Dark matter and Inflation in PeV scale SUSY

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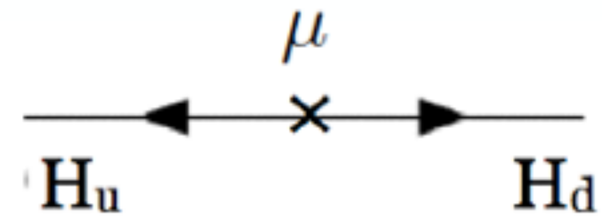
Natural SUSY

Barbieri, Giudice, 1988

$$\delta m_H^2 = \mu^2$$

Higgsino mass < 250 GeV

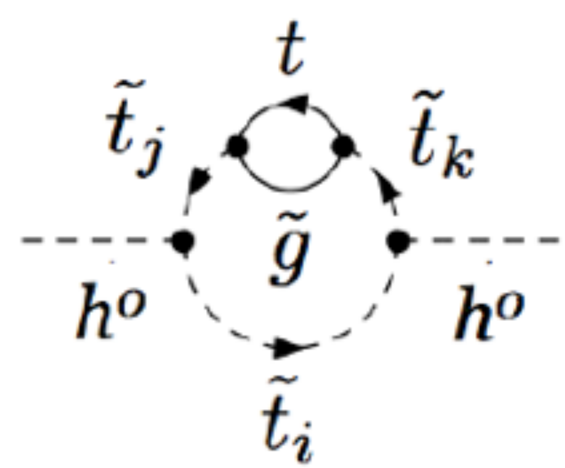


$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\text{stop}}^2 \log\frac{\Lambda}{Q}$$

Stop mass < 600 GeV

$$\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \left(\log\frac{\Lambda}{Q}\right)^2$$

Gluino mass < 1.4 TeV

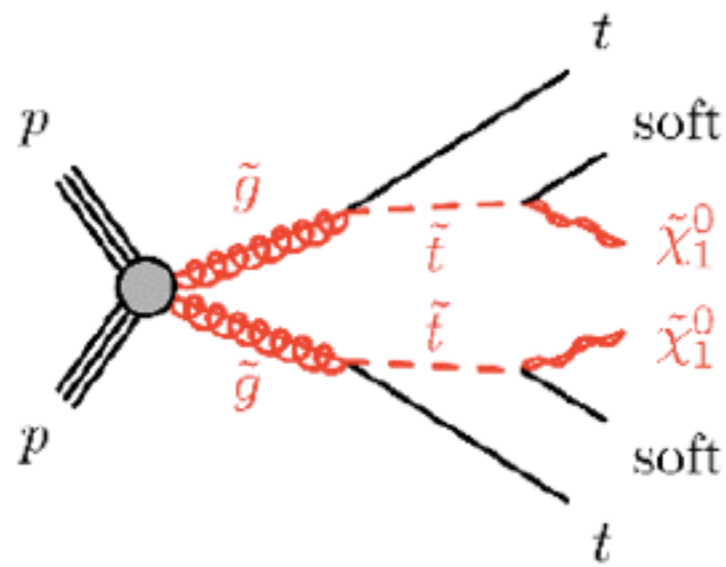


There are ways to evade the LHC constraints

1. R-parity violating MSSM
2. Compressed or degenerate spectrum
3. Split SUSY
4. …

1. R-Parity violating MSSM

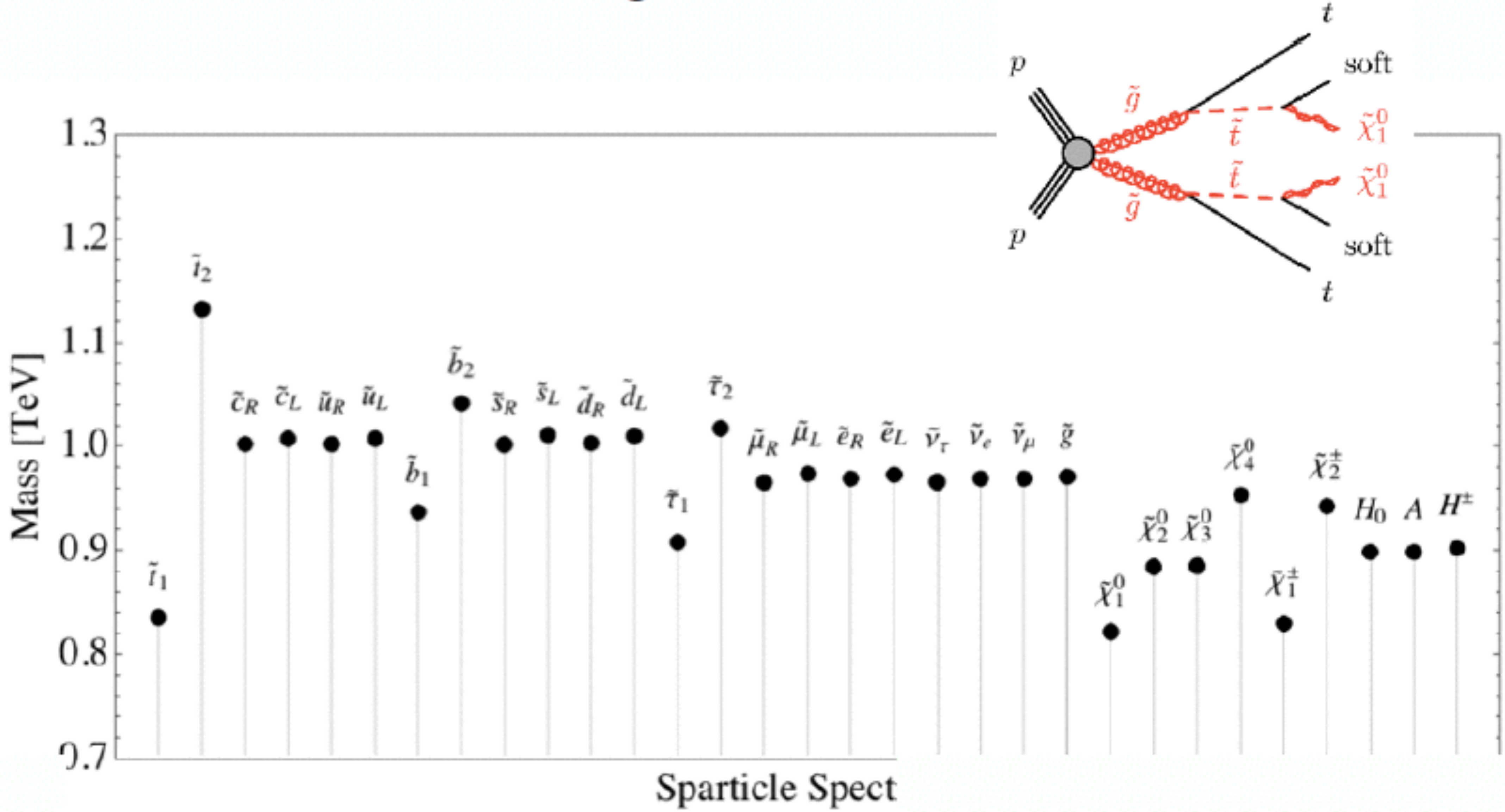
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k.$$



