ν Beyond the ν Standard Models

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"Pre SUSY" lecture 2
August 19, 2015

Recent Developments in ν BSM

Dark Matter

what the heck is it?
What handles do we have?
ν interaction?

From recent Particle Physics Project Prioritization Panel (P5) Report

"There are many well-motivated ideas for what dark matter could be. These include weakly interacting massive particles (WIMPs), gravitinos, axions, sterile neutrinos, asymmetric dark matter, and hidden sector dark matter. The masses and interaction strengths of these candidates span many orders of magnitude, and, of course, the dark matter could be composed of more than one type of particle."

How to theoretically progress?

- Top down inspiration? (WIMP, axion)
- Effective field theory bottom up?
- Decoupling--Many more models of fundamental physics than low energy parameters, low energy physics always underconstraining

Clues?
Great match between simulation and observation, except (see Slatyer lectures):

"missing satellites"
"too big to fail"
"core vs cusp"

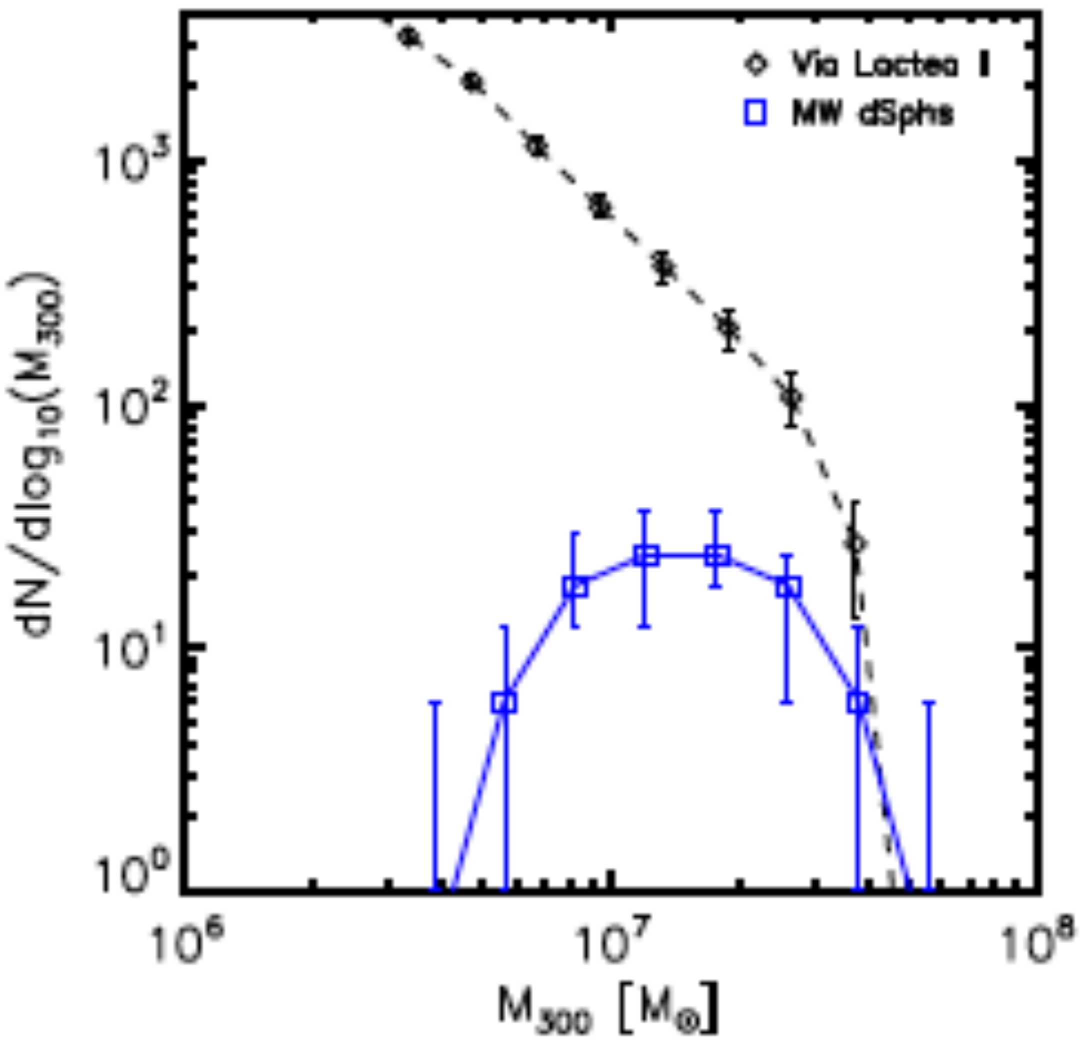


Fig. 1.6. Mass function for $M_{300} = M(< 300pc)$ for MW dSph satellites and dark subhalos in the Via Lactea II simulation within a radius of 400 kpc. The short-dashed curve is the subhalo mass function from the simulation. The solid curve is the median of the observed satellite mass function. The error bars on the observed mass function represent the upper and lower limits on the number of configurations that occur with a 98% of the time (from Wolf et al., in preparation). Note that the mismatch is about ~ 1 order of magnitude at $M_{300} \simeq 10^7 M_\odot$, and that it grows significantly towards lower masses.

