Portoroz, from the early universe to future colliders workshop, 13th April 2023



Cosmological approaches to naturalness problems

Tevong You

Introduction

- The good: QCD axion solution of strong CP problem
 - Most likely candidate for existing in nature
- The **bad**: Abbott relaxation of cosmological constant
 - Doesn't work
- The **ugly**: Cosmological relaxation of weak scale
 - Works, but wouldn't bet on it yet
- The exotic: Self-Organised Localisation
 - Requires eternal inflation (with notable exception for CC solution)
- Beyond cosmological solutions
 - Exotic UV theories with EFT-violating UV/IR properties?



(Many other nice proposals I won't have time to review here)



$$\mathcal{L} \supset \Lambda_p^4 \cos\left(\frac{\phi}{f_p}\right)$$

- Needs no introduction widely accepted cosmological solution
- First incarnation (Weinberg-Wilczek axion) ruled out ⇒ DFSZ / KSVZ invisible axion
- Has a 'halo of truth' to it, but also lack of attractive alternatives
- Still a PQ quality problem: requires additional UV model-building



- Vacuum energy relaxed by ϕ
- Periodic potential barriers **suppressed** by Hawking temperature
- **Unsuppressed** for small enough vacuum energy density ⇒ **trapped at small CC**
- However, ends in **cold empty universe**
- Reheating requires *e.g. null energy condition violation*

Alberte et al 1608.05715 Graham, Kaplan, Rajendran 1902.06793

- Assume Higgs mass is naturally large at cut-off M
 - $\mathcal{L} \supset (M^2 + \epsilon M\phi)|h|^2 + \epsilon M^3\phi + \dots + \Lambda_p^{4-n}v^n \cos\left(\frac{\phi}{f_p}\right)$
- Higgs quadratic term scanned by axion-like field φ during inflation
- φ protected by shift symmetry, explicitly broken by small parameter ε
- Backreaction when $< h > \sim v$ stops ϕ evolution at small electroweak scale v





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

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Relaxation with particle production

• Generically expect shift-symmetric axion coupling to gauge fields

$$\mathcal{L} \supset (M^2 + \epsilon M\phi)|h|^2 + \epsilon M^3\phi + \dots + \Lambda_p^4 \cos\left(\frac{\phi}{f_p}\right) + \frac{\alpha_V}{4\pi f_V}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Naturally leads to particle production
- Enhanced when reaching critical point Hook and Marques-Tavares [1607.01786], TY [1701.09167]

$$\ddot{\phi} + 3H\dot{\phi} - \epsilon M^3 + \frac{\alpha_V \langle EB \rangle}{\pi f_V} + \frac{\Lambda_p^4}{f_p} \sin\left(\frac{\phi}{f_p}\right) = 0$$



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e

Domcke, Mukaida 1806.08769 Domcke, Ema, Mukaida 1910.01205

- Non-perturbative production of fermions in strong electric and magnetic field background
- **Constraint equation** for **E** and **B** fields: •
- $E^2+B^2-\xi EB+\frac{e\,\theta_D E}{2H}\sum_i Q_i J_i^{\rm ind}=0$ n production $\xi\equiv\frac{\alpha_D\dot{\phi}}{2\pi f_D H}$ **Induced current** *suppresses* gauge boson production •

$$\theta_D Q_i J_i^{\text{ind}} = \frac{(e \,\theta_D |Q_i|)^3}{6 \,\pi^2} \frac{EB}{H} \coth\left(\frac{\pi B}{E}\right) \exp\left(-\frac{\pi m_i^2}{e \,\theta_D |Q_i|E}\right)$$

Standard Model fermions must be taken into account

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Minimal "dark relaxion portal"

$$\mathcal{L} \supset -\frac{1}{4} A^{\prime\mu\nu} A^{\prime}_{\mu\nu} - \frac{1}{4} X^{\prime\mu\nu} X^{\prime}_{\mu\nu} \left[-\frac{\theta_D}{2} A^{\prime\mu\nu} X^{\prime}_{\mu\nu} \right] + \frac{1}{2} m_X^2 X^{\prime}_{\mu} X^{\prime\mu} + \frac{\alpha_D}{4\pi f_D} \phi X^{\prime}_{\mu\nu} \tilde{X}^{\prime\mu\nu} + \sum_i i \bar{\psi}_i \gamma^{\mu} (\partial_{\mu} + i e Q_i A^{\prime}_{\mu}) \psi_i ,$$

