Cosmological Relaxation Models

Tevong You

UNIVERSITY OF CAMBRIDGE

Outline

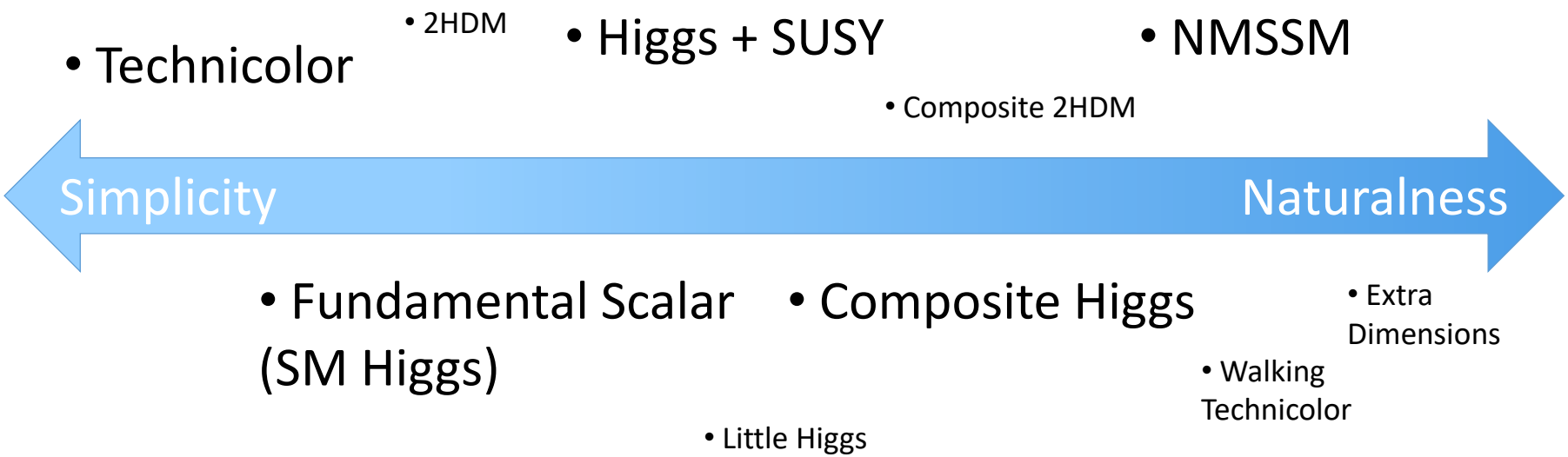
- Electroweak symmetry breaking and the hierarchy problem
- Cosmological relaxation of the weak scale
- Cosmological relaxation with particle production
- Towards a plausible cosmology: including Leptogenesis
- Conclusion

Outline

- **Electroweak symmetry breaking and the hierarchy problem**
- Cosmological relaxation of the weak scale
- Cosmological relaxation with particle production
- Towards a plausible cosmology: including Leptogenesis
- Conclusion

Electroweak symmetry breaking

- A priori many ways to break electroweak symmetry!



- But tension between simplicity and naturalness

The Hierarchy Problem

- Hierarchy problem is still a problem: $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$

$$\delta m_\phi^2 \propto m_{\text{heavy}}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\text{heavy}}}{\mu}\right)$$

- Earliest example of an unnatural, arbitrary feature of a fundamental theory:

$$m_{inertial} = q_{gravity}$$

- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{coulomb}}, \qquad \Delta E_{\text{coulomb}} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

- Pions, GIM mechanism, etc.

- Higgs? Expect new physics close to weak scale…

The Hierarchy Problem

- Hierarchy problem is still a problem: $(m_h)^2_{tree} + (m_h)^2_{radiative} = (m_h)^2_v$

$$\delta m_\phi^2 \propto m_{\text{heavy}}^2, \quad \delta m_\psi \propto m_\psi \log\left(\frac{m_{\text{heavy}}}{\mu}\right)$$

- Earliest example of an unnatural, arbitrary feature of a fundamental theory:

$$m_{inertial} = q_{gravity}$$

- Classical electromagnetism fine-tuning:

$$(m_e c^2)_{\text{obs}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{coulomb}}, \qquad \Delta E_{\text{coulomb}} = \frac{e^2}{4\pi\epsilon_0 r_e}$$

- Pions, GIM mechanism, etc.

