BARYON ASYMMETRY FROM A SCALE HIERARCHY

Based on arXiv:2401.13734
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06/13/2024 Crossroads between Theory and Phenomenology, CERN

INTRODUCTION

Fundamental Scales

- Plank mass $M_P = G^{-1/2} \sim 10^{19}$ GeV
- Electroweak scale $v \sim G_F^{-1/2} \sim 10^2$ GeV
- Hydrogen mass $m_H \sim \Lambda_{\mathrm{QCD}} \sim 1$ GeV

Hierarchy between scales

- $\frac{m_H}{v} \sim 10^{-2}$: Reasonable

- $\frac{v}{M_P} \sim \sqrt{\frac{G}{G_F}} \sim 10^{-17}$: Huge difference!

  ➤ The hierarchy problem

- We consider results of the scale hierarchy

Results from the scale hierarchy

- The number of atoms inside the Sun

$$N \sim \frac{M_\odot}{m_H} \sim 10^{57} \sim \left(\frac{M_P}{m_H}\right)^3$$

- This is not a simple coincidence!

$$M_\odot \sim \frac{M_P^3}{m_H^2}$$

The Chandrasekhar limit without prefactors

- Typical stars like the Sun have masses near the Chandrasekhar limit

- If $M_P \sim m_H$, the sun would be super tiny

Results from the scale hierarchy

- We can express an observed hierarchy with a fundamental scale hierarchy

$$\frac{M_\odot}{m_H} \sim \left(\frac{M_P}{m_H}\right)^3$$

- This may not be just a coincidence but a result of underlying fundamental physics

Scale hierarchy as a hint for new physics

- There is a hierarchy between the neutrino mass and the electroweak scale
- This can be explained between a hierarchy between the electroweak scale and the GUT scale: the seesaw mechanism

$$\frac{m_\nu}{v} \sim \frac{v}{M_{\text{GUT}}}$$

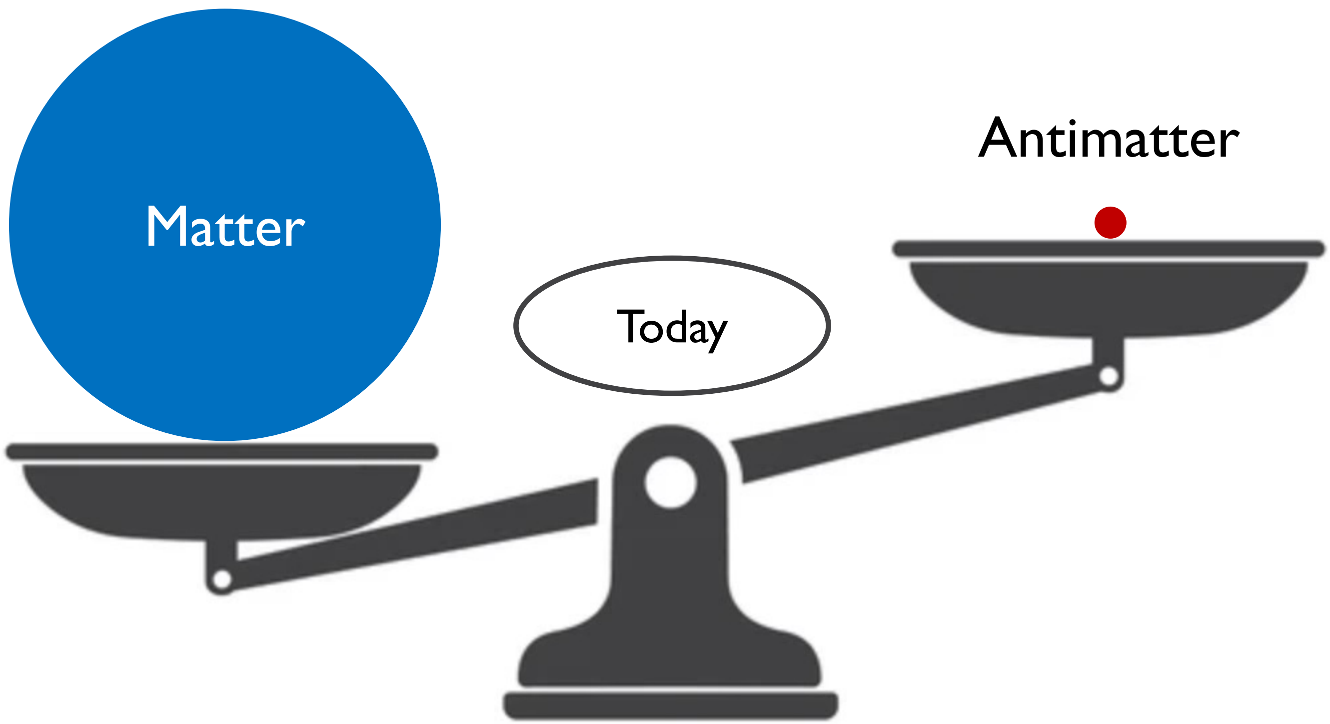
Scale hierarchy as a hint for new physics

- The relic abundance of dark matter today from the freeze-out mechanism can be expressed as

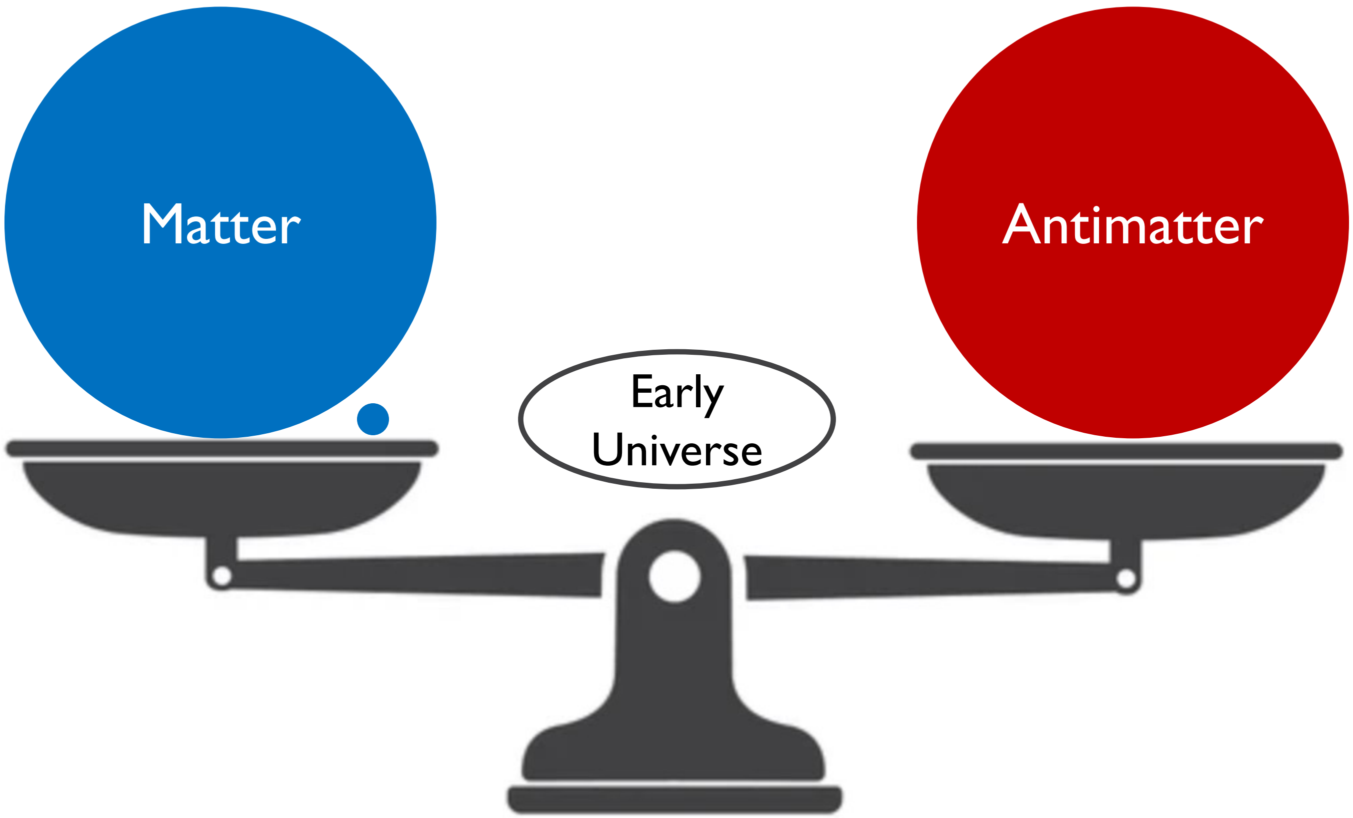
$$Y_{DM} \equiv \frac{n_{DM}}{s} \sim 10^{-12}\left(\frac{100\ \mathrm{GeV}}{m_{DM}}\right) \sim \frac{1}{g_* \alpha_{DM}^2} \frac{m_{DM}}{M_P}$$

