Cosmic-ray Neutrino Boosted DM (νBDM)

[PLB (2020), arXiv: 2101.11262 & In preparation]
with Y. Jho, S. C. Park & P.-Y. Tseng

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DM Landscape: A Very Wide Mass Range

Ultralight
(QCD) axion,
hidden photon,
scalar field,
fuzzy,
non-thermal

Superlight
sterile ν,
axino,
warm DM,
can be
thermal

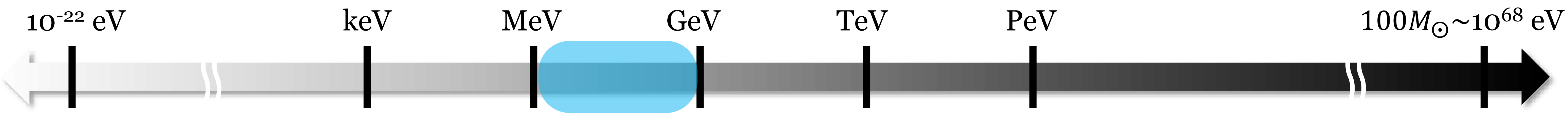
Light
SIMP,
ELDER,
can be
thermal

WIMP
well-motivated,
extensively
studied,
thermal
No firm signal yet!

Superheavy
composite,
WIMPzilla,
Q-ball,
Fermi-ball,
dark-quark
nugget,
non-thermal

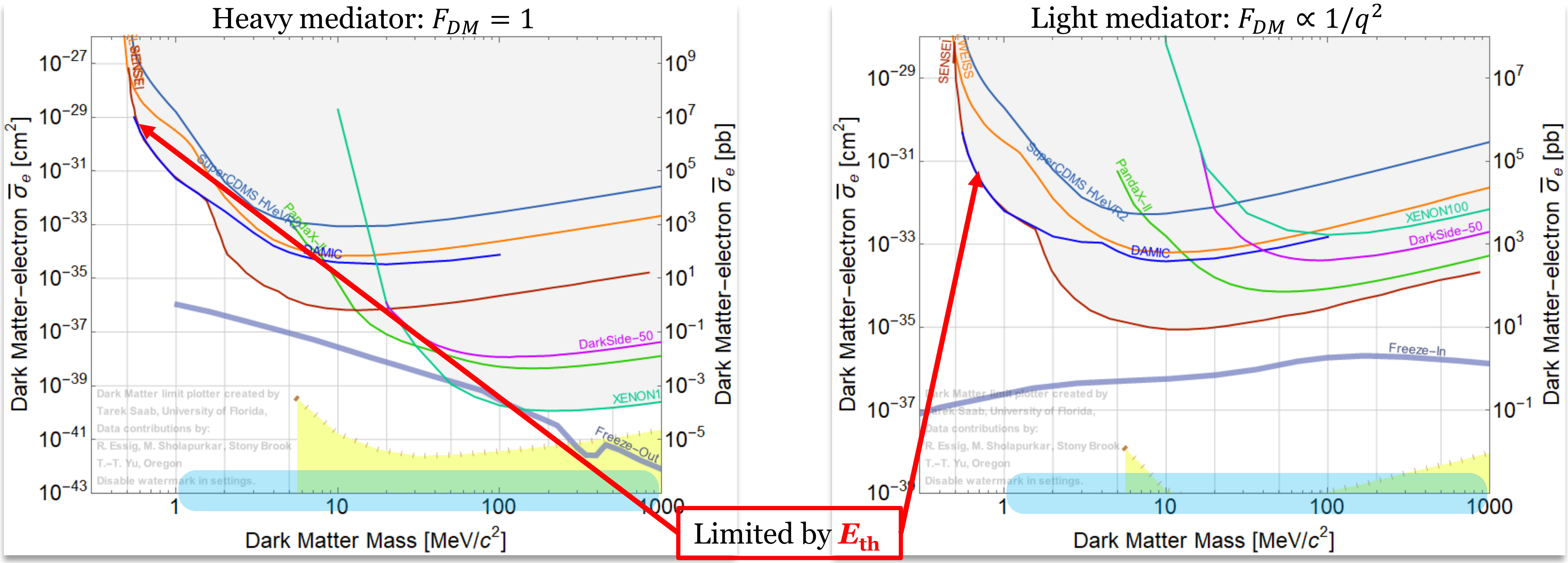
Astrophysical object
MACHO, PBH,
non-particle

Light DM Direct Search



- $E_k \sim mv^2$, $\Phi_\chi = n_\chi v_{rel}$ & $n_\chi = \rho_\chi / m_\chi$ ➔ lighter DM: **smaller E_r** but **lager flux** (**lighter** target particle)

  ➔ **low E_{th}** preferred but even OK with **small target mass** (**e-recoil**)



Dark Matter Limit Plotter v5.17, updated December 21, 2021

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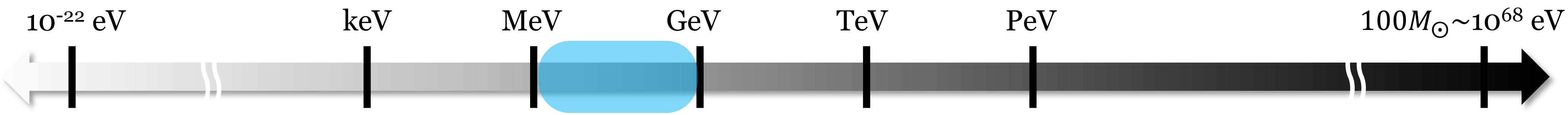

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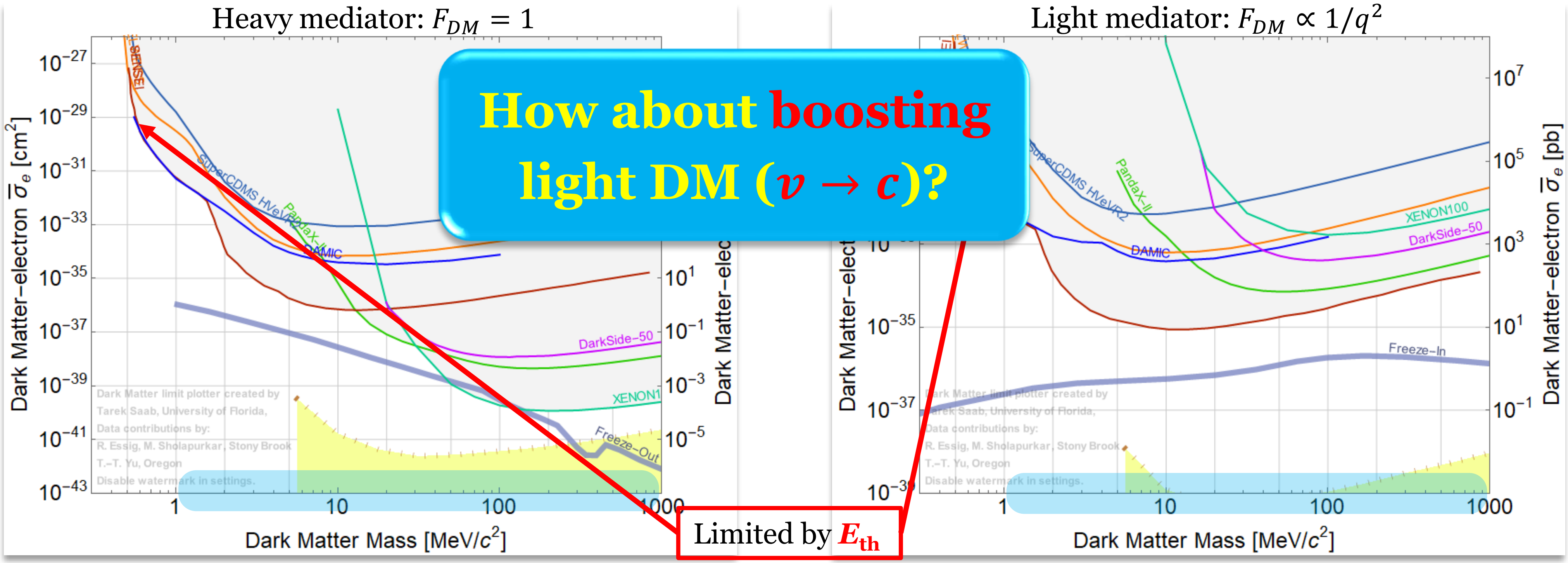

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DM Boosting Mechanisms: Dark Sector

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);
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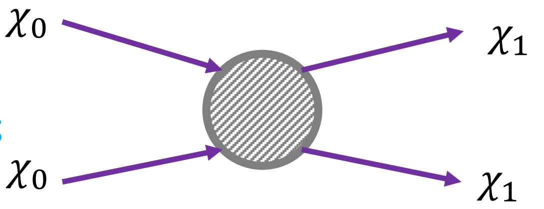
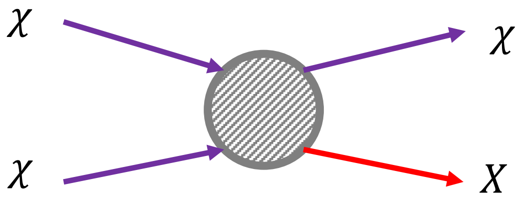


✓ Multi-component model
$m_0 \gg m_1$



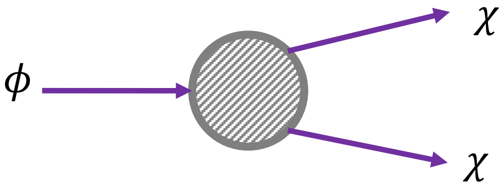
✓ Semi-annihilation model
$m_\chi \gg m_X$

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

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

- Relic component DM: non-relativistic!
- BDM signal: detectable at large Vol. DM & neutrino detectors

G. Mohlabeng's talk tomorrow!



✓ Decaying multi-component DM
$m_\phi \gg m_\chi$

[Bhattacharya et al., JCAP (2015);
Kopp et al., JHEP (2015);
Cline et al., PRD (2019);
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more]

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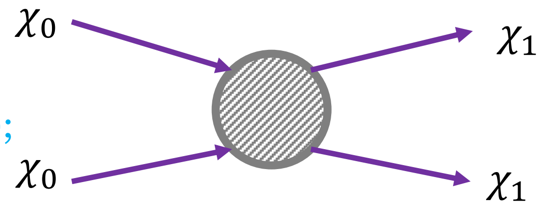

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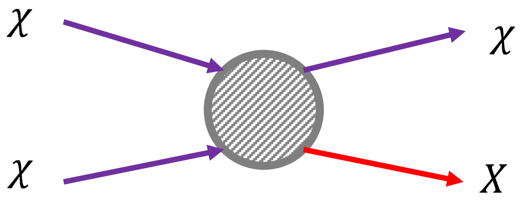

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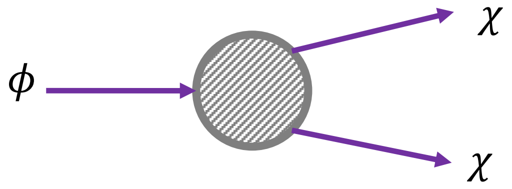

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- Heating via sizable self-scattering (natural for LDM) ➔ affect the thermal evolution of DM

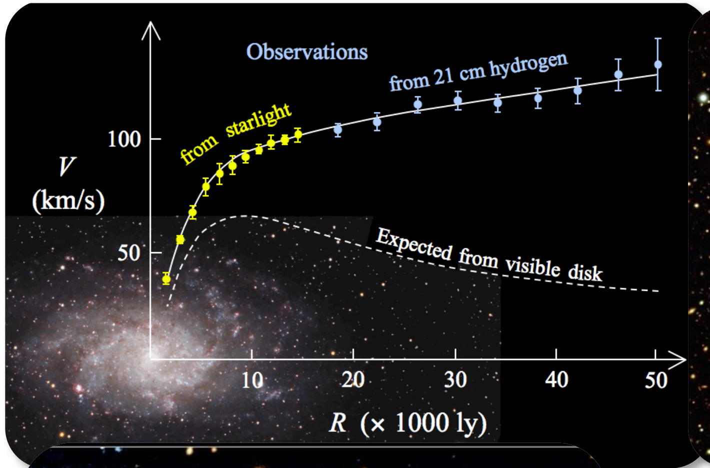
[Kamada, Kim, Kim & Sekiguchi, PRL (2018); Kamada, Kim, **JCP** & Shin, 2111.06808]

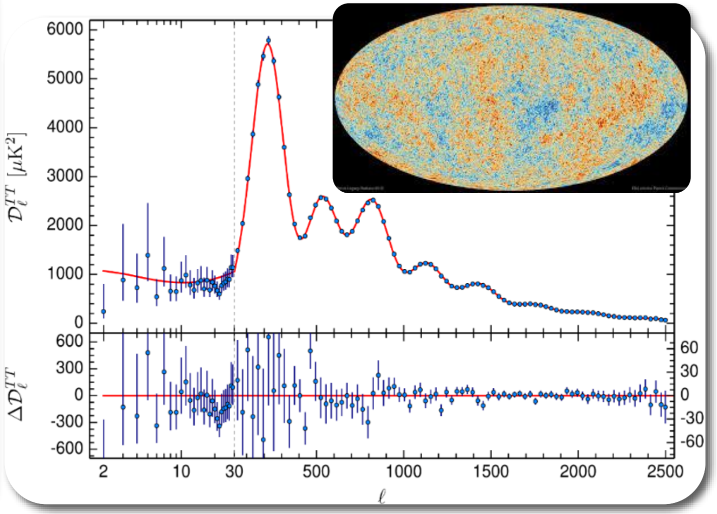
S. Shin's talk later today!

