Searching for Light Dark Matter:
Boosted Dark Matter (BDM)

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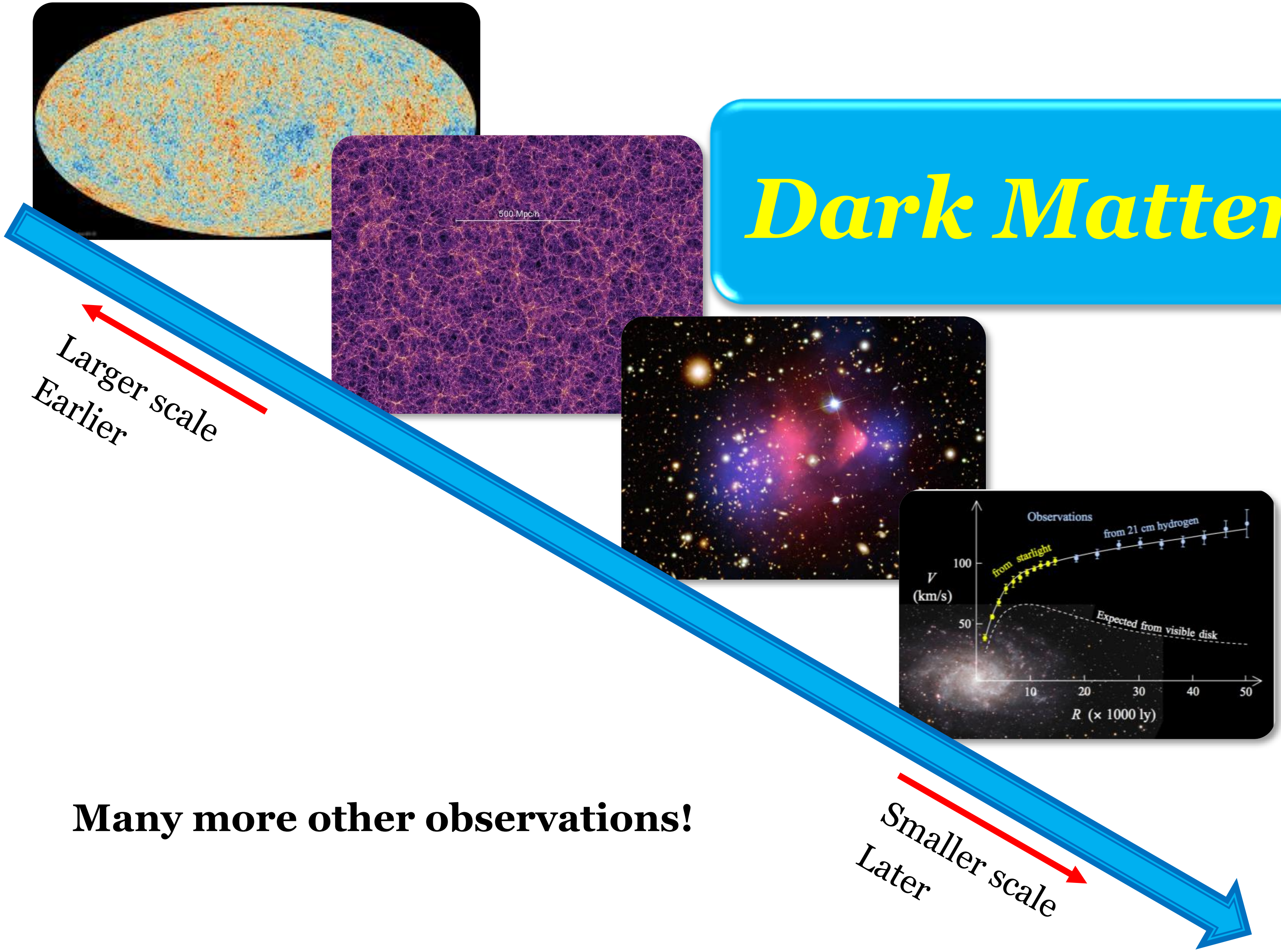
Outline

- ❖ **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)

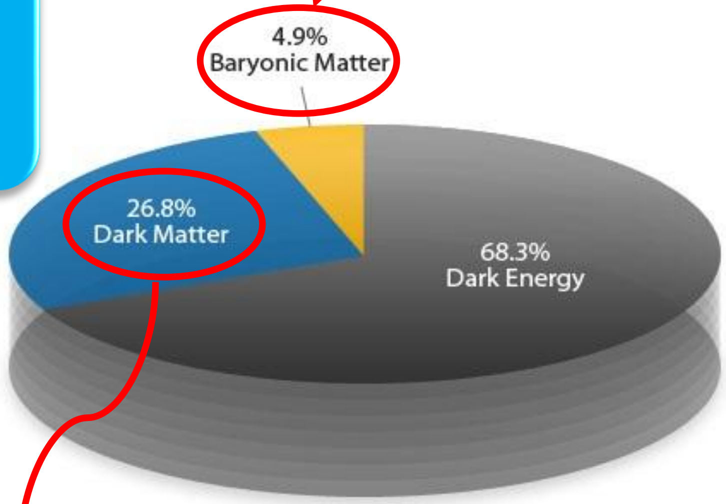


Dark Matter?

Many more other observations!

❖ **Modern cosmology**:

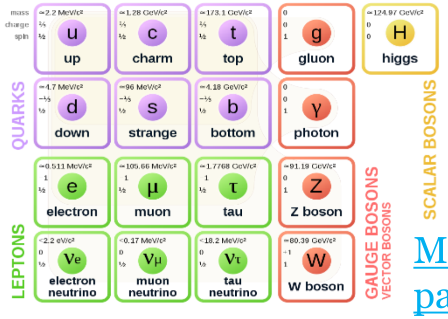
The Standard Model



❖ **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_μ-L_τ, …
- ✓ 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**

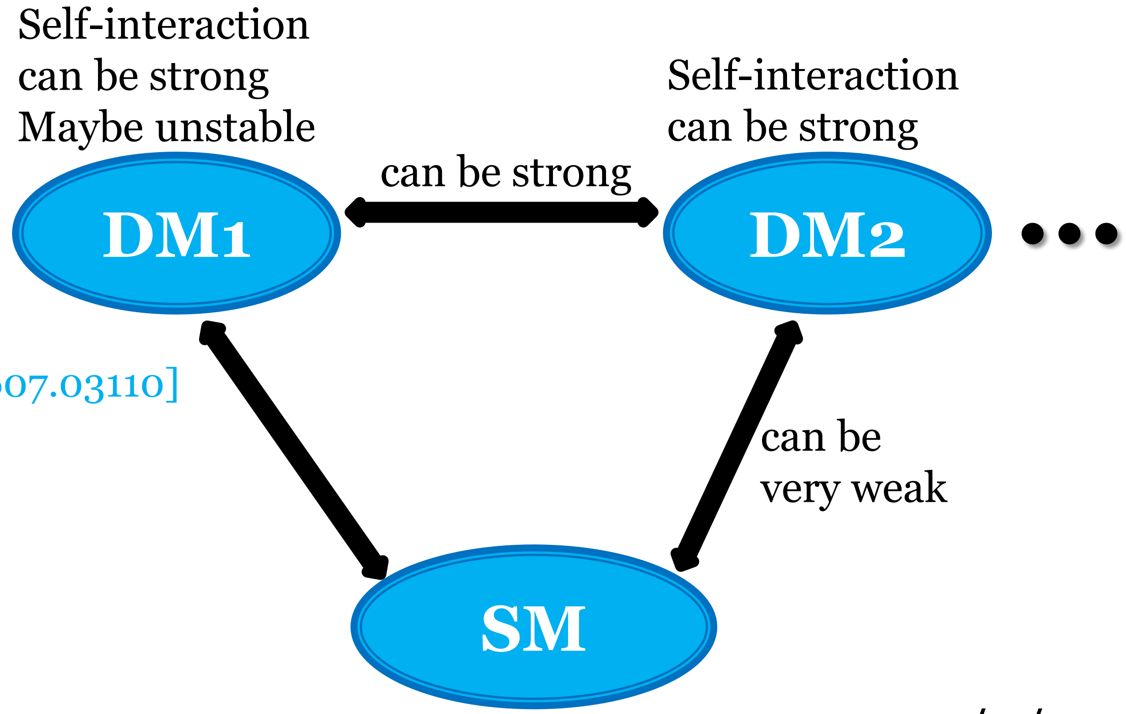
- ✓ DM spin: fermion, scalar, vector
- ✓ DM species: single-/two-/multi-component
- ✓ DM mass: light, heavy, light & heavy
- ✓ DM interaction: flavor-conserving (elastic),

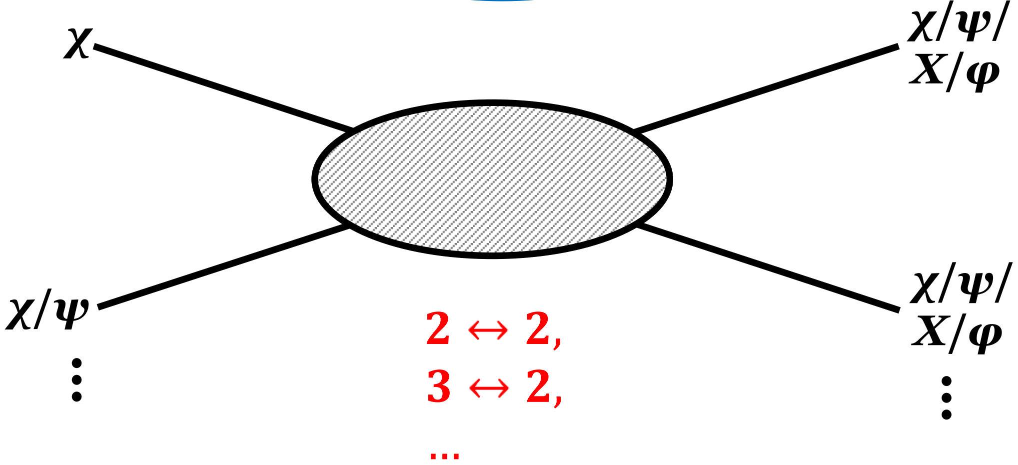
  flavor-changing (inelastic)
- ✓ ???

