Probing ultra-light dark photon dark matter from inverse Compton-like scattering

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Main structure

- The aim:
  Obtain experimental predictions for features of dark photon dark matter in the spectrum of X-rays generated by inverse Compton-like scattering.
- The not so-ancient tale:
  Cosmic-ray boosted dark matter, See Yu-Feng Zhou's talk
  The ultra-light dark matter, See Tianjun Li's talk
  X-ray experiments, See Ng's talk

Are there something new in our work?

Yes, I hope to make it clear after this talk

Dark Photon Dark Matter: Brief Review

Dark Photon Definition

- An additional abelian gauge group $U(1)_D$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)_D \quad \text{with Vector } V_\mu$$

- Two (or Four) new parameters: (κ, m_V)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V^\mu V_\mu - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + eJ_{\mathrm{em}}^\mu A_\mu$$

Stueckelberg case

$$\mathcal{L} \supset -\frac{1}{2}m_V V_\mu^2$$

"hard photon mass"

Higgsed case

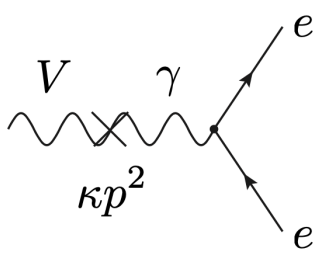
$$\mathcal{L} \supset -\frac{1}{2}m_V V_\mu^2 + e' m_V h' V_\mu^2 + \frac{1}{2}e'^2\, h'^2 V_\mu^2$$

+ h' self-interactions

Kinetic Mixing

Two ways to think about kinetic mixing

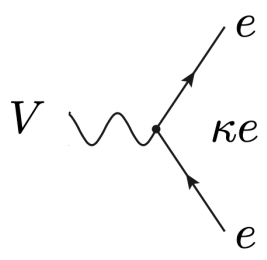
Keep the mixing:



$$eA_\mu J^\mu_{EM}$$

Photon-Dark Photon mixing manifest

Or diagonalize kinetic term:



$$eA'_\mu J^\mu_{EM} - \kappa e V'_\mu J^\mu_{EM}$$

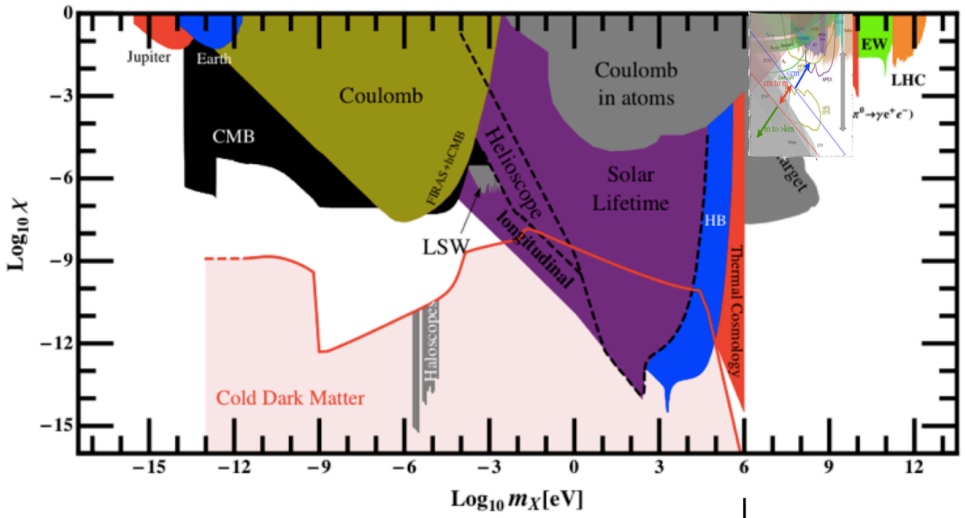
Ordinary matter has milli-charge under new force

When photon gets effective mass from medium, the oscillation can not be removed by diagonalization

Can we make Dark Photon Dark Matter?

