Guido D'Amico

Rollercoaster Cosmology, and a Gravity Wave Factory

GDA, N. Kaloper, arXiv:2011.09489
GDA, N. Kaloper, A. Westphal, arXiv:2101.05861; 2112.13861

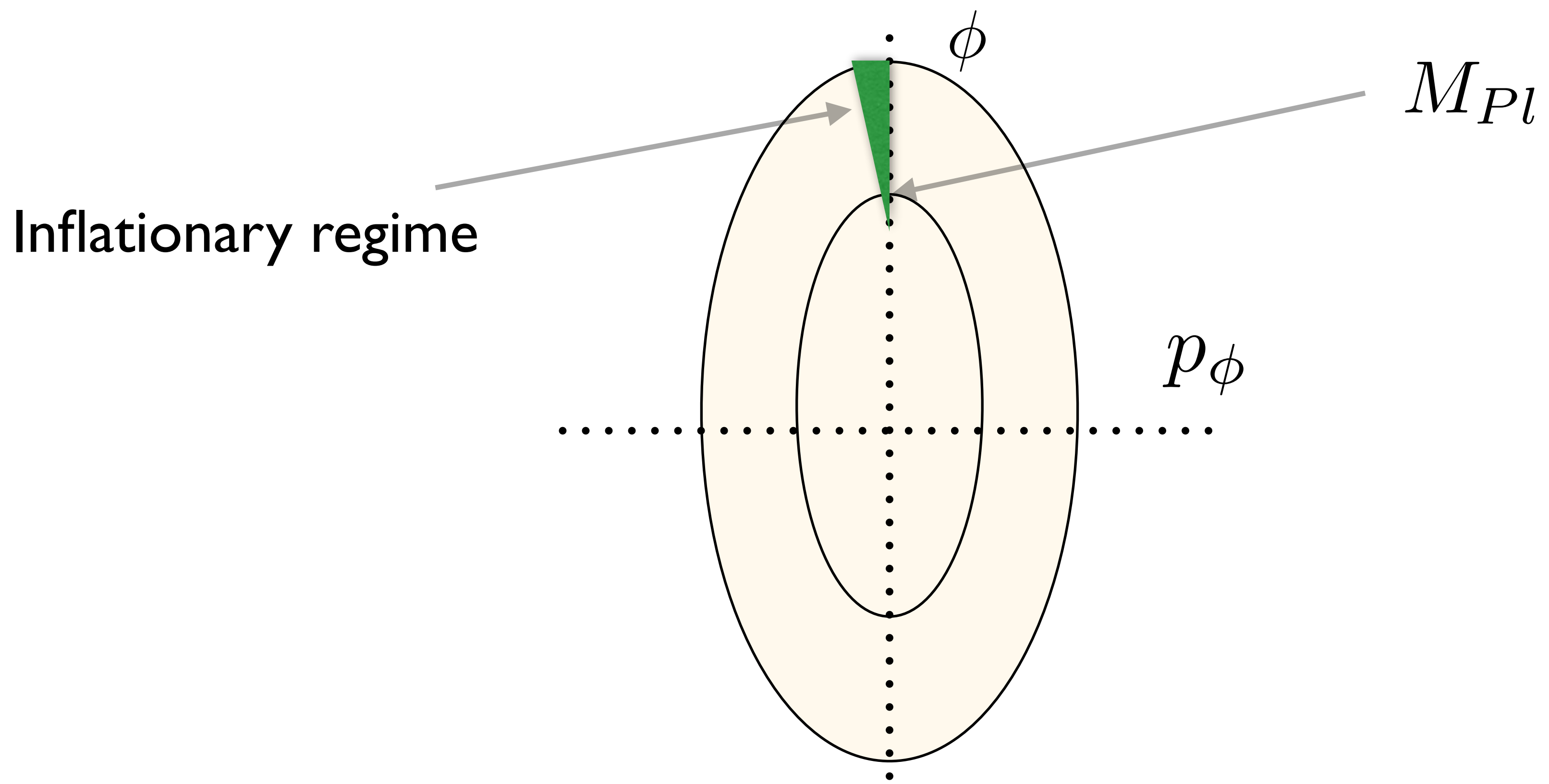
Particle Physics meets Cosmology, 11/10/2022

Inflation and naturalness

- Inflation was invented to explain the universe *naturally* — prior to inflation, our universe a set of measure zero in GR
- In turn: "cosmological" naturalness now becomes *naturalness of the EFT of inflation*
- In semiclassical gravity, easy-peasy: a derivatively coupled inflaton with a flat potential, *et voila*
- What about full-on QG? Current lore: no global symmetries survive, and field range should be short
- Moreover, experimental worries: too much tensor power!
- A possible answer: *monodromy + rollercoaster inflation*

Slow Roll Inflation

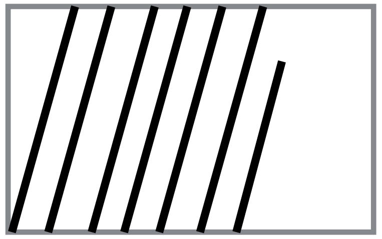
- Eg. quadratic potential $H = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}p_\phi^2$



- Inflation occurs at large field vevs $\phi > M_{Pl}$
- Getting > 60 efolds from ϕ^n requires $\frac{\phi}{M_{Pl}} > \sqrt{120n}$
- Can we trust EFT arguments beyond Planck scale?

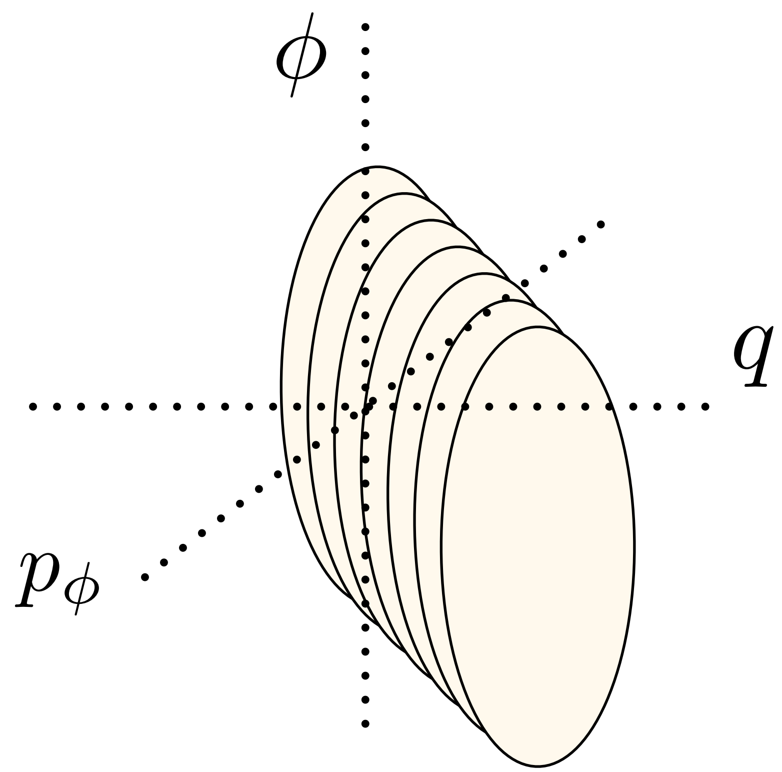
Guth, Linde, Albrecht & Steinhardt 80's

Monodromy Inflation



- Meaning: "running around singly"
- In other words: get large field excursion in (small) compact field space, such that theory is under control
- Simplest physical realization: a particle in a magnetic field

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



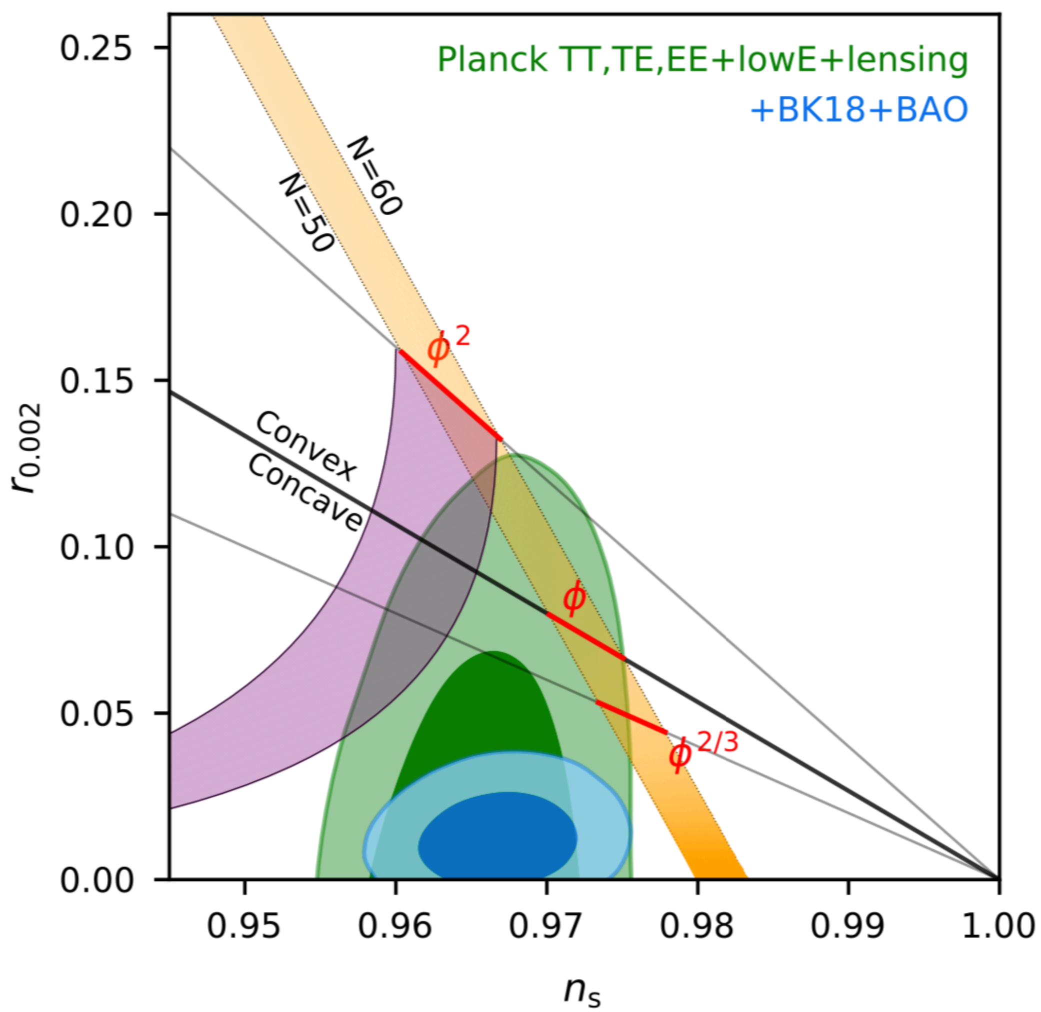
Silverstein & Westphal 2008;
McAllister, Silverstein & Westphal 2008;
Kaloper & Sorbo 2008;
Kaloper, Lawrence & Sorbo 2011

