Low Scale SUSY-breaking Naturally Admits *X*-ray lines

05/17/2014, 9'th TeV working group,Guangzhou

Zhaofeng Kang, CHEP

Outline

Start from WDM

keV *X*-ray line from the sky

Dynamical keV in SUSY

Dark gaugino sterilie neutrino

Compressed WIMPs

Conclusions

Start from WDM

Warm dark matter (WDM) ***VS*** cold dark matter (CDM)

Small scale problem, among others: free streaming scale (Jeans scale)

$$r_{Jeans} = 57.2\,\mathrm{kpc}\,\frac{\mathrm{keV}}{m}\left(\frac{100}{g_d}\right)^{\frac{1}{3}}$$

Smaller strucutre is thus erased, which is consistent with the observed size of subhalo, 1-100 kpc. While for 100 GeV CDM, r_{Jeans} becomes much smaller, only about 0.0001pc ~ the solar system

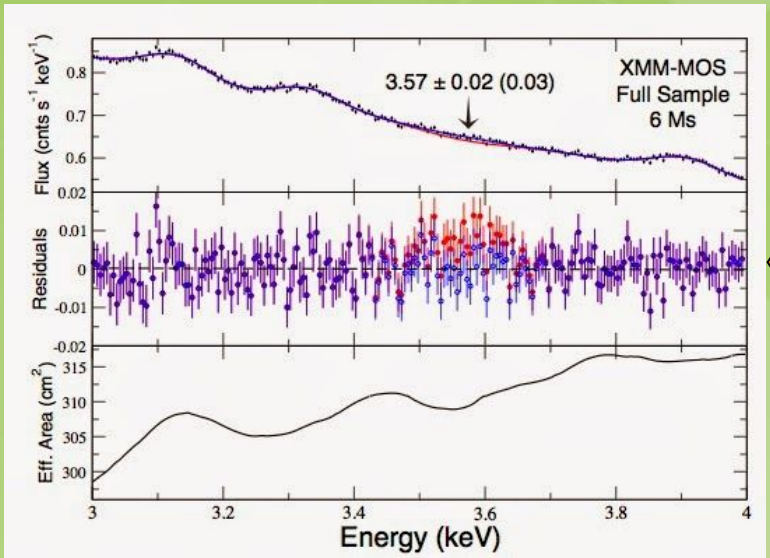
WDM Detections

Direct detection: $E_k \sim m_{\mathrm{WDM}}\, v\text{^}2/2 \ll \mathrm{keV}$, ***HOPELESS!?***
Indirect detection: ***only*** annihilation/decay into ***neutrino and photon*** are kinematically allowed, with spectrum lines at the keV region——*X*-ray line.
HOPEFUL!

keV *X*-ray line from the sky

3.5keV line， hint appears?

E.~Bulbul, etal, arXiv:1402.2301 use XMM-Newton (*X*-ray satellite) data to analyze the stacked *X*-ray spectra of many galaxy clusters



Explained by 7 keV DM two body decay into gamma+?, with lifetime 10^{28} *s*

Also claimed in an independent paper, A.~Boyarsky, et al, arXiv:1402.4119

I hope that the recently submitted manuscript by Bulbul et al. will convince NASA to fund more research into....
——from someone's blog

keV *X*-ray line from the sky

[4] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S. W. Randall, arXiv:1402.2301; A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, arXiv:1402.4119.

[5] R. Krall, M. Reece and T. Roxlo, arXiv:1403.1240 [hep-ph].

[6] M. Frandsen, F. Sannino, I. M. Shoemaker and O. Svendsen, arXiv:1403.1570 [hep-ph].

[7] H. Ishida, K. S. Jeong and F. Takahashi, arXiv:1402.5837; K. N. Abazajian, arXiv:1403.0954; S. Baek and H. Okada, arXiv:1403.1710.

[8] T. Higaki, K. S. Jeong and F. Takahashi, arXiv:1402.6965: J. Jaeckel, J. Redondo and A. Ringwald, arXiv:1402.7335; H. M. Lee, S. C. Park and W. -I. Park, arXiv:1403.0865: A. G. Dias, A. C. B. Machado, C. C. Nishi, A. Ringwald and P. Vaudrevange, arXiv:1403.5760.

