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Leptogenesis in Cosmological Relaxation with particle production

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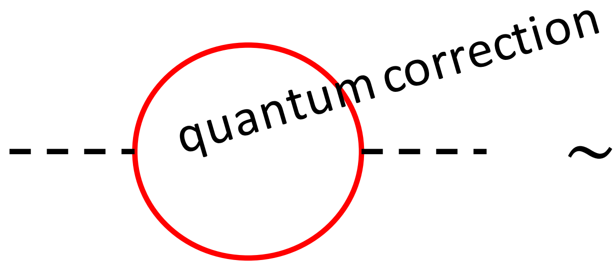
Based on
SON, Fang Ye, Tevong You 1804.06599

Naturalness problem

$\delta m_h^2 \sim$



$\sim E^2$

$\Delta x\, \Delta p \geq \hbar, \Delta E\, \Delta t \geq \hbar$

Natural size of Higgs mass predicted by QM.

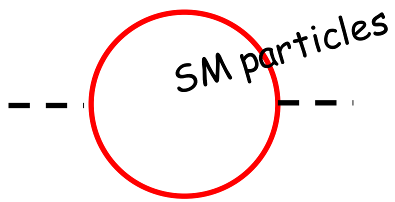
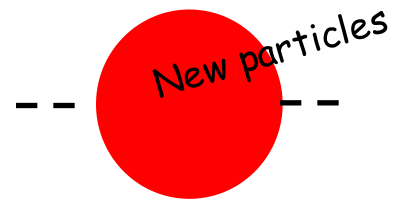
$(125\ \mathrm{GeV})^2 = m_{h\ \mathrm{obs.}}^2$ vs $\delta m_h^2 \sim \Lambda^2$

where Higgs theory is defined

E.g. $\Lambda \sim M_{pl} \sim 10^{18}\ \mathrm{GeV}$

Traditional way of softening quantum fluctuation

1. Algebraic cancellation

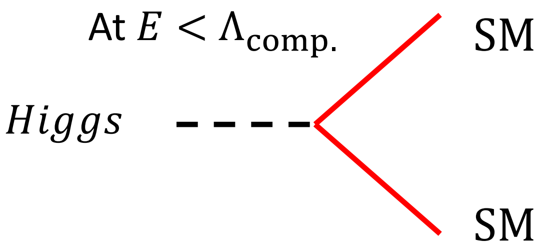
$\delta m_h^2 \sim$  $\sim \Lambda^2$ $+$  $\sim \Lambda^2$

