Zee-Babu model for neutrino mass and Dark Matter

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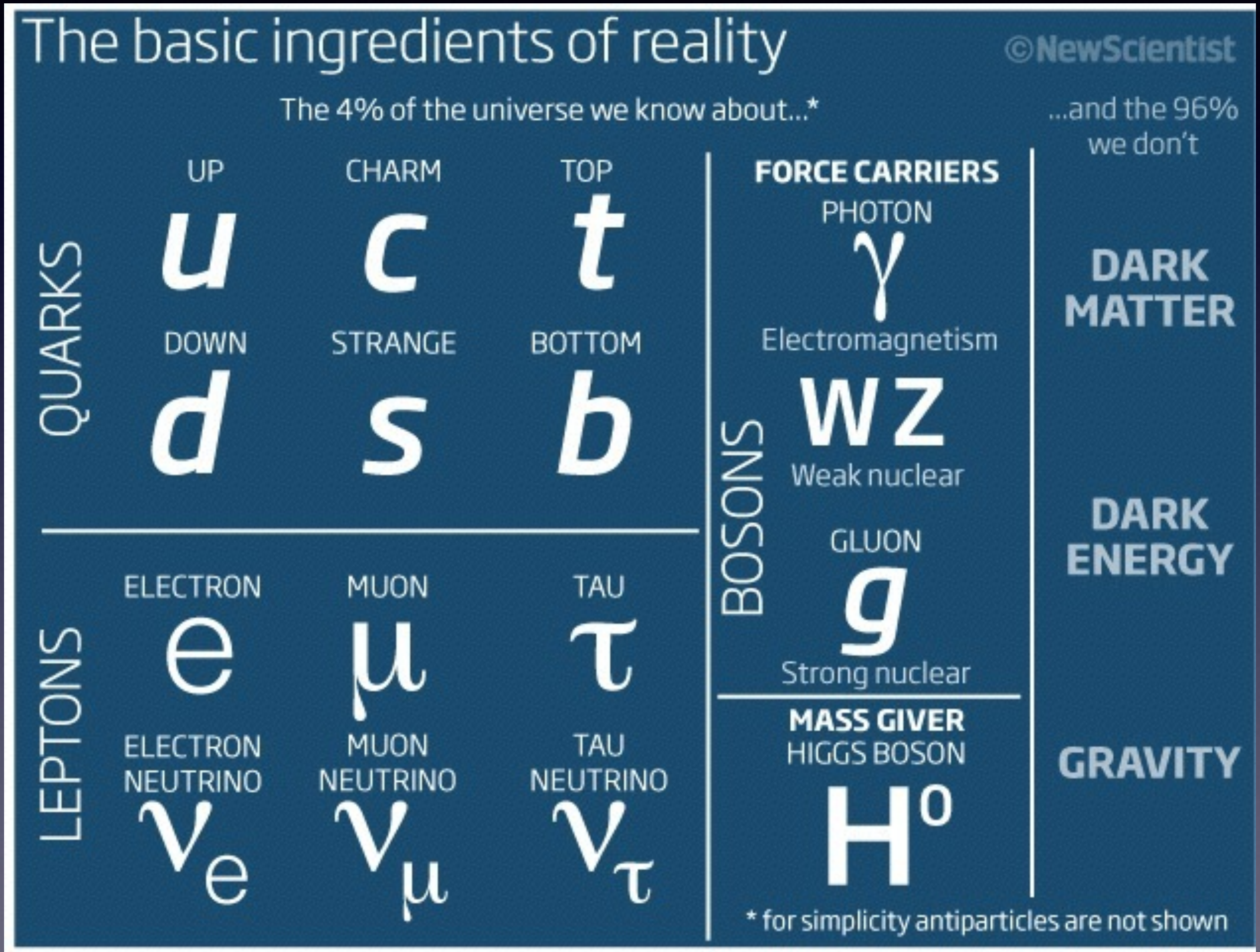
High1 2014, Feb. 9-15, 2014

based on 1209.1685, work in progress
In collaboration with P. Ko, H. Okada, E. Senaha

Standard Model



Neutrino Masses

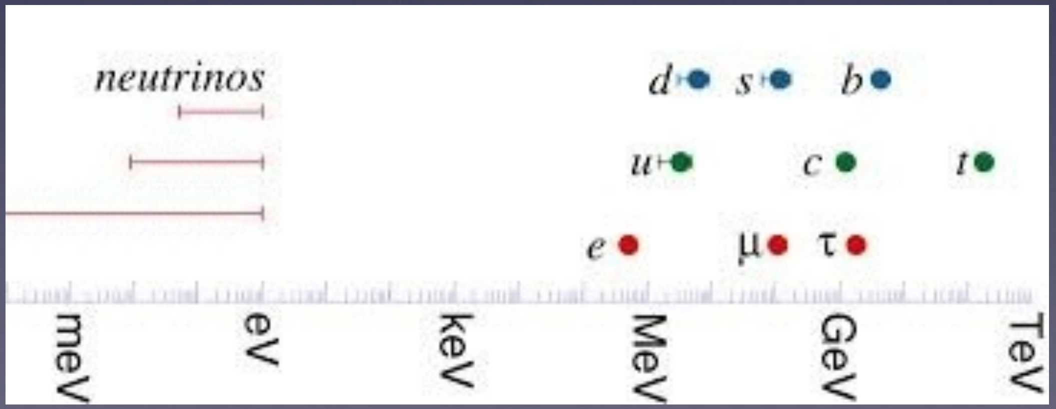
- In the SM, neutrinos are massless.

- Oscillation experiments suggest nonzero neutrino masses.

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	$2.43^{+0.06}_{-0.10}$ ($2.42^{+0.07}_{-0.11}$)	$2.19(2.17) - 2.62(2.61)$
$\sin^2\theta_{12}$	$0.307^{+0.018}_{-0.016}$	$0.259 - 0.359$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$ ($0.392^{+0.039}_{-0.022}$)	$0.331(0.335) - 0.637(0.663)$
$\sin^2\theta_{13}$ [173]	0.0241 ± 0.0025 ($0.0244^{+0.0023}_{-0.0025}$)	$0.0169(0.0171) - 0.0313(0.0315)$

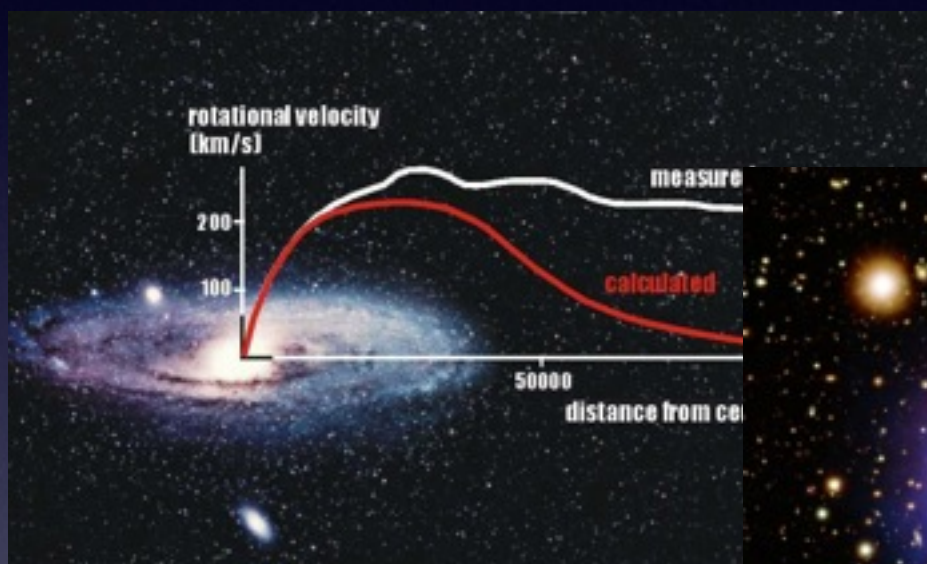
$\sum m_\nu < 0.933$ eV for Planck data only

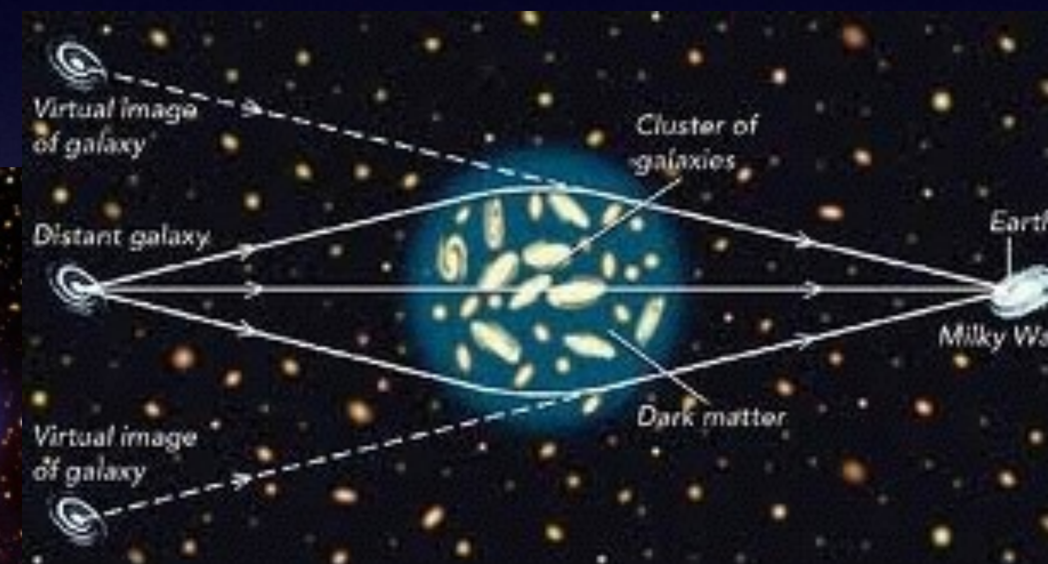
- Why are neutrino masses so tiny?