Cosmic-ray-induced BDM

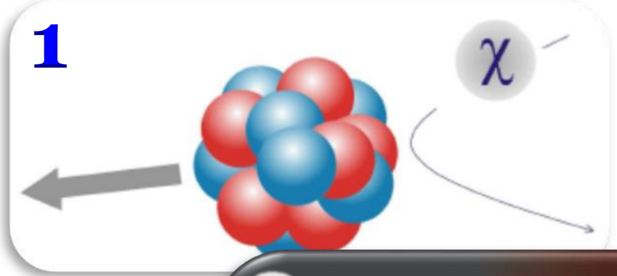
Road to DM Nature

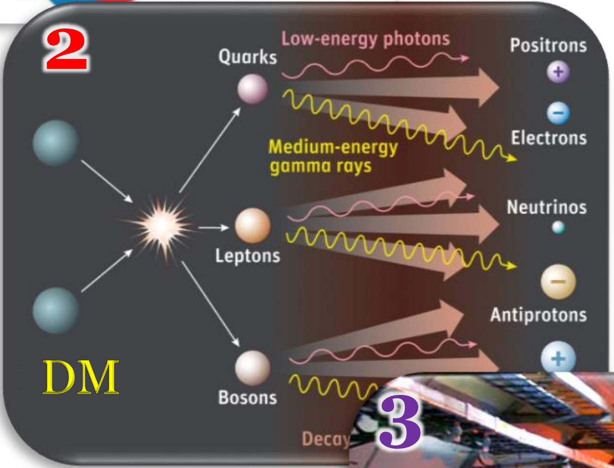
❖ **Currently evidence & observation**: only gravity

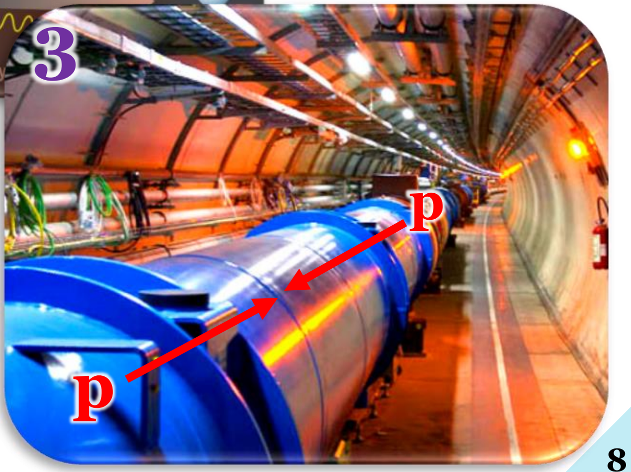




❖ **Particle nature**: interaction w/ SM via non-gravity

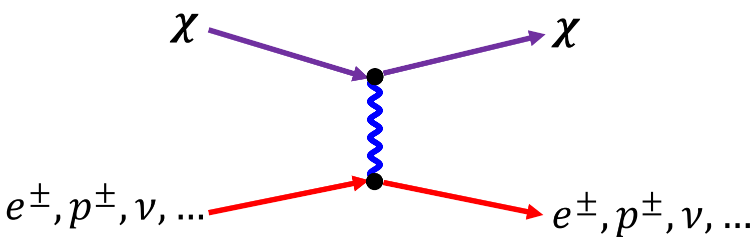






Road to DM Nature: Reversing

The other way around!



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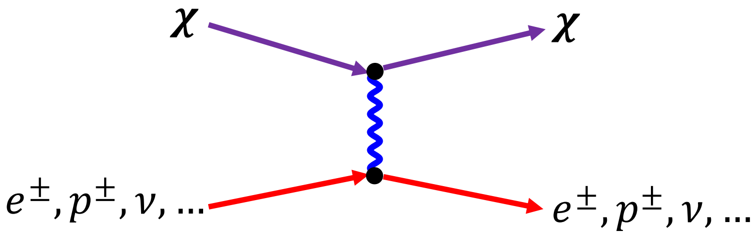
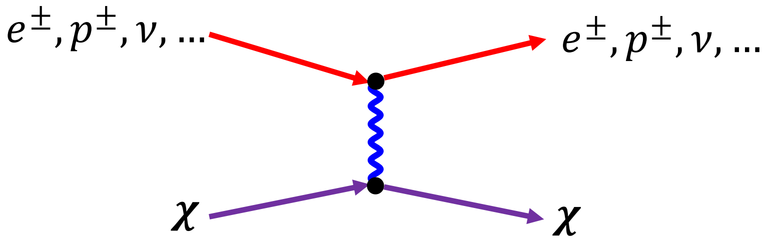
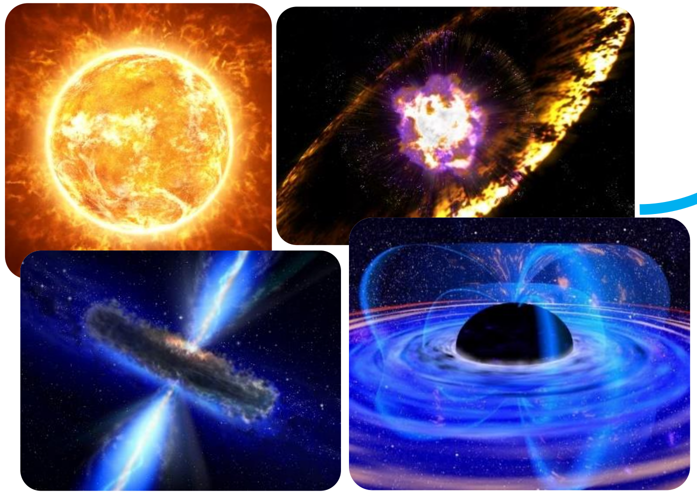
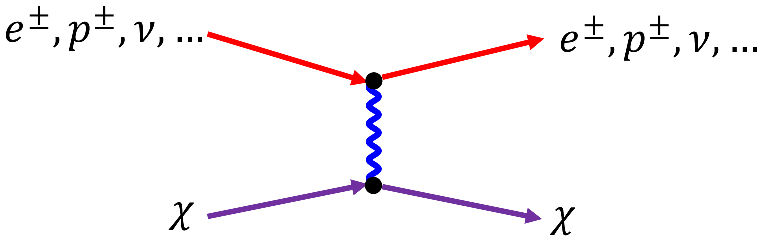




DM Boosting Mechanisms: Cosmic-Ray

Cosmic-Ray-Induced BDM





- Energetic cosmic-ray-induced BDM:

  energetic cosmic-rays kick DM

  (large $E_{e^{\pm},p^{\pm},\nu,\ldots}$ ➔ large E_{χ})

  ➔ Efficient for Light DM

Large E_k^{χ} due to E_k^{CR} transfer

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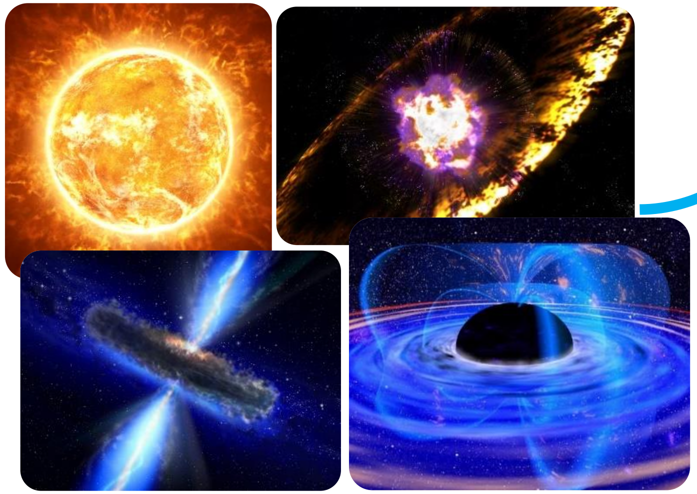
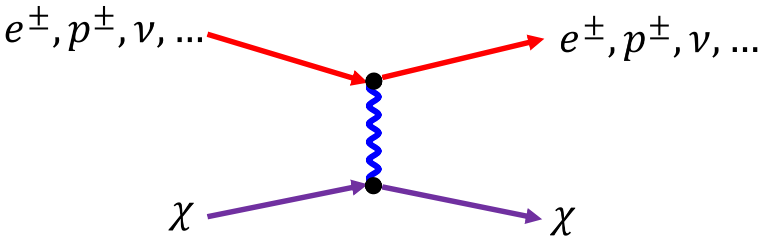
Cosmic-Ray-Induced BDM





- ✓ **Charged** cosmic-ray ($e^{\pm}, p^{\pm}$): [Bringmann & Pospelov, PRL (2019); Ema +, PRL (2019); Cappiello & Beacom, PRD (2019); Dent +, PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho +, PRD (2020); more]
- ✓ Cosmic-ray $\boldsymbol{\nu}$ (**$\boldsymbol{\nu}$BDM**): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; Chao, Li, Liao, 2108.05608; more]

❖ Energetic cosmic-ray-induced BDM:

energetic cosmic-rays kick DM

(large $E_{e^{\pm},p^{\pm},\nu,\ldots}$ ➔ large E_{χ})

➔ Efficient for Light DM

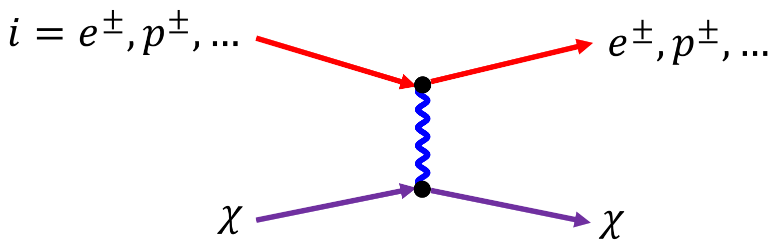
Large E_k^{χ} due to **E_k^{CR} transfer**

Calculation of BDM E-spectrum: quite similar even with different types of cosmic rays **except the neutrino-induced case**!

❖ Astrophysical processes: [Kouvaris, PRD (2015); Hu +, PLB (2017); An +, PRL (2018); Emken +, PRD (2018); Calabrese & Chianese +, PRD (2022); Wang +, PRL (2022); Cappiello's talk; more]

Cosmic-ray-induced BDM: $e^{\pm}, p^{\pm}, \ldots$

❖ Charged-cosmic-ray-induced BDM: charged cosmic-rays kick DM (large $E_{e^{\pm},p^{\pm},\ldots}$)



Large E_k^{χ} due to E_k^{CR} transfer

✓ DM-i interaction ➔ Non-relativistic halo DM can be boosted by high E charged cosmic-rays.

✓ BDM flux: by convolution of charged cosmic-ray fluxes & DM-i differential cross section

(charged cosmic-ray fluxes: AMS-02, DAMPE, Fermi-LAT, Voyager, …)

$$\frac{d\Phi_\chi}{dK_\chi} = \frac{1}{4\pi}\int d\Omega \int_{\text{l.o.s.}} ds \left(\frac{\rho_\chi(r(s,\theta))}{m_\chi}\right) \int_{K_i^{\min}}^{\infty} dK_i \frac{d\sigma_{i\chi\to i\chi}(K_i)}{dK_\chi}\frac{d\Phi_i^{\text{LIS}}}{dK_i}$$

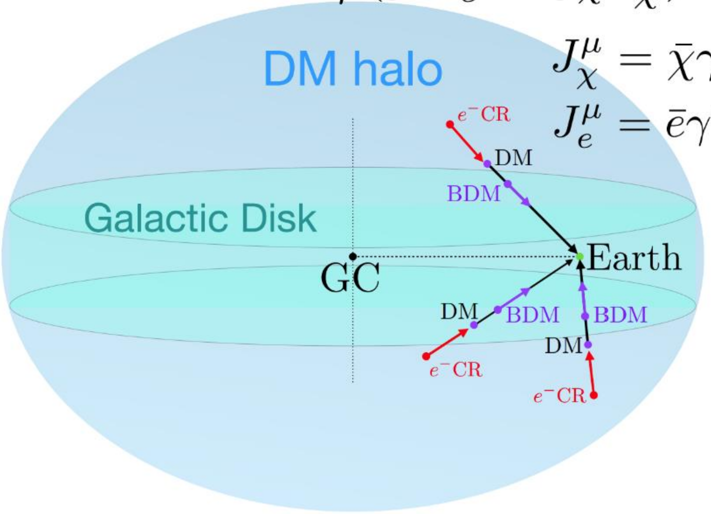
ρ_χ: the relic density of χ in the galaxy

$d\Phi_i^{\text{LIS}}/dK_i$: the local interstellar differential flux of the cosmic-ray particle i

$K_i^{\min}$: the minimum kinetic energy of the cosmic-ray particle i

$$\mathcal{L} \supset -X_\mu (g_e J_e^\mu + g_\chi J_\chi^\mu) + \ldots$$

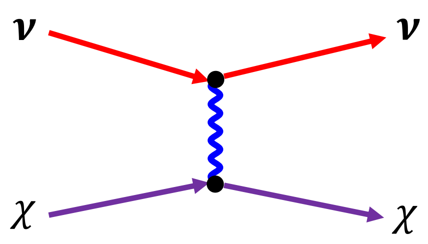
$$J_\chi^\mu = \bar{\chi}\gamma^\mu\chi$$
$$J_e^\mu = \bar{e}\gamma^\mu e$$



Cosmic-ray-induced BDM: νBDM

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

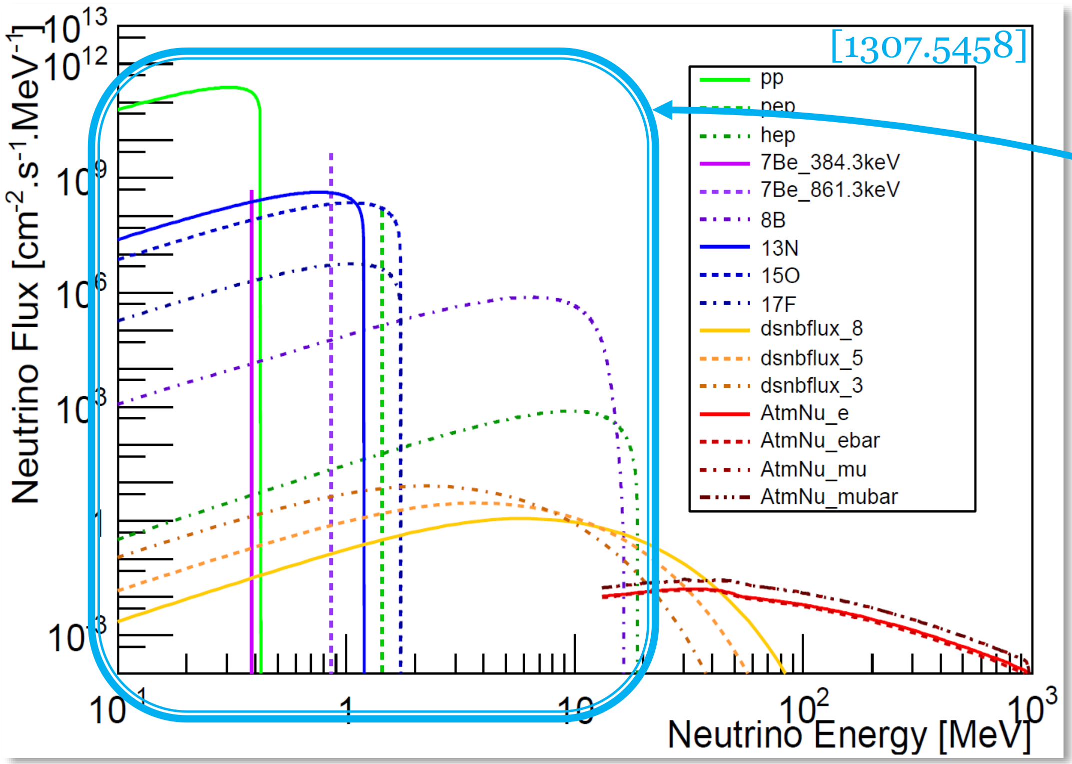
❖ **Cosmic-ray ν-induced BDM (νBDM)**: cosmic-ray neutrinos kick DM (large E_ν)

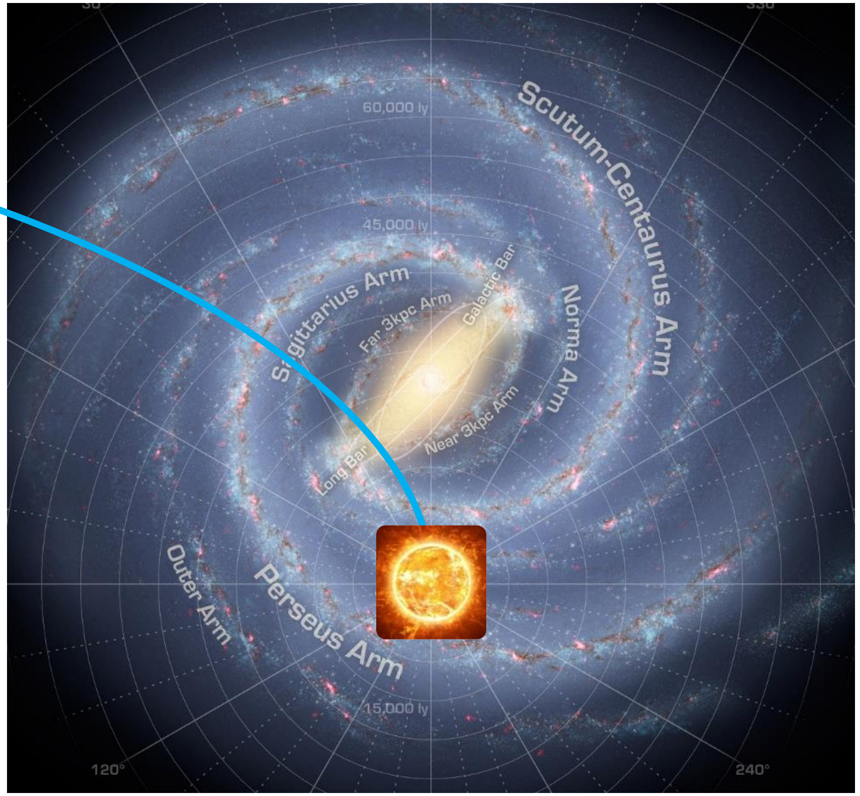


Large E_k^χ due to E_k^ν transfer

✓ DM-ν interaction ➔ Non-relativistic halo DM can be boosted by **ν's from stars in the galaxy**.