→ disappearance of Λ^2

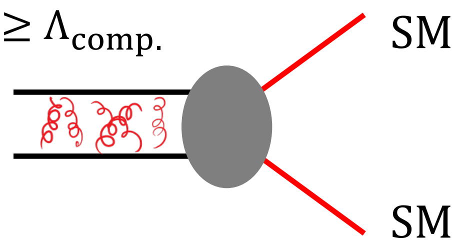
Cancellation is controlled by symmetry

2. Compositeness

At $E < \Lambda_{\text{comp.}}$



At $E \geq \Lambda_{\text{comp.}}$



Problematic scalar field realized as a composite

Alternative to
softening quantum fluctuation

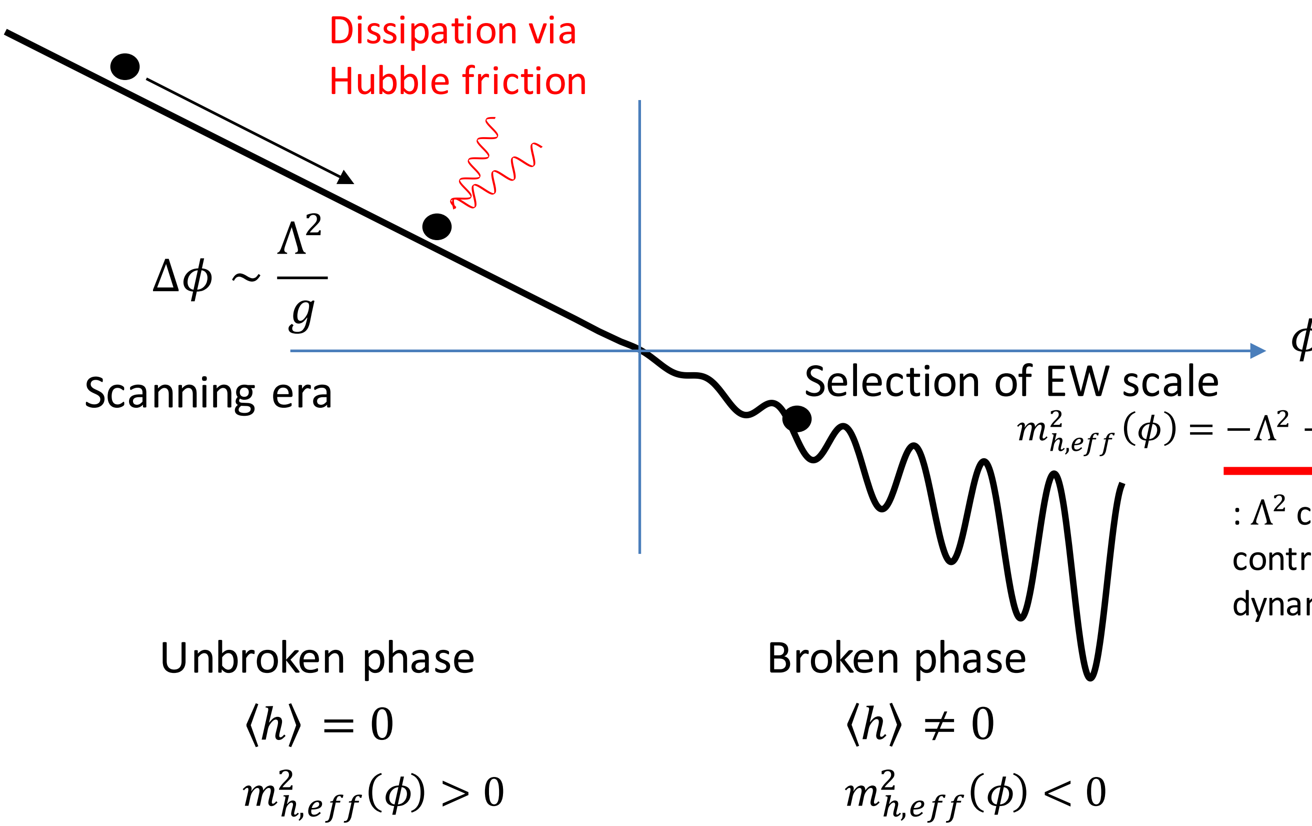
3. Relaxation

Graham, Kaplan, Rajendran 15'

$$\mathcal{L} = (-\Lambda^2 + \underline{g\phi})hh^+ + (g\Lambda^2\phi + g^2\phi^2 + \cdots) + g\phi\Lambda^2 + \Lambda_c^4 \cos\frac{\phi}{f}$$

$\sim \Lambda^2$

w/ $\Lambda_c^4 \propto \langle h \rangle^n$



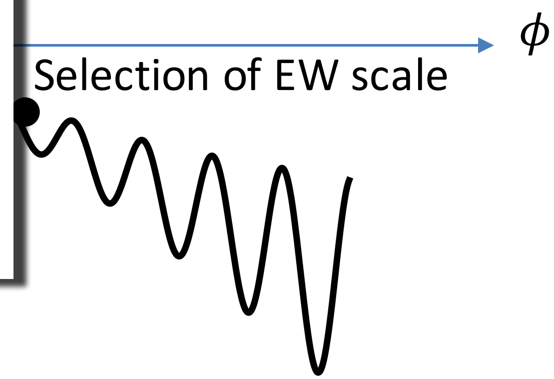
$m_{h,eff}^2(\phi) = -\Lambda^2 + g\phi \sim \mu_{EW}^2 < 0$

