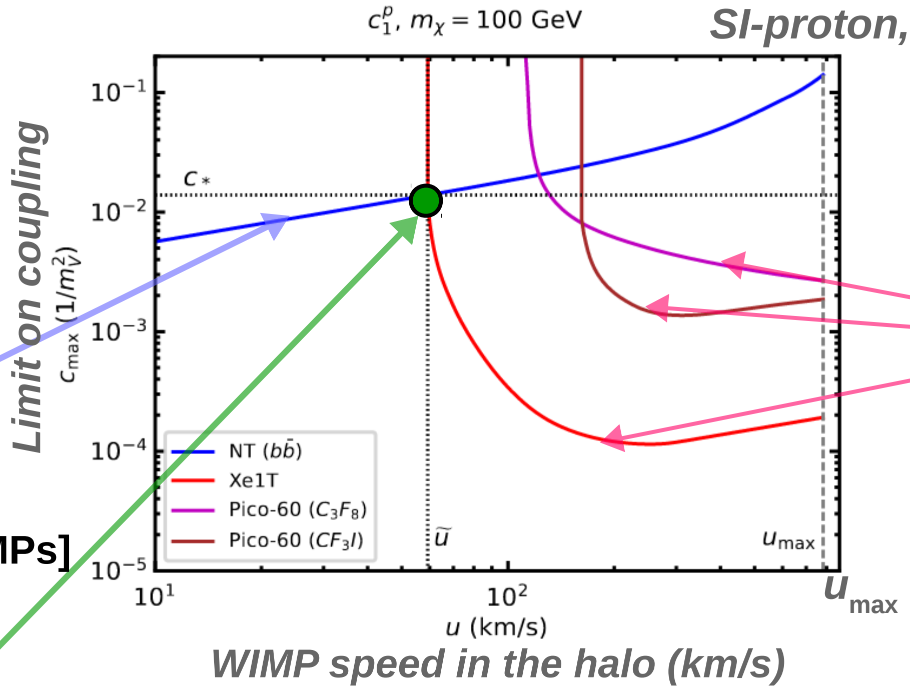
- **A finite Halo-independent bound requires Experimental sensitivity covering the full WIMP speed range [0 , $u_{\rm max}$]**

⇨ **Neutrino Telescope (NT) observations should be combined with Direct Detection (DD)**

Halo-independent approach



SI-proton, m_χ ***= 100 GeV***

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Halo-independent limit is determined by the weakest point of the experimental sensitivity

DD : **XENON, PICO**

NT : **IceCube, Super-K** $[\chi\chi \rightarrow b\bar{b}]$

- **A finite Halo-independent bound requires Experimental sensitivity covering the full WIMP speed range [0 , u_{max}]**

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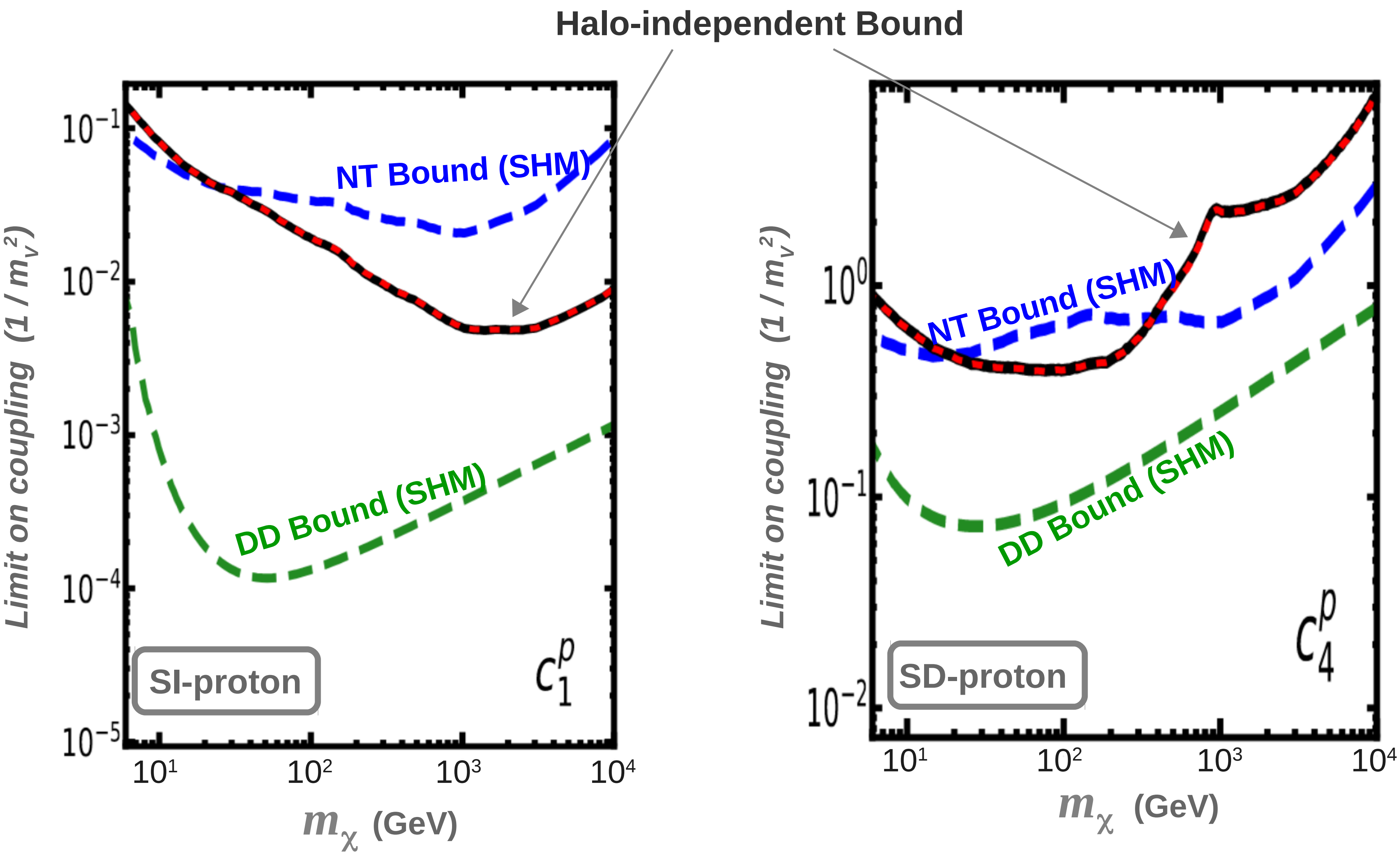
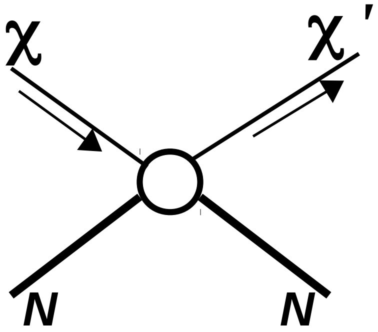
Halo-independent bounds on WIMP-nucleon couplings



[S. Kang, AK, S. Scopel, (JCAP 03 (2023) 011)]

What is the situation for Inelastic WIMP dark matter scenario?

Inelastic Dark Matter (IDM)



- WIMP DM χ scatters off a Nucleus N by making a transition to a slightly heavier state χ'
- $m_{\chi'} - m_{\chi} = \delta > 0$

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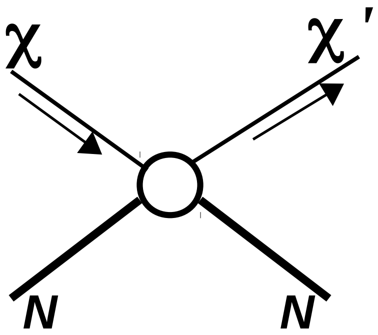

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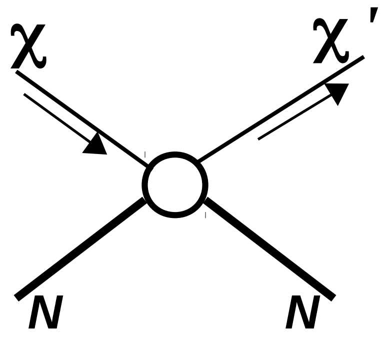
- $m_{\chi'} - m_{\chi} = \delta > 0$
- K.E. of the incoming DM particle χ should be large enough to overcome the mass splitting δ

$$\frac{1}{2}\,\mu_{\chi N}\,v_{\rm in}^2 \;>\; \delta\,, \qquad [\mu_{\chi N} \equiv {\rm reduced\,mass} = \frac{m_\chi m_N}{m_\chi + m_N}]$$

$$\Rightarrow \boxed{v_{\rm in} > \sqrt{\frac{2\delta}{\mu_{\chi N}}} = v_{N*}}$$

