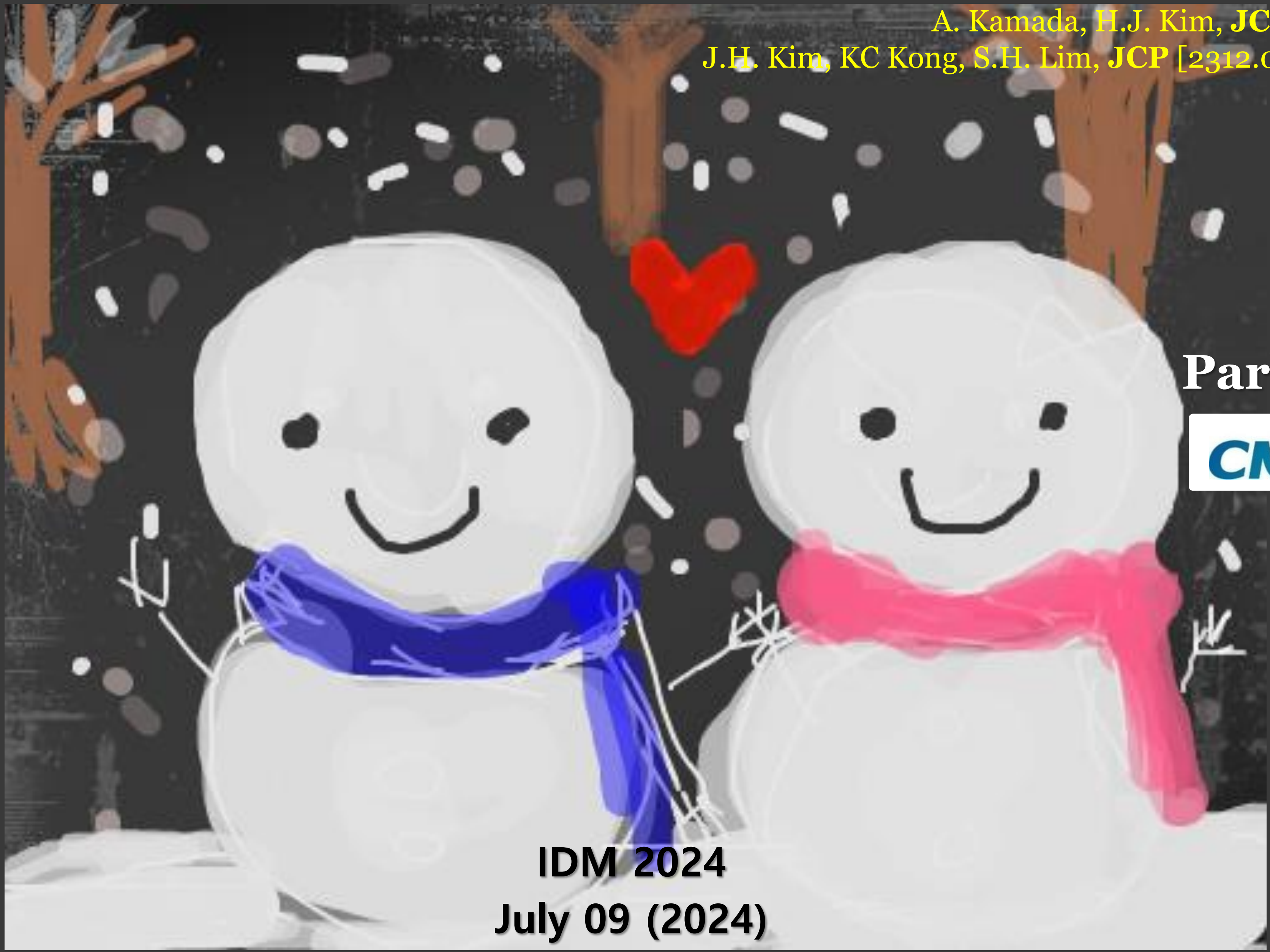
Warm Surprises from Cold Duets

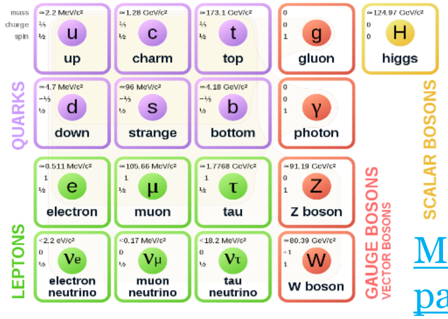
G. Belanger, **JCP** [1112.4491]
A. Kamada, H.J. Kim, **JCP**, S. Shin [2111.06808]
J.H. Kim, KC Kong, S.H. Lim, **JCP** [2312.07660 & in preparation]



Park, Jong-Chul

IDM 2024
July 09 (2024)

Dark Sector: Dark Particles & Portals



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: $\frac{1}{f_{a\gamma/ag}} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

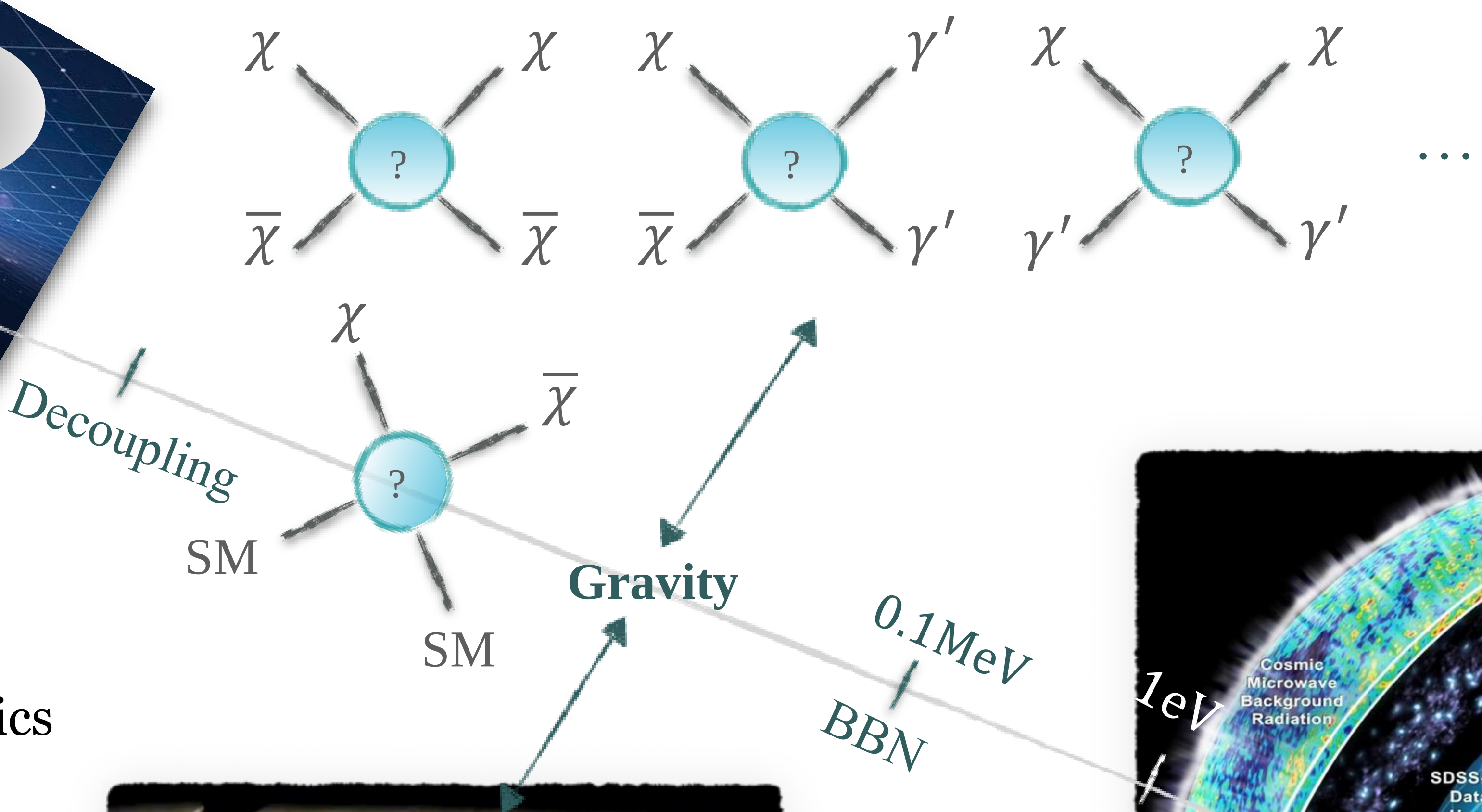
    $\frac{1}{f_{af}} \partial_\mu a(\bar{\psi}\gamma^\mu\gamma^5\psi)$
  - ✓ Dilaton portal: $\frac{\sigma}{f}(M_V^2 V_\mu V^\mu + \cdots + V_{\mu\nu}V^{\mu\nu} + \cdots)$
  - ✓ Gauged SM global #: B-L, L_μ-L_τ, …
  - ✓ Dark axion portal: $G_{a\gamma\gamma'} a F_{\mu\nu}\tilde{X}^{\mu\nu}$
  - ✓ Double portal: combination of portals [Belanger, Goudelis, **JCP** (2013)]
  - ✓ ???

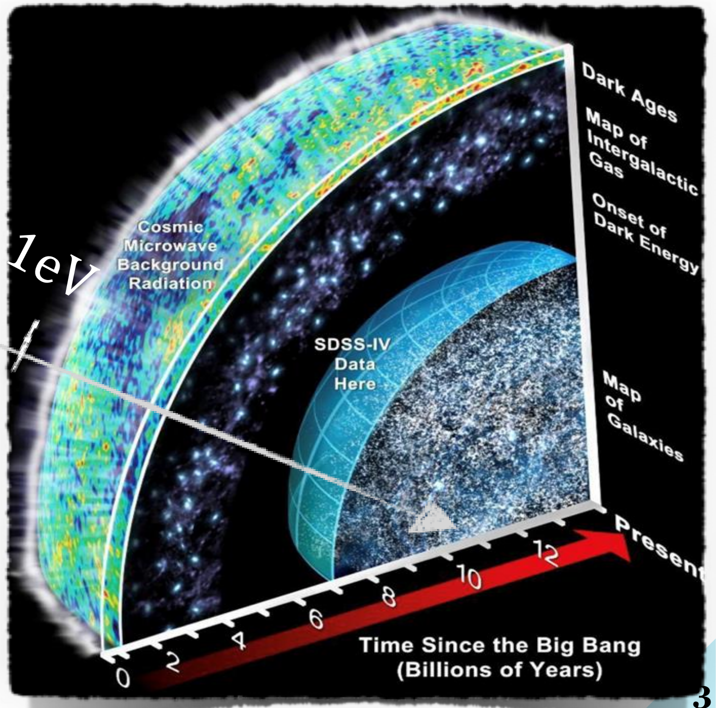
Multiple stable & unstable particles, Various interactions?

- **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)
  - ✓ ???

Cosmic Probes of Dark Sector





- ✓ What is a hidden dynamics of a dark sector?
- ✓ Use the gravitational interaction as a main source to probe the dark sector.

Current Status of DM Searches

Ultralight
axion, fuzzy,
hidden photon,

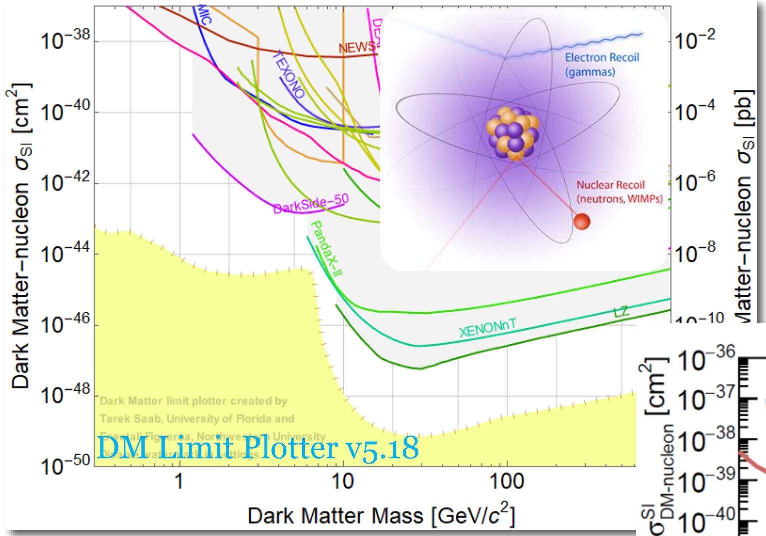
Superlight
sterile ν,
warm DM

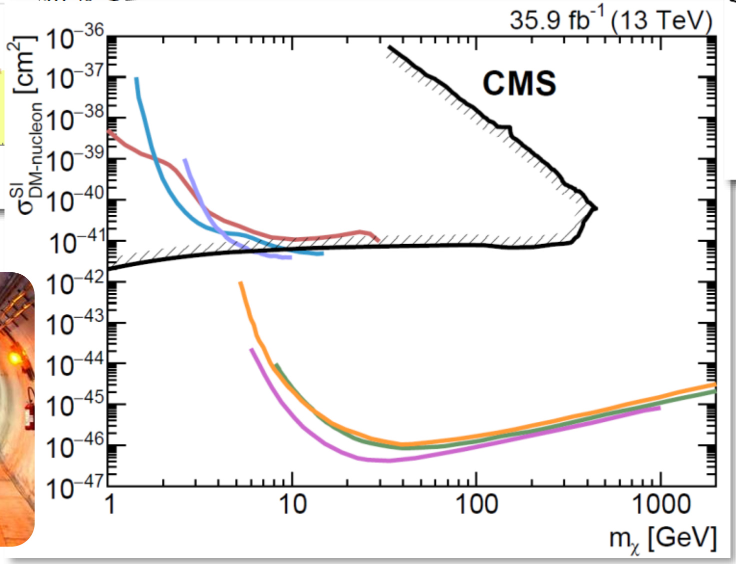
Light
SIMP,
ELDER

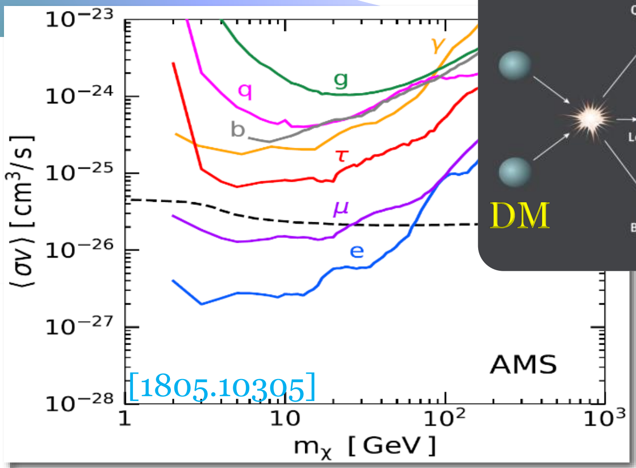
WIMP

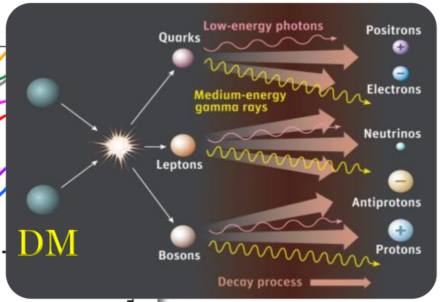
Superheavy
composite DM,
WIMPzilla

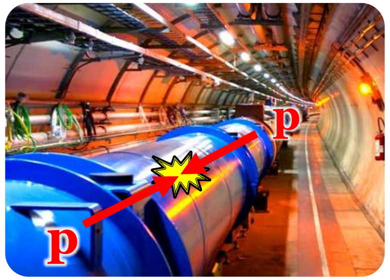
Astrophysical object
MACHO, PBH











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

Simple Extension of ΛCDM

Warm Dark Matter (WDM)