[9] K. Kong, J. -C. Park and S. C. Park, arXiv:1403.1536; K. -Y. Choi and O. Seto, arXiv:1403.1782; S. P. Liew, arXiv:1403.6621.

[10] C. im. E. Aisati, T. Hambye and T. Scarna, arXiv:1403.1280 [hep-ph].

keV *X*-ray line from the sky

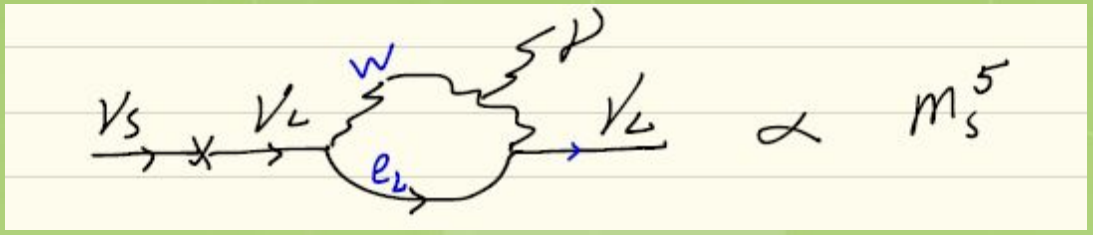
WDM and *X*-ray line

Decaying WDM candidates and signatures of *X*-ray

Spin 0: axion-like (CP-odd) but CP-even is also allowed, maybe saxion?

$$aF\tilde{F} \Rightarrow a \to \gamma\gamma$$

Spin 1/2: sterile neutrino-like, axino, decaying into a neutrino plus gamma



Spin 1: Impossible due to Landau-Yang therom

Spin 3/2: gravitino in RPV: $\tilde{G} \to \gamma\nu$, but rate is $\propto \frac{1}{M_{pl}^2}$, too small !

Relic density

Thermal keV scale WDM overcloses the Universe

$$\Omega h^2 \simeq 0.11 \left(\frac{m_{\tilde{X},\tilde{G}}}{10\mathrm{keV}}\right)\left(\frac{106.75}{g_{*S,f}}\right)\left(\frac{100}{\mathcal{S}}\right)$$

