AFFLECK-DINE LEPTOGENESIS WITH VARYING PQ SCALE

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INTRODUCTION

- ***Baryogenesis via Leptogenesis***

  - Due to (B-L)-conserving and (B+L)-violating process makes

    Lepton asymmetry $\longrightarrow$ Baryon asymmetry

  - Neutrino physics can show its footprints.

- ***Affleck-Dine mechanism***

  - scalar field dynamics in SUSY: *CPV in SUSY breaking parameters*

  - Along *LHu* direction: lepton number generation

  $\longrightarrow$ light neutrino mass required $<10^{-9}$ eV; neutrinoless double beta decay

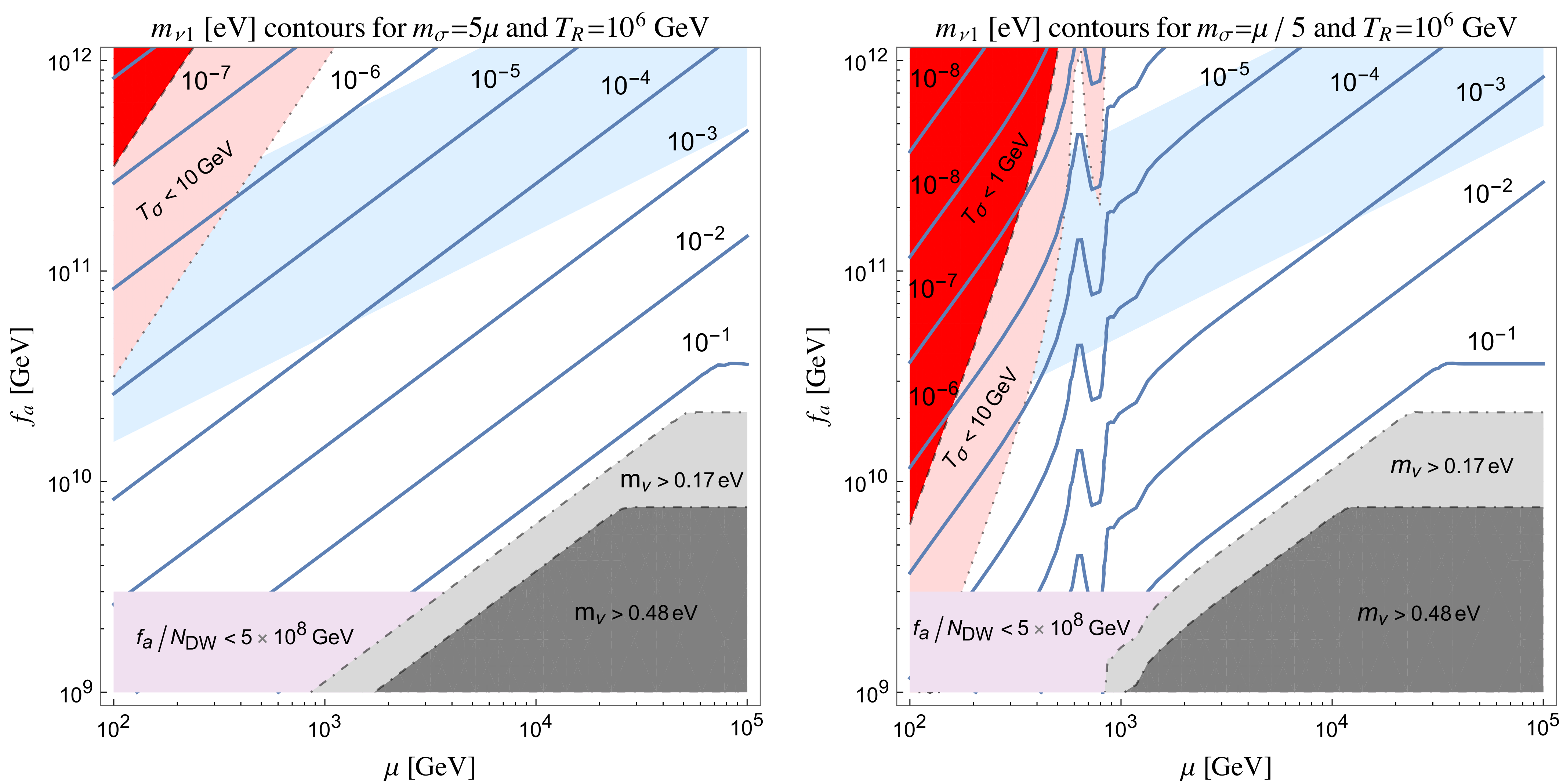
- ***Varying PQ scale***

  - PQ scale $\sim M_p$ during leptogenesis but $f_a \sim 10^{9\text{-}12}$ GeV afterwards

  $\longrightarrow$ neutrino mass $\sim 10^{-4}$ eV; suppress axion isocurvature

INTRODUCTION

- ***Dine-Fischler-Srednicki-Zhitnitsky model***
  - SUSY DFSZ model provides strong CP solution, mu-term, also RHN mass
  - *Dilution from saxion decay determines final lepton(baryon) asymmetry*
  - *suppress unwanted lepton number violation during saxion oscillation*



OUTLINE

1. Leptogenesis
2. AD mechanism along LHu direction
3. AD leptogenesis in DFSZ model with varying PQ scale
4. Summary

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BARYON ASYMMETRY

Baryon Asymmetry of the Universe:

observed: $\frac{n_B}{s} \simeq 10^{-10}$

cf) if universe were symmetric $\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \simeq 10^{-18}$

- Inflation dilutes all pre-existing particles.
- We need a source of *B* asym. *after inflation*.

Sakharov's conditions:

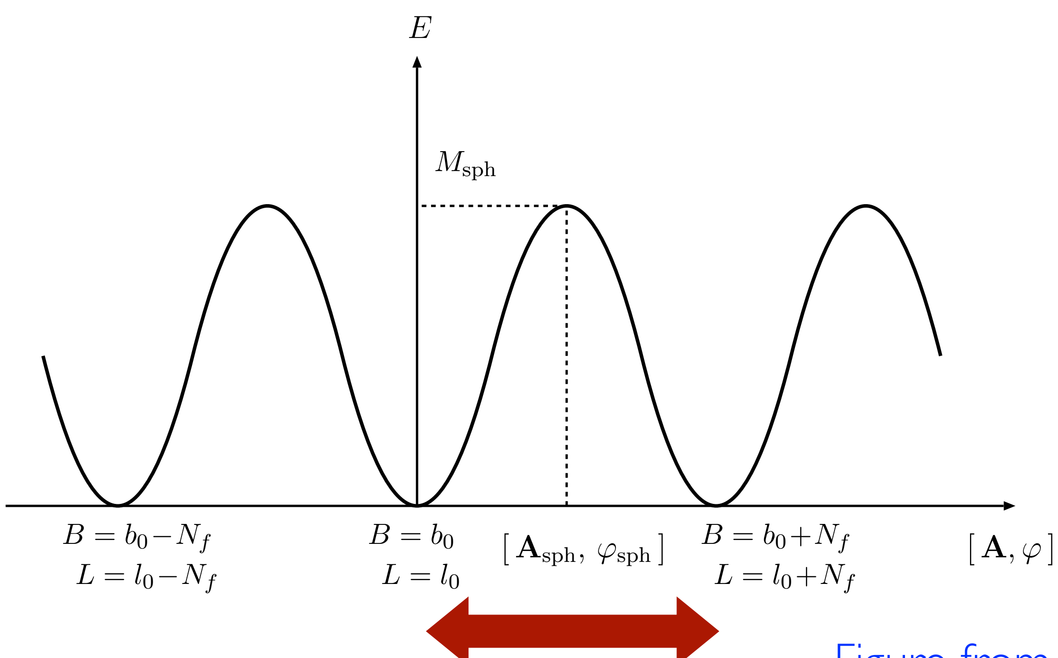
- *B* violation
- C & CP violation
- departure from thermal equilibrium

