Status of Boosted Dark Matter (BDM)

DARK MATTER
ZERO CARB CONCENTRATE

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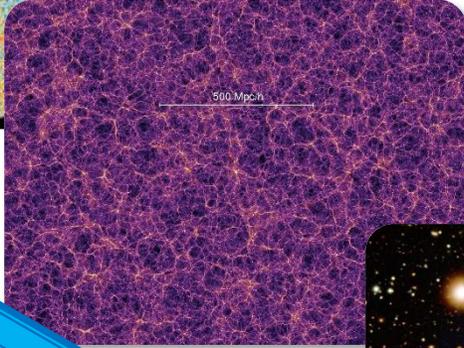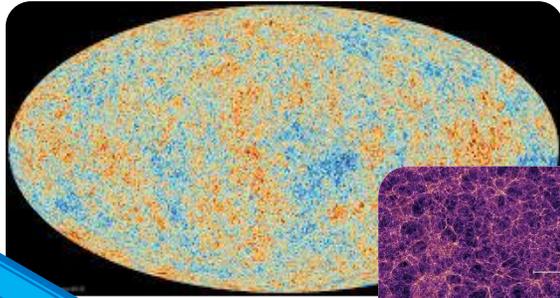
Outline

❖ **Dark Matter? Dark Sector?**

❖ **Boosted Dark Matter (BDM) & Its Searches**

❖ **Issues in BDM Searches**

❖ **Exciting Prospects for BDM Searches**
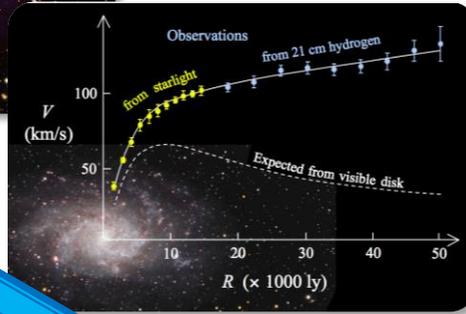
❖ **Cosmological & Astrophysical Effects**

❖ **Summary**

Dark Matter?
Dark Sector?

Message from Cosmology: Dark Matter (DM)

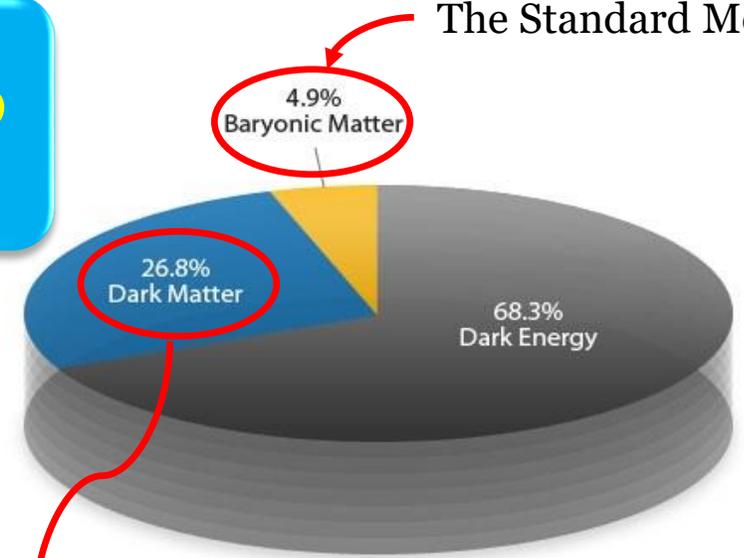*Dark Matter?*

❖ **Modern cosmology**:

The Standard Model

4.9% Baryonic Matter

26.8% Dark Matter

68.3% Dark Energy

Larger scale
Earlier

Smaller scale
Later

Many more other observations!

❖ **Compelling paradigm**:

✓ Massive,

✓ Non-relativistic ($v \ll c$),

✓ Non-luminous (no/tiny EM interaction),

✓ Stable particles

Dark Sector: Dark Particles & Portals

Portal

SM sector

Dark sector

$\chi_1, \chi_2, \chi_3, \dots$
$\phi_1, \phi_2, \phi_3, \dots$
$X_1, X_2, X_3, \dots$

Multiple stable & unstable particles, Various interactions

Multiple stable & unstable particles, Various interactions?

❖ **Portals**: mediators

- ✓ Vector portal (kinetic mixing): $\frac{\sin\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$

- ✓ Scalar (Higgs) portal: $\lambda_{H\phi}|H|^2|\phi|^2$

- ✓ Fermion (neutrino) portal: $\lambda_\chi HL\chi$

- ✓ Pseudo-scalar (axion) portal: $\frac{1}{f_{a\gamma/ag}} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

  $\frac{1}{f_{af}} \partial_\mu a (\bar{\psi}\gamma^\mu\gamma^5\psi)$

- ✓ Dilaton portal: $\frac{\sigma}{f}(M_V^2 V_\mu V^\mu + \dots + V_{\mu\nu}V^{\mu\nu} + \dots)$

- ✓ Gauged SM global #: B-L, L_μ-L_τ, …

- ✓ Dark axion portal: $G_{a\gamma\gamma'} a F_{\mu\nu}\tilde{X}^{\mu\nu}$

- ✓ Double portal: combination of portals [Belanger, Goudelis, **JCP** (2013)]

- ✓ ???
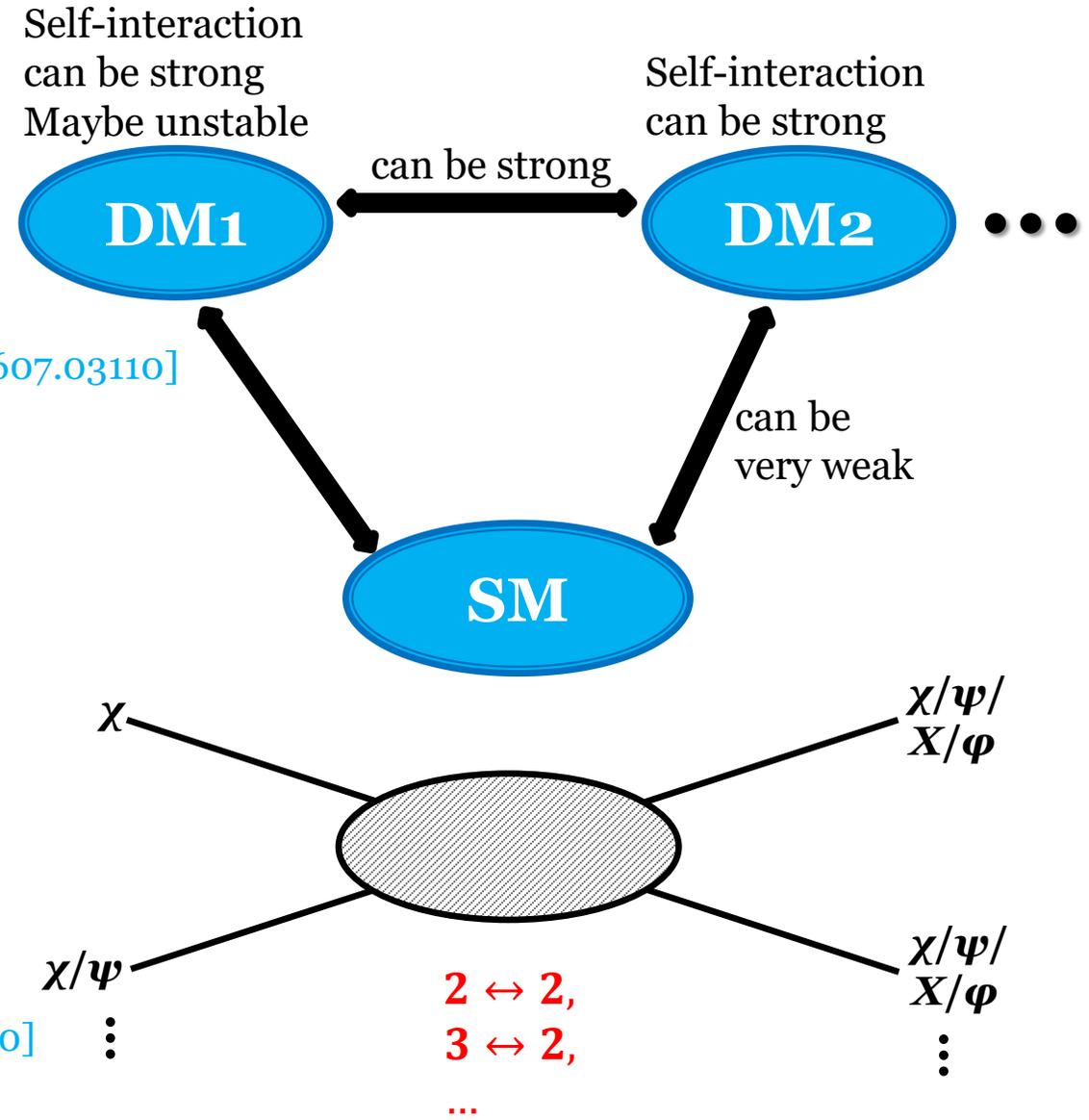
❖ **Dark sector particles**

- ✓ DM spin: fermion, scalar, vector

- ✓ DM species: single-/two-/multi-component

- ✓ DM mass: light, heavy, light & heavy

- ✓ DM interaction: flavor-conserving (elastic), flavor-changing (inelastic)

- ✓ ???

Various Ideas for DM

❖ **Various mechanisms** for DM relic determination:

- ✓ Assisted freeze-out [Belanger & **JCP**, 1112.4491]
- ✓ Asymmetric dark matter [0901.4117]
- ✓ Cannibal dark matter [1602.04219; 1607.03108]
- ✓ Co-annihilation [PRD43 (1991) 3191]
- ✓ Co-decaying dark matter [Bandyopadhyay, Chun, **JCP**, 1105.1652; 1607.03110]
- ✓ Continuum dark matter [2105.07035]
- ✓ Co-scattering mechanism [1705.08450]
- ✓ Dynamical dark matter [1106.4546]
- ✓ ELastically DEcoupling Relic (ELDER) [1512.04545]
- ✓ Freeze-in [0911.1120]
- ✓ Forbidden channels [PRD43 (1991) 3191; 1505.07107]
- ✓ Inverse decay dark matter [2111.14857]
- ✓ Pandemic dark matter [2103.16572]
- ✓ Semi-annihilation [0811.0172; 1003.5912]
- ✓ Strongly Interacting Massive Particle (SIMP) [1402.5143; 1702.07860]
- ✓ …

Self-interaction can be strong Maybe unstable

Self-interaction can be strong

DM1 — can be strong — **DM2** •••

can be very weak

SM

χ $\chi/\psi/X/\varphi$

χ/ψ $\chi/\psi/X/\varphi$

2 ↔ 2,
3 ↔ 2,
…

Current Status of DM Searches

10^{-21} eV	keV	MeV	GeV	TeV	PeV	$100 M_\odot \sim 10^{68}$ eV

Ultralight
axion, fuzzy, hidden photon,
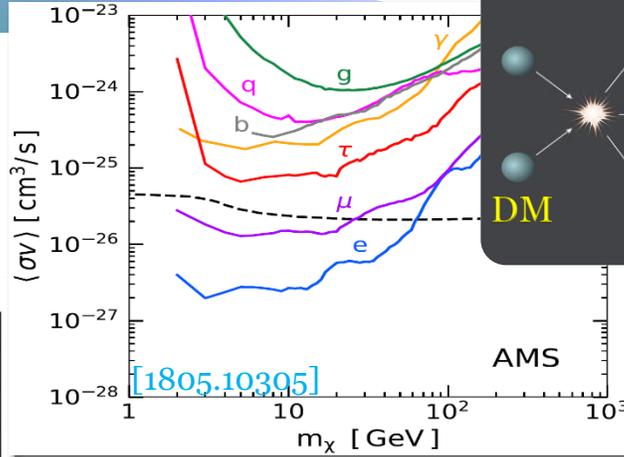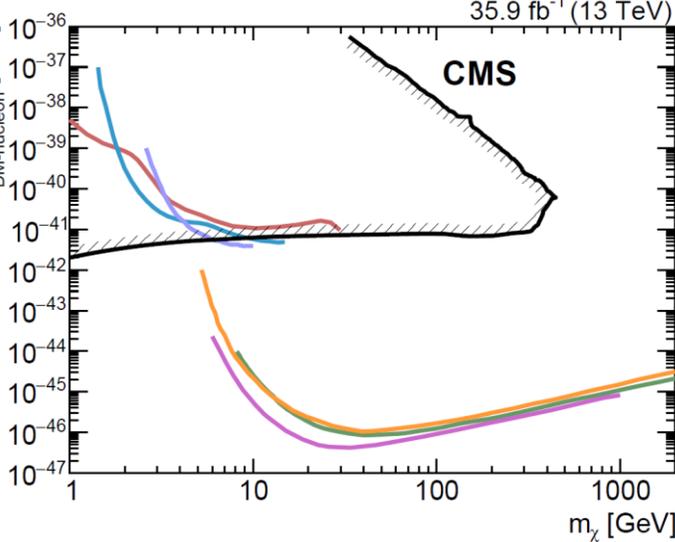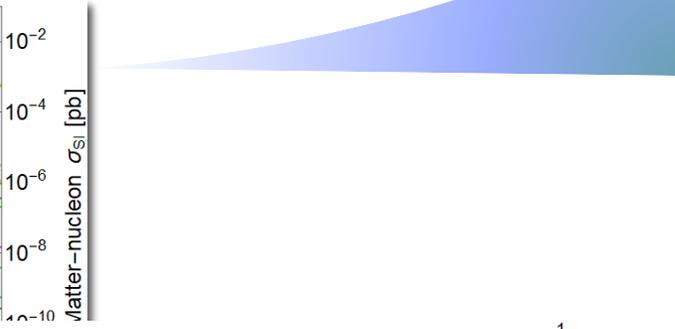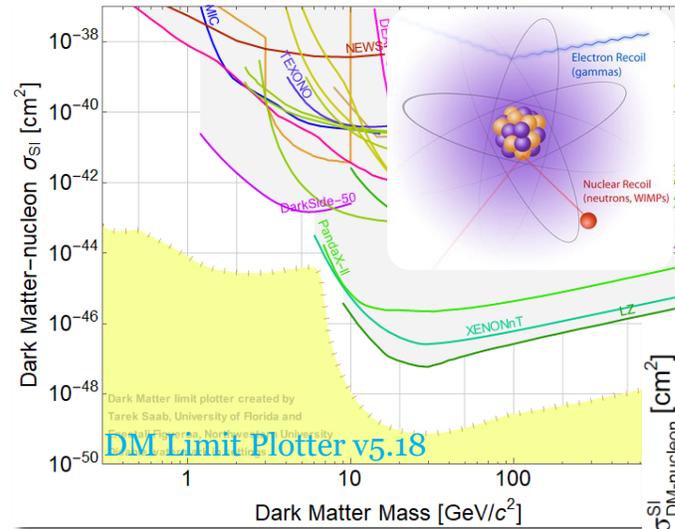
Superlight
sterile ν, warm DM

Light
SIMP, ELDER

WIMP

Superheavy
composite DM, WIMPzilla

Astrophysical object
MACHO, PBH

DM Limit Plotter v5.18

[1805.10305]   AMS

CMS   35.9 fb^{-1} (13 TeV)

✓ No concrete evidence of DM yet.

✓ Tight bounds are imposed on WIMP.

✓ Next decade: **A paradigm shift?**

Boosted Dark Matter (BDM)

Dark Sector: DM Boosting Mechanisms

Boosted DM (BDM) coming from the Universe

[Belanger & **JCP**, JCAP (2012);
Agashe et al., JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015);
Berger et al., JCAP (2015);
Kim, **JCP**, Shin, PRL (2017);
more]

$\chi_0 \rightarrow \chi_1$
$\chi_0 \rightarrow \chi_1$

$\chi \rightarrow \chi$
$\chi \rightarrow X$

[D'Eramo & Thaler, JHEP (2010);
Berger et al., JCAP (2015); more]

✓ Multi-component model
$$m_2 \gg m_1$$

✓ Semi-annihilation model
$$m_\chi \gg m_X$$

Large E_k^{DM} (monochromatic) due to **mass gap**

$\phi \rightarrow \chi$
$\rightarrow \chi$

[Bhattacharya et al., JCAP (2015);
Kopp et al., JHEP (2015);
Cline et al., PRD (2019);
Heurtier, Kim, **JCP**, Shin, PRD (2019);
more]

✓ Decaying multi-component DM
$$m_\phi \gg m_\chi$$

❖ Relic component DM: Non-relativistic!

❖ Very tiny fraction of DM: Relativistic!

