Gravitational Production of Hidden Photon Dark Matter and XENON1T Excess

Yong Tang (汤勇)

University of Chinese Academy of Sciences (UCAS)

Low Energy Recoils from Deep Underground

Peking University, Sep 26, 2020

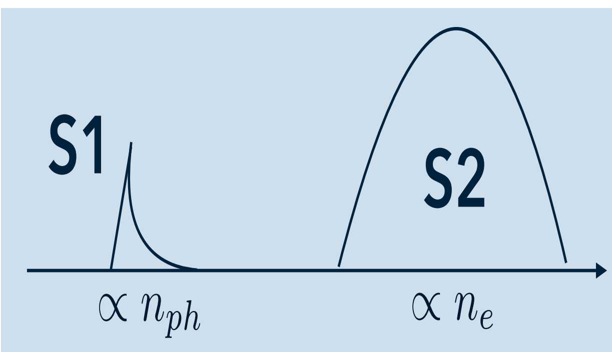
Based on *Nakayama, Tang*, arXiv:**2006.13159**

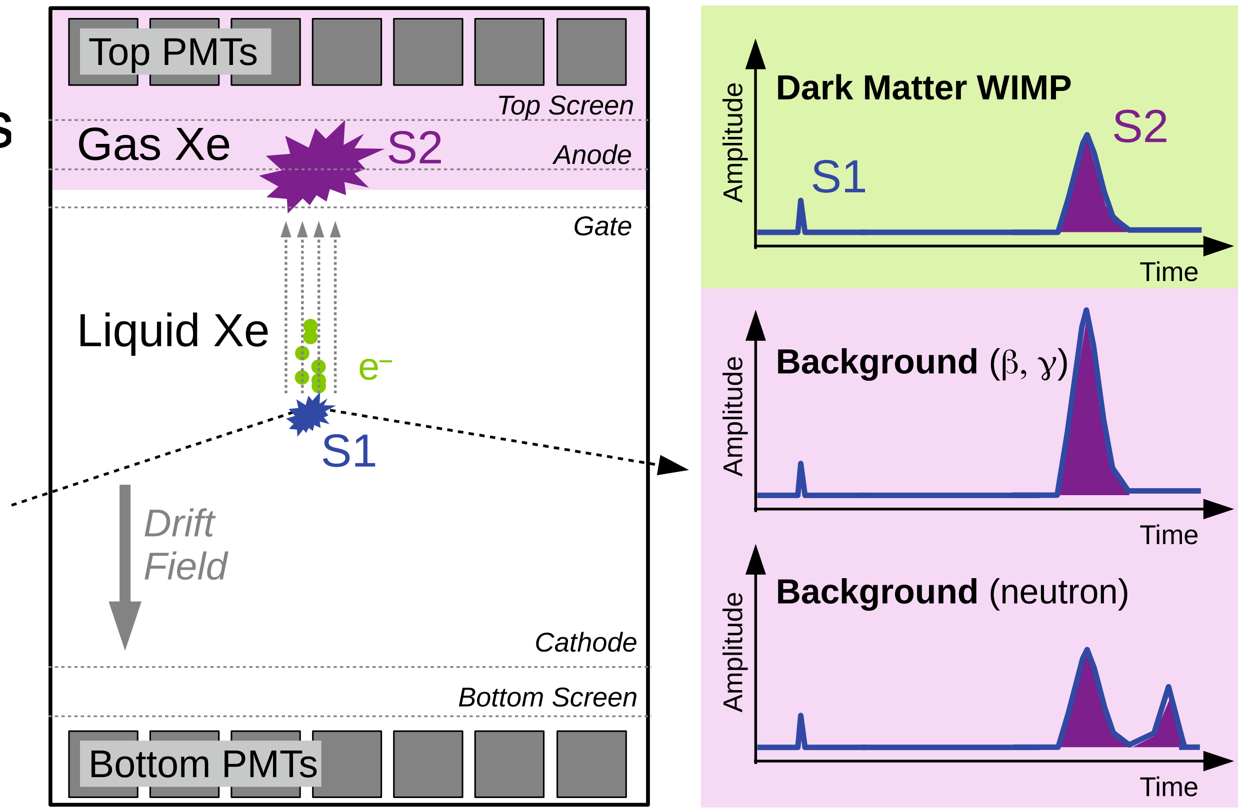
Contents

- Introduction
- Hidden Photon
- Production
  - Thermal Production
  - Gravitational Production
- A model
- Summary

Introduction

- XENON1T dark matter experiment
- Dual-phase with a liquid xenon (LXe) target
- S1, prompt scintillation light
- S2, delayed signal, induced by electrons