B & L VIOLATION

- In the SM, baryon & lepton number are (accidental) symmetry at the tree-level.
- Due to chiral nature of leptons & quarks, B & L have anomalies

$$\begin{aligned}\partial^\mu J^B_\mu &= \partial^\mu J^L_\mu \\ &= \frac{N_f}{32\pi^2}\left(-g^2 W^I_{\mu\nu}\widetilde{W}^{I\mu\nu} + g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)\end{aligned}$$

- At quantum level, (B-L) is conserved but (B+L) is violated.



$$\begin{aligned}\Gamma &\sim e^{-S_{\rm inst}} = e^{-\frac{4\pi}{\alpha}} \\ &= \mathcal{O}\left(10^{-165}\right)\ .\end{aligned}$$

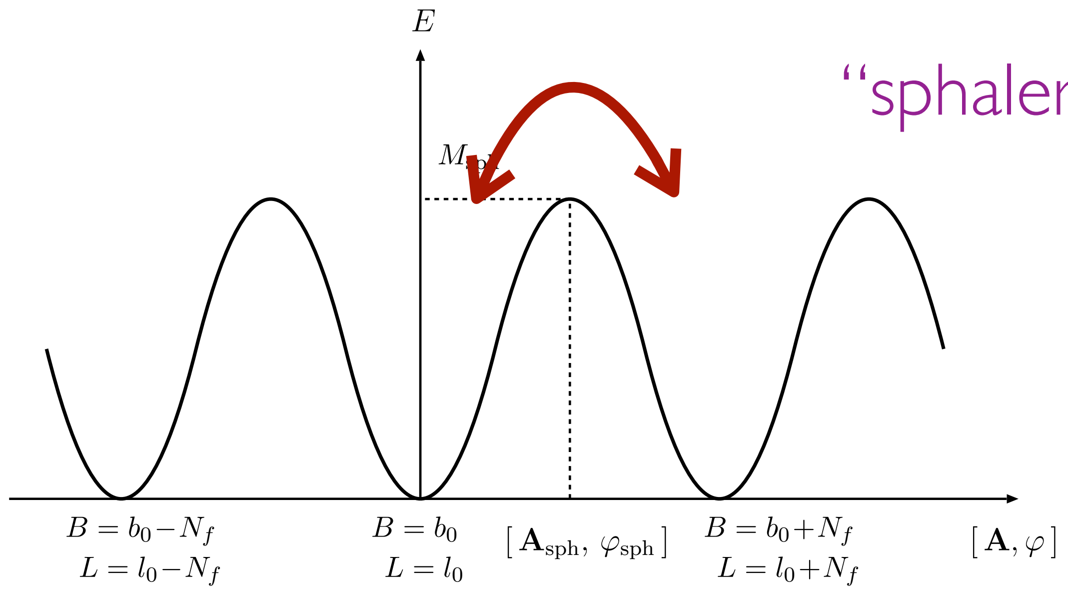
Figure from hep-ph/0212305

(B+L) violating vacuum transition

B & L VIOLATION

- At high temperature,

(B+L) violating transition
via thermal fluctuation



$$\Gamma_{B+L}/V \sim \alpha^5 \ln \alpha^{-1} T^4.$$

Figure from hep-ph/0212305

- (B+L) violating interaction is in thermal equilibrium for

$$100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$$

- L number can be transferred into B number and vice versa.

LEPTOGENESIS

- Number for asymmetry

$$n_i - \overline{n}_i = \frac{gT^3}{6} \begin{cases} \beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) , & \text{fermions} , \\ 2\beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) , & \text{bosons} . \end{cases}$$

- chemical potentials in equilibrium (SM)

$$\mu_{qi} - \mu_H - \mu_{dj} = 0 , \quad \mu_{qi} + \mu_H - \mu_{uj} = 0 , \quad \mu_{li} - \mu_H - \mu_{ej} = 0$$ (Yukawa)

$$\sum_i \left(\mu_{qi} + 2\mu_{ui} - \mu_{di} - \mu_{li} - \mu_{ei} + \frac{2}{N_f}\mu_H \right) = 0$$ (ΣY=0)

$$\sum_i (3\mu_{qi} + \mu_{li}) = 0$$ (SU(2) inst.)

$$\sum_i (2\mu_{qi} - \mu_{ui} - \mu_{di}) = 0$$ (QCD inst.)

- equations can be expressed by

$$\begin{aligned} \mu_e &= \frac{2N_f + 3}{6N_f + 3}\mu_l , \quad \mu_d = -\frac{6N_f + 1}{6N_f + 3}\mu_l , \quad \mu_u = \frac{2N_f - 1}{6N_f + 3}\mu_l , \\ \mu_q &= -\frac{1}{3}\mu_l , \quad \mu_H = \frac{4N_f}{6N_f + 3}\mu_l . \end{aligned}$$

LEPTOGENESIS

- B & L relations

$$B = \sum_i (2\mu_{qi} + \mu_{ui} + \mu_{di}) \ ,$$
$$L_i = 2\mu_{li} + \mu_{ei} \ , \quad L = \sum_i L_i$$

$$\boxed{\begin{aligned} &B = c_s(B-L); \quad L = (c_s - 1)(B-L) \\ &c_s = (8N_f + 4)/(22N_f + 13) \end{aligned}}$$

- *Non-zero B & L are generated if (B-L)≠0 in equilibrium*

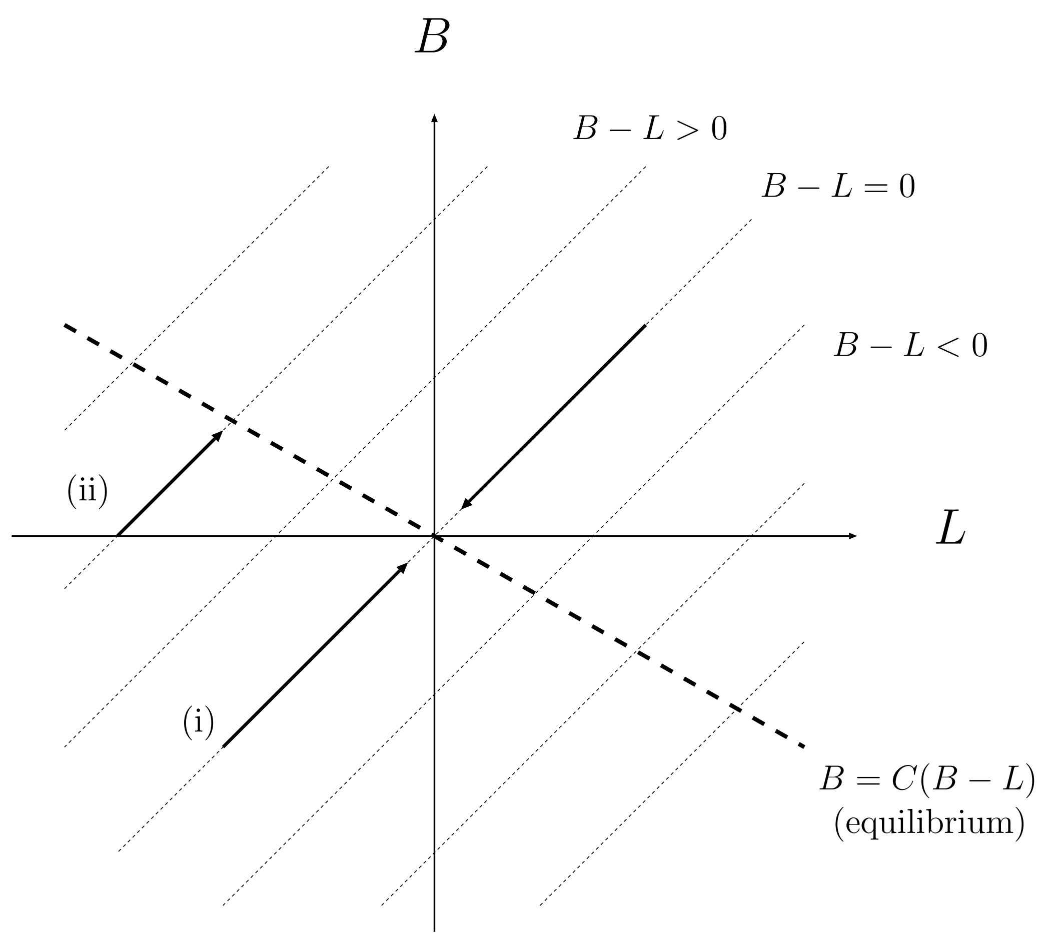


Figure from hep-ph/0212305

modified Sakharov 's condition

- B violation

↓

- (B-L) violation

Q: How do we generate (B-L)$\neq$0 in the early universe?

