3.5 keV X-ray line signal in local $U(1)_{B-L}$ extension of Zee-Babu model

Seungwon Baek (KIAS)

based on 1410.1992

Outline

- Introduction to 3.5 keV X-ray line signal
- Generalized decaying DM model for 3.5 keV X-ray line
- Decaying DM in Zee-Babu model
- Conclusions

3.5 keV X-ray line signal

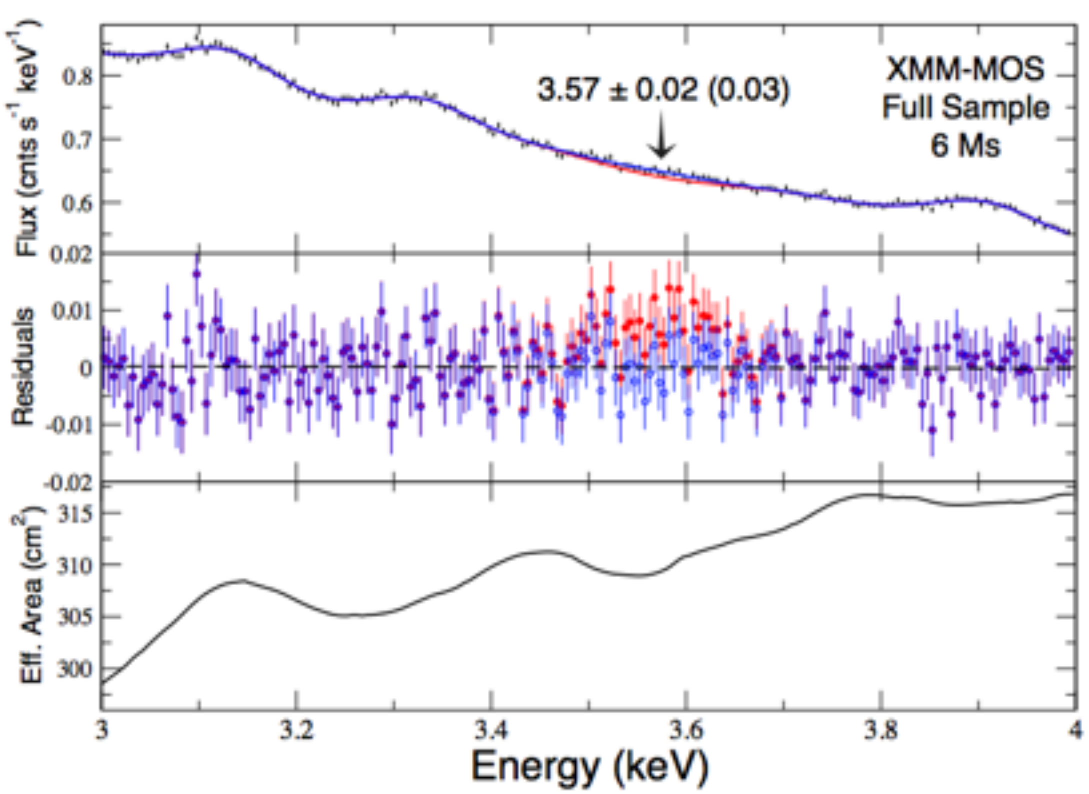
Unidentified 3.5 keV X-ray line was reported ~3σ

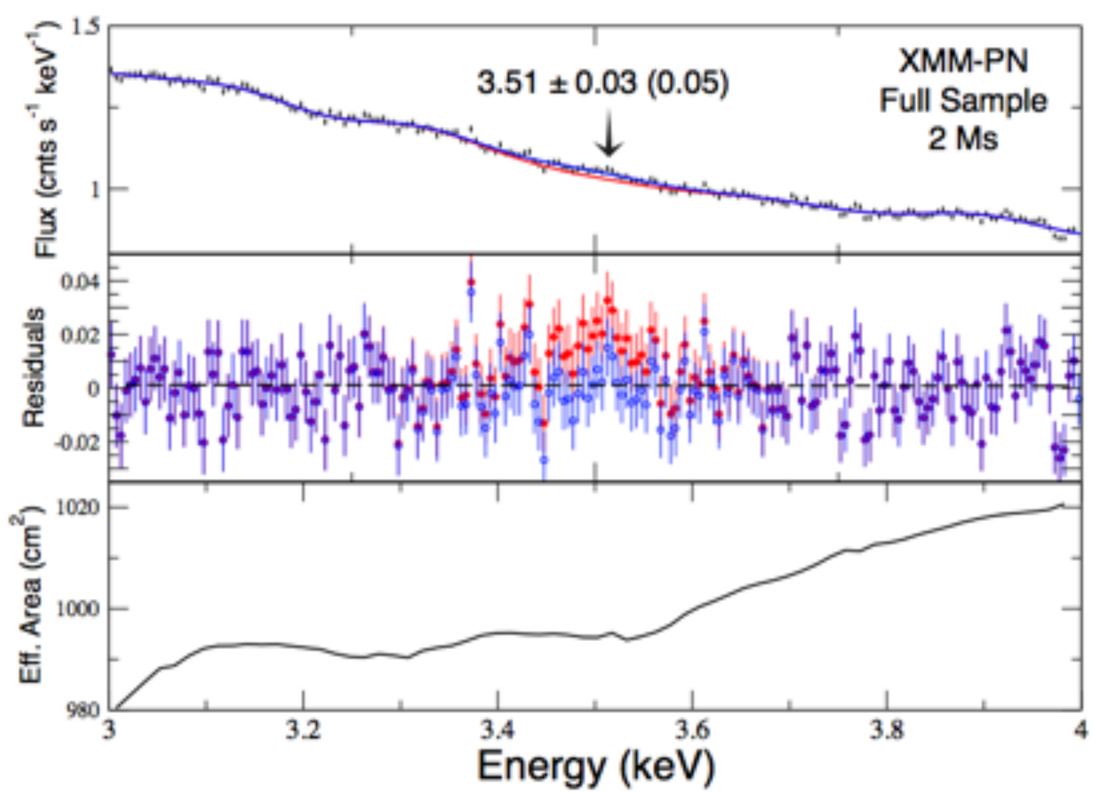
i) from the stacked analysis of 73 galaxy clusters

E. Bulbul, et.al,1402.2301

ii) from Andromeda galaxy and Perseus cluster

A. Boyarsky, et.al, 1402.4119





3.5 keV X-ray line signal

A. Boyarsky, et.al, 1402.4119

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

We identify a weak line at $E \sim 3.5$ keV in X-ray spectra of the Andromeda galaxy and the Perseus galaxy cluster – two dark matter-dominated objects, for which there exist deep exposures with the XMM-Newton X-ray observatory. Such a line was not previously known to be present in the spectra of galaxies or galaxy clusters. Although the line is weak, it has a clear tendency to become stronger towards the centers of the objects; it is stronger for the Perseus cluster than for the Andromeda galaxy and is absent in the spectrum of a very deep "blank sky" dataset. Although for individual objects it is hard to exclude the possibility that the feature is due to an instrumental effect or an atomic line of anomalous brightness, it is consistent with the behavior of a line originating from the decay of dark matter particles. Future detections or non-detections of this line in multiple astrophysical targets may help to reveal its nature.