Condition for Inelastic Scattering

Inelastic Dark Matter (IDM)



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Condition for Inelastic Scattering

- For Direct Detection (DD) : $\underbrace{\textbf{max. [} v_{\rm in} \textbf{]} \simeq \textbf{800 km/s}}_{\text{Galactic escape speed}}$ ⇨ **max. [δ]** that can be probed ≃ **200 keV**

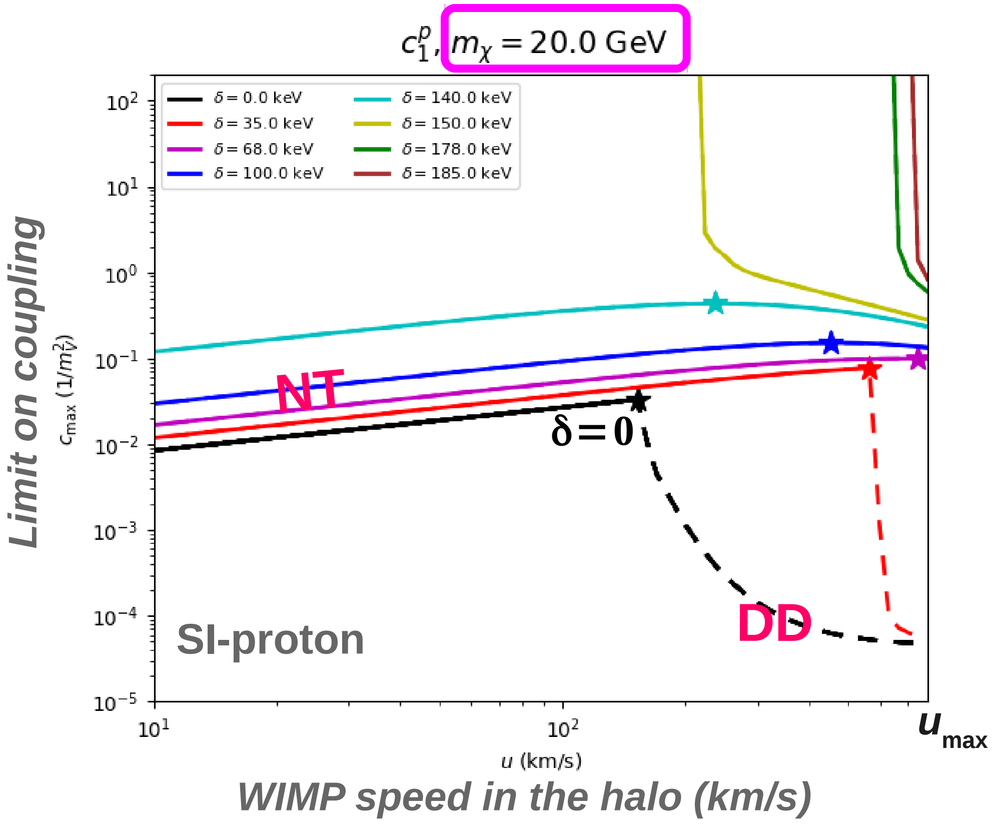
- For Capture in the Sun : $\underbrace{\textbf{max. [} v_{\rm in} \textbf{]} \simeq \textbf{1600 km/s}}_{\text{due to Solar gravity}}$ ⇨ **max. [δ]** that can be probed using a Neutrino Telescope ≃ **600 keV**

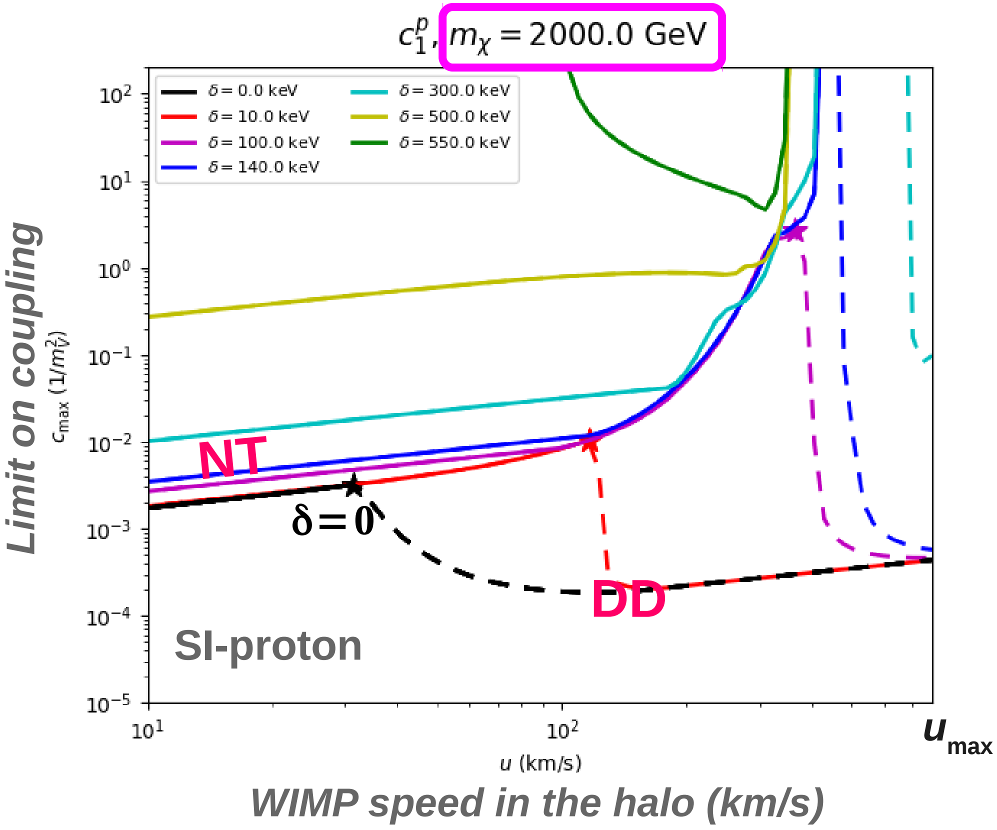
$$v_{\rm in} = \sqrt{u^2 + v_{\rm esc}(r)^2}$$

$v_{\rm esc}(r)$ = [620 , 1400] km/s
(from solar surface to center)

***IDM**: Experimental sensitivity to the WIMP speed*

NT : continues curves
DD : dashed curves





[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

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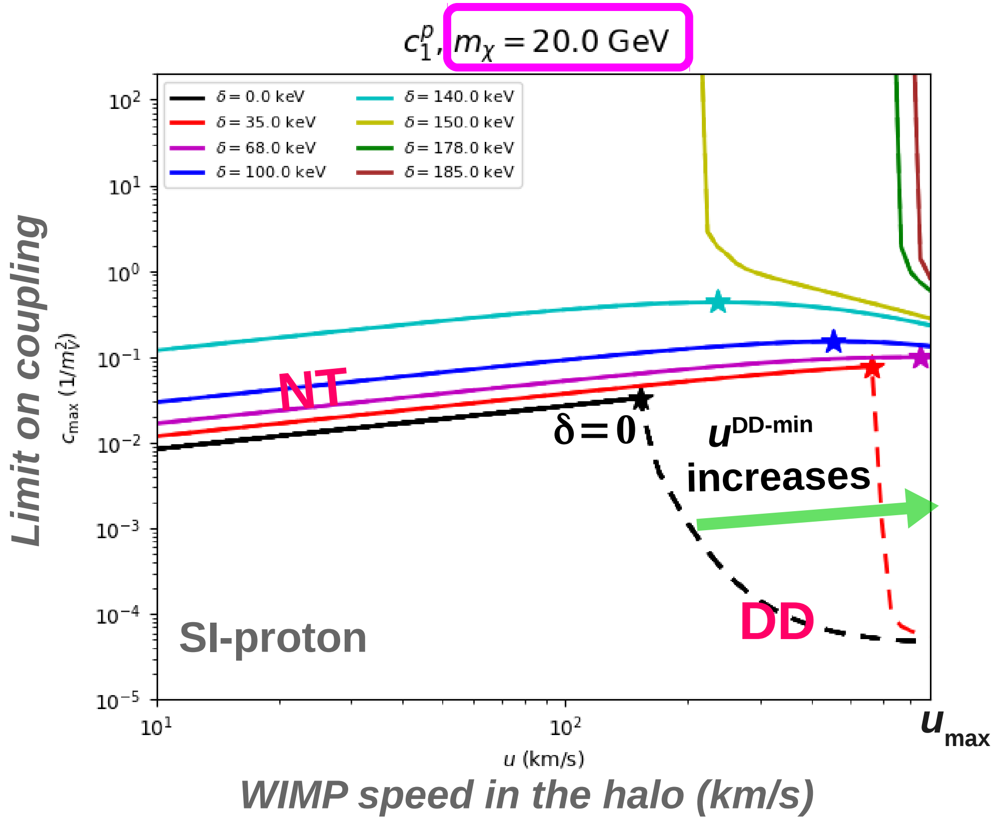