Squarks can decay to 2-jets due to UDD term and be hidden in the QCD background

Biplob Bhattacherjee, Amit Chakraborty, 2014

2. Degenerate MSSM

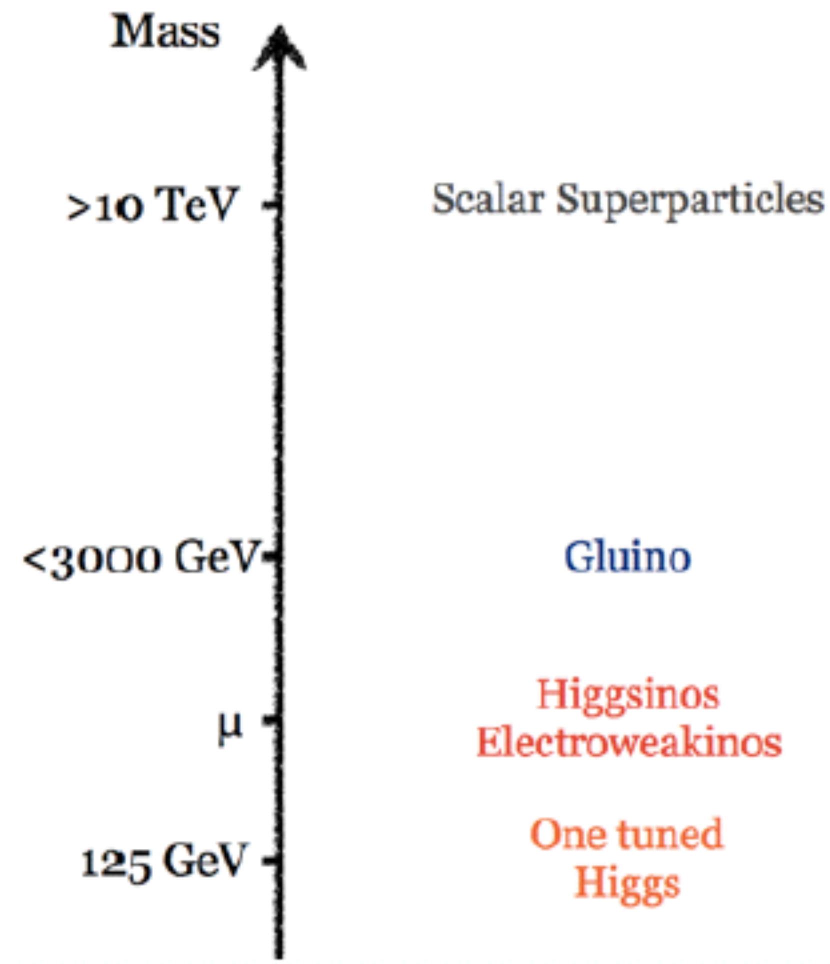


Typical spectrum in the case of $M_D \simeq 975$ GeV

D.Chowdhuri, K.M.Patel, X.Tata, S.K. Vempati 1612.06471

3. Split SUSY

- WIMP Dark Matter
- Coupling constant unification
- Fine tuned Higgs mass



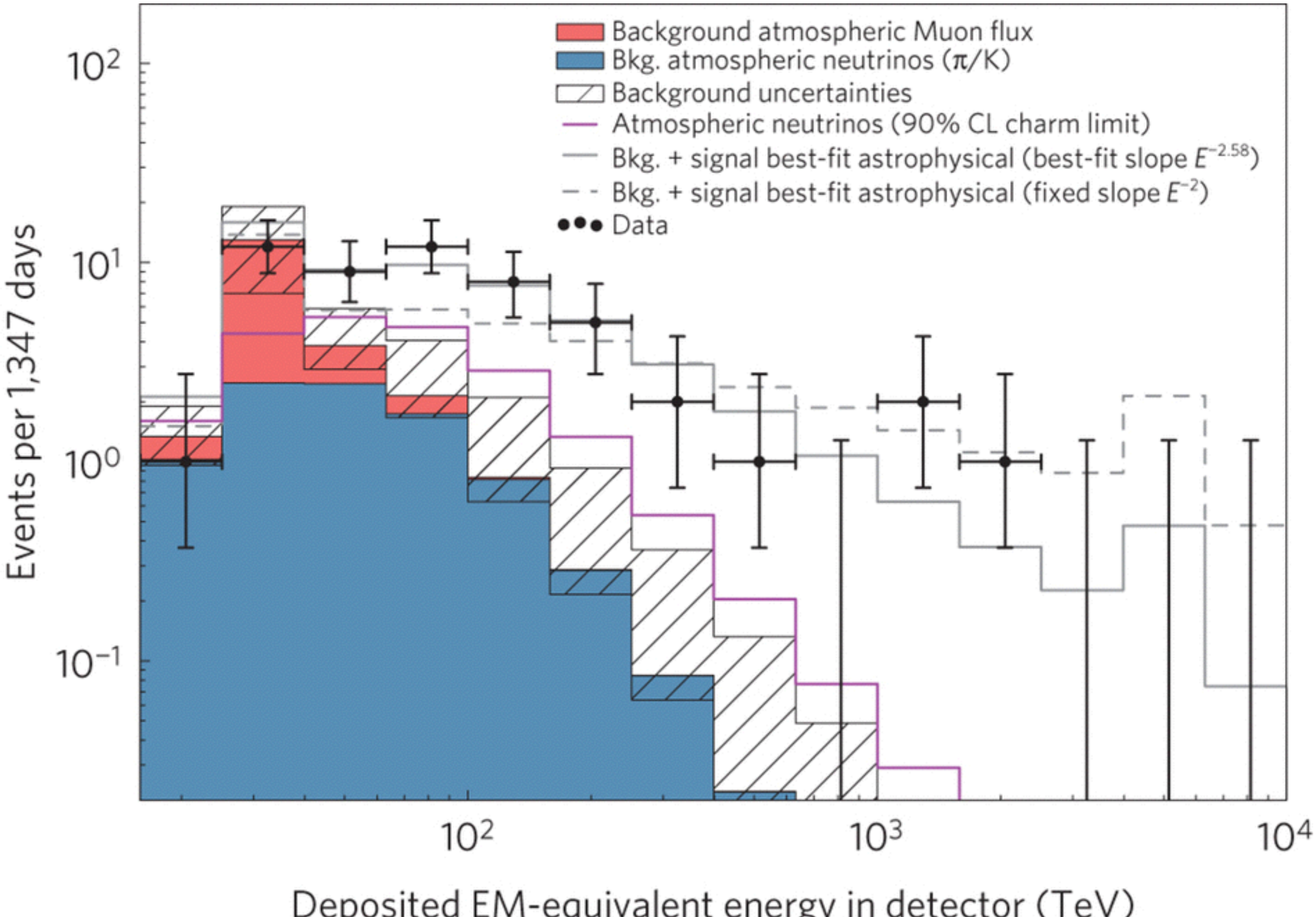
1. **PeV scale SUSY** - J.D.Wells (2005)

