Inflating with Goldstone bosons

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& Veronica Sanz, Jack Setford; arXiv:1503.08097

& Veronica Sanz JCAP 02 (2015) 008; arXiv:1411.7809

NExT

US

What I'll talk about

- Challenges for inflationary model building:
  - Exceptionally flat potential (*)
  - Robustness against UV corrections (**)
- Pseudo Goldstone (pGB) modes make attractive inflaton candidates as they are (or can be) natural
  - Automatically explain (*)
  - Particular models also satisfy (**)
- CMB data motivate a minimal single field model with a unique potential

Inflation recap

- Experimentally supported paradigm still lacking fundamental understanding
- Solves traditional problems in cosmology + offers framework for structure formation
- CMB data: power spectrum of density fluctuations $\Delta(k)$

$$n_s - 1 = \frac{d \log \Delta_s^2}{d \log k} \qquad r = \frac{\Delta_t^2(k)}{\Delta_s^2(k)}$$

- Popular: single scalar field slow roll models

CMB data: power spectrum of density fluctuations

$$\Delta_{s,t}(k) = A_{s,t}\left(\frac{k}{k_*}\right)^{(n_{s,t}-1)+\frac{1}{2}dn_{s,t}/d\log k\,\log(k/k_*)+\ldots}$$

CMB data: power spectrum of density fluctuations

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r

n_s

Inflation recap

- Single field slow roll inflation (SRA)

$$\epsilon = \frac{\tilde{M}_p^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \ll 1 \text{ and } \eta = \tilde{M}_p^2 \frac{V''(\phi)}{V(\phi)} \ll 1$$

- Amount of inflation (CMB: N≈60)

$$N = \log\frac{a(t_e)}{a(t_i)} = \int_{t_i}^{t_e} H dt \rightarrow N = \frac{1}{\sqrt{2}M_p}\int_{\phi_E}^{\phi_I}\frac{1}{\sqrt{\epsilon}}$$

- Observables can be expressed in SRA

$$n_s = 1 - 6\epsilon + 2\eta \qquad r = 16\epsilon$$

The hierarchy problem (*)

- Sufficient inflation + amplitudes of CMB anisotropy: $V(\phi)$ width >> height
  - Scale of inflation (~height): ~GUT scale
  - Field excursion (width): ~Planck scale (Lyth bound)

$$\Lambda^4 = (2.2 \times 10^{16}\,\mathrm{GeV})^4 \frac{r}{.2} \qquad\qquad \Delta\phi \geq M_p \sqrt{\frac{r}{4\pi}}$$

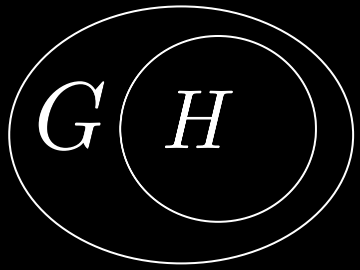
- Flat potential generically unstable under radiative corrections

Why a pGB?

- A shift symmetry can protect the potential

$$\phi = \phi + C$$

- The inflaton is the Goldstone boson of the breaking of a global symmetry G to subgroup H at scale f
  - Potential forbidden by shift symmetry



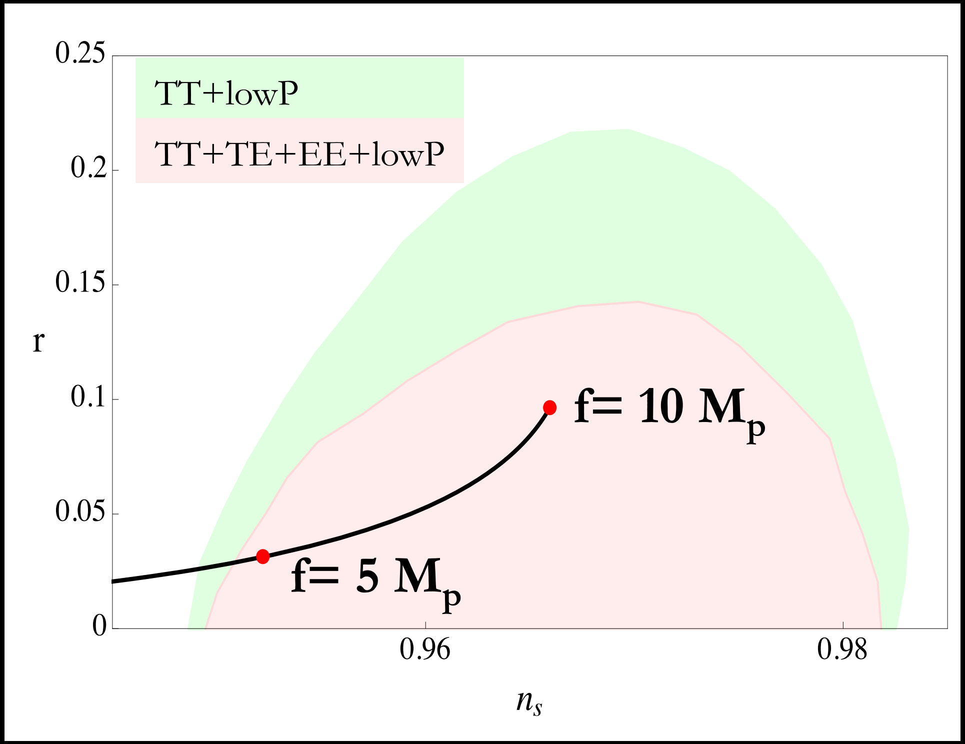
- Small potential generated when G is not exact
  - Well known examples: axions, pions, …

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)

