Title: Rollercoaster Cosmology, and a Gravity Wave Factory

Speakers: Guido D'Amico

Series: Cosmology & Gravitation

Date: April 12, 2022 - 11:00 AM

URL: https://pirsa.org/22040116

Abstract: Does inflation have to happen all in one go? The answer is no!

All cosmological problems can be solved by a sequence of bursts of cosmic acceleration, interrupted by short epochs of decelerated expansion.

In this rollercoaster cosmology, models that seem excluded for a single long stage become viable again, and high-scale inflation is more natural.

At the same time, we expect interesting predictions at several different length scales, such as gravitational wave signals potentially detectable by LISA.

I will describe the general framework, and focus on a realization with two stages of monodromy inflation.

Zoom Link: https://pitp.zoom.us/j/99206384855?pwd=dUpDdWVxV1lXc0g1bU9uZ2lrMzVXUT09

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*

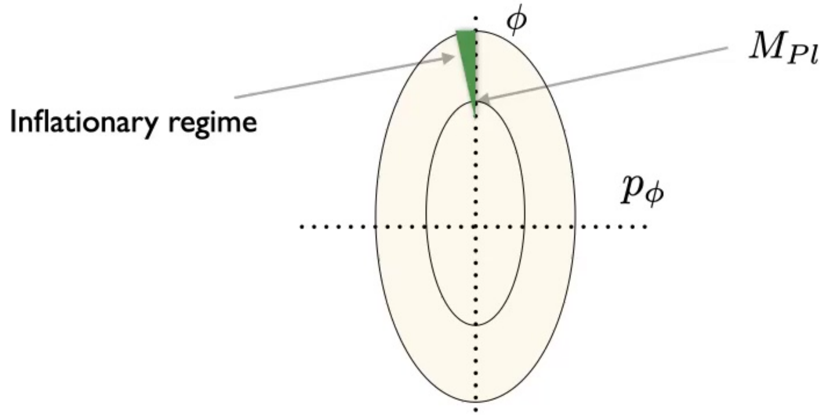
Perimeter Cosmology Seminar, 12/4/2022

# *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 $H = \frac{1}{2}\mu^2\phi^2 + \frac{1}{2}p_\phi^2$



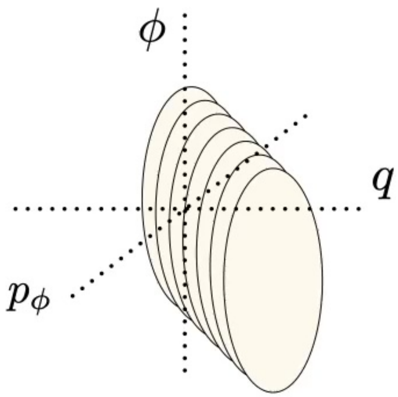

- Inflation occurs at large field vevs $\phi > M_{Pl}$
- Getting > 60 efolds from $\phi^n$ requires $\frac{\phi}{M_{Pl}} > \sqrt{120n}$
- Can we trust EFT arguments beyond Planck scale?

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

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

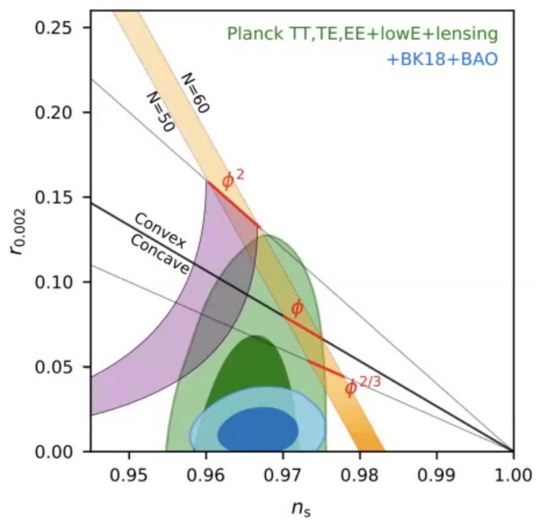



Silverstein & Westphal 2008;
McAllister, Silverstein & Westphal 2008;
Kaloper & Sorbo 2008;
Kaloper, Lawrence & Sorbo 2011

# *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*: $r < 0.036$

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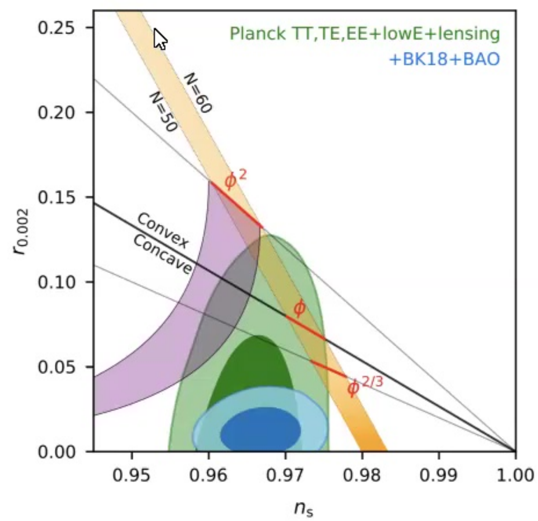
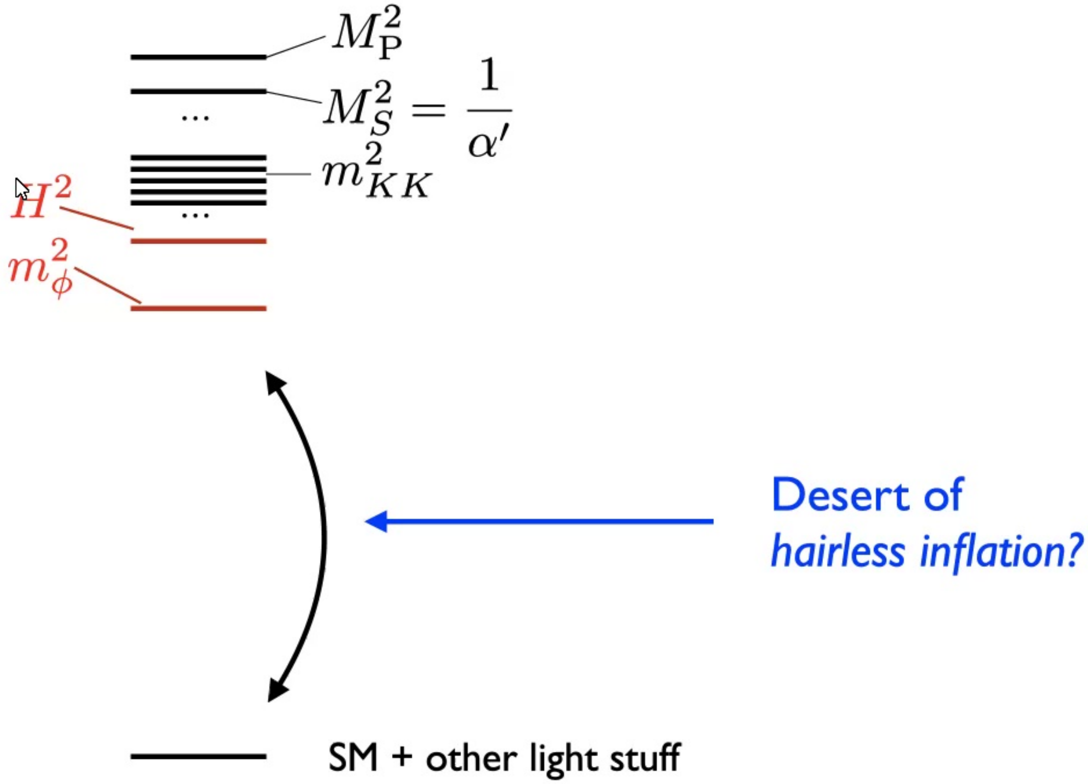


