# New Approaches in Search for Light DM:
# Boosted Dark Matter (BDM)


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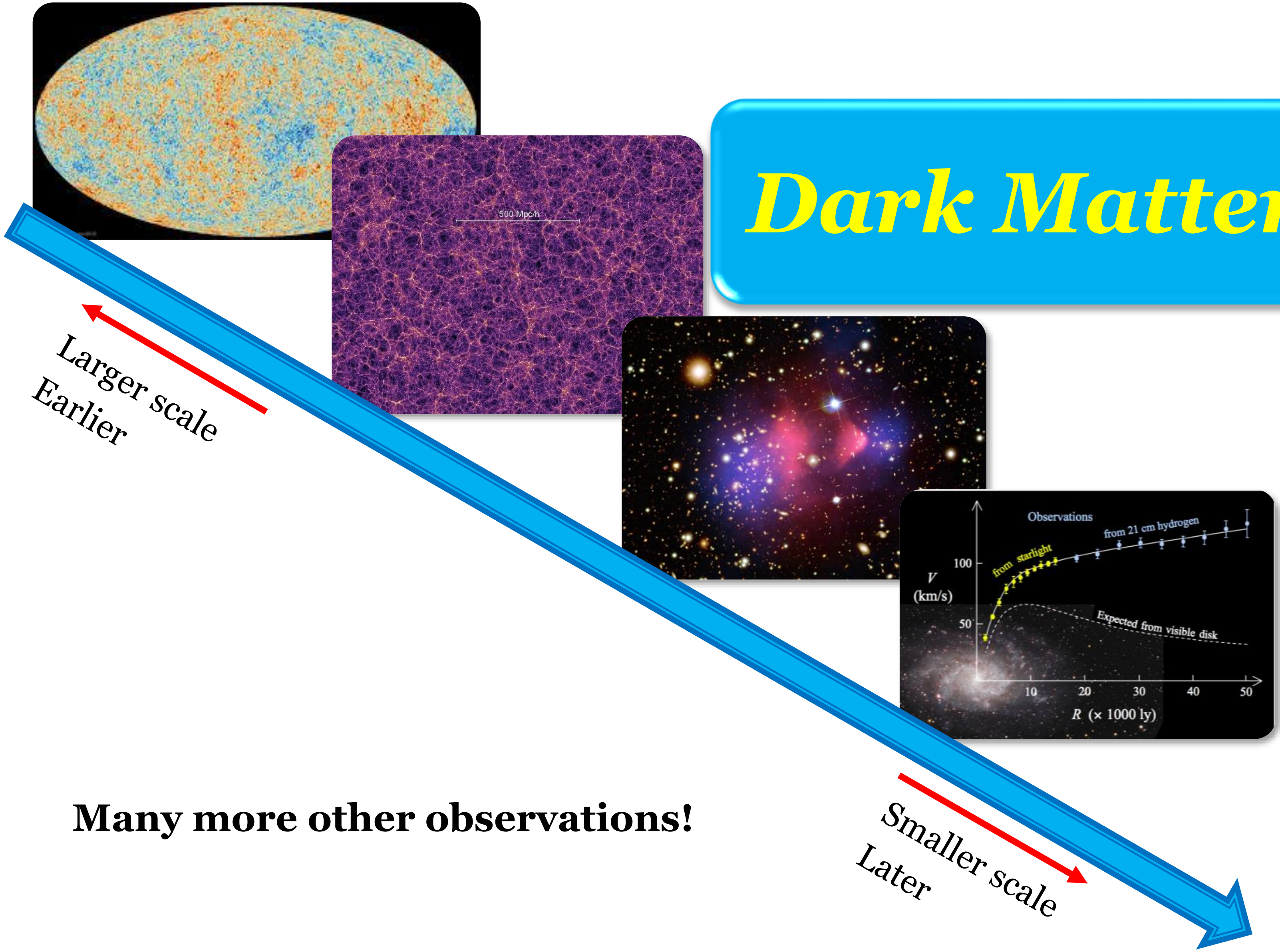
October 17 (2024)

# Outline

- ❖ **Dark Matter? Dark Sector?**
- ❖ **Boosted Dark Matter (BDM) & Its Searches**
- ❖ **Issues in BDM Searches**
- ❖ **Exciting Prospects for BDM Searches**
- ❖ **Summary**

# Dark Matter?
# Dark Sector?

# Message from Cosmology: Dark Matter (DM)

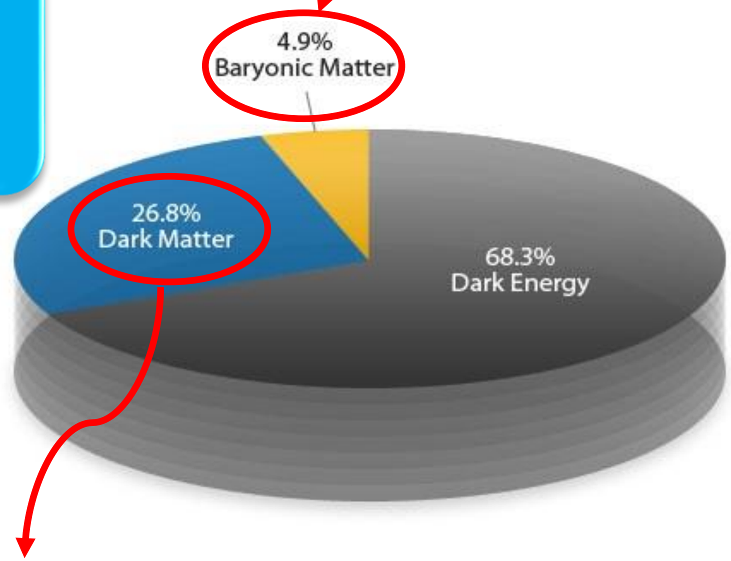



***Dark Matter?***

**Many more other observations!**

❖ **Modern cosmology**:

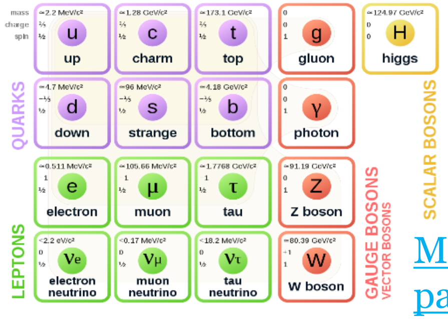
The Standard Model




❖ **Compelling paradigm**:

- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

# Dark Sector: Dark Particles & Portals





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: $\lambda_\chi H L \chi$
- ✓ 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: $\frac{\sigma}{f} (M_V^2 V_\mu V^\mu + \cdots + V_{\mu\nu} V^{\mu\nu} + \cdots)$
- ✓ Gauged SM global #: B-L, $L_\mu$-$L_\tau$, …
- ✓ 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**

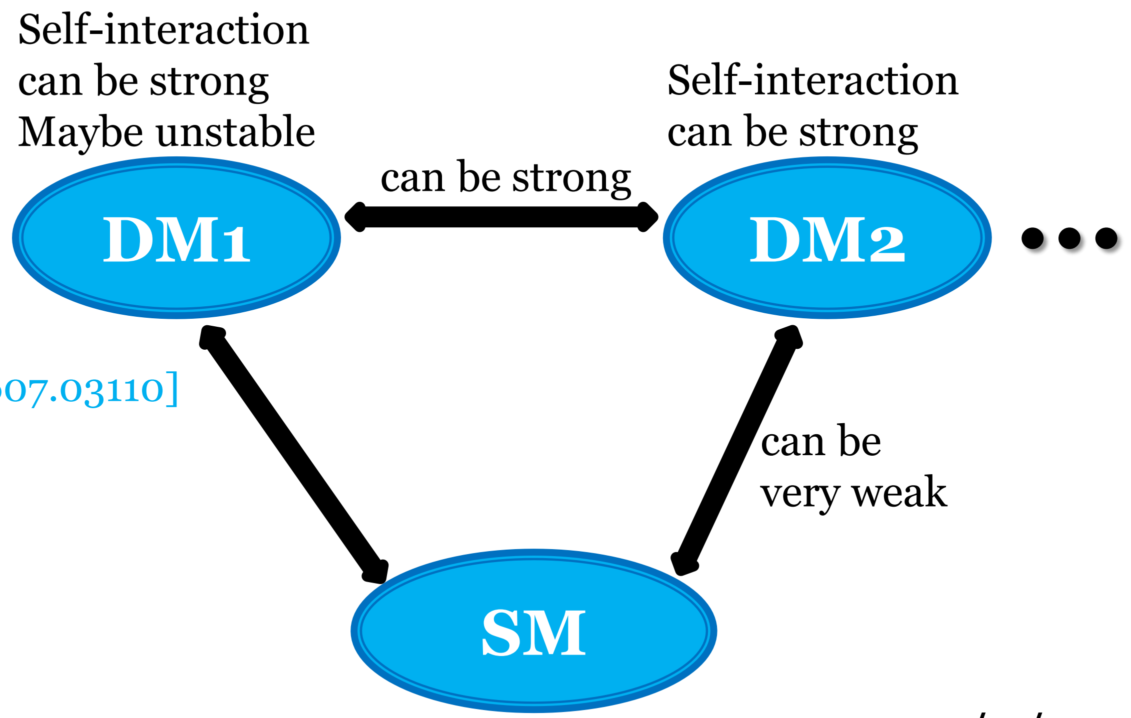
- ✓ DM spin: fermion, scalar, vector
- ✓ DM species: single-/two-/multi-component
- ✓ DM mass: light, heavy, light & heavy
- ✓ DM interaction: flavor-conserving (elastic),

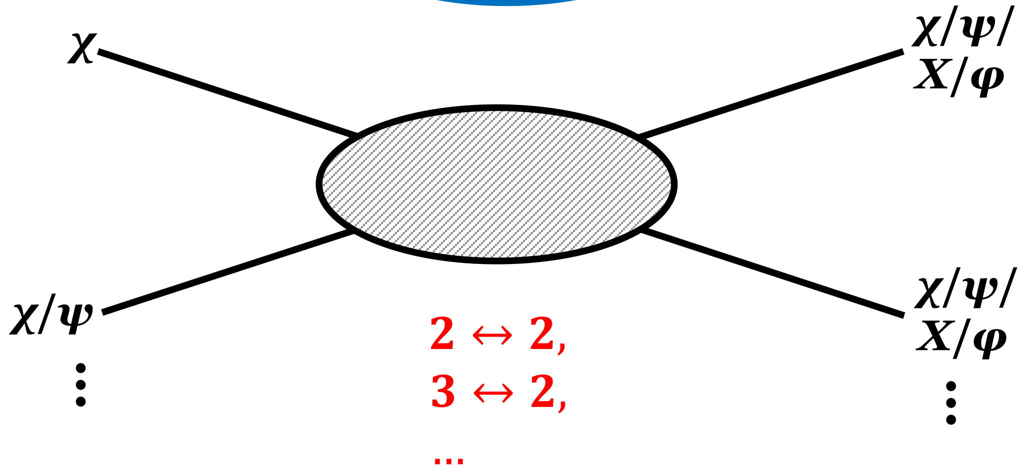
  flavor-changing (inelastic)
- ✓ ???

# Various Ideas for DM

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

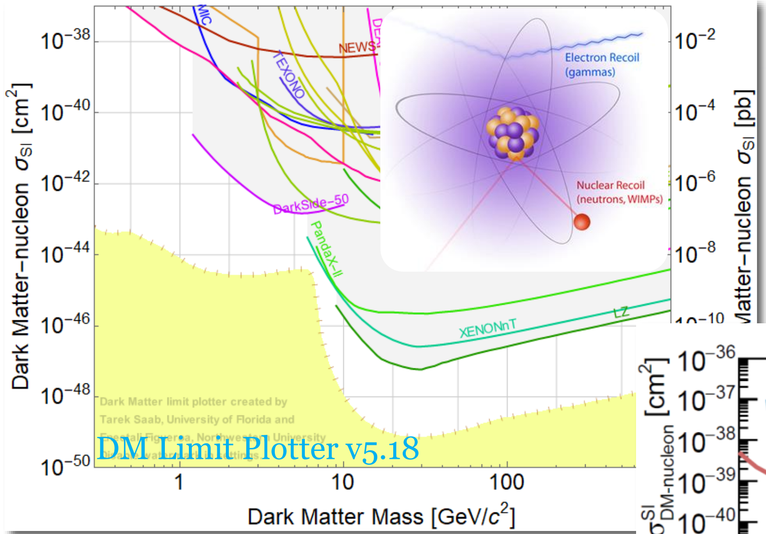
- ✓ Assisted freeze-out [Belanger & **JCP**, 1112.4491]
- ✓ Asymmetric dark matter [0901.4117]
- ✓ Cannibal dark matter [1602.04219; 1607.03108]
- ✓ Co-annihilation [PRD43 (1991) 3191]
- ✓ Co-decaying dark matter [Bandyopadhyay, Chun, **JCP**, 1105.1652; 1607.03110]
- ✓ Continuum dark matter [2105.07035]
- ✓ 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]
- ✓ ...

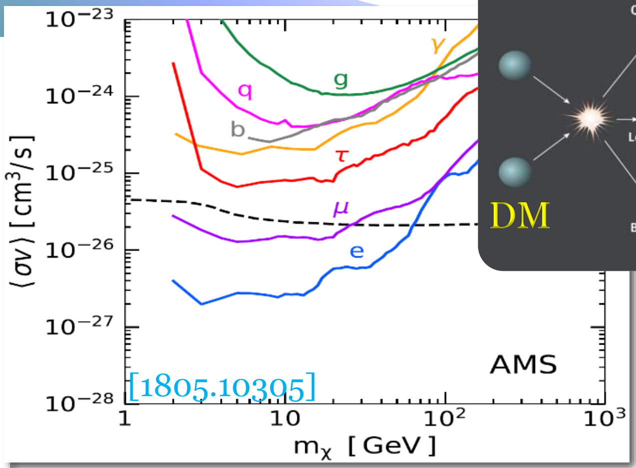


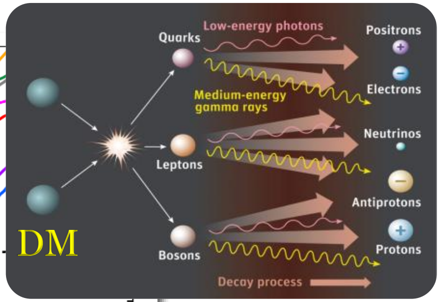



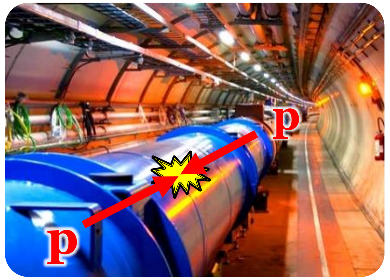
# Current Status of DM Searches

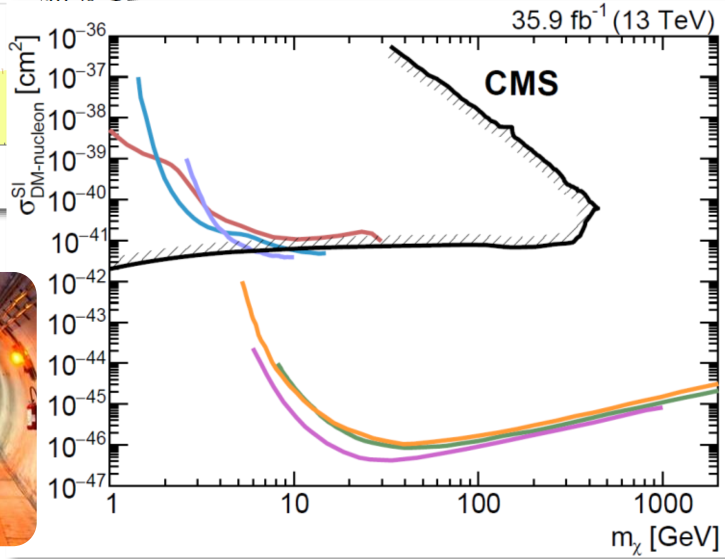

| Ultralight | Superlight | Light | WIMP | Superheavy | Astrophysical object |
|---|---|---|---|---|---|
| axion, fuzzy, hidden photon, | sterile ν, warm DM | SIMP, ELDER | | composite DM, WIMPzilla | MACHO, PBH |



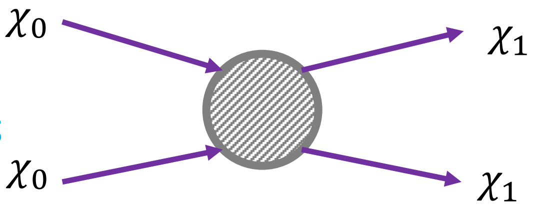

- ✓ No concrete evidence of DM yet.
- ✓ Tight bounds are imposed on WIMP.
- ✓ Next decade: **A paradigm shift?**

# Boosted Dark Matter (BDM)

# Dark Sector: DM Boosting Mechanisms

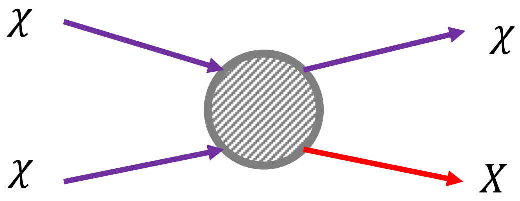
## *Boosted DM (BDM) coming from the Universe*

[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]




✓ Multi-component model

$m_2 \gg m_1$

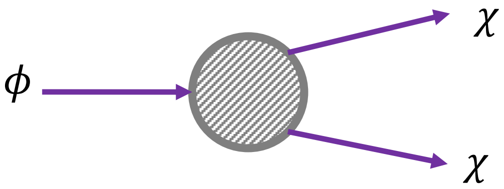



✓ Semi-annihilation model

$m_\chi \gg m_X$

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

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




✓ Decaying multi-component DM

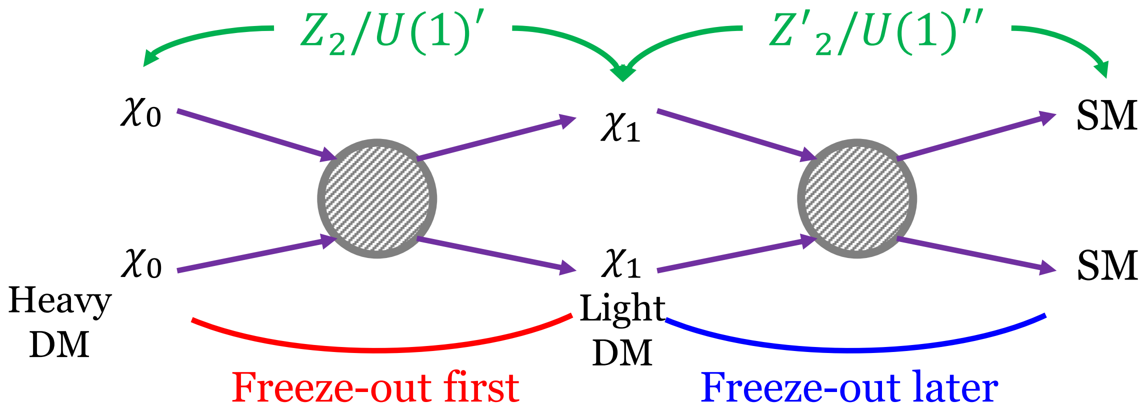
$m_\phi \gg m_\chi$

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

- Relic component DM: Non-relativistic!
- Tiny fraction of DM: Relativistic!

