

Radiative Neutrinos and Dark Matter

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imagine the impossible



University of Valencia, 2015-02-26

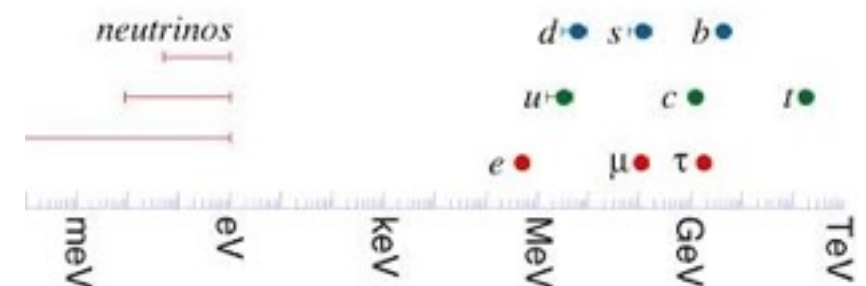
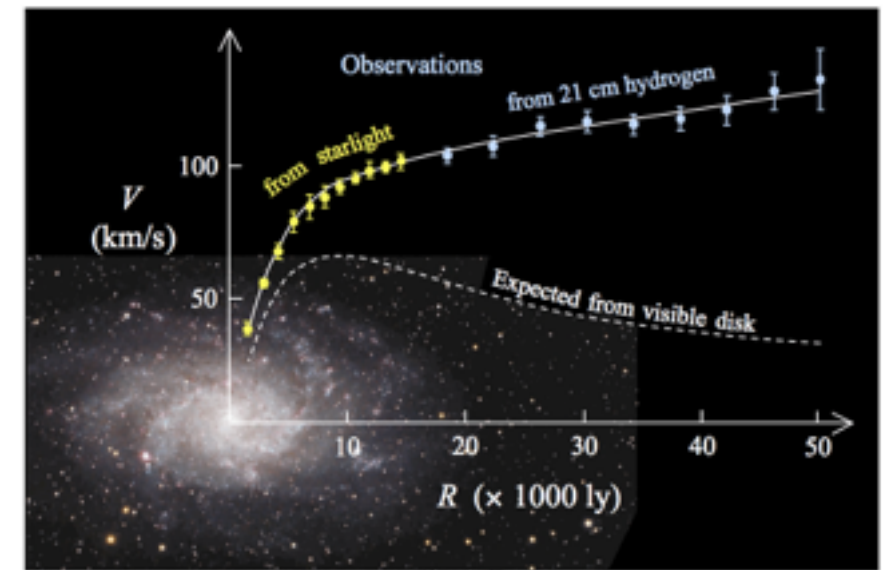


Outline

- Brief introduction to dark matter and neutrino
- 3.5keV X-ray line signal its explanation in DM models
- Radiative neutrino masses
- DM in Zee-Babu model and 3.5 keV X-ray line
- Conclusions

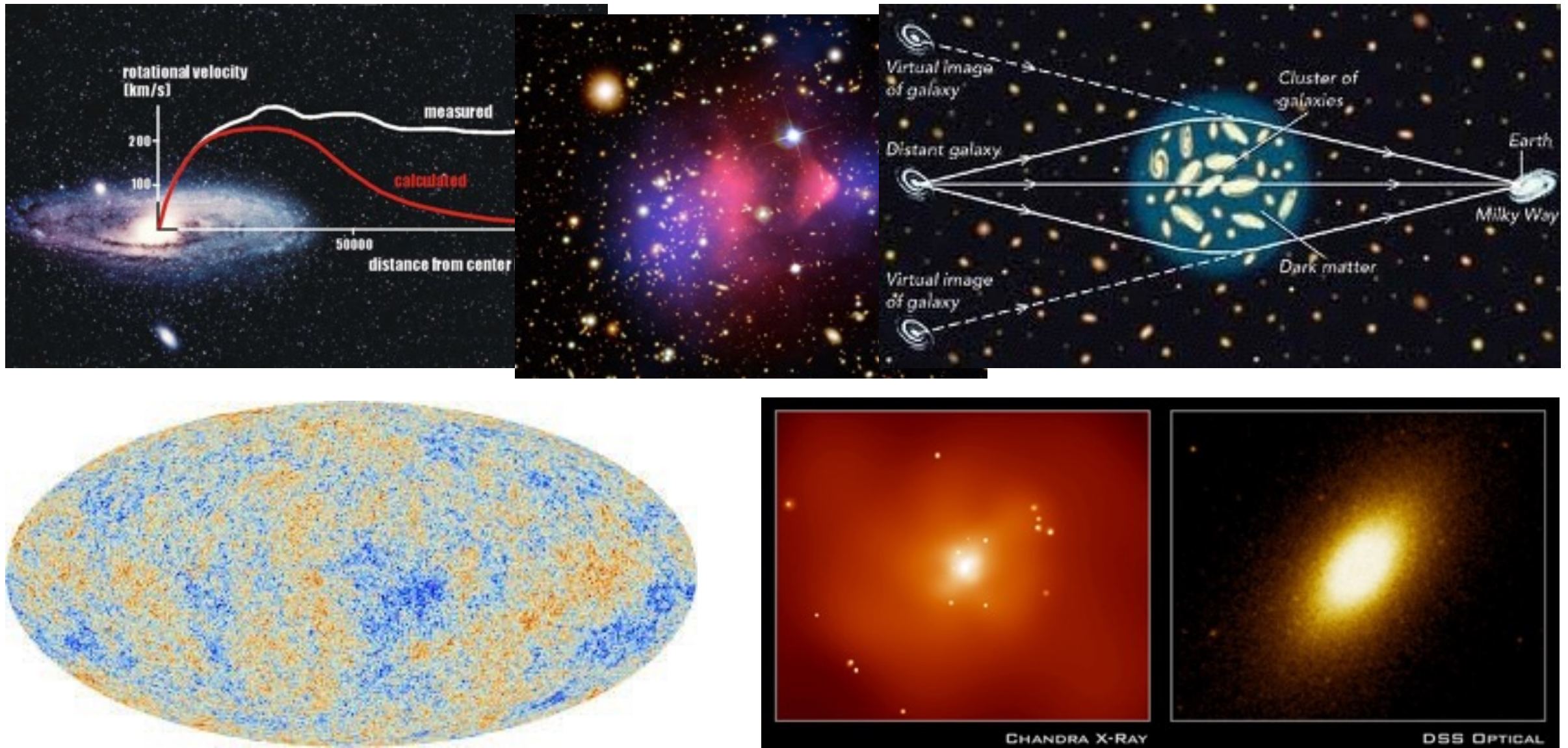
Two of Unsolved Problems in Particle Physics

- What is the identity of **dark matter**? Is it a particle?...
- Why are the **neutrino** masses are so small? Are they Dirac or Majorana? Is the mass hierarchy normal or inverted? Are the CP violating phases non-zero? ...

