Nemanja Kaloper

Rollercoaster Cosmology

G. D'Amico, NK, 2011.09489
G. D'Amico, NK, A. Westphal, 2101.05861; 2112.13861

more in progress

An astronomer, a physicist and a mathematician are riding a train through Scotland.

The astronomer looks out the window, sees a black sheep, and exclaims,

``Hey! They've got black sheep in Scotland!”

The physicist looks out the window and corrects the astronomer,

``Strictly speaking, all we know is that there's at least one black sheep in Scotland."

The mathematician looks out the window and corrects the other two,

``Strictly speaking, all we know is that at least one side of one sheep is black in Scotland."

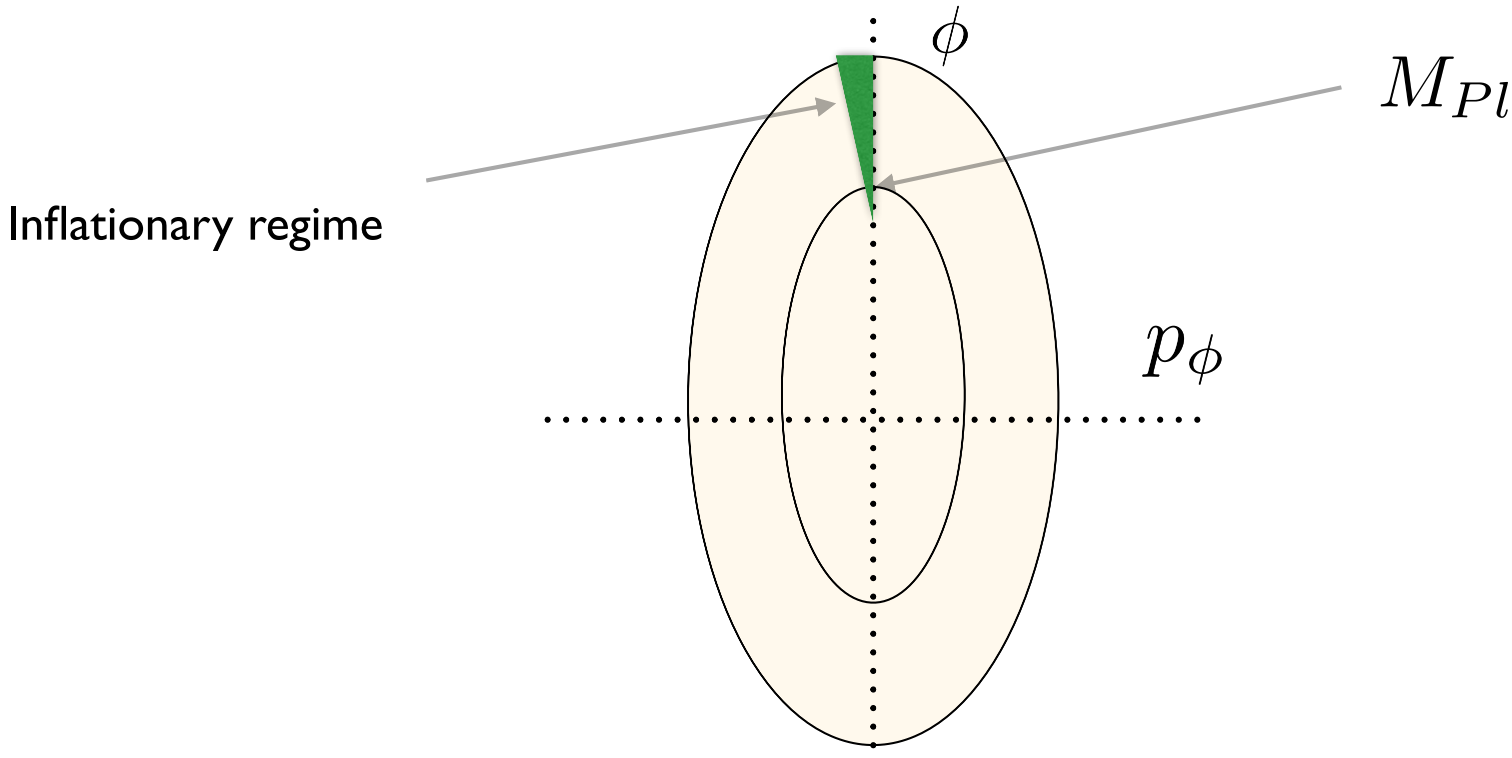
Inflation and Rollercoaster: A Lightning Review

- Prior to the advent of inflation: our universe a set of measure zero in GR (Collins & Hawking, 1973).
- Inflation: universe starts as a patch of dS space, whose (approximate) symmetries make it homogeneous and isotropic over large distances; one can translate this to mean one needs a spontaneously broken scaling symmetry!
- In semiclassical gravity: easy-peasy: a derivatively coupled inflaton with a flat potential, *et voila*
- Issues: experimental and theoretical
- Simple models tend to make too much gravity wave power
- EFT of inflation requires an approximate GLOBAL scaling symmetry; but Quantum Gravity thought to violate all global symmetries
- A possible way out - a repeated sequence of short bursts of acceleration!

Slow Roll Inflation

A. Linde, "Chaotic Inflation", 1983.

- Eg. quadratic potential $H = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}p_\phi^2$



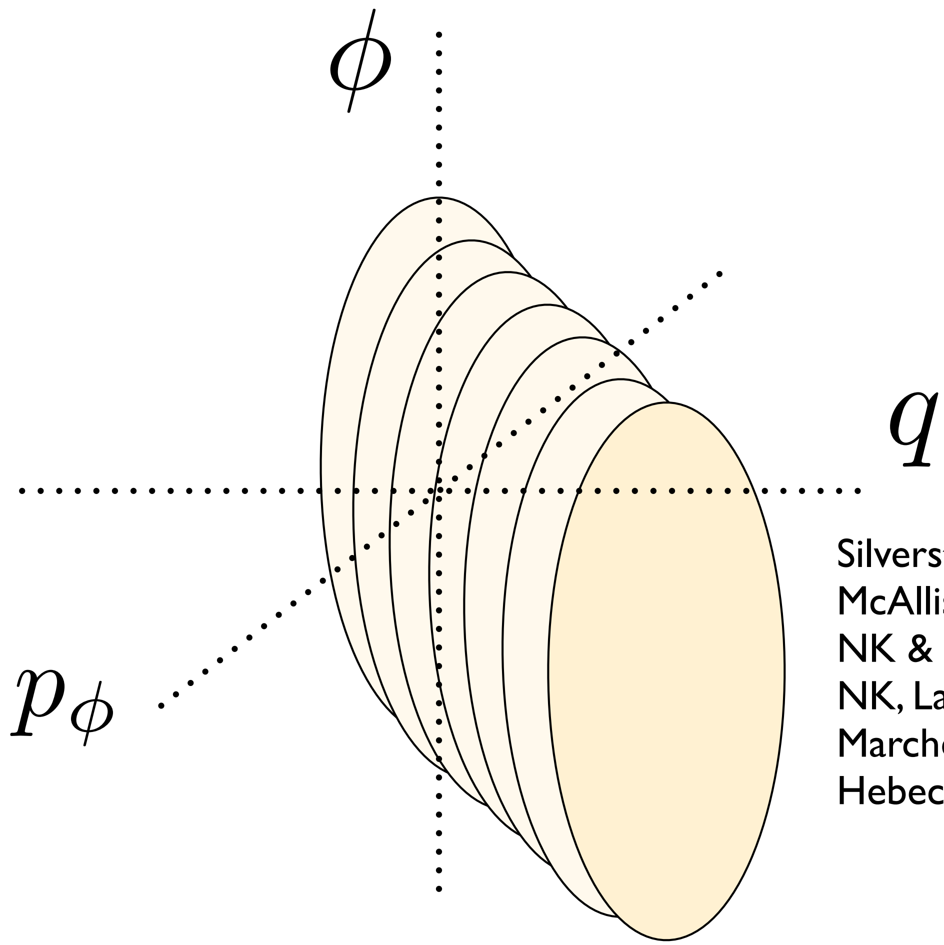
- Inflation occurs at large field vevs $\phi > M_{Pl}$; what about QG?

Monodromy Inflation

- The simplest physical realization: a particle in a magnetic field

$$-\frac{1}{2\cdot 4!}F_{\mu\nu\lambda\rho}F^{\mu\nu\lambda\rho}-\frac{1}{2}(\partial\phi)^2+\frac{\mu}{4!}\phi\epsilon^{\mu\nu\lambda\rho}F_{\mu\nu\lambda\rho} \longrightarrow \frac{1}{2}(q+\mu\phi)^2+\frac{1}{2}p_\phi^2$$

- Landau levels!



Silverstein & Westphal 2008;
McAllister, Silverstein & Westphal 2008;
NK & Sorbo 2008;
NK, Lawrence & Sorbo 2011;
Marchesano, Shiu, Uranga, 2014;
Hebecker, Rompineve, Westphal, 2015

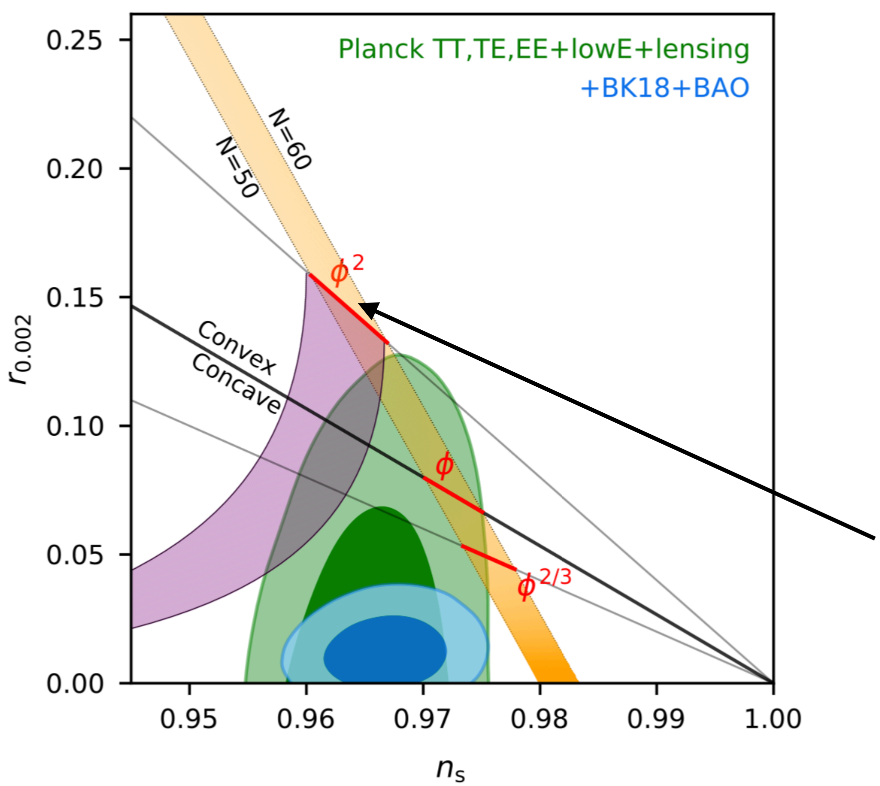
Fitting theory and data

- This can sort out issues with first principles constructions and can go around `*swampland conjectures*'
- Backreaction of large field variations: when monodromy works, backreaction flattens the potential — very helpful with suppressing gravity waves
- At the end, *data are the ultimate judge of theories*, and they are not kind… nor cruel. They are indifferent!

