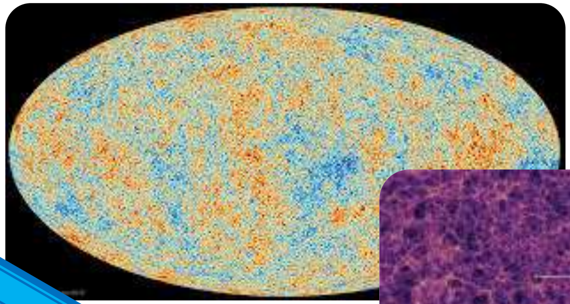
Warm Surprises from Cold Duets

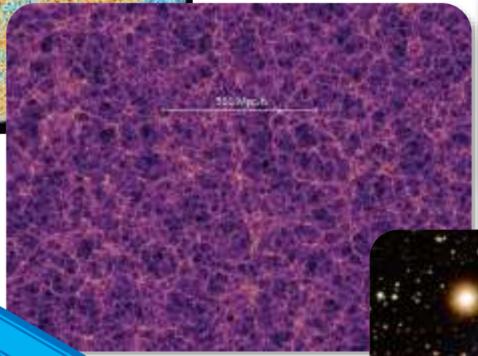
G. Belanger, **JCP** [1112.4491]
A. Kamada, H.J. Kim, **JCP**, S. Shin [2111.06808]
J.H. Kim, KC Kong, S.H. Lim, **JCP** [2312.07660 & in preparation]

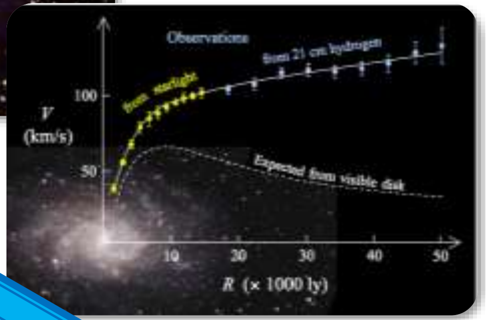
Park, Jong-Chul
CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

High1 Workshop on Particle, String & Cosmology
January 25 (2024)

Message from Cosmology: Dark Matter (DM)







Larger scale
Earlier

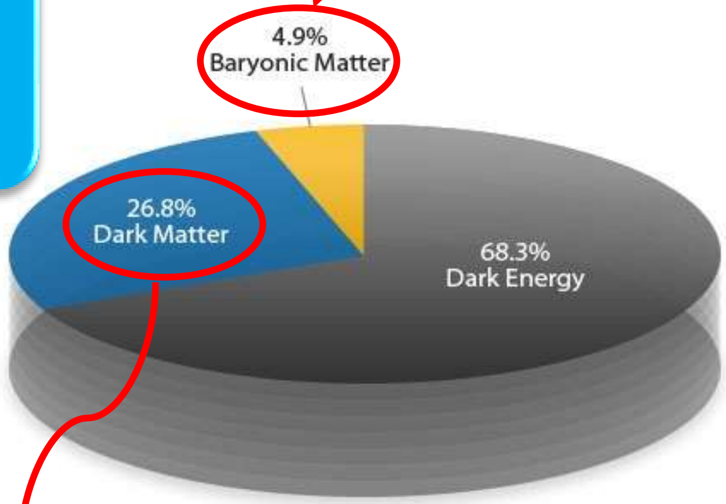
Dark Matter?

Smaller scale
Later

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

Minimal DM

Minimal Dark Matter

[hep-ph/0512090]

Marco Cirelli[a], Nicolao Fornengo[b], Alessandro Strumia[c].

$$\mathscr{L} = \mathscr{L}_{\rm SM} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin 1/2 fermionic multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin 0 bosonic multiplet} \end{cases}$$

$\mathcal{X}$ is an n-tuplet of the $\mathrm{SU}(2)_{\rm L}$ gauge group, with $n = \{1, 2, 3, 4, 5, \ldots\}$

The minimal model of fermionic dark matter

[hep-ph/0611069]

Yeong Gyun Kim, Kang Young Lee

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \mathcal{L}_{\rm int}$$

$$\mathcal{L}_{\rm DM} = \bar{\psi}\, i\gamma^\mu \partial_\mu \psi - m_0 \bar{\psi}\psi \qquad \mathcal{L}_{\rm int} = -\frac{1}{\Lambda} H^\dagger H \bar{\psi}\psi$$

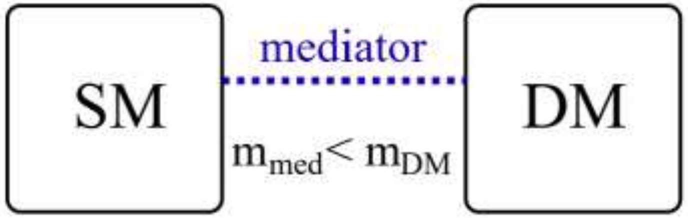
Secluded DM

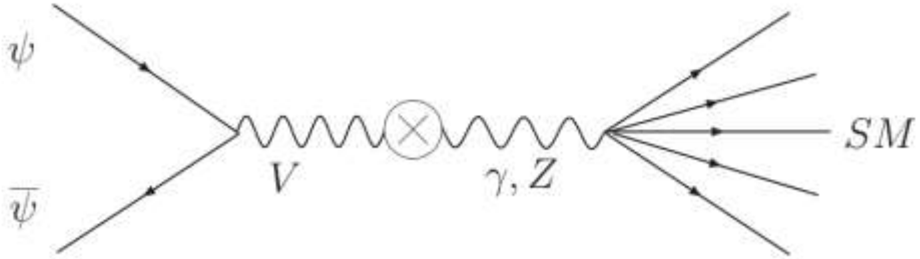
Secluded WIMP Dark Matter

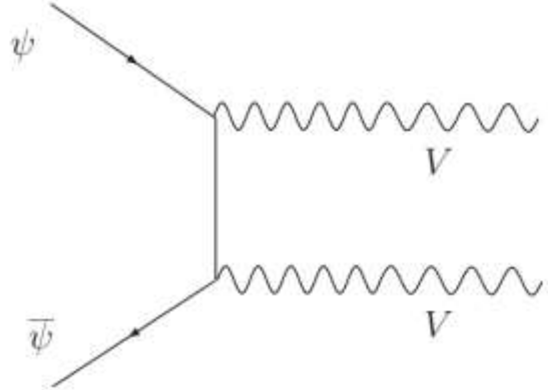
[0711.4866]

Maxim Pospelov [a,b], Adam Ritz [a] and Mikhail Voloshin [c,d]

$$\mathcal{L}_{\rm WIMP+mediator} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}B_{\mu\nu} - |D_\mu\phi|^2 - U(\phi\phi^*) + \bar{\psi}(iD_\mu\gamma_\mu - m_\psi)\psi.$$







Note added – As this paper was being finalized, we became aware of a recent preprint [36] that also deals with U(1)′ models of MeV-scale dark matter with kinetic mixing, and thus has some overlap with the discussion in Sect. 3(a,b).

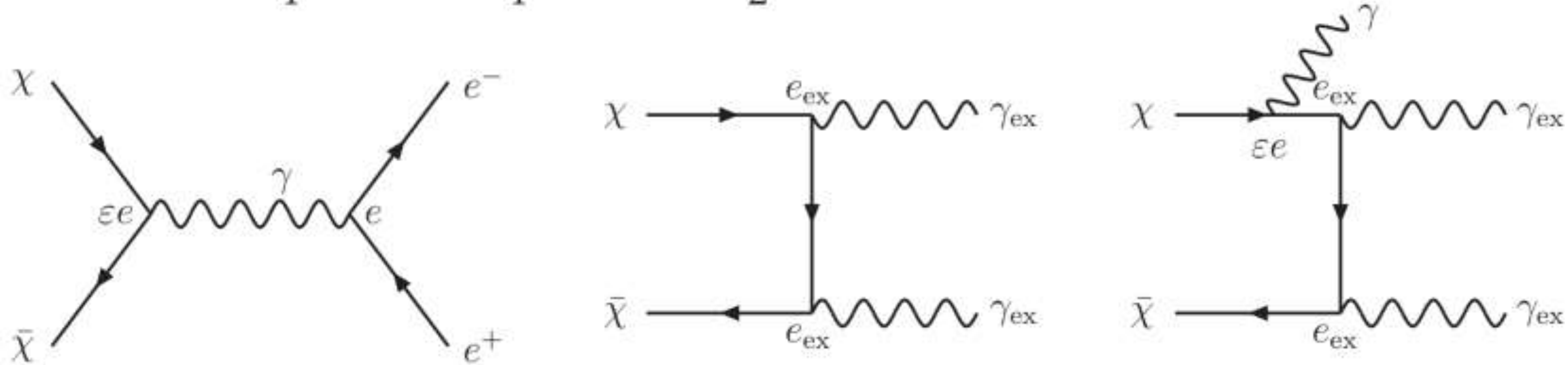
[0711.3528]

Secluded DM

Galactic 511 keV line from MeV millicharged dark matter [0711.3528]

Ji-Haeng Huh, Jihn E. Kim*, Jong-Chul Park† and Seong Chan Park‡

$$\mathcal{L} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\xi}{2}\hat{F}_{\mu\nu}\hat{X}^{\mu\nu}, \qquad \mathcal{L} = \bar{\chi}\left(\hat{e}_{\rm ex} Q_\chi \gamma^\mu\right)\chi \hat{X}_\mu,$$



[1011.3300]

Singlet fermionic dark matter [0803.2932]

Kang Young Lee Yeong Gyun Kim, Seodong Shin

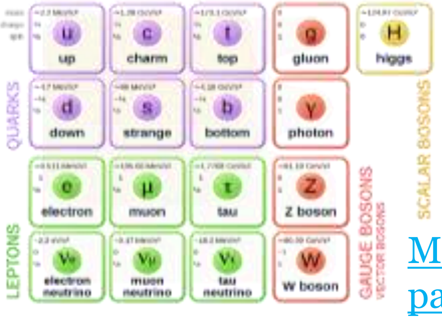
$$\mathcal{L}_{hid} = \mathcal{L}_S + \mathcal{L}_\psi - g_S\bar{\psi}\psi S, \ \mathcal{L}_{int} = -\lambda_1 H^\dagger H S - \lambda_2 H^\dagger H S^2.$$

Dark matter and a new gauge boson through kinetic mixing

Eung Jin Chun Jong-Chul Park Stefano Scopel

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\sin\epsilon\, \hat{B}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - g_X\hat{X}^\mu\bar{\psi}\gamma_\mu\psi + \frac{1}{2}m_{\hat{X}}^2\hat{X}^2 + m_\psi\bar{\psi}\psi$$

Dark Sector: Dark Particles & Portals



Multiple stable & unstable particles, Various interactions

Multiple stable & unstable particles, Various interactions?

