MOCA 2022

IMPACT OF OPERATOR INTERFERENCE IN DARK MATTER DETECTION EXPERIMENTS

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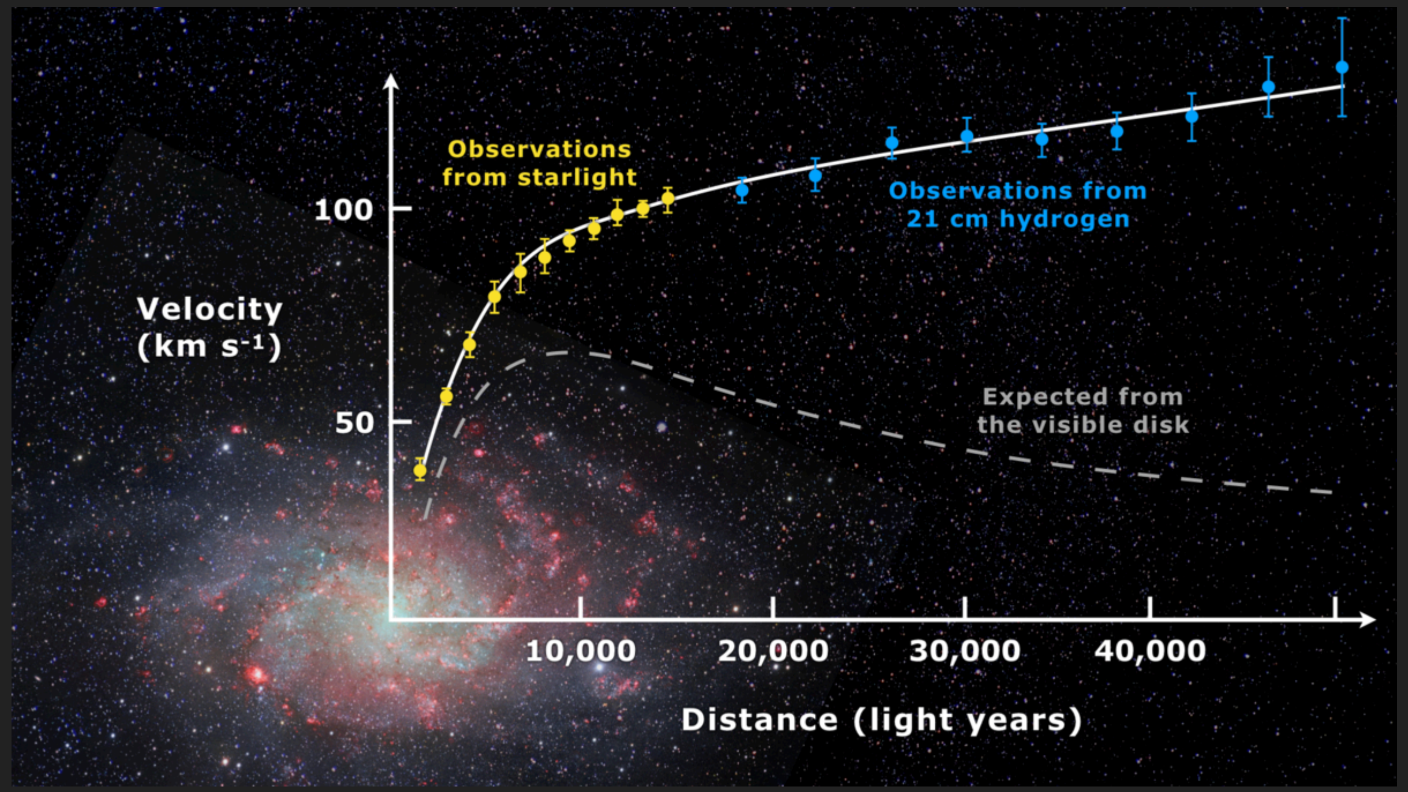
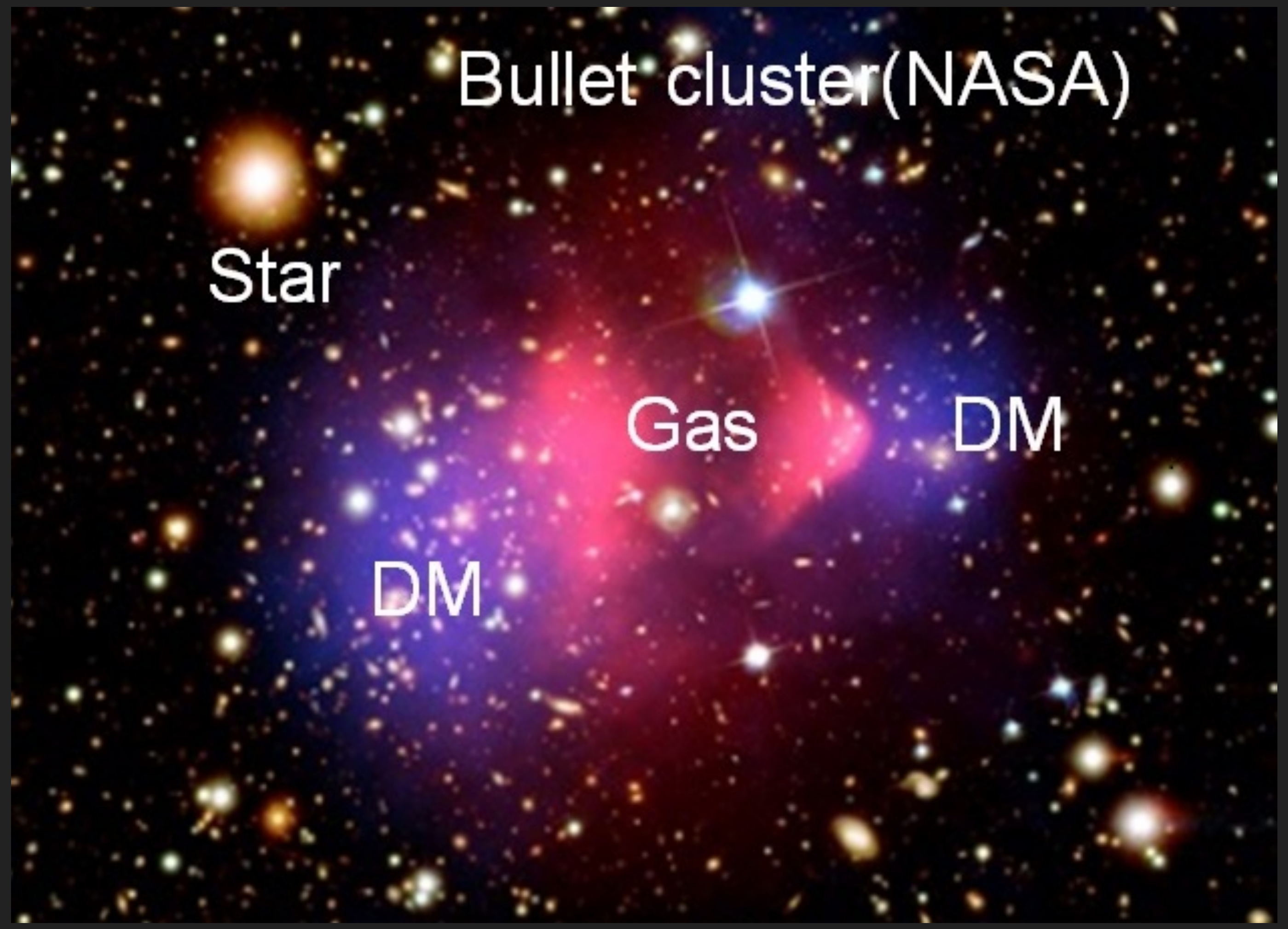
31 May 2022

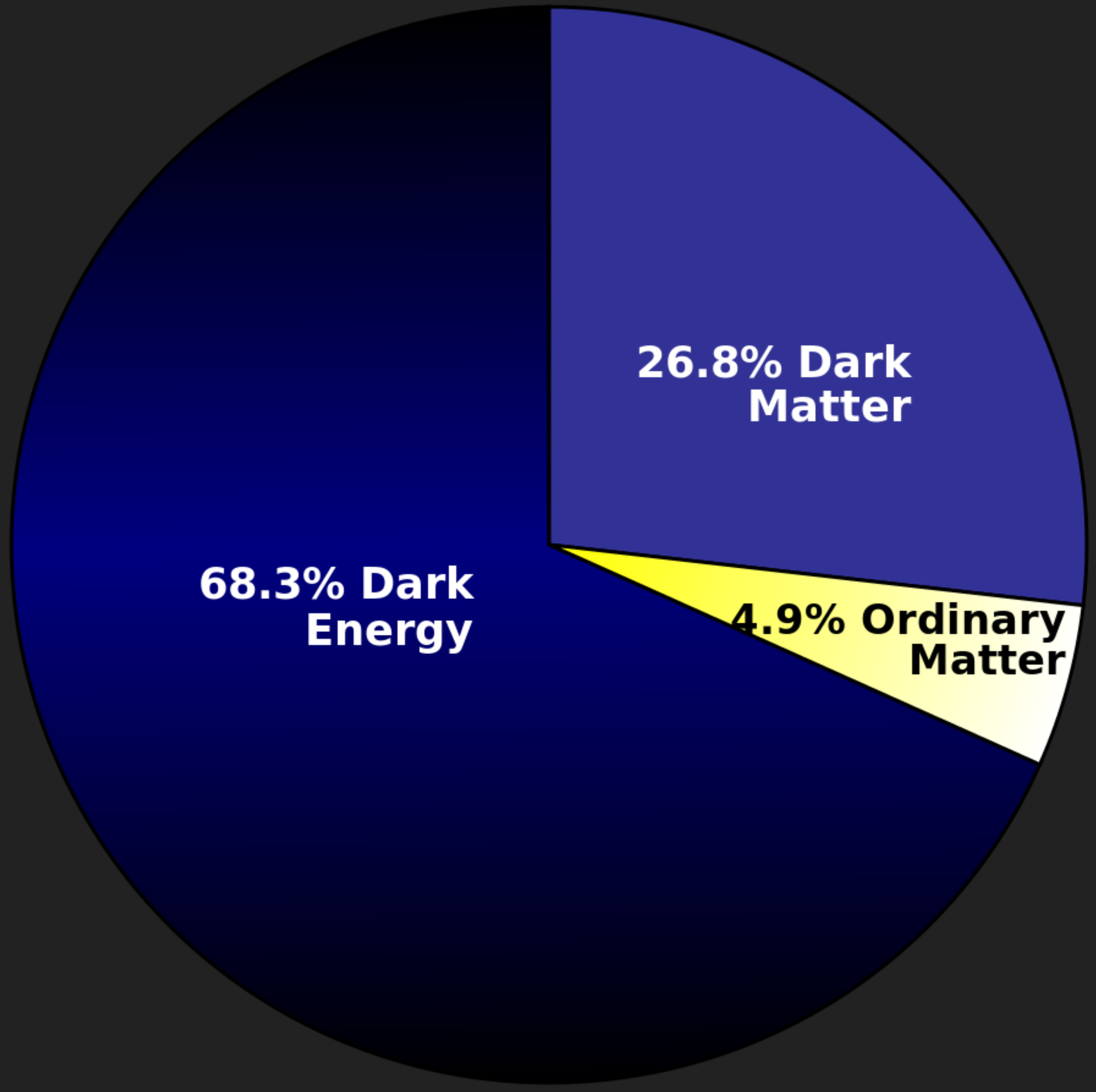
DARK MATTER IN THE UNIVERSE



2000, Corbelli et. al.