Stability and Production

1. Make it light, below $2m_e$. Prevents $V \to e^+e^-$ decay



Dark Photon becomes a dark matter candidate

Decays to leptons (and hadrons)

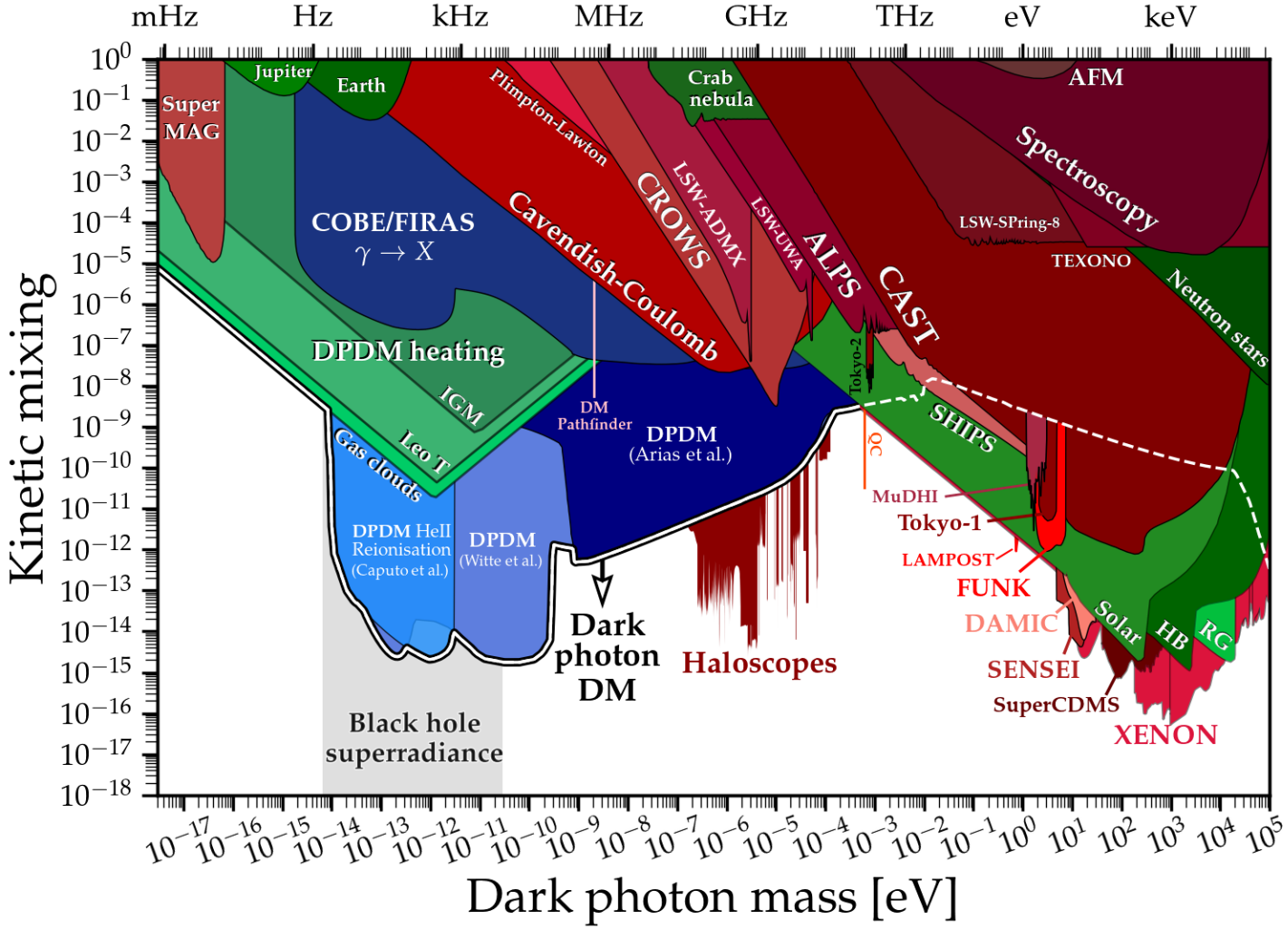
(Fig. from Jaeckel 2013)