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Domcke, Schmitz, TY 2108.11295

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Mechanism constraints

- Sub-dominant energy density
- Classic beats quantum
- Sufficient kinetic energy in unbroken phase
- Local minima
- Distance between minima less than weak scale
- Inefficient dissipation in unbroken phase
- Efficient dissipation in broken phase
- Avoid tuning
- Avoid eternal inflation
- (Fragmentation)

• Phenomenological constraints

- Supernova
- Stellar cooling
- Reheating temperature
- Dark radiation thermal production
- Dark radiation non-thermal production

- Parameter space scan fixing M



- Benchmark point H M ϵ Λ_p f_p f_D/α_D θ_D $5 \cdot 10^{-9} \text{ GeV}$ 10^5 GeV 10^{-25} $5 \cdot 10^{-2} \text{ GeV}$ 10^2 GeV 10^4 GeV 10^{-3}
- Parameter space scan fixing M



Satisfy mechanism constraints

Satisfy phenomenological constraints

Self-Organised Criticality

• Many systems in nature **self-tuned** to live near criticality



https://www.quantamagazine.org/to ward-a-theory-of-self-organizedcriticality-in-the-brain-20140403/ paramete

Self-Organised Criticality

- Fundamental self-organised criticality in our universe?
- Need a mechanism for self-organisation of fundamental parameters

e.g. Self-Organized Criticality in eternal inflation landscape: J. Khoury et al 1907.07693, 1912.06706, 2003.12594

- Self-Organised Localisation (SOL):
 - cosmological quantum phase transitions localise fluctuating scalar fields during inflation at critical points

Giudice, McCullough, TY 2105.08617

Phase Transitions (PT)

• Classical PT: varying background temperature



$$V = \frac{\lambda}{4} \left(\psi^2 - \rho^2\right)^2 + \kappa \phi \psi$$





Fokker-Planck Volume (FPV) equation

- Langevin equation: classical slow-roll + Hubble quantum fluctuations $\phi(t + \Delta t) = \phi(t) - \frac{V'}{2H}\Delta t + \eta_{\Delta t}(t)$
- Volume-averaged Langevin trajectories: **FPV for volume distribution** $P(\phi, t)$

$$\frac{\partial}{\partial \phi} \begin{bmatrix} \frac{\hbar}{8\pi^2} \frac{\partial (H^3 P)}{\partial \phi} + \frac{V'P}{3H} \end{bmatrix} + 3HP = \frac{\partial P}{\partial t} \qquad H(\phi) = \sqrt{\frac{V(\phi)}{3M_p^2}}$$
Quantum diffusion term Volume term

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$$\frac{\partial}{\partial \phi} \left[\frac{\hbar}{8\pi^2} \frac{\partial (H^{2+\xi} P)}{\partial \phi} + \frac{V' P}{3H^{2-\xi}} \right] + 3H^{\xi} P = H_0^{\xi-1} \frac{\partial P}{\partial t_{\xi}}$$

• Ambiguity in choosing time "gauge" $dt_{\xi}/dt = (H/H_0)^{1-\xi}$

- ϕ is *not* the inflaton: **spectator** field scanning parameters
- Restrict to **EFT** field range f $\varphi \equiv \frac{\phi}{f}$ $V = 3H_0^2 M_P^2 + g_\epsilon^2 f^4 \omega(\varphi)$, $\omega(\varphi) = \sum_{n=1}^{\infty} \frac{c_n}{n!} \varphi^n$
- Assume sub-dominant energy density
- Expand around constant inflationary background H_0 $H(\varphi) \simeq H_0 \left(1 + \frac{\epsilon^2 f^4 \omega(\varphi)}{6M_{\pi}^2 H_0^2}\right)$