- Choosing $m_{DM} = v$ and $\alpha_{DM} = \alpha_W$ gives the correct relic abundance, called the “WIMP miracle”

Matter-Antimatter Asymmetry



Matter-Antimatter Asymmetry



$$Y_B \equiv \frac{\bar{n}_B}{s} = (0.82 - 0.92)\times 10^{-10} \sim \frac{1}{g_*}\sqrt{\frac{v}{M_P}}$$

Baryon asymmetry from a scale hierarchy

- We propose a model that the baryon asymmetry directly comes from a scale hierarchy in a simple setup

- Two fundamental mass scales in nature
  - The reduced Planck mass : $M_P = (8\pi G)^{-1/2} = 2.4\times 10^{18}$ GeV
  - The electroweak scale : $v = \left(G_F\sqrt{2}\right)^{-1/2} = 246$ GeV

$$Y_B \sim \frac{1}{g_*}\sqrt{\frac{v}{M_P}} \sim 10^{-2}\sqrt{\frac{246\ \mathrm{GeV}}{2.4\times 10^{18}\ \mathrm{GeV}}} \sim 10^{-10}$$

Affleck-Dine baryogenesis during the radiation domination

Neutrino-Portal Affleck-Dine Baryogenesis

- We have a complex scalar filed ϕ, an AD field that carries a $B-L$ number

- If the AD mechanism happens during the radiation-dominated era, we get

$$Y_\phi = \mathcal{O}(0.01)\sqrt{\frac{m_\phi}{M_P}}$$

Neutrino-Portal Affleck-Dine Baryogenesis

- We have a complex scalar filed ϕ, an AD field that carries a $B - L$ number
- If the AD mechanism happens during the radiation-dominated era, we get

$$Y_\phi = \mathcal{O}(0.01)\sqrt{\frac{m_\phi}{M_P}}$$

- If $V(\phi) \supset m_\phi^2 |\phi|^2$ is radiatively stable due to the same mechanism for Higgs boson, we can expect

$$m_\phi \sim v \quad \Rightarrow \quad Y_\phi \sim 10^{-10}$$

- All the asymmetry of ϕ transfers to B and L sector through the neutrino portal and the weak sphaleron process
- The model predicts a relic Majoron, with $\sim \mathrm{keV}$ mass and $\sim v$ decay constant, which contributes to ΔN_{eff}

REVIEW OF AD BARYOGENESIS

Based on "A mini review on Affleck–Dine baryogenesis"
by Rouzbeh Allahverdi and Anupam Mazumdar, 2012

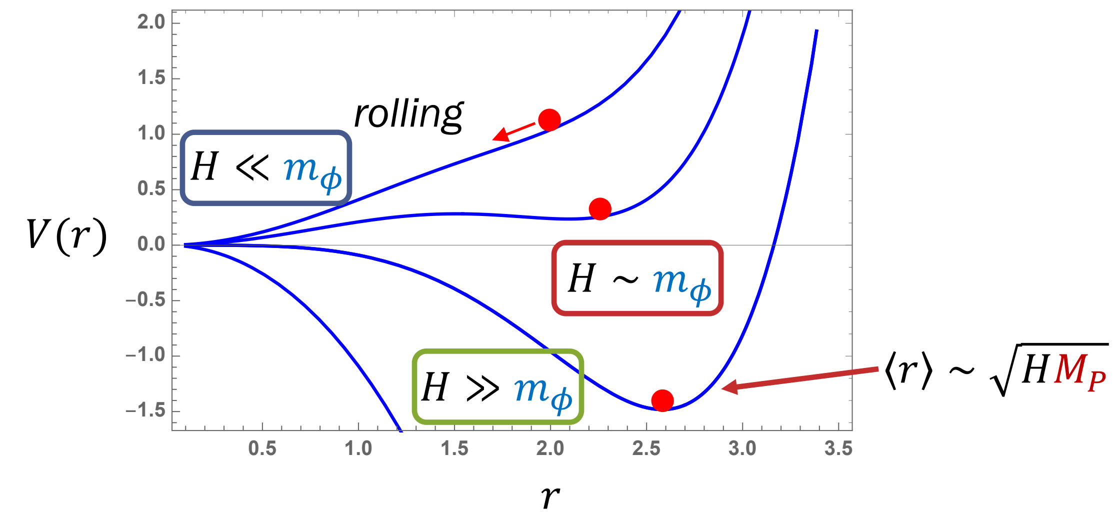
Scalar Potential

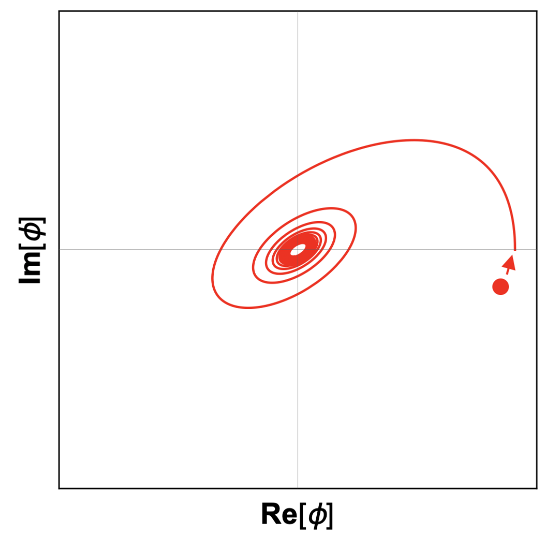
$$V = (m_\phi^2 - \kappa_H H^2)|\phi|^2 + \frac{\kappa^2}{M_P^2}|\phi|^6 - \alpha m_\phi \frac{\kappa}{4M_P}(\phi^4 + \phi^{*4})$$

