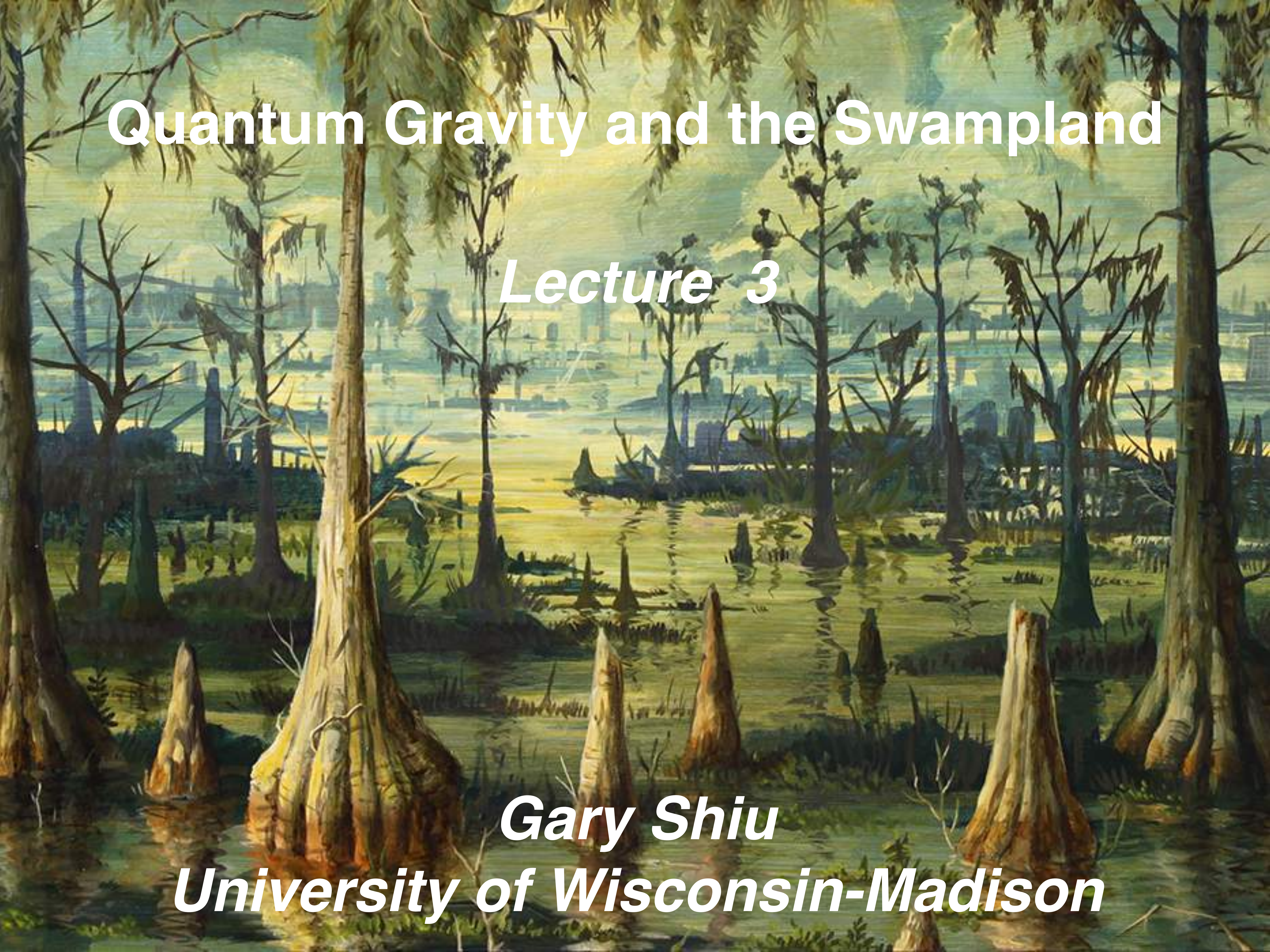
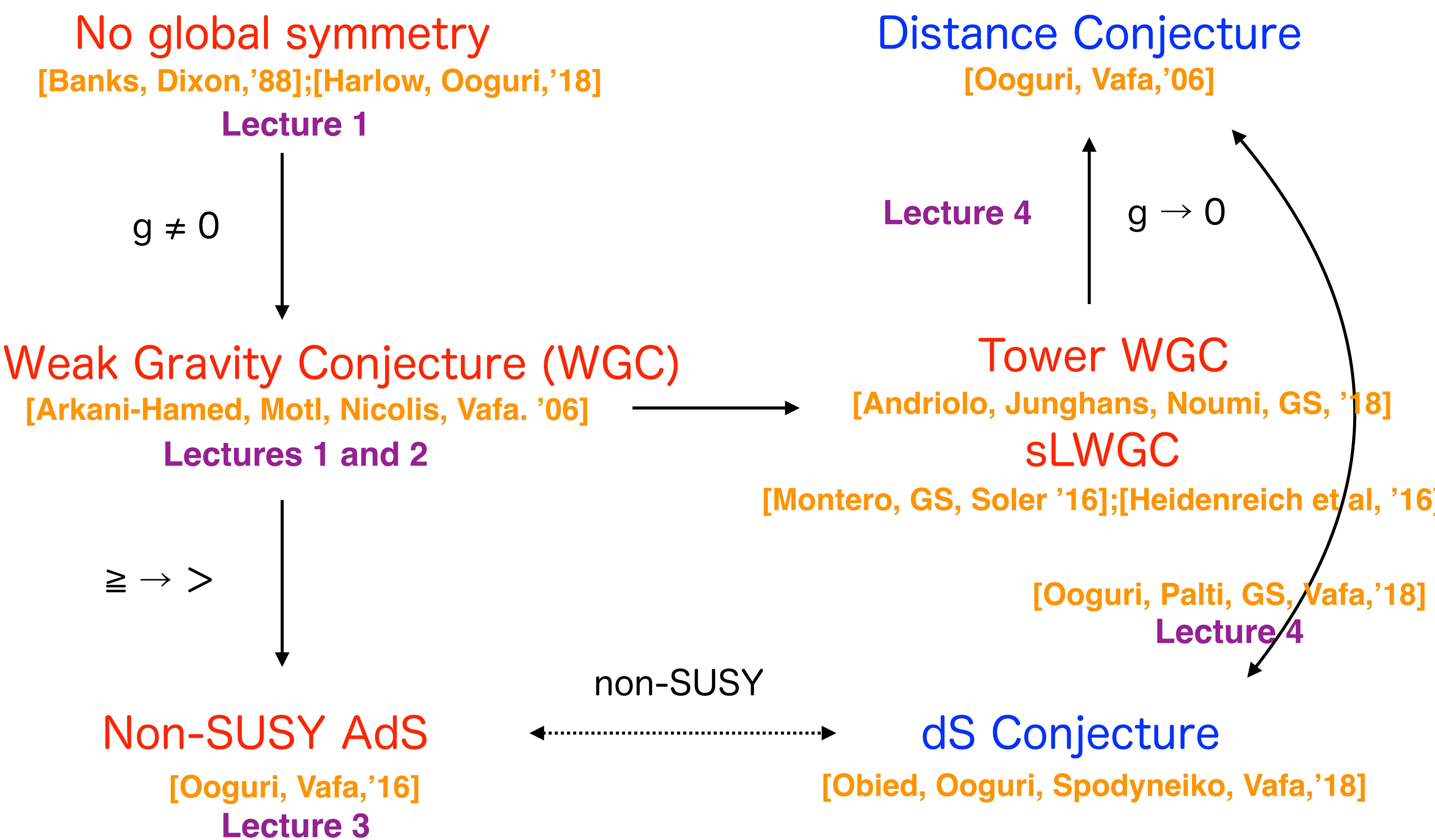


Quantum Gravity and the Swampland

Lecture 3

Gary Shiu
University of Wisconsin-Madison

Web of Conjectures



Swampland Conjectures and Cosmology

- The WGC constrains the mass of particles charged under gauge forces.
- The SDC constrains the field range within the validity of an EFT coupled consistently to gravity.
- **What does this web of conjectures have to do with cosmology?**
- While not all inflation models predict a detectable level of **gravitational waves**, some do (known as **large-field inflation**).
- Much of the efforts in the Swampland has been in constraining large-field inflation.
- We will see in this and the next lecture that:
  - Large field Inflation is constrained by the WGC & the SDC
  - SDC is connected to the dS conjecture at weak coupling points
  - The AdS instability conjecture relates neutrino masses/type with Λ.

WGC for Axions

Axions and ALPs

The QCD axion [Wilczek, '78]; [Weinberg, '78] was introduced in the context of the Pecci-Quinn mechanism and the strong CP problem.

An axion enjoys a **perturbative shift symmetry.**

String theory has many **higher-dimensional form-fields**:

e.g. $$F = \mathrm{d}A$$

3-form flux → F; A ← 2-form gauge potential:

gauge symmetry: $$A \to A + \mathrm{d}\Lambda$$

Integrating the 2-form over a 2-cycle gives an ***axion-like particle* (ALP)**:

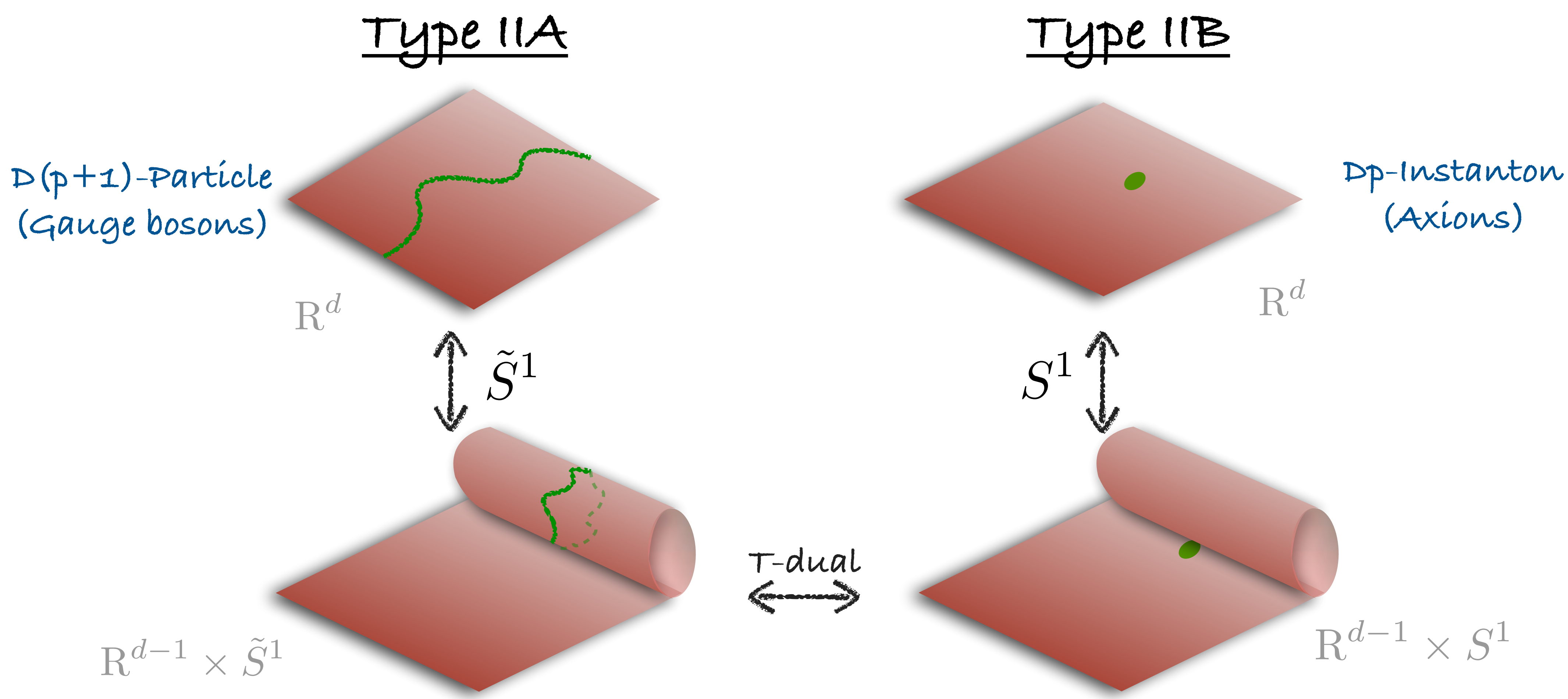
$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry,** that is broken by non-perturbative (instanton) effects**.**