BICEP/*Keck: r < 0.036*

actual statement is…(p3!)

$$r = 0.014^{+0.010}_{-0.011}$$



Rollercoaster cosmology

- We relax *both theoretical worries and data issues: we shorten the field variation and we get redder spectrum, and weaker tensors*
- Observationally, we **do not need** 60 efolds in one go: we only probe the first 10-15 (the **one side** of **a** black sheep!)
- Accelerated expansion may stop and go; this looks like a soft tuning of a few parameters - not atypical for inflation.
- Bottomline: multiple stages of accelerated expansion just fine!
- So far we are only probing the first (CMB) stage - this is an **OPPORTUNITY**! CMB constraints on models will be modified and predictions for short-scale experiments have to be figured out

Right about now, some folks might think, "…but this isn't a radically new idea…"

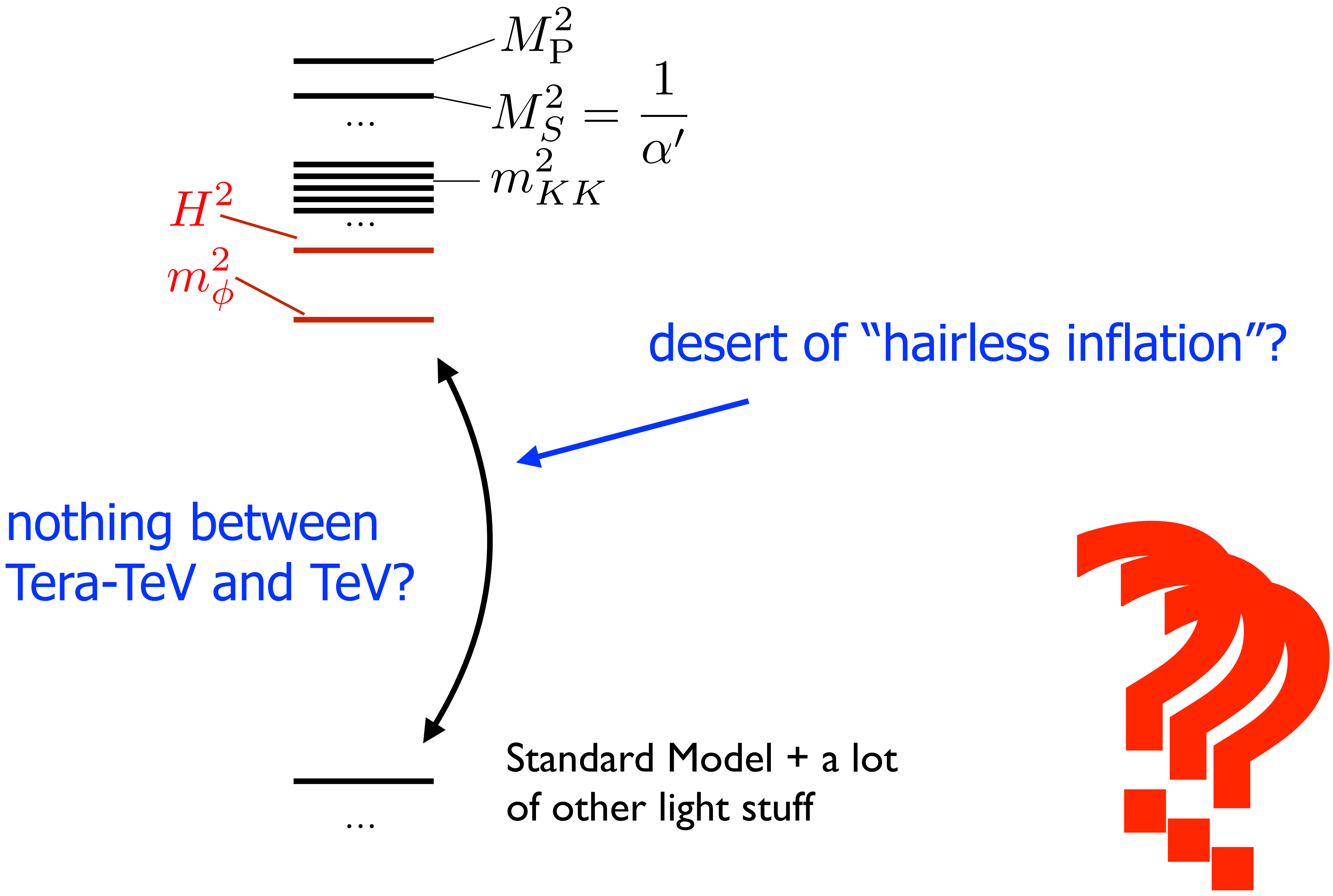
Mark Twain:

"There is no such thing as a new idea. It is impossible. We simply take a lot of old ideas and put them into a sort of mental kaleidoscope. We give them a turn and they make new and curious combinations. We keep on turning and making new combinations indefinitely; but they are the same old pieces of colored glass that have been in use through all the ages."

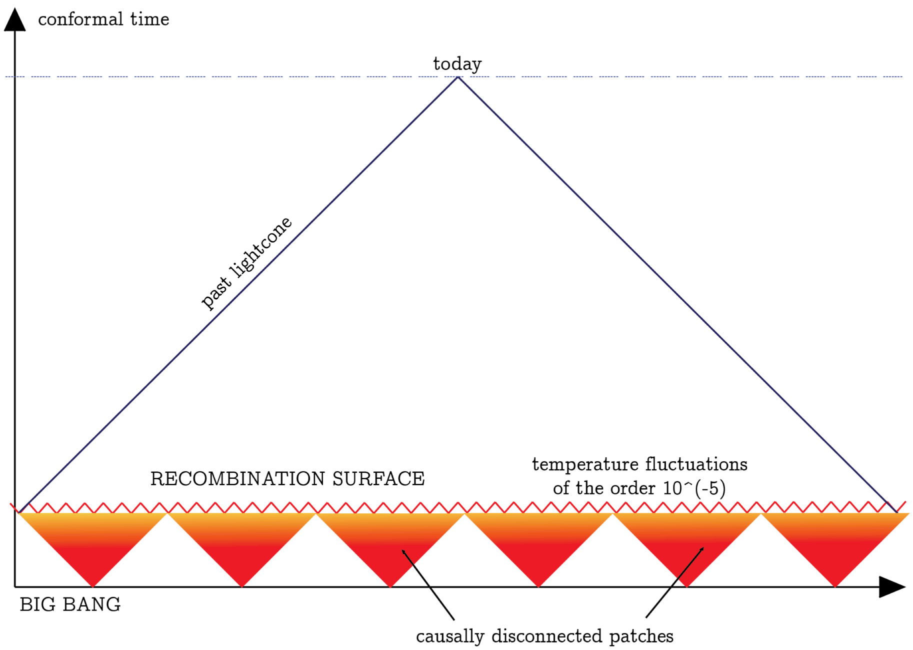
cf: check the refs in our paper arXiv:2011.09489 for precursors (Starobinsky, Linde, Mukhanov, Sarkar, Ross, Burgess…);

Our main new angle is we believe this should be taken **very** seriously right about **now** partly to respond to experimental/observational pressure, and partly to adjust to the changing and evolving theoretical prejudice…

“The World Spectrum” of long smooth inflation

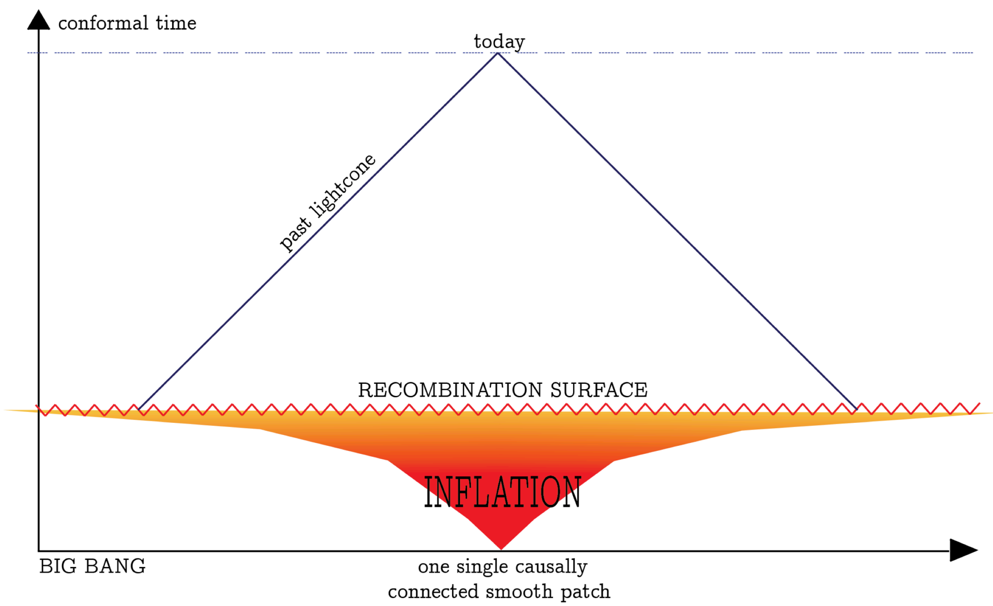


"Bring me that horizon..."