THERMAL LEPTO.

Fukugita, Yanagida; Luty; Campbell, Davidson, Olive; Buchmuller, Di Bari, Plumacher (02, 02)

Decay of thermally produced RHN:

If $T > m_N$, N is abundantly produced.

When $T < m_N$ (out-of-equilibrium decay),

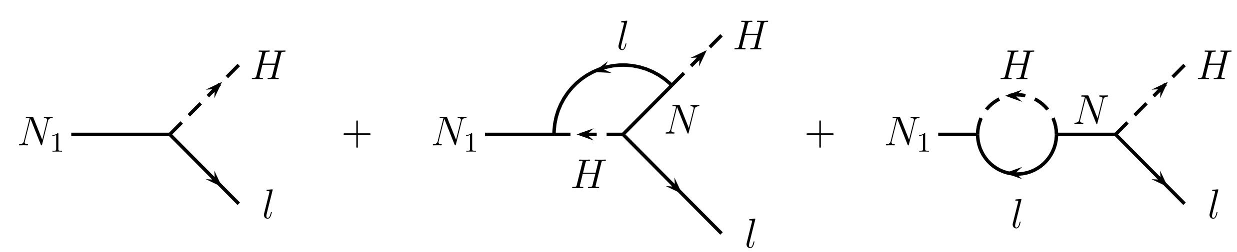
it decays through neutrino coupling.

$\cancel{L}$ $\cancel{CP}$

$$W \ni \frac{1}{2} M_i N_i N_i + h_{i\alpha} N_i L_\alpha H_u$$

CPV in coupling produces asymmetry

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to L H_u) - \Gamma(N_1 \to \bar{L} \bar{H}_u)}{\Gamma_{N_1}}$$



$$\sim 2 \times 10^{-10} \left(\frac{M_1}{10^6 \ \mathrm{GeV}} \right) \left(\frac{m_{\nu_3}}{0.05 \ \mathrm{eV}} \right) \delta_{\rm eff}$$

washout factor

N in equilibrium; $n_N / s \sim 1/g_* \sim 1/200$ $\quad n_L = \kappa \epsilon_1 n_N$

m_{N_1} //

$$\frac{n_B}{s} \simeq 0.35 \frac{n_L}{s} \simeq 0.3 \times 10^{-10} \left(\frac{\kappa}{0.1} \right) \left(\frac{M_1}{10^9 \ \mathrm{GeV}} \right) \left(\frac{m_{\nu_3}}{0.05 \ \mathrm{eV}} \right) \delta_{\rm eff}$$

Buchmuller, Di Bari, Plumacher (05)

requires (naively) $T_R \gtrsim 1.5 \times 10^9 \ \mathrm{GeV}$ for enough N production

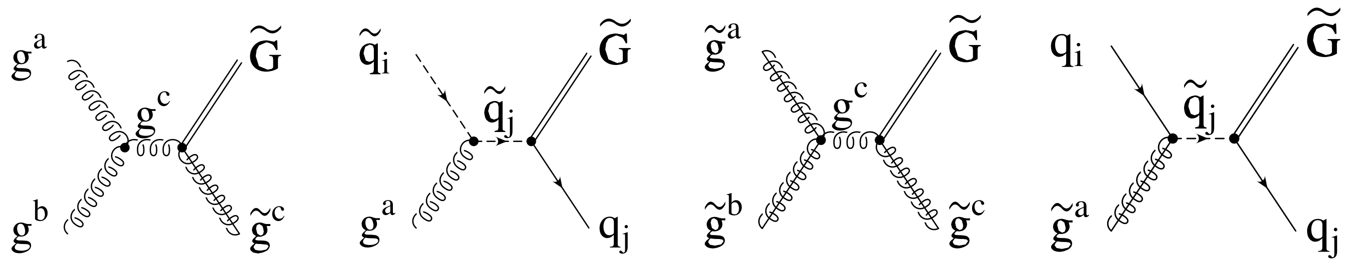
GRAVITINO PROBLEM

Gravitino problem:

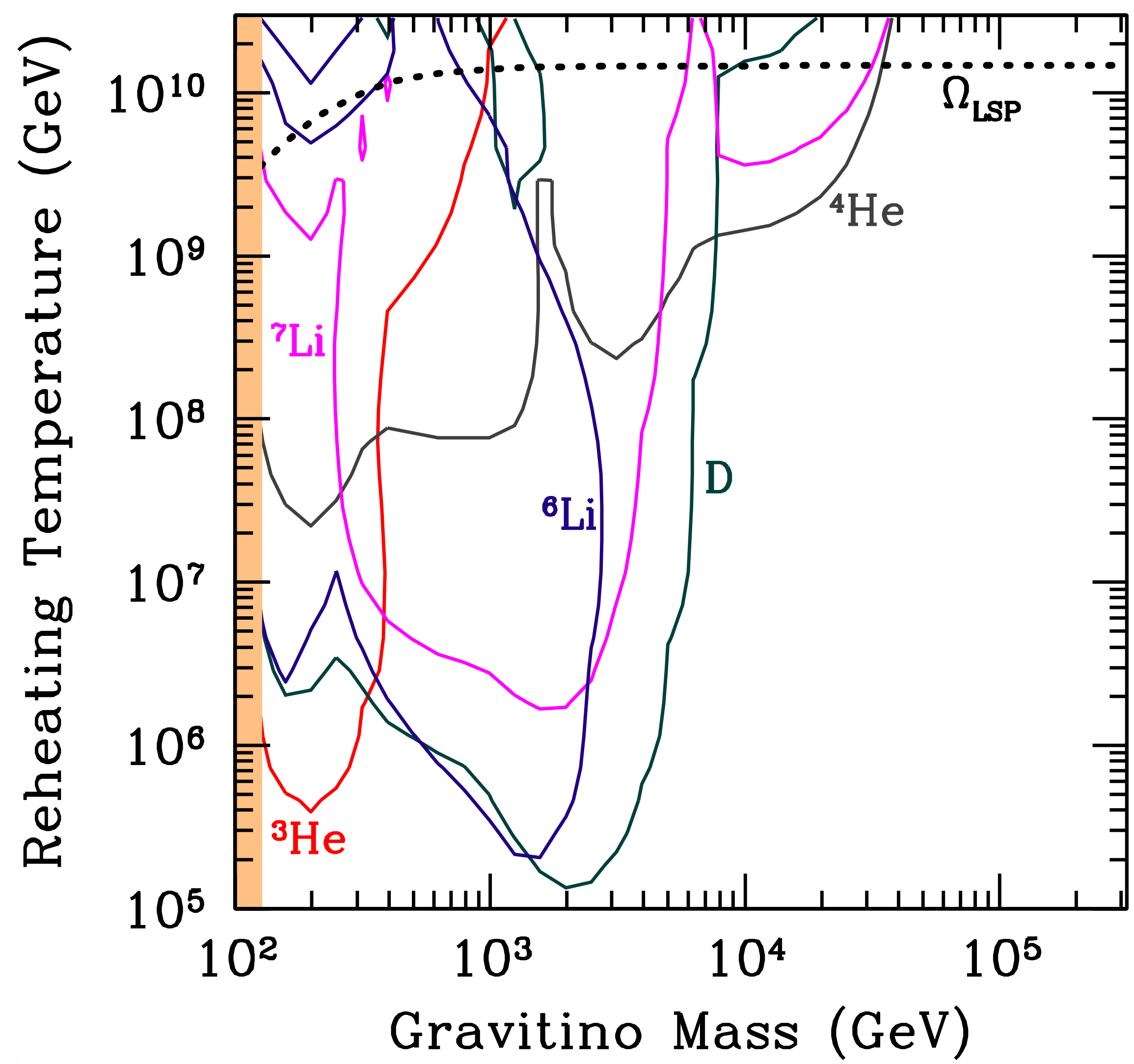
proportional to T_R

gravitinos are thermally produced $\Omega_{\widetilde{G}}^{\mathrm{TP}} h^2 = 0.21 \left(\frac{m_{\widetilde{g}}}{1\ \mathrm{TeV}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right) \left(\frac{T_R}{10^8\ \mathrm{GeV}}\right)$

