PEV SCALE SUPERSYMMETRIC NEUTRINO SECTOR

NEUTRINO MASSES, STERILE NEUTRINO DARK MATTER, PEV NEUTRINOS, AND A 3.5 KEV X-RAY LINE

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Based on hep-ph:1412.4791, 1506.08195, and 15.******

with Samuel Roland and James Wells

NEUTRINO MASSES AND THE SEESAW

- Neutrinos have mass ➜ **BSM Physics!**
- Add SM-singlet sterile right-handed neutrinos N_i

$$\mathcal{L} \supset y_{\alpha i} \bar{L}_\alpha H_u^\dagger N_i + M_i \bar{N}_i^c N_i$$

$$M \gg y\langle H_u \rangle \rightarrow m_a \sim (y\langle H_u \rangle)^2/M$$

- **What is the mass scale M?**

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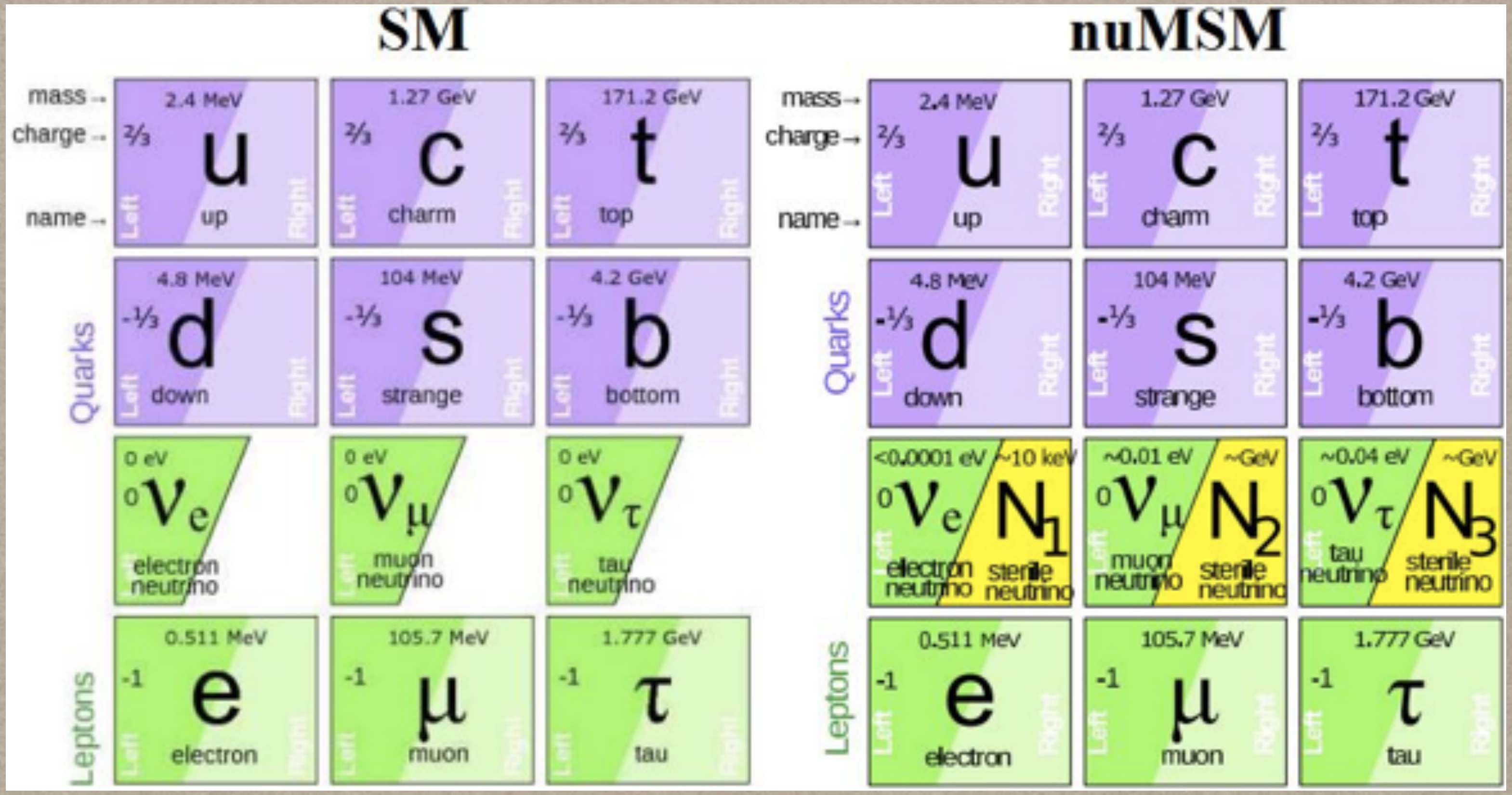
- **What is the mass scale M?**

- y~O(1), M~10^{14} GeV (GUT scale seesaw)

- N_1~keV can be dark matter (Dodelson-Widrow mechanism) (and N_2,N_3~GeV can give baryogenesis)!

Neutrino Minimal Standard Model (νMSM)



extensively studied,

explains neutrino masses, baryon asymmetry, and dark matter.

T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys.Lett. **B631**, 151 (2005), hep-ph/0503065.
T. Asaka and M. Shaposhnikov, Phys.Lett. **B620**, 17 (2005), hep-ph/0505013.
T. Asaka, M. Shaposhnikov, and A. Kusenko, Phys.Lett. **B638**, 401 (2006), hep-ph/0602150.

