Guido D'Amico

4π in the Sky

based on GDA, Kaloper, Lawrence
1709.thisweek

Belgrade, MPhys9, 19/9/2017

Large Field Inflation?

- Appealing theoretical simplicity
  Single field, simple monomial potential, direct coupling to matter for reheating

- Interesting experimental predictions
  Large tensor fluctuations, high-energy probe

- Just take $\varphi \gg M_{Pl}$, $m \ll M_{Pl}$ and things are good

- Except that… naturalness? And what about data?

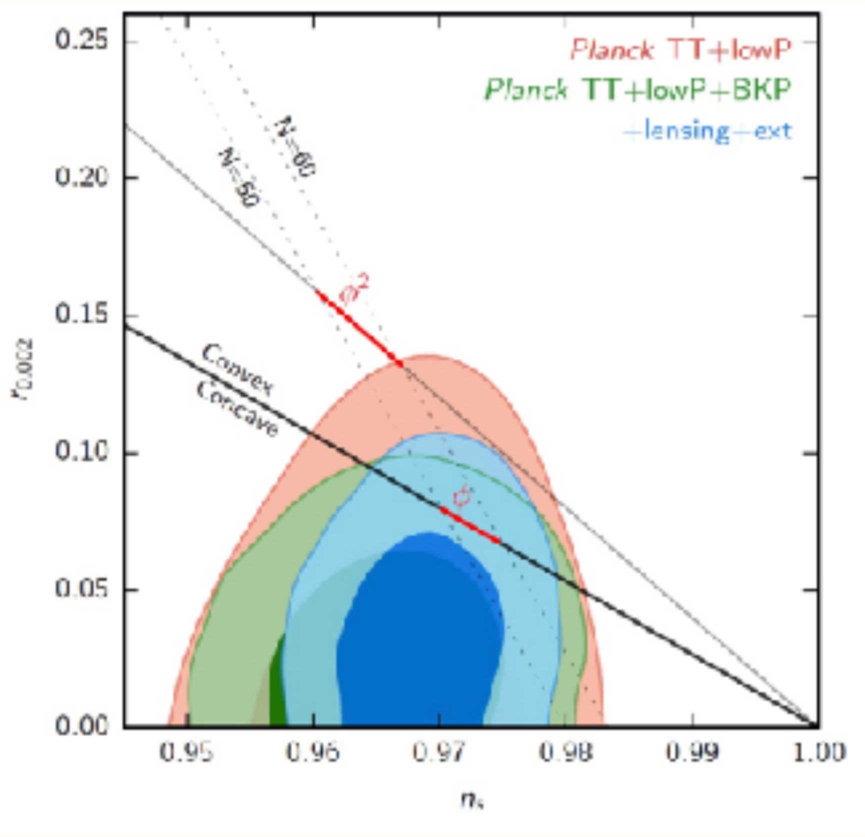
Large Field Inflation, the issues

- Theoretical simplicity: irrelevant operators?

$$V = M_{\rm Pl}^4 g_n \left(\frac{\phi}{M_{\rm Pl}}\right)^n$$

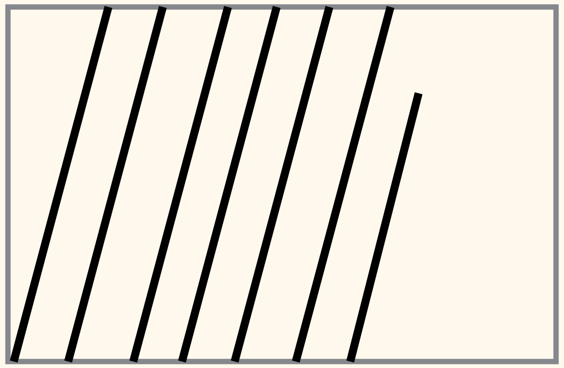
requires $g_2 < 10^{-12}$, $g_4 < 10^{-14}$
Also, non-perturbative quantum gravity corrections?

