NEUTRINO MASSES AND STERILE NEUTRINO DARK MATTER FROM THE PEV SCALE

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FERMILAB THEORY SEMINAR
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Based on hep-ph:1412.4791 and hep-ph:15xx.soon

with Samuel Roland and James Wells

WHAT IS THE SCALE OF NEW PHYSICS

(SUPERSYMMETRY)

???

THE PARTICLE PHYSICIST'S GUIDE TO PHYSICS BEYOND THE STANDARD MODEL

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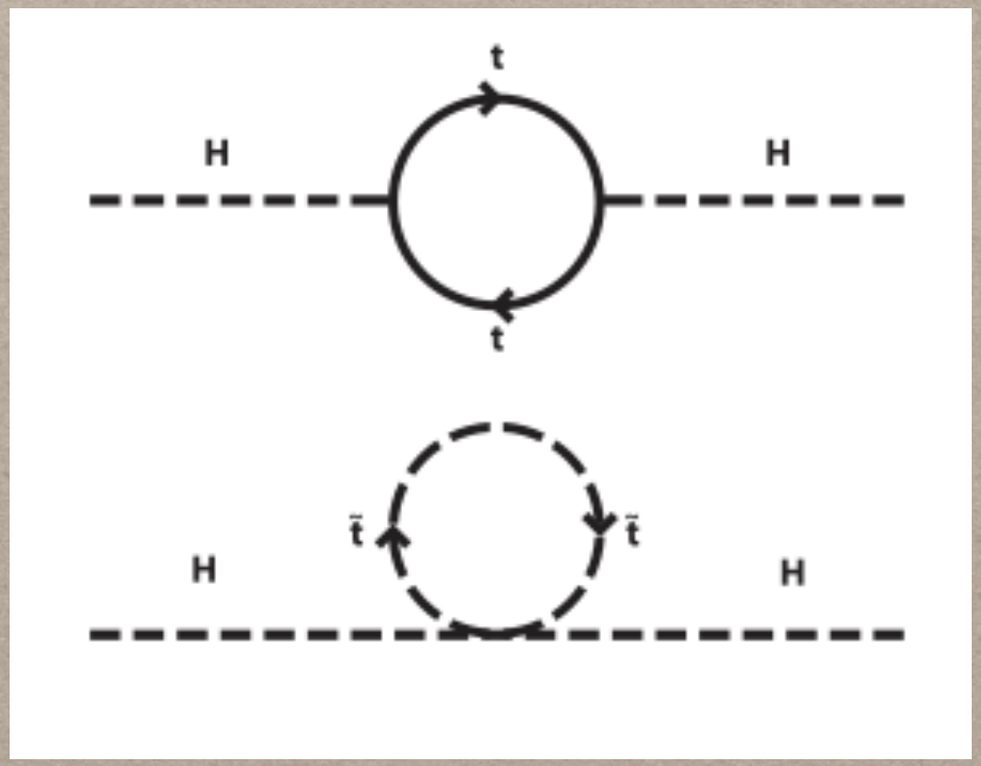
HIERARCHY PROBLEM

THE PARTICLE PHYSICIST'S GUIDE TO PHYSICS BEYOND THE STANDARD MODEL

HIERARCHY PROBLEM



One loop quantum corrections to Higgs mass/vev push them towards the Planck scale, need to be cancelled not too far above the electroweak scale

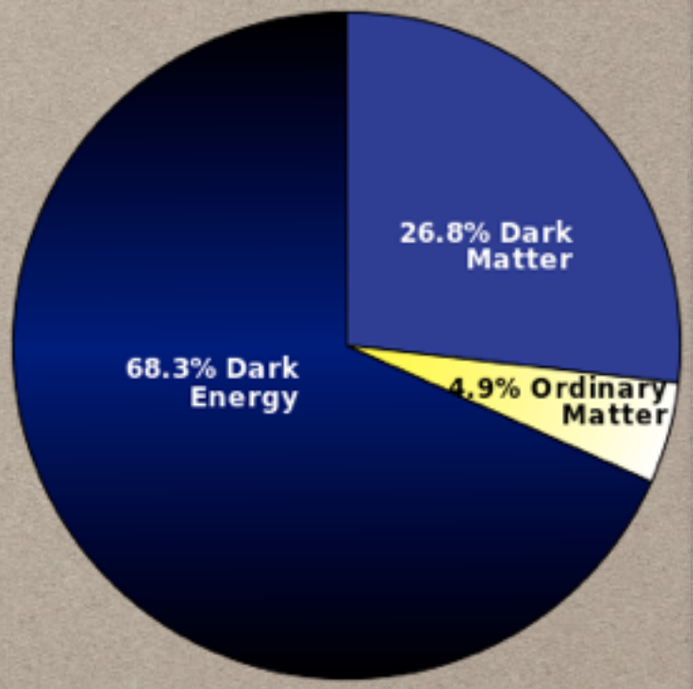
THE PARTICLE PHYSICIST'S GUIDE TO PHYSICS BEYOND THE STANDARD MODEL

WIMP MIRACLE

THE PARTICLE PHYSICIST'S GUIDE TO PHYSICS BEYOND THE STANDARD MODEL

WIMP MIRACLE

- dark matter requires physics beyond the SM
- freeze-out of a particle with weak scale mass and weak-force-strength interactions with the SM produces a relic abundance equal to the observed abundance of dark matter
- works with the lightest neutralino stabilized by R-parity in weak scale supersymmetry



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WIMP MIRACLE

→ WEAK SCALE SUPERSYMMETRY

WEAK SCALE SUPERSYMMETRY

PREDICTIONS:

1. Light Higgs ($m_h \sim m_Z$), possibly non SM-like due to mixing between H_u and H_d
2. Light stops, gluino within reach of the LHC first run
3. large direct detection signal within reach of current detectors

WEAK SCALE SUPERSYMMETRY

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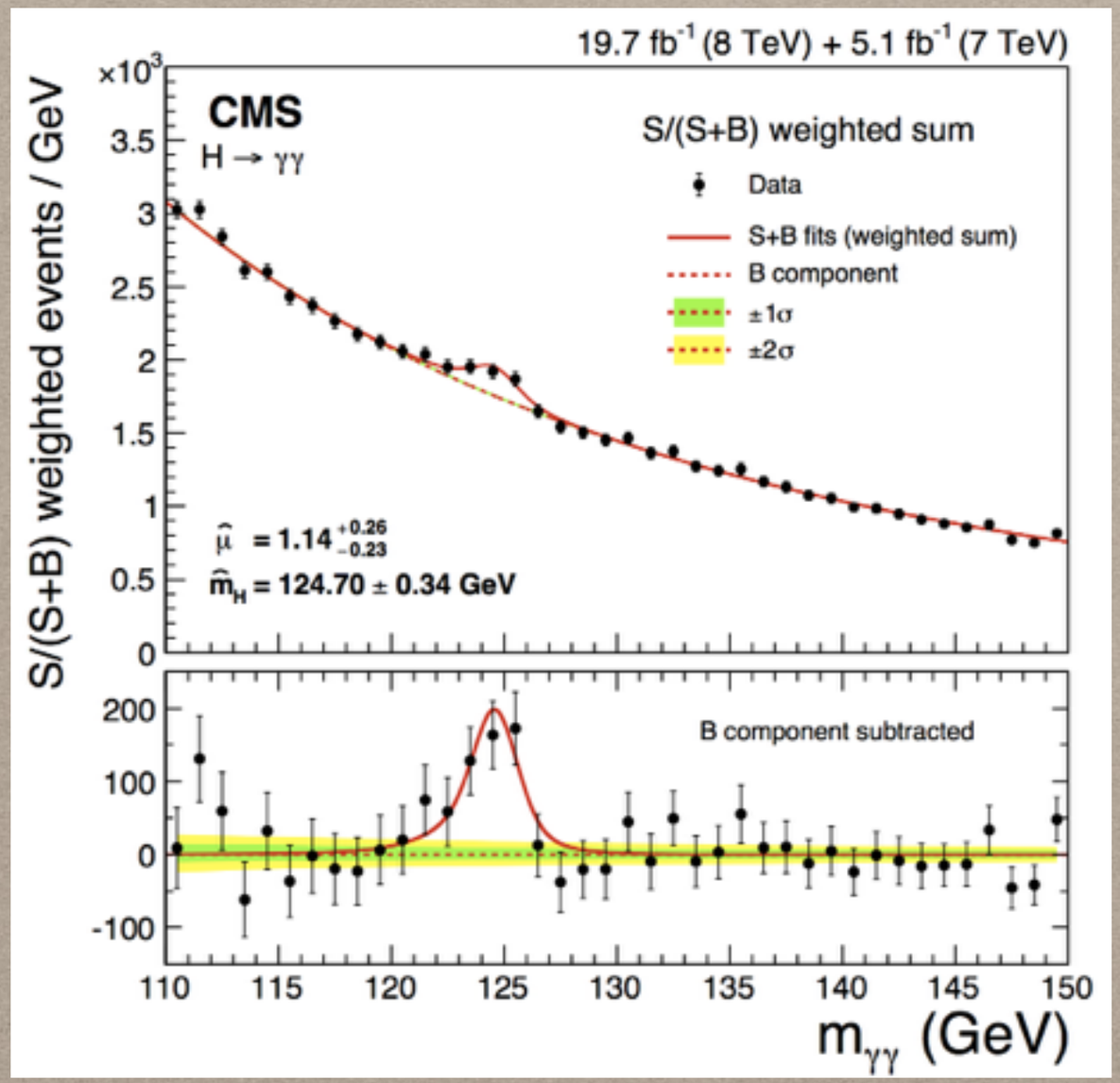
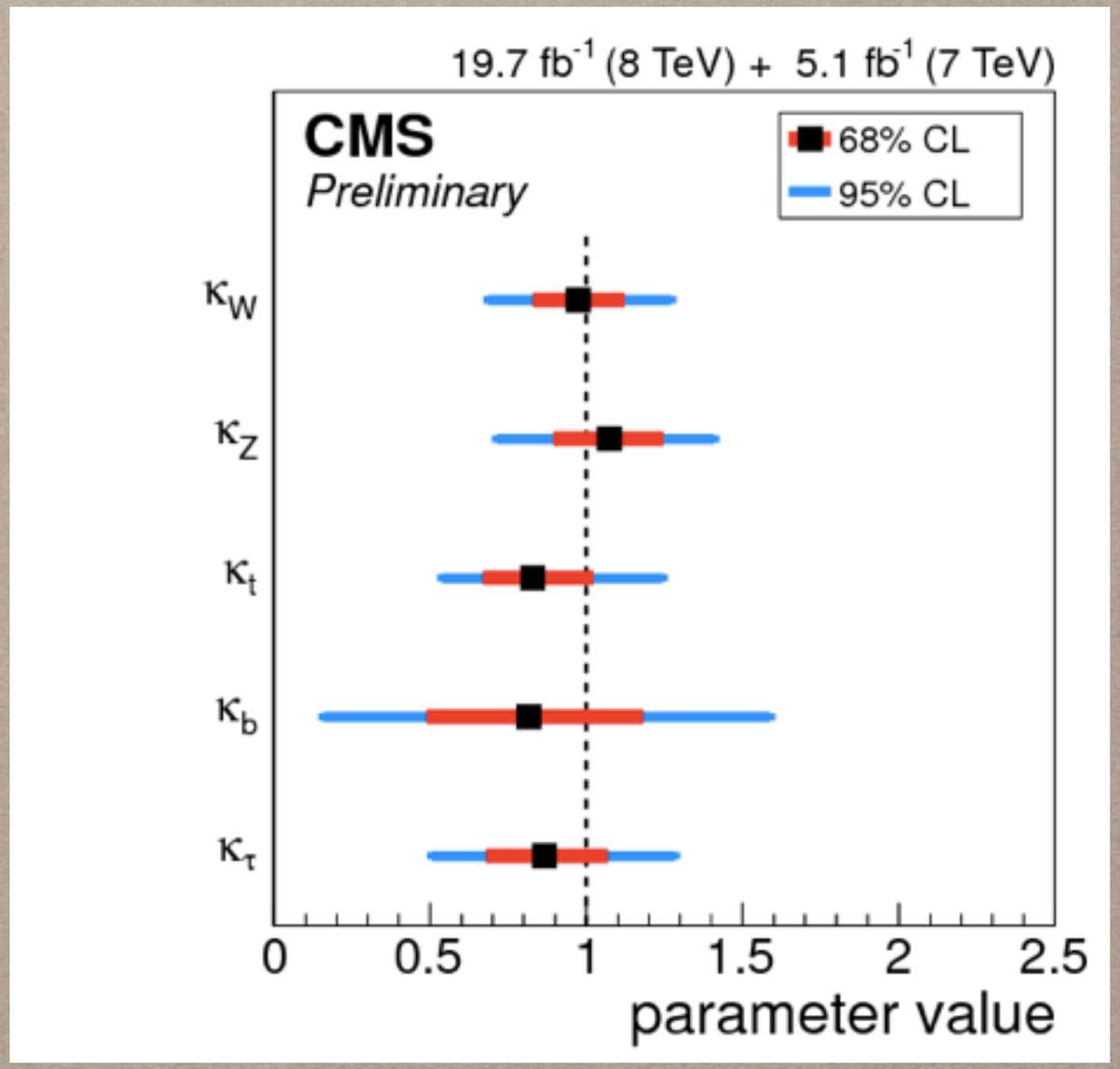
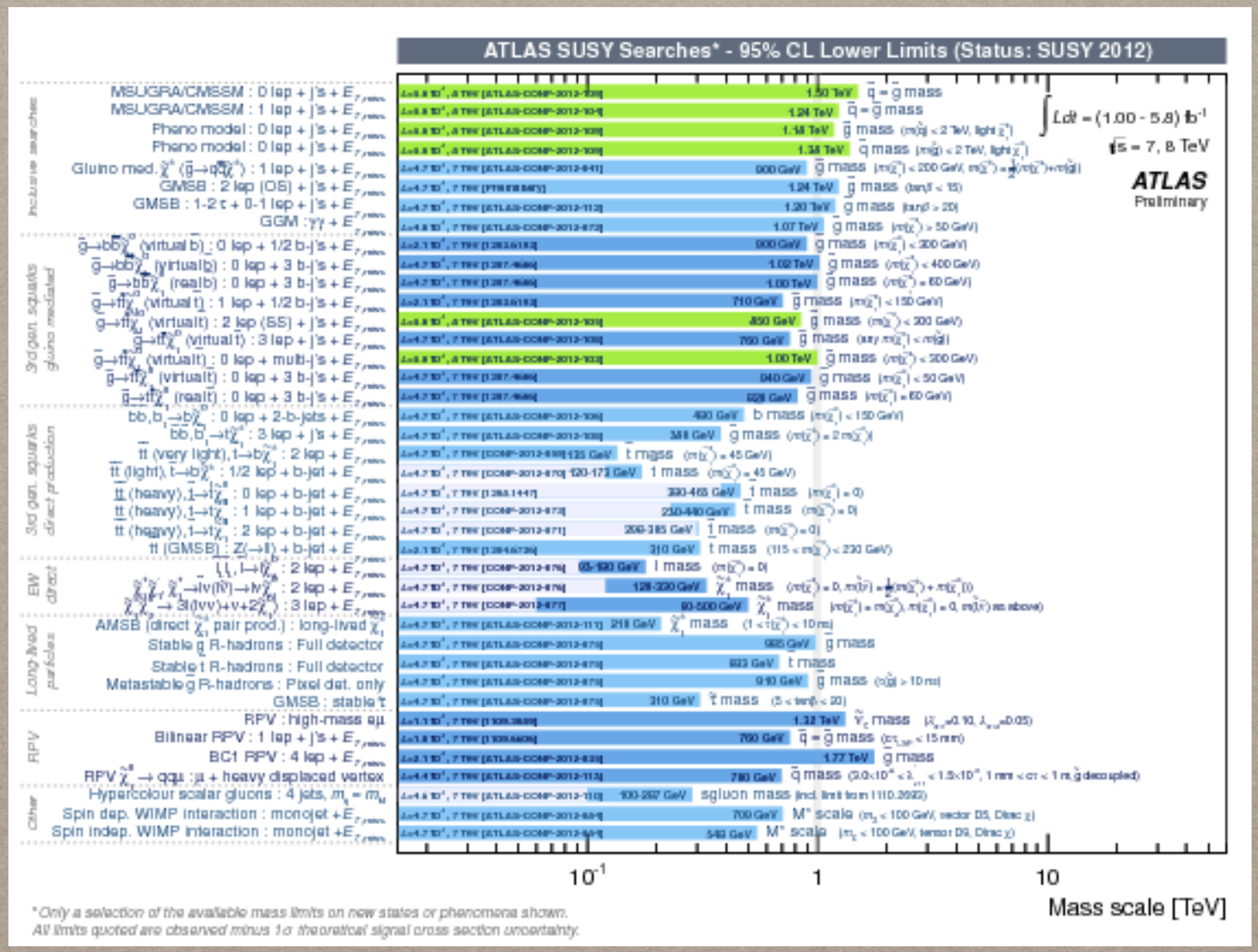