$\Phi_\nu \gg \Phi_{e,p}$





Cosmic-ray-induced BDM: νBDM

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

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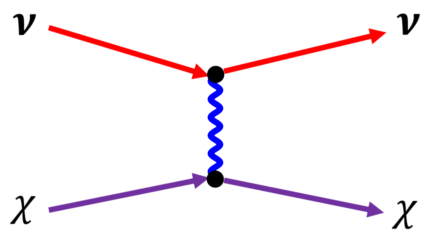
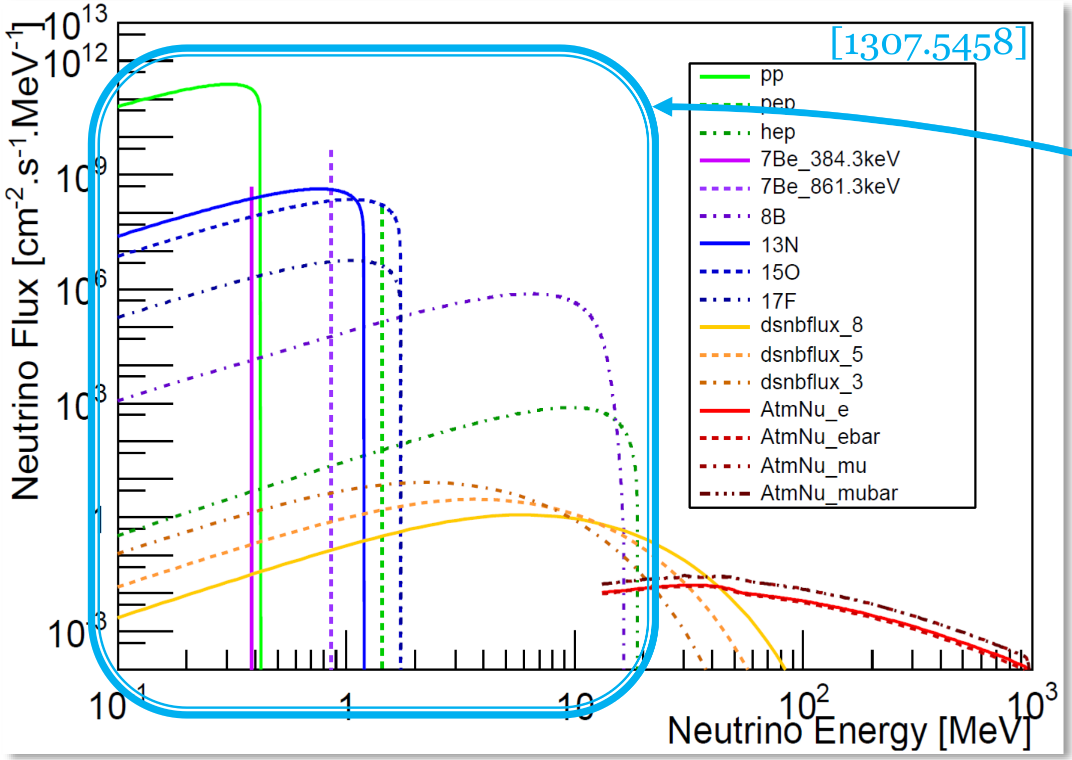
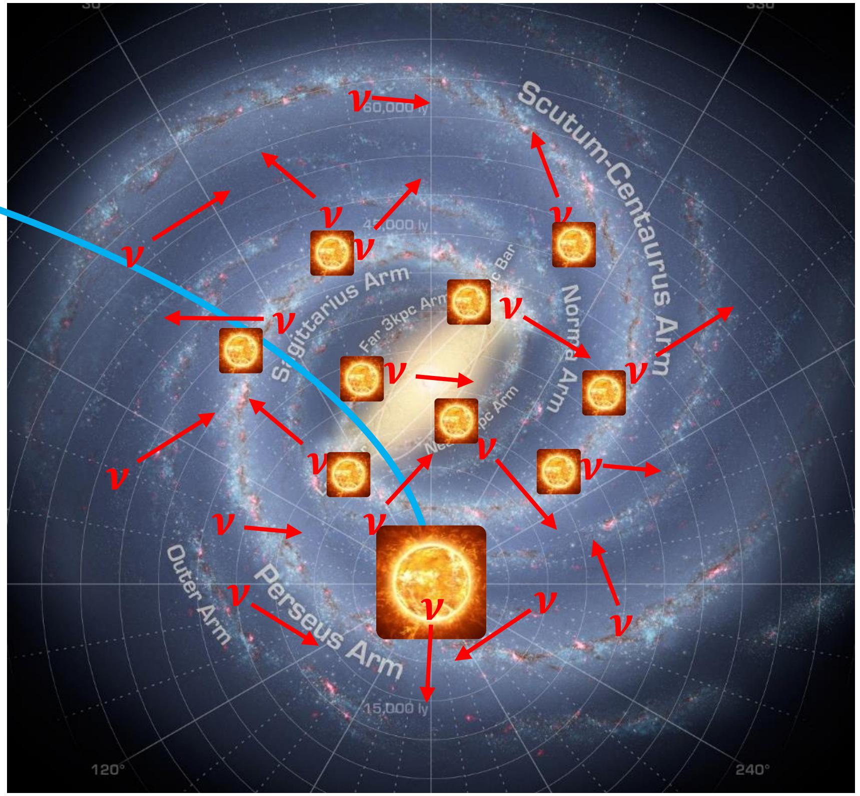


Large E_k^χ due to E_k^ν transfer

✓ DM-ν interaction ➔ Non-relativistic halo DM can be boosted by ***ν's from stars in the galaxy***.

$\Phi_\nu \gg \Phi_{e,p}$

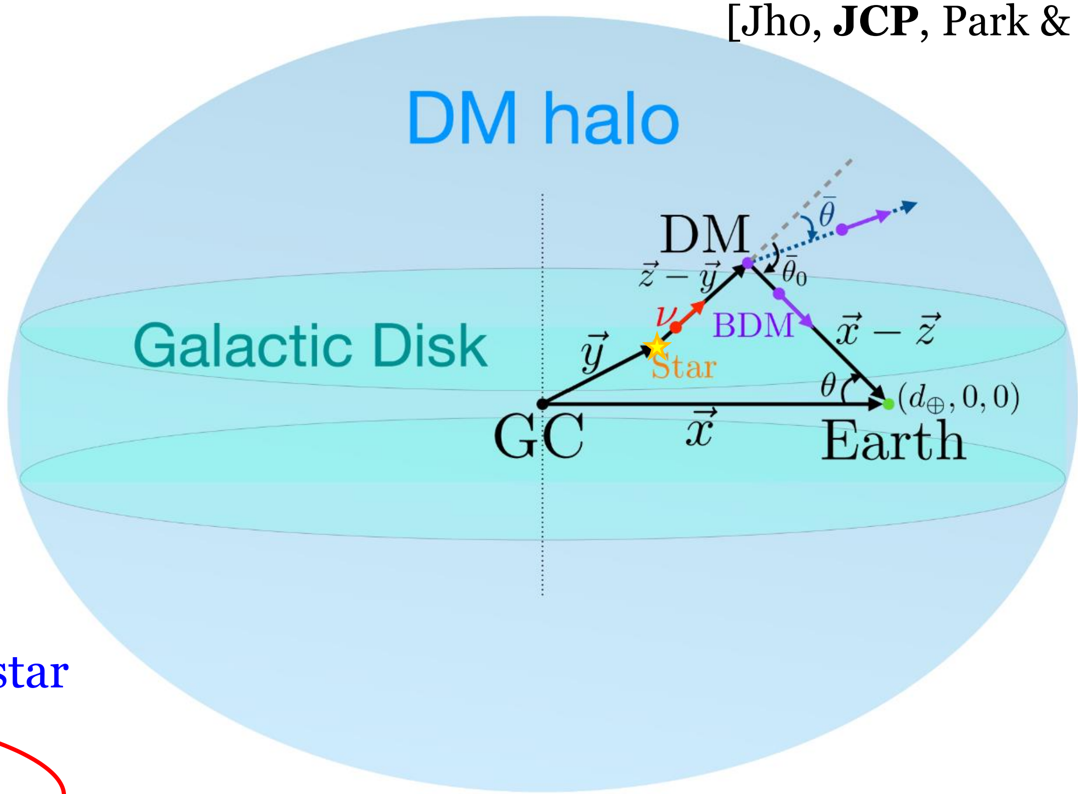




Cosmic-ray-induced BDM: νBDM

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

❖ BDM production by ν from a star



❖ BDM flux by ν's from a single Sun-like star

$$\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}} \simeq \frac{\mathcal{F}}{8\pi^2}\left(\tilde{f}_1 \frac{d\dot{N}_\nu^{\rm Sun}}{dK_\nu}\right)\int d^3\vec{z}\, \frac{\rho_{\rm DM}(|\vec{z}|)}{m_{\rm DM}} \frac{1}{|\vec{x}-\vec{z}|^2} \times \left(\frac{dK_\nu}{d\bar{\theta}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right)\left(\frac{d\sigma_{\nu\rm DM}}{dK_{\rm DM}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right) \times \frac{1}{\sin\bar{\theta}_0}\frac{1}{|\vec{z}-\vec{y}|^2} \times \exp\left(-\frac{|\vec{z}-\vec{y}|}{d_\nu}\right)$$

Neutrino emission rate for a Sun-like star

Variances of stellar properties from Sun

scattering angle=direction to the earth via kinematic relations

Attenuation of the ν flux due to propagation

Cosmic-ray-induced BDM: νBDM

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

❖ BDM production by ν from a Sun-like star

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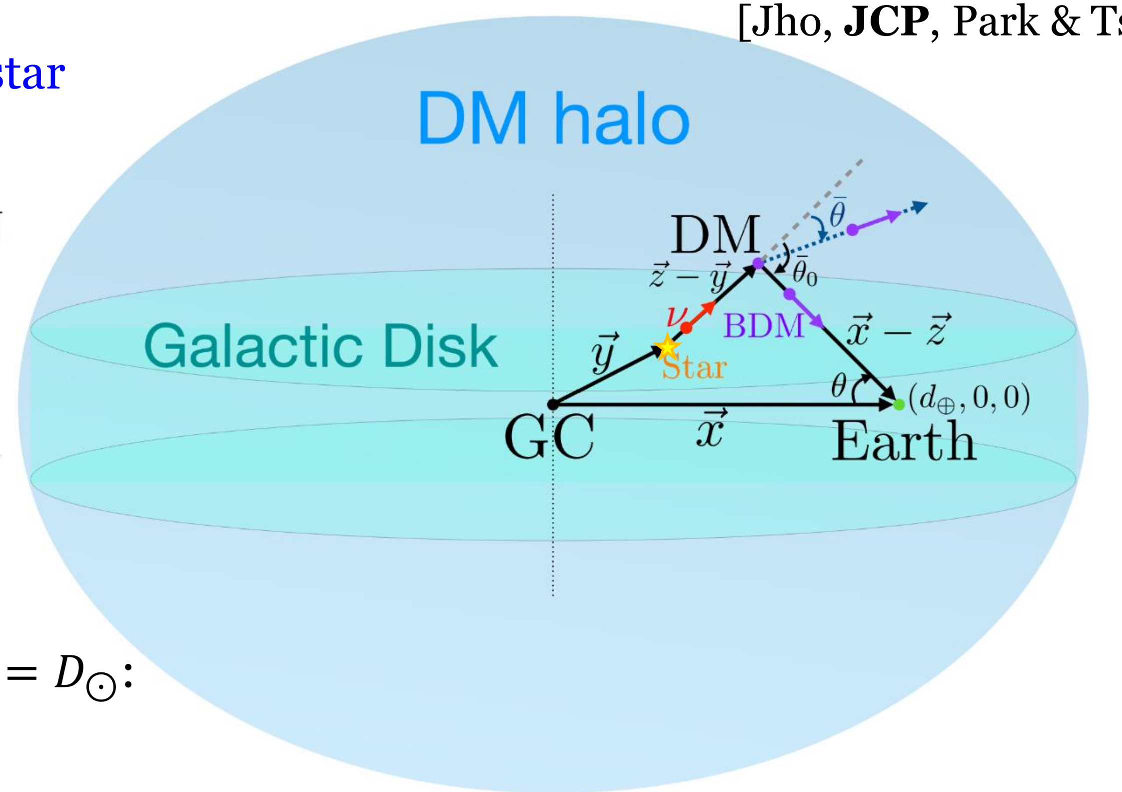


✓ BDM flux by ν's from Sun by taking $|\vec{x}-\vec{y}| = D_\odot$:

Sun provides the largest ν flux to Earth,

but only small volume of nearby low density DM halo comprises the BDM flux.

