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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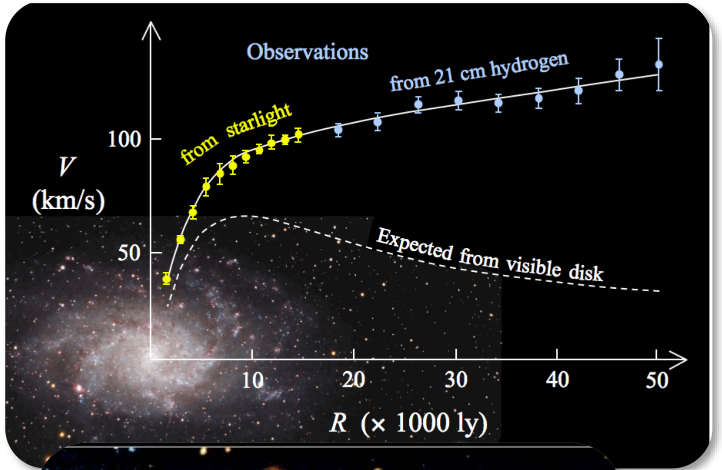
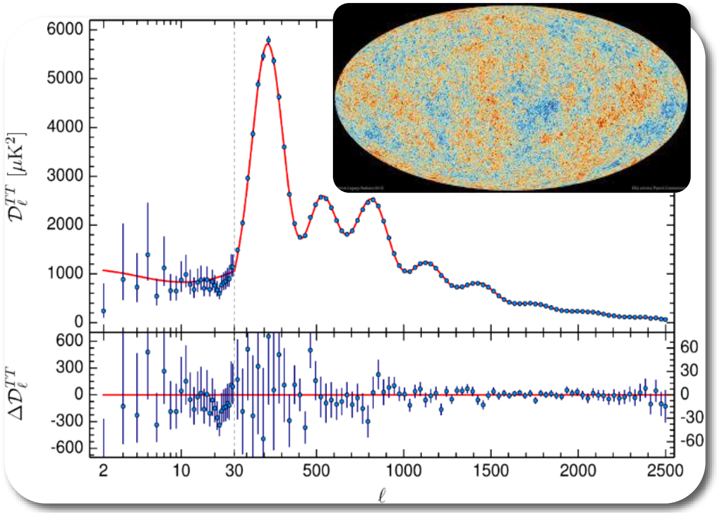
CHUNGNAM NATIONAL UNIVERSITY

CQUeST 2022 Workshop
2022.06.30

Message from Cosmology: Dark Matter (DM)

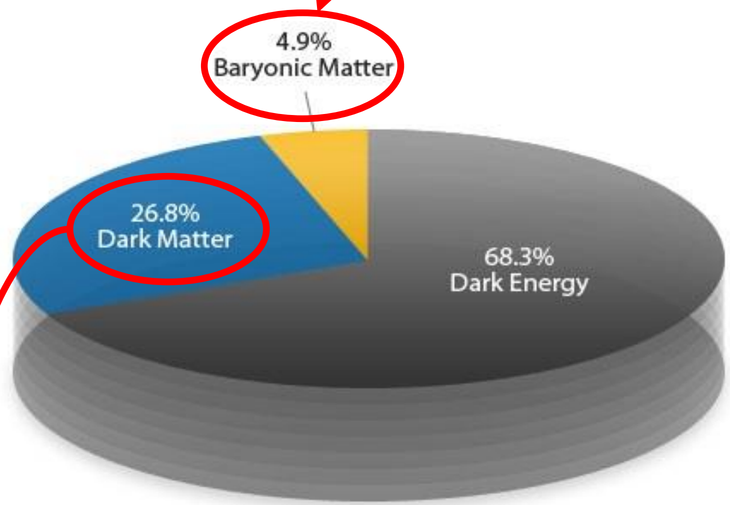




❖ **Evidence**: Galactic rotation curve, Bullet cluster, Coma cluster, Gravitational lensing, Structure formation, CMB, …

❖ **Modern cosmology**:

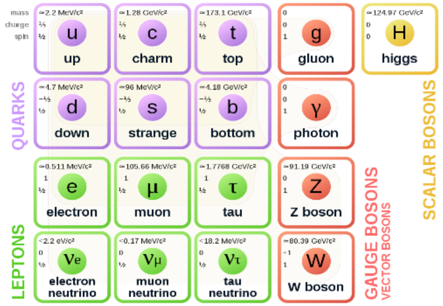
The Standard Model



❖ **Compelling paradigm**:

- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

Dark Sector: Dark Particles & Portals



$\chi_1, \chi_2, \chi_3, \ldots$

$\phi_1, \phi_2, \phi_3, \ldots$

$X_1, X_2, X_3, \ldots$

- **Portals**: <u>mediators</u>
  - ✓ 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: $\frac{1}{f_{a\gamma/ag}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

    $\frac{1}{f_{af}} \partial_\mu a (\bar{\psi} \gamma^\mu \gamma^5 \psi)$
  - ✓ 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: a combination of ≥ 2 portals
  - ✓ ???

- **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)
  - ✓ ???

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**

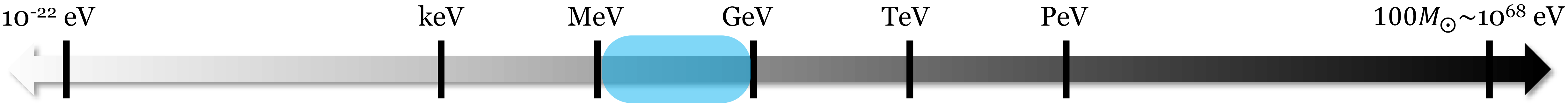
Light
SIMP, ELDER, can be **thermal**

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

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

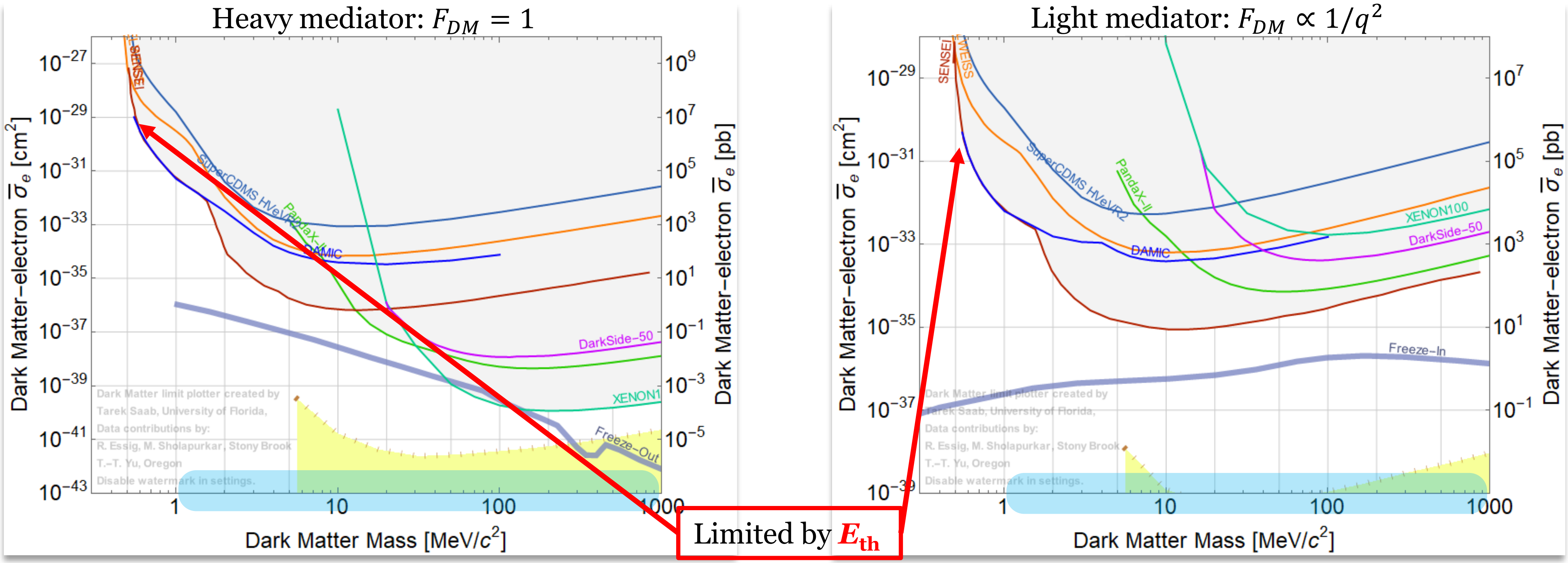
Astrophysical object
MACHO, PBH, non-particle

Light DM Direct Search



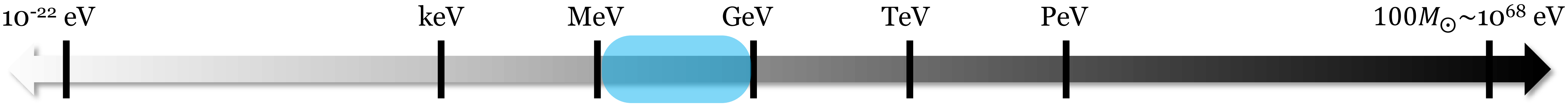
- ❖ $E_k \sim mv^2$, $\Phi_\chi = n_\chi v_{rel}$ & $n_\chi = \rho_\chi/m_\chi$ ➔ lighter DM: **smaller E_r** but lager flux (**lighter** target particle)

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



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

Light DM Direct Search



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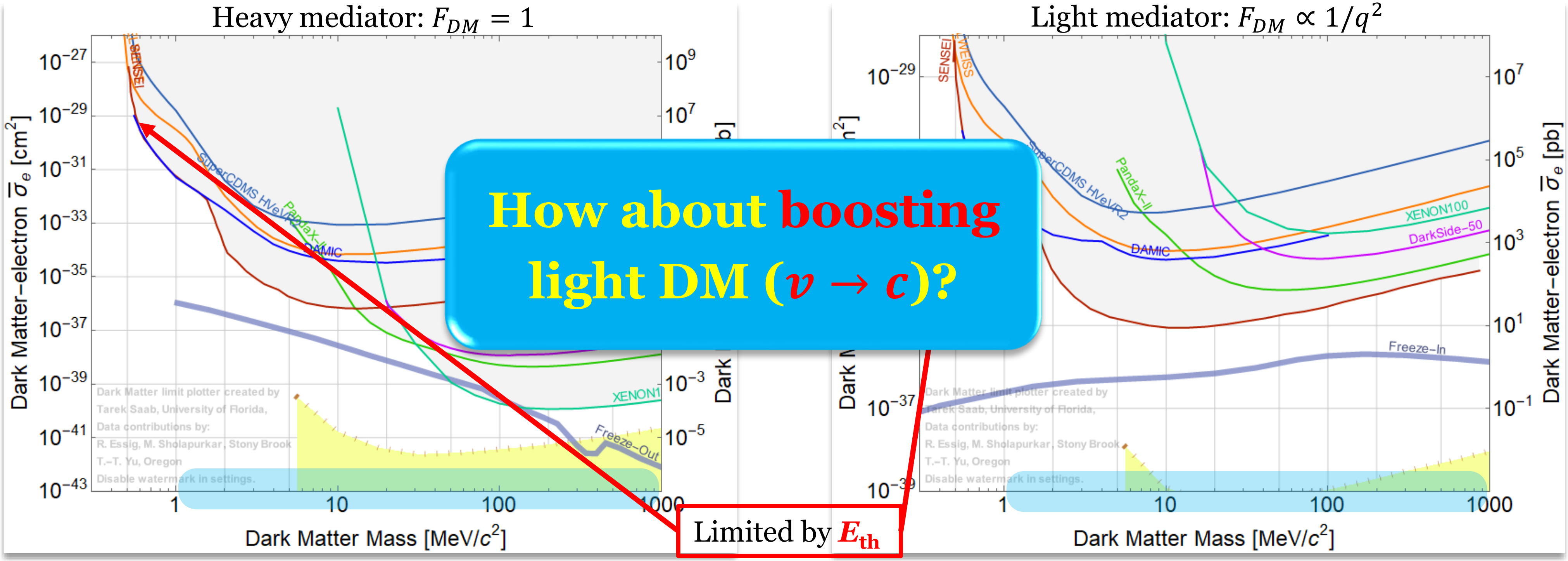


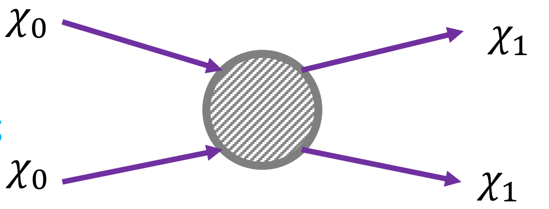
Dark Matter Limit Plotter v5.17, updated December 21, 2021

Boosted (Light) DM
& Its Searches

DM Boosting Mechanisms: Dark Sector

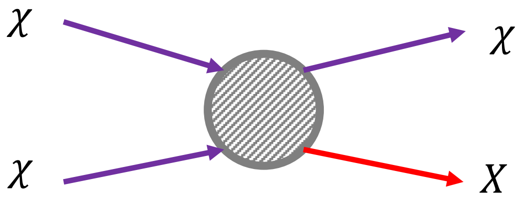
Boosted DM (BDM) coming from the Universe

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



✓ Multi-component model

$m_0 \gg m_1$



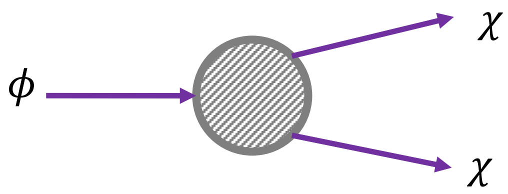
✓ Semi-annihilation model

$m_\chi \gg m_X$

[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
- Need extension of dark sector



✓ 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]

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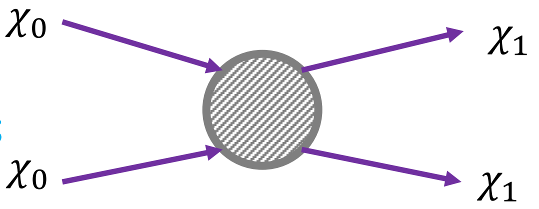

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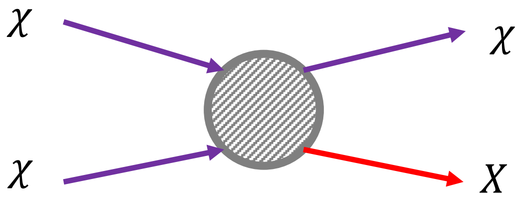

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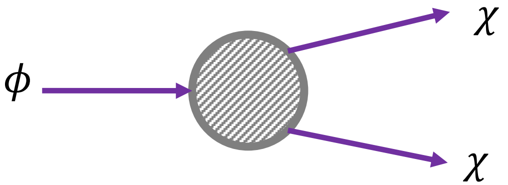

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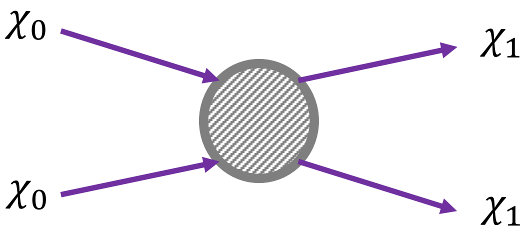
Cline et al., PRD (2019);
Heurtier, Kim, **JCP**, Shin, PRD (2019);
more]

- 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]

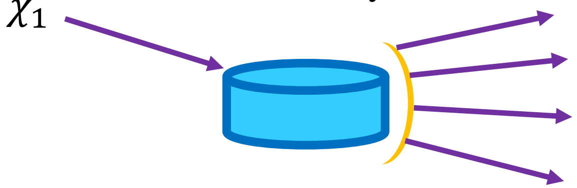
BDM: Production & Its Signatures



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

becomes boosted

($\gamma_1 = m_0/m_1$)

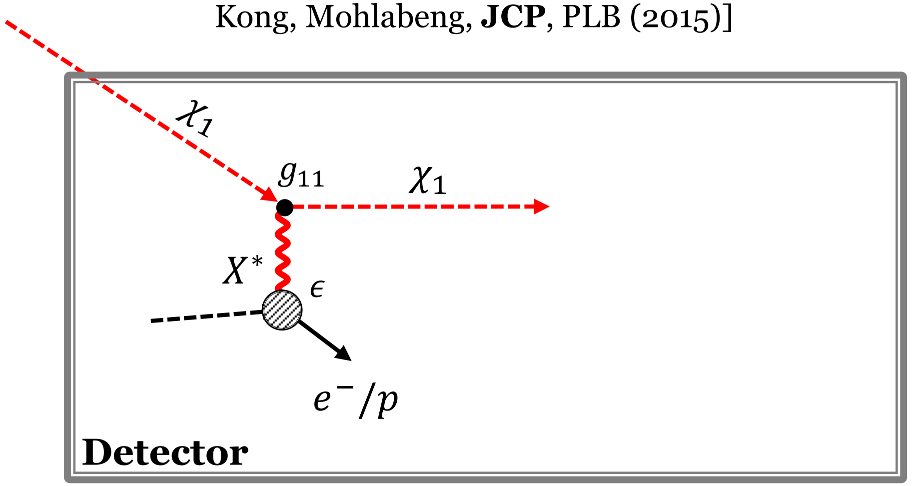


$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\text{l.o.s.}} ds \langle\sigma v\rangle_{\chi_0\bar{\chi}_0\to\chi_1\bar{\chi}_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$