Simulation predicts MANY more dwarf satellites than observed

James Bullock, arXiv:1009.4505

suppressed structure formation below $\sim 10^8$ solar masses?

Warning! Some (or all?) of these problems might be solved by properly including effects of baryons (esp. supernovae) in simulations!

see e.g. Pontzen and Governato, arXiv:1106.0499, "How supernova feedback turns dark matter cusps into cores"

Phenomenological, not derived from first principles

Suggested Resolution

“baryonic” (failure to form stars, supernovae feedback)

warm dark matter
(velocity dispersion too high to form small structures)
examples: few keV gravitino, few keV sterile neutrino

Strongly self-interacting dark matter

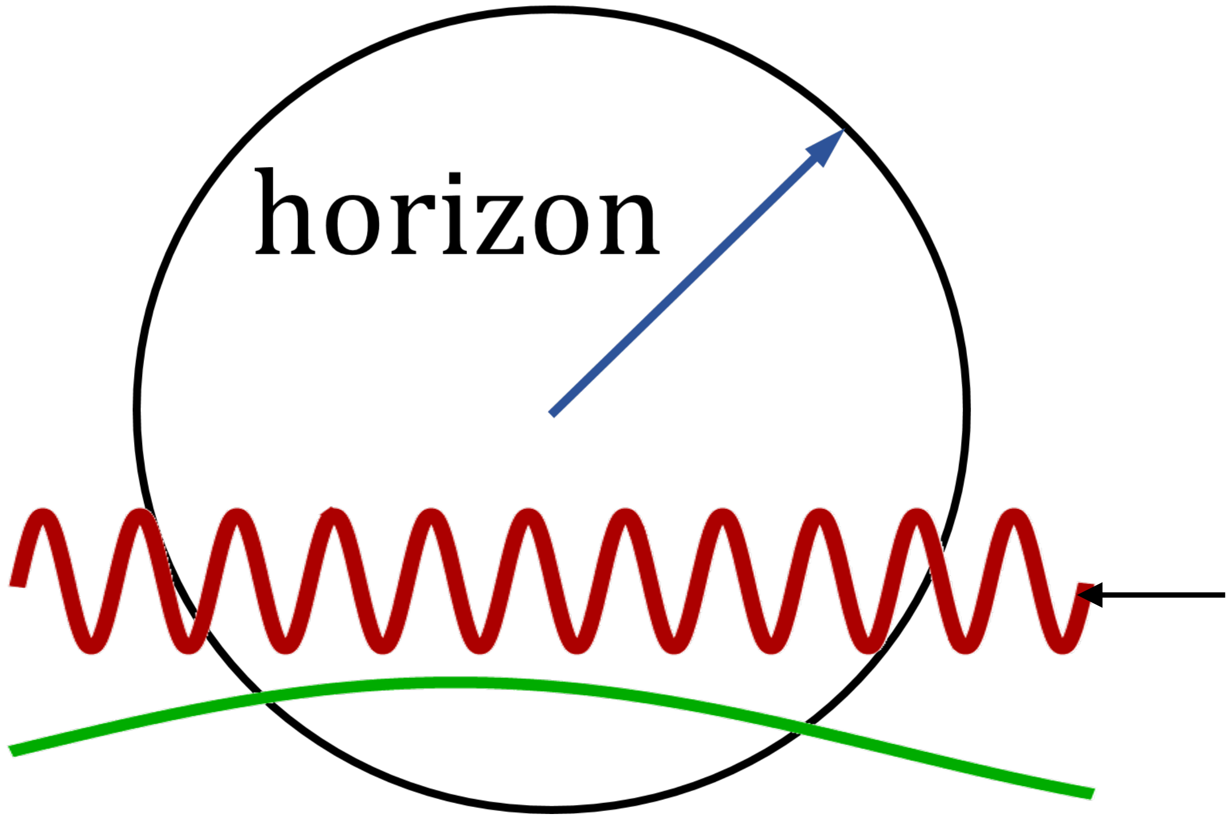
substantial v-dark matter interaction

Kinetic decoupling of Dark Matter from relativistic stuff and structure formation

Structure Formation and Dark Matter couplings

- Chemical decoupling first (freezeout, or asymmetric dark matter)

- Kinetic decoupling at temperature T_d



$T > T_d$

small scale perturbations coupled to ν's oscillate, don't grow

M_{ao}: suppressed structure

Loeb & Zaldarriaga, astro-ph/0504112

$$M_{\rm ao} \approx \rho_{DM} \frac{4\pi}{3} H_d^{-3} \approx 2 \times 10^8 M_\odot \sqrt{\frac{3.4}{g_{\rm eff}}} \left(\frac{\rm keV}{T_d} \right)^3$$

larger coupling=lower T_d= larger M_{ao}

$T < T_d$

- DM perturbations can grow due to gravity
- DM has velocity dispersion, also damps small scale structure due to free streaming (Green, Hofmann & Schwarz, astro-ph/0503387)