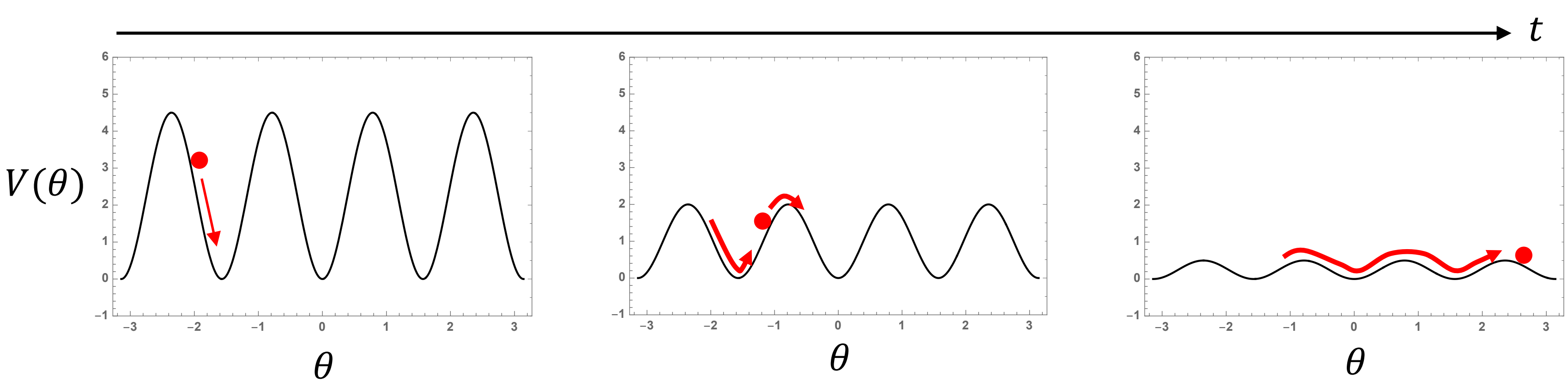
- ϕ is a flat direction with a global $U(1)$ symmetry
- $U(1)$ is explicitly broken by the Planck suppressed operator
- Note we have the Hubble induced mass term with a choice of a negative sign
- This potential is natural with SUSY, but it is not necessary

Affleck-Dine Mechanism

$$V(r,\theta) = \frac{1}{2}\left(m_\phi^2 - \kappa_H H^2\right) r^2 - \frac{\kappa \alpha m_\phi}{8M_P} r^4 \cos 4\theta + \frac{\kappa^2 r^6}{8M_P^2} + \cdots \quad \left(\phi = \frac{1}{\sqrt{2}} r e^{i\theta}\right)$$







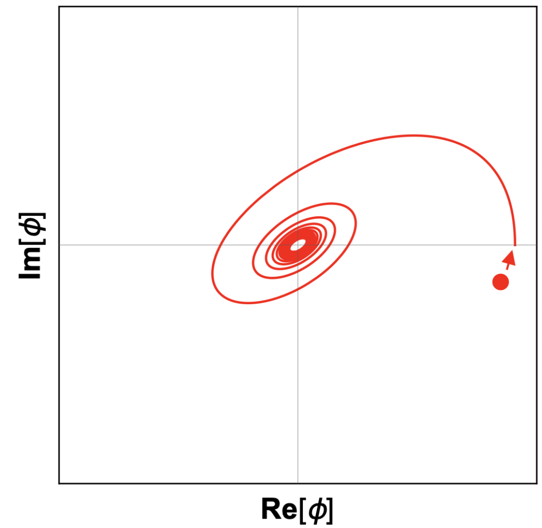
Affleck-Dine Mechanism

$$V(r,\theta) = \frac{1}{2}\left(m_\phi^2 - \kappa_H H^2\right) r^2 - \frac{\kappa \alpha m_\phi}{8 M_P} r^4 \cos 4\theta + \frac{\kappa^2 r^6}{8 M_P^2} + \cdots \quad \left(\phi = \frac{1}{\sqrt{2}} r e^{i\theta}\right)$$

- Net number density of ϕ is

$$\bar{n}_\phi = i\left(\dot{\phi}^* \phi - \phi^* \dot{\phi}\right) = r^2 \dot{\theta}$$

- Generation of angular momentum gives the asymmetry of ϕ
- AD mechanism happens during early-MD because the thermal potential $\lambda T^2 r^2$ spoils the scalar dynamics
- Final asymmetry depends on the reheating temperature $T_{\rm rh}$



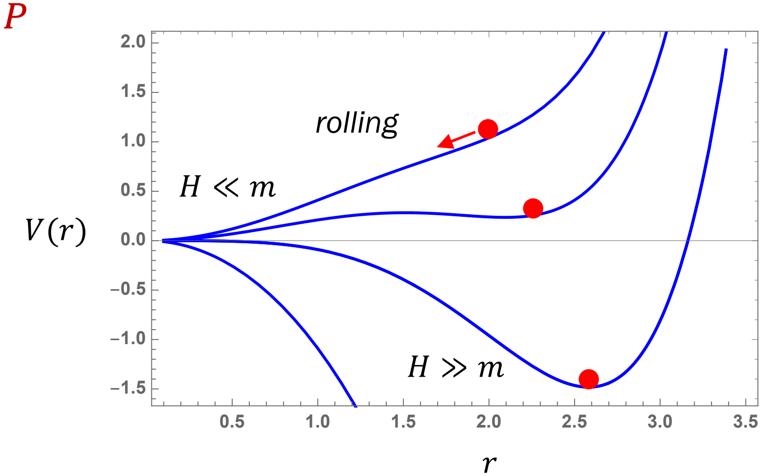
NEUTRINO-PORTAL AFFLECK-DINE MECHANISM

What's the difference?

$$V(r,\theta) = \frac{1}{2}\left(m_\phi^2 - \kappa_H H^2\right)r^2 - \frac{\kappa\alpha m_\phi}{8M_P}r^4\cos 4\theta + \frac{\kappa^2 r^6}{8M_P^2} + \cdots \qquad \left(\phi = \frac{1}{\sqrt{2}}re^{i\theta}\right)$$

