Dynamical Generation of the Baryon Asymmetry from a Scale Hierarchy

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@ Workshop on Dark Universe

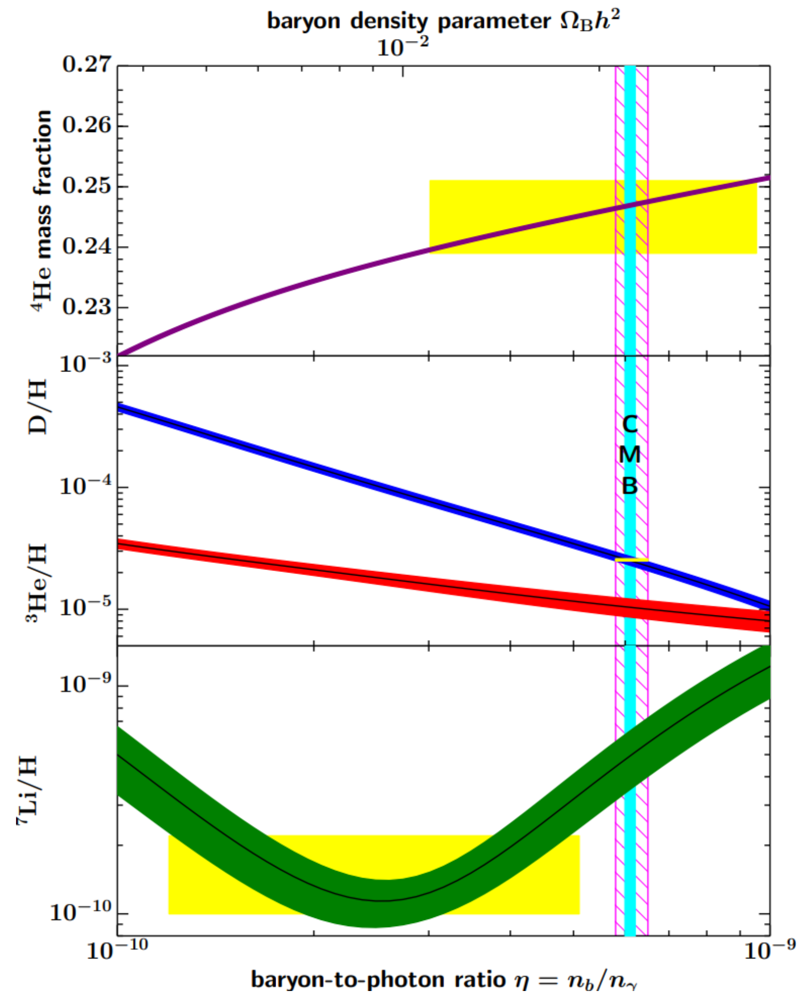
Introduction

Matter-Antimatter asymmetry in the Universe.

From BBN/CMB observations

$$\left(\frac{n_B}{s}\right)\bigg|_{T\leq \mathrm{MeV}} = (0.82 - 0.92) \times 10^{-10}$$

Particle Data Group 2021



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$\not{B}$, $\not{C}$, $\not{CP}$, and out-of-equilibrium process at high energy gives a number of $O(10^{-10}) \ll 1$

What kinds of New Physics provide such a small number?

small couplings, large wash-out effects, multiple suppressions, etc.

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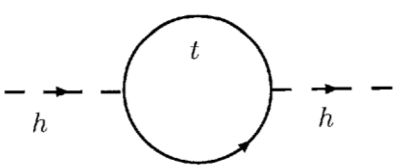
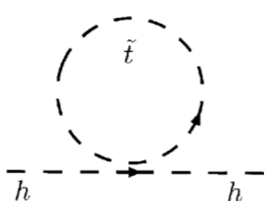
The famous example of a large hierarchy in particle physics:

$$v = \left(G_F\sqrt{2}\right)^{-1/2} = 246\ \mathrm{GeV}, \qquad M_P = (8\pi G)^{-1/2} = 2.4 \times 10^{18}\ \mathrm{GeV}$$

$$V(h) = -\frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4, \qquad \delta m^2 \sim y_t^2 M_P^2 \gg v^2 = m^2/\lambda$$





Supersymmetry (SUSY) stabilizing the weak scale from various quantum corrections

Introduction

Large hierarchy between the two scales

$$\sqrt{\frac{v}{M_P}} = \sqrt{\frac{2.46 \times 10^2}{2.4 \times 10^{18}}} \sim 10^{-8} \Rightarrow O(0.01) \times \sqrt{\frac{v}{M_P}} = O(10^{-10}) = O\left(\frac{n_B}{s}\right)$$

Is it just a coincidence?

Model of baryogenesis from such a scale hierarchy

$$\frac{n_B}{s} = O(0.01)\sqrt{\frac{m}{M_P}}$$

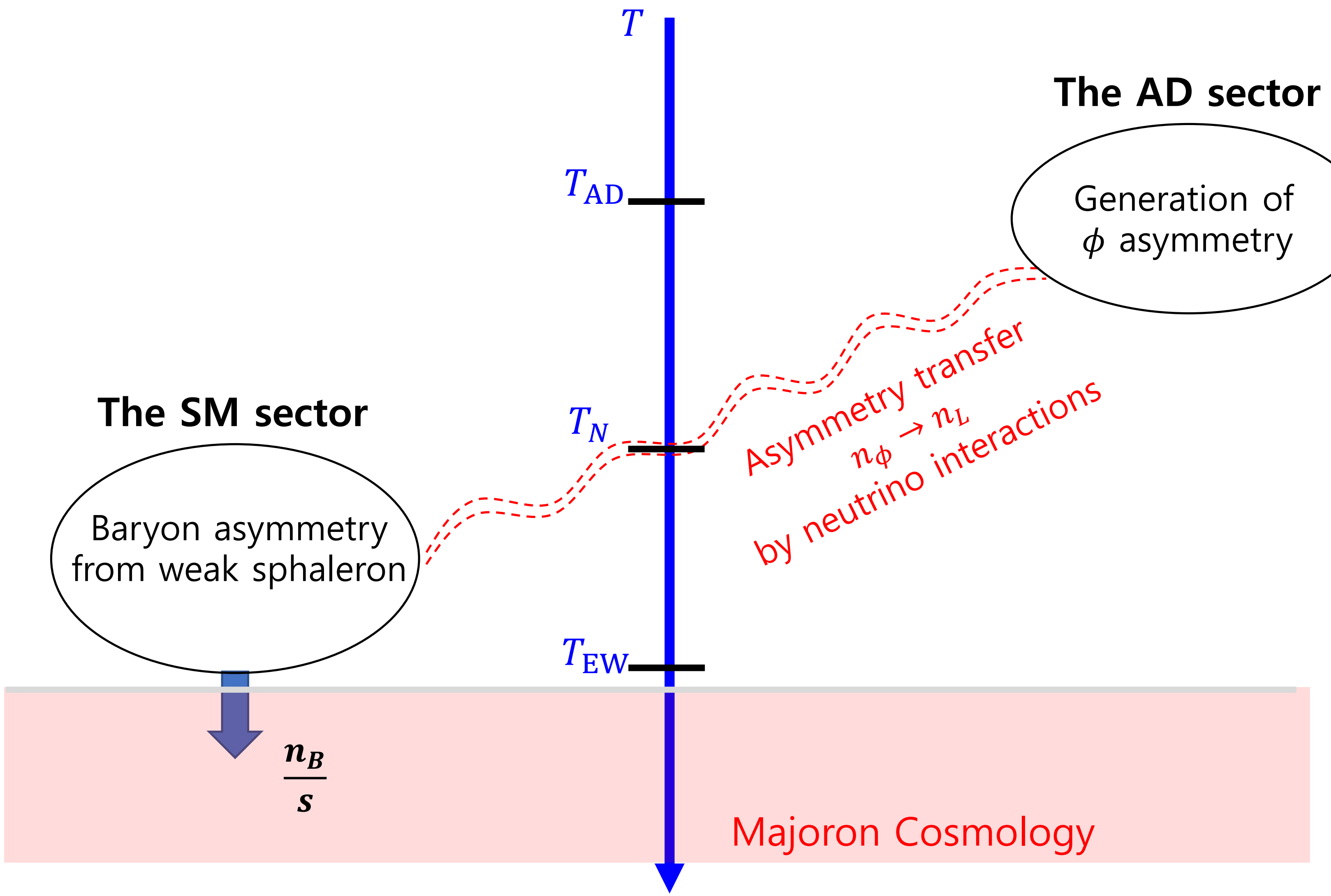
m : Soft breaking scale for symmetry (SUSY) protecting scalar masses

