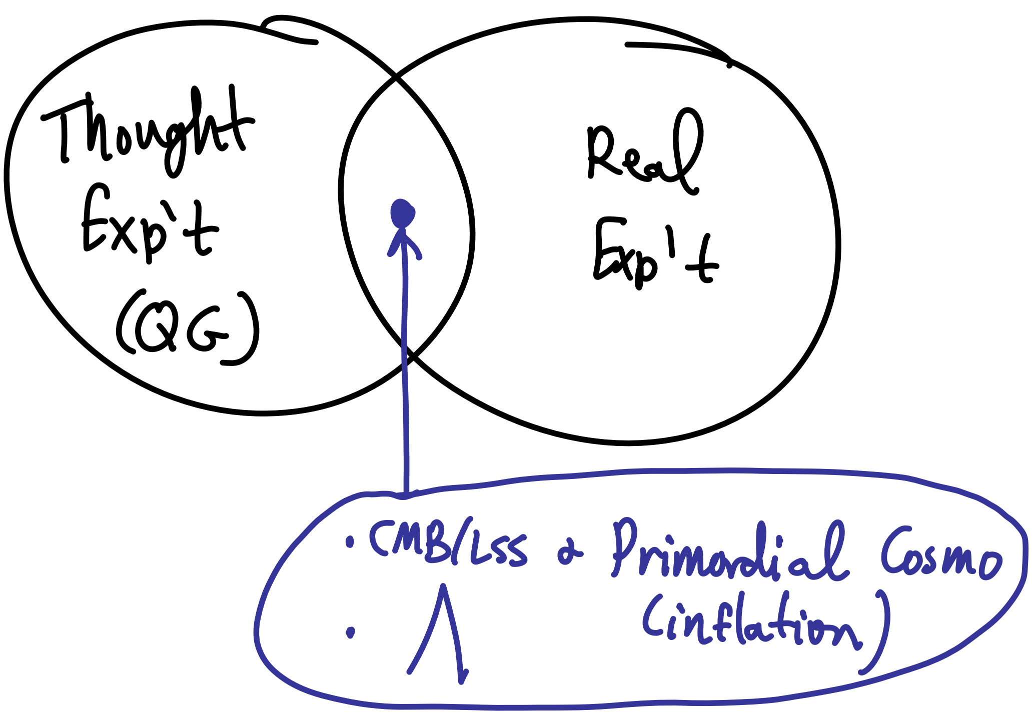
String theory

& astrophysics

Unsolved Problems

String theory: UV completion of GR

- Reproduces GR at long distance, no UV divergences
- "Holographic": Number of degrees of freedom $\sim \frac{\text{Area}}{4G_N}$
- QFT results (formal & model-building mechanisms)
- Math



Plan

I. Thought Experiments

II. Real Experiments

"The scientific theorist is not to be envied. For Nature, or more precisely experiment, is an exorable and not very friendly judge of his work. It never says "yes" to a theory. In the most favorable cases it says "Maybe," and in the great majority of cases simply "No." If an experiment agrees with a theory it means for the latter "Maybe," and if it does not agree it means "No." Probably every theory will some day experience its "No" - most theories, soon after conception."

--Entry into memory book for Professor Kammerling-Onnes, November 11, 1922; quoted in Dukas and Hoffmann, *Albert Einstein, the Human Side*, p.18.

I. Black Hole Physics:

$\Delta A \geq 0$ in classical GR

↑ area of event horizon

$\Delta M = \kappa \, \Delta A$ in classical GR

↑ surface gravity

$T \sim \kappa$ Quantum mechanically

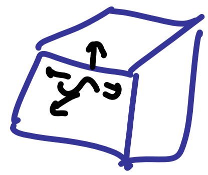
Dynamics of BHs ⇔ Thermodynamics

$\frac{\text{Area}}{G_N} \sim (\text{Area}\ M_p^2) \Leftrightarrow$ Entropy S

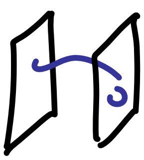
Gravity (d dimensions) $\neq$ Local QFT (d dimensions)

↑ If you pack too much entropy in local region ⇒ form a BH, $S \sim$ Area

↑



String theory : BH Stat. Mech.



