Halo-independent bounds of WIMP-nucleon couplings from direct detection and neutrino observations

Sunghyun Kang

Based on
JCAP03(2023)011(arXiv: 2212.05774) & JCAP11(2023)077(arXiv: 2308.13203)
in collaboration with Stefano Scopel and Arpan Kar

2024 PASCOS

SOGANG UNIVERSITY

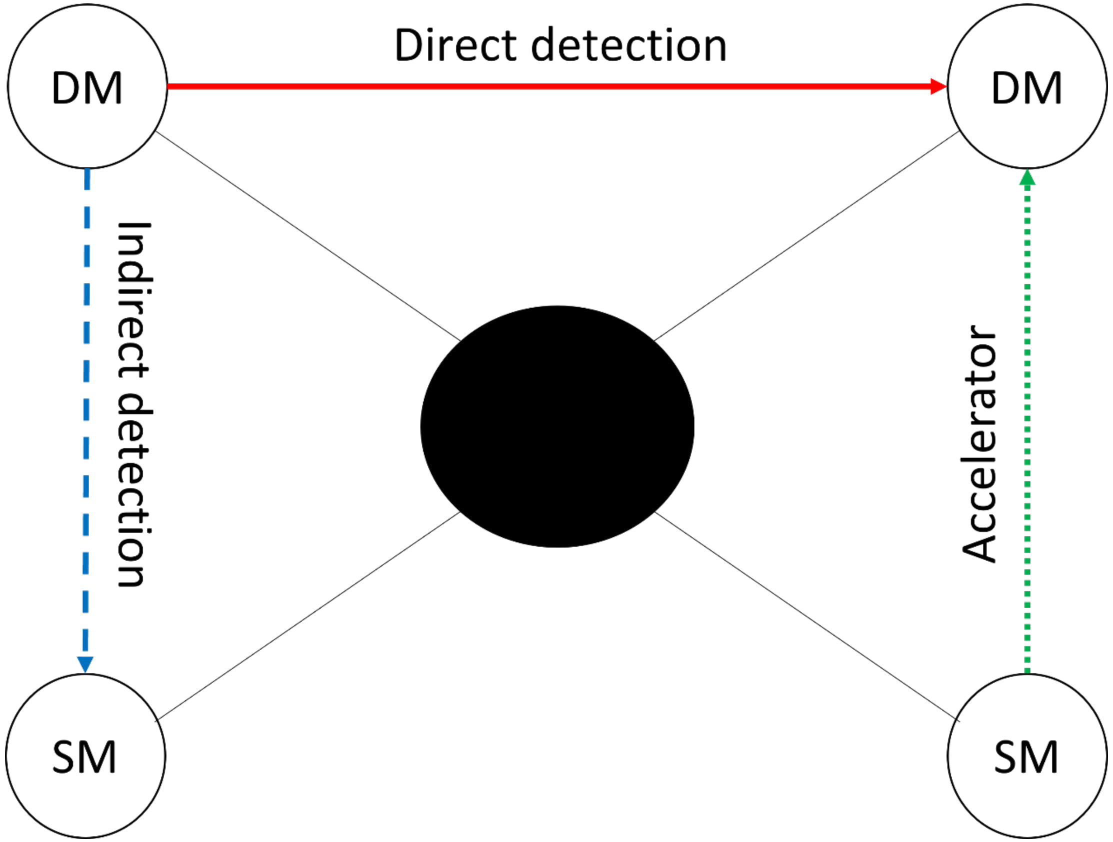
Center for Quantum SpaceTime

Dark Matter and WIMPs

- Many evidences of Dark Matter
  - Galaxy rotational curve
  - CMB
  - Lensing effect

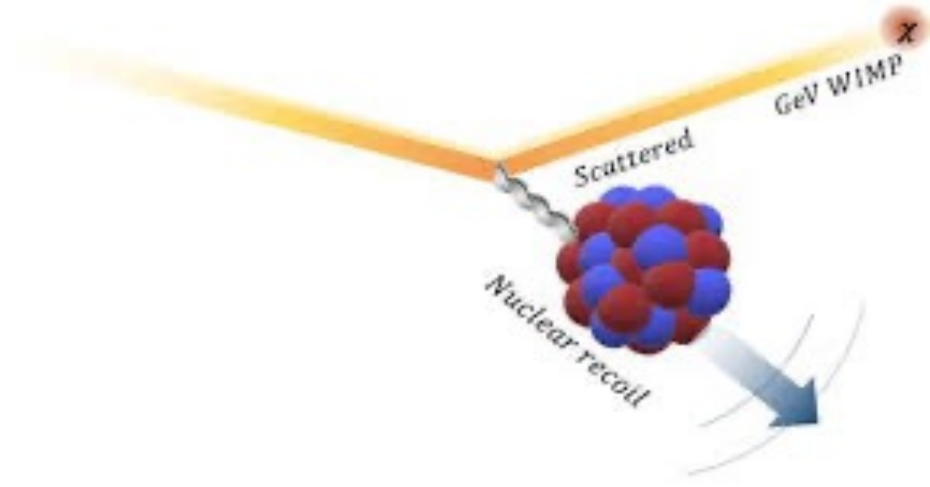
- Many candidates
  - Neutrino
  - Cold Dark Matter (CDM)
  - Weakly Interacting Massive Particle (WIMP)
  - Weak-type interaction
    - no electric charge, no color
  - Mass range in GeV-TeV range
  - WIMP miracle
    - correct relic abundance is obtained at WIMP $< \sigma v > = weak\ scale$
    - most extensions of SM are proposed independently at that scale.

Detection strategies



- Direct detection: DM interacts with SM particles (left to right)
- Indirect detection: DM annihilation (top to bottom)
- Accelerator: DM creation (bottom to top)

Direct Detection (DD)

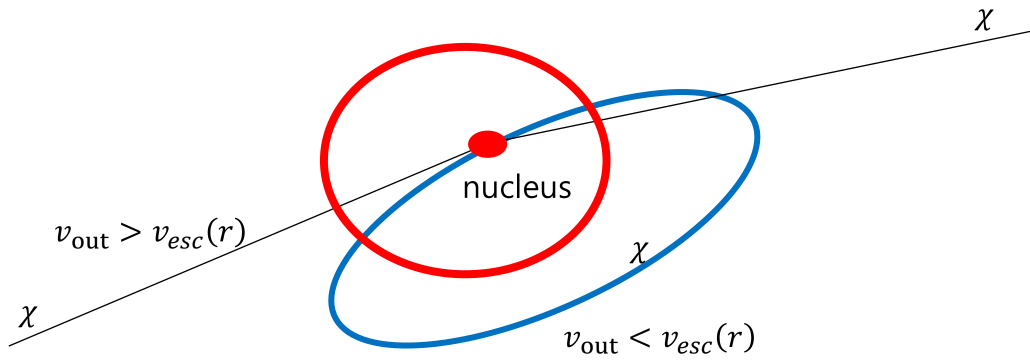


- The signals are WIMP-nucleus recoil events

- Low probability requires high exposure
- Underground to avoid background

- Depend on features of targets and experimental set-ups
- Different nuclear targets and background subtraction:
  - COSINE, ANAIS, DAMA, LZ, PandaX-4T, XENON-nT, PICO-60 and ect.

Indirect Detection (NT)



- Capture rate in the celestial body

- WIMP scatters off nucleus at distance r inside celestial body
  - same interaction probed by DD

- If its outgoing speed v_{out} is below the escape velocity $v_{esc}(r)$, it gets locked into gravitationally bound orbit and keeps scattering again and again

- Capture process is favored for low (even vanishing) WIMP speeds

Non-Relativistic Effective Theory (NREFT)

- WIMP is slow, so that the recoil events are non-relativistic
- NREFT provides a general and efficient way to characterize results with mass of WIMP and coupling constants

Operators spin up to 1/2

$$\mathcal{O}_1 = 1_\chi 1_N; \quad \mathcal{O}_2 = (v^\perp)^2; \quad \mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N; \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp); \quad \mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp; \quad \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp; \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}; \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}; \quad \mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N}); \quad \mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$$

$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}),$$

- Hamiltonian: $\Sigma_{i=1}^{N}\left(c_i^n \mathcal{O}_i^n + c_i^p \mathcal{O}_i^p\right)$
- Non-relativistic process
  - all operators must be invariant by Galilean transformations ($v \sim 10^{-3}c$ in galactic halo)
- Building operators using: $i\frac{\vec{q}}{m_N},\ \vec{v}^\perp,\ \vec{S}_\chi,\ \vec{S}_N$

Non-Relativistic Effective Theory (NREFT)

- Scattering amplitude:

$$\frac{1}{2j_\chi + 1}\frac{1}{2j_N + 1}\Sigma_{spins}|M|^2 \equiv \Sigma_k \Sigma_{\tau=0,1}\Sigma_{\tau'=0,1} R_k^{\tau\tau'}\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}, \left\{c_i^\tau, c_j^{\tau'}\right\}\right) W_k^{\tau\tau'}(y)$$

- Differential cross section : $\frac{d\sigma}{dE_R} = \frac{1}{10^6}\frac{2m_N}{4\pi}\frac{c^2}{v^2}\left[\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\,\Sigma_{spin}|M|^2\right]$

- Differential rate : $\frac{dR}{dE_R} = N_T \int_{v_{min}}^{v_{esv}} \frac{\rho_\chi}{m_\chi}\, v\, \frac{d\sigma}{dE_R}\, f(v)\, dv$

- With $E_R = \frac{\mu_{\chi N}^2\, v^2}{m_N}$, $v_{min} = \frac{1}{\sqrt{2m_N E_R}}\left|\frac{m_N E_R}{\mu_{\chi N}} + \delta\right|$

Non-Relativistic Effective Theory (NREFT)

- Scattering amplitude:
$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\Sigma_{spins}|M|^2 \equiv \Sigma_k \Sigma_{\tau=0,1}\Sigma_{\tau'=0,1} R_k^{\tau\tau'}\left(\vec{v}_T^{\perp\,2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{c_i^\tau, c_j^{\tau'}\right\}\right) W_k^{\tau\tau'}(y)$$

- $R_k^{\tau\tau'}$: WIMP response function
  - Velocity dependence: $\mathcal{R}_k^{\tau\tau'} = \mathcal{R}_{k,0}^{\tau\tau'} + \mathcal{R}_{k,1}^{\tau\tau'}\left(v^2 - v_{min}^2\right)$

- $W_k^{\tau\tau'}$: nuclear response function
  - $y = (qb/2)$^2
  - b: harmonic oscillator size parameter
  - $k = M,\ \Delta,\ \Sigma',\ \Sigma'',\ \widetilde{\Phi}' \text{ and } \Phi''$
  - allowed responses assuming nuclear ground state is a good approximation of P and T

DD event rate (elastic scattering)

- DD event rate

$$\mathrm{R_{DD}} = M\tau_{exp} \frac{\rho_\chi}{m_\chi} \int du\, f(u) u\, \Sigma_T\, N_T \int_{E_{R,th}}^{2\mu_{\chi T}^2 u^2 / m_T} dE_R\, \zeta_{exp} \frac{d\sigma_T}{dE_R}$$

  - $M\tau_{exp}$: exposure
  - $E_{R,th}$: experimental energy threshold
  - ζ_{exp} : experimental features such as quenching, resolution, efficiency, etc.

