# Light DM Detection in $\nu$ Experiments

# Boosted Dark Matter (BDM)


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Light Dark World 2025

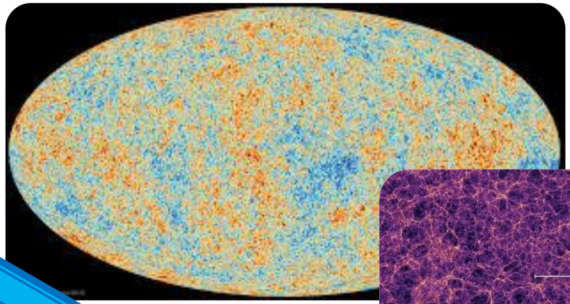
September 18 (2025)

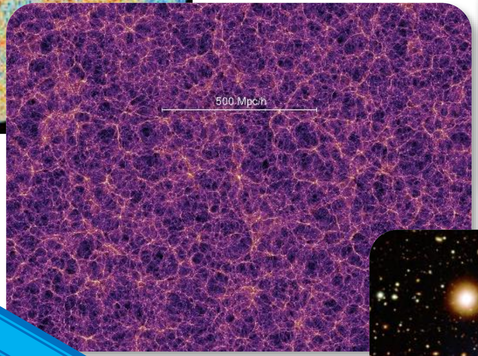
# Outline

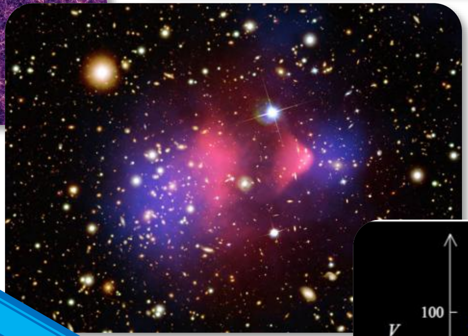
- ❖ Dark Matter? Dark Sector?
- ❖ Boosted Dark Matter (BDM) & Its Searches
- ❖ Issues in BDM Searches
- ❖ Exciting Prospects for BDM Searches
- ❖ Summary

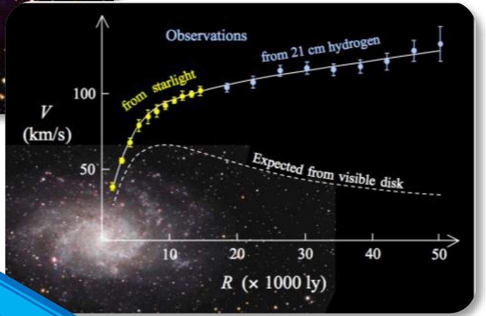
# Dark Matter?
# Dark Sector?

# Message from Cosmology: Dark Matter (DM)








Larger scale
Earlier

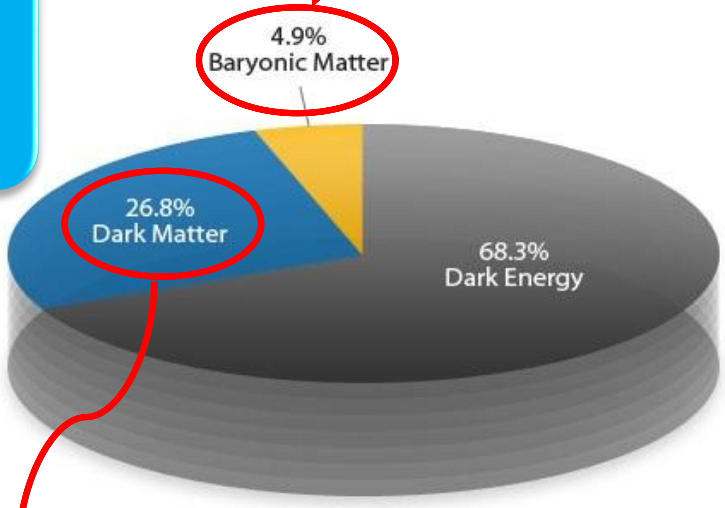
Smaller scale
Later

## Dark Matter?

**Many more other observations!**

❖ **Modern cosmology**:

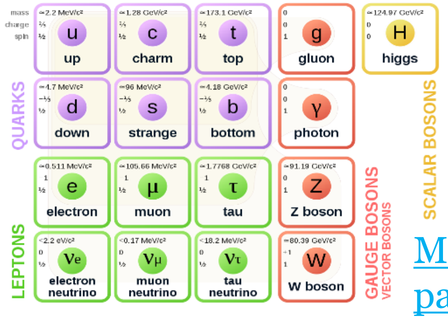
The Standard Model




❖ **Compelling paradigm**:

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

# Dark Sector: Dark Particles & Portals




**SM sector** — **Portal** — **Dark sector**

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

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: $G_{a\gamma\gamma'} a F_{\mu\nu}\tilde{X}^{\mu\nu}$ [Kaneta, Lee, Yun (2016)]
  - ✓ Double portal: combination of portals [Belanger, Goudelis, **JCP** (2013)]
  - ✓ ???

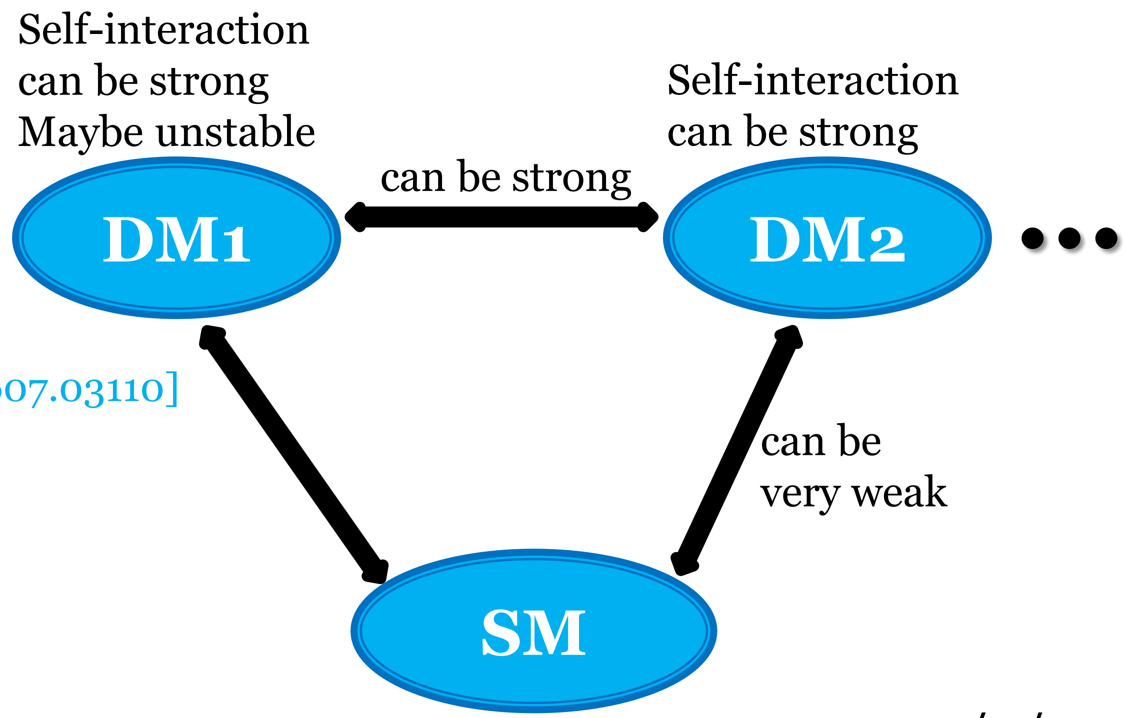
- ❖ **Dark sector particles**
  - ✓ DM spin: fermion, scalar, vector
  - ✓ DM species: single-/two-/multi-component
  - ✓ DM mass: light, heavy, light & heavy
  - ✓ DM interaction: flavor-conserving (elastic),

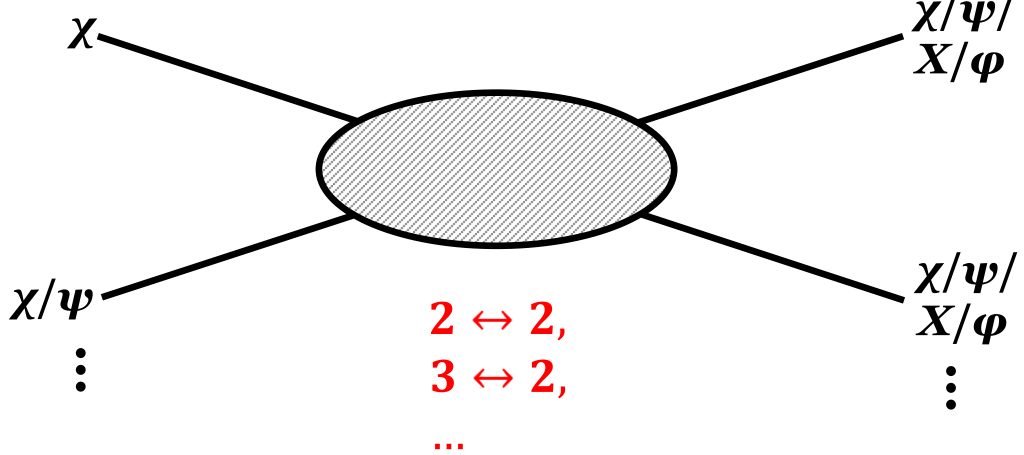
    flavor-changing (inelastic)
  - ✓ ???

# 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

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

**Ultralight**
axion, fuzzy,
hidden photon,

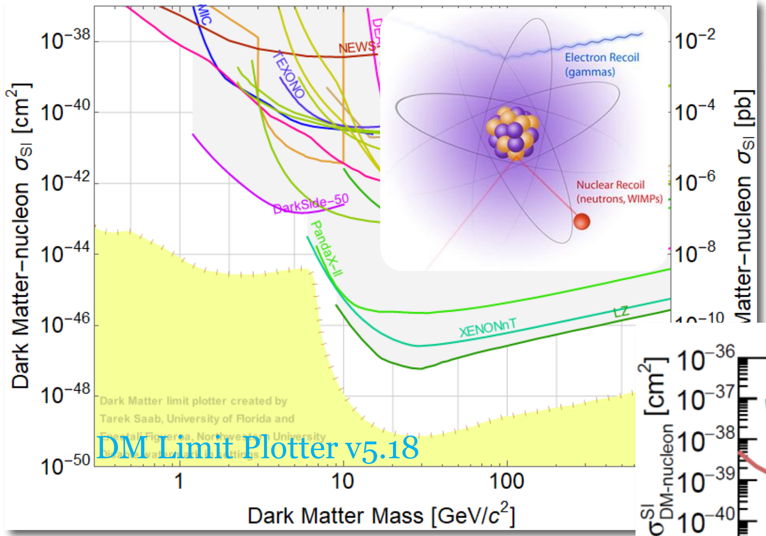
**Superlight**
sterile ν,
warm DM

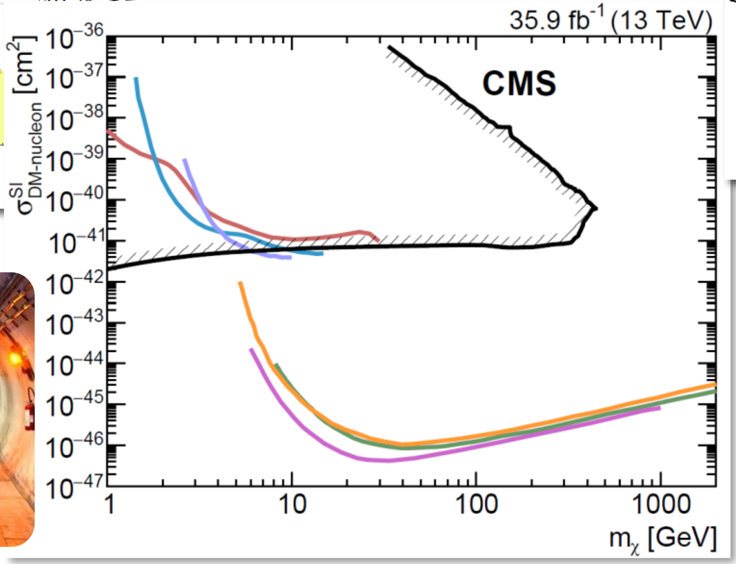
**Light**
SIMP,
ELDER

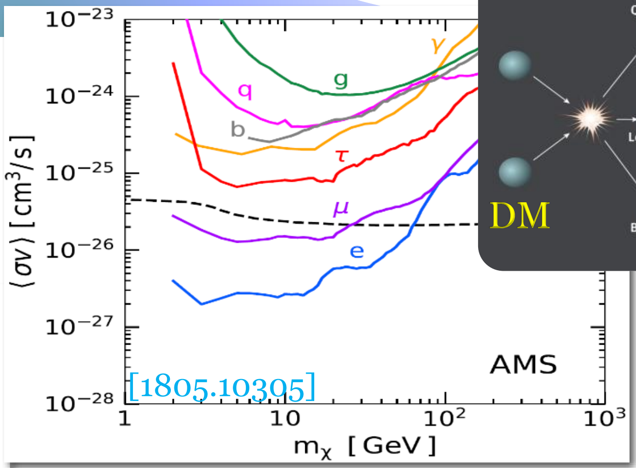
**WIMP**

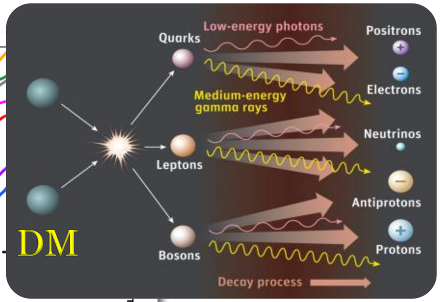
**Superheavy**
composite DM,
WIMPzilla

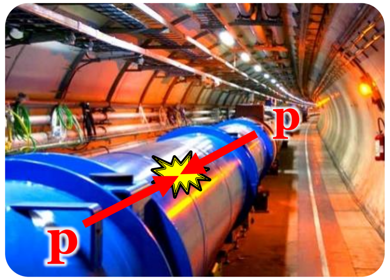
**Astrophysical object**
MACHO, PBH



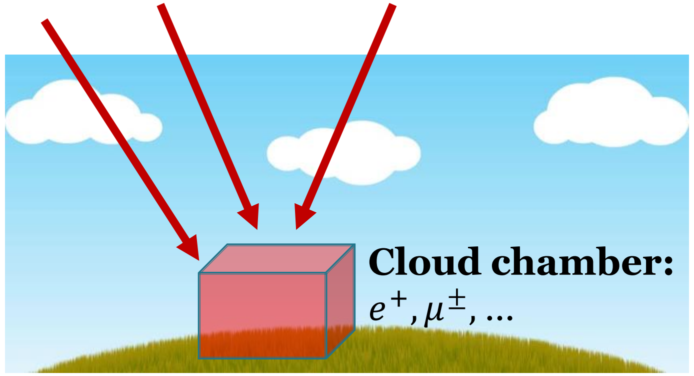



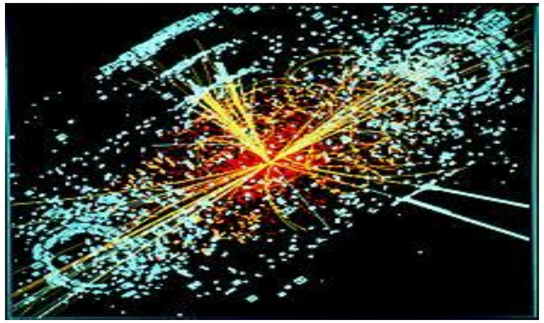

- ✓ No concrete evidence of DM yet.
- ✓ Tight bounds are imposed on WIMP.
- ✓ Next decade: **A paradigm shift?**

# Particle Searches: Passive ➔ Active

~5% visible sector

**Collider:** controlled environment



**Conventional colliders**

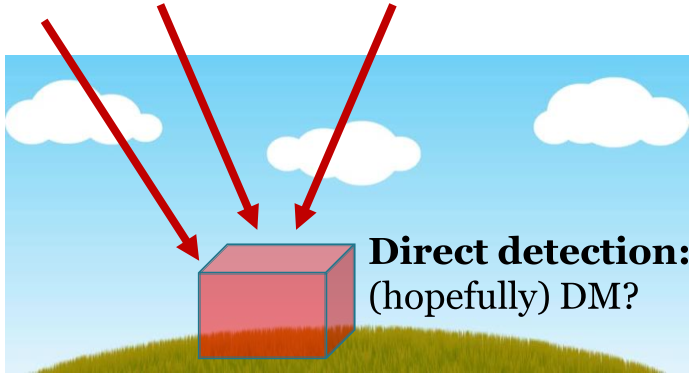
- ❑ Head-on collision of light SM-sector (stable) particles
- ❑ to produce heavier SM states
- ❑ and study resulting phenomenology

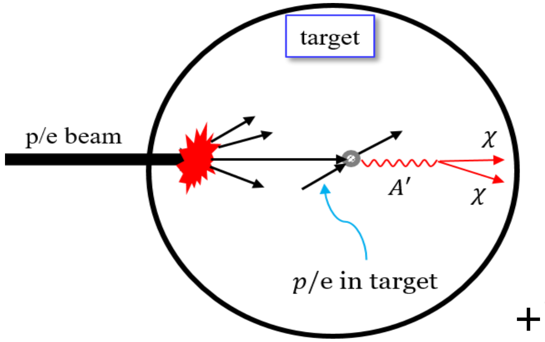
## Passive searches

## Active searches

~25% dark sector

**DM "Production"** (e.g. fixed target exp.)
: controlled environment




**Dark matter productions**

- ❑ Dump of SM-sector (stable) particles onto a target
- ❑ to produce dark-sector states
- ❑ and study resulting phenomonology

**+DM "Direct Detection"**

Talks @ This morning

Talks @ Tuesday & Wednesday morning

# Neutrino vs. Dark Matter

| | Neutrino | Dark Matter |
|---|---|---|
| **Population** | Many | Probably Many<br>(depending on $m_{\mathrm{DM}}$) |
| **Interaction** | Weak | Weakly or Feebly? |
| **Relativistic** | Mostly | Mostly Not |
| **Active Production** | Possible | Maybe |
| **Approaches** | Large Vol. (w/ high $E_{\mathrm{th}}$)<br>Beam-produced | Lager is better, but low $E_{\mathrm{th}}$<br>Beam-produced |
| **Experiments** | SK/HK, DUNE, IceCube, …<br>T2K, DUNE, SHiP, FASER, … | XENON, LZ, ANAIS, …<br>T2K, DUNE, SHiP, FASER, … |