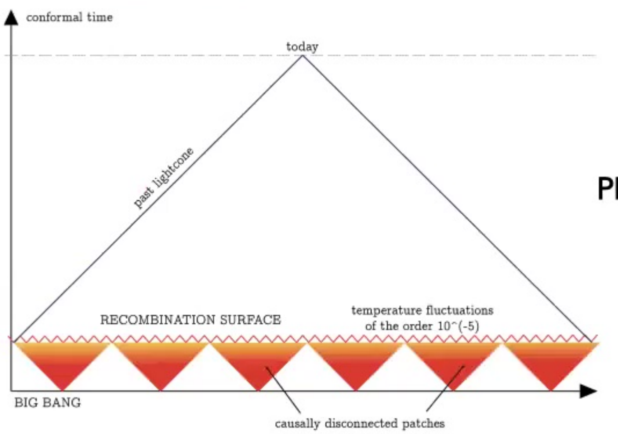

# Rollercoaster cosmology

- 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
- 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

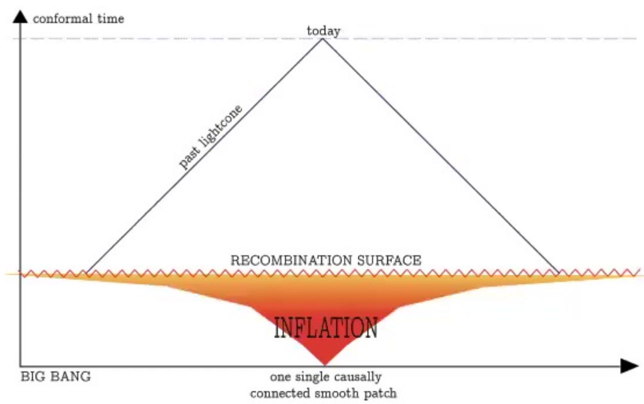



# "Bring me that horizon..."

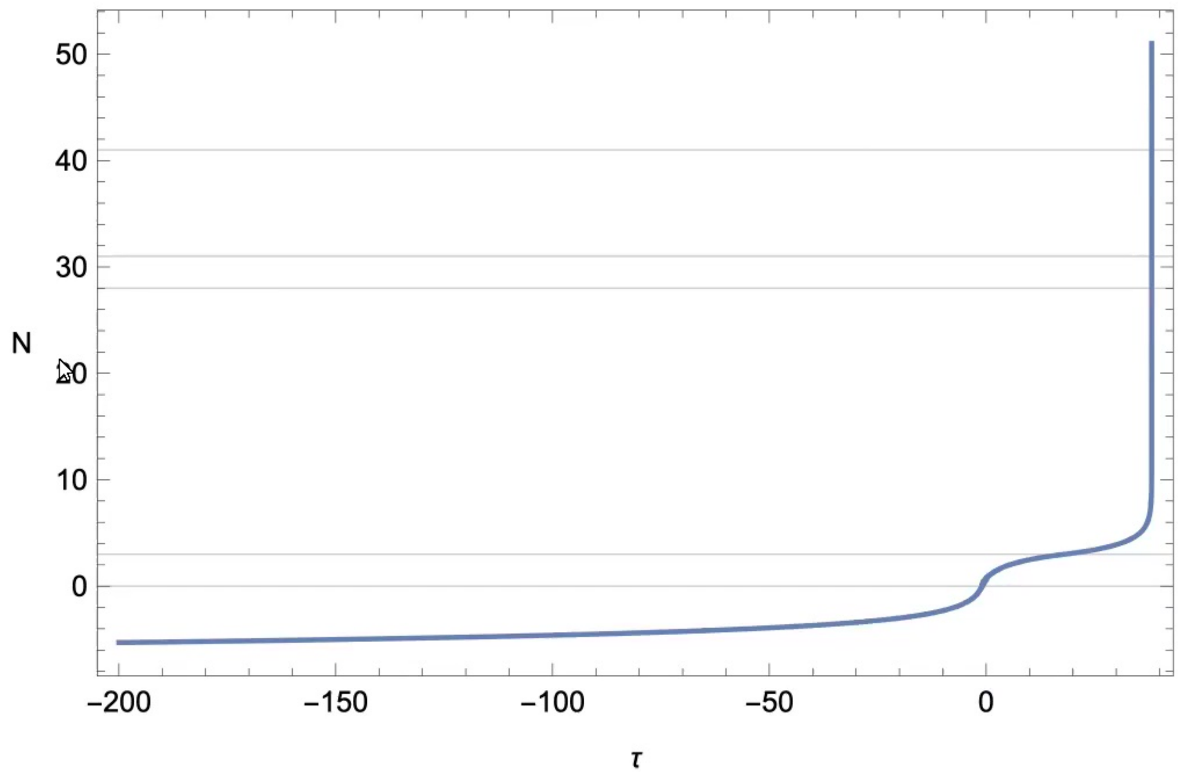



PROBLEM

SOLUTION




# Rollercoaster (simplest) architecture




# The Horizon Problem


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

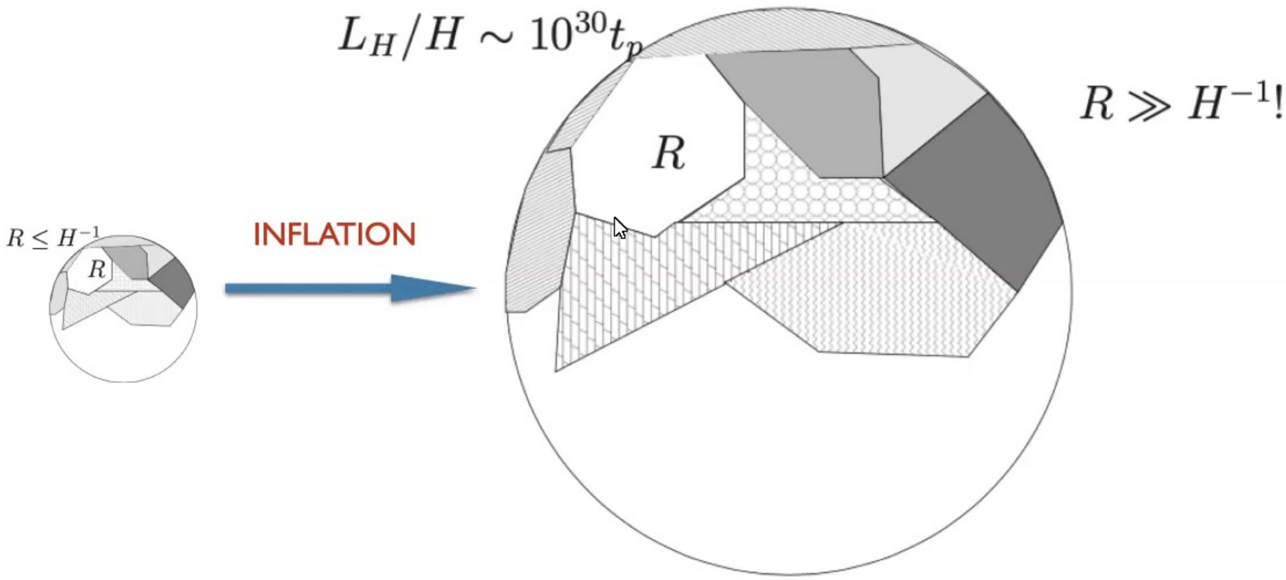
$$\frac{\ell}{L_H} \sim t^{-\frac{w+1/3}{w+1}}$$ Normal matter