WEAK SCALE SUPERSYMMETRY

2. Light stops, gluino within reach of the LHC first run



WEAK SCALE SUPERSYMMETRY

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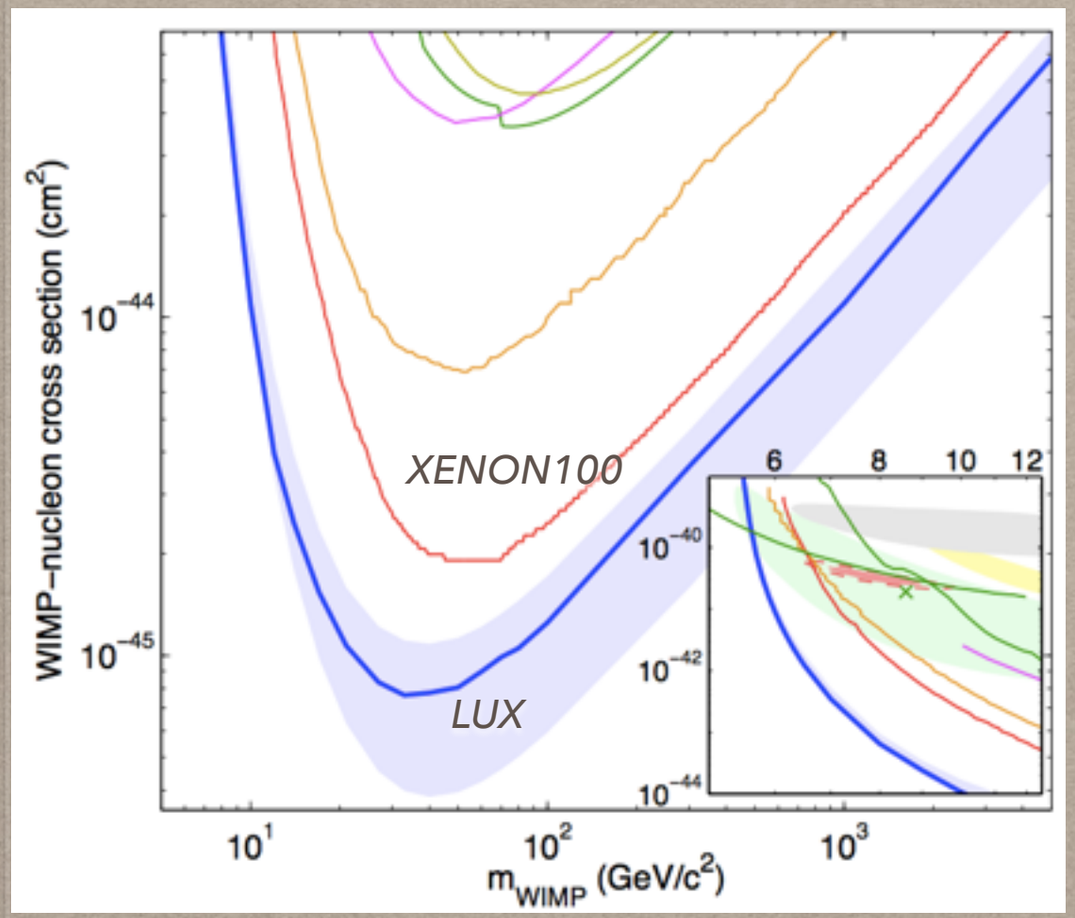

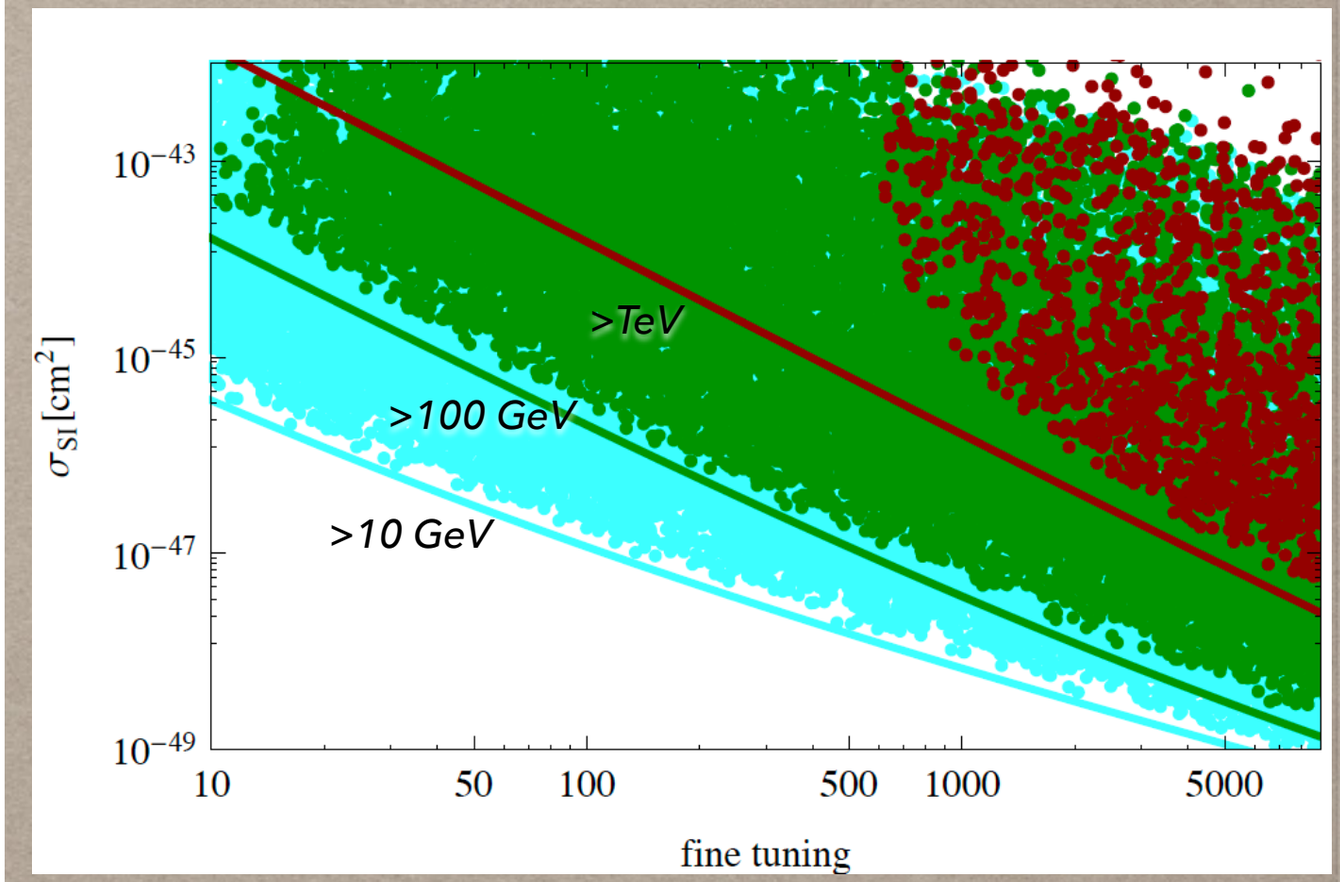

Perelstein & Shakya
1107.5048, 1208.0833

LIFE BEYOND THE WEAK SCALE ?

- Perhaps naturalness not a good guiding principle in this case, the Higgs mass/vev is fine-tuned, and supersymmetry exists at some higher scale (high scale SUSY/split SUSY)
- Dark matter might not necessarily be a WIMP

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A direct probe:

m_h=126 GeV

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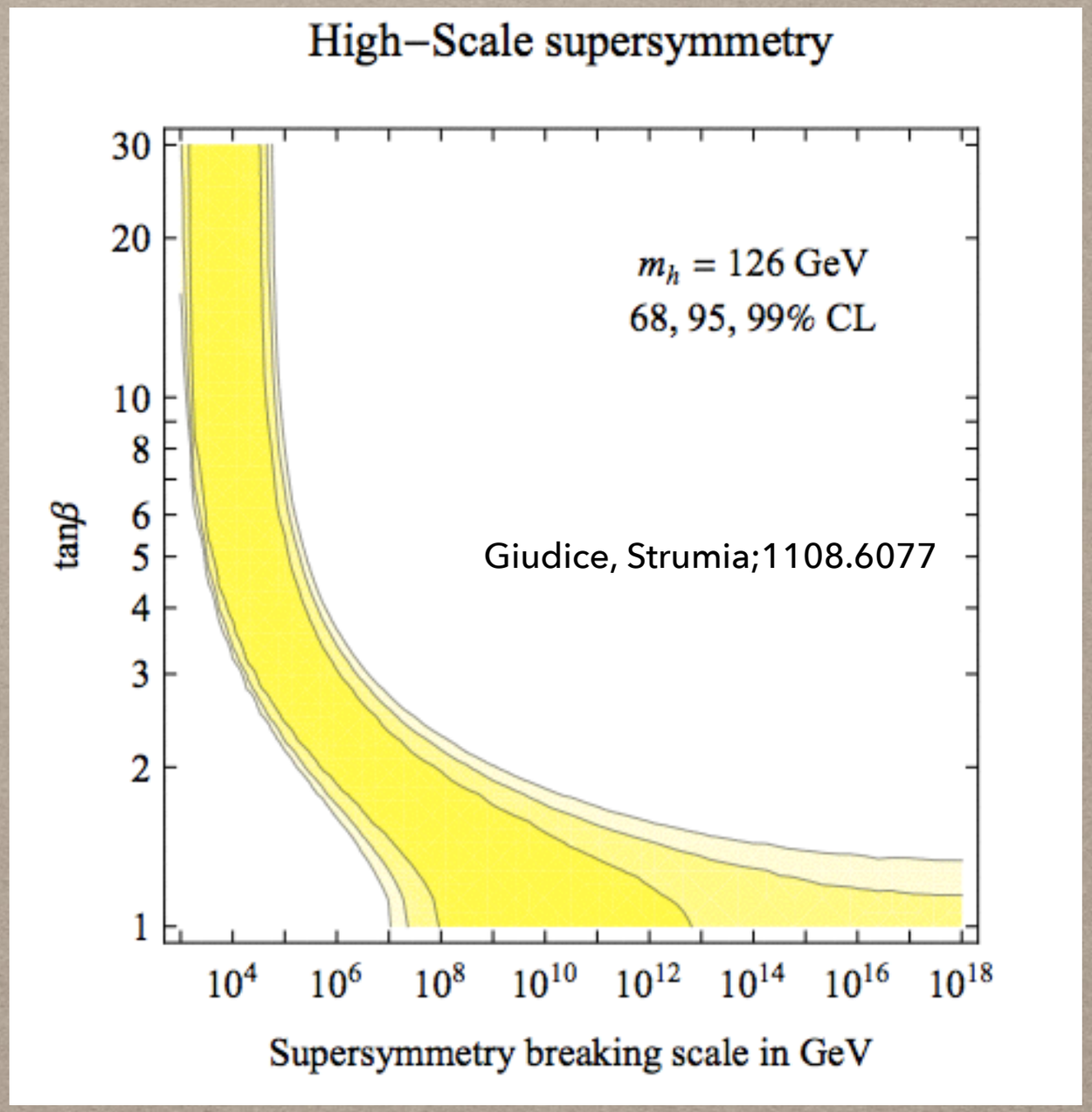
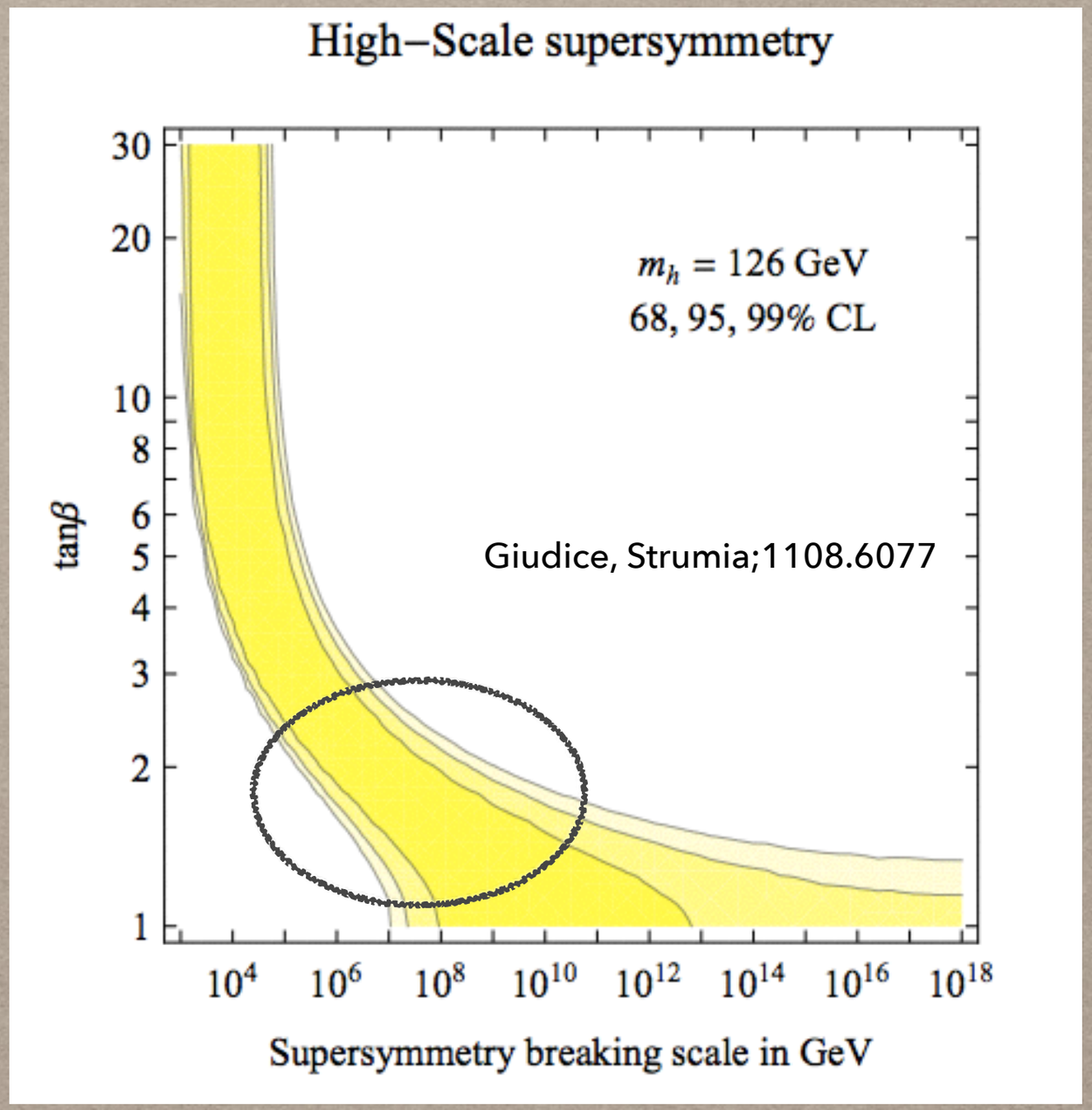


