Multifield Inflation in Supergravity and String Theory

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Swansea University

Strings: Geometry and Symmetries for Phenomenology

Casa Matemática Oaxaca (CMO)

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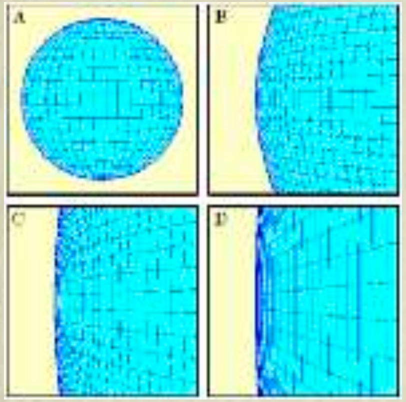
COSMOLOGICAL INFLATION

A period of accelerated quasi dS expansion in the very early universe

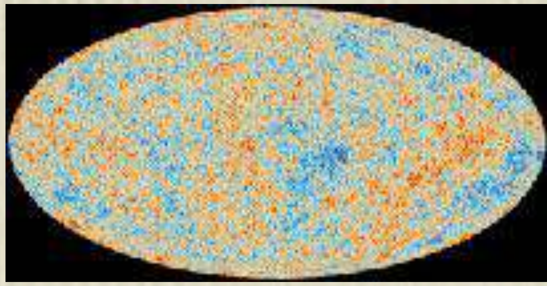
$$ds^2 = -dt^2 + a(t)^2 dx_i dx^i$$

$$a(t) = a(0)e^{Ht}, \qquad H = \frac{\dot{a}}{a} \sim \text{const.}$$

Can explains why the universe is approximately homogeneous and spatially flat (flatness, horizon problems).



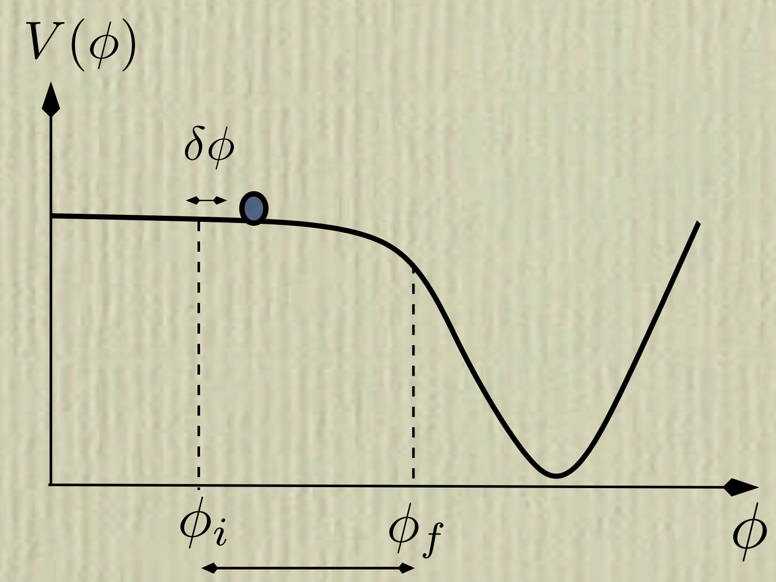
Accounts for the origin of primordial density fluctuation as observed in the CMB $(\delta\rho \rightarrow \delta T)$



COSMOLOGICAL INFLATION

In its simplest implementation with a **single scalar** field *slowly rolling* down along its flat potential $(\delta\phi \to \delta\rho \to \delta T)$

slow roll inflation



$$\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 - V(\varphi)$$

slow-roll conditions: $\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1\,, \quad \eta \equiv \frac{\dot{\epsilon}}{H\epsilon} \ll 1$

$$\left(H = \frac{\dot{a}}{a}\right)$$

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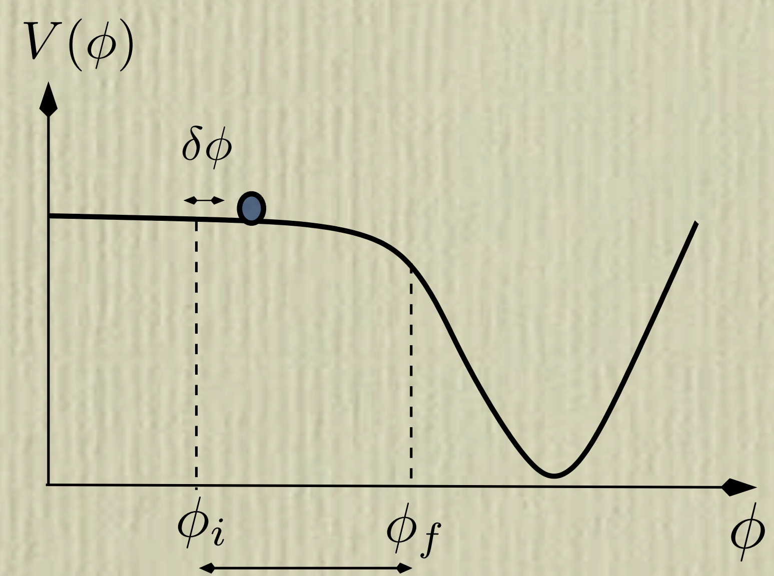

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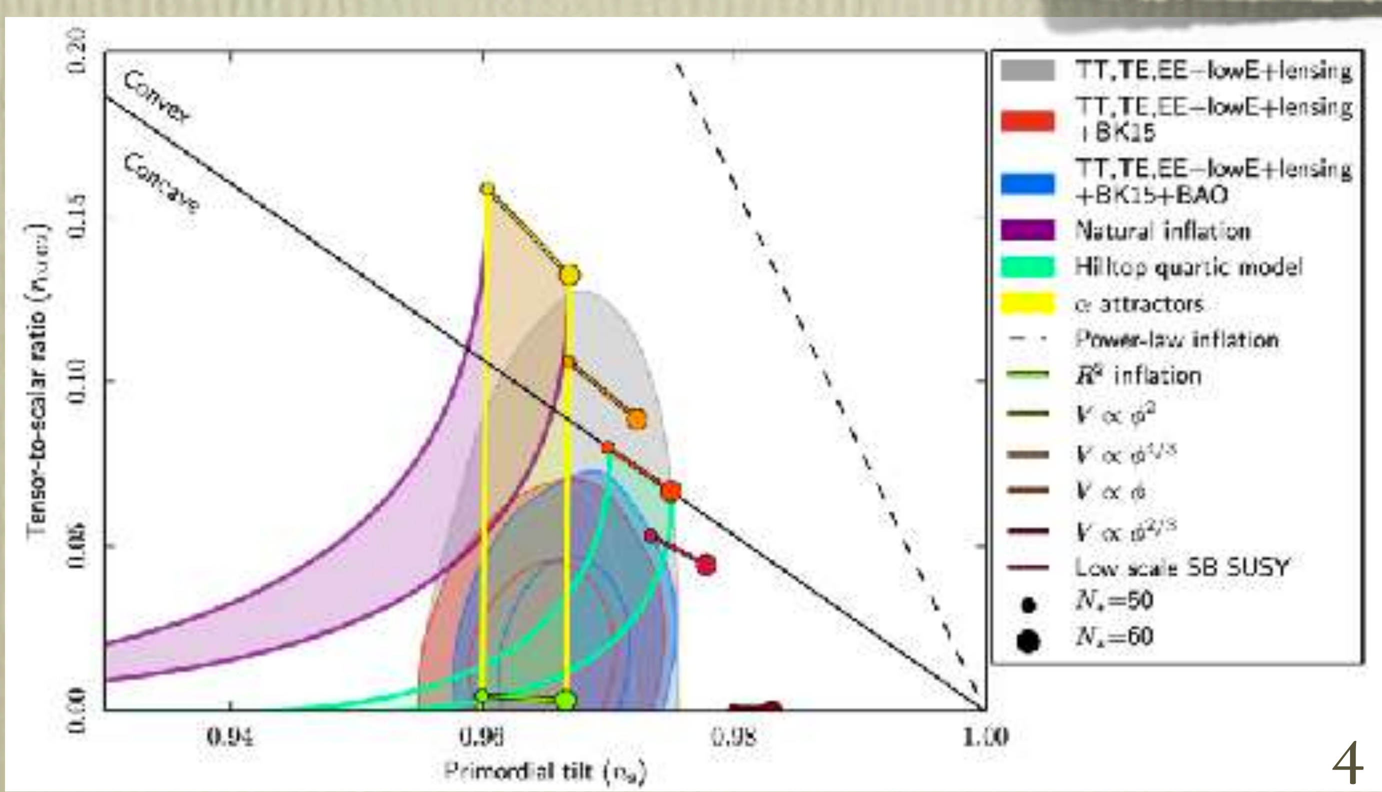
slow-roll conditions: $\dfrac{\dot{\varphi}^2}{2H^2} \ll 1\,, \quad \dfrac{|\ddot{\varphi}|}{H|\dot{\varphi}|} \ll 1 \quad \Rightarrow$

$$\epsilon_V \equiv \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,, \qquad \eta_V \equiv M_{Pl}^2\left|\frac{V''}{V}\right| \ll 1$$



Planck 2018 consistent with

- single field
- slow-roll

$$n_s = 0.9649 \pm 0.0042 \quad (68\%\mathrm{CL})\,,$$

[Planck '18]

$$r < 0.036$$

[BICEP2/Keck '21]

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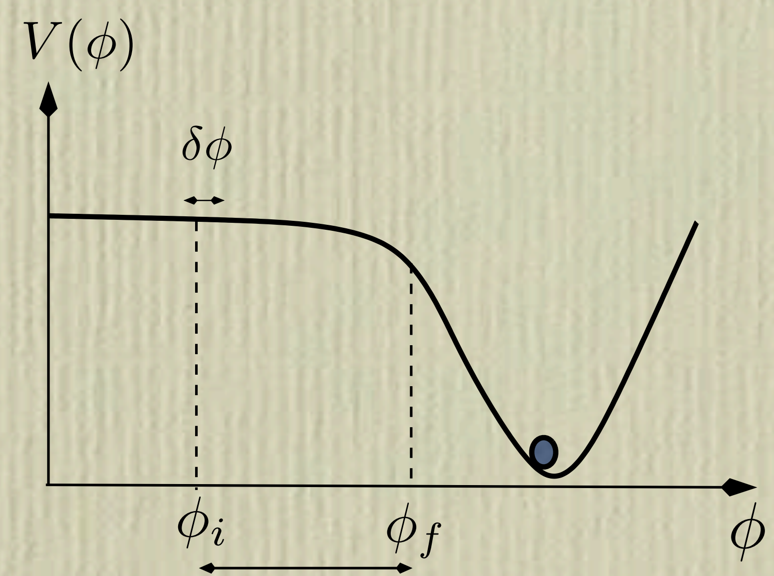

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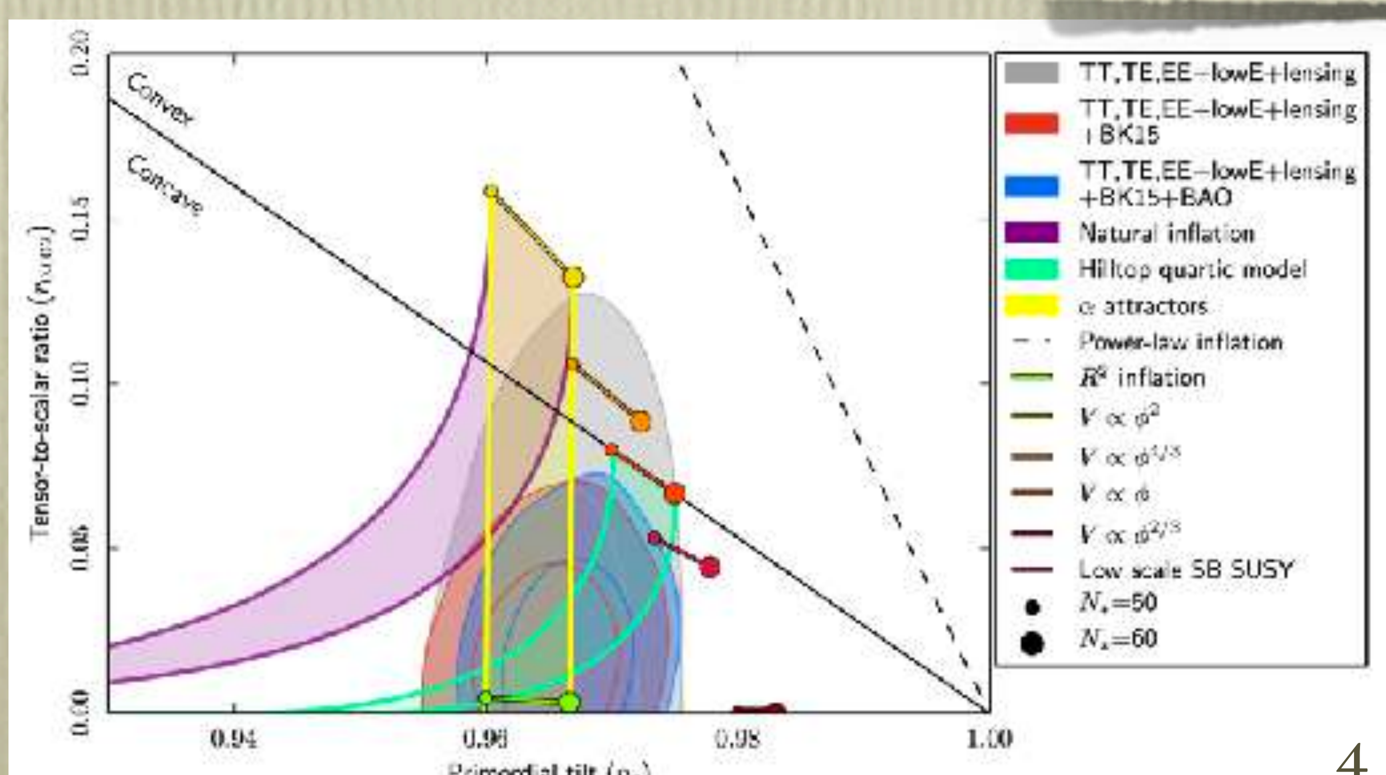

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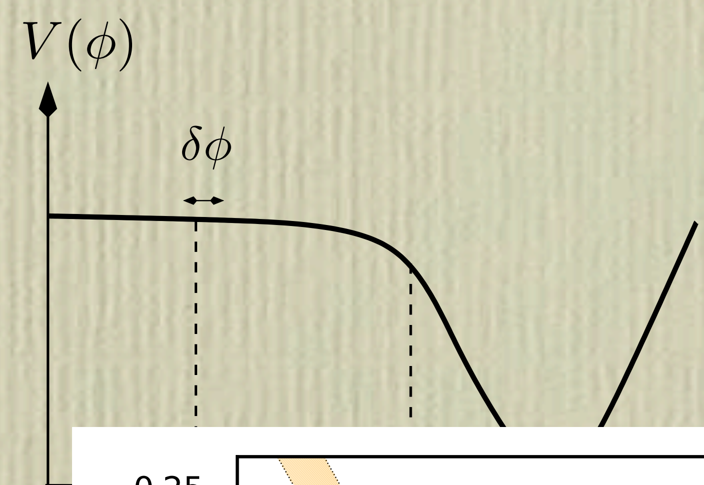

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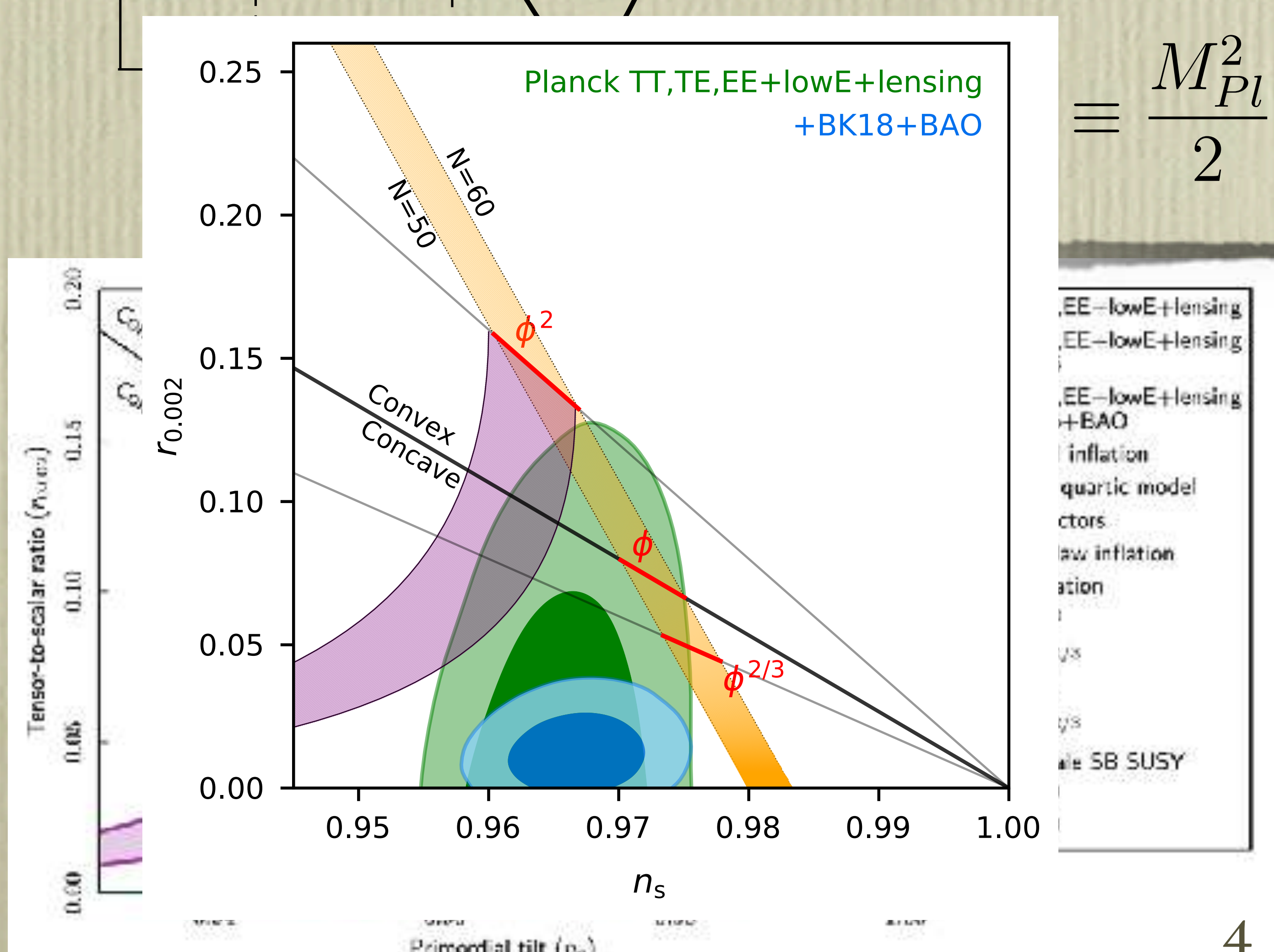

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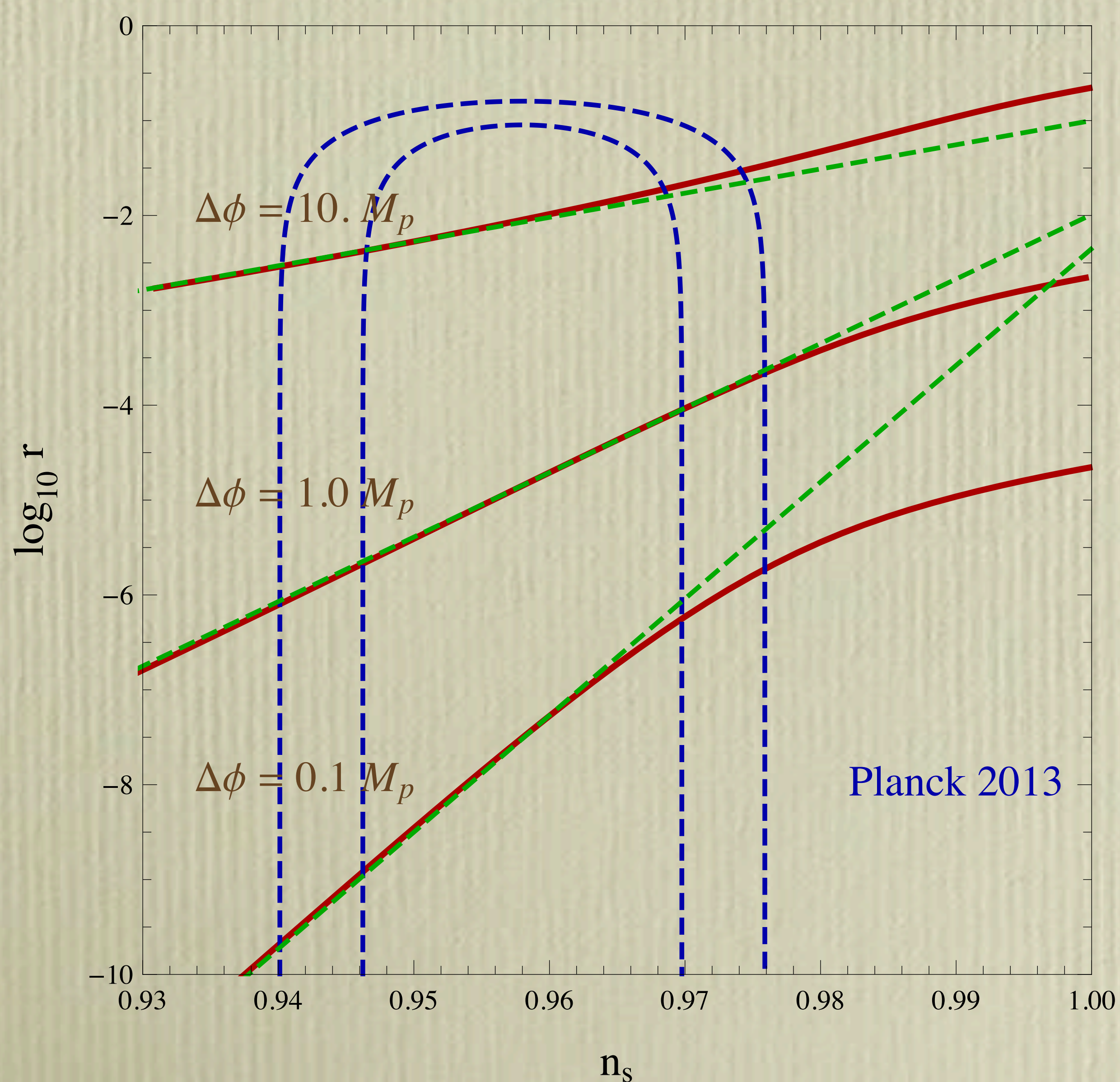
BEYOND THE VANILLA MODEL

There are several motivations to go beyond single (scalar) field inflation:

[Starobinsky, '85; ...]

- The energy scale of the very early universe when cosmic inflation occurred is likely to be extremely high and field range (super)-Planckian.



$$V^{1/4} \approx 1.8 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

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

$$\left(\frac{\Delta\phi}{M_P} \gtrsim 1\,, \qquad r \gtrsim 10^{-5}\right)$$

[Lyth, '96; Boubekeur-Lyth, '05]
[Garcia-Bellido, Roest, Scalisi, IZ '14]

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- The energy scale of the very early universe when cosmic inflation occurred is likely to be extremely high and field range (super)-Planckian.
- Likely to be described in the context of theories beyond the standard model of particle physics, e.g. **supergravity and string theory**.
- Within these theories, usually there are multiple degrees of freedom that could be relevant for inflation and give **interesting observational consequences** to be tested in forthcoming experiments (e.g. sourced gravitational waves, PBHs, non-Gaussianities, etc.)
- Recently revived quantum gravity constraints would seem to constraint single field inflation and large r.

PLAN

- **Revisiting *Multifield Inflation: fat inflatons, large turns and the η-problem***
- ***Multifield Inflation in Supergravity: large turns, fat tachyons, PBHs and GWs***
- **Fat inflation in string inflation: *D5-brane natural inflation***
- ***Kähler inflation and chiral gravitational waves****
- ***Summary***

MULTI FIELD (LIGHT) SLOW-ROLL INFLATION

The standard lore for driving inflation in the single and multi field cases is that **light fields**, wrt the Hubble scale, are needed to drive inflation, that is:

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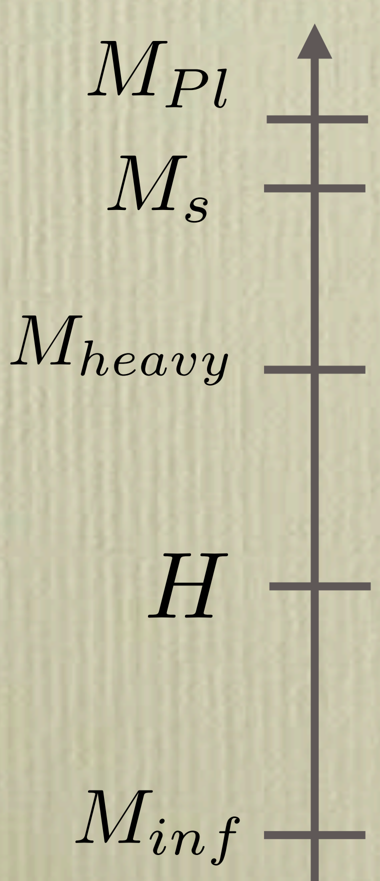
$$\eta_V \equiv M_{Pl}^2 \left| \frac{V''}{V} \right| \ll 1 \quad \Rightarrow \quad M_{inf}^2 \sim V'' \ll H^2.$$

$$\Rightarrow \quad M_{inf} < H < M_{heavy}$$



Higher order corrections to V

$$\mathcal{O}_{p\geq 6} \quad \rightarrow \quad V(\phi)\left(\frac{\phi}{M_P}\right)^{p-4}$$

would spoil slow-roll: **η-problem**

$$\Delta\eta_V \gtrsim 1$$

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In particular in string theory models $M_{Pl} > M_s > M_{KK} > H > M_{inf}$

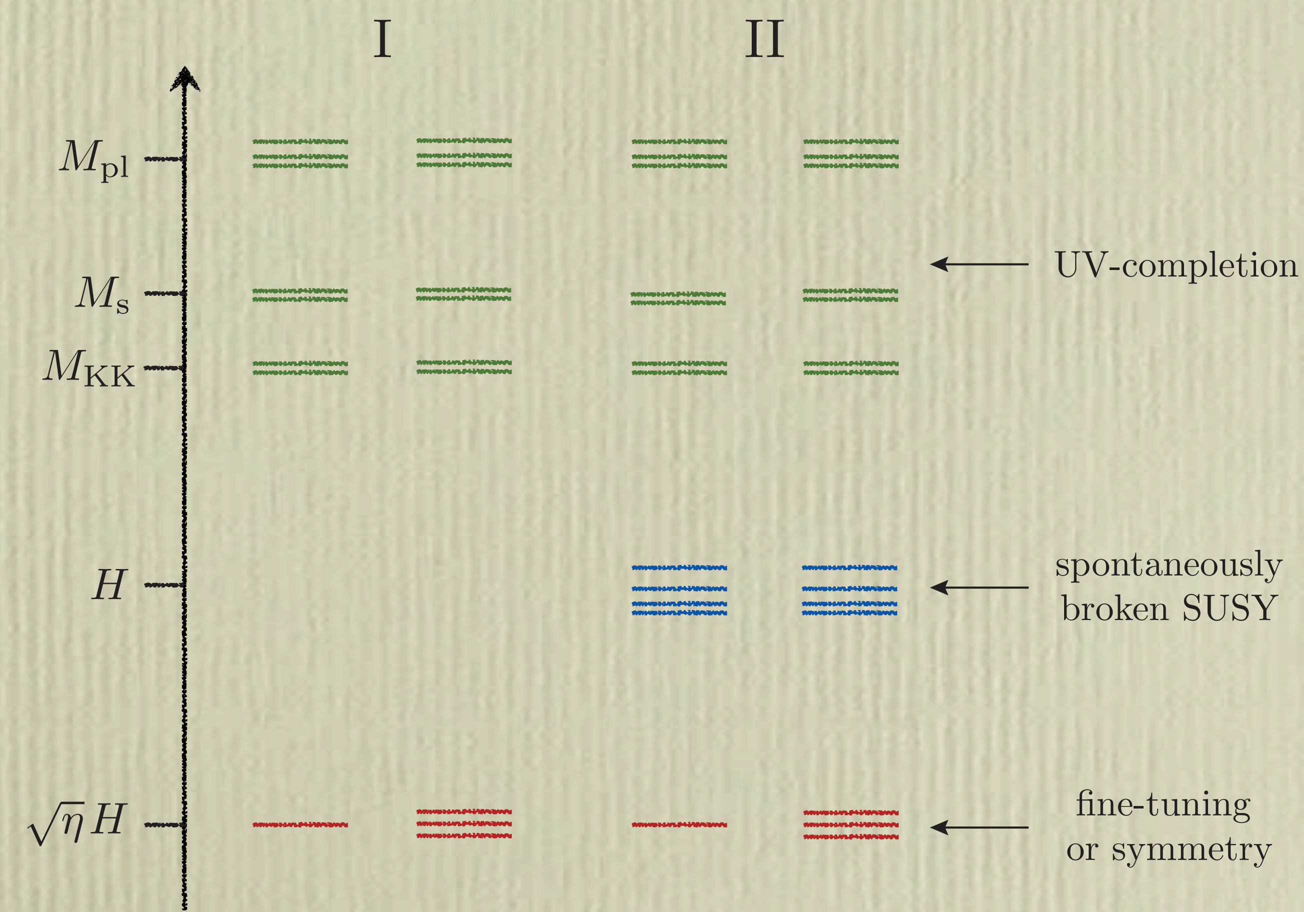

Fig. 4.1. Mass spectra of inflationary models. Phenomenological models of inflation frequently assume a large hierarchy between one or more light inflaton fields and the extra states of the UV completion (I). On the other hand, concrete examples of inflation in string theory often contain fields with masses of order the Hubble scale (II) arising from the spontaneous breaking of supersymmetry. Robust symmetries, or fine-tuning, are required to explain the presence of scalars with masses $m \sim \sqrt{\eta}H$.