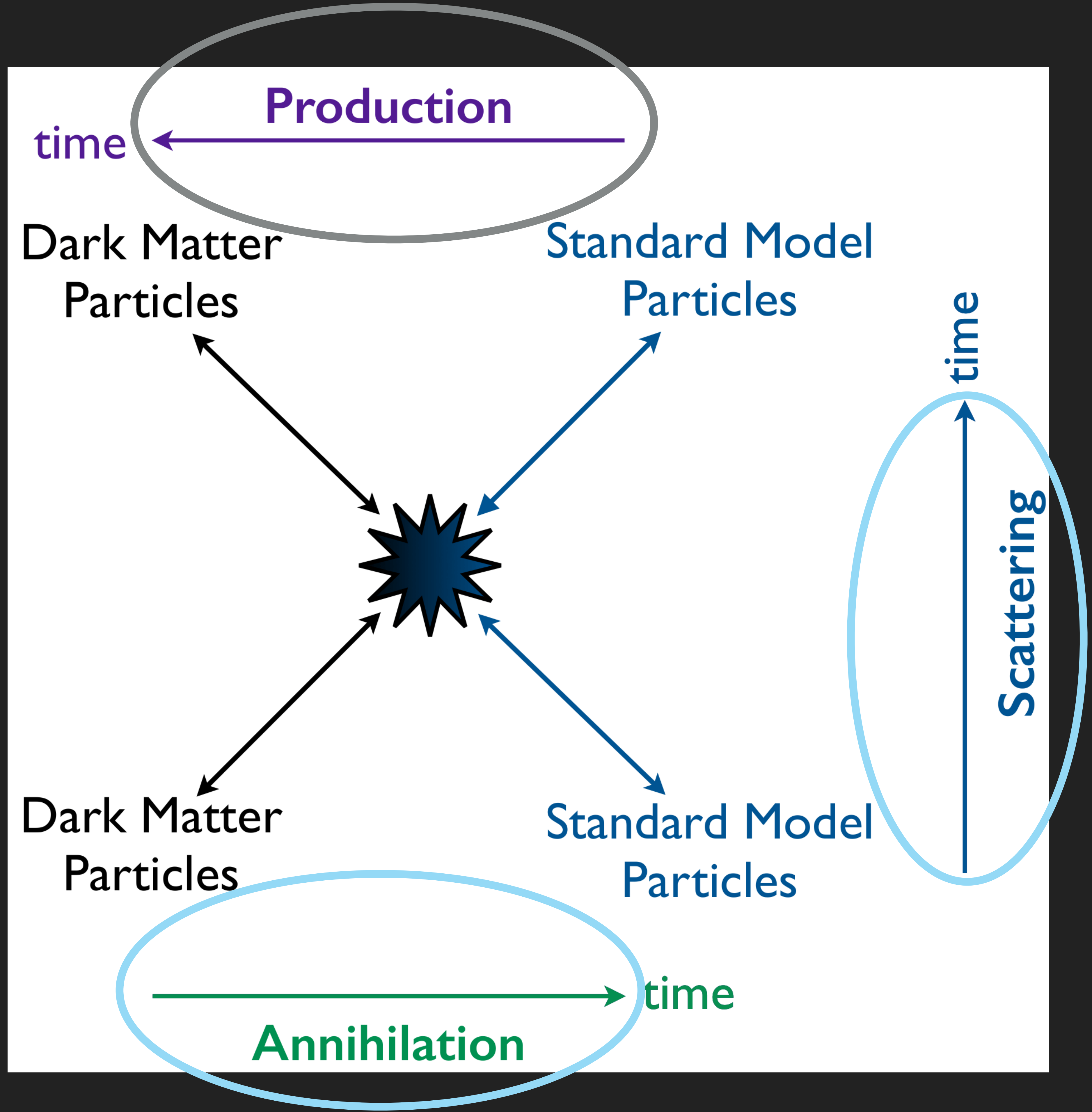
2013, NASA



2011, Caltech

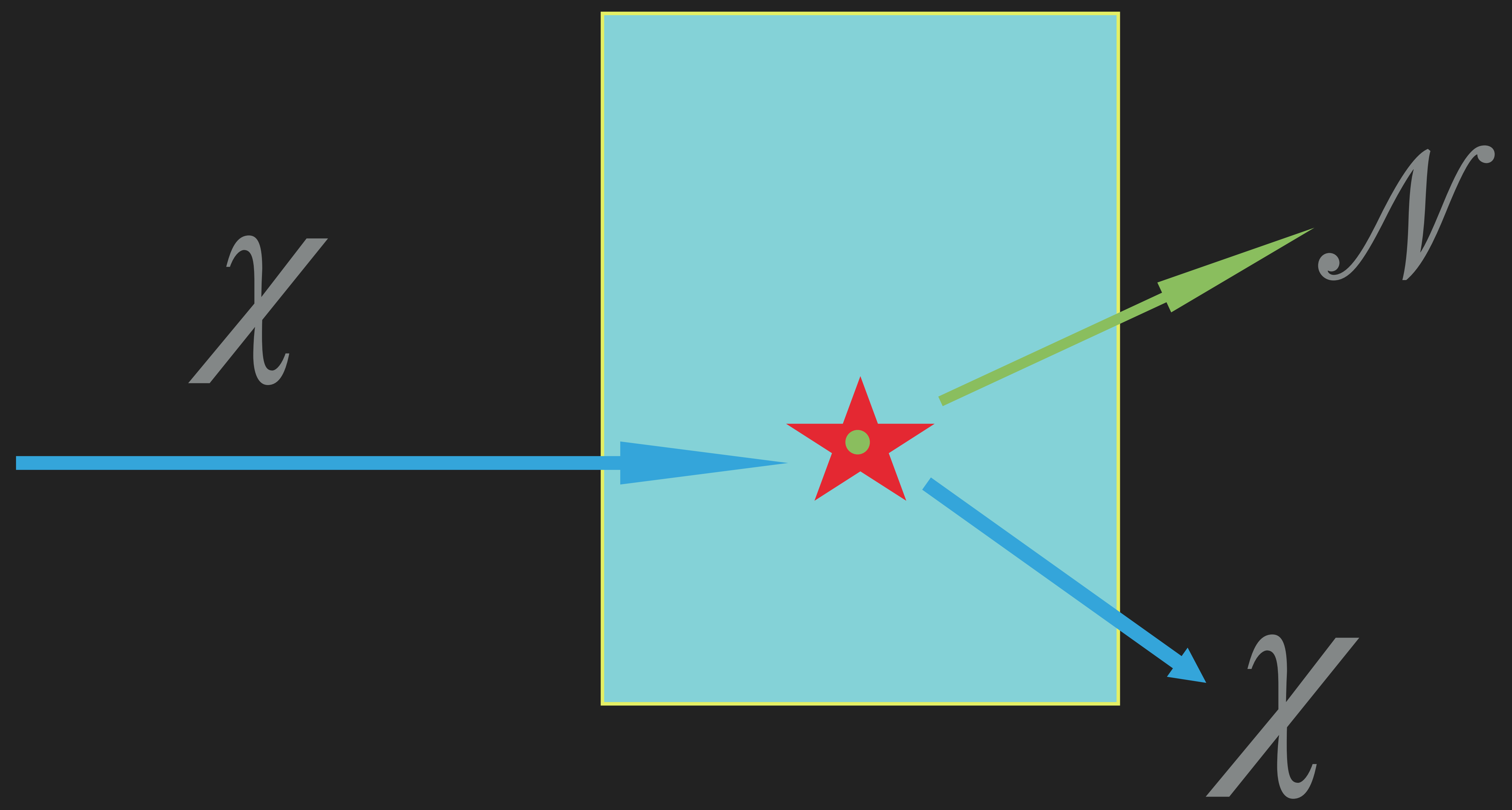
DARK MATTER SEARCHES

- Particle production
- Indirect Searches
- Direct Searches



Brown Particle Astrophysics Group

DIRECT DARK MATTER SEARCHES



$\Longrightarrow$ Upper limit on the dark matter-nucleon scattering rate R

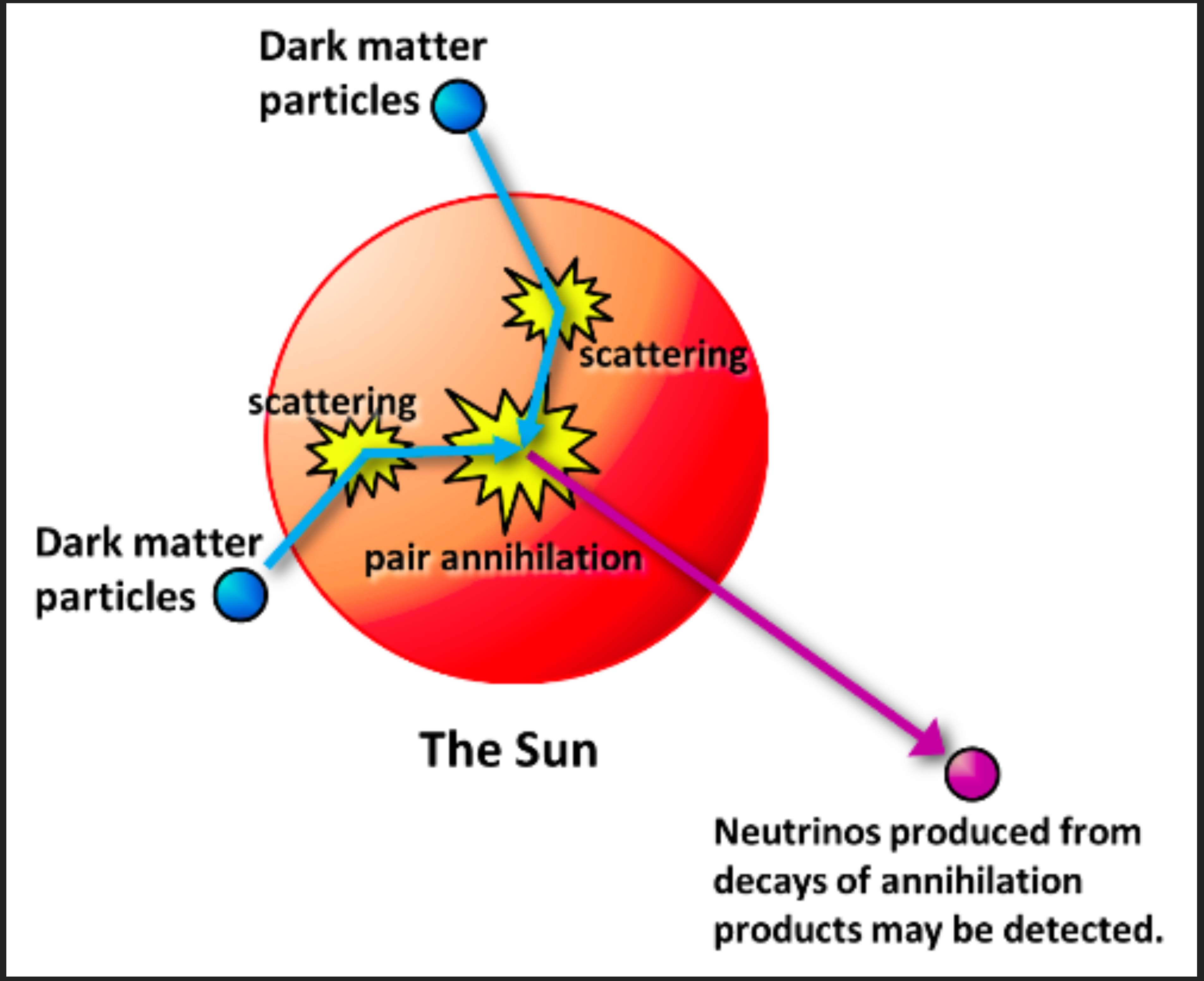
$$R_{\chi T} \propto c^2$$

$\Longrightarrow$ Upper limit on coupling strength c

INDIRECT DARK MATTER SEARCHES

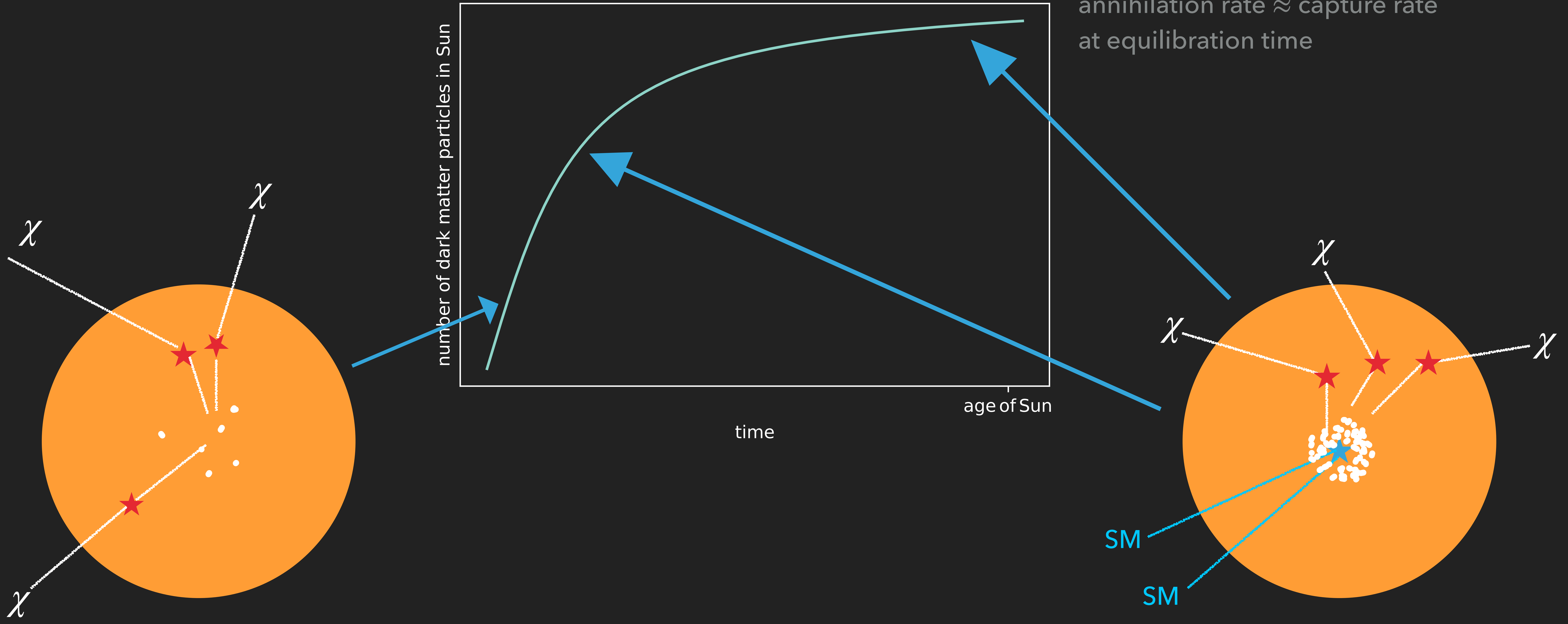
- Milky Way center
- Dwarf spheroidal galaxies
- Sun
- Earth
- …