THE PARTICLE PHYSICIST'S GUIDE TO PHYSICS BEYOND THE STANDARD MODEL

A direct probe:

m_h=126 GeV

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



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NEUTRINO MASSES

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DARK MATTER

NEUTRINO MASSES

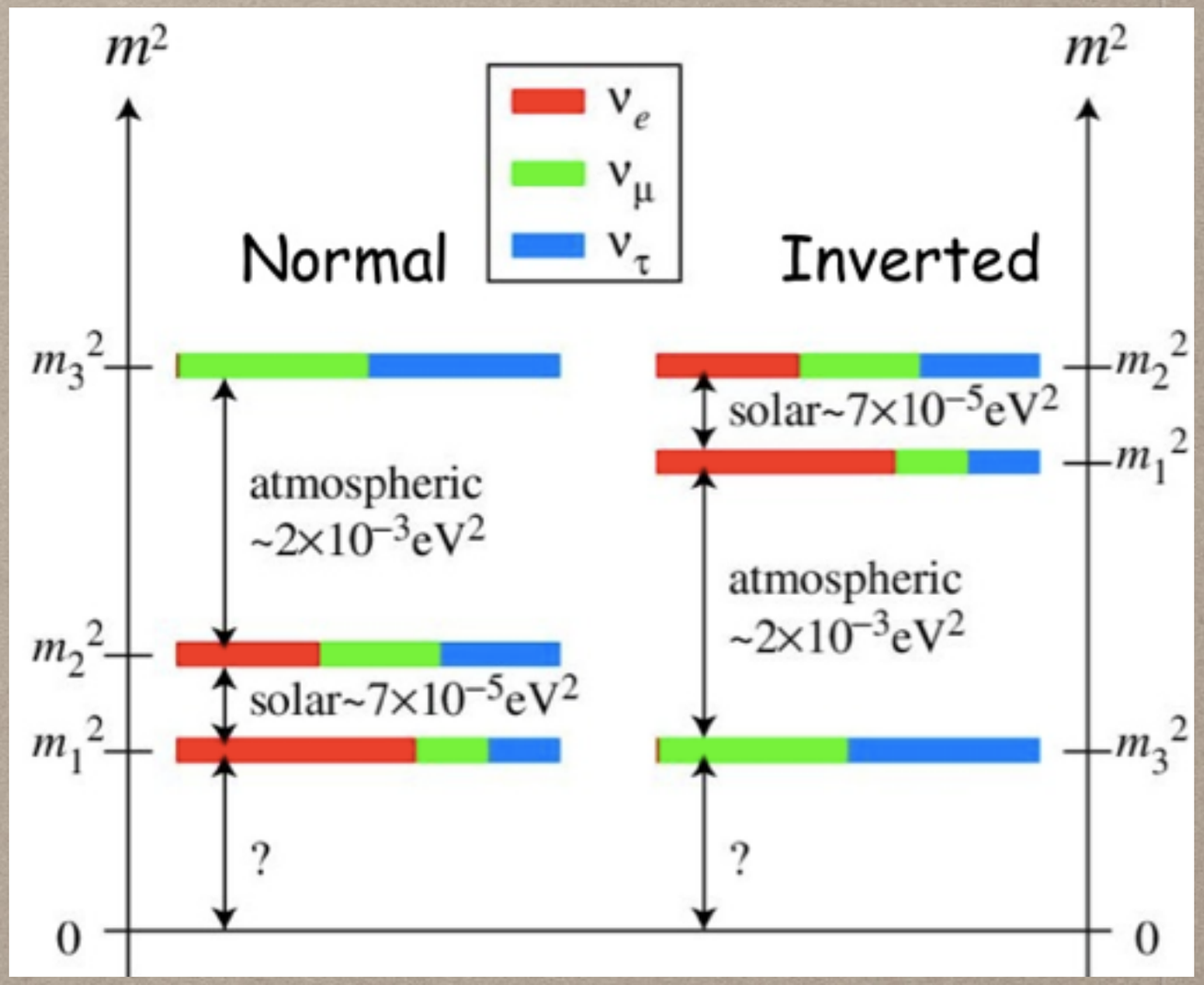
(BARYON ASYMMETRY)

NEUTRINO MASSES

Neutrinos are massless in the Standard Model

However, solar and atmospheric oscillation data require mass differences.

Absolute mass scale unknown. Measurements constrain the sum to be < 0.23 eV.



NEUTRINO MASSES FROM THE SEESAW

- Add SM-singlet sterile right-handed neutrinos N_i

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

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

- Couplings y and masses M_i unconstrained.
- For y~O(1), M~10^{14} GeV (GUT scale seesaw)

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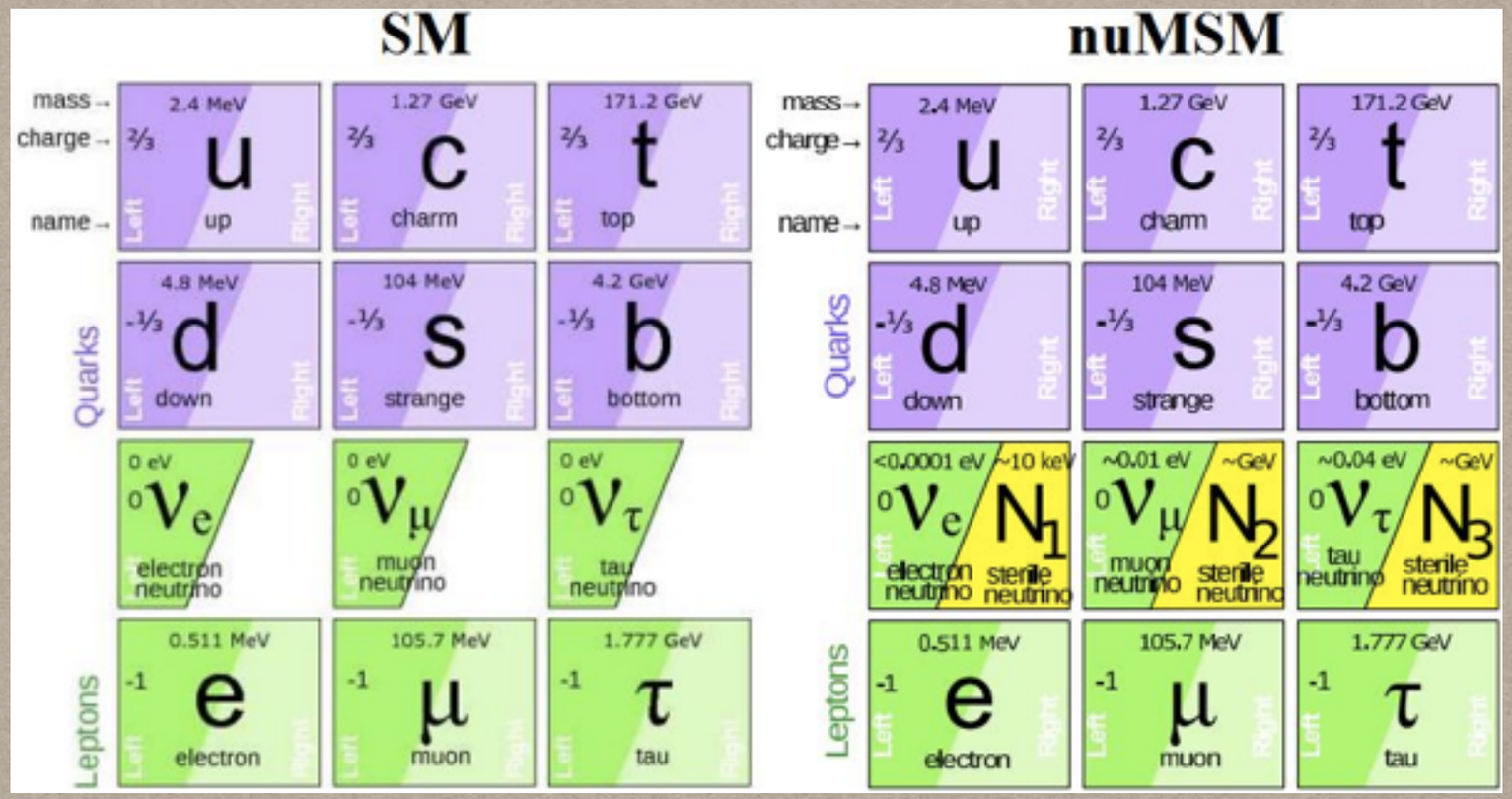
- Couplings y and masses M_i unconstrained.
- For y~O(1), M~10^{14} GeV (GUT scale seesaw)
- However, N_1~keV can provide a dark matter candidate, and N_2,N_3~GeV can give baryogenesis!

Neutrino Minimal Standard Model (vMSM)



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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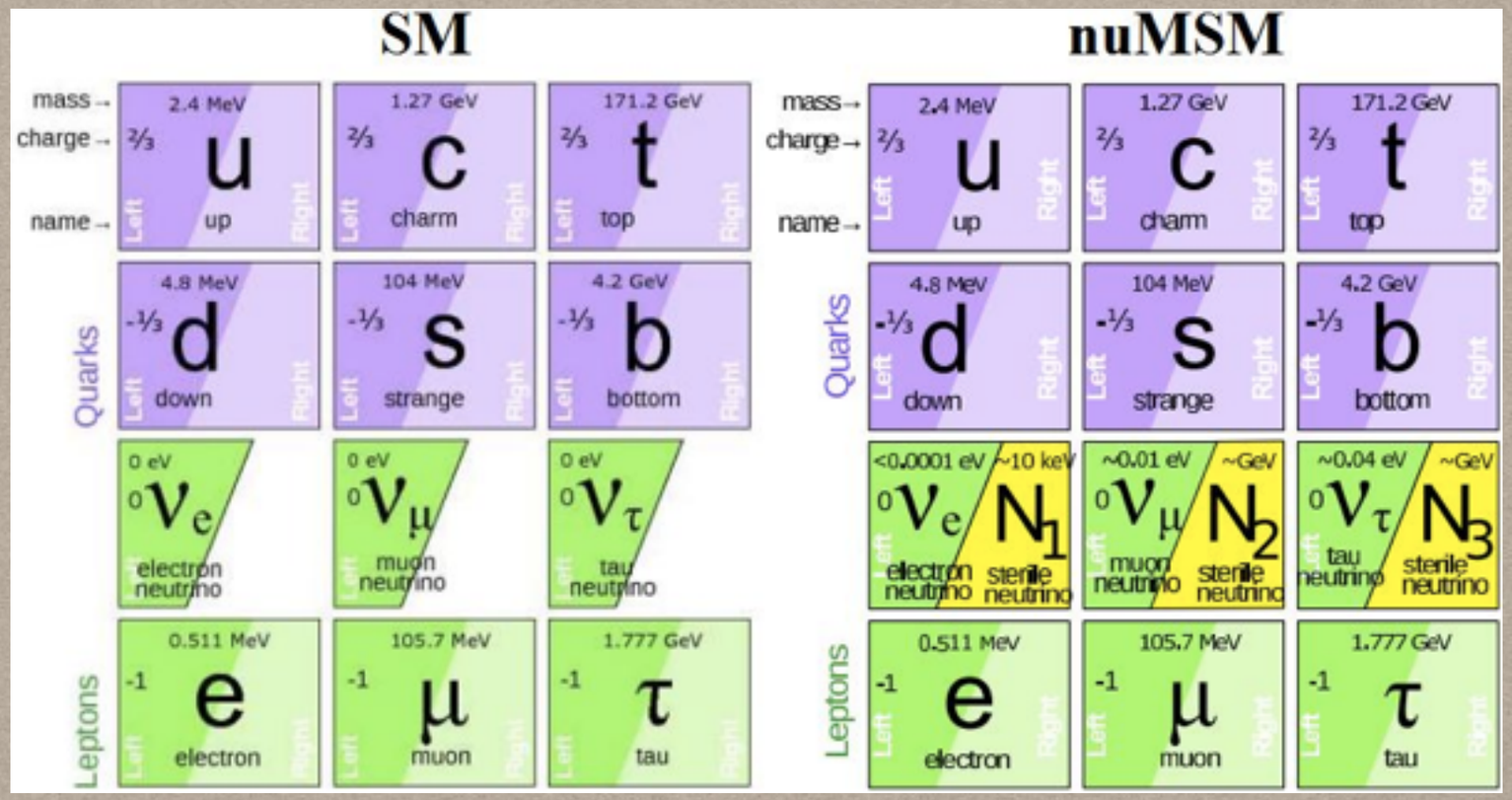

ISSUES:

$y \sim 10^{-7}$ to explain neutrino masses

keV, GeV mass scales put in by hand

not so straightforward to get keV sterile neutrino to be all of dark matter

A MODIFIED SEESAW MECHANISM

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- Assume they are charged under a U(1)'

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- Reasonable to assume they are singlet under the SM gauge group, but perhaps not under all symmetries of nature
- Assume they are charged under a U(1)'
- Prohibits the above terms; traditional seesaw not allowed!

A MODIFIED SEESAW MECHANISM

- Add additional content charged under the U(1)′: a field φ with opposite charge to N. New terms:

$$W \supset \frac{y}{M_*} L H_u N^c \phi + \frac{x}{M_*} N^c N^c \phi \, \phi$$

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

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

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

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

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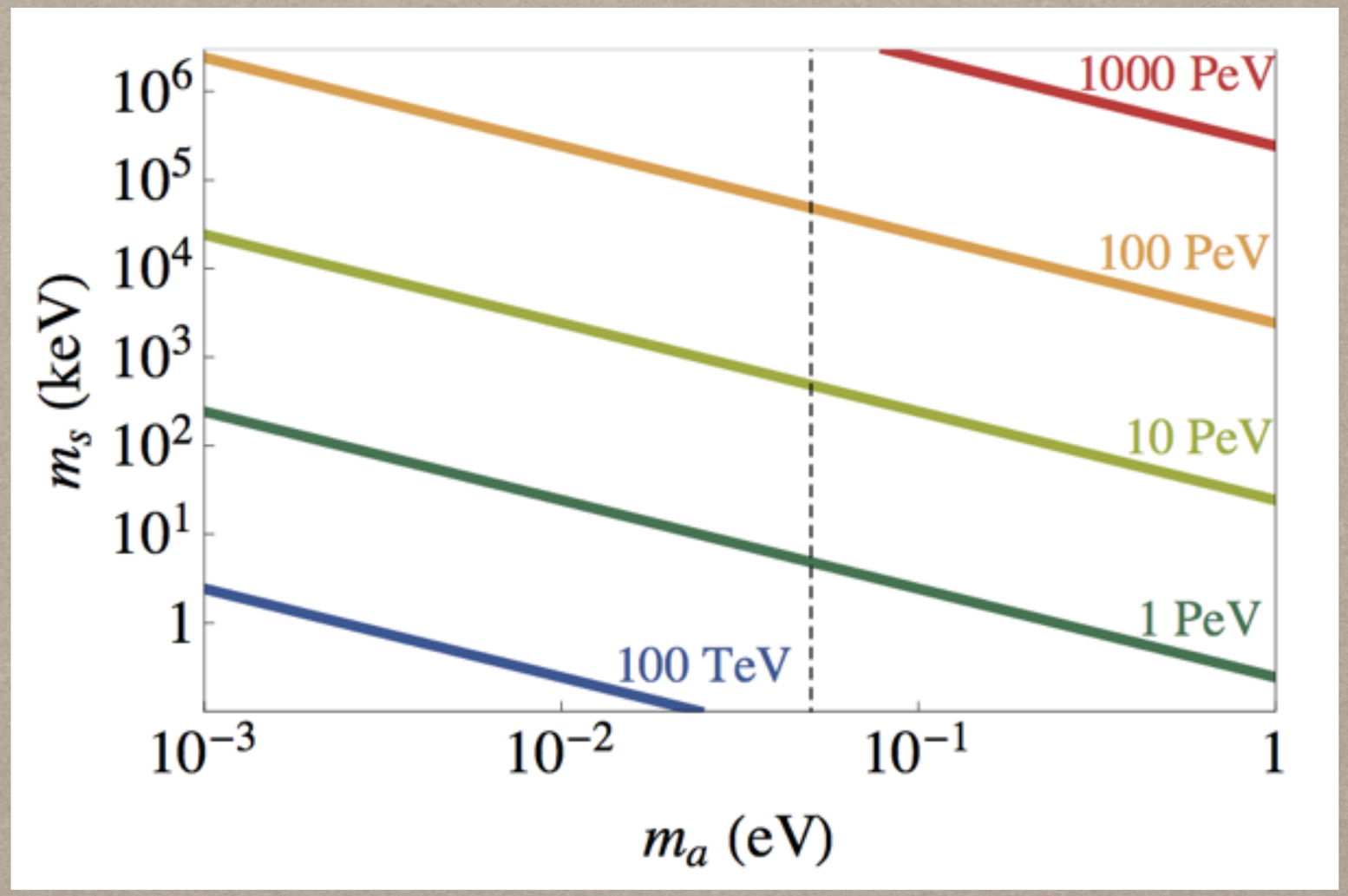