2. **PeV Neutrinos and a 3.5 keV X-Ray Line from a PeV Scale Supersymmetric Neutrino Sector** -
S. B. Roland, B. Shakya, J. D. Wells (2015)

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

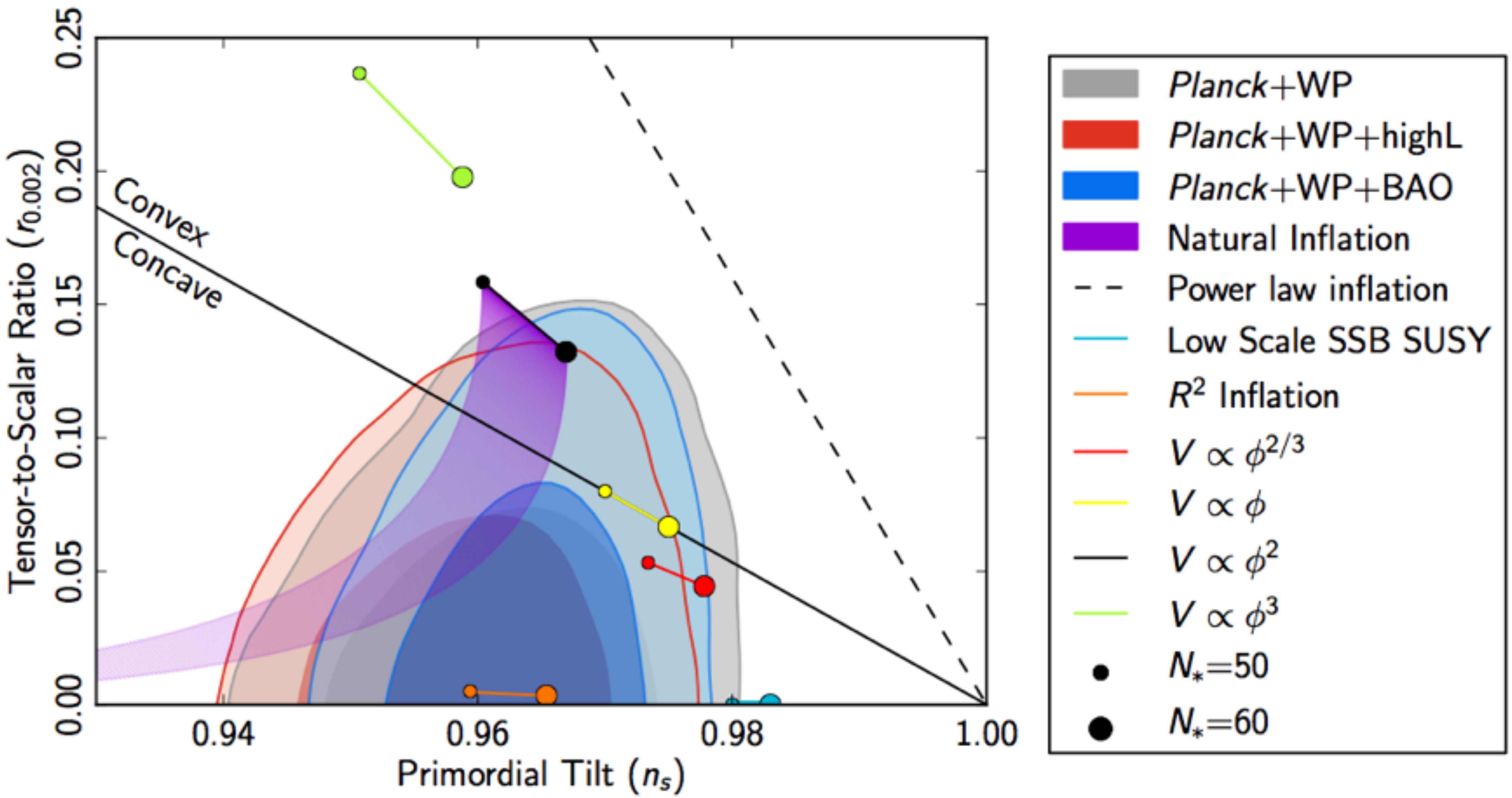
$$\tau_X \approx 10^{27}\,\mathrm{s} \left(\frac{1.5\times 10^{-3}}{\lambda_2}\right)^2 \left(\frac{M_*}{10^{16}\,\mathrm{GeV}}\right)^6 \left(\frac{100\,\mathrm{PeV}}{\langle\phi\rangle}\right)^6 \left(\frac{\mathrm{PeV}}{m_X}\right)$$