# Two-Component Scenario: Freeze-out

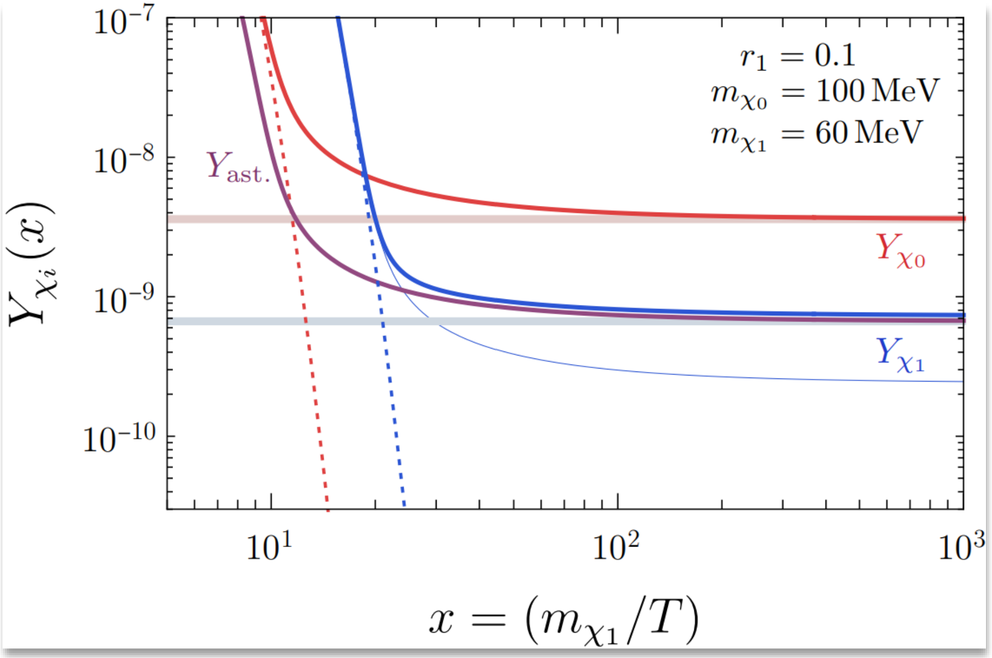
[Belanger, **JCP**, JCAP (2012)]
[Kamada, Kim, **JCP**, Shin, JCAP (2022)]




"**Assisted Freeze-out**" Mechanism

✓ Heavier relic $\chi_0$: hard to directly detect it due to tiny coupling to SM

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

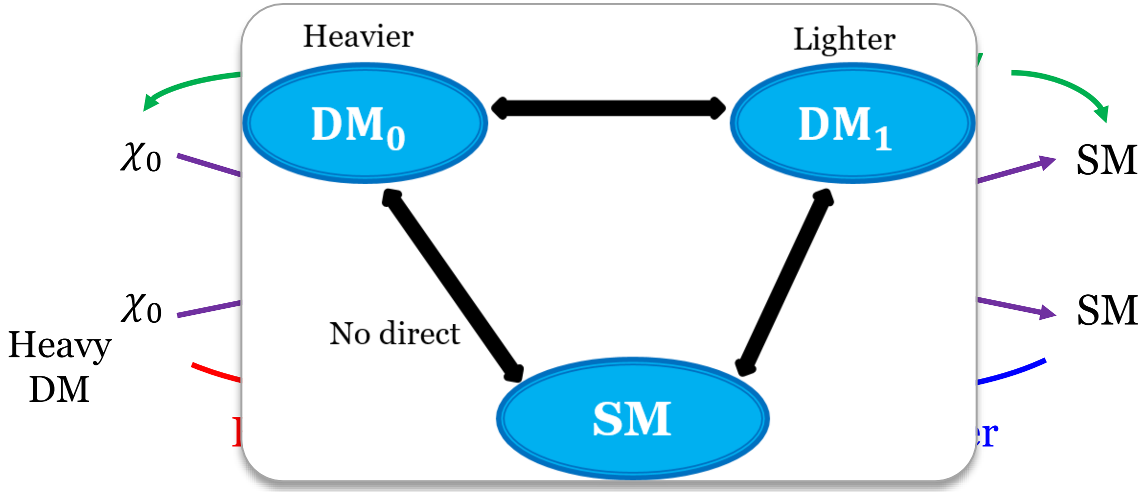



$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\rm eq}(x)}{Y_{\chi_1}^{\rm eq}(x)}\right)^2 Y_{\chi_1}^2\right],$$

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

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

# Two-Component Scenario: Freeze-out

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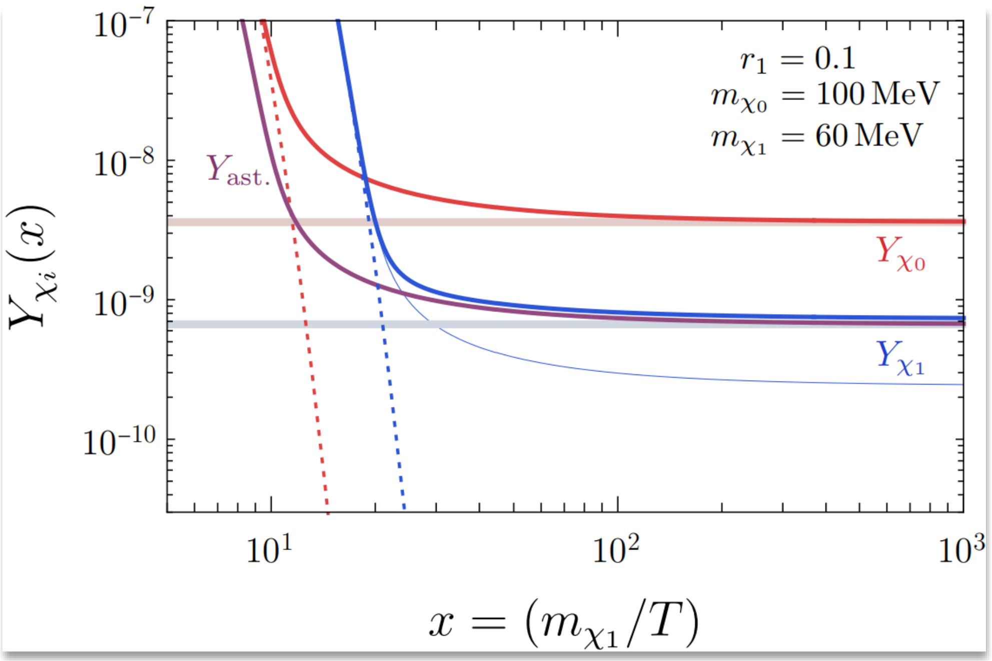


[Belanger, **JCP**, JCAP (2012)]
[Kamada, Kim, **JCP**, Shin, JCAP (2022)]

"**<u>Assisted Freeze-out</u>**" Mechanism

✓ Heavier relic $\chi_0$: hard to directly detect it due to tiny coupling to SM

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

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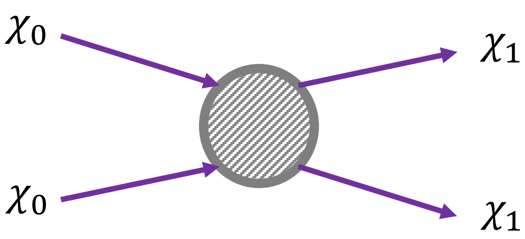
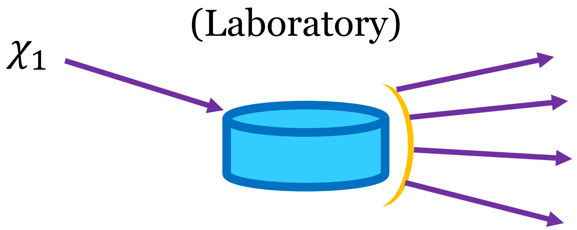
# Two-Component Scenario: BDM Signatures




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

becomes boosted

($\gamma_1 = m_0/m_1$)

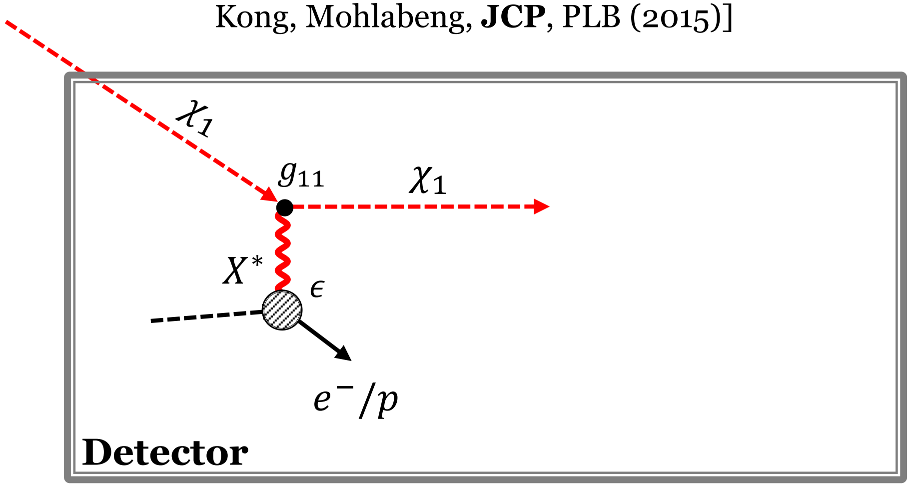



$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm l.o.s.} ds \langle\sigma v\rangle_{\chi_0\bar\chi_0\to\chi_1\bar\chi_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

$$= 8.0\times10^{-5}\ {\rm cm^{-2}s^{-1}} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\bar\chi_0\to\chi_1\bar\chi_1}}{5\times10^{-26}\ {\rm cm^3\,s^{-1}}}\right)\left(\frac{\rm GeV}{m_0}\right)^2\frac{dN_1}{dE_1}$$

**elastic scattering (eBDM)**

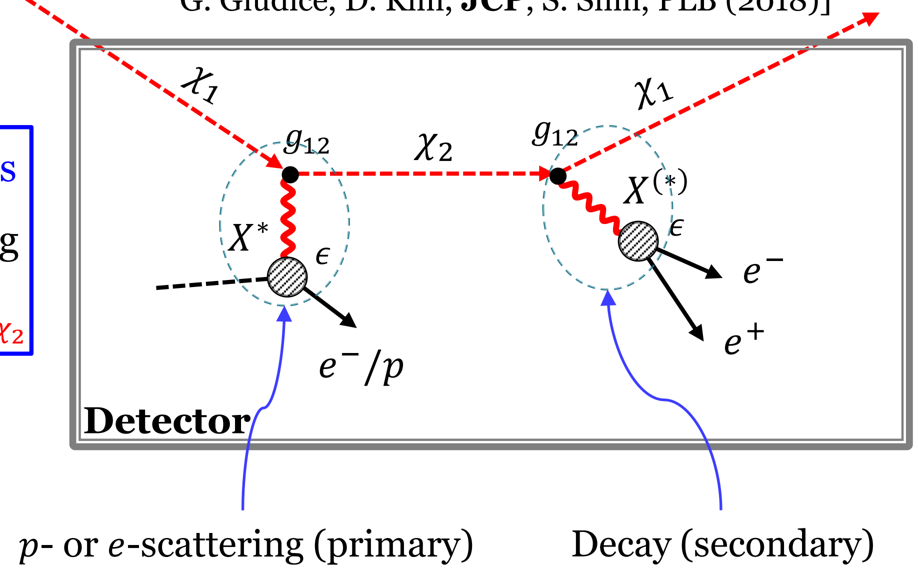
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]




1~3 tracks depending on $E_{\rm th}$ & $l_{\chi_2}$

**inelastic scattering (*i*BDM)**

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

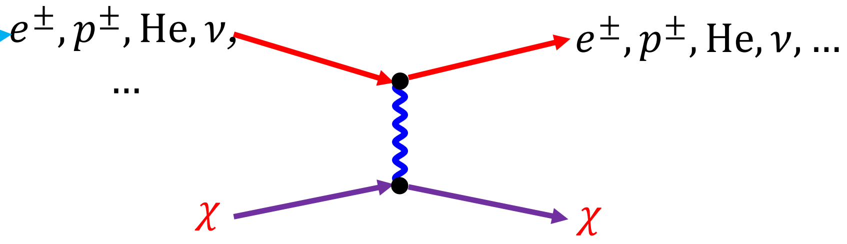


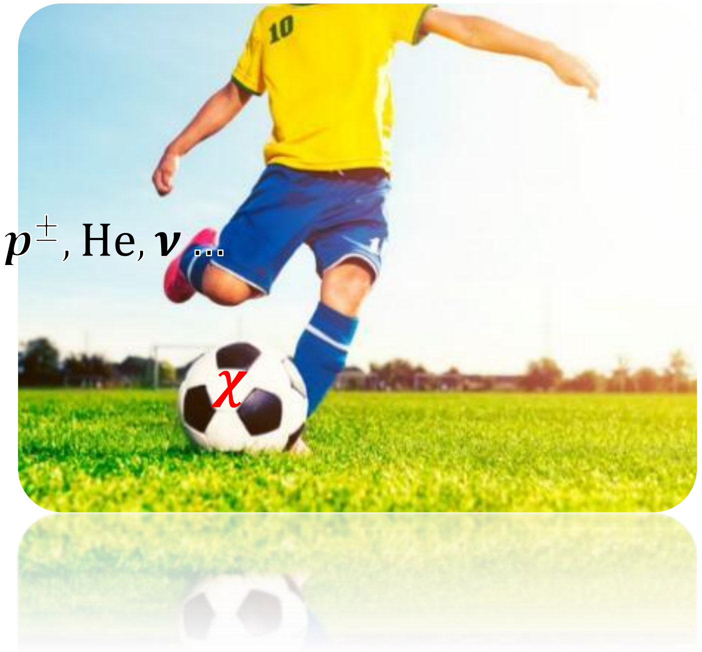

❖ BDM signal: detectable at **large volume** detectors

# DM Boosting Mechanisms: Cosmic-Rays (CRs)

## *Cosmic-Ray-Induced BDM*

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




- Energetic cosmic-ray-induced BDM: energetic cosmic-rays kick DM (large $E_{e^{\pm},p^{\pm},\mathrm{He},\boldsymbol{\nu},\ldots}$ ➔ large $E_{\chi}$)

  ➔ Efficient for Light DM

- 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

# BDM Searches @ Neutrino Experiments

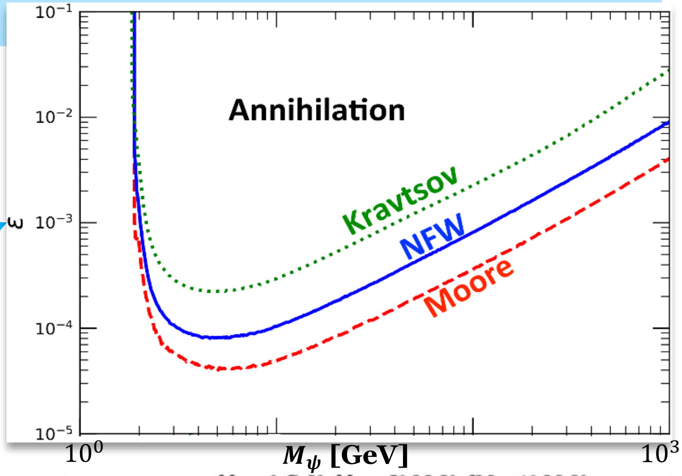
***Boosted DM (BDM) scenarios:***
***Receiving rising attention as an alternative scenario***

PHYSICAL REVIEW LETTERS **120**, 221301 (2018)

Editors' Suggestion

**Cherenkov radiation rings by electrons**

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




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

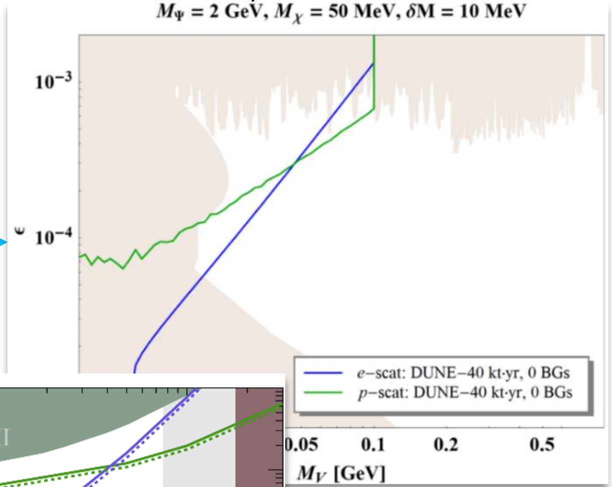
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