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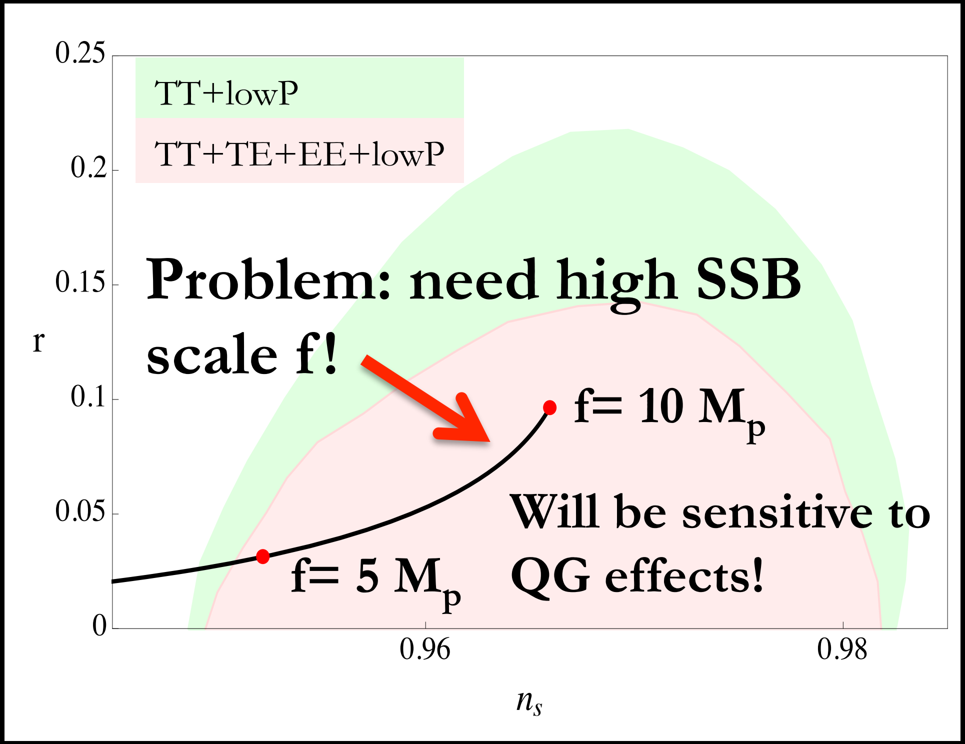
- NI™ + CMB:
  - (*) ✓
  - (**) ✗



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UV Robustness (**)

- Quantum Gravity does not preserve global symmetries (explicitly break G)

  Kallosh, Linde, Linde, Susskind, arXiv:9502069

  – Realistic potential will have large UV corrections

  – Demonstrated explicitly

  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

Can we find models with a

pGB inflaton and with sub-Planckian scales?

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pGB inflaton and with sub-Planckian scales?

Exceptionally flat potential (*)

Robustness against UV corrections (**)

Yes!

We show that the minimal cosmologically motivated[i] potential for a pGB inflaton is:

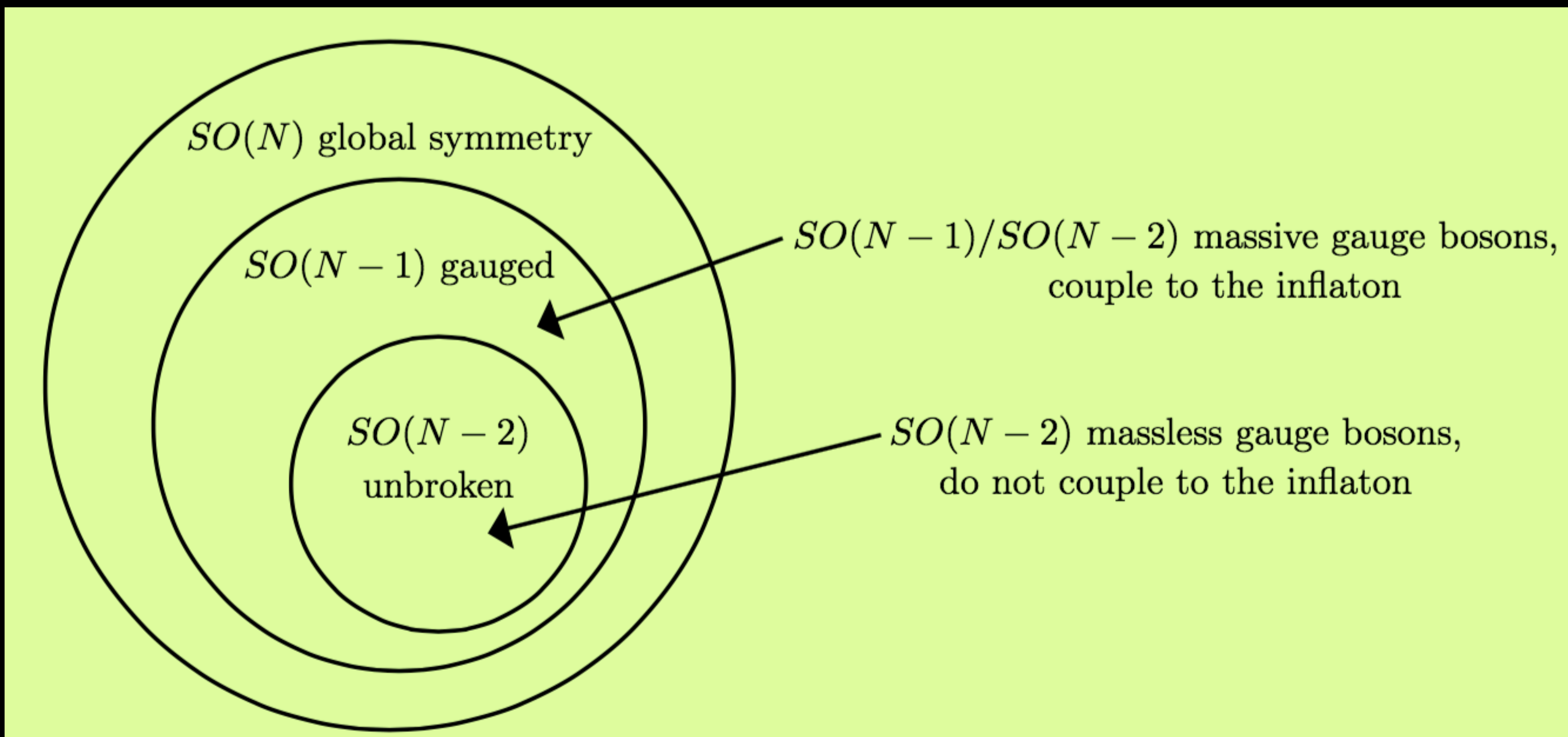
$$\boxed{V(\phi) = \Lambda^4 \left(C_\Lambda + \alpha \cos \phi/f + \beta \sin^2 \phi/f\right)}$$

With f and Λ sub-Planckian.