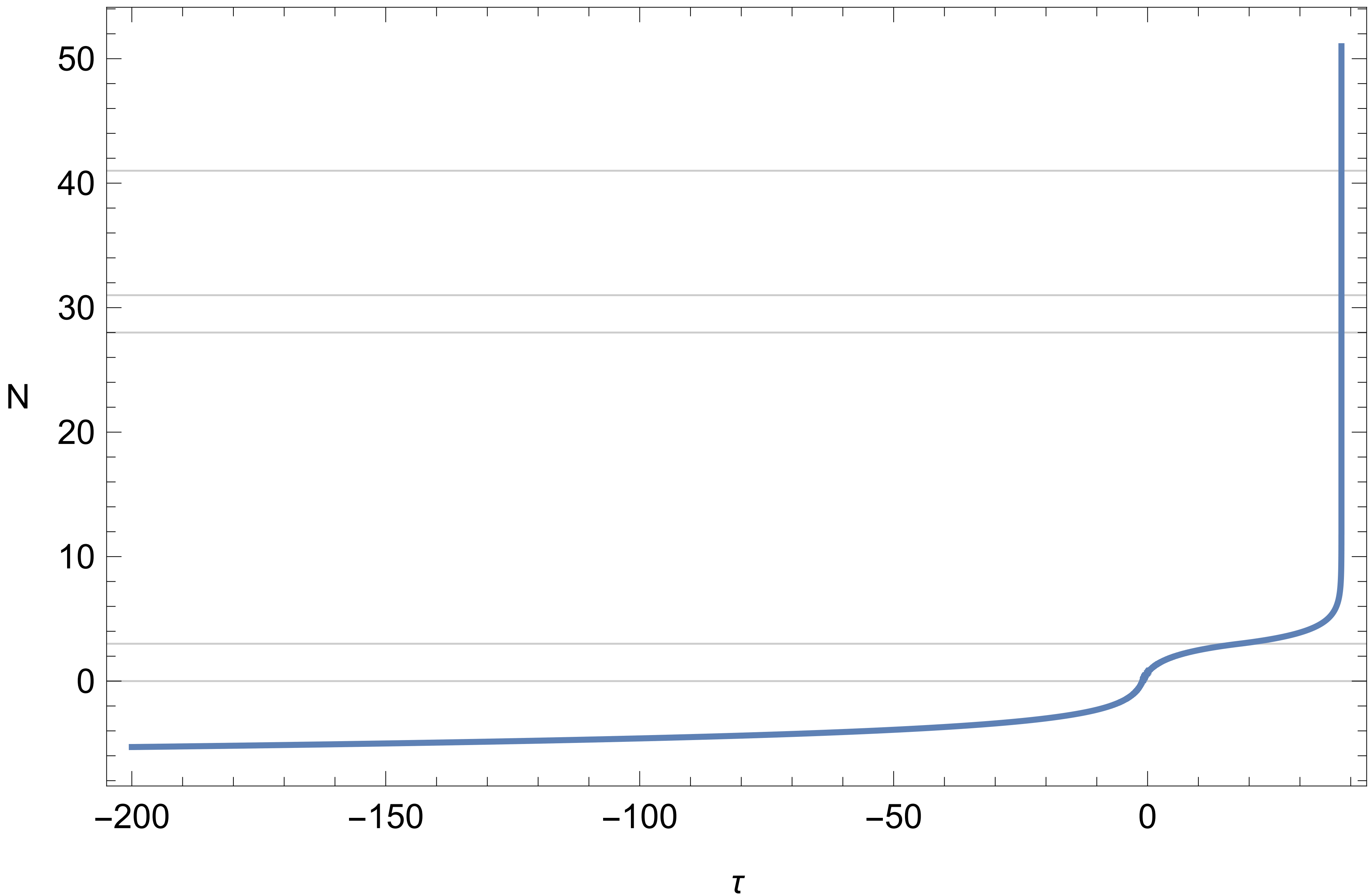


: PROBLEM

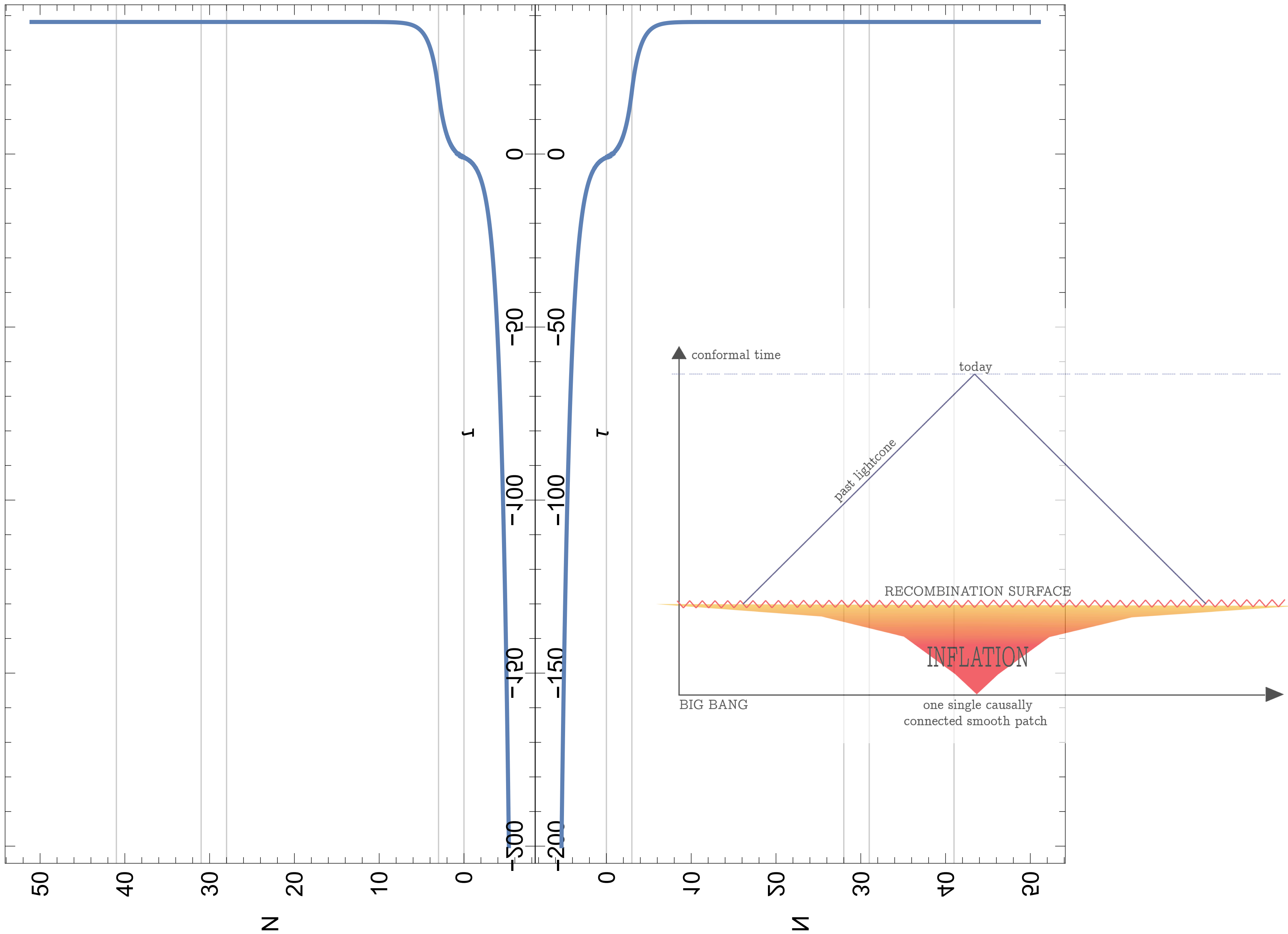
SOLUTION:



(a simplest) rollercoaster architecture



(even simpler) rollercoaster architecture II



The Horizon Problem

$$\ell(t) H_{\rm now} \sim \frac{a(t)}{a_{\rm now}} \qquad L_H = a(t) \int_{t_{\rm in}}^{t} \frac{{\rm d}t'}{a(t')}$$

$$\frac{\ell}{L_H} \sim t^{-\frac{w+1/3}{w+1}}$$

Normal matter

$$\frac{\ell}{L_H} \sim \text{const}$$

Inflation

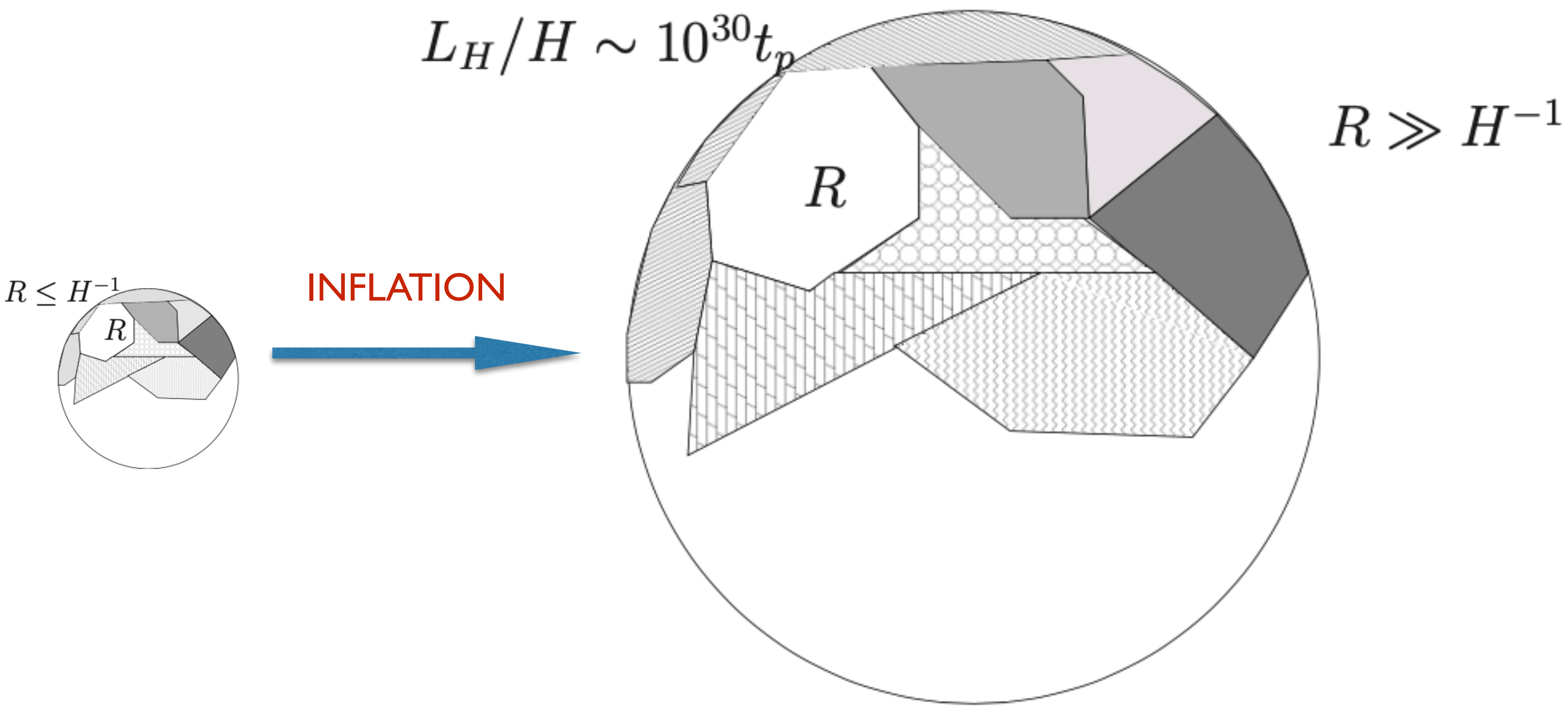
$$\int_{t_{\rm in}}^{t} \frac{{\rm d}t'}{a(t')} \simeq \frac{1}{\sqrt{H H_1}} \lesssim \frac{1}{H_1}$$