WDM $\boldsymbol{m \sim \mathcal{O}(\text{keV})}$

+

Cold Dark Matter (CDM)

CDM

Mixed Cold & Warm
Dark Matter (CWDM)
(~27 %)

Boyarsky et al. [0812.0010],
Anderhalden et al. [1212.2967],
Maccio et al. [1202.2858], ⋯

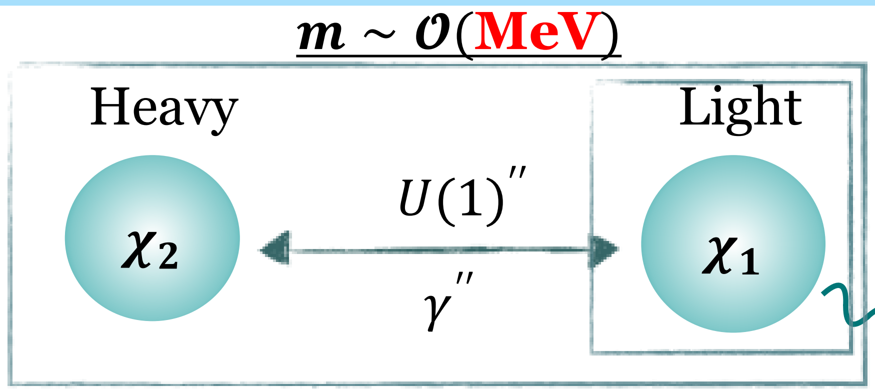
Dark Energy
(~68 %)

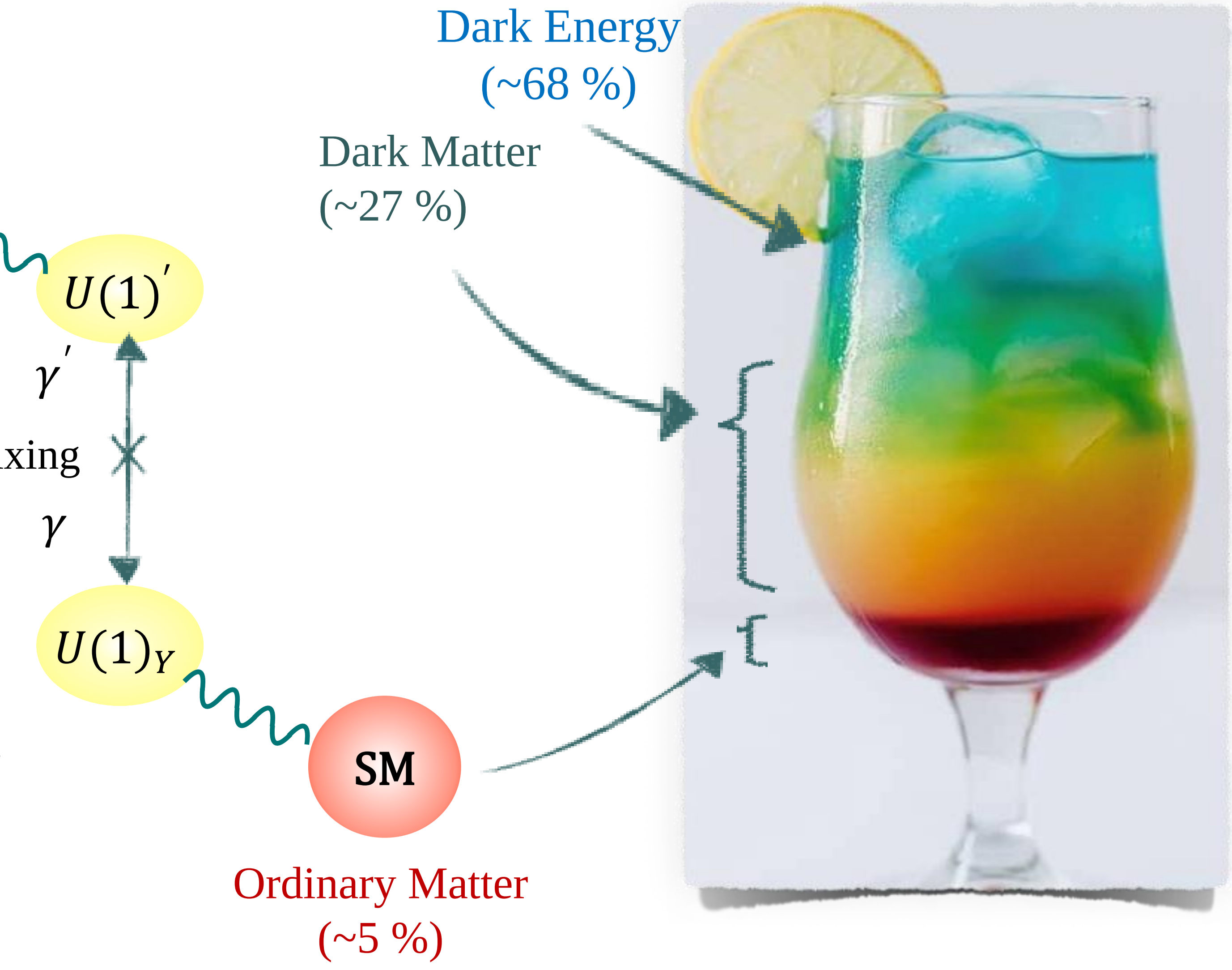
SM

Ordinary Matter
(~5 %)

- ✓ The WDM is able to free-stream and dampens density perturbations at small scales.
- ✓ To have a significant impact on astrophysical data, $\boldsymbol{m \sim \mathcal{O}(\text{keV})}$.

Simplified Two-Component DM



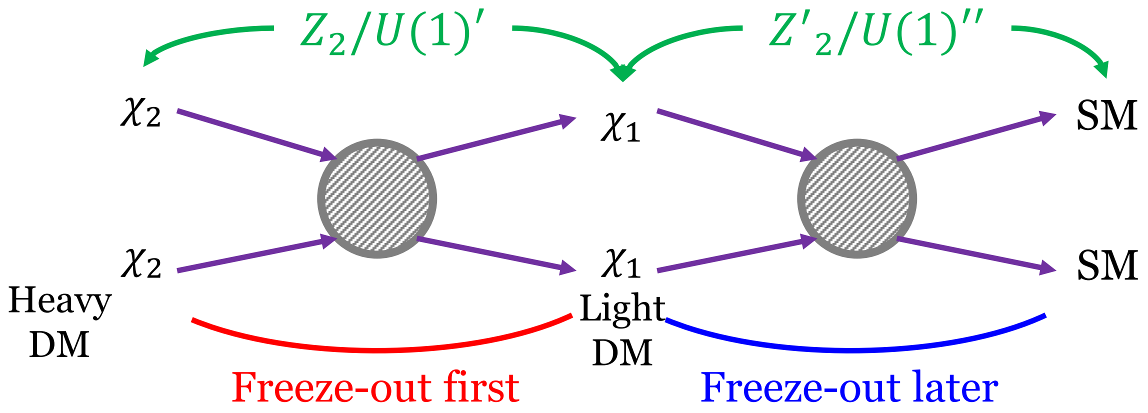


- ✓ How to achieve a similar outcome for DM with $\boldsymbol{m \gg \mathcal{O}}$(**keV**)?
- ✓ Introduce the mass gap Δm to kick out light species through annihilations.

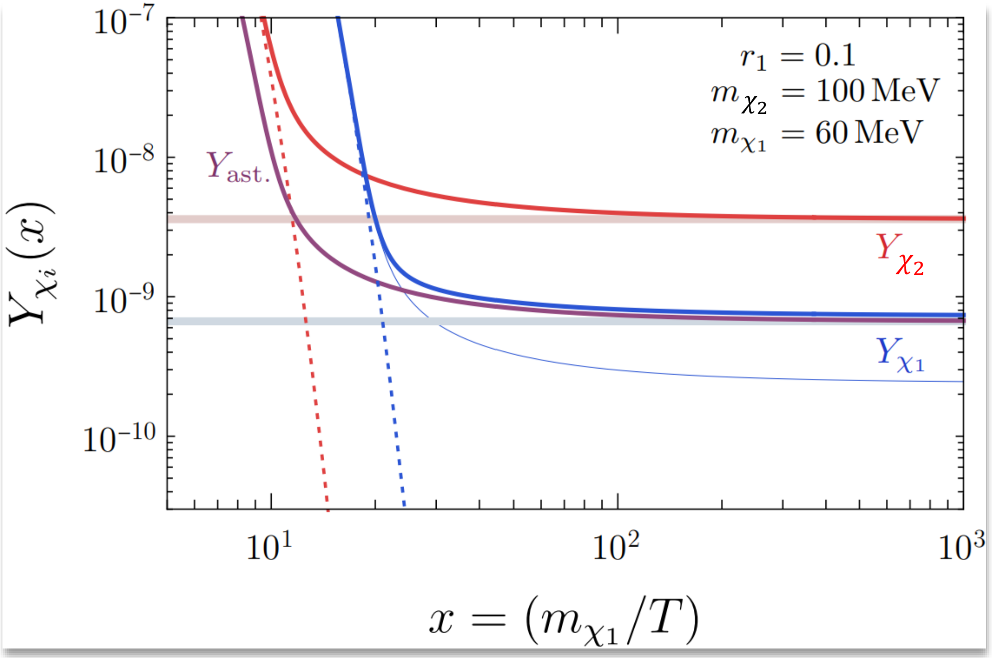
Belanger & **JCP**, JCAP [2012],

Agashe, Cui, Necib & Thaler JCAP [2014]

Two-Component DM: Assisted Freeze-out



Thermal relic: $Y_i = n_i/s$



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

"**Assisted Freeze-out**" Mechanism

- ✓ Their relic abundances depend on the relative size of interactions.
- ✓ Heavier relic χ_2: hard to directly detect it due to tiny coupling to SM.
- ✓ χ_1 from χ_2 annihilation today: **boosted DM (BDM)**

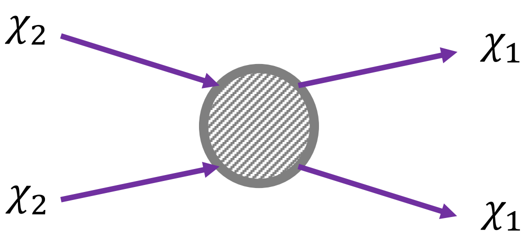
Agashe, Cui, Necib & Thaler JCAP [2014]

$$\frac{dY_{\chi_2}}{dx} = -\frac{\lambda_{\chi_2}(x)}{x}\left[Y_{\chi_2}^2 - \left(\frac{Y_{\chi_2}^{\mathrm{eq}}(x)}{Y_{\chi_1}^{\mathrm{eq}}(x)}\right)^2 Y_{\chi_1}^2\right],$$

$$\frac{dY_{\chi_1}}{dx} = -\frac{\lambda_{\chi_1}(x)}{x}\left[Y_{\chi_1}^2 - \left(Y_{\chi_1}^{\mathrm{eq}}(x)\right)^2\right] + \frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_2}^2 - \left(\frac{Y_{\chi_2}^{\mathrm{eq}}(x)}{Y_{\chi_1}^{\mathrm{eq}}(x)}\right)^2 Y_{\chi_1}^2\right]$$

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

Two-Component DM: BDM Signatures

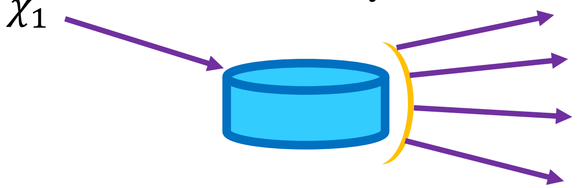


(cf. $\chi\chi \rightarrow \gamma\gamma$, $\boldsymbol{\nu\nu}$)

becomes boosted

$(\gamma_1 = m_0/m_1)$

(Laboratory)