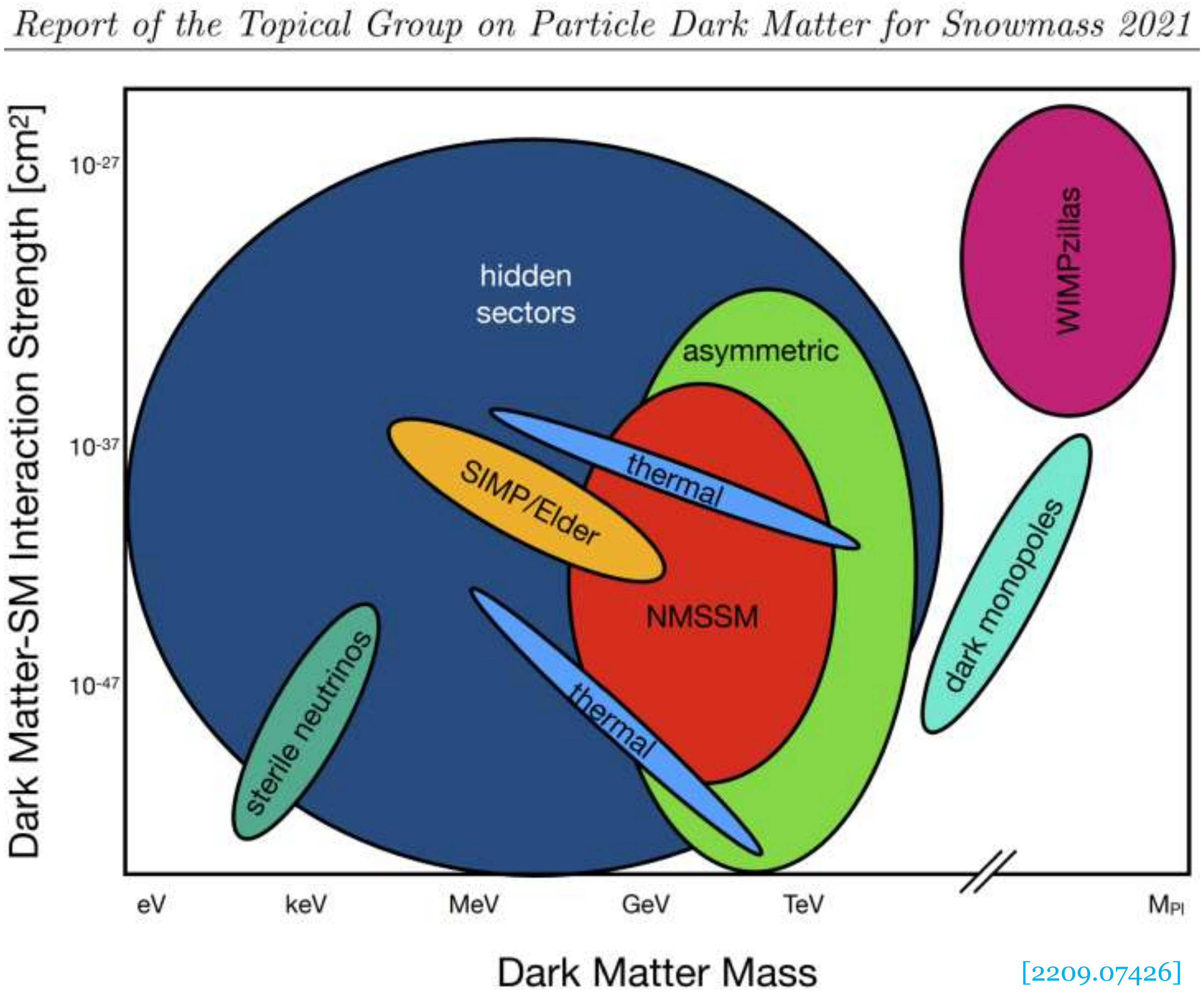
- **Portals**: mediators
  - ✓ Vector portal (kinetic mixing): $\frac{\sin\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$
  - ✓ Scalar (Higgs) portal: $\lambda_{H\phi} |H|^2 |\phi|^2$
  - ✓ Fermion (neutrino) portal: $\lambda_\chi H L \chi$
  - ✓ Pseudo-scalar (axion) portal: $\frac{1}{f_{a\gamma/ag}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

    $\frac{1}{f_{af}} \partial_\mu a (\bar{\psi} \gamma^\mu \gamma^5 \psi)$
  - ✓ 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_μ-L_τ, …
  - ✓ Dark axion portal: $G_{a\gamma\gamma'} a F_{\mu\nu} \tilde{X}^{\mu\nu}$
  - ✓ Double portal: combination of portals [Belanger, Goudelis, **JCP** (2013)]
  - ✓ ???

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

    flavor-changing (inelastic)
  - ✓ ???

Dark Sector or Hidden Sector

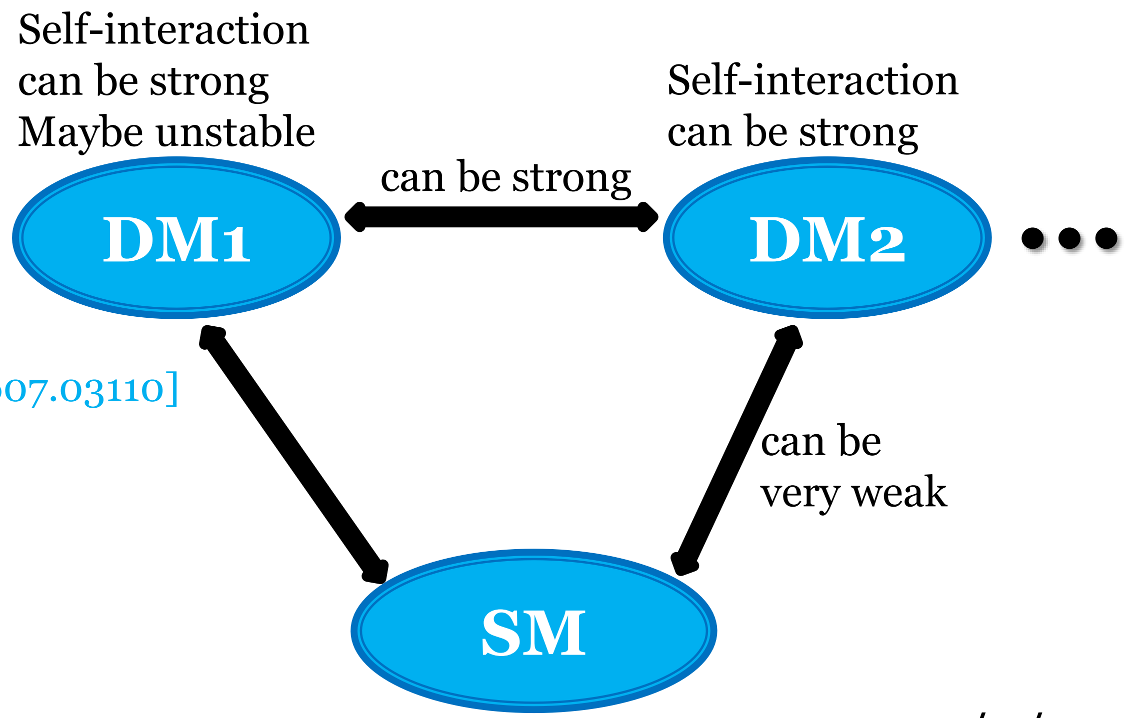


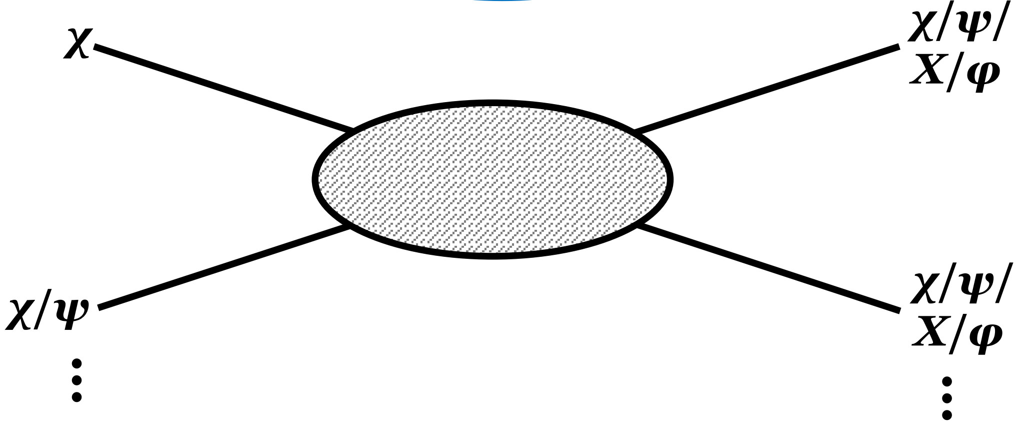
[2209.07426]

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]
- ✓ …

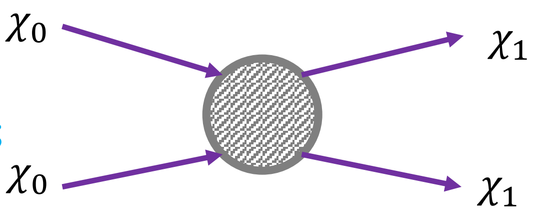




Dark Sector: DM Boosting Mechanisms

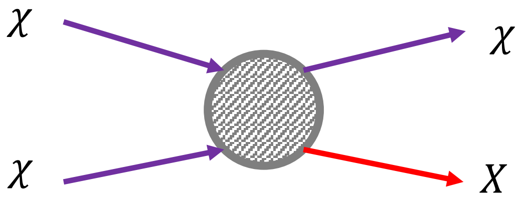
Boosted DM (BDM) coming from the Universe

[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

$m_0 \gg m_1$



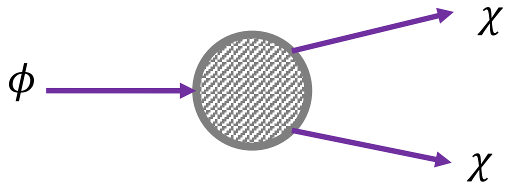
[D'Eramo & Thaler, JHEP (2010);
Berger et al., JCAP (2015)]

✓ Semi-annihilation model

$m_\chi \gg m_X$

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

- Relic component DM: Non-relativistic!