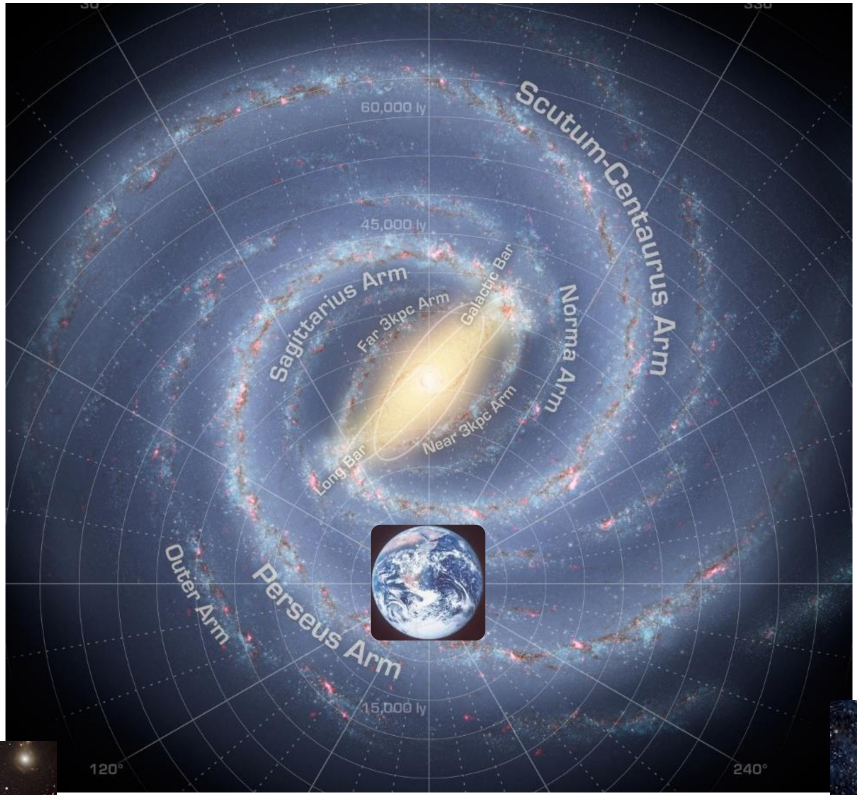
✓ Entire stellar contributions in the galaxy: $\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} = \int d^3\vec{y}\, n_{\rm star}(\vec{y})\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}}$

Cosmic-ray-induced BDM: νBDM

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

❖ **Extra-galactic(EG) contribution** to the νBDM flux

Dominant contribution:
ν & DM populated regions
➔ e.g., Galactic Center



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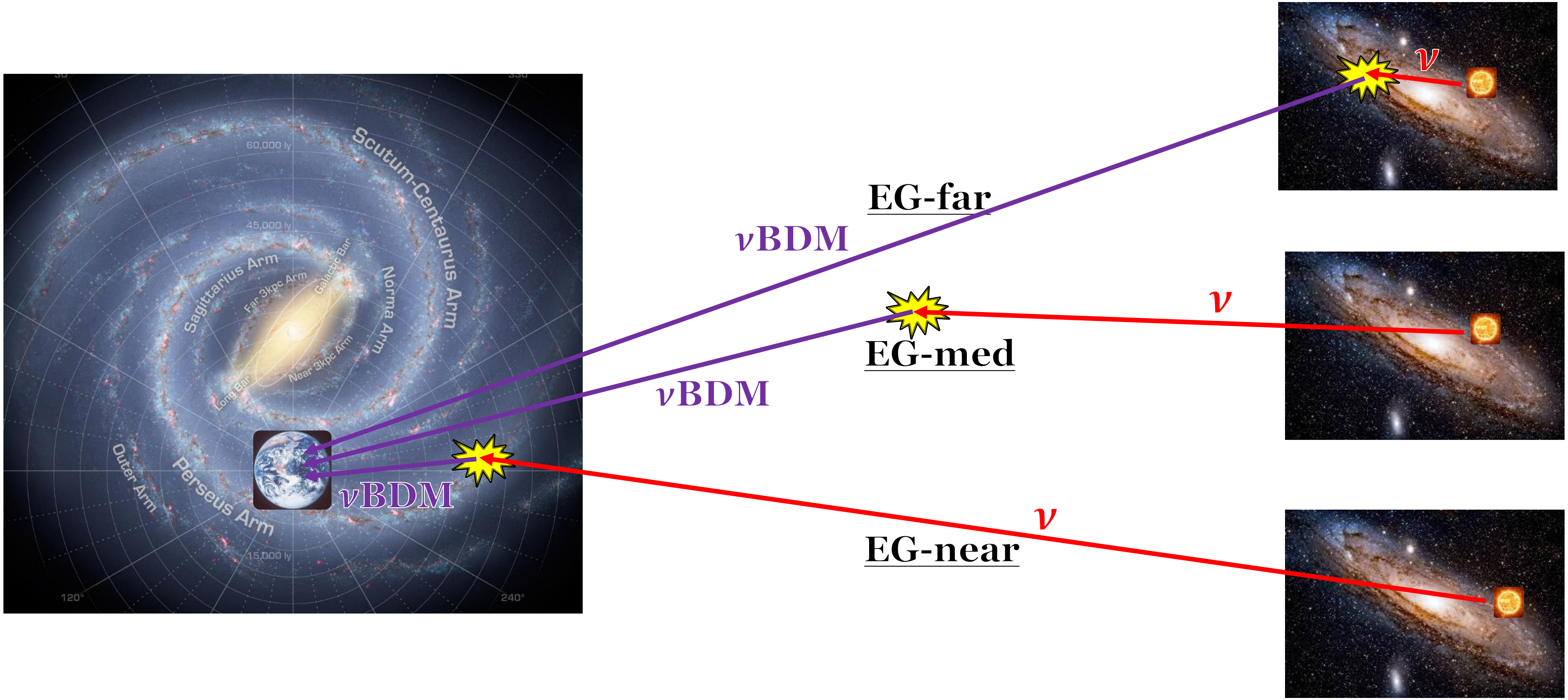

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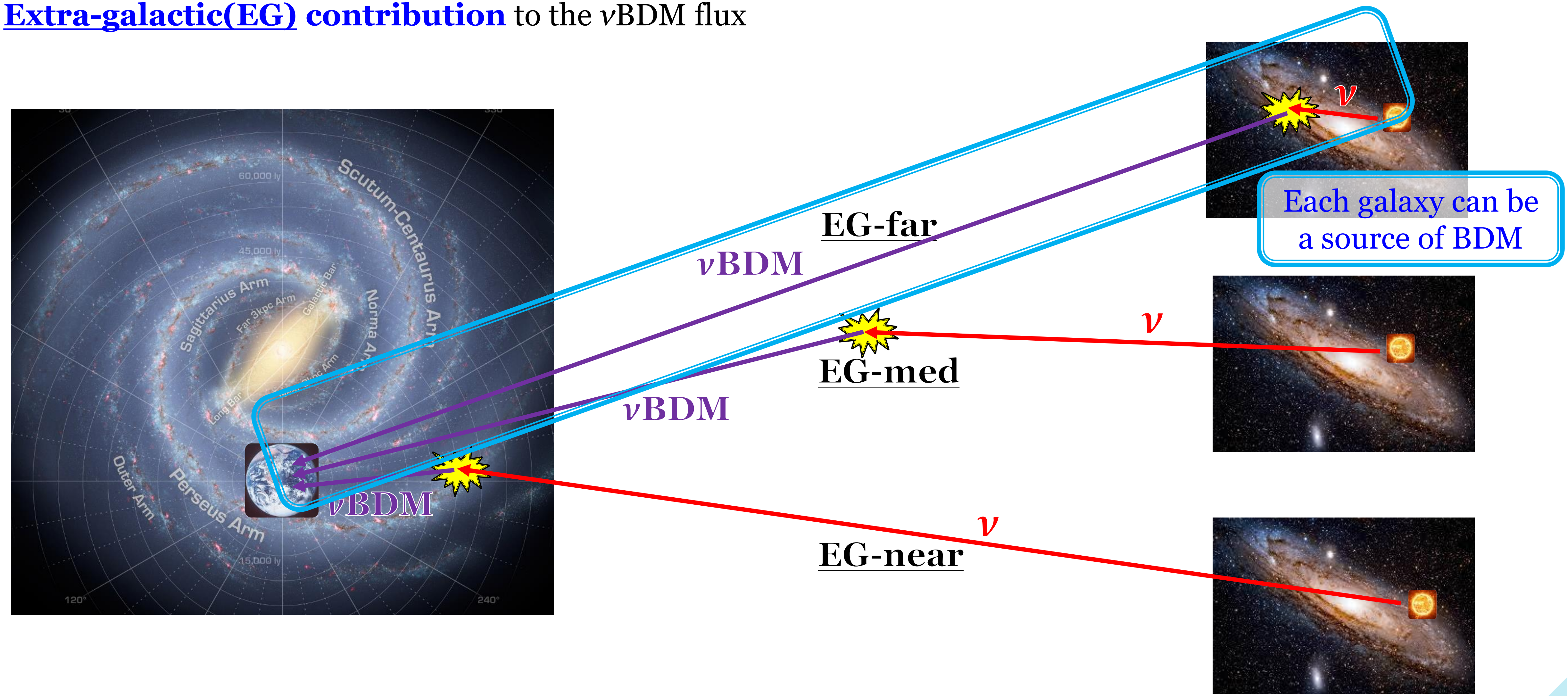
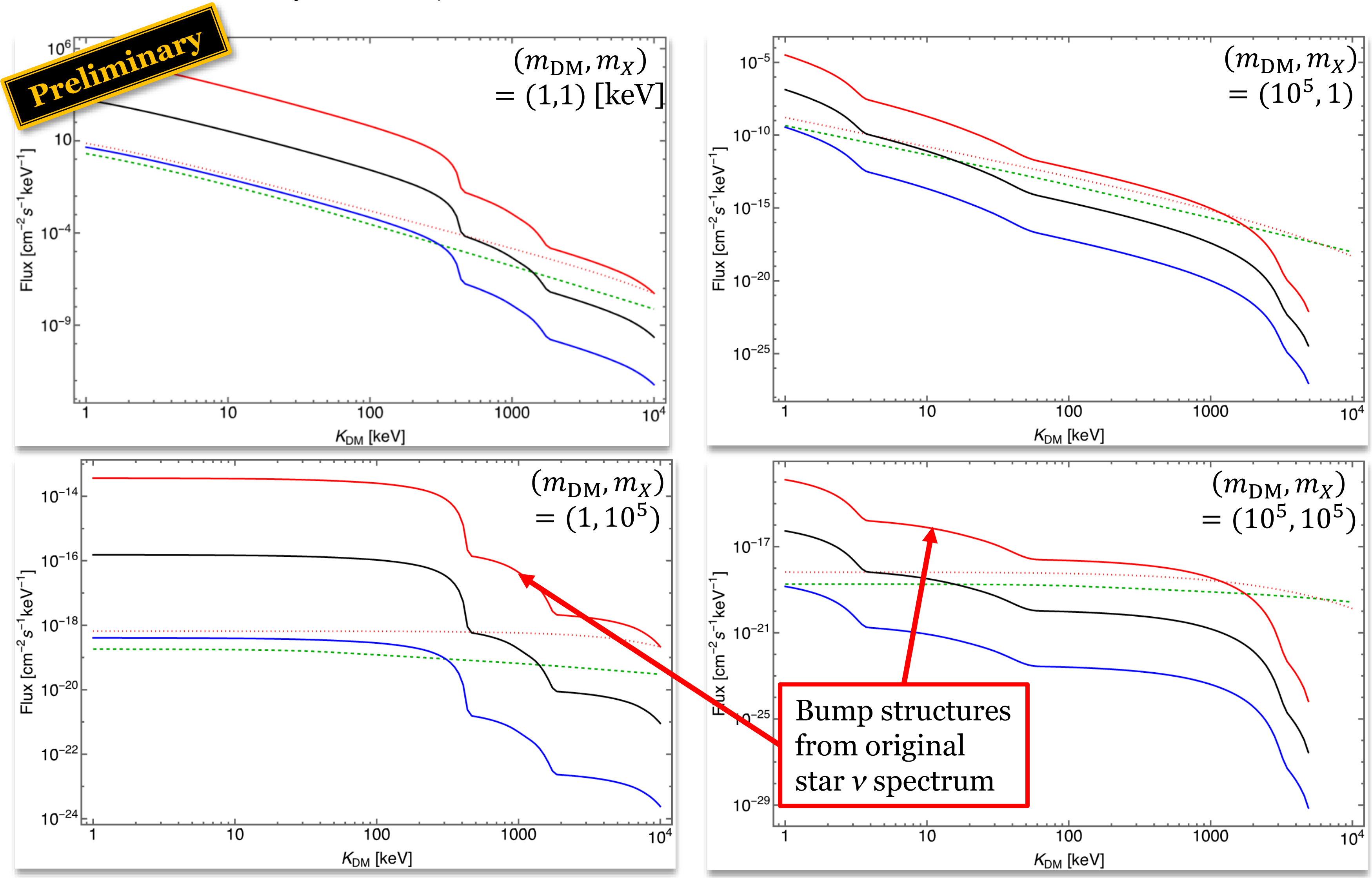