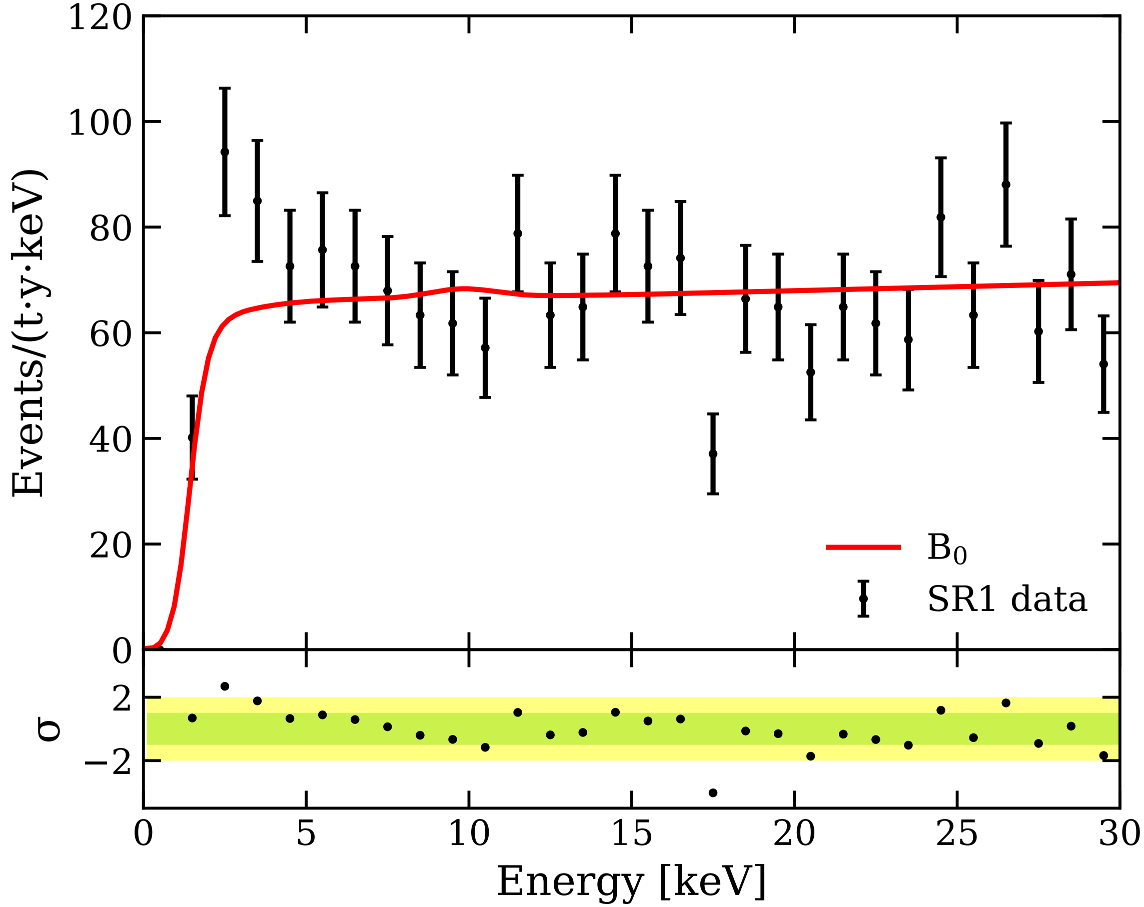




- Electron recoil (ER)
- Nuclear recoil (NR)

Introduction

- XENON1T, arXiv:2006.09721, "*Observation of Excess Electronic Recoil Events in XENON1T*"
- Interpretations
  - Tritium
  - Solar axion
  - Bosonic DM
  - DM
  - ……



Hidden Photon

- Also called dark photon A_μ

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2 A_\mu A^\mu + \frac{\epsilon}{2}F_{\mu\nu}\gamma^{\mu\nu} - \frac{1}{4}\gamma_{\mu\nu}\gamma^{\mu\nu}$$

$$\overline{\gamma}_\mu = \gamma_\mu - \epsilon A_\mu, \overline{A}_\mu = \sqrt{1-\epsilon^2}A_\mu, \overline{m} = \frac{m}{\sqrt{1-\epsilon^2}}$$

- We have

$$\mathcal{L} = -\frac{1}{4}\overline{F}_{\mu\nu}\overline{F}^{\mu\nu} - \frac{1}{2}\overline{m}^2\overline{A}_\mu\overline{A}^\mu - \frac{1}{4}\overline{\gamma}_{\mu\nu}\overline{\gamma}^{\mu\nu}$$

- Because of the kinetic mixing,

$$\epsilon e\overline{A}_\mu\bar{\psi}\boldsymbol{\gamma}^\mu\psi$$

- hidden photon can couple to charged fermions in the standard model.

Absorption of Hidden photon

- ~ 2.7 keV hidden photon
- DM candidate
- monoenergetic peak
- photoelectric effect
    - Cross section

$$\sigma_V \simeq \frac{\sigma_{\rm pe}}{\beta}\epsilon^2$$

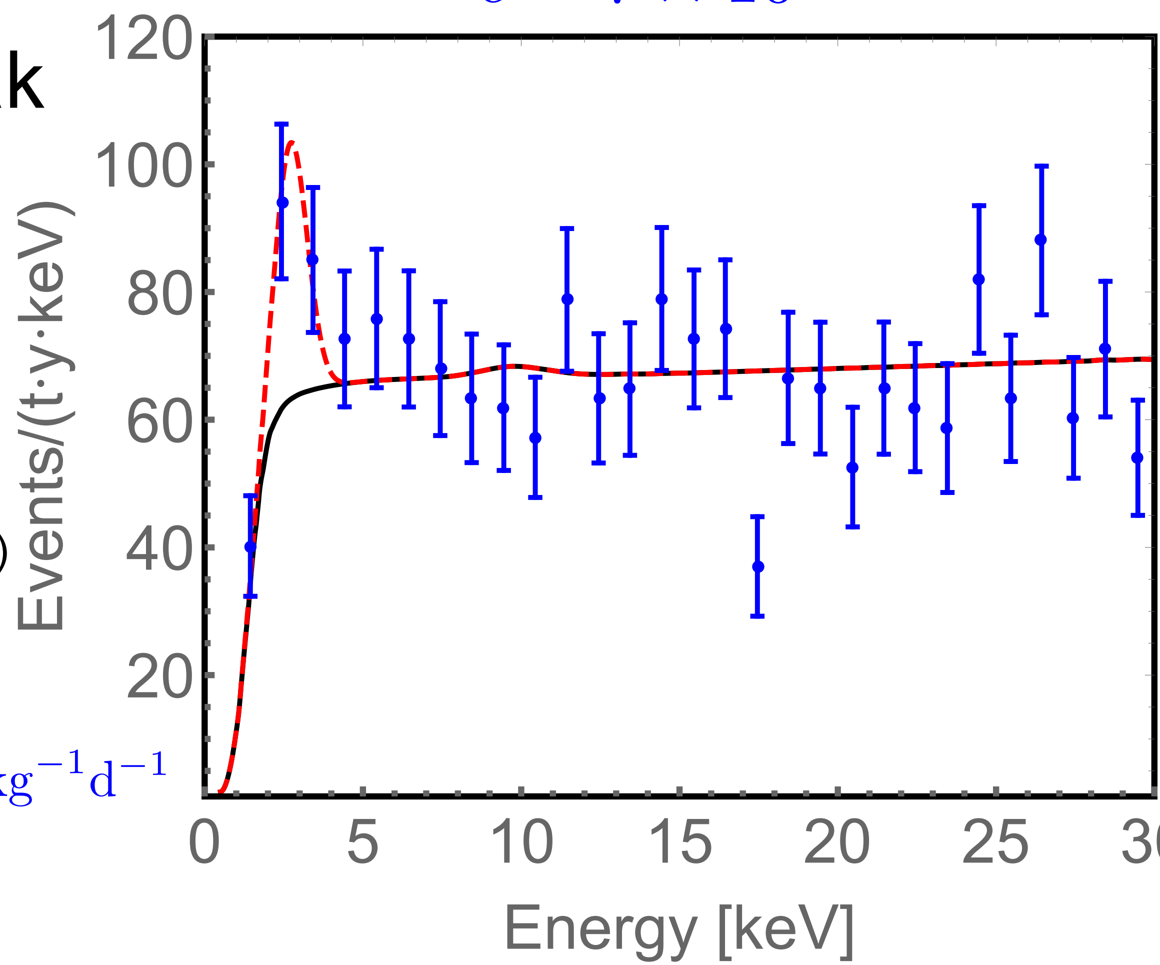
An, Pospelov, Pradler&Ritz, PLB(2015)