# Neutrino vs. Dark Matter

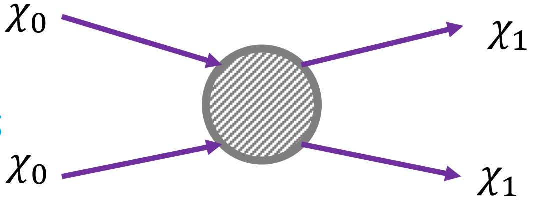
| | Neutrino | Dark Matter |
|---|---|---|
| **Population** | Many | Probably Many<br>(depending on $m_{\mathrm{DM}}$) |
| **Interaction** | Weak | Weakly or Feebly? |
| **Relativistic** | Mostly | ***Boosted DM*** |
| **Active Production** | Possible | Maybe |
| **Approaches** | Large Vol. (w/ high $E_{\mathrm{th}}$)<br>Beam-produced | Lager is better, but low $E_{\mathrm{th}}$<br>Beam-produced |
| **Experiments** | SK/HK, DUNE, IceCube, …<br>T2K, DUNE, SHiP, FASER, … | SK/HK, DUNE, IceCube, …<br>T2K, DUNE, SHiP, FASER, … |

# Boosted Dark Matter (BDM)

# DM Boosting Mechanisms: Dark Sector

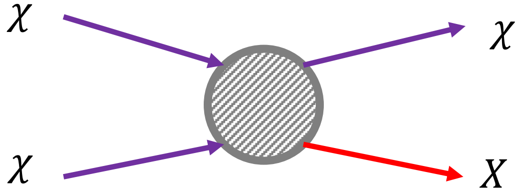
## *Boosted DM (BDM) coming from the Universe*

[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

$m_2 \gg m_1$

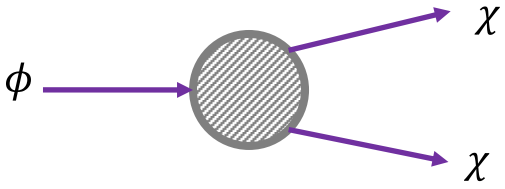



✓ Semi-annihilation model

$m_\chi \gg m_X$

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

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




✓ Decaying multi-component DM

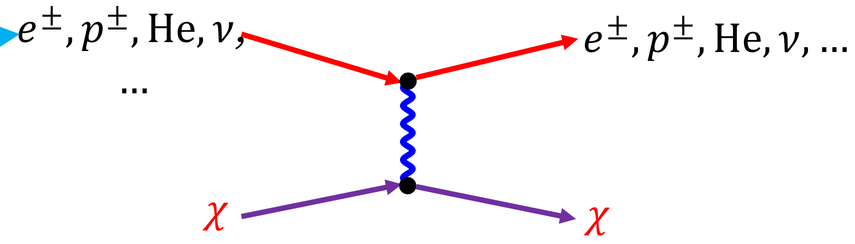
$m_\phi \gg m_\chi$

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

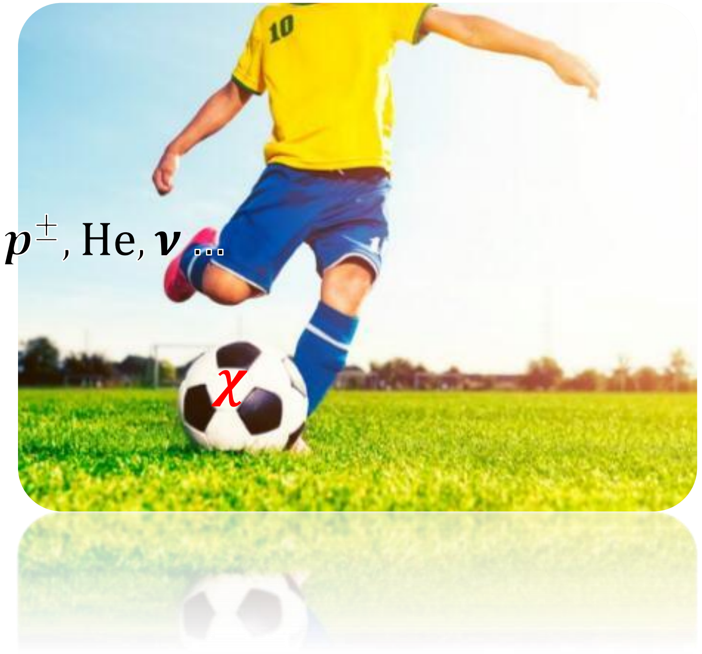
- Relic component DM: Non-relativistic!
- Only Tiny fraction of DM: Relativistic!

# DM Boosting Mechanisms: Cosmic-Rays (CRs)

## *Cosmic-Ray-Induced BDM*




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




- **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; Lin & Wu, 2404.08528; more]

- From **astrophysical processes:**

Solar evaporation - Kouvaris, PRD (2015)
Dark cosmic rays - Hu +, PLB (2017)
Solar reflection - An +, PRL (2018)
Solar acceleration - Emken +, PRD (2018)
Supernova - DeRocco +, PRD (2019)
Atmospheric collider - Alvey+, PRL (2019)
Earth attraction – Davoudiasl + PRD (2020); Acevedo + JHEP (2024)
PBH evaporation - Calabrese +, PRD (2022)
Blazar jets - Wang +, PRL (2022); more

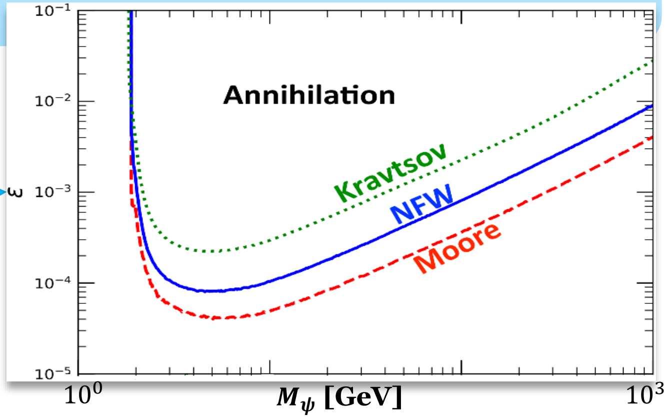
# BDM Searches @ Neutrino Experiments

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 for **LDM!**

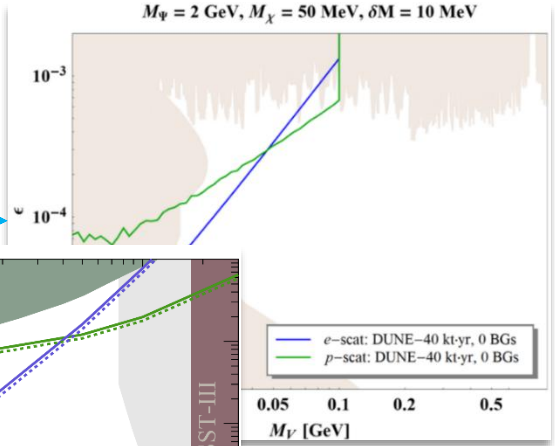
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

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**

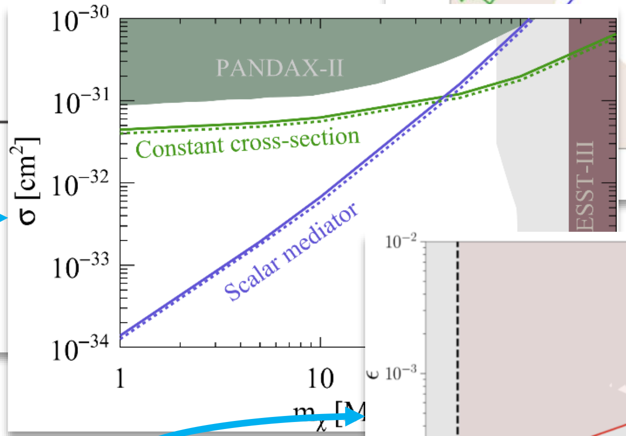



PHYSICAL REVIEW LETTERS **130**, 031802 (2023)

**Editors' Suggestion** **Featured in Physics**

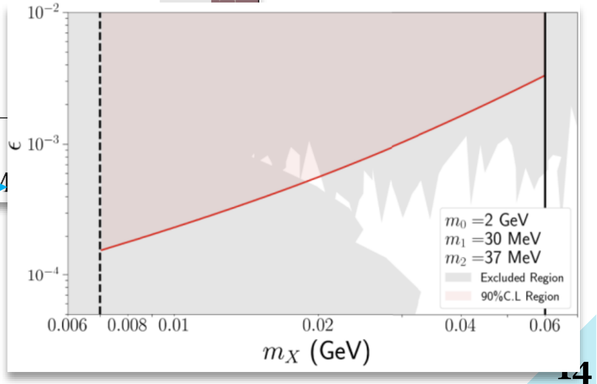
**Cherenkov radiation rings by protons**

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




PHYSICAL REVIEW D **111**, 092003 (2025)

**Search for inelastic boosted dark matter with the ICARUS detector at the Gran Sasso Underground National Laboratory**

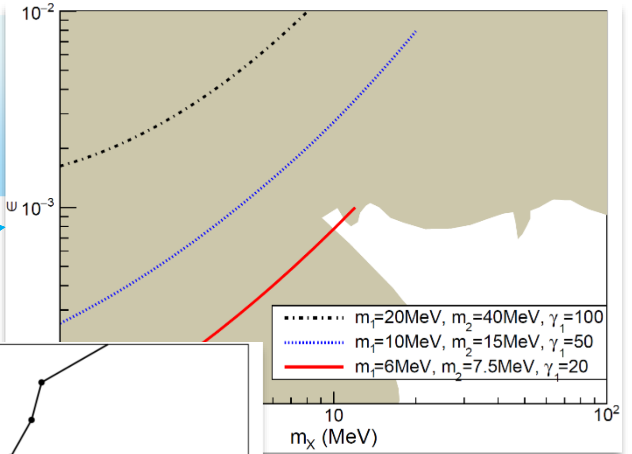


# BDM Searches @ DM Experiments

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

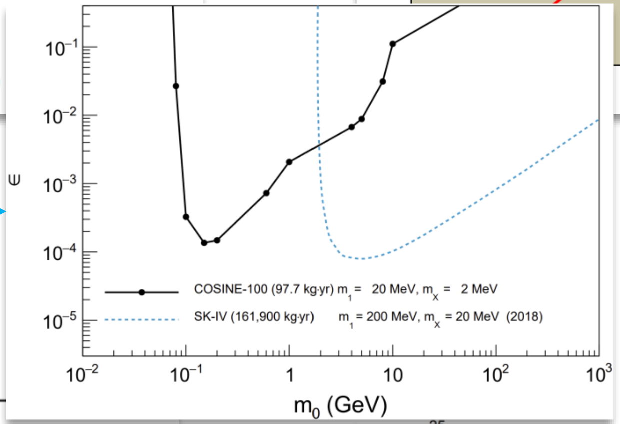
**Editors' Suggestion**

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




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

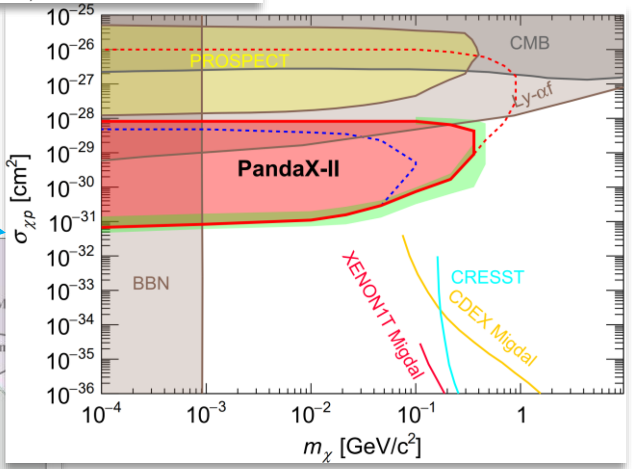
**Search for Boosted Dark Matter in COSINE-100**




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

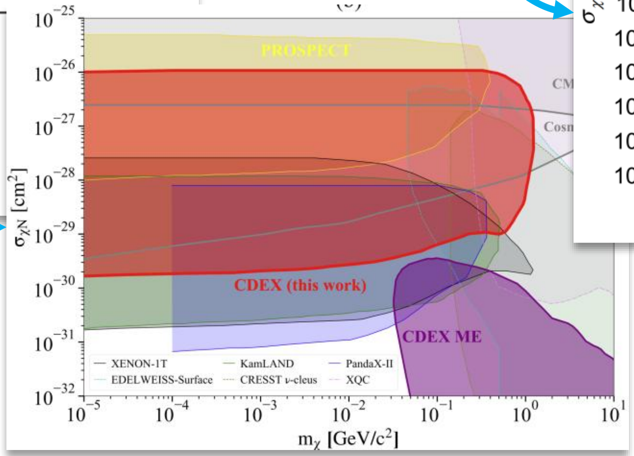
**Editors' Suggestion**

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




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

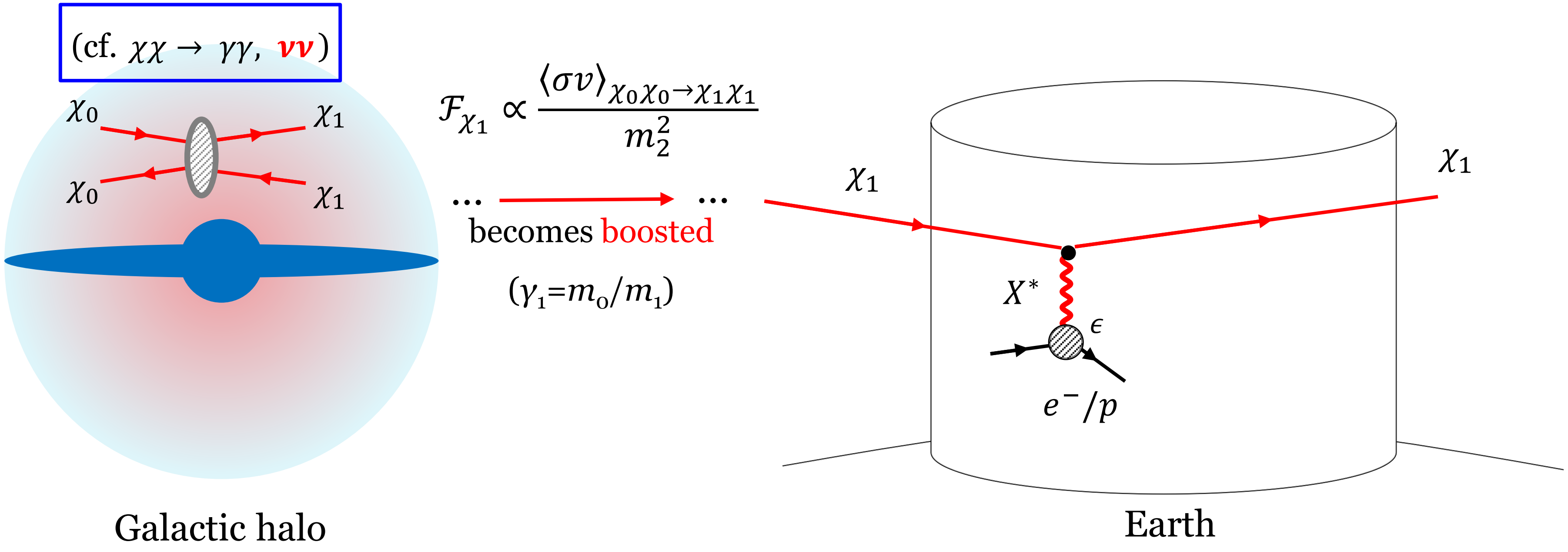
**Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory**




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

# Issues in BDM Searches

# Minimal Two-component Scenario

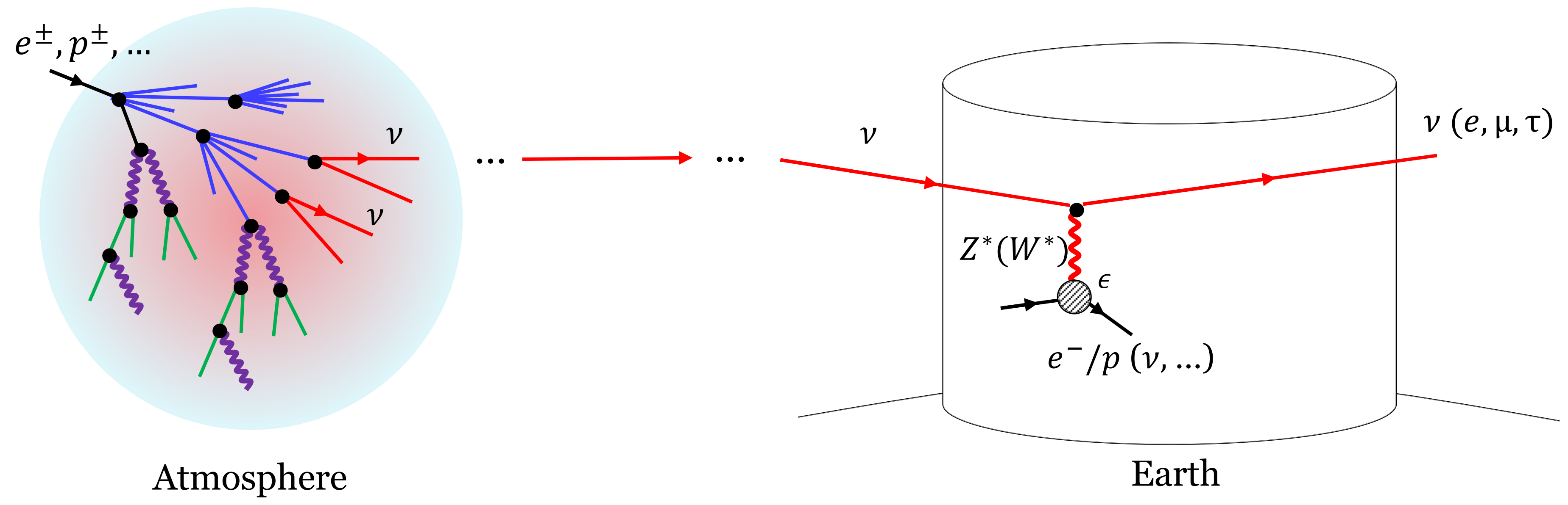



- **Example model**: fermionic heavier($\chi_0$)/lighter($\chi_1$) DM + dark gauge boson($X$)

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

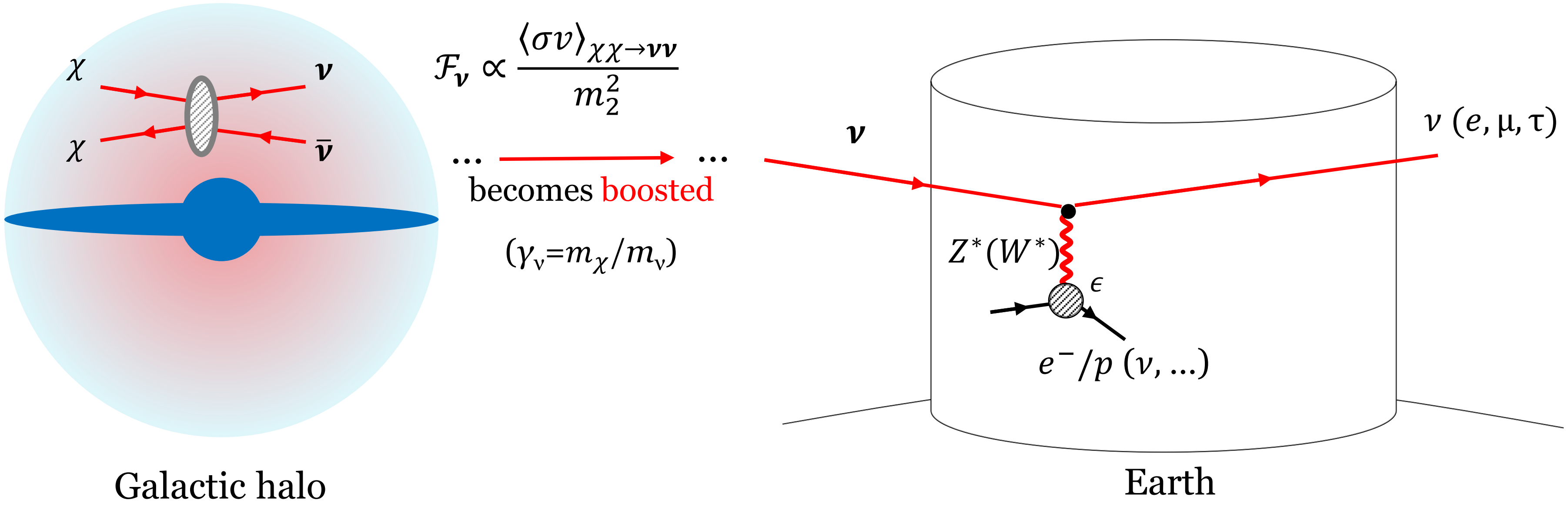
- Elastic electron [Agashe, Cui, Necib, Thaler (2014)] & elastic proton (even DIS @ e.g. DUNE) [P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)] scattering channels are available. ➔ Energetic recoil

# Issue 1: Background




- Atmospheric-neutrino-induced events: Irreducible backgrounds
- 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.