- Experimental predictions: too interesting

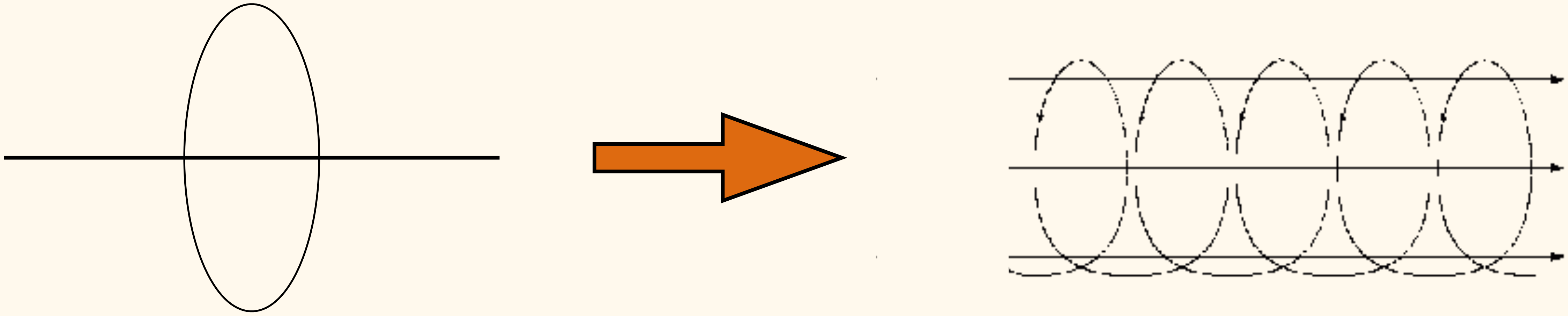


Monodromy Inflation

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



- Physical example: Landau levels



A Pedestrian View

- Below the string scale, string theory is a QFT + corrections
- Inflation is below string scale, so string constructions - if they work - must give consistent QFTs of inflation with corrections included
- If inflation is high-scale single-field there is a lightest inflaton and a mass gap in the spectrum of QFT; one can integrate out everything at and above the mass of the next lightest particle - which sets the cutoff
- Stringy constructions: they should exist, and they compute the mass parameters

The construction

Di Vecchia, Veneziano
Quevedo, Trugenberger
Dvali, Vilenkin
Kaloper, Sorbo
Kaloper, Lawrence, Sorbo

Axion, i.e. compact scalar, mixing with a U(1) 4-form

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{48}F_{\mu\nu\lambda\rho}F^{\mu\nu\lambda\rho} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\mu}{24}\phi\,\frac{\epsilon^{\mu\nu\lambda\rho}}{\sqrt{-g}}F_{\mu\nu\lambda\rho}\right]$$
$$+\frac{1}{6}\int d^4x\sqrt{-g}\nabla_\mu\left[F^{\mu\nu\lambda\rho}A_{\nu\lambda\rho} - \mu\phi\,\frac{\epsilon^{\mu\nu\lambda\rho}}{\sqrt{-g}}A_{\nu\lambda\rho}\right]$$

And what is this? Go to first order formalism, adding

$$S = \int d^4x\,\frac{q}{24}\epsilon^{\mu\nu\lambda\rho}\left(F_{\mu\nu\lambda\rho} - 4\partial_\mu A_{\nu\lambda\rho}\right)$$

Integrate F… And we have a massive scalar!

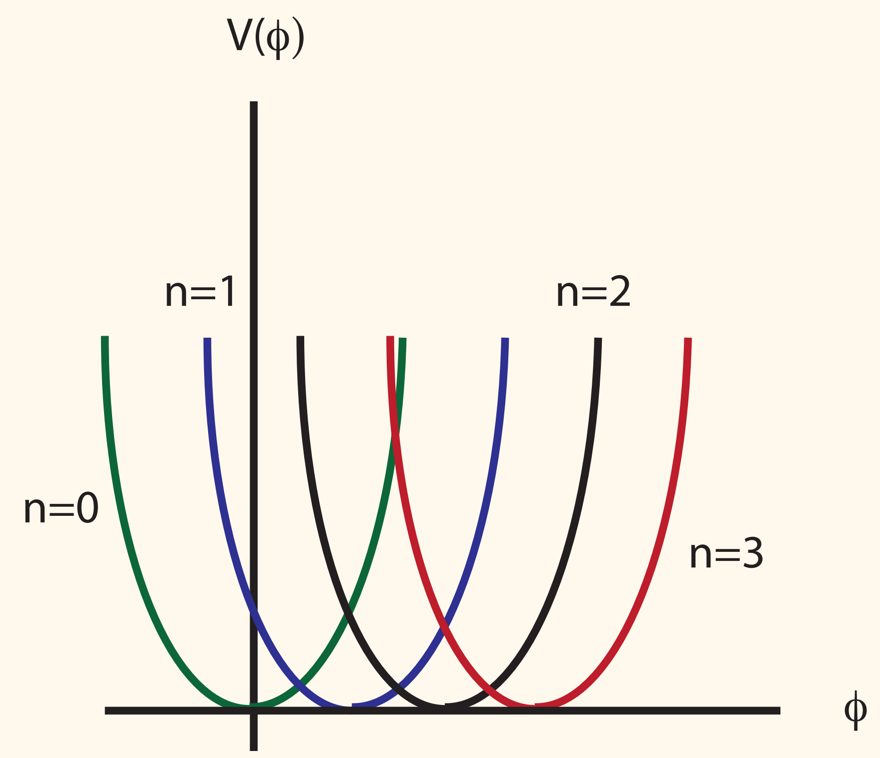
$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}(q+\mu\phi)^2 + \frac{1}{6}\frac{\epsilon^{\mu\nu\lambda\rho}}{\sqrt{-g}}A_{\nu\lambda\rho}\partial_\mu q\right]$$