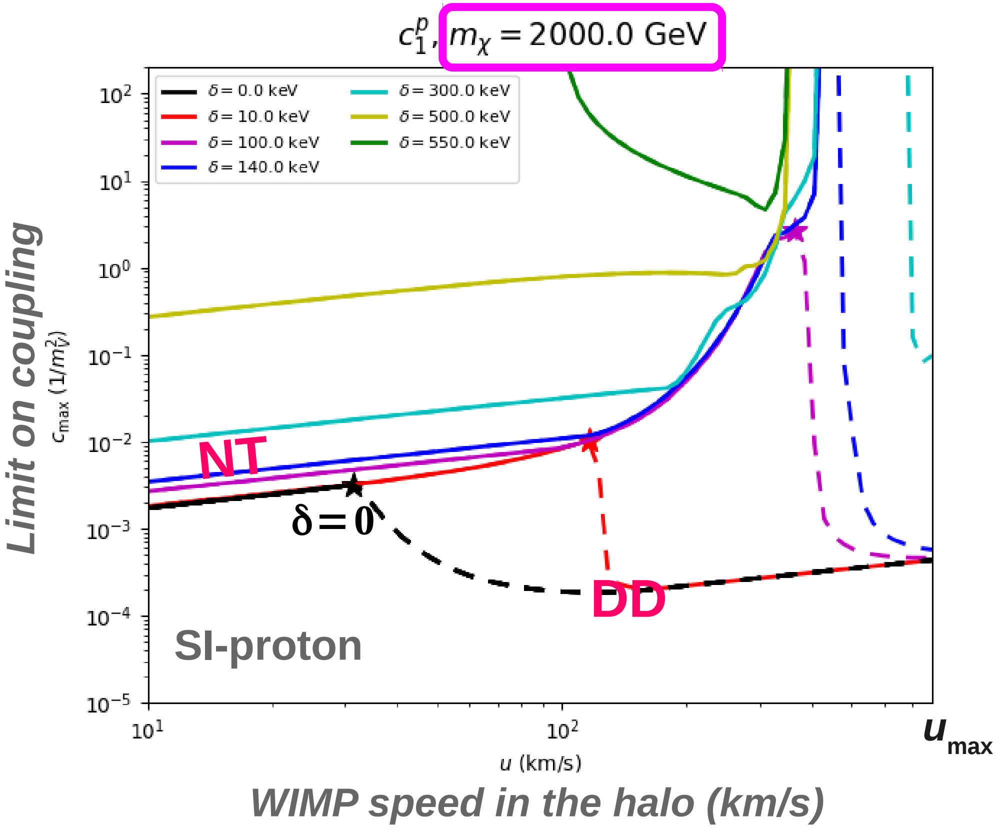

***$u^{DD\text{-min}}$* :** minimum WIMP speed required to produce a DD signal

[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

IDM: *Experimental sensitivity to the WIMP speed*

for larger δ 's, low u 's are not enough

to satisfy $v_{in}^2 = u^2 + v_{\rm esc}(r)^2 \geq \frac{2\delta}{\mu_\chi T}$

~~Condition for IDM scattering in the Sun~~

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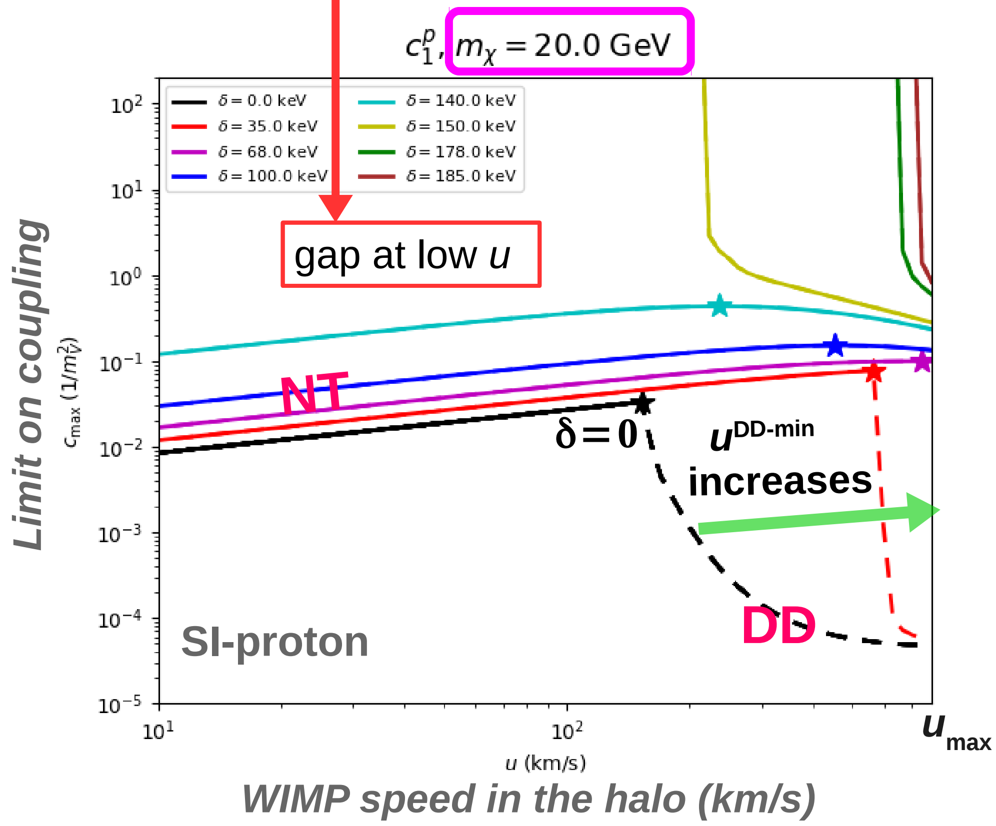

