Probing the dark photon in collinear dark matter splitting

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with J. Pei, C. Zhang, T. Nomura

Outline

1. The collinear splitting in the SM
2. Dark matter shower signature at the collider
3. Dark PDF in DM direct detection
4. The dark photon radiation in DM indirect detection

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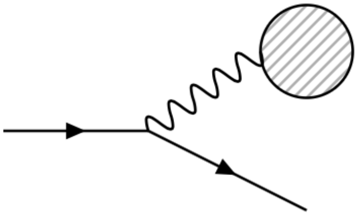
Photon radiation from charged particle

The probability of an electron to emit a collinear photon with a fraction x of its energy, is given by the Weizsaicker-Williams effective photon approximation



$$f_\gamma(x) \sim \frac{\alpha}{2\pi} P_{\gamma\ell}(x) \ln \frac{E^2}{m_\ell^2}$$

- The photon virtuality is $-p_T^2/(1-x)$, to the first order approximation.
- The spliting function $P_{\gamma/\ell}(x) = (1+(1-x)^2)/x$.
- The photon propagator $\frac{1}{(p_a-p_b)^2} \sim \frac{1}{2E_a E_b (1-\cos\theta)}$

The parton distribution function

At the high energy scattering ($E \gg m$), process of collinear emission of initial state can be factorized into PDFs, given the collinear factorization formula. At muon collider,

$$\sigma_{\mu^+\mu^- \to X}(s) = \sum_{ij} \int dz_1 dz_2 f_{i/\mu^+}(z_1) f_{j/\mu^-}(z_2) \hat{\sigma}_{ij \to X}(z_1 z_2 s)$$

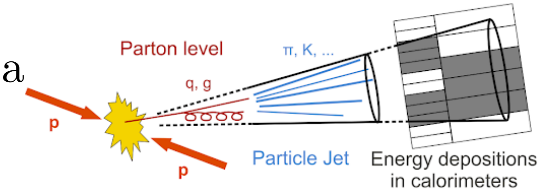
The large logarithms in the splitting can be resumed with the DGLAP equation:

$$\frac{df_i(x, Q^2)}{d\log Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{i,j}(x) \otimes f_j(x, Q^2)$$

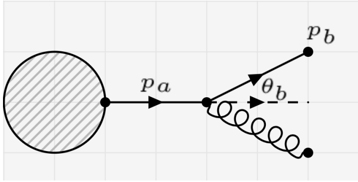
- The factorization scale Q
- The index I loops over all possible interactions of particle i
- The initial condition at $Q^2 = m_\mu^2$ is $f_\mu(x, m_\mu^2) = \delta(1-x)$, and other PDFs vanish

Jet formation: the parton shower

The copious collinear radiations produce a collimated spray of particles, dubled jet.



For a collinear emission:



$$\sigma_{n+1} \sim \sigma_n \int \frac{dp_a^2}{p_a^2} \int dz \frac{\alpha_s}{2\pi} \hat{P}(z) \equiv \sigma_n \int dt W(t)$$

splitting kernel $\hat{P}(z)$, $z = E_b/E_a$, *virtuality* $t = p_a^2$

With multiple emissions

$$\sigma_{n+m} \sim \sigma_n \cdot \int dt_1 \cdots \int dt_m W(t_1) \cdots W(t_m)$$

$$\equiv \sigma_n \cdot \frac{1}{m!} (\int dt W(t))^m$$

Jet formation: the parton shower

The probability for the next emission at t:

$$d\text{Prob}(t) = dt W(t) \exp(-\int_{t_0}^{t} dt W(t))$$

$\exp(-\int dt W(t))$ is Sudakov form factor = No emission probability

Monte Carlo description for the parton shower process

- Evolve the virtuality from t^{max} to t^{min}, calculate the Sudakov form factor for each step
- Use veto algorithm to find the next splitting scale t, determine the splitting process
- Construct the splitting kinematics

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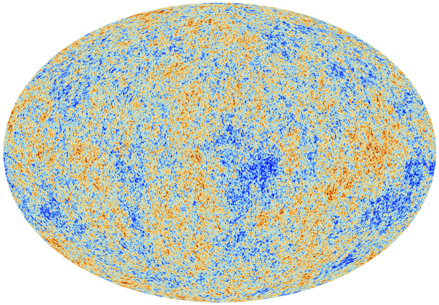
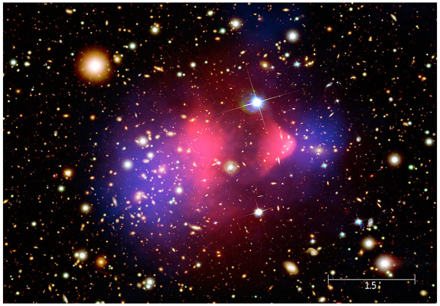
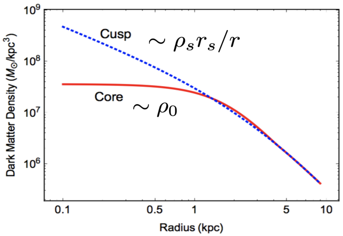
- Dark matter existence seems evident

