Title: Cosmology with Goldstone bosons

Date: Sep 22, 2015 01:00 PM

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Abstract: <p>I will discuss the appeal of pseudo-Goldstone bosons (pGBs) for the generation of scales in Early Universe cosmology. In particular, I will demonstrate how in Goldstone Inflation a pGB inflaton can solve the hierarchy problem of inflation (the tension between the Lyth bound and the inflationary scale as preferred by CMB anisotropies), while avoiding the problems with trans-Planckian scales that are typically associated with related models. A simple model based on the coset SU(4)/Sp(4) realises both the Higgs doublet and an inflaton singlet as Goldstone modes. A single setup can then give rise to Goldstone Inflation and the dynamical generation of the electroweak scale through a composite Higgs, thus also addressing the EW hierarchy problem. I will discuss perturbative reheating in this model, and show how it naturally connects to both EW physics and a UV completion. If time permits I will address our current studies on non-perturbative reheating and the possibility of electroweak baryogenesis in this setup. </p>

# Cosmology with Goldstone Bosons

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(University of Sussex)

Based on work with
Veronica Sanz, Jack Setford, and Ewan Tarrant (arXiv 1507.04653, 1503.08097 (JHEP), and 1411.7809(JCAP))

# Happy to be here!

# What I'll talk about

- Two hierarchy problems: EW, inflation
- Pseudo Goldstone bosons (pGBs) address these
  - Goldstone Inflation[1]
  - Composite Higgs models[2]

1) DC, Sanz, Setford [arXiv: 1411.7809]
2) Gripaios, Pomarol, Riva, Serra [arXiv: 0902.1483]

- Realizing both solutions in one model and meeting CMB and collider constraints
  - Deriving the scalar potential
  - Inflation in this model
  - Perturbative reheating in this model

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# Key message

- Scalar fields are popular protagonists in cosmological theories

But

- It has been long known that fundamental scalars suffer hierarchy problems

So

- Scalars may not be fundamental, but pGBs.

Here a shift symmetry stabilizes both the inflaton and the Higgs potential

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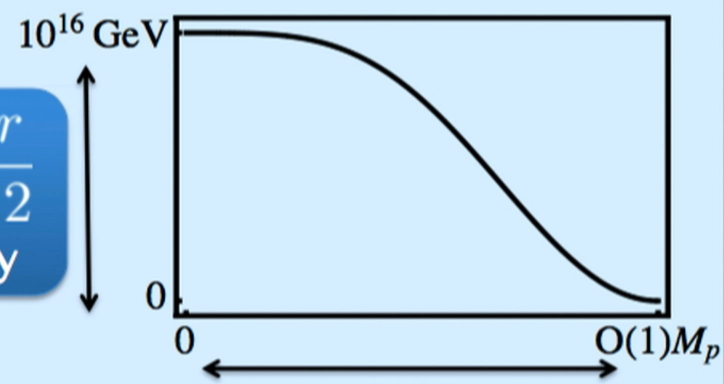
# Two hierarchy problems

1. Electroweak hierarchy problem
2. Inflationary hierarchy problem: V(ϕ) width >> height




$$\Lambda^4 = (2.2 \times 10^{16}\ \mathrm{GeV})^4 \frac{r}{.2}$$

Amplitudes of CMB anisotropy

$$\Delta\phi \sim \left(\frac{r}{.002}\right)^{1/2} \left(\frac{N}{60}\right) M_p$$

Sufficient inflation: Lyth bound

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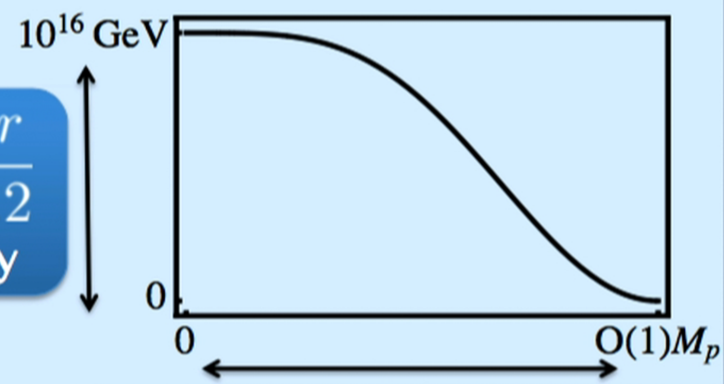