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

Ultralight
axion, fuzzy,
hidden photon,

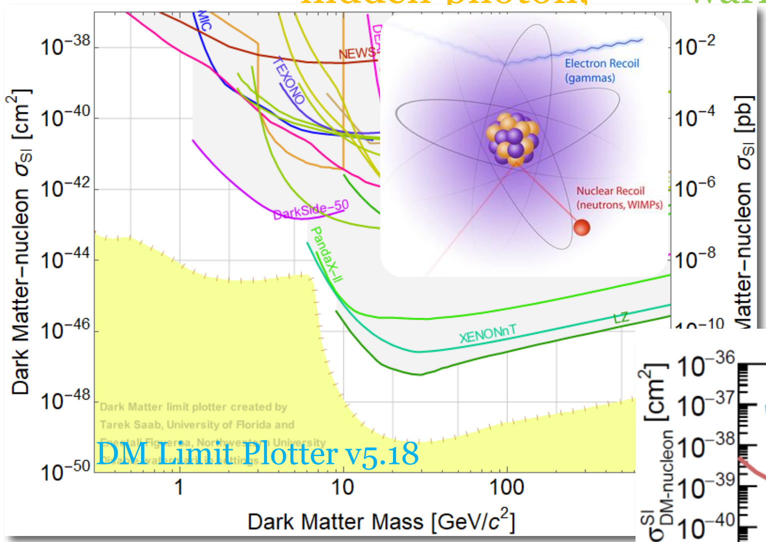
Superlight
sterile ν,
warm DM

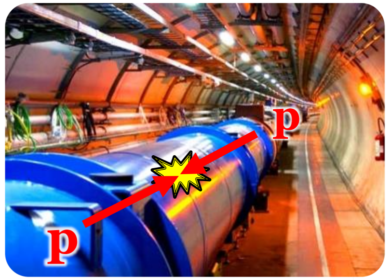
Light
SIMP,
ELDER

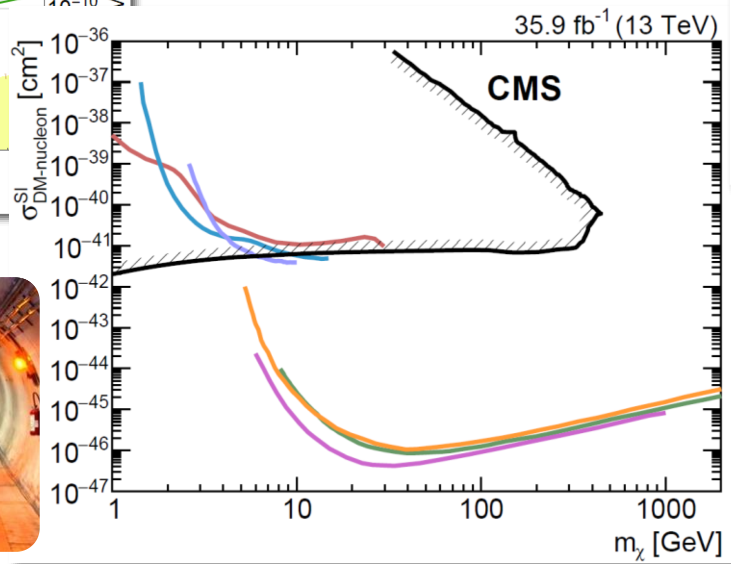
WIMP

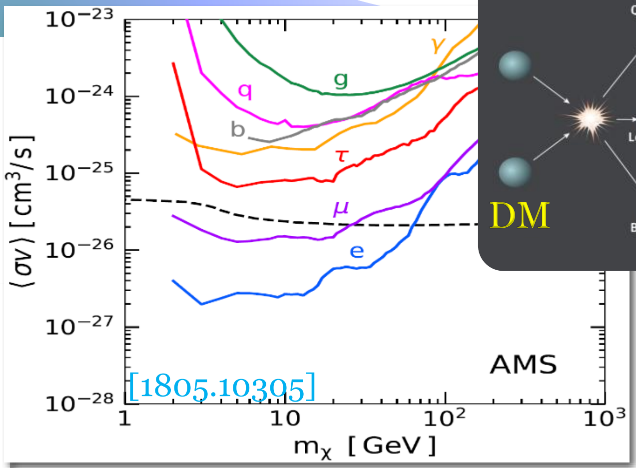
Superheavy
composite DM,
WIMPzilla

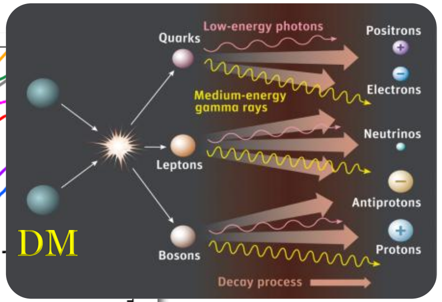
Astrophysical object
MACHO, PBH







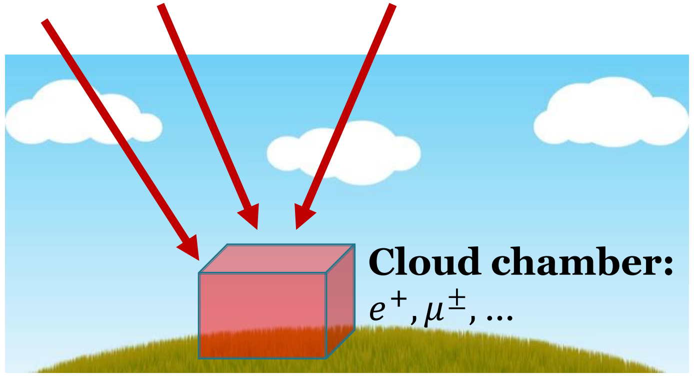




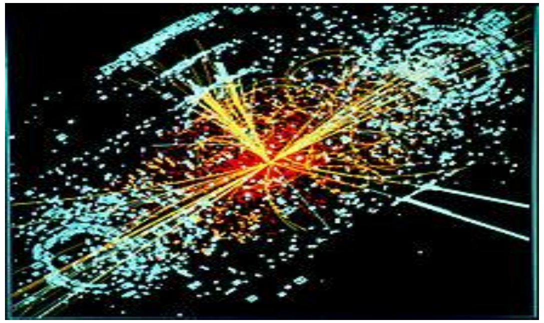
- ✓ No concrete evidence of DM yet.
- ✓ Tight bounds are imposed on WIMP.
- ✓ Next decade: **A paradigm shift?**

Particle Searches: Passive ➔ Active

~5% visible sector



Collider: controlled environment



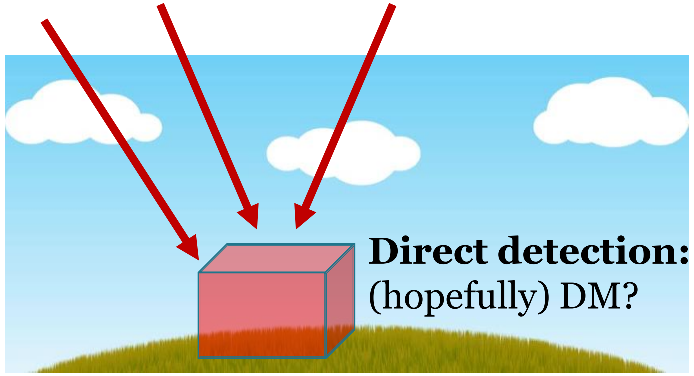
Conventional colliders

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

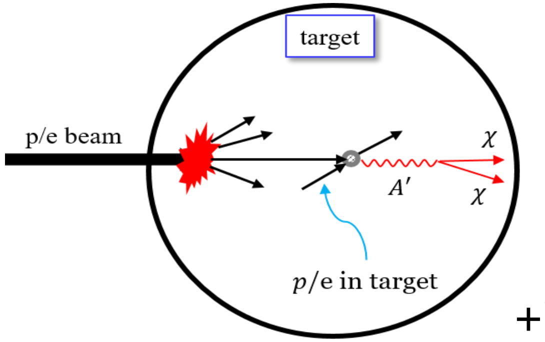
Passive searches

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: Gyunho Yu, Tao Li, Also Ianni, …

Neutrino vs. Dark Matter

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

Neutrino vs. Dark Matter

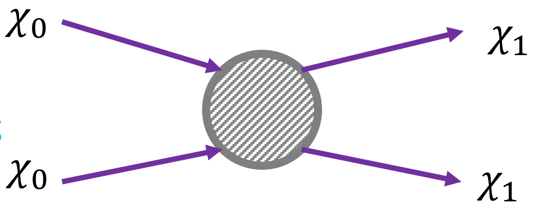
	Neutrino	Dark Matter
Population	Many	Probably Many (depending on m_{DM})
Interaction	Weak	Weakly or Feebly?
Relativistic	Mostly	***Boosted DM***
Active Production	Possible	Maybe
Approaches	Large Vol. (w/ high E_{th}) Beam-produced	Lager is better, but low E_{th} Beam-produced
Experiments	SK/HK, DUNE,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

Boosted Dark Matter (BDM)

DM Boosting Mechanisms: Dark Sector

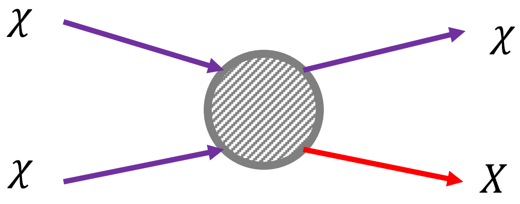
Boosted DM (BDM) coming from the Universe

[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

$m_2 \gg m_1$

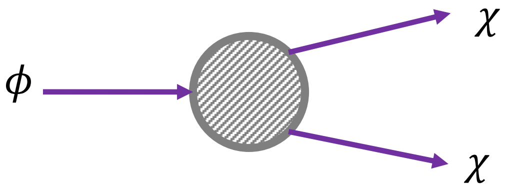


✓ Semi-annihilation model

$m_\chi \gg m_X$

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

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



✓ Decaying multi-component DM

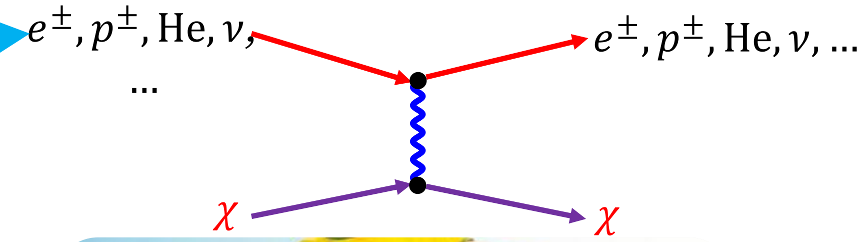
$m_\phi \gg m_\chi$

[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 $E_{e^{\pm},p^{\pm},\mathrm{He},\boldsymbol{\nu},\dots}$
  ➔ large E_{χ})
  ➔ 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

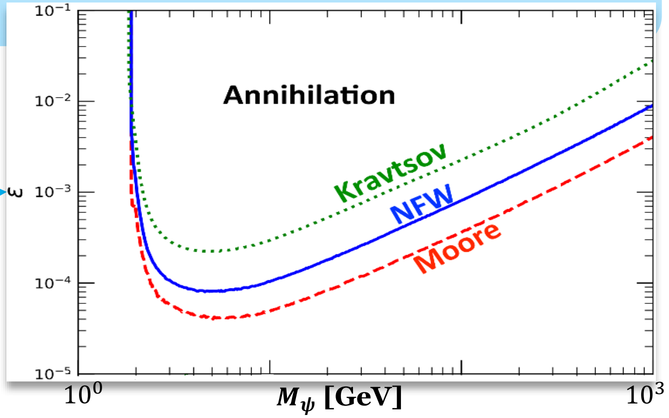
BDM Searches @ Neutrino Experiments

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 ν detector w/ high E_{th} is OK for **LDM!**

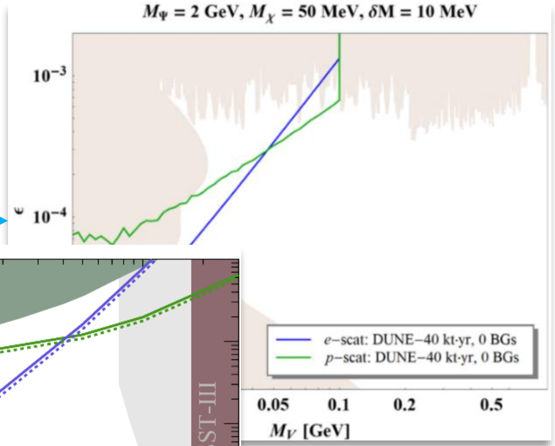
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