Dark matter capture in the Sun



DARK MATTER IN THE SUN

annihilation rate ≈ capture rate
at equilibration time



DARK MATTER IN THE SUN

$\implies$ Upper limit on neutrino flux / annihilation rate Γ_A

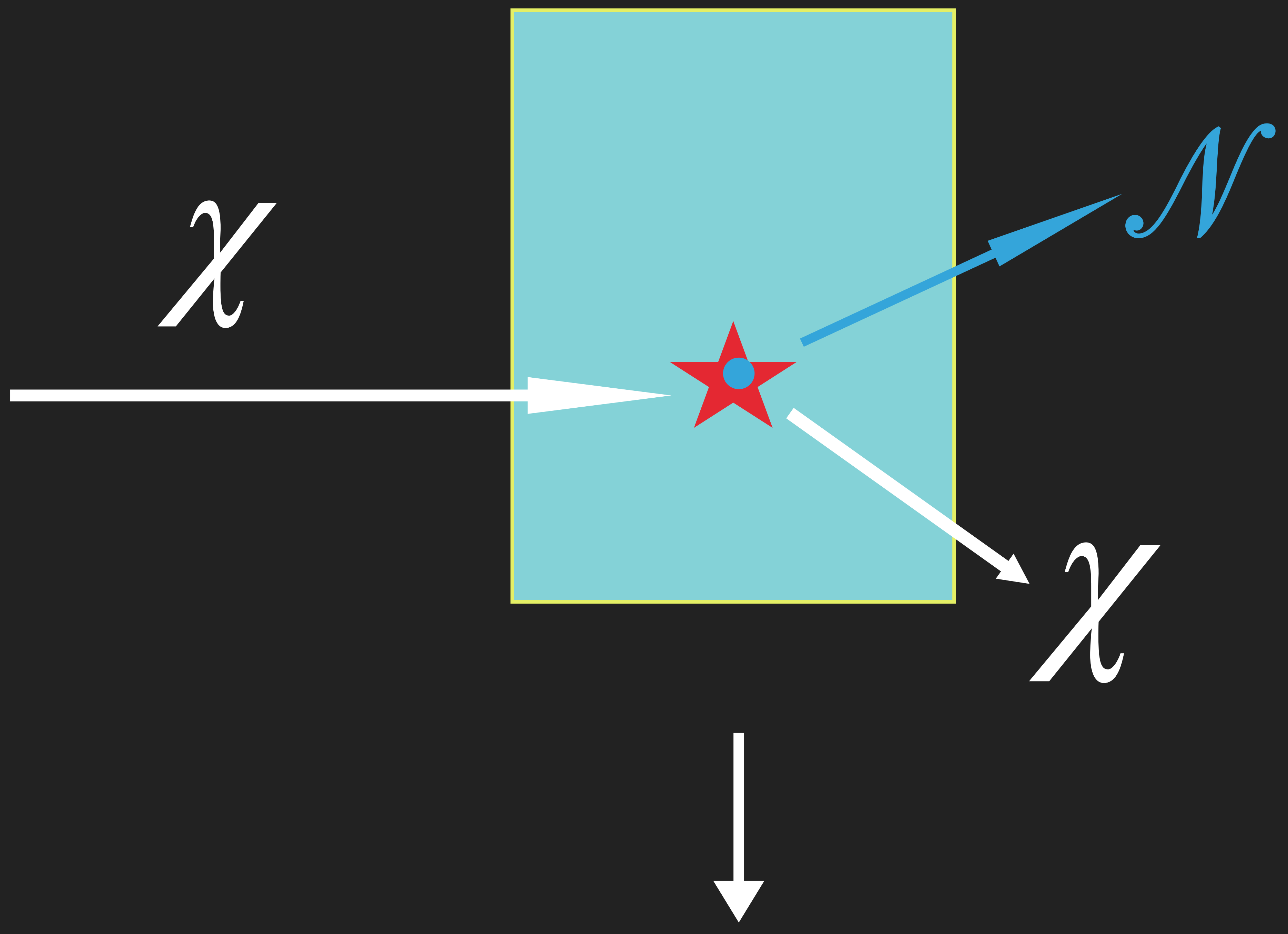
$$C = 2\Gamma_A$$

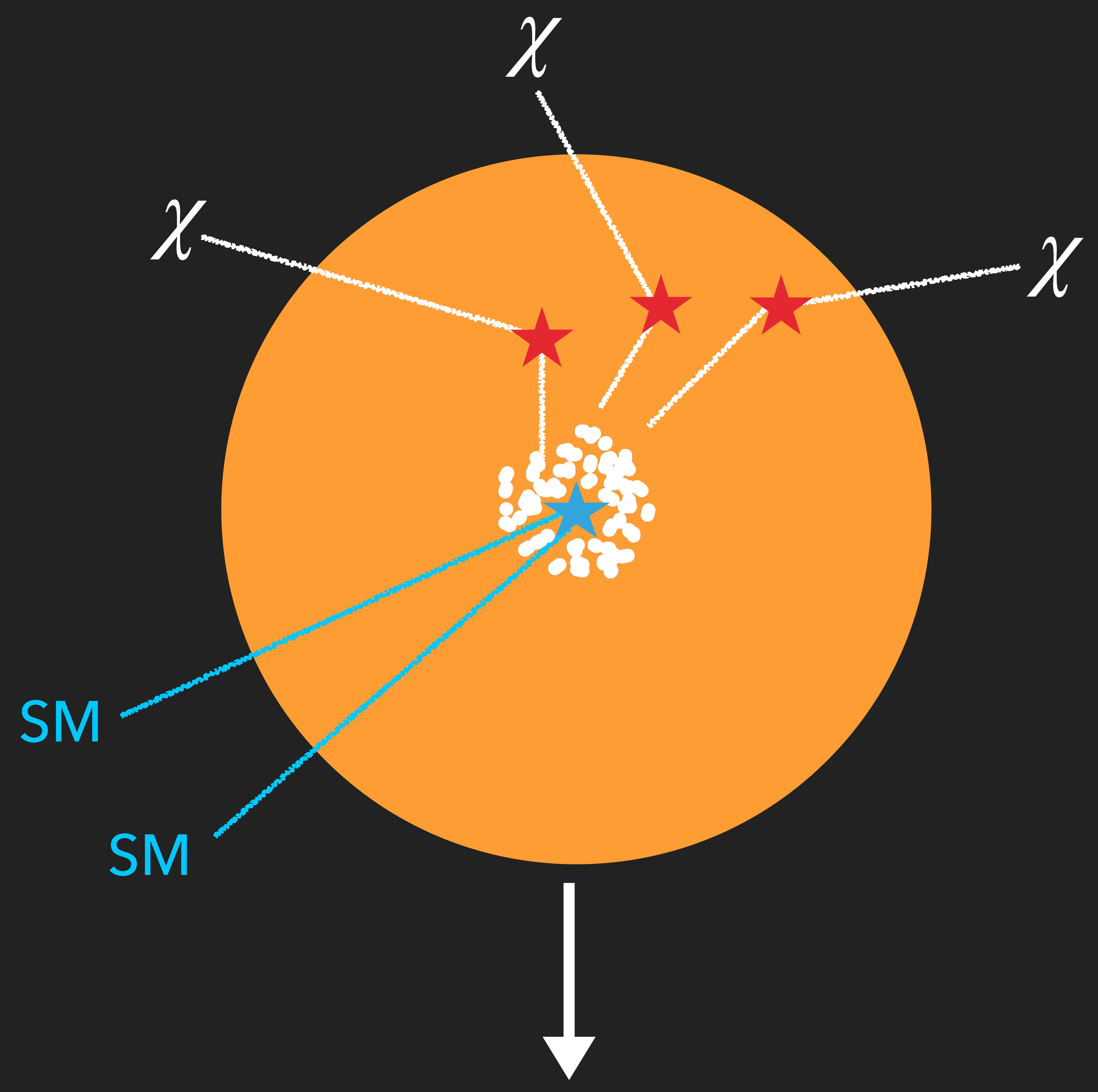
$\implies$ Upper limit on the dark matter capture rate C

$$C \propto c^2$$

$\implies$ Upper limit on the coupling strength

DIRECT AND INDIRECT DARK MATTER SEARCHES - SUMMARY





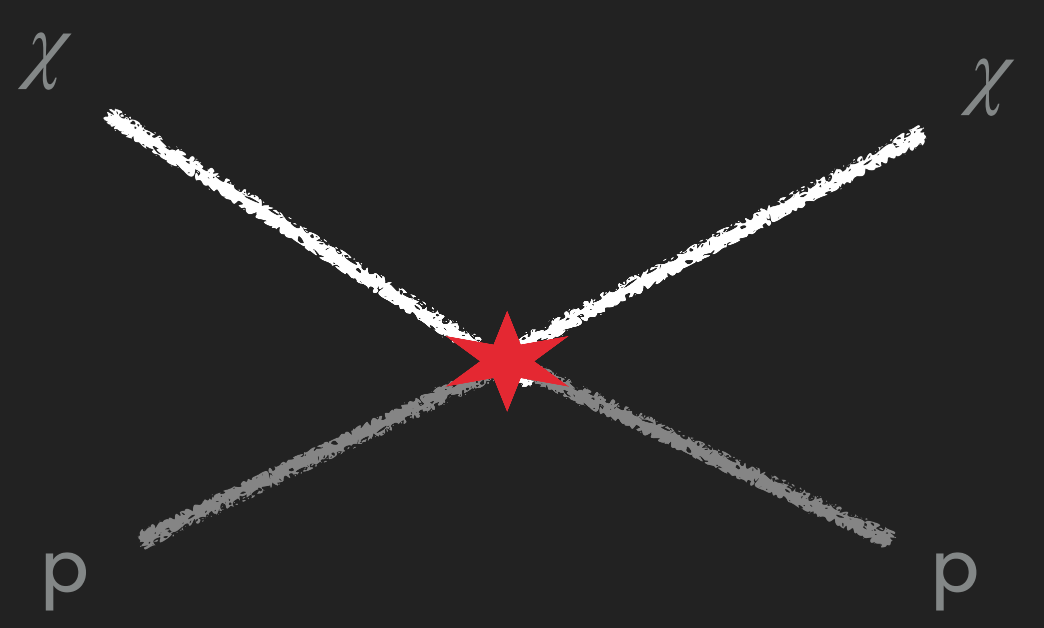
$\Longrightarrow$ Upper limit on the interaction rate

$\Longrightarrow$ Upper limit on the coupling strength

DARK MATTER INTERACTION RATE

Consider the interaction Hamiltonian $H = c^p(\bar{p}\chi)(\bar{\chi}p)$

e.g.



