

The WIMP Paradigm and Beyond: Status and Future Directions

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Weakly Interacting Massive Particle (WIMP)

Dark Matter (DM) Problem

Current energy density:

$$\Omega_{\text{DM}} h^2 = 0.120 \pm 0.001 \quad [\text{Planck 2018}]$$

Boltzmann eq.:

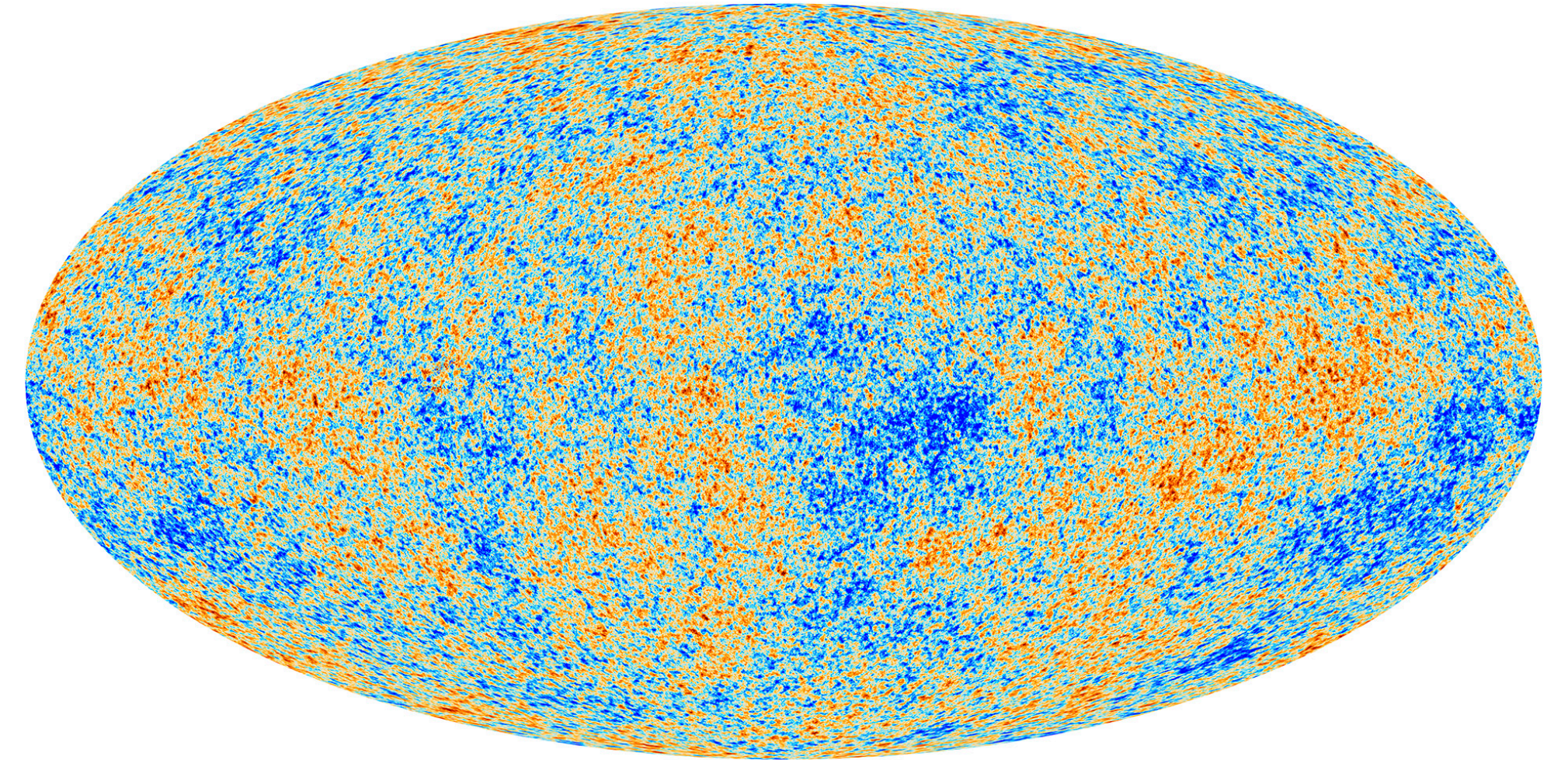
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\text{ann}}v\rangle(n_\chi^2 - n_{\chi,\text{eq}}^2)$$

WIMP approach

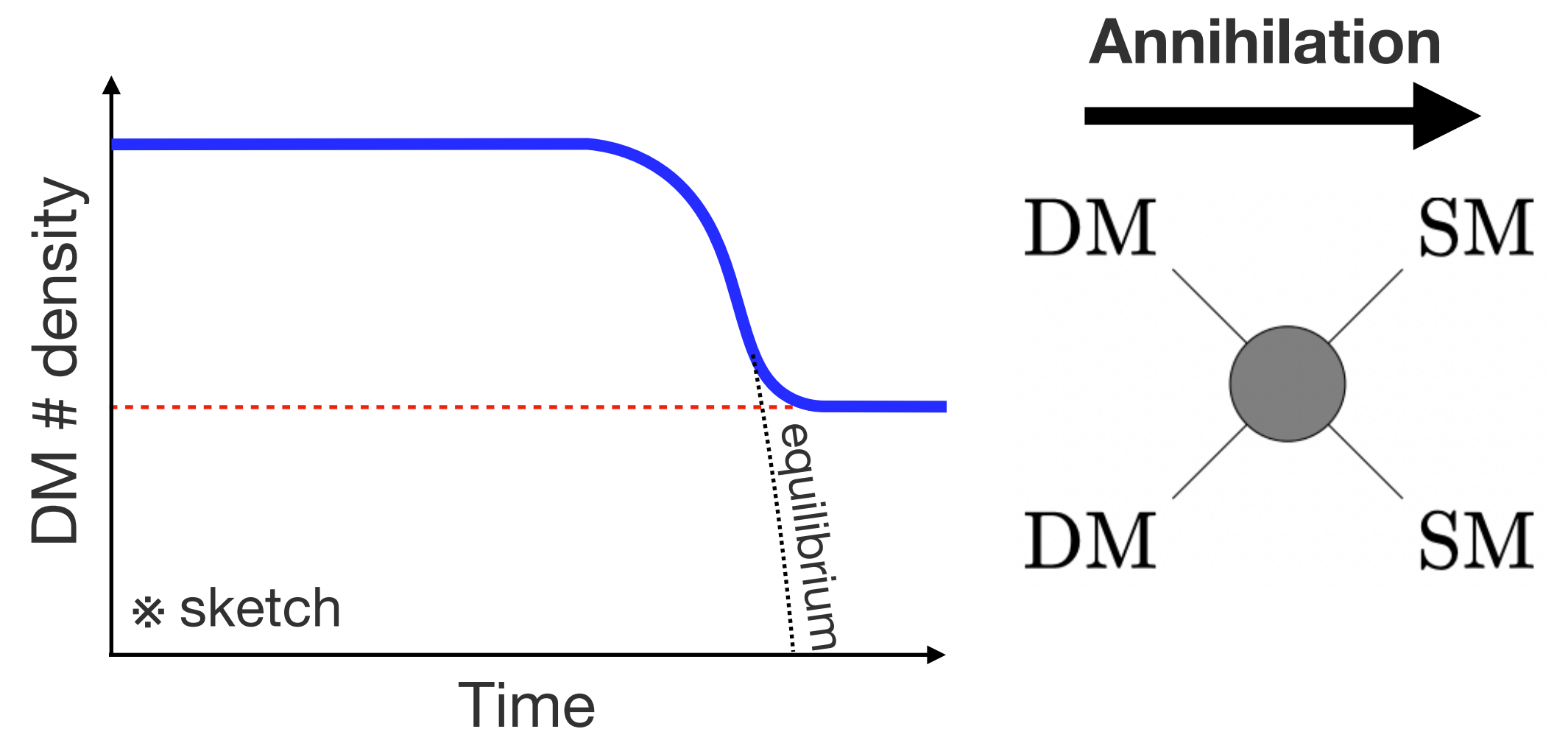
Weakly Interacting Stable & Neutral Particle

↪ thermalized in early universe

$$\langle\sigma_{\text{ann}}v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$



Map of temperature fluctuation [Planck]

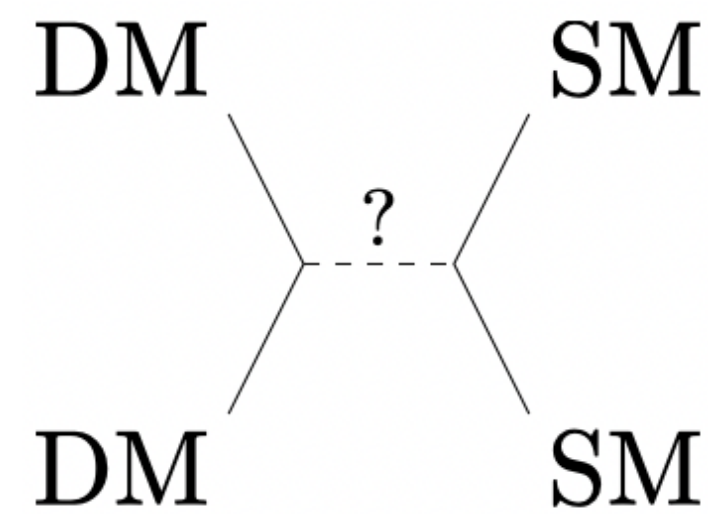
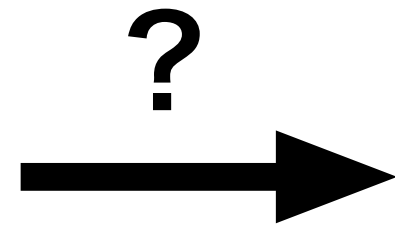
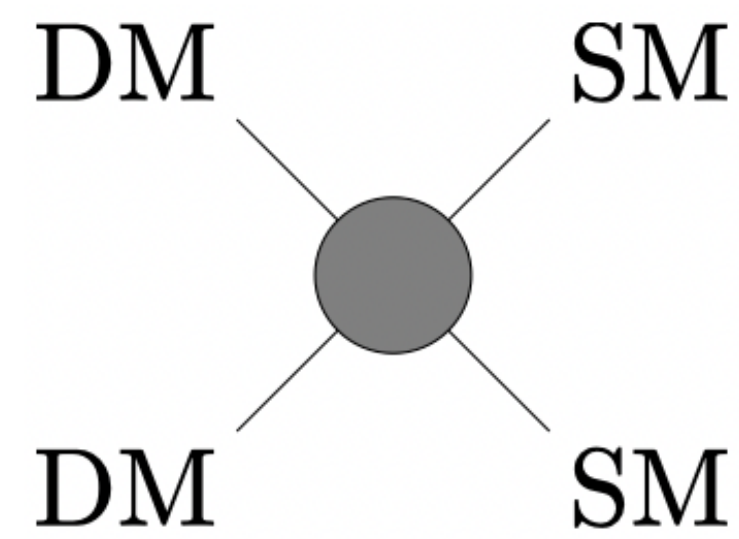


WIMP paradigm

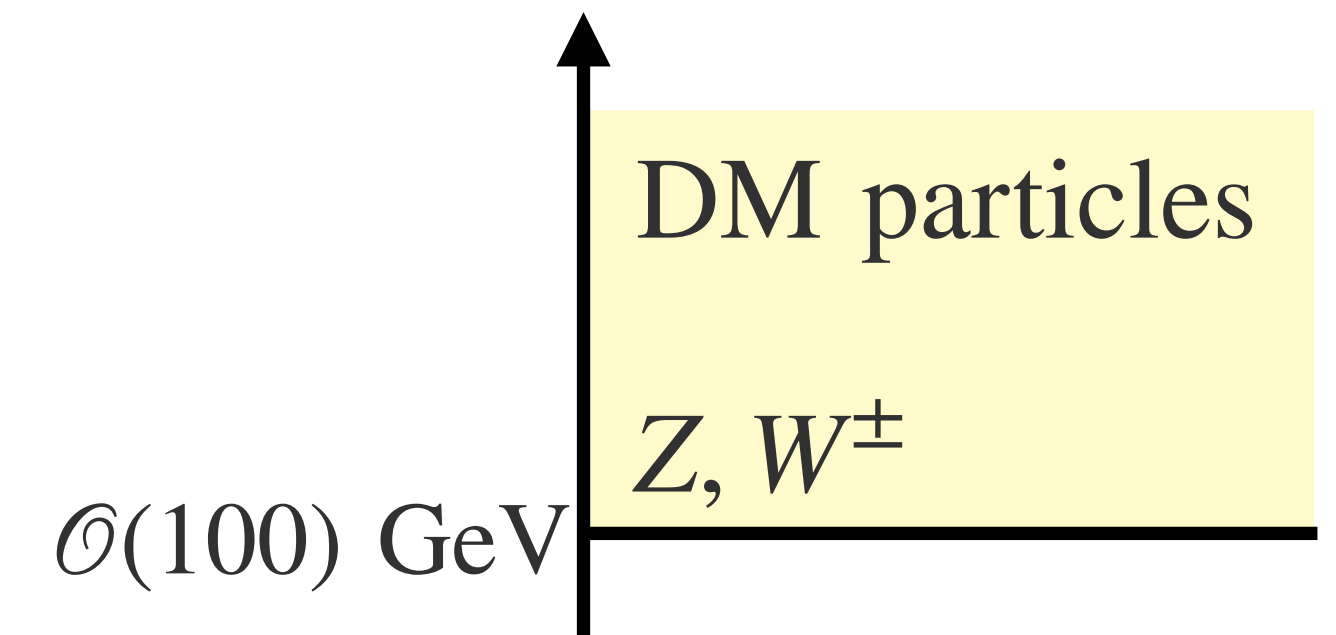
$$1 \text{ b} = 10^{-24} \text{ cm}^2$$

$$c = 3 \times 10^8 \text{ m/s}$$

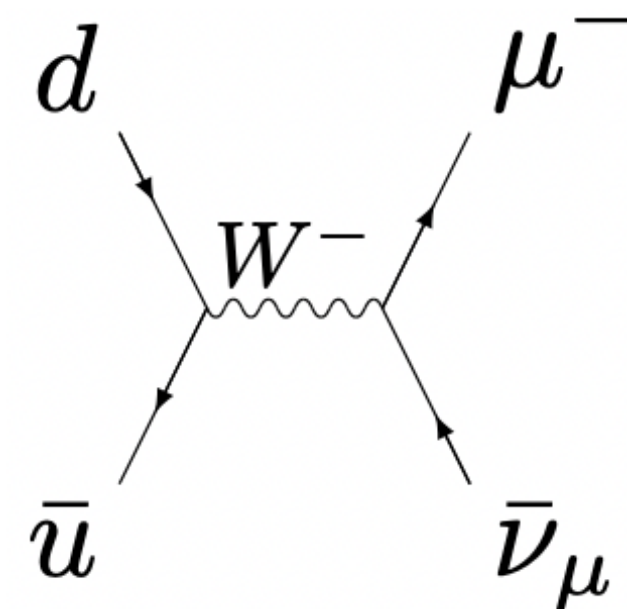
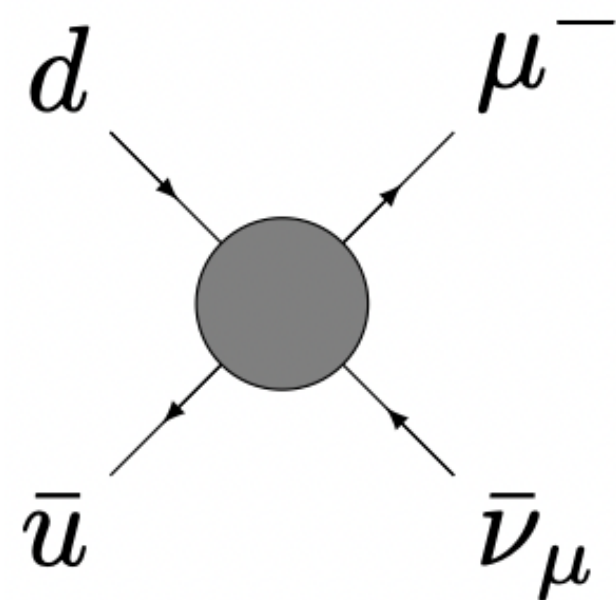
$$\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \sim 1 \text{ pb} \cdot c \rightarrow \text{Cross section for Electroweak (EW) interaction}$$



New physics for $\sim \text{EW scale}$?

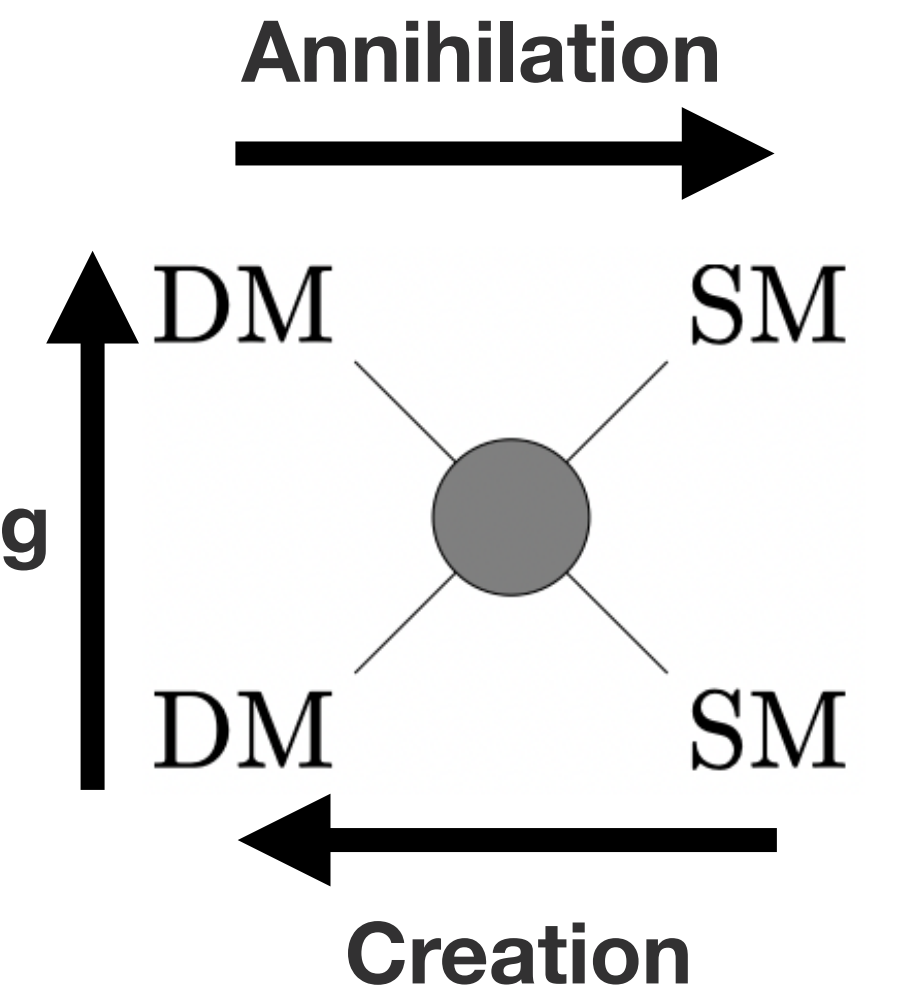


e.g. charged pion decay



EW int. mediated by $Z, W^\pm$
($m_W = 80.4 \text{ GeV}$: EW scale)

Scattering



Direct detection

Scattering rate of WIMP

$$\frac{dR}{dE_R} = N_T \cdot \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \cdot \int_{v > v_{\min}} d^3v \, v \, f(\vec{v} + \vec{v}_e) \times \frac{d\sigma}{dE_R}$$

- **Particle physics** inputs

- DM mass
- Differential cross section of WIMP-nucleon scatt.

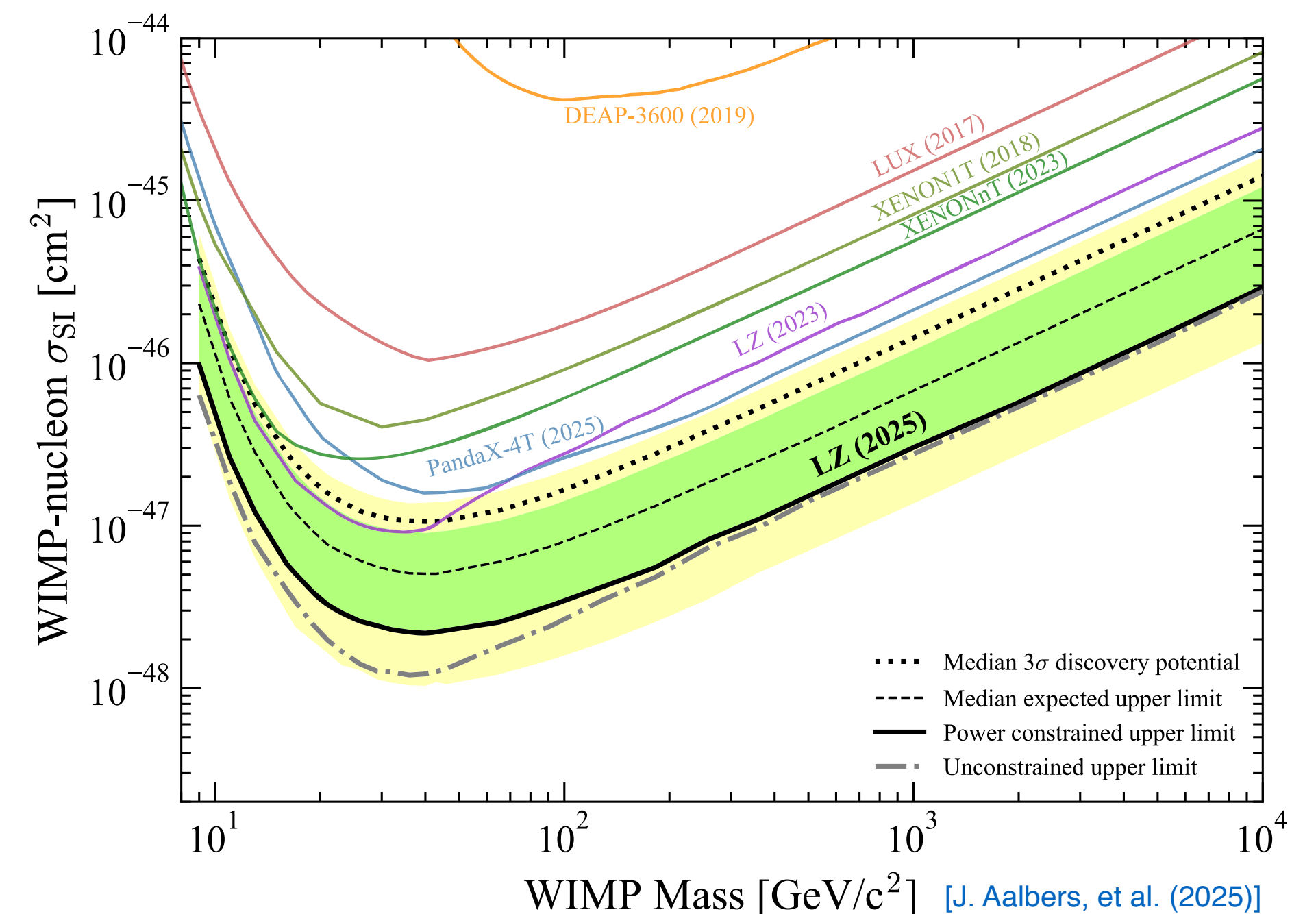
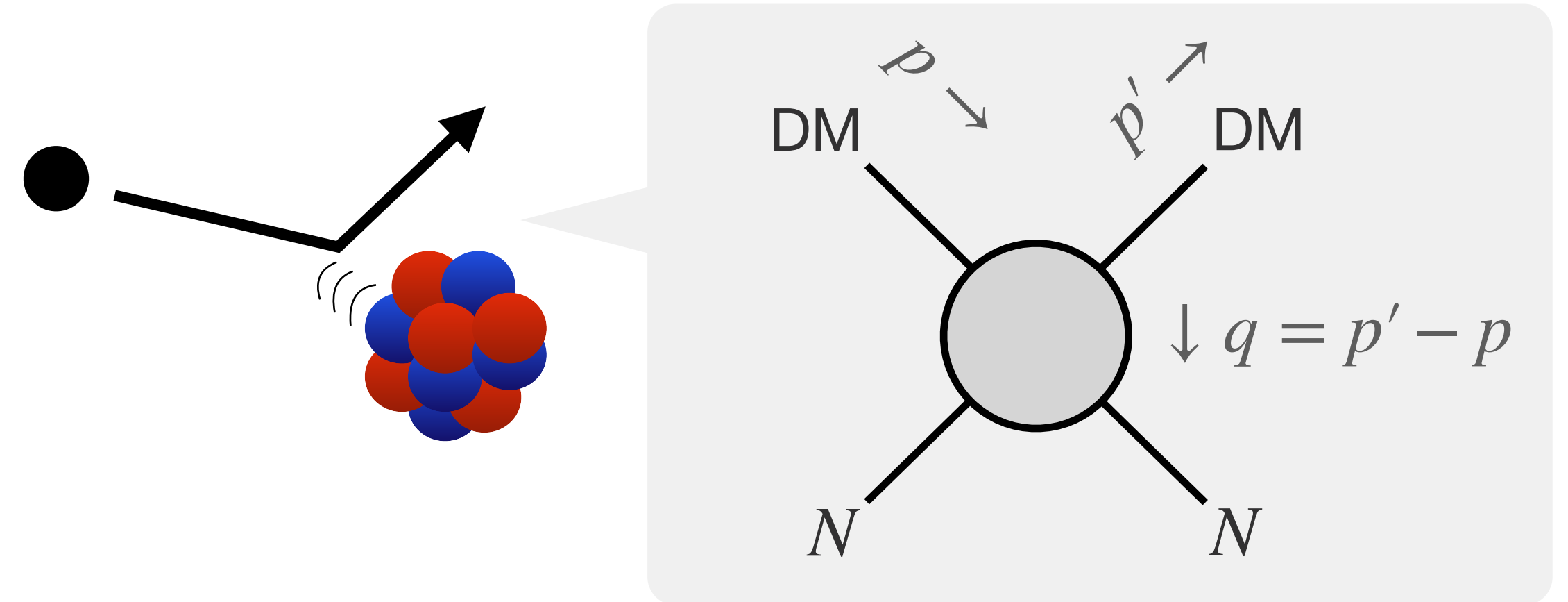
- **Astrophysical** inputs

- Local DM density (e.g. $\rho_{\text{DM}} = 0.3 \text{ GeV/cm}^3$)
- Velocity distribution (e.g. Maxwell-Boltzmann dist.)

Related Talks:

Tianyu Zhu || *Recent XENONnT results and current status*

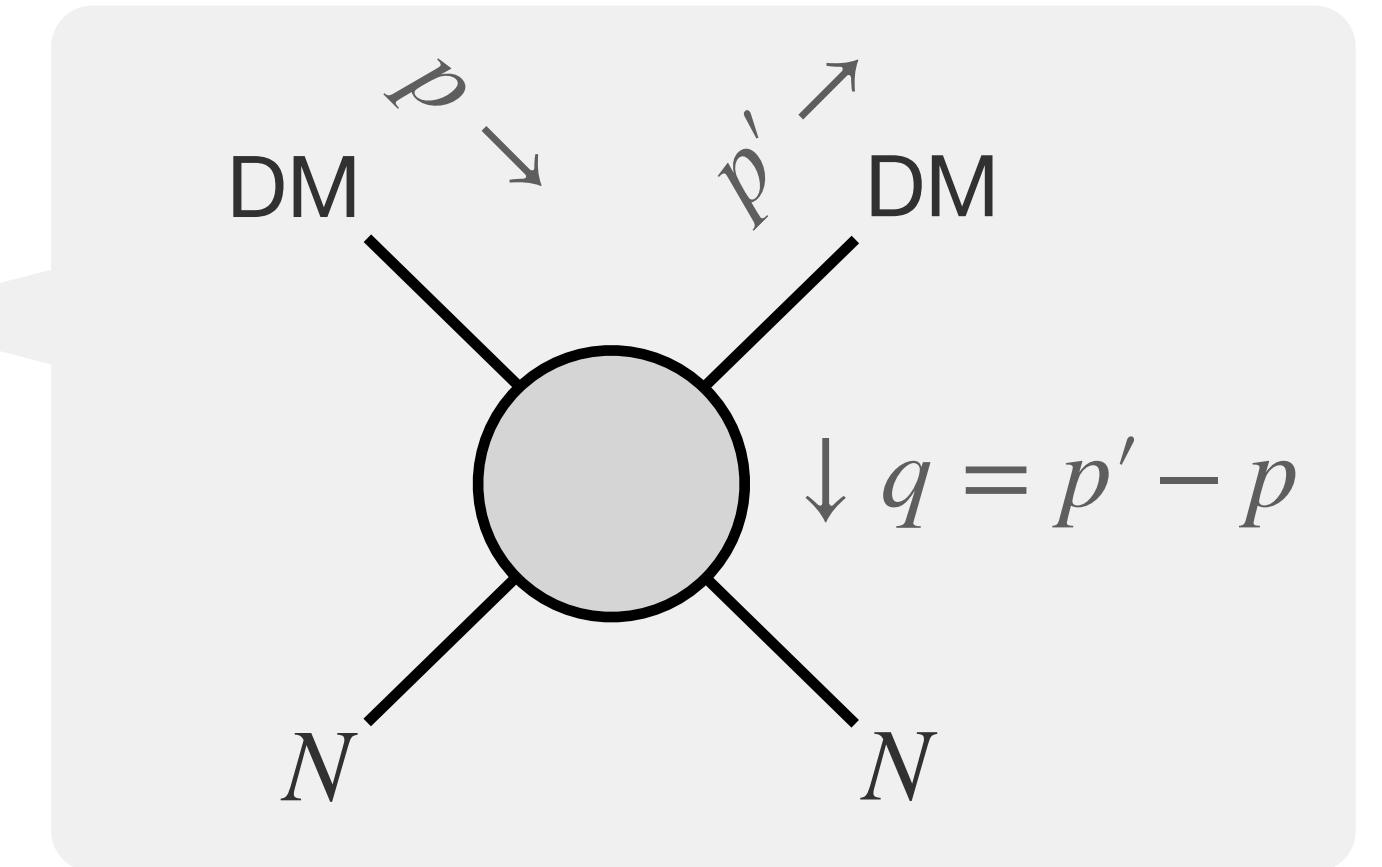
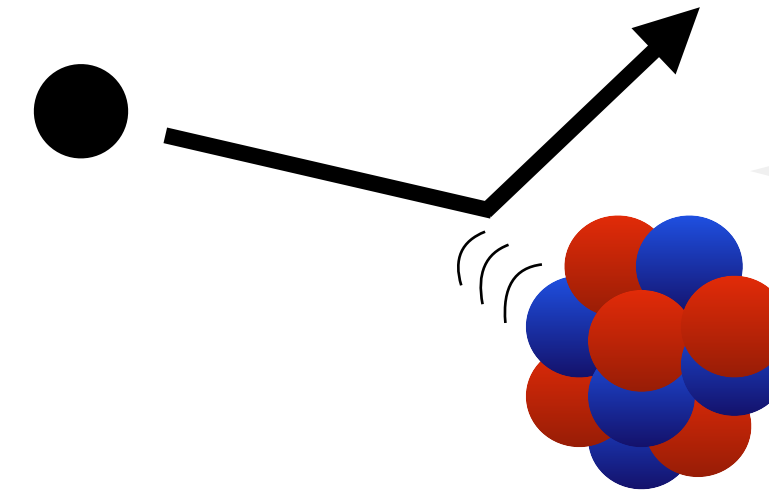
Henrique Araujo || *Towards new physics: from LZ to XLZD*



Connecting Experiment & Theory

Non-Relativistic EFT (NREFT)

- Non-relativistic WIMP-nucleon scattering
→ Described by Galilean & Hermitian invariant blocks
- Momentum transfer : $i\vec{q}$
- Relative velocity : $\vec{v}^\perp \equiv \vec{v} + \vec{q}/(2\mu_N)$
- Spin operator for DM : $\vec{S}_\chi$
- Spin operator for nucleon : $\vec{S}_N$



$\vec{v}$: relative velocity btw DM & nucleon
 μ_N : reduced mass of DM & nucleon

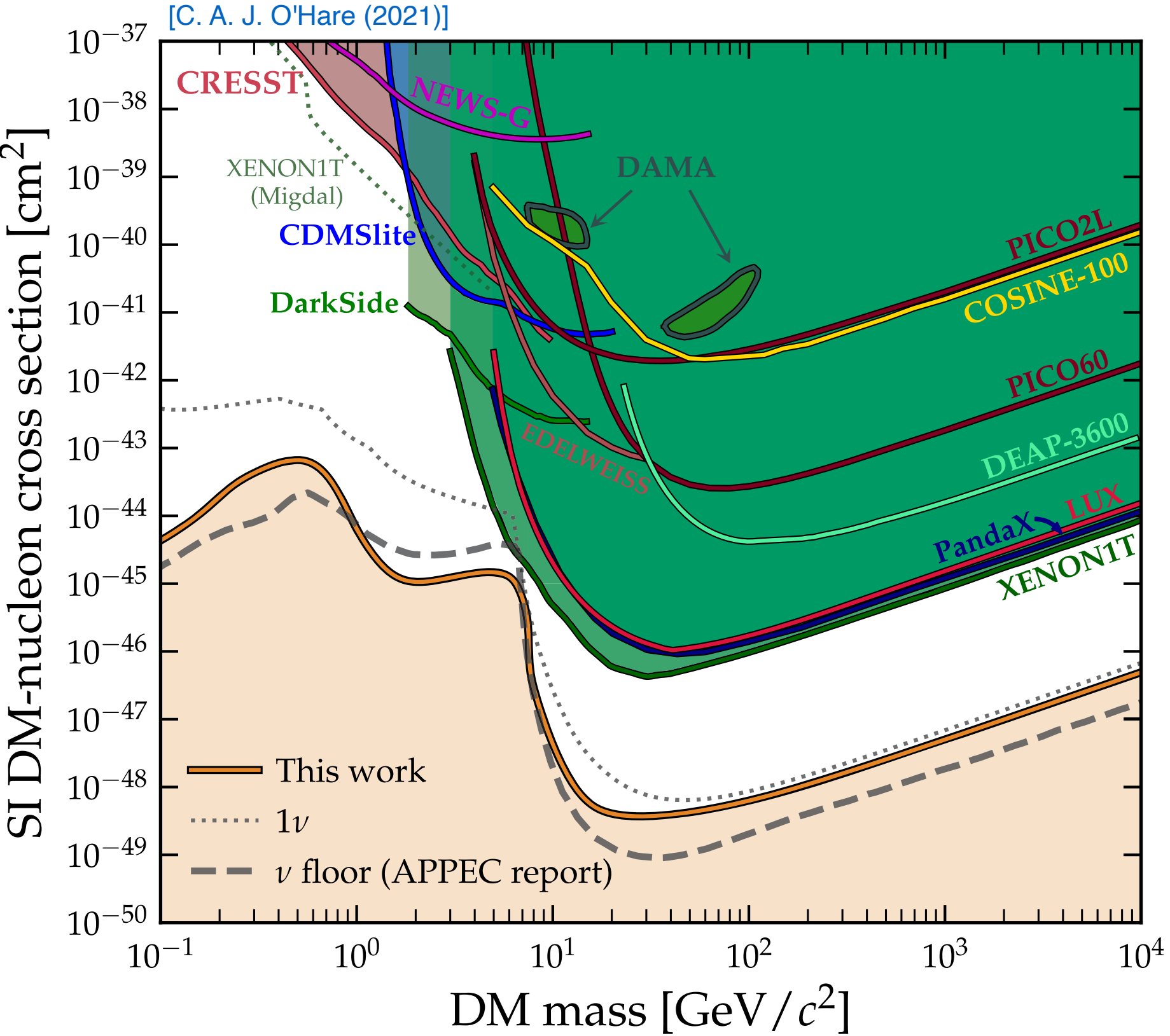
Connection w/ Relativistic theory (e.g. Majorana fermion DM χ)

WIMP-quark $\mathcal{L}_{\text{int}}$	plausible mediator	NREFT basis (LO)	SI/SD	momentum dep.
$\bar{\chi}\chi \bar{q}q$	Scalar	$\mathcal{O}_1 = \mathbf{1}_\chi \mathbf{1}_N$	SI	—
$\bar{\chi}i\gamma^5\chi \bar{q}i\gamma^5q$	Pseudoscalar	$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$	SD	$\mathcal{O}(q^2/(m_\chi m_N))$
$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu\gamma^5q$	Vector	$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	SD	—

Theoretical candidates

WIMP above ν Fog

- Tree-level Z boson exchange: $\sigma_{\text{SI}} \sim 10^{-39} \text{ cm}^2 \gg$ (current bounds)
- Reason for Suppression?
 - **Loop induced process** || (quantum loop suppression) $\lesssim 10^{-2}$
 - **Momentum dependence** || $\mathcal{O}(100) \text{ GeV} : q^2/(m_\chi m_N) \lesssim 10^{-4}$
 - **Spin dependence** || (w/o coherent scattering) $\sim 10^{-4}$



Connection w/ Relativistic theory (e.g. Majorana fermion DM χ)

WIMP-quark $\mathcal{L}_{\text{int}}$	plausible mediator	NREFT basis (LO)	SI/SD	momentum dep.
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$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu\gamma^5q$	Vector	$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	SD	—

1. Electroweak Multiplet Dark Matter (1/3)

Setup

- Definition: DM w/ Electroweak charge → connection w/ BSM scenarios (e.g. Supersymmetry, Extra-dimension)
 ✱ Electroweak Symmetry: $SU(2)_L \times U(1)_Y$, DM stability should be realized by other symme.