Two-Component Scenario: Freeze-out

[Belanger, **JCP**, JCAP (2012)]
[Kamada, Kim, **JCP**, Shin, JCAP (2022)]

$Z_2/U(1)'$ $Z'_2/U(1)''$

$\chi_0 \longrightarrow \chi_1 \longrightarrow$ SM
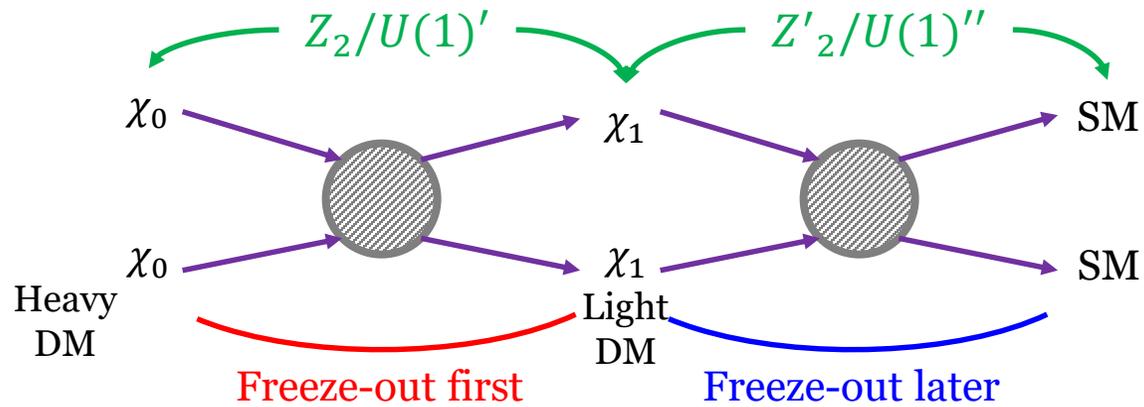
$\chi_0 \longrightarrow \chi_1 \longrightarrow$ SM

Heavy DM   Light DM

Freeze-out first   Freeze-out later

"**Assisted Freeze-out**" Mechanism

✓ Heavier relic χ_0: hard to directly detect it due to tiny coupling to SM

Thermal relic: $Y_i = n_i/s$

$$r_1 = 0.1$$
$$m_{\chi_0} = 100\,\text{MeV}$$
$$m_{\chi_1} = 60\,\text{MeV}$$

$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)}\right)^2 Y_{\chi_1}^2\right],$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\text{eq}}(x)\right)^2\right] + \frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)}\right)^2 Y_{\chi_1}^2\right]$$

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\text{eq}}(x)\right)^2 - Y_{\text{ast.}}^2(x)\right]$$

Two-Component Scenario: Freeze-out

Heavier

Lighter

DM$_0$

DM$_1$

χ_0

SM

χ_0

SM

Heavy DM

No direct

SM

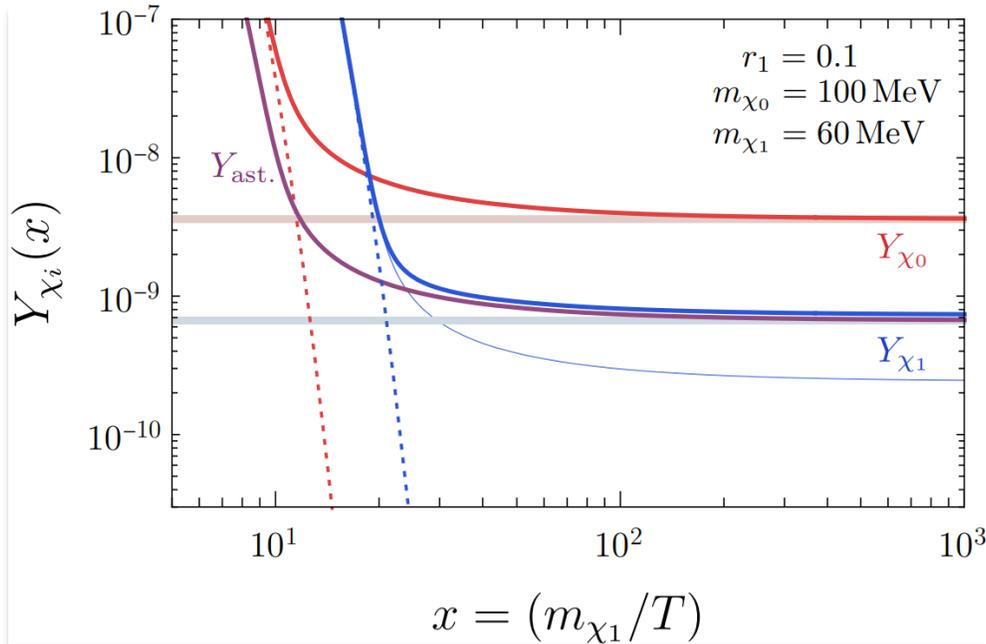**Thermal relic: $Y_i = n_i/s$**

[Belanger, **JCP**, JCAP (2012)]
[Kamada, Kim, **JCP**, Shin, JCAP (2022)]

"**Assisted Freeze-out**" Mechanism

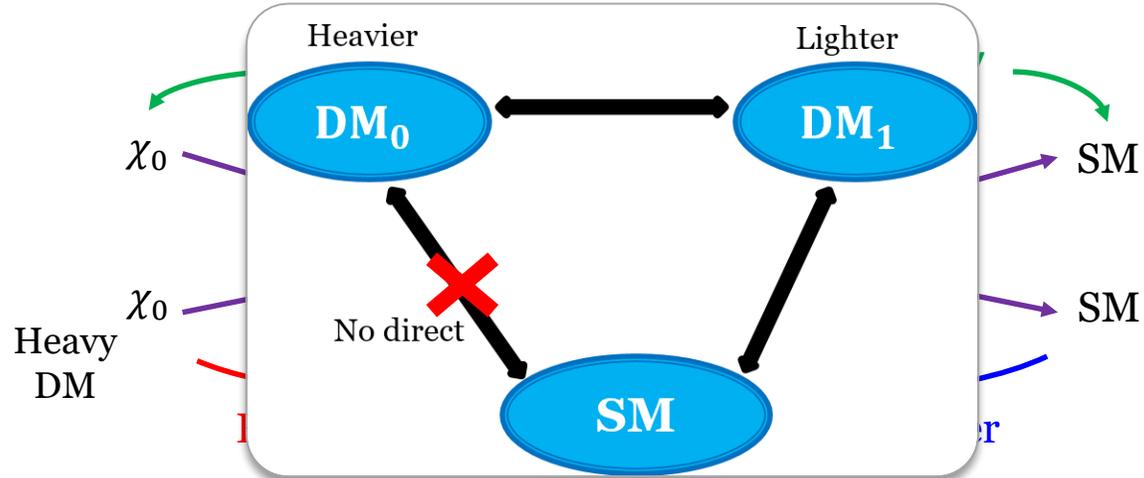✓ Heavier relic χ_0: hard to directly detect it due to tiny coupling to SM

$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)}\right)^2 Y_{\chi_1}^2\right],$$
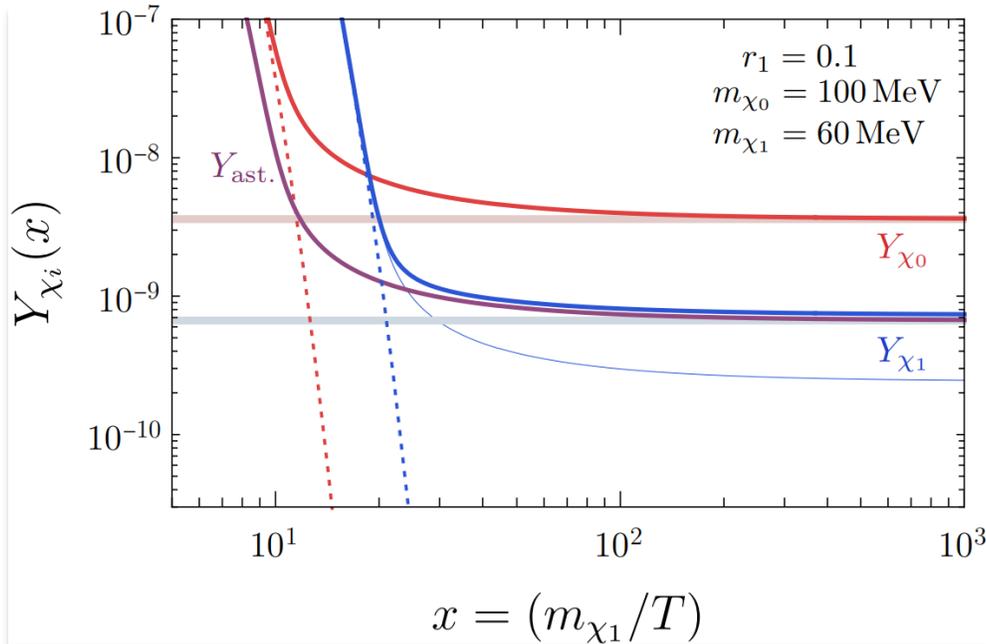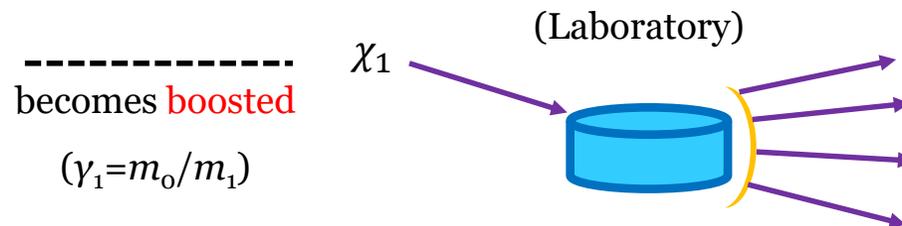
$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\text{eq}}(x)\right)^2\right] + \frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\text{eq}}(x)}{Y_{\chi_1}^{\text{eq}}(x)}\right)^2 Y_{\chi_1}^2\right]$$

$$\frac{dY_{\chi_1}}{dx} \simeq -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\text{eq}}(x)\right)^2 - Y_{\text{ast.}}^2(x)\right]$$

$r_1 = 0.1$
$m_{\chi_0} = 100\,\text{MeV}$
$m_{\chi_1} = 60\,\text{MeV}$

$Y_{\text{ast.}}$

Y_{χ_0}

Y_{χ_1}

$Y_{\chi_i}(x)$

$x = (m_{\chi_1}/T)$

Two-Component Scenario: BDM Signatures

χ_0 $\chi_0 \to \chi_1 \chi_1$ becomes **boosted**

$(\gamma_1 = m_0/m_1)$

(Laboratory)

χ_1

(cf. $\chi\chi \to \gamma\gamma$, **$\nu\nu$**)

$$\frac{d\Phi_1}{dE_1} = \frac{1}{4} \cdot \frac{1}{4\pi} \int d\Omega \int_{\text{l.o.s.}} ds \langle\sigma v\rangle_{\chi_0\bar\chi_0 \to \chi_1\bar\chi_1} \frac{dN_1}{dE_1} \left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

$$= 8.0 \times 10^{-5} \text{ cm}^{-2}\text{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\bar\chi_0 \to \chi_1\bar\chi_1}}{5 \times 10^{-26} \text{ cm}^3\text{s}^{-1}}\right)\left(\frac{\text{GeV}}{m_0}\right)^2 \frac{dN_1}{dE_1}$$

elastic scattering (eBDM)

[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]

χ_1
g_{11} χ_1
X^* ϵ
e^-/p

Detector

inelastic scattering (*i*BDM)

[D. Kim, **JCP**, S. Shin, PRL (2017);
G. Giudice, D. Kim, **JCP**, S. Shin, PLB (2018)]

χ_1
g_{12} χ_2 g_{12} χ_1
X^* ϵ $X^{(*)}$ ϵ
e^-/p e^- e^+

Detector

1~3 tracks depending on E_{th} & l_{χ_2}

p- or e-scattering (primary)   Decay (secondary)

❖ BDM signal: detectable at **large volume** detectors

DM Boosting Mechanisms: <u>Cosmic-Rays</u> (CRs)

Cosmic-Ray-Induced BDM

$e^\pm, p^\pm, \text{He}, \nu, \ldots$ → $e^\pm, p^\pm, \text{He}, \nu, \ldots$

χ → χ

$e^\pm, p^\pm, \text{He}, \boldsymbol{\nu}\ldots$

χ

❖ **Charged** CRs: [Bringmann & Pospelov, PRL (2019); Cappiello, Ng & Beacom, PRD (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent & Dutta et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho et al., PRD (2020); more]

❖ CR $\boldsymbol{\nu}$ ($\boldsymbol{\nu}$**BDM**): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; Chao, Li, Liao, 2108.05608; Lin, Wu, Wu, Wong, 2206.06864; more]

❖ BDM from astrophysical processes:
Solar evaporation - Kouvaris, PRD (2015)
Dark cosmic rays - Hu +, PLB (2017)
Solar reflection - An +, PRL (2018)
Solar acceleration - Emken +, PRD (2018)
Atmospheric collider – Alvey+, PRL (2019)
PBH evaporation - Calabrese +, PRD (2022)
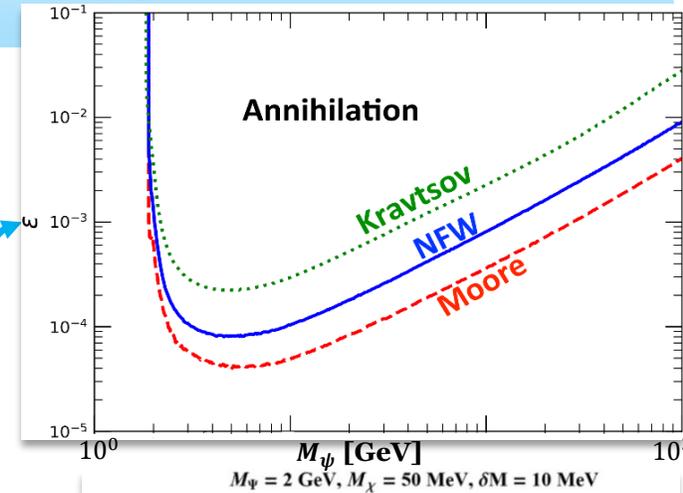Blazar jets - Wang +, PRL (2022)
more

❖ Energetic cosmic-ray-induced BDM: <u>energetic cosmic-rays kick</u> DM (large $E_{e^\pm, p^\pm, \text{He}, \boldsymbol{\nu}, \ldots}$ ➜ large E_χ)

➜ Efficient for Light DM

BDM Searches @ <u>Neutrino</u> Experiments

Boosted DM (BDM) scenarios:
Receiving rising attention as an alternative scenario

Editors' Suggestion

Cherenkov radiation rings by electrons

Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande

Regular Article - Experimental Physics

$v_{\mathrm{DM}} \sim c$ ➔ even ν detector
w/ high E_{th} is OK!

Ionization tracks by electrons and/or protons

Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment
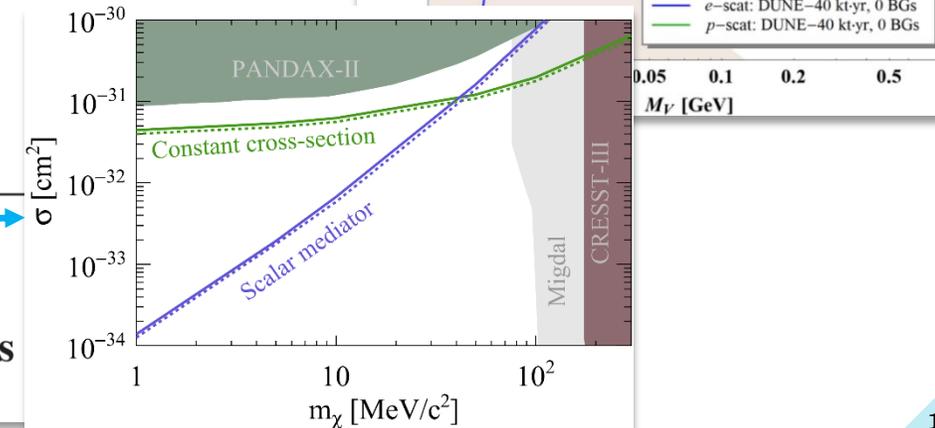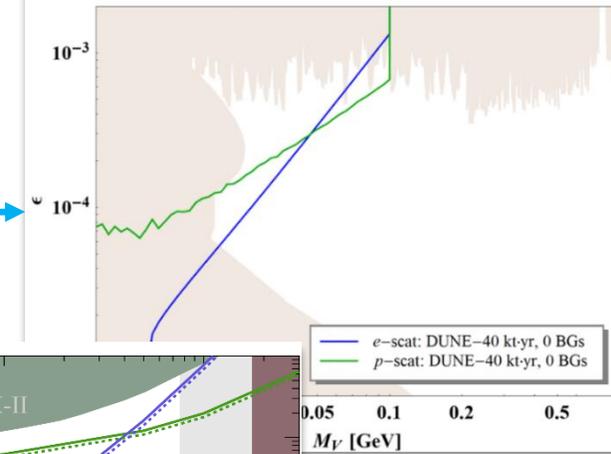
DUNE Collaboration

Editors' Suggestion   **Featured in Physics**

Cherenkov radiation rings by protons

Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande

BDM Searches @ DM Experiments

PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

Editors' Suggestion

First Direct Search for Inelastic Boosted Dark Matter with COSINE-100

PHYSICAL REVIEW LETTERS **131,** 201802 (2023)

Search for Boosted Dark Matter in COSINE-100

PHYSICAL REVIEW LETTERS **128,** 171801 (2022)

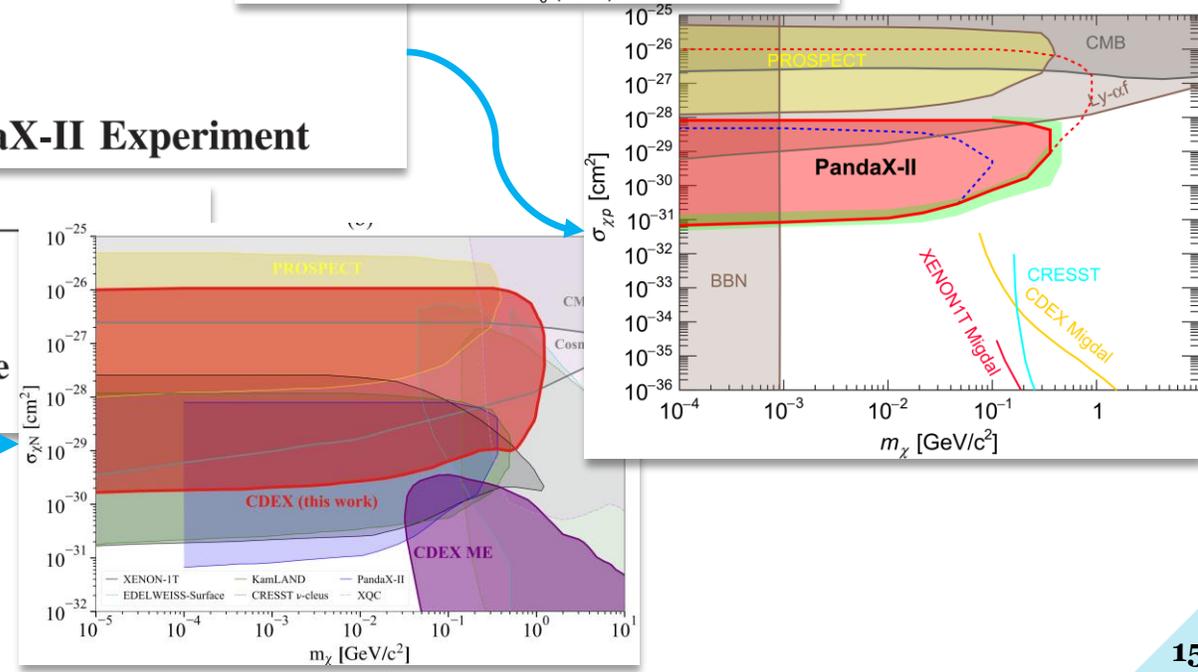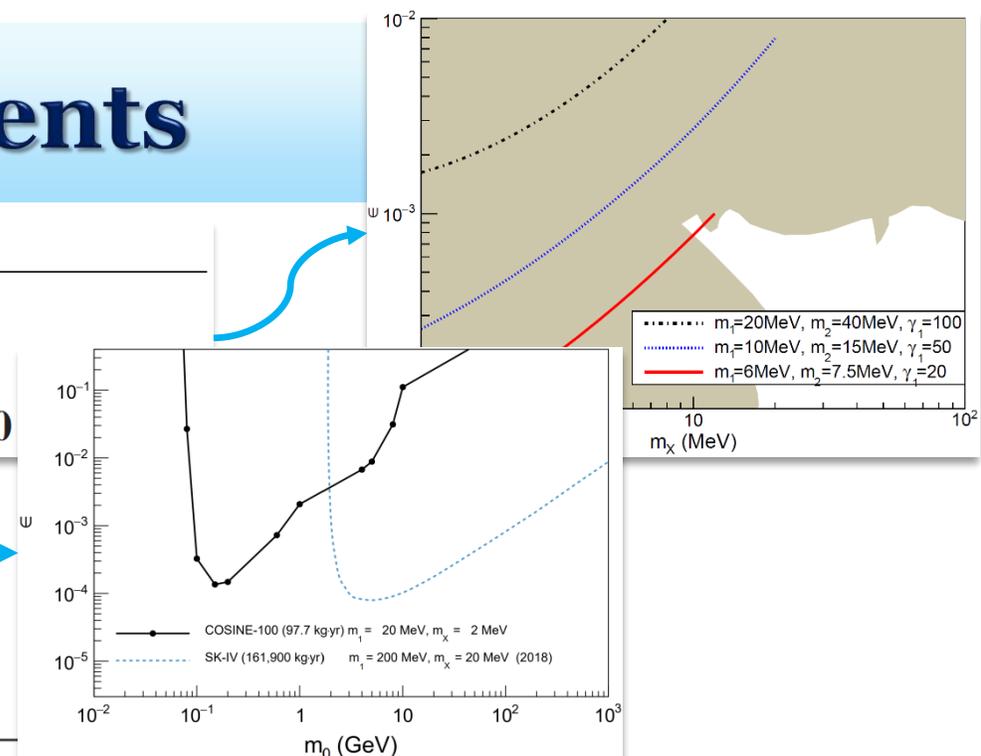Editors' Suggestion