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

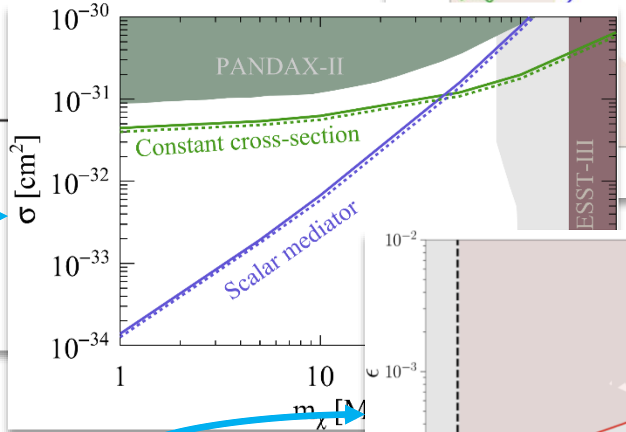


PHYSICAL REVIEW LETTERS 130, 031802 (2023)

Editors' Suggestion | Featured in Physics

Cherenkov radiation rings by protons

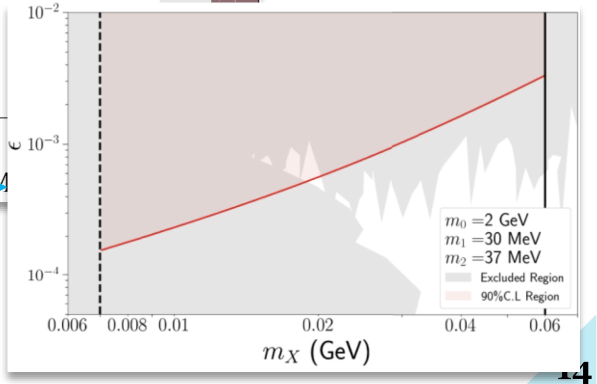
Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande



PHYSICAL REVIEW D 111, 092003 (2025)

Ionization tracks by electrons and/or protons

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

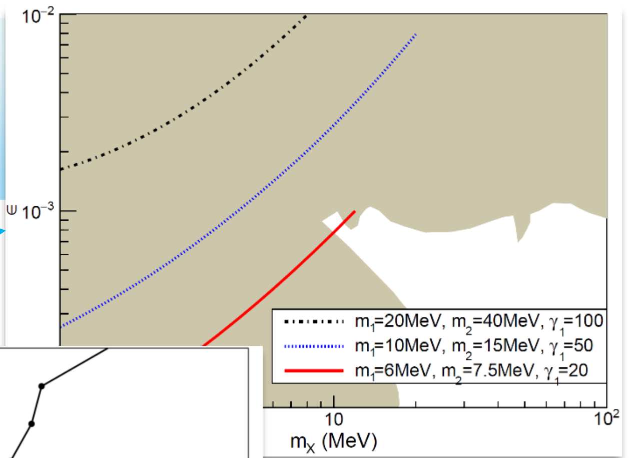


BDM Searches @ DM Experiments

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

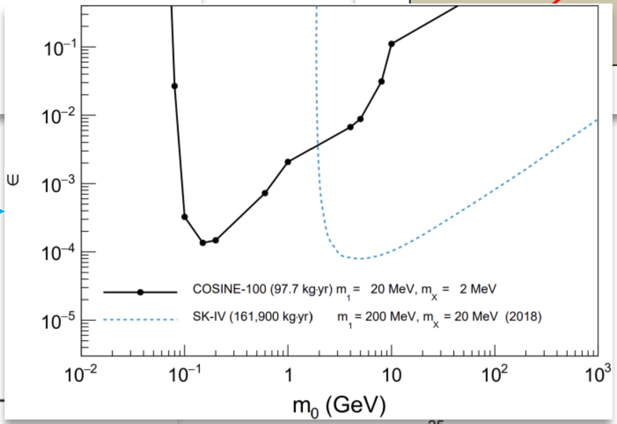
Editors' Suggestion

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



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

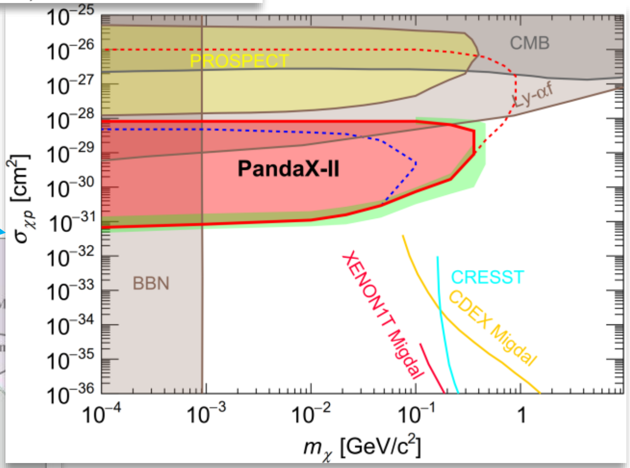
Search for Boosted Dark Matter in COSINE-100



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

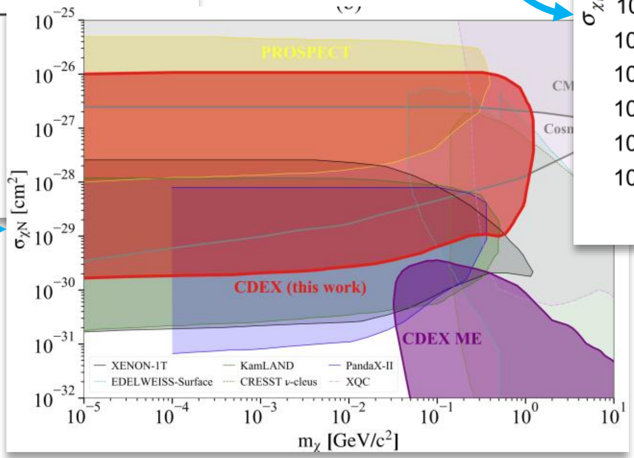
Editors' Suggestion

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



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

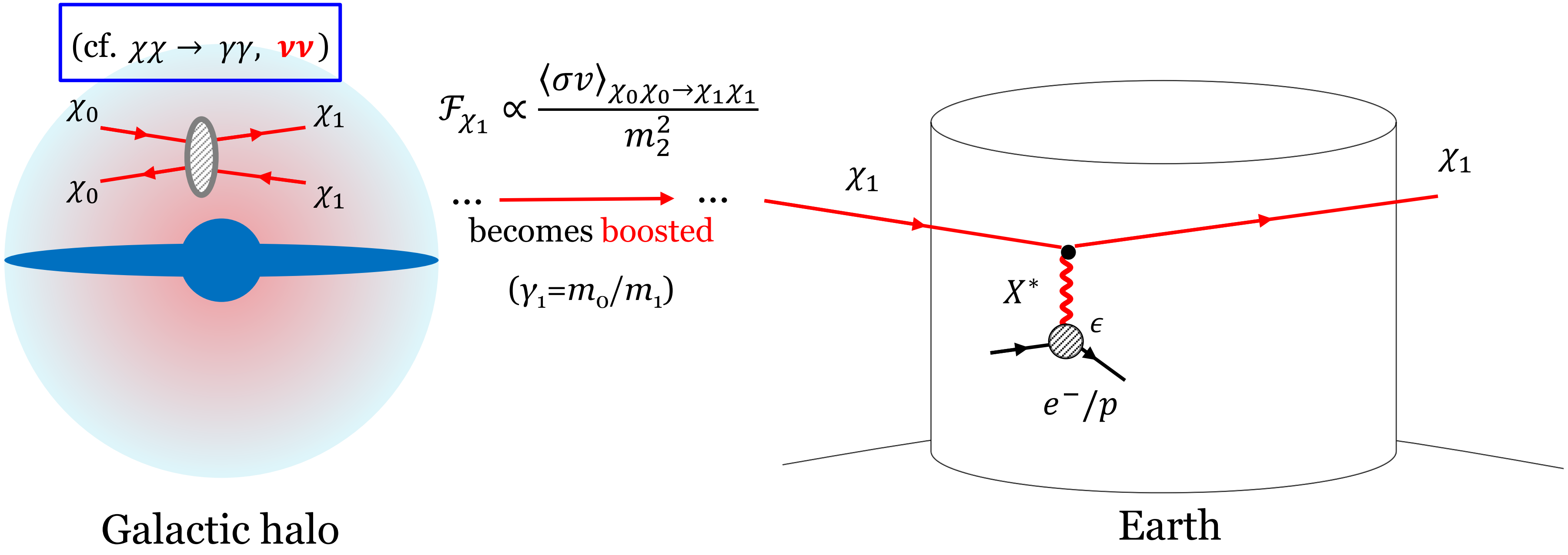
Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory



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

Issues in BDM Searches

Minimal Two-component Scenario

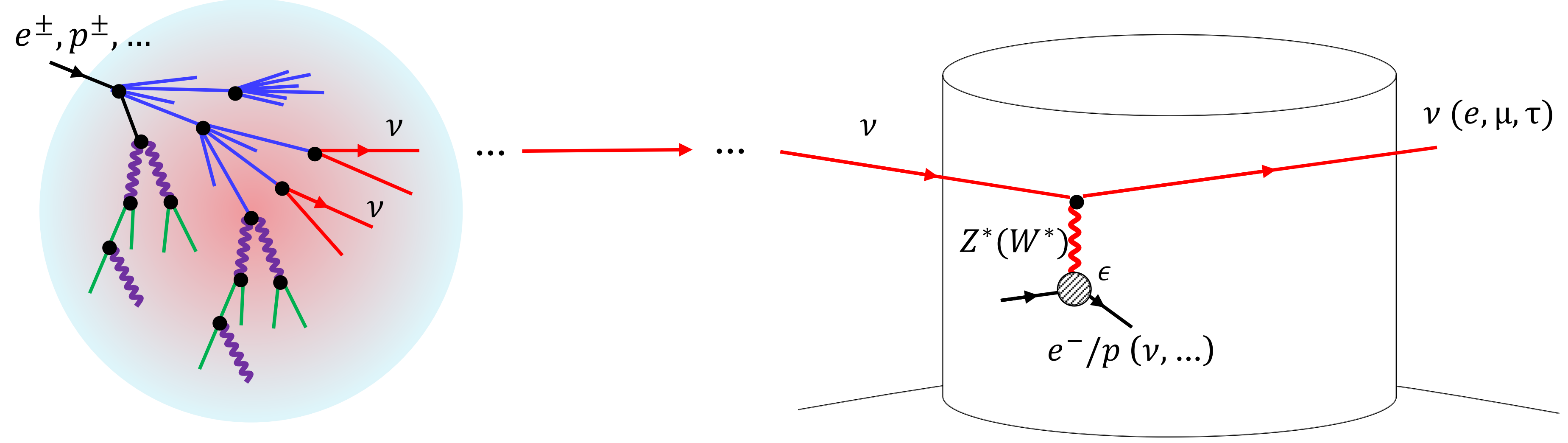


❖ Example model: fermionic heavier(χ_0) & lighter(χ_1) DM + dark gauge boson(X)