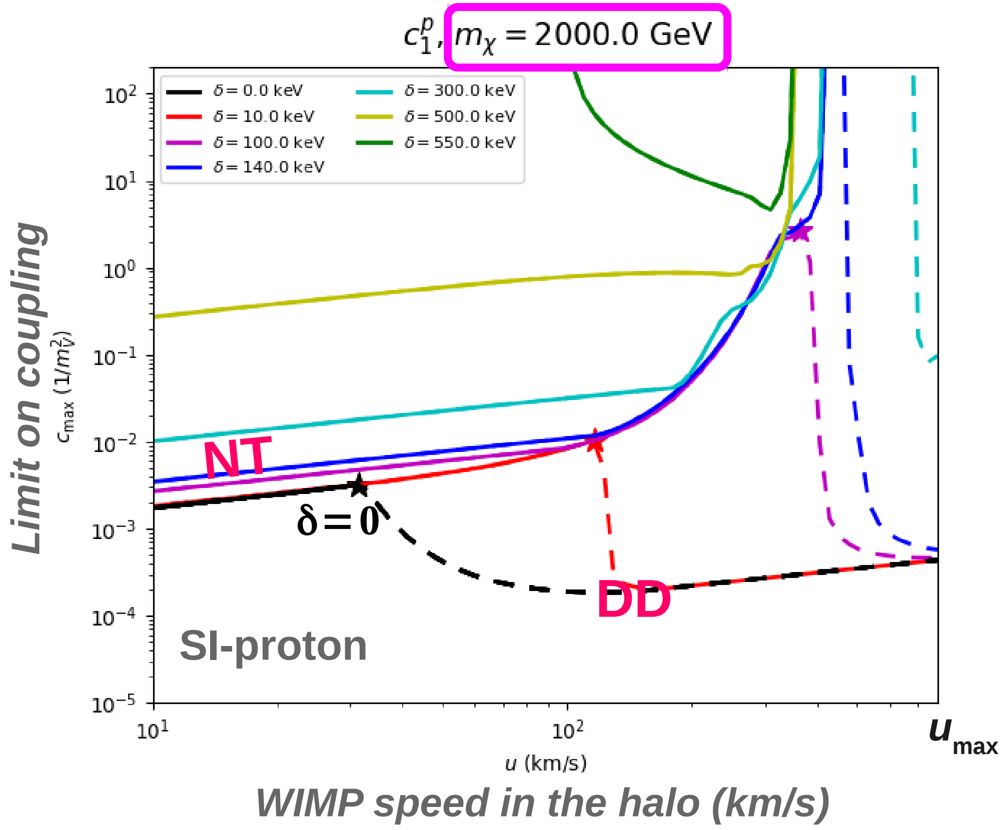

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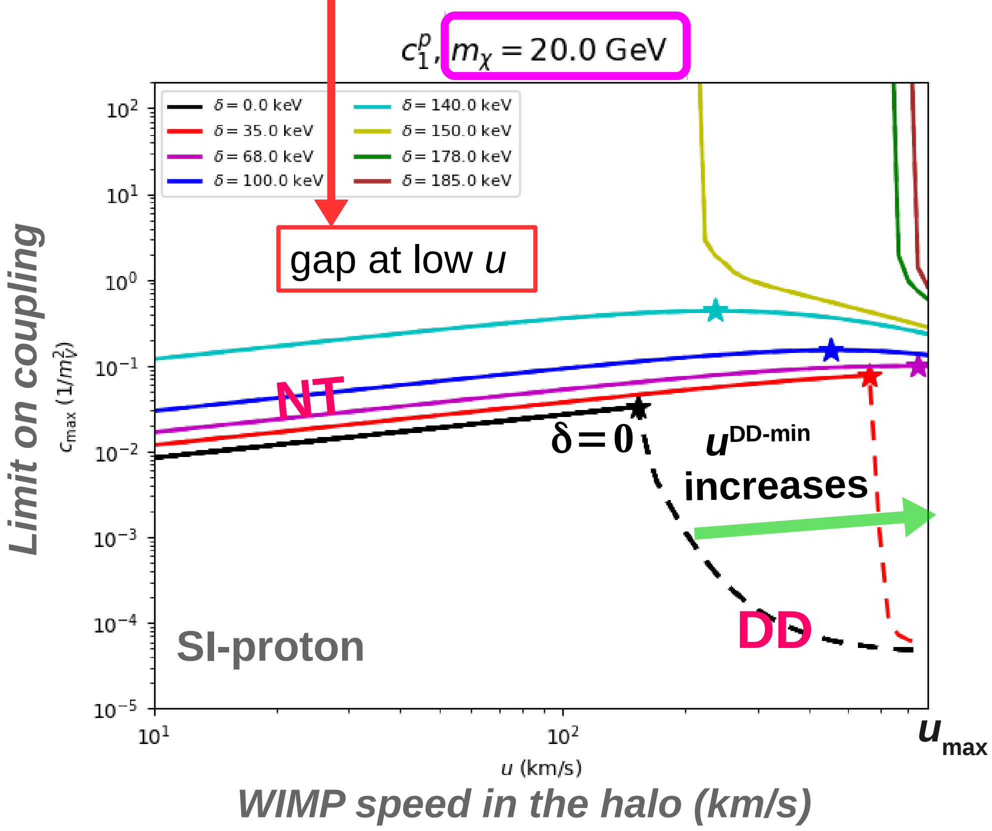


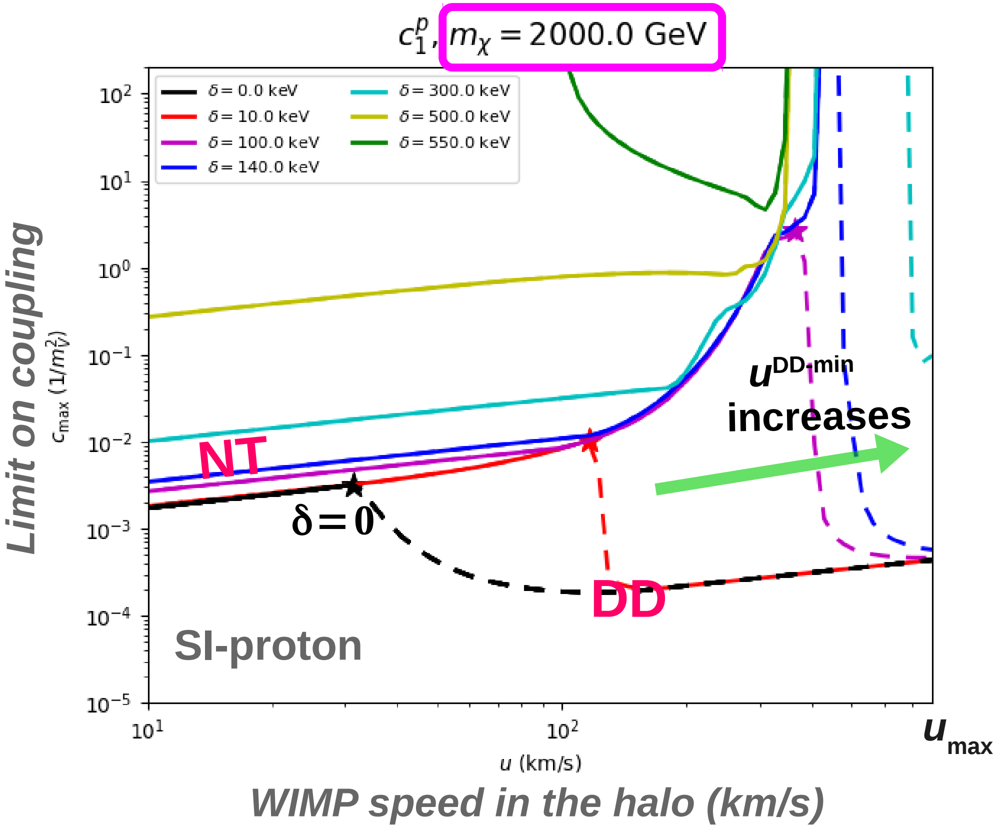
gap at low *u*

NT

$\delta = 0$

$u^{DD\text{-min}}$ increases

DD



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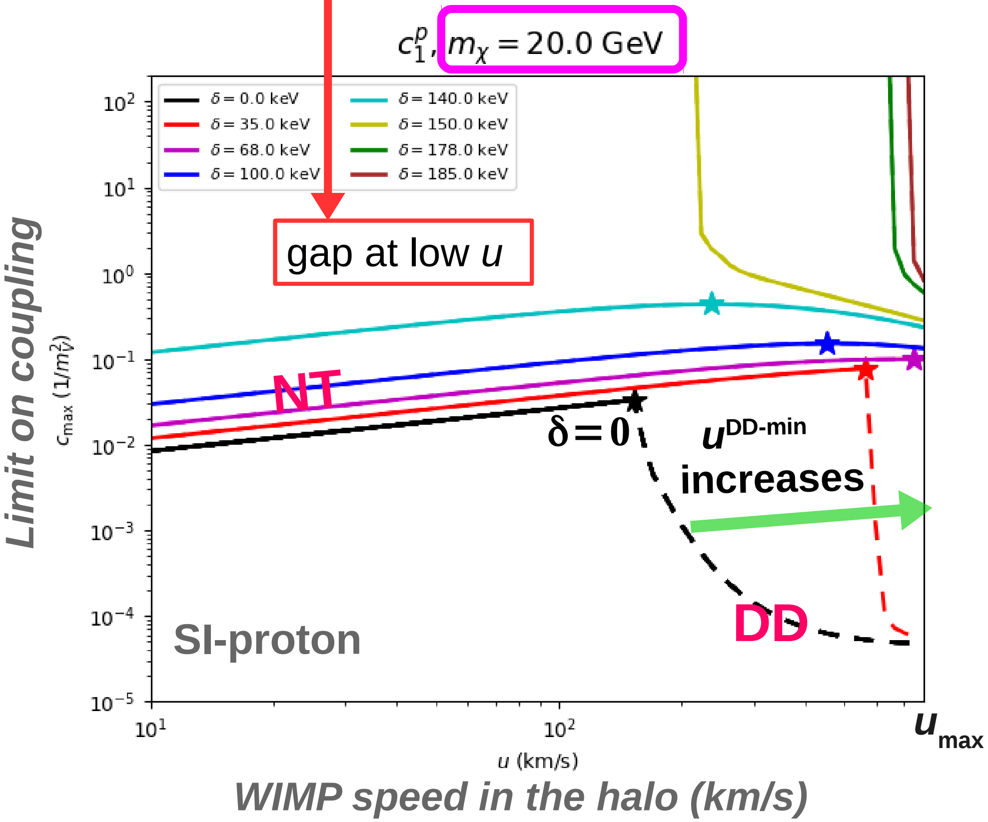
~~Condition for IDM scattering in the Sun~~

