A Multiverse Outside of the Swampland

[arXiv:2404.13109 [hep-ph]]

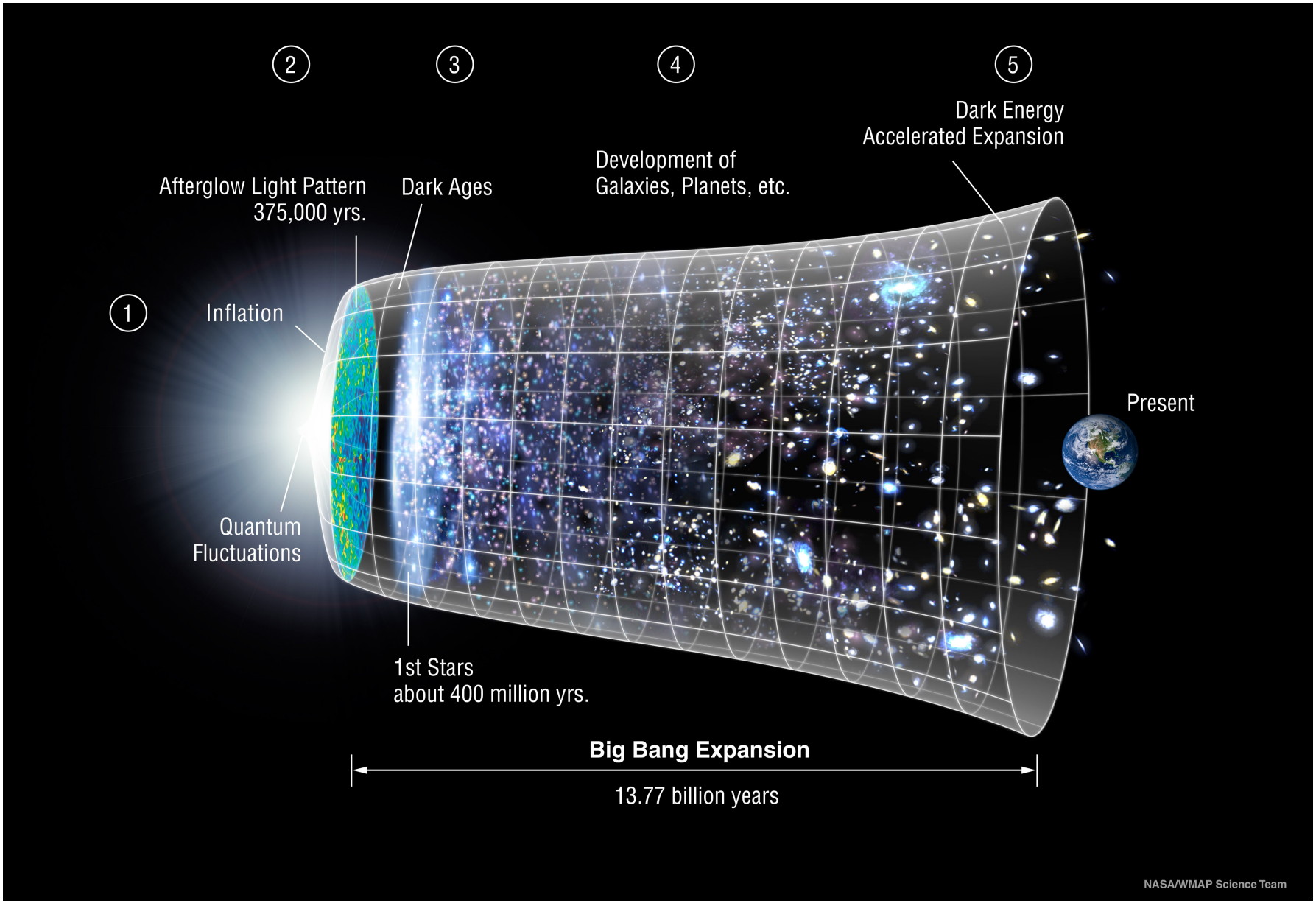
Gabriele Rigo (IPhT, Saclay)