Fitting theory and data

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

BICEP/*Keck*: $r < 0.036$

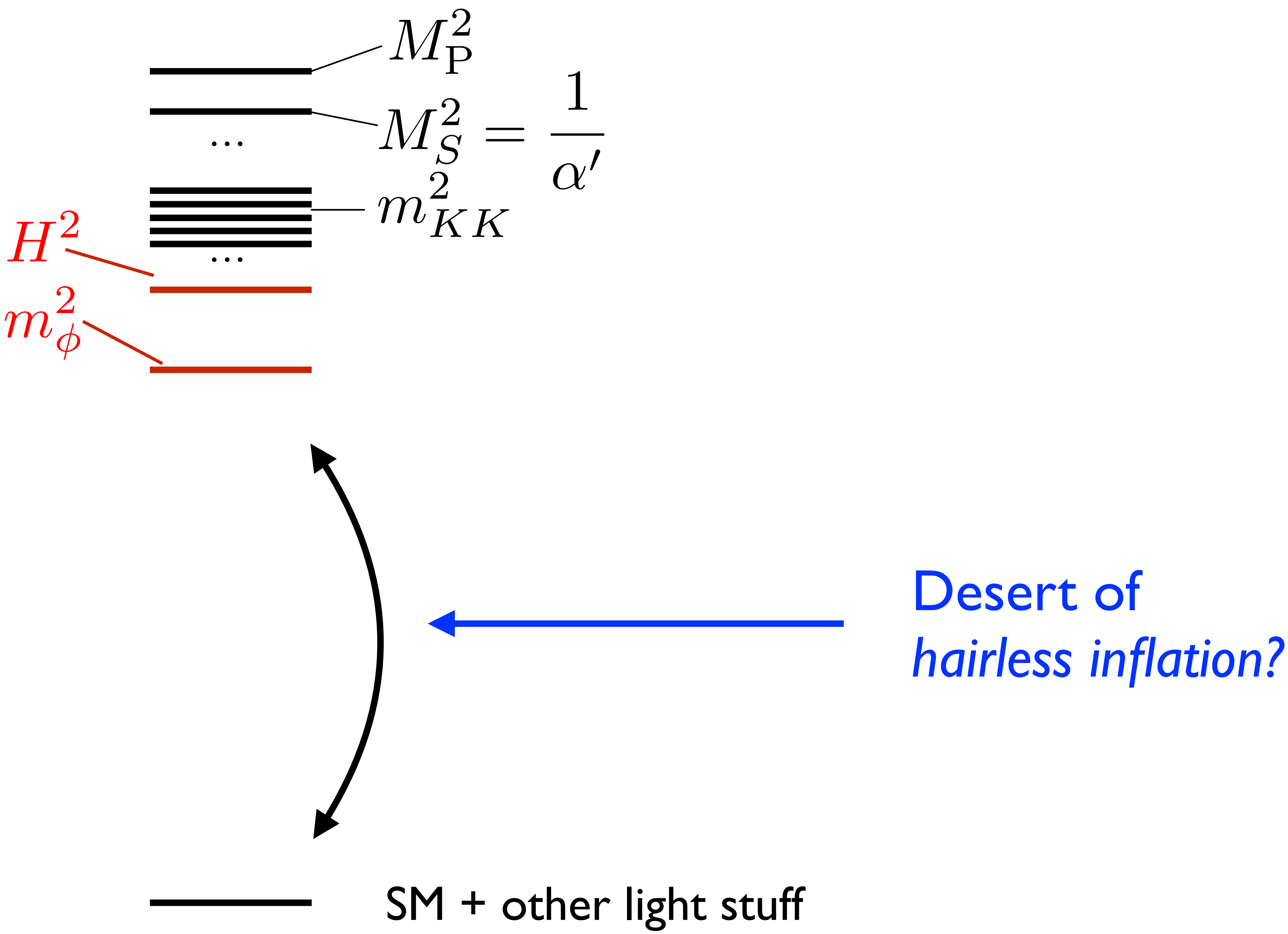
$$r = 0.014^{+0.010}_{-0.011}$$



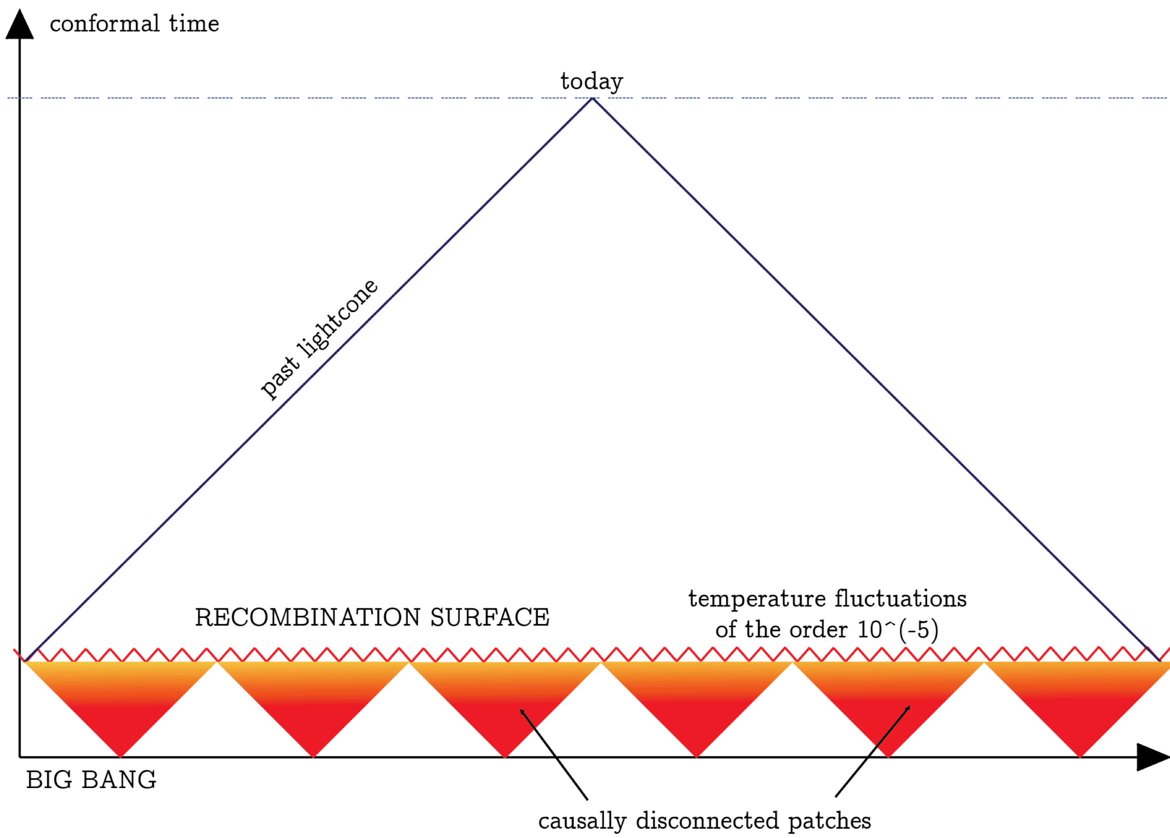
Rollercoaster cosmology

- We relax both theoretical worries and data issues: we shorten the field variation and we get redder spectrum, and smaller r
- A key insight: observationally, we do not need 60 efolds in one go: we only probe the first 10-15 (the one side of a black sheep!)
- And then? Accelerated expansion may stop and go. This looks like a tuning of a few parameters - not atypical for inflation
- Bottomline: several stages of accelerated expansion just fine!
- So far we are only probing the first (CMB) stage!
  CMB constraints on models will be modified and interesting predictions for short-scale experiments have to be figured out
- A win-win: even if new predictions don't pan out, we are testing longevity of inflation

"The World Spectrum" of long smooth inflation

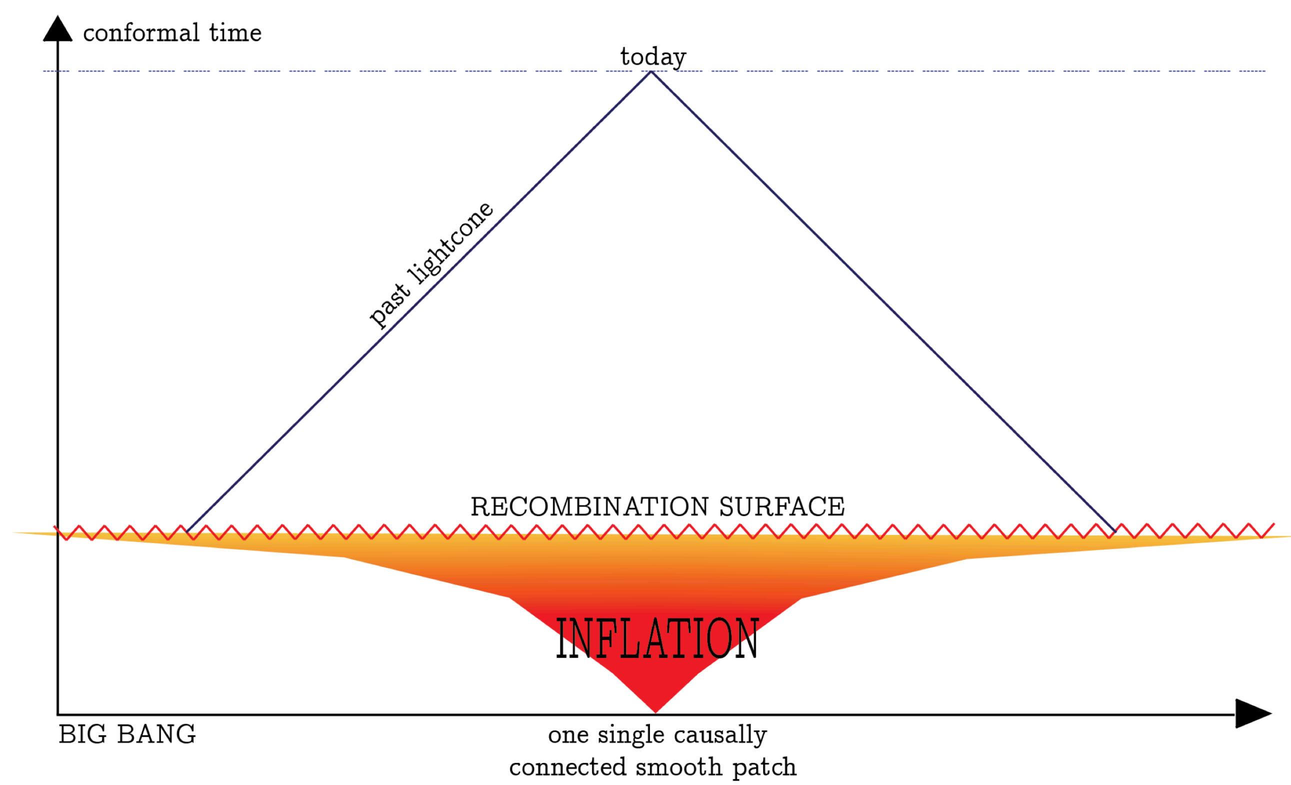


“Bring me that horizon...”

