TwInflation

Addressing the η Problem with a Z_2 symmetry

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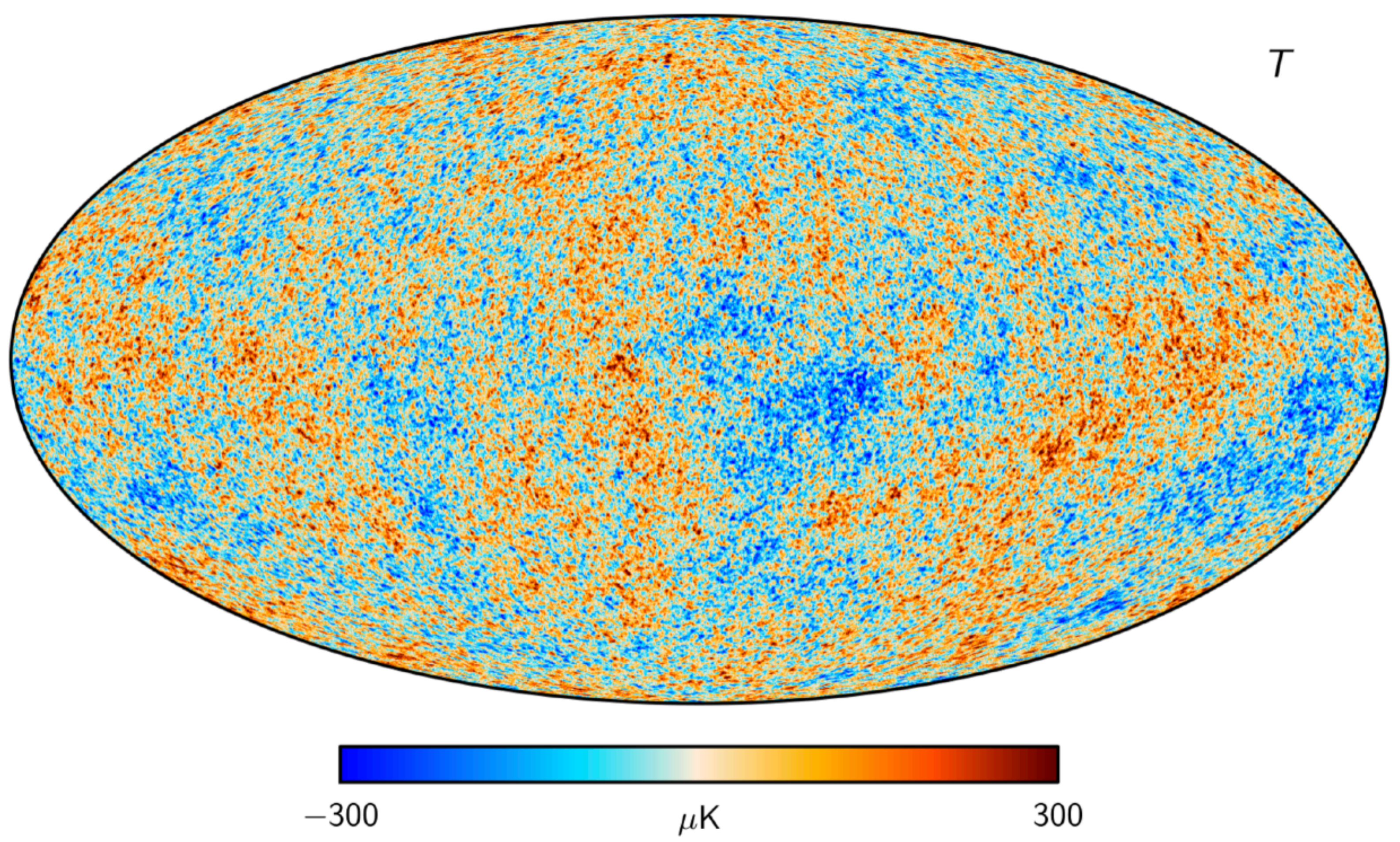
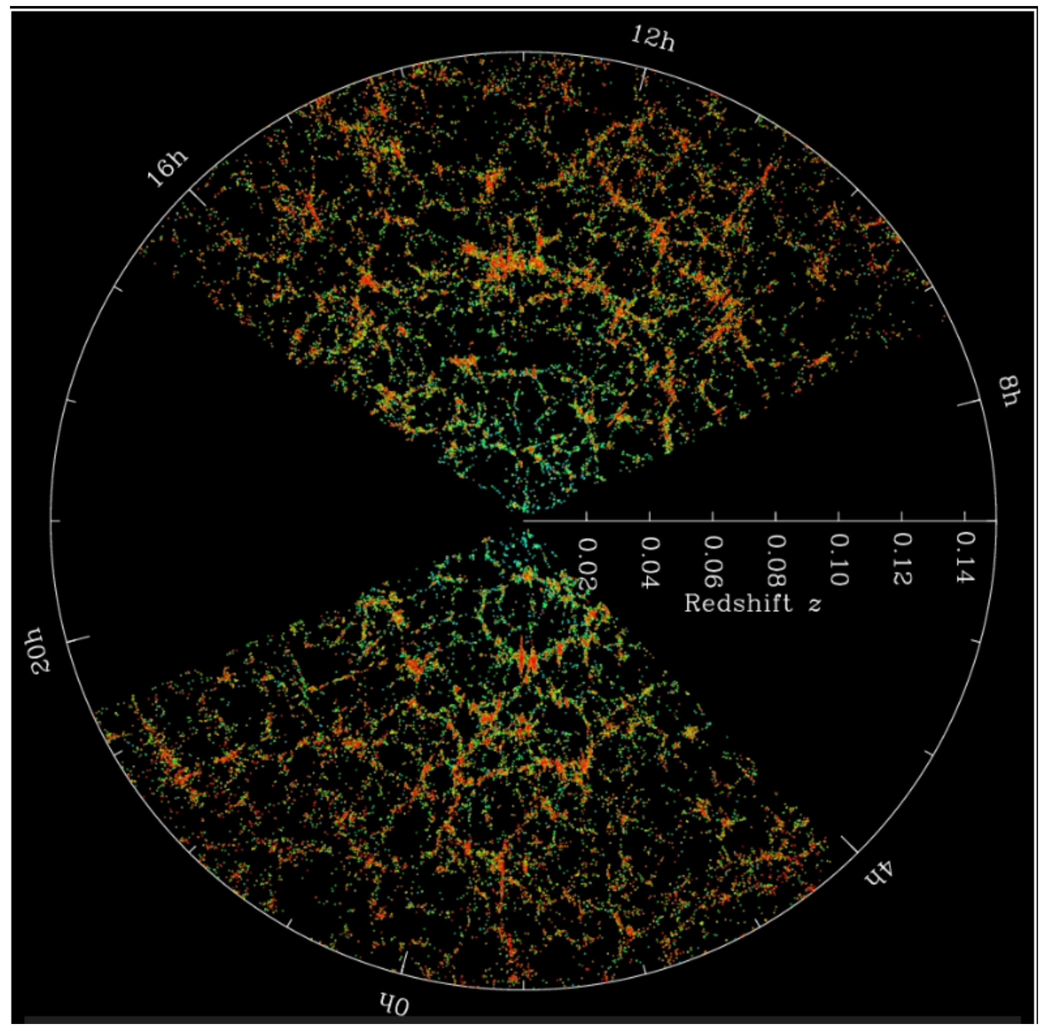
- The observed Universe is homogeneous and isotropic on very large scales

- However, we also see fluctuations at smaller scales ...