    - Event rate

$$R \simeq \frac{4.7\times 10^{23}}{A}\epsilon^2\left(\frac{\rm keV}{m}\right)\left(\frac{\sigma_{\rm pe}}{\rm b}\right){\rm kg^{-1}d^{-1}}$$

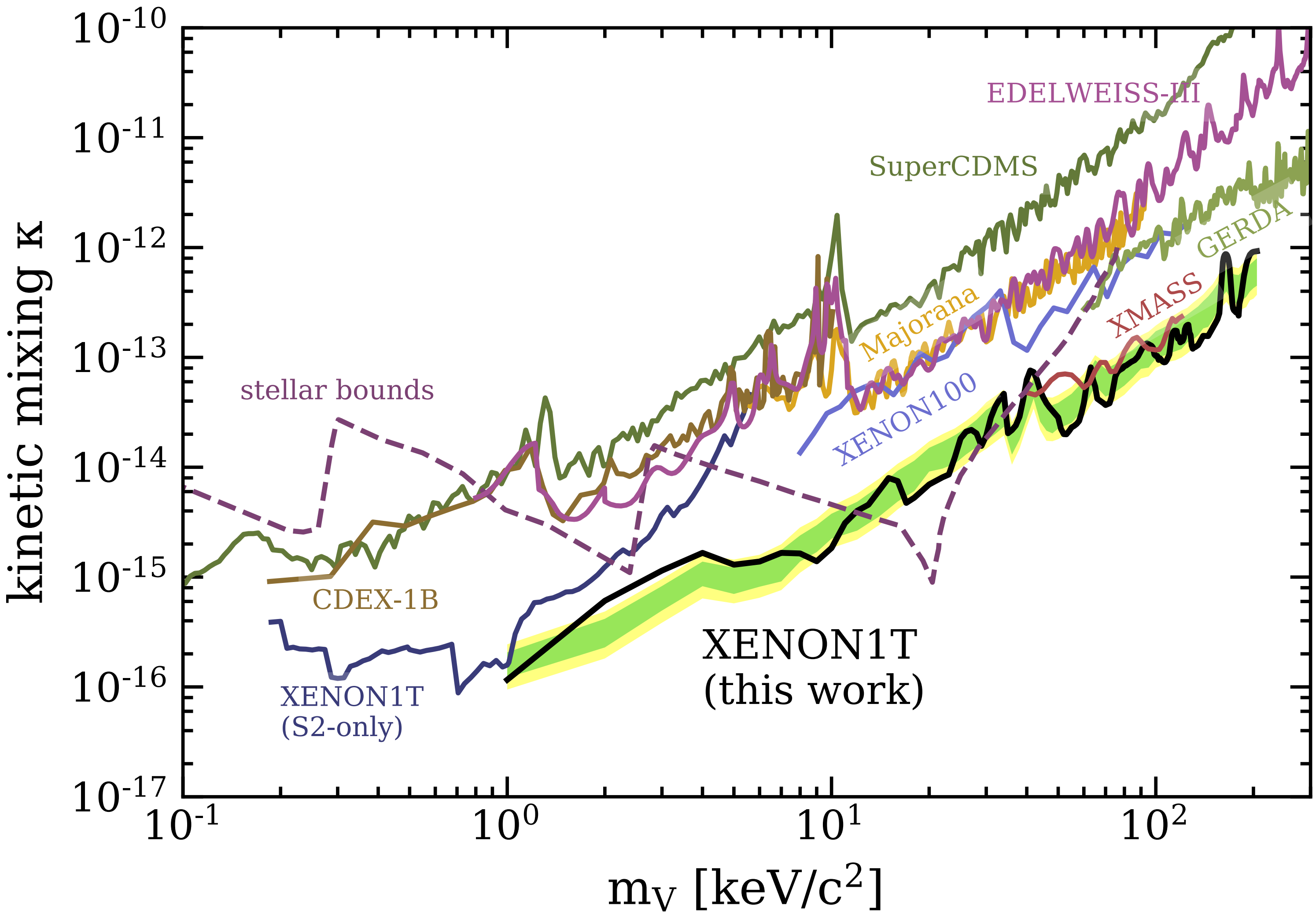
A~131u, average atomic mass

$\epsilon \simeq 7\times 10^{-16}$



Constraints

- $\kappa \equiv \epsilon \simeq 7 \times 10^{-16}$ is allowed



Production

- A viable production of keV DM is not trivial,
- Astrophysical constraints are very strong for keV DM produced from thermal plasma, Lyman-α gives the lower bound, $m > 5.3$ keV **(1911.09073)**
- Non-thermal production is needed.
- Since gravitational interaction is universal and unavoidable, it would be reasonable to consider how it can affect the production.
- We shall mainly discuss the production during inflation era where the contribution is usually the dominant part.