Search for Cosmic-Ray Boosted Sub-GeV Dark Matter at the PandaX-II Experiment

PHYSICAL REVIEW D **106,** 052008 (2022)

Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory
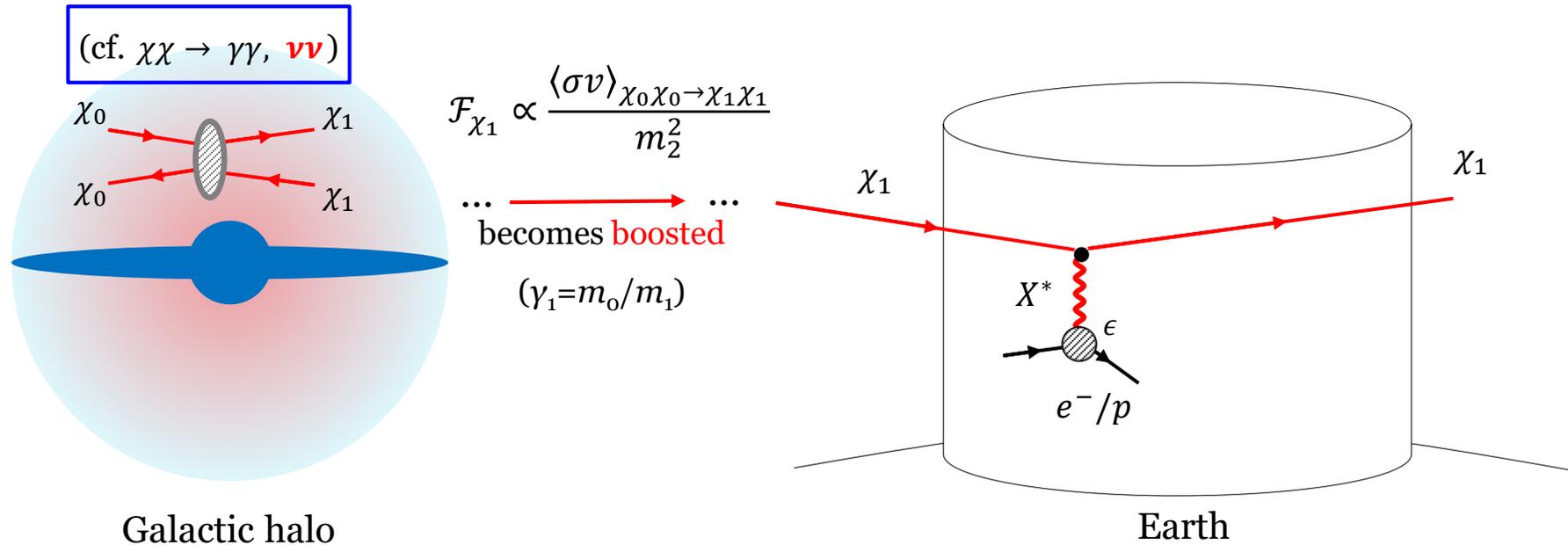
- ✓ Not restricted to primary physics goals
- ✓ Opened to other (unplanned) physics opportunities

Issues in BDM Searches

Minimal Two-component Scenario

(cf. $\chi\chi \to \gamma\gamma$, $\boldsymbol{\nu\nu}$)

χ_0 χ_1

χ_0 χ_1

$$\mathcal{F}_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{m_2^2}$$

... $\longrightarrow$ ...

becomes boosted

$(\gamma_1 = m_0/m_1)$

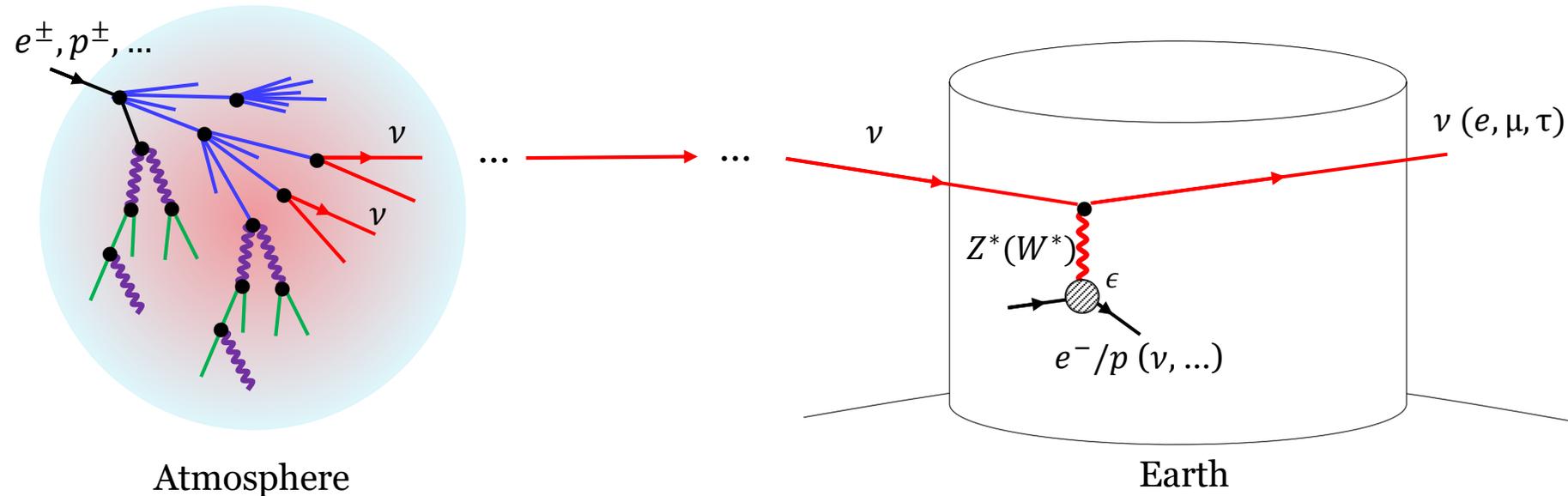χ_1 χ_1

X^*

ϵ

e^-/p

Galactic halo   Earth

❖ Example model: fermionic heavier(χ_0)/lighter(χ_1) DM + dark gauge boson(X)

[G. Belanger, **JCP** (2011)]

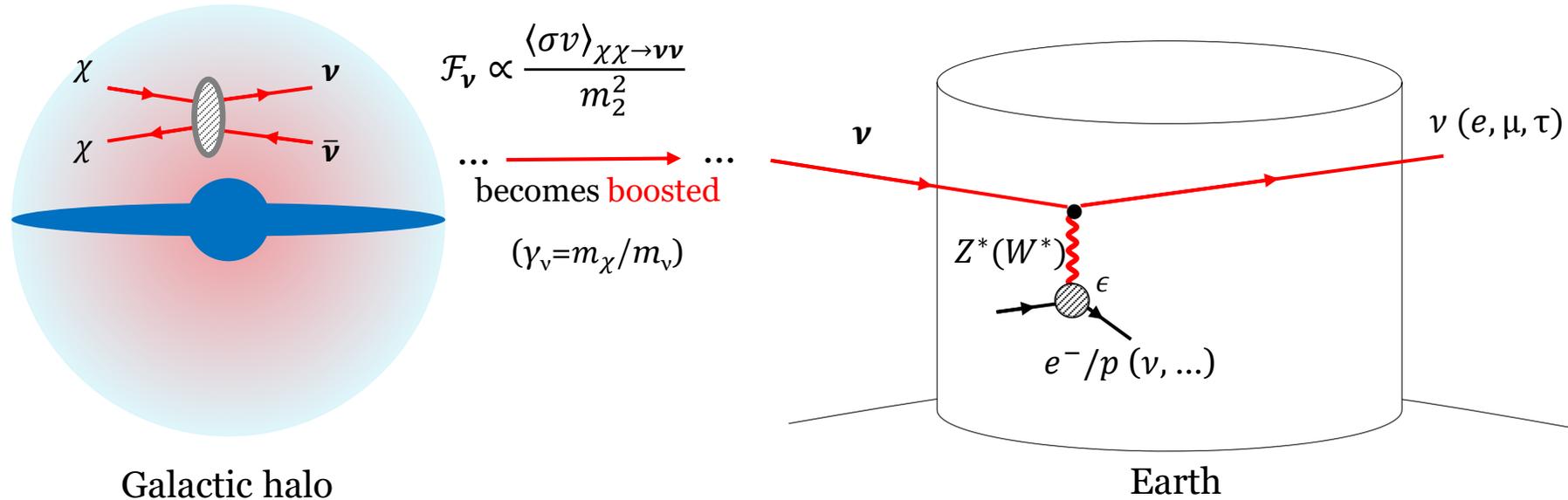❖ Elastic electron [Agashe, Cui, Necib, Thaler (2014)] & elastic proton (even DIS @ e.g. DUNE) [P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)] scattering channels are available. ➔ Energetic recoil

Issue 1: Background

$e^\pm, p^\pm, \ldots$

ν

ν

$\ldots$

$\ldots$

ν

$\nu\,(e, \mu, \tau)$

$Z^*(W^*)$

ϵ
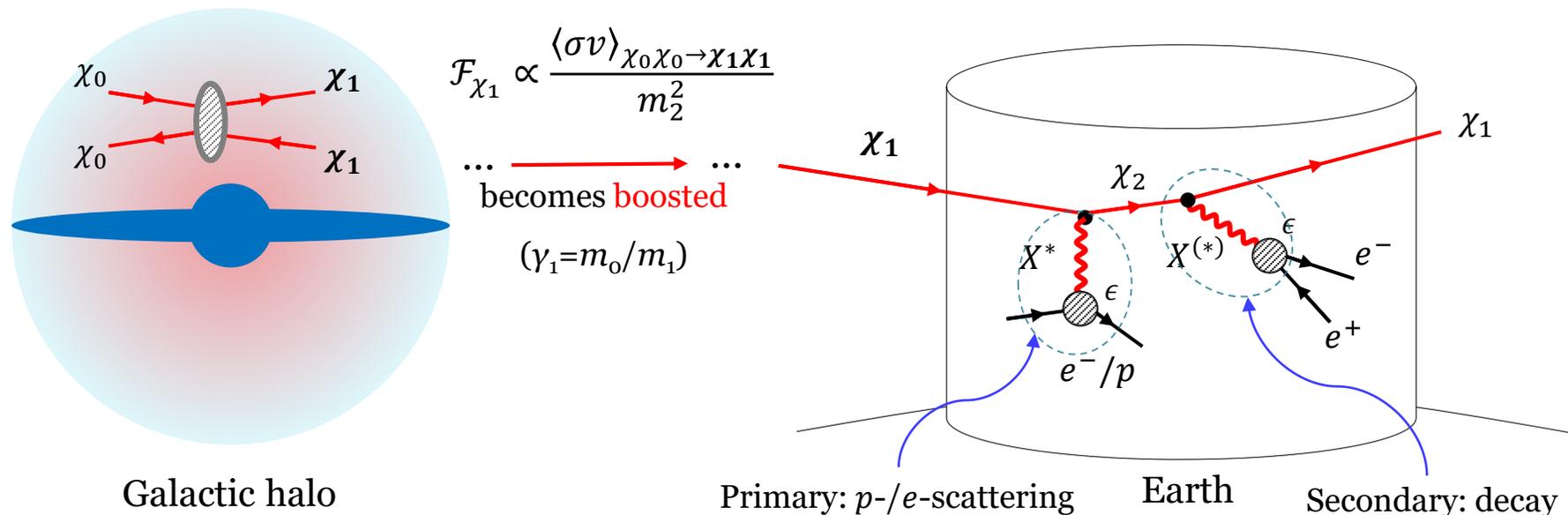
$e^-/p\,(\nu, \ldots)$

Atmosphere

Earth

- ❖ **Irreducible backgrounds**: atmospheric-neutrino-induced events

- ❖ **Neutral-** & **charged-current (even DIS)** scattering channels are available. ➜ Energetic recoil

- ❖ **Good angular resolution** allows to isolate source regions, especially very good for point-like sources such as the GC, Sun & dwarf galaxies.

Issue 2: Distinction from ν Scenario

$$\mathcal{F}_\nu \propto \frac{\langle \sigma v \rangle_{\chi\chi \to \nu\nu}}{m_2^2}$$

... $\longrightarrow$ ...
becomes boosted

$(\gamma_\nu = m_\chi / m_\nu)$

Galactic halo

Earth

❖ (Light) BDM behaves like a neutrino.

❖ Signature-wise, it is challenging to distinguish the BDM scenario from the neutrino one.

Issue 1 & 2: Avoidable by *i*BDM Scenario

$$\mathcal{F}_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{m_2^2}$$

... becomes boosted ($\gamma_1 = m_0/m_1$)

Galactic halo

Primary: p-/e-scattering   Earth   Secondary: decay
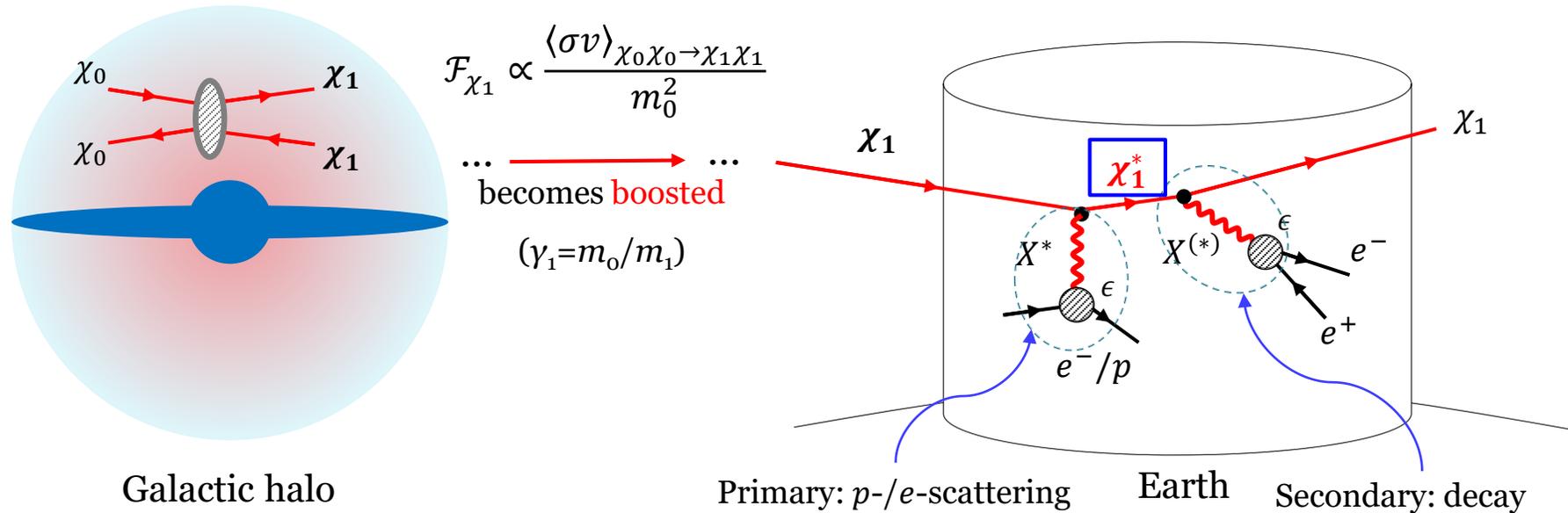
❖ *i*BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]

❖ Additional signatures from the decay of heavier unstable dark-sector state (or excited state)

χ_2 at the expense of "minimalism" of underlying BDM models.

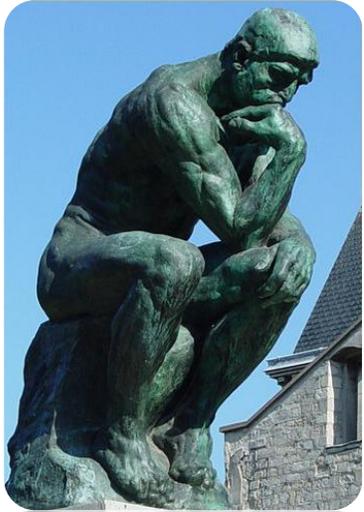# Is it possible to have distinctive signatures in the minimal scenario?