- Feature 1: Correct DM energy density is explained for **TeV scale DM**

$$\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s} \simeq \alpha_2^2 / m_{\text{DM}}^2 \Rightarrow m_{\text{DM}} \simeq \mathcal{O}(1) \text{ TeV} \quad \alpha_2: SU(2)_L \text{ fine structure const.}$$

- Feature 2: **Small mass splitting** btw electroweak multiplets

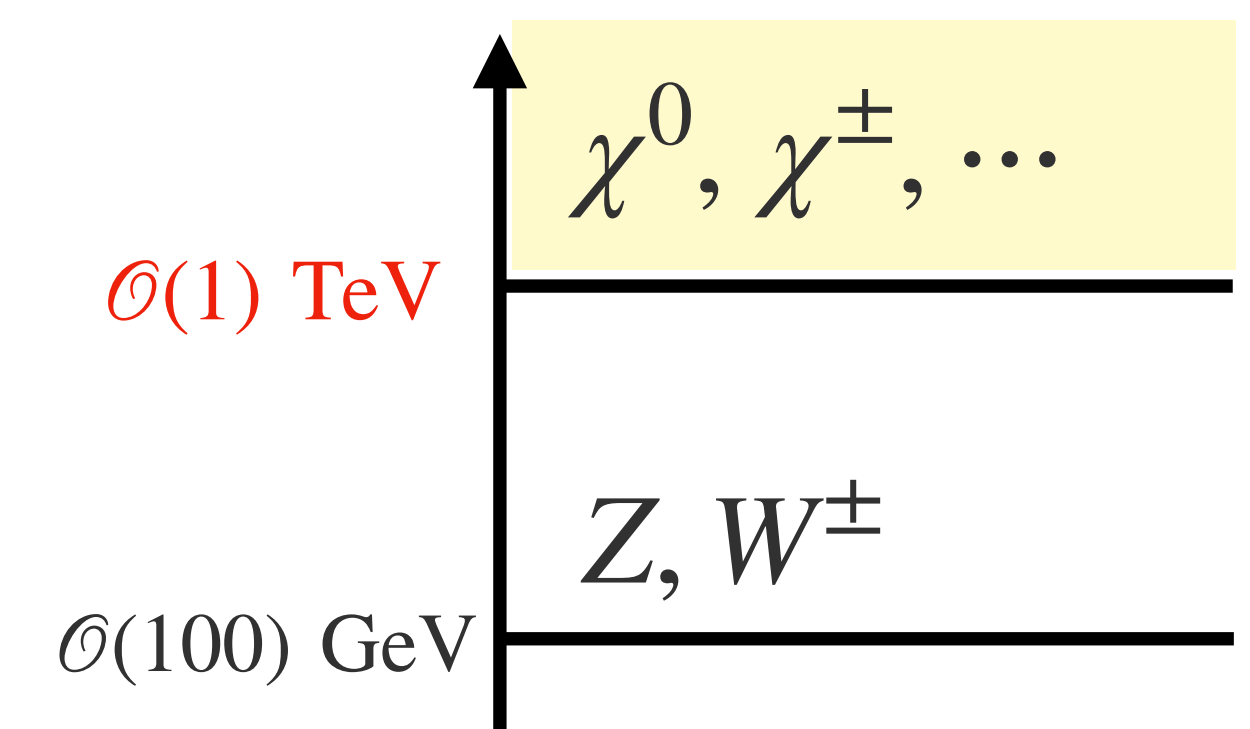
$$\Delta M_{\text{EW}} \simeq \alpha_2 m_W \simeq \mathcal{O}(100) \text{ MeV}$$

(Radiative correction, assuming $m_{\text{DM}} \gg m_W$)

Interaction for $SU(2)_L$ n -plet w/ Hypercharge Y :

$$\mathcal{L}_W = \frac{g_2}{4} \sqrt{n^2 - (2Y + 1)^2} \bar{\chi}^0 \gamma^\mu \chi^- W_\mu^+ + \frac{g_2}{4} \sqrt{n^2 - (2Y - 1)^2} \bar{\chi}^0 \gamma^\mu \chi^+ W_\mu^- + \text{h.c.}$$

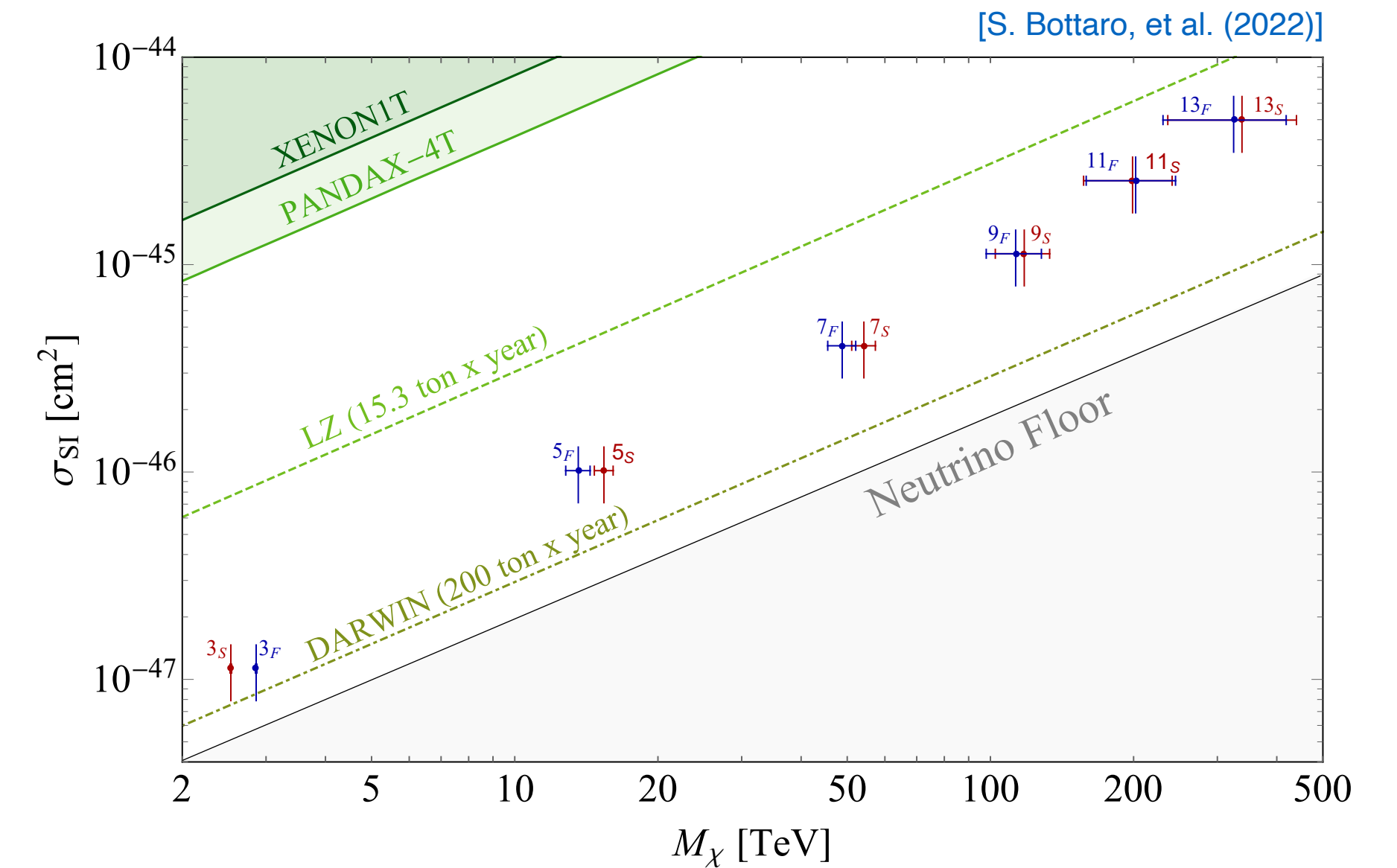
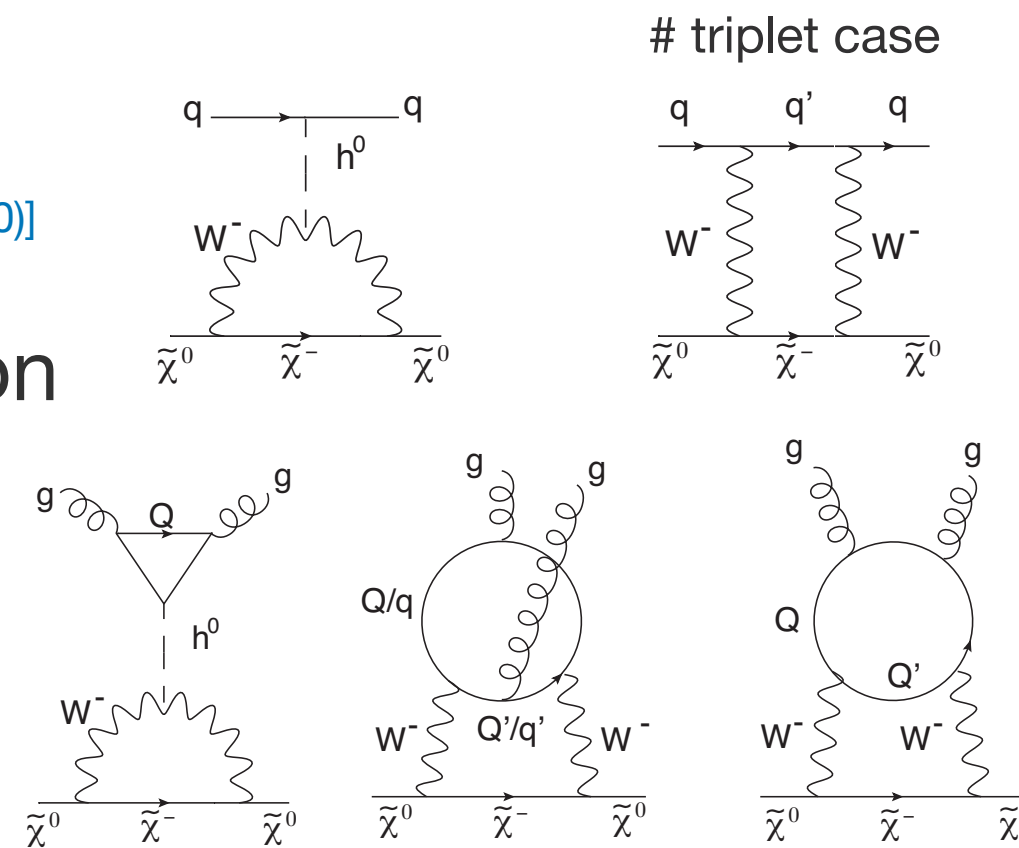
$$\mathcal{L}_Z = -i \frac{g_2}{\cos \theta_W} Y \bar{\chi}^0 \gamma^\mu \chi^0 Z_\mu \quad (\text{for } Y \neq 0 \text{ only})$$



1. Electroweak Multiplet Dark Matter (2/3)

Direct detection ($Y = 0$)

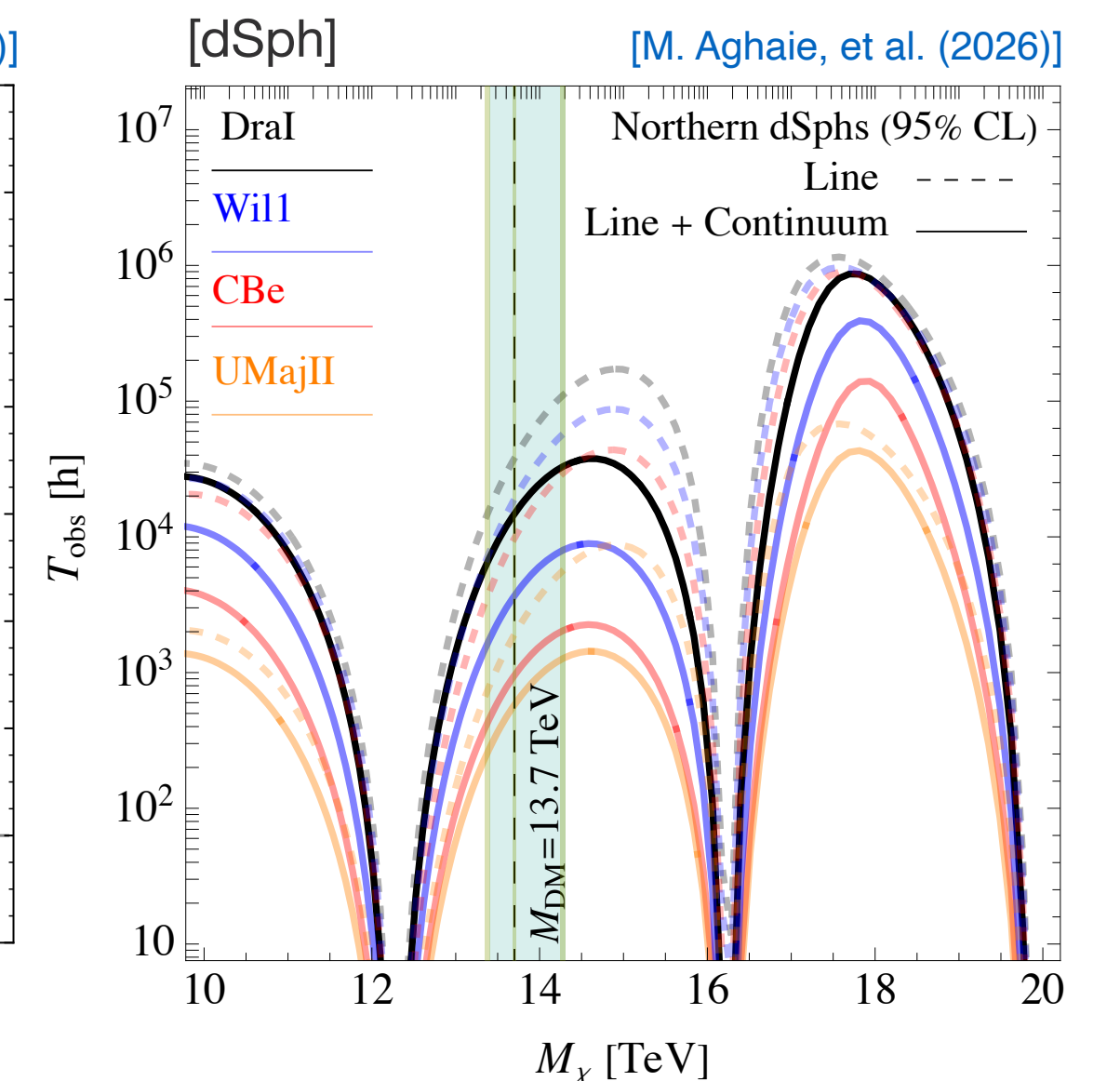
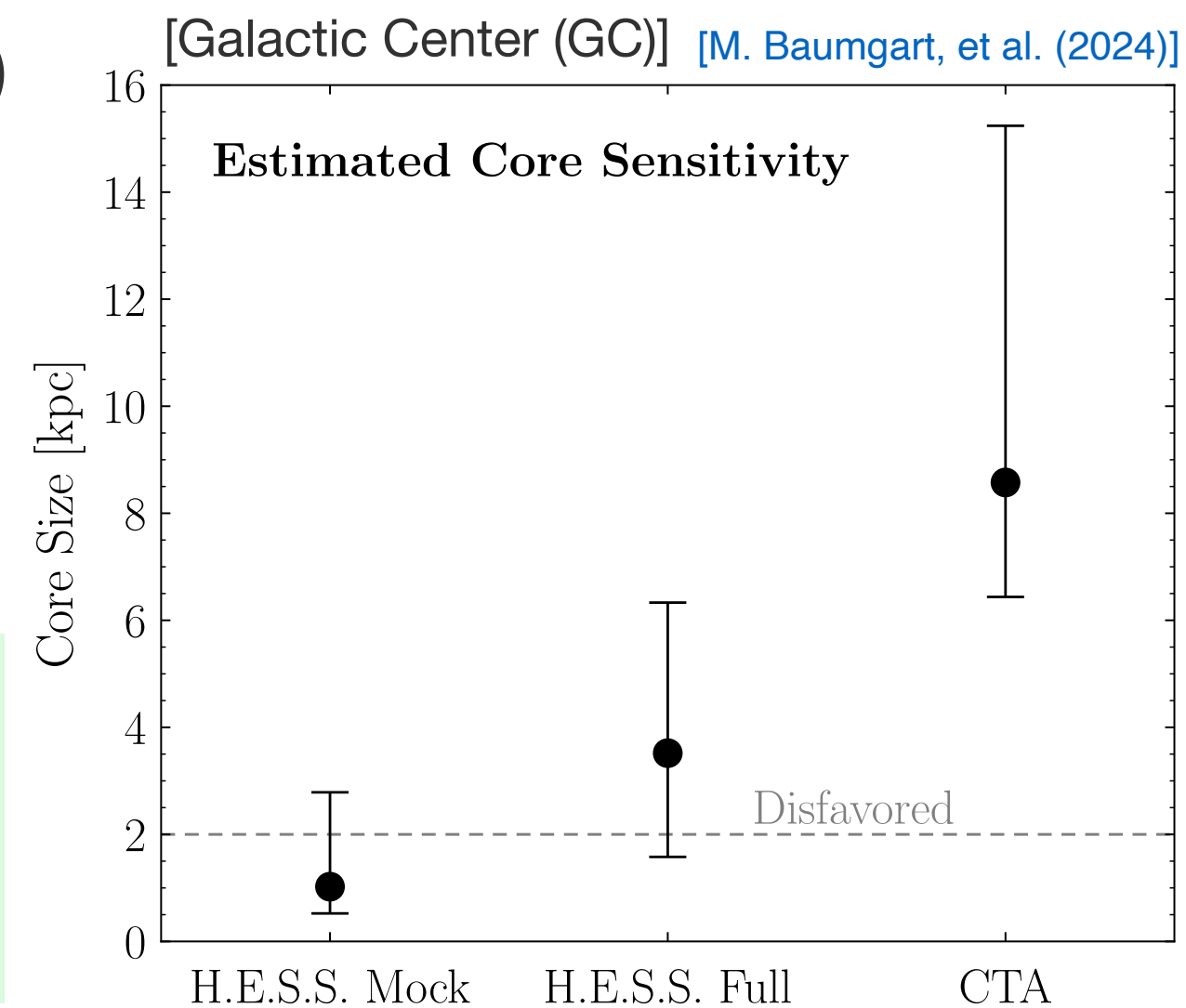
- SI & SD cross sections **via loop** [J. Hisano, et al. (2010)]
- Cancellation in effective coupling w/ nucleon
 - $\sigma_{\text{SI}} \sim \mathcal{O}(10^{-48} - 10^{-46}) \text{ cm}^2$
- Candidates are **above ν fog**



Indirect detection (5-fermion, $Y = 0$)

- GC : Constraint by H.E.S.S. (depending on core size)
- dSph : 95% CL limit @CTAO w/ $\mathcal{O}(10^3)$ h obs.
 - Coma Berenices || ~ 1000 hours
 - Willman || ~ 3700 hours

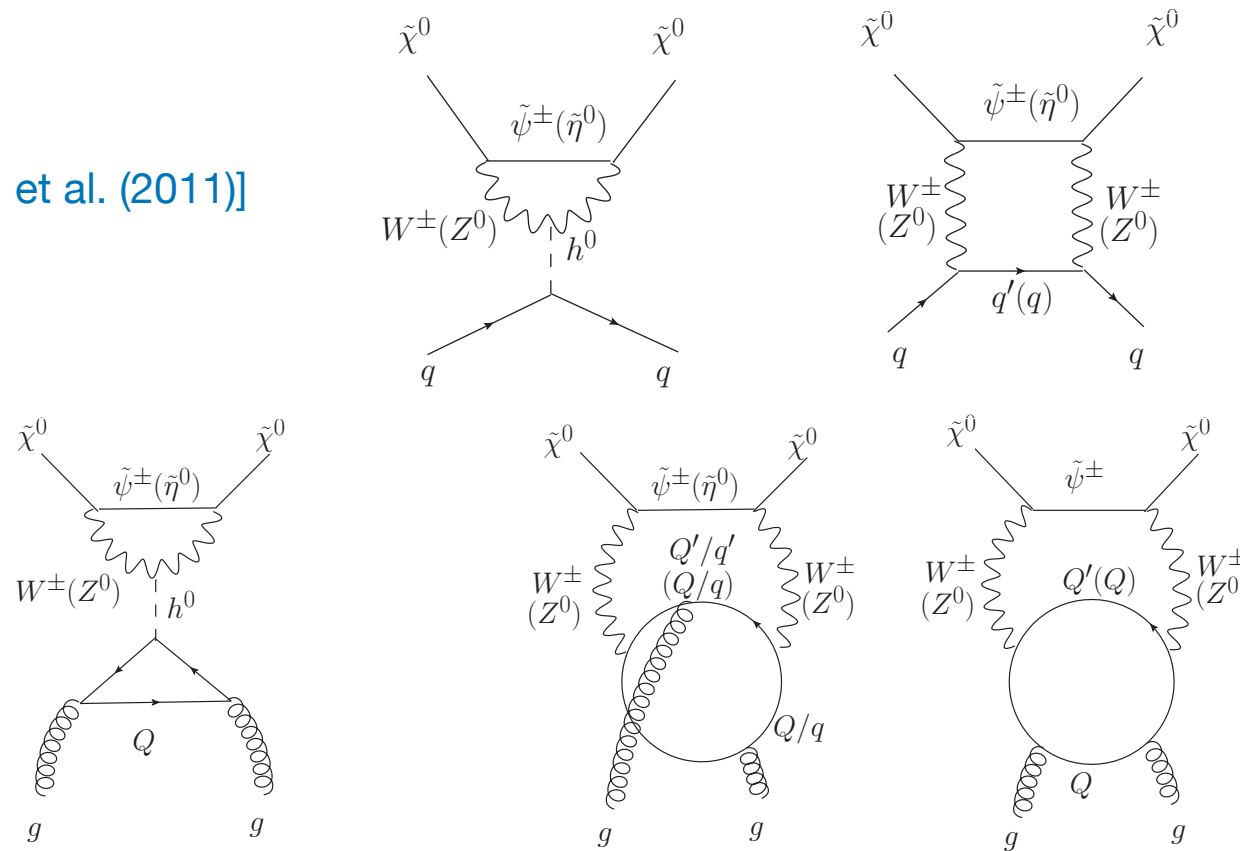
Direct : Probe loop-scattering above ν fog
Indirect: Crosscheck @CTAO (GC & dSph)



1. Electroweak Multiplet Dark Matter (3/3)

Direct detection ($Y \neq 0$)

- SI & SD cross sections **via loop** [J. Hisano, et al. (2011)]
- New contribution of neutral partner w/ Z boson exchange
- Some candidates are **below ν fog**



Complementary probes

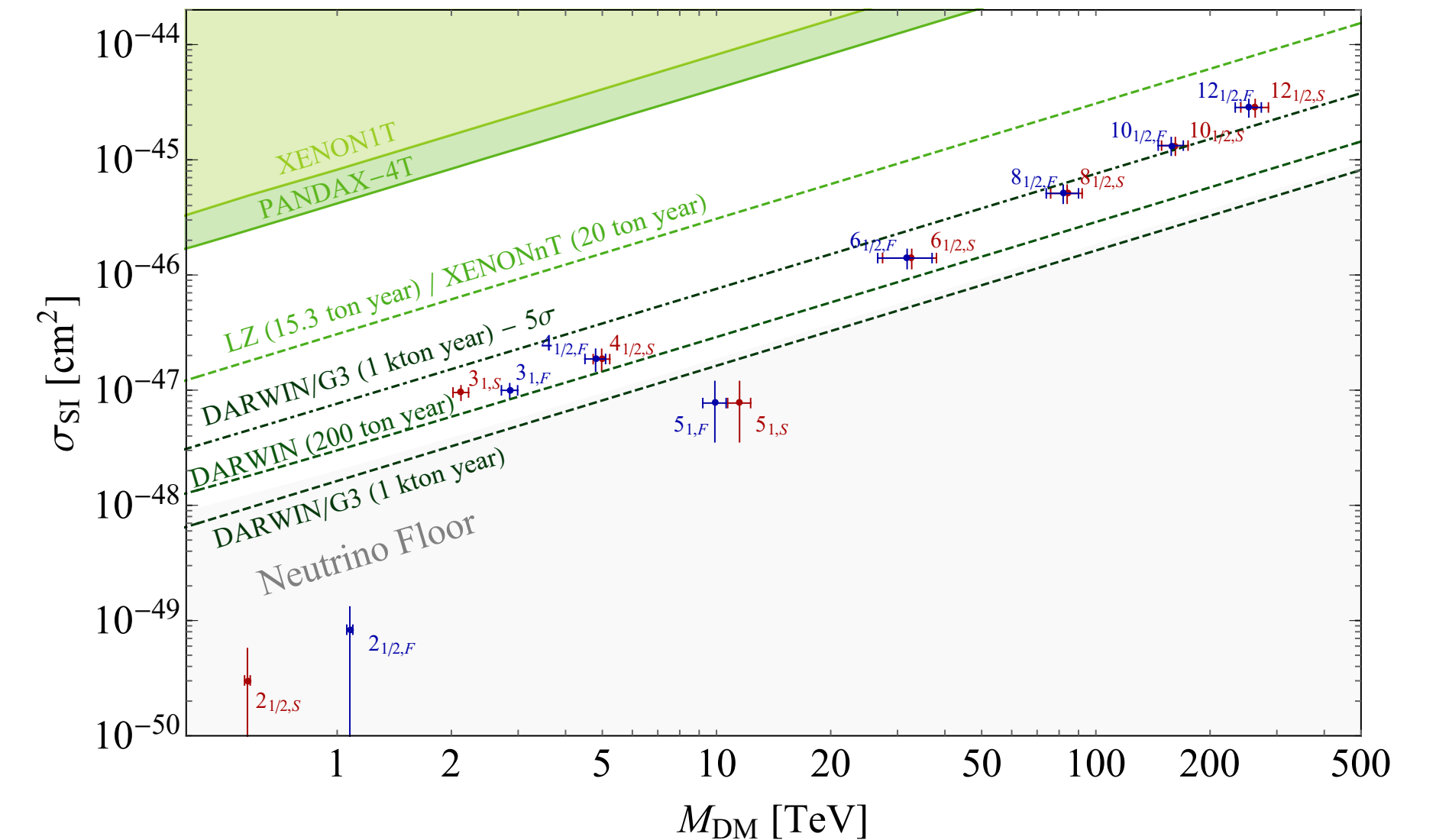
- Indirect: Estimation of CTAO discovery → within decades
- Precise measurements

Kiyoto Ogawa [E01] (publicly offered research) || p35
Full 3-loop EW multiplet contributions to the electron Electric Dipole Moment

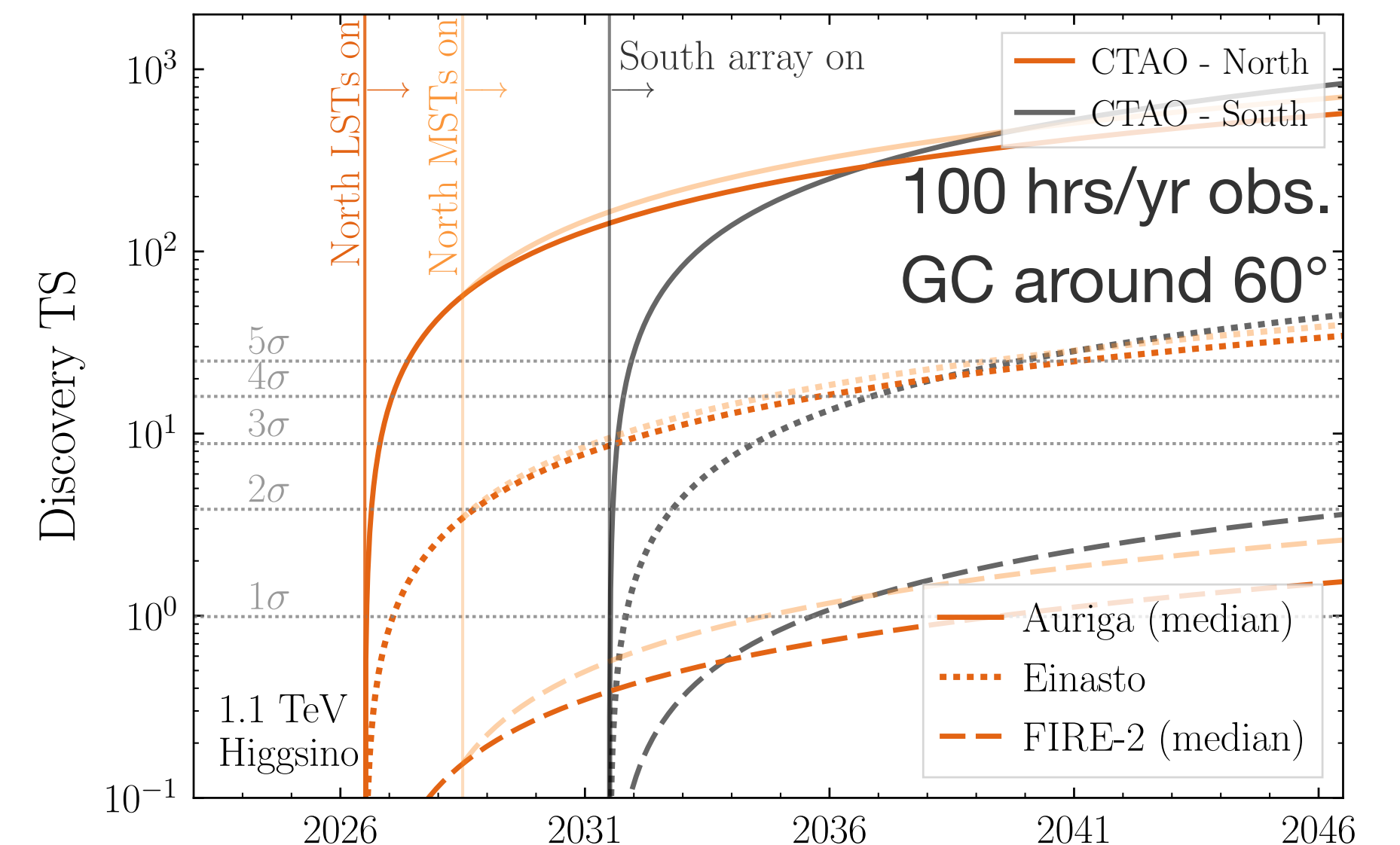
Above ν fog: future direct detections

Below ν fog: combined search-strategy is necessary

[S. Bottaro, et al. (2022)]



[S. Abe, et al. (2026)]



2. Pseudo-Nambu-Goldstone DM

[C. Gross, O. Lebedev, T. Toma (2017)]

Direct detection

- Setup : DM = pseudo-Nambu-Goldstone boson

- Tree-level: **Momentum-suppressed**

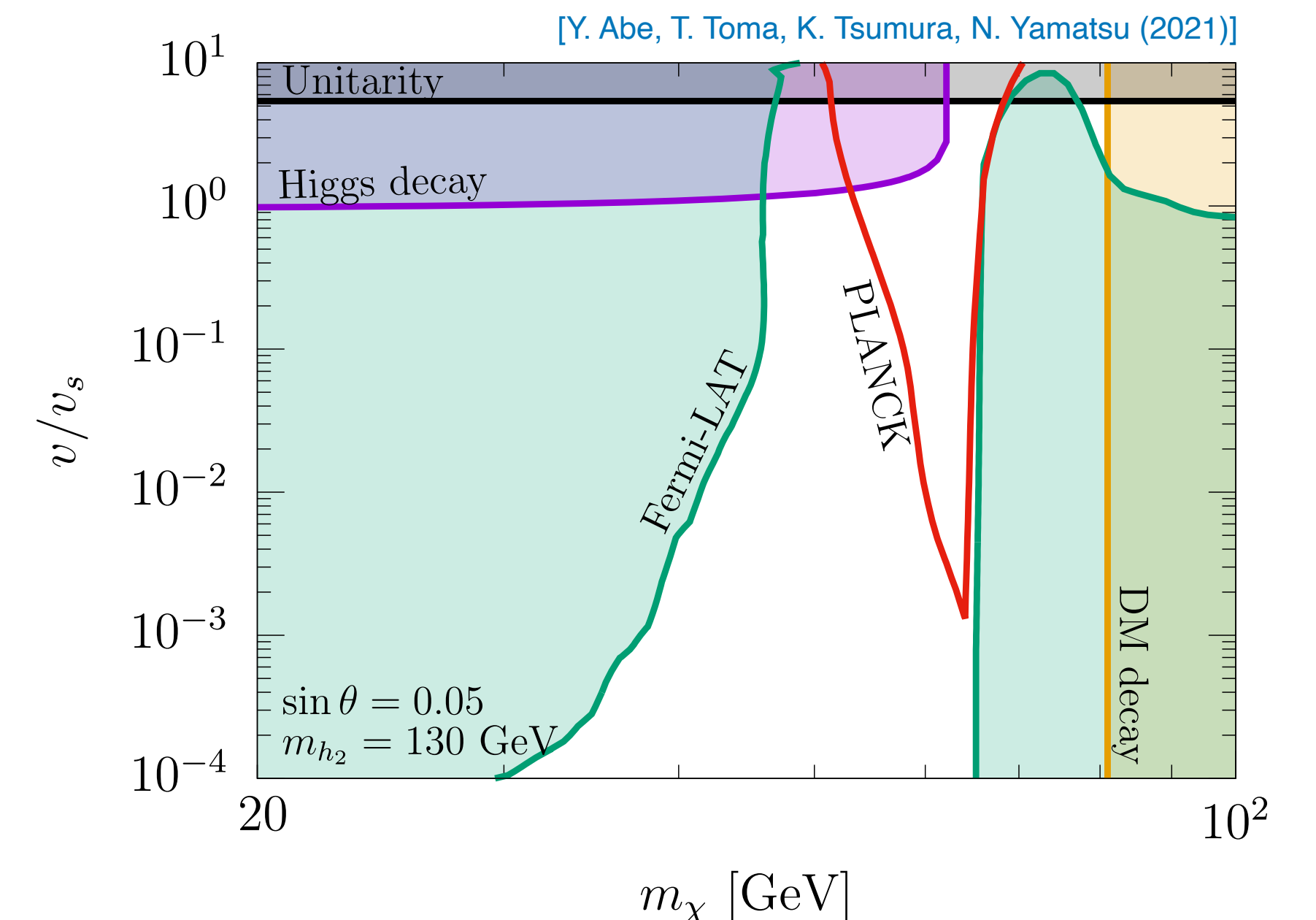
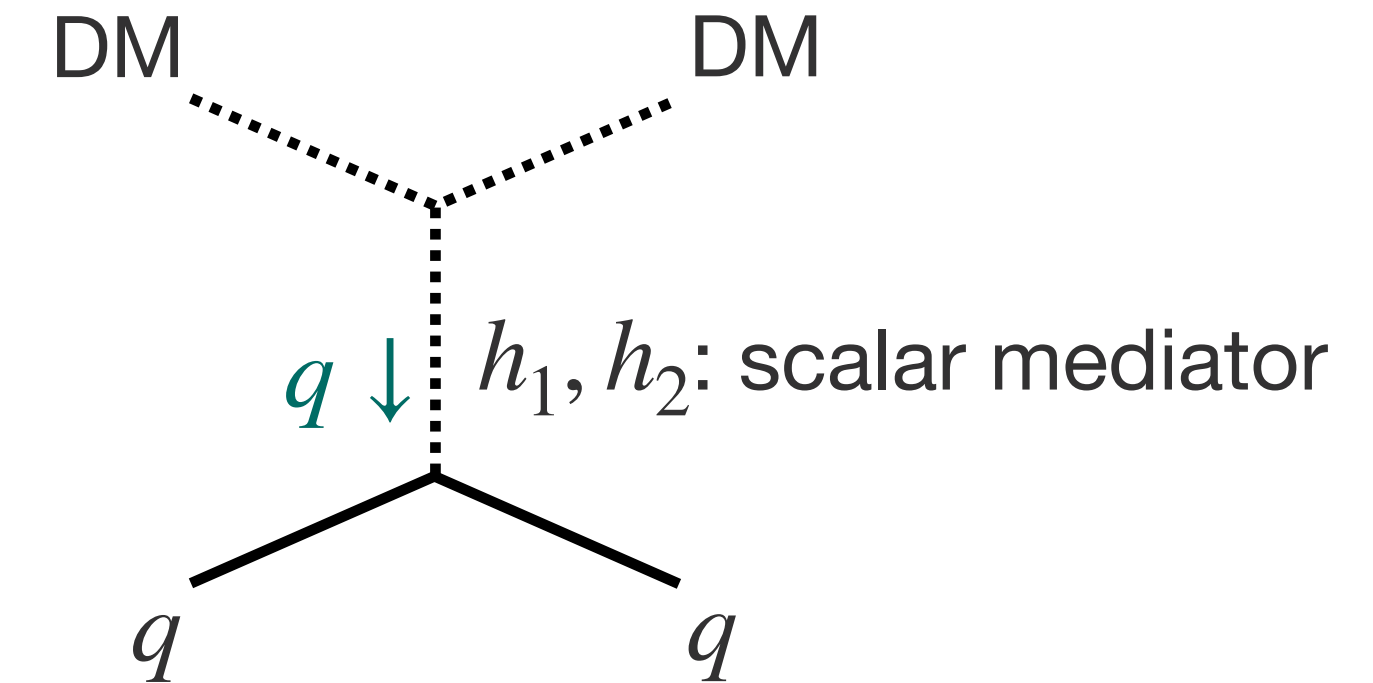
$$\mathcal{M} \propto \left(\frac{m_1^2}{t - m_1^2} - \frac{m_2^2}{t - m_2^2} \right) \sim \frac{m_2^2 - m_1^2}{m_1^2 m_2^2} t + \mathcal{O}(t^2) : \mathcal{O}(q^2/(m_\chi m_N))$$

