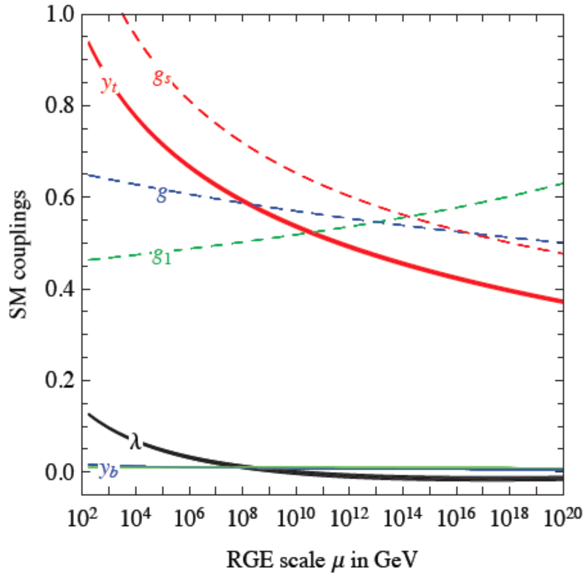
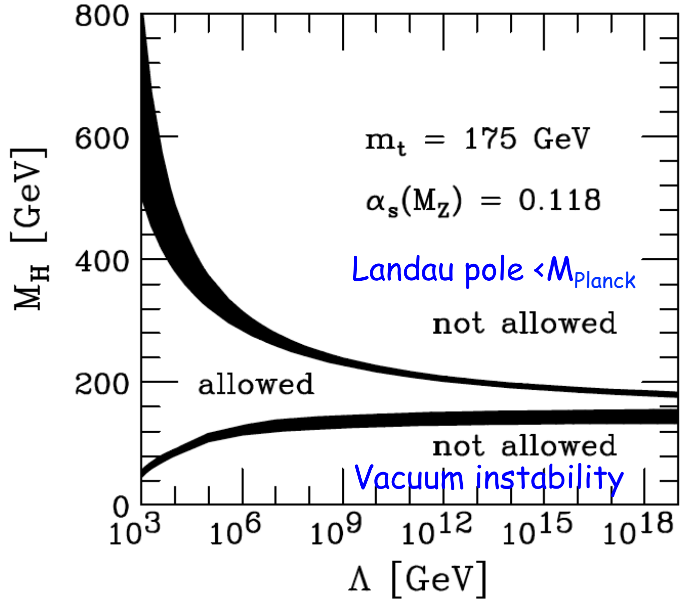
Implications of 125 GeV Higgs