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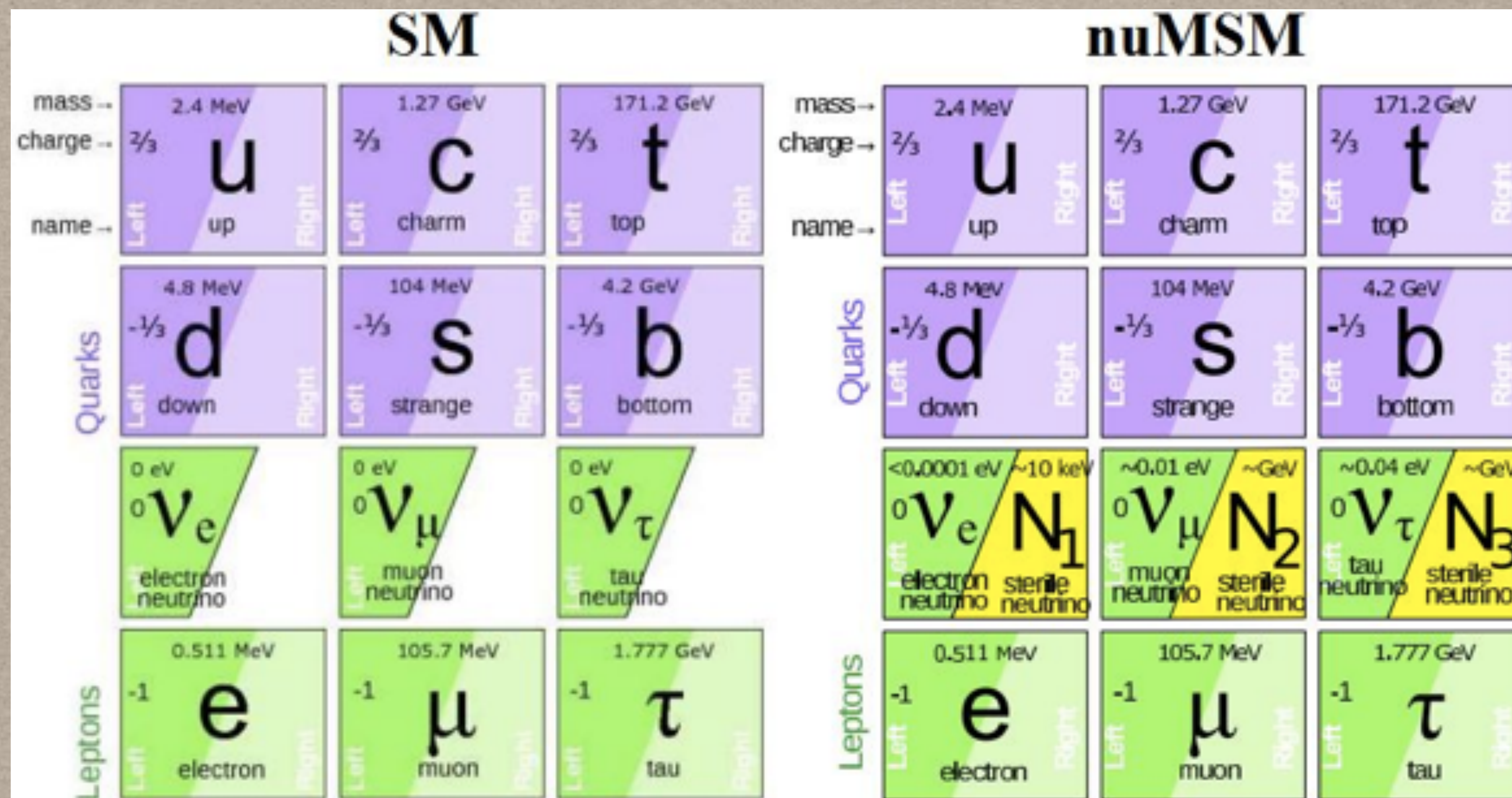

ISSUES:

y~10^{-7} to explain neutrino masses

keV, GeV mass scales put in by hand

sterile neutrino cannot be all of dark matter (X-ray + Lyman-α bounds)

Hints of an underlying structure?

A MODIFIED NEUTRINO SECTOR

- Recall: traditional seesaw requires

$$\mathcal{L} \supset y_{\alpha i} \bar{L}_\alpha H_u^\dagger N_i + M_i \bar{N}_i^c N_i$$

Naively: GUT/Planck scale

A MODIFIED NEUTRINO SECTOR

- Recall: traditional seesaw requires

$$\mathcal{L} \supset y_{\alpha i} \bar{L}_\alpha H_u^\dagger N_i + M_i \bar{N}_i^c N_i$$

Naively: GUT/Planck scale

- Assume RH neutrinos charged under a new symmetry: U(1)'

- Prohibits the above terms; traditional seesaw not allowed!

A MODIFIED NEUTRINO SECTOR

- Introduce an exotic field φ, equal and opposite U(1)′ charge to N
- This allows the following terms

$$\frac{y}{M_*} L H_u \mathcal{N} \Phi + \frac{x}{M_*} \mathcal{N} \mathcal{N} \Phi \Phi$$

A MODIFIED NEUTRINO SECTOR

- Introduce an exotic field φ, equal and opposite U(1)′ charge to N
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$$\frac{y}{M_*} L H_u \mathcal{N} \Phi + \frac{x}{M_*} \mathcal{N}\mathcal{N}\Phi\Phi$$

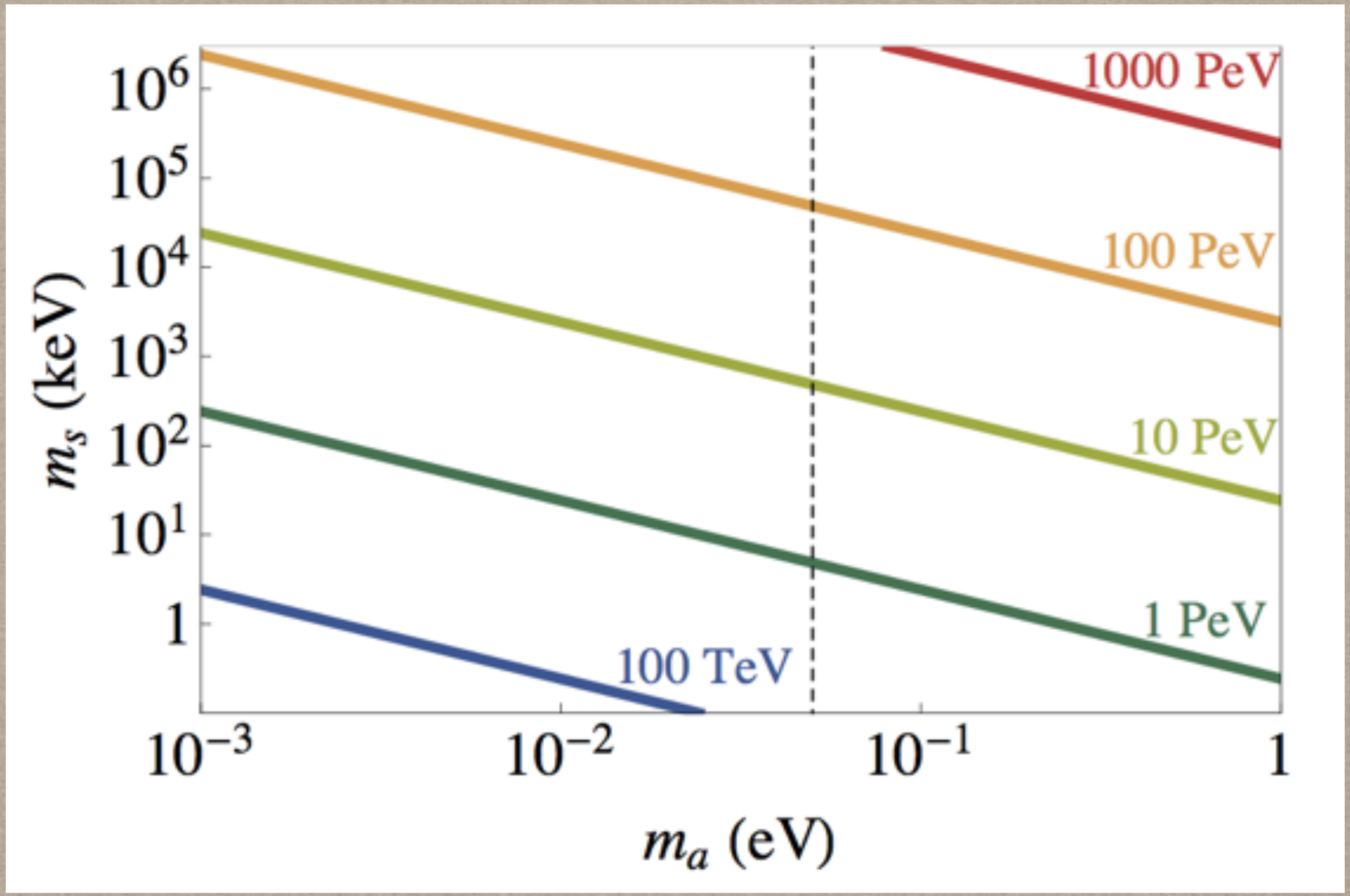
- If the scalar φ gets a vev, effective neutrino mass matrix:

$$M_\nu = \begin{pmatrix} 0 & \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y} \\ \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y}^\dagger & \frac{\langle\phi\rangle^2}{M_*}\mathbf{X} \end{pmatrix}$$

$$m_s = m_M = \frac{x\langle\phi\rangle^2}{M_*} \qquad m_a = \frac{m_D^2}{m_M} = \frac{y^2\langle H_u^0\rangle^2}{x M_*}$$

$$\theta \approx \sqrt{\frac{m_a}{m_s}} = \frac{y\langle H_u^0\rangle}{x\langle\phi\rangle} \qquad m_s = \frac{1}{m_a}\left(\frac{y\langle\phi\rangle\langle H_u^0\rangle}{M_*}\right)^2$$

A MODIFIED NEUTRINO SECTOR



Contours of y<φ>. $M_* = M_{GUT}(=10^{16}\,\text{GeV}),\ \tan\beta = 2$ $\quad 0.001 < x < 2$

Can get desired active and sterile masses with O(1) couplings and <φ>~O(1)-O(100) PeV

Maps onto νMSM

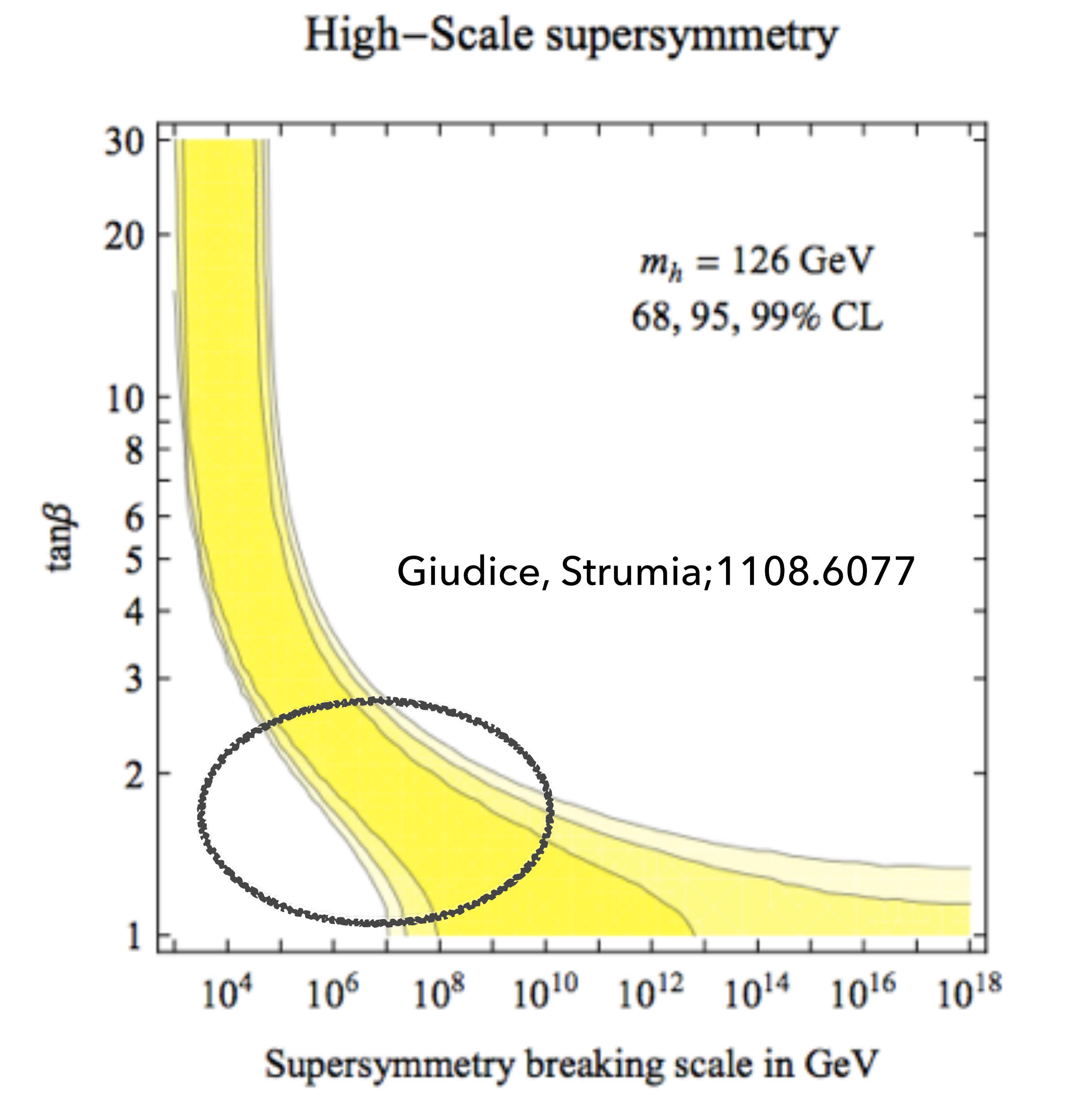
PEV SCALE...SUPERSYMMETRY?

