The Particle Physics Side of BDM

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N-Body Simulations with Two-Component DM

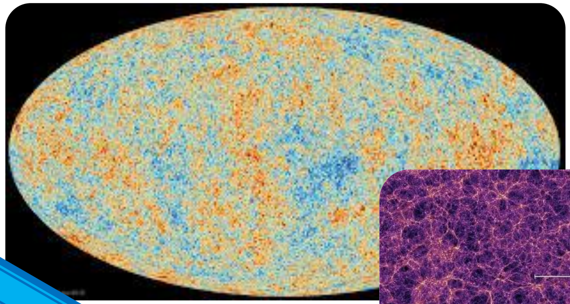
February 13 (2024)

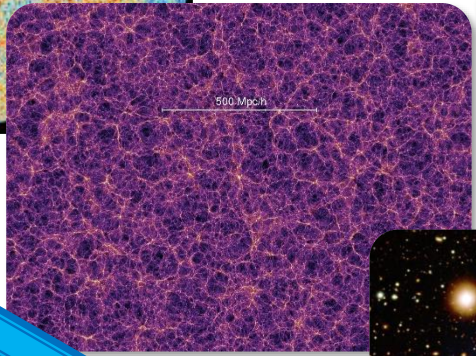
Outline

- ❖ **Dark Matter? Dark Sector?**
- ❖ **Boosted Dark Matter (BDM) & Its Searches**
- ❖ **Issues in BDM Searches**
- ❖ **Cosmological Effects**
- ❖ **Summary**

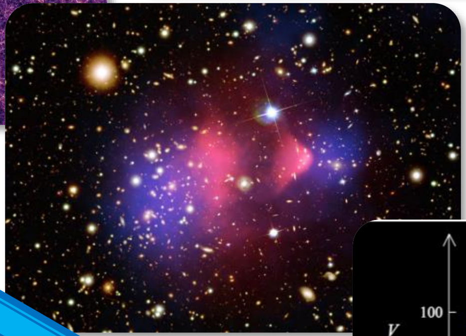
Dark Matter?
Dark Sector?

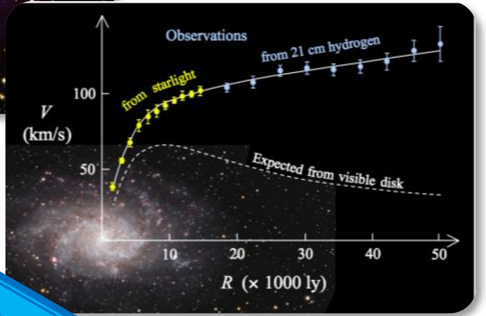
Message from Cosmology: Dark Matter (DM)





Dark Matter?





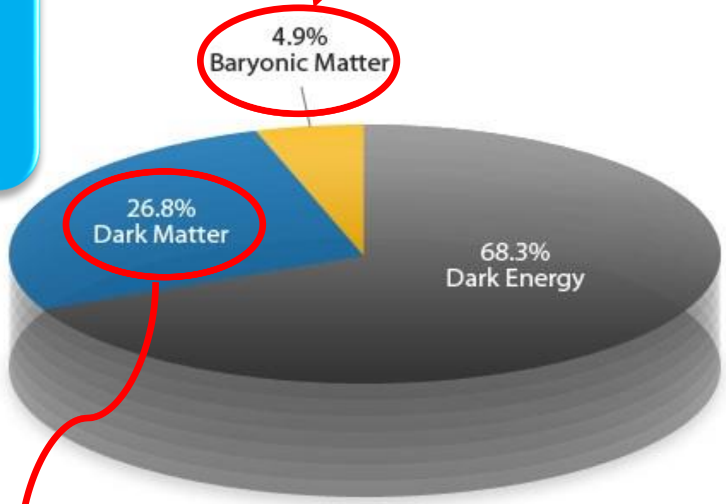
Larger scale
Earlier

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

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

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

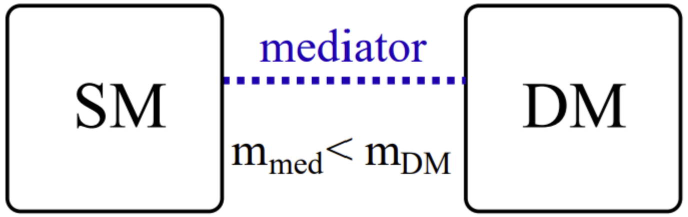
Secluded DM

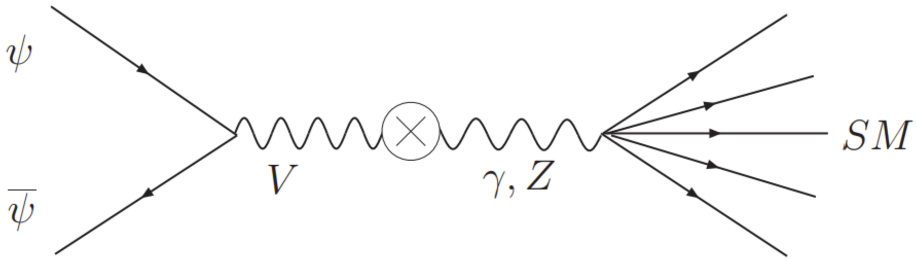
Secluded WIMP Dark Matter

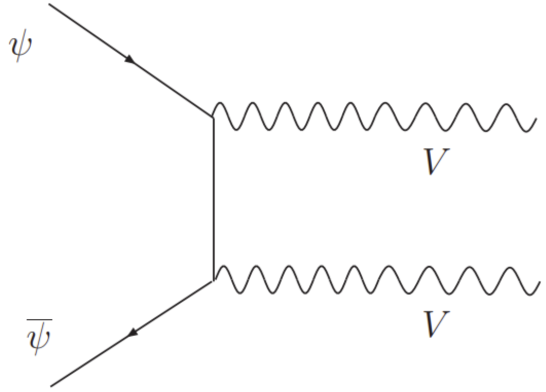
[0711.4866]

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

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







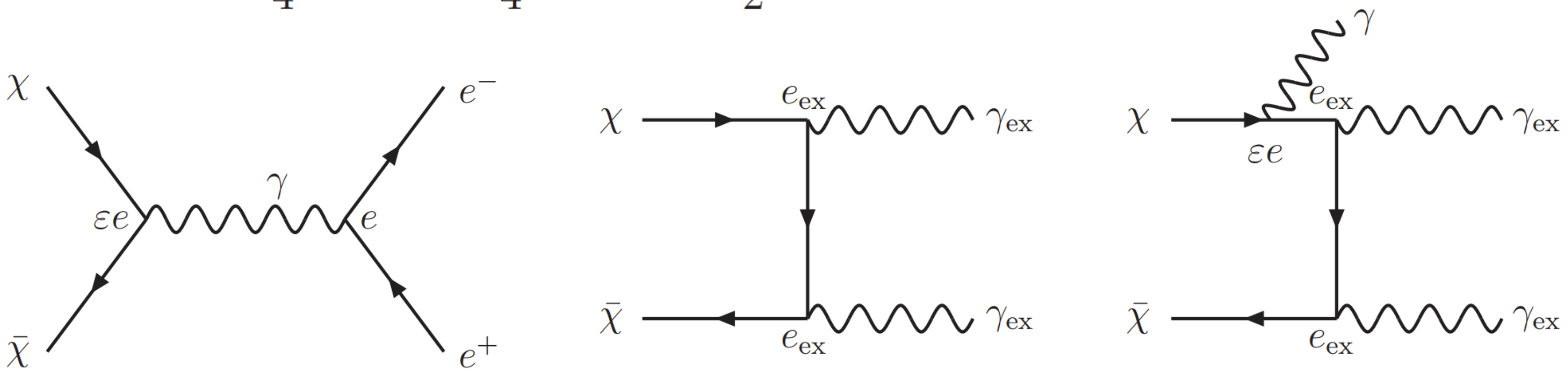
Note added – As this paper was being finalized, we became aware of a recent preprint [36] that also deals with U(1)′ models of MeV-scale dark matter with kinetic mixing, and thus has some overlap with the discussion in Sect. 3(a,b).

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

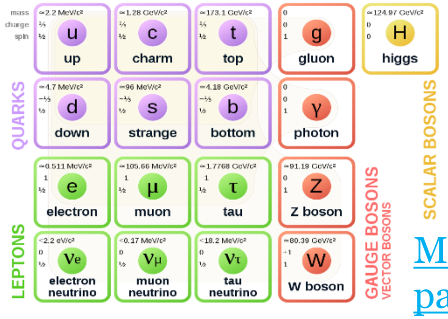
$$\mathcal{L}_{hid} = \mathcal{L}_S + \mathcal{L}_\psi - g_S\bar{\psi}\psi S, \; \mathcal{L}_{int} = -\lambda_1 H^\dagger H S - \lambda_2 H^\dagger H S^2.$$