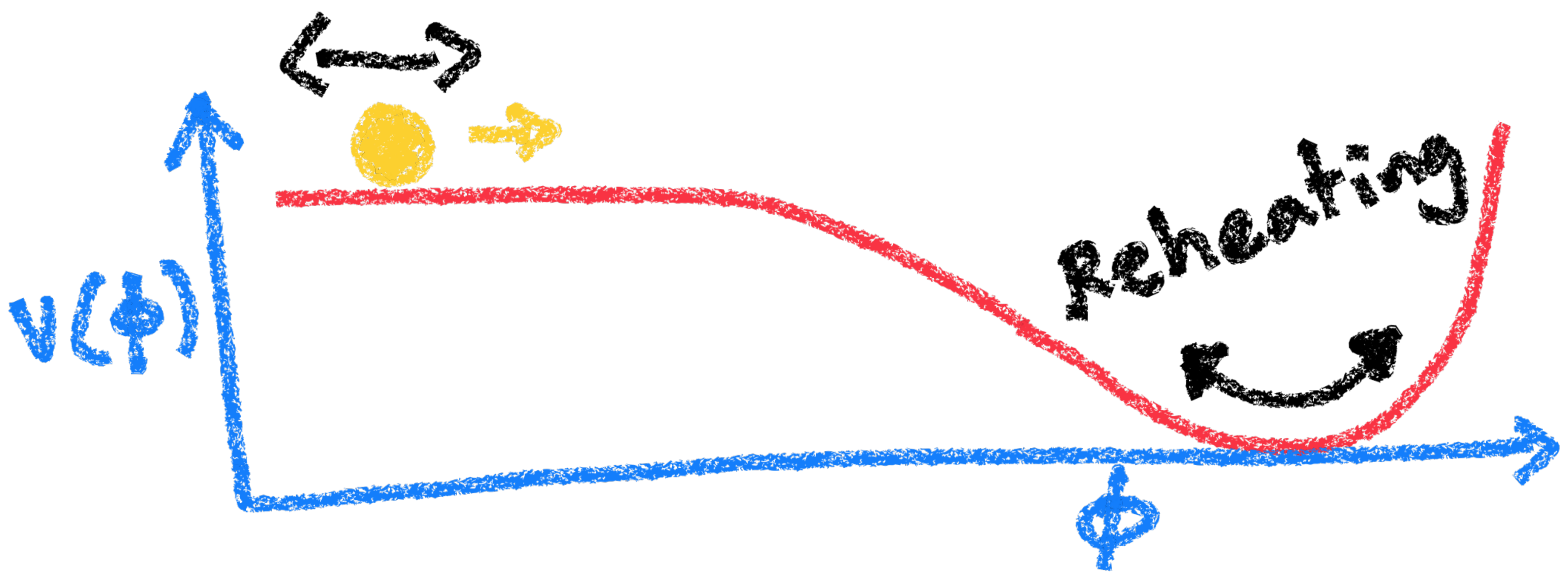
CMB: Planck



LSS: SDSS

- How to explain?

– The Inflationary Paradigm



long period of slow-roll on a flat potential

$$a \propto \exp(Ht) \quad \text{rapid expansion}$$

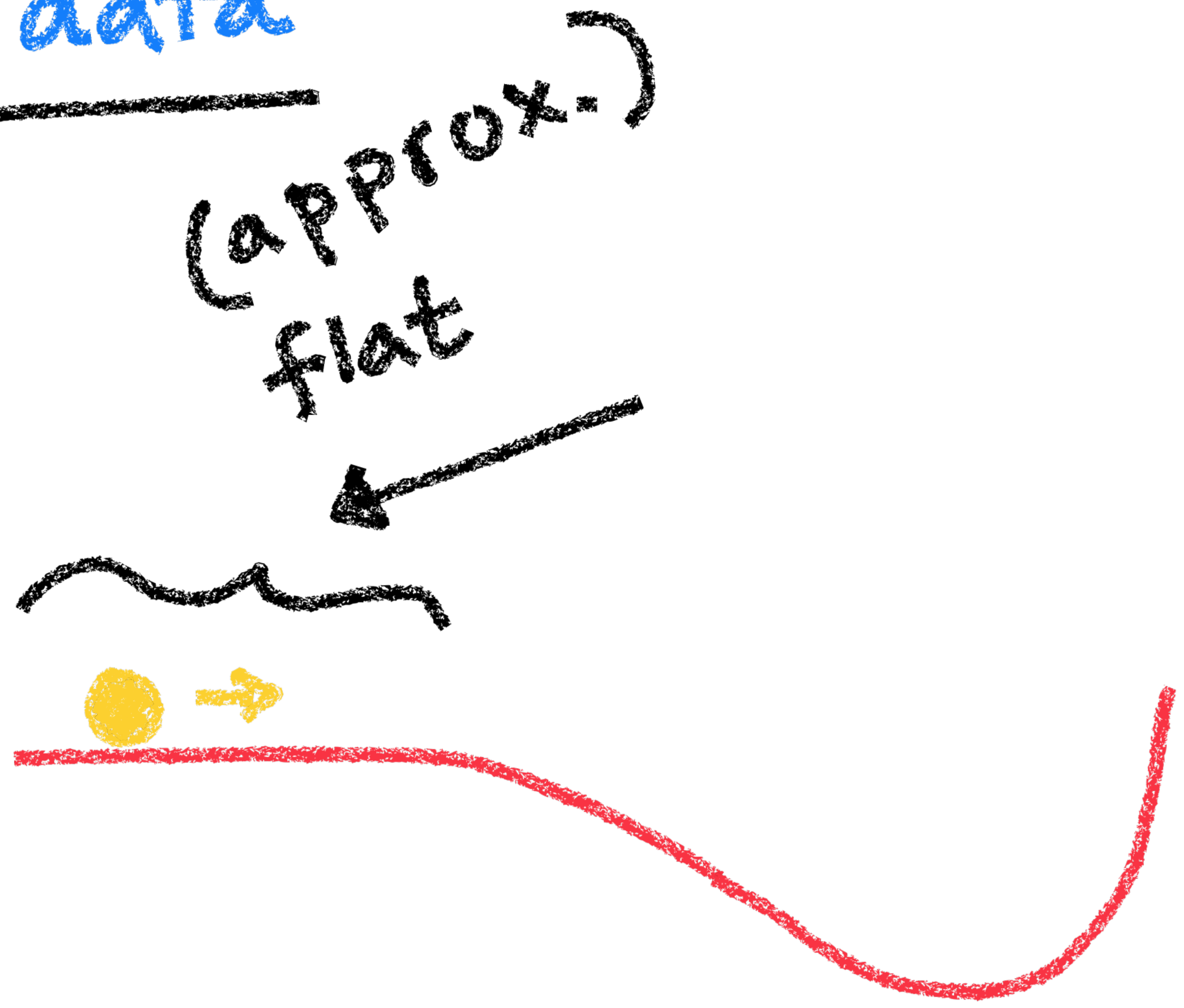
Quantum fluctuations

↳ Horizon exit ⤵

Reentry and sourcing density perturbation

- Predictions consistent with cosmological data

  - Scale invariant (approx.) $\leftarrow$ (approx.) time translation invariance



  - Adiabatic $\leftarrow$ single field (effectively)

  - Gaussian $\leftarrow$ small interactions (e.g. $V'''/H \ll 1$)

- Our quantitative knowledge

- know scalar power spectrum

$$\frac{k^3}{2\pi^2} P_s = \boxed{A_s} \left(k/k_p\right)^{\boxed{n_s}-1}$$

k_p = pivot scale (0.05/Mpc Planck 18)

$A_s \approx 2.2 \times 10^{-9}$ $n_s \approx 0.96$

"Scale Invariance"

- bounded tensor power spectrum

$$\frac{k^3}{2\pi^2} P_t = \boxed{A_t} \left(k/k_p\right)^{\boxed{n_t}-1}$$

Planck '18

$$r = A_t / A_s < 0.06$$

- Interpretation for single-field slow-roll inflation

$$\mathcal{L} \supset -\frac{1}{2}(\partial_\mu \phi)^2 - V(\phi)$$

ϕ = inflaton

can characterize flatness via

$$\epsilon \equiv \frac{1}{2} M_p^2 \left(V'/V\right)^2 \; ; \; \eta \equiv M_p^2 \left(V''/V\right)$$