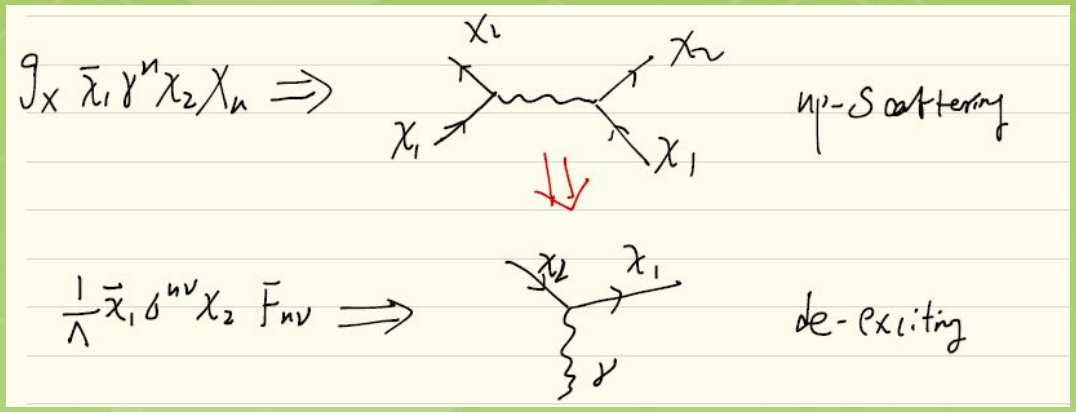
keV *X*-ray line from the sky

Ruling out CDM？NO！

Excited DM, originally to explain the 511 keV line

D. P. Finkbeiner and N. Weiner, Phys. Rev. D76, 083519 (2007).

$\delta \equiv m_{\chi_2} - m_{\chi_1} \sim 3.5\,\mathrm{keV}$



A broader setup: compressed WIMPs

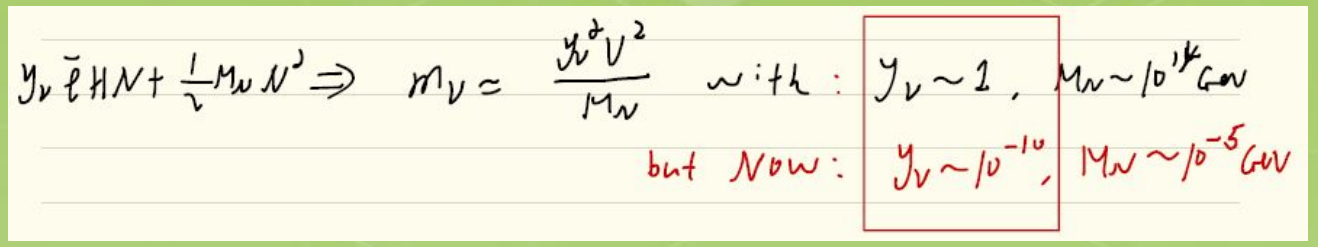
1. The WIMP system contains several states with keV scale mass splitting
2. The heavier one X_2 is sufficiently long lived so as to be DM component
3. Making a way for X_2 decay into gamma, among others

Dynamical keV in SUSY

Dark gaugino as sterilie neutrino

WDM with mass ~ keV

keV righ-handed neutrino betreys seesaw



Compressed WIMPs->keV mass splitting

Generically implies a huge fine-tuning ~ keV/GeV~10^{-6}.

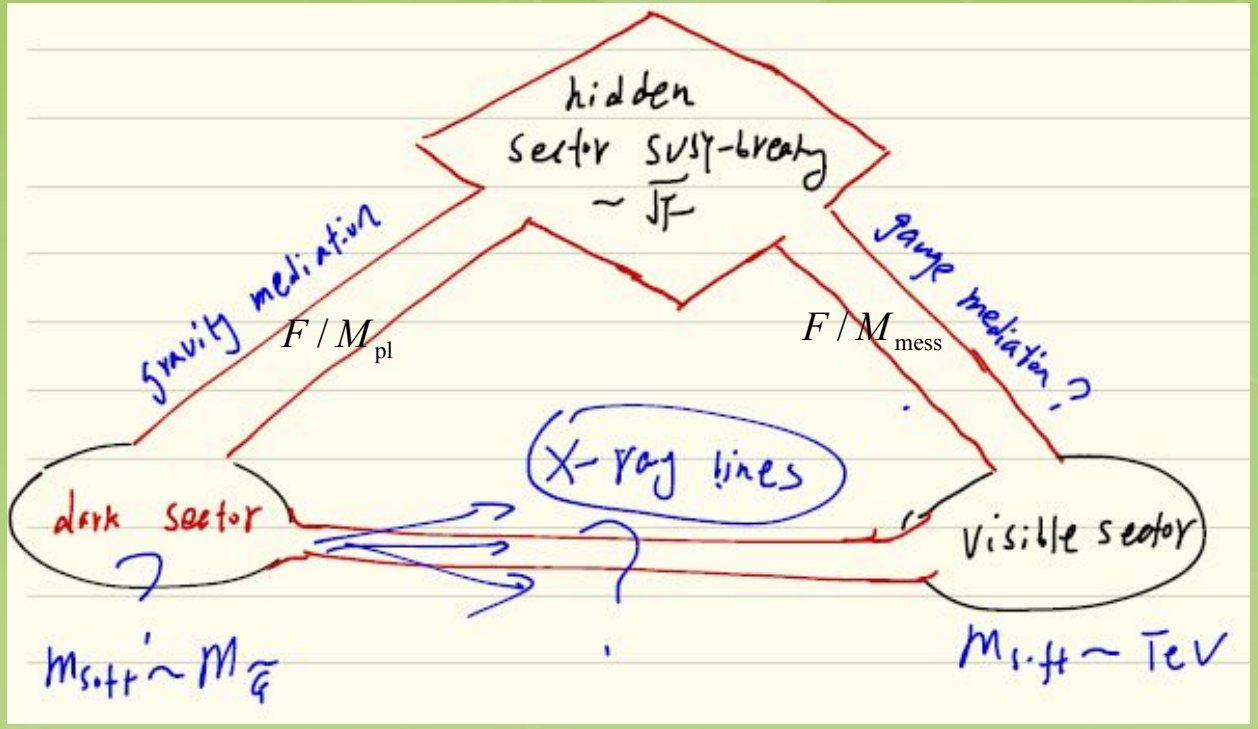
Ways out: Mass degeneracy due to symmetry, splitting due to its breaking

keV: the chosen scale in SUSY

SUSY-breaking generates a characteristic scale in low energy SUSY,
the gravitino mass $F / M_{\rm pl}$ —— If SUSY-breaking scale $F^{1/2}$ is as low as 10^3TeV,
gravitino mass will be ~ keV!