[i]Hilltop models are preferred by CMB data
(Martin, Ringeval, Trotta, Vennin JCAP 1403 (2014) 039)

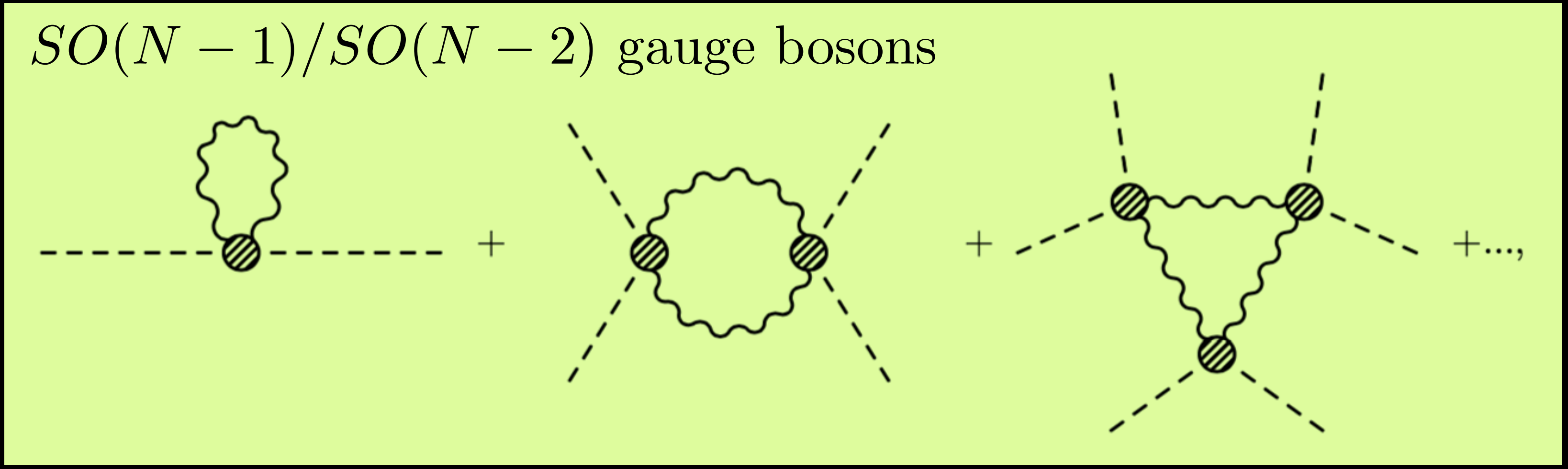
EFT for pGBs: CCWZ

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



CCWZ (gauge fields)

- Coleman Weinberg potential at 1-loop

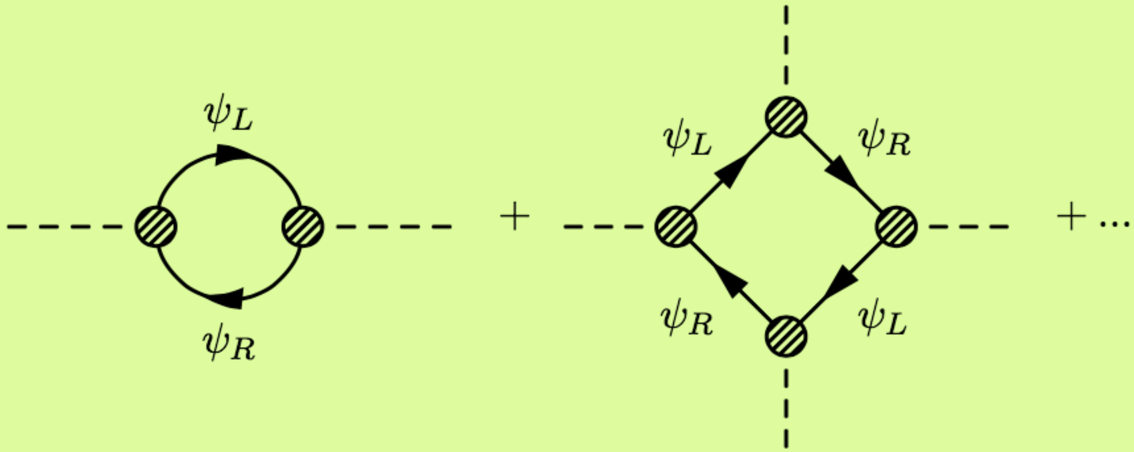


- Resumming diagrams: $V(\phi) = \beta_b \sin^2 \phi / f$

CCWZ (fermions)