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

elastic scattering (eBDM)

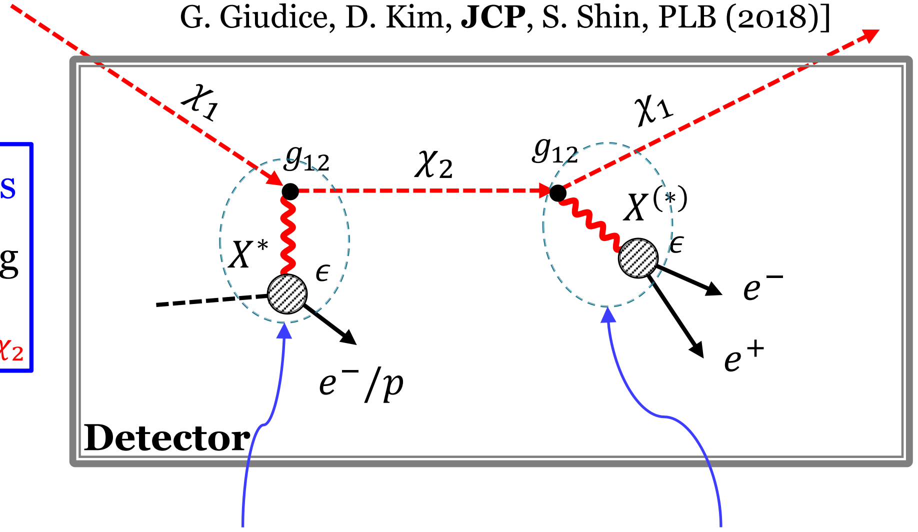
[Agashe, Cui, Necib, Thaler, JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015)]



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)

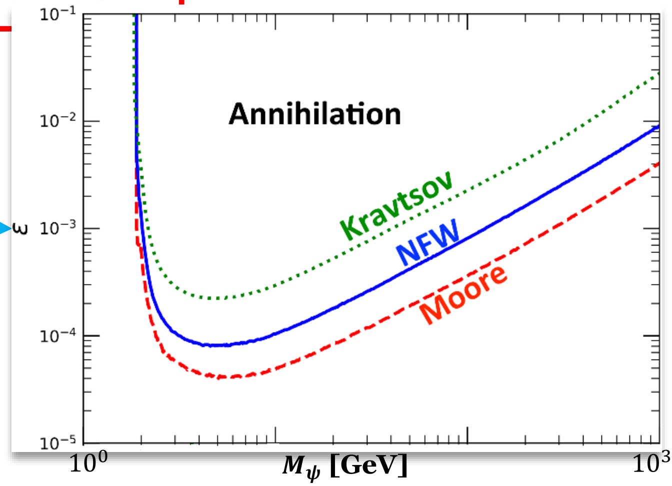
BDM Searches @ Neutrino Experiments

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



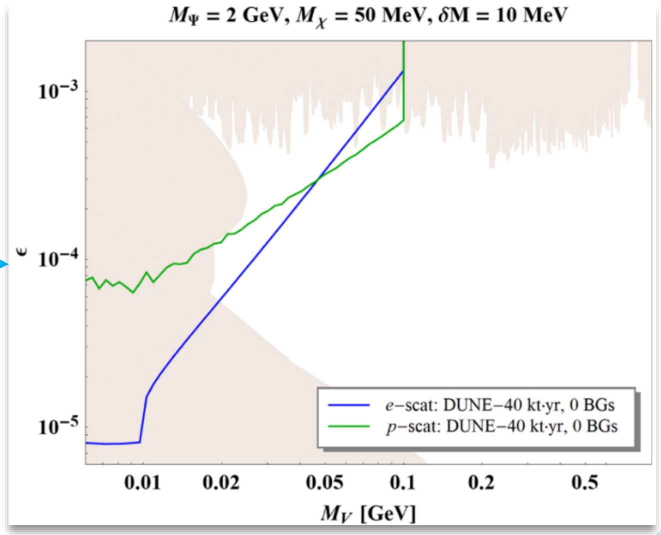
v~c ➔ even ν detector w/ high E_{th} is OK!

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

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

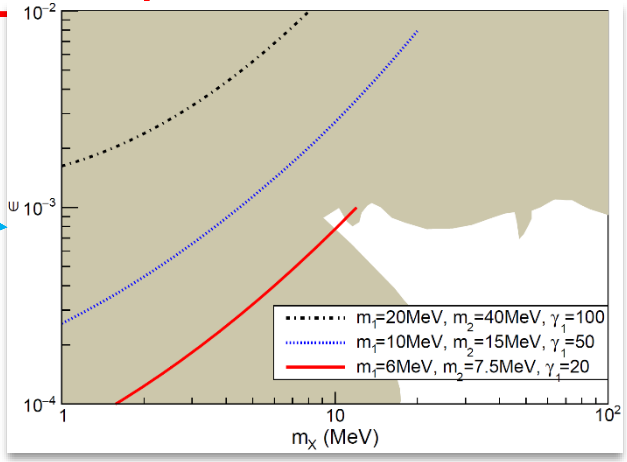
BDM Searches @ DM Experiments

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

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

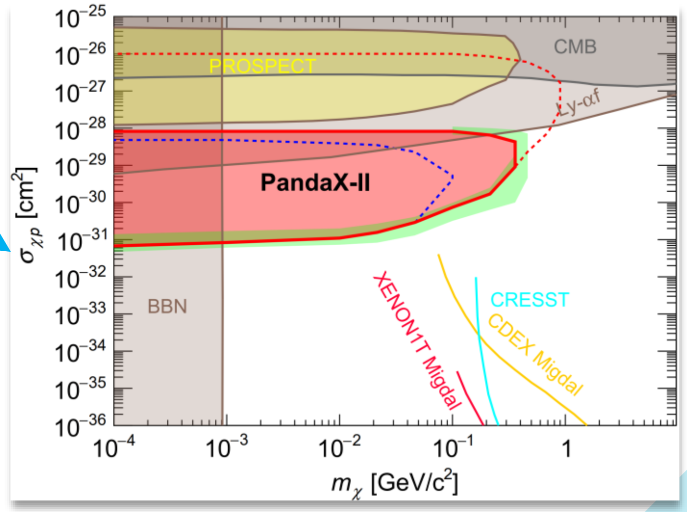
Editors' Suggestion

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

- 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

C. Ha,[1] G. Adhikari,[2] P. Adhikari,[2] E. Barbosa de Souza,[3] N. Carlin,[4] S. Choi,[5] M. Djamal,[6] A. C. Ezeribe,[7] I. S. Hahn,[8] E. J. Jeon,[1] J. H. Jo,[3] H. W. Joo,[5] W. G. Kang,[1] W. Kang,[9] M. Kauer,[10] G. S. Kim,[11] H. Kim,[1] H. J. Kim,[11] K. W. Kim,[1] N. Y. Kim,[1] S. K. Kim,[5] Y. D. Kim,[1,2] Y. H. Kim,[1,12] Y. J. Ko,[1] V. A. Kudryavtsev,[7] H. S. Lee,[1,*] J. Lee,[1] J. Y. Lee,[11] M. H. Lee,[1] D. S. Leonard,[1] W. A. Lynch,[7] R. H. Maruyama,[3] F. Mouton,[7] S. L. Olsen,[1] B. J. Park,[13] H. K. Park,[14] H. S. Park,[12] K. S. Park,[1] R. L. C. Pitta,[4] H. Prihtiadi,[6] S. J. Ra,[1] C. Rott,[9] K. A. Shin,[1] A. Scarff,[7,†] N. J. C. Spooner,[7] W. G. Thompson,[3] L. Yang,[15] and G. H. Yu[9]
(COSINE-100 Collaboration)

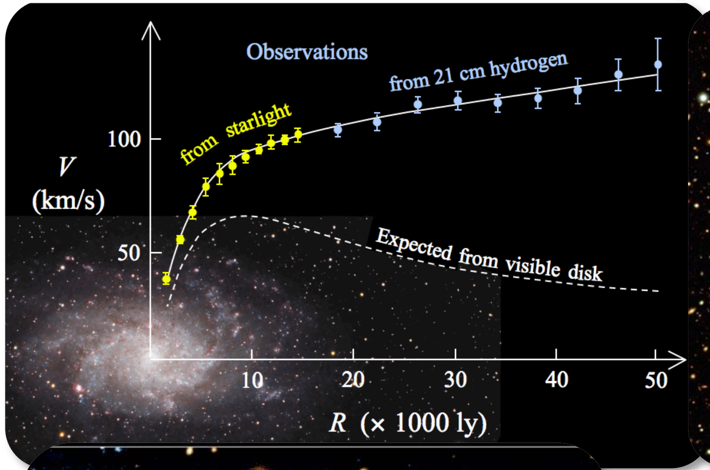
ACKNOWLEDGMENTS

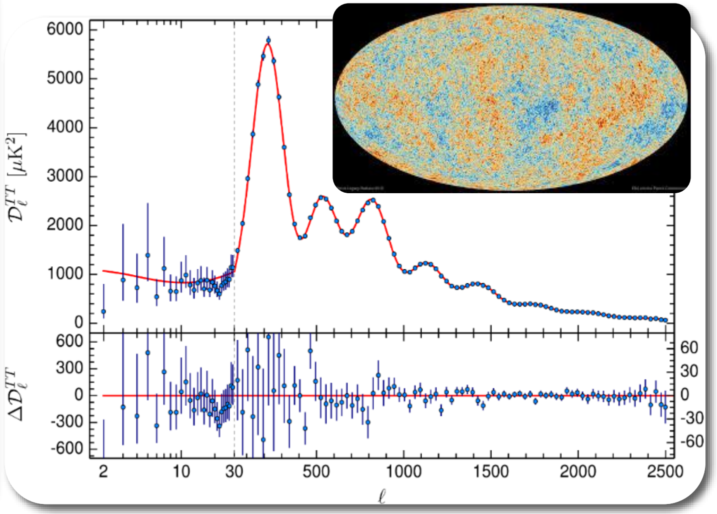
We thank Jong-Chul Park for encouraging this analysis and for insightful discussions. We also acknowledge Seodong Shin for insightful discussions. We thank

Cosmic-ray-induced BDM

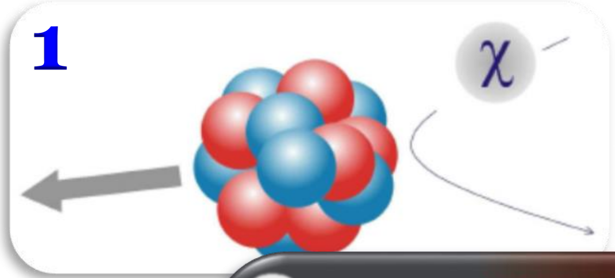
Road to DM Nature

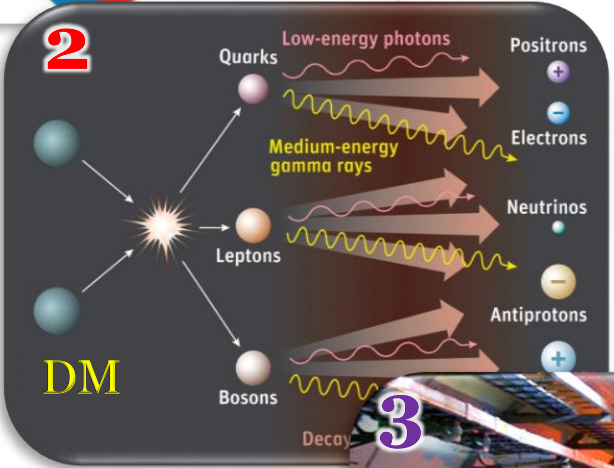
❖ **Currently evidence & observation**: only <u>gravity</u>

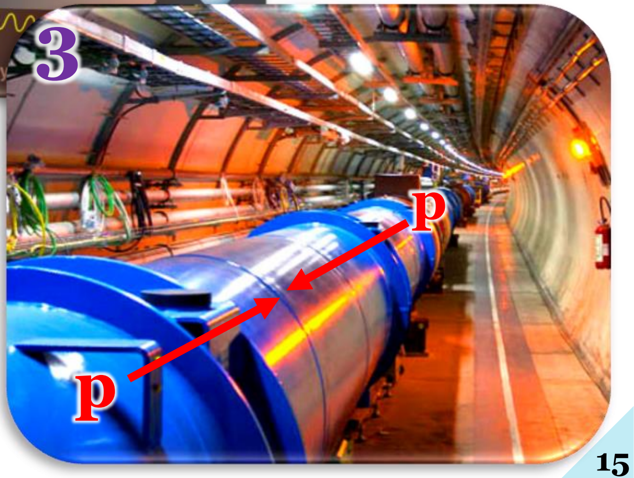




❖ **Particle nature**: interaction w/ <u>SM via non-gravity</u>





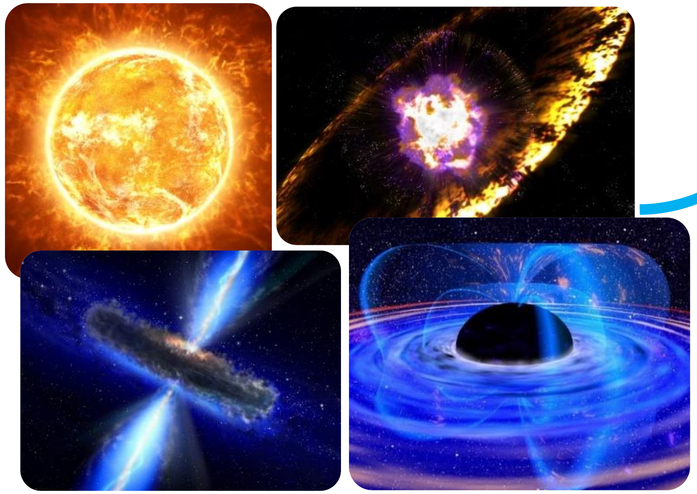


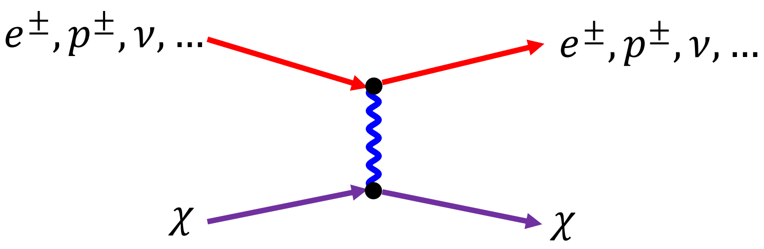
Road to DM Nature: Reversing

The other way around!

DM Boosting Mechanisms: Cosmic-Ray

Cosmic-Ray-Induced BDM





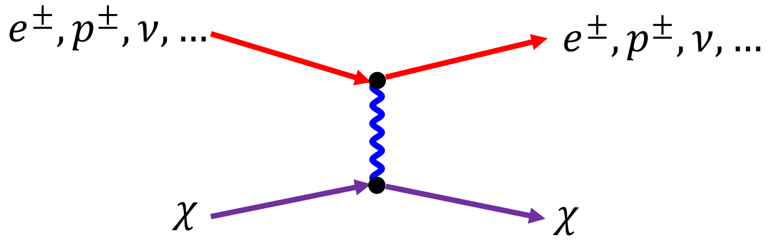
- ✓ Charged cosmic-ray: [Bringmann & Pospelov, PRL (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho, Choi & Yoo, PRd (2020); more]
- ✓ Cosmic- ν (νBDM): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; 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

Cosmic-ray-induced BDM

- Energetic cosmic-ray-induced BDM: cosmic-rays kick DM (large $E_{e^\pm,p^\pm,\nu,...}$)



Large E_k^χ due to
E_k^{CR} transfer

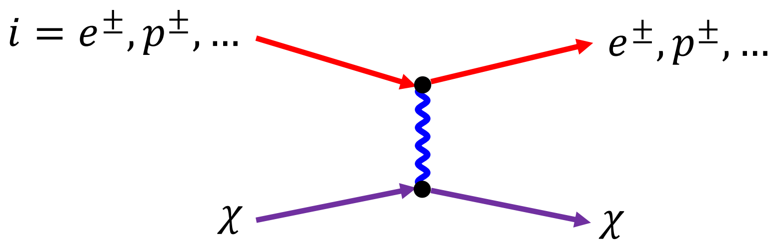
- Interactions between DM & SM particles
  - ✓ Couplings to proton: [Bringmann & Pospelov, 1810.10543; Dent et al., 1907.03782]
  - ✓ Couplings to electron: [Ema, Sala & Sato, 1811.00520]
  - ✓ Couplings to p & e: [Cappiello & Beacom, 1906.11283; Cho, Choi & Yoo, 2007.04555]
  - ✓ Couplings to leptons (e & ***ν***): [Jho, **JCP**, Park & Tseng, 2006.13910 & 2101.11262]

Calculation of BDM E-spectrum: quite similar even with different types of cosmic rays

Except the neutrino-induced case!