Interaction rate (R) $\propto$ $| < \text{final} \,|\, H \,|\, \text{initial} > |^2$

$\implies R = (c^p)^2 \, \mathbb{R}$

$\implies$ constrain coupling strength c^p for given upper limit on R

detector material

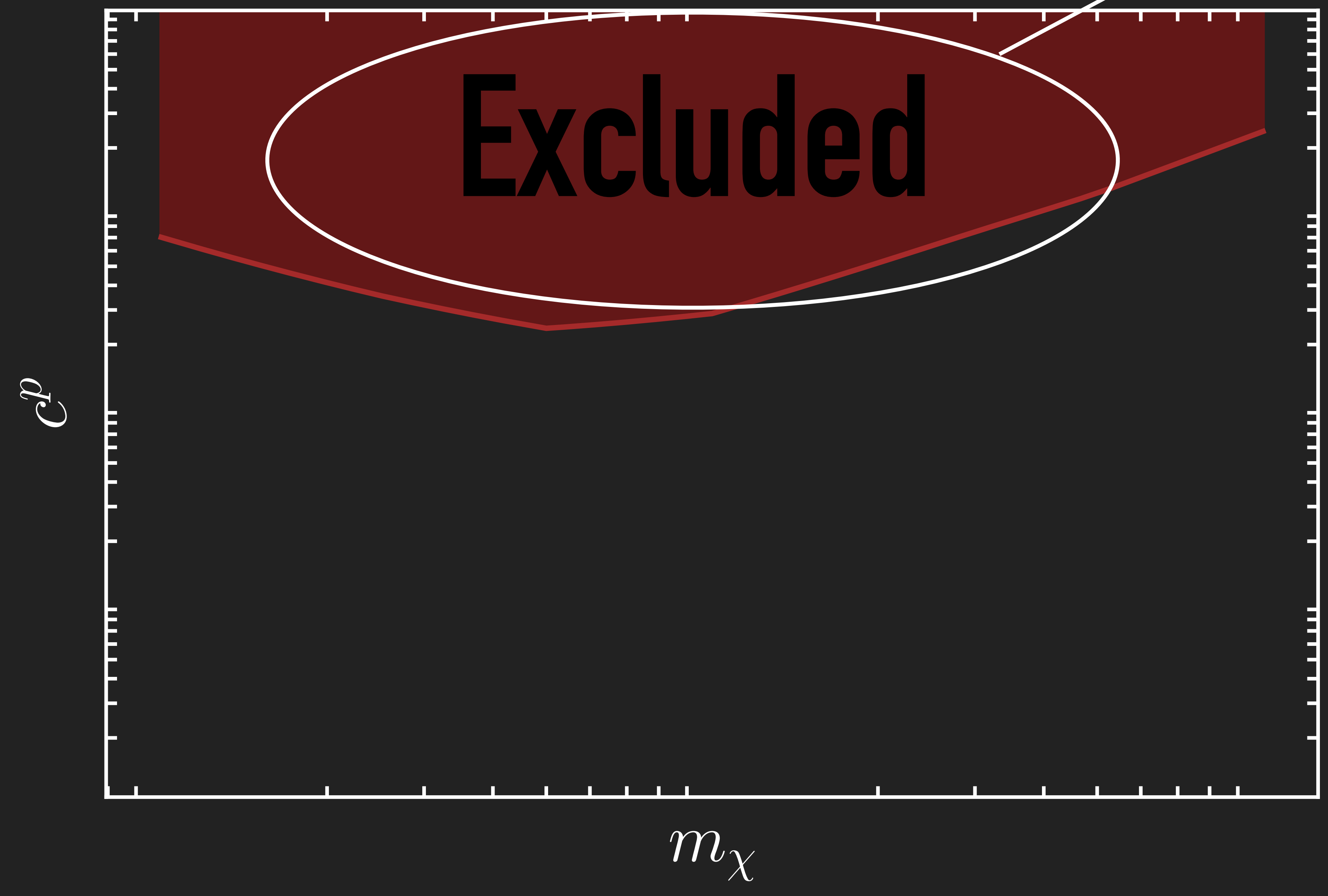
dark matter velocity distribution

local dark matter density

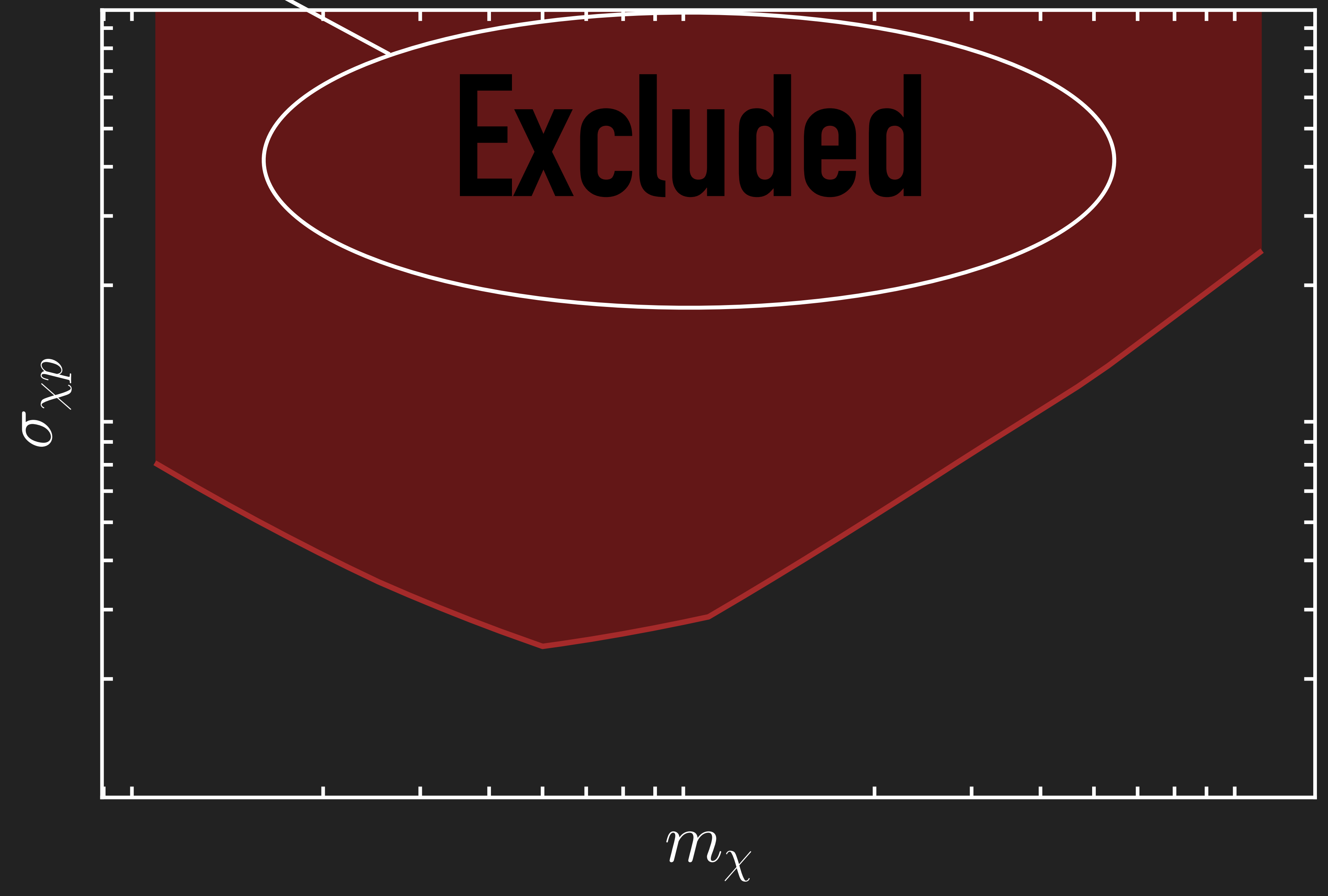
dark matter mass

LIMITS ON DARK MATTER-NUCLEON SCATTERING CROSS-SECTION

Assuming that $H = c^p(\bar{p}\chi)(\bar{\chi}p)$



$\longrightarrow \sigma_{\chi p} \propto \left(c^p\right)^2 \Longrightarrow$



BUT: What if other interactions are possible, too?

INTERACTION INTERFERENCE

In general, dark matter interacts with protons AND neutrons

$$\Longrightarrow H = c^p(\bar{p}\chi)(\bar{\chi}p) + c^n(\bar{n}\chi)(\bar{\chi}n)$$

$$\Longrightarrow R = \begin{pmatrix} c^p & c^n \end{pmatrix} \begin{pmatrix} \mathbb{R}_{pp} & \mathbb{R}_{pn} \\ \mathbb{R}_{np} & \mathbb{R}_{nn} \end{pmatrix} \begin{pmatrix} c^p \\ c^n \end{pmatrix} = c^T \mathbb{R}\, c$$

Remember:

$$H = c^p(\bar{p}\chi)(\bar{\chi}p)$$

$$R = (c^p)^2\, \mathbb{R}$$

Dark matter may interact also through other interactions (Fitzpatrick et. al. 2012)

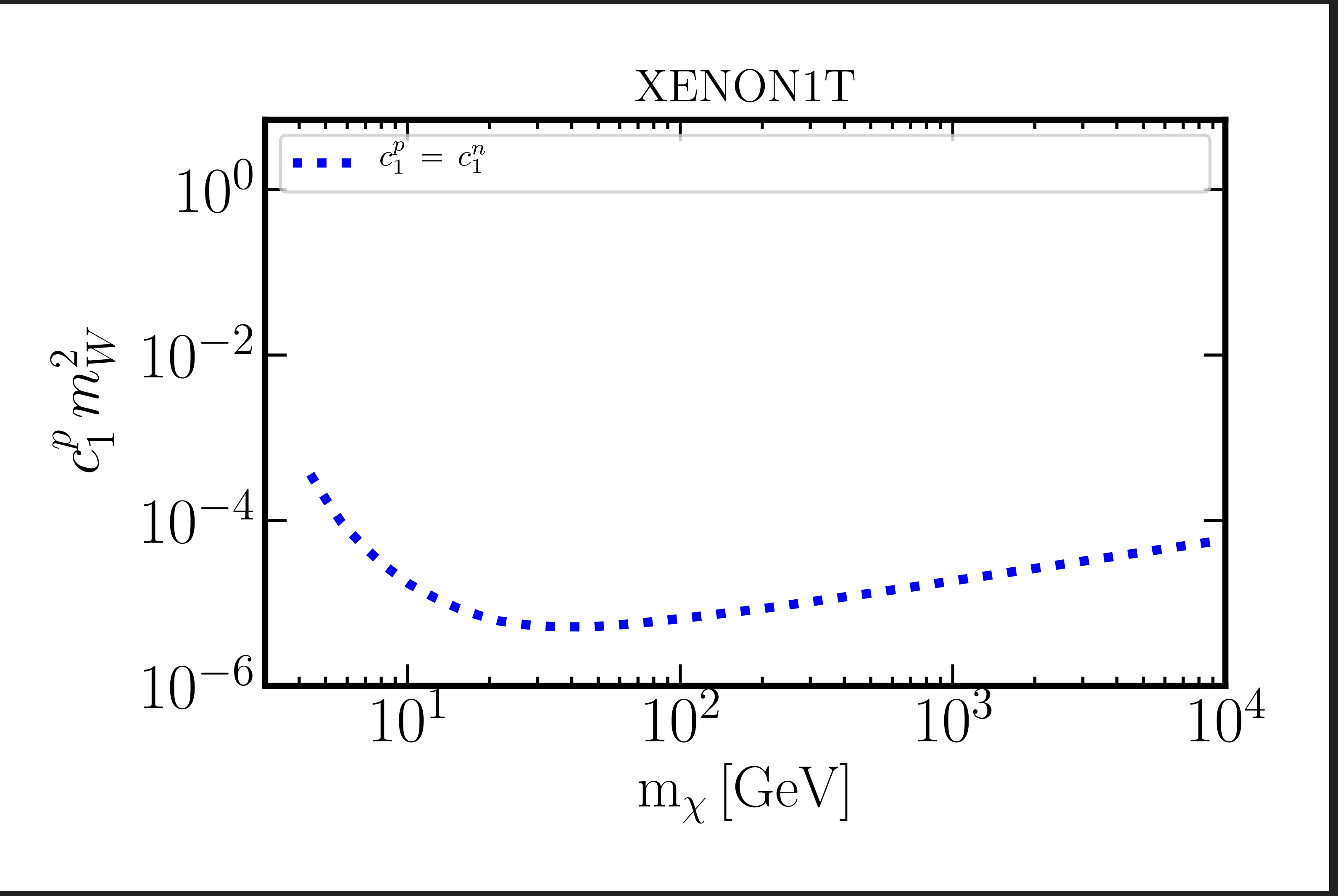
$$\Longrightarrow H = \sum_i c_i^p \mathcal{O}_i^p + c_i^n \mathcal{O}_i^n$$