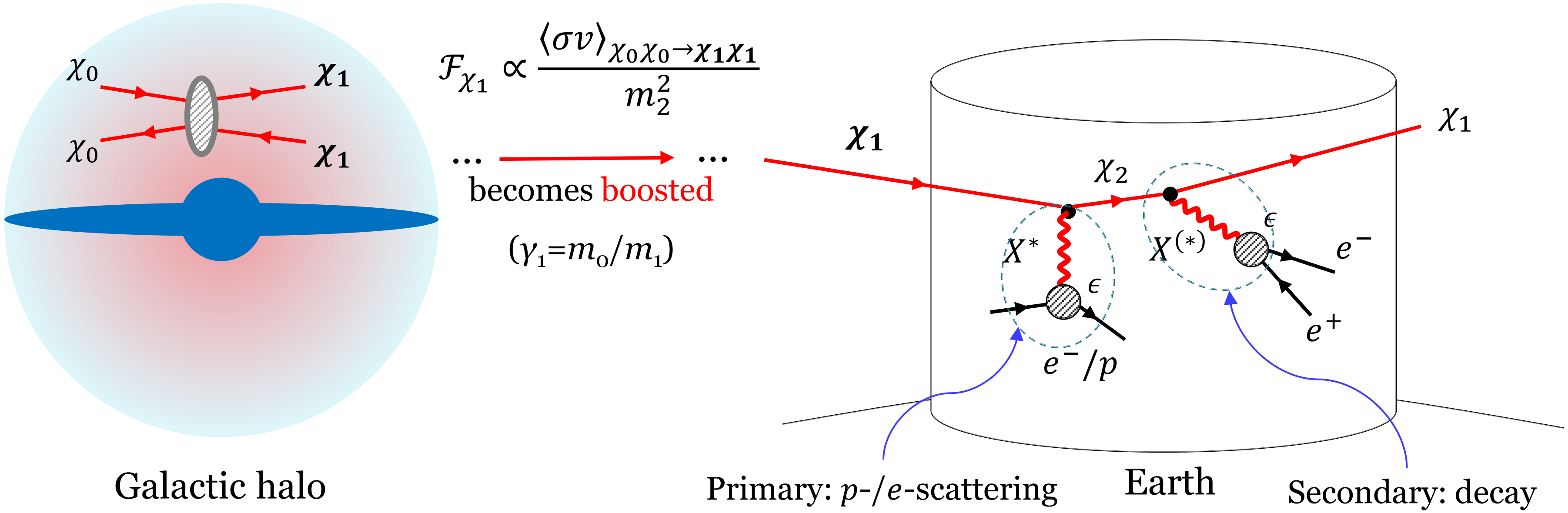
# Issue 2: Distinction from ν Scenario




❖ (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 *i*BDM Scenario



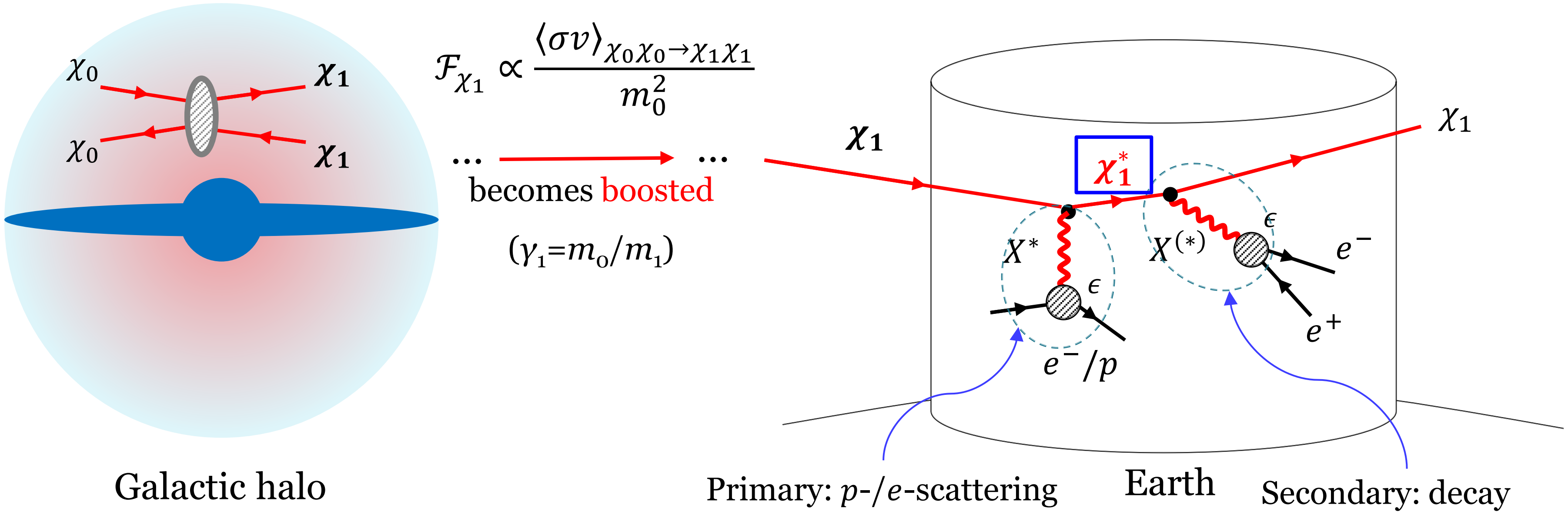

❖ *i*BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]

❖ Additional signatures from the decay of heavier unstable dark-sector state $\chi_2$ from inelastic scattering.

❖ Double-bang: also for $\nu$ w/ a heavier state [Coloma, Machado, Martinez-Soler, Shoemaker, PRL (2017)]

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

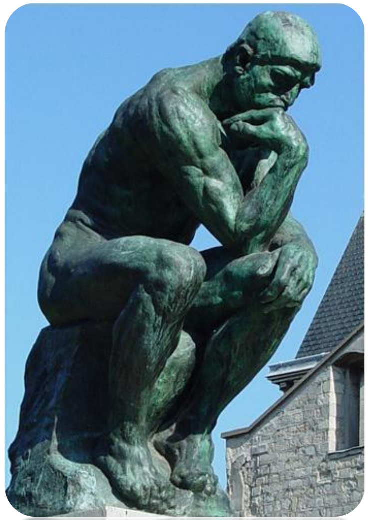
# Issue 2: Avoidable by Sub-leading Process




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

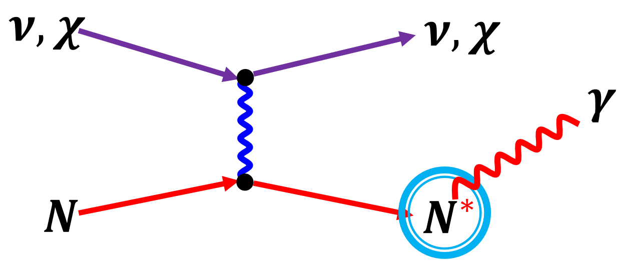
❖ A new BDM search strategy utilizing initial-/final-state dark gauge boson radiation, i.e. "**Dark-Strahlung**" from cosmogenic BDM [Kim, **JCP** & Shin, PRD (2019)]

# Only recoiled e/p?

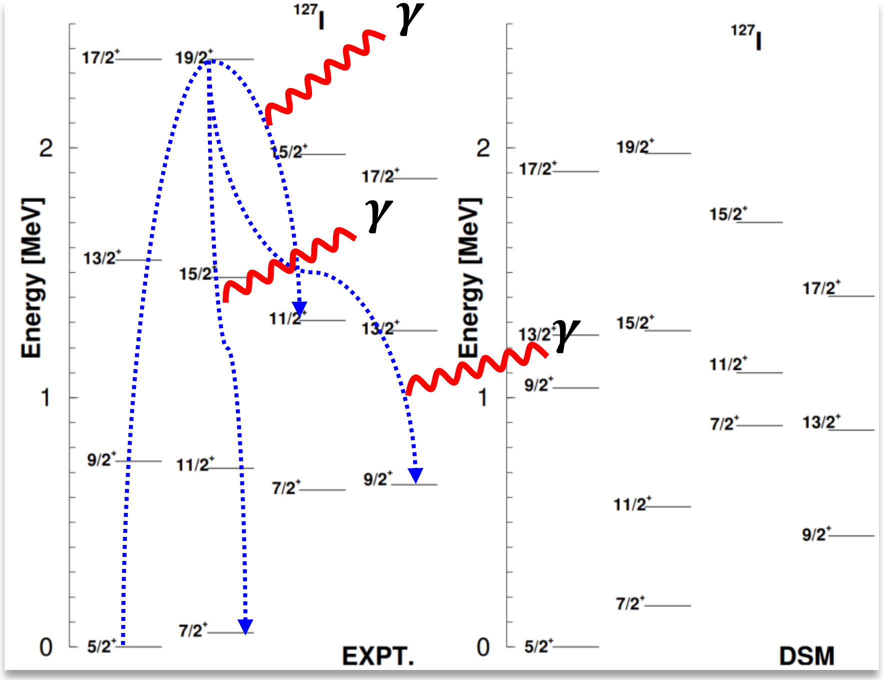


# Inelastic Nuclear Scattering

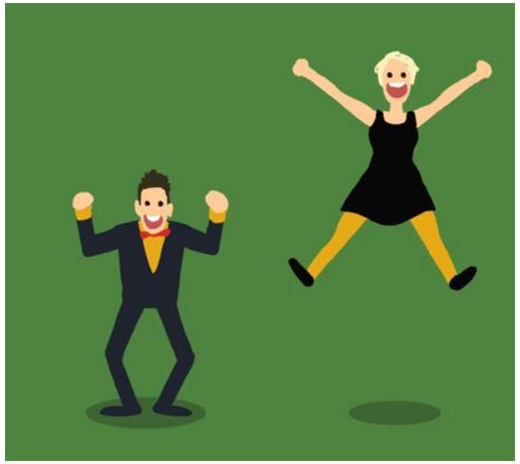
❖ Why **inelastic** channel?




$E_{in} \lesssim 50$ MeV




Sahu et al., [2004.04055]



➢ Signatures

✓ **Elastic**: low energy nuclear recoil

✓ **Inelastic**: $\gamma$ cascade ($\Delta E \lesssim 10$ MeV), $\gamma$ cascade + nucleons ($\Delta E \gtrsim 10$ MeV)

➢ Motivation

✓ A new channel to study

✓ Larger 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 CR-BDM

❖ Focus: the interaction between DM & quark

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

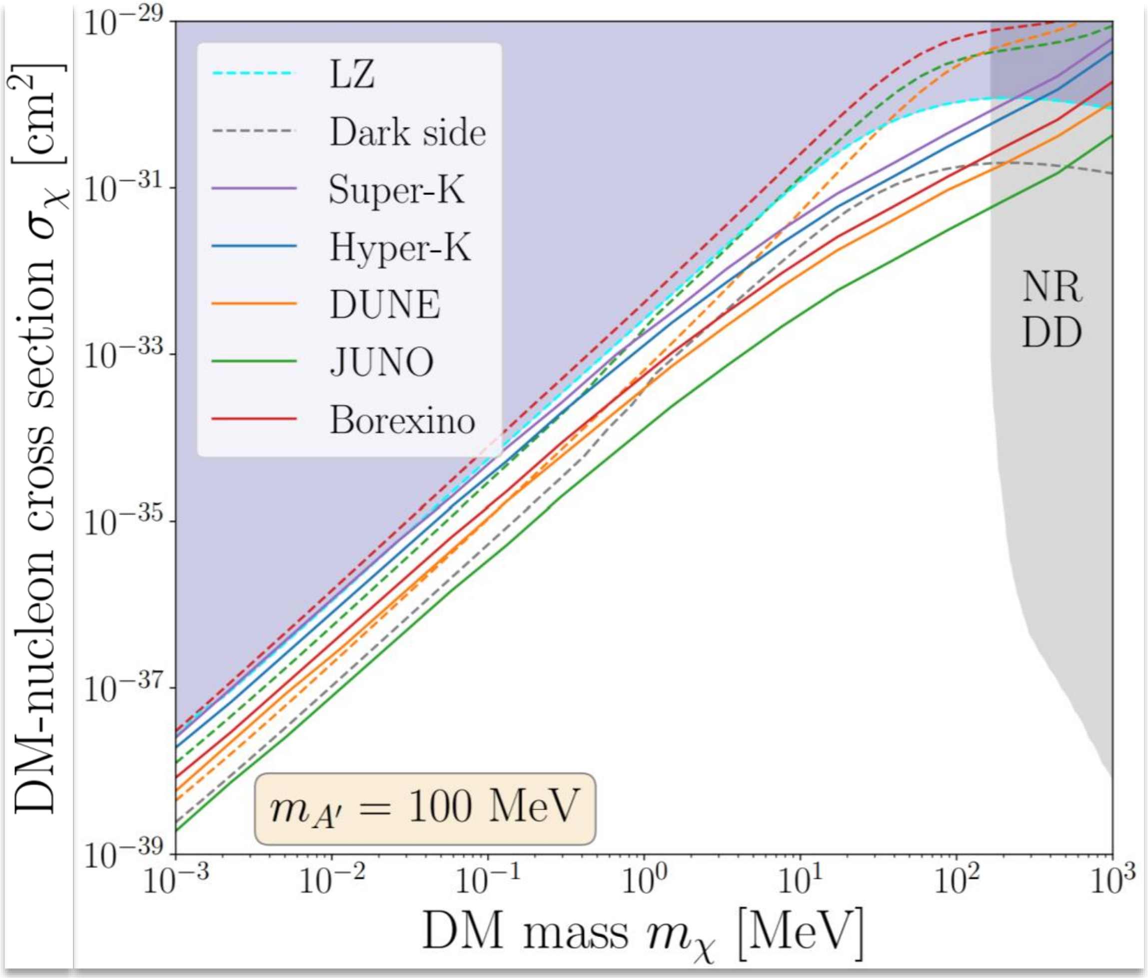
➔ DM boosted by cosmic rays (p, He)

❖ The expected # of signal events

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

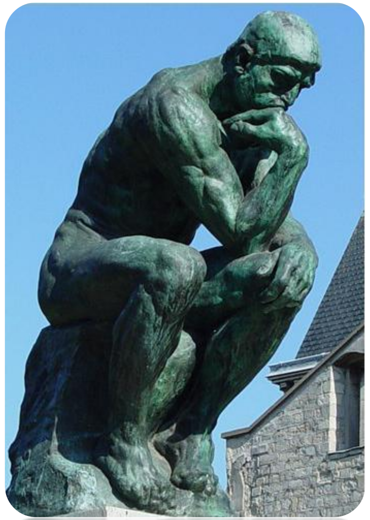
- ✓ LSC detectors (JUNO, Borexino): BGs in the signal zone are highly suppressed due to the good E resolution.
- ✓ Cherenkov detectors (SK, HK): de-excitation $\gamma$'s are buried in single e-like events.