Dynamical keV in SUSY

Challenge: How to tie this keV to that keV?



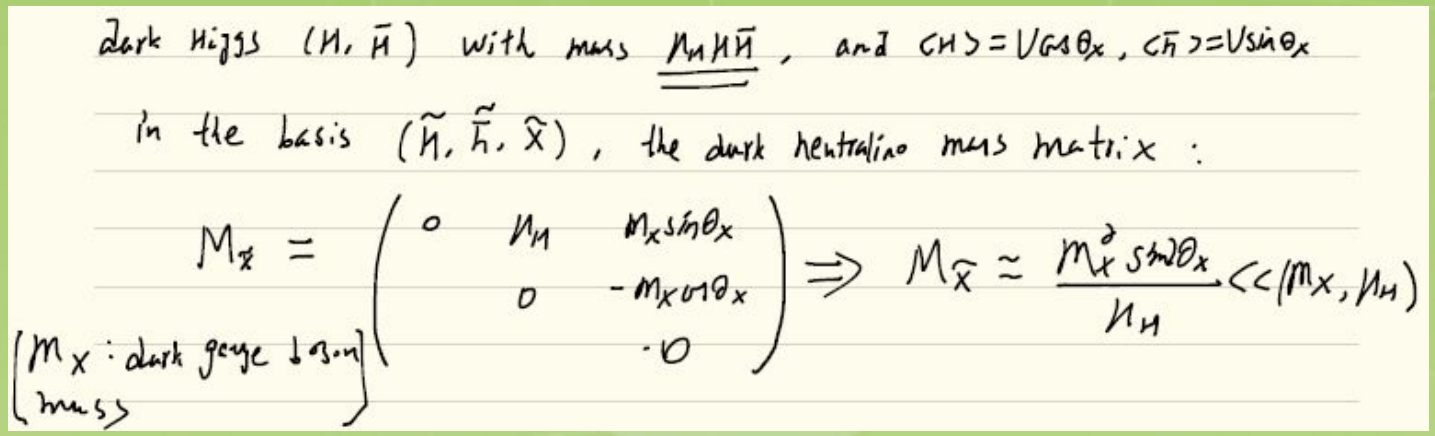
Dark gaugino sterilie neutrino

Supersymmetric $U(1)_X$ sector

kinematic sector with small $U(1)_Y$ and $U(1)_X$ mixing

$$\frac{1}{4}\int d^2\theta\,(W_Y W_Y + W_X W_X - 2\epsilon W_Y W_X) + c.c.,$$

A light dark gaugino survives even after higher $U(1)_X$ symmetry-breaking scale



Thus, in a large class of $U(1)_X$ models, a light dark gaugino can be presented, acquring mass ~ keV gravitino via gravity mediation

Dark gaugino sterilie neutrino

Becoming a sterile neutrino with RPV

Elimating kinematic mixing via gaugino shift $\tilde{X}' = \tilde{X} + \epsilon \tilde{B}$

$$\epsilon \mathcal{O}(m_{\tilde{X}}/m_{\tilde{B}}) \tilde{X} \tilde{J}_B + c.c., \text{ with } \tilde{J}_B = g_Y \sum_f Q_f \tilde{f}^\dagger f, \Rightarrow \tilde{X} \tilde{\nu}_L \nu_L$$

Blinear RPV generating sneutrino VEV thus dark gaugino & neutrino mixing

$$W_{\not R} = \mu_i L_i H_u \Rightarrow \langle \tilde{\nu}_L \rangle \neq 0 \Rightarrow \epsilon \frac{m_{\tilde{X}}}{m_{\tilde{B}}} g_Y \tilde{X} \langle \tilde{\nu}_L \rangle \nu_L + \frac{m_{\tilde{B}}}{2} \tilde{X} \tilde{X}$$

$$\Gamma_{\nu\gamma} \simeq 1.62 \times 10^{-28} \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}} \right) \left(\frac{m_{\tilde{X}}}{7\mathrm{keV}} \right)^5 \Rightarrow \sin 2\theta \simeq 2\epsilon \frac{g_Y}{2} \frac{m_{\tilde{X}}}{m_{\tilde{B}}} \frac{\langle \tilde{\nu}_L \rangle}{m_{\tilde{X}}} = \epsilon g_Y \frac{\langle \tilde{\nu}_L \rangle}{m_{\tilde{B}}}, \sim 10^{-5}$$