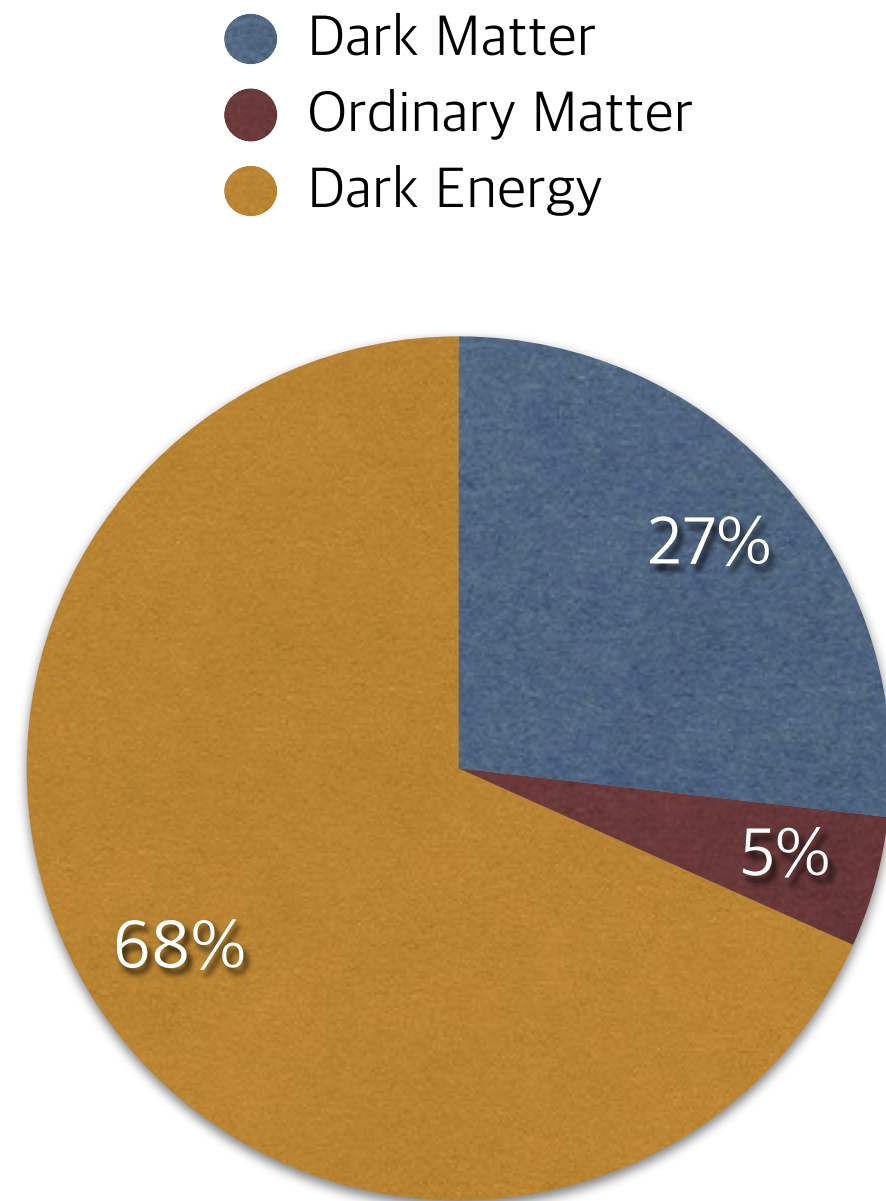


Dark Matter

- DM exists!



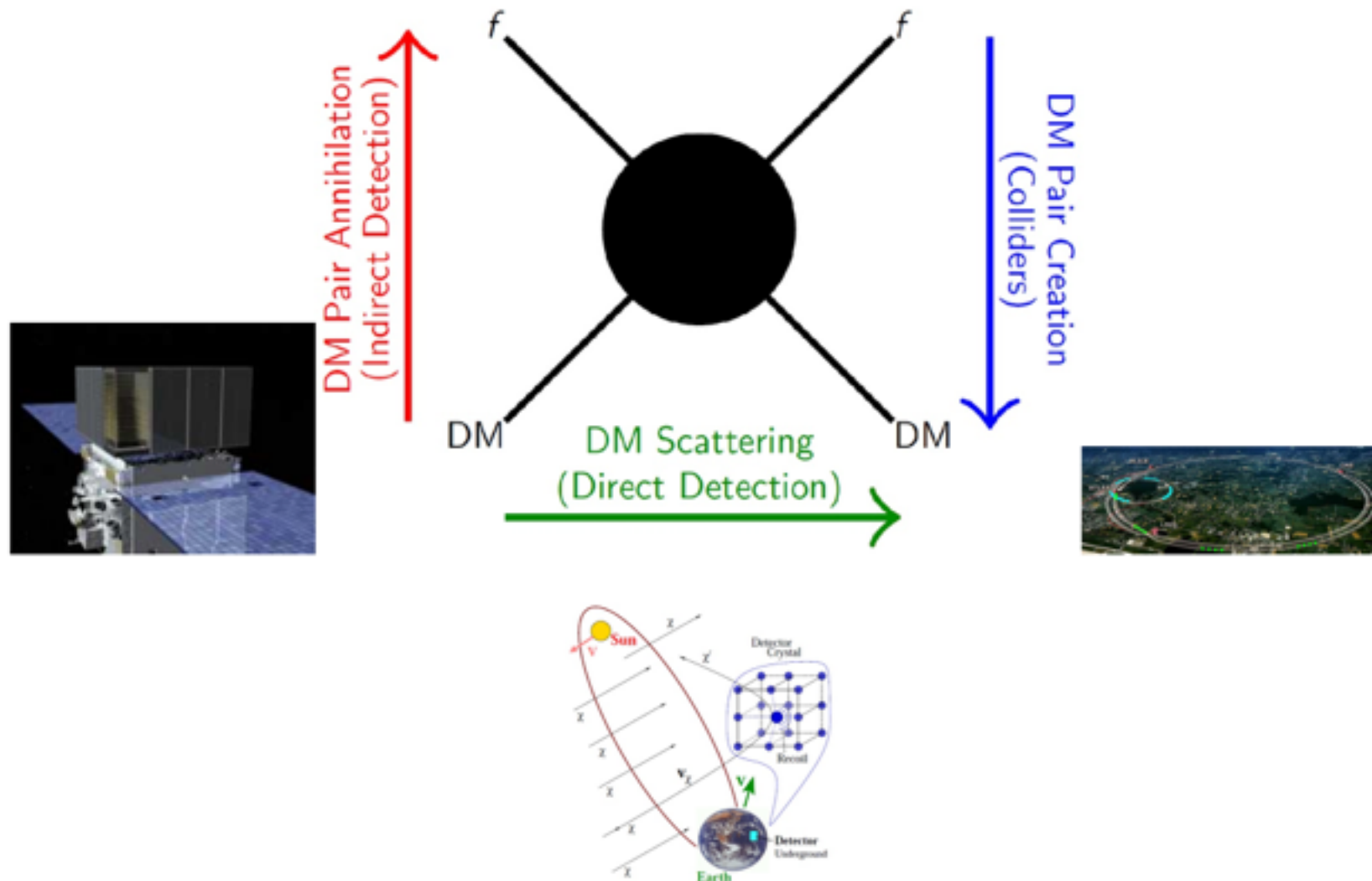
DM



- 27% of the universe is DM
- All the information about DM is from gravitational interaction
- We do not know much about its nature
 - Electrically neutral
 - Not a SM particle