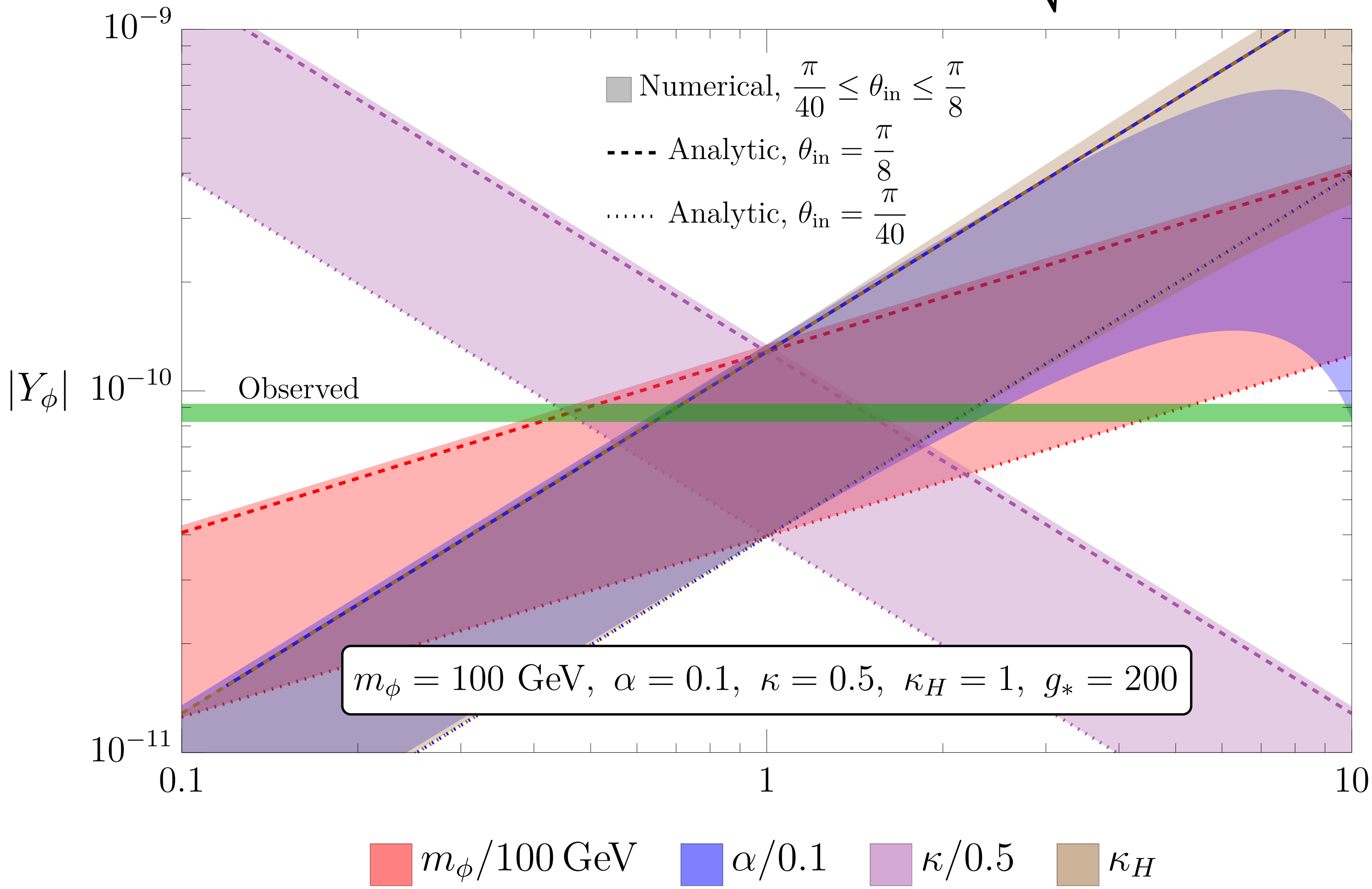
- AD mechanism happens during the radiation-dominated era
  - $H \sim \frac{T^2}{M_P} \quad \Rightarrow \quad T_{AD} \sim \sqrt{m_\phi M_P} \sim 10^{10}\ \mathrm{GeV}$
  - $\langle r\rangle \sim \sqrt{HM_P} \sim T \quad \Rightarrow \quad r(T_{AD}) \sim \sqrt{m_\phi M_P}$
  - $\dot\theta \sim m_\theta^2/H \sim \frac{1}{H}\frac{m_\phi}{M_P}\langle r^2\rangle \sim m_\phi$

- $Y_\phi = \frac{\bar n_\phi}{s} \sim \frac{r^2\dot\theta}{g_* T^3} \sim \frac{1}{g_*}\sqrt{\frac{m_\phi}{M_P}} \sim 10^{-10}$



More precisely

$$Y_\phi = -0.1\alpha \frac{\kappa_H}{\kappa} \sin 4\theta_{\text{in}} \left(\frac{200}{g_*}\right)^{1/4} \sqrt{\frac{m_\phi}{M_P}}$$



Another difference

- ϕ cannot be MSSM flat directions
  - MSSM flat directions couple to SM with the SM Yukawa couplings
  - In RD, ϕ easily thermalizes with SM bath and develop the thermal potential ($\lambda T^2 r^2$), which spoils the AD mechanism
  - AD mechanism needs to happens during the early matter-domination

- We use the neutrino-portal: $y_\nu \ell h N + \frac{1}{2}\lambda_N \phi N^2$
  - ϕ is a new degree of freedom
  - ϕ was decoupled with the SM bath due to the small Yukawa coupling
  - Initial abundance is negligible and does not develop thermal potential
  - ϕ is thermalized with the SM bath through a right-handed neutrino N much later than the AD mechanism happens

Neutrino-Portal Affleck-Dine Mechanism

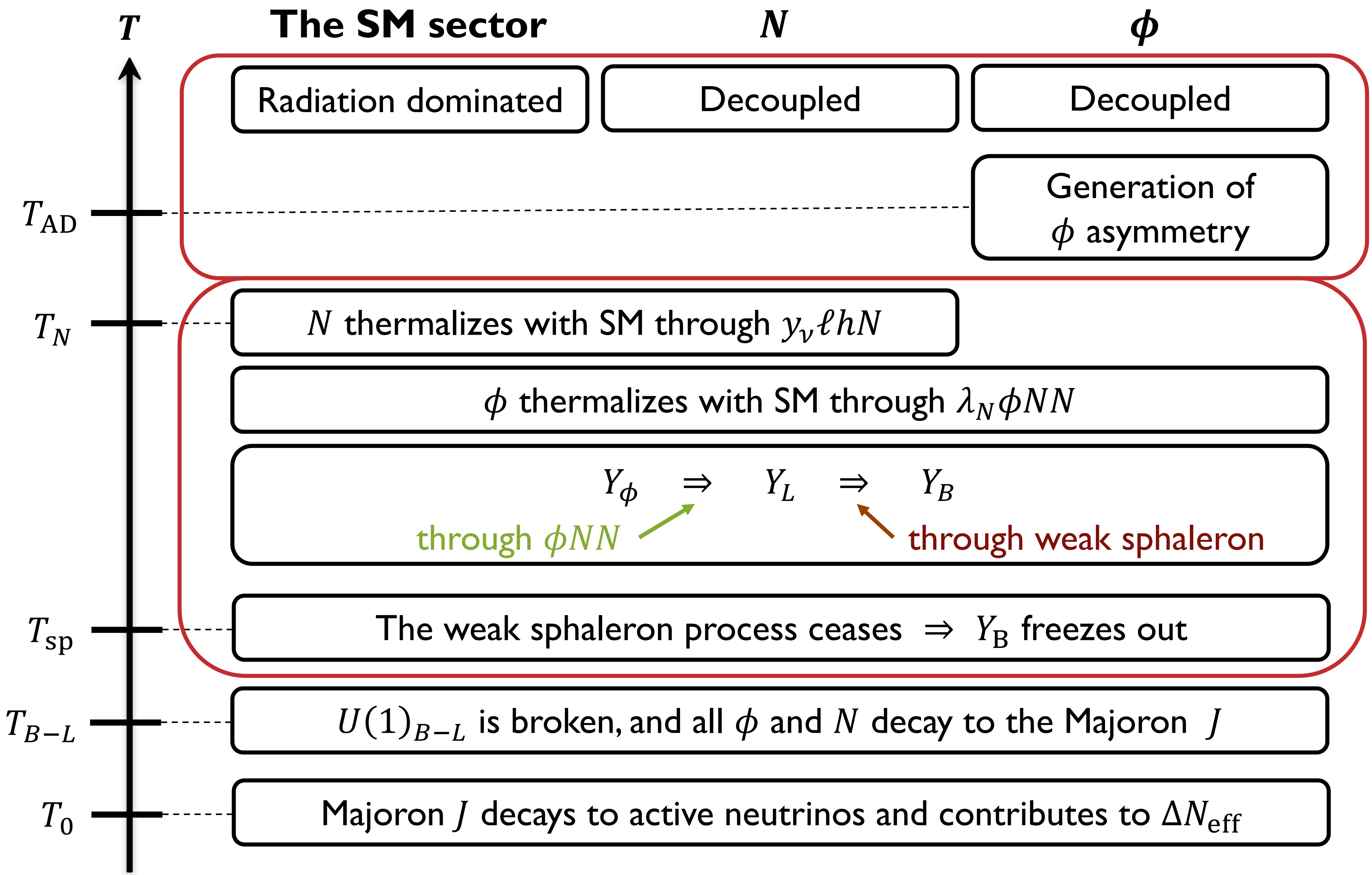
$$\mathcal{L} \supset \bar{N} i \bar{\sigma}^\mu \partial_\mu N - \left(y_\nu \ell h N + \frac{1}{2} \lambda_N \phi N N + h.c. \right)$$