[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



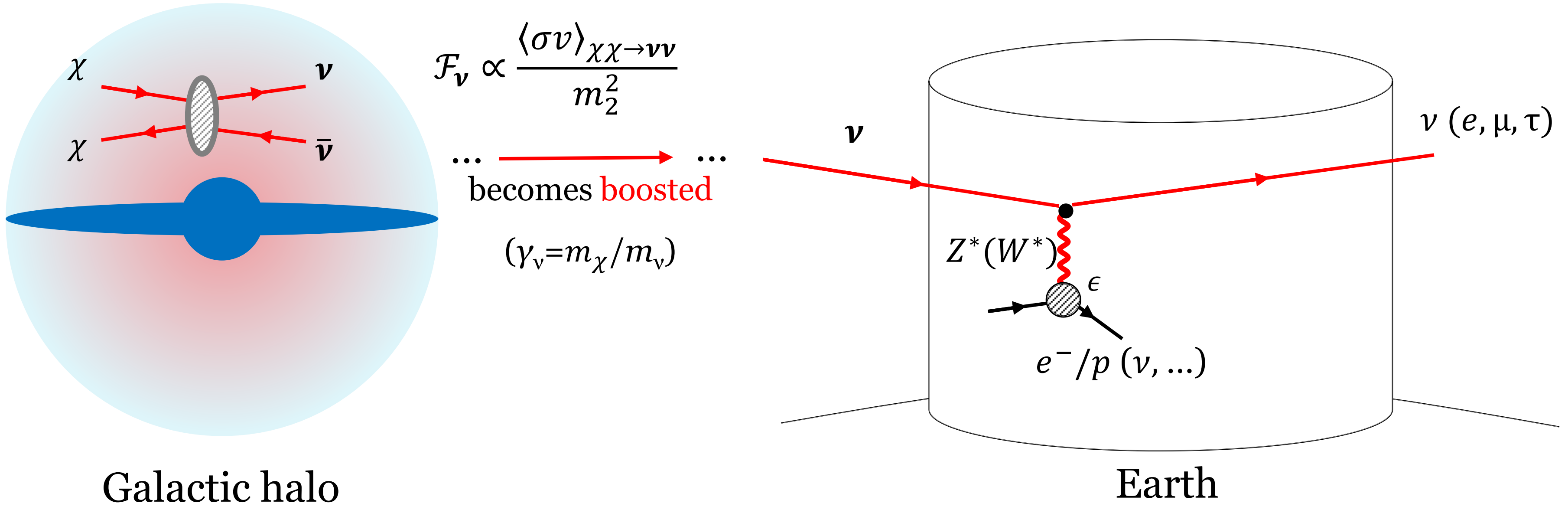
Atmosphere Earth

❖ 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.

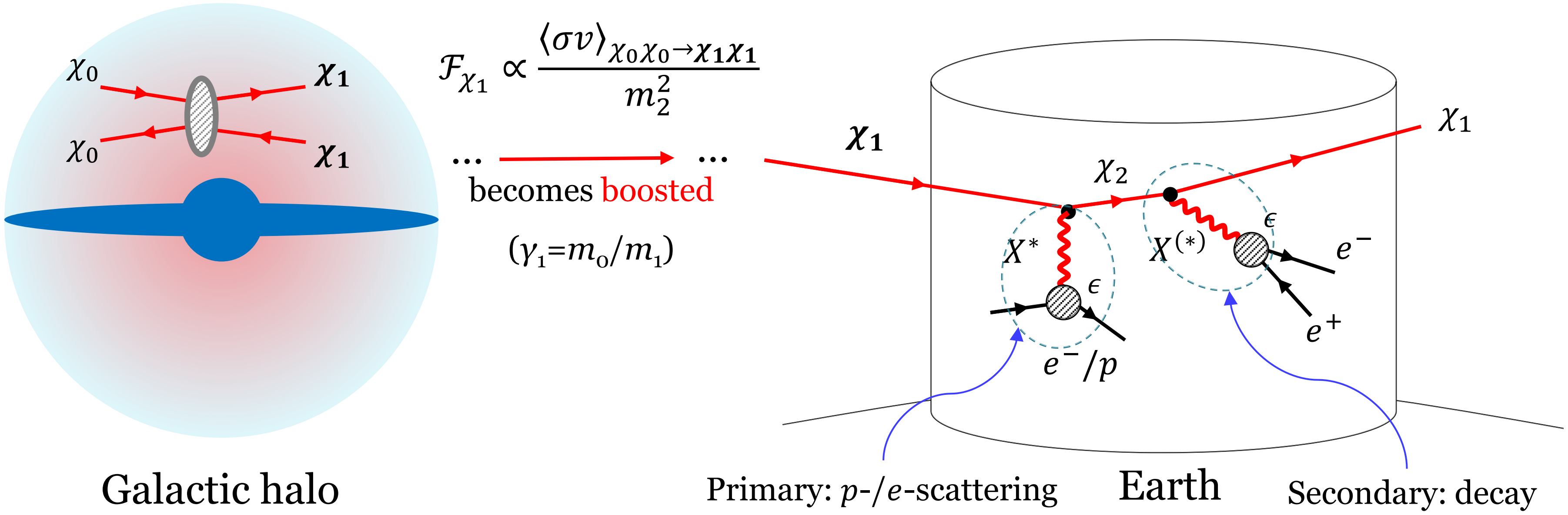
Issue 2: Distinction from ν Scenario



❖ (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



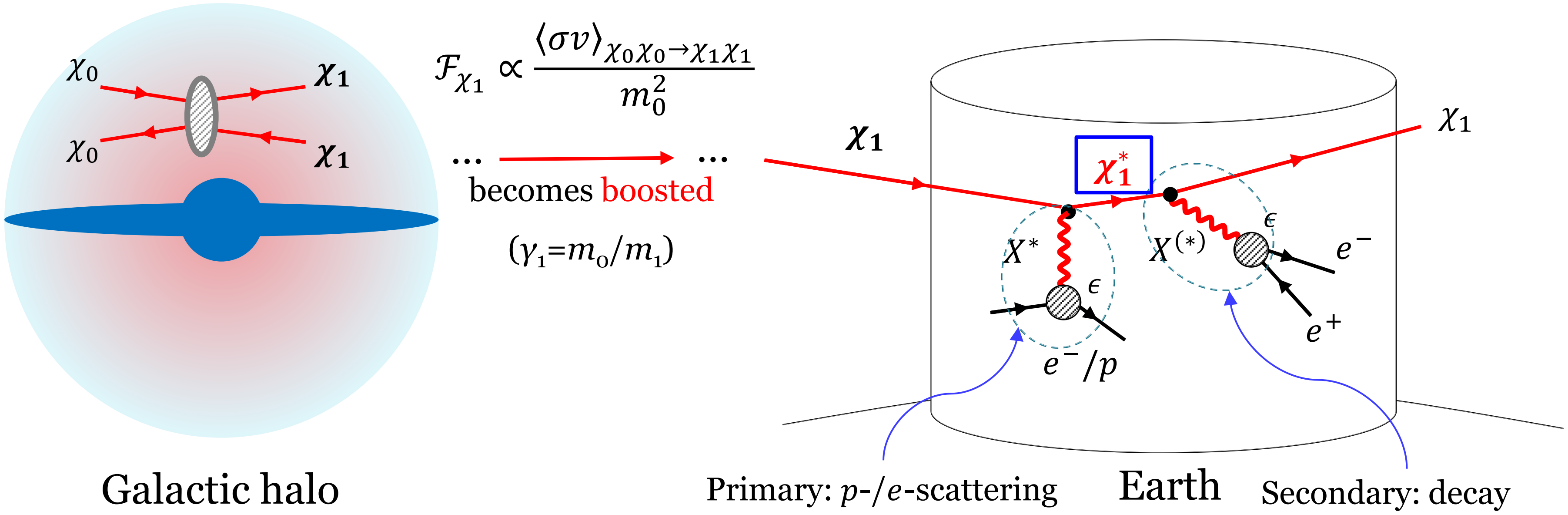
❖ *i*BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]

❖ Additional signatures from the decay of heavier unstable dark-sector state χ_2 from inelastic scattering.

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

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

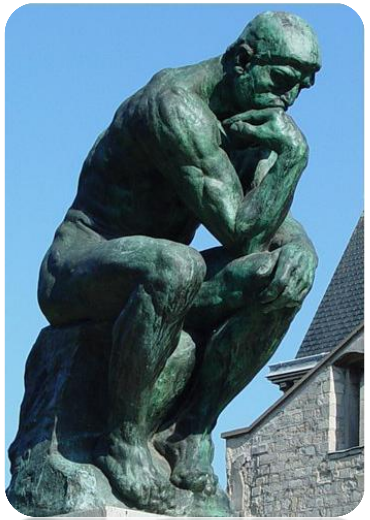
Issue 2: Avoidable by Sub-leading Process



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

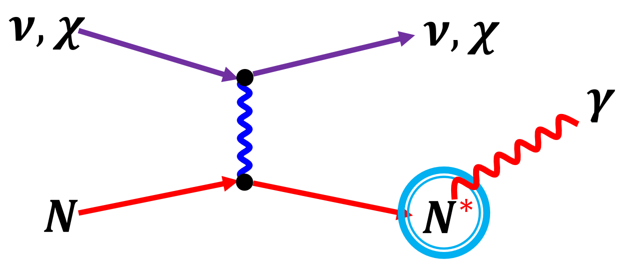
❖ A new BDM search strategy utilizing initial-/final-state dark gauge boson radiation, i.e. "**Dark-Strahlung**" from cosmogenic BDM [Kim, **JCP** & Shin, PRD (2019)]

Only recoiled e/p?

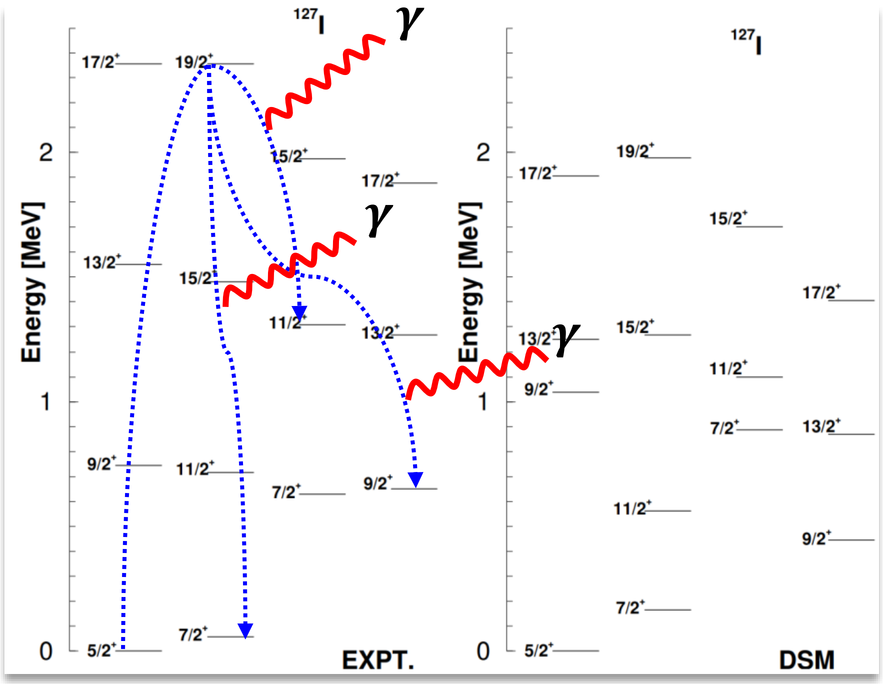


Inelastic Nuclear Scattering

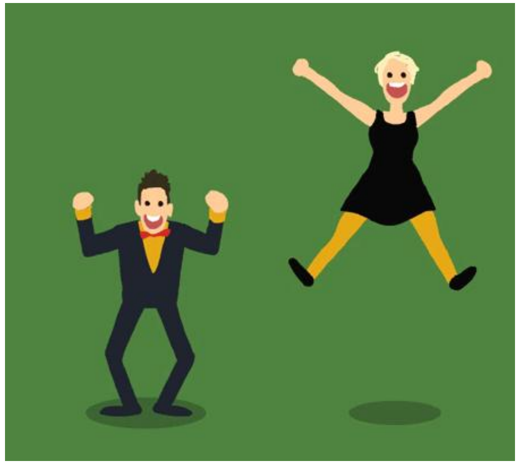
❖ Why **inelastic** channel?