- Loop-level: w/o q^2 -suppression (via soft breaking effect) [K. Ishiwata, T. Toma (2018)]

Status & Prospect

- Possible connection:
 - Gauged $U(1)_{B-L}$ symmetry [Y. Abe, T. Toma, K. Tsumura (2020)]
 - GUT inspired scenario w/ $SO(10)$ symmetry [Y. Abe, T. Toma, K. Tsumura, N. Yamatsu (2021)]
- Decaying Dark Matter signature via kinetic mixing

Complementary probe: Indirect (incl. decay) & Higgs decay



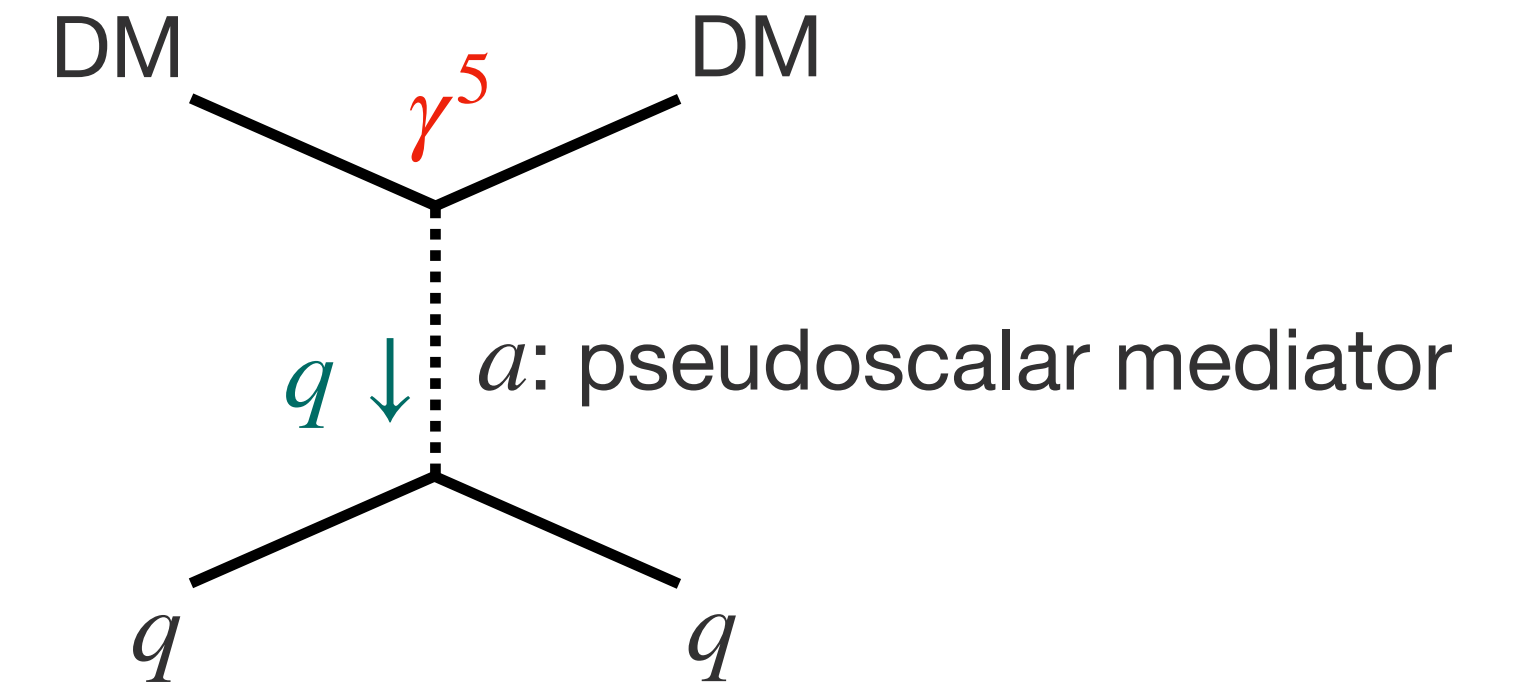
3. Pseudoscalar-portal DM

[S. Ipek, D. McKeen, A. E. Nelson (2014)]

Direct detection

- Setup : Pseudoscalar mediator & fermion DM
- Tree-level:
 - **Momentum suppressed**
 - **Spin-Dependent (SD)**
- Loop-level: Spin-Independent (SI) scattering (cf. $(\gamma^5)^2 = 1$)

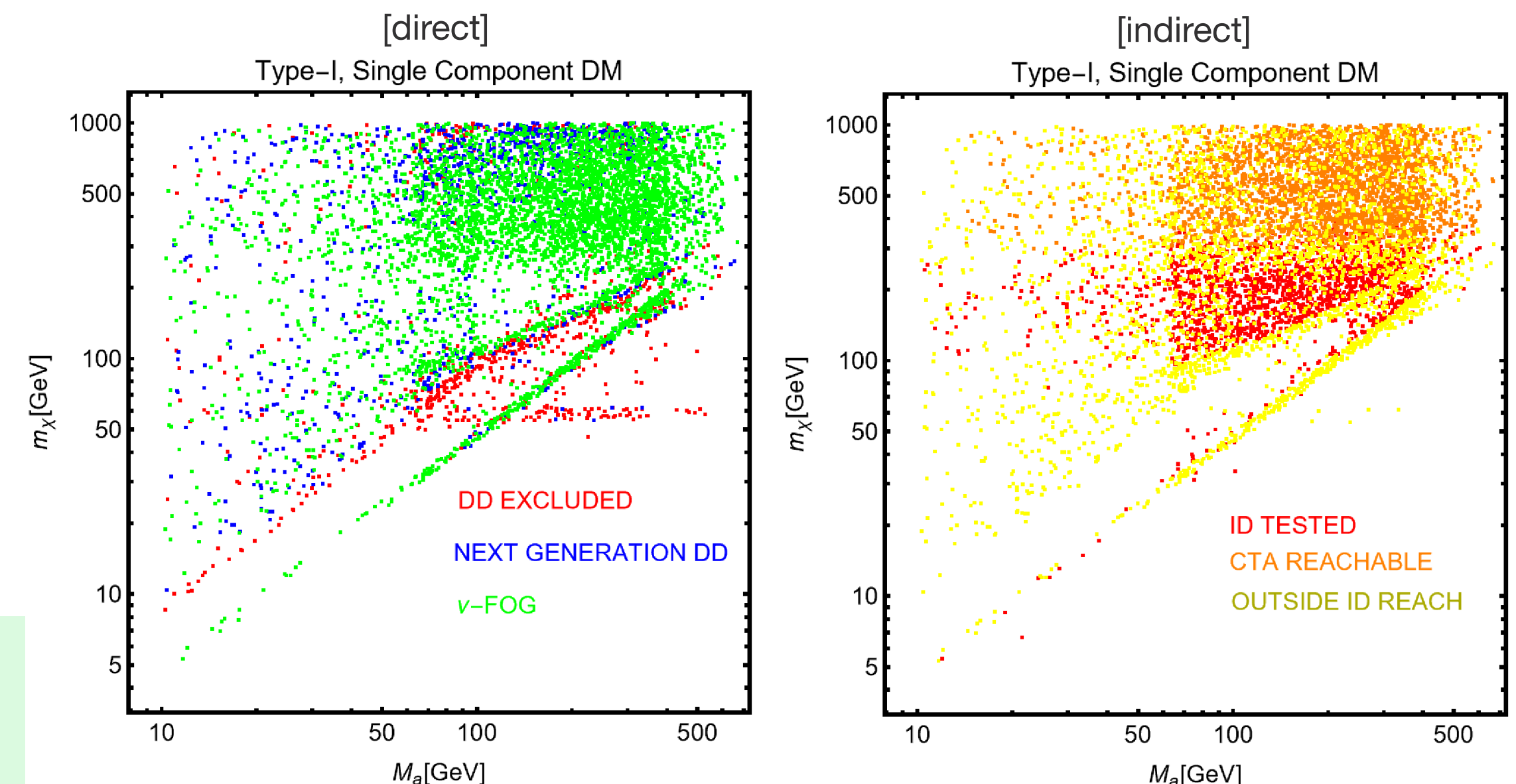
$$\mathcal{M} \propto (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}) \quad (\text{NR limit})$$



Status & Prospect

- Benchmark model for collider analysis
[T. Abe, et al. (2018)] [S. Argyropoulos, et al. (2024)]
- Parameter scan: direct v.s. indirect
[G. Arcadi, et al. [2606.23457]]
- Loop induced σ_{SI} from EFT
[N. Bell, et al. [2609.12336]]

Next-gen. (in)direct detection will be good probe





Non-relativistic scattering of Dark Matter @**TeV** scale

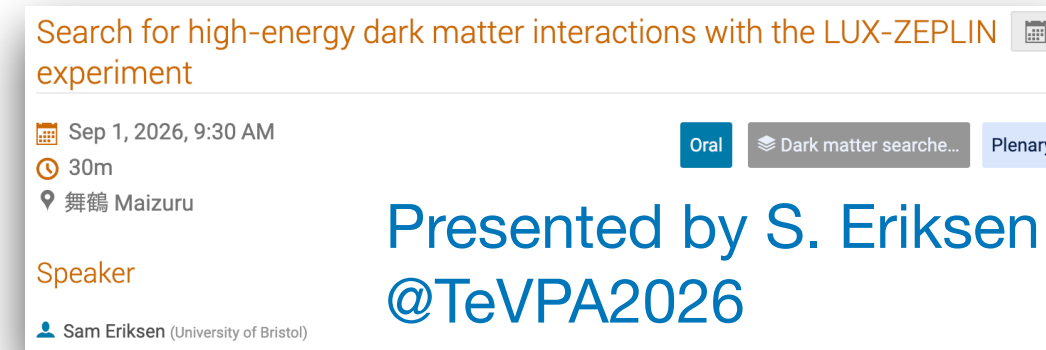
Beyond conventional WIMP search

1. **High energy** scattering
2. **Sub-GeV** Dark Matter

1. High energy scattering

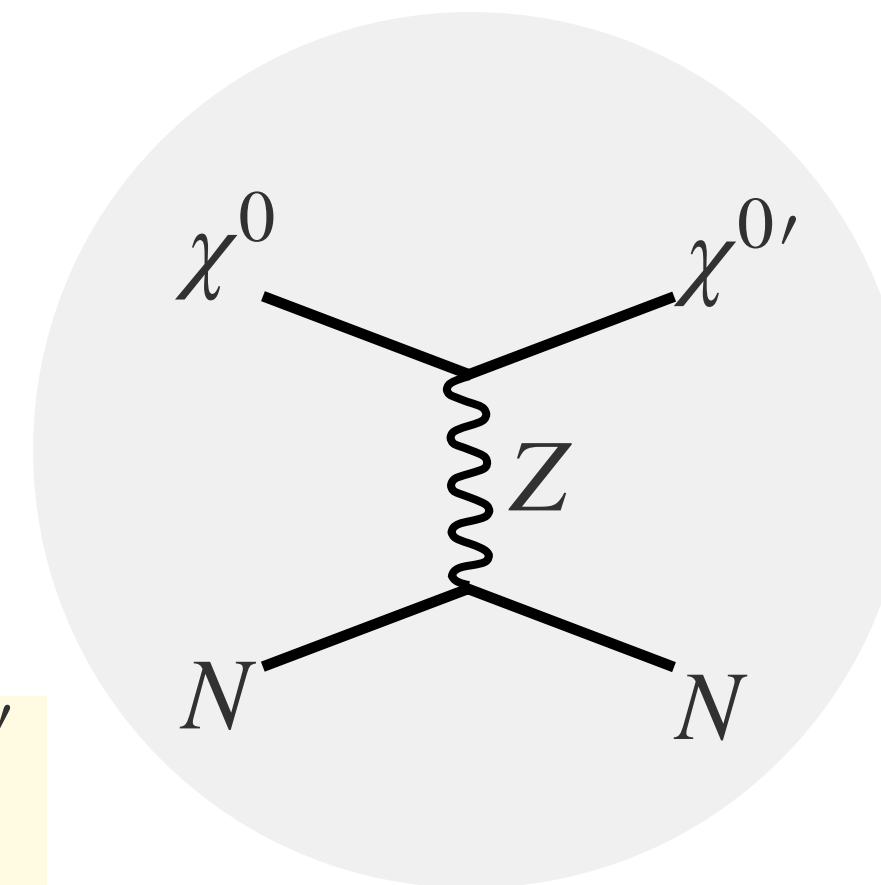
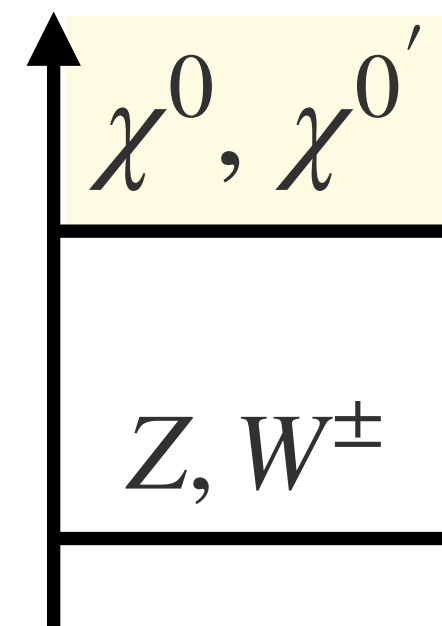
LZ event

- Dark Matter search w/ extended window of nuclear recoil energy
- Analyzed w/ NREFT
 - Exposure : 2.84 tonne-years
 - Recoil energy : $248 \pm 23(\text{stat}) \pm 23(\text{sys})$ keV

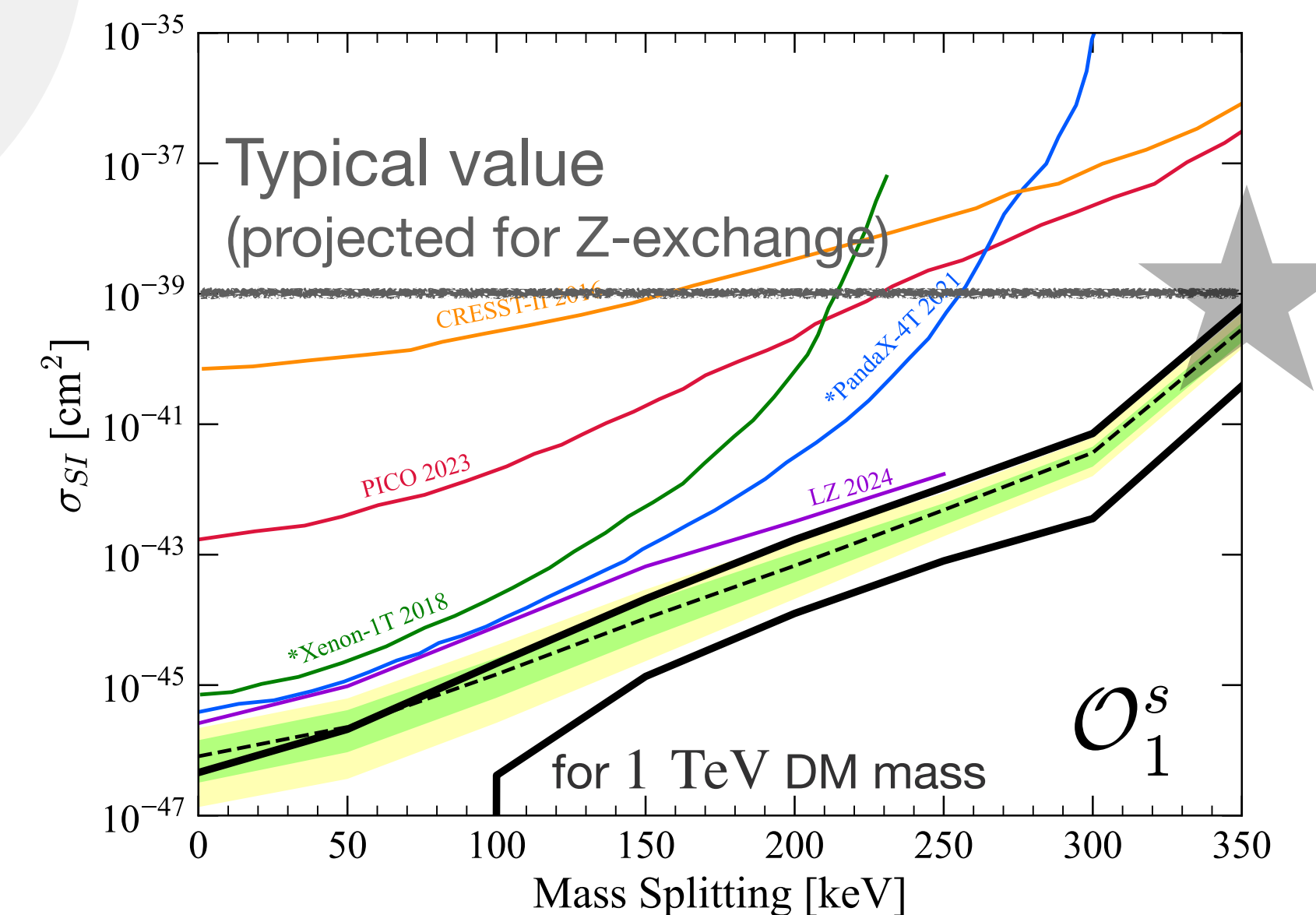
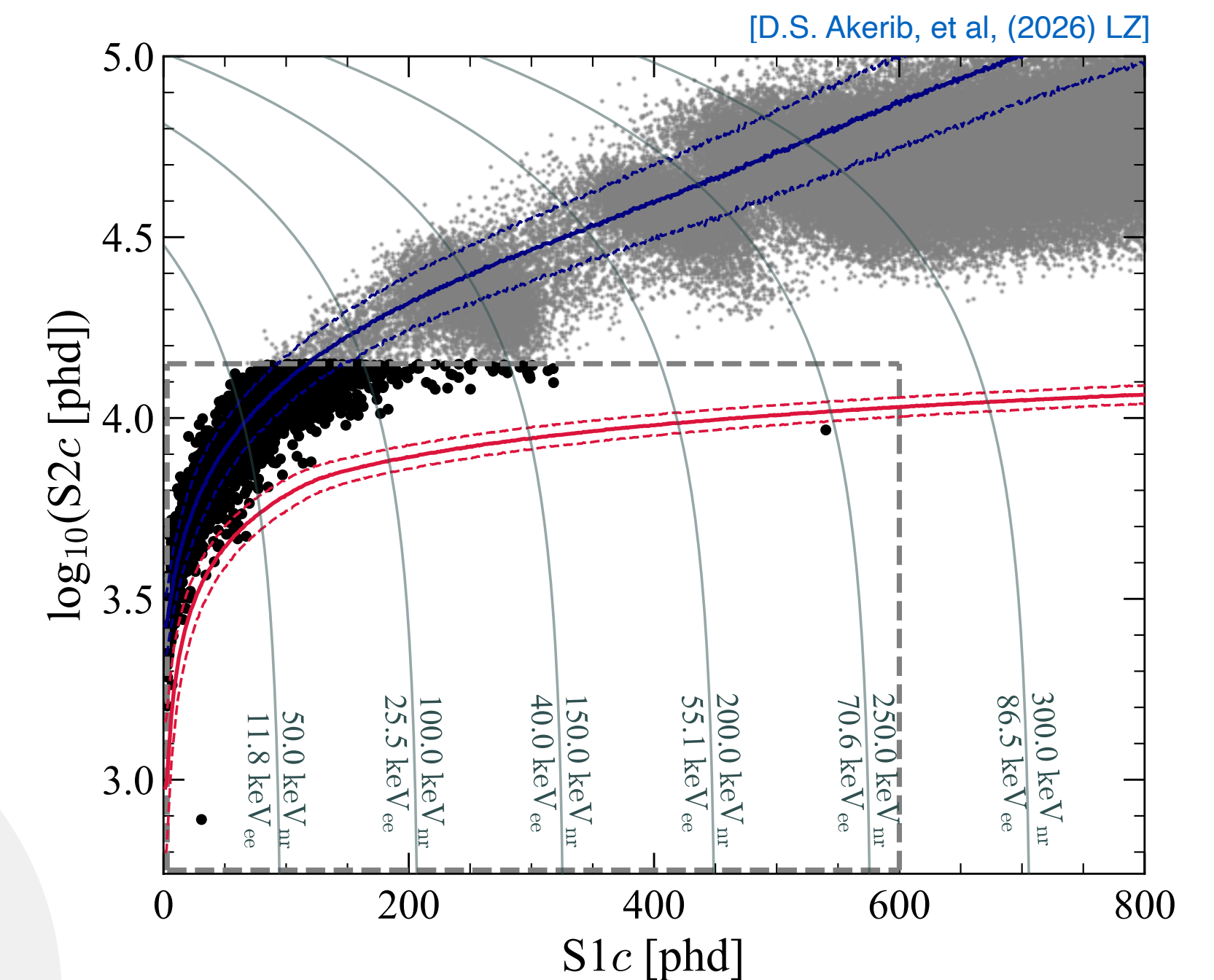


Inelastic scattering

- Higgsino ($SU(2)_L$ doublet, Majorana fermion)
 - Thermal mass: 1.1 TeV
 - Associate neutral partner (mass splitting δ)



LZ high energy event → Inelastic scattering?



Solar capture & IceCube bound (1/2) [2609.02775]

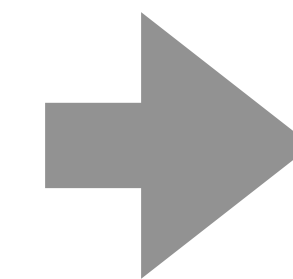
Terrestrial reach for mass splitting

- Accessible range of δ
→ fixed by kinematics (v.s. energy injection)
- Accessibility @underground detector
 - Limited by DM speed : $v \sim 230$ km/s (average @Milky Way)
 - Limited by target mass : $\mu_T \sim m_T \sim 130 m_p$ (Xenon target)

Mass splitting

Energy injection by DM

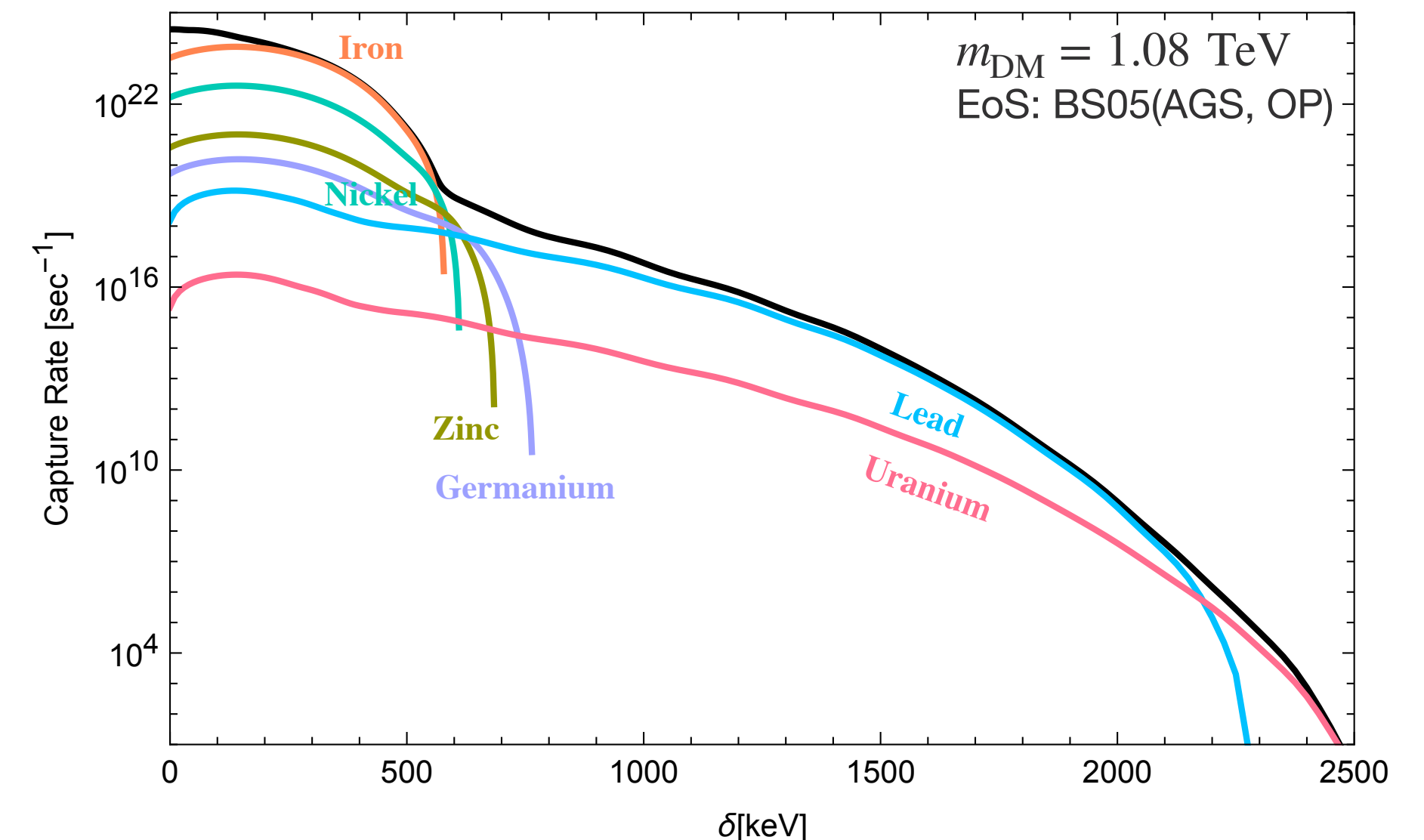
$$\delta \lesssim \frac{\mu_T v^2}{2}$$



Accessible for $\delta \lesssim 360$ keV

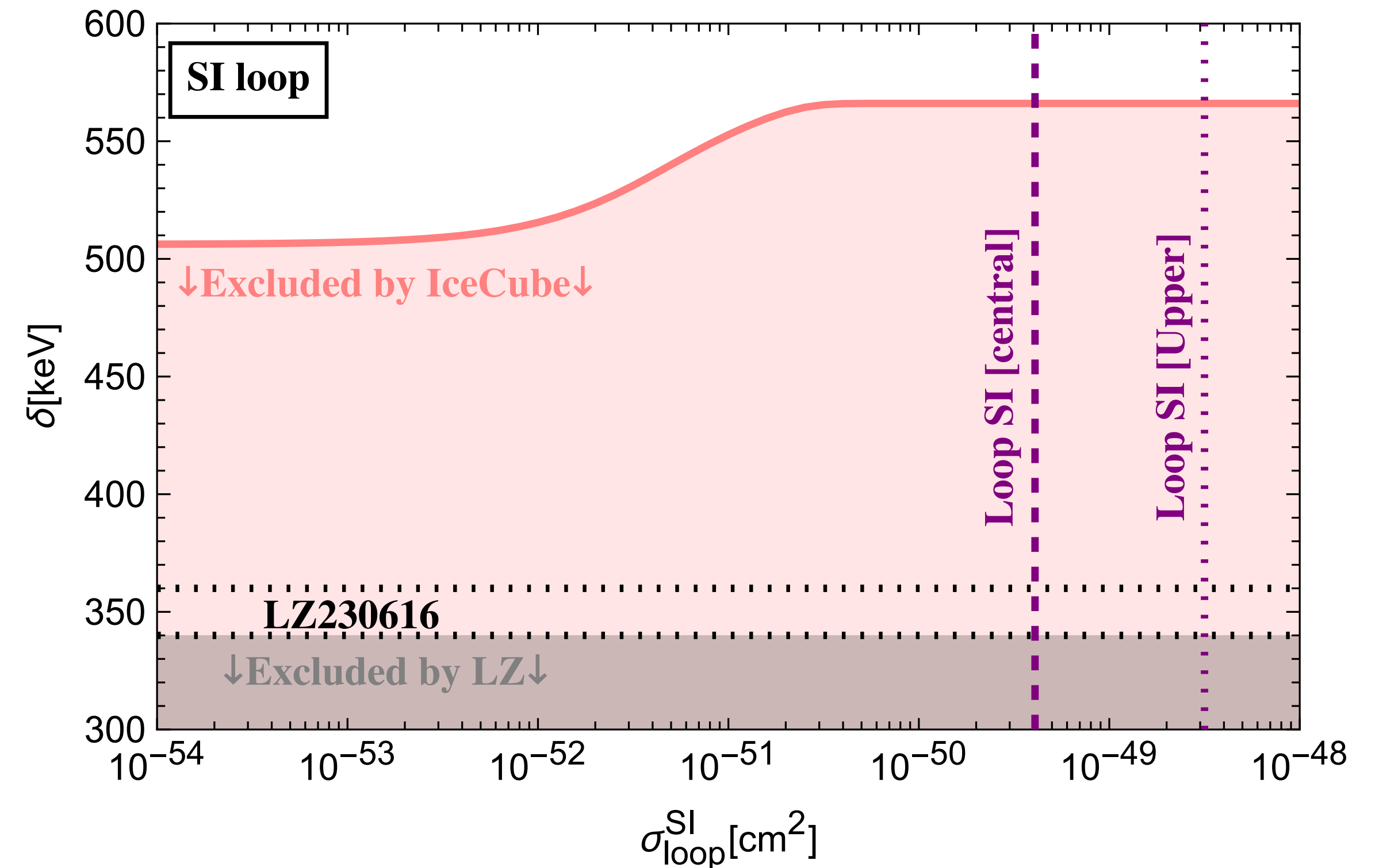
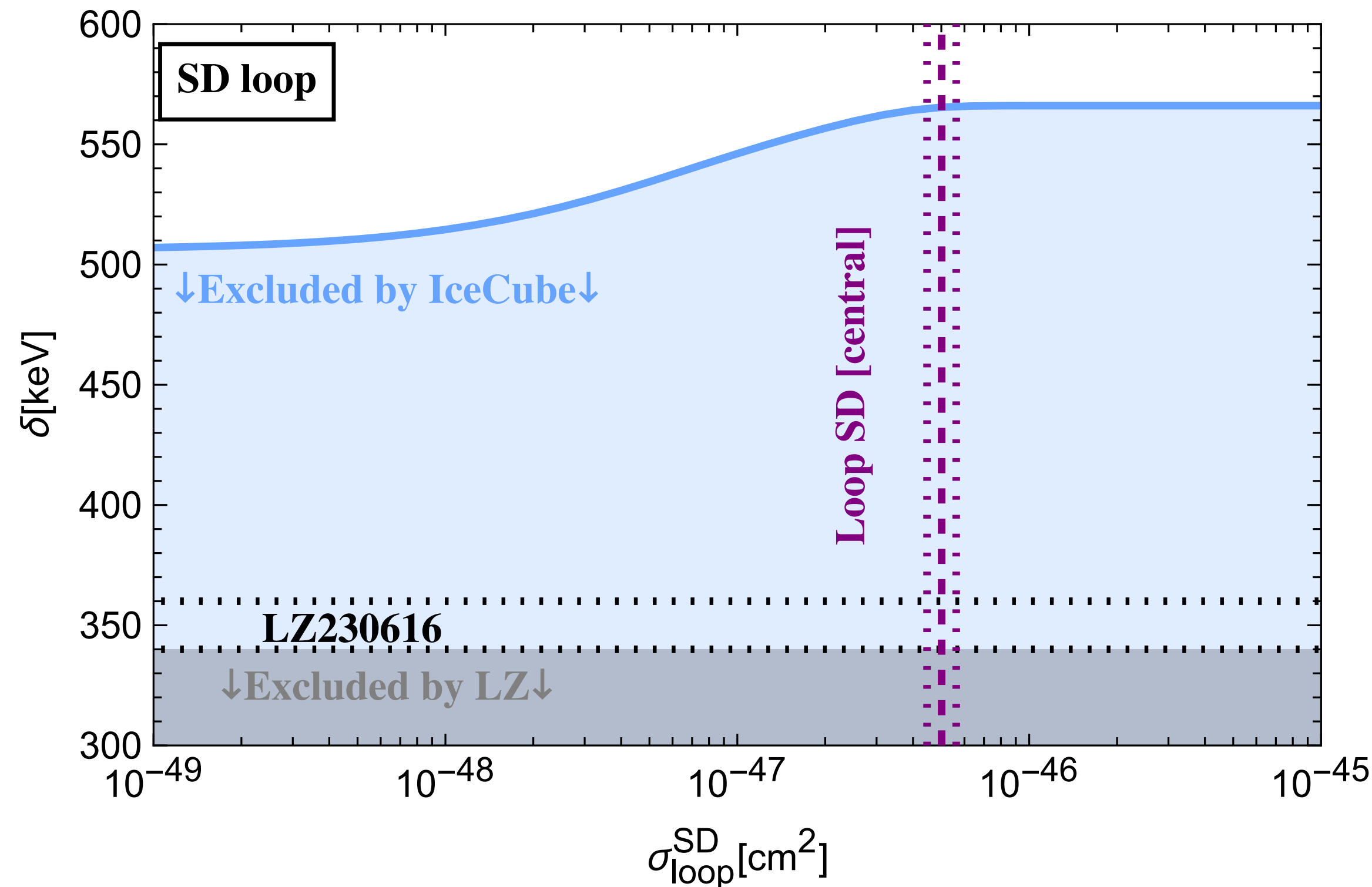
Solar capture

- The Sun can be **suitable target for inelastic scattering**
 - Maximum velocity : ~ 1300 km/s around core
 - Various targets : Fe(56), Ni(58), Zn(65), Ge(73), Pb(208), ...
- DM annihilation rate is fixed by Capture rate @equilibrium
→ **Constrained by TeV neutrino search @ IceCube** [2507.08457]



Solar capture & IceCube bound (2/2) [2609.02775]

Result



1 TeV Higgsino explanation for LZ ($\delta \sim 350$ keV)

→ Severe bound due to annihilation & loop-induced elastic scattering properties

Higgsino Parameter space [2609.01504]

- Standard Halo Model: Simplest option for DM analysis

$$f(\vec{v}) \propto e^{-v^2/v_0^2} \times \theta(v_{\text{esc}} - v), \quad (v_0 = 220 \text{ km/s}, v_{\text{esc}} = 540 \text{ km/s})$$

- Parameter fitting for LZ event (w/ inelastic interpretation)
→ **Highly depends on DM velocity distribution**

- Revisited fitting:

- Standard halo model (SHM) : $\delta = 340 - 360 \text{ keV}$
- Int. btw Milky Way & Large Magellan Cloud (LMC) : $\delta = 480 - 500 \text{ keV}$