Compatible with m_h=126 GeV

For tanβ ≈ O(1), m_h=126 GeV implies the **scale for supersymmetry (superpartners) is 1-100 PeV**

Suggests the vev of φ and the breaking of U(1)' might be related to SUSY breaking.

PeV Scale SUSY



J. D. Wells (2003), hep-ph/0306127.
N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005), hep-th/0405159.
G. Giudice and A. Romanino, Nucl.Phys. **B699**, 65 (2004), hep-ph/0406088.
J. D. Wells, Phys.Rev. **D71**, 015013 (2005), hep-ph/0411041.

STERILE NEUTRINO AS DARK MATTER

STERILE NEUTRINO AS DARK MATTER

- **(Ultraviolet) Freeze-in**

$$W \supset \frac{y}{M_*} L H_u \mathcal{N} \Phi + \frac{x}{M_*} \mathcal{N}\mathcal{N}\Phi\Phi$$

(If additional interactions keep φ in equilibrium with thermal bath)

(Doesn't need φ to be in equilibrium)

$$\phi\,\phi \rightarrow N_1\,N_1,\ \phi\,H_u \rightarrow \nu_a\,N_1,\ \phi\,\nu_a \rightarrow H_u\,N_1,\ \text{and}\ H_u, \nu_a \rightarrow \phi\,N_1$$

$$\Omega_{N_1} h^2 \simeq 0.1\, x^2 \left(\frac{m_s}{10\,\mathrm{GeV}}\right) \left(\frac{T_{RH}\, M_P}{M_*^2}\right)$$

F. Elahi, C. Kolda, and J. Unwin (2014), 1410.6157.
A. Kusenko, F. Takahashi, and T. T. Yanagida, Phys.Lett. **B693**, 144 (2010), 1006.1731.
M. Blennow, E. Fernandez-Martinez, and B. Zaldivar, JCAP **1401**, 003 (2014), 1309.7348.

STERILE NEUTRINO AS DARK MATTER

- **(Infrared) Freeze-in**

$$W \supset \frac{y}{M_*} L H_u \mathcal{N} \Phi + \frac{x}{M_*} \mathcal{N}\mathcal{N}\Phi\Phi$$

Once φ obtains a vev,

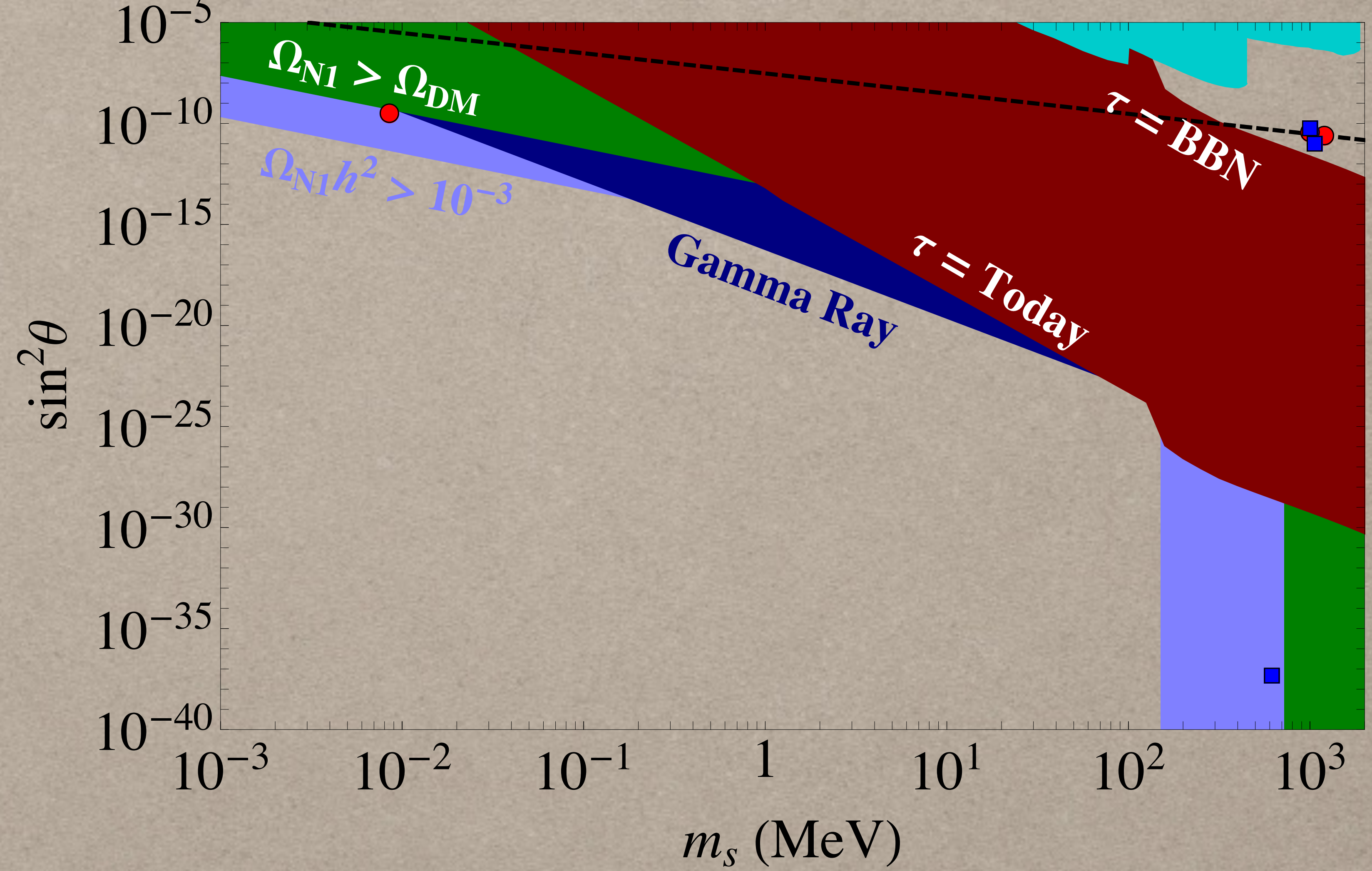
$$\phi \;\to\; N_1\, N_1 \qquad H_u \;\to\; N_1 \nu_a$$

$$x_1 \;=\; \frac{2\, x\, \langle\phi\rangle}{M_*} \qquad y_1 \;=\; \frac{y\,\langle\phi\rangle}{M_*}$$