[Baumann-McAllister, '14]

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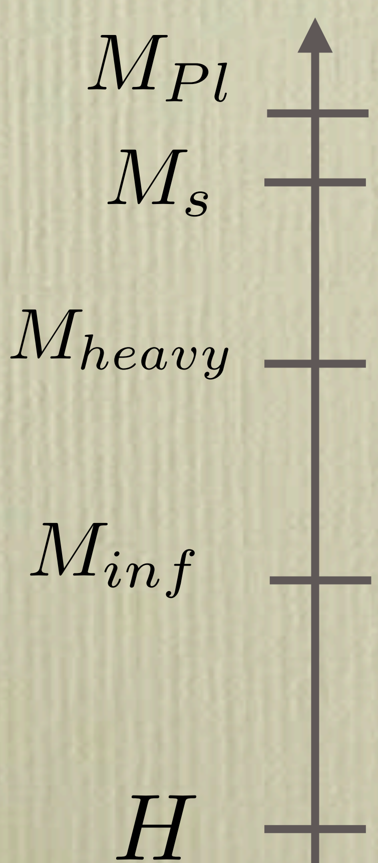
However, as I will show, it is possible to drive slow-roll inflation when all scalar fields are heavier than the Hubble scale, thus evading the η-problem:



$$H < M_{inf} < M_{heavy} \qquad (\forall\ \phi^a)$$

[See Berera, '04; Bastero-Gil et al, '19 for η-problem avoidance in warm inflation]

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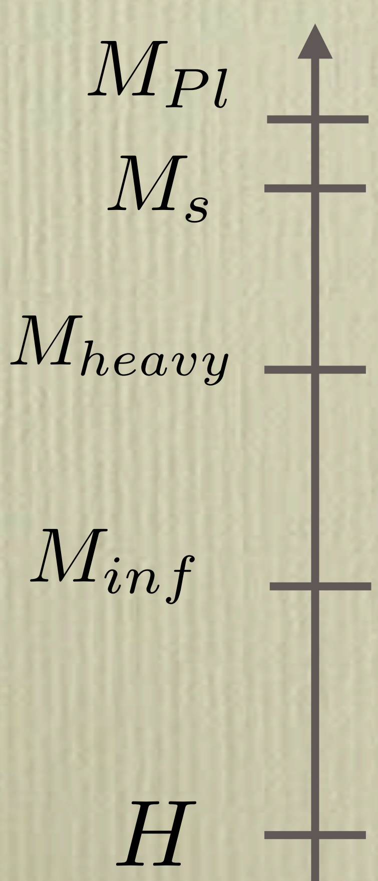

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Fat inflation welcomes heavy fields: no η-problem!

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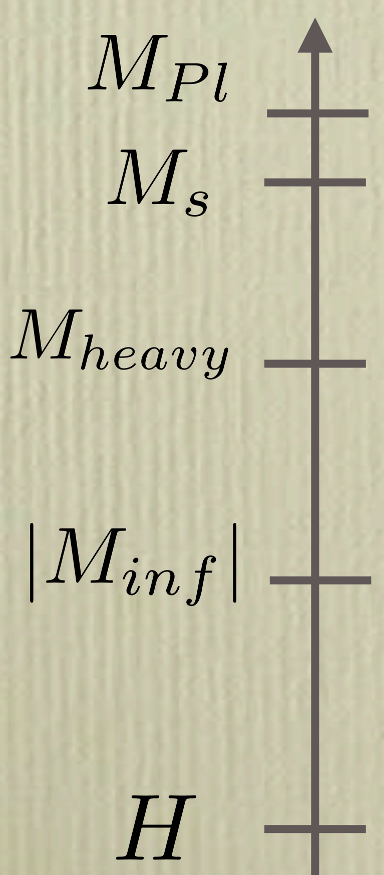

$$H < |M_{inf}| < M_{heavy} \qquad (\forall \;\; \phi^a)$$

Fat inflation welcomes heavy fields: no η-problem!

[See Berera, '04; Bastero-Gil, Berera, Ramos, Rosa, '19 for similar result in warm inflation]

MULTIFIELD INFLATION

Consider a typical low energy Lagrangean for several scalar fields, which may arise from some consistent theory of quantum gravity:

$$S = \int d^4x\sqrt{-\mathrm{g}}\left[M_{\mathrm{Pl}}^2\frac{R_4}{2} - \frac{g_{ab}}{2}\partial_\mu\phi^a\partial^\mu\phi^b - V(\phi^a)\right]$$

In FRW spacetime, equations of motion are

$$H^2 = \frac{1}{3M_P^2}\left(\frac{\dot{\varphi}^2}{2} + V(\phi^a)\right)$$

$$\ddot{\phi}^a + 3H\dot{\phi}^a + \Gamma^a_{bc}\dot{\phi}^b\dot{\phi}^c + g^{ad}V_d = 0$$

Here

$$\dot{\varphi}^2 = g_{ab}\dot{\phi}^a\dot{\phi}^b$$

Γ^a_{bc} : Christoffel symbols of field space metric g_{ab}

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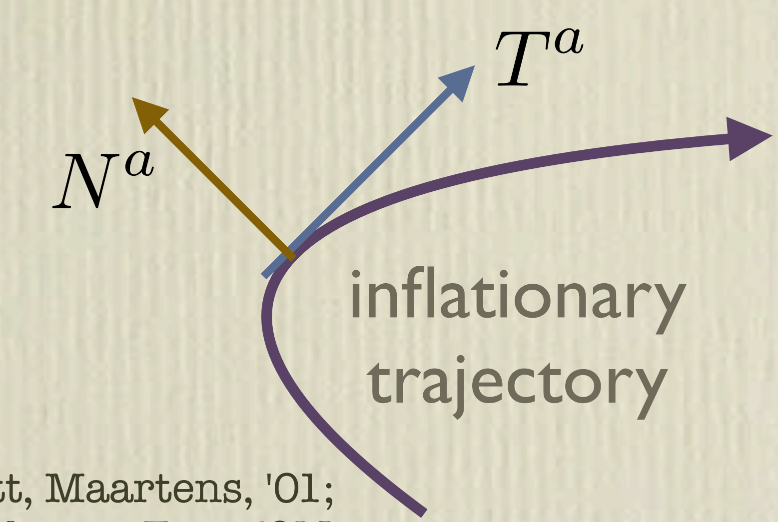
To learn more about multi field dynamics, it would be useful to project eoms in the basis:

- **Kinematic basis**: tangent and normal to inflationary trajectory (T^a, N^a) (most useful for perturbations' analysis)

$$T^a = \frac{\dot{\phi}^a}{\dot{\varphi}}\,, \qquad T^a T_a = 1\,,$$

$$N_a N^a = 1\,, \qquad T_a N^a = 0$$



[Gordon, Wands, Bassett, Maartens, '01; Groot Nibbelink, van Tent, '01]

MULTIFIELD INFLATION

- Projecting the eoms along these two directions, take the simple form

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\frac{\dot\varphi^2}{2} + V(\phi^a)\right)$$

$$\ddot\varphi + 3H\dot\varphi + V_T = 0\,,$$

$$D_t T^a = -\frac{V_N}{\dot\varphi}N^a \equiv -\Omega N^a\,,$$

where

$$V_T = V_a T^a, \quad V_N = V_a N^a$$

$$D_t T^a = \dot T^a + \Gamma^a_{bc} T^b \dot\phi^c$$

$$\Omega \equiv \frac{V_N}{\dot\varphi} \quad \textit{turning rate}$$

Define also dimensionless parameter

$\omega \equiv \dfrac{\Omega}{H}$: measures the departure from geodesic trajectory

MULTIFIELD INFLATION

- Furthermore, the projections of the Hessian elements along the normal and tangent directions can be written as (exact)

[Achucarro, et al. '10; Hetz, Palma, '16; Christodoulidis, Roest, Sfakianakis, '18; Chakraborty et al. '19; Aragam et al. '21]

$$\frac{V_{TT}}{3H^2} = \frac{\Omega^2}{3H^2} + \epsilon - \delta_\varphi - \frac{\xi_\varphi}{3}\,, \qquad \frac{V_{TN}}{H^2} = \omega\,(3 - \epsilon + 2\,\delta_\varphi + \nu)\,,$$

where

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\varphi}^2}{2M_{Pl}^2 H^2}\,, \qquad \delta_\varphi \equiv \frac{\ddot{\varphi}}{H\dot{\varphi}}\,, \qquad \xi_\varphi \equiv \frac{\dddot{\varphi}}{H^2\dot{\varphi}}\,, \qquad \nu \equiv \frac{\dot{\omega}}{H\omega}$$

$$V_{TT} = T^a T^b \nabla_a \nabla_b V, \text{ etc.}$$

SLOW-ROLL IN MULTIFIELD INFLATION

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- Slow-roll requires $\epsilon, \delta_\varphi, \xi_\varphi \ll 1 \quad \Rightarrow \quad 3H^2 \simeq V,$

$$\epsilon_T \equiv \frac{M_{Pl}^2}{2}\left(\frac{V_T}{V}\right)^2 \ll 1\,,$$

that is, the **tangent projection** of ϵ **has to be small**, but not necessarily the normal projection, nor ϵ_V .

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\frac{V^aV_a}{V^2} = \epsilon_T + \frac{\Omega^2}{9H^2}\epsilon = \epsilon\left(\frac{\epsilon_T}{\epsilon} + \frac{\Omega^2}{9H^2}\right)\,.$$

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if $\quad \epsilon_T \simeq \epsilon, \qquad \epsilon_V \simeq \epsilon\left(1 + \frac{\Omega^2}{9H^2}\right) \gtrsim \mathcal{O}(1)$ <u>if *turn* is large.</u>

[Hetz, Palma, '16; Achucarro, Palma, '18]

SLOW-ROLL IN MULTIFIELD INFLATION

- Slow-roll requires $\epsilon, \delta_\varphi, \xi_\varphi \ll 1 \quad \Rightarrow$

Furthermore:

[Chakraborty et al. '19;
Aragam, Paban, Rosati, '20;
Aragam et al. 21]

$$M_{Pl}^2 \frac{V_{TT}}{V} \simeq \frac{\Omega^2}{3H^2}\,, \qquad \frac{3}{\omega}\left(M_{Pl}^2 \frac{V_{TN}}{V} - \omega\right) \ll 1 \quad \& \quad \nu \ll 1$$

- Note that the minimal eigenvalue $\lambda \equiv \min(\nabla^a \nabla_b V)$, does not appear anywhere

- Typical models have *small* turns Ω/H and *small* V_{TT}/V

- A more interesting possibility arises when both terms are large and cancel each other (fat inflation)

FAT INFLATONS AND LARGE TURNS

- Consider the **minimal eigenvalue** of the field's mass matrix, λ,

$$\lambda \equiv \min(\nabla^a \nabla_b V) \, .$$

- Given any unit vector U^a, the following inequality is always satisfied

$$\lambda \leq U_a \nabla^a \nabla_b V U^b .$$

- Taking $U^a = T^a$ we then have:

$$\lambda \leq V_{TT}$$

FAT INFLATION

- Consider now the case $H^2 \ll \lambda$ that is, ***all scalar fields are heavier*** *than the Hubble scale* $\Rightarrow$ $V_{TT}/H^2 \gg 1$

$$\Rightarrow \quad \frac{\Omega^2}{H^2} \gg 1$$

$$M_{Pl}^2 \frac{V_{TT}}{V} \simeq \frac{\Omega^2}{3H^2} \,,$$

Large turning rates / strongly non-geodesic trajectories

- Note that this new inflationary attractor is also possible for tachyonically fat fields

$$\left| \frac{\lambda}{H^2} \right| \gg 1$$

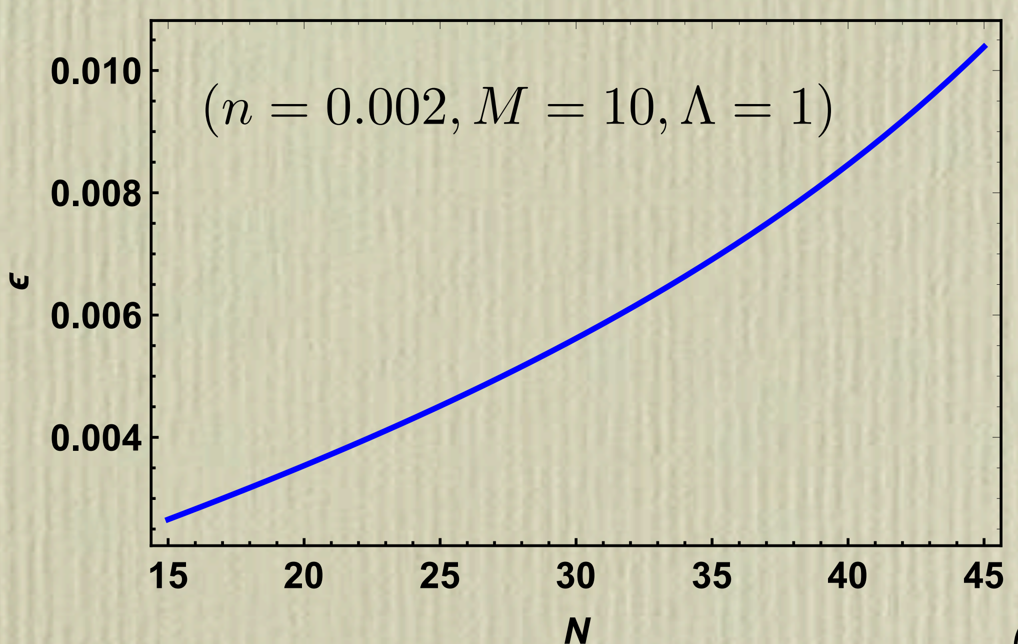
[Chakraborty et al. '19; Aragam et al. 21]

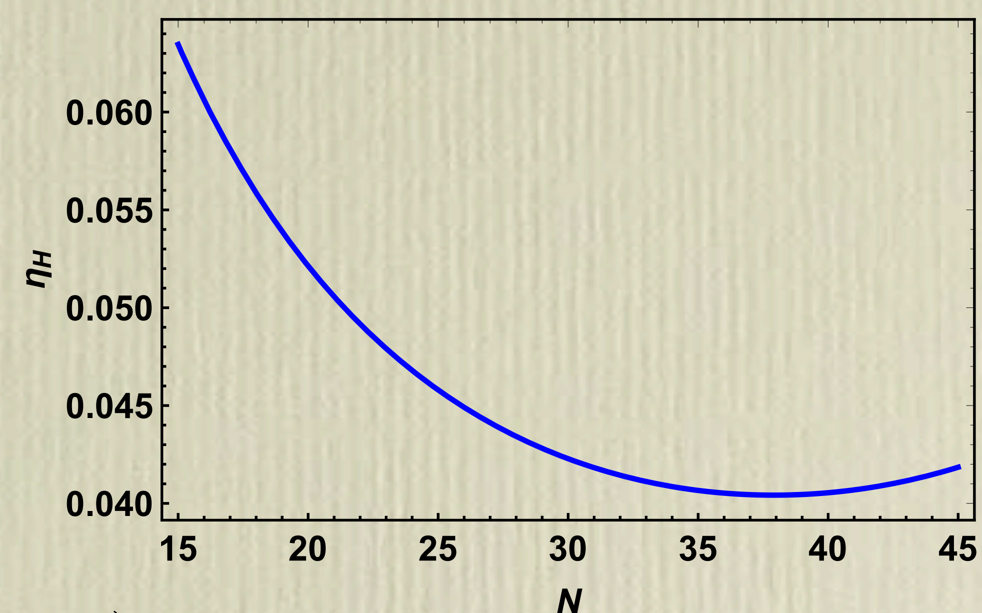
FIELD THEORY FAT INFLATION EXAMPLES

[Achúcarro, Atal, Welling, '15;
Chakraborty et al. '19;]

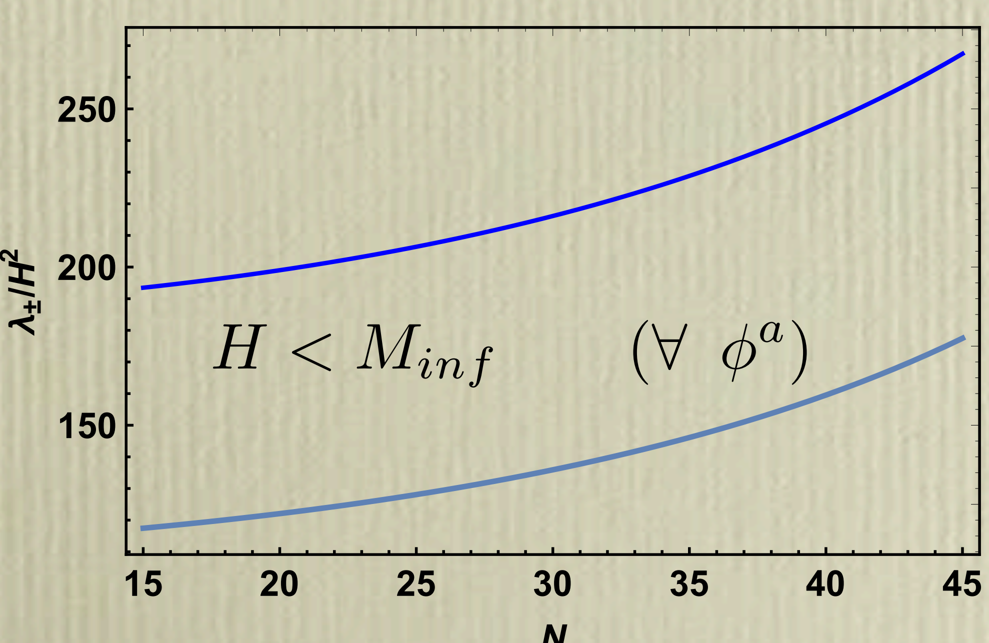
- Consider $\mathcal{L} = -\frac{1}{2}(\partial\rho)^2 - \frac{1}{2}\rho^2(\partial\theta)^2 - V(\rho,\theta)$ with $(\text{note } \mathbb{R} = 0)$

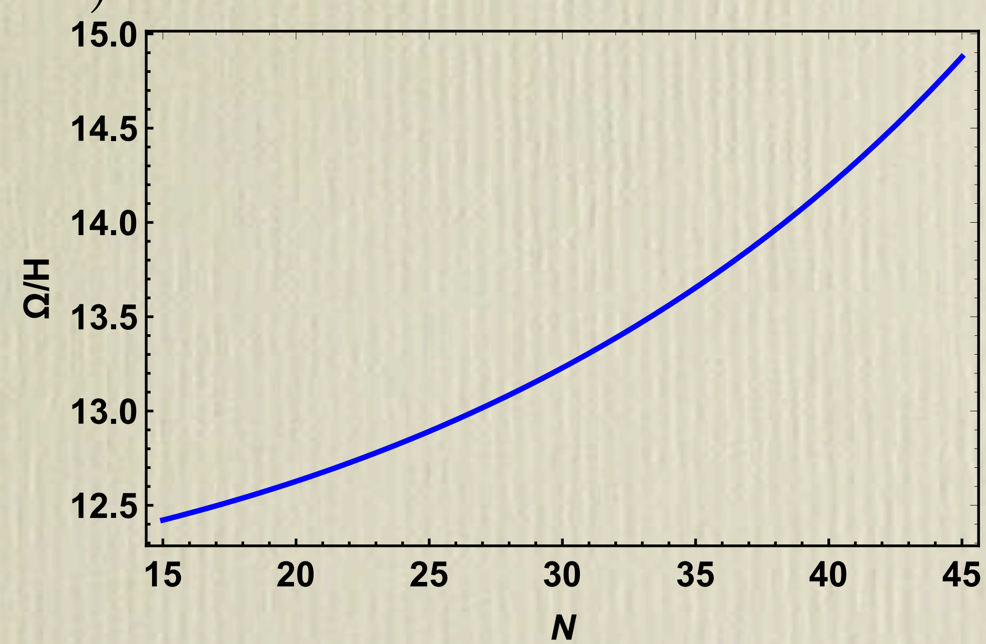
$$V(\rho,\theta) = \frac{M^2}{2}\rho^2 + W(\theta)\,, \qquad W(\theta) = \Lambda^4(1+\cos[n\theta])\,, \quad \Lambda \ll M$$





$(N_{\text{fin}} = 80)$





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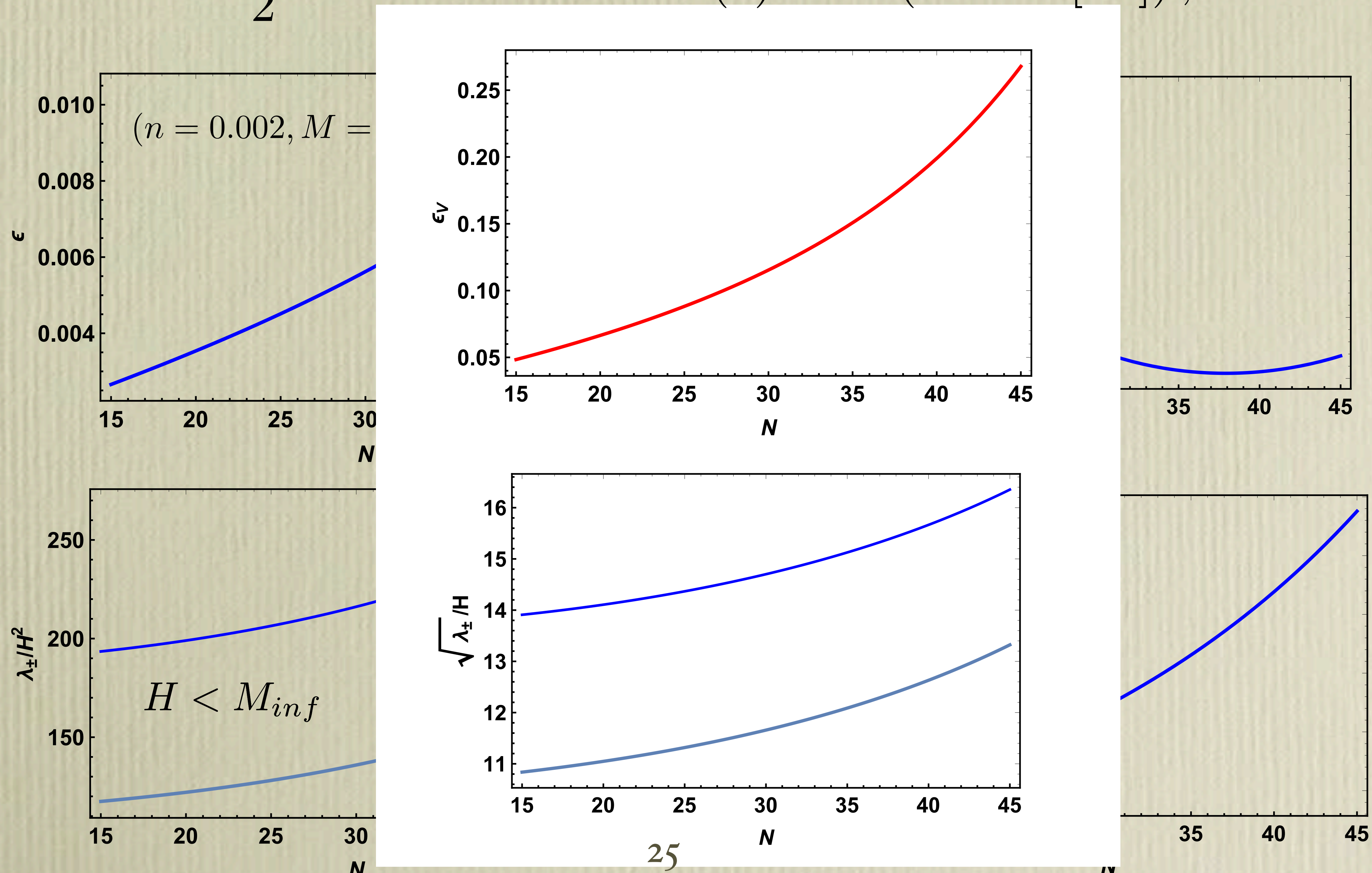


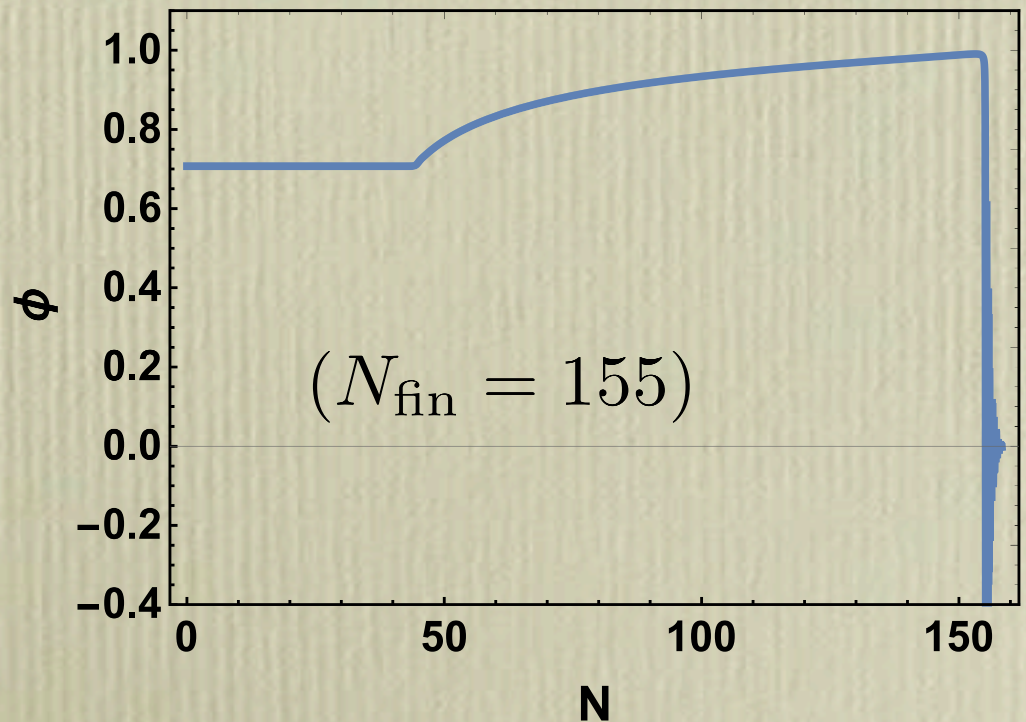
FIELD THEORY TACHYONIC FAT: ANGULAR INFLATION