- Higgs? Expect new physics close to weak scale…

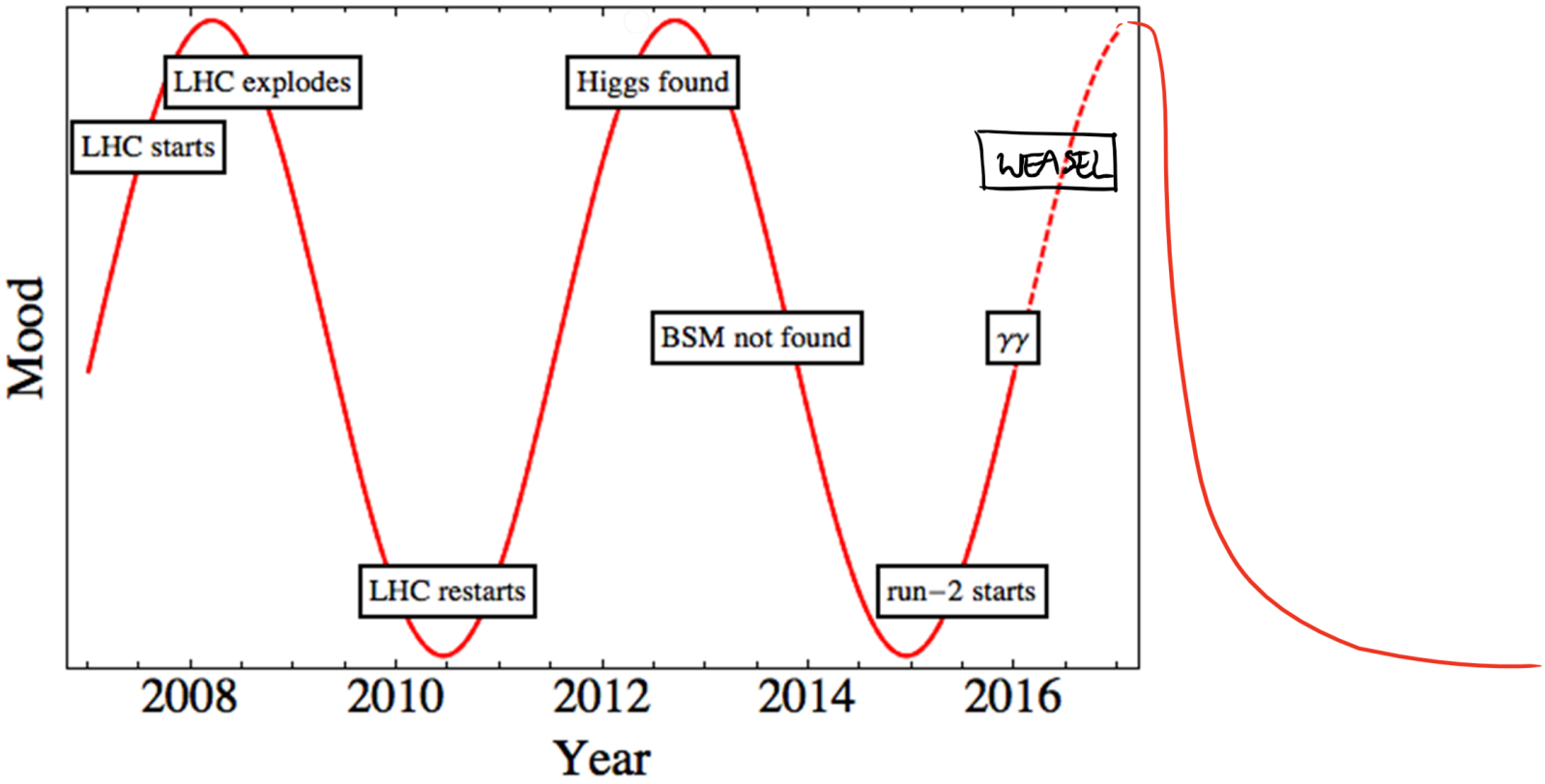
Lots of misconceptions about this lately

