PQ-sym for neutrino mass
and
cosmic neutrino flux

[WIP, arXiv:1402.6523]

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Neutrino mass

In SM

- Neutrino is massless

$$\mathcal{L}^{\rm SM}_{\rm Yukawa} = -Y_u \overline{Q_L} \tilde{\Phi}^* u_R - Y_d \overline{Q_L} \Phi d_R - Y_e \overline{\ell_L} \Phi e_R - Y_\nu \overline{\ell_L} \tilde{\Phi}^* \nu_R$$

- but observation told us

$$|\Delta m^2_{21}| \simeq 7.5 \times 10^{-5}\,{\rm eV}^2\,, \quad |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,{\rm eV}^2$$

(solar oscillation) (atmospheric oscillation)

$$\sum m_\nu = 0.320 \pm 0.081\,{\rm eV}$$

[R. A. Battye and A. Moss, Phys. Rev. Lett. 112, 051303 (2014)]

- Yukawa couplings are hierarchical

$$\mathcal{L}_{\text{Yukawa}}^{\text{SM}} = -Y_u \overline{Q_L} \tilde{\Phi}^* u_R - Y_d \overline{Q_L} \Phi d_R - Y_e \overline{\ell_L} \Phi e_R - Y_\nu \overline{\ell_L} \tilde{\Phi}^* \nu_R$$

$$Y_u^t = \frac{m_t}{\langle \Phi_0 \rangle} \sim 1$$

$$Y_d^b = \frac{m_b}{\langle \Phi_0 \rangle} \sim 2 \times 10^{-2}$$

$$Y_e^\tau = \frac{m_\tau}{\langle \Phi_0 \rangle} \sim 10^{-2}$$

$$Y_\nu^{\nu_\tau} = \frac{\nu_\tau}{\langle \Phi_0 \rangle} \sim 10^{-12}$$

Q1. Is this natural?

Q2. How can we obtain it in a natural way?