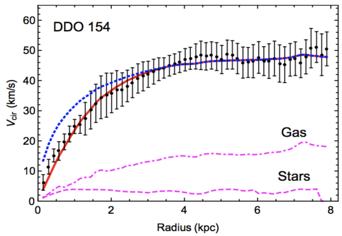




- Small scale structure problems

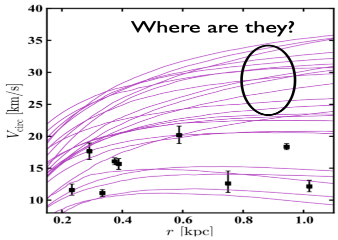
Core-vs-cusp (dwarfs, LSBs)





Central densities of halos are too shallow.

Too-Big-to-Fail (MW dwarf galaxies)

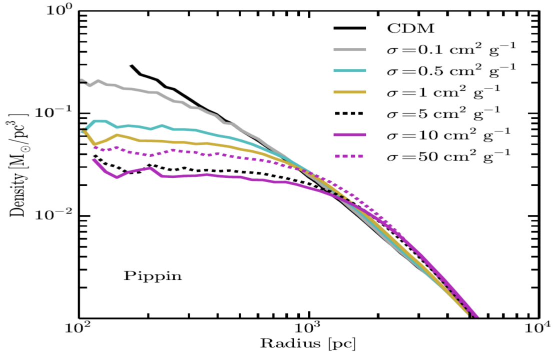


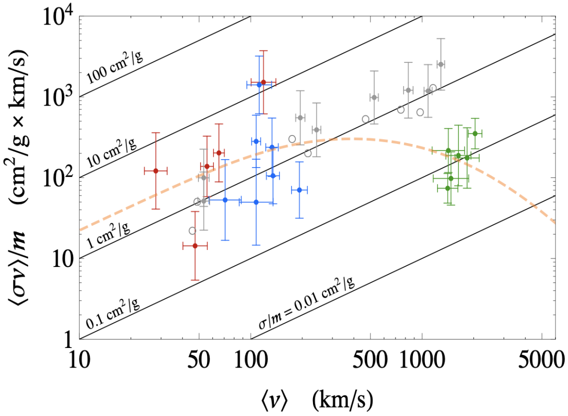
- Biggest predicted subhalos from CDM simulations
- Brightest observed galaxies in the MW

Predicted Milky Way satellites more massive (larger velocity dispersions) than observed ones.

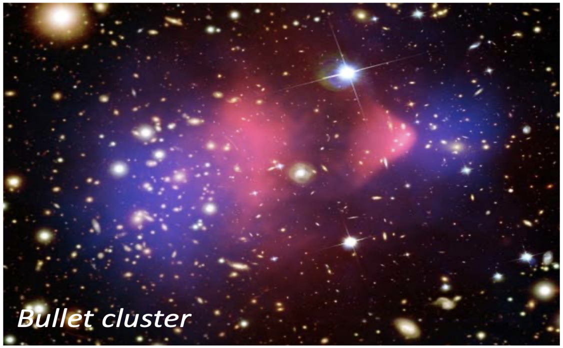
Interactions in the dark matter sector

$\sigma/m \sim [1, 10]\ \mathrm{cm}^2/\mathrm{g}$





$\sigma/m \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$



. *Kaplinghat, Tulin, Yu (PRL 2015)*

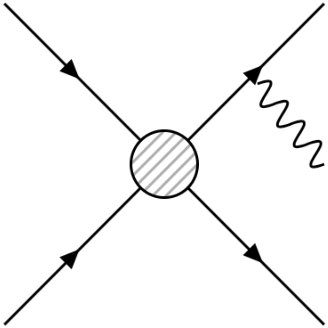
Favors a mild v-dependence

- Dwarfs
- LSBs
- Galaxy clusters

Boosted dark matter with new interactions?

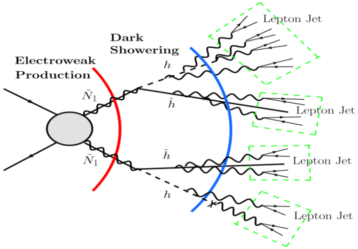
Dark matter shower at collider

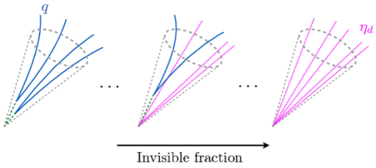
At the collider, if the dark matter is produced with energy much higher than the mass, the emission and split of dark matter and force mediator receive strong enhancement in the collinear direction. This will lead to high multiplicity dark jets.