Understanding the origin of EWSB

- The SM has many *arbitrary* features put in by hand which hint at **underlying structure**
  - *Pattern of Yukawa couplings, CKM*
  - *QCD Theta term*
  - *Neutrino mass*
  - *Higgs potential*
  - *…*
- Maybe it just is what it is ¯_(ツ)_/¯
- but we would like a **deeper understanding** i.e. an *explanation* for why things are the way they are
  - *e.g. PQ axion for Theta term, see-saw for neutrino mass, Froggat-Nielsen for Yukawas…*
- In SM, **no understanding** of Higgs sector: Higgs potential and couplings *put in by hand and unexplained*
- Just like in condensed matter systems, we feel there must be some underlying system that **explains the origin of EWSB**
- In any such theory in which the Higgs potential is calculable, there is a **UV sensitivity** to the Higgs mass (that is no longer a free parameter) which requires fine-tuned cancellations
- Unlike solutions to other arbitrary features, this one points to **weak-scale new physics**

No new physics at the weak scale?

http://resonaances.blogspot.com.es/2016/01/do-or-die-year.html



- Possibly implies **decoupled** new physics
- Could **cosmological dynamics** be responsible for naturally decoupling BSM Higgs sector?

Outline

- Electroweak symmetry breaking and the hierarchy problem
- **Cosmological relaxation of the weak scale**
- Cosmological relaxation with particle production
- Towards a plausible cosmology: including Leptogenesis
- Conclusion

Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

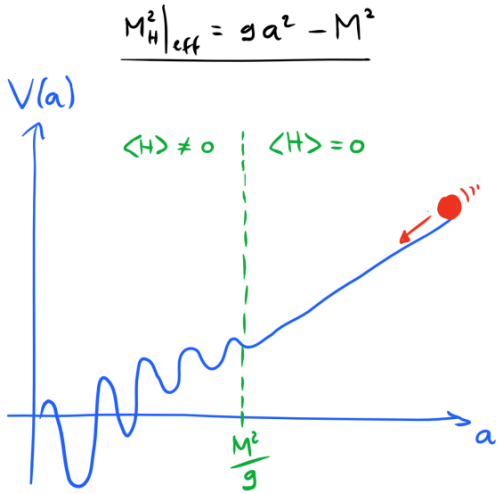
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

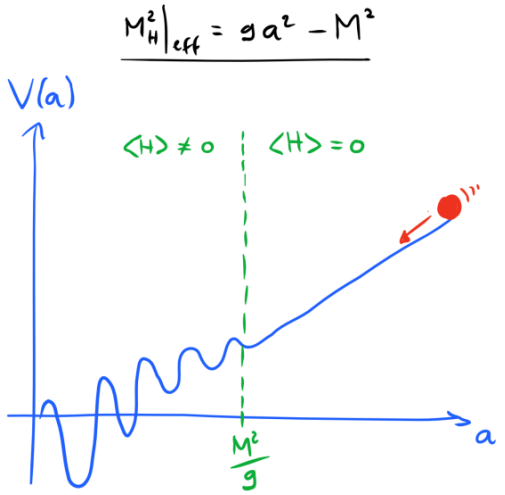
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

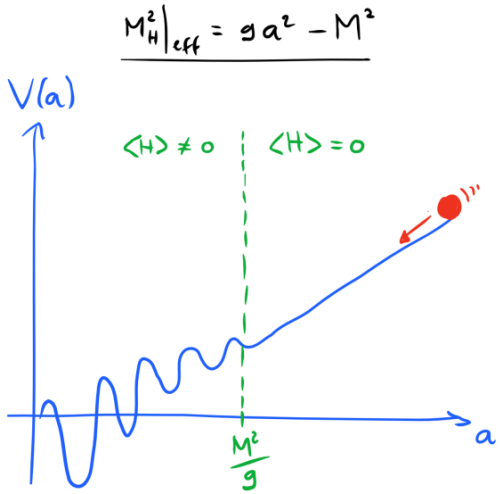
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter g