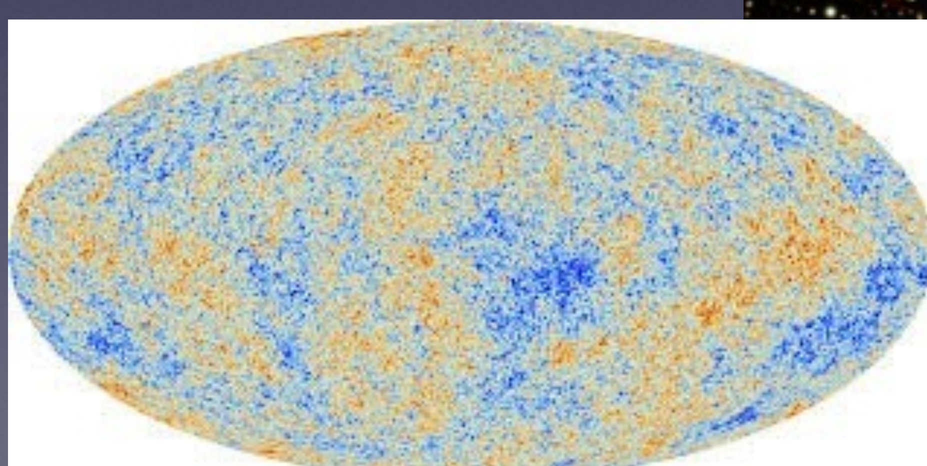


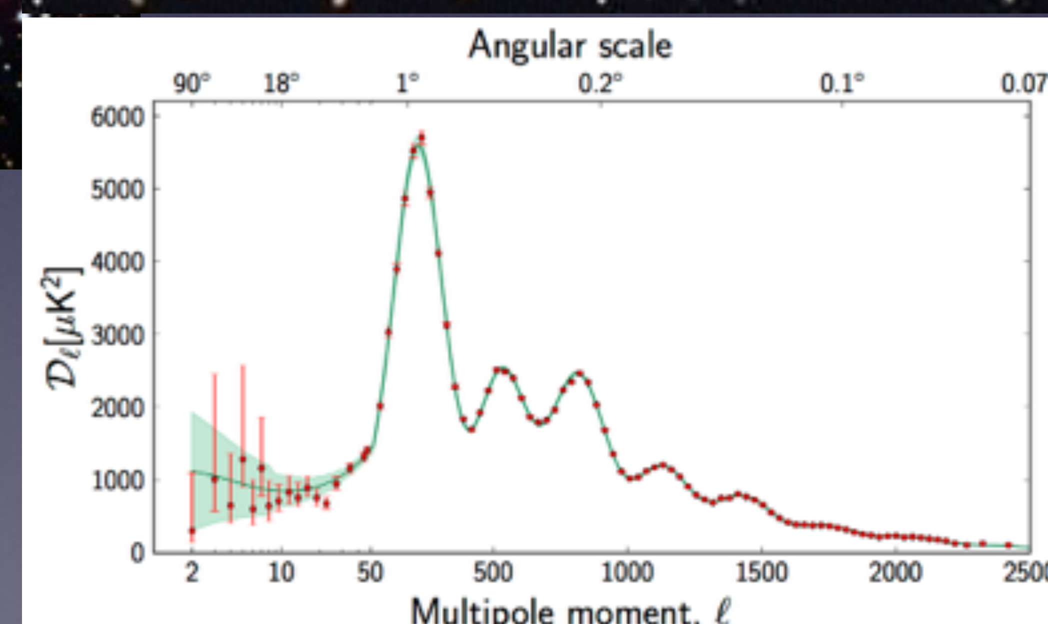
Dark Matter

- Many evidences for the DM





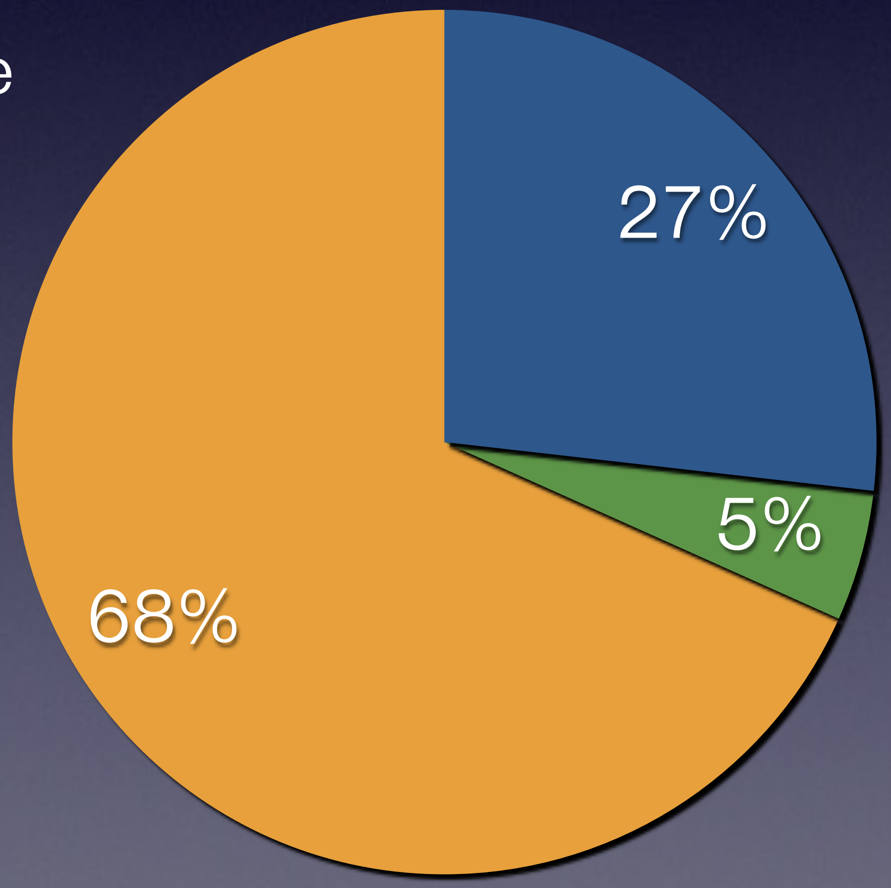




Dark Matter

- 27% of the universe is DM
- We do not new its nature
- None of the SM particles can be a DM candidate

Dark Matter
Ordinary Matter
Dark Energy



Neutrino masses and Dark Matter

- Neutrino and DM require New Physics beyond the SM

- Radiative generation of neutrino masses is a viable scenario and testable at colliders

- Interplay between Neutrino masses and DM

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

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

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \qquad (\eta^+, \eta^0) \sim (2, 1/2; -). \tag{4}$$

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

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

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

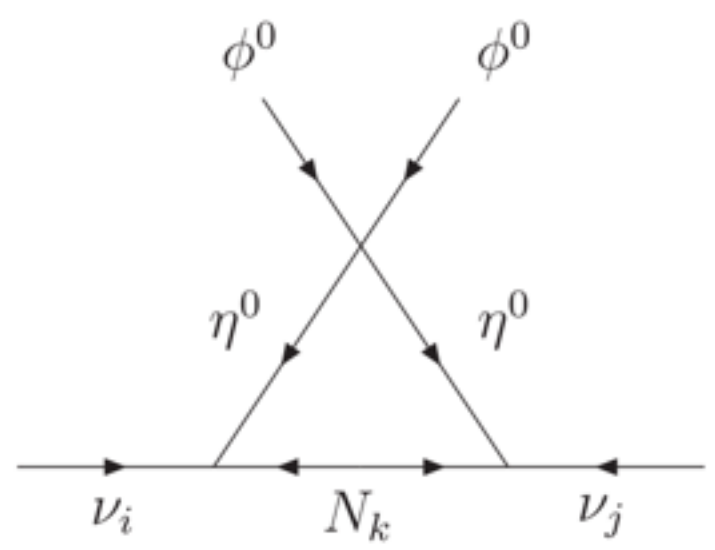
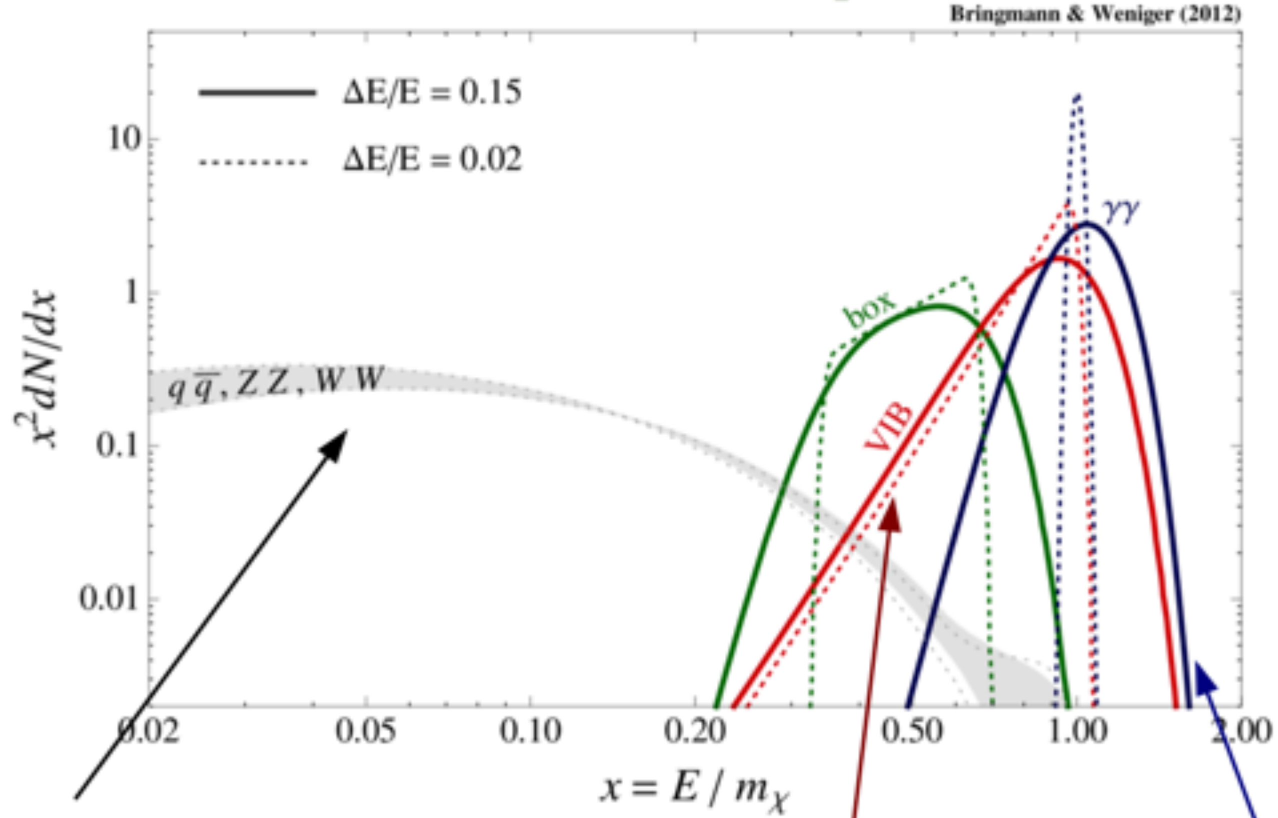