: Λ^2 cancellation is controlled by cosmological dynamics

$$\mathcal{L} = (-\Lambda^2 + g\phi)hh^+ + (g\Lambda^2\phi + g^2\phi^2 + \cdots) + g\phi\Lambda^2 + \Lambda_c^4 \cos\frac{\phi}{f}$$

List of constraints

Constraint	Meaning
$g \sim \frac{\Lambda_c^4}{f\,\Lambda^2}$	: slope of linear potential ~ slope of cosine potential
$H > g$	: Hubble friction gives slow-rolling, e.g. $\ddot{\phi} + 3H\dot{\phi} + g\phi = 0$
$g > \frac{H^2 M_{pl}}{\Lambda^2}$	: slow-rolling of relaxion, e.g. $\epsilon, \eta < 1$
$N > \frac{H^2}{g}$	: E-folding from large field excursion, e.g. $\Delta\phi \geq \frac{\Lambda^2}{g}$
$H < \Lambda_c$	: Barrier forms inside the Hubble sphere, e.g. $H^{-1} > \Lambda_c^{-1}$
$H < (g\Lambda^2)^{1/3}$	: classical rolling beats quantum fluctuation, e.g. $\dot{\phi}\,\Delta t > H$
$H > \frac{\Lambda^2}{M_{pl}}$	: $V_{inflaton} > V_{relaxion}$ during inflation, e.g. $H^2 M_{pl}^2 > \Lambda^4$



Last two conditions gives rise to

$$\Lambda < \left(\frac{\Lambda^4 M_{pl}^3}{f}\right)^{1/6} \sim 10^7\ \mathrm{GeV} \times \left(\frac{10^9 GeV}{f}\right)^{1/6}$$

Issues →

1. Super-Planckian
2. Too large e-folding
3. Small scale inflation

....

Particle Production

: dropping Hubble friction as a source of friction improves many problems in the original relaxion model

Particle production
Hook, Marques-Tavares 16’

$$\mathcal{L} = (\Lambda^2 - g\phi)hh^+ + g\phi\Lambda^2 + \frac{\phi}{f}F\tilde{F} + \Lambda_c^4 \cos\frac{\phi}{f'}$$