For $T_{\rm d} \lesssim 100\ {\rm keV} \left(\frac{m_\chi}{10\ {\rm MeV}}\right)$

M_{ao} dominates over free streaming

ν mixing, ν force

$$\mathcal{L} \supset -m_{ij}\frac{H^2}{v^2}\ell_i\ell_j - MN_1N_2 - \lambda_i N_1 H\ell_i - y_1\phi^* N_1\chi - y_2\phi N_2\chi$$

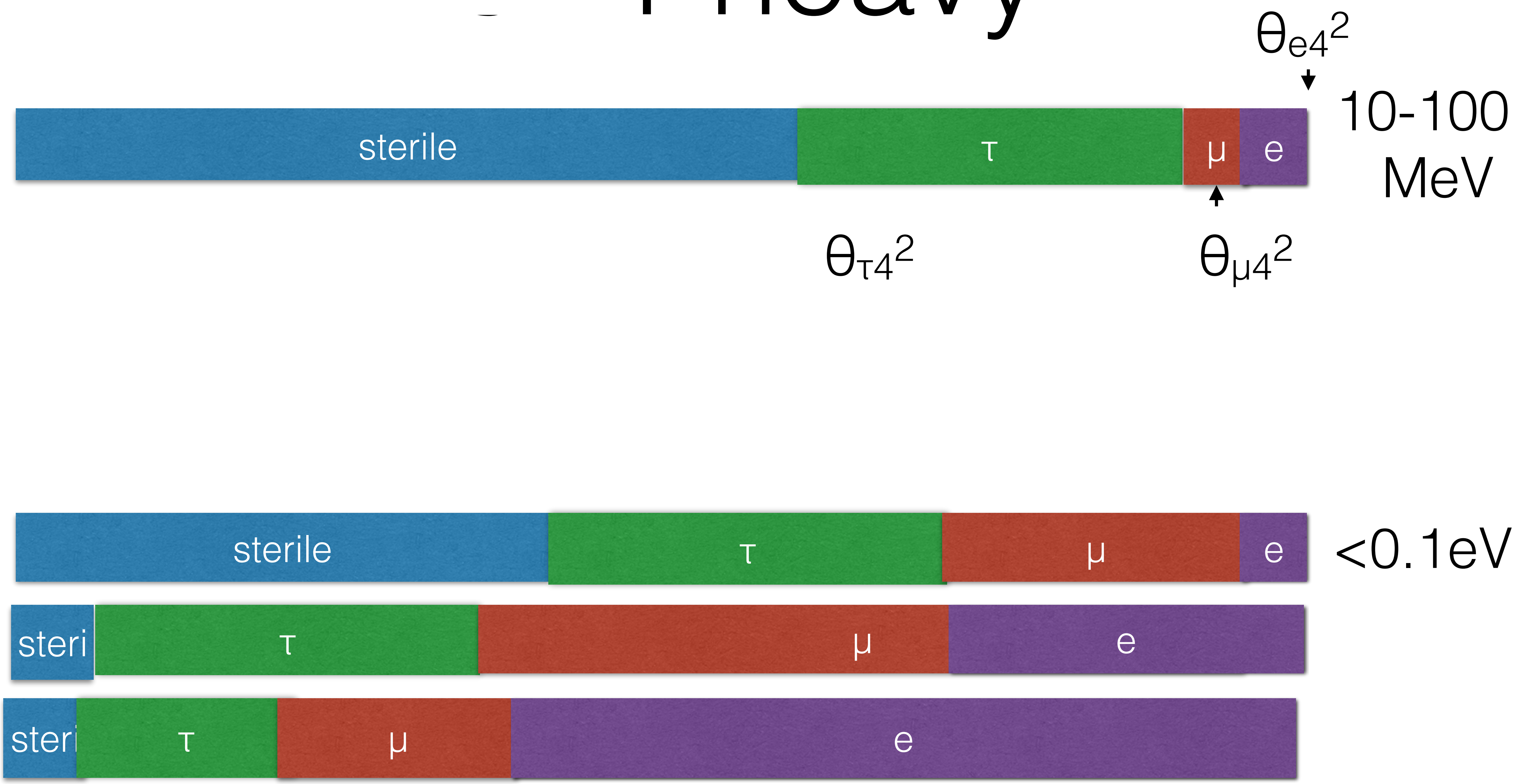
- first term gives tiny Majorana ν masses
- last four terms conserve lepton number
- mass matrix from first three terms:

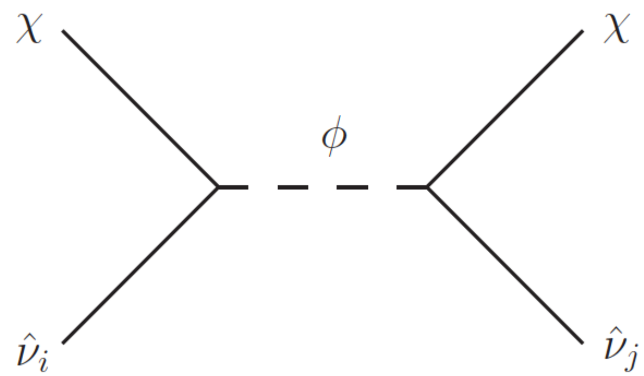
$$\begin{pmatrix} m_{ij} & \lambda_j v & 0 \\ \lambda_i v & 0 & M \\ 0 & M & 0 \end{pmatrix}.$$