$E_{in} \lesssim 50$ MeV



Sahu et al., [2004.04055]



➢ Signatures

✓ **Elastic**: low energy nuclear recoil

✓ **Inelastic**: γ cascade ($\Delta E \lesssim 10$ MeV), γ 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

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

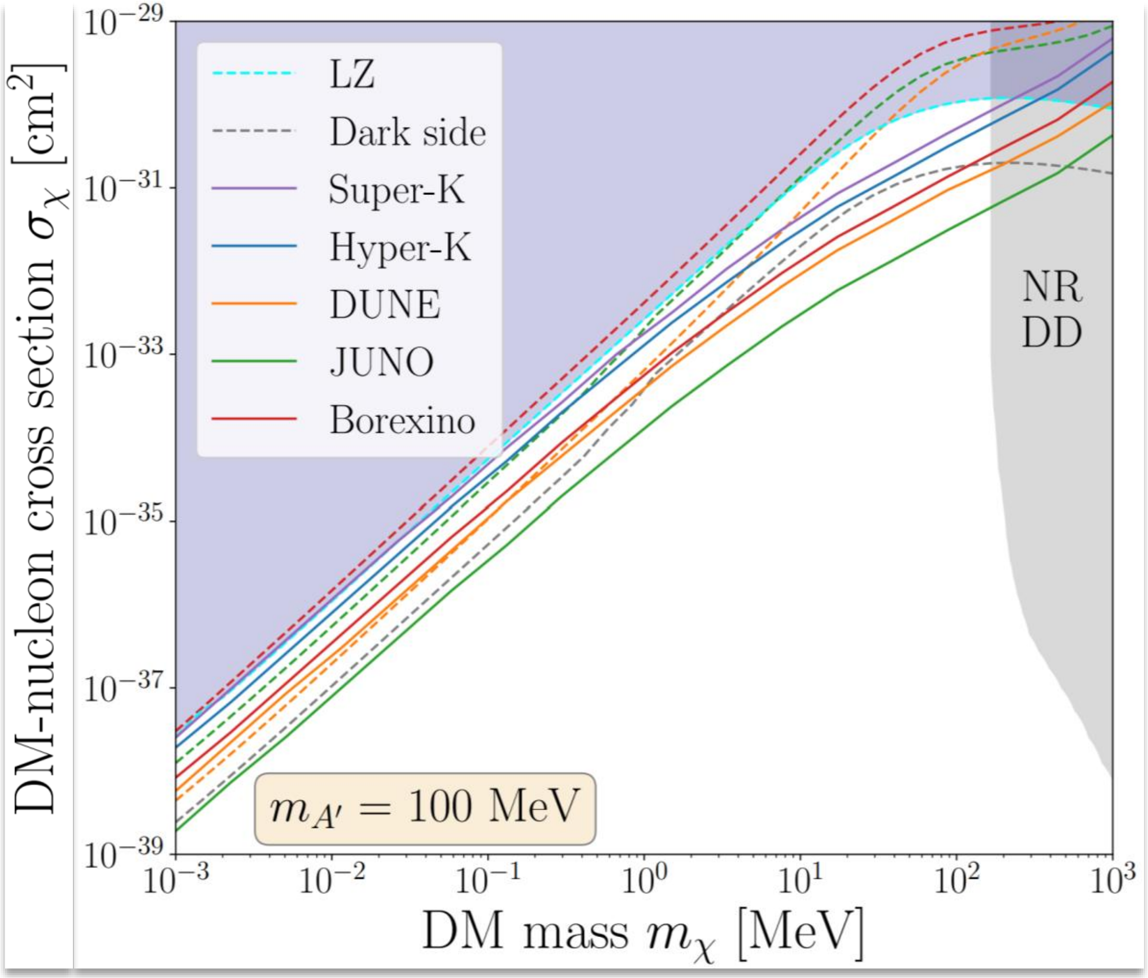
- Focus: the <u>interaction between DM & quark</u>

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

➔ DM boosted by cosmic rays (p, He)

- The expected # of signal events

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

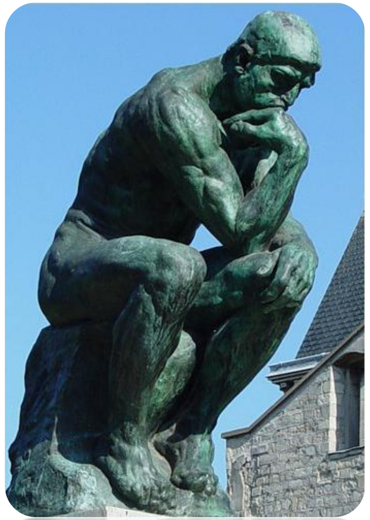


✓ Inelastic (solid) better than elastic (dashed)

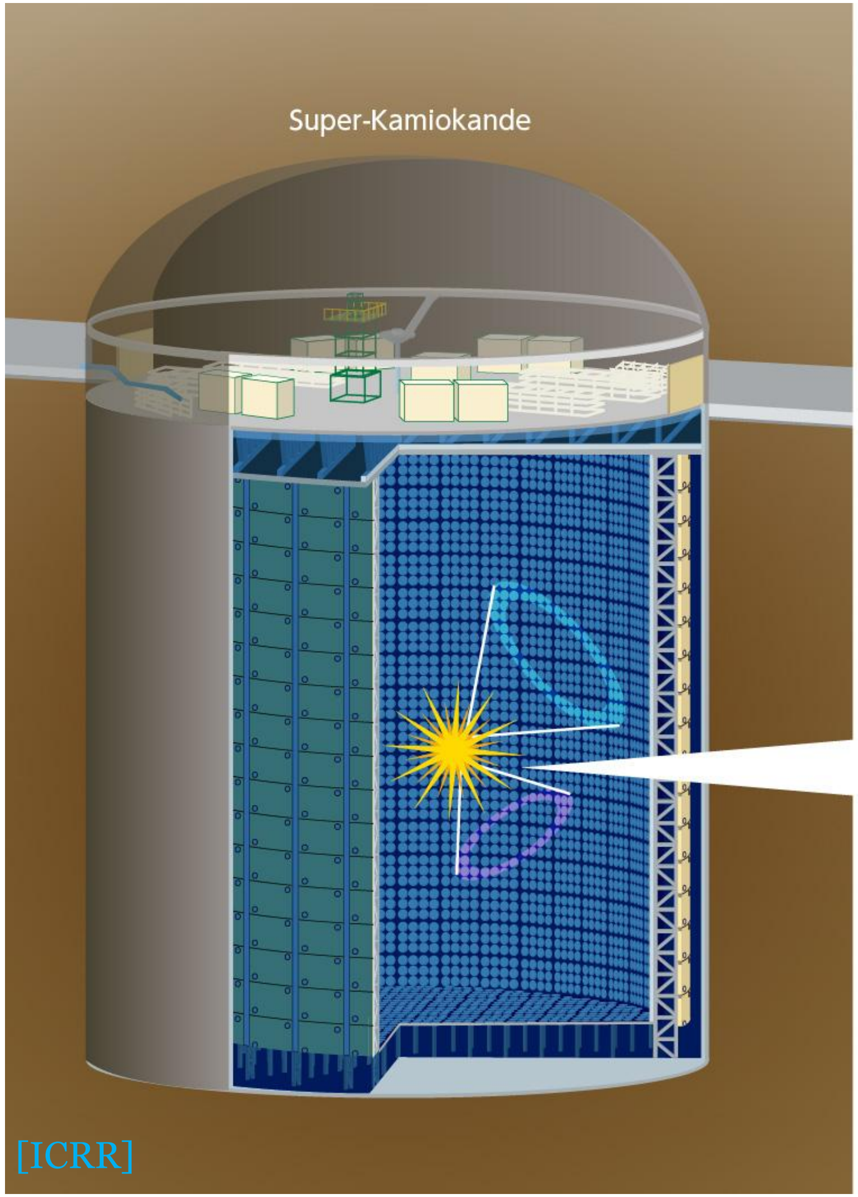
✓ LSC detectors (JUNO, Borexino): BGs in the signal zone are highly suppressed due to the good E resolution.

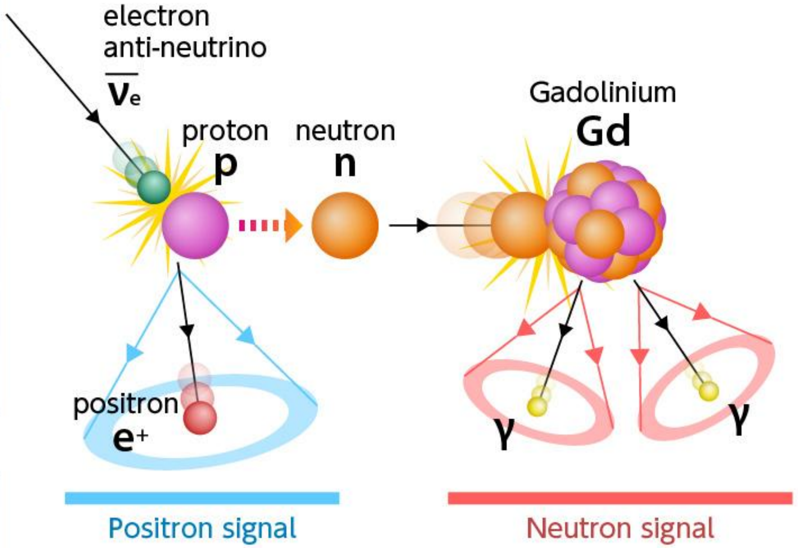
✓ Cherenkov detectors (SK, HK): de-excitation γ's are buried in single e-like events.

Neutrons?



Water-Cherenkov Detectors w/ Gadolinium



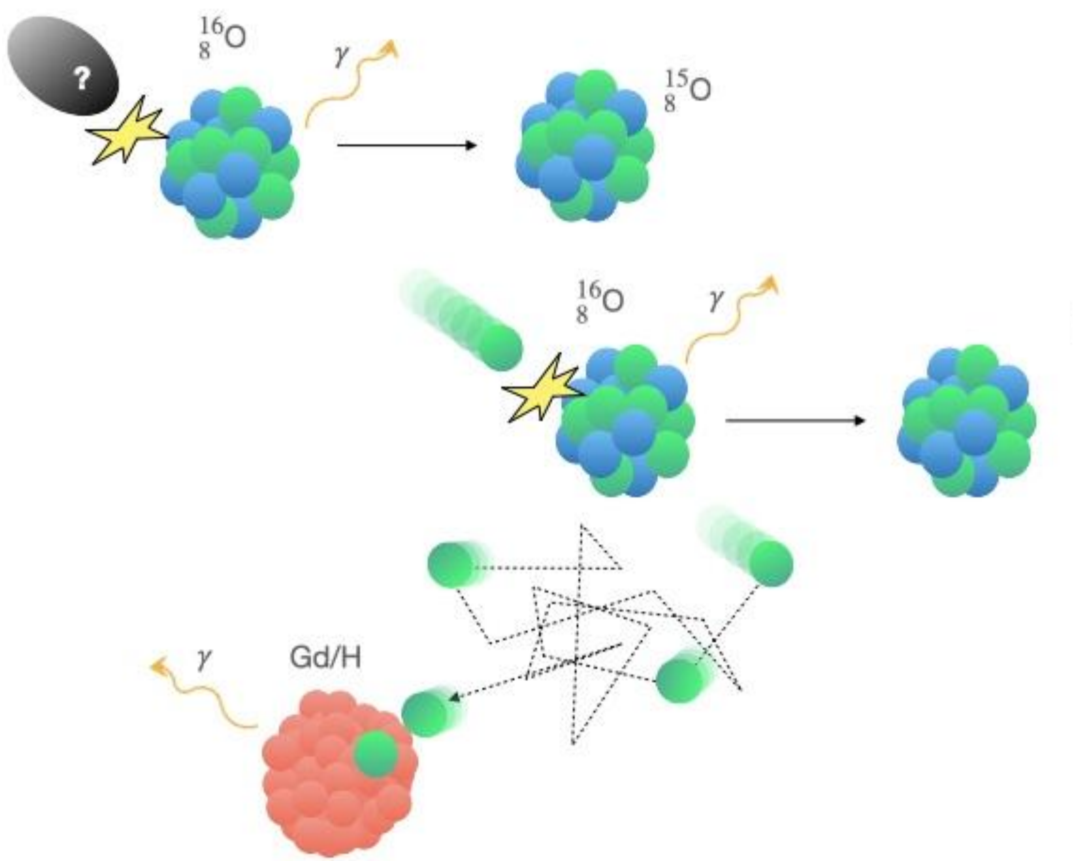


- **Gd**: high n-capture rate & γ's w/ characteristic E ➔ the addition of Gd greatly enhances n detection efficiency.
- **SK-Gd**: mainly for supernova relic neutrinos