FIG. 1. One-loop generation of neutrino mass.

E. Ma, PRD73 (2006)

Indirect Dark Matter Signal: γ

Annihilation spectra



Continuum emission/ secondary photons

- often largest component
- featureless spectrum
- difficult to distinguish from astrophysical background

$$\chi\chi \to \bar{q}q \to \pi^0 \ldots$$

$$\pi^0 \to \gamma\gamma$$

Internal Bremsstrahlung (IB)

- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f}f\gamma$$

Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

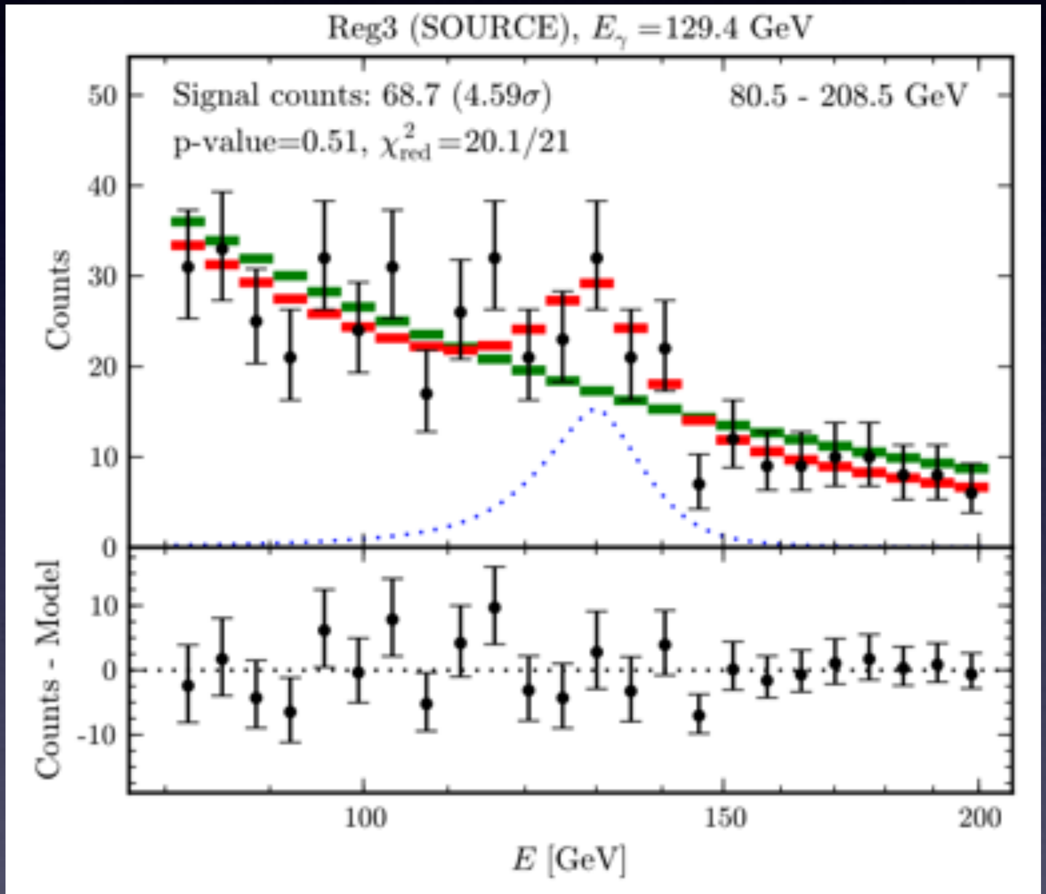
$$\chi\chi \to \gamma\gamma$$

(smoking guns)

Taken from Weniger, Light Dark Matter WS (2013)

Indirect Signature: γ-line

- FermiLAT data



Bringmann, et.al, Weniger (2012)

$$m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}\ \mathrm{GeV}$$

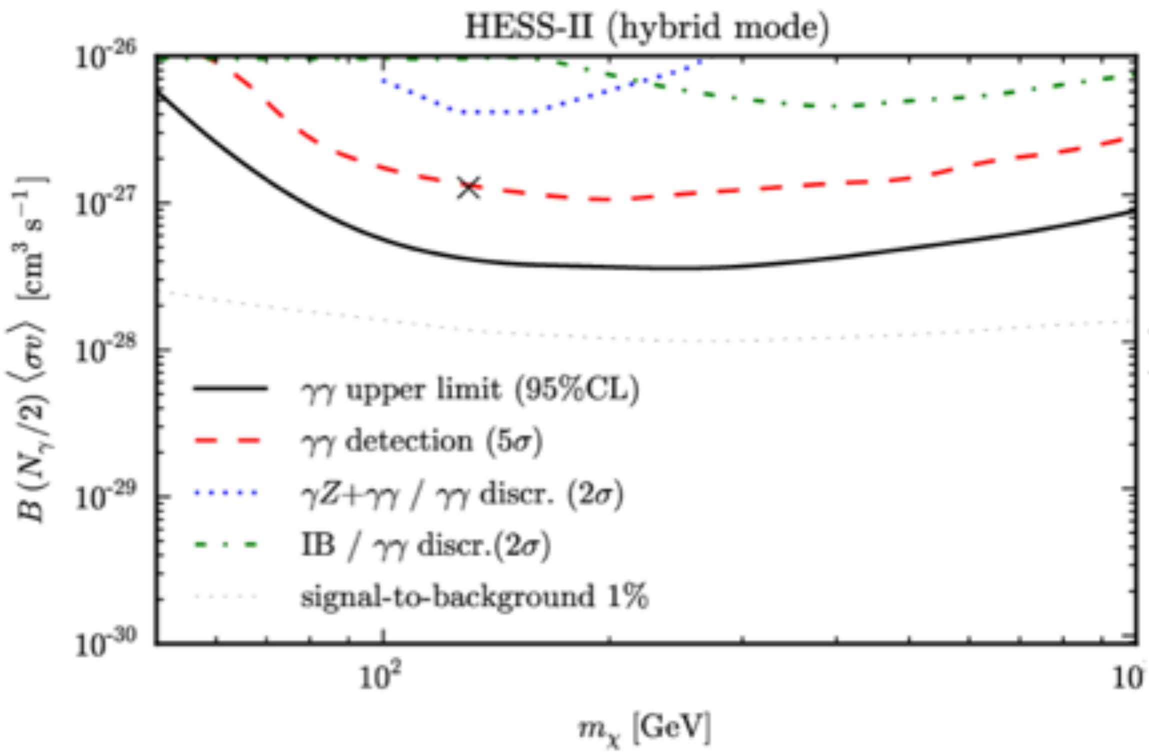
$$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = \left(1.27 \pm 0.32\,^{+0.18}_{-0.28}\right) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