Cosmic-ray-induced BDM: Fluxes

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

❖ BDM fluxes by Galactic/EG star neutrinos, DSNB & cosmic electrons



$$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$$

$$g_e = g_\nu = 10^{-6}$$
$$g_{\rm DM} = 1$$

EG-νBDM (far) — EG-νBDM (near)
DSNB-BDM — CRe-BDM
Galactic-νBDM

✓ **EG-νBDM (far)**: most dominant

for $m_{\rm DM}$~1 keV ➔ $K_{\rm DM} \lesssim 10$ MeV

for $m_{\rm DM}$~100 MeV ➔ $K_{\rm DM} \lesssim 1$ MeV

✓ **CRe-νBDM**: dominant for high $K_{\rm DM}$

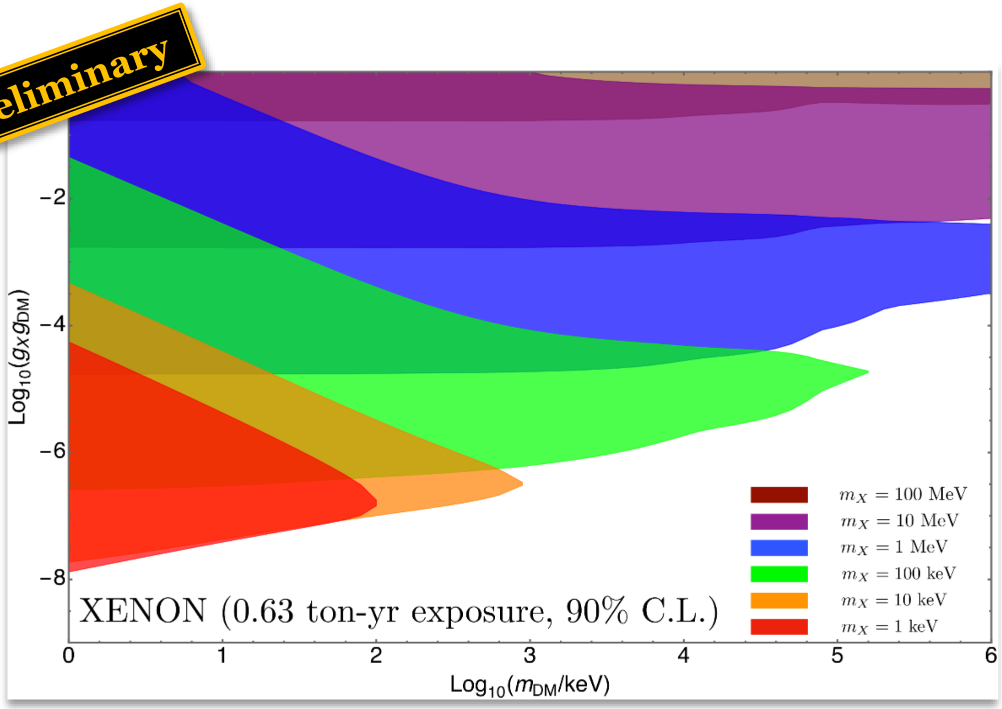
✓ **DSNBG**: dominant in-between

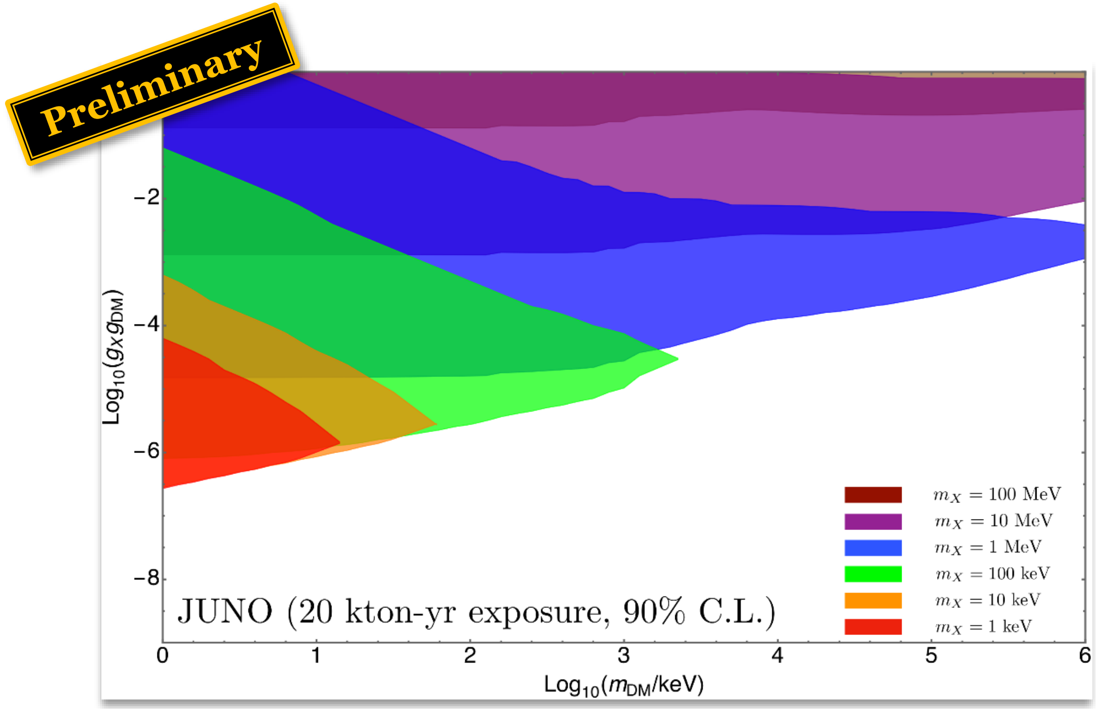
Cosmic-ray-induced BDM: Limits - Coupling

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

❖ Experimental status

$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$ with $g_e = g_\nu \equiv g_X$





✓ XENON1T [$E_{\rm th} \sim O(1$ keV) & 1 t & 3,600 m.w.e.] vs. JUNO [$E_{\rm th} \sim O(100$ keV) & 20 kt & 2,000 m.w.e.]

✓ More squeezed lower constraint lines for lighter m_X ← Less flux change for light m_X

Cosmic-ray-induced BDM: Limits - Coupling

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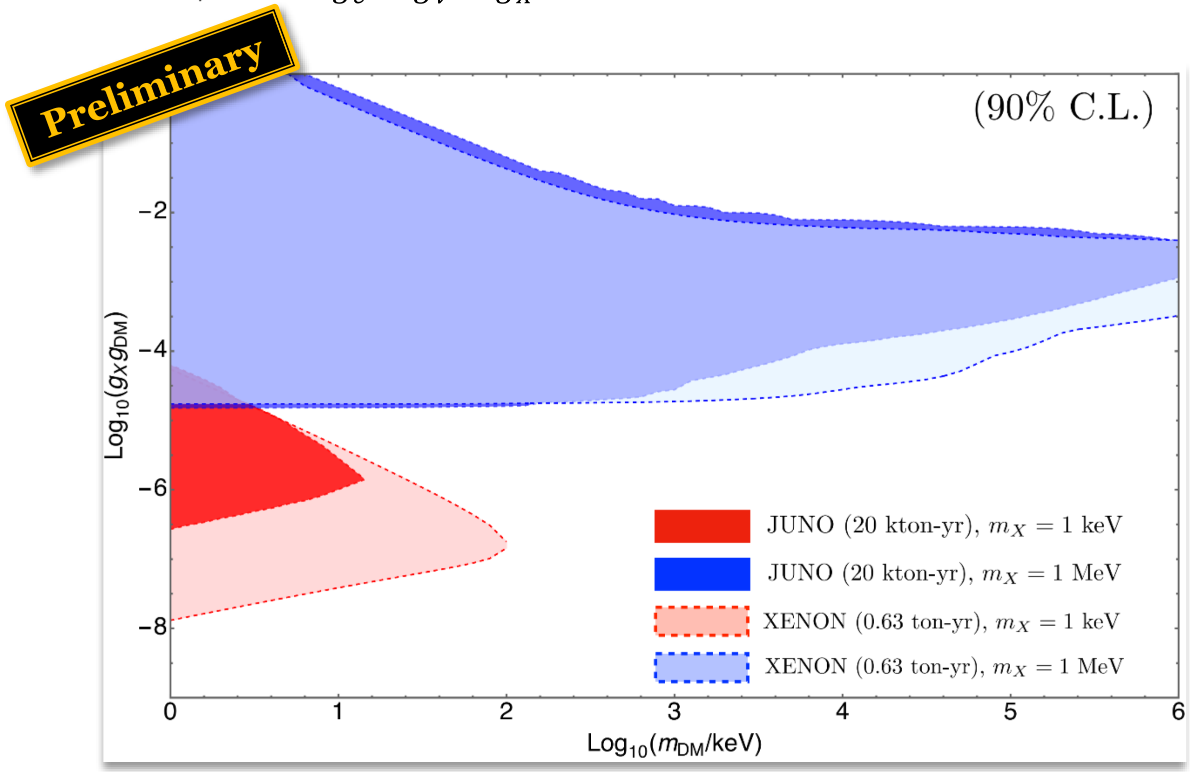


✓ XENON1T: mostly better limits (lower $E_{\rm th}$)

✓ JUNO: competitive upper limits (less attenuation) & better limits for heavier m_X with lighter $m_{\rm DM}$ (high flux even for $K_{\rm DM} \sim O(100\ \mathrm{keV})$)

Cosmic-ray-induced BDM: Limits - Cross Section

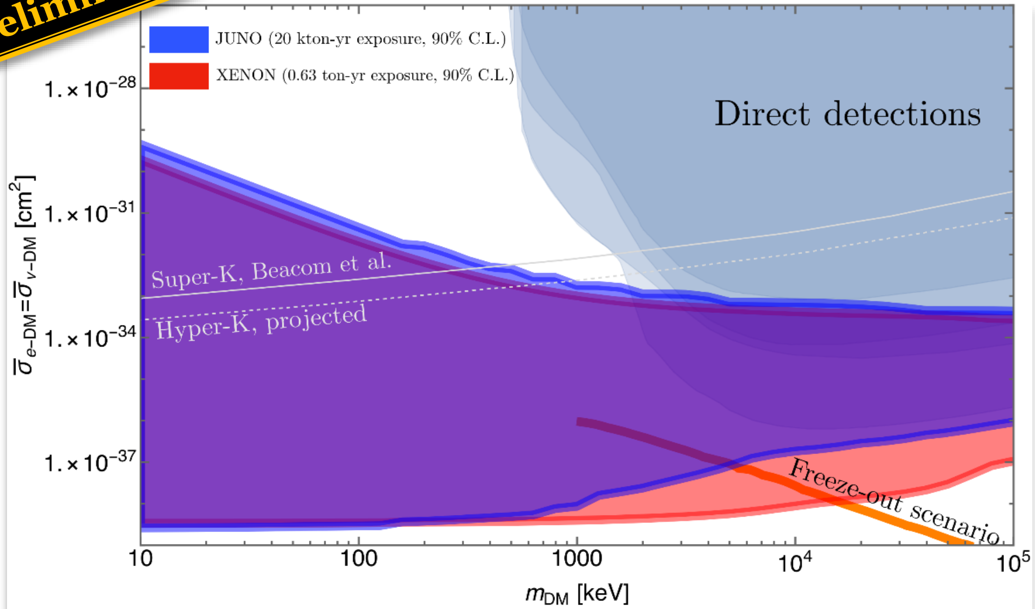
[Jho, **JCP**, Park & Tseng
2101.11262 & In preparation]

❖ Experimental status

$$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu \quad \text{with } g_e = g_\nu \equiv g_X$$

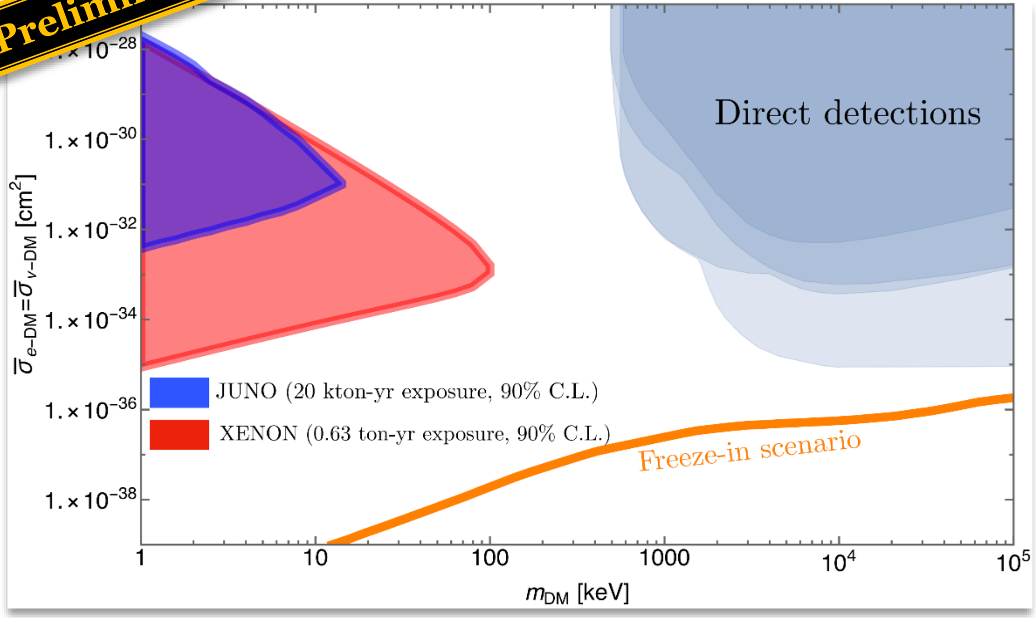
Preliminary

Heavy mediator: $F_{DM} = 1$



Preliminary

Light mediator: $F_{DM} = (\alpha_e m_e/q)^2$



✓ νBDM+CRe-BDM contributions to XENON1T/JUNO e-recoils

✓ Expected sensitivities for sub-GeV DM from various current & future detectors:

the νBDM provides stringent constraints on unexplored parameter space for light DM ($\lesssim$ MeV)

Summary

- To understand the particle nature of DM, we need non-gravitational DM-SM interactions.
- **Reversing** DM direct detection process

  ➔ Energetic **Cosmic-Rays**-induced BDM: $e^{\pm}, p^{\pm}, \boldsymbol{\nu}, \ldots$

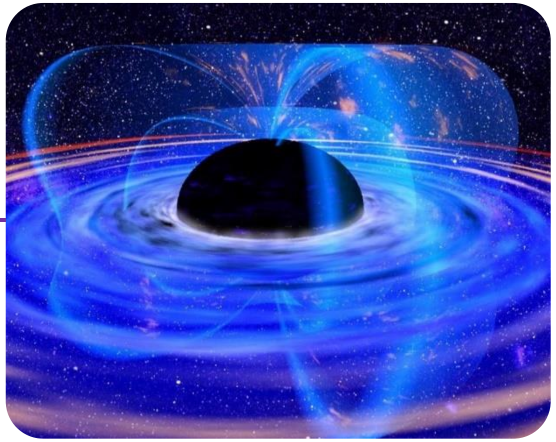
- **Light DM ≲ O(10 MeV)**: we can get enough BDM flux even for ton-scale DM detectors.
- $m_\nu \ll m_{e,p}(m_{\rm DM})$ but $\boldsymbol{\Phi_\nu} \gg \boldsymbol{\Phi_{e,p}}$ ➔ Flux: **νBDM > CRe-BDM** for $K_{\rm DM} \lesssim O(1-10)$ MeV.
- The **EG contribution** is the dominant component of the νBDM flux: EG > $O(100) \times$ Galactic.