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

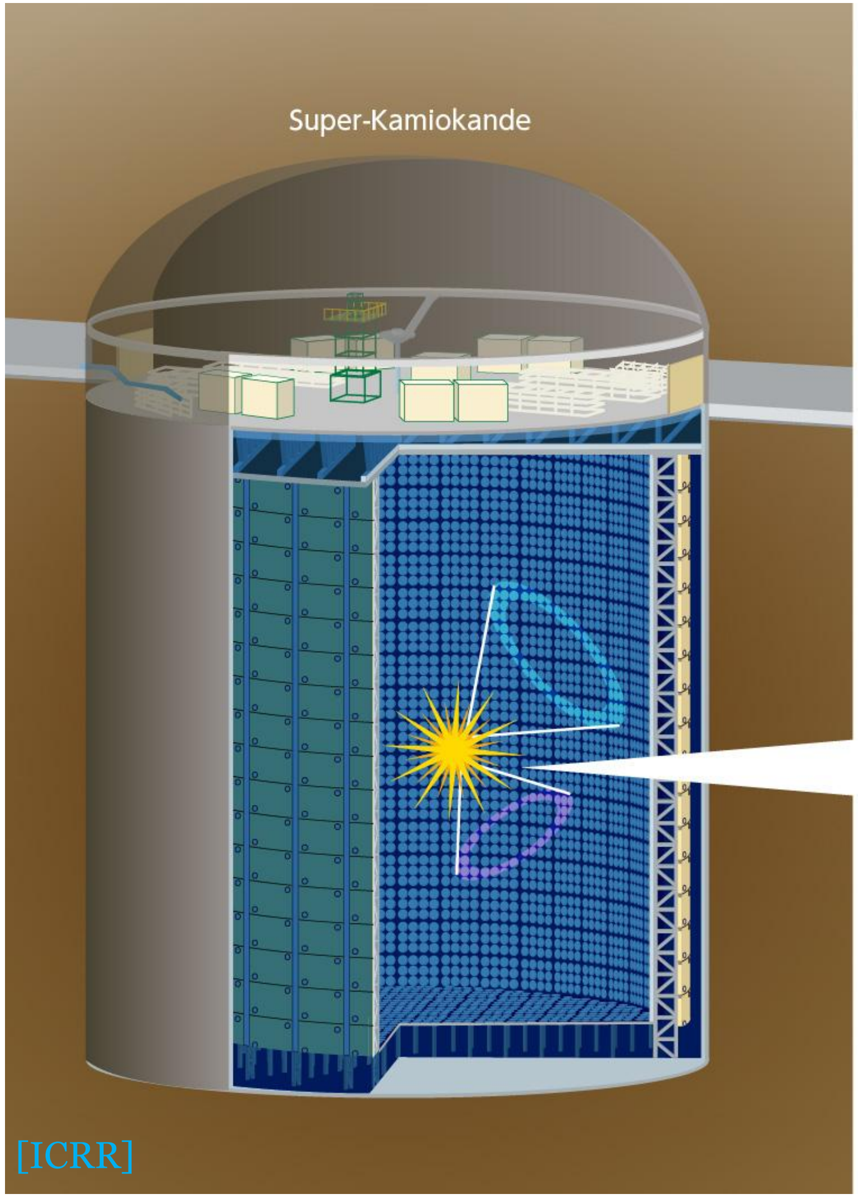


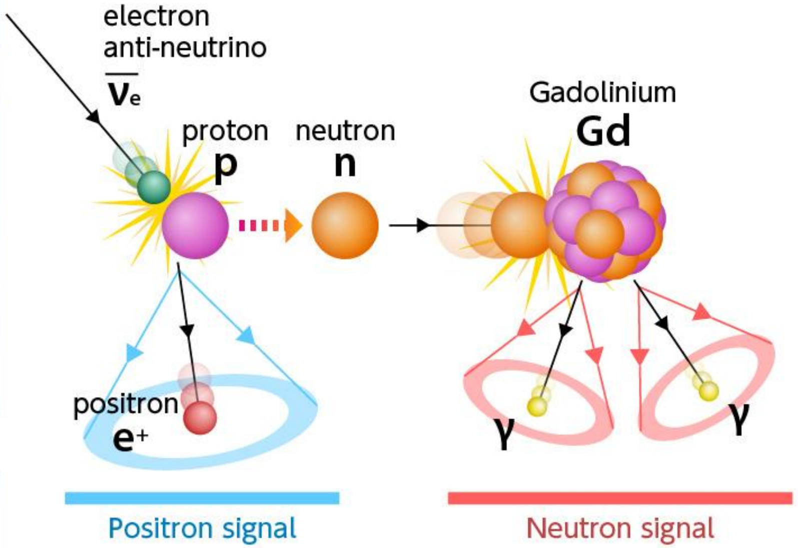

✓ Inelastic (solid) better than elastic (dashed)

# Neutrons?



# Water-Cherenkov Detectors w/ Gadolinium



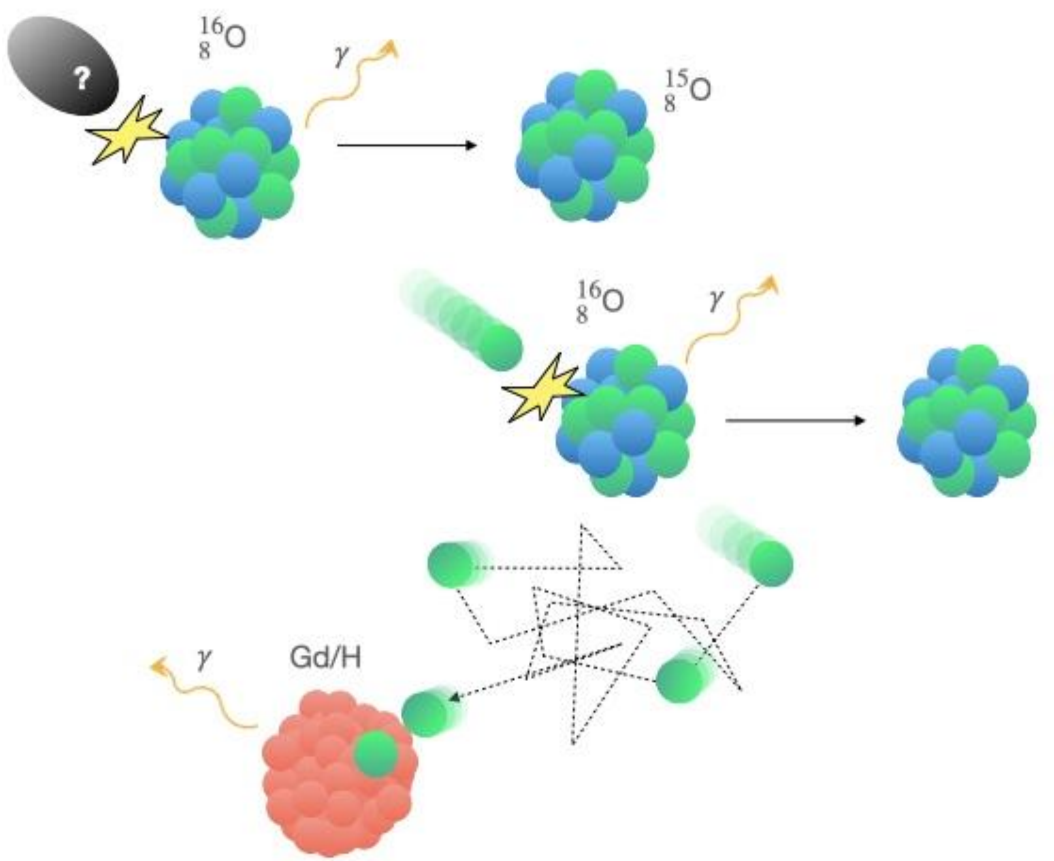




- **Gd**: high n-capture rate & $\gamma$'s w/ characteristic E ➔ the addition of Gd greatly enhances n detection efficiency.
- **SK-Gd**: mainly for supernova relic neutrinos

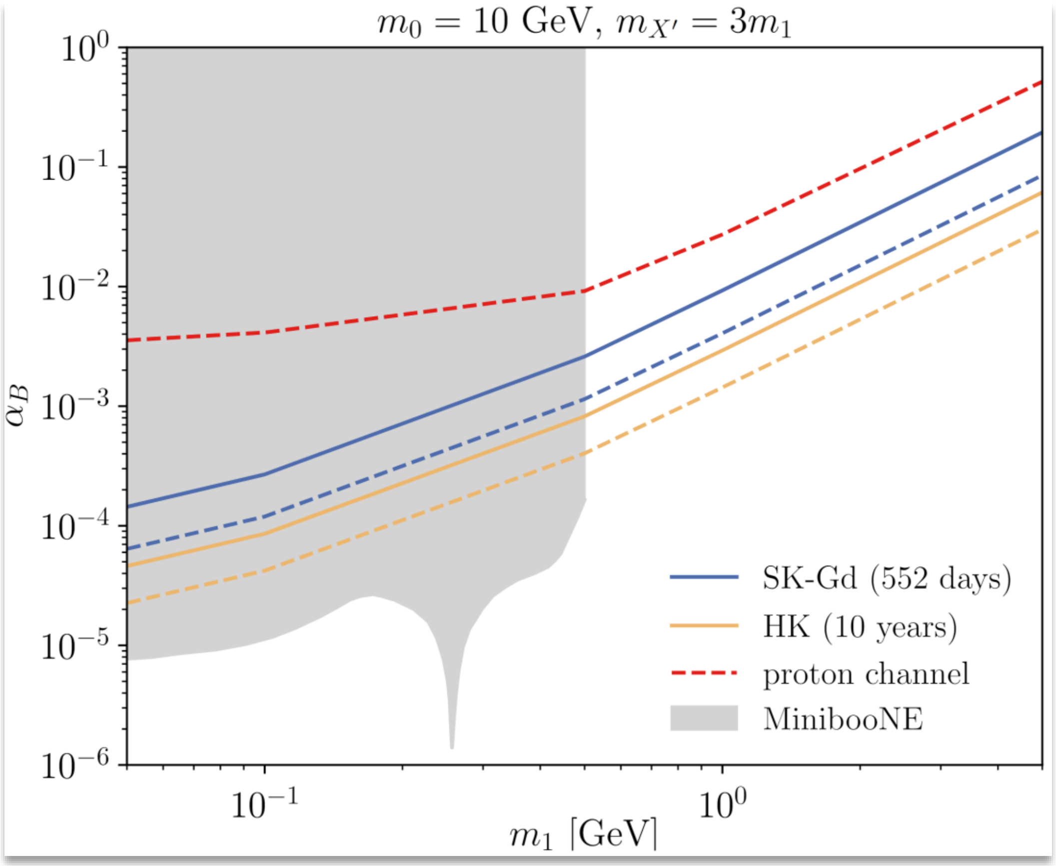
# Knockout Neutrons @ Cherenkov Detectors

- So far only p, but 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**



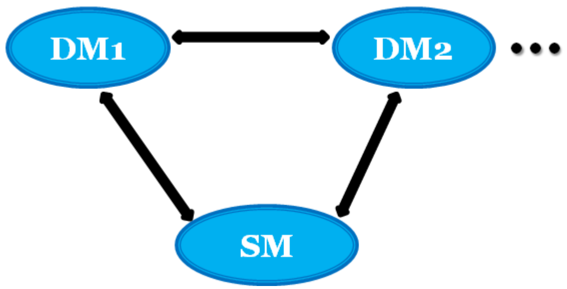

[K. Choi & **JCP**, 2409.05646]



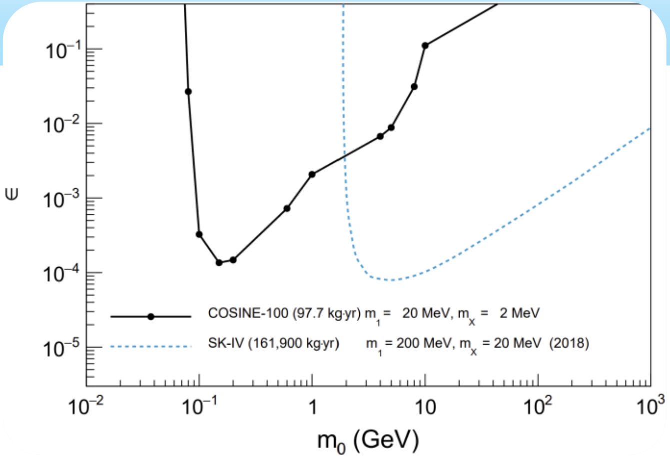

✓ Two-component $(\chi_0, \chi_1)$ BDM model w/ the following interaction between lighter DM $(\chi_1)$ & the SM sector,

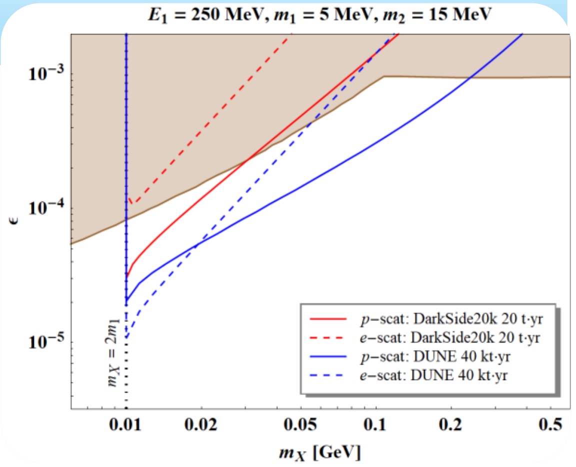
$$\mathcal{L} \supset iq_B g_B X'_\mu [\chi_1^\dagger \partial^\mu \chi_1 - (\partial^\mu \chi_1^\dagger)\chi_1] + \frac{1}{3} g_B X'_\mu \bar{q}\gamma^\mu q$$

# Summary







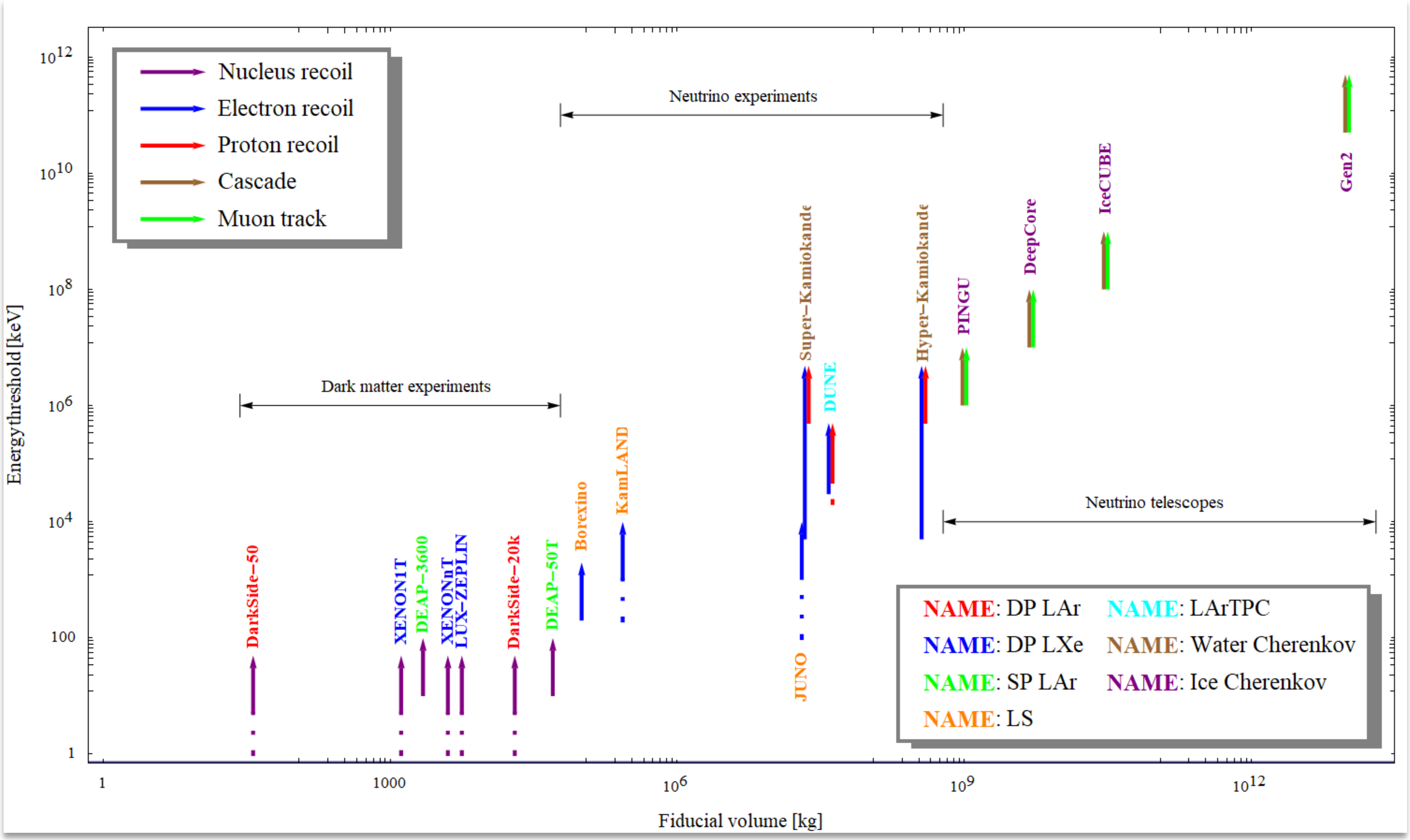

- ❖ Rising interest in dark sector (multi-component) scenarios & BDM (Energetic DM)
- ❖ Various BDM production scenarios: Dark sector, Reversing direct detection, Astrophysical
- ❖ Various detection channels: elastic e/p, DIS, inelastic N, n-capture, …
- ❖ BDM searches are promising & provide a new direction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

**Thank you**

# Supplemental

# Many More Well-Motivated Exps.

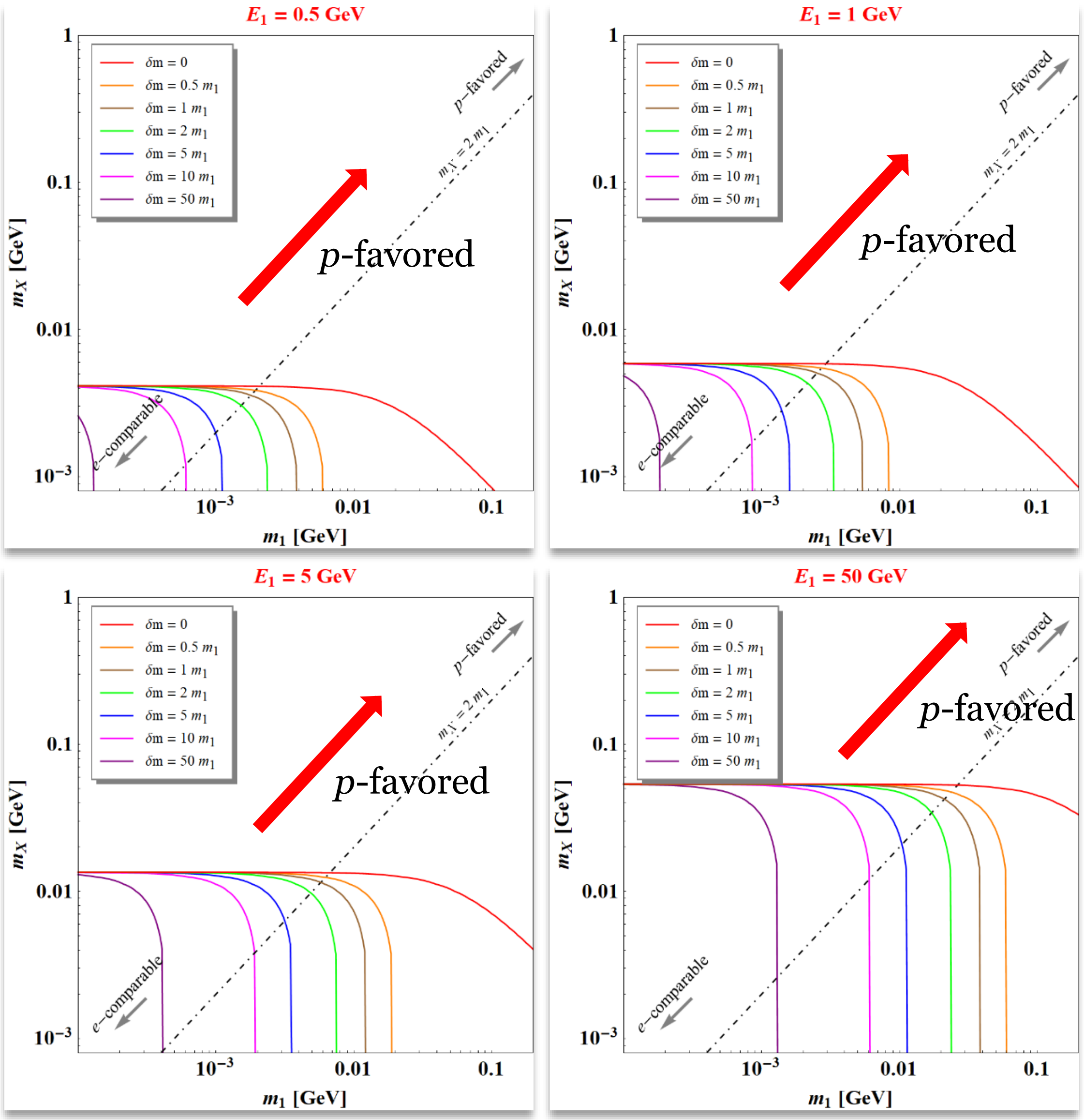
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]