M_P : Gravitational explicit breaking scale of $U(1)_{B-L}$ symmetry

➔ **Study the cosmological predictions**

Summary of Cosmological History

Neutrino-Portal Affleck-Dine (AD) Baryogenesis : $y_\nu \ell h N + \frac{1}{2}\lambda_N \phi N^2 + V(\phi)$



Asymmetry Generation

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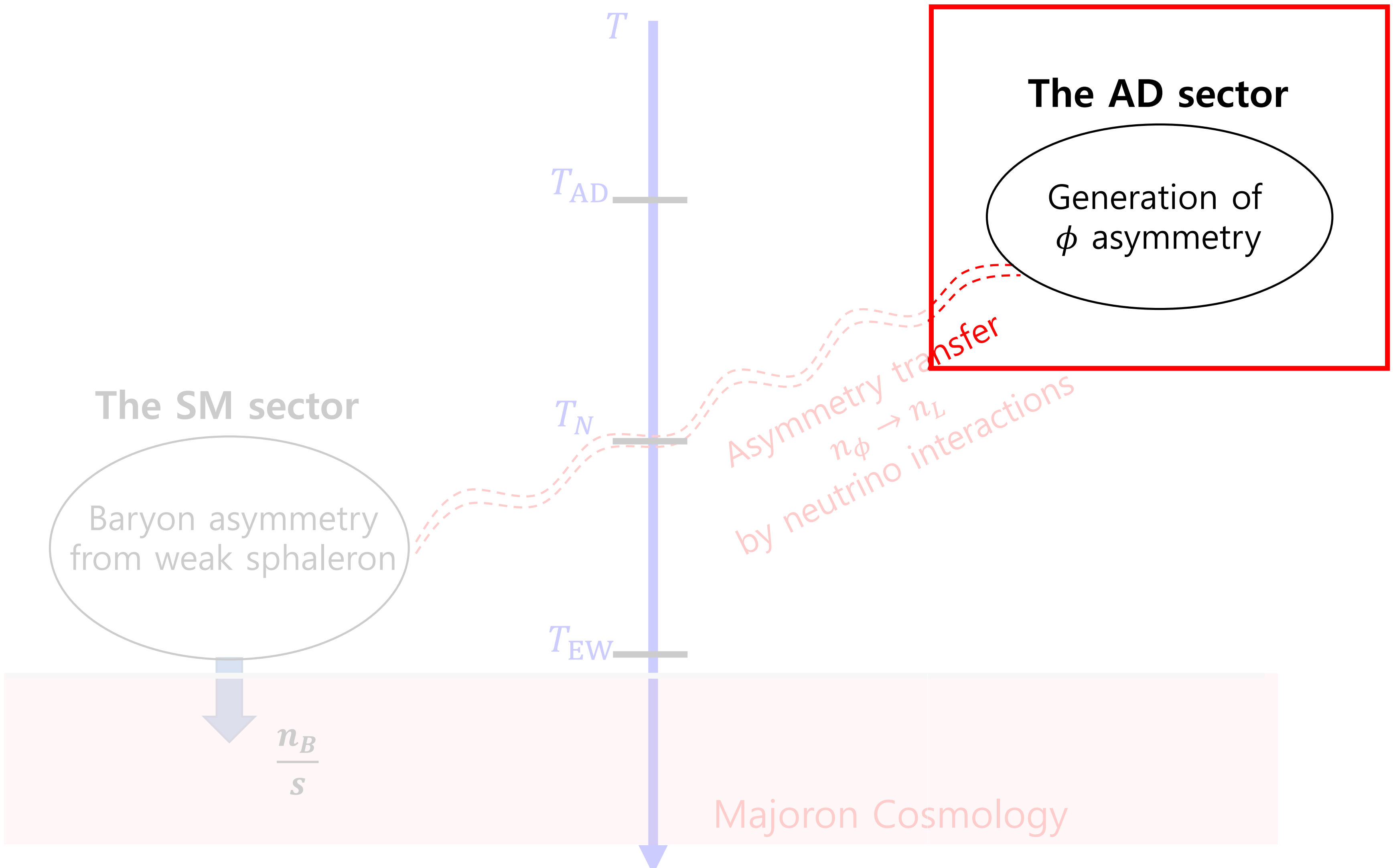

Scalar Potential

The global symmetry

$$U(1) : \phi \rightarrow e^{ic}\phi$$

is explicitly broken by the Planck suppressed operators in superpotential as $W = \frac{\kappa}{4M_P}\phi^4$.

Corresponding **supersymmetric** and soft **SUSY** breaking scalar potential is

$$V(\phi, \phi^*) = m^2|\phi|^2 - \left(\alpha m \frac{\kappa}{8M_P}\phi^4 + c.c.\right) + \frac{\kappa^2}{M_P^2}|\phi|^6$$

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Soft breaking terms

$U(1)$ breaking terms

In addition, **the Hubble induced mass terms** can be important at high temperatures

$$\mathcal{L} \ni \frac{|\phi|^2}{M_P^2}\bar{\psi}\, i\gamma^\mu D_\mu \psi \;\Rightarrow\; \frac{|\phi|^2}{M_P^2}T^4 \Rightarrow \kappa_H H^2|\phi|^2 \qquad \left(\rho_{tot} = \frac{\pi^2 g_*}{30}T^4 = 3H^2M_P^2\right)$$

[Kawasaki, Takesako 2012]

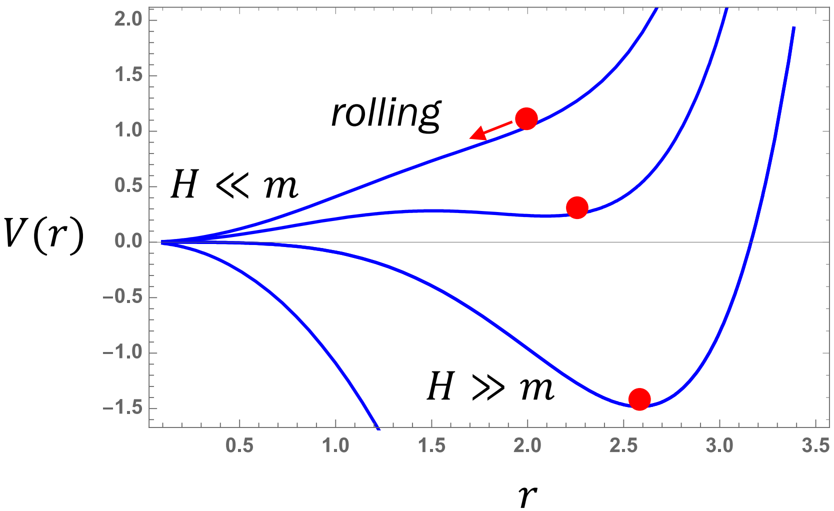
Including this contribution,

$$V(\phi,\phi^*) = (m^2 - \kappa_H H^2)|\phi|^2 - \left(\alpha m \frac{\kappa}{8M_P}\phi^4 + c.c.\right) + \frac{\kappa^2}{M_P^2}|\phi|^6$$

