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Rollercoaster Cosmology (and a Gravity Wave Factory)

G. D'Amico, NK, arXiv:2011.09489
G. D'Amico, NK, A. Westphal, arXiv:2101.05861

Kavli IPMU 07/28/2021

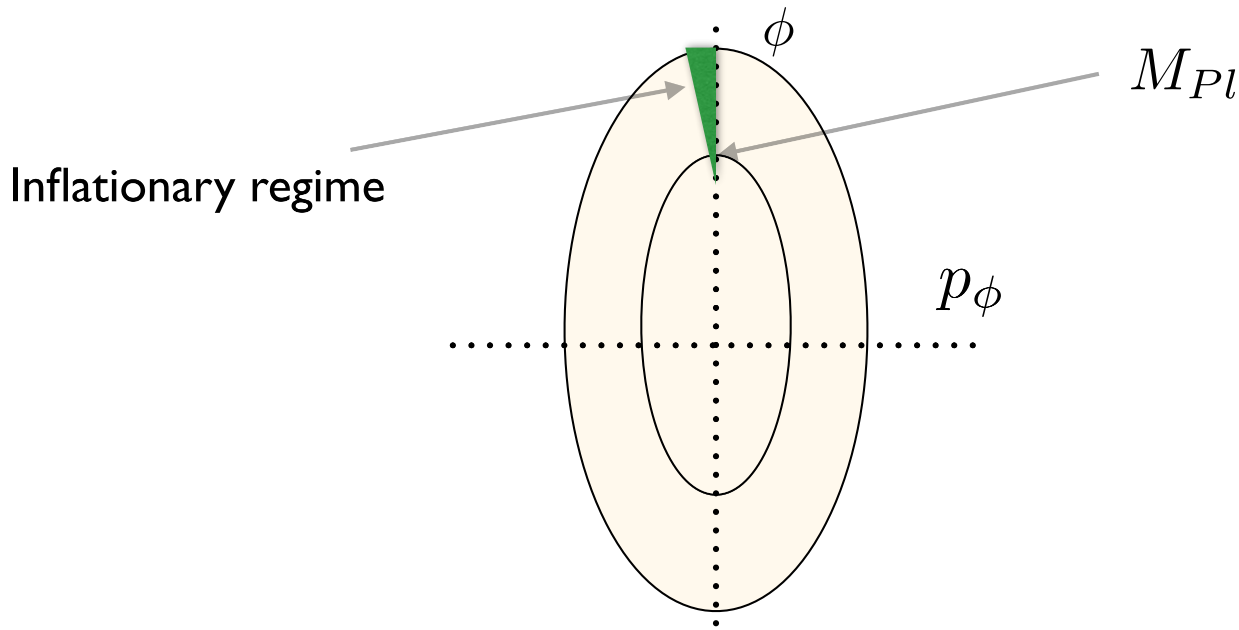
Inflation and naturalness

- Inflation was invented to explain the universe *naturally* - ie to "outlaw" a huge, bad, portion of the space of initial conditions
- Prior to inflation, our universe a set of measure zero in GR (Collins & Hawking, 1973).
- 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
- A possible answer: ***monodromy inflation*** (lots of nonlinearly realized gauge symmetries come to the rescue)

Slow Roll Inflation

Guth, Linde, Albrecht & Steinhardt 80's

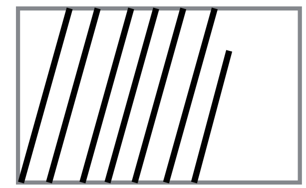
- Eg. quadratic potential $H = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}p_\phi^2$



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

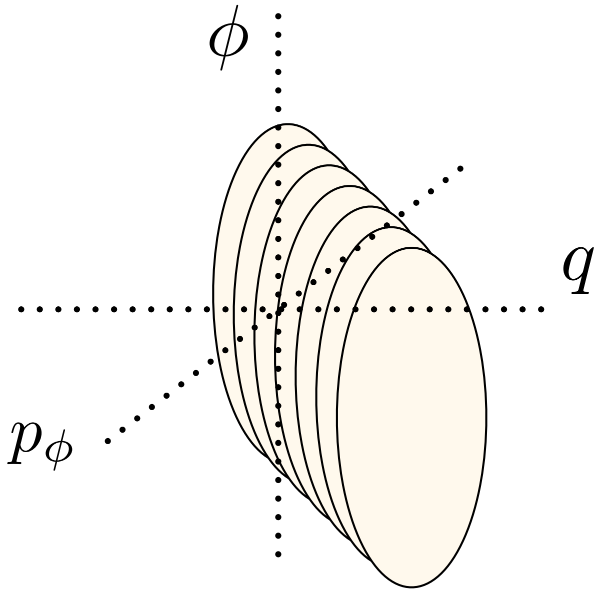
Monodromy Inflation

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

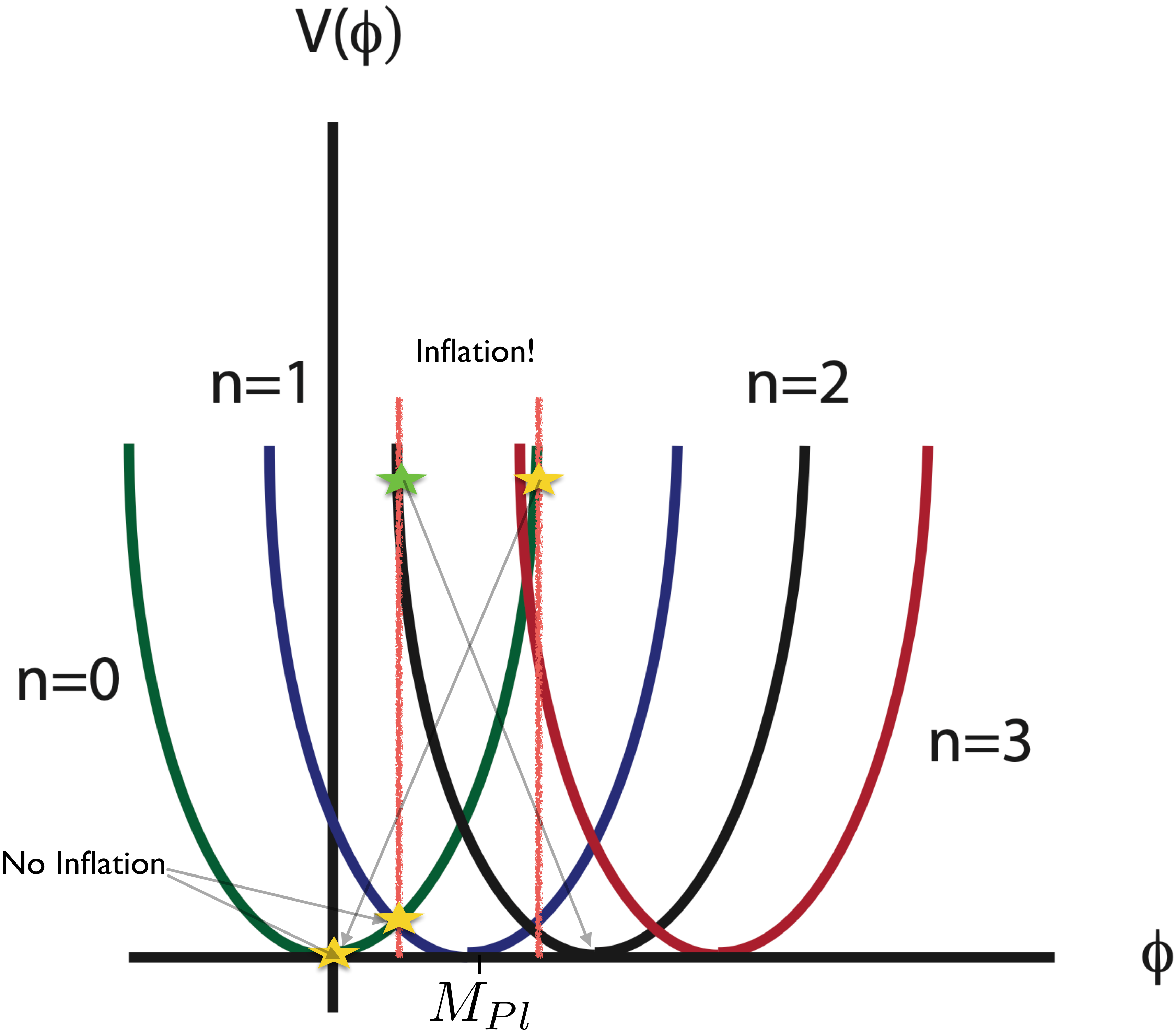


- Physical realization: a particle in a magnetic field

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

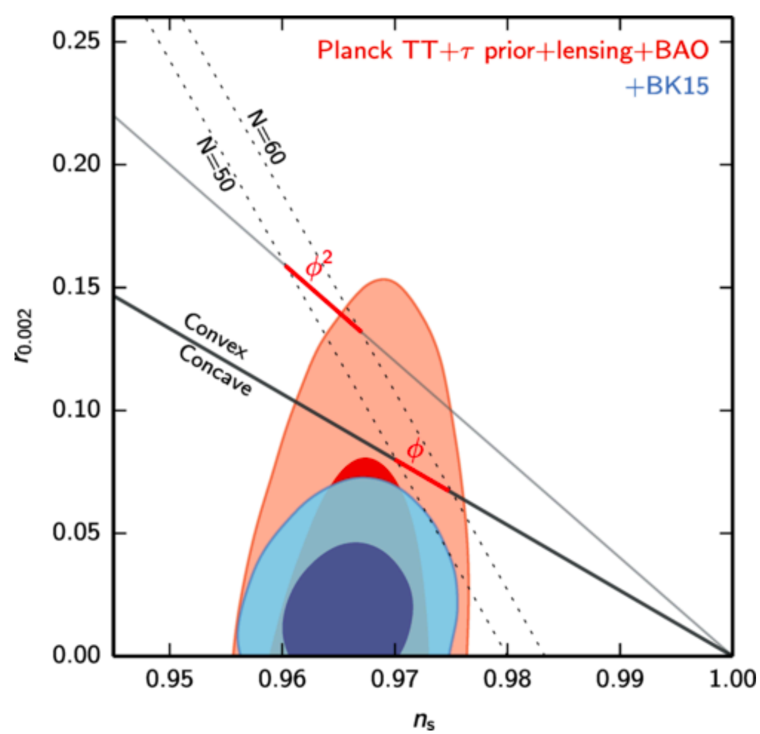


Silverstein & Westphal 2008;
McAllister, Silverstein & Westphal 2008;
Kaloper & Sorbo 2008;
Kaloper, Lawrence & Sorbo 2011
Marchesano, Shiu, Uranga, 2014
Hebecker, Rompineve, Westphal, 2015