Issue 2: Avoidable by Sub-leading Process

$$\mathcal{F}_{\chi_1} \propto \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$$

... $\longrightarrow$ ...
becomes boosted

$(\gamma_1 = m_0/m_1)$

Galactic halo

Primary: p-/e-scattering   Earth   Secondary: decay

❖ Distinctive signatures may arise even under the minimal setup, once higher-order

corrections are taken into account.

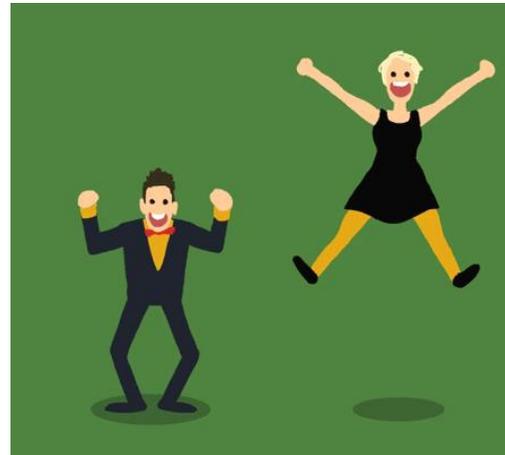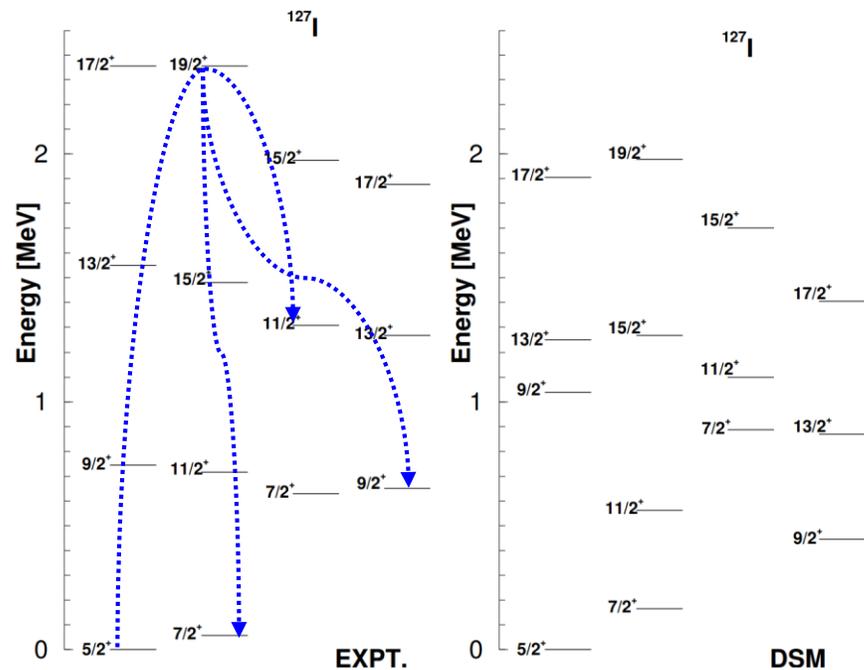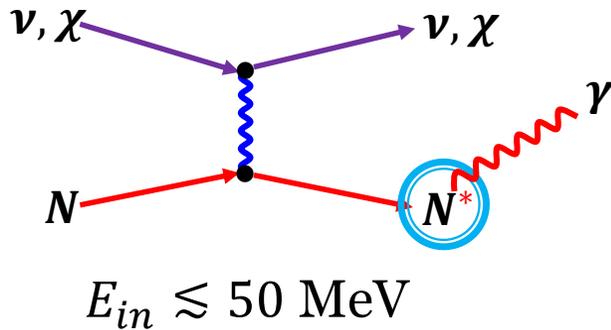❖ A new BDM search strategy utilizing initial-/final-state dark gauge boson radiation, i.e.

"**Dark-Strahlung**" from cosmogenic BDM [Kim, **JCP** & Shin, PRD (2019)]

Only recoiled e/p?

Inelastic Nuclear Scattering

❖ Why **inelastic** channel?

$E_{in} \lesssim 50$ MeV

Sahu et al., [2004.04055]

➤ Signatures

  ✓ γ cascade ($\Delta E \lesssim 10$ MeV)

  ✓ γ cascade + nucleons ($\Delta E \gtrsim 10$ MeV)

➤ Motivation

  ✓ A new channel to study

  ✓ Large energy $\sim O(1-10)$ MeV

  ✓ Better S/B ratio

➤ Recent improvements

Dutta, Newstead et al., [2206.08590]

  ✓ Inclusion of multiple excited states

  ✓ Consistent handling of hadronic currents

  ✓ Exclusive cross sections for each state

Inelastic Nuclear Scattering of DM

❖ **Focus**: the <u>interaction between DM & quark</u>

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi} \gamma^\mu \chi + \epsilon Q_b A'_\mu \bar{q} \gamma^\mu q$$

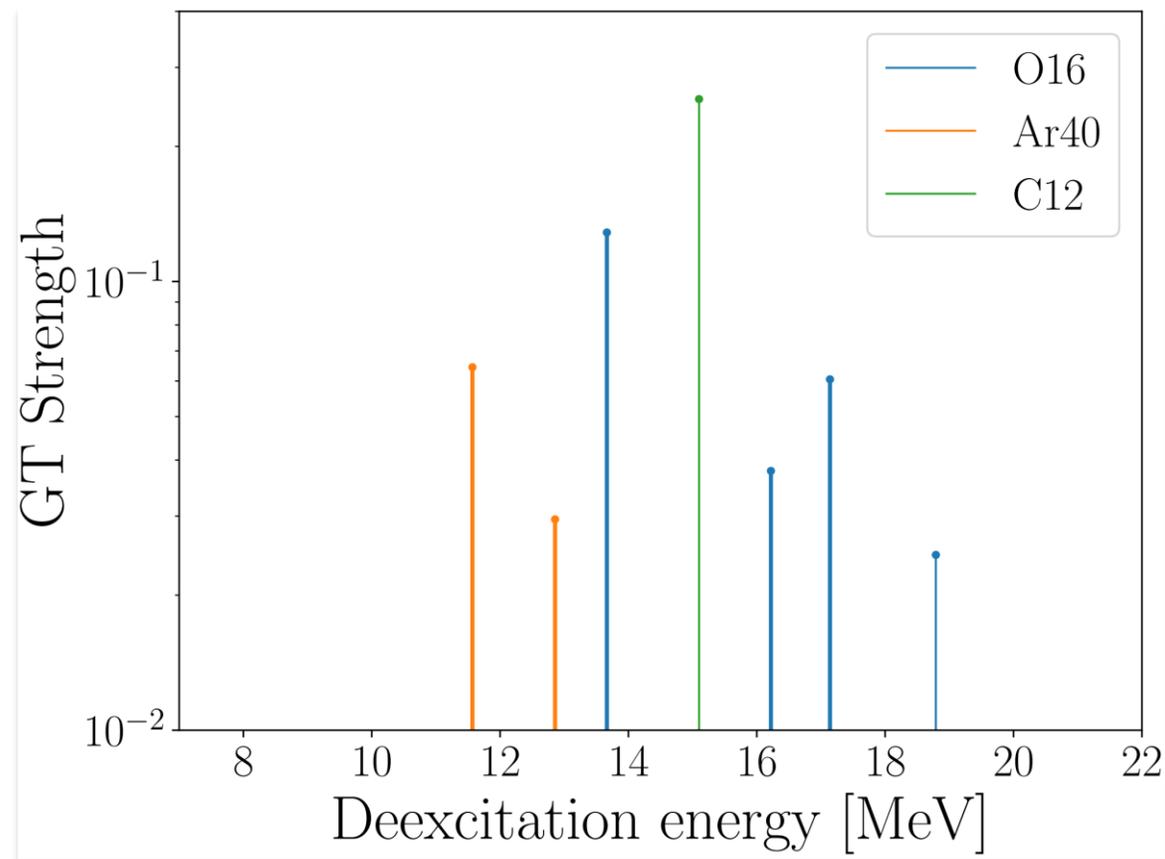❖ **Gamow-Teller (GT) transitions** are the dominant contribution to the inelastic cross section.

$$\frac{d\sigma_{\chi N}^{\text{inel}}}{d\cos\theta} = \frac{2\epsilon^2 g_D^2 E'_\chi p'_\chi}{(2m_T E_R + m_{A'}^2 - \Delta E^2)^2} \frac{1}{2\pi} \frac{4\pi}{2J+1}$$

$$\times \sum_{s_i, s_f} \vec{l} \cdot \vec{l}^* \frac{g_A^2}{12\pi} |\langle J_f || \sum_{i=1}^A \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2 \, ,$$

$$\sum_{s_i, s_f} \vec{l} \cdot \vec{l}^* = 3 - \frac{1}{E_\chi E'_\chi} \left[\frac{1}{2} \left(p_\chi^{\,2} + p'_\chi{}^2 - 2m_T E_R \right) + \frac{3m_\chi^2}{4} \right]$$

* For more details, See e.g. Dutta et al., [2206.08590].

[Dutta, Huang, Kim, Newstead, **JCP** & Shaukat Ali, PRL (2024)]

The GT strengths are derived from experimental results & the large-scale shell model code BIGSTICK.
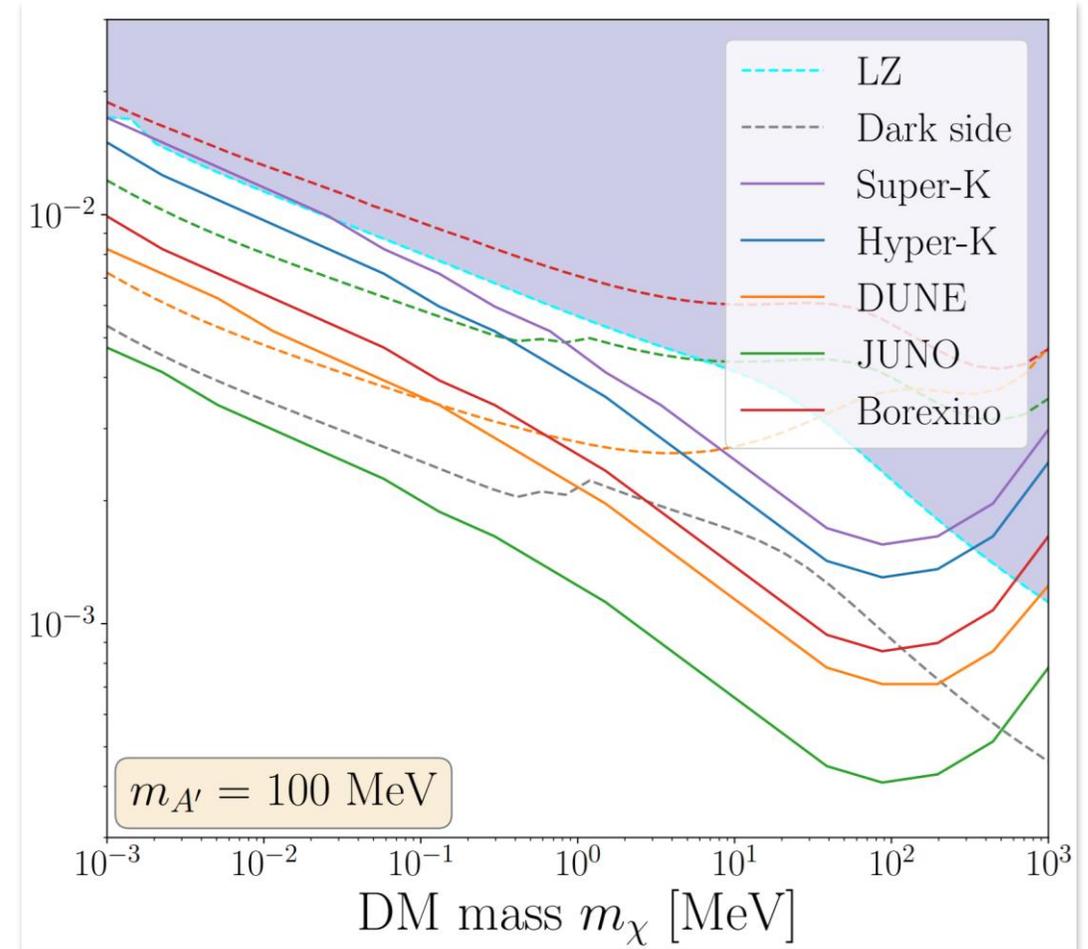
Inelastic Nuclear Scattering of CR-BDM

❖ Focus: the interaction between DM & quark

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi} \gamma^\mu \chi + \epsilon Q_b A'_\mu \bar{q} \gamma^\mu q$$

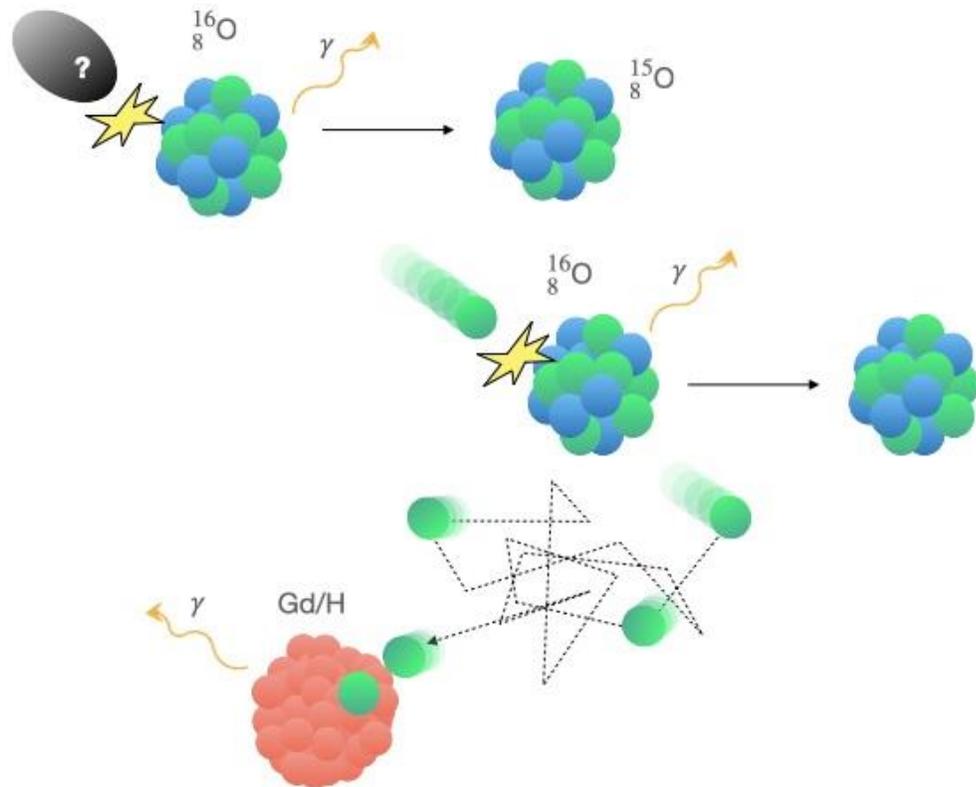➔ DM boosted by cosmic rays (p, He)

❖ The expected # of signal events

$$N_\chi = N_T \Delta t \int \sigma_{\chi N}^{\text{inel}}(E_\chi) \frac{d\Phi_\chi}{dE_\chi} dE_\chi \cdot \frac{\Gamma_{N^* \to N\gamma}}{\Gamma_{\text{total}}}$$

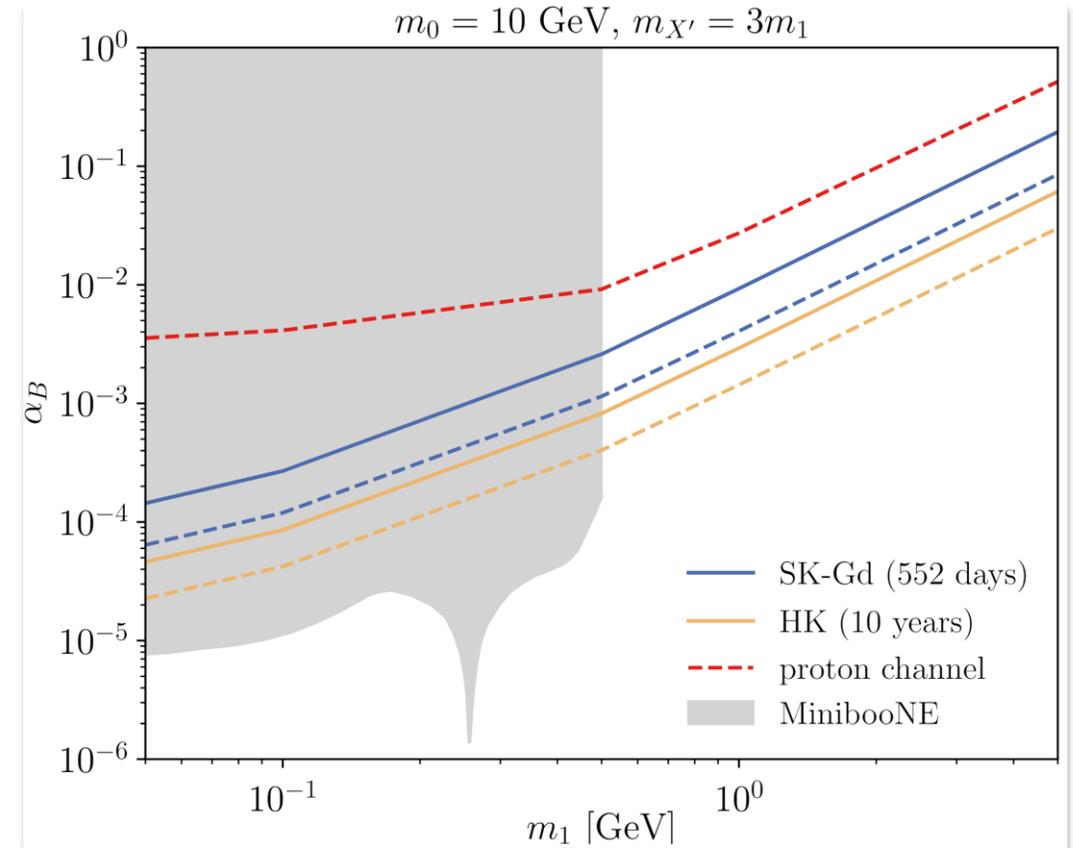✓ Inelastic (solid) better than elastic (dashed)