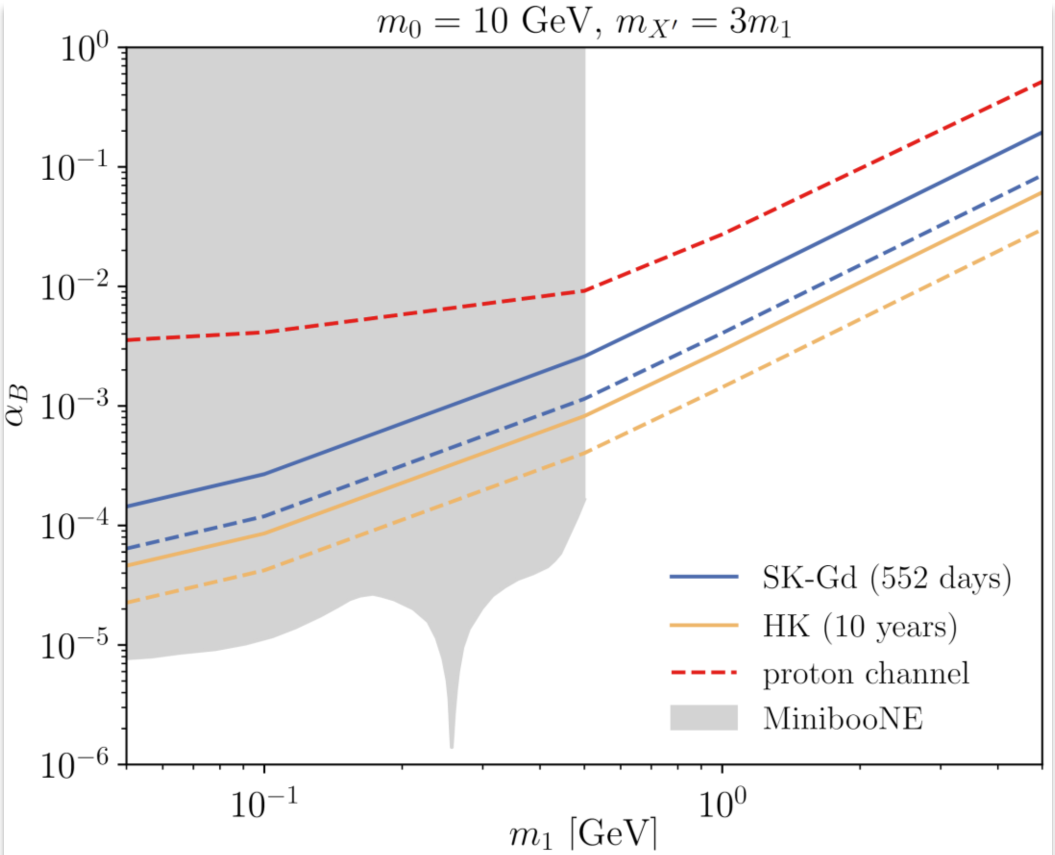
Knockout Neutrons @ Cherenkov Detectors

- So far only p, but higher $p_{th} > 1.07$ GeV.
- For n, no Cherenkov radiation but γ's from capture

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



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

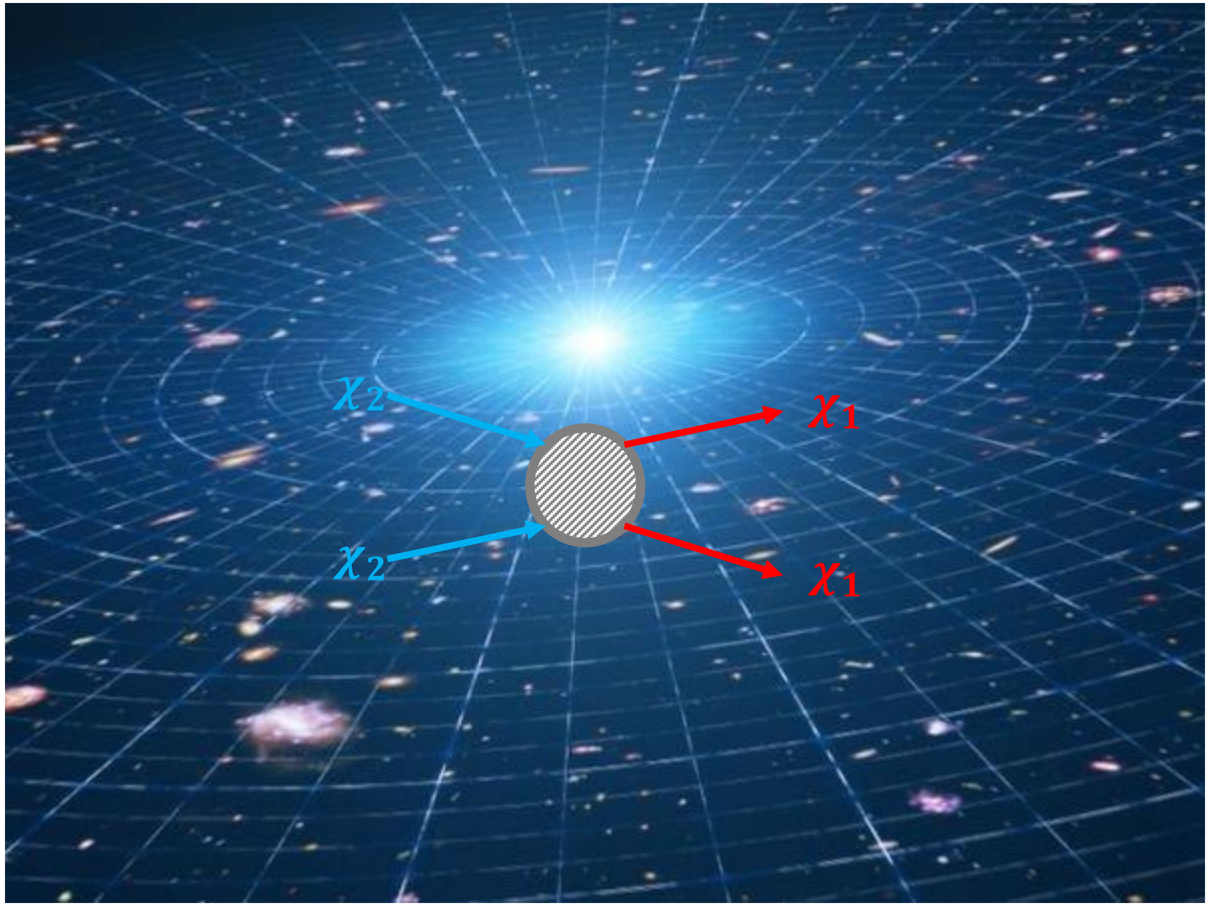


✓ Two-component (χ_0, χ_1) BDM model w/ the following interaction between lighter DM (χ_1) & the SM sector,

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

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?

➢ $\chi_2\chi_2 \to \boldsymbol{\chi_1\chi_1}$ 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 $\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

Self-Heating Effects?

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

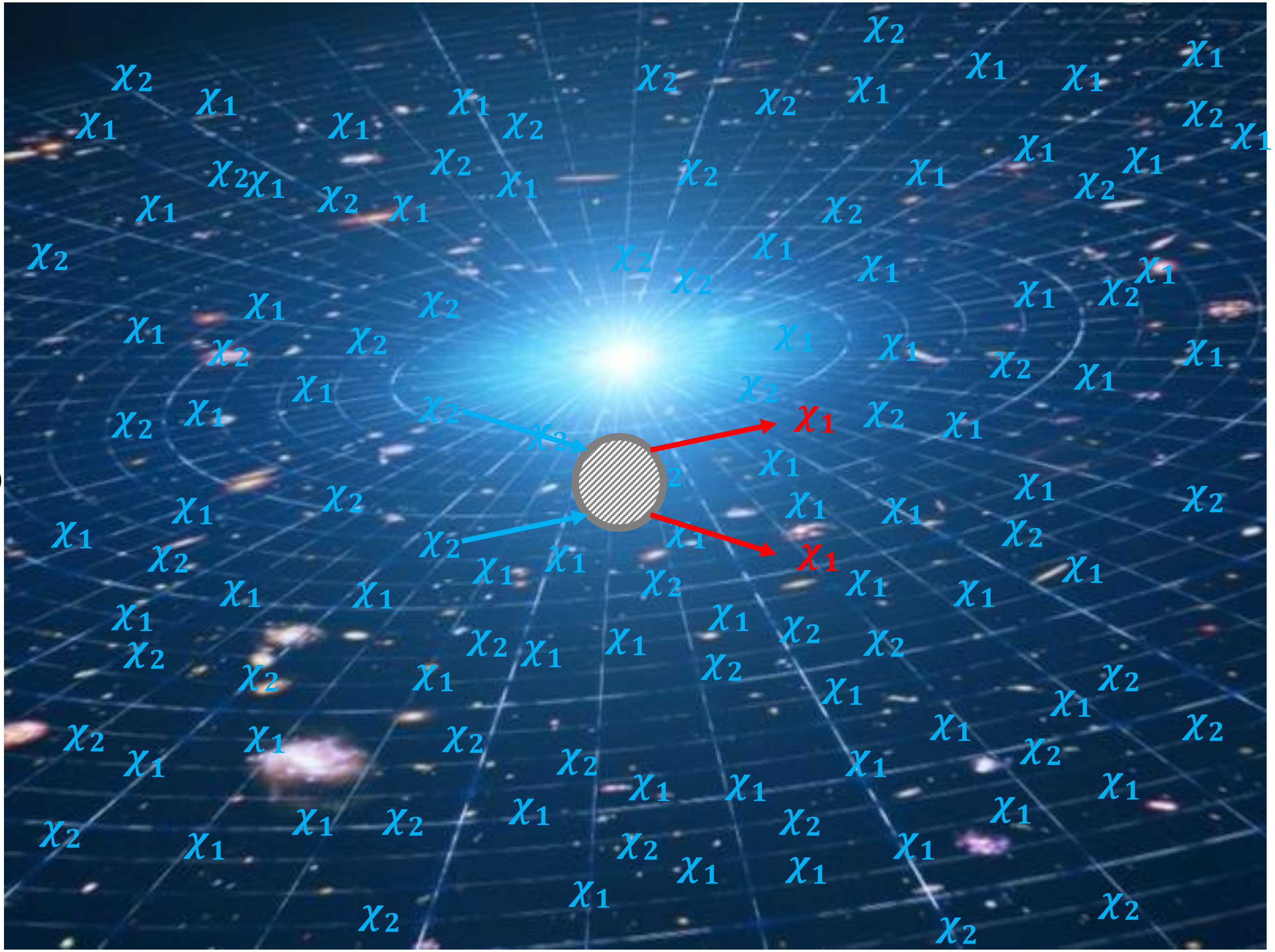
Large self-scattering is quite natural for light dark sector!