WGC and Axions

Brown, Cottrell, GS, Soler

- Formulate the WGC in a duality frame where the axions and instantons turn into gauge fields and particles, e.g.



model-dependent, calculable

- The WGC takes the form $f \cdot S_{\text{instanton}} \leq \mathcal{O}(1) M_P$

WGC and Axions: An Example

Brown, Cottrell, GS, Soler

Type IIA

Gauge fields: $A_i \sim \int_{\Sigma_2^{(i)}} C_3$

Particles: D2 on $\Sigma_2^{(i)}$

WGC

$$\tilde{m}_k = m_k \frac{\sqrt{g_{33}}}{2\pi\, l_s}$$

$$\tilde{q}_k^i = (f_k^i)^{-1} \frac{\sqrt{2}}{4\pi\, l_s}$$

"Couplings":

$$\tilde{g}_s = \frac{g_s}{\sqrt{g_{33}}}$$

$$\tilde{M}_P = M_P \sqrt{g_{33}}$$

Type IIB

Axions: $\phi_i \sim \int_{\Sigma_2^{(i)}} C_2$

Instantons: D1 on $\Sigma_2^{(i)}$

$$S_{inst_k} \sim -m_k + i(f_k^i)^{-1}\phi_i$$

"Couplings":

$$g_s$$

$$M_P$$

WGC and Axions: An Example

Brown, Cottrell, GS, Soler

4d Type IIB D1-instantons	**4d Type IIA D2-particles**	**5d M-theory M2-particles**
m_i	$\tilde{m}_i \sim m_i$	$M_i^{(5d)} \sim m_i$
f_i	$\tilde{q}_i \sim f_i^{-1}$	$Q_i^{(5d)} \sim f_i^{-1}$
$g_s \ll 1$	$\tilde{g}_s \gg 1$	$R_M \to \infty$

- Apply the WGC to 5d particles:

$$\frac{Q^{(5d)}}{M_i^{(5d)}} M_P^{(5d)} = \frac{M_P^{(IIB)}}{\sqrt{2} f_i\, m_i} \geq \text{“}1\text{”} \equiv \left(\frac{Q}{M} M_P \right)_{\mathrm{Ext}_{5d}} = \sqrt{\frac{2}{3}}$$

WGC and Axions: An Example

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WGC and axions

- Consider a U(1) gauge theory in 5d, and compactify on S to 4d. Upon dimensional reduction: $A_M(x, x_4) \rightarrow (A_\mu(x), \phi(x))$

$$S = \int d^5x \, \frac{-1}{4g_5^2} F_{MN}F^{MN} \quad \longrightarrow \quad \int d^4x \left(\frac{-1}{4g_4^2} F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \right)$$

The gauge symmetry leads to an axion shift symmetry $\phi = \phi + c$

- Topologically non-trivial Euclidean configurations (instantons) with charged fields wrapping the 5d circle generate a potential

$$V(\phi) = e^{-S_{inst}} \cos\left(\frac{\phi}{f}\right)$$

$$S_{inst} = 2\pi R m_5$$
$$f = q_5\sqrt{2\pi R}$$

- The 5d WGC for charged particles $m_5 < q_5 M_{p,5d}^3$ translates into:

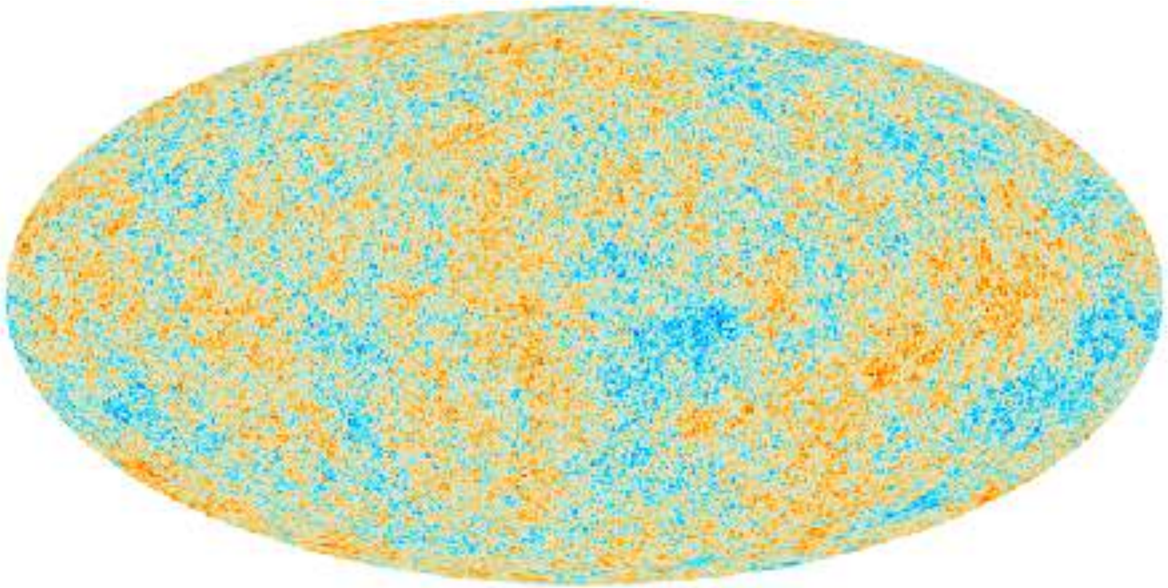
$$f \cdot S_{inst} \leq \mathcal{O}(1)\; M_P$$

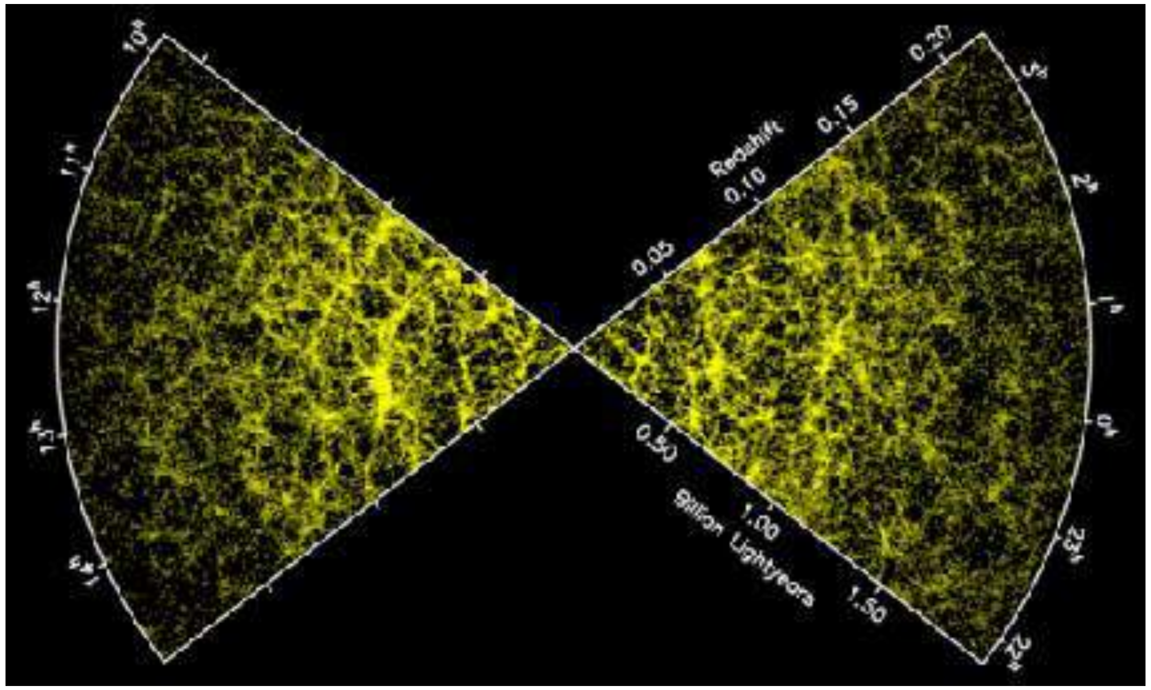
WGC and Inflation

Inflation

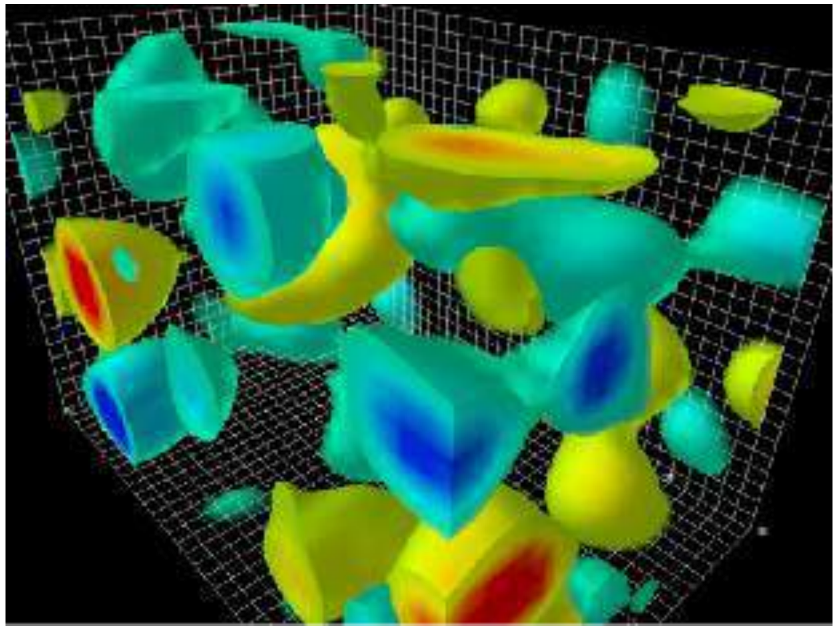
[Starobinsky];[Guth];[Linde];[Albrecht, Steinhardt];…