Knock-out Neutron @ Cherenkov Detectors

[K. Choi & **JCP**, 2409.05646]

❖ So far, only p for nuclear recoils

❖ For p, higher $p_{th} > 1.07$ GeV

❖ For n, no Cherenkov radiation but γ's from capture

➔ **n can be better than p,** especially e.g. @ **SK-Gd**

$m_0 = 10$ GeV, $m_{X'} = 3m_1$

Legend:
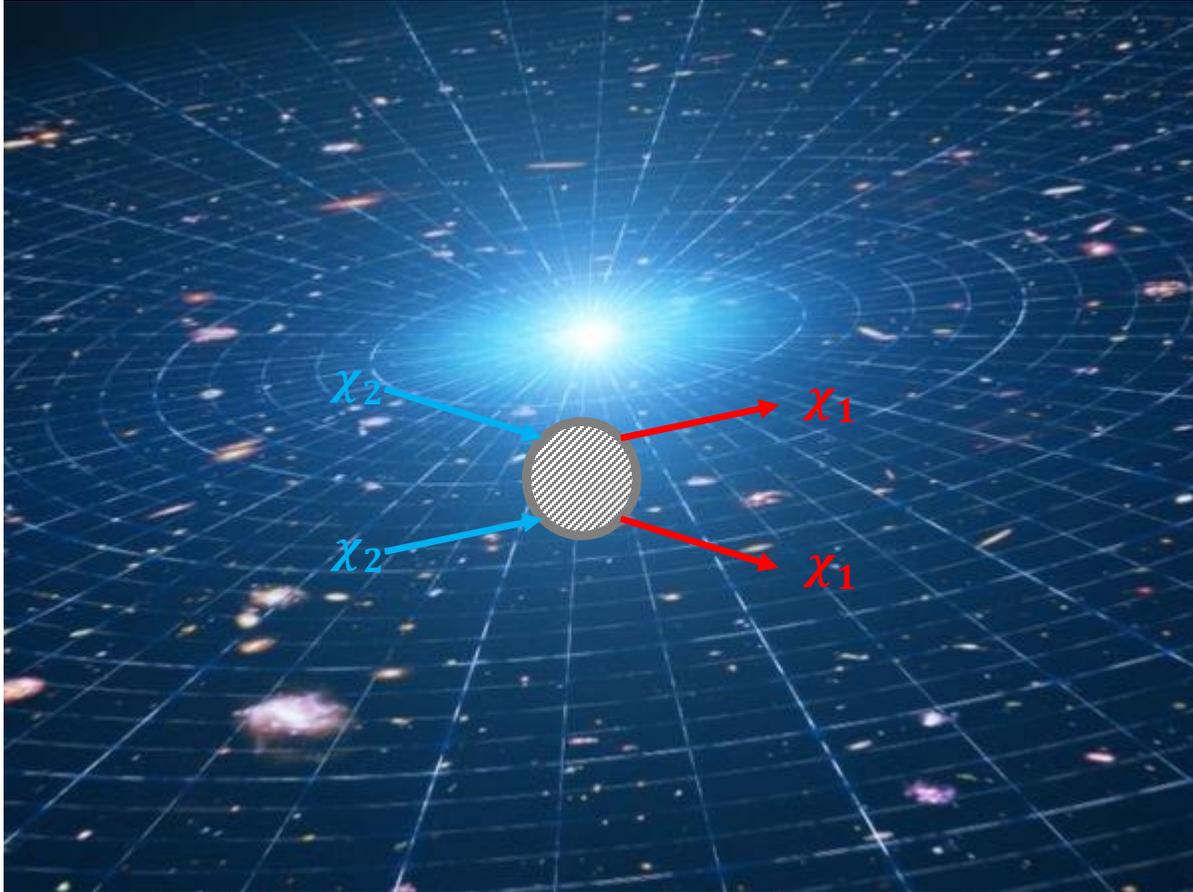- SK-Gd (552 days)
- HK (10 years)
- proton channel
- MinibooNE

✓ Two-component (χ_0, χ_1) BDM model w/ the following interaction between lighter DM (χ_1) & the SM sector,

$$\mathcal{L} \supset iq_B g_B X'_\mu [\chi_1^\dagger \partial^\mu \chi_1 - (\partial^\mu \chi_1^\dagger)\chi_1] + \frac{1}{3} g_B X'_\mu \bar{q}\gamma^\mu q$$

Any Effects of Energetic DM on Cosmology?

BDM=Hot DM?

✓ χ_2: heavy DM, χ_1: light DM

❖ BDM=hot DM ➔ Strong constraints from cosmological evolution, structure formation, etc?

➢ $\chi_2\chi_2 \rightarrow \boldsymbol{\chi_1\chi_1}$ Vs $\chi\chi \rightarrow \boldsymbol{\nu\nu}$

➢ $n_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_2\chi_2\rightarrow\chi_1\chi_1}}{m_2^2}$ with $\langle\sigma v\rangle_{\chi_2\chi_2\rightarrow\chi_1\chi_1} \sim 10^{-26}$ cm^3/s
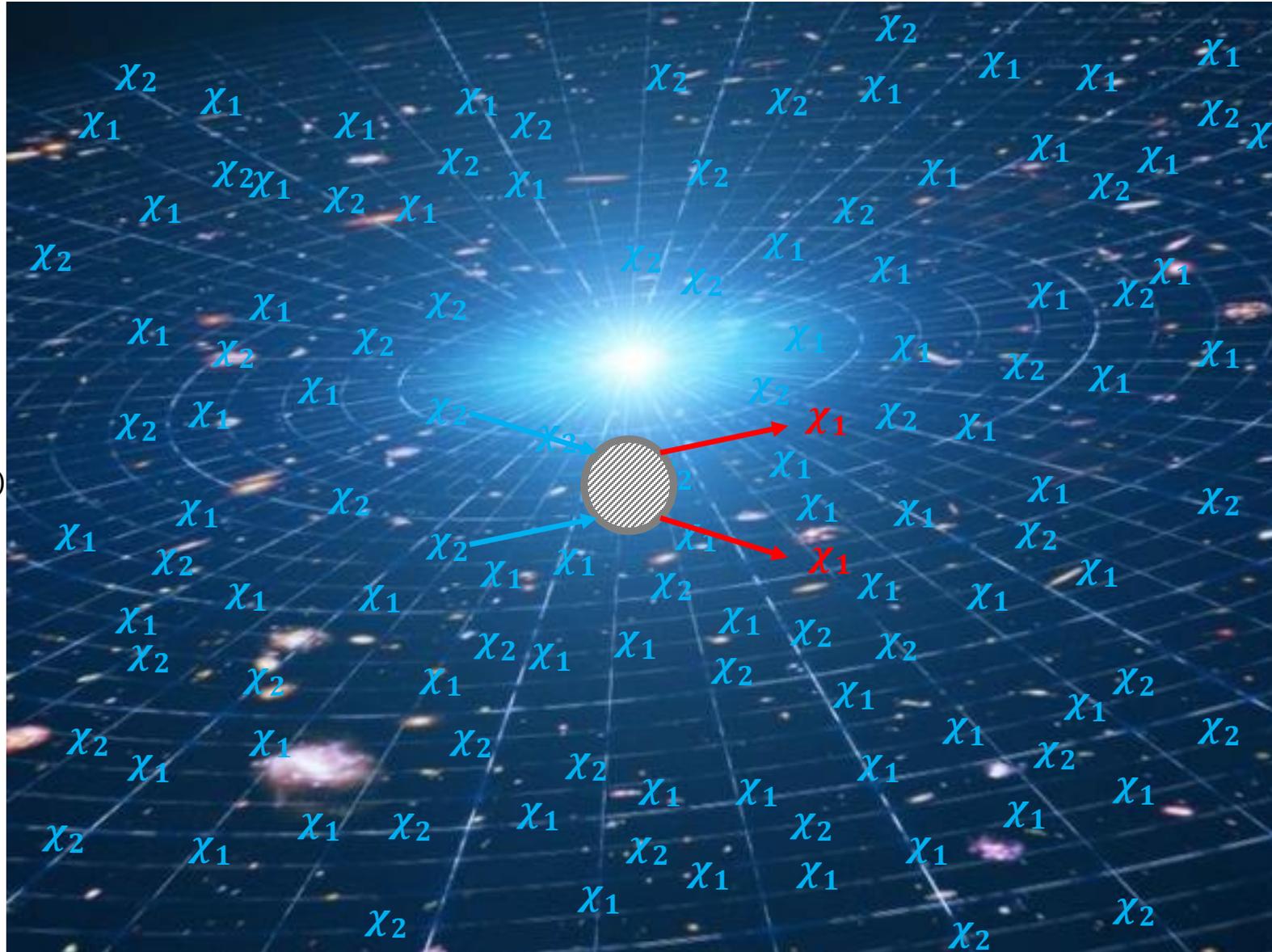
Self-Heating Effects?

Large self-scattering is quite natural for light dark sector!

For $g_{\chi_1} \approx O(1)$

& $m \approx O(10 \text{ MeV})$,

$\sigma_{\chi_1}^{\text{self}} \approx \frac{g_{\chi_1}^4}{\pi} \frac{m_{\chi_1}^2}{m_{\text{med}}^4}$

➔ $\sigma_{\chi_1}^{\text{self}}/m_{\chi_1} \approx \boldsymbol{O(1 \text{ cm}^2/\text{g})}$

1. The heavy χ_2 annihilates to light χ_1 which becomes boosted.
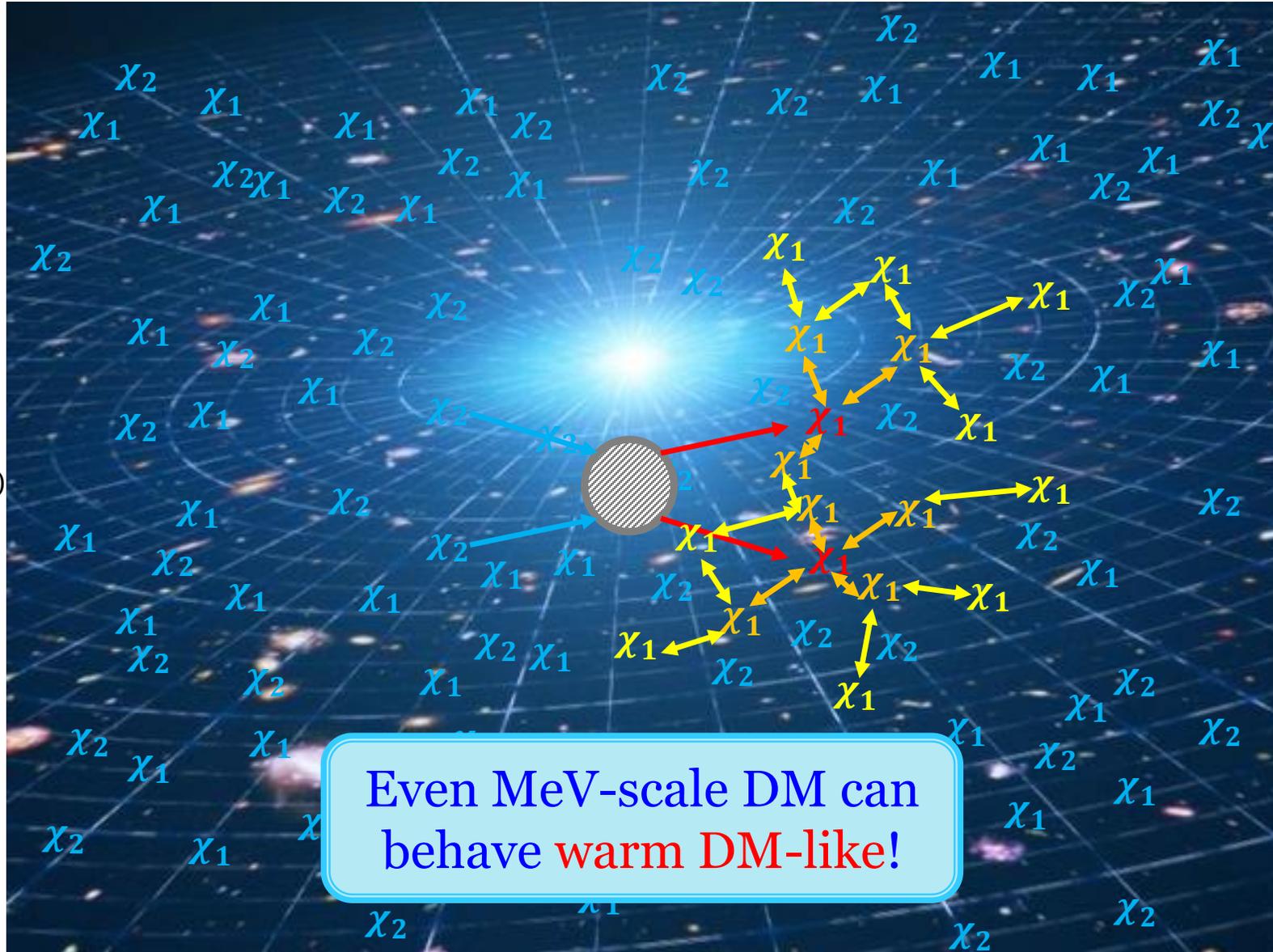
Self-Heating Effects**!**

Large self-scattering is quite natural for light dark sector!

For $g_{\chi_1} \approx O(1)$

& $m \approx O(10 \text{ MeV})$,

$\sigma^{\text{self}}_{\chi_1} \approx \frac{g^4_{\chi_1}}{\pi} \frac{m^2_{\chi_1}}{m^4_{\text{med}}}$

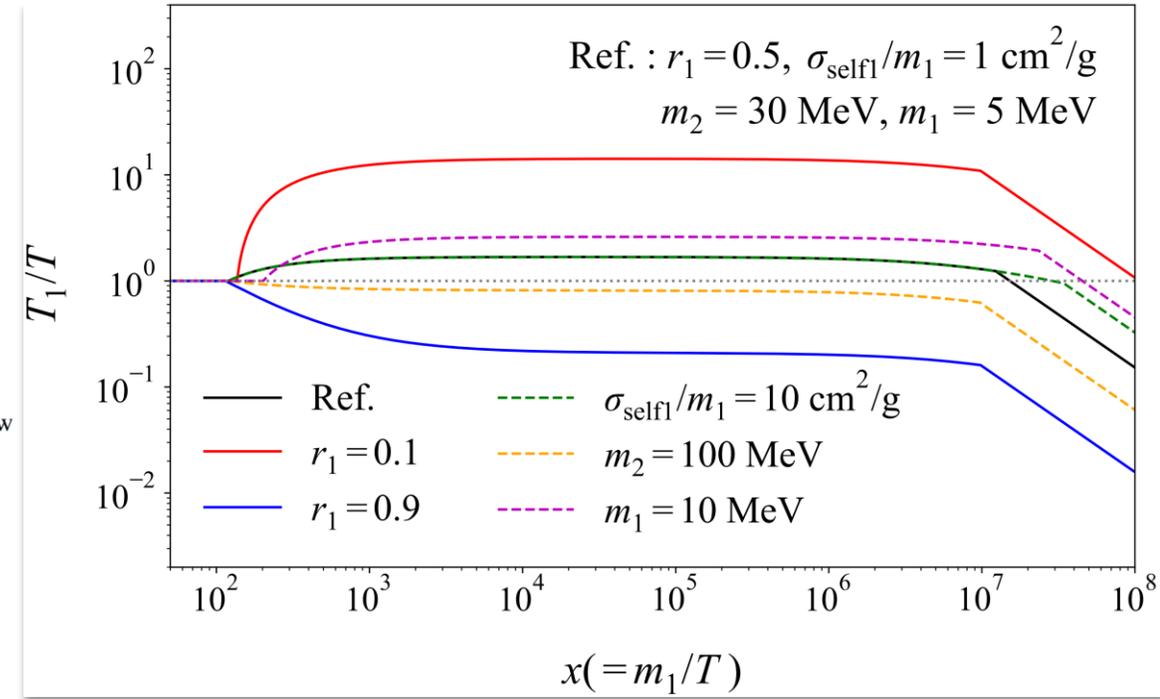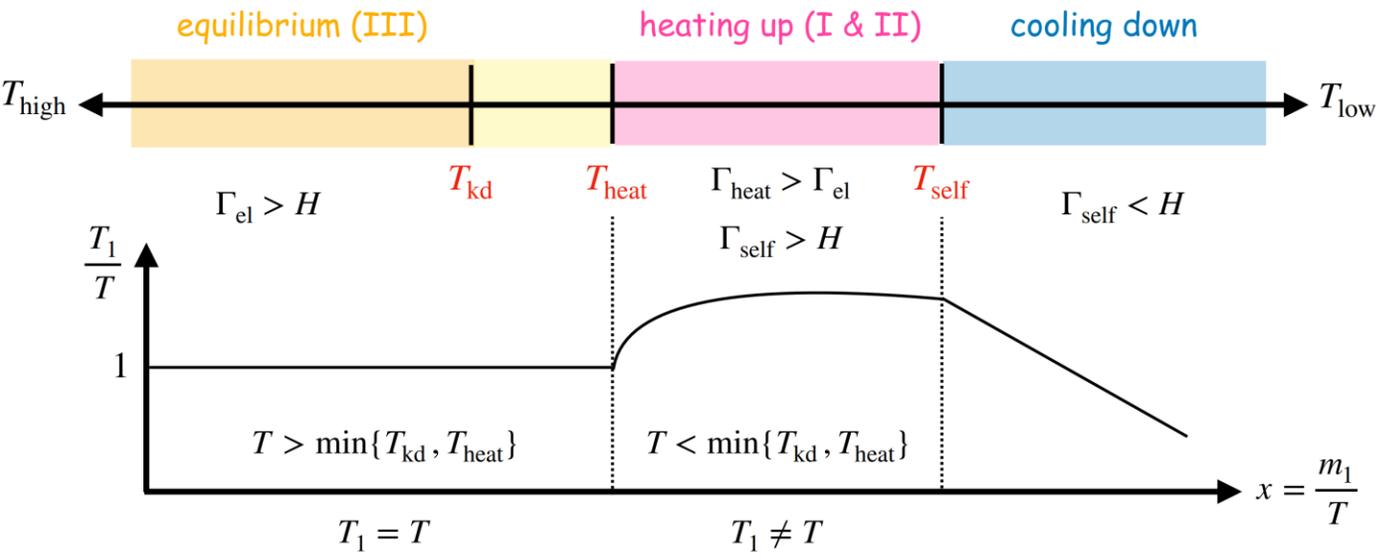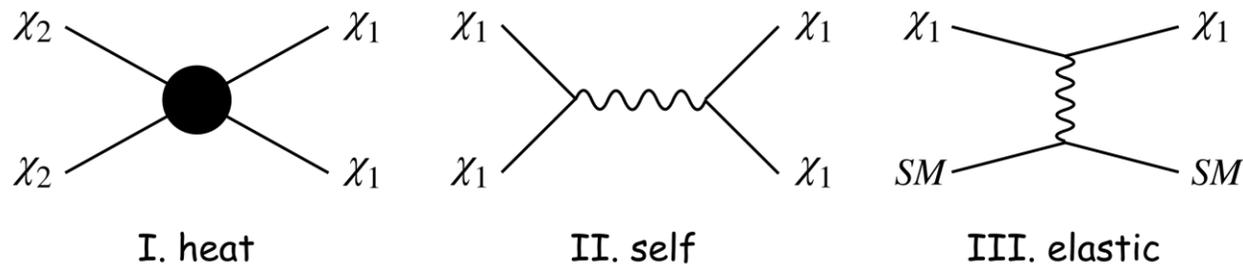➔ $\sigma^{\text{self}}_{\chi_1}/m_{\chi_1} \approx \boldsymbol{O(1\ \text{cm}^2/\text{g})}$

1. The heavy χ_2 annihilates to light χ_1 which becomes boosted.

2. Sharing energies through self-interaction $\sigma^{\text{self}}_{\chi_1}$ which increases the χ_1 temperature.

Even MeV-scale DM can behave warm DM-like!