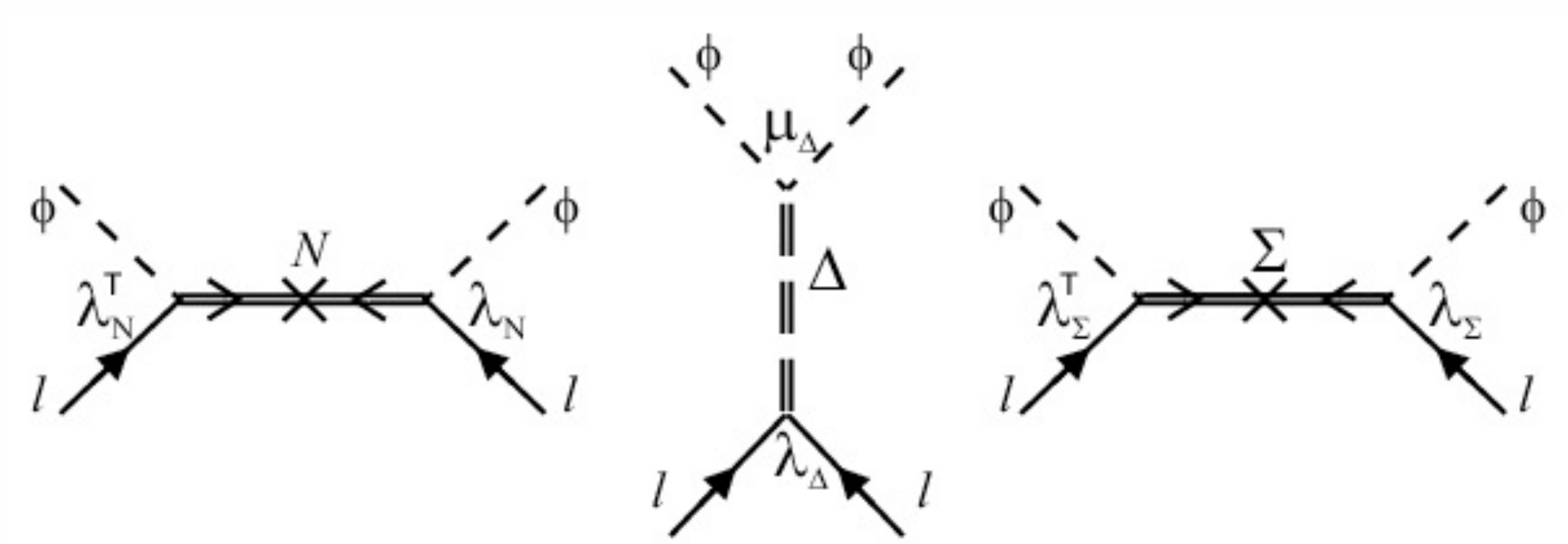
Seesaw mechanisms

- Basic idea (A large Majorana mass introduced)

For $M_{\rm M} \gg m_{\rm D}$,

$$\mathbb{M} = \begin{pmatrix} 0 & m_{\rm D} \\ m_{\rm D} & M_{\rm M} \end{pmatrix} \Rightarrow m_\nu = \begin{cases} m_{\rm D}^2/M_{\rm M} \\ M_{\rm M} \end{cases}$$

- Realizations



(I) singlet RH-neutrino

(II) triplet scalar

(III) triplet fermion

- ☞ Have you ever seen a Majorana particle in nature?
- ☞ A small Yukawa coupling may have a dynamical origin.

The Model

[WIP, arXiv:1402.6523]

A SUSY extension of SM

- Super-potential

$$W = W_{\mathrm{MSSM}-\mu} + \lambda_\mu \frac{X^2}{M_*} H_u H_d + \lambda_\nu \left(\frac{X}{M_*}\right)^2 L H_u N^c + \lambda_\Psi X \Psi \bar{\Psi}$$

- Organizing symmetries

$$U(1)_{\mathrm{PQ}} \times U(1)_L$$

	X	$H_u H_d$	$L H_u$	N	$\Psi\bar{\Psi}$
q_{PQ}	1	-2	-2	0	-1
q_L	0	0	1	1	0

- Generating mu-term and small Yukawa

$$\mu = \lambda_\mu \frac{X_0^2}{M_*} \quad , \quad \lambda_{\nu,\mathrm{eff}} = \lambda_\nu \left(\frac{X_0}{M_*} \right)^2$$

$$M_* \sim M_{\mathrm{GUT}},\ X_0 \sim 10^{10-11}\mathrm{GeV} \Rightarrow \lambda_\nu \sim \mathcal{O}(10^{-2} - 1)$$

☞No need for extremely small Yukawa coupling.
☞No need for ad hoc Majorana mass term.

Cosmology

- Dark matters

LSP: axino
NLSP: RH-sneutrino

Production:
1. non-thermally via particle decay
2. coherent oscillation (for scalar particles)

☞Low T_R is necessary to avoid axino over-production

- Decay rates of LOSP & RH-sneutrino

$$\Gamma_{\chi\to\tilde{a}+\mathrm{SM}} = \frac{\gamma_\chi}{16\pi}\frac{m_\chi^3}{X_0^2}$$

$$\simeq 2\times 10^{-15}\,\mathrm{GeV}\,\gamma_\chi\left(\frac{m_\chi}{1\,\mathrm{TeV}}\right)^2\left(\frac{10^{11}\,\mathrm{GeV}}{X_0}\right)^2$$

$$\Gamma_{\chi\to\tilde{N}+\nu} \simeq \frac{1}{16\pi}|\lambda_{\nu,\mathrm{eff}}\Theta^\chi_{\tilde{H}_u}|^2\left(1-\frac{m^2_{\tilde{N}}}{m^2_\chi}\right)^2 m_\chi$$

$$\simeq 8.0\times 10^{-25}\,\mathrm{GeV}\left(\frac{\lambda_{\nu,\mathrm{eff}}}{2\times 10^{-13}}\right)^2\left(\Theta^\chi_{\tilde{H}_u}\right)^2\left(1-\frac{m^2_{\tilde{N}}}{m^2_\chi}\right)^2\left(\frac{m_\chi}{1\,\mathrm{TeV}}\right)$$