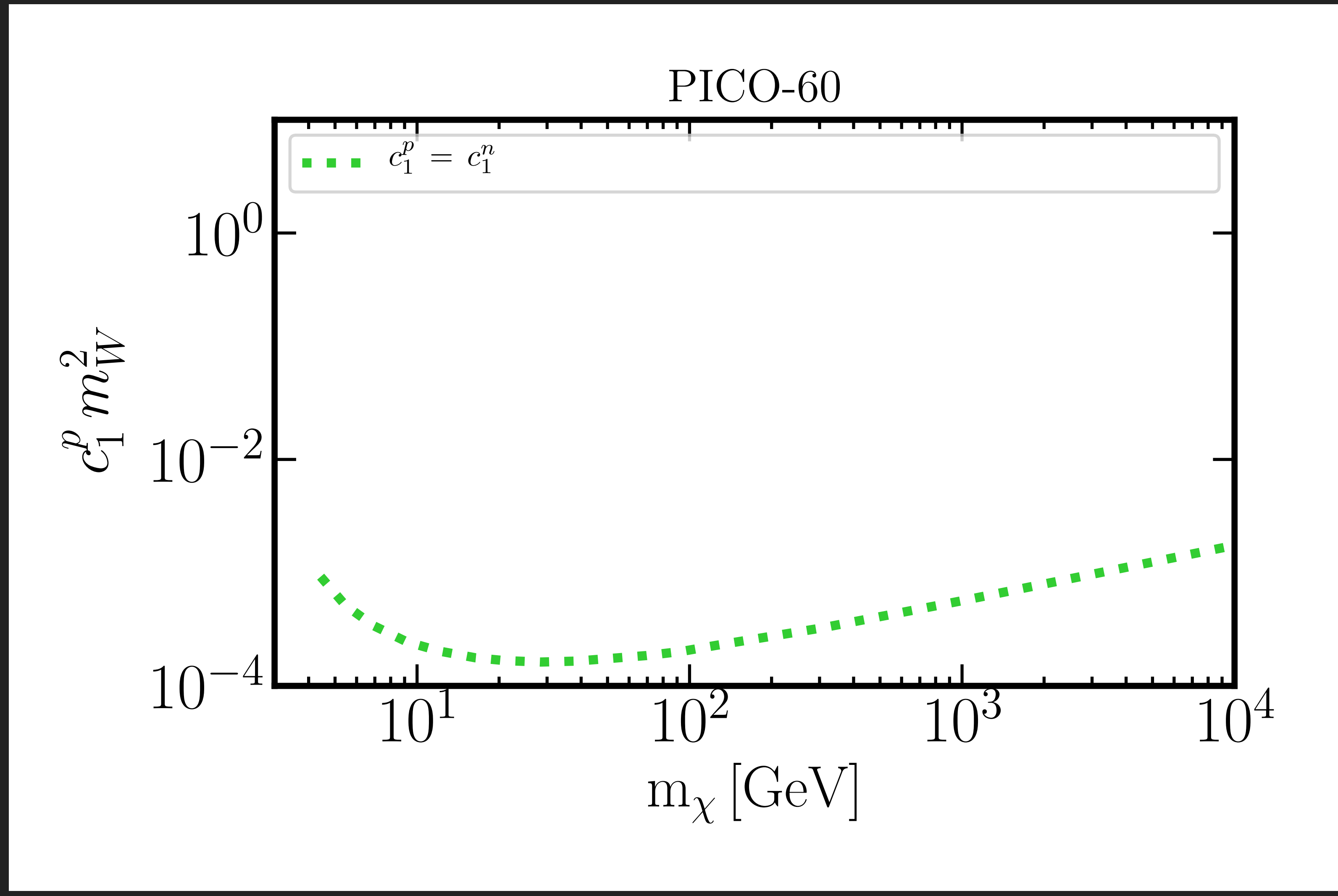
4 independent operators for spin-0 dark matter
14 for spin-1/2 dark matter

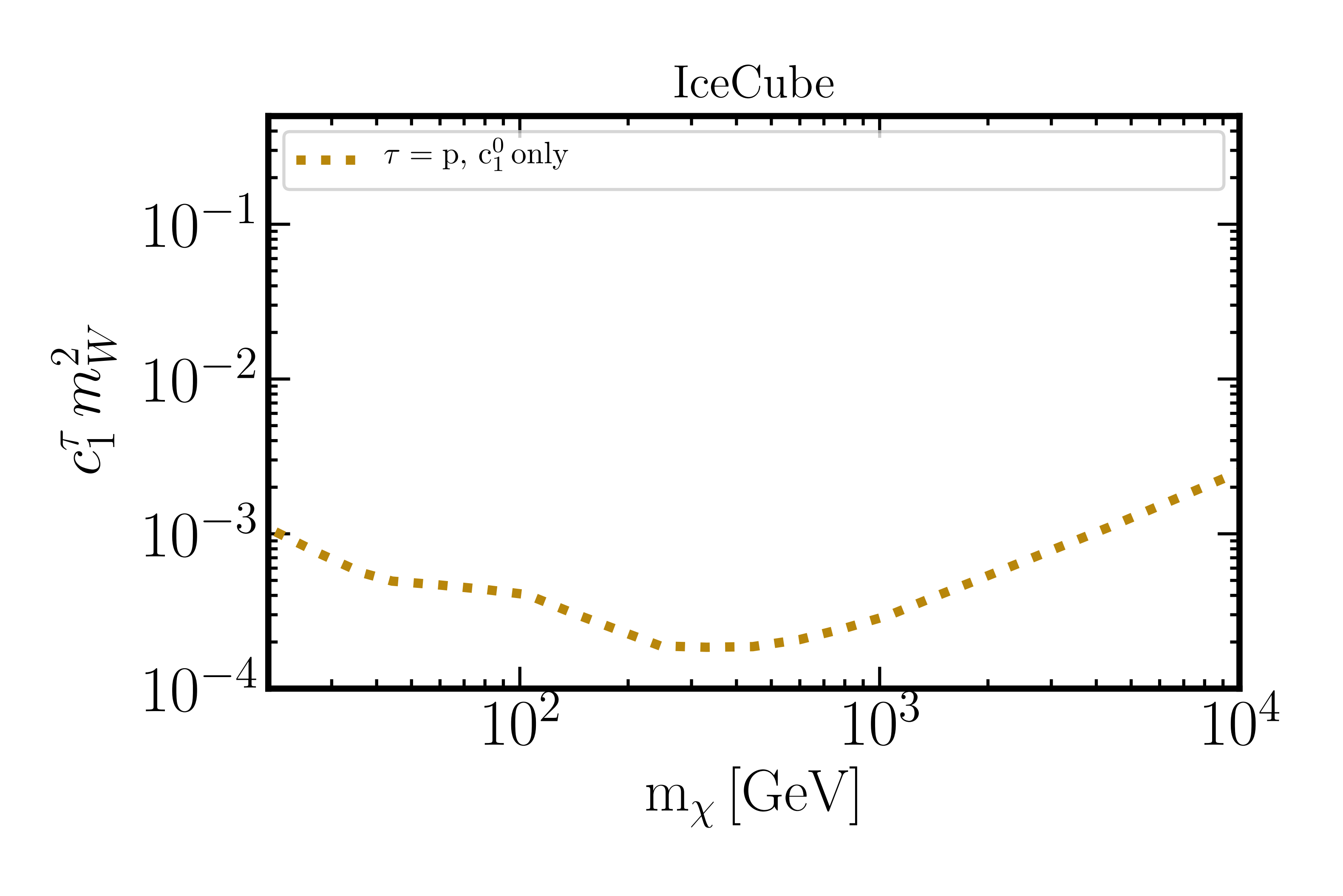
$$\Longrightarrow R = c^T \mathbb{R}\, c$$

$\mathbb{R} \mathrel{\hat{=}} 8\text{x}8$-matrix (spin-0)
$\mathbb{R} \mathrel{\hat{=}} 28\text{x}28$-matrix (spin-1/2)

CURRENT LIMITS (SI) F XENON1T, PICO-60 AND ICECUBE







Assuming that $c^p = c^n$

BUT: What happens if $c^p \neq c^n$?

EFFECT OF INTERACTION INTERFERENCE

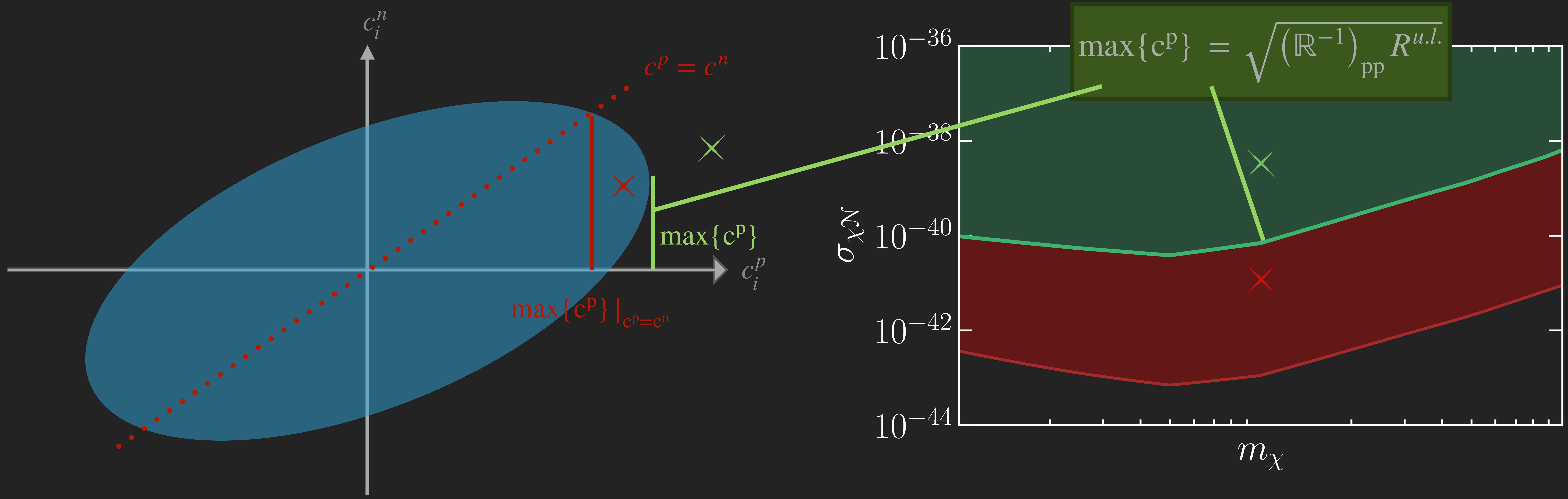
Brenner et al. (arXiv:2011.02929)

Example: interference between c^p and c^n

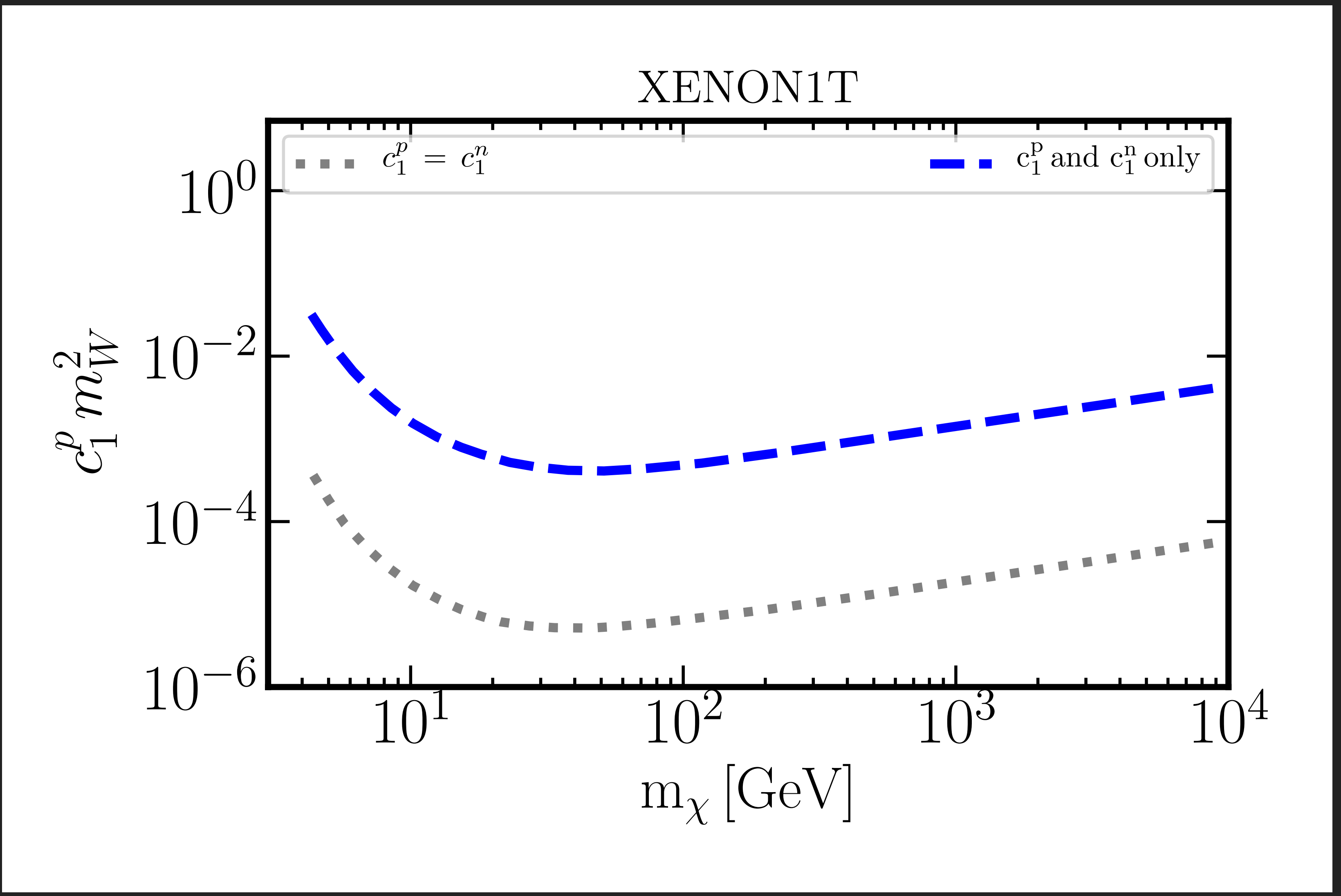
$$\Longrightarrow R = \left(c^p\, c^n\right) \begin{pmatrix} \mathbb{R}_{pp} & \mathbb{R}_{pn} \\ \mathbb{R}_{np} & \mathbb{R}_{nn} \end{pmatrix} \begin{pmatrix} c^p \\ c^n \end{pmatrix} \leq R^{u.l.} \longrightarrow \text{2D ellipse}$$