Affleck-Dine Mechanism

Dynamical generation of phi-number

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



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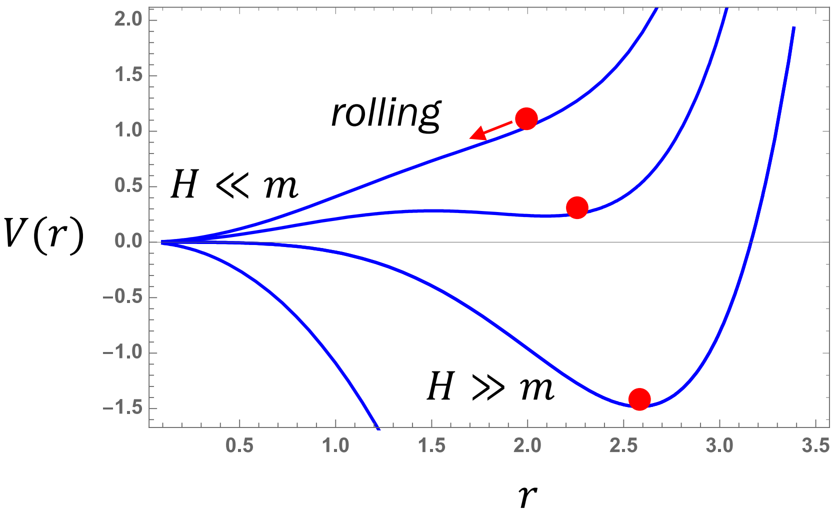

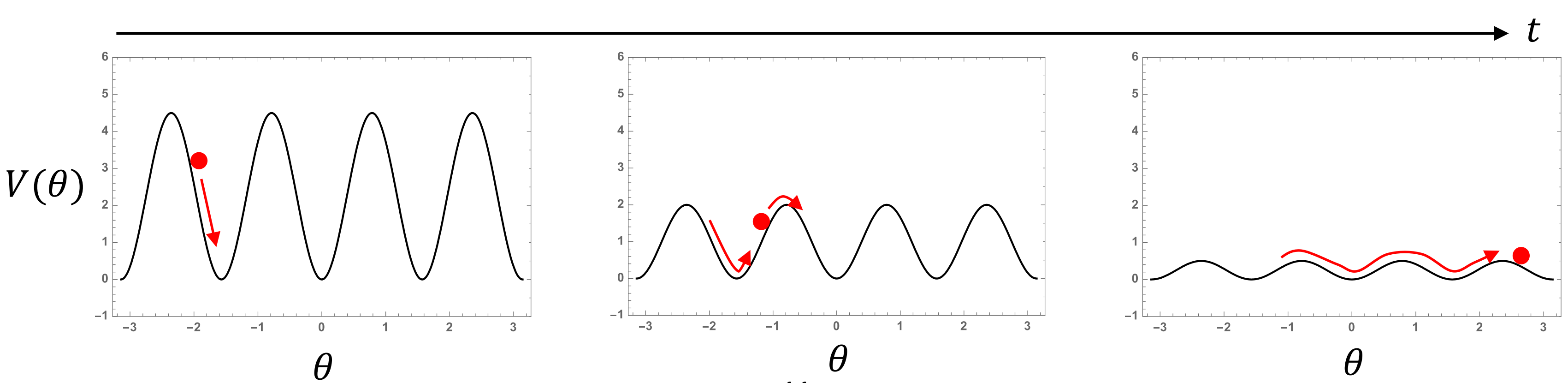

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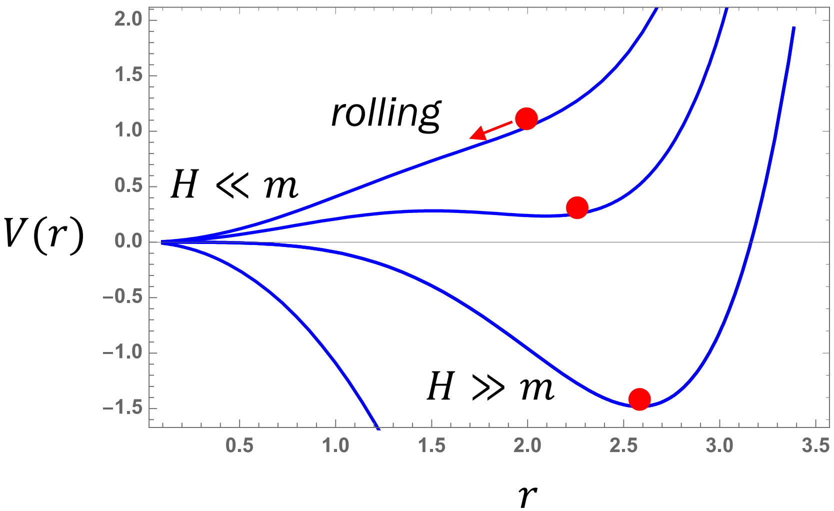