- N is a right-handed neutrino with $B - L = 1$
- ϕ carries $B - L = -2$

- Global $U(1)_{B-L}$ only allows the seesaw operators
- $U(1)_{B-L}$ breaking terms arising from quantum gravity effects are suppressed by M_P

- Asymmetry of ϕ transfers to the lepton sector through N
- Asymmetry of the baryon sector is induced form the weak sphaleron process

Cosmological History



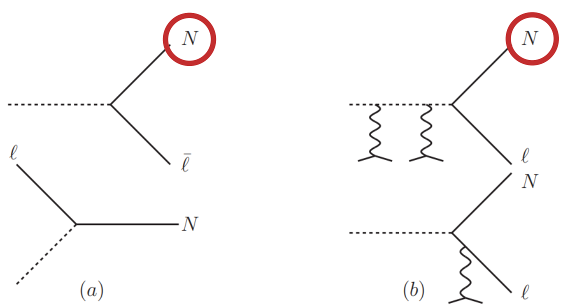
ASYMMETRY TRANSFER

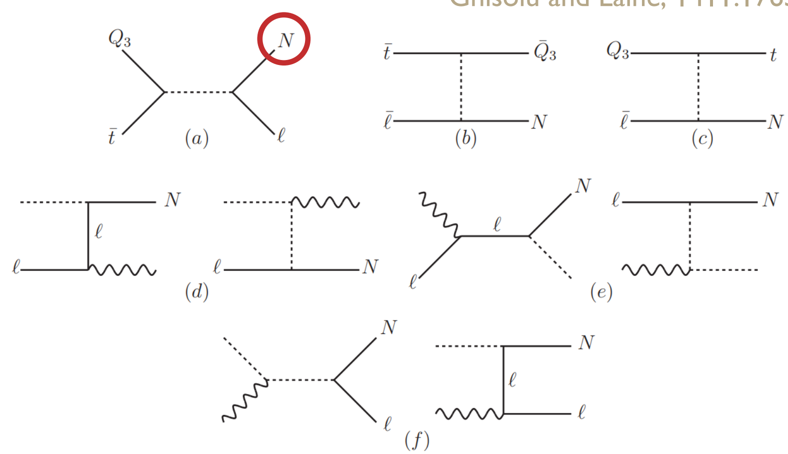
Thermalization of N

$$\mathcal{L} \supset \bar{N} i \bar{\sigma}^\mu \partial_\mu N - \left(y_\nu \ell h N + \frac{1}{2} \lambda_N \phi N N + h.c. \right)$$

- The production rate of N from the SM bath

Besak and Bodeker, 1202.1288
Garbrecht, Glowna, and Schwaller, 1303.5498
Ghisoiu and Laine, 1411.1765





$$\Gamma_N \approx 4 \times 10^{-3} y_\nu^2 T$$

$$\Rightarrow T_N \approx 5\, m_N \left(\frac{\sum m_\nu}{0.05\text{eV}} \right) \quad \text{with} \;\; m_\nu = \frac{y_\nu^2 v^2}{m_N}, \quad m_N = \lambda_N \langle \phi \rangle_{T=0}$$

Escudero and Witte, 1909.04044

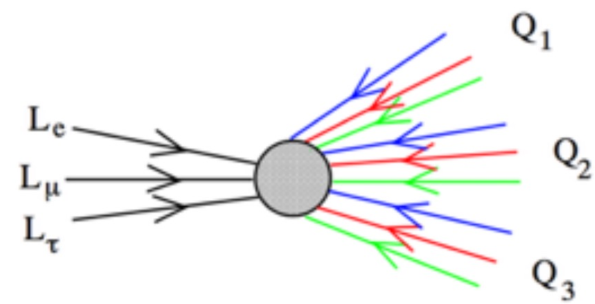
- We need $T_{AD} > T_N > T_{sp}$ $\quad \Rightarrow \quad$ weak scale $\langle \phi \rangle$ works well

Thermalizaion of ϕ and Asymmetry transfer

$$\mathcal{L} \supset \bar{N} i \bar{\sigma}^{\mu} \partial_{\mu} N - \left(y_{\nu} \ell h N + \frac{1}{2} \lambda_N \phi N N + h.c. \right)$$

- We assume $\lambda_N \sim \mathcal{O}(1)$
  - ϕ thermalizes with the SM bath as soon as N thermalizes
  - Asymmetry of ϕ transfers to the lepton sector

- Asymmetry transfers to baryon sector through the weak sphaleron process



$$\mu_{\phi} = 2\mu_L = -2\mu_B$$

- After ϕ decays, the asymmetry of ϕ $(B - L = -2)$ evenly distributed to leptons and baryons

$$Y_B = -Y_L = -Y_{\phi,\mathrm{in}}$$

- The sphaleron process ceases at $T_{\mathrm{sp}} \approx 132\ \mathrm{GeV}$, and Y_B freezes out

LATE-TIME PHENOMENOLOGY

Cosmological History

T | **The SM sector** | N | ϕ

Radiation dominated | Decoupled | Decoupled

$T_{\rm AD}$: Generation of ϕ asymmetry

T_N: N thermalizes with SM through $y_\nu \ell h N$

ϕ thermalizes with SM through $\lambda_N \phi N N$

$Y_\phi \Rightarrow Y_L \Rightarrow Y_B$

through $\phi N N$ | through weak sphaleron

$T_{\rm sp}$: The weak sphaleron process ceases $\Rightarrow$ $Y_{\rm B}$ freezes-out

T_{B-L}: $U(1)_{B-L}$ is broken, and all ϕ and N decay to the Majoron J

T_0: Majoron J decays to active neutrinos and contributes to $\Delta N_{\rm eff}$