RGE - just the Standard Model

Higgs coupling small

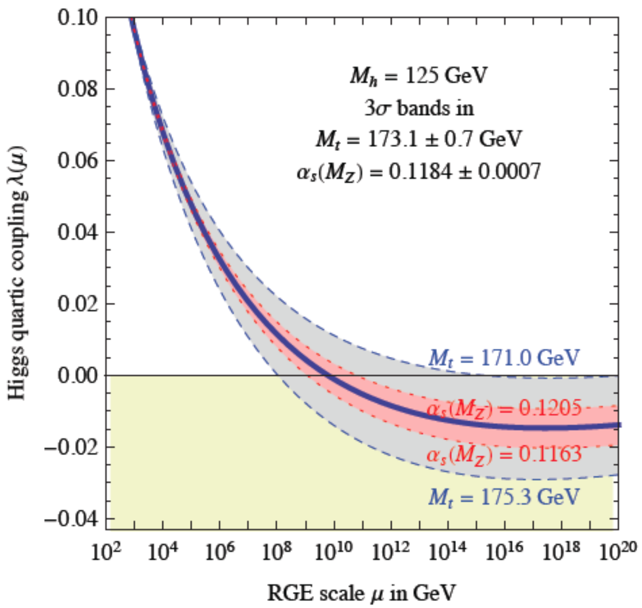
Hambye, Riesselmann

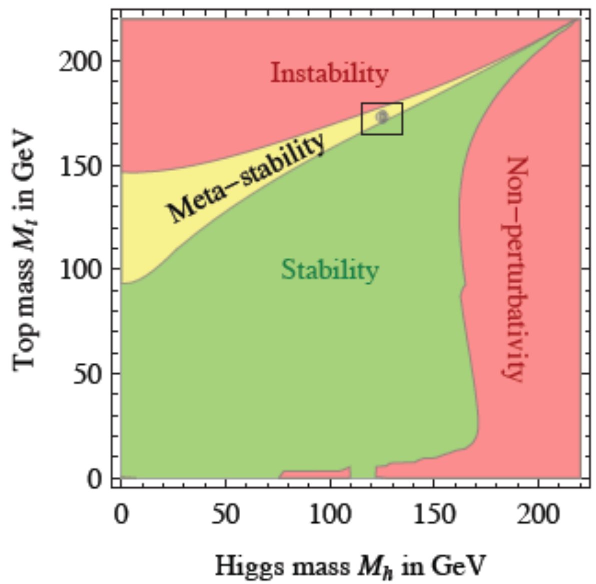
Implications of 125 GeV Higgs – vacuum instability

$$V(H) = -\frac{1}{2}M_H^2|H|^2 + \frac{\lambda}{4}|H|^4$$

Tunneling probability: $p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(\mu)|} - \Delta S\right]$