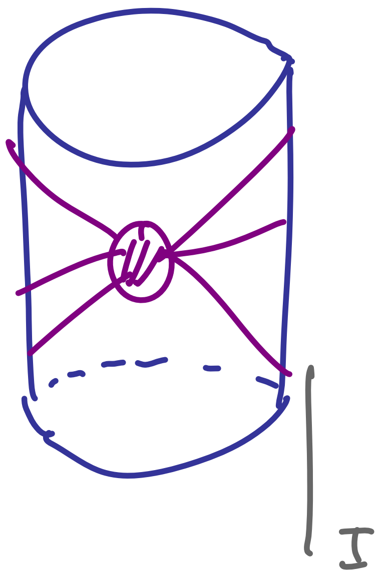
Explicit microstate count for tractable BH's ... →

Gravity (d dimensions, e.g. AdS) = Local QFT (d-1 dimensions) !

⇒ Unitary BH evolution

$\Lambda < 0$ (AdS_4) has a precise non-perturbative formulation.

4d GR + strings | QFT_3, no gravity

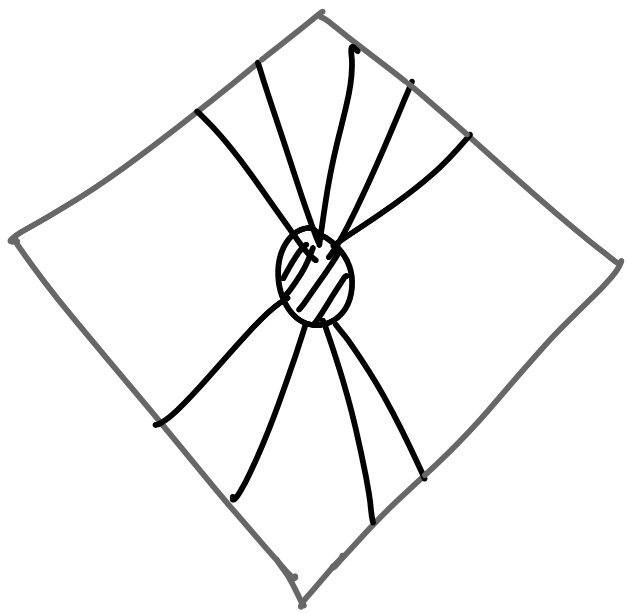


$\cong$ CFT_3

many distinct examples, don't mix, no horizon

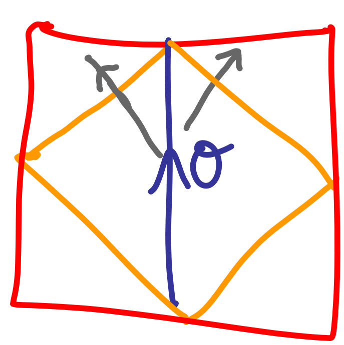
Observables = QFT Correlation Functions.

For $\Lambda = 0$, the general framework (an S-matrix) is also known



An observer can causally collect the results.

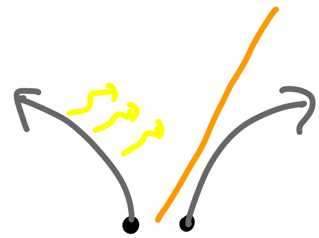
In contrast, in dS:



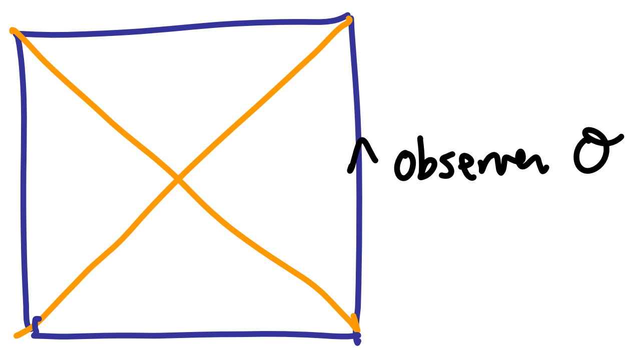
Classically appears as though info lost (cf Black Holes)

