Accidentally light scalars and Hybrid Natural Inflation

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Scalars are heavy.*

*Conditions apply.

The natural mass scale of an elementary scalar field is the mass of the heaviest states it couples to (directly or indirectly).

- SM Higgs mass: electroweak hierarchy problem
- How to protect inflaton potential from radiative corrections?

Zoology of light scalar fields

Nambu–Goldstone bosons (NGB)
(exactly massless)

SUSY moduli
(exactly massless)

pseudo–NGBs

pseudo–moduli

accidentally
massless
scalars

Terminology

An accidentally light scalar is a scalar field which obtains no tree-level mass from the most general renormalizable potential compatible with symmetry.

- **Not an example I**:

$$V = \lambda_\Phi(\Phi^2 - v^2)^2 + \kappa(\Phi^2 - v^2)\varphi^2 + \lambda_\varphi\varphi^4$$

  has $m_\varphi = 0$. Here φ is light not by accident but by fine-tuning.

- **Not an example II**: (symmetry of V) $>$ (symmetry of full model)

  e.g. $\phi = \mathbf{3}_1$ of gauged SU(2) $\times$ U(1)
  $\Rightarrow V = -\mu^2|\phi|^2 + \lambda|\phi|^4$ has "custodial" SO(6) symmetry

  2 tree-level massless scalars (3 more eaten by gauge bosons): not accidentally light but pseudo-NGBs of SO(6) $\to$ SO(5) $\to$ Weinberg '73

- **Actual examples**: historic ones $\to$ Bars&Lane '73, Georgi&Pais '75, … tend to be complicated

This talk

- Accidentally light scalars can be found in simple models
  e.g. $G = \mathrm{SU}(N) \times \mathrm{U}(1)$ (1 multiplet) or $G = \mathrm{SO}(3) \times \mathbb{Z}_2$ (2 multiplets)
- Key ingredient: (moderately) large representations, e.g. **5** of SO(3)
- Vacuum manifolds have an interesting structure
- An Accident field can be used as the inflaton
  to marry natural inflation with hybrid inflation
  - natural inflation = inflaton potential flat at LO
  - hybrid inflation = inflation ends with the fast-roll of a second scalar field
- Other applications are be waiting to be explored

A simple Accident® model

$G = \mathrm{SO}(3)$ gauge symmetry, with scalars $\phi = \mathbf{5}$ and $\chi = \mathbf{3}$

- Most general renormalizable $G \times \mathbb{Z}_2$-invariant potential

$$V = -\frac{1}{2}\mu_\phi^2\phi^2 - \frac{1}{2}\mu_\chi^2\chi^2 + \frac{\lambda_\phi}{4}(\phi^2)^2 + \frac{\lambda_\chi}{4}(\chi^2)^2 + \frac{\epsilon}{4}\phi^2\chi^2 + \frac{\zeta}{4}\, T^a_{AC} T^b_{CB}\phi_A\phi_B\chi^a\chi^b$$

  $A, B = 1\ldots 5$; $a, b = 1\ldots 3$; T^a_{AB} = generators of **5** representation.
- No continuous symmetry larger than G
- For $\mu_\phi^2 > 0$, $\mu_\chi^2 < 0$ and quartics > 0, vacuum is at $\langle\chi\rangle = 0$ and $\langle\phi\rangle \neq 0$
- 4 flat directions = 3 Goldstones from SO(3) $\rightarrow \emptyset$ (eaten by gauging G)
  + 1 accidentally flat direction a

What happened?

The most general G-invariant quartic potential does not give a mass to all states that should get one.

One flat direction goes unexplained.
This is not a pNGB since V has no enhanced symmetry $> G$.
This is what we call an Accident.

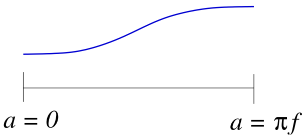
Violation of naive expectation from symmetry selection rules.

Intuitively: many d.o.f. (8 real scalars) but “not enough invariants”

One-loop effective potential

The tree-level flat direction *a* is lifted by scalar and vector boson loops

$$V_{\text{eff}}^{(1)} \sim V_0 + M^4 \cos(a/f)$$



Here M^4 is calculable and finite.