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

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

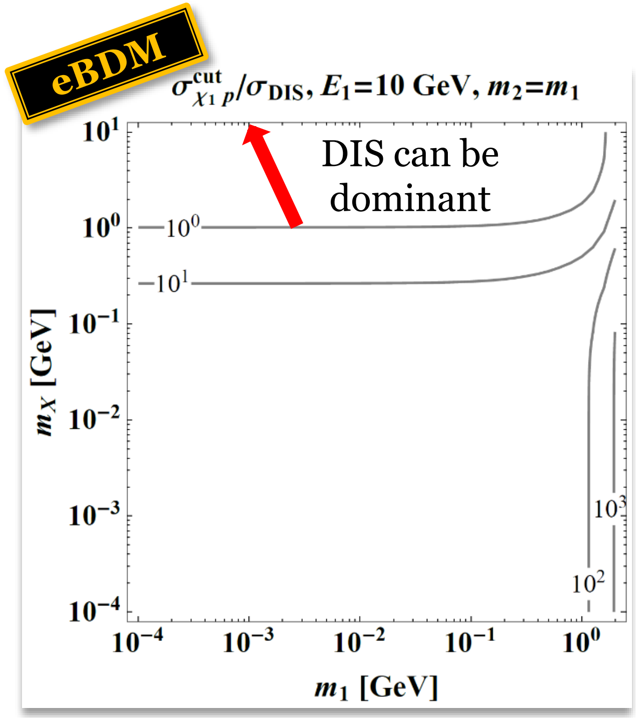
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

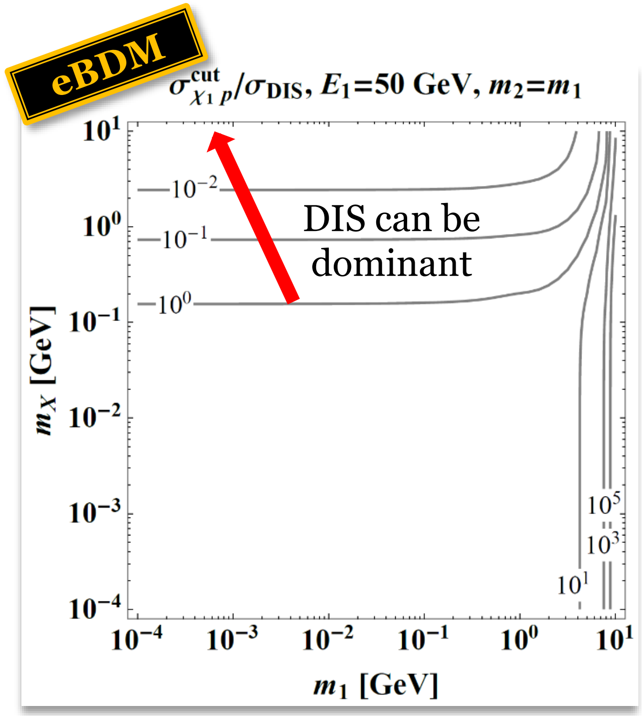


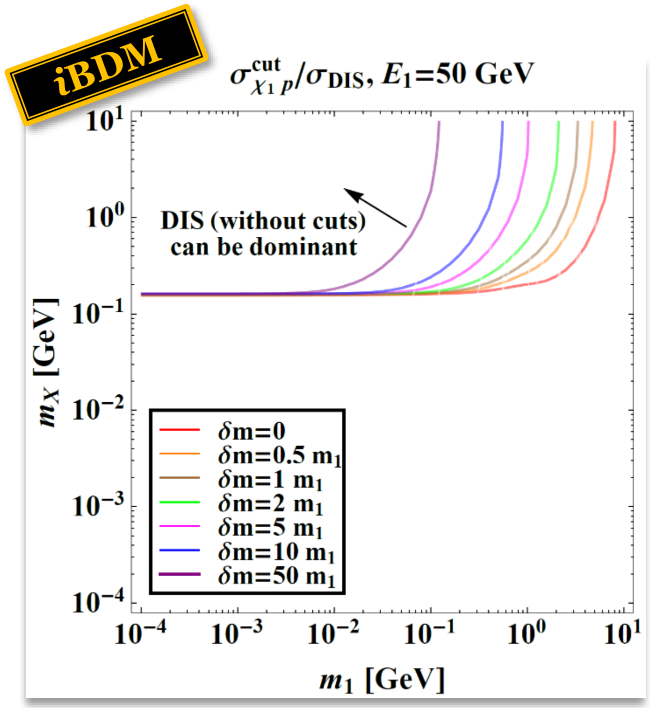

- ✓ If a BDM search hypothesizes a heavy dark photon (say, sub-GeV range), the *p*-channel may expedite discovery.
- ✓ If a model conceiving iBDM signals allows for large mass gaps between $\chi_1$ and $\chi_2$, the *p*-channel is more advantageous.
- ✓ The *e*-channel becomes comparable in probing the 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

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

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

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

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

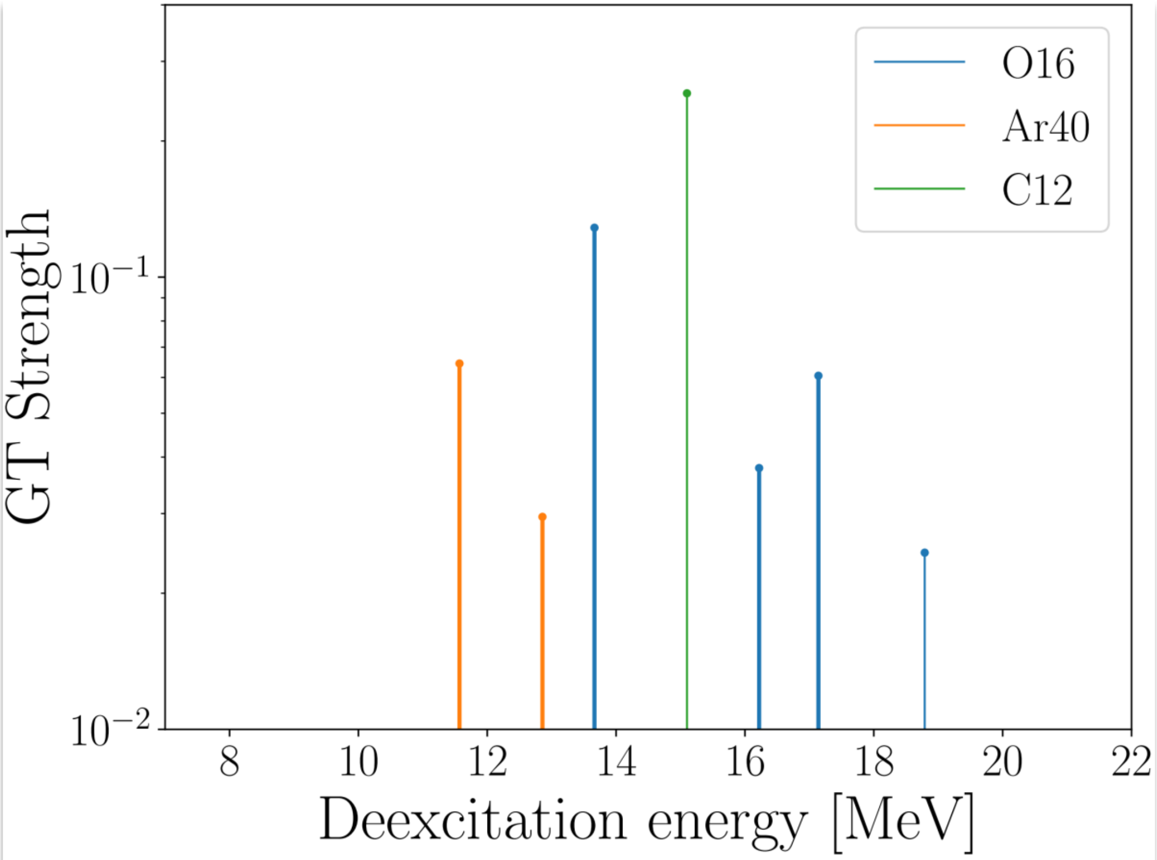
* For more details, See e.g. Dutta et al., [2206.08590].

- The expected # of signal events

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

* $\gamma$-line @ JUNO by $\nu$'s [Suliga & Beacom, PRD (2023)]

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

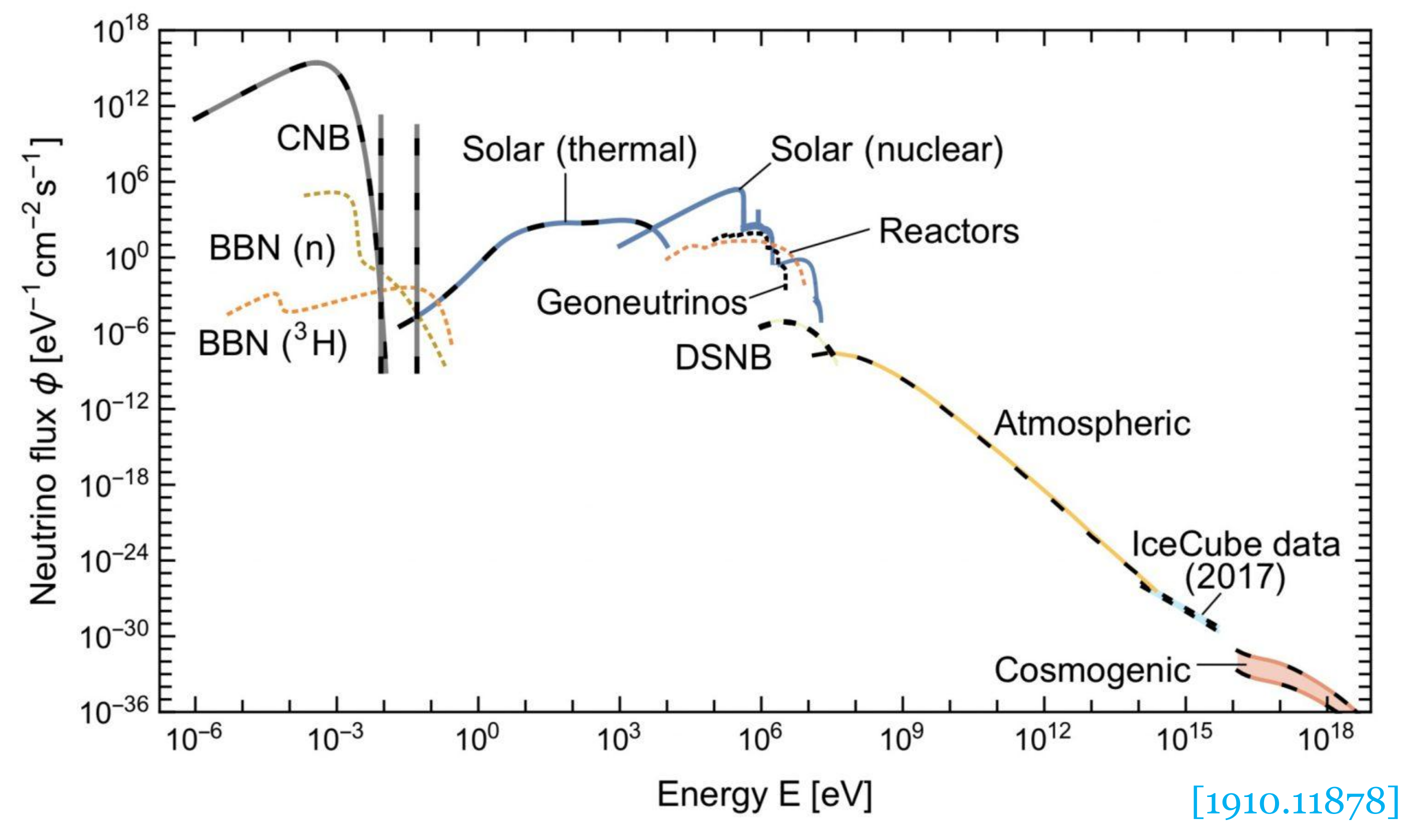



The GT strengths are derived from experimental results & the large-scale shell model code BIGSTICK.

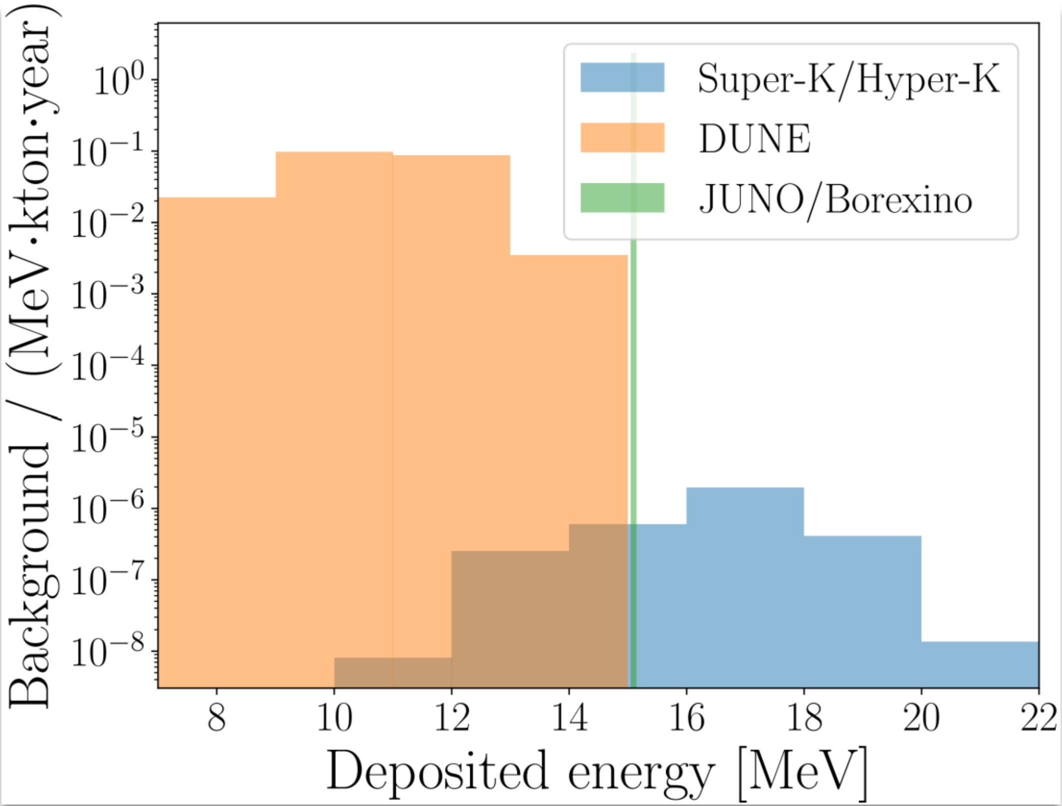
# Estimated Background Rates for Line Searches

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

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




[1910.11878]



# Benchmark Scenario: $p$ of Knockout Nucleons

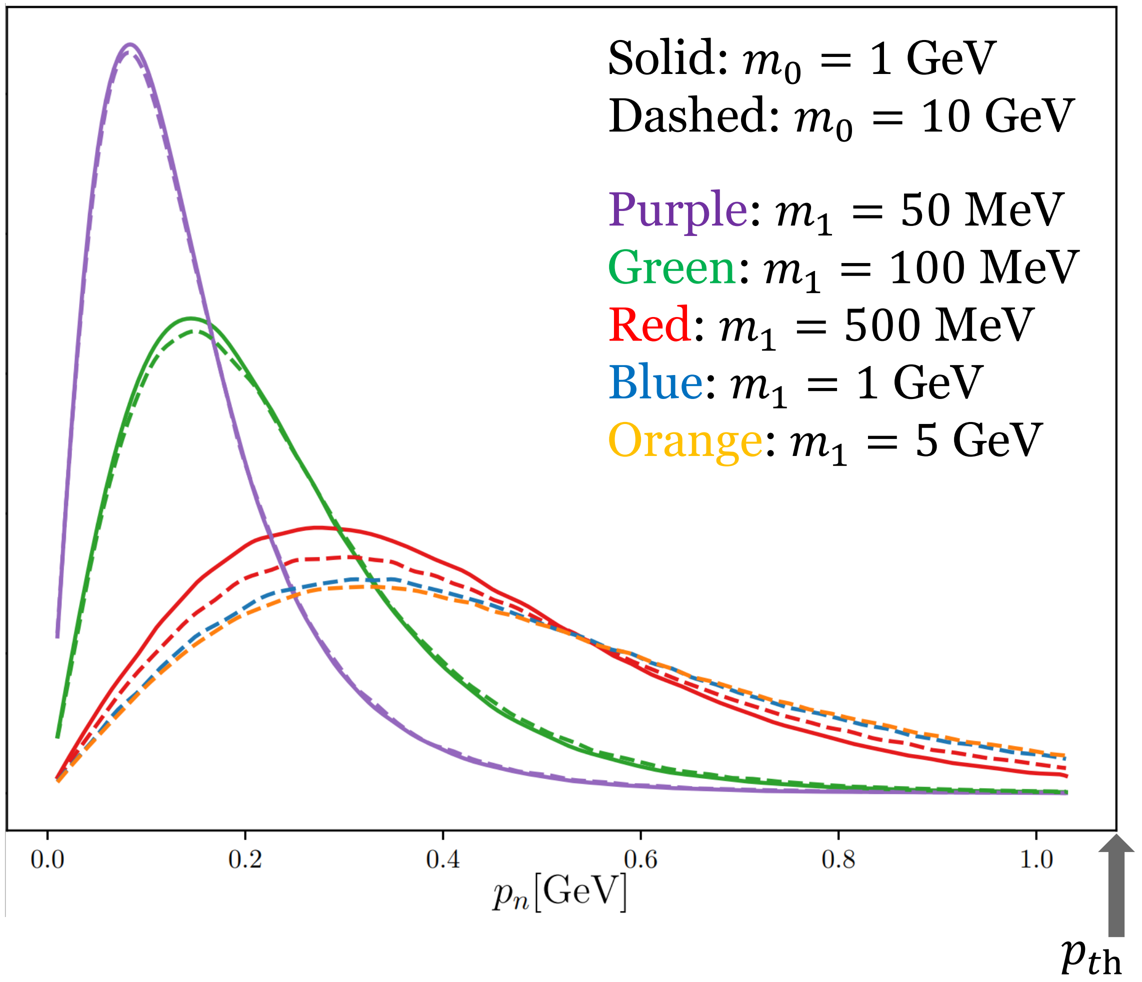
[K. Choi & **JCP**, 2409.05646]