Mysteries of Dark Energy

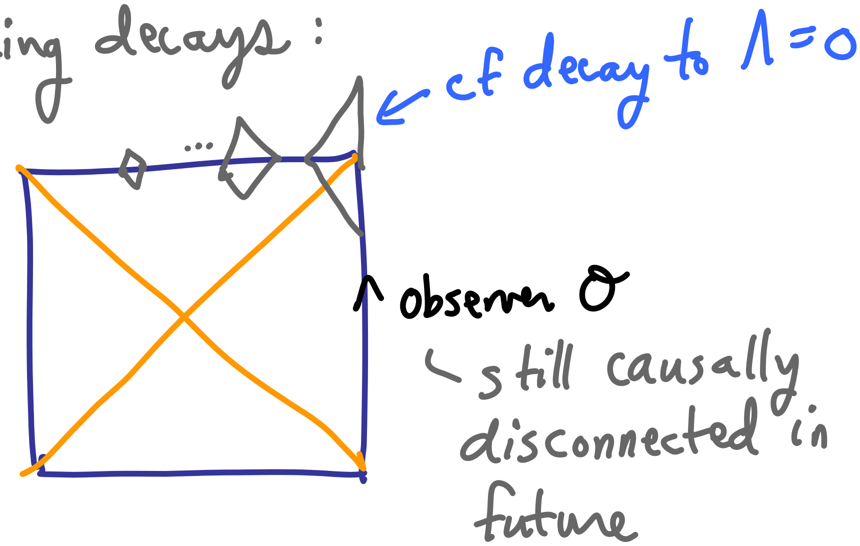
$w < -\frac{1}{3} \Rightarrow$ horizon



e.g. dS $w = -1$



Including decays:



Dynamical connections between different Λ, & different D, topology, fluxes, ...

Gibbons/Hawking: de Sitter

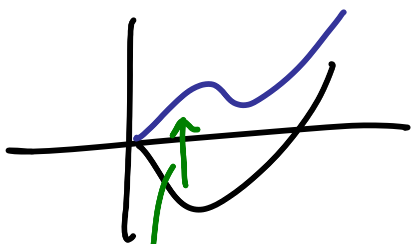
Horizon $\Rightarrow$ $S \sim \dfrac{M_p^2}{H^2}$

Invites a microstate count.

↳ Get parametrically by building up from AdS/CFT

add ingredients to "uplift"

interpret new ingredients



magnetic matter

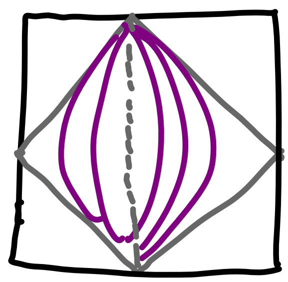
heavy branes overcoming $AdS \times S^5$ curvature

- Attempts to build up from AdS/CFT make some progress, but leave propagating Gravity in the dual

<u>dS/dS</u>

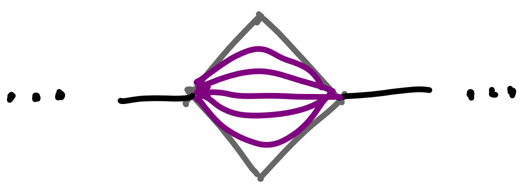
$$ds^2_{dS_4} = \sin^2\frac{w}{L}\, ds^2_{dS_3} + dw^2$$

$\Rightarrow$ 2 QFT_3 + GR_3



- UV-complete construction, concrete dual $\to$ dS_4 entropy (order of magnitude)

<u>FRW/CFT</u>

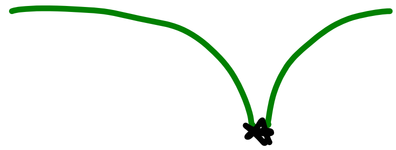


Euclidean AdS_3/CFT_2
+ 2d Gravity

- Attempts at probability "measures" interesting but still ad hoc.