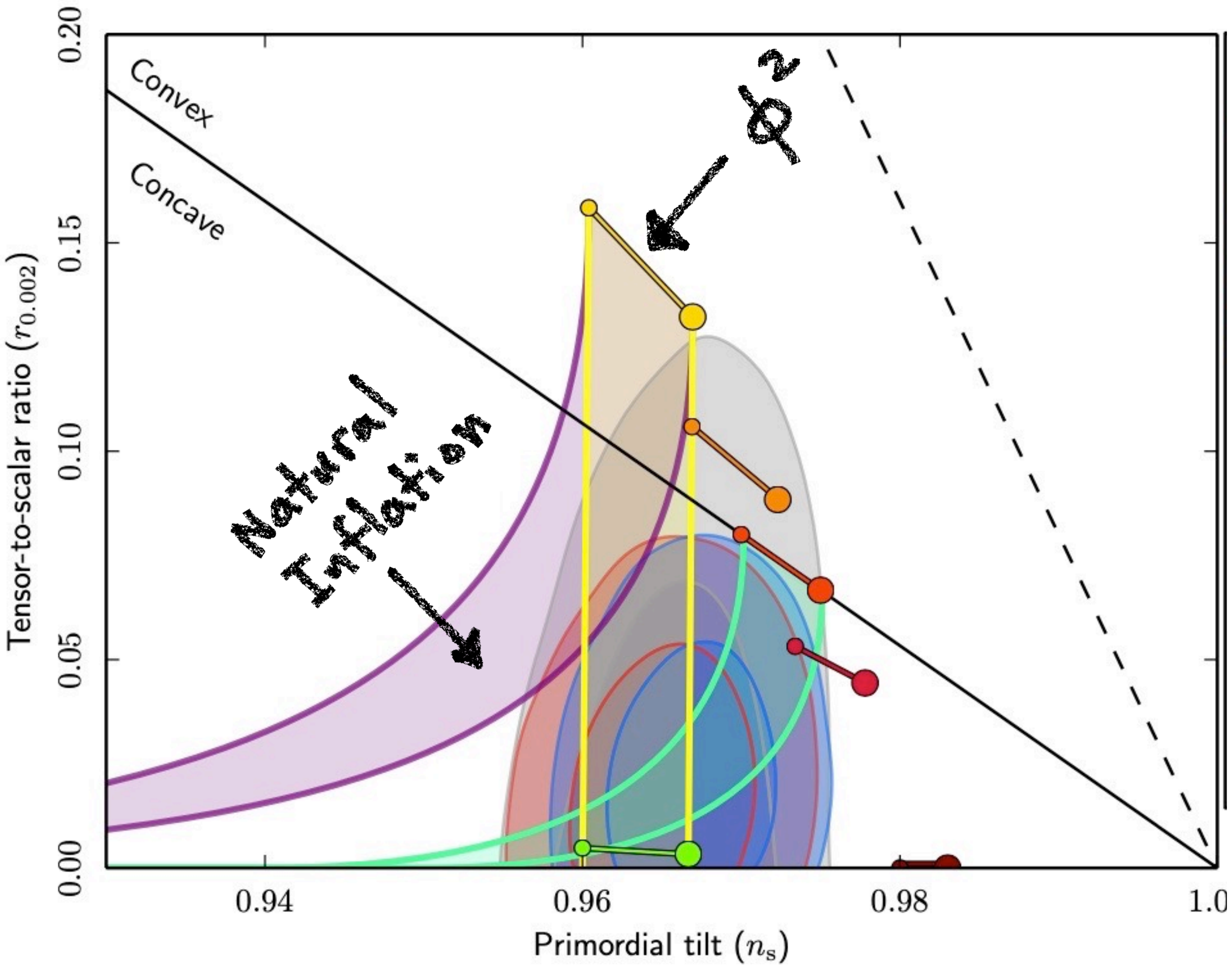
$$\frac{A_t}{A_s} = 16\epsilon < 0.06$$

$\Rightarrow$ $\boxed{\begin{array}{l} \eta \simeq -0.02 \\ \epsilon < 0.004 \end{array}}$ Planck '18

& $n_s - 1 = -2\eta + 6\epsilon$

$= -0.04$

- The n_s vs. r plot



Planck '18 + BICEP Keck

$\propto V'/V$ $\qquad$ $\propto V''/V$ $\qquad$ $\eta \simeq -0.02$, $\epsilon < 0.004$

$$|\epsilon| \ll |\eta| \ll 1$$

$$\& \quad \eta < 0$$

$\downarrow$

$\boxed{?}$ Initial Condition ?

$\boxed{?}$ $m_\phi^2/H^2 \simeq \eta$, how to keep it light ?

$\boxed{?}$ how to achieve $|\epsilon| \ll |\eta|$?

Outline

1. Schematic way to have $|\epsilon| \ll |\eta|$

2. Hybrid Inflation and Its Issues

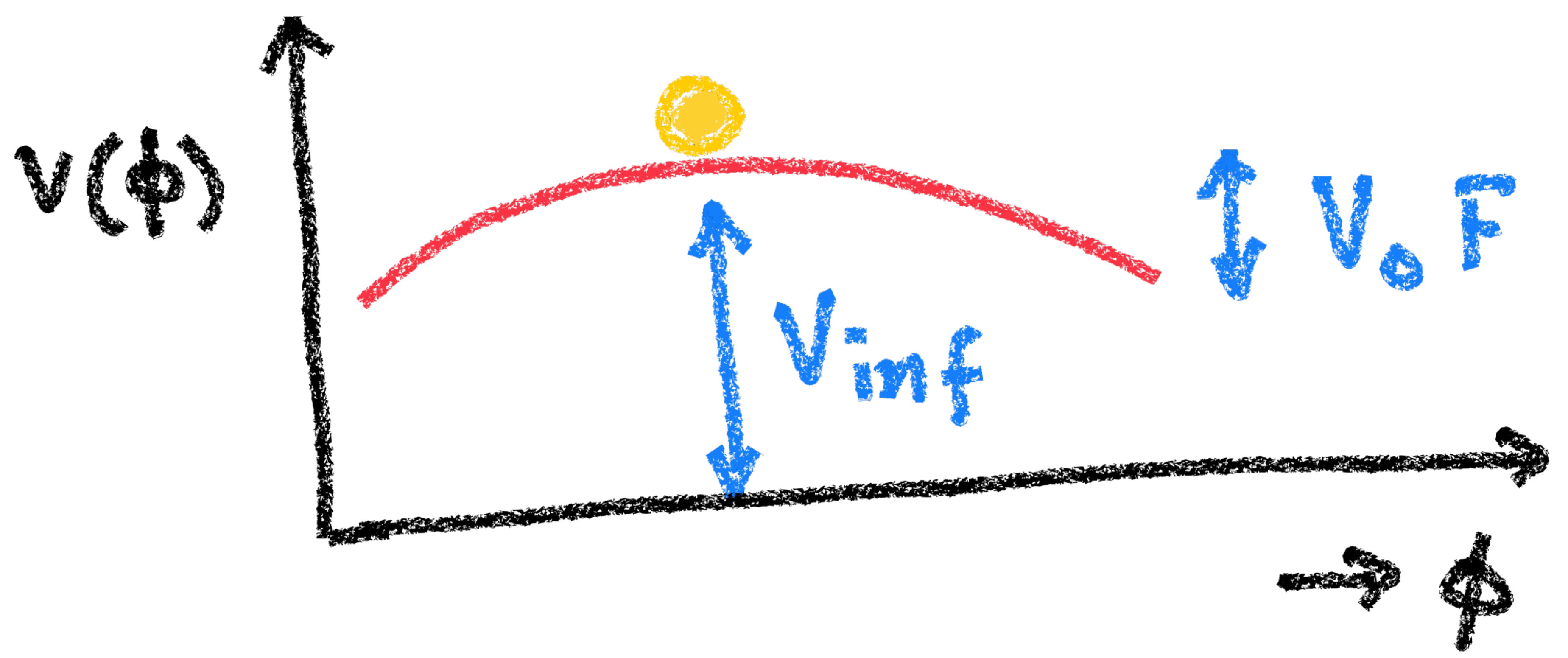
3. Hybrid TwInflation
   - Basic Model
   - PNGB Realization

   lower bound on H during inflation

4. Domain Wall problem

$\boxed{?}$ how to achieve $|\epsilon| \ll |\eta|$?

$$V(\phi) = \overset{\text{constant}}{V_{inf}} + \underbrace{V_0 F(\phi/f)}_{\mathcal{O}(\phi)}$$