Rollercoaster, $H > H_1$ start and end of first interruption

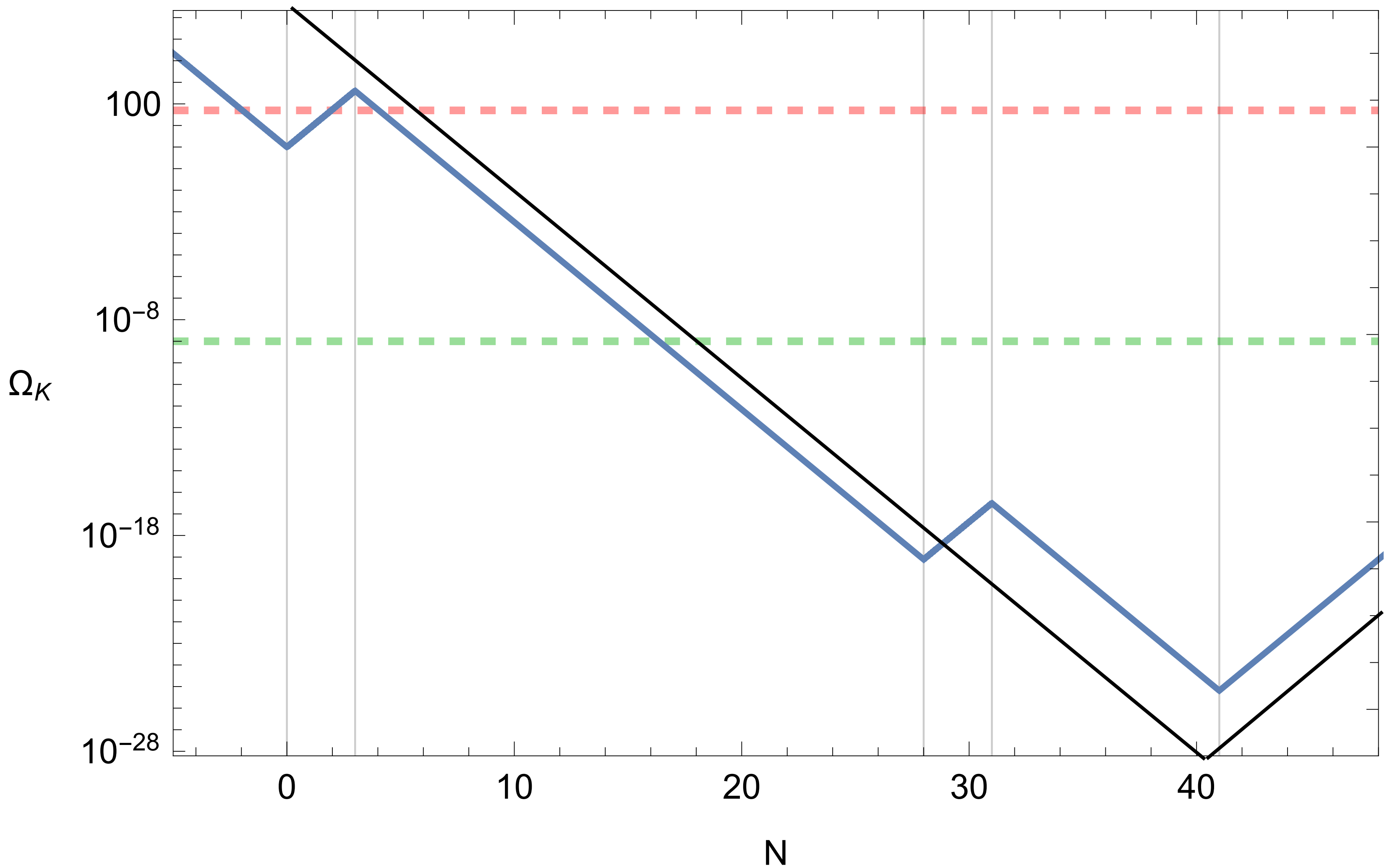
$$\frac{\ell}{L_H} \gtrsim l_{\rm in} H_1$$

This solves horizon problem in rollercoaster

The Curvature (and Homogeneity & Isotropy) Problem(s)



The Curvature Problem



The Curvature Problem

$$\frac{\Omega_{\mathrm{K},0}}{\Omega_{\mathrm{K},*}} = \left(\frac{H_*}{H_0}\right)^{2\frac{w+1/3}{w+1}}$$

Normal matter

$$\frac{\Omega_{\mathrm{K,end}}}{\Omega_{\mathrm{K,in}}} = \left(\frac{a_{\mathrm{in}}}{a_{\mathrm{fin}}}\right)^2 = e^{-2N}$$

Inflation

$$\frac{\Omega_{\mathrm{K,end}}}{\Omega_{\mathrm{K,in}}} = \frac{H_1}{H_{\mathrm{end}}} e^{-2N}$$

Rollercoaster

Perturbations

- Prototype: Starobinsky - as done by Chibisov and Mukhanov, 1982

$$S_{Starobinsky} \to \int d^4x \sqrt{g}\, c\, R^2$$

- This is GR + matter in disguise! ANY solution breaks scaling symmetry spontaneously so there is a Goldstone scalar; CC is an integration constant

$$\int d^4x \sqrt{g}\, c\, R^2 \equiv \int d^4x \sqrt{\tilde{g}} \Big(\frac{M_{Pl}^2(\text{eff})}{2} \tilde{R} - \frac{1}{2} (\tilde{\nabla}\phi)^2 - \Lambda(\text{eff}) \Big)$$

- *Fluctuating mode is buried in (or fed to) the curvature term*

$$M_{Pl}(\text{eff})^2 = 48 c H^2 \qquad \Lambda(\text{eff}) = 144 c H^4$$

$$\delta\phi = \sqrt{\frac{c}{2}} \frac{\delta R}{H} = \frac{\varphi}{a}$$

- *The **challenge** is to get scaling symmetry from full UV theory - aka quantum gravity - and not have it too disrupted*