Isidori, Ridolfi, Strumia





$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

$$M_h > 129.4 \pm 1.8\ \text{GeV}$$

2σ away from stability

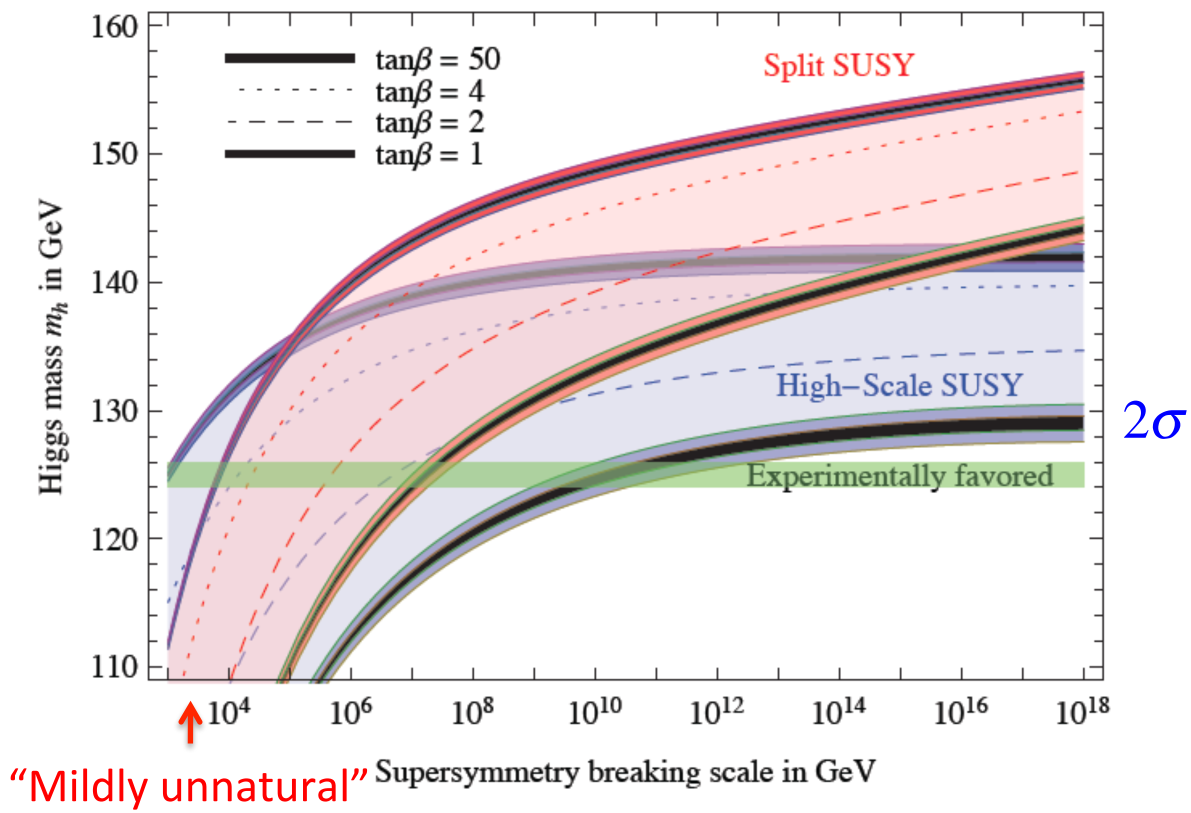
De Grassi et al

Supersymmetry

$$\lambda(\tilde{m}) = \frac{1}{8}\left[g^2(\tilde{m}) + g'^2(\tilde{m})\right]\cos^2 2\beta$$

$$\delta\lambda(M_{\rm Pl}) \approx \frac{1}{(4\pi)^2}\left[-0.25 + 0.12\ln\frac{m_{\tilde{t}}}{M_2} + 0.05\ln\frac{m_A}{M_2}\right]$$

Predicted range for the Higgs mass



De Grassi et al

Just the Standard Model

RH neutrinos

$$\nu SM: \quad SM + N_{i=1,2,3}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \overline{N_I} i \partial\!\!\!/ N_I - F_{\alpha I} \overline{L_\alpha} N_I \Phi + \frac{M_I}{2} \overline{N_I^c} N_I + \text{h.c.}$$

? Inflation - Higgs inflation

? Hierarchy problem - scale invariance ?

? Dark matter - keV neutrino, N_1

? Baryogenesis - Leptogenesis via sterile neutrino oscillation

? Dark energy ?

Higgs inflation

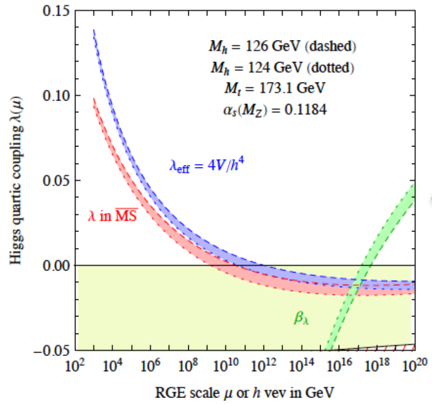
Flattens potential above $M_{Planck}/\sqrt{\xi}$

Bezrukov, Shaposhnikov

(i) $\xi|H|^2 R. \quad \xi \approx 5 \times 10^4 \sqrt{\lambda}.$

$\lambda(M_P) \geq 0 \quad (2\sigma \text{ off})$

Perturbative unitarity?



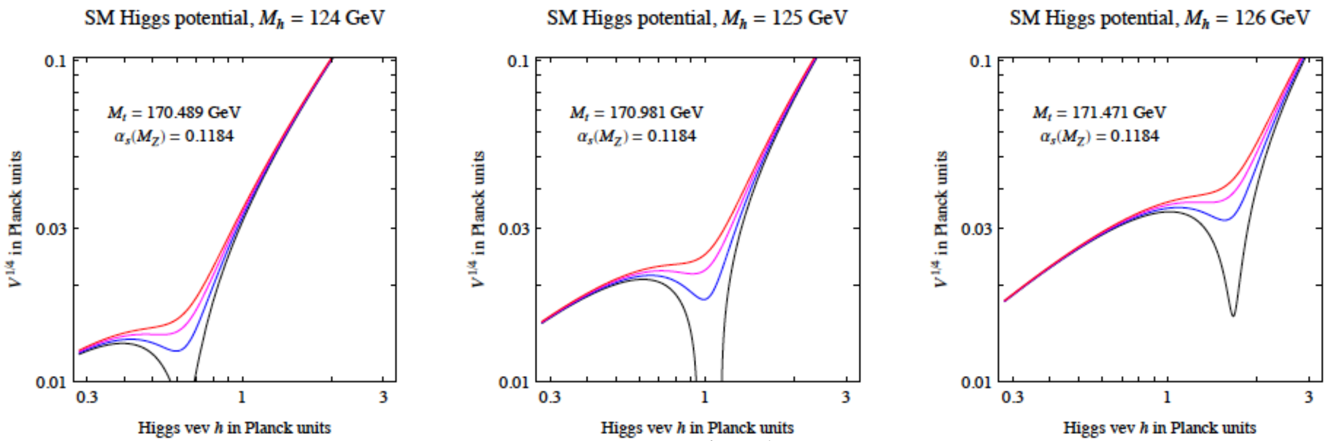
$$\beta_\lambda = \frac{d}{d\ln\mu}\lambda(\mu)$$