Bolz, Brandenburg, Buchmüller; Strumia



decays into LSP with long life-time; either *producing too much DM* or *spoiling BBN*; upper bound for T_R



Kawasaki, Kohri, Moroi, Yotsuyanagi

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AFFLECK-DINE

For a review, Dine, Kusenko (03)

- Scalar field with B (or L) number,

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2|\phi|^2 \qquad j_B^\mu = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*)$$

- small quartic couplings

$$\mathcal{L}_I = \lambda|\phi|^4 + \epsilon\phi^3\phi^* + \delta\phi^4 + c.c.$$

$\cancel{B}$ $\cancel{CP}$ (for complex couplings)

- Eq. of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \xrightarrow{H \ll m} \phi = \frac{\phi_o}{(mt)^{3/4}} \sin(mt) \quad \text{(radiation)}$$
$$\frac{\phi_o}{(mt)} \sin(mt) \quad \text{(matter)}$$

If $\phi = \phi_o$ is real

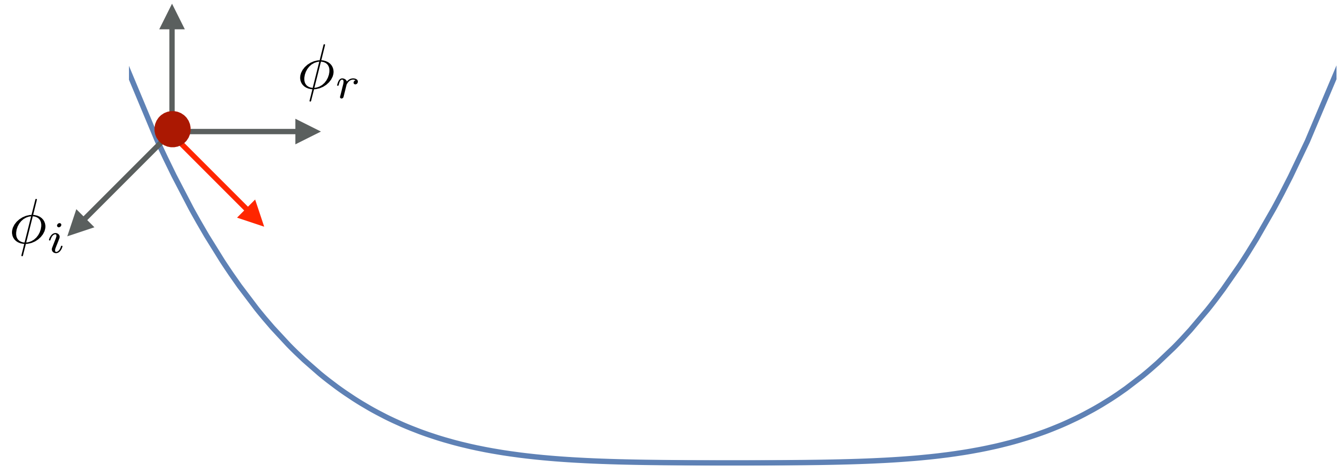
$$\ddot{\phi}_i + 3H\dot{\phi}_i + m^2\phi_i \approx \mathrm{Im}(\epsilon+\delta)\phi_r^3 \longrightarrow \phi_i = a_r \frac{\mathrm{Im}(\epsilon+\delta)\phi_o^3}{m^2(mt)^{3/4}} \sin(mt+\delta_r) \quad \text{(radiation)}$$
$$a_m \frac{\mathrm{Im}(\epsilon+\delta)\phi_o^3}{m^2(mt)} \sin(mt+\delta_m) \quad \text{(matter)}$$

- Baryon number

$$n_B = 2a_r \frac{\mathrm{Im}(\epsilon+\delta)\phi_o^4}{m(mt)^{3/2}} \sin(\delta_r + \pi/8) \quad \text{(radiation)}$$
$$2a_m \frac{\mathrm{Im}(\epsilon+\delta)\phi_o^4}{m(mt)^2} \sin(\delta_m) \quad \text{(matter)}$$

POTENTIAL

Complex quartic kicks scalar field to phase direction



Q: How do we get large initial value?

SUSY BREAKING BY INFLATION

Dine, Randall, Thomas (95, 96)

- Large vacuum energy during inflation breaks SUSY
  - SUSY breaking potential arises and ~H>>m

$$V_H \supset c_H H^2 |\phi|^2$$

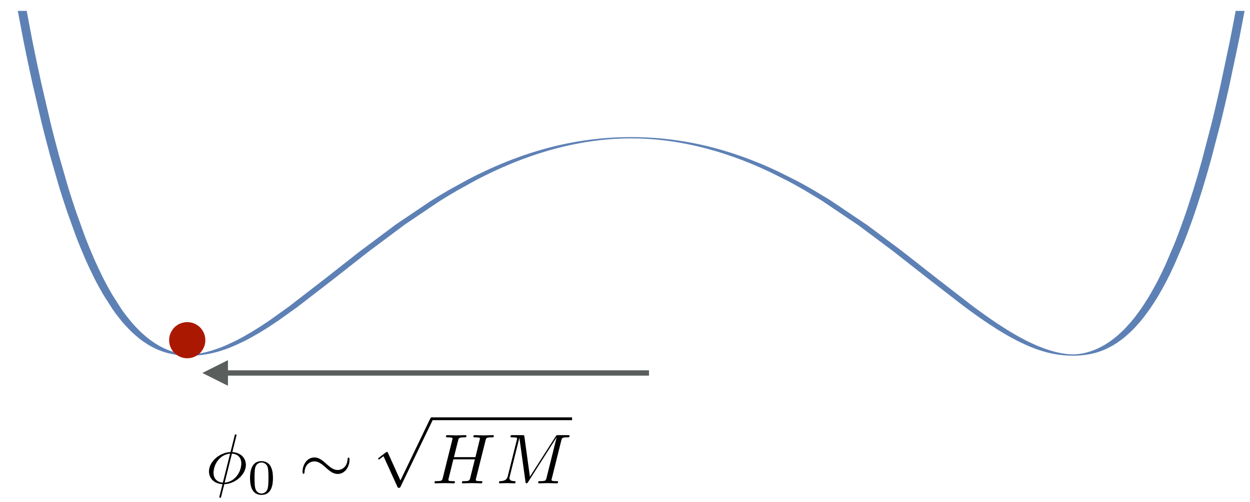
negative c_H is possible in non-minimal Kähler potential