• FPV becomes

$$\frac{\alpha}{2} \frac{\partial^2 P}{\partial \varphi^2} + \frac{\partial(\omega' P)}{\partial \varphi} + \beta \omega P = \frac{\partial P}{\partial T}$$

$$\alpha \equiv \frac{3\hbar H_0^4}{4\pi^2 \epsilon^2 f^4} \quad , \quad \beta \equiv \frac{3}{2} \frac{\xi f^2}{M_p^2} \quad , \quad T \equiv \frac{t}{t_R} \quad , \quad t_R \equiv \frac{3H_0}{g_\epsilon^2 f^2} = \frac{\alpha\beta S_{ds}}{3\xi H_0} \qquad S_{ds} = \frac{8\pi^2 M_p^2}{\hbar H^2}$$
Classical drift
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• Maximum number of e-folds for non-eternal inflation: $N_{e-folds} < S_{ds} = \frac{8\pi^2 M_p^2}{\hbar H^2}$

• Stationary FPV distributions $P(\varphi, T) = \sum_{\lambda} e^{\lambda T} p(\varphi, \lambda)$

$$\frac{\alpha}{2}p'' + \omega'p' + (\omega'' + \beta\omega - \lambda)p = 0$$

$$\alpha \equiv \frac{3\hbar H_0^4}{4\pi^2 \epsilon^2 f^4} \quad , \quad \beta \equiv \frac{3}{2} \frac{\xi f^2}{M_p^2} \quad , \quad T \equiv \frac{t}{t_R} \quad , \quad t_R \equiv \frac{3H_0}{g_\epsilon^2 f^2} = \frac{\alpha\beta S_{ds}}{3\xi H_0} \qquad S_{ds} = \frac{8\pi^2 M_p^2}{\hbar H^2}$$

• Largest eigenvalue $\lambda = \lambda_{max}$ inflates most

- Eigenvalue determines peak location
- Note: **boundary conditions** necessary input for solution





• C regime: $\alpha\beta \ll 1$. Peak is located as far down the potential as allowed by boundary condition.

- QV regime: $\alpha\beta \gg 1$, $\alpha^2\beta \ll 1$. Peak is a distance $1/(\alpha\beta)$ from the top with width $\sigma \simeq 1/\sqrt{\beta}$.
- $Q^2 V$ regime: $\alpha^2 \beta \gg 1$. Peak as close to the top as possible, with a distance comparable to the width $\sigma \simeq (\alpha/\beta)^{1/3}$.



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- Discontinuity in V' leads to discontinuous P'
- Requiring continuity of FPV across the critical point gives a junction condition to satisfy



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• **Coexistence** of branches of different phases, require continuity of P_V and $P_V + P_h$ in FPV at ϕ_T : **flux conservation** junction conditions

$$P_h(\phi_T) = 0 \qquad \Delta P'_v = -P'_h(\phi_T) \qquad \Delta P_v = 0$$

Higgs mass naturalness

$$V(\varphi,h) = \frac{M^4}{g_*^2}\,\omega(\varphi) - \frac{\varphi M^2 h^2}{2} + \frac{\lambda(h)\,h^4}{4}$$



- Unbroken to broken transition **not sufficient**

- Use broken IR to broken UV phase transition

- Need lower instability scale Λ_I : ~TeV through VL fermions

 - (Naturalness motivation: scalars and vectors heavy, only VL fermions at TeV scale)

Higgs mass naturalness



- Phase h: hidden vacuum with vanishing Cosmological Constant and superpotential by supersymmetry and R-symmetry
- Phase v: visible vacuum with broken supersymmetry but SOL localises at critical point with vanishing CC



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SOL take-home message

- Scalar fields undergoing quantum fluctuations during inflation can be localised at the critical points of quantum phase transitions: SOL
- SOL suggests our Universe lives at the critical boundary of coexistence of phases
- Measure problem: ambiguous choice of time parametrisation (recall $\beta \equiv \frac{3}{2} \frac{\xi f^2}{M^2}$
- Related to regularisation of infinite reheating surface
- We have not specified the inflaton sector: decoupled from our scalar
- SOL prediction is quantitative but dependent on chosen solution of measure problem: exponential localisation can remain a feature

Exotic UV?

- Cosmological approach may not be the right solution
- Could some exotic UV theory have **non-trivial UV/IR relations**?

e.g. 1909.01365 Craig & Koren

- UV consistency conditions could constrain IR in surprising ways
 - e.g. 5th force detection ⇒ *Higgs mass upper bound* from **weak gravity conjecture**

$$m < q M_p$$

1402.2287 Cheung & Remmen 1709.01790 Lust & Palti 1904.08426 Craig, Garcia Garcia, Koren

• Are there **other low-energy measurements** that could *in principle restrict Higgs mass spectrum* by UV consistency?