Contours of y<φ>. $M_* \;\; = M_{GUT}(=10^{16}\,\mathrm{GeV}),\;\; \tan\beta = 2 \qquad 0.001 < x < 2$

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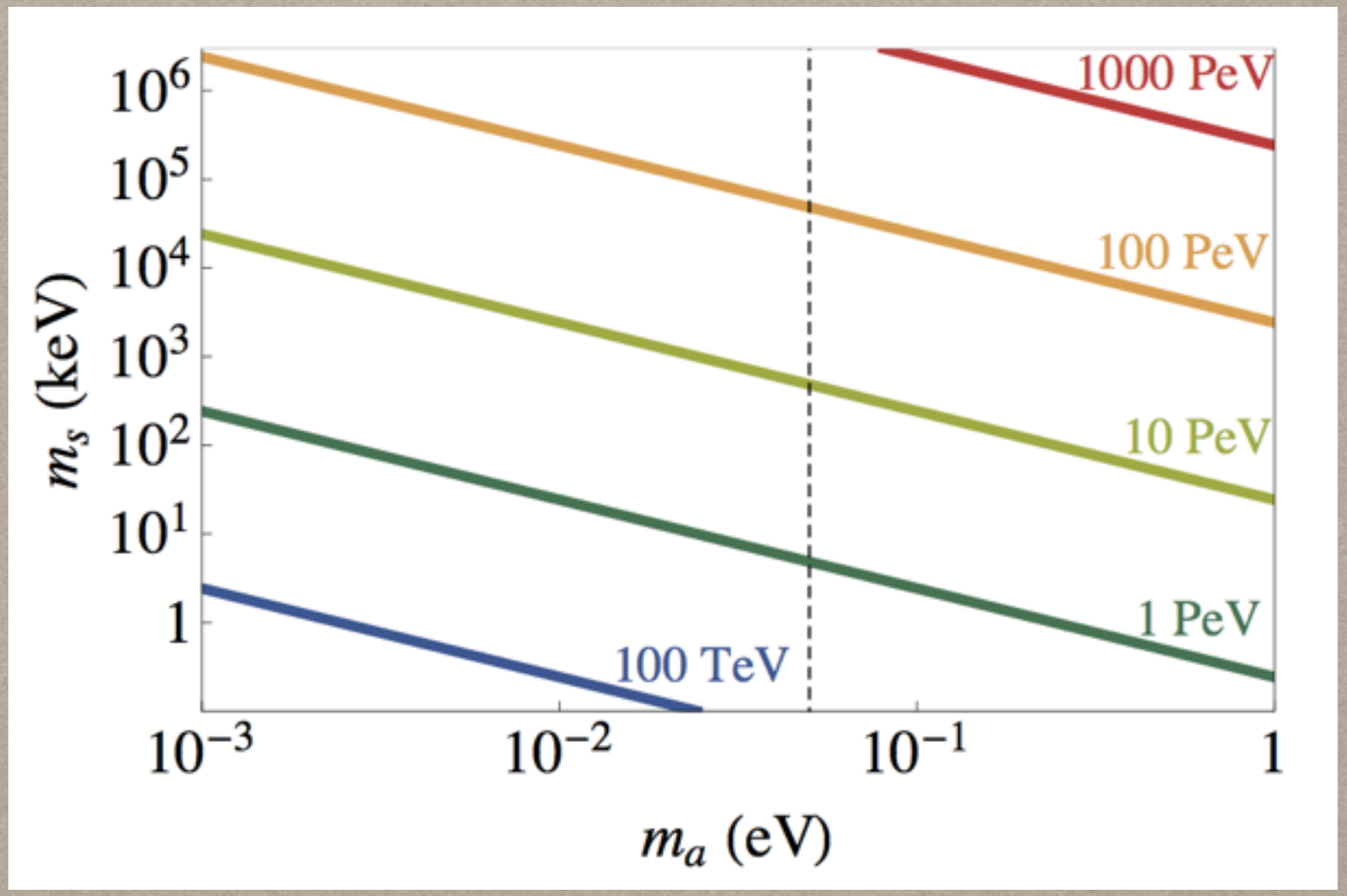


Contours of y<φ>. $M_* = M_{GUT}(=10^{16}\,\mathrm{GeV}),\ \tan\beta = 2 \qquad 0.001 < x < 2$

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

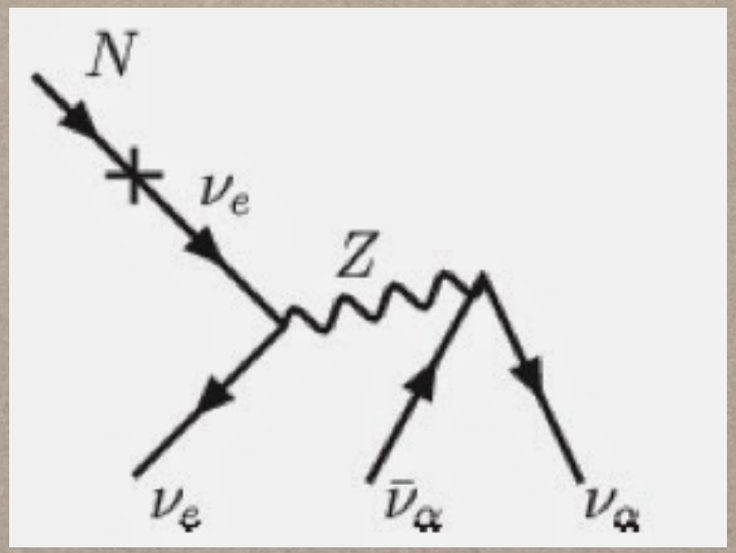
STERILE NEUTRINO AS DARK MATTER

STERILE NEUTRINO AS DARK MATTER

- coupling too weak for thermal freeze-out
- produced through active-sterile oscillation due to mixing between the two (Dodelson-Widrow mechanism).
- if at keV scale, can be dark matter

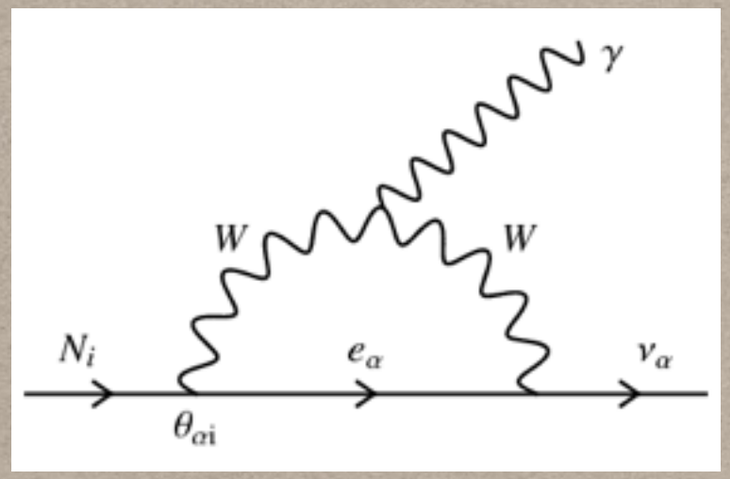
$$\Omega_{N_i} \sim 0.2 \left(\frac{\sin^2\theta}{3 \times 10^{-9}} \right) \left(\frac{m_s}{3 \ \text{keV}} \right)^{1.8}$$

- lifetime set by 3 body decays



STERILE NEUTRINO AS DARK MATTER

Main constraint from X-ray line searches



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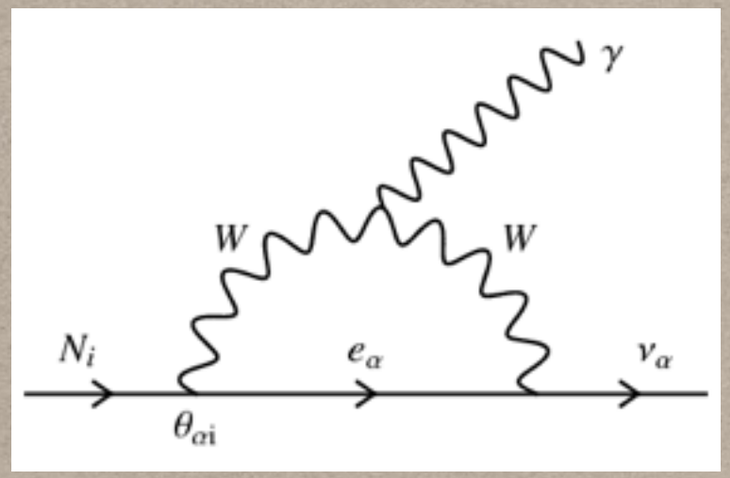

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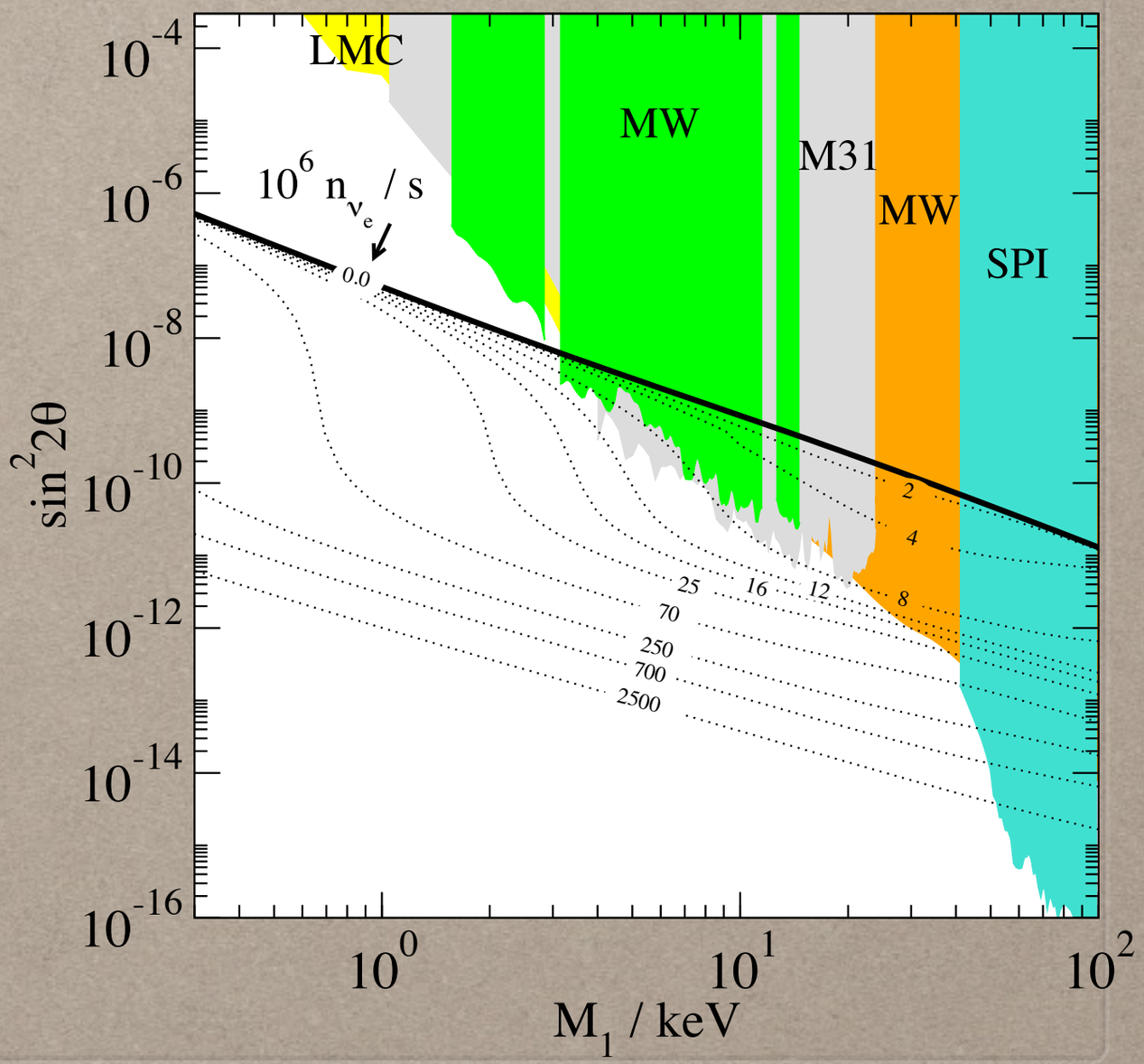
Laine, Shaposhnikov, 0804.4543



XMM-Newton observation constrains $m_\nu < 2$ keV for sterile neutrino to be all of dark matter

STERILE NEUTRINO AS DARK MATTER

- Lyman-alpha measurements constrain free streaming lengths of warm dark matter candidates (from structure formation)

$$\Lambda_{FS} \approx 1.2\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_s}\right)\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx 1\mathrm{keV}}$$

- required to be less than 0.11 Mpc from Lyman-alpha
- SDSS analysis gives $m_\nu > 28$ keV for production through DW mechanism (Viel et al, 0709.0131).