Regular Article - Experimental Physics

**Ionization tracks by electrons and/or protons**

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

**DUNE Collaboration**

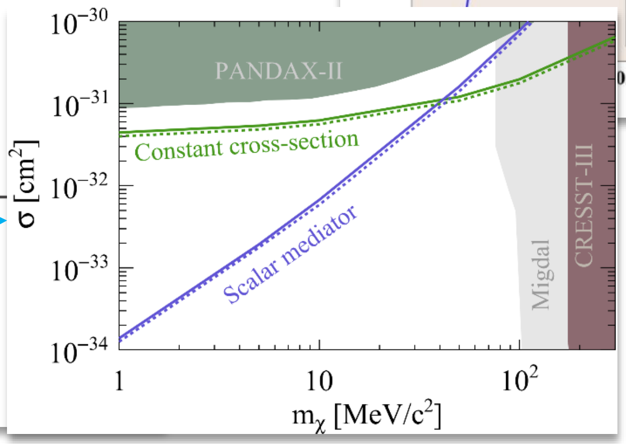



PHYSICAL REVIEW LETTERS **130**, 031802 (2023)

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**

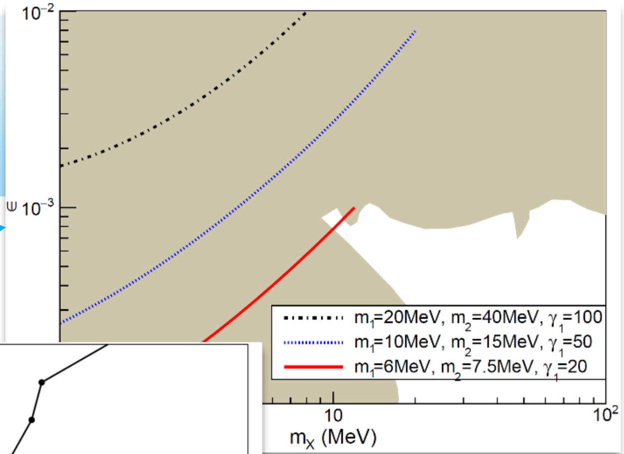


# BDM Searches @ DM Experiments

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

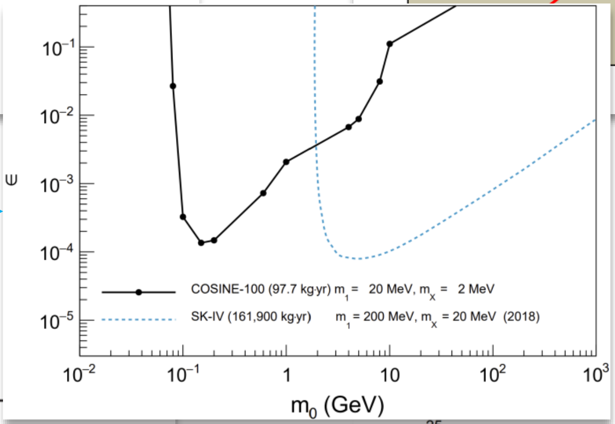
Editors' Suggestion

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




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

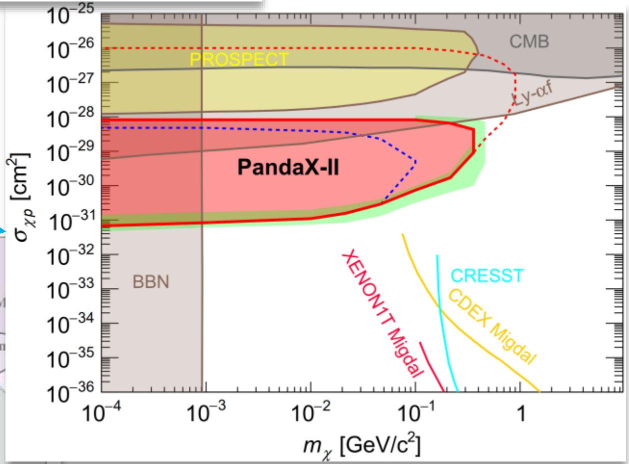
**Search for Boosted Dark Matter in COSINE-100**




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

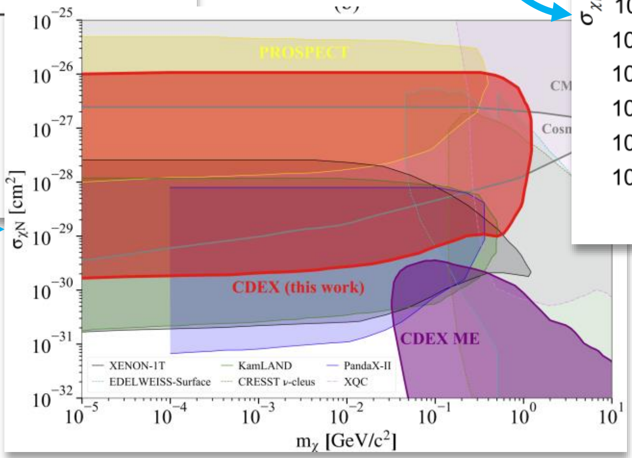
Editors' Suggestion

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




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

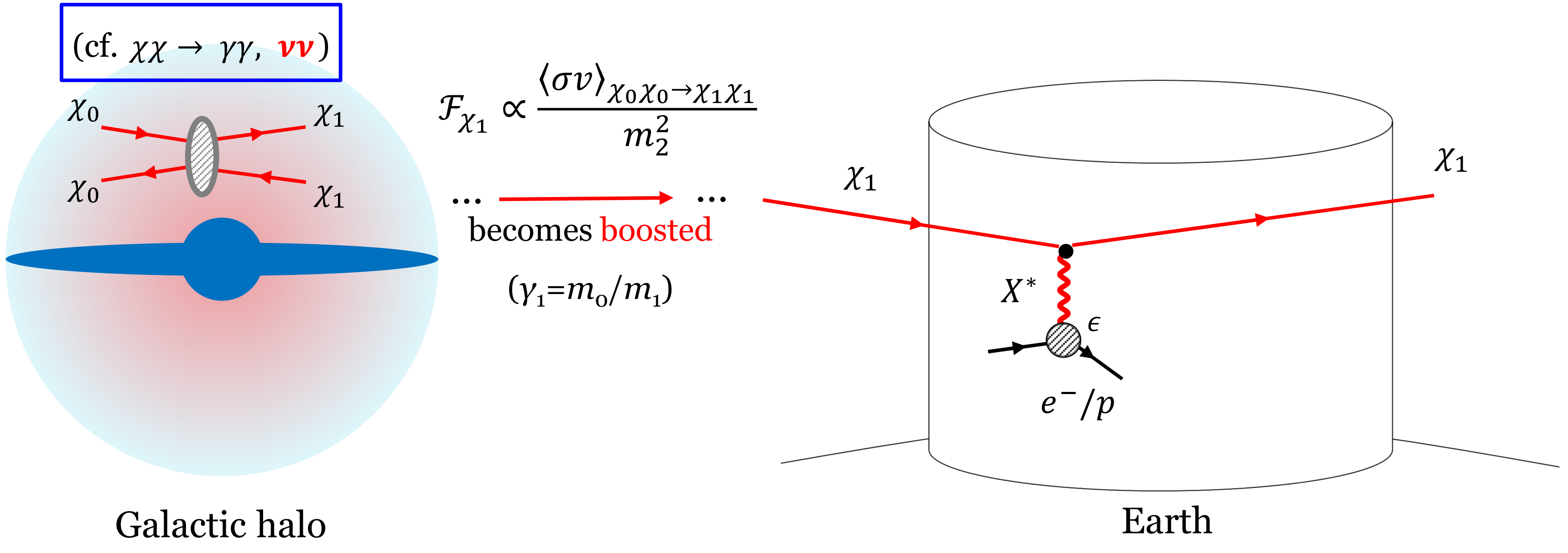
**Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory**




- ✓ Not restricted to primary physics goals
- ✓ Opened to other (unplanned) physics opportunities

# Issues in BDM Searches

# Minimal Two-component Scenario

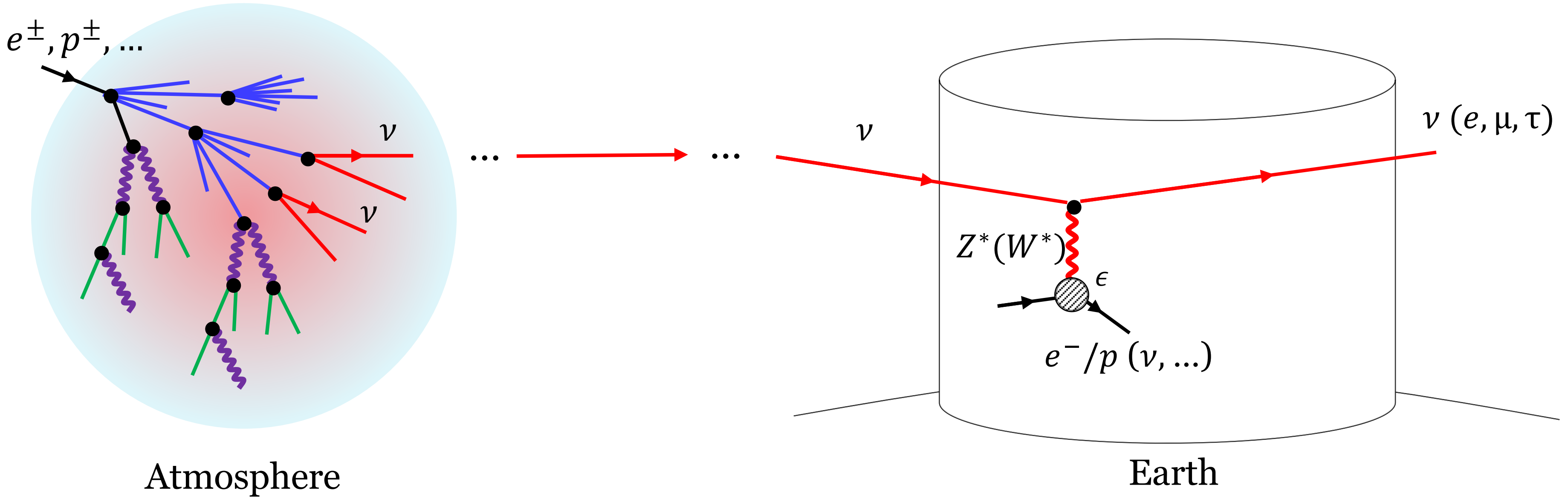



- Example model: fermionic heavier($\chi_0$)/lighter($\chi_1$) DM + dark gauge boson($X$)

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

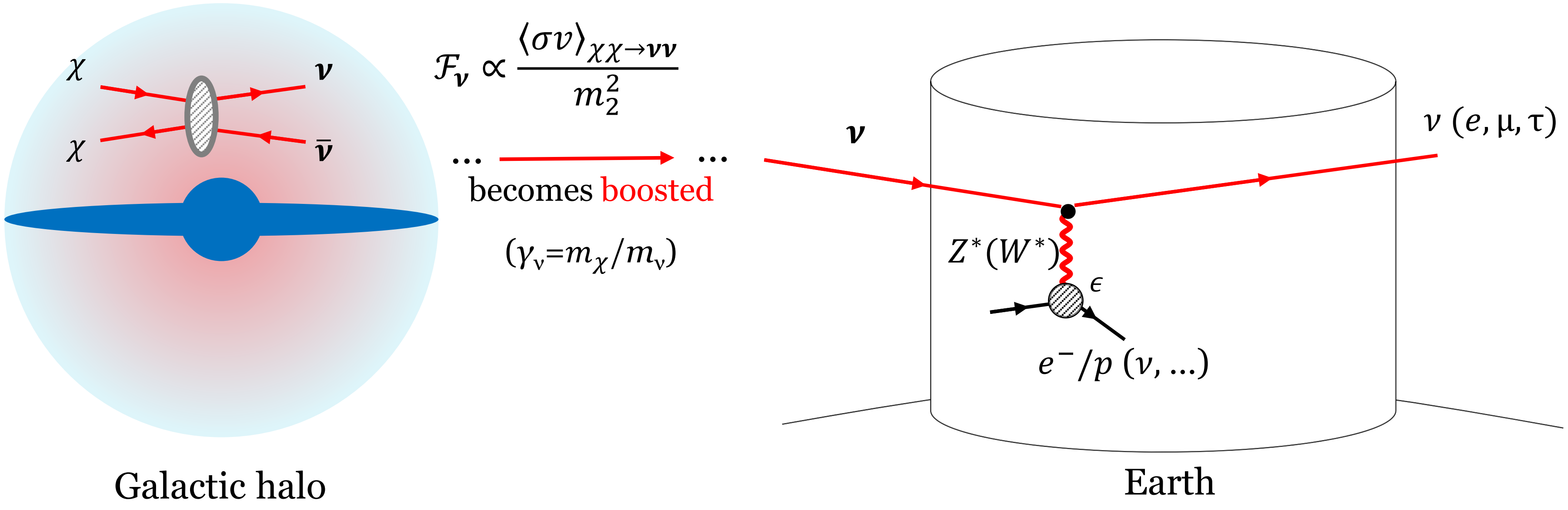
- Elastic electron [Agashe, Cui, Necib, Thaler (2014)] & elastic proton (even DIS @ e.g. DUNE) [P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)] scattering channels are available. ➔ Energetic recoil

# Issue 1: Background



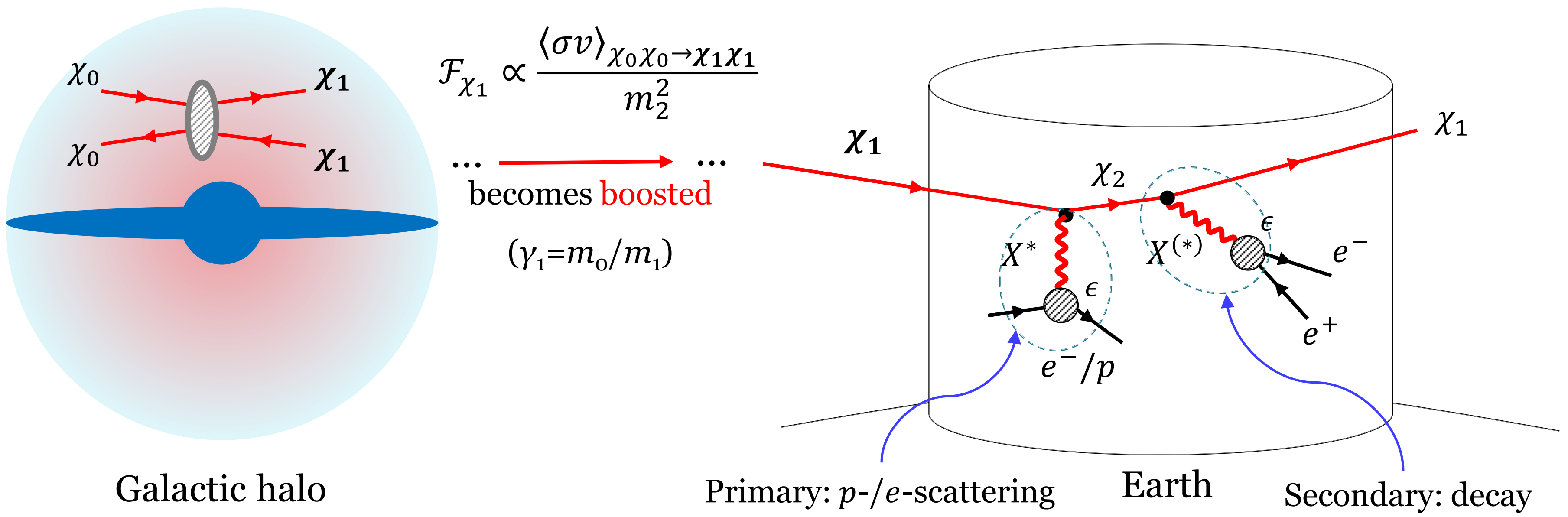

- ❖ Irreducible backgrounds: atmospheric-neutrino-induced events
- ❖ Neutral- & charged-current (even DIS) scattering channels are available. ➔ Energetic recoil
- ❖ Good angular resolution allows to isolate source regions, especially very good for point-like sources such as the GC, Sun & dwarf galaxies.

# Issue 2: Distinction from ν Scenario




- ❖ (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 iBDM Scenario

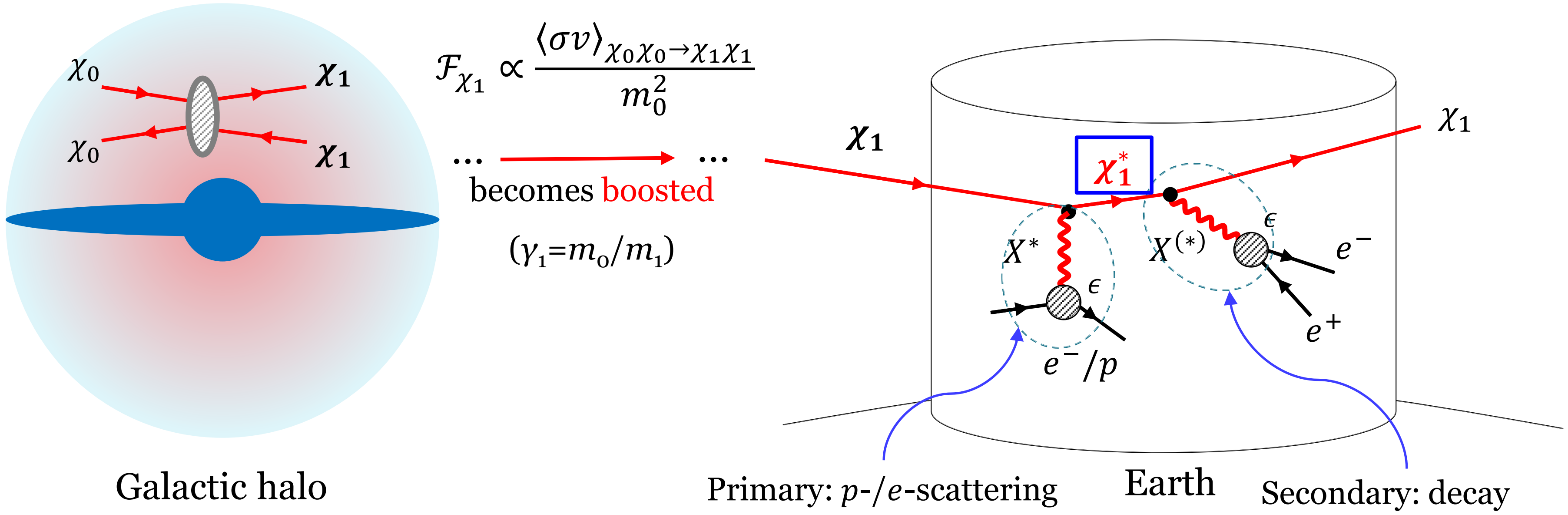



❖ *i*BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]

❖ Additional signatures from the decay of heavier unstable dark-sector state (or excited state) $\chi_2$ at the expense of "minimalism" of underlying BDM models.