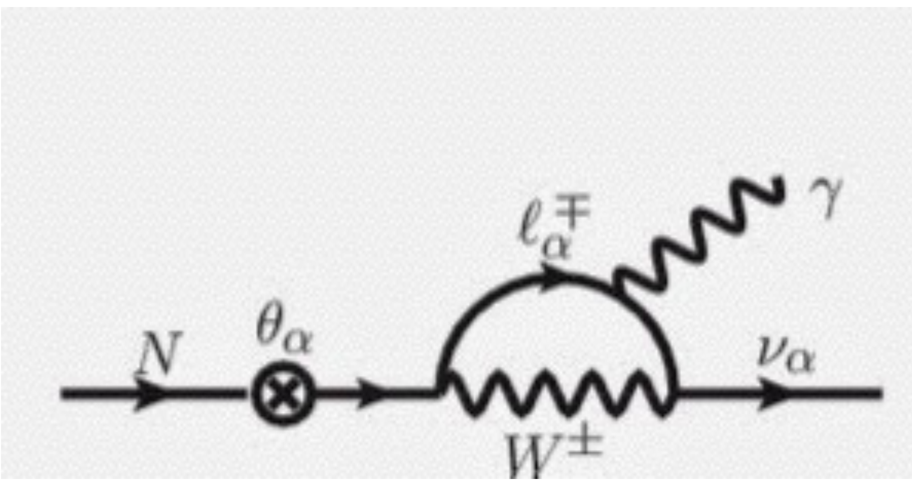
3.5 keV X-ray line signal

- There are some debates on the existence of the signal M. Anderson, et.al., 1408.4115
  - Suzaku X-ray search did not see the signal in the Perseus cluster T. Tamura (2014)
- Signal from the center of the Milky Way?
  - Chandra X-ray observation: rules out the signal @95% CL S. Riemer-Sorensen:1405.7943
  - XMM-Newton data: consistent with the signal A. Boyarsky et.al., 1408.2503
- No signal in the dwarf galaxies. D. Malyshev et.al.,1408.3531
- A Particular form of DM? J. Cline and A. Frey, 1410.7766

Decay of sterile neutrino

$\nu_s \to \nu + \gamma$

E. Bulbul, et.al,1402.2301;
A. Boyarsky, et.al, 1402.4119



$$m_s = 7.06 \pm 0.5\text{keV}$$

$$\sin^2 2\theta = (2 - 20) \times 10^{-11}$$

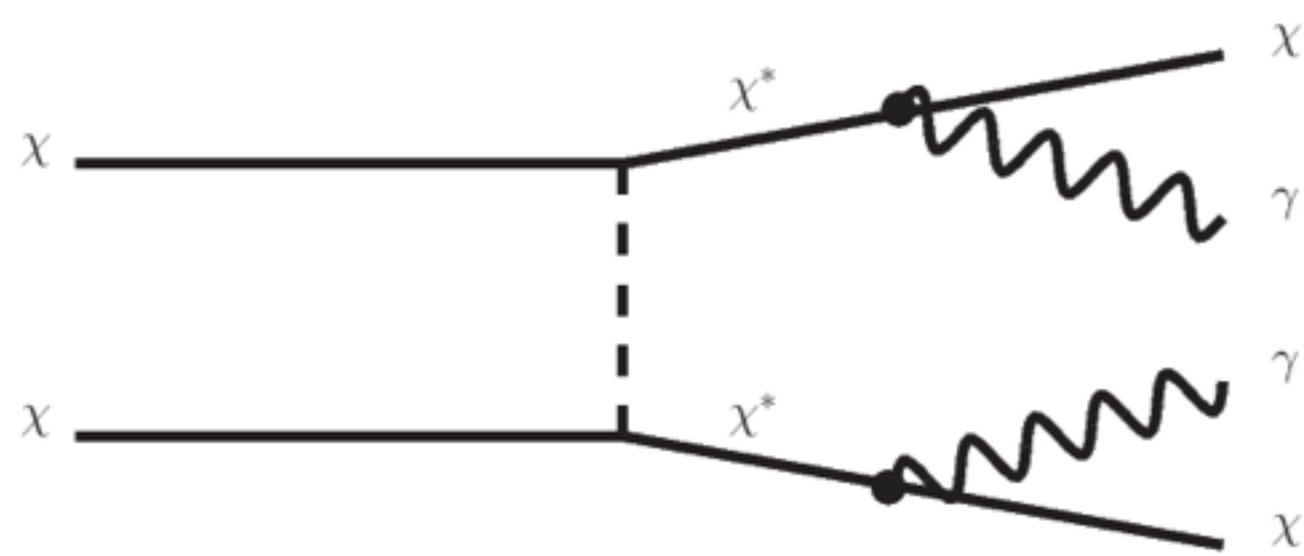
$$
\begin{aligned}
{}_{X-ray} \propto n_s \Gamma_s &= 1.39 \times 10^{-22} s^{-1} \sin^2 2\theta \left(\frac{m_s}{\text{keV}}\right)^5 \rho_{DM}/m_s \\
&= \left(1.5 \times 10^{-25} - 2.7 \times 10^{-24}\right) \text{cm}^{-3}\text{s}^{-1},
\end{aligned}
$$

$$\tau_s = 1.6 \times 10^{27} - 2.8 \times 10^{28}\,\text{sec}$$

Exciting DM

$$\chi_g + \chi_g \to \chi_e + \chi_e.$$

Frandsen, et.al., 1403.1570

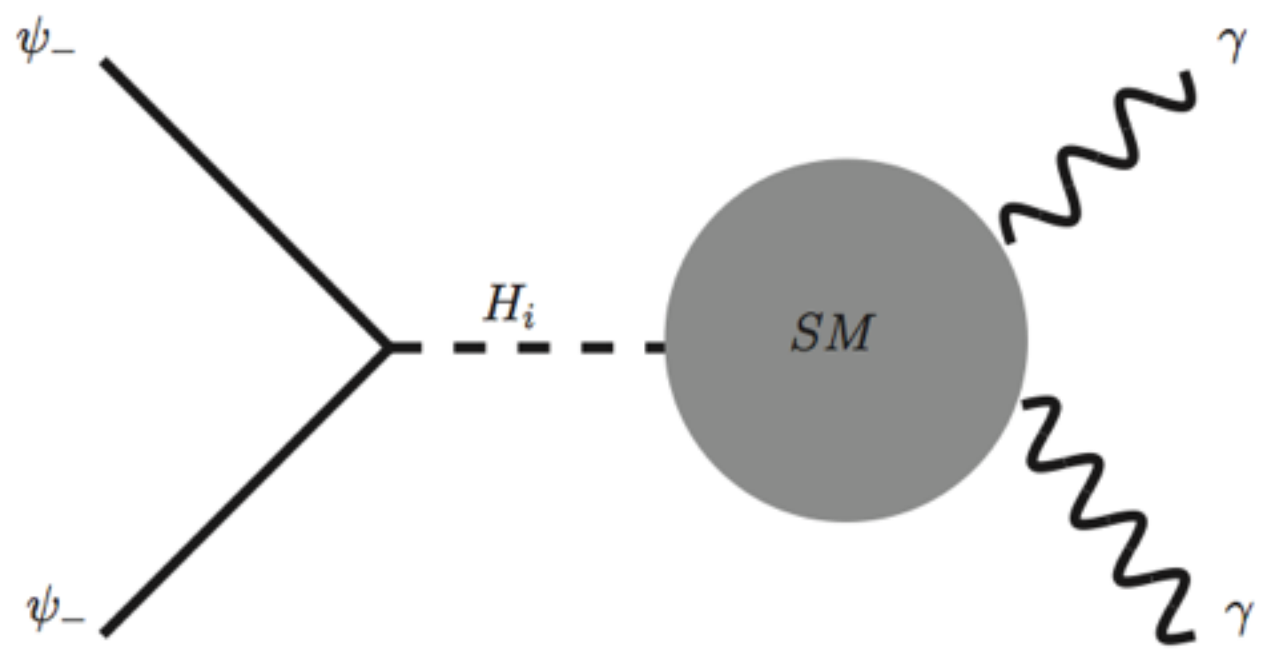


$$\Phi_{X-ray} \propto n_\chi^2 \times \sigma_{\chi_g+\chi_g\to\chi_e+\chi_e} \times \mathrm{BR}(\chi_\mathrm{e} \to \gamma + \chi_\mathrm{g}),$$
$$= \left(1.5 \times 10^{-25} - 2.7 \times 10^{-24}\right) \mathrm{cm}^{-3}\mathrm{s}^{-1}$$

$$(\sigma_{\chi\chi} v_{rel}) \times BR \simeq (1.7 \times 10^{-22} - 3.0 \times 10^{-21})\ \mathrm{cm}^3\mathrm{s}^{-1}(m_\chi/\mathrm{GeV})^2$$