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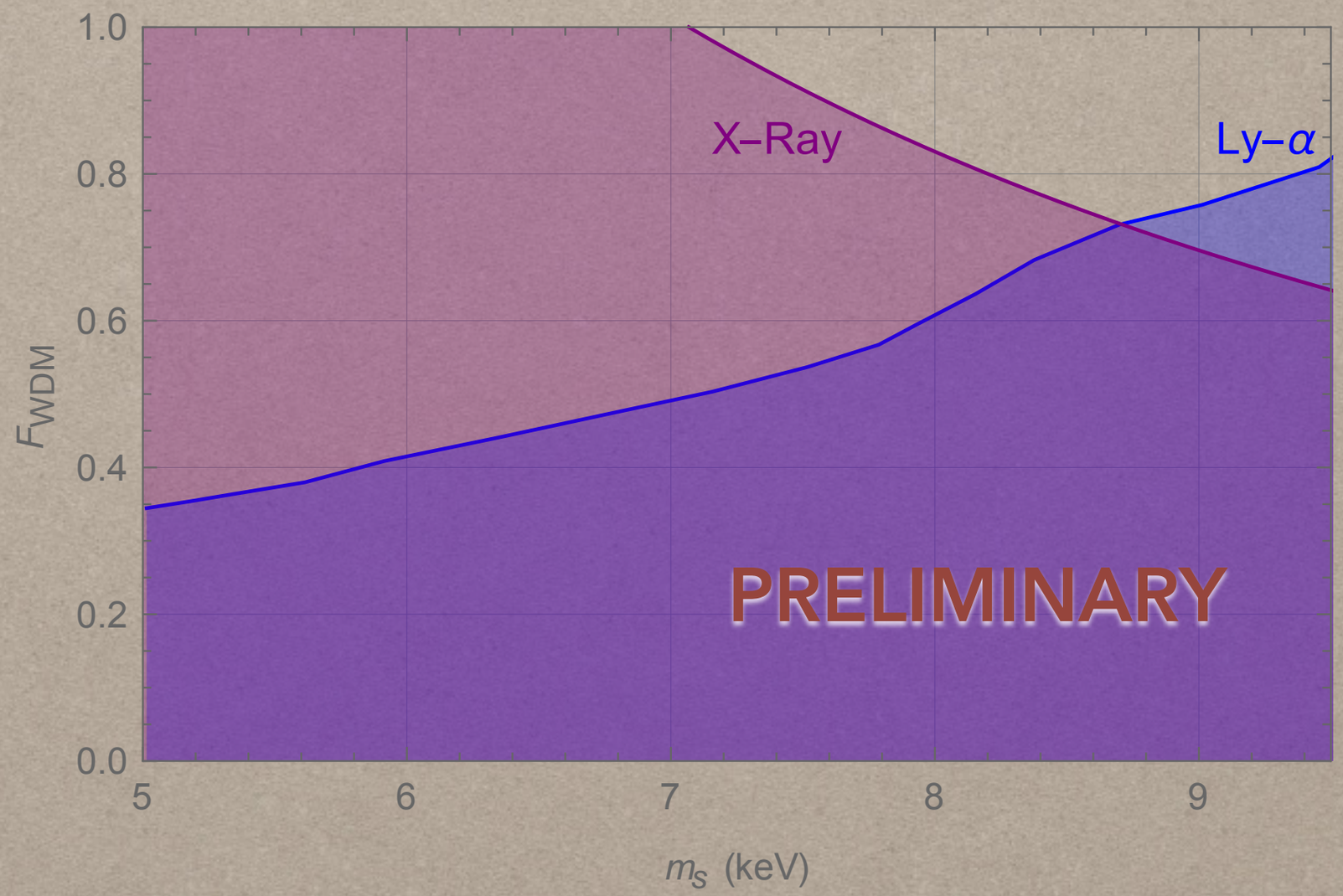
- SDSS analysis gives $m_\nu > 28$ keV for production through DW mechanism (Viel et al, 0709.0131).
  - **Taken together with the X-ray constraint, rules out sterile neutrino as a dark matter candidate!**

STERILE NEUTRINO AS DARK MATTER

- However, it can still constitute an O(1) fraction of dark matter



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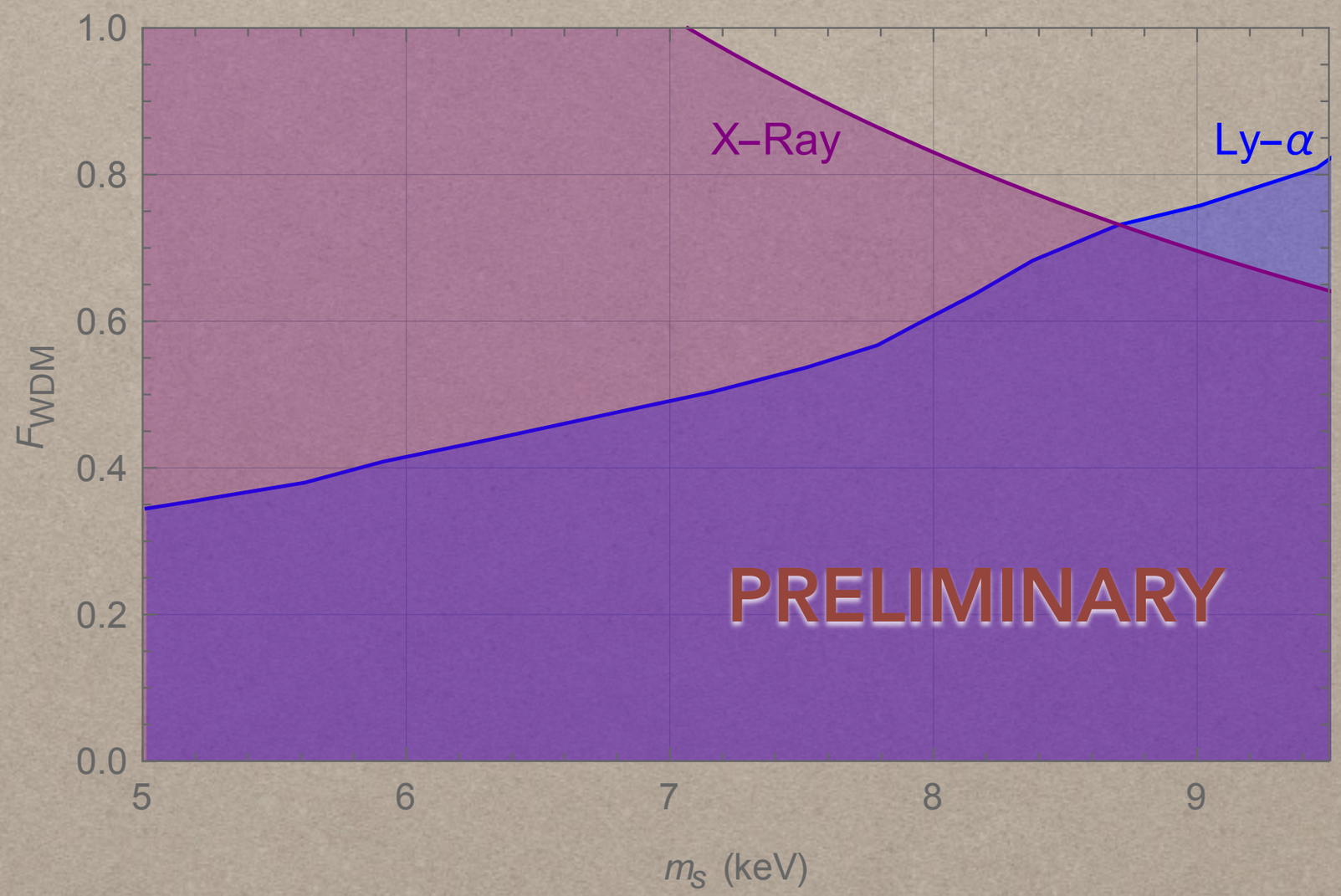


Boyarski et. al. (0812.0010) found that m_ν > 5 keV warm component constituting <60% of DM is consistent with all observations.

STERILE NEUTRINO AS DARK MATTER

Other alternatives:

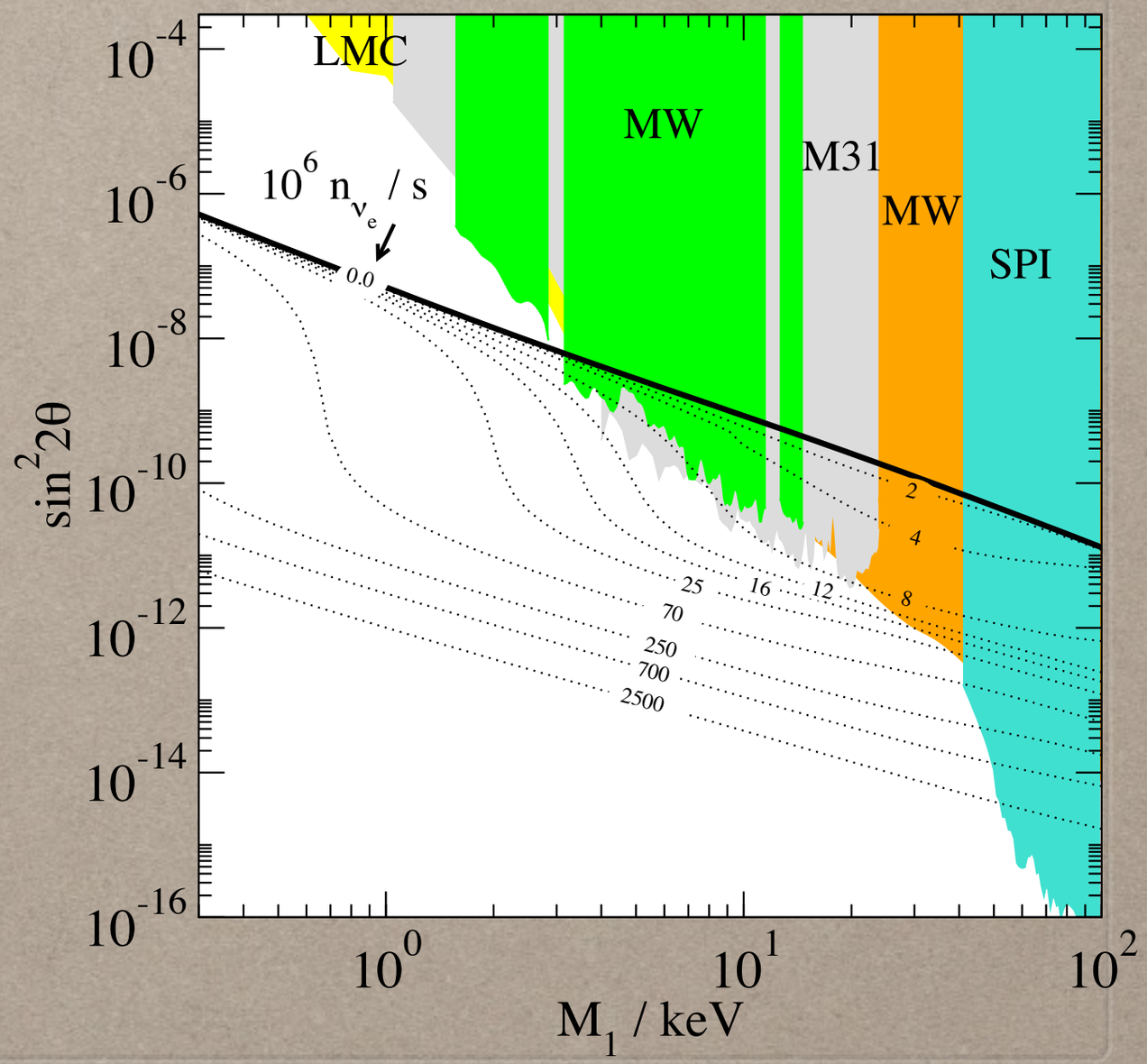
STERILE NEUTRINO AS DARK MATTER

Other alternatives:

Shi-Fuller mechanism:

- Presence of lepton chemical potential in plasma can lead to resonantly amplified production of N_1.
- colder non thermal distribution, evades Lyman-alpha bounds
- requires fine-tuning of 10^{11} in order to generate large lepton asymmetry through CP-violating oscillations.

Laine, Shaposhnikov, 0804.4543



STERILE NEUTRINO AS DARK MATTER

Other alternatives:

Extended Higgs Sector (beyond vMSM)

Kusenko, 0609081; Petraki, Kusenko, 0711.4646

- Extend Higgs sector by a singlet field S

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{f_a}{2} S\, \bar{N}_a^c N_a \\ &- V(H,S) + h.c.\end{aligned}$$

- Singlet vev gives the sterile neutrino masses, singlet decay in or out of equilibrium contributes to abundance of N_1

STERILE NEUTRINO AS DARK MATTER

Alternatives:

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$$\left(\frac{\langle p_s\rangle}{3.15\,T}\right)_{T\approx\mathrm{keV}} = \begin{cases} 0.8-0.9, & \text{for DW} \\ \approx 0.6, & \text{for } L\neq 0, \text{resonance} \\ \lesssim 0.2, & \text{for } T_{\mathrm{prod}} \gtrsim 100\,\mathrm{GeV} \end{cases}$$

(Shi-Fuller)

Petraki, Kusenko, 0711.4646

STERILE NEUTRINO AS DARK MATTER

Additional production mechanisms through the scalar φ

STERILE NEUTRINO AS DARK MATTER

Additional production mechanisms through the scalar φ (assume φ is in equilibrium with the thermal bath at high temperatures through unspecified interactions)

STERILE NEUTRINO AS DARK MATTER

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- **(Ultraviolet) freeze-in**

$$W \supset \frac{y}{M_*} L H_u N^c \phi + \frac{x}{M_*} N^c N^c \phi \, \phi$$

If early Universe temperature sufficiently high,

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

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

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

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Once φ obtains a vev,

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

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

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

STERILE NEUTRINO AS DARK MATTER

If not in equilibrium, φ itself can accumulate via freeze-in and then decay into N_1

very model dependent, will not be considered

STERILE NEUTRINOS: COSMOLOGY

- N_2, N_3 mixing angles with active neutrinos are determined by ratio of masses
- strongly constrained by several recombination era observables, generally required to decay before Big Bang Nucleosynthesis (BBN)

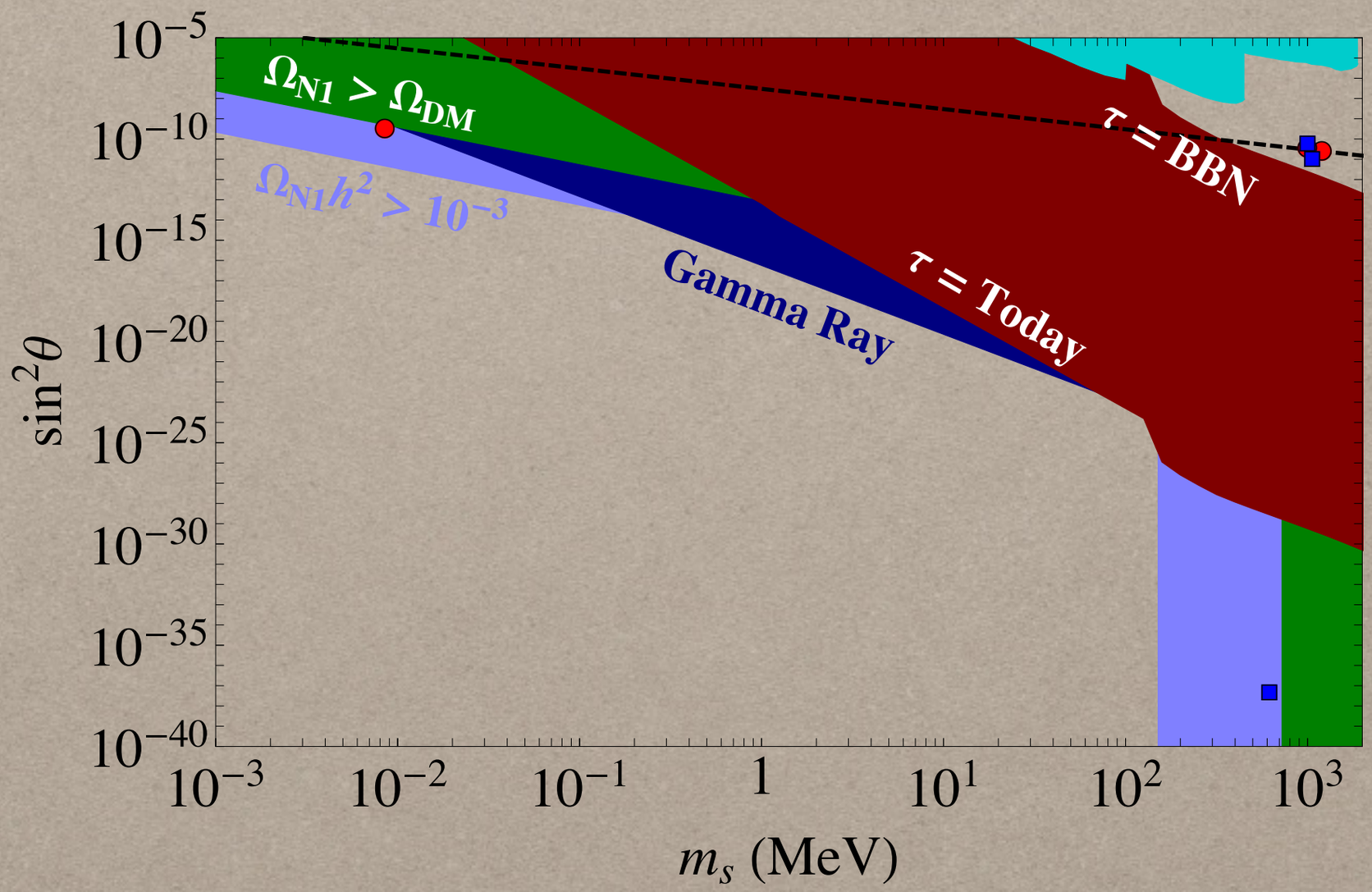
A. Kusenko, Phys.Rept. **481**, 1 (2009), 0906.2968
P. Hernandez, M. Kekic, and J. Lopez-Pavon, Phys.Rev. **D90**, 065033 (2014), 1406.2961.
A. C. Vincent, E. F. Martinez, P. Hernandez, M. Lattanzi, and O. Mena (2014), 1408.1956.