- $R_{DD} = \int_0^{u_{esc}} f(u)\, H_{DD}(u)$

$$H_{DD}(u) = u\, M\tau_{exp} \frac{\rho_\chi}{m_\chi}\ \Sigma_T\, N_T \int_{E_{R,th}}^{2\mu_{\chi T}^2 u^2 / m_T} dE_R\, \zeta_{exp} \frac{d\sigma_T}{dE_R}$$

Capture rate (elastic scattering)

- Capture rate

$$C_{\odot} = \frac{\rho_\chi}{m_\chi} \int du\, f(u) \frac{1}{u} \int_0^{R_\odot} dr\, 4\pi r^2\, w^2\ \Sigma_T\, \rho_T(r)\, \Theta\left(u_T^{C-max} - u\right) \int_{m_\chi u^2/2}^{2\mu_{\chi T}^2 w^2/m_T} dE_R \frac{d\sigma_T}{dE_R}$$

  - ρ_T: the number of density of target
  - r: distance from the center of the Sun for Standard Solar Model AGSS09ph
  - u: DM velocity asymptotically far away from the Sun
  - $v_{esc}(r)$: escape velocity at distance r
  - $w^2(r) = u^2 + v_{esc}^2(r)$
- Neutrino Telescope (NT):
  - the neutrino flux from the annihilation of WIMPs captured in the Sun
  - DM annihilations into $b\bar{b}$

Capture rate (elastic scattering)

- with assumption of equilibrium between capture and annihilation: $\Gamma_{\odot} = C_{\odot}/2$

- $C_{\odot} = \int_0^{u^{c-max}} du\, f(u)\, H_C(u)$

$$H_C = \frac{\rho_\chi}{m_\chi}\frac{1}{u}\int_0^{R_\odot} dr\, 4\pi r^2\, w^2\, \Sigma_T\, \rho_T(r)\, \Theta\left(u_T^{C-max} - u\right) \int_{m_\chi u^2/2}^{2\mu_{\chi T}^2 w^2/m_T} dE_R \frac{d\sigma_T}{dE_R}$$

  - $u_T^{C-max} = v_{esc}(r)\sqrt{\frac{4m_\chi m_T}{\left(m_\chi - m_T\right)^2}}$: maximum WIMP speed for capture possible

Halo independent approach

- Scattering count rate:
  $R \sim \int dv\, H(v)\, f(v)$
  interaction
  velocity distribution
- Two parts of interaction and velocity distribution
  - needs to avoid uncertainty
  - interaction: include all possible interaction types
  - velocity distribution: halo independent approaches
- Model independent method: the most general scenarios

Halo independent approach

- Halo independent approach with arbitrary speed distribution, $f(u)$
  - The only constraint: $\int_{u=0}^{u_{max}} f(u)\, du = 1$

- Direct detection experiments have a threshold $u > u_{th}^{DD}$
  - Due to the energy threshold of experimental detectors

- Capture in the Sun is favored for low WIMP speeds
  - $u < u_T^{C-max}$

- In order to cover full speed range: combine DD and capture

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

Halo independent approach

- Considering one effective coupling (c_i) at a time:
  - $R_{exp}\left(c_i^2\right) = \int du\, f(u)\, H_{exp}\left(c_i^2, u\right) \leq R_{max}$
  - R_{max} : corresponding maximum experimental bound

- Using relation : $H\left(c_i^2, u\right) = c_i^2 H(c_i = 1, u)$
  - $H\left(c_{i,max}^2(u), u\right) = R_{max}$
  - $c_{i,max}^2(u) = \frac{R_{max}}{H(c_i=1,u)}$
  - $c_{i,max}(u)$: upper limit on c_i at single speed stream u

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

Halo independent approach

- $R_{exp}(c_i^2) = \int du\, f(u)\, H_{exp}(c_i^2, u) \leq R_{max}$

$$
\begin{aligned}
R(c_i^2) &= \int_0^{u_{\max}} du\, f(u)\, H(c_i^2, u) \\
&= \int_0^{u_{\max}} du\, f(u)\, \frac{c_i^2}{c_{i\,\max}^2(u)} H(c_{i\,\max}^2(u), u) \\
&= \int_0^{u_{\max}} du\, f(u)\, \frac{c_i^2}{c_{i\,\max}^2(u)} R_{\max} \quad \leq \quad R_{\max}
\end{aligned}
$$

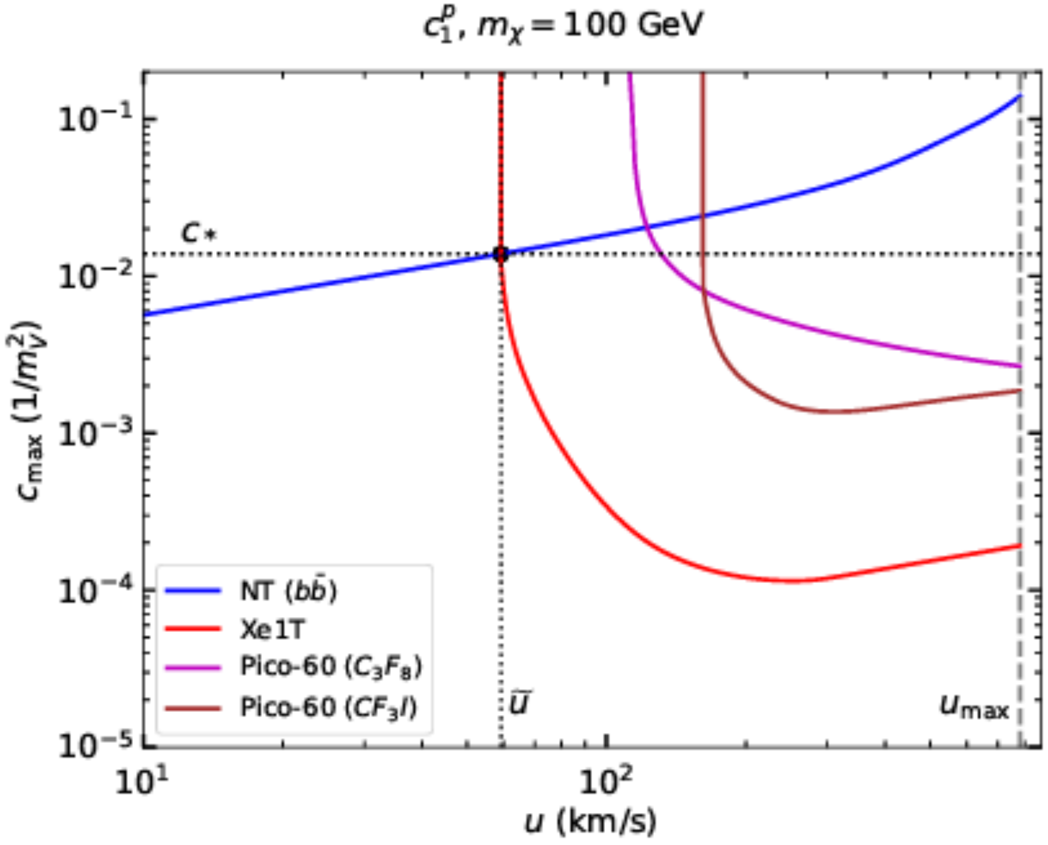
- upper limit on i-th coupling c_i:

$$c_i^2 \leq \left[\int_0^{u_{max}} du\, \frac{f(u)}{c_{i,max}^2(u)} \right]^{-1}$$

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

Halo independent approach

- $c_* = c_{max}^{NT}(\tilde{u}) = c_{max}^{DD}(\tilde{u})$: halo independent limit
- $\tilde{u}$: intersection speed of NT and DD



S. Kang, A. Kar, S. Scopel, JCAP03(2023)011

- To cover whole speed range, one may combine DD and NT
  - $u_T^{C-max} = v_{esc}(r)\sqrt{\frac{4m_\chi m_T}{(m_\chi - m_T)^2}}$
  - $\left(u_{th}^{DD}\right)^2 = \frac{m_T}{2\mu_{\chi T}^2} E_{R,th}$