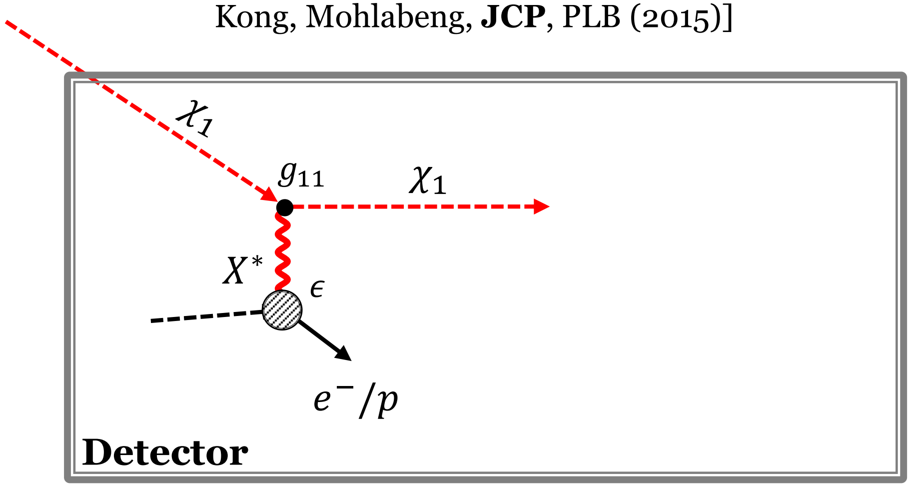


$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm l.o.s.} ds \langle\sigma v\rangle_{\chi_2\bar{\chi}_2\rightarrow\chi_1\bar{\chi}_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

$$= 8.0\times10^{-5}\ {\rm cm^{-2}s^{-1}}\times\left(\frac{\langle\sigma v\rangle_{\chi_2\bar{\chi}_2\rightarrow\chi_1\bar{\chi}_1}}{5\times10^{-26}\ {\rm cm^3\,s^{-1}}}\right)\left(\frac{\rm GeV}{m_0}\right)^2\frac{dN_1}{dE_1}$$

elastic scattering (eBDM)

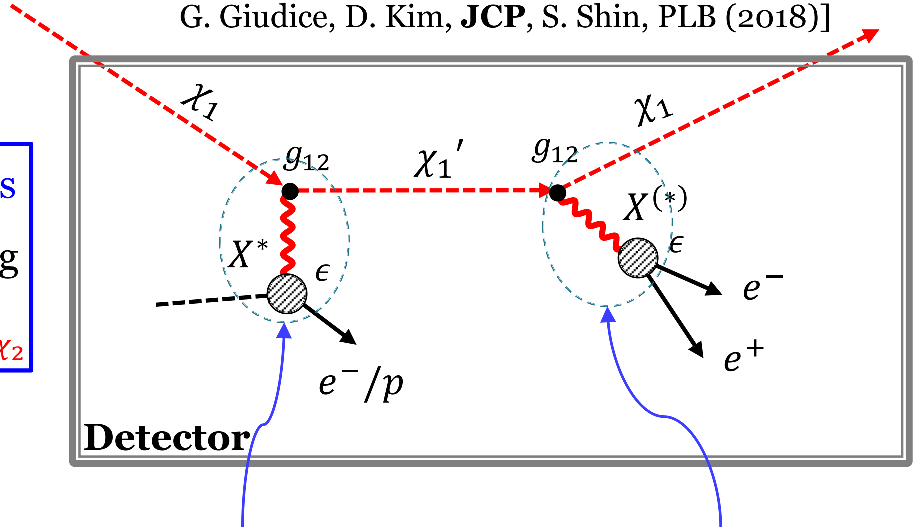
[Agashe, Cui, Necib, Thaler, JCAP (2014); Kong, Mohlabeng, **JCP**, PLB (2015)]



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

inelastic scattering (*i*BDM)

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



p- or *e*-scattering (primary)

Decay (secondary)

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

BDM Searches @ Neutrino Experiments

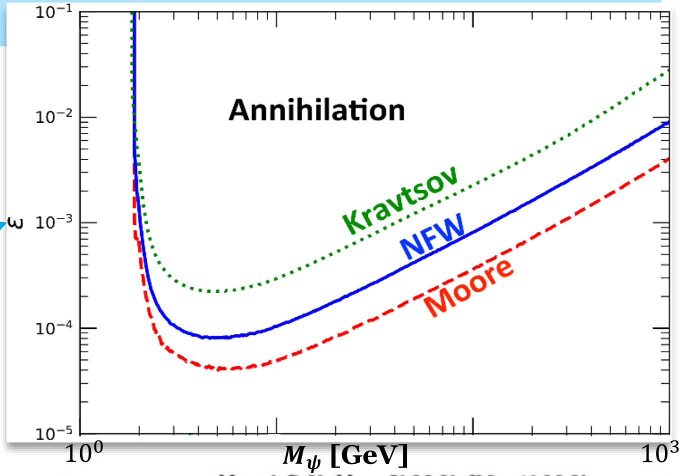
Boosted DM (BDM) scenarios:
Receiving rising attention as an alternative scenario

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

Editors' Suggestion

Cherenkov radiation rings by electrons

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



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

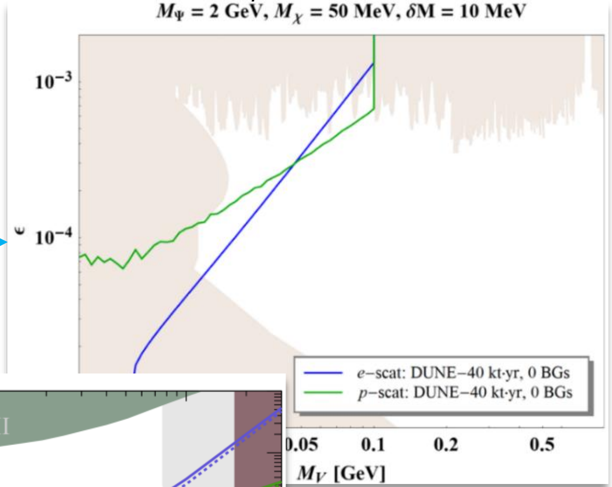
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

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

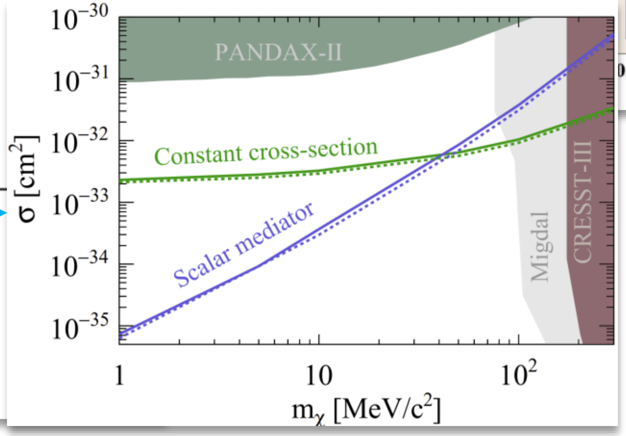


PHYSICAL REVIEW LETTERS **130,** 031802 (2023)

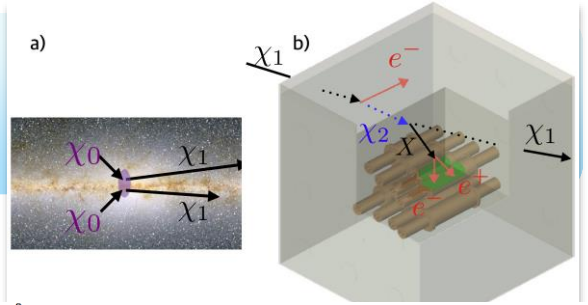
Editors' Suggestion **Featured in Physics**

Cherenkov radiation rings by protons

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



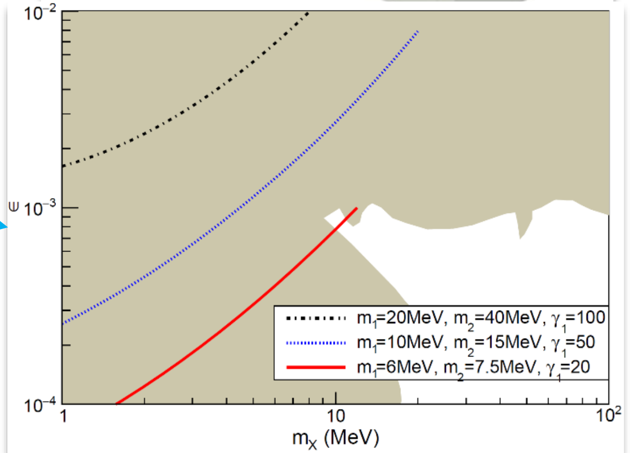
BDM Searches @ DM Experiments



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

Scintillation photons

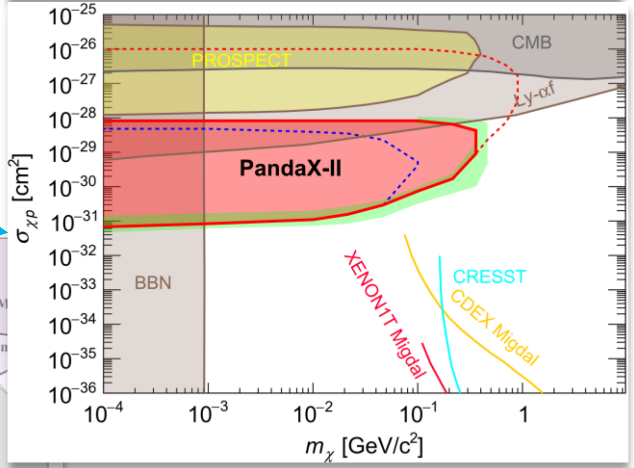
PHYSICAL REVIEW LET

Editors' Suggestion

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

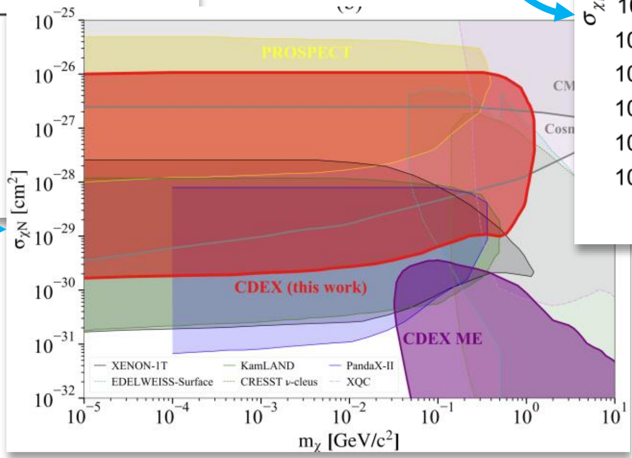
Pumping up the flux

➔ DM detector is OK!



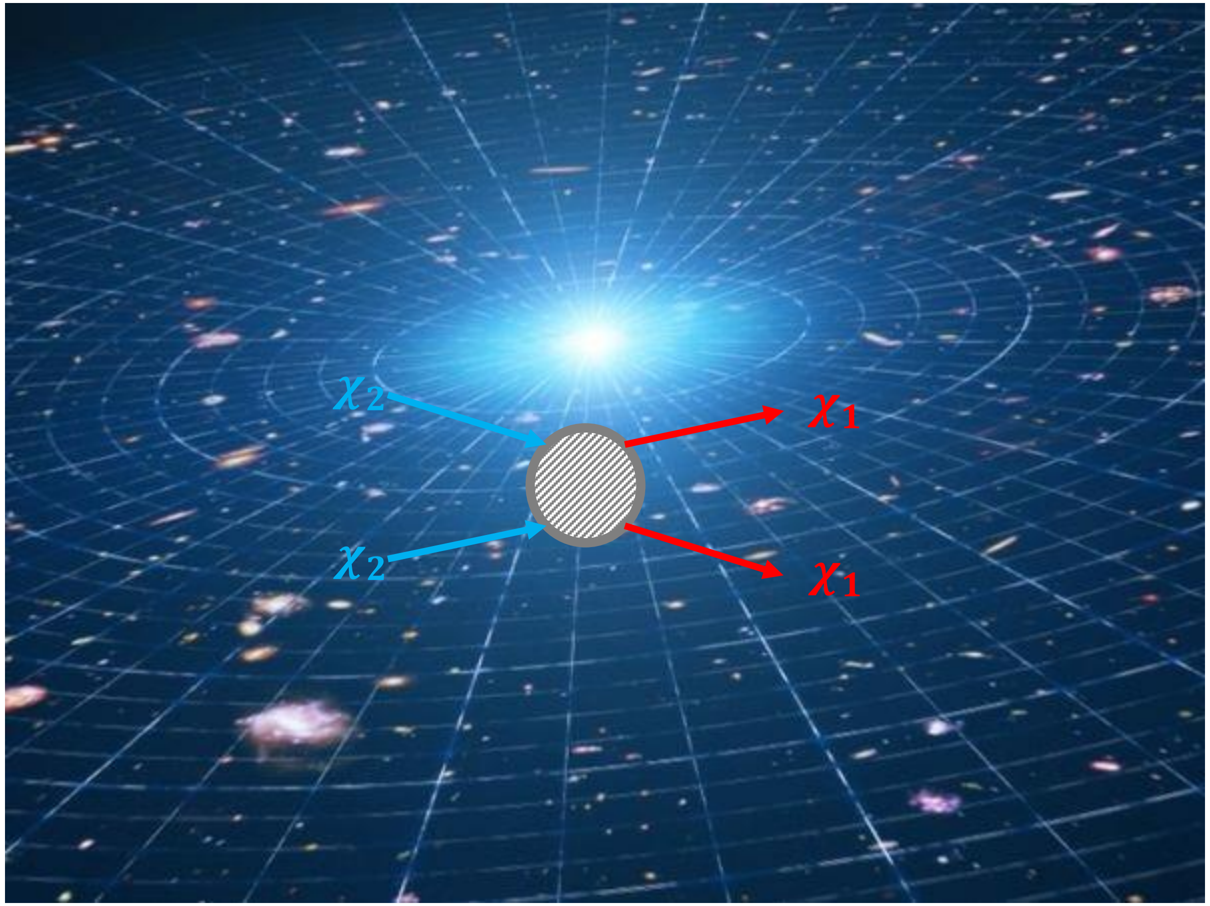
PHYSICAL REVIEW D **106,** 052008 (2022)

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

BDM=Hot DM?