Raffaele Tito D'Agnolo, Paolo Mangini, Lian-Tao Wang

New Approaches to Naturalness

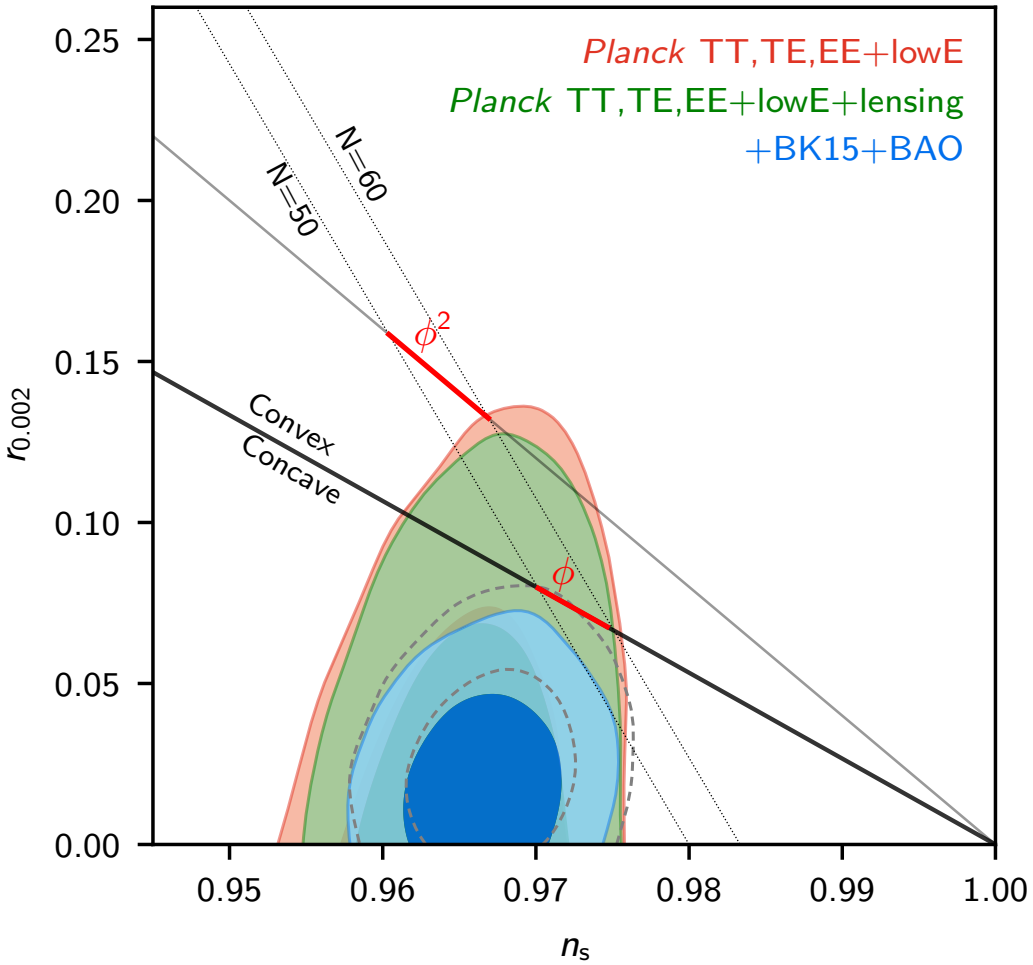
21 May 2025

The Importance of Stretching



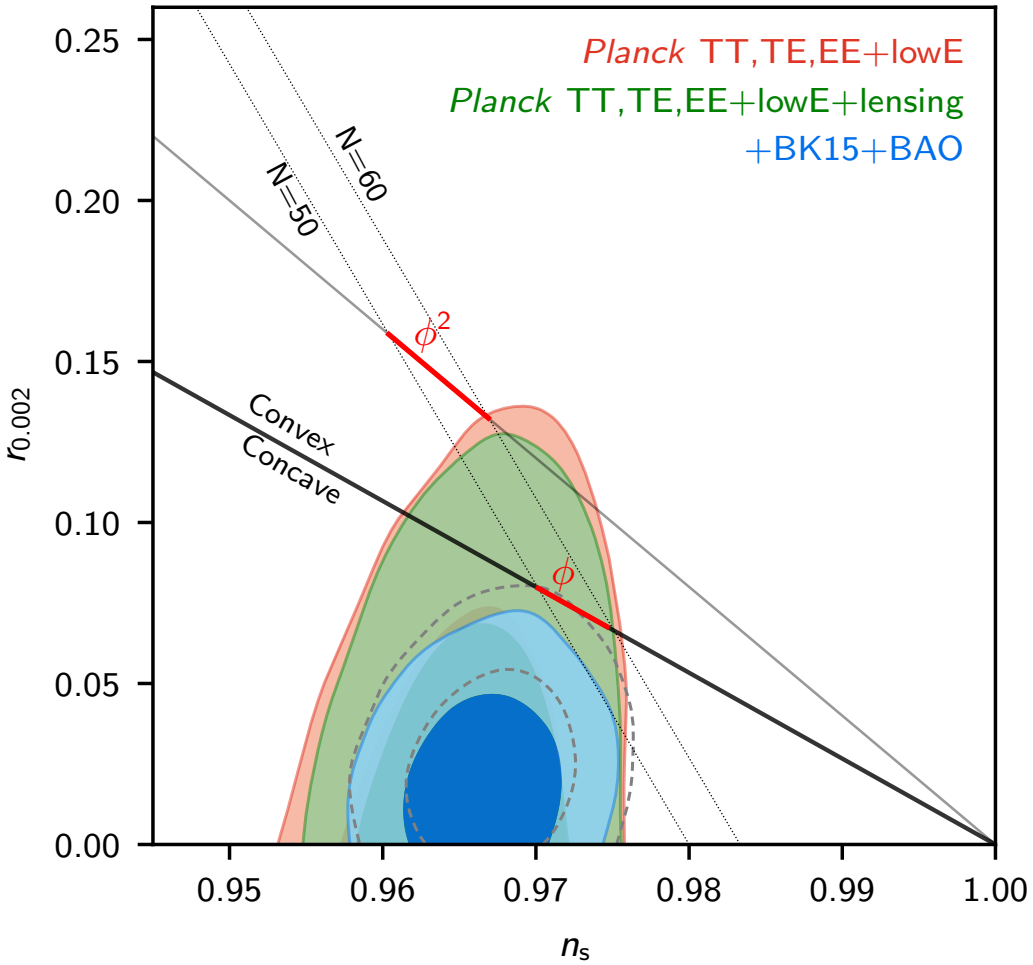
Challenges for Inflation

Experimental constraints



Challenges for Inflation

Experimental constraints



Theoretical considerations

- S-matrix, $t_q \sim M_{Pl}^2/\Lambda^{3/2}$
- Swampland program

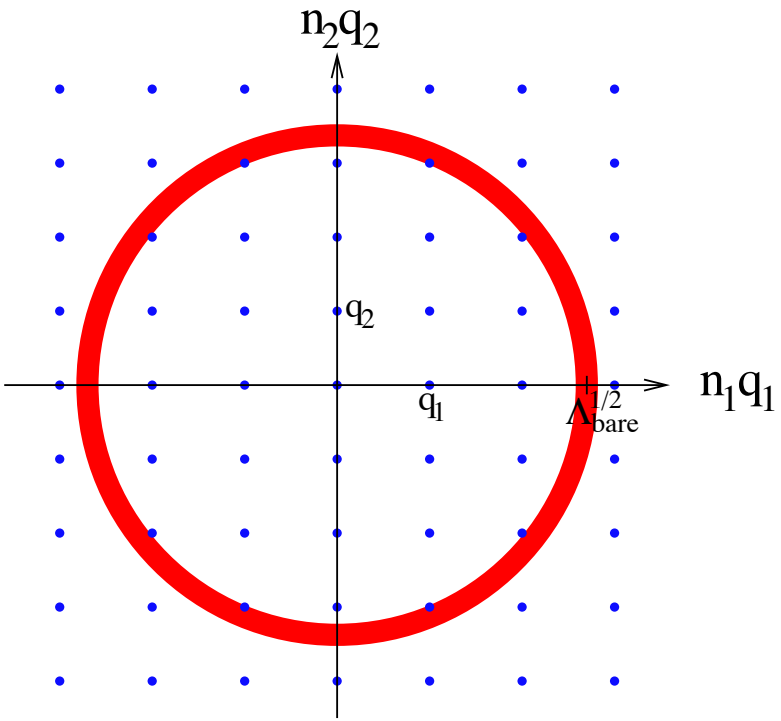
Outline

1. **Why Should We Care?**

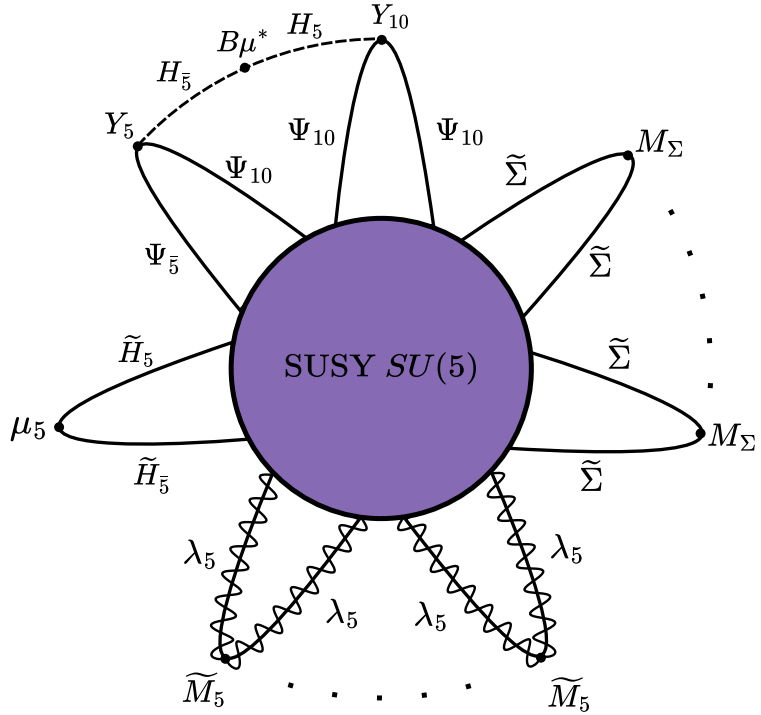
2. **A Model of the Multiverse**

Fine-Tuning and Symmetry

Bousso–Polchinski

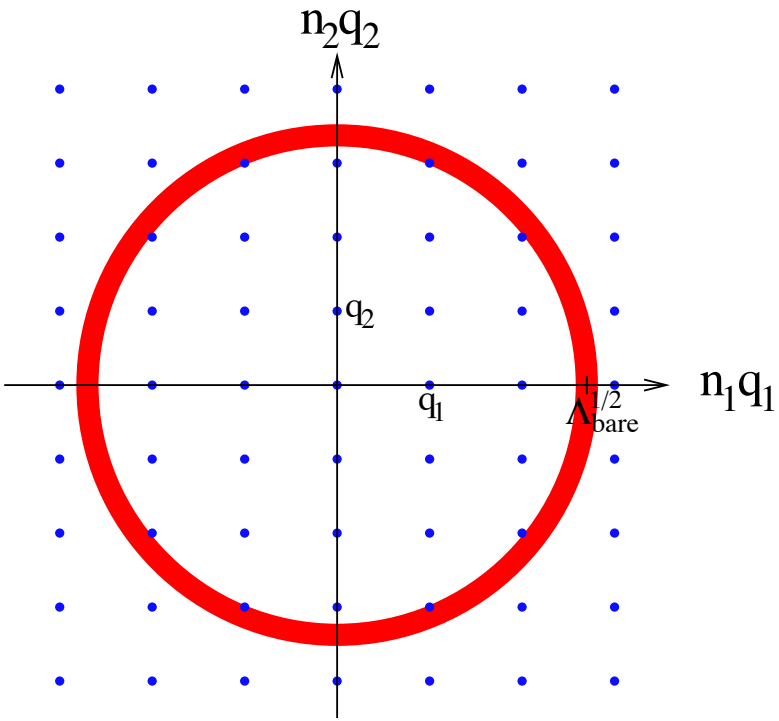


Sliding Naturalness

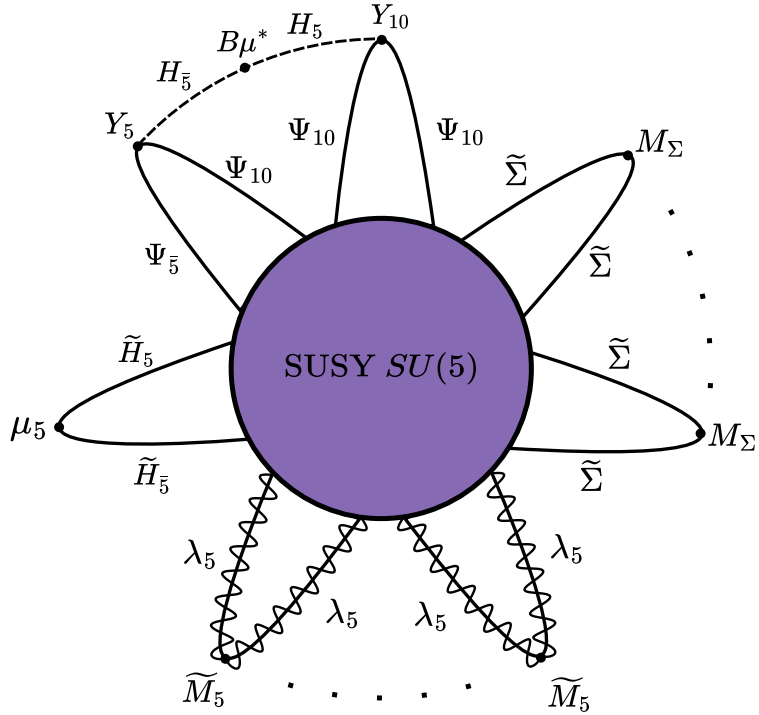


Fine-Tuning and Symmetry

Bousso–Polchinski



Sliding Naturalness



TAKE-HOME MESSAGE

No symmetry $\longrightarrow$ Different signatures

What Is a Multiverse?

What Is a Multiverse?

- Causally disconnected patches

What Is a Multiverse?

- Causally disconnected patches
- Cosmological lifetime

What Is a Multiverse?

- Causally disconnected patches
- Cosmological lifetime
- Scan Λ and/or m_h^2

Outline

1. Why Should We Care?

2. A Model of the Multiverse

The Swampland

Distance conjecture:

$$\Delta\phi \leq M_{\rm Pl}$$

The Swampland

Distance conjecture:

$$\Delta\phi \leq M_{\rm Pl}$$

Refined de Sitter conjecture:

$$|\nabla V| \geq \frac{c}{M_{\rm Pl}} V \qquad \text{or} \qquad \min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_{\rm Pl}^2} V$$

Step by Step

1. Landscape of Minkowski and AdS minima

Step by Step

1. Landscape of Minkowski and AdS minima
2. Eternal inflation and bubble nucleation

Step by Step

1. Landscape of Minkowski and AdS minima
2. Eternal inflation and bubble nucleation
3. Uptunnel to larger vacuum energy

Step by Step

1. Landscape of Minkowski and AdS minima
2. Eternal inflation and bubble nucleation
3. Uptunnel to larger vacuum energy
4. Explain last 60 e-folds

Eternal Inflation

Hilltop potential:

$$V = m^2 f^2 \left(1 - \frac{\phi^2}{2f^2} + \mathcal{O}(\phi/f)^4\right)$$

Eternal Inflation

Hilltop potential:

$$V = m^2 f^2 \left(1 - \frac{\phi^2}{2f^2} + \mathcal{O}(\phi/f)^4\right)$$

Classical vs quantum:

$$\Delta\phi_{\rm c} = \frac{V'}{aH^2} \qquad \text{vs} \qquad \Delta\phi_{\rm q} = \frac{H}{2\pi}$$