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 χ_2 annihilates to light χ_1 which becomes boosted.

Self-Heating Effects!

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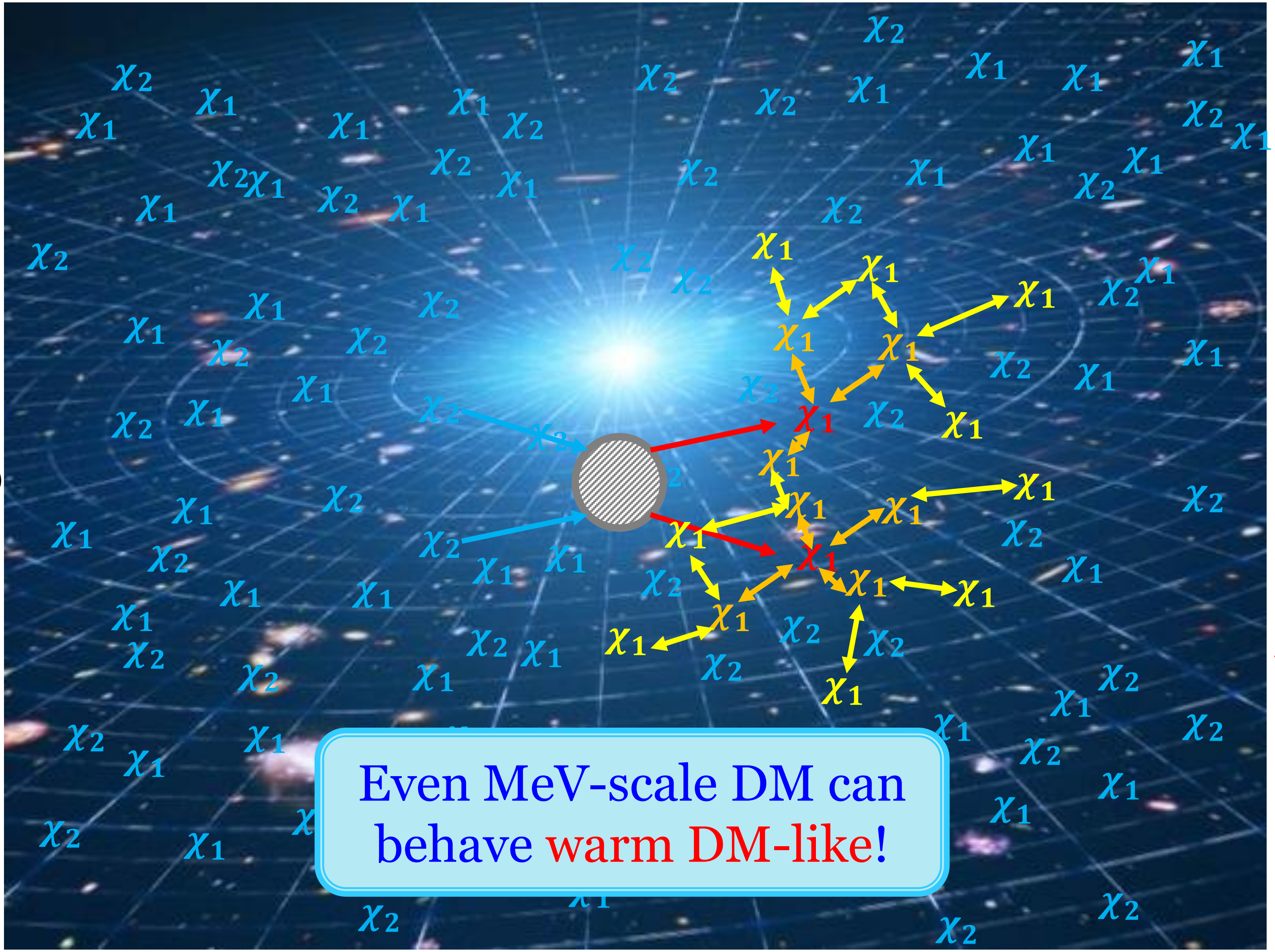
➔ $\sigma_{\chi_1}^{\text{self}}/m_{\chi_1} \approx \boldsymbol{O(1\ \text{cm}^2/\text{g})}$



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

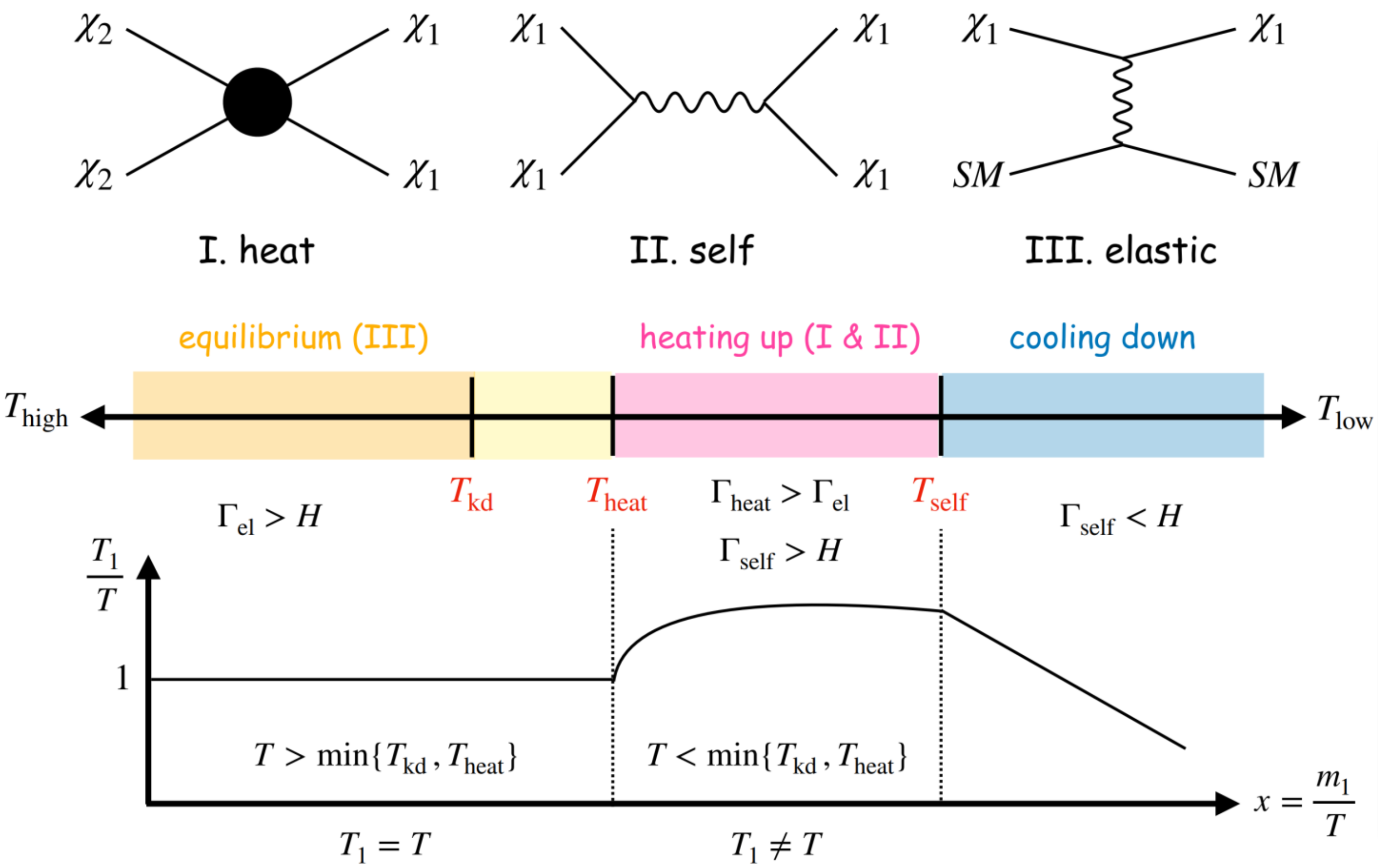
1. The heavy χ_2 annihilates to light χ_1 which becomes boosted.

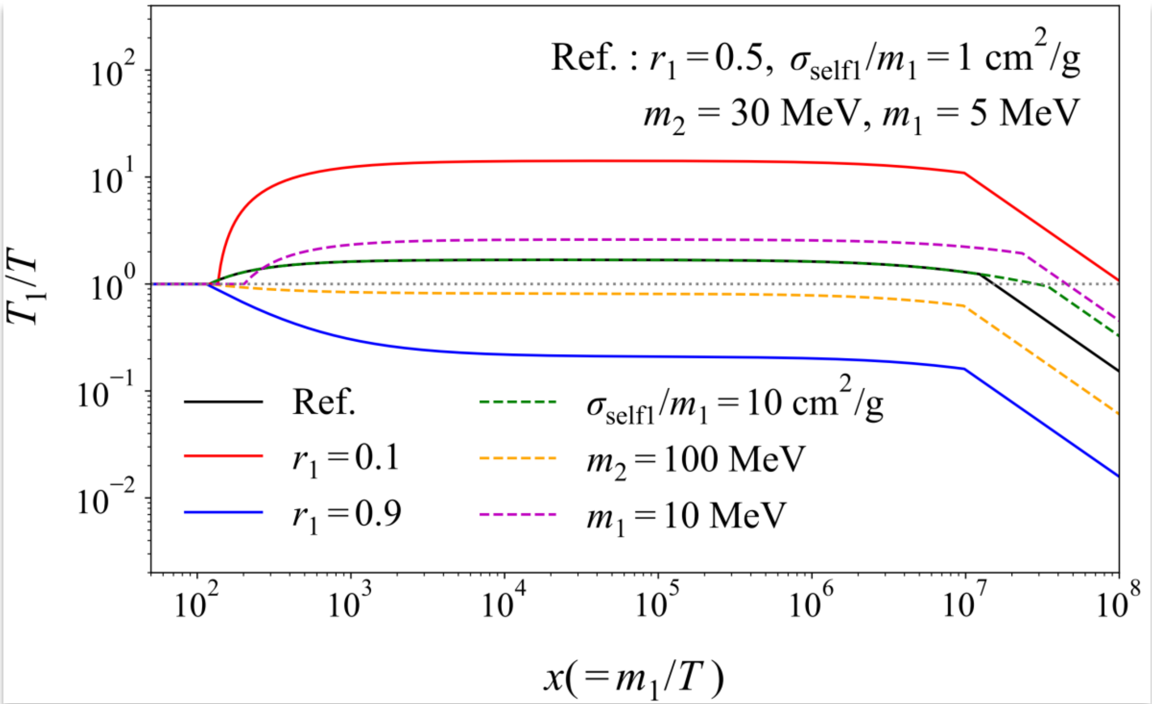
2. Sharing energies through self-interaction $\sigma_{\chi_1}^{\text{self}}$ which increases the χ_1 temperature.