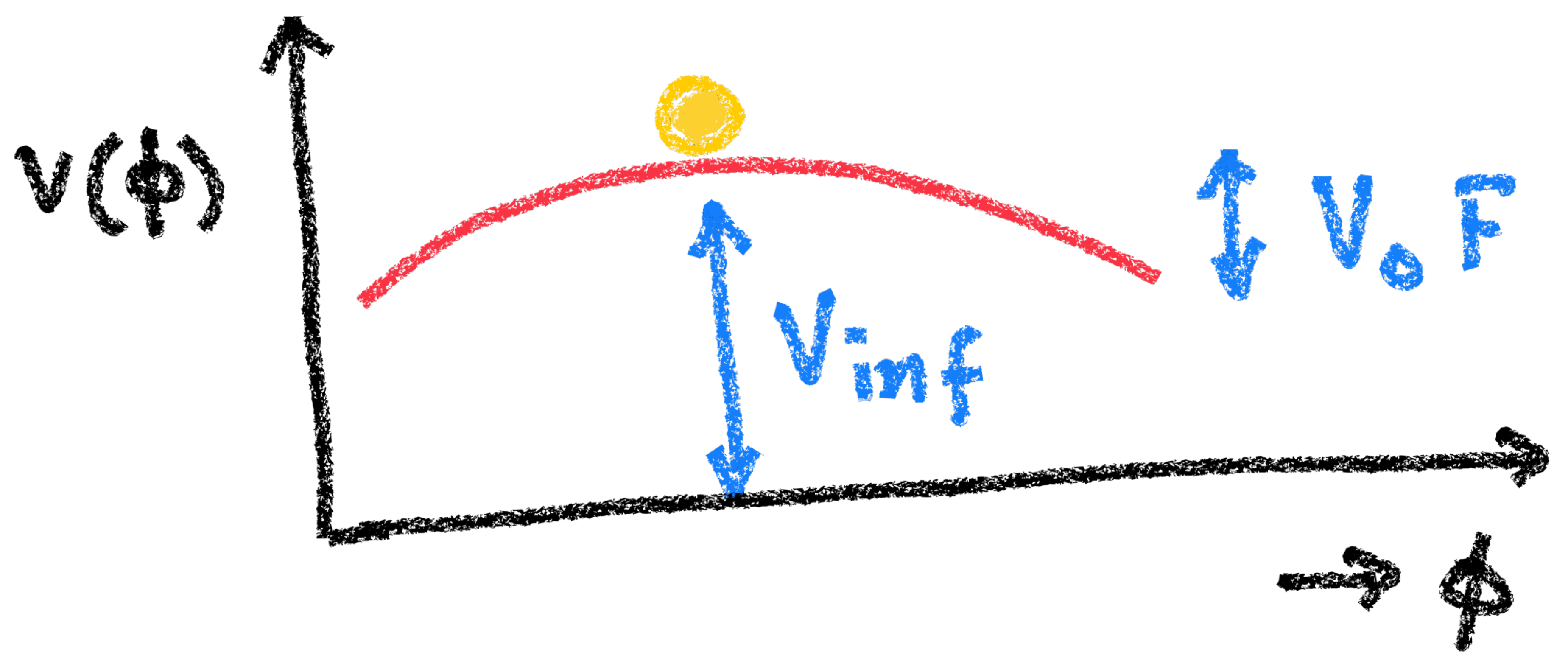
$$\epsilon \equiv \frac{1}{2} M_p^2 \left(V'/V\right)^2$$

$$\eta \equiv M_p^2 \left(V''/V\right)$$

$$\Rightarrow \quad \frac{\epsilon}{\eta} \sim \underbrace{\frac{V_0}{V_{inf}}}_{\text{Parametric Suppression} \ll 1} \cdot \underbrace{\frac{F'^2}{F''}}_{\mathcal{O}(1)}$$

$\boxed{\checkmark}$

$\boxed{?}$ how to achieve $|\epsilon| \ll |\eta|$?



$$V(\phi) = \overset{\text{constant}}{V_{inf}} + \underbrace{V_0 F(\phi/f)}_{\mathcal{O}(\phi)}$$

$$\epsilon \equiv \frac{1}{2} M_p^2 \left(V'/V\right)^2$$

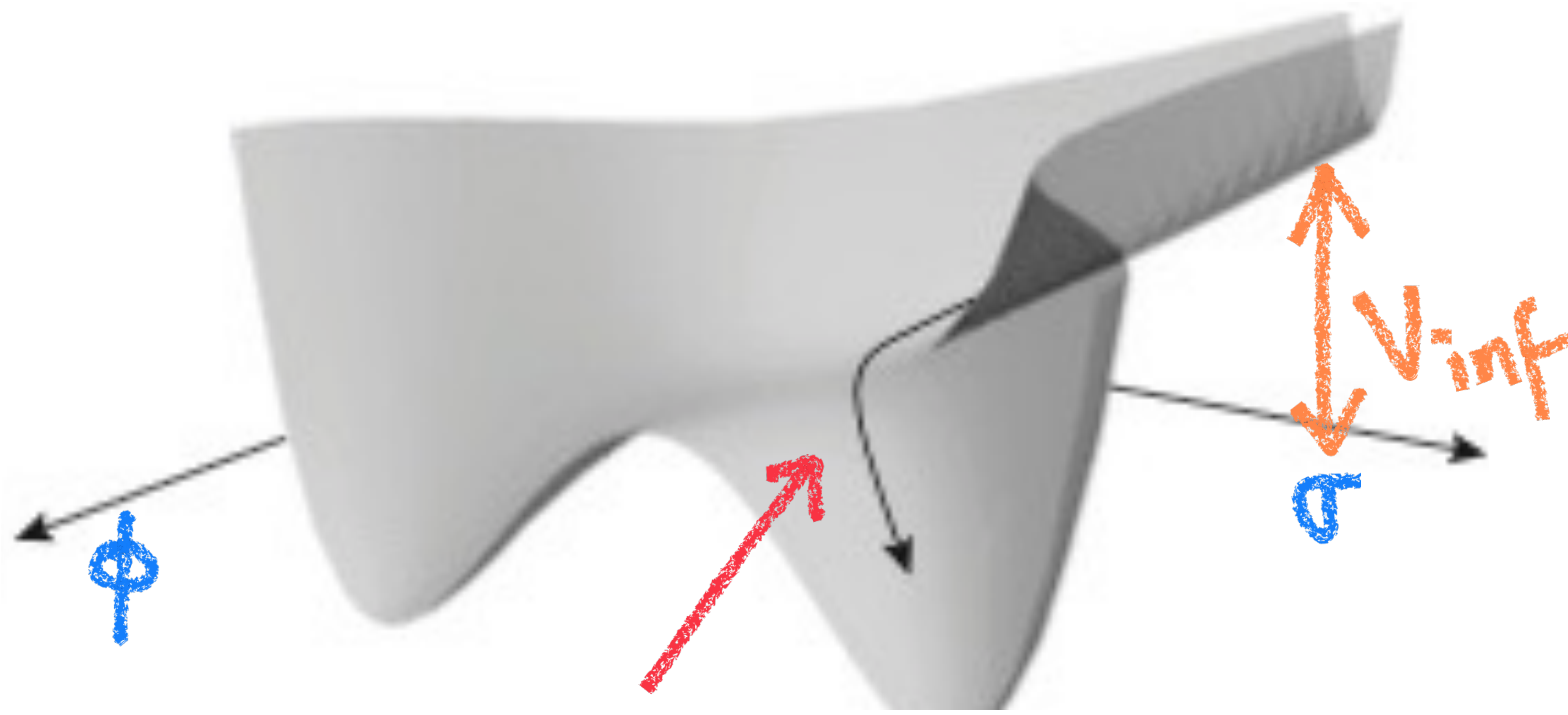
$$\eta \equiv M_p^2 \left(V''/V\right)$$

- One field for V_{inf}
  - ↳ inflates
- Another for dynamics
  - ↳ fluctuates

$$\Rightarrow \frac{\epsilon}{\eta} \sim \underbrace{\frac{V_0}{V_{inf}}}_{\text{Parametric Suppression} \ll 1 \ \checkmark} \cdot \underbrace{\frac{F'^2}{F''}}_{\mathcal{O}(1)}$$

Basic Mechanism Hybrid Inflation (Linde '93)

Inflaton ϕ ; Waterfall σ



$$V(\phi,\sigma) = V_{inf} + \mathcal{V}(\phi)$$

$$+ \frac{1}{2}\underbrace{(M_\sigma^2 - g\phi^2)}_{\phi_* = M_\sigma/\sqrt{g}}\sigma^2 + \frac{1}{4}\lambda_\sigma\sigma^4$$

Inflation ends through tachyonic instability

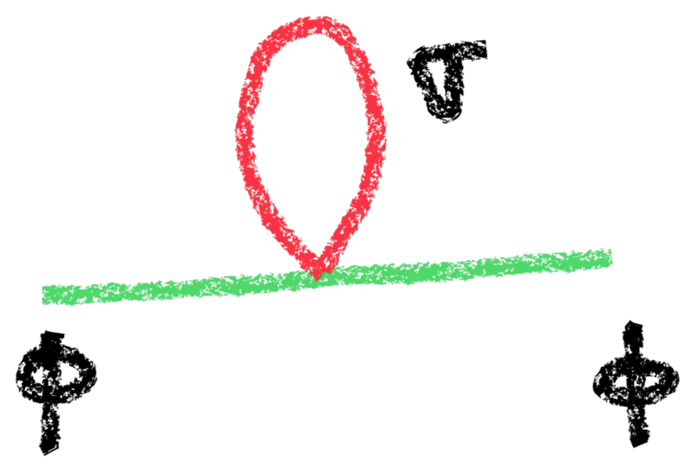
During Inflation: $V(\phi,\sigma) \simeq V_{inf} + \mathcal{V}(\phi)$

inflates ↗ ↖ fluctuates

$$\mathcal{V}(\phi) = -\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4$$ ← Also explains tilt