↓

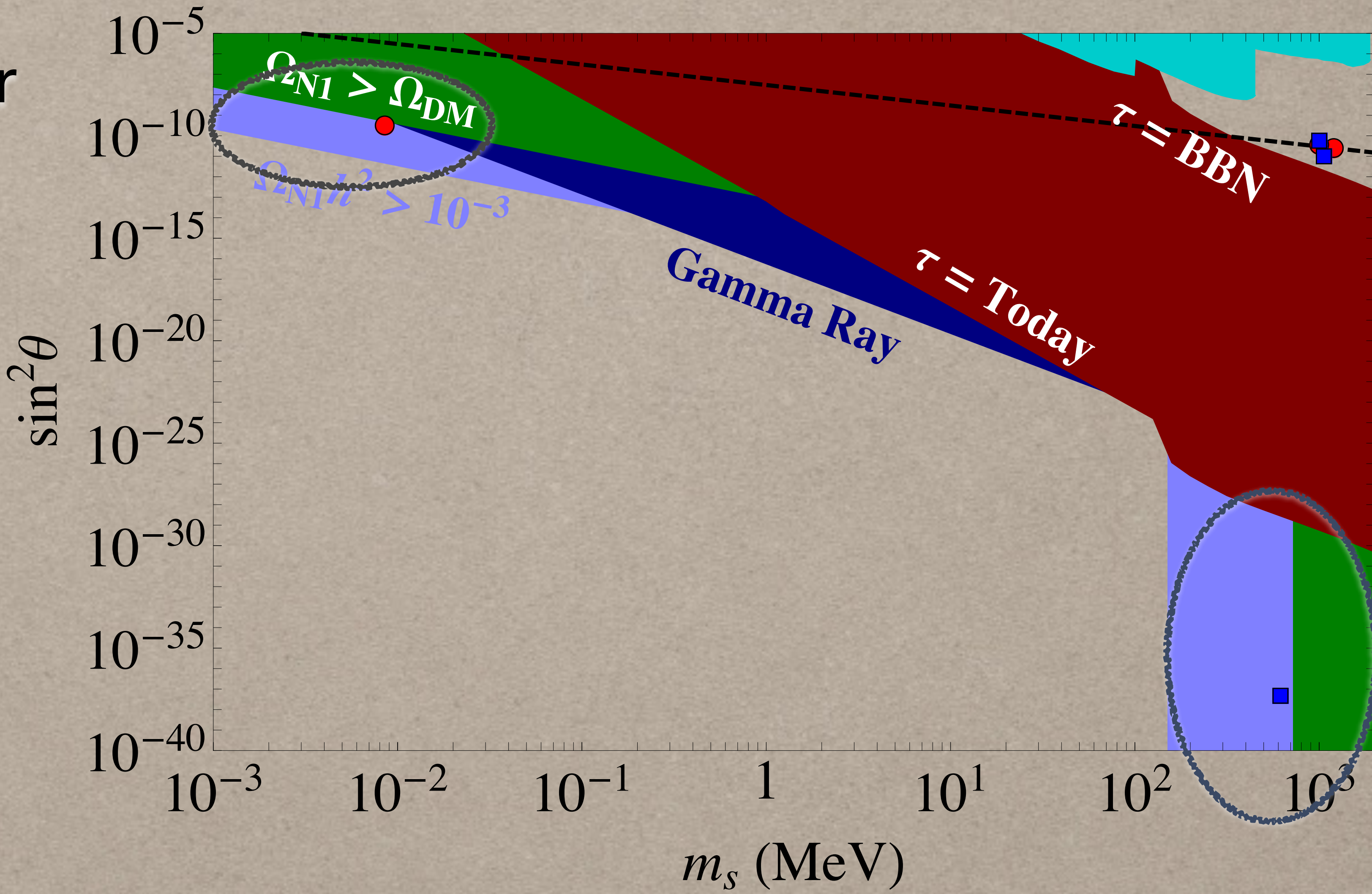
$$\Omega_{N_1} h^2 \sim 0.1 \left(\frac{x_1}{1.4\times 10^{-8}}\right)^3 \left(\frac{\langle\phi\rangle}{m_\phi}\right)$$

PARAMETER SPACE OF STERILE NEUTRINOS



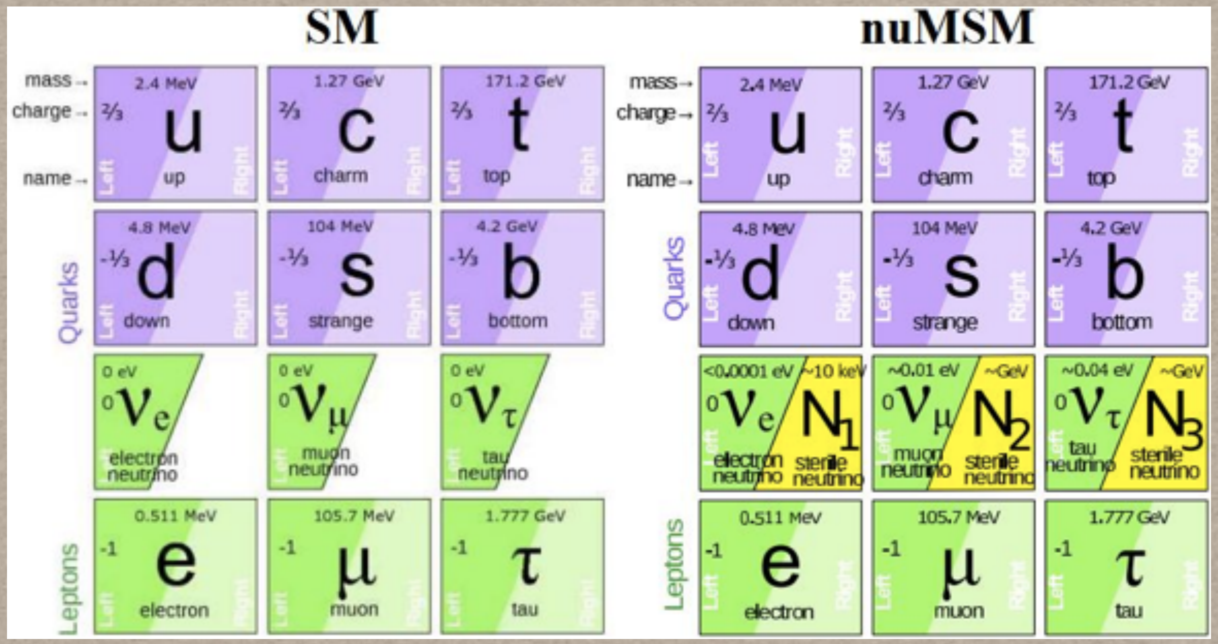
PARAMETER SPACE OF STERILE NEUTRINOS

keV dark matter through DW mechanism (nuMSM)