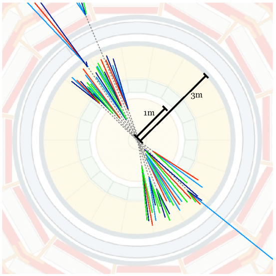


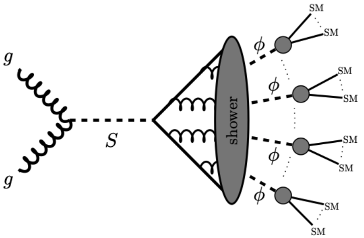
Dark jet signatures:

- lepton jet
- semi-visible
- emerging jets
- soft bomb









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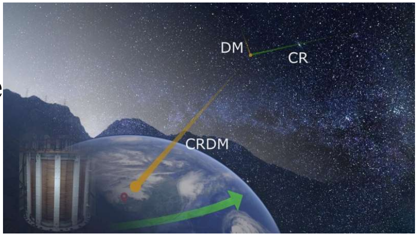
Boosted DM in direct detection

The halo DM in space can be kicked by cosmic rays to have relativistic speed, and probed by detector on ground



Electron-philic interaction:

$$\mathcal{L} \supset \epsilon \times g_{\rm em} A'_\mu \bar{e}\gamma^\mu e + g' A'_\mu \bar{\chi}\gamma^\mu \chi$$

The recoil flux of CR-induced DM (CRDM):

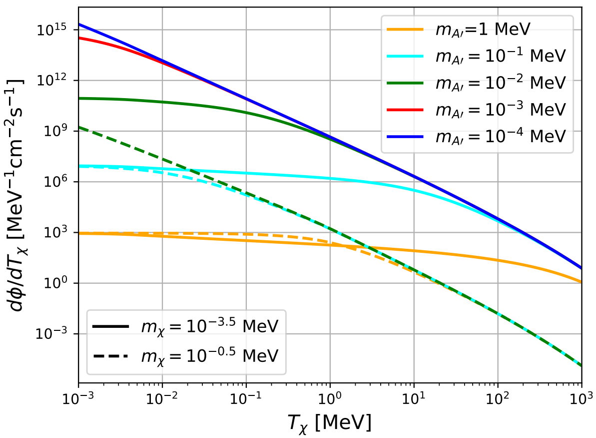
$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff} \frac{\rho_\chi^{\rm local}}{m_\chi} \int_{T_{\rm CR}^{\rm min}}^{\infty} dT_{\rm CR} \frac{d\Phi_e}{dT_{\rm CR}} \frac{d\sigma_{\chi e}}{dT_\chi}$$

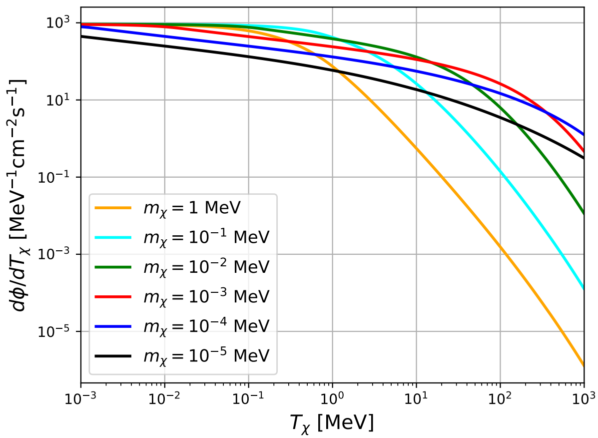
DM scattered by energetic cosmic ray (CR):

$$\frac{d\sigma_{\chi e}}{dT_\chi} = g'^2 \left(\epsilon g_{\rm em}\right)^2 \frac{2m_\chi \left(m_e + T_{\rm CR}\right)^2 - T_\chi \left(\left(m_e + m_\chi\right)^2 + 2m_\chi T_{\rm CR}\right) + m_\chi T_\chi^2}{4\pi \left(2m_e T_{\rm CR} + T_{\rm CR}^2\right) \left(2m_\chi T_\chi + m_A^2\right)^2}$$

CR boosted dark matter flux

Taking $g' = 1$, $\epsilon = 1$, $m_{A'} = 1$ MeV





- For light DM and low T_χ, the flux is proportional to $m_{A'}^{-4}$
- The differential flux is more flat for lighter DM and heavier dark photon, *i.e.*, higher fraction of high energy DM