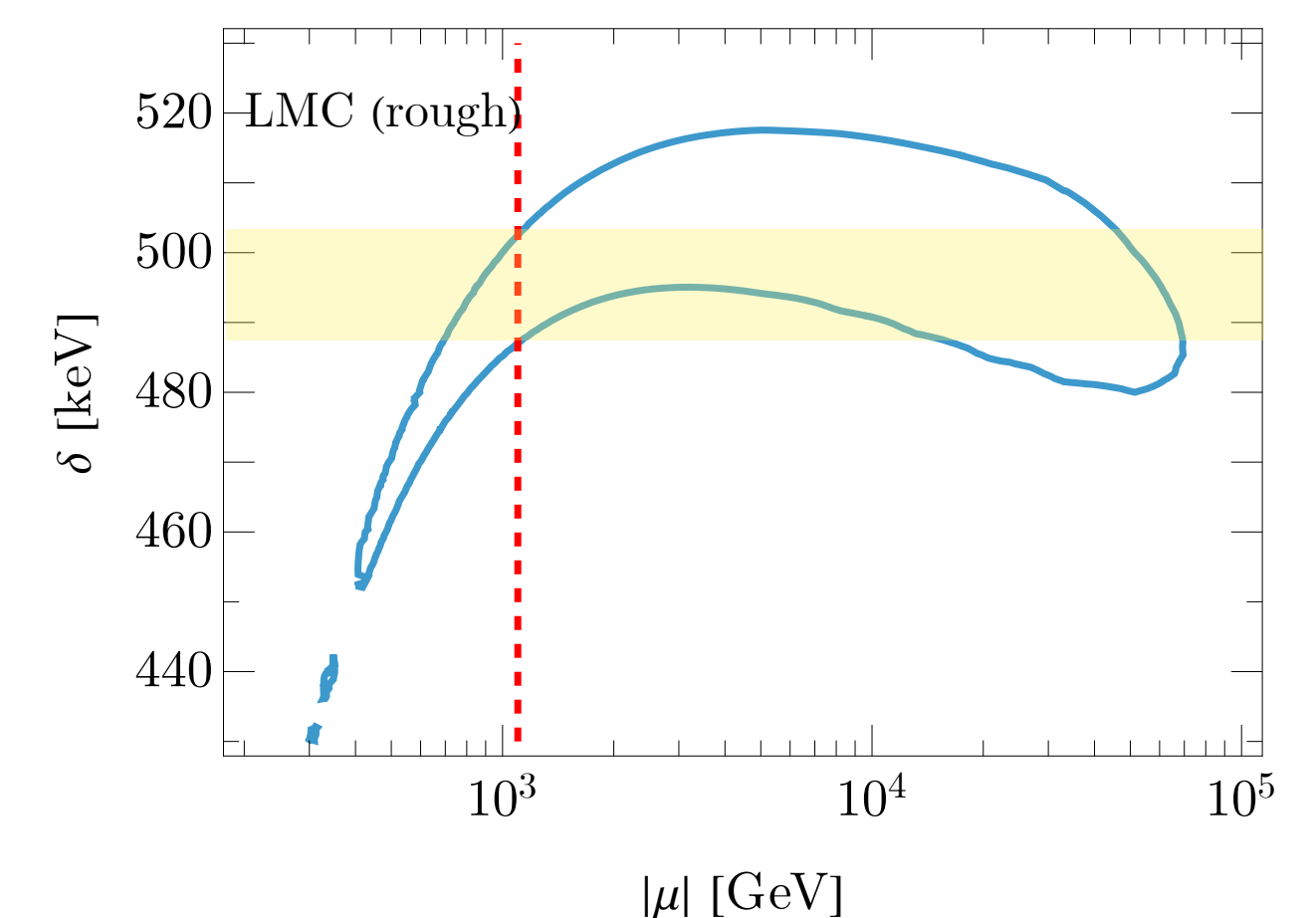
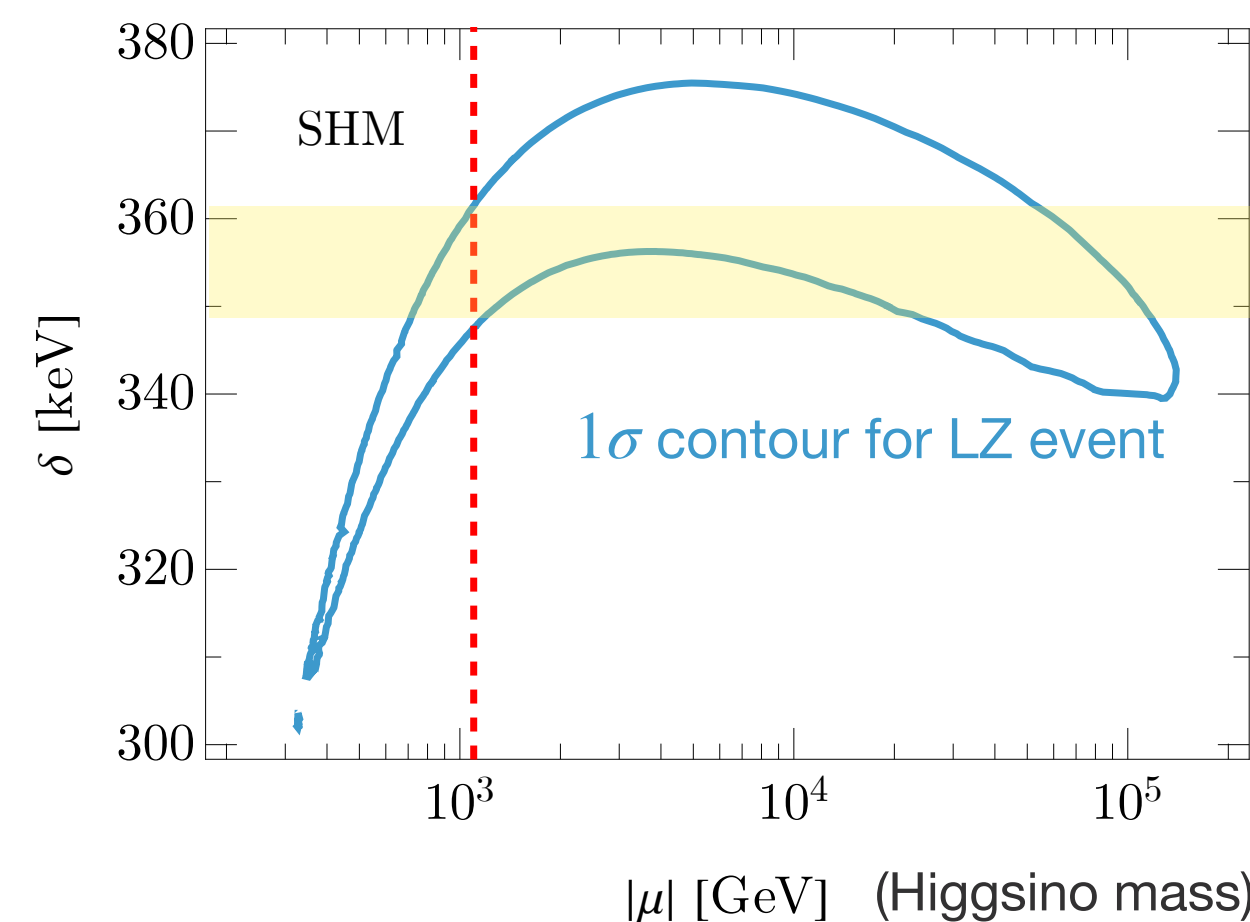
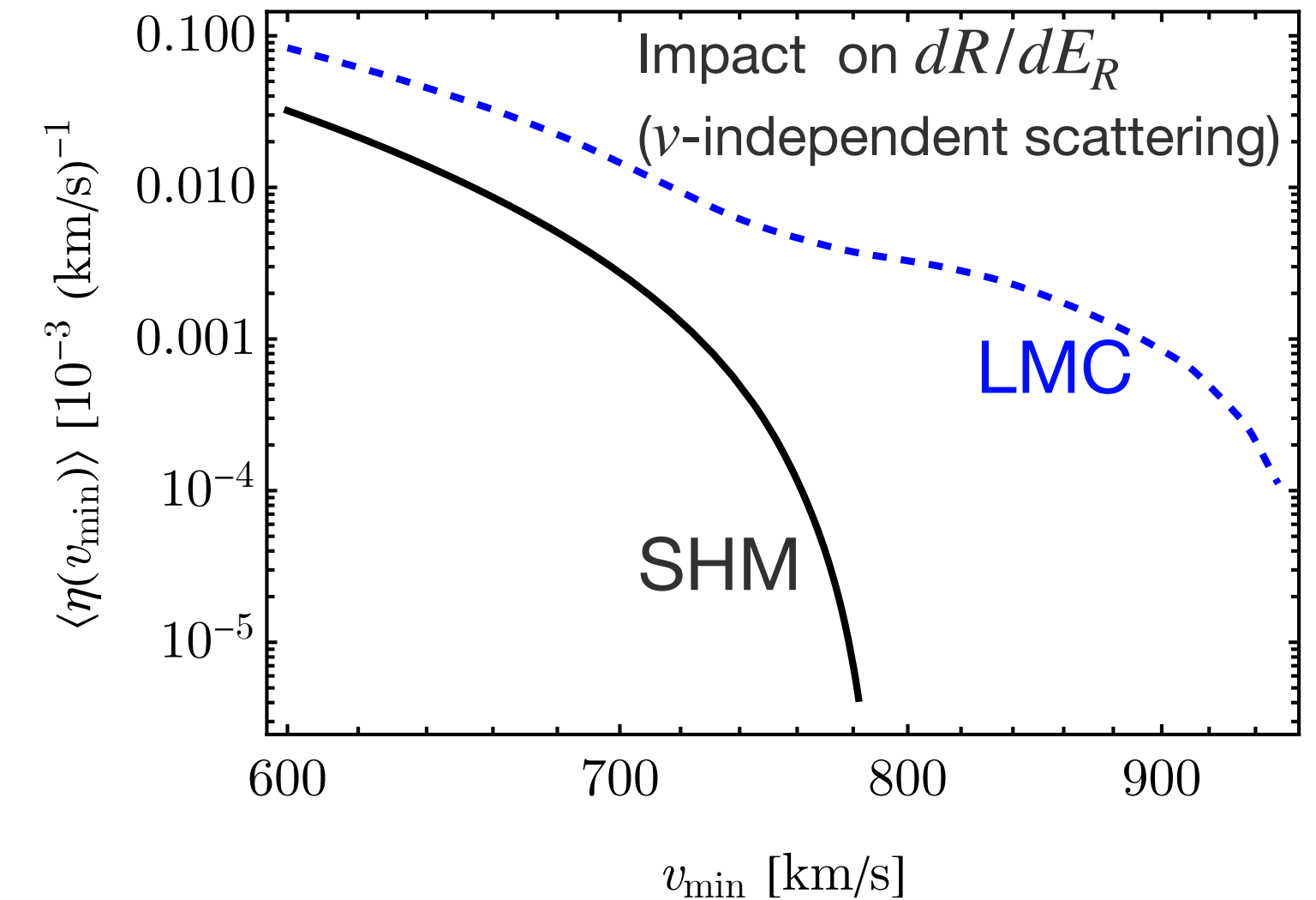
- Annihilation constraints:

- IceCube : $\delta > 566 \text{ keV}$
- γ -ray : to be checked near future @CTAO

Crucial for inelastic interpretation:

- High-speed tail of DM
- Annual modulation

$$\eta(v_{\text{min}}, t) = \int_{v > v_{\text{min}}} d^3v \frac{1}{v} f^{\text{gal}}(\vec{v} + \vec{v}_e(t))$$



Elastic scattering? (1/2)

Operator analysis [D.S. Akerib, et al, (2026) LZ]

- Local significance for NREFT leading-order operators

► **SI operator:** $\mathcal{O}_1 = \mathbf{1}_\chi \mathbf{1}_N$

- Spectrum concentrate on low- E_R
(cf. $q|_{E_R=248 \text{ keV}} \sim 200 \text{ MeV} \sim 1 \text{ fm}^{-1}$)

► **SD operator:** $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

- Controlled by spin structure func.

- $\mathcal{L}_{\text{int}}$ -fit

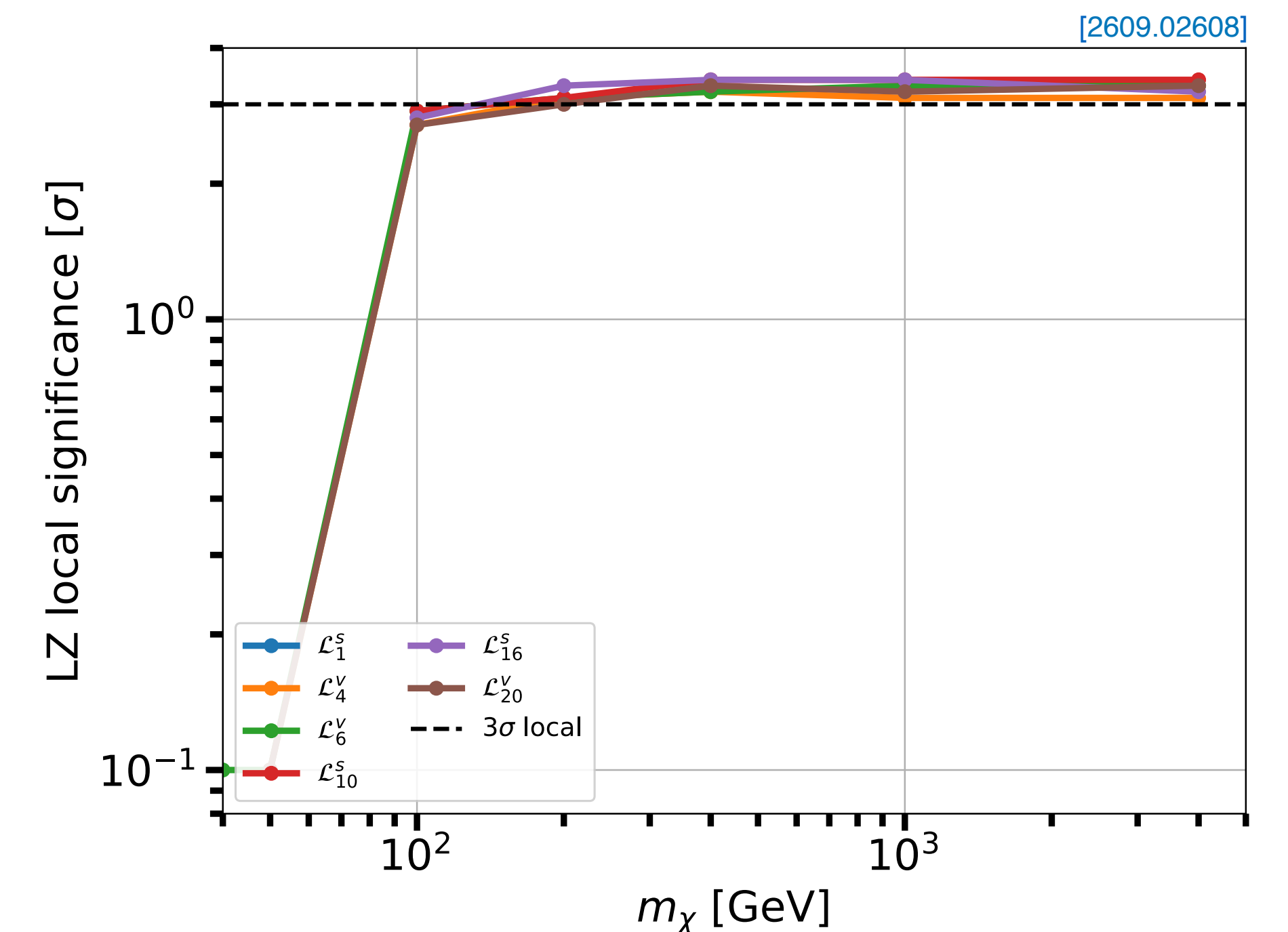
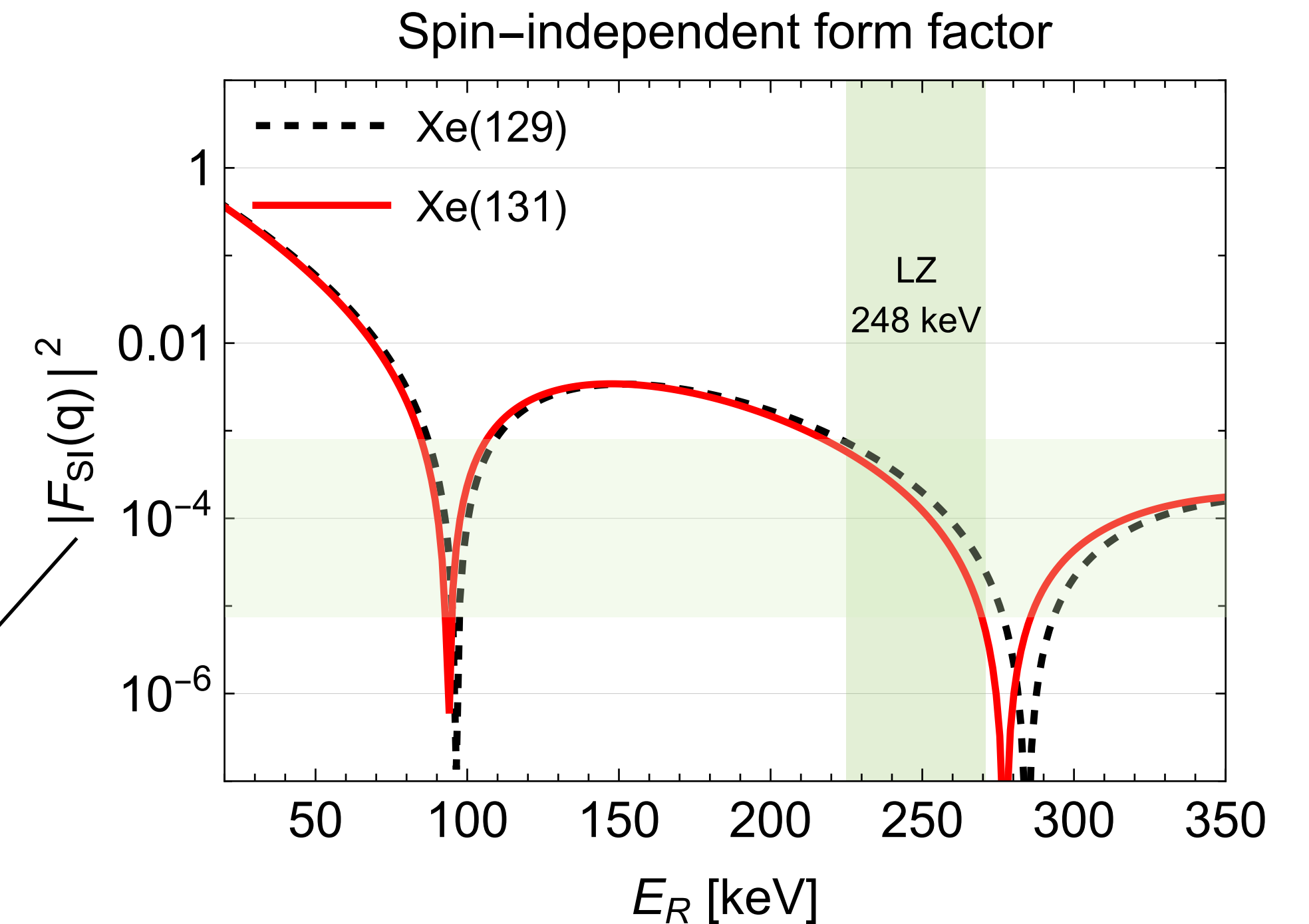
► Interaction types

- Several interaction types explain similar local significance
(exception: interaction corresponds to $\mathcal{O}_1$ @LO)

► DM mass

- Mass dependence turns irrelevant for $\gtrsim 200 \text{ GeV}$

Interaction	Mass (GeV/c ²)	elastic ($\delta = 0$)
$\mathcal{O}_1^s$	400	0.0
	1000	0.0
	4000	0.0
$\mathcal{O}_1^v$	400	0.8
	1000	1.3
	4000	1.1
$\mathcal{O}_4^s$	400	2.6
	1000	2.7
	4000	2.8
$\mathcal{O}_4^v$	400	2.6
	1000	2.7
	4000	2.8



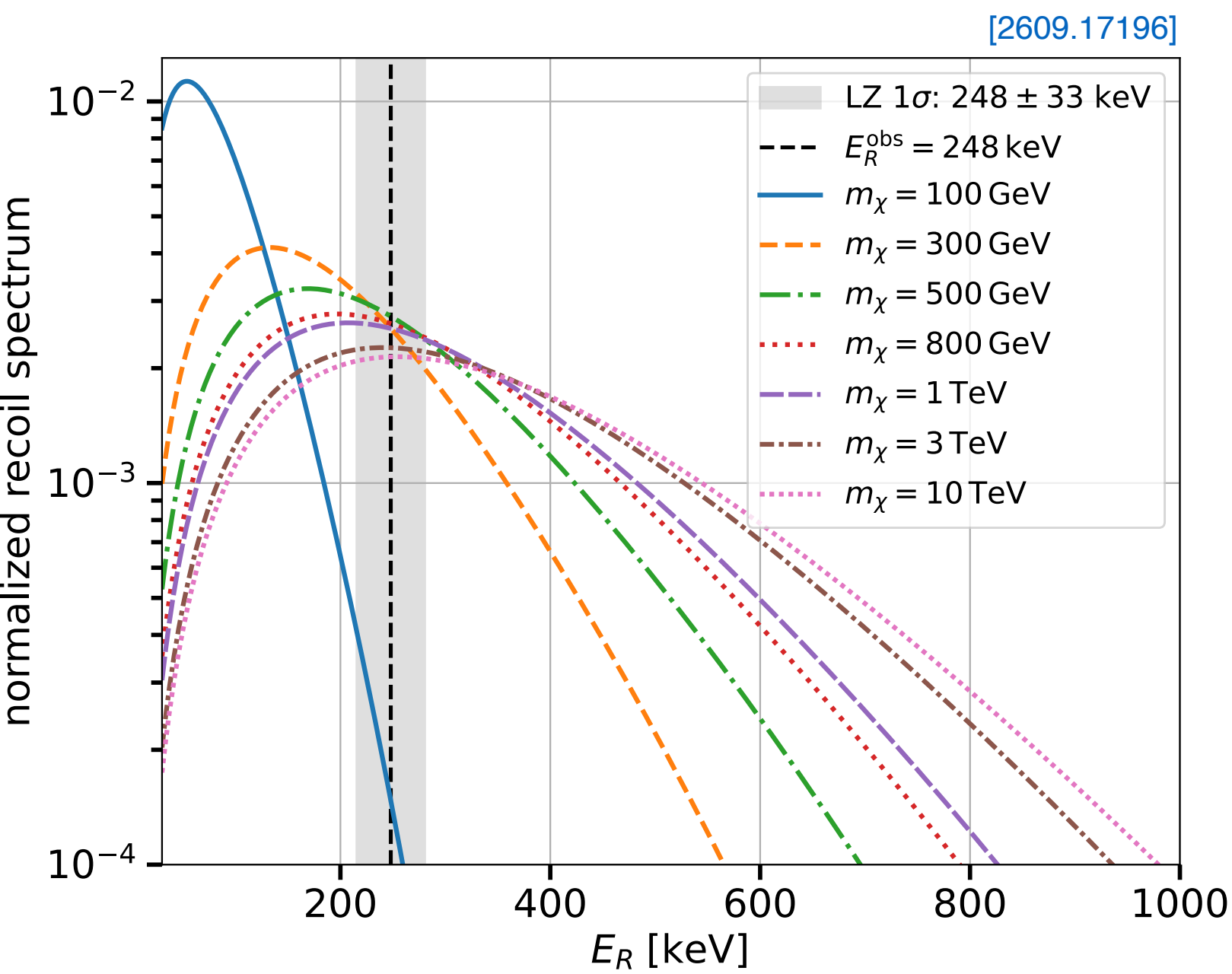
Elastic scattering? (2/2)

Pseudoscalar-portal [2609.04186]

- Challenge: non-observation of low- E_R
- Possible solution: **Pseudoscalar-portal**
 - Tree-level pseudoscalar-exchange $\rightarrow \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$
 - q^2 -dependence**: peak-shift toward high E_R -region
 - Spin-dependent**: relatively weak constraint on σ_{SD}

Kaede Furukawa || p24 cf. talk by Yuuki Nakano [D01]
Estimation of background events induced by solar- ν in CF₄-based DM detectors

$$\frac{d\sigma_T}{dE_R} = \frac{m_T}{32\pi v_E^2} \frac{Q^4}{m_N^2 m_\chi^2} \sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{NN'}(Q^2),$$



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$\bar{\chi}i\gamma^5\chi \bar{q}i\gamma^5q$	Pseudoscalar	$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$	SD	$\mathcal{O}(q^2/(m_\chi m_N))$
$\bar{\chi}\gamma^\mu\gamma^5\chi \bar{q}\gamma_\mu\gamma^5q$	Vector	$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	SD	—

2. Sub-GeV Dark Matter

Condition to detect dark matter recoil:

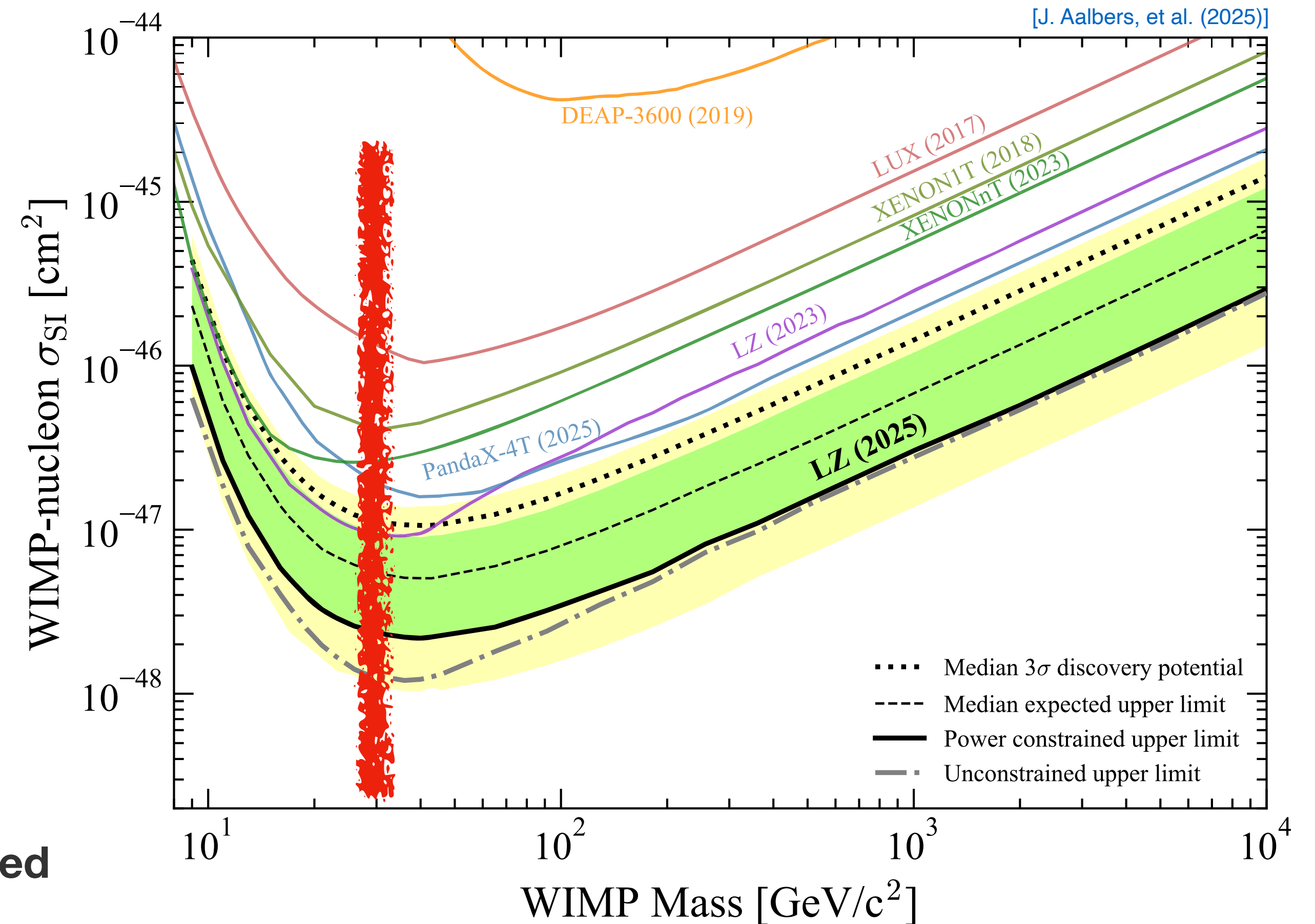
$$E_{\text{th}} < E_{\text{recoil}} \sim \frac{(m_{\text{DM}} v)^2}{m_T}$$

Kinematics of direct detection:

- Threshold energy : $E_{\text{th}} \sim \text{keV}$
- Averaged velocity : $v \sim 10^{-3}$
- mass of target nucleus : $m_T \sim 100 \text{ GeV}$

➔ $m_{\text{DM}} \gtrsim 10 \text{ GeV}$: Intensively searched

We need another probe for $m_{\text{DM}} \lesssim 10 \text{ GeV}$



How to approach

Develop new experiments

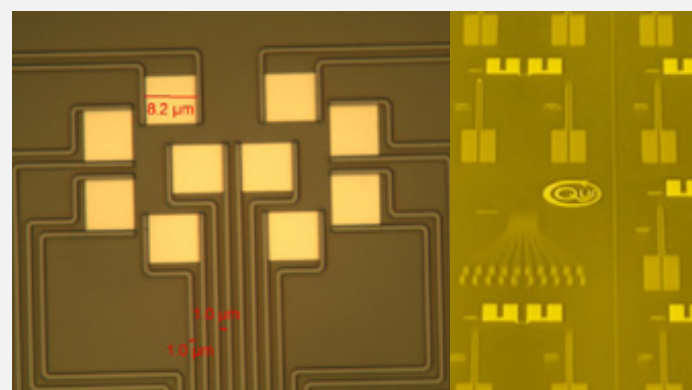
- Optimize detection technology for light Dark Matter mass

MeV scale:

Kaori Hattori [A01] (POR) || p32
Superconducting Transition-Edge Sensors

meV scale:

Shunsuke Adachi [B01] (POR) || p11
Millimeter-Wave Receivers



[introduction for Publicly Offered Research (POR)]

Celestial capture

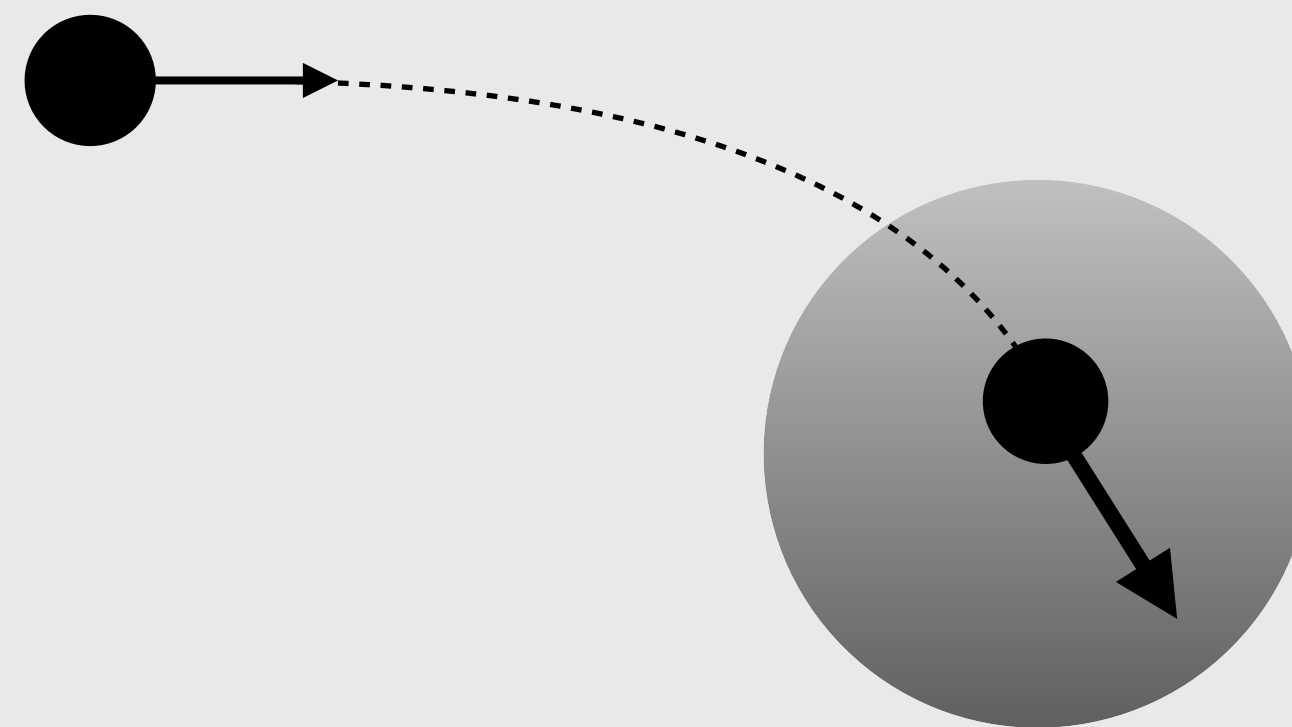
- Gravitational capture of Dark Matter (@Sun, White dwarf, Neutron star, BH)

► Pros.

- (Effectively) large target mass
- Gravitational acceleration

► Cons.