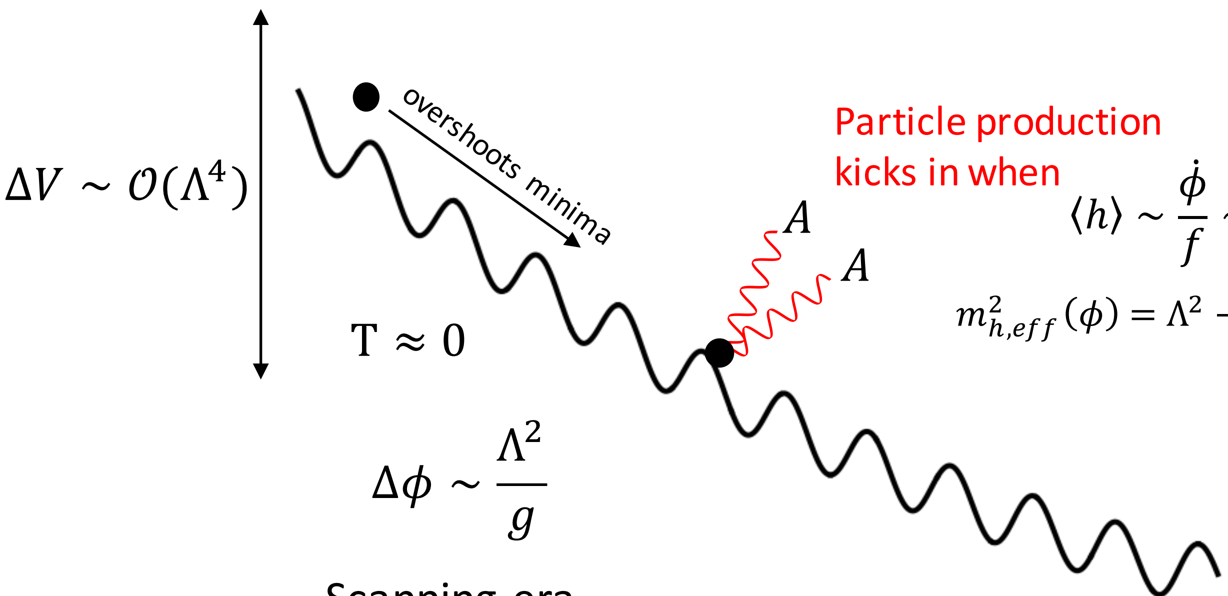
$m_{h,eff}^2(\phi) < 0$

w/ $\Lambda_c^4 \propto$ const.

$$\ddot{A}_\pm + \underbrace{\left(k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}\right)}_{=\,\omega_\pm^2} A_\pm = 0$$