Note: dark gaugino in our case can be in thermal equilibrium via many ways, like dark gauge interactions, and the dark states may provide source of entropy to dilute the WDM relic density

Compressed WIMPs

Highly supersymmetric dark sector

A toy model for supersymmetric dark sector, receiving tiny SUSY-breaking

$$W = \frac{M_X}{2} X^2,$$
$$\mathcal{L}_{\text{soft}} = c_1 m_{\tilde{G}}^2 |X|^2 + \left(c_2 \frac{m_{\tilde{G}} M_X}{2} X^2 + c.c. \right).$$

$$\Rightarrow \quad m_{\tilde{X}} = M_X, \quad m_{X_{R/I}} \approx M_X \left(1 + \frac{c_1}{2} \frac{m_{\tilde{G}}^2}{M_X^2} \pm \frac{c_2}{2} \frac{m_{\tilde{G}}}{M_X} \right)$$

SUSY ***holomorphy***, which leads to an enlarged $U(1)$ for scalars, along with its small breaking by soft terms, naturally give rises to compressed WIMPs

Needs a light mediator!

All three dark states can be stable and only $X_{R/I}$ are of interest

To make X_R decay into gamma, consider $\mathcal{L}_{decay} = \mu_a a X_R X_I + \frac{\alpha}{4\pi} \frac{1}{8\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu}.$

$$\Gamma_{eff} \simeq \mu_a^2 \frac{\alpha^2}{107520\pi^5} \frac{\delta^7}{m_{X_R}^2 m_a^4 \Lambda^2} \left(\frac{\delta}{m_{X_R}} \right)$$
$$= 1.14 \times 10^{-28} s^{-1} \left(\frac{\mu_a}{1\,\text{GeV}} \right)^2 \left(\frac{\delta}{7.0\,\text{keV}} \right)^8 \left(\frac{1.0\,\text{GeV}}{m_{X_R}} \right)^3 \left(\frac{40\,\text{GeV}}{\Lambda} \right)^2 \left(\frac{0.1\,\text{GeV}}{m_a} \right)^4$$

Naturally small decay rate, actually, too small thus favoring light mediator!

Compressed WIMPs

Working model

A realistic model needs mediator S and a pair of charged particle C:

$$W = \frac{M_X}{2}X^2 + \frac{\lambda_X}{2}X^2 S + \frac{M_S}{2}S^2 + \lambda_C S C\bar{C} + m_C C\bar{C}.$$

$$\mu_a = -\lambda_X M_S, \qquad \Lambda = \frac{1}{4\lambda_C}\frac{m_C}{N_C Q_C^2}.$$

We require $F_S=0$ so as that it would not contribute large mass splitting to dark states X_R and X_I

It contains quite a few scales, and here is an updata to single scale model:

$$W = \frac{\lambda_X}{2}X^2 S + \left(\mathcal{F}S - \frac{\kappa}{3}S^3\right) + \lambda_C S C\bar{C}$$

$$M_X = \frac{\lambda_X}{\sqrt{\kappa}}\sqrt{\mathcal{F}}, \quad m_C = \frac{\lambda_C}{\sqrt{\kappa}}\sqrt{\mathcal{F}}, \quad M_S = 2\sqrt{\kappa\mathcal{F}}.$$

Axionic models

Dark sector may experience an approximate $U(1)$ break, giving rise to PGSB

The NMSSM in the PQ-limit may provide the elements

$$\lambda N H_u H_d + \kappa N^3/3 \qquad \text{PQ-limit } \kappa \to 0.$$

Conclusions

X-ray line may be a smoking gun of WDM, but CDM can also account for it in a compressed WIMP system

Origins of keV are of interest, and they may be found in the low scale SUSY-breaking models

We propose dark gaugino, with mass$\sim$gravitno mass, as a sterile neutrino-like WDM to explain the *X*-ray line

We also propose a highly supersymmetric dark sector, with mass splitting$\sim$gravitno mass, as a compressed WIMP system to explain the *X*-ray line

Thank you!