- Period of **accelerated expansion** in early universe
  - Solves flatness, horizon, and monopole problems
  - Predicts **nearly scale-invariant**, **Gaussian** curvature fluctuations
    - Source anisotropies in CMB, inhomogeneities in LSS
- A myriad of models. Taxonomy done mostly through their observables (n_s, r)

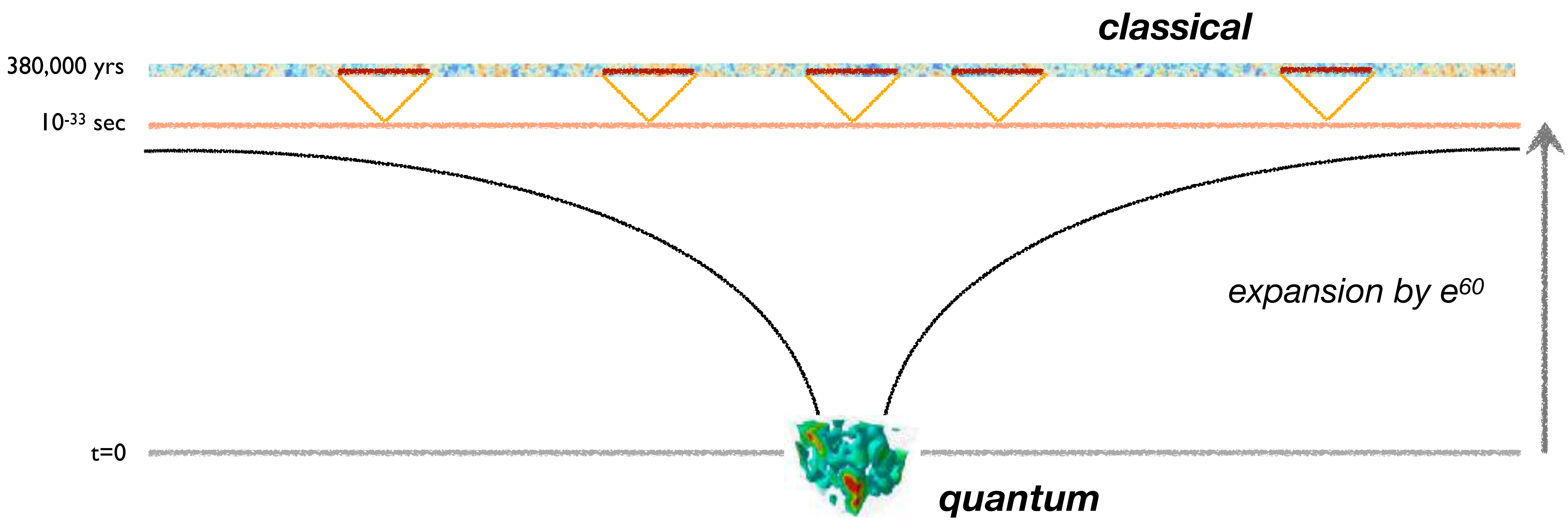




Any massless field experiences quantum fluctuations during inflation:



Inflation stretches these to macroscopic scales:



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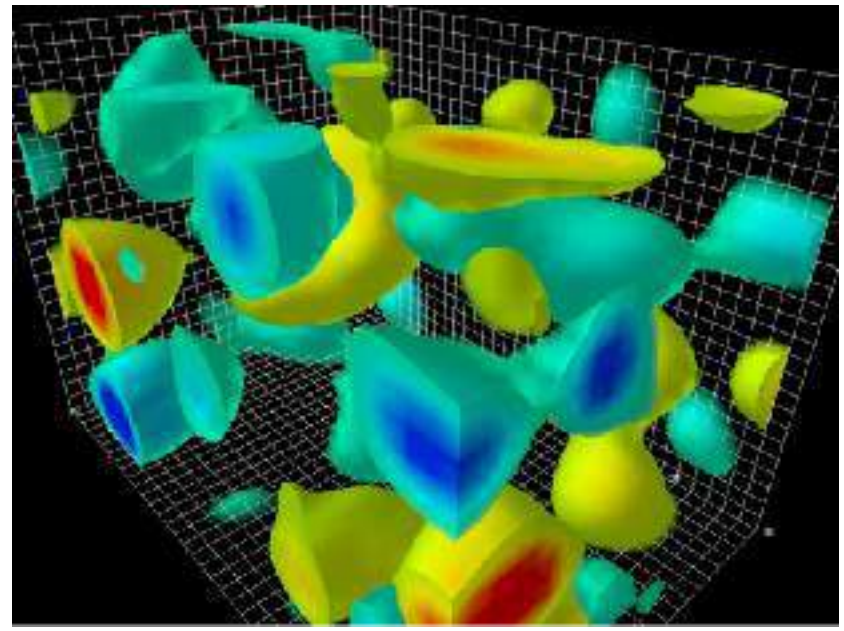

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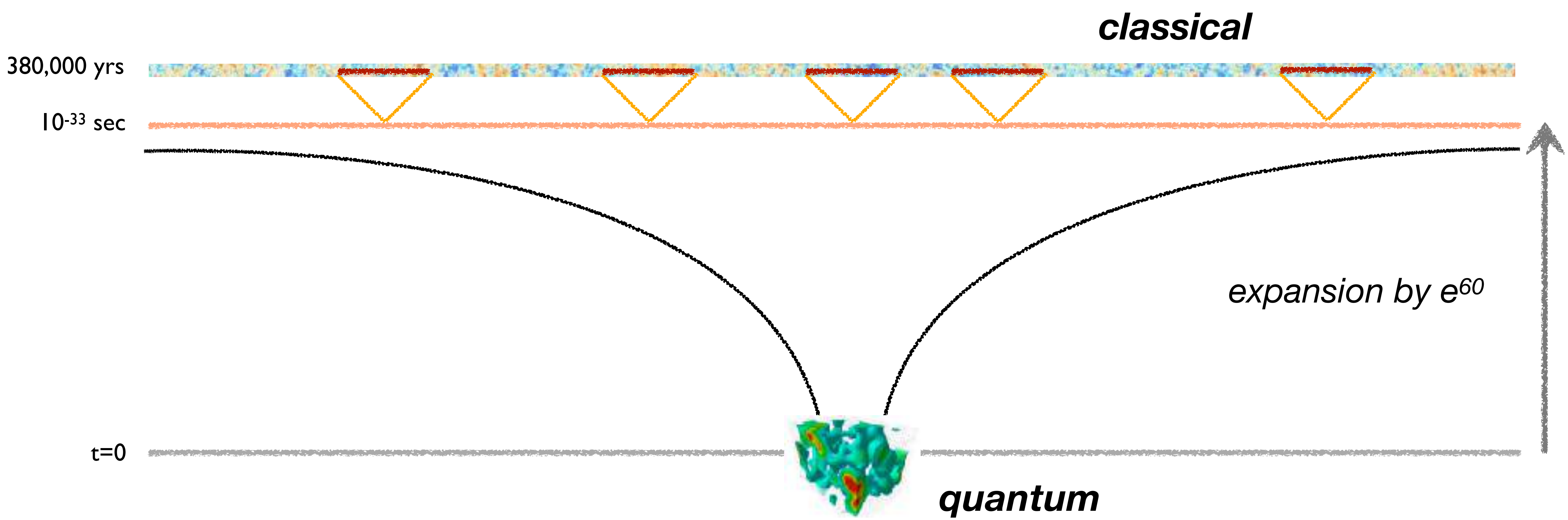

Two massless fields that are guaranteed to exist are:

ζ **Goldstone boson**

of broken time translations

h_{ij} **graviton**

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of broken time translations

$$\Delta_s^2 = \frac{1}{4\pi^2} \frac{H^4}{f_\pi^4}$$

symmetry breaking scale

($= \dot{\phi}^2$ for slow-roll inflation)

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expansion rate

$$\Delta_t^2 \equiv \frac{2}{\pi^2} \frac{H^2}{M_{\rm pl}^2}$$

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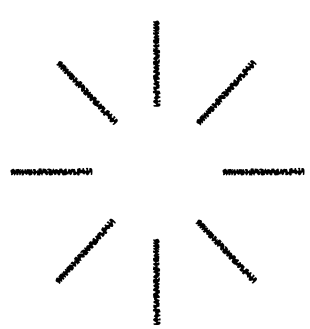
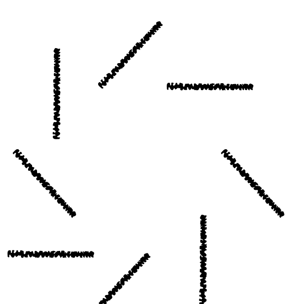
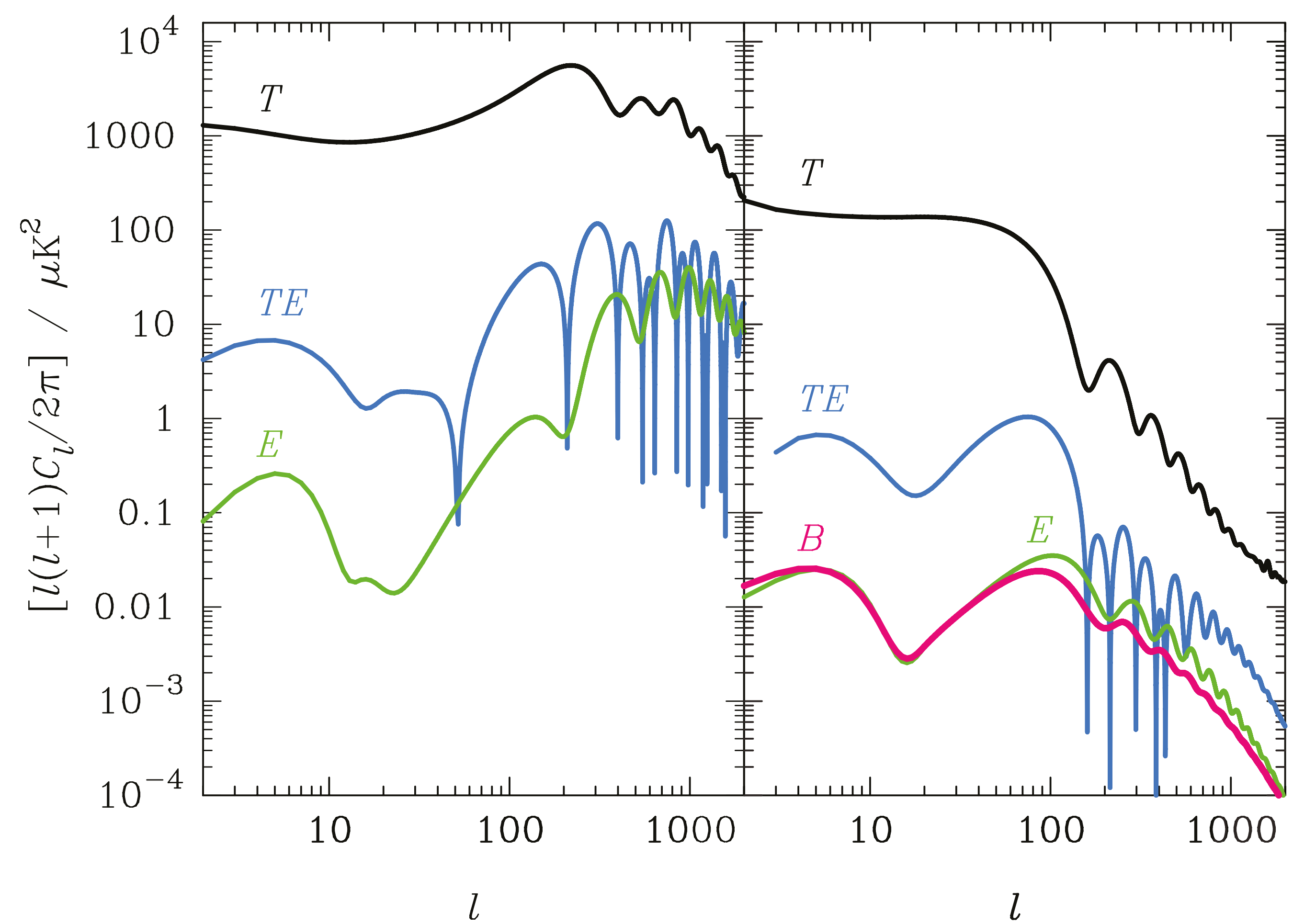
E-modes:



B-modes:





Inflation and Gravity Waves

- Assuming i) single field slow-roll inflation, ii) the observed fluctuations are generated by the vacuum fluctuation of the inflaton:

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = 16\epsilon \quad \text{where} \quad \epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$

where we have used the fact that for slow-roll:

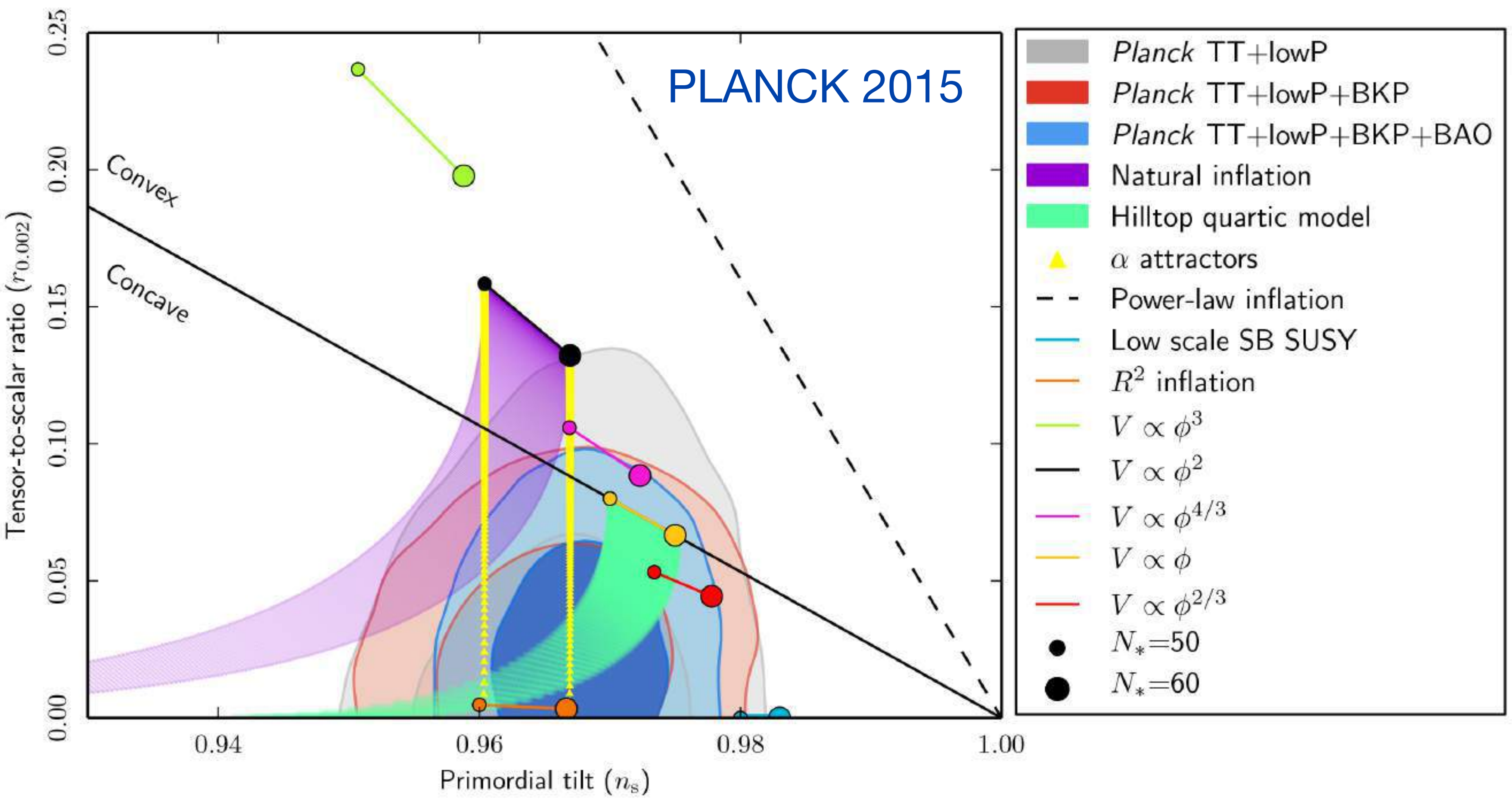
$$\dot{\phi}^2 = \frac{V'^2}{9H^2} = \frac{M_P^2}{3}\frac{V'^2}{V} = \frac{2}{3}\epsilon V \; ; \qquad \frac{d\phi}{dN} = \frac{\dot{\phi}}{H} = M_P\sqrt{2\epsilon} = M_P\sqrt{\frac{r}{8}}$$

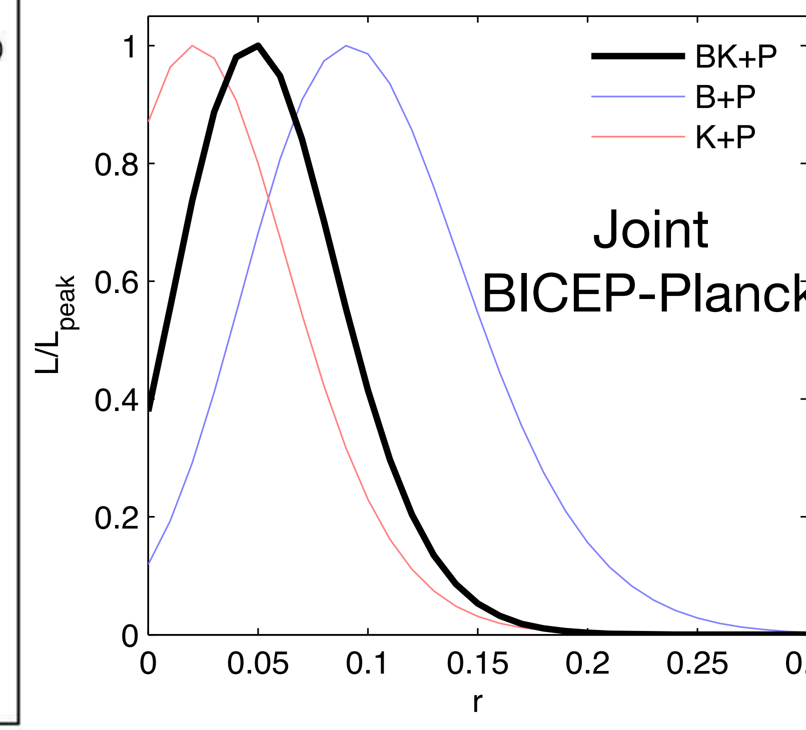
$$\frac{\Delta\phi}{M_P} = \int \sqrt{\frac{r(N)}{8}} dN \sim \sqrt{\frac{r_{CMB}}{2.5 \times 10^{-3}}}$$

Lyth bound

$$\text{for } 50 - 60 \text{ e} - \text{folds and } \frac{dr}{d\log N} \sim \mathcal{O}(\epsilon)$$

Primordial Gravitational Waves





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD, … can potentially detect primordial B-mode at the sensitivity r~10^{-2}.

Further experiments, such as CMB-S4, PIXIE, LiteBIRD, DECIGO, Ali, .. may improve further the sensitivity to eventually reach r ~ 10^{-3}.

B-mode and Inflation

<u>If</u> primordial B-mode is detected, natural interpretations:

- Inflation took place at an energy scale around the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- The inflaton field excursion was super-Planckian

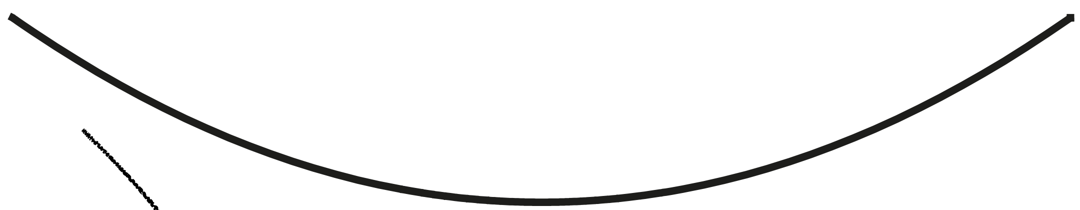
$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

- Great news for string theory due to strong UV sensitivity!