Eternal Inflation

Hilltop potential:

$$V = m^2 f^2 \left(1 - \frac{\phi^2}{2f^2} + \mathcal{O}(\phi/f)^4\right)$$

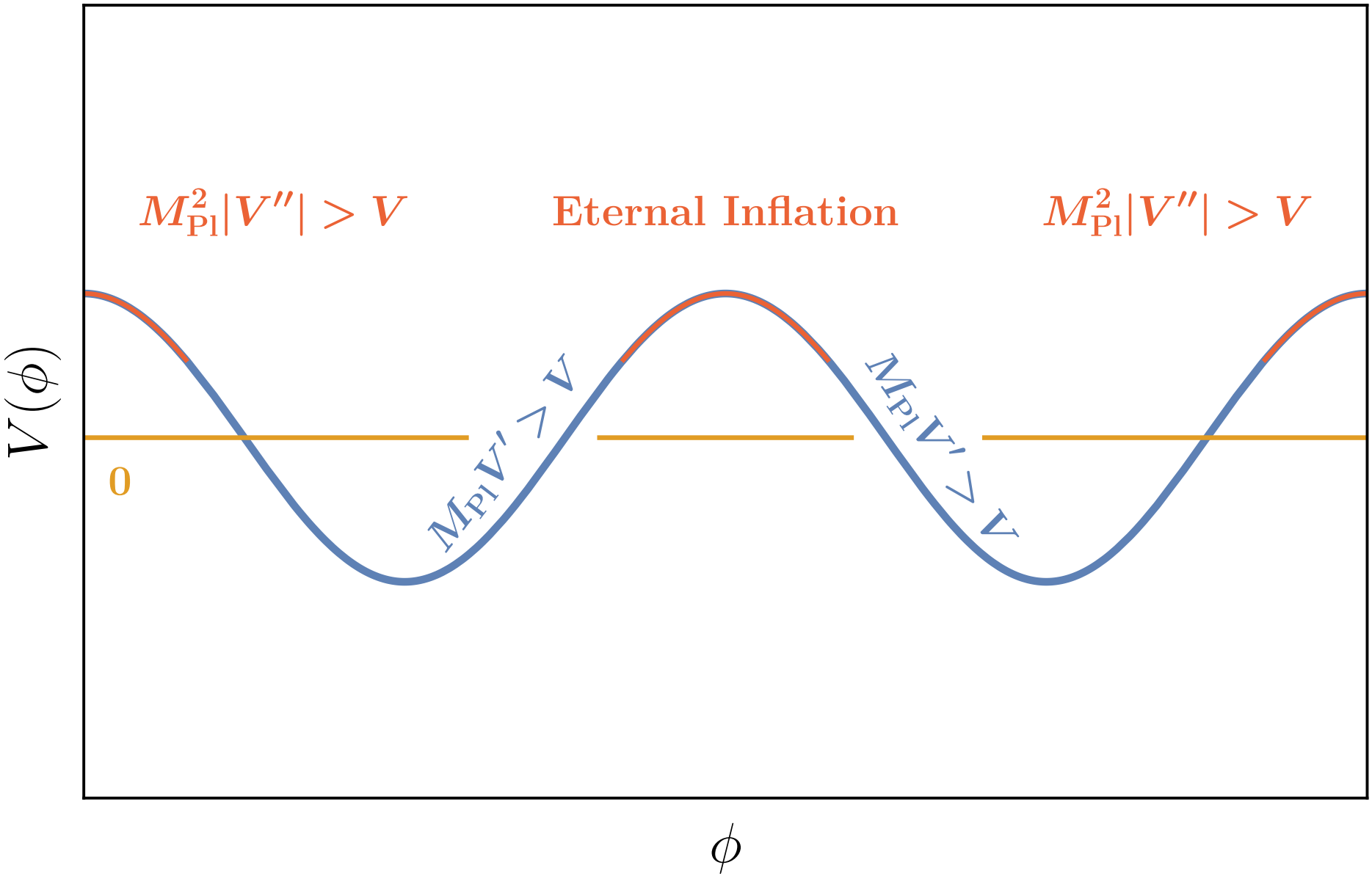
Classical vs quantum:

$$\Delta\phi_{\rm c} = \frac{V'}{aH^2} \qquad \text{vs} \qquad \Delta\phi_{\rm q} = \frac{H}{2\pi}$$

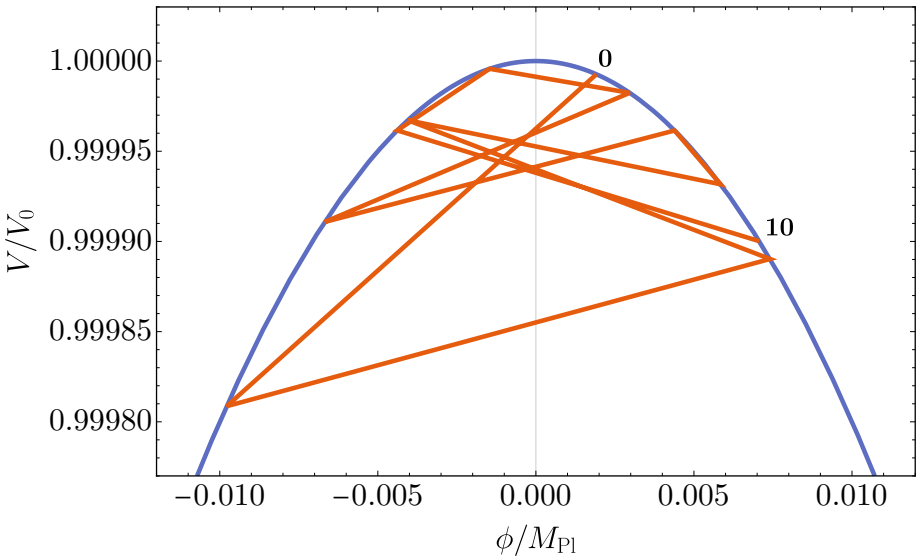
Mild initial tuning

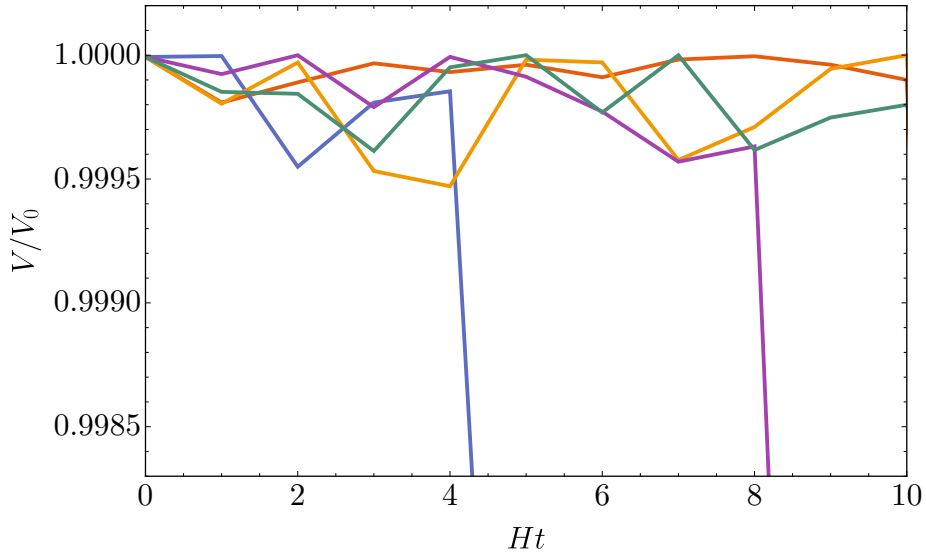
$$\frac{\phi_{\rm I}}{f}\frac{\dot\phi_{\rm I}}{mf} \simeq \frac{m}{M_{\rm Pl}}\left(\frac{f}{M_{\rm Pl}}\right)^3$$

What About the Swampland?