II. Thought Exp't ∩ Real Exp't

General Relativity describes gravity accurately at long distances



$$S = \int d^4x \sqrt{g}\, \frac{R}{G_N} + S_{matter} \rightarrow R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

GR breaks down for $\lambda_G \rightarrow 1$ (or before)

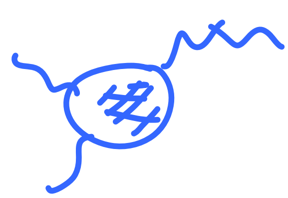
Quantum fluctuations / Classical UV physics →

$$S = \int \left(\frac{R}{G_N} - V(\phi)\right)\left(1 + R\left(\frac{c_1}{M_*^2} + \tilde{c}_1 G_N\right) + \cdots \right)$$

$$+ \int (\partial\phi)^2 + k_1 \frac{(\partial\phi)^4}{M_*^2} + \cdots$$

M_* ← scale of "new physics"

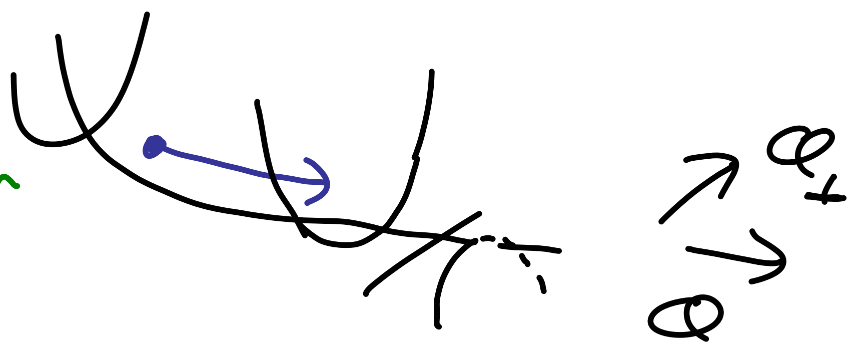
with corrections sensitive to short-distance physics



2) These corrections <u>matter</u> for inflation

e.g. A seemingly simple way to obtain inflation is to postulate a very flat potential for the inflaton $\phi(x)$.

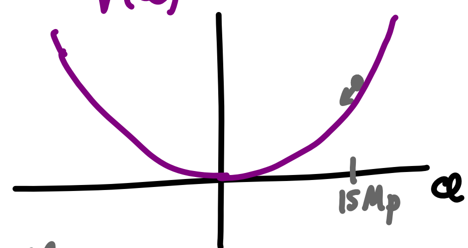
Linde '93
hybrid inflation



$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \equiv M_p^2 \left|\frac{V''}{V}\right| \ll 1$$

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\phi, \partial\phi)$: $\frac{V(\phi-\phi_0)^2}{M_p^2} \to \Delta\eta \sim 1$

This UV Sensitivity is greatest in the case of "chaotic inflation" A. Linde '83 where the inflaton φ ranges over more than a distance M_p e.g. $V(\varphi) = \frac{1}{2}m^2\varphi^2$



$$\left\{\begin{aligned} \varepsilon &= \tfrac{1}{2}\left(\frac{V'}{V}M_p\right)^2 \\ \eta &= M_p^2\left|\frac{V''}{V}\right| \end{aligned}\right\} \sim \left(\frac{M_p}{\varphi}\right)^2 \Rightarrow \varphi \sim 15\,M_p$$

In General:

★ "Lyth Bound": $\frac{\Delta\varphi}{M_p} \sim \left(\frac{r}{0.01}\right)^{\frac{1}{2}}$

UV sensitive if $\gtrsim 1$ — observable

→ Control with approximate shift symmetry (Wilsonian 'natural')

UV Sensitivity of Inflation

① Terms of order $V \cdot \frac{(\varphi-\varphi_0)^2}{M_p^2}$
(dimension 6)

in the effective action can ruin inflation

② $\frac{\Delta\varphi}{M_p} \simeq r^{\frac{1}{2}} \frac{N_e}{\sqrt{24}}$ (Lyth)

GUT-scale inflation (with observable tensor modes) $\Leftrightarrow \Delta\varphi > M_p$

③ General Single-field inflation involves higher derivative terms which affect solution & perturbations

cf Non-Gaussianity

④ $g^2\varphi^2\chi^2$ couplings ⇒ temporarily light fields affect evolution. . . .