Issue

- Critical to have $V(\phi,\sigma) \supset + \frac{1}{2}\left(M_\sigma^2 - g\phi^2\right)\sigma^2$ to have ϕ-activated switching, but...



$$\delta m_\phi^2 \sim g\Lambda^2/(16\pi^2)$$

Λ = heavy physics scale

- $\delta m_\phi^2 < m_\phi^2$

$$\Rightarrow \quad \Lambda^2 < (16\pi^2\eta)\, H^2/g$$

- For σ to be static

$$M_\sigma^2 \simeq g\phi_0^2 > H^2$$

ϕ_0 = some typical ϕ value during inflation

Issue

$$g < (16\pi^2\eta)\, H^2/\Lambda^2$$

conflict

$$g > H^2/\phi_0^2$$

$\Rightarrow$

For any g & $\eta \simeq 0.01$

$$\phi_0 \gtrsim \Lambda$$

Sensitivity to heavy physics, uncontrolled $(\phi/\Lambda)^n$ expansion

– Goal: Couple to waterfall field so as to remove the sensitivity

First try: Soft Breaking

- why not change $g\phi^2\sigma^2 \to \mu\phi\sigma^2$?

$$V(\phi,\sigma) = V_{inf} + \vartheta(\phi) + \underbrace{\frac{1}{2}\left(M_\sigma^2 - \mu\phi\right)}_{\phi_* = M_\sigma^2/\mu}\sigma^2 + \frac{1}{4}\lambda_\sigma\sigma^4$$

- only log sensitivity

$$\delta m_\phi^2 \sim \mu^2 \ln\Lambda/(16\pi^2)$$ no Λ^2 sensitivity $\boxed{\checkmark}$

- no large displacement

$$M_\sigma^2 \sim \mu\phi_0 > H^2 \quad \Rightarrow \quad H/\phi_0 \lesssim \mu/H \lesssim 4\pi\sqrt{\eta}$$ easy to satisfy $\boxed{\checkmark}$

Soft breaking → Large tadpole

- $\phi \to -\phi$ is not a symmetry anymore

$$V(\phi,\sigma) \supset \frac{\mu\Lambda^2}{16\pi^2}\phi$$

- Absorb by

$$\delta\phi \sim \frac{\mu\Lambda^2}{16\pi^2 m_\phi^2} \sim \frac{\mu\Lambda^2}{H^2} \qquad (\eta \simeq 0.01)$$

- But this changes

$$\frac{\delta M_\sigma^2}{M_\sigma^2} \sim \frac{\delta\phi}{\phi} \sim \frac{M_\sigma^2}{H^2}\cdot\frac{\Lambda^2}{\phi_0^2} \longrightarrow \delta M_\sigma^2/M_\sigma^2 < 1$$

$$\Rightarrow \phi_0/\Lambda > M_\sigma/H > 1.$$

Summary so far

Original Coupling

$$(M_\sigma^2 - g\phi^2)\sigma^2$$

✓ $\phi \to -\phi$ sym; no tadpole

✗ $\delta m_\phi^2 \propto g\Lambda^2$

Soft Coupling

$$(M_\sigma^2 - \mu\phi)\sigma^2$$

✗ $\phi \not\to -\phi$ sym; large tadpole

✓ $\delta m_\phi^2 \propto \mu^2 \ln \Lambda$

Want to have best of both

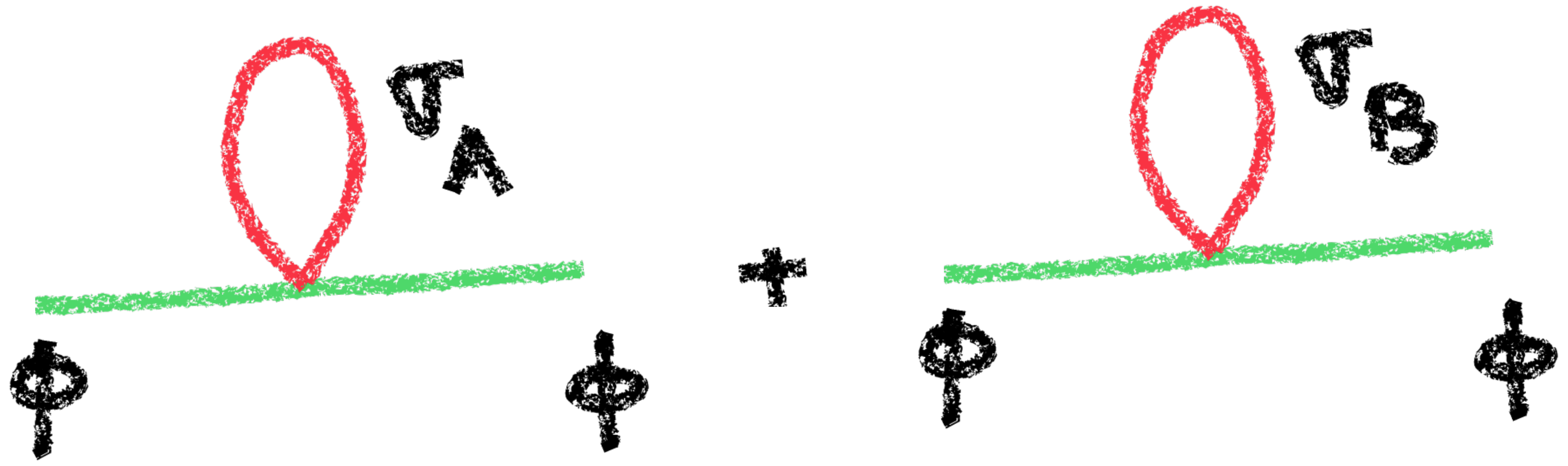
Hybrid TwInflation

Chacko, Goh
Harnik '06

- A twin sector to remove Λ^2 : $\frac{1}{2}(M_\sigma^2 - g\phi^2)\sigma^2$

$$g\phi^2\sigma^2 \longrightarrow g\phi^2(\sigma_A^2 - \sigma_B^2)$$

naively,



$$\longrightarrow \delta m_\phi^2 \propto \cancel{g\Lambda^2} - \cancel{g\Lambda^2}$$

but not protected by symmetry

- Hence try
$$\mu\phi\sigma^2 \longrightarrow \mu\phi(\sigma_A^2 - \sigma_B^2)$$

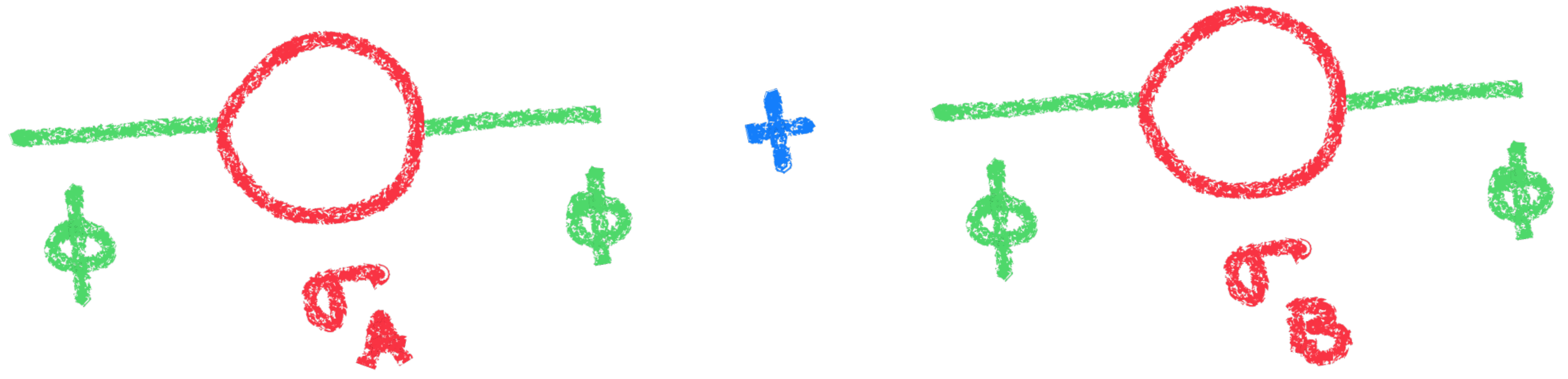
Protected via $\{\phi \to -\phi\ ,\ \sigma_A \to \sigma_B\}$