$$\frac{\ell}{L_H} \sim {\rm const}$$ 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 Curvature (and Homogeneity & Isotropy) Problem(s)




# The Curvature Problem

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

Normal matter

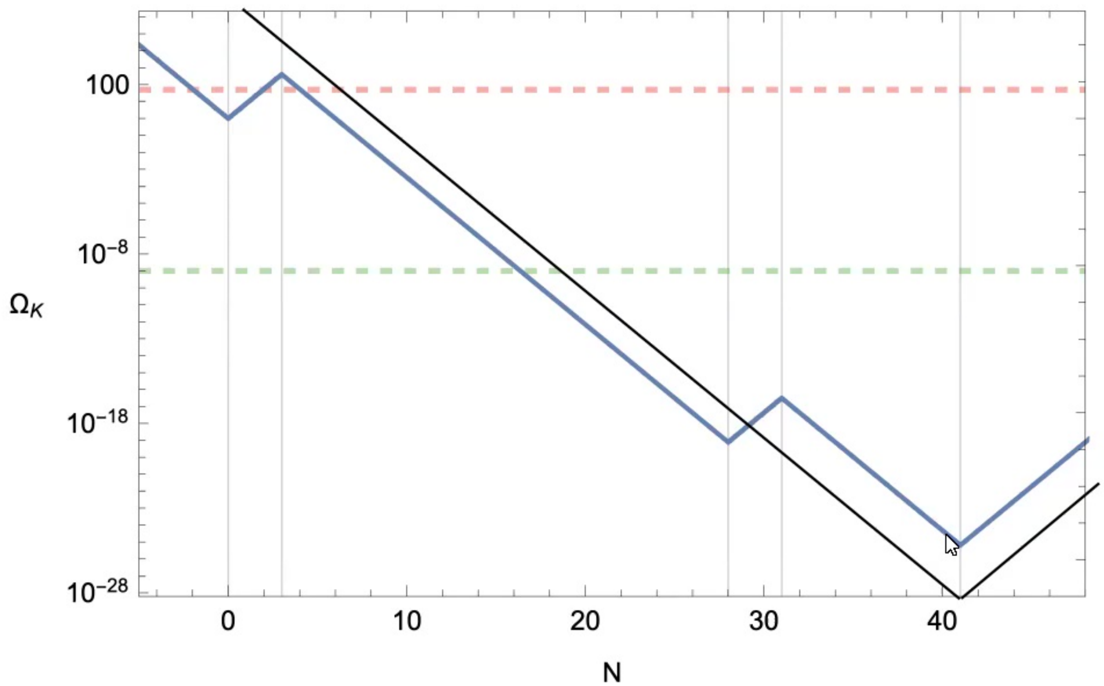
$$\frac{\Omega_{K,\mathrm{end}}}{\Omega_{K,\mathrm{in}}} = \left(\frac{a_{\mathrm{in}}}{a_{\mathrm{fin}}}\right)^2 = e^{-2N}$$

Inflation

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

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*

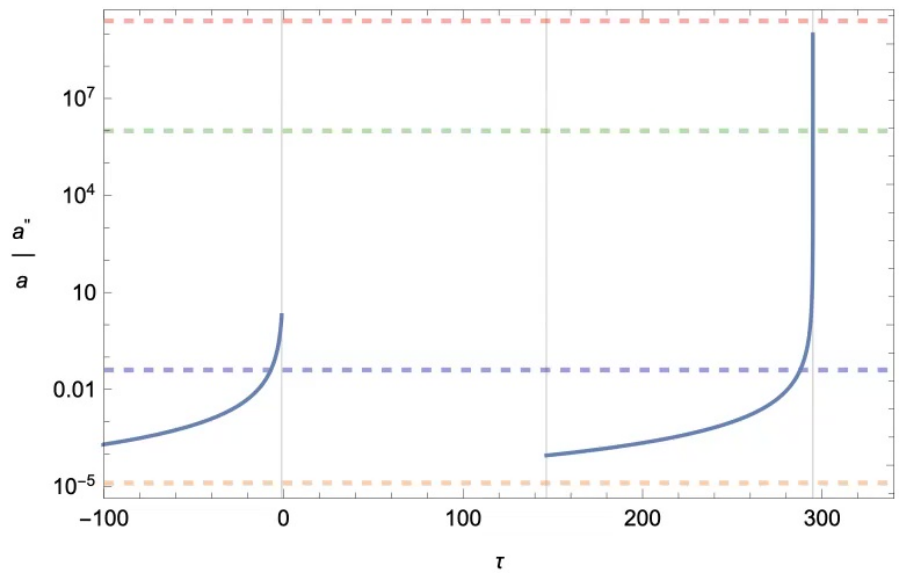
# Perturbations II

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

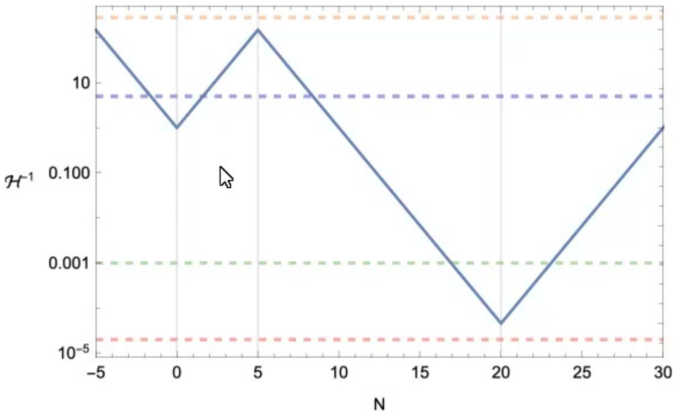
Same as Schroedinger's eq., with anti-tunnelling b.c. !