GeV DM through IR freeze-in (model dependent)

Neutrino Minimal Standard Model (νMSM)



ISSUES:

RESOLUTION: $\langle \phi \rangle \sim \mathrm{PeV}$

y~10^{-7} for neutrino masses? $\sim \frac{\langle \phi \rangle}{M_{GUT}}$

keV, GeV mass scales? $\sim \frac{\langle \phi \rangle^2}{M_{GUT}}$

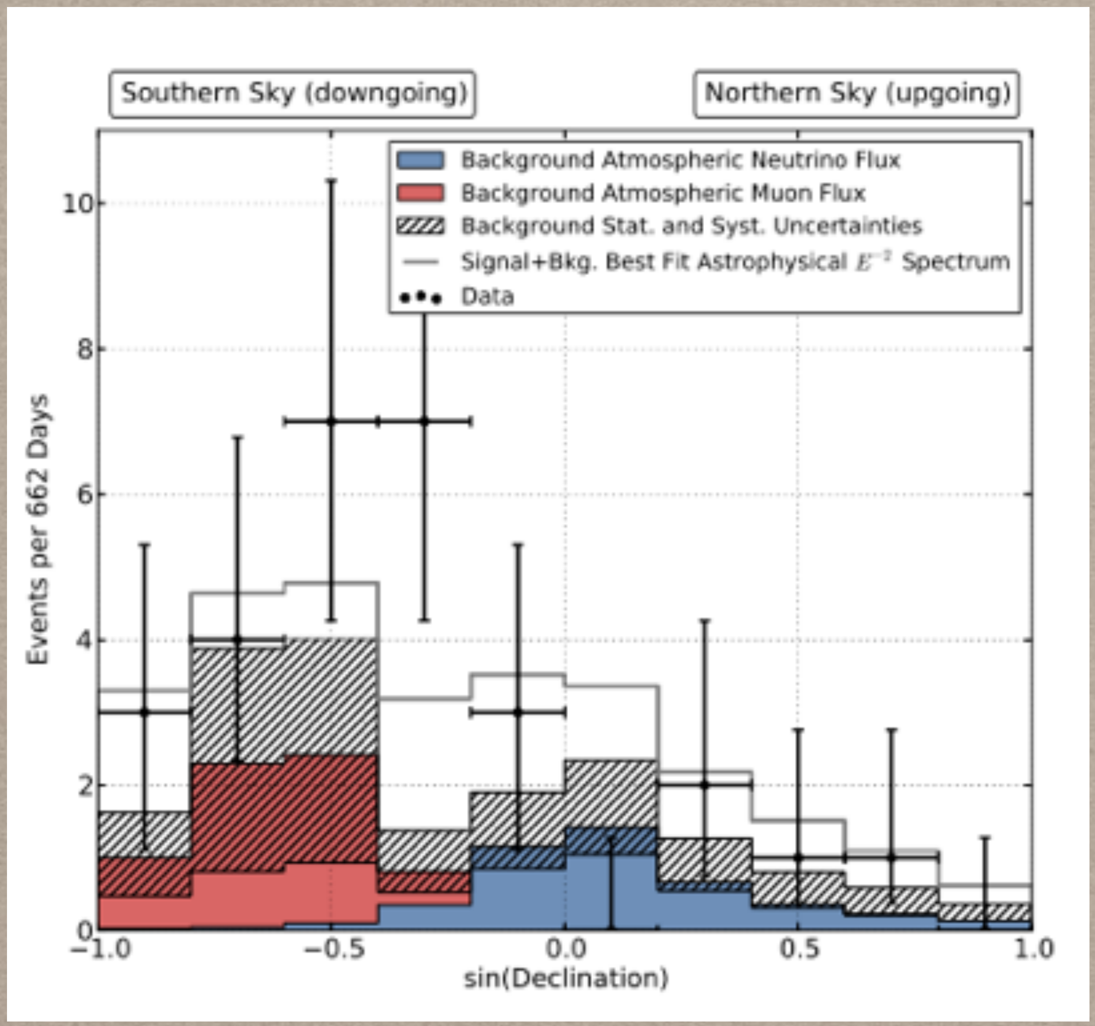
dark matter? freeze-in, small coupling $\sim \frac{\langle \phi \rangle}{M_{GUT}}$