V(ϕ)
Inflation!
n=1
n=2
n=0
n=3
No Inflation
ϕ
M_{Pl}

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!



Is there a way out?

- We would like to shorten the field variation
- We would like to have red spectrum, and weaker tensors

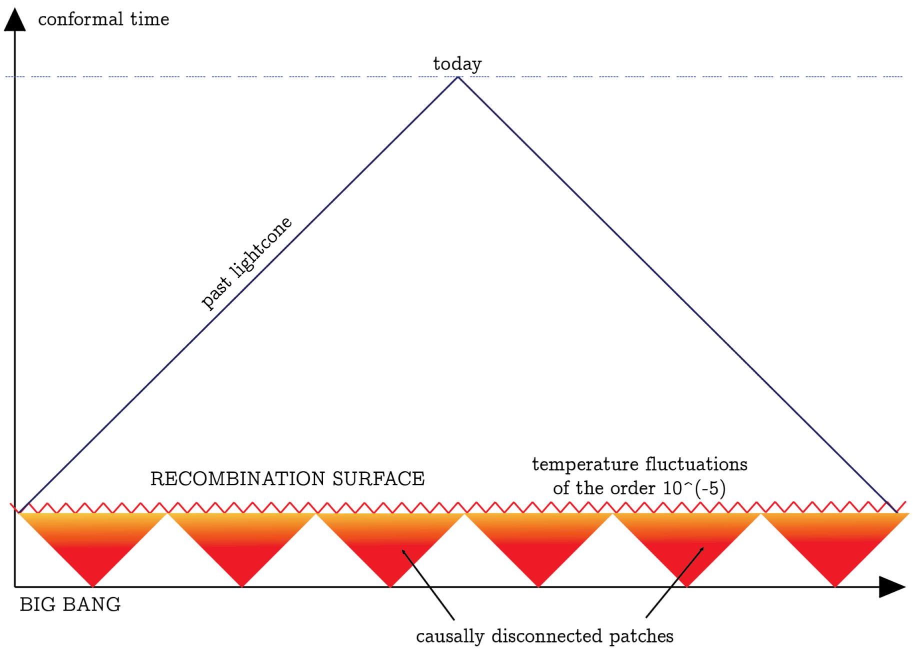
ROLLERCOASTER DYNAMICS!

… let's go for a ride…

Rollercoaster cosmology

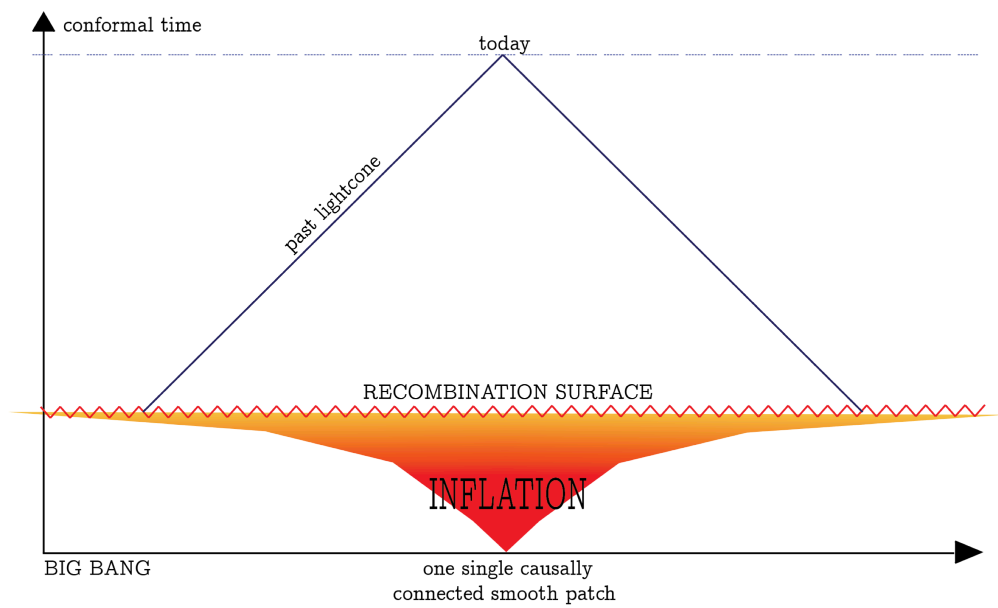
- We address and relax *both theoretical worries and data issues*
- A key insight: observationally, we do not need 60 efolds in one go: we only probe the first 10-15
- And then? Accelerated expansion may stop and go; from the bottom-up side this may look like a fine tuning (a soft tuning of a few parameters). But who's to say what a fine tuning is from the top-down?
- Bottomline: several stages of accelerated expansion just fine!
- So far we are only probing the first (CMB) stage - party time! 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 - an assumption that is not necessary; but driven by perhaps too naive a sense of "simplicity"

"Bring me that horizon..."

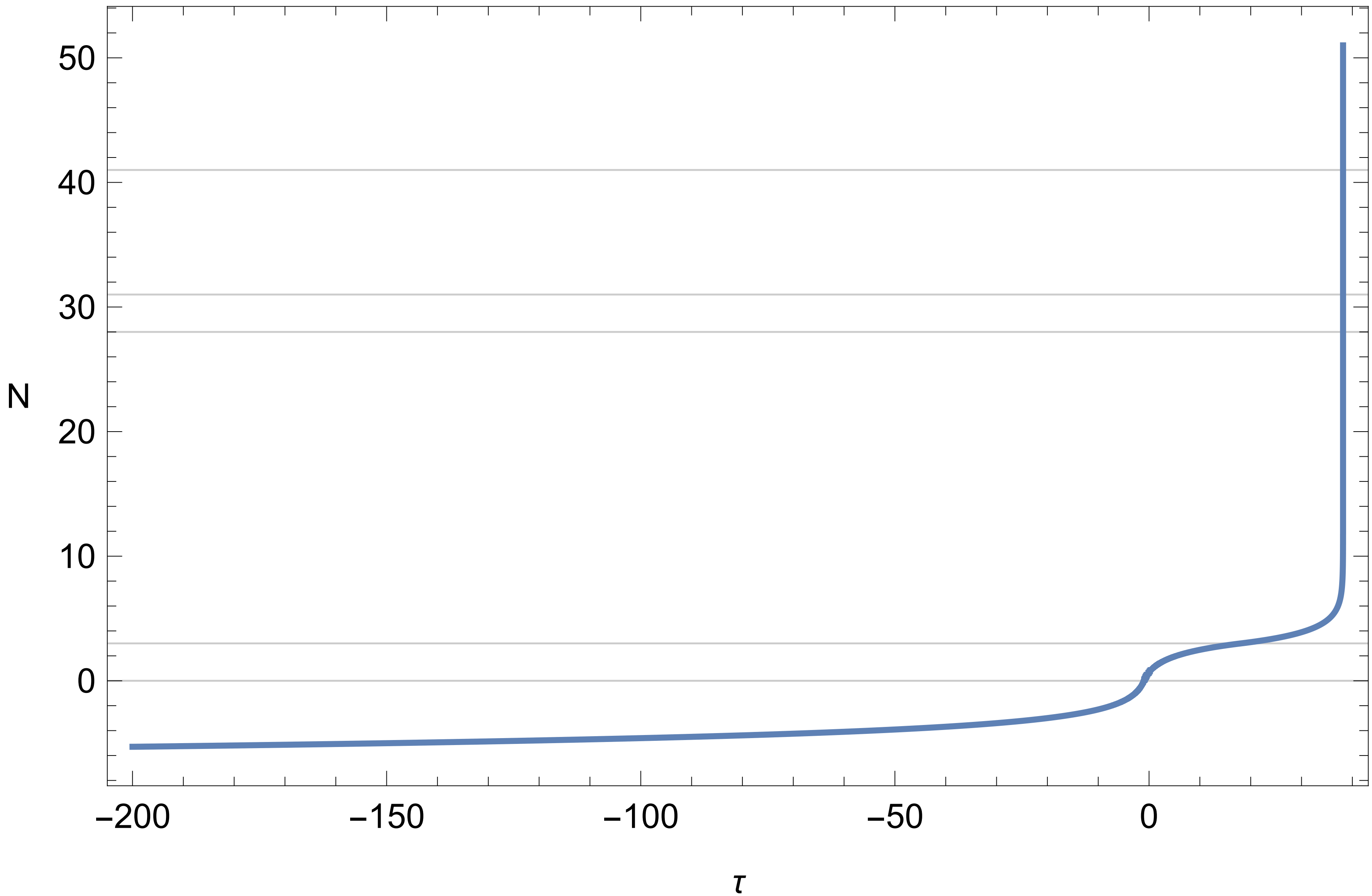


: PROBLEM

SOLUTION:



Rollercoaster (simplest) architecture



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

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

Inflation

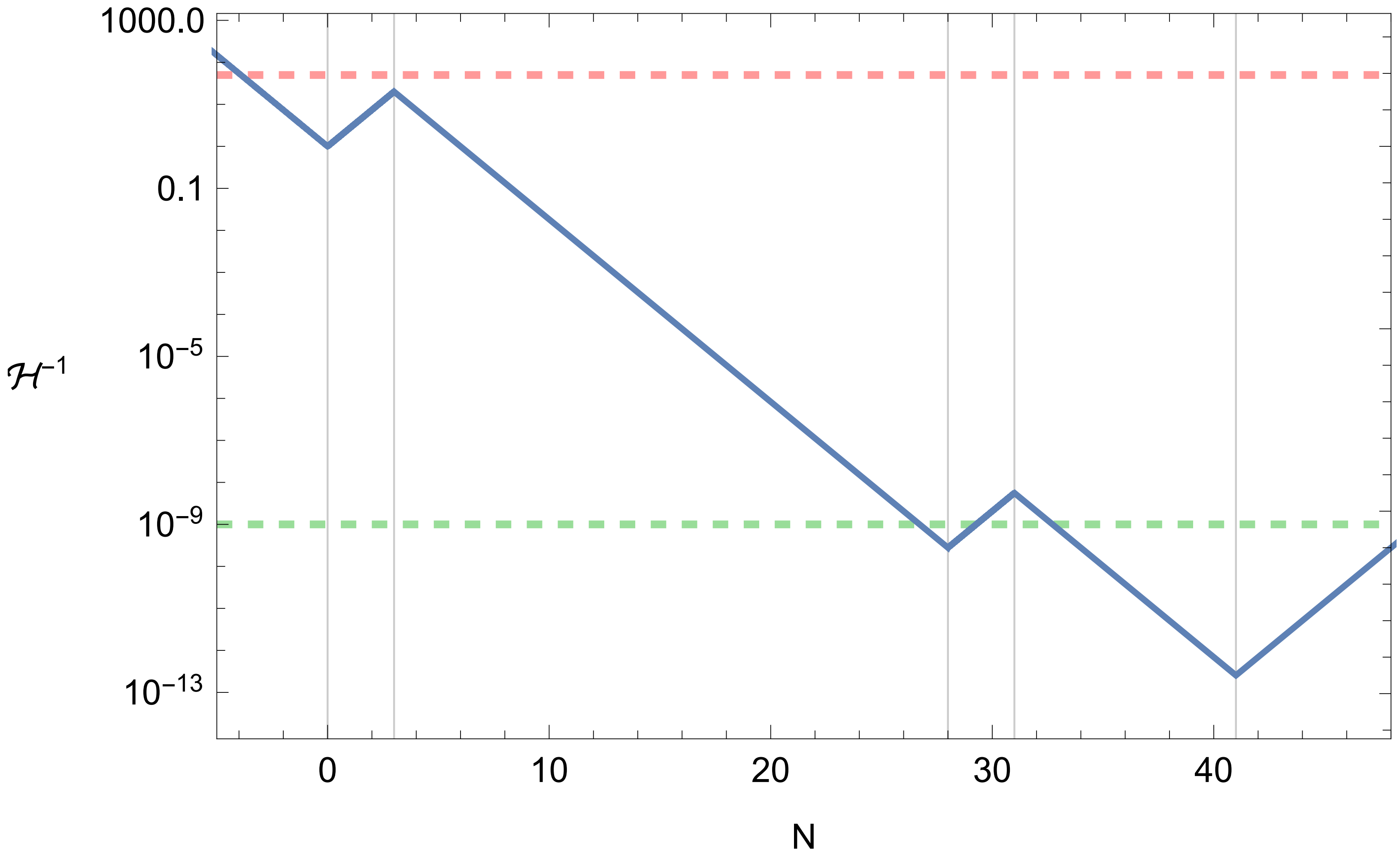
$$\int_{t_{\rm in}}^{t} \frac{{\rm d}t'}{a(t')} \simeq \frac{1}{\sqrt{H H_1}} \lesssim \frac{1}{H_1}$$

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

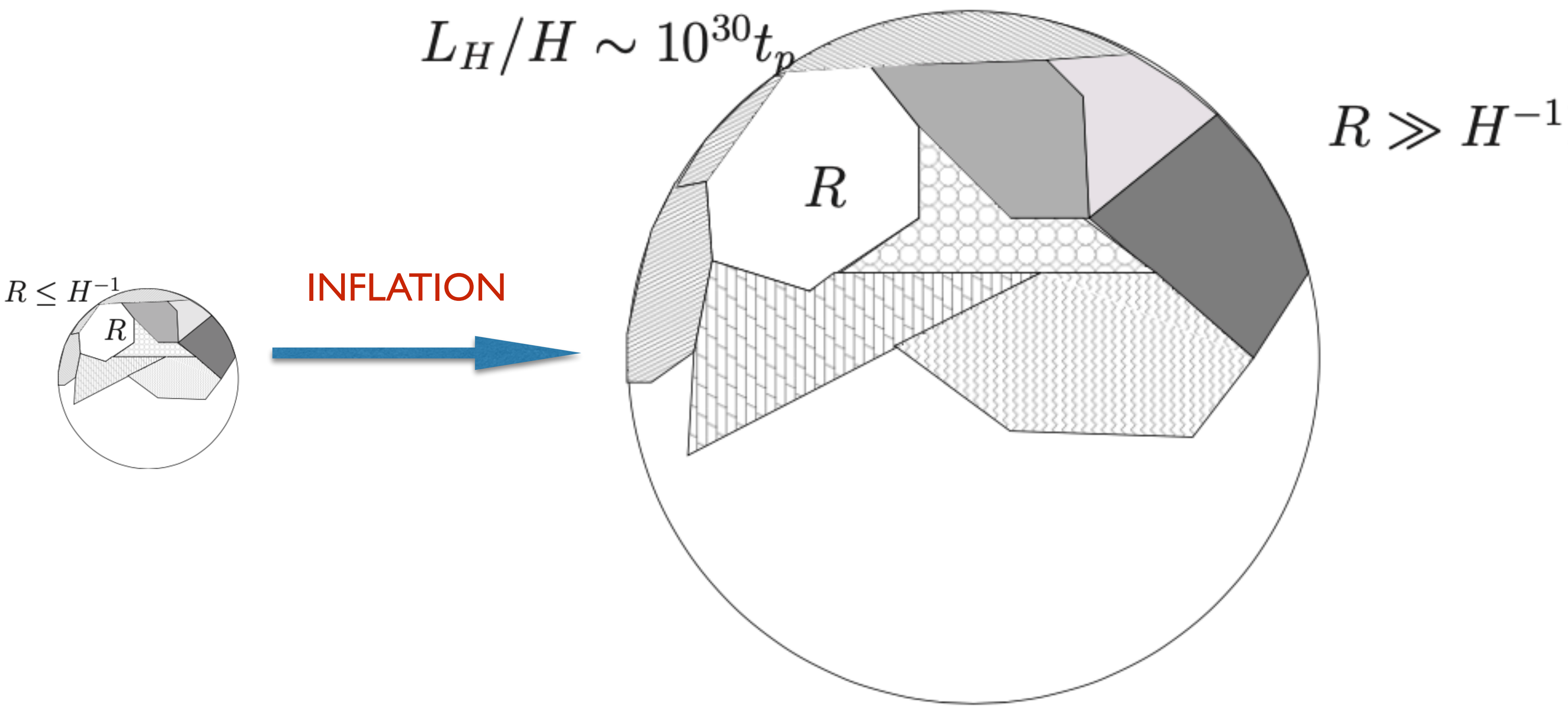
$$\frac{\ell}{L_H} \gtrsim l_{\rm in} H_1$$