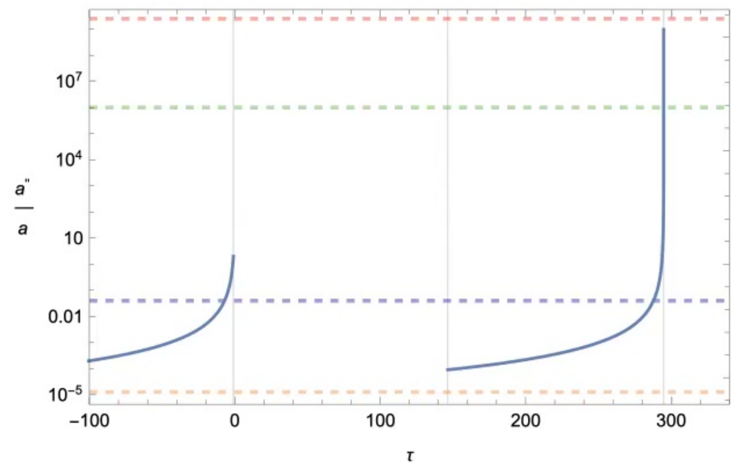
$$u_k(\tau_-) = u_k(\tau_+)$$

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



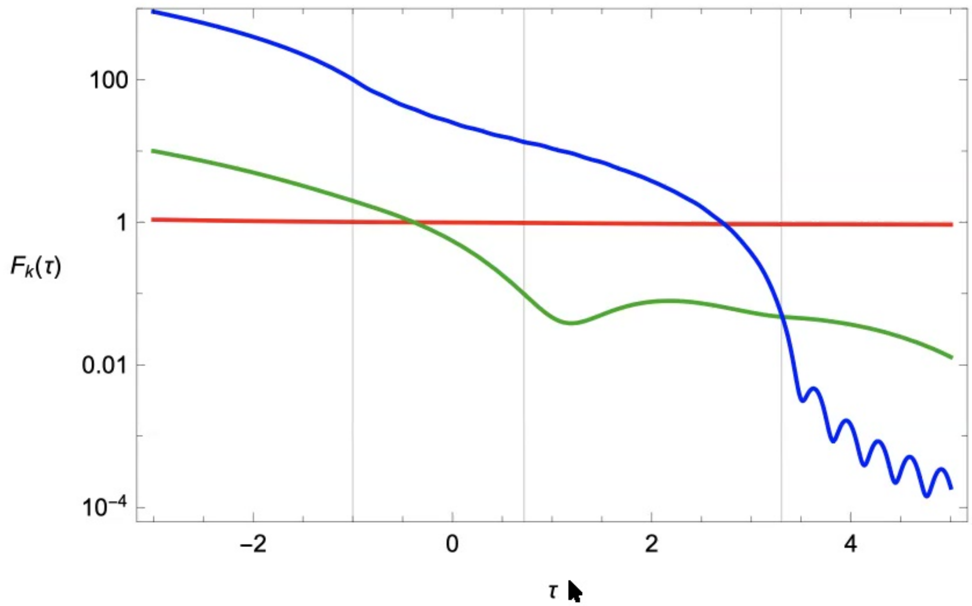

# Cosmologia con quattro stagioni



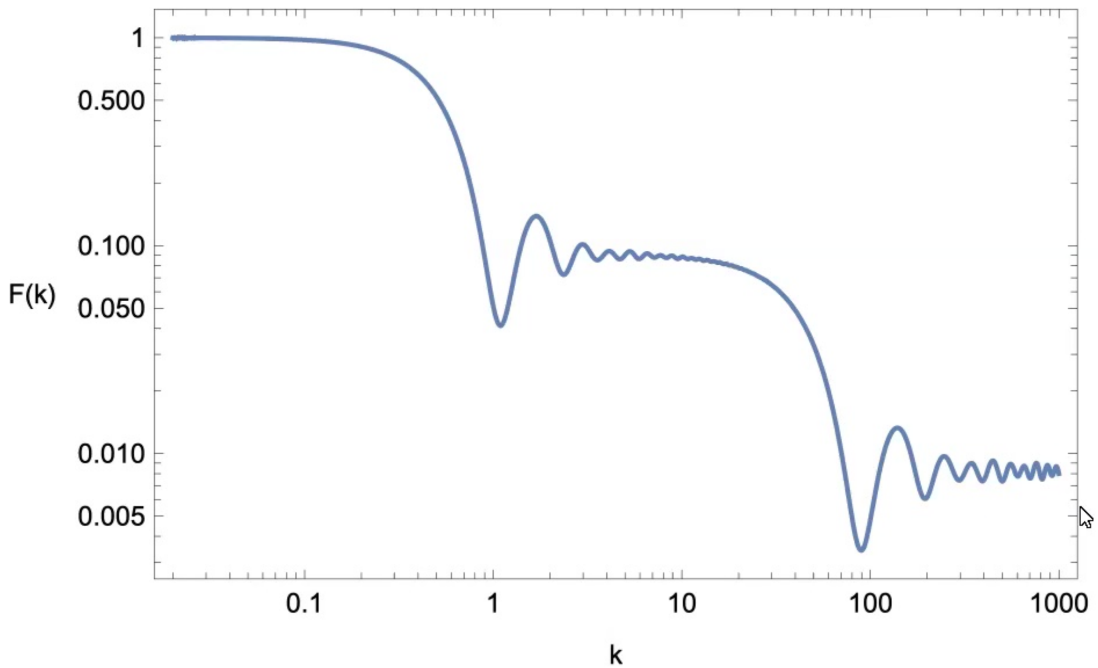



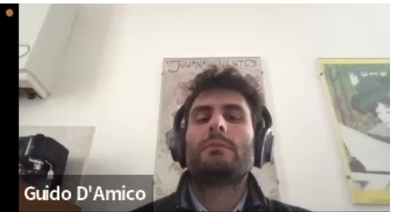

# Cosmologia con quattro stagioni

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

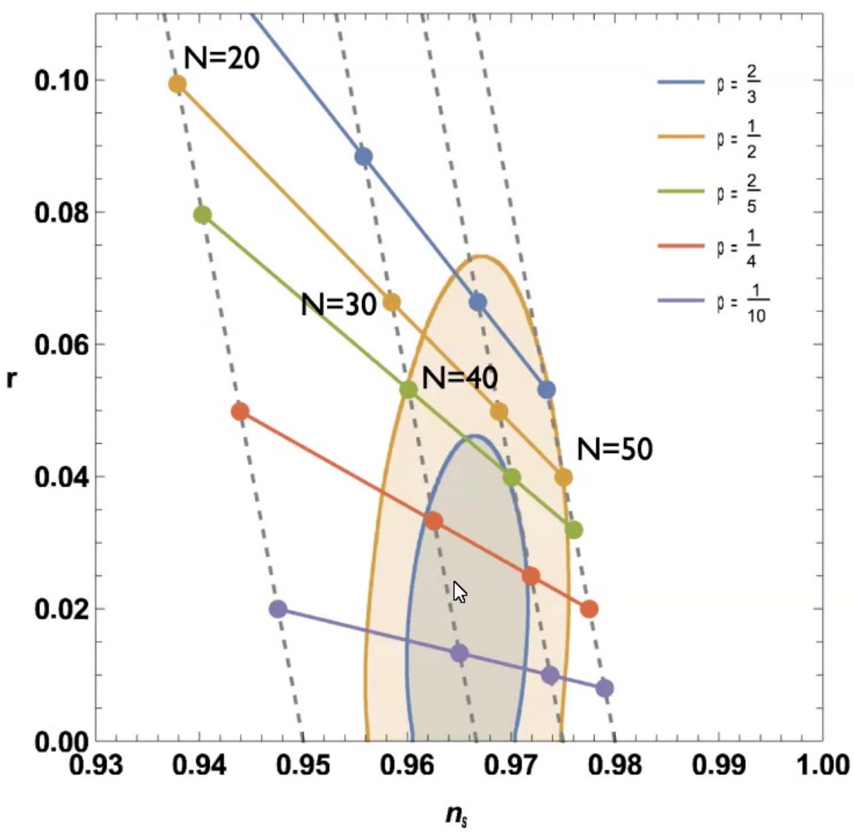



# Power spectrum, more realistic case



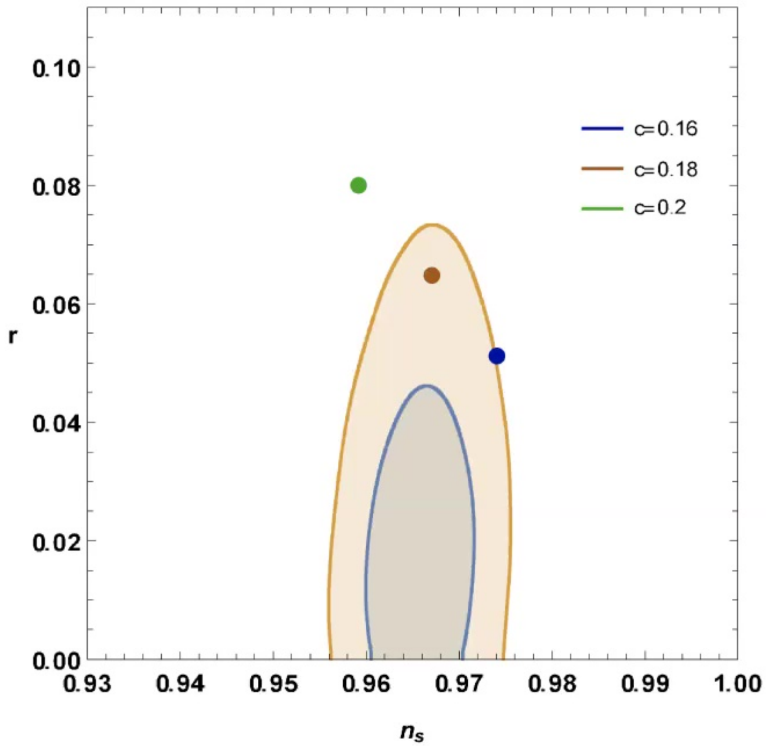



# Power-law inflation, viable again!




# Model building open again

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

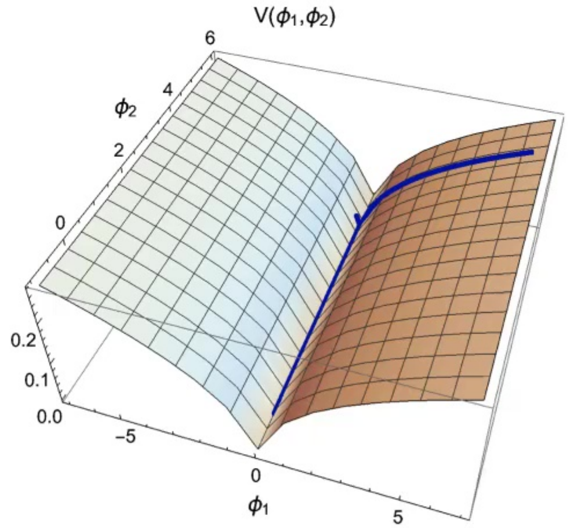



$$V(\phi) = V_0 e^{c\phi/M_{Pl}}$$

# Doublecoaster cosmology

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

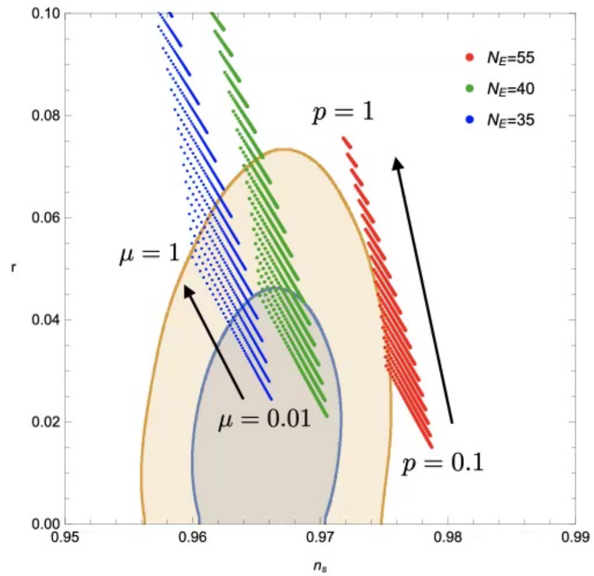