2. Have small κ, to slow down $V \to 3\gamma$. From now on, we change κ to be ϵ

Existing Constraints for Dark Photon

From https://cajohare.github.io/AxionLimits/

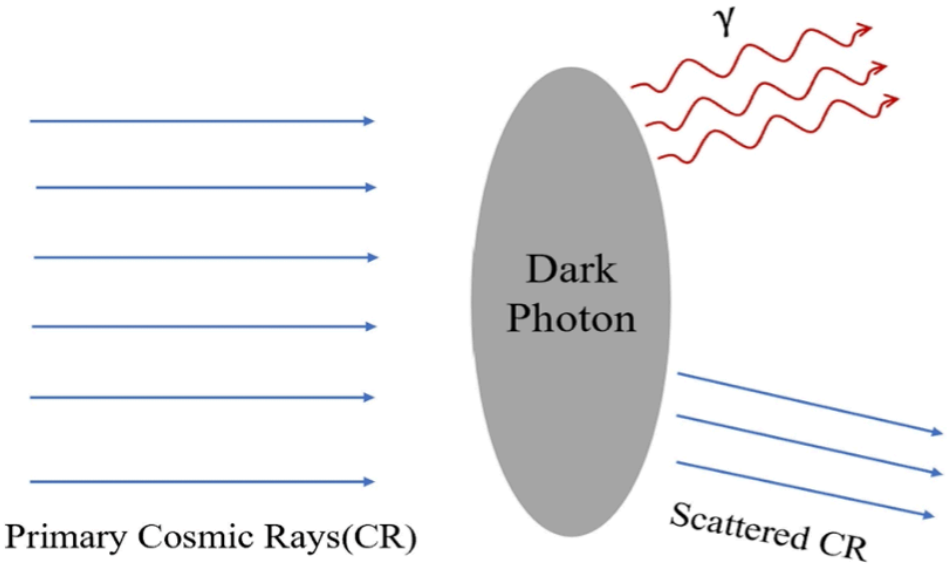
Green = Astrophysics, Blue = Cosmology, Red = Experiment



Cosmic-ray boosted dark photon

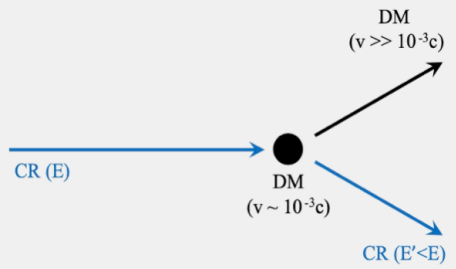
A Direct method :Inverse Compton-like Scattering

$$\gamma'(p_1) + p(p_2) \to \gamma(k_1) + p(k_2)$$

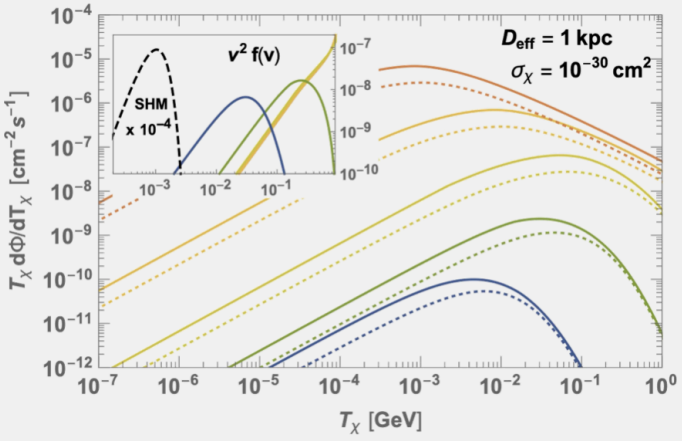


Focus on gamma → X-ray experiment; Focus on the proton → Reverse Direct Detection

Concept of CR acceleration



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



Ordinary DM

- $\langle v \rangle \sim 220\mathrm{km/s}$
- bounded by the Galactic escape velocity

Cosmic-ray DM

- NOT bounded by the Galactic escape velocity
- Even small flux

Why do we favor the cosmic-ray scattering experiment?

Kinematical Reason

The minimum energy of the CRs proton

$$E_p^{\min} = \frac{\omega - m_V}{2} + \frac{\sqrt{m_V \omega^2 \left(m_V - 2\omega\right)\left(m_V^2 - 2m_V\omega - 4m_p^2\right)}}{2m_V\left(2\omega - m_V\right)}$$
$$\simeq \omega/2 + m_p\sqrt{\omega/2m_V}$$

We need very high energy cosmic rays to probe ultra-light dark photon!

Why can we probe the ultra-light dark photon?