This solves horizon problem in rollercoaster

The Horizon Problem



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

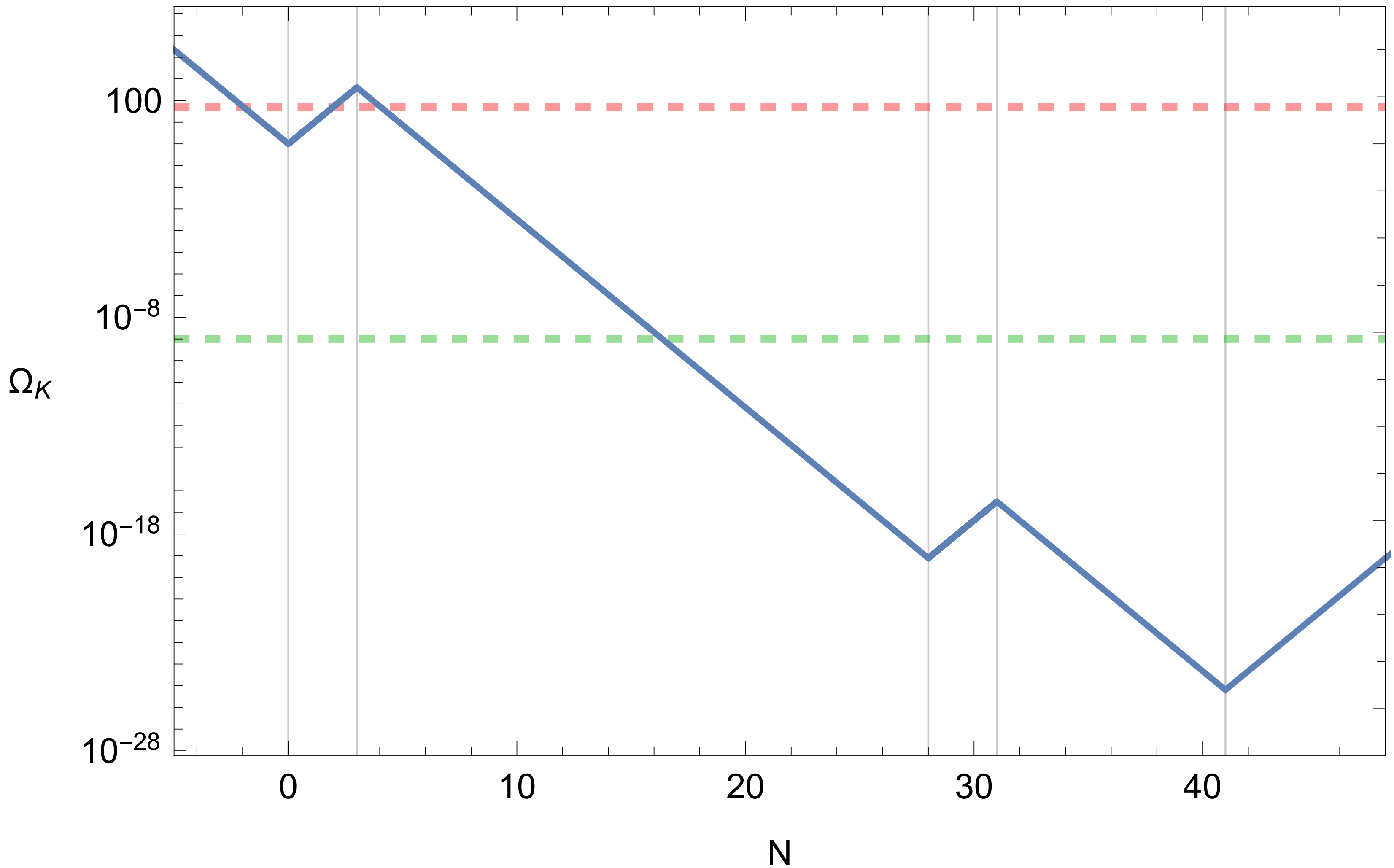
$$\frac{\Omega_{\mathrm{K,end}}}{\Omega_{\mathrm{K,in}}} = \left(\frac{a_{\mathrm{in}}}{a_{\mathrm{fin}}}\right)^2 = e^{-2N}$$

Inflation

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

Rollercoaster

The Curvature Problem



Perturbations I

- Tensors are straightforward, by equivalence principle - 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 controlling the `substrate' yielding accelerated expansion
- *Generically modeled as a scalar field to preserve covariance*
- Multiple stages, multiple fields.
  They need to be governed by 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*

Perturbations II

- Prototype: Starobinsky - as done by Chibisov and Mukhanov

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

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

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

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

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

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

A Different Way to Phrase...

- This may be the `ultimate' EFT of the background and leading order perturbations for inflationary cosmology
- *The **task** is to develop an EFT coupled to gravity which has an approximate scaling symmetry*
- *The **challenge** is to get scaling symmetry from full UV theory - aka quantum gravity - and not have it too disrupted*
- Rollercoaster idea: maybe we can do it piecemeal - a little bit at a time…
- *An interesting aside:* $\left(\frac{\delta\rho}{\rho}|_{\mathrm{T}}\right)^2 = \frac{2}{(2\pi)^2}\left(\frac{H}{M_{Pl}}\right)^2 = \frac{1}{384\pi^2 c} \simeq \frac{2.6\cdot 10^{-4}}{c}$
- *Tensors measure the difference between inflation scale and gravity strong coupling*

Perturbations III

The rest is just the standard approach to quantizing & computing 2pt function - use Mukhanov-Sasaki formalism

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

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

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

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

Perturbations IV

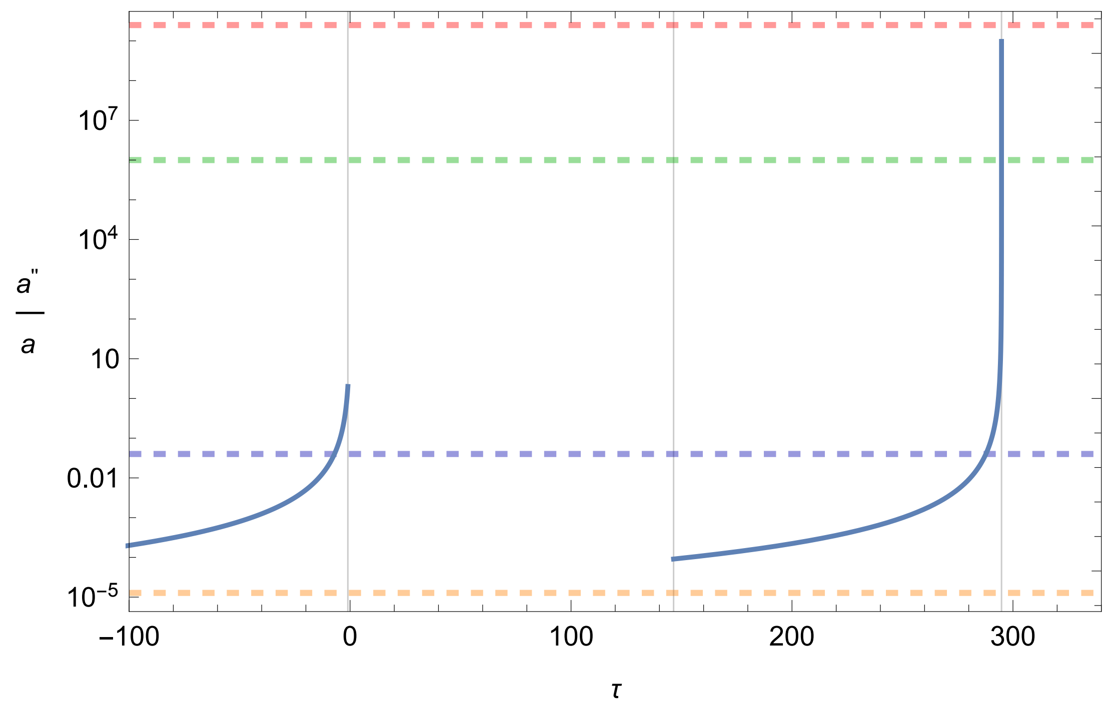
$$\varphi(\tau,\vec{x}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^{3/2}} \left[u_k(\tau) b_{\vec{k}} e^{i\vec{k}\cdot\vec{x}} + u_k^*(\tau) b_{\vec{k}}^\dagger e^{-i\vec{k}\cdot\vec{x}} \right]$$

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

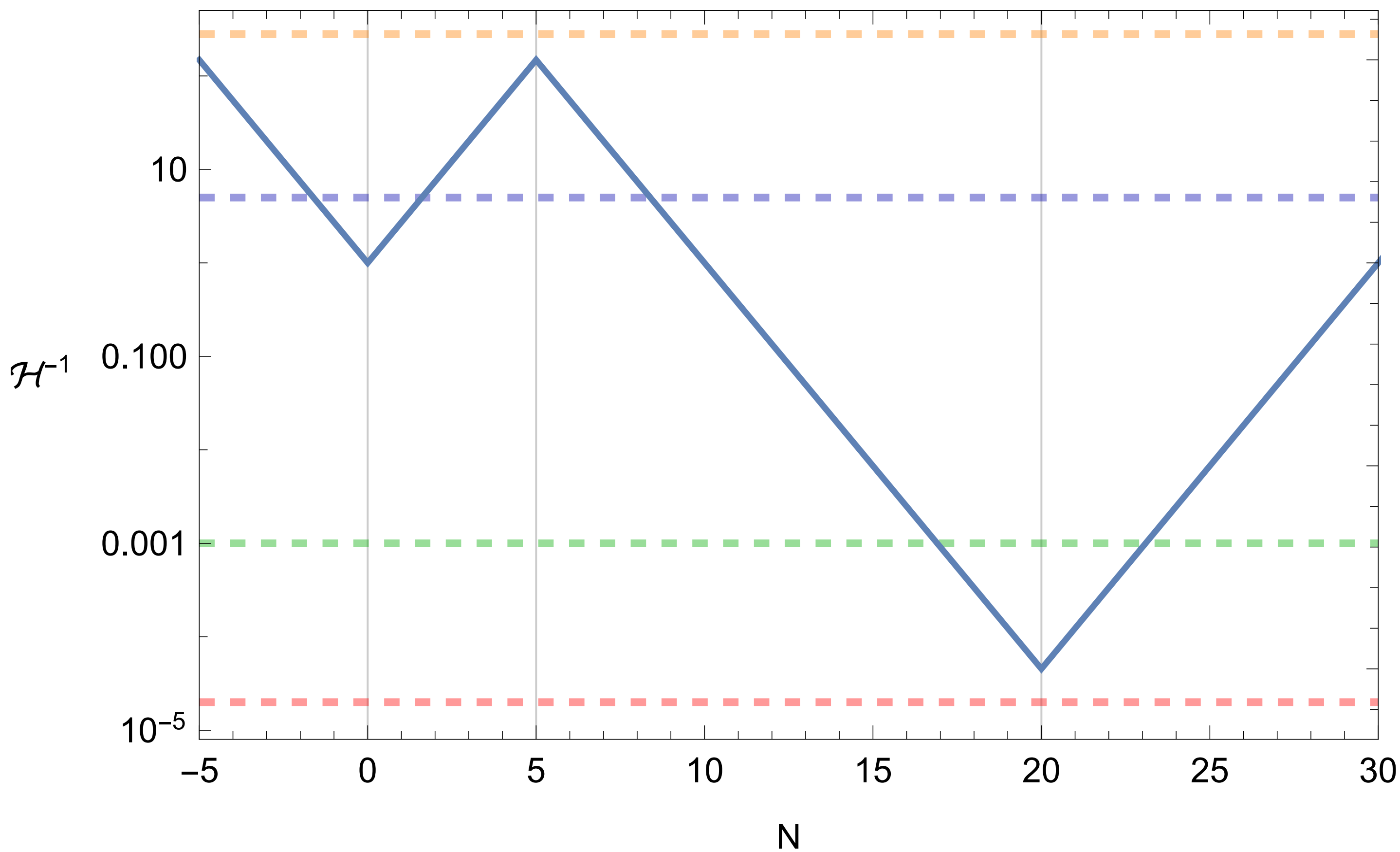
Same as Schroedinger's eq., with anti-tunnelling!