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

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

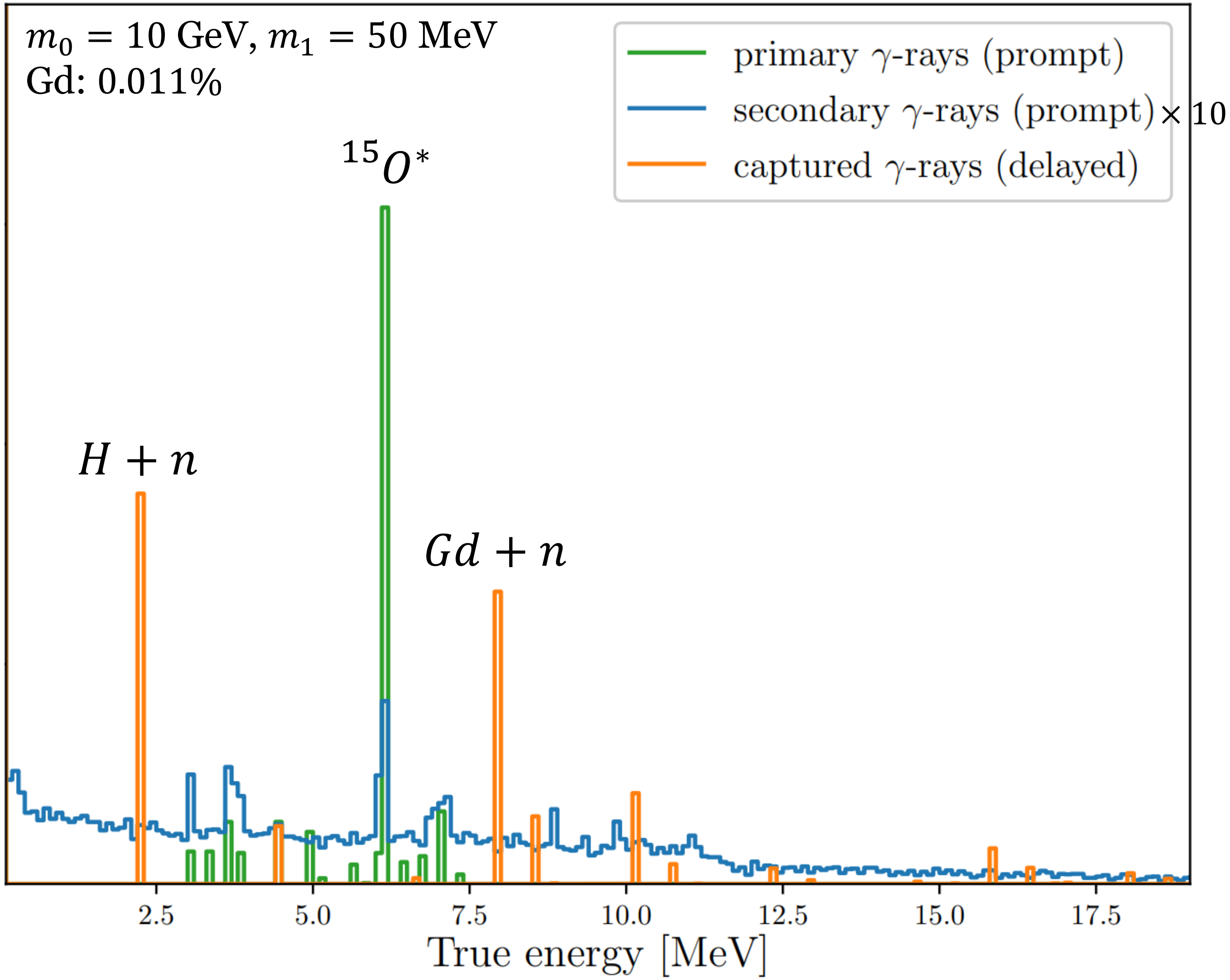
- This sort of scenarios can arise with various new gauge bosons, e.g., $U(1)_{B-L}$, $U(1)_B$, $U(1)_{B-3L_{\mu,\tau}}$, and $U(1)_{T3R}$.

Initial momentum of knockout nucleons

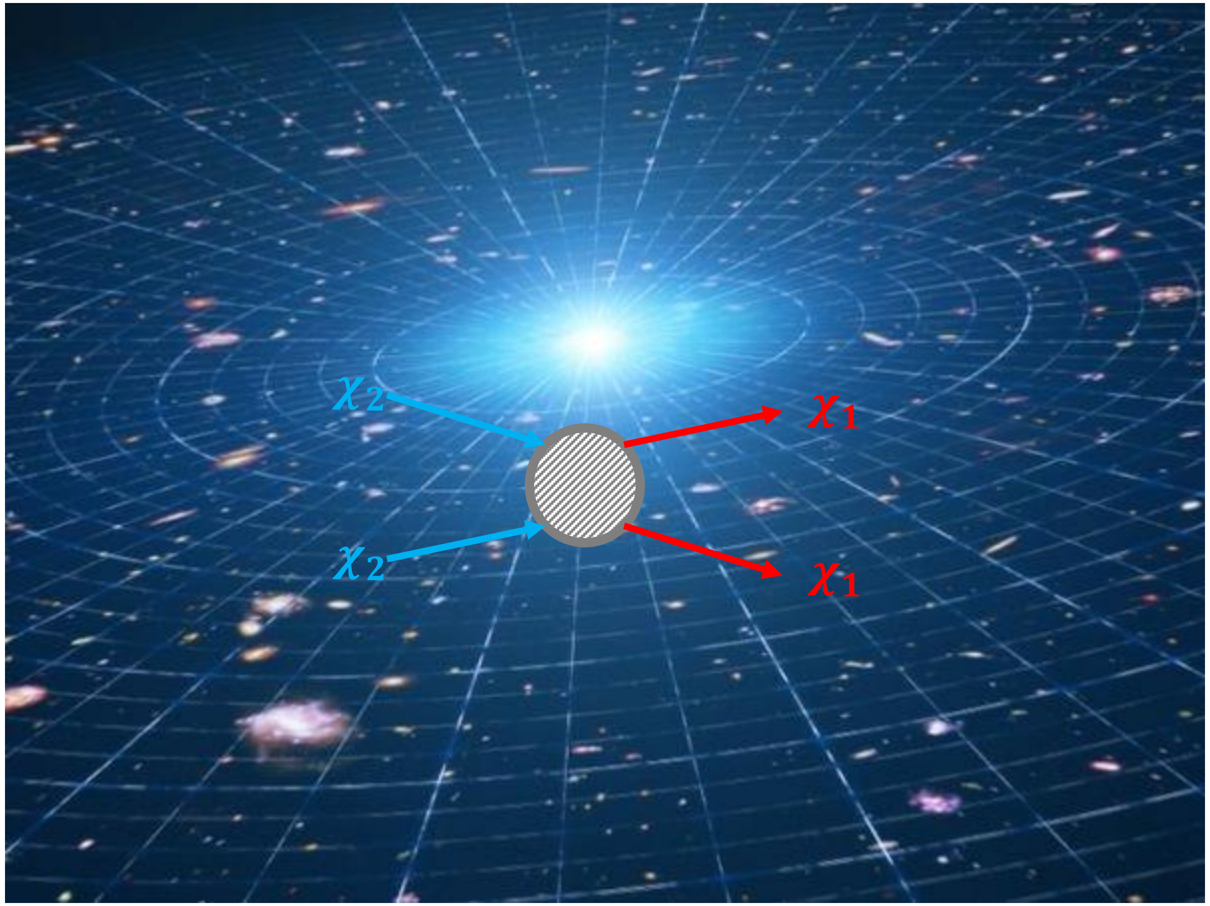


# Simulated Energies of γ rays

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



# BDM=Hot DM?




✓ $\chi_2$: heavy DM, $\chi_1$: light DM

- BDM=hot DM ➔ Strong constraints from cosmological evolution, structure formation, etc?
  - $\chi_2\chi_2 \to \boldsymbol{\chi_1\chi_1}$ Vs $\chi\chi \to \boldsymbol{\nu\nu}$
  - $n_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_1}}{m_2^2}$ with $\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm^3/s}$

# Self-Heating Effects?

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

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

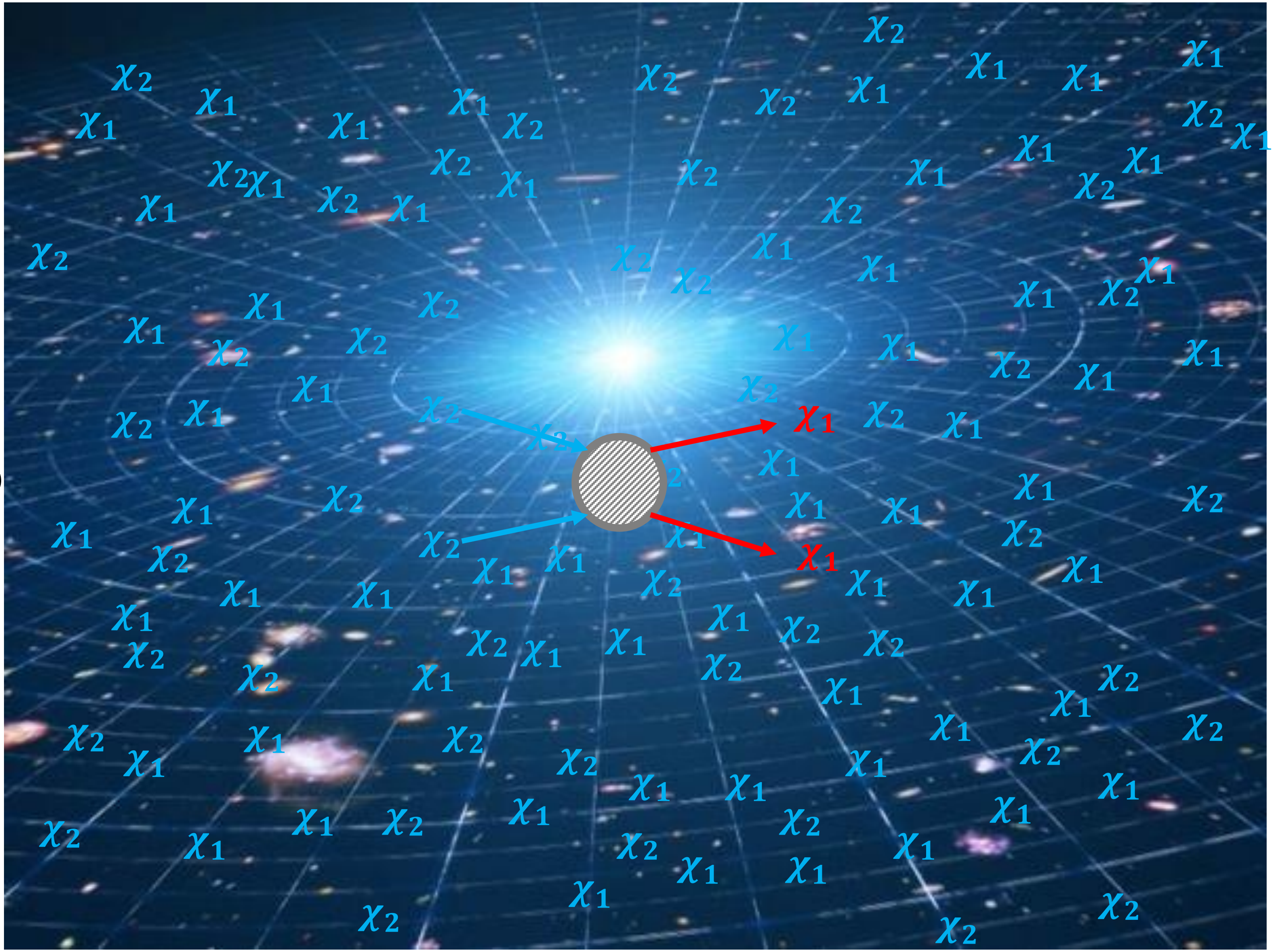
Large self-scattering is quite natural for light dark sector!

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

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

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

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




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

# Self-Heating Effects!

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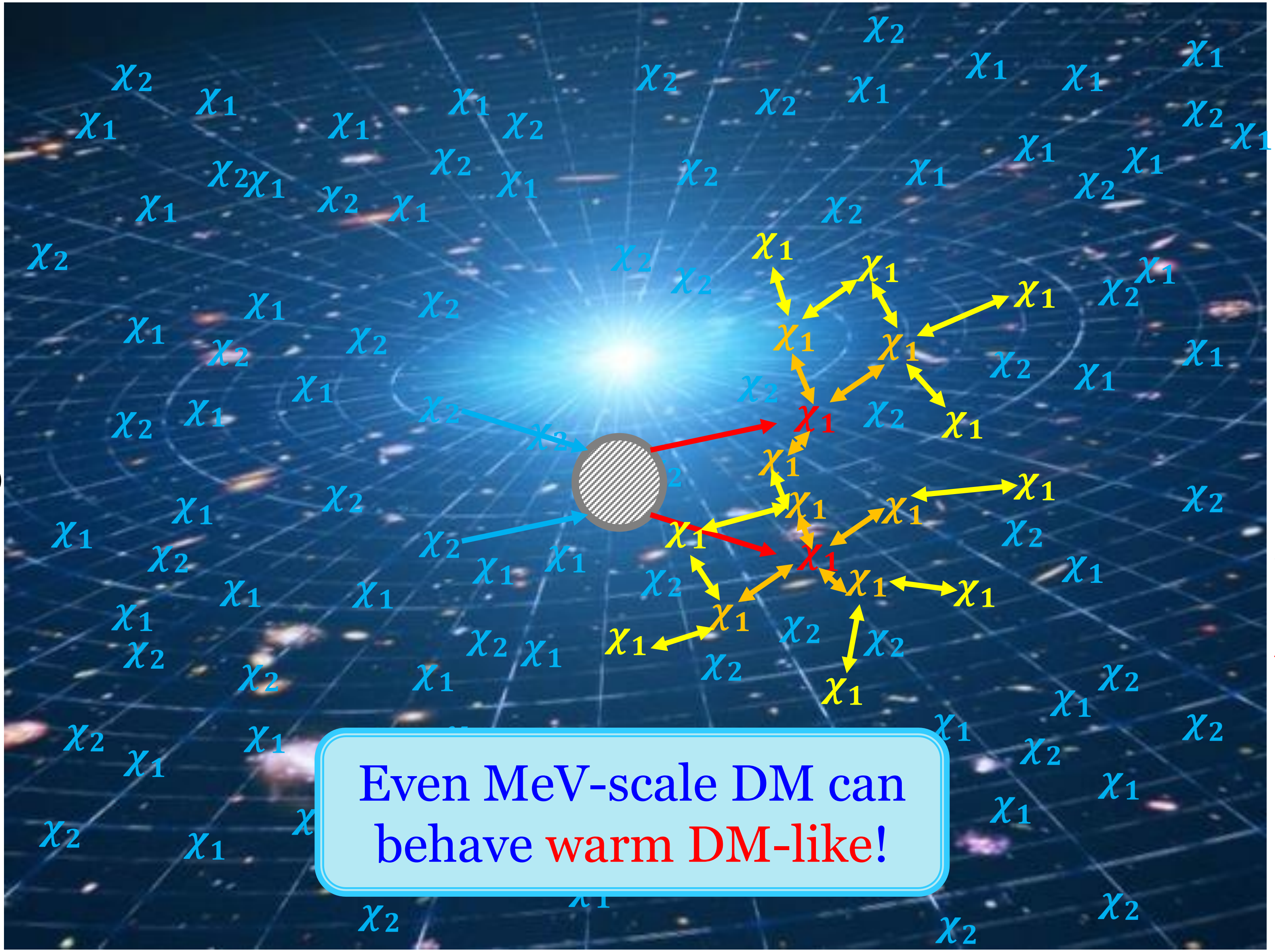
➔ $\sigma_{\chi_1}^{\mathrm{self}} / m_{\chi_1} \approx \boldsymbol{O(1\ \mathrm{cm}^2/\mathrm{g})}$