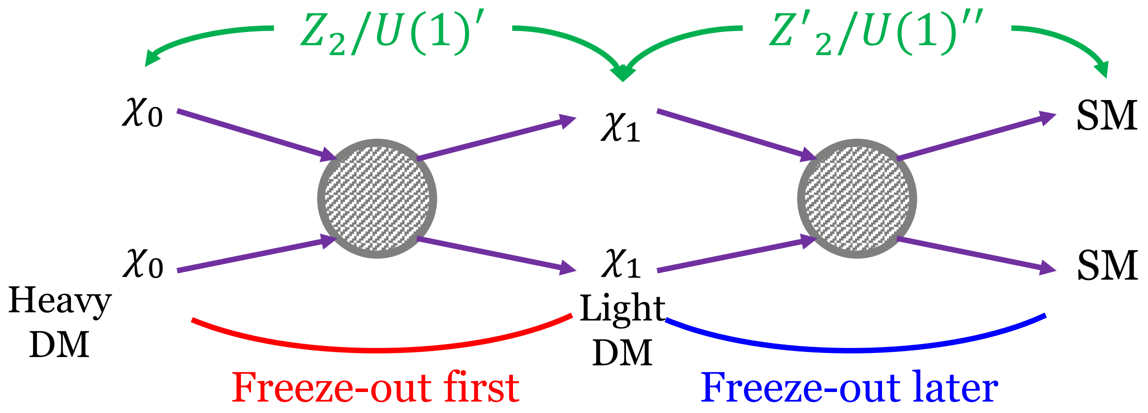
[Bhattacharya et al., JCAP (2015);
Kopp et al., JHEP (2015);
Cline et al., PRD (2019);
Heurtier, Kim, **JCP**, Shin, PRD (2019);
more]

✓ Decaying multi-component DM

$m_\phi \gg m_\chi$

Two-Component Scenario: Freeze-out

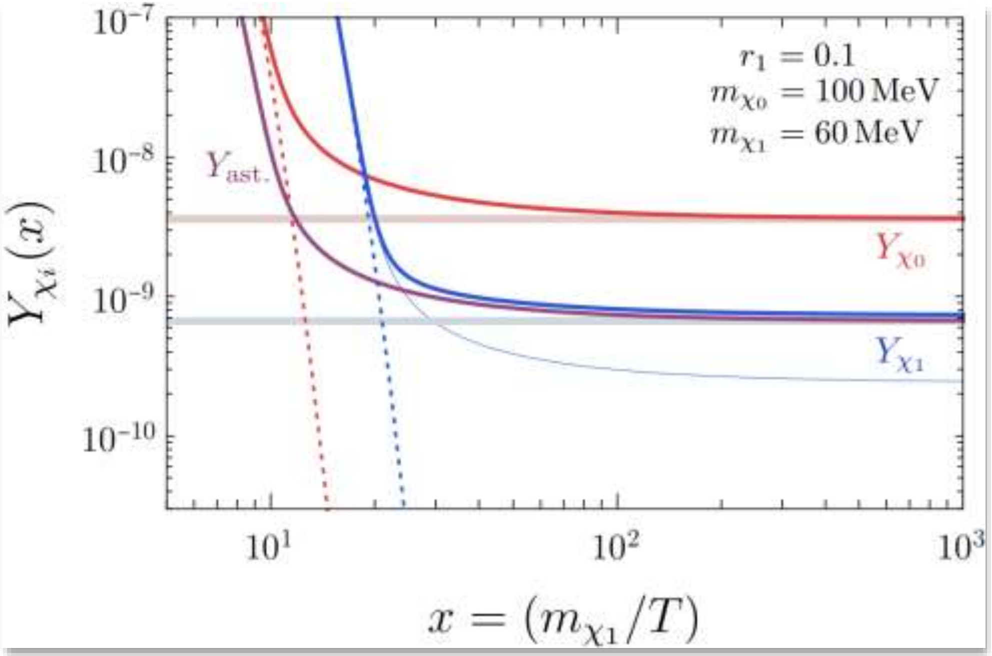
[Belanger, **JCP**, JCAP (2012)]
[Kamada, Kim, **JCP**, Shin, JCAP (2022)]



"Assisted Freeze-out" Mechanism

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

Thermal relic: $Y_i = n_i/s$

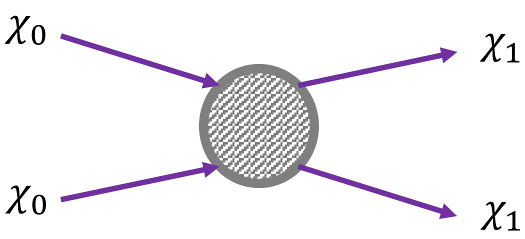


$$\frac{dY_{\chi_0}}{dx} = -\frac{\lambda_{\chi_0}(x)}{x}\left[Y_{\chi_0}^2 - \left(\frac{Y_{\chi_0}^{\mathrm{eq}}(x)}{Y_{\chi_1}^{\mathrm{eq}}(x)}\right)^2 Y_{\chi_1}^2\right],$$

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

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

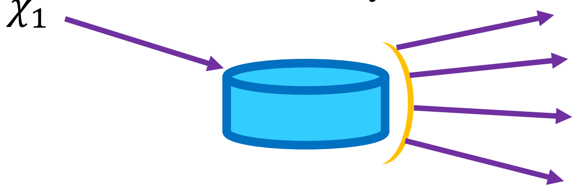
Two-Component Scenario: BDM Signatures



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

becomes boosted

($\gamma_1 = m_0/m_1$)

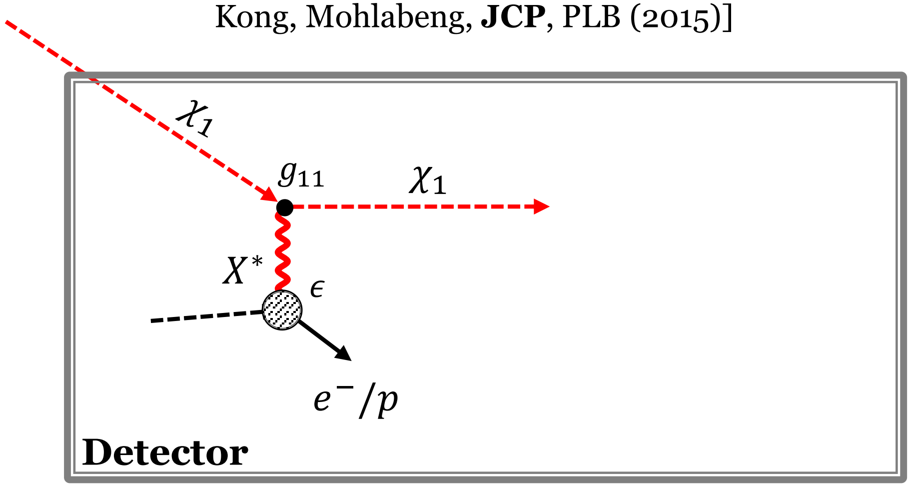


$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\text{l.o.s.}} ds \langle\sigma v\rangle_{\chi_0\bar{\chi}_0\rightarrow\chi_1\bar{\chi}_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

$$= 8.0\times10^{-5}\ \text{cm}^{-2}\text{s}^{-1}\times\left(\frac{\langle\sigma v\rangle_{\chi_0\bar{\chi}_0\rightarrow\chi_1\bar{\chi}_1}}{5\times10^{-26}\ \text{cm}^3\text{s}^{-1}}\right)\left(\frac{\text{GeV}}{m_0}\right)^2\frac{dN_1}{dE_1}$$

elastic scattering (eBDM)

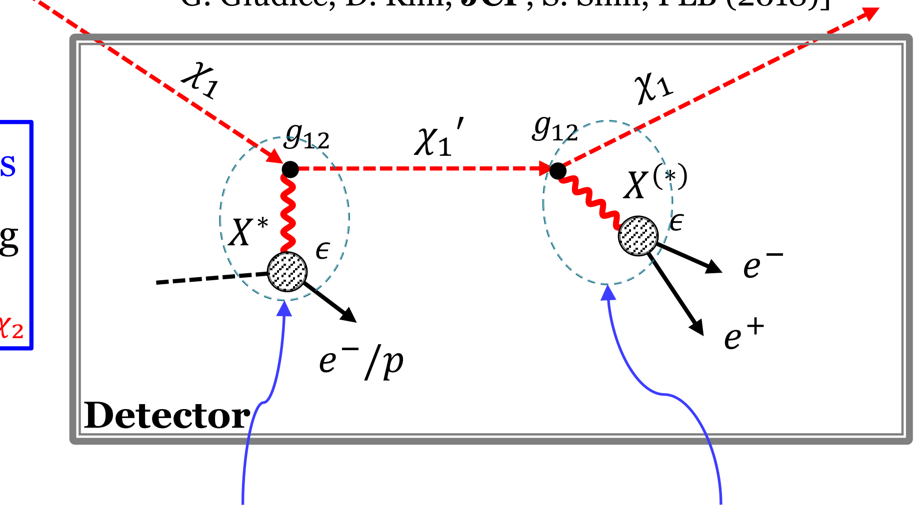
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]



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

inelastic scattering (*i*BDM)

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

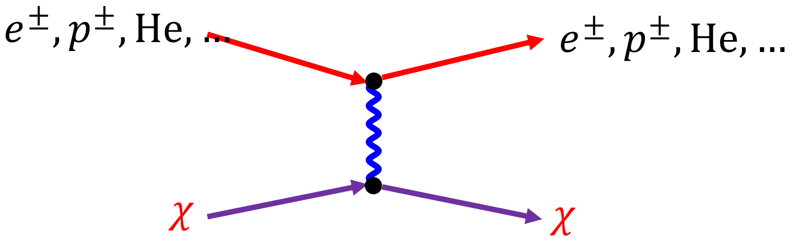


p- or e-scattering (primary) Decay (secondary)

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

DM Boosting Mechanisms: Cosmic-Ray

Cosmic-Ray-Induced BDM



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

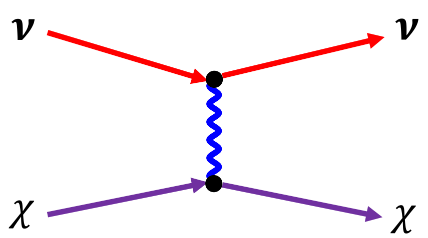
- Charged cosmic-ray:
  [Bringmann & Pospelov, PRL (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent & Dutta et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho et al., PRD (2020); more]

- 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), Plestid & Takhistov+, PRD (2020)
  PBH evaporation - Calabrese +, PRD (2022)
  Blazar jets - Wang +, PRL (2022)
  Supernova shocks – Cappiello
  more