Formalism

- We start with the following Lagrangian

$$S=\int d^4x\sqrt{-g}\left[-\frac{1}{4}g^{\mu\rho}g^{\nu\sigma}F_{\mu\nu}F_{\rho\sigma}-\frac{1}{2}m^2g^{\mu\nu}A_\mu A_\nu\right],$$

- In Friedmann-Robertson-Walker background

$$ds^2=-dt^2+a^2(t)\delta_{ij}dx^idx^j=a^2(\tau)\left(-d\tau^2+\delta_{ij}dx^idx^j\right)$$

- Rewrite Lagrangian as

$$S=\int d\tau d^3x\left[-\frac{1}{4}\eta^{\mu\rho}\eta^{\nu\sigma}F_{\mu\nu}F_{\rho\sigma}-\frac{1}{2}a^2m^2\eta^{\mu\nu}A_\mu A_\nu\right].$$

- The kinetic mixing has negligible effects on the production in the relevant parameter range.

Formalism

- Working in Fourier space

$$A_\mu(\vec{x},t) = \int \frac{d^3k}{(2\pi)^3} A_\mu(\vec{k},t) e^{i\vec{k}\cdot\vec{x}}.$$

- The action is

$$S = S_T + S_L,$$

$$S_T = \int \frac{d^3k d\tau}{(2\pi)^3} \frac{1}{2} \left(|\partial_\tau \vec{A}_T|^2 - (k^2 + a^2 m^2)|\vec{A}_T|^2 \right),$$

$$S_L = \int \frac{d^3k d\tau}{(2\pi)^3} \frac{1}{2} \left(\frac{a^2 m^2}{k^2 + a^2 m^2} |\partial_\tau A_L|^2 - a^2 m^2 |A_L|^2 \right).$$

- 2 transverse + 1 longitudinal modes
- Refs. Ema, Nakayama, Tang, 1903.10973(JHEP)

  Graham, Mardon, Rajendra, 1504.02102(PRD)

Transverse modes

- Expand

$$\vec{A}_T(\vec{k},\tau) = \sum_{h=\pm}\left[\mathcal{A}_T(\vec{k},\tau)\vec{\epsilon}_h a_{\vec{k},h} + \mathcal{A}_T^*(\vec{k},\tau)\vec{\epsilon}_h^{\,*} a^\dagger_{-\vec{k},h}\right],$$

$$\left[a_{\vec{k},h}, a^\dagger_{\vec{k}',h'}\right] = (2\pi)^3\delta_{hh'}\delta(\vec{k}-\vec{k}'),\ \ \left[a_{\vec{k},h}, a_{\vec{k}',h'}\right] = \left[a^\dagger_{\vec{k},h}, a^\dagger_{\vec{k}',h'}\right] = 0.$$

- The mode function $\mathcal{A}_T(\vec{k},\tau)$ has EoM

$$\mathcal{A}_T'' + (k^2 + a^2 m^2)\mathcal{A}_T = 0.$$

- During inflation

$$\mathcal{A}_T(k,\tau) = e^{\frac{i(2\nu+1)\pi}{4}}\frac{1}{\sqrt{2k}}\sqrt{\frac{-\pi k\tau}{2}}H_\nu^{(1)}(-k\tau),\ \nu^2 \equiv \frac{1}{4} - \frac{m^2}{H^2},$$

- With boundary condition

$$\mathcal{A}_T(k,\tau) \to \frac{1}{\sqrt{2k}}e^{-ik\tau}$$

Longitudinal mode

- Longitudinal mode is different

$$S_L = \int \frac{d^3k d\tau}{(2\pi)^3}\frac{1}{2}\left(\frac{a^2m^2}{k^2+a^2m^2}|\partial_\tau A_L|^2 - a^2m^2|A_L|^2\right)$$

- Define

$$\widetilde{A_L} \equiv f(\tau)A_L,\ f(\tau)\equiv \frac{am}{\sqrt{k^2+a^2m^2}}$$

$$S_L = \int \frac{d^3k d\tau}{(2\pi)^3}\frac{1}{2}\left(|\partial_\tau \widetilde{A_L}|^2 - \omega_L^2|\widetilde{A_L}|^2\right),\ \omega_L^2 = \frac{a^2m^2}{f^2} - \frac{f''}{f} \equiv k^2 + m_L^2$$

- Then, we can work with

$$m_L^2 = a^2m^2 - \frac{k^2}{k^2+a^2m^2}\left(\frac{a''}{a} - \frac{a'^2}{a^2}\frac{3a^2m^2}{k^2+a^2m^2}\right)$$

$$\widetilde{A_L}(\vec{k},\tau) = \mathcal{A}_L(\vec{k},\tau)a_{\vec{k}} + \mathcal{A}_L^*(\vec{k},\tau)a^\dagger_{-\vec{k}}$$

$$\mathcal{A}_L'' + \omega_L^2(k,\tau)\mathcal{A}_L = 0,\ \omega_L^2 = k^2 + m_L^2.$$

Energy density

- The energy-momentum tensor is defined as

$$T_{\mu\nu} = \frac{-2}{\sqrt{-g}} \frac{\delta(\sqrt{-g}\mathcal{L})}{\delta g^{\mu\nu}}.$$

$$T_{\mu\nu} = g^{\rho\sigma} F_{\mu\rho} F_{\nu\sigma} - \frac{1}{4} g_{\mu\nu} g^{\rho\alpha} g^{\sigma\beta} F_{\rho\sigma} F_{\alpha\beta} + m^2 \left(A_\mu A_\nu - \frac{1}{2} g_{\mu\nu} g^{\rho\sigma} A_\rho A_\sigma \right)$$