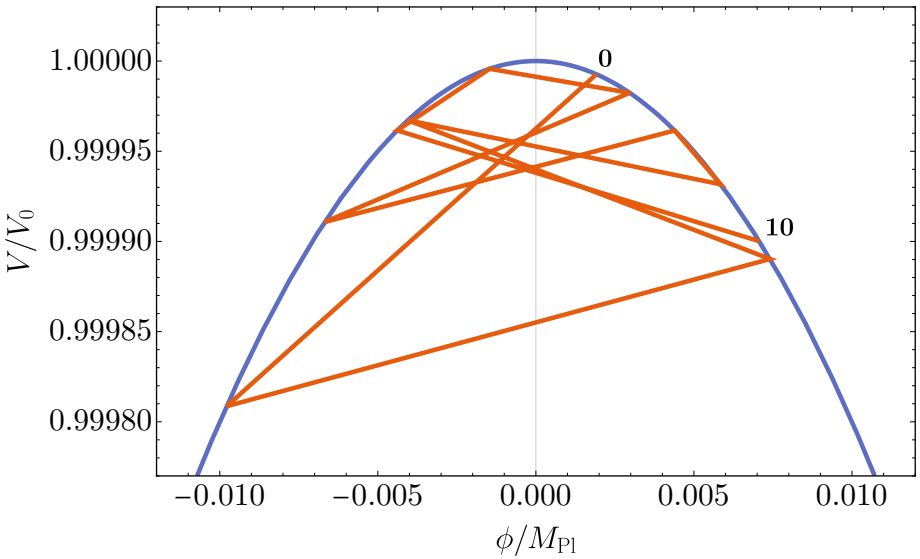
Inflaton Dynamics

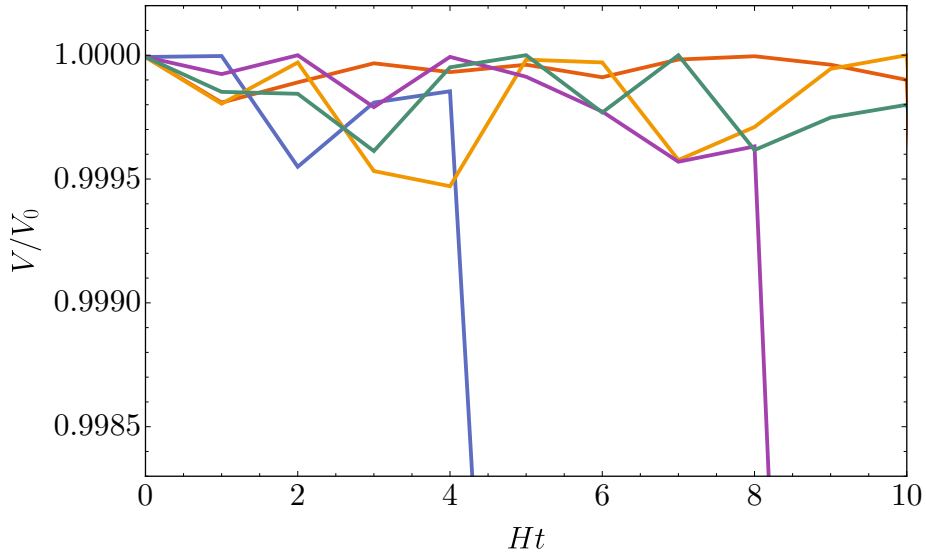




- Sample quantum fluctuations

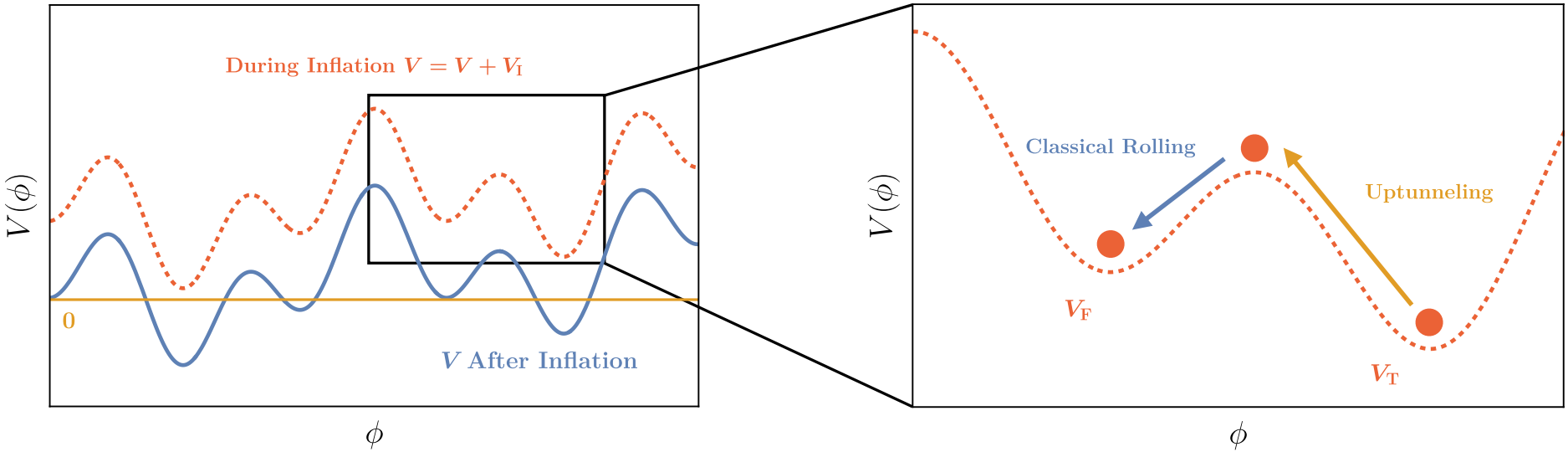
Inflaton Dynamics





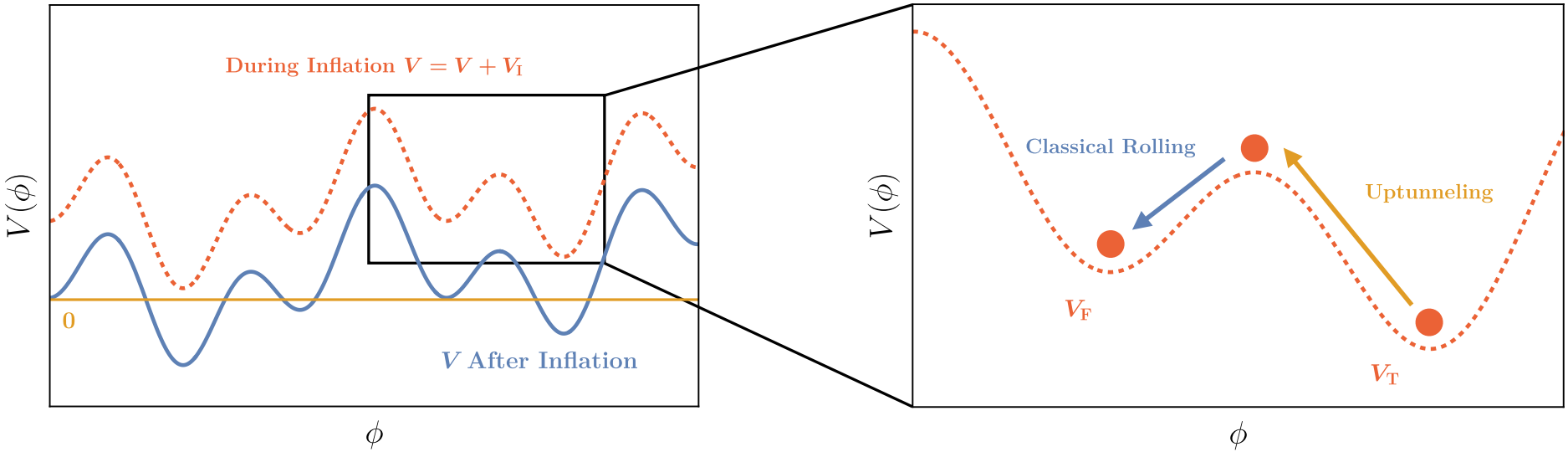
- Sample quantum fluctuations
- Patches vs dynamics

This Multiverse



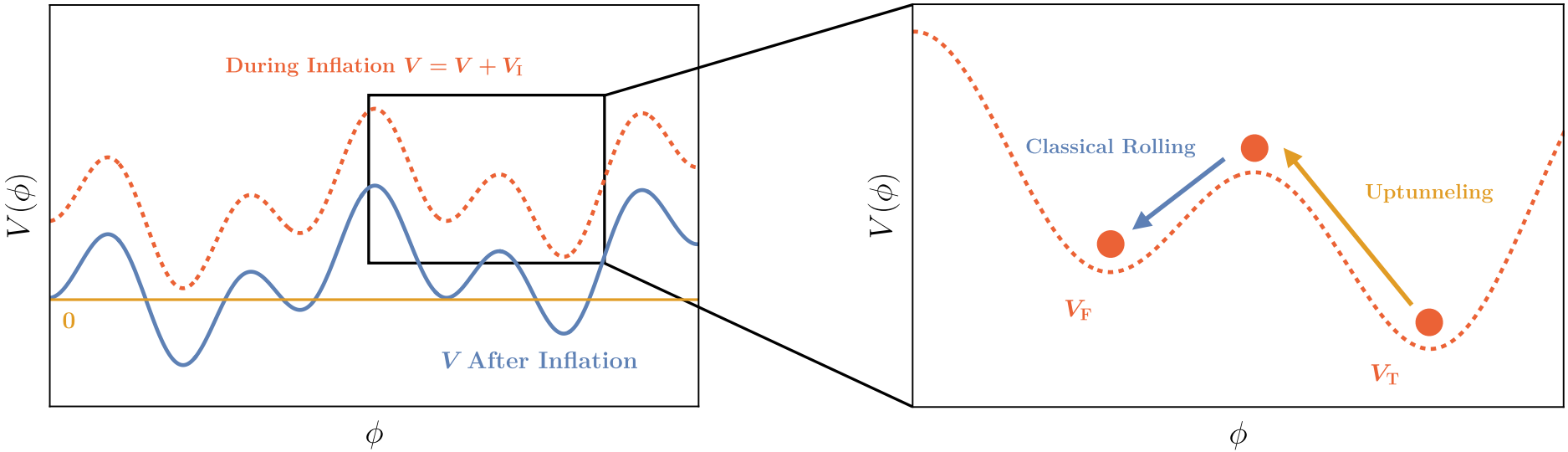
- All vacua M or AdS of $\mathcal{O}(-M_{\rm Pl}^4)$

This Multiverse



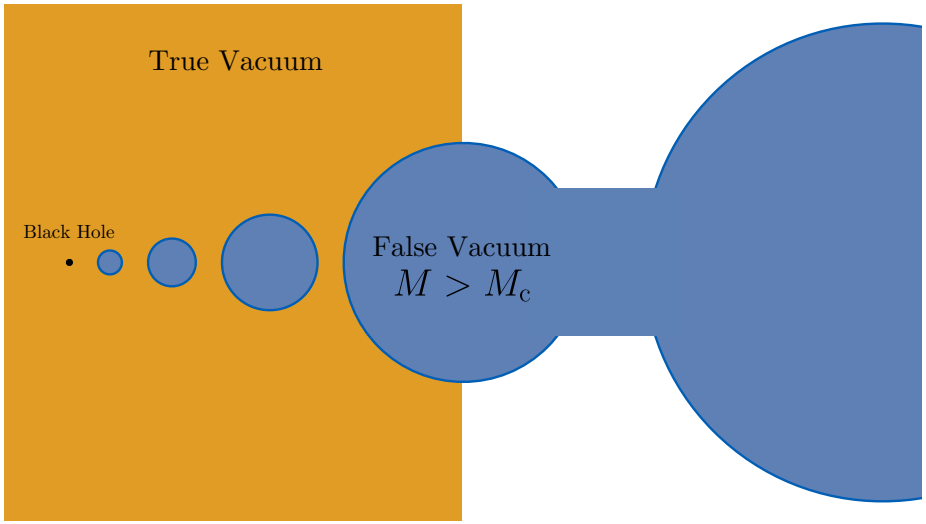
- All vacua M or AdS of $\mathcal{O}(-M_{\rm Pl}^4)$
- Uplifted during eternal inflation