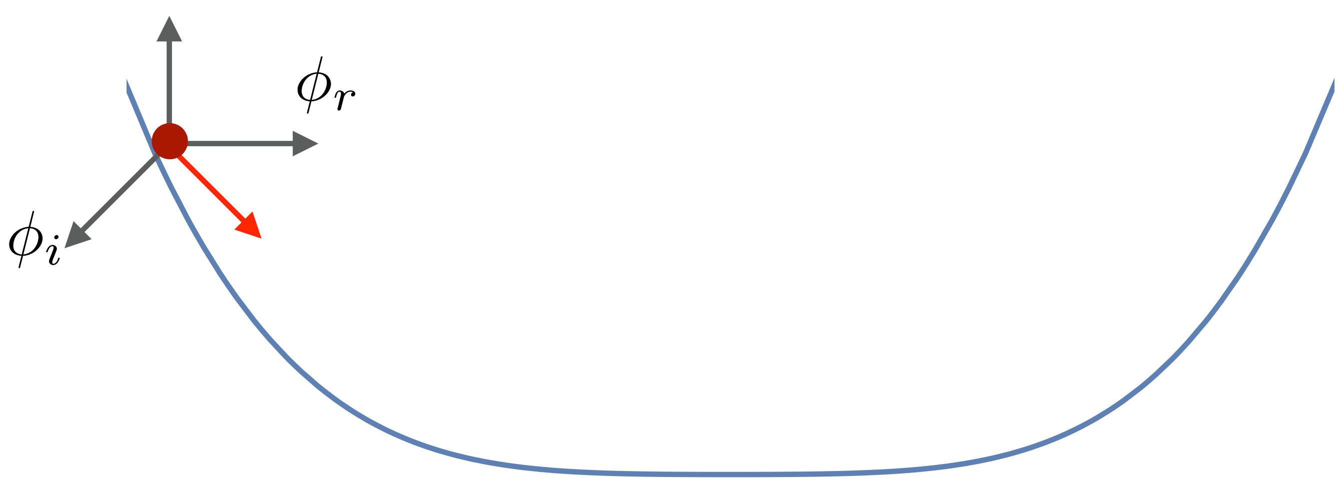
- Together with ϕ^4 or ϕ^6 terms in F-term potential,

$$V = -H^2|\phi|^2 + \frac{1}{M^2}|\phi|^6 \longrightarrow \phi_0 \sim \sqrt{HM}$$

POTENTIAL

When H>>m, scalar field stays at the potential minimum





When H~m, scalar field starts oscillation

AD LEPTOGENESIS

Affleck, Dine; Dine, Randall, Thomas (95, 96)
Murayama, Yanagida; Gherghetta, Kolda, Martin

To realize AD mechanism, we need

- light scalar (flat direction) carrying B or L number
- small B (or L) and CP violating quartic potential

In SUSY model,

- LHu direction is flat (in SUSY limit) $H_u = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad L_1 = \begin{pmatrix} v \\ 0 \end{pmatrix}$
- quartic can be generated

$$W \ni \frac{1}{2M_i}(L_i H_u)(L_i H_u) \quad \longrightarrow \quad \frac{m_{\mathrm{SUSY}}}{8M}(a_m \phi^4 + h.c.) \qquad \cancel{L} \; \cancel{CP}$$

linked to (*lightest*) neutrino mass

$$m_{\nu 1} \sim \frac{v^2}{M}$$

AD LEPTOGENESIS

Affleck, Dine; Dine, Randall, Thomas (95, 96)
Murayama, Yanagida; Gherghetta, Kolda, Martin

AD mechanism via ***LH_u***:

$$W \ni \frac{1}{2M_i}(L_i H_u)(L_i H_u) \longrightarrow W = \frac{1}{8M}\phi^4$$

$$V_F = \frac{1}{4M^2}|\phi|^6$$ (F-term potential)

$$V_{SB} = m_\phi^2|\phi|^2 + \frac{m_{\rm SUSY}}{8M}(a_m\phi^4 + h.c.)$$ (soft SUSY breaking)

$$V_H = \underbrace{-c_H H^2|\phi|^2}_{\text{negative mass}^2} + \frac{H}{8M}(a_H\phi^4 + h.c.)$$ (Hubble-induced SUSY breaking)

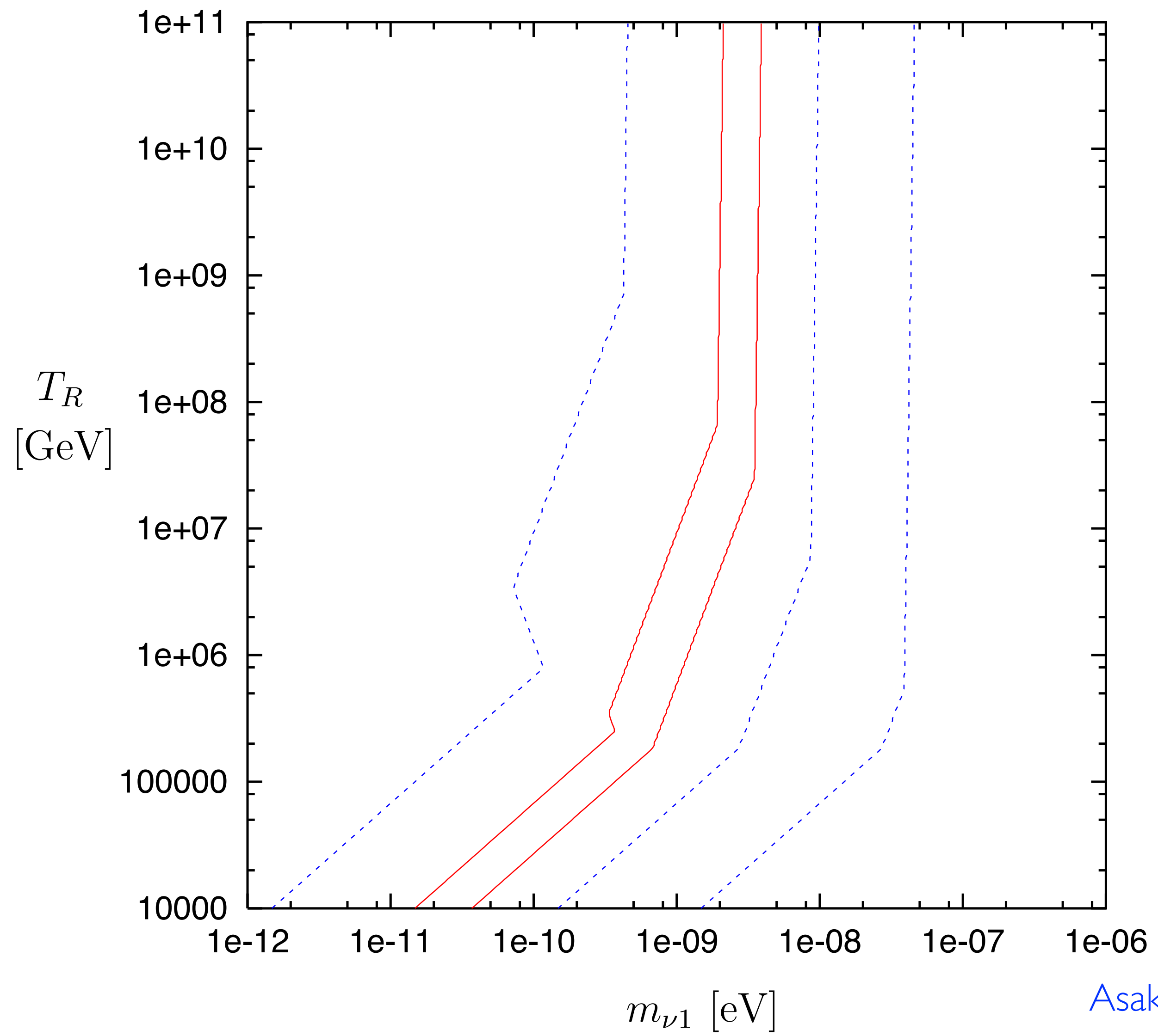
$\Rightarrow$ $\phi \simeq \sqrt{MH}$ Large VEV for $H \gg m_\phi$

initial amplitude

$n_L = \frac{i}{2}(\dot\phi^*\phi - \phi^*\dot\phi)$ Eq. of motion: $\dot n_L + 3Hn_L = \frac{m_{\rm SUSY}}{2M} Im(a_m\phi^4)$

$$\Rightarrow \frac{n_L}{s} = \frac{MT_R}{12M_P^2}\left(\frac{m_{\rm SUSY}|a_m|}{H_{\rm osc}}\right)\delta_{\rm ph} \qquad \delta_{\rm ph} = \sin(4\arg\phi + \arg a_m)$$