- Energy density $\rho = \langle 0 | T_{00} | 0 \rangle$

$$\rho = \rho_T + \rho_L,$$

$$\rho_T = 2 \int \frac{d^3k}{(2\pi)^3} \frac{1}{2a^4} \left[|\mathcal{A}'_T(k)|^2 + (k^2 + a^2 m^2) |\mathcal{A}_T(k)|^2 \right],$$

$$\rho_L = \int \frac{d^3k}{(2\pi)^3} \frac{1}{2a^4} \left[\frac{a^2 m^2}{k^2 + a^2 m^2} |\mathcal{A}'_L(k)|^2 + a^2 m^2 |\mathcal{A}_L(k)|^2 \right],$$

Solution

- Useful parametrization

$$\mathcal{A}_T(k,\tau) = \frac{\alpha_k(\tau)}{\sqrt{2\omega_k}} e^{-i\int^{\tau}\omega_k(\tau')d\tau'} + \frac{\beta_k(\tau)}{\sqrt{2\omega_k}} e^{i\int^{\tau}\omega_k(\tau')d\tau'},$$

- where $\omega_k \equiv \sqrt{k^2 + a^2 m^2}$ and

$$\alpha'_k(\tau) = \frac{\omega'_k}{2\omega_k} e^{2i\int^{\tau}\omega_k(\tau')d\tau'}\beta_k,\ \ \beta'_k(\tau) = \frac{\omega'_k}{2\omega_k} e^{-2i\int^{\tau}\omega_k(\tau')d\tau'}\alpha_k$$

$$|\alpha_k(\tau)|^2 - |\beta_k(\tau)|^2 = 1$$

- Then the energy density is expressed as

$$a^4(\tau)\rho_T(\tau) = 2\int \frac{d^3k}{(2\pi)^3}\omega_k f_T(k,\tau),\ \ f_T(k,\tau) = |\beta_k(\tau)|^2.$$

Abundance

- In term of the energy-to-entropy ratio

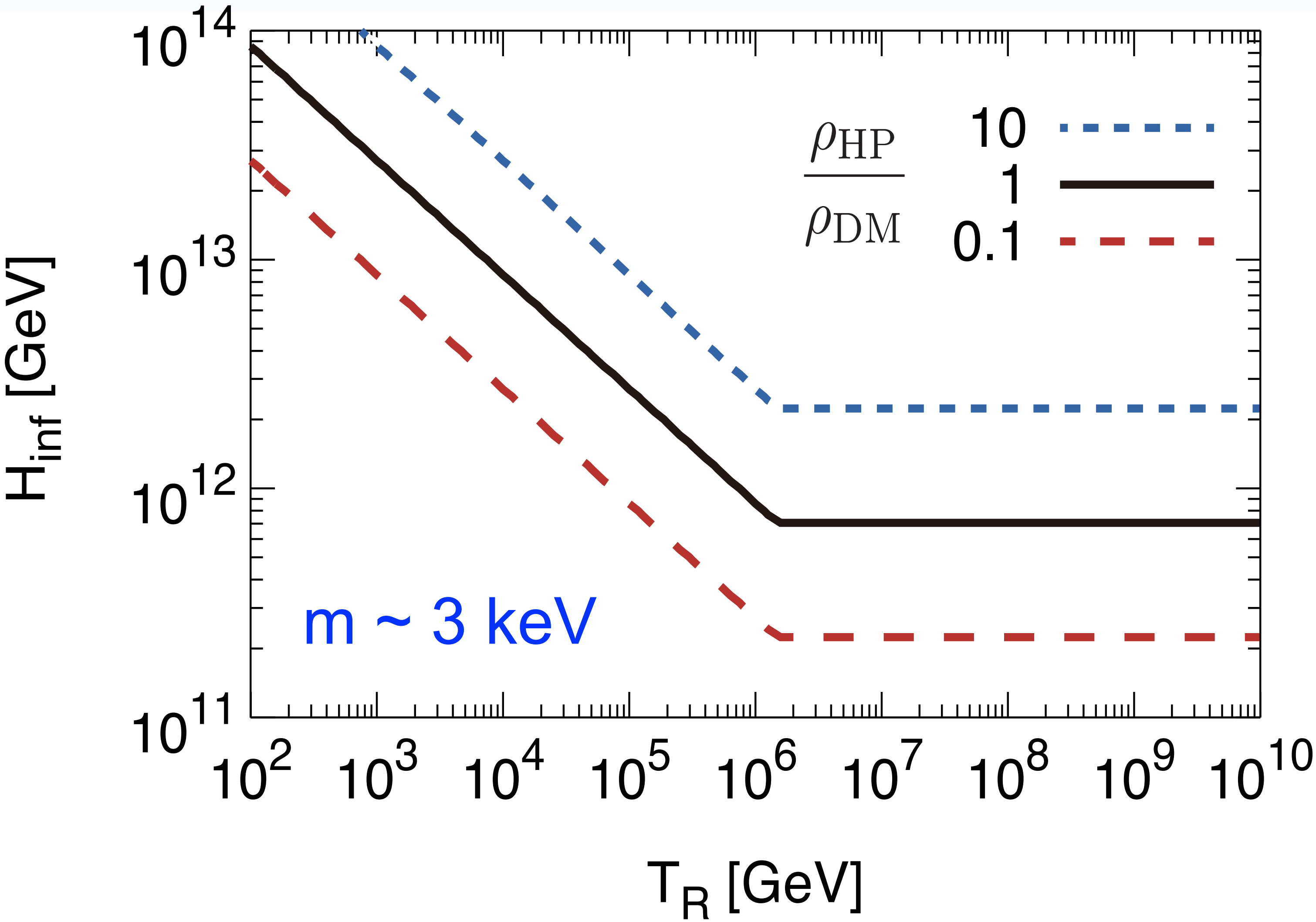
$$\frac{\rho_{\rm HP}}{s} \simeq \begin{cases} \frac{3}{2048\pi}\frac{m T_{\rm R} H_{\rm inf}}{M_{\rm Pl}^2} & \text{for} \quad H_{\rm inf} < m \\ \frac{1}{32\pi^2}\frac{T_{\rm R} H_{\rm inf}^2}{M_{\rm Pl}^2} & \text{for} \quad H_{\rm R} < m < H_{\rm inf} \\ \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \frac{1}{32\pi^2}\frac{m^{1/2} H_{\rm inf}^2}{M_{\rm Pl}^{3/2}} & \text{for} \quad m < H_{\rm R} \end{cases},$$