$$V(\phi_1, \phi_2) = M_1^4 \left[ \left( 1 + \frac{\phi_1^2}{\mu_1^2} \right)^{p_1/2} - 1 \right] + M_2^4 \left[ \left( 1 + \frac{\phi_2^2}{\mu_2^2} \right)^{p_2/2} - 1 \right] \qquad \begin{array}{l} M_1 > M_2 \\ \mu_i \sim \mathcal{O}(0.1 M_{\rm Pl}) \end{array}$$




- 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.
- 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

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

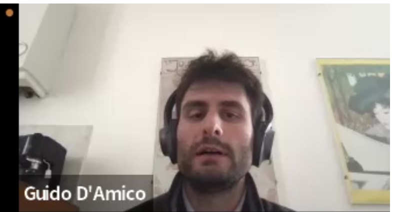
$$Q \propto m\phi \quad \text{by gauge symmetry :} \quad Q \to \frac{4\pi Q}{M^2}$$

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

restore combinatorial factors to reproduce Feynman diagrams

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

# Doublecoaster + Higher Derivatives



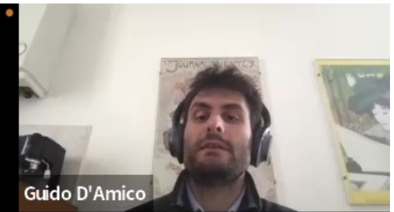

In addition to potential flattening, strong coupling also induces higher-derivative operators correcting kinetic terms

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

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

GDA, Kaloper, Lawrence
1709.07014 [hep-th]