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, …)

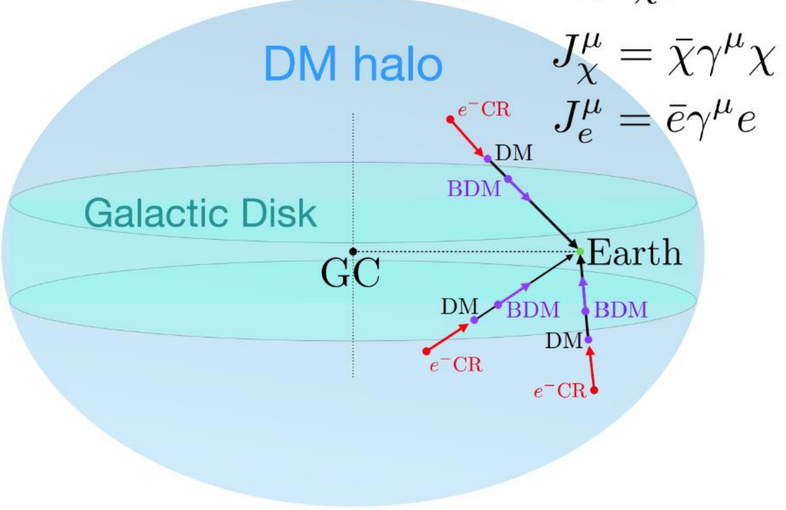
$$\frac{d\Phi_\chi}{dK_\chi} = \frac{1}{4\pi}\int d\Omega \int_{\text{l.o.s.}} ds \left(\frac{\rho_\chi(r(s,\theta))}{m_\chi}\right) \int_{K_i^{\min}}^{\infty} dK_i \frac{d\sigma_{i\chi\to i\chi}(K_i)}{dK_\chi}\frac{d\Phi_i^{\text{LIS}}}{dK_i}$$

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

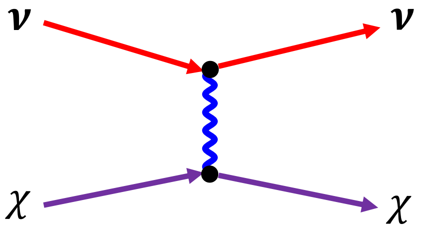
$$\mathcal{L} \supset -X_\mu(g_e J_e^\mu + g_\chi J_\chi^\mu) + \ldots$$



Cosmic-ray-induced BDM: νBDM

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

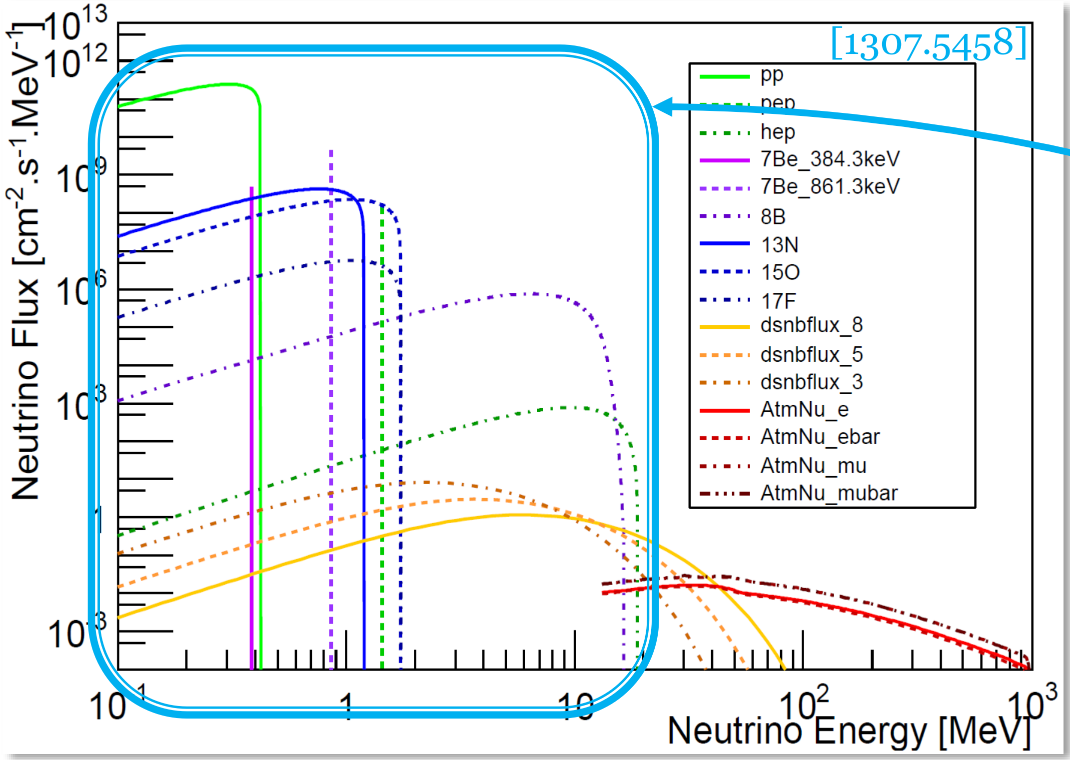
- **Cosmic-ν-**induced BDM (**νBDM**): cosmic neutrinos kick DM (large E_ν)

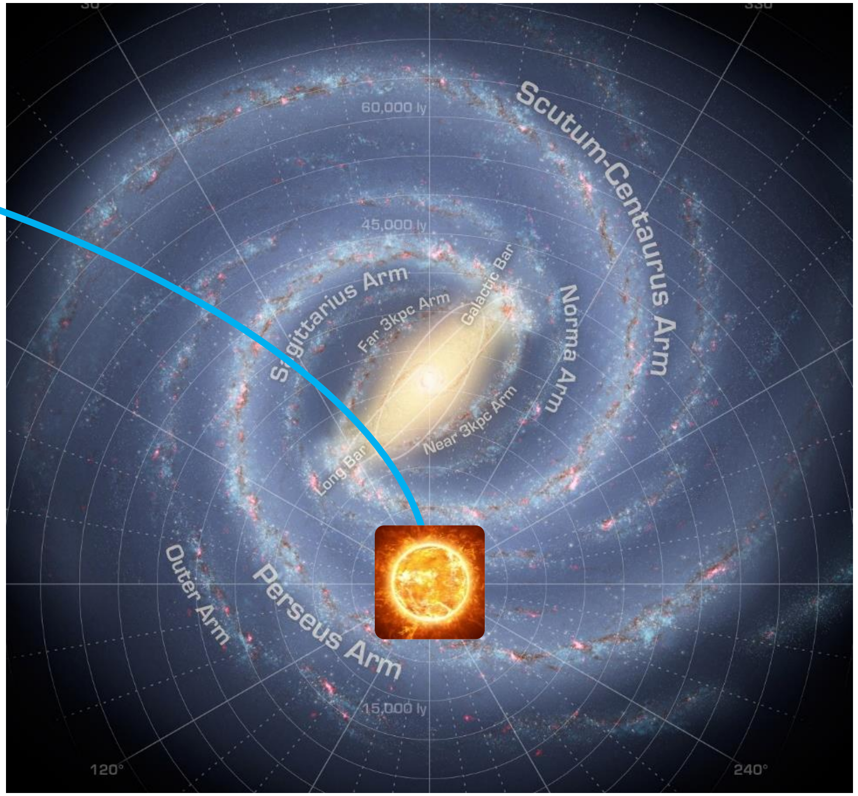


Large E_k^χ due to E_k^ν transfer

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

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

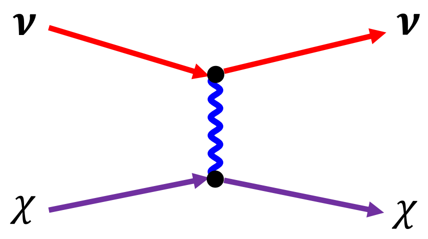




Cosmic-ray-induced BDM: νBDM

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

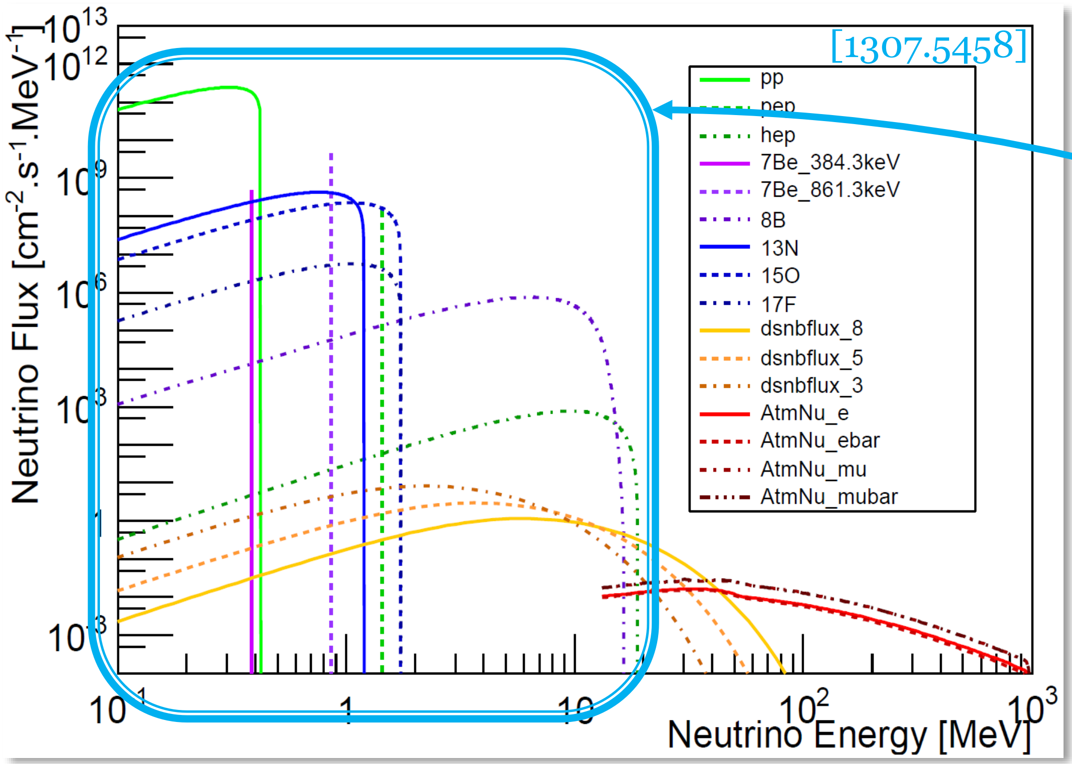
❖ **Cosmic-ν**-induced BDM (**νBDM**): cosmic neutrinos kick DM (large E_ν)

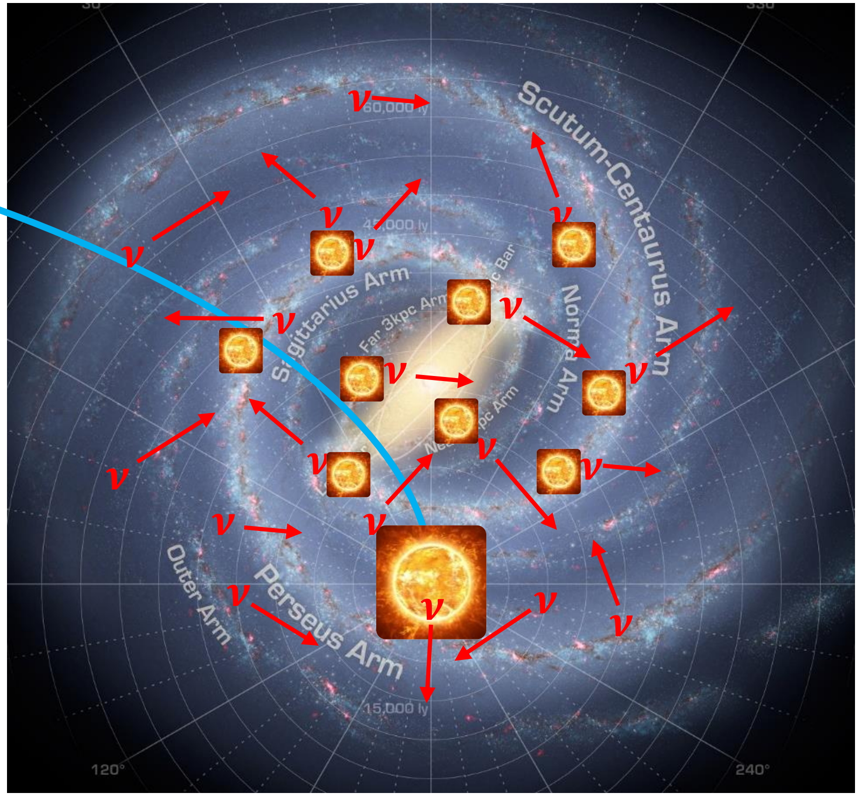


Large E_k^χ due to E_k^ν transfer

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

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

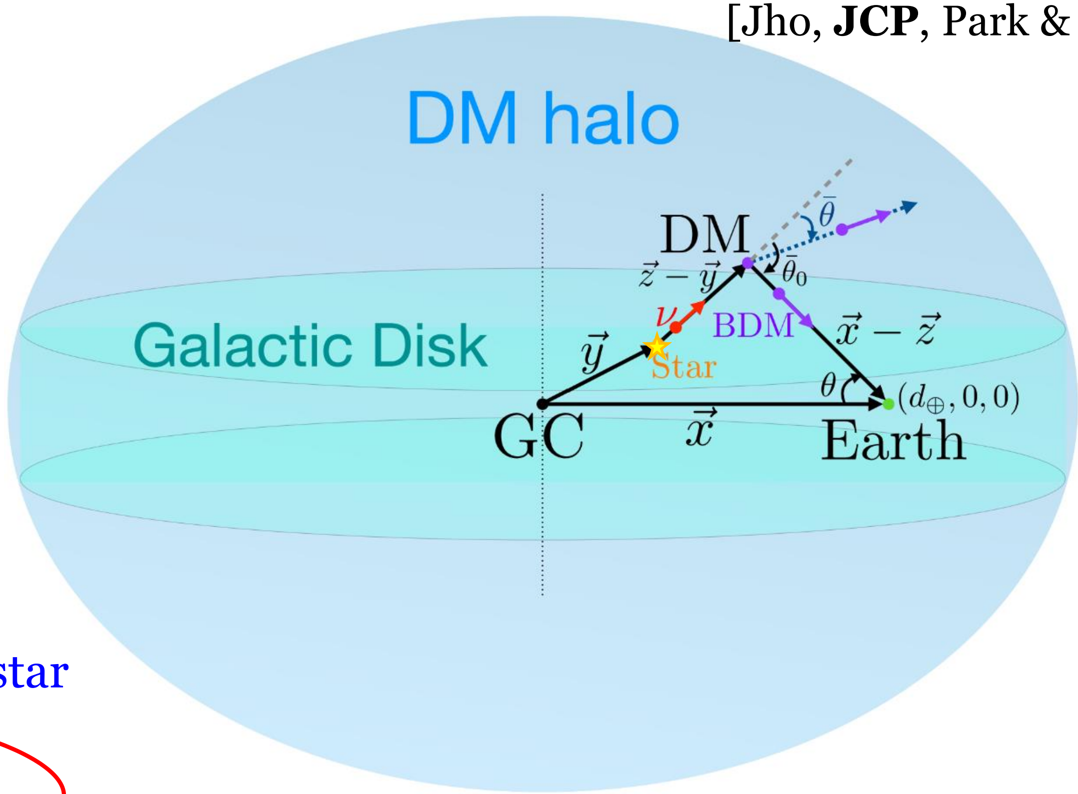




Cosmic-ray-induced BDM: νBDM

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

- ❖ BDM production by ν from a star



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

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

→ Neutrino emission rate for a Sun-like star

→ Variances of stellar properties from Sun

→ scattering angle=direction to the earth via kinematic relations

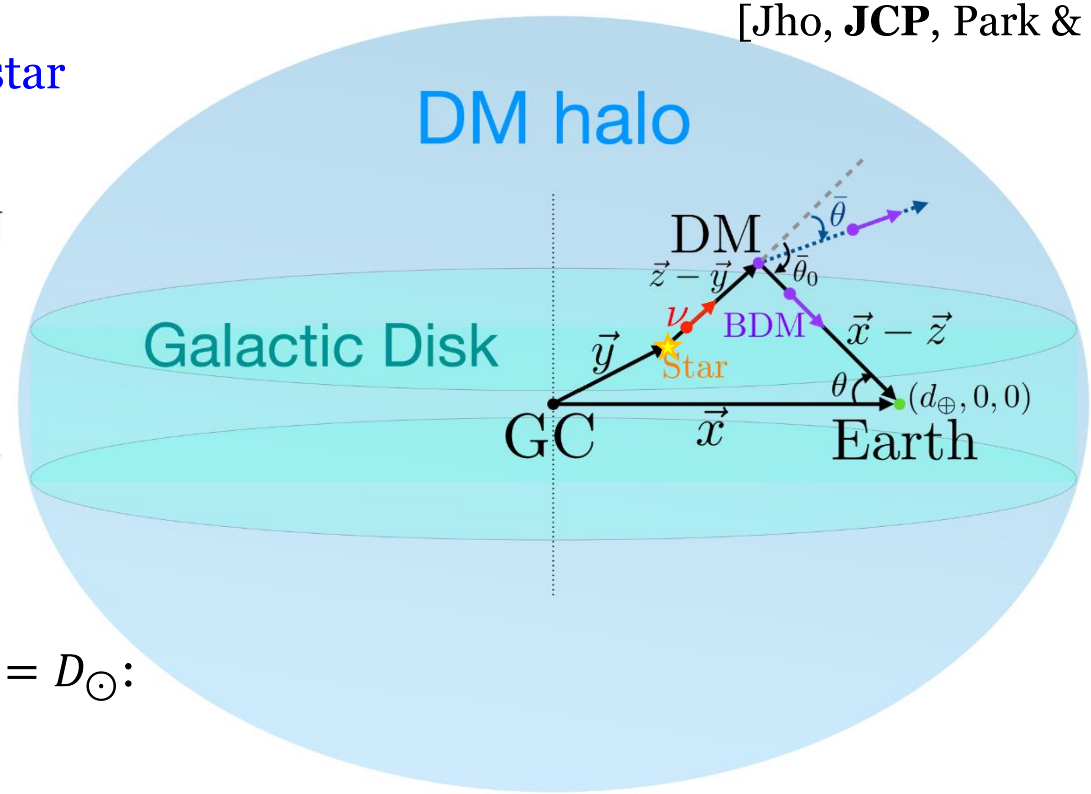
→ Attenuation of the ν flux due to propagation