Annihilating DM

Annihilating DM with mass 3.5 keV



Frandsen, et.al., 1403.1570
SB, Ko, Park, 1405.3730

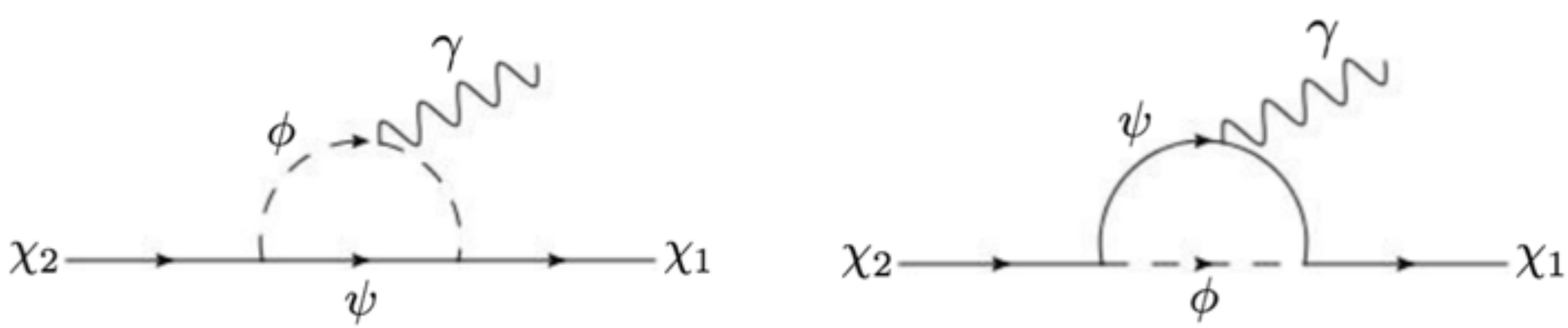
$$\langle \sigma_{\chi\bar{\chi}\to\gamma\gamma} v_{rel} \rangle \simeq (2\times 10^{-33} - 4\times 10^{-32})\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

Generalized Decaying DM

- Unstable χ*, but τ(χ*)≫age of universe, decays into stable χ: χ*→χ+γ

$$\Phi_{X-ray} \propto n_s\Gamma_s \;=\; 1.39\times 10^{-22}s^{-1}\sin^2 2\theta\left(\frac{m_s}{\mathrm{keV}}\right)^5 \rho_{DM}/m_s$$

H. M. Lee, 1404.5446; G. Faisel, S. Ho, J. Tandean, 1408.5887; SB, 1410.1992



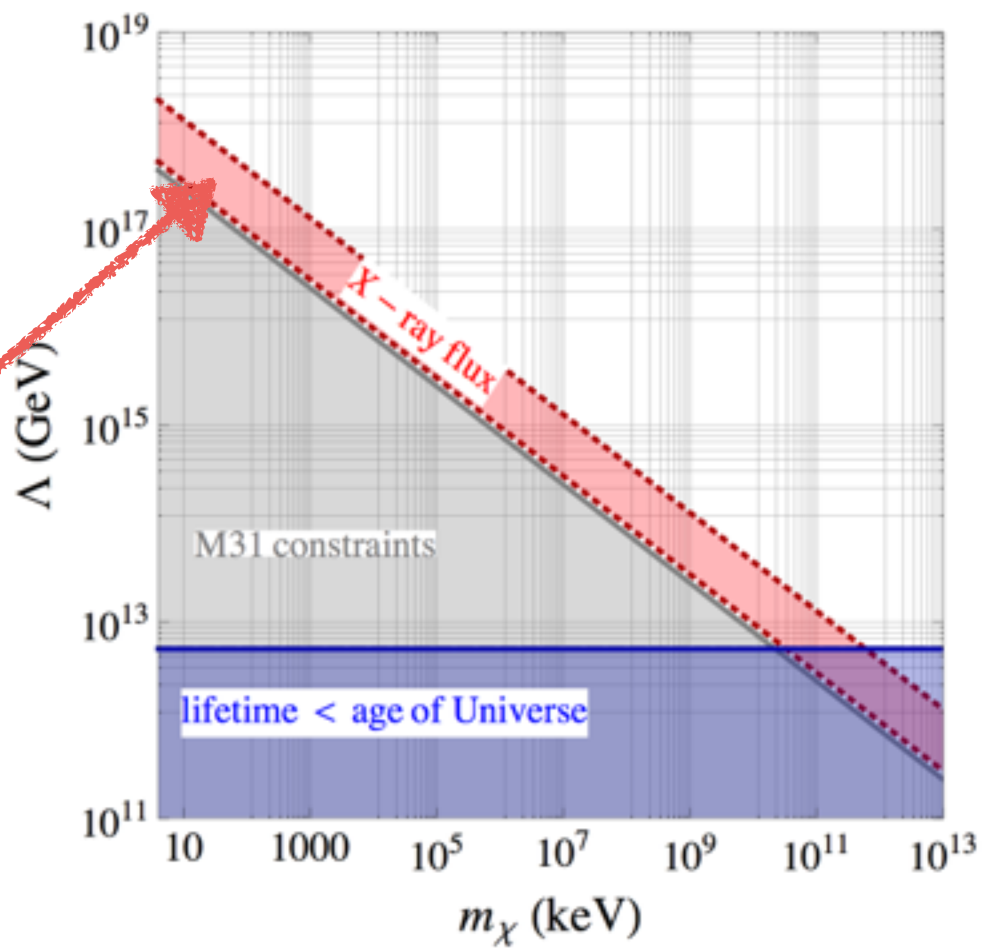
Generalized Decaying DM

- The decay can be described by transition dipole moment operator

$$\frac{1}{\Lambda}\bar{\chi}_e \sigma_{\mu\nu} \chi_g F^{\mu\nu}$$

$$\boxed{\begin{aligned}\Gamma &= \frac{8(\Delta m)^3}{\pi \Lambda^2} \\ &= (3.3 \times 10^{-48} - 5.9 \times 10^{-47})\mathrm{GeV}\left(\frac{m_g}{\mathrm{GeV}}\right)\end{aligned}}$$

$$\Delta m = 3.5\,\mathrm{keV}$$



Frandsen, et.al., 1403.1570

Generalized Decaying DM

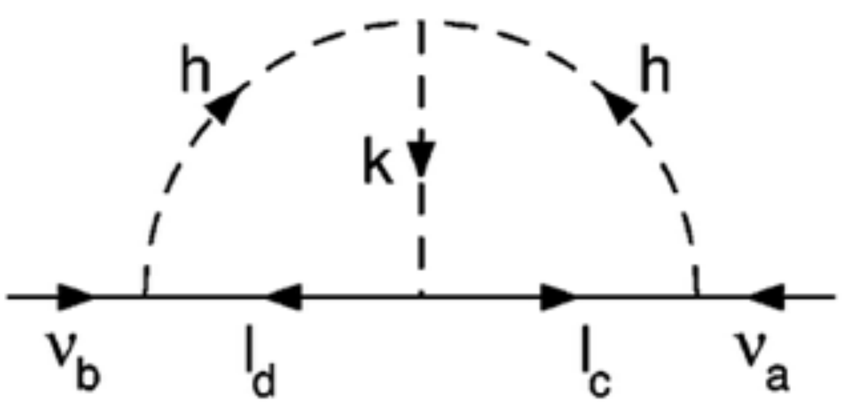
- Decaying DM for X-ray line signal can be realized in a specific model for neutrino masses: Zee-Babu model
  Babu, PLB(1988)

- Zee-Babu model for Majorana neutrinos: two charged scalars h^+, k^{++} with L=-2 are introduced in addition to the SM

$$\mathcal{L}_Y = f_{ab}(\psi^{Ti}_{aL} C \psi^j_{bL})\epsilon_{ij} h^+ + h'_{ab}(l^T_{aR} C l_{bR}) k^{++} + \mathrm{H.c.}$$

$$\mathcal{L}_{h-k} = -\mu h^+ h^+ k^{--} + \mathrm{H.c.}$$ L-violating soft term

$$\boxed{(\mathcal{M}_\nu)_{ab} = 8\mu f_{ac} m_c h^*_{cd} m_d f_{db} I_{cd}}$$



- The model can be extended to incorporate DM

Local U(1)$_{B-L}$ symmetry

$i = 1, 2, 3$

Fields	q_i	ℓ_i	h^+, k^{++}	φ	η	N_{R_i}	ψ_i
$B-L$	$1/3$	-1	2	2	0	-1	$1/3, 7/3, 13/3$
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$\pm$

ψ (Dirac DM) generate transition MD op.