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

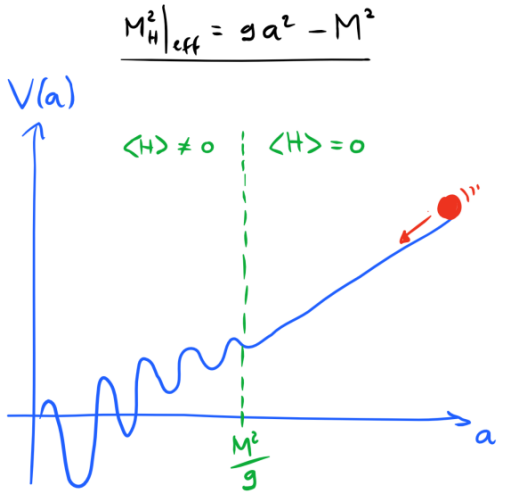
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

L. F. Abbott, Phys. Lett. B 150 (1985) 427

- Higgs mass is naturally at large cut-off M

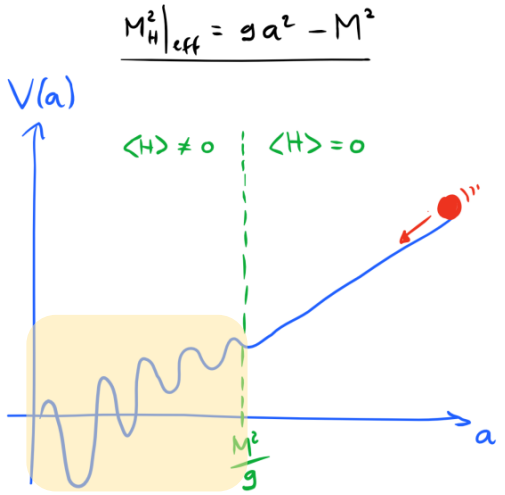
$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

- Axion-like particle *a* protected by shift symmetry, explicitly broken through technically-small parameter *g*

- Scans an effective Higgs mass

- Barriers switch on after EWSB

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$



Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

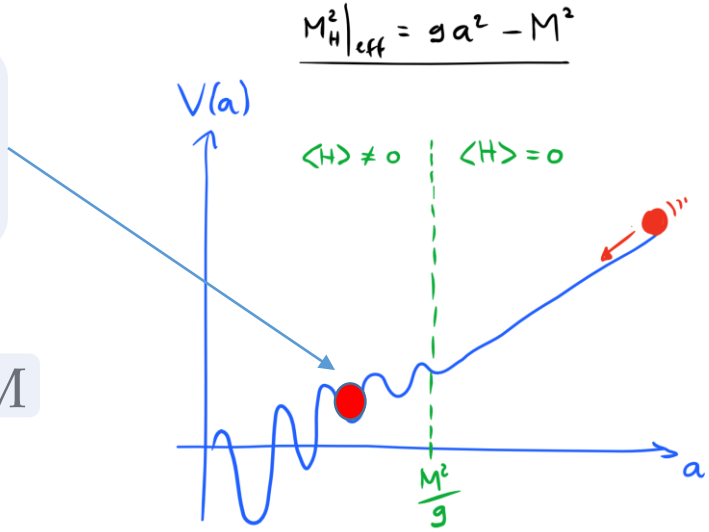
L. F. Abbott, Phys. Lett. B 150 (1985) 427