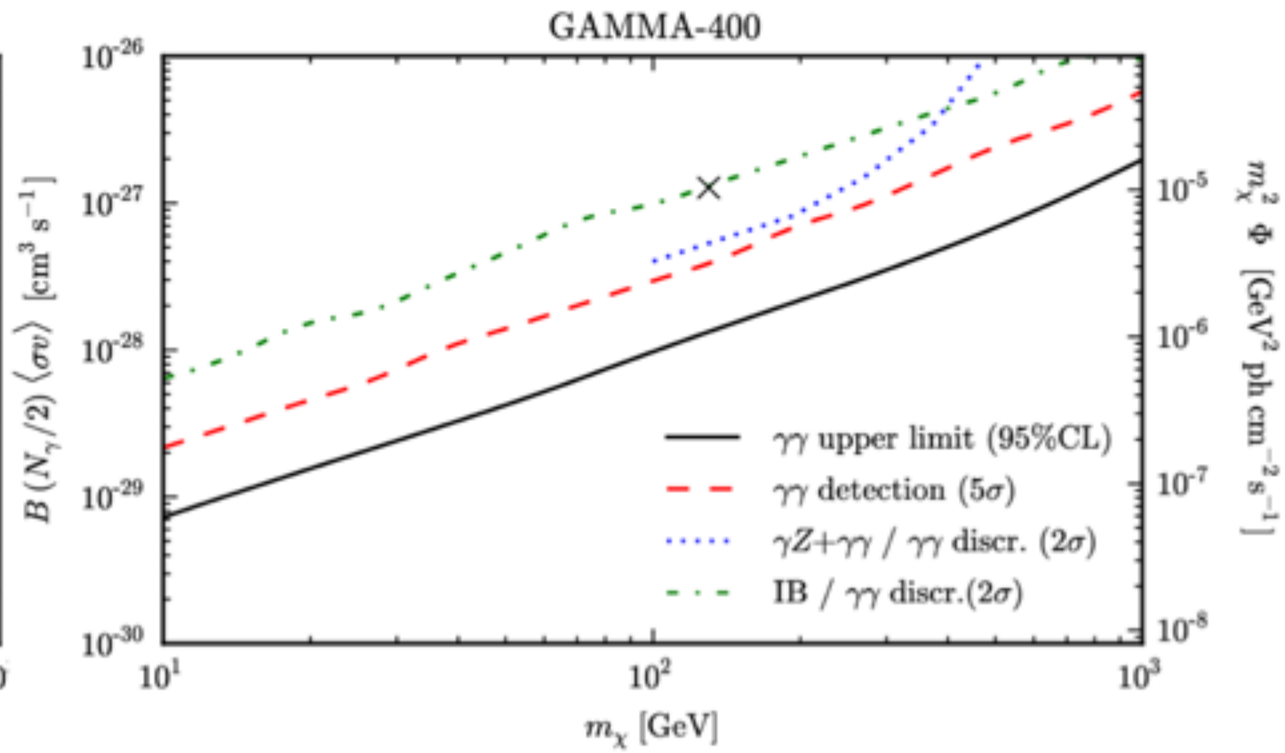
~4% of thermal relic density

- 130 GeV line from Galactic center: 3.3~6.5σ.
- Other sources (Earth Limb, etc): ~3σ

→The current situation is confusing.

HESS-II / GAMMA-400 to the rescue?





[Bergström et al., 2012]

HESS-II (hybrid mode)

- 50 hours of observation of galactic center
- enough to rule out signature or confirm it at 5 sigma (if systematics are under control)
- GC close to zenith from March 2013 on
- 230 hours per season in principle possible
- results end of 2014?

[parameters from J. Lefaucheur+ (Gamma 2012, Heidelberg)]

GAMMA-400

- 5 years of survey mode (5sigma detection would take ~10 months)
- Allows discrimination between VIB and monochromatic photons
- detection of γZ down to 20% relative branching ratio
- launch in 2018?

Taken from Weniger, Light Dark Matter WS (2013)

Outline

- Introduction to Zee-Babu model for radiative neutrino mass
- Introduction of DM in Zee-Babu model
    - Z_2-model
    - $U(1)_{B-L}$ model
    - Phenomenology of DM
    - FermiLAT 130GeV gamma-line anomaly
- Conclusions

The Zee-Babu model

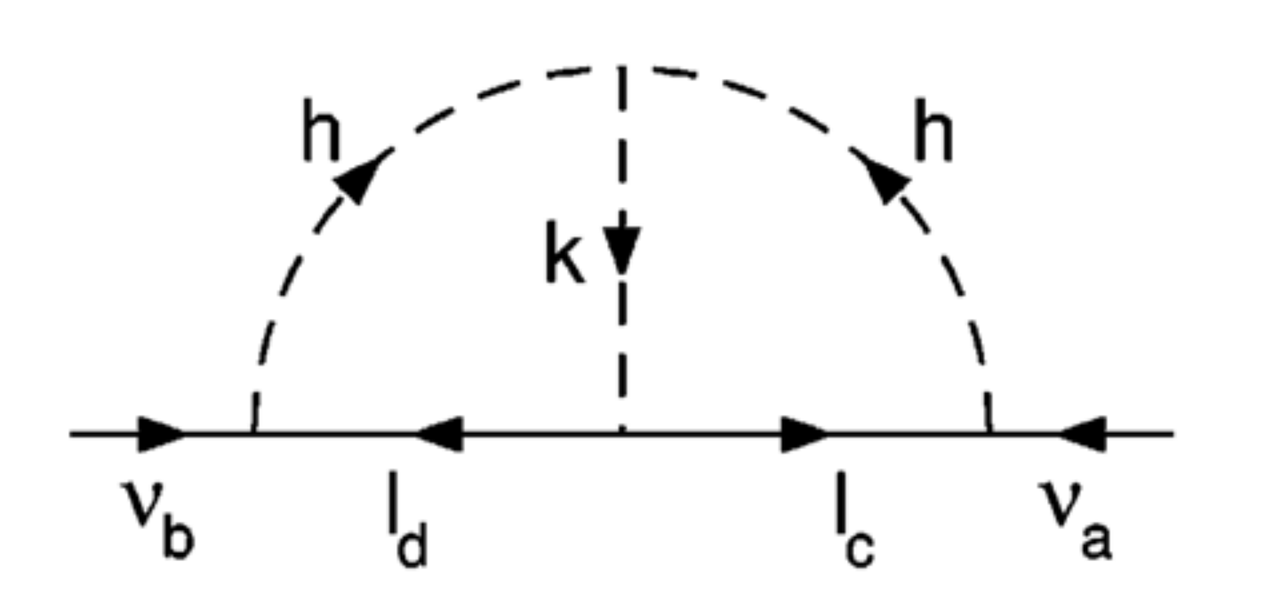
- Two charged scalars h^+ & k^{++} with L=-2 are introduced in addition to the SM

Babu, PLB(1988)

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

$$V = \mu_1^2 \phi^\dagger\phi + \mu_2^2 h^+ h^- + \mu_3^2 k^{++}k^{--} + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(h^+h^-)^2 + \lambda_3(k^{++}k^{--})^2 + \lambda_4(\phi^\dagger\phi)(h^+h^-) + \lambda_5(\phi^\dagger\phi)(k^{++}k^{--}) + \lambda_6(h^+h^-)(k^{++}k^{--}) + \boxed{\mu(h^+h^+k^{--} + h^-h^-k^{++})}.$$

L (or B-L)—violating term



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

$$m_{\nu_1} = 0$$

$$m_{\nu_2} = (3 \times 10^{-5})\left[\frac{\mu}{200\text{GeV}}\right]$$

$$m_{\nu_3} = (1 \times 10^{-2})\left[\frac{\mu}{200\text{GeV}}\right]$$

The Zee-Babu Model

- Right-handed neutrino is NOT necessary
- Smallness of neutrino mass comes from loop-suppression factor
- Det(M)=0: one massless ν
- No Dark Matter

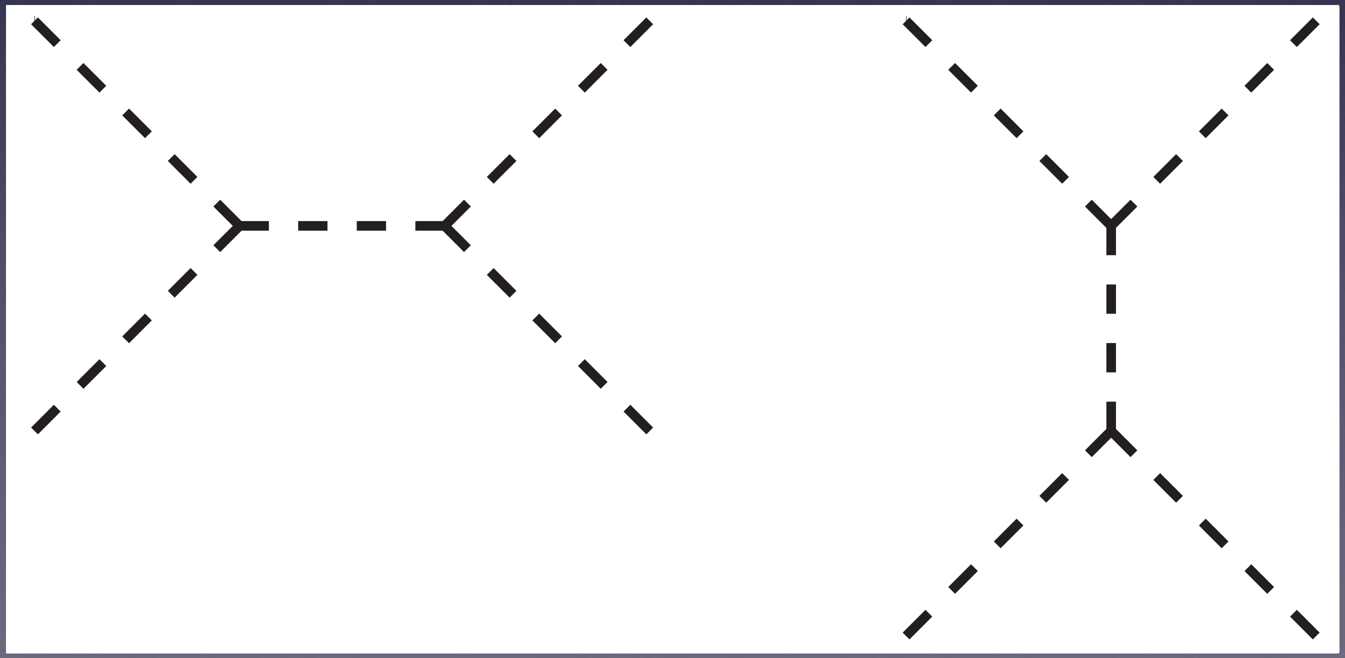
Z_2 Model

- Introduce DM X and Z_2-symmetry: X→-X

- Simplest extension to incorporate DM

$$\Delta V = \frac{1}{2}\mu_X^2 X^2 + \frac{1}{4}\lambda_X X^4 + \frac{1}{2}\lambda_{HX} H^\dagger H X^2 + \frac{1}{2}\lambda_{Xh} X^2 h^+ h^- + \frac{1}{2}\lambda_{Xk} X^2 k^{++} k^{--}$$