IceCube neutrino spectrum



Halzen, Nature Physics (2016)

Inflation models compatible with CMB data



Starobinsky model

$$S_{\mathrm{S}} = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\ \left(M_{\mathrm{p}}^2 R + \frac{1}{6M^2}R^2\right)$$

Jordan frame

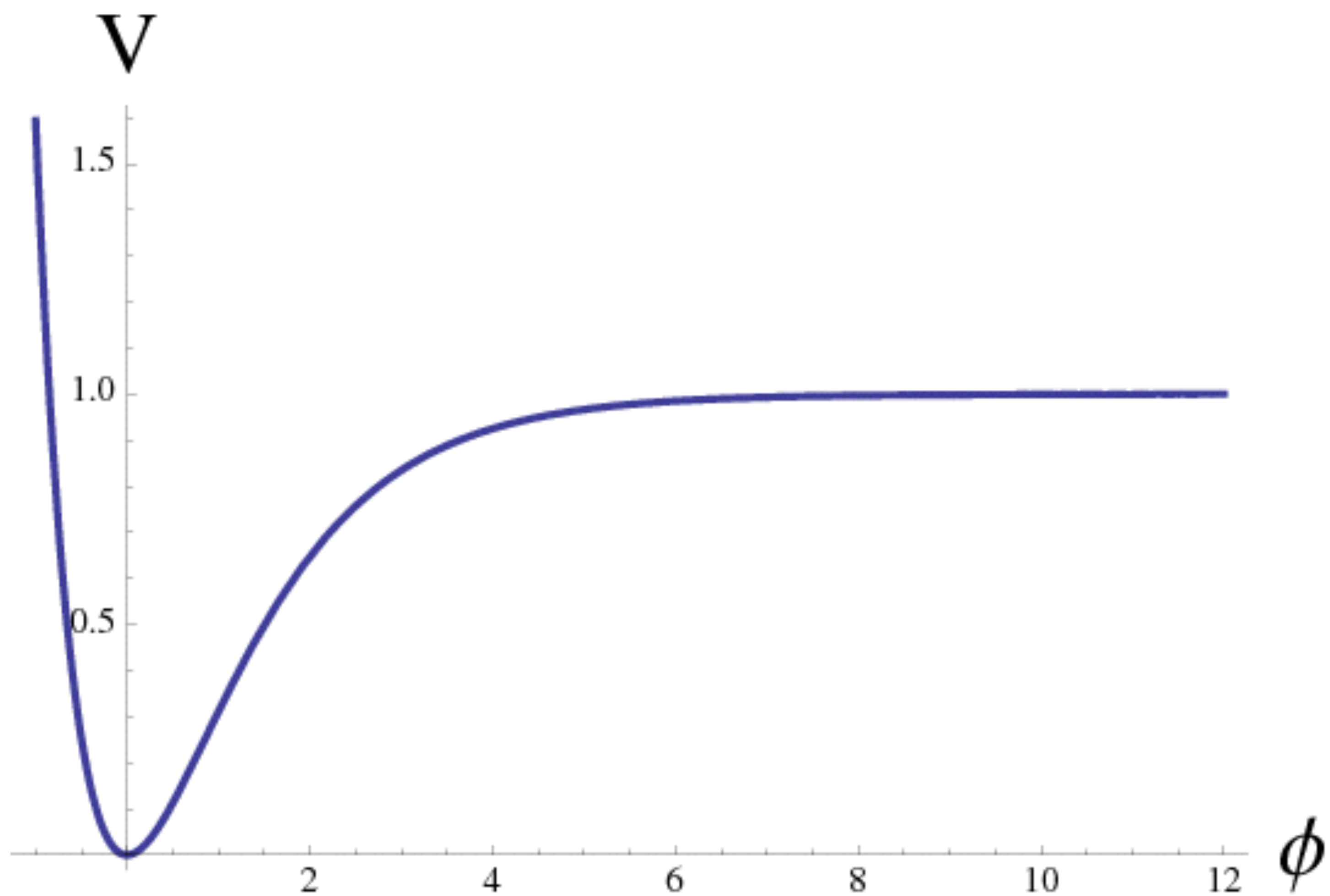
$$S_{\mathrm{S}} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{p}}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{3}{4}M_{\mathrm{p}}^4 M^2\left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_{\mathrm{p}}}\right)^2\right]$$