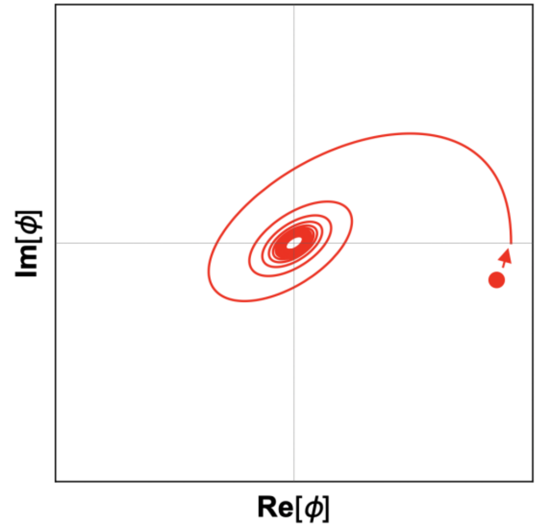

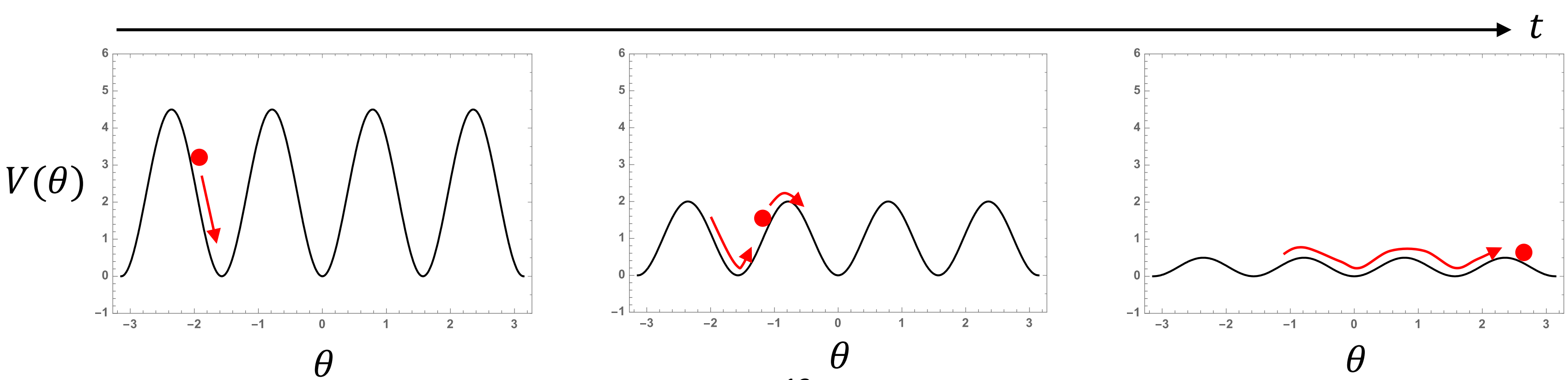

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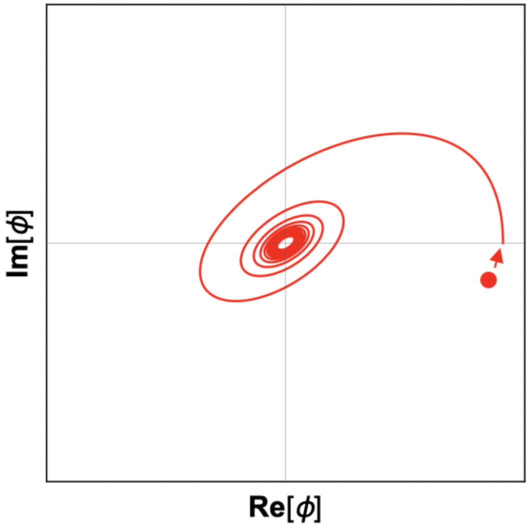
$$V(r,\theta) = \frac{1}{2}(m^2 - \kappa_H H^2) r^2 - \frac{\kappa\alpha m}{8M_P} r^4 \cos 4\theta + \frac{\kappa^2 r^6}{8M_P^2} + \cdots \qquad \left(\phi = \frac{1}{\sqrt{2}} r e^{i\theta}\right)$$

At generation of phi-number ($H \sim T^2/M_P \sim m$)

$$n_\phi = r^2 \dot{\theta} \sim (m M_P)(\alpha m)$$

$$s = \frac{2\pi^2 g_*}{45} T^3 \sim g_* (m M_P)^{3/2}$$



Therefore

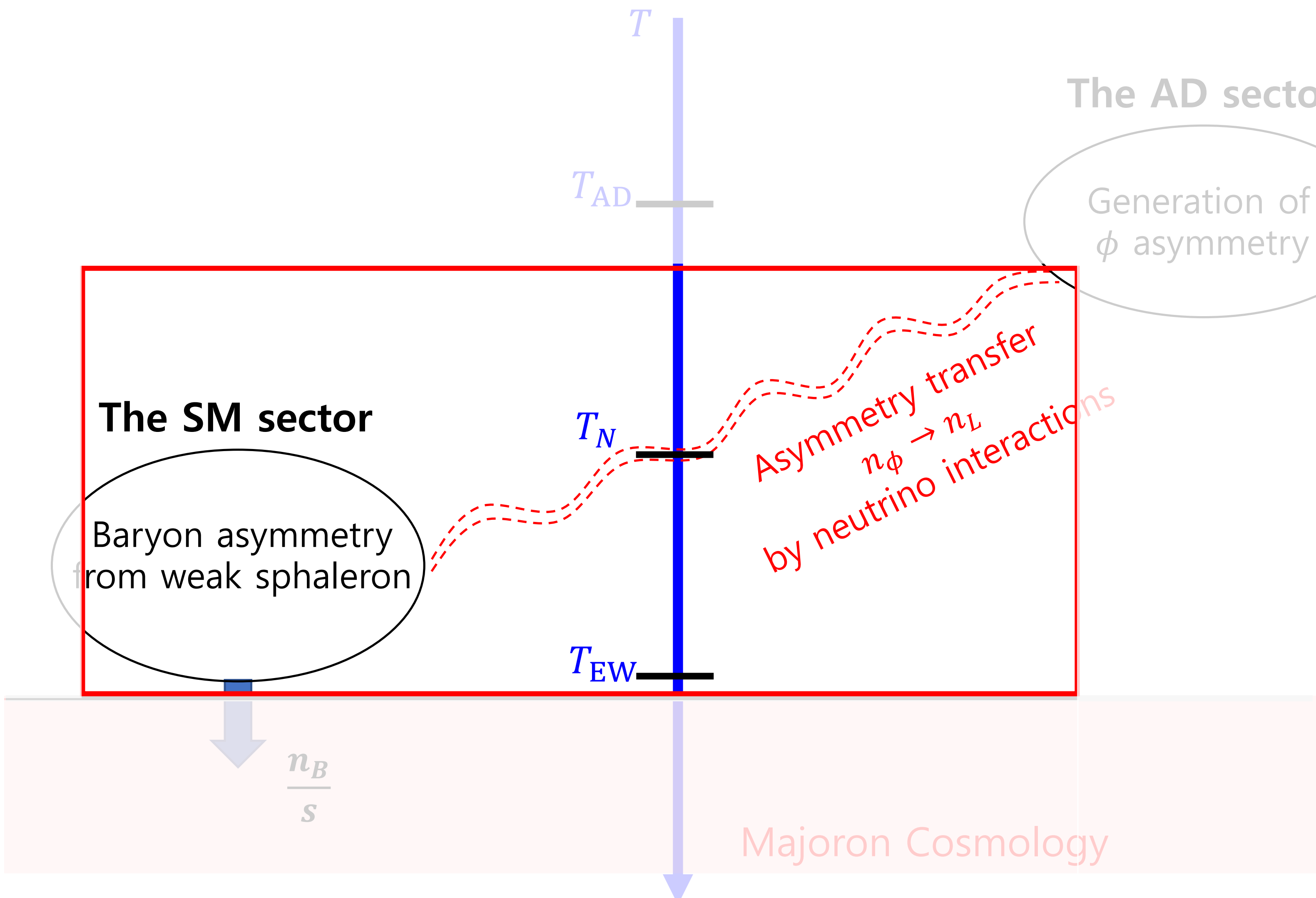
$$\frac{n_\phi}{s} \sim \frac{\alpha}{g_*}\sqrt{\frac{m}{M_P}}$$

More precisely

$$\frac{n_\phi}{s} = 0.1\alpha \frac{\kappa_H}{\kappa} \sin 4\theta_{in} \sqrt{\frac{m}{M_P}} = -\frac{1}{2}\left(\frac{n_{B-L}}{s}\right)$$

Asymmetry Transfer

Neutrino-Portal Affleck-Dine (AD) Baryogenesis : $y_\nu \ell h N + \frac{1}{2}\lambda_N \phi N^2 + V(\phi)$