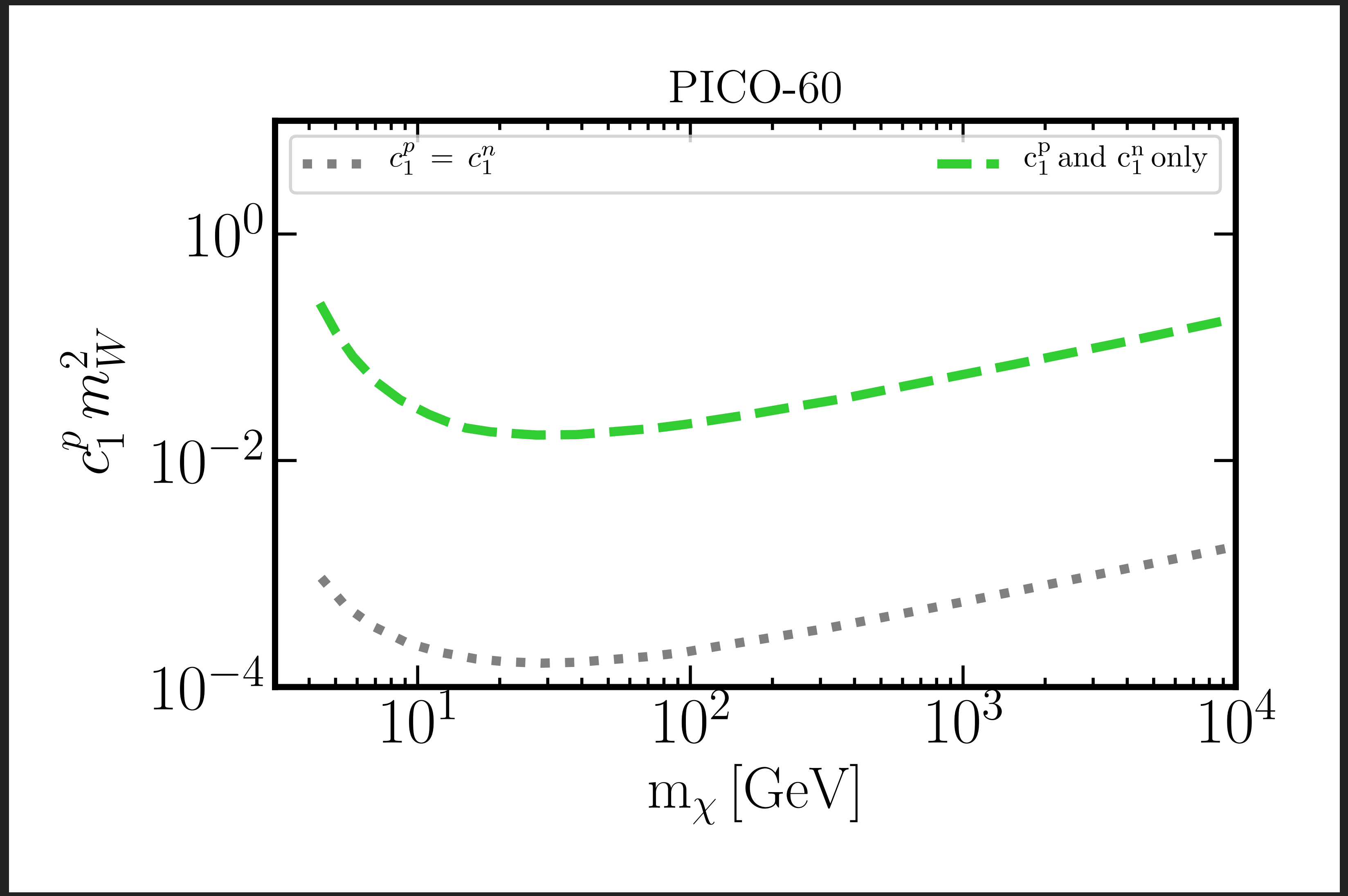
× Ruled out by „plot“, but not by data!

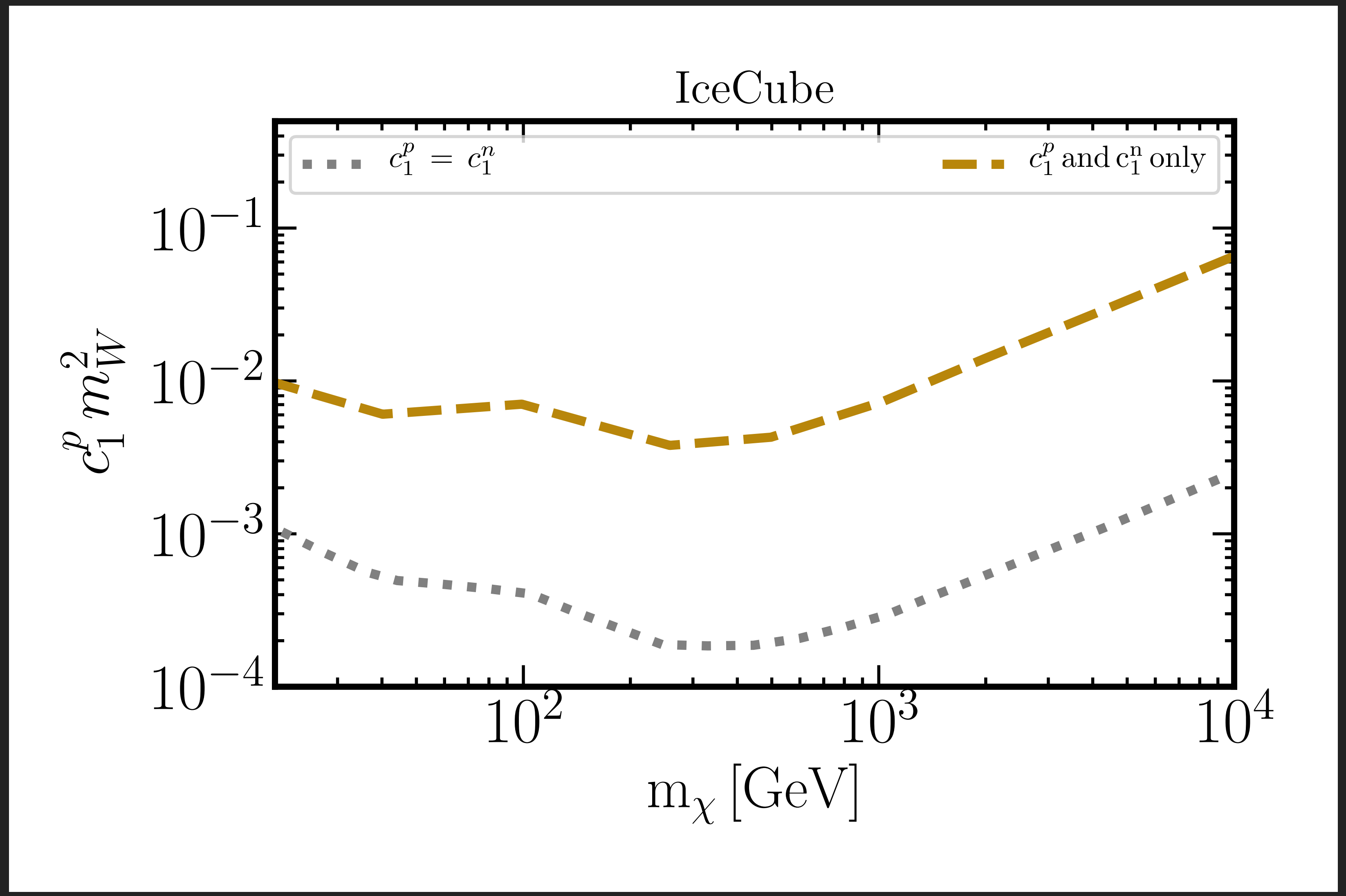
× Ruled out in model independent way



EFFECT OF INTERACTION INTERFERENCE ON XENON1T, PICO60 AND ICECUBE RESULTS







$$\Longrightarrow R = (c^p\, c^n) \begin{pmatrix} \mathbb{R}_{pp} & \mathbb{R}_{pn} \\ \mathbb{R}_{np} & \mathbb{R}_{nn} \end{pmatrix} \begin{pmatrix} c^p \\ c^n \end{pmatrix} = c^T \mathbb{R}\, c$$