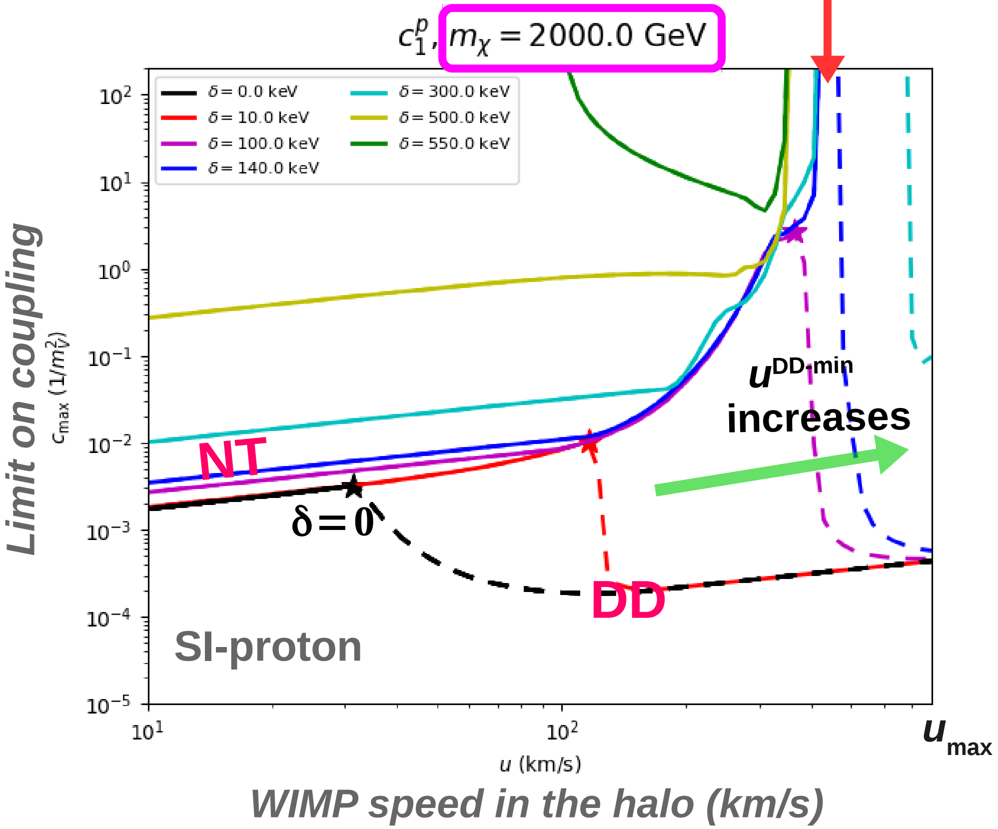
NT : continues curves

DD : dashed curves

$u^{\text{C-max}} < u^{\text{DD-min}}$

gap at high *u*





$u^{\text{DD-min}}$ **:** minimum WIMP speed required to produce a DD signal

$u^{\text{C-max}}$ **:** maximum WIMP speed beyond which the WIMP can not be captured in the Sun

[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

IDM*: parameter space in Halo-independent approach*

~~**Condition for IDM scattering in the Sun**~~

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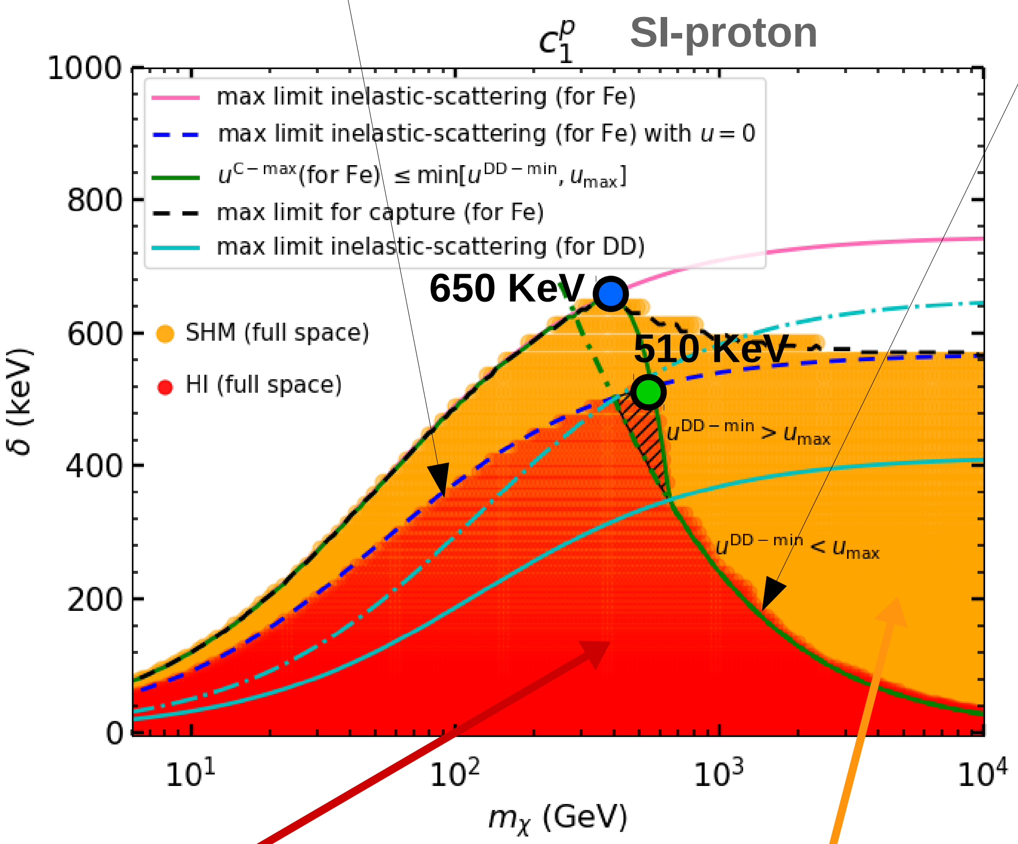

Halo-independent method

Standard Halo Model (SHM)

[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

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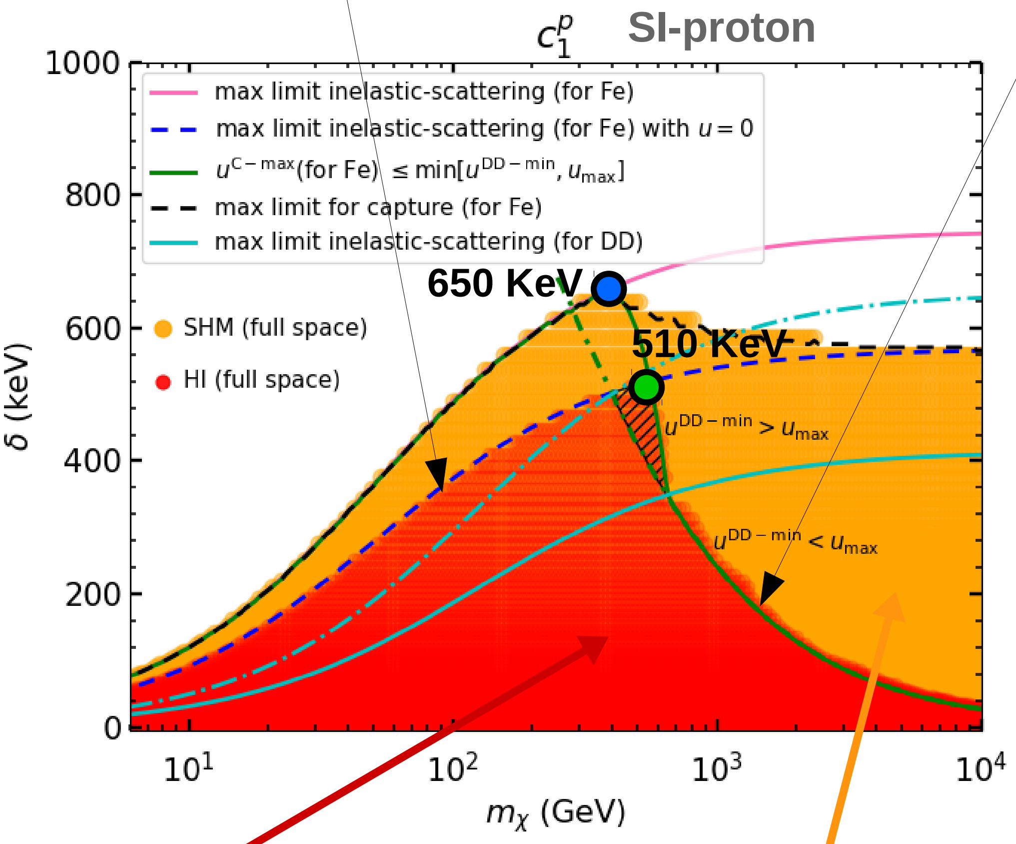