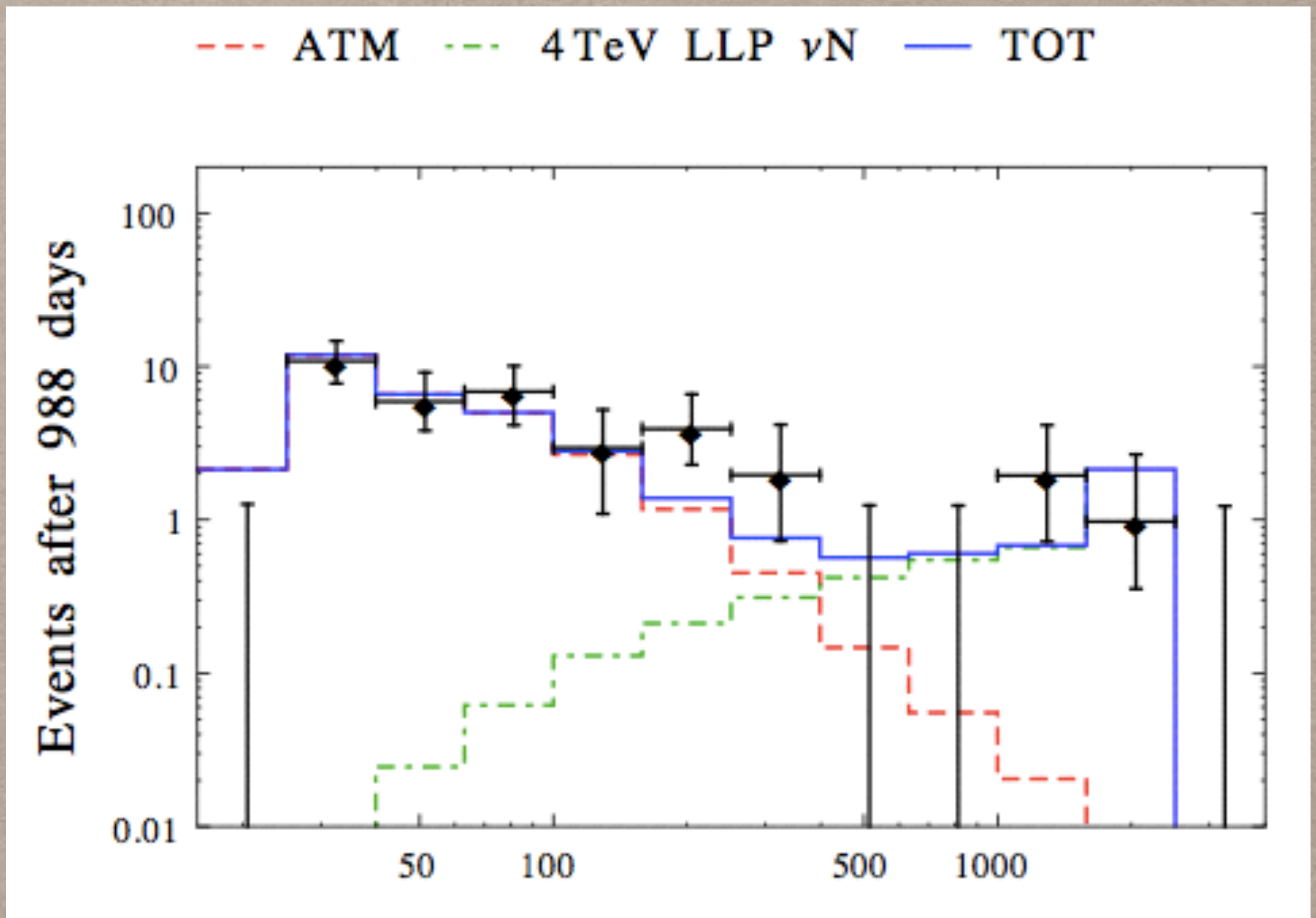
CONNECTIONS TO RECENT DARK MATTER “HINTS”

3.5 KEV X-RAY LINE

- unidentified emission line at ~3.5 keV in stacked XMM-Newton observations of 73 galaxy clusters, Perseus cluster, Andromeda (Bulbul et.al (2014), Boyarsky et. al.(2014))
- many papers fitting to ~7 keV sterile neutrino dark matter
- potential mismodeling of background (Jeltema and Profumo (2014)), situation unclear
- **~7 keV sterile neutrino that is 25-50% of dark matter, with mixing $\sin^2(2\theta) \sim 4.0\times 10^{-10}$ can fit the signal (Harada, Kamada, Yoshida, 1412.1592)**
- **sterile neutrino being only a fraction of dark matter might help evade some constraints**

PEV NEUTRINOS AT ICECUBE: A HINT OF PEV DARK MATTER?





Fong et al, 1411.5318

37 high energy neutrinos between 30 TeV and 2 PeV

Several papers fitting to decaying dark matter, lifetime ~10^{28} s

A PEV DARK MATTER CANDIDATE (X)

- So far :

$$\mathcal{W} \supset \frac{\zeta_{ij}}{M_*} L_i H_u \mathcal{N}_j \Phi + \frac{\eta_i}{M_*} \mathcal{N}_i \mathcal{N}_i \Phi\Phi \, .$$

A PEV DARK MATTER CANDIDATE (X)

- Add additional fields X,Y with the same structure

$$\mathcal{W} \supset \frac{\zeta_{ij}}{M_*} L_i H_u \mathcal{N}_j \Phi + \frac{\eta_i}{M_*} \mathcal{N}_i \mathcal{N}_i \Phi\Phi$$
$$+ \frac{\alpha_i}{M_*} L_i H_u \mathcal{X}\mathcal{Y} + \frac{\lambda_1}{M_*} \mathcal{X}\mathcal{X}\mathcal{Y}\mathcal{Y} + \frac{\beta_i}{M_*} \mathcal{N}_i \Phi \mathcal{X}\mathcal{Y} + \frac{1}{5!}\frac{\lambda_2}{M_*^3} \mathcal{X}\Phi^5 + \frac{1}{5!}\frac{\lambda_3}{M_*^3} \mathcal{Y}\mathcal{N}_i^5$$

Supermultiplet	spin 0, 1/2	$U(1)'$	Remarks
$\mathcal{N}_i$	$\tilde{N}_i$, N_i	+1	N_i sterile neutrinos
Φ	ϕ, ψ_ϕ	-1	$\langle\phi\rangle$ ~PeV breaks $U(1)'$
$\mathcal{X}$	X, ψ_X	+5	m_X ~PeV, dark matter
$\mathcal{Y}$	Y, ψ_Y	-5	$U(1)'$ partner of $\mathcal{X}$

A PEV DARK MATTER CANDIDATE (X)

RELIC DENSITY :

$$\mathcal{W} \supset \frac{\zeta_{ij}}{M_*} L_i H_u \mathcal{N}_j \Phi + \frac{\eta_i}{M_*} \mathcal{N}_i \mathcal{N}_i \Phi\Phi$$
$$+ \frac{\alpha_i}{M_*} L_i H_u \mathcal{X}\mathcal{Y} + \frac{\lambda_1}{M_*} \mathcal{X}\mathcal{X}\mathcal{Y}\mathcal{Y} + \frac{\beta_i}{M_*} \mathcal{N}_i \Phi \mathcal{X}\mathcal{Y} + \frac{1}{5!}\frac{\lambda_2}{M_*^3} \mathcal{X}\Phi^5 + \frac{1}{5!}\frac{\lambda_3}{M_*^3} \mathcal{Y}\mathcal{N}_i^5$$

- Produce via annihilation processes

$$l\,h \to X\,\psi_Y, \qquad l\,\tilde{H} \to X\,Y, \qquad \tilde{l}\,\tilde{H} \to X\,\psi_Y$$

- X abundance accumulates via UV freeze-in

$$\Omega_X h^2 \sim 0.12 \left(\frac{m_X}{10\ \text{PeV}}\right)\left(\frac{\alpha}{10^{-4}}\right)^2\left(\frac{T_{RH}}{1.5\times 10^{10}\ \text{GeV}}\right)$$

F. Elahi, C. Kolda, and J. Unwin (2014), 1410.6157.
A. Kusenko, F. Takahashi, and T. T. Yanagida, Phys.Lett. **B693**, 144 (2010), 1006.1731.
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A PEV DARK MATTER CANDIDATE (X)