- 3 very light Majorana ν's, mass from first term
- 1 heavy (e.g. eV—TeV) Dirac ν, mass $\sqrt{M^2 + \sum_i \lambda_i^2 v^2}$
- 4x4 ν mixing matrix

$$\nu_i = U_{ij}\hat{\nu}_j ,$$

$\nu_i = U_{ij}\hat{\nu}_j$, 1 heavy





$$T_d \sim \text{keV} \left(\frac{g_{\text{eff}}}{3.4}\right)^{1/8} \left(\frac{M_\chi}{10\ \text{MeV}}\right)^{1/4} \left(\frac{\Lambda}{60\ \text{MeV}}\right)$$

$$g \equiv y_2\sqrt{|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2} \qquad \Lambda \sim \sqrt{m_\phi^2 - m_\chi^2}/g$$

- kinetic decoupling of Dark Matter at ~keV suppresses structure below ~ 10^8 solar masses
  - to address missing satellite problem, want DM mass~ 10 MeV, $|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2$ >~.1

Impact on ν physics searches

- ν propagation in matter: standard flavor basis

$$H_{\text{eff}} = \frac{m^2}{2E} + \begin{pmatrix} V_{ee} & & \\ & & \\ & & \end{pmatrix} + \begin{pmatrix} V_{nc} & & \\ & V_{nc} & \\ & & V_{nc} \end{pmatrix}$$

has no effect, $\propto$ Identity

non-standard interactions (NSI)

4x4, 3 small eigenvalues

$$H_{\text{eff}} = \frac{m^2}{2E} + \begin{pmatrix} V_{ee} & & & \\ & & & \\ & & & \\ & & & \end{pmatrix} + \begin{pmatrix} V_{nc} & & & \\ & V_{nc} & & \\ & & V_{nc} & \\ & & & 0 \end{pmatrix}$$

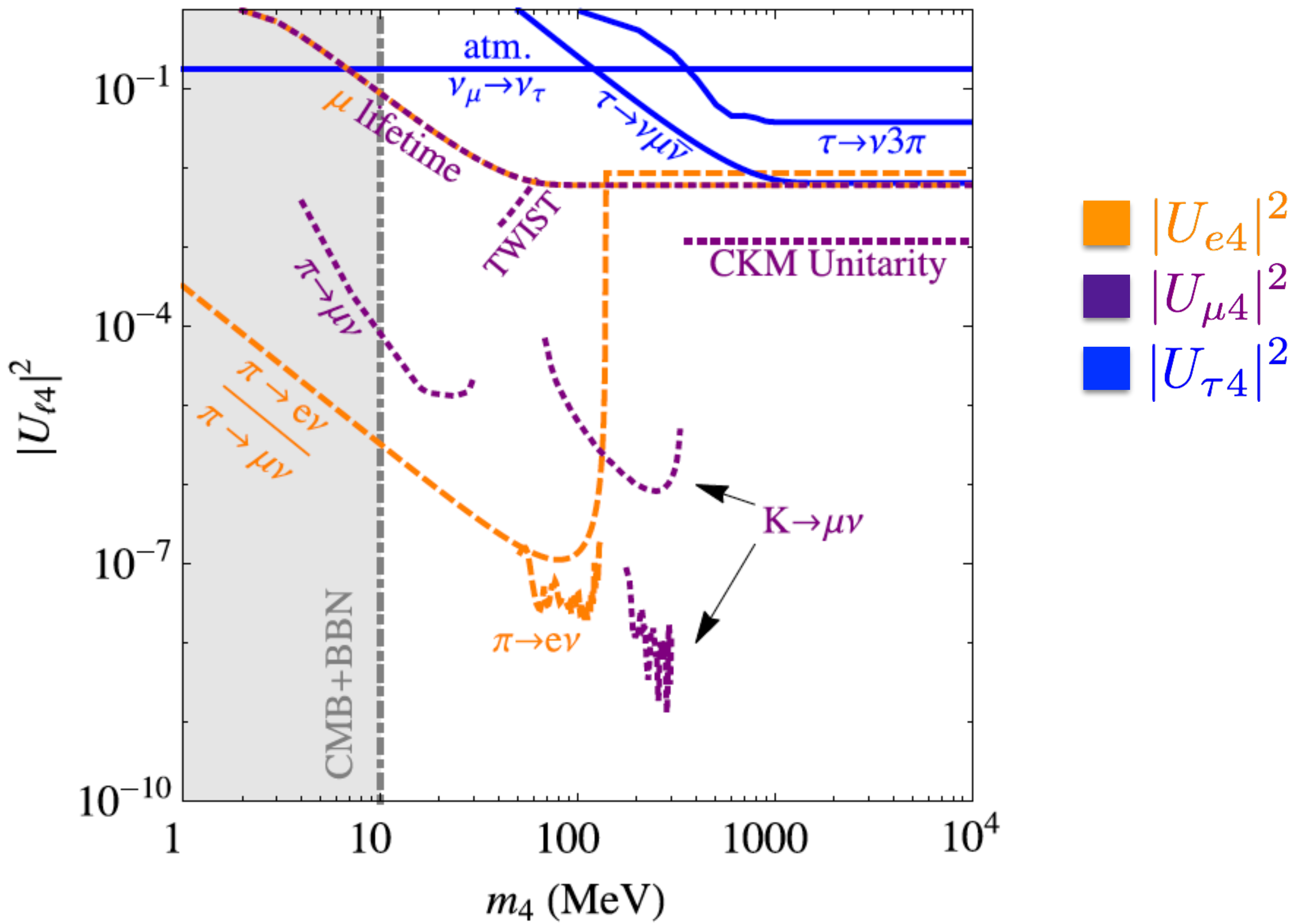
- may have complicated pattern of 4 neutrinos mixing
- in 3+1 scenario could integrate out heavy neutrino
- 3 light neutrinos have non-standard Neutral and Charged current interactions