Cosmic-ray-induced BDM: νBDM

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

❖ BDM production by ν from a Sun-like star

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



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

Sun provides the largest ν flux to Earth,

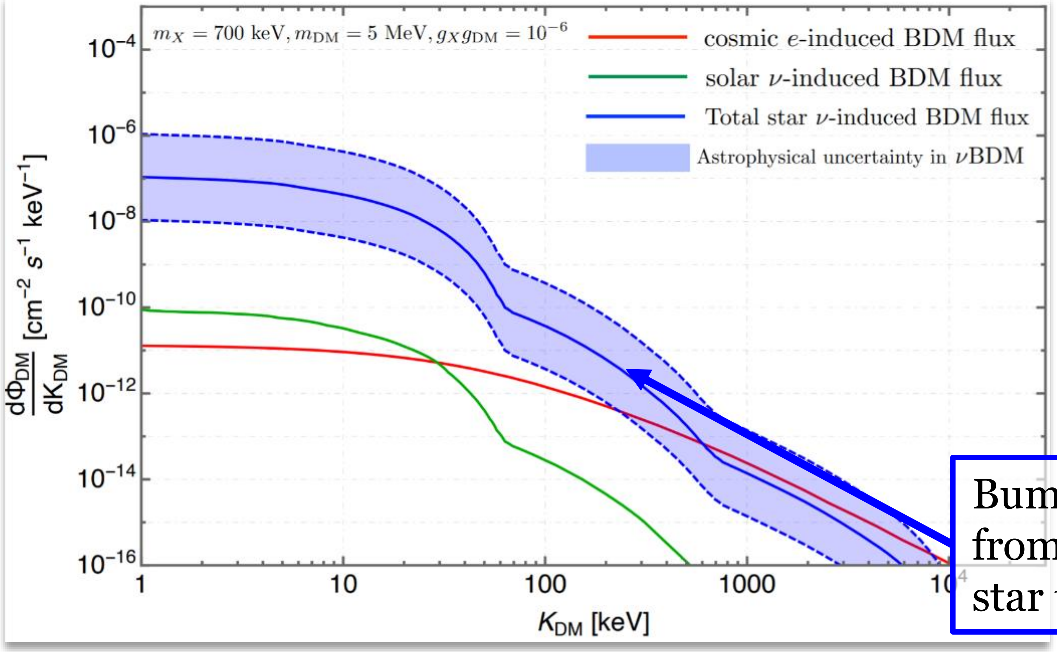
but only small volume of nearby low density DM halo comprises the BDM flux.

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

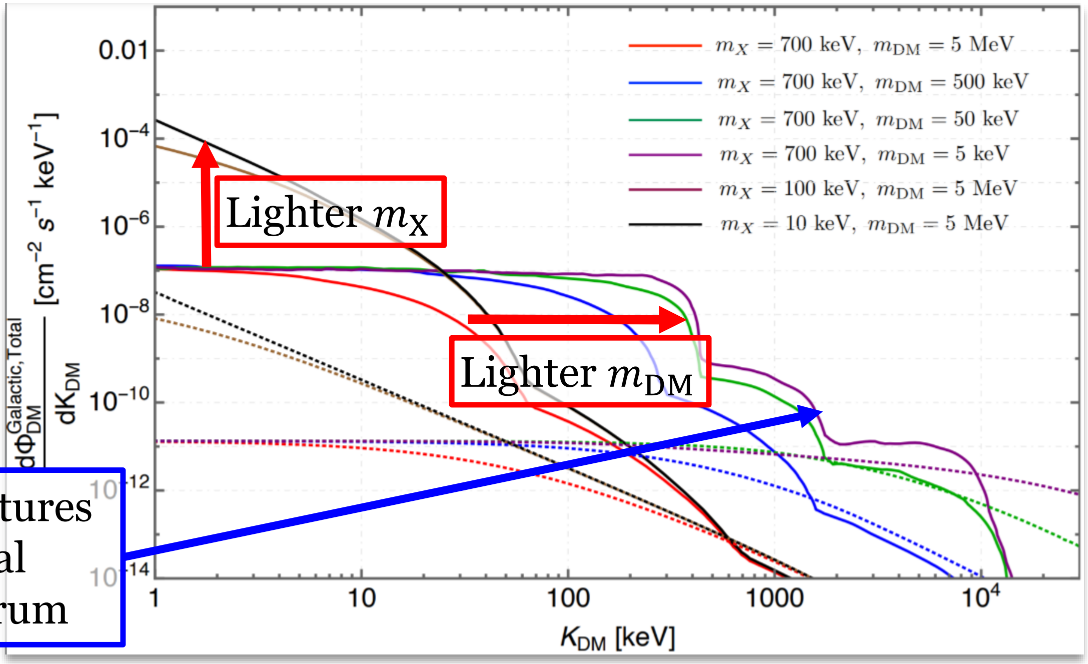
Cosmic-ray-induced BDM: νBDM

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

❖ BDM fluxes by solar/star neutrinos & cosmic electrons



❖ BDM fluxes for different mediator & DM masses



Bump structures from original star ν spectrum

✓ **νBDM** ~ 10^3 ×BDM by solar ν

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

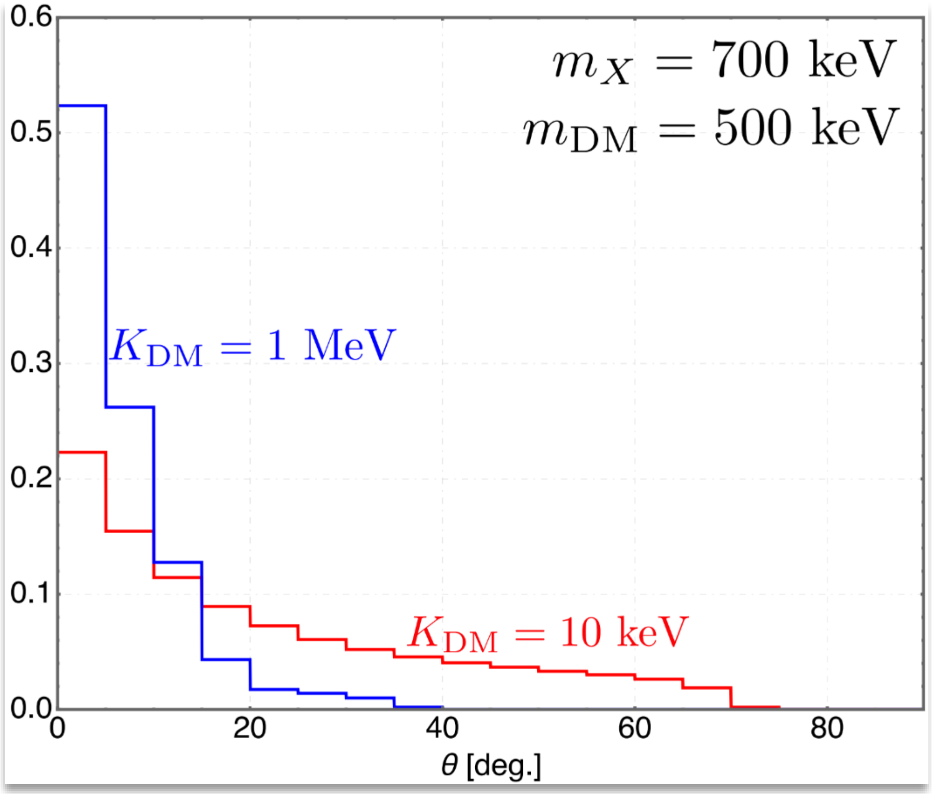
✓ **ν**BDM (**solid**) vs. **Ce**BDM (**dashed**)

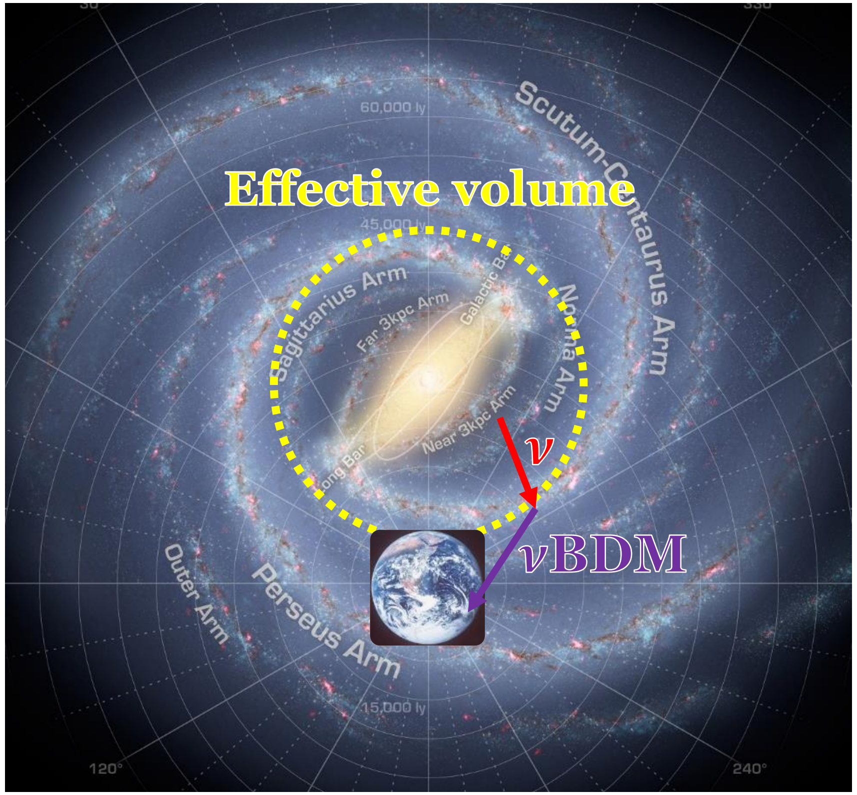
Solar/star neutrinos can very efficiently boost light DM ($\lesssim 10$ MeV)!

Cosmic-ray-induced BDM: νBDM

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

❖ Arrival direction distribution of the νBDM flux





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

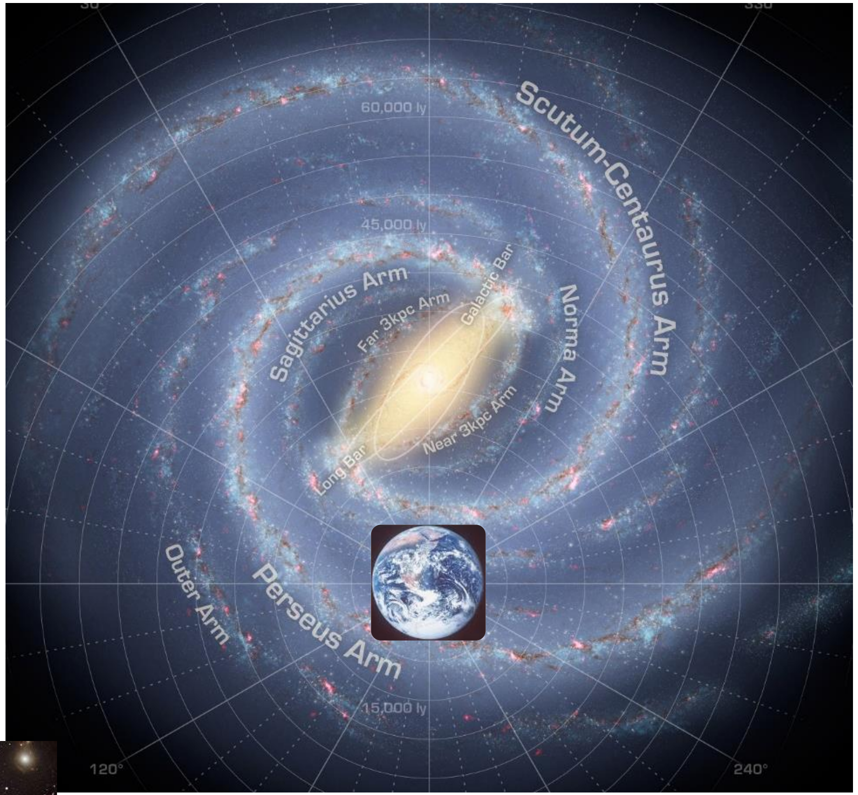
✓ $K_{\rm DM} \gg m_{\rm DM}$: forward scattering is preferred. ➔ GC contribution: dominant ➔ small effective Vol.

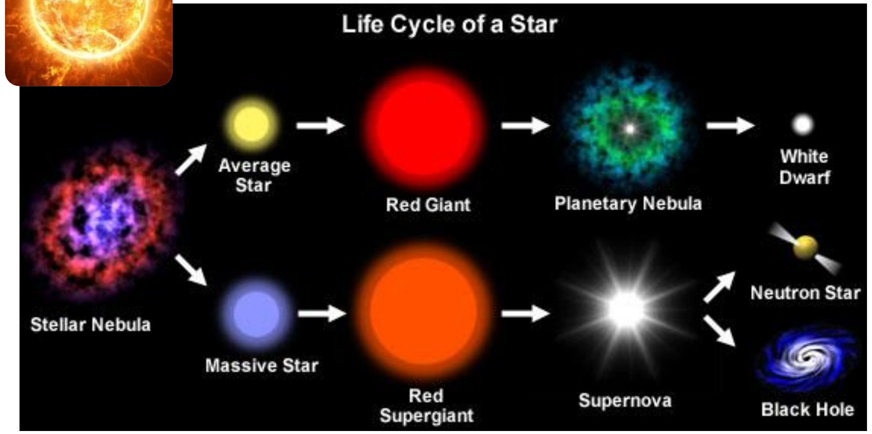
Cosmic-ray-induced BDM: νBDM

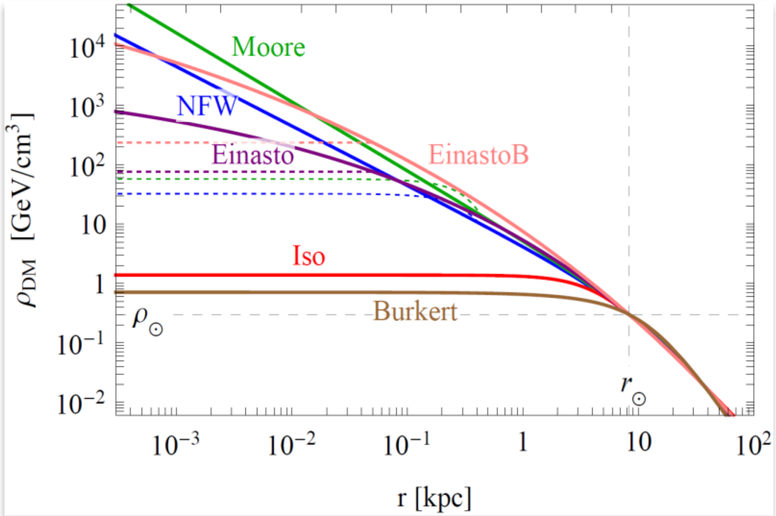
[Jho, **JCP**, Park & Tseng
2101.11262 & In preparation]

❖ 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)?