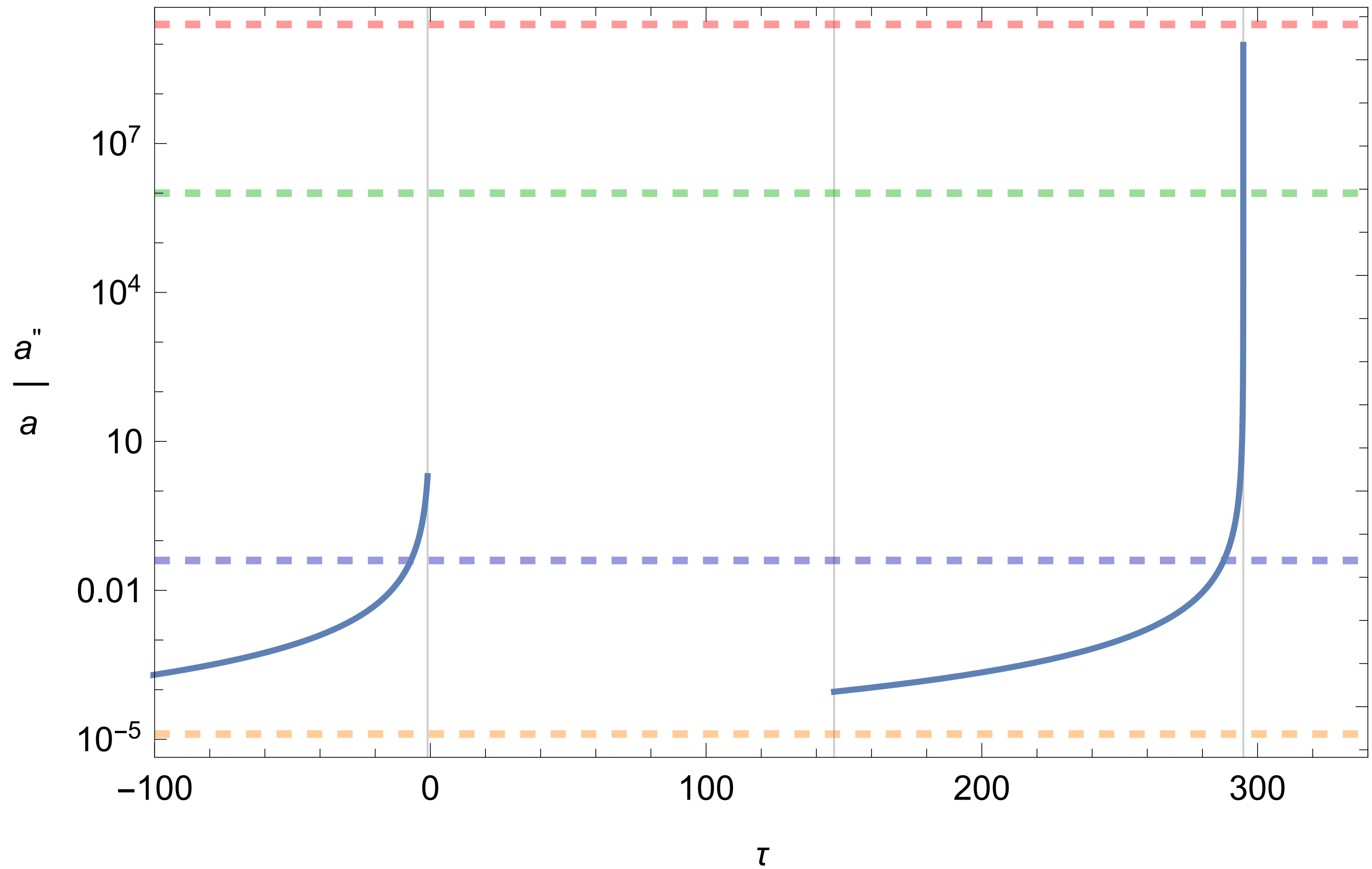
Perturbations II

$$u_k'' + \left(k^2 - \frac{a''}{a}\right) u_k = 0$$

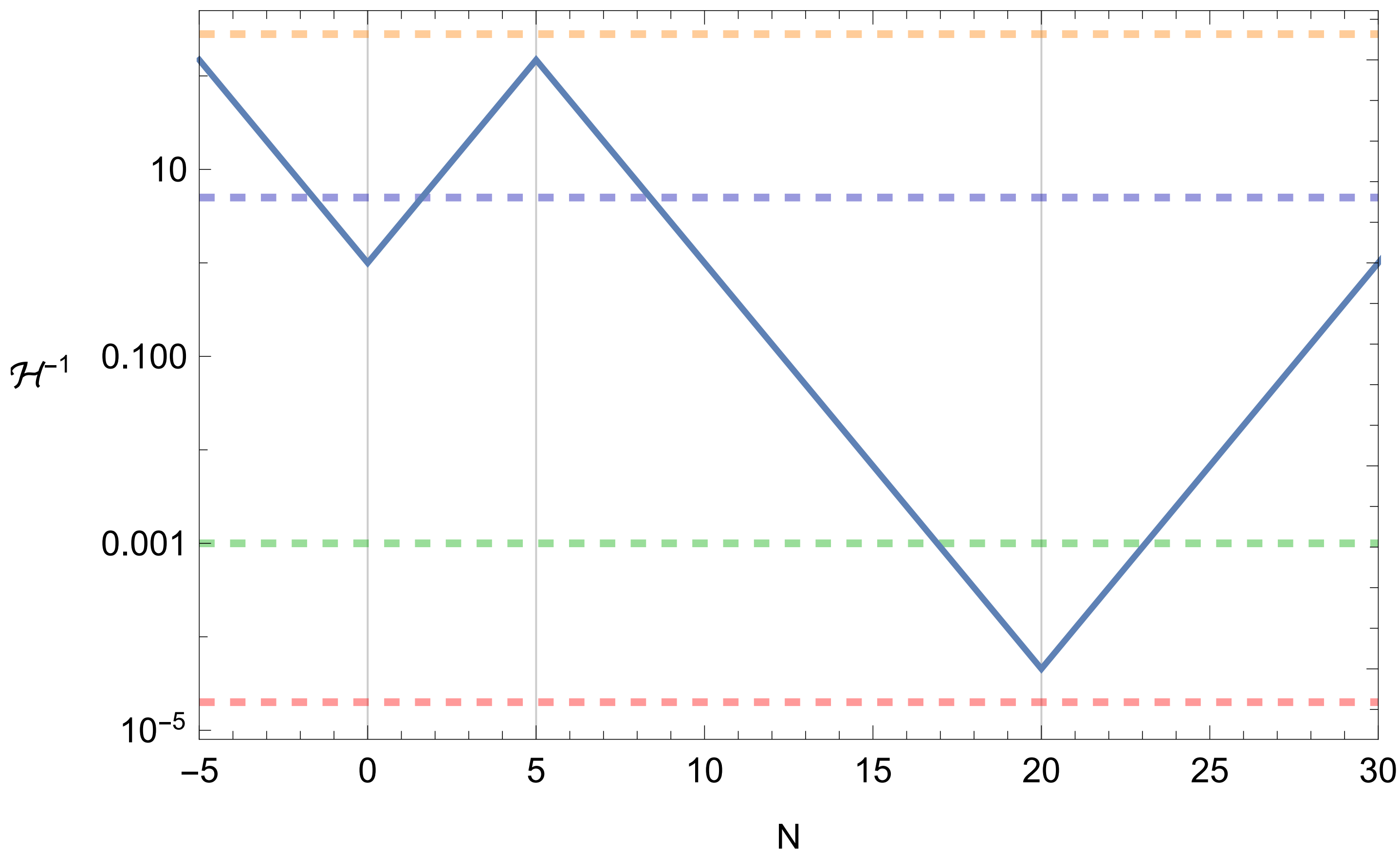
The same as Schroedinger's eq., but with anti-tunnelling bc!

$$u_k(\tau_-) = u_k(\tau_+)$$
$$u_k'(\tau_-) = u_k'(\tau_+)$$

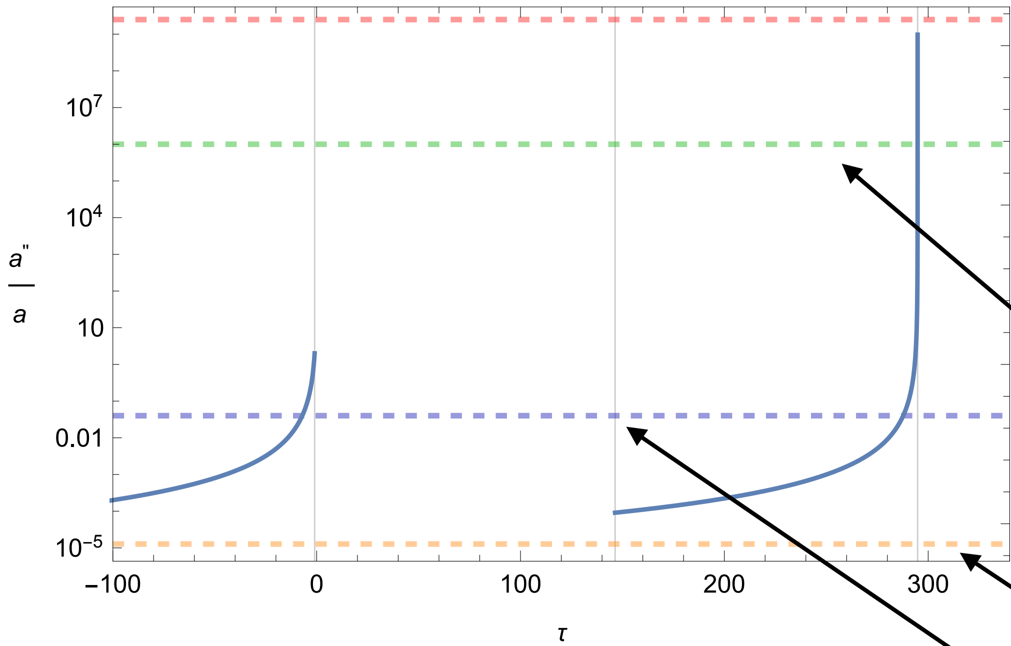
G. Breit, 1928: ZITTERBEWEGUNG



Cosmologia con quattro stagioni

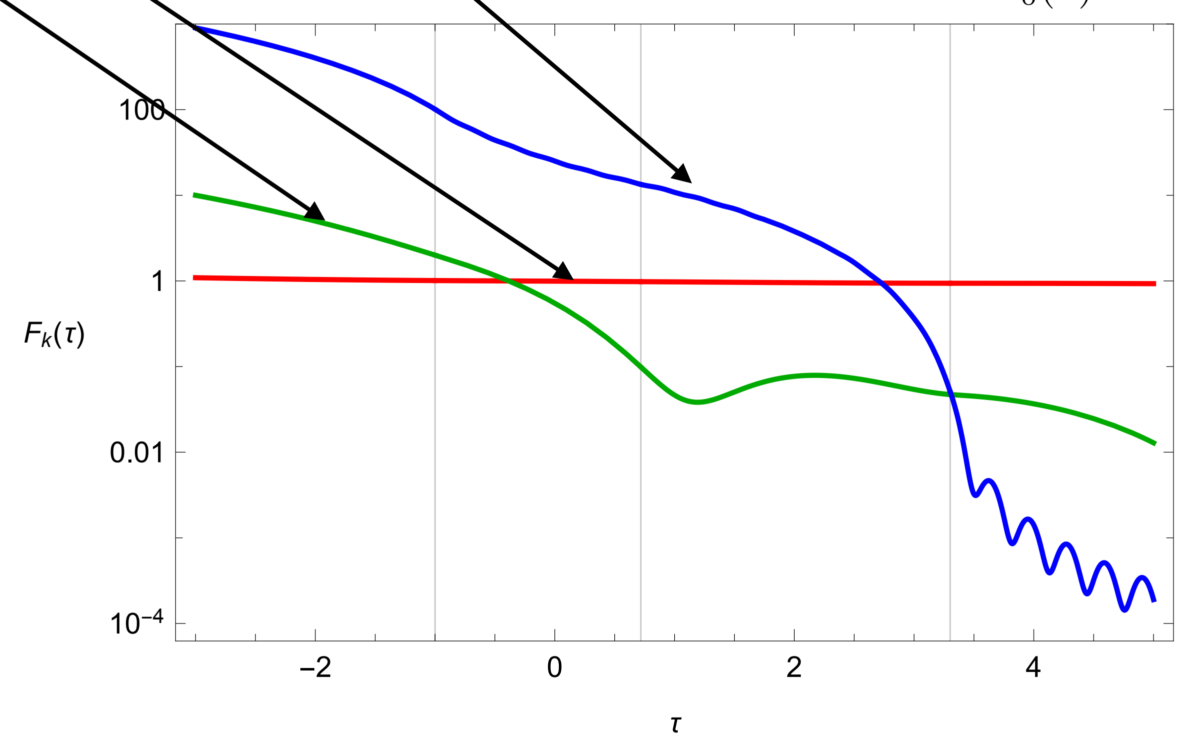


Cosmologia con quattro stagioni



(color coding flipped! 🙁)