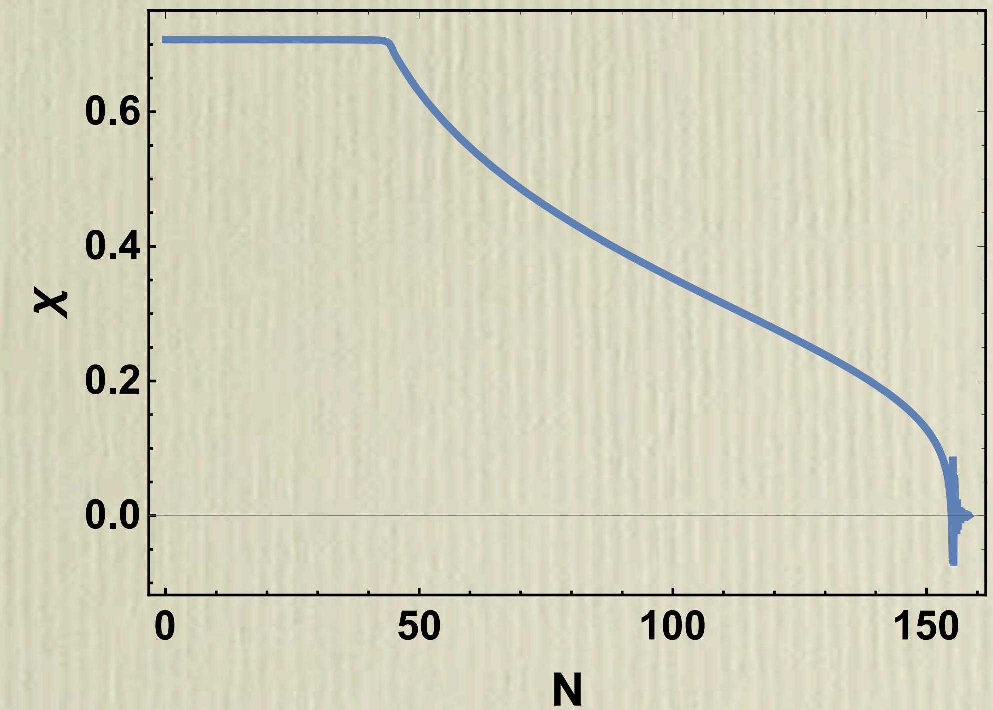
[Christodoulidis, Roest, Sfakianakis, '18,'19]

- Supergravity inspired **α**-attractor

$$g_{ab} = \frac{6\alpha}{(1-\phi^2-\chi^2)}\delta_{ab} \qquad \left(\mathbb{R} = -\frac{4}{3\alpha}\right)$$

$$V(\phi^a) = \frac{\alpha}{2}\left(m_\phi^2\,\phi^2 + m_\chi^2\,\chi^2\right)$$





[See also sidetrack inflation: Garcia-Saenz, Renaux-Petel, Ronayne, '18]

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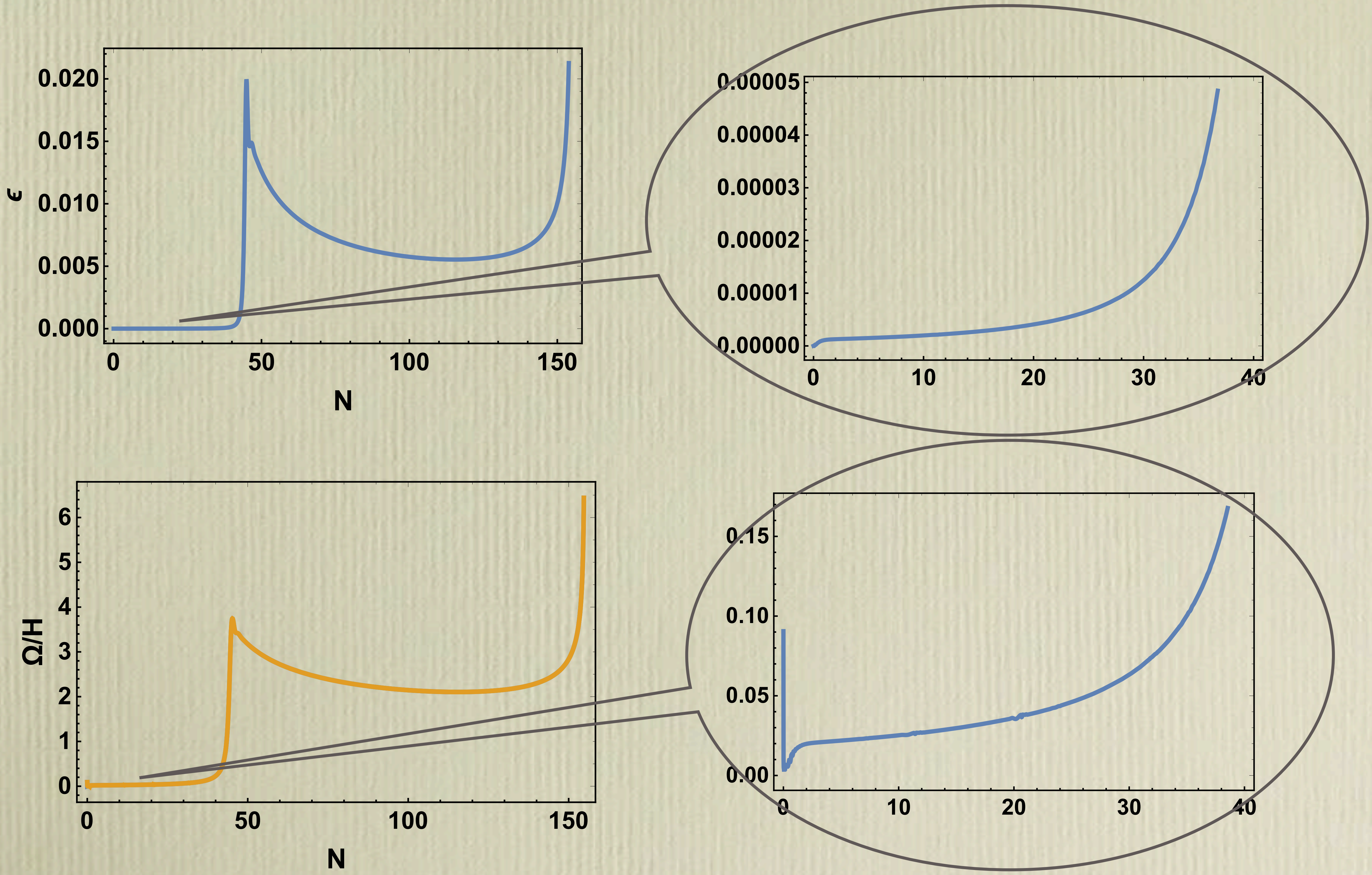

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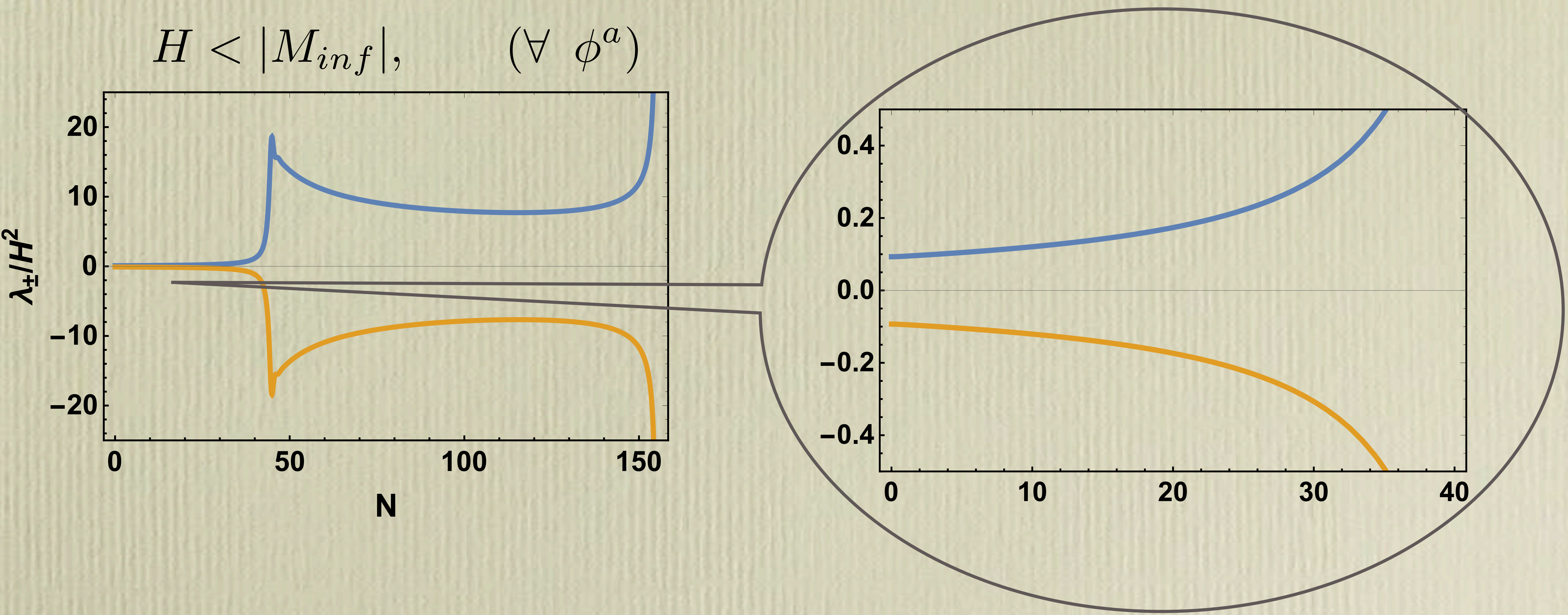

MULTIFIELD INFLATION: DEMYSTIFYING LARGE TURNS/NON-GEODESIC TRAJECTORIES

[Chakraborty et al. '19;
Aragam et al. '21]

- Slow-roll multifield inflation does not require light fields $(|M_{inf}| \ll H)$
- Large turning rates in multifield inflation do not require complicated, fine tuned potentials
- Strong non-geodesic inflation does not require negative fields space curvature

MULTIFIELD INFLATION: DEMYSTIFYING LARGE TURNS/NON-GEODESIC TRAJECTORIES

[Chakraborty et al. '19; Aragam et al. '21]

- Slow-roll multifield inflation does not require light fields $(|M_{inf}| \ll H)$
- Large turning rates in multifield inflation do not require complicated, fine tuned potentials
- Strong non-geodesic inflation does not require negative fields space curvature
- A natural way to generate **transient large turns** arises through **transient violations of slow-roll***

[Bhattacharya, IZ, in progress]

FAT (MULTIFIELD) INFLATION AND THE SWAMPLAND

Recently proposed *asymptotic* dS conjectures require that

[Obied, Ooguri, Spodyneiko, Vafa; Garg, Krishnan; Ooguri, Palti, Shiu, Vafa, '18]

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

- In multi field inflation, these conditions can be satisfied as (multi field inflation ☞ non-geodesic trajectories)
  - **Fat inflation** has $H^2 \ll \lambda \leq V_{TT}$, second condition is not satisfied, while first condition may be satisfied in strongly non-geodesic trajectories [Hetz, Palma, '16; Achucarro, Palma, '18] [Chakraborty et al. '19]

$$\epsilon_V \simeq \epsilon \left(1 + \frac{\Omega^2}{9H^2}\right) \gtrsim \mathcal{O}(1) \qquad \text{if turn is large.}$$

  - **Fat tachyonic inflation** has $|\lambda/H^2| \gg 1 \quad \Rightarrow$ second condition is satisfied, while first condition may be satisfied in strongly non-geodesic trajectories

[Aragam et al. '21]

PART II:

LARGE TURN MULTI FIELD ATTRACTOR IN SUPERGRAVITY

LARGE TURNING RATES IN SUGRA INFLATION

$$S = \int d^4x\sqrt{-\mathrm{g}}\left[M_{\mathrm{Pl}}^2\frac{R}{2} - K_{i\bar{\jmath}}\partial_\mu\Phi^i\partial^\mu\bar{\Phi}^{\bar{\jmath}} - V(\Phi^k,\bar{\Phi}^k)\right]$$

- Scalar potential for complex scalars: $\Phi^I = r^I + i\theta^I$

$$V = e^{K/M_{\mathrm{Pl}}^2}(K^{i\bar{\jmath}}D_iW\,D_{\bar{\jmath}}\bar{W} - 3|W|^2M_{\mathrm{Pl}}^{-2})$$

$K(\Phi,\bar{\Phi}) =$ Kähler potential

$W(\Phi) =$ superpotential

$$K_{i\bar{\jmath}} = \frac{\partial^2 K}{\partial\Phi^i\partial\bar{\Phi}^{\bar{\jmath}}}$$

$$D_i = W_i + K_iW$$

LARGE TURNING RATES IN SUGRA INFLATION

[Aragam, Chivoloni, Paban, Rosati, IZ, '21

- Large scan in literature reported single example!

LARGE TURNING RATES IN SUGRA INFLATION

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- Large scan in literature reported single example!

- Focus on two superfields with nilpotent Goldstino $S^2 = 0$

[Kallosh et al, '10-14]

$$K(\Phi, \bar{\Phi}; S, \bar{S}) : \; S \to -S, \quad \Phi \to \Phi + i\alpha \;\; \Rightarrow \;\; K(S\bar{S}, S^2 + \bar{S}^2; \Phi + \bar{\Phi})$$

$$W = SF(\Phi)$$

- Scalar potential for inflaton is

$$V = e^{K(\Phi,\bar{\Phi},0,0)/M_{\rm Pl}^2} K^{-1}_{S\bar{S}}(\Phi, \bar{\Phi}, 0, 0) \, |F(\Phi)|^2$$

LARGE TURNING RATES IN SUGRA INFLATION

[Aragam, Chivoloni, Paban, Rosati, IZ, '21

We can use knowledge from field theory models to understand non-geodesic trajectories in sugra.

- For this class of models, we can readily write

$$\epsilon_T = -\frac{M_{Pl}^2}{4K_{\Phi\bar{\Phi}}}\left(\frac{F_\Phi \bar{F} - F\bar{F}_{\bar{\Phi}}}{F\bar{F}}\right)^2$$

$$\frac{\Omega}{H} \simeq -M_{\rm Pl}^2 \frac{i\left(F_\Phi \bar{F} - F\bar{F}_{\bar{\Phi}}\right)}{F\bar{F}} \frac{\left(2K_{\Phi\bar{\Phi},\Phi}\right)}{\left(2K_{\Phi\bar{\Phi}}\right)^2}\,, \simeq -M_{\rm Pl}\sqrt{2\,\epsilon_T}\,\frac{\left(2K_{\Phi\bar{\Phi},\Phi}\right)}{\left(2K_{\Phi\bar{\Phi}}\right)^{3/2}}\,.$$

- Tune F to ensure slow-roll, tune K to increase Ω/H

LARGE TURNING RATE INFLATION IN SUPERGRAVITY: EXAMPLE 1

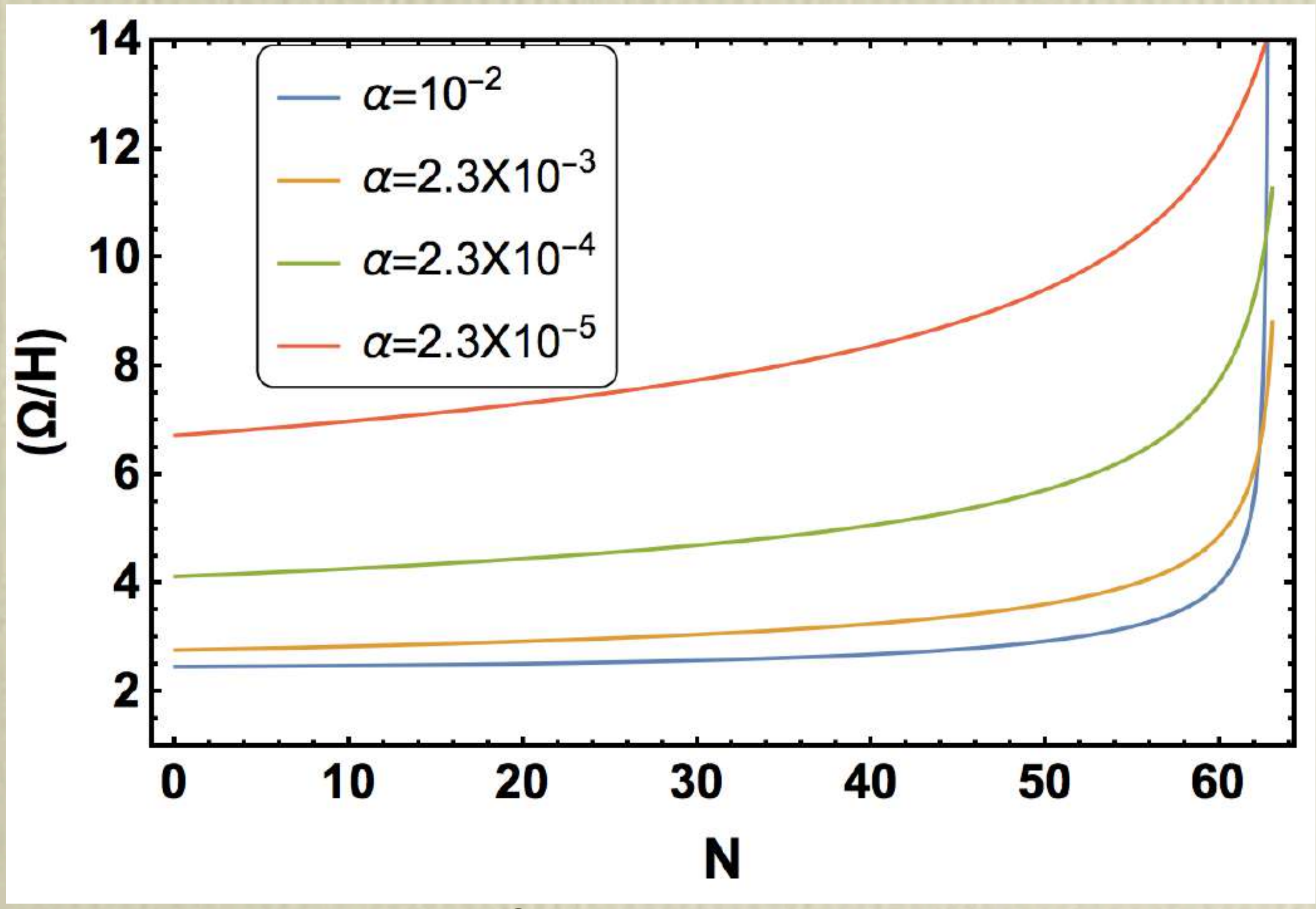
[Aragam, Chivoloni, Paban, Rosati, IZ, '21]

- No-scale inspired model

$$K = -3\,\alpha M_{\rm Pl}^2 \log[(\Phi + \bar{\Phi})/M_{\rm Pl}] + S\bar{S}\,, \qquad F(\Phi) = p_0 + p_1 \Phi\,.$$

$$V = \frac{M_{\rm Pl}^{3\alpha}\,|F|^2}{(\Phi + \bar{\Phi})^{3\alpha}}\,, \qquad \frac{\Omega}{H} \simeq \frac{2\sqrt{\epsilon_T}}{\sqrt{3\,\alpha}}\,. \qquad \left(\mathbb{R} = -\frac{4}{3\alpha}\right)$$

- By tuning α, Ω/H can be made large



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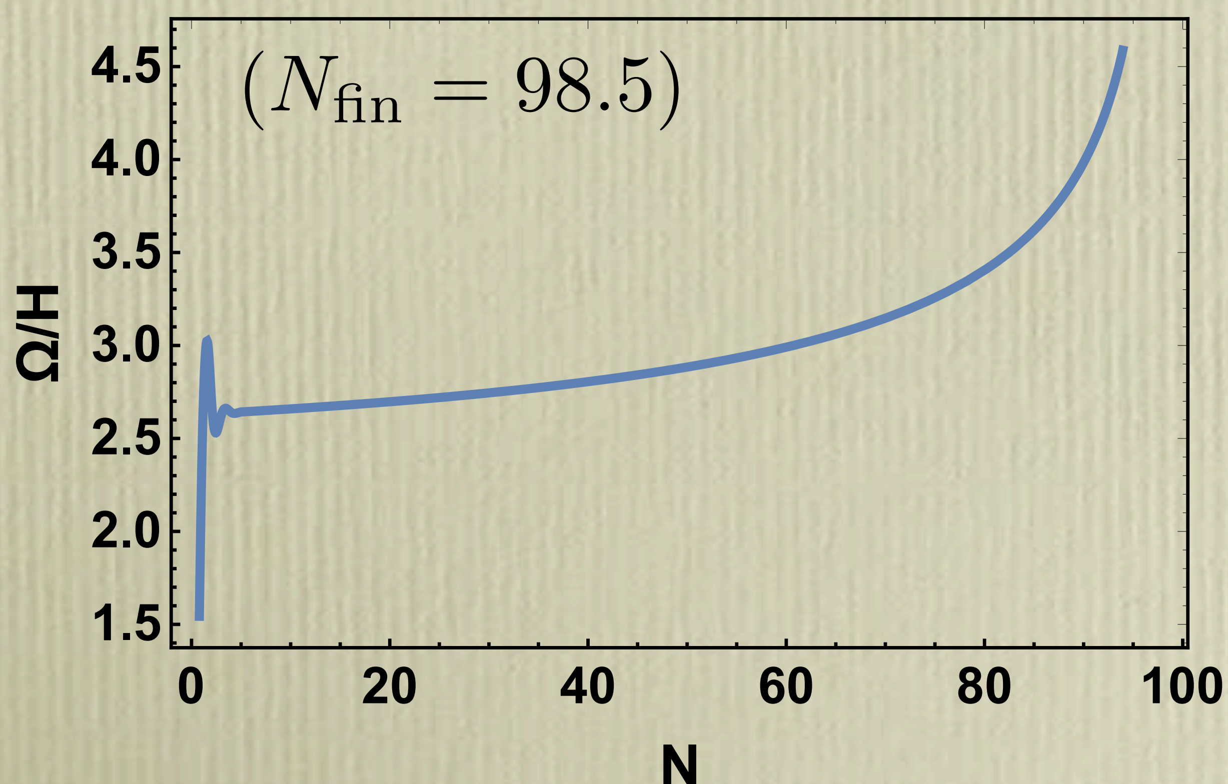
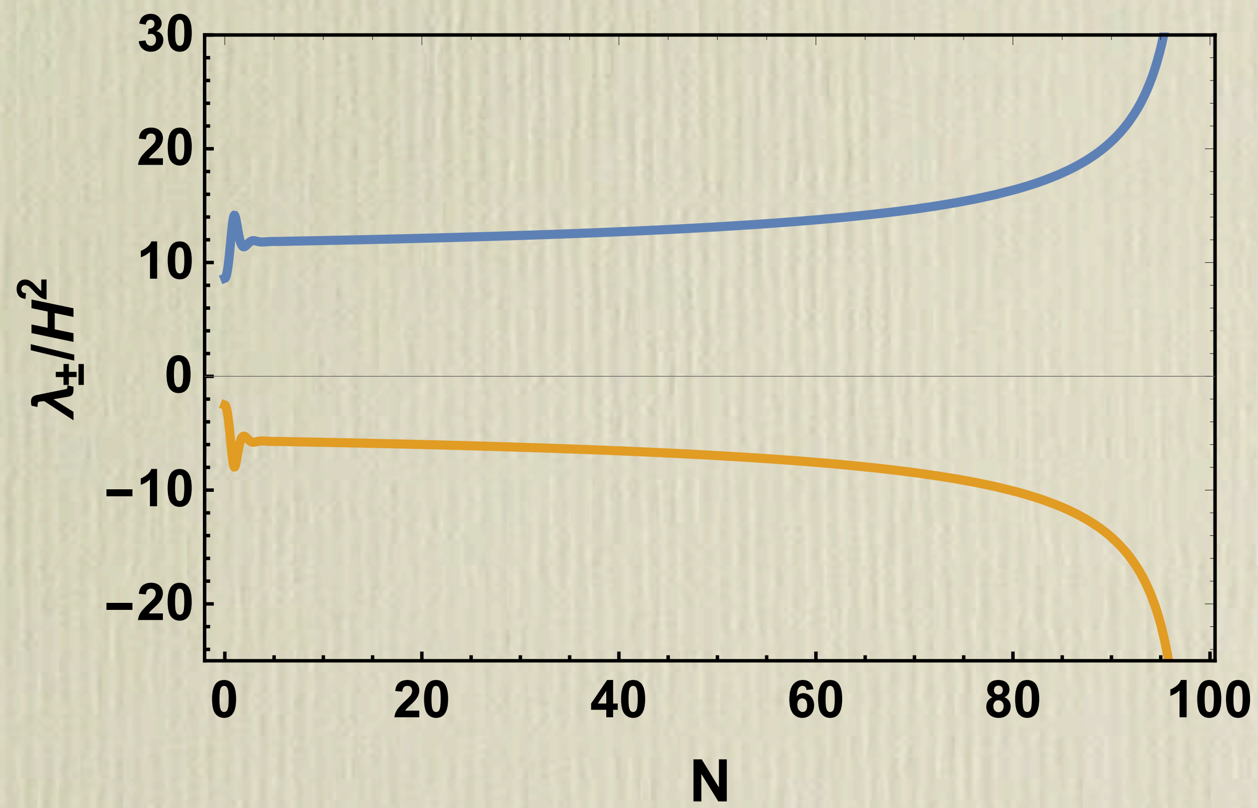
- By tuning α, Ω/H can be made large
- How about masses: fat & tachyonic (SdSC ✓)





LARGE TURNING RATE INFLATION IN SUPERGRAVITY: EXAMPLE 2

- EGNO model

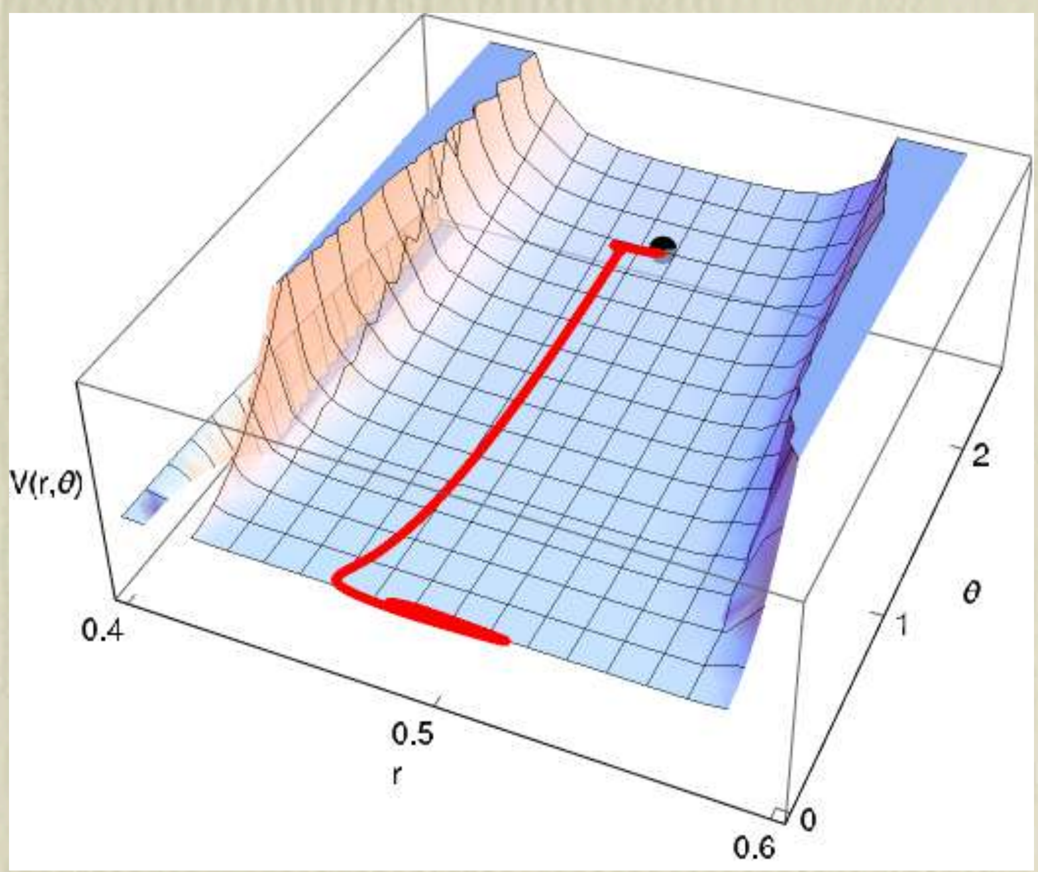
[Ellis, Garcia, Nanopoulos, Olive, '14; Aragam et al. '21]

$$K = -3\,\alpha \log\left[\Phi + \bar{\Phi} - c(\Phi + \bar{\Phi} - 1)^4\right] + \frac{S\bar{S}}{(\Phi + \bar{\Phi})^3}\,, \qquad (\mathbb{R}(c, \alpha))$$

$$W = SF(\Phi)\,, \quad F(\Phi) = \sqrt{\frac{3}{4}}\,\frac{M}{a}\,(\Phi - a)\,,$$

$$V = \frac{3}{4}\frac{M^2}{a^2}\frac{(\Phi + \bar{\Phi})^3\,(a - \Phi)(a - \bar{\Phi})}{\left(\Phi + \bar{\Phi} - c\left[(\Phi + \bar{\Phi} - 1)\right]^4\right)^{3\alpha}}$$

$$= \frac{6M^2 r^3\left(2r - c(1 - 2r)^4\right)^{-3\alpha}\left((a - r)^2 + \theta^2\right)}{a^2}\,,$$