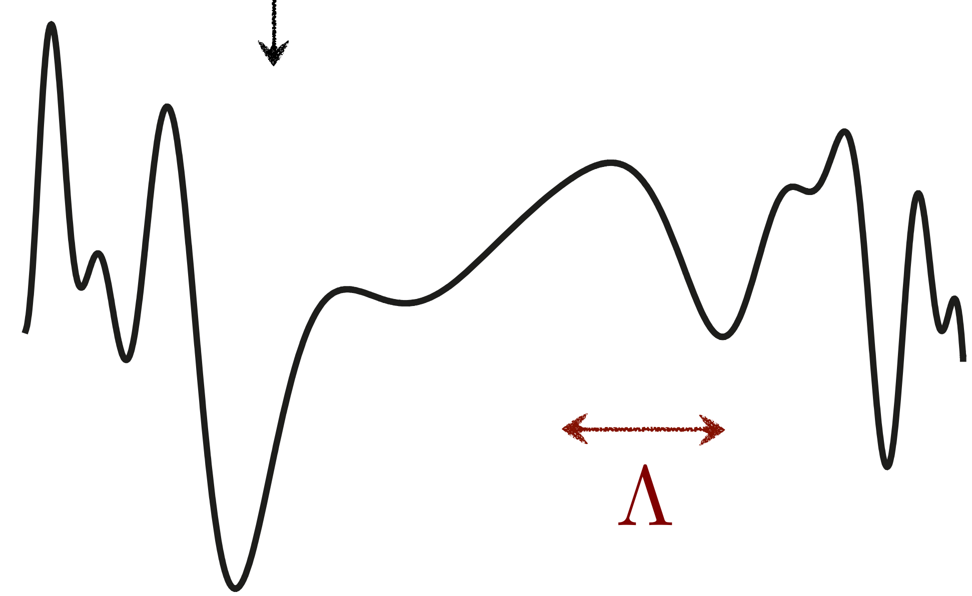
Large field inflation and UV Sensitivity

UV sensitivity of large field inflation:



$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

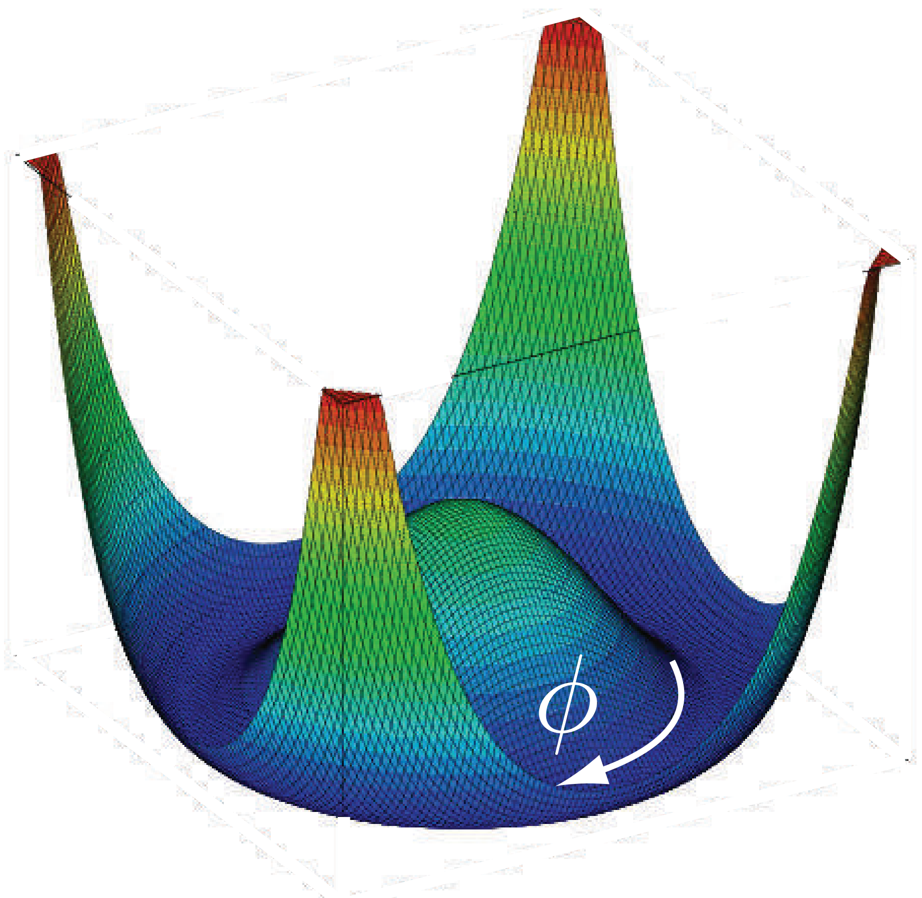
$c_i \sim \mathcal{O}(1)$



Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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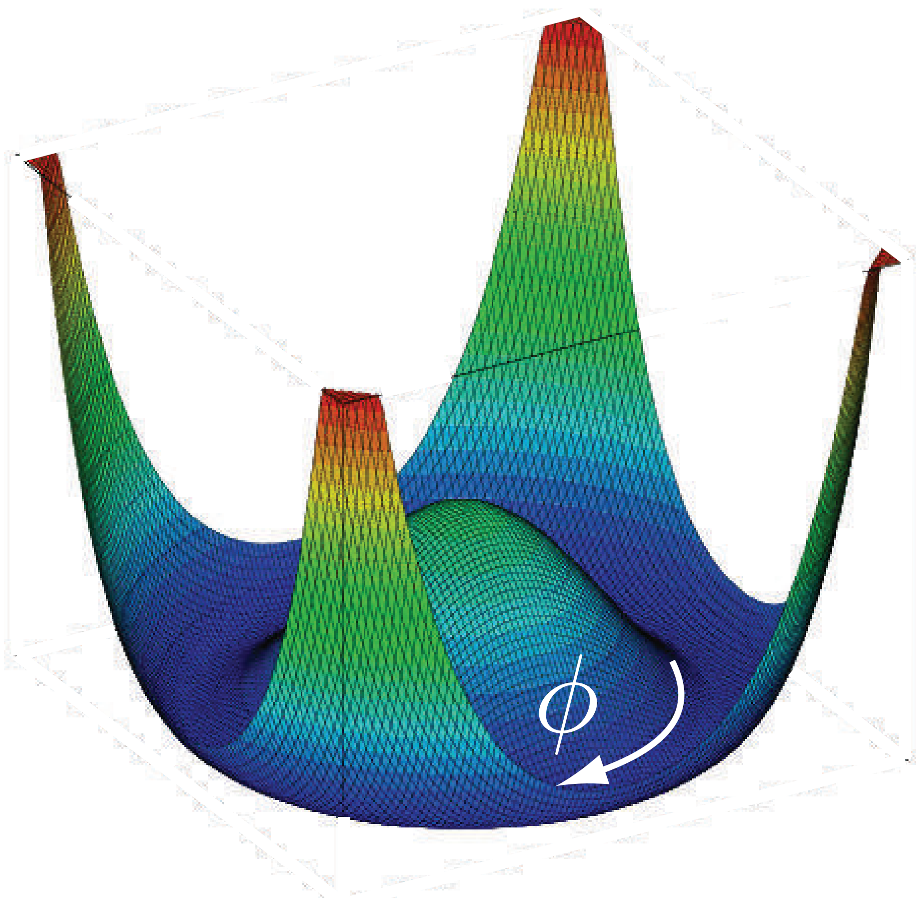
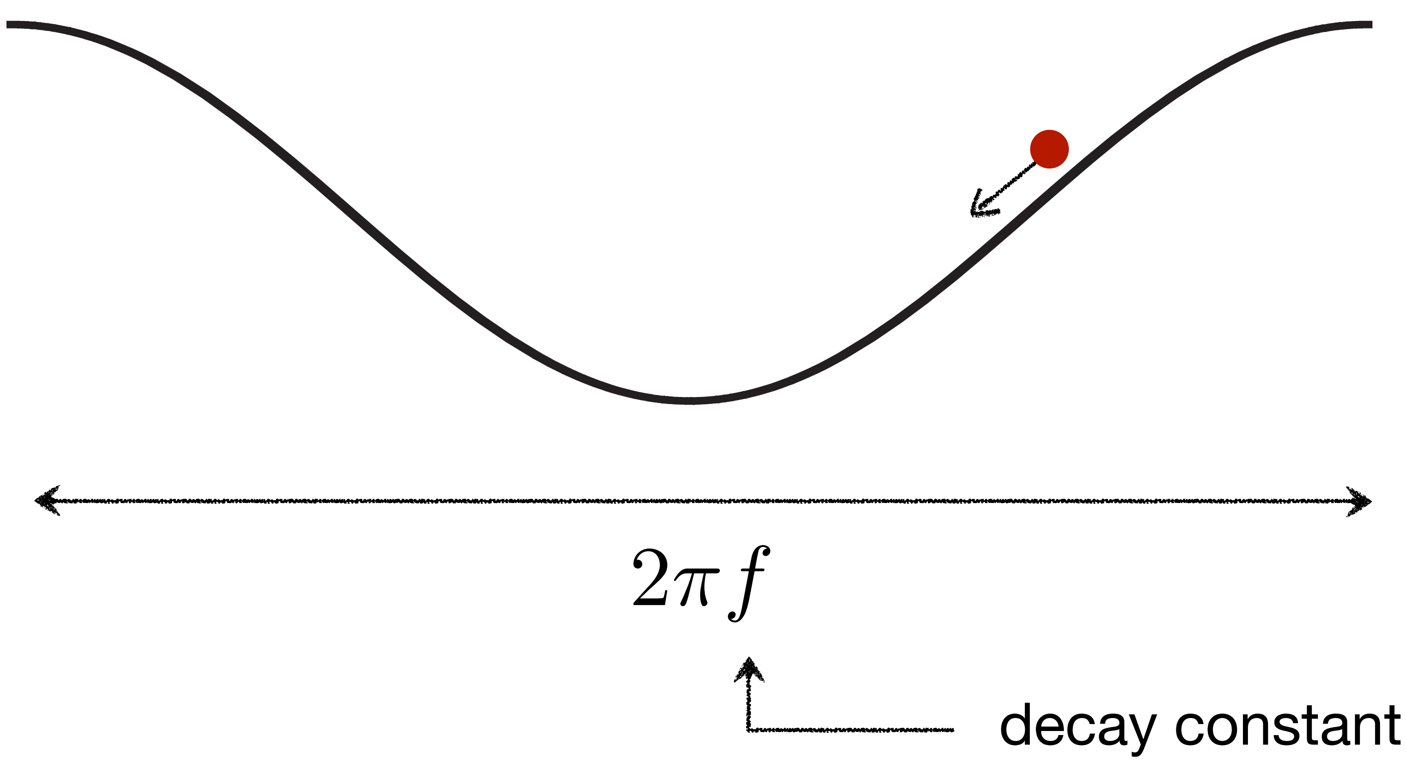


They satisfy a shift symmetry that is only broken by non-perturbative effects:



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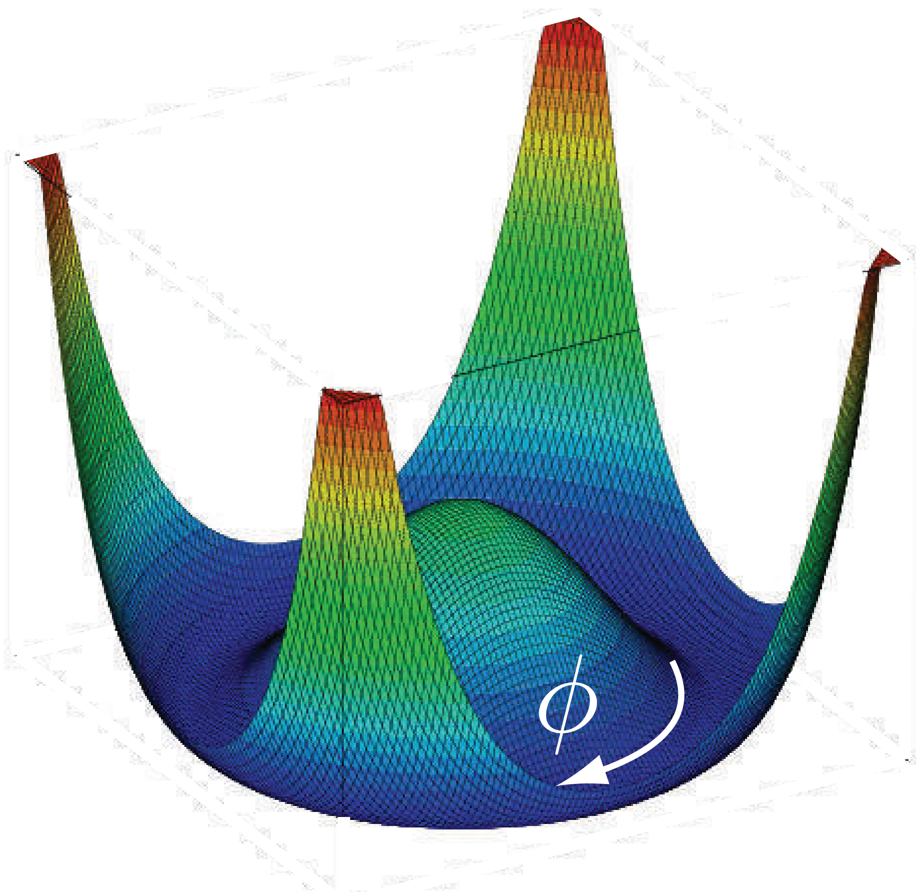

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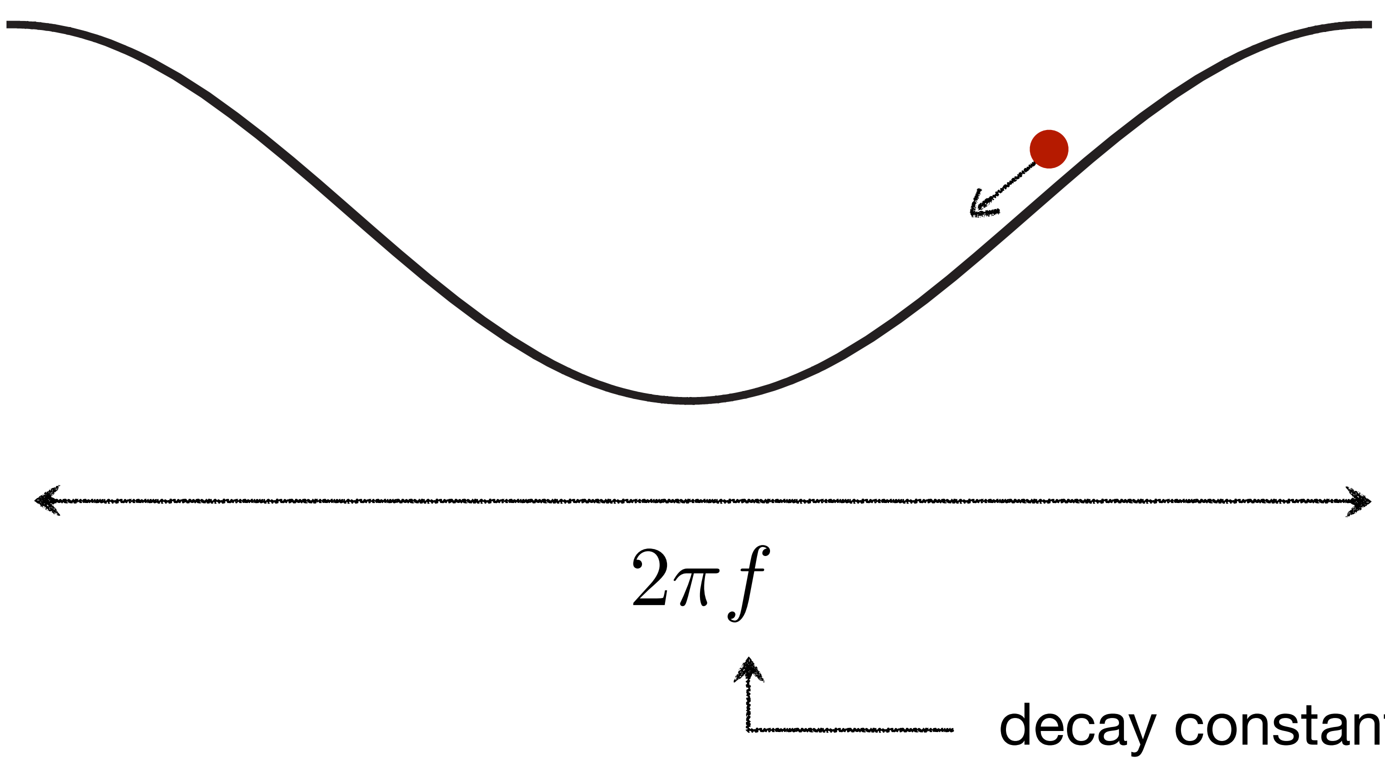

Slow roll: $f > M_P$

$$V(\phi) = 1 - \Lambda^{(1)}\cos\left(\frac{\phi}{f}\right) + \sum_{k>1}\Lambda^{(k)}\left[1-\cos\left(\frac{k\phi}{f}\right)\right] \quad \text{if} \quad \frac{\Lambda^{(n+1)}}{\Lambda^{(n)}} \sim e^{-S_{\text{inst}}} << 1$$

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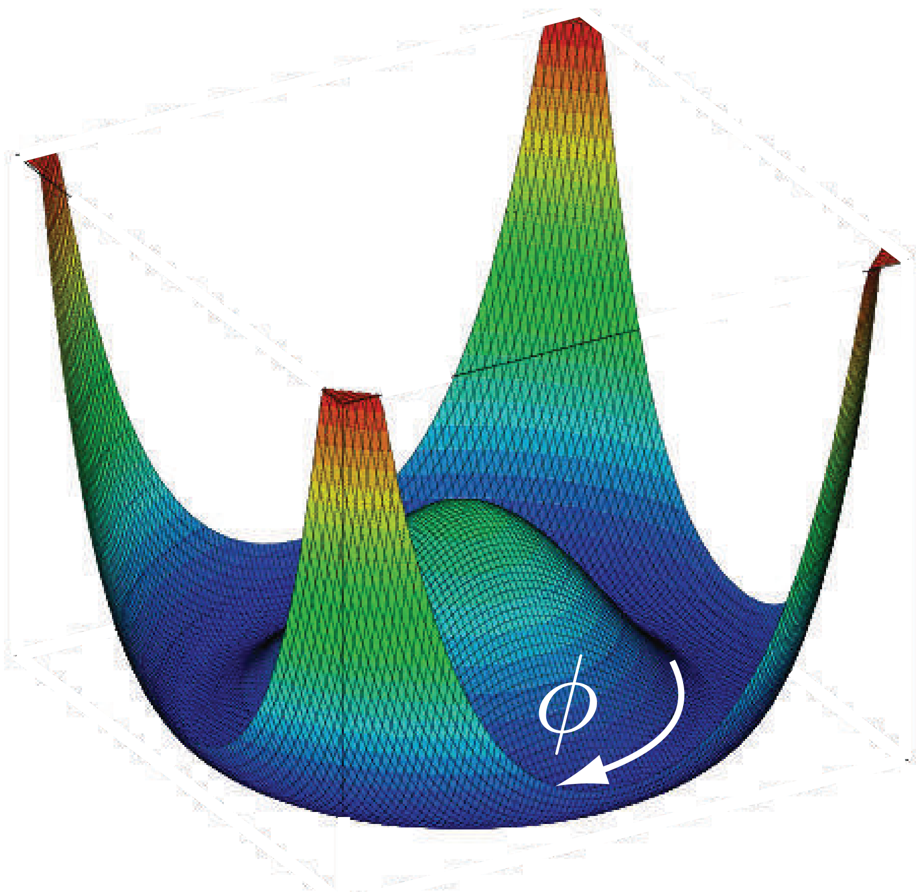

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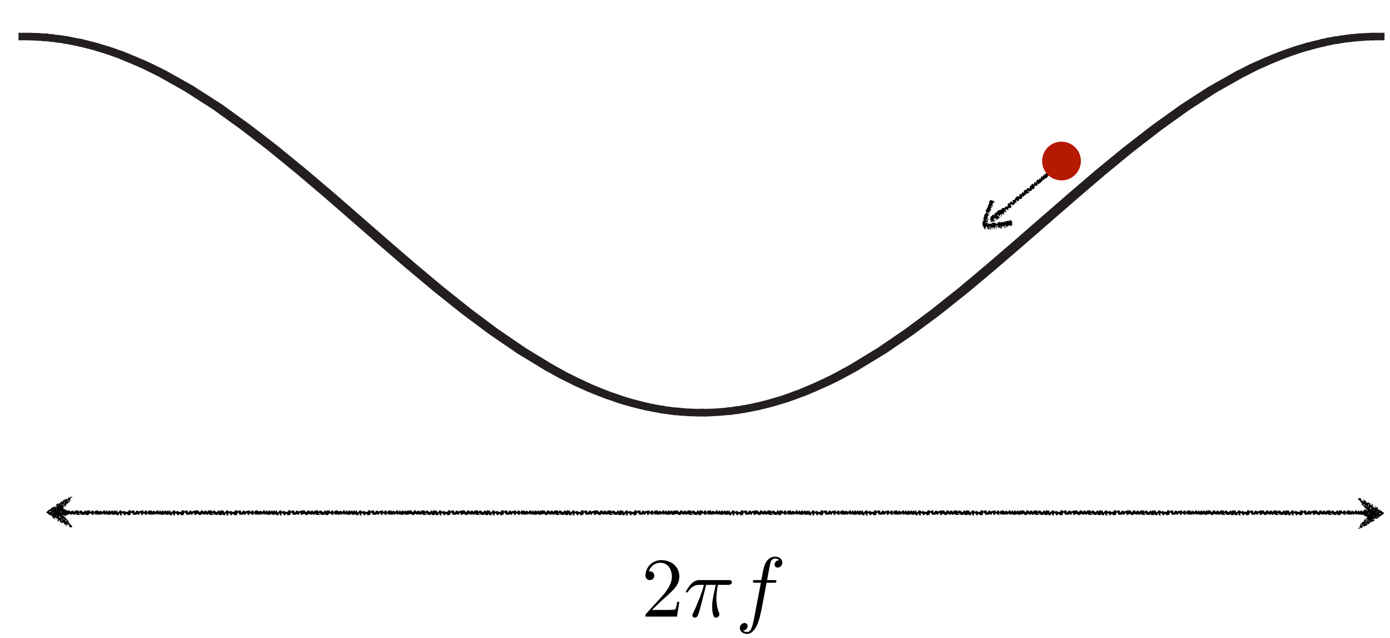