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



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

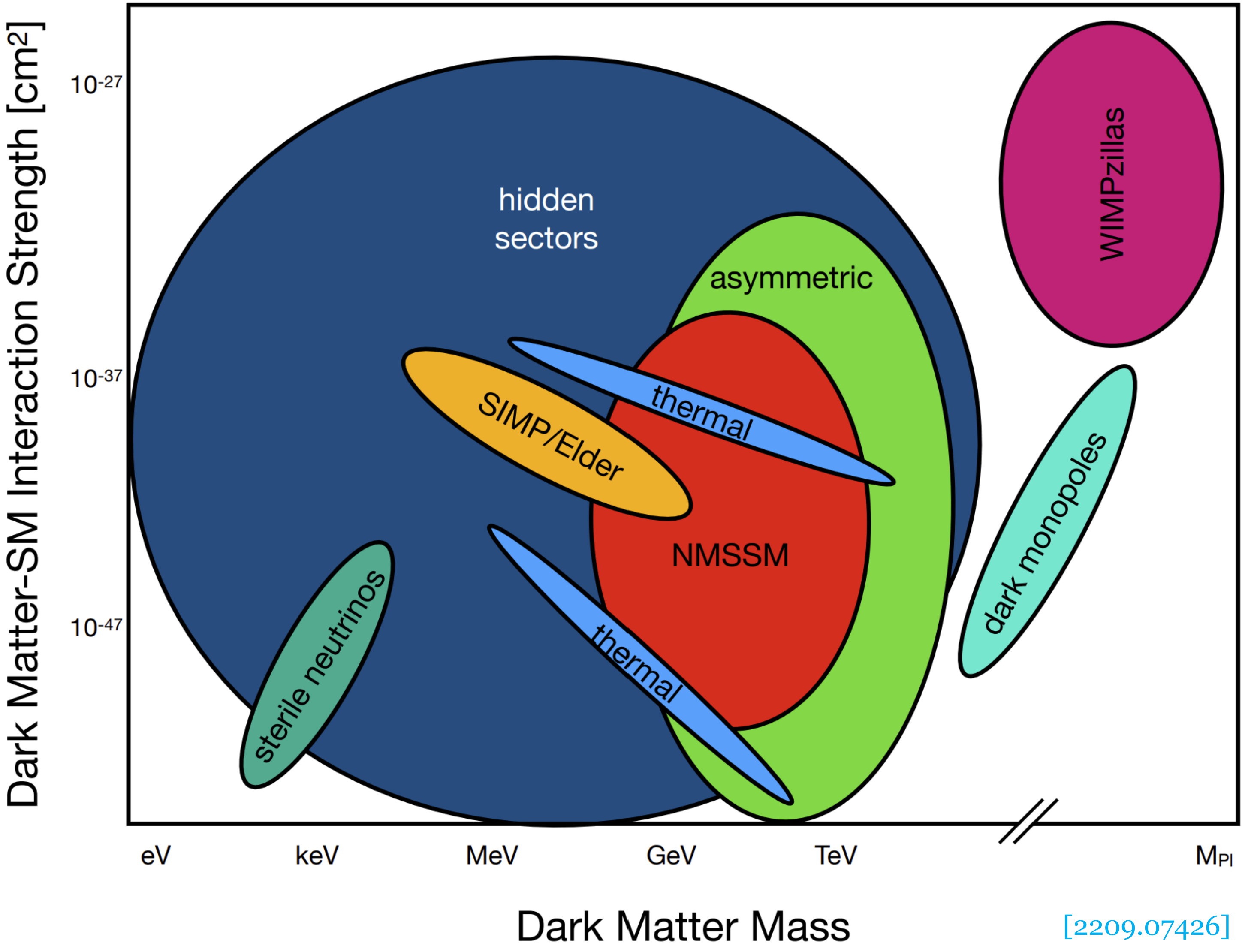
❖ **Dark sector particles**

- ✓ 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

Report of the Topical Group on Particle Dark Matter for Snowmass 2021

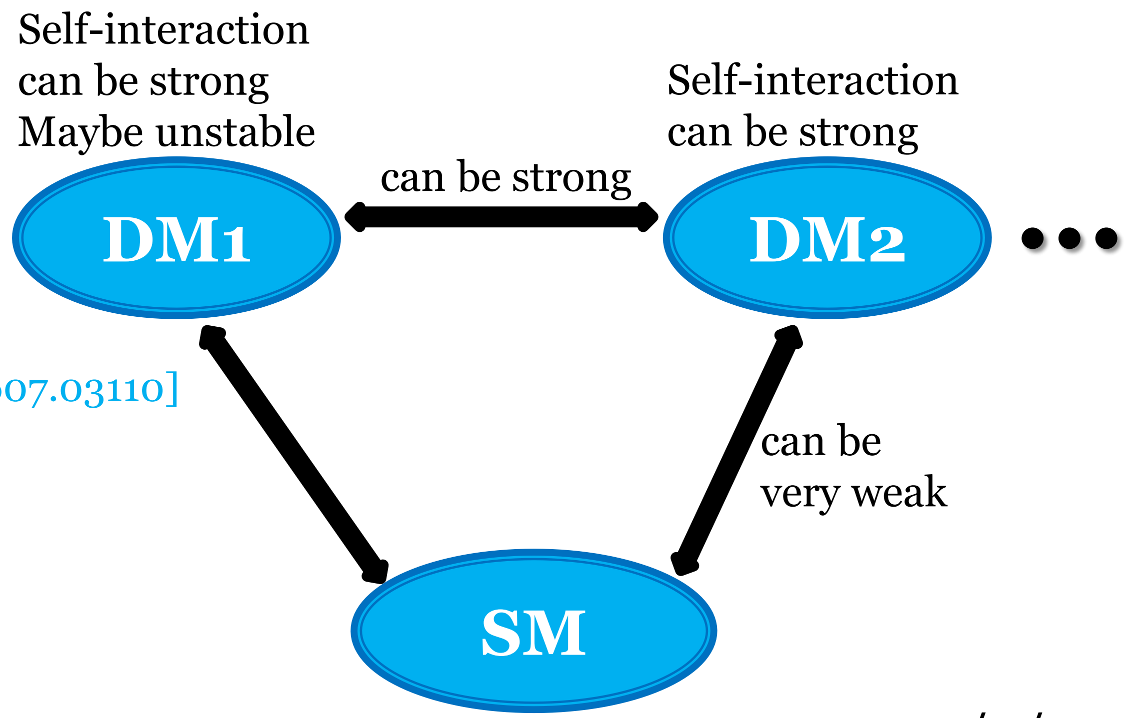


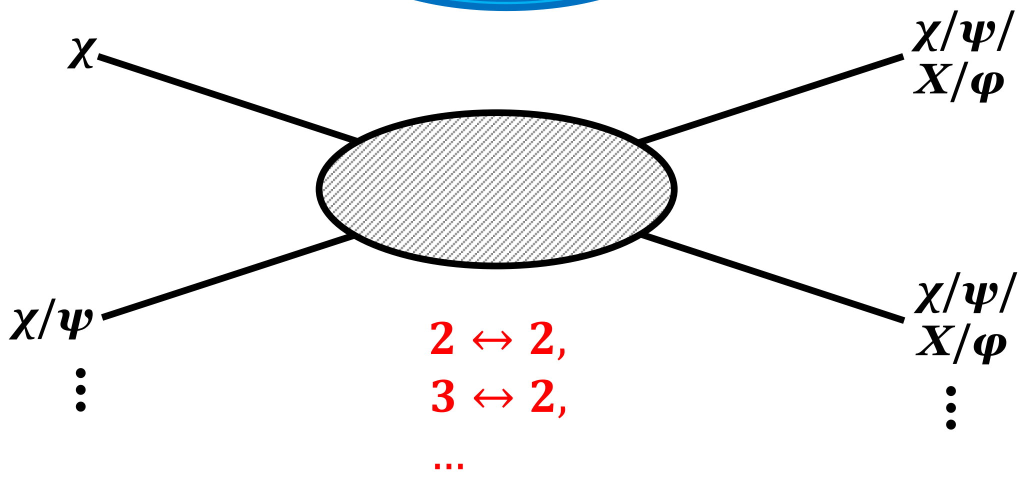
[2209.07426]

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]
- ✓ …



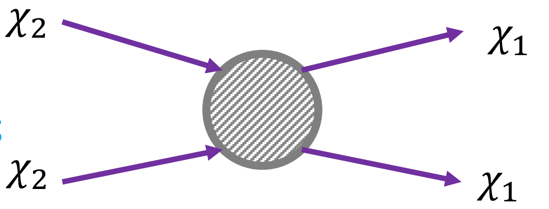


Boosted Dark Matter (BDM)

Dark Sector: DM Boosting Mechanisms

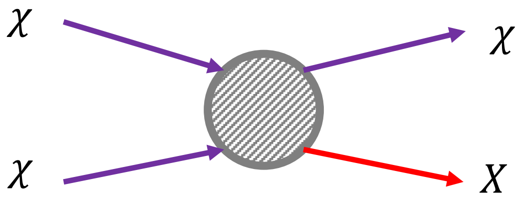
Boosted DM (BDM) coming from the Universe

[Belanger & **JCP**, JCAP (2012);
Agashe et al., JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015);
Berger et al., JCAP (2015);
Kim, **JCP**, Shin, PRL (2017);
more]



✓ Multi-component model

$m_2 \gg m_1$



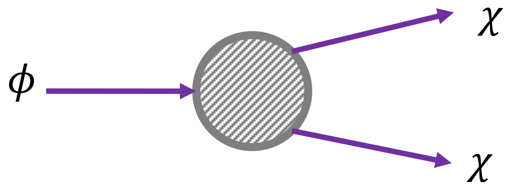
✓ Semi-annihilation model

$m_\chi \gg m_X$

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

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

- Relic component DM:
  Non-relativistic!

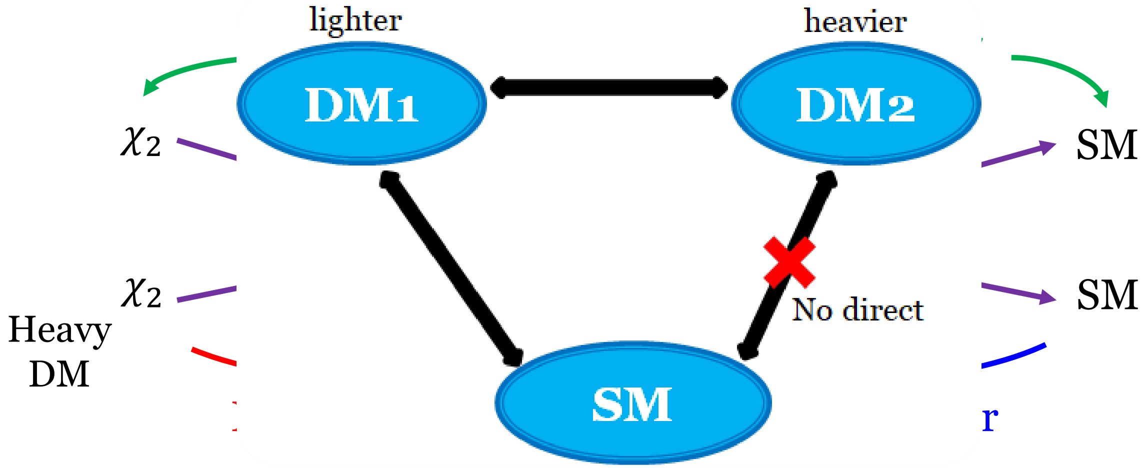


✓ Decaying multi-component DM

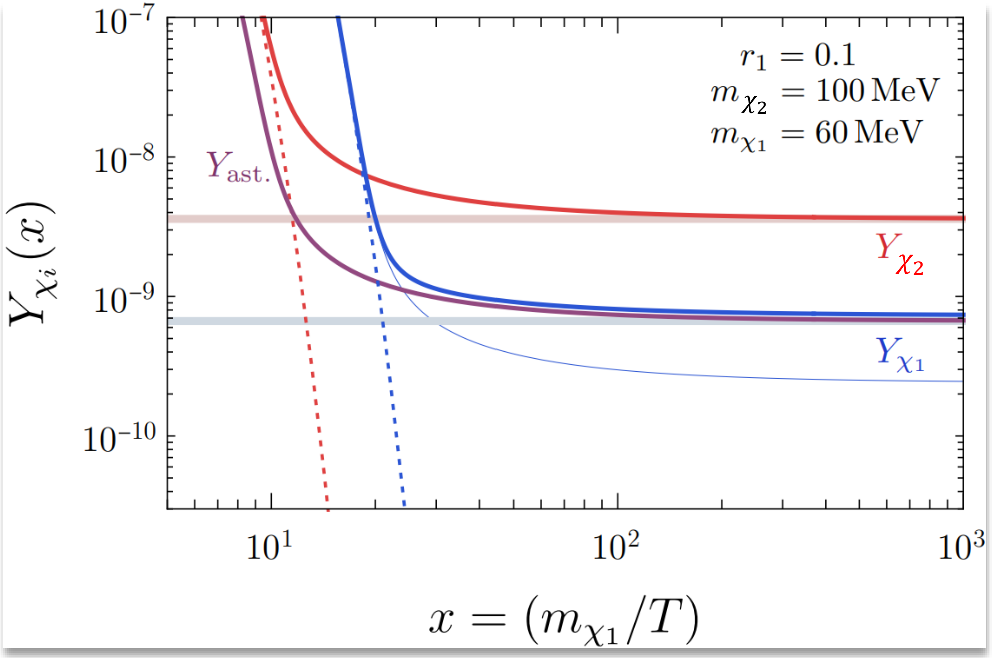
$m_\phi \gg m_\chi$

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

Two-Component Scenario: Freeze-out



Thermal relic: $Y_i = n_i/s$



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

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

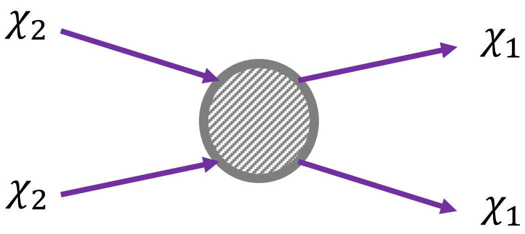
✓ Heavier relic χ_2: hard to directly detect it due to tiny coupling to SM

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

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

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

Two-Component Scenario: BDM Signatures

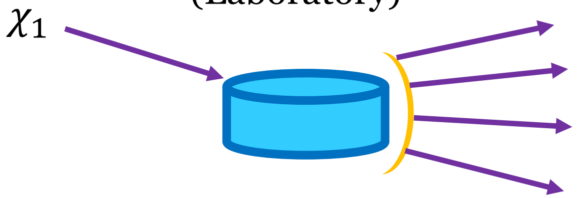


(cf. $\chi\chi \rightarrow \gamma\gamma$, $\boldsymbol{\nu\nu}$)

becomes boosted

($\gamma_1 = m_0/m_1$)

(Laboratory)