# Doublecoaster + Higher Derivatives



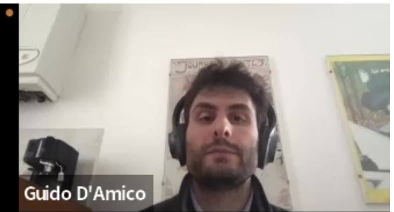

This means that the action is

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

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

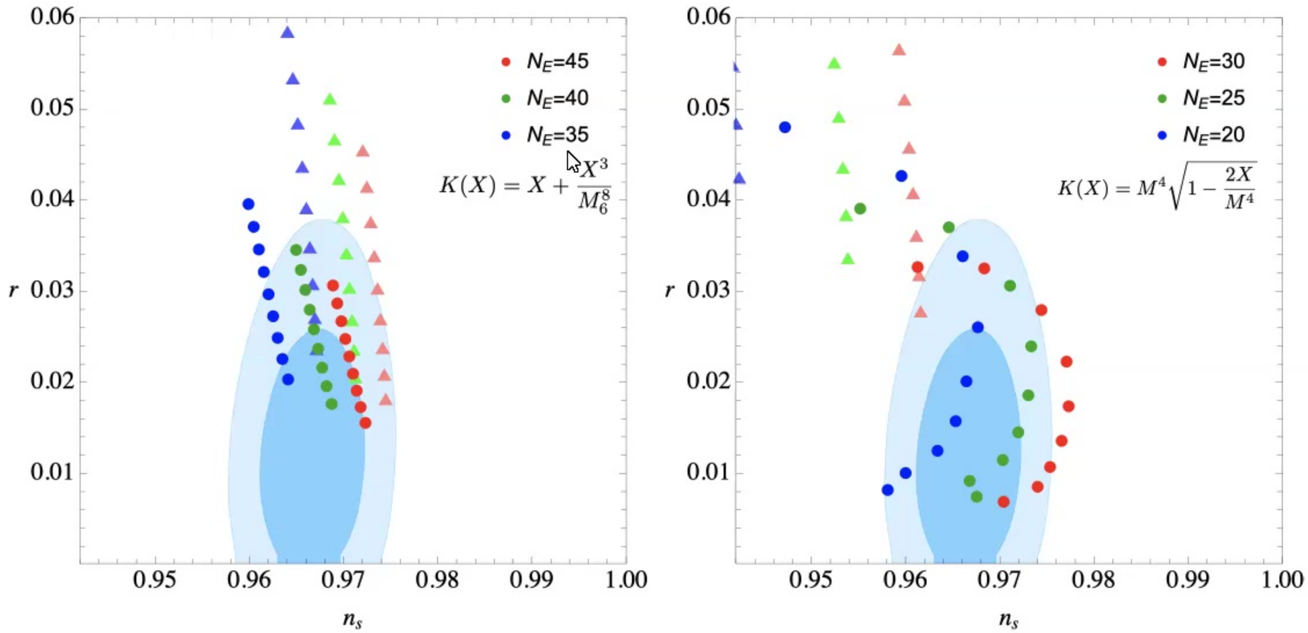
Armendariz-Picon, Damour, Mukhanov '99

# *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!

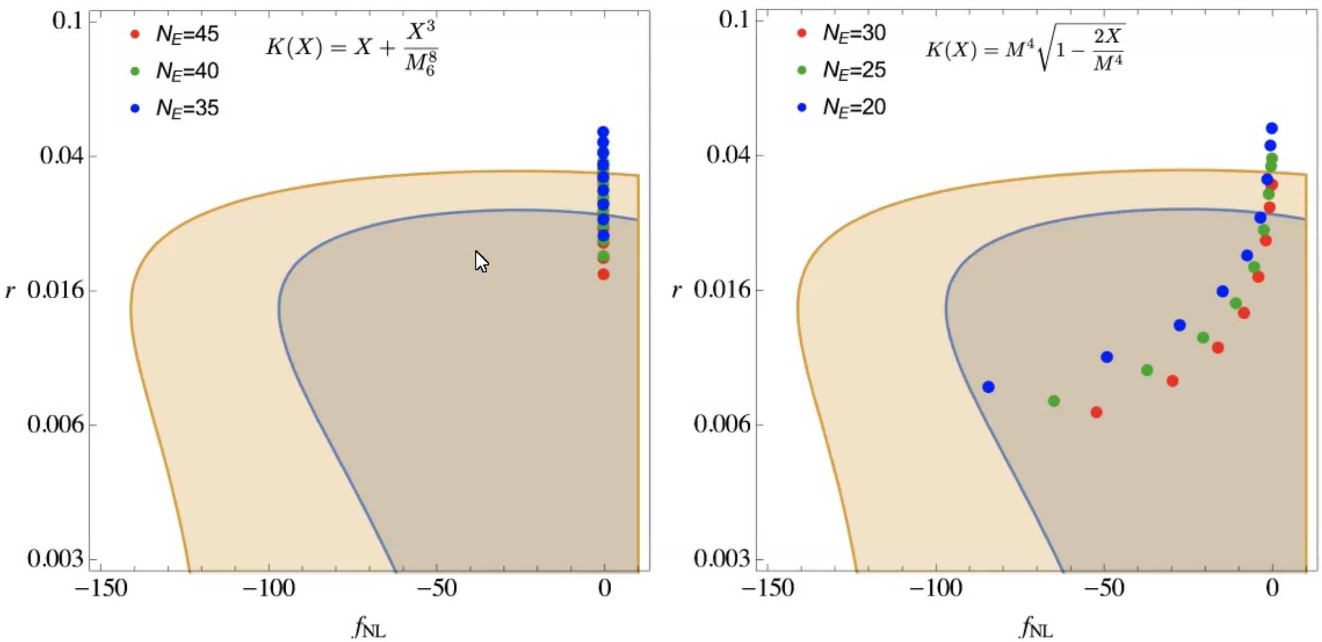
# Simple monodromy in strong coupling



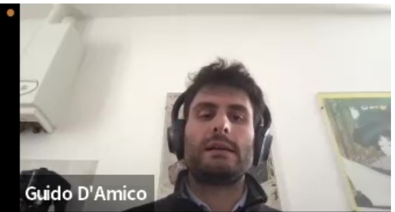

0.96 < $n_s$ < 0.97

0.006 < r < 0.035

# nGs vs r

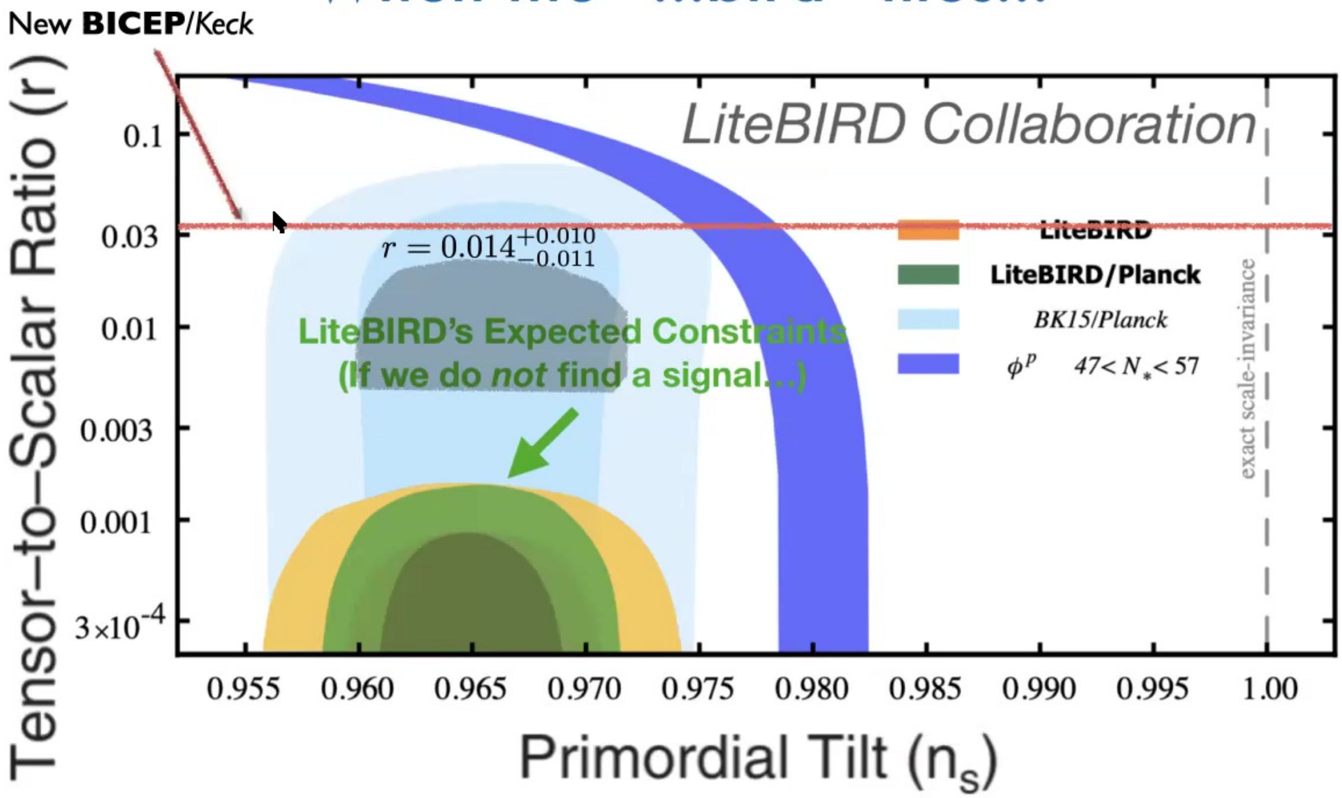


$N_E$=45
$N_E$=40
$N_E$=35
$K(X) = X + \frac{X^3}{M_6^8}$
0.1
0.04
$r$ 0.016
0.006
0.003
−150
−100
−50
0
$f_{\mathrm{NL}}$
$N_E$=30
$N_E$=25
$N_E$=20
$K(X) = M^4\sqrt{1 - \frac{2X}{M^4}}$
0.1
0.04
$r$ 0.016
0.006
0.003
−150
−100
−50
0
$f_{\mathrm{NL}}$

Guido D'Amico