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

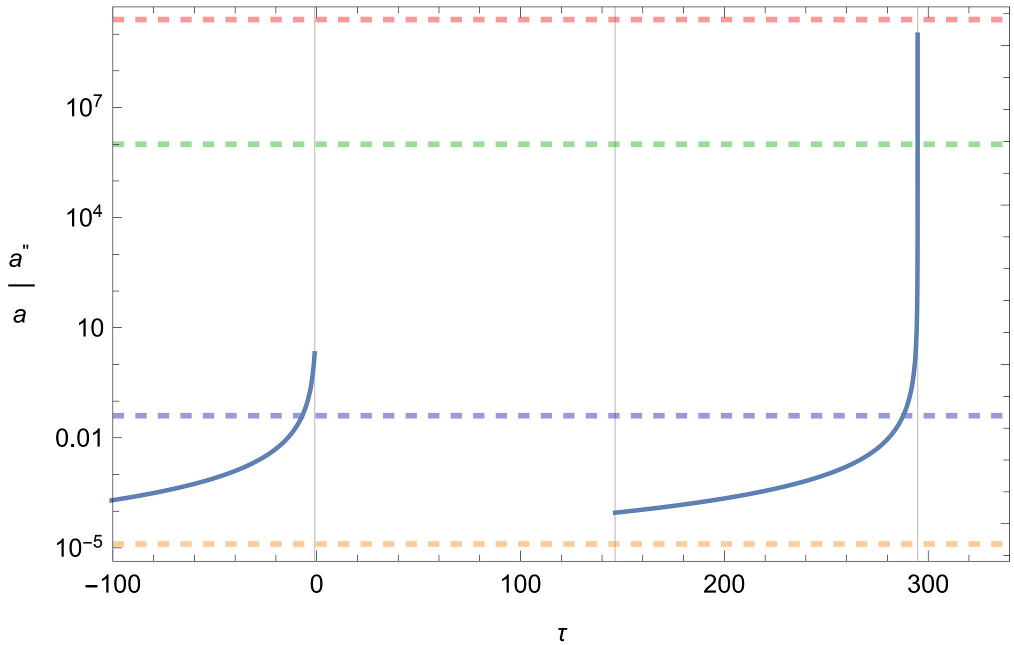
$$u_k'(\tau_-) = u_k'(\tau_+)$$



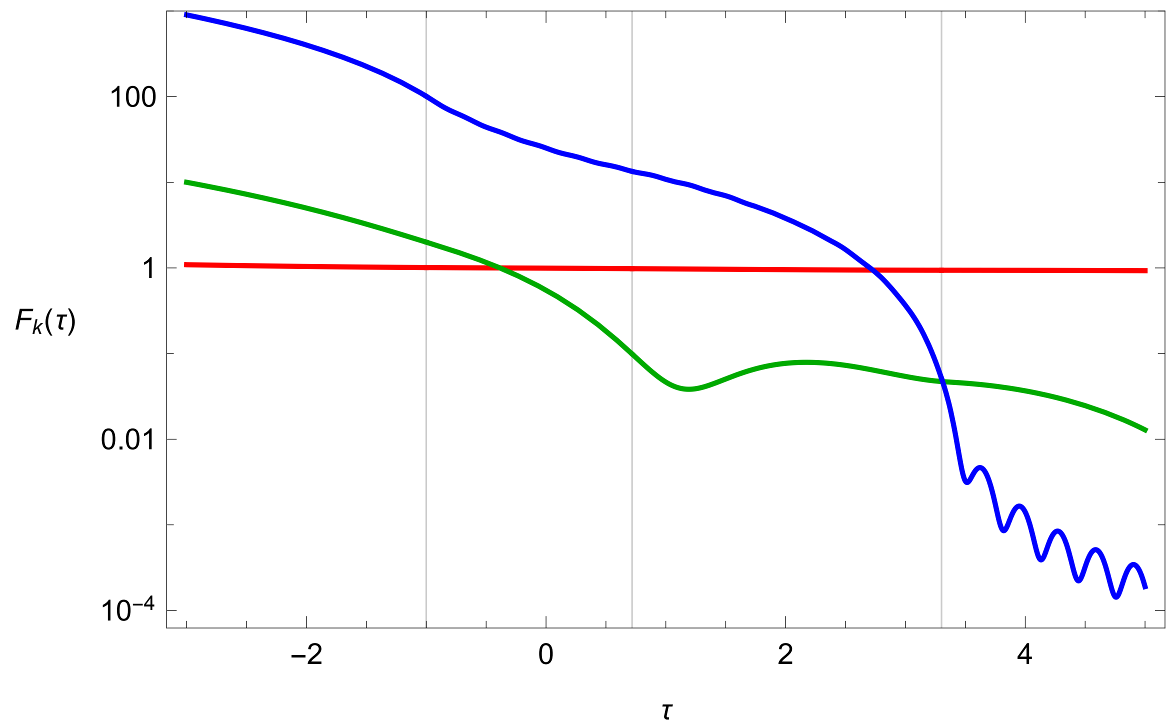
Cosmologia con quattro stagioni



Cosmologia con quattro stagioni



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

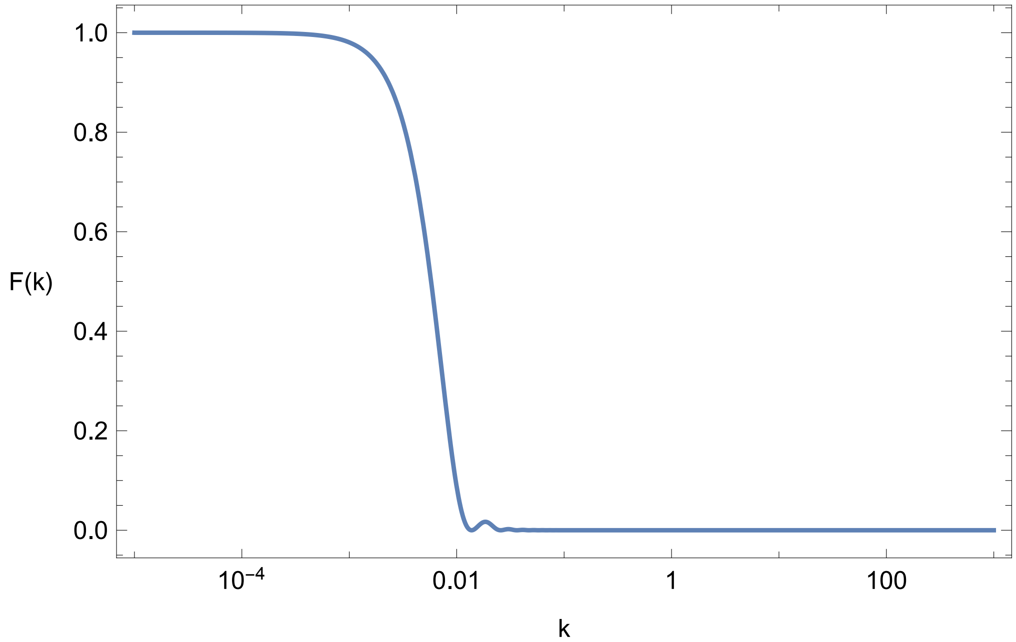


$$P_S = \left(\frac{H_j}{\dot{\phi}_j}\right)^2 |\varphi_k|^2_{\text{ren.}} = \left(\frac{H_j^2}{2\pi\dot{\phi}}\right)^2$$