This Multiverse



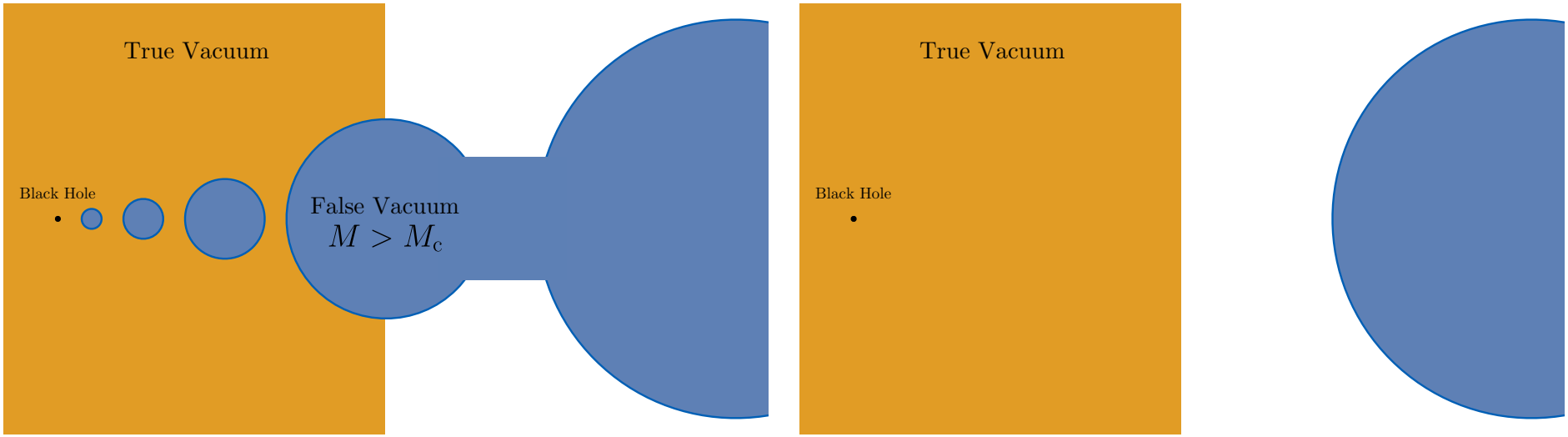
- All vacua M or AdS of $\mathcal{O}(-M_{\rm Pl}^4)$
- Uplifted during eternal inflation
- Uptunneling becomes possible

Bubble Wall Dynamics



creation of a baby Universe

Bubble Wall Dynamics



creation of a baby Universe

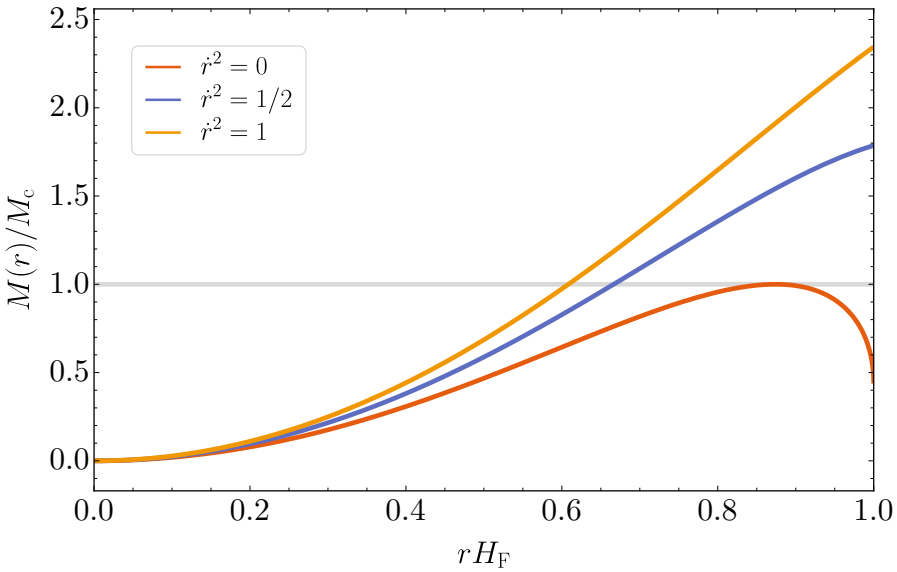
Bubbles of False Vacuum

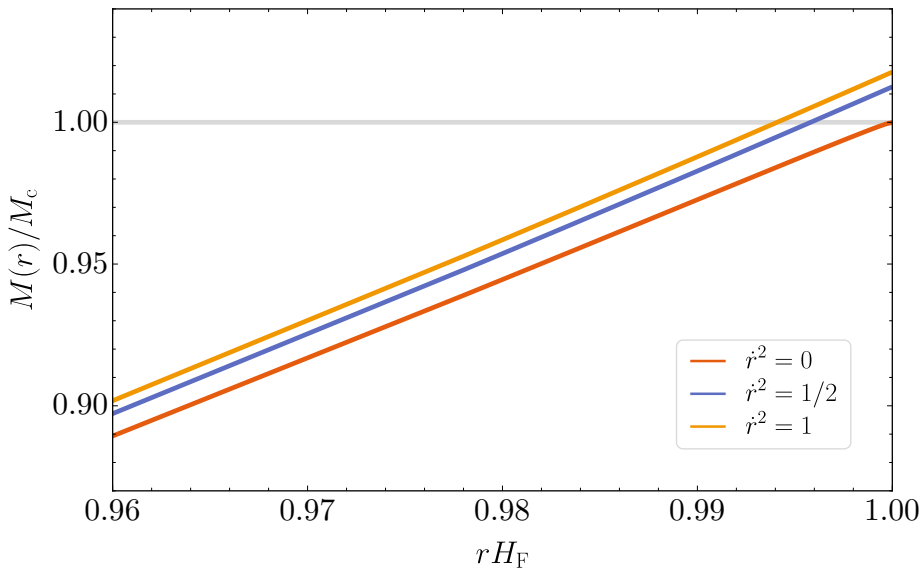
$$\beta_{\mathrm{F}} - \beta_{\mathrm{T}} = 4\pi G_{\mathrm{N}} \sigma r \longrightarrow M(r, \dot{r})$$

[Blau, Guendelman, Guth 1987]

Bubbles of False Vacuum

$$\beta_{\mathrm{F}} - \beta_{\mathrm{T}} = 4\pi G_{\mathrm{N}} \sigma r \longrightarrow M(r, \dot{r})$$





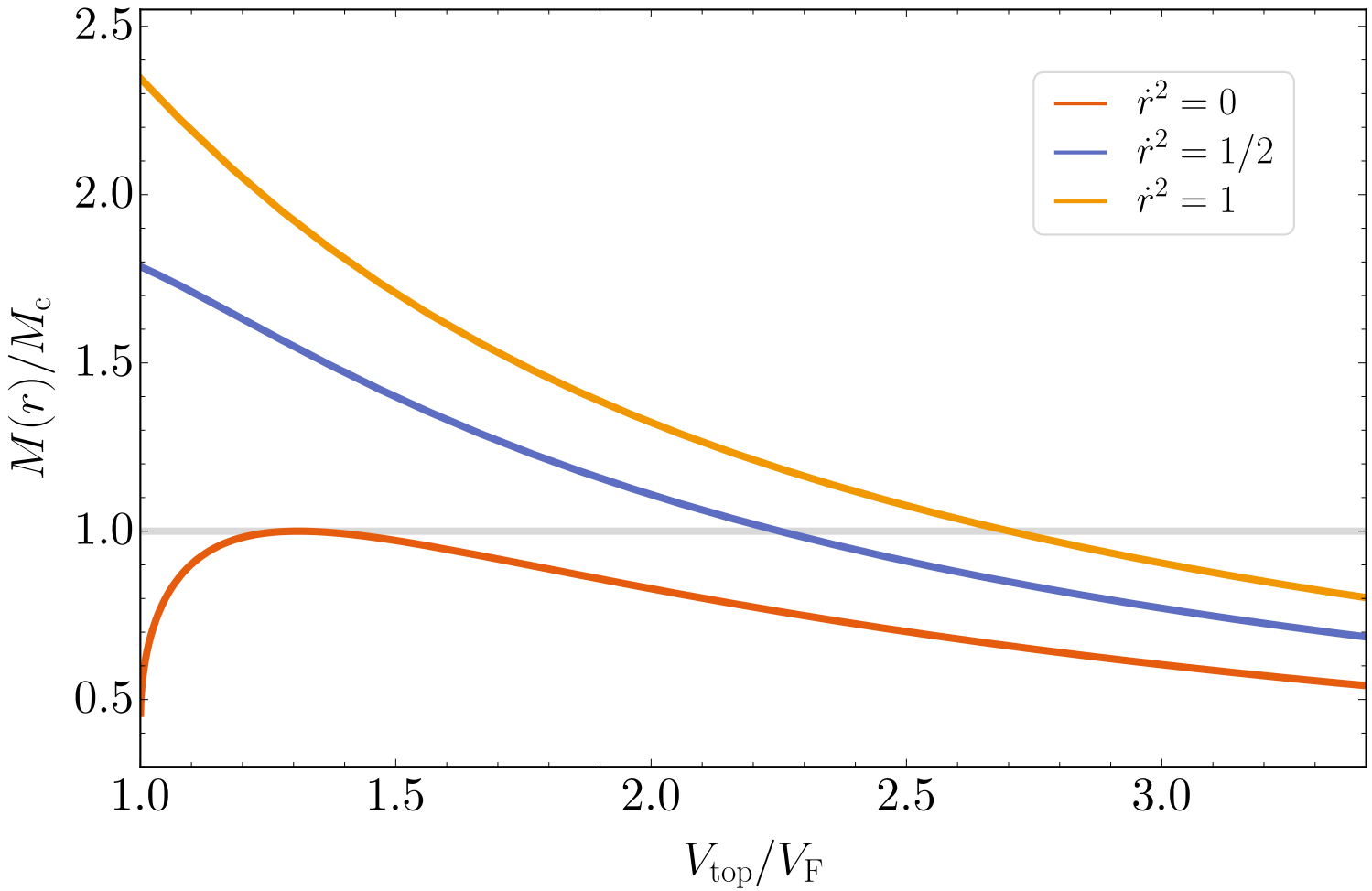
[Blau, Guendelman, Guth 1987]