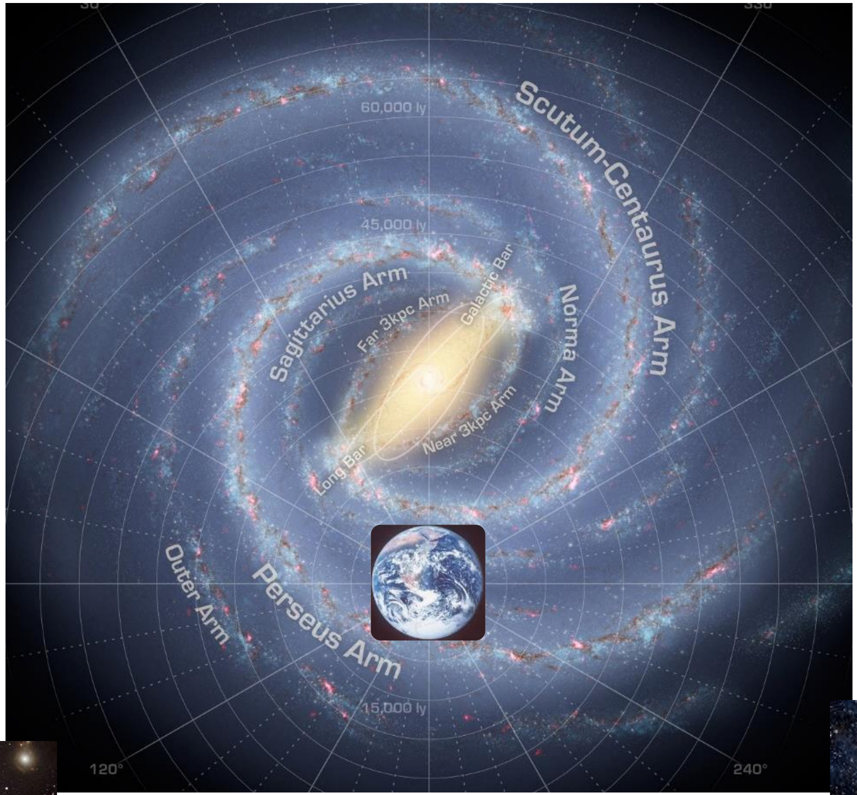


Cosmic-ray-induced BDM: νBDM

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

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

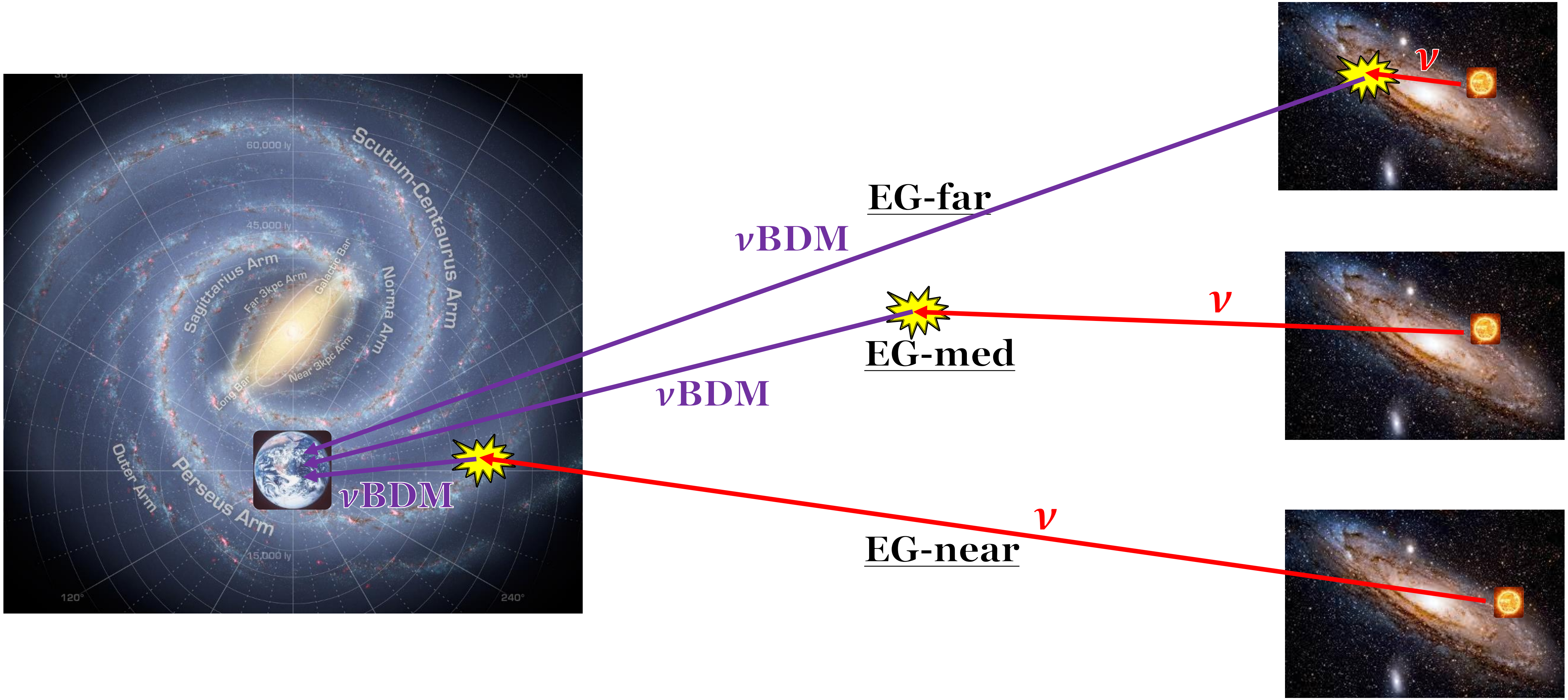
Dominant contribution:
ν & DM populated regions
➔ e.g., Galactic Center



Cosmic-ray-induced BDM: νBDM

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

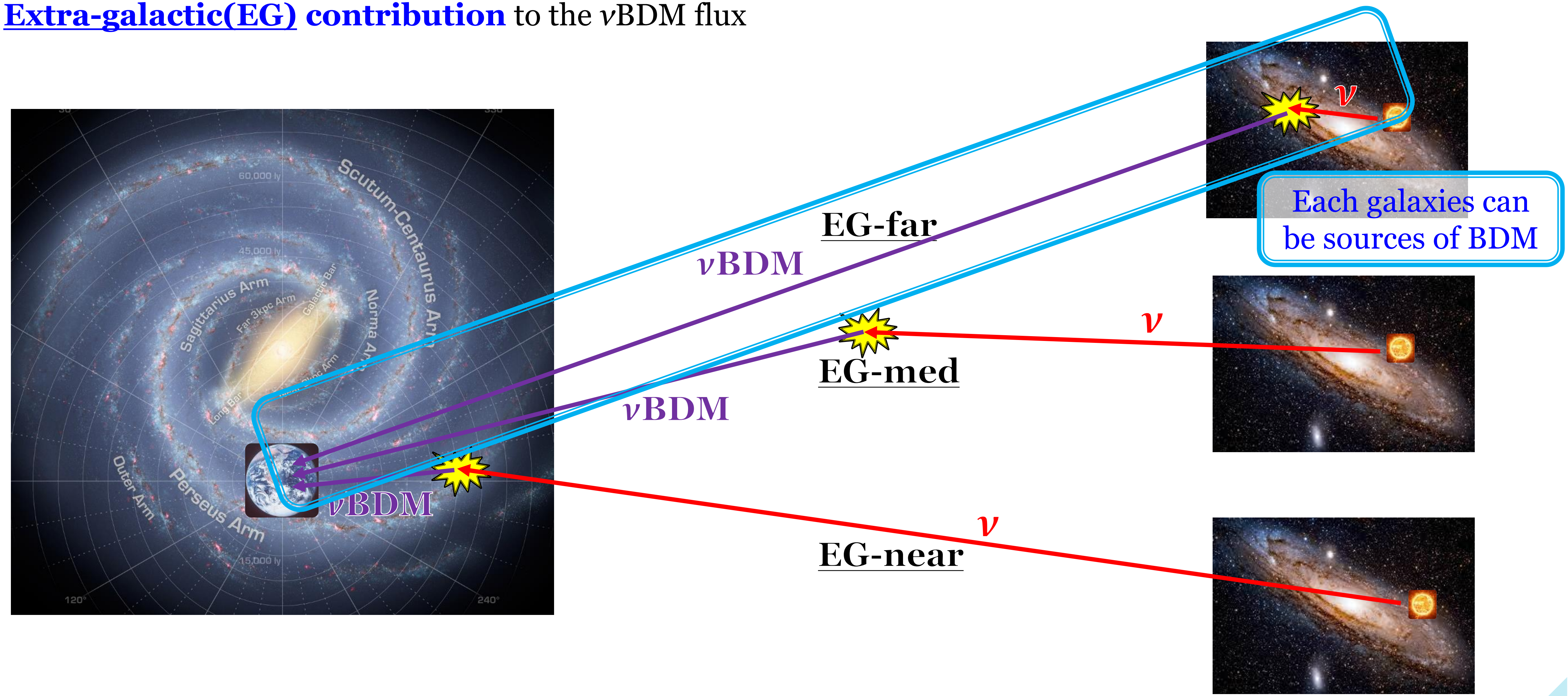
❖ **Extra-galactic(EG) contribution** to the νBDM flux



Cosmic-ray-induced BDM: νBDM

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

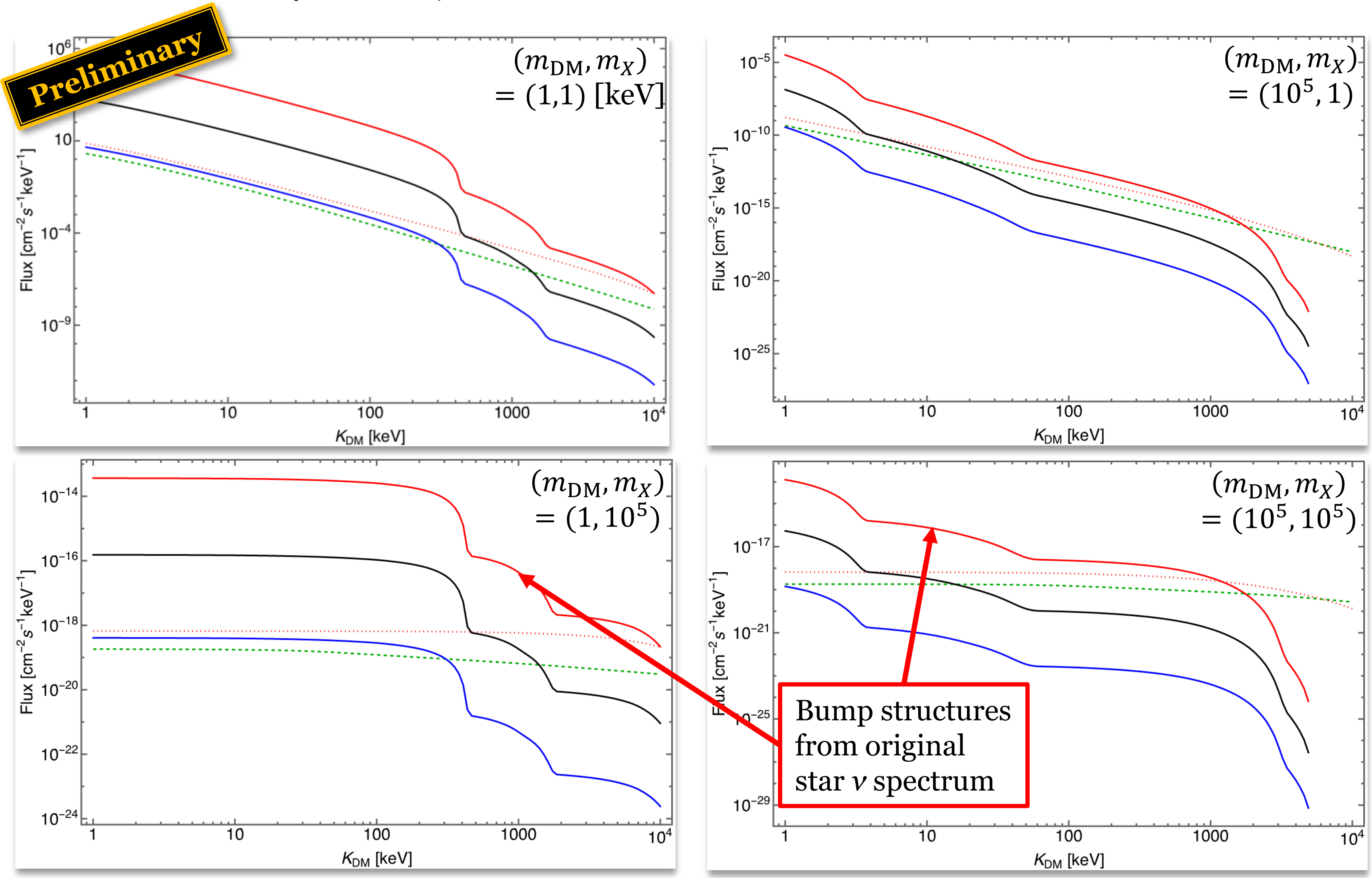
❖ **Extra-galactic(EG) contribution** to the νBDM flux



Cosmic-ray-induced BDM: Fluxes

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

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



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

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

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

✓ **EG-νBDM (far)**: most dominant
for $m_{\mathrm{DM}} \sim 1$ keV ➔ $K_{\mathrm{DM}} \lesssim 10$ MeV
for $m_{\mathrm{DM}} \sim 100$ MeV ➔ $K_{\mathrm{DM}} \lesssim 1$ MeV

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

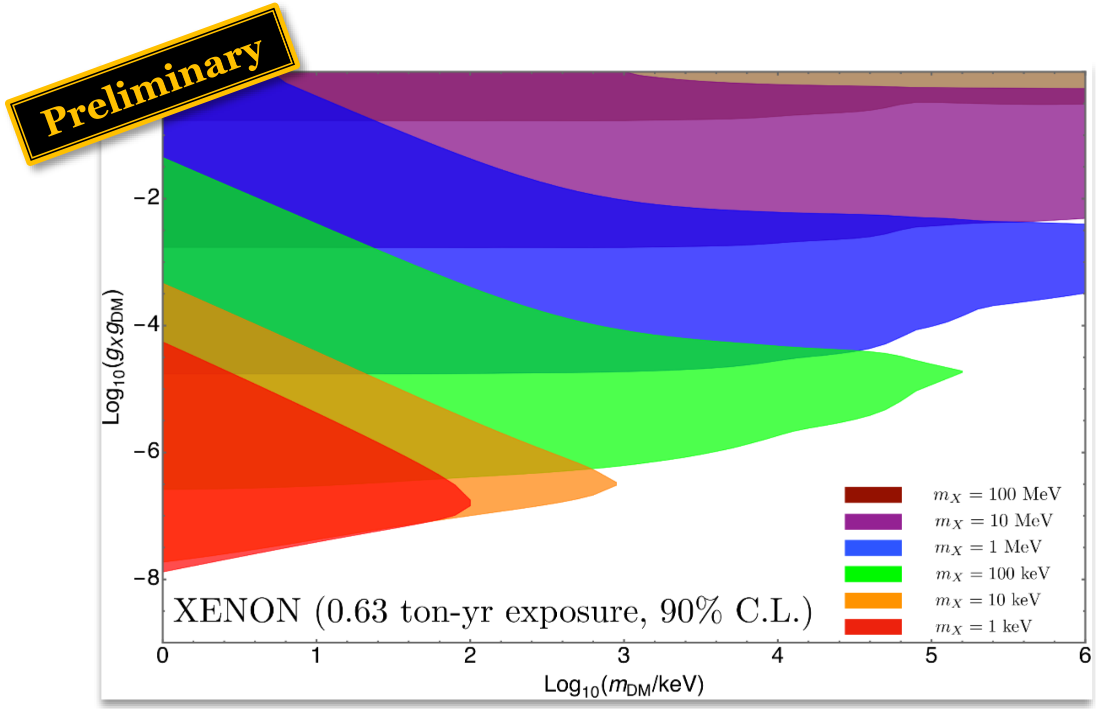
✓ **DSNBG**: dominant in-between

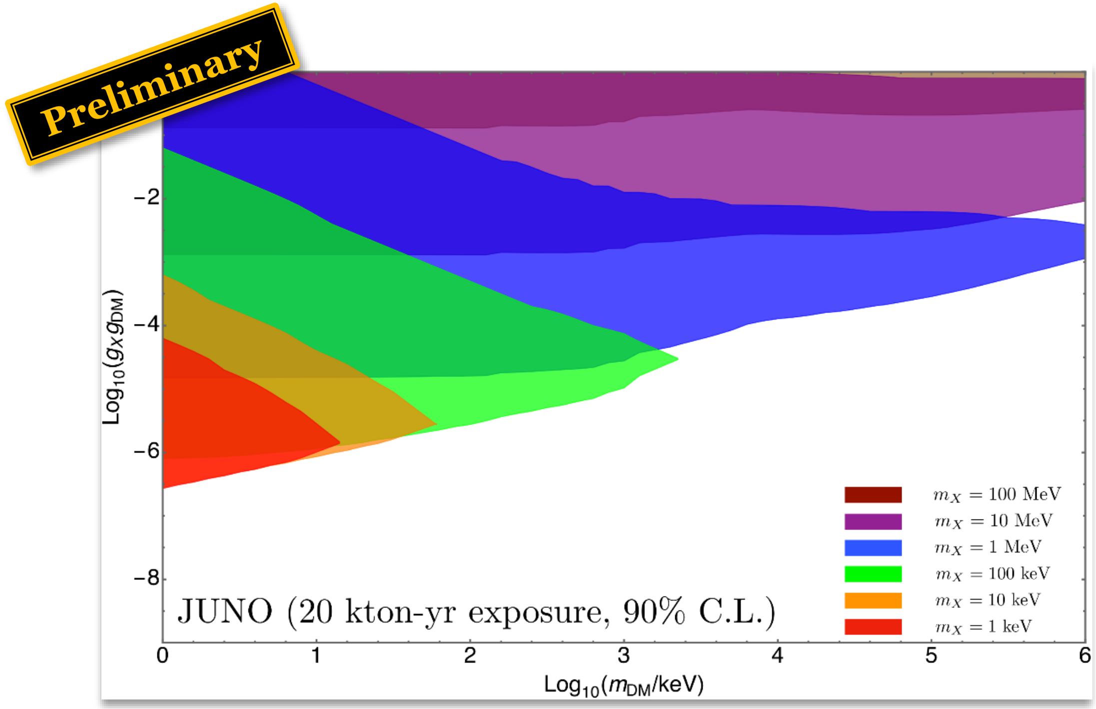
Cosmic-ray-induced BDM: Limits - Coupling

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

❖ Experimental status

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





✓ 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.]