(ii) "Conventional"

$$V = \Delta^4 + m^2|H|^2 + \ldots, \quad m \ll H = \Delta^2 / M_P$$

Isidori et al

$$\frac{dV}{dh} = \left(\lambda_{\text{eff}} + \frac{\beta_{\text{eff}}}{4}\right) h^3$$



Higgs vev in Planck units

Hierarchy problem revisited

I. Dilatation (scale) invariance: Scalar mass terms forbidden

$$x^\mu \to x'^\mu = e^\omega x^\mu \qquad\qquad \phi(x) \to e^\omega \phi(x')$$

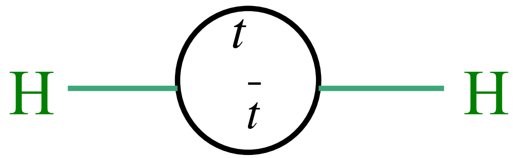
$$S = \int d^4x [\frac{1}{2}\partial_\mu \phi(x) \partial^\mu \phi(x) - \frac{\lambda}{4}\phi^4(x)]$$

Classical theory invariant

Quantum corrections + dimensional regularisation:

$$\delta^{\tilde{t}} M_H^2 \simeq \frac{h_t^2}{8\pi^2}\left(\Lambda^2 - m_t^2 \ln(\frac{\Lambda^2}{m_t^2})\right)$$

$\Lambda^2 \to 0$



$\Longrightarrow$ if Higgs does not couple to heavy states RC OK!

Origin of mass terms: spontaneous symmetry breaking

$$\mathcal{L}' = \Big(\bar{L}^i \Phi Y^E_{ij} E^j + \bar{Q}^i \epsilon \Phi^* Y^D_{ij} D^j + \bar{Q}^i \epsilon \Phi^* Y^U_{ij} U^j + \\ + \bar{L}^i \epsilon \Phi^* Y^\nu_{ij} \nu^j_R + \varphi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + \text{h.c.}\Big) \\ - \frac{\lambda_1}{4}(\Phi^\dagger\Phi)^2 - \frac{\lambda_2}{2}\varphi^2(\Phi^\dagger\Phi) - \frac{\lambda_3}{4}\varphi^4$$

$$V^{(1)}_{\text{eff}}(H,\varphi) = \frac{N-1}{256\pi^2}(\lambda_1 H^2 + \lambda_2\varphi^2)^2 \ln\left(\frac{\lambda_1 H^2 + \lambda_2 \varphi^2}{v^2}\right) \\ + \frac{M-1}{256\pi^2}(\lambda_2 H^2 + \lambda_3\varphi^2)^2 \ln\left(\frac{\lambda_2 H^2 + \lambda_3 \varphi^2}{v^2}\right) \\ + \frac{1}{64\pi^2} F_+^2 \ln\left(\frac{F_+}{v^2}\right) + \frac{1}{64\pi^2} F_-^2 \ln\left(\frac{F_-}{v^2}\right)$$

$\overline{MS}$ regularisation

Meissner, Nicolai

$$\lambda_1 = 3.4,\ \lambda_2 = 2.6,\ \lambda_3 = 3.3,\ g_t = 1,\ g_M^2 = 0.4.$$
$$\langle H \rangle = 4.15 \cdot 10^{-6}\, v,\ \langle \varphi \rangle = 25.06 \cdot 10^{-6}\, v$$

$$\langle H \rangle = 174 \text{ GeV},\ \langle \varphi \rangle = 1050 \text{ GeV},\ v = 2.41 \cdot 10^5 \langle H \rangle$$
$$m_{H'} = 217 \text{ GeV}, \qquad m_{\varphi'} = 439 \text{ GeV}$$