Late-time Scalar Potential

$$\Delta V = \left(\lambda_N^2|\phi|^2 - m_{\widetilde{N}}^2\right)\left|\widetilde{N}\right|^2 + \left(\frac{\alpha\lambda_N m_\phi}{2}\phi\widetilde{N}^2 + h.c.\right) + \frac{\lambda_N^2}{4}\left|\widetilde{N}\right|^4$$

- We have one more scalar in the model: $\widetilde{N}$ (a superpartner of N)

Late-time Scalar Potential

$$\Delta V = \left(\lambda_N^2|\phi|^2 - m_{\tilde{N}}^2\right)\left|\tilde{N}\right|^2 + \left(\frac{\alpha\lambda_N m_\phi}{2}\phi\tilde{N}^2 + h.c.\right) + \frac{\lambda_N^2}{4}\left|\tilde{N}\right|^4$$

- We have one more scalar in the model: $\tilde{N}$ (a superpartner of N)
- We assume $\tilde{N}$ also has a weak scale mass, but with a negative mass-squared
- In the early time $\langle\phi\rangle \gg m_{\tilde{N}}$, $\tilde{N}$ is trapped at the origin
- Late-time when $\langle\phi\rangle$ drops below $m_{\tilde{N}}$, scalar fields get vev, and $U(1)_{B-L}$ is spontaneously broken.
- Assuming $m_{\tilde{N}} \sim m_\phi$, $\langle\phi\rangle \sim \frac{\alpha m_\phi}{\lambda_N}$ and $\left\langle\tilde{N}\right\rangle \sim \frac{m_\phi}{\lambda_N}$

Majoron

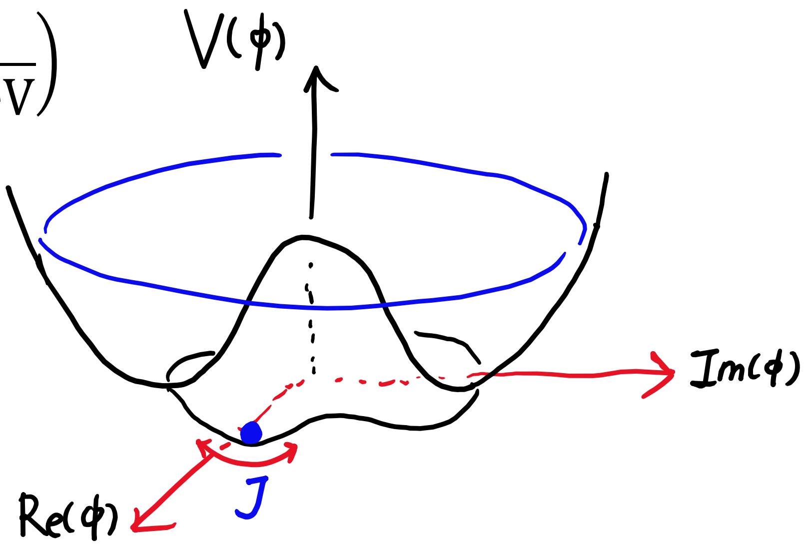
- Majoron J is a pseudo-Nambu-Goldstone boson associated with $U(1)_{B-L}$

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu J)^2 - \frac{1}{2}m_J^2 J^2 - \frac{1}{2}\left(\frac{m_\nu}{f_J} J\nu\nu + h.c.\right)$$

$$m_J \sim f_J\sqrt{\frac{\alpha m_\phi}{M_P}} \sim O(0.1-1)\text{keV}\left(\frac{f_J}{100\text{GeV}}\right)$$

$$f_J = \sqrt{4r_\phi^2 + r_N^2} \sim m_\phi$$

$$\Gamma_J(J \to \nu\nu) = \frac{m_J}{16\pi f_J^2}\Sigma m_\nu^2$$



- Both baryon asymmetry and m_J come from the $U(1)_{B-L}$ breaking term

$$V_J \sim -\frac{\kappa\alpha m_\phi}{8M_P} r^4 \cos 4\theta$$

Majoron Contribution to $\Delta N_{\rm eff}$

- Majorons decouples with the SM bath at $T = T_d \sim 0.1\, m_N$ Escudero and Witte, 2103.03249

- Depending on the decoupling time, $\Delta N_{\rm eff}$ contribution is

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\frac{g_{*,S}(T_0)}{g_{*,S}(T_d)}\right)^{4/3}$$

- However, the Majoron can be non-relativistic before it decays. The energy density of non-relativistic matter redshifts slowly, so

$$F_{\rm NR} \approx \frac{m_J}{T_{J,\rm decay}} \approx \left(\frac{g_{*,S}(T_0)}{g_{*,S}(T_d)}\right)^{-1/3} \frac{m_J}{\boxed{T_{\rm decay}}}$$