$$V_{\rm soft}(a) \simeq (ga - M^2)|h|^2 + gM^2 a + \ldots$$

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n$$

- Trapped when barrier height = slow-roll slope

$$gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$



- Technically natural $v \ll M$

Cosmological Relaxation

P. W. Graham, D. E. Kaplan and S. Rajendran, [arXiv:1504.07551]

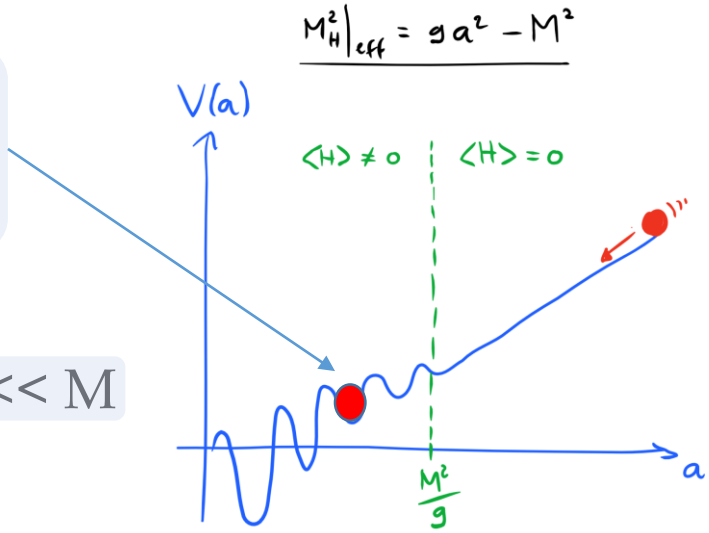
L. F. Abbott, Phys. Lett. B 150 (1985) 427

Constraints: H < v, classical rolling vs quantum, inflaton energy density dominates relaxion, etc.

Very small *g* and natural scanning range lead to super-planckian field excursions, exponential e-foldings…

- Trapped when barrier height = slow-roll slope

$$gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$



- Technically-natural for $v \ll M$

Outline

- Electroweak symmetry breaking and the hierarchy problem
- Cosmological relaxation of the weak scale
- **Cosmological relaxation with particle production**
- Towards a plausible cosmology: including Leptogenesis
- Conclusion

Relaxation Models

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n \qquad gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$

- **n=1 models** Graham et al [1504.07551]
  - G=QCD: Need additional ingredients to overcome strong-CP problem
  - New gauge group G: new physics at weak scale + coincidence problem

- **n=2 models** Espinosa et al [1506.09217]
  - G can be at higher scales, raises M cut-off too
  - Requires second scalar to relax relaxion barriers: double-scanning mechanism

- **n=0 models** Hook and Marques-Tavares [1607.01786], **TY** [1701.09167]
  - More promising, make use of axial gauge coupling $\mathcal{L} = \frac{1}{32\pi^2}\frac{a}{f}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}G_{\mu\nu}G_{\rho\sigma}$

Relaxation Models

$$V_{\cos}(a) = \Lambda_G^4 \cos(a/f) \qquad \Lambda_G^4 \equiv \Lambda_G^{4-n} v^n \qquad gM^2 \sim \frac{\Lambda_G^{4-n} v^n}{f_\phi}$$

- **n=1 models** Graham et al [1504.07551]
  - G=QCD: Need additional ingredients to overcor problem
  - New gauge group G: new physics at weak scale problem

Particle production also used in n=1 models for side-effects:

Choi, Kim, Sekiguchi [1611.08569]

Tangarife, Tobioka, Ubaldi, Volansky [1706.03072]

- **n=2 models** Espinosa et al [1506.09217]
  - G can be at higher scales, raises M cut-off too
  - Requires second scalar to relax relaxion barriers: double-scanning mechanism

- **n=0 models** Hook and Marques-Tavares [1607.01786], **TY** [1701.09167]
  - More promising, make use of axial gauge coupling $\mathcal{L} = \frac{1}{32\pi^2}\frac{a}{f}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}G_{\mu\nu}G_{\rho\sigma}$

Relaxation backreaction on inflation

TY [arXiv:1701.09167]

- Minimal relaxion setup, **no v-dependence in relaxion sector**

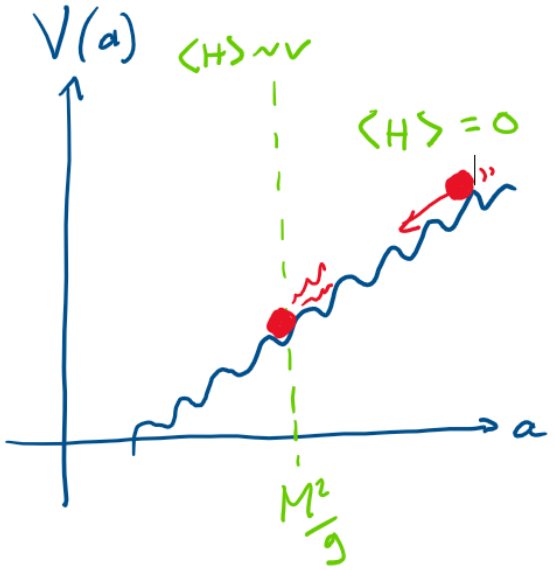
$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + ... + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\,,$$