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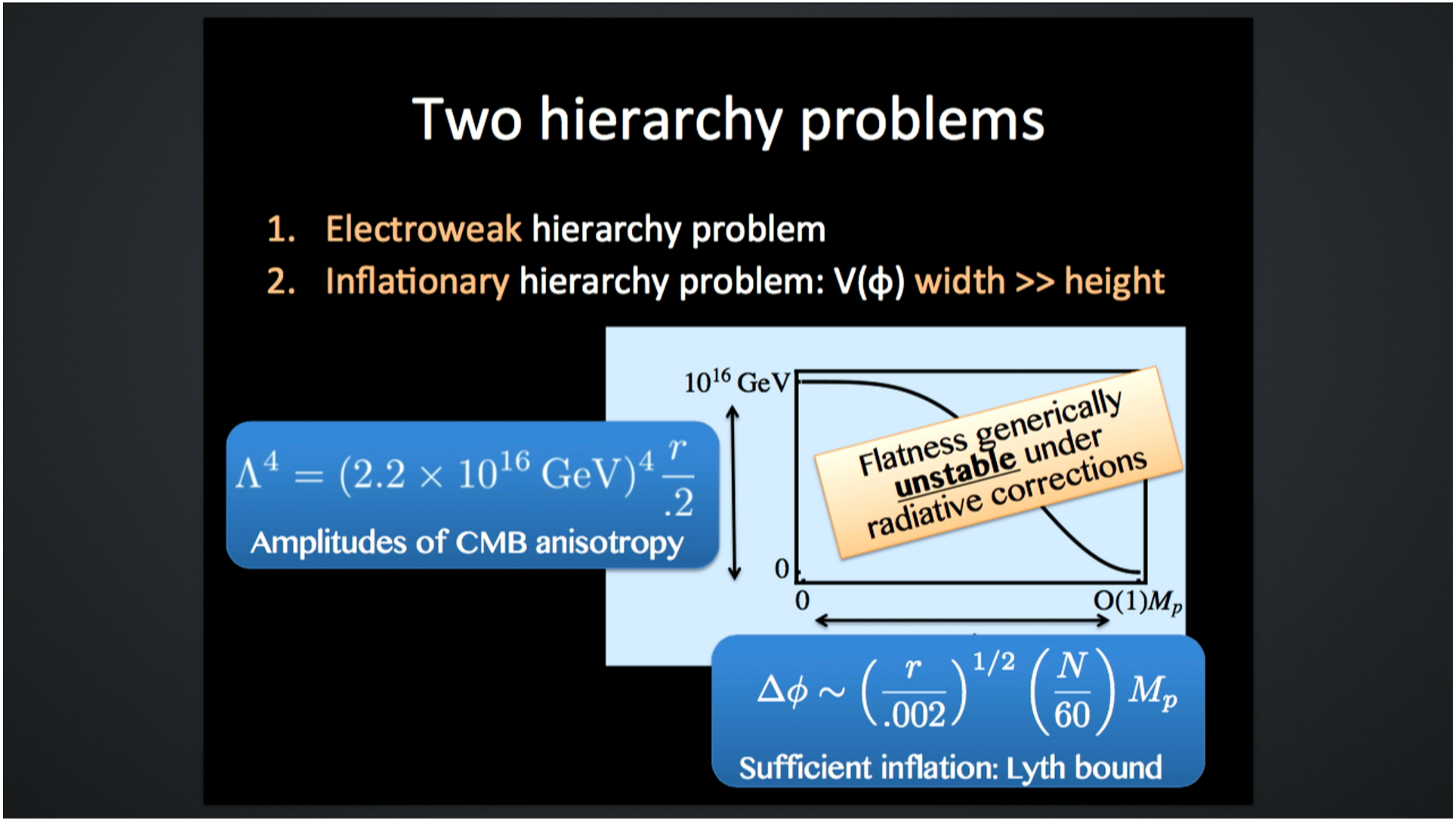
Two hierarchy problems
1. Electroweak hierarchy problem
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$\Lambda^4 = (2.2 \times 10^{16}\,\mathrm{GeV})^4 \frac{r}{.2}$
Amplitudes of CMB anisotropy
$10^{16}$ GeV
0
0
$O(1)M_p$
Flatness generically unstable under radiative corrections
$\Delta\phi \sim \left(\frac{r}{.002}\right)^{1/2} \left(\frac{N}{60}\right) M_p$
Sufficient inflation: Lyth bound

# pGBs solve hierarchy problems!

- A (discrete) shift symmetry can protect a scalar potential from HDOs
- The scalar is the GB of a global symmetry G broken to its subgroup H at scale f
  - Potential forbidden at tree level by (continuous) shift symmetry


- Small potential (with discrete shift symmetry) generated when G is not exact
  - Well known examples: axions, pions, ...

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# The pGB Higgs we already knew…

> **The Minimal Composite Higgs Model**
>
> Kaustubh Agashe[a], Roberto Contino[a], Alex Pomarol[b]
>
> [a] *Department of Physics and Astronomy, Johns Hopkins University Baltimore, Maryland 21218, USA*
> [b] *IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*