- $T_{\rm R}$ is the reheating temperature,

  $H_{\rm R}$ is the Hubble parameter $H_{\rm R} \sim T_{\rm R}^2/M_{\rm P}$

  g_* is the relativistic degree of freedoms

Abundance



$$H_{\rm inf} \gtrsim 10^{12}{\rm GeV},\ T_R > 10^2{\rm GeV}$$

A Model

Weyl Symmetry

- Weyl symmetry was referred to

$$g_{\mu\nu}(x) \to g'_{\mu\nu}(x) = e^{2\theta(x)} g_{\mu\nu}(x)$$

$$W_\mu(x) \to W'_\mu(x) = W_\mu(x) - \partial_\mu \theta(x)$$

- First proposed by Weyl around 1919 in order to unify general relativity and electromagnetic interaction.
- Later Weyl modified it to

$$\psi(x) \to \psi'(x) = e^{i\theta(x)} \psi(x) \qquad \partial_\mu \to \partial_\mu - igW_\mu$$

$$W_\mu(x) \to W'_\mu(x) = W_\mu(x) - \partial_\mu \theta(x)$$

Gauge symmetry

- To describe electron after quantum mechanics.

Weyl-Einstein Gravity

- Covariant derivative

$$\partial_\mu g_{\rho\sigma} \to \left(\partial_\mu + 2W_\mu\right) g_{\rho\sigma}$$

$$D_\mu = \partial_\mu + qW_\mu$$

- The modified connection

$$\hat{\Gamma}^\rho_{\mu\nu} = \Gamma^\rho_{\mu\nu} + \left[W_\mu \delta^\rho_\nu + W_\nu \delta^\rho_\mu - W^\rho g_{\mu\nu}\right],$$
$$\Gamma^\rho_{\mu\nu} = \frac{1}{2} g^{\rho\sigma}\left(\partial_\mu g_{\sigma\nu} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu}\right)$$

- And the modified Ricci tensor and scalar $\hat{R}$

$$\hat{R}^\rho{}_{\sigma\mu\nu} = \partial_\mu \hat{\Gamma}^\rho_{\sigma\nu} - \partial_\nu \hat{\Gamma}^\rho_{\sigma\mu} + \hat{\Gamma}^\rho_{\mu\tau}\hat{\Gamma}^\tau_{\sigma\nu} - \hat{\Gamma}^\rho_{\nu\tau}\hat{\Gamma}^\tau_{\sigma\mu},$$
$$\hat{R}_{\sigma\nu} = \hat{R}^\rho{}_{\sigma\rho\nu}, \hat{R} = g^{\sigma\nu}\hat{R}_{\sigma\nu}$$

Weyl-Einstein Gravity

- First consider the Weyl $\hat{R}$ gravity

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\phi^2\hat{R} + \frac{1}{2}\zeta D^\mu\phi D_\mu\phi - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} - \lambda\phi^4\right]$$

- It is invariant under scaling transformation

$$g_{\mu\nu} \to g'_{\mu\nu} = f^2 g_{\mu\nu}$$

$$W_\mu \to W'_\mu = W_\mu - \partial_\mu \ln f$$

$$\phi \to \phi' = f^{-1}\phi$$

- We have $\hat{\Gamma}'^\rho_{\mu\nu} = \hat{\Gamma}^\rho_{\mu\nu}, \hat{R}'^\rho_{\sigma\mu\nu} = \hat{R}^\rho_{\sigma\mu\nu}, D'_\mu\phi' = f D_\mu\phi$
- One can write in a familiar form by using

$$\hat{R} = R + 6W_\mu W^\mu + 6\nabla_\mu W^\mu, \nabla_\mu W^\mu = \frac{6}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}W^\mu\right)$$

$$\phi^2\hat{R} = \phi^2 R - 6\partial_\mu\phi\partial^\mu\phi + 6D_\mu\phi D^\mu\phi$$

Weyl-Einstein Gravity

- First consider the Weyl $\hat{R}$ gravity

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\phi^2\hat{R} + \frac{1}{2}\zeta D^\mu\phi D_\mu\phi - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} - \lambda\phi^4\right]$$