$$\Gamma_{\tilde{N}\to\tilde{a}+\nu} \simeq \frac{1}{2\pi}|\lambda_{\nu,\mathrm{eff}}|^2\left(\frac{v\sin\beta}{X_0}\right)^2\left(1-\frac{m^2_{\tilde{a}}}{m^2_{\tilde{N}}}\right)^2 m_{\tilde{N}}$$

$$\simeq 2\sin^2\beta\times 10^{-41}\,\mathrm{GeV}\left(\frac{10^{11}\,\mathrm{GeV}}{X_0}\right)^2\left(1-\frac{m^2_{\tilde{a}}}{m^2_{\tilde{N}}}\right)^2\left(\frac{m_{\tilde{N}}}{1\,\mathrm{TeV}}\right)$$

- Abundances of LSP and NLSP before decay

Axinos from flaton decay:

Sym-ph➡ $$\Omega_{\tilde a} \simeq 0.36 \frac{\Gamma_X^{1/2}}{\Gamma_{X\to \mathrm{SM}}^{1/2}} \left(\frac{10}{g_*^{1/2}(T_\mathrm{d})}\right) \left(\frac{\alpha_{\tilde a}}{0.1}\right)^2 \left(\frac{m_{\tilde a}}{1\,\mathrm{GeV}}\right)^3 \left(\frac{10\,\mathrm{GeV}}{T_\mathrm{d}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{X_0}\right)^2$$

Broken-ph➡ $$\Omega_{\tilde a} = 3.2\times 10^{-13} \left(\frac{\alpha_{\tilde a}}{0.1}\right)^2 \left(\frac{m_{\tilde a}}{1\,\mathrm{GeV}}\right)^3 \left(\frac{500\,\mathrm{GeV}}{m_X}\right)^2 \left(\frac{T_\mathrm{R}}{m_\mathrm{PQ}}\right) \left(\frac{X_0}{10^{11}\,\mathrm{GeV}}\right)^2 \times \left[1 + 16\left(1 - \frac{|B|^2}{m_A^2}\right)^2 \left(\frac{\mu}{m_\mathrm{PQ}}\right)^4 f(m_h^2/m_\mathrm{PQ}^2)\right]^{-1}$$

Axinos from neutralino decay:

Sym-ph➡ $$\Omega_{\tilde a} \sim 0.19\gamma_\chi \frac{\Gamma_\mathrm{SM}^{1/2}}{\Gamma_X^{1/2}} \left(\frac{10^3 g_*(T_\mathrm{d})^{3/2}}{g_*(T_\chi)^3}\right) \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right) \left(\frac{m_{\tilde a}}{1\,\mathrm{GeV}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{X_0}\right)^2 \left(\frac{T_\mathrm{d}}{m_\chi/25}\right)^7$$

Broken-ph➡ $$\Omega_{\tilde a} \simeq 0.265\gamma_\chi \left(\frac{m_{\tilde a}}{1\,\mathrm{GeV}}\right) \left(\frac{m_\chi}{500\,\mathrm{GeV}}\right) \left(\frac{10^{11}\,\mathrm{GeV}}{X_0}\right)^2 \left(\frac{x_\mathrm{R}}{15}\right)^{5/2} \mathrm{Exp}\left[-x_\mathrm{R} + 15\right]$$

RH-sneutrinos from coherent osc.:

Broken-ph ➡ $$Y_{\tilde{N}} \sim \left(\frac{\tilde{N}_0}{M_{\rm Pl}}\right)^2 \frac{T_{\rm R}}{m_{\tilde{N}}}$$

Sym-ph ➡ $$Y_{\tilde{N}} \sim \frac{\pi^2 \, g_{*S}(T_c)}{30} \frac{T_c^3 T_d}{V_0} \left(\frac{\tilde{N}_0}{M_{\rm Pl}}\right)^2 \frac{T_{\rm R}}{m_{\tilde{N}}}$$