- Coleman Weinberg potential at 1-loop

Fermions in spinor representation

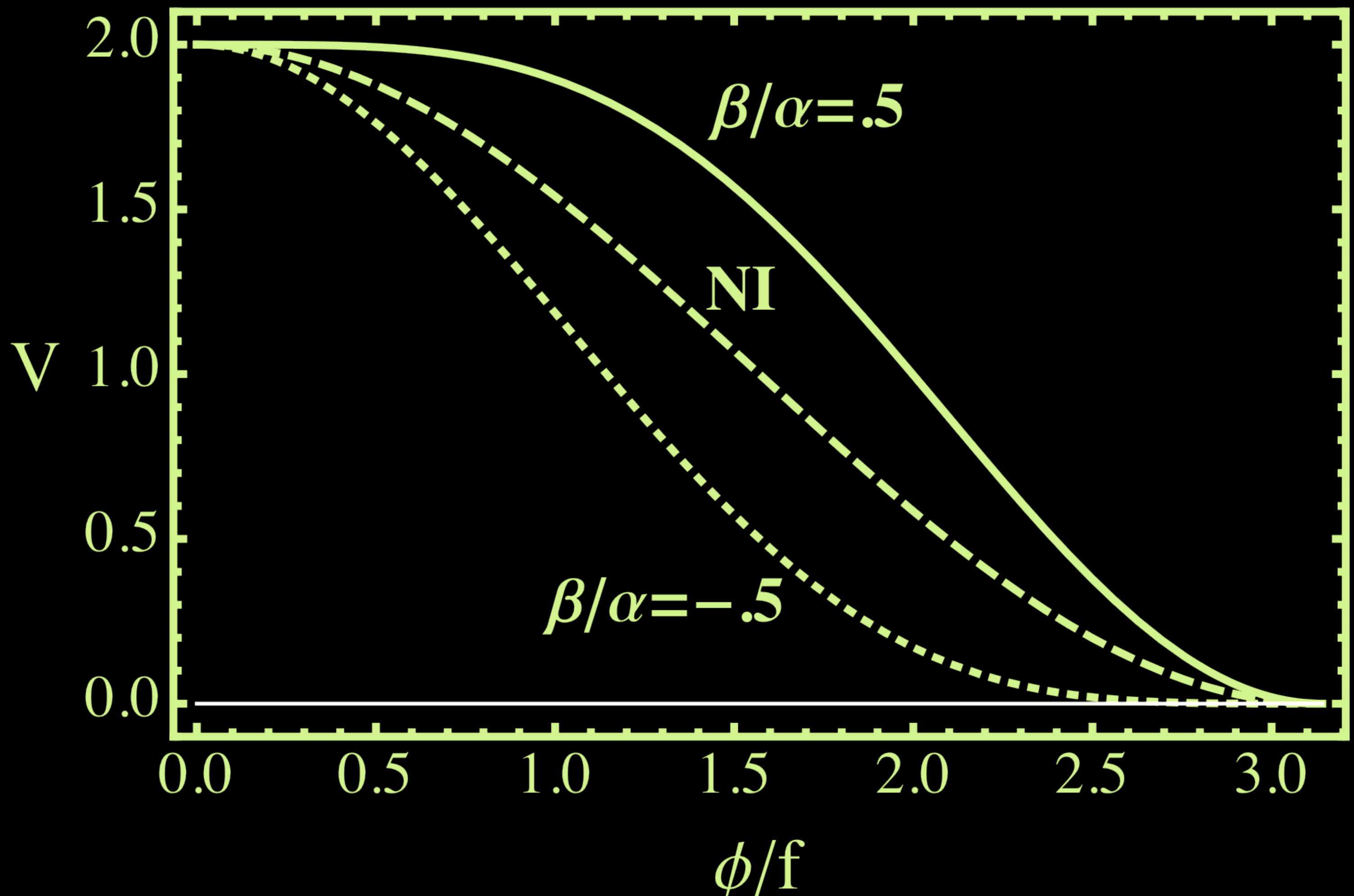


- Resumming diagrams:

$$V(\phi) = \alpha \cos \phi/f + \beta_f \sin^2 \phi/f$$

Bosonic + Fermionic contributions:

$$\boxed{V(\phi) = \Lambda^4 \left(C_\Lambda + \alpha \cos \phi/f + \beta \sin^2 \phi/f\right)}$$