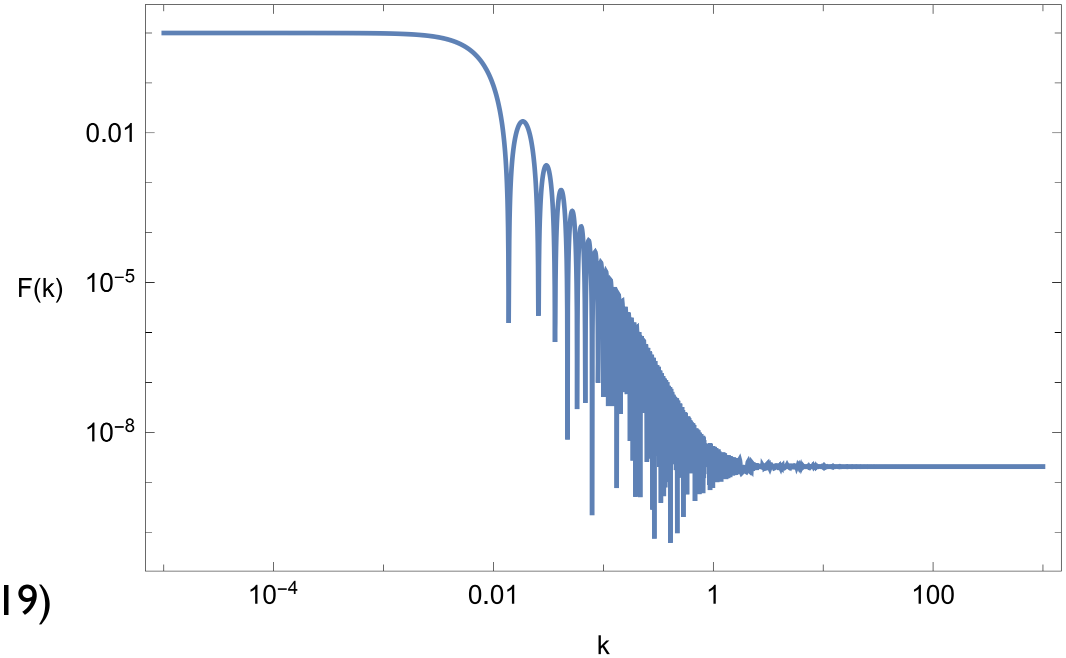
$$P_T = \frac{2|h_k|^2_{\text{ren.}}}{M_{\text{Pl}}^2} = \frac{2H_j^2}{(2\pi)^2 M_{\text{Pl}}^2}$$

$$k < H_j$$

Cosmologia con quattro stagioni

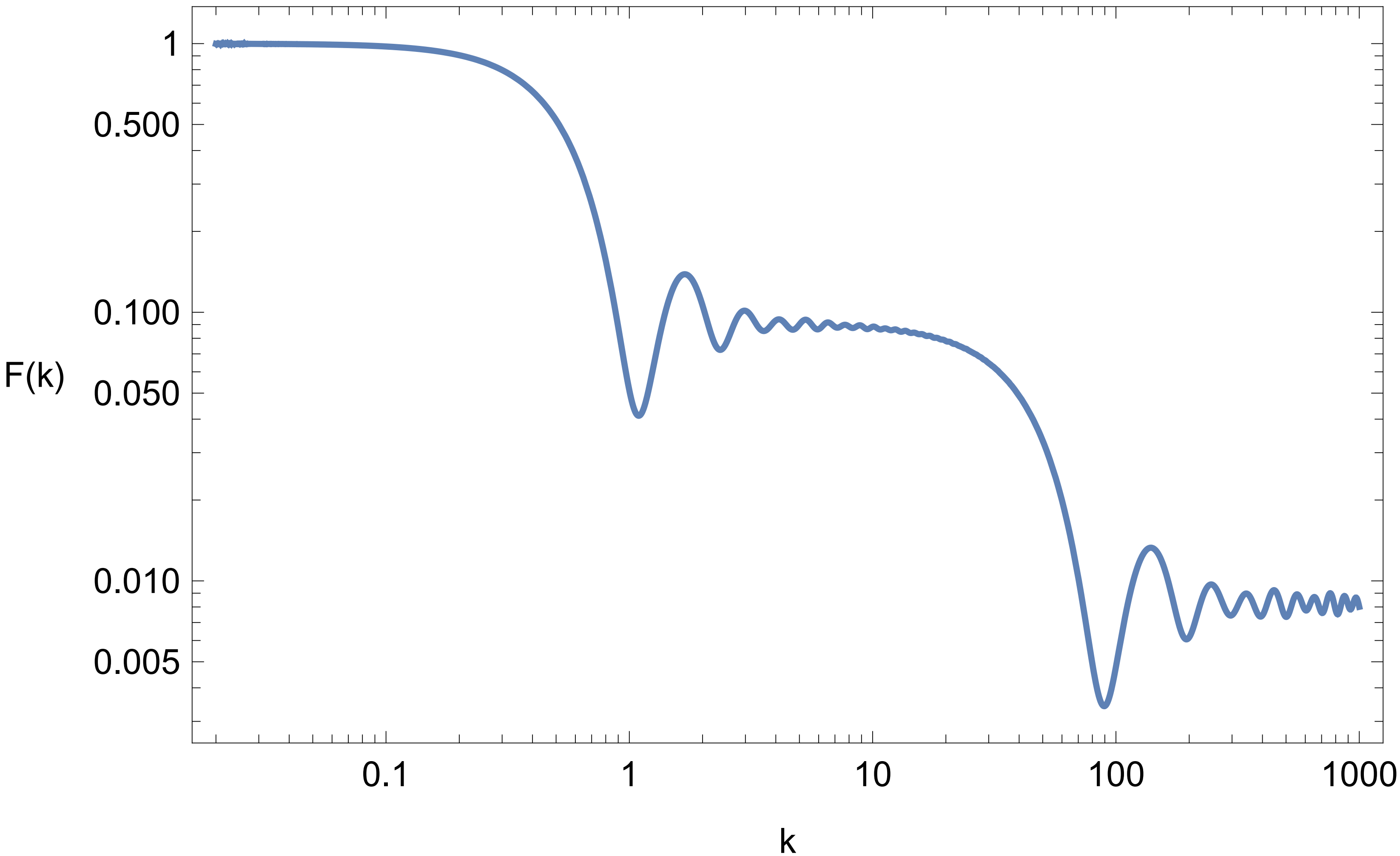


$$F(k) = \frac{P(k)}{P_0(k)}$$

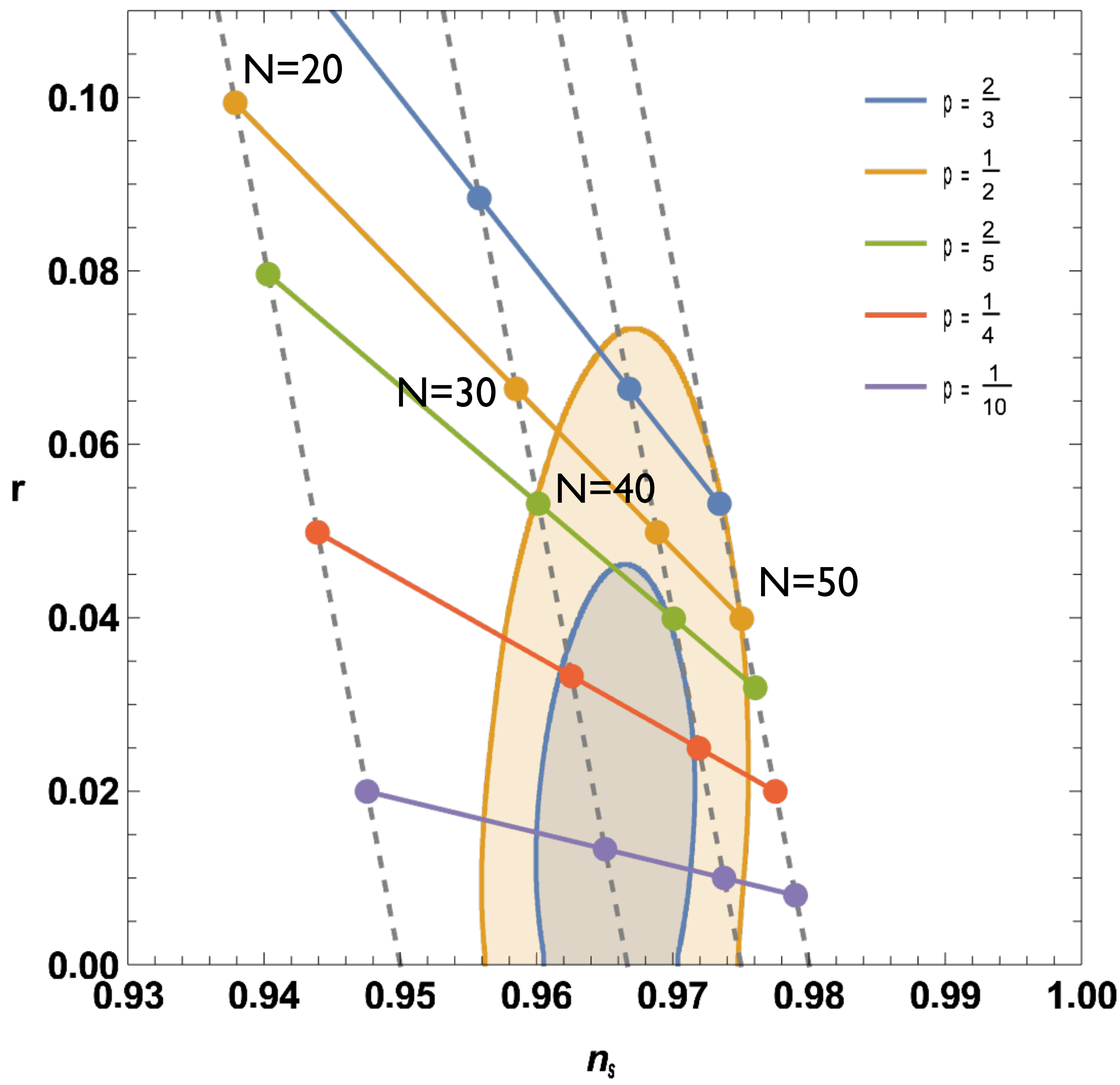


See also S. Pi, M. Sasaki and Y. l. Zhang, JCAP 06, 049 (2019)