# 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

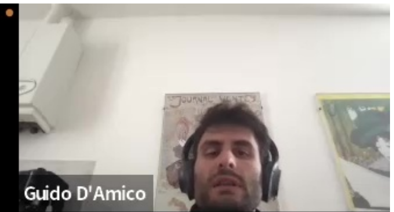
$$-F^2_{abcd} + \epsilon_{a_1 \ldots a_{11}} A^{a_1 \cdots} F^{a_4 \cdots} F^{a_8 \ldots a_{11}} \ni$$

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

Kaloper, Lawrence, Sorbo 2011

- 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

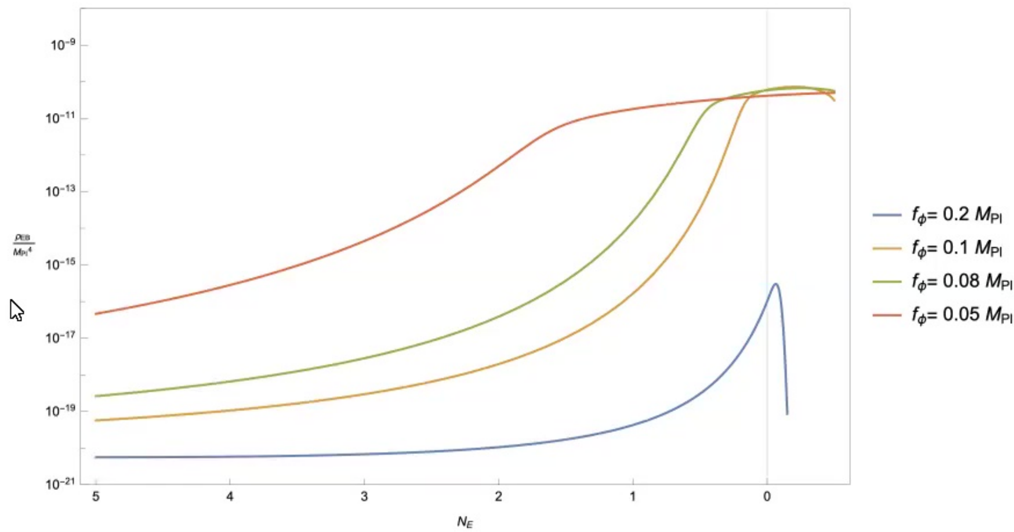
Anber & Sorbo 2009
many others


# Solutions...

Full solution is complicated.

For constant ξ, we have exponential production

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



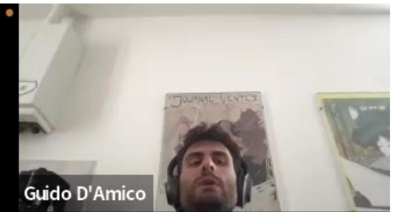
# Solutions...

- 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

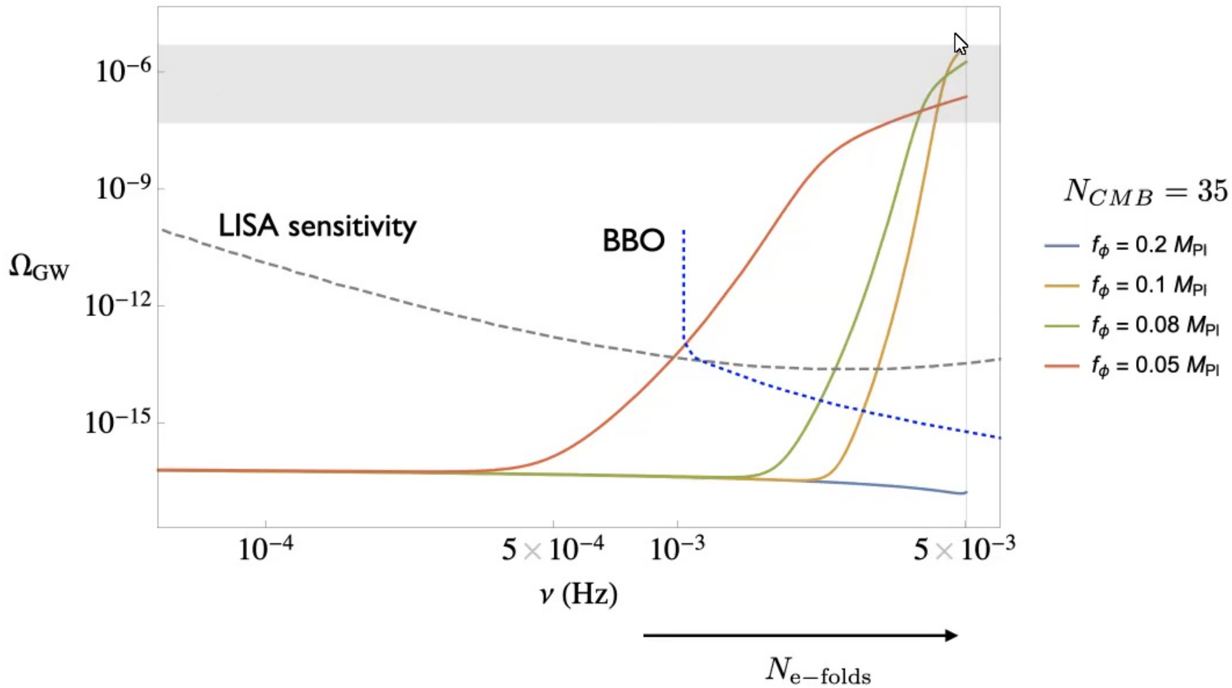
  Domcke, Guidetti, Welling, Westphal 2020
- Observables? At small scales large, non-Gaussian scalar perturbations and gravitational waves!
- Gravitational waves are *chiral*, and they are