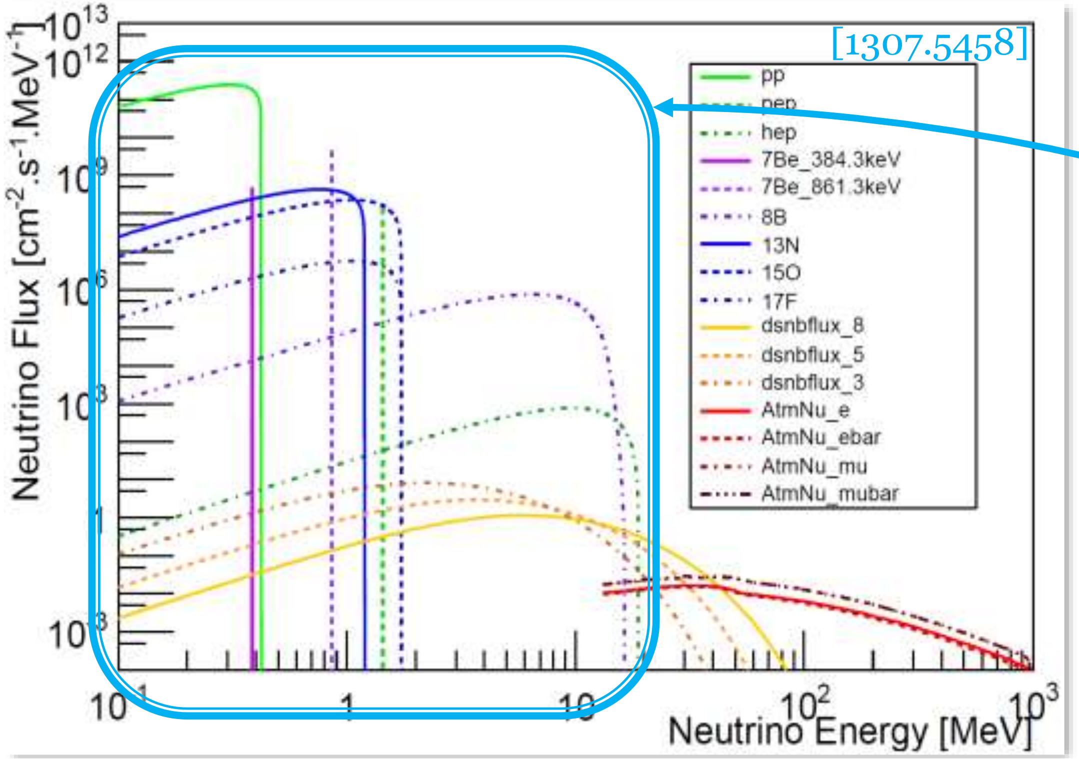
Cosmic-ray Neutrino BDM: νBDM

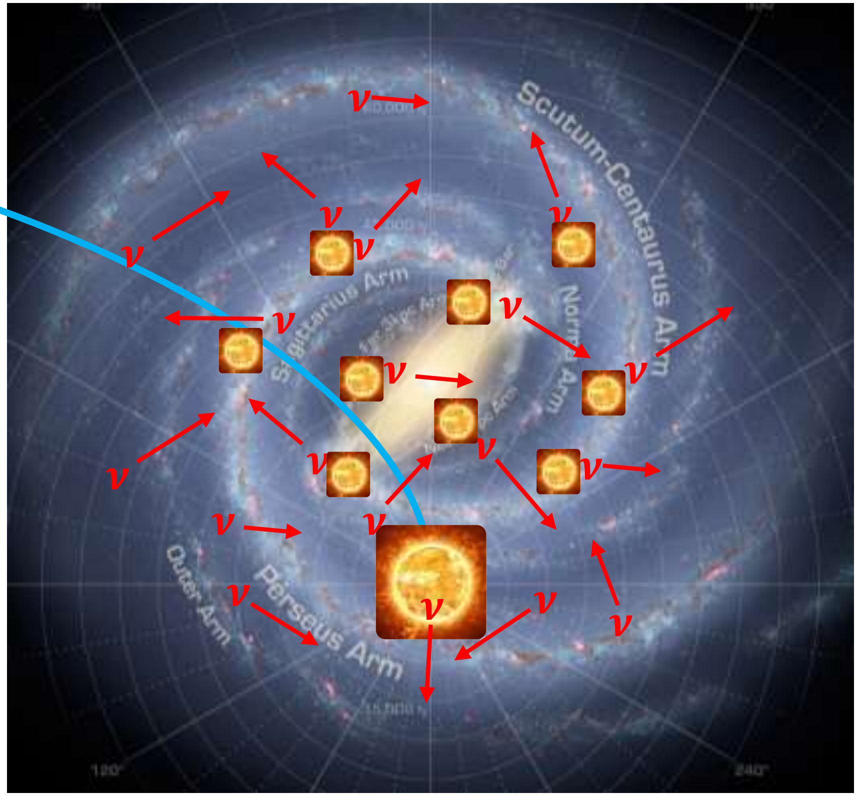
[Jho, **JCP**, Park & Tseng, 2101.11262]

- ✓ $g_\nu^{med} \simeq g_e^{med}$ & $\Phi_\nu \gg \Phi_e$
- ✓ Non-relativistic **halo DM** can be boosted by **<u>ν's in the galaxy</u>** **& <u>extra galaxies</u>.**



Large E_k^χ due to **E_k^ν transfer**





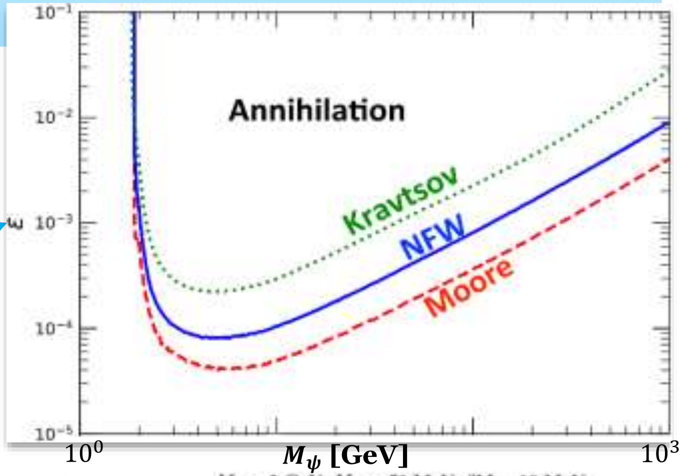
BDM Searches @ Neutrino Experiments

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

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

Editors' Suggestion

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



v_{DM}~c → even ν detector
w/ high E_{th} is OK!

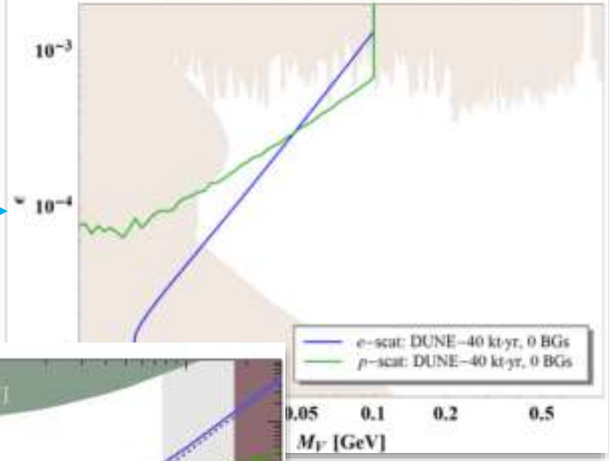
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

Regular Article - Experimental Physics

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

DUNE Collaboration

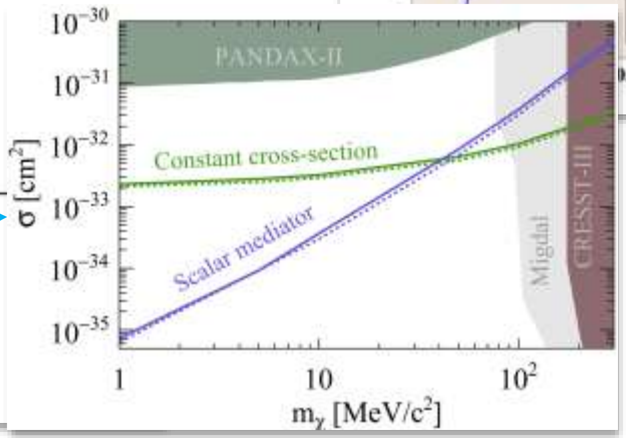
M_Ψ = 2 GeV, M_χ = 50 MeV, δM = 10 MeV



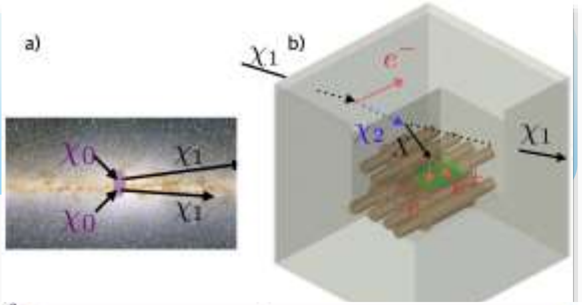
PHYSICAL REVIEW LETTERS **130,** 031802 (2023)

Editors' Suggestion | Featured in Physics

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



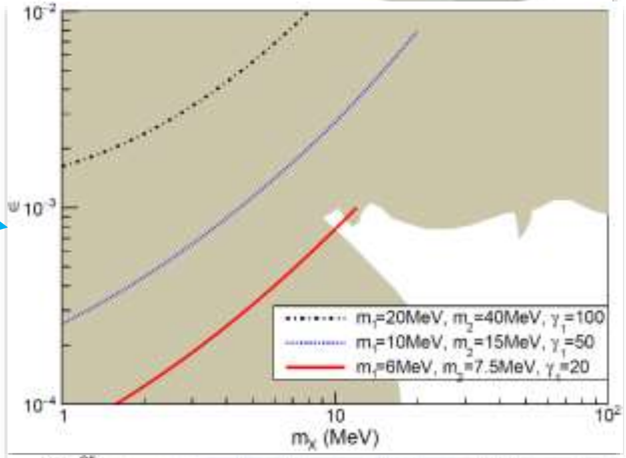
BDM Searches @ DM Experiments



PHYSICAL REVIEW LETTERS 122, 131802 (2019)

Editors' Suggestion

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

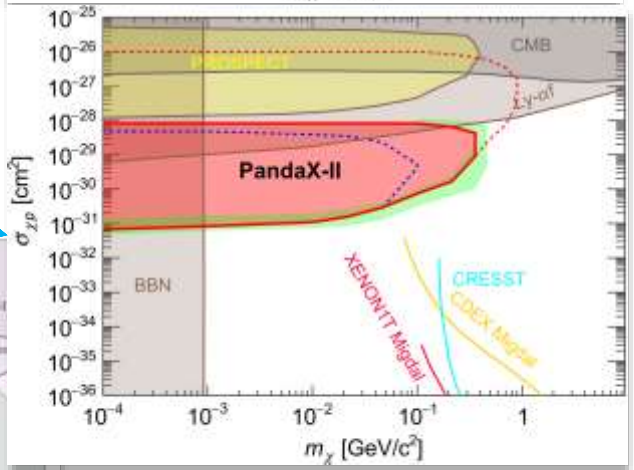


PHYSICAL REVIEW LETTERS 128, 171801 (2022)

Editors' Suggestion

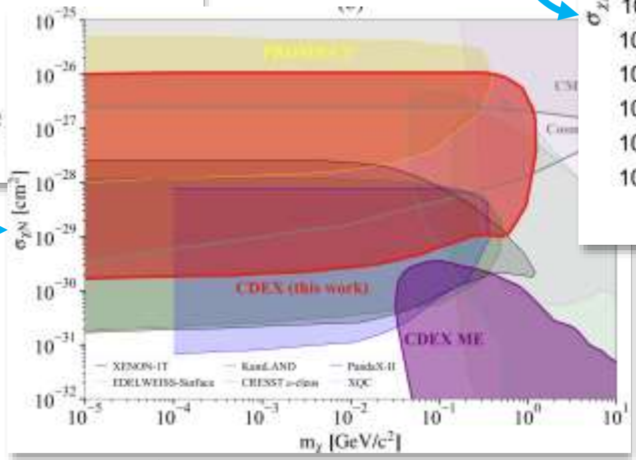
Search for Cosmic-Ray Boosted Sub-GeV I

Pumping up the flux
➔ DM detector is OK!