φ U(1)$_{B-L}$ breaking scalar

η Light scalar for relic density & small scale problems

N_R (Majorana) cancel gauge anomaly

Local U(1)$_{B-L}$ symmetry

Fields	q_i	ℓ_i	h^+, k^{++}	φ	η	N_{R_i}	ψ_i
$B-L$	$1/3$	-1	2	2	0	-1	$1/3, 7/3, 13/3$
Z_2	$+$	$+$	$+$	$+$	$+$	$-$	$\pm$

LHN_R forbidden by Z2

$LH\psi$ forbidden by B-L charge assignment

Local U(1)$_{B-L}$ symmetry

$$\boxed{+(\lambda_\mu \varphi k^{++} h^- h^- + h.c)} \longrightarrow \mu k^{++} h^- h^-$$

dynamically generates LV μ term

$$\boxed{\mathcal{L}_\Psi = \overline{\psi_i} i\gamma^\mu D_\mu \psi_i - m_{\psi_i} \overline{\psi_i}\psi_i - f_{12}\left(\overline{\psi_1}\psi_2\varphi^* + \overline{\psi_2}\psi_1\varphi\right) - f_{23}\left(\overline{\psi_2}\psi_3\varphi^* + \overline{\psi_3}\psi_2\varphi\right)}$$

ψ's have "flavor" changing Z' and φ interaction

<φ>: U(1)$_{B-L}$ → Z_6: guarantees absolute stability of DM

$$\boxed{\mathcal{L}_{N_R} = \overline{N_{R_i}} i\gamma^\mu D_\mu N_{R_i} - \frac{1}{2}\left(\lambda_{N_{ij}} \varphi \overline{N^c_{R_i}} N_{R_j} + h.c.\right)}$$

N_R's do not have flavor changing Z'/φ interaction:

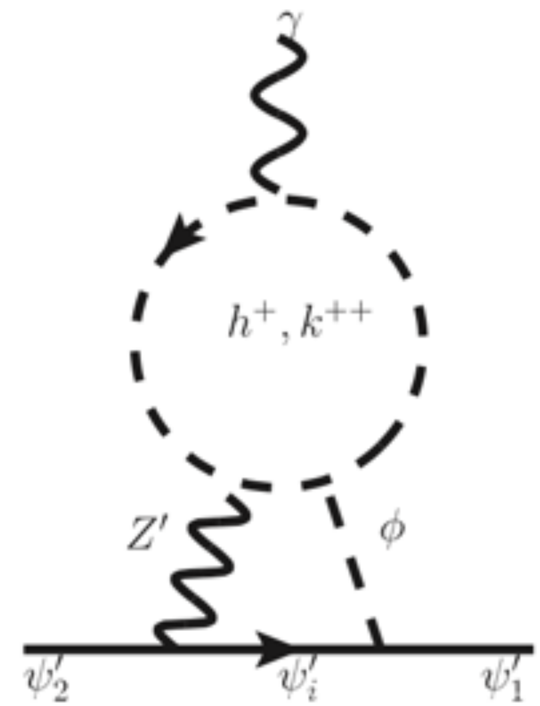
cannot explain X-ray line through TDO

Decaying DM in Z-B model

- Through two-loop Barr-Zee

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda}\overline{\psi_1'}\sigma_{\mu\nu}\psi_2' F^{\mu\nu}$$

is generated



$$\frac{1}{\Lambda} \simeq \sum_{s=h^+,k^{++}} \frac{8eg_{Z'}^2 \Delta Q_\psi Q_s Q_s' \lambda_{\varphi s}\delta^2 \cos 2\theta_{12} s_{13} s_{23}}{(4\pi)^4} \times \int_0^1 dx \int [d\beta] \frac{x\beta_4^2 m_{\psi_3'}^2}{\left(\beta_1 m_{Z'}^2 + \beta_2 m_\phi^2 + \beta_3 m_s^2/(x(1-x)) + \beta_4^2 m_{\psi_1'}^2\right)^2},$$

$$\delta = \Delta m_{31}/m_{\psi_3'}$$

Decaying DM in Z-B model

- To explain 3.5 keV X-ray line, we need

$$\Lambda = (6.94 \times 10^{14} - 2.95 \times 10^{15}) \left(\frac{m_{\psi'_2}}{\text{GeV}} \right)^{-1/2} \text{GeV}.$$

- In our case it is obtained not by heavy particle but by loop suppression

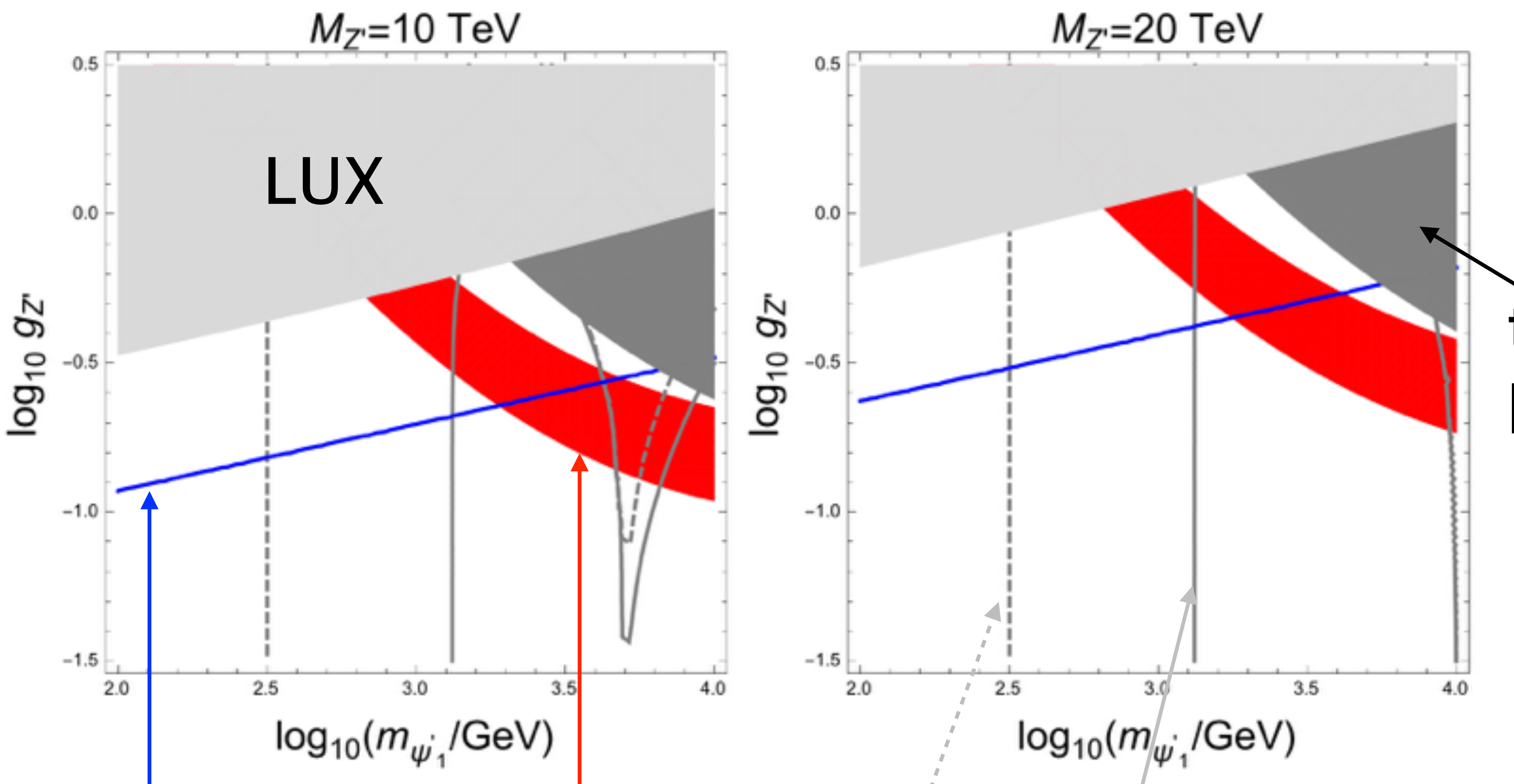
- Benchmark point

$$\delta = 0.2,\ \theta_{12} = \theta_{23} = 0.2,\ m_\phi = m_{h^+} = m_{k^{++}} = 1\ \text{TeV}$$

$$\lambda_{\varphi h} = \lambda_{\varphi k} = 1. \qquad m_\eta = 1\,\text{MeV}$$

- Constraints: LUX DM direct search, perturbativity, DM relic abundance, $\frac{M_{Z'}}{g_{Z'}} > 7\,\text{TeV}$