$\chi_2 \rightarrow \chi_1$, $\chi_2 \rightarrow \chi_1$

$\chi_1 \rightarrow \chi_1$, $\chi_1 \rightarrow \chi_1$

$\chi_1 \rightarrow \chi_1$, $SM \rightarrow SM$

I. heat **II. self** **III. elastic**

equilibrium (III)   heating up (I & II)   cooling down

T_high ← → T_low

$\Gamma_\text{el} > H$ T_kd T_heat $\Gamma_\text{heat} > \Gamma_\text{el}$ T_self $\Gamma_\text{self} < H$

$\Gamma_\text{self} > H$

$\dfrac{T_1}{T}$

1

$T > \min\{T_\text{kd}, T_\text{heat}\}$ $T < \min\{T_\text{kd}, T_\text{heat}\}$

$x = \dfrac{m_1}{T}$

$T_1 = T$ $T_1 \neq T$

Ref. : $r_1 = 0.5$, $\sigma_\text{self1}/m_1 = 1 \text{ cm}^2/\text{g}$
$m_2 = 30$ MeV, $m_1 = 5$ MeV

T_1/T

— Ref.   - - - $\sigma_\text{self1}/m_1 = 10 \text{ cm}^2/\text{g}$
— $r_1 = 0.1$ - - - $m_2 = 100$ MeV
— $r_1 = 0.9$ - - - $m_1 = 10$ MeV

$x(= m_1/T)$

$r_1 = \Omega_{\chi_1}/(\Omega_{\chi_1} + \Omega_{\chi_2})$

$$\dot{T}_{\chi_1} + 2HT_{\chi_1} \simeq \gamma_\text{heat} T - 2\gamma_{\chi_1 \text{sm}}(T_{\chi_1} - T) \qquad \gamma_{\chi_1 \text{sm}} \simeq (\delta E/T) n_\text{sm} \langle \sigma v \rangle_{\chi_1 \text{sm}}$$
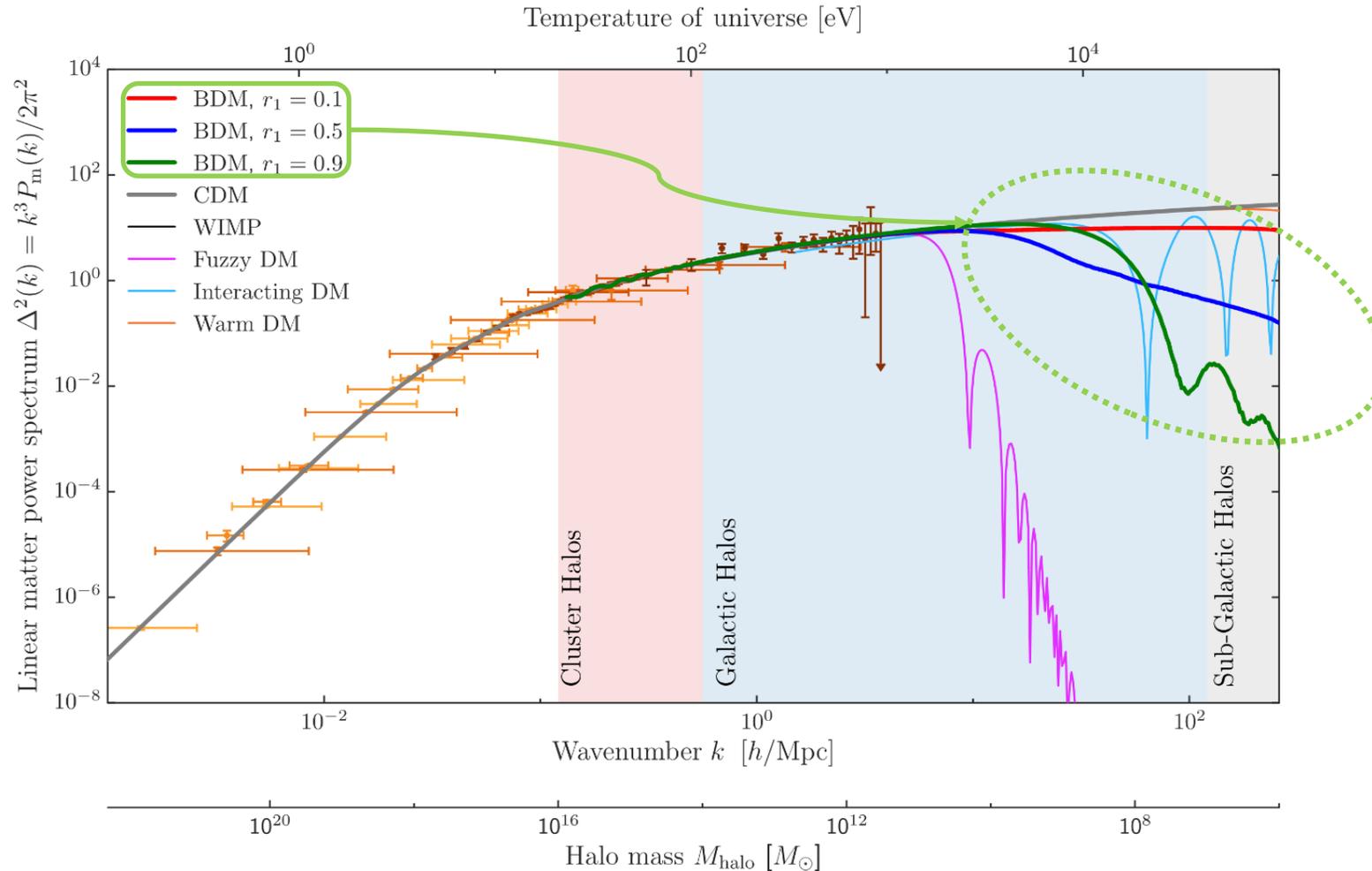
Kinetic scattering of χ_1 with a thermal bath

$$\gamma_\text{heat} = \frac{2 n_{\chi_2}^2 \langle \sigma v \rangle_{22 \rightarrow 11}}{3 n_{\chi_1} T}(m_{\chi_2} - m_{\chi_1})$$

32

Linear Matter Power Spectrum

❖ Comparison of dimensionless linear matter power spectra

N-Body Simulation

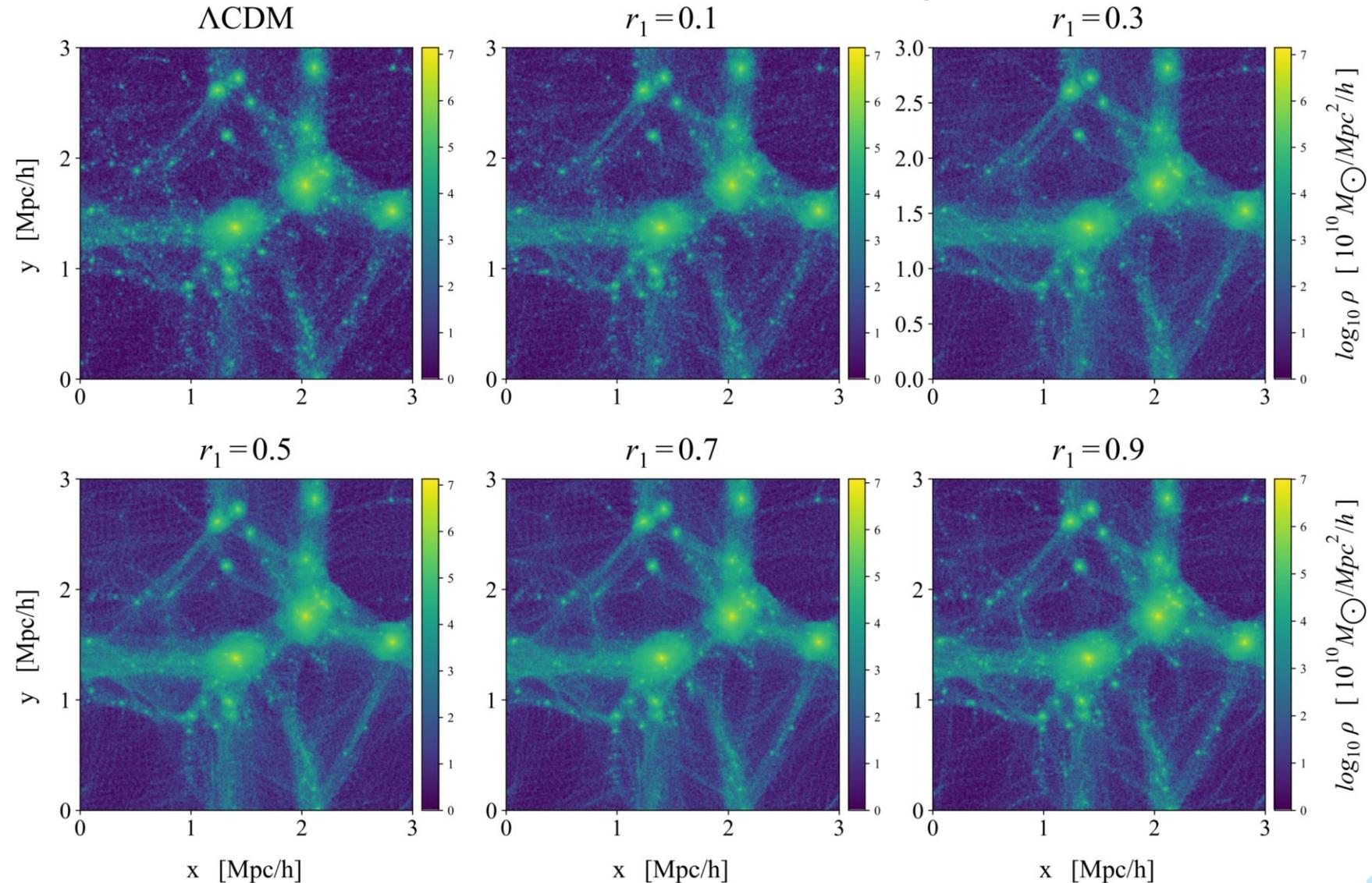❖ *N*-body simulations: two-component DM simulation built on *GADGET-3* to investigate the non-linear effects

❖ Visualization of DM density in the periodic 3 h^{-1}Mpc box at $z = 0$ ➡ fewer sub-halos

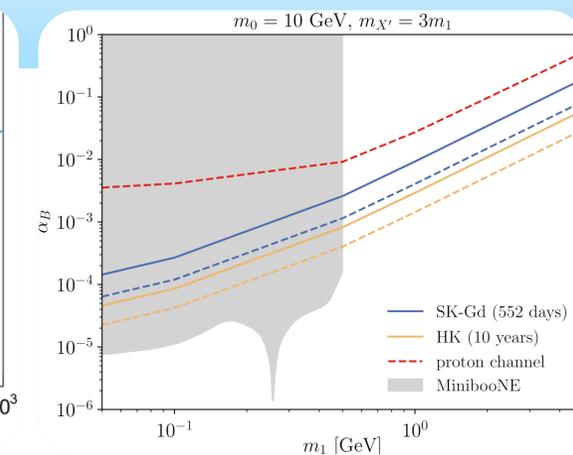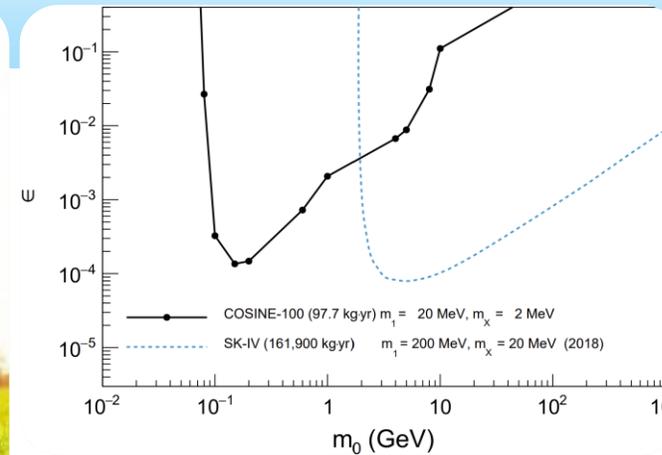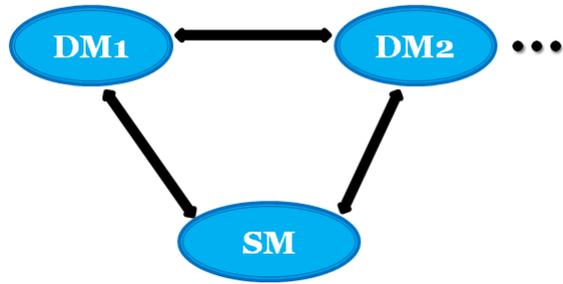✓ $\dfrac{\sigma_1^{\text{self}}}{m_{\chi_1}} = 1 \text{ cm}^2/\text{g}$

✓ $m_{\chi_2} = 30 \text{ MeV}$

✓ $m_{\chi_1} = 5 \text{ MeV}$

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & 2410.05382]

Summary

❖ Rising interest in dark sector (multi-component) scenarios & BDM (Energetic DM)

❖ Various BDM production scenarios: Dark sector, Reversing direct detection, Astrophysical, …

❖ Various detection channels: elastic e/p, DIS, inelastic N, n-capture, …

❖ BDM searches are promising & provide a new direction to explore dark sector physics.