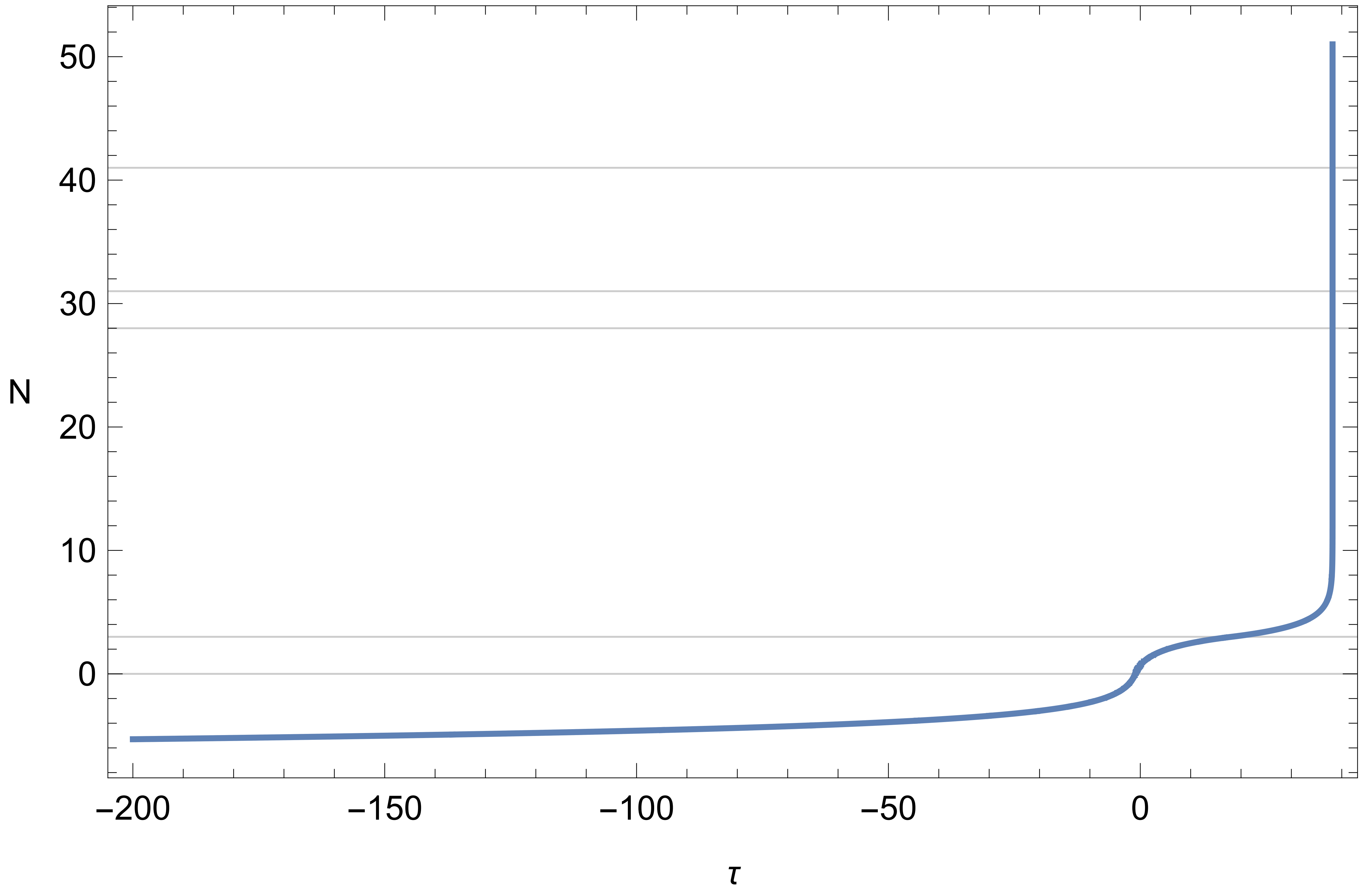


PROBLEM

SOLUTION



Rollercoaster (simplest) architecture



The Horizon Problem

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

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

Normal matter

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

Inflation

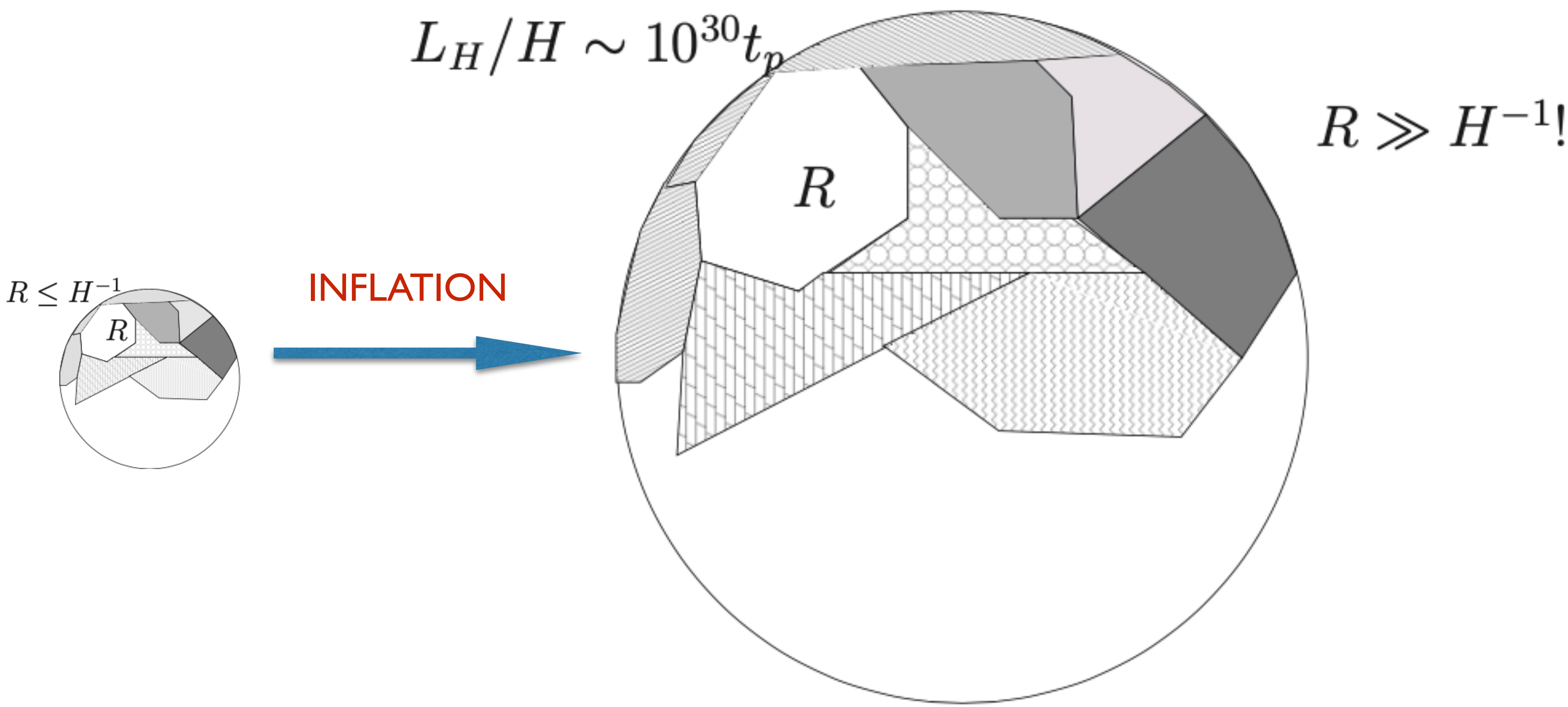
$$\int_{t_{\text{in}}}^{t} \frac{\mathrm{d}t'}{a(t')} \simeq \frac{1}{\sqrt{H H_1}} \lesssim \frac{1}{H_1}$$

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

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

This solves horizon problem in rollercoaster

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



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

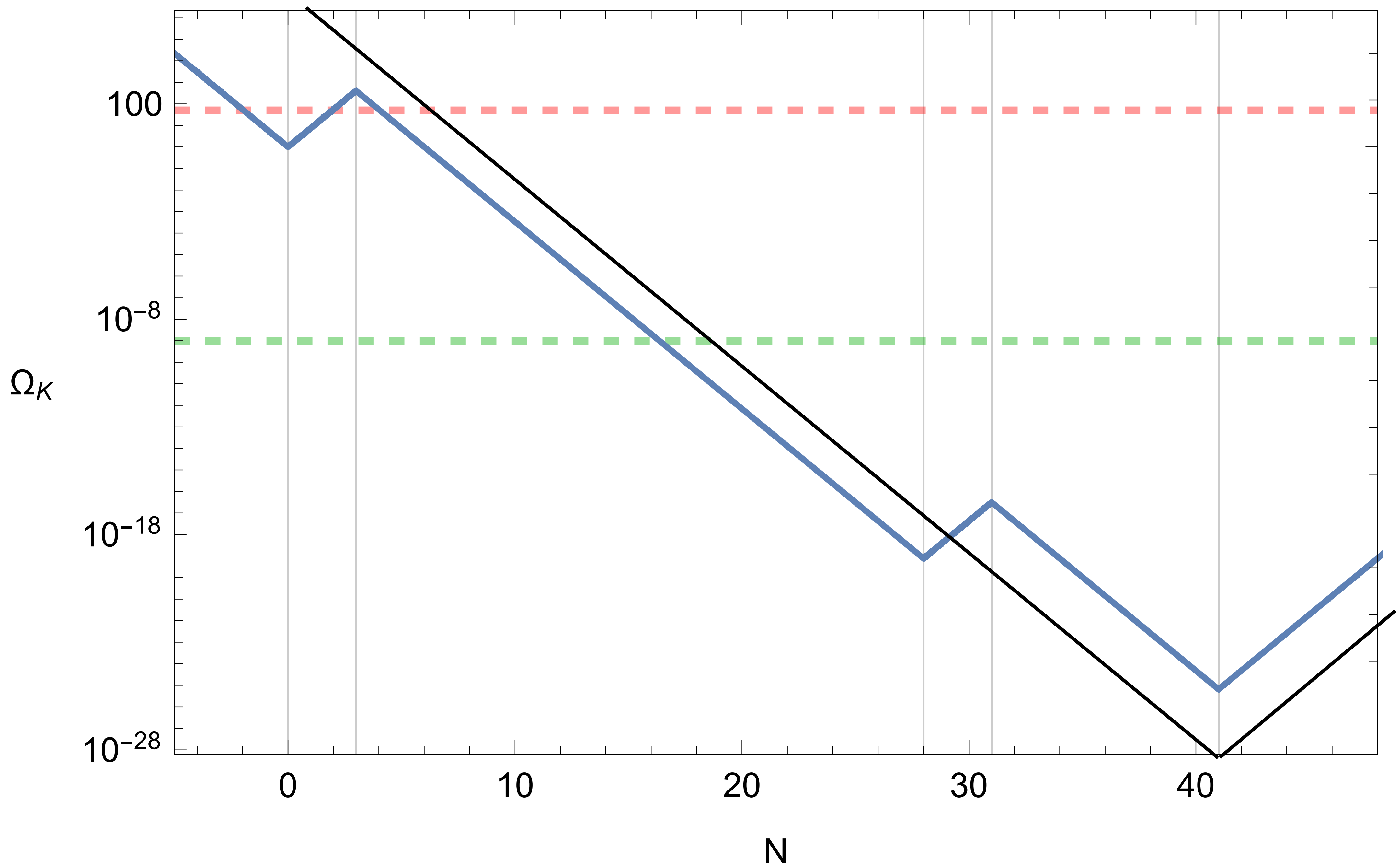
$$\frac{\Omega_{\mathrm{K,end}}}{\Omega_{\mathrm{K,in}}} = \left(\frac{a_{\mathrm{in}}}{a_{\mathrm{fin}}}\right)^2 = e^{-2N}$$

Inflation

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

Rollercoaster

The Curvature Problem



Perturbations

- Tensors are straightforward - there is metric and theory is covariant
- Scalar perturbations are a dynamical input since GR has no scalar mode, we need to provide it.
  It is the order parameter yielding accelerated expansion, generically modeled as a scalar field to preserve covariance
- Multiple stages, multiple fields.
  Must have little hierarchies, clearly a tuning; yet this is no worse a tuning than the standard selection of "right" parameters in any inflation
- *What is needed is approximate scale invariance of the theory for long enough, even piecemeal*

Perturbations I

- Prototype: Starobinsky - as done by Chibisov and Mukhanov

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

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

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

$$M_{Pl}(\mathrm{eff})^2 = 48cH^2 \qquad\qquad \Lambda(\mathrm{eff}) = 144cH^4$$

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

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

Perturbations II

The rest is just the standard approach to quantizing & computing 2pt function

$$\mathcal{R} = \frac{H}{\dot\phi}\delta\phi = \frac{H}{a\dot\phi}\varphi$$

$$S_{\rm scalar} = \frac{1}{2}\int {\rm d}\tau {\rm d}^3x \left[(\varphi')^2 - (\nabla\varphi)^2 + \frac{z''}{z}\varphi^2\right] \qquad z = \frac{a\dot\phi}{H}$$

$$h = \frac{\sqrt{2}}{M_{\rm Pl}}\frac{v}{a}$$

$$S_{\rm tensor} = \frac{1}{2}\int {\rm d}\tau {\rm d}^3x \left[(v')^2 - (\nabla v)^2 + \frac{a''}{a}v^2\right]$$