PHYSICAL REVIEW D 106, 052008 (2022)

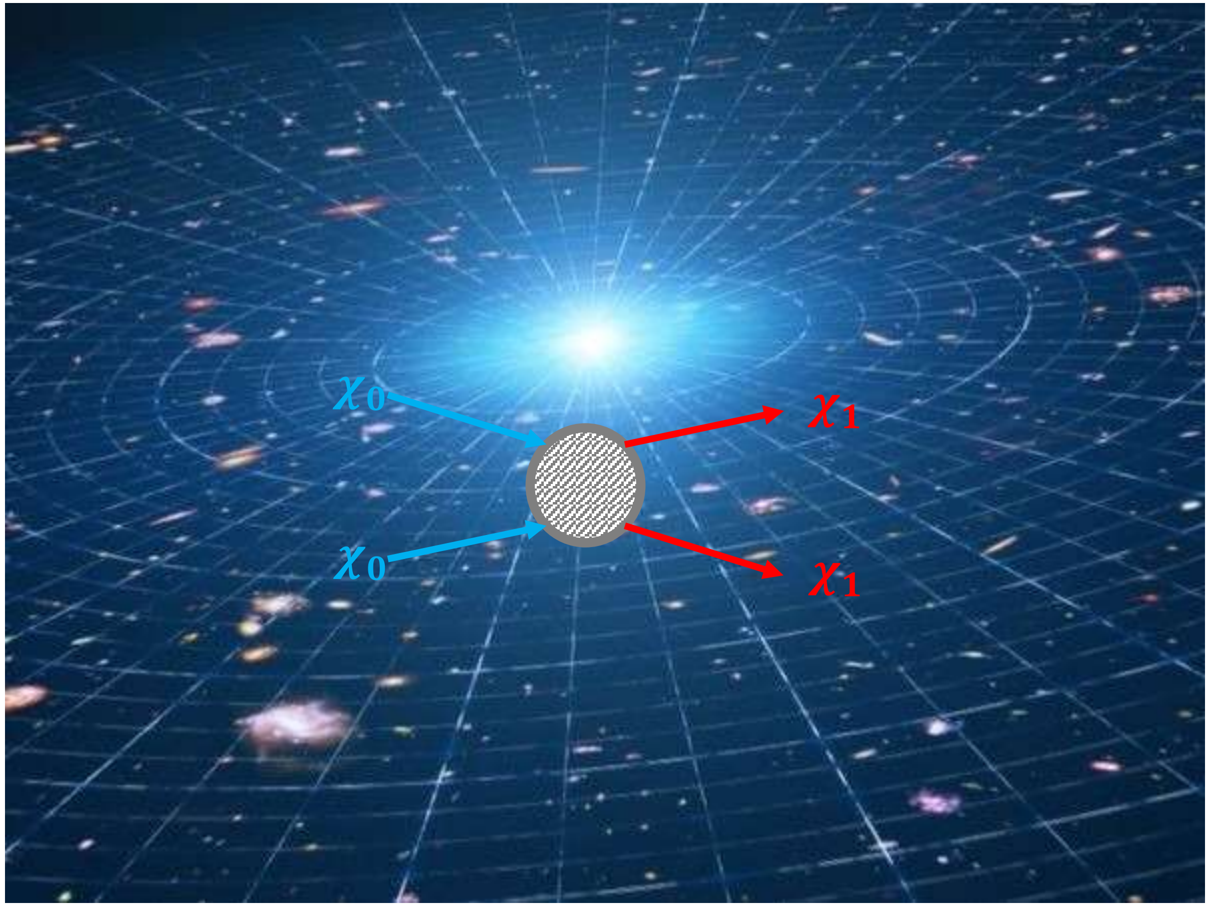
Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory



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

Any Effects of Energetic DM on Cosmology?

BDM=Hot DM?

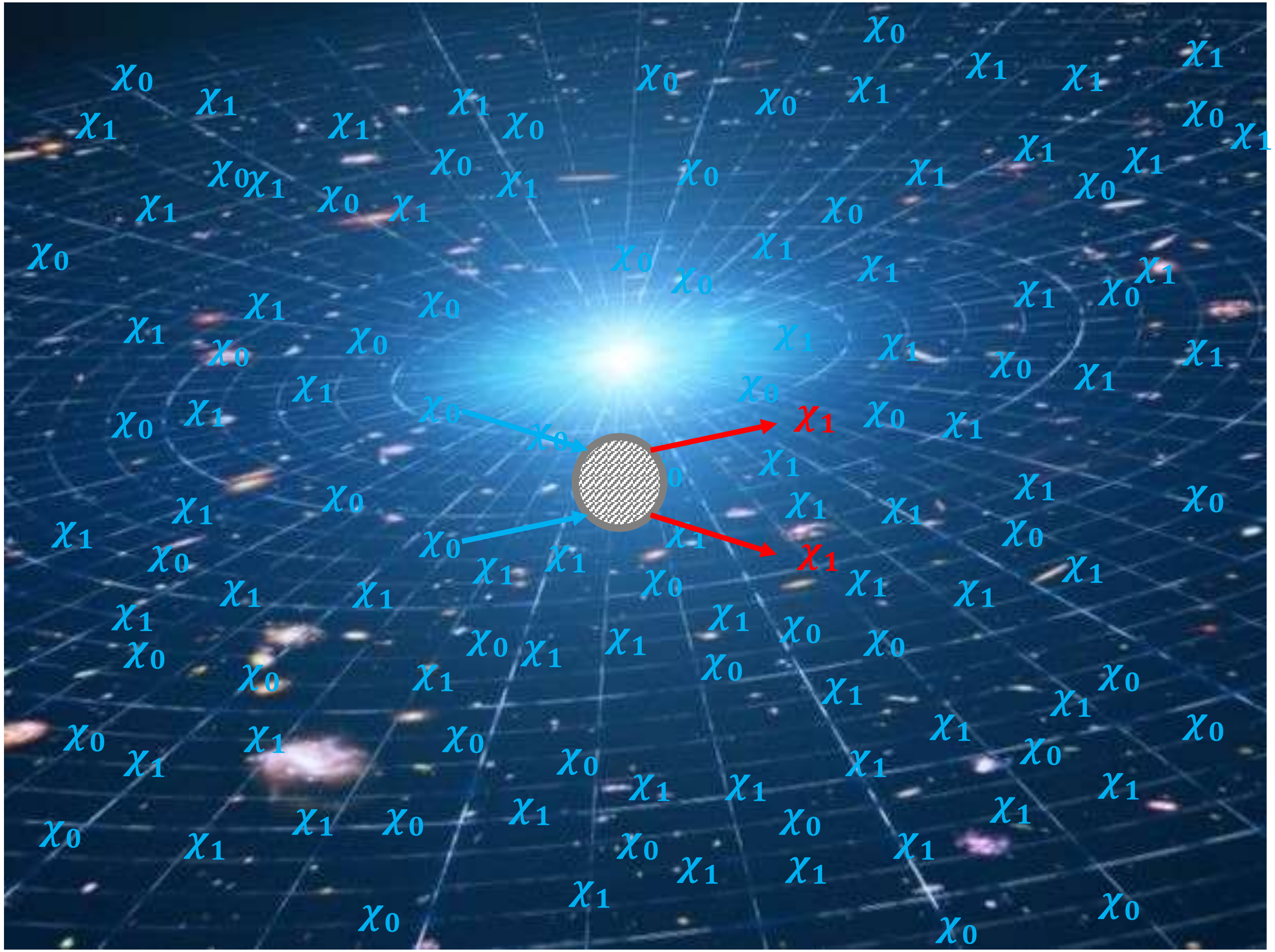


✓ χ_0: heavy DM, χ_1: light DM

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

- $\chi_0\chi_0 \to \boldsymbol{\chi_1\chi_1}$ Vs $\chi\chi \to \boldsymbol{\nu\nu}$
- $n_{\chi_1} \propto \frac{\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{m_0^2}$ with $\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1} \sim 10^{-26}\ \mathrm{cm^3/s}$

Heating via Self-Scattering?



Heating via Self-Scattering?

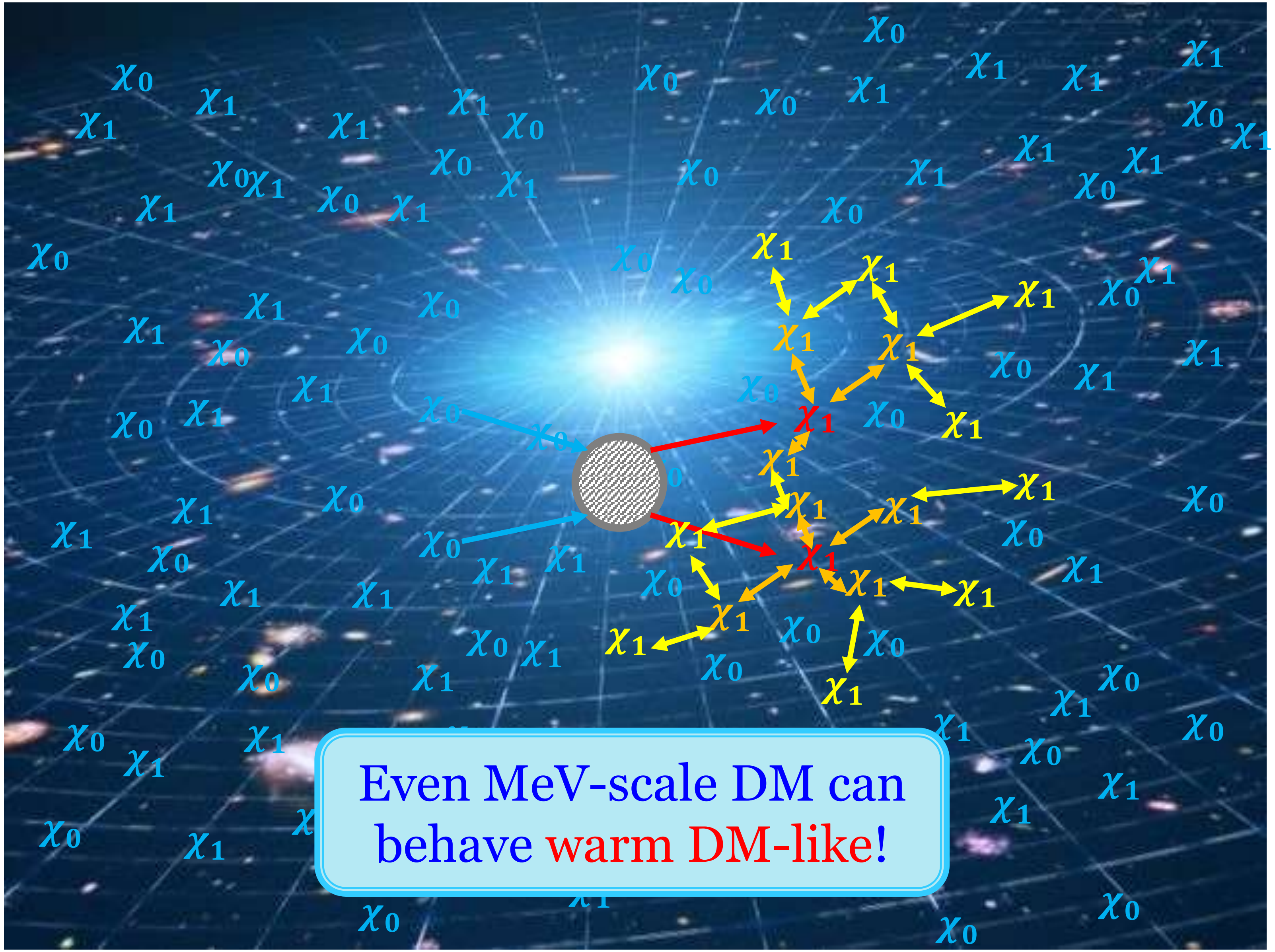
Large self-scattering is quite natural for light dark sector!