DM

- Do DMs have interactions other than gravity? e.g. WIMP



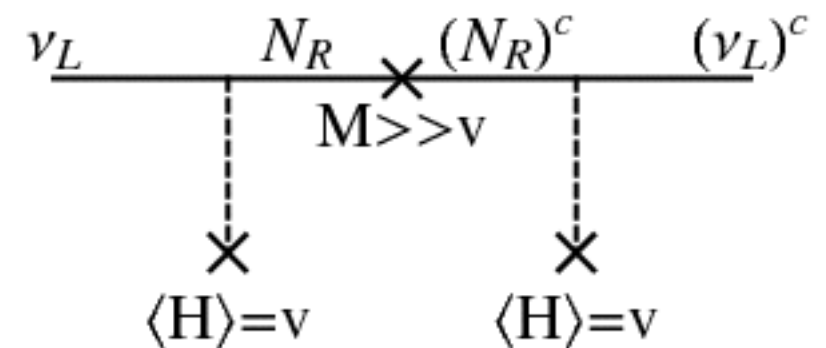
Neutrinos

- The most natural scenario for neutrino mass is seesaw mechanism

$$\mathcal{L} = -y_\nu L H N_R - \frac{1}{2} M N_R N_R$$

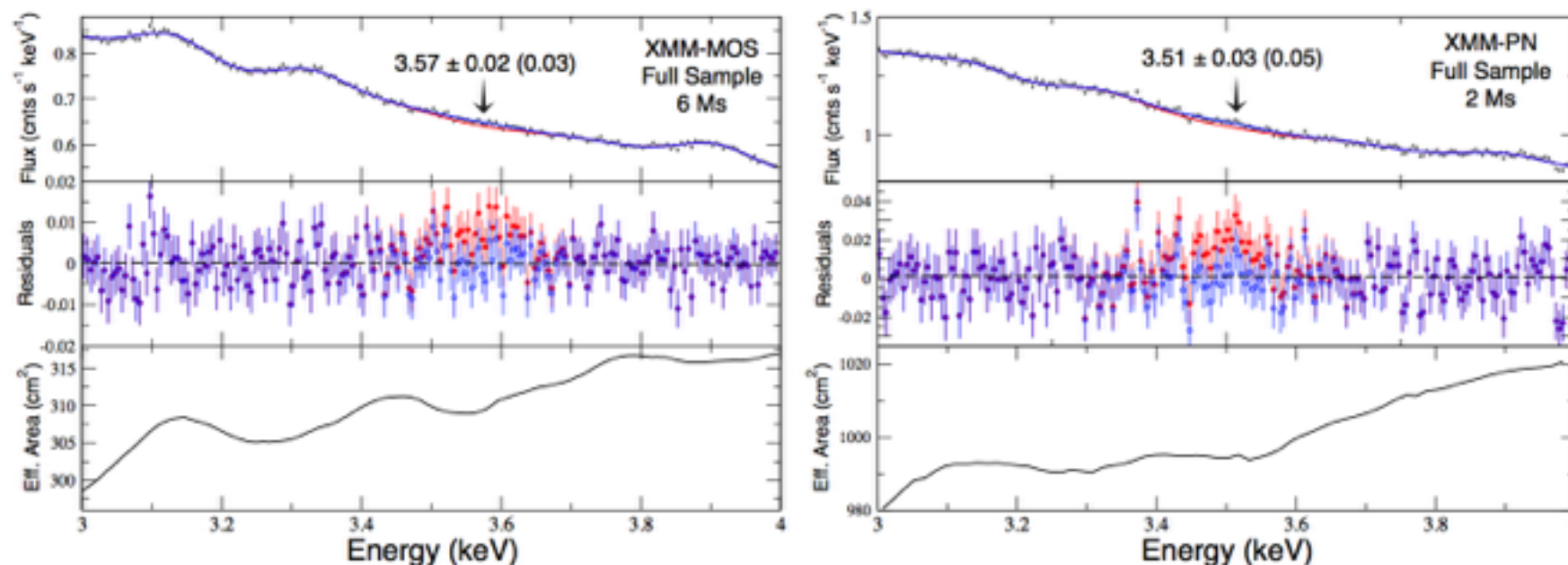
$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$

- Difficult to test at colliders.



3.5 keV X-ray line signal

- Unidentified 3.5 keV X-ray line from the XMM-Newton satellite data was reported ($>3\sigma$) in the direction of
 - i) the stacked analysis of 73 low redshift galaxy clusters [E. Bulbul, et.al, 1402.2301](#)
 - ii) from Andromeda galaxy and Perseus cluster [A. Boyarsky, et.al, 1402.4119](#)
- Suzaku search in four X-ray brightest galaxy clusters: Perseus, Coma, Virgo and Ophiuchus also finds evidence [Urban, et.al, 1411.0050](#)



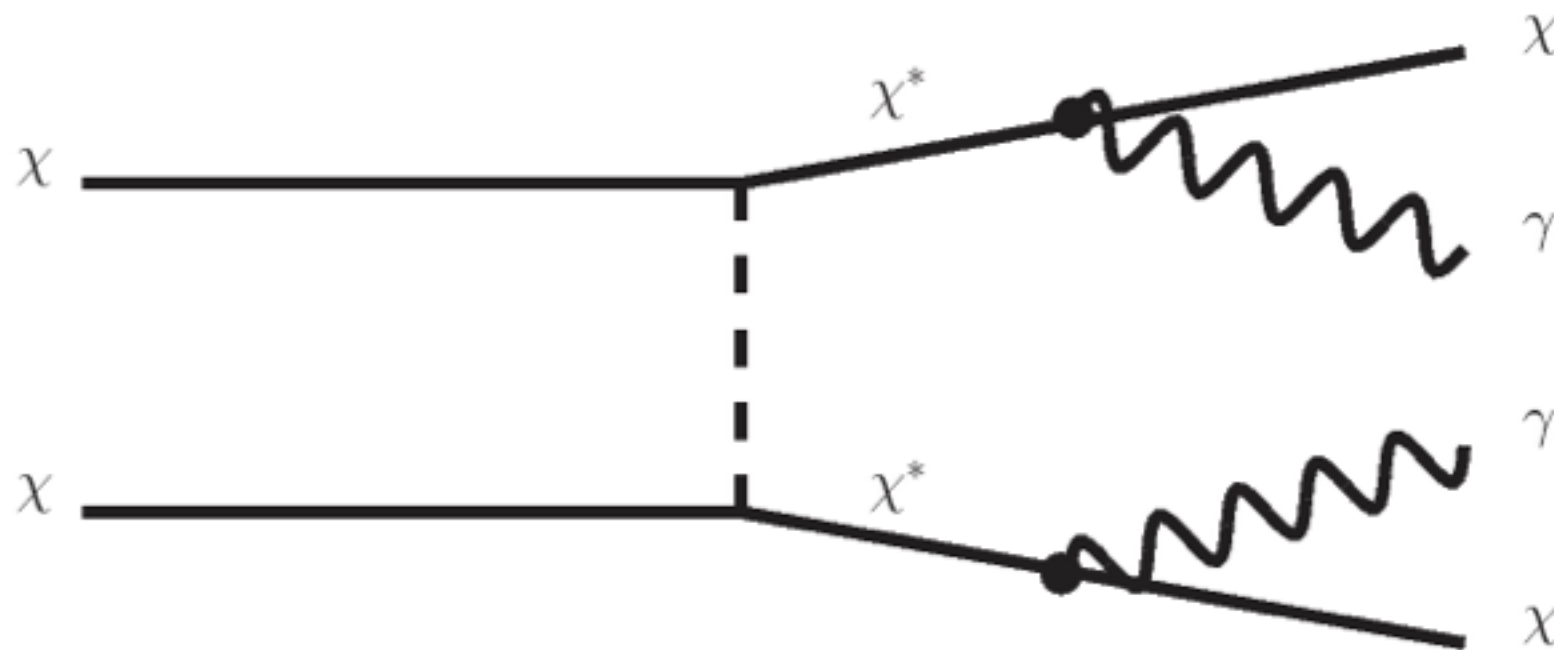
3.5 keV X-ray line signal

- A similar analysis with more data of Chandra and XMM-Newton data did not see the signal [M. Anderson, et.al., 1408.4115](#)
- 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](#)
 - Exciting DM may be an explanation: low velocity dispersion →no signal [J. Cline and A. Frey, 1410.7766](#); [A. Berlin, A. DiFranzo, D. Hooper, 1501.03496](#)

Exciting DM

Frandsen, et.al., 1403.1570

$$\chi_g + \chi_g \rightarrow \chi_e + \chi_e.$$



$$\Phi_{X-ray} \propto n_{\chi}^2 \times \sigma_{\chi_g + \chi_g \rightarrow \chi_e + \chi_e} \times \text{BR}(\chi_e \rightarrow \gamma + \chi_g),$$

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

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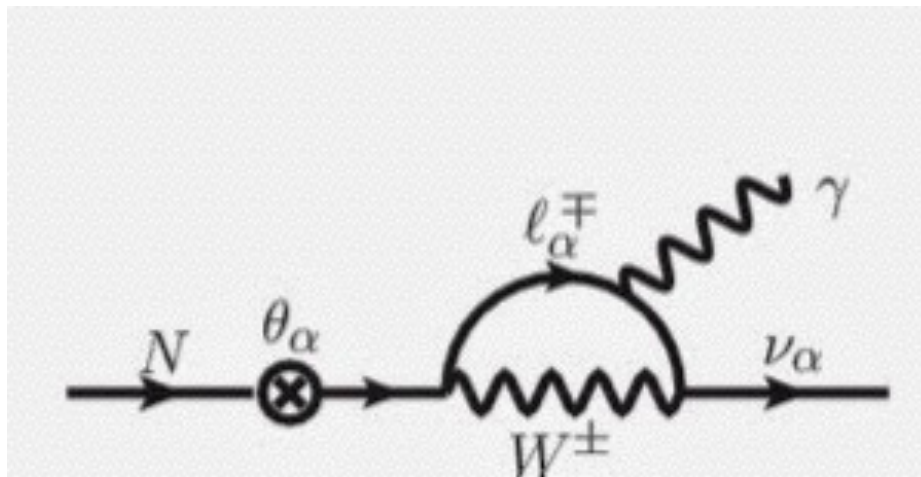
⁵Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

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.