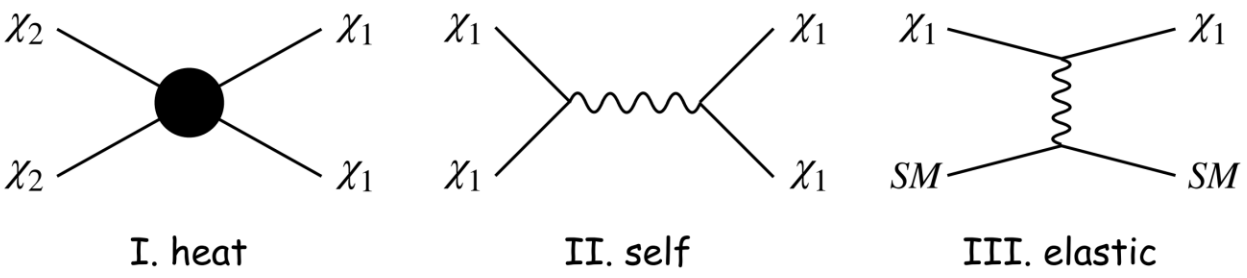


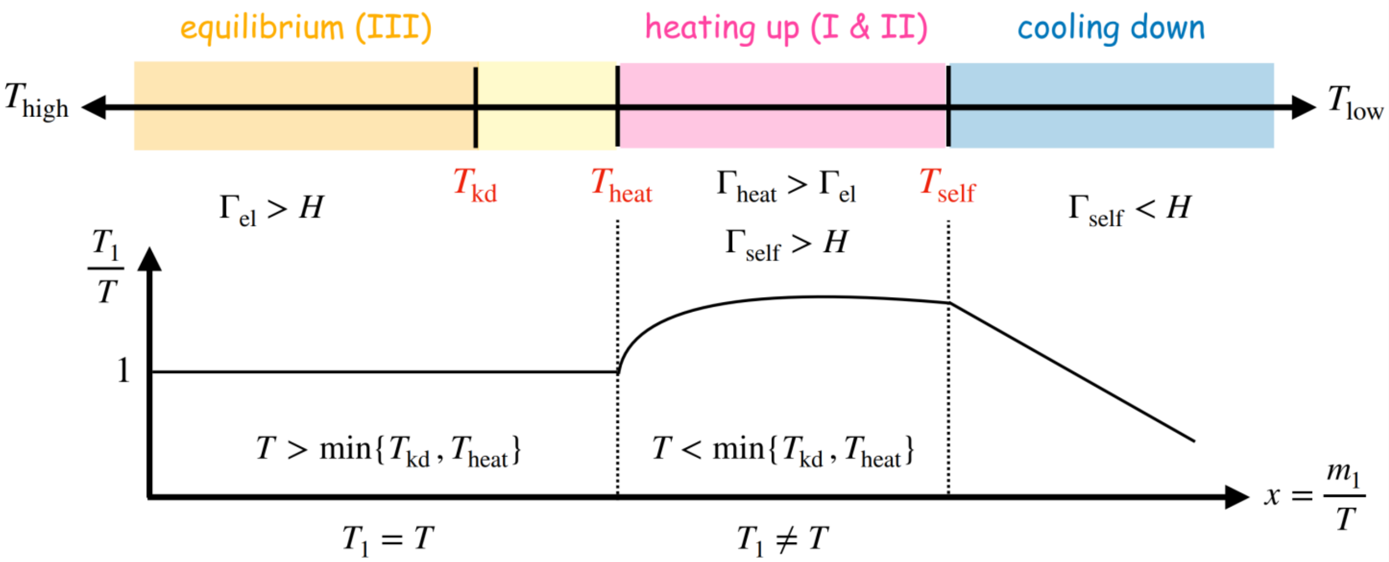

1. The heavy $\chi_2$ annihilates to light $\chi_1$ which becomes boosted.

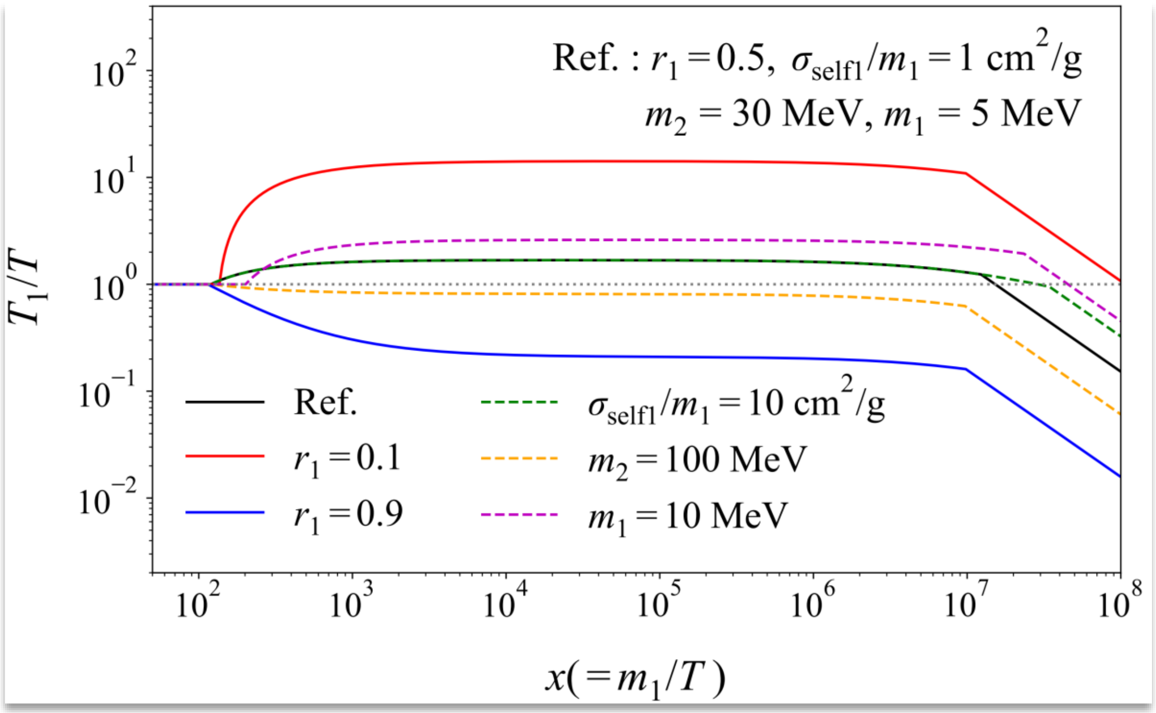
2. Sharing energies through self-interaction $\sigma_{\chi_1}^{\mathrm{self}}$ which increases the $\chi_1$ temperature.

# Thermal Evolution

[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]
[J. Kim, Lim, **JCP** & Kong, PTEP (2024)]




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

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

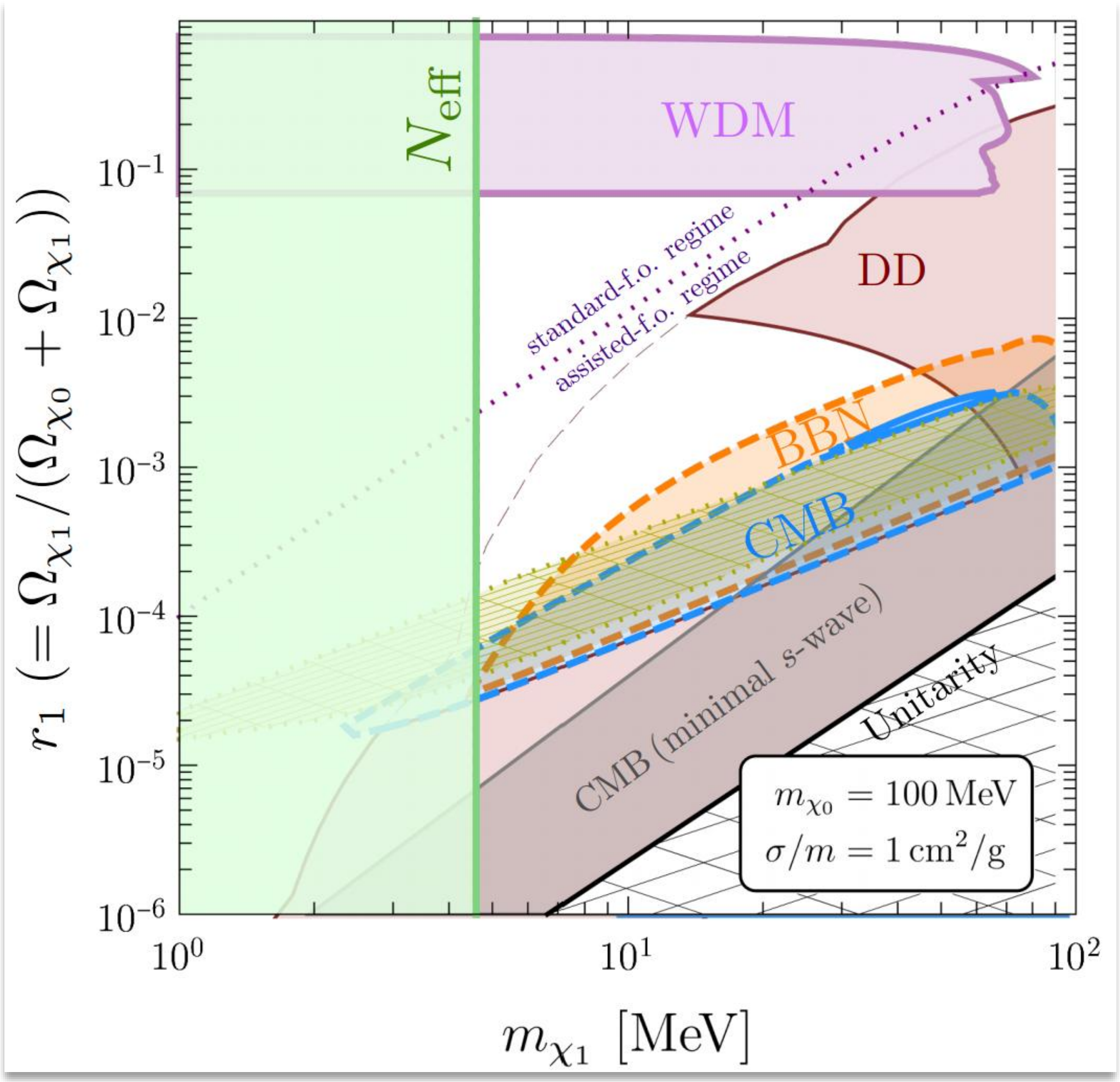
$$\gamma_{heat} = \frac{2n_{\chi_2}^2 \langle\sigma v\rangle_{22\to 11}}{3n_{\chi_1} T}(m_{\chi_2} - m_{\chi_1})$$

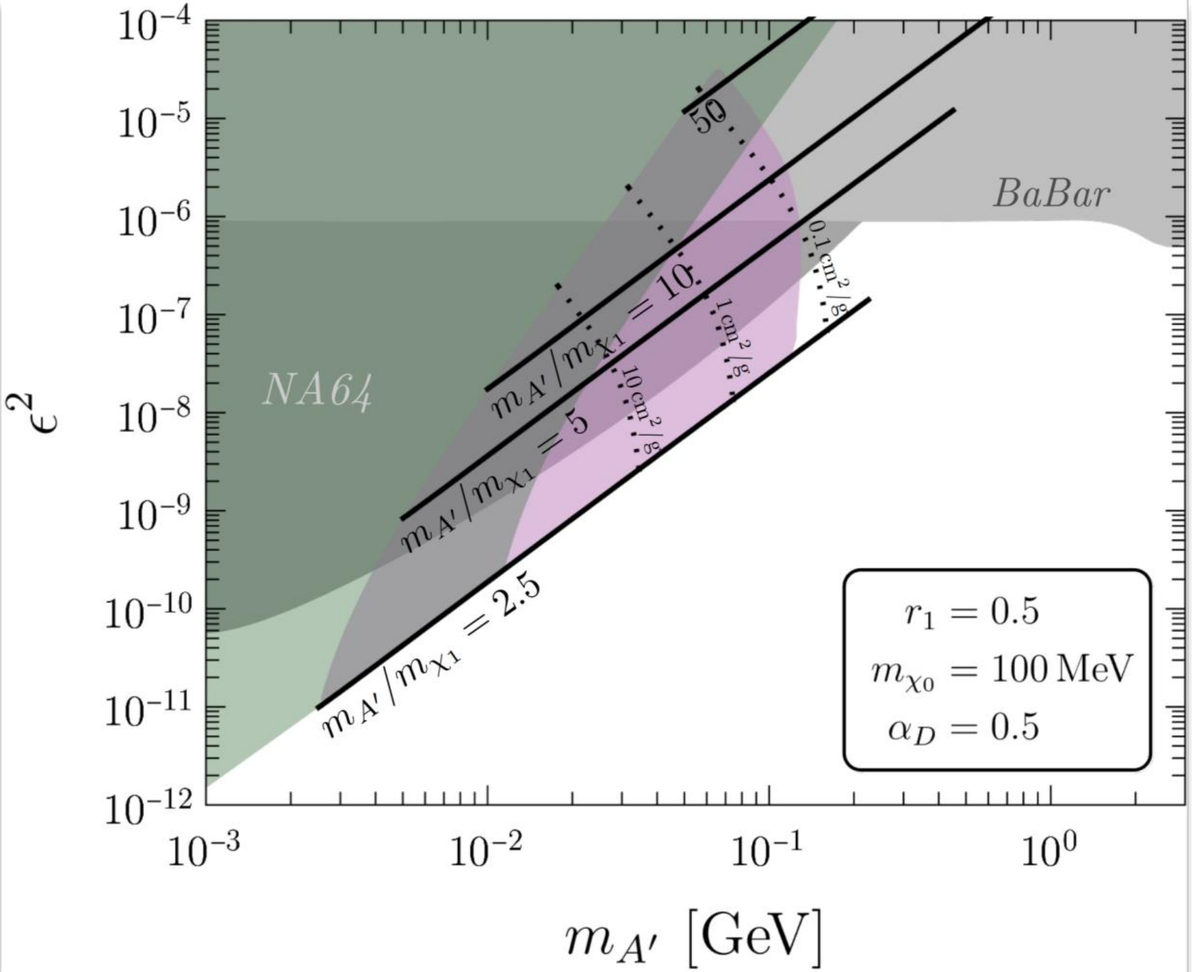
$$\gamma_{\chi_1 sm} \simeq (\delta E/T) n_{sm} \langle\sigma v\rangle_{\chi_1 sm}$$

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, PTEP (2024) & JCAP (2025)]

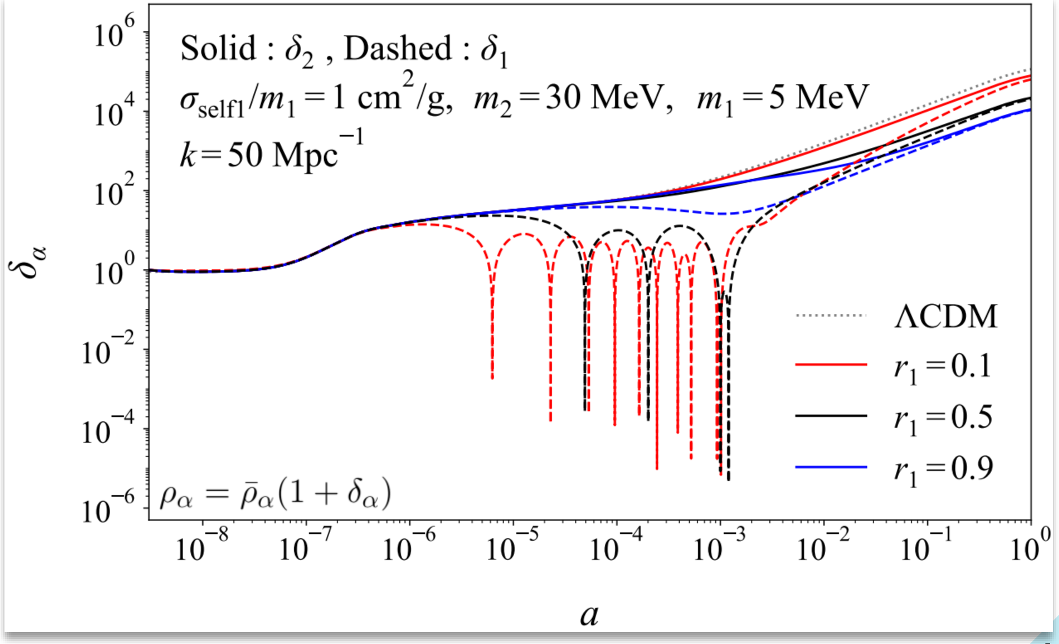
❖ Coupled equations for the density perturbation

$$\frac{d\delta_2}{dt}+\frac{\theta_2}{a}-3\frac{d\Phi}{dt}=\frac{\langle\sigma v\rangle_{22\to 11}}{m_2\bar{\rho}_2}\left(-\Psi\left(\bar{\rho}_2^2-\frac{\bar{\rho}_{2,\rm eq}^2}{\bar{\rho}_{1,\rm eq}^2}\bar{\rho}_1^2\right)-\bar{\rho}_2^2\delta_2+\frac{\bar{\rho}_{2,\rm eq}^2}{\bar{\rho}_{1,\rm eq}^2}\bar{\rho}_1^2\left(2\delta_{2,\rm eq}-\delta_2-2\delta_{1,\rm eq}+2\delta_1\right)\right),$$

$$\frac{d\theta_2}{dt}+H\theta_2+\frac{\nabla^2\Psi}{a}=\frac{\langle\sigma v\rangle_{22\to 11}}{m_2\bar{\rho}_2}\frac{\bar{\rho}_{2,\rm eq}^2}{\bar{\rho}_{1,\rm eq}^2}\bar{\rho}_1^2\left(\theta_1-\theta_2\right),$$

$$\frac{d\delta_1}{dt}+\frac{\theta_1}{a}-3\frac{d\Phi}{dt}=-\frac{\langle\sigma v\rangle_{22\to 11}}{m_2\bar{\rho}_1}\left(-\Psi\left(\bar{\rho}_2^2-\frac{\bar{\rho}_{2,\rm eq}^2}{\bar{\rho}_{1,\rm eq}^2}\bar{\rho}_1^2\right)-\bar{\rho}_2^2(2\delta_2-\delta_1)+\frac{\bar{\rho}_{2,\rm eq}^2}{\bar{\rho}_{1,\rm eq}^2}\bar{\rho}_1^2\left(2\delta_{2,\rm eq}+\delta_1-2\delta_{1,\rm eq}\right)\right)$$
$$+\frac{\langle\sigma v\rangle_{11\to XX}}{m_1\bar{\rho}_1}\left(-\Psi\left(\bar{\rho}_1^2-\bar{\rho}_{1,\rm eq}^2\right)-\bar{\rho}_1^2\delta_1+\bar{\rho}_{1,\rm eq}\left(2\delta_{1,\rm eq}-\delta_1\right)\right)$$

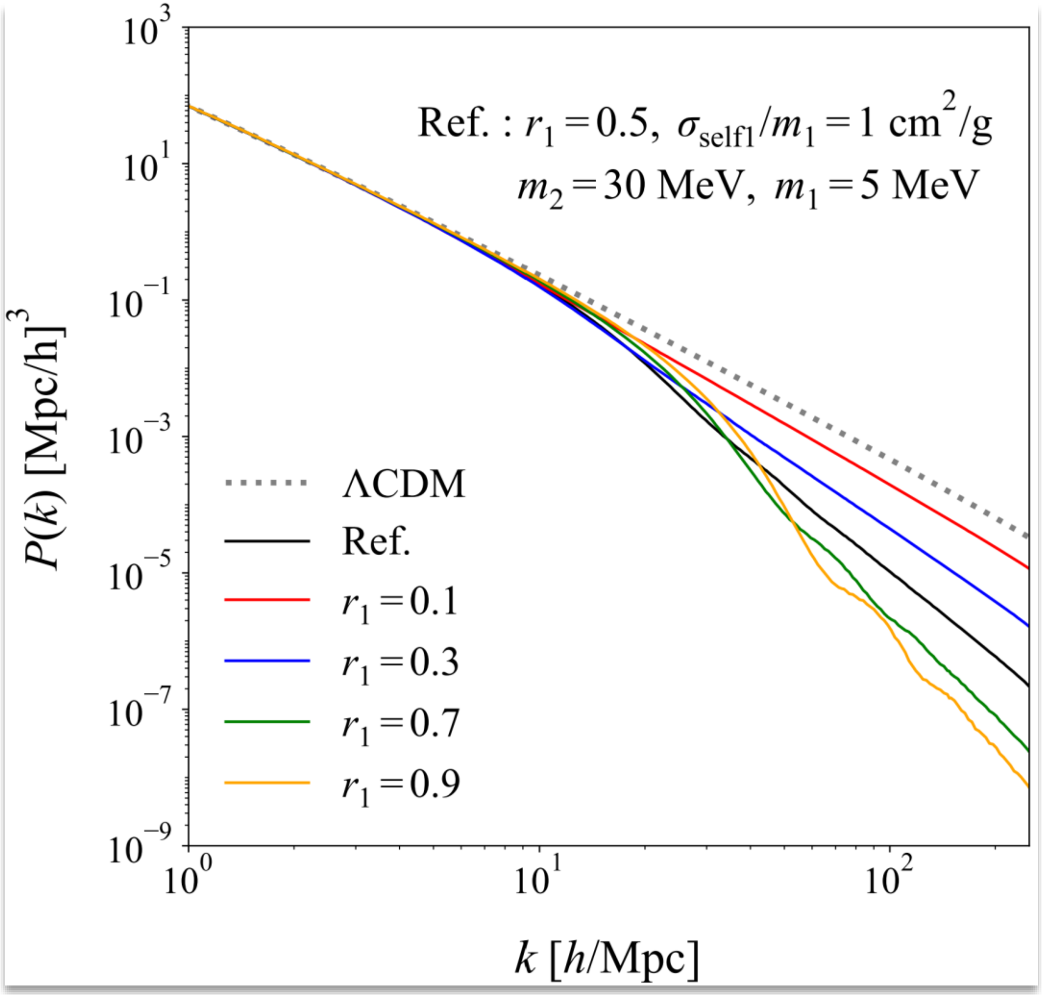
$$\frac{d\theta_1}{dt}+H\theta_1+\frac{\nabla^2\Psi}{a}+c_{s,1}^2\frac{\nabla^2\delta_1}{a}=\frac{\langle\sigma v\rangle_{22\to 11}}{m_2\bar{\rho}_1}\bar{\rho}_2^2\left(\theta_2-\theta_1\right),$$