- The SM Higgs is a mediator between the DM X and the SM sector



Z_2 Model

relic density, direct detection: OK, small γ-line signal

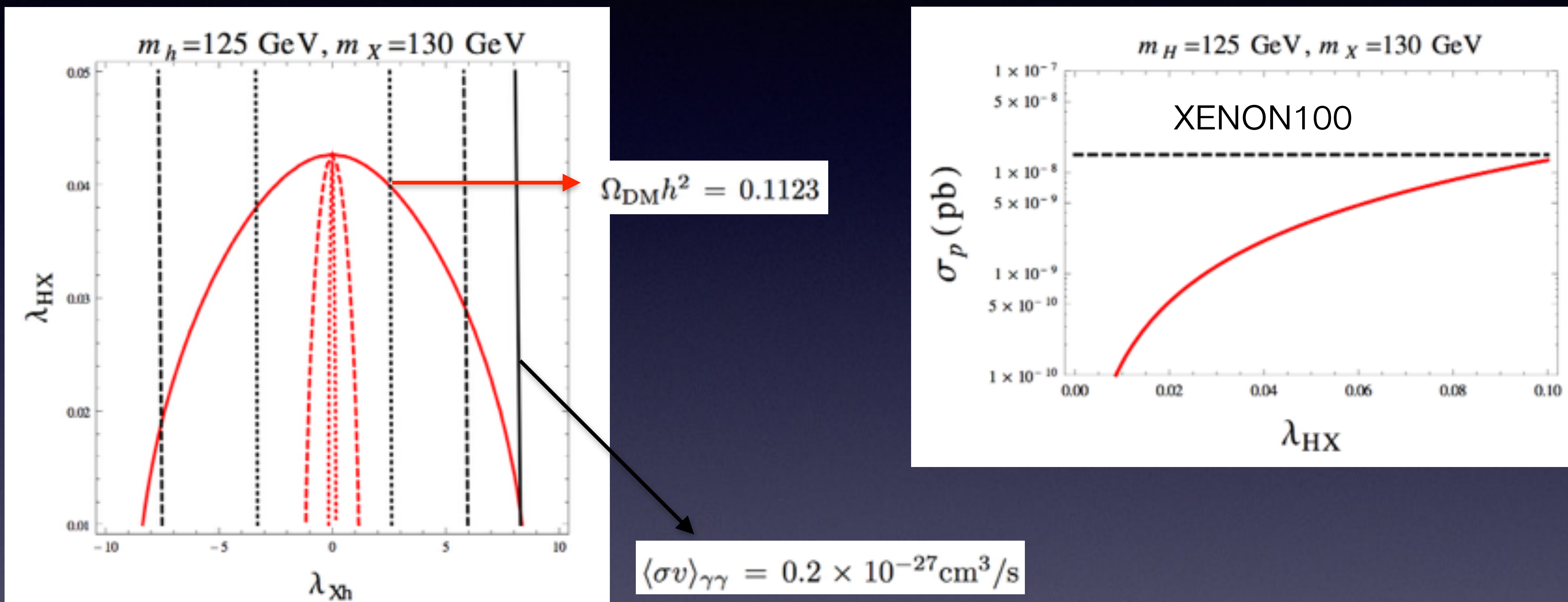


Figure 3. The contour plot of $\Omega_{DM}h^2 = 0.1123$ (red lines) and $\langle\sigma v\rangle_{\gamma\gamma} = 0.2 \times 10^{-27}\mathrm{cm}^3/\mathrm{s}$ (black lines) in the (λ_{Xh},λ_{HX}) plane for the choices m_{h^+} 150, 140, 130 GeV (solid, dashed, dotted lines). For other parameters we set $m_X = 130$ GeV, $m_H = 125$ GeV, $m_k = 500$ GeV, $\lambda_{Xk} = 5$, $\lambda_{Hh} = \lambda_{Hk} = 0.5$.

Z_2 Model

- Correlation with H→γγ

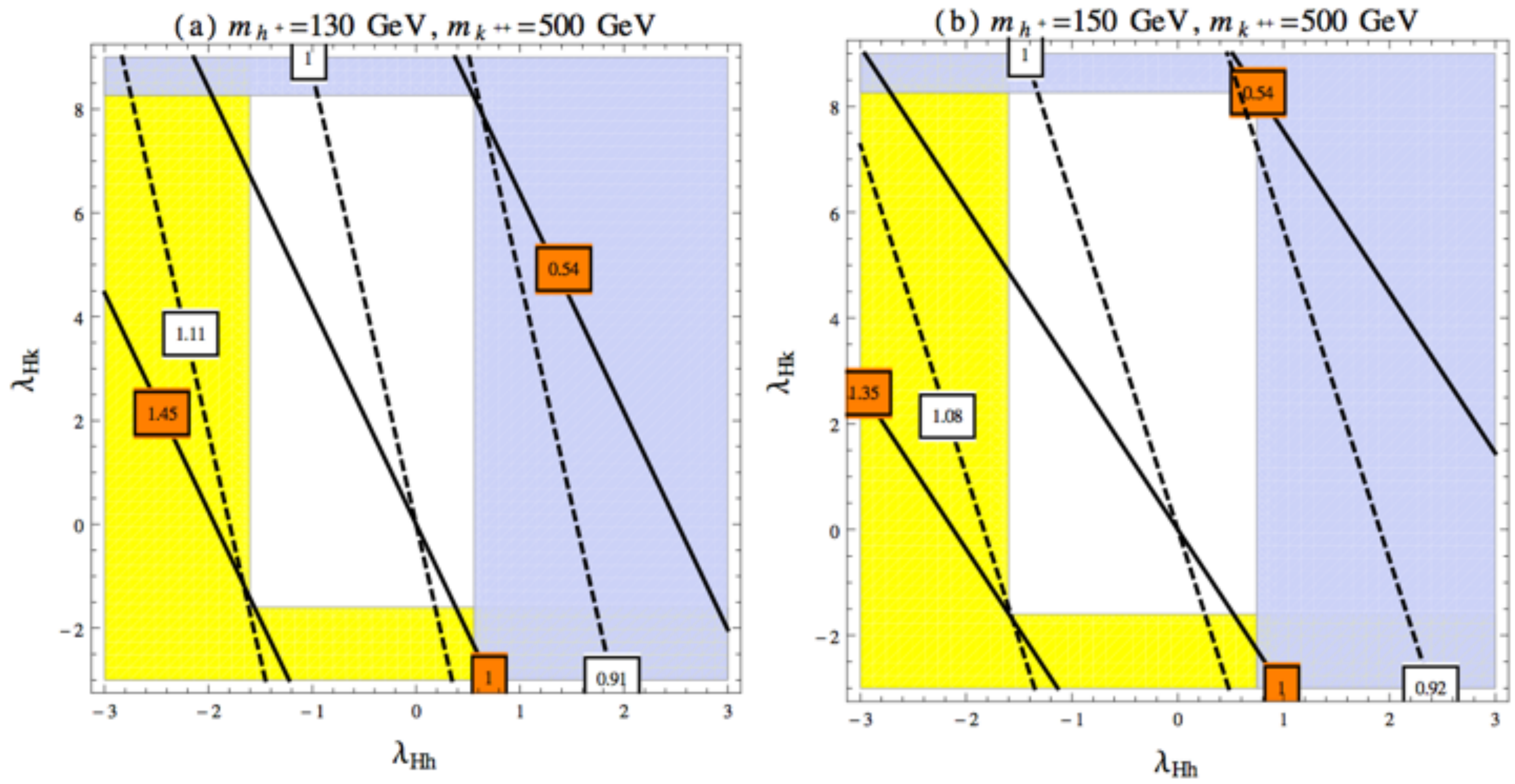


Figure 5. A contour plot for constant $\Gamma(H \to \gamma\gamma)/\Gamma(H \to \gamma\gamma)^{\rm SM}$ (black solid lines) and $\Gamma(H \to Z\gamma)/\Gamma(H \to Z\gamma)^{\rm SM}$ (black dashed lines) in the $(\lambda_{Hh}, \lambda_{Hk})$ plane. The shaded regions are disfavored by (2.5) (blue) and by (2.7) (yellow). We set $m_{h^+} = 130$ (150) GeV for the left (right) panel and fixed $m_{k^{++}} = 500$ GeV.