3+1 with 1 heavy ν

- Integrate out heavy ν
- 3 light ν are linear combinations of active flavor and sterile flavor state
- Add higher dimension operators to low energy effective theory to modify couplings of light ν
- Allows "instant" flavor change, e.g. "ν_τ" produced in β-decay (very constrained for ν_e appearance in ν_μ beam)
- ν propagation:

$$H_{\text{eff}} = \frac{m^2}{2E} + \begin{pmatrix} V_{ee}\cos^2\theta_{e4} & & \\ & & \\ & & \end{pmatrix} + \begin{pmatrix} V_{nc}\cos^2\theta_{e4} & & \\ & V_{nc}\cos^2\theta_{\mu 4} & \\ & & V_{nc}\cos^2\theta_{\tau 4} \end{pmatrix}$$

Constraints



Recall: $|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2 > 0.1$ needed for sufficient DM interaction

sub MeV Sterile ν

$$x_{ij} \equiv \frac{1.27|m_i^2 - m_j^2|\frac{L}{E}}{eV^2\frac{km}{GeV}}$$

- laboratory constraints from oscillations
- start with this formula $$P_{ab} = \left|\sum_j U_{aj} U_{bj}^* e^{-2ix_{1j}}\right|^2$$
- but for m4 heavier than 100 eV no observable interference between heavy and light states *i=1,2,3* $\langle e^{-2ix_{i4}} \rangle = 0$
- Even at *L=0*, $$P_{ab} = 2\left|U_{a4} U_{b4}^*\right|^2$$

sub MeV Sterile ν cont

- strong constraints from ν_e appearance in ν_μ beam on $\left|U_{e4}U_{\mu 4}^*\right|^2$
- For > 1 heavy neutrino, can still get destructive interference, constrain $$\left|\sum_{j>3} U_{ej}U_{\mu j}^*\right|^2$$

But what about cosmology?

- New particles lighter than ~ 10 MeV may be highly constrained by
  - nucleosynthesis
  - CMB constraint on number of relativistic states
  - CMB and large scale structure constraints on new particles between ~0.3 eV and several keV

Steigman talk at INT Program
"Neutrino Astrophysics and Fundamental Properties"

BBN & The CMB WITH A Light WIMP

Very light WIMPs, relics that were in thermal equilibrium in the early Universe when T > m, annihilate late in the early Universe, when T ≈ m, changing the energy and entropy densities at BBN and at recombination.

The light WIMPs need not be the Dark Matter. They could be a subdominant DM component.