$$F(k) = \frac{P(k)}{P_0(k)}$$

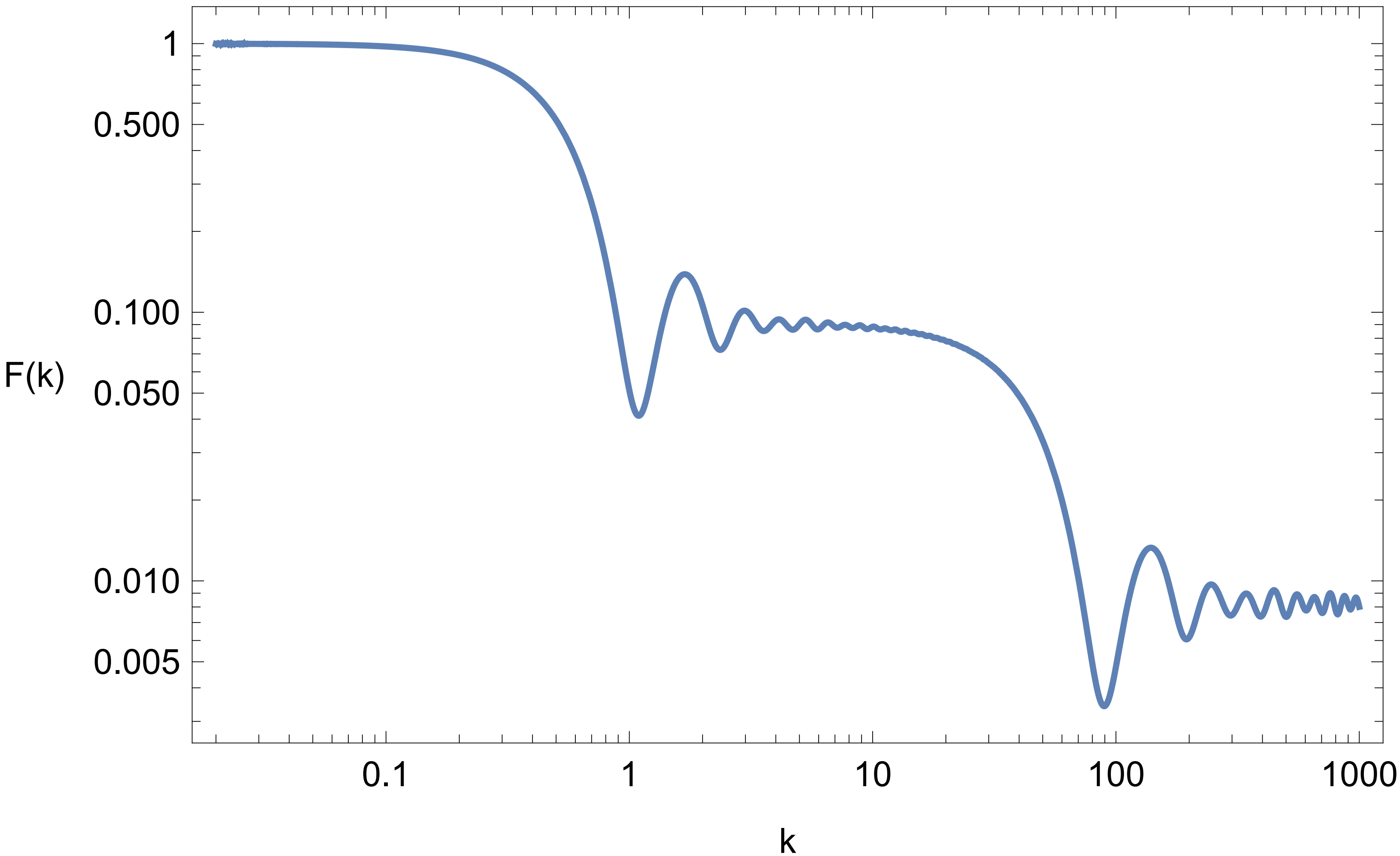


$$P_S = \left(\frac{H_j}{\dot{\phi}_j}\right)^2 |\varphi_k|^2_{\text{ren.}} = \left(\frac{H_j^2}{2\pi\dot{\phi}}\right)^2$$

$$P_T = \frac{2|h_k|^2_{\text{ren.}}}{M_{\text{Pl}}^2} = \frac{2H_j^2}{(2\pi)^2 M_{\text{Pl}}^2}$$

$$k < H_j$$

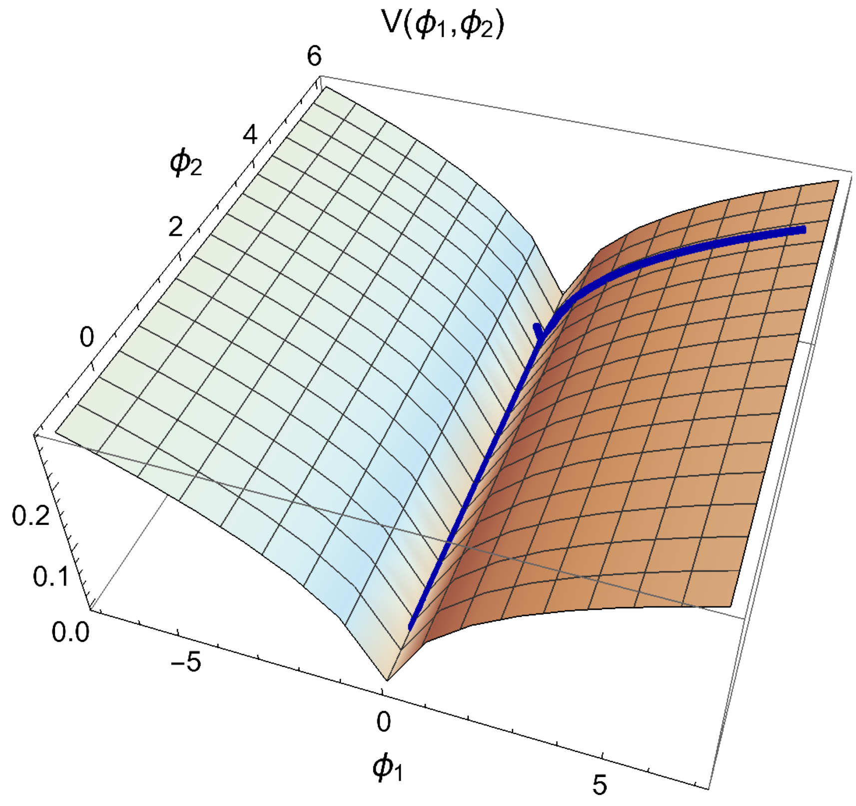
Power spectrum, more realistic case



A Humble Beginning: Doublecoaster Cosmology

Two stages of monodromy inflation, separated by matter domination when the first ends; this is motivated by string constructions

$$V(\phi_1, \phi_2) = M_1^4 \left[\left(1 + \frac{\phi_1^2}{\mu_1^2} \right)^{p_1/2} - 1 \right] + M_2^4 \left[\left(1 + \frac{\phi_2^2}{\mu_2^2} \right)^{p_2/2} - 1 \right] \qquad \begin{array}{l} M_1 > M_2 \\ \mu_i \sim \mathcal{O}(0.1 M_{\rm Pl}) \end{array}$$



D'Amico, NK & Westphal

- reduced field ranges
- probably more generic in UV setups

Monodromy at Strong Coupling

Hard; but we can use EFT methods developed for heavy quarks - specifically Naive Dimensional Analysis + gauge symmetries

Georgi & Manohar

Monodromies naturally arise from massive 4-forms, which make gauge symmetries manifest, which helps organize the EFT expansion; these ideas were pioneered by Julia & Toulouse; Aurilia & Nicolai & Townsend; Veneziano & de Vecchia; Quevedo & Truegenberger; Dvali; ...

The massive 4-form have one propagating dof, a massive axion; we can dualize to this axial gauge. We normalize operators using NDA.

NK & Lawrence

$$\phi \to \frac{4\pi\phi}{M}, \qquad \partial, m \to \frac{\partial}{M}, \frac{m}{M}$$

$$Q \propto m\phi \quad \text{by gauge symmetry :} \quad Q \to \frac{4\pi Q}{M^2}$$

$$\text{overall normalization : } \mathcal{L} \to \frac{M^4}{(4\pi)^2}\mathcal{L}_{dimensionless}$$

$$\text{restore combinatorial factors to reproduce Feynman diagrams}$$

$$\left(4! \times 3! \simeq (4\pi)^2\right)$$

Doublecoaster + Higher Derivatives

In addition to flattening strong coupling also induces higher derivative operators correcting kinetic terms

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}(m\phi+Q)^2 - \sum_{n>2} c'_n \frac{(m\phi+Q)^n}{n!(\frac{M^2}{4\pi})^{n-2}}$$
$$-\sum_{n>1} c''_n \frac{(\partial_\mu\phi)^{2n}}{2^n n!(\frac{M^2}{4\pi})^{2n-2}} - \sum_{k\geq1,l\geq1} c'''_{k,l} \frac{(m\phi+Q)^l}{2^k k!l!(\frac{M^2}{4\pi})^{2k+l-2}}(\partial_\mu\phi)^{2k}$$

Note that the symmetries control the expansion; c ~ O(1)

$$\frac{M^4}{16\pi^2}\frac{1}{n!}\Big(\frac{4\pi m\varphi}{M^2}\Big)^n, \qquad \frac{M^4}{16\pi^2}\frac{1}{2^n n!}\Big(\frac{16\pi^2(\partial_\mu\phi)^2}{M^2}\Big)^n \qquad \varphi = \phi + Q/m$$

This means the axial gauge action is

$$\mathcal{L} = -\frac{M^4}{16\pi^2}\mathcal{K}\Big(\frac{4\pi m\varphi}{M^2}, \frac{16\pi^2 X}{M^4}\Big) - \frac{M^4}{16\pi^2}\mathcal{V}_{eff}\Big(\frac{4\pi m\varphi}{M^2}\Big), \qquad X = (\partial\varphi)^2$$

EFT of strongly coupled monodromy is a special case of k-inflation! Mukhanov et al

(not surprising since k-inflation is designed as EFT avatar of inflation)

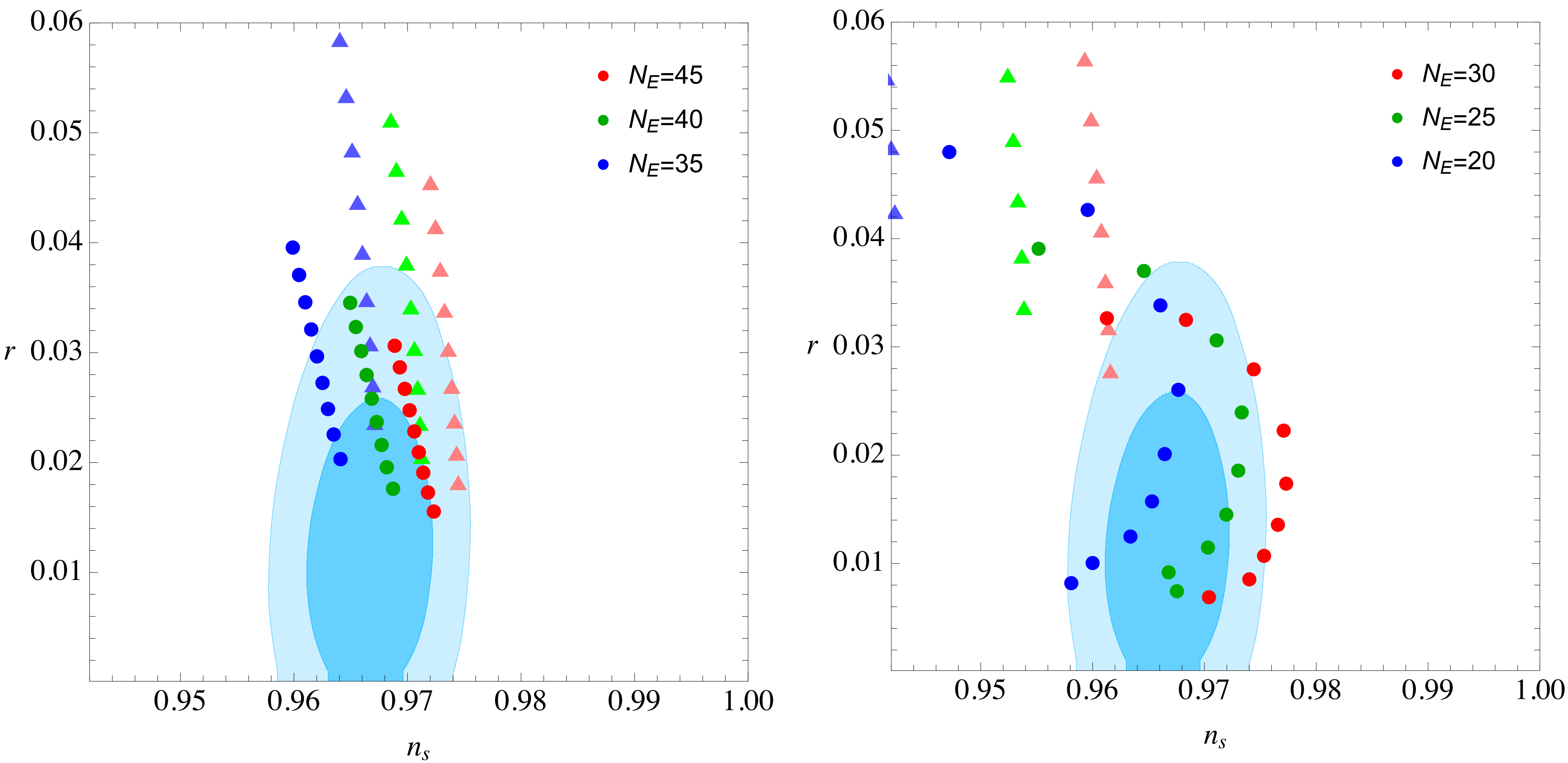
D'Amico, NK, Lawrence
1709.07014 [hep-th]