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

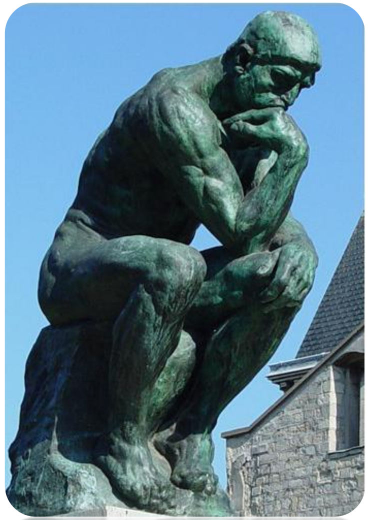
# Issue 2: Avoidable by Sub-leading Process




❖ Distinctive signatures may arise even under the minimal setup, once higher-order corrections are taken into account.

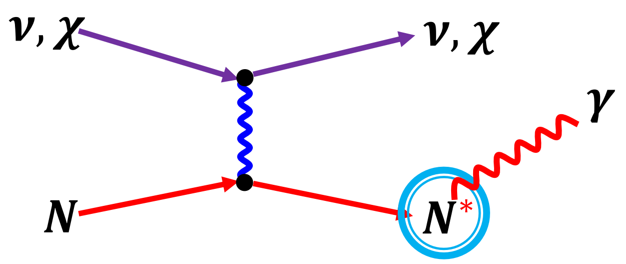
❖ A new BDM search strategy utilizing initial-/final-state dark gauge boson radiation, i.e. "**Dark-Strahlung**" from cosmogenic BDM [Kim, **JCP** & Shin, PRD (2019)]

# Only recoiled e/p?

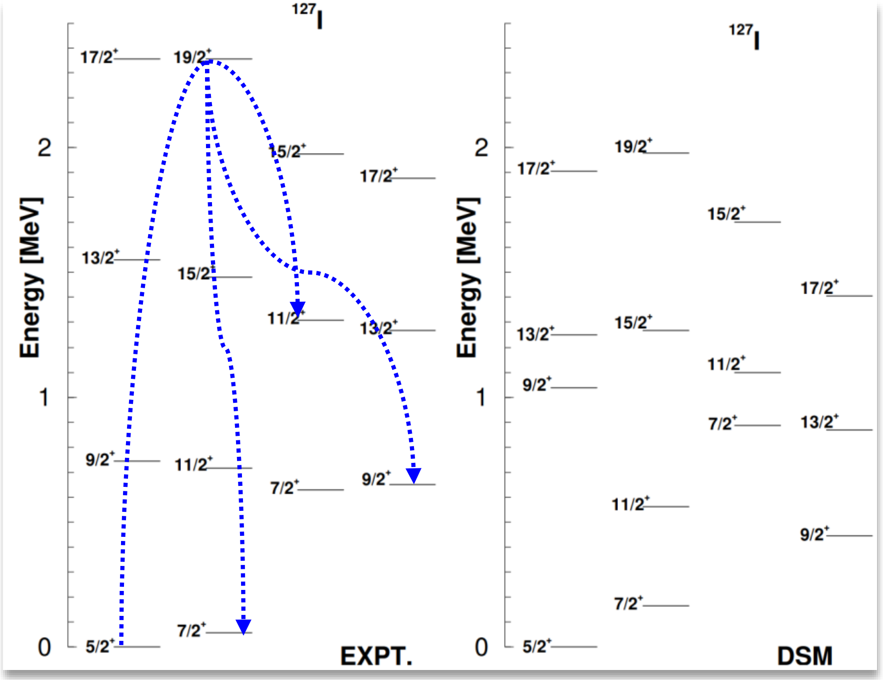


# Inelastic Nuclear Scattering

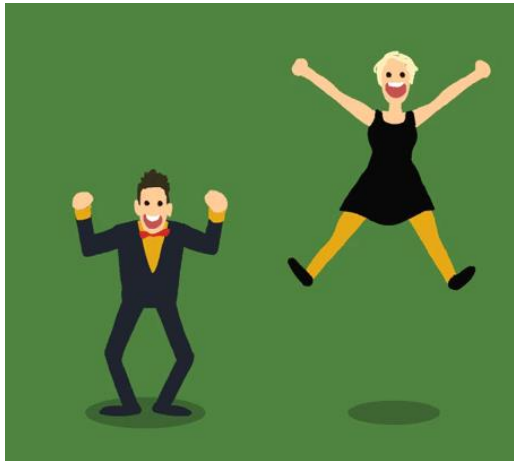
❖ Why **inelastic** channel?




$E_{in} \lesssim 50$ MeV




Sahu et al., [2004.04055]



- **Signatures**
  - ✓ $\gamma$ cascade ($\Delta E \lesssim 10$ MeV)
  - ✓ $\gamma$ 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**
  - ✓ Inclusion of multiple excited states
  - ✓ Consistent handling of hadronic currents
  - ✓ Exclusive cross sections for each state

Dutta, Newstead et al., [2206.08590]

# Inelastic Nuclear Scattering of CR-BDM

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

- Focus: the interaction between DM & quark

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

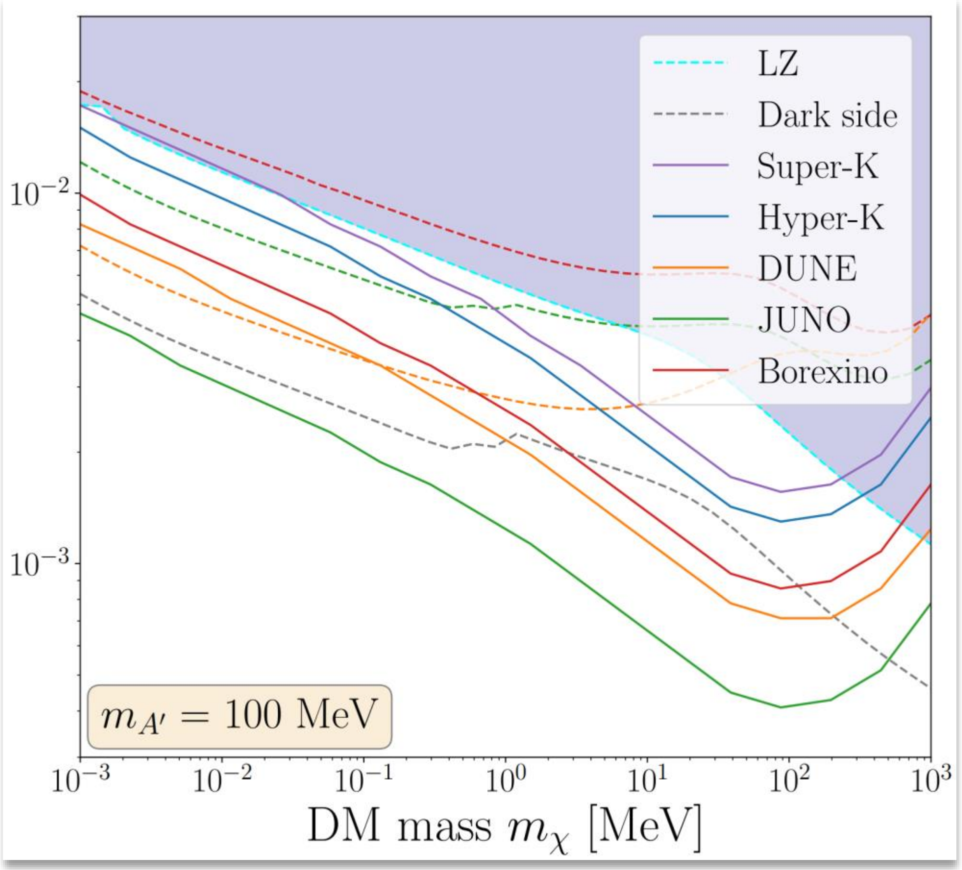
➔ DM boosted by cosmic rays (p, He)

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

$$\frac{d\sigma^{\rm inel}_{\chi N}}{d\cos\theta} = \frac{2\epsilon^2 g_D^2 E'_\chi p'_\chi}{(2m_T E_R + m_{A'}^2 - \Delta E^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1} \times \sum_{s_i,s_f} \vec{l}\cdot\vec{l}^* \frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A}\frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2 ,$$

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

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

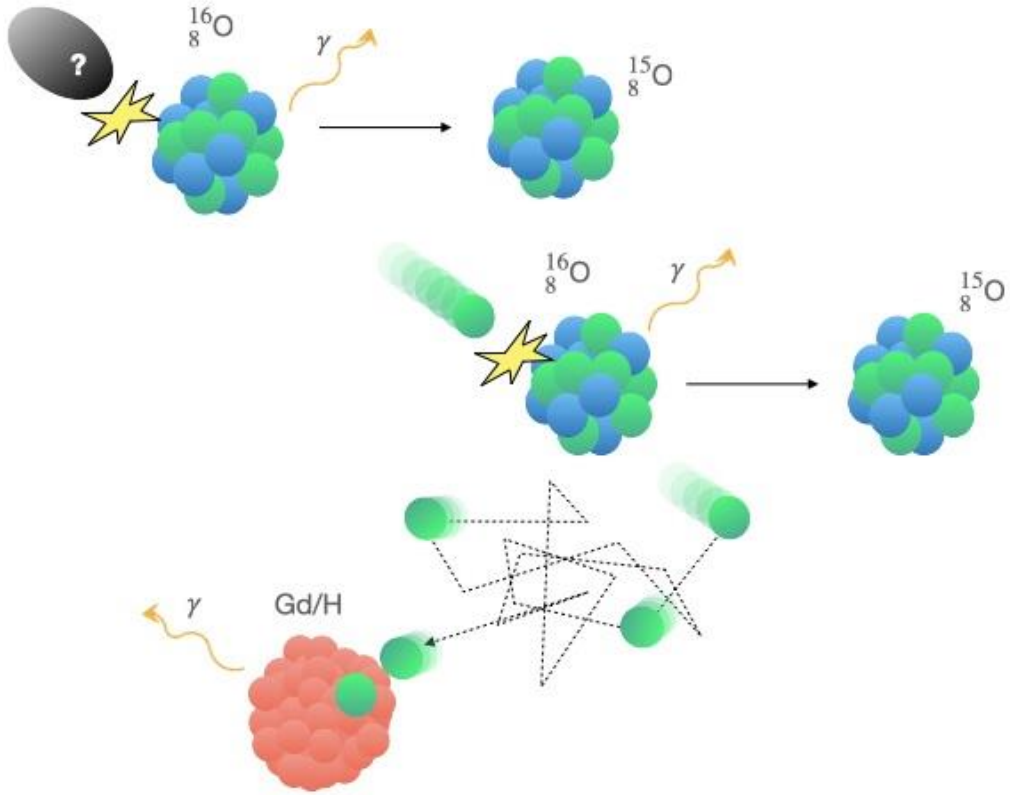



✓ Inelastic (solid) better than elastic (dashed)

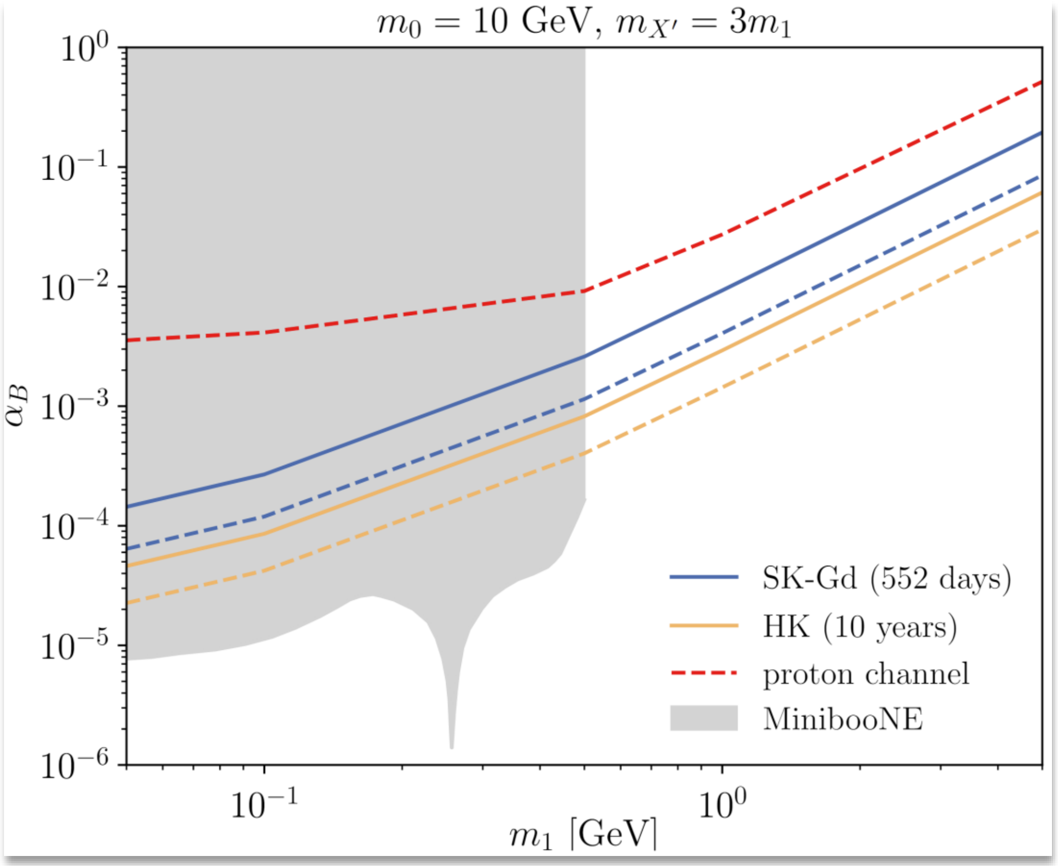
# Knockout Neutron @ Cherenkov Detectors

- For p, higher $p_{th} > 1.07$ GeV
- For n, no Cherenkov radiation but $\gamma$'s from capture

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



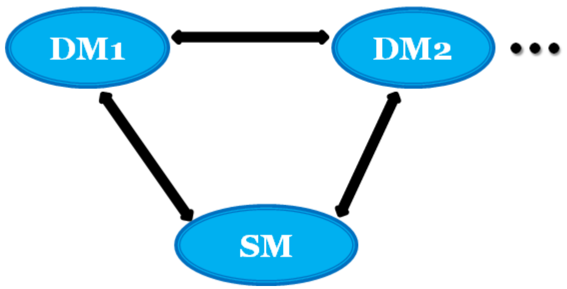

[K. Choi & **JCP**, 2409.05646]



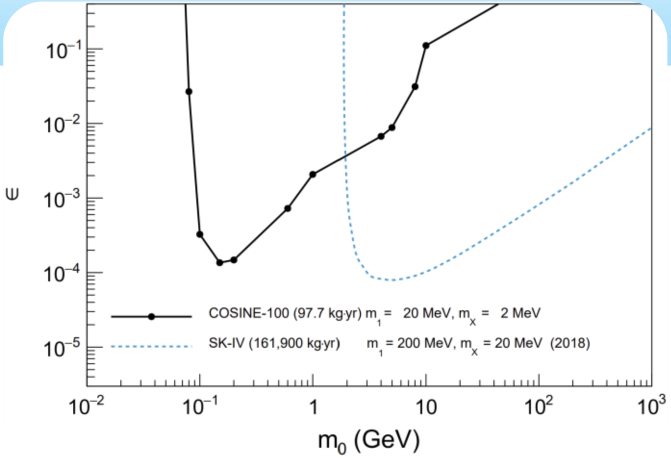

✓ Two-component $(\chi_0, \chi_1)$ BDM model w/ the following interaction between lighter DM $(\chi_1)$ & the SM sector,

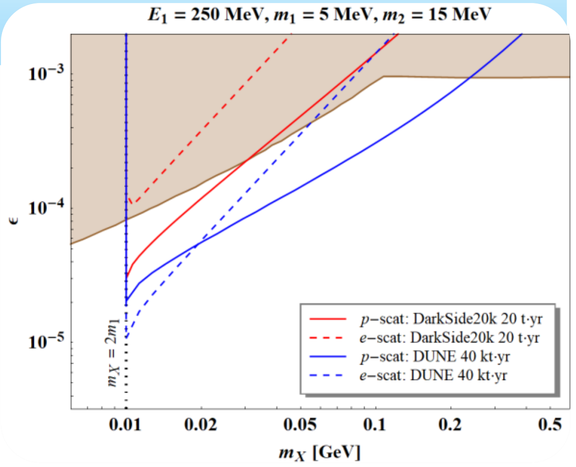
$$\mathcal{L} \supset iq_B g_B X'_\mu [\chi_1^\dagger \partial^\mu \chi_1 - (\partial^\mu \chi_1^\dagger)\chi_1] + \frac{1}{3} g_B X'_\mu \bar{q}\gamma^\mu q$$