Dynamical Reason

The differential cross-section of inverse compton scattering is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \frac{1}{32\pi m_V \left|\vec{p}_2\right|^2} \left(\frac{1}{6}\sum \left|\mathcal{M}\right|^2\right)$$

- $\left|\mathcal{M}\right|^2 \sim 16e^4\epsilon^2 + \mathcal{O}\left(m_V\right)$ for dark photon
- $\left|\mathcal{M}\right|^2 \sim 8\omega^2 m_a^2 / \left(m_p^2 - s\right)^2 + \mathcal{O}\left(m_a^3\right)$

$1/m_V$ enhancement is the reason

The difference comes from the dark photon polarization.

Computational Framework

Photon Flux

$$\frac{\mathrm{d}\Phi}{\mathrm{d}\omega\mathrm{d}\Omega} = \frac{D}{m_V}\int_{E_p^{\min}(\omega)} \mathrm{d}E_p \frac{\mathrm{d}\sigma}{\mathrm{d}\omega}\frac{\mathrm{d}\Phi_p}{\mathrm{d}E_p}$$

- D depends on the DM density distribution.

$$D(\phi) = \int_{l.o.s} \mathrm{d}l\rho_{\mathrm{DM}}(r(l,R,\phi))$$

- $d\sigma/d\omega$ is the differential cross section of inverse compton scattering
- $\mathrm{d}\Phi_p/\mathrm{d}E_p$ is the incoming high energy protons

High-energy Cosmic Rays Spectrum below GZK limit

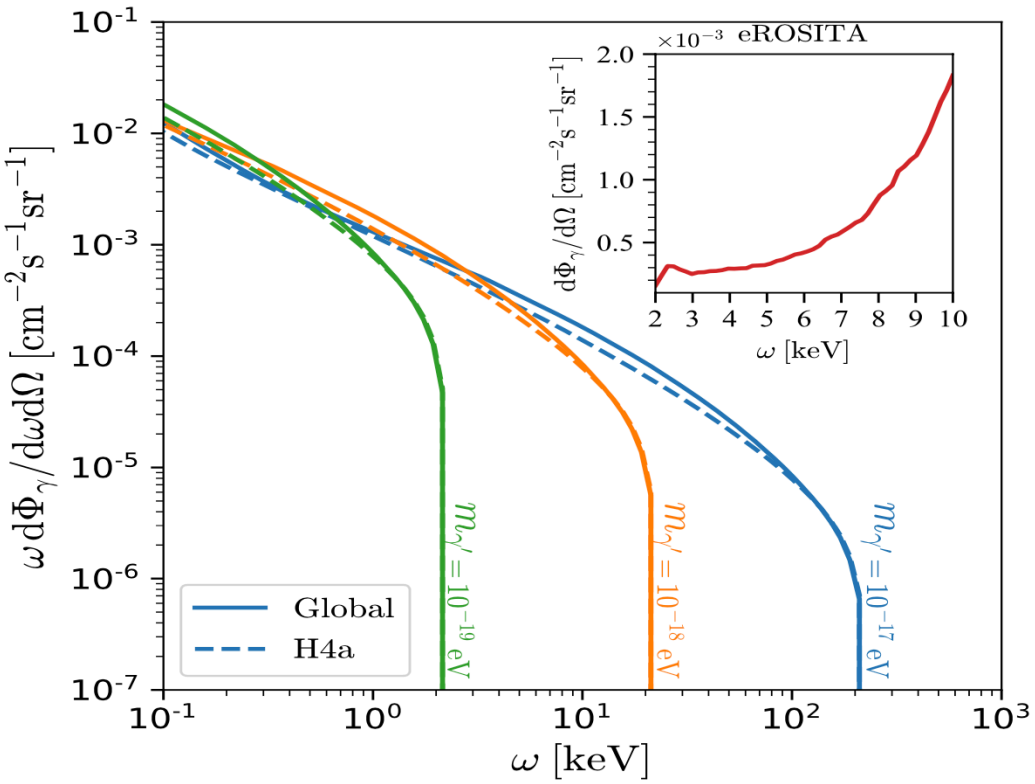
Chen Xia, Yan-Hao Xu, Yu-Feng Zhou[arxiv:2009.00353]

$$\frac{\mathrm{d}\Phi_{\mathrm{p}}}{\mathrm{d}E_p} = \sum_{i=1}^{4} c_i E_p^{-\alpha_i} \exp\left(-\frac{E_p}{R_i}\right)$$