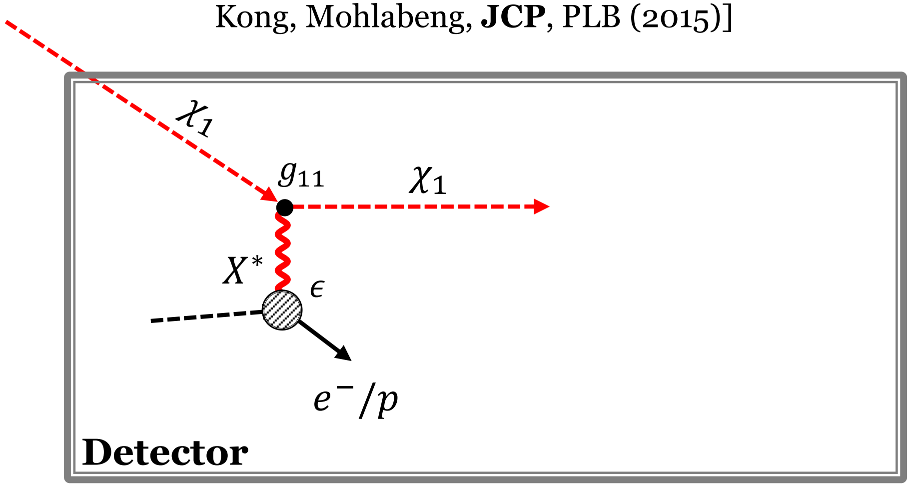


$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm l.o.s.} ds \langle\sigma v\rangle_{\chi_2\bar{\chi}_2\rightarrow\chi_1\bar{\chi}_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

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

elastic scattering (eBDM)

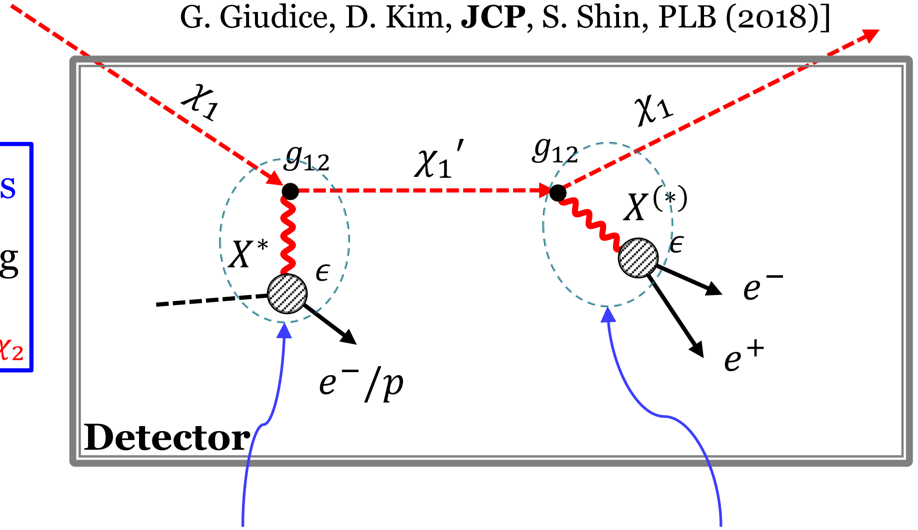
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]



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)]

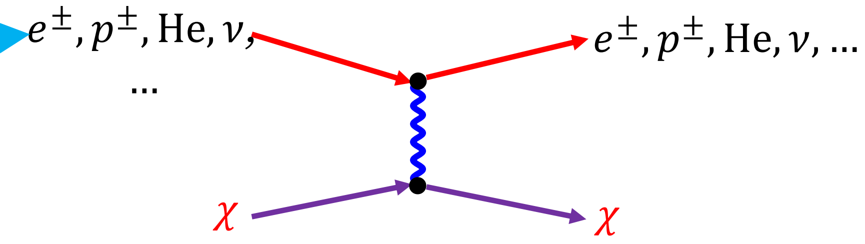


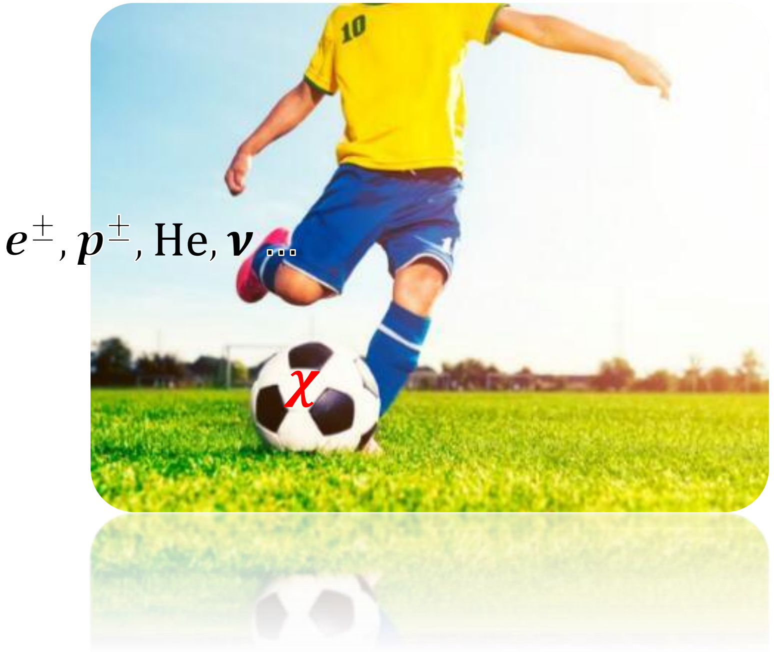
p- or *e*-scattering (primary) Decay (secondary)

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

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
more

BDM Searches @ Neutrino Experiments

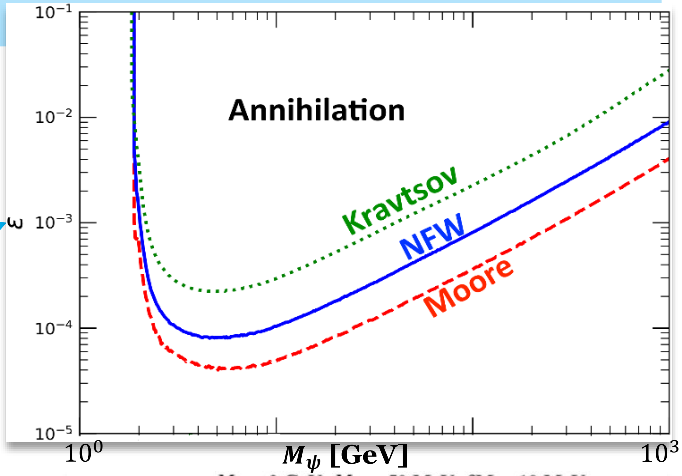
Boosted DM (BDM) scenarios:
Receiving rising attention as an alternative scenario

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

Editors' Suggestion

Cherenkov radiation rings by electrons

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



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

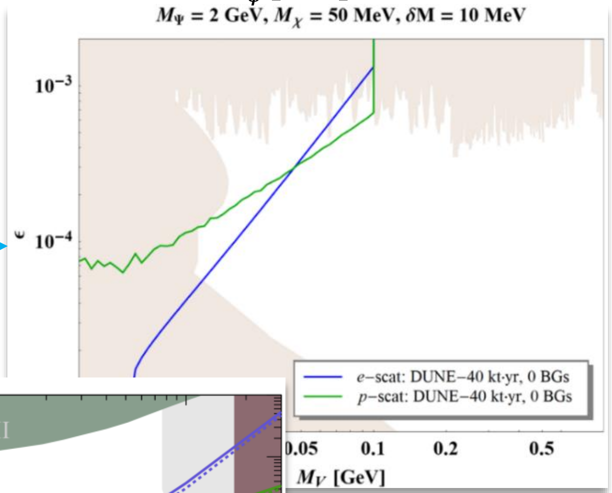
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

Regular Article - Experimental Physics

Ionization tracks by electrons and/or protons

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

DUNE Collaboration

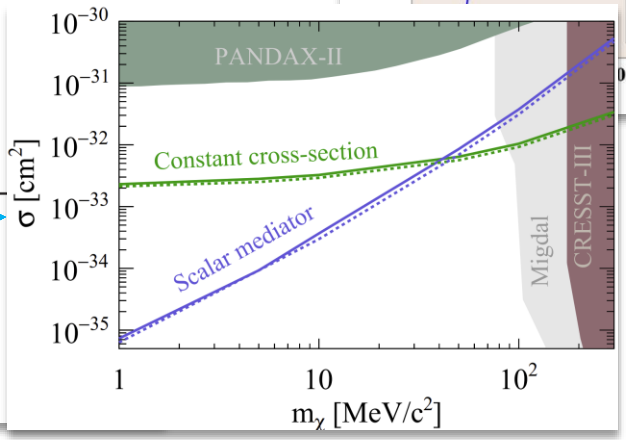


PHYSICAL REVIEW LETTERS **130,** 031802 (2023)

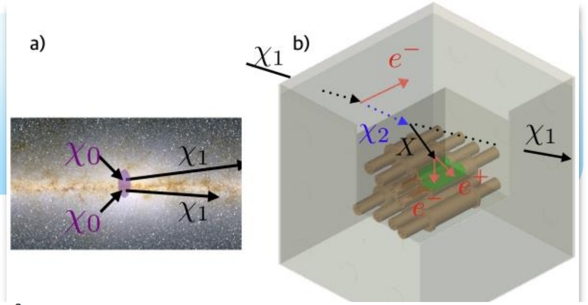
Editors' Suggestion **Featured in Physics**

Cherenkov radiation rings by protons

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



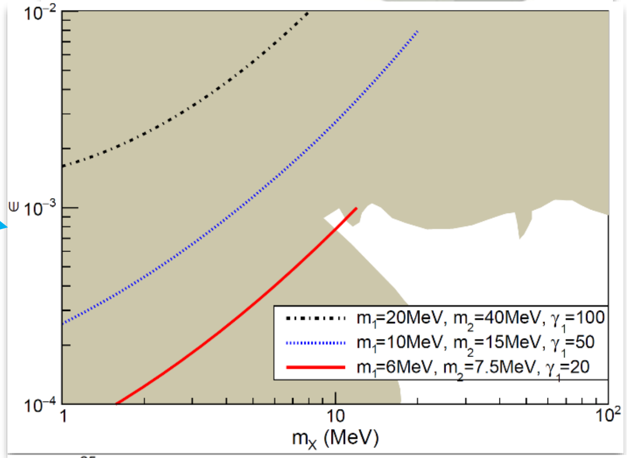
BDM Searches @ DM Experiments



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

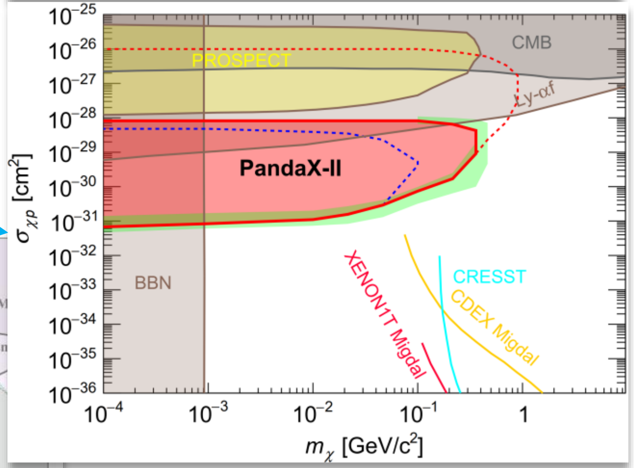
Scintillation photons

PHYSICAL REVIEW LET

Editors' Suggestion

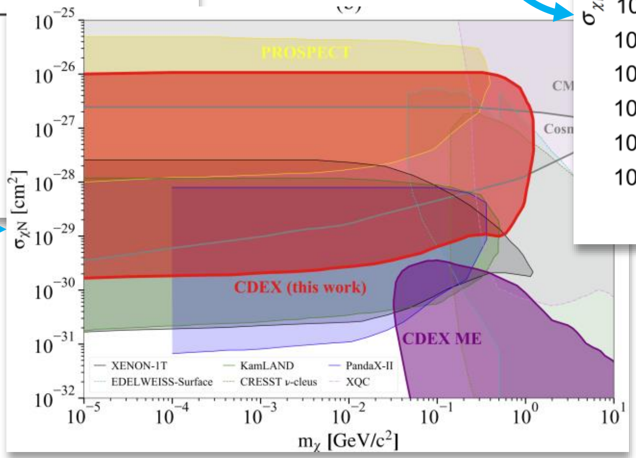
Pumping up the flux
➔ DM detector is OK!