# Summary







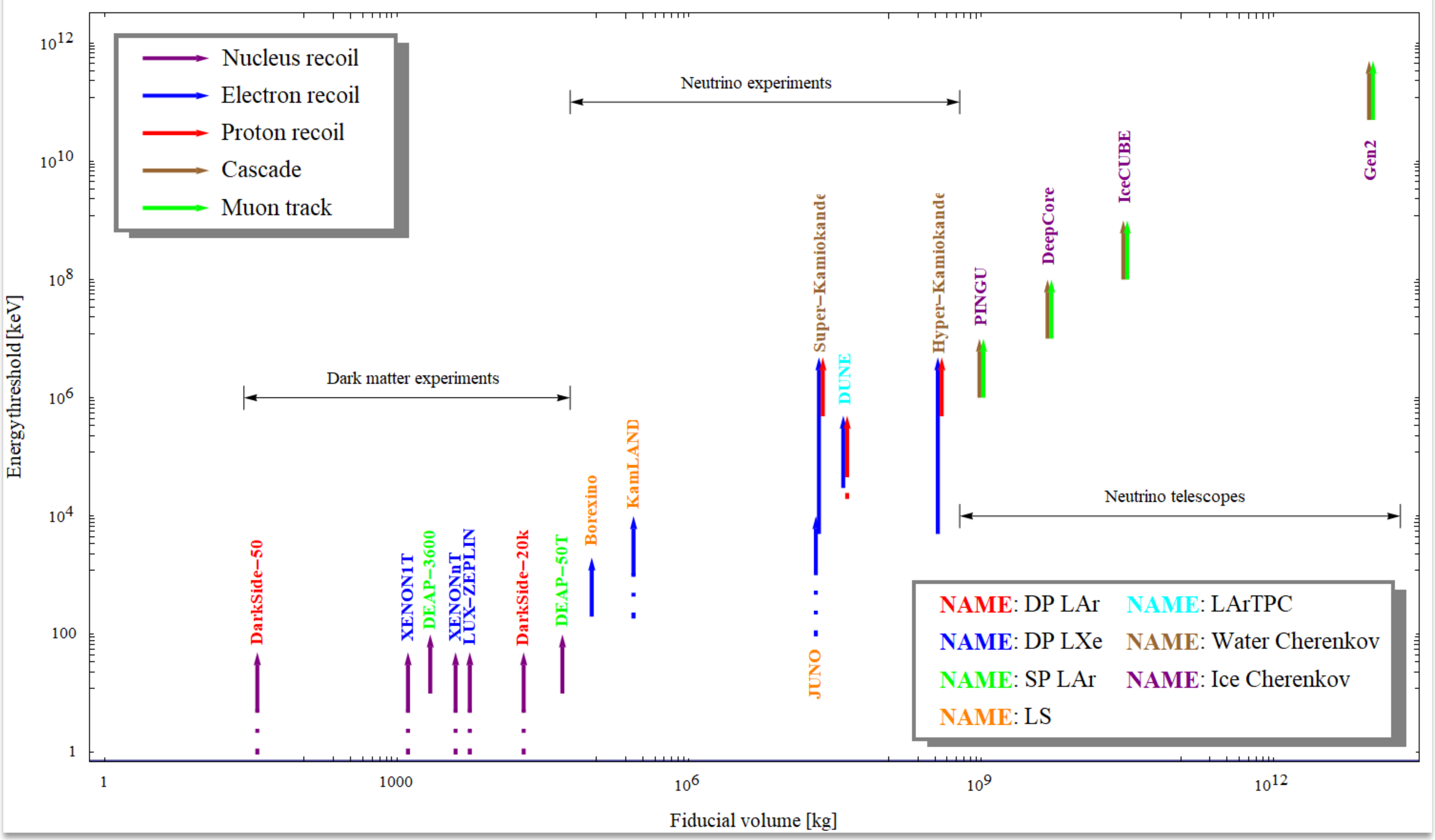

- ❖ Rising interest in dark sector (multi-component) scenarios & BDM (Energetic DM)
- ❖ Various BDM production scenarios: Dark sector, Reversing direct detection, Astrophysical
- ❖ Various detection channels: elastic e/p, DIS, inelastic N, n-capture, …
- ❖ BDM searches are promising & provide a new direction to explore dark sector physics.
- ❖ Experimental studies have already begun, e.g. SK, COSINE-100, Panda-X, CDEX, NEWSdm, DUNE, …

**Thank you**

# Supplemental

# Many More Well-Motivated Exps.

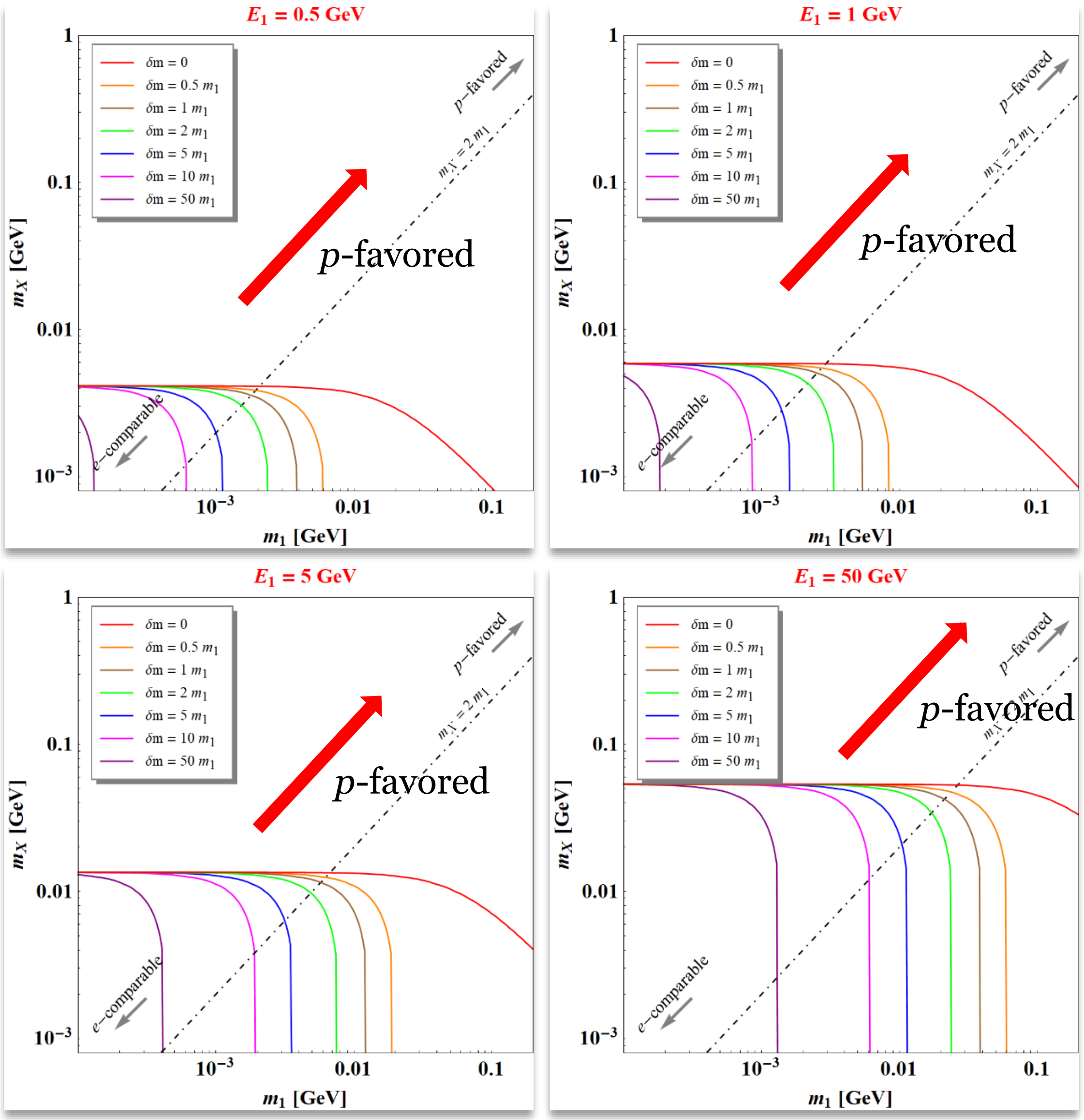
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]




Detectors are complementary to one another rather than superior to the other!

# *p*-Scattering vs. *e*-Scattering

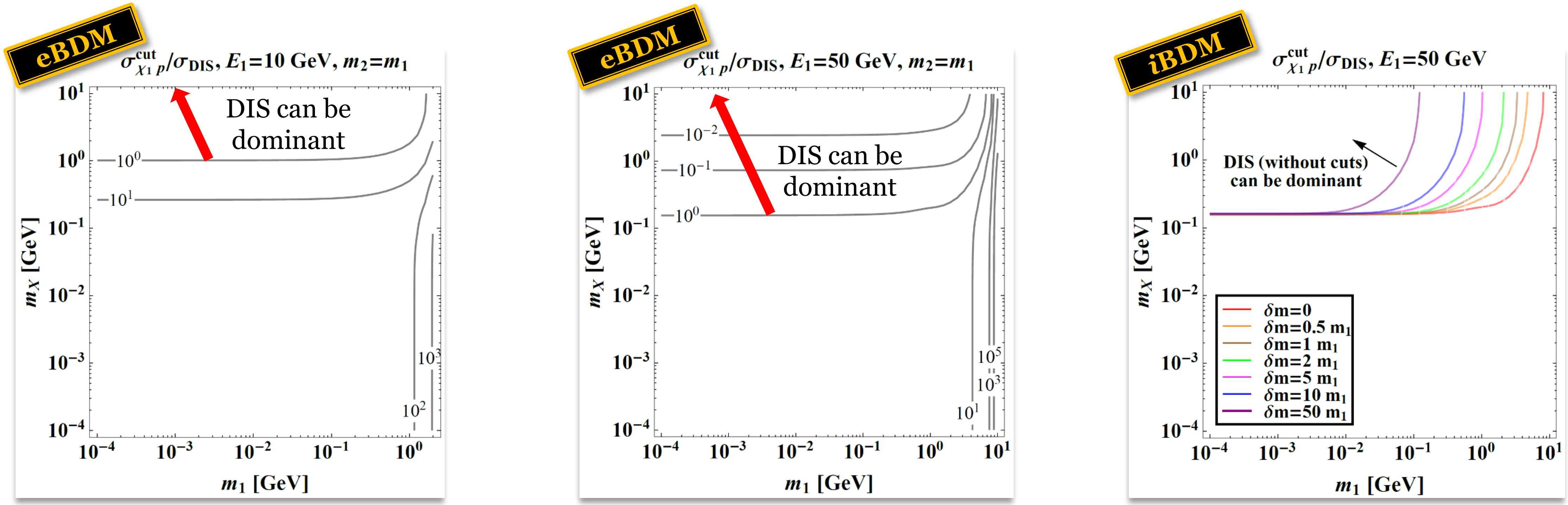
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]




- ✓ 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 $\chi_1$ and $\chi_2$, 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 $\chi_1$ 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 $\sigma^{cut}_{\chi_1 p}/\sigma_{DIS}$ where 200 MeV $< p_p <$ 2 GeV is applied to $\sigma_{\chi_1 p}$ while no cuts are imposed to $\sigma_{DIS}$.
- ✓ $p$-scattering dominates over DIS for $m_X$ < O(GeV) (cf. $\nu$ 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 $E_1$.

# Inelastic Nuclear Scattering of DM

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

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

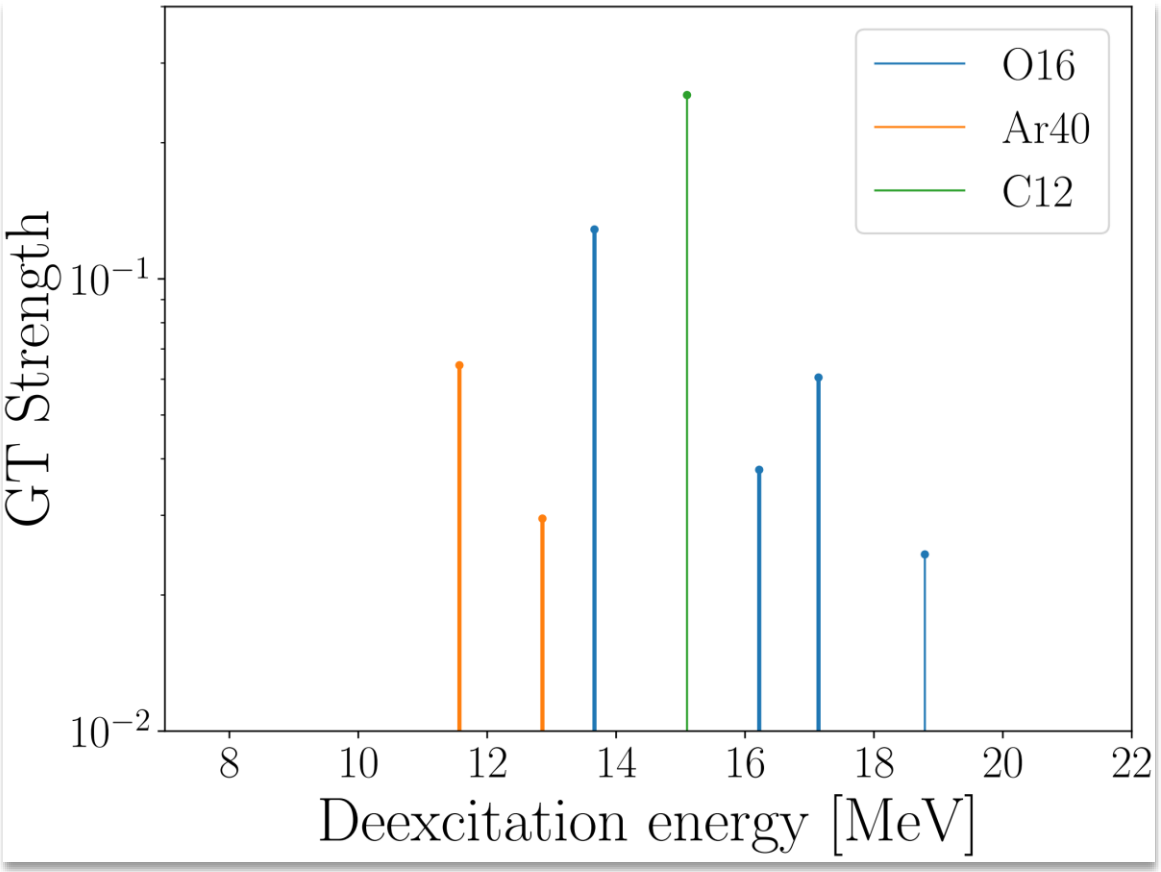
$$\frac{d\sigma^{\rm inel}_{\chi N}}{d\cos\theta} = \frac{2\epsilon^2 g_D^2 E'_\chi p'_\chi}{(2m_T E_R + m_{A'}^2 - \Delta E^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1} \times \sum_{s_i,s_f} \vec{l}\cdot\vec{l}^*\frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A}\frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2 ,$$

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

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

- The expected # of signal events

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

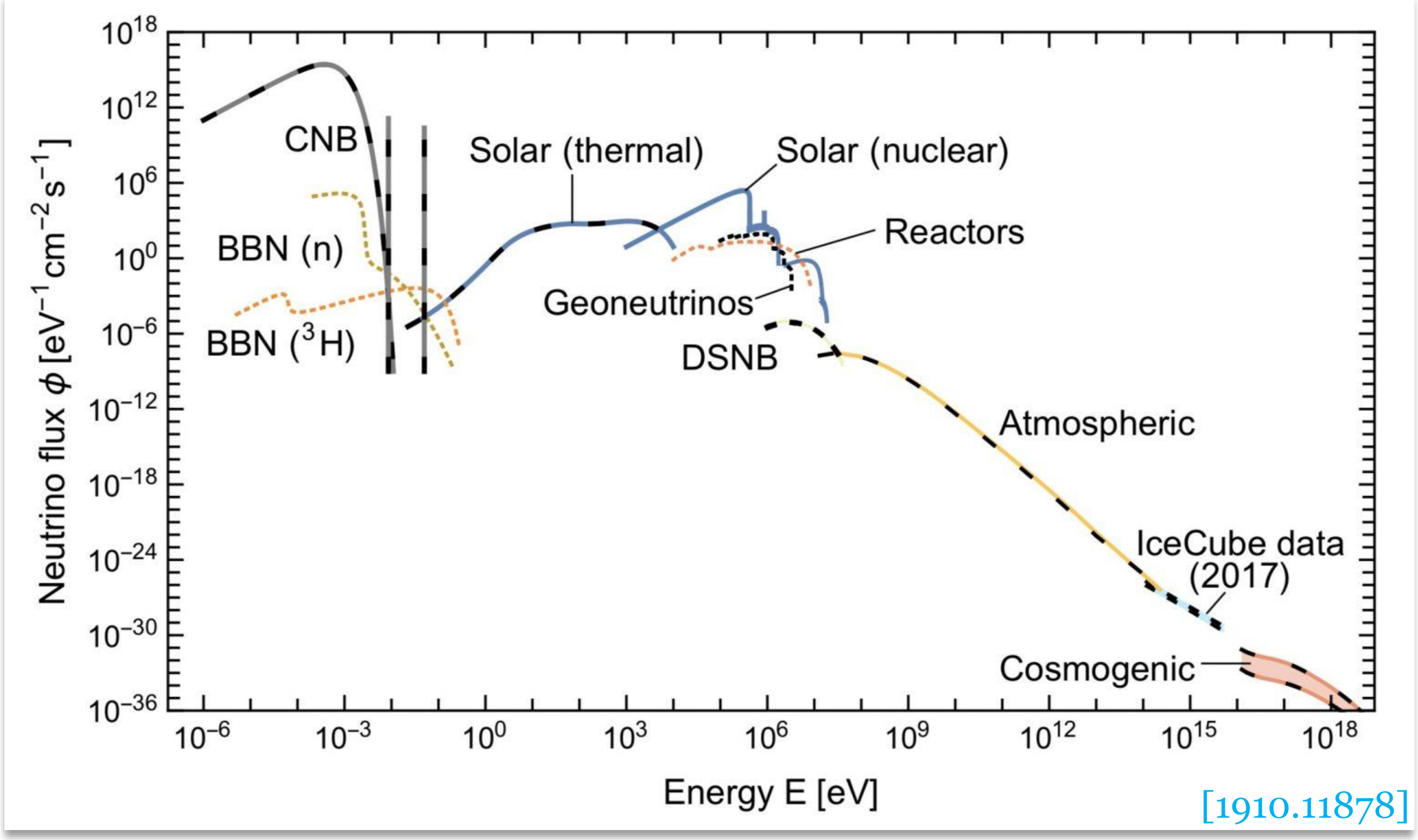



The GT strengths are derived from experimental results & the large-scale shell model code BIGSTICK.