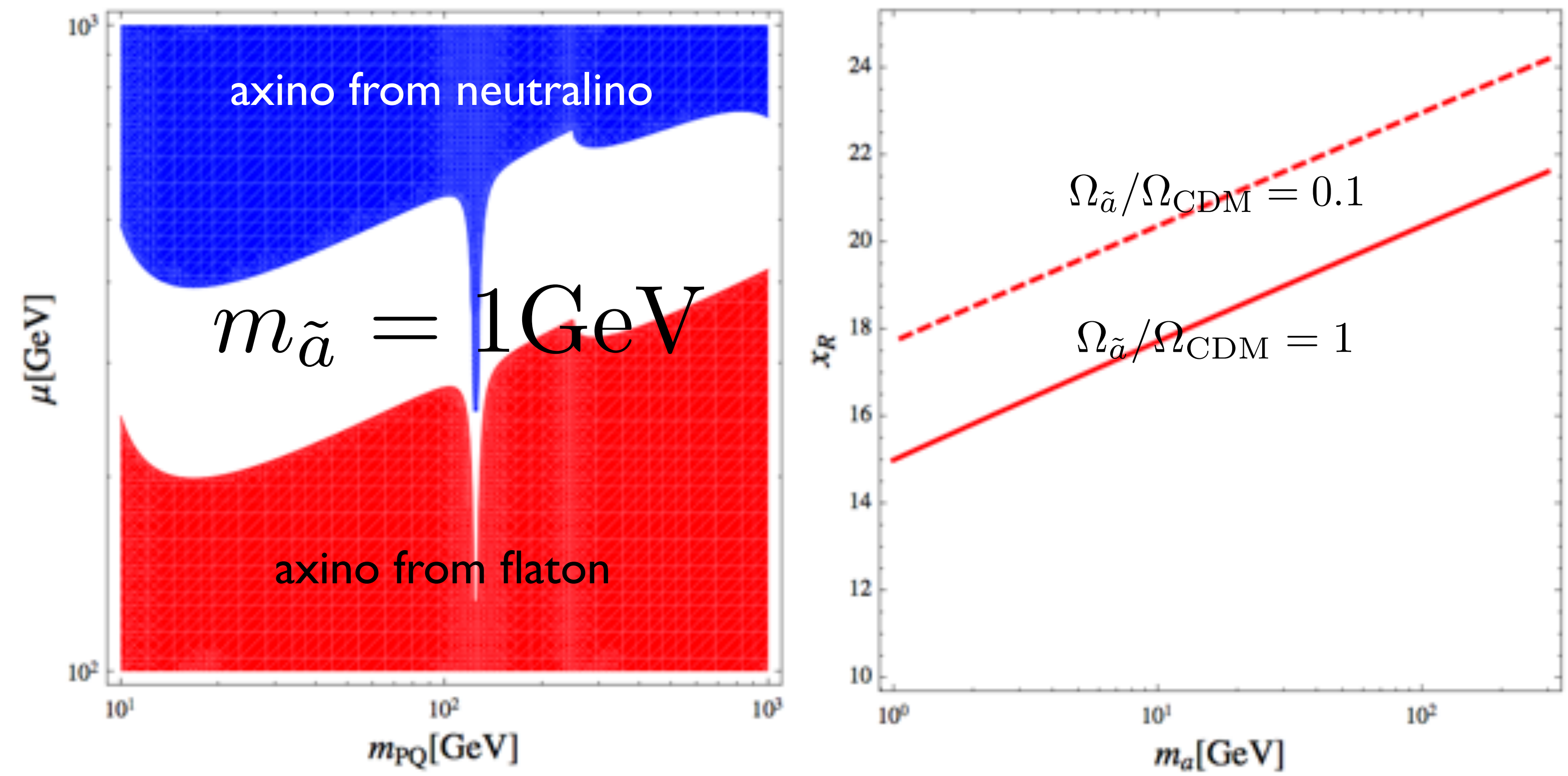
RH-sneutrinos from neutralino decay:

$$\frac{\Gamma_{\chi\to\tilde{N}+\nu}}{\Gamma_{\chi\to\tilde{a}+{\rm SM}}} = \frac{|\lambda_{\nu,{\rm eff}}\Theta^{\chi}_{\tilde{H}_u}|^2}{\gamma_\chi}\left(\frac{X_0}{m_\chi}\right)^2\left(1-\frac{m^2_{\tilde{N}}}{m^2_\chi}\right)^2$$
$$= 5.6\times10^{-9}\frac{|\Theta^{\chi}_{\tilde{H}_u}|^2}{\gamma_\chi}\left(\frac{\lambda_{\nu,{\rm eff}}}{3\times10^{-13}}\right)^2$$
$$\times\left(\frac{X_0}{2\times10^{11}\,{\rm GeV}}\right)^2\left(\frac{800\,{\rm GeV}}{m_\chi}\right)^2\left(1-\frac{m^2_{\tilde{N}}}{m^2_\chi}\right)^2$$

Axinos:

Sym. -phase

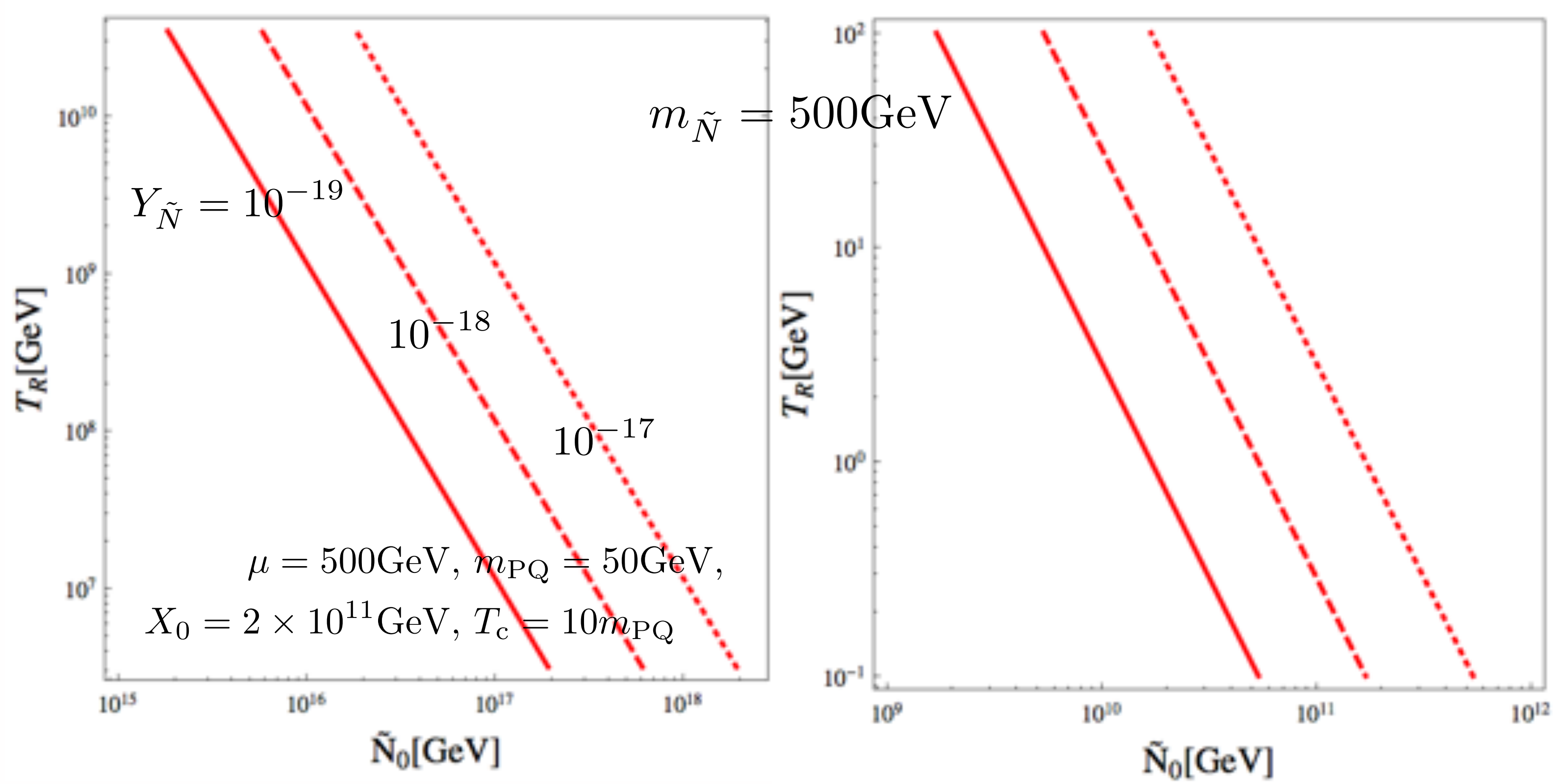
Broken-phase



RH-sneutrinos:

Sym. -phase

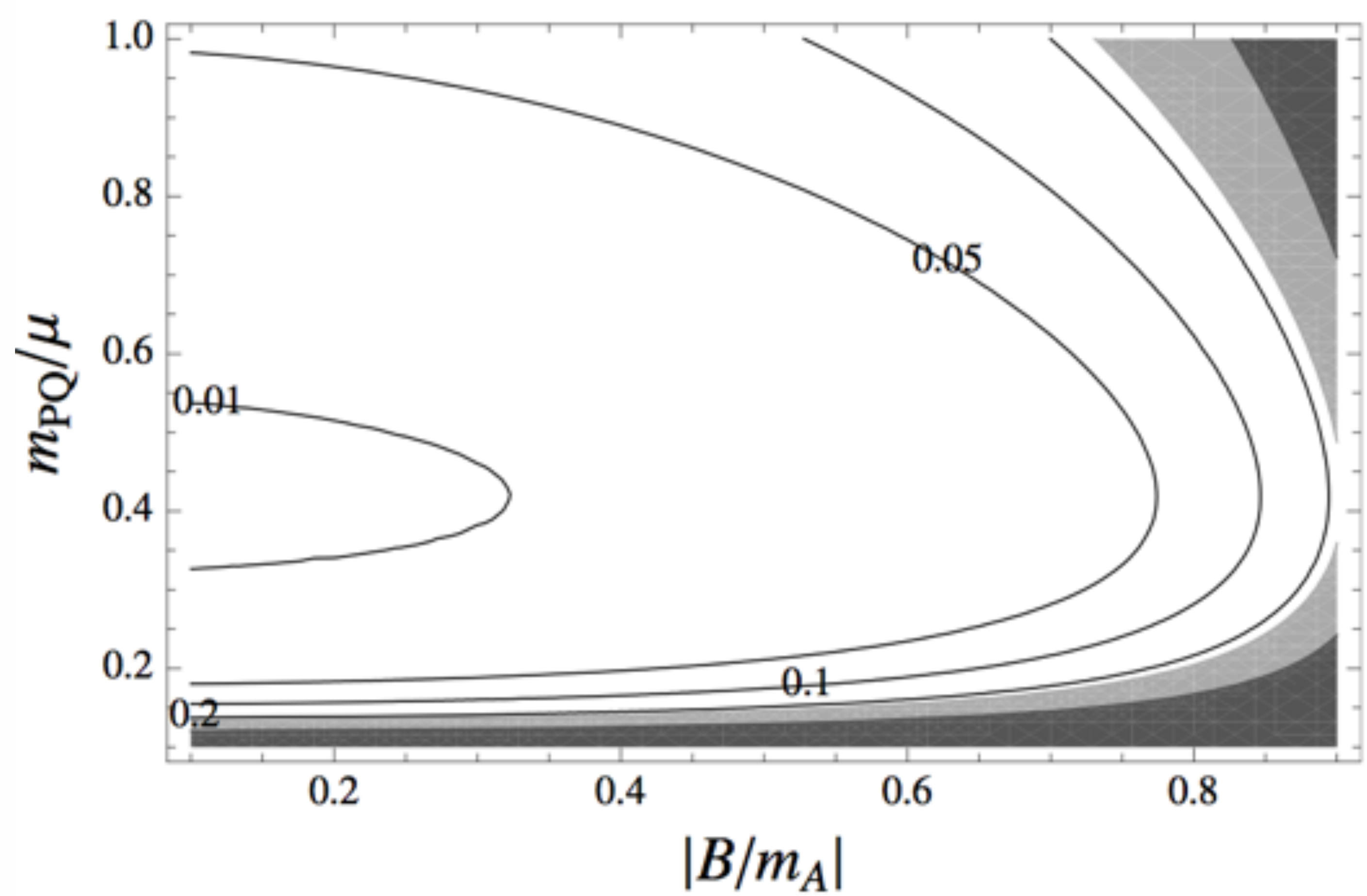
Broken-phase



Dark radiation

- Relativistic axion in the decay of saxion

$$\begin{aligned}\Delta N_{\nu,\text{eff}} &= \frac{\rho_a}{\rho_\nu} = \left(\frac{11}{4}\right)^{4/3}\left(\frac{g_*(T\simeq 1\,\text{MeV})}{2}\right)\frac{\rho_a}{\rho_\text{r}}\bigg|_{t_\text{BBN}} \\ &\simeq \left(\frac{11}{4}\right)^{4/3}\left(\frac{g_*(T\simeq 1\,\text{MeV})}{2}\right)\left(\frac{g_{*S}(T\simeq 1\,\text{MeV})}{g_{*S}(T_\text{d})}\right)^{1/3}\frac{\Gamma_{X\to aa}}{\Gamma_{X\to \text{SM}}} \\ &\simeq \frac{10.8}{16}\left(1-\frac{|B|^2}{m_A^2}\right)^{-2}\left(\frac{m_\text{PQ}}{\mu}\right)^4 f^{-1}(m_h^2/m_\text{PQ}^2)\end{aligned}$$