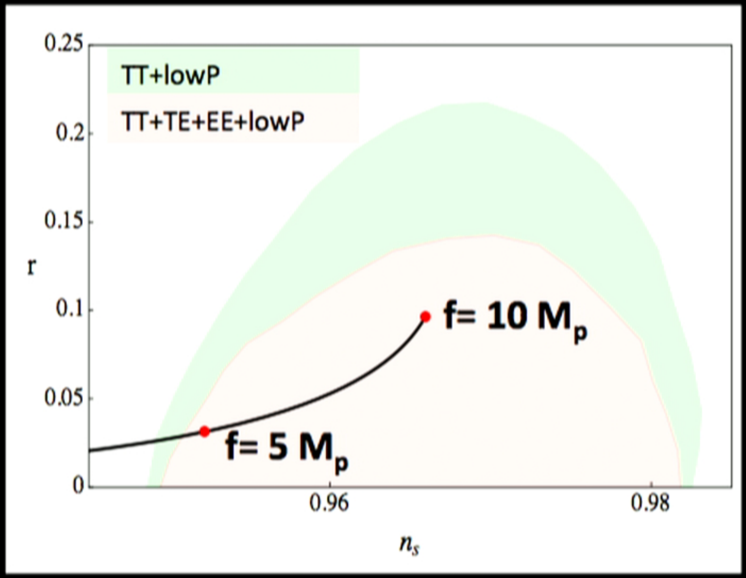
- Higgs doublet is a GB of G/H
  - G/H contains an SU(2) doublet
  - H contains the SM group (and custodial symmetry)
- Potential generated radiatively
  - Weakly gauge a subgroup of G
  - Fermions couple to the Higgs through partial compositeness: $\lambda\bar{\psi}\mathcal{O}$
  - Loops of bosons and fermions generate a potential as a periodic function of h/f
- Couplings deviate from SM with $\xi = v^2/f^2$

# The pGB inflaton we already knew…

- Natural Inflation™
  - pGB is an axion

$$V(\phi) = \Lambda^4 \left(1 + \cos\frac{\phi}{f}\right)$$

- NI™ + CMB:




Freese, Frieman, Olinto (PRL, 1990)
Planck 2015

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# The pGB inflaton we already knew…

- Natural Inflation™
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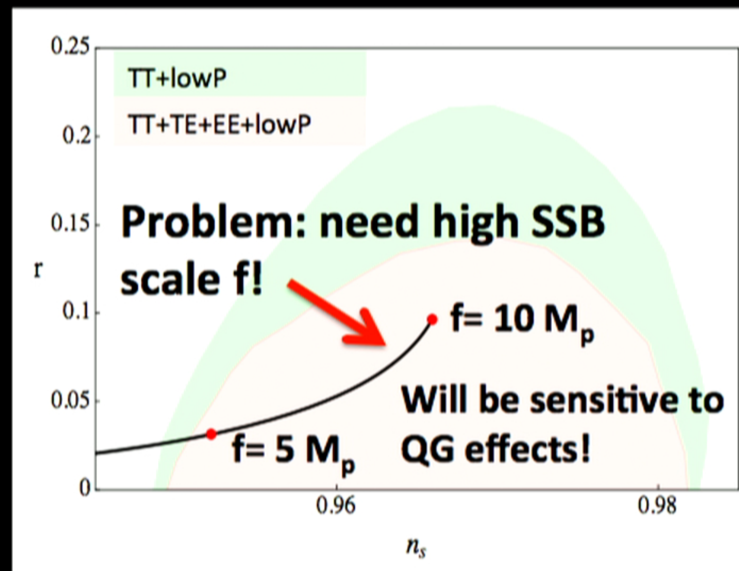
$$V(\phi) = \Lambda^4 \left(1 + \cos\frac{\phi}{f}\right)$$