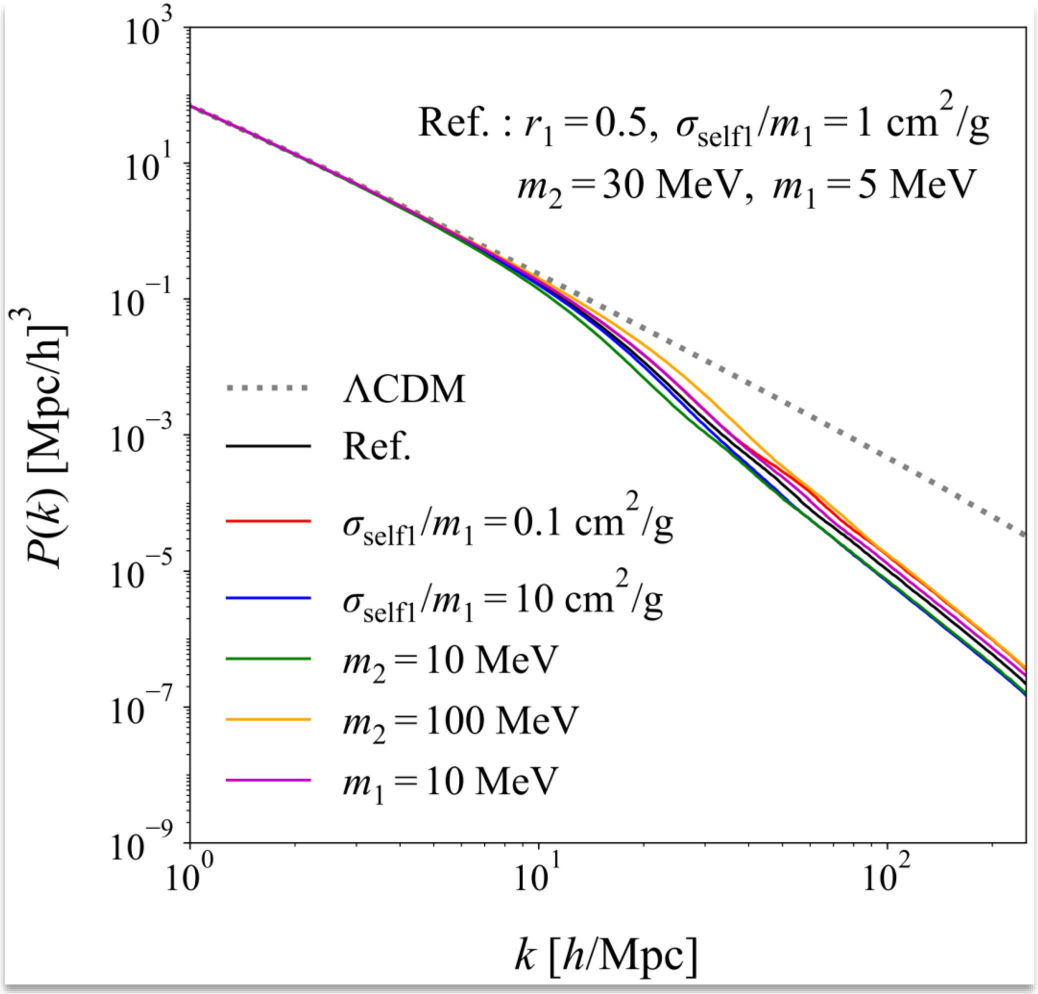


# Linear Matter Power Spectrum

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]

❖ Linear power spectrum by *CLASS*

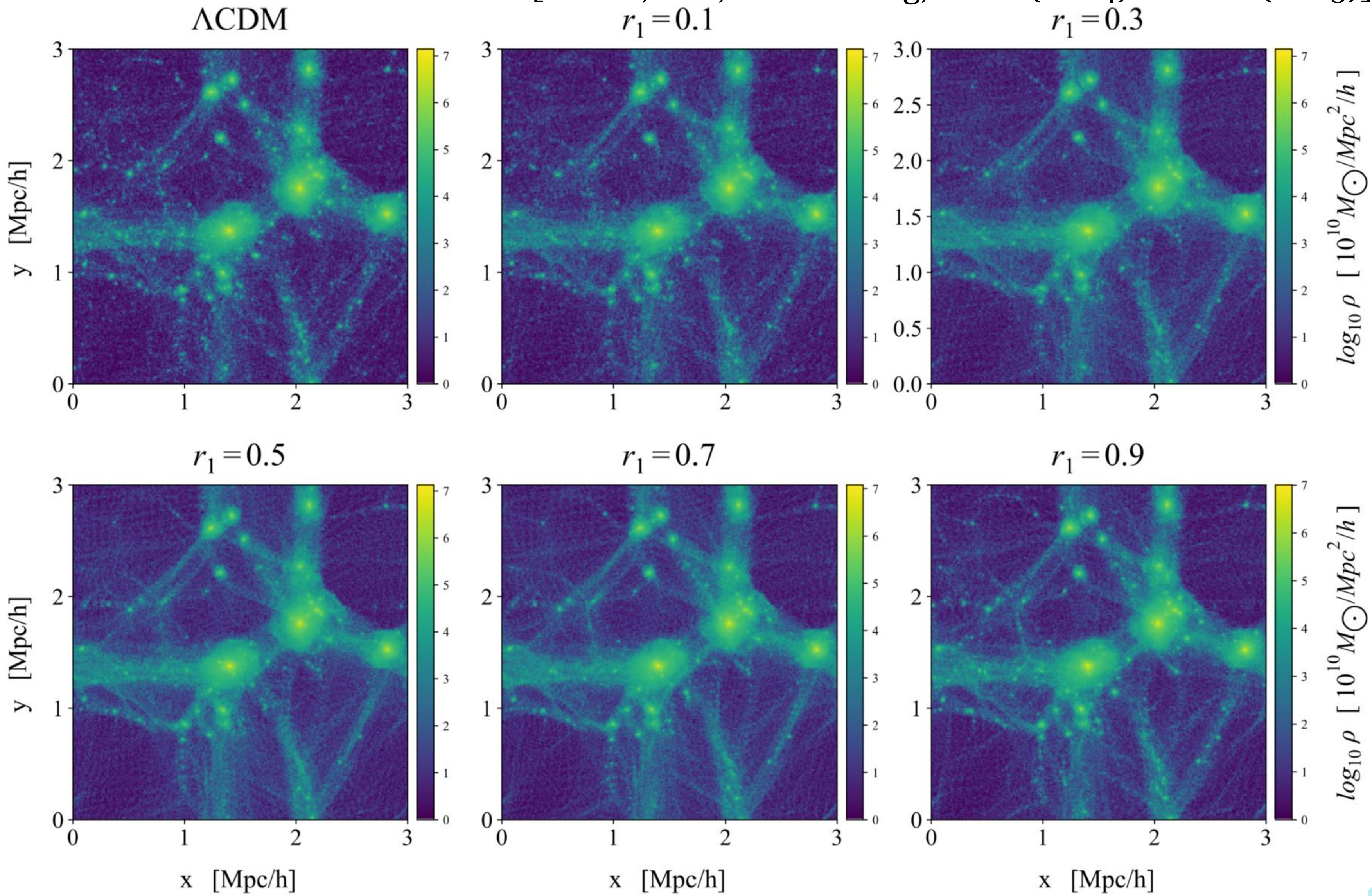


# *N*-Body Simulation

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]

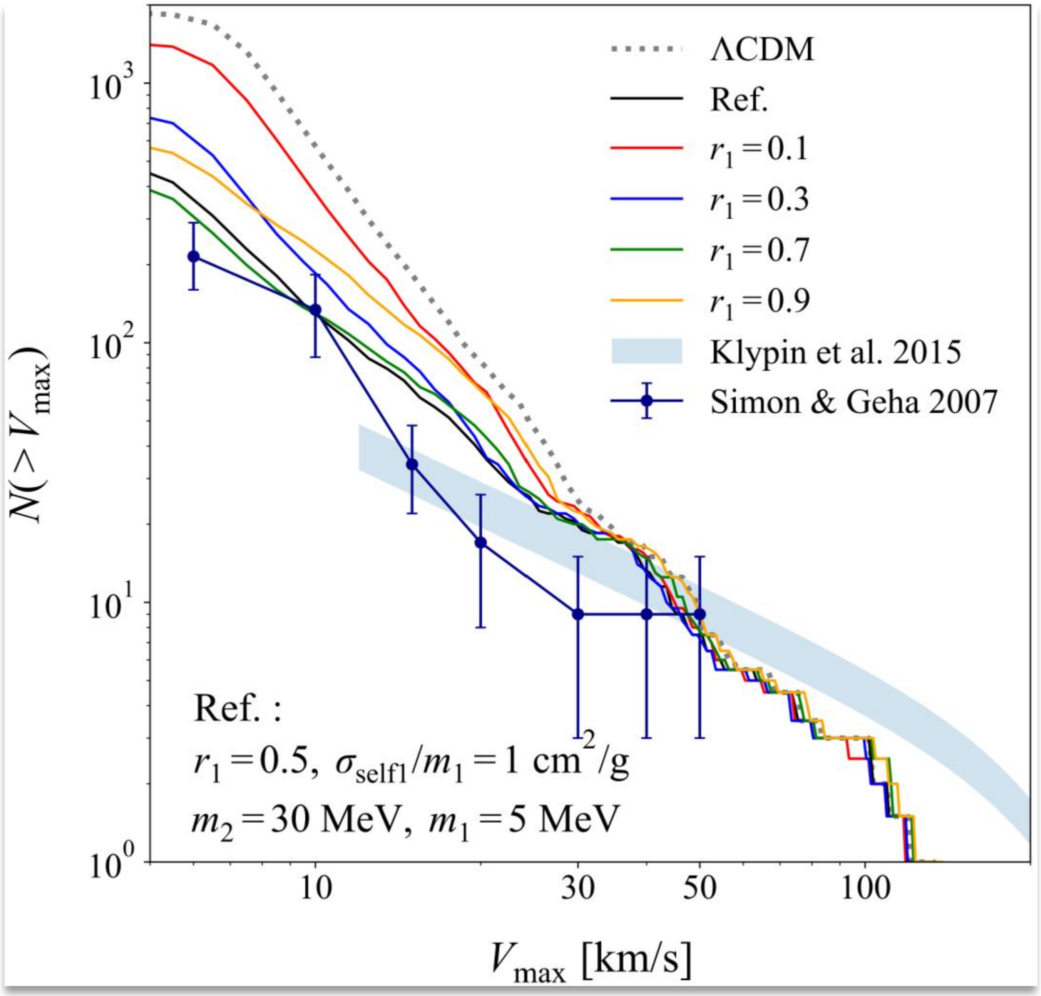
- ❖ *N*-body simulations: two-component DM simulation built on *GADGET-3* to investigate the non-linear effects
- ❖ Visualization of DM density in the periodic 3 $h^{-1}$Mpc box at $z = 0$ ➔ fewer sub-halos
  - ✓ $\frac{\sigma_1^{\rm self}}{m_{\chi_1}} = 1\ {\rm cm}^2/{\rm g}$
  - ✓ $m_{\chi_2} = 30$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

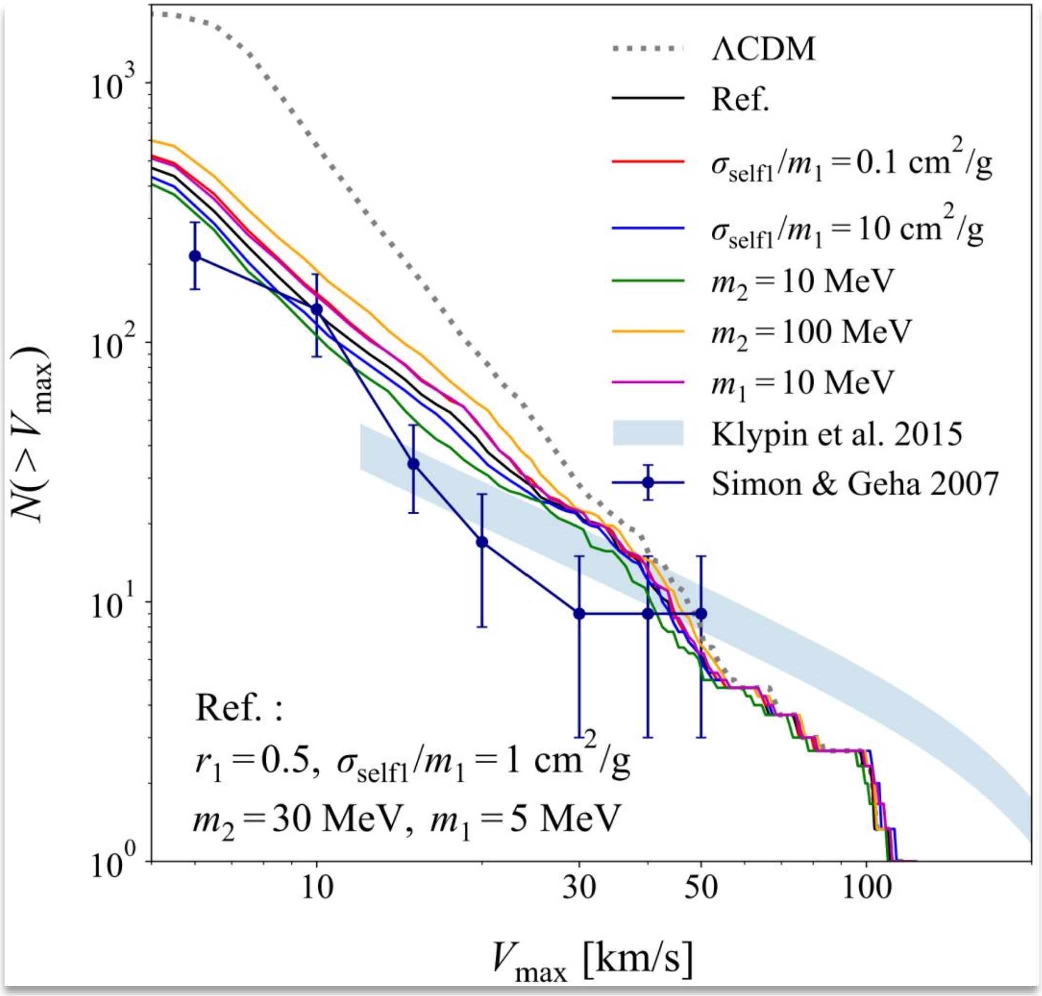


# N-Body Simulation: Observational Constraints

❖ Maximum circular velocity distribution of sub-halos

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]

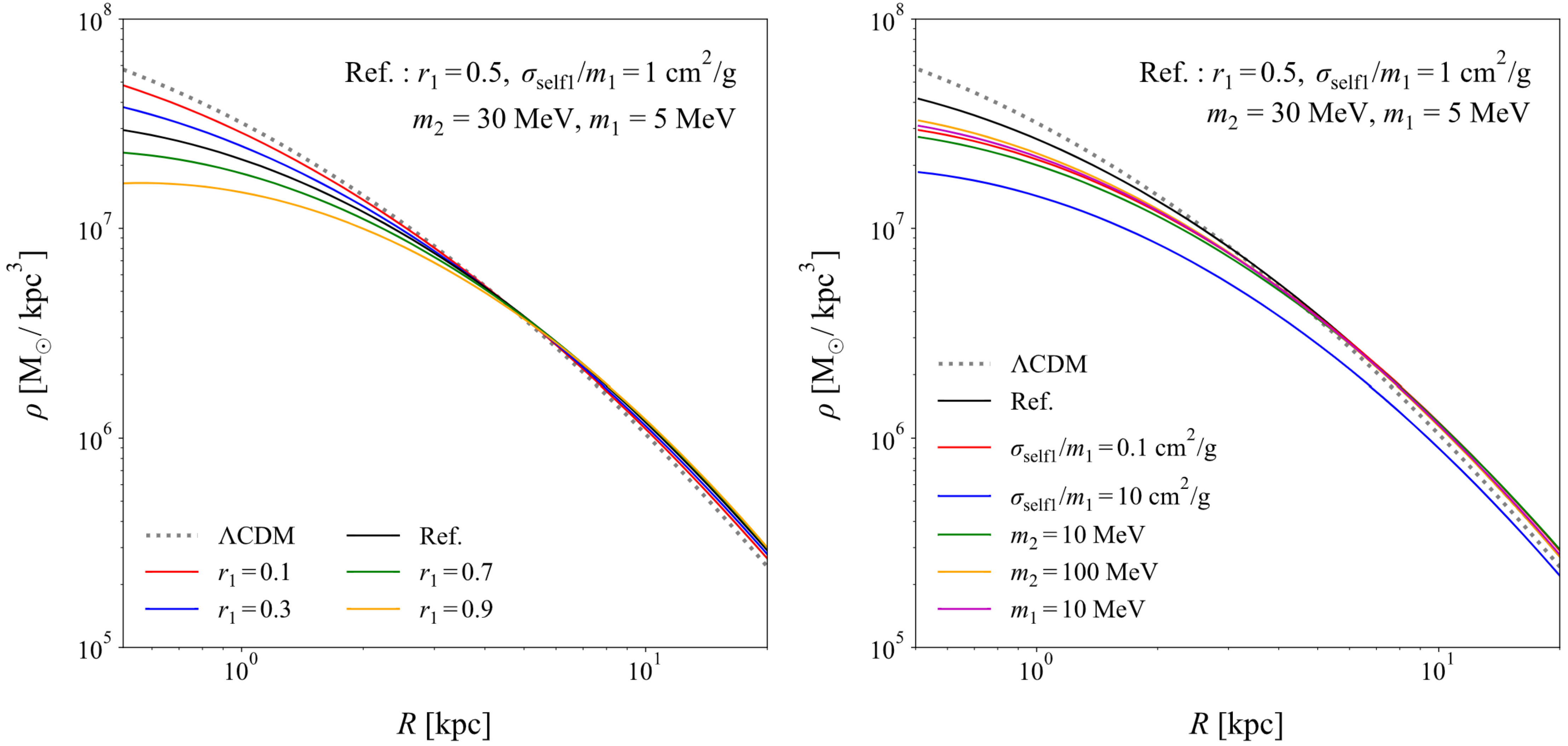



✓ The number of sub-halos is more reduced with smaller $m_{\chi_1}$ & $m_{\chi_2}$, larger $\sigma_1^{\rm self}/m_{\chi_1}$.

# Galactic Density Profile: Total

❖ Averaged total density profiles of halos with $M > 10^{10} M_{\odot}$ [J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]



# Galactic Density Profile: Individual

[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]

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