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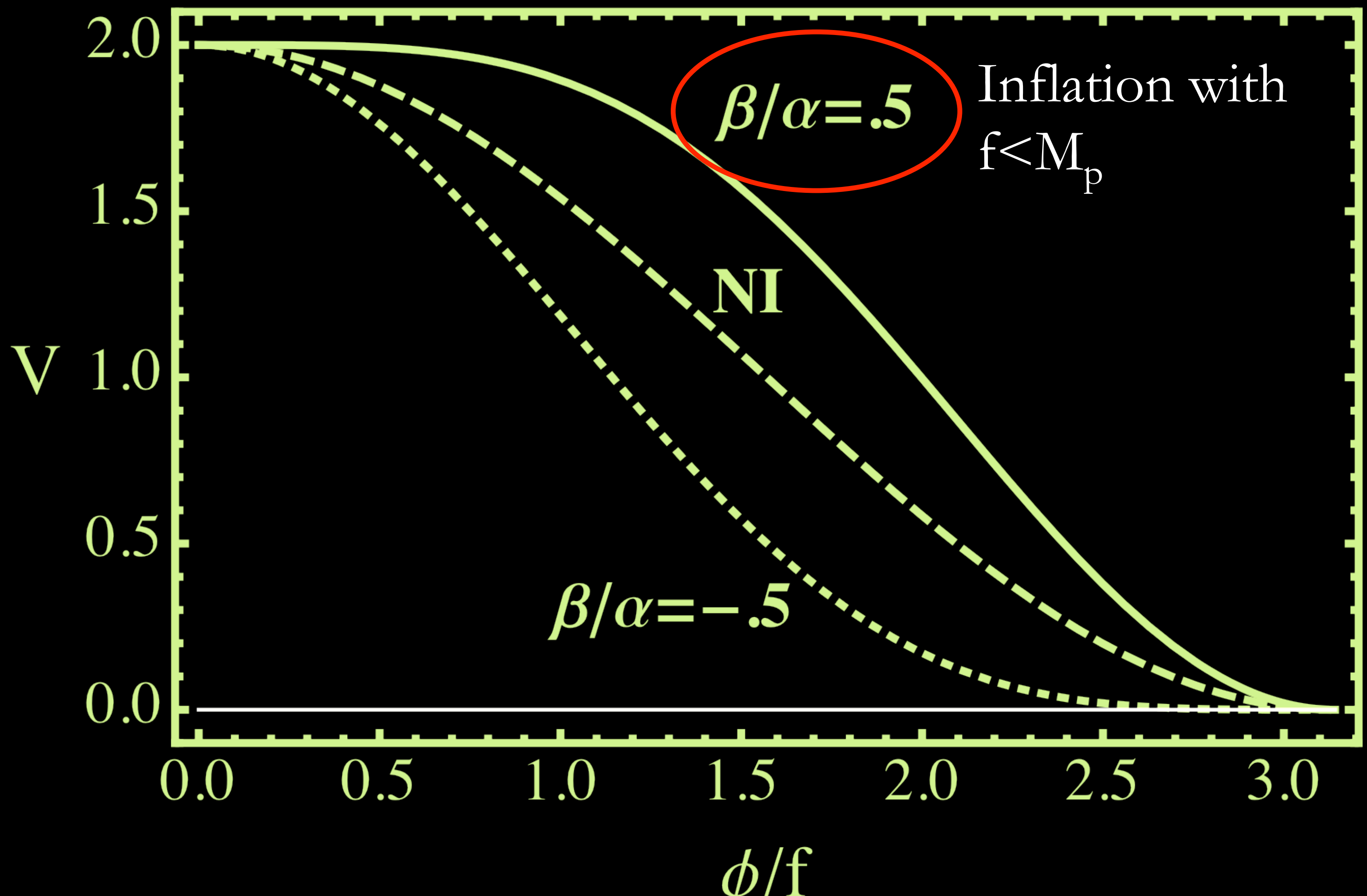
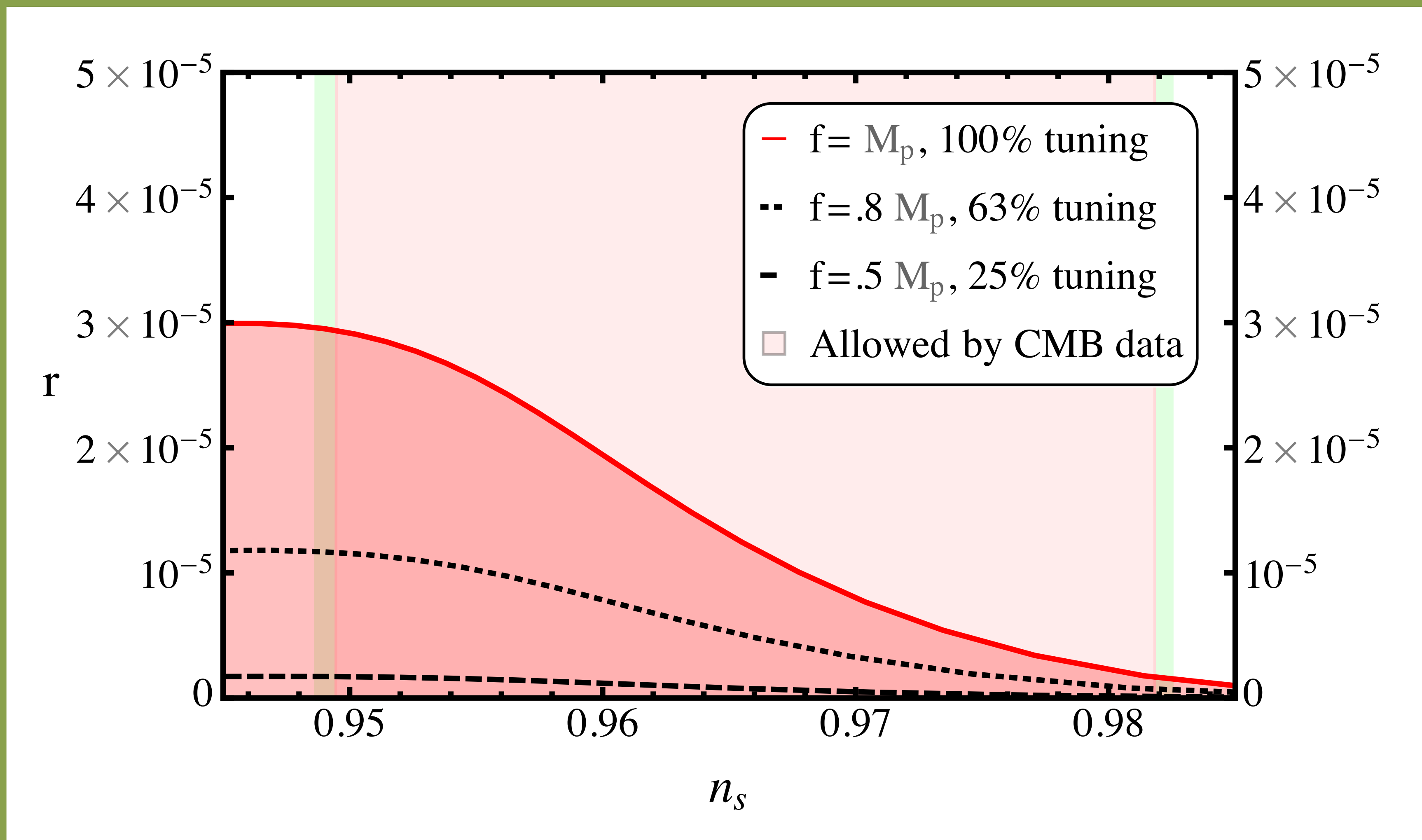


Inflation with $f<M_p$

V(ϕ) and Planck (2015) data



Planck Collaboration, arXiv:1502.02114 [astro-ph.CO]

Portal to the UV theory

- $\beta / \alpha \approx 1/2$ is a relation between fermions and bosons of the UV sector:

$$\alpha = \alpha\left(\frac{\Pi_1^L}{\Pi_0^L}, \frac{\Pi_1^R}{\Pi_0^R}\right) \qquad\qquad \beta = \beta\left(\frac{\Pi_1^A}{\Pi_0^A}, \frac{M^2}{\Pi_0^L \Pi_0^R}\right)$$

- Indicates a symmetry in the UV sector
  - Similar example: cancelations between resonances in walking Technicolor models
  - Can think of inflation as a BC for the UV theory

(Hirn & Sanz, arXiv:0807.2465; Agashe, Csaki, Grojean & Reece, arXiv:0704.1821)

To Conclude

- Goldstone models solve the hierarchy problem of inflation (*): a flat potential is natural
- A good effective theory also has sub-Planckian scales (**)
- The unique form of single field pGB inflation satisfying (*) and (**) is

$$V(\phi) = \Lambda^4 \left(C_\Lambda + \alpha \cos \phi/f + \beta \sin^2 \phi/f \right)$$

- Compatible with CMB data

Thank you!

Please ask me questions!