$A_\pm \propto e^{i\omega_\pm t}$ where $\omega_\pm^2 < 0$

for $|\dot{\phi}| \gtrsim 2 f m_A \sim 2 f\langle h\rangle$



Particle production kicks in when

$$\langle h\rangle \sim \frac{\dot{\phi}}{f} \sim \mu_{EW}$$

$$m_{h,eff}^2(\phi) = \Lambda^2 - g\phi \sim \mu_{EW}^2 < 0$$

$$\Lambda_c^4 \cos\frac{\phi}{f'}$$

$$\Delta\phi \sim \frac{\Lambda^2}{g}$$

Scanning era

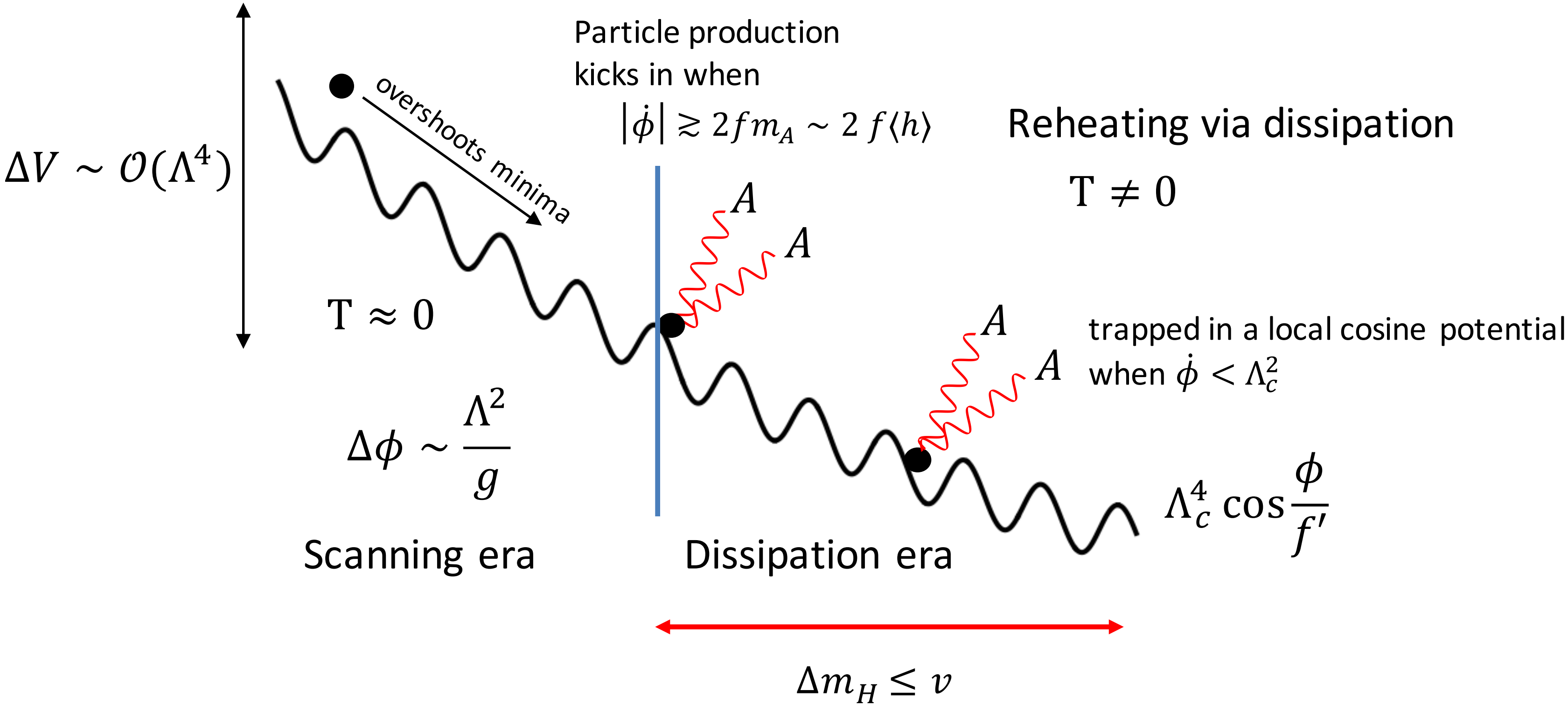
over zero-T Higgs mass
in broken phase

$$\langle h\rangle \neq 0$$

Particle production Hook, Marques-Tavares 16'

$$\mathcal{L} = (\Lambda^2 - g\phi)hh^+ + g\phi\Lambda^2 + \frac{\phi}{f}F\tilde{F} + \Lambda_c^4 \cos\frac{\phi}{f'}$$

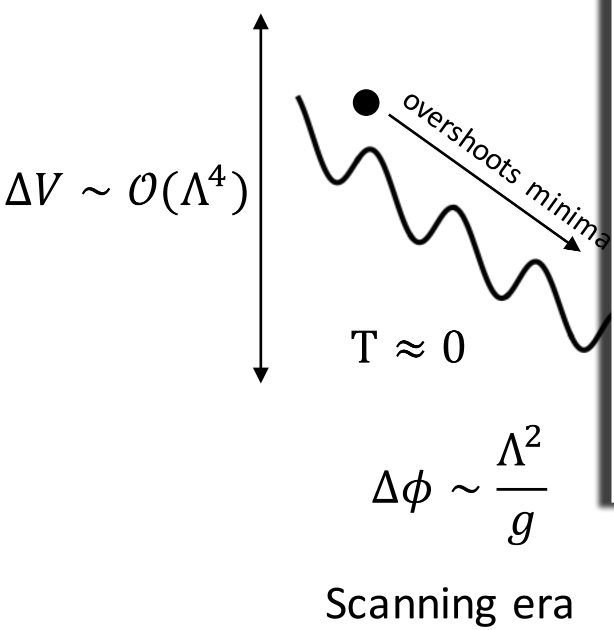
w/ $\Lambda_c^4 \propto$ const.



Particle production

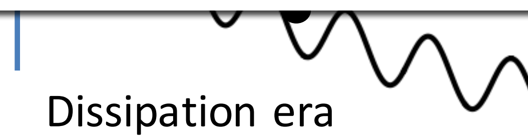
Hook, Marques-Tavares 16'

$$\mathcal{L} = (\Lambda^2 - g\phi)hh^+ + g\phi\Lambda^2 + \frac{\phi}{f}F\tilde{F} + \Lambda_c^4 \cos\frac{\phi}{f'}$$