The splitting functions for the dark sector

Interaction between Dirac fermion DM χ ($\bar{\chi}$) and dark photon A':

$$\mathcal{L} \supset g' A'_\mu \bar{\chi} \gamma^\mu \chi$$

Splitting function:

$$\frac{d\mathcal{P}_{A\to B+C}}{dz dk_T^2} \simeq \frac{1}{N} \frac{1}{16\pi^2} \frac{z\bar{z}\left|M_{\text{split}}\right|^2}{(k_T^2 + \bar{z}m_B^2 + zm_C^2 - z\bar{z}m_A^2)^2}$$

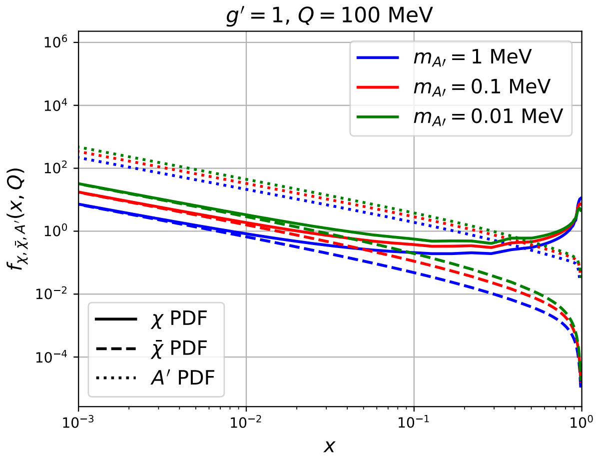
$A \to B + C$	$\frac{d\mathcal{P}_{A\to B+C}}{dzdk_T^2} = P_{A\to B+C}(z)$
$\chi/\bar{\chi} \to A'_T + \chi/\bar{\chi}$	$\frac{\alpha'}{2\pi} k_T^2 \frac{\frac{1+\bar{z}^2}{z} - \frac{\bar{z}}{z} \frac{2m_\chi^2 z^2 + m_{A'}^2\left(1+\bar{z}^2\right)}{k_T^2 + m_\chi^2 z^2 + m_{A'}^2 \bar{z}}}{k_T^2 + m_\chi^2 z^2 + m_{A'}^2 \bar{z}}$
$\chi/\bar{\chi} \to A'_L + \chi/\bar{\chi}$	$\frac{\alpha'}{\pi} k_T^2 \frac{m_{A'}^2 \bar{z}^2}{z\left(k_T^2 + m_\chi^2 z^2 + m_{A'}^2 \bar{z}\right)^2}$
$A'_T \to \bar{\chi}/\chi + \chi/\bar{\chi}$	$\frac{\alpha'}{2\pi} k_T^2 \frac{z^2 + \bar{z}^2 + \frac{z\bar{z}\left(2m_\chi^2 + m_{A'}^2\left(z^2+\bar{z}^2\right)\right)}{k_T^2 + m_\chi^2 - m_{A'}^2 z\bar{z}}}{k_T^2 + m_\chi^2 - m_{A'}^2 z\bar{z}}$
$A'_L \to \bar{\chi}/\chi + \chi/\bar{\chi}$	$\frac{2\alpha'}{\pi} k_T^2 \frac{m_{A'}^2 z^2 \bar{z}^2}{\left(k_T^2 + m_\chi^2 - m_{A'}^2 z\bar{z}\right)^2}$

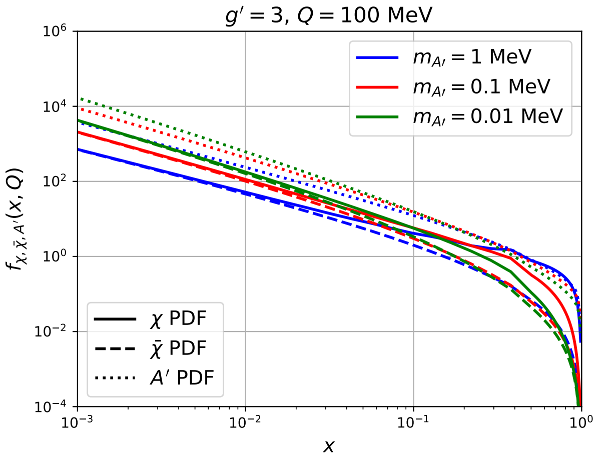
Table 1: Splitting functions involving χ, $\bar{\chi}$, and A'.