Light Higgs restricted by UV positivity

- Higgs coupling to scalar at dimension 10 can contribute to dimension-8 2 → 2 scattering amplitude in broken phase
- $C_8 + C_{10} \frac{v^2}{\Lambda^2} > 0$ • UV **unitary**, **local**, **causal** (Positivity bound): Positivity satisfied Positive ယိ **C**8 Positive Positivity violated Davighi, Melville, TY, in progress **C**₁₀
- IR measurement of suppressed $c_8/c_{10} \Rightarrow$ Higgs mass upper bound from UV consistency
- UV theories populating this region of EFT parameter space must have **non-trivial UV/IR properties**

Conclusion

- Cosmology could still lead to new insights on fundamental problems
- Alternatively, **UV** could be *stranger than anticipated*
- Some hints at potential UV/IR relations

Backup



Deriving positivity bounds

• Residue theorem isolates coefficient of simple pole in Laurent expansion

• Analyticity of f(z) allows deformation of the contour in complex plane

$$\int \frac{dz}{2\pi} f(z) = b,$$

- Use contour integrals to isolate higher-dimension operator contributions to amplitudes
- Analyticity of amplitude allows deformation of contour to high energies sensitive to UV properties

Effective field theory (EFT)

• EFT Lagrangian can be written schematically as

$$\mathcal{L} = \Lambda^4 + \Lambda^2 \mathcal{O}^{(2)} + m \mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{1}{\Lambda} \mathcal{O}^{(5)} + \frac{1}{\Lambda^2} \mathcal{O}^{(6)} + \frac{1}{\Lambda^3} \mathcal{O}^{(7)} + \frac{1}{\Lambda^4} \mathcal{O}^{(8)} + \dots$$

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- Modern point of view: our quantum field theories are really effective field theories. Include *all* operators allowed by symmetries.

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Non-renormalizable (though renormalizable order-by-order)

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Effective field theory (EFT)

• EFT Lagrangian can be written schematically as

$$\left[\mathcal{L} = \Lambda^{4} + \Lambda^{2}\mathcal{O}^{(2)} + m\mathcal{O}^{(3)} + \mathcal{O}^{(4)} + \frac{1}{\Lambda}\mathcal{O}^{(5)} + \frac{1}{\Lambda^{2}}\mathcal{O}^{(6)} + \frac{1}{\Lambda^{3}}\mathcal{O}^{(7)} + \frac{1}{\Lambda^{4}}\mathcal{O}^{(8)} + \dots\right]$$

- 1960s point of view: renormalizability of a finite number of parameters a key criteria for sensible quantum field theory
- Modern point of view: our quantum field theories are really effective field theories. Include *all* operators allowed by symmetries.

We've always been doing EFT...

- ...even before we knew what an EFT was:
- e.g. QED EFT = QED + Euler-Heisenberg + Fermi theory

$$\begin{aligned} \mathcal{L}_{AEP}^{\text{EFT}} &= \Psi; \& P D_{\mu} \Psi - m \Psi \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \end{aligned} \\ Fermi theory \\ (1933) &+ \sum_{i} \frac{\mathcal{L}_{i}^{(i)}}{\mathcal{R}} (\Psi P \Psi) (\Psi P \Psi) \qquad P = \{\mathbf{1}, \forall_{5}, \&_{\mu}, \&_{\mu} \&_{5}, &_{6\mu\nu}\} \end{aligned} \\ \\ \frac{\text{Euler-}}{\text{Heisenberg}} &+ \frac{\mathcal{L}_{i}^{(i)}}{\mathcal{A}^{4}} (F_{\mu\nu} F^{\mu\nu})^{2} + \frac{\mathcal{L}_{i}^{(2)}}{\mathcal{A}^{4}} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu} + \dots \end{aligned}$$

- EFT fits to experimental data established V-A structure
- Standard Model is a UV completion of this EFT at higher energies

We've always been doing EFT...

Wilson coefficients: generated by "integrating out" UV physics

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