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

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

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

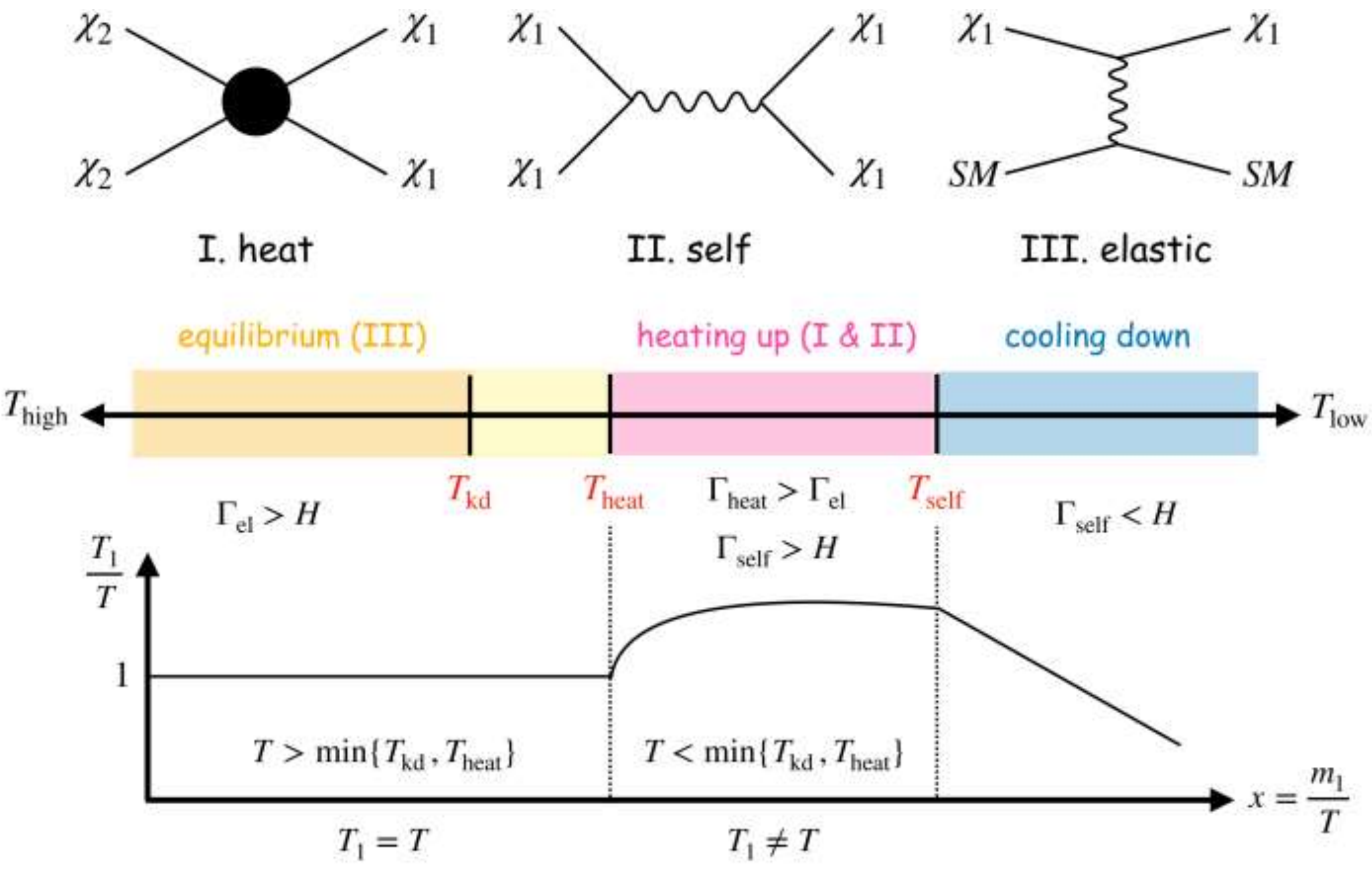
➔ $\sigma_{\chi_1}^{\text{self}} / m_{\chi_1} \approx O(1\ \text{cm}^2/\text{g})$