List of constraints

$g\Lambda^2 < \frac{\Lambda_c^4}{f'}$	: slope of linear potential < slope of cos potential
$\frac{T^2 f^3}{\dot{\phi}_c^3} < H^{-1}$	: energy loss within one Hubble time
$\Delta m_H^2 \sim g\Delta\phi \sim gf' < v^2$	: enough precision
$\Delta m_H \sim \frac{\Delta m_H^2}{m_H} \sim \frac{g}{v}\int dt\, \dot{\phi}$	: do not overshoot correct Higgs mass
$M_p > \frac{\Lambda^2}{g}$	: sub-planckian field excursion



$$\Lambda < \left(M_p v^5\right)^{1/6} \sim 5 \times 10^4 \text{ GeV}$$

We consider relaxation after inflation

Inflation

Inflation can provide the initial condition for $\dot{\phi}$ for the era of the relaxation

Relaxation

needs

$\mathrm{T} \approx 0$

era for scanning over zero-T Higgs mass

needs initial condition to start scanning

arXiv:1805.04543 for a detailed discussion

Reheating-era Leptogenesis

$$\mathcal{L} = \mathcal{L}_{SM-\phi} + \frac{1}{\Lambda_6^2}\lambda_{6,ijkl}\left(\bar{L}_i\gamma^\mu L_j\right)\left(\bar{e}_i\gamma_\mu e_j\right) + \frac{1}{\Lambda_7^3}\lambda_{7,i}L_i h\bar{e}_i{}^c\,\bar{u}^c d^c$$

→ Negligible neutrino mass

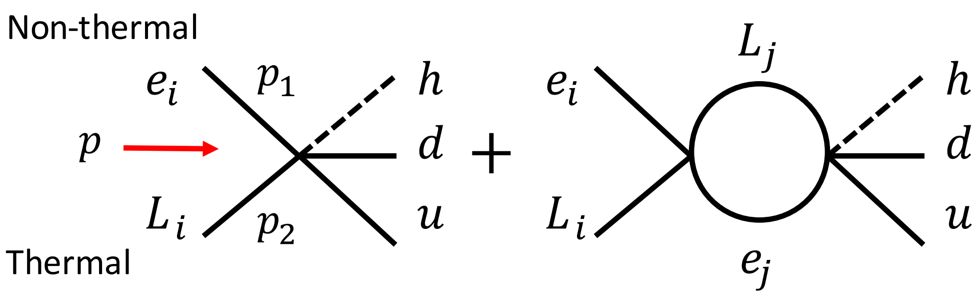
→ Other dim-7 ops are also possible

E.g. $\left(H^\dagger D^\mu \widetilde{H}\right)\left(\bar{e}_i\gamma_\mu H^\dagger l_j\right)$

Loop-induced CP violating process via dimension-6, 7 operators

* Much larger cutoff scale for dim-5,6 ops

Hamada, Kawana 16'



CP violation $\epsilon \sim \dfrac{\sigma_{\bar{L}_i e_i\to\bar{h}u\bar{d}} - \sigma_{L_i\bar{e}_i\to h\bar{u}d}}{\sigma_{\bar{L}_i e_i\to\bar{h}u\bar{d}} + \sigma_{L_i\bar{e}_i\to h\bar{u}d}} \propto p^2 \quad \to \dfrac{4}{\Lambda_6^2}\times\dfrac{p^2}{8\pi}\times\sum_j \dfrac{\lambda_{7,j}\mathrm{Im}(\lambda_{6,ij})}{\lambda_{7,i}}$

$$\frac{n_L}{s} \sim \frac{n'_\phi}{s}\sum_i 2\epsilon_i\ \mathrm{Br}_i\frac{\Gamma_{\mathrm{LNV},i}}{\Gamma_{\mathrm{th}}}$$

$$\Gamma_{\mathrm{LNV},i} \sim \frac{3}{512\pi^5}\zeta(3)\ p^4\left(\frac{\lambda_{7,i}}{\Lambda_7^3}\right)T^3$$

$$\Gamma_{\mathrm{th}} \sim \alpha_2 T$$

Unification of

Relaxation

(naturalness problem)