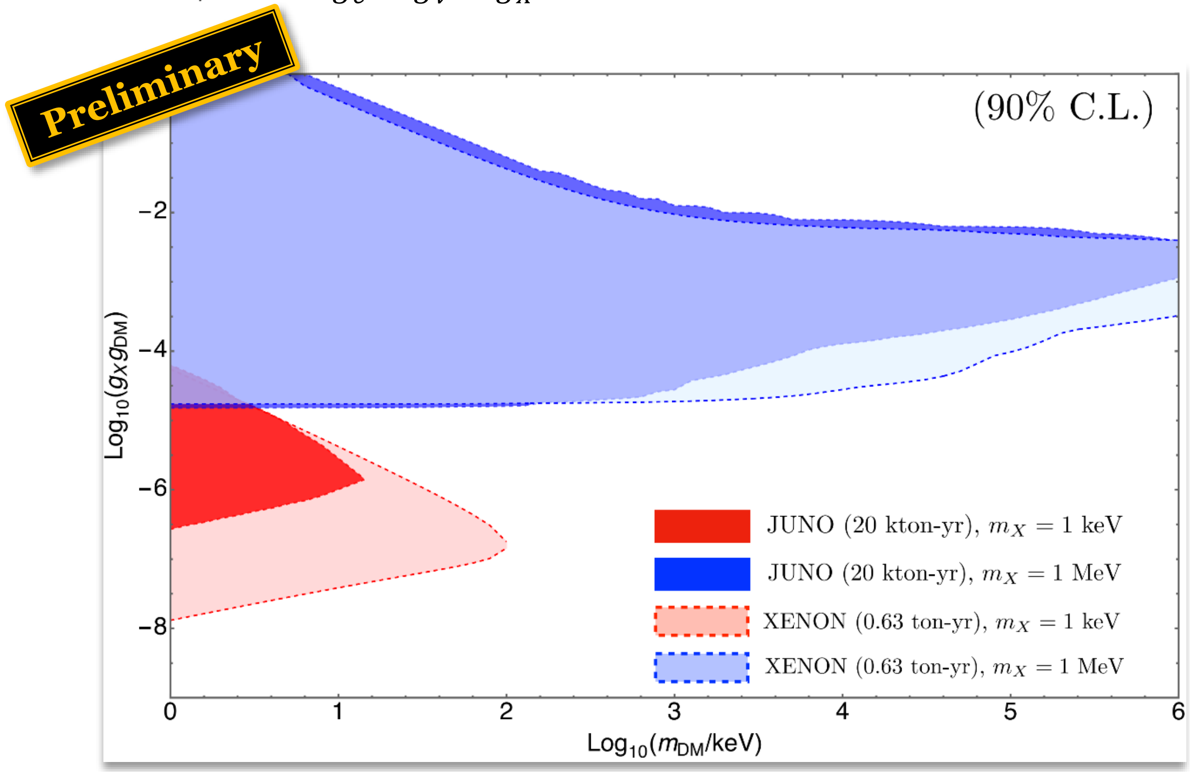
✓ More squeezed lower constraint lines for lighter m_X ← Less flux change for light m_X

Cosmic-ray-induced BDM: Limits - Coupling

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

❖ Experimental status

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



✓ 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

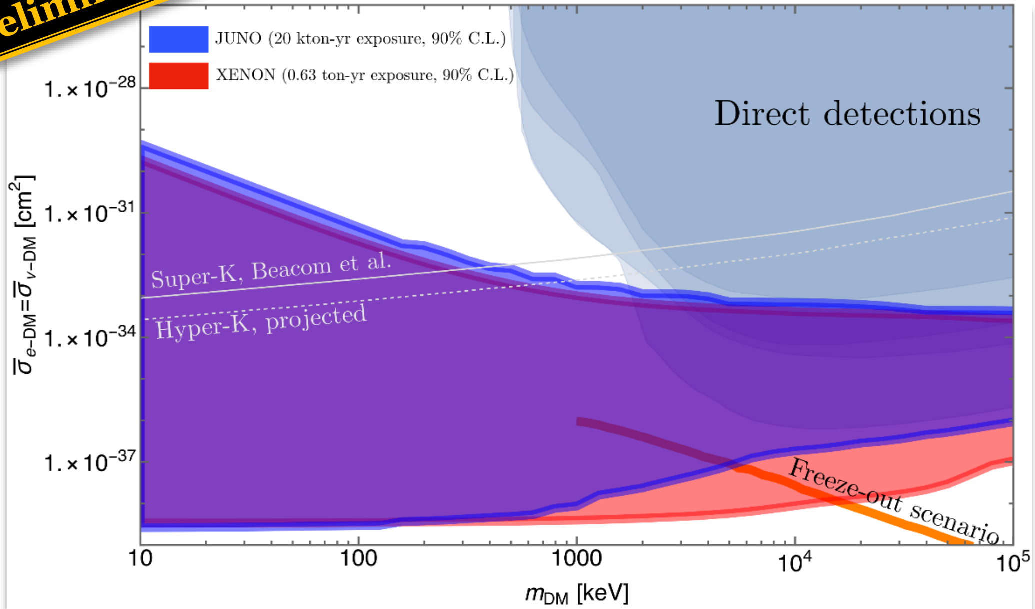
[Jho, **JCP**, Park & Tseng
2101.11262 & In preparation]

❖ Experimental status

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

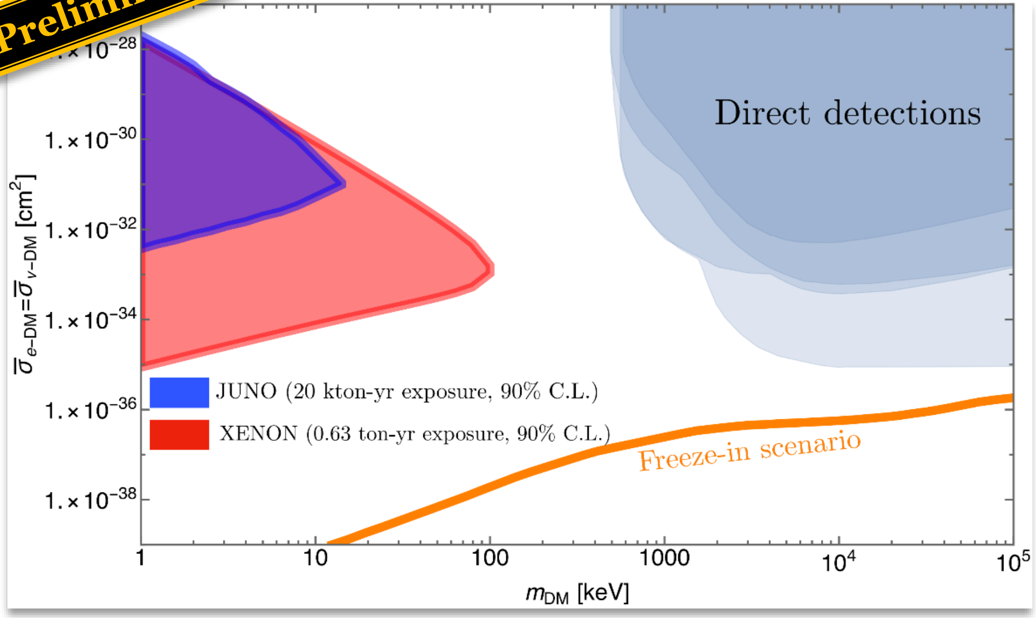
Preliminary

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 $\lesssim$ 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.

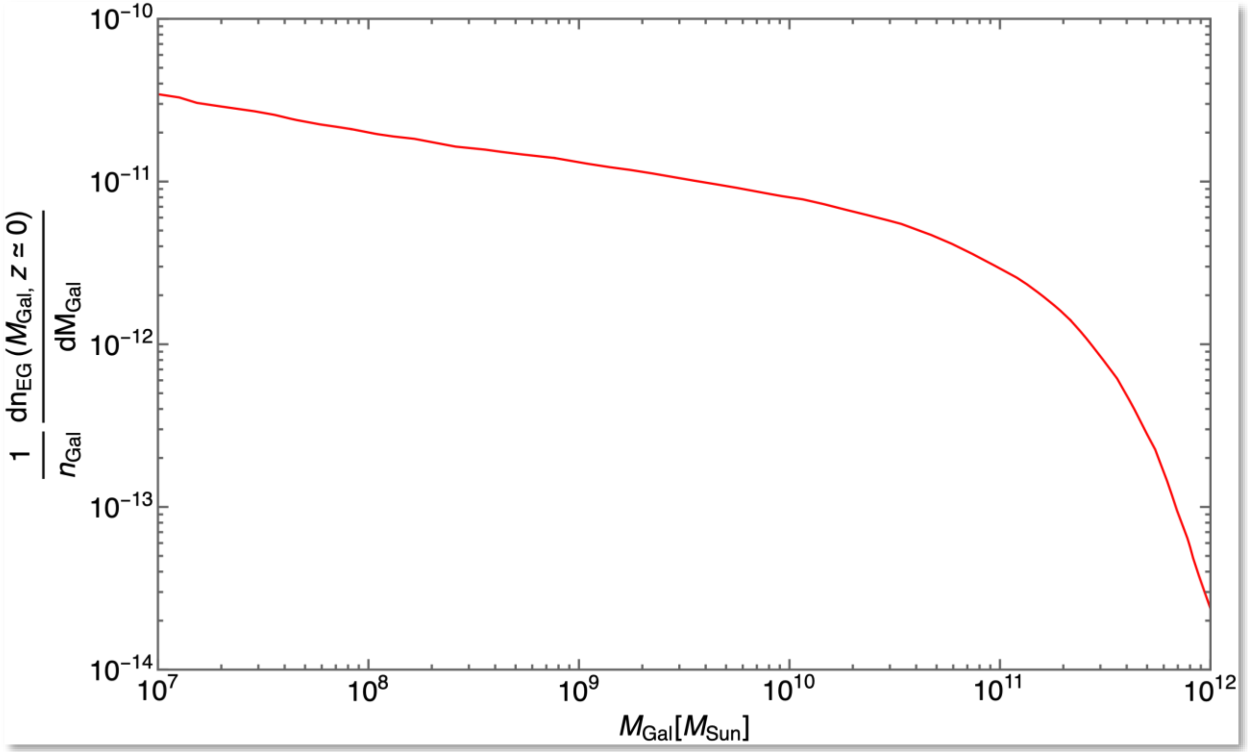
Thank you

Back-Up

Cosmic-ray-induced BDM: νBDM

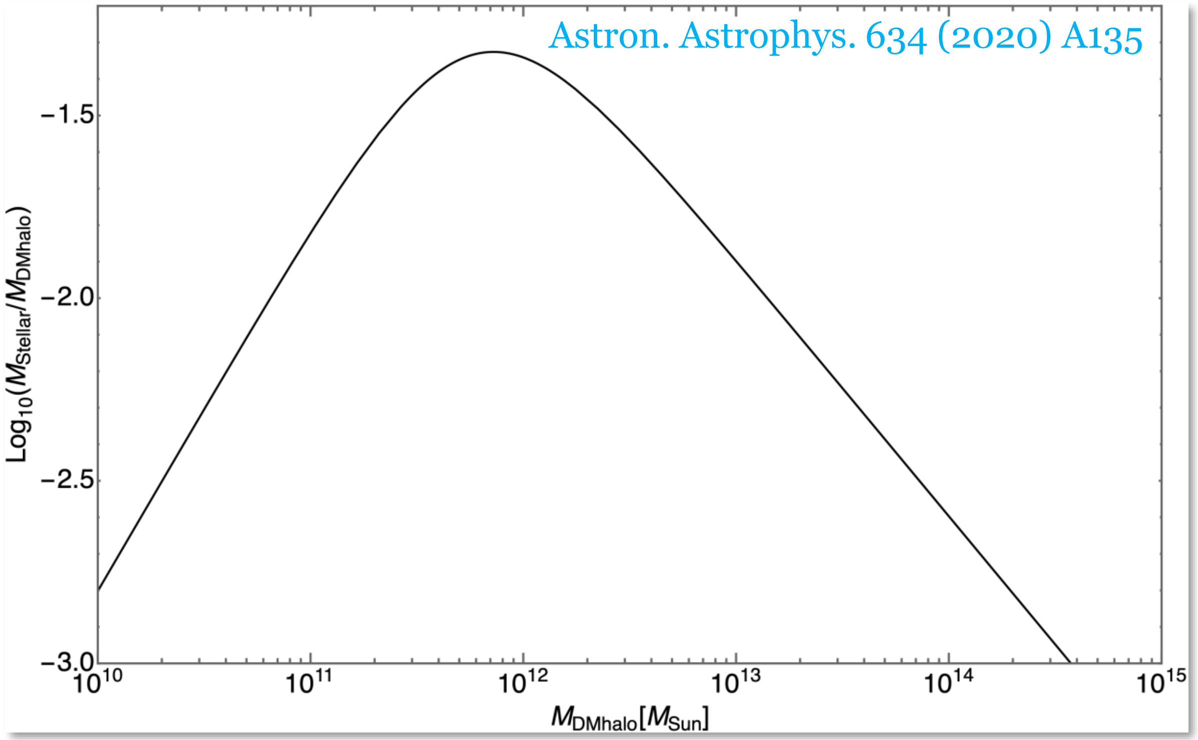
[Jho, **JCP**, Park & Tseng
2101.11262 & In preparation]

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



Mass composition of Galaxies

(based on Hubble deep field survey)



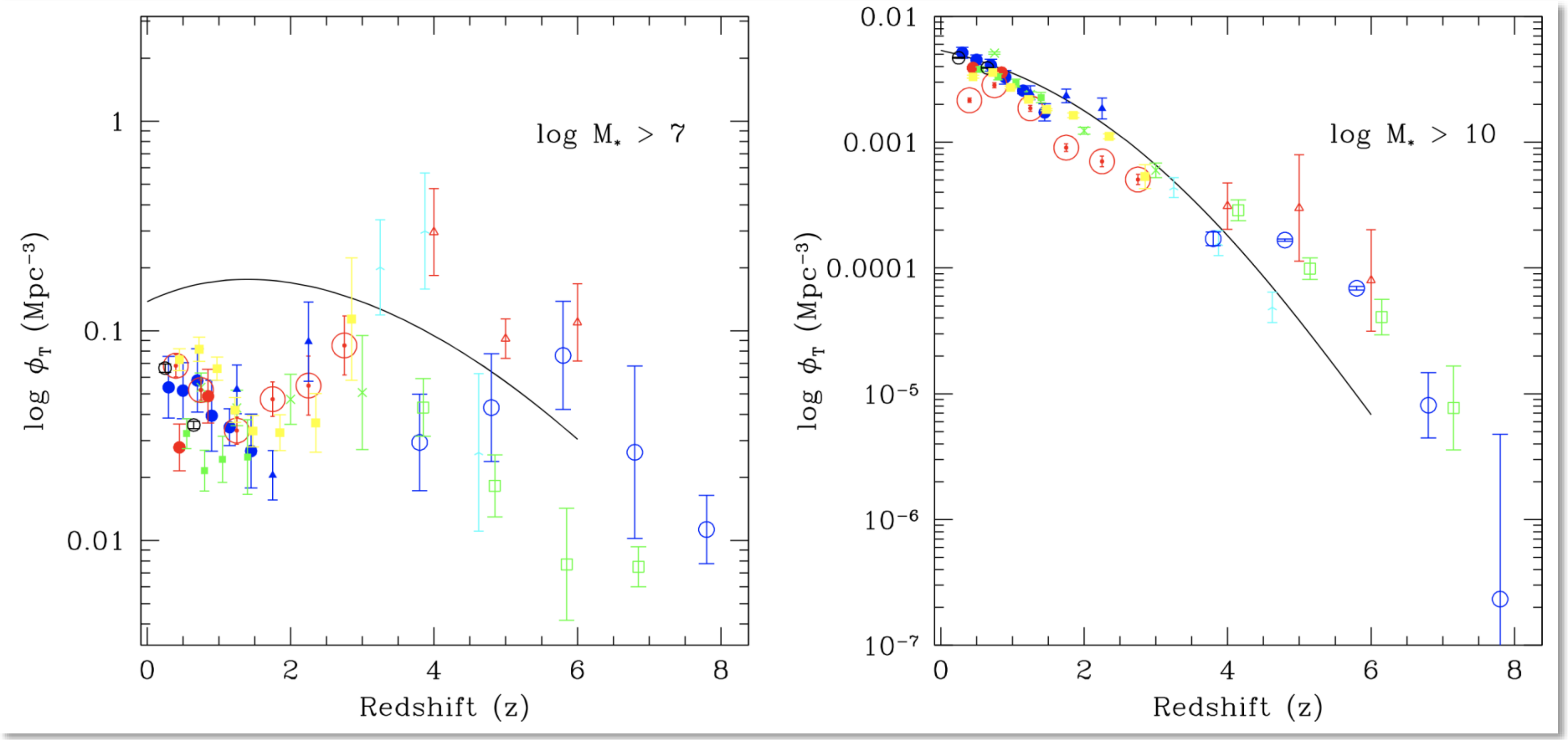
Stellar-to-Halo Mass ratio

(based on N-body simulation)