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



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

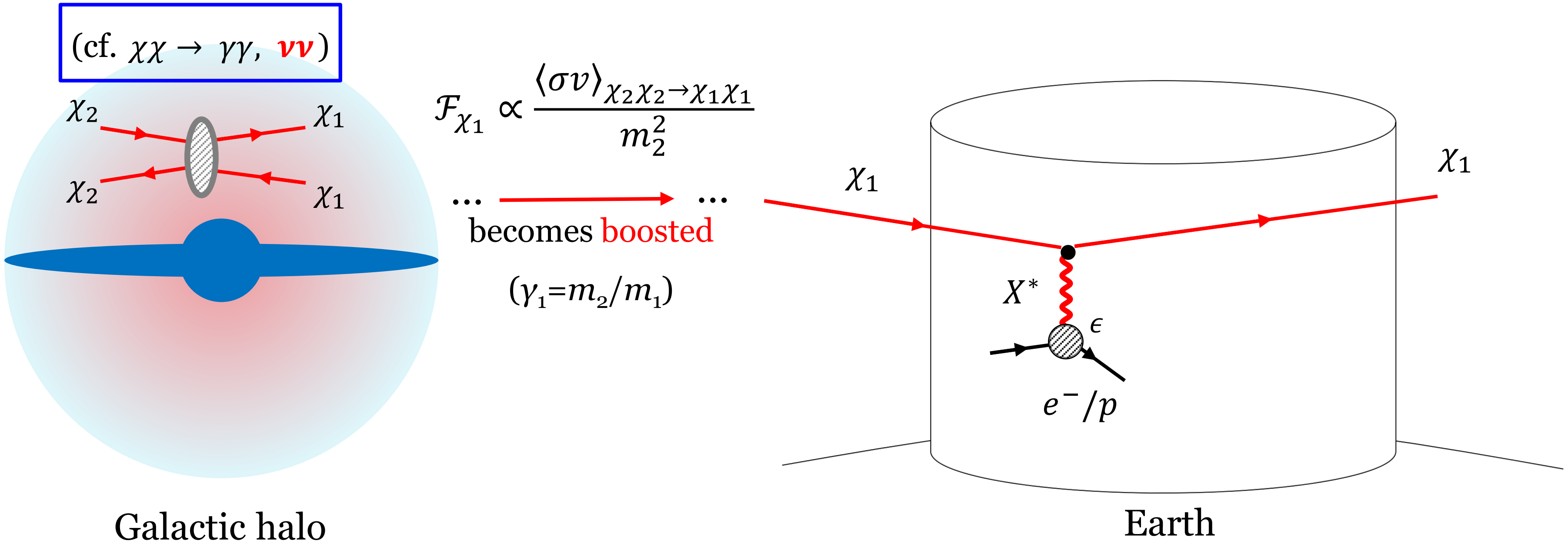
Constraints on sub-GeV dark matter boosted by cosmic rays from the CDEX-10 experiment at the China Jinping Underground Laboratory



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

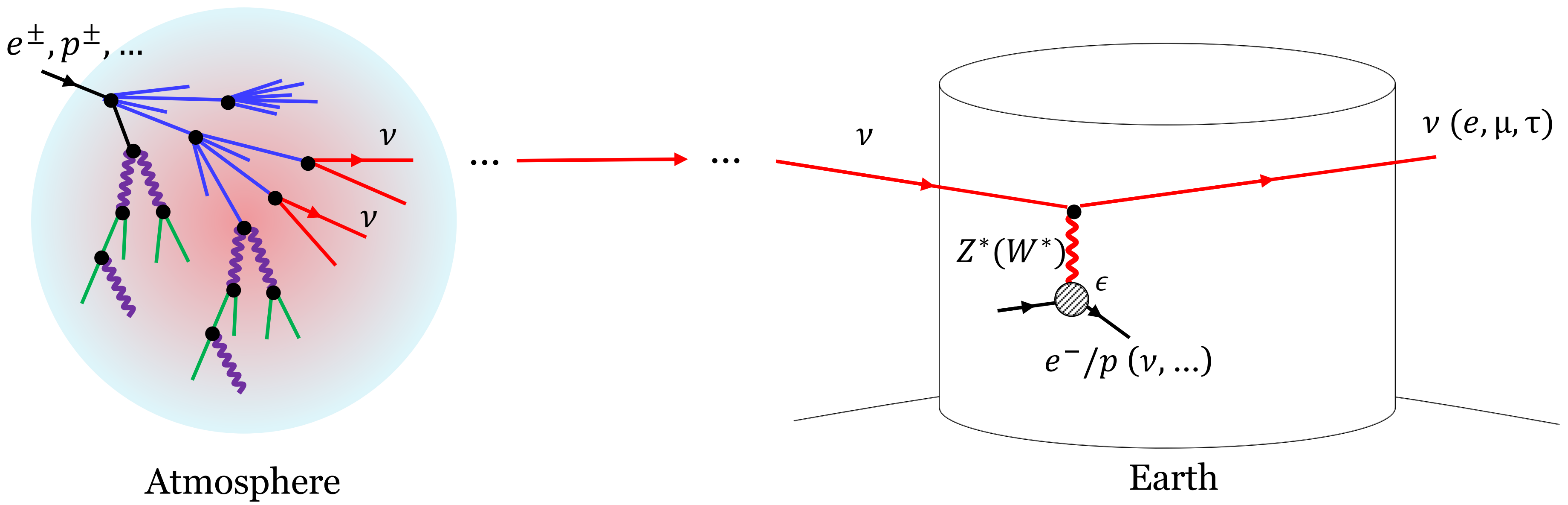
Issues in BDM Searches

Minimal Two-component Scenario



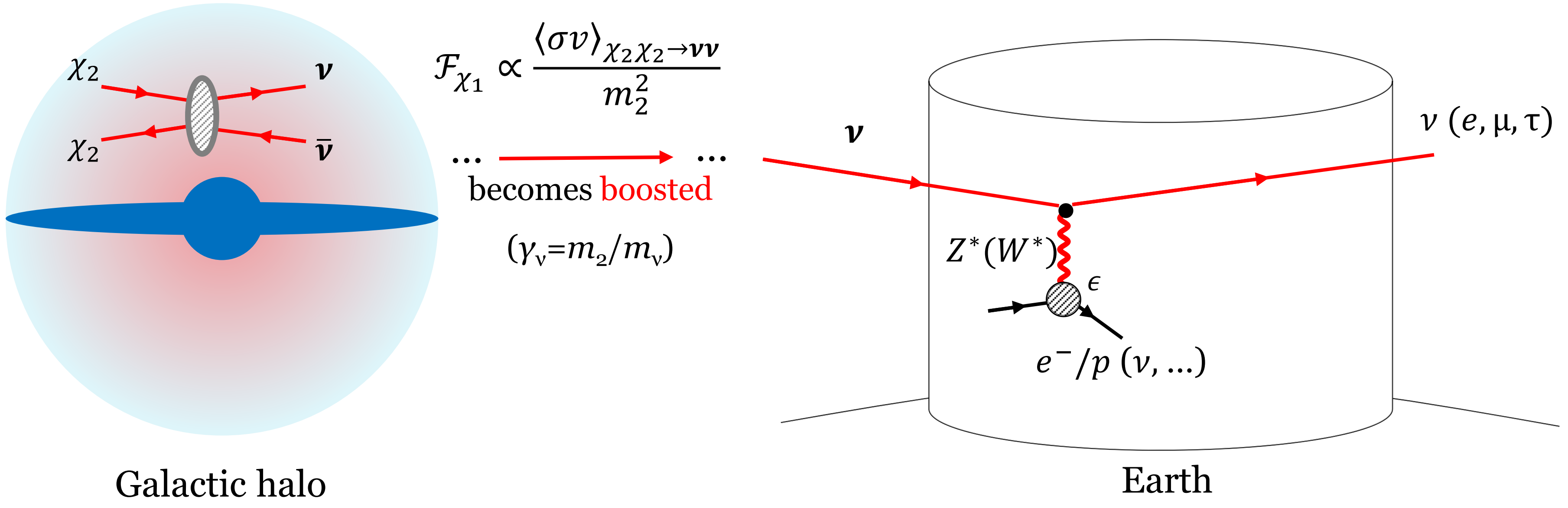
- Example model: fermionic heavier(χ_2)/lighter(χ_1) DM + dark gauge boson(X)
  [G. Belanger, **JCP** (2011)]
- Elastic electron [Agashe, Cui, Necib, Thaler (2014)] & proton (even DIS) scattering channels are available. ➔ Energetic recoil

Issue 1: Background



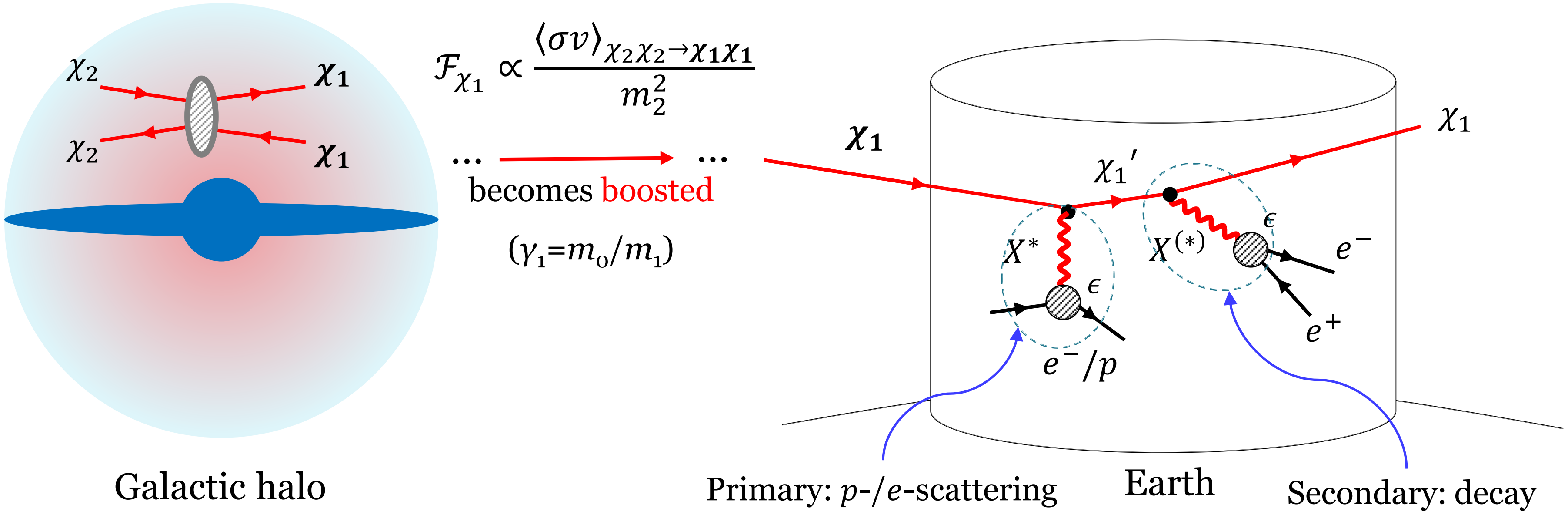
- Irreducible backgrounds: atmospheric-neutrino-induced events
- Neutral- & charged-current (even DIS) scattering channels are available. ➔ Energetic recoil
- Good angular resolution allows to isolate source regions, especially very good for point-like sources such as the Sun & dwarf galaxies.

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.