Einstein frame

$$n_s - 1 \approx -\frac{2}{N},\ \ r \approx \frac{12}{N^2}$$

$$M \simeq 10^{-5}\,, \quad N = 55$$

Plateau potential



SUGRA Inflation

Kahler potential $K(\phi_i, \phi_i^*)$

Superpotential $W(\phi_i)$

$$\mathcal{L}_{kin} = -K_{ij^*} g^{\mu\nu} \partial_\mu \phi^i \partial_\nu \phi^{*j}$$

$$K_{ij^*} = \frac{\partial^2 K}{\partial \phi^i \partial \phi^{*j}}.$$

Scalar potential

$$V(\phi_i, \phi_i^*) = V_F(\phi_i, \phi_i^*) + V_D(\phi_i, \phi_i^*).$$

SUGRA Model of Starobinsky potential

Ellis, Nanopoulos, Olive , PRL, 2013

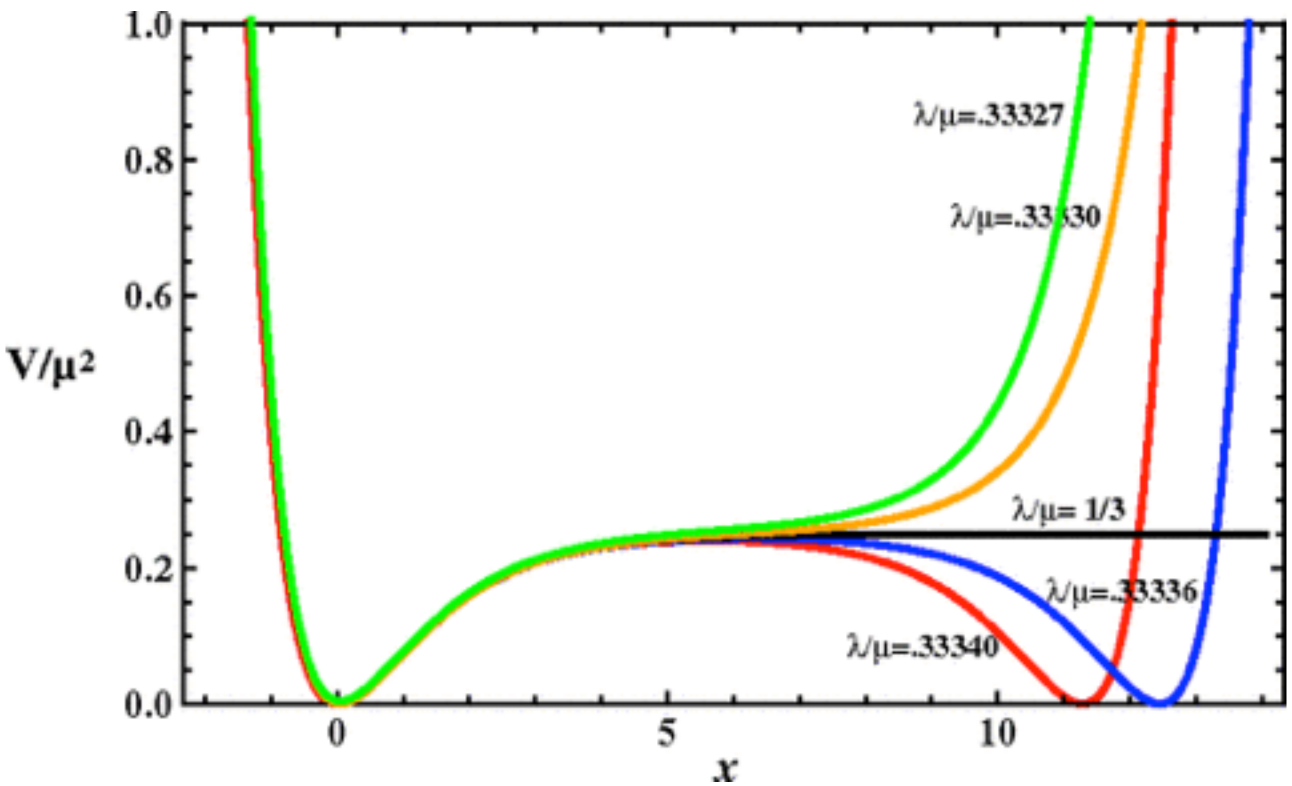
$$K = -3\ln\left[T + T^* - \frac{\phi\phi^*}{3}\right]$$