Doublecoaster + Higher Derivatives

There are also irrelevant operators with derivatives, as this is dictated by naturalness of the EFT…

- They generate non-gaussianities
- The stronger the coupling the larger the nonlinearities…
- But non-gaussianities cannot be much larger than O(1)!
- So coupling cannot be excessively strong
- But the stronger the coupling, the smaller the tensors… (flattening!)
- THIS IMPLIES A LOWER BOUND ON r !!!

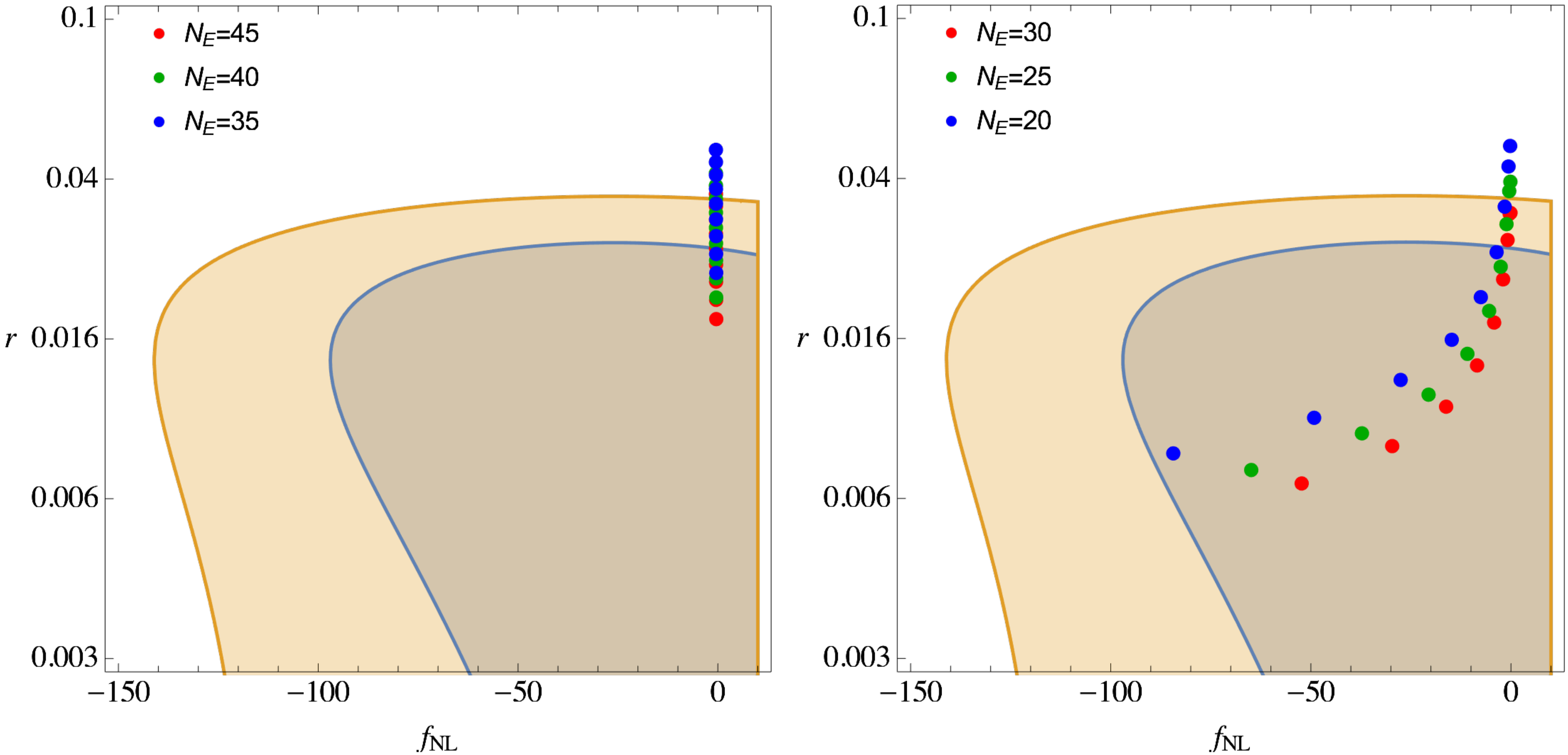
Simple monodromy mimicry again!



$0.96 < n_s < 0.97$ $0.006 < r < 0.035$

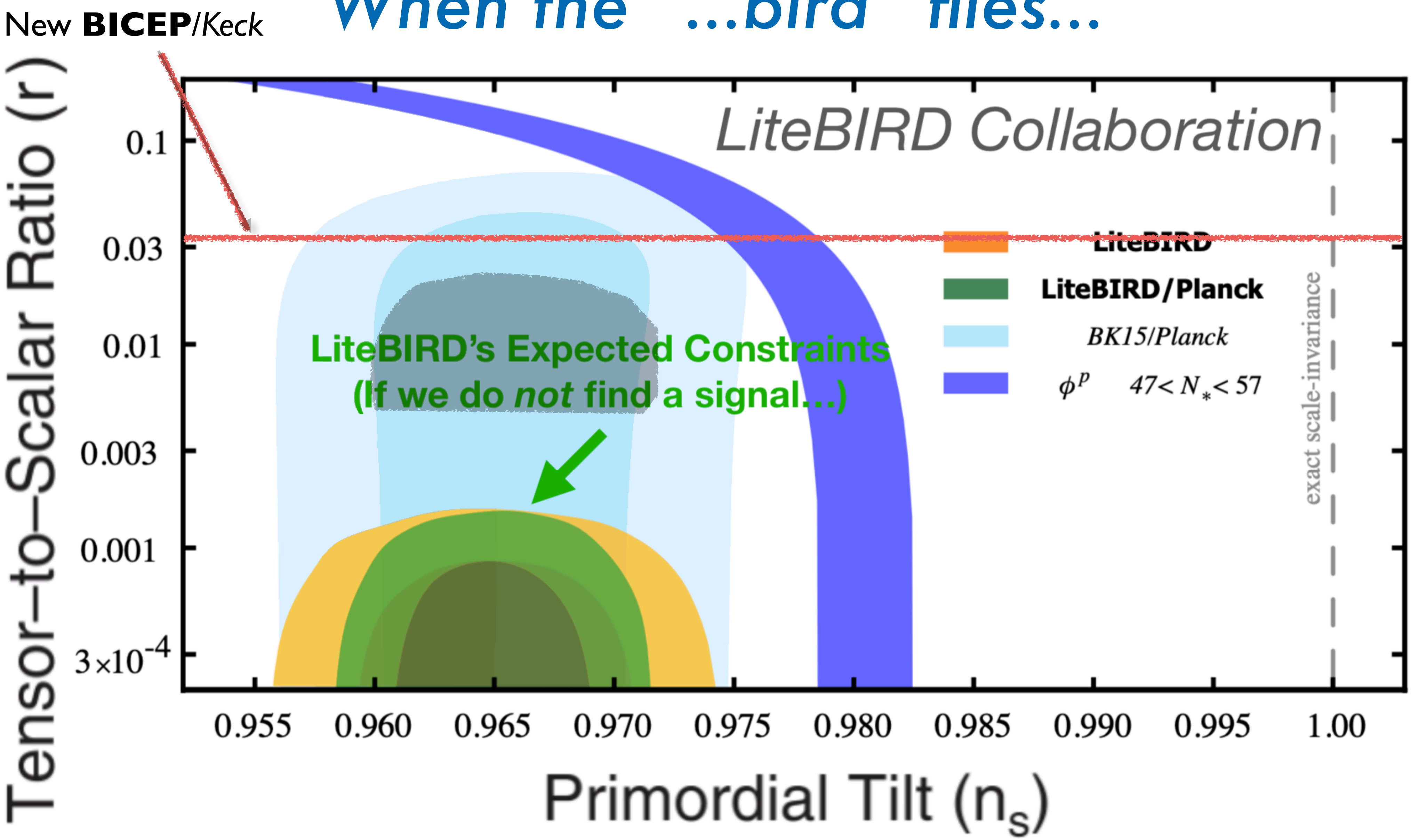
this is with the NEW BICEP/*Keck* data

nGs vs r



this is with the NEW BICEP/*Keck* data

When the "…bird" flies…



edited from a talk by E. Komatsu

Additional signatures

- More surprises: from string theory constructions it is natural to expect couplings to gauge fields

NK & Sorbo 2008;
NK, Lawrence & Sorbo 2011

$$-F^2_{abcd} + \epsilon_{a_1 \ldots a_{11}} A^{a_1 \cdots} F^{a_4 \cdots} F^{a_8 \ldots a_{11}} \ni$$

$$-F^2_{\mu\nu\lambda\sigma} - (\partial\phi_1)^2 - \mu\phi_1 \epsilon_{\mu\nu\lambda\sigma} F^{\mu\nu\lambda\sigma} - \sum_k F^2_{\mu\nu\,(k)} - \frac{\phi_1}{f_\phi} \sum_{k,l} \epsilon_{\mu\nu\lambda\sigma} F^{\mu\nu}{}_{(k)} F^{\lambda\sigma}{}_{(l)}$$