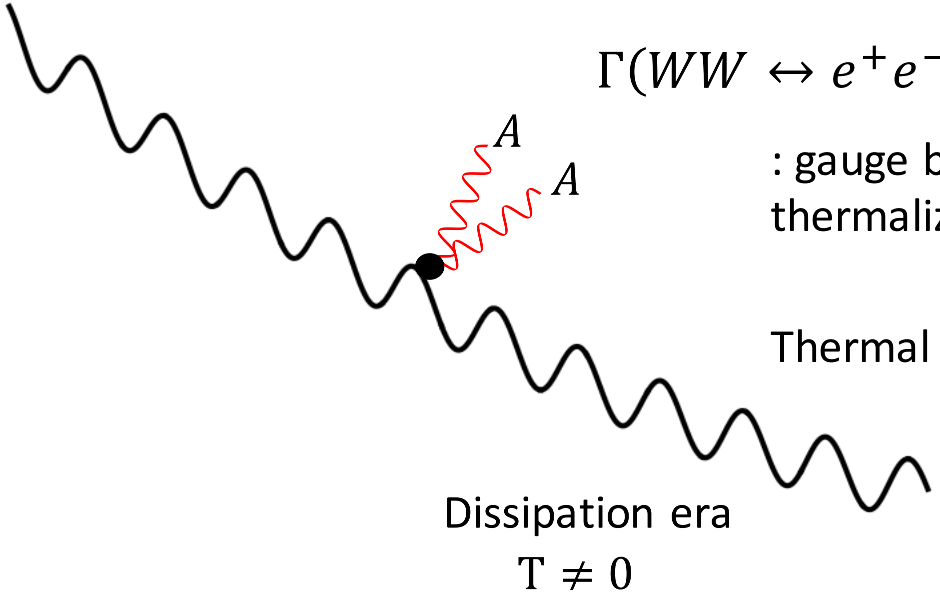
+

Reheating-era Leptogenesis

(matter-anti-matter asym)

: two problems are explained within an EFT with the same cutoff scale in such a way that all ingredients for leptogenesis are provided from the relaxation

Thermal leptons



$$\Gamma(WW \leftrightarrow e^{+}e^{-}) \gg \Gamma_A \sim v$$

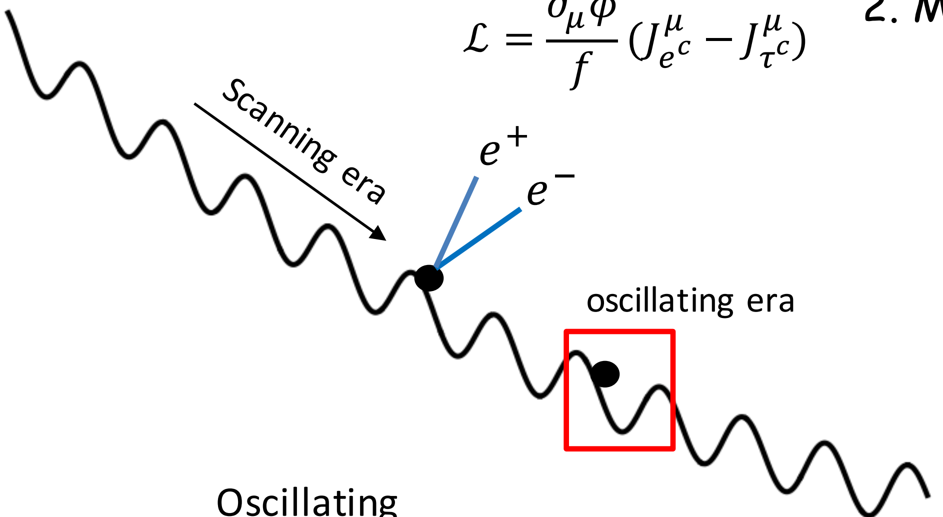
: gauge bosons from particle production quickly thermalize before they decay