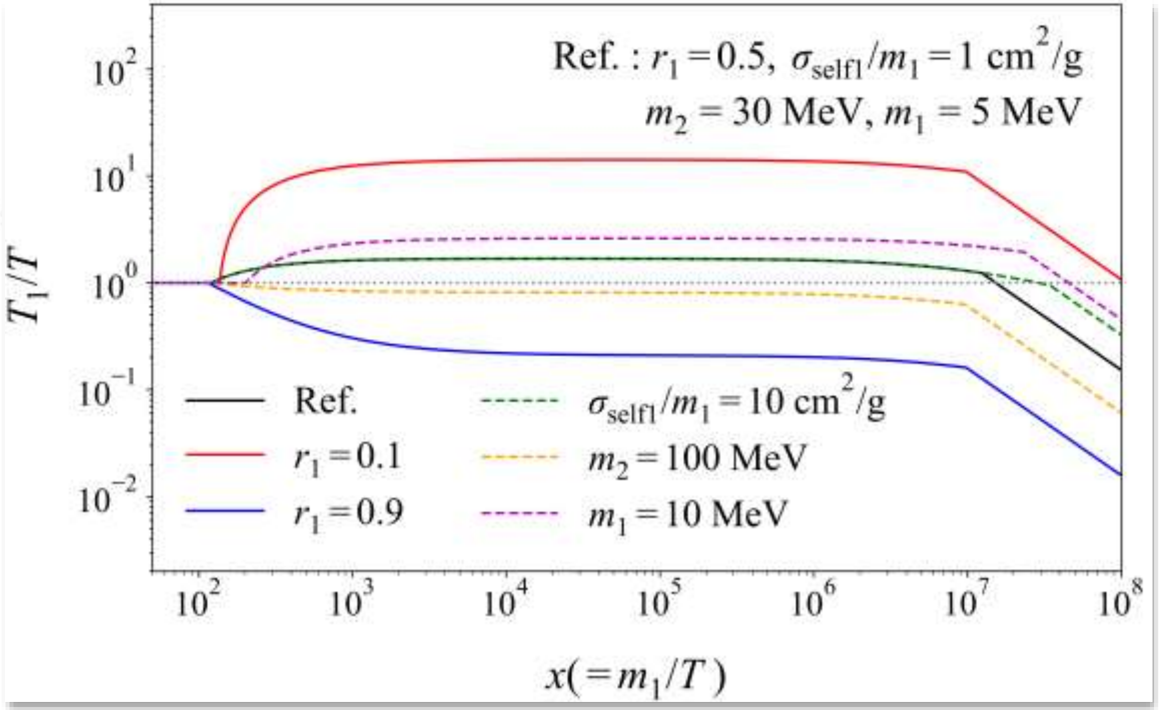


Thermal Evolution

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

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



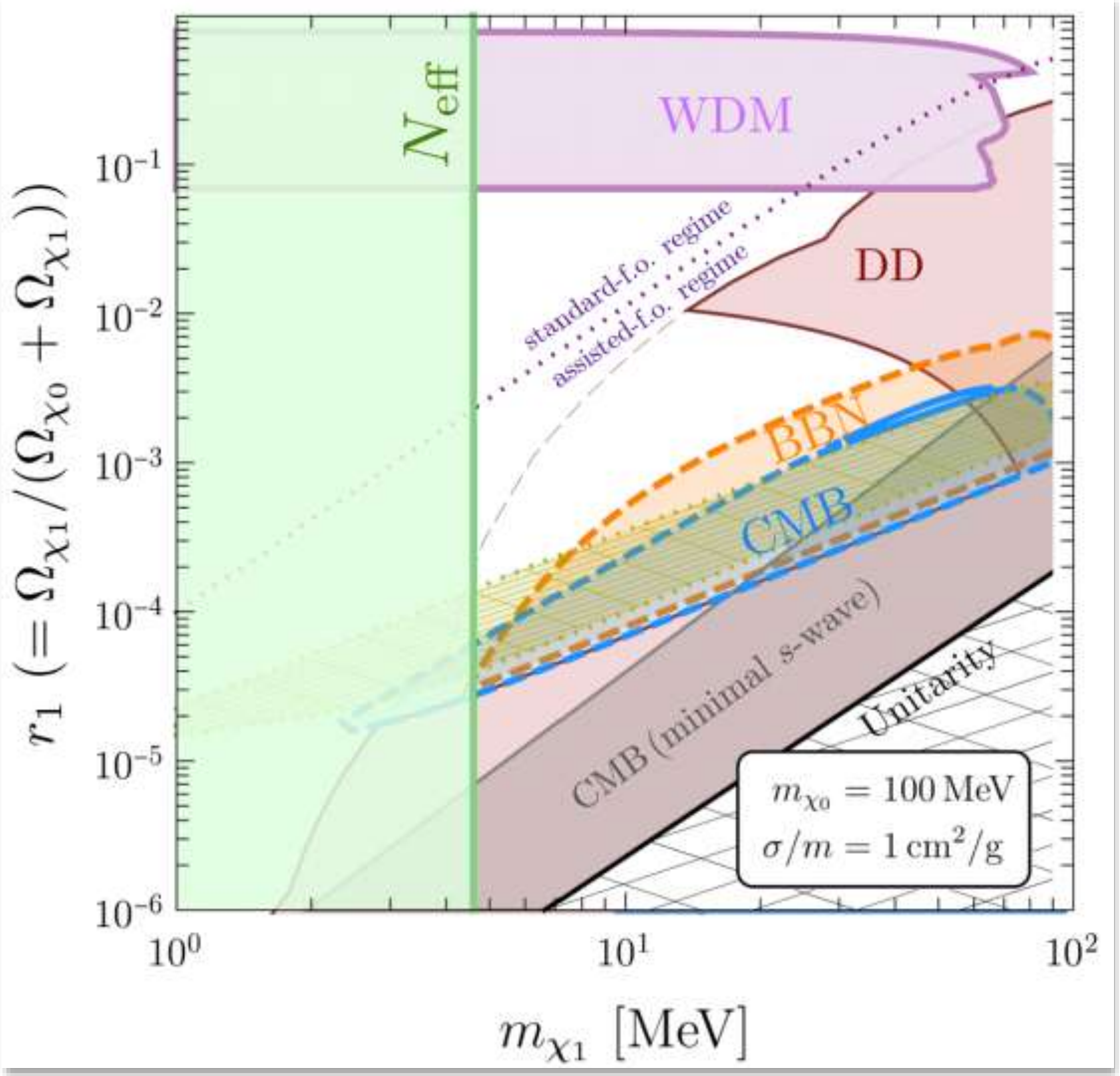


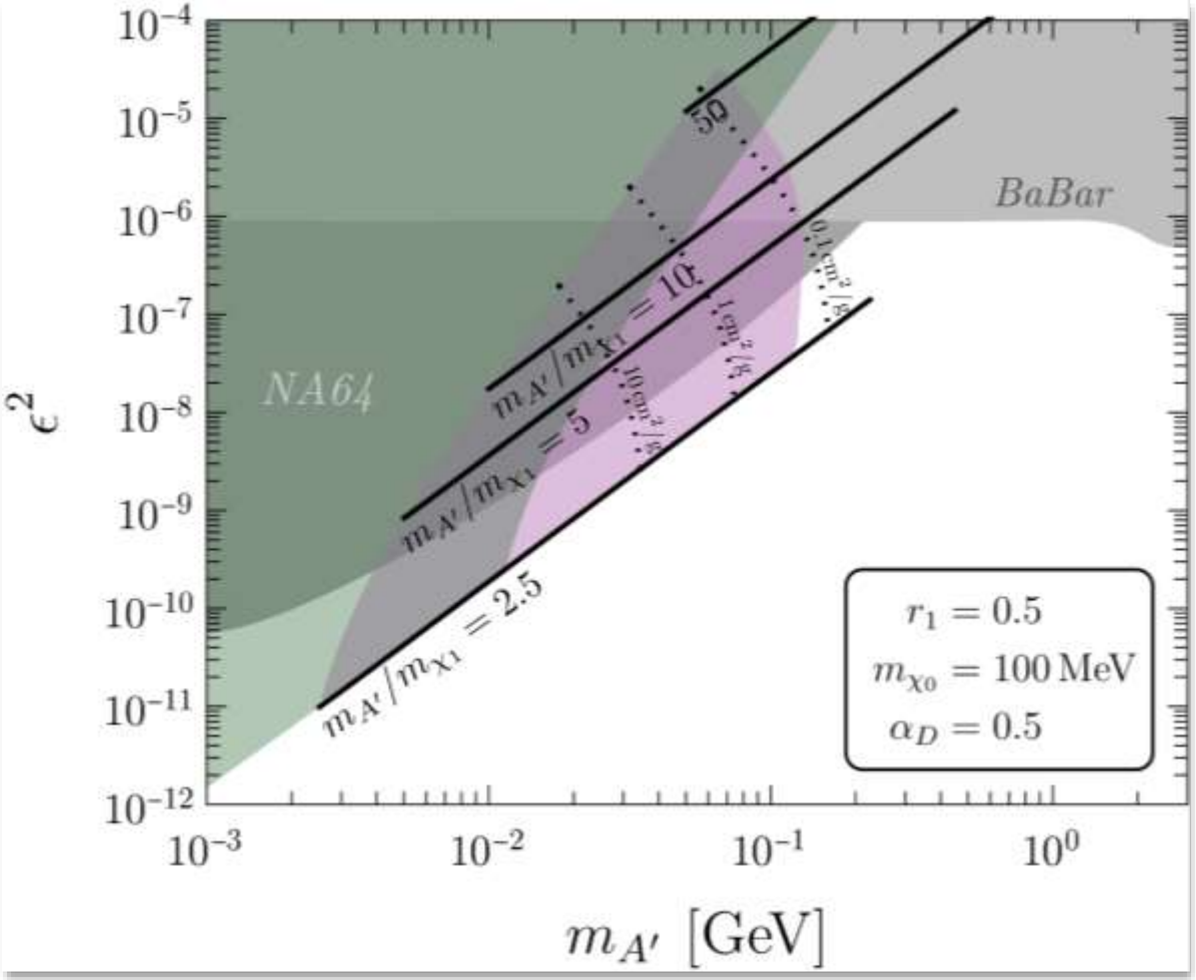
$$\dot{T}_{\chi_1} + 2HT_{\chi_1} \simeq \gamma_{heat} T - 2\gamma_{\chi_1 sm}(T_{\chi_1} - T)$$

✓ χ_2: heavy DM, χ_1: light DM

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]

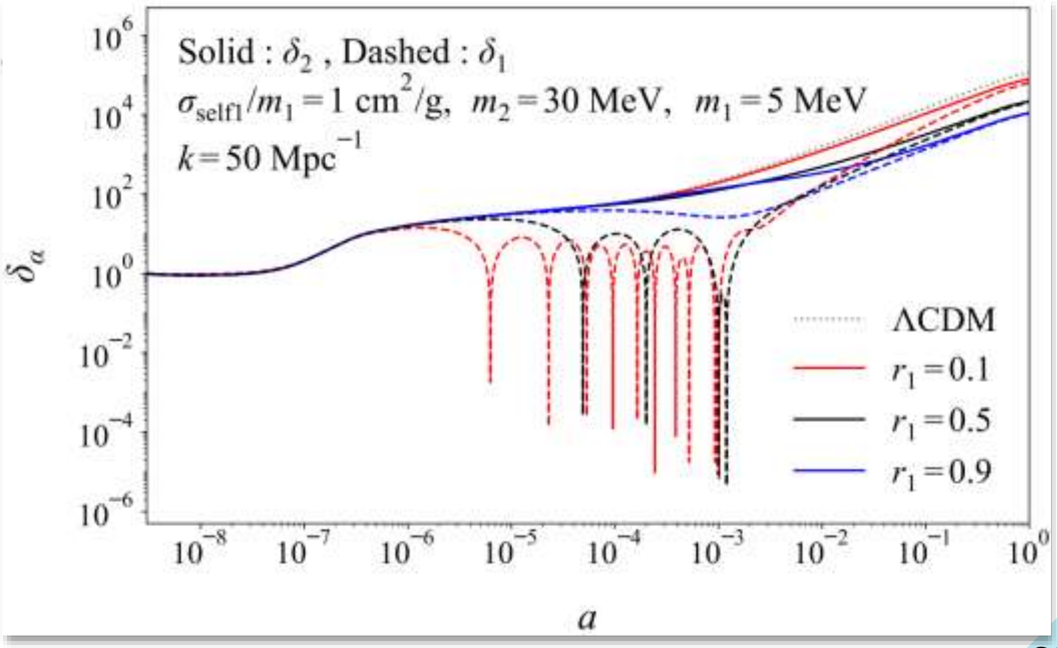
❖ Coupled equations for the density perturbation

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

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

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

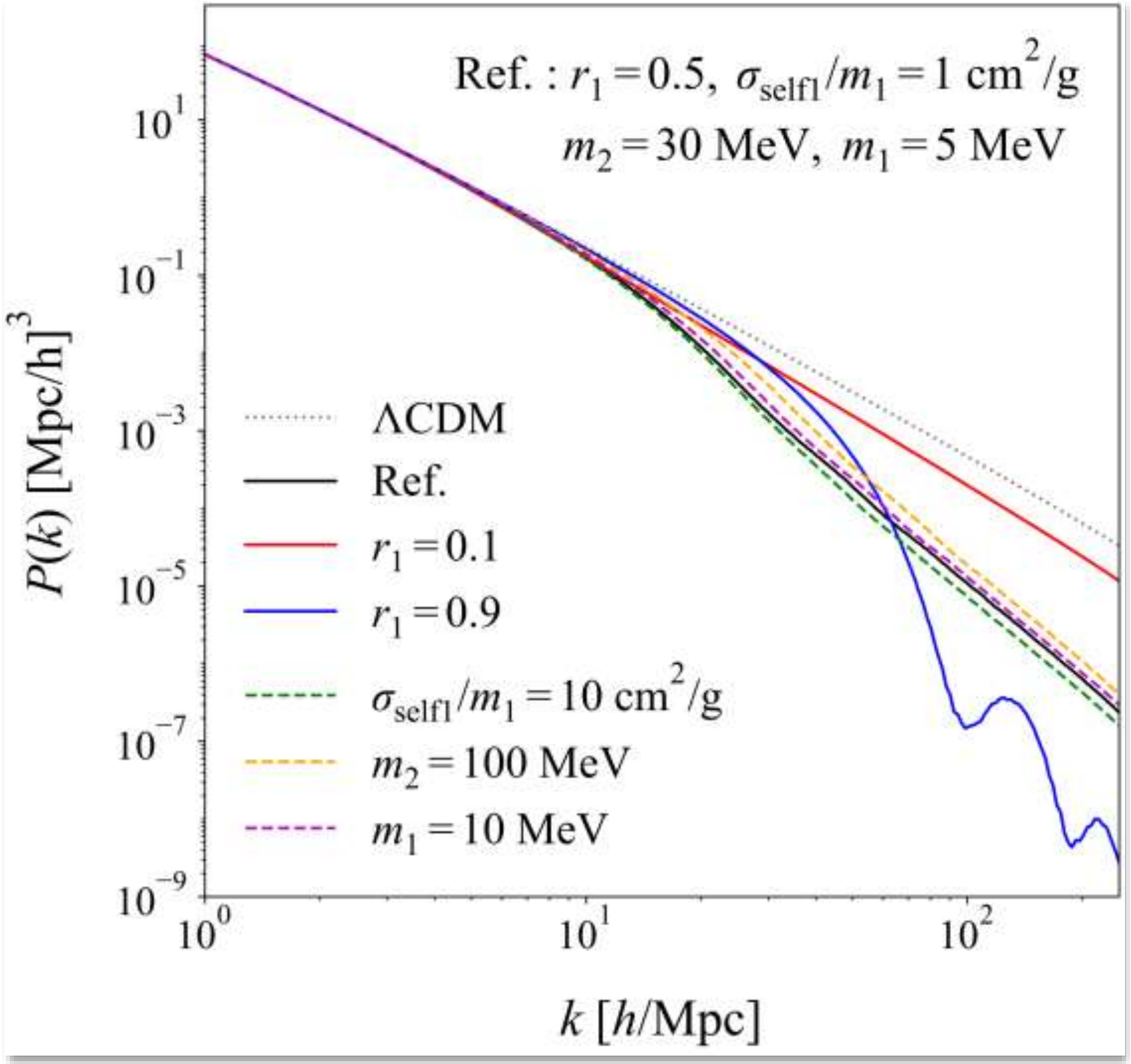
$$\frac{d\theta_1}{dt} + H\theta_1 + \frac{\nabla^2\Psi}{a} + c_{s,1}^2\frac{\nabla^2\delta_1}{a} = \frac{\langle\sigma v\rangle_{22\to 11}}{m_2\bar{\rho}_1}\bar{\rho}_2^2\left(\theta_2 - \theta_1\right),$$