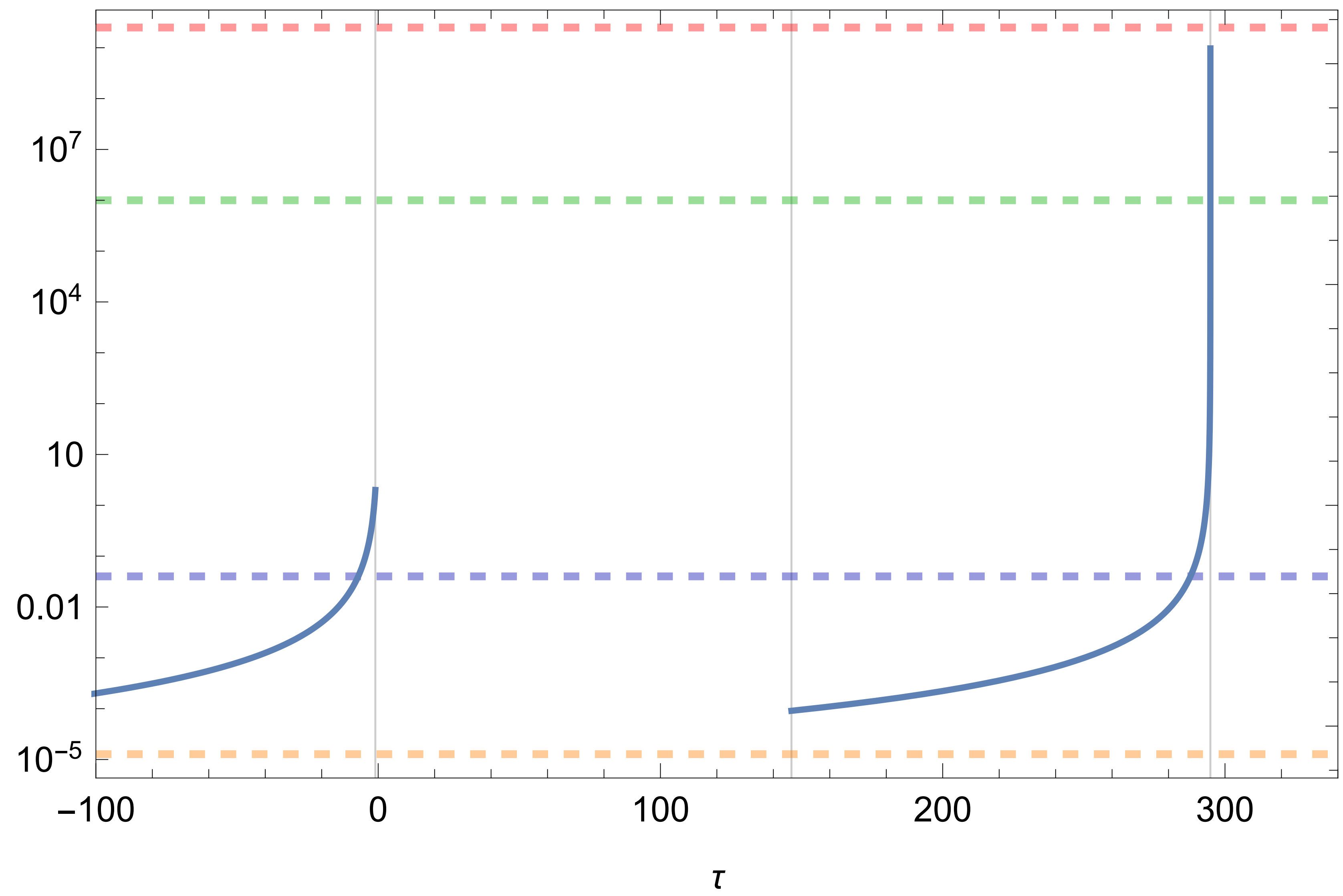
Perturbations III

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

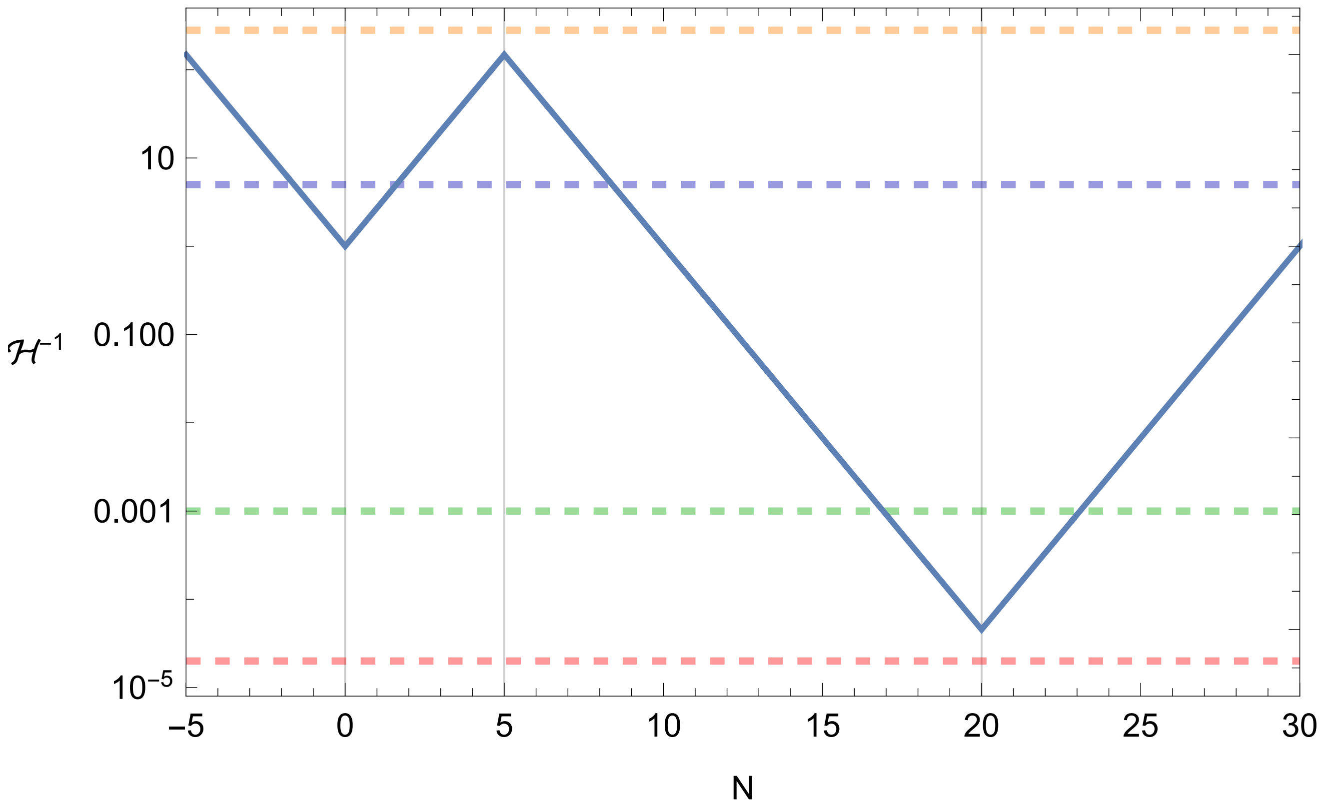
Same as Schroedinger's eq., with anti-tunnelling b.c. !