II. Nonlinear scale invariance:

$$V_0(\varphi^\dagger\varphi) = a + \mu\varphi^\dagger\varphi + \tfrac{\lambda}{2}(\varphi^\dagger\varphi)^2$$

V can be made (nonlinearly) scale invariant:

dilaton

$$\mu \to \mu e^{2\sigma/f}, \quad a \to a e^{4\sigma/f}$$

Dilatations: $\sigma(x), \quad \sigma \to \sigma + f\omega, \quad \varphi \to \varphi e^{\omega}$

Symmetry breaking and the mass hierarchy

$$\overline{V}(\varphi^{\dagger}\varphi) = e^{4\sigma/f}\left(a(\overline{M}) + \mu(\overline{M})G^{2}(\overline{M})\varphi^{\dagger}\varphi + \tfrac{\lambda(\overline{M})}{2}(G^{2}(\overline{M})\varphi^{\dagger}\varphi)^{2}\right)$$

RG equation:

$$\left[M\frac{\partial}{\partial M}+\mu^2\beta_a\frac{\partial}{\partial a}+\mu\beta_\mu\frac{\partial}{\partial \mu}+\beta_{g_i}\frac{\partial}{\partial g_i}-2\gamma z\frac{\partial}{\partial z}\right]V=0$$

$$\frac{\mathrm{d}}{\mathrm{d}M}V\left(G^2(M)\varphi^\dagger\varphi;a(M),\mu(M),g_i(M);M\right)=0$$

$$G(M)=\exp\left(-\int_{M_0}^{M}\frac{\mathrm{d}M'}{M'}\gamma(g_i(M'))\right)$$

dependence of normalisation of φ on M

Scale invariant case:

$\varphi=e^{\sigma/f}\phi$

$$\bar{V}\equiv V\left(G^2(M)\varphi^\dagger\varphi;a(M)\mathrm{e}^{4\sigma/f},\mu(M)\mathrm{e}^{2\sigma/f},g(M);M\right)$$

$$=\mathrm{e}^{4\sigma/f}\,V\left(G^2(M)\phi^\dagger\phi;a(M),\mu(M),g(M);M\,\mathrm{e}^{-\sigma/f}\right),$$

$$\bar{V}=\mathrm{e}^{4\sigma/f}\,V\left(G^2(\bar{M})\phi^\dagger\phi;a(\bar{M}),\mu(\bar{M}),g(\bar{M});M\right)$$

$$\bar{M}=M\,\mathrm{e}^{\sigma/f}$$

Symmetry breaking and the mass hierarchy

$$\overline{V}(\varphi^\dagger\varphi) = e^{4\sigma/f}\left(a(\overline{M}) + \mu(\overline{M})G^2(\overline{M})\phi^\dagger\phi + \tfrac{\lambda(\overline{M})}{2}(G^2(\overline{M})\phi^\dagger\phi)^2\right)$$

$Me^{\sigma_0/f}$

$$\left.\frac{\partial\bar{V}}{\partial\phi}\right|_{\phi_0,\sigma_0} = 0, \quad \left.\frac{\partial\bar{V}}{\partial\sigma}\right|_{\phi_0,\sigma_0} = 0 \quad \Rightarrow \quad a(\bar{M}_0) = \frac{\mu^2(\bar{M}_0)}{2\lambda(\bar{M}_0)}\left(1 - \frac{\lambda(\bar{M}_0)}{8\pi^2}\ln(2\lambda(\bar{M}_0))\right)$$

Not scale invariant

Gravity described by Brans Dicke theory: $\sqrt{g}\left(\tfrac{1}{2}\kappa R + \tfrac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma\right)$

+ scale invariant SM theory: $-e^{2\sigma/f}D_\mu\phi^\dagger D^\mu\phi - e^{4\sigma/f}V_0(\phi^\dagger\phi)$