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

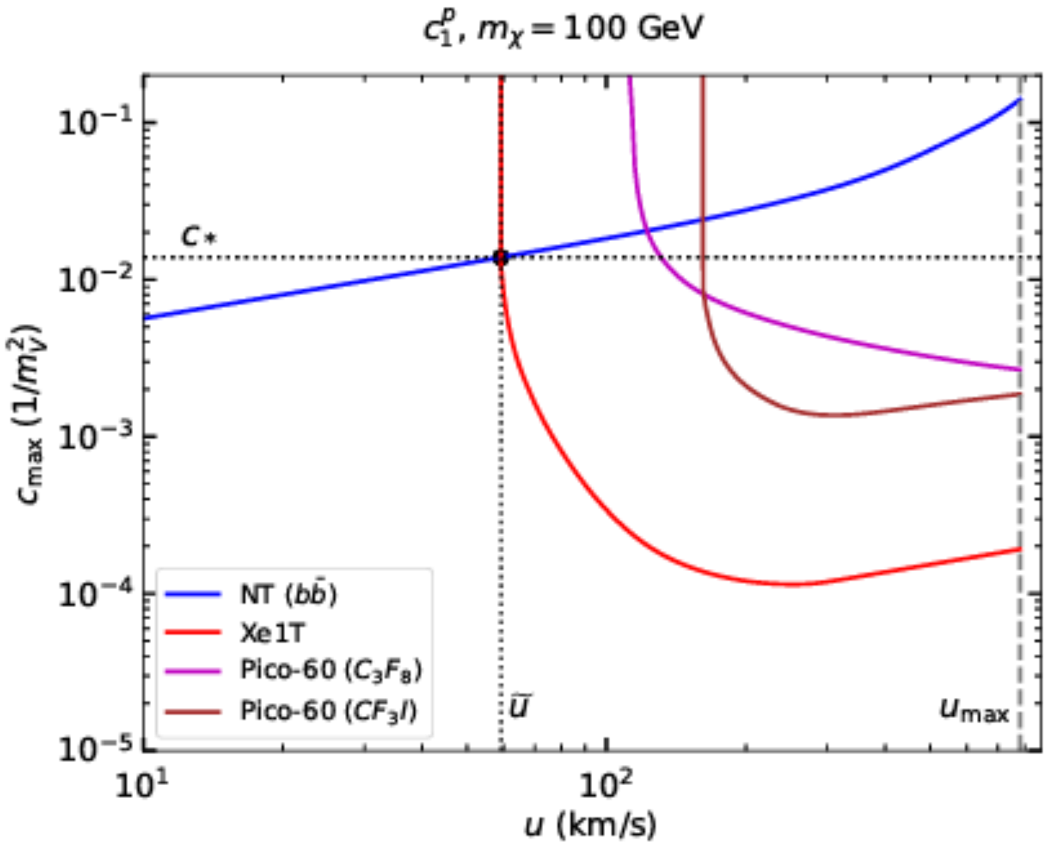
Halo independent approach

- Intersection:

$$(c^{NT})^2_{max}(u) \leq c_*^2 \quad \text{for } 0 \leq u \leq \tilde{u}$$
$$(c^{DD})^2_{max}(u) \leq c_*^2 \quad \text{for } \tilde{u} \leq u \leq u_{max}$$

$$c^2 \leq c_*^2 \left[\int_0^{\tilde{u}} du\, f(u)\right]^{-1} = \frac{c_*^2}{\delta}$$
$$c^2 \leq c_*^2 \left[\int_{\tilde{u}}^{u_{max}} du\, f(u)\right]^{-1} = \frac{c_*^2}{1-\delta}$$
$$\delta = \int_0^{\tilde{u}} du\, f(u)$$

$$c^2 \leq 2c_*^2$$



S. Kang, A. Kar, S. Scopel, JCAP03(2023)011

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

Halo independent approach

- If $(c^{DD})^2_{max}(u) > c_*^2$ at $u = u_{max}$:

$$c^2 \leq c_*^2 \left[\int_0^{\tilde{u}} du\, f(u)\right]^{-1} = \frac{c_*^2}{\delta}$$

$$c^2 \leq (c^{DD})^2_{max}(u_{max})\left[\int_{\tilde{u}}^{u_{max}} du\, f(u)\right]^{-1} = \frac{(c^{DD})^2_{max}(u_{max})}{1-\delta}$$

$$c^2 \leq (c^{DD})^2_{max}(u_{max}) + c_*^2$$

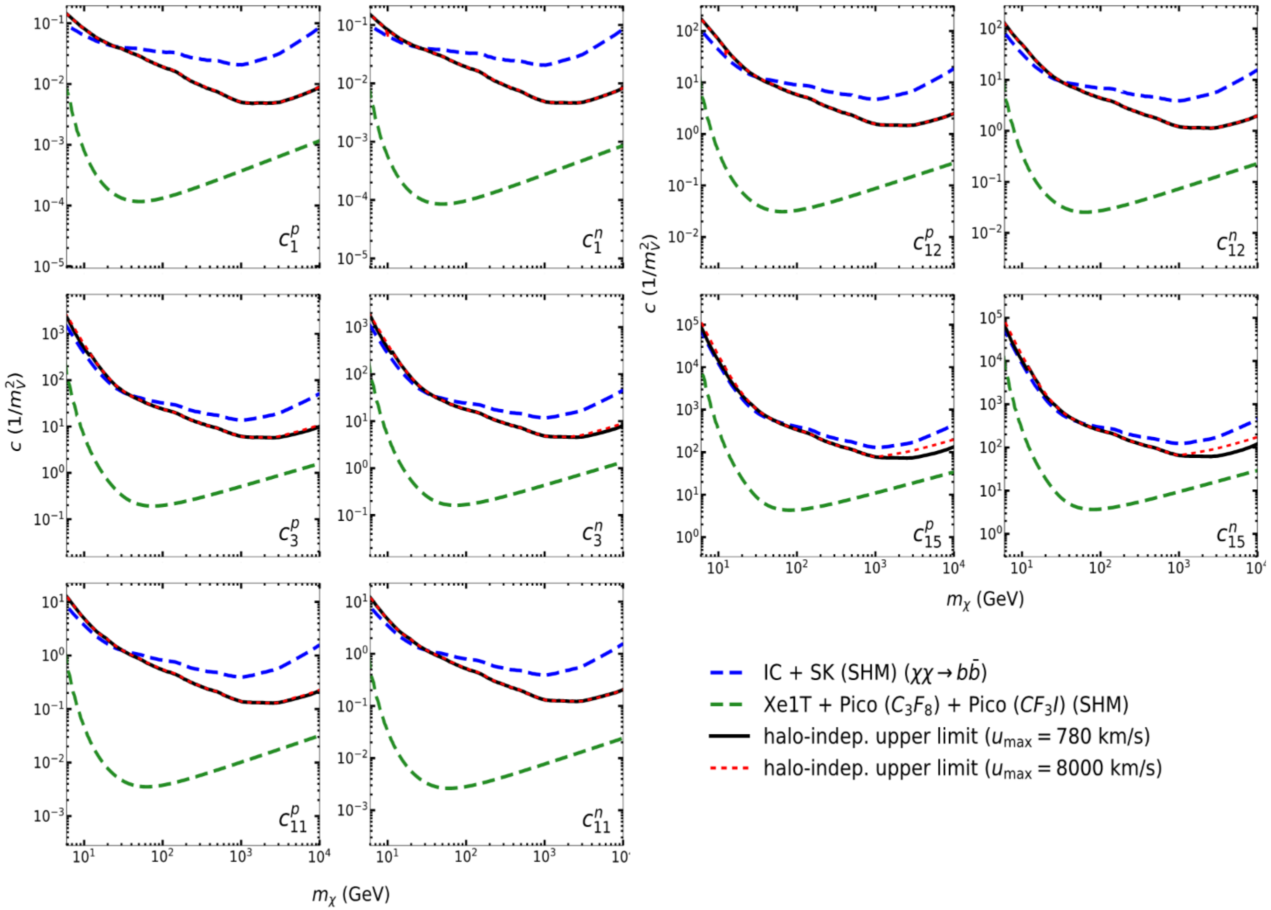
- If $u_{th}^{DD} > u_{max}$:

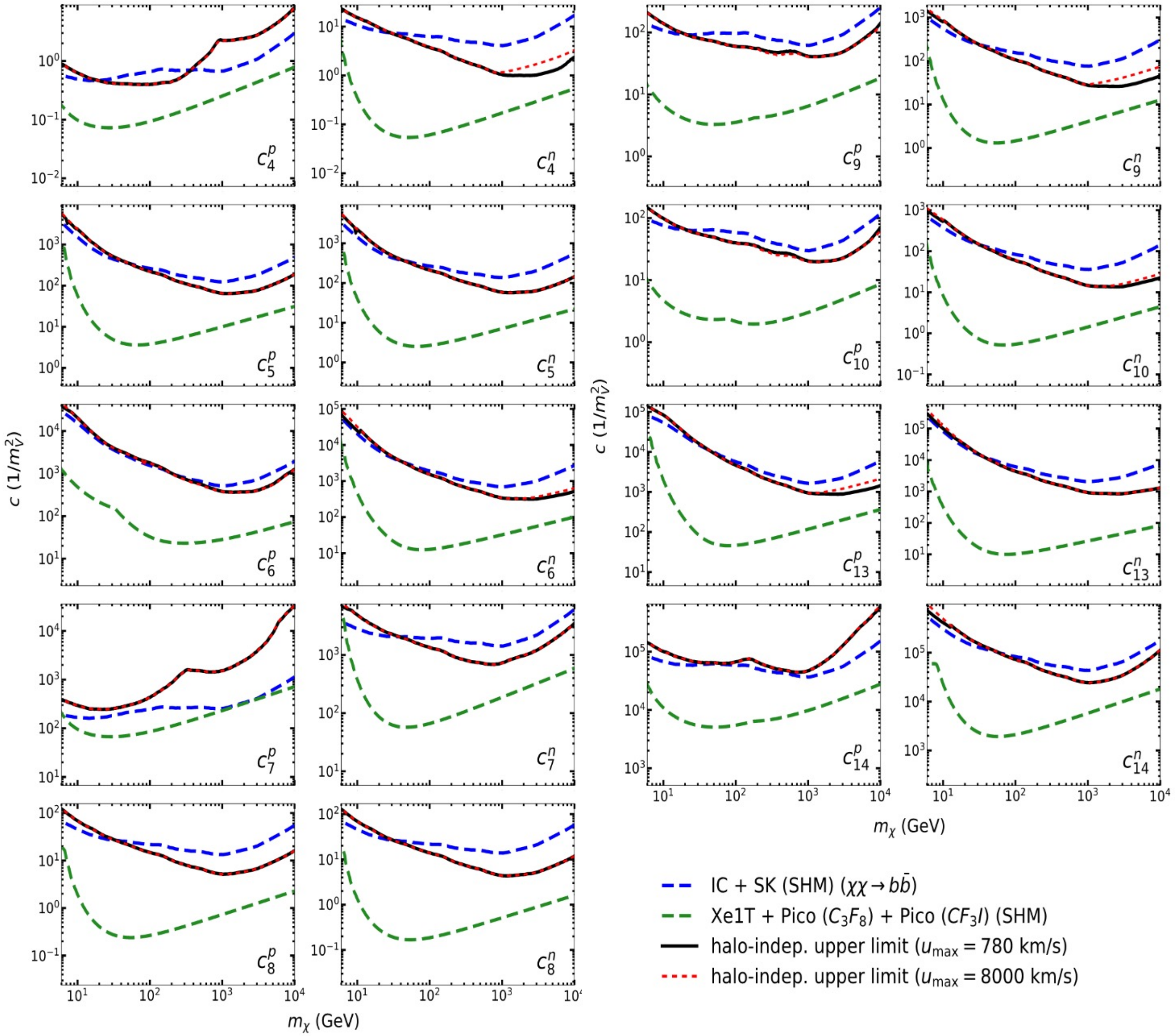
$$c^2 \leq (c^{NT})^2(u_{max})$$

- Halo independent limit may depend on u_{max}

F. Ferrer, A. Ibarra, S. Wild A novel approach to derive halo-independent limits on dark matter properties, JCAP09(2015)052