Backup slides

CCWZ

Fine-tuning

Non-Gaussianity

Uniqueness of $V(\phi)$

CCWZ (gauge fields)

Parameterize GBs as Σ (x)

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

SO(N) GB Lagrangian (low energy)

$$\mathcal{L}_{eff} = \frac{1}{2}(P_T)^{\mu\nu}\left[\Pi_0^A(p^2)\mathrm{Tr}(A_\mu A_\nu) + \Pi_1^A(p^2)\Sigma^T A_\mu A_\nu \Sigma\right]$$

Set to zero unphysical fields

$$\mathcal{L}_{eff} = \frac{1}{2}(P_T)^{\mu\nu}\left[\Pi_0^A(p^2) + \frac{1}{2}\Pi_1^A(p^2)\sin^2(\phi/f)\right] A_\mu^{\tilde{a}} A_\nu^{\tilde{a}}$$

Fine-tuning

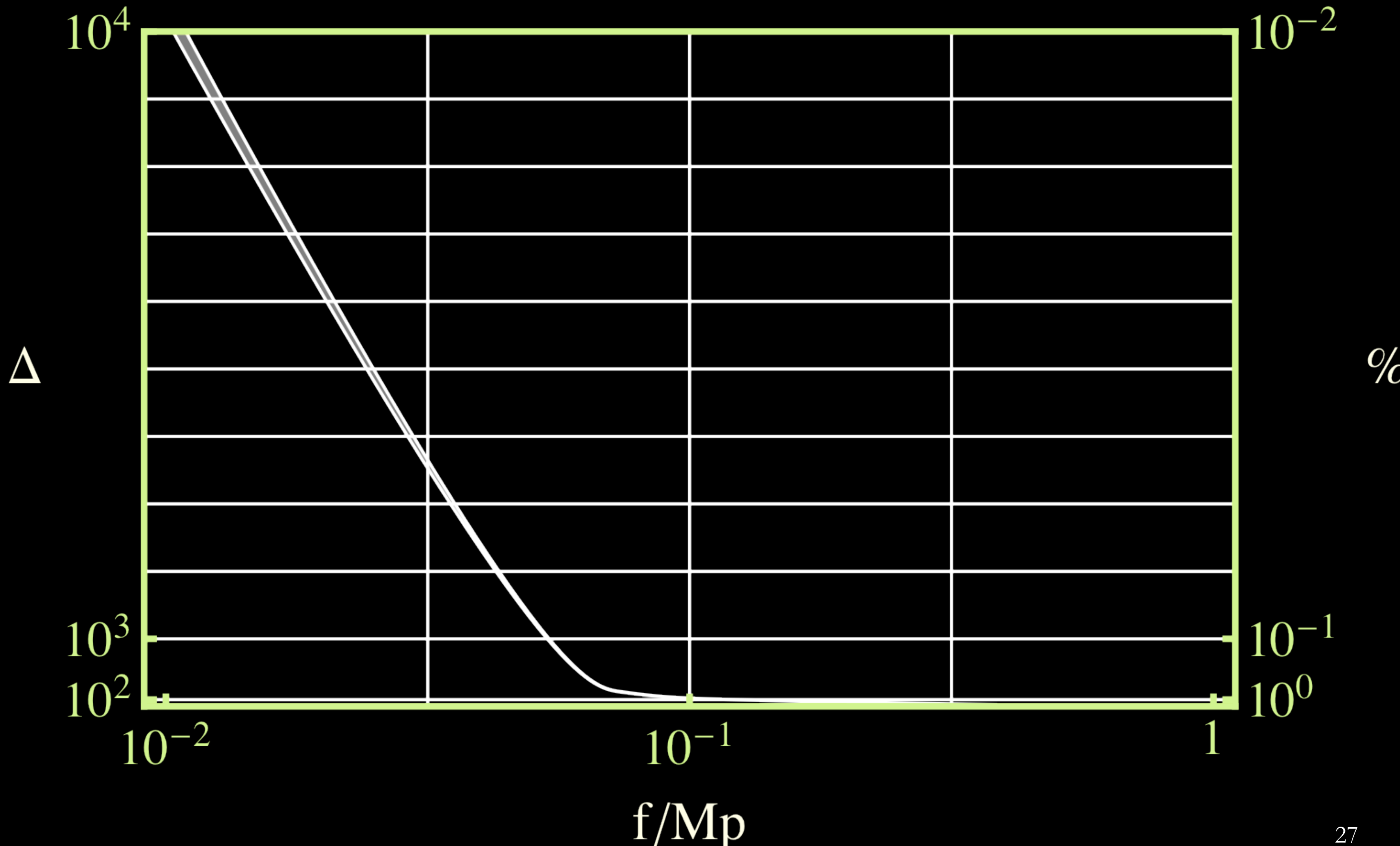
- Customary definition

$$\Delta = \left| \frac{\partial \log n_s}{\partial \log \tilde{\beta}} \right| = \left| \frac{\tilde{\beta}}{n_s} \frac{\partial n_s}{\partial \tilde{\beta}} \right| \approx [1.02 - 1.05] \left(\frac{f}{M_p} \right)^{-2}$$

- In percentage,

$$\text{Percentage tuning} = \frac{100}{\Delta}\% \approx 95 \left(\frac{f}{M_p} \right)^2 \%$$

Fine-tuning



Speed of sound / non Gaussianity

- Goldstone modes have strong momentum dependent self-couplings
- χ PT:

$$\mathcal{L} = \sum_n \frac{c_n}{f^{2n-4}} X^n, \text{ with } X = \frac{1}{2}\partial_\mu \Sigma \partial^\mu \Sigma^\dagger$$

- Implies a nontrivial speed of sound $\left(f_{NL}^{eq} \sim \frac{1}{c_s^2} \right)$
  - Imprinted in the CMB as non-Gaussianity