Cosmic-ray-induced BDM: νBDM

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

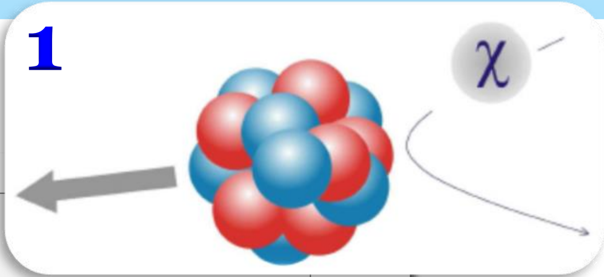
❖ **Extra-galactic(EG) contribution** to the νBDM flux: **Properties of extra-galaxies**

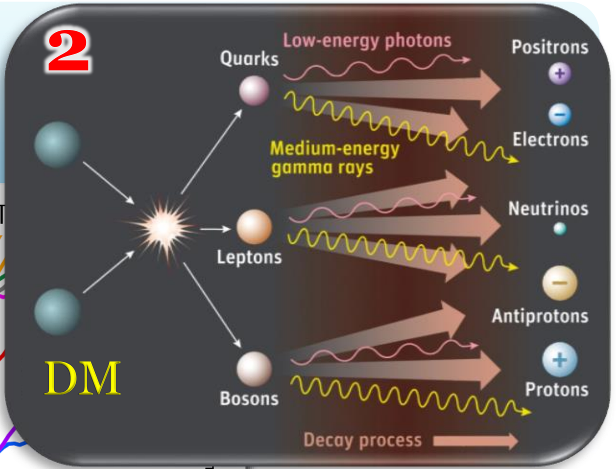


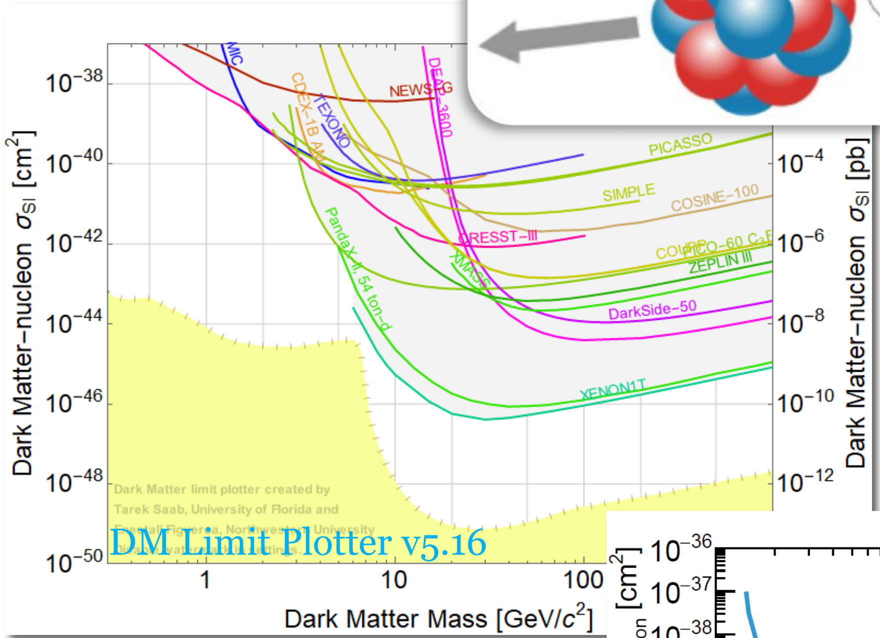
The Astrophysical J. 830 (2016) 83

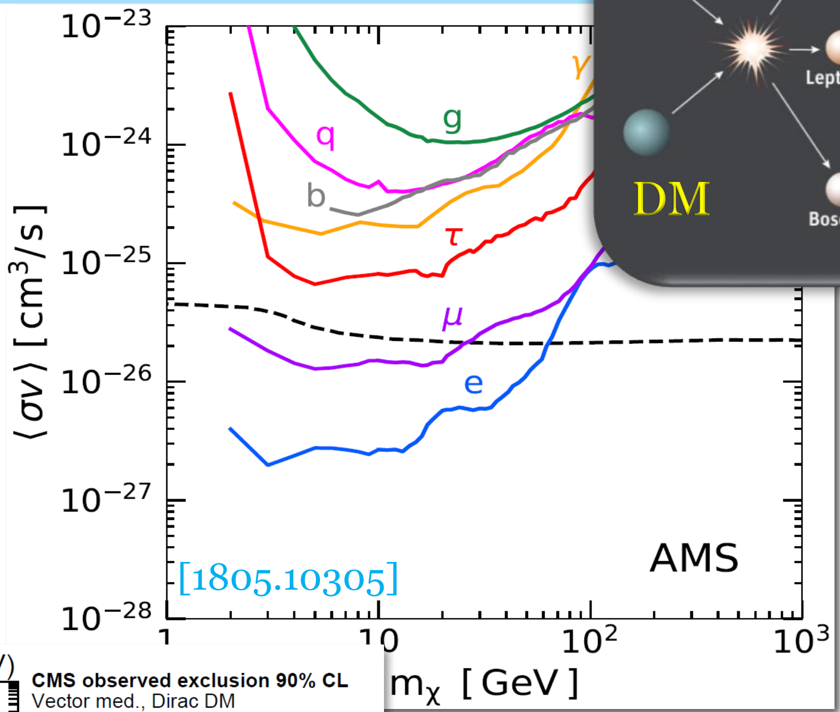
Evolution of galaxy number density at $z < 8$

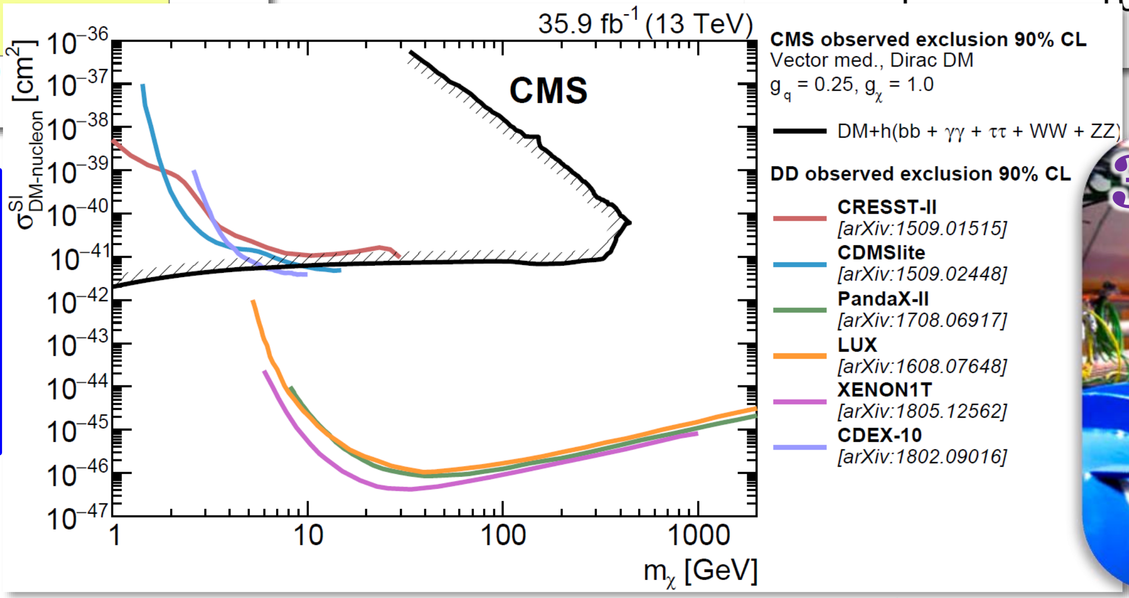
Current Search Status of DM (WIMP)

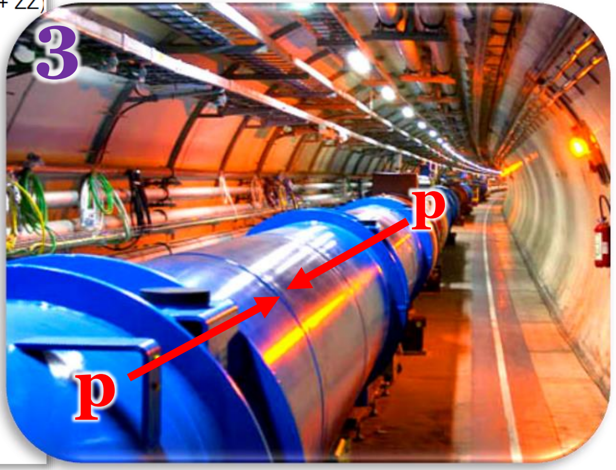










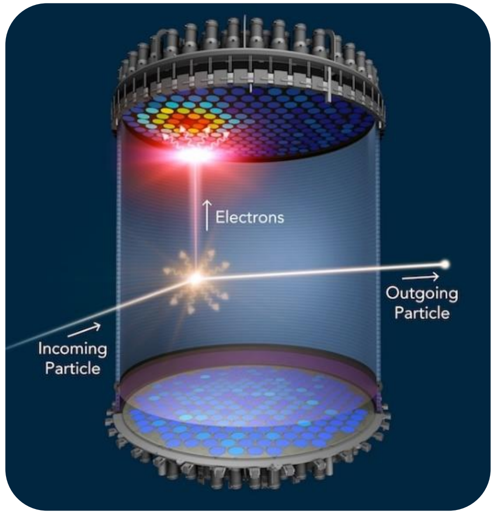


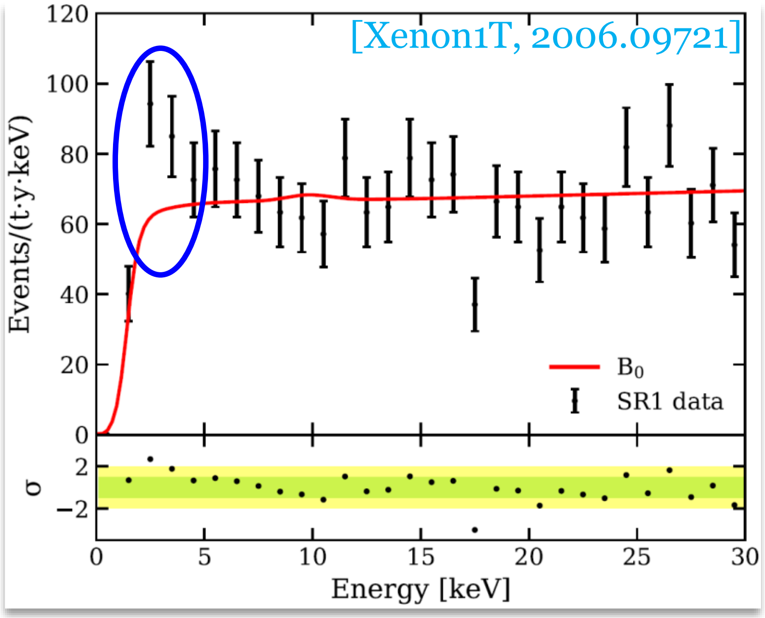
❖ **No solid observation**

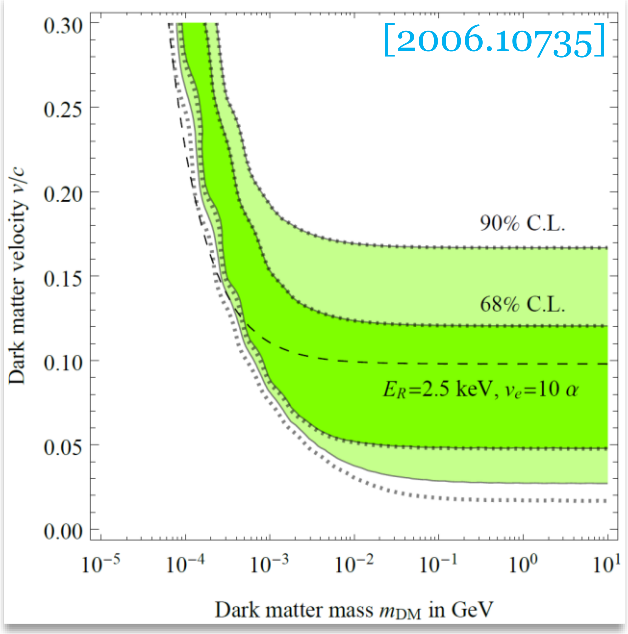
➔ Stringent constraints

on WIMP

XENON1T Anomaly







❖ An excess of **electron recoil** events over known(?) BGs around 2-4 keV.

❖ The interpretation with conventional (elastic & $v/c \sim 10^{-3}$) DM is less favored:

$\because$ $\boldsymbol{E_r \sim m_e v^2 \sim O(eV)}$ even for $m_{\rm DM} \gg m_e$, [Kannike, Raidal, Veermae & Strumia, 2006.10735].

❖ This problem may be avoidable with non-conventional dark-sector scenarios:

e.g., ALP, dark photon, inelastic and/or, ***$v \sim c$* (→ BDM!)** etc.

XENON1T Anomaly: BDM & e-Recoil

- ❖ DM direct detection experiments including XENON1T would be sensitive enough to energetic e-recoils induced by BDM by pumping up the BDM flux. [G. Giudice, D. Kim, **JCP**, S. Shin, PLB (2018)]
- ❖ Fast moving DM, $v/c \gtrsim O(0.1)$, is needed for ~keV electron recoil events. [PRD (2020)]

⇓

- ❖ Various BDM studies for the XENON1T anomaly.
  - ✓ Multi-component model: [Fornal et al., 2006.11264; Alhazmi, Kim, Kong, Mohlabeng, **JCP** & Shin, 2006.16252]
  - ✓ Charged cosmic-ray induced BDM: [Su et al., 2006.11837; Cao, Ding & Xiang 2006.12767; Jho, **JCP**, Park & Tseng, 2006.13910]
  - ✓ Cosmic-Neutrino-Boosted DM (νBDM): [Jho, **JCP**, Park & Tseng, 2101.11262; Das & Sen, 2104.00027; Chao et al., 2108.05608; …]
  - ✓ …

Inner shell electrons?
Type of DM & mediator?

✓ Spectral shape: strong dependence on spin of DM & mediator (+ efficiency & smearing + **ionization factor**) ➔ For more details, [2006.16252 & **in preparation**]

How Many e's in Xe?

Label	Orbital	eV [literature reference]
K	1s	34561 [1]
L I	2s	5453 [1]
L II	$2p_{1/2}$	5107 [1]
L III	$2p_{3/2}$	4786 [1]
M I	3s	1148.7 [2]
M II	$3p_{1/2}$	1002.1 [2]
M III	$3p_{3/2}$	940.6 [2]
M IV	$3d_{3/2}$	689 [2]
M V	$3d_{5/2}$	676.4 [2]
N I	4s	213.2 [2]
N II	$4p_{1/2}$	146.7 [1]
N III	$4p_{3/2}$	145.5 [2]
N IV	$4d_{3/2}$	69.5 [2]
N V	$4d_{5/2}$	67.5 [2]
N VI	$4f_{5/2}$	-
N VII	$4f_{7/2}$	-
O I	5s	23.3 [2]
O II	$5p_{1/2}$	13.4 [2]
O III	$5p_{3/2}$	12.1 [2]

- For e-recoil, electron binding E is important.
  - ➔ Only some fraction of e's can be targets.
  - ➔ Atomic-excitation/Ionization form factor.
- Three outermost orbitals (5p, 5s & 4d): dominant contribution for the Xe1T anomaly ➔ a conservative choice $N_e^{\rm eff} = 18$ ($\because \lesssim 0.1$ keV level uncertainty is buried in the detector resolution of 0.45 keV.)
- Caution: For energetic recoils, even inner shall electrons can contribute scatterings. Detailed study in preparation.

https://www.webelements.com/xenon/atoms.html

Recoil E Spectrum by BDM

[H. Alhazmi, D. Kim, KC Kong, G. Mohlabeng, **JCP** & S. Shin, JHEP (2021)]

❖ To study model-dependence of BDM scattering

$$\frac{d\sigma_{1e}}{dE_r} = \frac{(g_j^i g_e^i)^2 m_e}{8\pi\lambda(s, m_e^2, m_1^2)(2m_e E_r + m_i^2)^2}\overline{|\mathcal{A}|}^2$$

$i \in \{V, A, a, \phi\}, j \in \{\chi, \varphi\}, \lambda(x, y, z) = (x - y - z)^2 - 4yz$

$\overline{|A|}^2$ where the denominator of the propagator contribution is factored out