AD LEPTOGENESIS



Asaka, Fujii, Hamaguchi

- Successful leptogenesis requires $m_{\nu 1} \sim 10^{-9}$ eV

$$\Delta m_{21}^2 \cong 7.4 \times 10^{-5}\ \mathrm{eV}^2\,, \quad |\Delta m_{31}^2| \cong 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

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AD LEPTOGENESIS WITH PQ

- Scale of M (RHN mass) can be generated by PQ breaking

$$W_{\rm AD} = \frac{1}{2}\lambda XNN + y_\nu NLH_u, \quad W_{\rm PQ} = \eta Z(XY - f^2) + \frac{g_\mu Y^2}{M_P}H_u H_d,$$

	X	Y	Z	N	L	H_u	H_d
PQ	-2	2	0	1	1	-2	-2
L	0	0	0	-1	1	0	0

once X has large vev (~f)

$$\longrightarrow \qquad W_{\rm AD,eff} = -\frac{1}{2}\frac{y_\nu^2 (LH_u)^2}{\lambda X}.$$

- AD leptogenesis works with M~<X>

PQ breaking determines RHN mass; lepton number & light neutrino mass

$$\frac{n_B}{s} \simeq 0.029\frac{M_* T_R}{M_P^2}\left(\frac{m_{\rm soft}|a_m|}{H_{\rm osc}}\right)\delta_{\rm ph} \qquad m_{\nu 1} = \frac{y_\nu^2 \langle H_u\rangle^2}{\lambda f} \simeq \frac{v^2}{M_{\rm eff}}$$

$$\frac{y_\nu^2}{\lambda X_0} = \frac{1}{M_{\rm eff}}\left(\frac{f}{X_0}\right) \equiv \frac{1}{M_*}$$

AD LEPTOGENESIS WITH PQ

- What if PQ scale is dynamical?

$$\langle X \rangle_{\rm AD} \gg \langle X \rangle_{\rm now} \sim f$$

- LHu flat direction is "flatter", AD works more efficiently with large initial $\phi_0 \sim \sqrt{H M_*}$

$$M_* = 7.2 \times 10^{23} {\rm GeV} \left(\frac{10^{-4}\ {\rm eV}}{m_{\nu 1}} \right) \left(\frac{10^{12}\ {\rm GeV}}{f} \right) \left(\frac{X_0}{M_P} \right)$$

(scale for AD mechanism)

$$\frac{n_B}{s} \simeq 0.029 \frac{M_* T_R}{M_P^2} \left(\frac{m_{\rm soft} |a_m|}{H_{\rm osc}} \right) \delta_{\rm ph}$$

$$\simeq 3.6 \times 10^{-8} \delta_{\rm ph} \left(\frac{T_R}{10^7\ {\rm GeV}} \right) \left(\frac{10^{-4}\ {\rm eV}}{m_{\nu 1}} \right) \left(\frac{10^{12}\ {\rm GeV}}{f} \right) \left(\frac{X_0}{M_P} \right)$$

- If PQ scale during AD ~ M_P and becomes f afterwards,

AD leptogenesis is possible for ***sizable neutrino mass ~10^{-4} eV***

POTENTIAL

- Hubble induced potential realizes such a scenario.

$$K = |X|^2 + |Y|^2 + |Z|^2 + |I|^2 + \underline{\frac{b}{M_P^2}|I|^2|X|^2},$$

$$W = \eta Z(XY - f^2),$$

$$V = e^{K/M_P^2}\left(D_i W K^{i\bar{j}} D_{\bar{j}} W^* - \frac{3}{M_P^2}|W|^2\right)$$

I: inflaton

$$V = e^{(|X|^2+|Y|^2)/M_P^2}\left(\eta^2|XY - f^2|^2 + \frac{|F_I|^2}{1 + b|X|^2/M_P^2}\right)$$

$$\boxed{\langle X\rangle = (1 - 1/b)^{1/2} M_P}$$ for $|F_I|^2/M_P^2 \gg m_{3/2}^2 \quad (H^2 \gg m_{3/2}^2)$

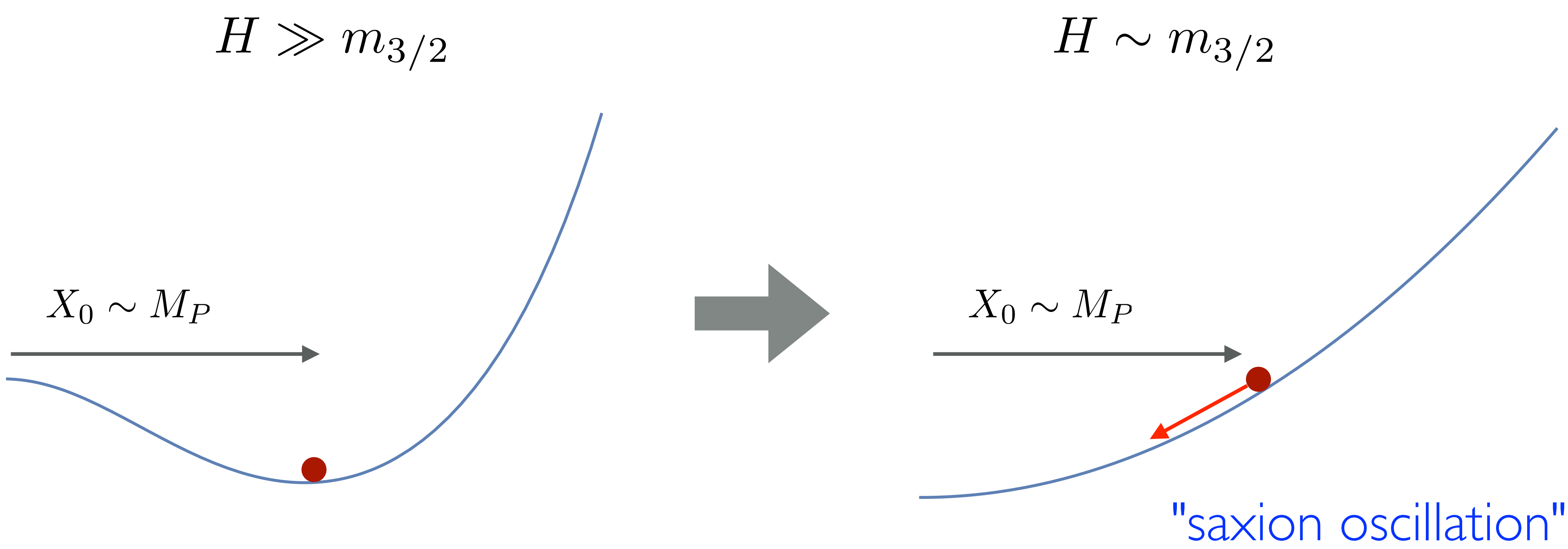
$b > 1$

- When $H \sim m_{3/2}$, PQ field (saxion) starts oscillation with amplitude M_P.