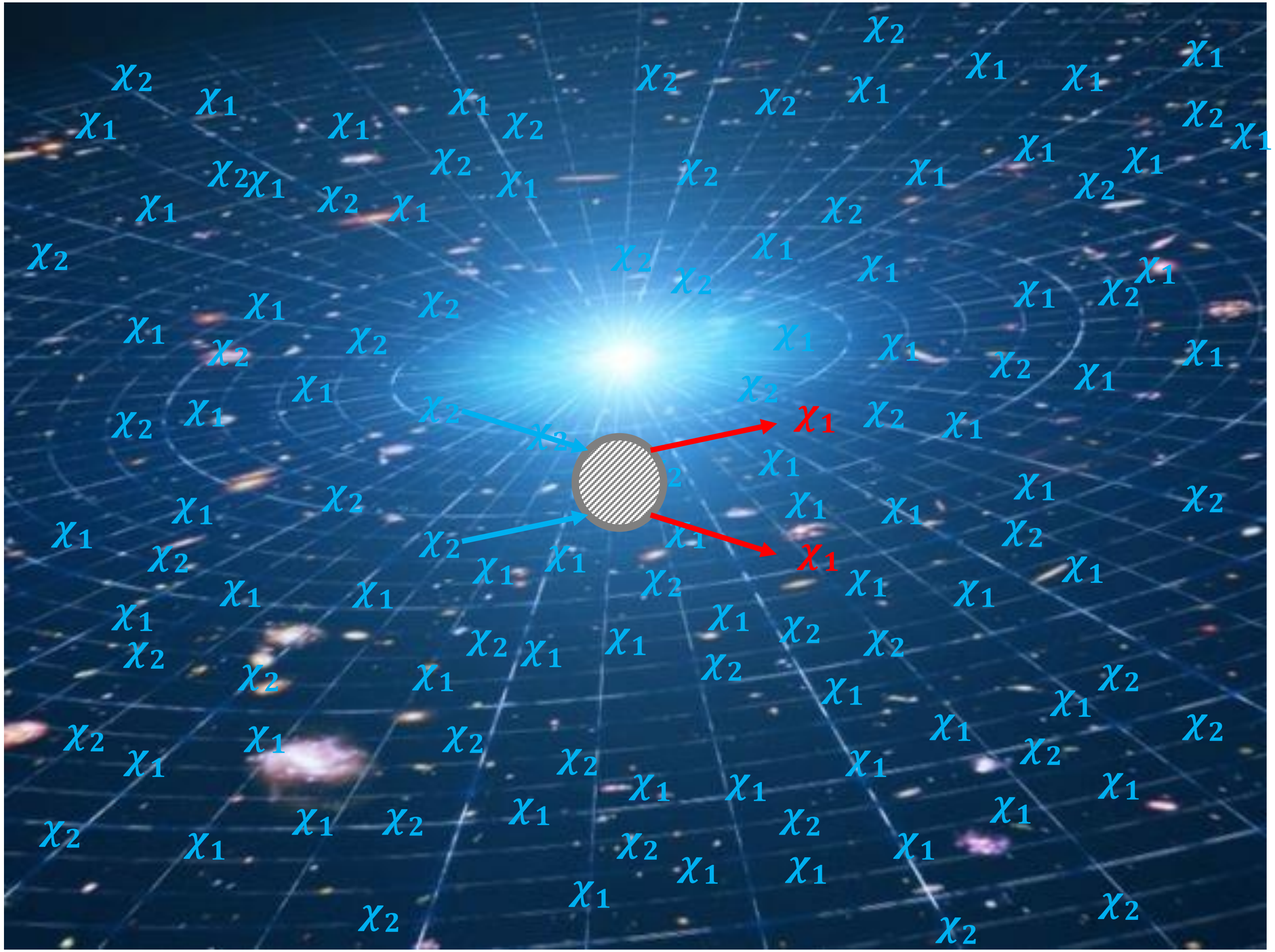
- ✓ χ_2: heavy DM, χ_1: light DM

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

- ➢ $\chi_2\chi_2 \rightarrow \boldsymbol{\chi_1\chi_1}$ Vs $\chi\chi \rightarrow \boldsymbol{\nu\nu}$
- ➢ $n_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_2\chi_2\rightarrow\chi_1\chi_1}}{m_2^2}$ with $\langle\sigma v\rangle_{\chi_2\chi_2\rightarrow\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm^3/s}$

Self-Heating Effects?

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



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

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

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

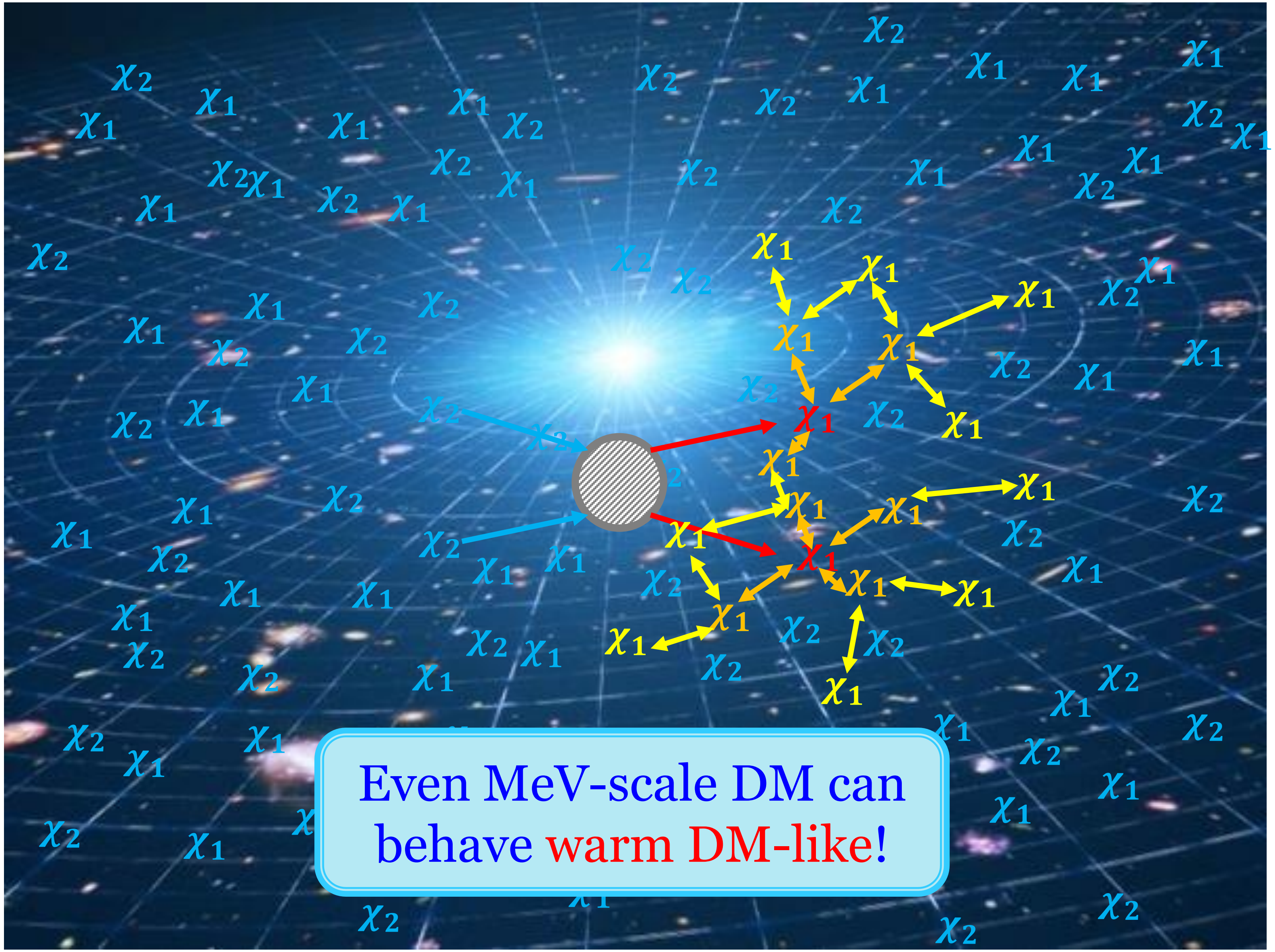
$\sigma^{\text{self}}_{\chi_1} \approx \frac{g^4_{\chi_1}}{\pi} \frac{m^2_{\chi_1}}{m^4_{\text{med}}}$

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

Self-Heating Effects!

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

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



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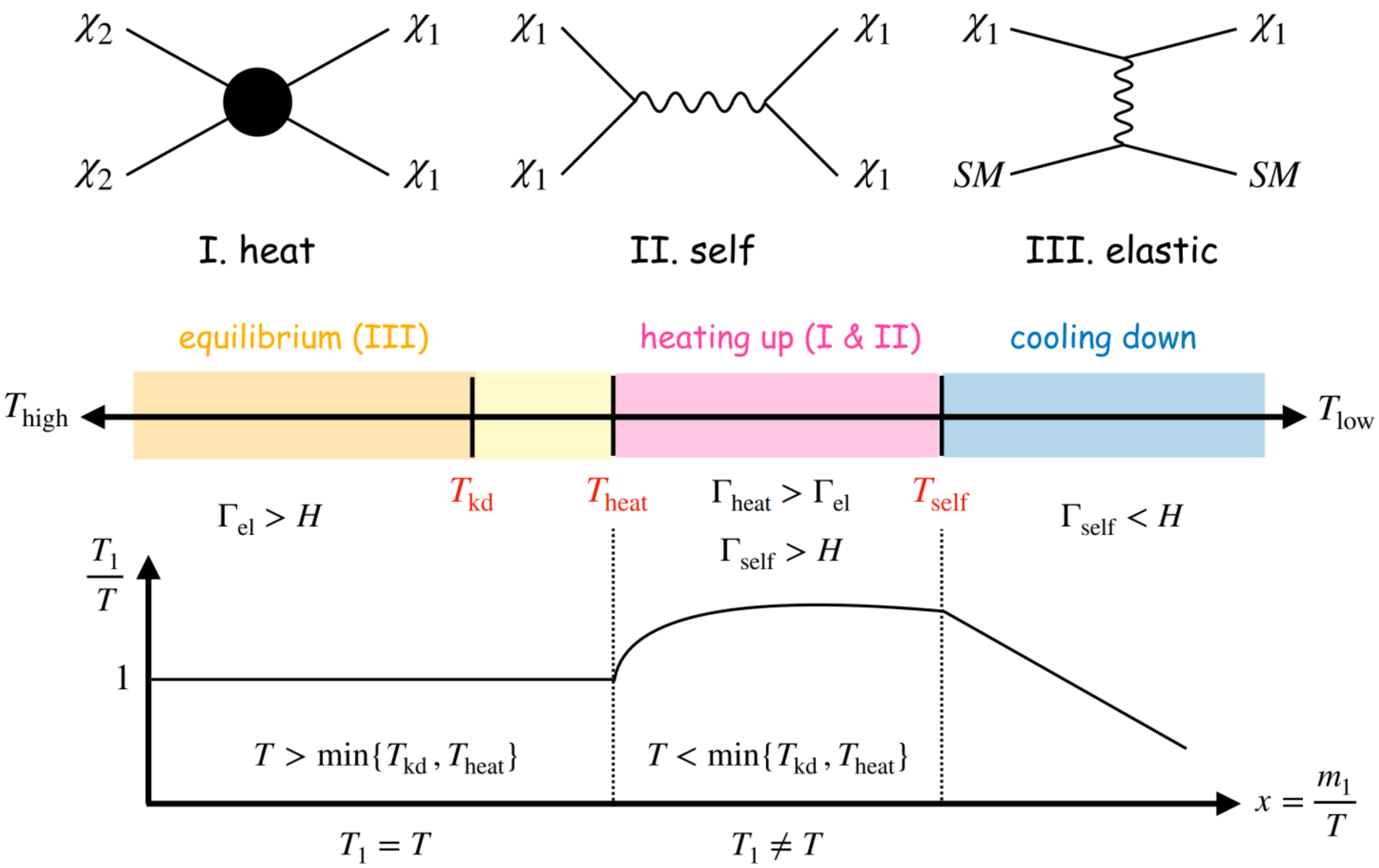
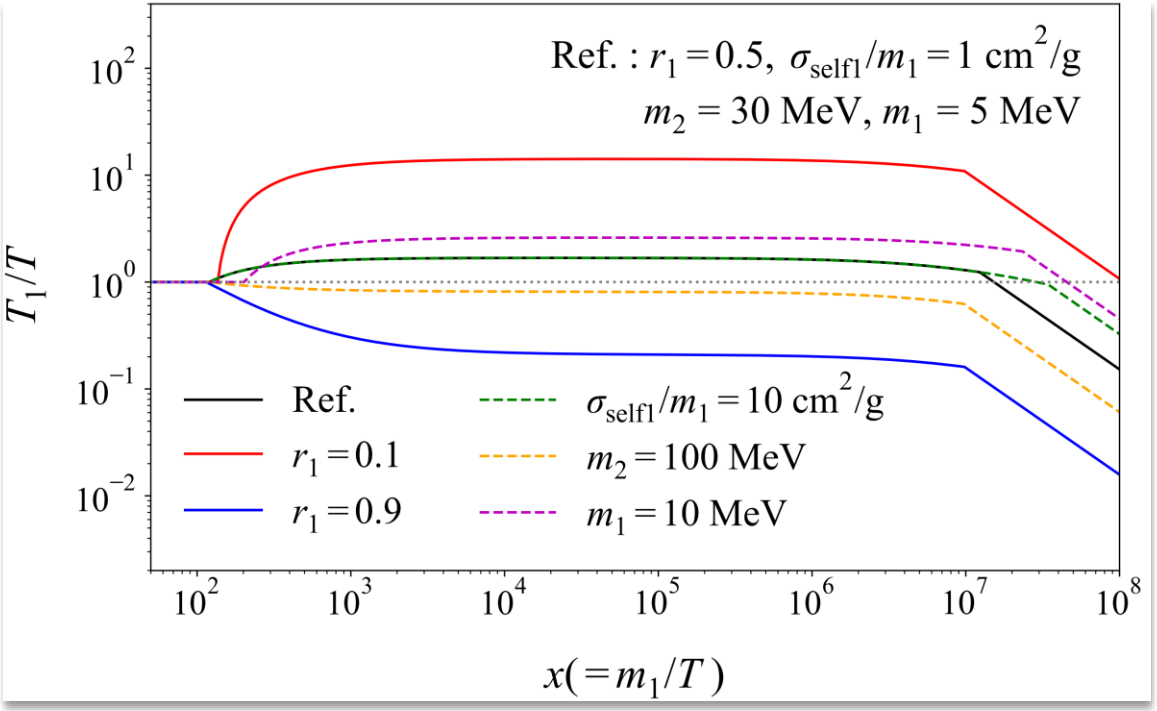
➔ $\sigma^{\rm self}_{\chi_1}/m_{\chi_1} \approx \boldsymbol{O(1\ cm^2/g)}$