- Astro. uncertainty
- Signature v.s. background



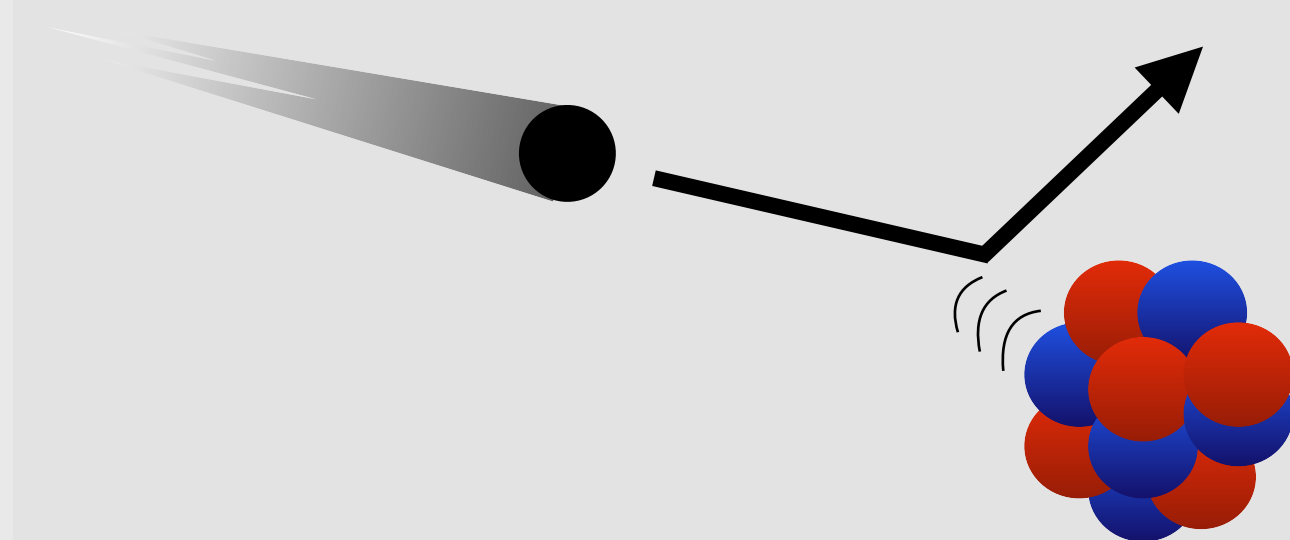
Boosted Dark Matter

- Boosted Dark Matter
→ easy to exceed energy threshold

- Ordinary direct detection (ν -detector) may probe sub-GeV mass region

► How to boost

- Solar reflection
- Cosmic-ray
- Blazar
- Dark Matter particle interactions



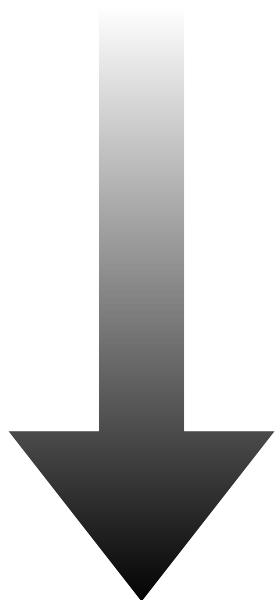
Boost Mechanism (1/2)

Scattering w/ high energy particles

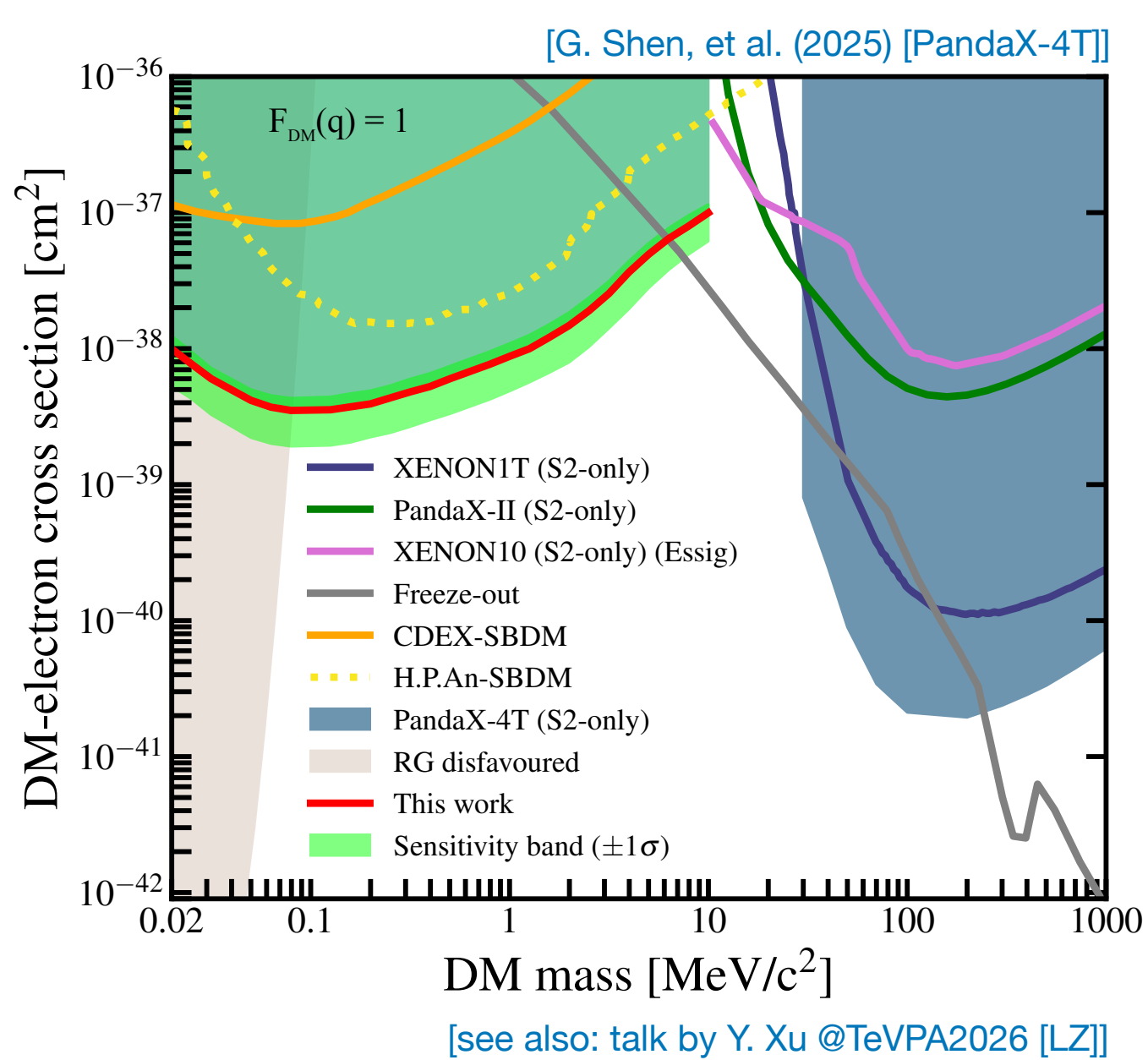
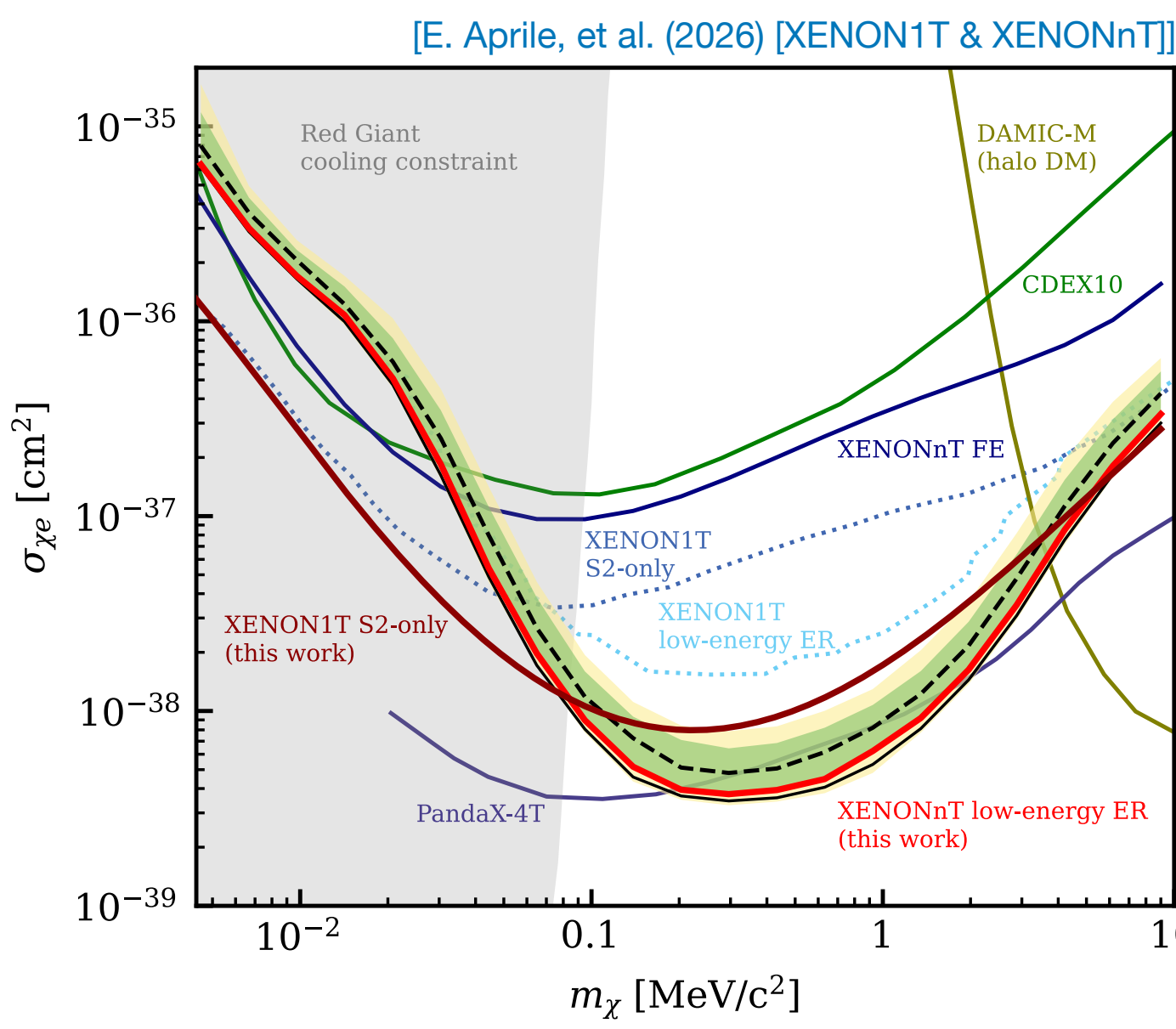
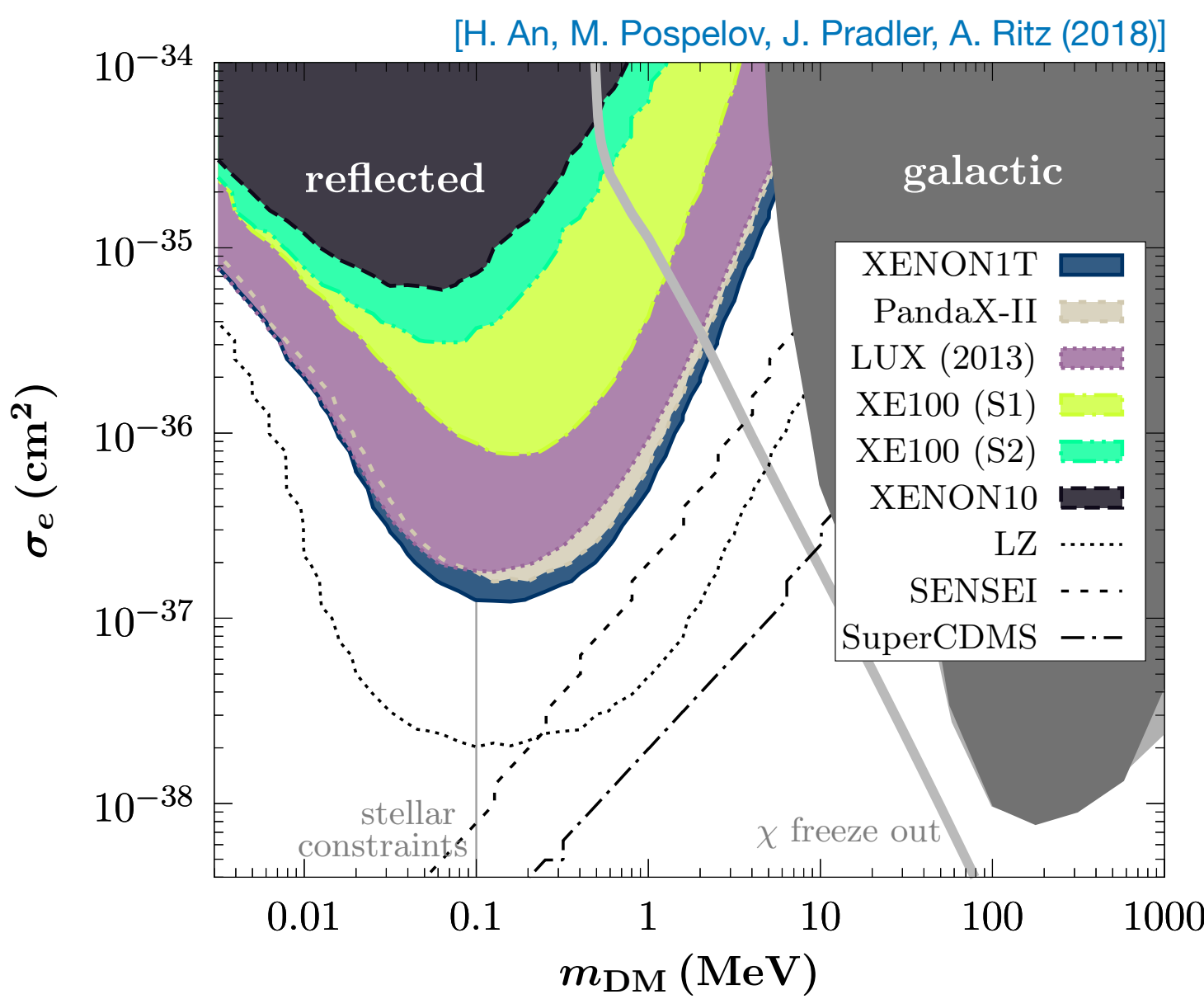
- Solar reflection
 - p -scattering [T. Emken, C. Kouvaris, N. G. Nielsen (2018)]
 - e -scattering [H. An, M. Pospelov, J. Pradler, A. Ritz (2018)]
[H. An, H. Nie, M. Pospelov, J. Pradler, A. Ritz (2021)]
- Cosmic-ray boosted
 - p -scattering [T. Bringmann, M. Pospelov (2019)]
 - e -scattering [Y. Ema, F. Sala, R. Sato (2019)]
- Blazar boosted
 - p -scattering [J-W. Wang, A. Granelli, P. Ulli (2022)]
 - e -scattering [A. Granelli, P. Ullio, J-W. Wang (2022)]

Theoretical estimation of sensitivity
→ Constraint by dedicated analysis

Theoretical estimation:



Experimental constraints



[see also: talk by Y. Xu @TeVPA2026 [LZ]]

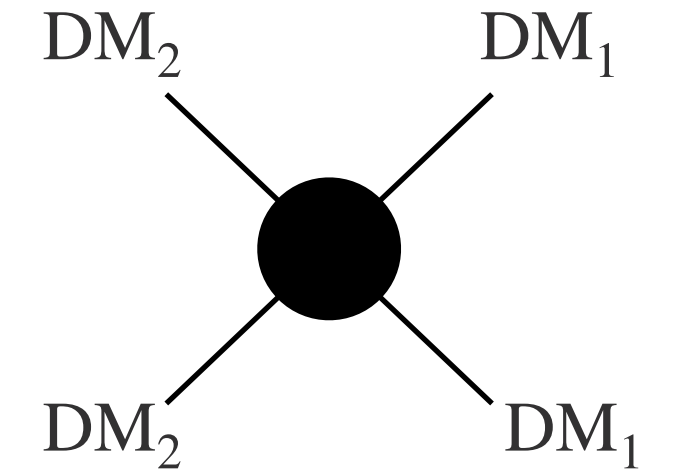
Boost Mechanism (2/2)

Multi-component Dark Matter

- Heavier Dark Matter components inject energy to final-state [\[K. Agashe, et al. \(2014\)\]](#)
- Relativistic acceleration is possible → **Search target incl. large volume ν -detector** (e.g. Super-K, IceCube)

Satoshi Higashino [B03] || *Direction-sensitive dark matter search using low pressure gaseous detectors*

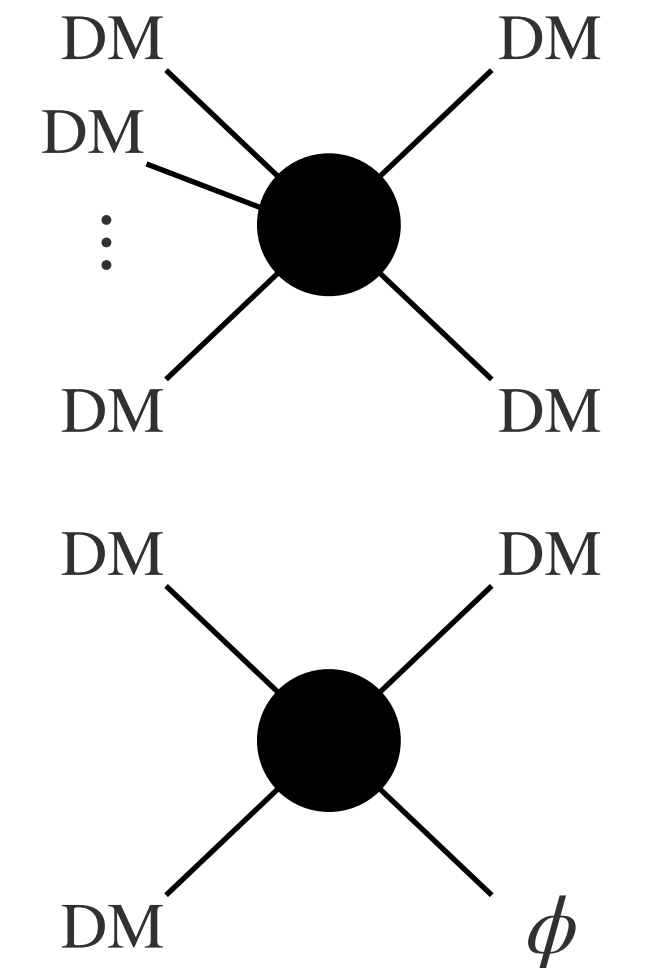
Natsuki Chin [B03] || *Directional Search for Boosted Dark Matter @NEWSdm Experiment*



Number changing process

- Number changing process fixes Dark Matter mass scales
- Semi-relativistic acceleration → **Search target @low-threshold experiments**

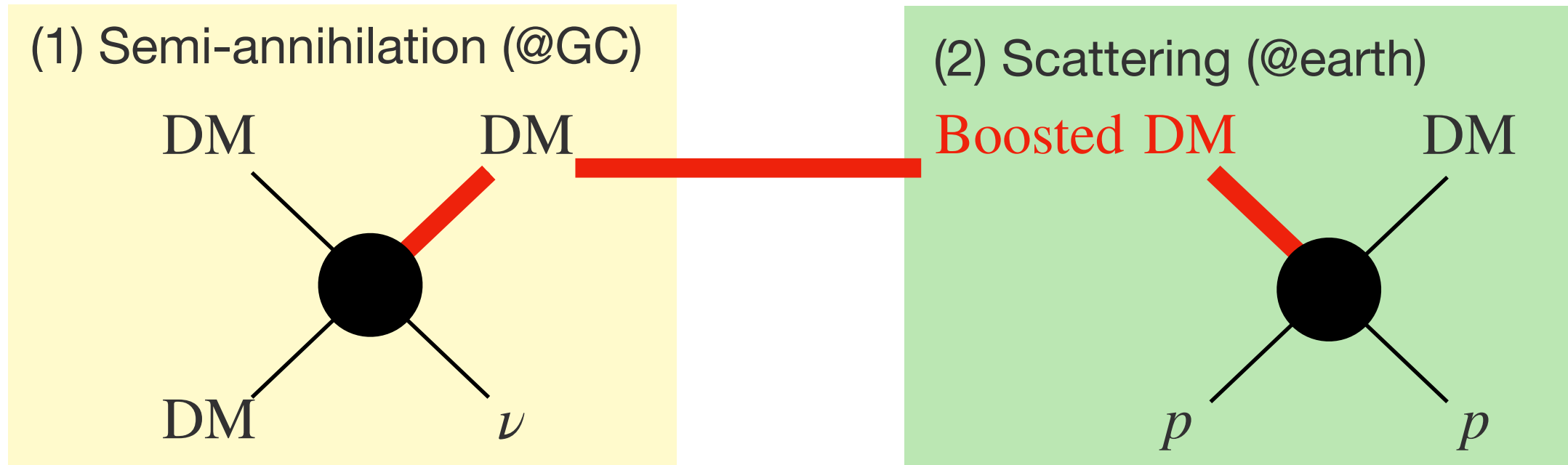
- $4 \rightarrow 2$ e.g. [\[J. Herms, et al. \(2018\)\]](#) : $m_{\text{DM}} \sim 0.1 \text{ MeV}$, $\langle \sigma_{4 \rightarrow 2} v^3 \rangle \sim 10^{-78} \text{ cm}^9/\text{s}$, $E_{\text{DM}} \sim 2m_{\text{DM}}$
- $3 \rightarrow 2$ (cf. SIMP) [\[Y. Hochberg, et al. \(2014\)\]](#) : $m_{\text{DM}} \sim 100 \text{ MeV}$, $\langle \sigma_{3 \rightarrow 2} v^2 \rangle \sim 10^{-57} \text{ cm}^6/\text{s}$, $E_{\text{DM}} \sim 3m_{\text{DM}}/2$
- $2 \rightarrow 1$ (Semi-annihilation) [\[F. D'Eramo, et al. \(2010\)\]](#) : $m_{\text{DM}} \sim 1 \text{ GeV}$, $\langle \sigma_{2 \rightarrow 1} v \rangle \sim 10^{-26} \text{ cm}^3/\text{s}$, $E_{\text{DM}} \sim 5m_{\text{DM}}/4$



$2 \rightarrow 1$ **Boosted flux from Galactic Center:** $\Phi_{\text{BDM}} \simeq 3.2 \times 10^{-3} \text{ cm}^3/\text{s} \left(\frac{m_{\text{DM}}}{100 \text{ MeV}} \right) \left(\frac{\langle \sigma_{2 \rightarrow 1} v \rangle}{10^{-26} \text{ cm}^3/\text{s}} \right)$ [\[Betancourt, et al. \(2025\)\]](#)

Semi-annihilation Boosted DM

[Betancourt-Kaminetskaia, MF, Ibarra, Toma (2025) PLB]



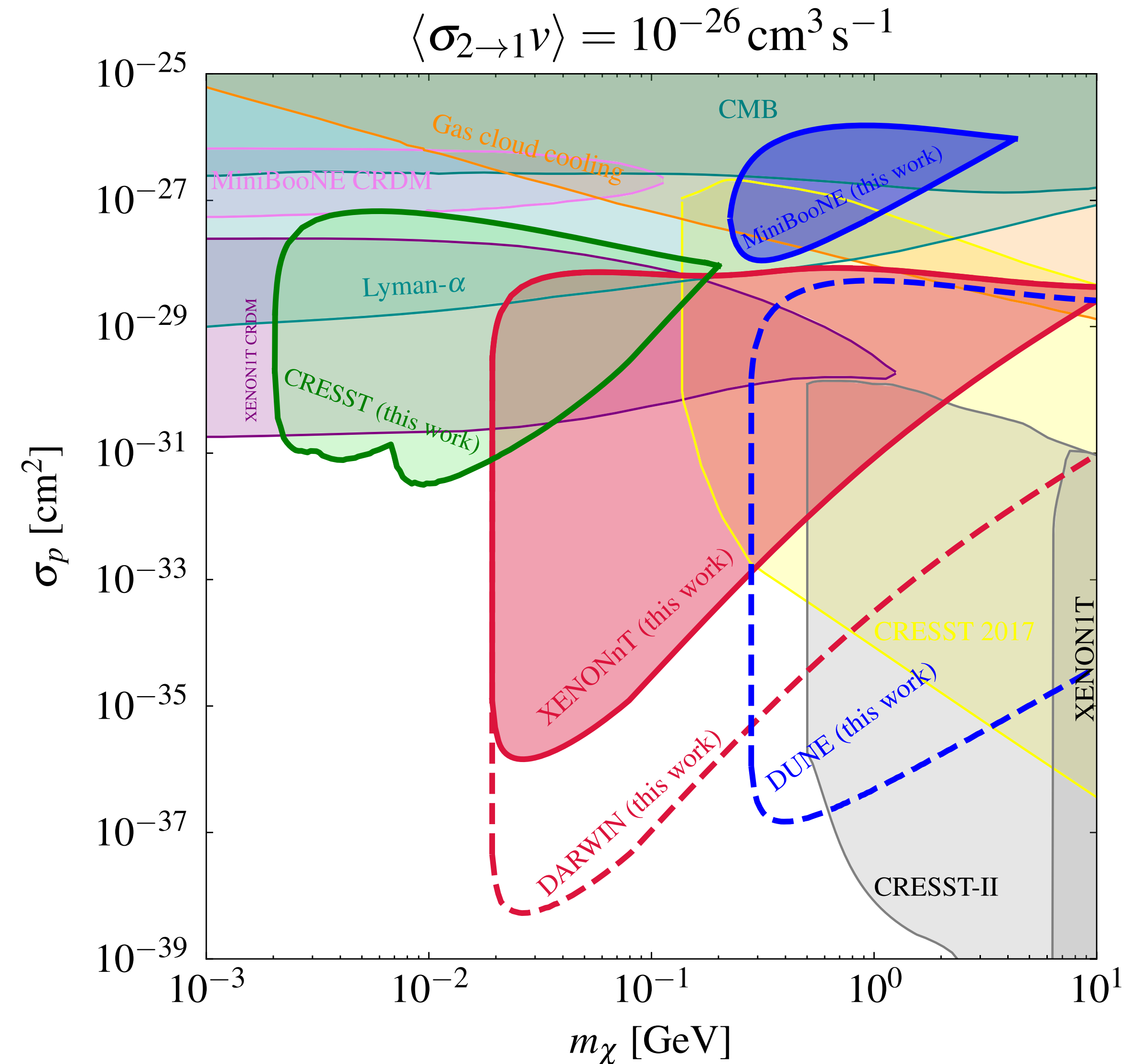
Sensitivity & Scenario

- $\chi\chi \rightarrow \chi\nu$: Semi-relativistic DM flux
- Symmetry behind semi-annihilation?
→ Z_3 symmetry
- ▶ BSM scenario: Radiative ν -mass model [MF, Toma (2026)]

Takashi Toma [E01] (publicly offered research) || p12
A radiative neutrino mass model w/ semi-annihilating BDM

Accessible to $\mathcal{O}(10 - 100)$ MeV & $\sigma_p \sim 10^{-37} \text{ cm}^2$

Possible connection w/ Neutrino mass generation



Summary

WIMP paradigm

- Direct Detection: excellent probe for TeV WIMP
- Targets for next-generation: WIMP above neutrino fog
 - Loop induced interaction
 - Momentum suppression
 - Spin-dependent scattering

Beyond conventional WIMP search

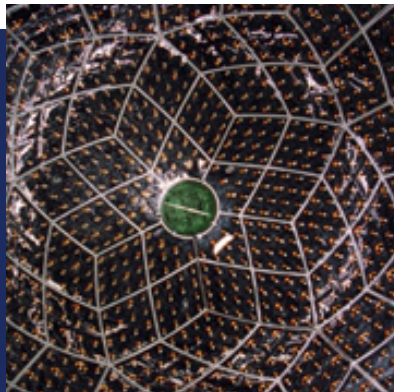
- High energy scattering
 - Inelastic scatt. w/ mass splitting & elastic scatt. w/ high- E_R spectrum
- Sub-GeV Dark Matter
 - Boosted Dark Matter (Sun, Cosmic-ray, Blazer, particle processes)

Let's continue to explore WIMP landscape!

極稀事象で探る宇宙物質の起源と進化 新たな宇宙物質観創生のフロンティア

Investigation on the Origin and Evolution of Matter in the Universe by Extremely Rare Events
Frontier of Creating a New Insight on the Matter in the Universe

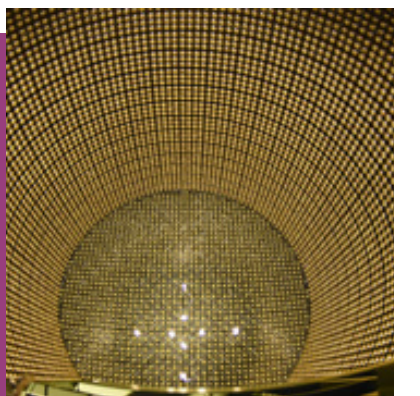
物質優勢の謎に挑む、
ニュートリノを伴わない二重ベータ崩壊の実験的研究



銀河を育んだ未知の重力源、
暗黒物質の正体解明を目指す実験的研究



宇宙の重元素の製造と拡散の現場、
超新星ニュートリノの
詳細観測と超新星予報を推進する実験的研究



稀事象探索の基盤技術の普遍化と拡大を
推進する開発・研究

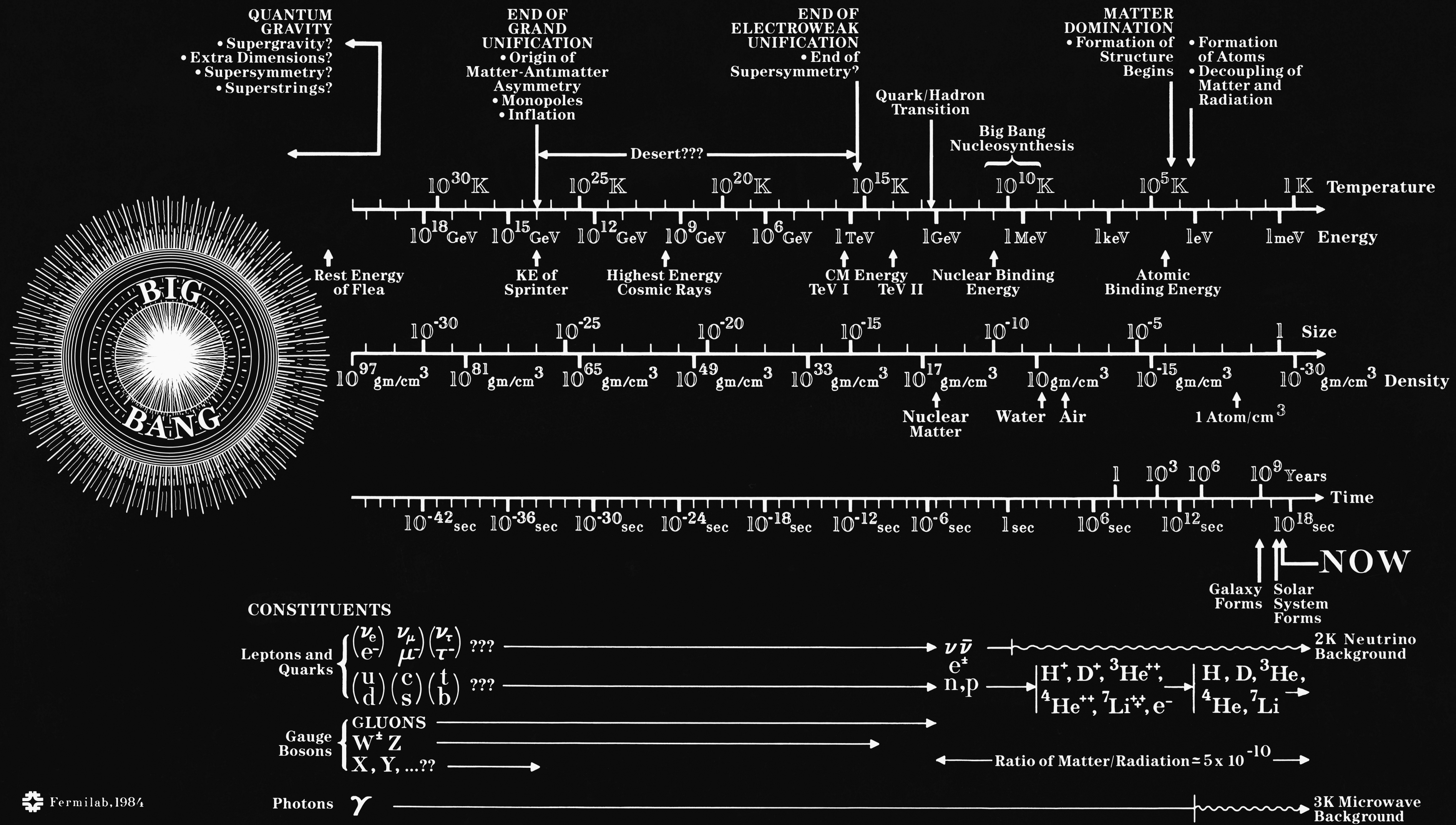


Investigation on the Origin and Evolution of Matter in the Universe by Extremely Rare Events
Frontier of Creating a New Insight on the Matter in the Universe

稀事象研究から宇宙物質の起源と進化を
体系化する理論的研究



Backup





BU:

Indirect detection for Electroweak Multiplet DM



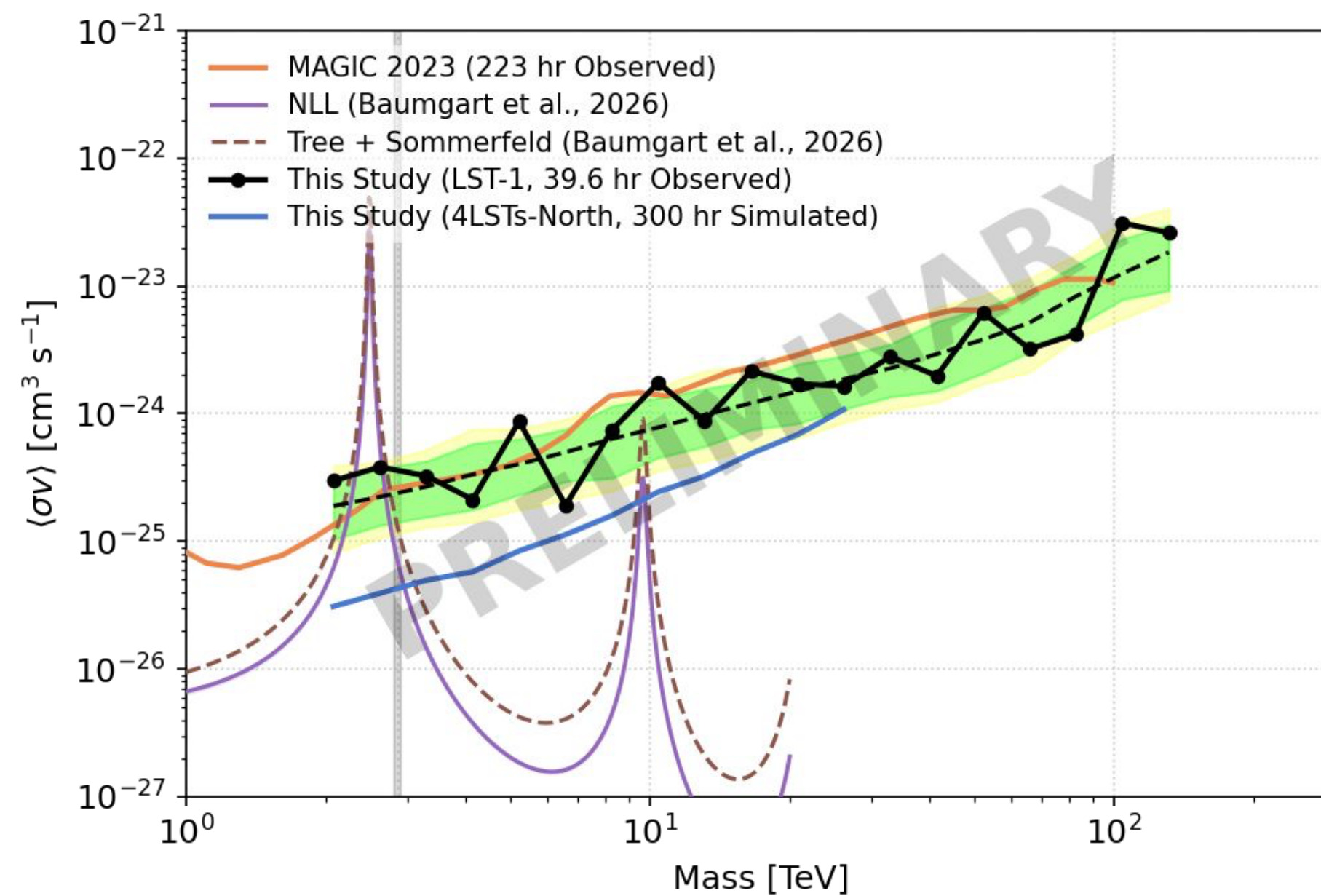
CTAO LST-1 Preliminary result

Constraints on Real WIMPs with LST-1

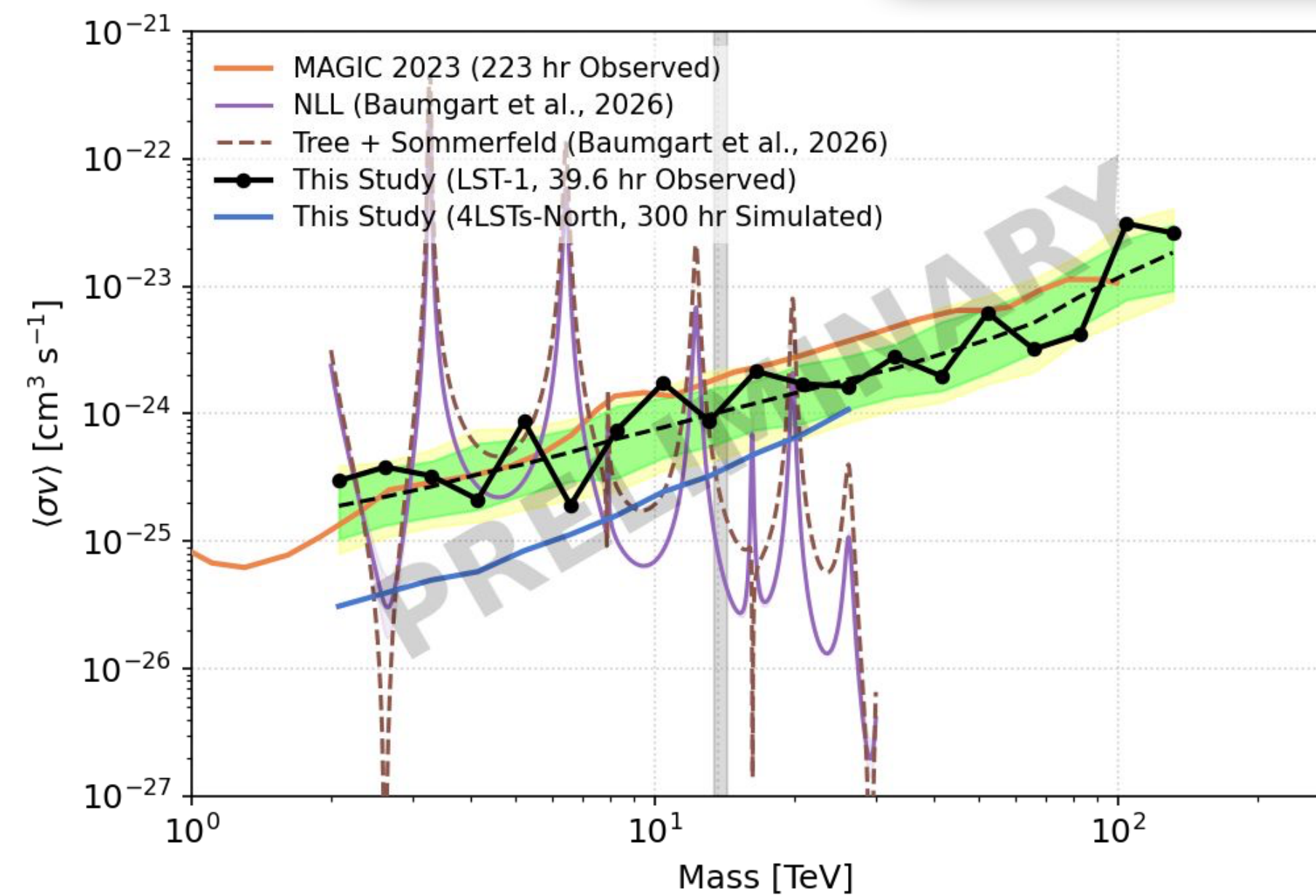
* The Burkert case, the most conservative one, shown here.