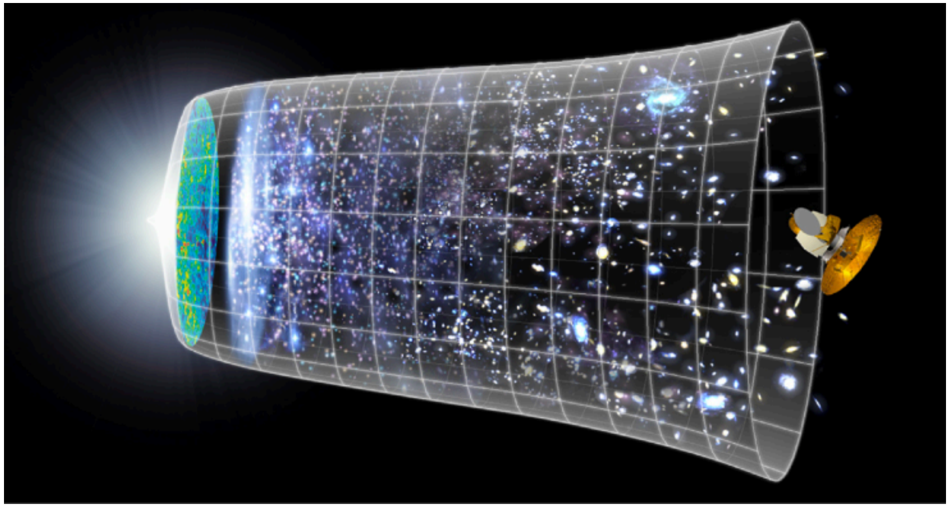
- Einstein frame is set by $\phi^2 = 1$

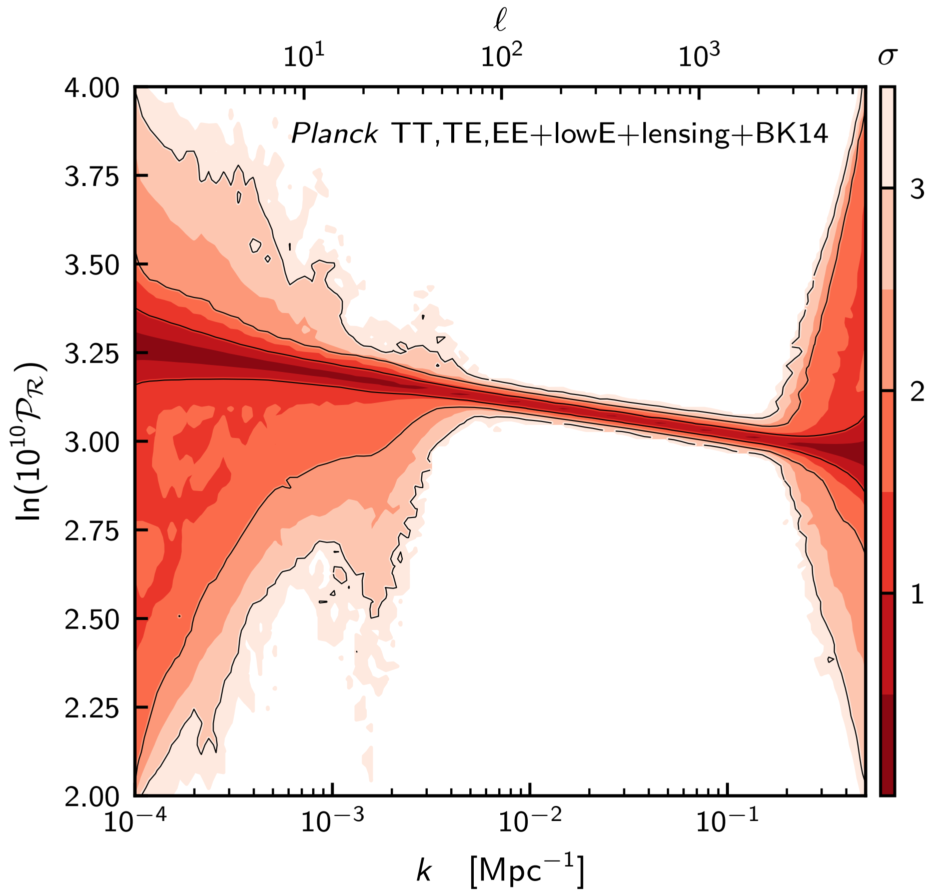
$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}R - \lambda - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\zeta + 6\right)W_\mu W^\mu\right]$$

- Massive W_μ with discrete symmetry, might be a dark matter candidate,
- However, inflation is not provided and extension is needed.

Inflation

- Inflation is a very attractive solution to many cosmic problems
  - flatness & horizon
  - conformal/Weyl symmetry
  - breaking uncertain yet





$$\Delta^2_\mathcal{R} \equiv \mathcal{P}_\mathcal{R} = A_\mathcal{R}\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$n_s \simeq 0.9649 \pm 0.0042$$

Weyl $\hat{R}^2$ Gravity

YT, Y.L.Wu, arXiv:2006.02811
Ghilencea, arXiv:1906.11572
Ferreira et al,arXiv:1906.03415

- Now let us consider

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\phi^2\hat{R} + \frac{\alpha}{12}\hat{R}^2 + \frac{1}{2}\zeta D^\mu\phi D_\mu\phi - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} - \lambda\phi^4\right]$$

- We can introduce an auxiliary field χ

$$\sqrt{-g}\left[\frac{1}{2}\left(\phi^2 + \frac{\alpha}{3}\chi^2\right)\hat{R} - \frac{\alpha}{12}\chi^4 + \frac{1}{2}\zeta D^\mu\phi D_\mu\phi - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} - \lambda\phi^4\right]$$