DECAY INTO NEUTRINOS:

$$\mathcal{L} \supset -\frac{\lambda_2}{12}\left(\frac{\langle\phi\rangle}{M_*}\right)^3 X\,\psi_\phi\,\psi_\phi$$

$$\mathcal{W} \supset \frac{\zeta_{ij}}{M_*} L_i H_u \mathcal{N}_j \Phi + \frac{\eta_i}{M_*}\mathcal{N}_i\mathcal{N}_i\Phi\Phi$$

$$+\frac{\alpha_i}{M_*} L_i H_u \mathcal{X}\mathcal{Y} + \frac{\lambda_1}{M_*}\mathcal{X}\mathcal{X}\mathcal{Y}\mathcal{Y} + \frac{\beta_i}{M_*}\mathcal{N}_i\Phi\mathcal{X}\mathcal{Y} + \frac{1}{5!}\frac{\lambda_2}{M_*^3}\mathcal{X}\Phi^5 + \frac{1}{5!}\frac{\lambda_3}{M_*^3}\mathcal{Y}\mathcal{N}_i^5$$

- Decays via

$$X \to \psi_\phi\,\psi_\phi \qquad \psi_\phi \to N\tilde{H}\nu\,,\psi_\phi \to N\tilde{H}^\pm l^\mp \qquad N_i \to 3\nu$$

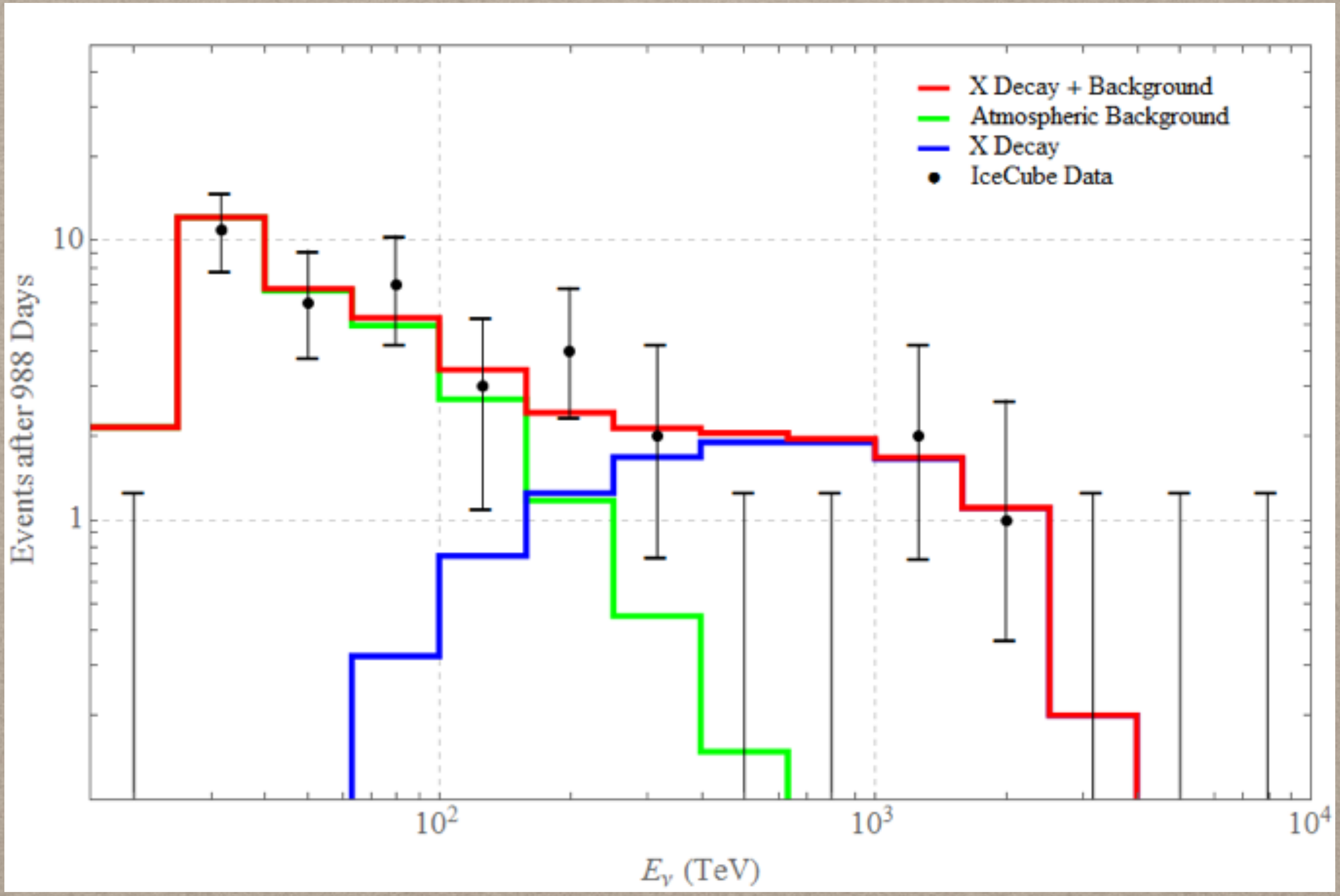
(and others)

[Higgsinos can decay via small RPV couplings or make a fraction of DM (with sub-TeV masses)]

- Lifetime for X :

$$\tau_X \approx 10^{27}\,\mathrm{s}\left(\frac{1.5\times10^{-3}}{\lambda_2}\right)^2\left(\frac{M_*}{10^8\langle\phi\rangle}\right)^6\left(\frac{\mathrm{PeV}}{m_X}\right)$$

FITTING TO ICECUBE



$$\frac{\alpha_i}{M_*} L_i H_u \mathcal{X}\mathcal{Y} + \frac{1}{5!}\frac{\lambda_2}{M_*^3}\mathcal{X}\Phi^5$$

$\alpha = 0.007$ $\quad m_X = 7$ PeV

$\lambda_2 = 0.0002$ $\quad m_{\psi_\phi} = 2$ PeV

SUMMARY

NEUTRINO MASSES

keV-GeV sterile neutrinos, some/all of DM ⟷ *3.5 keV X-ray line*

PEV SCALE SUPERSYMMETRIC NEUTRINO SECTOR
WITH ADDITIONAL SYMMETRY (U(1)′)

m_h=126 GeV with tanβ ≈ O(1), PeV scale squarks

PeV sector, PeV DM ⟷ *PeV neutrinos at IceCube*