Halo independent approach





- Effect of large u_{max} is mild
  - factor less than 2

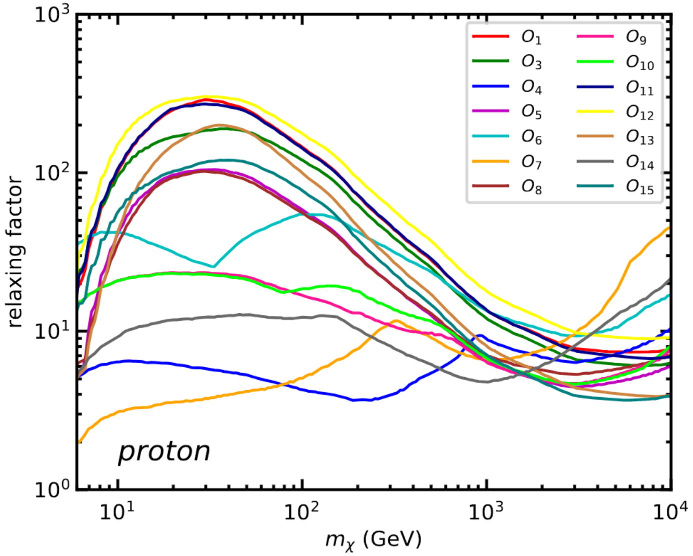
S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

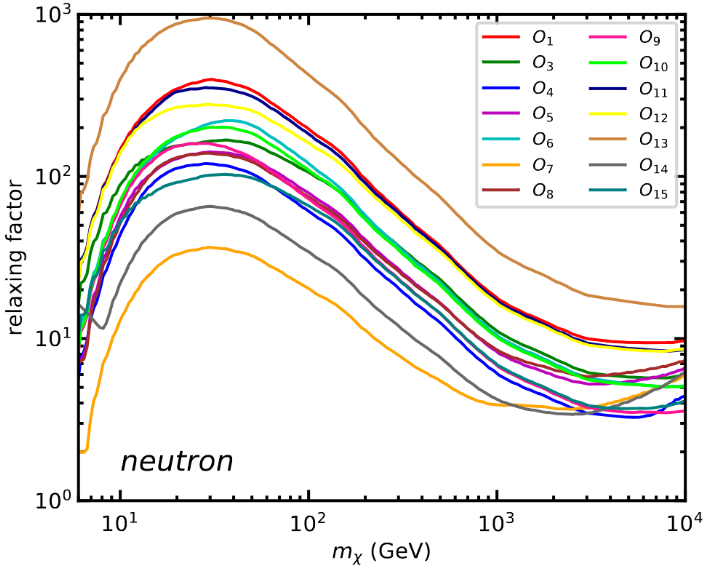
Halo independent approach

- Relaxing factor

$$r_f^2 = \frac{2c_*^2}{\left(c_{SHM}^{exp}\right)^2} = 2c_*^2 \int_0^{u_{max}} du \frac{f_M(u)}{(c^{exp})^2_{max}(u)} = 2c_*^2 < \frac{1}{(c^{exp})^2_{max}} > \cong 2c_*^2 < \frac{1}{(c^{exp})^2_{max}} >_{bulk}$$

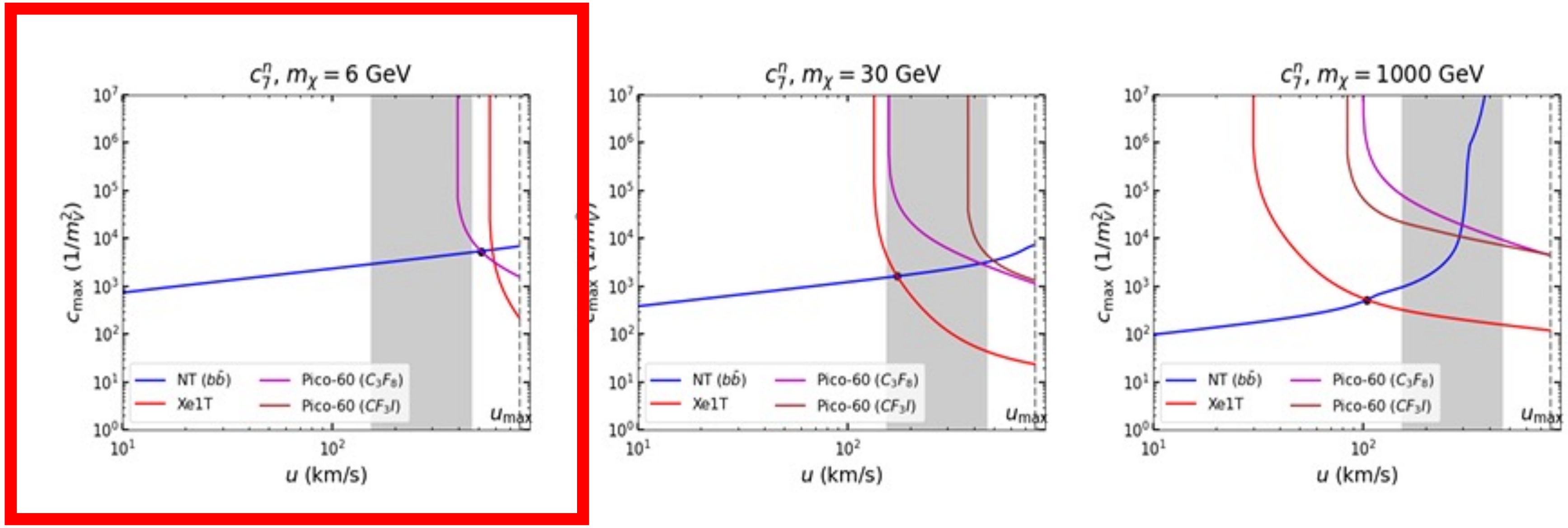
$$\int_{bulk} du\, f_M(u) \approx 0.8$$



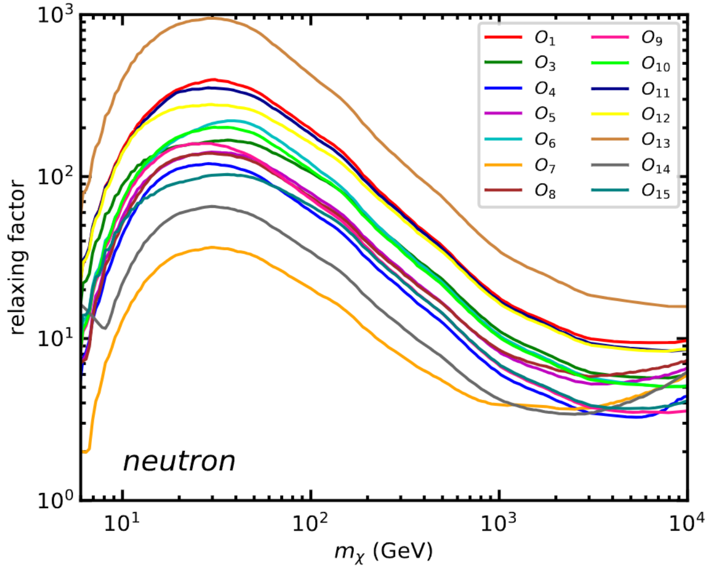


S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

Halo independent approach



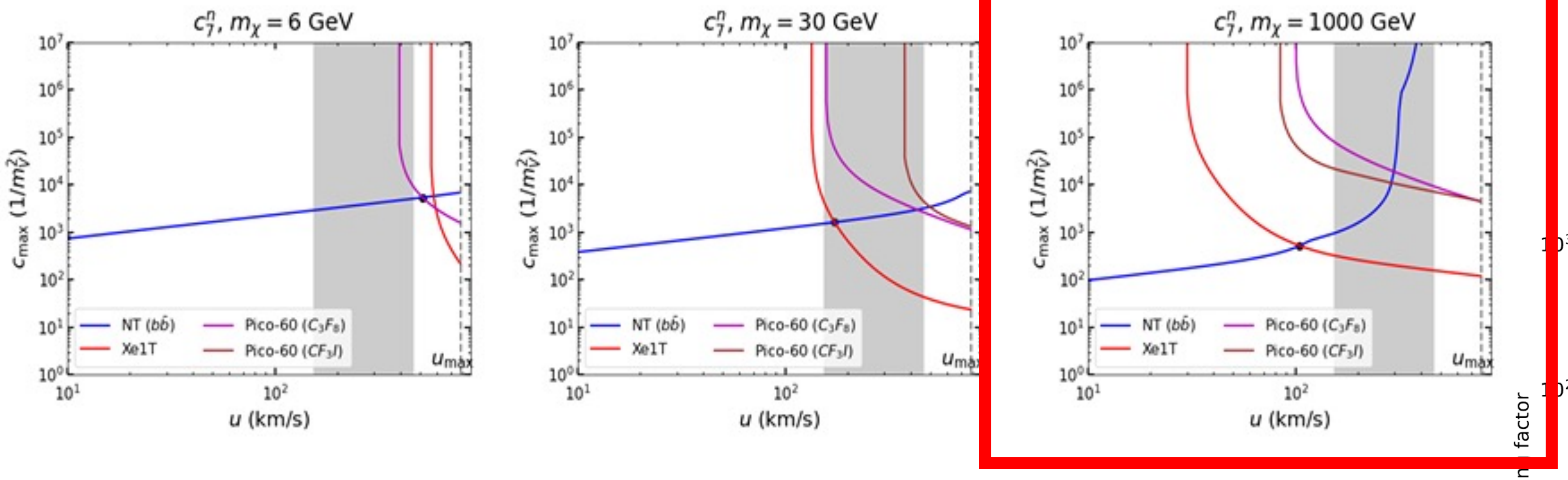
- small or large mass range
  - outside the bulk of Maxwellian
  - smooth dependence on u
- intermediate range (10 ~ 200 GeV)
  - inside the bulk of Maxwellian
  - steep dependence on u