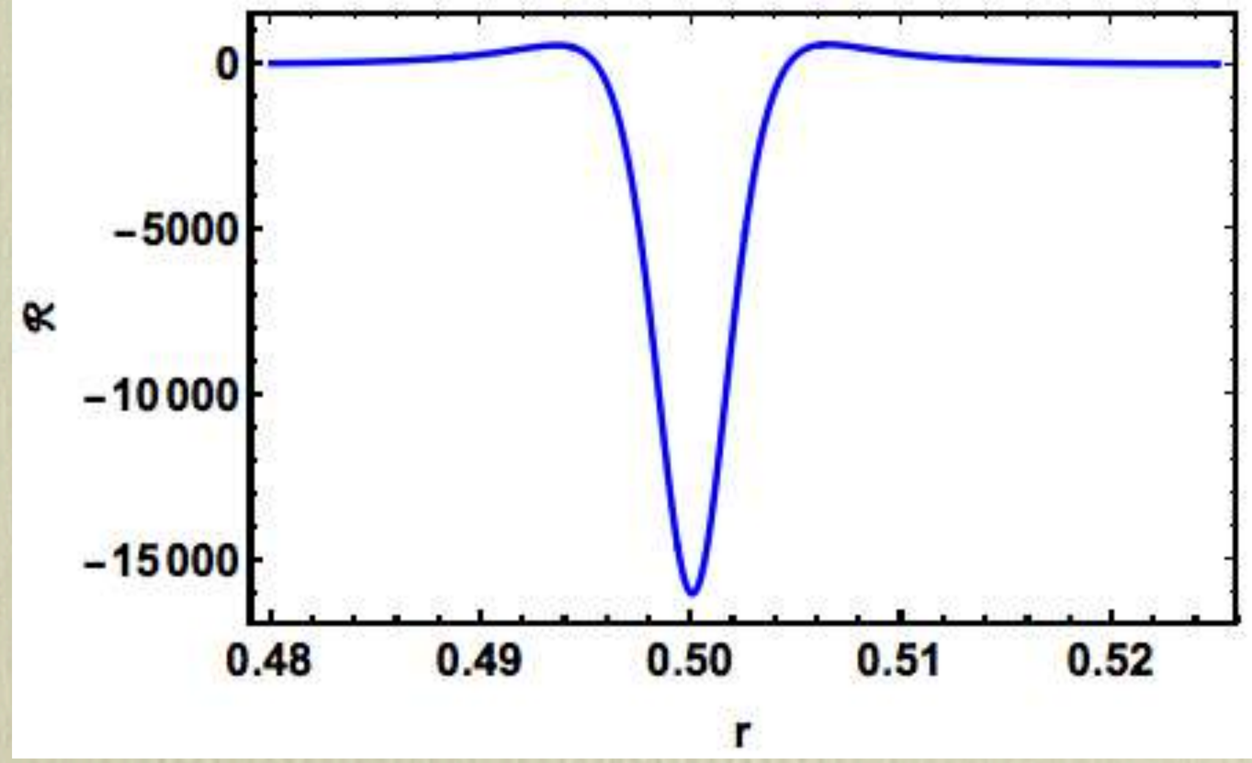


- Tune K, ☞ tuning (c, α) to increase Ω/H

LARGE TURNING RATE INFLATION IN SUPERGRAVITY: EXAMPLE 2

- Scalar curvature

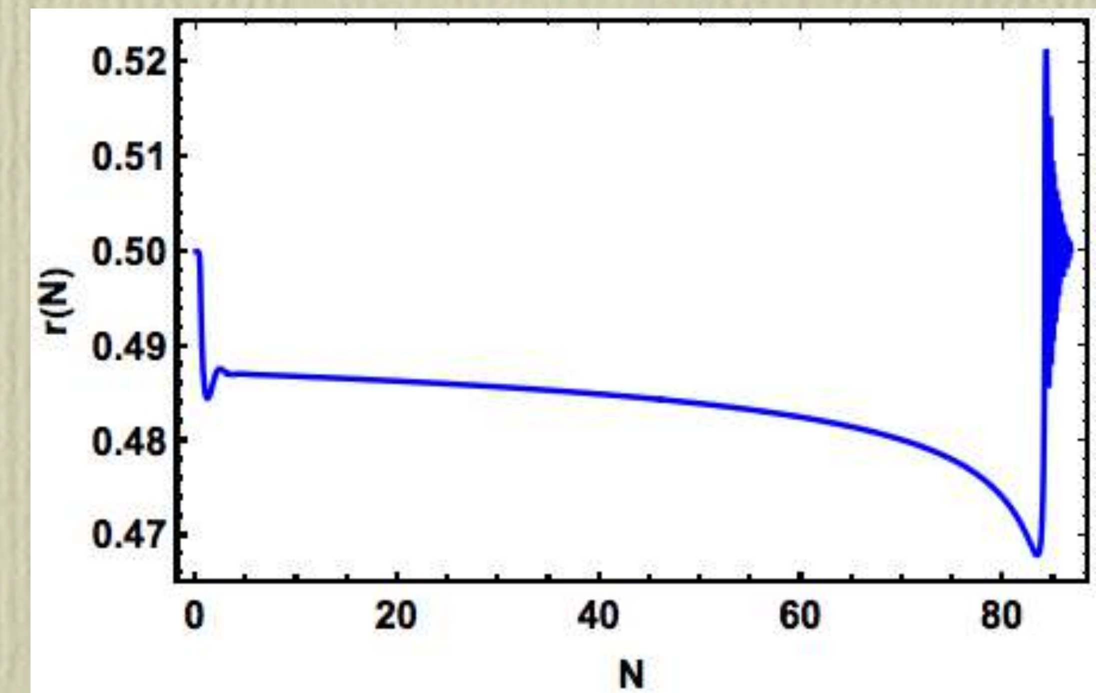
$$\left(\alpha = 1, \quad a = 1/2, \quad M = 10^{-3}, \quad c = 10^3\right)$$

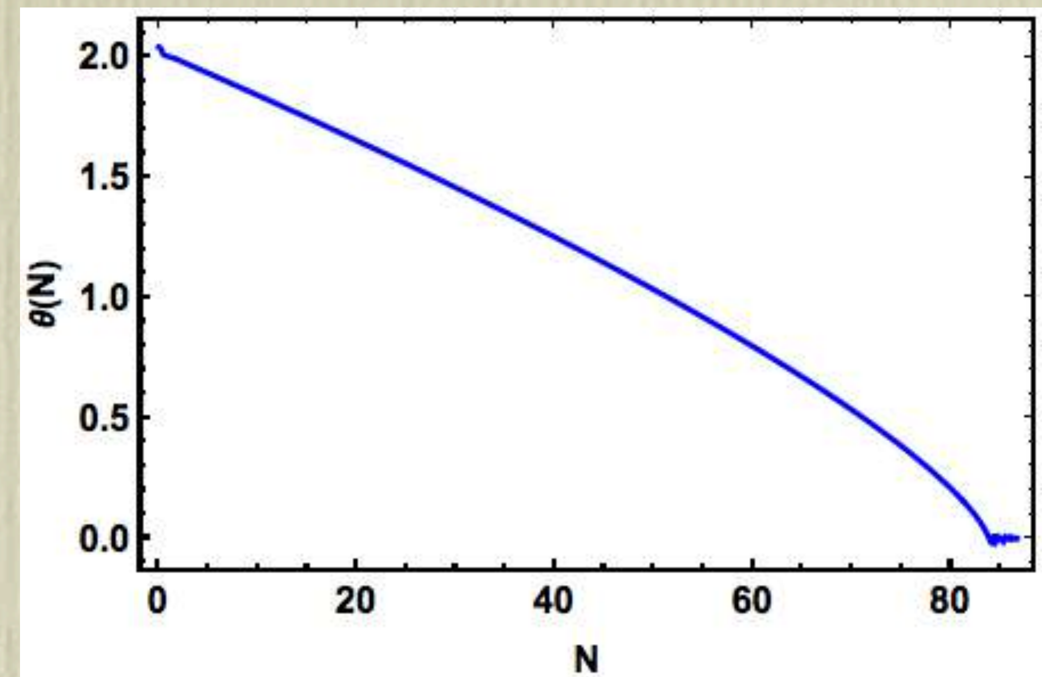


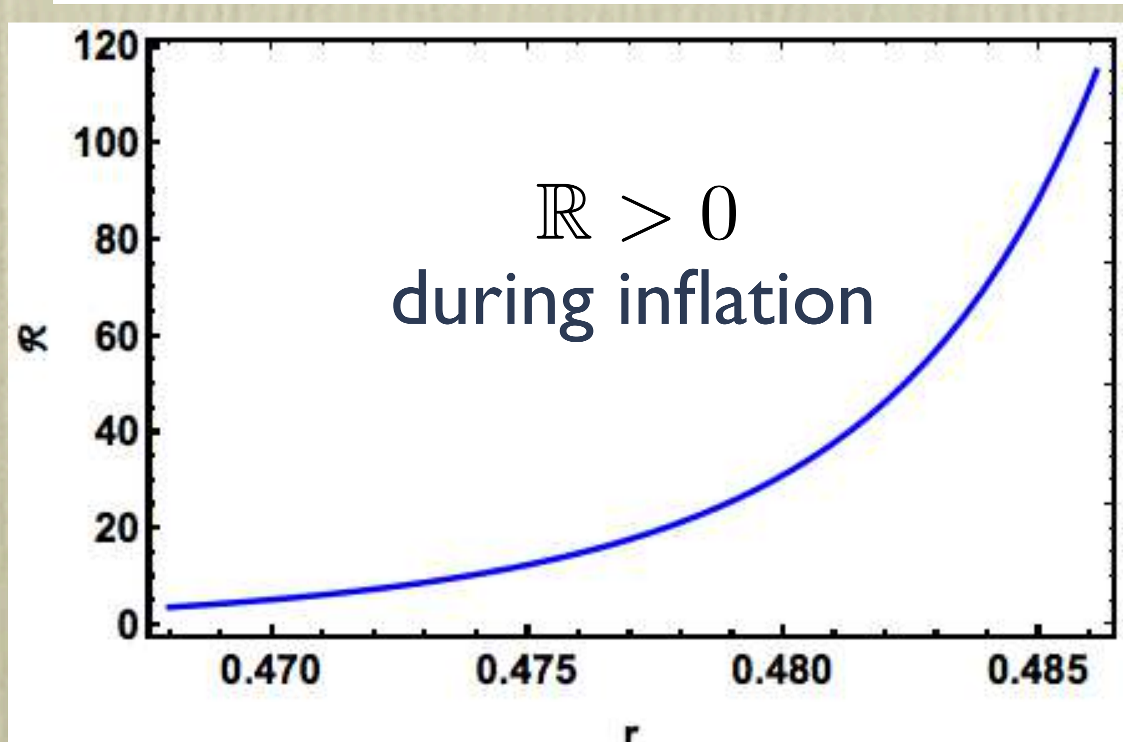
$$\mathbb{R} \to -1/3\alpha \quad (r \to \infty)$$

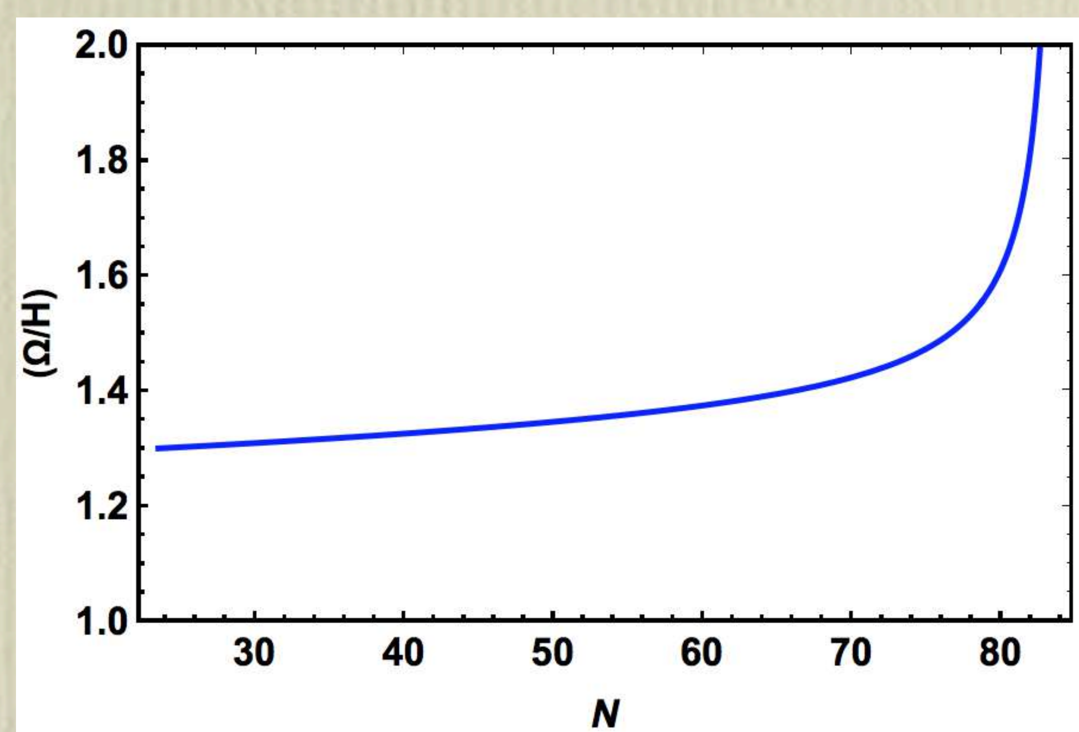
LARGE TURNING RATE INFLATION IN SUPERGRAVITY: EXAMPLE 2

- EGNO inflation $(\alpha = 1, \quad a = 1/2, \quad M = 10^{-3}, \quad c = 10^{3})$





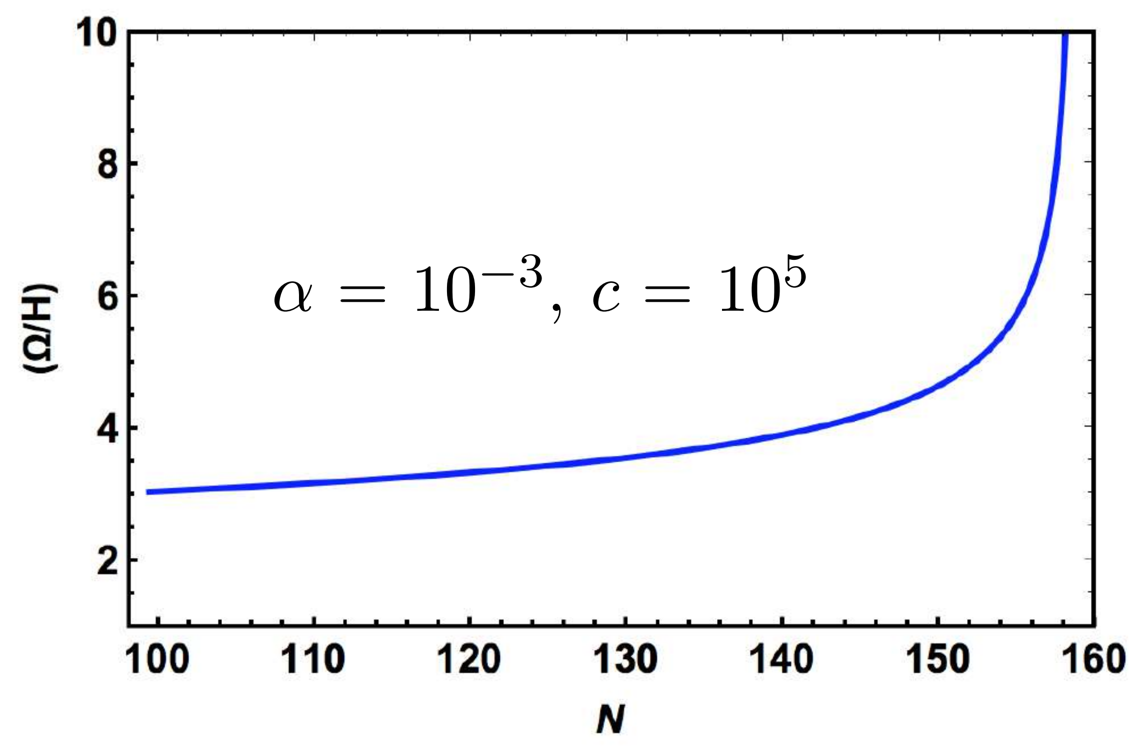


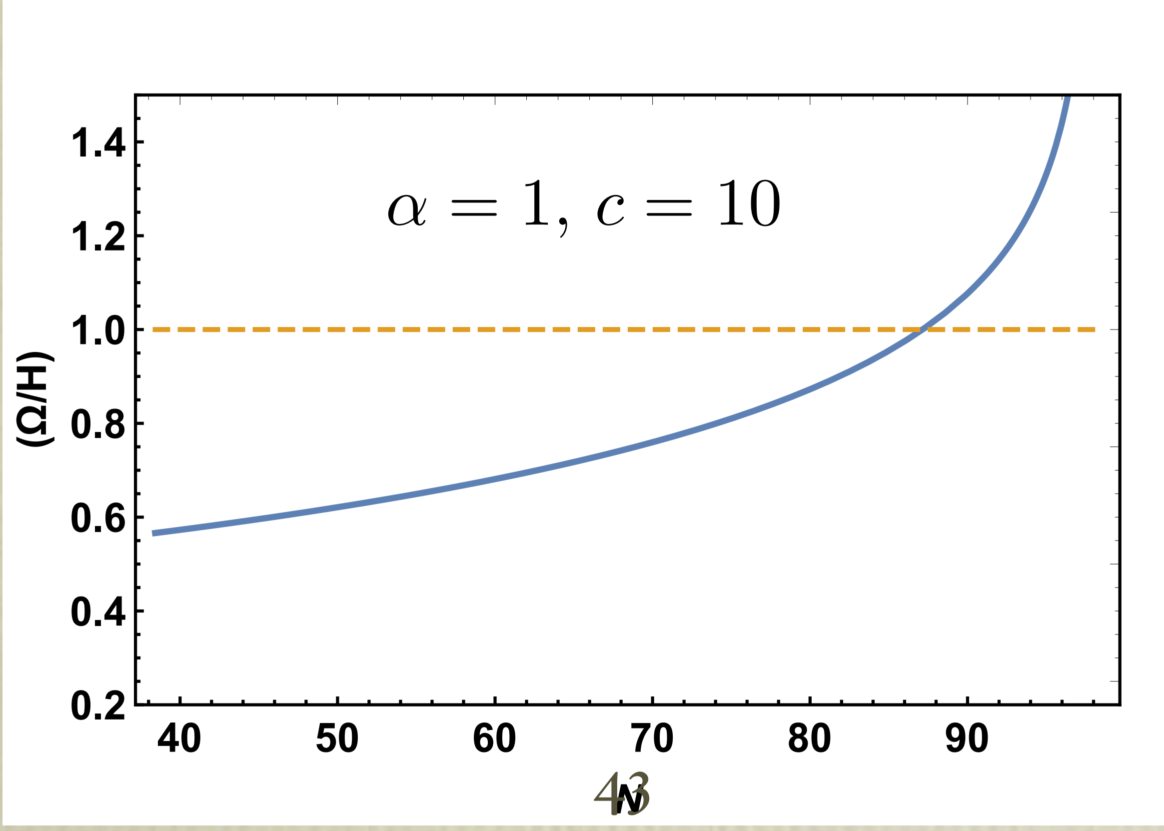


- Minimal eigenvalue, large and tachyonic (SdSC ✓)

LARGE TURNING RATE INFLATION IN SUPERGRAVITY: EXAMPLE 2

- Tuning further (c, α) can increase Ω/H





PART III:

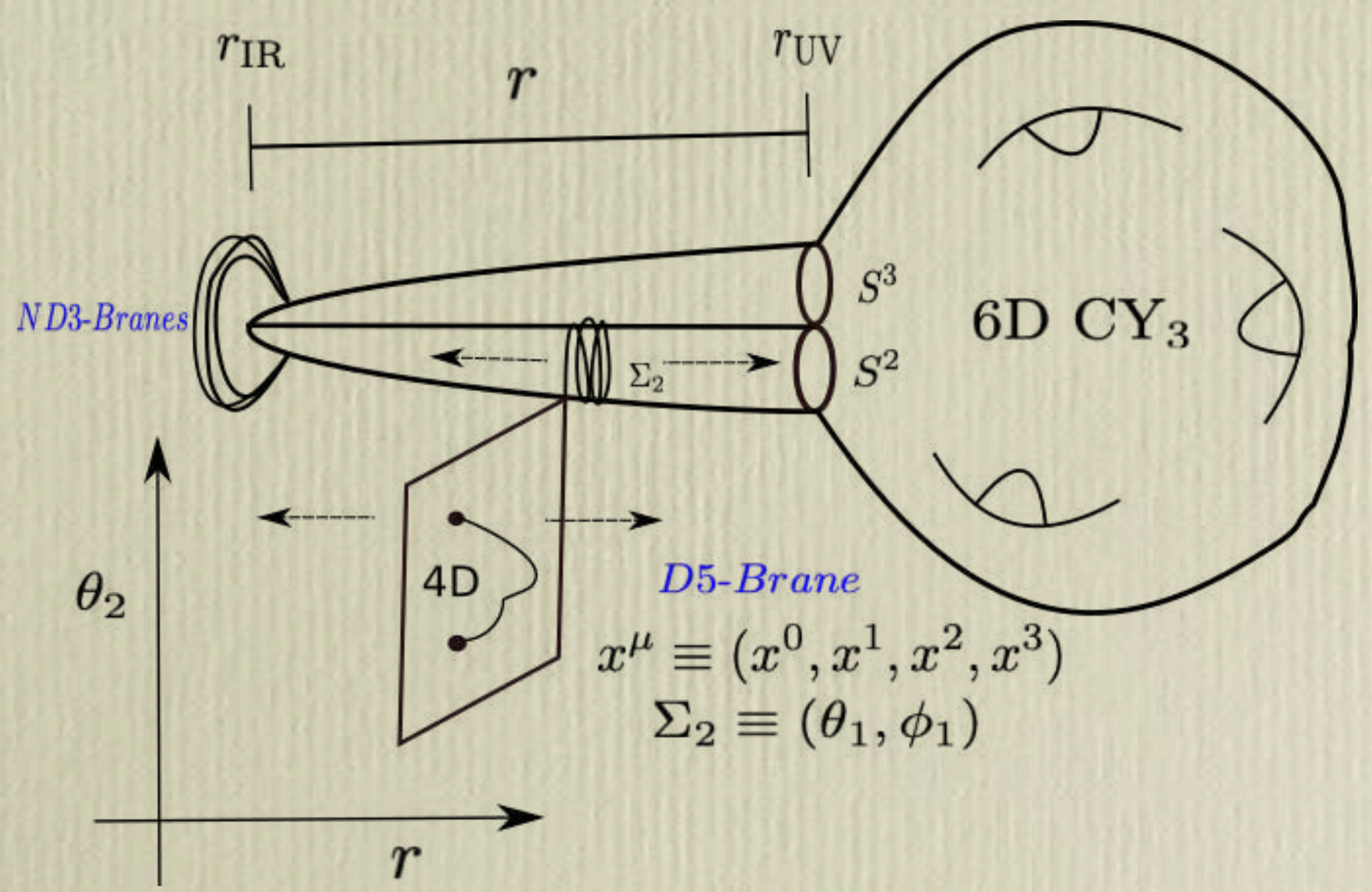
FAT INFLATION IN STRING THEORY

D5-BRANE FAT INFLATION

D5-BRANE INFLATION

- Consider a *warped* compactification in type IIB string theory. A probe **D5-brane** moving in the radial and angular directions in a **warped resolved conifold**

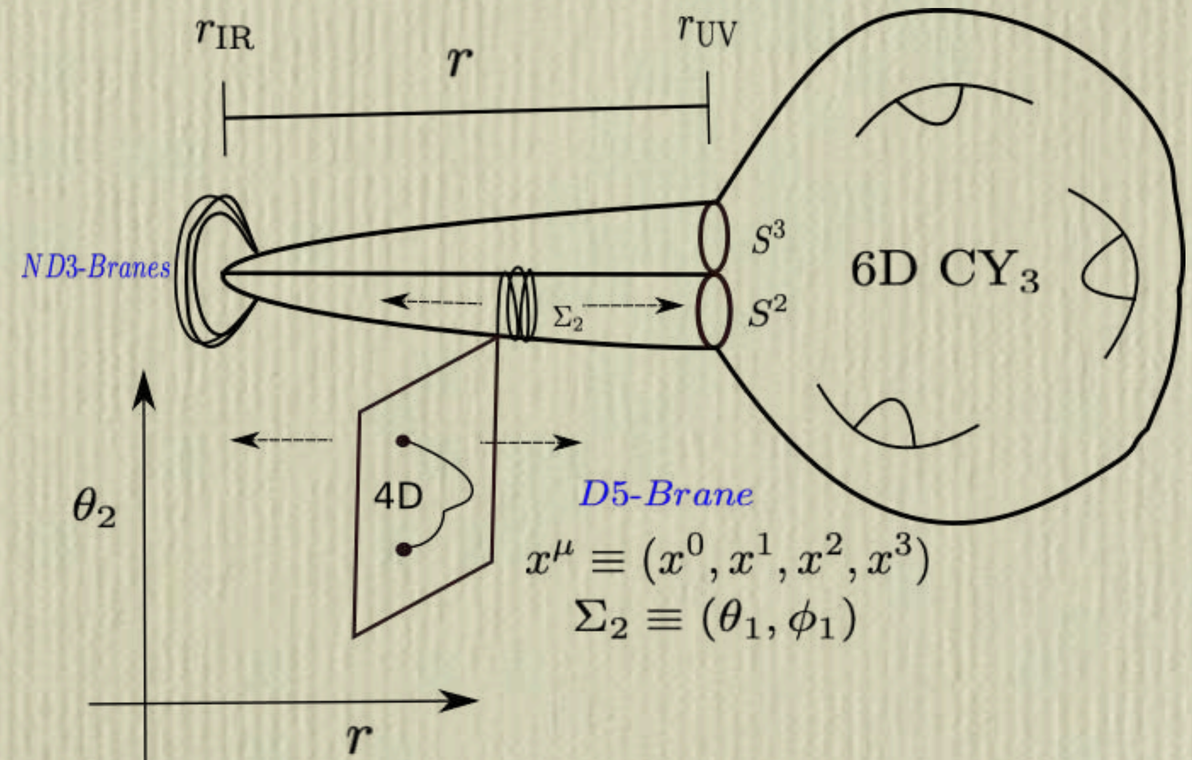
[Becker, Leblond, Shandera, '07]
[(Single field) Kenton-Thomas, '14; Chakraborty et al. '19]



WARPED GEOMETRY AND D5-BRANE DYNAMICS

- The 10D metric for the WRC we consider takes the form

[Pando Zayas, Tseytlin, 00;
Klebanov, Murugan, '07]



$$ds^2 = \underbrace{\mathcal{H}^{-1/2}}_{\text{Warp factor}}(\rho,\theta_2)ds^2_{FRW} + \mathcal{H}^{1/2}(\rho,\theta_2)\underbrace{ds^2_{RC}}_{\text{6D resolved conifold metric}} \,,$$