Hawking–Moss

$$\Gamma \simeq V M_*^4 e^{-S_{\rm HM}}, \qquad S_{\rm HM} = 8\pi^2 M_{\rm Pl}^4 \left(\frac{1}{V_{\rm T}} - \frac{1}{V_{\rm top}} \right)$$

Hawking–Moss

$$\Gamma \simeq V M_*^4 e^{-S_{\rm HM}}, \qquad S_{\rm HM} = 8\pi^2 M_{\rm Pl}^4 \left(\frac{1}{V_{\rm T}} - \frac{1}{V_{\rm top}} \right)$$



The Last 60 e-Folds

Tension between slow roll and Swampland:

$$\left|\frac{d\phi}{dN_e}\right| \simeq \sqrt{2\epsilon_V} M_{\rm Pl} \longrightarrow \Delta\phi \geq c N_e M_{\rm Pl}$$

The Last 60 e-Folds

Tension between slow roll and Swampland:

$$\left|\frac{d\phi}{dN_e}\right| \simeq \sqrt{2\epsilon_V} M_{\rm Pl} \longrightarrow \Delta\phi \geq c N_e M_{\rm Pl}$$

Possible solutions:

- Multifield inflation

The Last 60 e-Folds

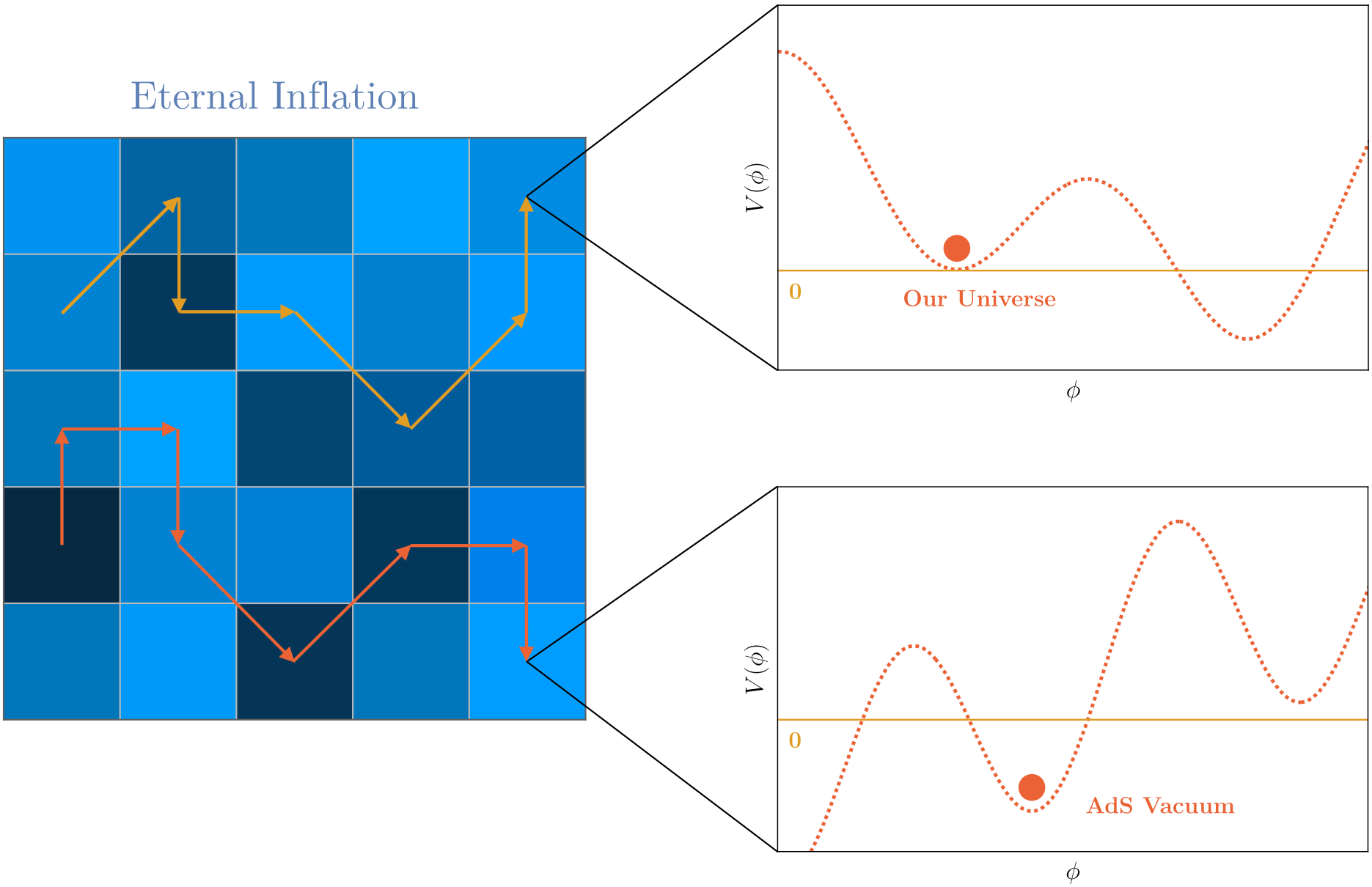
Tension between slow roll and Swampland:

$$\left|\frac{d\phi}{dN_e}\right| \simeq \sqrt{2\epsilon_V} M_{\rm Pl} \longrightarrow \Delta\phi \geq c N_e M_{\rm Pl}$$

Possible solutions:

- Multifield inflation
- Warm inflation

Overall Picture

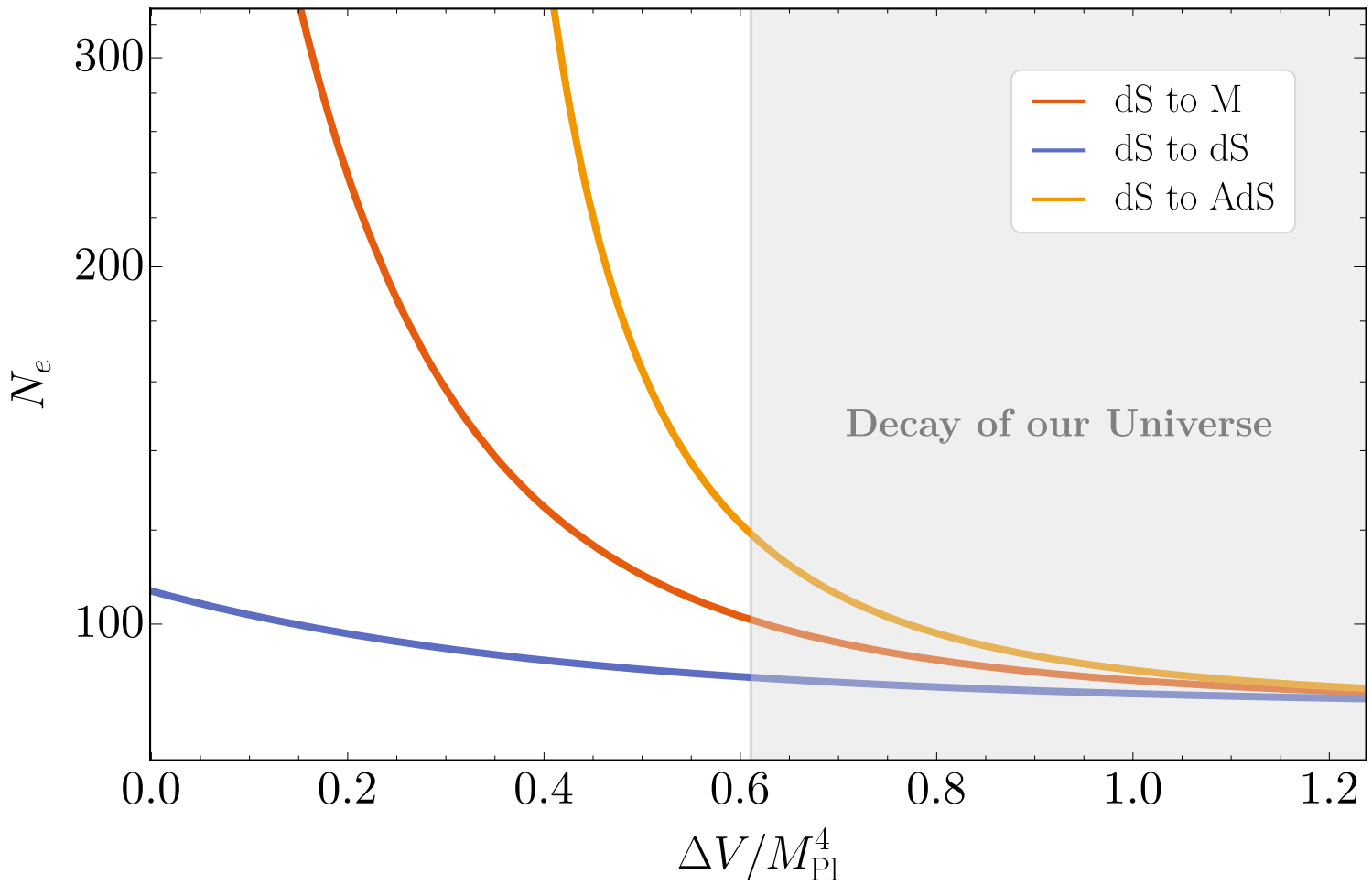


Getting de Sitter Back

$$\langle N_{\rm b}\rangle(N_e) \simeq 10^{120}, \qquad \frac{\Gamma}{V} \simeq M_{\rm Pl}^4 e^{-B}$$

Getting de Sitter Back

$$\langle N_{\rm b}\rangle(N_e) \simeq 10^{120}, \qquad \frac{\Gamma}{V} \simeq M_{\rm Pl}^4 e^{-B}$$



Conclusions

Contrary to the lore:

- The Swampland is compatible with eternal inflation

Conclusions

Contrary to the lore:

- The Swampland is compatible with eternal inflation
- We can build a Multiverse with only M and AdS

Conclusions

Contrary to the lore:

- The Swampland is compatible with eternal inflation
- We can build a Multiverse with only M and AdS
- With dS, we need $\mathcal{O}(100)$ e-folds

Conclusions

Contrary to the lore:

- The Swampland is compatible with eternal inflation
- We can build a Multiverse with only M and AdS
- With dS, we need $\mathcal{O}(100)$ e-folds
- Main challenge from last 60 e-folds

Thank you!