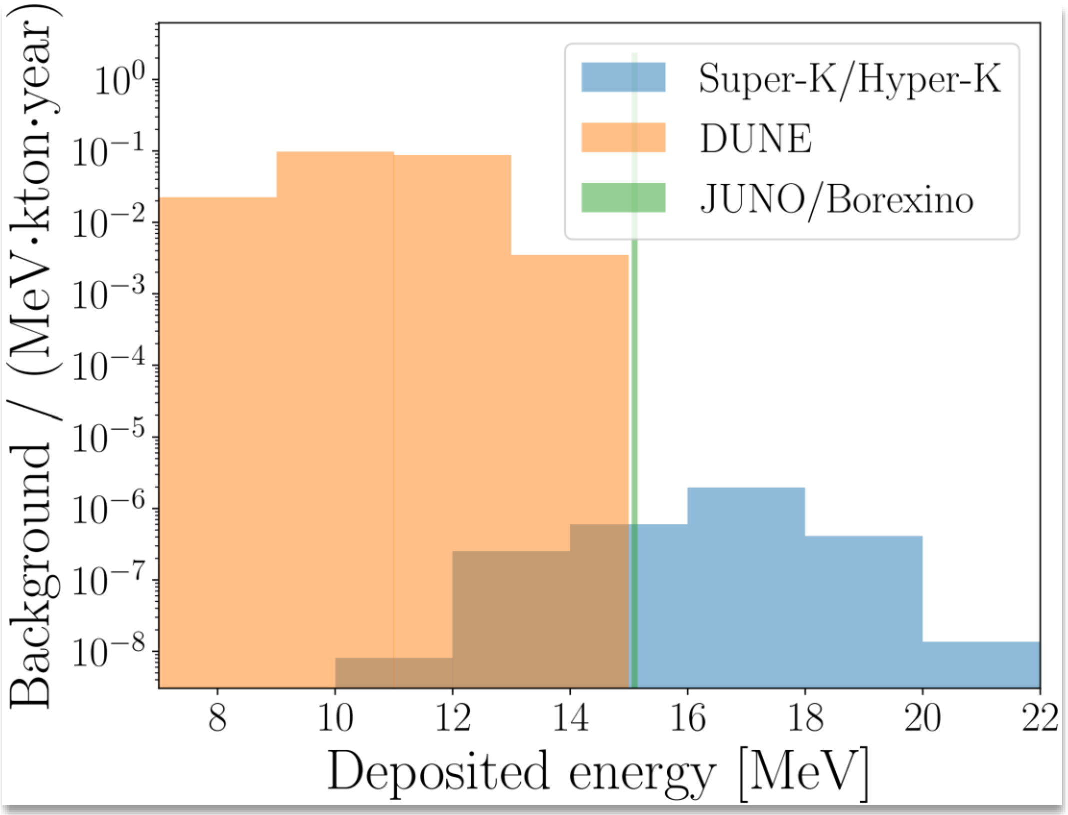
# Estimated Background Rates

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

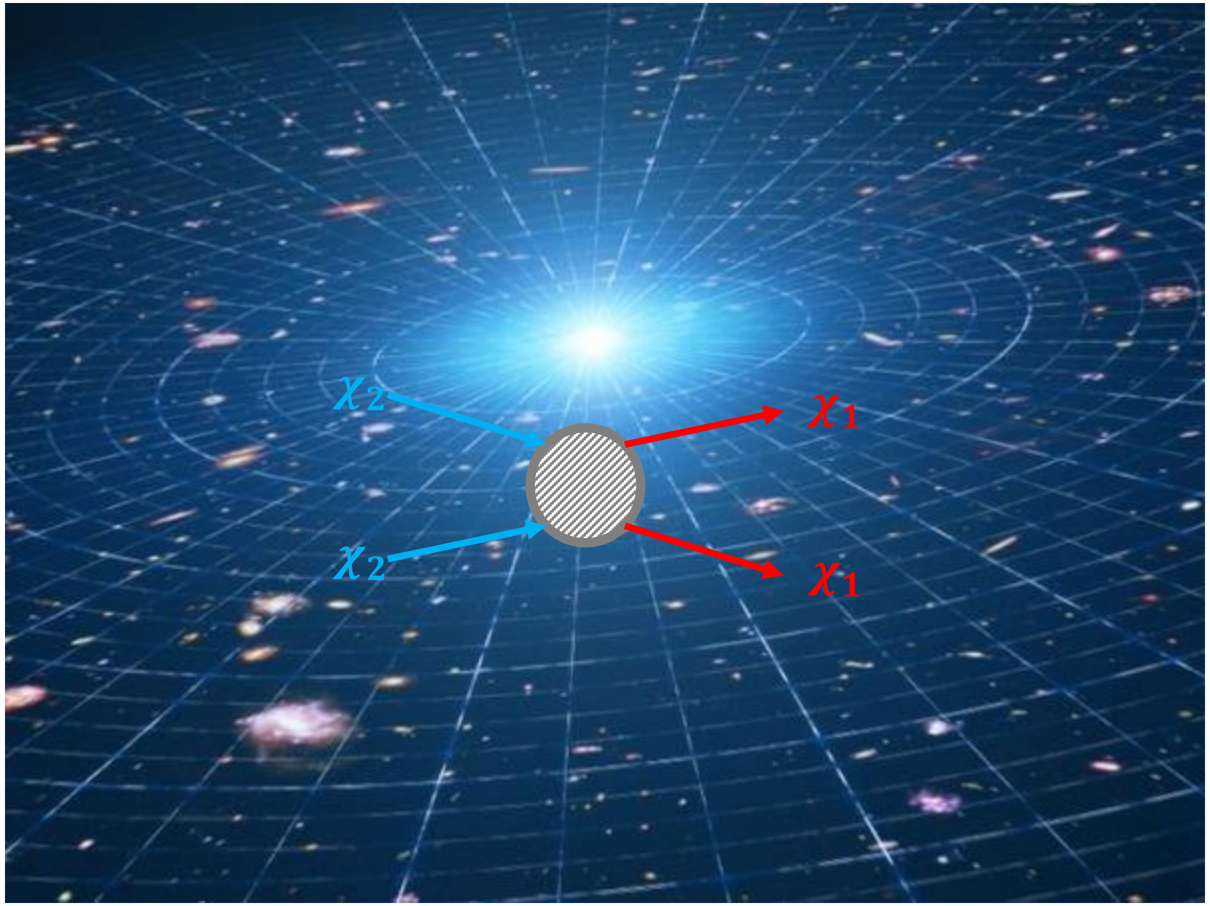
- The main irreducible background: the elastic & inelastic neutral-current scattering of solar & atmospheric neutrinos.




[1910.11878]



# BDM=Hot DM?




✓ $\chi_2$: heavy DM, $\chi_1$: 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 $\langle\sigma v\rangle_{\chi_2\chi_2\rightarrow\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm^3/s}$

# Self-Heating Effects?

[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

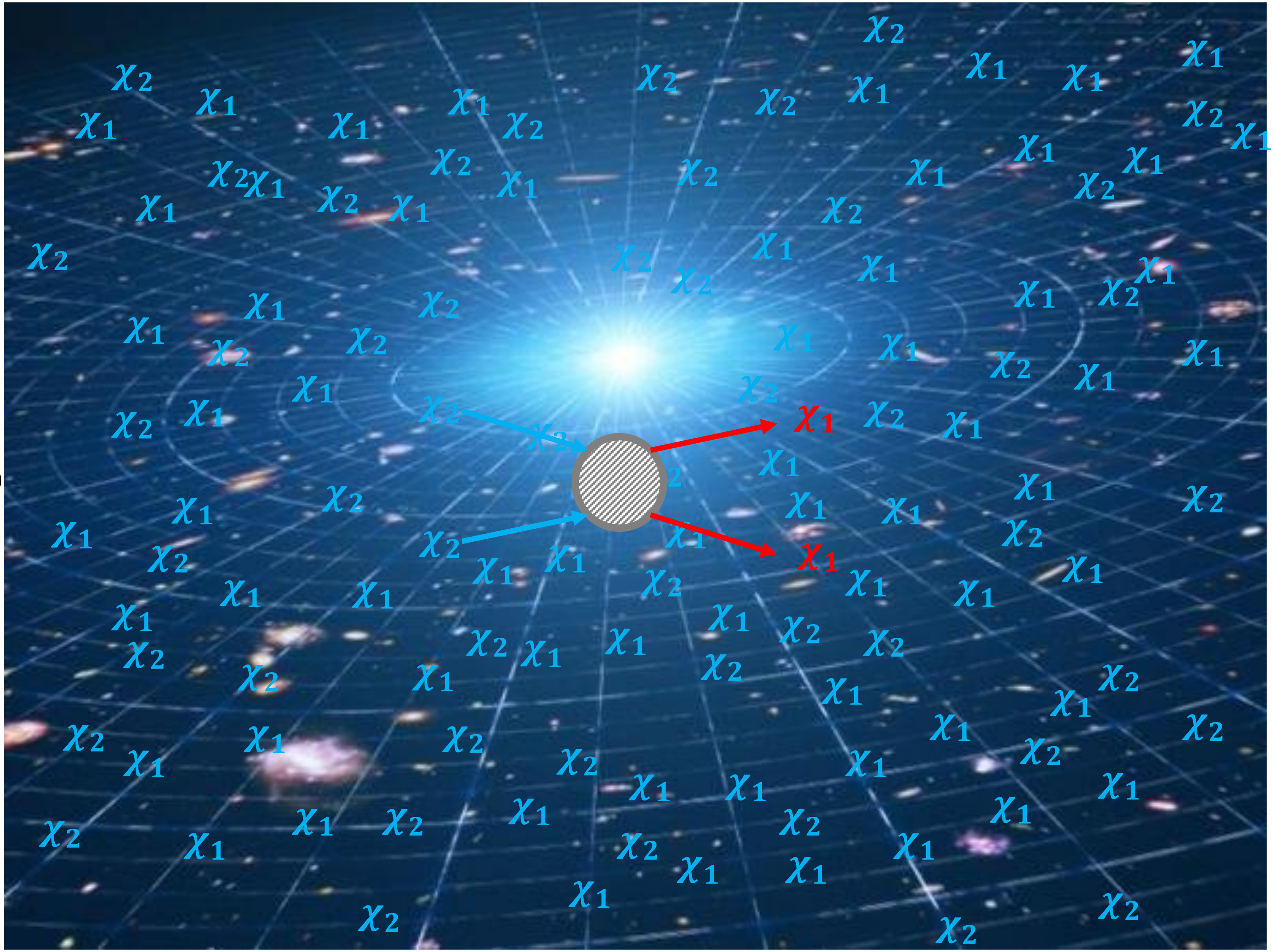
Large self-scattering is quite natural for light dark sector!

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

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

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

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




1. The heavy $\chi_2$ annihilates to light $\chi_1$ which becomes boosted.

# Self-Heating Effects!

[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

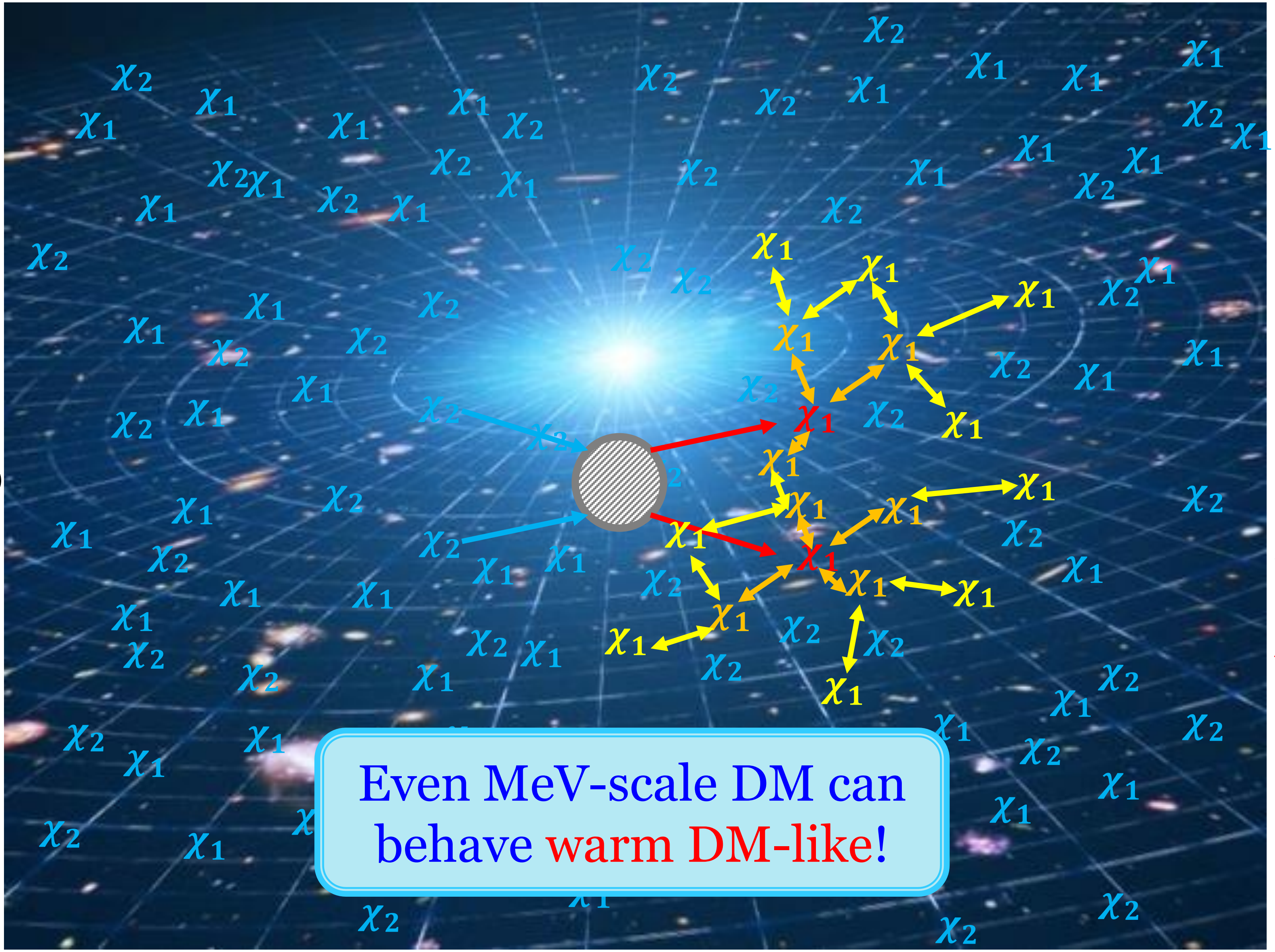
Large self-scattering is quite natural for light dark sector!

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

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

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

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



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

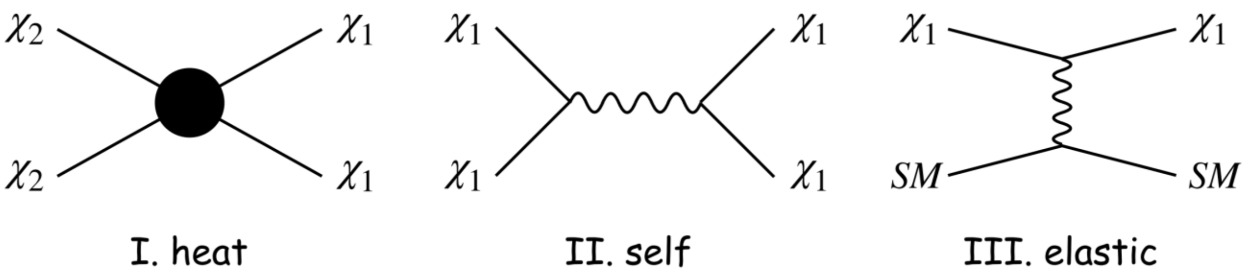
1. The heavy $\chi_2$ annihilates to light $\chi_1$ which becomes boosted.

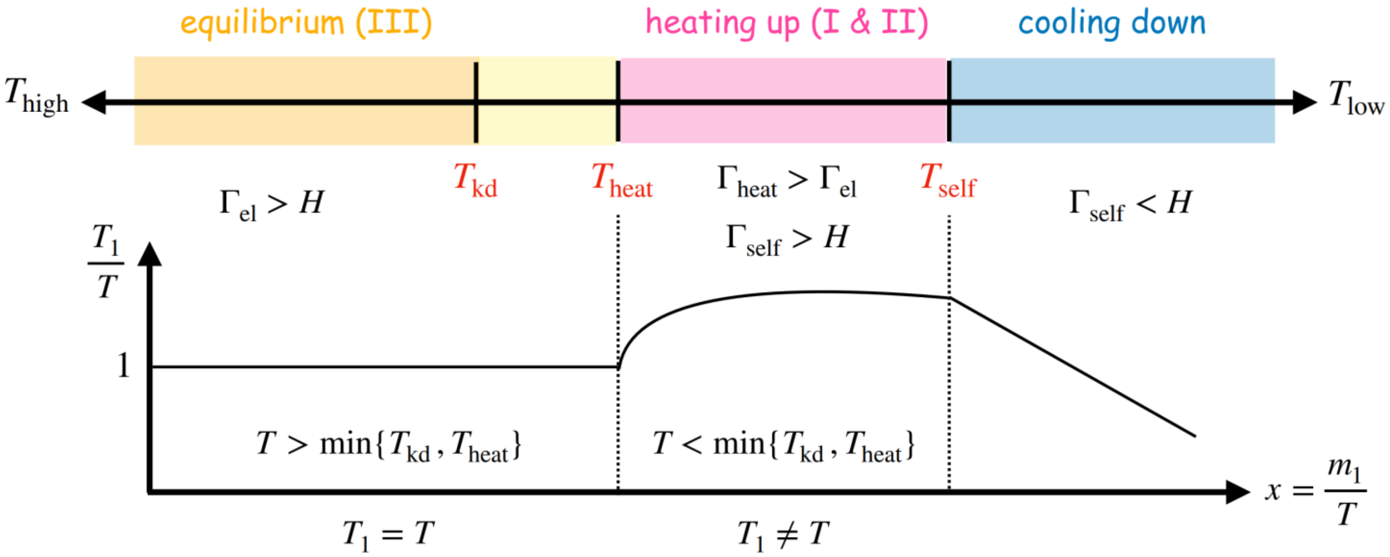
2. Sharing energies through self-interaction $\sigma_{\chi_1}^{\text{self}}$ which increases the $\chi_1$ temperature.