Speed of sound / non Gaussianity

- Inflation breaks Lorentz invariance. Non-canonical kinetic term implies

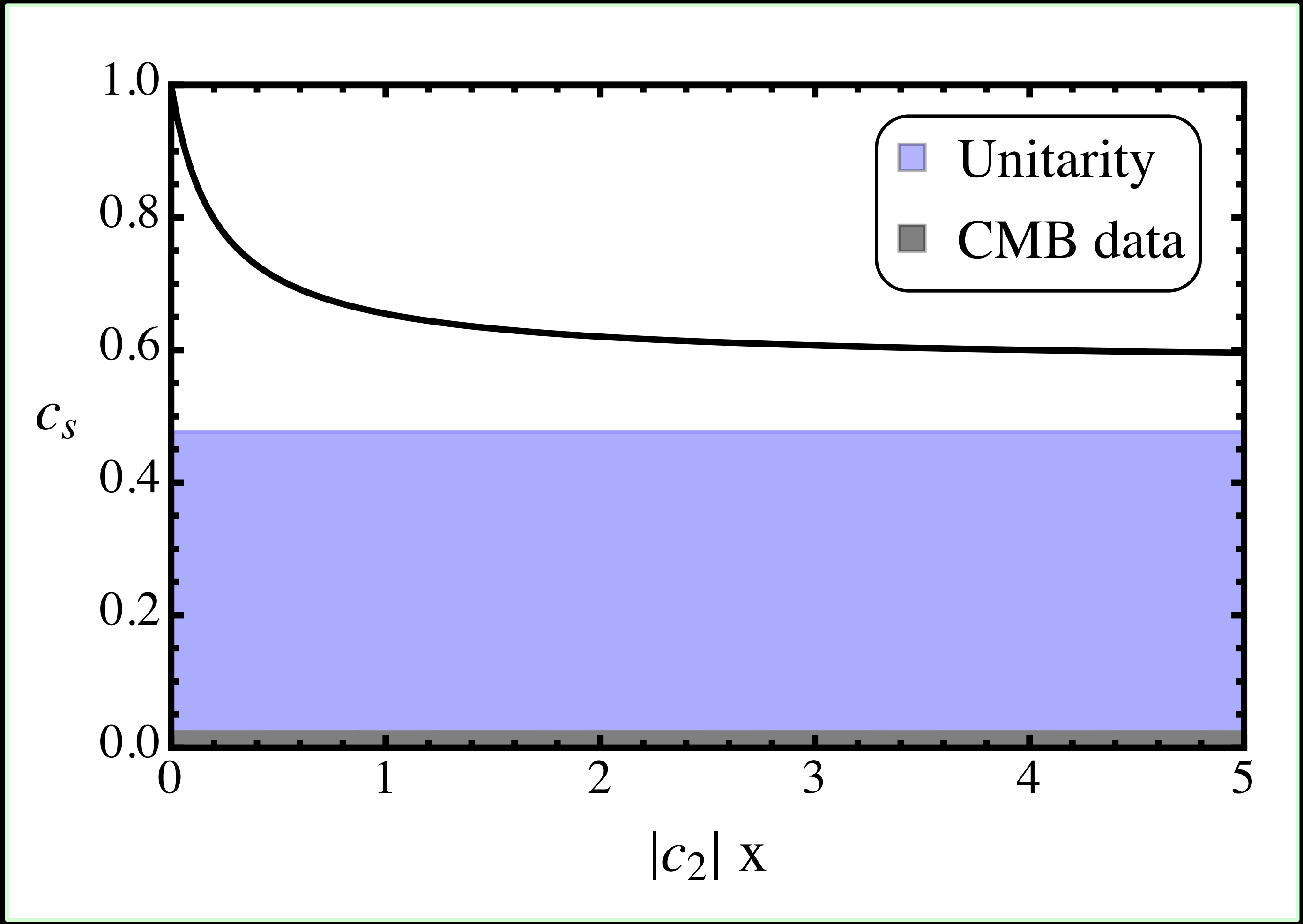
$$(\partial_\mu \phi)^2 = (\partial_t \phi)^2 - (\partial_i \phi)^2 \rightarrow (\partial_t \phi)^2 - c_s^2 (\partial_i \phi)^2$$

$$c_s = \left(1 + 2\frac{2c_2 x}{1+2c_2 x}\right)^{-1/2} \quad \text{with } x = X/f^2$$

- EFT breaks down for:

$$\Lambda_u^4 = \frac{24\pi}{5}\left(\frac{2M_p^2|\dot{H}|(c_s)_*^5}{1-(c_s)_*^2}\right) < f^4$$

Speed of sound prediction



Uniqueness of V(ϕ)

- Instead using fermions in a vector representation of SO(N) yields

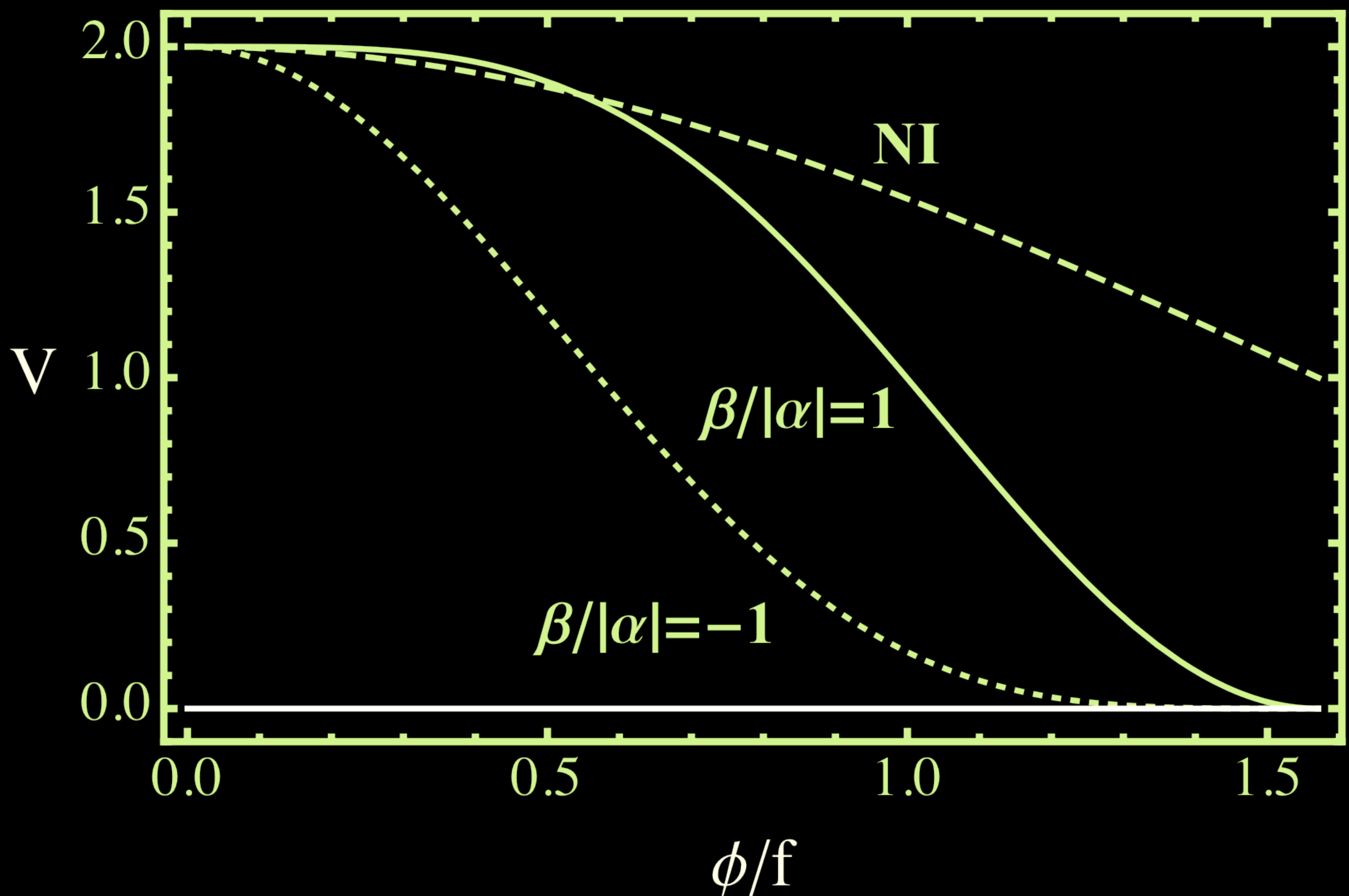
$$\boxed{V(\phi) = \alpha \sin^2(\phi/f) + \beta \sin^2(\phi/f)\cos^2(\phi/f)}$$