- NI™ + CMB:
  - Radiatively stable ✓
  - UV robust ✗




Freese, Frieman, Olinto (PRL, 1990)
Planck 2015

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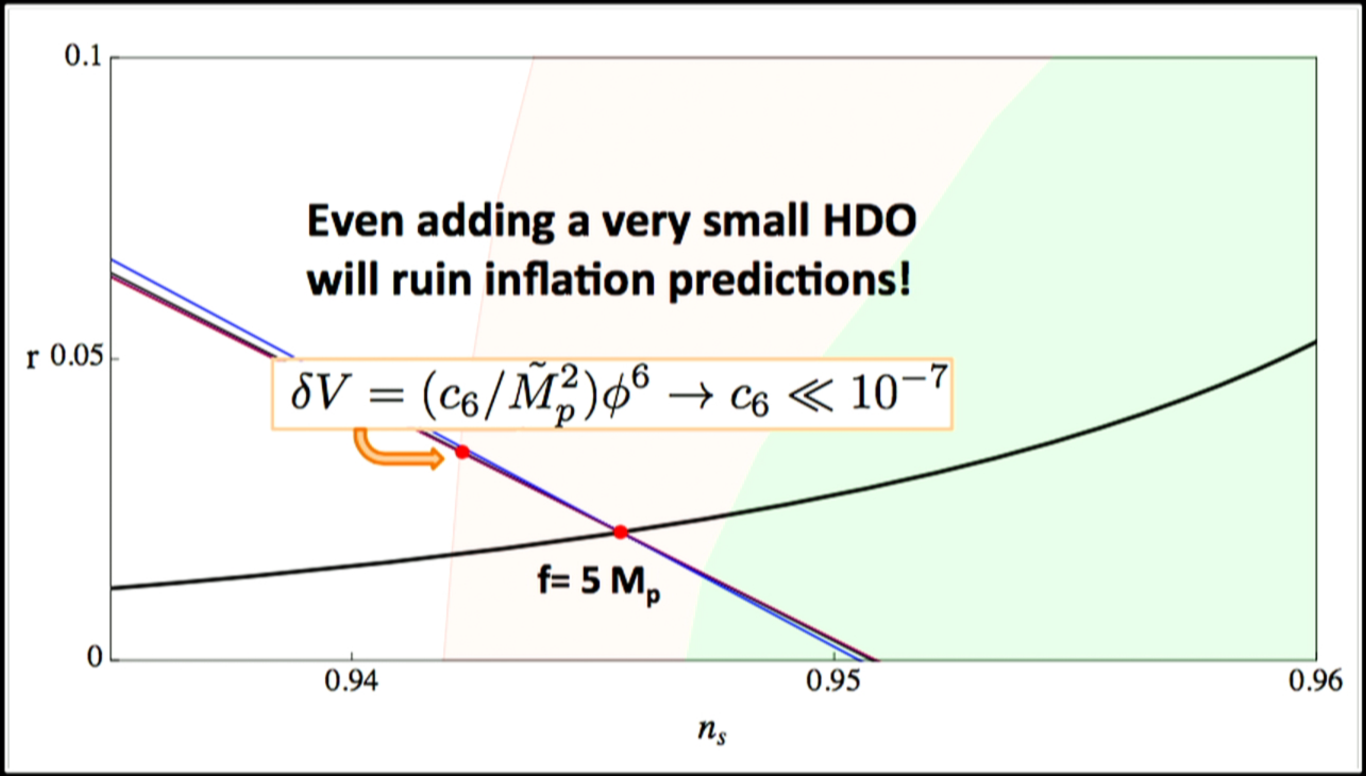
# UV Robustness

- Quantum Gravity does not preserve global symmetries (explicitly breaks G) Kallosh, Linde, Linde, Susskind, arXiv:9502069
  - Realistic potential will have large UV corrections
  - Demonstrated explicitly for NI Montero, Uranga, Valenzuela, arXiv:1503.03886

- Not robust against UV corrections ✗
  - ➔ pGB inflation (such as NI™) with $f > M_p$ is not a good effective theory, i.e. predictivity is lost

# NI$^{TM}$ is very sensitive to HDO effects!

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Can we find models with a pGB inflaton and with sub-Planckian scales?

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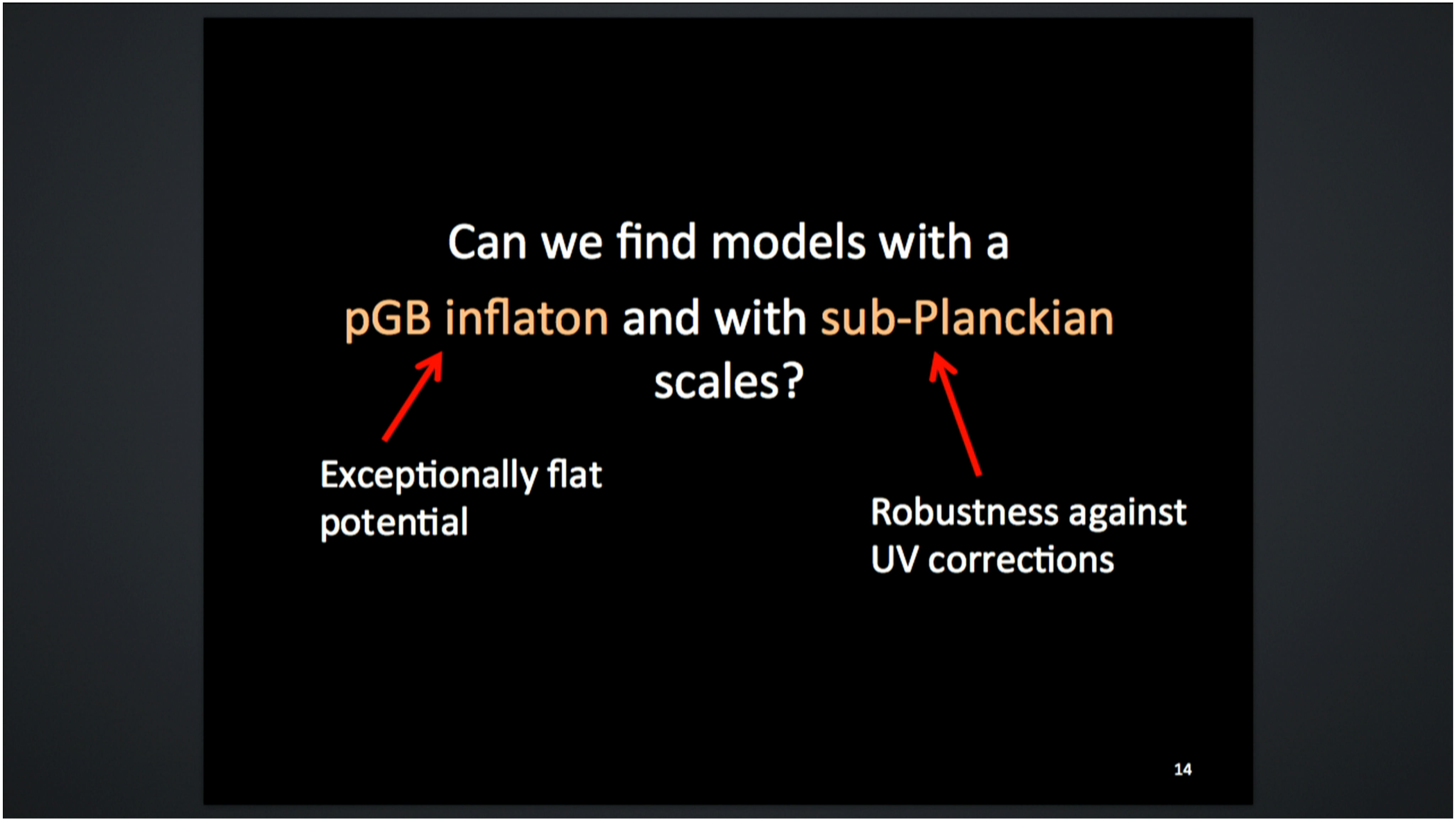
Can we find models with a
pGB inflaton and with sub-Planckian
scales?
Exceptionally flat
potential
Robustness against
UV corrections
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# Double-double* solution