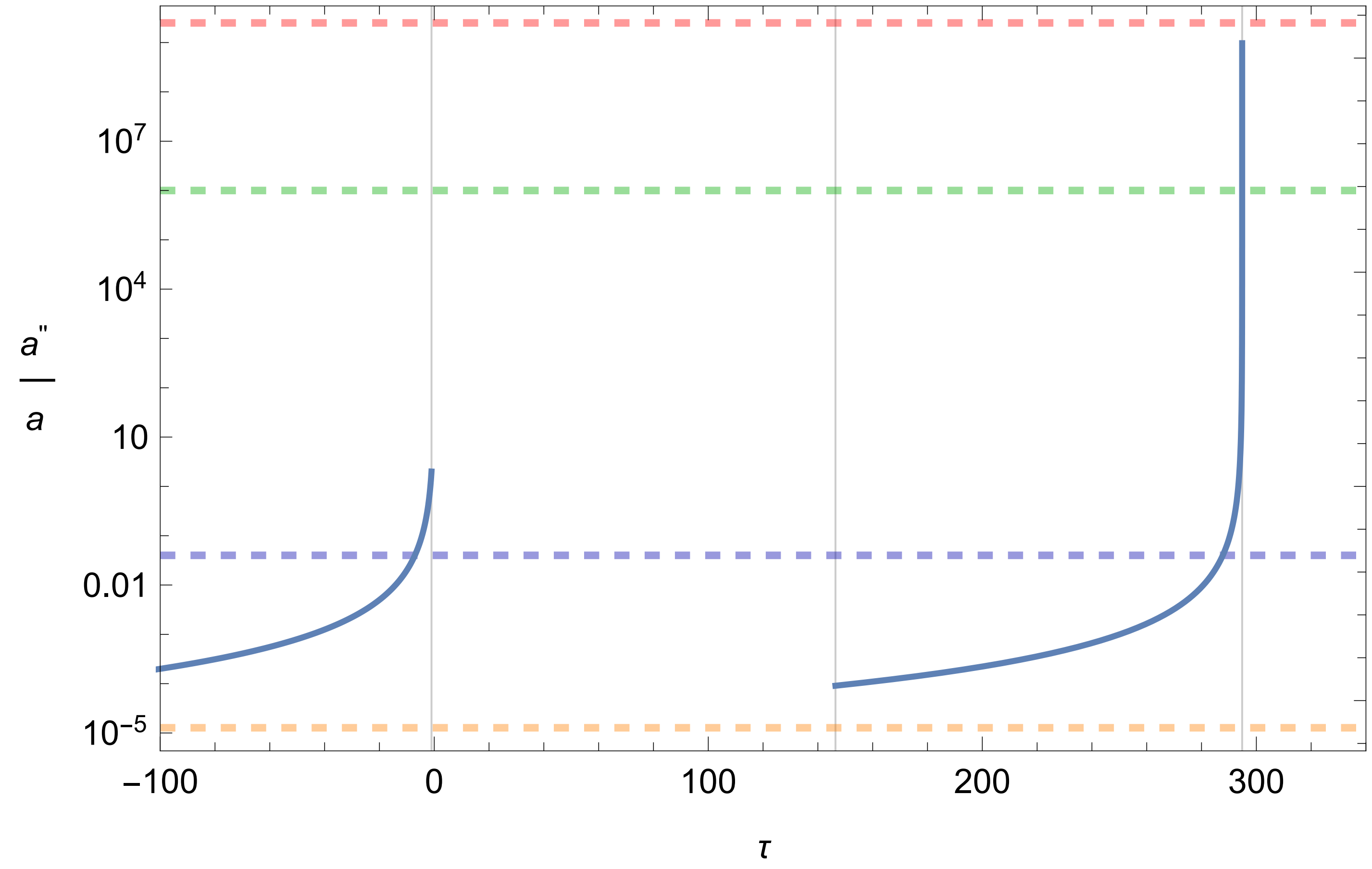
$$u_k(\tau_-) = u_k(\tau_+)$$

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



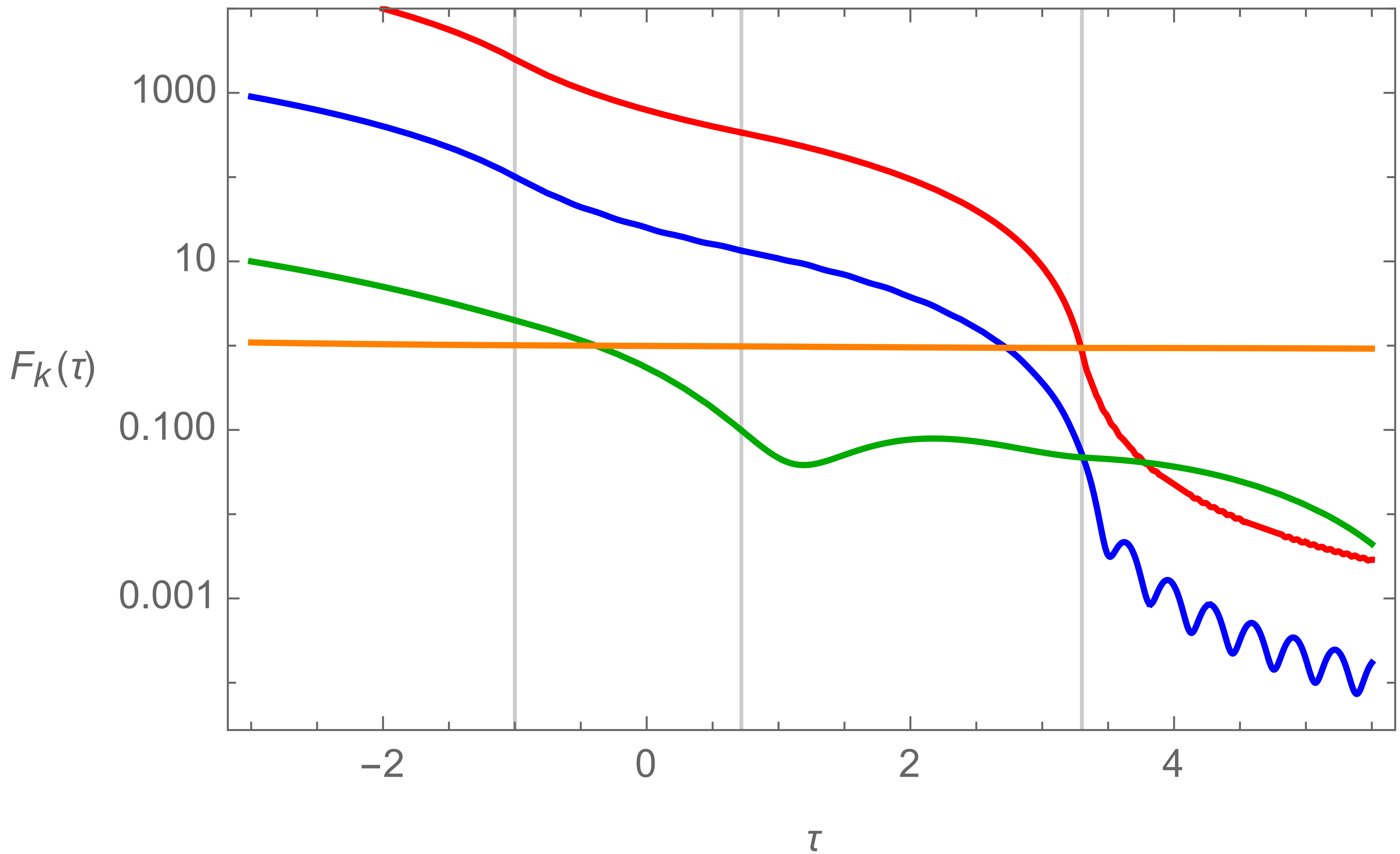
Cosmologia con quattro stagioni



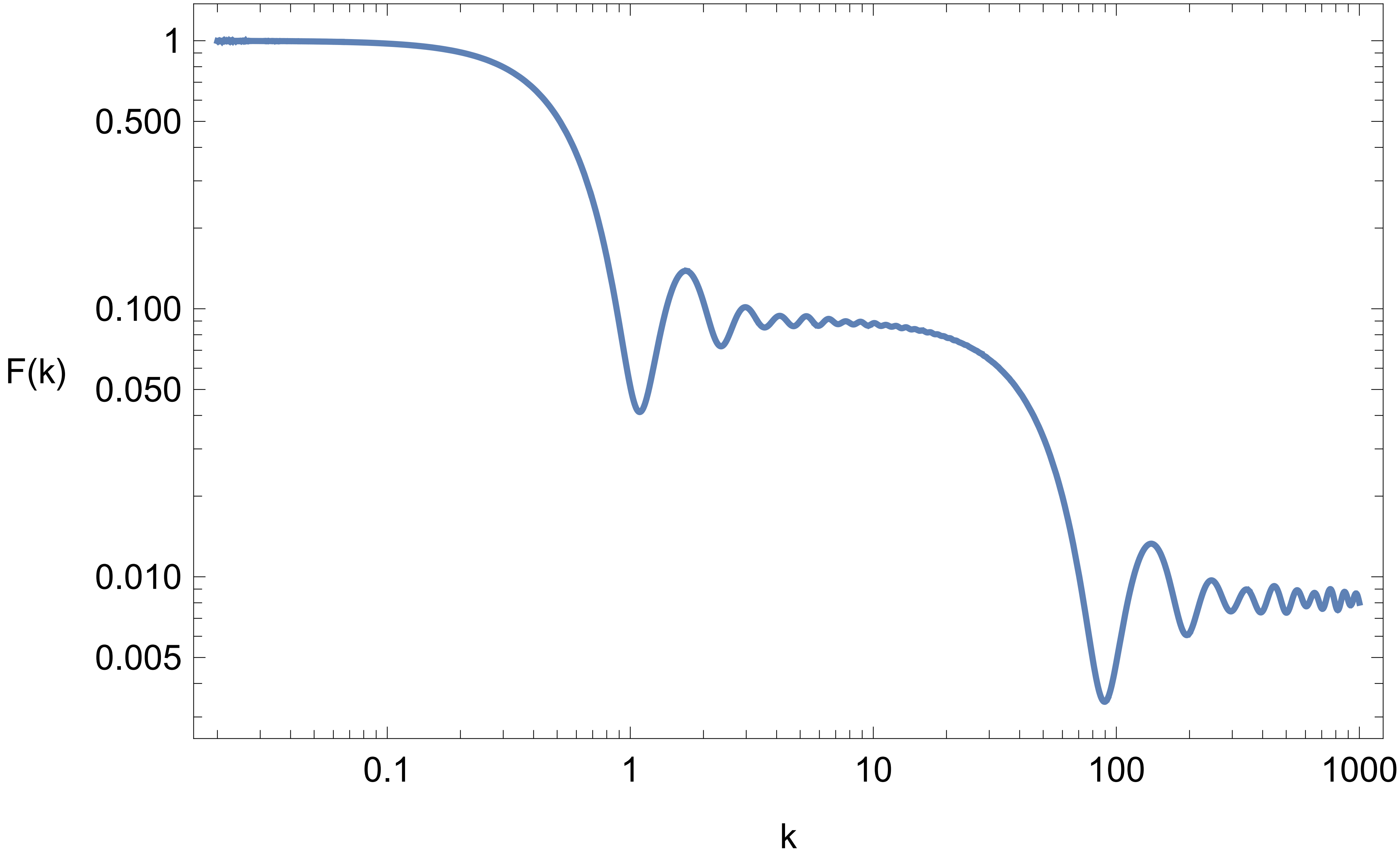


Cosmologia con quattro stagioni

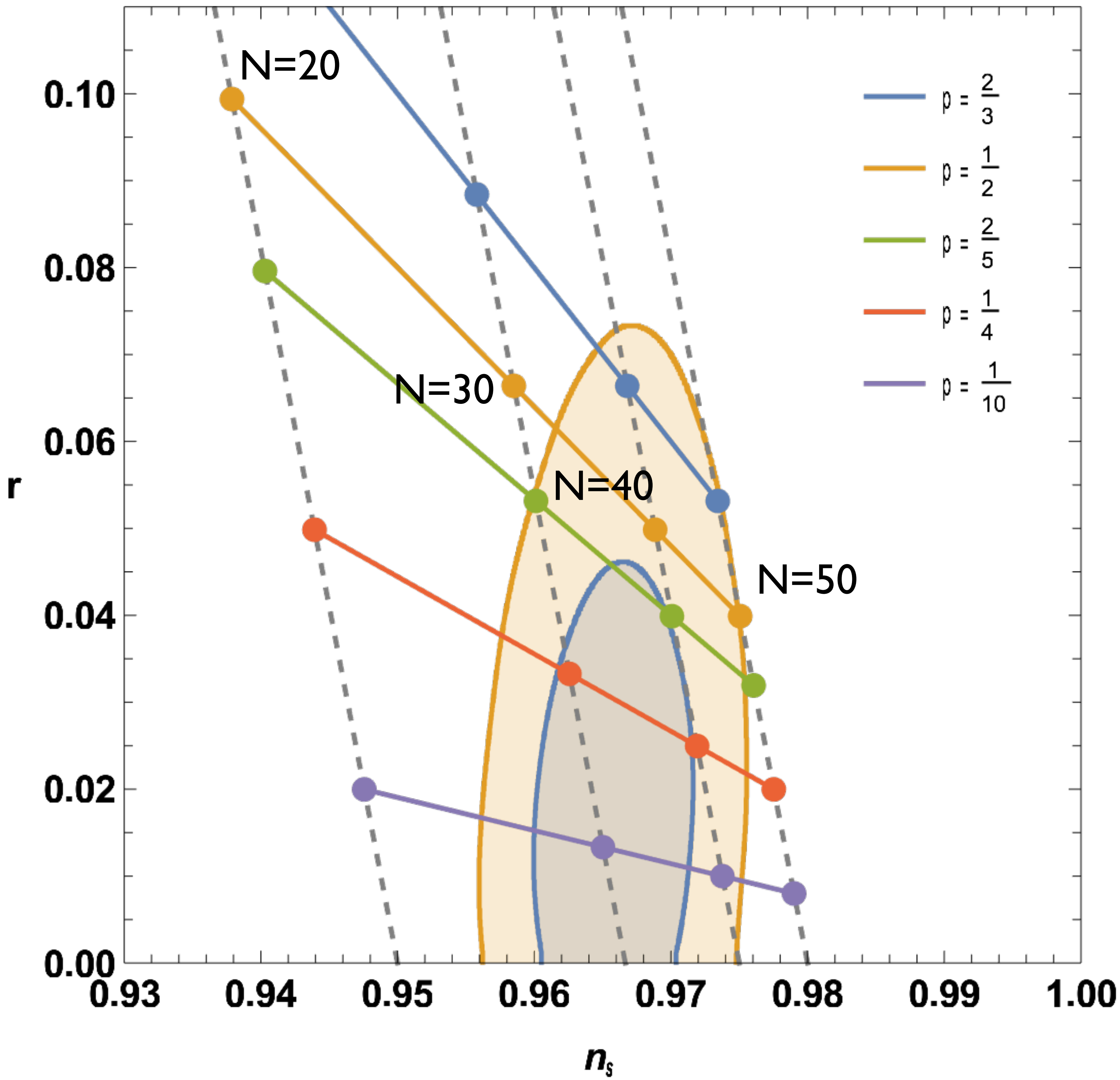
$$P_S = \left(\frac{H_j}{\dot{\phi}_j}\right)^2 |\varphi_k|^2_{\text{ren.}} = \left(\frac{H_j^2}{2\pi\dot{\phi}}\right)^2 \qquad P_T = \frac{2|h_k|^2_{\text{ren.}}}{M_{\text{Pl}}^2} = \frac{2H_j^2}{(2\pi)^2 M_{\text{Pl}}^2} \qquad k < H_j$$



Power spectrum, more realistic case



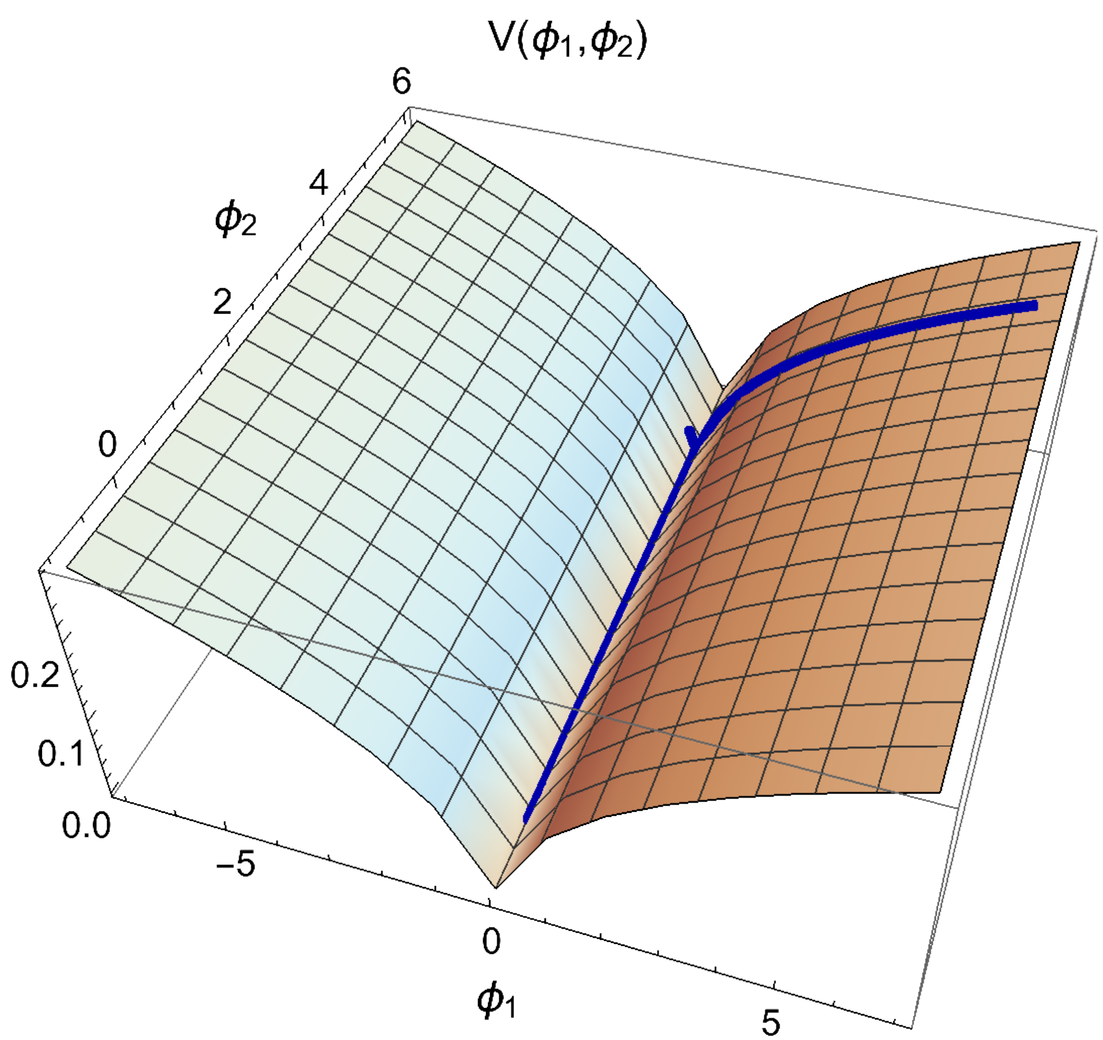
Power-law inflation, viable again!