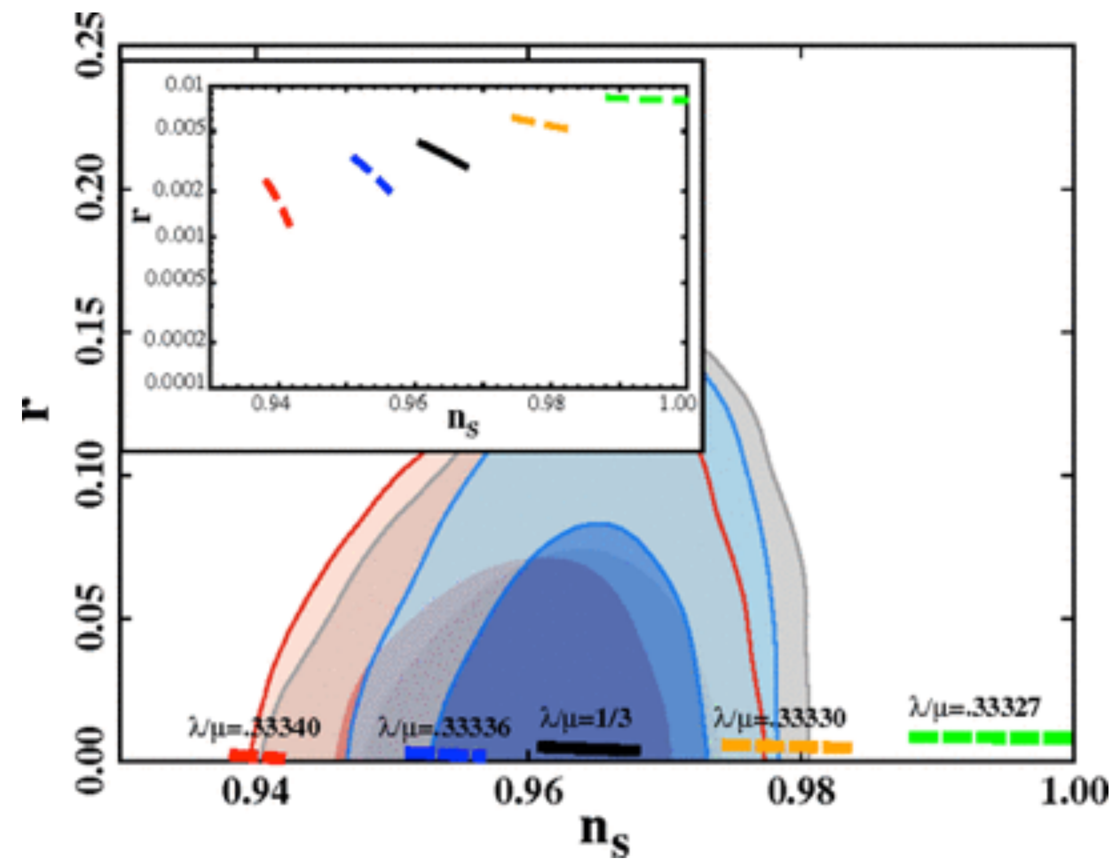
$$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

$$\mathcal{L}_{eff} = \frac{1}{(c - |\phi|^2/3)^2}\left[c|\partial_\mu\phi|^2 - \hat{V}\right]$$

$$\phi = c\sqrt{3}\tanh\frac{\chi}{\sqrt{3}}$$

$$V_F = \frac{\mu^2}{4}\left(1 - e^{-\sqrt{\frac{2}{3}}x}\right)^2$$





Dark matter and Inflation in PeV scale SUSY

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ArXiv: 1707.1947759

R-PARITY VIOLATING MSSM MODEL

$$K = 3\ln\Big[1 + \frac{1}{3M_p^2}\Big(H_u^\dagger H_u + H_d^\dagger H_d + L^\dagger L + Q^\dagger Q$$
$$+ \tilde{e}_R^* \tilde{e}_R + \tilde{u}_R^* \tilde{u}_R + \tilde{d}_R^* \tilde{d}_R\Big)\Big] + ZZ^* + \frac{\alpha}{2}(ZZ^*)^2$$

$$W = \mu\, H_u \cdot H_d - Y_d\, Q \cdot H_d\, \tilde{d}_R + Y_u\, Q \cdot H_u\, \tilde{u}_R$$
$$- Y_e\, L \cdot H_d\, \tilde{e}_R + \frac{\lambda}{M_p}(H_u \cdot H_d)^2 + \mu_z^2\, Z + \mu_{zz}\, Z^3$$

$$W_{int} = \lambda_{ijk} L_i L_j e^c_{Rk} + \lambda'_{ijk} L_i Q_j d^c_{Rk} + \frac{1}{2}\lambda''_{ijk} u^c_{Ri} d^c_{Rj} d^c_{Rk}$$

D-flat directions

$$\phi_u^+ = \phi_d^- = \phi_\tau = \tilde{u}_L = \tilde{d}_L = \tilde{e}_R = \tilde{d}_R = \tilde{u}_R = 0\,,$$
$$\phi_u^0 = \phi\ \sin[\beta]\,,$$
$$\phi_d^0 = \phi\ \cos[\beta]\,,$$
$$\phi_\nu = \phi\sqrt{\sin^2[\beta] - \cos^2[\beta]}\,,$$

$$\begin{aligned}V_F(\chi) =& \frac{27}{16}\lambda^2 \cot[\beta]^2 \tanh\left(\chi/\sqrt{6}\right)^6 \left[1 + \tanh\left(\chi/\sqrt{6}\right)^2\right]^3 \\ &\times \left[8\csc[\beta]^2 + (8 + 39\cot[\beta]^2)\tanh\left(\chi/\sqrt{6}\right)^2 + 49\cot[\beta]^2\tanh\left(\chi/\sqrt{6}\right)^4\right].\end{aligned}$$

$$\lambda = 7.6 \times 10^{-7}$$
$$\tan\beta = 1.8$$

$$\Rightarrow$$

$$A_s = 3.1 \times 10^{-10}$$

$$n_s = 0.9664$$

$$r = 0.0033$$

Two parameter fit to inflation.