decay constant

Slow roll: $f > M_P$

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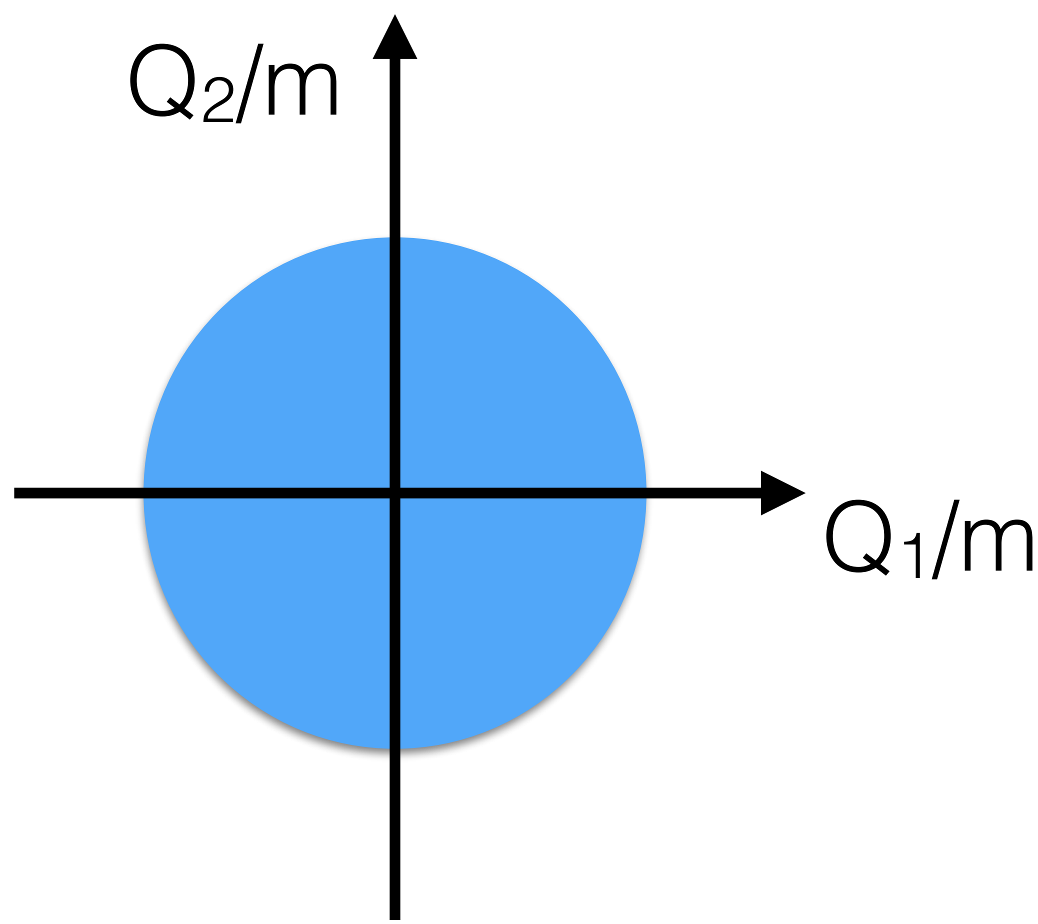
The WGC implies that these conditions cannot be *simultaneously* satisfied.

WGC and Axion Inflation

- Effective models of natural inflation in direct conflict with WGC.
- Thorough searches for transplanckian axions in the string landscape have not been successful. Banks et al. '03 …
- Models with multiple axions have been proposed but they violate the **convex hull condition**. Recall the WGC implies:



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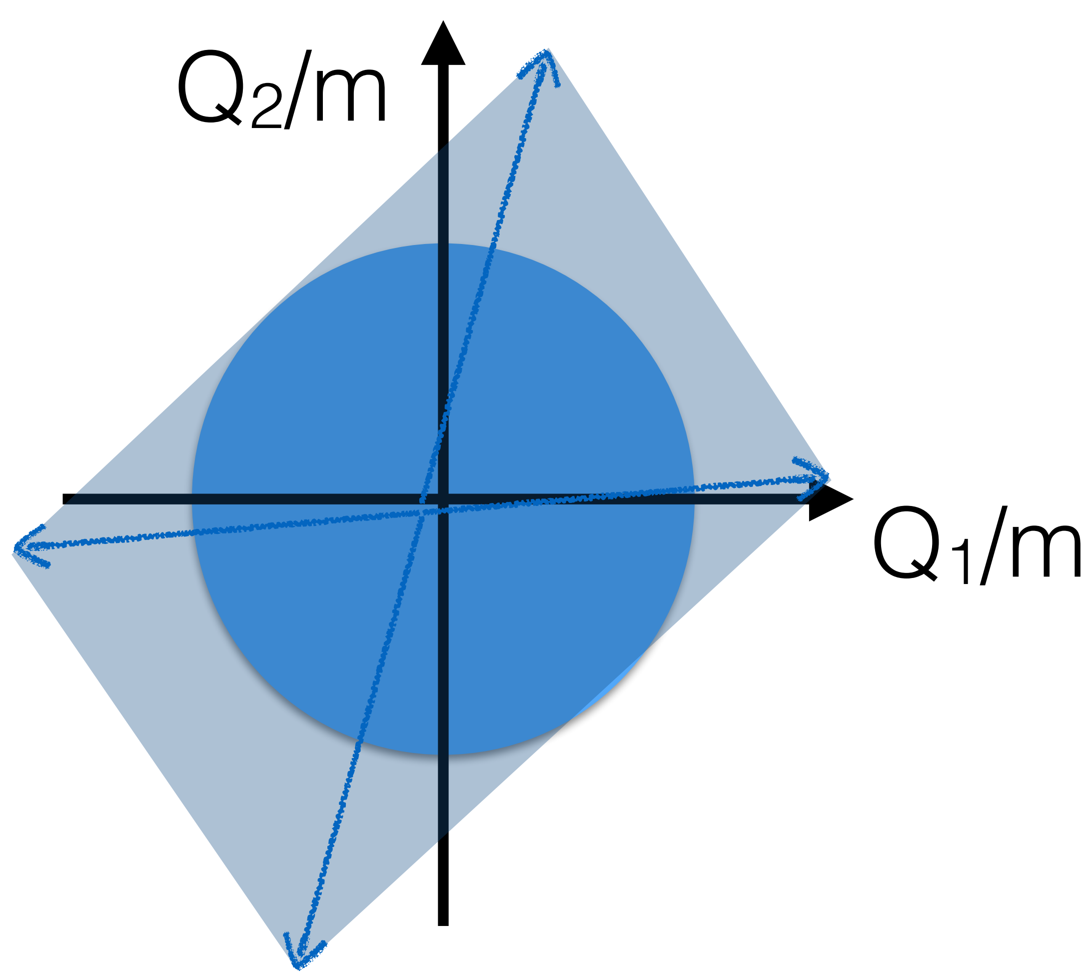


WGC and Axions

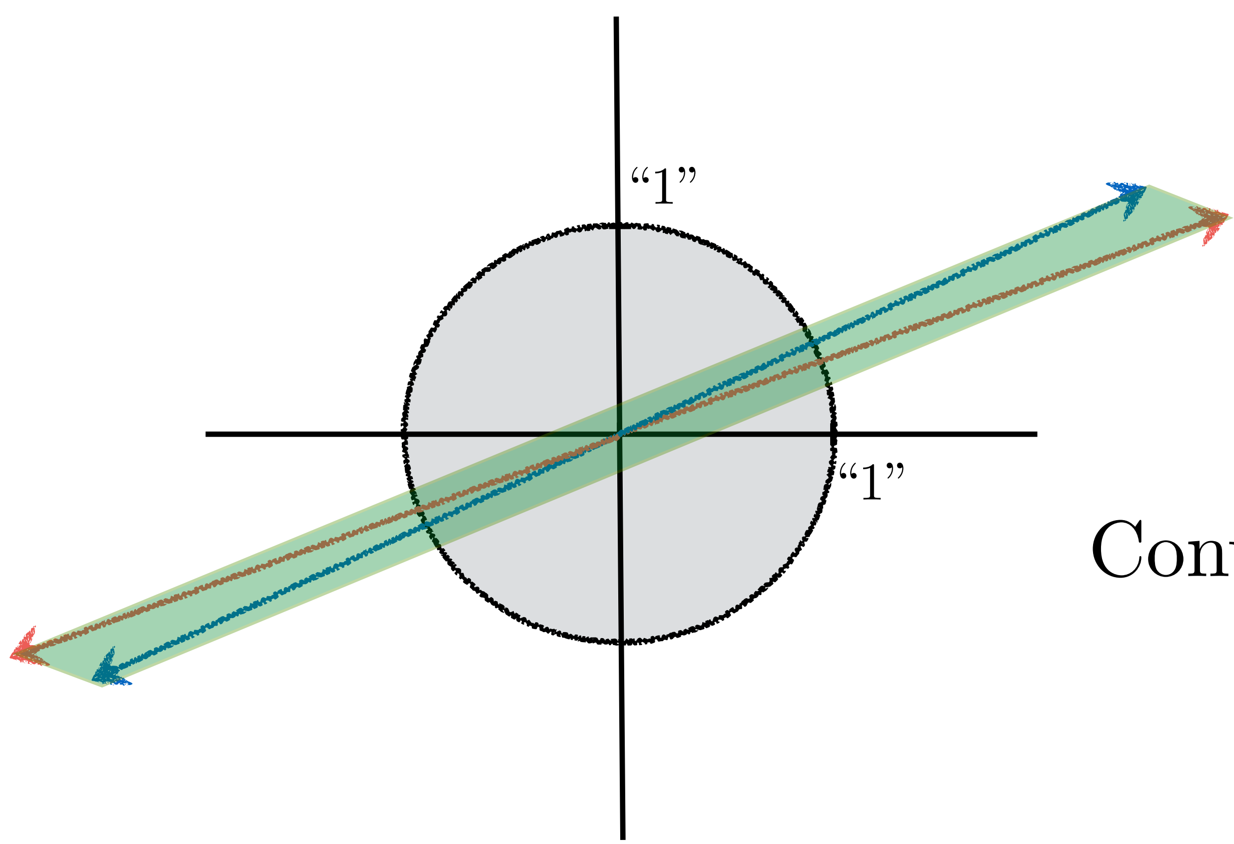
Multiple axions/U(1)s

Brown, Cottrell, GS, Soler '15
Rudelius '15

- Consider two U(1) bosons (axions): there must be 2 particles (instantons) i=1,2, so that BH's can decay.

$$\vec{z}_i \equiv \frac{M_P}{M_i}\left(Q_i^1 \quad Q_i^2 \right) \qquad \left(= \frac{M_P}{\sqrt{2}\, m_i}\left(1/f_i^1 \quad 1/f_i^2 \right) \right)$$

KNP



WGC

$$|\vec{z}| = \text{"1"}$$
$$\cap$$
$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