- Hilltop model (good!) for β >0, but:

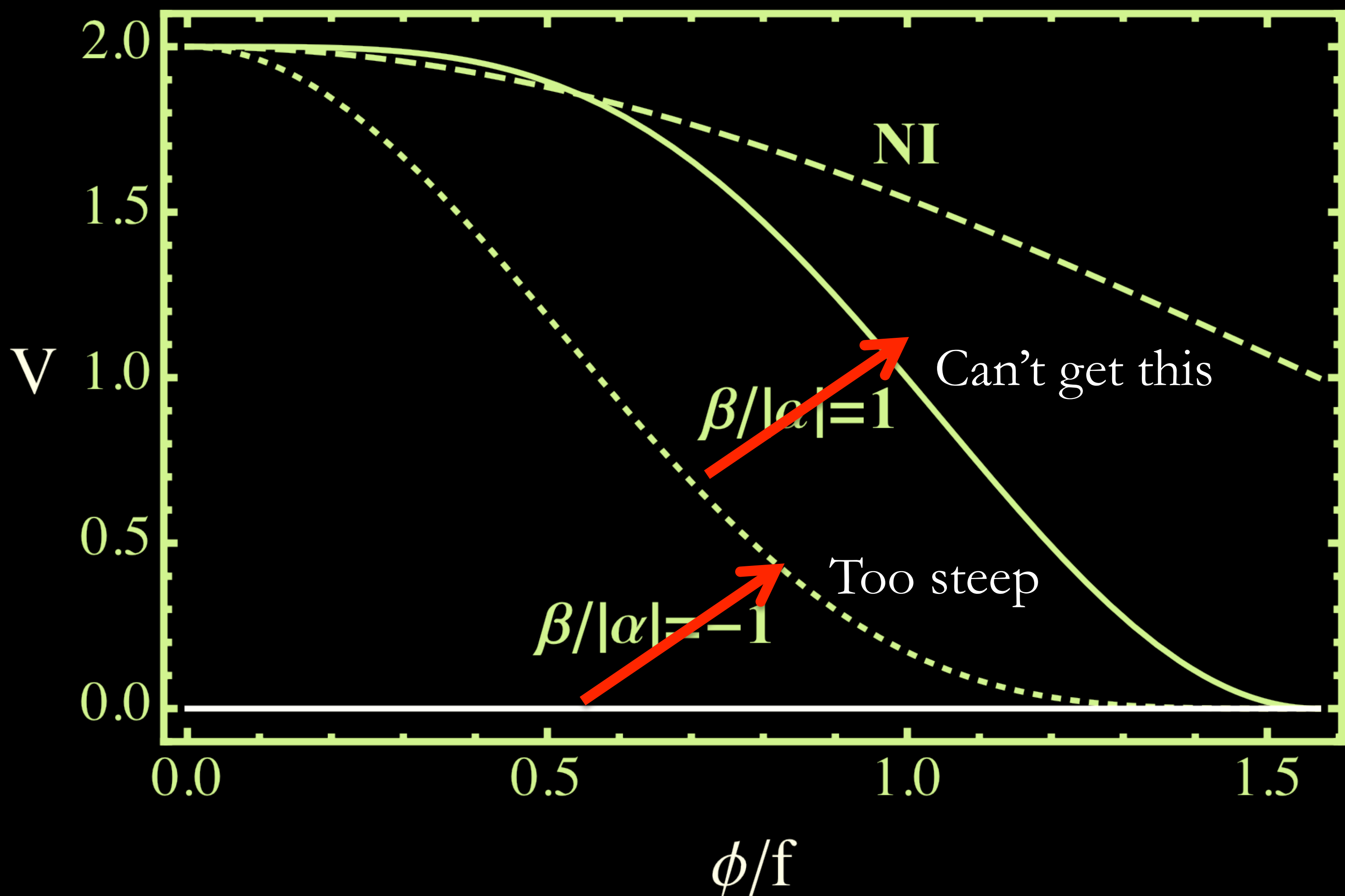
$$\beta = -2N_c \int \frac{d^4 p_E}{(2\pi)^4} \left(\frac{\Pi_1^L}{\Pi_0^L} \frac{\Pi_1^R}{\Pi_0^R} + \frac{M^2}{p_E^2 \Pi_0^L \Pi_0^R} \right) < 0$$

- Not good.

Not good.



Not good.



V
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
ϕ/f
NI
Can't get this
$\beta/|\alpha|=1$
Too steep
$\beta/|\alpha|=-1$

Inflation?

Not finding a hilltop potential turns out to be generic for models with fermions in vector (or tensor) representations: all invariants in the Lagrangian are with even powers of $\Sigma(x)$.

One has to use a spinor representation to get couplings $\Gamma^a \Sigma^a(x)$.

Spinor representations

- With fermions in a spinor rep one finds that the fermions and gauge bosons contribute to terms in the potential at different orders in $\Sigma(x)$
- As advertised, with fermions in a spinor rep:

$$V(\phi) = \Lambda^4 \left(C_\Lambda + \alpha \cos \phi/f + \beta \sin^2 \phi/f\right)$$

Looking at the group theory in detail one can convince herself that the first term will be a cos (not a sin).