$U(1)_{B-L}$ Model

- Add φ with B-L charge 2
  - μ-term is replaced by B-L symmetric Chang, Keung, Pal, PRL(1988)

    Lindner, Schmidt, Schwetz, PLB705(2011)

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

  - spontaneous B-L symmetry breaking $\langle \varphi \rangle = v_\varphi/\sqrt{2}$ generates neutrino mass

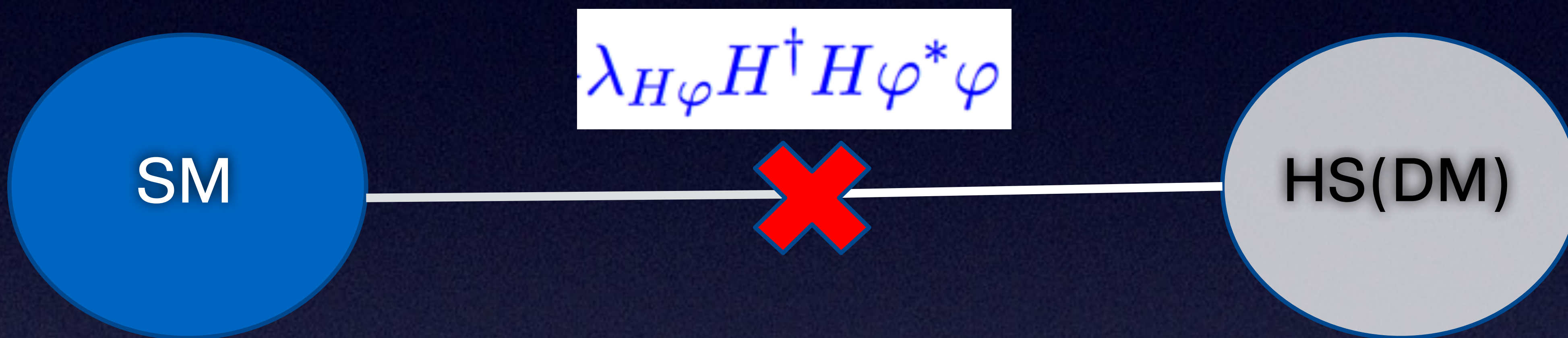
$$\begin{aligned}
-\mathcal{L}_{\text{Higgs+DM}} = & -\mu_H^2 H^\dagger H + \mu_X^2 X^* X + \mu_h^2 h^+ h^- + \mu_k^2 k^{++} k^{--} - \mu_\varphi^2 \varphi^* \varphi \\
& + (\mu_{\varphi X} \varphi X X + h.c.) \\
& + (\lambda_\mu \varphi h^- h^- k^{++} + h.c.) \\
& + \lambda_H (H^\dagger H)^2 + \lambda_\varphi (\varphi^* \varphi)^2 + \lambda_X (X^* X)^2 + \lambda_h (h^+ h^-)^2 + \lambda_k (k^{++} k^{--})^2 \\
& + \lambda_{H\varphi} H^\dagger H \varphi^* \varphi + \lambda_{HX} H^\dagger H X^* X + \lambda_{Hh} H^\dagger H h^+ h^- + \lambda_{Hk} H^\dagger H k^{++} k^{--} \\
& + \lambda_{\varphi X} \varphi^* \varphi X^* X + \lambda_{\varphi h} \varphi^* \varphi h^+ h^- + \lambda_{\varphi k} \varphi^* \varphi k^{++} k^{--} \\
& + \lambda_{Xh} X^* X h^+ h^- + \lambda_{Xk} X^* X k^{++} k^{--} + \lambda_{hk} h^+ h^- k^{++} k^{--}, \qquad (3.1)
\end{aligned}$$

  - Stability of DM X: remnant Z_2 symmetry after $\langle \varphi \rangle = v_\varphi/\sqrt{2}$

$U(1)_{B\text{-}L}$ Model

- "Higgs" portal term

$$\lambda_{H\varphi} H^\dagger H \varphi^* \varphi$$



- annihilation into the SM particles for relic density

- direct detection cross section

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h) \end{pmatrix}, \quad \varphi = \frac{1}{\sqrt{2}}(v_\varphi + \phi) e^{-2i\alpha/(2v_\varphi)},$$

$$|\sin\alpha_H| \lesssim 0.32$$

$$\begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{H\varphi} v_H v_\varphi \\ \lambda_{H\varphi} v_H v_\varphi & 2\lambda_\varphi v_\varphi^2 \end{pmatrix}$$

$$\begin{pmatrix} h \\ \varphi \end{pmatrix} = \begin{pmatrix} c_H & s_H \\ -s_H & c_H \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

$U(1)_{B-L}$ Model

- mass split between Re and Im part of X: X_R (DM)

$$X = \frac{X_R + iX_I}{\sqrt{2}}$$

$$\begin{aligned}
\mu_X^2 &= \frac{1}{2}(m_R^2 + m_I^2 - \lambda_{HX} v_H^2 - \lambda_{\varphi X} v_\varphi^2), \\
\mu_{\varphi X} &= \frac{m_R^2 - m_I^2}{2\sqrt{2} v_\varphi}, \\
\mu_h^2 &= m_{h+}^2 - \frac{1}{2}\lambda_{Hh} v_H^2 - \frac{1}{2}\lambda_{h\varphi} v_\varphi^2, \\
\mu_k^2 &= m_{k++}^2 - \frac{1}{2}\lambda_{Hk} v_H^2 - \frac{1}{2}\lambda_{k\varphi} v_\varphi^2,
\end{aligned}$$

- Total 22 parameters in the scalar potential

$$\begin{aligned}
&v_H(\simeq 246\ \text{GeV}), \quad v_\varphi, \quad m_1(\simeq 125\ \text{GeV}), \quad m_2, \quad \alpha_H, \\
&m_R, \quad m_I, \quad m_{h^+}, \quad m_{k^{++}}, \\
&\lambda_\mu, \quad \lambda_h, \quad \lambda_k, \quad \lambda_X, \\
&\lambda_{Hh}, \quad \lambda_{Hk}, \quad \lambda_{HX}, \quad \lambda_{\varphi X}, \quad \lambda_{\varphi h}, \quad \lambda_{\varphi k}, \quad \lambda_{Xh}, \quad \lambda_{Xk}, \quad \lambda_{hk},
\end{aligned}$$

U(1)$_{B\text{-}L}$ Model

- Enhancement of $X_R X_R \to \gamma\gamma$

$$\sigma v_{\rm rel}(X_R X_R \to \gamma\gamma) = \frac{\alpha_{\rm em}^2}{32\pi^3 s}\left|\frac{(\sqrt{2}\mu_{\varphi X} + \lambda_{\varphi X} v_\varphi)v_\varphi}{s - m_\phi^2 + i m_\phi \Gamma_\phi}\sum_{i=h,k} Q_i^2 \lambda_{\varphi i}[1-\tau_i f(\tau_i)] + \sum_{i=h,k} Q_i^2 \lambda_{X i}[1-\tau_i f(\tau_i)]\right|^2,$$

$$\mu_{\varphi X} = \frac{m_R^2 - m_I^2}{2\sqrt{2} v_\varphi},$$

Resonance, large v_φ

$\sigma v(X_R X_R \to \gamma\gamma) = 0.04$ (pb)

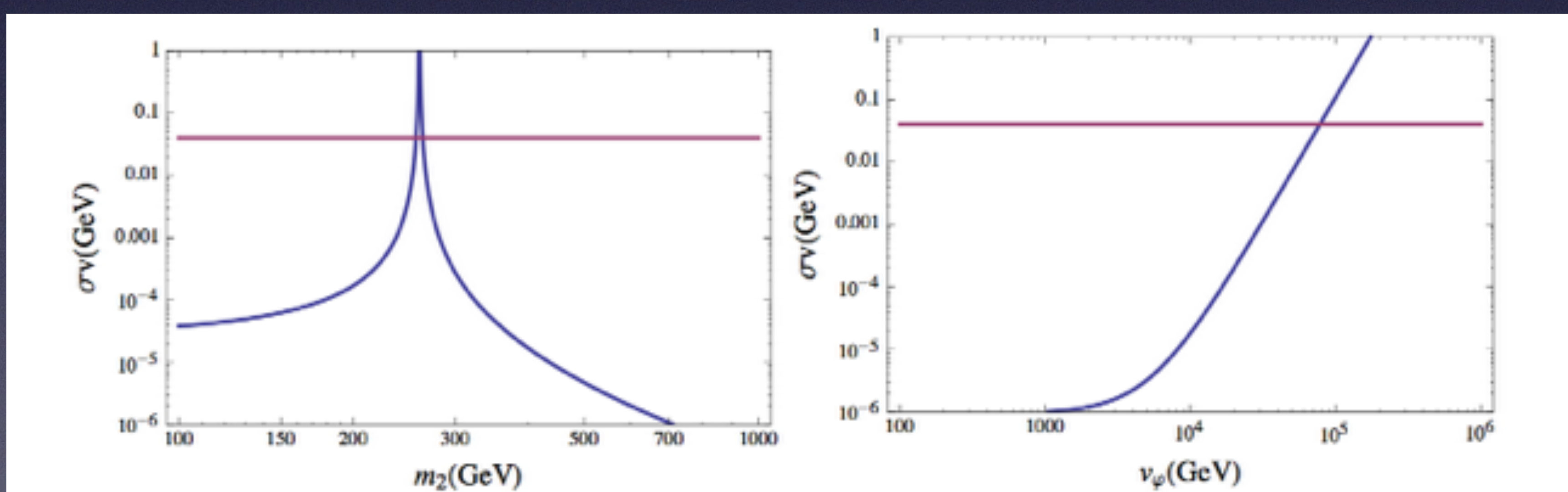
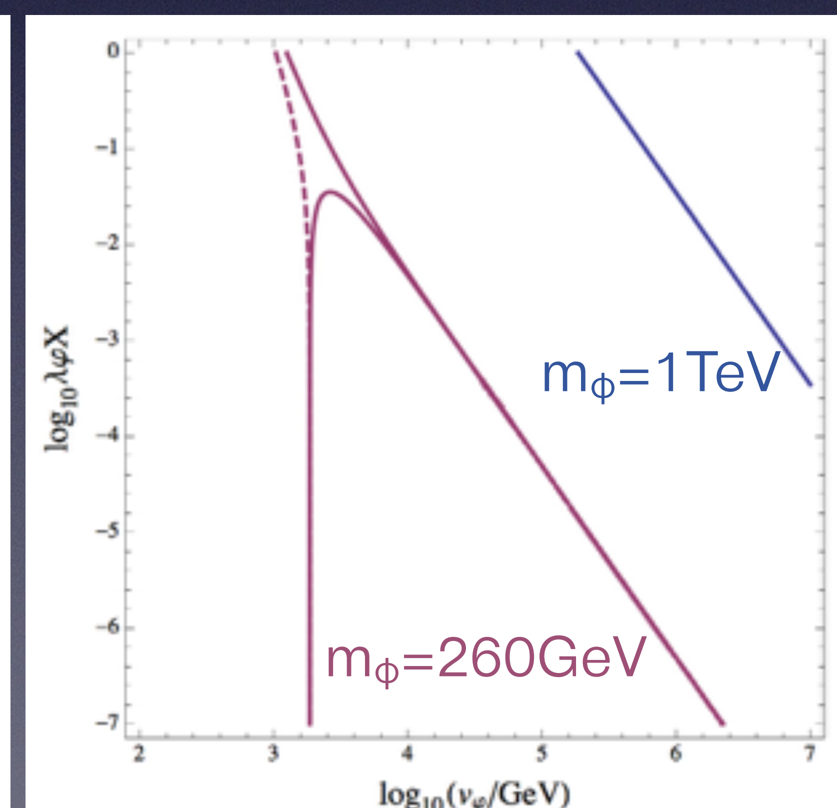