Doublecoaster cosmology

Two stages of monodromy inflation, separated by matter domination when the first ends

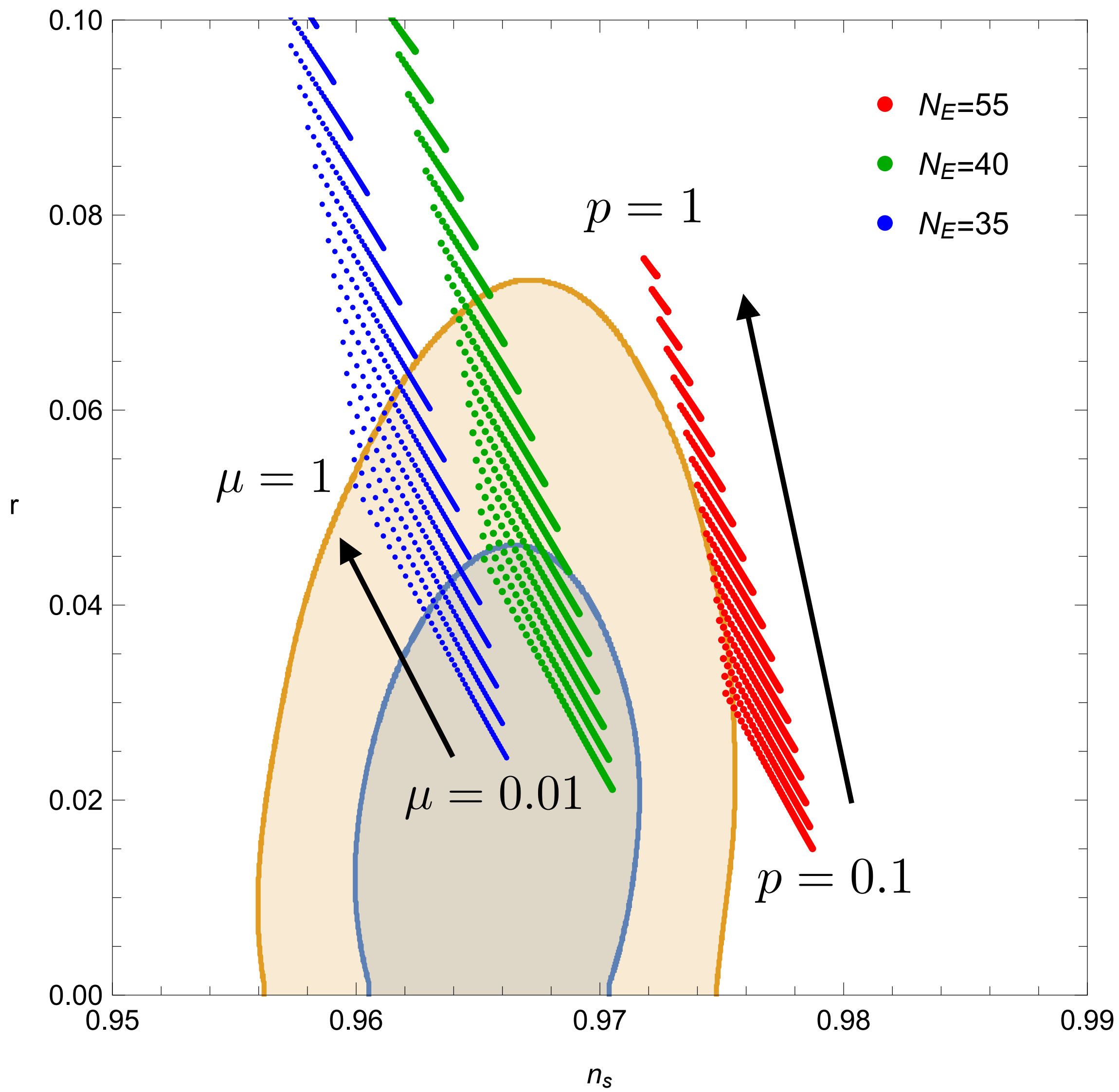
$$V(\phi_1, \phi_2) = M_1^4 \left[\left(1 + \frac{\phi_1^2}{\mu_1^2} \right)^{p_1/2} - 1 \right] + M_2^4 \left[\left(1 + \frac{\phi_2^2}{\mu_2^2} \right)^{p_2/2} - 1 \right] \qquad \begin{array}{l} M_1 > M_2 \\ \mu_i \sim \mathcal{O}(0.1 M_{\rm Pl}) \end{array}$$



- reduced field ranges
- probably more generic in UV setups

CMB predictions

- Solution is easy given the hierarchy: effective single-field with *different pivot scale*
- First stage can last only 30-40 efolds. The rest of inflation is given by the second stage.
- But… Bicep is pushing *r* down, what to do?



Monodromy at Strong Coupling

- Hard; but we can use EFT methods developed for heavy quarks
  Specifically Naive Dimensional Analysis + gauge symmetries
  Manohar, Georgi

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

- The massive 4-form have one propagating dof, a massive axion.
  Dualize to this axial gauge and normalize operators using NDA.
  Kaloper, Lawrence '16

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

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

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

restore combinatorial factors to reproduce Feynman diagrams

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

Doublecoaster + Higher Derivatives

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

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

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

GDA, Kaloper, Lawrence
1709.07014 [hep-th]

Doublecoaster + Higher Derivatives

This means that the action is

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

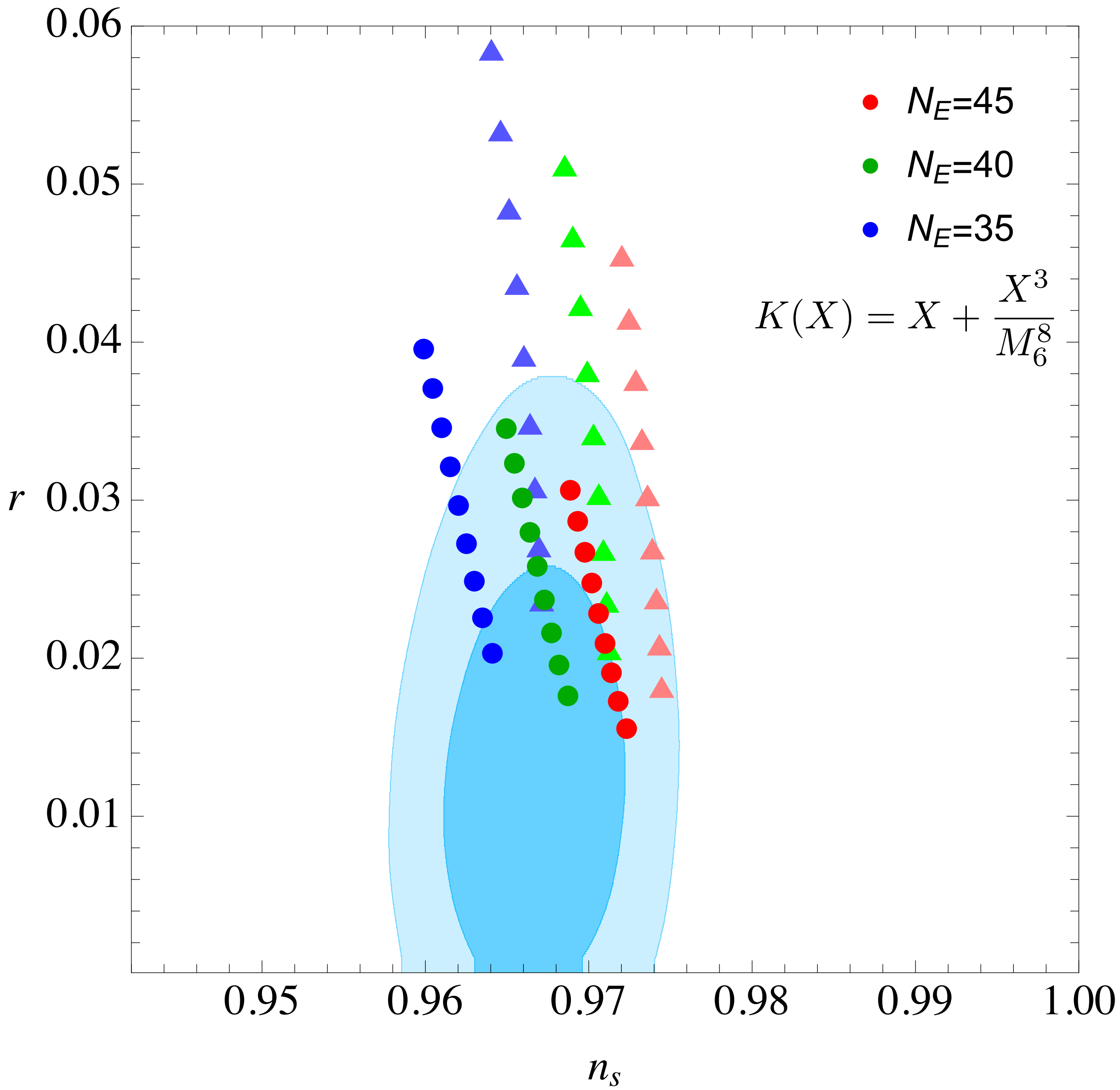
EFT of strongly coupled monodromy is a special case of k-inflation!

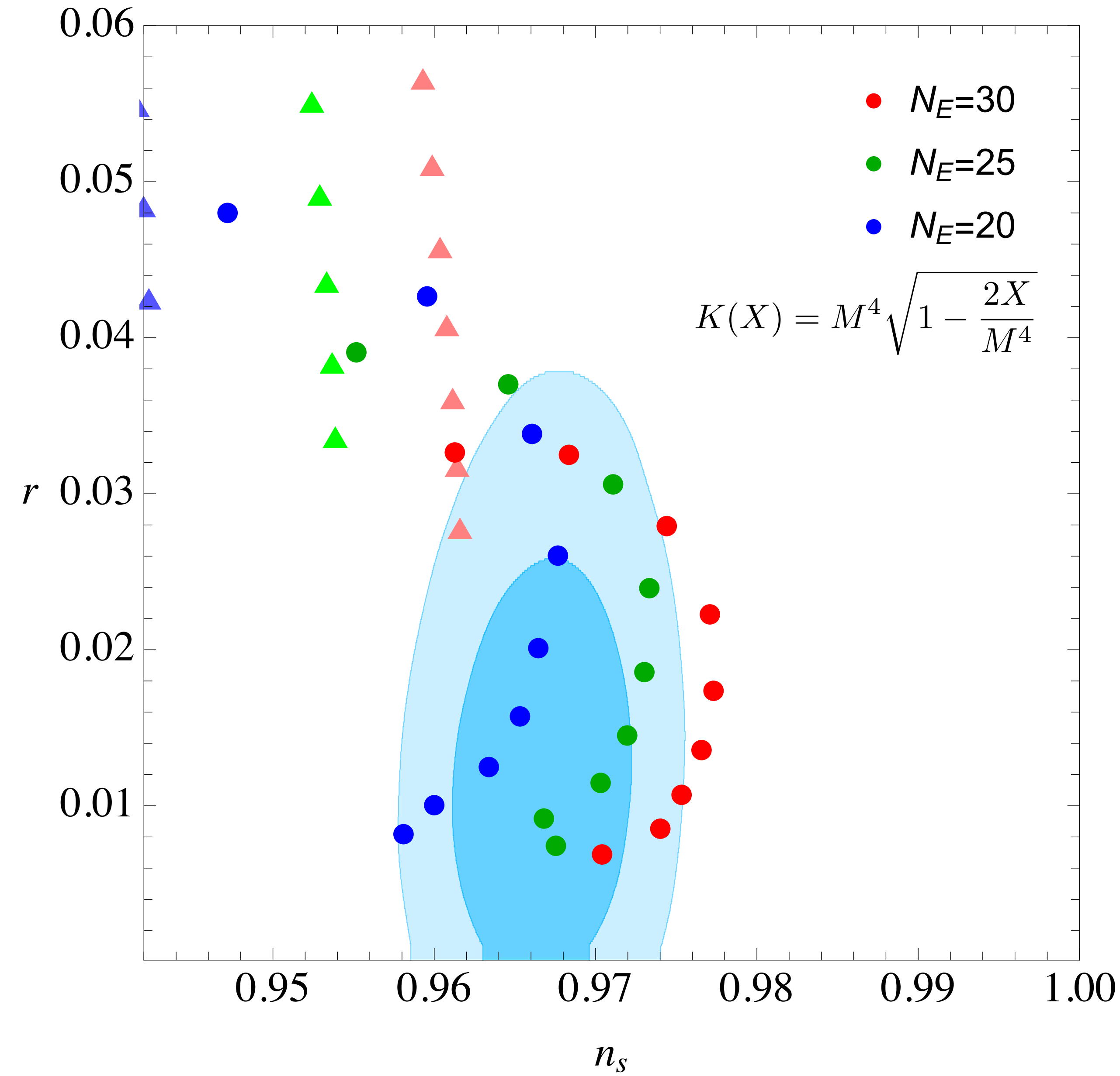
Armendariz-Picon, Damour, Mukhanov '99

Doublecoaster + Higher Derivatives

- Higher-derivative operators:
  they give flattening (smaller *r*)
  but generate non-Gaussianities
- Data: NG cannot be much larger than O(10)
- So coupling cannot be too strong
- Stronger coupling gives smaller tensor/scalar ratio
- So lower bound on r!