⑤ (mass > H)

Heavy fields affect results in a different way: they adjust in response to inflationary potential energy.

QFT toy model

$$V(\varphi_L, \varphi_H) = g^2 \varphi_L^2 \varphi_H^2 + m^2(\varphi_H - \varphi_0)^2$$

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2 \varphi_L^2}{g^2 \varphi_L^2 + m^2} m^2 \varphi_0^2$$

($\dot{\varphi}_H^2$ term subdominant)

flatter: energetically favorable.

⑥ Exit physics: defects, strings, oscillons, ...?

⑦ Entry Physics ?? bubble nucleation..

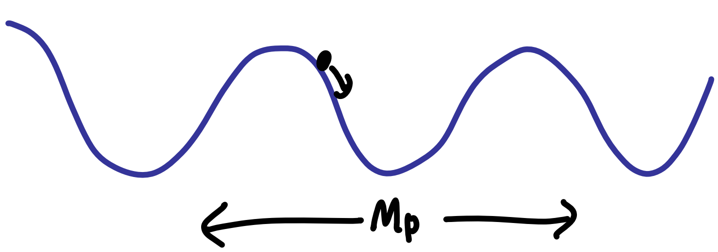
Tensor Modes

Large $\frac{\Delta\phi}{M_p}$.

Axions naturally respect an (approximate) shift symmetry $\phi \to \phi + \alpha$

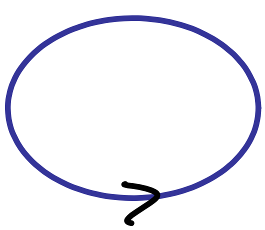
(couple via their derivatives)

→ "Natural Inflation"



$\Lambda^4 \sim e^{-\frac{\text{const}}{g^2}}$

Naturally small



$a \simeq a + (2\pi)^2$

$\phi_a = f_a a$ — canonical scalar field

→ Does $\frac{\Delta\phi}{M_p} \gtrsim 1$, protected by shift symmetry, arise in string theory?