❖ Experimental studies: e.g. SK, COSINE-100, Panda-X, CDEX, NEWSdm, DUNE, …

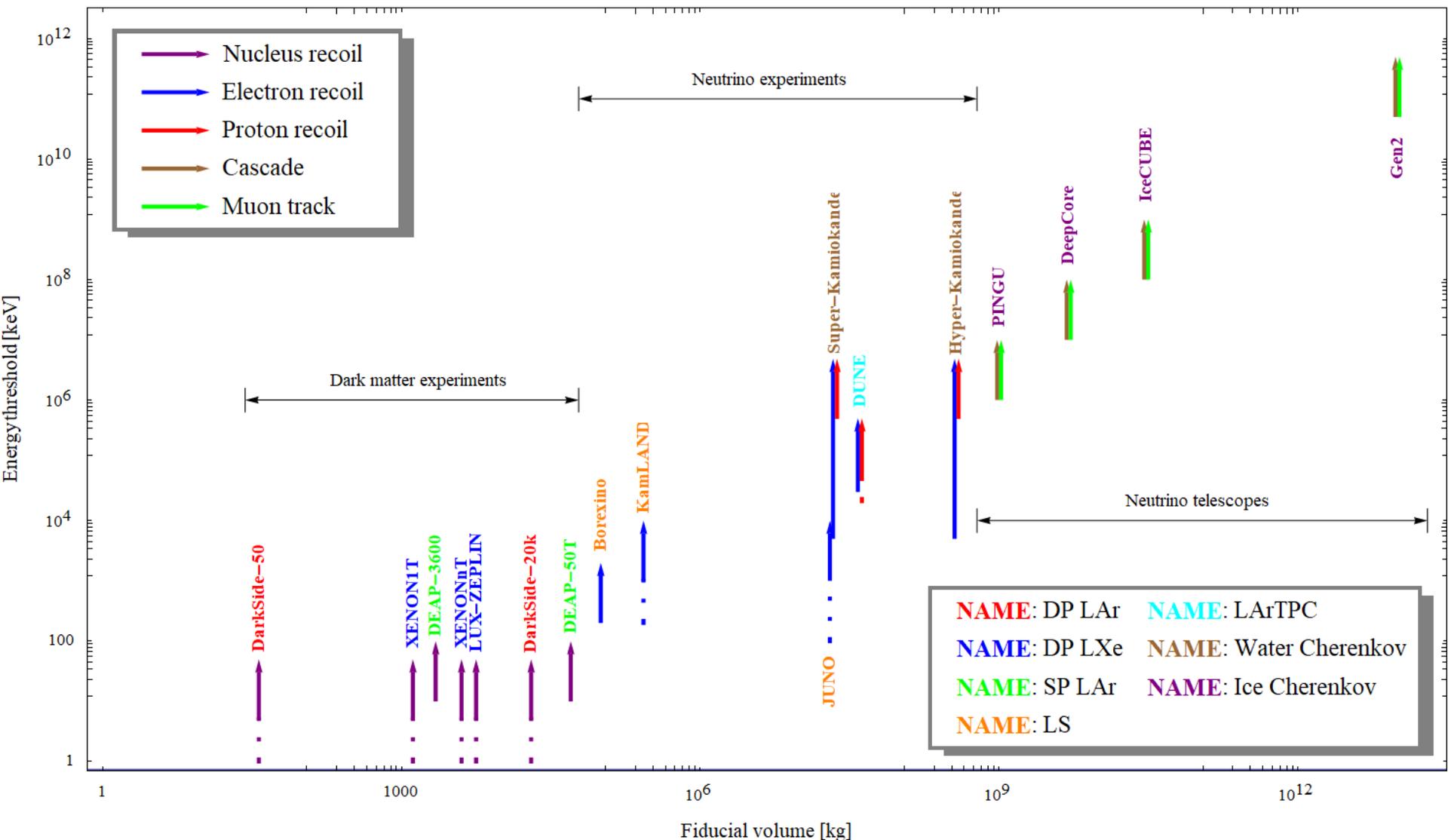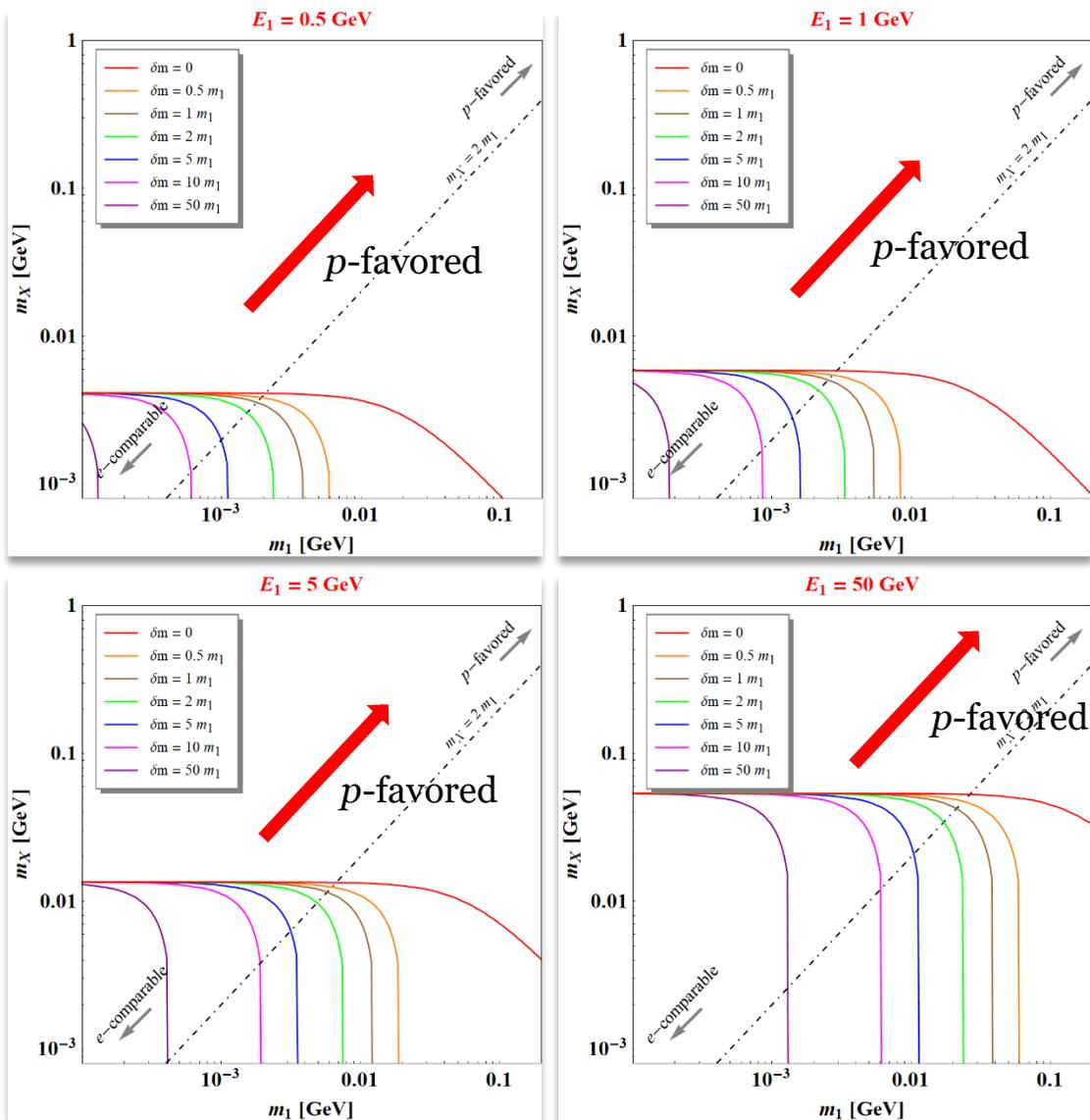❖ Studies on potential cosmological & astrophysical effects

Thank you

Supplemental

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

Detectors are complementary to one another rather than superior to the other!
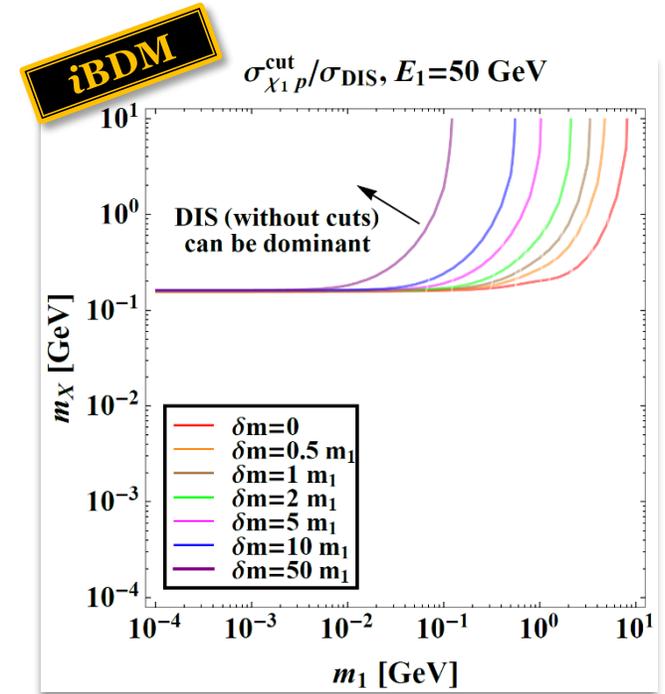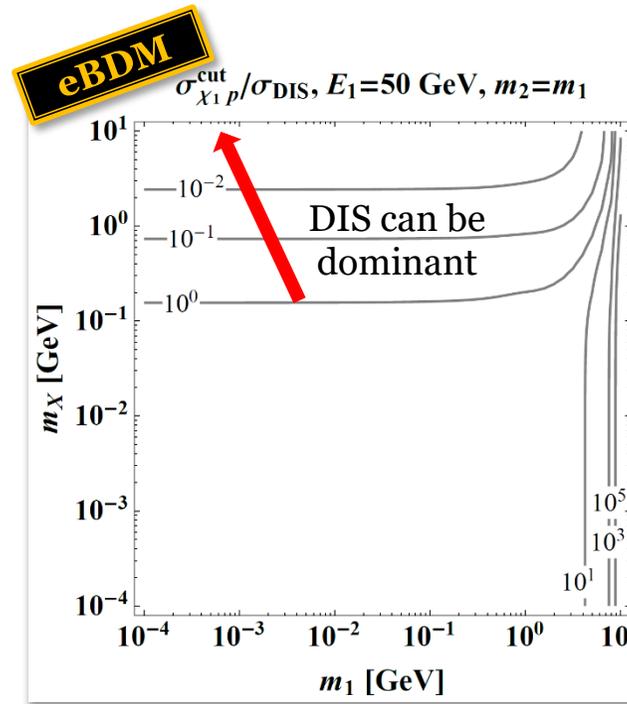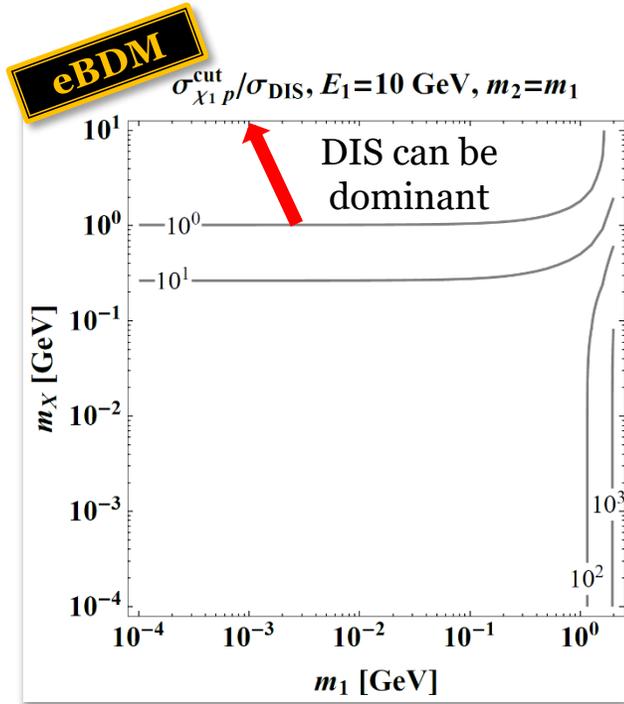
p-Scattering vs. *e*-Scattering

✓ If a BDM search hypothesizes a heavy dark photon (say, sub-GeV range), the *p*-channel may expedite discovery.

✓ If a model conceiving iBDM signals allows for large mass gaps between χ_1 and χ_2, the *p*-channel is more advantageous.

✓ The *e*-channel becomes comparable in probing the parameter regions with smaller m_1 and m_X.

✓ As the boosted χ_1 comes with more energy, more parameter space where the *e*-channel is comparable opens up.

✓ With cuts, more *e*-channel favored region.

p-Scattering vs. DIS: Numerical Study

[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

- ✓ We study $\sigma_{\chi_1 p}^{\mathrm{cut}}/\sigma_{\mathrm{DIS}}$ where 200 MeV $< p_p < 2$ GeV is applied to $\sigma_{\chi_1 p}$ while no cuts are imposed to σ_{DIS}.

- ✓ *p*-scattering dominates over DIS for $m_X < O(\mathrm{GeV})$ (cf. ν scattering via W, Z).

- ✓ As the process becomes more "inelastic", *p*-scattering dominates over DIS for a given E_1.

- ✓ DIS-preferred region expands in increasing E_1.

Nuclear Scattering: *Inelastic Neutrino*

❖ **Inelastic *ν*-Nucleus Scattering (I*ν*NS)**

TESTING THE STRUCTURE OF WEAK NEUTRAL CURRENTS BY INELASTIC NEUTRINO SCATTERING FROM NUCLEI★

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Institute of Theoretical Physics, Department of Physics,
Stanford University, Stanford, California 94305

Received 13 June 1976
Revised manuscript received 17 September 1976

By using selected nuclear transitions specific pieces of the weak neutral current may be greatly enhanced, leading to widely different results for different models of the weak neutral current. Predictions for low-energy inelastic neutrino scattering from ^{12}C are examined within the framework of a variety of SU(2)$_W$ × U(1) gauge theory models.

PLB (1976)

First observation of the neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ (1^+, 1)

KARMEN Collaboration

PLB (1991)

The neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ (1^+, 1; 15.1 MeV) has been observed for the first time. For ν_e and $\bar{\nu}_\mu$ from μ^+-decay at rest the flux averaged cross section was determined to be $\langle\sigma_{NC}(\nu_e + \bar{\nu}_\mu)\rangle = [10.8 \pm 5.1(\text{stat.}) \pm 1.1(\text{syst.})] \times 10^{-42}$ cm^2.

➤ **Recent improvements**

Dutta, Newstead et al., [2206.08590]

✓ Inclusion of multiple excited states

✓ Consistent handling of hadronic currents

✓ Exclusive cross sections for each state

Estimated Background Rates

❖ The main irreducible background: the elastic & inelastic neutral-current scattering of solar & atmospheric neutrinos.

[1910.11878]

[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]

$$\mathcal{L} \supset \epsilon A'_\mu J^\mu_{\text{em}} - i g_D A'_\mu \left(\chi_1^* \partial^\mu \chi_1 - \chi_1 \partial^\mu \chi_1^* \right) - \frac{\lambda_{\text{ast.}}}{4} |\chi_1|^2 |\chi_0|^2$$

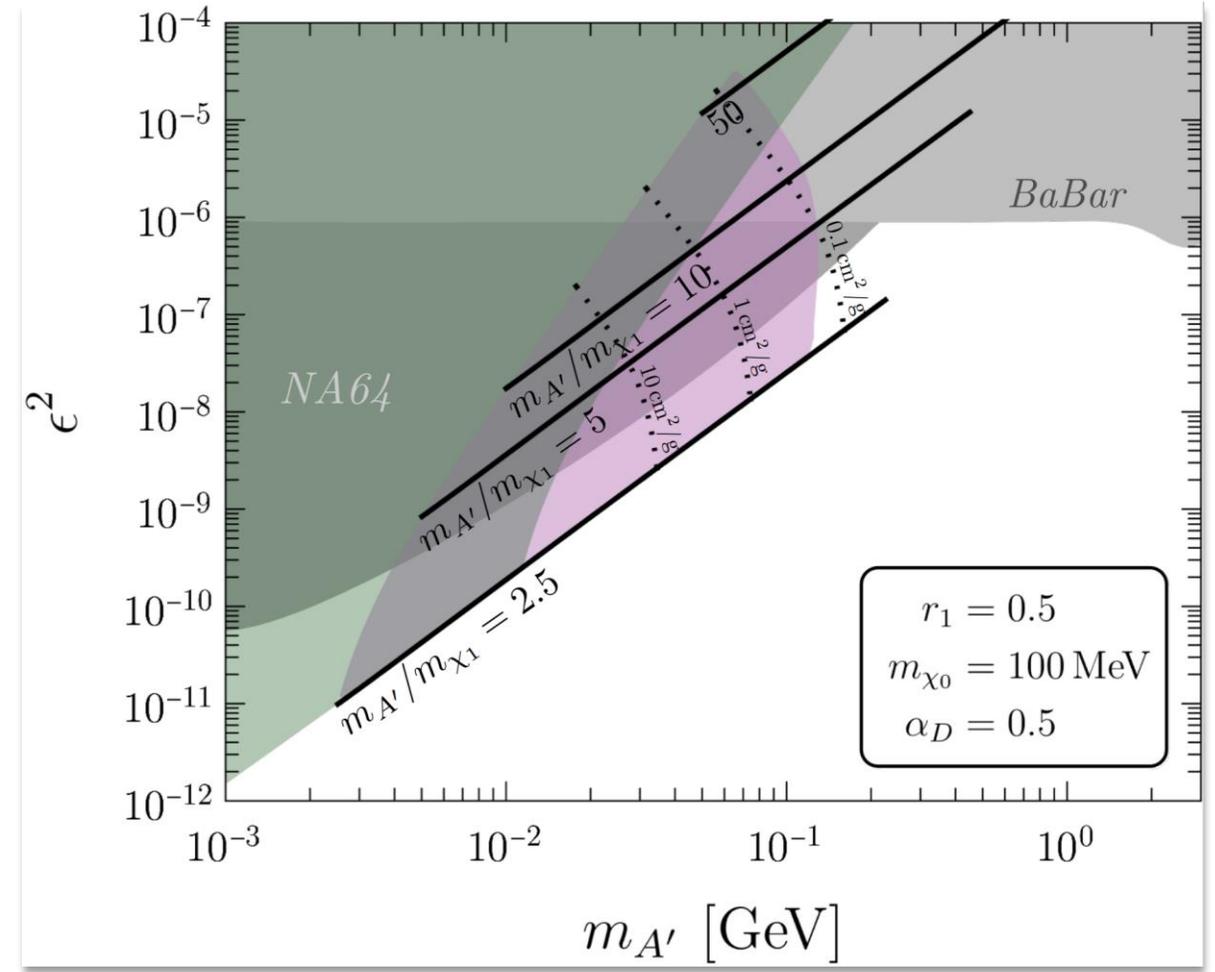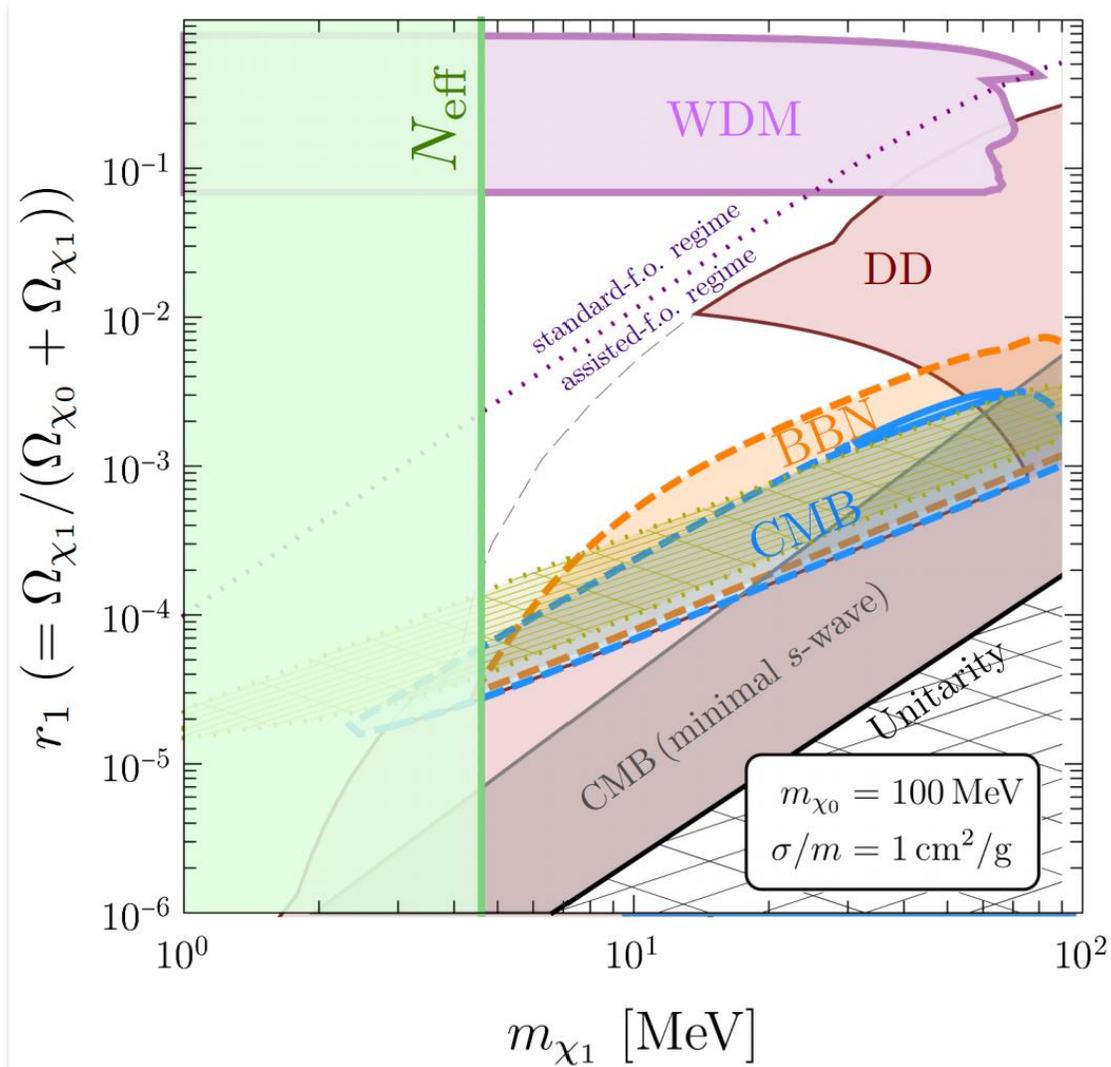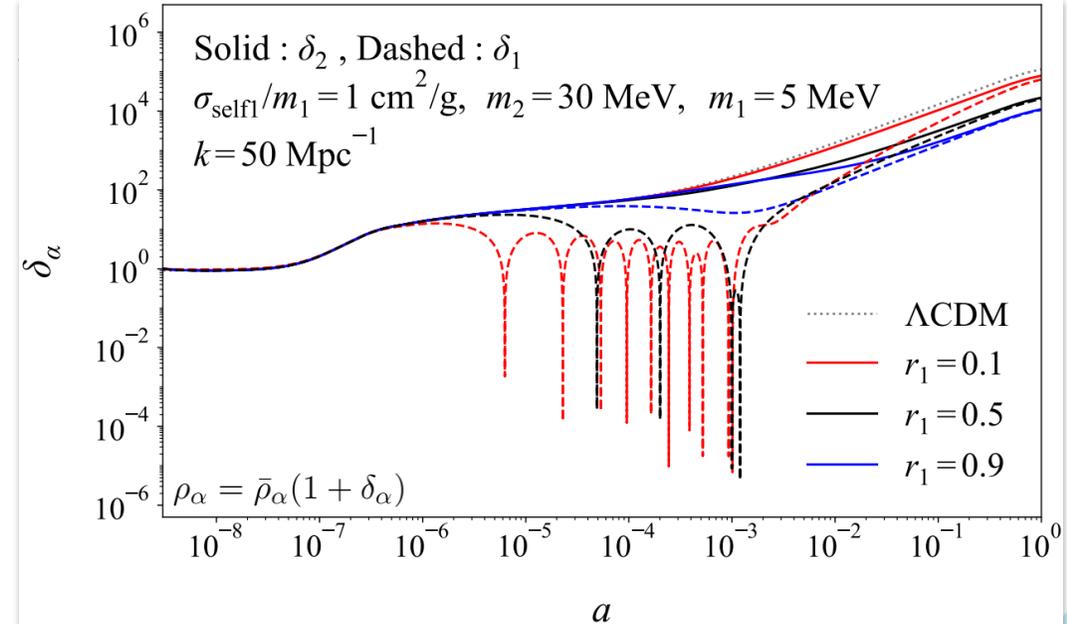❖ Coupled equations for the density perturbation