The symmetries?

- The scalar seemed to have a *global* shift symmetry
- But this is not there anymore! Instead, we have a *discrete gauge symmetry* for the scalar, and a U(1) for the 3-form

$$\phi \equiv \phi + 2\pi f_\phi \qquad \delta A_{\mu\nu\rho} = \partial_{[\mu}\Lambda_{\nu\lambda]}$$

- And q? It is locally constant! In fact, it is quantized in units of the membrane charge q = ne^2, and there is the constraint $\mu f_\phi = k e^2$



A gauge theory of inflation

- We have a non-linearly realized gauge symmetry: discrete scalar plus U(1)
- These are just redundancies of the description, they can't be broken by gravity
- In particular, mass=charge, thus radiatively protected!
- Of course, we expect corrections: but now we know that they must respect these symmetries

$$\delta\mathcal{L}_1 = c_n \frac{F^n}{M^{2n-4}} \qquad \delta\mathcal{L}_2 = d_n \frac{m^{2n}}{M^{4n-4}} A^{2n} \qquad \delta\mathcal{L}_3 = e_{k,n} \frac{m^{2k} A^{2k} F^n}{M^{4k+2n-4}}$$

What is really going on?

- Note that inflaton is the gauge flux!

$$F_{\mu\nu\lambda\rho} \sim (m\phi + q)\epsilon_{\mu\nu\lambda\rho}$$

- Physical inflaton is

$$m\varphi = m\phi + q$$

- Large when F is large - or, when Q is large.

- m can be dialed by hand since it is radiatively stable.
  It makes the effective scalar super-Planckian even when everything is safely sub-Planckian

- Gauge symmetries prohibit large corrections which violate this structure

- What sets the scale of energy density is the flux of F - it can be huge as long as its energy density is below the cutoff

And what does Nature demand?

- Planck+BICEP: the primordial tensors are small $r<0.1$
- So, inflation is not a weakly coupled quadratic potential
- Silverstein et al: constructions include corrections from heavy fields which display “flattening”, $\varphi^2 \rightarrow \varphi^p$ with $p<2$
- But then, there must be a description of this in single-field EFT…
- Strong coupling! Take large field vevs and derivatives
- But, how can we control the theory? Does it even inflate?
- Well, we got gauge redundancies: as long as we are below the cutoff, we know what we’re doing!

EFT of strongly coupled inflation

- A technical point: how to correctly normalize all the additional operators?
- Let's go back to the most famous strongly coupled theory… QCD.
  Georgi and Manohar developed Naive Dimensional Analysis (NDA) to study heavy quarks in the 80's
- The idea: take the theory to strong coupling but below the cutoff M
- Impose naturalness: all operators are equally important thanks to strong coupling.
- Then can normalize the operators correctly by including loop factors

The rules

- Replace φ by the dimensionless quantity $4\pi\varphi/M$
- Include the overall normalization $M^4/(4\pi)^2$ to normalize the Lagrangian
- Include factorials in the denominators to account for the symmetry factors in the physical S-matrix elements
- Impose naturalness: all operators are equally important thanks to strong coupling.
- Then can normalize the operators correctly by including loop factors

The action

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

Here all the operators are important!
Typical value for the c is O(1)

Weird? No, k-inflation!