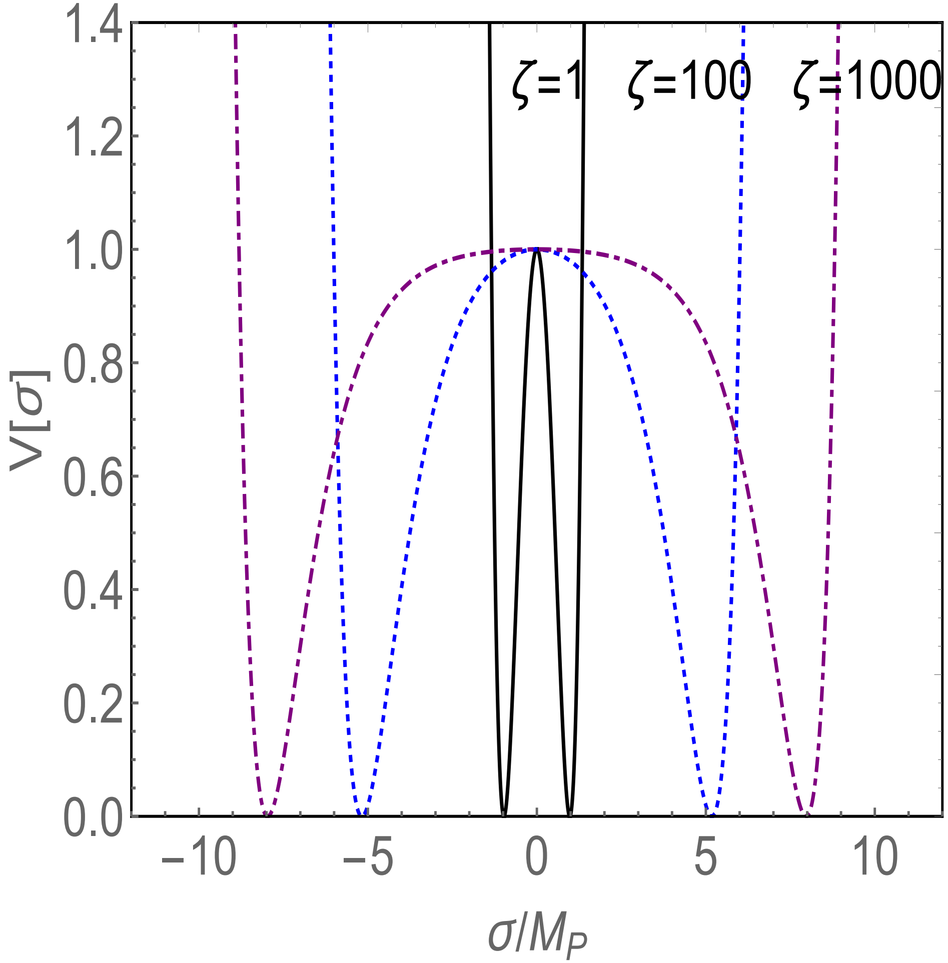
- The equivalence can be shown with $\frac{\delta\mathcal{L}}{\delta\chi} = 0 \Rightarrow \chi^2 = \hat{R}$
- Fix to Einstein frame $\phi^2 + \frac{\alpha}{3}\chi^2 = 1$

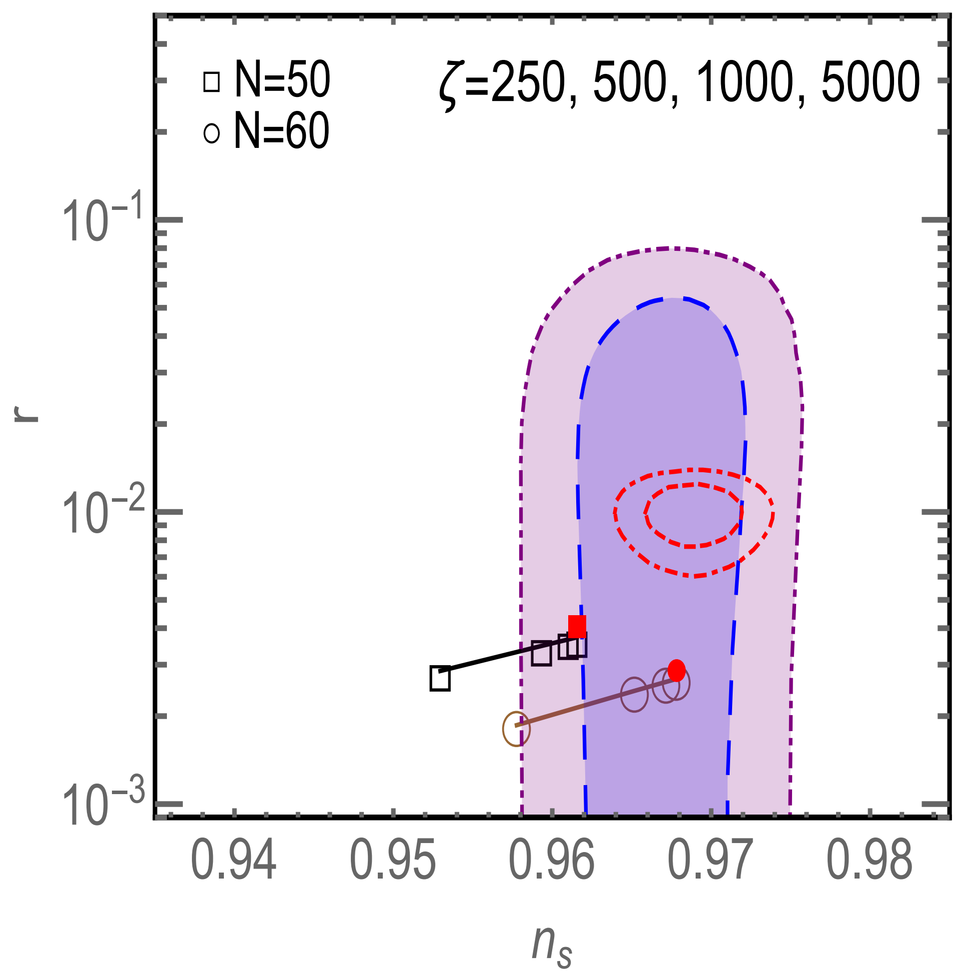
$$\phi = \sqrt{\frac{6}{+\zeta}}\sinh\frac{\pm\sigma}{\sqrt{6}}$$

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}R + \frac{1}{2}\zeta D^\mu\phi D_\mu\phi - \frac{1}{4g_W^2}F_{\mu\nu}F^{\mu\nu} + 3W^\mu W_\mu - \frac{3}{4\alpha}\left(1-\phi^2\right)^2 - \lambda\phi^4$$

Inflation

$$V(\sigma) \simeq \frac{3}{4\alpha}\left[1-\frac{6}{\zeta}\sinh^2\left(\frac{\sigma}{\sqrt{6}}\right)\right]^2 \xrightarrow{\zeta\to\infty} V(\bar{\sigma}) = \frac{3}{4\alpha'}\left[1-\exp\left(-\sqrt{\frac{2}{3}}\bar{\sigma}\right)\right]^2$$





Summary

- XENON1T has observed an excess (3.5σ) in the electronic recoil events between 2 - 3 keV.
- New physics may provide possible explanations.
- Absorption of ~2-3 keV hidden photon DM.
- Such light DM can not be thermally produced, due to astrophysical bounds.
- Gravitational production is a viable mechanism.
- A model of hidden photon and inflation.