Thank you

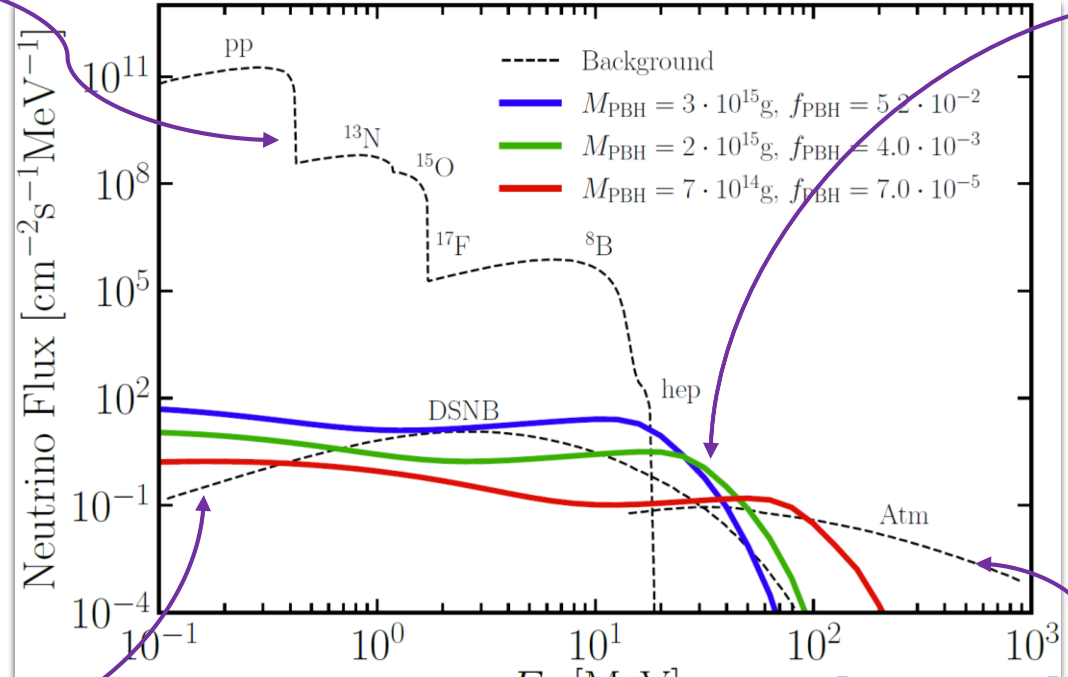
Back-Up

Cosmic Neutrino Sources & Fluxes

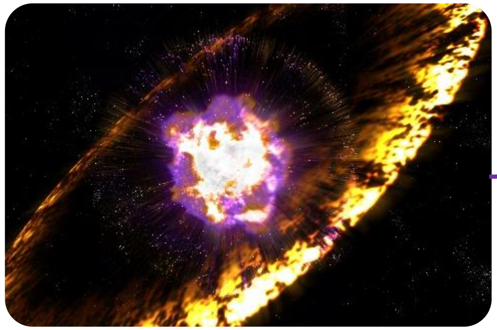
[Star ν-BDM, 2101.11262]



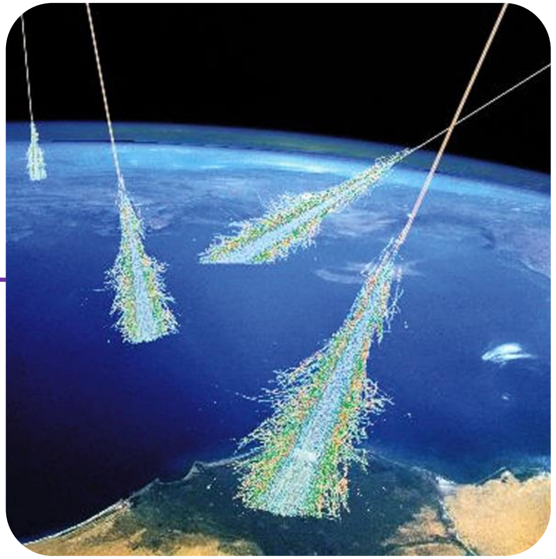
[PBH ν-BDM, 2108.05608]



[2106.02492]



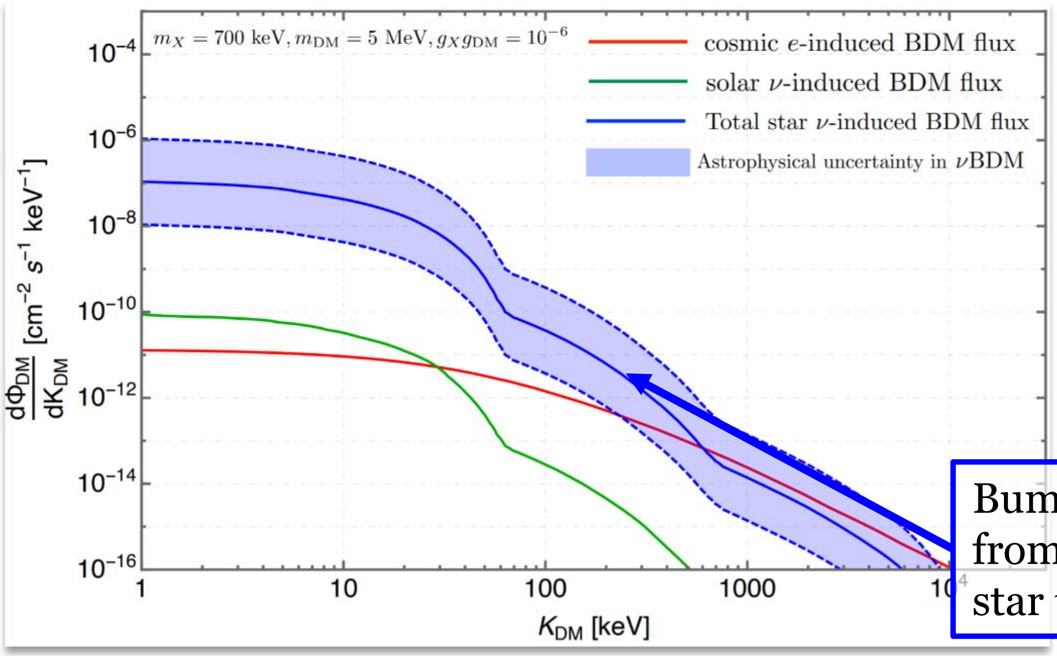
[DSNB-BDM, 2104.00027]



Cosmic-ray-induced BDM: νBDM

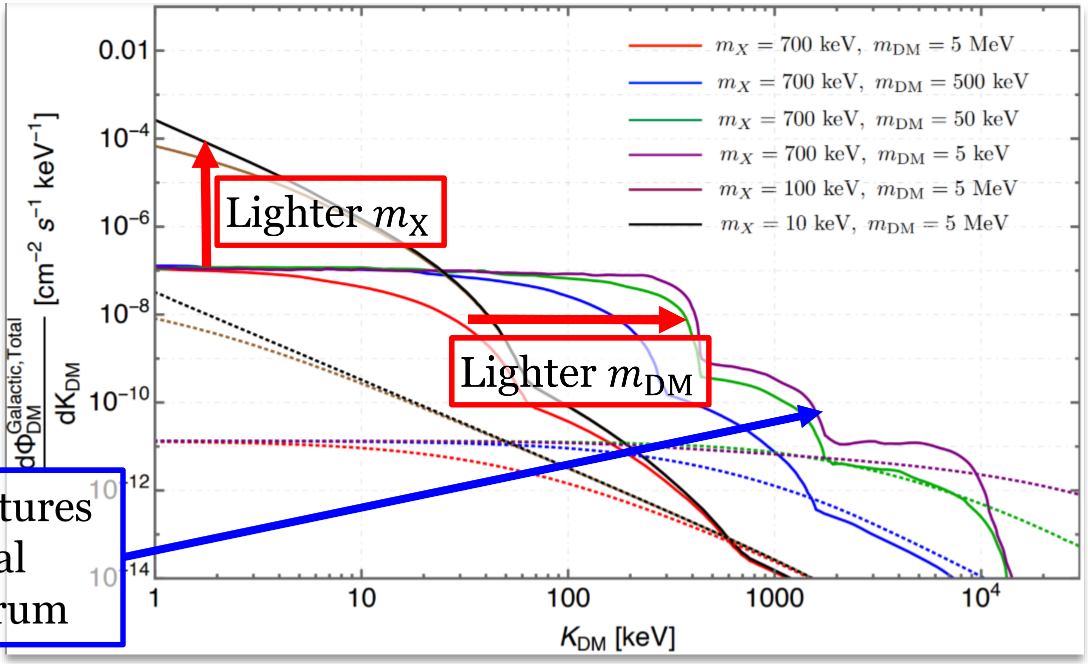
[Jho, **JCP**, Park & Tseng, 2101.11262]

❖ BDM fluxes by solar/star neutrinos & cosmic electrons



- ✓ **νBDM** ~ 10^3 ×BDM by solar ν
- ✓ **νBDM** ~ 10^{2-4} ×CeBDM for $K_{DM} \lesssim 50$ keV

❖ BDM fluxes for different mediator & DM masses



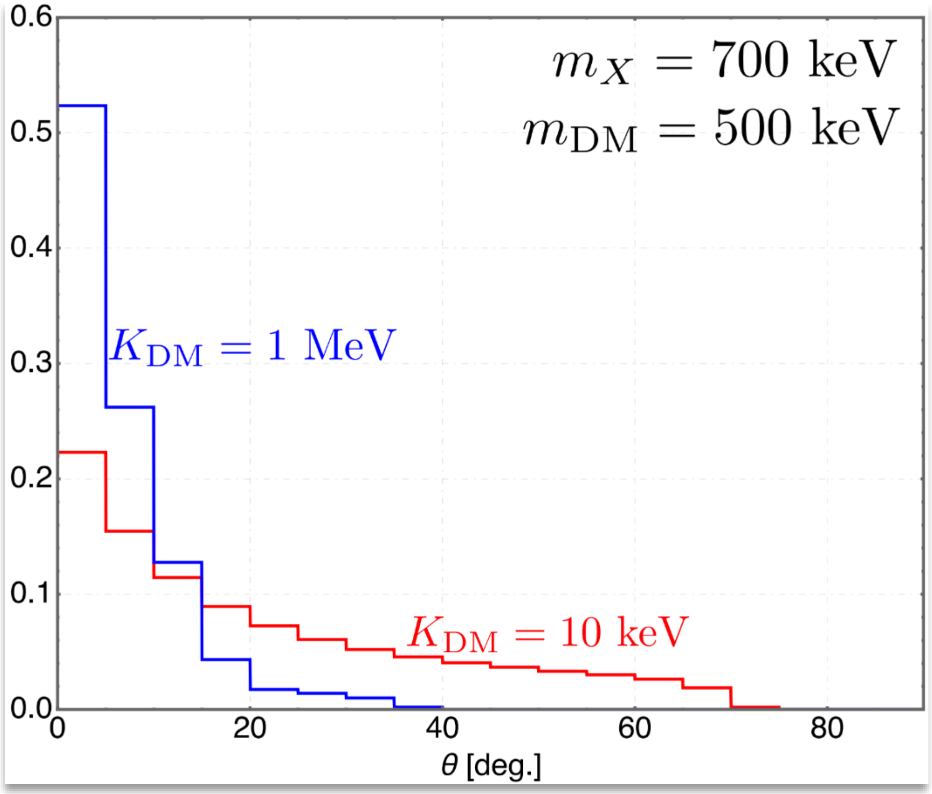
- ✓ νBDM (**solid**) vs. **Ce**BDM (**dashed**)

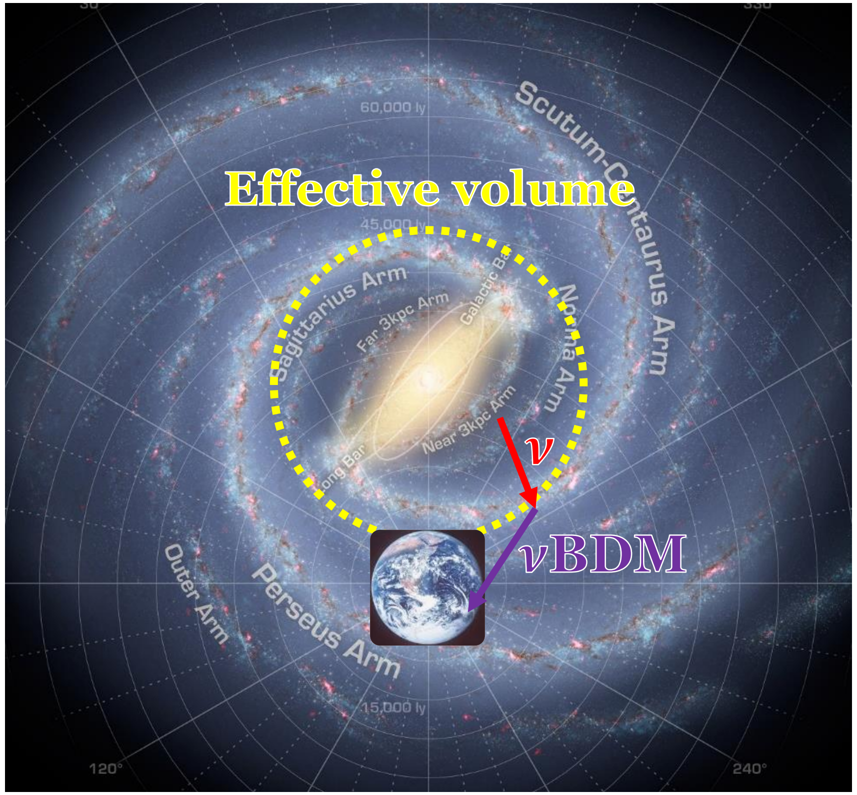
Solar/star neutrinos can very efficiently boost light DM ($\lesssim$ 10 MeV)!

Cosmic-ray-induced BDM: νBDM

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

❖ Arrival direction distribution of the νBDM flux





✓ $K_{DM} \ll m_{DM}$: large-angle scattering is allowed. ➔ Contributions: relatively far from the GC ➔ large effective Vol.

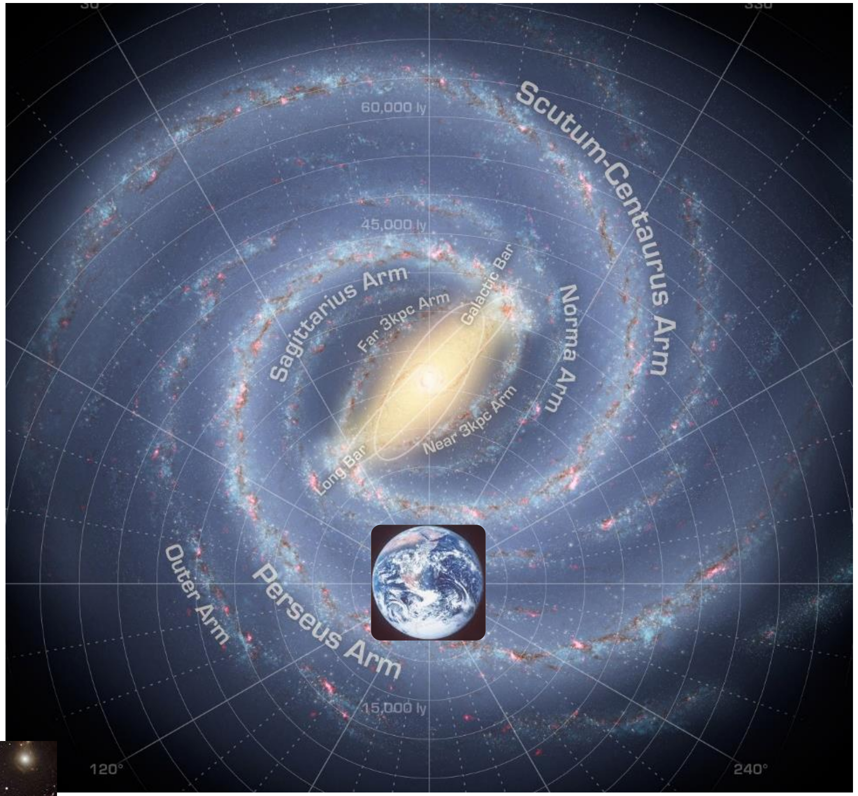
✓ $K_{DM} \gg m_{DM}$: forward scattering is preferred. ➔ GC contribution: dominant ➔ small effective Vol.