Warp factor

6D resolved conifold metric

$$S_5 = -T_5 p\int_{\mathcal{W}_6} d^6\xi\sqrt{-\det(P_6\left[g_{ab}+B_{ab}+2\pi\alpha' F_{ab}\right])} + \mu_5 p\int_{\mathcal{W}_6} P_6\left[C_6 + C_4\wedge(B_2+2\pi\alpha' F_2)\right]$$

q

$T_5 = \mu_5 g_s^{-1}$ $\quad (g_s = \text{string coupling})$

$\mu_5 = \left[(2\pi)^5 \ell_s^6\right]^{-1}$ $\quad (\ell_s = \text{string scale})$

$p = \text{wraping number}$

$$V(r,\theta) = \phi(r) + \gamma(\overline{\Phi}_-(r) + \Phi_h(r,\theta))$$

[Kenton-Thomas, '14;
Bauman et al. '07-10]

D5-BRANE FAT INFLATION

- At the end of the day, the 4D action takes the form

$$S_4 = \int d^4x\sqrt{-\mathrm{g}}\left[\frac{M_{\rm Pl}^2}{2}R_4 + \frac{1}{2}g_{ij}v^iv^j - V(r,\theta)\right]$$

where

$$g_{ij} = 4\pi p T_5 \mathcal{F}^{1/2}\mathrm{diag}\left(\frac{r^2+6u^2}{r^2+9u^2}, \frac{1}{6}(r^2+6u^2)\right), \qquad v^i = (\dot{r}, \dot{\theta}_2), \qquad \left(M_{Pl}^2 = V_w\left(\frac{1}{2}(2\pi)^7 g_s^2\ell_s^8\right)^{-2}\right)$$

$$\mathcal{F} \equiv \frac{\mathcal{H}}{9}(r^2+3u^2)^2 + (\pi\ell_s^2 q)^2,$$

$$\mathcal{H} = \left(\frac{L_{T^{1,1}}}{3u}\right)^4\left(\frac{2}{\rho^2} - 2\ln\left(\frac{1}{\rho^2}+1\right)\right), \qquad L_{T^{1,1}}^4 = \frac{27\pi}{4}Ng_s\ell_s^4. \qquad (\rho = r/3u)$$

$$V(r,\theta) = V_0 + 4\pi p T_5\mathcal{H}^{-1}\left[\mathcal{F}^{1/2} - \ell_s^2\pi q g_s\right] + \gamma\left[\overline{\Phi}_- + \Phi_h\right], \qquad (\gamma = 4\pi^2\ell_s^2 pqT_5 g_s)$$

$$\overline{\Phi}_- = \frac{5}{72}\left[81\left(9\rho^2-2\right)\rho^2 + 162\log\left(9\left(\rho^2+1\right)\right) - 9 - 160\log(10)\right]$$

$$\Phi_h = a_0\left[\frac{2}{\rho^2} - 2\log\left(\frac{1}{\rho^2}+1\right)\right] + 2a_1\left[6 + \frac{1}{\rho^2} - 2(2+3\rho^2)\log\left(1+\frac{1}{\rho^2}\right)\right]\cos\theta + \frac{b_1}{2}\left(2+3\rho^2\right)\cos\theta.$$

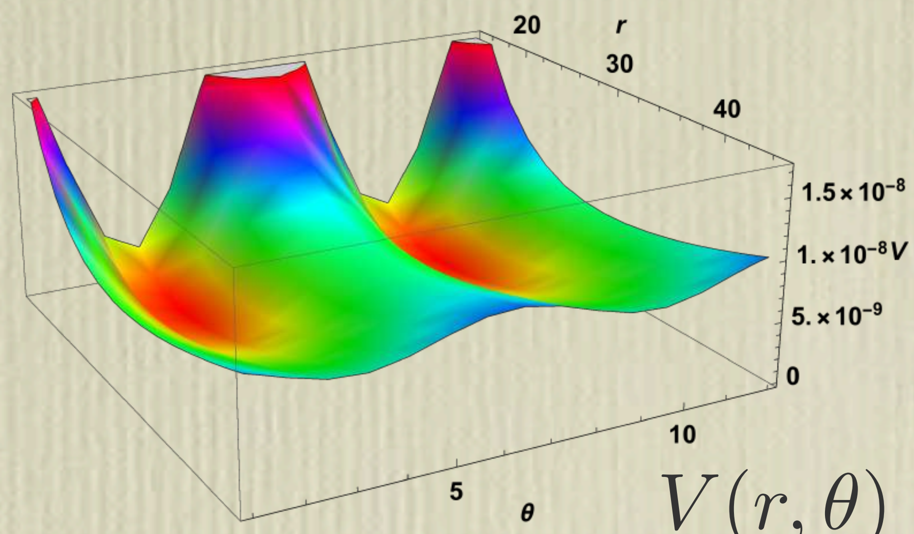
D5-BRANE FAT INFLATION

$$S_4 = \int d^4x \sqrt{-\mathsf{g}} \left[\frac{M_{\rm Pl}^2}{2} R_4 + \frac{1}{2} g_{ij} v^i v^j - V(r,\theta) \right]$$

where

$$g_{ij} = \mathrm{diag}(g_{rr}(r), g_{\theta\theta}(r))$$

$$V(r,\theta) = V(r) + W(r)\cos\theta$$



$V(r,\theta)$

D5-BRANE FAT INFLATION

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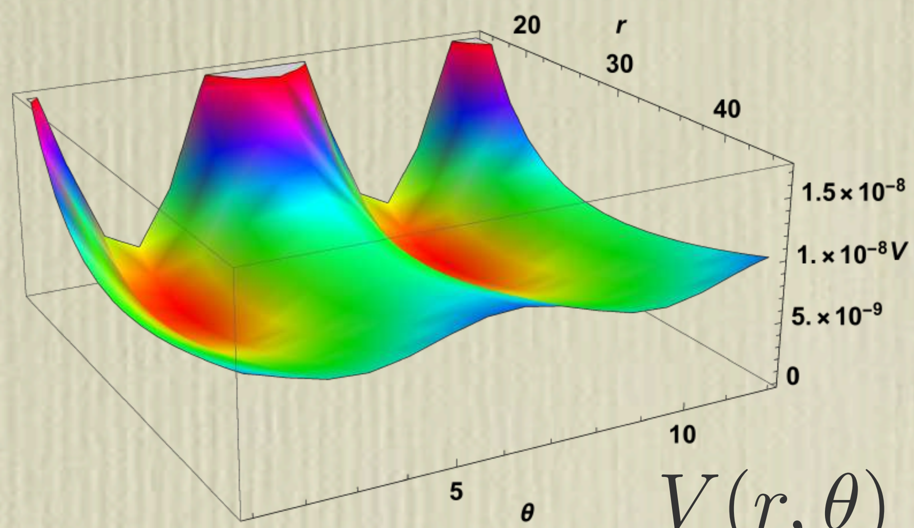
Parameters and constraints



$V(r,\theta)$

- String theory models of inflation relay on 4D LEEFT, weakly coupled, perturbative string expansion

$$g_s < 1\,, \quad L/\ell_s > 1$$

- For a 4D effective field theory description to be valid during inflation, requires compactification scale smaller than string scale $(L_c/\ell_s > 1)$

- Thus we require the hierarchy:

$$\lesssim M_{KK} \lesssim M_s \lesssim M_{Pl}$$

D5-BRANE FAT INFLATION

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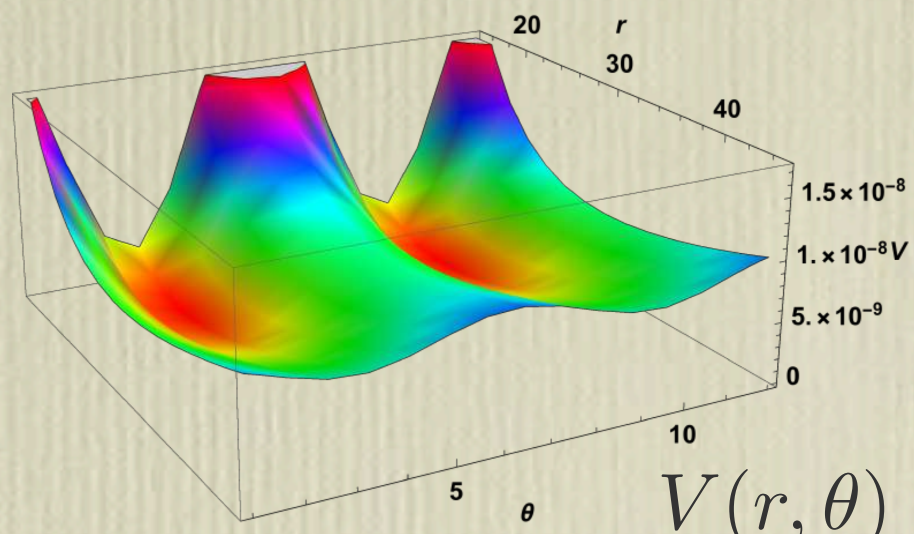

$V(r,\theta)$

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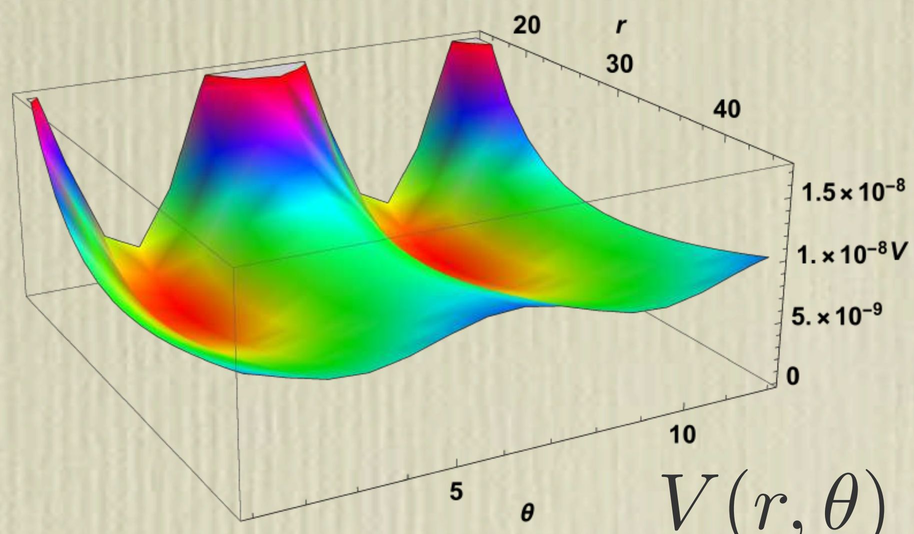

$V(r,\theta)$

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- Thus we require the hierarchy:

$$M_{inf} \lesssim H \lesssim M_{KK} \lesssim M_s \lesssim M_{Pl}$$ *for light inflation*

D5-BRANE FAT INFLATION

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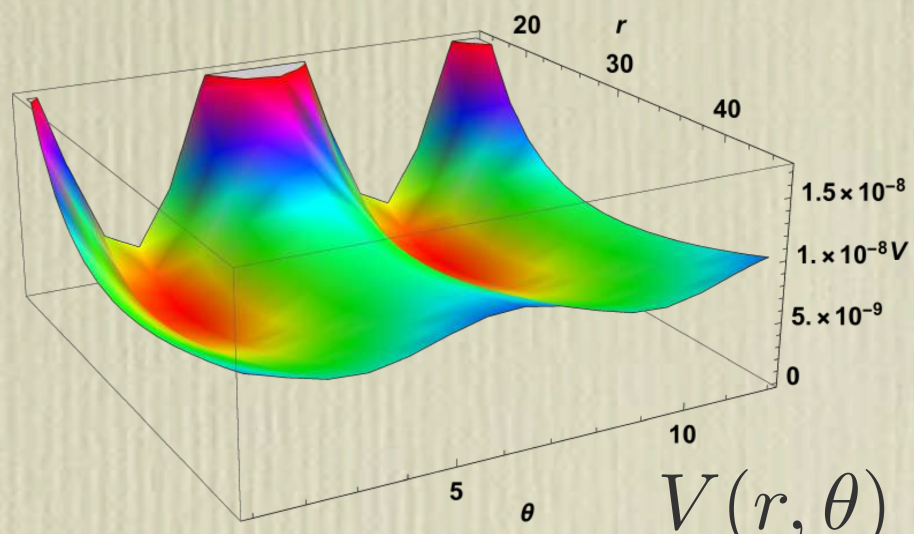
Parameters and constraints



$V(r,\theta)$

- String theory models of inflation relay on 4D LEEFT, weakly coupled, perturbative string expansion

$$g_s < 1\,, \quad L/\ell_s > 1$$

- For a 4D effective field theory description to be valid during inflation, requires compactification scale smaller than string scale $(L_c/\ell_s > 1)$

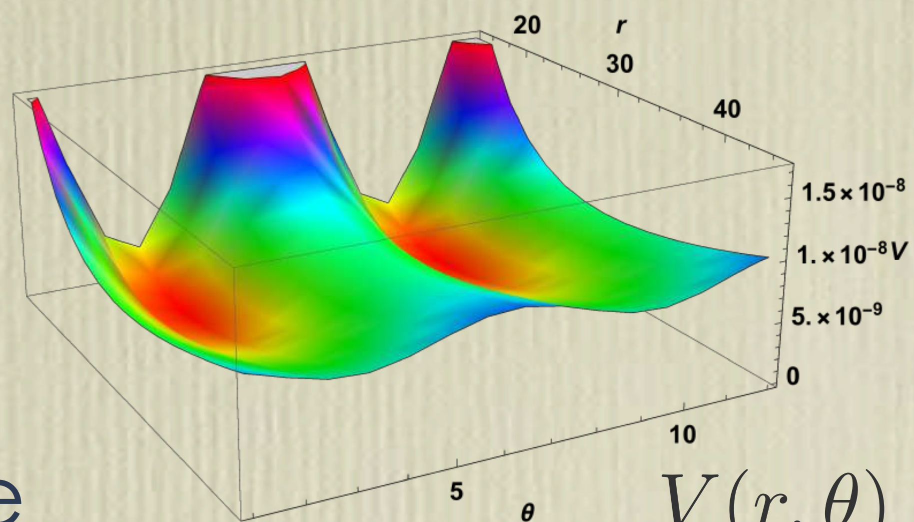
- Thus we require the hierarchy:

$$H \lesssim M_{inf} \lesssim M_{KK} \lesssim M_s \lesssim M_{Pl} \qquad \text{for fat inflation}$$

D5-BRANE FAT INFLATION

$$S_4 = \int d^4x\sqrt{-\mathrm{g}}\left[\frac{M_{\rm Pl}^2}{2}R_4 + \frac{1}{2}g_{ij}v^iv^j - V(r,\theta)\right]$$

Parameters and constraints



$V(r,\theta)$

- The parameter, u, is the natural length of the throat, so $u > \ell_s$
- The constants (a_0, a_1, b_1) appearing in the potential are undetermined but small. (Coefficients of indep. solutions of the Laplace equation on the RC)
- The parameters (p,q) are the D5-brane wrapping and flux numbers, and N is the number of D3-branes sourcing the RC geometry. Backreaction constraints require

[Becker, Leblond, Shandera, '07; Kooner, S. Parameswaran, IZ, '15

$$N \gg 1\,, \qquad p \ll 12N(2\pi)^2\mathcal{H}^{-1/2}\frac{\ell_s^2}{r^2}\,, \qquad pq \ll 4\pi N$$

$$\left(\mathcal{H}_{min}^{-1/2} = \mathcal{H}_{tip}^{-1/2}\right)$$

D5-BRANE FAT INFLATION

$$S_4 = \int d^4x\sqrt{-\mathrm{g}}\left[\frac{M_{\rm Pl}^2}{2}R_4 + \frac{1}{2}g_{ij}v^iv^j - V(r,\theta)\right]$$

- We fix the parameters (g_s, N, u) to ensure hierarchy of scales:

$$M_c \lesssim M_s \lesssim M_{Pl}$$

- Vary the parameters (p, q), keeping track of the backreaction constraints.

- We then choose the coefficients (a_0, a_1, b_1) such that the amplitude of the scalar perturbations matches with observations.

N	g_s	ℓ_s	u	q	a_0	a_1	b_1
1000	0.01	501.961	$50\ell_s$	1	0.001	0.0005	0.001

$$(M_s \sim 10^{-3}M_{Pl},\ \ M_c \sim 10^{-4}M_{Pl},\ \ H \sim 10^{-5}M_{Pl})$$

D5-BRANE FAT INFLATION

- We expect *natural inflationary like* solutions, but predictions to differ from single field, due to *massive inflatons* and thus *large turning rates*

- *Instantaneous decay "constant"* can be defined as

$$f = \sqrt{g_{\theta\theta}(r)}$$

D5-BRANE FAT INFLATION

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- *Instantaneous decay "constant"* can be defined as

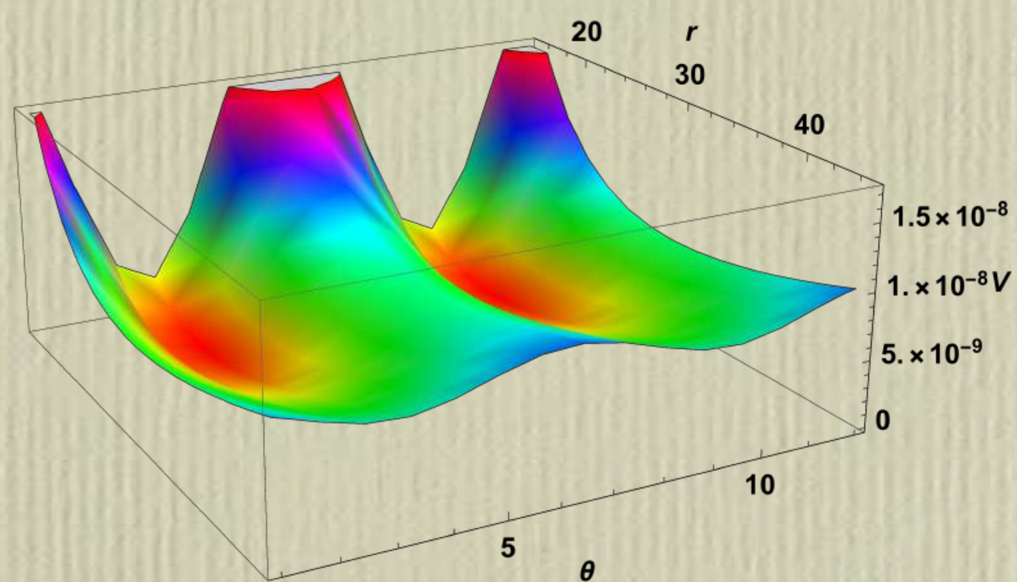
$$f = \sqrt{g_{\theta\theta}(r)}$$

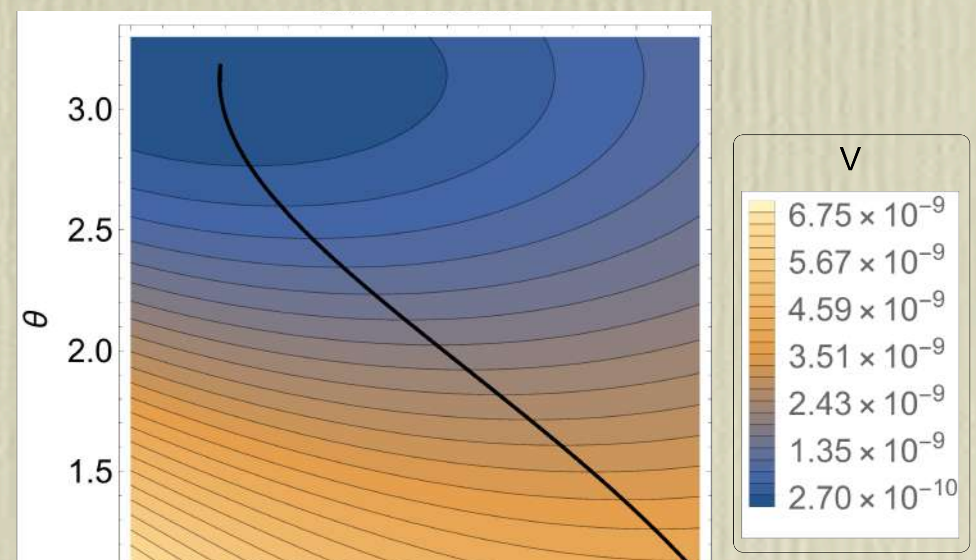
p	$f/M_{\rm Pl}$
7	7.49
6	6.89
5	6.22
4	5.51
3	4.71