Buchmuller, Busch

Logarithmic variation of couplings require exponentially large hierarchy

$\varphi_0 \sim f\,e^{\sigma_0/f}$ (σ_0 large and negative)

Dark Matter

$$L = L_{SM} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \overline{L}_\alpha N_I H - \frac{M_{IJ}}{2} \overline{N}_I^c N_J + h.c.$$

Neutrino masses

$$\begin{pmatrix} 0 & vF \\ vF & M \end{pmatrix} \longrightarrow \begin{pmatrix} \frac{v^2F^2}{M} & 0 \\ 0 & M \end{pmatrix}$$

Take $F \sim 10^{-7}$ and $M_{2,3} \sim 10$ GeV to give light neutrino masses $m_\nu \sim 10$ meV

$(\Delta m^2_{\text{sun}} \approx 77\ \text{meV}^2, \quad |\Delta m^2_{\text{atm}}| \approx 2400\ \text{meV}^2)$

Keep N_1 light to provide dark matter $(M_1 << M_{2,3})$

Shaposhnikov et al

Dark Matter

$-F_{\alpha I}\bar{L}_{\alpha}N_{I}H$

- Below $T_{\rm EW}$, N_1 mixes slightly with active neutrinos to form a mass eigenstate. This mixing is of the order

$$\theta_1^2 \equiv \frac{v^2 \sum_\alpha F_{\alpha 1}^2}{M_1^2}$$

and is the only way N_1 can interact (except gravitationally)

X-ray constraint

- There is a 1-loop decay channel $N_1 \to \nu + \gamma$ that would be visible in the X-ray spectrum for M_1 in the $1 - 100$ keV range
- Lack of X-ray signature from dark matter dominated galaxies gives the constraint

$$\theta_1^2 \lesssim 5 \times 10^{-7} \left(\frac{\rm keV}{M_1}\right)^{4.4}$$

$$F_1 \leq 4 \times 10^{-12} \left(\frac{keV}{M_1}\right)^{1.2}, \quad m_{\nu\perp} < 0.5 meV$$

Dark Matter

- The largest production of N_1 is through active-sterile neutrino oscillations below $T_{\rm EW}$
- Assuming negligible lepton asymmetry (Dodelson-Widrow), the rate of N_1 production is given by

$$\Gamma_{N_1} \sim \theta_M^2 \Gamma_\nu$$

where θ_M^2 is the temperature-dependent mixing angle

$$\theta_M^2 \sim \frac{\theta_1^2}{\theta_1^2 + \left(1 + \frac{T}{M_1^2}\Gamma_\nu\right)^2}, \qquad \Gamma_\nu \sim G_F^2 T^5$$

- Γ_{N_1} and hence N_1 production is sharply peaked at

$$T_{\rm max} \sim 130 \left(\frac{M_1}{\rm keV}\right)^{1/3} \ {\rm MeV}$$

Dark Matter

- Integrating Γ_{N_1} over time (using the Boltzmann equation) gives the total amount of N_1 production as

$$\Omega_{N_1} \approx 0.4 \left(\frac{\theta_1^2}{10^{-8}}\right)\left(\frac{M_1}{\text{keV}}\right)^2$$

- Setting $\Omega_{N_1} \approx 0.22$ (to produce 100% of dark matter) gives the relation