Case	Mediator	Dark matter	$\mathcal{L}_{\rm int}$	$\overline{\|\mathcal{A}\|}^2$
VF	V_μ	χ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\chi^V \bar{\chi}_1\gamma^\mu\chi_1)V_\mu$	$8m_e\{m_e(2E_1^2 - 2E_1E_r + E_r^2) - (m_e^2 + m_1^2)E_r\}$
VS	V_μ	φ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\varphi^V \varphi_1^*\partial^\mu\varphi_1 + \text{h.c.})V_\mu$	$8m_e\{2m_eE_1(E_1 - E_r) - m_1^2E_r\}$
AF	A_μ	χ_1	$(g_e^A \bar{e}\gamma^\mu\gamma^5 e + g_\chi^A \bar{\chi}_1\gamma^\mu\gamma^5\chi_1)A_\mu$	$8m_e\{m_e(2E_1^2 - 2E_1E_r + E_r^2) + (m_e^2 + m_1^2)E_r\}$ $+32m_e^2m_1^2\left(2\frac{E_r^2m_e^2}{m_A^4} + 2\frac{E_rm_e}{m_A^2} + 1\right)$
PF	a	χ_1	$(ig_e^a \bar{e}\gamma^5 e + ig_\chi^a \bar{\chi}_1\gamma^5\chi_1)a$	$4m_e^2E_r^2$
PS	a	φ_1	$(ig_e^a \bar{e}\gamma^5 e + ig_\varphi^a m_1\varphi_1^*\varphi_1)a$	$8m_em_1^2E_r$
SF	ϕ	χ_1	$(g_e^\phi \bar{e}e + g_\chi^\phi \bar{\chi}_1\chi_1)\phi$	$4m_e(E_r + 2m_e)(2m_1^2 + m_eE_r)$
SS	ϕ	φ_1	$(g_e^\phi \bar{e}e + g_\varphi^\phi m_1\varphi_1^*\varphi_1)\phi$	$8m_em_1^2(E_r + 2m_e)$

Recoil E Spectrum by BDM

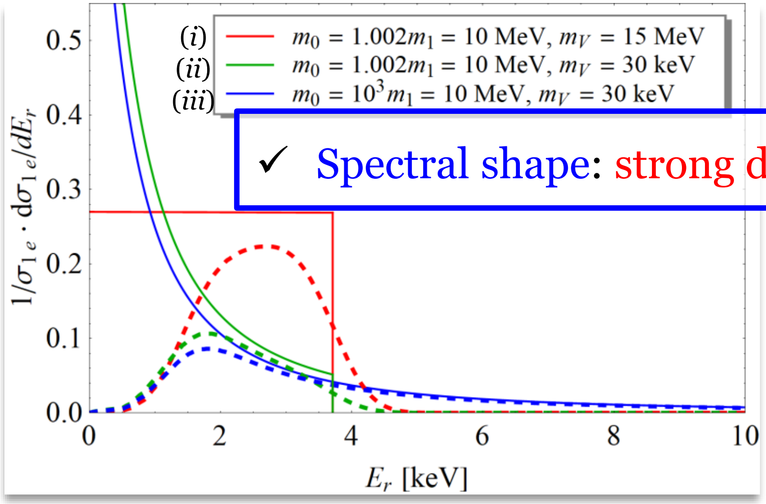
[H. Alhazmi, D. Kim, KC Kong, G. Mohlabeng, **JCP** & S. Shin, JHEP (2021)]

Solid: Unit-normalized e-recoil E spectra

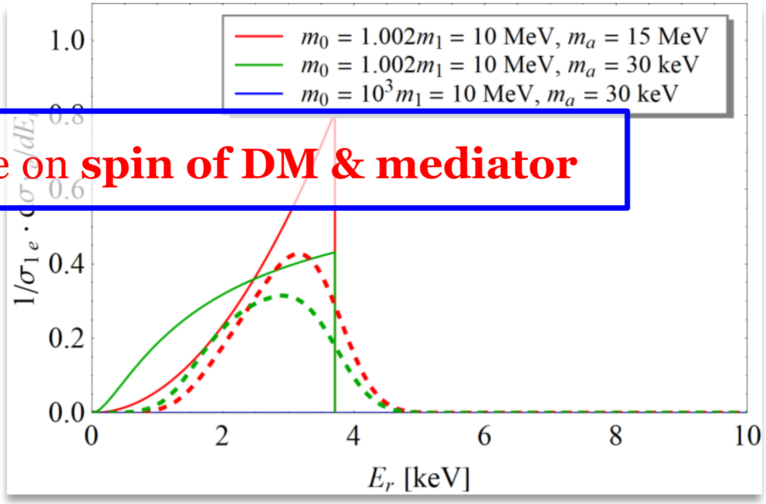
Dashed: w/ detector resolution & efficiency

✓ Spectral shape: strong dependence on **spin of DM & mediator**

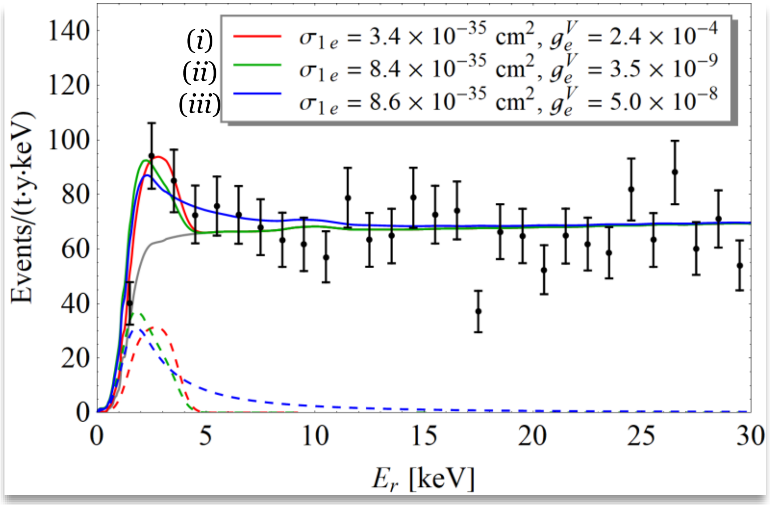
VF case

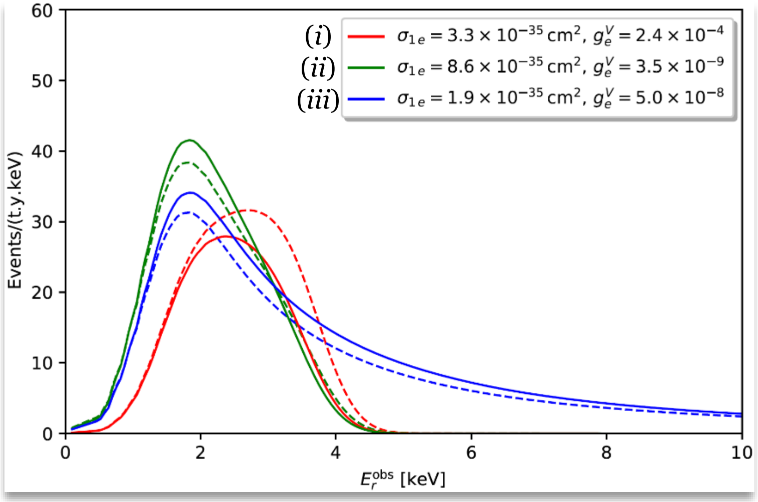


PF case



For the VF case: sample E spectra fits to the data



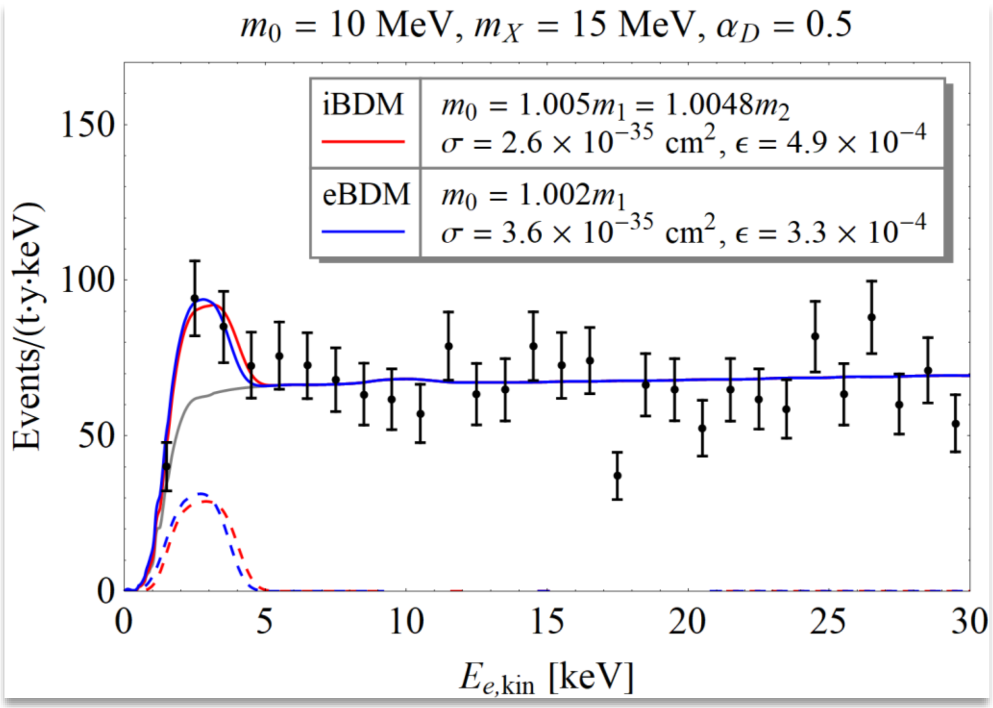


For the VF case: sample E spectra w/ the ionization factor (solid)

XENON1T Anomaly: eBDM vs *i*BDM

[H. Alhazmi, D. Kim, KC Kong, G. Mohlabeng, **JCP** & S. Shin, JHEP (2021)]

❖ Along the line of our previous paper [1712.07126], we tried to fit the observed excess events with e/iBDM models.



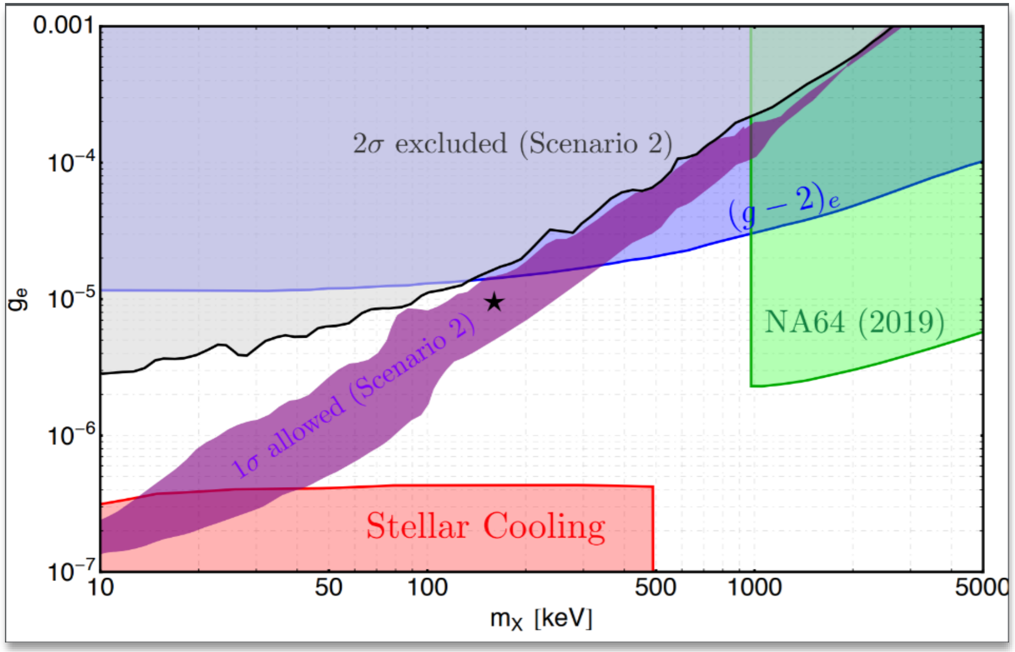
✓ eBDM & *i*BDM: very good fits to the data

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

[Jho, **JCP**, Park & Tseng, PLB (2020)]

❖ We tried to fit the observed e-recoil excess @ XENON1T by introducing new leptophilic interactions.

New interaction between DM & e



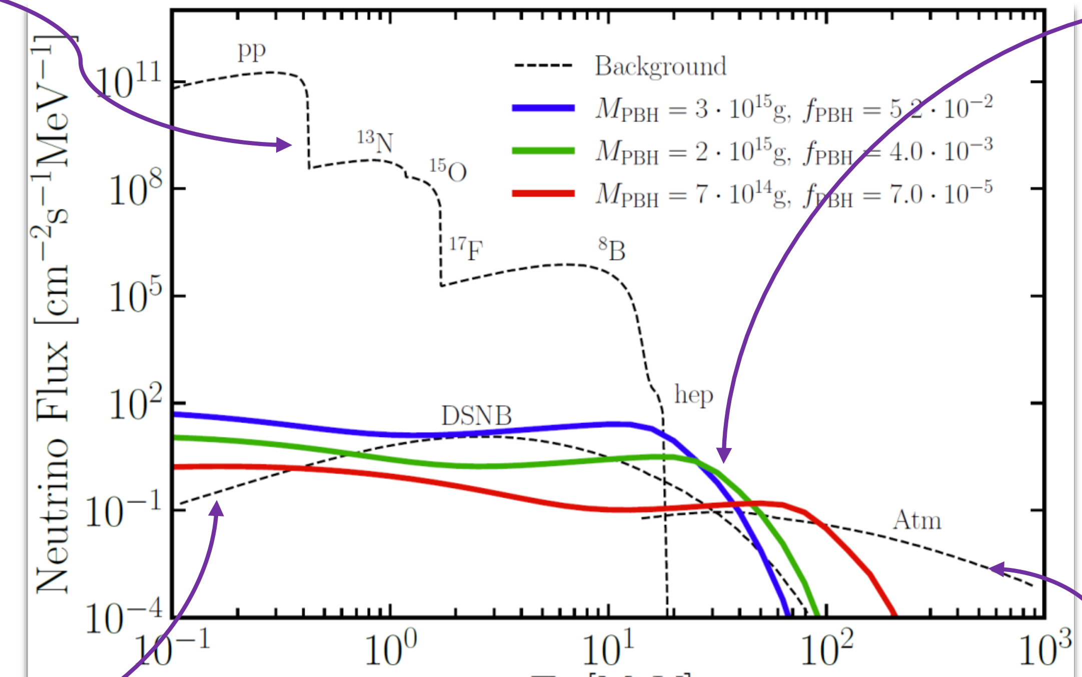
✓ good fit to the data & satisfying existing limits

purple (<u>preferred</u> at 1σ) vs. gray-shaded (<u>excluded</u> > 2σ)

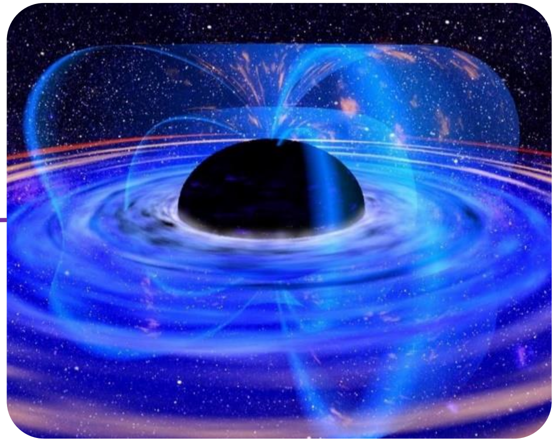
Effects from Neutrinos?

Cosmic Neutrino Sources & Fluxes

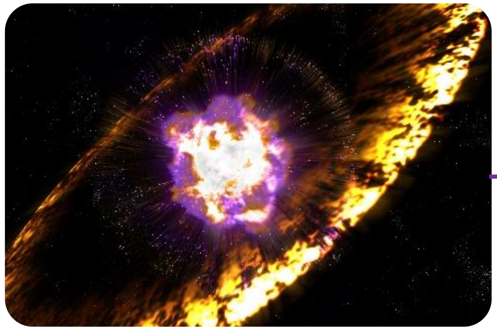
[Star ν-BDM, 2101.11262]



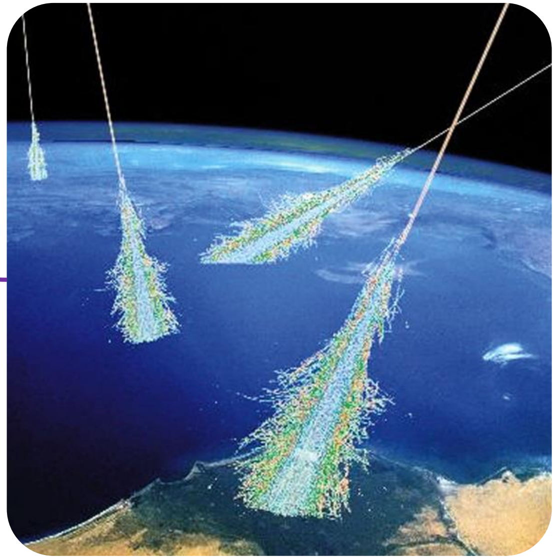
[2106.02492]



[PBH ν-BDM, 2108.05608]



[DSNB-BDM, 2104.00027]



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

$m_{\rm DM}$=1 keV | 10 keV | 100 keV | 1 MeV | 10 MeV | 100 MeV

m_X= 1 keV, 10 keV, 100 keV, 1 MeV, 10 MeV