Power spectrum, more realistic case

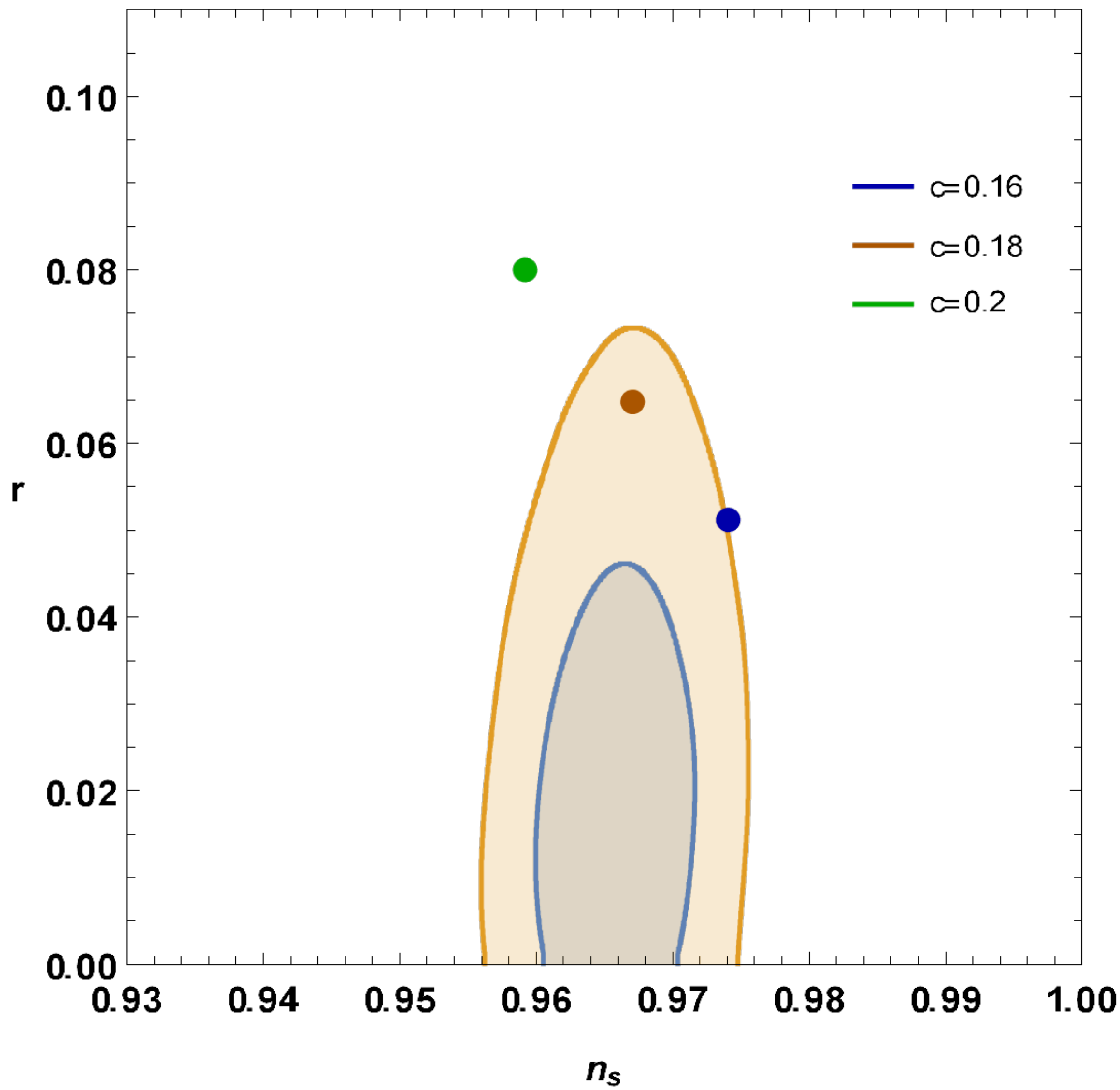


Power-law inflation, viable again!



Model building open again

Nontrivial job: not everything goes; for example consider exponential potentials…

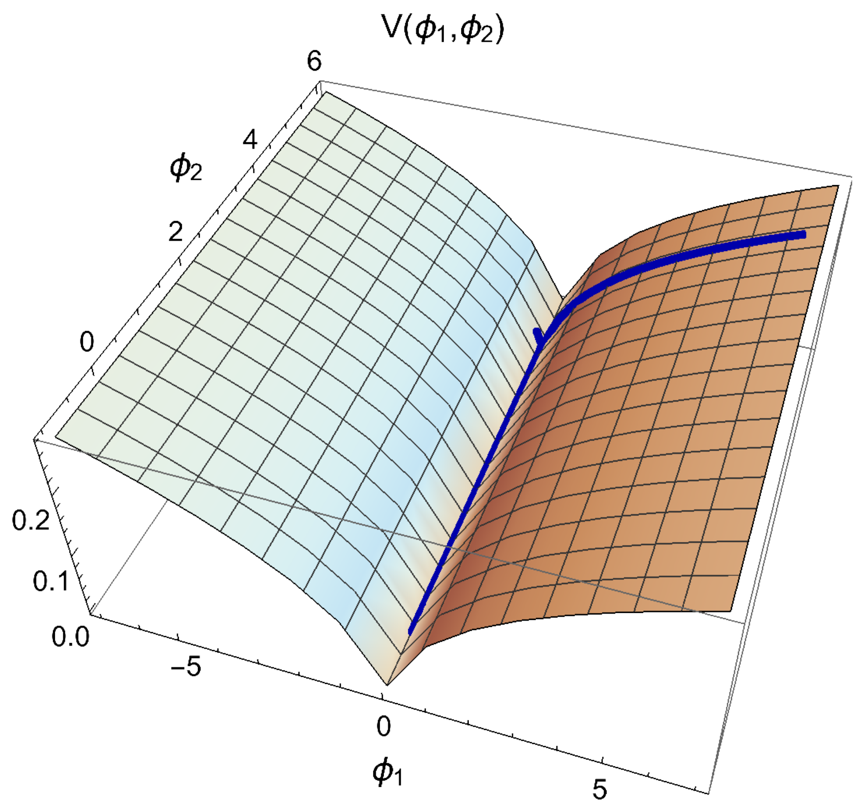


$$V(\phi) = V_0 e^{c\phi/M_{Pl}}$$

Doublecoaster cosmology

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

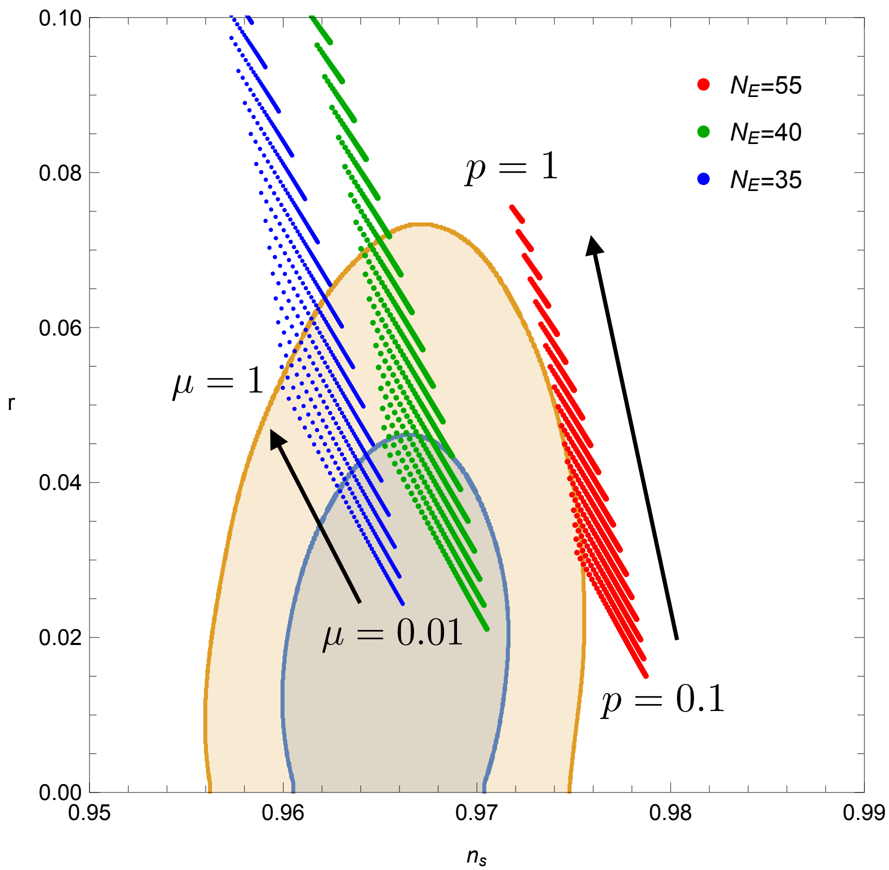
$$V(\phi_1,\phi_2) = M_1^4\left[\left(1+\frac{\phi_1^2}{\mu_1^2}\right)^{p_1/2}-1\right] + M_2^4\left[\left(1+\frac{\phi_2^2}{\mu_2^2}\right)^{p_2/2}-1\right] \qquad \begin{array}{l} M_1 > M_2 \\ \mu_i \sim \mathcal{O}(0.1 M_{\rm Pl}) \end{array}$$



- 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.