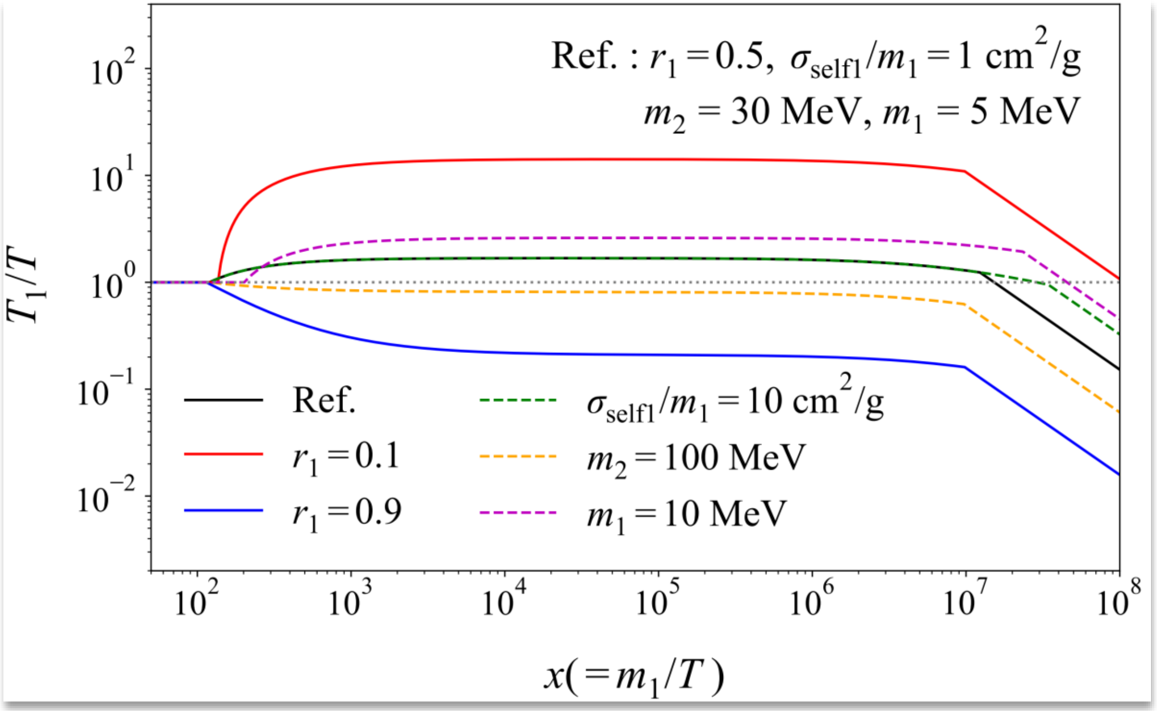
# Thermal Evolution

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

[J. Kim, Lim, **JCP** & Kong, 2312.07660]




$$\dot{T}_{\chi_1} + 2HT_{\chi_1} \simeq \gamma_{\rm heat} T - 2\gamma_{\chi_1 {\rm sm}} (T_{\chi_1} - T)$$

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

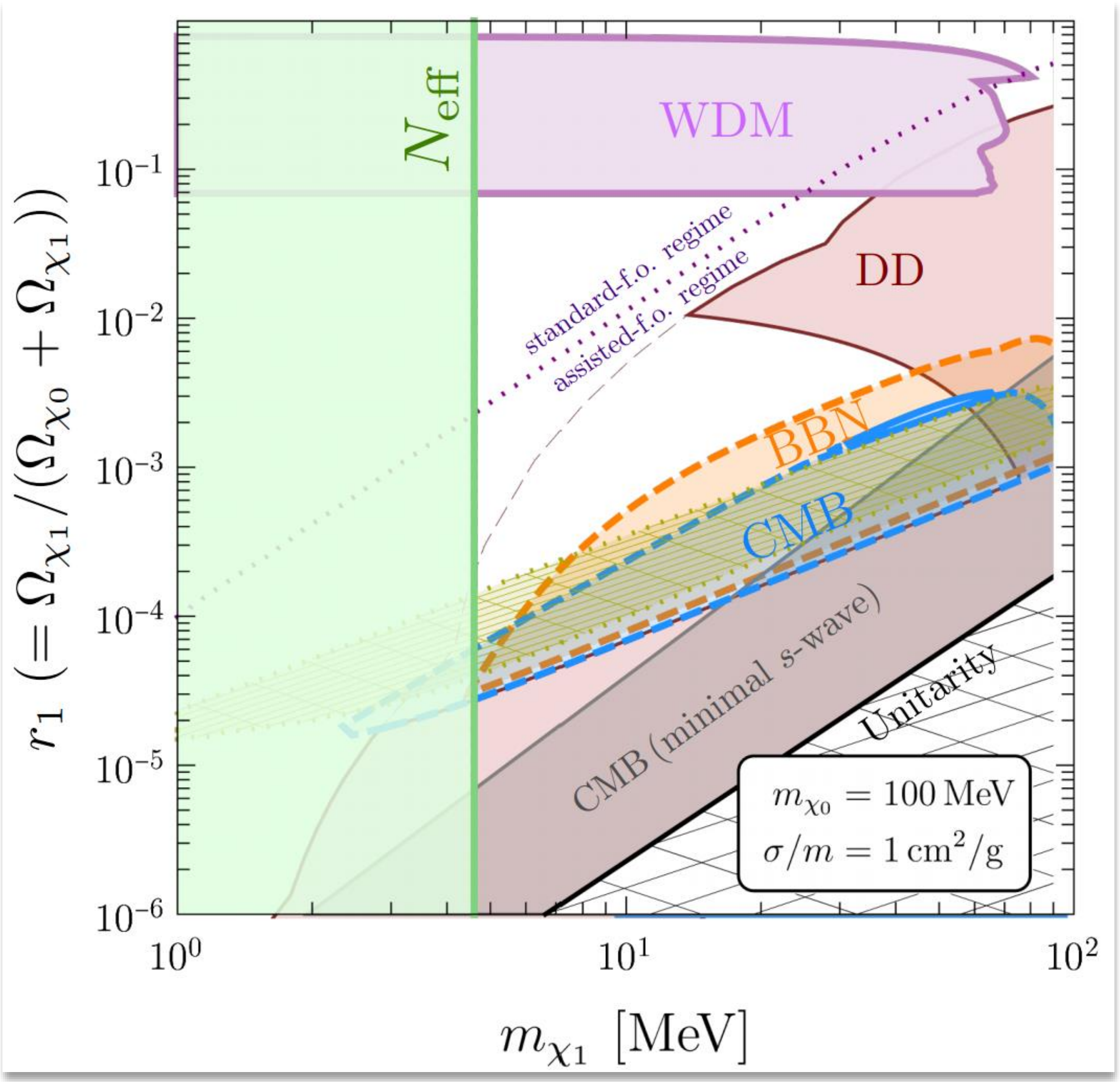
$$\gamma_{\rm heat} = \frac{2n_{\chi_2}^2 \langle \sigma v \rangle_{22\to 11}}{3n_{\chi_1} T}(m_{\chi_2} - m_{\chi_1})$$

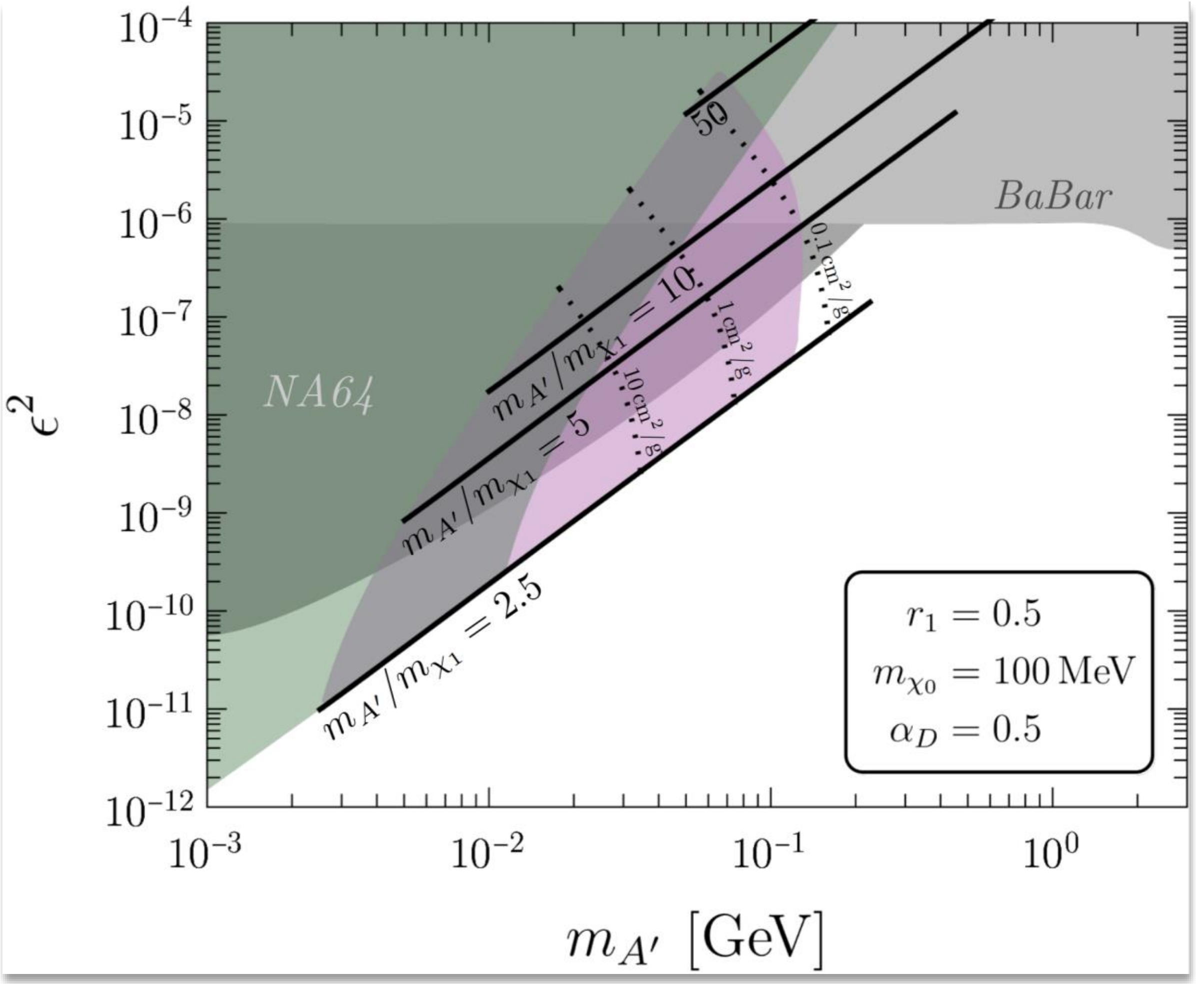
$\gamma_{\chi_1 {\rm sm}} \simeq (\delta E/T) n_{\rm sm} \langle \sigma v \rangle_{\chi_1 {\rm sm}}$

Kinetic scattering of $\chi_1$ with a thermal bath

# Cosmological Constraints & Dark Photon Searches

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




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

# Perturbation Evolution

[J. Kim, Lim, **JCP** & Kong, 2312.07660 & 2410.05382]

❖ Coupled equations for the density perturbation

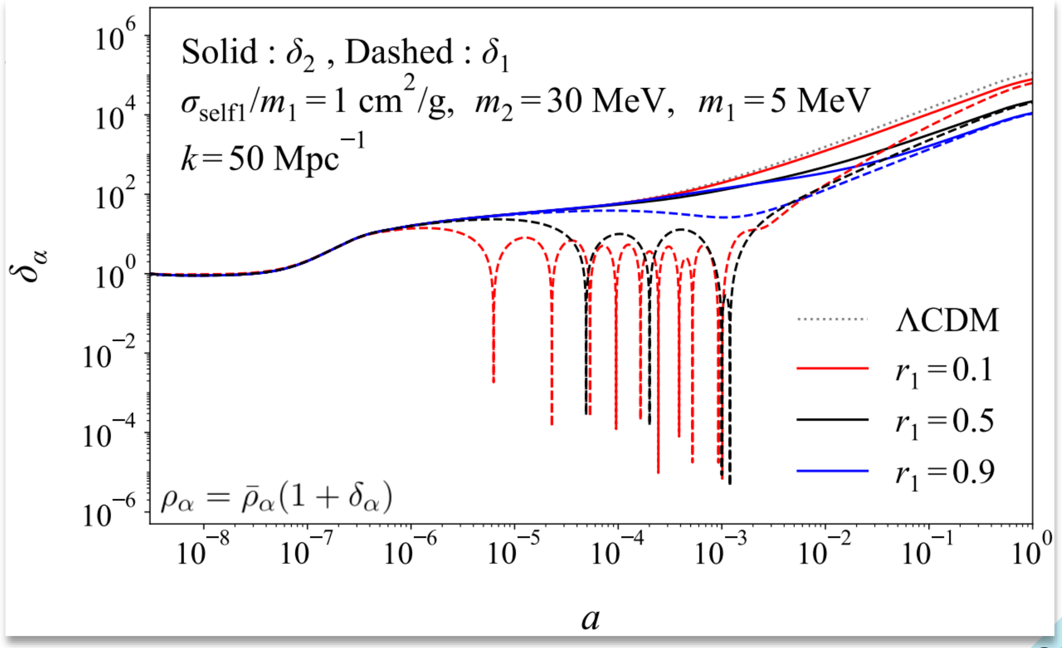
$$\frac{d\delta_2}{dt} + \frac{\theta_2}{a} - 3\frac{d\Phi}{dt} = \frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_2}\left(-\Psi\left(\bar{\rho}_2^2 - \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\right) - \bar{\rho}_2^2\delta_2 + \frac{\bar{\rho}_{2,\text{eq}}^2}{\bar{\rho}_{1,\text{eq}}^2}\bar{\rho}_1^2\left(2\delta_{2,\text{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

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

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

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

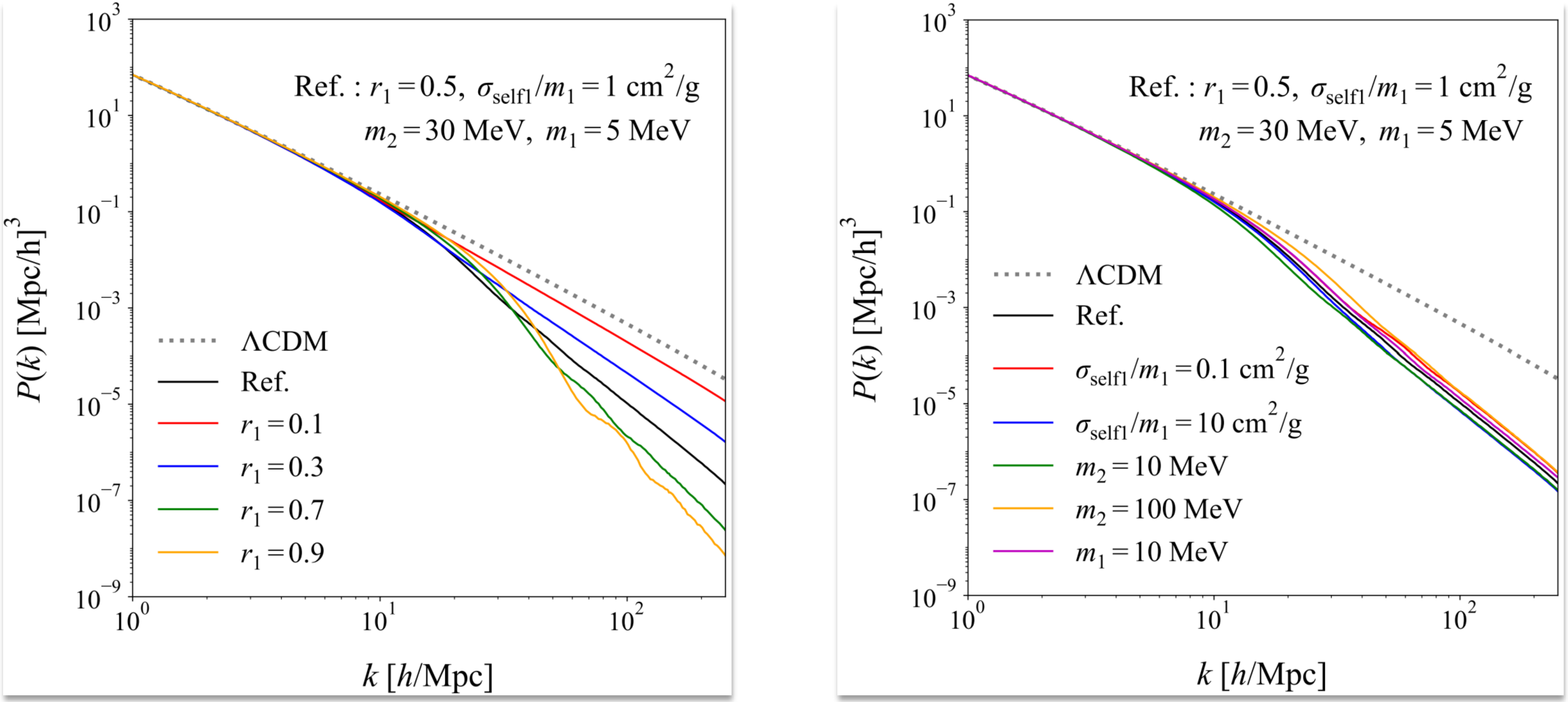
$$\frac{d\theta_1}{dt} + H\theta_1 + \frac{\nabla^2\Psi}{a} + c_{s,1}^2\frac{\nabla^2\delta_1}{a} = \frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar{\rho}_1}\bar{\rho}_2^2\left(\theta_2 - \theta_1\right),$$



# Linear Matter Power Spectrum

[J. Kim, Lim, **JCP** & Kong, 2312.07660 & 2410.05382]