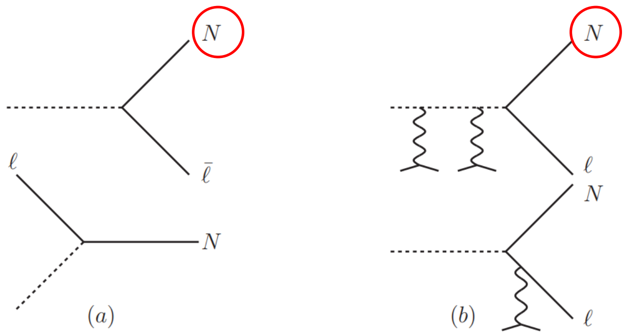


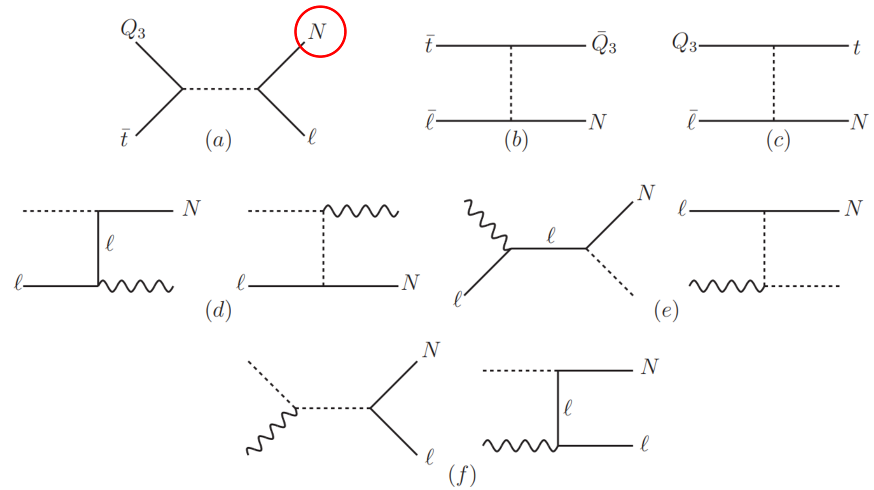
Thermalization of Right handed Neutrino

Neutrino couplings induces the thermal population of RH neutrino & phi particles

$$y_\nu \ell h N + \frac{1}{2}\lambda_N \phi N N \; + h.c.$$

[Besak Bodeker 2012
Garbrecht, Glowna, Schwaller 2013,
Ghisoiu, Laine 2014]





The production rate of RH neutrinos from the SM plasma

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

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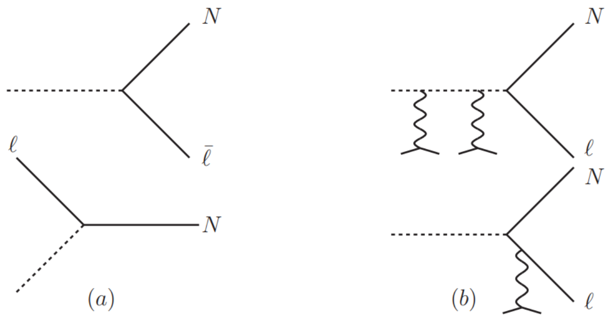

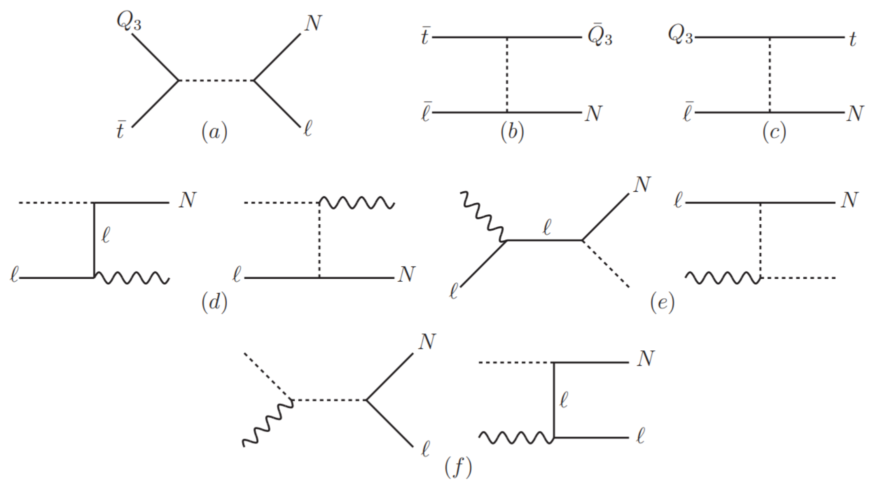

The production rate of RH neutrinos from the SM plasma

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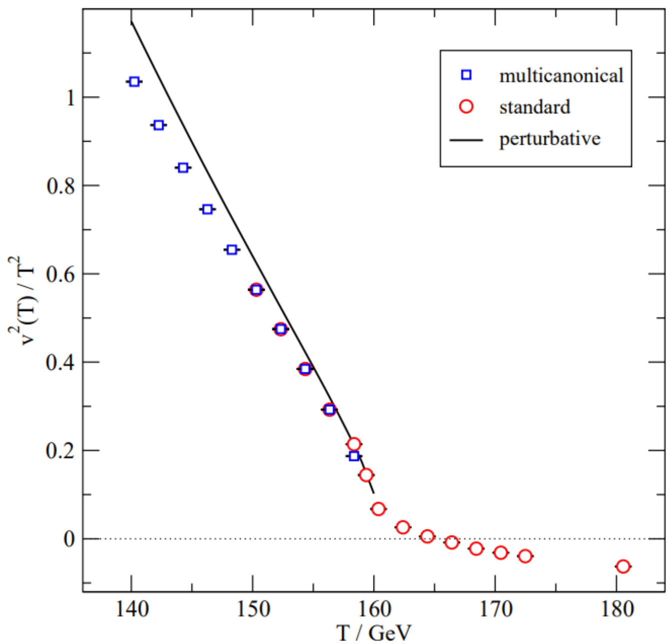
As $T \lesssim T_N$, where $\Gamma_N(T_N) = H(T_N)$, N and ϕ are fully thermalized and the kinetic energy of the angular field is successfully transferred to the asymmetry of the SM sector: $\boldsymbol{n_\phi} \rightarrow \boldsymbol{n_L}$

$$T_N \simeq 5\, m_N \left(\frac{m_\nu}{0.05\mathrm{eV}}\right) \qquad \text{for } m_N = \lambda_N \langle\phi\rangle_{T=0}, \qquad m_\nu = y_\nu^2 v^2 / m_N$$

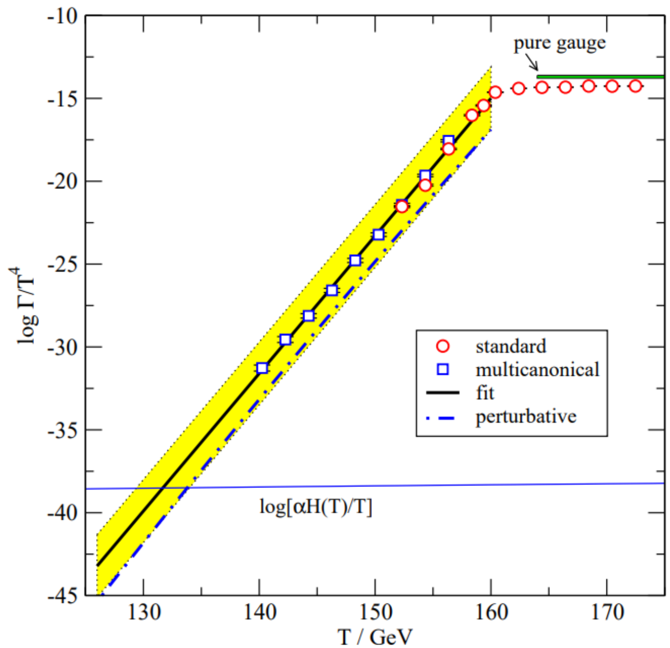
Weak Sphaleron for Baryon Asymmetry

The AD sector should be thermalized before the freeze-out of weak sphaleron process

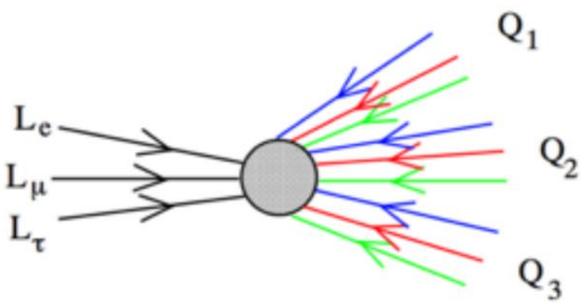
[D'Onofrio, Rummukainen, Tranberg 2014]