- Backreaction instead ends inflation
  - e.g. Inflation supported by electroweak dissipation $\mathcal{L} \supset -\frac{\alpha}{f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\ddot{\sigma} + 3H\dot{\sigma} + V'_\sigma(\sigma) = -I\frac{\alpha}{f}\left(\frac{H}{\xi}\right)^4 e^{2\pi\xi}\,, \qquad \xi \equiv \frac{\alpha}{2f}\frac{\dot{\sigma}}{H}$$

See e.g. Anber and Sorbo 0908.4089

- Hubble falls
- Dark dissipation increases
- Relaxion loses KE and is trapped



Relaxation backreaction on inflation

TY [arXiv:1701.09167]

- Minimal relaxion setup, **no v-dependence in relaxion sector**

$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + ... + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\,,$$

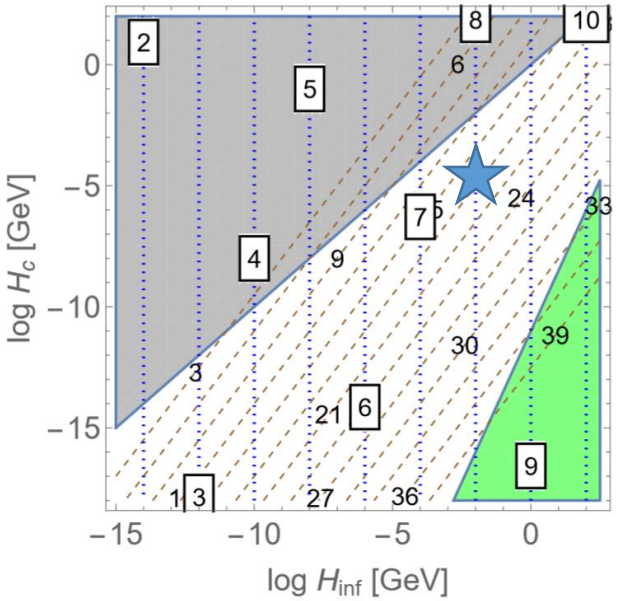
- Backreaction instead ends inflation
  - e.g. Inflation supported by electroweak dissipation $\mathcal{L} \supset -\frac{\alpha}{f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\ddot{\sigma} + 3H\dot{\sigma} + V'_\sigma(\sigma) = -I\frac{\alpha}{f}\left(\frac{H}{\xi}\right)^4 e^{2\pi\xi}\,, \qquad \xi \equiv \frac{\alpha}{2f}\frac{\dot{\sigma}}{H}$$

See e.g. Anber and Sorbo 0908.4089

- Hubble falls
- Particle production increases
- Relaxion loses KE and is trapped

	M	g	H_I	H_c	N_e	Λ_G	f_ϕ	f_D/α_D
$\sim$ [GeV]	10^8	10^{-11}	10^{-2}	10^{-5}	10^{18}	$10^{3.5}$	10^9	10^{15}

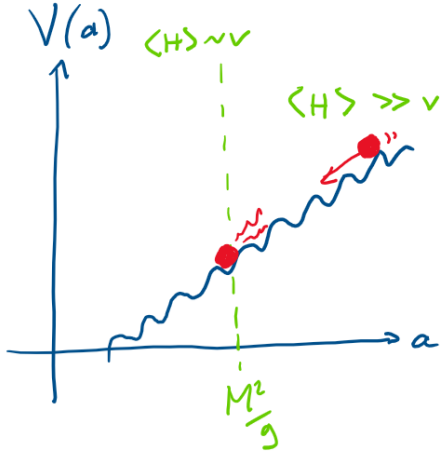


Relaxation backreaction on particle production

Hook and Marques-Tavares [arXiv:1607.01786]