STERILE NEUTRINOS: DIRECT SEARCHES

- peak searches: look at two body decay of charged pion or K meson into lepton+neutrino, look for secondary positron peak coming from decay into sterile neutrino
- fixed target experiments: produce sterile neutrinos in decays of mesons, look for their decay products

M. Aoki et al. (PIENU Collaboration), Phys.Rev. **D84**, 052002 (2011), 1106.4055.
F. Bergsma et al. (CHARM Collaboration), Phys.Lett. **B166**, 473 (1986).
O. Ruchayskiy and A. Ivashko, JHEP **1206**, 100 (2012), 1112.3319.

PARAMETER SPACE OF STERILE NEUTRINOS



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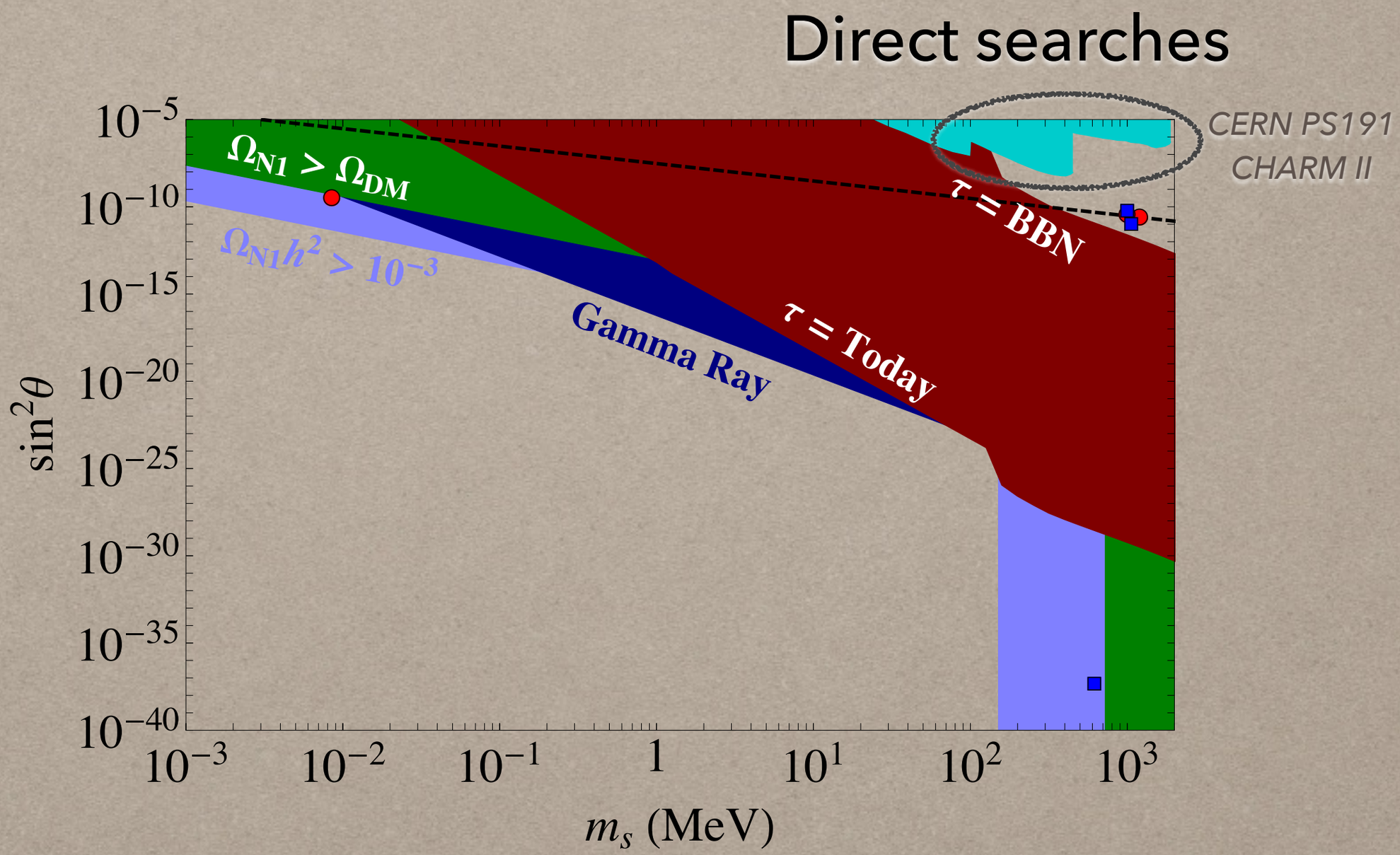

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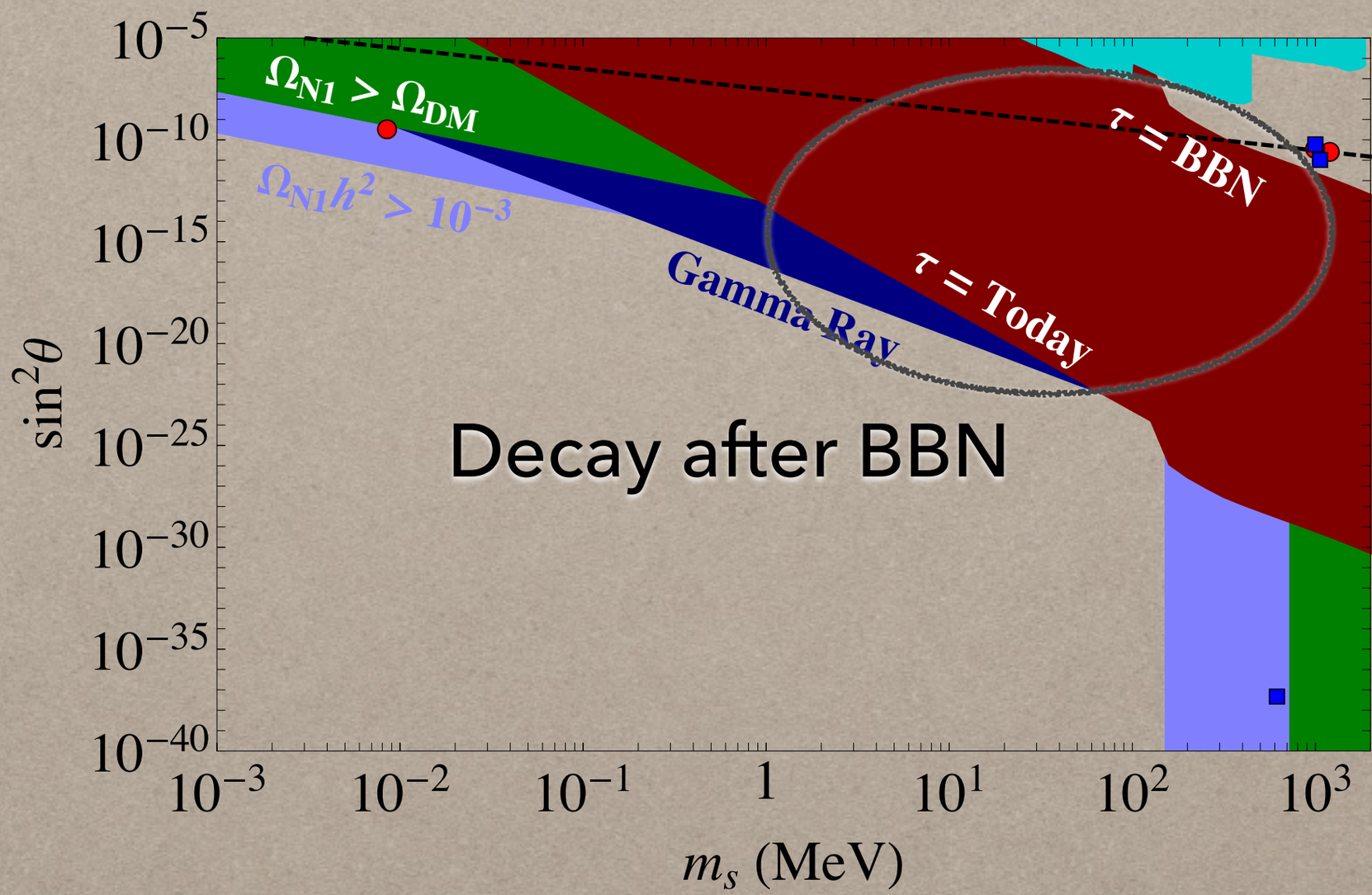

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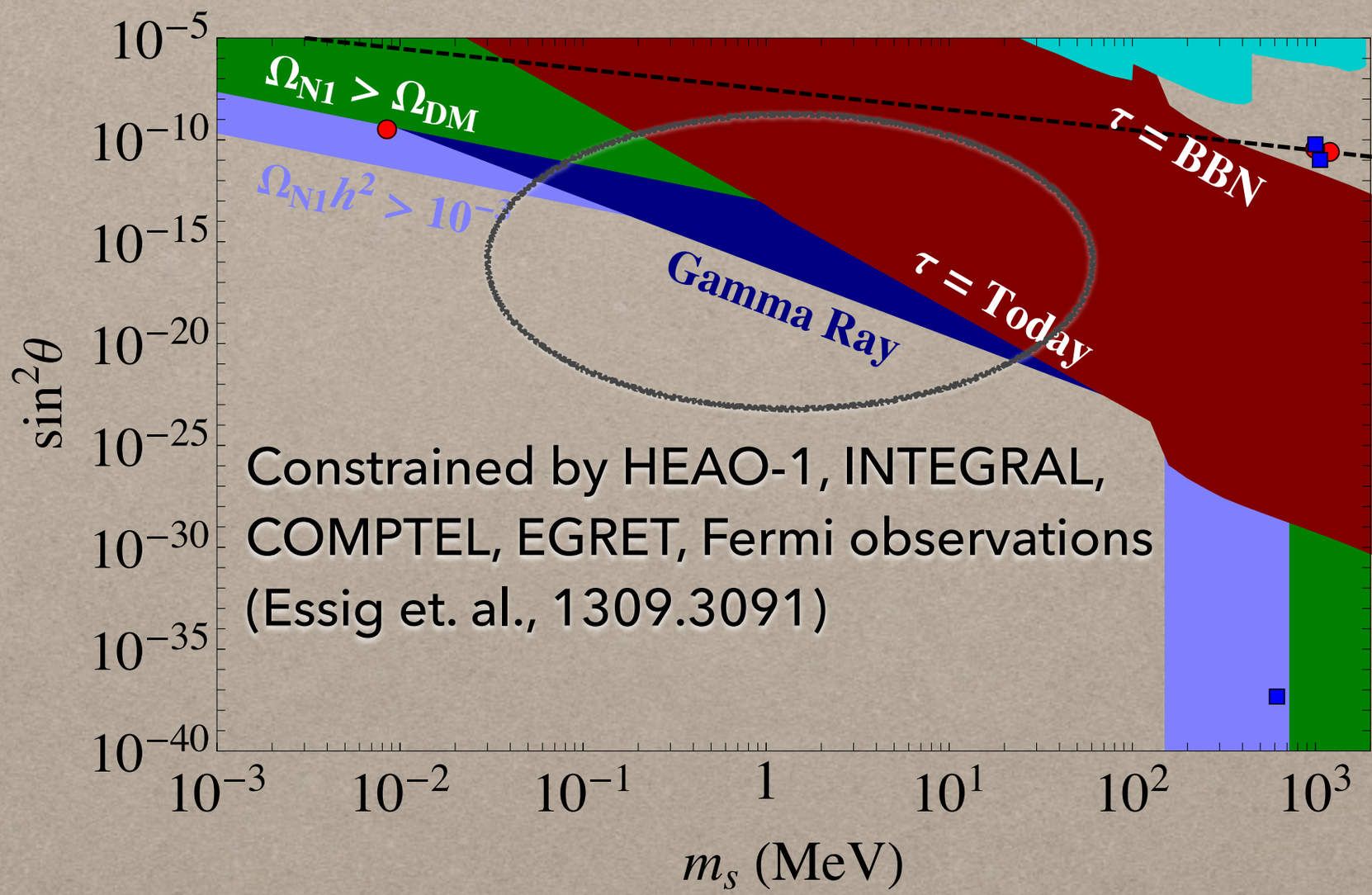
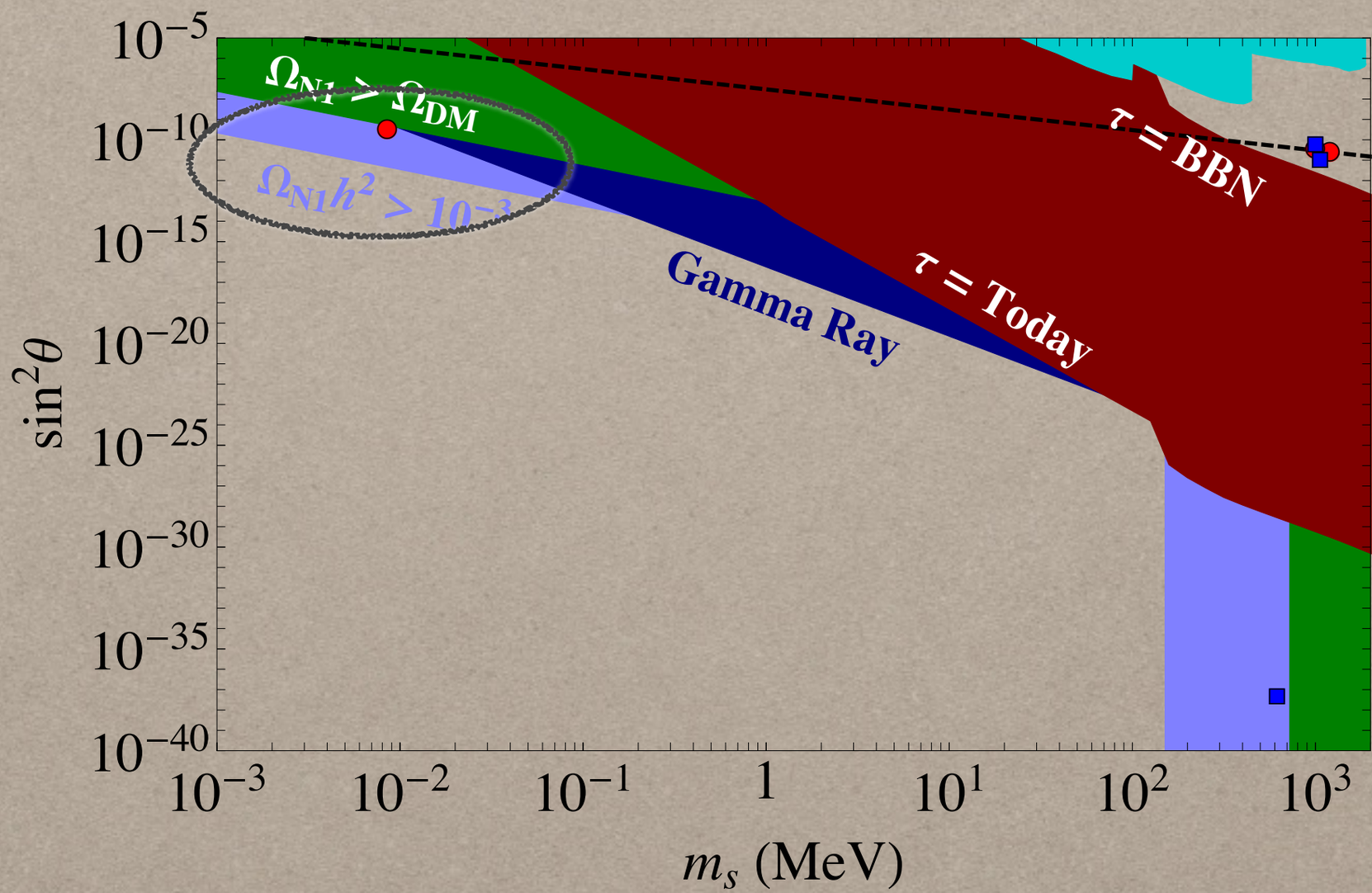