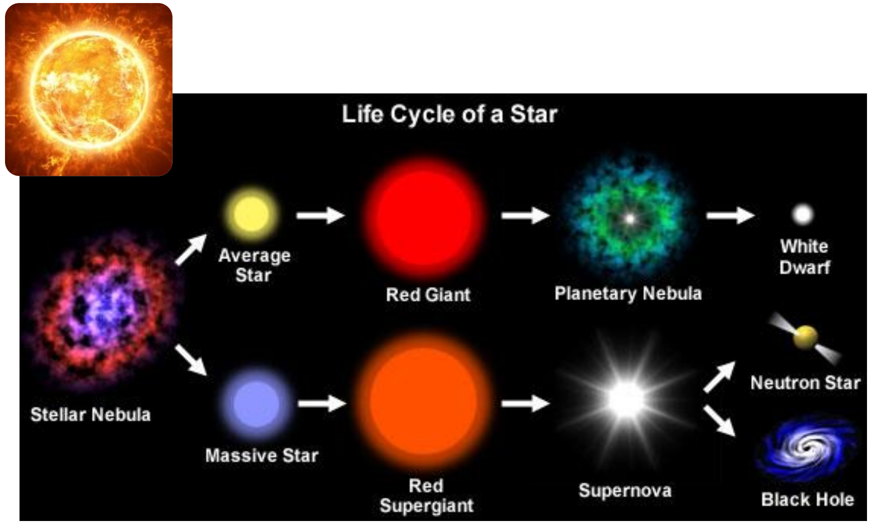
Cosmic-ray-induced BDM: νBDM

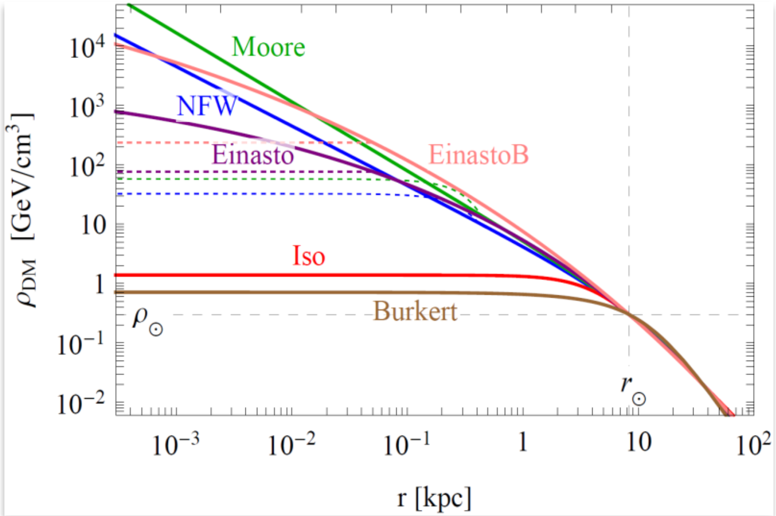
[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ Some issues in more realistic estimation of the νBDM flux

- ✓ Extra-galactic contribution?
- ✓ All of the stars are not Sun-like: enhanced neutrino luminosity for red-giants
- ✓ DM halo profile & Star distribution (Spiral vs Elliptic)?



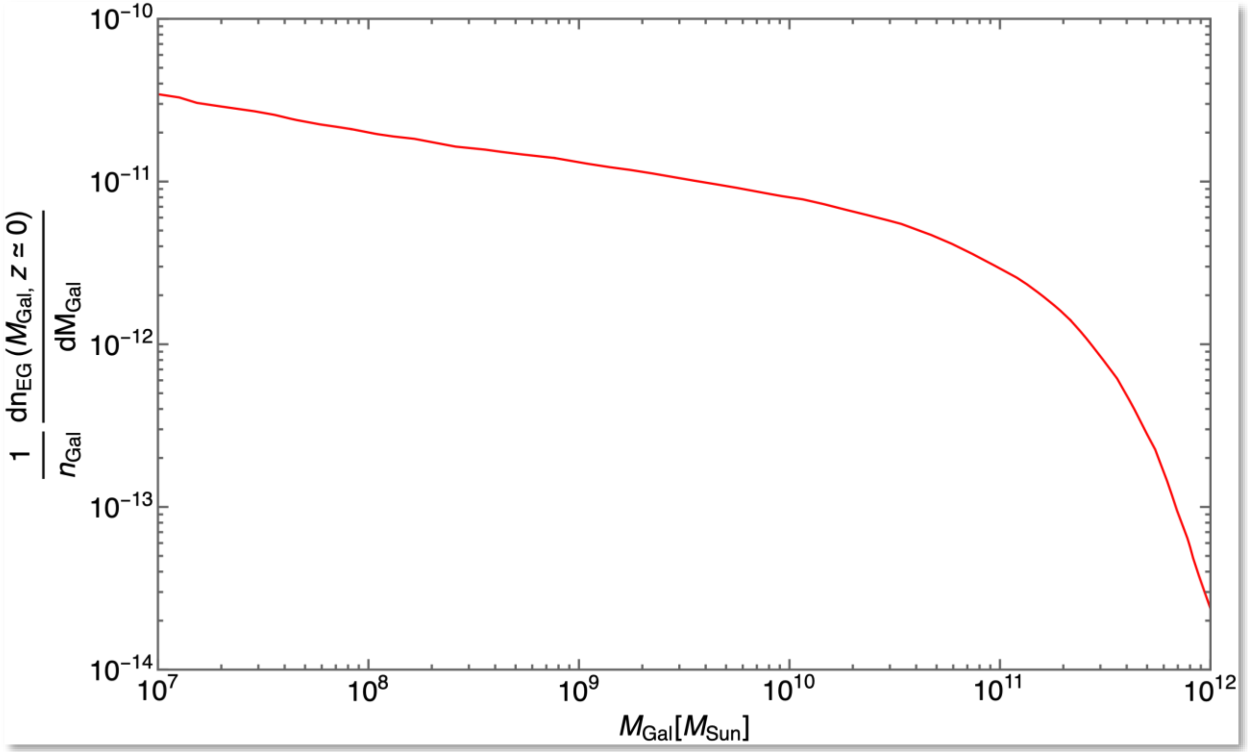




Cosmic-ray-induced BDM: νBDM

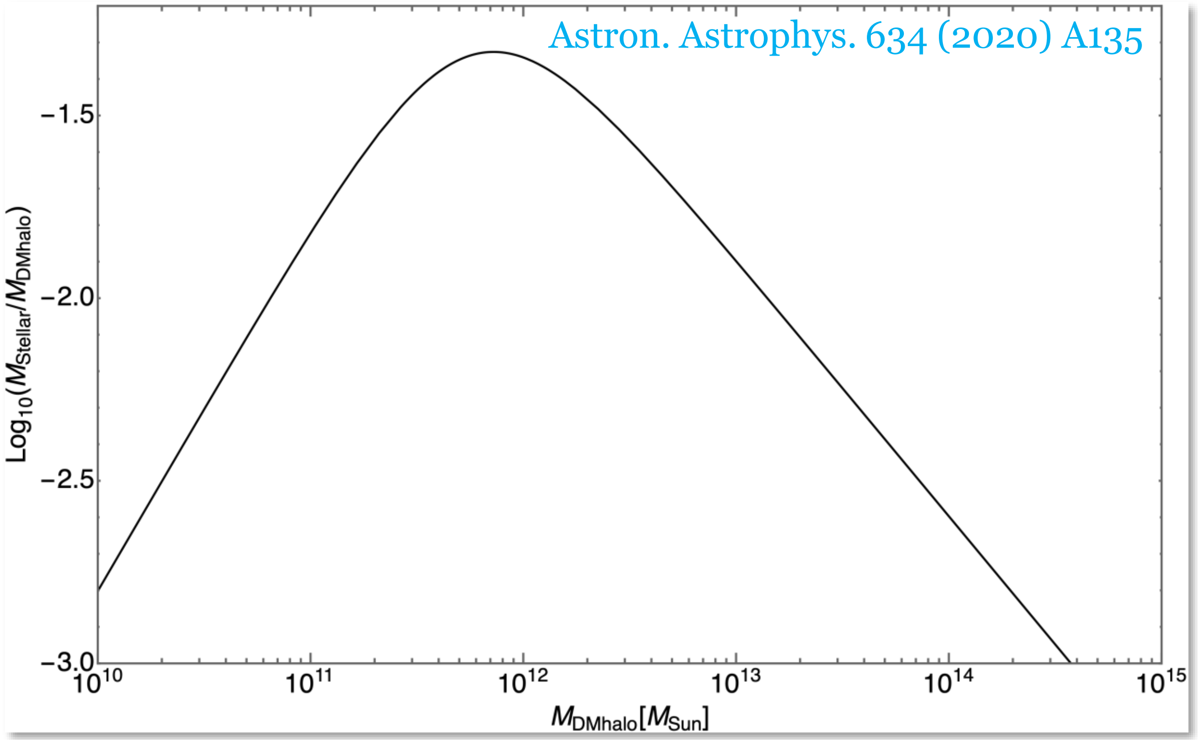
[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ **Extra-galactic(EG) contribution** to the νBDM flux: **Properties of extra-galaxies**



Mass composition of Galaxies

(based on Hubble deep field survey)



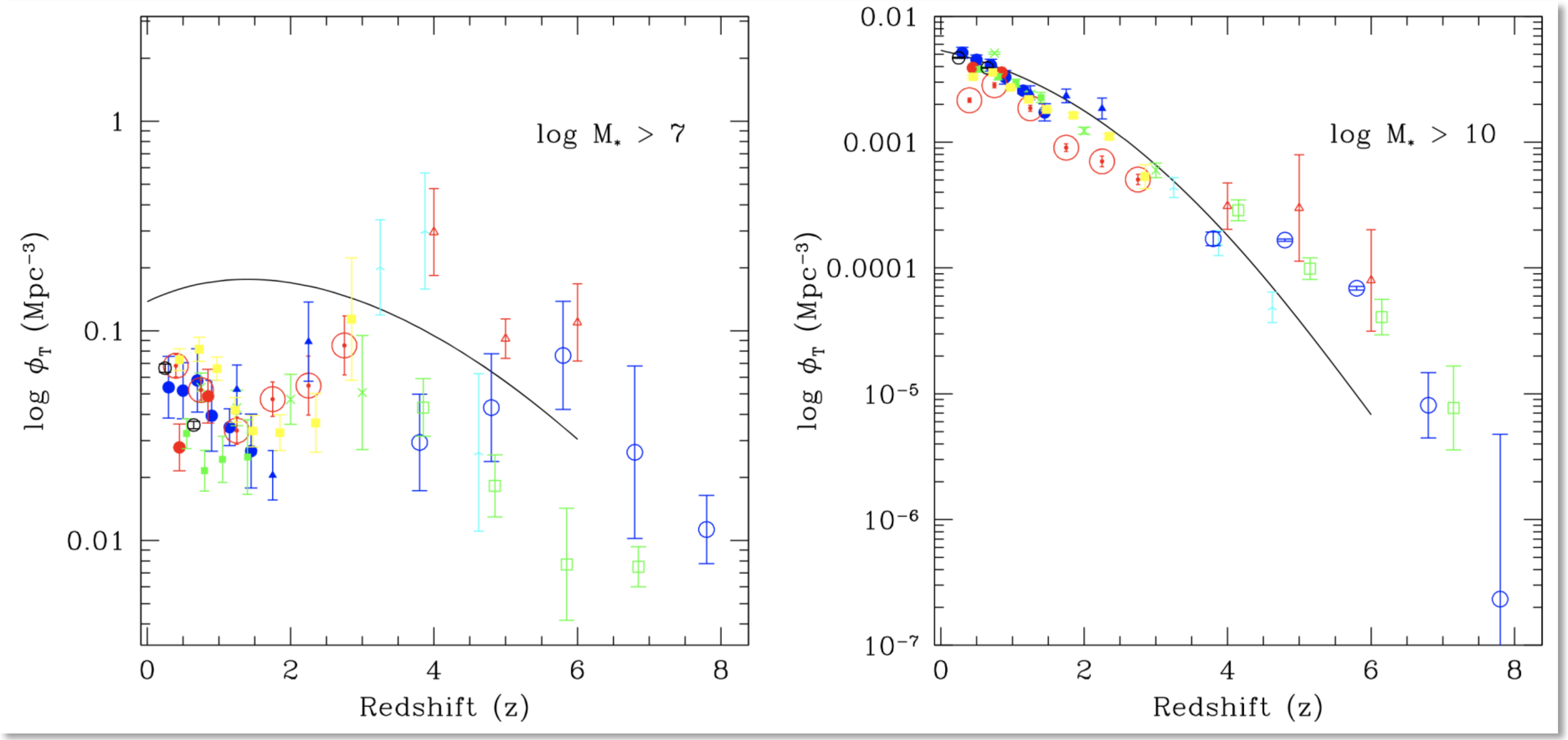
Stellar-to-Halo Mass ratio

(based on N-body simulation)

Cosmic-ray-induced BDM: νBDM

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

❖ **Extra-galactic(EG) contribution** to the νBDM flux: **Properties of extra-galaxies**