Decay of sterile neutrino

$$\nu_s \rightarrow \nu + \gamma$$

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



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

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

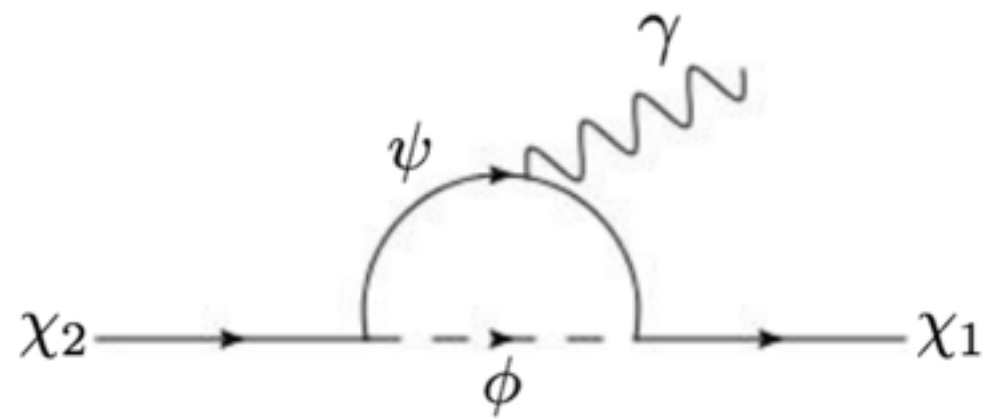
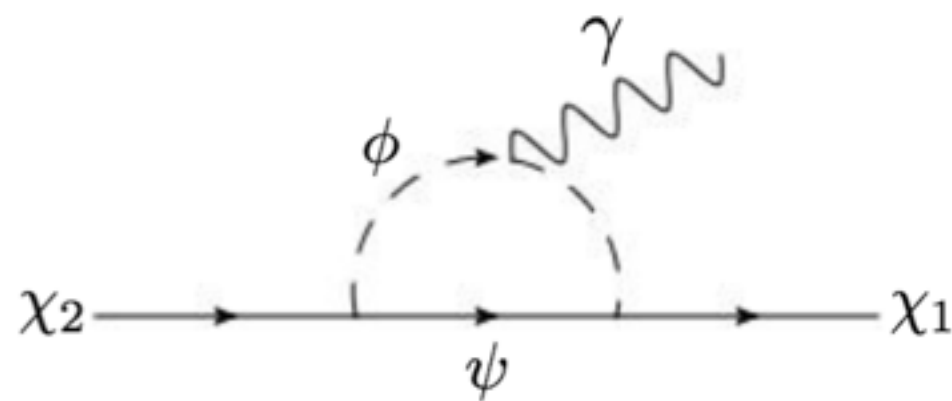
$$\begin{aligned} n_s \Gamma_s &= 1.39 \times 10^{-22} \text{ s}^{-1} \sin^2 2\theta \left(\frac{m_s}{\text{keV}} \right)^5 \rho_{DM}/m_s \\ &= (1.5 \times 10^{-25} - 2.7 \times 10^{-24}) \text{ cm}^{-3} \text{ s}^{-1}, \end{aligned}$$

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

Generalized Decaying DM

- Generalization of sterile neutrino DM
- Unstable χ^* , but $\tau(\chi^*) \gg \text{age of universe}$, decays into stable χ : $\chi^* \rightarrow \chi + \gamma$ $m_{\chi^*} - m_{\chi} = 3.5 \text{ keV}$

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



Generalized Decaying DM

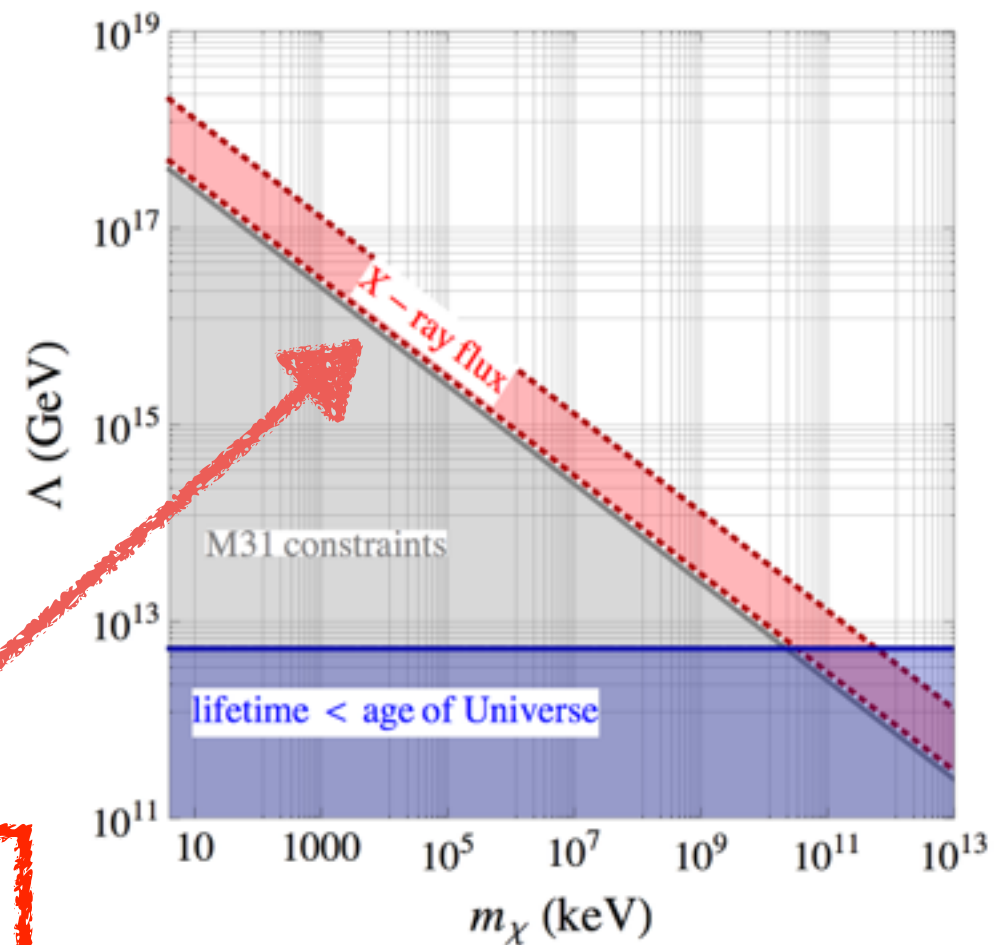
- The decay can be described by transition dipole moment operator

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

$$\Gamma = \frac{4(\Delta m)^3}{\pi \Lambda^3}$$

$$\Delta m = 3.5 \text{ keV}$$

$$\Lambda = (6.94 \times 10^{14} - 2.75 \times 10^{15}) \left(\frac{m_\chi}{\text{GeV}} \right)^{-1/2} \text{ GeV}$$



Frandsen, et.al., 1403.1570

Radiative Neutrino Masses: Ma Model

- Alternative scenario for the generation of neutrino masses to the seesaw mechanism
- The simplest one is Ma model. Small masses are due to loop suppression. DM is there (scotogenic).