* Basic period small compared to M_p

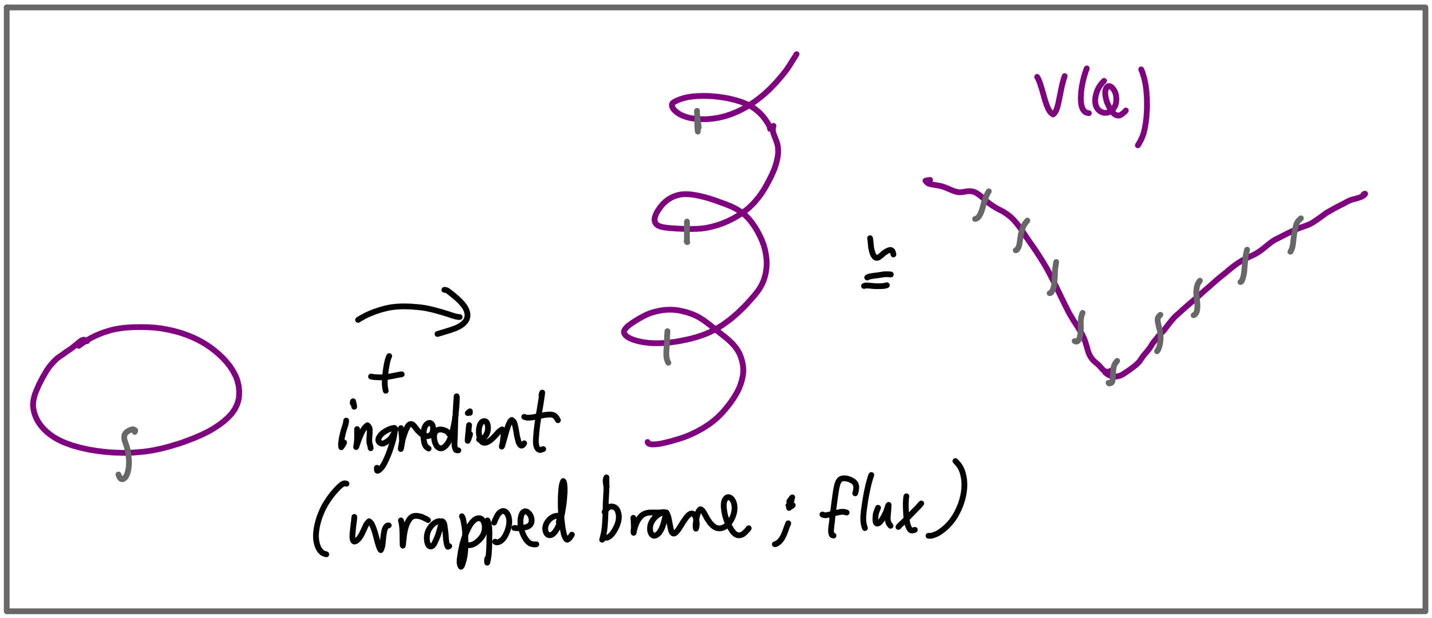
For axions, $f \ll M_p$

in currently controlled regions of the landscape. (size $L \gg M_p^{-1}$)

$$\int d^4x \sqrt{-g}\, \underbrace{|dC_p|^2}_{g^{i_1 j_1} \cdots g^{i_{p+1} j_{p+1}}} = \int d^4x \sqrt{-g}\, \frac{M_p^2}{(LM_p)^{2p}} (\partial\theta)^2$$

* Not "anything goes" in the landscape!

... But must take into account Monodromy in string compactifications

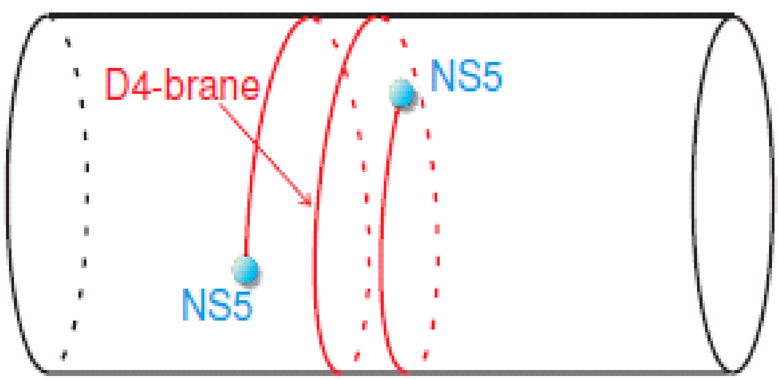


unwraps the would-be periodic direction. → Large field range with distinctive potential, with

$$V(\phi > M_p) \sim \begin{cases} \phi^{2/3} & \text{twisted torus} \\ \phi & \text{axions} \end{cases}$$

the so far worked out examples.

The basic mechanism is very simple :

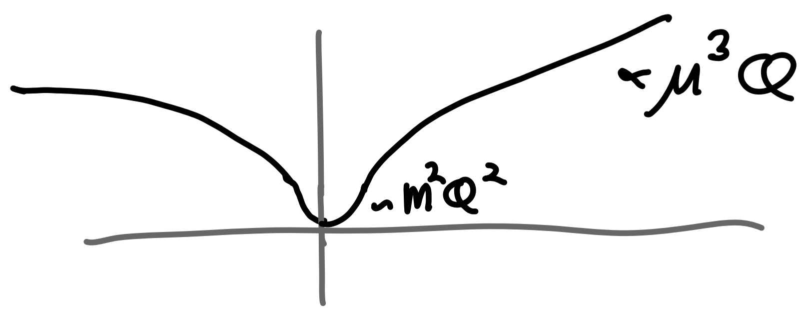


["T-dual" to axions]