Decaying DM in Z-B model



too short lifetime

XENON1T

X-ray

$y_i = 1$ $y_i = 2$

relic density $\Omega_\psi h^2 = 0.1199 \pm 0.0027$

Decaying DM in Z-B model

- X-ray signal can be mainly controlled by M3-M1 mass difference.
- Direct detection is suppressed by large $M_{Z'}$
- Although Z_2 protects N_R's from decaying, the discrete symmetry can be broken by quantum gravity

$$\lambda_{ij}\ell_i H N_{R_j}, \quad \frac{1}{M_{\rm Pl}}\ell_i H N_{R_j}\eta, \quad \frac{1}{M_{\rm Pl}^2}N_{R_i}\ell_j\ell_k\bar{e}_l, \quad \frac{1}{M_{\rm Pl}^2}N_{R_i}\bar{d}_j\bar{d}_k\bar{u}_l,$$

$$\longrightarrow \quad |\lambda_{ij}| \ll 10^{-26} \qquad \tau_R \approx (10^5\,{\rm s})\left(\frac{10\,{\rm TeV}}{m_R}\right)^3$$

- Light m_η (1—10 MeV) can enhance $\psi'_{1(2)},\psi'_{1(2)} \to \psi'_{1(2)},\psi'_{1(2)}$ and can explain small scale structure problems, core-vs-cusp and too-big-to-fail problems, if $\sigma_T/m_{\psi'_1} \sim 0.1 - 10\,{\rm cm}^2/{\rm g}$,

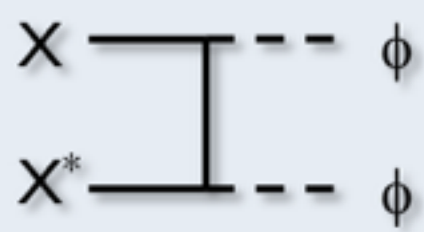
Decaying DM in Z-B model

- For $y_i \sim \mathcal{O}(1)$ the self-interaction occurs in the non-perturbative $(\alpha_y m_{\psi'}/m_\eta \gtrsim 1 \text{ with } \alpha_y \equiv y^2/4\pi)$ and classical $(m_{\psi'} v_{\rm rel}/m_\eta \gg 1)$ regime

$$\sigma_T = \int d\Omega (1-\cos\theta)\frac{d\sigma}{d\Omega} = \begin{cases} \frac{4\pi}{m_\eta^2}\beta^2 \ln(1+\beta^{-1}) & \text{for } \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\eta^2}\beta^2/(1+1.5\beta^{1.65}) & \text{for } 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\eta^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \text{for } \beta \gtrsim 10^3, \end{cases}$$

$\beta \equiv 2\alpha_y m_\eta/(m_\psi v_{\rm rel}^2)$ S. Tulin, et.al., 1302.3898

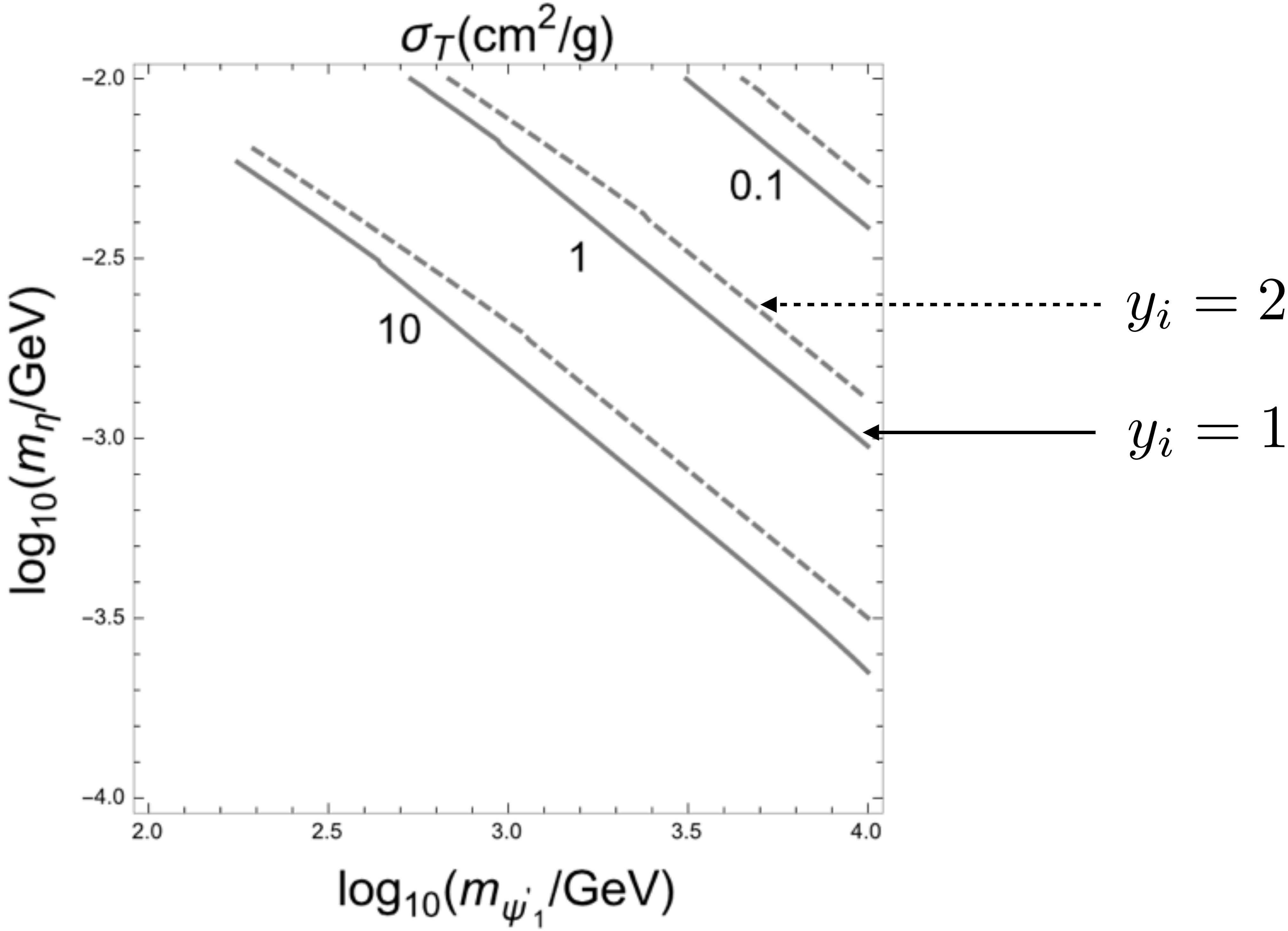
Dark force:



relic density

DM-DM elastic scattering

Decaying DM in Z-B model



Conclusions

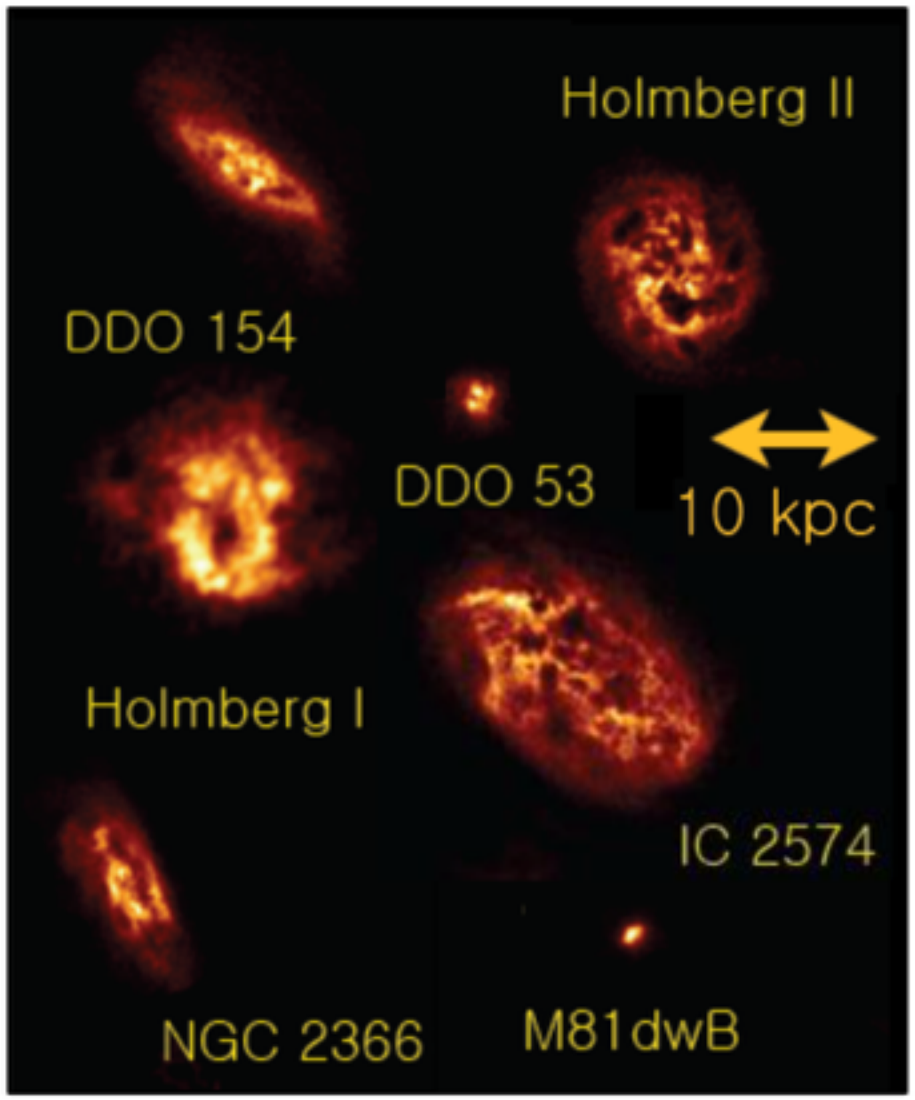
- 3.5 keV X-ray line signal can be explained by generalized decaying dark matter scenario in an extended Zee-Babu model
- Some parameter region is sensitive to the next generation DM direct search
- Light η achieves the correct relic abundance and also solves the small scale structure problems, core-vs-cusp and too-big-to-fail problem
- Discovery of h^+, k^{++} at LHC will support our scenario

Backups

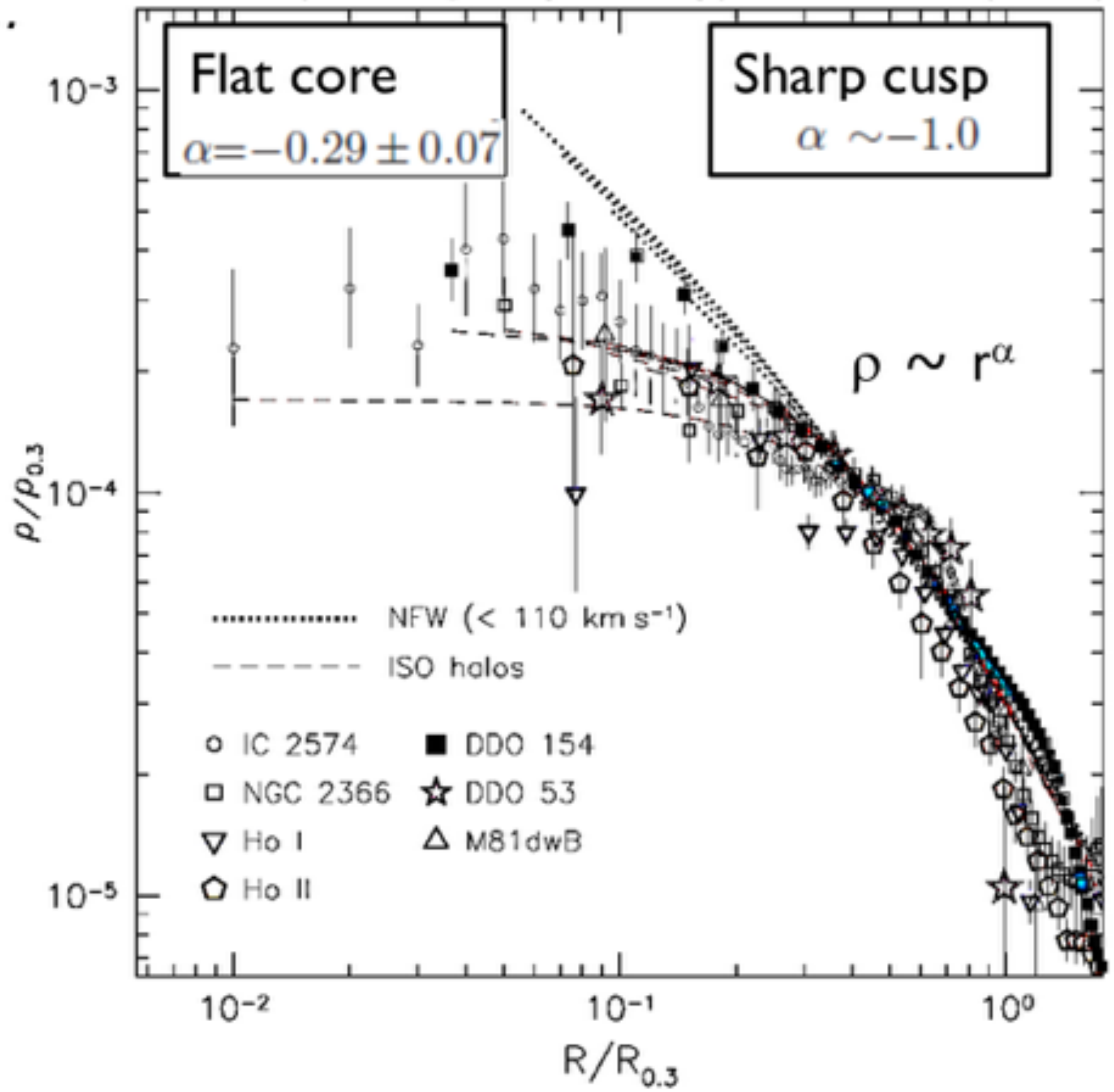
Small scale anomalies

1. Core vs cusp problem

Moore (1994), Flores & Primack (1994), ...



THINGS (dwarf galaxy survey) - Oh et al. (2011)



Tulin (2013)

Small scale anomalies

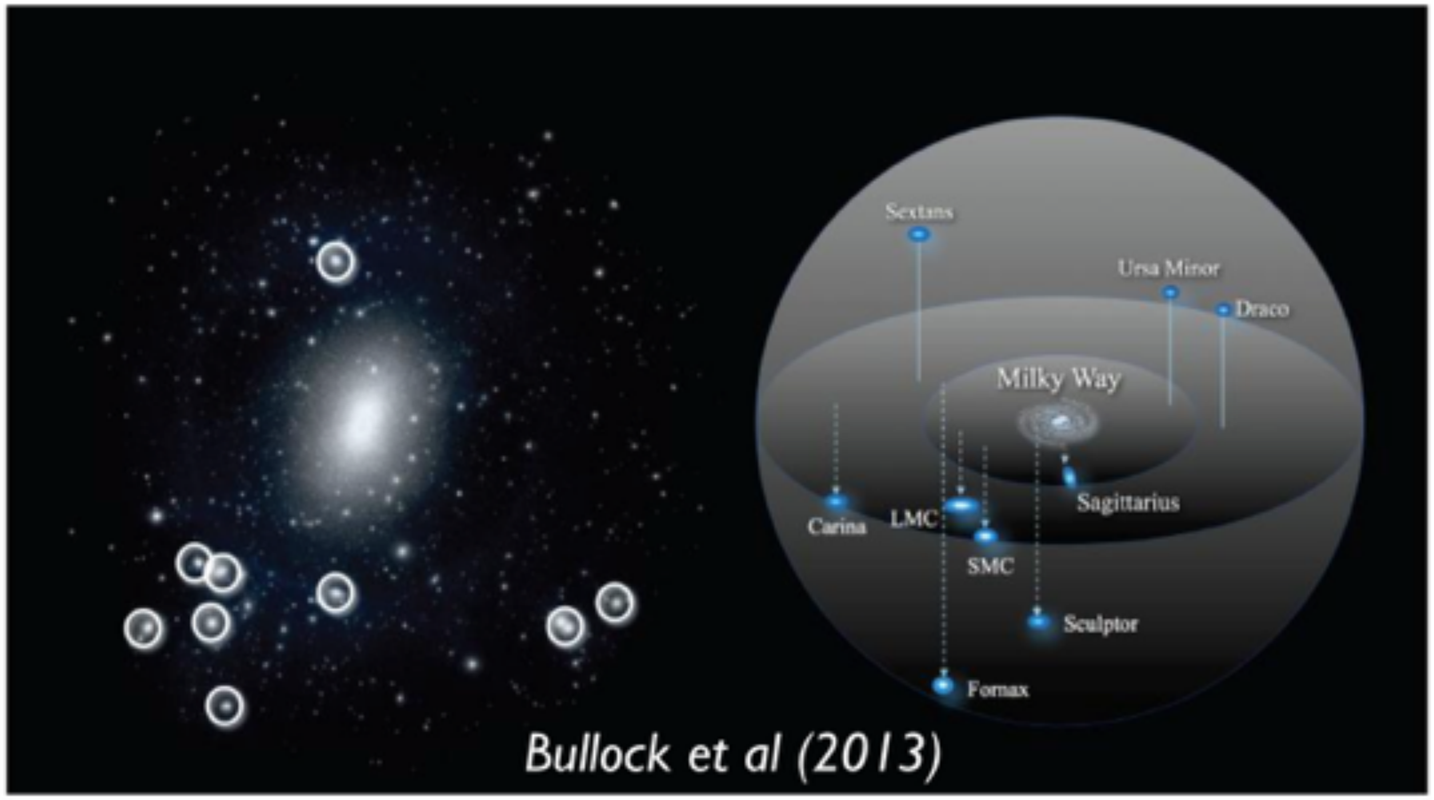
2. Missing satellite problem *Bullock (2010) [review]*