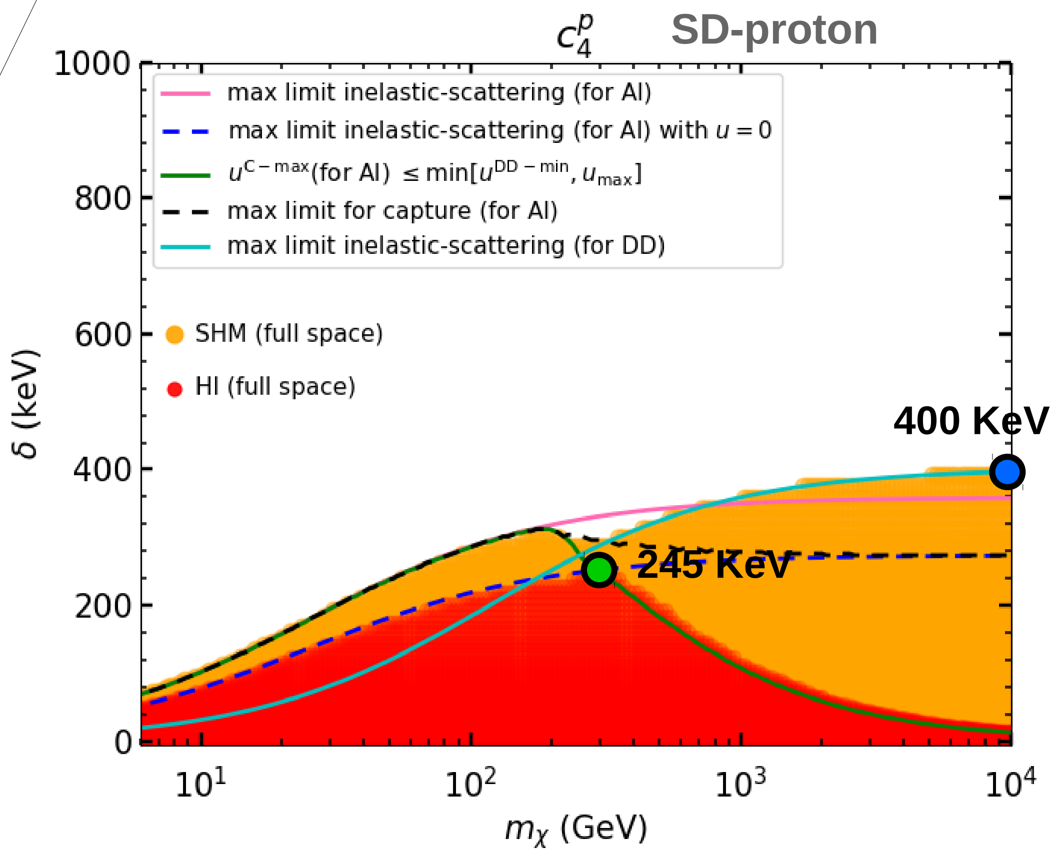

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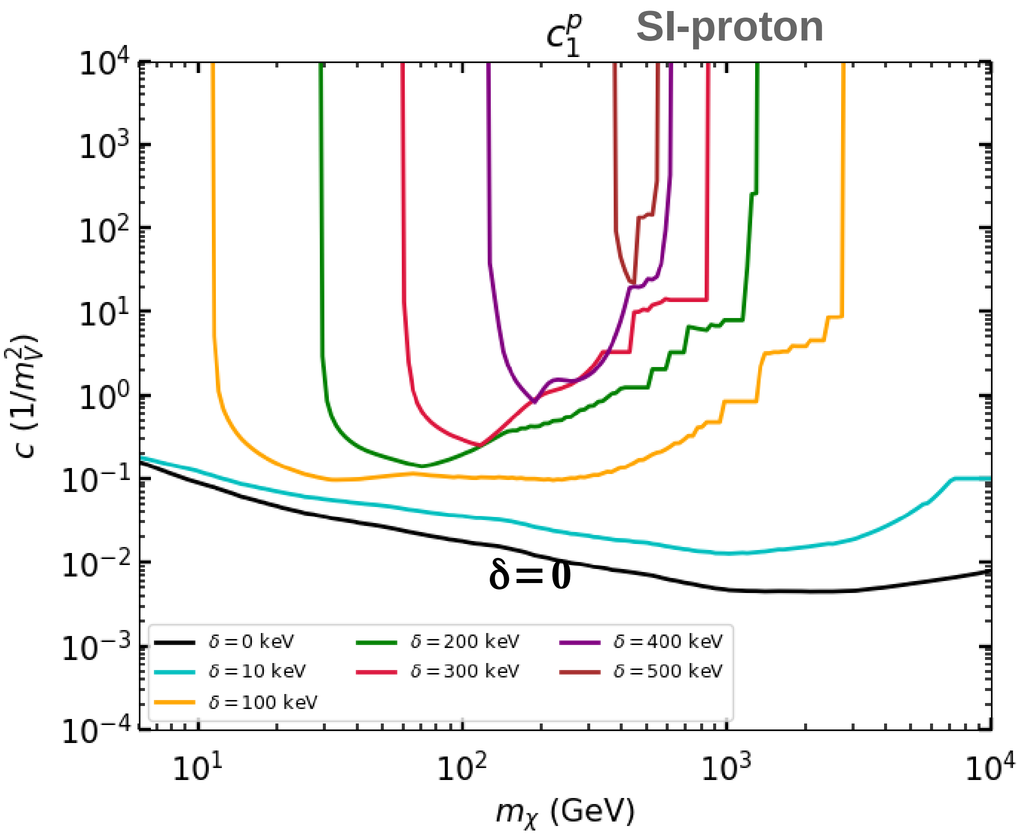
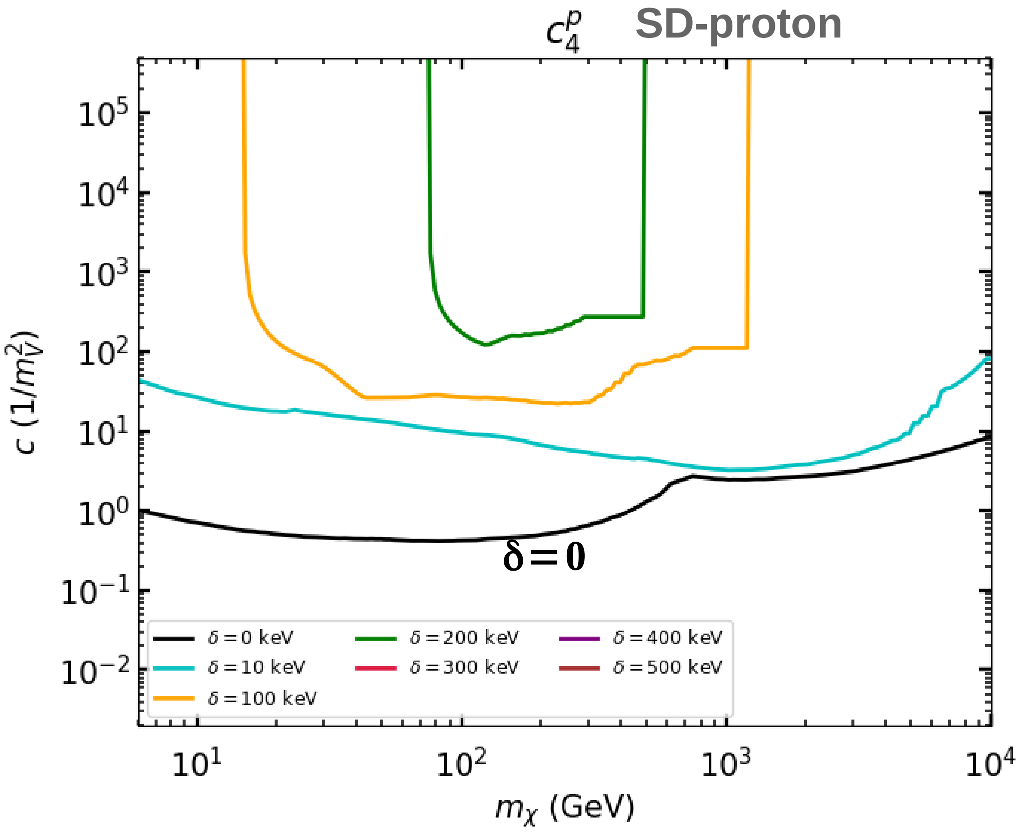
IDM*: Halo-independent bound on WIMP-nucleon coupling*