- v-dependence in gauge particle production

$$\mathcal{L} \supset \left(M^2 - g\phi\right)|h|^2 + gM^2\phi + \ldots + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) - \frac{\alpha_D}{f_D}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\,,$$



$$\ddot{A}_\pm + \omega_\pm^2 A_\pm = 0$$

$$\omega_\pm^2 = k^2 + m_A^2 \pm k\frac{\dot{\phi}}{f_V}$$

$$A_\pm(k) \propto \exp(i\omega_\pm t)$$

- For M ~ 10-100 TeV sub-Planckian field excursions, no tiny parameters
- Model can be realised before, during, or after inflation

Outline

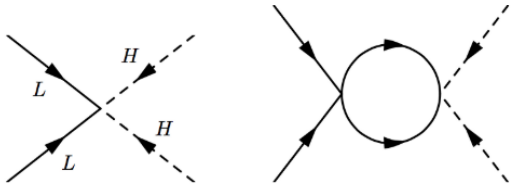
- Electroweak symmetry breaking and the hierarchy problem
- Cosmological relaxation of the weak scale
- Cosmological relaxation with particle production
- **Towards a plausible cosmology: including Leptogenesis**
- Conclusion

Leptogenesis in Cosmological Relaxation with Particle Production

Minho Son, Fang Ye, **TY** [1804.06599]

- Difficult to accommodate naturally in original GKR approach
- Low-scale inflation, low reheating temperatures, and no new physics below cut-off
- In relaxation after inflation, relaxion particle production can reheat universe (plus, inflation can be at high scale)
- Leptogenesis during reheating: L and CP violation by higher-dimensional operators parametrising decoupled new physics

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\lambda_{1,ij} H H \bar{L}_j^c L_i + \frac{1}{\Lambda_2^2}\lambda_{2,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{L}_k\gamma_\mu L_l) + \frac{1}{\Lambda_3^2}\lambda_{3,ijkl}(\bar{L}_i\gamma^\mu L_j)(\bar{E}_k\gamma_\mu E_l) + h.c.$$



Hamada & Kawana [arXiv:1510.05186]

Leptogenesis in Cosmological Relaxation with Particle Production

Minho Son, Fang Ye, **TY** [1804.06599]

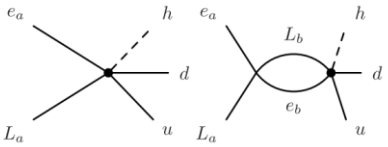
- *Minimal EFT setup* for naturally decoupled new physics

$$\mathcal{L}_{\rm SMEFT} \supset \mathcal{L}_{\rm SM} + \frac{c^{(5)}}{\Lambda_5}\mathcal{O}^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_{6,i}^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_{7,i}^3}\mathcal{O}_i^{(7)} + \ldots$$

$$\mathcal{L}_{\rm SMEFT+\phi} \supset (\Lambda^2 - g\phi)|h|^2 + g\Lambda^2\phi + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) \qquad \mathcal{L}_\phi \supset -\frac{1}{4}\frac{\alpha_V}{f_V}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu \phi}{f_L} J^{5\mu}$$

- Out-of-equilibrium leptons produced by relaxion scatter with leptons in thermal bath

- Dim-7 LNV operators + CP-violation from interference including dim-6 operators



$$\epsilon_a = \frac{\sigma(\bar{L}_a e_a \to \bar{h} u \bar{d}) - \sigma(L_a \bar{e}_a \to h \bar{u} d)}{\sigma(\bar{L}_a e_a \to \bar{h} u \bar{d}) + \sigma(L_a \bar{e}_a \to h \bar{u} d)}$$

- Generates sufficient baryon asymmetry

$$\frac{n_L}{s} \simeq \frac{n'_\phi}{s} \sum_a 2\epsilon_a \mathcal{B}_a \frac{\Gamma_{{\rm LNV}a}}{\Gamma_{\rm th.}}$$

$$\frac{n_B}{s}\Big|_{\rm pert.} \sim 10^{-10} \left(\frac{\mathcal{B}}{10^{-2}}\right) \left(\frac{T}{10^5\ {\rm GeV}}\right)^3 \left(\frac{m_\phi}{100\ {\rm GeV}}\right) \times \left(\frac{\Lambda_c}{10^5\ {\rm GeV}}\right)^4 \left(\frac{10^5\ {\rm GeV}}{\Lambda_7}\right)^6 \left(\frac{10^5\ {\rm GeV}}{\Lambda_6}\right)^2$$