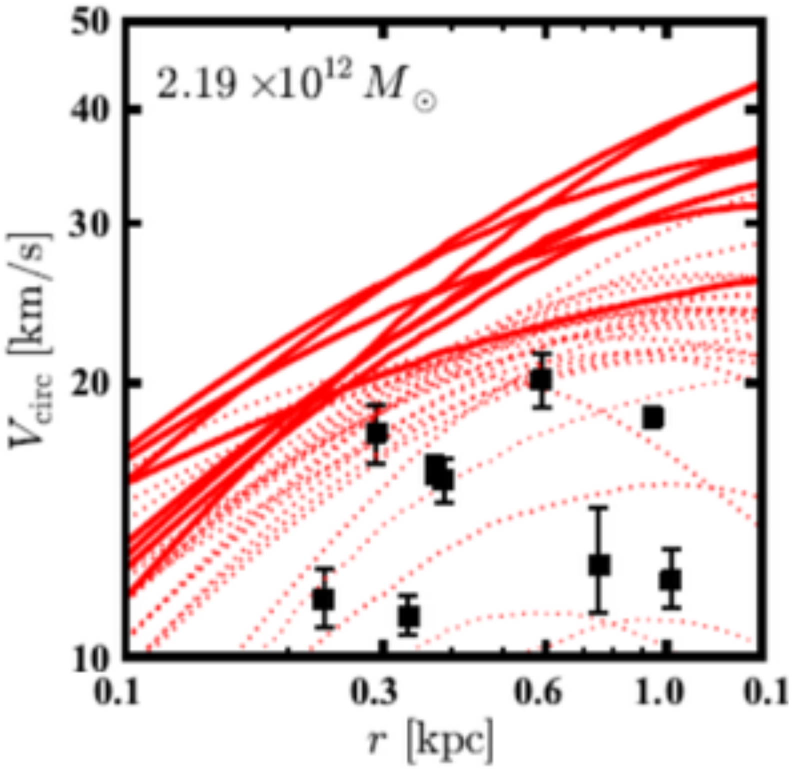
- CDM simulations predict O(10) times more satellite halos for MW than observed satellite galaxies
- Last 10 years: Sloan Digital Sky Survey has found many more low luminosity satellites
- "Missing" satellites are there, but difficult to detect due to quenched star formation

Tulin (2013)

Small scale anomalies

3. "Too big to fail" problem *Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)*
   - Milky Way galaxy should have O(10) satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals
   - Where are they?





Tulin (2013)

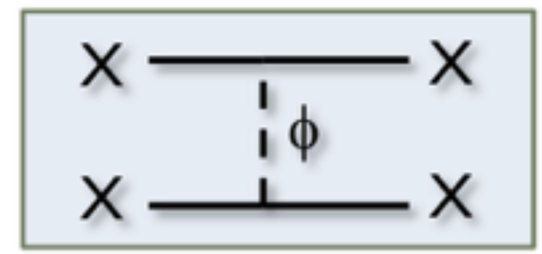
Small scale anomalies

- Failure of CDM-only simulations
- Can baryonic effects solve these problems? Maybe

  Navarro et al. (1996), Governato et al. (2009+2012), Brook et al. (2011), Pontzen et al. (2011), see also Purcell & Zenter (2012), Strigari et al (2010)

- Self-interacting DM can solve all problems

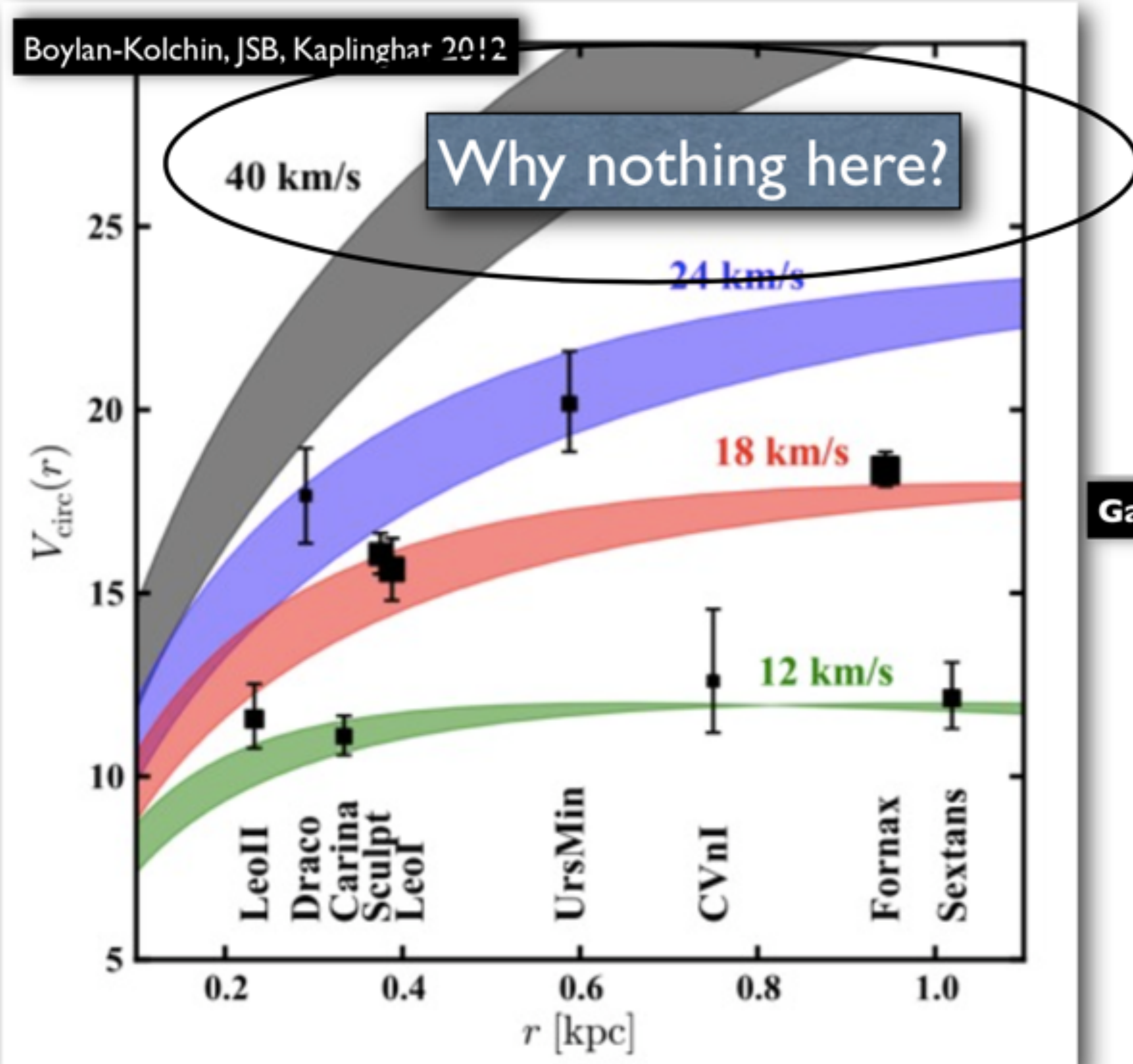
  Spergel & Steinhardt (1999)