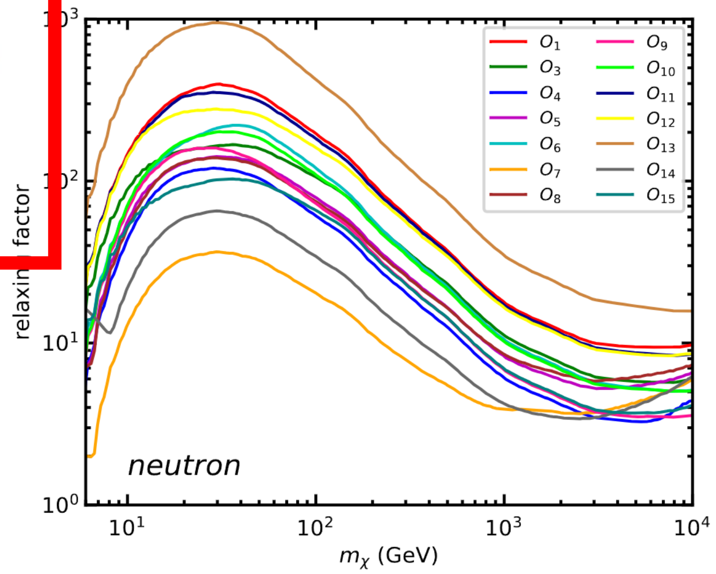
$$r_f^2 \simeq 2c_*^2 \left\langle \frac{1}{(c^{\exp})^2_{\max}} \right\rangle_{\text{bulk}},$$

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

Halo independent approach



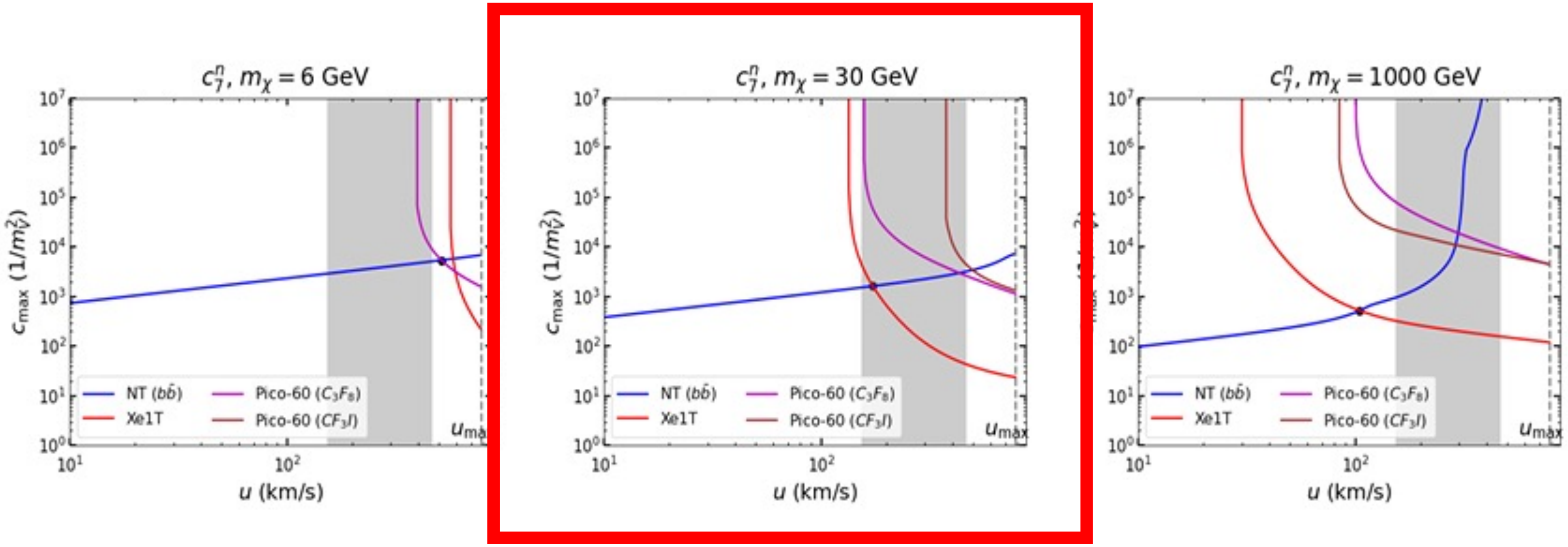
- small or large mass range
  - outside the bulk of Maxwellian
  - smooth dependence on u
- intermediate range (10 ~ 200 GeV)
  - inside the bulk of Maxwellian
  - steep dependence on u

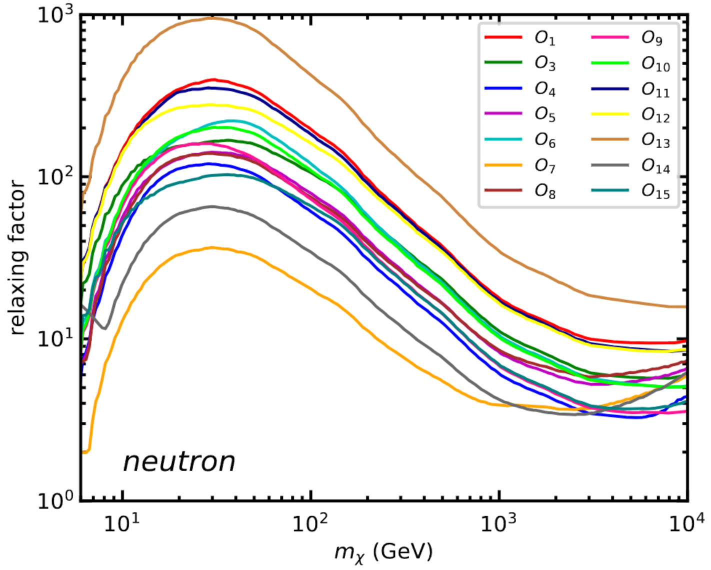


$$r_f^2 \simeq 2c_*^2 \left\langle \frac{1}{(c^{\exp})^2_{\max}} \right\rangle_{\rm bulk},$$

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

Halo independent approach





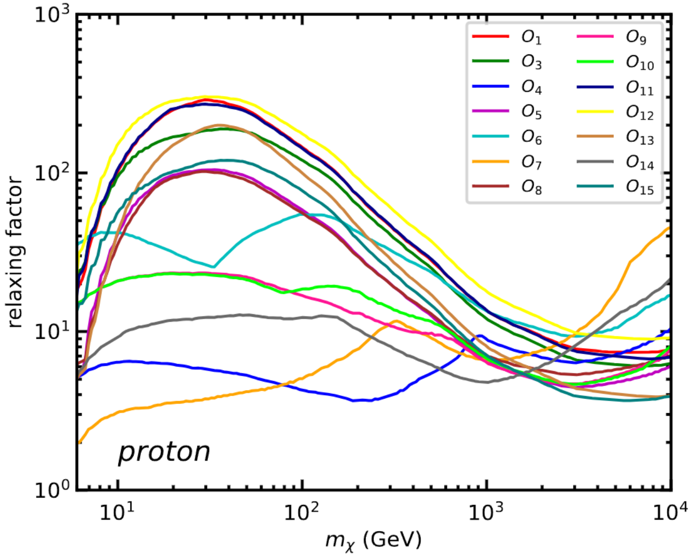
- small or large mass range
  - outside the bulk of Maxwellian
  - smooth dependence on u
- intermediate range (10 ~ 200 GeV)
  - inside the bulk of Maxwellian
  - steep dependence on u

$$r_f^2 \simeq 2c_*^2 \left\langle \frac{1}{(c^{\exp})^2_{\max}} \right\rangle_{\text{bulk}},$$

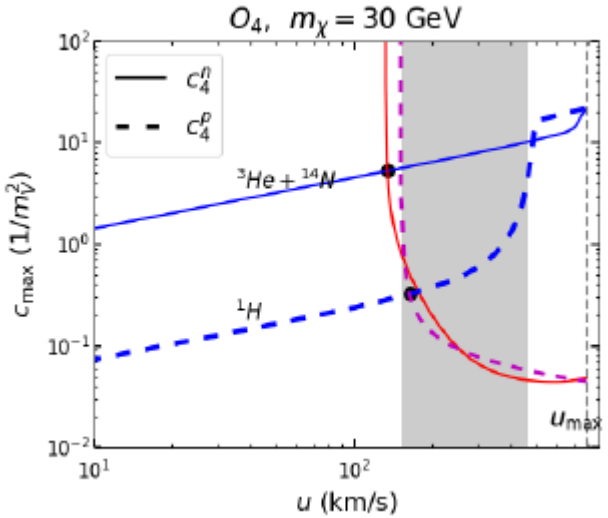
S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

Halo independent approach

- small relaxing factors
  - $O_{4,7}$: SD with no q suppression
  - $O_{9,10,14}$: SD with q^2 suppression
  - O_6 : SD with q^4 suppression



operator	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$	operator	$R_{0k}^{\tau\tau'}$	$R_{1k}^{\tau\tau'}$
1	$M(q^0)$	-	3	$\Phi''(q^4)$	$\Sigma'(q^2)$
4	$\Sigma''(q^0)$,$\Sigma'(q^0)$	-	5	$\Delta(q^4)$	$M(q^2)$
6	$\Sigma''(q^4)$	-	7	-	$\Sigma'(q^0)$
8	$\Delta(q^2)$	$M(q^0)$	9	$\Sigma'(q^2)$	-
10	$\Sigma''(q^2)$	-	11	$M(q^2)$	-
12	$\Phi''(q^2)$,$\tilde{\Phi}'(q^2)$	$\Sigma''(q^0)$,$\Sigma'(q^0)$	13	$\tilde{\Phi}'(q^4)$	$\Sigma''(q^2)$
14	-	$\Sigma'(q^2)$	15	$\Phi''(q^6)$	$\Sigma'(q^4)$