As a demonstration based on first real data from the CTAO telescope,
the test of minimal DM candidates proven feasible

Wino, SU(2) triplet @ 2.86 TeV



Quintuplet @ 13.7 TeV



Search for Line-Like Gamma-Ray Signals from Dark Matter in the Galactic Center with CTAO LST-1

Sep 1, 2026, 2:18 PM

18m

舞鶴 Maizuru

Speaker

Dr Shotaro Abe (Kyoto U)

LST-1 result [3&5plet]
by Shotaro Abe



BU:

Celestial capture



Dark Matter @celestial body

Time evolution of DM number

$$\frac{dN_{\text{DM}}}{dt} = \underbrace{C}_{\text{Capture}} - E N_{\text{DM}}(t) - A N_{\text{DM}}^2(t)$$

N_{DM} : DM number trapped at the body

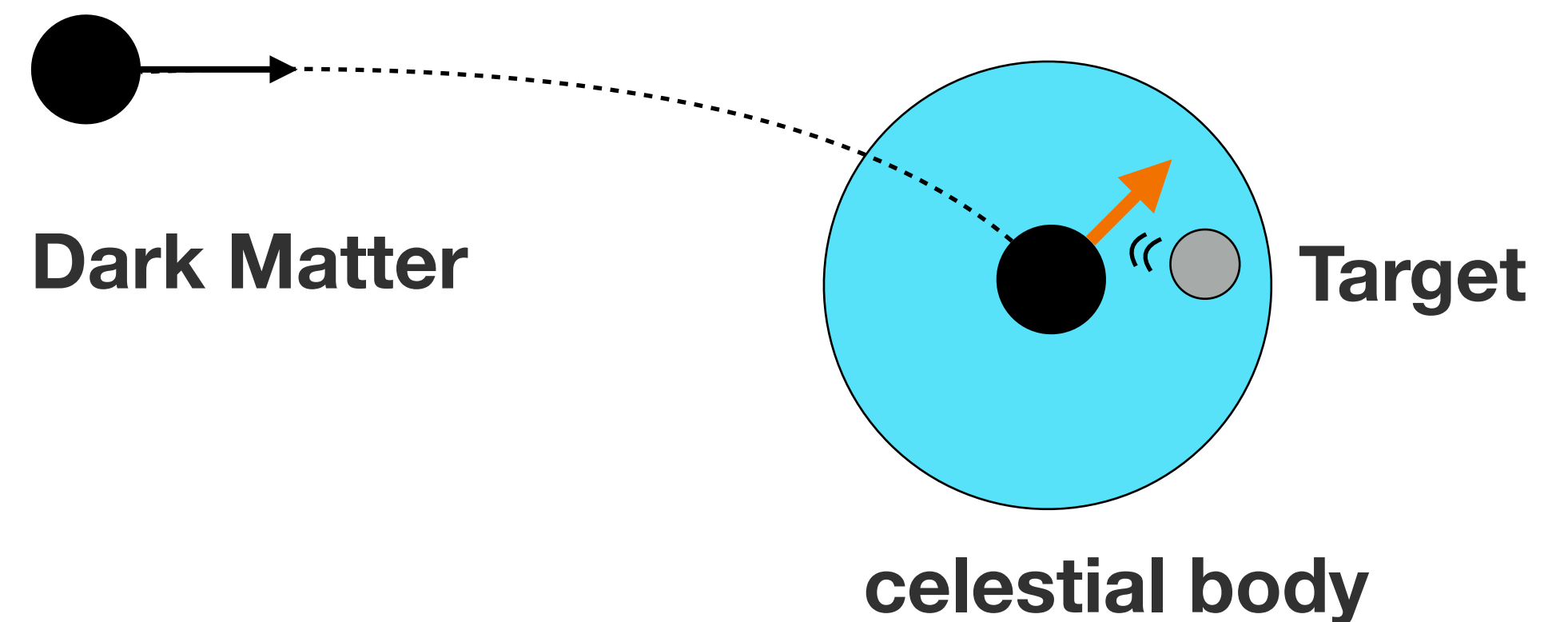
C : DM capture rate

E : DM evaporation rate

A : DM annihilation rate/vol.

- **Gravitational capture**

Kinetic energy is lost via scattering w/ targets (e.g. nucleons)



Dark Matter @celestial body

Time evolution of DM number

$$\frac{dN_{\text{DM}}}{dt} = C - \underbrace{E}_{\text{Evaporation}} N_{\text{DM}}(t) - A N_{\text{DM}}^2(t)$$

N_{DM} : DM number trapped at the body

C : DM capture rate

E : DM evaporation rate

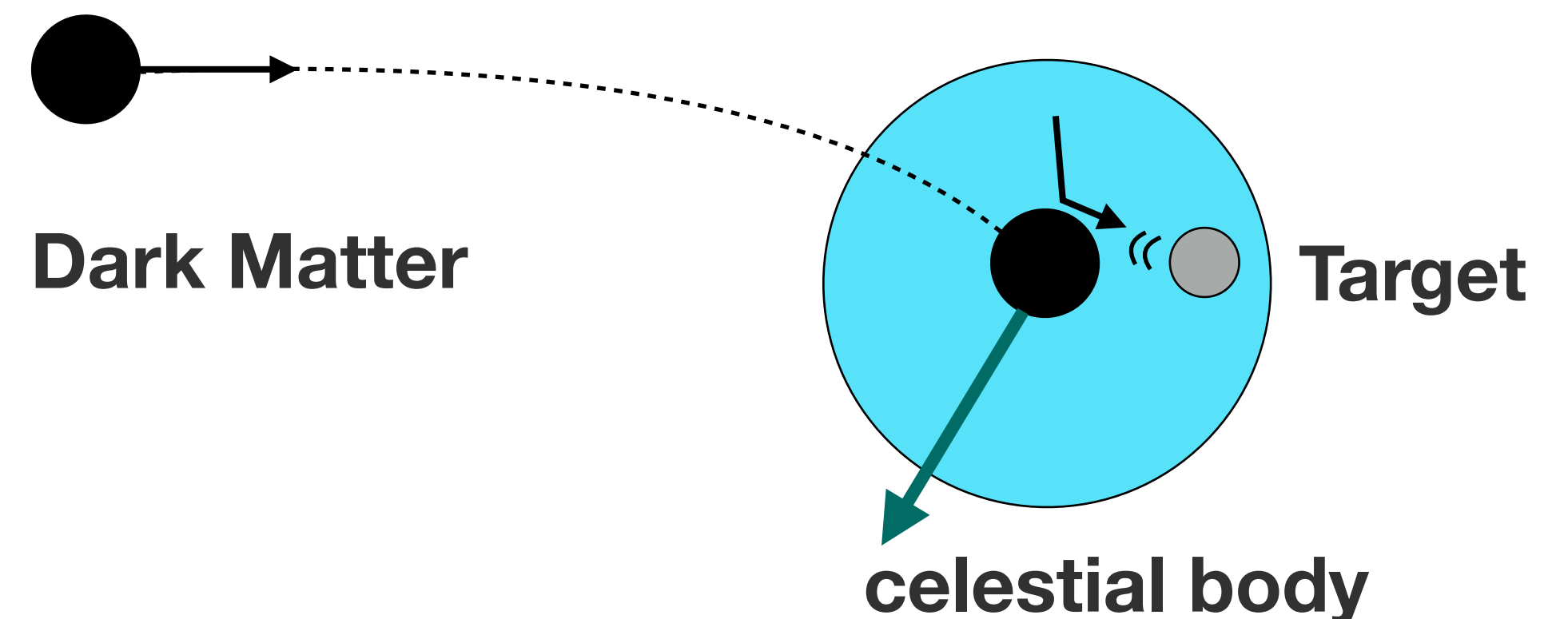
A : DM annihilation rate/vol.

- **Gravitational capture**

Kinetic energy is lost via scattering w/ targets (e.g. nucleons)

- **Evaporation** (= escape from object)

DM is kicked-out due to scattering w/ energetic targets



Dark Matter @celestial body

Time evolution of DM number

$$\frac{dN_{\text{DM}}}{dt} = C - E N_{\text{DM}}(t) - \boxed{A} N_{\text{DM}}^2(t)$$

Annihilation

N_{DM} : DM number trapped at the body

C : DM capture rate

E : DM evaporation rate

A : DM annihilation rate/vol.

- **Gravitational capture**

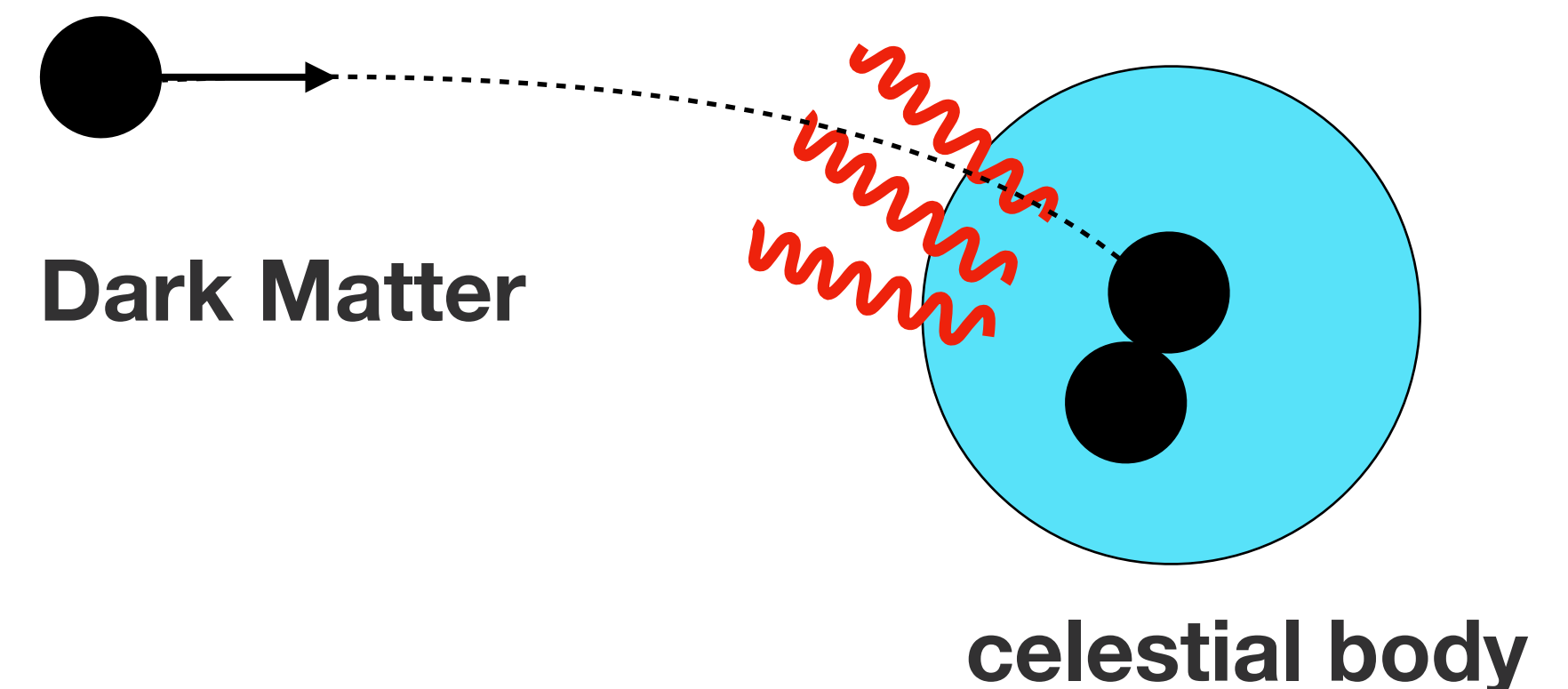
Kinetic energy is lost via scattering w/ targets (e.g. nucleons)

- **Evaporation** (= escape from object)

DM is kicked-out due to scattering w/ energetic targets

- **Annihilation**

DM number is lost via pair annihilation



Dark Matter @celestial body

Time evolution of DM number

$$\frac{dN_{\text{DM}}}{dt} = \boxed{C} - \boxed{E} N_{\text{DM}}(t) - \boxed{A} N_{\text{DM}}^2(t)$$

N_{DM} : DM number trapped at the body

C : DM capture rate

E : DM evaporation rate

A : DM annihilation rate/vol.

- **Gravitational capture**

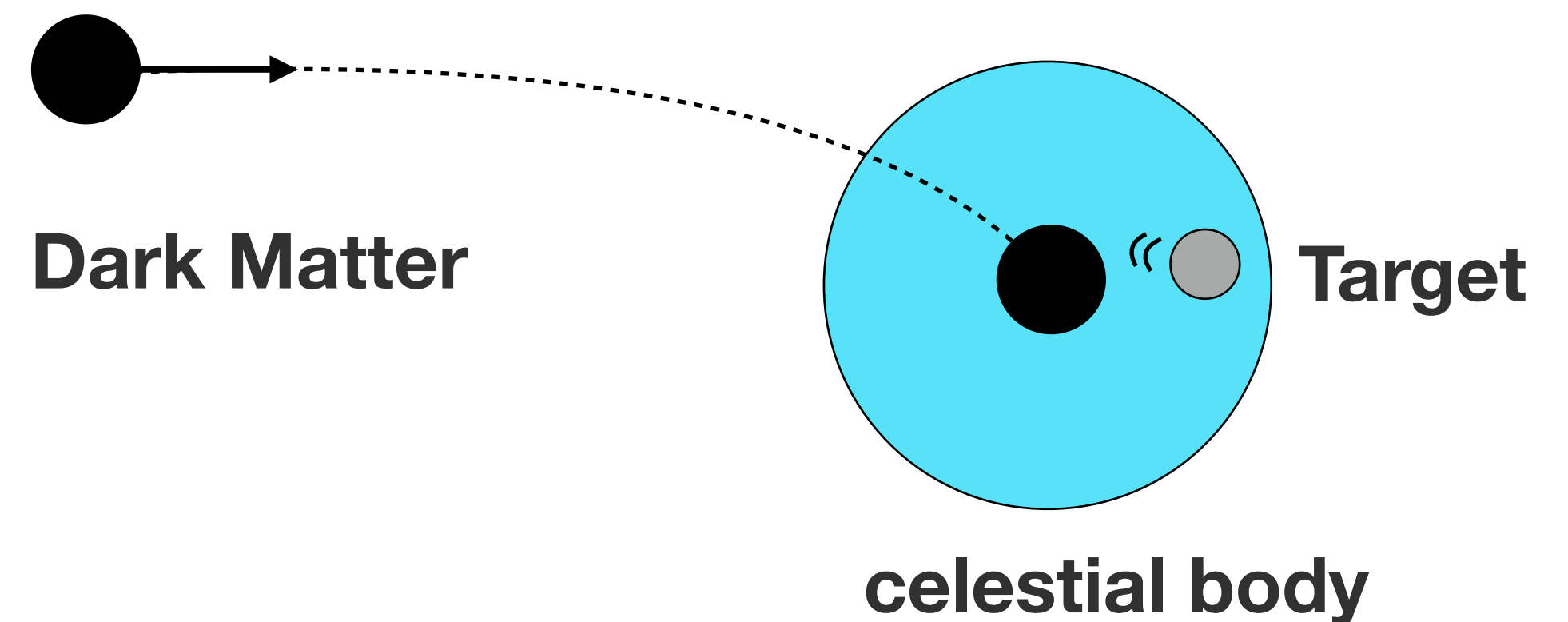
Kinetic energy is lost via scattering w/ targets (e.g. nucleons)

- **Evaporation** (= escape from object)

DM is kicked-out due to scattering w/ energetic targets

- **Annihilation**

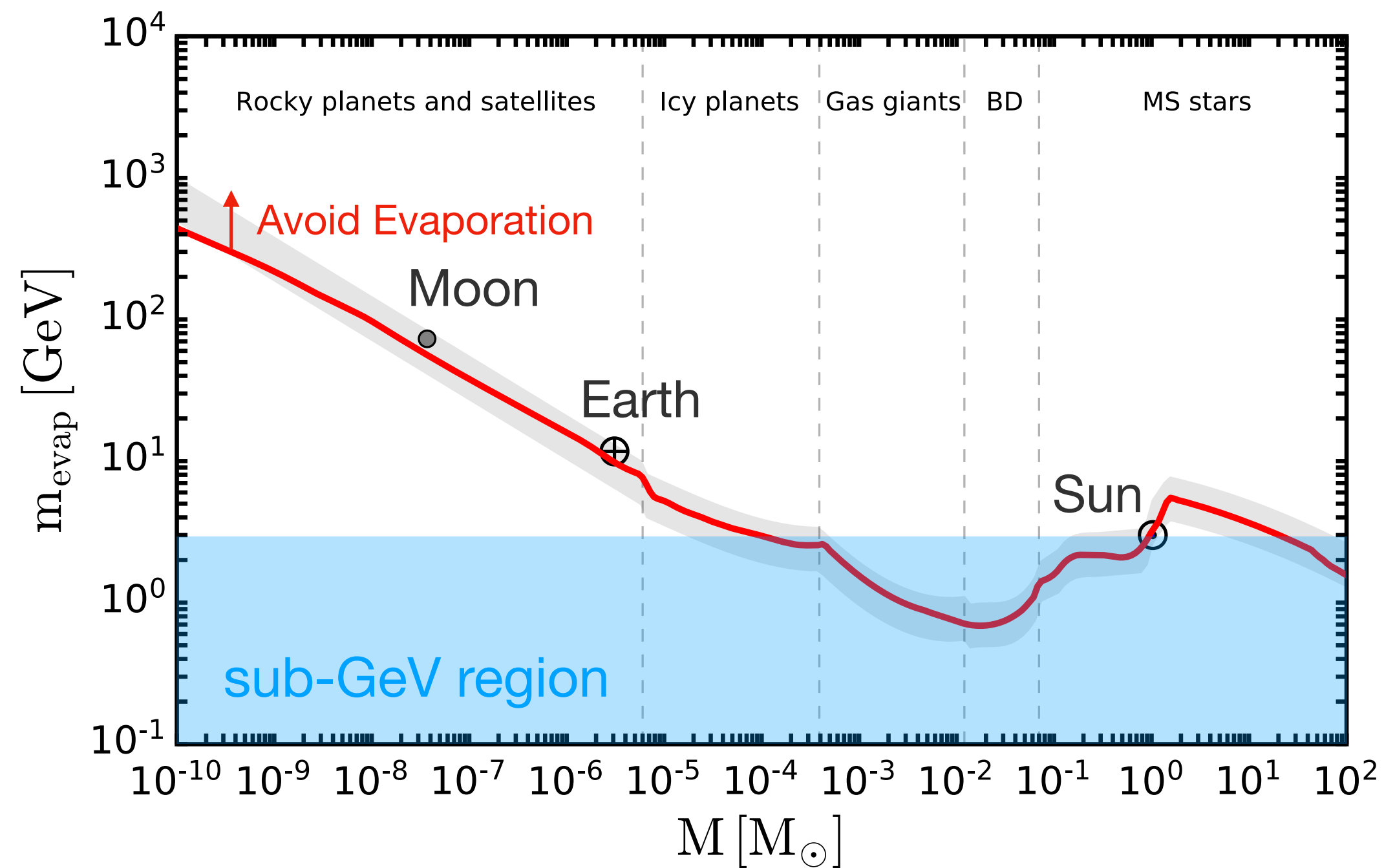
DM number is lost via pair annihilation



Capture / **Evaporation** / **Annihilation** reach equilibrium

→ DM number rate turns to be constant

Evaporation mass

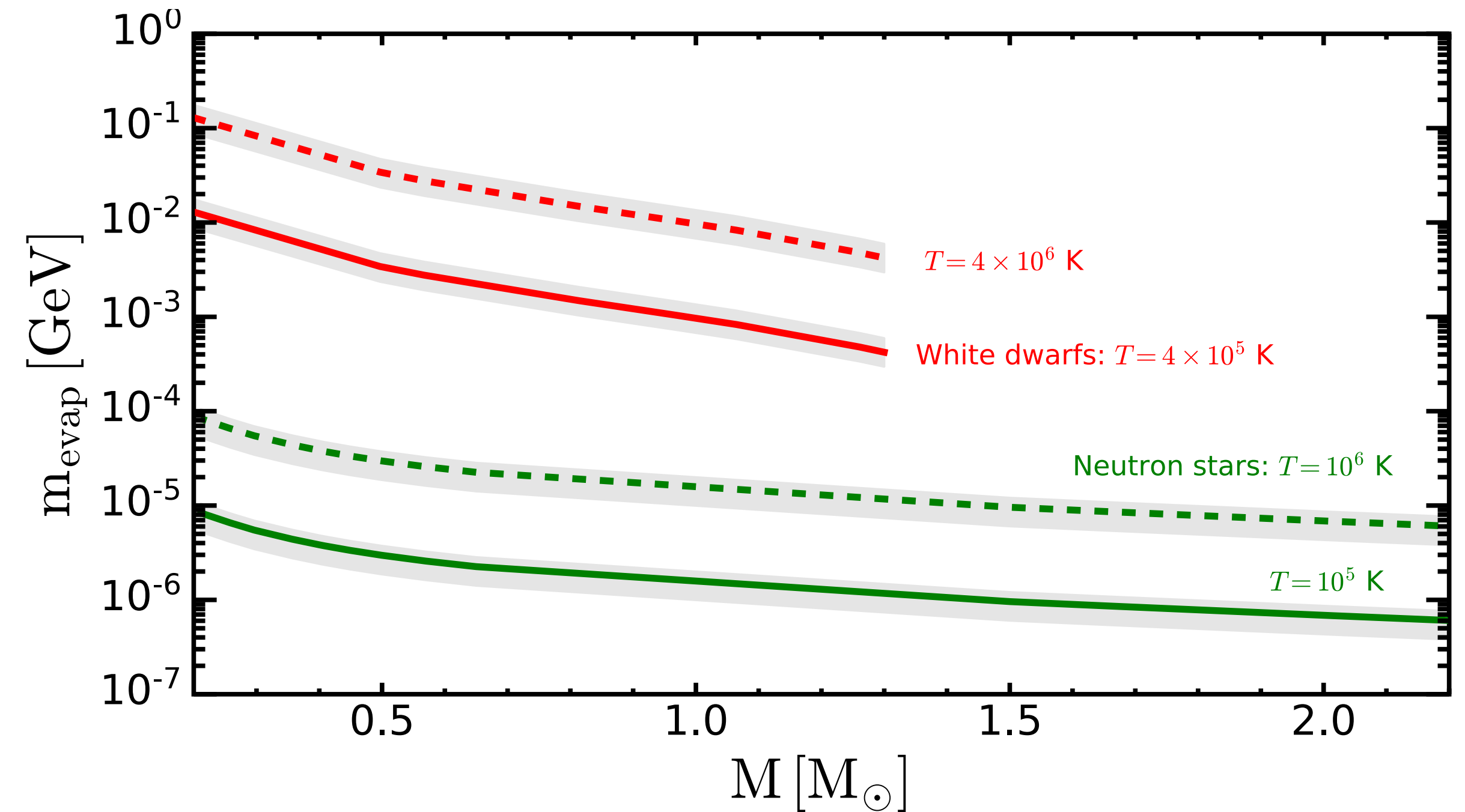


Celestial body w/ less density

- Evaporation mass = lowest DM mass @celestial body (escape velocity v.s. temperature)
- $\gtrsim \mathcal{O}(1)$ GeV region can be touched
e.g. Brown dwarf, Gas giants, Sun

$$\langle \sigma_{\text{ann}} v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

assuming velocity indep.



Compact & Cold object (white dwarf & neutron star)

- White dwarf : compactness & low temperature avoid evaporation
→ sensitive to **MeV region**
- Neutron star : Efficient trapping for $\gtrsim$ GeV ($\because$ Pauli blocking)

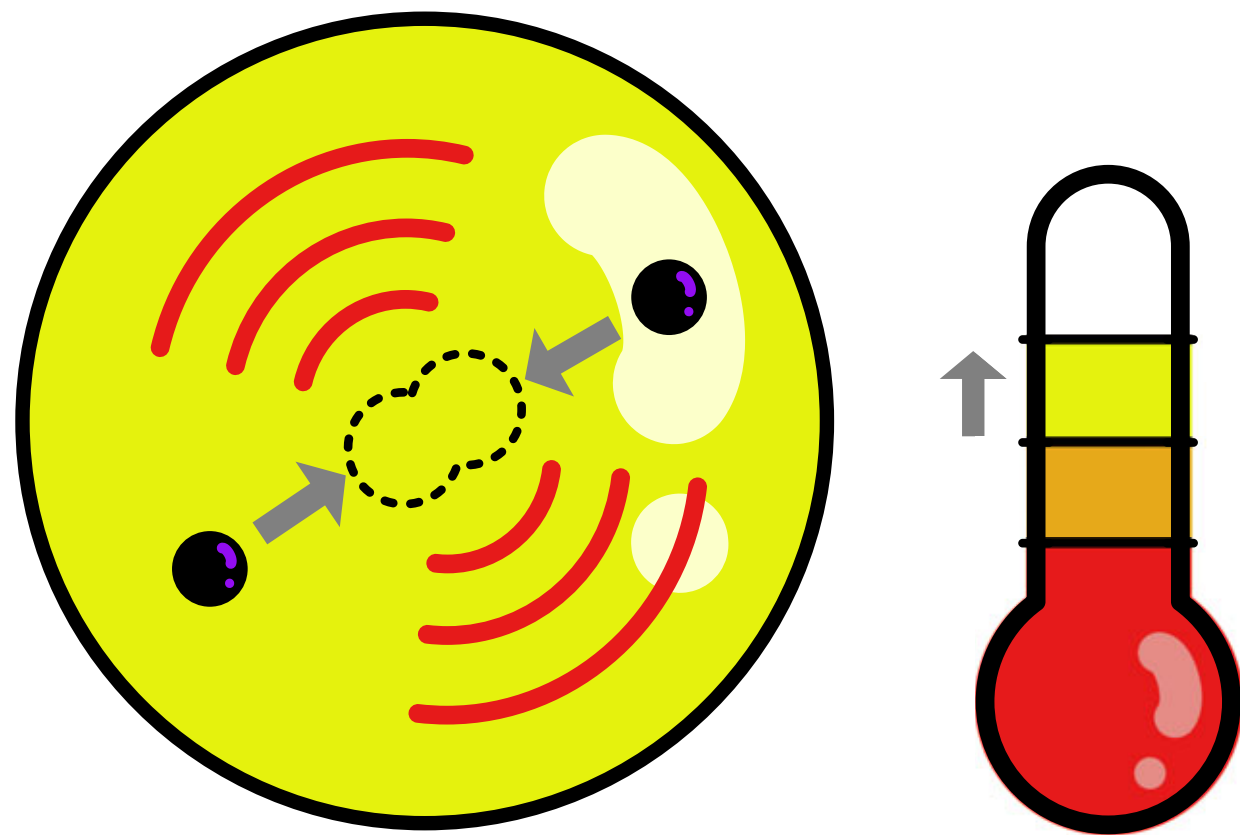
Target for Sub-GeV region? → **Compact & Cold object**

How to probe Dark Matter?

A. Dark Matter signature from celestial body depends on **annihilation properties**

(1) Annihilate inside

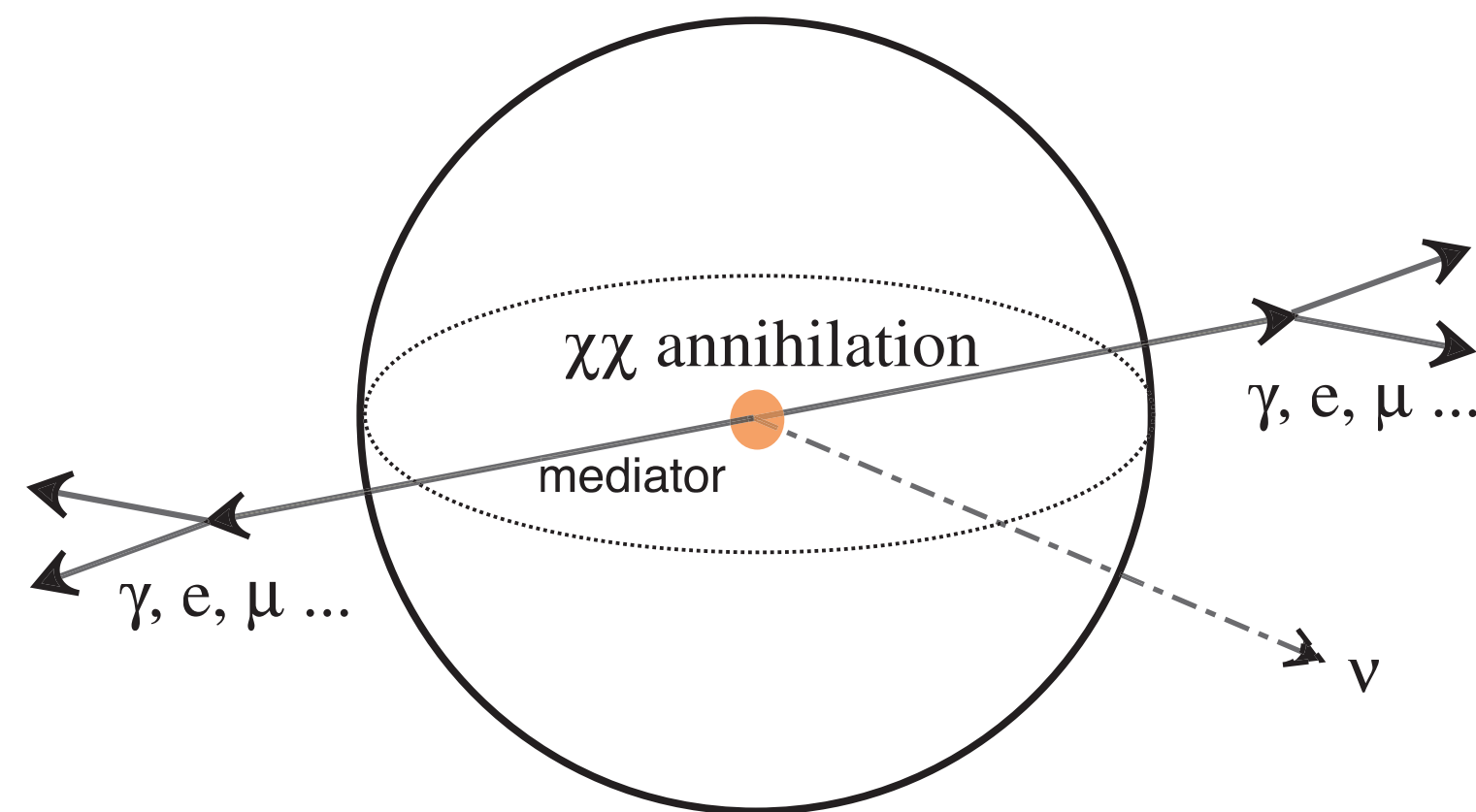
Dark Matter inject energy to the body
→ **Anomalous heating** occurs



[N. Raj, P. Tanedo, H-B. Yu (2018)]

(2) Annihilate outside

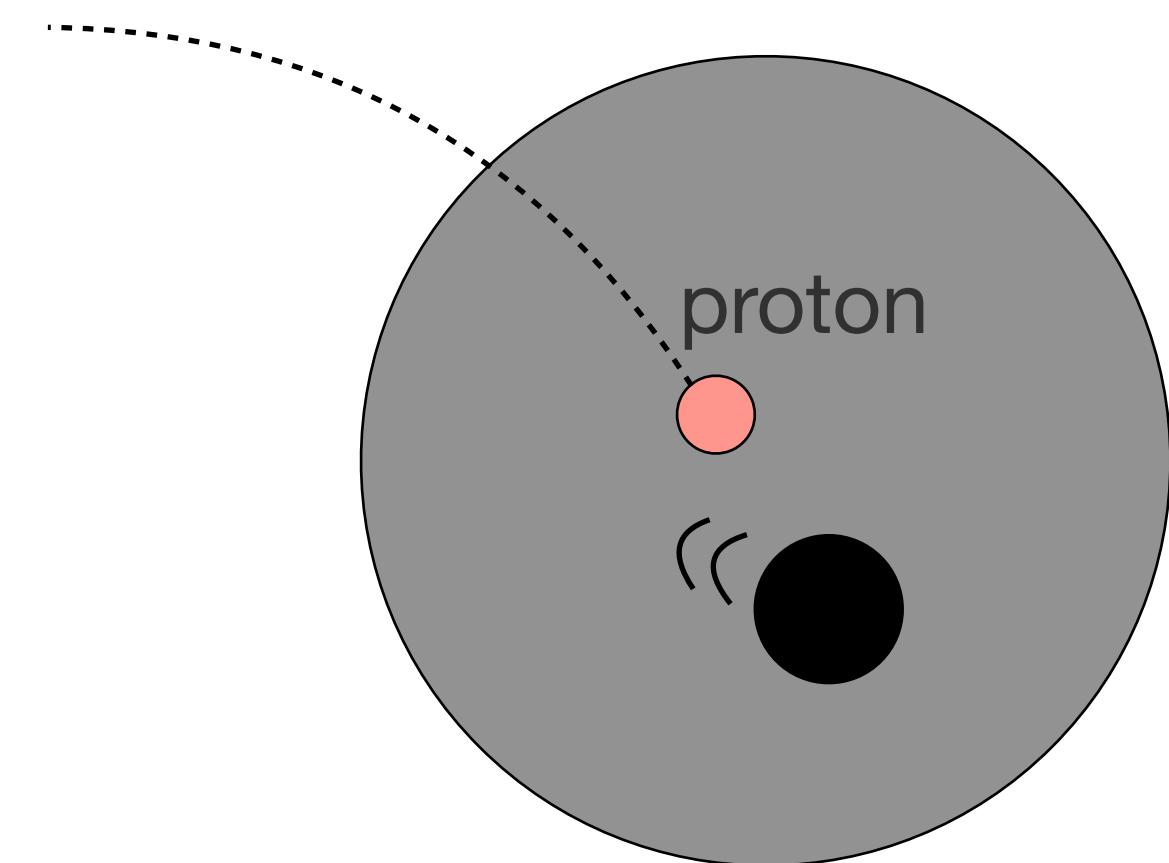
Long-lived mediator escapes from the body
→ Annihilation can be directly searched



[B. Batell, et al. (2010)]