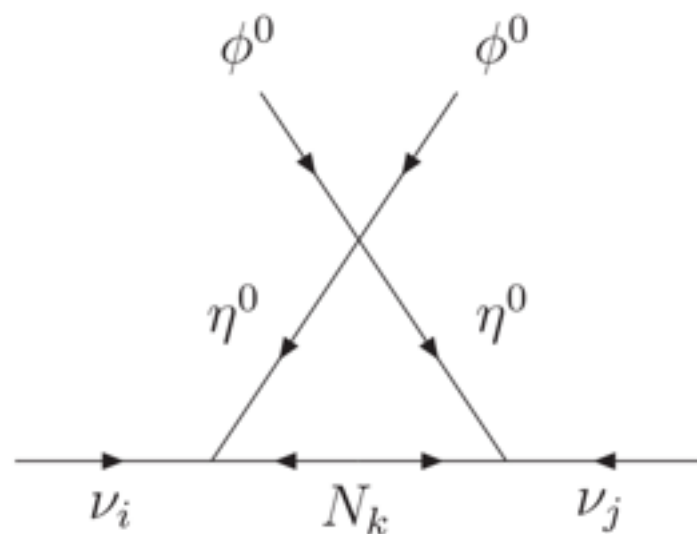


FIG. 1. One-loop generation of neutrino mass.

Under $SU(2)_L \times U(1)_Y \times Z_2$, the particle content is given by

$$(\nu_i, l_i) \sim (2, -1/2; +), \quad l_i^c \sim (1, 1; +), \quad N_i \sim (1, 0; -), \quad (3)$$

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \quad (\eta^+, \eta^0) \sim (2, 1/2; -). \quad (4)$$

$$\mathcal{L}_Y = f_{ij}(\phi^- \nu_i + \bar{\phi}^0 l_i) l_j^c + h_{ij}(\nu_i \eta^0 - l_j \eta^+) N_j + \text{H.c.}$$

$$\frac{1}{2} M_i N_i N_i + \text{H.c.}$$

E. Ma, PRD73 (2006)

$$\frac{1}{2} \lambda_5 (\Phi^\dagger \eta)^2 + \text{H.c.}$$

- Colliders may produce new particles at the ew scale

Radiative Neutrino Masses: Zee-Babu model

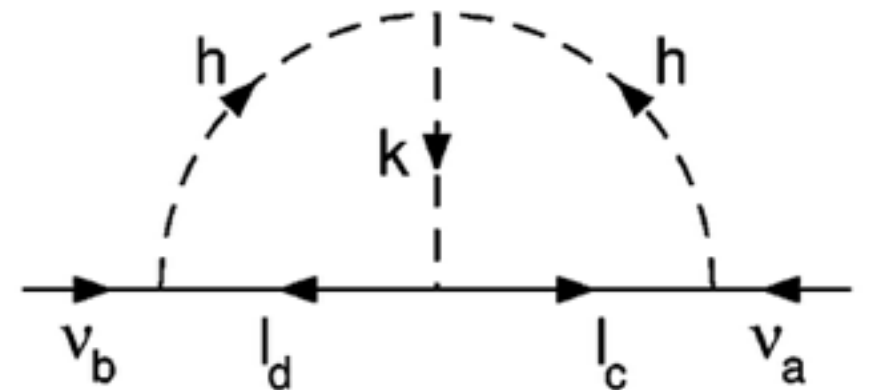
- Zee-Babu model for Majorana neutrinos: two charged scalars h^+ , k^{++} with $L=-2$ are introduced in addition to the SM [Babu, PLB\(1988\)](#)

$$\mathcal{L}_Y = f_{ab}(\psi_{aL}^{Ti} C \psi_{bL}^j) \epsilon_{ij} h^+ + h'_{ab}(l_{aR}^T C l_{bR}) k^{++} + \text{H.c.}$$

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

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

- Testable at LHC
- 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_{Ri}	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

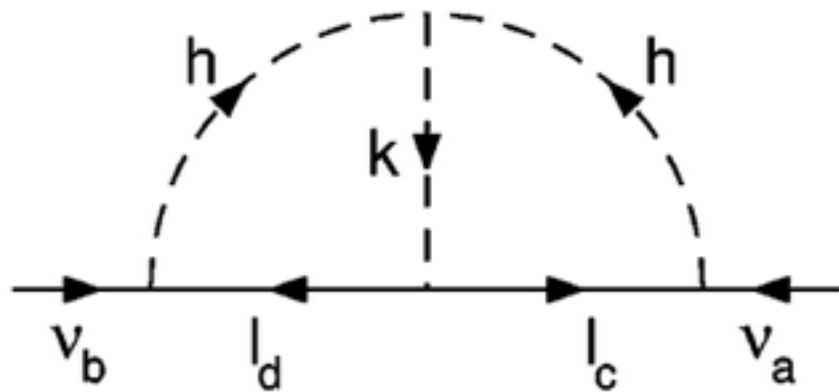
N_R (Majorana) cancel gauge anomaly

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

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

$LH N_R$ forbidden by Z_2

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



: dominant mechanism for neutrino masses

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

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Zee-Babu}} + \mathcal{L}_{\text{kin}} + \mathcal{L}_{\Psi} - V, \\
\mathcal{L}_{\text{Zee-Babu}} &= f_{ab} l_{aL}^T C l_{bL}^j \epsilon_{ij} h^+ + h'_{ab} l_{aR}^T C l_{bR}^j k^{++} + h.c., \\
\mathcal{L}_{N_R} &= \overline{N_{R_i}} i \gamma^\mu D_\mu N_{R_i} - \frac{1}{2} \left(\lambda_{N_{ij}} \varphi \overline{N_{R_i}^c} N_{R_j} + h.c. \right) \\
\mathcal{L}_{\Psi} &= \overline{\psi_i} i \gamma^\mu D_\mu \psi_i - m_{\psi_i} \overline{\psi_i} \psi_i - f_{12} \left(\overline{\psi_1} \psi_2 \varphi^* + \overline{\psi_2} \psi_1 \varphi \right) - f_{23} \left(\overline{\psi_2} \psi_3 \varphi^* + \overline{\psi_3} \psi_2 \varphi \right) \\
&\quad - \eta (y_1 \overline{\psi_1} \psi_1 + y_2 \overline{\psi_2} \psi_2 + y_3 \overline{\psi_3} \psi_3), \\
\mathcal{L}_{\text{kin}} &= |\mathcal{D}_\mu h^+|^2 + |\mathcal{D}_\mu k^{++}|^2 + |\mathcal{D}_\mu \varphi|^2 + \frac{1}{2} (\partial_\mu \eta)^2 + \sum_{i=1}^3 \overline{\psi_i} i \gamma^\mu \mathcal{D}_\mu \psi_i - \frac{1}{4} \hat{Z}'_{\mu\nu} \hat{Z}'^{\mu\nu} - \frac{\sin \chi}{2} \hat{Z}'_{\mu\nu} \hat{B}^{\mu\nu}, \\
V &= \mu_H^2 H^\dagger H + \mu_\varphi^2 \varphi^* \varphi + \frac{1}{2} \mu_\eta^2 \eta^2 + \mu_h^2 h^+ h^- + \mu_k^2 k^{++} k^{--} \\
&\quad + (\lambda_\mu \varphi k^{++} h^- h^- + h.c.) \\
&\quad + \lambda_H (H^\dagger H)^2 + \lambda_\varphi (\varphi^* \varphi)^2 + \frac{1}{4} \lambda_\eta \eta^4 + \lambda_h (h^+ h^-)^2 + \lambda_k (k^{++} k^{--})^2 \\
&\quad + \lambda_{H\varphi} H^\dagger H \varphi^* \varphi + \lambda_{Hh} H^\dagger H h^+ h^- + \lambda_{Hk} H^\dagger H k^{++} k^{--} \\
&\quad + \lambda_{\varphi h} \varphi^* \varphi h^+ h^- + \lambda_{\varphi k} \varphi^* \varphi k^{++} k^{--} + \lambda_{hk} h^+ h^- k^{++} k^{--} \\
&\quad + \frac{1}{2} \lambda_{H\eta} H^\dagger H \eta^2 + \frac{1}{2} \lambda_{\varphi\eta} \varphi^* \varphi \eta^2 + \dots,
\end{aligned}$$