Relaxation by up to two orders of magnitude

OPERATORS OF THE EFT

Most general Hamiltonian

- ✓ Energy and momentum conservation
- ✓ Galilean invariance
- ✓ Hermiticity

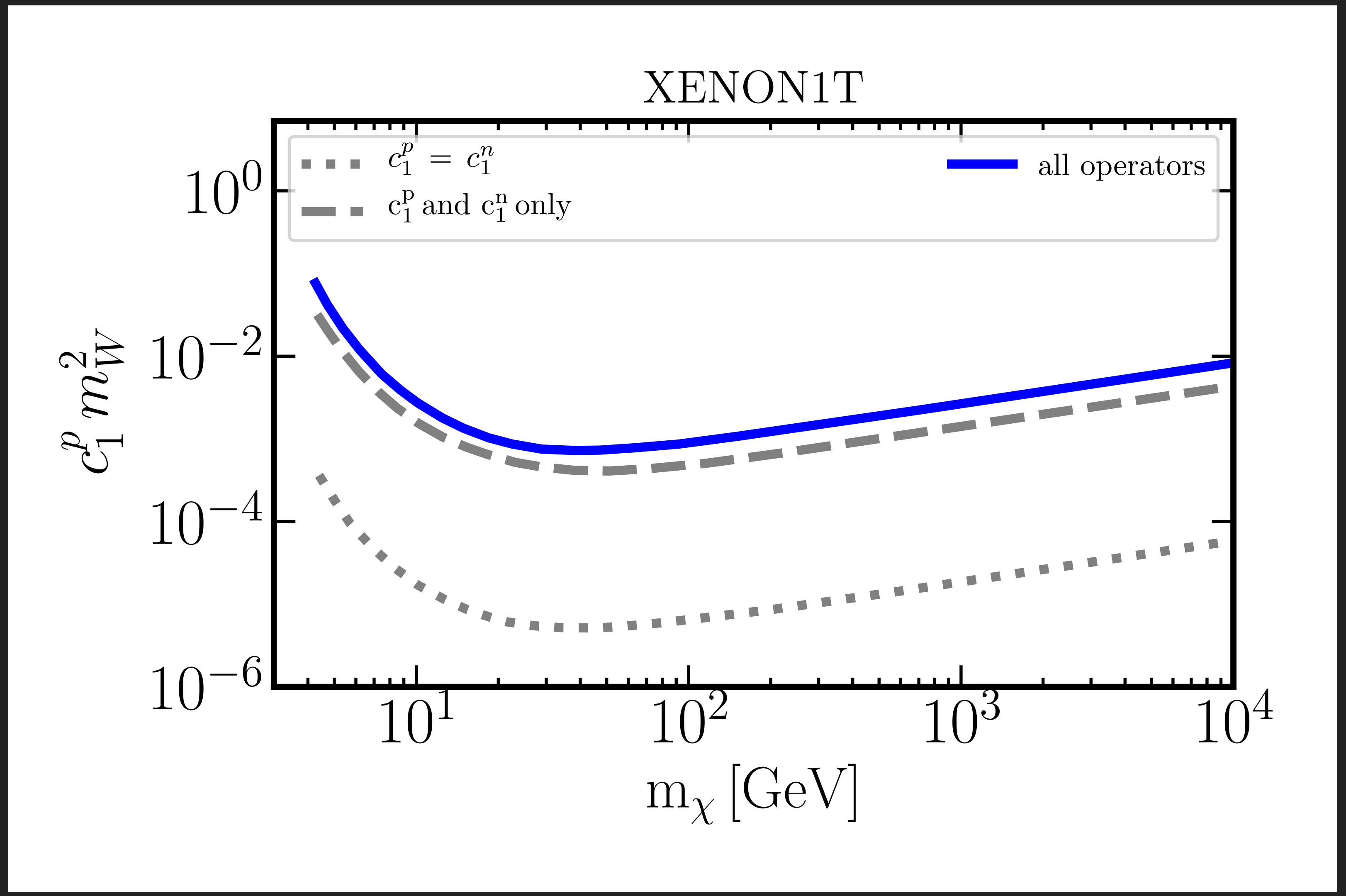
↓

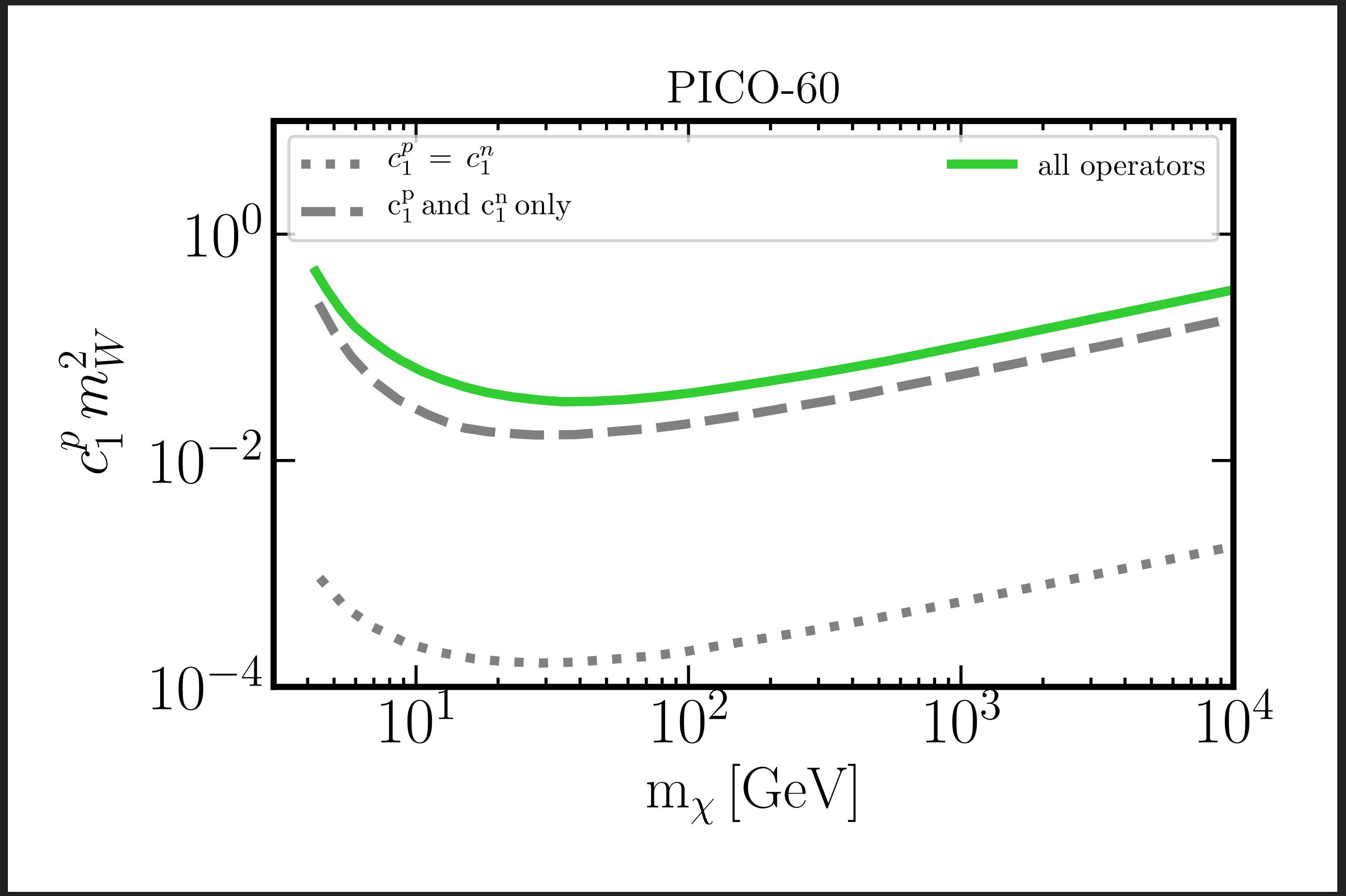
$$1 \qquad i\hat{\vec{q}} \qquad \hat{\vec{v}}^{\perp} \qquad \hat{\vec{S}}_{\chi} \qquad \hat{\vec{S}}_{N}$$

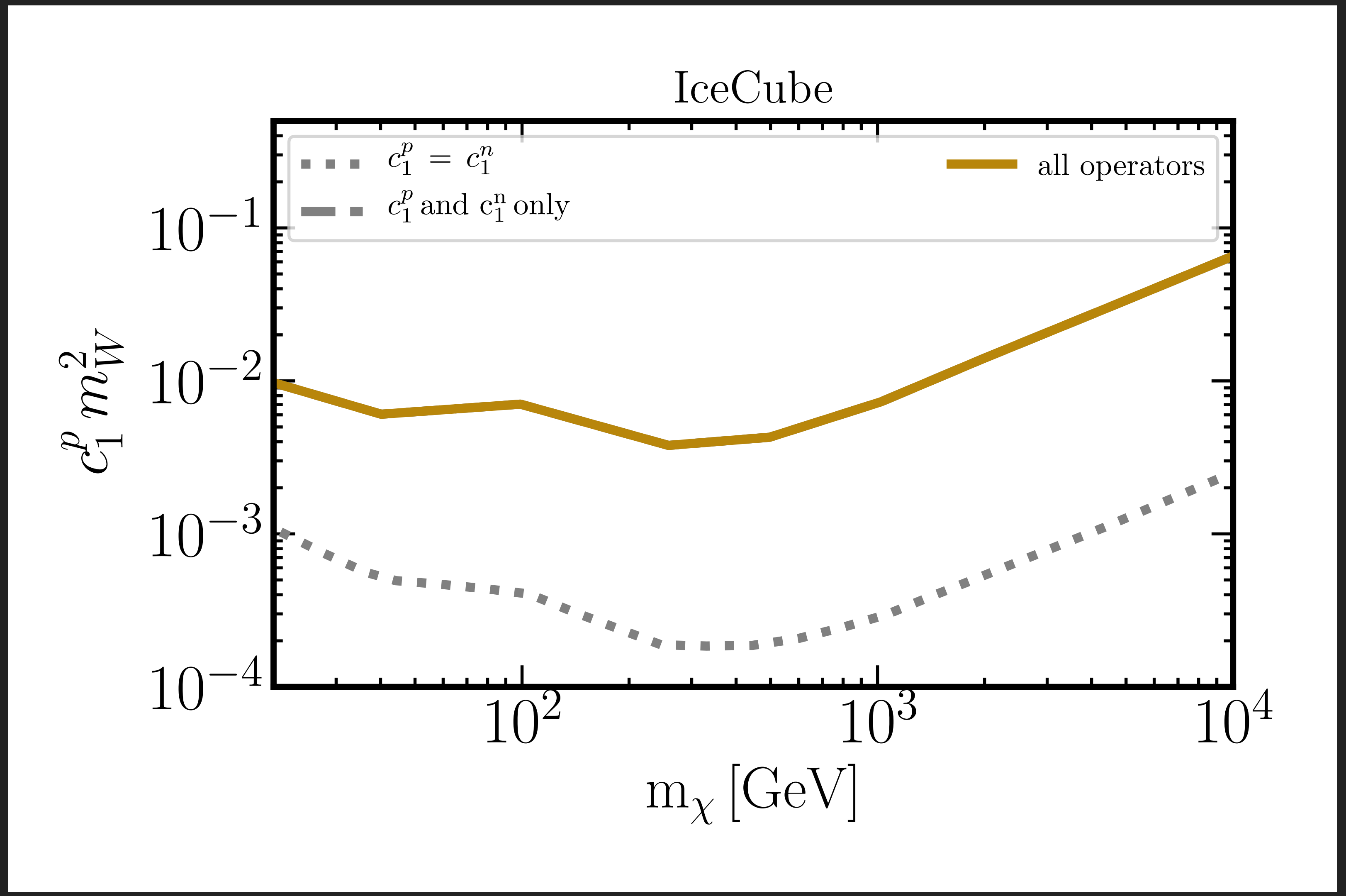
OPERATORS OF THE EFT

Standard SI	$\widehat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_\mathcal{N}$
Standard SD	$\widehat{\mathcal{O}}_4 = \widehat{\mathbf{S}}_\chi \cdot \widehat{\mathbf{S}}_\mathcal{N}$

EFFECT OF INTERACTION INTERFERENCE ON XENON1T, PICO60 AND ICECUBE RESULTS







$$\Longrightarrow R = (c^p\, c^n) \begin{pmatrix} \mathbb{R}_{pp} & \mathbb{R}_{pn} \\ \mathbb{R}_{np} & \mathbb{R}_{nn} \end{pmatrix} \begin{pmatrix} c^p \\ c^n \end{pmatrix} = c^T \mathbb{R}\, c$$

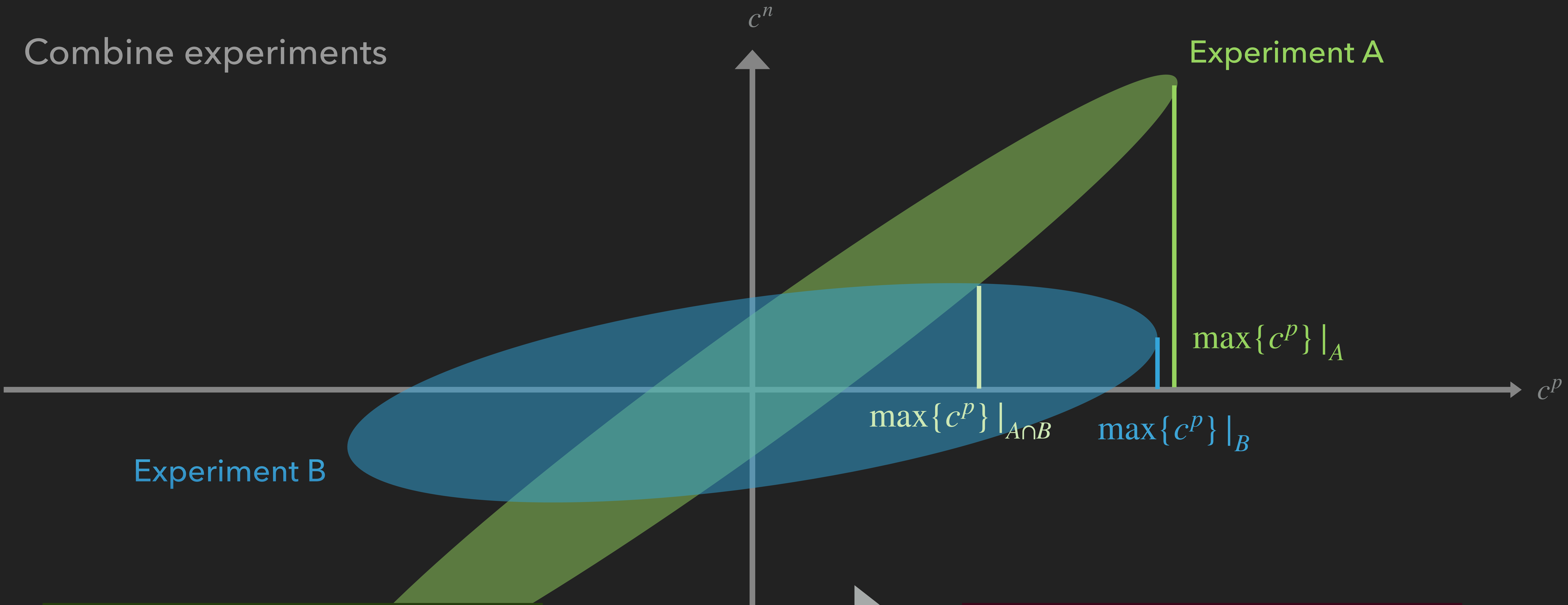
Relaxation by up to two orders of magnitude

$$\Longrightarrow R = c^T \mathbb{R}\, c \qquad \mathbb{R} \mathrel{\hat{=}} 28\text{x}28\text{-matrix}$$