Brown–Teitelboim

3-form field $A_{\mu\nu\rho}$ and 4-form field strength $F_{\mu\nu\rho\sigma}$:

$$S \supset \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{48}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma} + \frac{M_{\mathrm{Pl}}^2}{2}R - \Lambda_0\right)$$

Brown–Teitelboim

3-form field $A_{\mu\nu\rho}$ and 4-form field strength $F_{\mu\nu\rho\sigma}$:

$$S \supset \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{48}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma} + \frac{M_{\mathrm{Pl}}^2}{2}R - \Lambda_0\right)$$

Solve EOM:

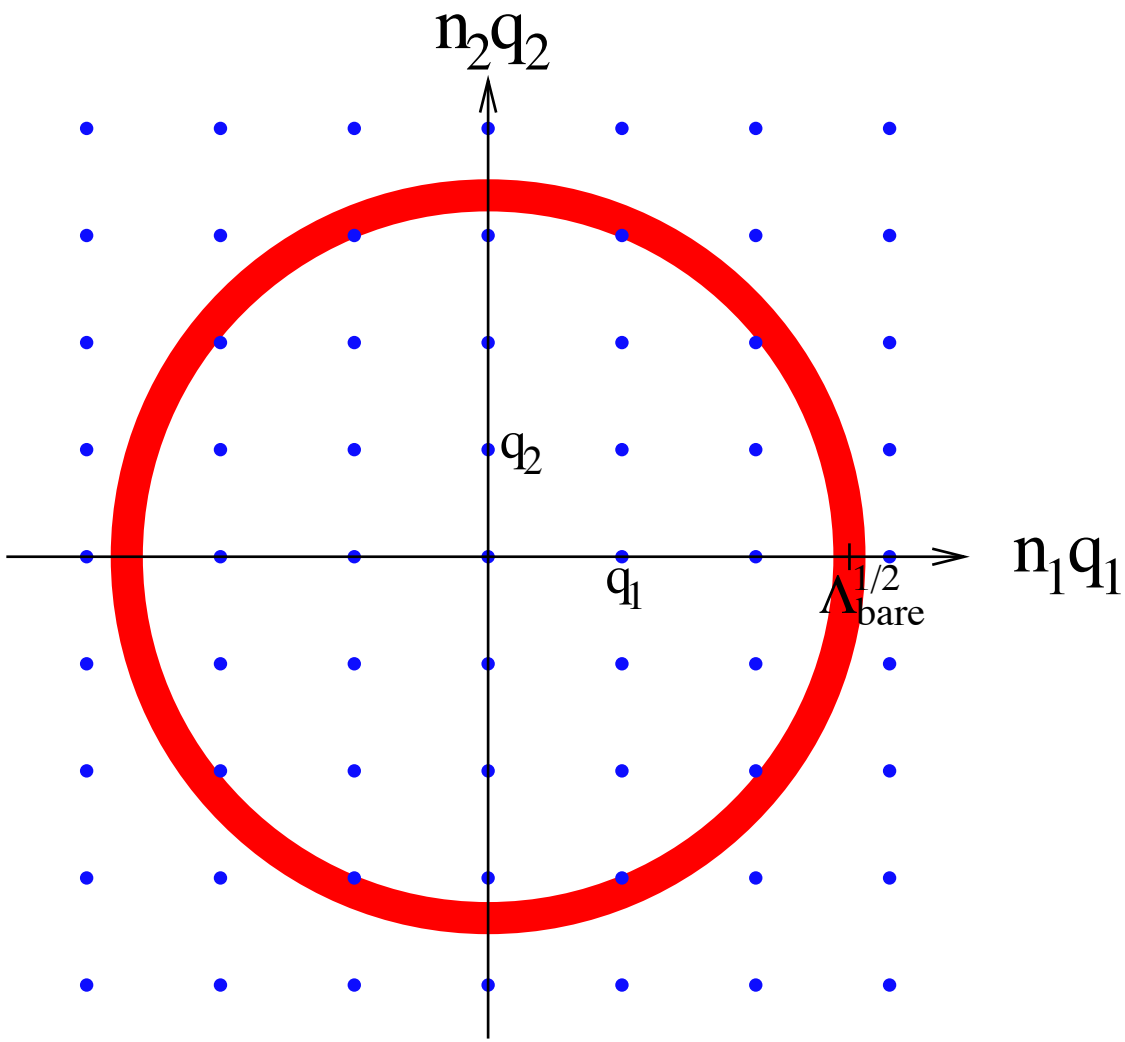
$$F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma} \longrightarrow \Lambda = \Lambda_0 - \frac{c^2}{2}$$

Bousso–Polchinski

$$\Lambda = \Lambda_0 - \frac{1}{2}\sum_{i=1}^{J} e_i^2 n_i^2$$

Bousso–Polchinski

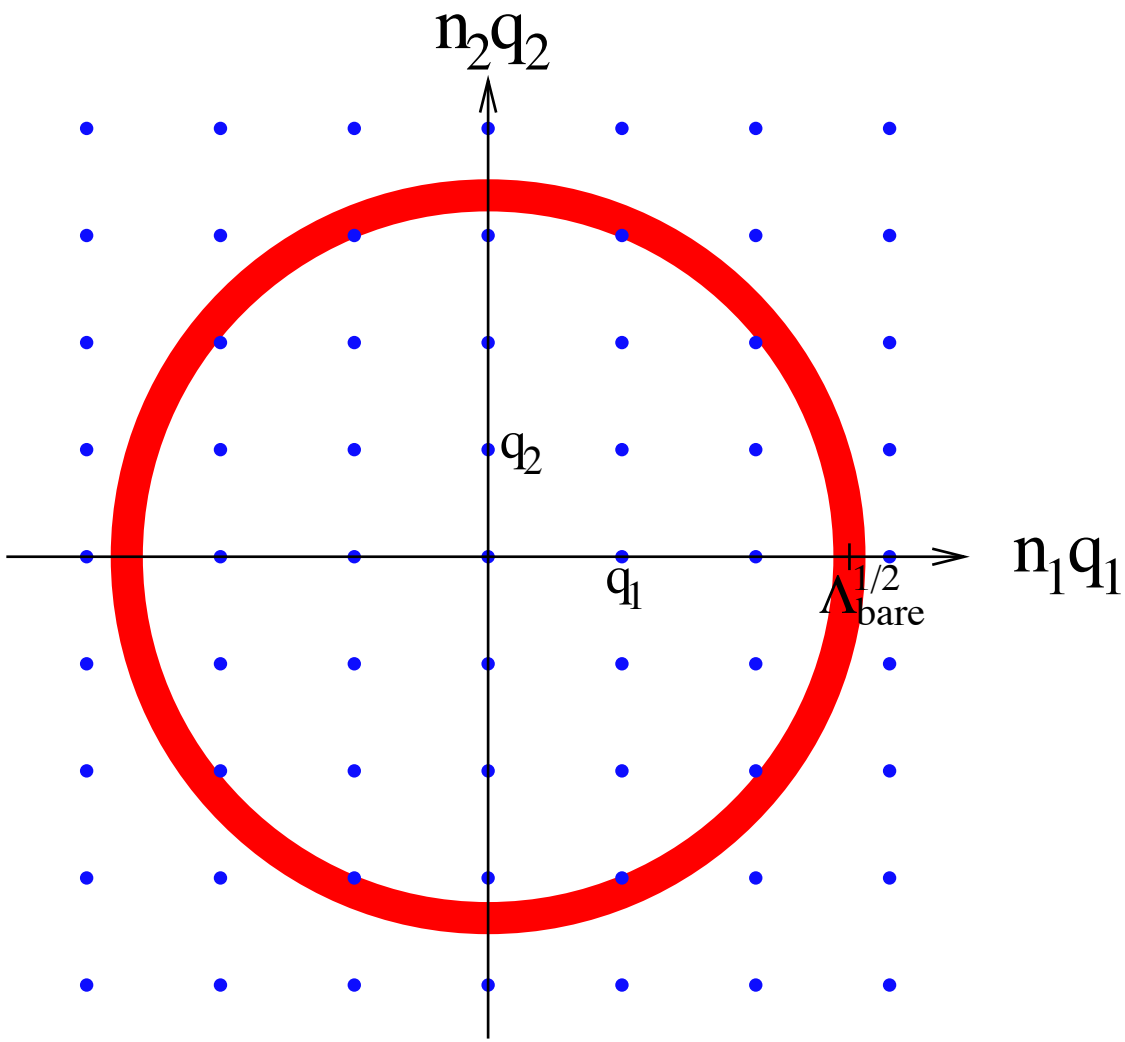
$$\Lambda = \Lambda_0 - \frac{1}{2}\sum_{i=1}^{J} e_i^2 n_i^2$$



Bousso–Polchinski

$$\Lambda = \Lambda_0 - \frac{1}{2}\sum_{i=1}^{J} e_i^2 n_i^2$$

$$\frac{2\pi^{J/2}}{\Gamma(J/2)}\Lambda_0^{J/2}\frac{\Lambda_{\rm obs}}{\Lambda_0} \gtrsim \prod_{i=1}^{J} e_i$$