Steigman, cont

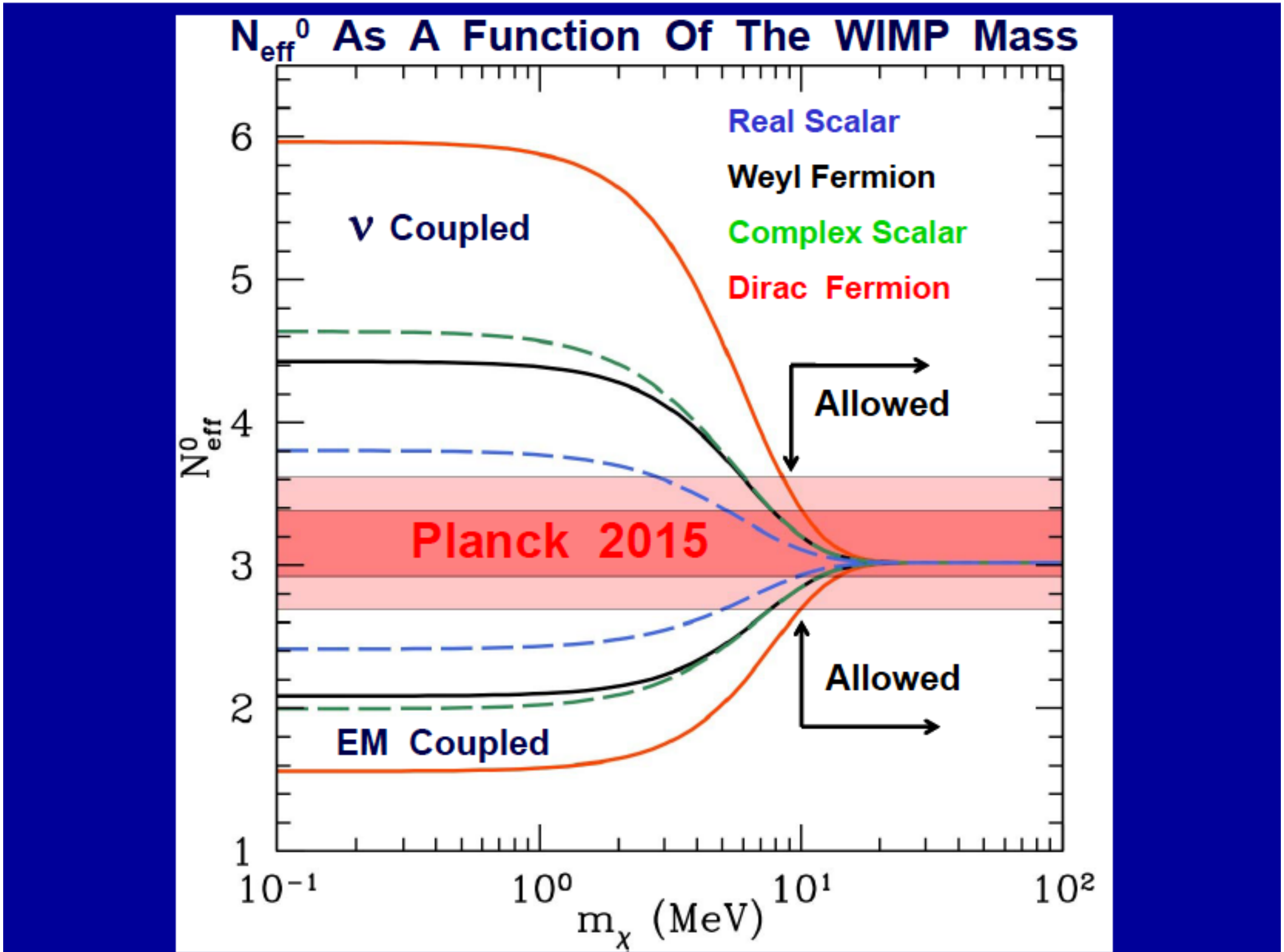
An Electromagentically Coupled Light WIMP

A light WIMP that annihilates to $e^{\pm}$ pairs and / or photons, after the neutrinos have decoupled, heats the photons relative to the neutrinos.

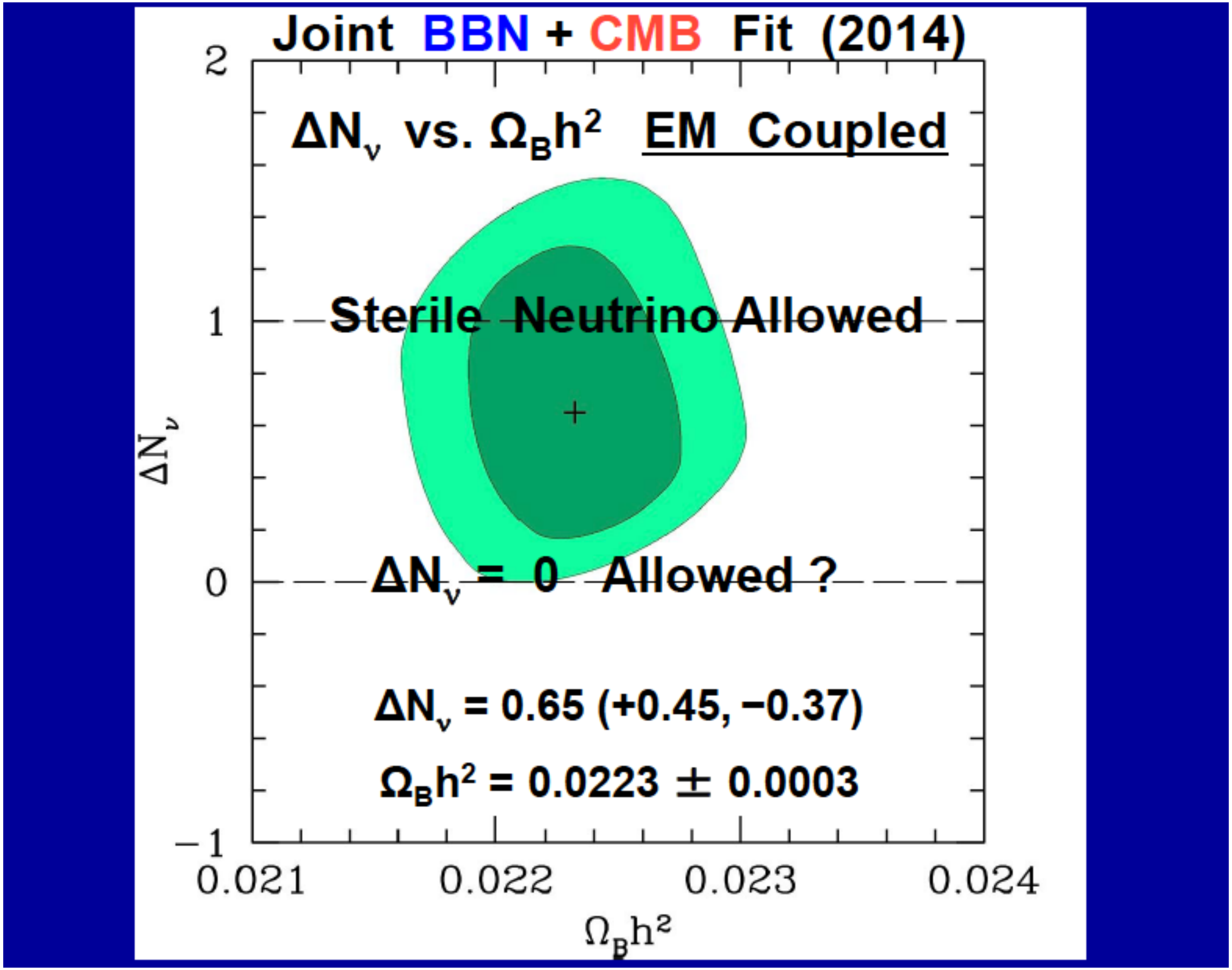
$\Rightarrow$ $(T_\nu / T_\gamma)_0 < (4/11)^{1/3}$ $\Rightarrow$ $N^0_{eff} < 3$, where $N^0_{eff} = N_{eff}$ in the absence of Dark Radiation.