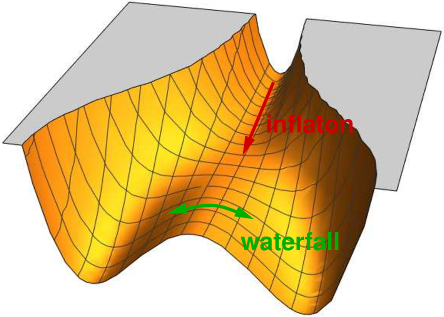
This looks like Natural Inflation: $\rightarrow$ Freese/Frieman/Olinto ’90

- inflaton = pNGB of approximate global symmetry
- inflaton potential $\sim$ cosine
- $\gtrsim$ 60 e-folds require $f \sim M_P$ ☹
- Planck (constraints on r and n_s) rules out NI completely ☹

Hybrid inflation

But our model includes a second scalar field χ: can promote it to waterfall field of hybrid inflation $\rightarrow$ Linde '93

- Single-field inflation ends as the inflaton starts fast-rolling
- Hybrid inflation ends as a second field starts fast-rolling: waterfall transition



Hybrid inflation with Accidents

In terms of accident-inflaton a and waterfall field χ_3, now for $\mu_\chi^2 > 0$:

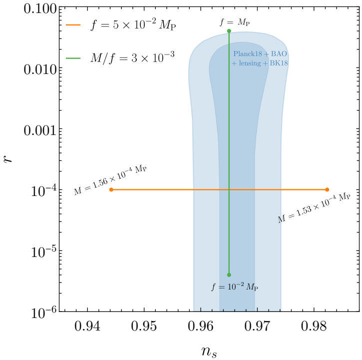
$$V_{\rm infl} = V_0 - M^4 \cos\frac{a}{f} + \frac{1}{2}\left(-\mu_\chi^2 + 36\zeta f^2 \sin^2\frac{a}{6f}\right){\chi_3}^2 + \frac{\lambda_\chi}{4}{\chi_3}^4$$

Several nice properties:

- Hybrid inflation $\Rightarrow$ can take $f < M_P$. No transplanckian field excursions.
- No continuous global symmetries whose fate at the Planck scale is unclear
- Models of Natural Hybrid Inflation ($\rightarrow$ Kaplan/Weiner '03, German/Ross '00s...) need tuning parameters or engineering non-abelian discrete symmetries to couple the waterfall field to the inflaton without spoiling flatness.

  Hybrid inflation with accidents is much more economical.
- V is sensitive to Planck-scale quantum corrections only at two loops (similar to $\rightarrow$ Little Higgs...)

Testing the model



- Predictions on CMB parameters: $n_r > 0$, $n_{rr} > 0$. Present constraints: $n_r = 10^{-3} \pm 10^{-2}$, $n_{rr} = 10^{-2} \pm 10^{-2}$. May be testable soon.
- Gravitational waves from preheating at Einstein Telescope. . .
  . . . if scale of inflation is very low (unnatural)
- Extended versions of the model ⇒ annihilating topological defects (cosmic strings, unstable domain walls) ⇒ stochastic GW background. Already ruled out unless scale of inflation is unnaturally low.

More Accidents

Another Accident model has a single scalar $\phi = \mathbf{10}_1$ of SU(3) $\times$ U(1):

- 2-dimensional tree-level vacuum manifold, 2 Accidents 
- At a generic point, SU(3) $\times$ U(1) $\to \emptyset$
- At a special point,
  - SU(3) $\times$ U(1) $\to$ U(1)^2
  - this is the minimum of the one-loop effective potential
  - now 6 light scalars
- Application: e.g. dark matter (see also $\to$ Frigerio/Grinbaum-Yamamoto/Hambye ’22)

Can generalize to $\phi = \square\square\square$ of SU(N):

- many more Accidents, and U(1)s at the symmetry-enhanced point. . .

Are there models with non-abelian residual symmetries? $\to$ EWSB

Conclusions

- Accidents (accidentally light scalars) are light scalar fields whose mass suppression does not follow (obviously?) from selection rules/NDA
- They appear in models with larg(ish) representations because of the restrictive structure of the scalar potential
- It would be worthwile to better understand what precisely are the conditions to find Accidents in some given model
- The inflaton can be an Accident: elegant realization of small-field hybrid natural inflation
- Application to EWSB?