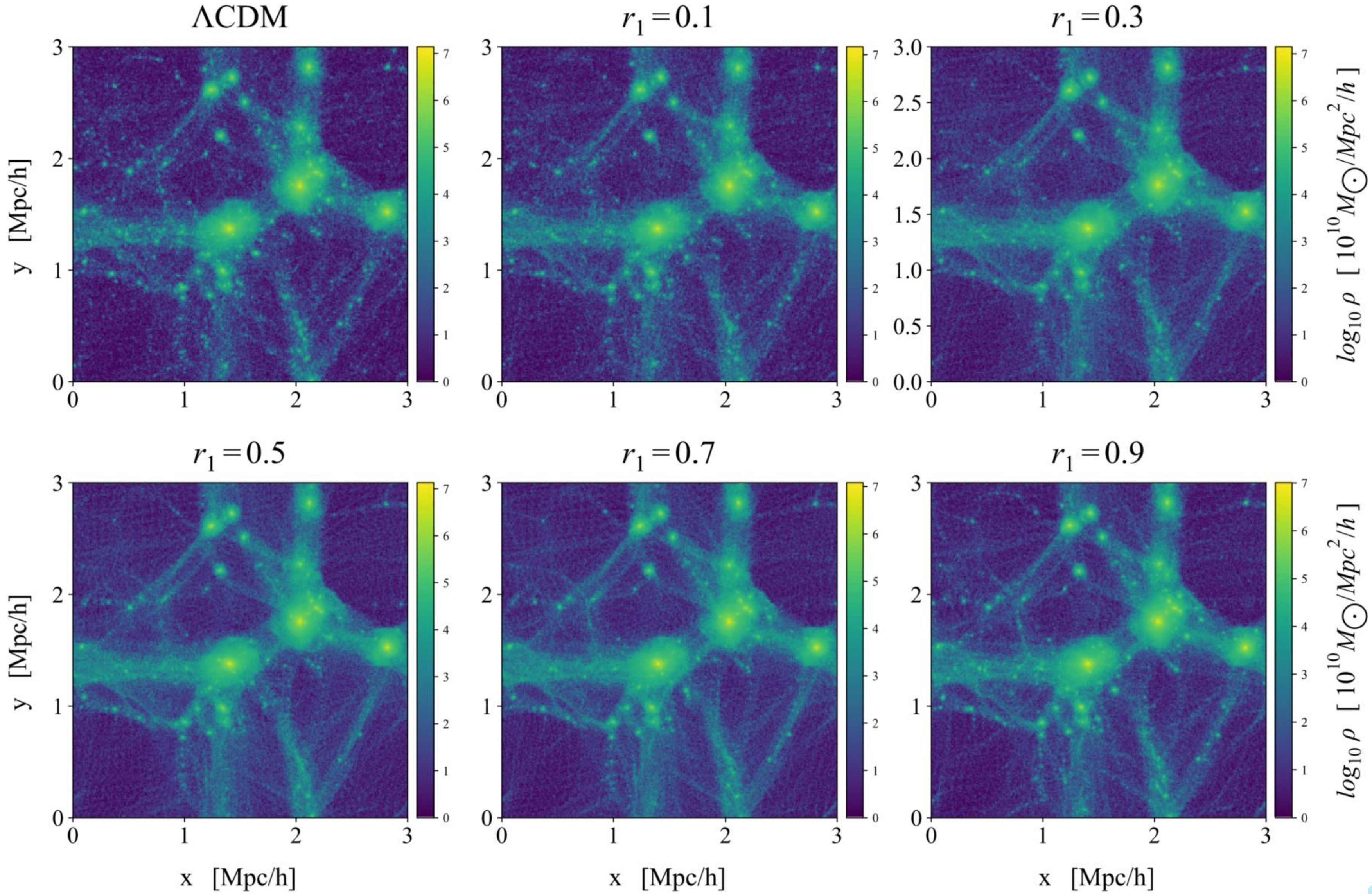
❖ Linear power spectrum by *CLASS*



# *N*-Body Simulation

[J. Kim, Lim, **JCP** & Kong, 2312.07660 & 2410.05382]

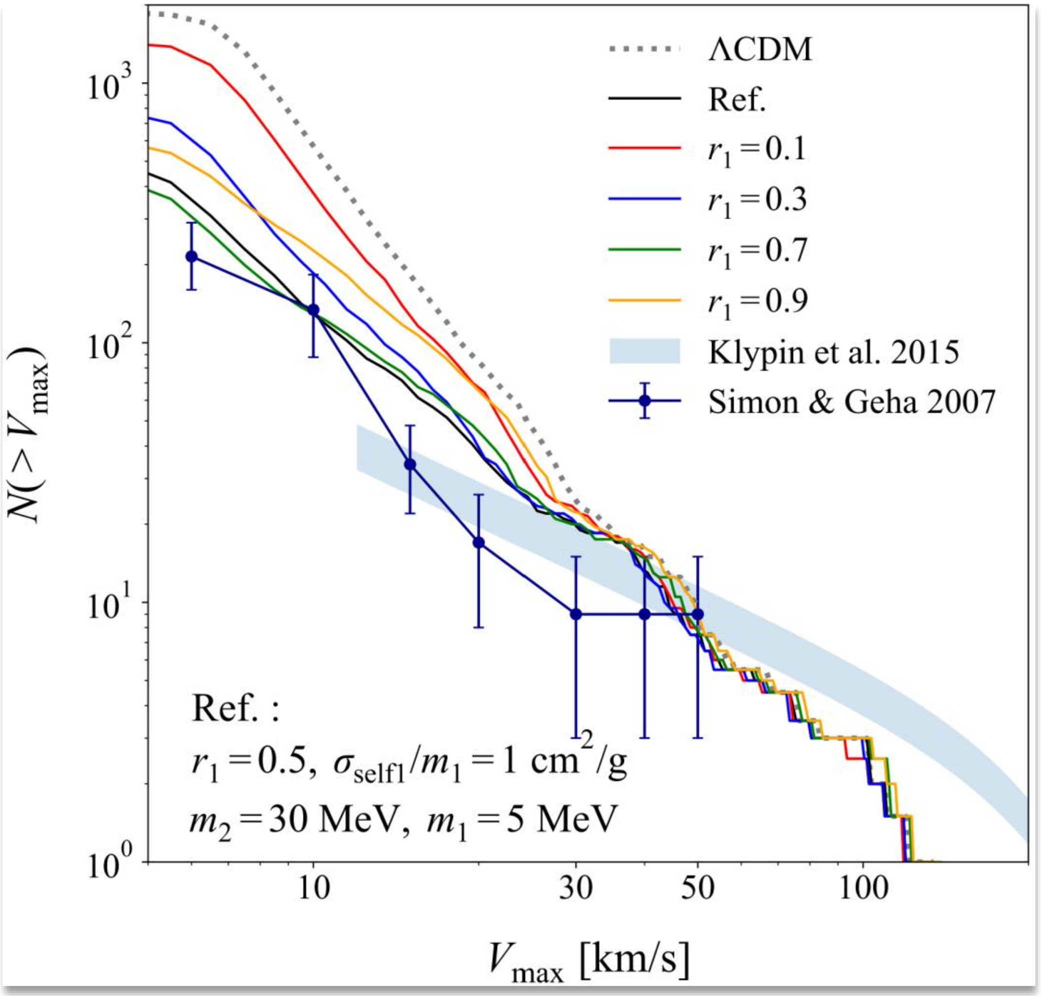
- *N*-body simulations: two-component DM simulation built on *GADGET-3* to investigate the non-linear effects
- Visualization of DM density in the periodic 3 $h^{-1}$Mpc box at $z = 0$ ➔ fewer sub-halos
  - ✓ $\frac{\sigma_1^{\rm self}}{m_{\chi_1}} = 1\ {\rm cm}^2/{\rm g}$
  - ✓ $m_{\chi_2} = 30$ MeV
  - ✓ $m_{\chi_1} = 5$ MeV

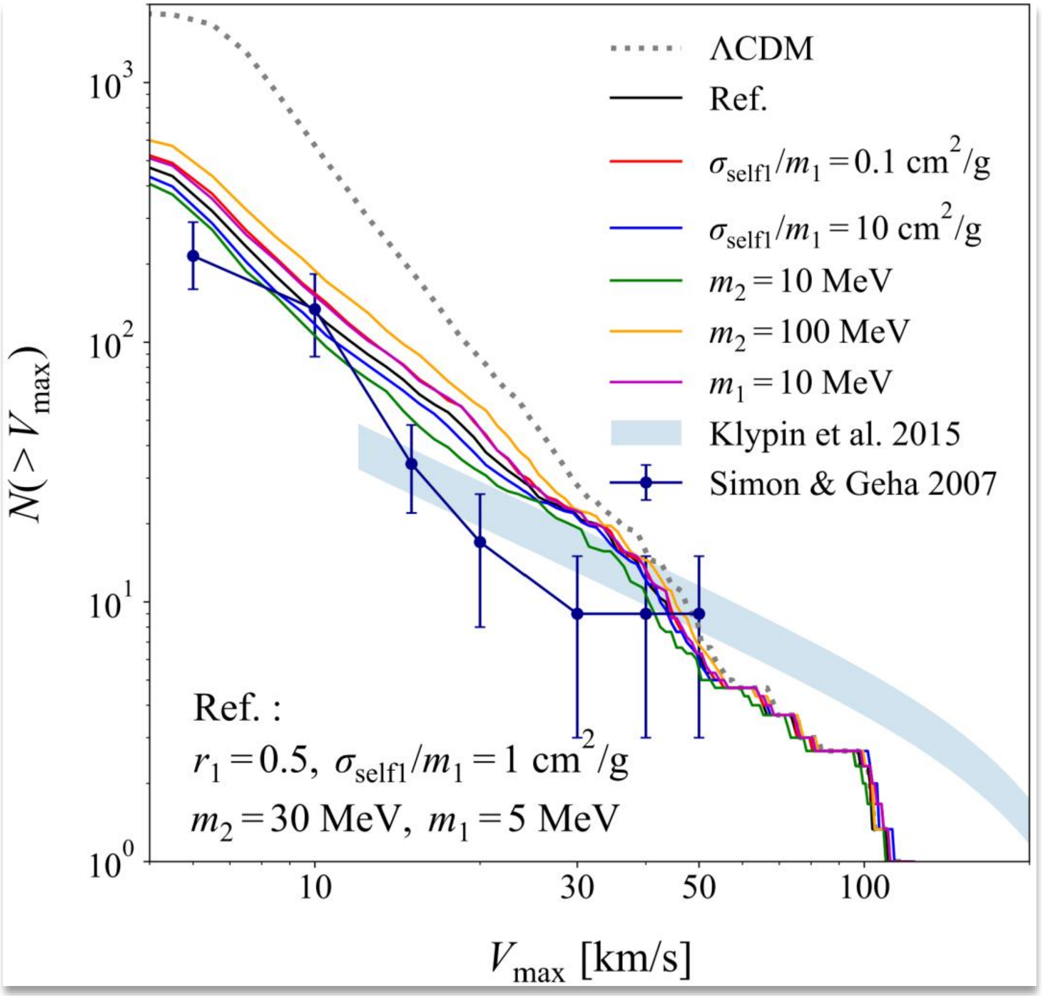


# $N$-Body Simulation: Observational Constraints

[J. Kim, Lim, **JCP** & Kong, 2312.07660 & 2410.05382]

❖ Maximum circular velocity distribution of sub-halos



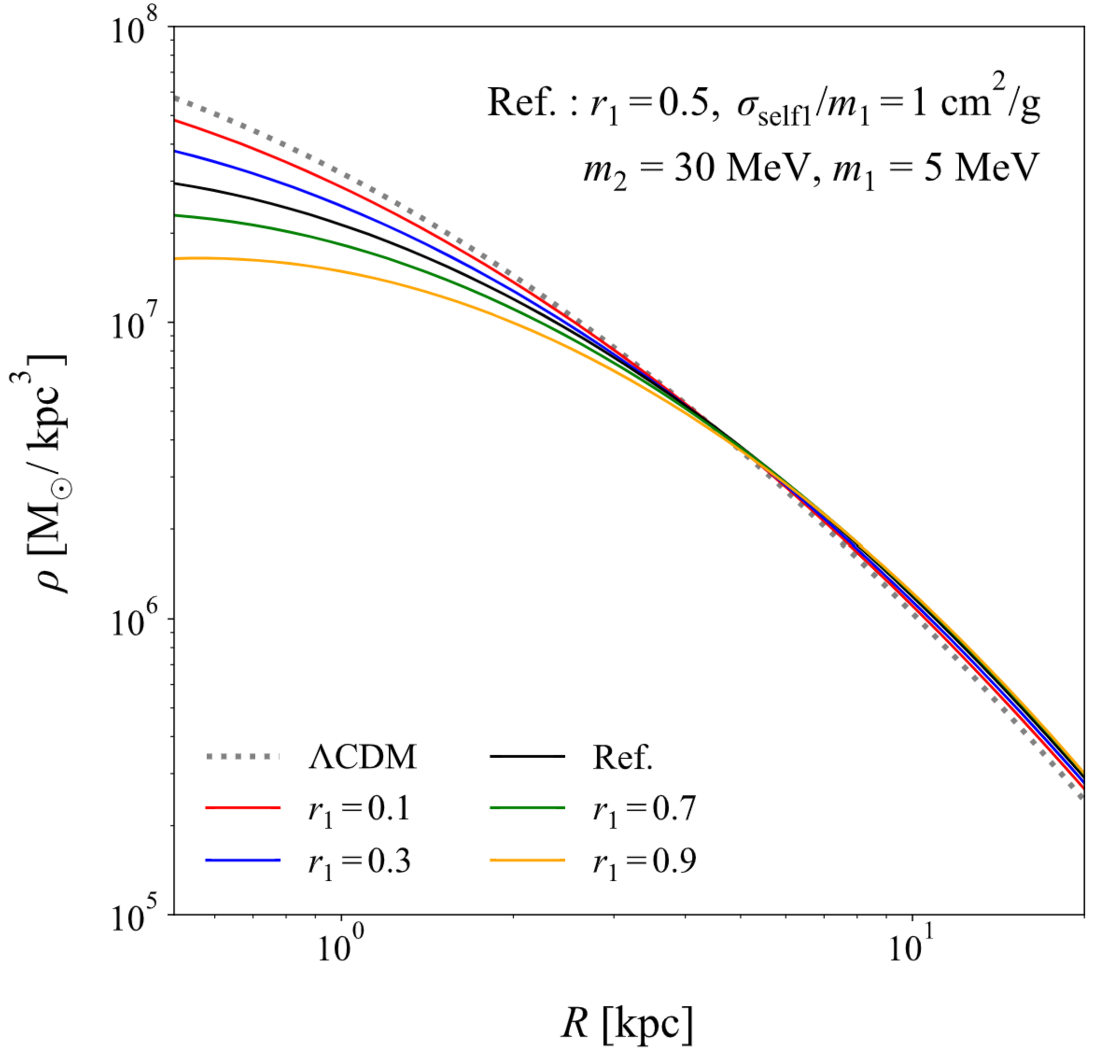



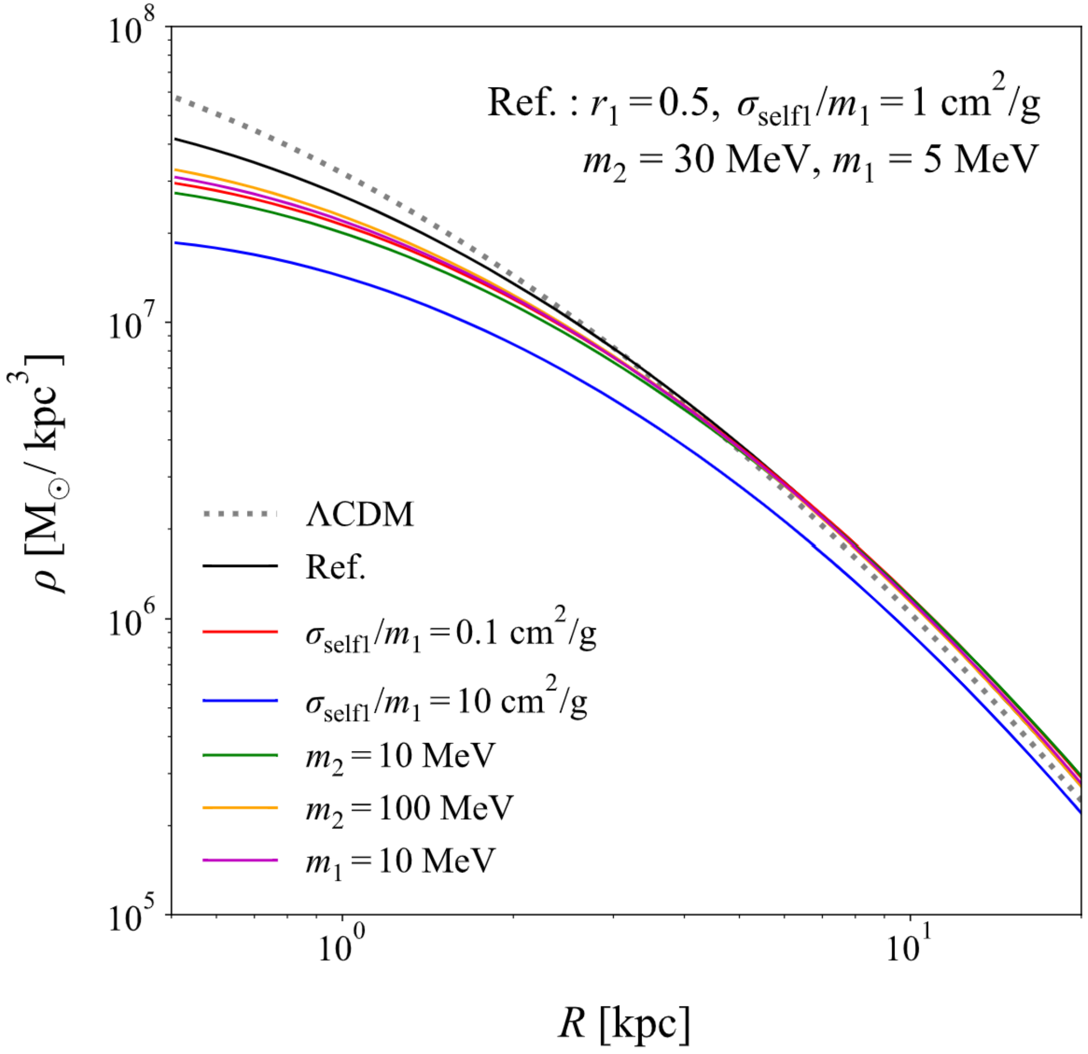

✓ The number of sub-halos is more reduced with smaller $m_{\chi_1}$ & $m_{\chi_2}$, larger $\sigma_1^{\rm self}/m_{\chi_1}$.

# Galactic Density Profile: Total

[J. Kim, Lim, **JCP** & Kong, 2410.05382]

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



# Galactic Density Profile: Individual

[J. Kim, Lim, **JCP** & Kong, 2410.05382]

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