Thermal Evolution

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

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





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

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

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

Kinetic scattering of χ_1 with a thermal bath

Perturbation Evolution

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

❖ Coupled equations for the density perturbation

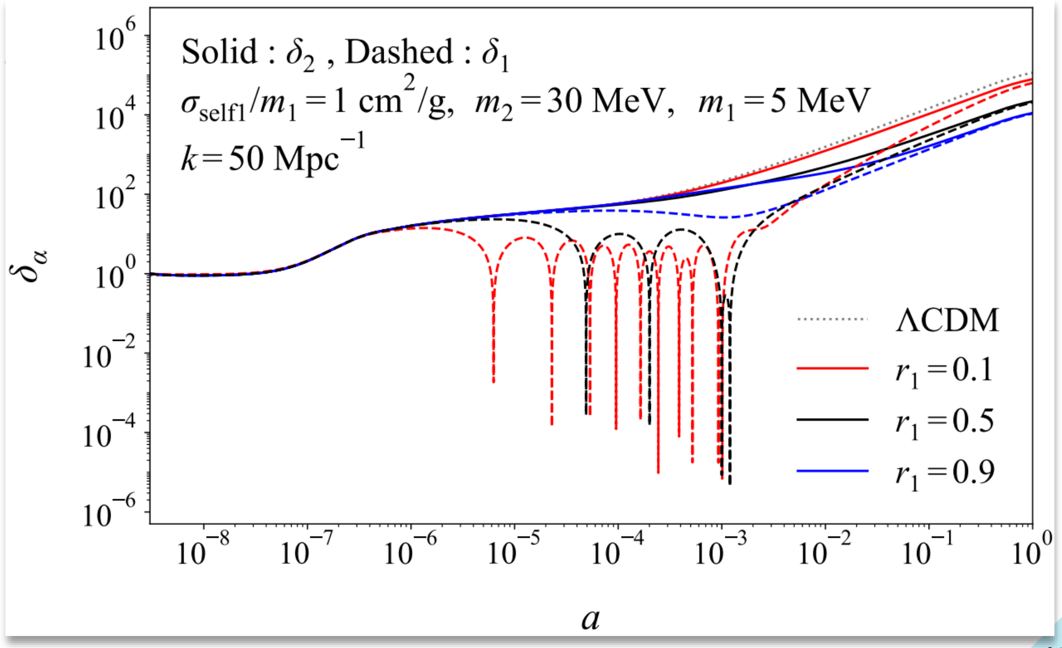
$$\frac{d\delta_2}{dt}+\frac{\theta_2}{a}-3\frac{d\Phi}{dt}=\frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar\rho_2}\left(-\Psi\left(\bar\rho_2^2-\frac{\bar\rho_{2,\mathrm{eq}}^2}{\bar\rho_{1,\mathrm{eq}}^2}\bar\rho_1^2\right)-\bar\rho_2^2\delta_2+\frac{\bar\rho_{2,\mathrm{eq}}^2}{\bar\rho_{1,\mathrm{eq}}^2}\bar\rho_1^2\left(2\delta_{2,\mathrm{eq}}-\delta_2-2\delta_{1,\mathrm{eq}}+2\delta_1\right)\right),$$

$$\frac{d\theta_2}{dt}+H\theta_2+\frac{\nabla^2\Psi}{a}=\frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar\rho_2}\frac{\bar\rho_{2,\mathrm{eq}}^2}{\bar\rho_{1,\mathrm{eq}}^2}\bar\rho_1^2\left(\theta_1-\theta_2\right),$$

$$\frac{d\delta_1}{dt}+\frac{\theta_1}{a}-3\frac{d\Phi}{dt}=-\frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar\rho_1}\left(-\Psi\left(\bar\rho_2^2-\frac{\bar\rho_{2,\mathrm{eq}}^2}{\bar\rho_{1,\mathrm{eq}}^2}\bar\rho_1^2\right)-\bar\rho_2^2(2\delta_2-\delta_1)+\frac{\bar\rho_{2,\mathrm{eq}}^2}{\bar\rho_{1,\mathrm{eq}}^2}\bar\rho_1^2\left(2\delta_{2,\mathrm{eq}}+\delta_1-2\delta_{1,\mathrm{eq}}\right)\right)$$

$$+\frac{\langle\sigma v\rangle_{11\to XX}}{m_1\bar\rho_1}\left(-\Psi\left(\bar\rho_1^2-\bar\rho_{1,\mathrm{eq}}^2\right)-\bar\rho_1^2\delta_1+\bar\rho_{1,\mathrm{eq}}\left(2\delta_{1,\mathrm{eq}}-\delta_1\right)\right)$$

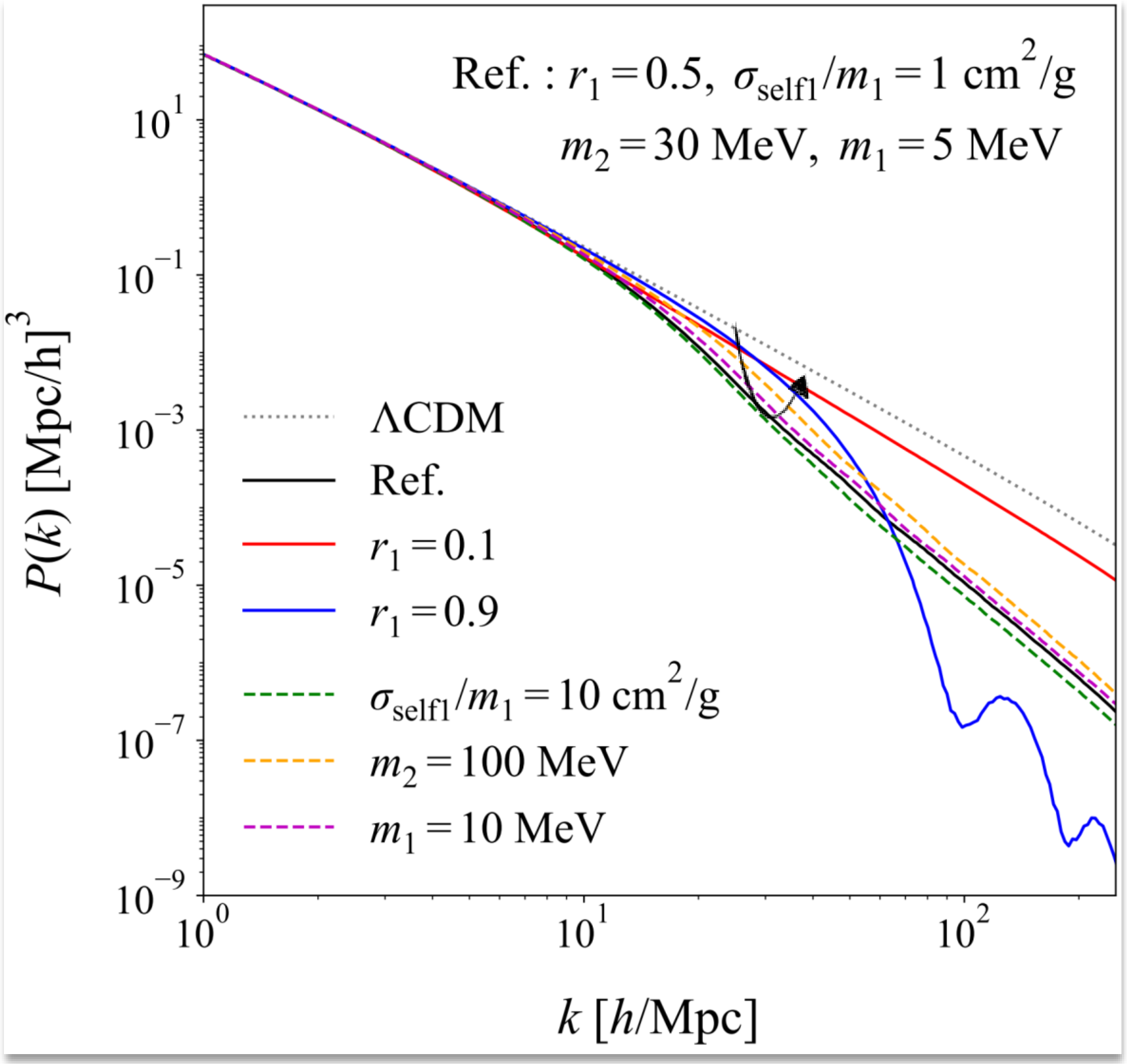
$$\frac{d\theta_1}{dt}+H\theta_1+\frac{\nabla^2\Psi}{a}+c_{s,1}^2\frac{\nabla^2\delta_1}{a}=\frac{\langle\sigma v\rangle_{22\to11}}{m_2\bar\rho_1}\bar\rho_2^2\left(\theta_2-\theta_1\right),$$