$T_{\mathrm{EW}} \simeq 159\ \mathrm{GeV}$



$T_{\mathrm{sp}} \simeq 132\ \mathrm{GeV}$

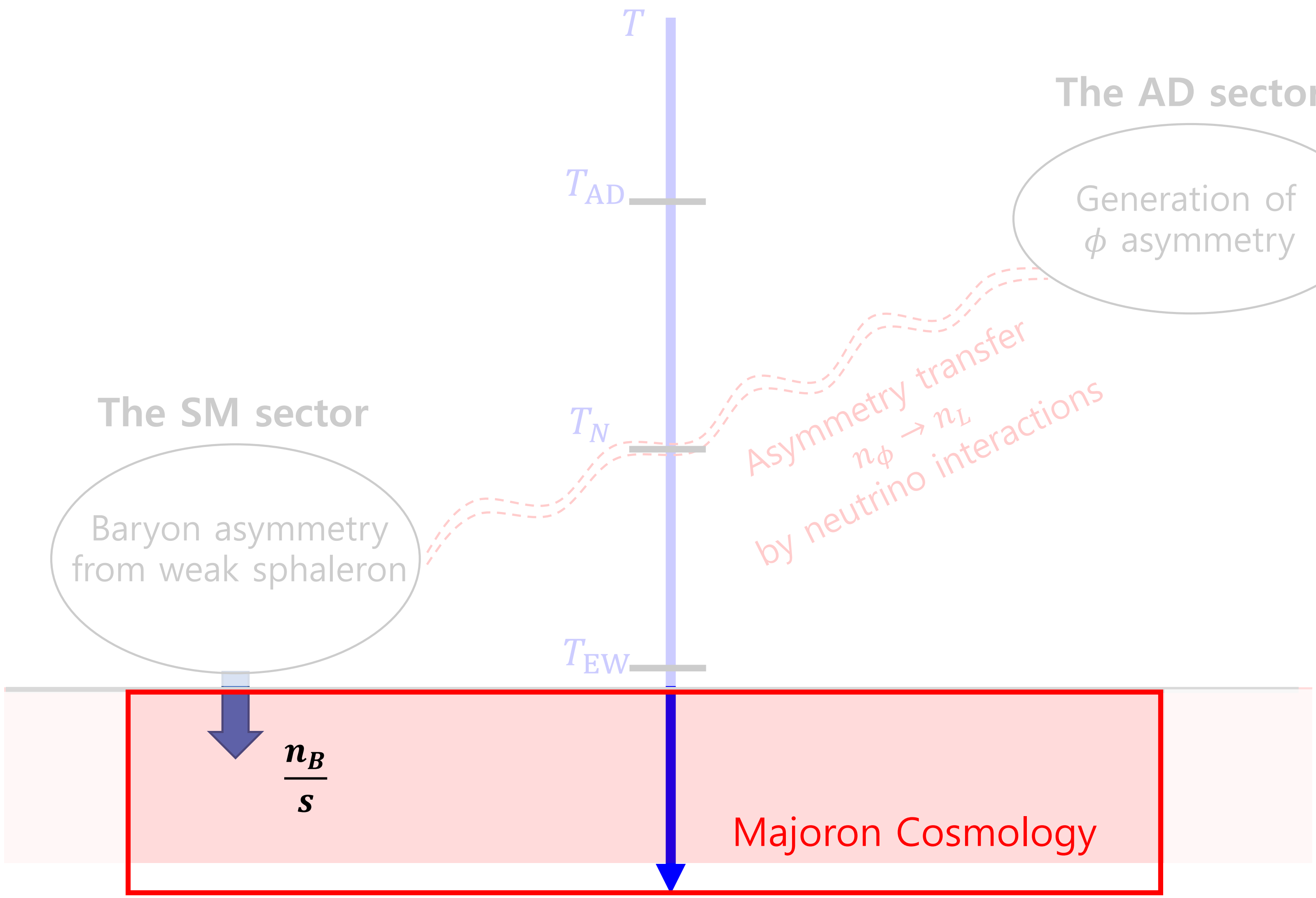


$$n_\phi \to n_L \to n_B \simeq -n_\phi \simeq \frac{n_{B-L}}{2}$$

$$T_N > T_{\mathrm{sp}} \quad \Rightarrow \quad m_N = \lambda_N \langle \phi \rangle \geq 26\ \mathrm{GeV}$$

Majoron Cosmology

Neutrino-Portal Affleck-Dine (AD) Baryogenesis : $y_\nu \ell h N + \frac{1}{2}\lambda_N \phi N^2 + V(\phi)$



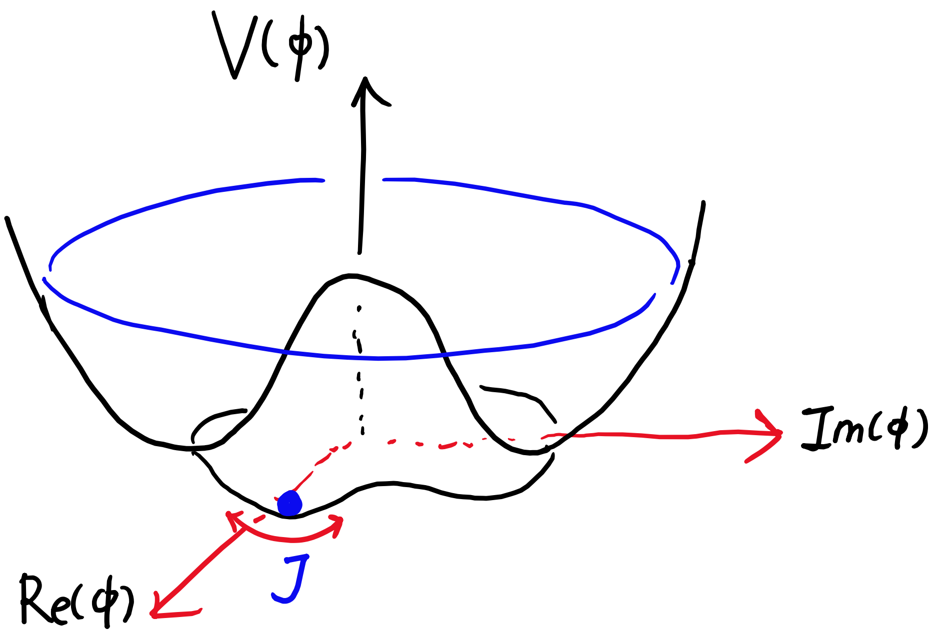
Majoron

After EWPT, $U(1)_{B-L}$ should be eventually spontaneously broken by $\langle\phi\rangle > 26\ \mathrm{GeV}$

(At T=0, phi gets a nonzero VEV induced by that of scalar partner of RH neutrino.
U(1)B-L is dominantly broken by the VEV of RH scalar neutrino)

The Majoron field $J(x)$ the pseudo-Nambu-Goldstone boson for the $U(1)_{B-L}$ is produced.