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

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

dynamically generates LV μ -term

$$\mathcal{L}_\Psi = \bar{\psi}_i i \gamma^\mu D_\mu \psi_i - m_{\psi_i} \bar{\psi}_i \psi_i - f_{12} (\bar{\psi}_1 \psi_2 \varphi^* + \bar{\psi}_2 \psi_1 \varphi) - f_{23} (\bar{\psi}_2 \psi_3 \varphi^* + \bar{\psi}_3 \psi_2 \varphi)$$

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

$\langle \varphi \rangle: U(1)_{B-L} \rightarrow Z_6$: not broken by quantum gravity $\rightarrow$

guarantees absolute stability of DM

$$q(\psi) \rightarrow e^{i2\pi/6} q(\psi), \quad l(N_R) \rightarrow e^{i3\pi/6} l(N_R),$$

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

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

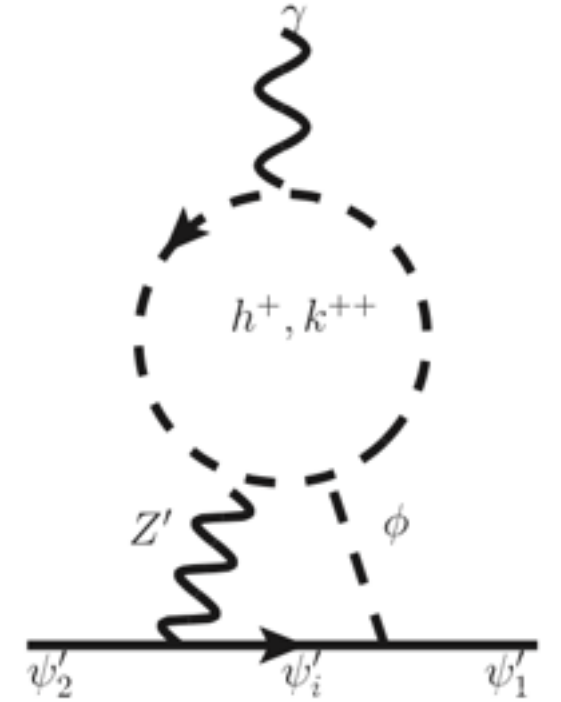
$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} \overline{\psi'_1} \sigma_{\mu\nu} \psi'_2 F^{\mu\nu}$$

is generated

$$\frac{1}{\Lambda} \simeq - \sum_{s=h^+, k^{++}} \frac{8eg_{Z'}^2 \Delta Q_\psi Q_s Q'_s \lambda_{\varphi s} \delta^2 \cos 2\theta_{12} s_{13} s_{23}}{(4\pi)^4} \times \int_0^1 dx \int [d\beta] \frac{x\beta_4^2 m_{\psi'_3}^3}{\left(\beta_1 m_{Z'}^2 + \beta_2 m_\phi^2 + \beta_3 m_s^2/(x(1-x)) + \beta_4^2 m_{\psi'_1}^2\right)^2}$$

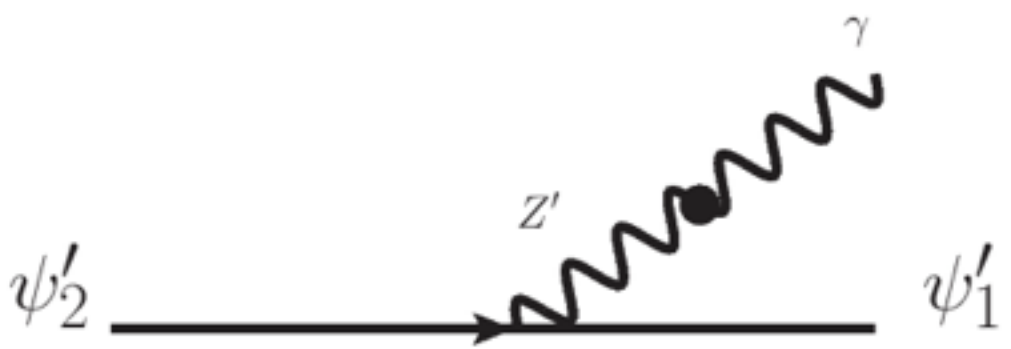
$$\Lambda \sim 10^8 \times \left(\frac{0.2}{\delta}\right)^2 \times \frac{\max(m_{Z'}^4, m_\phi^4, m_{h^+}^4, m_{k^{++}}^4, m_{\psi'_1}^4)}{m_{\psi'_3}^3},$$

for $g_{Z'} \sim 0.3$, $\theta_{12} \sim \theta_{23} \sim 0.2$. For $m_{Z'} \sim 10$ TeV, $m_{\psi'_3} \sim 1$ TeV, $\delta \sim 0.2$, we get $\Lambda \sim 10^{15}$



$$\delta = \Delta m_{31}/m_{\psi'_3}$$

Kinetic mixing

- Z'- γ mixing: $-\sin \chi \hat{Z}'_{\mu\nu} \hat{F}^{\mu\nu} / 2$
- Tree-level TMDO? No. 

- Canonical kinetic energy by non-unitary transf.

$$\begin{pmatrix} \hat{A} \\ \hat{Z}' \end{pmatrix} = \begin{pmatrix} 1 & -\tan \chi \\ 0 & \sec \chi \end{pmatrix} \begin{pmatrix} A \\ Z' \end{pmatrix} \quad \Delta\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu,$$

- The transformation is unique for massive Z'

- Covariant derivative
$$D_\mu = \partial_\mu + i\hat{e}Q\hat{A}_\mu + i\hat{g}_{Z'}Q_{Z'}\hat{Z}'_\mu$$

$$= \partial_\mu + i\hat{e}QA_\mu + \frac{i}{\cos \chi}(\hat{g}_{Z'}Q_{Z'} - \hat{e}Q \sin \chi)Z'_\mu.$$

- Photon couples only to EM-charge

- (cf) milli-charged DM:
$$D_\mu = \partial_\mu + i \left(\frac{\hat{e}}{\cos \chi} Q - \hat{g}_{Z'} Q_{Z'} \tan \chi \right) A_\mu + i\hat{g}_{Z'} Q_{Z'} Z'_\mu$$

Fine-Tuning

- Small parameters in the model: $\Delta m_{12} \ll m_\psi$
- 't Hooft naturalness criterion “A parameter is **naturally** small if setting it to zero increases the symmetry of the theory”
- Setting Δm_{12} to zero increases the symmetry U(2)-flavor symmetry in (ψ_1, ψ_2) flavor space
- Small Δm_{12} is technically natural