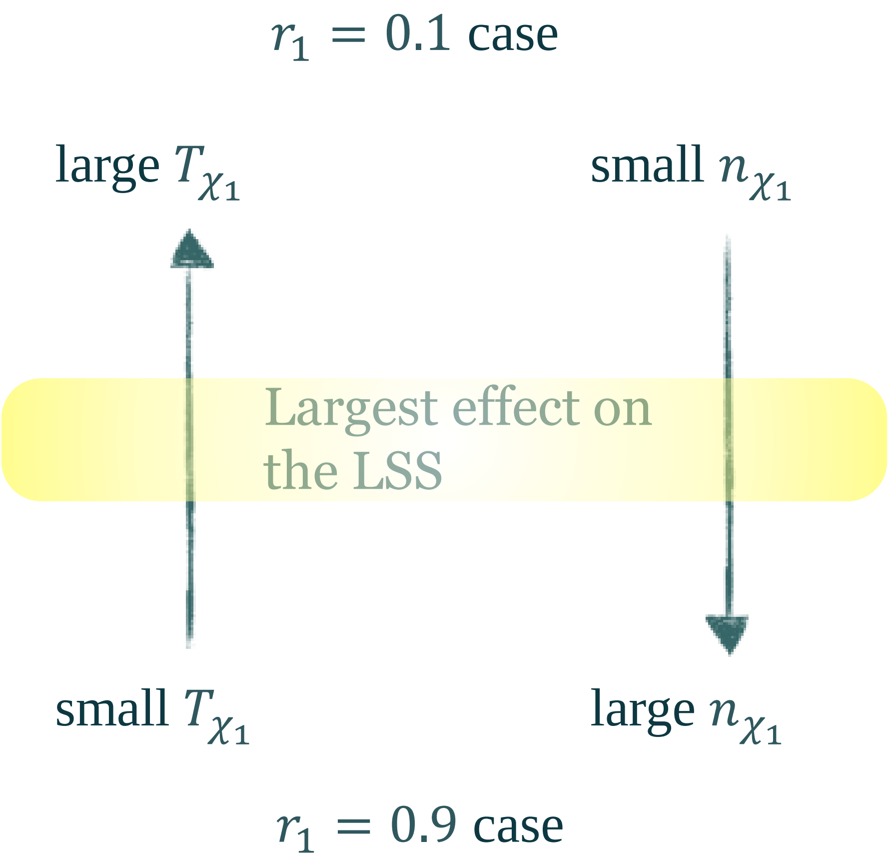


Linear Matter Power Spectrum

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

❖ Linear power spectrum by *CLASS*





N-Body Simulation

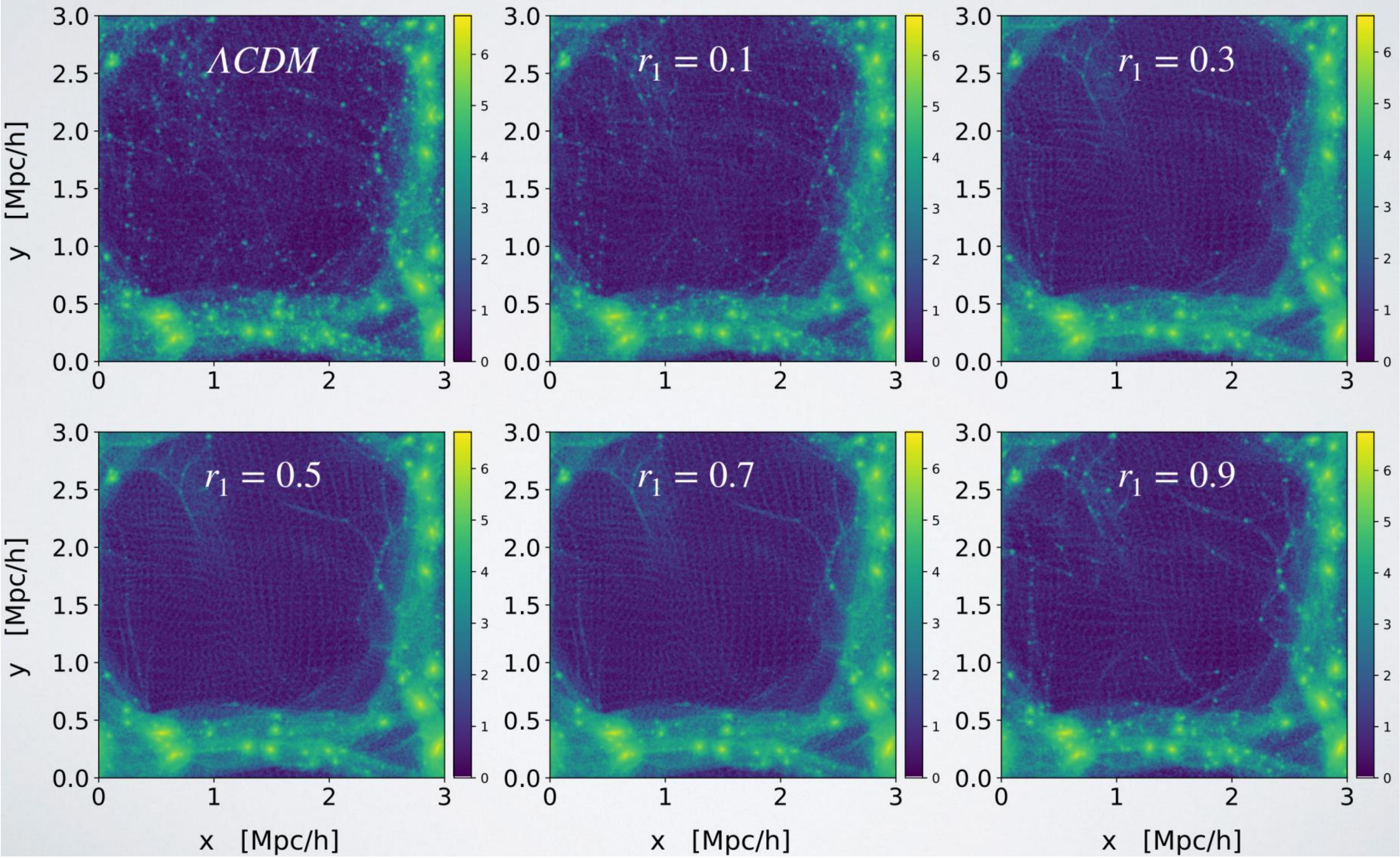
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

❖ *N*-body simulations: two-component DM simulation built on *GADGET-3* to investigate the non-linear effects ➔ There seem to be fewer sub-halos in the two-component Universe.

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

✓ $m_{\chi_2} = 30$ MeV

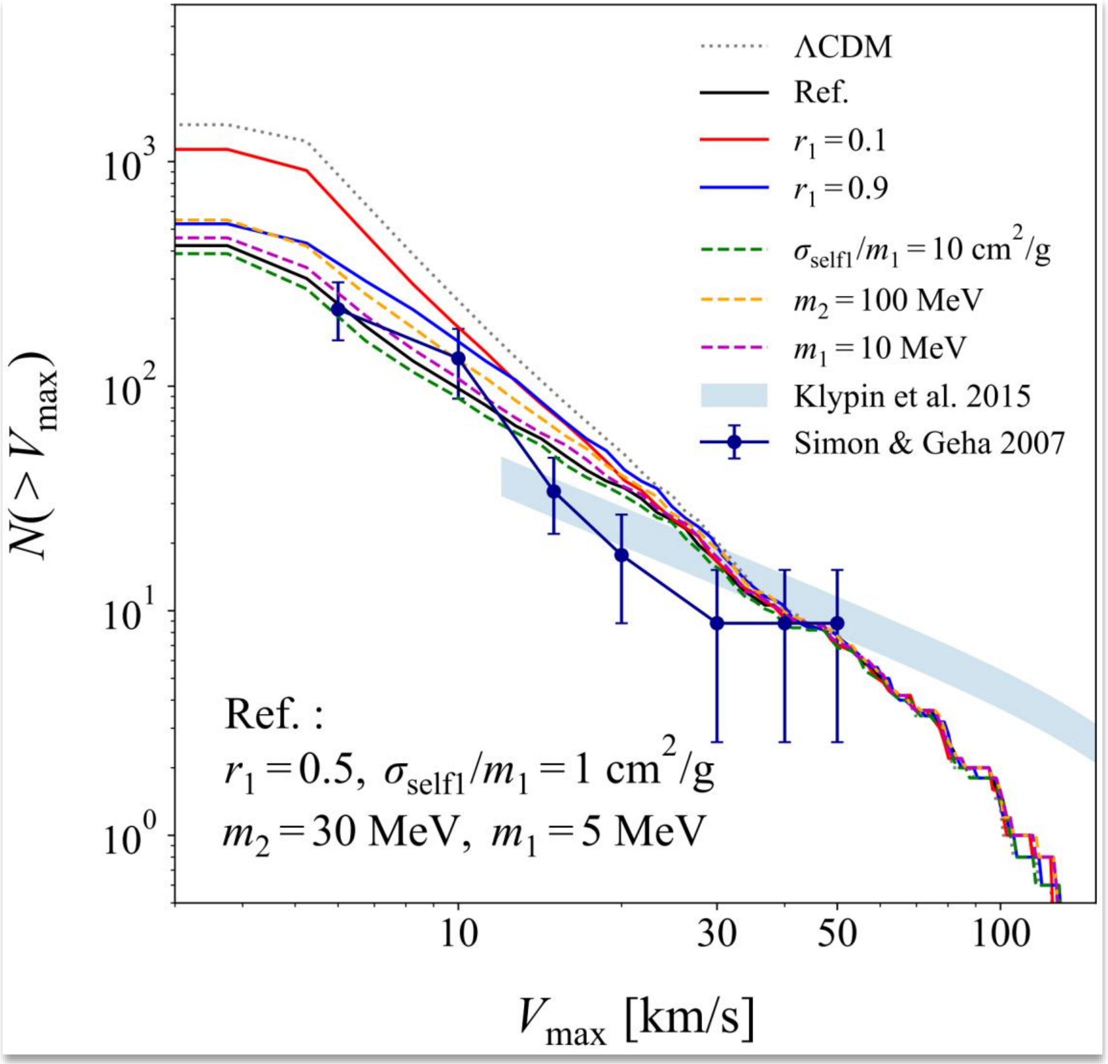
✓ $m_{\chi_1} = 5$ MeV



N-Body Simulation: Observational Constraints

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

❖ Maximum circular velocity distribution of sub-halos

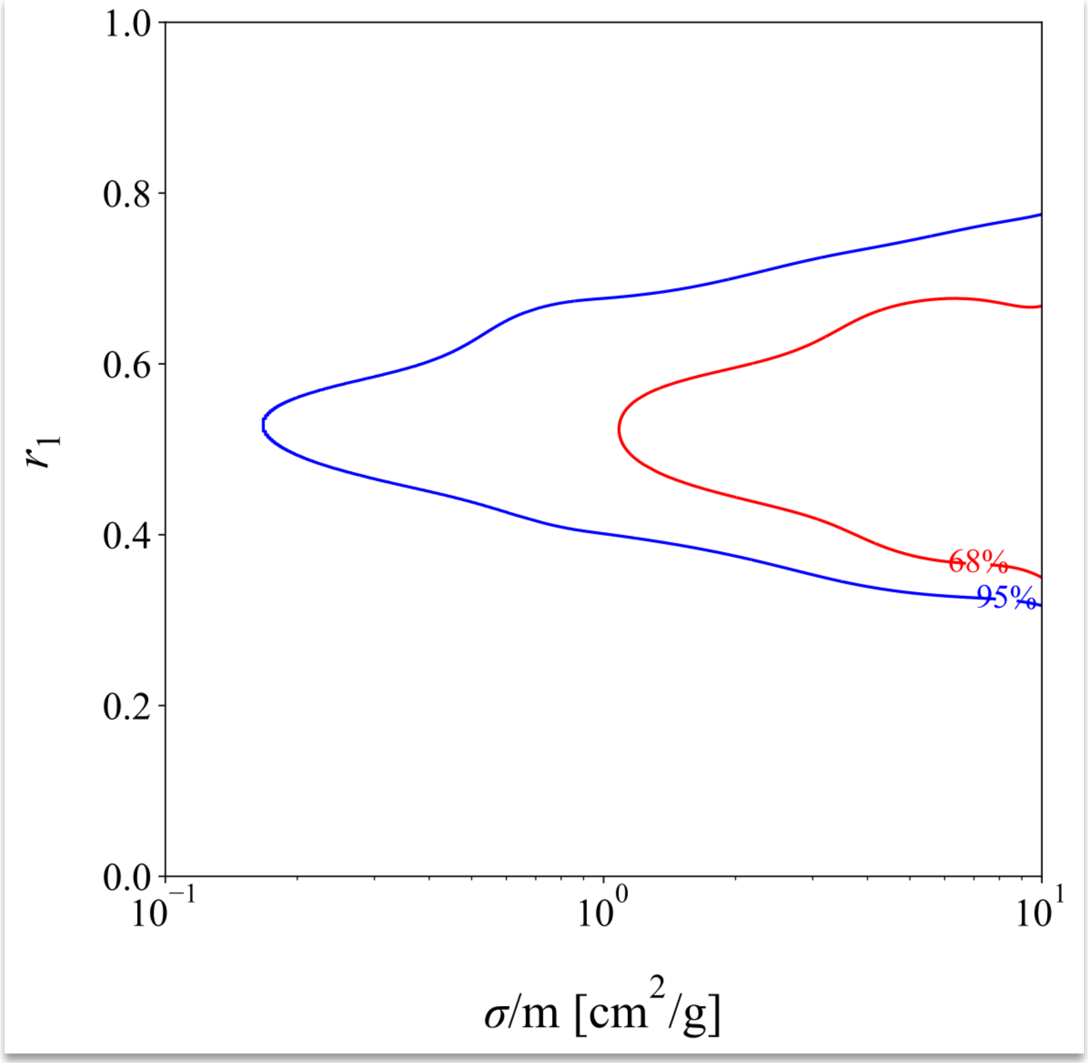


✓ The number of sub-halos is more reduced with smaller m_{χ_1} & m_{χ_2}, larger $\sigma_1^{self}/m_{\chi_1}$.

N-Body Simulation: Observational Constraints

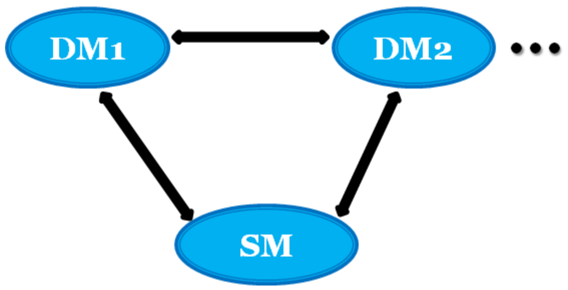
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

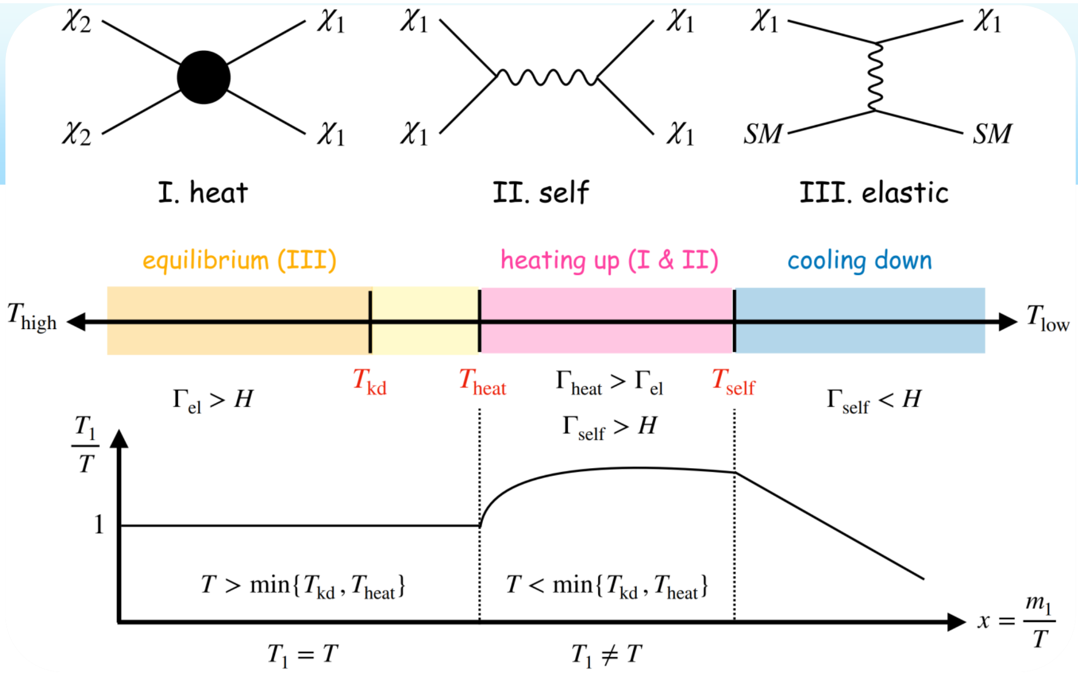
$m_{\chi_2} = 30$ MeV, $m_{\chi_1} = 5$ MeV



- ✓ We perform a chi-square test using the maximum circular velocity distribution.
- ✓ Single-component limits ($r_1 \sim 1$ or $r_1 \sim 0$) are disfavored.
- ✓ Larger $\sigma_{11\to11}/m_{\chi_1}$ is favored.