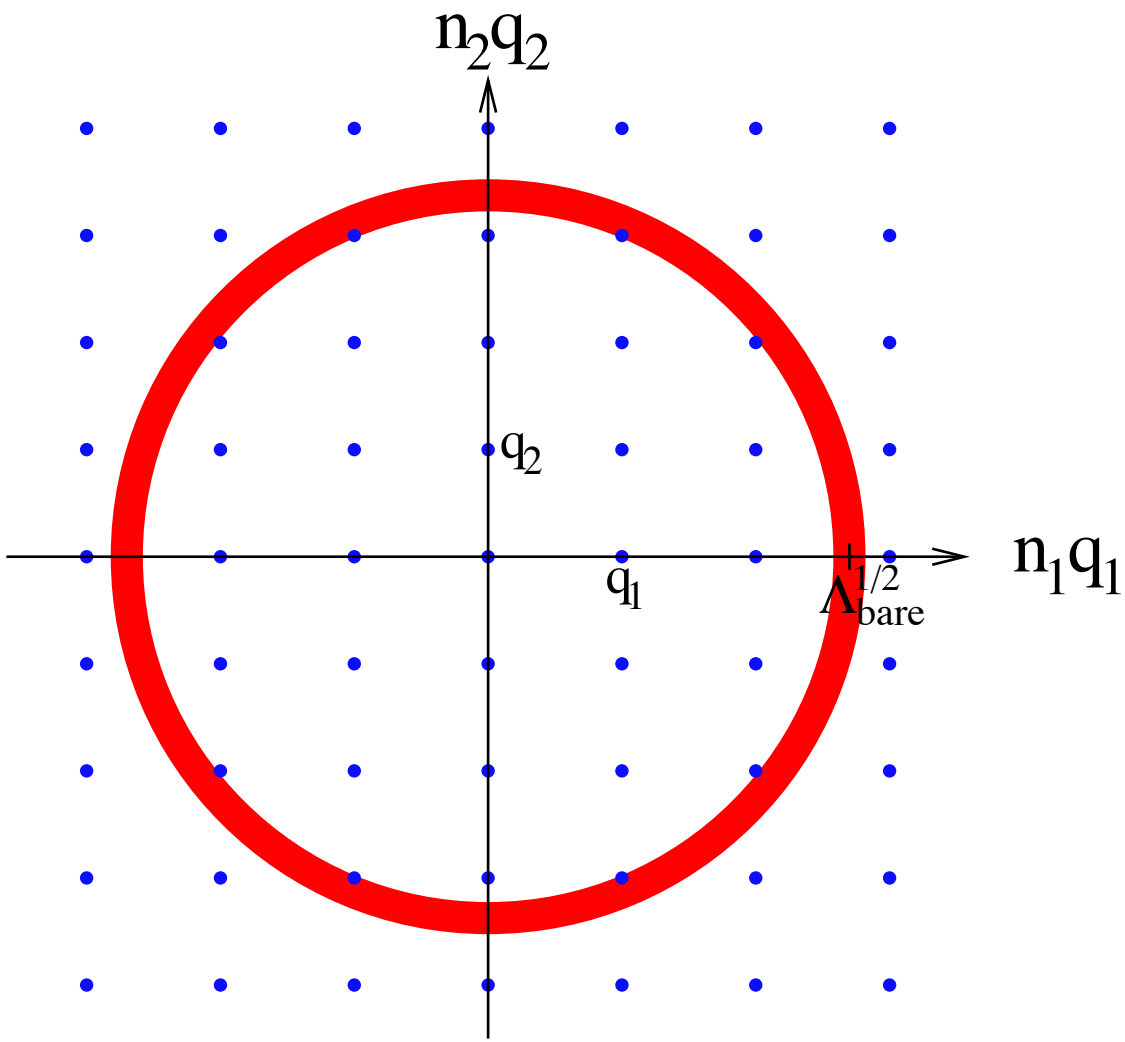


Bousso–Polchinski

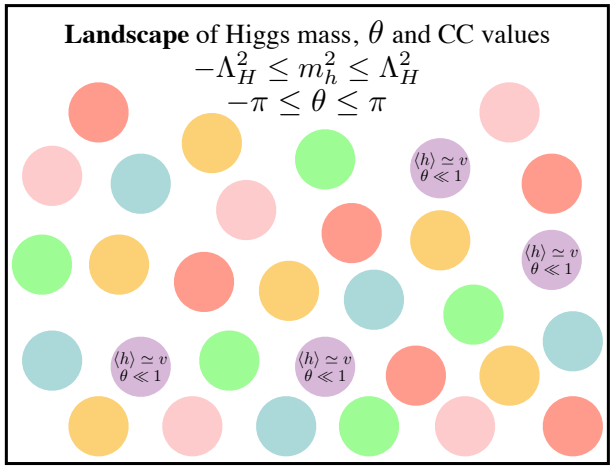
$$\Lambda = \Lambda_0 - \frac{1}{2}\sum_{i=1}^{J} e_i^2 n_i^2$$

$$\frac{2\pi^{J/2}}{\Gamma(J/2)}\Lambda_0^{J/2}\frac{\Lambda_{\rm obs}}{\Lambda_0} \gtrsim \prod_{i=1}^{J} e_i$$

$$J = 100, \quad e_i \simeq (0.01 M_{\rm Pl})^2$$

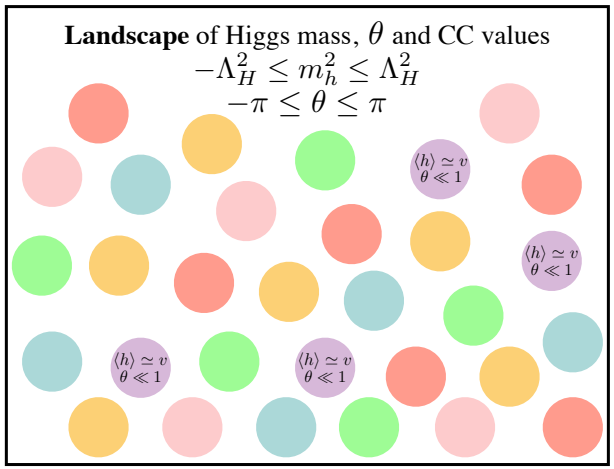


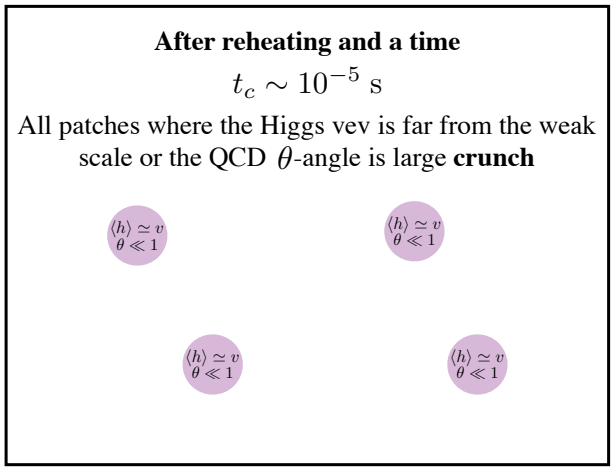
Sliding Naturalness



[D'Agnolo, Teresi 2021]

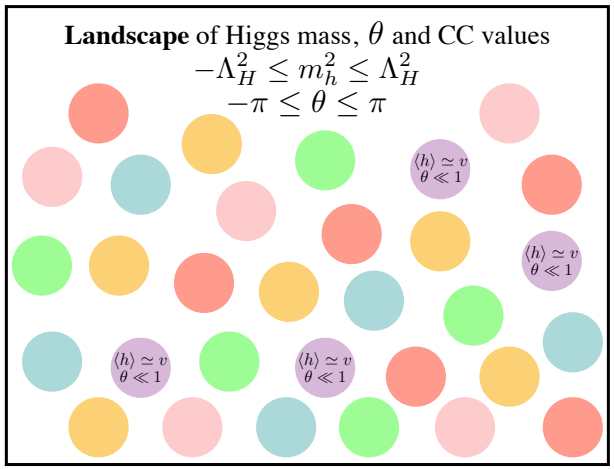
Sliding Naturalness

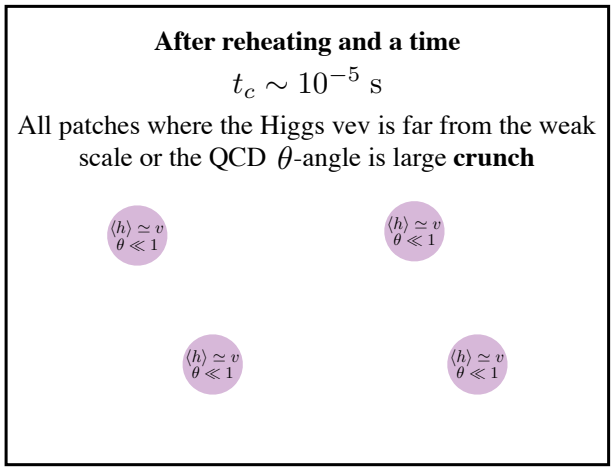


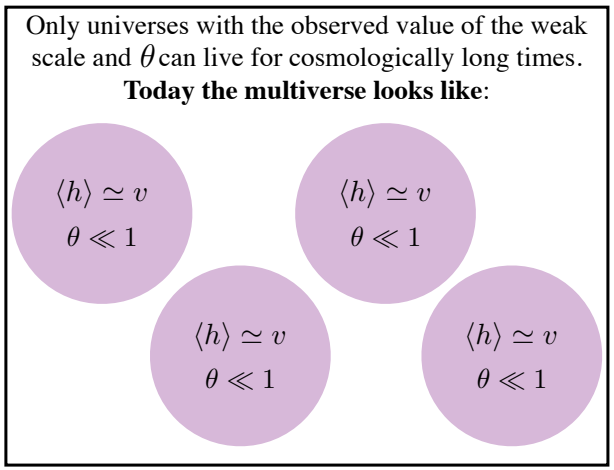


[D'Agnolo, Teresi 2021]

Sliding Naturalness







[D'Agnolo, Teresi 2021]

An Example Model

$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2}\phi^2_\pm - \frac{m^2_{\phi_\pm}}{4M^2_\pm}\phi^4_\pm, \qquad V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$

An Example Model

$$V_{\phi_\pm} = \mp \frac{m^2_{\phi_\pm}}{2}\phi^2_\pm - \frac{m^2_{\phi_\pm}}{4M^2_\pm}\phi^4_\pm, \qquad V_{\phi H} = -\frac{\alpha_s}{8\pi}\left(\frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} + \theta\right) G\tilde{G}$$