For m > ~ 1 keV, the extra photons thermalize, diluting the post – BBN baryon to photon ratio.

Steigman, cont



Steigman: Light EM coupled DM allows New ν!



Other cute ν tricks

- masses, mixing depend on new scalar vev (not Higgs)
- If scalar is light, vev can be highly environment dependent
- MassVaryingNeutrinos (MaVaNs), can decouple terrestrial, cosmological, supernovae constraints.

Dark Energy

what the heck is it?
What handles do we have?
ν interaction?

ν physics beyond the standard model at the meV scale?

- Dark Energy Density: $\rho_{DE}^{1/4} \sim 2\times10^{-3}$ eV
  - See Saw Scale: $M_W^2/M_{Pl} \sim 10^{-4}$ eV
- gravitino mass in some supersymmetric models $\sim 10^{-3}$ eV
- new scalar mass in hidden nearly supersymmetric sector could be naturally sub meV
- Neutrino masses: $(\Delta m^2_{solar})^{1/2} \sim 9\times10^{-3}$ eV
  - $(\Delta m^2_{atmospheric})^{1/2} \sim 5\times10^{-2}$ eV

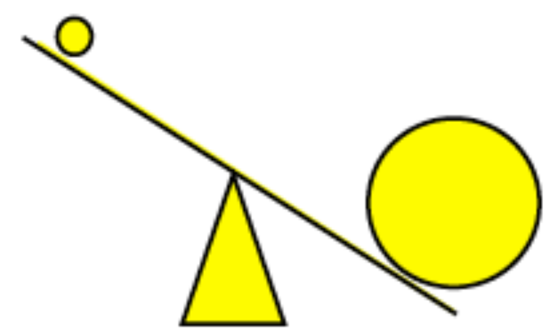
Mass Varying Neutrinos (MaVaNs)

connection between neutrino mass and dark energy?

The 'mini-seesaw' MavaN Model

Assume "Dark Sector" (= unknown particles with no standard Model charges) contains light

- "Acceleron" scalar field A
- fermion fields n (aka 'sterile' or 'righthanded' ν)
- Yukawa couplings $\lambda A n n$
- Scalar potential $V(A)$