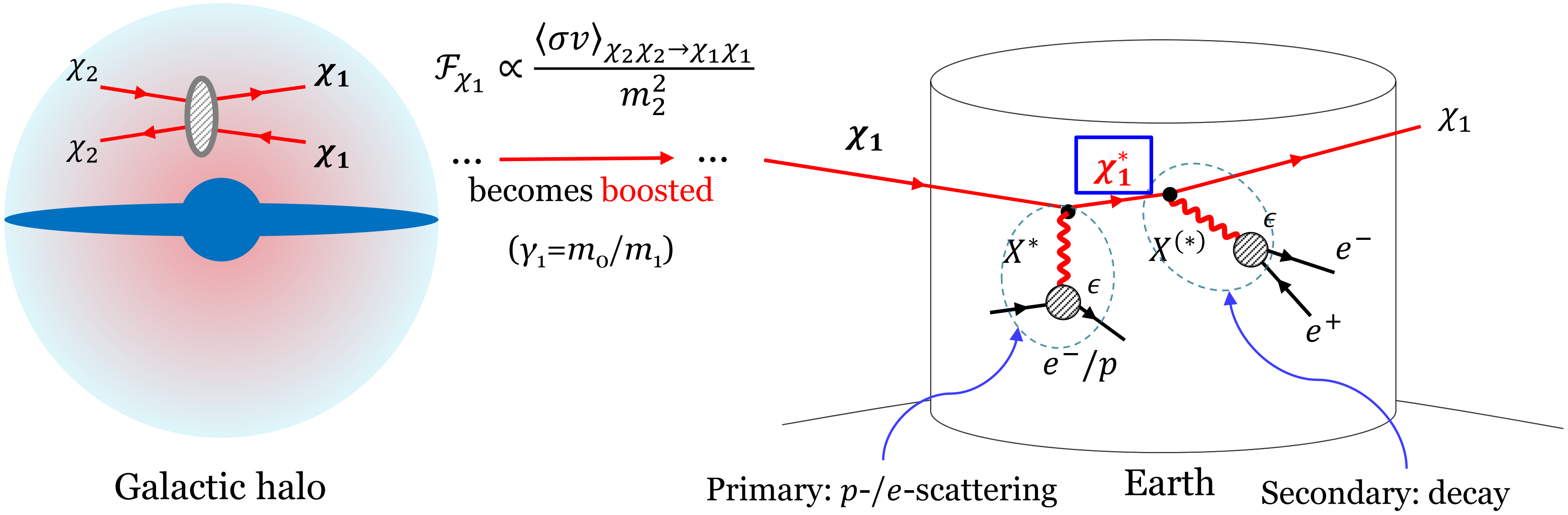
Issue 1 & 2: Avoidable by *i*BDM Scenario



- *i*BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]
- Additional signatures from the decay of heavier unstable dark-sector state (or excited state) χ_2 at the expense of "minimalism" of underlying BDM models.

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

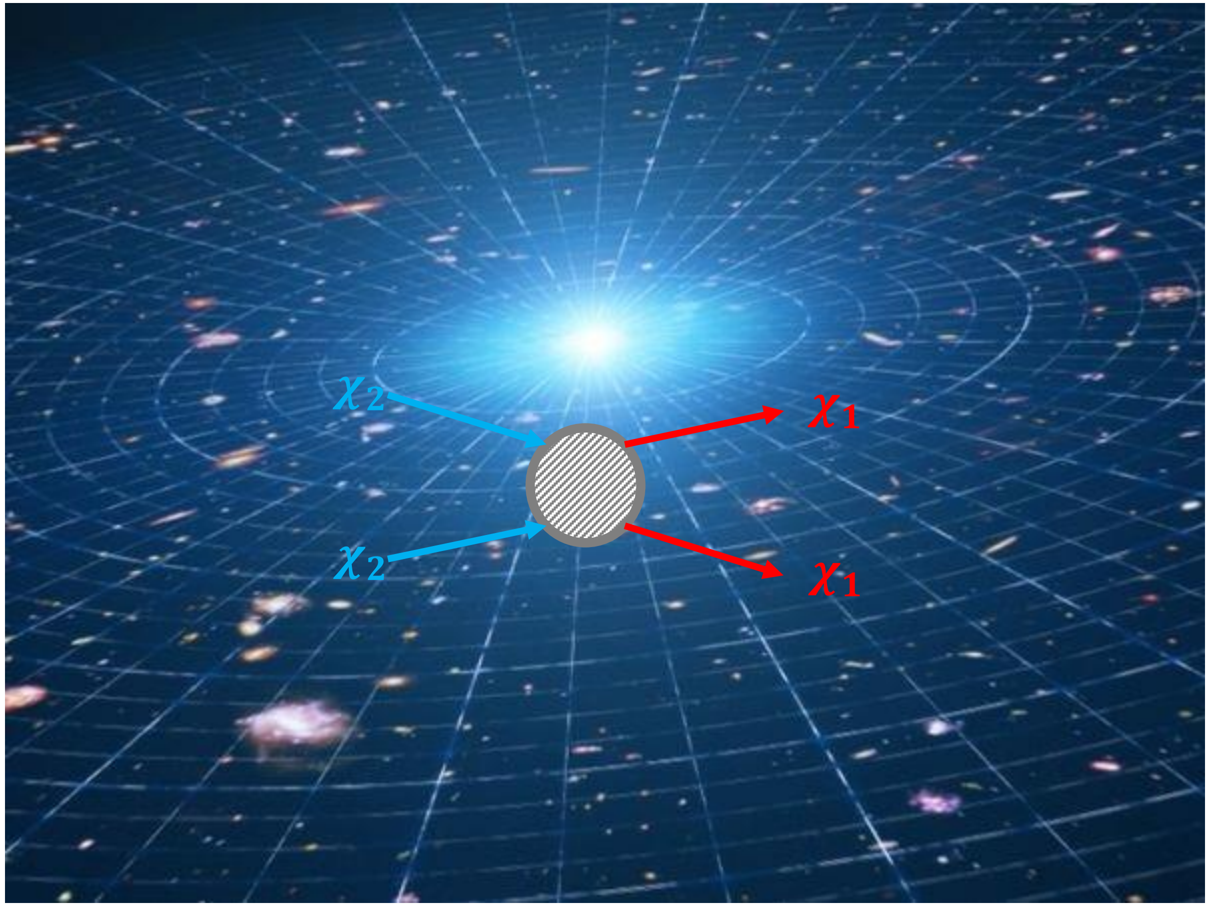
Issue 2: Avoidable by Subleading Process



- 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)]

Any Effects of Energetic DM on Cosmology?

BDM=Hot DM?

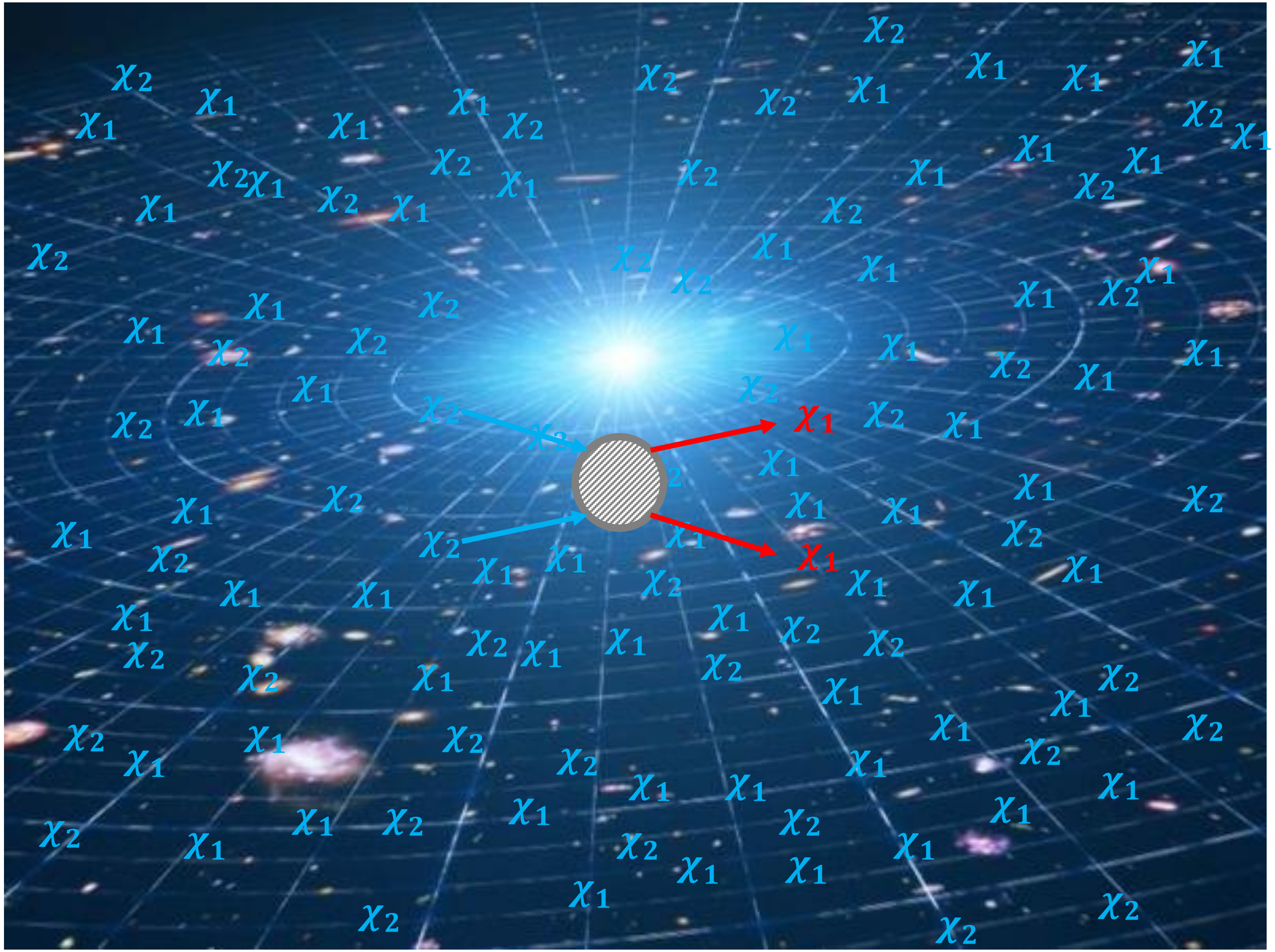


- ✓ χ_2: heavy DM, χ_1: light DM

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

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

Heating via Self-Scattering?



Heating via Self-Scattering?

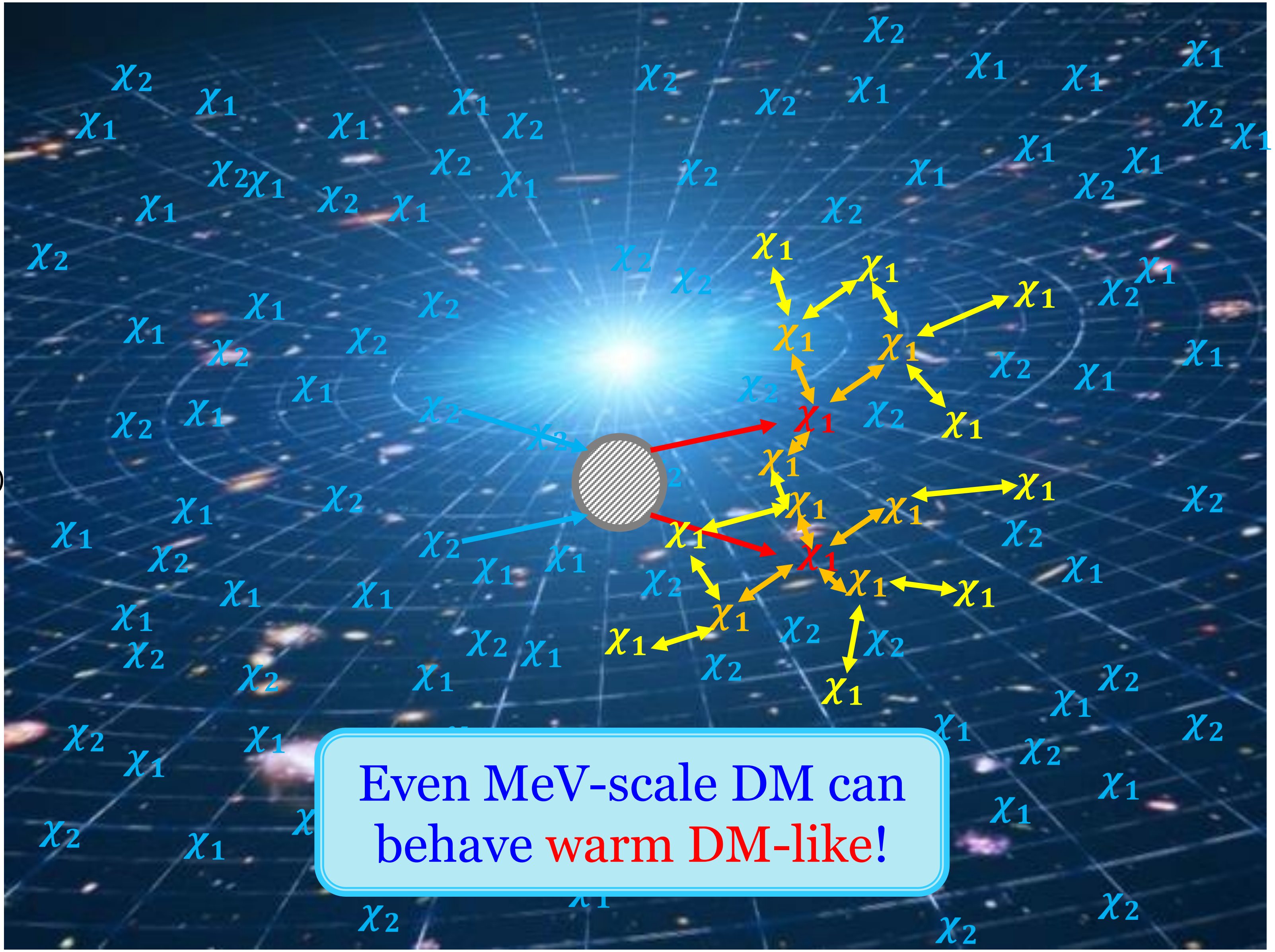
Large self-scattering is quite natural for light dark sector!