Figure 6. Plots of $\sigma v(X_R X_R \to \gamma\gamma)$ for $\alpha_H = 0$ as functions of $m_\phi(= m_2)$ and v_φ. We set $m_R = 130$, $m_I = 2000$, $m_{h^+} = 300$, $m_{k^{++}} = 500$ (GeV), $\lambda_{\varphi X} = -0.1$, $\lambda_{\varphi h} = \lambda_{\varphi k} = \lambda_{Xh} = \lambda_{Xk} = 0.1$, $v_\varphi = 1000$ (GeV) for the left panel and $m_\phi = 1000$ (GeV) for the right panel. The horizontal purple line represent $\sigma v(X_R X_R \to \gamma\gamma) = 0.04$ (pb) which can explain the Fermi/LAT gamma-line signal.



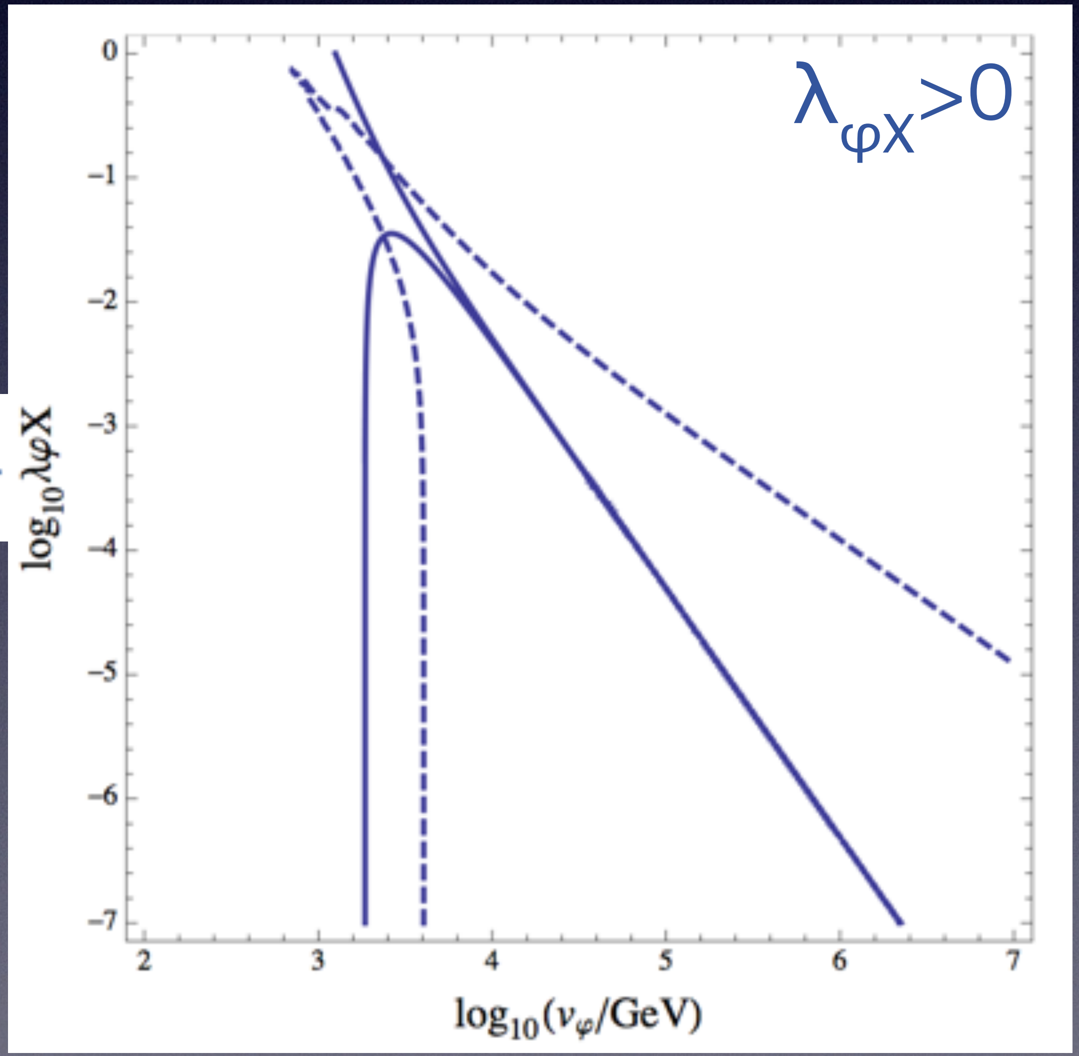
$U(1)_{B\text{-}L}$ Model

- Does X_R give correct relic density, $\Omega_{DM}h^2=0.12$?
- $X_R X_R \rightarrow \alpha\alpha$ is dominant in wide region of parameter space.

$$\Omega_X h^2 \approx \frac{1.07\times 10^9\,\mathrm{GeV}^{-1}}{M_{\rm Pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{(a+3b/x_F)}$$

$$\langle \sigma v\rangle = a + b\langle v^2\rangle + \mathcal{O}(\langle v^4\rangle) \approx a + 6b/x$$

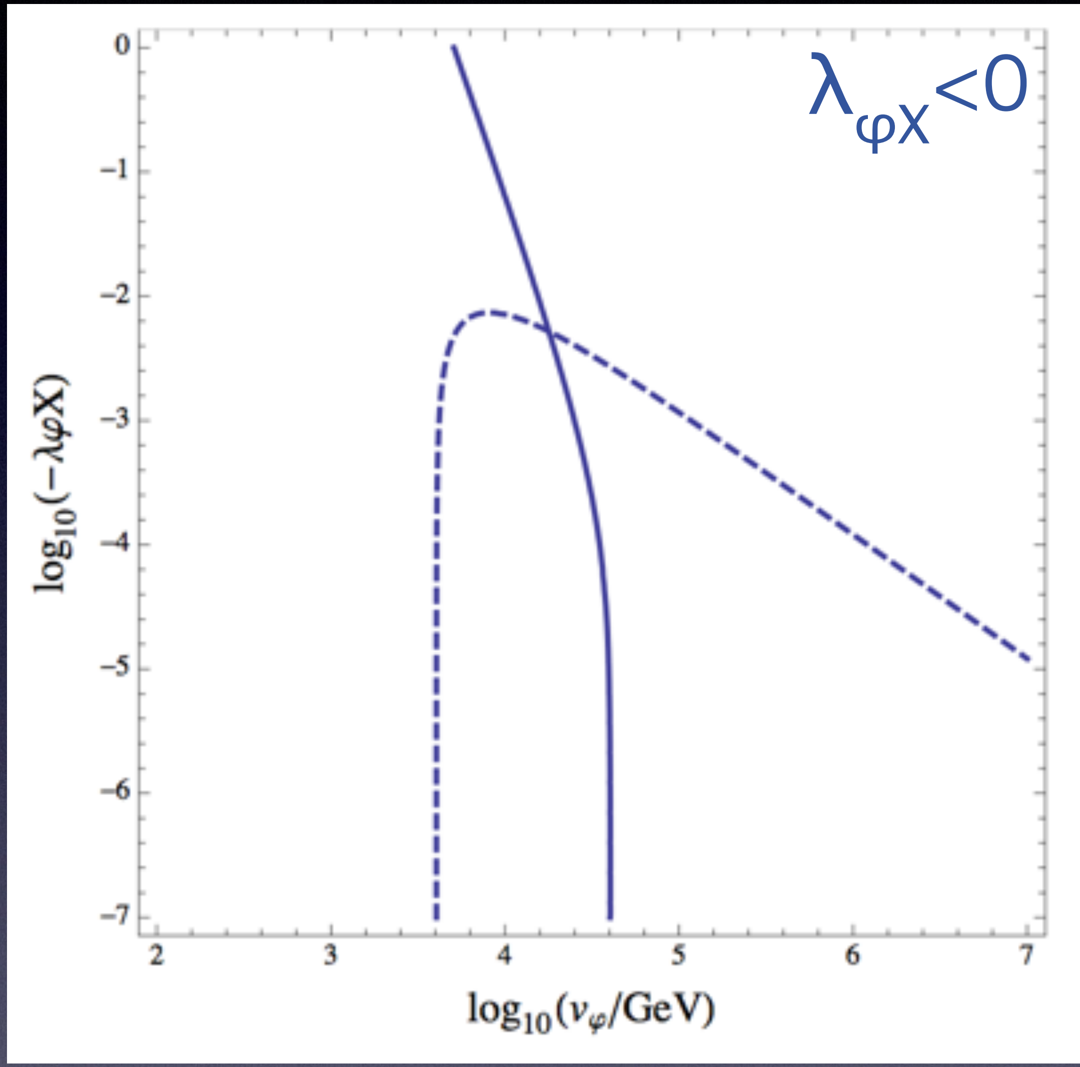
$$\sigma v_{\rm rel} = \frac{m_R^2[4v_\varphi(\sqrt{2}\mu_{X\varphi} + \lambda_{\varphi X}v_\varphi)(m_I^2+m_R^2) + (m_I^2-m_R^2)(4m_R^2-m_\phi^2)]^2)}{64\pi v_\varphi^4(m_I^2+m_R^2)[(m_\phi^2-4m_R^2)^2+m_\phi^2\Gamma_\phi^2]} + \mathcal{O}(v^2).$$