Summary





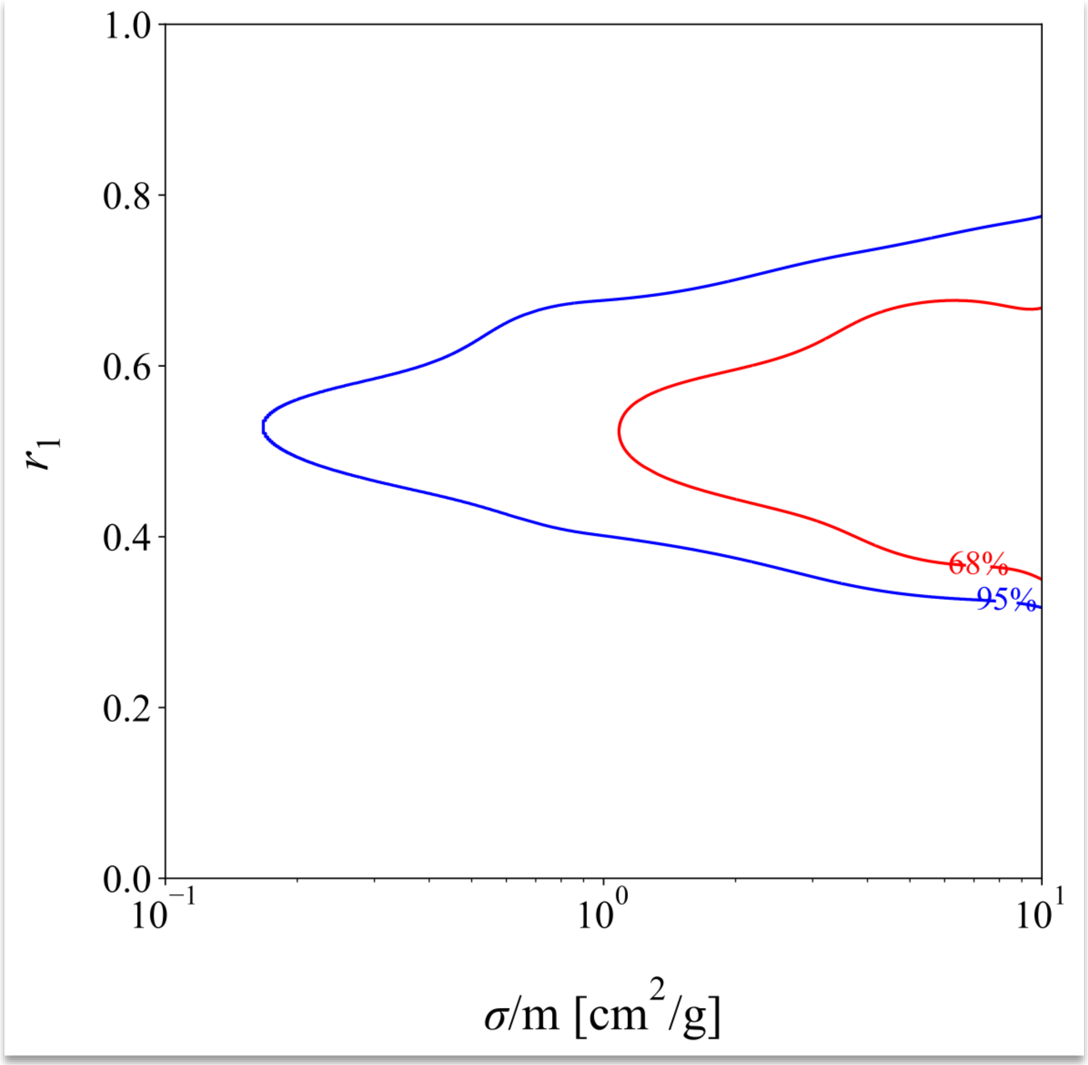
- ❖Rising interest in the dark-sector (multi-particles) scenarios & BDM (Energetic DM)
- ❖BDM searches are promising & provide a new direction to explore the dark sector physics.
- ❖Multi-comp. CDM: changes in the thermal evolution ➔ cosmic probes of the dark sector
- ❖The **even MeV-scale DM** can **behave like WDM**.
- ❖Systematic cosmological studies including *N*-body simulations ➔ interesting features!

Thank you

Supplemental

N-Body Simulation: Future Studies

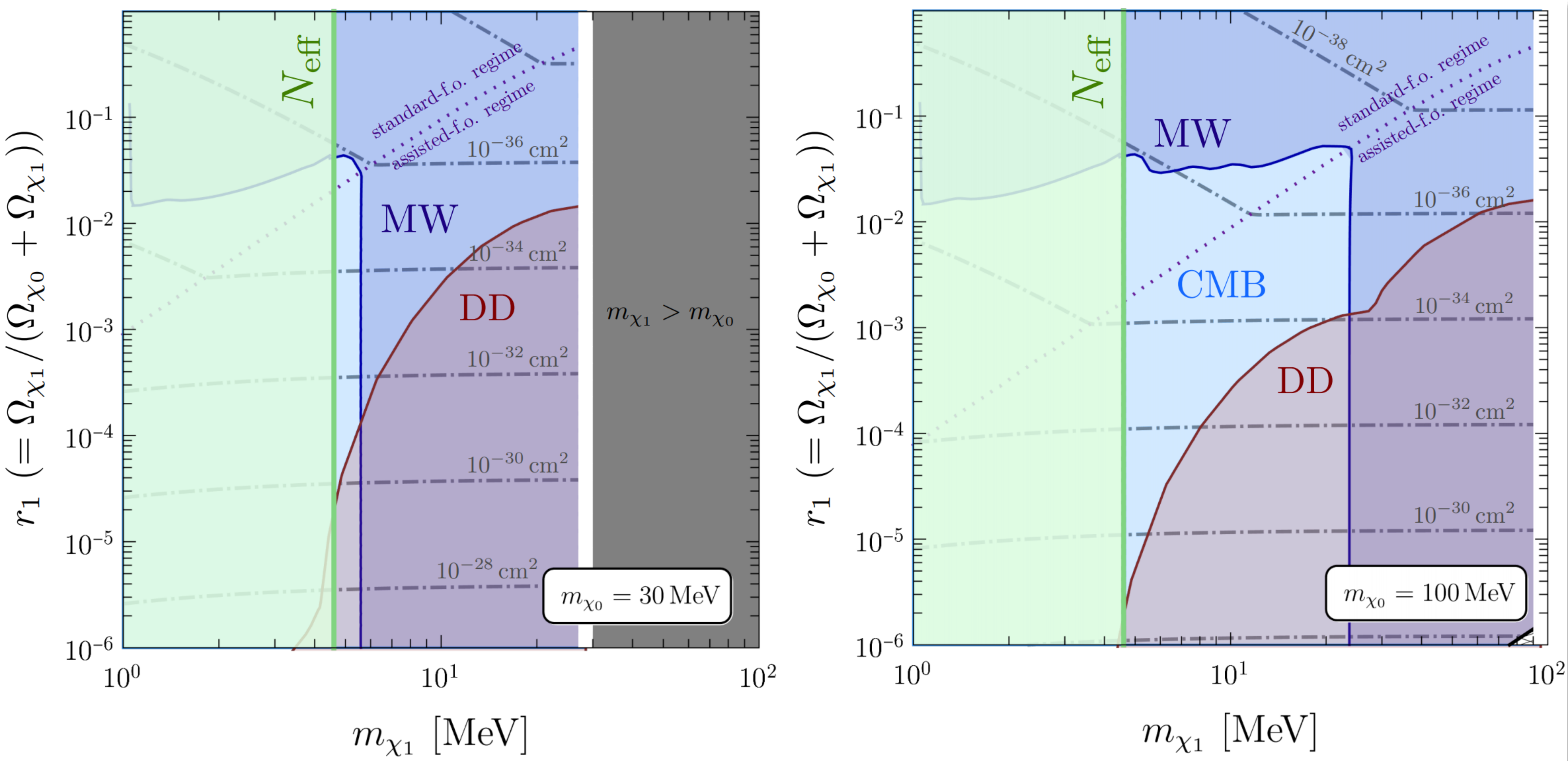
$m_{\chi_2} = 30$ MeV, $m_{\chi_1} = 5$ MeV



- ✓ How does the bound change if we include baryons in the simulation ?
- ✓ How does the bound change for different masses, m_{χ_1} and m_{χ_2} ?
- ✓ How does the bound change if we include the self-interaction of χ_2?
- ✓ What are other observables in the small scale structure?
- ✓ Is the bound compatible with direct detection experiments?

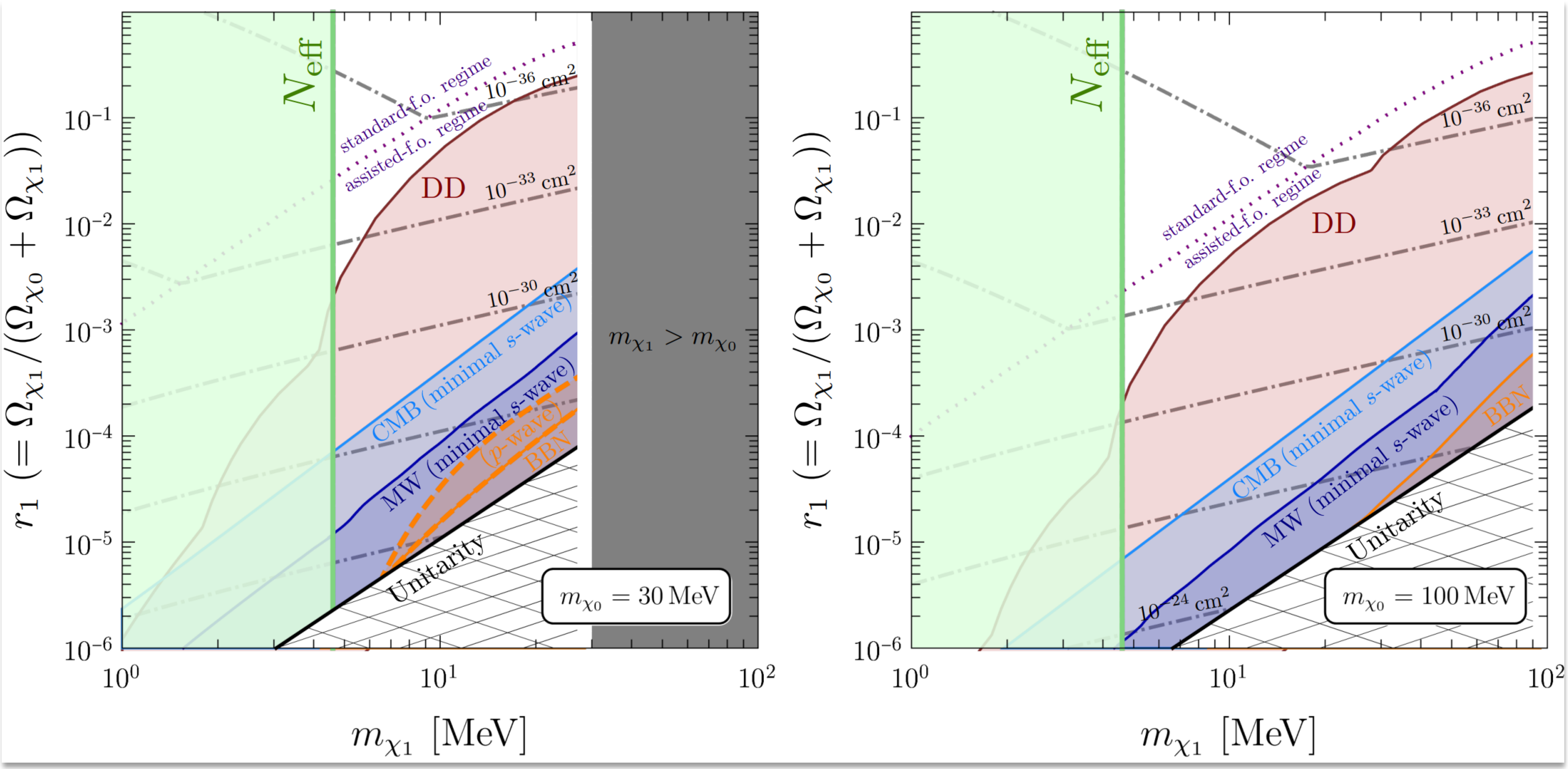
Constraints: s-wave Annihilating χ_1 w/o Self-heating