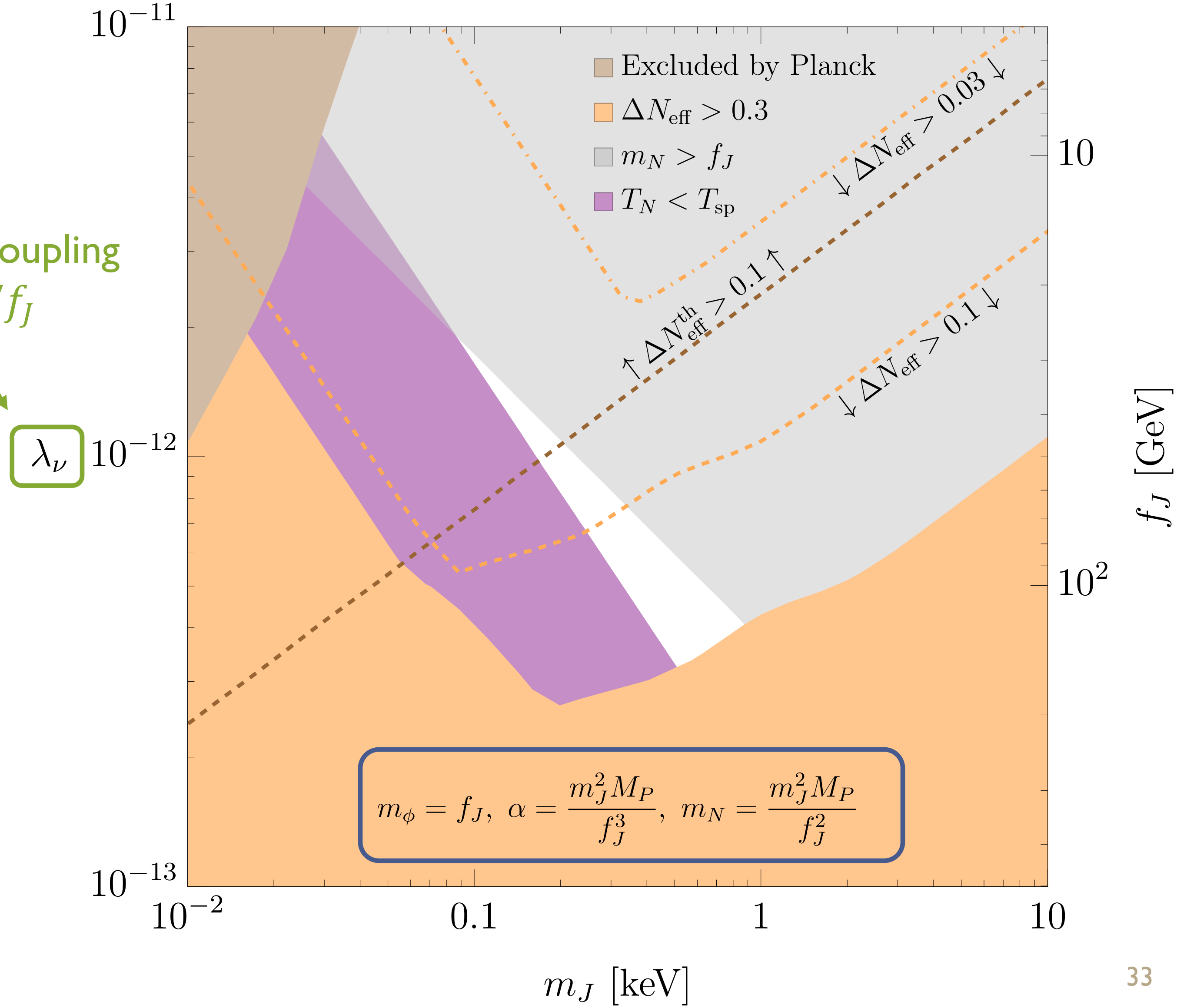
From $\Gamma_J = H$

should be included:

$$\boxed{\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\frac{g_{*,S}(T_0)}{g_{*,S}(T_d)}\right)^{4/3} \max[1, F_{\rm NR}]}$$

ΔN_{eff} Constraints and future sensitivities

Majoron-neutrino coupling
$\lambda_\nu \approx 0.05\ \text{eV}/f_J$



$\Delta N_{\rm eff}$ Constraints and future sensitivities

Constrained from thermal production $J \leftrightarrow \nu\nu$ by Planck

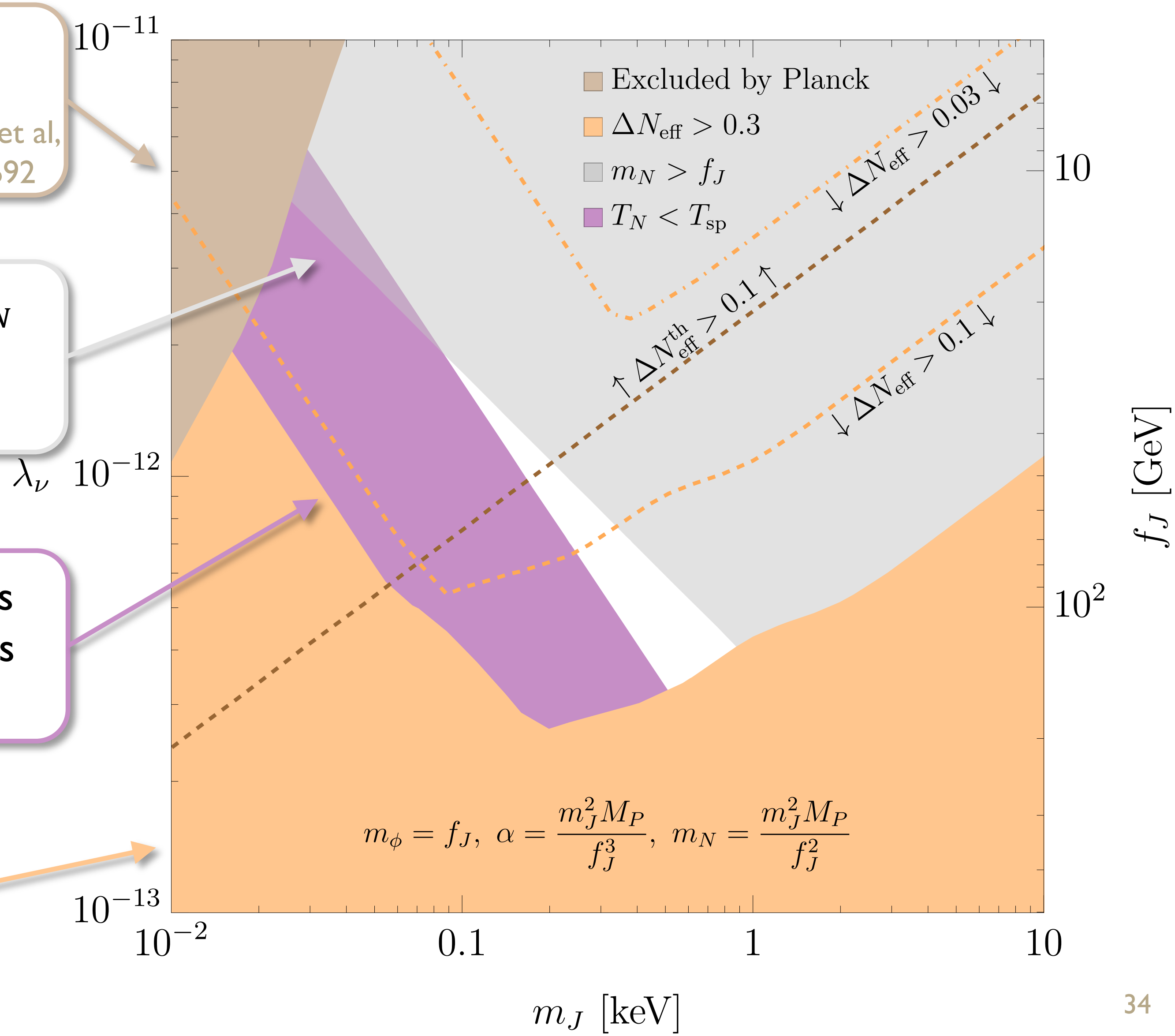
Sandner et al, 2305.01692

Perturbativity bound on λ_N

$m_N \sim \lambda_N \langle\phi\rangle$ needs to be larger than $f_J > \langle\phi\rangle$