$$\frac{d\delta_2}{dt} + \frac{\theta_2}{a} - 3\frac{d\Phi}{dt} = \frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_2}\left(-\Psi\left(\bar{\rho}_2^2 - \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\right) - \bar{\rho}_2^2\delta_2 + \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\left(2\delta_{2,\text{eq}} - \delta_2 - 2\delta_{1,\text{eq}} + 2\delta_1\right)\right),$$

$$\frac{d\theta_2}{dt} + H\theta_2 + \frac{\nabla^2\Psi}{a} = \frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_2}\frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\left(\theta_1 - \theta_2\right),$$

$$\frac{d\delta_1}{dt} + \frac{\theta_1}{a} - 3\frac{d\Phi}{dt} = -\frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_1}\left(-\Psi\left(\bar{\rho}_2^2 - \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\right) - \bar{\rho}_2^2(2\delta_2 - \delta_1) + \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\left(2\delta_{2,\text{eq}} + \delta_1 - 2\delta_{1,\text{eq}}\right)\right)$$

$$+ \frac{\langle\sigma v\rangle_{11\to XX}}{m_1\bar{\rho}_1}\left(-\Psi\left(\bar{\rho}_1^2 - \bar{\rho}_{1,\text{eq}}^2\right) - \bar{\rho}_1^2\delta_1 + \bar{\rho}_{1,\text{eq}}\left(2\delta_{1,\text{eq}} - \delta_1\right)\right)$$

$$\frac{d\theta_1}{dt} + H\theta_1 + \frac{\nabla^2\Psi}{a} + c_{s,1}^2\frac{\nabla^2\delta_1}{a} = \frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_1}\bar{\rho}_2^2\left(\theta_2 - \theta_1\right),$$

Solid : δ_2 , Dashed : δ_1
$\sigma_{\text{self1}}/m_1 = 1~\text{cm}^2/\text{g}$, $m_2 = 30~\text{MeV}$, $m_1 = 5~\text{MeV}$
$k = 50~\text{Mpc}^{-1}$
$\rho_\alpha = \bar{\rho}_\alpha(1 + \delta_\alpha)$
ΛCDM
$r_1 = 0.1$
$r_1 = 0.5$
$r_1 = 0.9$

Linear Matter Power Spectrum

❖ Linear power spectrum by *CLASS*

N-Body Simulation: Observational Constraints

❖ Maximum circular velocity distribution of sub-halos

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & 2410.05382]

✓ The number of sub-halos is more reduced with smaller m_{χ_1} & m_{χ_2}, larger $\sigma_1^{\text{self}}/m_{\chi_1}$.
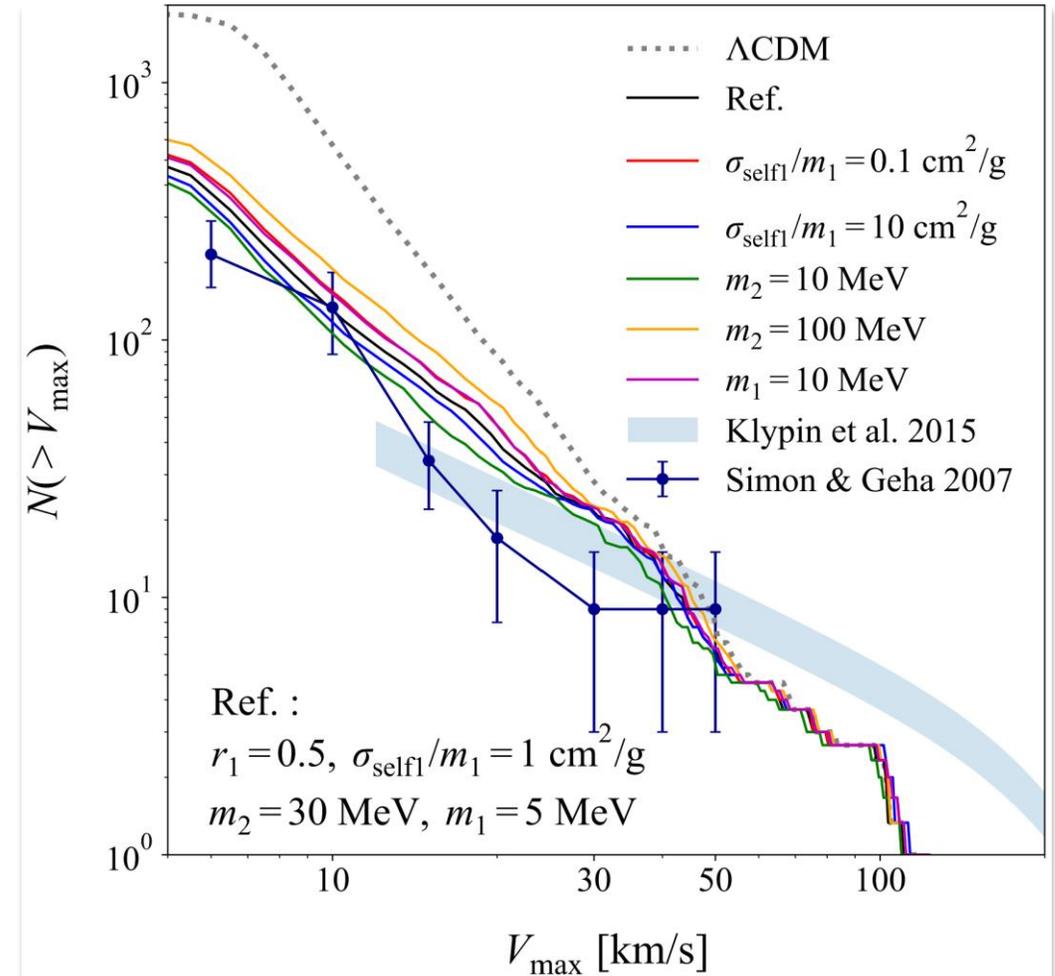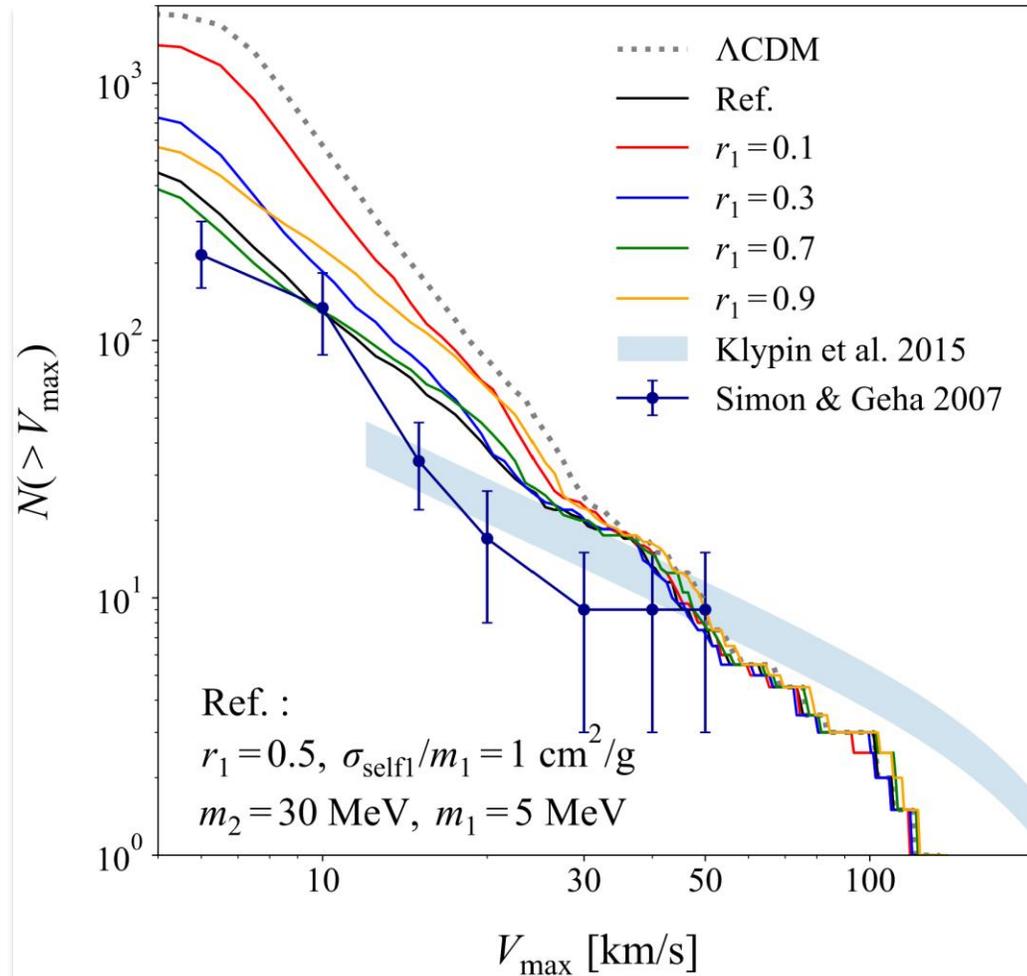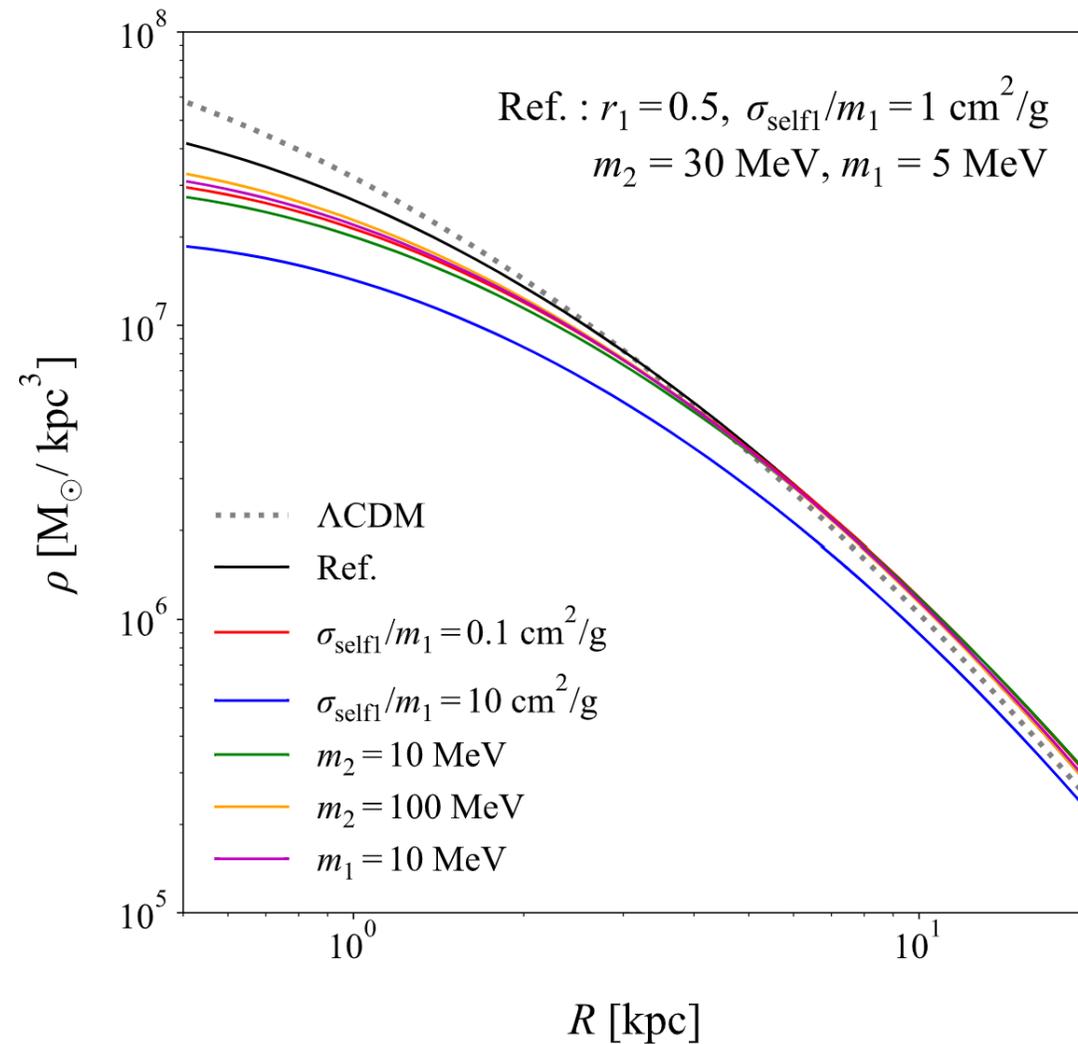
Galactic Density Profile: Total

❖ Averaged total density profiles of halos with $M > 10^{10} M_\odot$

Left panel:
Ref. : $r_1 = 0.5$, $\sigma_{\text{self1}}/m_1 = 1$ cm^2/g
$m_2 = 30$ MeV, $m_1 = 5$ MeV

Legend (left):
- ⋯⋯ ΛCDM
- — Ref.
- — $r_1 = 0.1$
- — $r_1 = 0.3$
- — $r_1 = 0.7$
- — $r_1 = 0.9$

Axes (left): ρ [M$_\odot$/ kpc^3] vs R [kpc]

Right panel:
Ref. : $r_1 = 0.5$, $\sigma_{\text{self1}}/m_1 = 1$ cm^2/g
$m_2 = 30$ MeV, $m_1 = 5$ MeV

Legend (right):
- ⋯⋯ ΛCDM
- — Ref.
- — $\sigma_{\text{self1}}/m_1 = 0.1$ cm^2/g
- — $\sigma_{\text{self1}}/m_1 = 10$ cm^2/g
- — $m_2 = 10$ MeV
- — $m_2 = 100$ MeV
- — $m_1 = 10$ MeV

Axes (right): ρ [M$_\odot$/ kpc^3] vs R [kpc]

❖ Averaged individual density profiles of halos with $M > 10^{10} M_\odot$

Left figure legend:
- Ref.
- $r_1 = 0.1$
- $r_1 = 0.3$
- $r_1 = 0.7$
- $r_1 = 0.9$

Ref. : $r_1 = 0.5$, $\sigma_{\text{self1}}/m_1 = 1$ cm^2/g
$m_2 = 30$ MeV, $m_1 = 5$ MeV
Solid : χ_2 , Dashed : χ_1

Right figure legend:
- Ref.
- $\sigma_{\text{self1}}/m_1 = 0.1$ cm^2/g
- $\sigma_{\text{self1}}/m_1 = 10$ cm^2/g
- $m_2 = 10$ MeV
- $m_2 = 100$ MeV
- $m_1 = 10$ MeV

Solid : χ_2 , Dashed : χ_1
Ref. : $r_1 = 0.5$, $\sigma_{\text{self1}}/m_1 = 1$ cm^2/g
$m_2 = 30$ MeV, $m_1 = 5$ MeV