The Astrophysical J. 830 (2016) 83

Evolution of galaxy number density at $z < 8$

Cosmic-ray-induced BDM: Fluxes

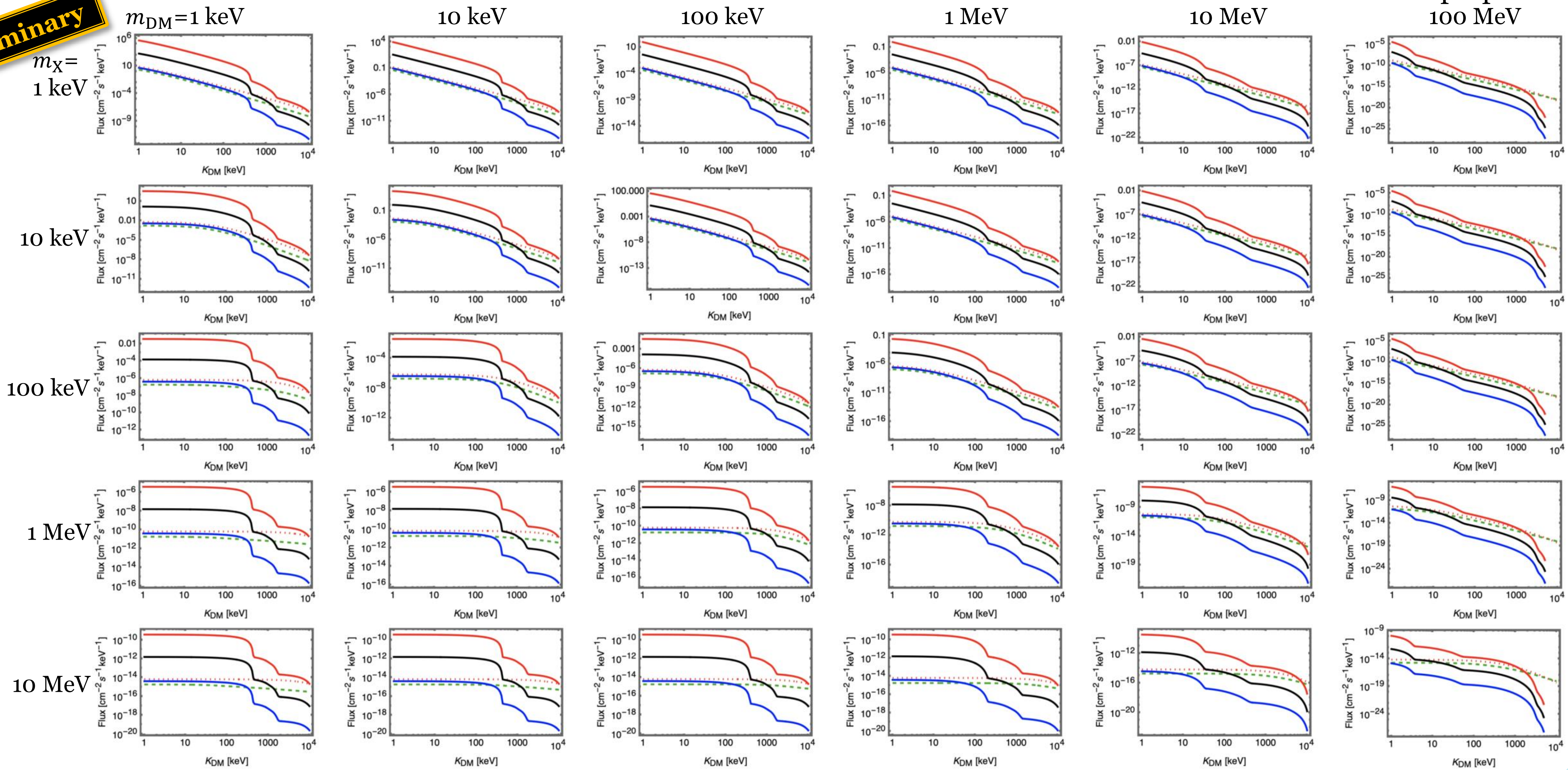
$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$

$g_e = g_\nu = 10^{-6}$
$g_{\rm DM} = 1$

EG-νBDM (far) — EG-νBDM (near) — Galactic-νBDM
DSNB-BDM — CRe-BDM

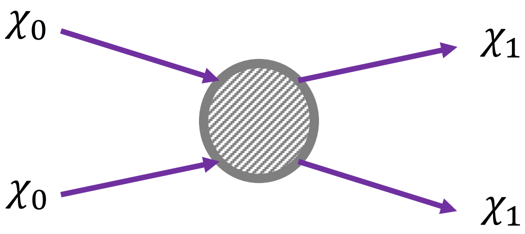
[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

Preliminary



Boosted (Light) DM & Its Searches

BDM: Production & Its Signatures

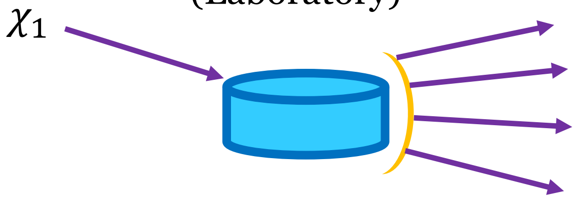


(cf. $\chi\chi \to \gamma\gamma$, $\nu\nu$)

becomes boosted

($\gamma_1 = m_0/m_1$)

(Laboratory)

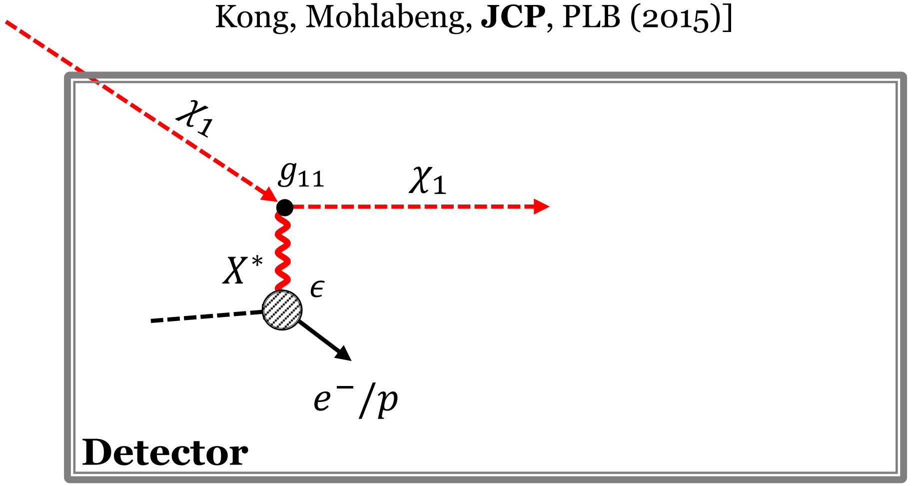


$$\frac{d\Phi_1}{dE_1} = \frac{1}{4} \cdot \frac{1}{4\pi} \int d\Omega \int_{\text{l.o.s.}} ds \langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1} \frac{dN_1}{dE_1} \left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0} \right)^2$$

$$= 8.0 \times 10^{-5}\ \text{cm}^{-2}\text{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}}{5 \times 10^{-26}\ \text{cm}^3\,\text{s}^{-1}} \right) \left(\frac{\text{GeV}}{m_0} \right)^2 \frac{dN_1}{dE_1}$$

elastic scattering (eBDM)

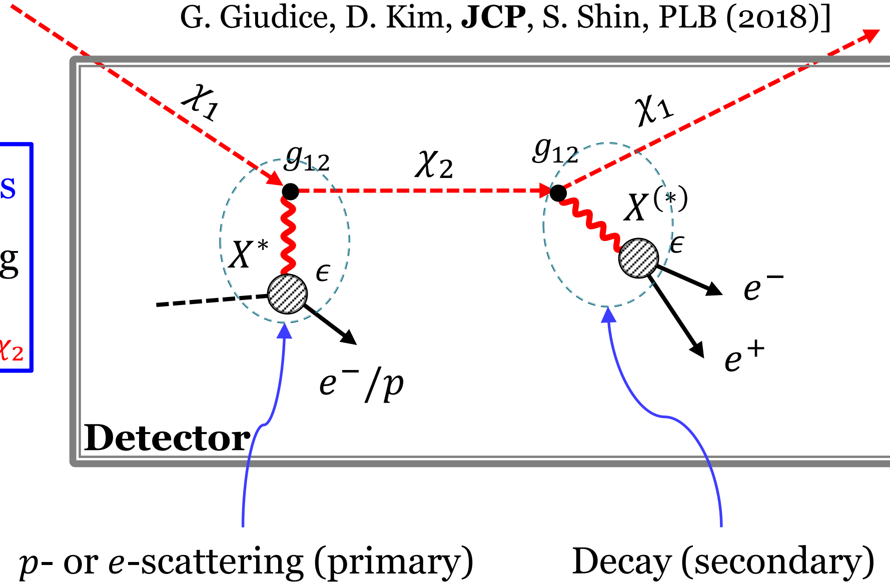
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]



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)]



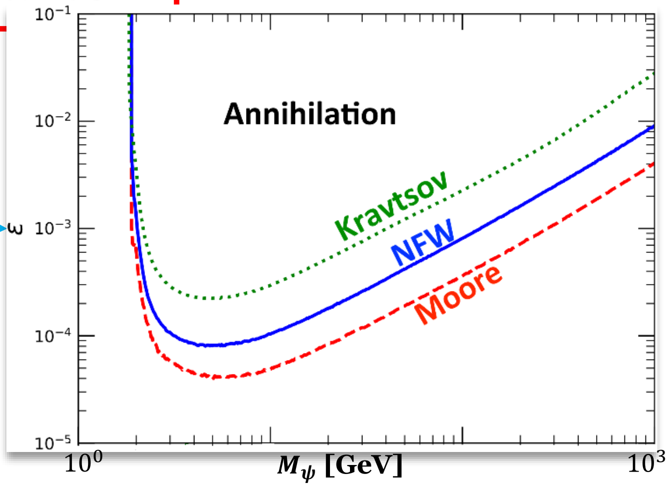
BDM Searches @ Neutrino Experiments

Boosted DM (BDM) models:
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~c ➔ even ν detector
w/ high E_{th} is OK!

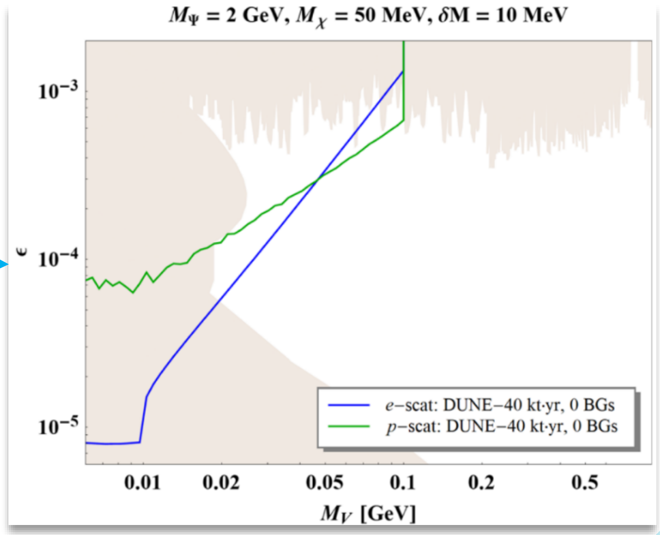
Eur. Phys. J. C (2021) 81:322
https://doi.org/10.1140/epjc/s10052-021-09007-w

THE EUROPEAN PHYSICAL JOURNAL

Regular Article - Experimental Physics

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

DUNE Collaboration



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

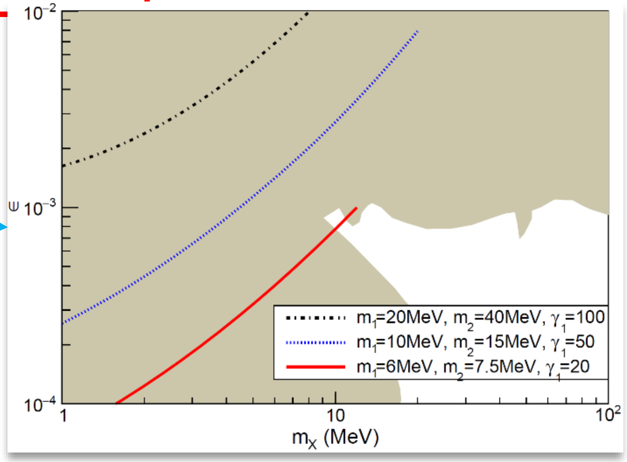
BDM Searches @ DM Experiments

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

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

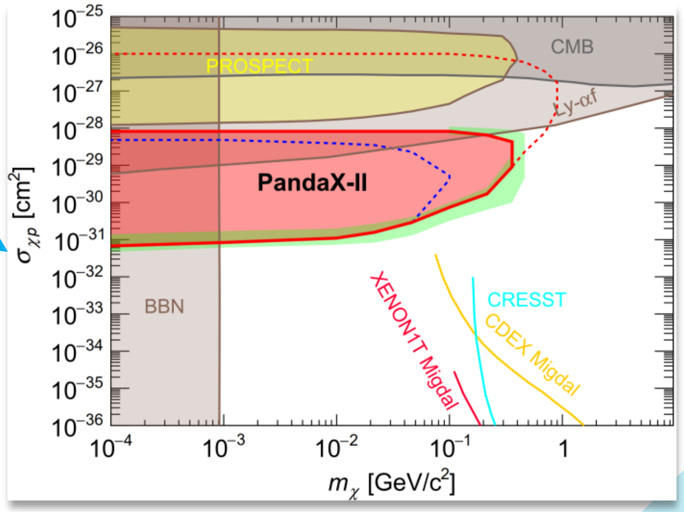
Editors' Suggestion

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



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

[PandaX-II, 2112.08957]



Constraints on sub-GeV Dark Matter Boosted by Cosmic Rays from CDEX-10 Experiment at the China Jinping Underground Laboratory

[CDEX, 2201.01704]

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

e-Recoil @ DM Detectors by BDM

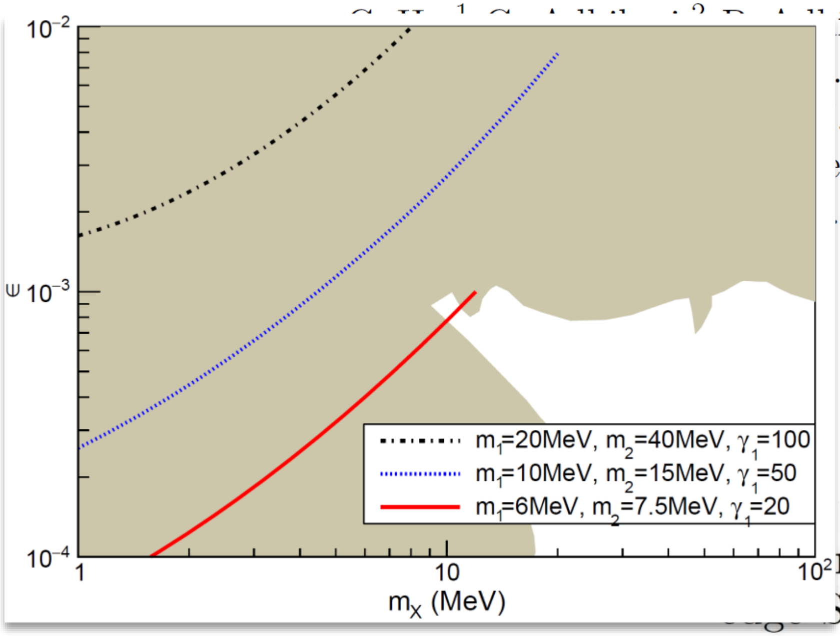
[G. Giudice, D. Kim, **JCP**, S. Shin, PLB (2018)]

❖ We, for the first time, pointed out that **DM direct detection experiments** including XENON1T would be **sensitive enough to energetic e-recoils induced by BDM** by pumping up the BDM flux:

e.g. $\mathcal{F}_{\chi_1} \propto \frac{\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{m_0^2}$.

❖ COSINE-100: First official direct search for *i*BDM [COSINE-100, PRL (2019)]

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



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(COSINE-100 Collaboration)

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