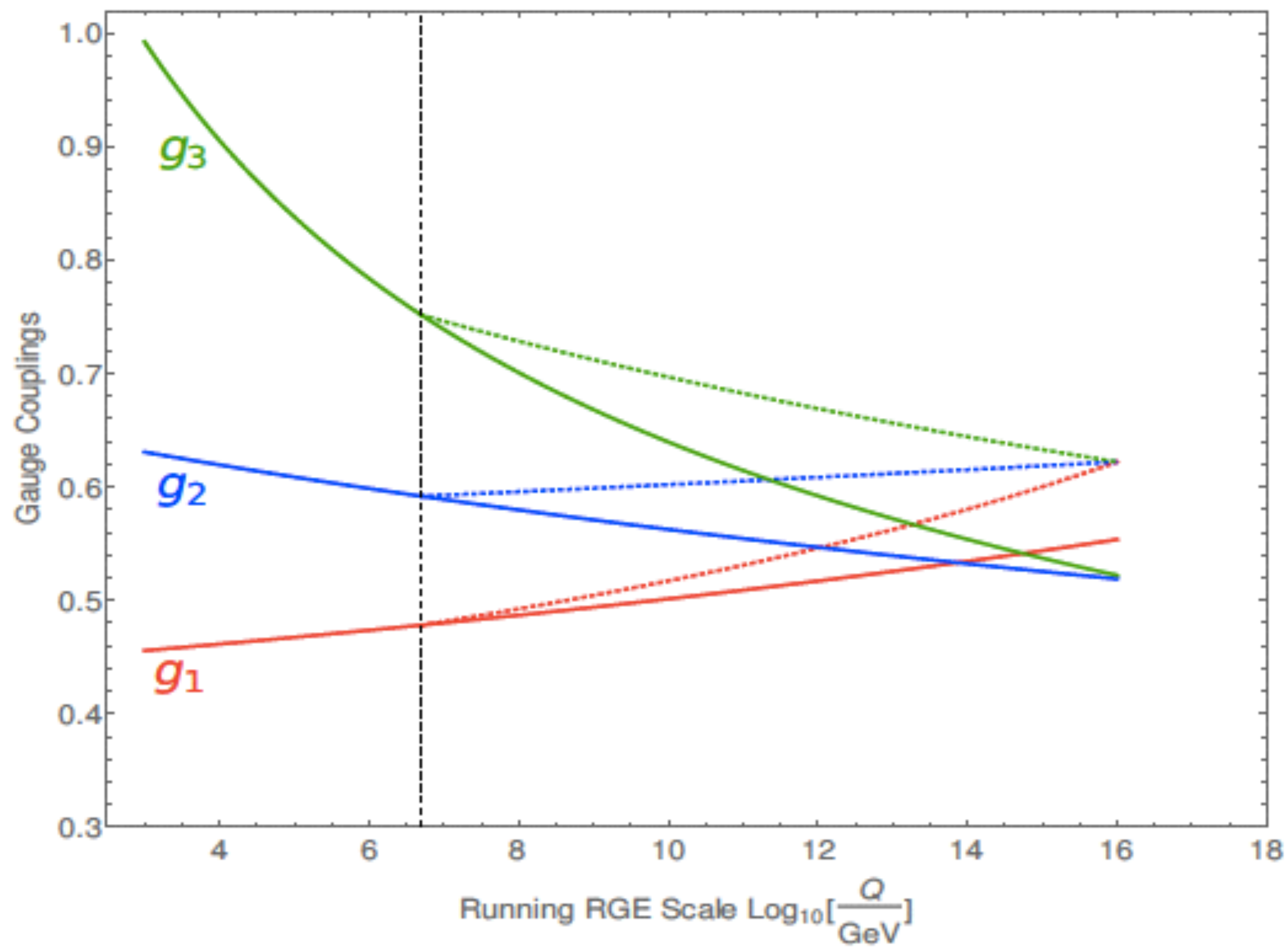
SUSY breaking is by the Polonyi field

$\tan\beta$	Masses in PeV			RPV couplings	
	m_0	$M_{1/2}$	A_0	λ''_{121}	λ_{121}
1.8	10	8	-15.42	3.56×10^{-22}	1.58×10^{-28}