Simple monodromy in strong coupling

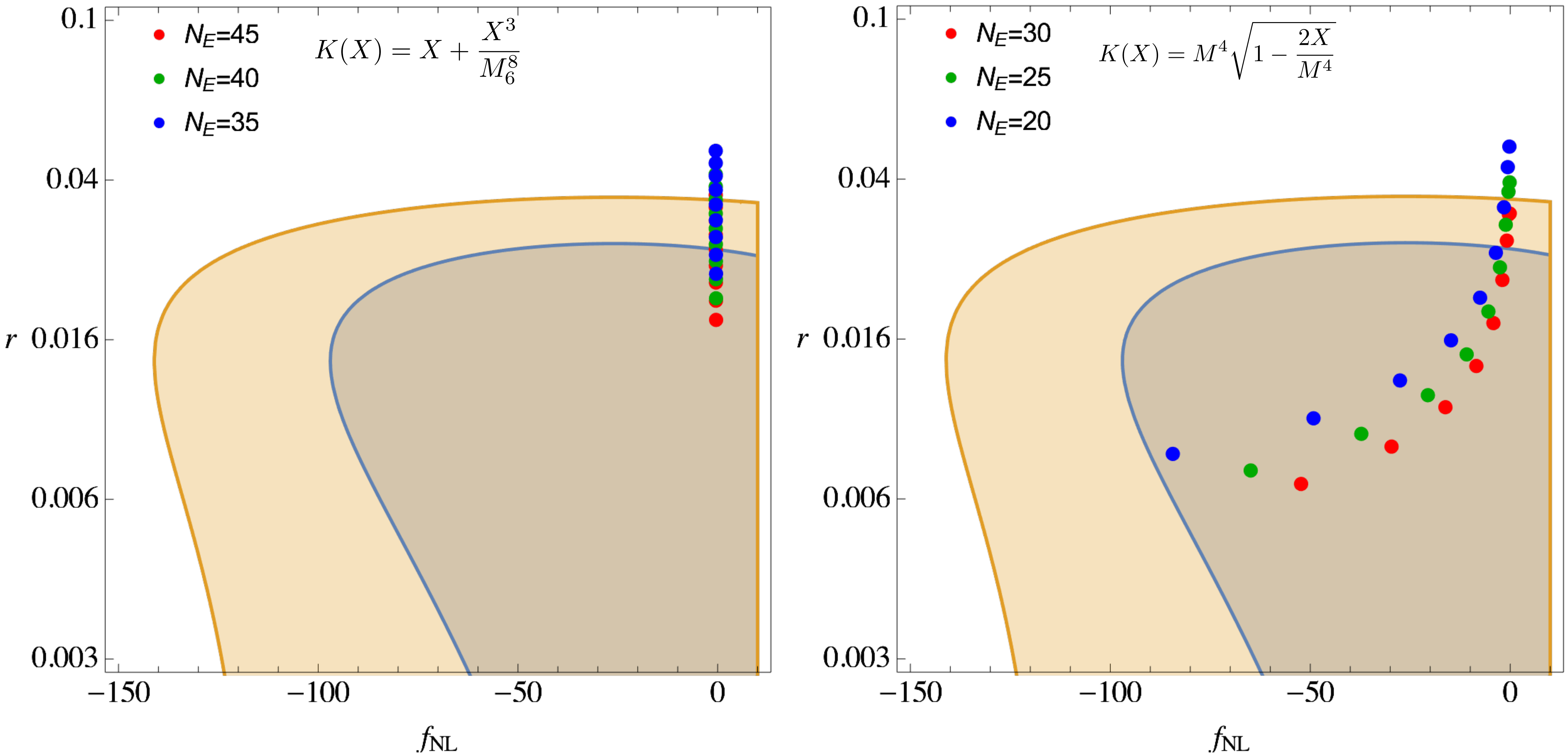




$0.96 < n_s < 0.97$

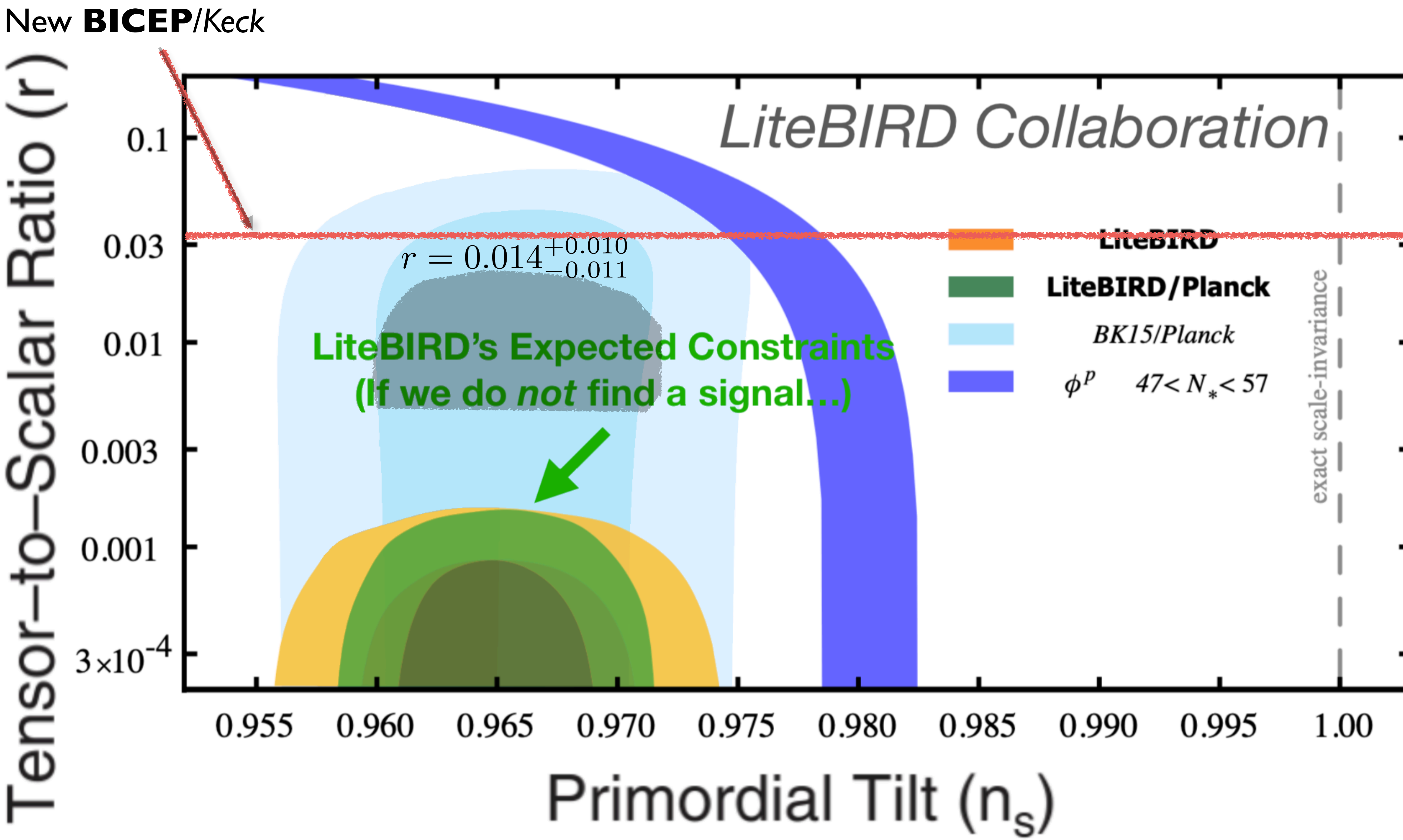
$0.006 < r < 0.035$

nGs vs r



N_E=45
N_E=40
N_E=35
$K(X) = X + \frac{X^3}{M_6^8}$
0.1
0.04
0.016
0.006
0.003
r
−150
−100
−50
0
f_{NL}
N_E=30
N_E=25
N_E=20
$K(X) = M^4\sqrt{1 - \frac{2X}{M^4}}$

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

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

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

Kaloper, Lawrence, Sorbo 2011

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

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

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

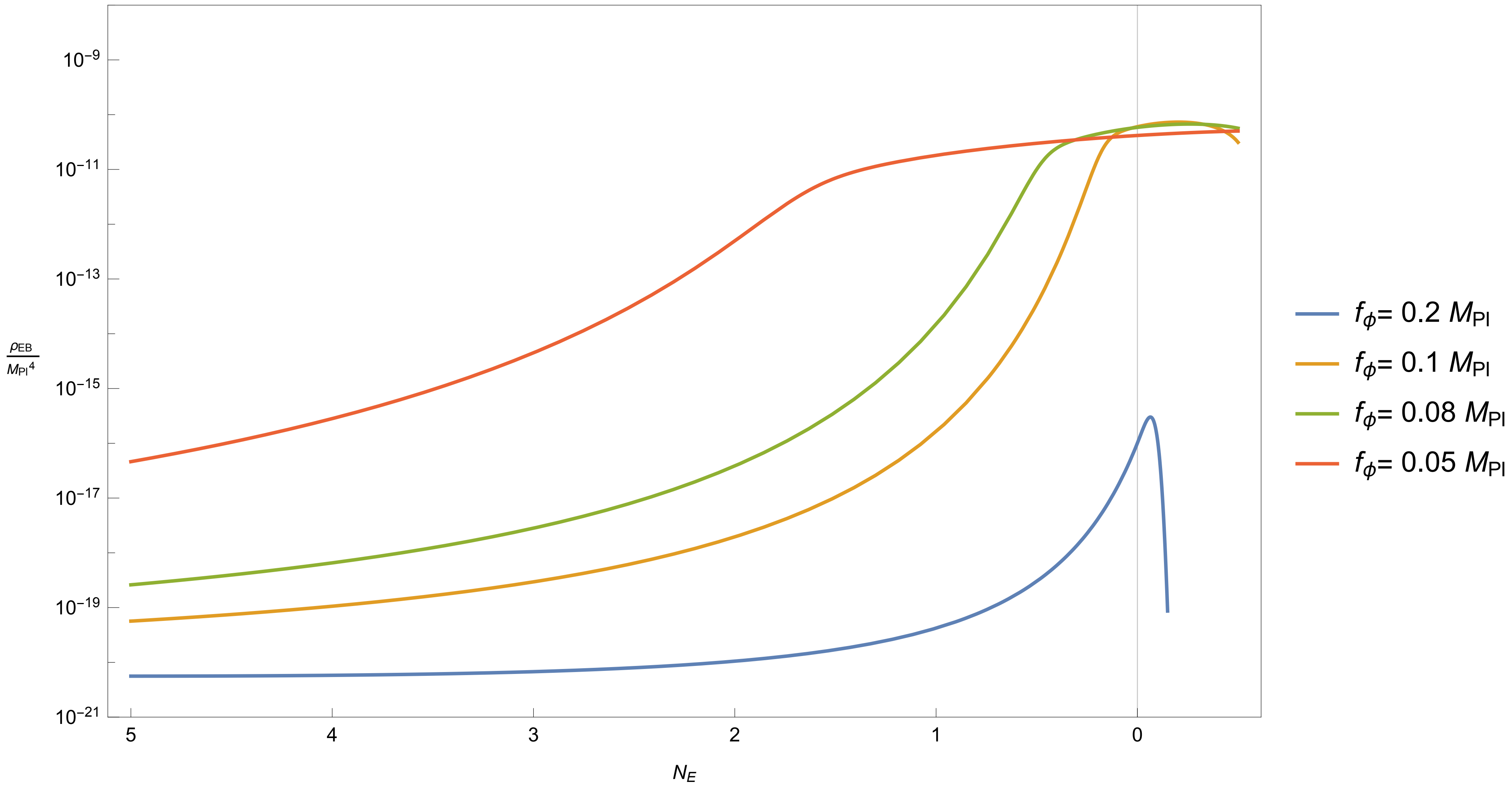
Campbell, Kaloper, Madden, Olive 1995
Anber & Sorbo 2009
many others

Solutions...

Full solution is complicated.

For constant ξ, we have exponential production

$$A_{-\lambda}(\tau,\vec{k}) = \frac{e^{\pi\xi/2}}{\sqrt{2k}} W_{-i\xi,\frac{1}{2}}(2ik\tau) \qquad \rho_{EB} \simeq 1.3\cdot 10^{-4} H^4 \frac{e^{2\pi\xi}}{\xi^3} \qquad \langle \vec{E}\cdot\vec{B}\rangle \simeq -2.4\cdot 10^{-4}\lambda H^4 \frac{e^{2\pi\xi}}{\xi^4}$$



Solutions...