"Our sector" contains

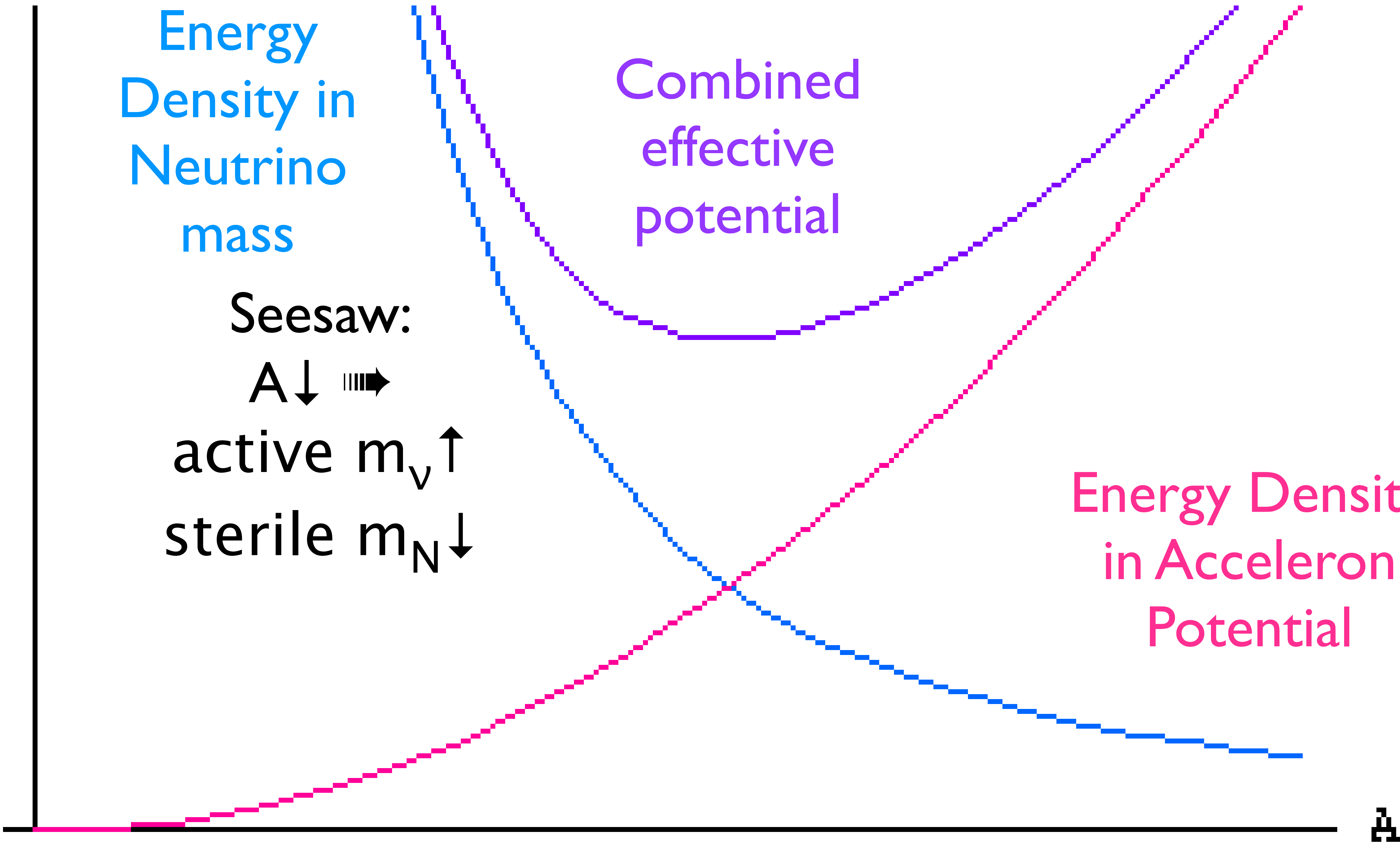
- Active Neutrinos ν
- Higgs Field H

Allow tiny $(y = O(10^{-11} - 10^{-15}))$ coupling $y H n \nu$

⇛ Neutrino mass matrix $\begin{pmatrix} 0 & y\langle H\rangle \\ y\langle H\rangle & \lambda \langle A\rangle \end{pmatrix}$

'Dirac' Mass
$m_D = y\langle H\rangle$
~1 eV-0.0001 eV

Varying Effective Potential for A as Neutrino density decreases



General considerations for varying parameters

Varying Parameter ➡ New Field

(e.g. varying mass ➡ Higgs)

Significant effects require fields which are lighter than scale of affected physics—for cosmology, this means new sub-meV bosons
(not necessarily as light as H~10^{-33} eV)

Is a light, weakly coupled new sector
natural?
consistent with expt?

A Technically Natural Model

(except cosmological constant)

Gauge Mediated Susy Breaking Model with

$m_{3/2} \sim 10^{-3}$ eV

Nearly hidden nearly supersymmetric sector containing

A, n chiral superfields

$W \supset y\, H\nu n + \lambda\, A n n\,,\ \lambda \sim 1,\ y \sim 10^{-11}$

susy breaking masses for A, ñ scalars

$\mathcal{M}_{\tilde{n}}, \mathcal{M}_A < 10^{-3}$ eV

$V \supset \lambda^2\, |\tilde{n}|^4 + 4\lambda^2\, |A\tilde{n}|^2 - \mathcal{M}_{\tilde{n}}^2\, |\tilde{n}|^2 +$

$y^2\, |H\tilde{n}|^2 + \mathcal{M}_A^2\, |A|^2 + \text{constant}$

Cosmology test of SUSY MaVaNs

- early universe: higher neutrino density, effective potential favors large $\langle \tilde{A} \rangle$
  - Heavy sterile neutrinos, light active neutrinos
- Today: $\langle \tilde{A} \rangle$ stuck in local minimum with eV sterile neutrinos, dark energy
- Future: true minimum with nonvanishing $\langle \tilde{n} \rangle$, vanishing $\langle \tilde{A} \rangle$ no dark energy.

Summary

- ν mass is new physics, even in minimal case requires new “sterile” fermion
- “sterile”=no standard model interactions
- ν oscillations signatures of light and heavy sterile ν
- ν possible interactions for “sterile” particle
    - ν interacting dark matter
    - ν interactions with dark energy scalar field
        - MaVaNs
- $SUSY$+ gauge mediation, natural light scalar for MaVaNs
- MaVaNs allow *“cosmologically inconsistent”* ν mass and sterile ν*’s*