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

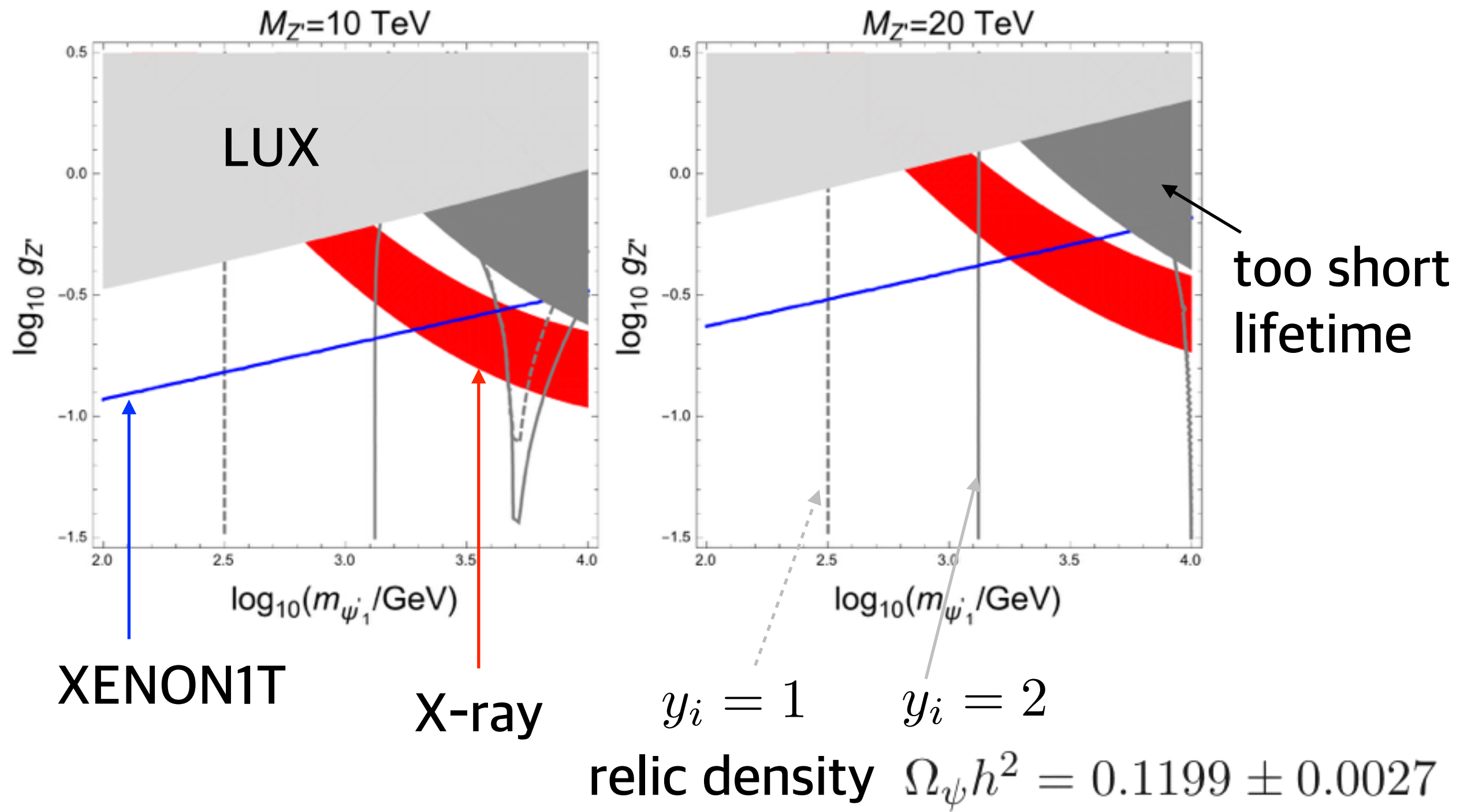
- Benchmark point

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

$$\lambda_{\phi h} = \lambda_{\phi k} = 1. \quad m_\eta = 1 \text{ MeV}$$

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

Decaying DM in Z-B model



The fate of N_R

- Although Z_2 protects N_R 's from decaying, the discrete symmetry can be broken by quantum gravity

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

$$\tau(N_R) \sim \left(\frac{10^{-5}}{\lambda_{ij}}\right)^2 \left(\frac{10 \text{ TeV}}{m_R}\right) 10^{-16} \text{ sec.} \quad \tau_R \approx (10^5 \text{ s}) \left(\frac{10 \text{ TeV}}{m_R}\right)^3$$

$$m_\nu \sim \left(\frac{\lambda_{ij}}{10^{-5}}\right)^2 \left(\frac{10 \text{ TeV}}{m_R}\right) 0.5 \text{ eV.}$$

$10^{-24} \lesssim \lambda_{ij} \ll 10^{-5}$: NR can decay very fast w/o affecting cosmology or neutrino masses

η phenomenology

- The lifetime of η is of order 1 sec, for mass 10 MeV, mixing angle 10^{-5}

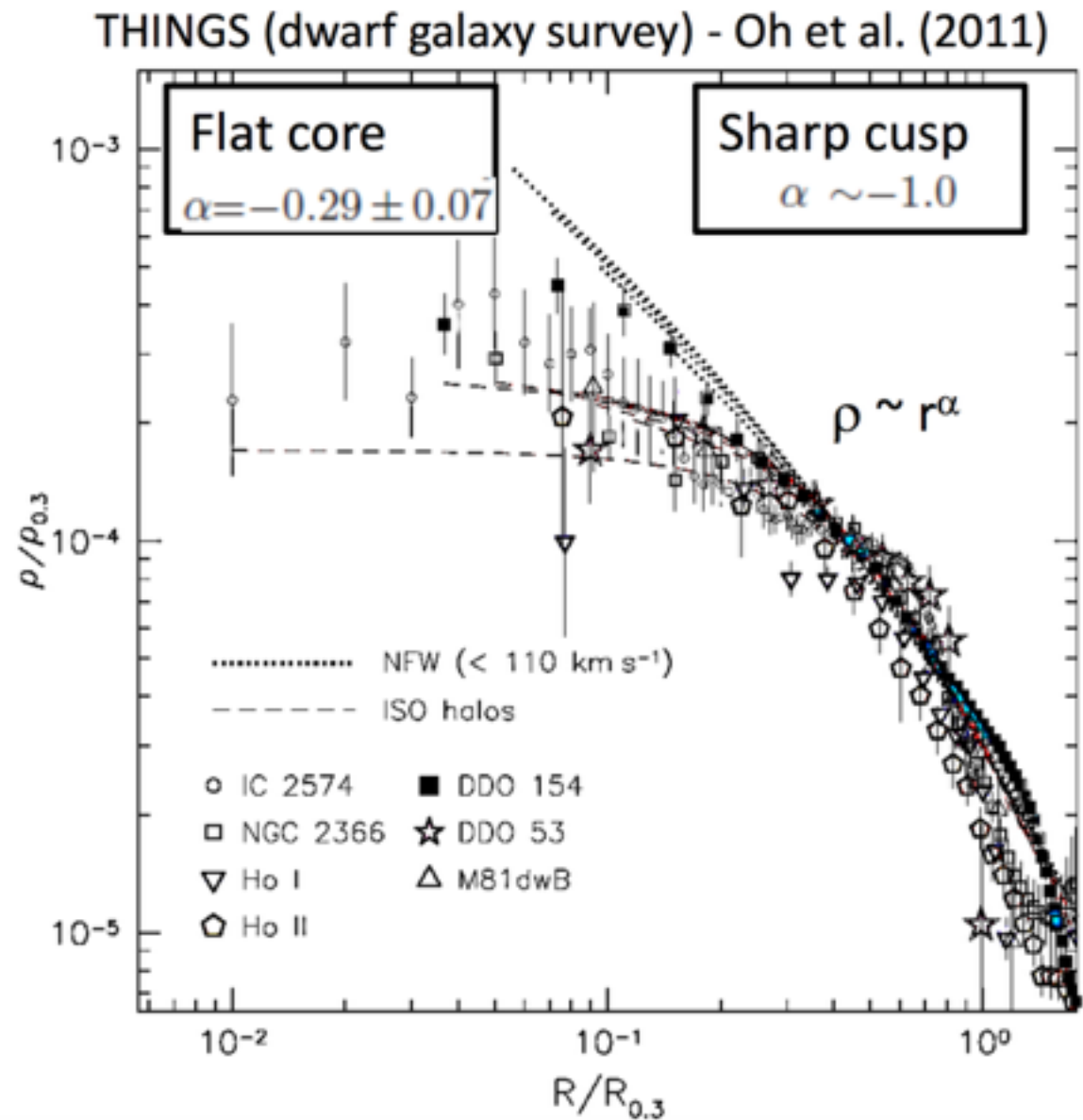
$$\Gamma(n \rightarrow e^+ e^-) = \frac{G_F \sin^2 \alpha_{\eta H}}{4\sqrt{2}\pi} m_n m_e^2 \beta_e^3,$$

$$\Gamma(n \rightarrow \gamma\gamma) = \frac{\alpha_{\text{em}}^2}{64\pi^3 m_n} \left| (\mu_{\eta h} + 2\lambda_{\eta h} v_\eta)(1 - \tau_h f(\tau_h)) + 4(\mu_{\eta k} + 2\lambda_{\eta k} v_\eta)(1 - \tau_k f(\tau_k)) \right|^2_{(3,12)}$$