$$\phi(x) \sim \frac{1}{\sqrt{2}}\,(f_J + \sigma(x))\,e^{i\,J(x)/f_J}$$



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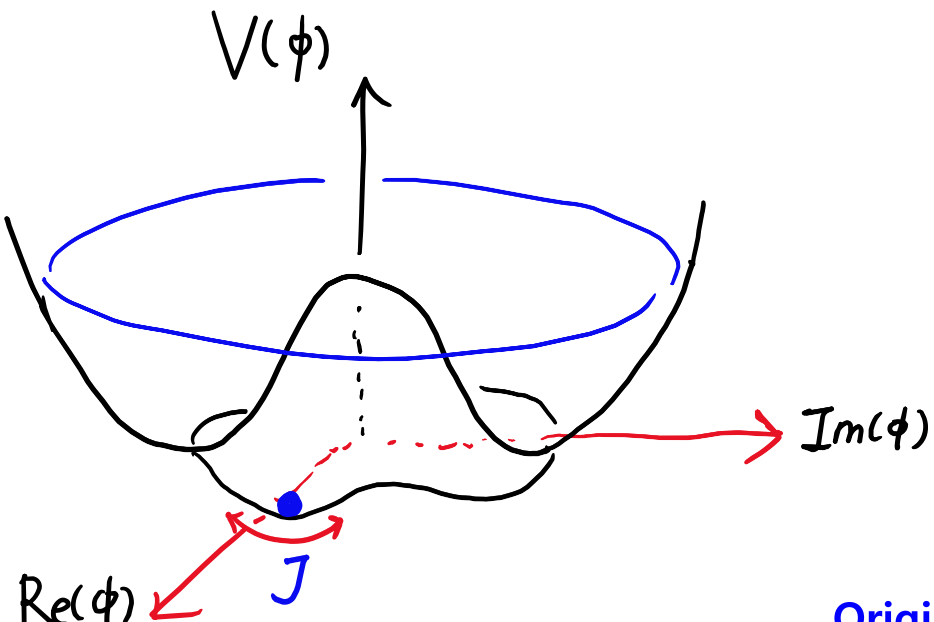

$$V_J \sim -\frac{\kappa \alpha m}{8 M_P} r^4 \cos 4\theta$$

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

$$m_J \simeq f_J \sqrt{\frac{\alpha m}{M_P}} = O(0.1 - 1)\text{keV} \left(\frac{f_J}{100\text{GeV}}\right)$$

$$\tau_J(J \to \nu\nu) \simeq 1\ \text{yr} \left(\frac{f_J}{100\ \text{GeV}}\right)^2 \left(\frac{\text{keV}}{m_J}\right)$$

Origin of baryon asymmetry → Majoron mass

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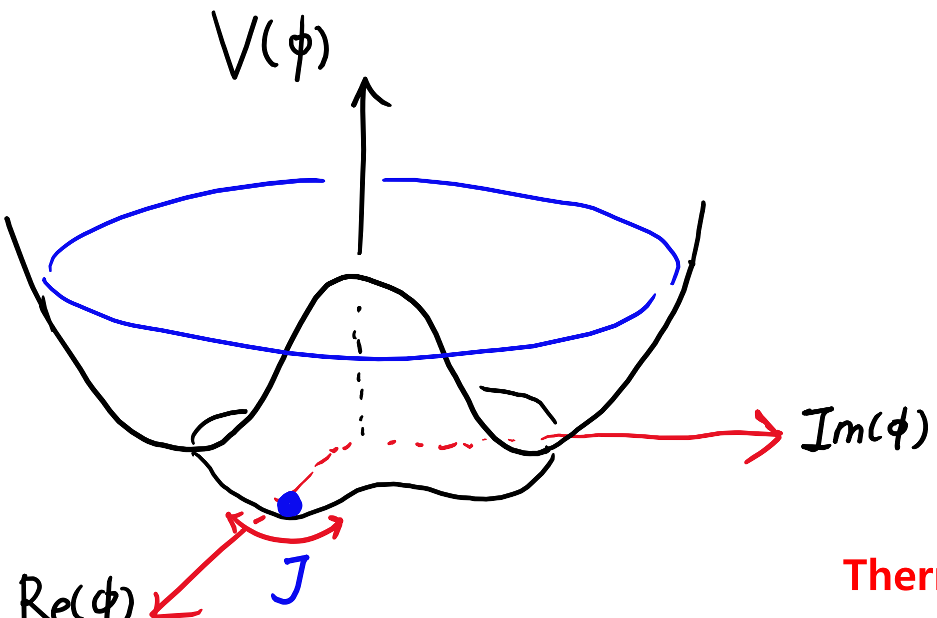

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Thermal Majoron and neutrinos from its decay
→ Additional Relativistic Degrees of Freedom

Majoron Contribution to N_{eff}

1) Majorons are in thermal equilibrium until $T > T_d = 0.1\, m_N$ and decoupled.

2) Majorons decay to neutrinos before or after they become nonrelativistic.

Considering all these effects, we get Delta Neff at CMB era

$$\Delta N_{\mathrm{eff}} = 0.015 \times \max\left[\left(\frac{100}{g_{*S}\,(T_d)}\right)^{4/3}, \left(\frac{m_J}{1\ \mathrm{keV}}\right)^{\frac{1}{2}}\left(\frac{f_J}{100\ \mathrm{GeV}}\right)\left(\frac{100}{g_{*S}(T_d)}\right)\right]$$

f_J cannot be too large due to the ΔN_{eff} constraints

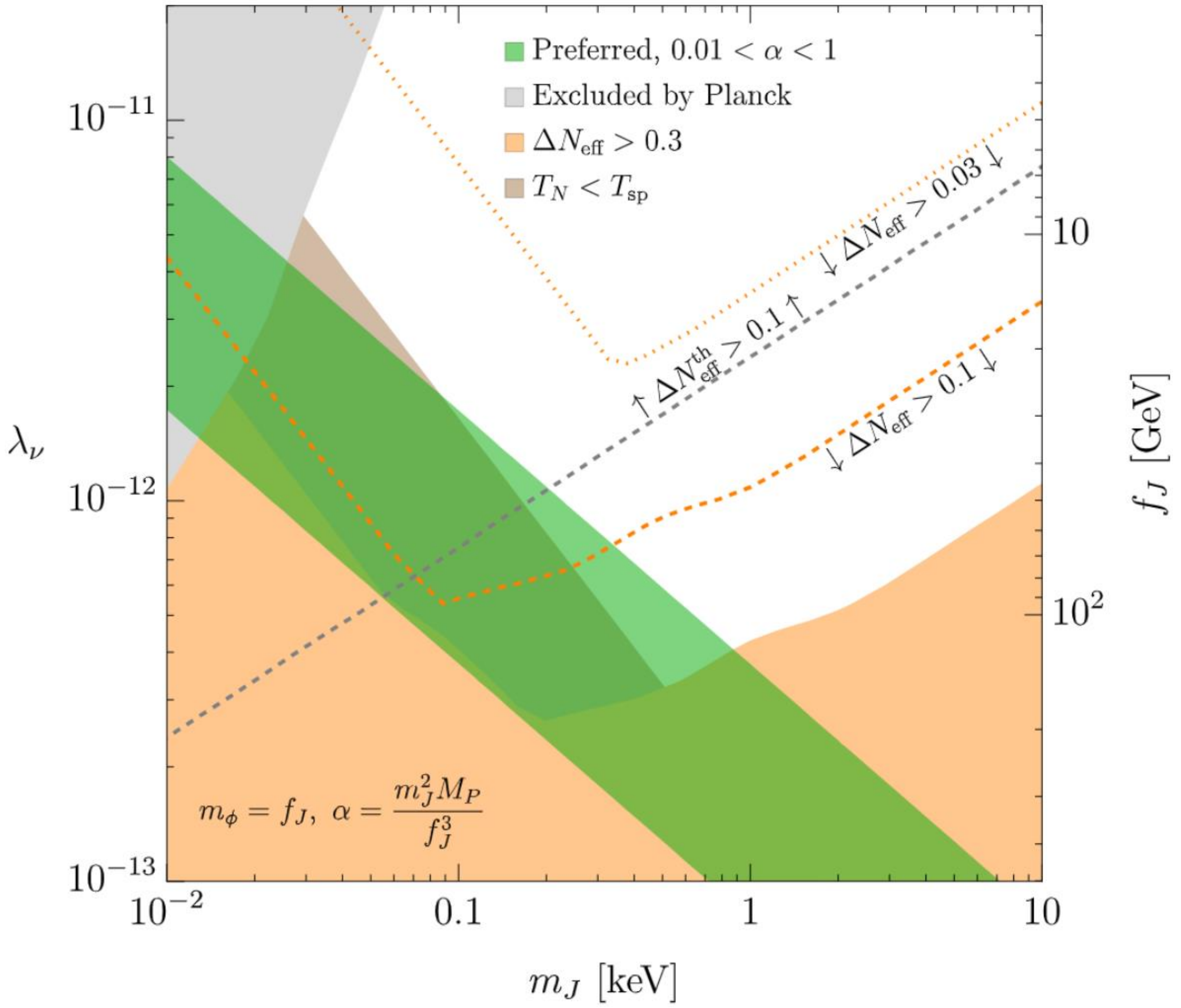
The Majoron decay constant f_J is cosmologically restricted as $f_J = O(100\ \mathrm{GeV})$