Leptogenesis in Cosmological Relaxation with Particle Production

Minho Son, Fang Ye, **TY** [1804.06599]

- *Minimal EFT setup* for naturally decoupled new physics

$$\mathcal{L}_{\rm SMEFT} \supset \mathcal{L}_{\rm SM} + \frac{c^{(5)}}{\Lambda_5}\mathcal{O}^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_{6,i}^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_{7,i}^3}\mathcal{O}_i^{(7)} + \ldots$$

$$\mathcal{L}_{\rm SMEFT+\phi} \supset (\Lambda^2 - g\phi)|h|^2 + g\Lambda^2\phi + \Lambda_G^4 \cos\left(\frac{\phi}{f_\phi}\right) \qquad \mathcal{L}_\phi \supset -\frac{1}{4}\frac{\alpha_V}{f_V}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu \phi}{f_L} J^{5\mu}$$

- For **O(100) TeV** cut-off, achieve naturalness and baryon asymmetry with **no new physics below cut-off** and **sub-planckian** field range

	$\Lambda, \Lambda_c, \Lambda_{6,7}, T$	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}

- Conceptually attractive: tying relaxion to leptogenesis combines "**censorship**" and "**dynamical**" selection mechanisms of weak scale hierarchy explanations

Many directions to pursue…

(apologies for lack of references)

- Cosmological relaxation is not a solution to the *full* hierarchy problem

- Expect a UV completion e.g. supersymmetry, composite Higgs, extra-dimensions

  Batell, Giudice, McCullough [1509.00834]
  Evans, Gherghetta, Nagata, (Thomas) [1704.03695 (1602.04812)]
  Batell, Fedderke, Wang [1705.09666]
  Fonseca, von Harling, de Lima, Machado [1712.07635]
  …

- Rescue original QCD relaxion?

  Nelson, Prescod-Weinstein [1708.00010]
  Davidi, Gupta, Perez, Redigolo, Shalit [1711.00858]
  …

- Other scanning or trapping backreaction mechanisms?

  Hardy [1507.07525]
  Matsedonskyi [1509.03583]
  …

- Phenomenology

  Flacke, Frugiele, Fuchs, Gupta, Perez [1610.02025]
  Choi, Im [1610.00680]
  …

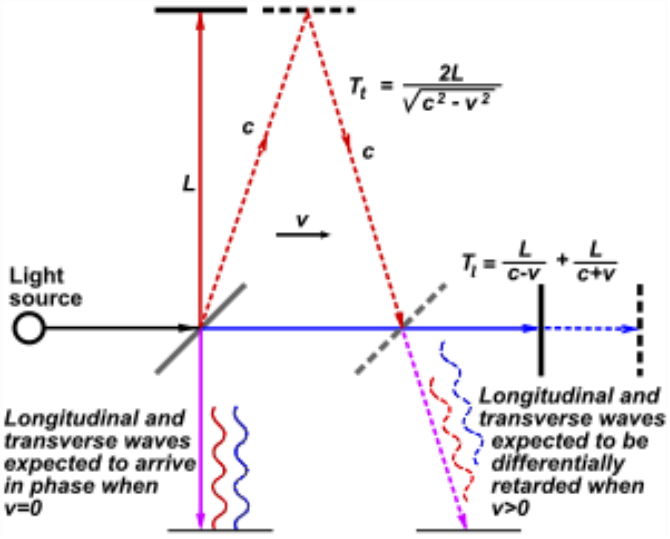
Conclusion

- **Hierarchy problem** is even more of a problem now than before
- **Cosmological relaxation** a natural way of decoupling new physics
- Original model a **proof of concept**
- Many other implementations possible; variety of **Higgs-dependent phenomena** in early universe can be used as a weak-scale backreaction
- Relaxation with **particle production** a step closer to a realistic model

Conclusion

- A SM-like Higgs boson and no direct signs of new physics may turn out to be a significant experimental **null result**

- Null results may still lead to **deeper understanding**



- *No new physics at the TeV scale could be our "Michelson-Morley" moment*

Backups