Relaxation by up to an additional factor of ~ 2

COMBINING EXPERIMENTS

Combine experiments

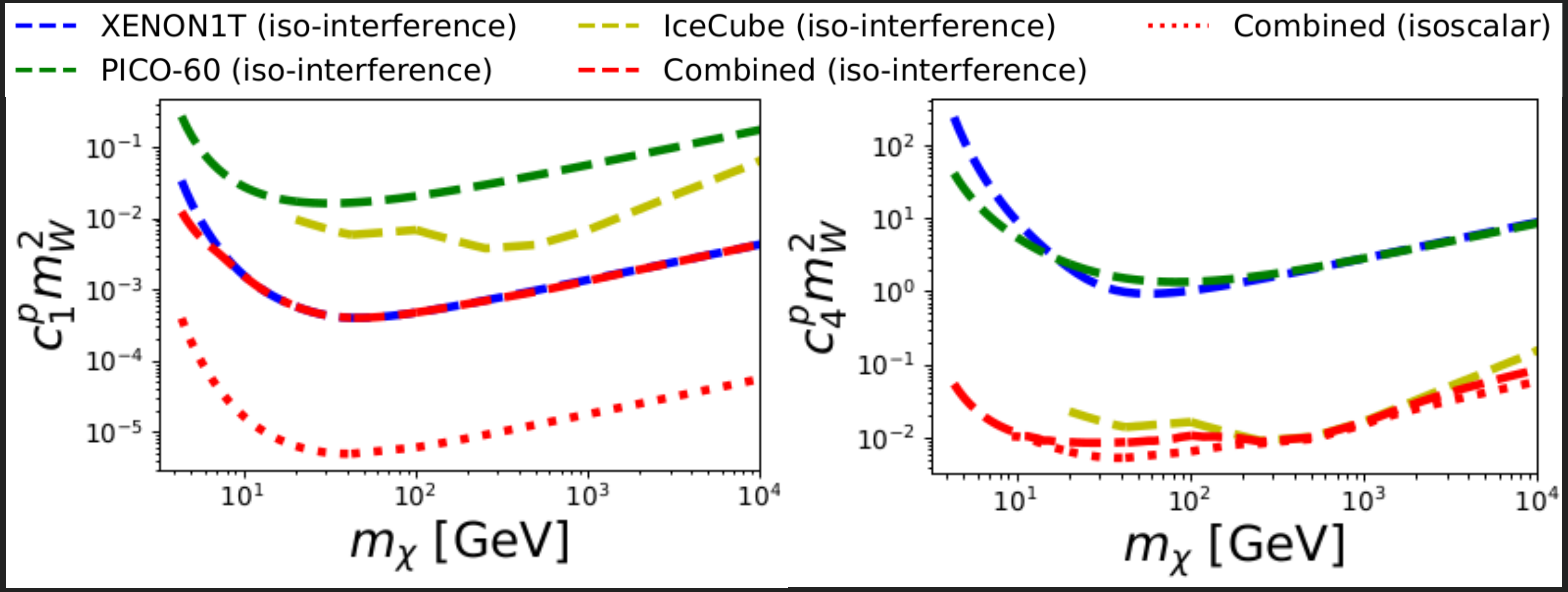


$$\max\{c^p\} = \sqrt{\left(\mathbb{R}^{-1}\right)_{pp} R^{u.l.}}$$

→

$$\max\{c^p\}(\mathbb{R}, N_j^{obs}, N_j^{back})$$

RESULTS: COMBINING EXPERIMENTS



Operator 1

Little impact for very small DM masses

SUMMARY

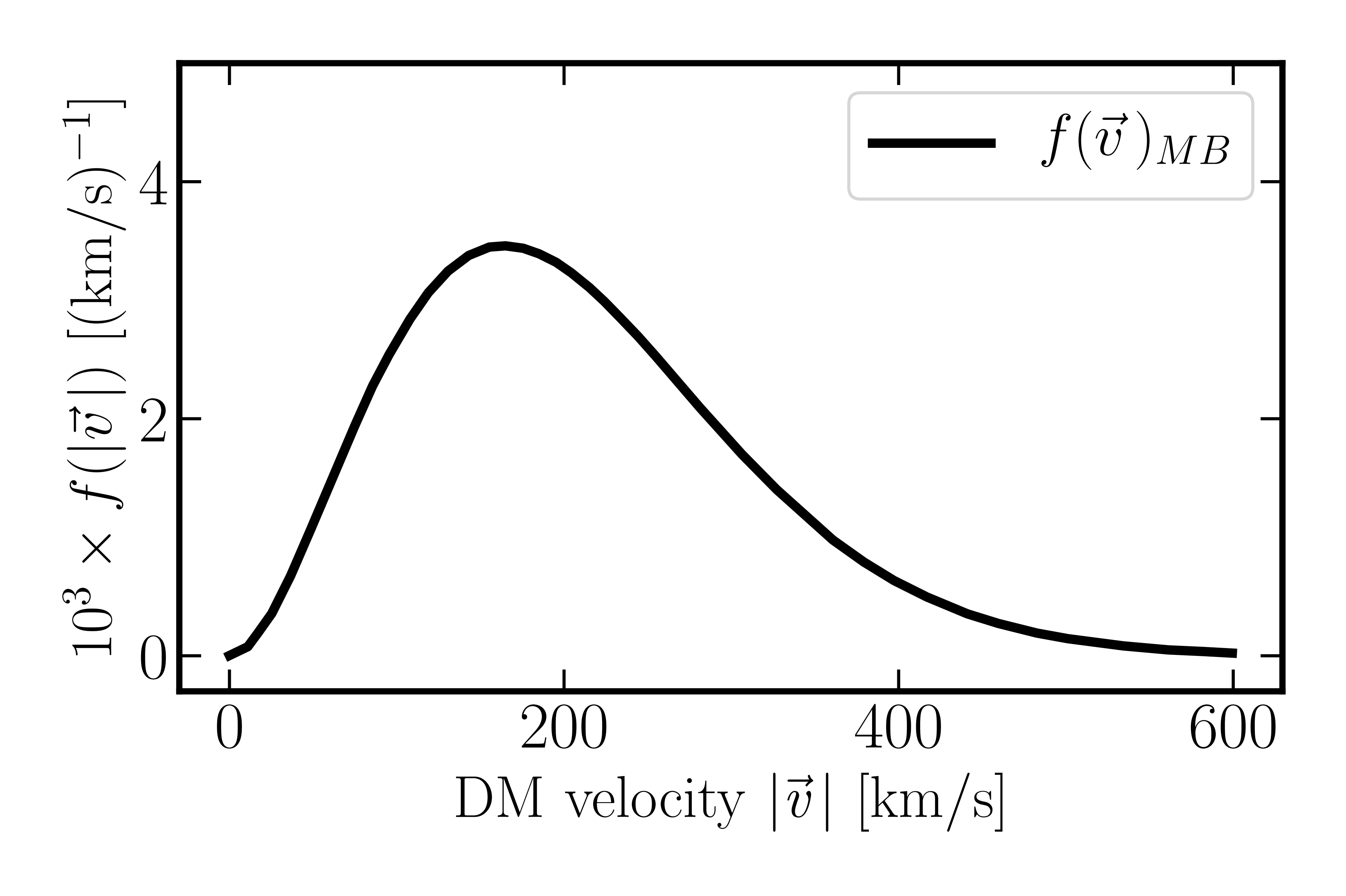
- common assumption for limits on the dark matter-nucleon coupling strength: dark matter couples equally to protons and neutrons
- new method to get most conservative limits on the coupling strength

  ⟶ taking interaction interference into account can relax the coupling strength limits by up to two orders of magnitude
- apply method to get combined limits

  ⟶ stronger limits for the cross-section

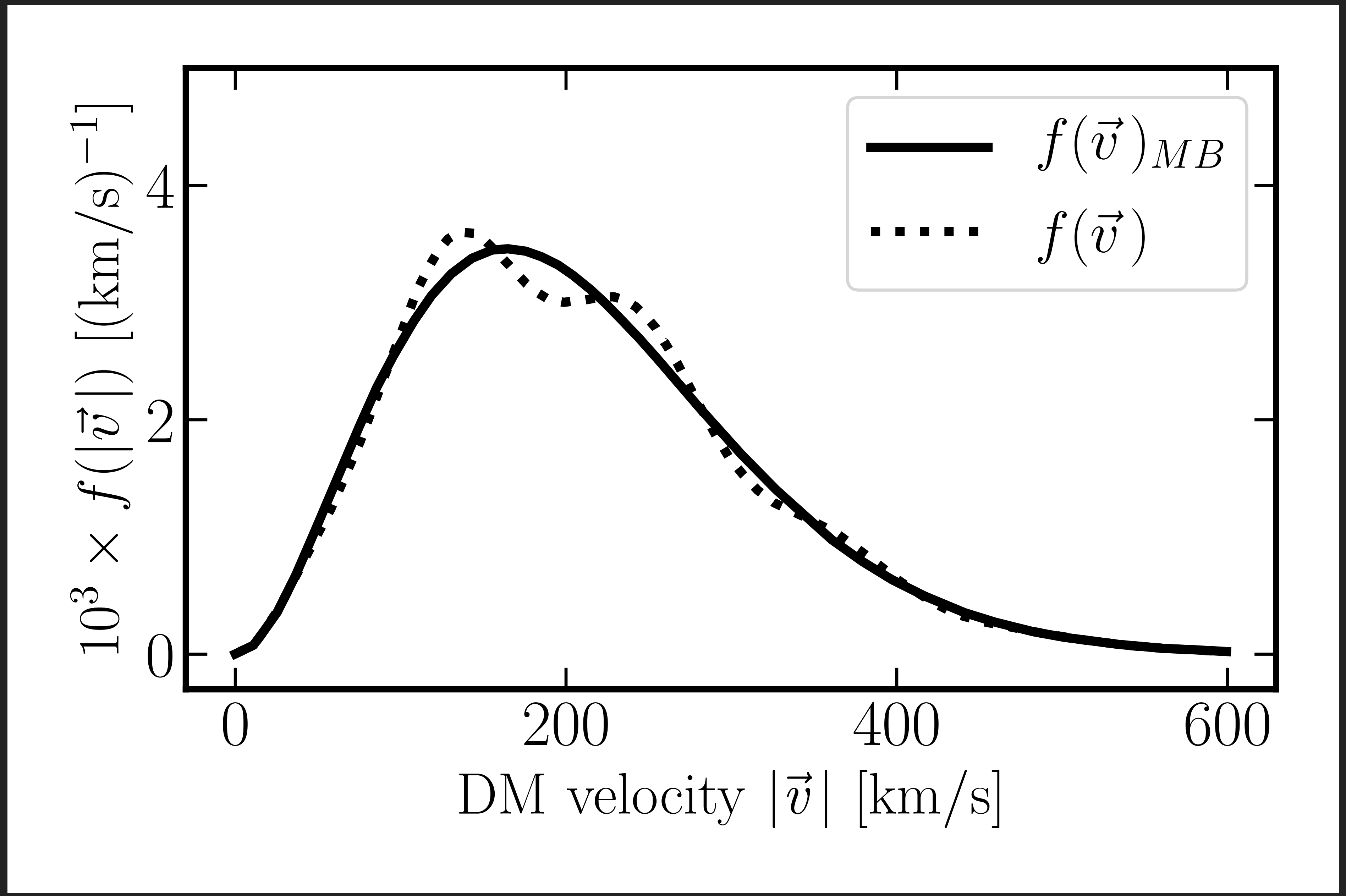
OUTLOOK – HALO-INDEPENDENT ANALYSIS

Assumption for velocity distribution: Maxwell-Boltzmann (MB)



BUT: What if the velocity distribution is different to MB?

OUTLOOK - HALO-INDEPENDENT ANALYSIS



OUTLOOK - HALO-INDEPENDENT ANALYSIS