- Flatness of inflation potential and lightness of the Higgs have a common origin
  - Higgs doublet and inflaton η are pGBs of the same symmetry breaking
  - Goldstone Inflation and Composite Higgs scenarios
- Reheating: η ➔ 2 h ➔ SM, perturbative
- Minimal realization, G/H= SU(4)/Sp(4) (≅ SO(6)/SO(5))

* I was told this is Canadian slang

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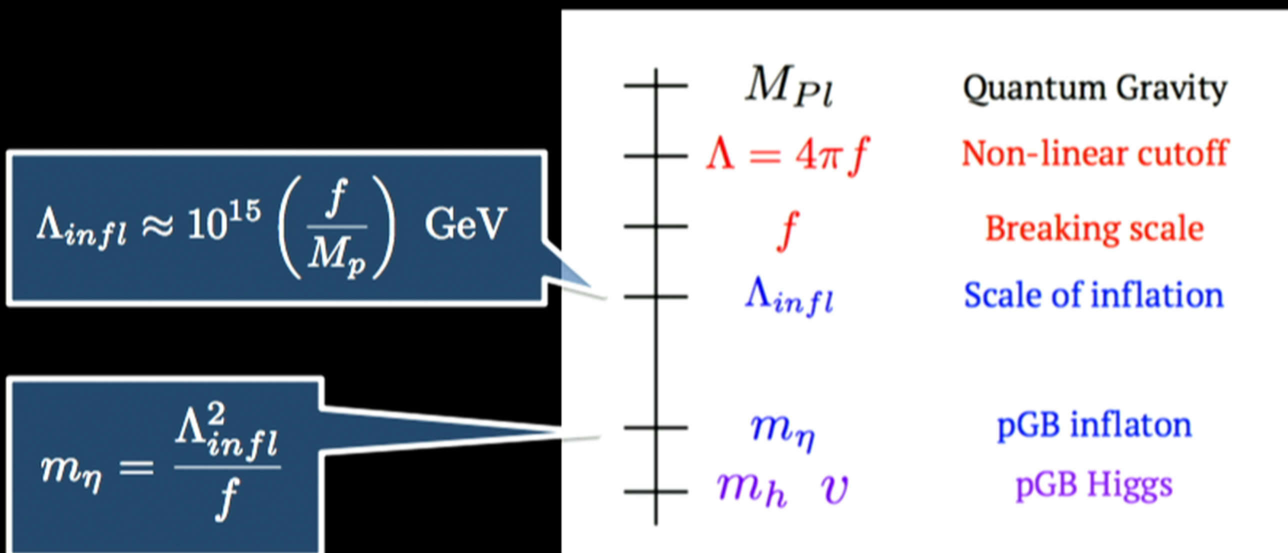
# pGBs realize mass hierarchies

- CMB data and constraints on perturbative reheating fix the spectrum in terms of f and $M_p$



# EFT for pGBs: CCWZ

Callan, Coleman, Wess and Zumino (CCWZ), PRL 1969

- We want:
  - Global SO(6) of the strong sector spontaneously broken to SO(5) (at scale f) ➔ 5 GBs
  - SO(6) explicitly broken by gauging the SM group
  - 3 GBs form the longitudinal components of the SU(2) gauge fields
  - 2 GBs form the inflaton and the Higgs
- We describe the effective theory using CCWZ