Safety from radiative corrections

$$\mu\phi\sigma^2 \longrightarrow \mu\phi(\sigma_A^2 - \sigma_B^2)$$

Protected via $\{\phi \to -\phi\,,\ \sigma_A \to \sigma_B\}$

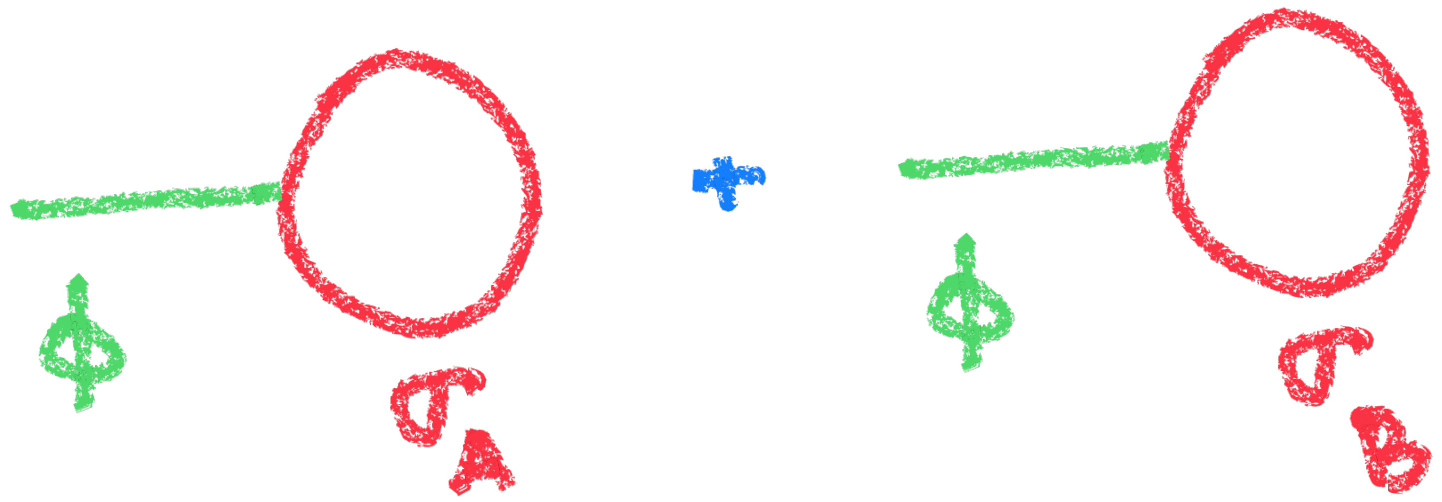
- $\delta m_\phi^2 \to$



$\sim \mu^2 \ln\Lambda / 16\pi^2$

no cancellation, <u>but</u> only log sensitivity

- tadpole $\to$



$\sim \cancel{\mu\Lambda^2} - \cancel{\mu\Lambda^2}$

cancellation!

since linear in ϕ violates symmetry

Summary so far

Original Coupling

$$(M_\sigma^2 - g\phi^2)\sigma^2$$

✓ $\phi \to -\phi$ sym; no tadpole

✗ $\delta m_\phi^2 \propto g\Lambda^2$

Soft Twin Coupling

$$(M_{\sigma_A}^2 - \mu\phi)\sigma_A^2 + (M_{\sigma_B}^2 + \mu\phi)\sigma_B^2$$

✓ $\phi \to -\phi$ sym; NO large tadpole
$\sigma_A \to \sigma_B$

✓ $\delta m_\phi^2 \propto \mu^2 \ln \Lambda$

Now have best of both

Basic Model

- Symmetry to obey $\phi \to -\phi$ & $\sigma_A \to \sigma_B$

$$V(\phi, \sigma_A, \sigma_B) = V_{inf} + \left(-\frac{1}{2} m_\phi^2 \phi^2 + \frac{\lambda_\phi}{4} \phi^4 + \dots\right)$$

$$+ \left[\left(\frac{1}{2} M_\sigma^2 \sigma_A^2 + \frac{\lambda_\sigma}{4} \sigma_A^4\right) + (A \to B)\right] + \frac{\bar{\lambda}_\sigma}{4} \sigma_A^2 \sigma_B^2$$

$$+ \frac{1}{2} \mu \phi \left(\sigma_A^2 - \sigma_B^2\right) + \kappa \phi^2 \left(\sigma_A^2 + \sigma_B^2\right) + \dots$$

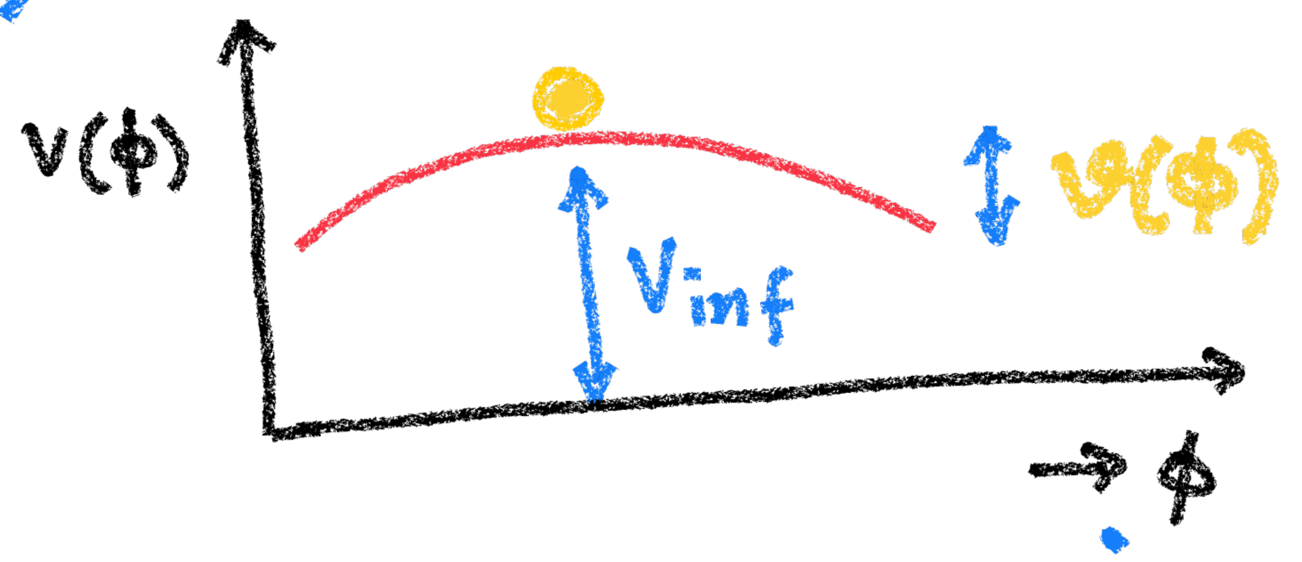
$\left.\begin{array}{l} \mu, m_\phi \ll M_\sigma \\ \kappa, \lambda_\phi \ll \lambda_\sigma, \bar{\lambda}_\sigma \end{array}\right\}$ Approx. shift symmetry for ϕ

- Consider $\mu \phi < M_{\sigma_{A,B}}^2$ during inflation
- σ_A, σ_B stabilized at $\langle \sigma \rangle = 0$.

Dynamics during inflation

- σ_A, σ_B stable during inflation at $\langle \sigma_{A,B} \rangle = 0$

$$V_{eff}(\phi) \simeq V_{inf} + \underbrace{\left(-\frac{1}{2} m_\phi^2 \phi^2 + \frac{\lambda_\phi}{4} \phi^4 + \dots\right)}_{v(\phi)}$$



Standard Dynamics

- Towards the end of inflation,

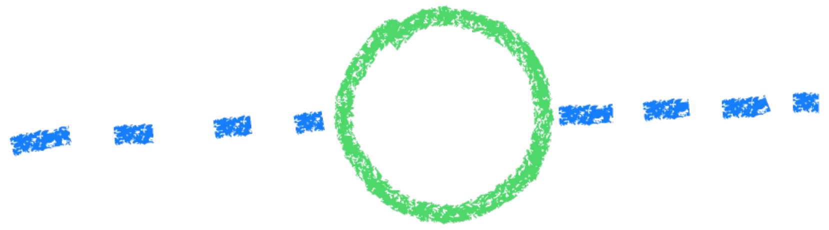
$$\underset{\text{remains at } \langle \sigma_A \rangle = 0 \quad\quad \text{symmetry breaking}}{M^2_{\sigma_{A,B}}(\phi) = M^2_\sigma \pm \mu \phi}$$