- Exponentials are never physical all the way: energy conservation gives saturation.

- We can trust the solutions up to "end of inflation", where we switch regimes and match to numerical solutions

Domcke, Guidetti, Welling, Westphal 2020

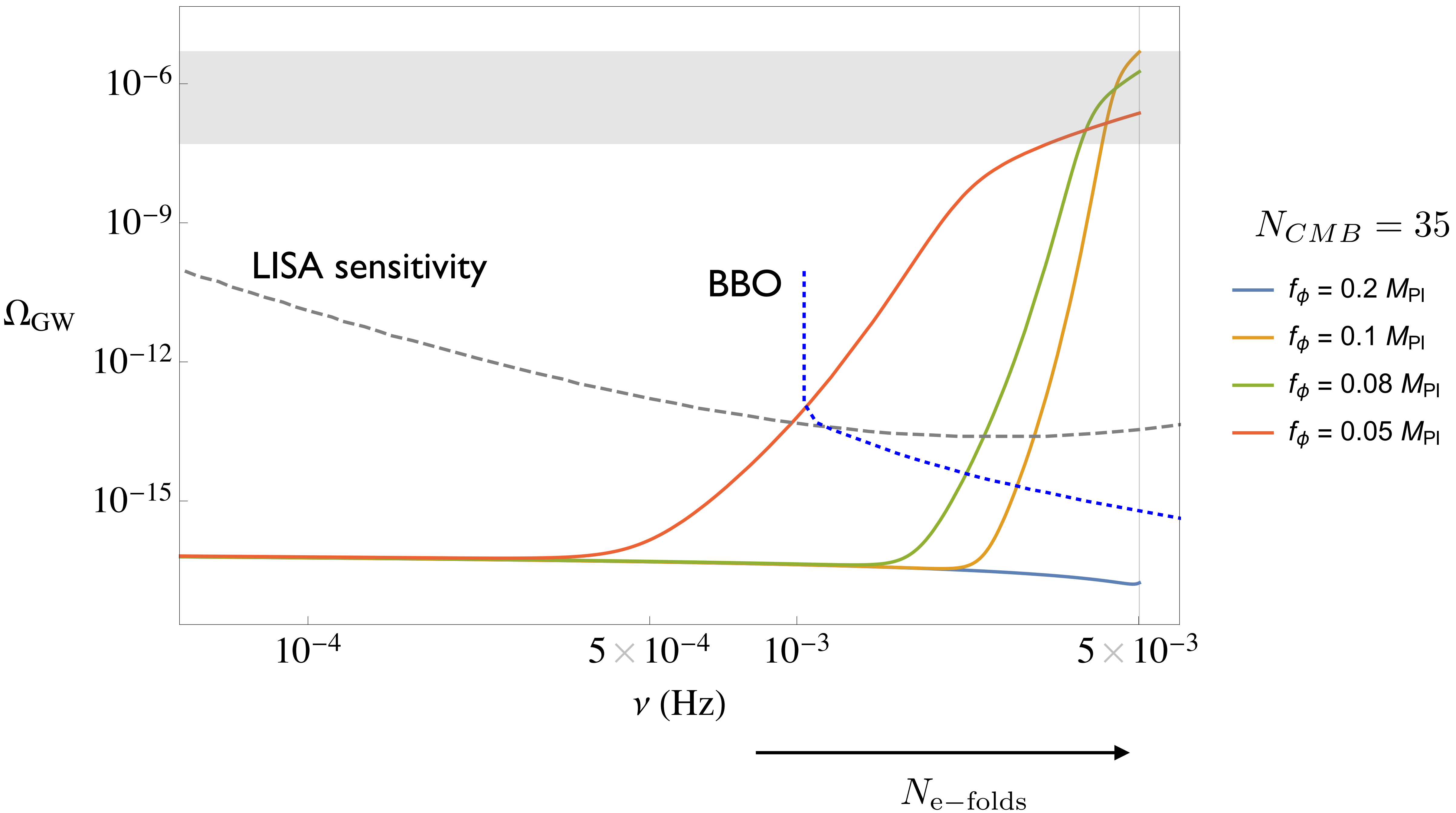
- Observables? At small scales large, non-Gaussian scalar perturbations and gravitational waves!

- Gravitational waves are *chiral*, and they are

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

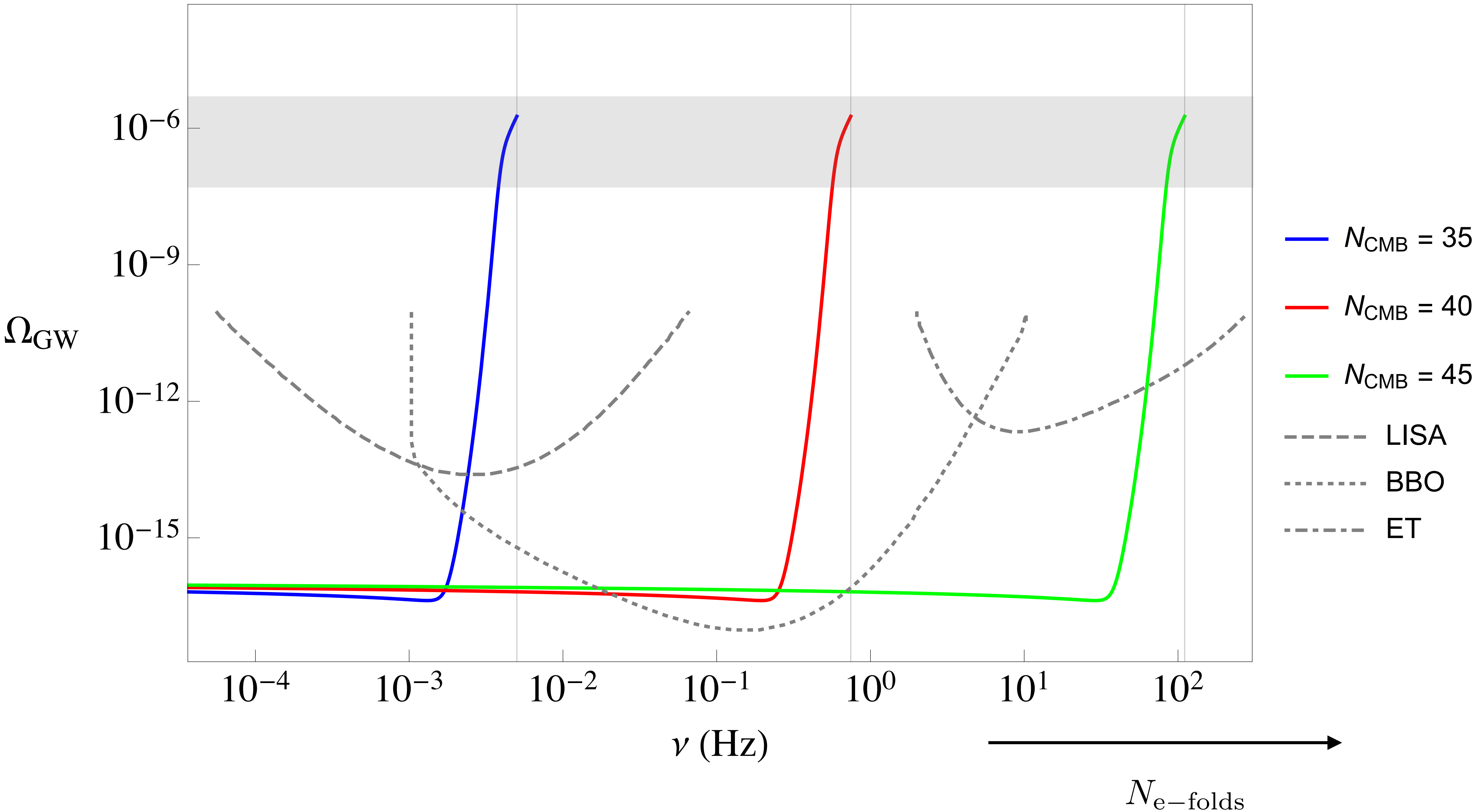
$$N = N_{CMB} + \ln\frac{k_{\rm CMB}}{0.002{\rm Mpc}^{-1}} - 44.9 - \ln\frac{\nu}{10^2{\rm Hz}}$$

Small-scale predictions



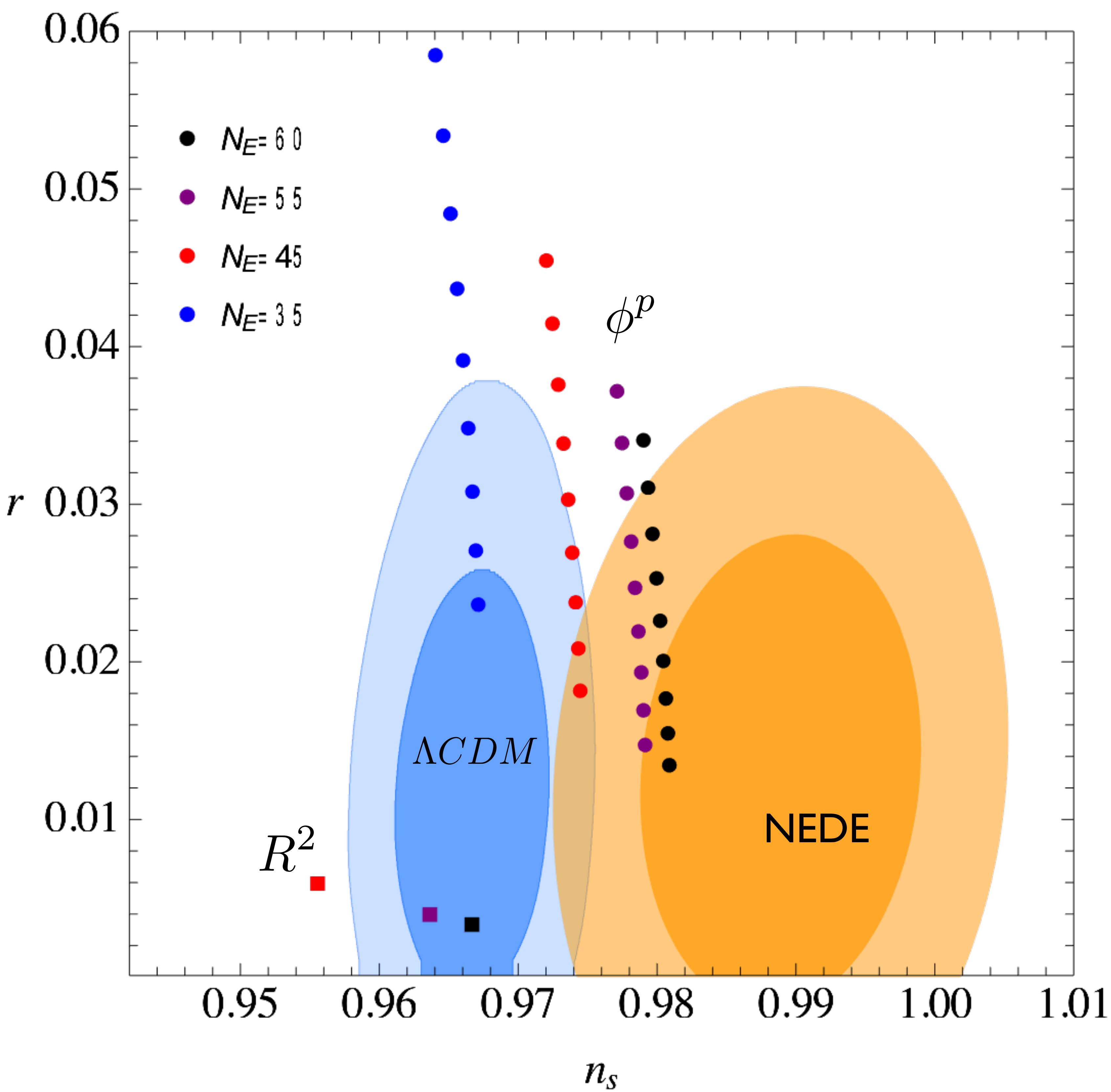
A very loud signal for LISA/BBO

Small-scale predictions



Varying N_{CMB}, signal in the range of different instruments (NANOgrav, SKA, LISA, Decigo, Big Bang Observatory, Einstein Telescope...)

A "Caveat"? H0 & LCDM???



Conclusions

- Why does inflation have to happen all in one go? It does not!
- Interrupting may help with naturalness
  It definitely helps with fitting data for large-field models
- Horizon and curvature problems are easily solved
- Model building reopens
  Interruptions give correlated signals at large and small scales
  what are other interesting observables?
- One simple, realistic example:
  Double monodromy inflation, a gravity waves factory for CMB *and* small-scale GW experiments
- What else?

Gracias!