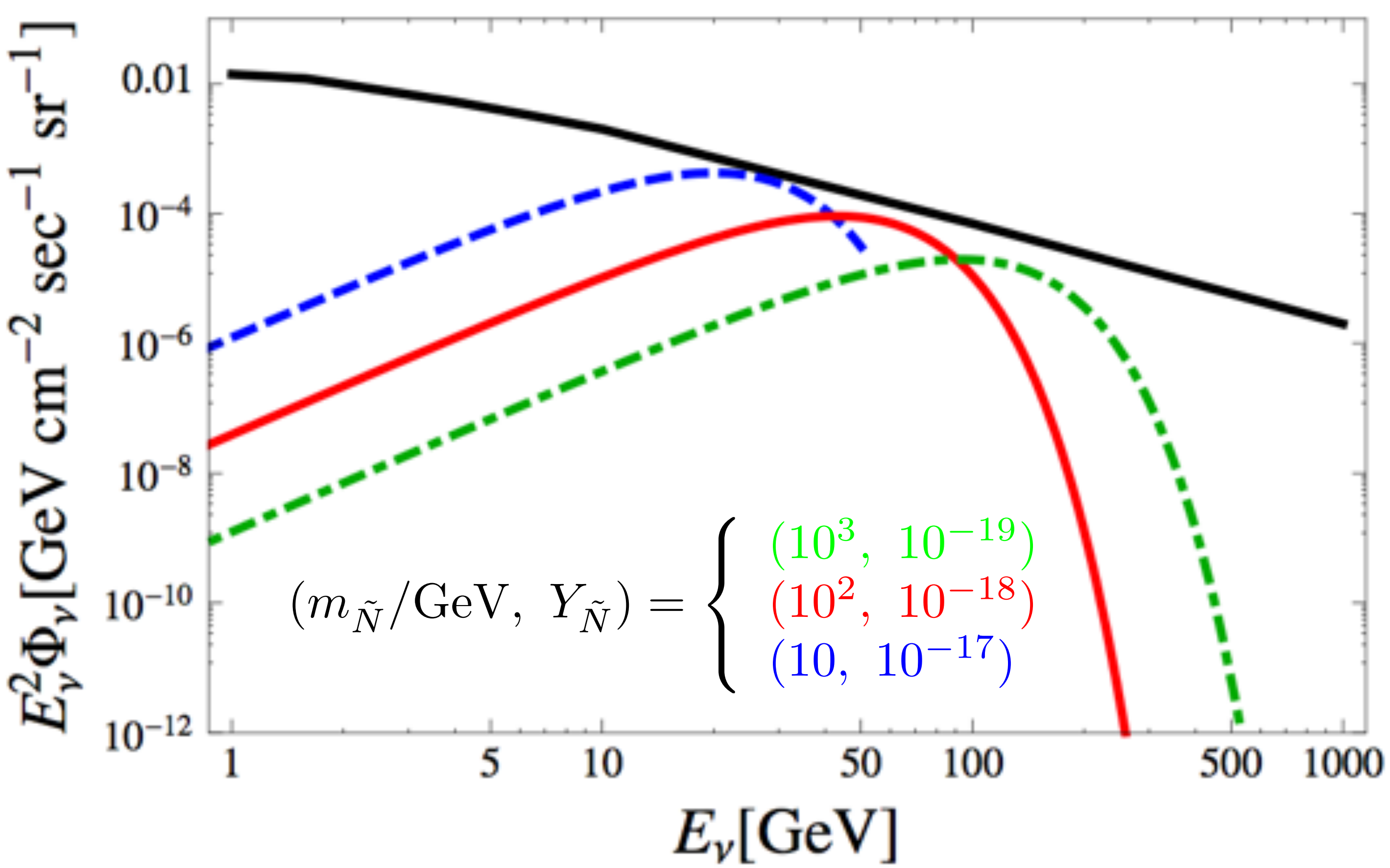


Cosmic neutrino flux

- Expected neutrino flux

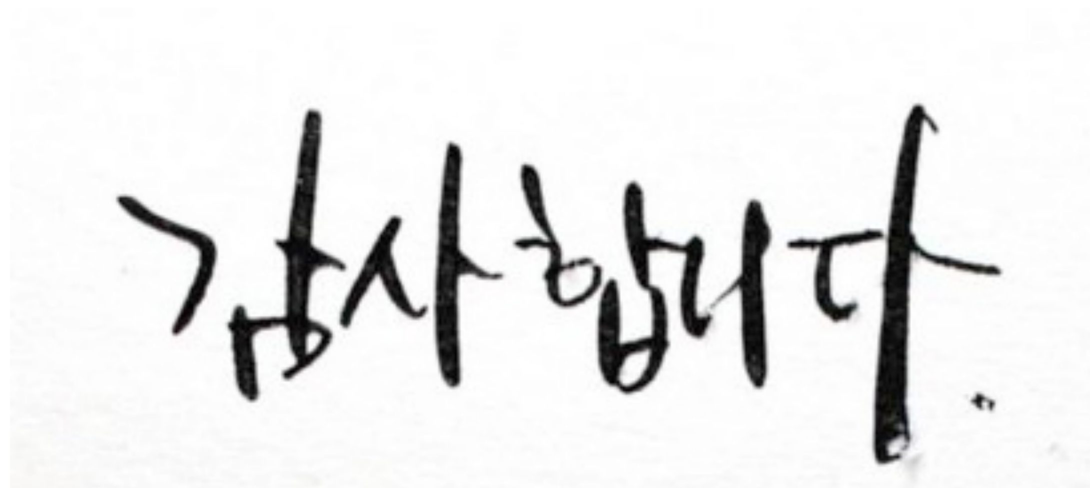
$$\frac{dN_\nu}{dE} = \delta(E - E_{\rm ini}), \quad E_{\rm ini} = \frac{m_{\tilde{N}}}{2}\left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{N}}^2}\right)$$

$$\Phi_\nu(E) = \frac{1}{4\pi}\frac{Y_{\tilde{N}} s_0}{\tau_{\tilde{N}} E}\left[\frac{e^{-t/\tau_{\tilde{N}}} D_\nu(E, z(t))}{H(t)}\right]_{1+z(t)=E_{\rm ini}/E}$$



Summary of Part II

- Mu-term and small Dirac neutrino mass term can be obtained simultaneously via dynamic symmetry breaking of $U(1)_{PQ}$.
- Right amount of axino (+ axion) can be obtained for low T_d or T_R
- Observable cosmic neutrino flux exists for energy around 10-100 GeV.



Thank you!