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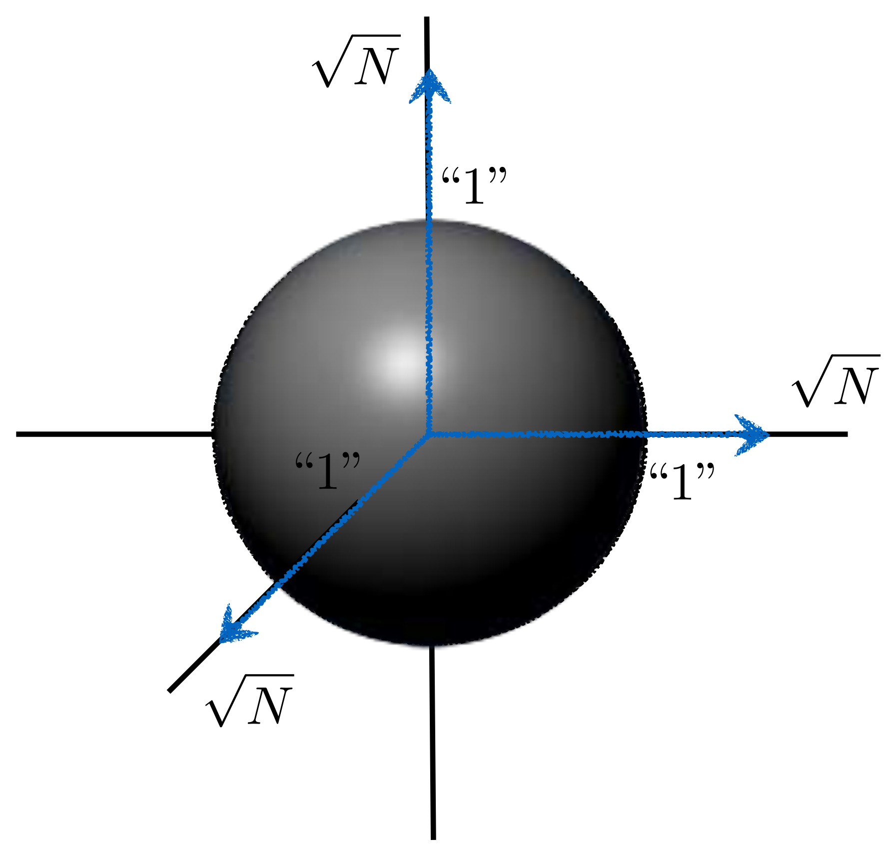
N-flation

$$z_i^k \geq \sqrt{N}\delta_i^k$$



WGC

$$|\vec{z}| = \text{“1”}$$
$$\cap$$
$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

A possible loophole

[Brown, Cottrell, GS, Soler, '15]

- The WGC requires f·m<1 for ONE instanton, but not ALL

$$V = e^{-m}\left[1-\cos\left(\frac{\Phi}{F}\right)\right] + e^{-M}\left[1-\cos\left(\frac{\Phi}{f}\right)\right]$$

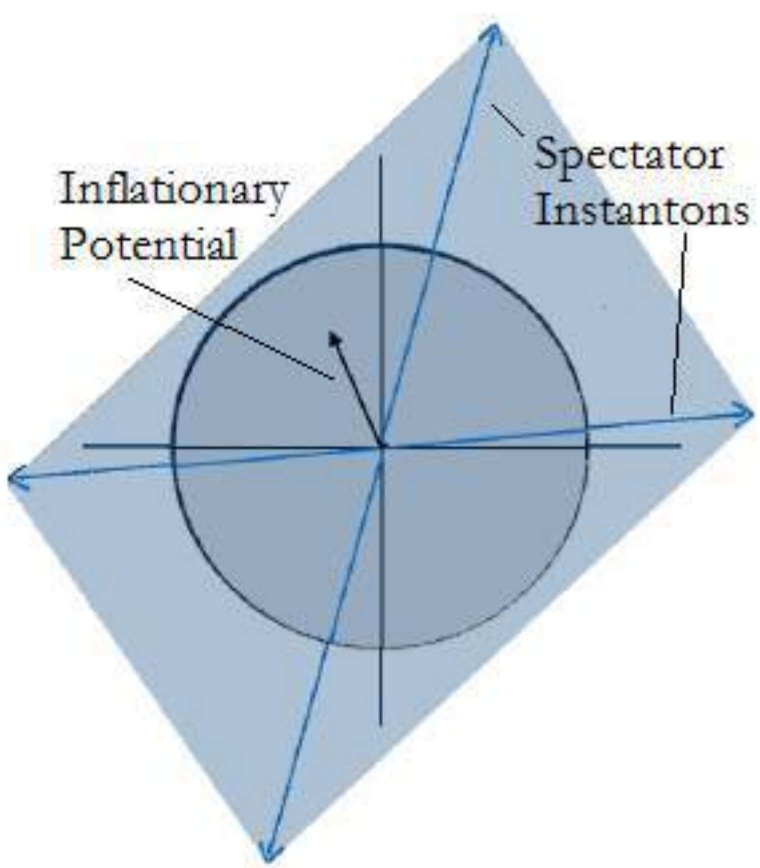
with $1 < m \ll M,$ $\quad F \gg M_P > f,$ $\quad M \times f \ll 1$

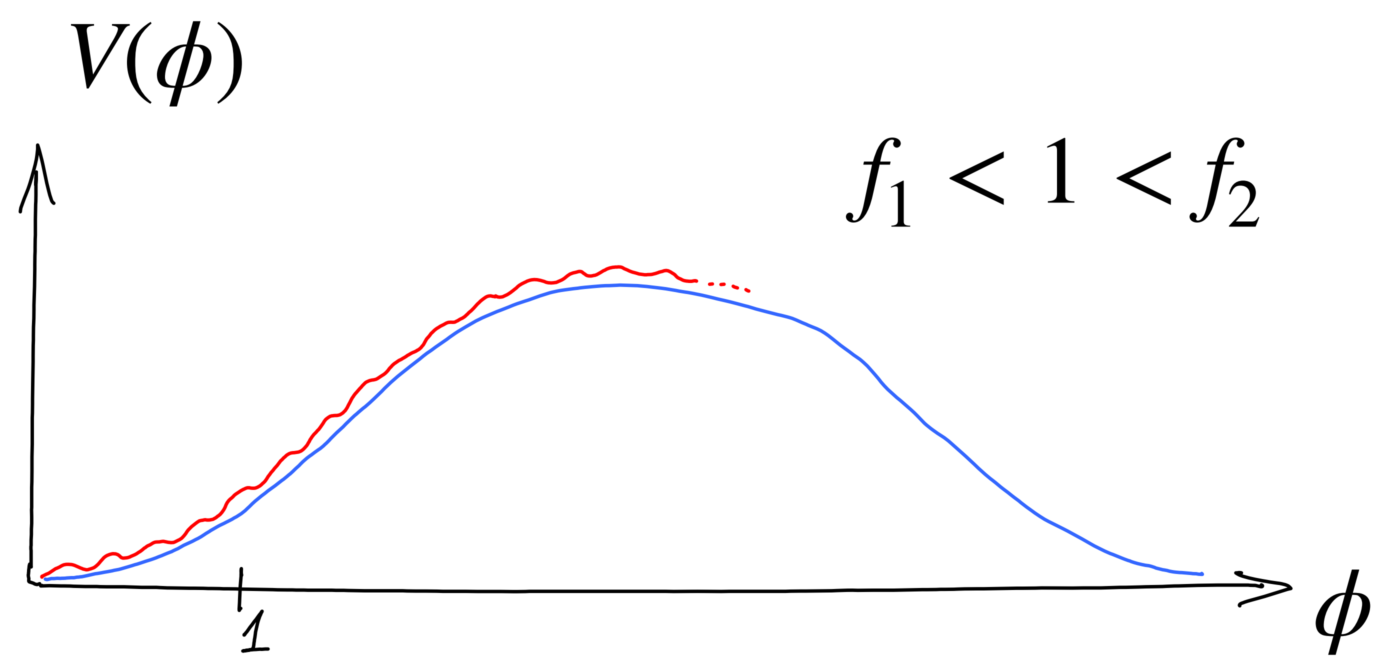
- The second instanton fulfills the WGC, but is negligible, an "spectator". Inflation is governed by the first term.

A possible loophole

[Brown, Cottrell, GS, Soler, '15]

- "Spectator" instantons satisfy the WGC, while dominant instantons can generate an inflationary potential

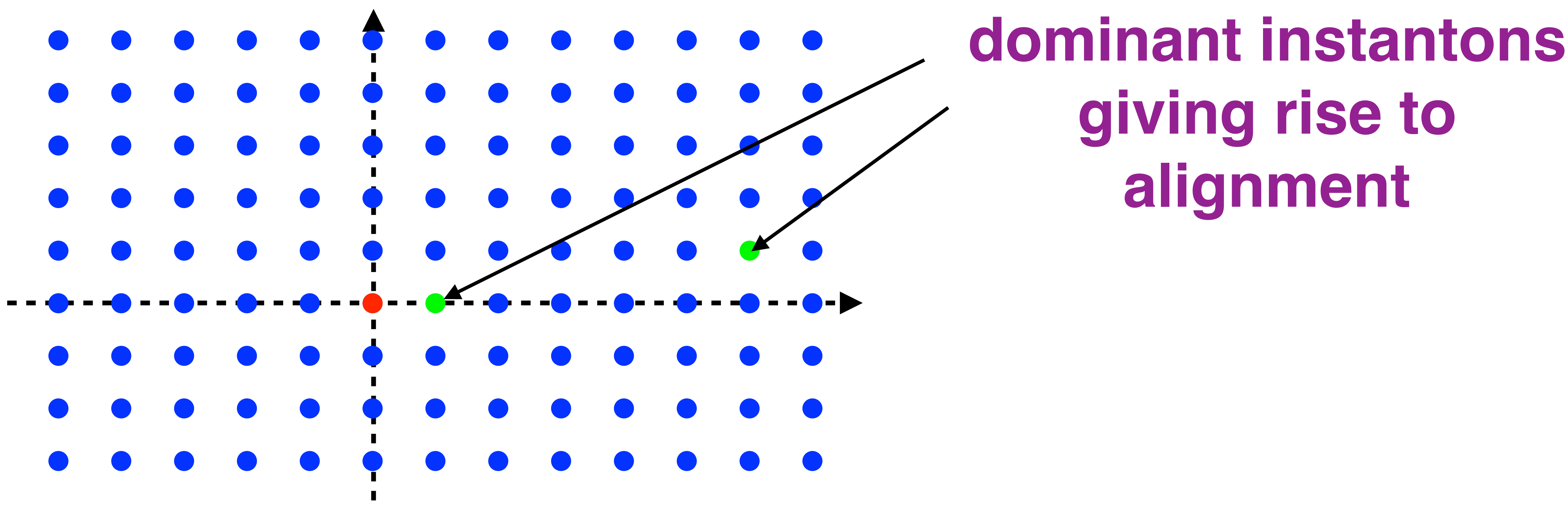




- Tiny wiggles in the potential may lead to interesting signatures e.g, non-Gaussianity.

Stronger forms of the WGC

- Even stronger forms (e.g., sLWGC, tower WGC, lightest state,…) can be satisfied with **spectator instantons**.



- **Main message** is not that these loopholes are natural or can be realized easily, but that models satisfying the WGC come with **extra baggage** that may lead to new signatures.