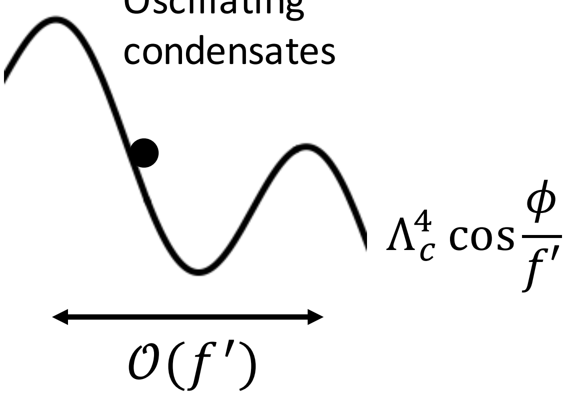
Thermal leptons would have energies $\mathrm{E} \sim 2\times\frac{3}{2}\,\mathrm{T}$

Out-of-equilibrium leptons

Min, SON, Suh, arXiv:1808.00939

$$\mathcal{L} = \frac{\partial_\mu \phi}{f}\left(J^\mu_{e^c} - J^\mu_{\tau^c}\right)$$





1. Fermion production (in progress)

May produce non-thermal leptons. How large?

2. Misalignment condensate

Condensates tend to be depleted via scattering than decaying to non-thermal leptons

Ratio of non-thermal leptons to depletion-rate

$$\sim \frac{\Gamma_{\phi\to e^+e^-}}{\Gamma_{\phi_{\rm depl}}} \sim \frac{m_\phi^2}{T^2}$$

Non-thermal leptons would have energies

$\mathrm{E} \sim [\frac{m_\phi}{2},\ \mathcal{O}(\mathrm{T})]$

3. keep #(non-thermal lepton) as free parameters to cover a broad possibility

$$\frac{\Lambda_c^4}{m_\phi}\left(\frac{m_\phi}{T}\right)^2 \lesssim n'_\phi \lesssim n_\phi$$

From misalignment condensate

Benchmark points for two sources of out-of-equilibrium leptons

2. Misalignment condensate

	$\Lambda, \Lambda_c, \Lambda_{6,7}, T$	f_p	m_ϕ	f_L	f_V	g
$p^2_{\rm max}$	10^5	10^8	100	10^7	5×10^7	10^{-8}
$p^2_{\rm min}$	10^5	5×10^6	2×10^3	10^9	5×10^7	10^{-8}

w/ $6mT \sim p^2_{min} < p^2 < p^2_{max} \sim T^2$

$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{B}{10^{-2}}\right)\left(\frac{T}{10^5\ \mathrm{GeV}}\right)^3\left(\frac{m_\phi}{100\ \mathrm{GeV}}\right)\left(\frac{\Lambda_c}{10^5\ \mathrm{GeV}}\right)^4\left(\frac{10^5\ \mathrm{GeV}}{\Lambda_7}\right)^6\left(\frac{10^5\ \mathrm{GeV}}{\Lambda_6}\right)^2$$

3. keep #(non-thermal lepton) as free parameters to cover a broad possibility

	$\Lambda, \Lambda_c, \Lambda_6, T$	Λ_7	f_p	m_ϕ	f_L, f_V	g
$p^2_{\rm max}$	10^5	10^7	5×10^{11}	0.02	5×10^7	10^{-8}
$p^2_{\rm min}$	5×10^6	10^7	4×10^9	6×10^3	2×10^{11}	10^{-5}

$$\frac{n_B}{s} \sim 10^{-10}\left(\frac{B}{1}\right)\left(\frac{T}{10^5\ \mathrm{GeV}}\right)^8\left(\frac{n_\phi/s}{4\times 10^5}\right)\left(\frac{10^7\ \mathrm{GeV}}{\Lambda_7}\right)^6\left(\frac{10^5\ \mathrm{GeV}}{\Lambda_6}\right)^2$$

See arXiv:1805.04543 for phenomenological and cosmological constraints

Summary

- Naturalness problem and Matter-anti-Matter asymmetry are two big problems in High energy physics. These two problems might be solved by the same New Physics.
- We provided a proof-of-concept example in the context of leptogenesis in cosmological relaxation scenario.

Thanks!