D5-BRANE FAT INFLATION

- With this set of parameters we have $\lambda_{-}/H^2 \sim 10$

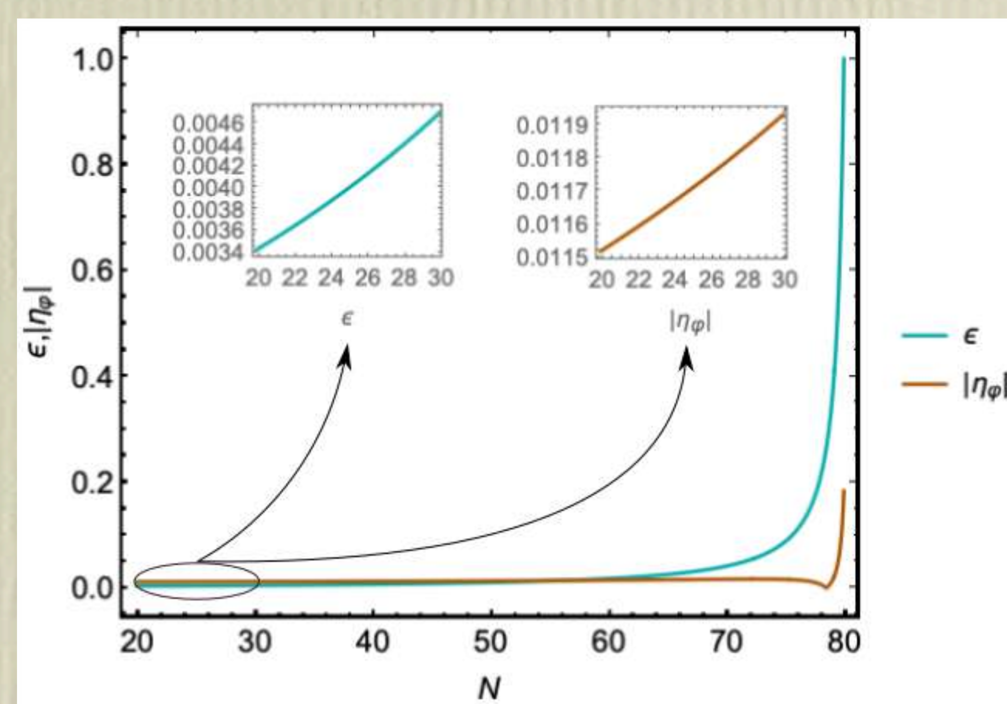
- Inflationary trajectory





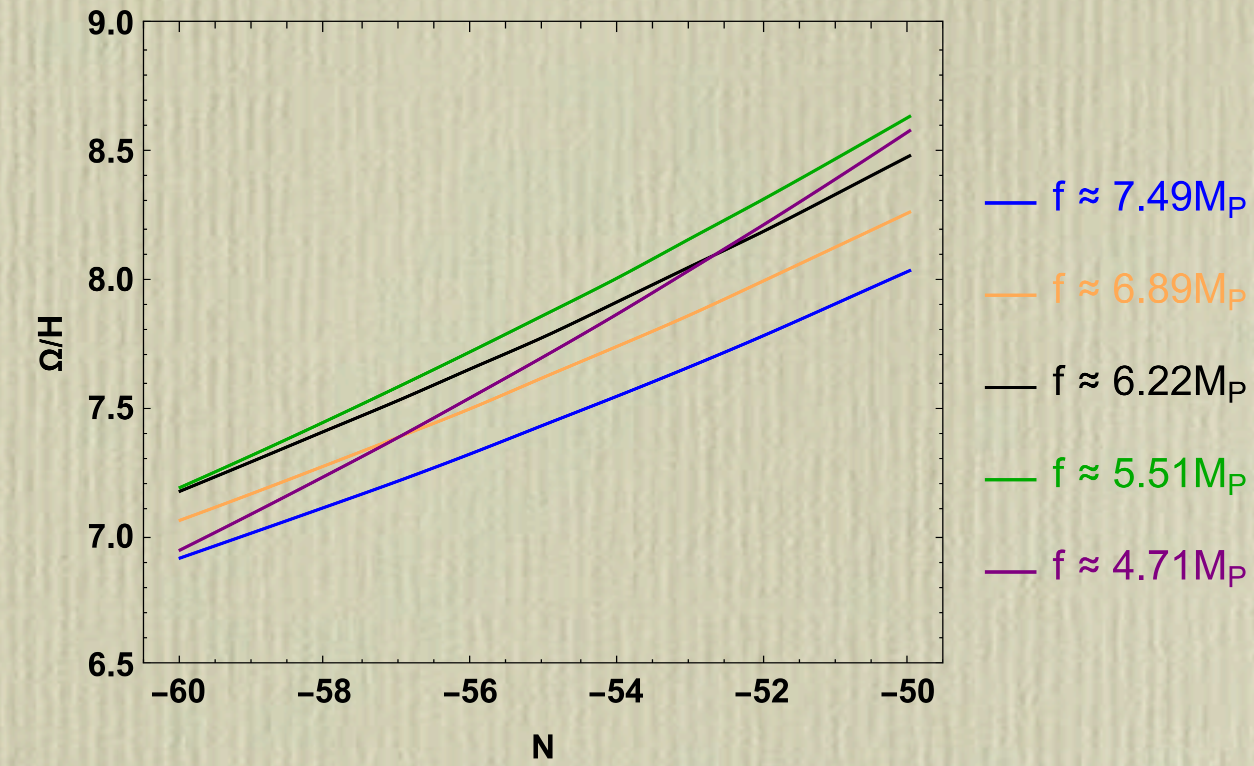
$f \simeq 6.22$

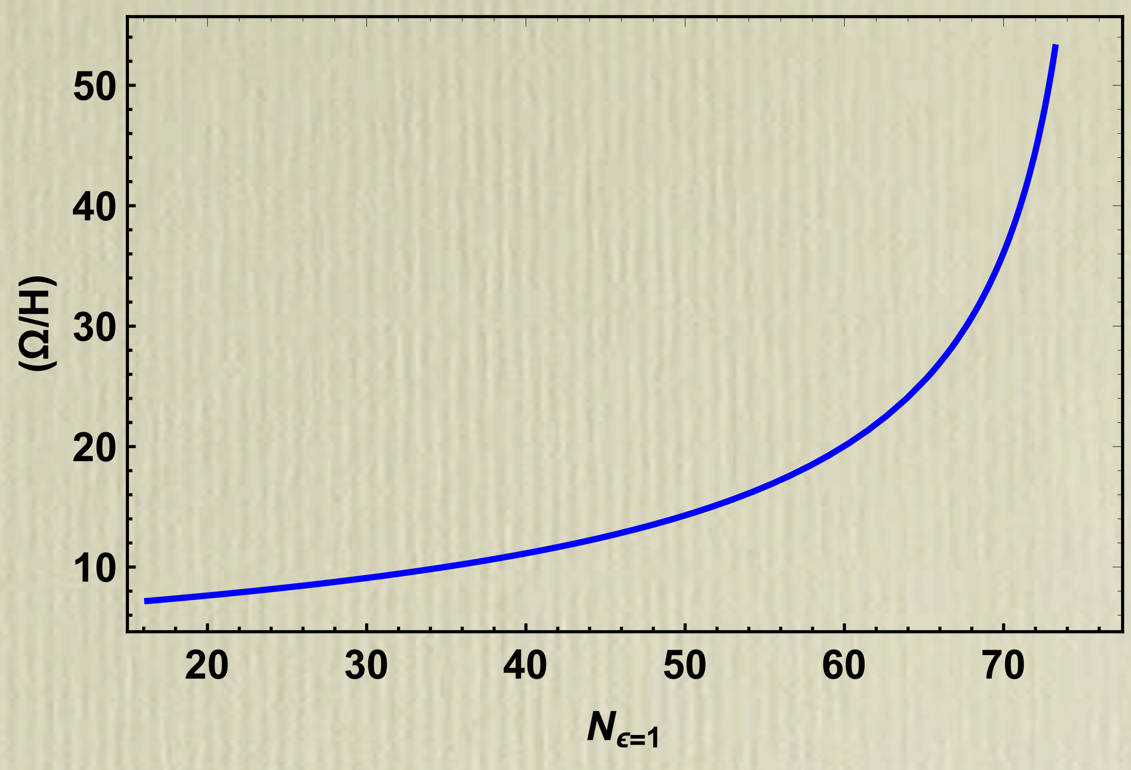
- Slow-roll parameters



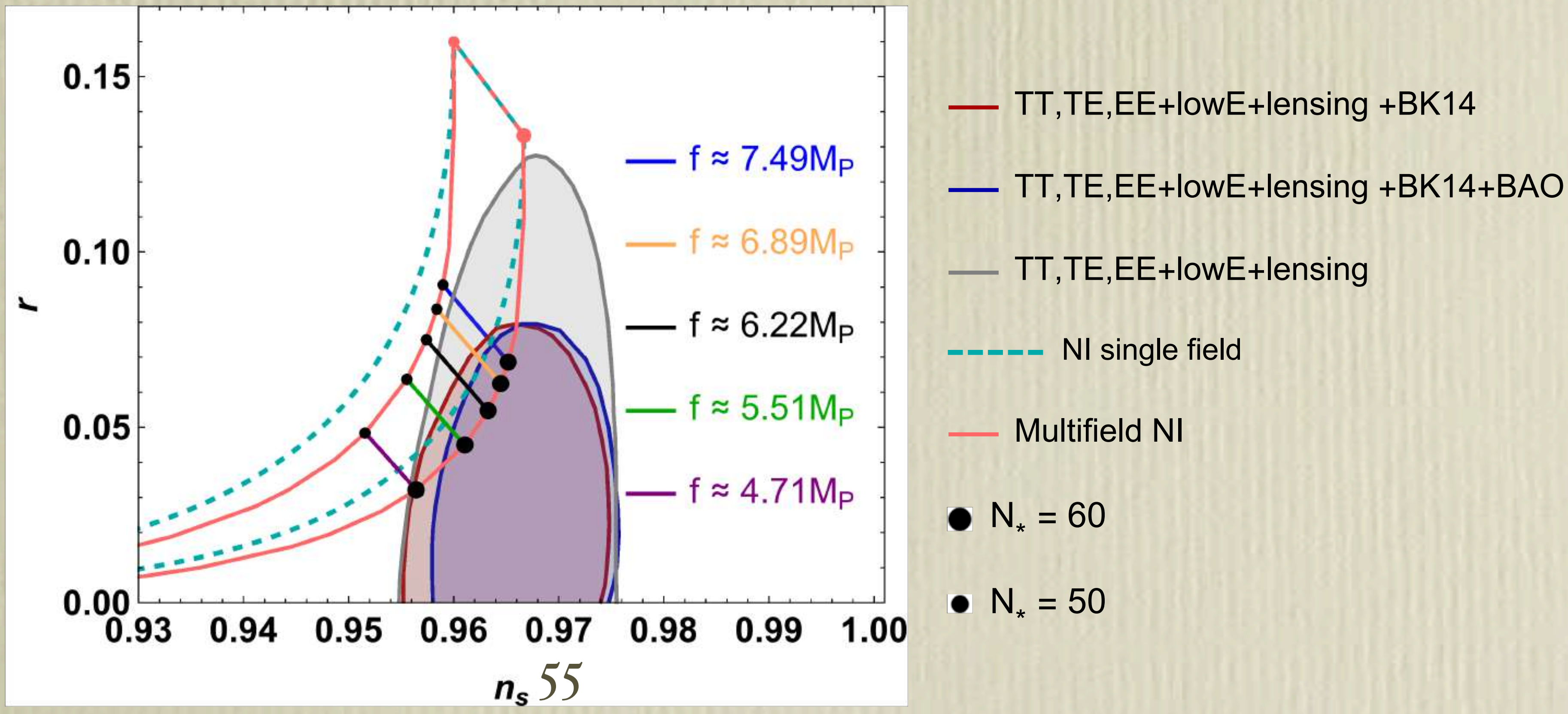
D5-BRANE FAT INFLATION

- Turning rates





- Cosmological parameters: clear departure from SF

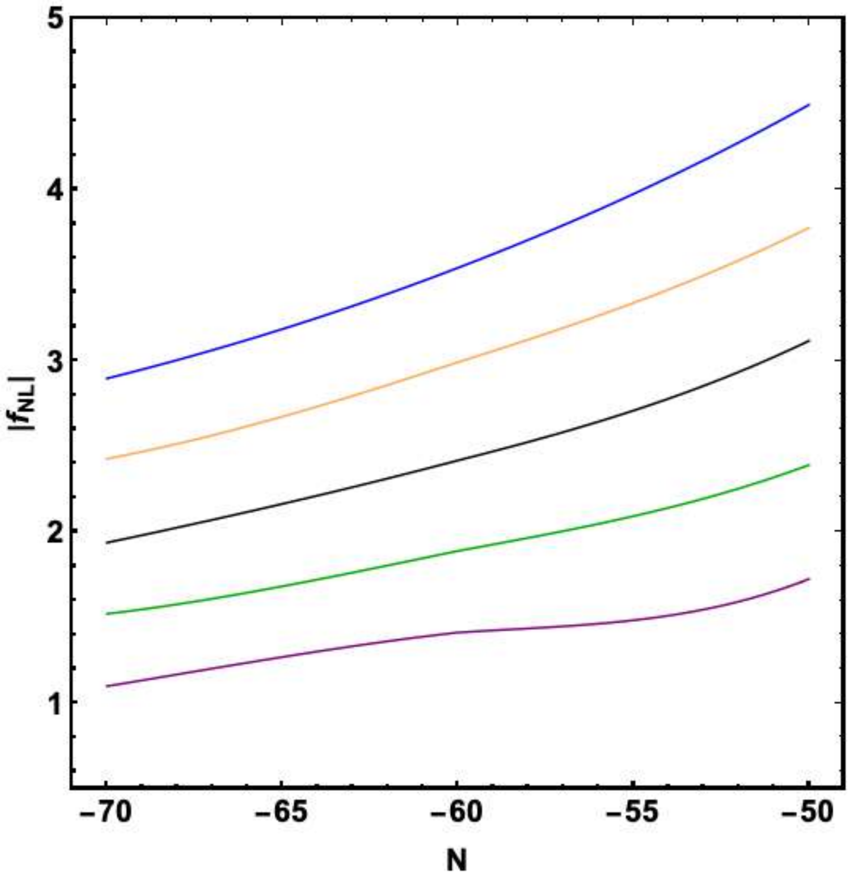


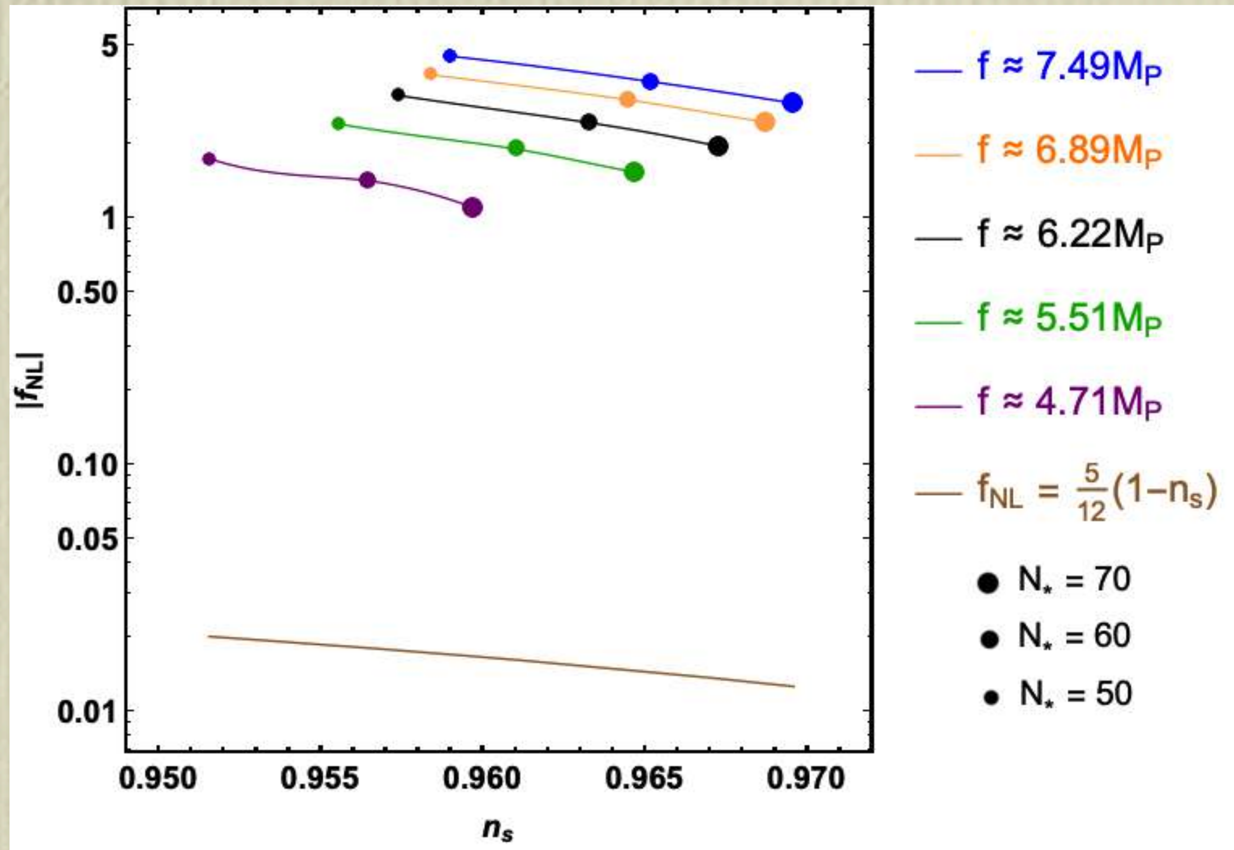
D5-BRANE FAT INFLATION

- Non-Gaussianity

[Kaiser, Mazenc, Sfakianakis, '12]

$$f_{\rm NL} = -\frac{5}{6}\frac{N^{,i}N^{,j}N_{;ij}}{(N_{,k}N^{,k})^2}\,,$$





D5-BRANE LIGHT INFLATION

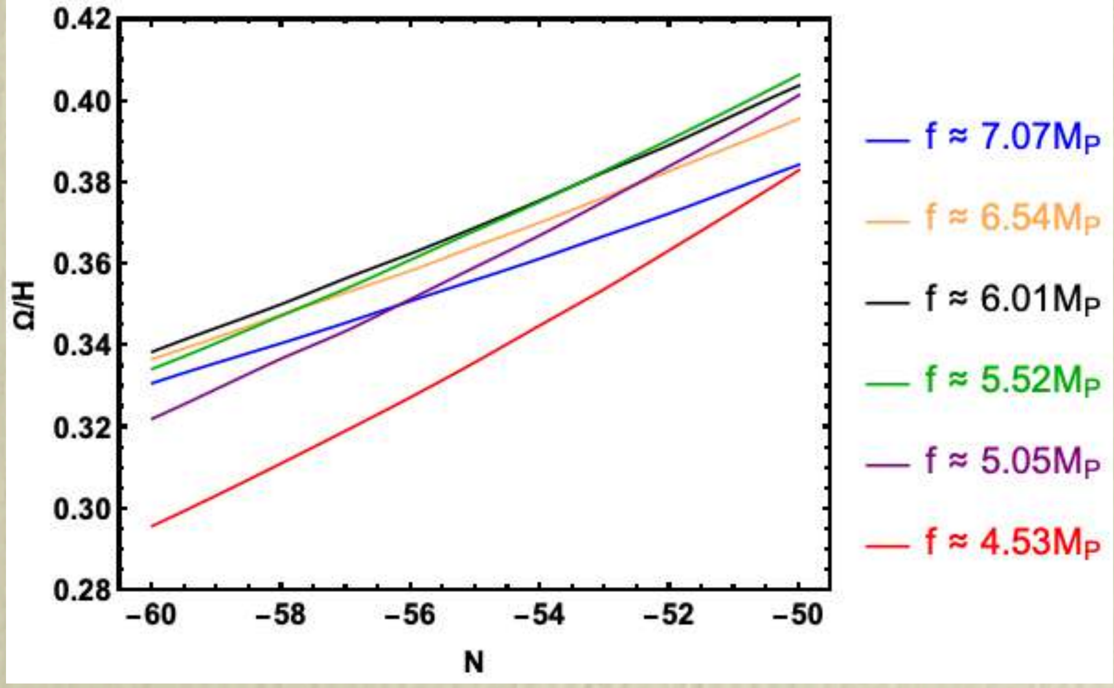
- For a different choice of parameters, D5-brane model gives rise to *light inflation* with single field predictions

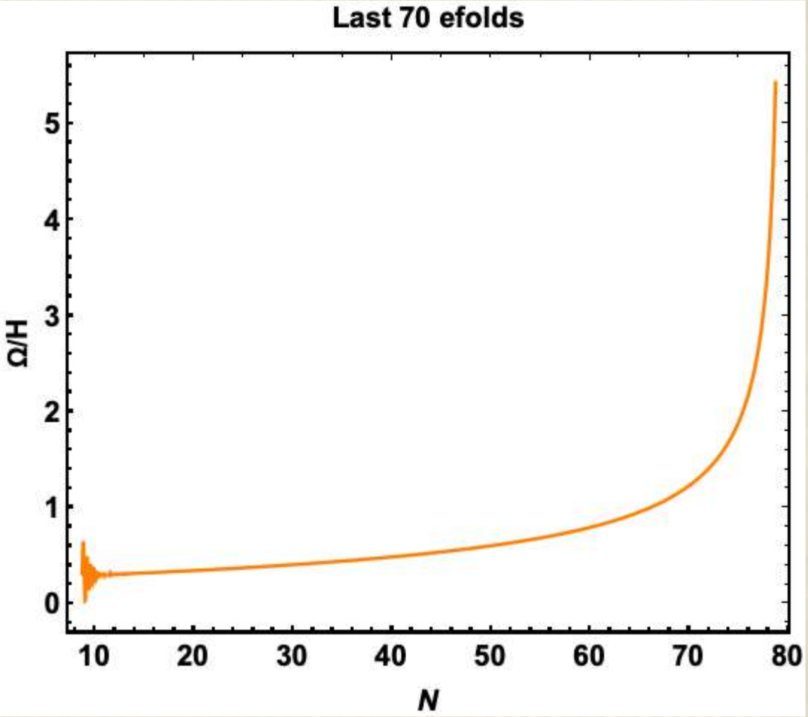
N	g_s	q	u	ℓ_s	a_0	a_1	b_1
1000	0.01	70	$50l_s$	501.961	0.1	0.0001	0.0001

$\mathbb{R} \sim -10^2 M_{\rm Pl}^{-2}$

with these parameters, *the masses satisfy standard hierarchy* $M_1 \lesssim H < M_2$ *with* $M_1/H \sim 0.35$

p	$f/M_{\rm Pl}$
90	7.07
77	6.54
65	6.01
55	5.52
46	5.05
37	4.53



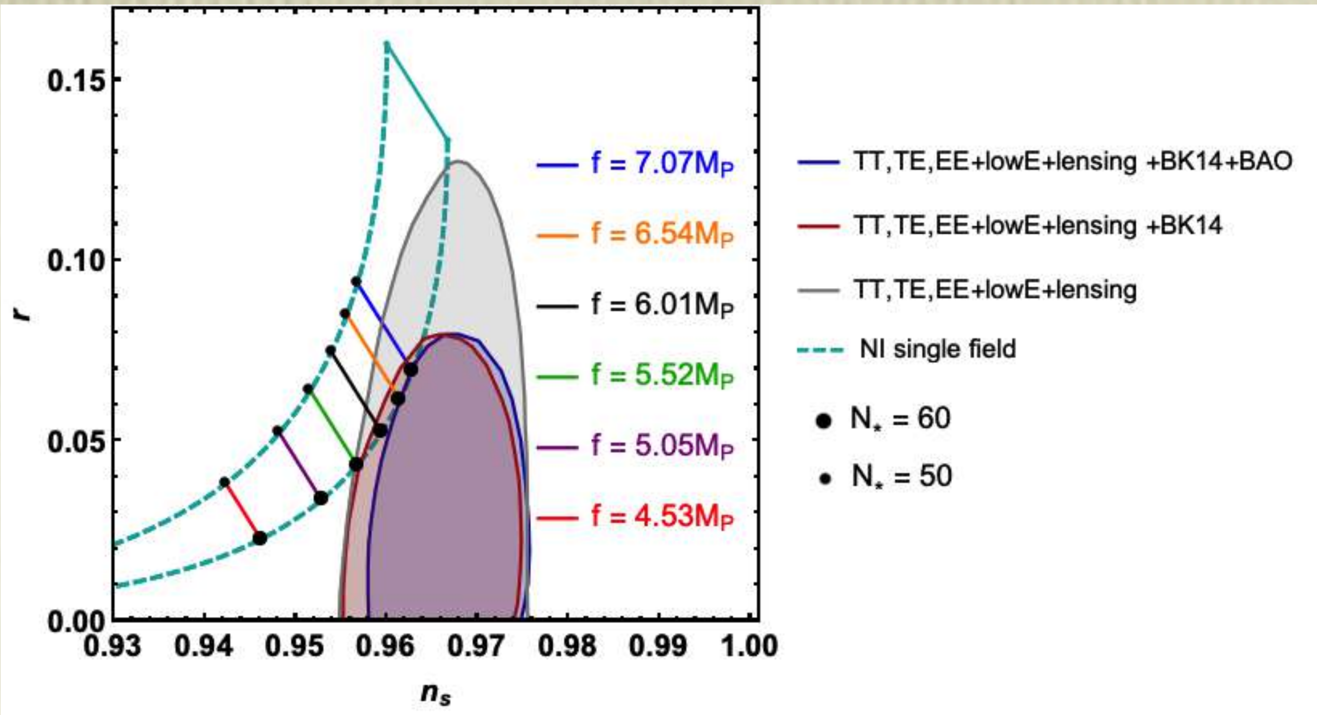


$[(p,q)_{KT} = (0.22, 5929)]$

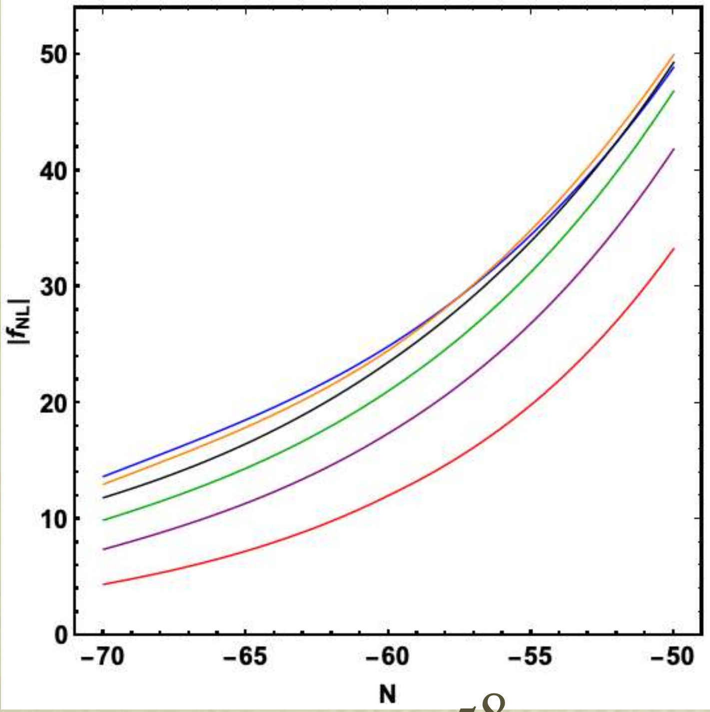
D5-BRANE LIGHT INFLATION

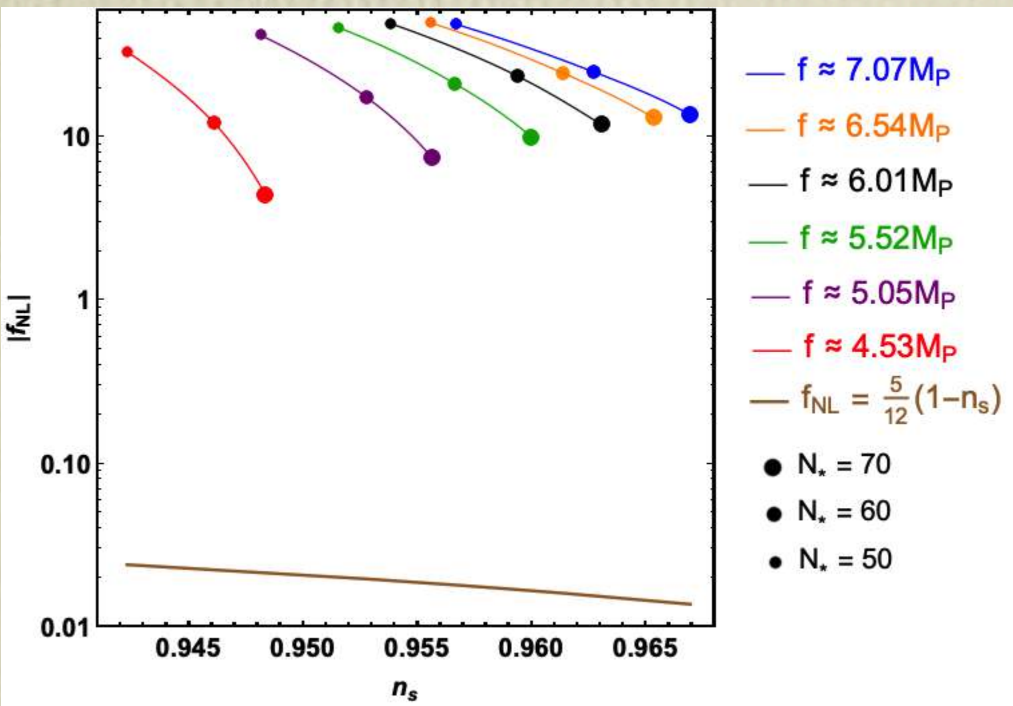
- Cosmological parameters:

Indistinguishable from single field



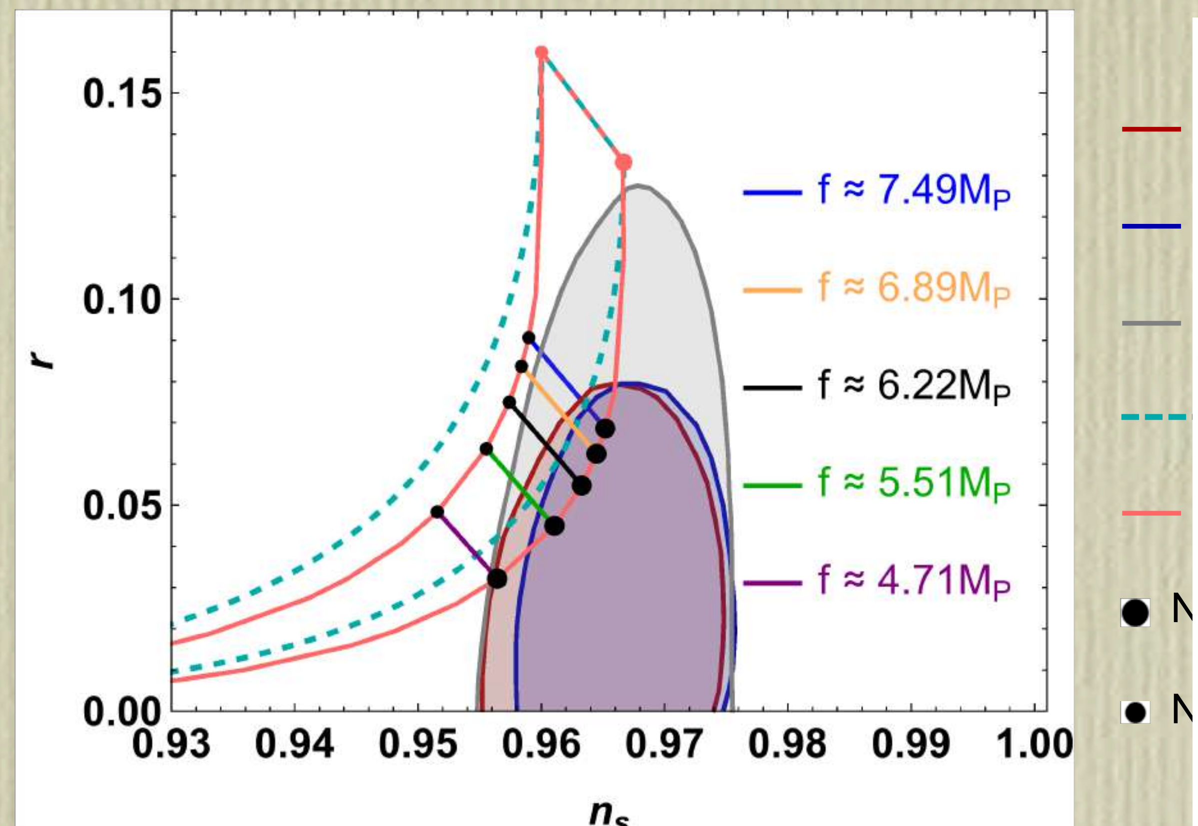
too large NG





Fat natural inflation

N	g_s	ℓ_s	u	q	a_0	a_1	b_1
1000	0.01	501.961	$50\ell_s$	1	0.001	0.0005	0.001



p	f/M_{Pl}
7	7.49
6	6.89
5	6.22
4	5.51
3	4.71

$$\mathbb{R} - 3\times 10^4 M_{Pl}^{-2}$$

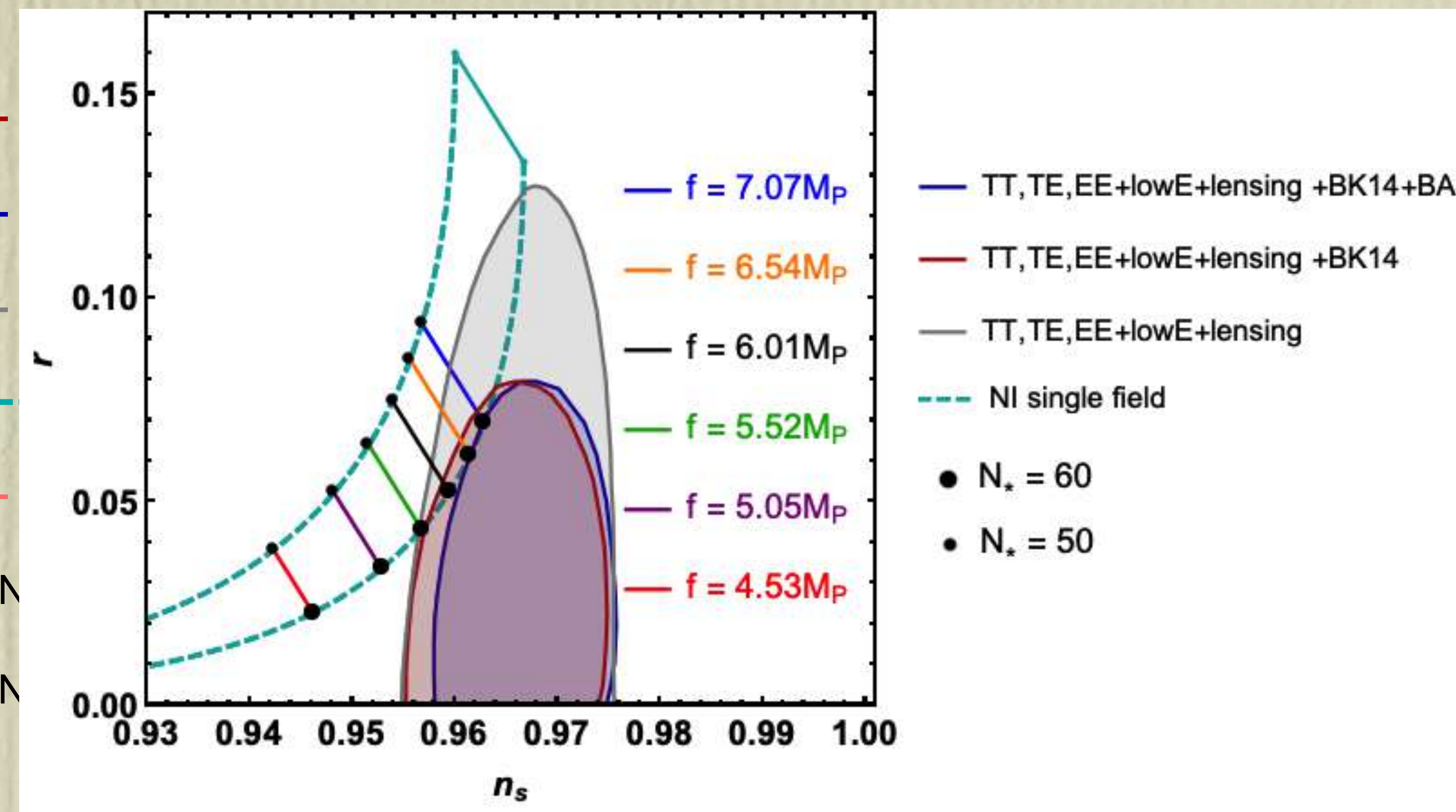
$$\lambda_-/H^2 \sim 10$$

$$\Omega/H \sim 10$$

$$f_{NL} \sim \mathcal{O}(1)$$

Light natural inflation

N	g_s	q	u	ℓ_s	a_0	a_1	b_1
1000	0.01	70	$50l_s$	501.961	0.1	0.0001	0.0001



p	f/M_{Pl}
90	7.07
77	6.54
65	6.01
55	5.52
46	5.05
37	4.53

$$\mathbb{R} \sim -10^2 M_{\mathrm{Pl}}^{-2}$$

$$\lambda_1/H^2 \sim 0.1$$

$$\Omega/H \sim 0.4$$

$$f_{NL} \sim \mathcal{O}(10)$$

FINAL COMMENTS

- Multifield inflation allows new inflationary attractor with (strong) non-geodesic trajectories.
- Light fields are not needed, *all* fields can be heavy. Avoid η-problem
- Large-turns in supergravity rare and tachyonic, SdSC satisfied, but theoretically unmotivated
- Fat D5-brane model has challenges that would need to be addressed in a more complete model (moduli stabilisation, heaviest inflaton too heavy)
- Transient large turns induced from transient slow-roll violations in sugra. Rich phenomenology [Bhattacharya, IZ, in progress]
- Fat trajectories in D3-antiD3-brane multi-field inflation?