Additional benefits

- Compatible with CMB. Moreover, very predictive since lower bound on r
- More surprises, from string theory constructions it is natural to expect couplings to gauge fields

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

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

- 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

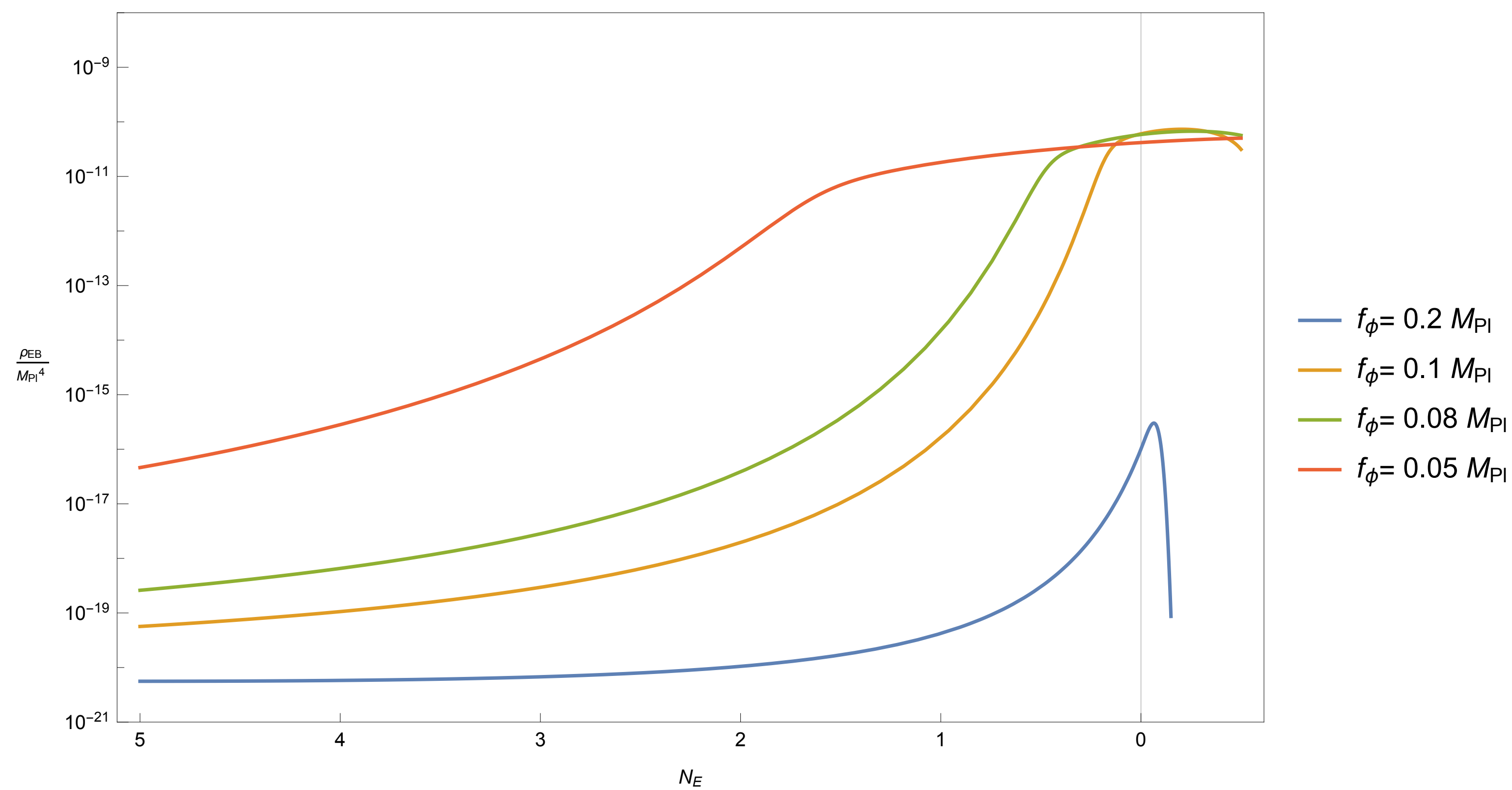
Campbell, NK, Madden, Olive, 1995
Anber & Sorbo 2009
many others

Solutions...

Full solution is complicated.

For constant ξ, we have exponential production

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



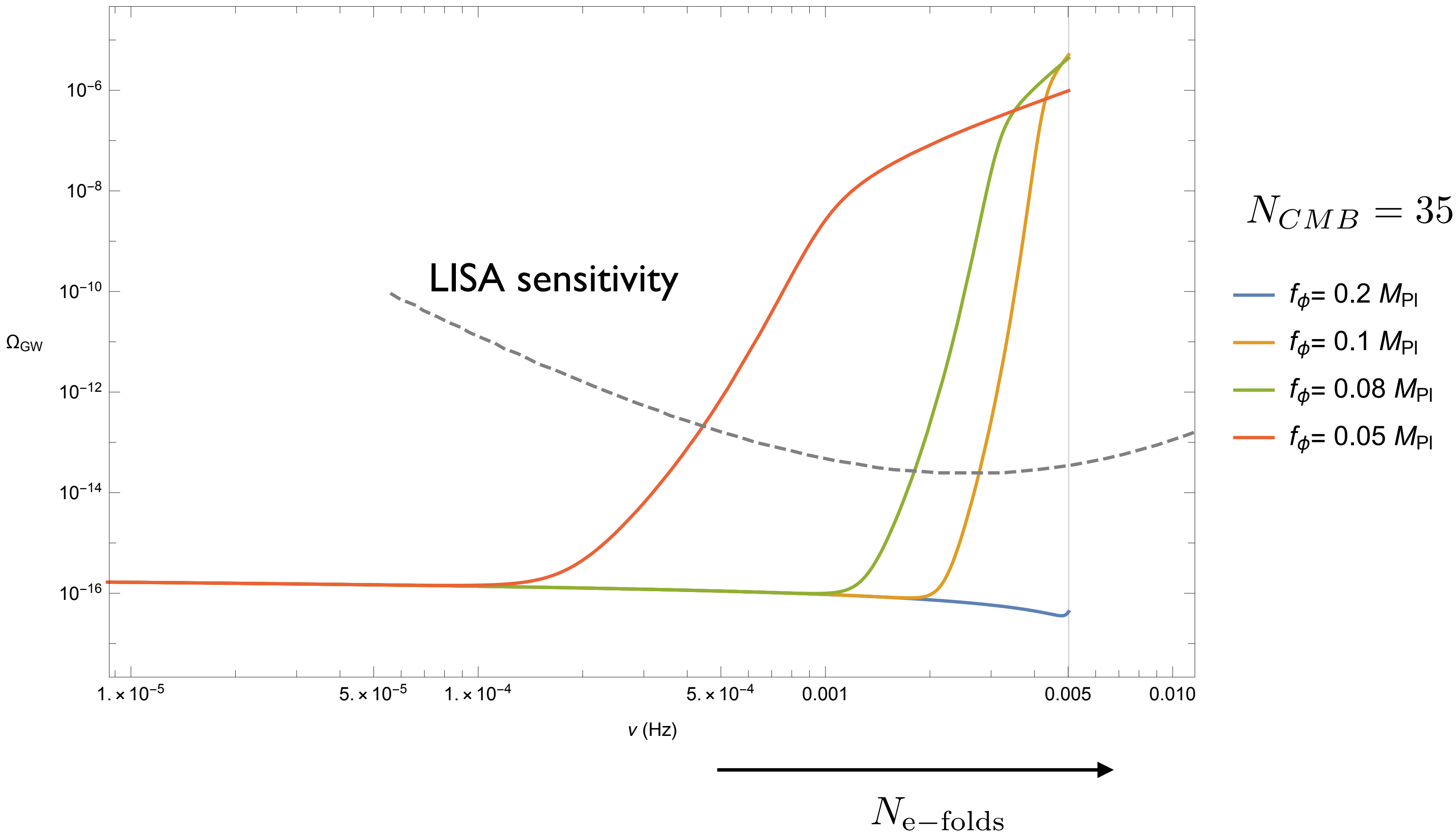
Solutions...

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



A very loud signal for LISA

Summary

- Why does inflation have to happen all in one go?
- Interrupting may help with naturalness relieving the pressure from the UV; it definitely helps with fitting data for large-field models; tuning to accomplish this is minimal
- Horizon and curvature problems are easily solved
- Model building reopens: possibility of correlated signals at large and small scales; what are the other interesting observables?
- An interesting realistic example: Double monodromy inflation: a gravity waves factory for CMB *and* LISA
- Let's find more examples!

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