- "NS5" branes position periodic on this circle, until add stretched "D4" brane

$$V(\phi) \sim \mu^3 \sqrt{\phi^2 + M_p^2}$$

→ Novel prediction for inflaton potential

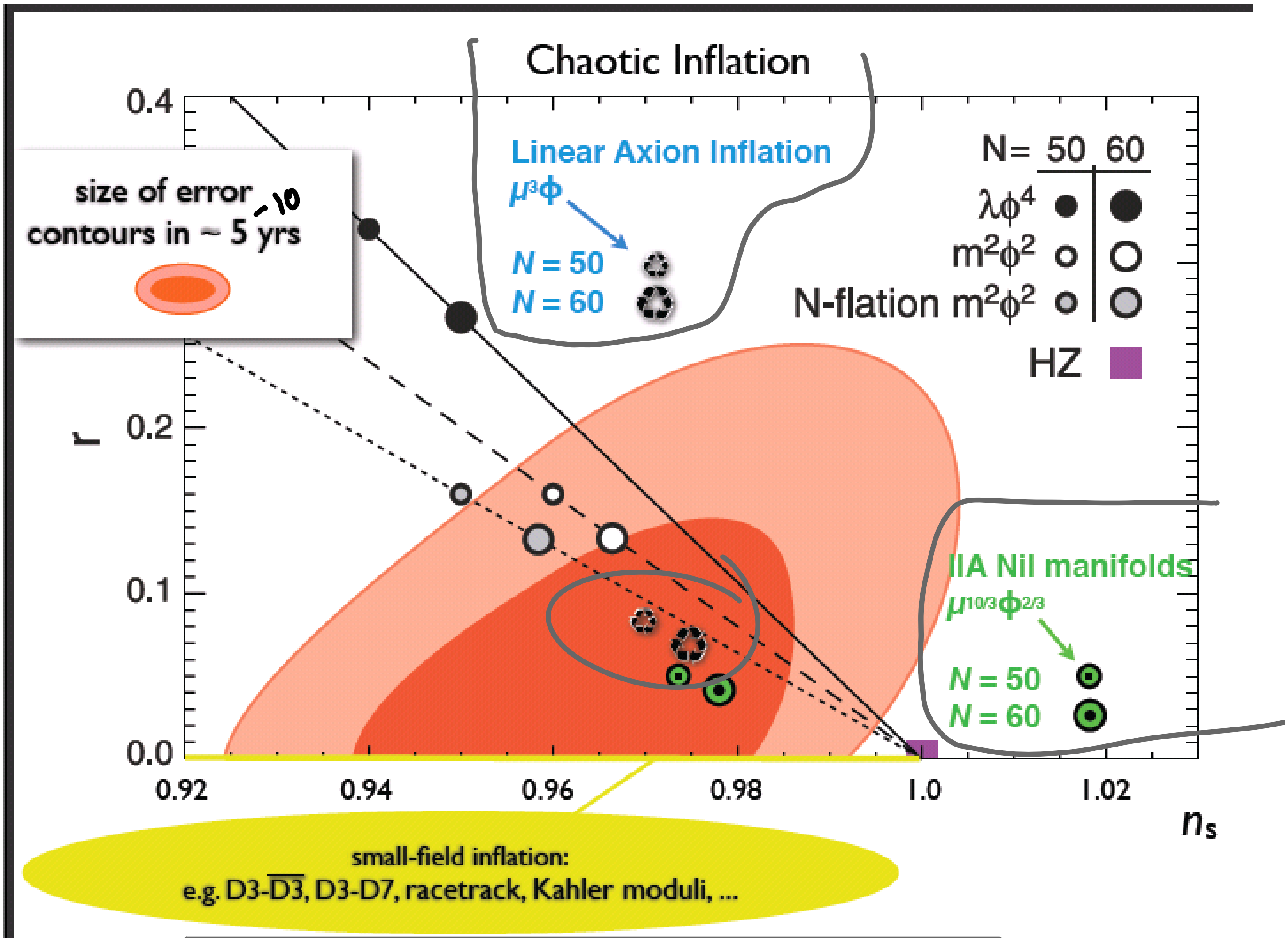


+

$(e^{-\frac{8\pi^2}{g^2}} \cos \frac{\phi}{f}$

Result:

WMAP

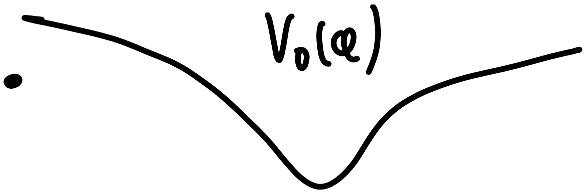


$r = 0.07$

$n_s \simeq 0.98$

$V(\varphi) \simeq \mu^3 \varphi + \Lambda^4 \cos\left(\frac{\varphi}{2\pi f}\right)$

Because of the symmetry, and oscillating nature of the (instanton-suppressed) corrections, these predictions are robust $\Rightarrow$ falsifiable

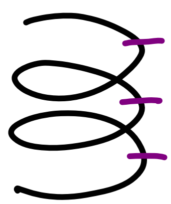
- 

  Flattened potential is the result of the adjustment of heavy fields

- Model-dependent oscillations

  $$V(\varphi) = V_0(\varphi) + \Lambda^4 \cos\frac{\varphi}{f}$$

  can lead to visible signatures in $\langle \zeta \cdots \zeta \rangle$

- 

  repeated production of particles/strings

  → novel signatures

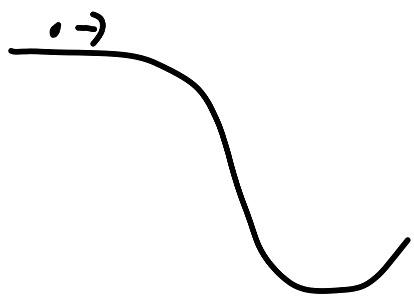
  Open direction: new discovery window(s), Systematics of detailed signatures.

- Small-field inflation also possible, in other directions in field space.

Non-Gaussianity

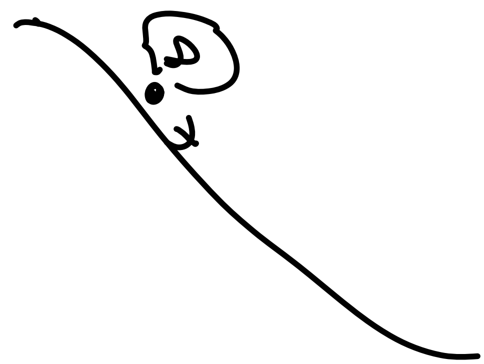
Roughly Speaking, 2 classes of Inflation Mechanisms:

→ Slowly diluting potential energy



Flat potential

NG only from substructure, e.g. oscillations, in $V(\phi)$



Steep potential, but interactions slow the field. ⇒ NG.

↳ e.g. brane motion limited by XD speed of light (DBI)

Now Systematic (EFT) understanding for single-field; new effects for multiple fields

Summary (part II)

- Inflation UV sensitive
- String theory → simple mechanisms
  some (focused on here) with
  distinctive signatures. e.g.

  $V \sim m^2 \phi^2$ ← distinguishable

  ↓

  $V \sim \mu^3 \sqrt{\phi^2 + M_p^2}$ Pythagorean

  ↖ UV degrees of freedom

- Motivated systematic
  analysis in QFT & data analysis.
- Further opportunities – UV sources
  of different NG shapes
  - resonant NG data analysis
  - strings

Summary (Part I)

- Spacetime defined by $S \sim \frac{A}{4G_N}$ independent degrees of freedom
- In certain systems (symmetric BHs) String theory has provided a precise microstate count
- Unsolved Problem: extend to a precise formulation of cosmology (and of realistic BH's)

recent progress (guided by AdS/CFT & structure of string theory), not complete framework