[Bhattacharya, Chakraborty, IZ, in progress]

DISCUSSION SLIDES

PART IV:

CHIRAL GRAVITATIONAL WAVES IN STRING INFLATION?

(SPECTATOR) CHROMONATURAL KÄHLER INFLATION

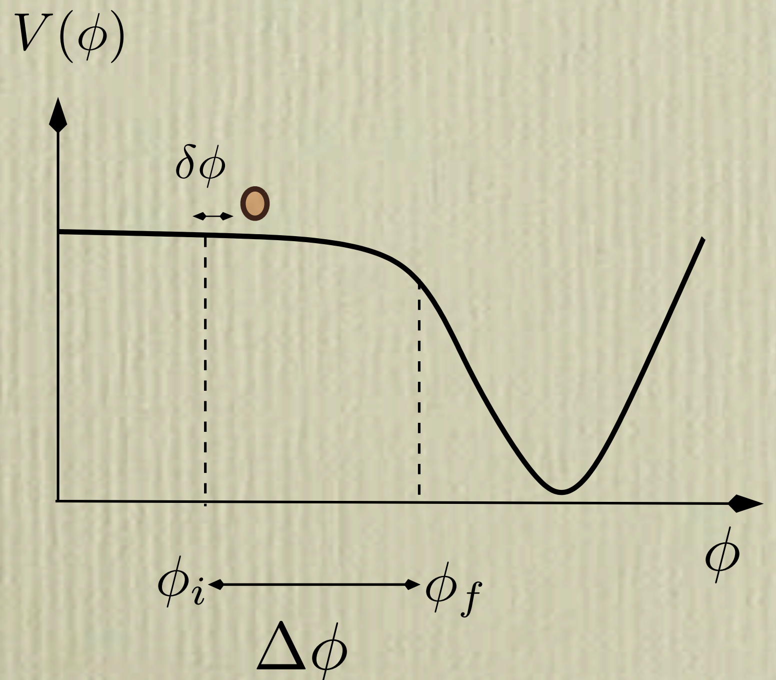
PRIMORDIAL GRAVITATIONAL WAVES AND THE LYTH BOUND

In scalar single field inflation, r is related to field displacement and scale of inflation: Lyth bound

[Lyth, '96; Boubekeur-Lyth, '05]

[Garcia-Bellido, Roest, Scalisi, IZ '14]

slow-roll inflation



$$V^{1/4} \approx 1.8 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4} \sim 10^{-2} M_{Pl}$$

$$\frac{\Delta\phi}{M_{Pl}} \gtrsim \mathcal{O}(1) \left(\frac{r}{0.002}\right)^{1/2}$$

SOURCED PRIMORDIAL GRAVITATIONAL WAVES

- However if spectator fields are around during inflation, can have interesting effects.

- E.g. in *chromonatural inflation* originally proposed to relax need for super-Planckian decay constant. A spectator SU(2) sources tensor fluctuations:

[Adshead-Wyman, '12;
Dimastrogiovanni, Peloso, '12
Adshead, Martinec, Wyman, '13]

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 2a^2\pi^T_{ij}$$

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$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 2a^2\pi^T_{ij}$$

  - sources tensor fluctuations may be distinguishable on the basis of its chirality,
  - if large enough, may *disentangle* tensor-2-scalar ratio from inflationary scale and field range (Lyth bound)

SPECTATOR CHROMONATURAL INFLATION

- A modified version, compatible with observation recently proposed, *spectator* CNI (SCNI):

[Dimastrogiovanni, Fassiello, Fujita, '16; Fujita, Namba, Tada, '17]

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \underbrace{\frac{1}{2}(\partial\phi)^2 - V(\phi)}_{\text{inflationary sector}} - \underbrace{\frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\lambda\,\chi}{4f}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}}_{\text{spectator sector}}\right].$$

$(F^a = dA^a - g\,A^a \wedge A^a)$

- ➠ Successful cosmological evolution requires $\frac{M_{Pl}}{f}\lambda \gg 1$
- ➠ Backreaction from the amplified tensor fluctuations $g \ll 1$
- ➠ Theoretical control is problematic $\lambda \propto g^2$

[Agrawal, Fan, Reece, '18]

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- CNI-like PGW enhancement in supergravity and string theory?

[Dall'Agata, 18; McDonough, Alexander, 18]
[See also Obata-Soda, '16]
[Holland, IZ, Tasinato, '20]

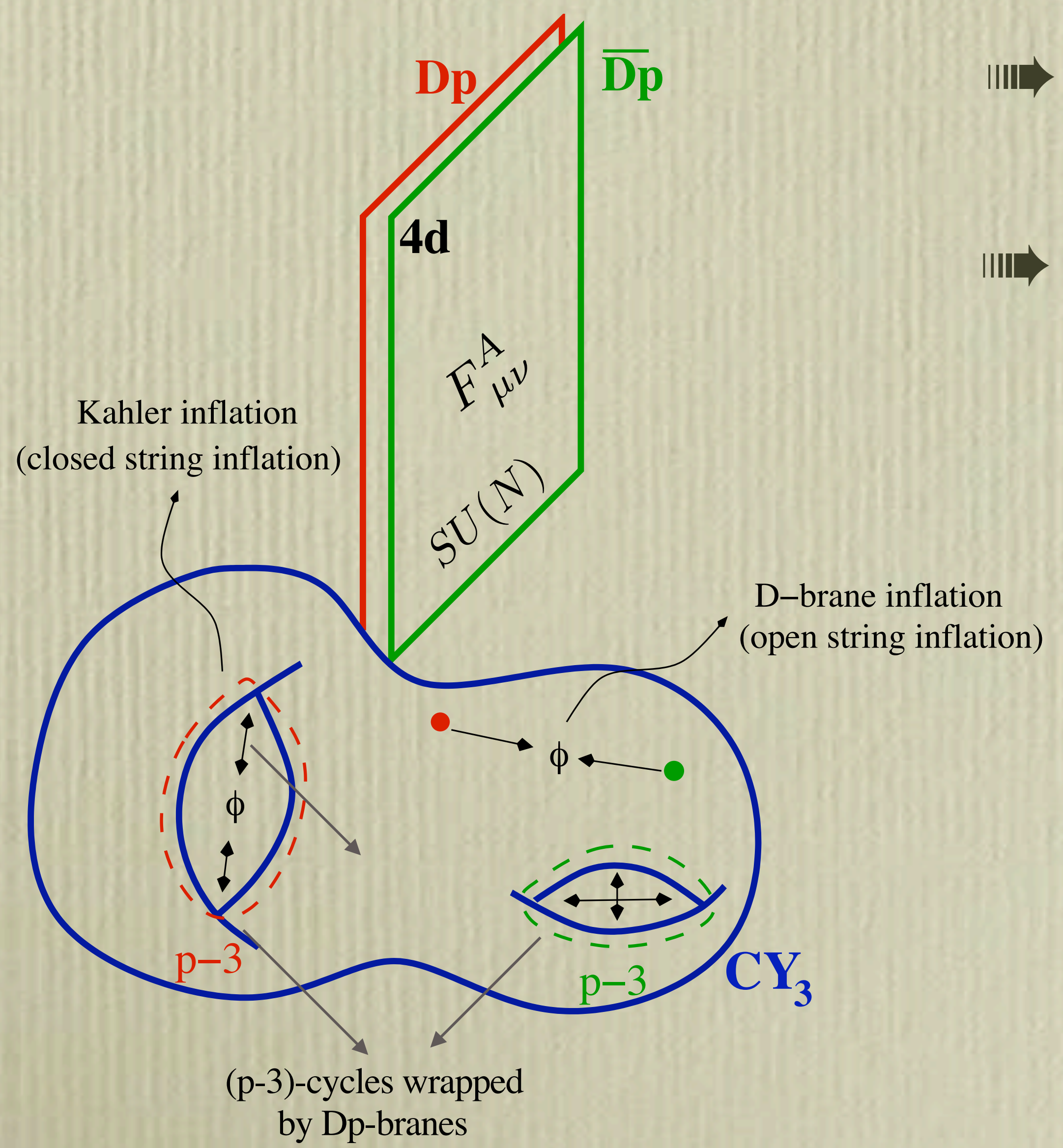
KÄHLER INFLATION AND SCNI

[Holland, IZ, Tasinato, '20]

We consider a *modified Kähler inflation* ($r \lesssim 10^{-7}$) model as host with *multiply wrapped magnetised D7-branes*, as spectator CN sector.

[Conlon-Quevedo, '05; Bond et al, '06; Blanco-Pillado et al., '09]

[Similar set up to: Long, L. McAllister, and P. McGuirk, '14; Ben-Dayan, F. G. Pedro, and A. Westphal , '15; McDonough, Alexander, 18]



➠ From SU(N) ☞ (N/2)SU(2) [Caldwell, Devulder, '17-18]

➠ This set-up contains three parameters that we can use to realise SCNI

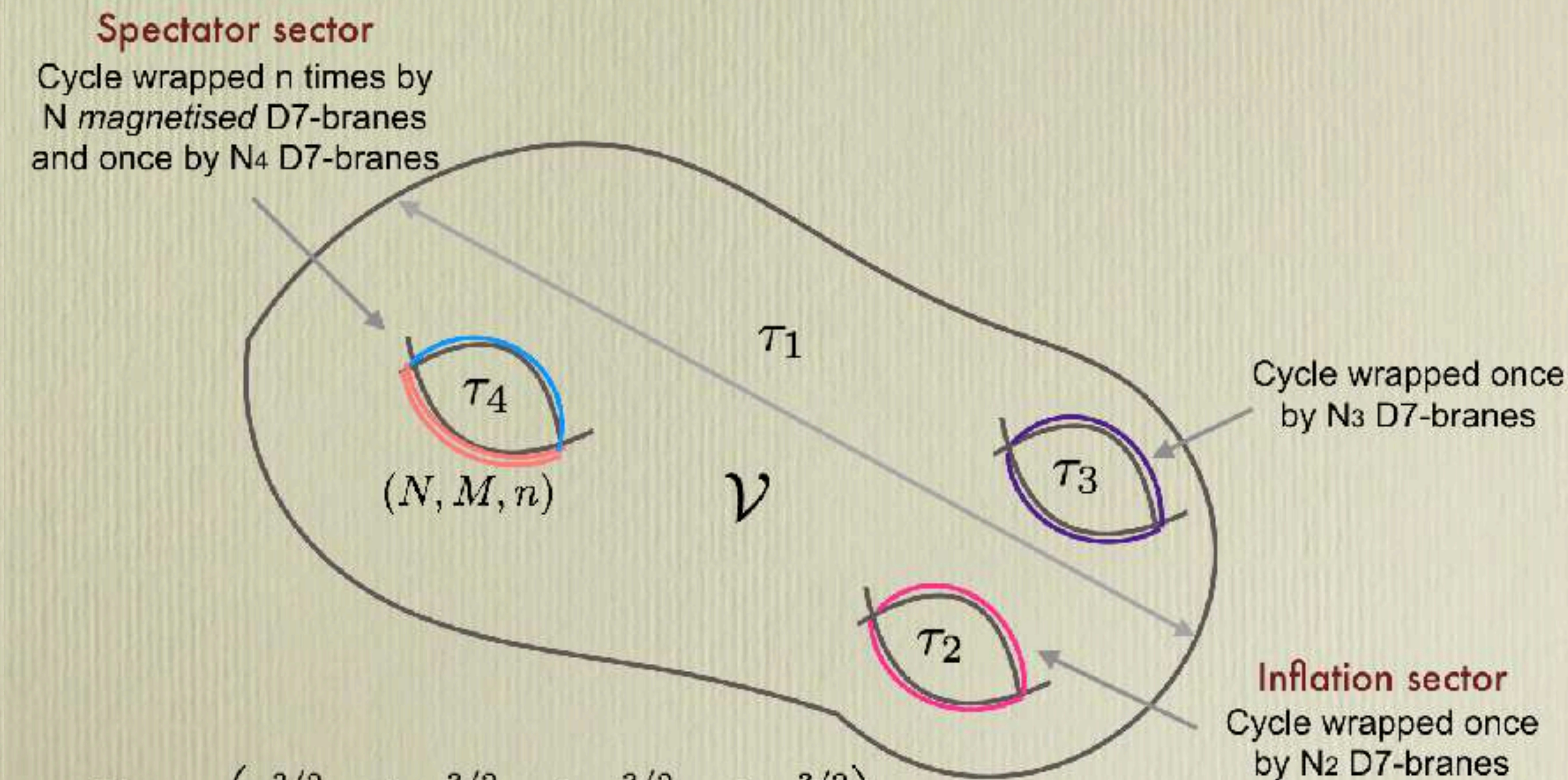
$$(N, M, n)$$

$N =$ condensing group degree

stringy parameters $\begin{cases} M = \text{D7-brane magnetic flux} \\ n = \text{D7-brane wrapping number} \end{cases}$

KÄHLER INFLATION AND SCNI

[Holland, IZ, Tasinato, '20]



$$\mathcal{V} = \alpha\left(\tau_1^{3/2} - \lambda_2\tau_2^{3/2} - \lambda_3\tau_3^{3/2} - \lambda_4\tau_4^{3/2}\right)$$

configuration cartoon

KÄHLER INFLATION AND SCNI

[Holland, IZ, Tasinato, '20]

- We aim at realising three goals when choosing the parameters of the model:

  - A successful cosmological background evolution
  - A sufficiently large enhancement of the tensor fluctuations which become chiral and potentially detectable by future experiments
  - A controllable backreaction from the tensor gauge fluctuations

KÄHLER INFLATION AND SCNI

[Holland, IZ, Tasinato, '20]

- The four dimensional $\mathcal{N}$=1 supergravity effective action including gauge fields is given by

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{Pl}^2}{2}R - K_{i\bar{j}}\partial_\mu T^i\partial^\mu \overline{T}^{\bar{j}} - V(T^k) - \frac{\mathrm{Re}(f_A(T^i))}{4}F^A_{\mu\nu}F^{A\,\mu\nu} + \frac{\mathrm{Im}(f_A(T^i))}{4}F^A_{\mu\nu}\tilde{F}^{A\,\mu\nu}\right]$$

$T_i =$ Kähler moduli

$K_{i\bar{j}}(T_i, \overline{T}_i) =$ scalar manifold metric

$F = dA - A\wedge A$ non-Abelian D7-brane gauge field

(the three lines above) Scalars and gauge field not canonically normalised

$f_A(T_i) =$ gauge kinetic function

$g^2 = 1/\mathrm{Re}(f_A)$ gauge coupling

$M_{Pl}^2 = 4\pi\mathcal{V}M_s^2/g_s^2$

[Holland, IZ, Tasinato, '20]

- The action in terms of the real fields relevant for inflation is

$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R-\frac{\gamma_{ab}(\phi^c)}{2}\partial_\mu\phi^a\partial^\mu\phi^b-V(\phi^a)-\frac{f(\phi^a)}{4}F^A_{\mu\nu}F^{A\,\mu\nu}+\frac{h(\phi^a)}{4}F^A_{\mu\nu}\tilde{F}^{A\,\mu\nu}\right]$$

Scalars and gauge field not canonically normalised

$$F=dA-\mathrm{g}A\wedge A\,,\quad \mathrm{g}\equiv 1/\sqrt{n\,N/2}\,,\quad \phi_a=M_{Pl}(\tau_2,\tau_4,b)$$

[Note that g is not the gauge coupling, which is given by $g^2=1/f(\phi^a)$]

$$f(\tau_4)=\tau_4,\qquad h(b)=Mb,$$

$N =$ condensing group degree

$M =$ D7-brane magnetic flux

$n =$ D7-brane wrapping number

$$\gamma_{ab}=\begin{pmatrix}\frac{3\alpha\lambda_2}{4\sqrt{\tau_2}\mathcal{V}} & 0 & 0\\ 0 & \frac{3\alpha\lambda_4}{4\sqrt{\tau_4}\mathcal{V}} & 0\\ 0 & 0 & \frac{2g_s\sqrt{\tau_4}}{\sqrt{\gamma}\mathcal{V}}\end{pmatrix}.$$

$$\gamma_{\tau_2\tau_2}(\tau_2)\,(\partial\tau_2)^2+\gamma_{\tau_4\tau_4}(\tau_4)\,(\partial\tau_4)^2+\gamma_{bb}(\tau_4)\,(\partial b)^2$$

$$V=\frac{e^{K_{cs}}(g_sM_{\rm Pl})^4}{8\pi}\left[V_2+V_4+\frac{3\xi W_0}{4\mathcal{V}^3}+\frac{\beta}{\mathcal{V}^2}+V_3\right]$$

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$$V_4=\frac{8\tilde{a}^2\tilde{A}^2\sqrt{\tau_4}}{3\alpha\lambda_4\mathcal{V}}e^{-\frac{2\tilde{a}}{m}\tau_4}+\frac{16\tilde{a}\tilde{A}a_4A_4\sqrt{\tau_4}}{3\alpha\lambda_4\mathcal{V}}e^{-(a_4+\frac{\tilde{a}}{m})\tau_4}\cos\left[a_4b_4-\tilde{a}\left(b+\frac{b_4}{m}\right)\right]$$
$$+\frac{4\tilde{a}\tilde{A}W_0\tau_4}{\mathcal{V}^2}e^{-\frac{\tilde{a}}{m}\tau_4}\cos\left[\tilde{a}\left(b+\frac{b_4}{m}\right)\right]+\frac{8(a_4A_4)^2e^{-2a_4\tau_4}\sqrt{\tau_4}}{3\alpha\lambda_4\mathcal{V}}$$
$$+\frac{4W_0a_4A_4e^{-a_4\tau_4}\cos\left(a_4b_4\right)\tau_4}{\mathcal{V}^2}$$

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$$S=\int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R-\frac{\gamma_{ab}(\phi^c)}{2}\partial_\mu\phi^a\partial^\mu\phi^b-V(\phi^a)-\frac{f(\phi^a)}{4}F^A_{\mu\nu}F^{A\,\mu\nu}+\frac{h(\phi^a)}{4}F^A_{\mu\nu}\tilde{F}^{A\,\mu\nu}\right]$$

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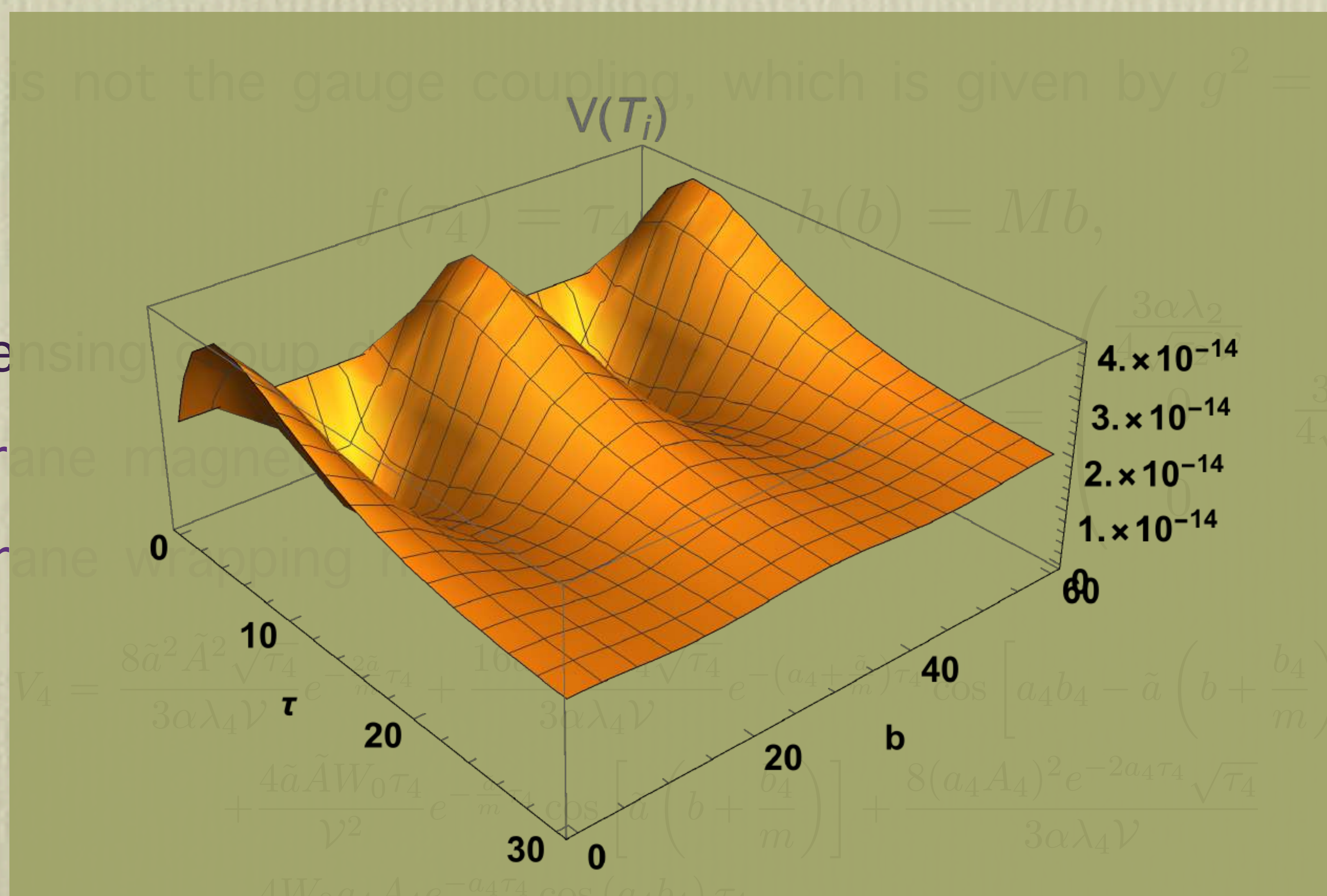


$N =$ conde...

$M =$ D7-br...

$n =$ D7-br...

$$+\frac{4W_0a_4A_4e^{-a_4\tau_4}\cos(a_4b_4)\,\tau_4}{\mathcal{V}^2}$$

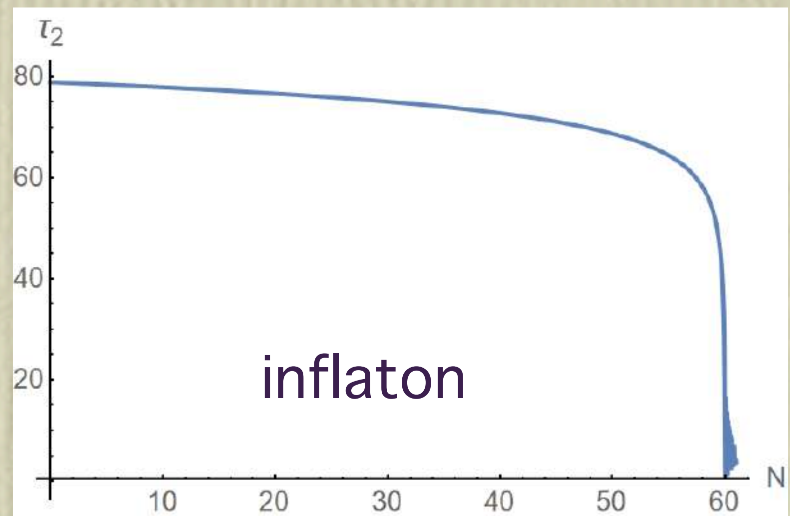
RESULTS

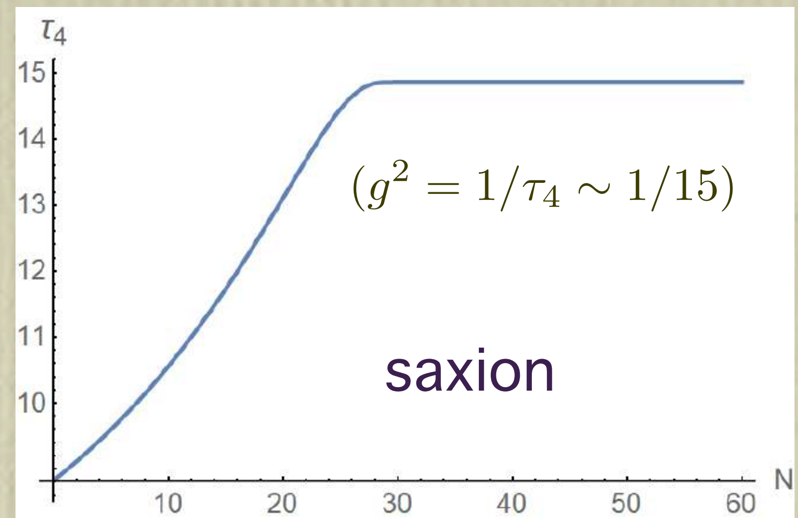
- For the following parameters's values:

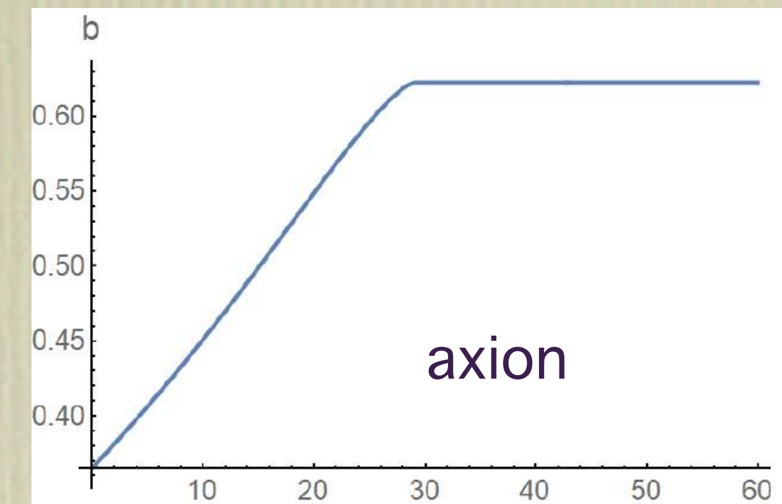
$$M = 10000,\ N \sim 10^5,\ n \sim 25 \qquad \left(g = \frac{1}{2000}\right)$$