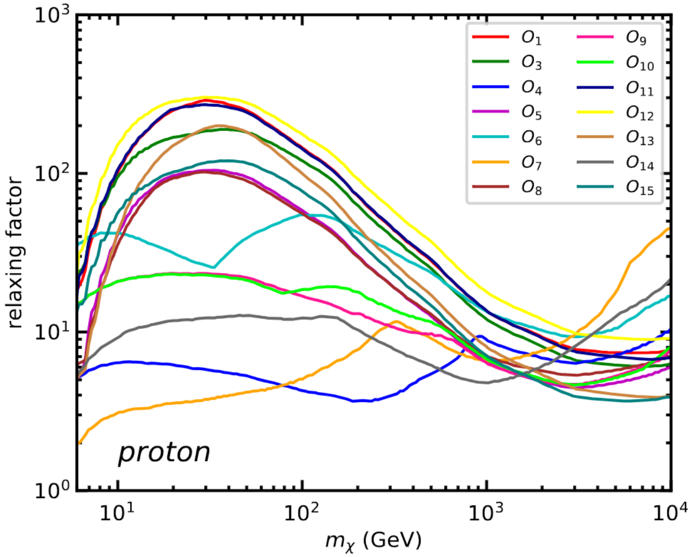


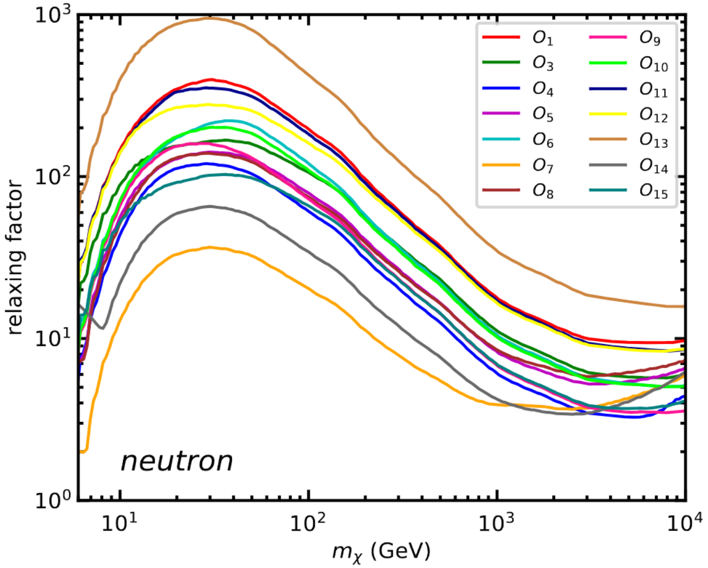
S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

Halo independent approach

- High relaxing factor:
  the halo-independent method can weaken the bound

$$r_f^2 = \frac{2c_*^2}{\left(c_{SHM}^{exp}\right)^2} = 2c_*^2 \int_0^{u_{max}} du \frac{f_M(u)}{(c^{exp})_{max}^2(u)} = 2c_*^2 < \frac{1}{(c^{exp})_{max}^2} > \cong 2c_*^2 < \frac{1}{(c^{exp})_{max}^2} >_{bulk}$$





S. Kang, A. Kar, S. Scopel, Halo-independent bounds on the non-relativistic effective theory of WIMP-nucleon scattering from direct detection and neutrino observations, JCAP03(2023)011 (arXiv:2212.05774)

DD event rate (inelastic scattering)

- DD event rate

$$\mathrm{R_{DD}} = M\tau_{exp}\frac{\rho_\chi}{m_\chi}\int du\, f(u)u\,\Sigma_T\, N_T\int_{E_{R,th}}^{2\mu_{\chi T}^2 u^2/m_T} dE_R\,\zeta_{exp}\frac{d\sigma_T}{dE_R}$$

$$\mathrm{R_{DD}} = M\tau_{exp}\frac{\rho_\chi}{m_\chi}\int du\, f(u)u\,\Sigma_T\, N_T\Theta(u^2 - v_{T*}^2)\int_{E_{min}}^{E_{max}} dE_R\,\zeta_{exp}\frac{d\sigma_T}{dE_R}$$

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

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

Capture rate (inelastic scattering)

- Capture rate

$$C_{\odot} = \frac{\rho_\chi}{m_\chi} \int du \frac{f(u)}{u} \int_0^{R_\odot} dr\, 4\pi r^2\, w^2\, \Sigma_T\, \rho_T(r)\, \Theta\left(u_T^{C-max} - u\right) \int_{m_\chi u^2/2}^{2\mu_{\chi T}^2 w^2/m_T} dE_R \frac{d\sigma_T}{dE_R}$$

$$\downarrow$$

$$C_{\odot} = \frac{\rho_\chi}{m_\chi} \int du \frac{f(u)}{u} \int_0^{R_\odot} dr\, 4\pi r^2\, w^2\, \Sigma_T\, \rho_T(r)\, \Theta(\omega^2 - v_{T*}^2)\Theta\left(E_{max}^\chi - E_{cap}^\chi\right) \int_{max\left(E_{min}^\chi, E_{cap}^\chi\right)}^{E_{max}^\chi} dE_R \frac{d\sigma_T}{dE_R}$$

$$E_{max,min}(u) = \frac{1}{2}\, m_\chi \omega^2 \left(1 - \frac{\mu_{\chi T}^2}{m_T^2}\left(1 \pm \frac{m_T}{m_\chi}\sqrt{1 - \frac{v_{T*}^2}{\omega^2}}\right)^2\right)^2$$

$$E_{cap}^\chi(u) = \frac{1}{2} m_\chi u^2 - \delta$$

Kinematic conditions

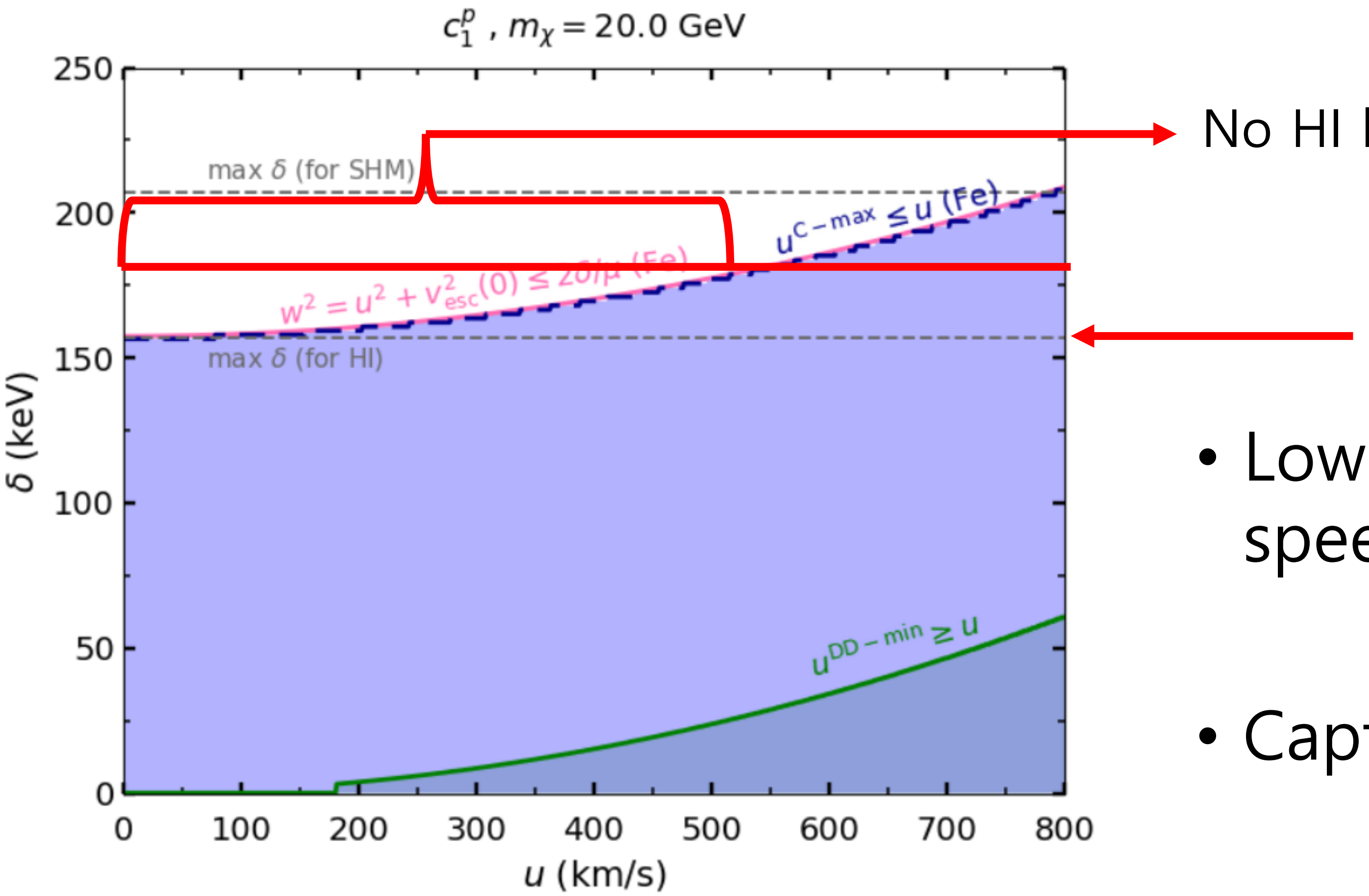
- $u^2 + v_{esc}^2(r = 0) > v_{T*}^2$
  - for inelastic scattering process to be kinematically possible

- $u > u^{DD-min}$
  - for the recoil energy to be above the DD experimental threshold

- $u < u^{C-max}$
  - for outgoing speed to be below the escape velocity in the Sun