Constrained by HEAO-1, INTEGRAL, COMPTEL, EGRET, Fermi observations (Essig et. al., 1309.3091)

PARAMETER SPACE OF STERILE NEUTRINOS

keV dark matter through
DW mechanism



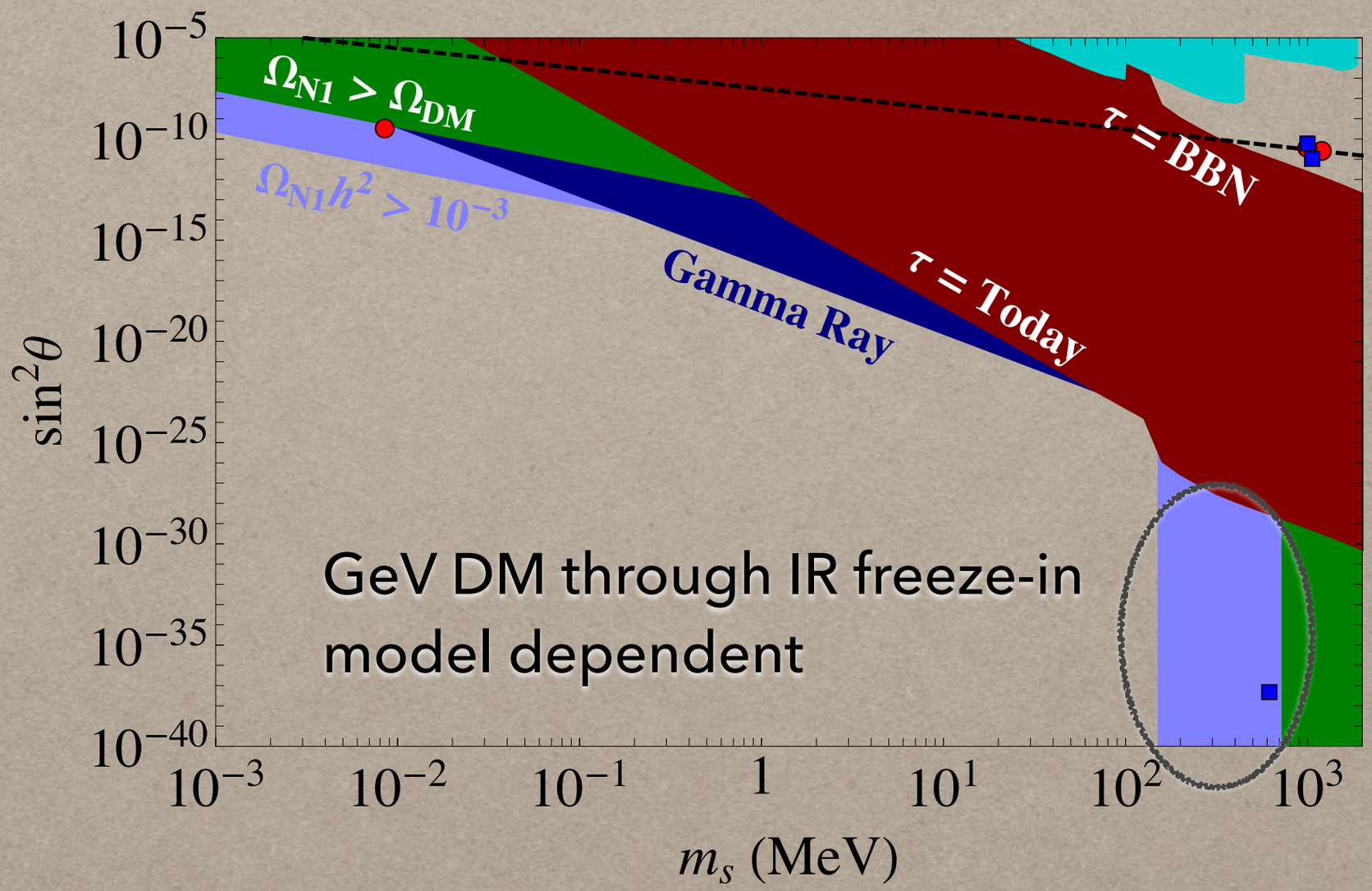
BENCHMARK MODEL A

$\langle\phi\rangle$	$\mathbf{Y}$	$\mathrm{diag}\,(\,\mathbf{X}\,)$	m_a (eV)	m_s	$\Omega_s h^2$
79.4 PeV	$\begin{pmatrix} -1.70 & -0.20 & 9\times10^{-5} \\ 1.49 & -3.96 & -3\times10^{-5} \\ 3.91 & -2.21 & 5\times10^{-5} \end{pmatrix}$	1.91 1.58 0.000013	0.049 0.0087 2.4×10^{-6}	1.2 GeV 1.0 GeV 8.5 keV	0.058

$M_* = M_{GUT} = 10^{16}$ $\tan\beta = 2$ normal hierarchy

- 8.5 keV sterile neutrino dark matter, 53% of total abundance
- UV and IR freeze-in ineffective
- hierarchy of 5 orders of magnitude in entries of X and Y, generic for keV WDM.

PARAMETER SPACE OF STERILE NEUTRINOS



GeV DM through IR freeze-in
model dependent

BENCHMARK MODEL B

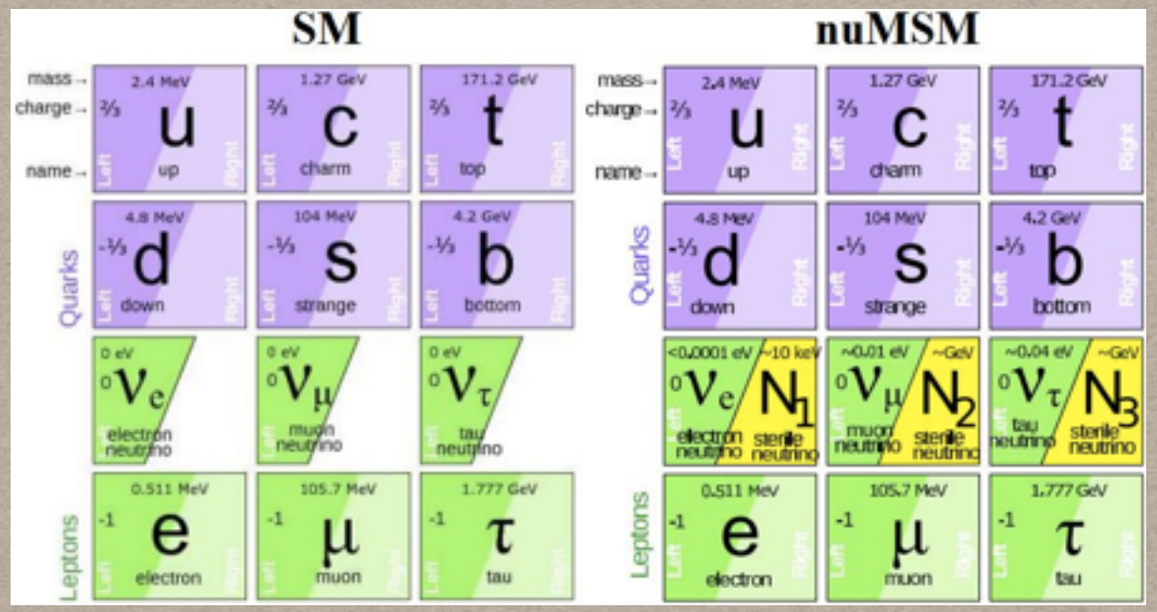
$\langle\phi\rangle$	$\mathbf{Y}$	$\mathrm{diag}\,(\,\mathbf{X}\,)$	m_a (eV)	m_s	$\Omega_s h^2$
85.1 PeV	$\begin{pmatrix} -1.31 & 0.73 & \sim 0 \\ -1.25 & -3.71 & \sim 0 \\ 1.45 & -3.65 & \sim 0 \end{pmatrix}$	1.46 1.38 0.85	0.049 0.0087 ~ 0	1.1 GeV 1.0 GeV 617 MeV	0.11

$M_* = M_{GUT} = 10^{16}$ $\tan\beta = 2$ normal hierarchy

GeV scale dark matter through IR freeze in, essentially zero mixing with active neutrinos

all three striles at ~GeV scale; if dark matter is something else, all couplings can be O(1)

Neutrino Minimal Standard Model (vMSM)



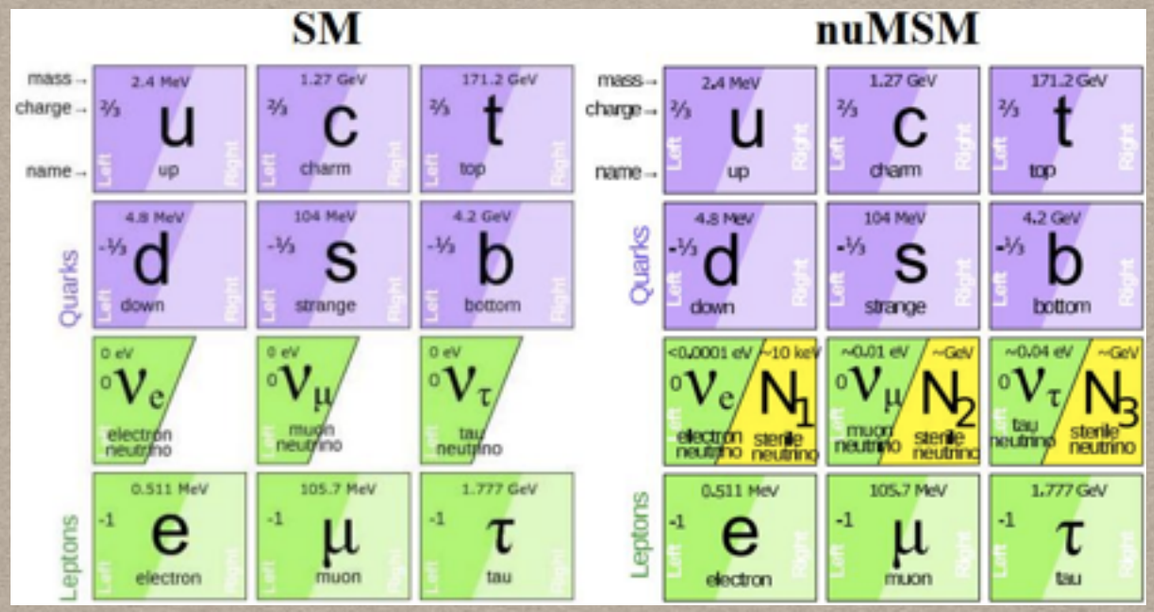
ISSUES:

$y \sim 10^{-7}$ for neutrino masses?

keV, GeV mass scales?

dark matter?

Neutrino Minimal Standard Model (vMSM)



ISSUES:

y~10^{-7} for neutrino masses?

keV, GeV mass scales?

dark matter?

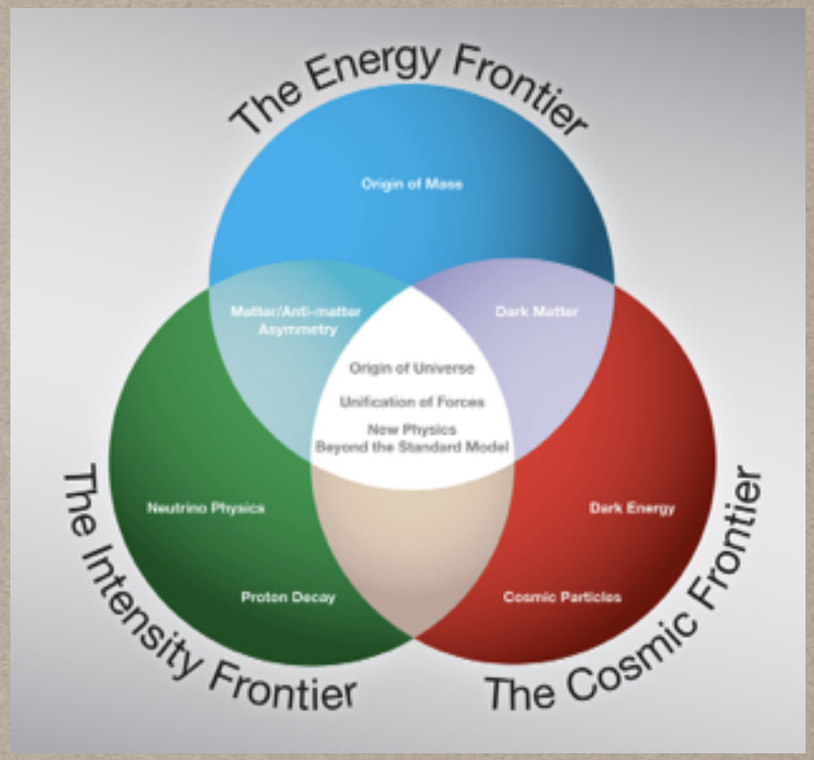
RESOLUTION: $\langle\phi\rangle \sim \mathrm{PeV}$

$$\sim \frac{\langle\phi\rangle}{M_{GUT}}$$

$$\sim \frac{\langle\phi\rangle^2}{M_{GUT}}$$

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

PHENOMENOLOGY



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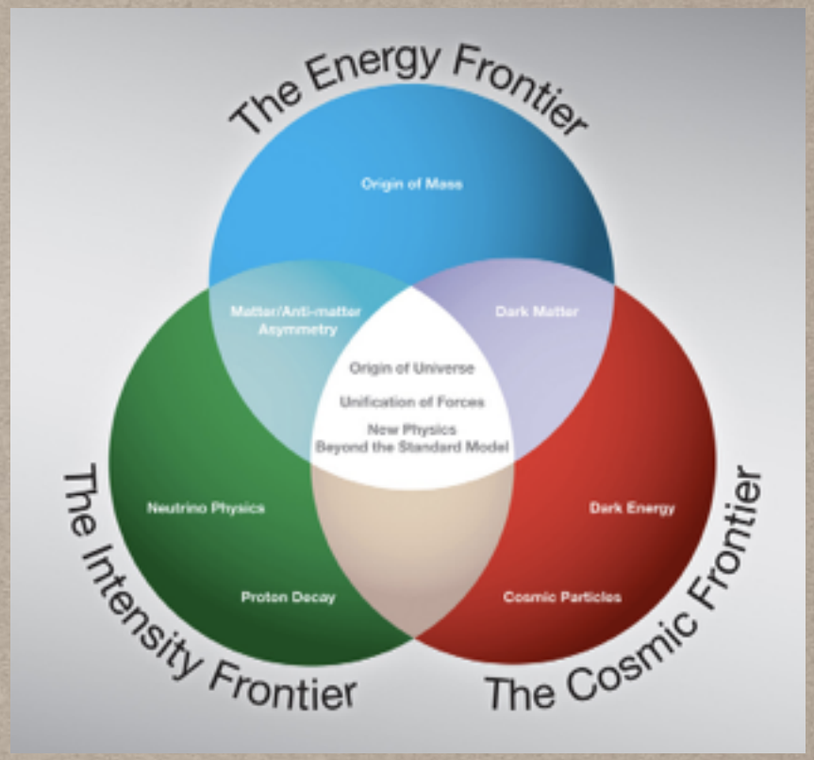
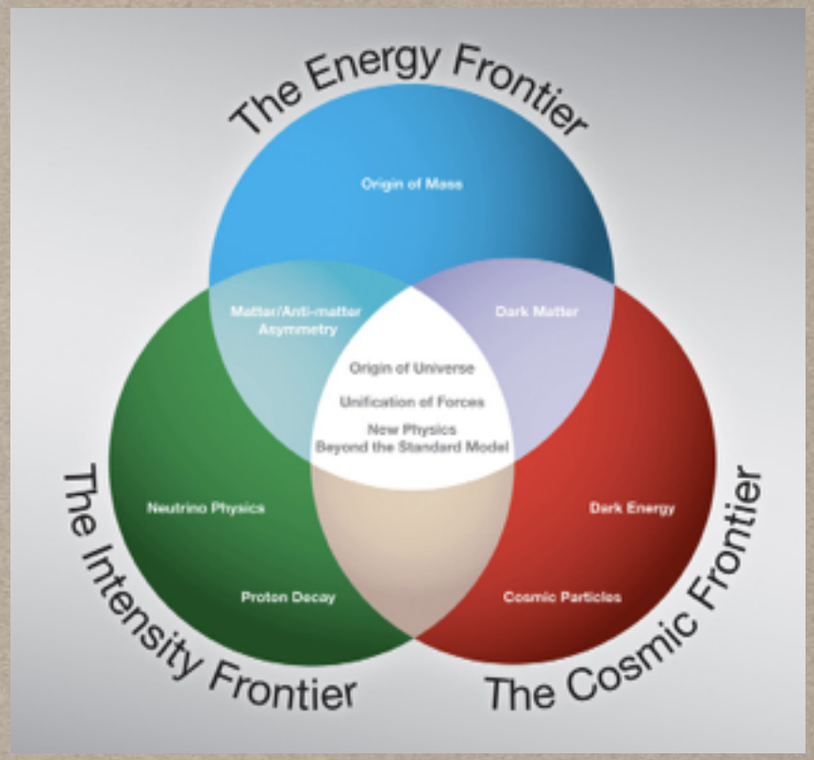