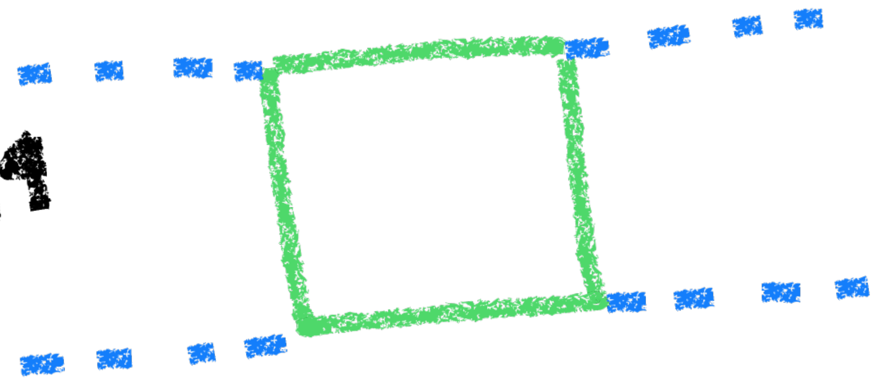
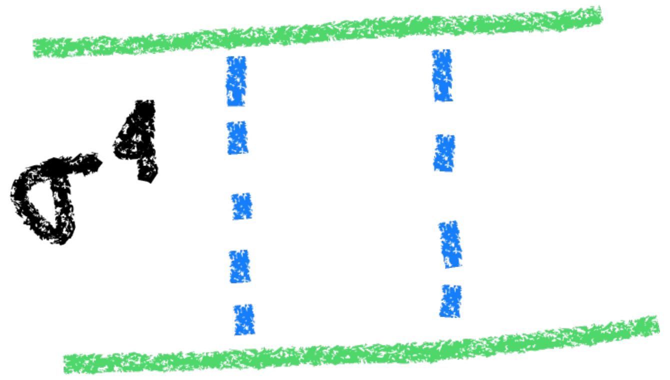
$$V_{inf} = \frac{M_\sigma^4}{4\lambda_\sigma}\left(\frac{\phi_{min}}{\phi_*} - 1\right)^2$$

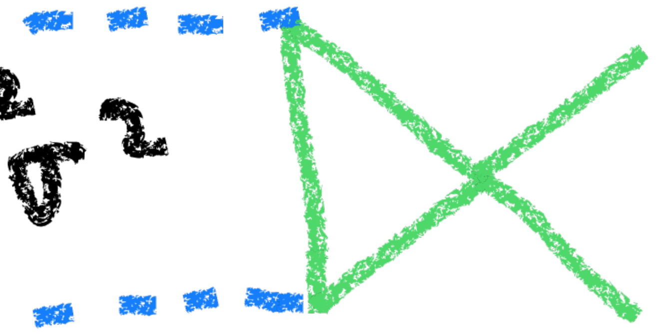
Drop in CC

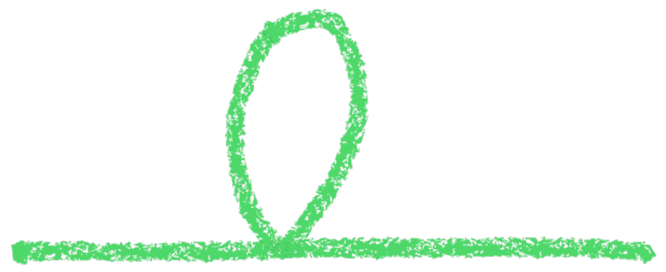
Radiative Stability and Naturalness

* Source of ϕ-shift symmetry breaking $= \mu \phi \sigma_{A,B}^2$

$\underline{\phi^2}$  $\delta m_\phi^2 \sim \mu^2 \ln \Lambda / 16\pi^2$

ϕ^4  σ^4  $\delta(\lambda_\sigma, \bar{\lambda}_\sigma, \lambda_\phi) \sim \dfrac{\mu^4}{16\pi^2 M_\sigma^4}$

$\phi^2\sigma^2$  $\delta \kappa \sim \dfrac{\lambda_\sigma \mu^2}{16\pi^2 M_\sigma^2}$

 $\delta M_\sigma^2 \sim \dfrac{\lambda_\sigma \Lambda^2}{16\pi^2}$

– These determine the natural sizes of parameters

Getting consistent inflation

$$\mu^2 \sim 16\pi^2 \eta H^2 \quad \Rightarrow \quad \mu \simeq H \quad \text{(correct } \eta \text{ parameter)}$$

$$A_s = \frac{1}{8\pi^2} \frac{H^2}{M_p^2 \epsilon} \sim \frac{10^{-2}}{\eta^2} \frac{H^2}{\phi_0^2} \quad \Rightarrow \quad \phi_0 / H \sim 10^6 \quad \text{(correct } A_s\text{)}$$

← typical inflaton value

$$\frac{M_\sigma^4}{\lambda_\sigma} \sim H^2 M_p^2 \quad \Rightarrow \quad \frac{\mu^2 \phi_0^2}{\lambda_\sigma} \sim H^2 M_p^2$$

$$\Rightarrow \quad H/M_p \sim 10^{-6} \sqrt{\lambda_\sigma} \quad \text{(satisfies } r\text{)}$$

How small can H be?

$$\frac{M_\sigma^4}{\lambda_\sigma} \sim \frac{\mu^2 \phi_0^2}{\lambda_\sigma} \sim H^2 M_p^2$$

$$\Rightarrow \lambda_\sigma \sim \frac{\mu^2}{M_p^2} \cdot \left(\frac{\phi_0}{H}\right)^2$$

but also, radiative corrections,

$$\lambda_\sigma > \frac{\mu^2}{16\pi^2 \phi_0^2}$$

$H \gtrsim 10^5$ GeV

- Lower T_{RH}, avoids overclosure due to unwanted relics
- suppresses axion DM isocurvature

PNGB Realization

- model ϕ as a PNGB of U(1) field $\Phi \propto \langle\Phi\rangle e^{i\phi/\langle\Phi\rangle}$

$$\phi \to \phi + c \quad \Leftarrow \quad \Phi \to \Phi\, e^{ic/\langle\Phi\rangle}$$

$$\mathcal{L}_{UV} = -|\partial\Phi|^2 - V(|\Phi|^2) + \mathcal{L}[\sigma_A, \sigma_B]$$

same as before

$$+\left\{\mu\Phi(\sigma_A^2 - \sigma_B^2) + (\mu\Phi)^2 + \text{h.c.}\right\} - g|\Phi|^2(\sigma_A^2 + \sigma_B^2)$$
$$- V_{inf}$$

$$\{\Phi \to -\Phi\,,\ \sigma_A \to \sigma_B\}$$

μ = U(1) "spurion" to denote soft U(1) breaking

The IR Lagrangian

$$\mathcal{L}_{IR} = \mathcal{L}[\sigma_A, \sigma_B]$$

same as before

$$+ \frac{1}{2}(\partial\phi)^2 - \frac{\mu f}{2} \sin(\phi/f)(\sigma_A^2 - \sigma_B^2) - \mu^2 f^2 \cos(2\phi/f) - V_{inf}$$