Linear Matter Power Spectrum

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

❖ Linear power spectrum by *CLASS*



N-Body Simulation

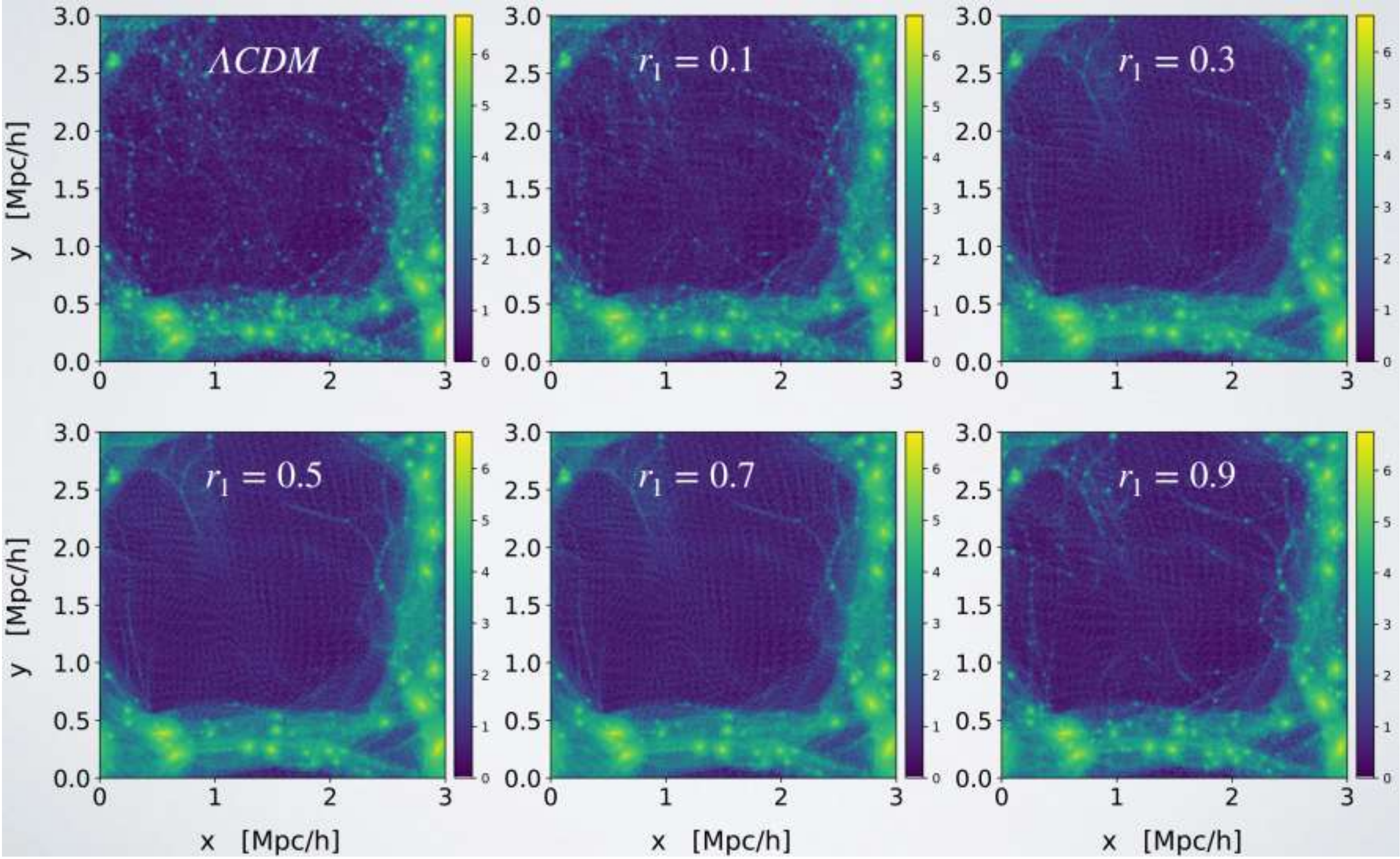
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

❖ *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

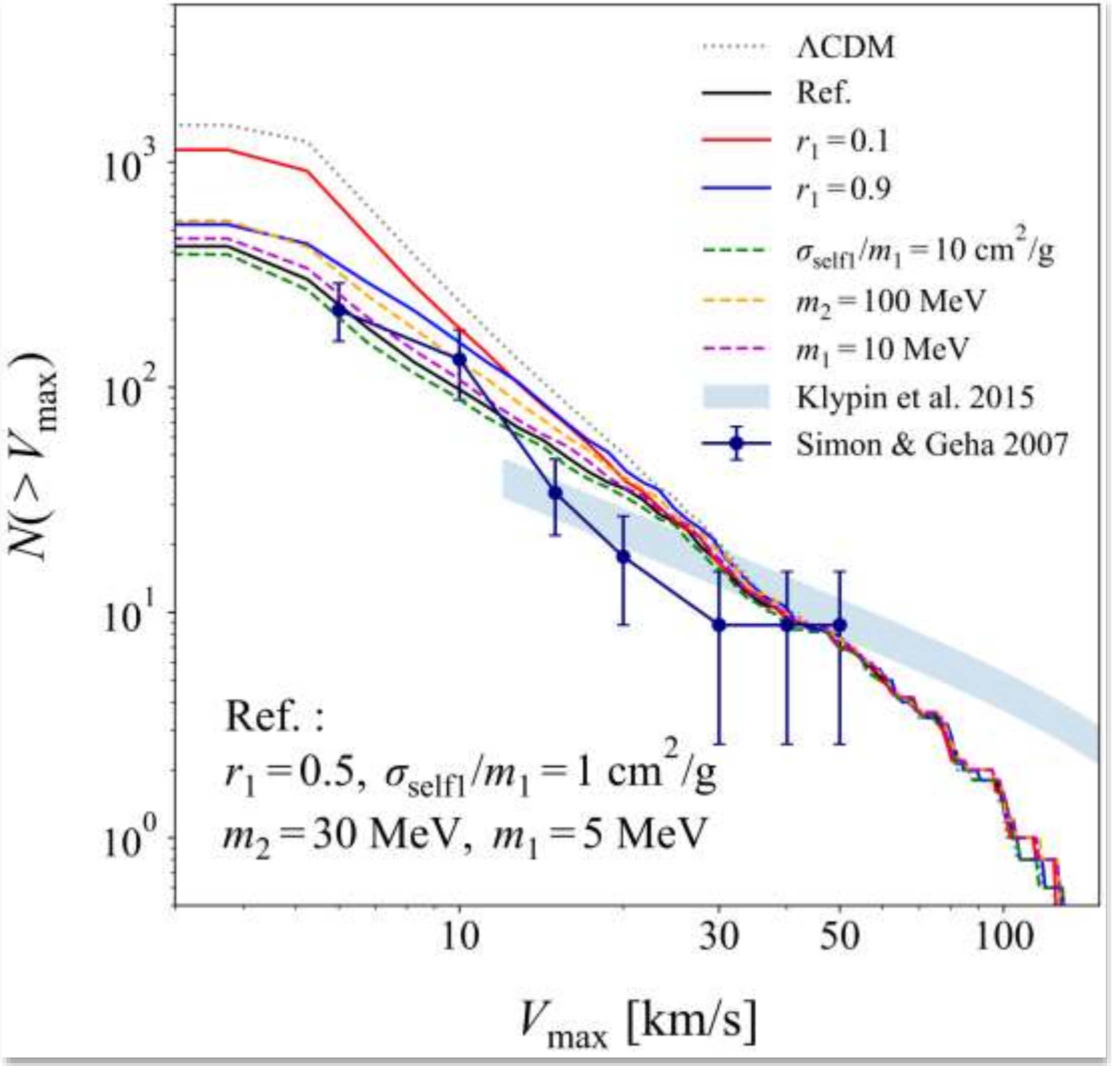
✓ $m_{\chi_1} = 5$ MeV



N-Body Simulation

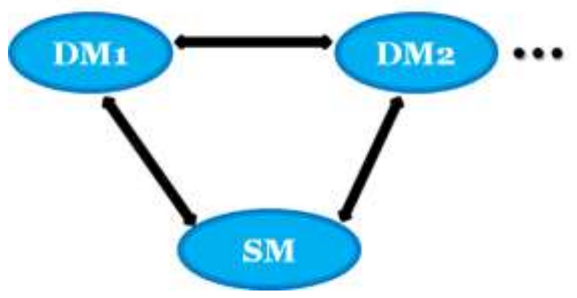
[J. Kim, Lim, **JCP** & Kong, 2312.07660]

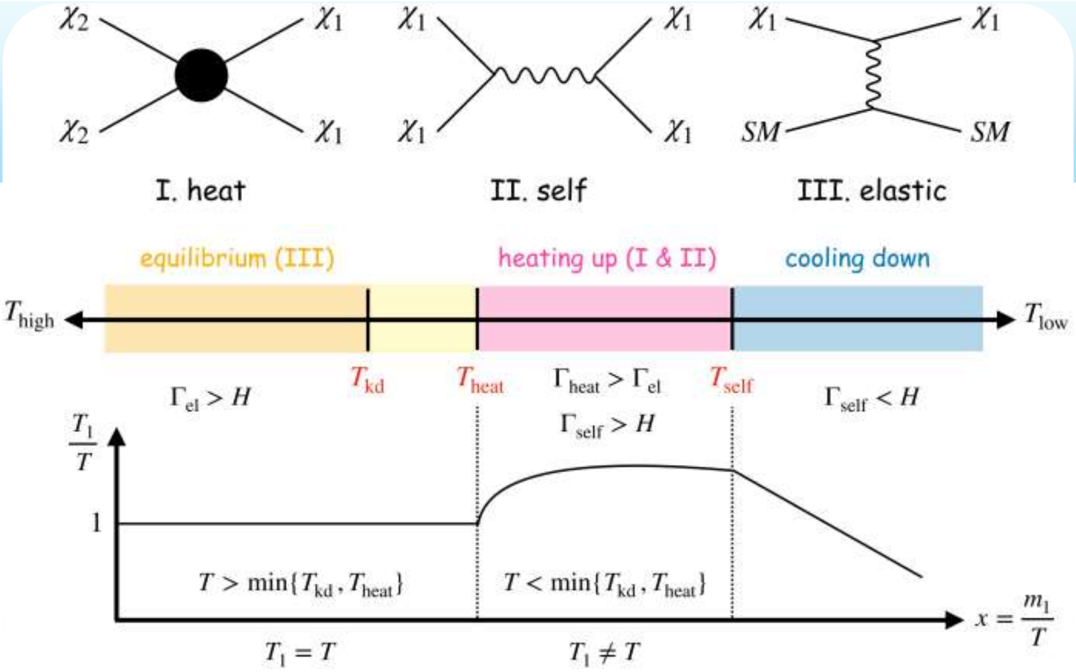
❖ Maximum circular velocity distribution of sub-halos



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

Summary





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

Thank you