The DGLAP equations and DM PDF

DGLAP equations of PDFs:

$$\frac{df_i(k_T,x)}{d\ln k_T^2} = \sum_{m,n} N \int_x^1 \frac{dz}{z} P_{m\to i+n}(z) f_m\left(k_T, \frac{x}{z}\right) - \sum_{j,k} \int_0^1 dz P_{i\to j+k}(z) f_i(k_T,x)$$





- There are large fractions of $\bar{\chi}$ and A' in the DM PDF, for large g', small x and lighter A' ($m_\chi = 0.01$ MeV).
- Approaching the perturbative limit $g' = 3$, f_χ no longer has the peak around $x \sim 1$

CRDM signal at the neutrino detectors: higher energy threshold

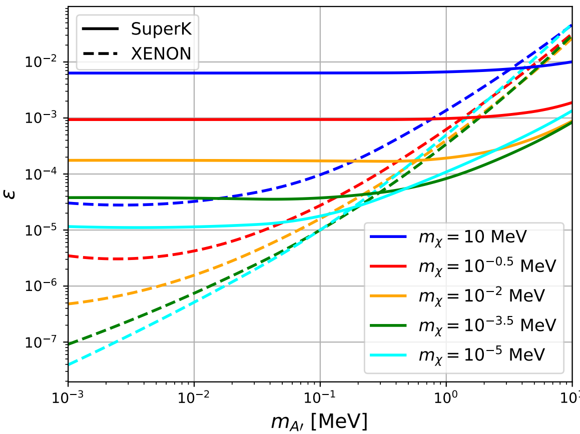
- Considering the DM PDFs becomes necessary as we primarily focus on a parameter region where the masses of DM and dark photon are significantly smaller than the typical energy scale of DM-electron scattering in neutrino detectors.
- The ionization rate:

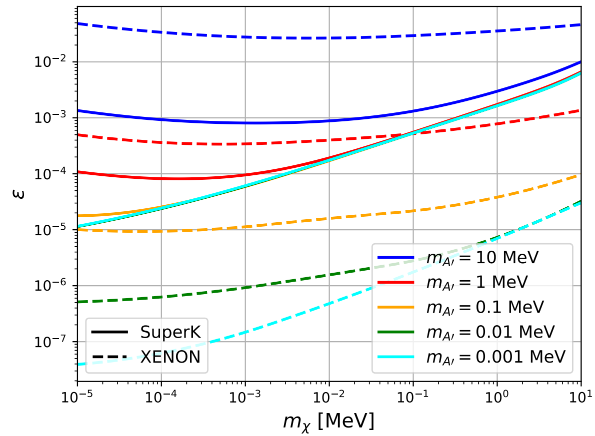
$$\frac{dR_{ion}}{d\ln T_R} = N_T^{SK} \sum_i \int dT_\chi^0 \int_0^{x_{\max}} dx \frac{d\sigma^i}{d\ln T_R} f_i(Q,x) \frac{d\phi_\chi}{dT_\chi^0} \Theta(xE_\chi^0 - E_i^{\min}) + N_T^{SK} \int dT_\chi \frac{d\sigma_\chi}{d\ln T_R} \frac{d\phi_\chi}{dT_\chi} \Theta(T_\chi - T_\chi^{\min}) \int_{x_{\max}}^1 f_\chi(Q,x)$$

- The index i in the PDF runs over χ, $\bar{\chi}$, and A', corresponding to the scattering processes $\chi + e^- \to \chi + e^-$, $\bar{\chi} + e^- \to \bar{\chi} + e^-$, and $A' + e^- \to \gamma + e^-$, respectively.

Electron scattering signal at the Super-K

- Using the Super-K 161.9 kiloton-year exposure data, the total measured number of events $N_{\rm sk}$ is 4042 in the bin $0.1 < T_e/\text{GeV} < 1.33$.
- We require the DM signal $\xi \times N_{\rm DM} < N_{\rm sk}$, with signal efficiency $\xi = 0.93$.
- $N_{\rm DM}$ is calculated by integrating $\frac{dR_{ion}}{dT_R}$ over the region $T_R > 100$ MeV, with total number of electrons inside the Super-K detector $N_e = 7.5 \times 10^{33}$ and data-taking period of 2628.1 days.





The dark photon signal: dark Compton scattering

Dark Compton scattering:

$$A' + e^- \to \gamma + e^-$$

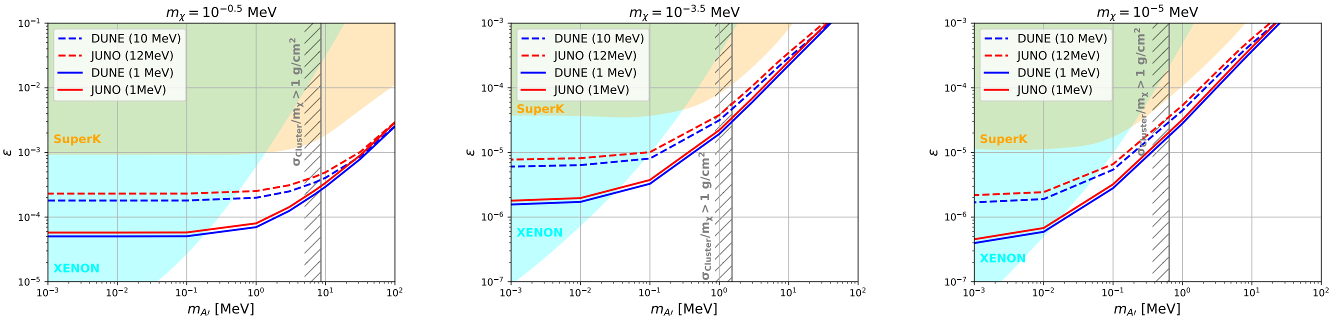
The corresponding recoil rate:

$$\frac{dR}{d\ln E_\gamma} = N_T^{SK} \int dT_\chi^0 \int_0^{x_{\max}} dx \frac{d\sigma^{A'}}{d\ln E_\gamma} f_{A'}(Q,x) \frac{d\phi_\chi}{dT_\chi^0} \times \Theta(xE_\chi^0 - E_{A'\gamma}^{\min})\Theta(E_{A'\gamma}^{\max} - xE_\chi^0)$$

The Super-K is a water-based Cherenkov detector in which the Cherenkov rings produced by photons and electrons exhibit similarities. It is challenging to distinguish a mono-energetic photon with a threshold of $\mathcal{O}(1) \sim \mathcal{O}(10)$ MeV.

Detecting the dark photon at DUNE and JUNO

- The DUNE and JUNO detectors possess high-efficiency photon identification capabilities.
- In these detectors, an energetic single photon signal can be considered background-free
- For DUNE detector, the sensitivity reach with active LAr of 40 kilotons, which corresponds to 1.085×10^{34} electrons inside the detector.
- The JUNO experiment will be equipped with liquid scintillator detector with fiducial mass of 20 kilotons, total number of electrons is 6.314×10^{33}.



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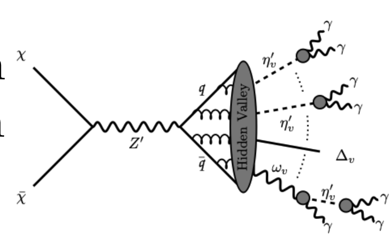
Dark matter splitting in indirect detection

DM annihilation through a hidden Z' to hidden quark, followed by shower to hidden meson, can explain the Galactic Centre Excess



A heavy component of relic DM annihilates into a lighter DM species, giving boosted DM.

- We introduce a hidden local $U(1)_H$ symmetry and SM singlet field contents

$$\text{Dirac fermions: } \chi\ (Q_\chi),\ \psi(Q_\psi), \quad \text{Scalar: } \varphi(2)\ ,$$

  requiring $|Q_\chi| \neq |Q_\psi|$, $|2Q_\chi| \neq 2$, $|2Q_\psi| \neq 2$ and $|Q_\chi \pm Q_\psi| \neq 2$.
- The relevant Lagrangian for the Dirac fermions is

$$\mathcal{L} = \bar{\chi}(i\not{D} - m_\chi)\chi + \bar{\psi}(i\not{D} - m_\psi)\psi,$$

  where $D_\mu\chi(\psi) = (\partial_\mu + iQ_{\chi(\psi)}g_H Z'_\mu)\chi(\psi)$ is the covariant derivative with g_H being gauge coupling of $U(1)_H$.

Dark matter phenomenology

- Assume $m_\chi > m_\psi$ and $g_{Z'\psi\psi} > g_{Z'\chi\chi}$,
- Relic density of χ is dominantly determined by annihilation cross section of $\bar{\chi}\chi \to Z' \to \bar{\psi}\psi$
- Relic density of ψ is small, $\psi\psi \to Z'Z'$

$$\Omega h_V^2 \sim (0.05) \left(\frac{1.0}{g_{Z'\psi\psi}}\right)^2 \left(\frac{0.01}{g_{Z'\chi\chi}}\right)^2 \left(\frac{m_\chi}{20 \text{ GeV}}\right)^2,$$

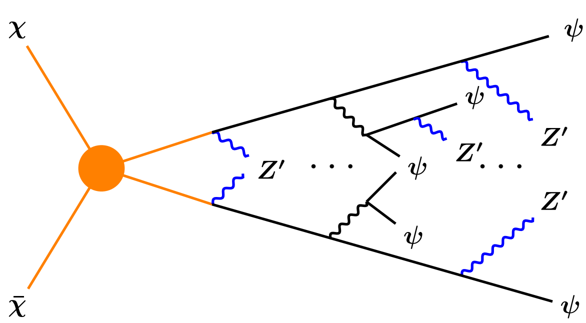
m_χ [GeV]	100	10	1000	10	1000
m_ψ [GeV]	1	1	1	0.1	10
$m_{Z'}$	0.5	0.5	0.5	0.05	5
$g_{Z'\chi\chi}$	0.029	0.003	0.3	0.003	0.3
α_D	0.2	0.2	0.2	0.2	0.2
Ω_χ	0.111	0.115	0.101	0.115	0.101
Ω_ψ	$2 \cdot 10^{-7}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-6}$