- $u^{DD-min} < u^{C-max}$
  - for DD and capture intersect

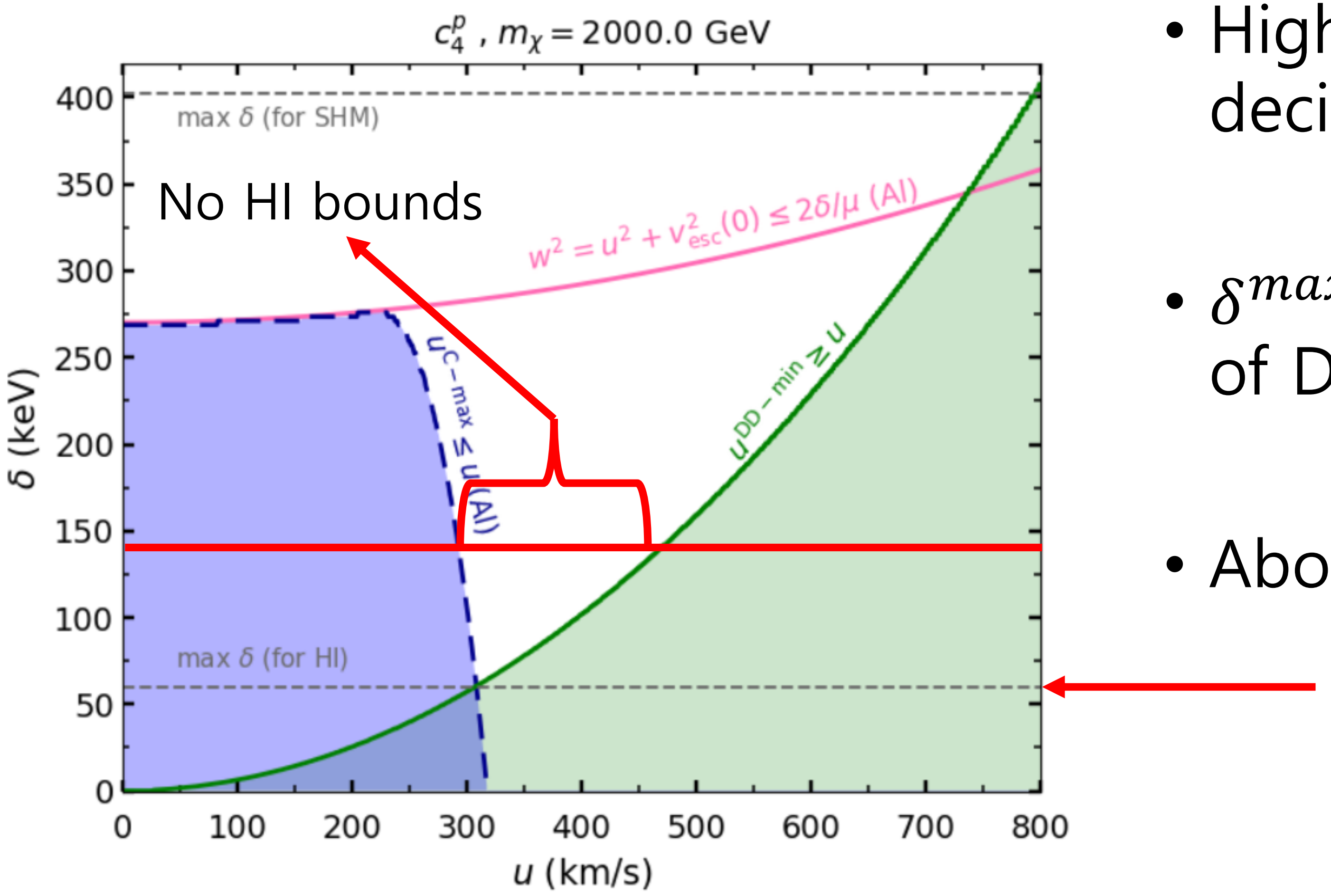
Determining δ_{max}



- Low m_χ region, capture can cover full speed range alone up to δ^{max}
- Capture alone can determine δ^{max}
- Above δ^{max}, no HI bounds

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

Determining δ_{max}



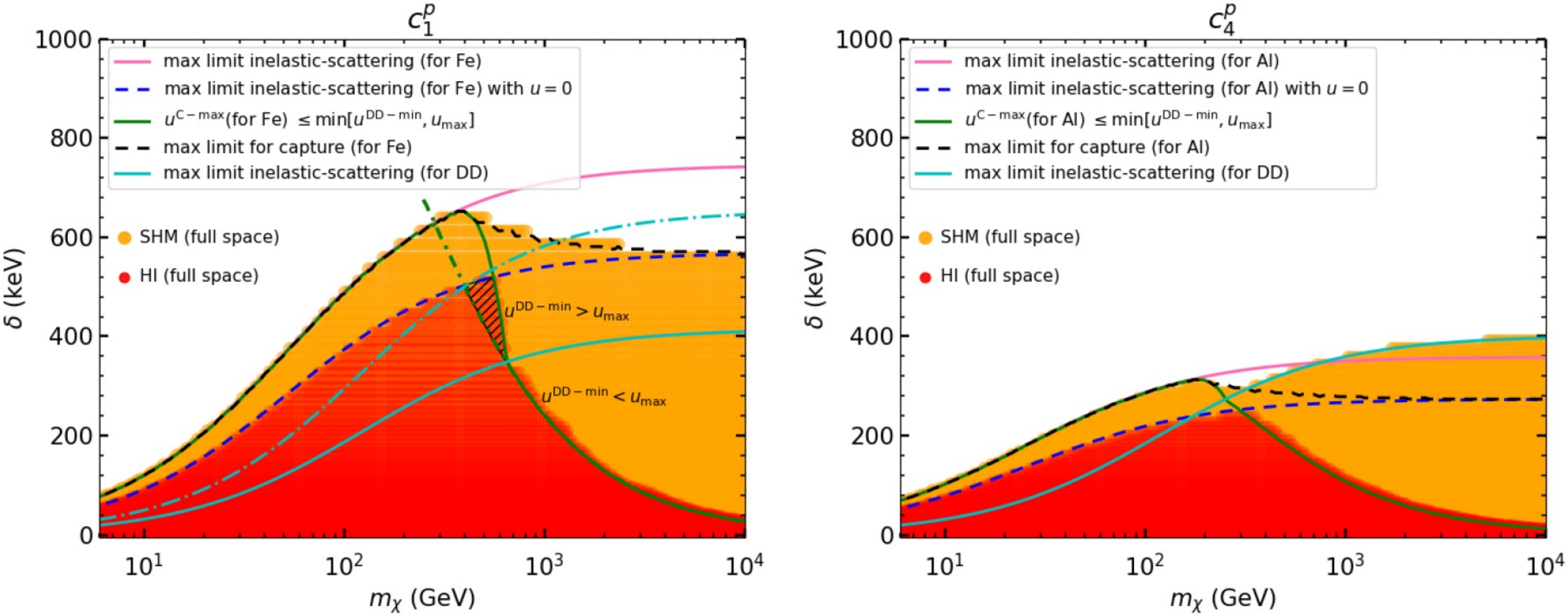
- High m_χ region, DD and capture decide δ^{max} together

- δ^{max} is determined by a combination of DD and capture

- Above δ^{max}, no HI bounds

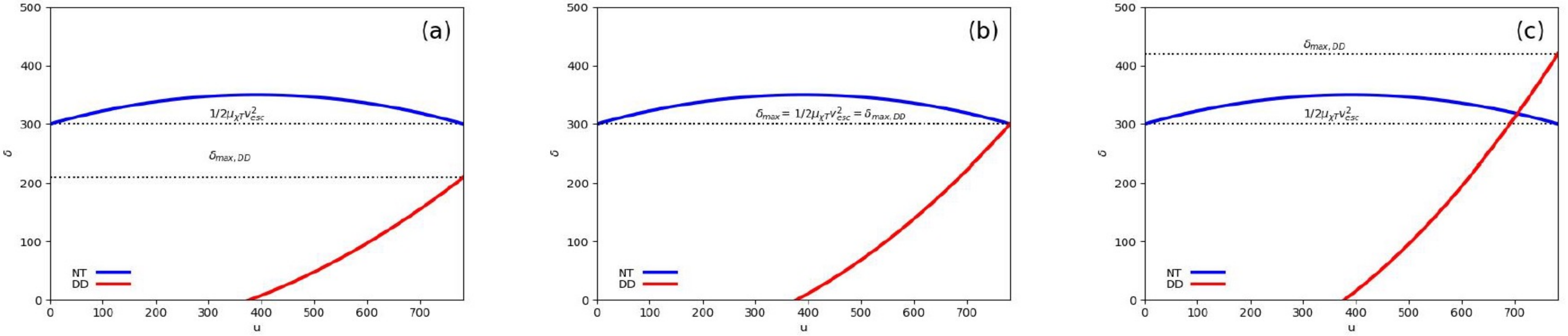
S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

$m_\chi - \delta$ planes



S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

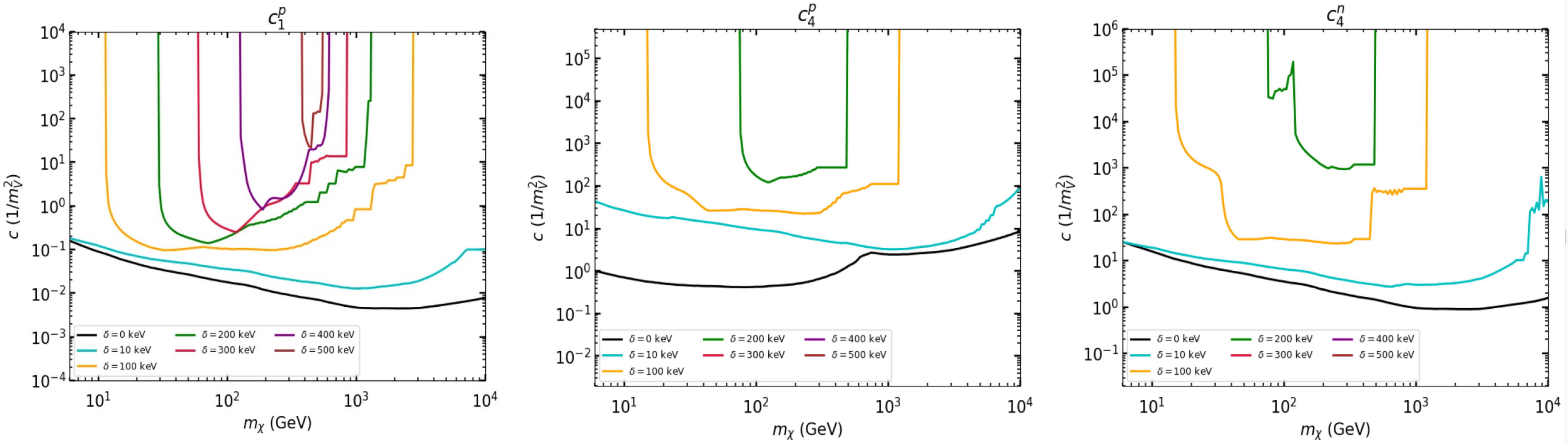
Role of DD



- $r = \frac{m_N}{m_T} \geq r_{min} \simeq 3.9$
  - below this value, only Capture determines δ_{max}
- SI ($T = {}^{56}Fe$, N = Xe)
  - r $\simeq$ 2.3
- SD ($T = {}^{27}Al$, $N = Xe$ (I))
  - r $\simeq$ 4.86 (4.7)