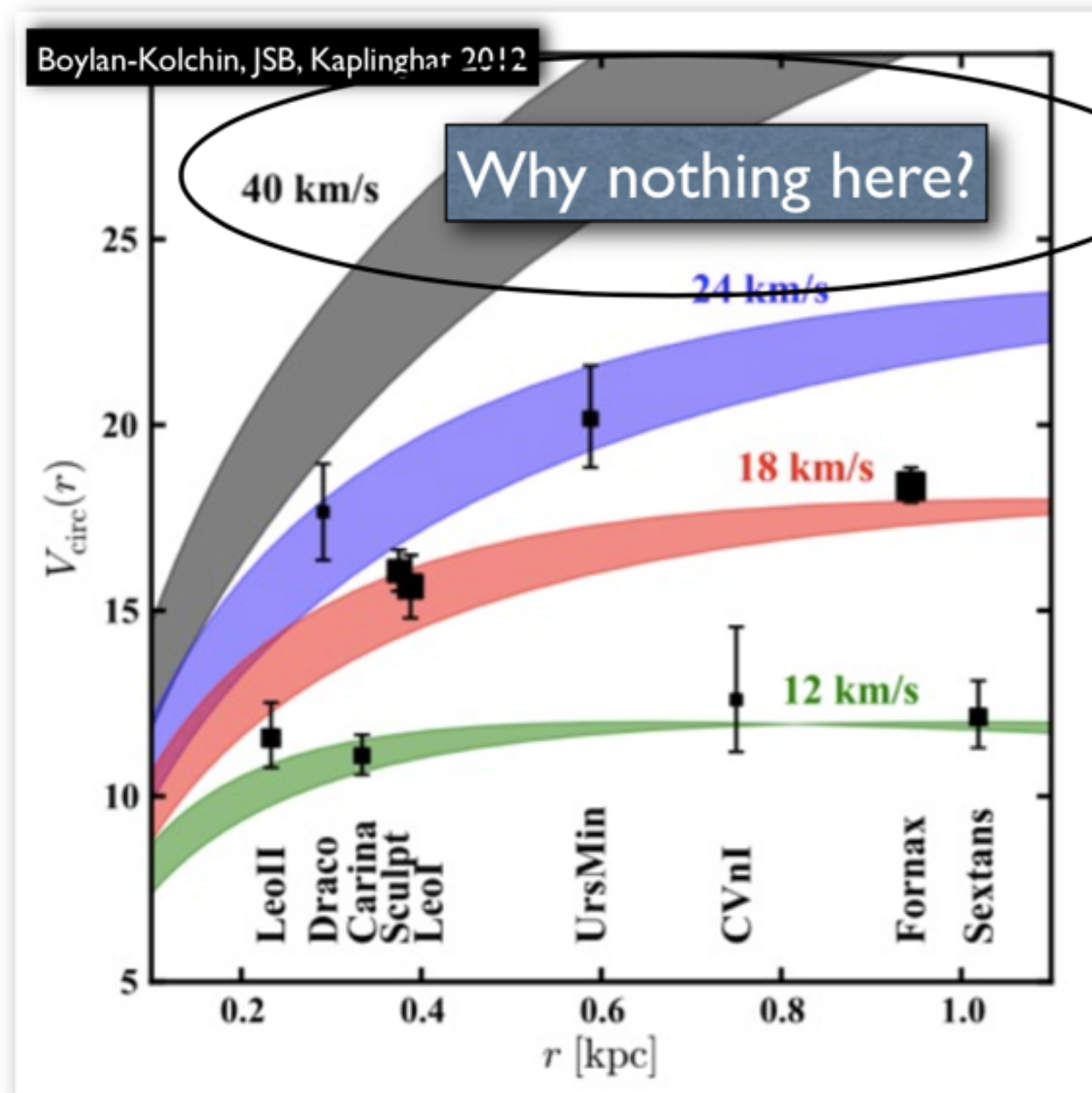
- $h \rightarrow \eta\eta$ can saturate the current Higgs invisible decay width
- η can also mediate elastic scattering of DM, which can solve the small scale problems in CDM simulations

Small scale anomalies

- Core-vs-cusp problem
- Simulations with CDM predict cuspy DM distribution at the center of galaxies
- However, observations show flat core



Summary of the Too Big To Fail problem:



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

(from 44 simulations)

Garrison-Kimmel et al. in prep

Small scale anomalies

- Light m_η (1—10 MeV) can enhance $\psi'_{1(2)}, \psi'_{1(2)} \rightarrow \psi'_{1(2)}, \psi'_{1(2)}$ and can explain small scale structure problems, core-vs-cusp and too-big-to-fail problems, if

$$\sigma_T / m_{\psi'_1} \sim 0.1 - 10 \text{ cm}^2/\text{g},$$



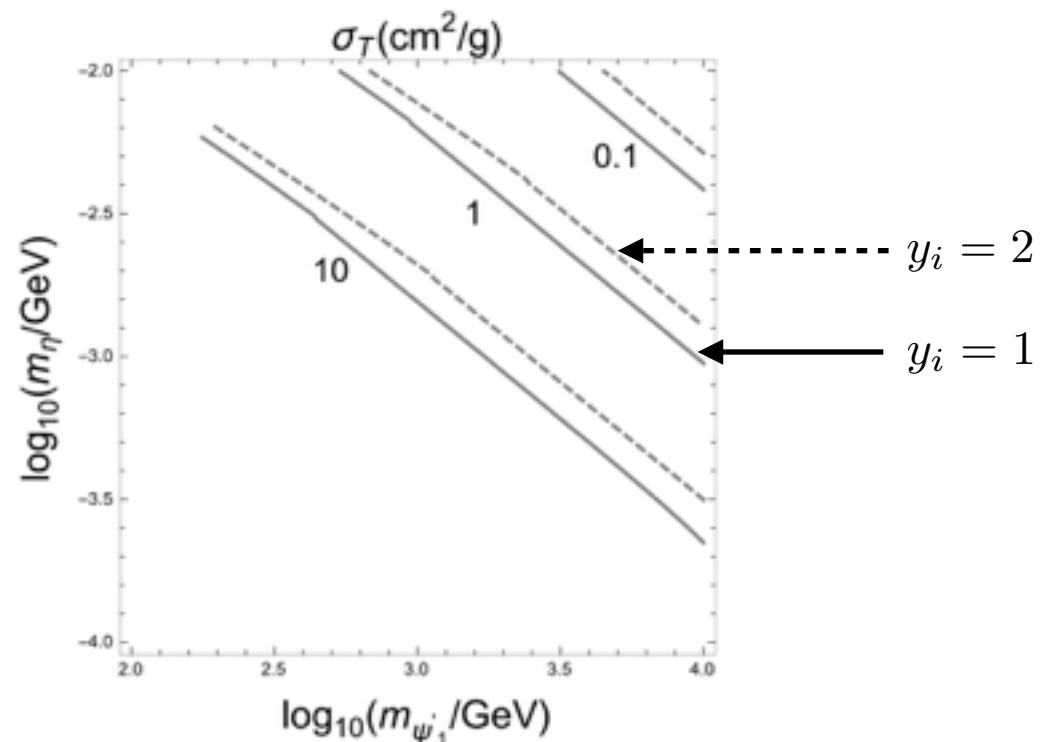
Small scale anomalies

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

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

$$\beta \equiv 2\alpha_y m_\eta / (m_\psi v_{\text{rel}}^2)$$

S. Tulin, et.al., 1302.3898



Conclusions

- Radiative neutrino models can be alternative to seesaw mechanism. DM can be naturally included.
- 3.5keV X-ray line signal can be explained in extended Zee-Babu model with decaying DM
- Light η achieves the correct relic abundance and also solves the small scale structure problems, core-vs-cusp and too-big-to-fail problem
- h^+ , k^{++} and invisible Higgs decay ($H \rightarrow \eta\eta$) is LHC signature