From model building point of view, we can easily obtain the result

$$f_J \sim \langle \phi \rangle = O(m) = O(100\ \mathrm{GeV})$$

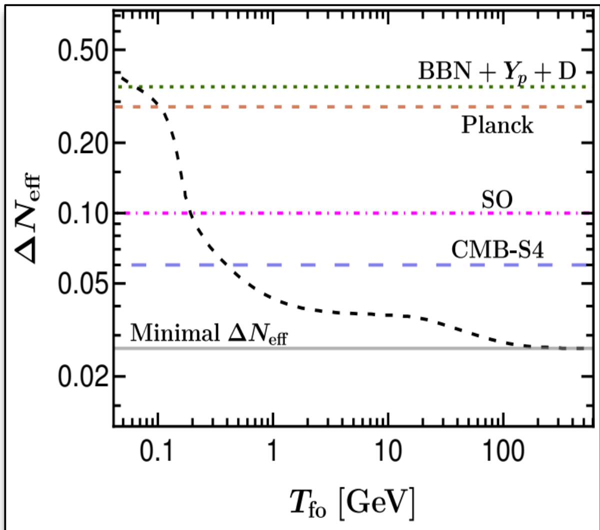
Observational Consequence

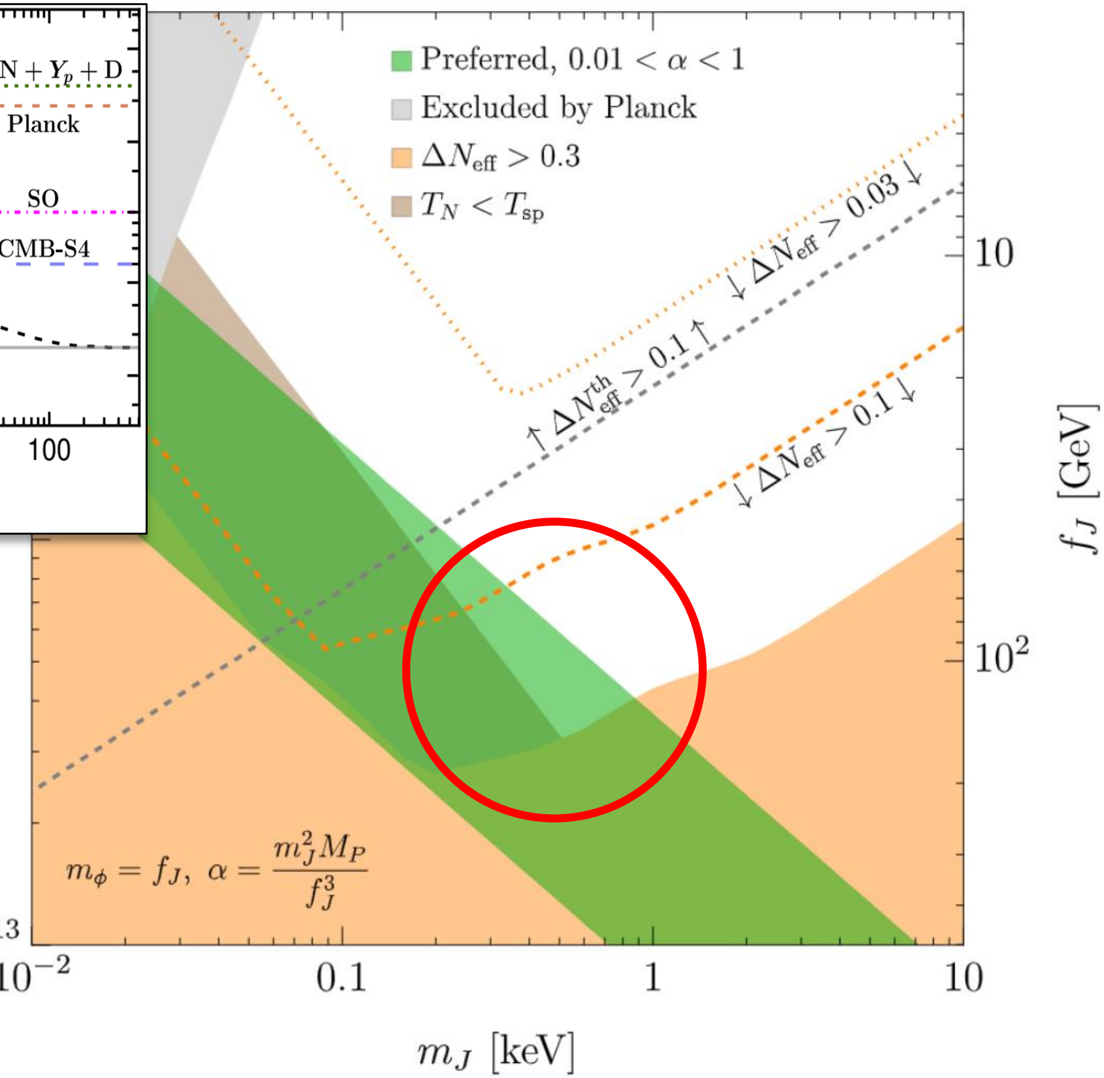
Allowed Parameter Space from Baryogenesis and Majoron Cosmology



Observational Consequence

Strong predictions on $\Delta N_{\rm eff}$ detectable in near-future CMB observations





$$\text{Planck}: \Delta N_{\rm eff} < 0.285\,,$$

$$\text{BBN} + Y_p + \text{D}: \Delta N_{\rm eff} < 0.347\,,$$

$$\text{SO}: \Delta N_{\rm eff} < 0.1\,,$$

$$\text{CMB-S4}: \Delta N_{\rm eff} < 0.06\,.$$

Discussion

We provide a simple model of baryogenesis in which the hierarchy between the weak scale and the Planck scale is the origin of the observed baryon asymmetry.

In our discussion the weak scale has several important implications:

1) **Scalar mass related to the mechanism to protect it from various quantum corrections**

2) **RH neutrino mass crucial for the transfer of the asymmetry from the AD to Baryons**

3) **The majoron mass and lifetime relevant for future CMB observations**

There is still tension between the mass of SM superpartners (greater than 1-10 TeV), and the SM singlet masses discussed in this talk. A more detailed study regarding SUSY breaking mediation mechanism is needed for complete understanding.