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

Halo-independent exclusion plots

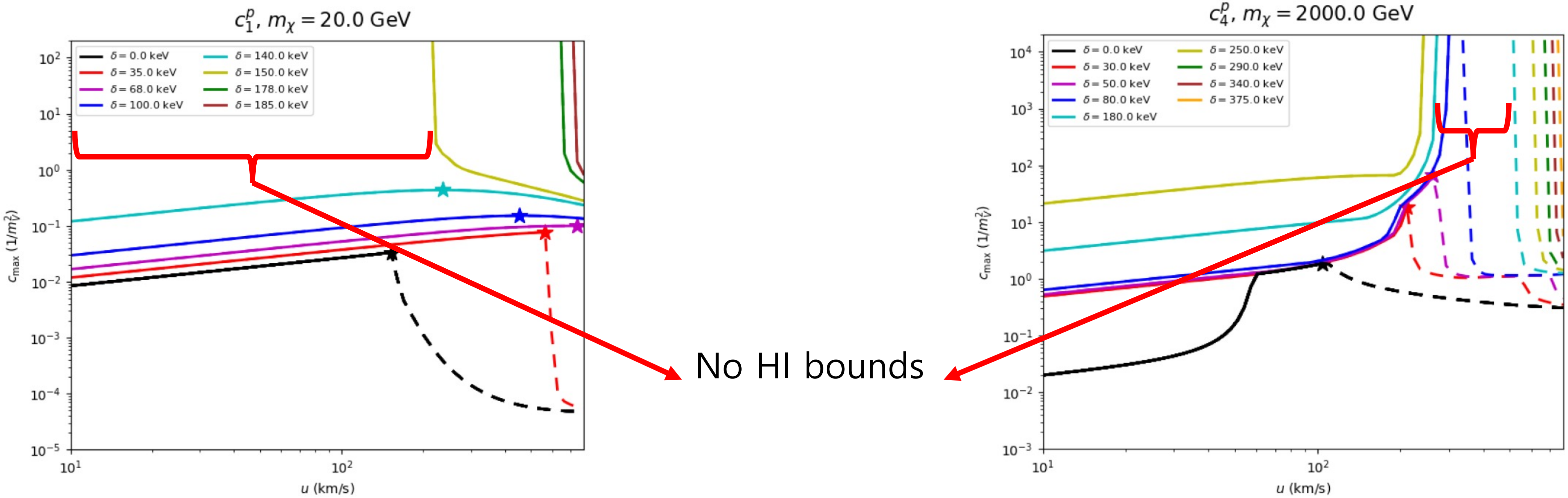


- HI exclusion plots of SI and SD couplings

- For increasing δ the constraints get weaker and WIMP mass range for HI bounds is shrinking

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

Halo-independent exclusion plots

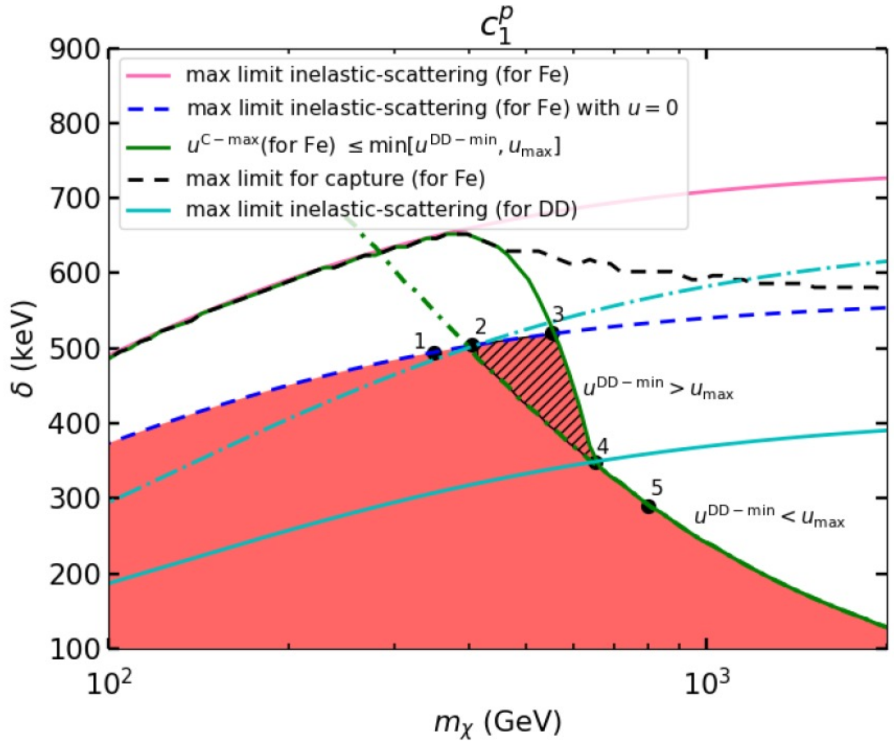


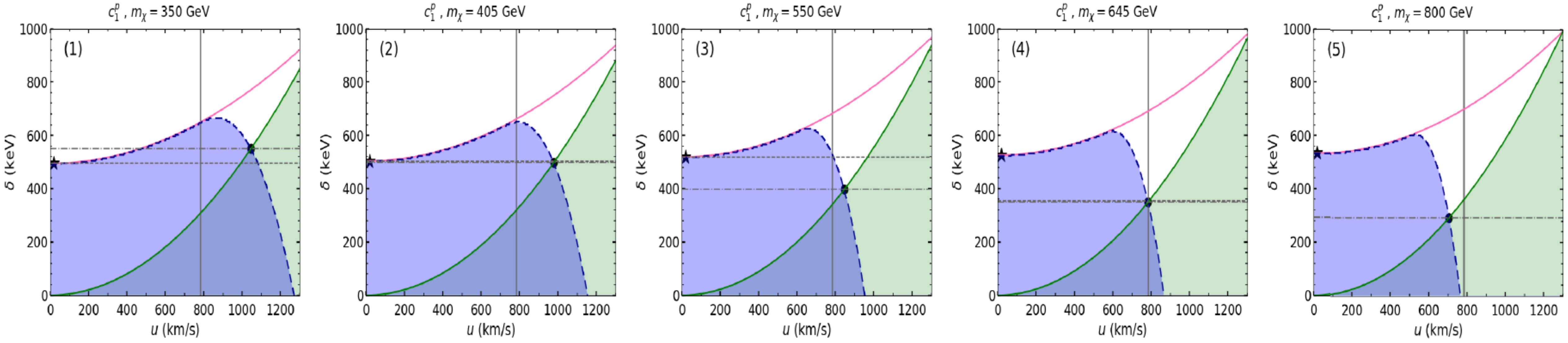
- low m_χ: capture is kinematically impossible
- high m_χ: DD and capture doesn't intersect

S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

Dependence on u_{max}

- HI might be sensitive to u_{max}
- except point (3), δ_{max} does not change even if we extend the value of u_{max}
- Only happens is SI case and δ_{max} does not decrease dramatically





S. Kang, A. Kar, S. Scopel, Halo-independent bounds on Inelastic Dark Matter, JCAP11(2023)077 (arXiv:2308.13203)

WimPyDD

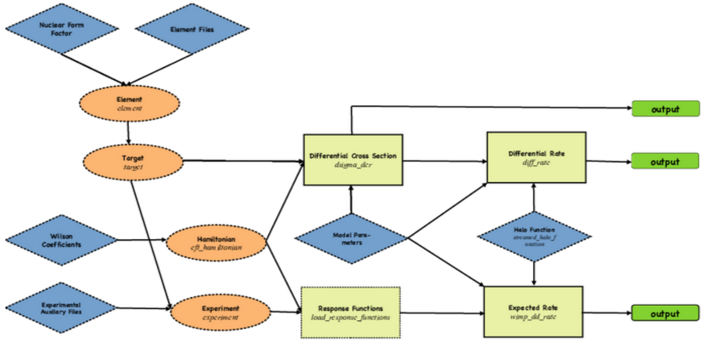
- User-friendly Python code
- Calculates expected rates in any scenarios:
  - arbitrary spins
  - inelastic scattering
  - generic WIMP velocity distribution
- Published and can be downloaded:
  - https://wimpydd.hepforge.org/

- Home
- Download
- The code
  - Getting Started
  - Examples
  - Nuclear Targets
  - Effective Hamiltonian
  - Experiment
  - Nuclear Response Functions
  - Halo Function
  - Formulas and definitions
- Contact

WimPyDD

WimPyDD is a object-oriented and customizable Python code that calculates accurate predictions for the expected rates in WIMP direct-detection experiments within the framework of Galilean-invariant non-relativistic effective theory. WimPyDD handles different scenarios including inelastic scattering, WIMP of arbitrary spin and a generic velocity distribution of WIMP in the Galactic halo.

WimPyDD is written by **Stefano Scopel, Gaurav Tomar, Sunghyun Kang, and Injun jeong**.



I. Jeong, S. Kang, S. Scopel, G. Tomar, WimPyDD: An object-oriented Python code for the calculation of WIMP direct detection signals, Computer Physics Communications, 2022.108342

Summary

- Halo independent method can be applied to any speed distribution
- Combining results of direct detection experiments and capture in the Sun may provide halo-independent bounds according to the value of δ

- In elastic scattering,
  - In most cases the relaxation of halo independent bounds is moderate in low and high m_χ
  - More moderate values of the relaxation is obtained with c_{SD}^p
  - High relaxing factor: halo independent method weaken the bounds → sensitive on speed distribution

- In inelastic scattering,
  - There is a specific region in $m_\chi - \delta$ plane where Halo independent bounds is possible
  - Unless $\frac{m_N}{m_T}$ is larger than about 4, direct detection does not play any role