(3) No annihilation

- Gravitational effect via accumulation
- Compact object made of Dark Matter



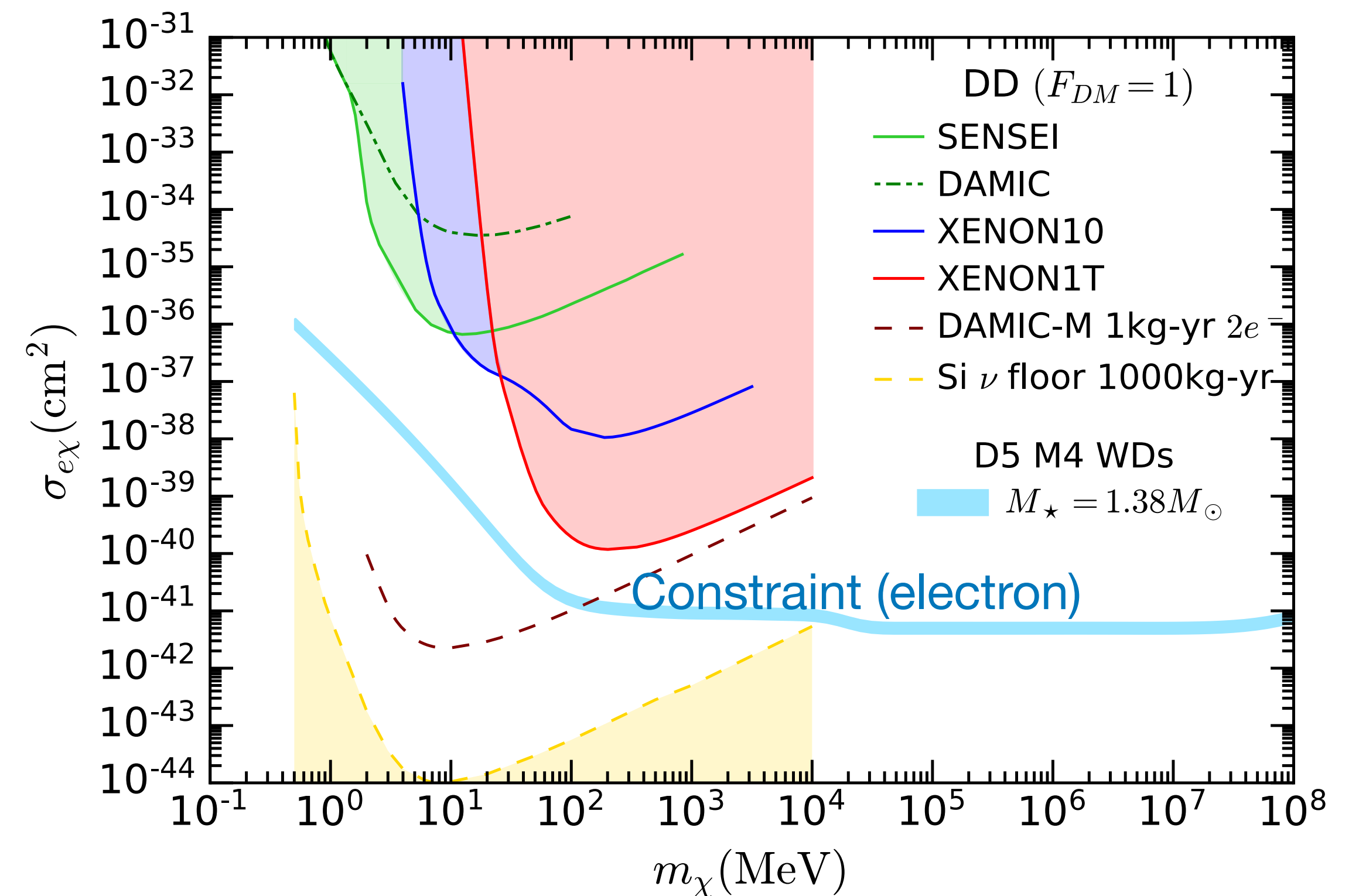
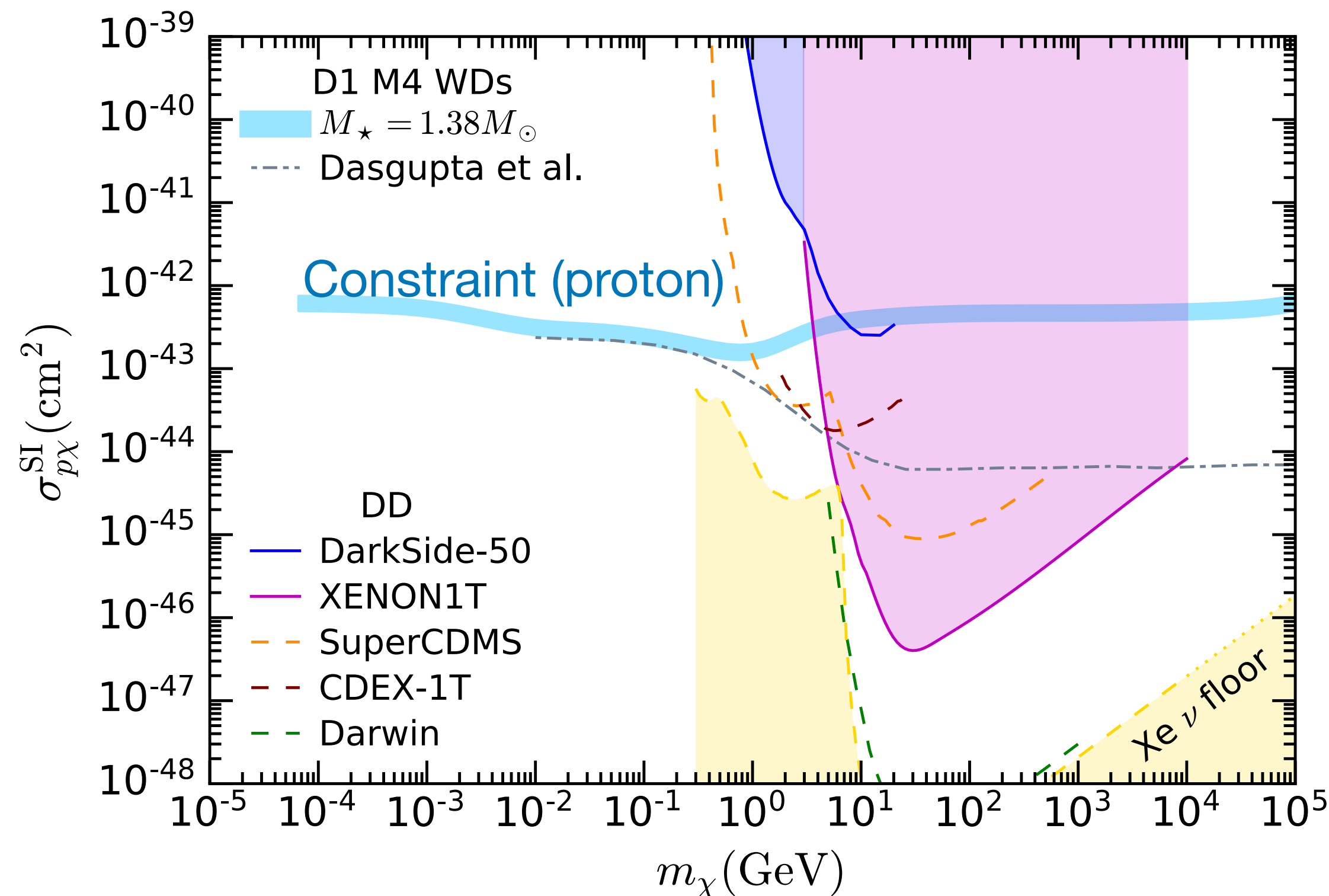
Dark Matter object

Annihilate inside

White dwarf [B. Dasgupta, et al. (2019)] [N. F. Bell (2021)]

Efficient probe for Sub-GeV Dark Matter? → **White dwarf!** ✓

- Search for anomalously hot white dwarf from globular cluster Messier 4
- p -scattering (spin-indep.): Complementary against direct detection for $\lesssim \mathcal{O}(1)$ GeV
- e -scattering (spin-indep.) : More sensitive than direct detection



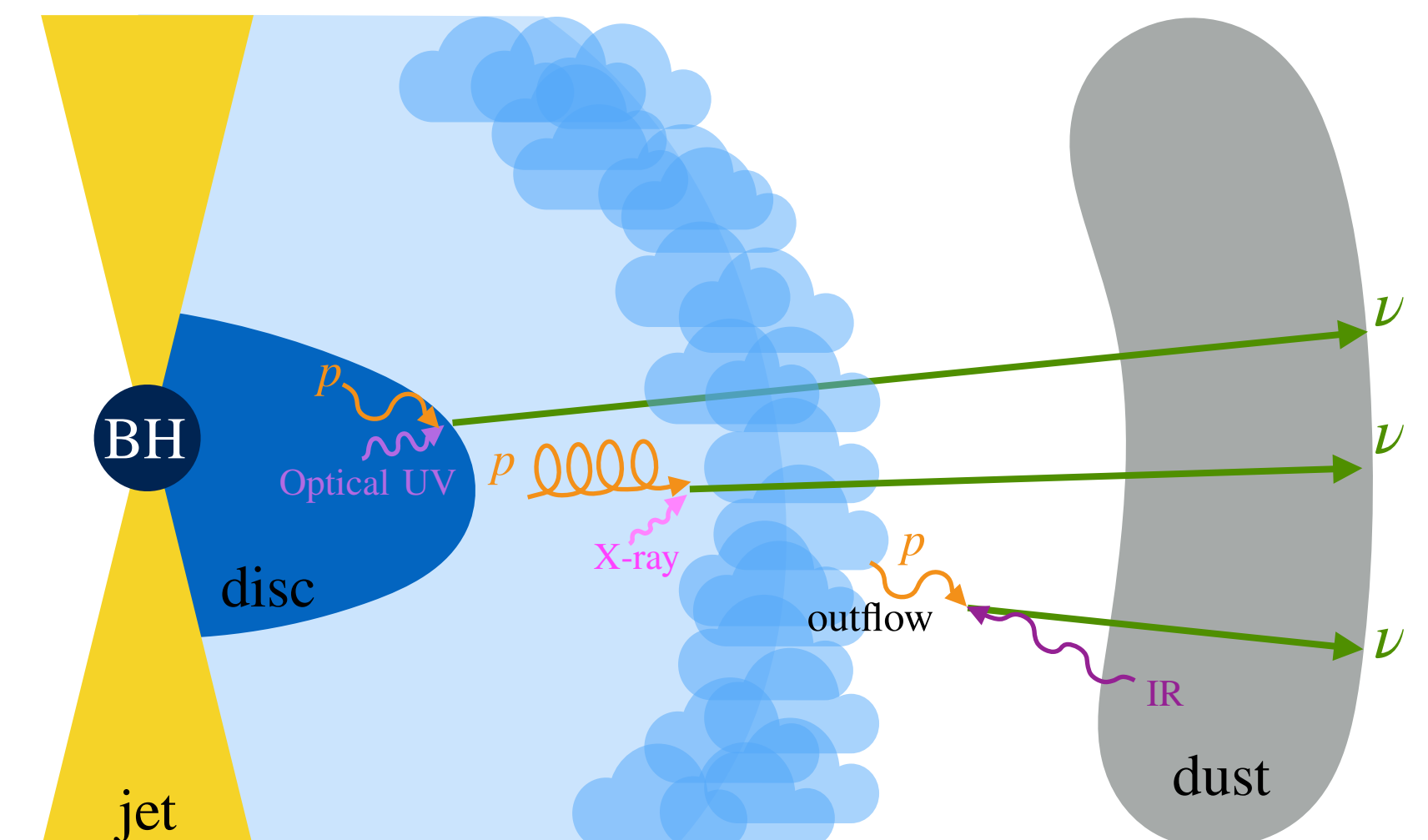
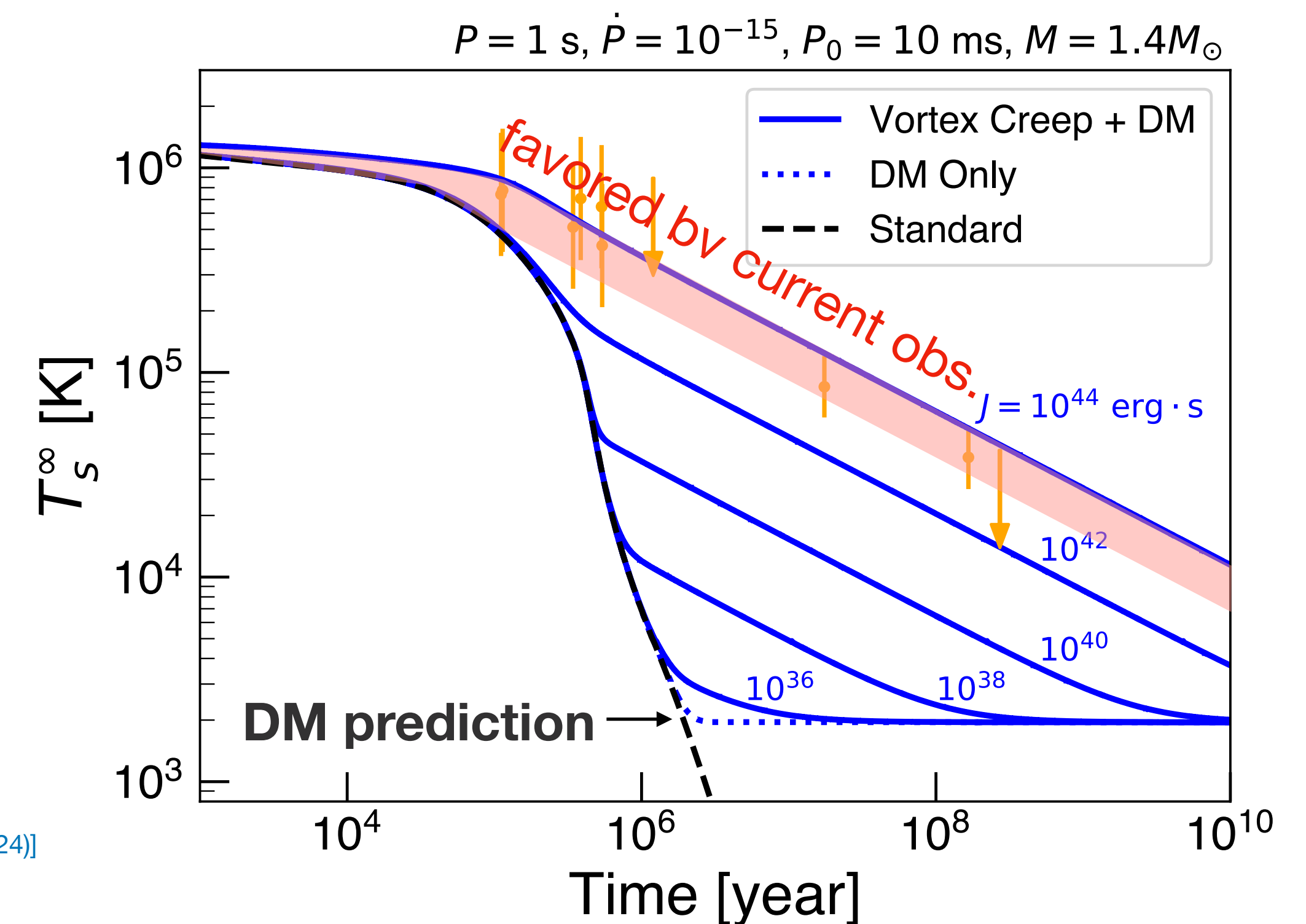
Further compact?

Neutron star

- Scattering & annihilation can anomalously heat old stars
- Several challenges to probe DM
 - Faint flux ($\sim \text{nJy}$) even from the target within $\sim 10 \text{ pc}$
[M. Baryakhtar et al. (2017)] [Chatterjee, et al. (2023)]
 - Background heating (friction by neutron superfluid properties)
[Alpar, et al. (1984)] [Shibazaki, et al. (1989)] [Gonzalez, et al. (2010)] [MF, Hamaguchi, Nagata, Ramirez-Quezada JCAP & PLB (2024)]

(Supermassive) Blackhole

- Gravitational potential of Blackhole attracts Dark Matter
- High energy particle emission around blackhole
 - Scatter w/ Dark Matter before reaching telescope
 - Constrain Dark Matter scattering cross section
- Neutrino sources
 - TXS 0506+056 [J. M. Cline, et al. (2023)] [F. Ferrer, G. Herrera, A. Ibarra (2023)]
 - NGC1068 [J. M. Cline, M. Puel (2023)]
 - Candidates of Tidal Disruption Event [MF, G. Herrera (2024)]



sketch for Tidal disruption event



BU:

NREFT (Majorana fermion)



NREFT

Operator basis

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_2 = (v^\perp)^2$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$

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

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

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

$$\mathcal{O}_{16} = -\left((\vec{S}_\chi \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right).$$

WIMP-nucleon interaction $\mathcal{L}_{\text{int}}$

Interaction basis (e.g. Majorana fermion)

- Building block : $\{\chi, N, \Gamma, P^\mu, K^\mu\}$
 - Scalar operator

Majorana DM

Nucleon

• Scalar

$\parallel \bar{\chi}\chi$

$\bar{N}N$

• Pseudoscalar

$\parallel \bar{\chi}i\gamma^5\chi$

$\bar{N}i\gamma^5N$
 - 4-vector operator

• Scalar + Momentum

$\parallel \bar{\chi}P^\mu\chi$

$\bar{N}K_\mu N$

• Pseudoscalar + Momentum

$\parallel \bar{\chi}P^\mu\gamma^5\chi$

$\bar{N}K_\mu\gamma^5N$

• Axial vector

$\parallel \bar{\chi}\gamma^\mu\gamma^5\chi$

$\bar{N}\gamma_\mu\gamma^5N$

• Tensor + Momentum

$\parallel \bar{\chi}\sigma^{\mu\nu}q_\nu\chi$

$\bar{N}\sigma_{\mu\nu}q_\nu N$

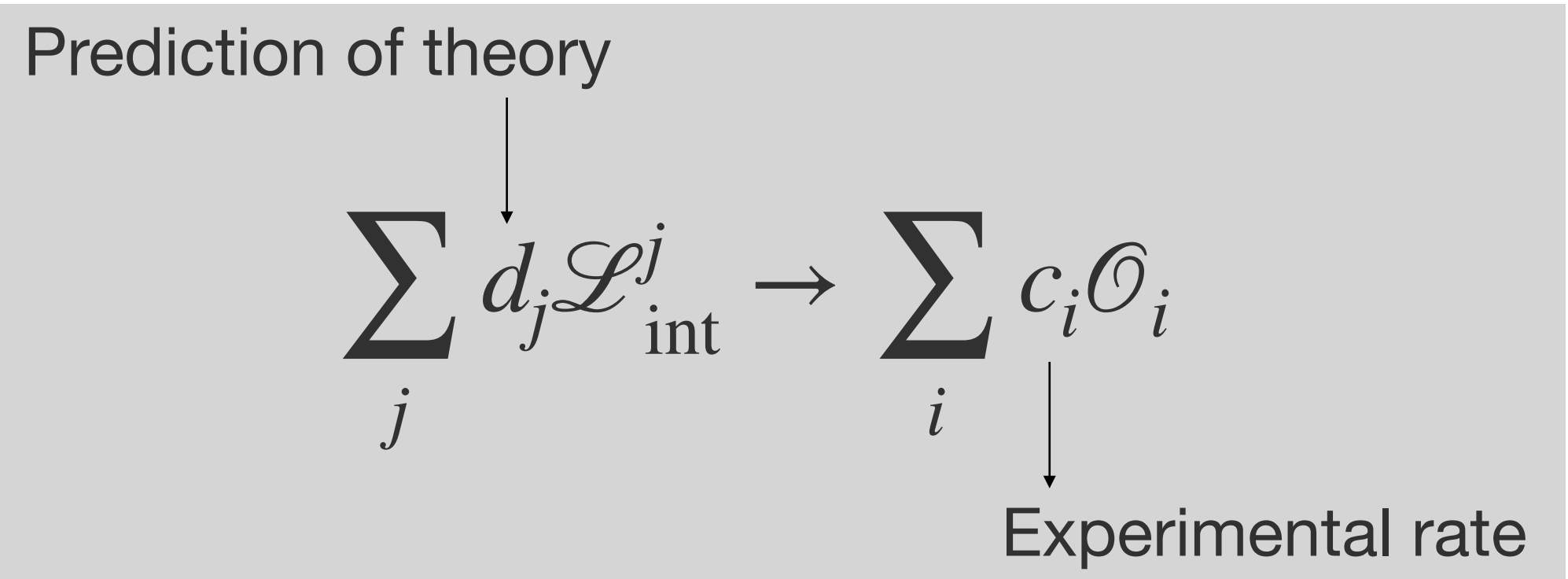
Lorentz invariant operator basis : $2^2 + 4^2 = 20$

j	$\mathcal{L}_{\text{int}}^j$
1	$\bar{\chi}\chi\bar{N}N$
2	$i\bar{\chi}\chi\bar{N}\gamma^5N$
3	$i\bar{\chi}\gamma^5\chi\bar{N}N$
4	$\bar{\chi}\gamma^5\chi\bar{N}\gamma^5N$
5	$\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}N$
6	$\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$
7	$\frac{P^\mu}{m_M}\bar{\chi}\chi\bar{N}\gamma_\mu\gamma^5N$
8	$i\frac{P^\mu}{m_M}\bar{\chi}\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5N$
9	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}N$
10	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$
11	$\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar{N}\gamma^\mu\gamma^5N$
12	$i\bar{\chi}i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5N$
13	$\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$
14	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$
15	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma^\mu\gamma^5N$
16	$i\bar{\chi}\gamma^\mu\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5N$
17	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}N$
18	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$
19	$i\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\bar{N}\gamma_\mu\gamma^5N$
20	$\frac{P^\mu}{m_M}\bar{\chi}\gamma^5\chi\frac{K_\mu}{m_M}\bar{N}\gamma^5N$

Matching

Procedure (e.g. Majorana fermion)

- Writing down all combination of WIMP-nucleon op.
- Non-relativistic reduction of amplitude
- Matching w/ NREFT operators
 - $\mathcal{L}_{\text{int}} \quad : \{ \chi, N, \Gamma, P^\mu, K^\mu \}$
 - $\mathcal{M}_{\text{NR}} \quad : \{ \vec{S}_\chi, \vec{S}_N, \vec{q}, \vec{v}^\perp \}$
 - $\mathcal{O}_i \quad : \{ \mathcal{O}_1 = \mathbf{1}_\chi \mathbf{1}_N, \cdots \}$



j	$\mathcal{L}_{\text{int}}^j$	Nonrelativistic Reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar{\chi} \chi \bar{N} N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i \bar{\chi} \chi \bar{N} \gamma^5 N$	$i \frac{\vec{q}}{m_N} \cdot \vec{S}_N$	$\mathcal{O}_{10}$	O/O
3	$i \bar{\chi} \gamma^5 \chi \bar{N} N$	$-i \frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi$	$-\frac{m_N}{m_\chi} \mathcal{O}_{11}$	O/O
4	$\bar{\chi} \gamma^5 \chi \bar{N} \gamma^5 N$	$-\frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi \frac{\vec{q}}{m_N} \cdot \vec{S}_N$	$-\frac{m_N}{m_\chi} \mathcal{O}_6$	E/E
5	$\frac{P^\mu}{m_M} \bar{\chi} \chi \frac{K_\mu}{m_M} \bar{N} N$	$4 \frac{m_\chi m_N}{m_M^2} 1_\chi 1_N$	$4 \frac{m_\chi m_N}{m_M^2} \mathcal{O}_1$	E/E
6	$\frac{P^\mu}{m_M} \bar{\chi} \chi \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} N$	$-\frac{m_\chi}{m_N} \frac{\vec{q}^2}{m_M^2} 1_\chi 1_N - 4i \frac{m_\chi}{m_M} \vec{v}^\perp \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$-\frac{m_\chi}{m_N} \frac{\vec{q}^2}{m_M^2} \mathcal{O}_1 + 4 \frac{m_\chi m_N}{m_M^2} \mathcal{O}_3$	E/E
7	$\frac{P^\mu}{m_M} \bar{\chi} \chi \bar{N} \gamma_\mu \gamma^5 N$	$-4 \frac{m_\chi}{m_M} \vec{v}^\perp \cdot \vec{S}_N$	$-4 \frac{m_\chi}{m_M} \mathcal{O}_7$	O/E
8	$i \frac{P^\mu}{m_M} \bar{\chi} \chi \frac{K_\mu}{m_M} \bar{N} \gamma^5 N$	$4i \frac{m_\chi}{m_M} \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$4 \frac{m_\chi m_N}{m_M^2} \mathcal{O}_{10}$	O/O
9	$\bar{\chi} i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \frac{K_\mu}{m_M} \bar{N} N$	$\frac{m_N}{m_\chi} \frac{\vec{q}^2}{m_M^2} 1_\chi 1_N + 4i \frac{m_N}{m_M} \vec{v}^\perp \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right)$	$\frac{m_N}{m_\chi} \frac{\vec{q}^2}{m_M^2} \mathcal{O}_1 - 4 \frac{m_N^2}{m_M^2} \mathcal{O}_5$	E/E
10	$\bar{\chi} i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} N$	$4 \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$4 \left(\frac{\vec{q}^2}{m_M^2} \mathcal{O}_4 - \frac{m_N^2}{m_M^2} \mathcal{O}_6 \right)$	E/E
11	$\bar{\chi} i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \bar{N} \gamma^\mu \gamma^5 N$	$-4i \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \cdot \vec{S}_N$	$-4 \frac{m_N}{m_M} \mathcal{O}_9$	O/E
12	$i \bar{\chi} i \sigma^{\mu\nu} \frac{q_\nu}{m_M} \chi \frac{K_\mu}{m_M} \bar{N} \gamma^5 N$	$\left[i \frac{\vec{q}^2}{m_\chi m_M} - 4 \vec{v}^\perp \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_\chi \right) \right] \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$\frac{m_N}{m_\chi} \frac{\vec{q}^2}{m_M^2} \mathcal{O}_{10} + 4 \frac{\vec{q}^2}{m_M^2} \mathcal{O}_{12} + 4 \frac{m_N^2}{m_M^2} \mathcal{O}_{15}$	O/O
13	$\bar{\chi} \gamma^\mu \gamma^5 \chi \frac{K_\mu}{m_M} \bar{N} N$	$4 \frac{m_N}{m_M} \vec{v}^\perp \cdot \vec{S}_\chi$	$4 \frac{m_N}{m_M} \mathcal{O}_8$	O/E
14	$\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} N$	$-4i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$	$4 \frac{m_N}{m_M} \mathcal{O}_9$	O/E
15	$\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma^\mu \gamma^5 N$	$-4 \vec{S}_\chi \cdot \vec{S}_N$	$-4 \mathcal{O}_4$	E/E
16	$i \bar{\chi} \gamma^\mu \gamma^5 \chi \frac{K_\mu}{m_M} \bar{N} \gamma^5 N$	$4i \vec{v}^\perp \cdot \vec{S}_\chi \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$4 \frac{m_N}{m_M} \mathcal{O}_{13}$	E/O
17	$i \frac{P^\mu}{m_M} \bar{\chi} \gamma^5 \chi \frac{K_\mu}{m_M} \bar{N} N$	$-4i \frac{m_N}{m_M} \frac{\vec{q}}{m_M} \cdot \vec{S}_\chi$	$-4 \frac{m_N^2}{m_M^2} \mathcal{O}_{11}$	O/O
18	$i \frac{P^\mu}{m_M} \bar{\chi} \gamma^5 \chi \bar{N} i \sigma_{\mu\alpha} \frac{q^\alpha}{m_M} N$	$\frac{\vec{q}}{m_M} \cdot \vec{S}_\chi \left[i \frac{\vec{q}^2}{m_N m_M} - 4 \vec{v}^\perp \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right) \right]$	$\frac{\vec{q}^2}{m_M^2} \mathcal{O}_{11} + 4 \frac{m_N^2}{m_M^2} \mathcal{O}_{15}$	O/O
19	$i \frac{P^\mu}{m_M} \bar{\chi} \gamma^5 \chi \bar{N} \gamma_\mu \gamma^5 N$	$4i \frac{\vec{q}}{m_M} \cdot \vec{S}_\chi \vec{v}^\perp \cdot \vec{S}_N$	$4 \frac{m_N}{m_M} \mathcal{O}_{14}$	E/O
20	$\frac{P^\mu}{m_M} \bar{\chi} \gamma^5 \chi \frac{K_\mu}{m_M} \bar{N} \gamma^5 N$	$-4 \frac{\vec{q}}{m_M} \cdot \vec{S}_\chi \frac{\vec{q}}{m_M} \cdot \vec{S}_N$	$-4 \frac{m_N^2}{m_M^2} \mathcal{O}_6$	E/E



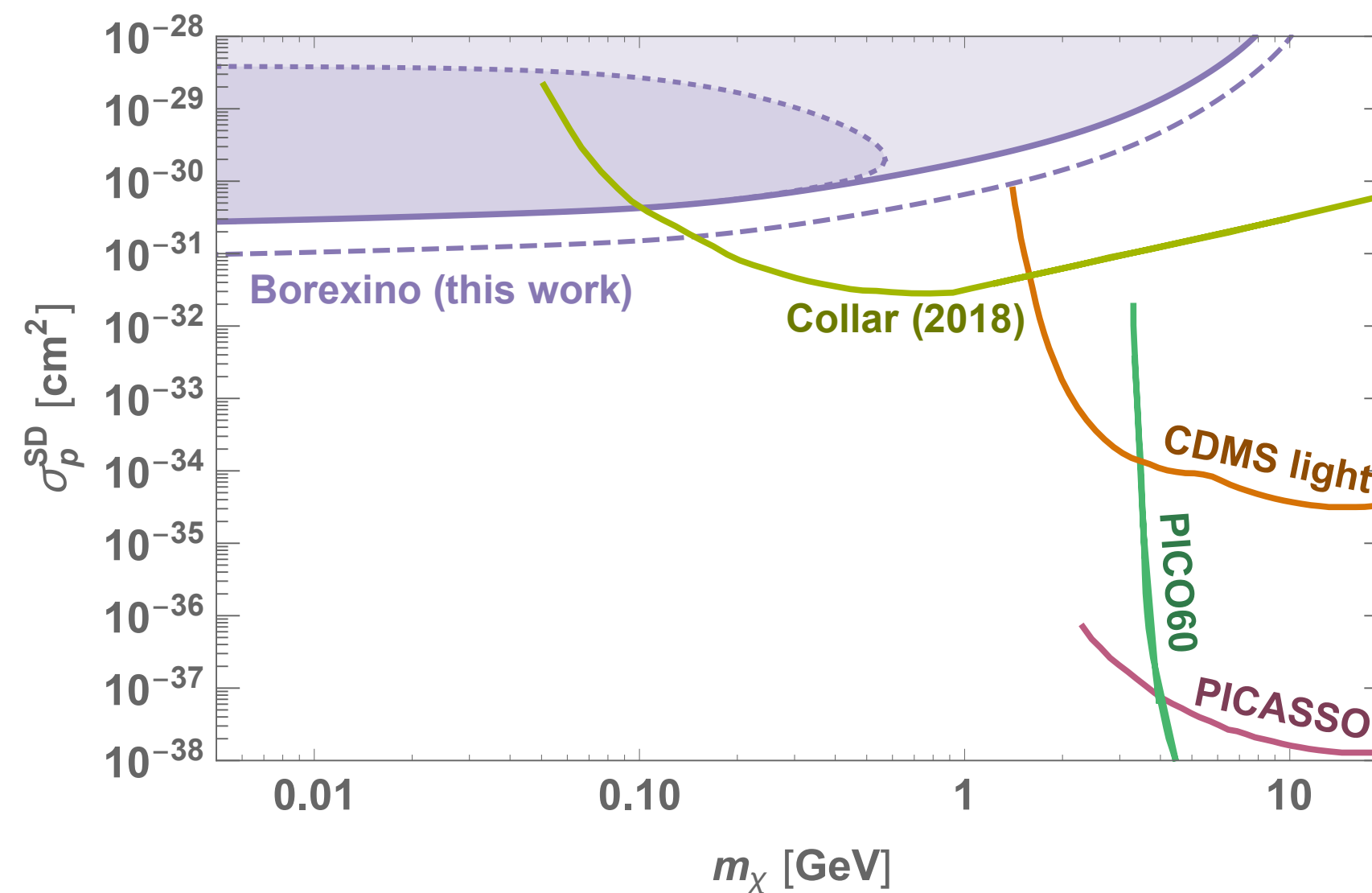
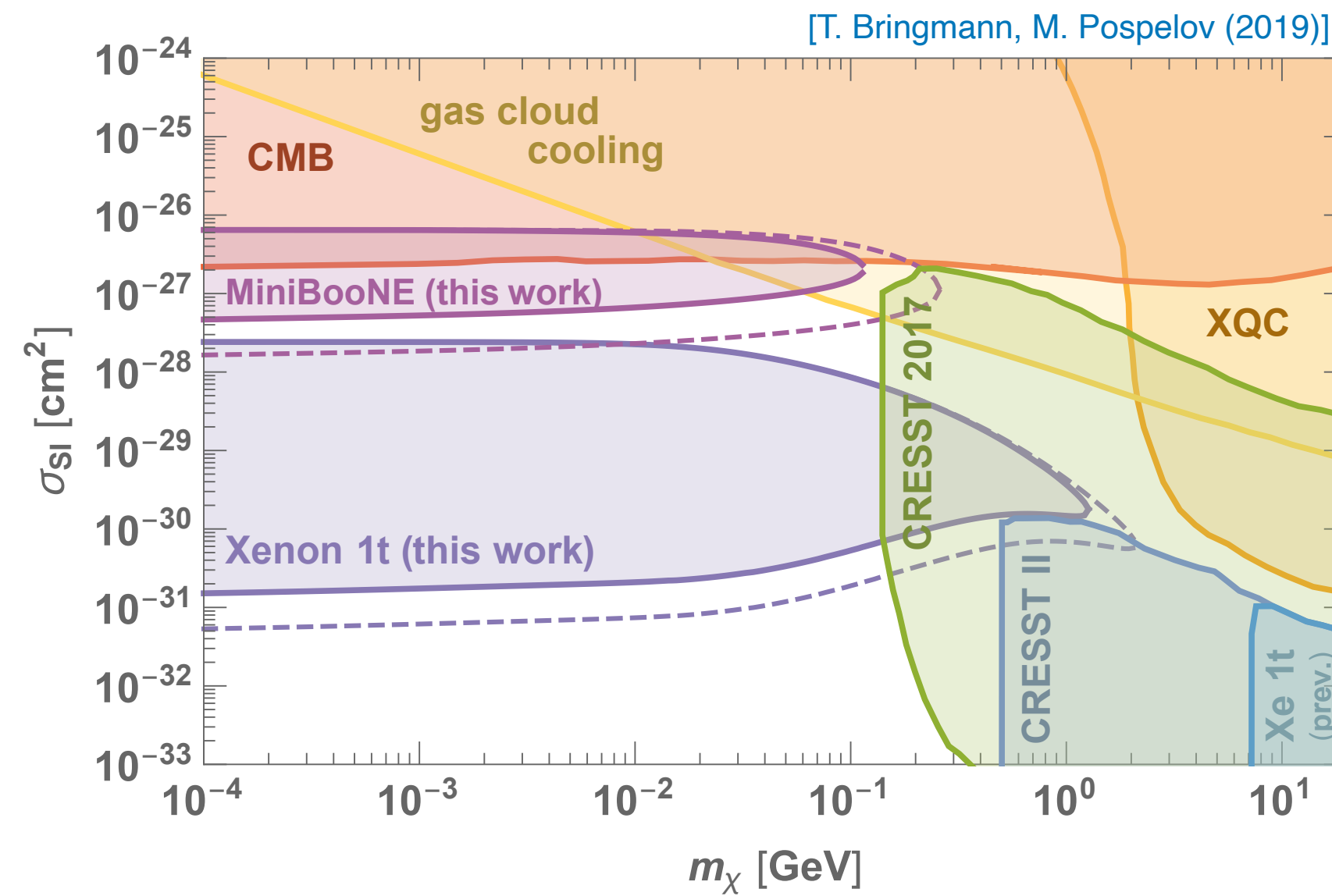
BU:

Details on Boosted DM

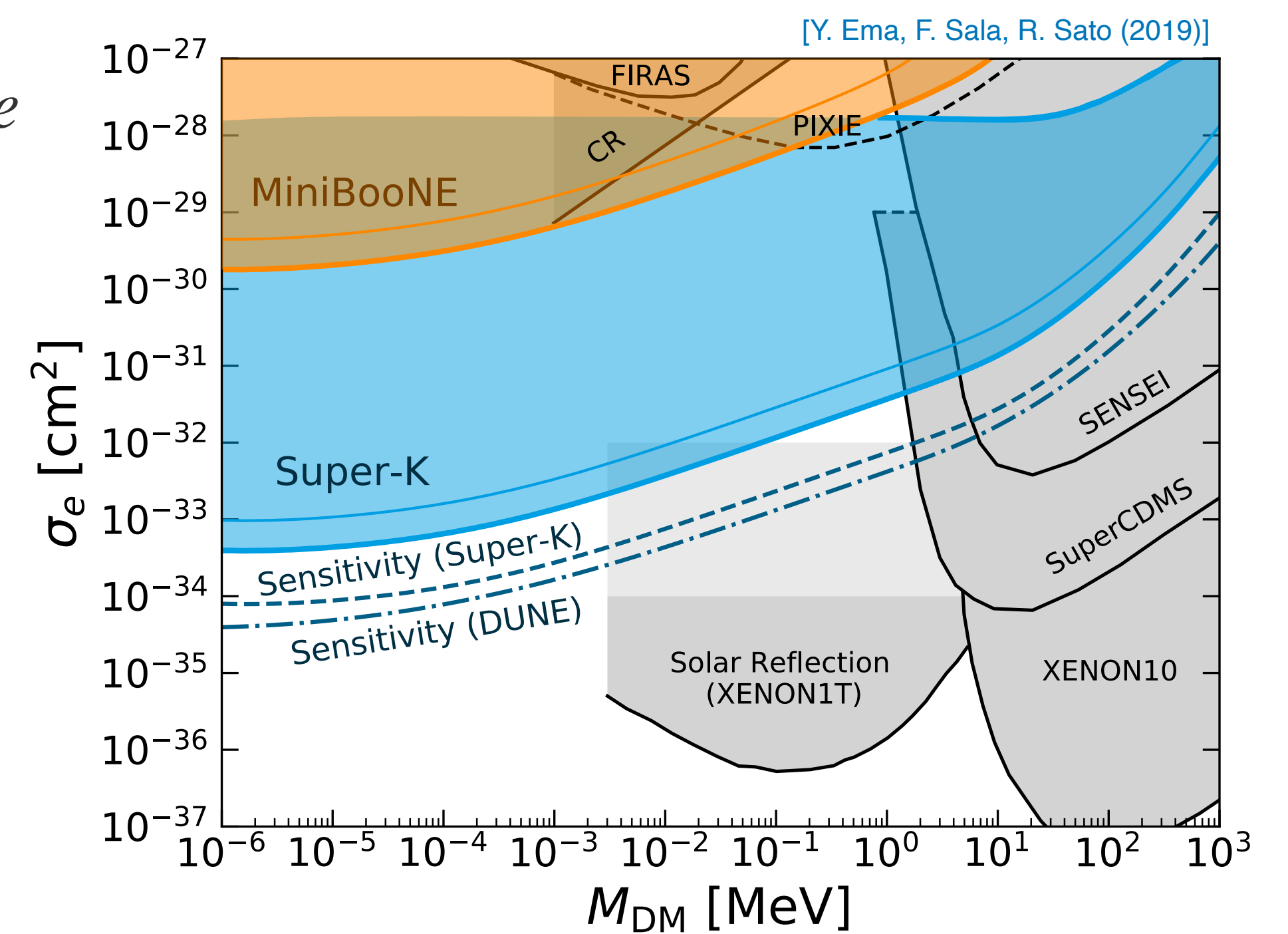


Cosmic-ray Boosted DM

$\chi - p$

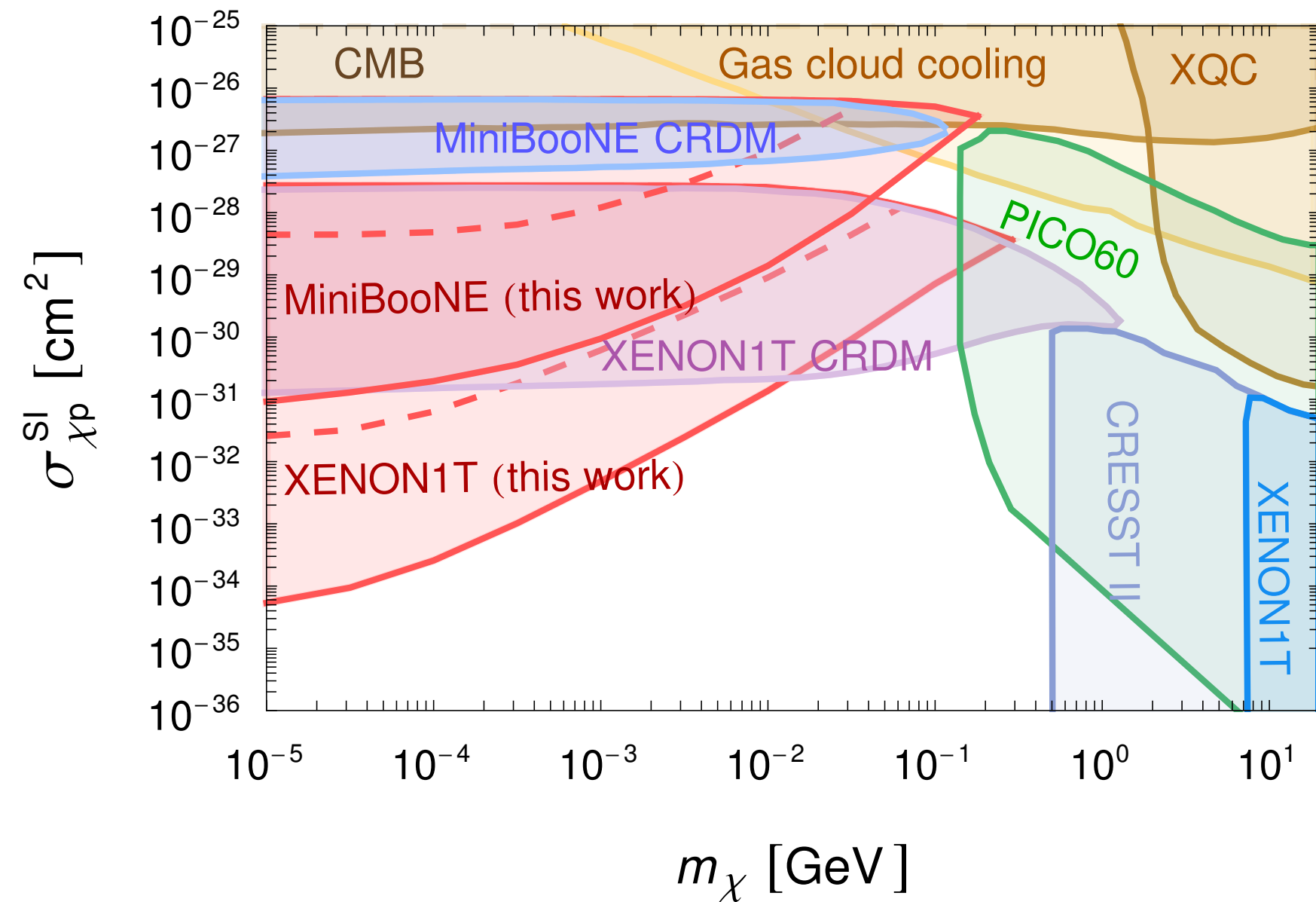
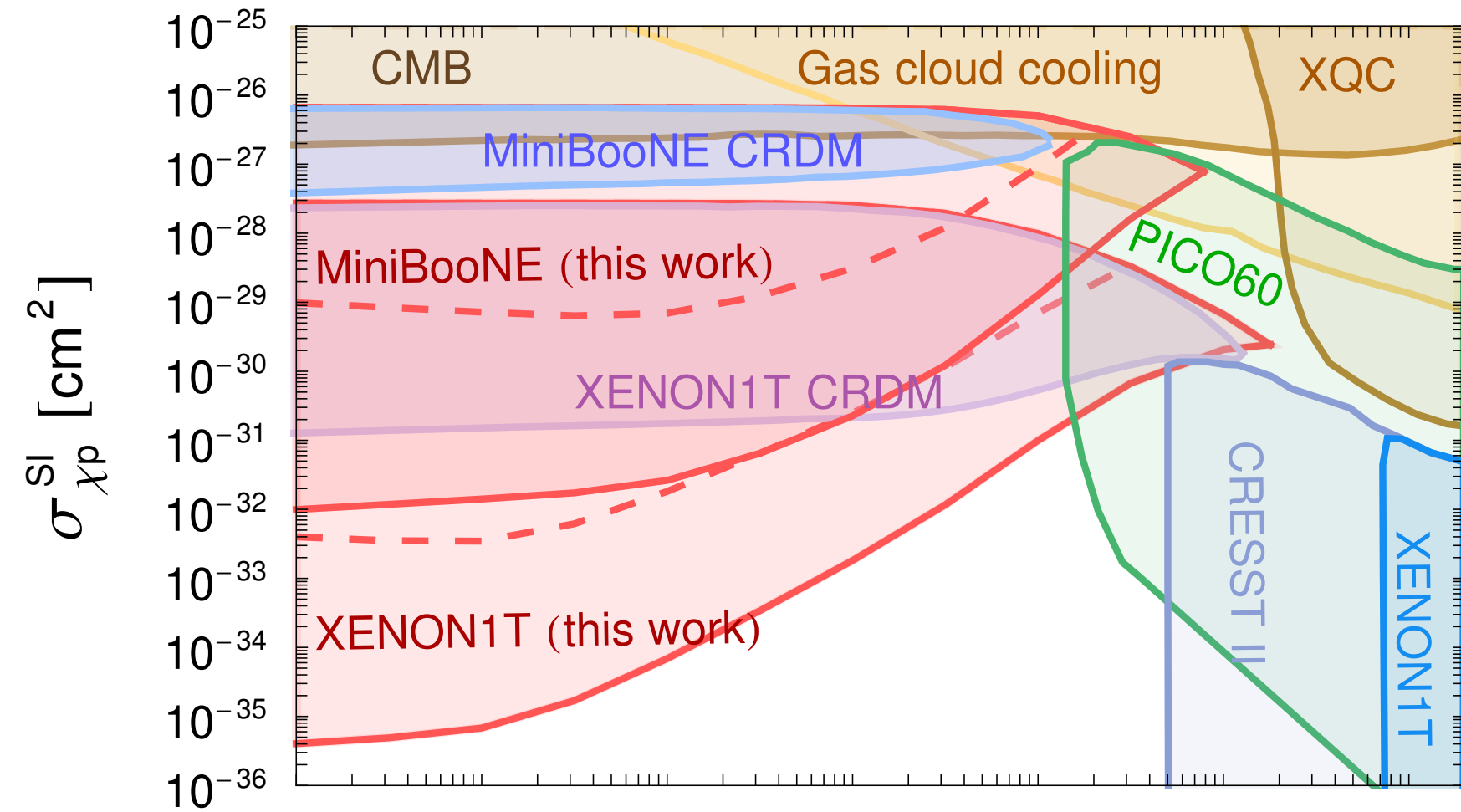


$\chi - e$



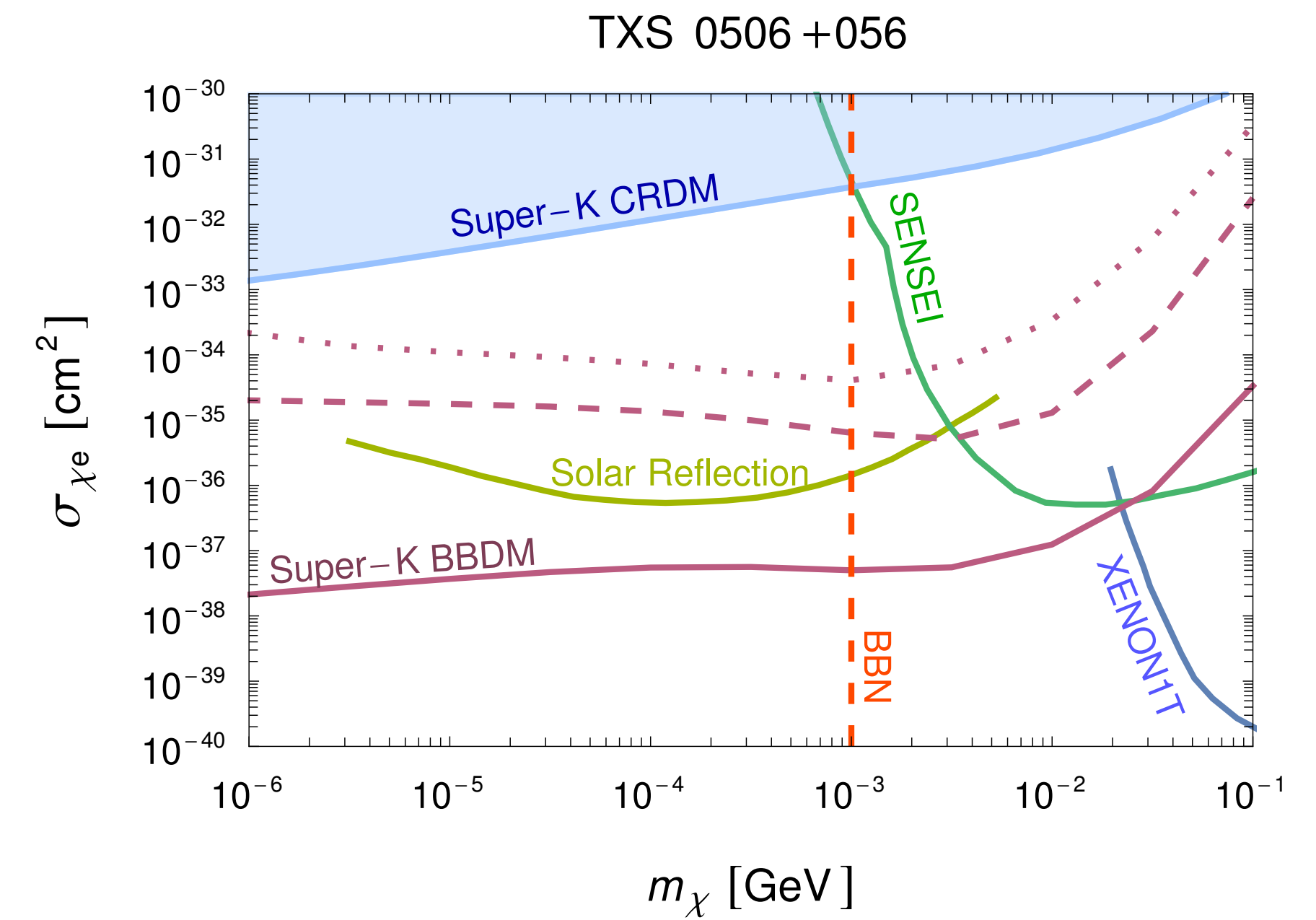
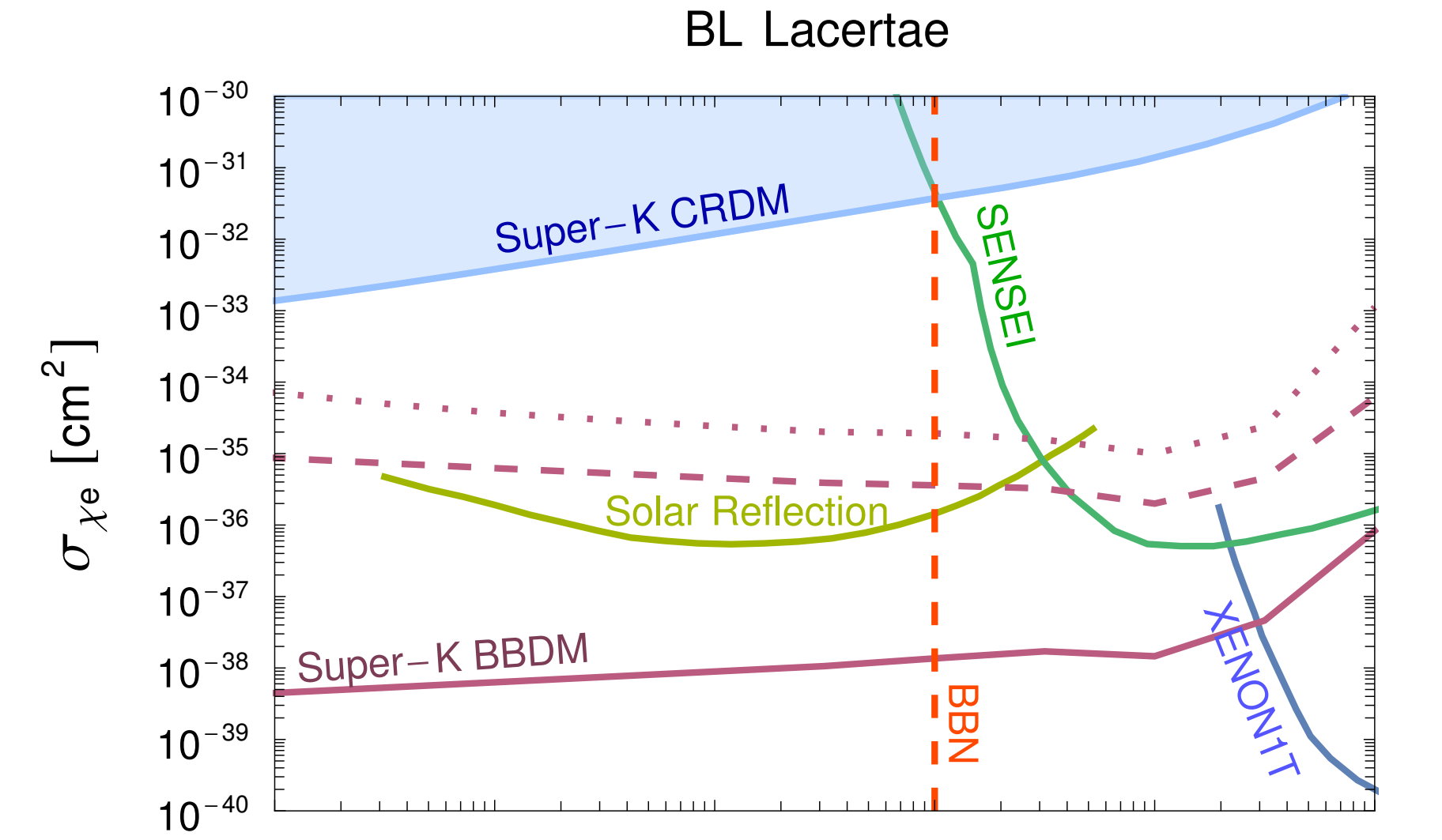
Blazar Boosted DM

$\chi - p$



[J-W. Wang, A. Granelli, P. Ulli (2022)]

$\chi - e$



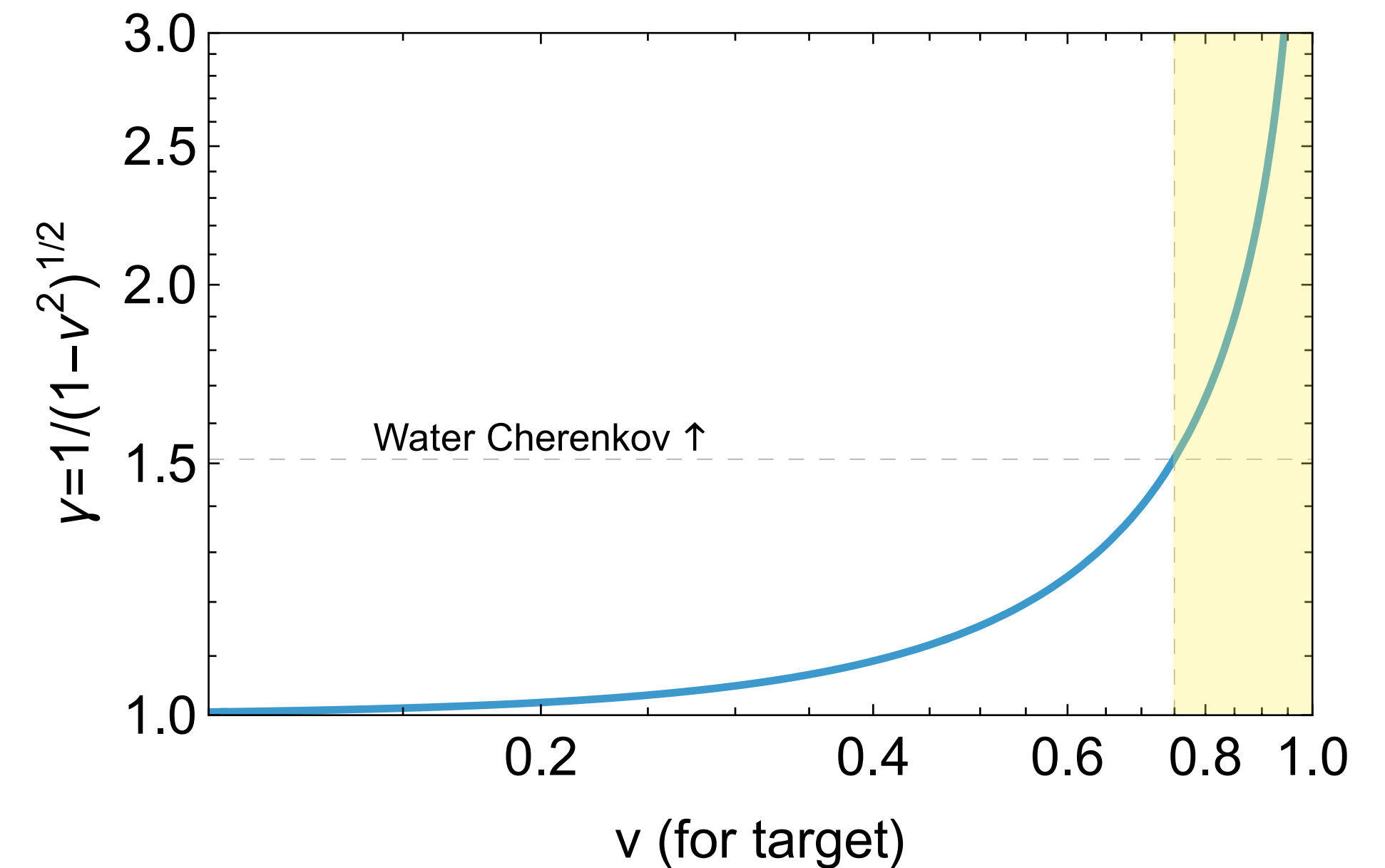
[A. Granelli, P. Ullio, J-W. Wang (2022)]

Semi-annihilation

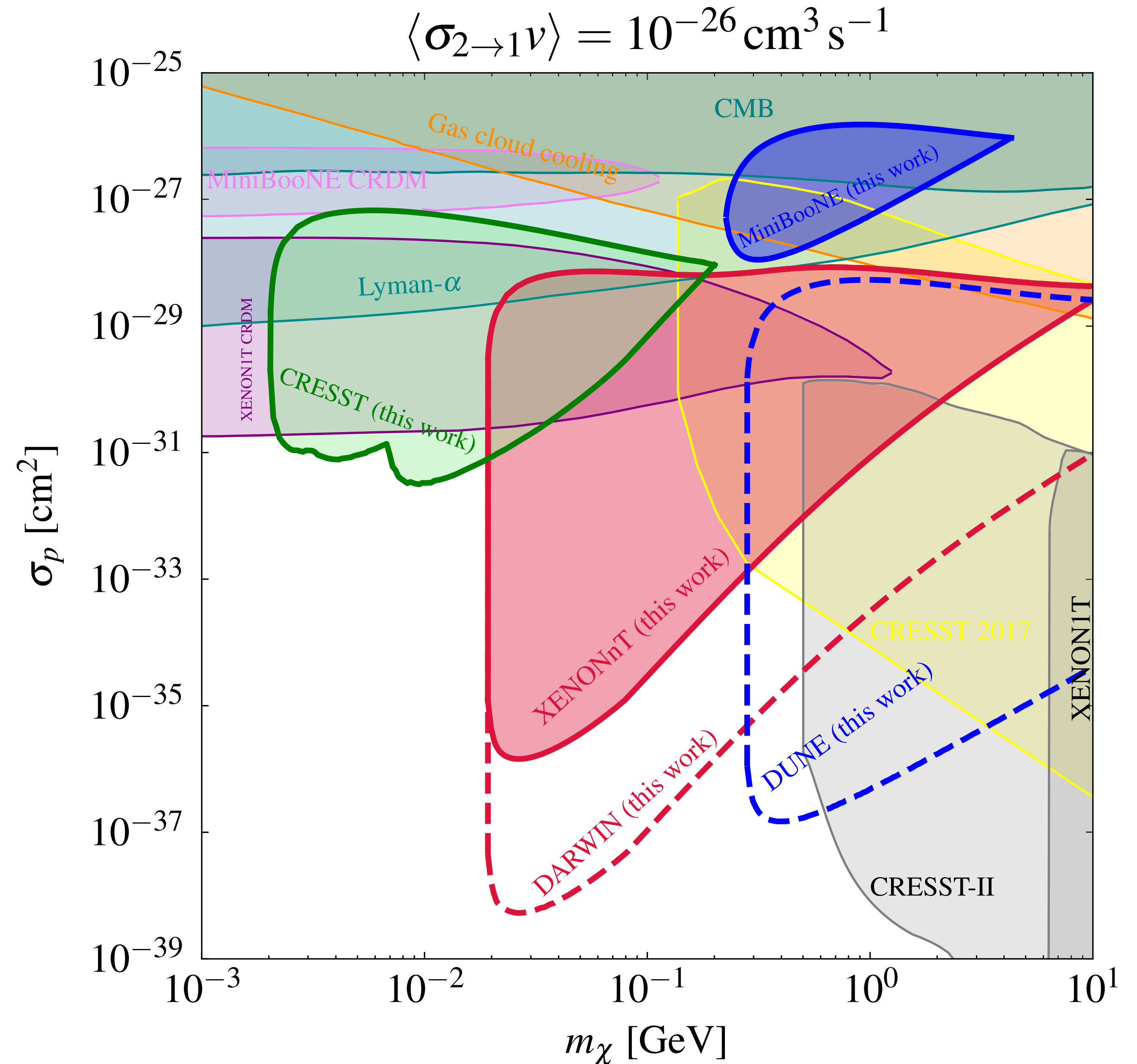
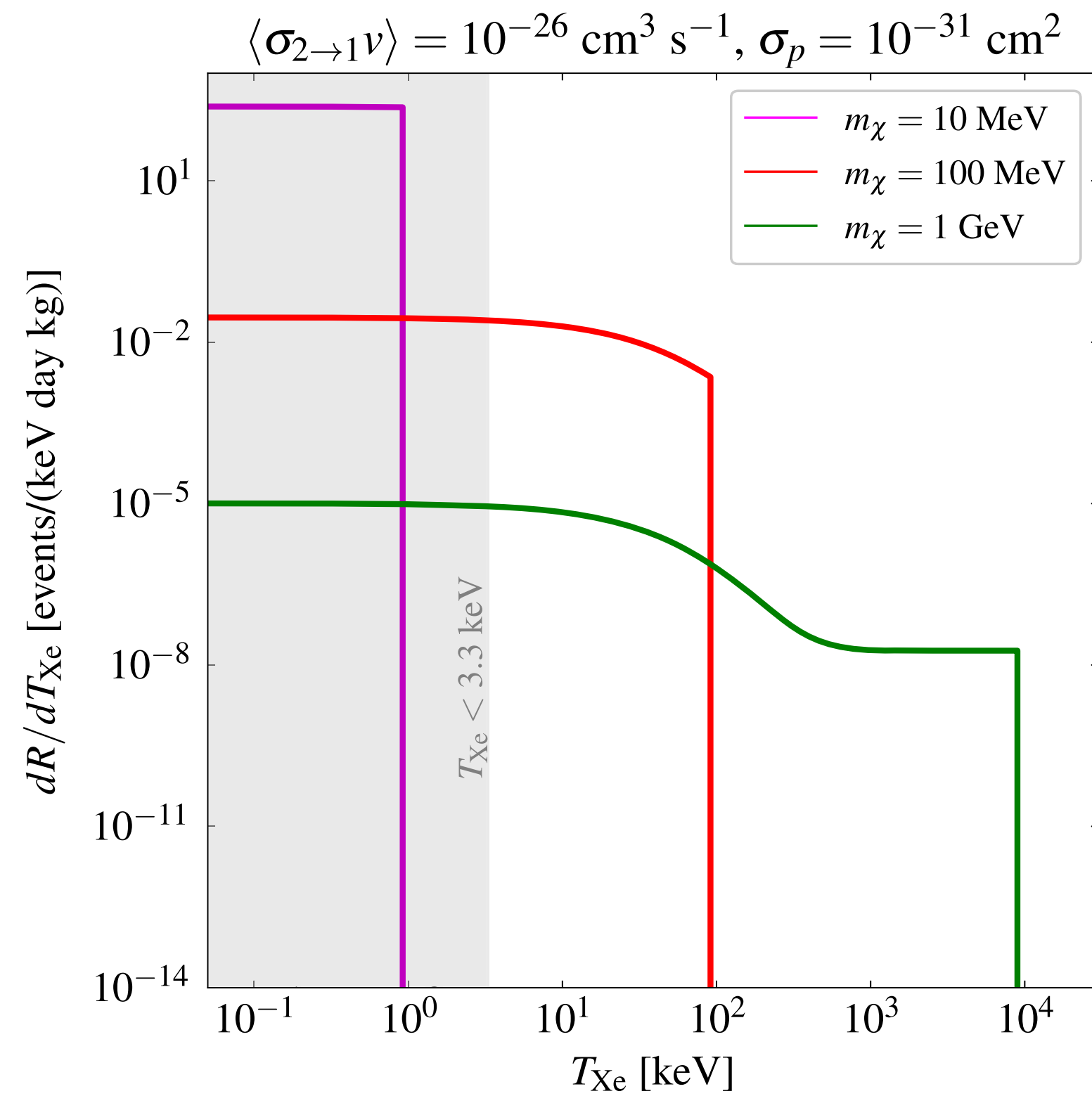
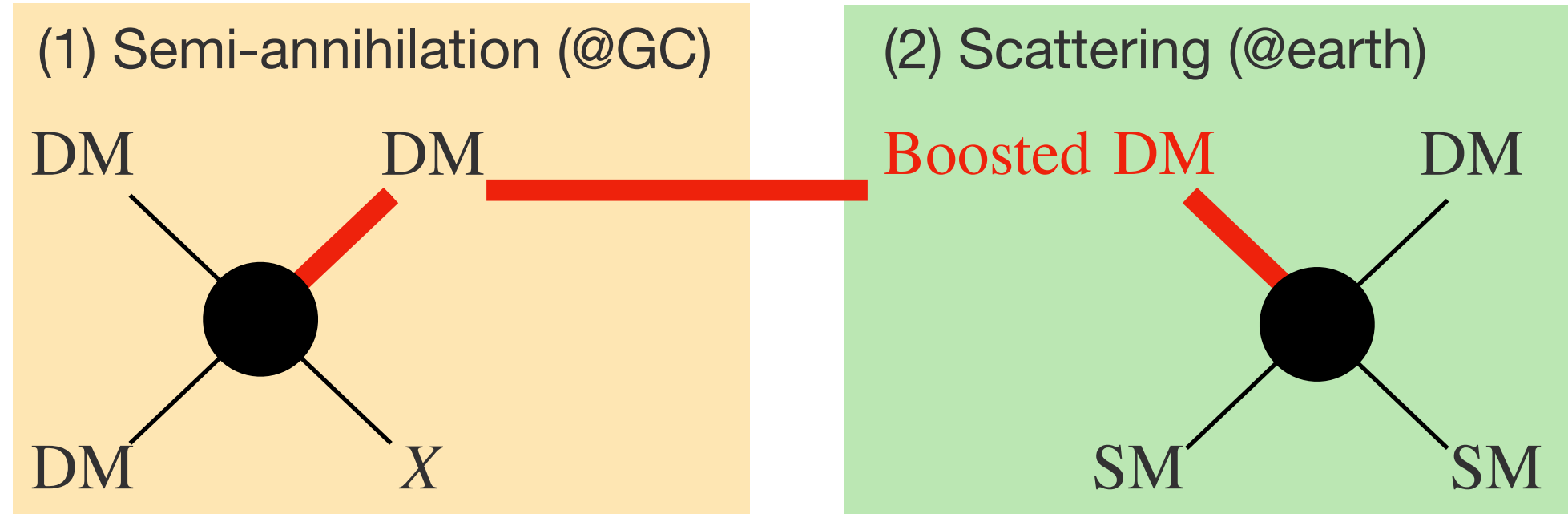
Kinematics

- $\chi + \chi \rightarrow \chi + \phi$ (ϕ :annihilation partner)
- For (effectively) massless partner
 - Initial DM pair : $(2m_{\text{DM}}, \mathbf{0})$
 - Final DM (boosted) : $\left(\sqrt{|\mathbf{p}|^2 + m_{\text{DM}}^2}, \mathbf{p} \right)$
 - Annihilation partner : $(|\mathbf{p}|, -\mathbf{p})$
- Momentum conservation determines kinematics for boosted DM

semi-annihilation	$\parallel$	$3 \rightarrow 2$	$\parallel$	$4 \rightarrow 2$
• Energy	$\parallel$	$E_{\text{DM}} = \frac{5}{4}m_{\text{DM}}$	$\parallel$	$E_{\text{DM}} = \frac{3}{2}m_{\text{DM}} \parallel E_{\text{DM}} = 2m_{\text{DM}}$
• Velocity	$\parallel$	$v = \frac{ \mathbf{p} }{E} = 0.6$	$\parallel$	$v = 0.7 \parallel v = 0.87$
- Cherenkov threshold @ Water : $\gamma_{\text{Cherenkov}} = 1.51 \Rightarrow v_{\text{Cherenkov}} = 0.76$



Energy spectrum





BU:

LZ high energy scattering

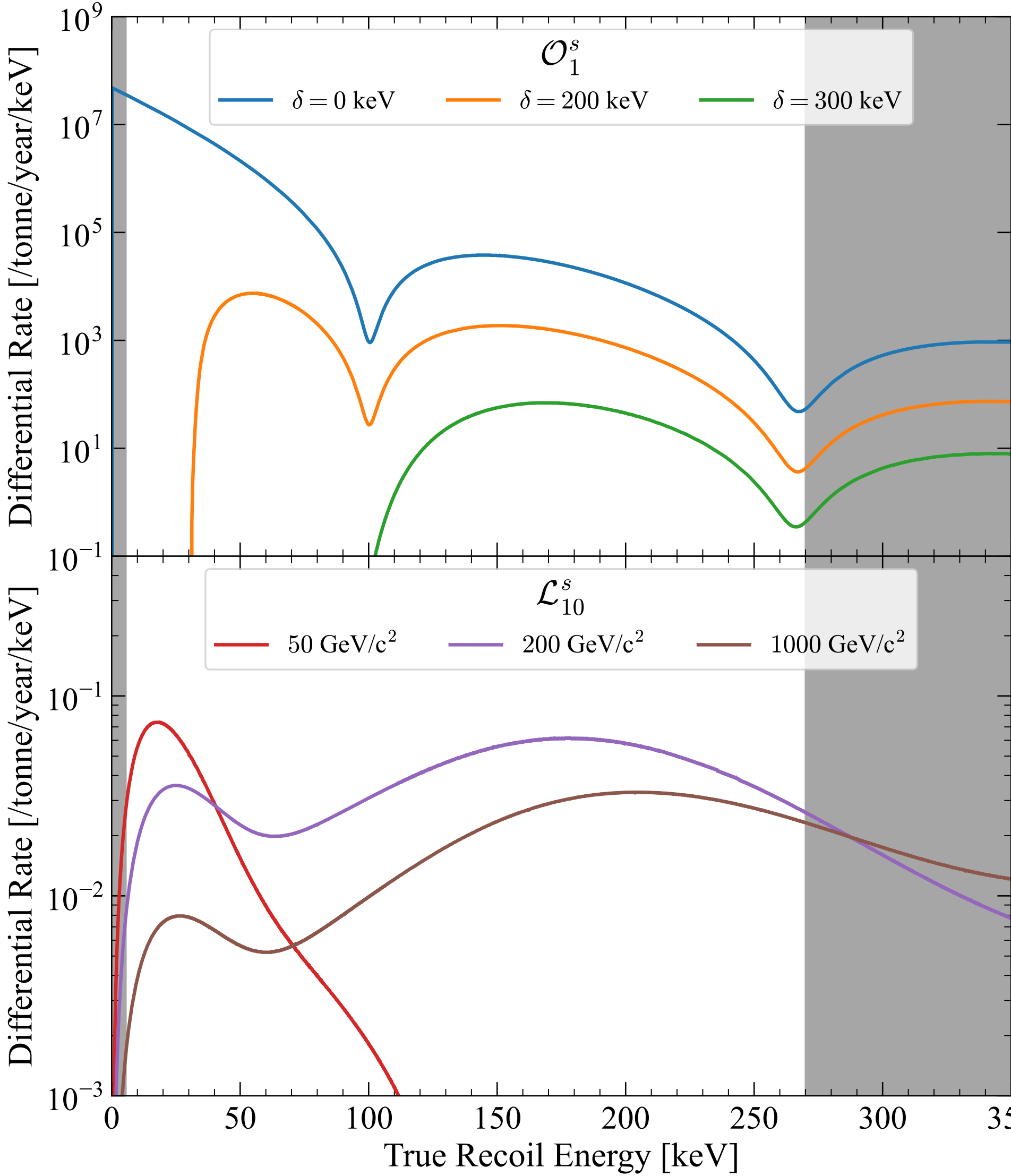


Operator analysis by LZ

L_i	WIMP Mass (GeV/c ²)												
	10	12	14	17	21	30	40	50	100	200	400	1000	4000
L_1^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L_1^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.3	1.2
L_2^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.8	2.9	3.0	3.1
L_2^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.5	3.0	3.1	3.1
L_3^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.5	1.7	1.8
L_3^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.2	2.5	2.6	2.7
L_4^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.6	3.1	3.1	3.1	3.0
L_4^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.7	3.1	3.2	3.1	3.1
L_5^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L_5^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.3	1.3
L_6^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	2.2	2.6	2.6	2.6
L_6^v	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	2.9	3.1	3.2	3.3	3.3
L_7^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	2.5	2.7	2.7	2.7
L_7^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	2.3	2.7	2.7	2.8
L_8^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.8	2.9	3.0	3.0
L_8^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.9	2.9	3.0	3.0
L_9^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.9	2.9	3.0	3.1
L_9^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	3.0	3.1	3.2	3.1
L_{10}^s	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	3.1	3.4	3.4	3.4
L_{10}^v	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.2	3.3	3.4	3.4
⋮													

Interaction	Mass (GeV/c ²)	Mass-splitting, δ (keV)							
		0	50	100	150	200	250	300	350
O_1^s	400	0.0	0.0	0.8	2.2	2.6	2.9	2.9	-
	1000	0.0	0.0	0.8	2.2	2.7	2.9	3.0	3.3
	4000	0.0	0.0	1.0	2.3	2.7	2.9	3.0	3.3
O_1^v	400	0.8	1.4	2.6	2.8	2.8	2.8	3.1	-
	1000	1.3	1.6	2.6	2.8	2.9	3.0	3.4	3.4
	4000	1.1	1.7	2.6	2.9	2.9	3.1	3.4	3.4
O_4^s	400	2.6	2.7	2.8	3.1	3.2	3.2	3.3	-
	1000	2.7	2.8	2.8	3.0	3.2	3.2	3.4	3.4
	4000	2.8	3.0	3.0	3.1	3.2	3.3	3.4	3.4
O_4^v	400	2.6	2.7	2.8	3.1	3.2	3.2	3.3	-
	1000	2.7	2.8	2.8	3.0	3.2	3.2	3.3	3.4
	4000	2.8	3.0	3.0	3.1	3.2	3.3	3.4	3.4

s : isoscalar $\parallel c^{(s)} \propto c_p + c_n$
 v : isovector $\parallel c^{(v)} \propto c_p - c_n$



Annual modulation

Velocity dep. of inelastic signature

- Inelastic scattering interpretation of High energy event @LZ
→ Depending on velocity tail
- Annual modulation can be important
- Interesting parameter regions show 50-100% modulation
- Further large volume detector (e.g. XLZD & PandaX) could be direct test

Inelastic explanation depends on velocity tail
→ **Annual modulation can be significant**