Thermal Evolution

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

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





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

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

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

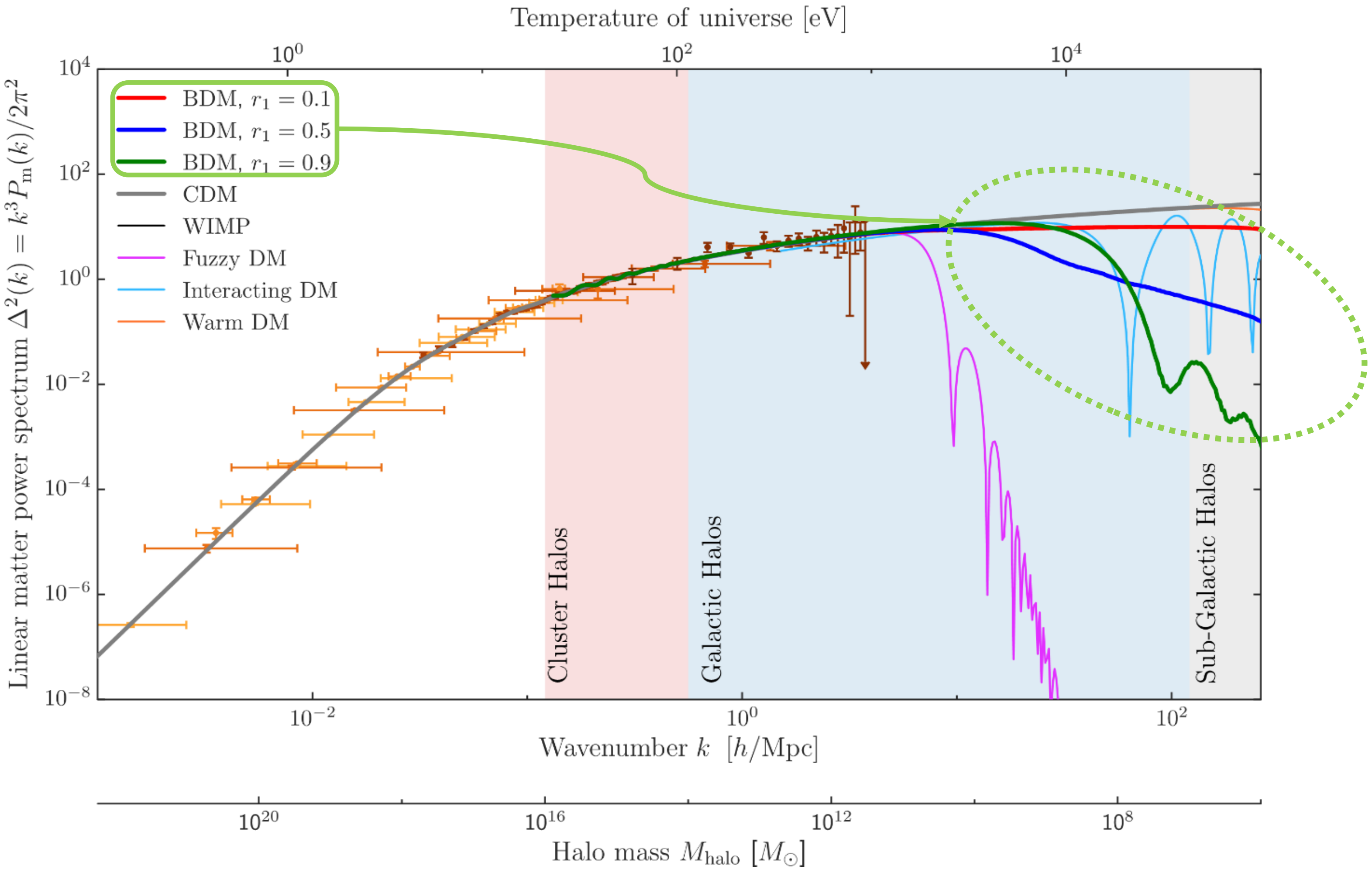
$\gamma_{\chi_1 sm} \simeq (\delta E/T) n_{sm} \langle\sigma v\rangle_{\chi_1 sm}$

Kinetic scattering of χ_1 with a thermal bath

Linear Matter Power Spectrum

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

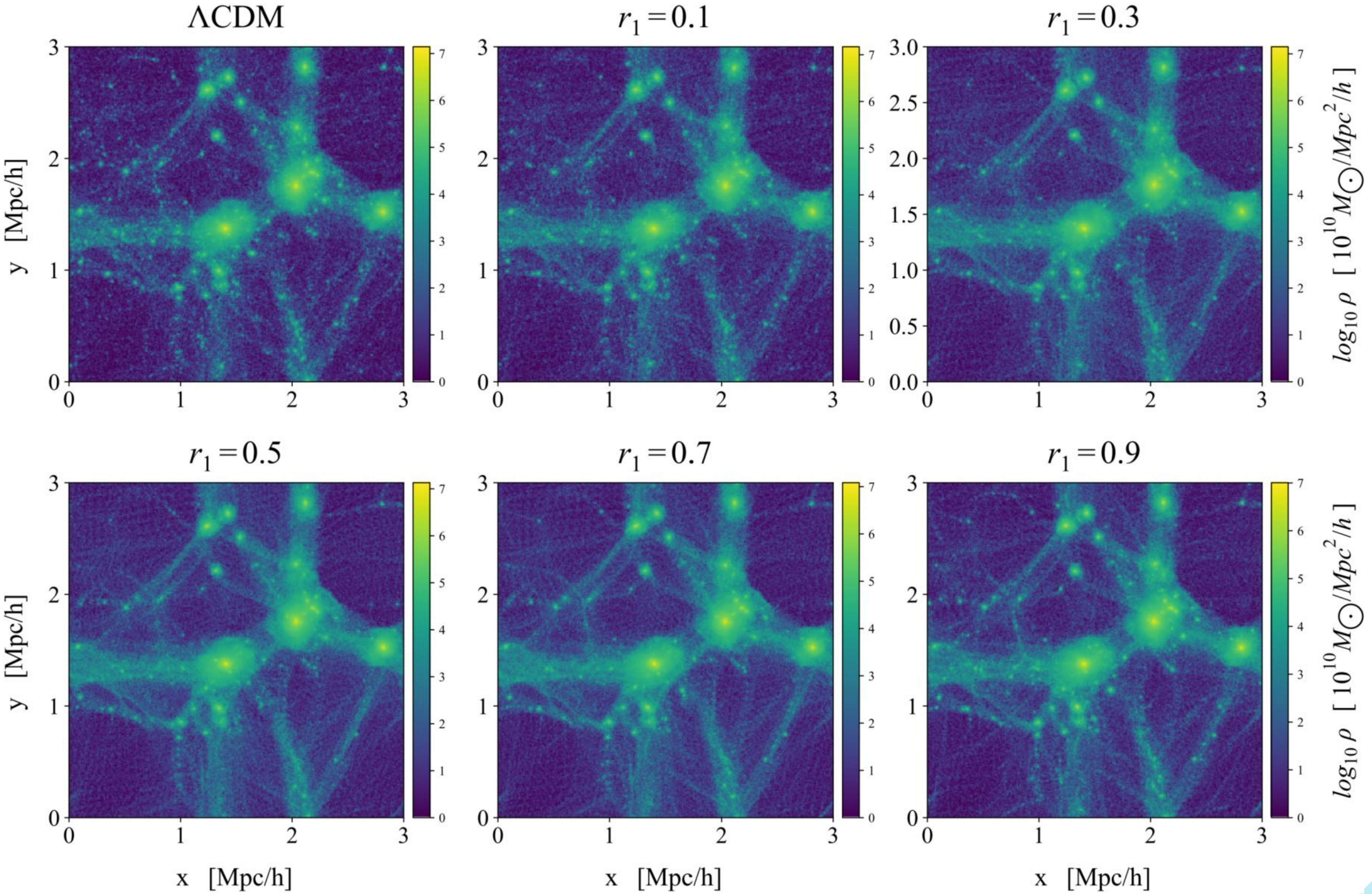
❖ Comparison of dimensionless linear matter power spectra



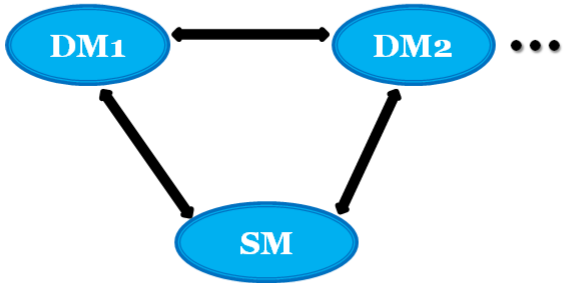
N-Body Simulation

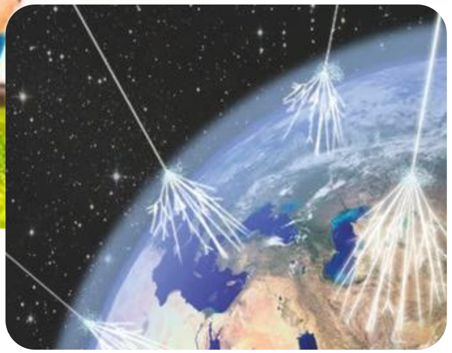
[J. Kim, Lim, **JCP** & Kong, PTEP (2024) & JCAP (2025)]

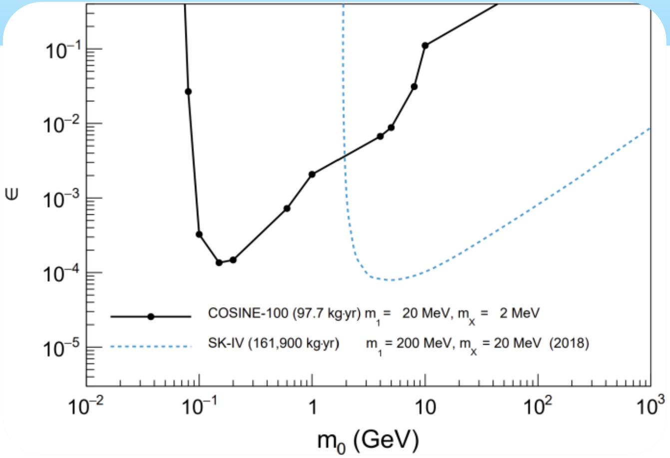
- *N*-body simulations: two-component DM simulation built on *GADGET-3* to investigate the non-linear effects
- Visualization of DM density in the periodic 3 h^{-1}Mpc box at $z = 0$ ➔ fewer sub-halos
  - ✓ $\frac{\sigma_1^{\text{self}}}{m_{\chi_1}} = 1\ \text{cm}^2/\text{g}$
  - ✓ $m_{\chi_2} = 30$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

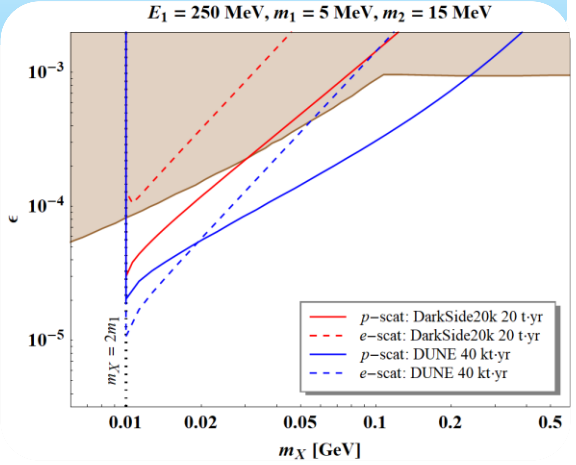


Summary









- ❖ 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: e.g. SK, COSINE-100, Panda-X, CDEX, NEWSdm, ICARUS, DUNE, ...
- ❖ Studies on potential cosmological & astrophysical effects

Thank you