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# EFT for pGBs: CCWZ

- Parameterize GBs non-linearly, general vacuum[1]

$$\Sigma_0 = \begin{pmatrix} 0 & e^{i\alpha}\cos(\theta) & \sin(\theta) & 0 \\ -e^{i\alpha}\cos(\theta) & 0 & 0 & \sin(\theta) \\ -\sin(\theta) & 0 & 0 & -e^{-i\alpha}\cos(\theta) \\ 0 & -\sin(\theta) & e^{-i\alpha}\cos(\theta) & 0 \end{pmatrix}$$

$$\Sigma(x) = \Sigma_0 \exp(iT^{\hat{a}}\phi^{\hat{a}}(x)/f)$$

1) Galloway, Evans, Luty, Tacchi [arXiv: 1001.1361]

- Σ is a fundamental of SO(6)
  - GBs ϕ exhibit shift symmetry

$$\Sigma \rightarrow e^{iT^{\hat{a}}\alpha^{\hat{a}}}\Sigma$$
$$\phi^{\hat{a}} \rightarrow \phi^{\hat{a}} + f\alpha^{\hat{a}}$$

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# A CW potential from fermion loops

- Implement fermions in SU(4) representation
  - Decomposes under $SU(2)_L$ x $SU(2)_R$

$$\mathbf{6} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1})$$

- Write down the effective low energy Lagrangian in terms of form factors:

$$\mathcal{L}_{eff} = \sum_{r=q,u,q',d} \left[\Pi_0^r \mathrm{Tr}[\overline{\Psi}_r \not{p} \Psi_r] + \Pi_1^r \mathrm{Tr}\left[\overline{\Psi}_r \Sigma\right] \not{p} \mathrm{Tr}[\Psi_r \Sigma^\dagger]\right]$$

$$+ M_u \mathrm{Tr}\left[\overline{\Psi}_q \Sigma\right] \mathrm{Tr}[\Psi_u \Sigma^\dagger] + M_d \mathrm{Tr}\left[\overline{\Psi}_{q'} \Sigma\right] \mathrm{Tr}[\Psi_d \Sigma^\dagger]$$

# A CW potential from fermion loops

- Loops generate a Coleman Weinberg potential

$$V(h,\eta) = m_h^2 h^2 + \lambda_h h^4 + m_\eta^2 \eta^2 + c_\eta \eta^3$$
$$+\lambda_\eta \eta^4 + c_3 \eta h^2 + c_4 h^2 \eta^2$$

- Coleman-Weinberg potential is in terms of integrals over form factors, for instance,

$$m_\eta^2 = -2N_c f^2 \int \frac{d^4p}{(2\pi)^4} \frac{(\epsilon_u^2-1)^2}{\Pi_0} \left( \Pi_1^t (\Pi_0^q + \Pi_0^{q'}) - \frac{3(\Pi_1^t)^2 (\epsilon_u^2 - 1)(\Pi_0^q + \Pi_0^{q'})^2}{2\Pi_0} \right)$$

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Find the other coefficients in
**Hep-ph 1507.04653**

Can we find models with a

pGB inflaton and with sub-Planckian scales

&

which also allow for perturbative reheating to a pGB Higgs?

YES WE CAN!

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# A model for inflation, reheating, EWSB

- CCWZ in general vacuum of SU(4)/Sp(4) + fermions in 6 of SU(4)

$$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta)^2}{f^2 - h^2 - \eta^2}$$

- Coleman Weinberg potential:

$$V(h,\eta) = m_h^2 h^2 + \lambda_h h^4 + m_\eta^2 \eta^2 + c_\eta \eta^3 + \lambda_\eta \eta^4 + c_3 \eta h^2 + c_4 h^2 \eta^2$$

Functions of UV dynamics, fermion representation and choice of vacuum

# A model for inflation, reheating, EWSB

- CCWZ + fermions in 6 of SU(4) + Coleman Weinberg mechanism:

$$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}\frac{(h\partial_\mu h + \eta\partial_\mu \eta)^2}{f^2 - h^2 - \eta^2}$$

- CP breaking terms:

$$V(h,\eta) = m_h^2 h^2 + \lambda_h h^4 + m_\eta^2 \eta^2 + c_\eta \eta^3 + \lambda_\eta \eta^4 + c_3 \eta h^2 + c_4 h^2 \eta^2$$

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# A model for inflation, reheating, EWSB

- During inflation Higgs sits at its minimum,

$$\mathcal{L}_{kin} = \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}\frac{(\eta \partial_\mu \eta)^2}{f^2 - \eta^2}$$

- Canonically normalize inflaton field by field redefinition:

$$\phi = f \arcsin(\eta / f)$$

$$V_{CP}(\phi) = m_\eta^2 f^2 \left( \sin(\phi/f)^2 + \frac{\lambda_\eta f^2}{m_\eta^2} \sin(\phi/f)^4 \right)$$

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# A model for inflation, reheating, EWSB