$$\theta_1^2 \approx 6 \times 10^{-9} \left(\frac{\text{keV}}{M_1}\right)^2$$

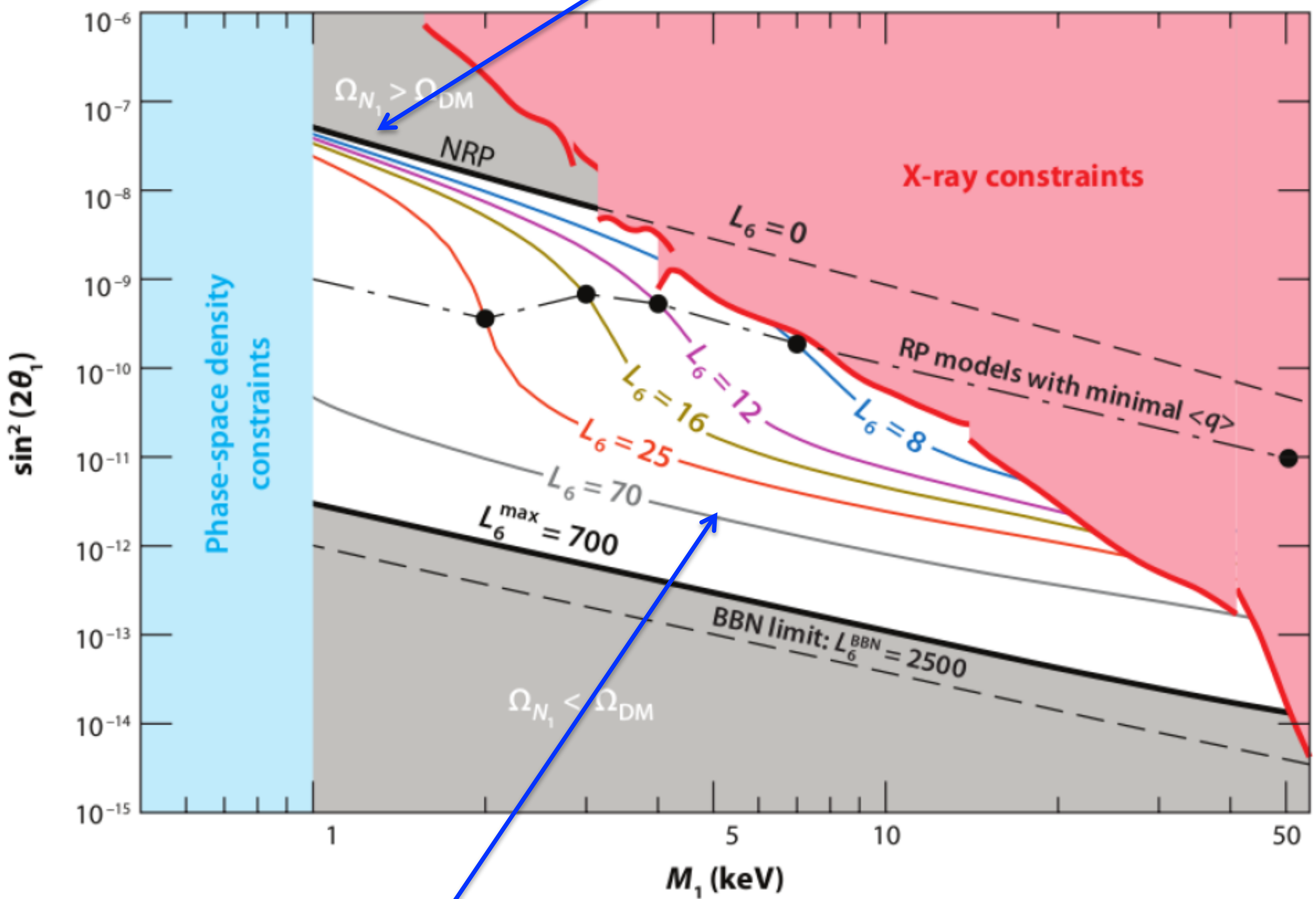
Dodelson-Widrow production bound

- Combining this relation with the X-ray constraint gives

$$M_1 \lesssim 4 \text{ keV}$$

Dark Matter

DW production rate



large lepton asymmetry $\Rightarrow \Delta M = M_2 - M_3 \leq 10^{-7}\, eV$ ...problematic

But…

Lyman-α bound

- Absorption lines in the spectra of distant quasars give information about density fluctuations of hydrogen gas
- Free streaming N_1 would wipe out small scale density fluctuations unless its velocity is small enough, giving

$$M_1 \gtrsim 8 \text{ keV}$$

If the Lyman-α bound is robust need to add something, eg singlet scalar

(c.f. need for additional singlet for conformal symmetry or for inflation.)