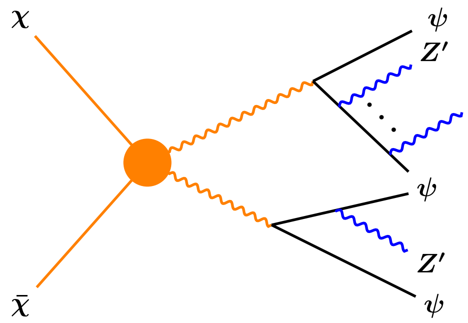
The splitting function

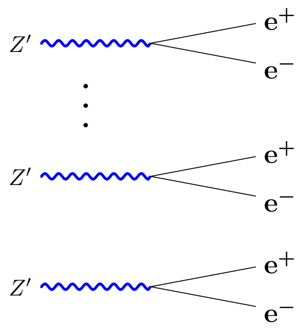
$$\frac{d\mathcal{P}_{a\to b+c}}{dzd\ln Q^2} \approx \frac{1}{N}\frac{1}{16\pi^2}\frac{Q^2}{\left(Q^2-m_a^2\right)^2}\left|M_{\rm split}\ \right|^2\ ,$$

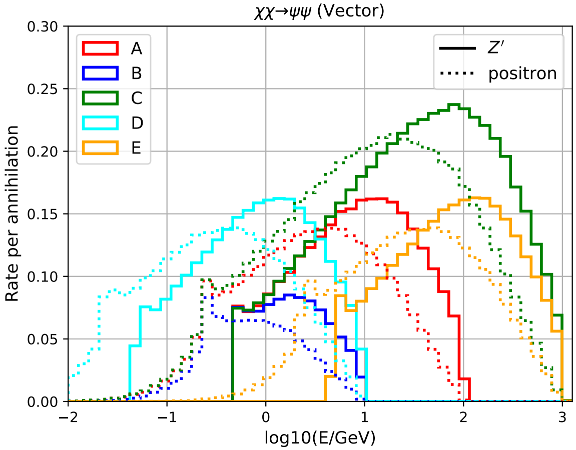
Process	$\lambda_a(\lambda_b),\ \lambda_c$	$\left\|M_{\rm split}\right\|^2$
$Z'_{\rm T}\to\psi+\bar{\psi}$	$\lambda_b=\lambda_c$	$2g^2_{Z'\psi\psi}\frac{m_\psi^2}{z(1-z)}$
$Z'_{\rm T}\to\psi+\bar{\psi}$	$\lambda_b=-\lambda_c$	$2g^2_{Z'\psi\psi}\left(z^2+(1-z)^2\right)\left(Q^2-\frac{m_\psi^2}{z(1-z)}\right)$
$Z'_{\rm L}\to\psi+\bar{\psi}$	$\lambda_b=\lambda_c$	0
$Z'_{\rm L}\to\psi+\bar{\psi}$	$\lambda_b=-\lambda_c$	$8g^2_{Z'\psi\psi}m^2_{Z'}z(1-z)$
$\psi/\bar{\psi}\to Z'_{\rm T}+\psi/\bar{\psi}$	$\lambda_a=\lambda_c$	$2g^2_{Z'\psi\psi}\frac{\left(1+(1-z)^2\right)}{z}\left(Q^2-\frac{\left(m^2_{Z'}(1-z)+m^2_\psi z\right)}{z(1-z)}\right)$
$\psi/\bar{\psi}\to Z'_{\rm T}+\psi/\bar{\psi}$	$\lambda_a=-\lambda_c$	$2g^2_{Z'\psi\psi}\frac{m_\psi^2z^2}{1-z}$
$\psi/\bar{\psi}\to Z'_{\rm L}+\psi/\bar{\psi}$	$\lambda_a=\lambda_c$	$4g^2_{Z'\psi\psi}\frac{m^2_{Z'}(1-z)}{z^2}$
$\psi/\bar{\psi}\to Z'_{\rm L}+\psi/\bar{\psi}$	$\lambda_a=-\lambda_c$	0