RH neutrino N thermalizes after the sphaleron process cease, so no Y_B generated

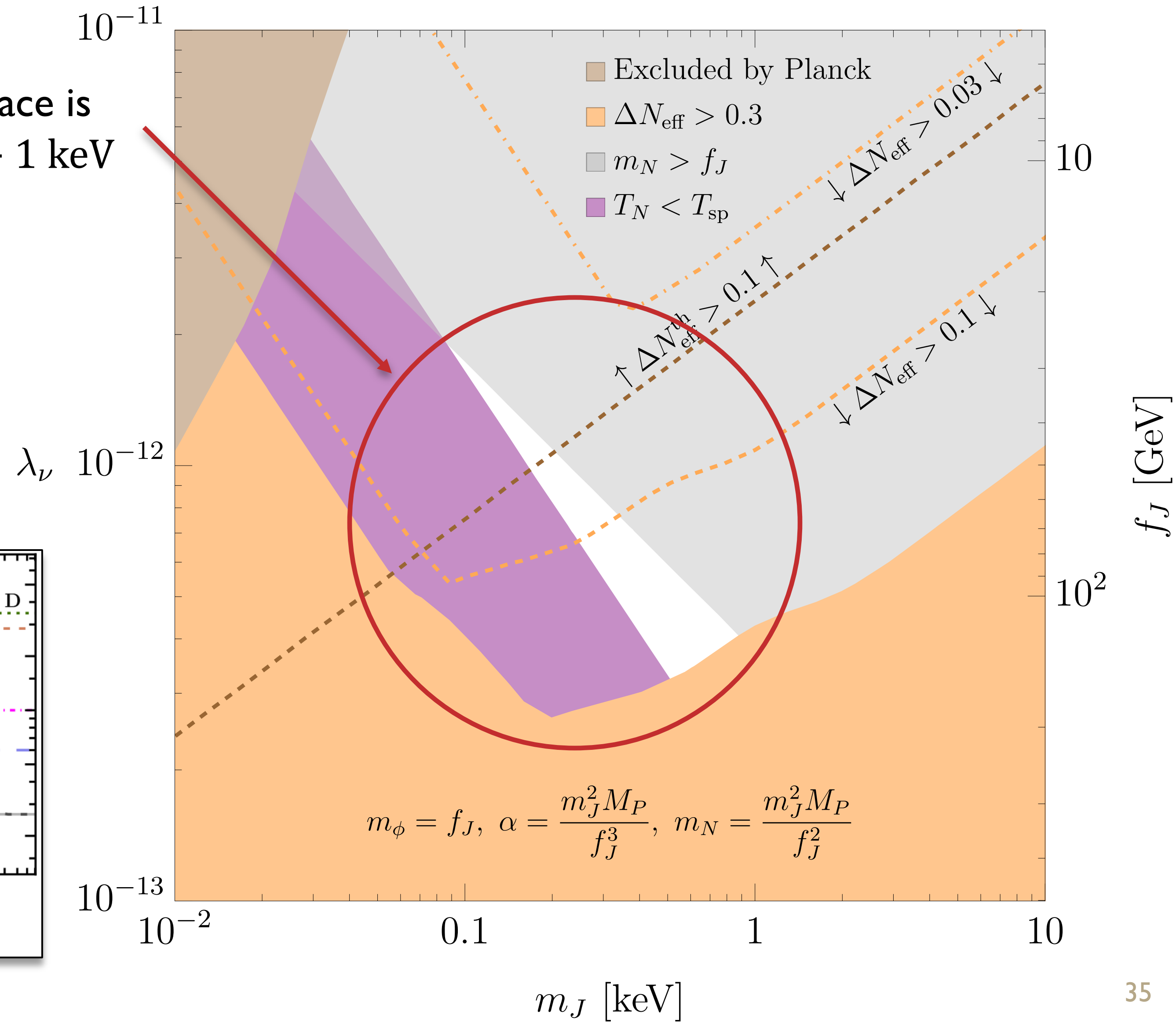
Constrained from $\Delta N_{\rm eff} > 0.3$

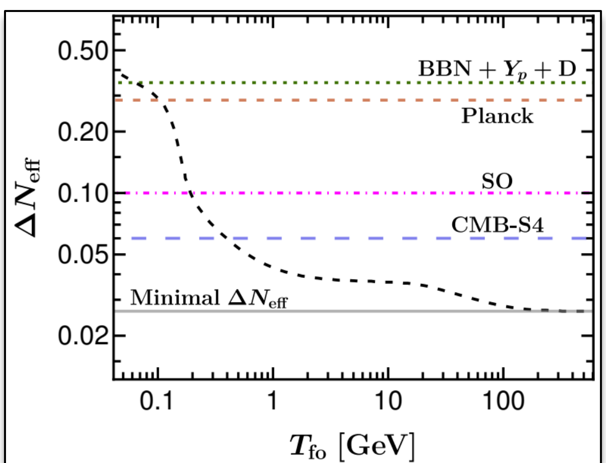


$\Delta N_{\rm eff}$ Constraints and future sensitivities

The allowed parameter space is $f_J \sim 100$ GeV, $m_J \sim 0.1 - 1$ keV

We get $f_J \sim m_\phi \sim v$ as well from observations, independent on the theoretical motivation





DISCUSSION

Reheating Temperature T_{rh}

- T_{rh} needs to be higher than T_{AD}
- But it cannot be much higher
- Constraints from isocurvature perturbations
- ϕ before AD has negative damping if there's a displacement from the fixed point
- We use $T_{\mathrm{rh}} \gtrsim T_{AD}$ to avoid these issues

Role of SUSY

- All the results I mentioned yield consistent results as long as we have the same scalar potentials

- SUSY is not necessary, but it's a good tool for organizing scalar potentials
  - e.g. ϕ has a flat direction naturally ($\lambda|\phi|^4$ term doesn't appear)

- With all the superpartners, we have another observable
  - The lightest neutrino should be very light : $m_{\text{light}} \sim \frac{m_N}{M_P} \sum m_\nu$
  - This explains the small neutrino mass sum from recent DESI data
  - We leave this for future work as it is model-dependent

Summary

- We propose a baryogenesis model where baryon asymmetry arises directly from a scale hierarchy between the weak scale and the Plank scale:

$$Y_B = \mathcal{O}(0.01)\sqrt{\frac{v}{M_P}}$$

- The model is based on Neutrino-Portal Affleck-Dine mechanism, where AD mechanism happens in RD

- The model predicts a relic Majoron with a keV mass and a weak scale decay constant

- This relic Majoron contributes to ΔN_{eff} and the allowed parameter space agrees with the theoretical prediction

- All allowed parameter space can be probed by near-future CMB observations

THANK YOU

BACK UP

Scalar Potential

$$V = (m_\phi^2 - \kappa_H H^2)|\phi|^2 + \frac{\kappa^2}{M_P^2}|\phi|^6 - \alpha m_\phi \frac{\kappa}{4M_P}(\phi^4 + \phi^{*4})$$

- ϕ is a supersymmetric flat direction with a global $U(1)$ symmetry
- $U(1)$ is explicitly broken by the Planck suppressed operators in the superpotential

$$W = \frac{\kappa}{4M_P}\phi^4, \qquad V = \left|\frac{\partial W}{\partial \phi}\right|^2 - \left(\alpha m_\phi W + h.c.\right)$$

- The Hubble induced mass term comes from the Kähler potential,

$$\frac{\rho}{M_P^2}|\phi|^2 \quad \Rightarrow \quad \kappa_H H^2 |\phi|^2$$

More precisely

- The analytic expression for Y_ϕ can be calculated from the equation of motion of Y_ϕ,

$$\frac{dY_\phi}{dt} = -\frac{1}{s}\frac{\partial V}{\partial \theta} = -\frac{1}{s}\frac{\kappa \alpha m_\phi}{2M_P} r^4 \sin 4\theta$$

- To integrate the e.o.m over t analytically with some assumptions
  - $H > m_\phi$: $r(t) = \langle r \rangle = \left(\frac{4\kappa_H}{3\kappa^2}\right)^{1/4} \sqrt{H M_P}$ and $\theta(t) = \theta_{\text{in}}$
  - $H < m_\phi$: $r(t) = \langle r(t_*) \rangle a^{-3/2} \cos(m_\phi(t - t_*))$ and $\theta(t) = \theta_{\text{in}}$ near maxima (t_* is the time at $H = m_\phi$)

- The final analytic result is

$$Y_\phi = -0.1\alpha \frac{\kappa_H}{\kappa} \sin 4\theta_{\text{in}} \left(\frac{200}{g_*}\right)^{\frac{1}{4}} \sqrt{\frac{m_\phi}{M_P}}$$

- With $g_* = 200$ and $\mathcal{O}(0.1 - 1)$ coefficients, we get $Y_\phi \sim 10^{-10}$