→ gives the previous structure for $\phi \ll f$

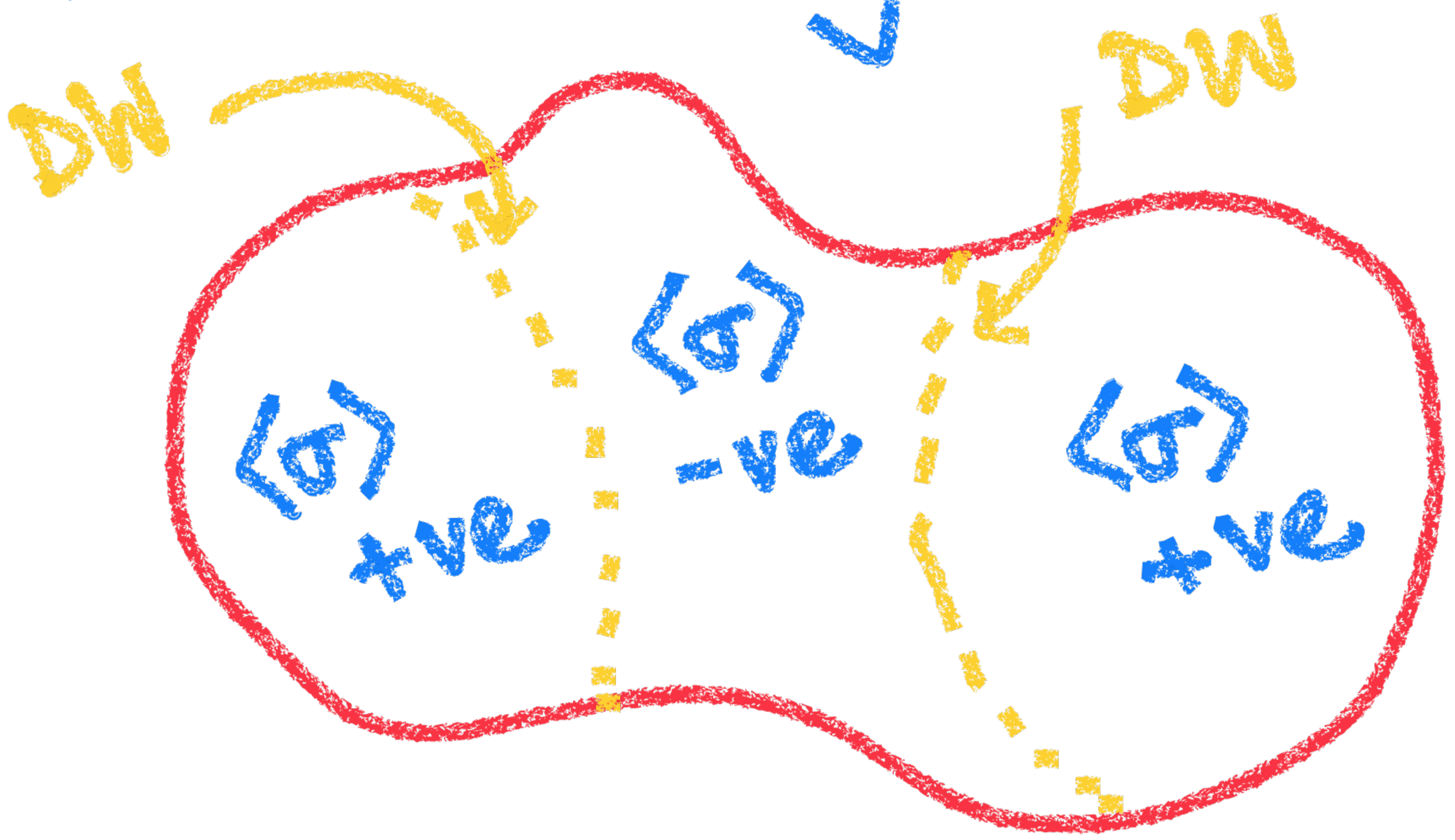
→ other dynamics same as before

→ $\phi_{initial}/f \simeq 0.1\pi$ gives 60 e-foldings

no fine tuning of initial position is needed

Addressing the Domain Wall Problem

- Spontaneous breaking of $\sigma \to -\sigma$ symmetry



not essential in our mechanism

- Can be avoided by breaking $\sigma_i \to -\sigma_i$ symmetry

$$\mathcal{L} \supset M \sigma_i^3$$

biases one vacuum, annihilation of DW

- Breaking affects inflaton potential, increases $H \gtrsim 10^7$ GeV

Summary

- Current data is increasing favoring low(ish)-scale, hilltop models $\epsilon \ll |\eta|, \quad \eta < 0$
- Hybrid inflation achieves $\epsilon < |\eta|$ parametrically
- Constructed a natural, EFT controlled version with Z_2 twin symmetry
- Low-scale $H \gtrsim 10^7$ GeV [axion isocurvature, overclosure]

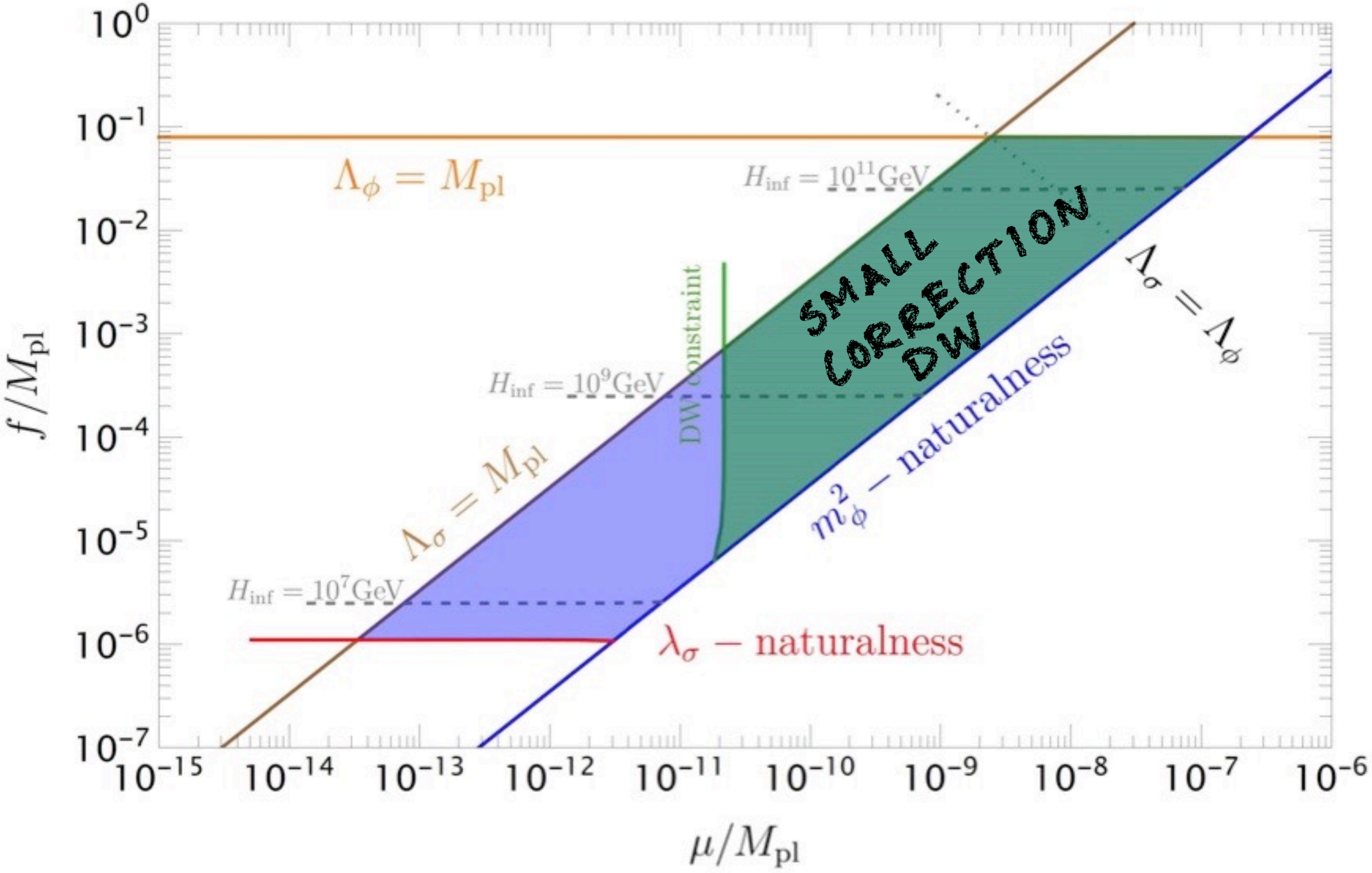
$\boxed{\text{Gravitational Waves ?}}$

Full Parameter Space

$\Lambda_\sigma \approx 4\pi \frac{M_\sigma}{\sqrt{\lambda_\sigma}}$

$\sim 4\pi \cdot \frac{H M_p}{M_\sigma}$

$\Lambda_\phi \approx 4\pi f$



Details on Domain Wall Problem

$$V(\phi, \sigma_i) \supset M \sigma_i^3 \rightarrow \Delta V_{bias}/V_{inf} \sim M/(M_\sigma \sqrt{\lambda_\sigma})$$

Annihilation before domination

$$\mathcal{O}(1) \gtrsim \Delta V_{bias}/V_{inf} \gtrsim \frac{M_\sigma^2}{\lambda_\sigma M_p^2}$$

M generates a tadpole $V \supset M \Lambda_\sigma^2 \sigma_i / (16\pi^2)$

$$\delta\sigma_i \sim \frac{M M_\sigma^2}{\lambda_\sigma M_{\sigma_i}^2} \Rightarrow \delta V_{eff} \sim \frac{M M_\sigma^2}{\lambda_\sigma} \cdot \frac{M M_\sigma^2}{\lambda_\sigma M_{\sigma_i}^2}$$

Ensure $\delta V_{eff} < V_{eff}$ itself