Global-Fit4	R_1 (120 TeV)	R_2 (4 PeV)	R_3 (1.5 EeV)	R_4 (40 EeV)
c_i	7000	150	12	1.2
α_i	2.66	2.4	2.4	2.4
H4a	R_1 (4 PeV)	R_2 (30 PeV)	R_3 (60 EeV)	
c_i	7860	20	200	
α_i	2.66	2.4	2.6	

Resulting Photon flux

$D = 10^{22}\mathrm{GeV/cm^2}$ and $\epsilon = 0.1$



eROSITA

an abbreviation for extended Roentgen Survey with an Imaging Telescope Array. It is an X-ray telescope and together with the Russian Astronomical Roentgen Telescope–X-ray Concentrator (ART-XC) it is launched in Spring on 13 July 2019 from Baikonur Kazakhstan, aboard the Russian Spektrum- Roentgen-Gamma satellite

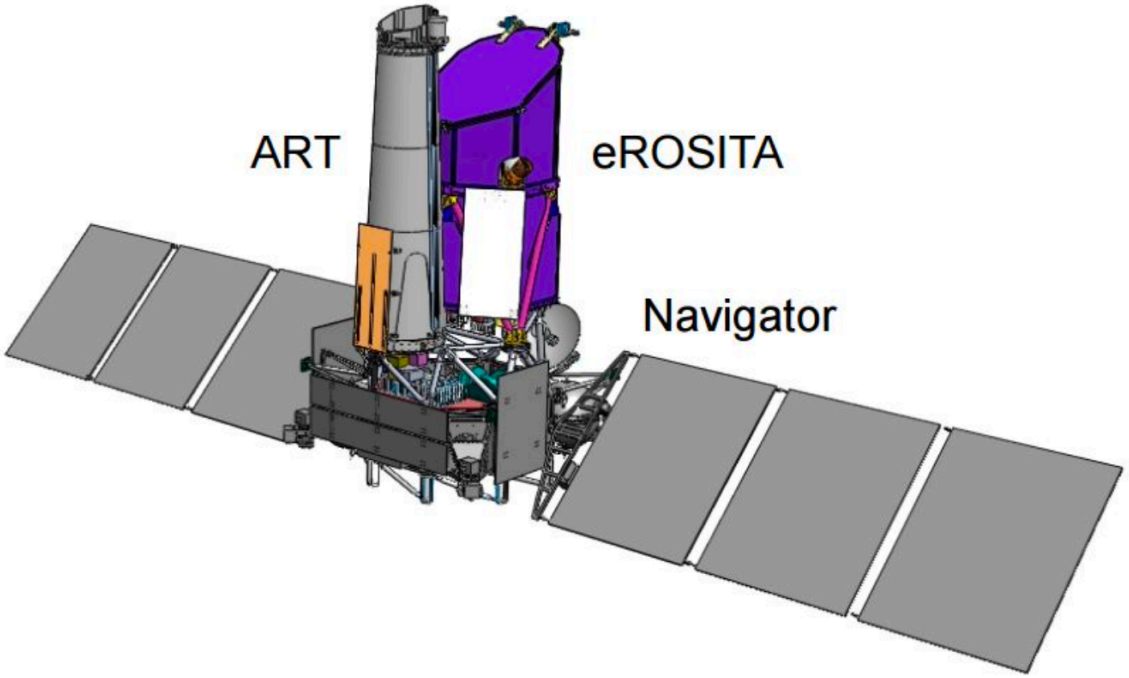


Figure 1.1.: SRG with ART-XT and eROSITA on its Navigator platform (taken from Predehl, 2010)

Goal of eROSITA

Main Goal: To build a map of the brightest X-ray sources on the sky

- Find all the galaxy clusters emitting X-rays $\rightarrow$ probe dark energy
- Active Galactic Nuclei $\rightarrow$ one more population to investigate BAO
- Search for new sources of X-rays $\rightarrow$ probe dark matter

Natural instrument for dark photon

sensitive energy range is $[0.2, 10]\mathrm{keV}$

How to simulate the signal of eROSITA?

https://erosita.mpe.mpg.de/

The procedure follows Kenny Ng's paper arxiv:2103.13241.