➡ saxion-dominated universe after reheating

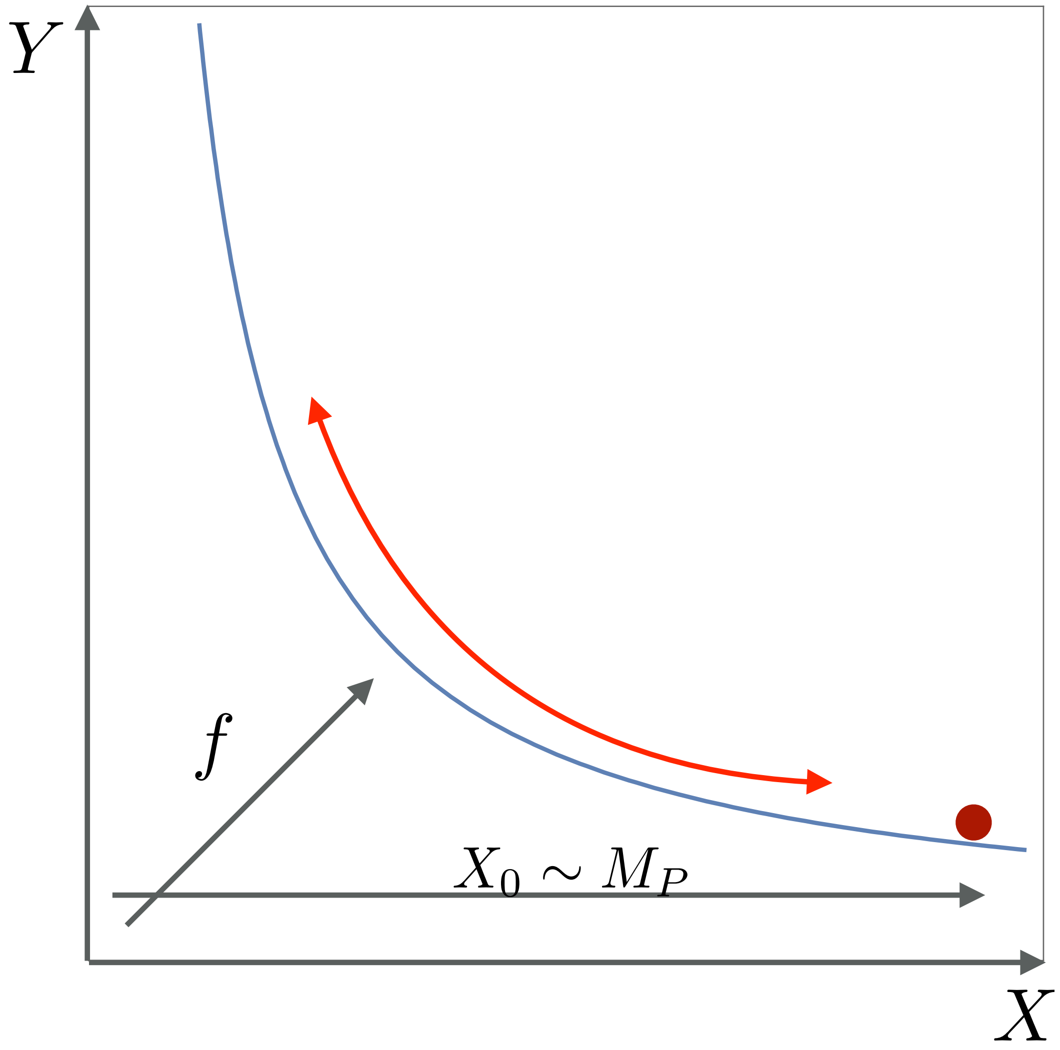
POTENTIAL

- Along flat direction $XY = f^2$



SAXION OSCILLATION

- Saxion oscillates along $XY = f^2$



When X is very small,

$$W_{\mathrm{AD,eff}} = -\frac{1}{2}\frac{y_\nu^2 (LH_u)^2}{\lambda X}. \qquad \text{valid?}$$

SAXION OSCILLATION

- DFSZ plays a role

$$W_\mu = \frac{g_\mu Y^2}{M_P} H_u H_d \longrightarrow V_{eff} \supset \frac{g_u^2 f^8}{M_P^2} \left| \frac{\phi}{X^2} \right|^2$$

$$\longrightarrow X_{\min} \sim \frac{f^2}{M_P} \left(\frac{g_\mu |\phi|}{m_X} \right)^{1/2}$$

During saxion oscillation, AD field $\phi^2_{H=m_X} \sim m_\phi M_* (m_X/m_\phi)^2 \gg m_X$

RHN mass is much larger than soft mass scale

$$W_{\mathrm{AD,eff}} = -\frac{1}{2} \frac{y_\nu^2 (L H_u)^2}{\lambda X}.$$ is valid

SAXION OSCILLATION

- Lepton number violation during saxion oscillation (after AD works)

$$\dot{n}_L + 3Hn_L = \frac{y_\nu^2 m_{\rm soft}}{\lambda X}{\rm Im}(a_m \phi^4).$$

When X is small, it could make large Lepton number change

DFSZ prevents X from being too small $\quad X_{\rm min} \sim \frac{f^2}{M_P}\left(\frac{g_\mu|\phi|}{m_X}\right)^{1/2}$

- Total Lepton number change is

$$\left(\frac{\Delta n_L}{n_L}\right)_{H\sim m_X} \sim \frac{y_\nu^2}{\lambda}\frac{\phi_{H=m_X}^2}{m_X M_P} \sim \frac{m_X}{m_\phi} \ll 1$$

for $m_X \ll m_\phi$ $\longleftarrow$ *neccessary for AD before saxion oscillation*

SAXION DECAY

- Saxion osc. with ~M_P dominates the Universe.
- Saxion decay is determined by

$$W_\mu = \frac{g_\mu Y^2}{M_P} H_u H_d$$

$$X \sim Y \sim f \quad \longrightarrow \quad \mu \sim \frac{g_\mu f^2}{M_P}$$

$$\Rightarrow \quad \Gamma(\sigma \to 2\widetilde{H}) \simeq \frac{1}{4\pi}\left(\frac{\mu}{f_a}\right)^2 m_\sigma$$

- Saxion decay dilutes generated lepton number

$$\Delta = \max\left[\frac{1}{8}T_R\left(\frac{X_0}{M_P}\right)^2 \frac{4}{3T_\sigma}, 1\right]$$

(dilution factor)

$$\Rightarrow \quad \frac{n_B}{s} = 1.1\times 10^{-12}\,\delta_{\rm ph}\left(\frac{10^{-4}\ {\rm eV}}{m_{\nu 1}}\right)\left(\frac{10^{12}\ {\rm GeV}}{f_a}\right)^2\left(\frac{X_0}{M_P}\right)^{-1}\left(\frac{90}{g_*}\right)^{1/4}\underline{\left(\frac{\mu}{\rm TeV}\right)\left(\frac{m_\sigma}{10\ {\rm TeV}}\right)^{1/2}}$$

$\mu(m_{sax})$-dependent!

AXION ISOCURVATURE

PQ is broken during inflation and never restored

- Isocurvature pert.

$$\mathcal{P}_{S_{\rm CDM}} \simeq r^2 \left(\frac{H_{\rm inf}}{\pi X_{\rm inf} \theta_a} \right)^2$$