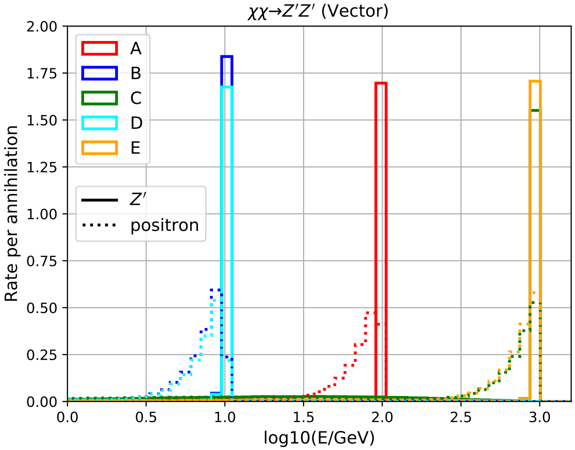
Radiated dark photon in the indirect detection











Event rate at the AMS detector

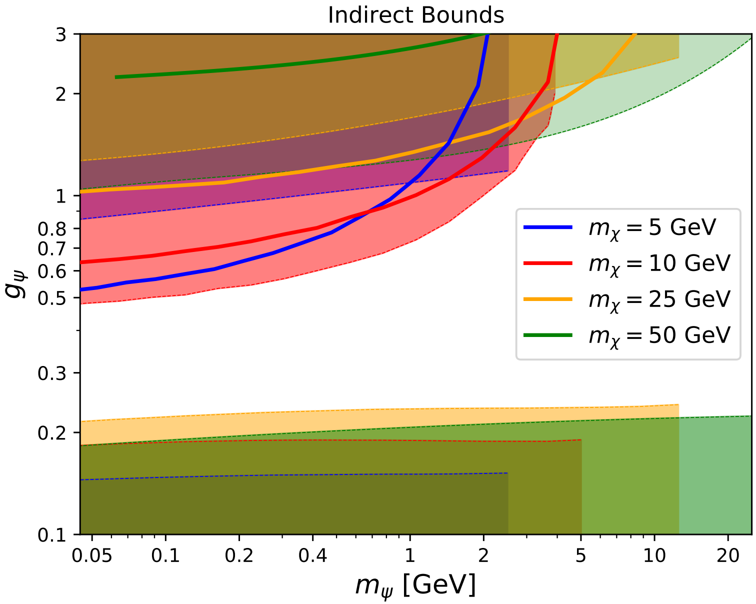
- The differential flux of positron at the location of the earth can be calculated by convoluting the spectra at production with the propagation functions:

$$\frac{d\Phi_{e^+}}{dE_{e^+}}(E) = \frac{v_{e^+}}{4\pi b(E, r_{\rm sun})} \frac{1}{\eta} \left(\frac{\rho(r_{\rm sun})}{m_\chi} \right)^2 \times \sum_{f=\psi,Z'} \langle \sigma v \rangle_f \int_E^{m_\chi} dE_{\rm s} \frac{dN^f_{e^+}}{dE}(E_{\rm s})\, I\left(E, E_{\rm s}, r_{\rm sun}\right)$$

- Thermal averaged annihilation cross sections for the vector portal model are given by

$$\langle \sigma v \rangle_f = \begin{cases} g^4_{Z'\chi\chi} \frac{(m_\chi^2 - m_{Z'}^2)^{3/2}}{4\pi m_\chi (m_{Z'}^2 - 2m_\chi^2)^2} & \chi\chi \to Z'Z' \\ g^2_{Z'\chi\chi} g^2_{Z'\psi\psi} \frac{\sqrt{m_\chi^2 - m_\psi^2}(2m_\chi^2 + m_\psi^2)}{2\pi m_\chi (m_{Z'}^2 - 4m_\chi^2)^2} & \chi\chi \to \psi\psi \end{cases} .$$

The AMS-02 positron bounds



- Assume positron flux from AMS-02 measurement arises solely from the astrophysical backgrounds and fitted with degree 6 polynomial
- Fit DM-induced flux allowing the parameters to float within 30% around the best fit
- 95% C.L. limit obtained by $\Delta\chi^2 = 2.71$

- Upper exclusion regions are induced by the dark showers subsequent to $\chi\chi \to \psi\psi$, larger mass splitting between the χ and ψ can lead to stronger dark showering effects, *i.e.* stronger bound.
- Lower exclusion regions are induced by $\chi\chi \to Z'Z'$, small g_ψ means larger g_χ

Conclusion

- Boosted DM exists in DM collider search, direct detection, and indirect detection.
- The PDF effects in CRDM detection can be significant. The collinear splitting induces dark Compton scattering, the mono-photon signal can possibly be probed at DUNE and JUNO.
- In a two-component DM model with large mass splitting, the dark photon produced from dark shower of the boosted DM can be probed in the AMS-02.


Thank you!
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