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

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

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

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

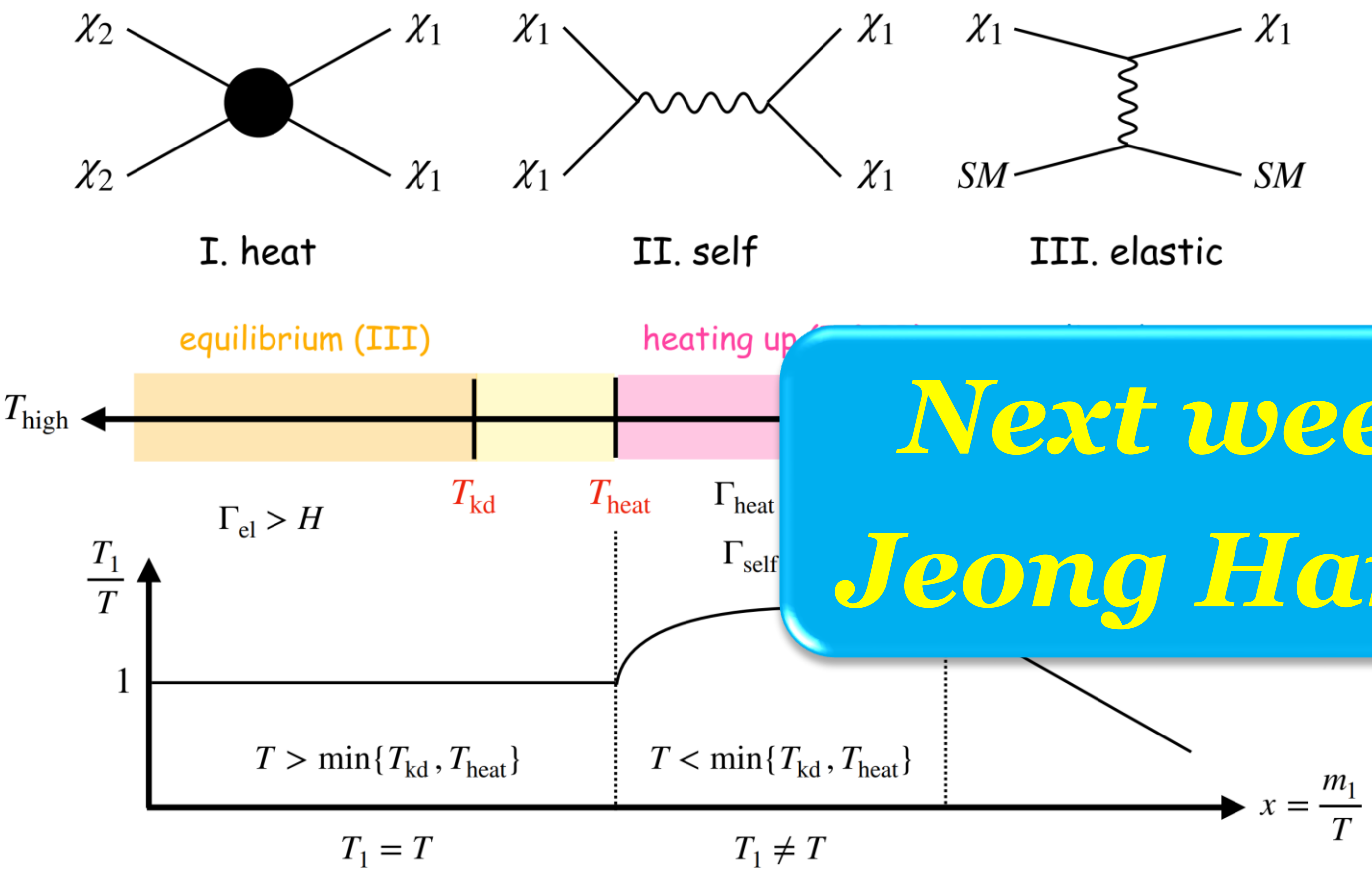


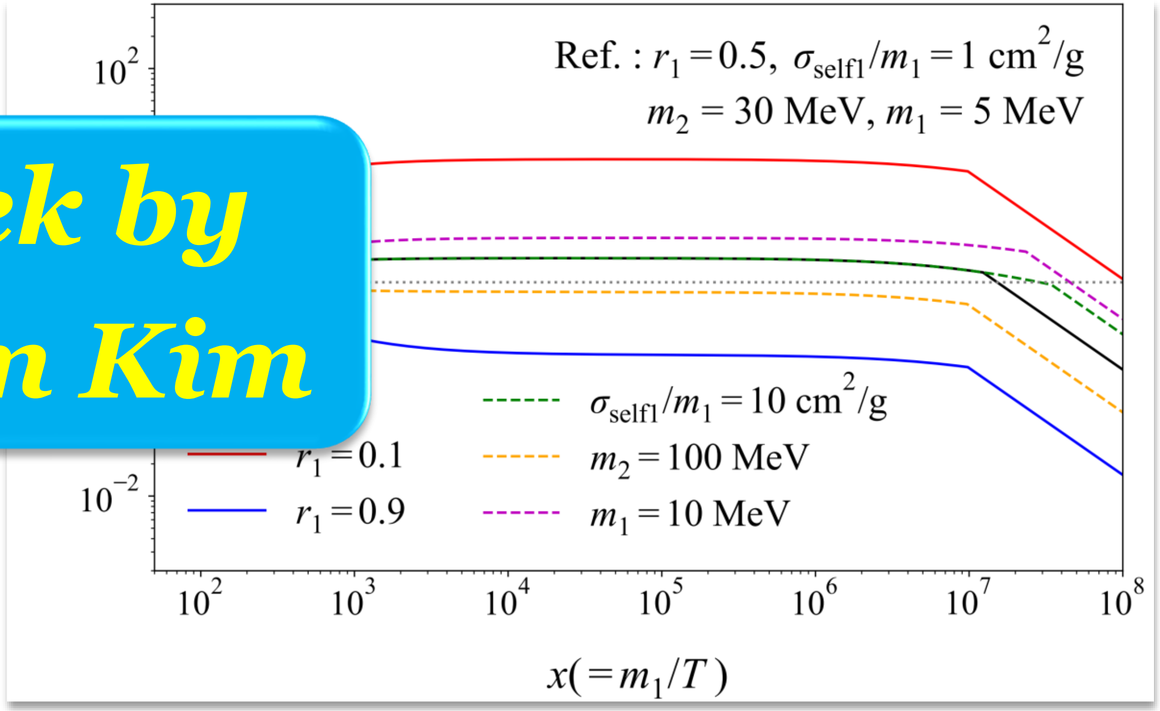
Even MeV-scale DM can behave warm DM-like!