K. Allison

Baryon asymmetry

- In the νMSM, baryogenesis proceeds via leptogenesis; sterile neutrino oscillations produce a lepton asymmetry above T_{EW} that is converted into a baryon asymmetry by sphalerons
- More specifically,
    - N_I are produced by Yukawa interactions in a CP-invariant state ($\Delta N_I = 0$)
    - N_I then oscillate and second-order Yukawa interactions produce asymmetries in each flavour L_α but no total asymmetry ($\Delta L = \sum_\alpha \Delta L_\alpha = 0$)
    - Third-order Yukawa interactions then convert the flavour asymmetries in L_α into a total asymmetry $\Delta N \neq 0$ and hence a total asymmetry $\Delta L = -\Delta N$
    - Sphalerons convert the asymmetry ΔL into a baryon asymmetry ΔB until sphalerons freeze-out at T_{EW}

Baryon asymmetry

- Quantitatively, density matrices are used to describe neutrino oscillations and interactions in the early universe
- Solving their kinetic equations perturbatively gives

$$\frac{n_B}{s} \sim 10^{-8}\left(\frac{F_{2,3}}{10^{-7}}\right)^6\left(\frac{\mathrm{GeV}}{M_{2,3}}\right)^{2/3}\left(\frac{\mathrm{keV}}{\Delta M_{32}}\right)^{2/3}\left(\frac{160\ \mathrm{GeV}}{T_{\mathrm{EW}}}\right)$$

Actual value is $\frac{n_B}{s} \sim 10^{-10}$

Baryon asymmetry

- Baryon asymmetry production requires
  - Yukawa couplings in the range $10^{-7.5} \lesssim F_2, F_3 \lesssim 10^{-6}$
  - Mass degeneracy $\Delta M_{32} = M_3 - M_2$ on the order of a keV

Roy, Shaposhnikov

Just the Standard Model - summary

RH neutrinos

$$\nu SM : \quad SM + N_{i=1,2,3}$$

$$L = L_{SM} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \overline{L}_\alpha N_I H - \frac{M_I}{2} \overline{N}_I^c N_I + h.c.$$

- $1 \text{ keV} \lesssim M_1 \lesssim 4 \text{ keV}$
- $150 \text{ MeV} \lesssim M_2, M_3 \lesssim 100 \text{ GeV}$ with $\Delta M_{32} \sim \text{keV}$
- $F_1 \lesssim 4 \times 10^{-12}$
- $10^{-7.5} \lesssim F_2, F_3 \lesssim 10^{-6}$

Origin – additional symmetries.

e.g.

$$L = L_{SM} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \overline{L}_\alpha N_I H - \frac{\lambda_{IJ}}{2} \phi \overline{N}_I^c N_J + h.c.$$

	N_1	N_2	N_3	ϕ	$\bar{L}_\alpha$	Φ	ϑ
Z_2	1	0	0	0	0	0	0
$\mathrm{U(1)_{FN}}$	3	-3	6	0	-1	0	-1

$$\lambda_{IJ} \sim \begin{pmatrix} \eta^6 & 0 & 0 \\ 0 & \eta^6 & \eta^3 \\ 0 & \eta^3 & \eta^{12} \end{pmatrix} \quad F_{\alpha I} \sim \begin{pmatrix} 0 & \eta^4 & \eta^5 \\ 0 & \eta^4 & \eta^5 \\ 0 & \eta^4 & \eta^5 \end{pmatrix}$$

$$\eta = \frac{\langle \vartheta \rangle}{M_{Planck}} \sim 0.01$$

K.Allison

Summary of BSM@LHC

- No direct evidence for BSM physics ($\not{E}_T$, new resonances, …)
- Higgs @ 125GeV puts low-fine-tuned SUSY under great tension
  (GNMSSM, natural SUSY, mirage mediation,compressed spectrum, $\not{R}_P$ …)
- Tests of composite/elementary Higgs favours elementary
- Indirect BSM signals: $g-2, \quad H \to \gamma\gamma \quad \Rightarrow$ light sleptons?
- Just the Standard Model – not impossible?

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Little hierarchy problem needs LHC@14TeV