- This is a hilltop potential,

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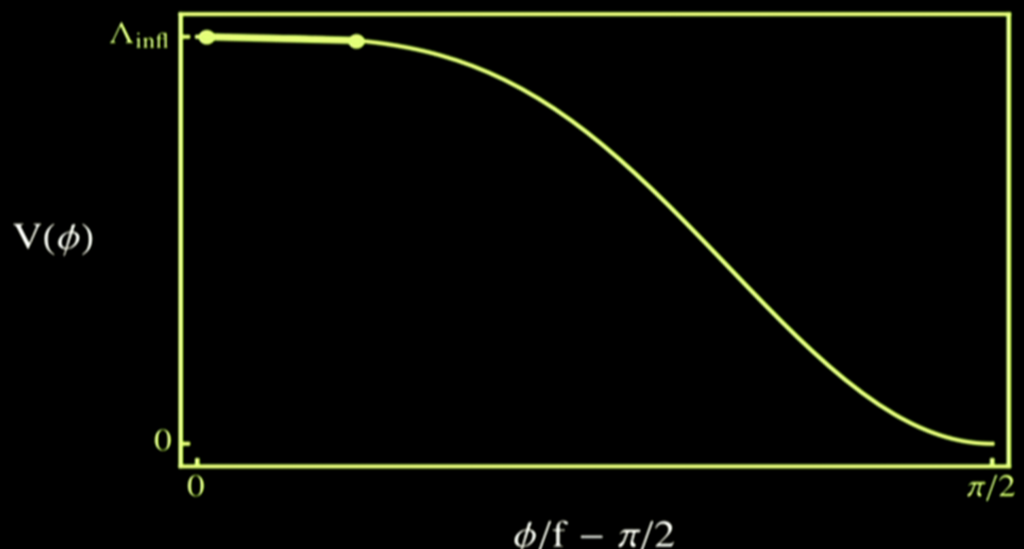

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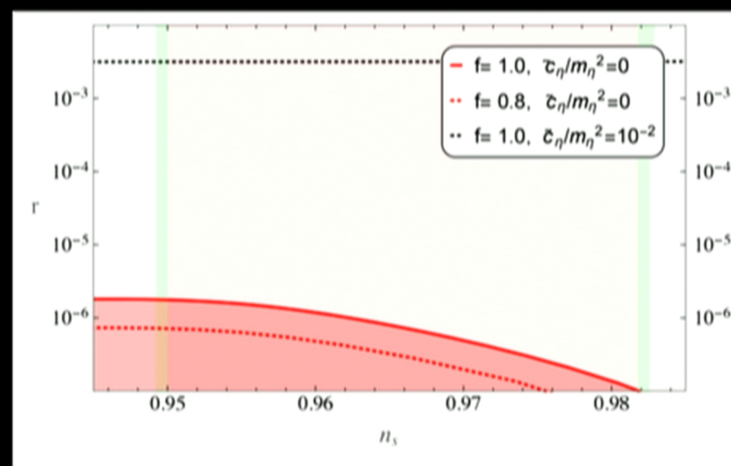
$n_s = [.948 - .982]$

for $\quad \lambda_\eta f^2 \gtrsim -m_\eta^2/2$

$r \leq .1$

for $c_\eta \leq \mathcal{O}(10^{-1})\, m_\eta^2/f$



# Assumptions for Perturbativity

- Mathieu equation

$$\frac{\mathrm{d}^2\mu_k}{\mathrm{d}z^2} + \left[A_k - 2q_i\ \cos(2z)\right]\mu_k = 0$$