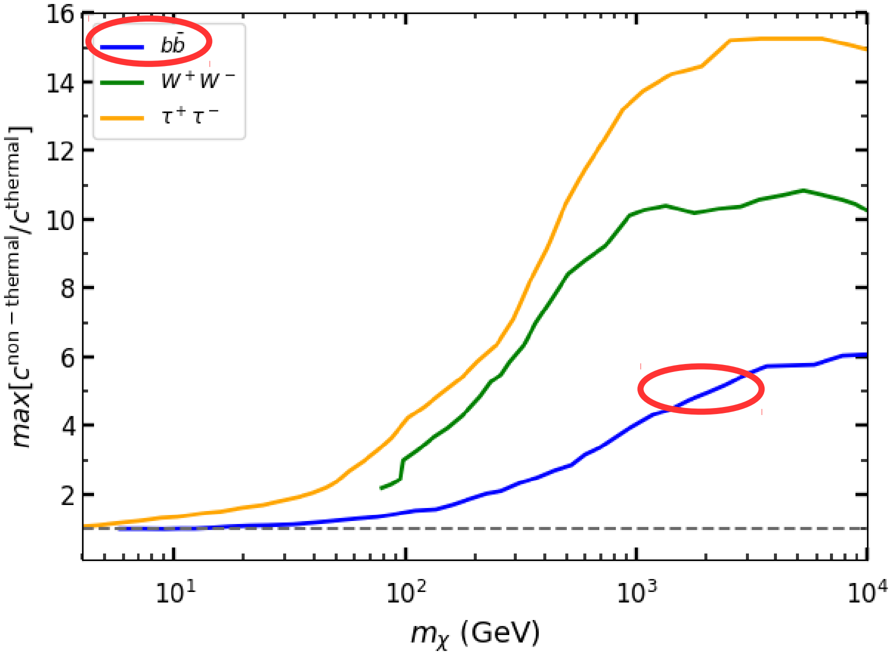
[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

IDM*: *issue of thermalization

Relaxation of the Neutrino Telescope bounds on the coupling when the assumption of thermalization of the WIMPs with the solar plasma is not made

$$\left.\right\} \quad \frac{c^{\text{non-thermal}}}{c^{\text{thermal}}}$$

$$\text{max.}\left[\frac{c^{\text{non-thermal}}}{c^{\text{thermal}}}\right]$$



$$\frac{c^{\text{non-thermal}}}{c^{\text{thermal}}} \simeq \left(\frac{V_\odot}{2\langle\sigma v\rangle t_\odot^2 \Gamma_{\text{exp}}}\right)^{1/4}$$

[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]

Summary

- We discuss **halo-independent bounds** (bounds independent of the WIMP speed distribution in the halo) on the **Inelastic Dark Matter (IDM)** scenario $\chi + N \rightarrow \chi' + N$ $m_{\chi'} - m_{\chi} = \delta > 0$

- A finite halo-independent bound requires experimental sensitivity over the full WIMP speed range

  → combine **Direct detection (DD) & Neutrino Telescope (NT)** [**complementary**]

  (searches for the signal from WIMPs captured in the Sun)

- **For δ larger than some value (depending on m_χ) the complementarity between DD & NT is lost (the full WIMP speed range cannot be probed anymore)**

  → **A halo-independent bound is Not possible anymore for such larger δ's**

  → **In such cases a specific model for the WIMP speed distribution in the halo** (e.g., the SHM) **is required to obtain a constraint on the WIMP-nucleon coupling**

- When the assumption of thermalization of IDM in the Sun is relaxed the effect on the bounds is relatively mild

Backup slides

IDM*: Direct Detection (DD) signal*

scattering cross-section

$$R_{\rm DD} = M\tau_{\rm exp}\underbrace{\left(\frac{\rho_\odot}{m_\chi}\right)}_{\text{local DM density}}\int du\, f(u)\, u \sum_T N_T\, \Theta\left(u^2 - v_{T*}^2\right)\int_{E_{\rm min}(u)}^{E_{\rm max}(u)} dE\, \zeta_T\, \frac{d\sigma_T}{dE}$$

T = Target Nucleus in DD

$$E_{\rm min,max}(u) = \frac{\mu_{\chi T}^2 u^2}{2m_T}\left(1 \mp \sqrt{1 - \frac{2\delta}{\mu_{\chi T} u^2}}\right)^2 \qquad v_{T*} = \sqrt{\frac{2\delta}{\mu_{\chi T}}}$$

- Kinematic conditions:

  1) Incoming WIMP speed $u \geq v_{T*} = \sqrt{\frac{2\delta}{\mu_{\chi T}}}$ [condition for IDM scattering]

  2) $E_{\rm max} \geq \max.[\, E_{\rm min}, E_{\rm th}\,]$ $E_{\rm th}$: threshold energy of the DD experiment

$$\Longrightarrow\ u \geq u^{\text{DD-min}} = \max.\left[\sqrt{\frac{2\delta}{\mu_{\chi T}}}\,,\ \frac{1}{\sqrt{2m_T E_{\rm th}}}\left(\frac{m_T E_{\rm th}}{\mu_{\chi T}} + \delta\right)\right]$$

- **For a finite δ, the minimum WIMP speed to produce a DD signal increases**

IDM: *Capture in the Sun*

$$\Gamma_\odot = \frac{C_\odot}{2}\tanh^2(t_\odot/\tau_\odot)$$

Annihilation rate of WIMPs
captured in the Sun
that produces the neutrino flux

$C_\odot$: Capture rate $t_\odot$: Solar age $\tau_\odot = (C_\odot C_A)^{-\frac{1}{2}}$: equilibration time for Capture & Annihilation

$$C_\odot = \underbrace{\left(\frac{\rho_\odot}{m_\chi}\right)}_{\text{local DM density}} \int du\, \frac{f(u)}{u} \int_0^{R_\odot} dr\, 4\pi r^2\, w^2 \sum_T \Theta\left(w^2 - v_{T*}^2\right)\ \Omega_T$$

T = Target Nucleus in Sun

with $$\Omega_T = \eta_T(r)\ \Theta(E_{\rm max} - E_{\rm cap}) \int_{\max[E_{\rm min}, E_{\rm cap}]}^{E_{\rm max}} dE\, \frac{d\sigma_T}{dE}$$

scattering
cross-section

$$\left\{\begin{array}{l} w(u,r) = \sqrt{u^2 + v_{\rm esc}(r)^2} = v_{\rm in} \quad \text{(incoming WIMP speed inside Sun)} \\[2ex] E_{\rm min,max}(w) = \dfrac{1}{2} m_\chi w^2 \left[1 - \dfrac{\mu_{\chi T}^2}{m_T^2}\left(1 \pm \dfrac{m_T}{m_\chi}\sqrt{1 - \dfrac{v_{T*}^2}{w^2}}\right)^2\right] - \delta \\[2ex] E \geq E_{\rm cap}(u) = \dfrac{1}{2} m_\chi u^2 - \delta \end{array}\right.$$

u = WIMP speed in the Halo

$v_{\rm esc}(r)$ = solar escape speed

$$v_{T*} = \sqrt{\frac{2\delta}{\mu_{\chi T}}}$$

minimum energy to be deposited by the WIMP
so that $v_{\rm out} < v_{\rm esc}(r)$ and the WIMP is captured

IDM: *Capture in the Sun*

u = WIMP speed in the Halo

$v_{\rm esc}(r)$ = solar escape speed

$w(u,r) = \sqrt{u^2 + v_{\rm esc}(r)^2}$ = $\boldsymbol{v}_{\rm in}$ (incoming WIMP speed inside Sun)

$$E_{\rm min,max}(w) = \frac{1}{2} m_\chi w^2 \left[1 - \frac{\mu_{\chi T}^2}{m_T^2}\left(1 \pm \frac{m_T}{m_\chi}\sqrt{1-\frac{v_{T*}^2}{w^2}}\right)^2\right] - \delta \qquad v_{T*} = \sqrt{\frac{2\delta}{\mu_{\chi T}}}$$

$E \geq E_{\rm cap}(u) = \frac{1}{2} m_\chi u^2 - \delta$ minimum energy to be deposited by the WIMP so that $\boldsymbol{v}_{\rm out} < \boldsymbol{v}_{\rm esc}(\boldsymbol{r})$ and the WIMP is captured

- <u>Kinematic conditions:</u>

1) **[Condition for IDM scattering]**

Incoming WIMP speed $w(u,r) = \sqrt{u^2 + v_{\rm esc}(r)^2} \geq \boldsymbol{v}_{T*} = \sqrt{\frac{2\delta}{\mu_{\chi T}}}$

$\Rightarrow\ u^2 + v_{\rm esc}(r)^2 \geq \frac{2\delta}{\mu_{\chi T}}$

$v_{\rm esc}(r)$ = [620 , 1400] km/s (from solar surface to center)