Thermal Evolution

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

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





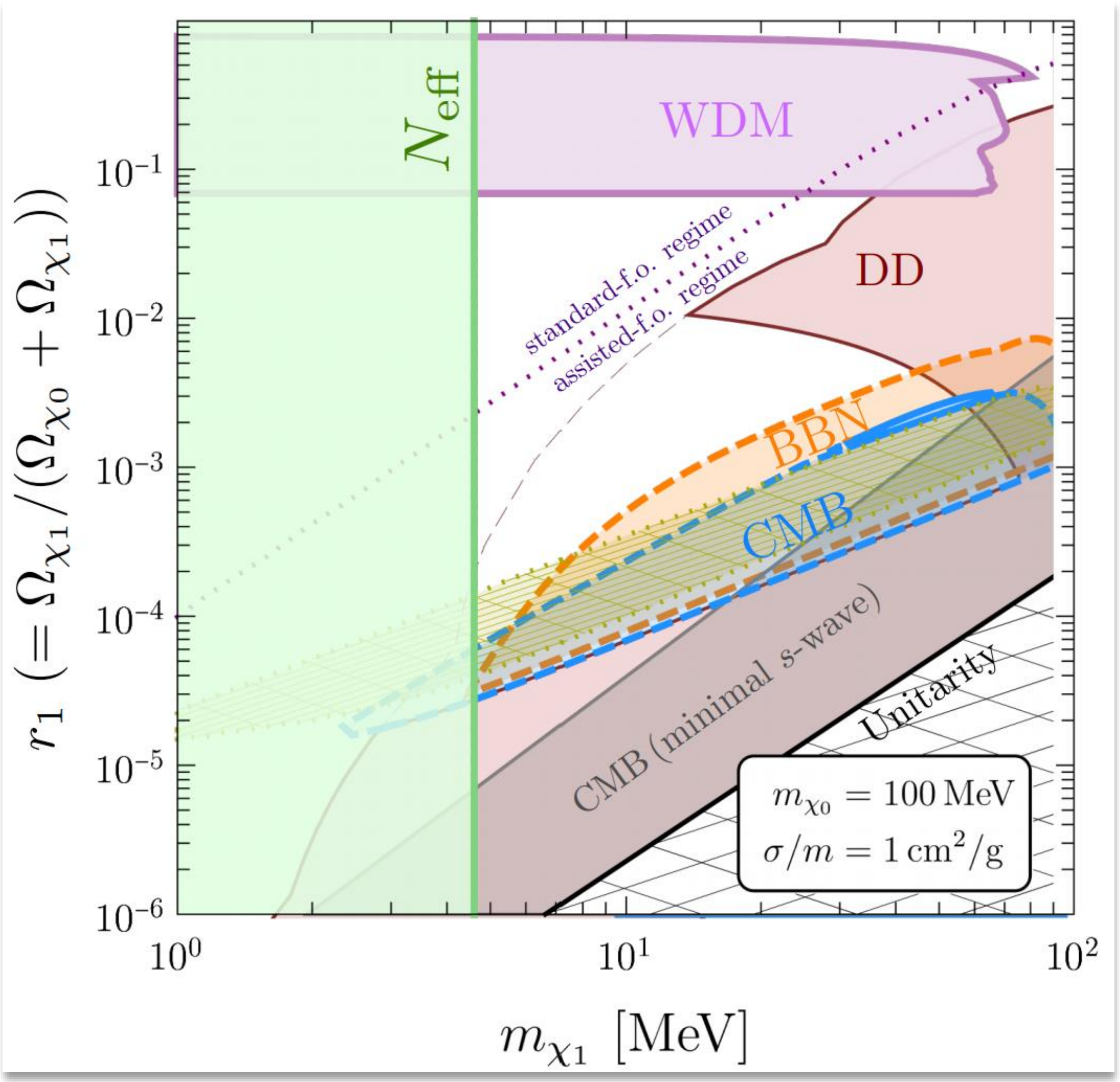
Next week by Jeong Han Kim

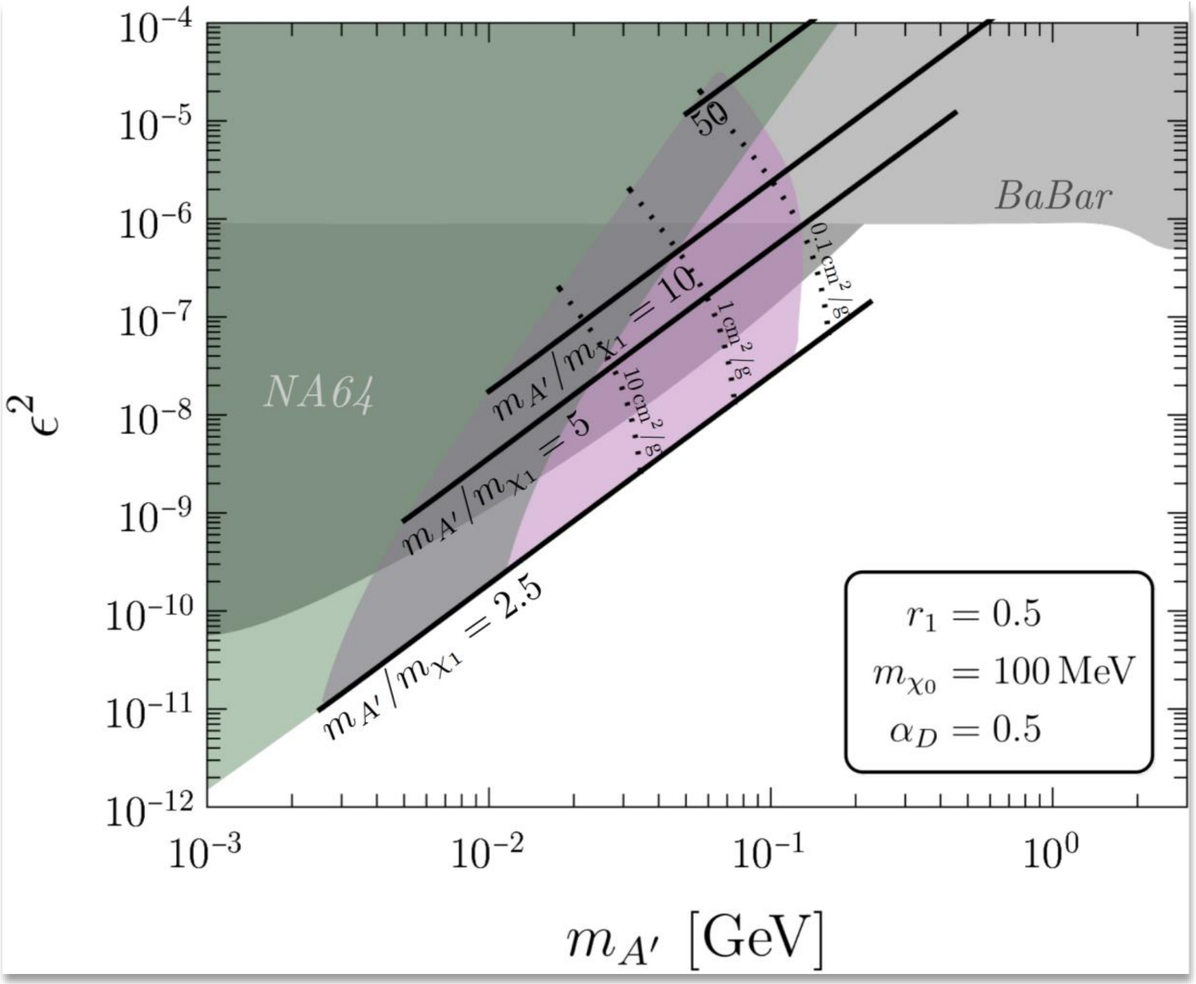
$$\dot{T}_{\chi_1} + 2HT_{\chi_1} \simeq \gamma_{\rm heat} T - 2\gamma_{\chi_1 {\rm sm}} (T_{\chi_1} - T)$$

✓ χ_2: heavy DM, χ_1: light DM

Cosmological Constraints & Dark Photon Searches

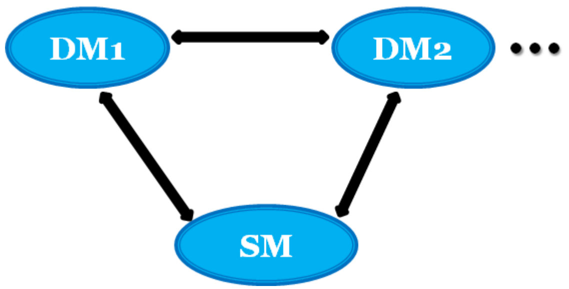
[Kamada, H. Kim, **JCP** & Shin, JCAP (2022)]

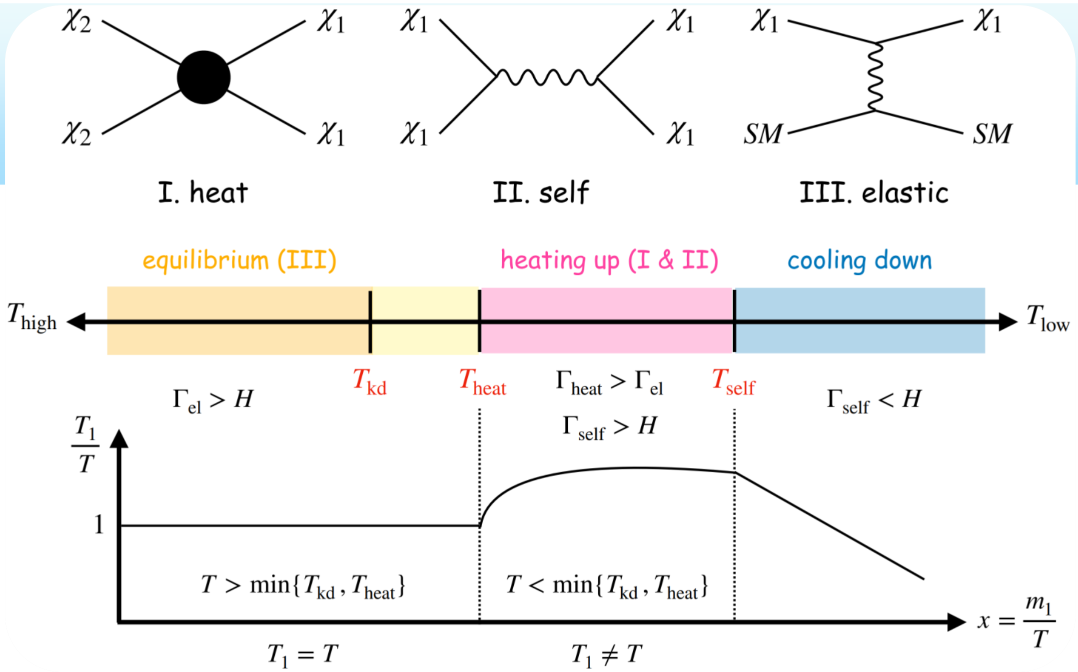




$$\mathcal{L} \supset \epsilon A'_\mu J^\mu_{\rm em} - i g_D A'_\mu \left(\chi_1^* \partial^\mu \chi_1 - \chi_1 \partial^\mu \chi_1^*\right) - \frac{\lambda_{\rm ast.}}{4} |\chi_1|^2 |\chi_0|^2$$

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.
- ❖ Experimental studies have already begun, e.g. SK, COSINE-100, Panda-X, CDEX, DUNE, …
- ❖ Effects of multi-comp. CDM: change in the thermal evolution
- ❖ The **lighter DM(> MeV)** can **behave like WDM**.
- ❖ Systematic cosmological studies are required!

Thank you

Supplemental

Optimizing Future BDM Searches

Many More Well-Motivated Exps.

Dark Matter Experiments	Target Material	Volume [t] Active	Volume [t] Fiducial	Depth [m]	$E_{\rm th}$ [keV]	Resolution: Position [cm]	Resolution: Angular [°]	Resolution: Energy [%]	PID	Run Time	Refs.
DarkSide –50	LAr DP-TPC	46.4 kg	36.9 kg	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	2013-	[112]
DarkSide –20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	goal: 2021–	[79]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	2016 –2018	[113, 114]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	goal: 2020–	[113]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10-20$	–	2016-	[99–101]
DEAP –50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[99]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	1,500	$\mathcal{O}(1)$	$\sim 0.1-1$	–	2.5 MeV: 2	–	goal: 2020–	[115, 116]

Neutrino Experiments	Target Material	Volume [kt] Active	Volume [kt] Fiducial	Depth [m]	$E_{\rm th}$ [MeV]	Resolution: Vertex [cm]	Resolution: Angular [°]	Resolution: Energy [%]	PID	Run Time	Refs.
Borexino	organic LS	0.278	0.1	3,800 m.w.e.	~ 0.2	~9-17	–	$\frac{5}{\sqrt{E\,(\rm MeV)}}$	–	> 5.6 year	[117]
KamLAND	LS	1	0.2686	1,000	0.2–1	$\frac{12-13}{\sqrt{E\,(\rm MeV)}}$	–	$\frac{6.4-6.9}{\sqrt{E\,(\rm MeV)}}$	–	~ 10 year?	[118, 119]
JUNO	LS	–	20	700	< 1, goal: 0.1	$\frac{12}{\sqrt{E\,(\rm MeV)}}$	μ: $L > 5$ m: < 1, $L > 1$ m: < 10	$\frac{3}{\sqrt{E\,(\rm MeV)}}$	$\mu^\pm$ vs $\pi^\pm$, $e^\pm$ vs π^0: difficult	goal: 2021–	[120–122]
DUNE	LArTPC	Total: 17.5 $\times 4$	$\gtrsim 10$ $\times 4$	1500	$e: 30$, p: 21-50	$\lesssim 1-2$	$e, \mu: 1$, $\pi^\pm, p, n: 5$	$e: 20$ $(E < 0.4\,{\rm GeV})$, 10 $(E < 1.0\,{\rm GeV})$, $2 + \frac{8}{\sqrt{E/{\rm GeV}}}$ $(E > 1.0\,{\rm GeV})$ $p: 10$ $(E < 1.0\,{\rm GeV})$, $5 + \frac{5}{\sqrt{E/{\rm GeV}}}$ $(E > 1.0\,{\rm GeV})$	good $e, \mu, \pi^\pm, p$ separation	10 kt: 2026-, 20 kt: 2027–	[77, 80–84]
SK	Water Cherenkov	Total: 50	22.5	1,000	$e: 5$, $p: 485$	5 MeV: 95, 10 MeV: 55, 20 MeV: 40	10 MeV: 25, 0.1 GeV: 3, 1.33 GeV: 1.2	10 MeV: 16, 1 GeV: 2.5	e, μ: good	$\gtrsim 14$ year	[123–125]
HK	Water Cherenkov	Total: 258 $\times 2$	187 $\times 2$	Japan: 650, Korea: 1,000	$e: < 5$, $p: 485$	5 MeV: 75, 10 MeV: 45, 15 MeV: 40, 0.5 GeV: 28	similar to SK	better than SK	e, μ: good, $\pi^0, \pi^\pm$: mild	goal: 2027–	[85–87]