- 2 $m_R=m_\phi=260$GeV, $\lambda_{\varphi X}>0$
  $m_I=m_h=m_K=1$TeV, λ's=0.01

$U(1)_{B\text{-}L}$ Model

- 2 $m_R = m_\phi = 260\,\text{GeV}$, $\lambda_{\varphi X} < 0$
- TeV scale v_φ can explain FermiLAT gamma_line: too small relic density
- Need to decouple $X_R X_R \to \gamma\gamma$: $m_h = m_k = 20$ TeV
- $m_l = 1\,\text{TeV}$, $\lambda\text{'s} = 0.01$

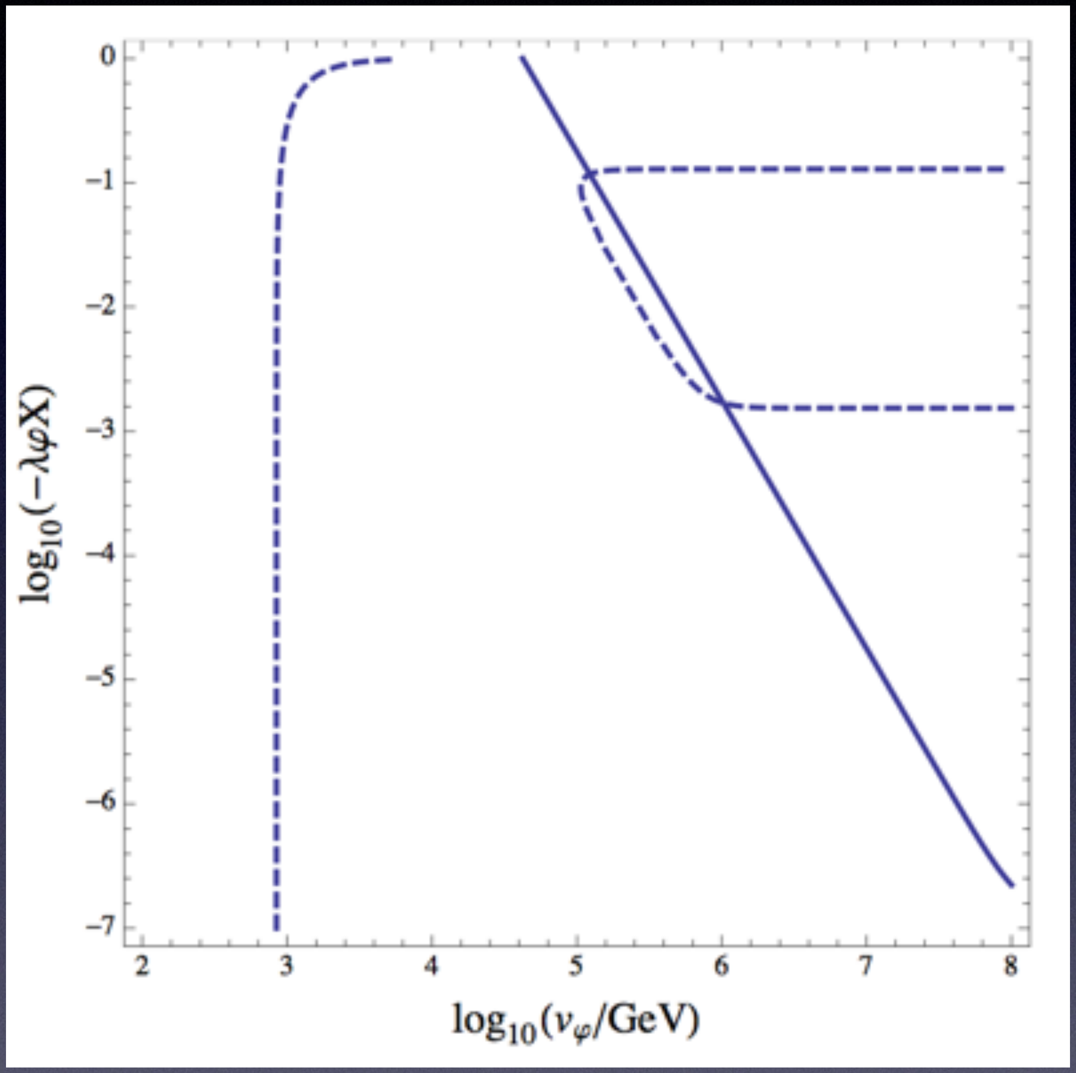


$U(1)_{B-L}$ Model

- Off-resonance

- $X_R X_R \rightarrow \alpha\alpha$ cross section is too small and we need other channels for relic density: m_h=150 GeV, m_k=500 GeV

- m_ϕ=1TeV, m_l=1TeV, λ's=0.01



Conclusions

- Extended Zee-Babu model for radiative neutrino mass generation to include a DM candidate X and SM singlet scalar
- Z_2 model is consistent with relic density and direct detection but cannot explain FermiLAT gamma-ray line
- $U(1)_{B-L} \to Z_2$
  - Guarantees stability of DM X_R
  - Goldstone boson plays an important role in DM annihilation
- $X_R X_R \to \gamma\gamma$ can be enhanced to explain the possible anomaly in FermiLAT gamma-ray data

Backups

EW scale Goldstone boson

- Chang, Keung, Pal, PRL(1988)

$$i g_{\bar{e}e_J} \bar{e} \gamma_5 e J$$

$$\boxed{g_{\bar{e}e_J} \lesssim 10^{-12}}$$

Model indep. bound from
stellar energy loss

$$\gamma + e \longrightarrow e + J .$$

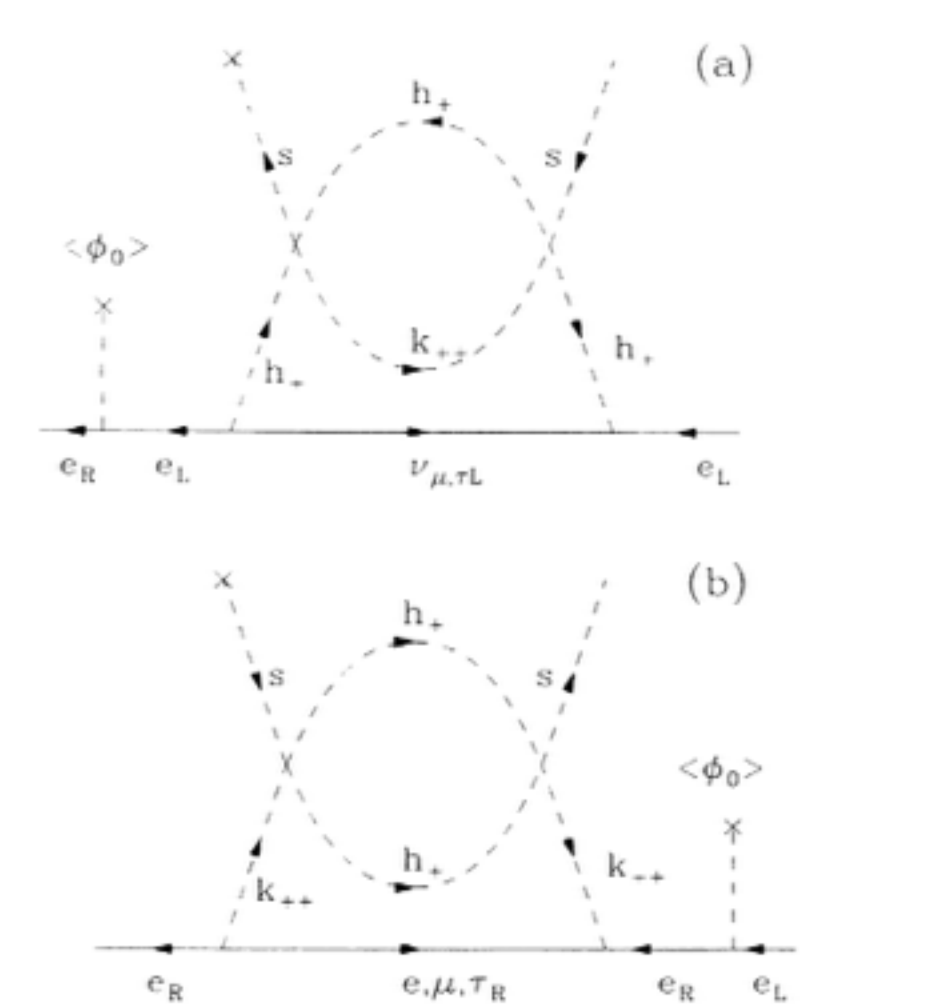


FIG. 1. The loop diagrams for the majoron coupling to the

$$\lambda h_- h_- k_{++} s + \mathrm{H.c.} \, ,$$

$$g_{\bar{e}eJ} \sim \frac{1}{(16\pi^2)^2} \frac{\lambda^2 v_1 m_e}{M^2} \sum_l (|F_{el}|^2 + 2|f_{el}|^2) \, .$$

$$g_{\bar{e}eJ} \sim 2 \times 10^{-10} \lambda^2 \left(\frac{v_1}{100\ \mathrm{GeV}} \right) \left(\frac{100\ \mathrm{GeV}}{M} \right)^2 \times \sum_l (|F_{el}|^2 + 2|f_{el}|^2) \, .$$

Small enough due to
two-loop suppression