- Much less mess than it seems! Redefine, the field, and then

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

- Mukhanov, Garriga et al. "k-inflation"!
  Perturbative potential + large corrections, without and with derivatives

- But this is now a stable, quantum theory

- Now, let's derive some of the weird monodromy effects. EFT of inflation involves actions like

$$\mathcal{L} = -\frac{1}{2}\mathcal{Z}_{eff}(\frac{4\pi m\varphi}{M^2})(\partial_\mu\varphi)^2 - \frac{M^4}{16\pi^2}\mathcal{V}_{eff}(\frac{4\pi m\varphi}{M^2}) + \text{higher derivatives}\,,$$

- This is where flattening is hidden!

A worked example

- Suppose exponential model

$$\sum_{n>2} c_n' \frac{m^n \varphi^n}{n!(\frac{M^2}{4\pi})^{n-2}} \rightarrow \frac{M^4}{(4\pi)^2}\left[e^{\frac{4\pi m\varphi}{M^2}} - 1 - \frac{4\pi m\varphi}{M^2}\right] \simeq \frac{M^4}{(4\pi)^2} e^{\frac{4\pi m\varphi}{M^2}}$$

- But we should also expect

$$\frac{1}{2} e^{\frac{4\pi m\varphi}{M^2}} (\partial_\mu \varphi)^2$$

- Canonically normalize

$$\chi = \frac{M^2}{2\pi m} e^{\frac{2\pi m\varphi}{M^2}}$$

- The effective theory, at large field

$$\mathcal{L}^{(2)} = -\frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{4} m^2 \chi^2 + \text{corrections}$$

- I have renormalized down the mass!

A few comments

- As long as $4\pi M_{pl}/M^2$ the potential stays FLAT!!! - i.e. below the cutoff M
- We only need ~60 efolds… benefiting all the while from $16\pi^2=158$
- Not the whole story!
  Flattening & irrelevant operators with derivatives
- Flattening increases spectral index
- Higher derivatives generate non-gaussianities
- So the stronger coupling reduces r but it increases n_s and f_{NL}
- This means that coupling cannot be excessively strong
- This all suggests a lower bound on r!
- The strongly coupled EFT of monodromy either yields an observable prediction for tensors, or too large non-Gaussianities - it is on the edge, very falsifiable…

A crash course on NG

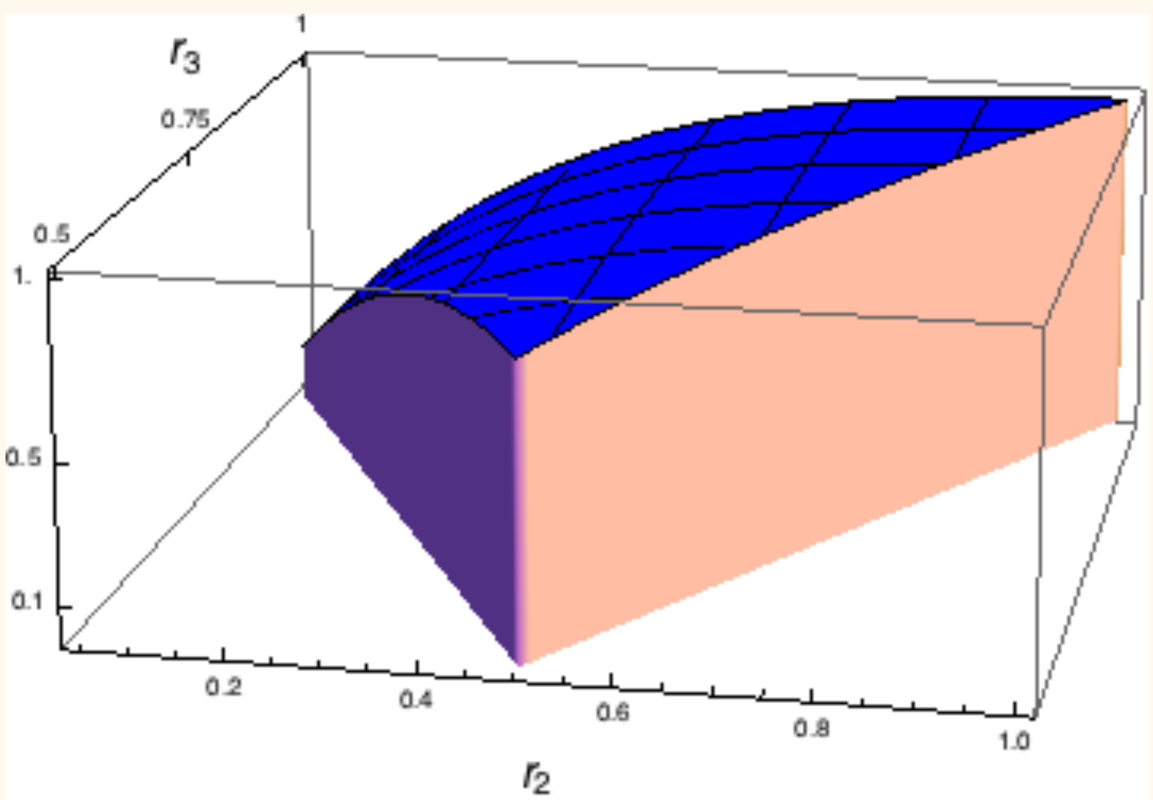
- So far, we talked about free field predictions… Interesting, but can we get something more?
- Cubic order: measure scattering in the sky!
- Observable: 3-point function of the curvature perturbation.
  Not just a function of momentum, but of a whole triangle in momentum space!
- Different operators in Lagrangian give different shapes