- Signal: the expected numbers of photon

$$N(l,b) = T \int_{\Delta E} \mathrm{d}E A_{\text{eff}}(E) \int dE' P(E,E') \int_{\Delta\Omega} \mathrm{d}\Omega \frac{\mathrm{d}\Phi}{\mathrm{d}E'\mathrm{d}\Omega}$$

- Diffuse Cosmic X-ray Background(CXB)

$$\Phi_{\mathrm{CXB}} = 8.44 \cdot \left(\frac{\omega}{1\mathrm{keV}}\right)^{-1.42} \mathrm{cts/cm^2/s/sr/keV}$$

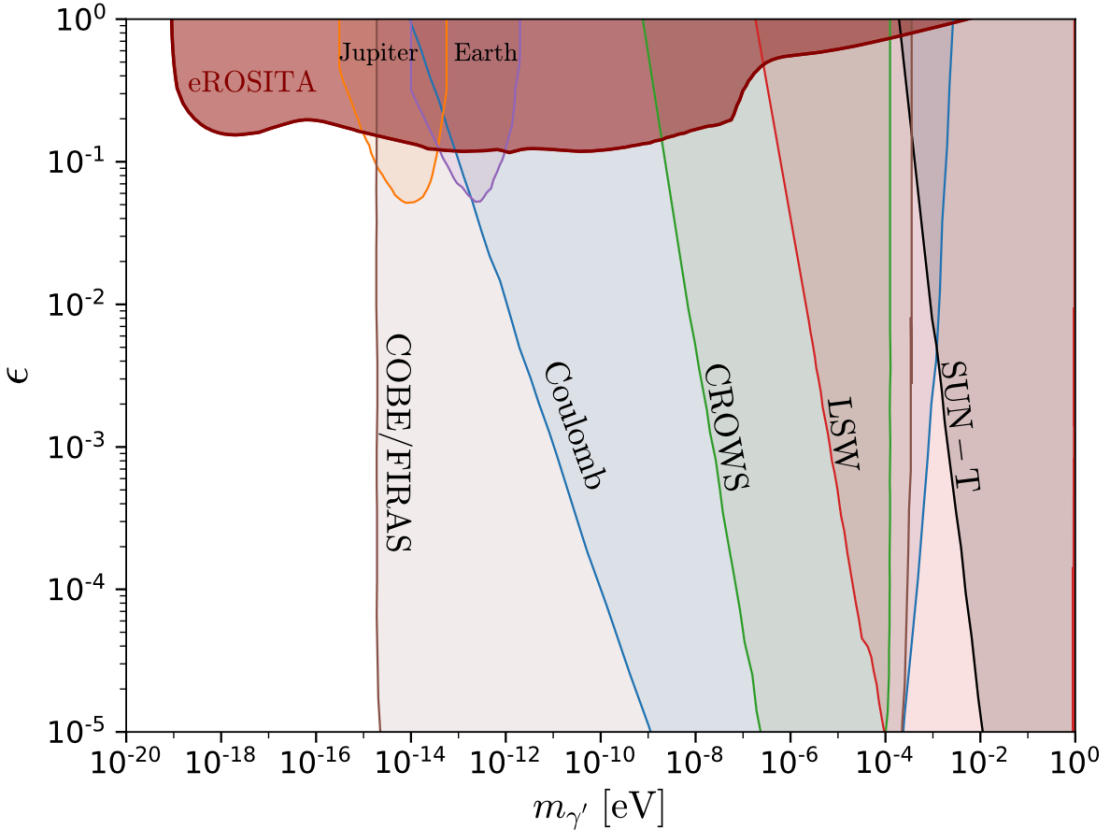
- The Detector Background

$$\Phi_{\mathrm{DB}} = 1151\mathrm{cts/s/sr/keV}$$

- Analysis: likelihood

$$\mathcal{L}(\Gamma) = \prod_i P\left[n_i \mid \mu_i(\Gamma)\right] = \prod_i \frac{\mu_i(\Gamma)^{n_i} e^{-\mu_i(\Gamma)}}{n_i!}$$

Results



Advantage: wide mass range from 10^{-6}eV to 10^{-19}eV
Problems: not-good sensitivity because of the low flux of high energy cosmic-rays

Conclusion and Outlook

Conclusion

- Ultra-high energy cosmic rays help us probe Ultra-light dark photon
- The polarization of the dark photon contributes $1/m_V$ enhancement to maintain the sensitivity
- eROSITA is a natural target to capture the keV X-rays.

Outlook

- The directional information might improve the limit
- We do not include the Bose enhancement for the dark photon

Back up