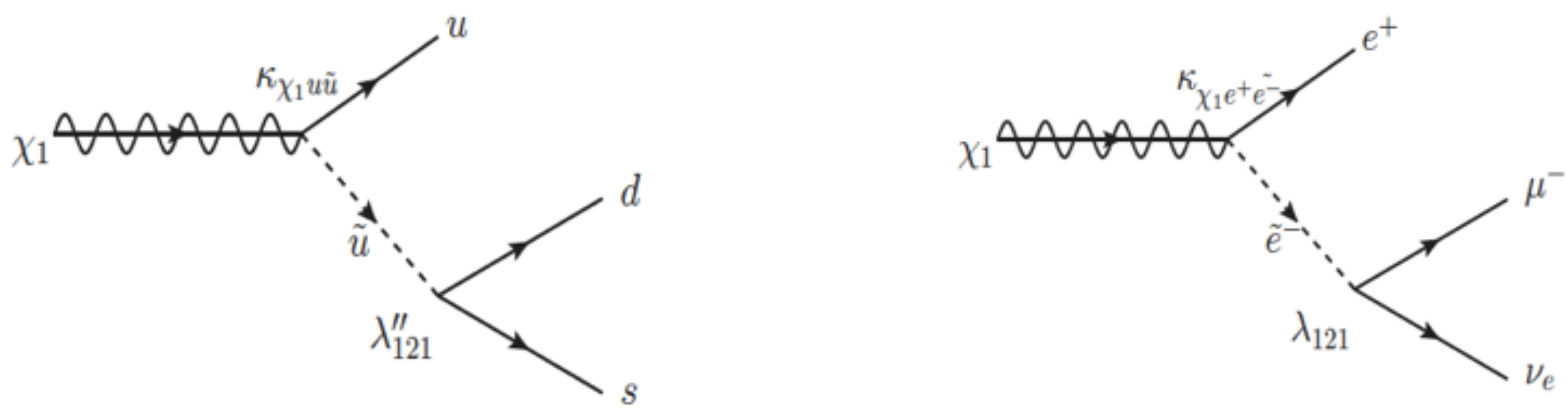
Sparticle spectrum

SUSY Fields		Masses in PeV
$\tilde{d}_{iL,R}$	$(i = d, s, b)$	$M_{\tilde{d}_{i,L,R}} \approx (11.22, \ \ 12.53)_d \quad (12.53, \ \ 12.53)_s \quad (13.05, \ \ 13.05)_b$
$\tilde{u}_{iL,R}$	$(i = u, c, t)$	$M_{\tilde{u}_{iL,R}} \approx (8.45, \ \ 11.22)_u \quad (12.61, \ \ 12.61)_c \quad (13.05, \ \ 13.05)_t$
$\tilde{e}_{iL,R}$	$(i = e, \mu, \tau)$	$M_{\tilde{e}_{iL,R}} \approx 10.32, \ \ 10.32)_e \quad (10.32, \ \ 10.78)_\mu \quad (10.78, \ \ 10.78)_\tau$
$\tilde{\nu}_i$	$(i = e, \mu, \tau)$	$M_{\tilde{\nu}_i} \approx (10.78)_e \quad (10.78)_\mu \quad (10.78)_\tau$
h		$M_h \approx 124$ [GeV]
H		$M_h \approx 17.53$
A^0		$M_{A^0} \approx 17.53$
H^-		$M_{H^-} \approx 17.53$
$\tilde{g}_i$	$(i = 1 ... 8)$	$M_{\tilde{g}_i} \approx 11.44$
$\tilde{\chi}^0$	$(i = 1 ... 4)$	$M_{\tilde{\chi}_1}(DM) \approx 5.00 \quad M_{\tilde{\chi}_2} \approx 7.37 \quad M_{\tilde{\chi}_3} \approx 10.21 \quad M_{\tilde{\chi}_2} \approx 10.21$
$\tilde{\chi}^-$		$M_{\tilde{\chi}_1^-} \approx 7.37 \quad M_{\tilde{\chi}_2^-} \approx 10.21$

Gauge coupling unification from PeV particles

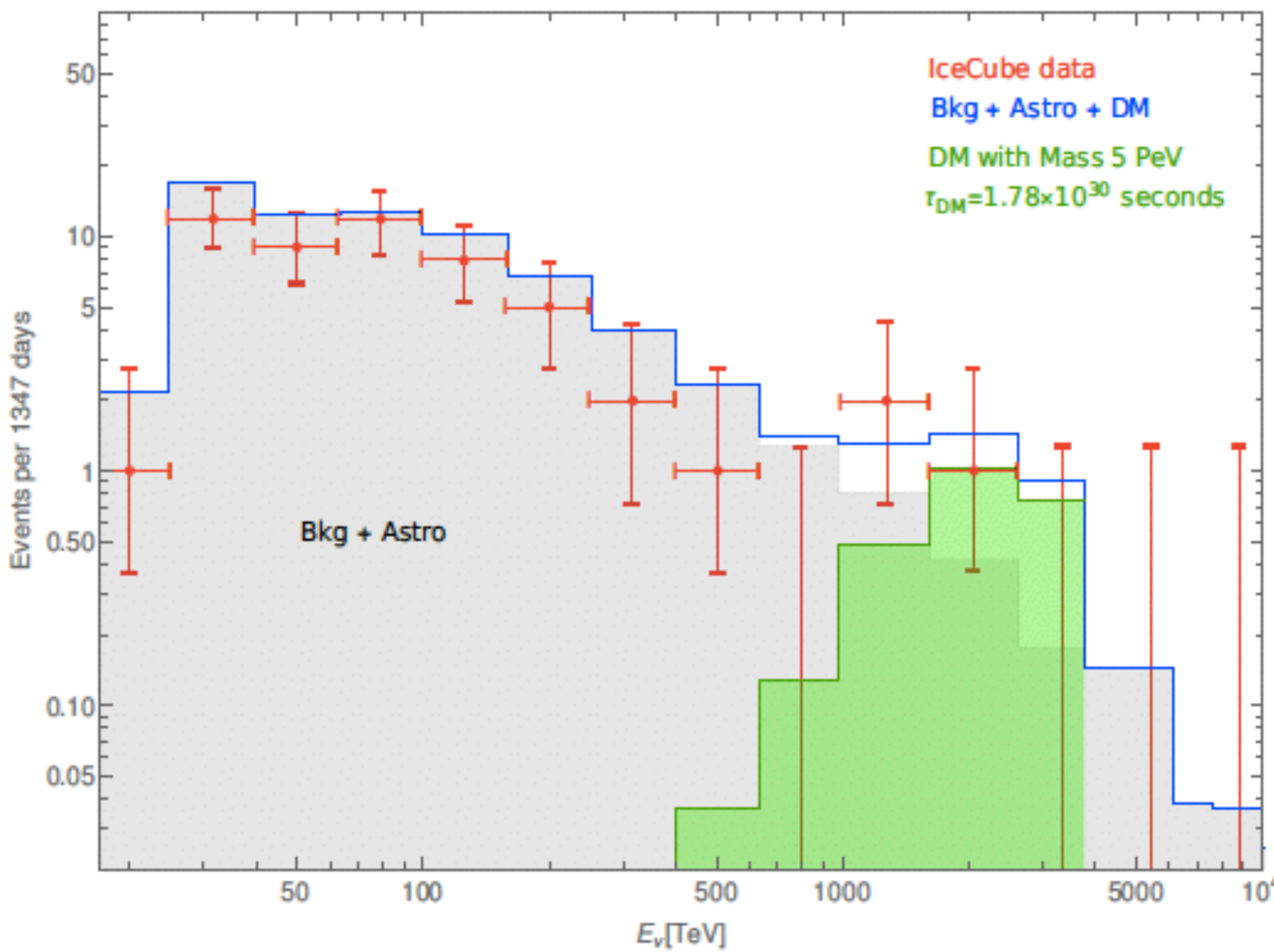


$$W_{int} = \lambda_{ijk} L_i L_j e^c_{Rk} + \lambda'_{ijk} L_i Q_j d^c_{Rk} + \frac{1}{2}\lambda''_{ijk} u^c_{Ri} d^c_{Rj} d^c_{Rk}$$



$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right) - n \sum_i \frac{1}{\tau_{i,DM}}.$$

5 PeV DM decay gives IceCube neutrino events



Thank You