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

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

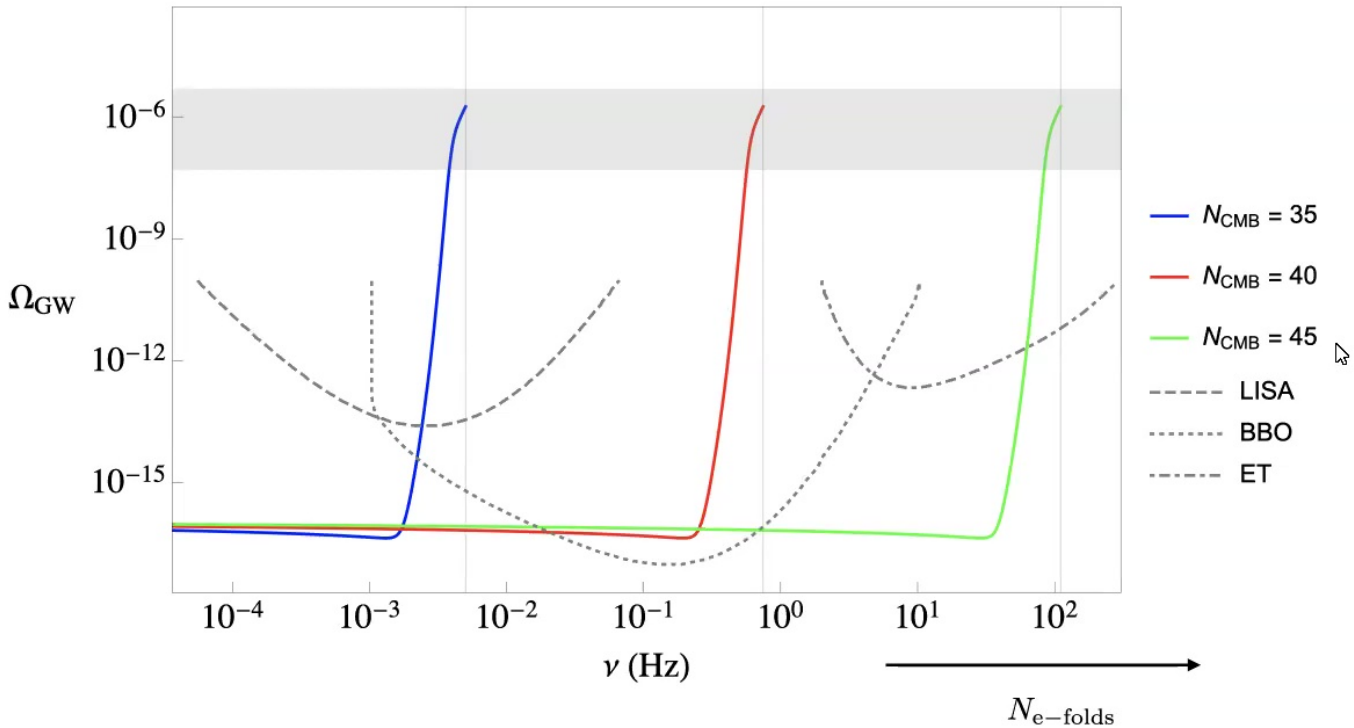


# Small-scale predictions



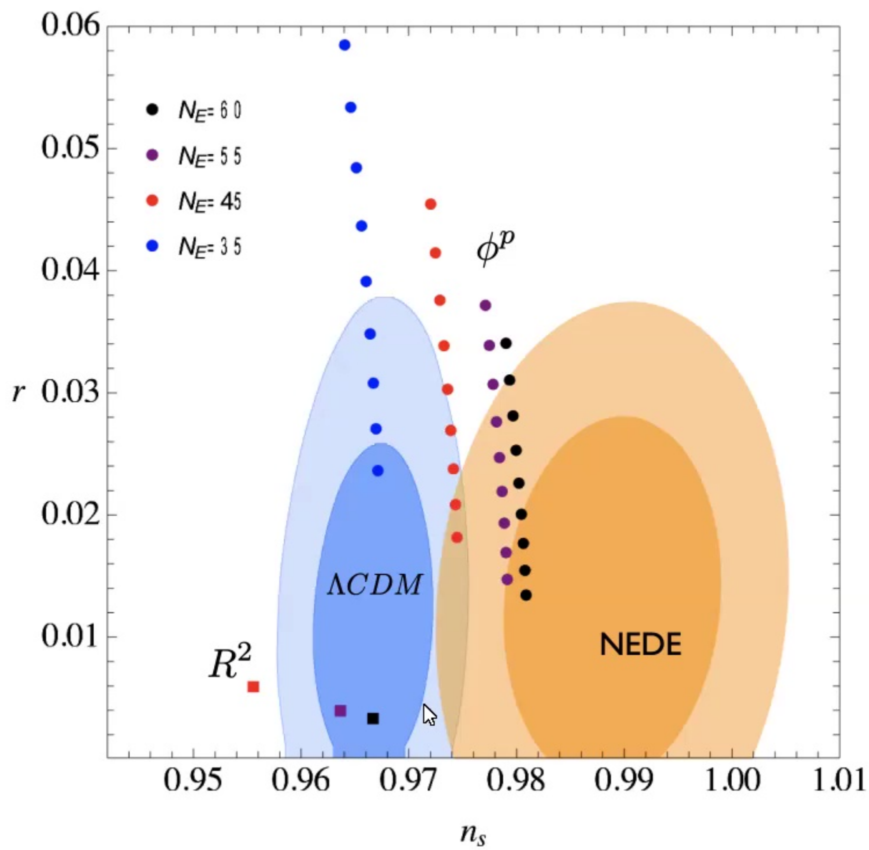

A very loud signal for LISA/BBO

# 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?
- 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
- Let's find more examples!