- keV-GeV sterile neutrino N_1, O(1) fraction of DM
- GeV steriles N_2, N_3, mixing constrained to match neutrino oscillation data
- PeV scale scalar φ, couplings to sterile neutrinos constrained

PHENOMENOLOGY



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(and possibly an entire supersymmetric sector at the PeV scale)

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

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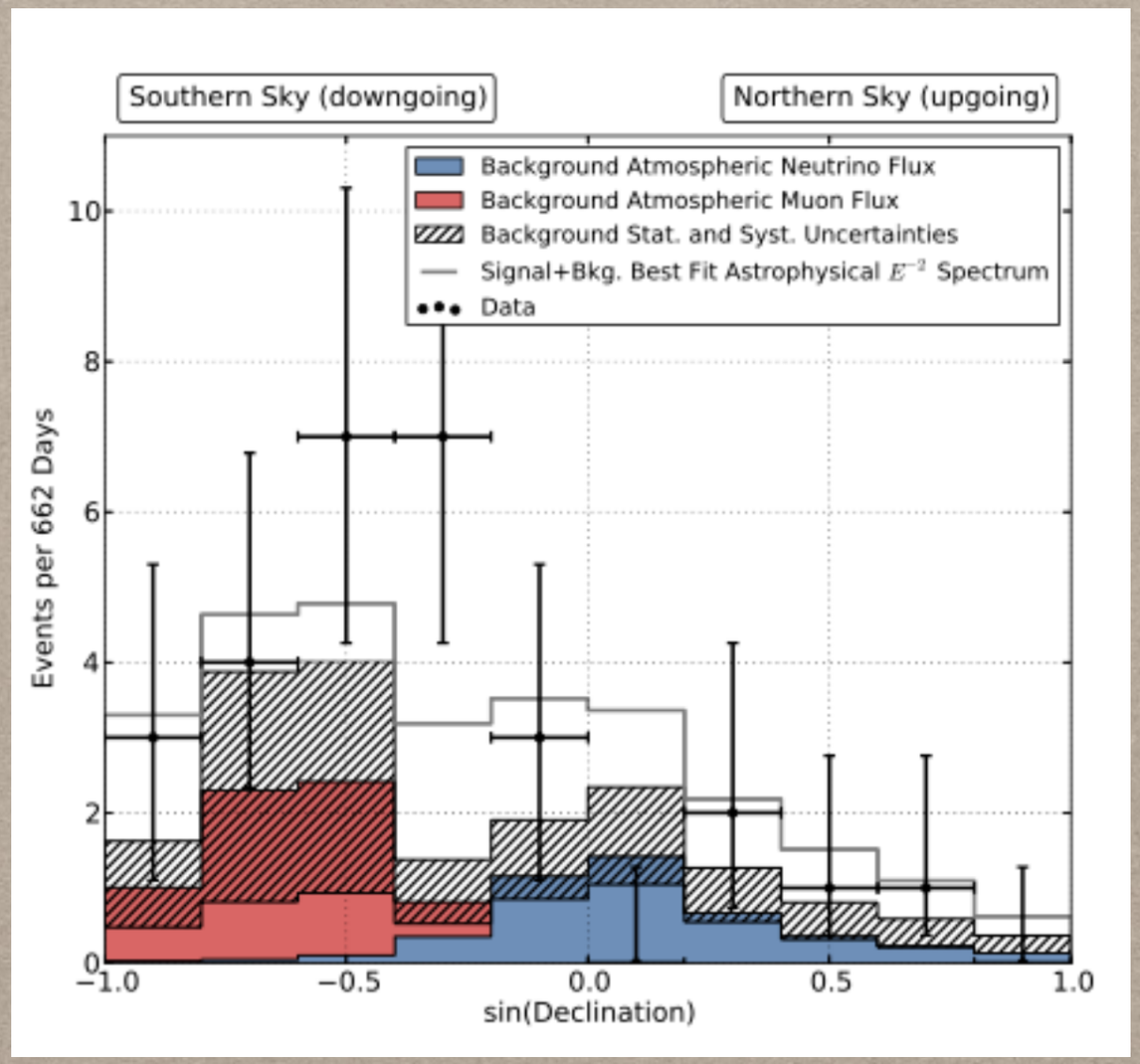
- potential mismodelling of background (Jeltema and Profumo (2014)), situation unclear
- ~7 keV sterile neutrino that is 25-50% of dark matter, with mixing $\sin^2(2\theta) \sim 4.0\times 10^{-10}$ can fit the signal (Harada, Kamada, Yoshida, 1412.1592)
- sterile neutrino being only a fraction of dark matter might help evade some constraints

Φ AND PEV SECTOR

- present interactions suppressed by M_*, too small to give detectable interactions.
- most promising possibility: a particle from the PeV sector makes up an O(1) fraction of dark matter? (recall that keV sterile neutrino cannot be all of dark matter)
- cannot come from freezeout, getting the correct relic density requires some work

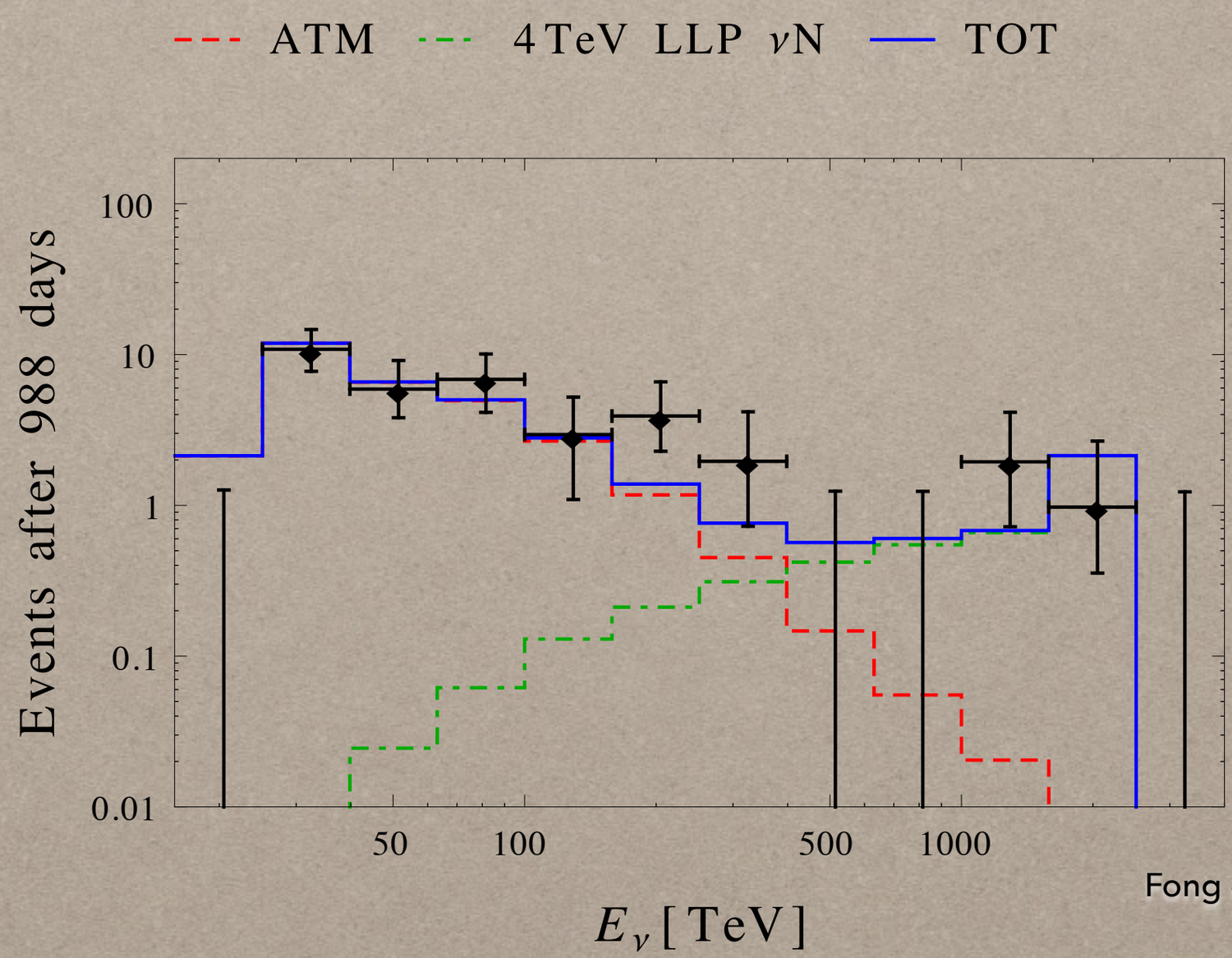
PEV NEUTRINOS AT ICECUBE: A HINT OF PEV DARK MATTER?



- 37 high energy neutrinos between 30 TeV and 2 PeV; hint of PeV scale dark matter?

PEV NEUTRINOS AT ICECUBE

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



Fong et al, 1411.5318

PEV DARK MATTER

- Consider a dark matter particle X in the PeV sector, that constitutes an O(1) fraction of dark matter

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- If φ carries charge +1 under the U(1)′ and X carries charge -2/3, lowest dimension term in the superpotential involving X:

$$\frac{1}{M_*^2} X^3 \phi^2$$

- This gives the decay channel

$$X \to \phi \psi \psi$$

- decay has lifetime ~10^{28} s

PEV DARK MATTER

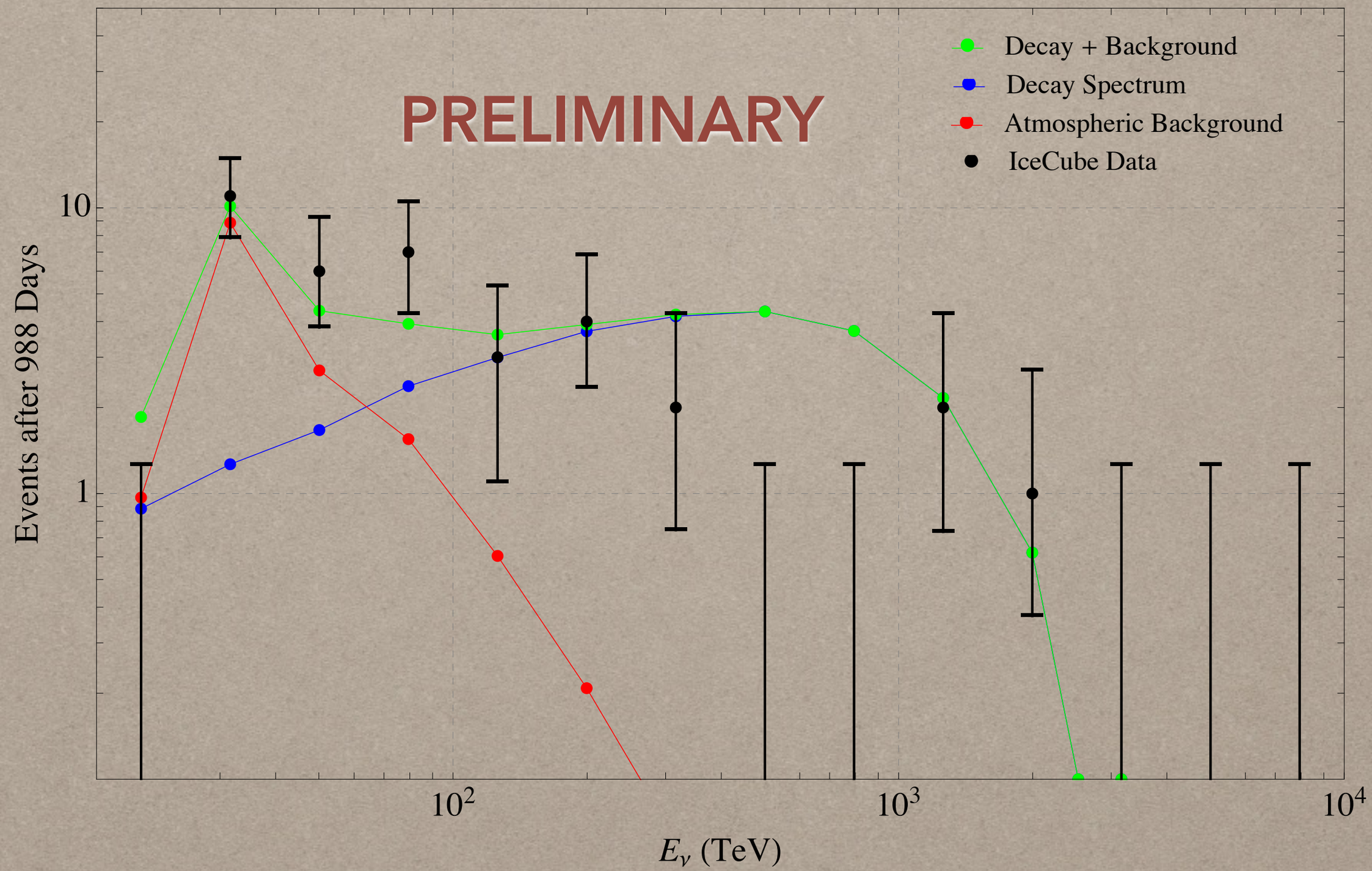
- decay process

$$X \to \phi\psi\psi$$

$$\phi \to N_i N_i$$

$$N_i \to 3\nu$$ (and others)

PEV DARK MATTER



SUMMARY

- Connecting SUSY, dark matter to the neutrino sector
- Higgs mass hints at heavy superpartners, high (PeV) scale SUSY
- neutrino masses generated via a modified seesaw setup when the new scalar gets a vev at the PeV scale (maps on to vMSM at low scales)
- new production mechanisms for sterile neutrino dark matter (UV and IR freeze in)
- PeV sector can provide O(1) fraction of dark matter, can produce the PeV neutrino events seen at IceCube