  - Core vs cusp: energy transfer from outer to inner halo
  - Missing satellites: smaller halos stripped in hot MW halo
    - Doesn’t work – requires too large cross section
  - Too big to fail: rotation curves modified by self-interactions

Tulin (2013)

Summary of the Too Big To Fail problem:

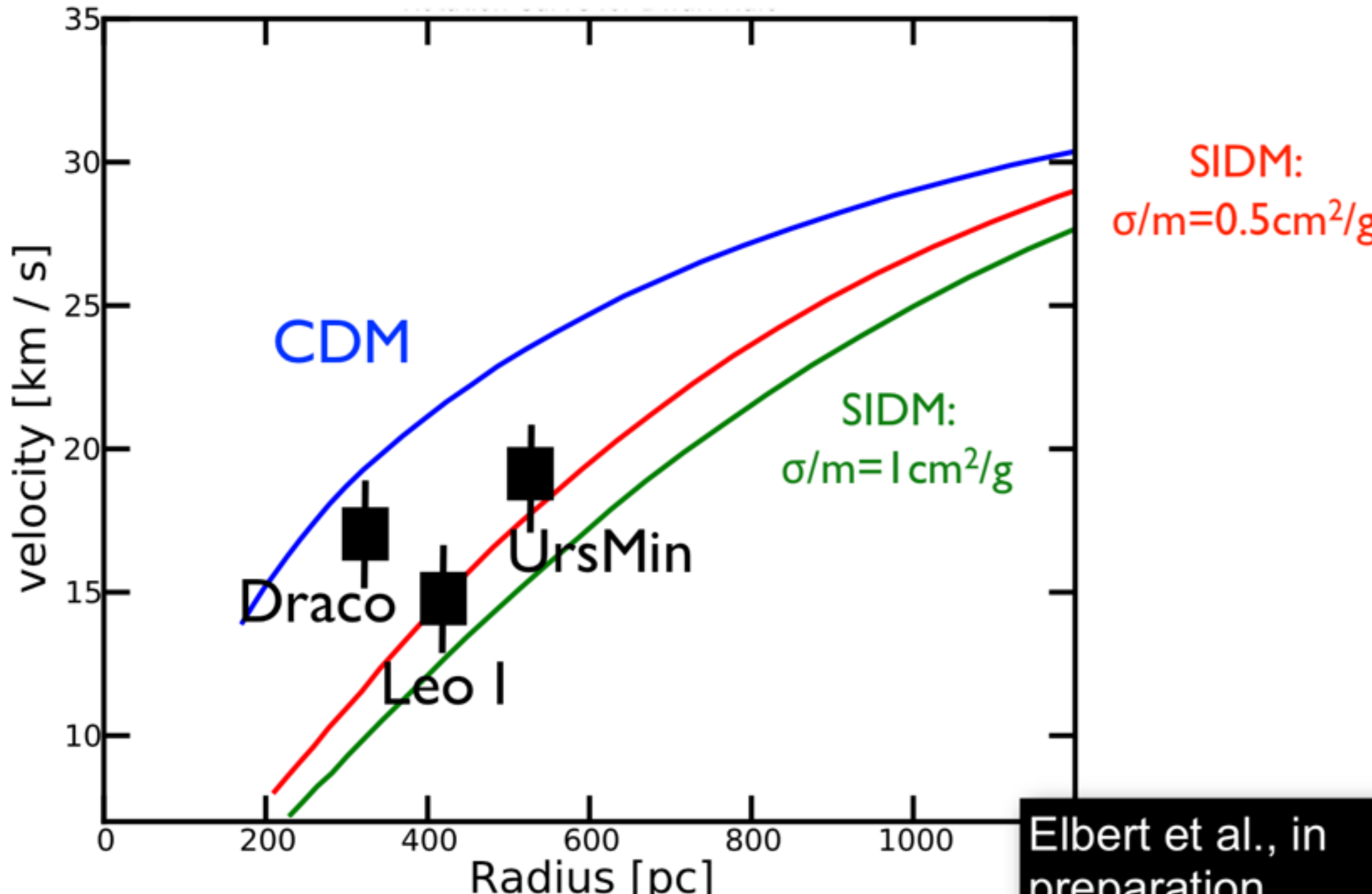


Expect 5-40 subhalos with V_{max} >25 km/s

(from 44 simulations)

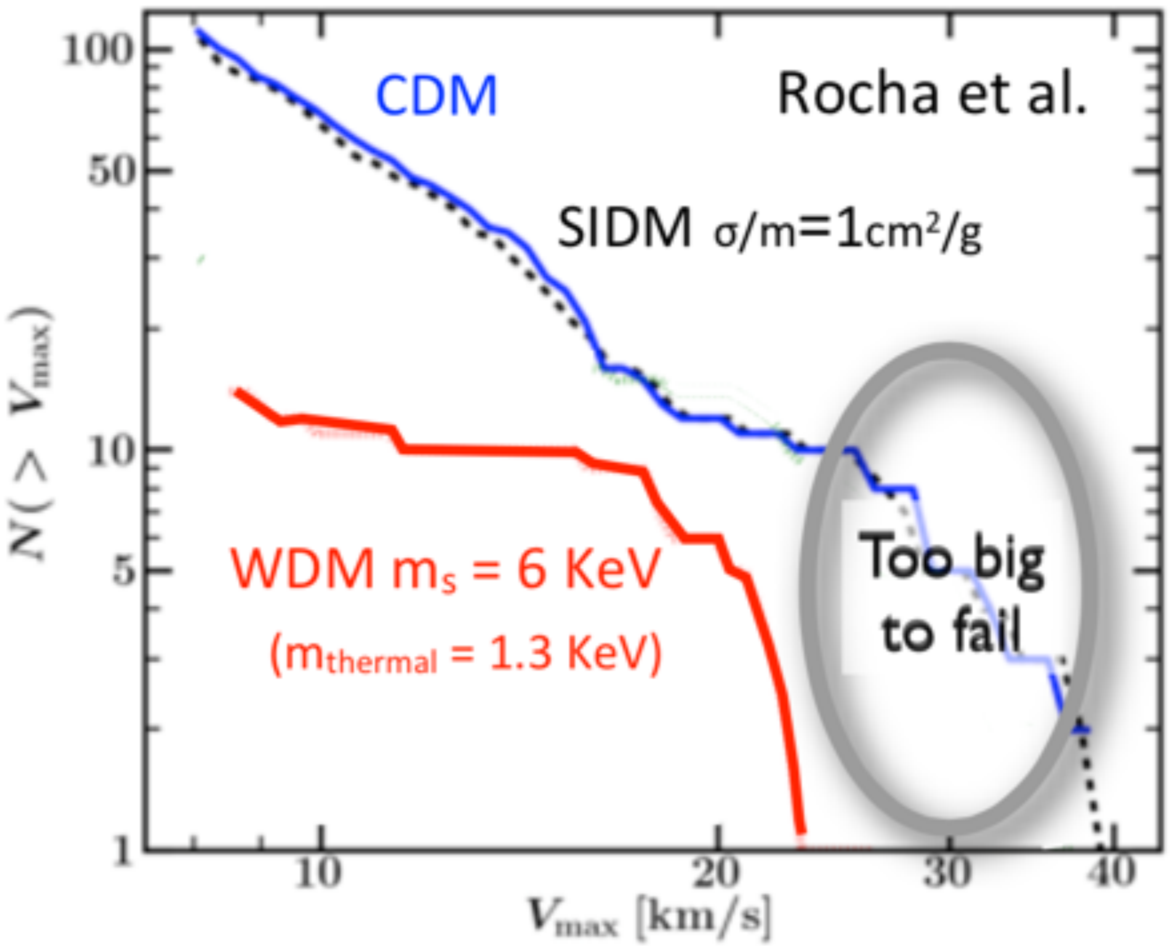
Garrison-Kimmel et al. in prep

SIDM with $\sigma/m=(0.5-1)cm^2/g$ Solves Too Big To Fail Problem



Elbert et al., in preparation.

Dark Matter Phenomenology in the Milky Way Halo



WDM:
- Many fewer subhalos

SIDM:
- Roughly same *number* of subhalos
- Solves Too Big To Fail by creating cores in all halos