- In 4D, we study the coupling to a dark U(1)

$$\mathcal{L}_{\rm int} = -\sqrt{-g}\,\frac{\phi_1}{4 f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

The coupled axion-gauge field system

$$\ddot{\phi}_1 + 3H\dot{\phi}_1 + \partial_{\phi_1} V(\phi_1) - \frac{1}{f_\phi}\langle \vec{E}\cdot\vec{B}\rangle = 0$$

$$3H^2 = \frac{\dot{\phi}_1^2}{2} + V(\phi_1) + \frac{1}{2}\rho_{EB}$$

$$A''_\pm(\tau,\vec{k}) + \left[k^2 \pm 2\lambda\xi k a H\right] A_\pm(\tau,\vec{k}) = 0 \qquad \lambda = \mathrm{sgn}(\dot{\phi}) \qquad \xi = \frac{\dot{\phi}}{2Hf_\phi}$$

$$\rho_{EB} = \frac{1}{2}(\vec{E}^2 + \vec{B}^2) \qquad \vec{E} = -\frac{1}{a^2}\frac{\mathrm{d}\vec{A}}{\mathrm{d}\tau} \qquad \vec{B} = \frac{1}{a^2}\vec{\nabla}\times\vec{A}$$

Tachyonic dependence of one helicity for fast field

Campbell, NK, Madden, Olive, 1995
Anber & Sorbo 2009
many others

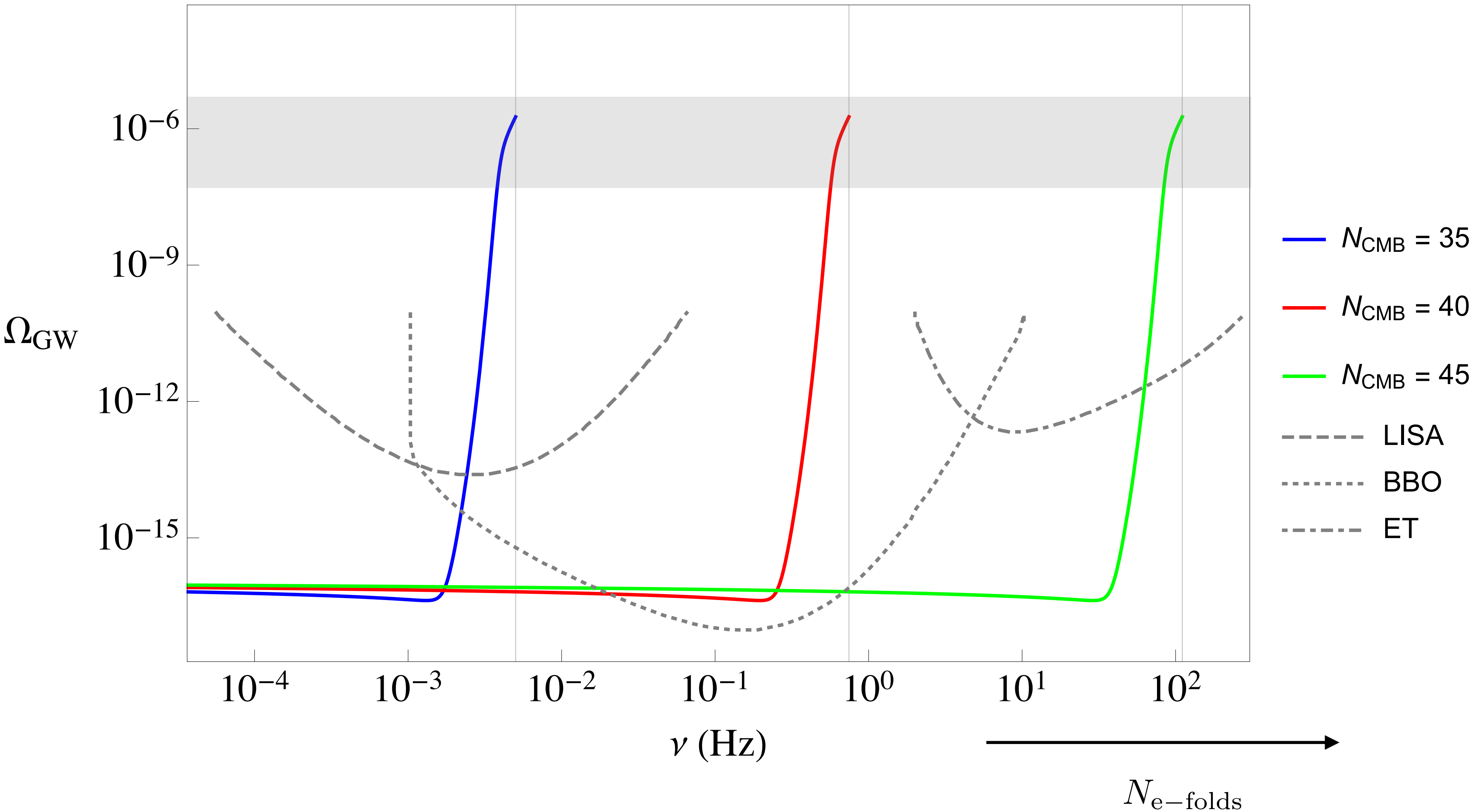
Solutions

- Find numerical solutions; the vector tachyon is rapidly cranked up and then it sources tensors.
- Observables? At small scales large, non-Gaussian scalar perturbations and gravitational waves!
- Because only one vector helicity is tachyonic, gravitational waves are *chiral*, turning in a preferred mode, and they are given by

$$\Omega_{GW} \simeq \frac{\Omega_{r,0}}{12} \left(\frac{H}{\pi M_{\rm Pl}} \right)^2 \left(1 + 4.3 \cdot 10^{-7} \frac{H^2}{M_{\rm Pl}^2 \xi^6} e^{4\pi\xi} \right)$$

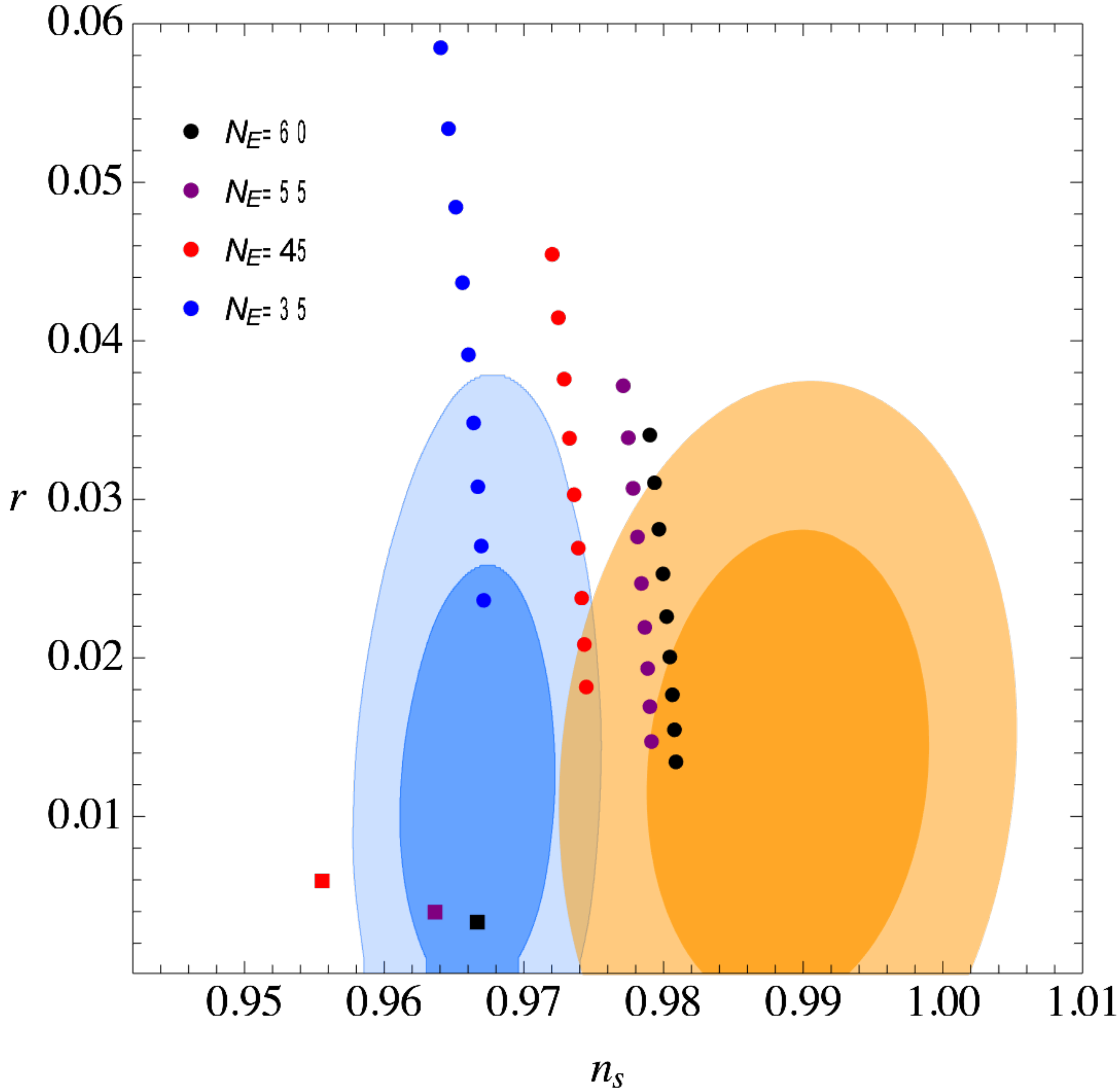
$$N = N_{CMB} + \ln \frac{k_{\rm CMB}}{0.002 {\rm Mpc}^{-1}} - 44.9 - \ln \frac{\nu}{10^2 {\rm Hz}}$$

Small-scale predictions: very hairy!



A very loud signal for LISA (for other N_{CMB}, signal in the range of other instruments (NANOgrav, SKA, Decigo, Big Bang Observatory, Einstein Telescope...)

A "Caveat"? H0 & LCDM???



Summary

- *Why does inflation have to happen all in one go?*

IT DOES NOT!!!

- Interrupting helps with naturalness relieving the pressure from the UV; it definitely helps with fitting data for large-field models
- Horizon, curvature and other problems all easily solved
- Interruptions yield correlated signals at large and small scales; what are the other interesting observables?
- One example: *Multi-monodromy inflation: a gravity waves factory for CMB and forthcoming GW instruments; more coming…*
- What else??!!…