$$q_0 = \frac{\Phi_0^2}{4f^2a^3}$$

$$q_3 = \frac{\sigma\Phi_0}{m_\phi^2 a^{3/2}}$$

$$q_4 = \frac{g^2\Phi_0^2}{4m_\phi^2 a^3}$$

$$A_k = \frac{k^2 + m_\chi^2}{m_\phi^2 a^2} + 2q_{(0,4)}$$

- Perturbative for $q_i \ll 1$

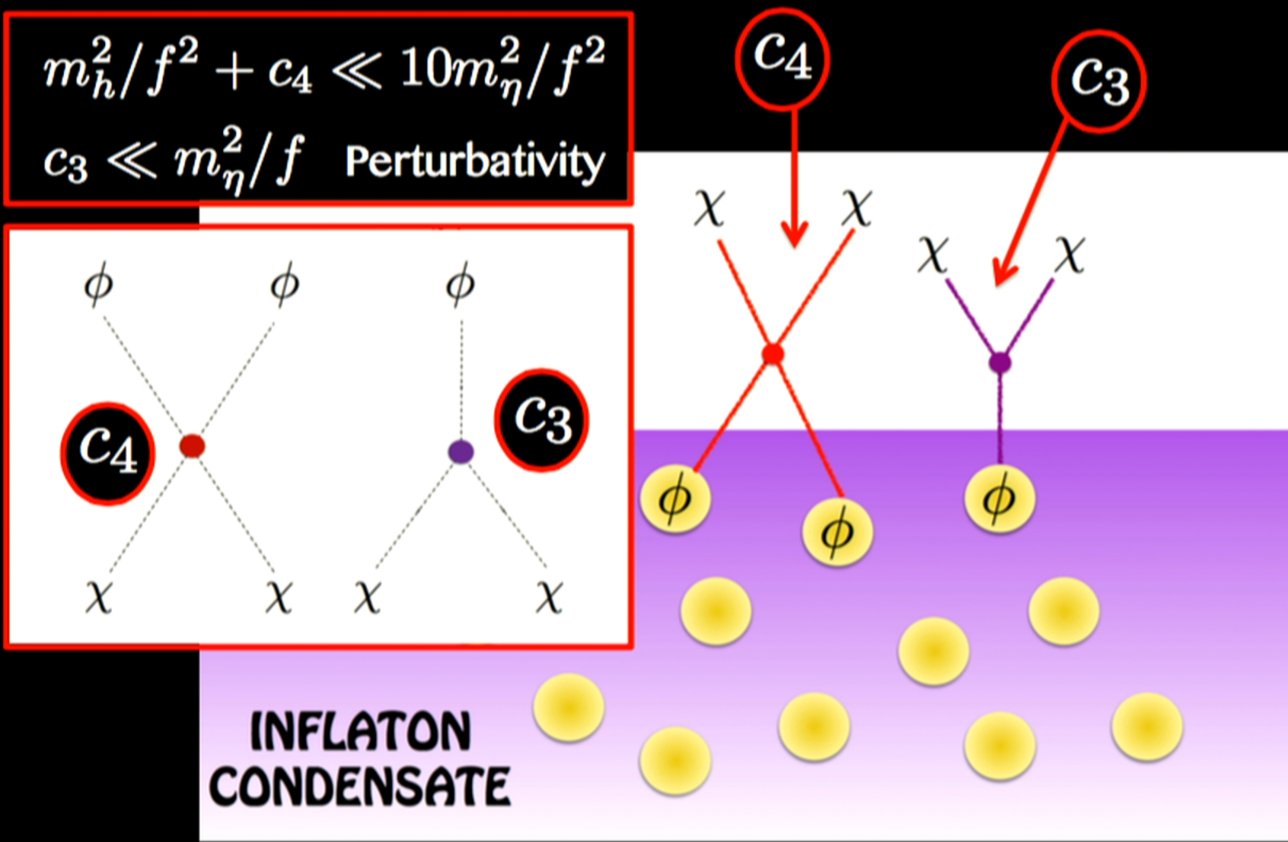
$$m_h^2/f^2 + c_4 \ll 10m_\eta^2/f^2$$

$$c_3 \ll m_\eta^2/f$$

# A model for inflation, reheating, EWSB

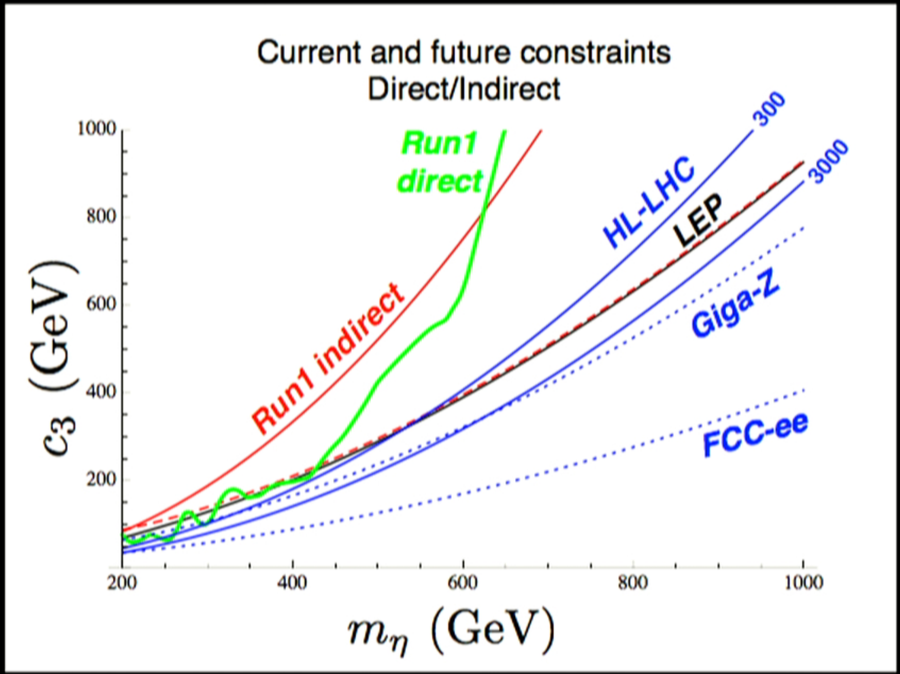
$$m_h^2/f^2 + c_4 \ll 10 m_\eta^2/f^2$$

$c_3 \ll m_\eta^2/f$ Perturbativity



# A model for inflation, reheating, EWSB

- Constraints on inflaton-Higgs mixing



# Cosmology with Goldstone bosons

- Can address in a single model
  - Hierarchy problem of inflation (naturally flat potential)
  - EW hierarchy problem
- A minimal model realizes
  - Inflation compatible with Planck 2015 data
  - Perturbative reheating
- Connects to EW data and gives boundary conditions for UV completion

# Thank you!

Let me know if you have questions,

Now

or

~~Never~~ Later!