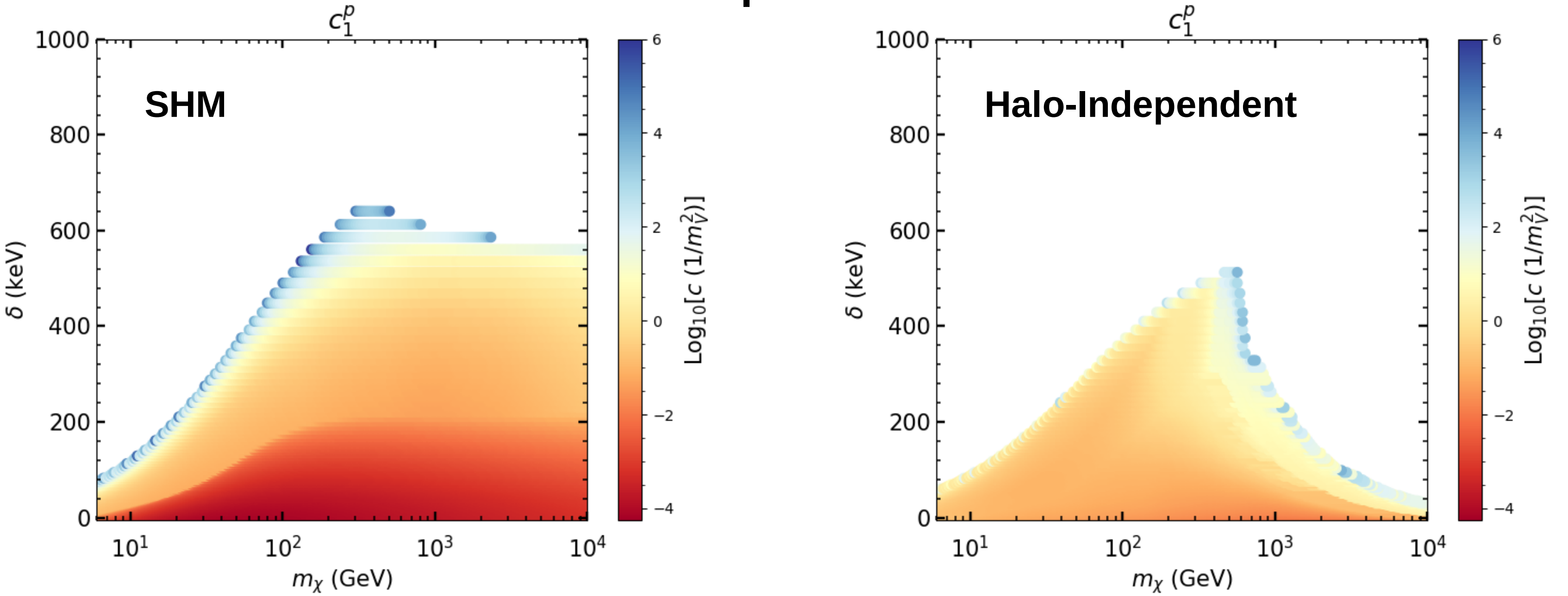
⇒ **If** $\frac{2\delta}{\mu_{\chi T}} \geq v_{\rm esc}(r)^2$ **IDM scattering for $\boldsymbol{u} \rightarrow$ 0 is Not possible, needs a larger $\boldsymbol{u}$**

2) $E_{\rm max} \geq E_{\rm cap}$

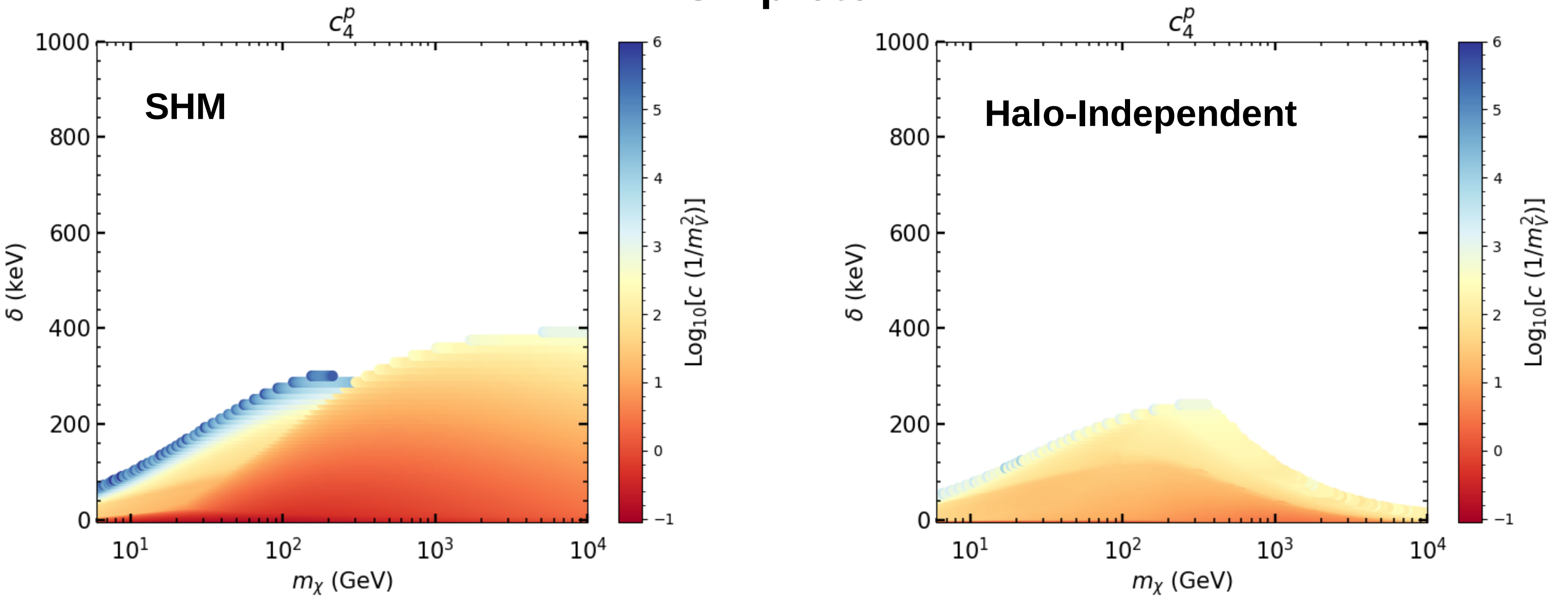
⇒ $\boldsymbol{u} \leq \boldsymbol{u}^{\text{C-max}}(r, m_\chi, m_T, \delta)$

If the WIMP speed $\boldsymbol{u}$ crosses the maximum limit $\boldsymbol{u}^{\text{C-max}}$, it is Not captured by the Sun

SI-proton



SD-proton



[S. Kang, AK, S. Scopel, (JCAP11(2023)077)]

IDM: *issue of thermalization*

$$\Gamma_\odot = \frac{C_\odot}{2}\tanh^2(t_\odot/\tau_\odot) = \frac{C_\odot}{2}\tanh^2(t_\odot\sqrt{C_\odot C_A})$$

$$\tau_\odot = (C_\odot C_A)^{-\frac{1}{2}}$$ equilibration time for Capture & Annihilation

$C_\odot$: WIMP Capture rate in the Sun

Annihilation coefficient : $$C_A = \frac{\langle\sigma v\rangle 4\pi \int_0^{R_\odot} r^2 n_\chi^2(r)\,dr}{\left[4\pi \int_0^{R_\odot} r^2 n_\chi(r)\,dr\right]^2}$$

$$\langle\sigma v\rangle = 3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$n_\chi(r) = n_0 e^{-m_\chi\phi(r)/T_c} \simeq n_0 e^{-r^2/r_\chi^2}$$

$$r_\chi^2 = \frac{3k_B T_c}{2\pi G\rho_c m_\chi},$$

$$\phi(r) = \int_0^r \frac{GM(r)}{r^2}\,dr$$

$$T_c \simeq 1.55\times10^7\ {}^\circ\mathrm{K}$$

$$C_A = \langle\sigma v\rangle\frac{V_2}{V_1^2}$$

$$V_n = 4\pi\int_o^{r_\odot} r^2 e^{-nr^2/r_\chi^2}\,dr$$

$$C_A^{\text{min}} = \frac{\langle\sigma v\rangle}{V_\odot} \Longrightarrow \Gamma_\odot^{\text{min}}$$

(for $n_\chi(r) = n_0$)

[S. Kang, AK, S. Scopel, (JCAP 11 (2023) 077)]