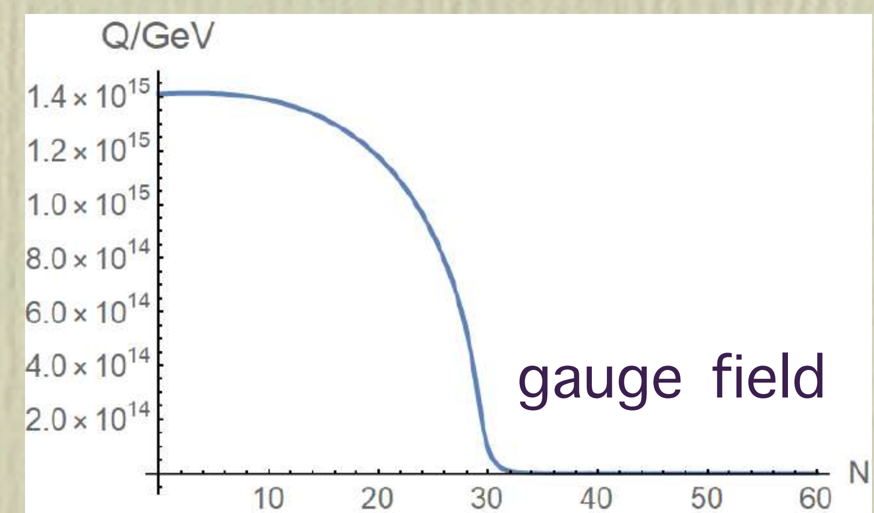
- We achieve our three objectives:
  - Successful cosmological evolution
  - Large enhancement of tensor spectrum and
  - Controllable backreaction

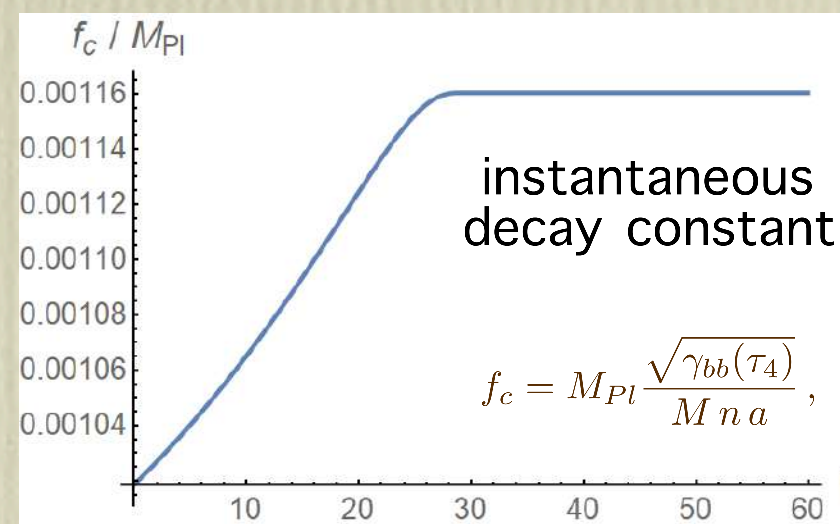
Successful cosmological evolution



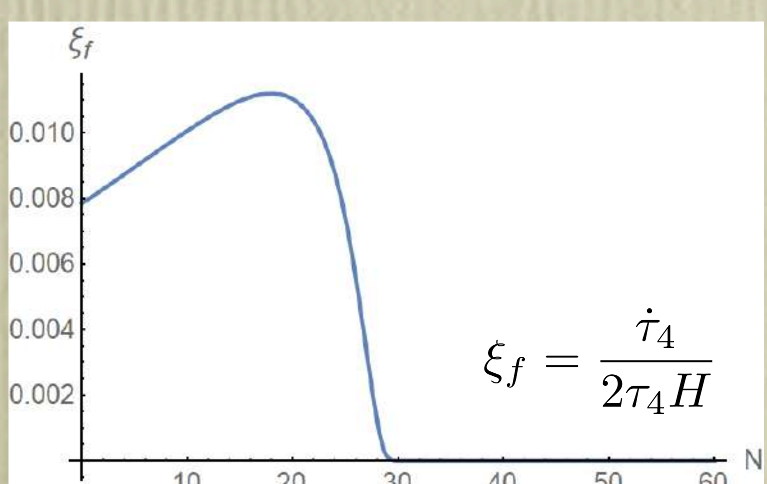


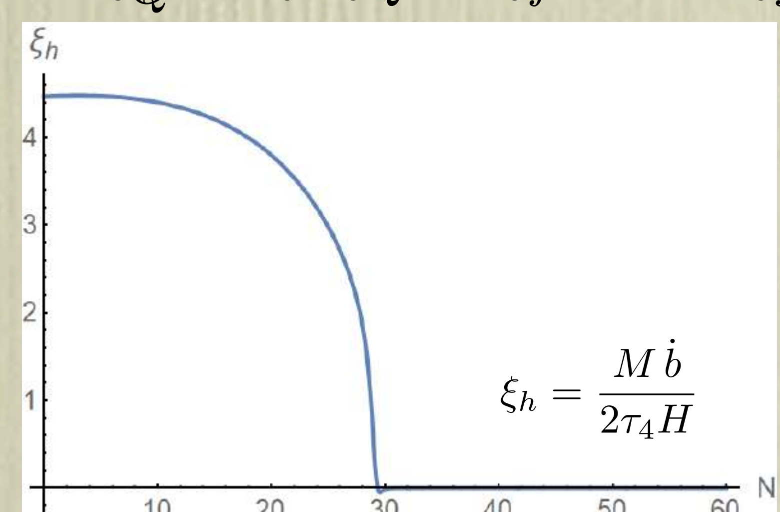


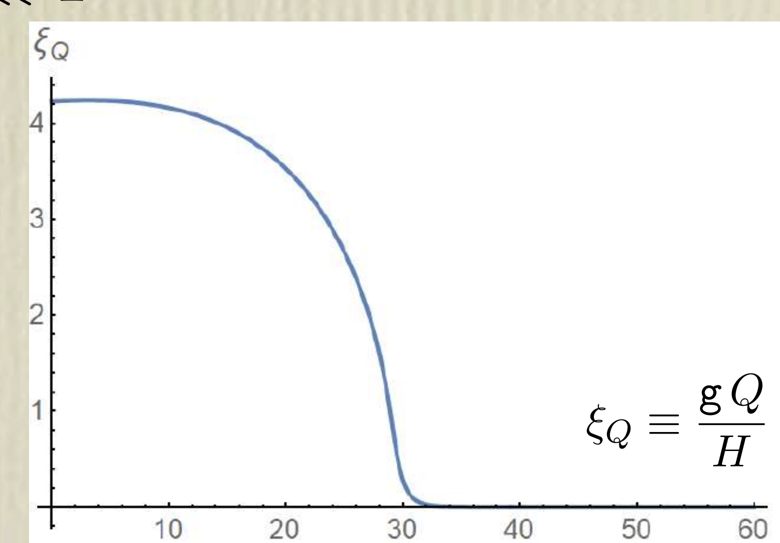




$$1 + \xi_Q^2 \simeq \xi_h \xi_Q - \xi_f \, , \qquad \xi_f \ll 1$$

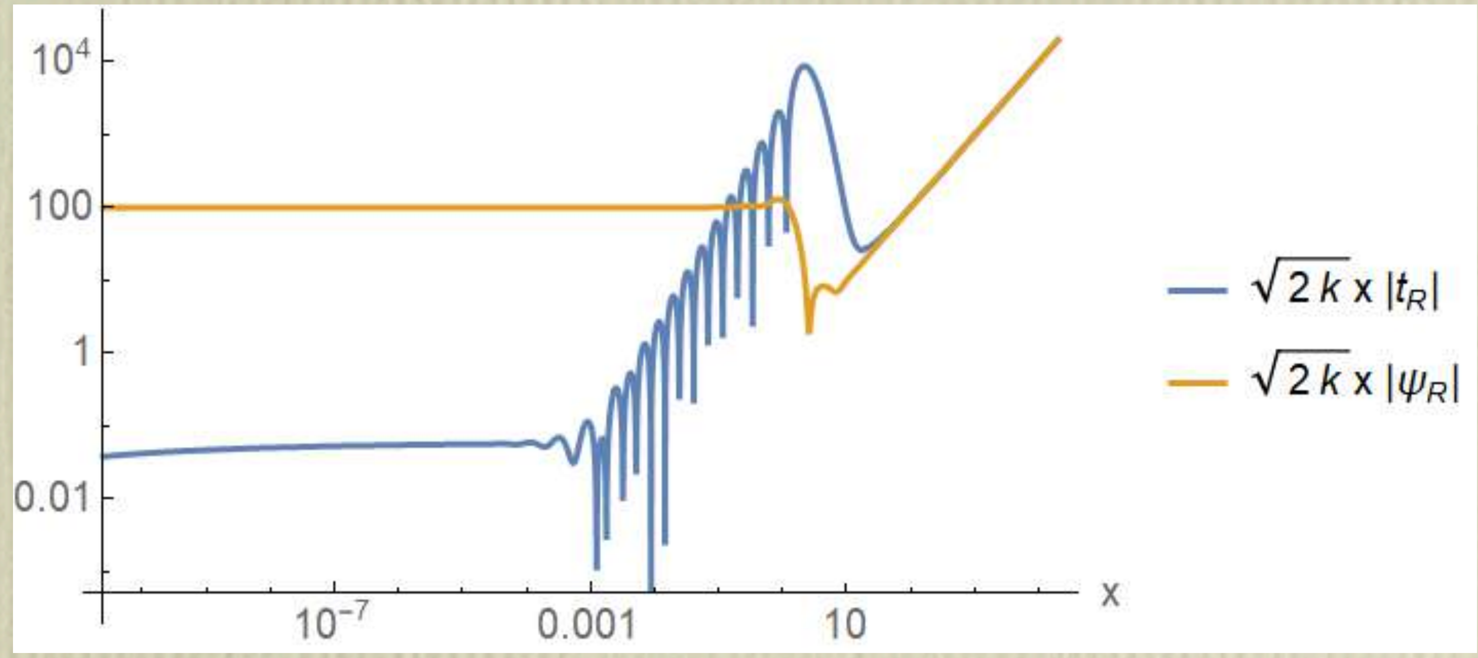




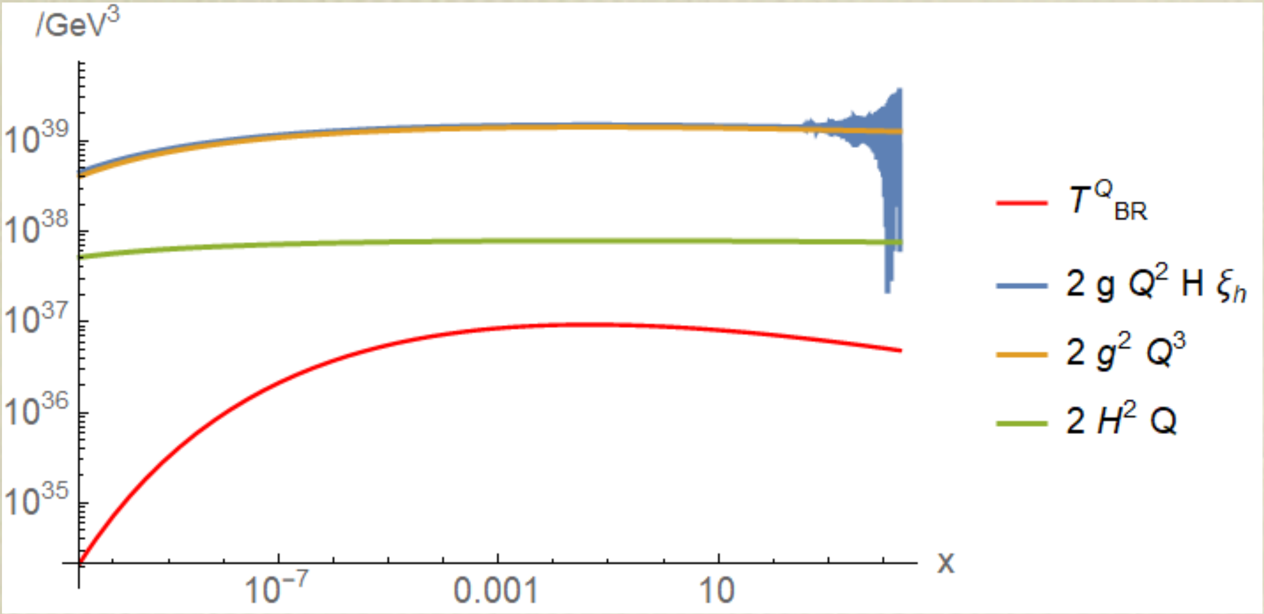


- Large enhancement of tensor spectrum

$$r_b = 4.48 \times 10^{-7} \longrightarrow r = 2.29 \times 10^{-3}$$



- Controllable backreation



RESULTS

- The values of the parameters however, represent a challenge for the string model construction

$$M = 10000,\ N \sim 10^5,\ n \sim 25$$

- Considering Fibre inflation as host, it is possible to improve on these values with a potentially observable chiral spectrum

$$M = 500,\ N = 5000,\ n = 1$$

$$r \sim 10^{-3} \to r \sim 10^{-2}$$

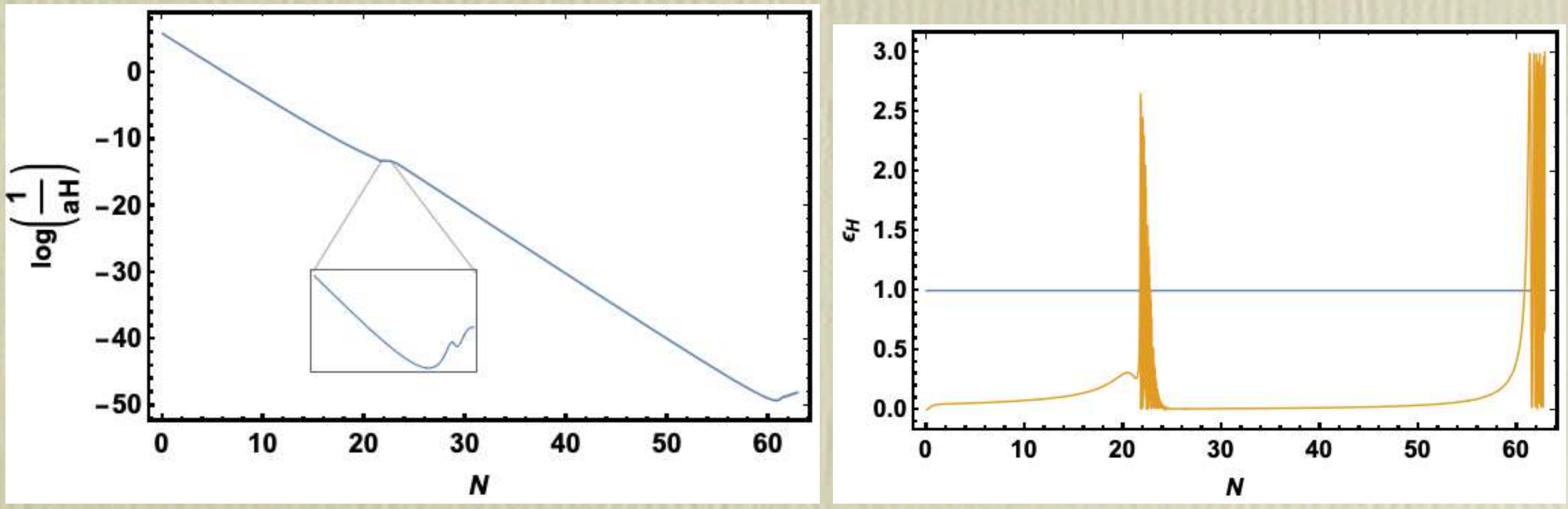
FURTHER DISCUSSION SLIDES ON MULTI-FIELD INFLATION

D5-BRANE DOUBLE INFLATION

[Chakraborty, Chiovoloni, Loaiza-Brito, Niz, IZ, '19]

- For a different choice of parameters one could have a double inflation model. Interesting phenomenological implications

N	g_s	q	u	ℓ_s	a_0	a_1	b_1	p
1000	0.01	70	$50\ell_s$	501.96	0.00025	10^{-5}	10^{-5}	53



- However initial condition for r is inconsistent with approximations.

DYNAMICS OF LINEAR PERTURBATIONS

- The dynamics of the linear perturbations and cosmological predictions will depend on the hierarchies of the adiabatic and entropy modes' masses relative to each other, the Hubble parameter and the turning rate Ω.

[Sasaki, Stewart, '96; Gordon, Wands, Bassett, Maartens, '00;
Groot Nibbelink, van Tent,'01; Langlois, Renaux-Petel, '08]
[Achucarro, Gong, Hardeman, Palma, Patil, '10;
Achucarro, Atal, Cespedes, Gong, Palma, Patil, '12;
Cespedes, Atal, Palma, '12 ...]

- The curvature of the scalar manifold $\mathbb{R}$ may also play an important role if negative and large, as it may trigger geometric destabilisation of the entropy modes

[Renaux-Petel, Turzynski, '15]

DYNAMICS OF LINEAR PERTURBATIONS

[Sasaki, Stewart, '96; Gordon, Wands, Bassett, Maartens, '00;
Groot Nibbelink, van Tent,'01; Langlois, Renaux-Petel, '08]

- The equations for the adiabatic and entropy modes is given by (Q_N, Q_T are the projections of the fluctuations Q_a)

$$\ddot{Q}_T + 3H\dot{Q}_T + \left(\frac{k^2}{a^2} + m_T^2\right) Q_T = (2\Omega Q_N)^{\cdot} - \left(\frac{\dot{H}}{H} + \frac{V_T}{\dot{\varphi}}\right) 2\Omega Q_N \,,$$

$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M^2\right) Q_N = -2\Omega\frac{\dot{\varphi}}{H}\dot{\mathcal{R}}$$

$$\left(\mathcal{R} = \frac{H}{\dot{\varphi}} Q_T\right)$$

where:

$$\frac{m_T^2}{H^2} \equiv -\frac{3}{2}\eta - \frac{1}{4}\eta^2 - \frac{1}{2}\epsilon\eta - \frac{1}{2}\frac{\dot{\eta}}{H}\,, \qquad \frac{M^2}{H^2} = \frac{V_{NN}}{H^2} + M_{\rm Pl}^2\,\epsilon\,\mathbb{R} - \frac{\Omega^2}{H^2}\,,$$

$$(\mathbb{R} = \mathrm{scalar's\ \ manifold\ \ curvature})$$

at superhorizon scales:

$$\ddot{Q}_N + 3H\dot{Q}_N + \underbrace{\left(M^2 + 4\Omega^2\right)}_{M_{eff}^2} Q_N \approx 0\,,$$

M_{eff}^2 is related to the adiabatic perturbations speed of sound

$$c_s^{-2} = \frac{M_{eff}^2}{M^2}$$

[Achucarro et al. 10-12]

LARGE TURNING RATE WITH SMALL ℝ

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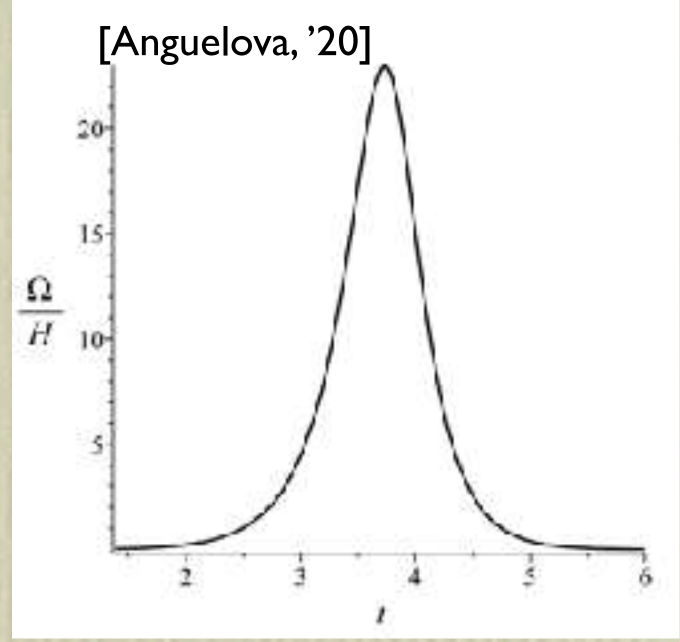
[Anguelova, Chen, Barausse, Braglia, Domenech, Finelli, Fumagalli, Hazra, Palma, Renaux-Petel, Riquelme, Ronayne, Scheihing, Sypsas, Slosar, Smoot, Sriramkumar, Starobinsky, Witkowski, Zenteno, ... '18-'21]



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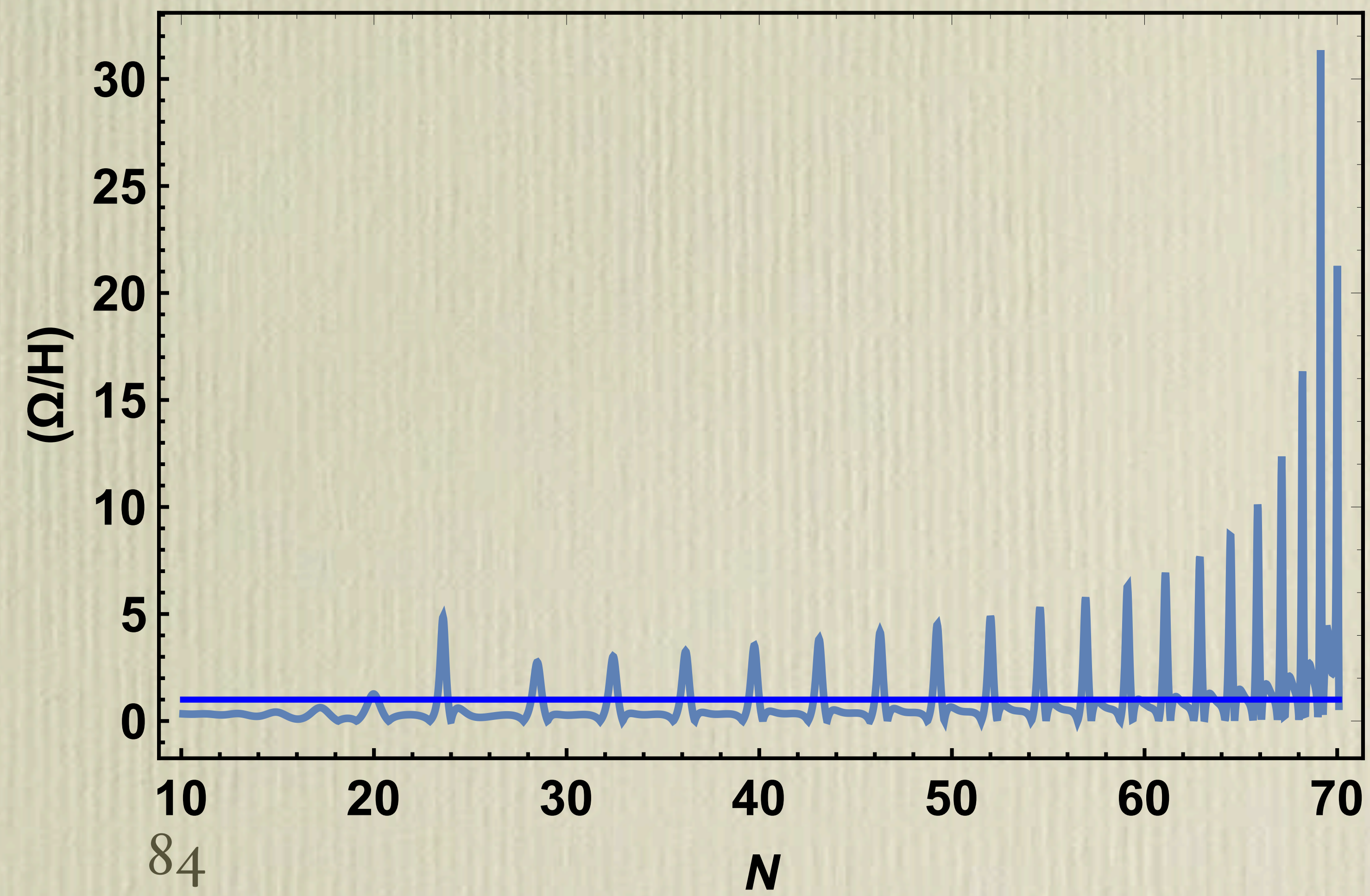
- A natural way to generate **transient large turns** in supergravity without large (negative) curvatures arises through **transient violations of slow-roll**

[Bhattacharya, IZ, in progress]

$$K = -\log[\Phi + \bar{\Phi} - S\bar{S}]\,,$$
$$(\mathbb{R} = -4)$$
$$W = S(M\Phi + ie^{-b\Phi})$$

[Cabo-Bizet, Loaiza-Brito, IZ, '16; Özsoy, Parameswaran, Tasinato, IZ, '18]



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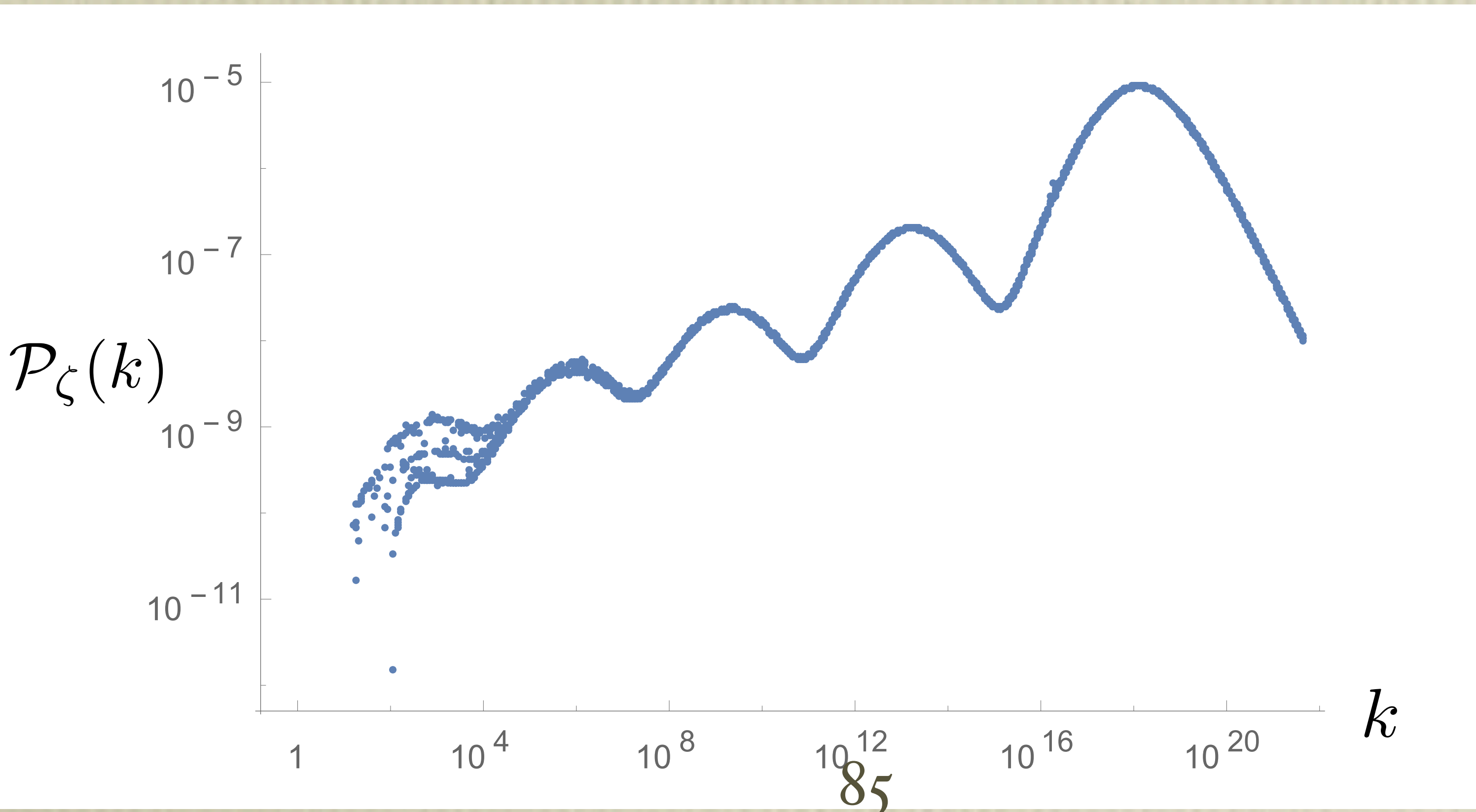
[Anguelova, Chen, Barausse, Braglia, Domenech, Finelli, Fumagalli, Hazra, Palma, Renaux-Petel, Riquelme, Ronayne, Scheihing, Sypsas, Slosar, Smoot, Sriramkumar, Starobinsky, Witkowski, Zenteno, ... '18-'21]

- A natural way to generate **transient large turns** in supergravity without large (negative) curvatures arises through **transient violations of slow-roll** [Bhattacharya, IZ, in progress]

- Enhancement of primordial spectra ➠ PBHs, PGWs



[See also Ketov, '21]