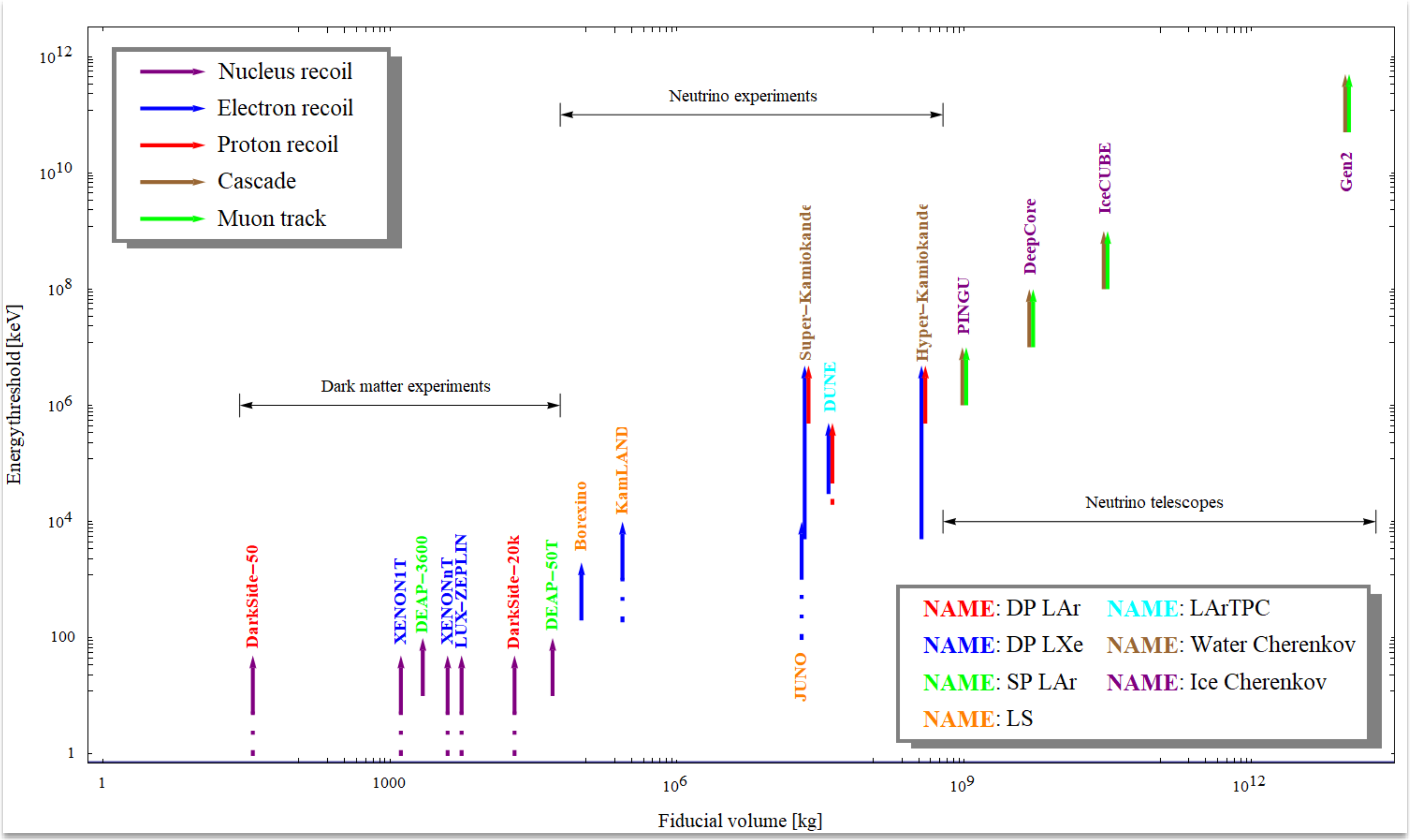
Neutrino Telescopes	Target Material	Effective Volume [Mt]	Depth [m]	$E_{\rm th}$ [GeV]	Resolution: Vertex [m]	Resolution: Angular [°]	Resolution: Energy [%]	PID	Run Time	Refs.
IceCube	Ice Cherenkov	100 GeV: ~ 30, 200 GeV: ~ 200	1,450 Ice	~ 100	vertical: 5, horizontal: 15	μ-track: ~ 1, shower: ~ 30	100 GeV: 28, 1 TeV: 16	only μ	2011– (2008)	[89, 126]
DeepCore	Ice Cherenkov	10 GeV: ~ 5, 100 GeV: ~ 30	2,100 Ice	~ 10	better	μ-track: $\sim$1, shower: $\gtrsim 10$	–	only μ	2011– (2010)	[88, 89]
IceCube Upgrade	Ice Cherenkov	–	2,150 Ice	$\mathcal{O}(1)$	much better	5 GeV: ~ 20, 10 GeV: ~ 15	–	only μ	goal: 2023	[127]
PINGU	Ice Cherenkov	1 GeV: $\gtrsim 1$, 10 GeV: ~ 5	2,100 Ice	~ 1	much better	1 GeV: 25, 10 GeV: 10	1 GeV: 55, 10 GeV: 25	only μ	$>$ 2023	[128, 129]
Gen2	Ice Cherenkov	~ 10 Gt	1,360 Ice	~ 50 TeV	worse	μ-track: < 1 shower: ~ 15	–	only μ	–	[130]

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

- Many existing/upcoming experiments are potentially capable of testing models conceiving BDM signals.
- Additional physics opportunity on top of the main mission of each experiment.

Many More Well-Motivated Exps.

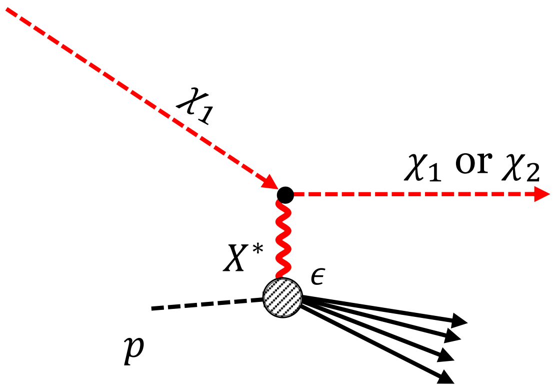
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]

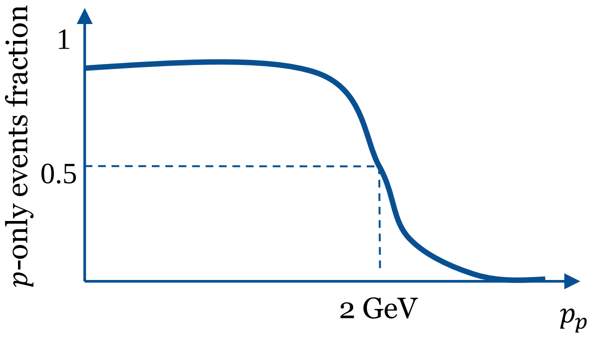


Detectors are complementary to one another rather than superior to the other!

p-Scattering vs. DIS

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

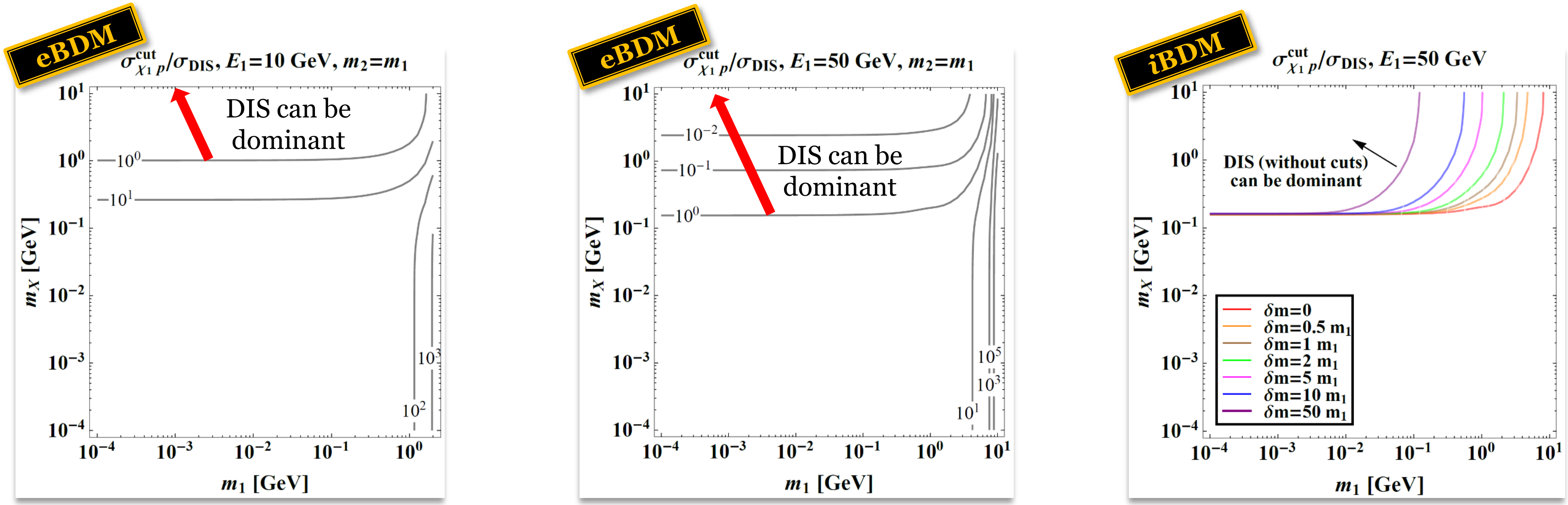




- If a momentum transfer is too large, a proton may break apart.
- What is large? ➔ A SK simulation study [Fechner et al, PRD (2009)] showed about 50 % events accompany (at least) a pion or a secondary particle for $p_p \approx 2$ GeV.
- We categorize any event with $p_p < 2$ GeV as the p-scattering (i.e., simplified step-function-like transition).

p-Scattering vs. DIS: Numerical Study

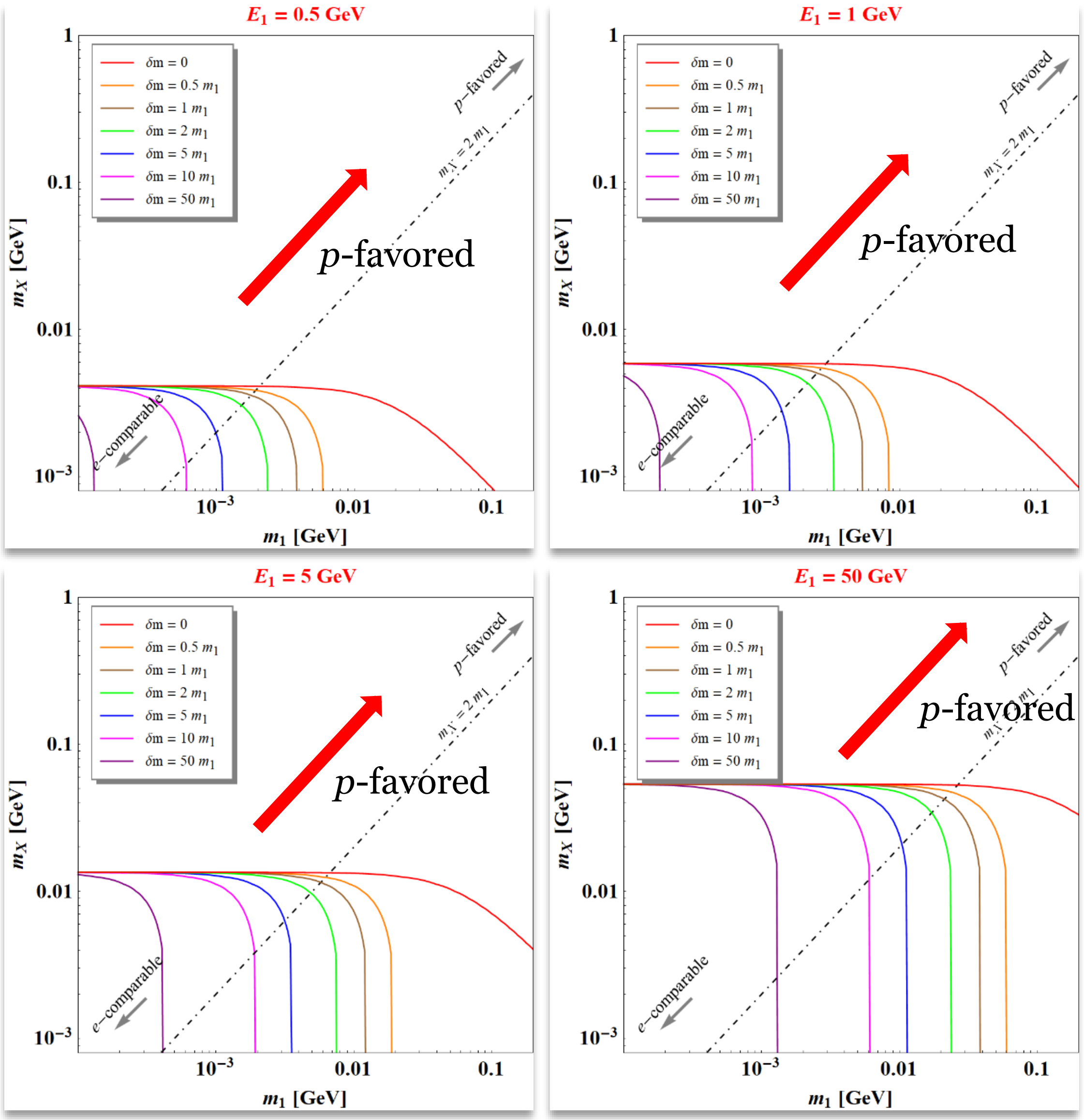
[P. Machado, D. Kim, **JCP** & S. Shin, JHEP (2020)]



- ✓ 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 σ_{DIS}.
- ✓ *p*-scattering dominates over DIS for m_X < O(GeV) (cf. *ν* 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.

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 χ_1 and χ_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 χ_1 comes with more energy, more parameter space where the e-channel is comparable opens up.
- ✓ With cuts, more e-channel favored region.