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



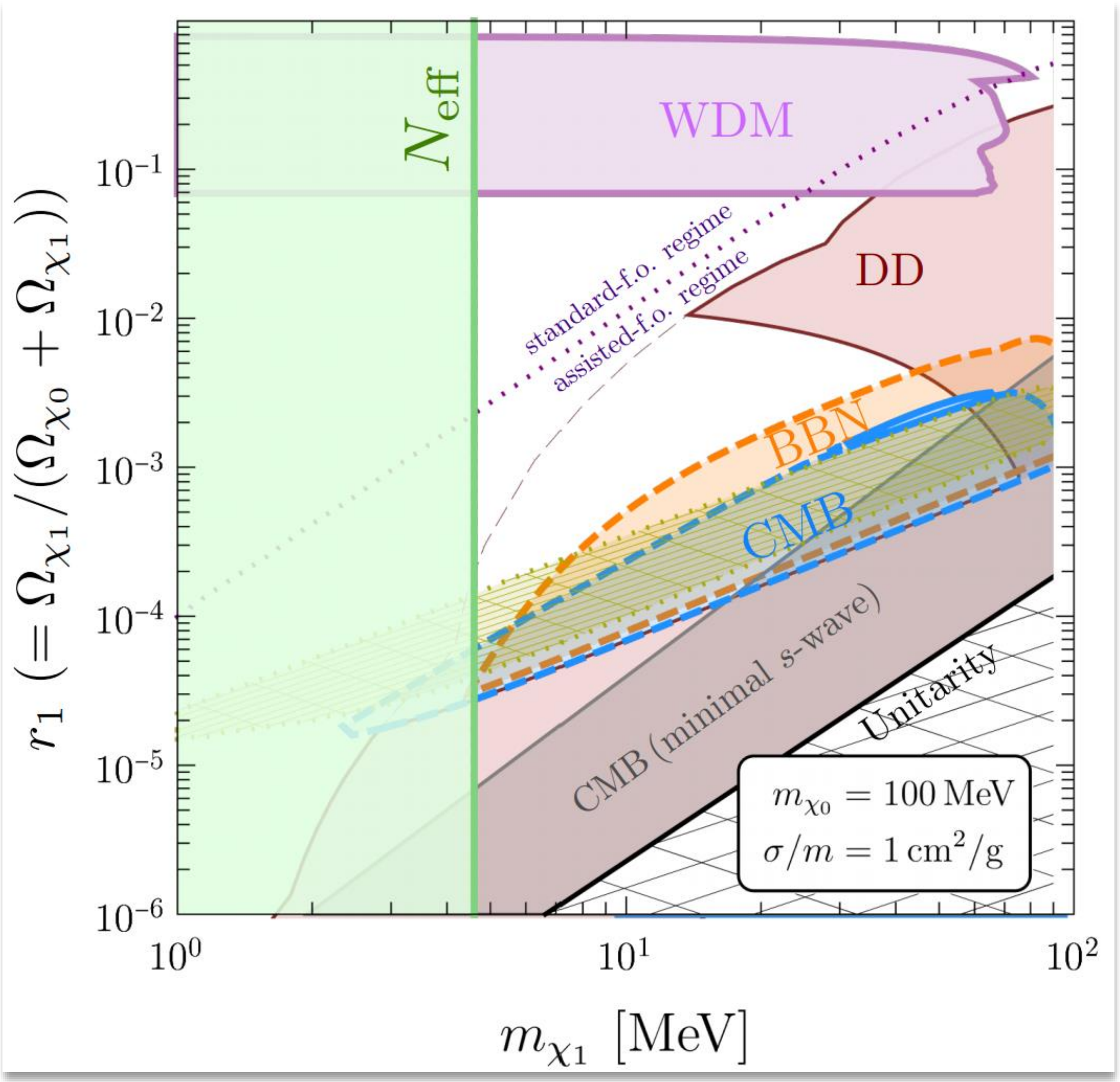
Constraints: p-wave Annihilating χ_1 w/o Self-heating

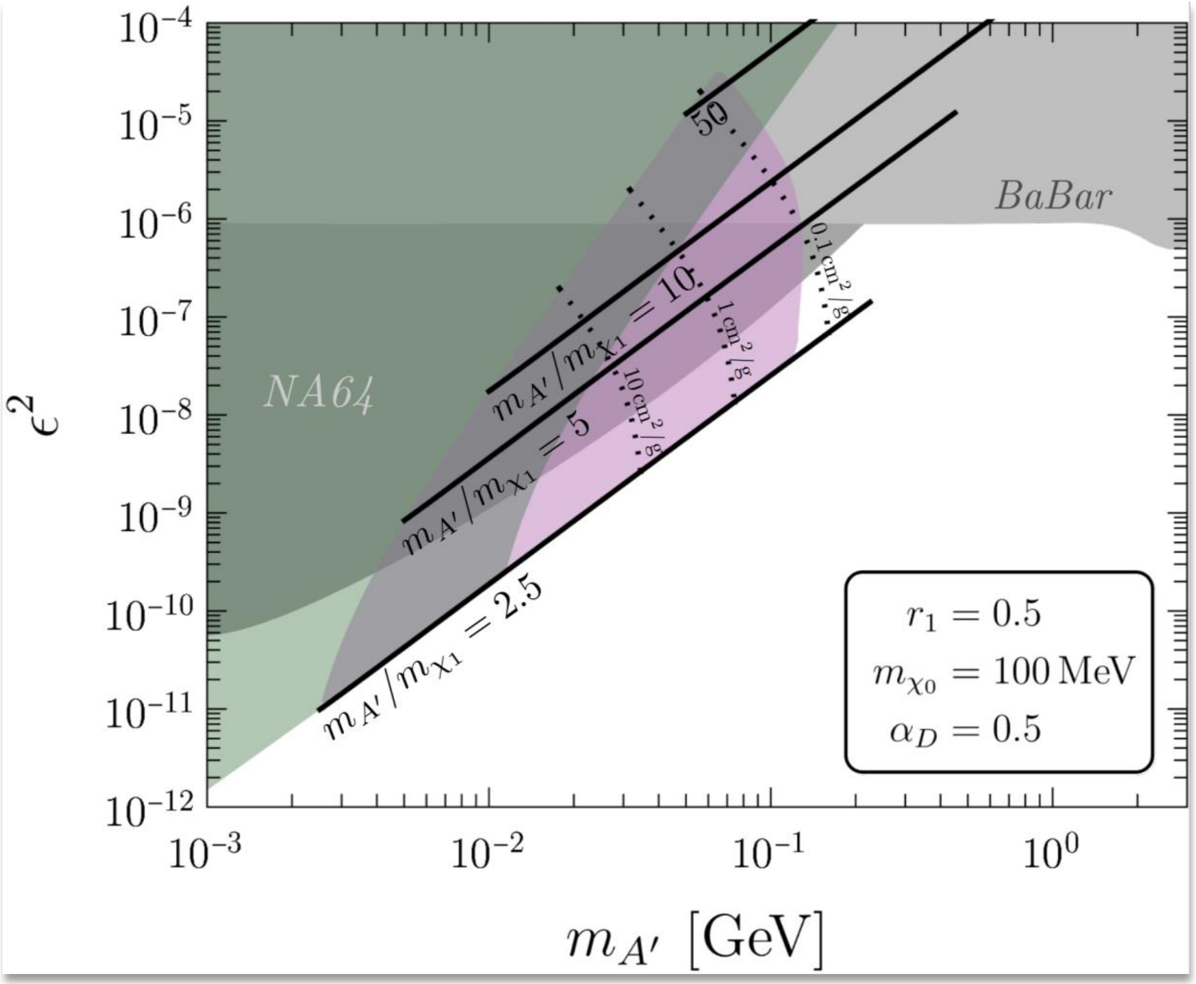
[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]



Cosmological Constraints & Dark Photon Searches

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



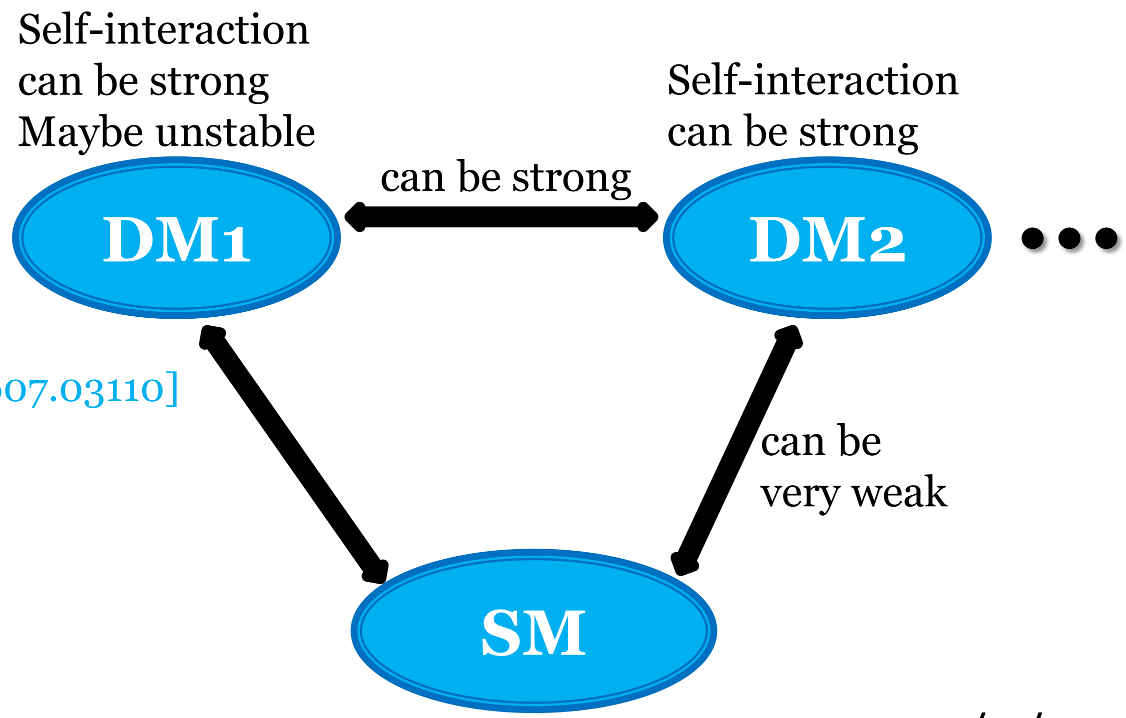


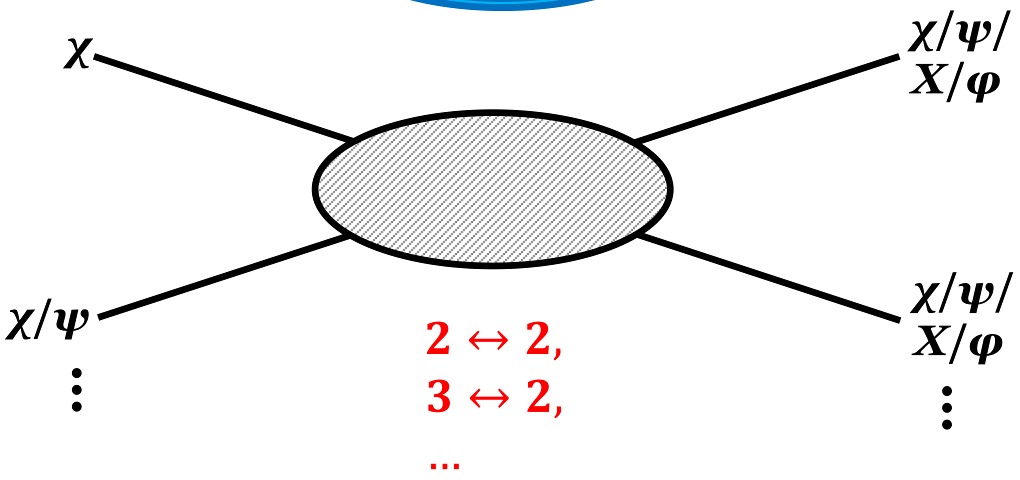
$$\mathcal{L} \supset \epsilon A'_\mu J^\mu_{\rm em} - i g_D A'_\mu \left(\chi_1^* \partial^\mu \chi_1 - \chi_1 \partial^\mu \chi_1^*\right) - \frac{\lambda_{\rm ast.}}{4} |\chi_1|^2 |\chi_0|^2$$

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]
- ✓ …

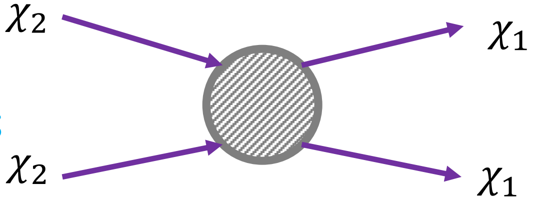




Dark Sector: DM Boosting Mechanisms

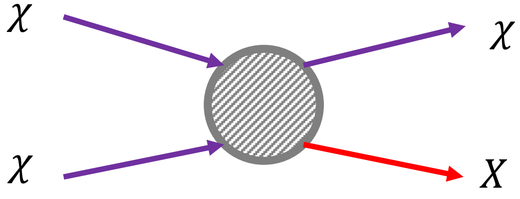
Boosted DM (BDM) coming from the Universe

[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

$m_2 \gg m_1$



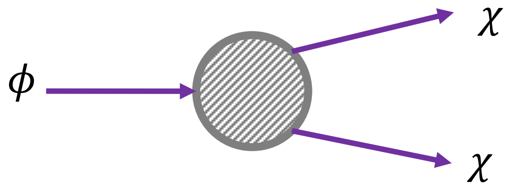
✓ Semi-annihilation model

$m_\chi \gg m_X$

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

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

❖ Relic component DM: Non-relativistic!



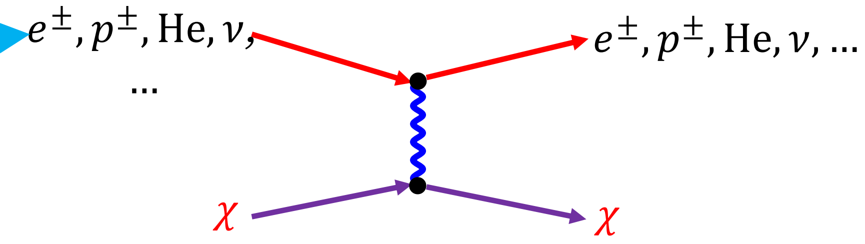
✓ Decaying multi-component DM

$m_\phi \gg m_\chi$

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

DM Boosting Mechanisms: Cosmic-Rays (CRs)

Cosmic-Ray-Induced BDM



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

  ➔ Efficient for Light DM

- **Charged** CRs: [Bringmann & Pospelov, PRL (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent & Dutta et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho et al., PRD (2020); more]
- CR $\boldsymbol{\nu}$ (**$\boldsymbol{\nu}$BDM**): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; Chao, Li, Liao, 2108.05608; Lin, Wu, Wu, Wong, 2206.06864; more]

- BDM from astrophysical processes:

Solar evaporation - Kouvaris, PRD (2015)
Dark cosmic rays - Hu +, PLB (2017)
Solar reflection - An +, PRL (2018)
Solar acceleration - Emken +, PRD (2018)
Atmospheric collider – Alvey+, PRL (2019)
PBH evaporation - Calabrese +, PRD (2022)
Blazar jets - Wang +, PRL (2022)
Supernova shocks – Cappiello
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