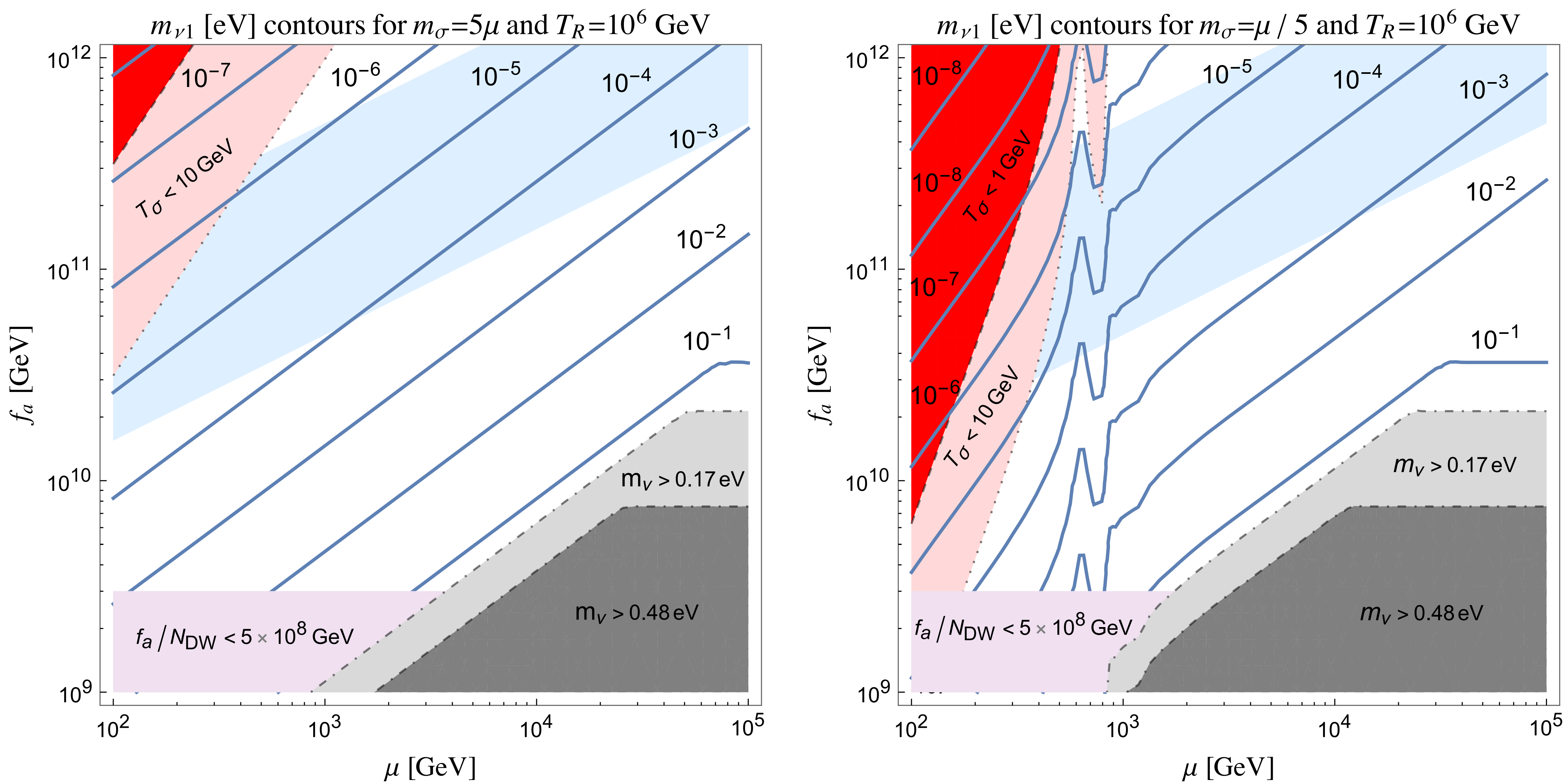
$$r \equiv (\Omega_a h^2)/(\Omega_m h^2) \qquad \Omega_a h^2 \simeq 0.18\, \theta_a^2 \left(\frac{f_a/N_{\rm DW}}{10^{12}\,{\rm GeV}} \right)^{1.19}$$

- Planck constraint

$$H_{\rm inf} \lesssim 7 \times 10^{13}\,{\rm GeV}\, \theta_a^{-1} \left(\frac{10^{12}\,{\rm GeV}}{f_a/N_{\rm DW}} \right)^{1.19} \left(\frac{X_{\rm inf}}{M_P} \right)$$

$X_{\rm inf} \sim M_P \gg f_a$ $\longrightarrow$ accommodates most of inflation models

RESULTS



- *Contours for $n_B/s = 10^{-10}$.*

SUMMARY

- Simple AD leptogenesis along LHu requires very light neutrino.
- If AD leptogenesis works with varying PQ scale, successful leptogenesis is possible with (relatively) large neutrino mass.
- Non-minimal Kähler for a PQ field realizes varying PQ scale.
- DFSZ is good to suppress unwanted L violation during saxion oscillation; Saxion decay determines the final BAU.
- Axion isocurvature is suppressed.

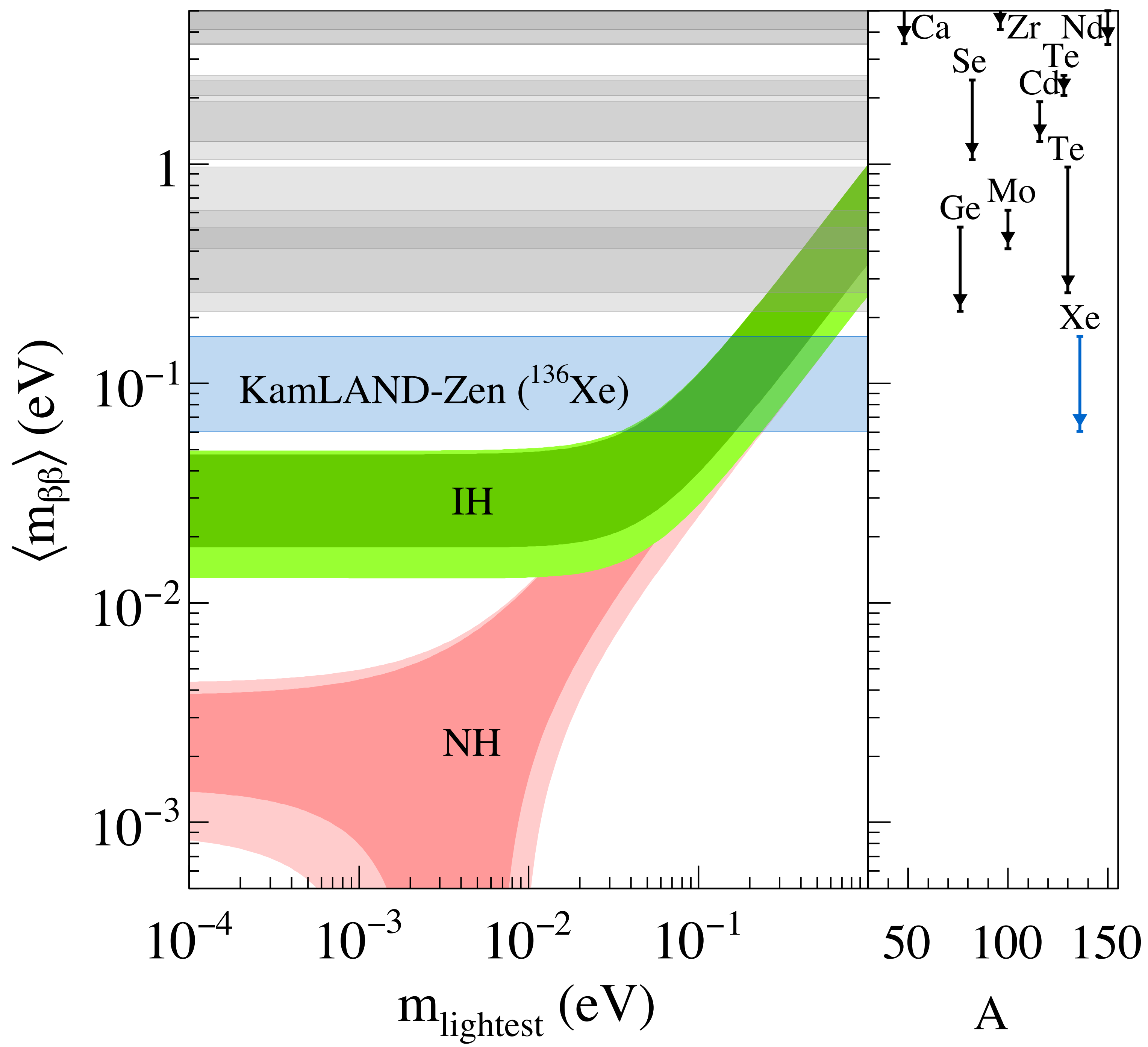


Figure from Phys. Rev. Lett. 117, 082503 (2016)