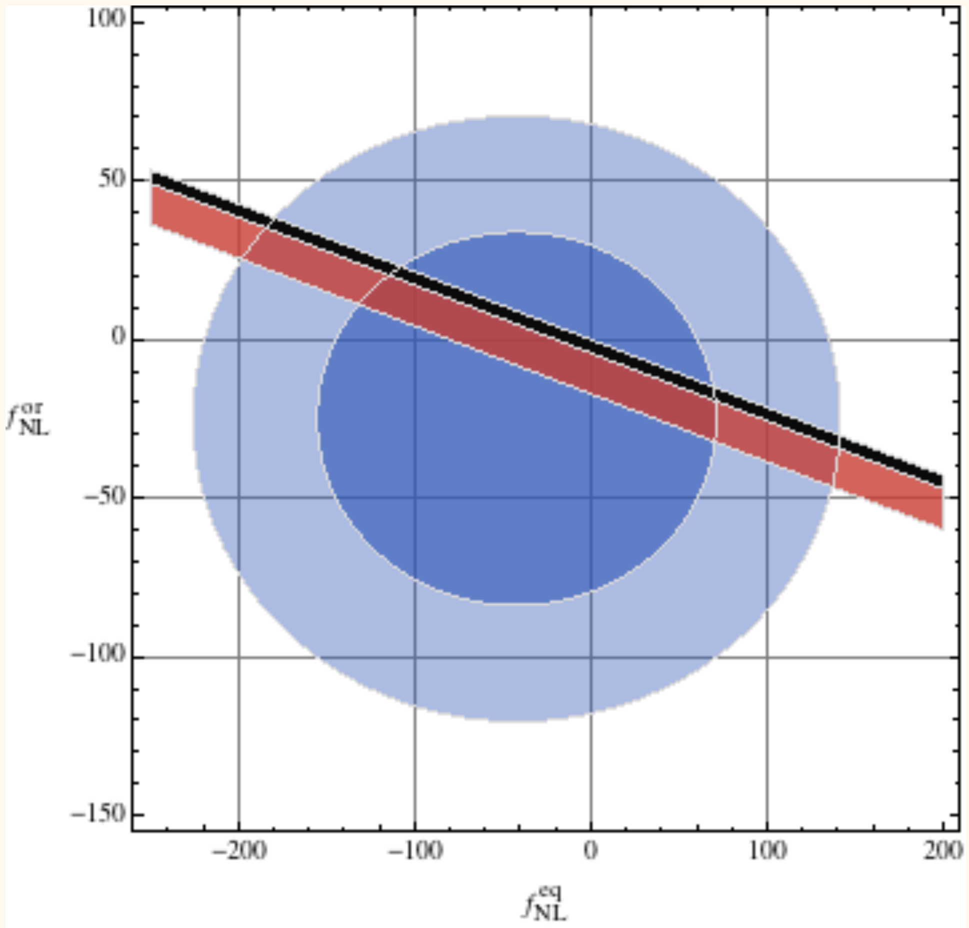
Our predictions

see also GDA, Kleban

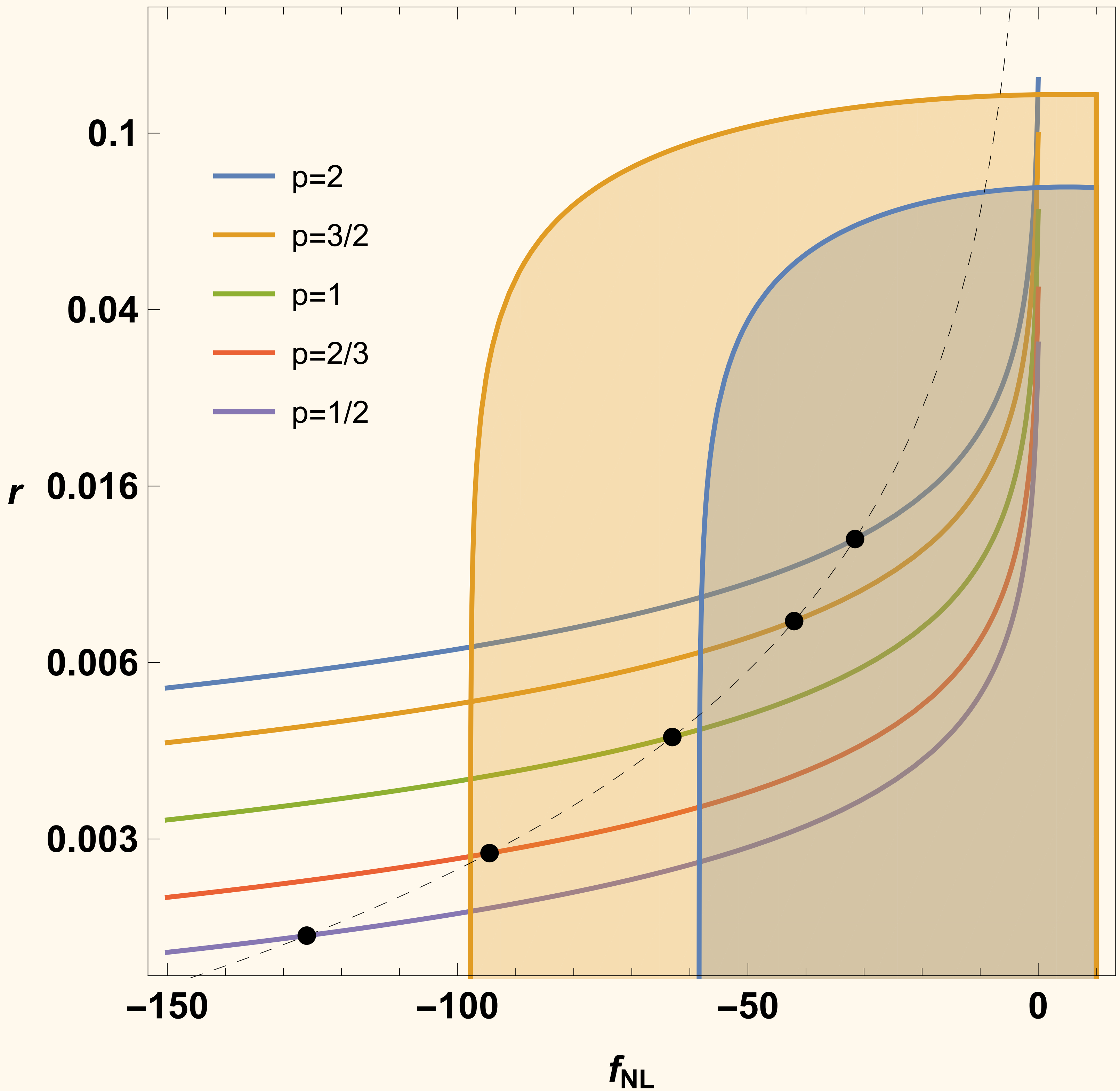
$$S = -\int dt d^3\vec{x}\, a^3 M_{\rm Pl}^2 \dot{H}\left[\frac{1}{c_s^2}\dot{\pi}^2 - \frac{(\partial_i\pi)^2}{a^2} + \left(\frac{1}{c_s^2}-1\right)\left(\dot{\pi}^3 + \frac{2}{3}c_3\dot{\pi}^3 - \dot{\pi}\frac{(\partial_i\pi)^2}{a^2}\right)\right]$$

$$r = 16\epsilon c_s \qquad\qquad n_s - 1 = -4\epsilon - \delta - s$$

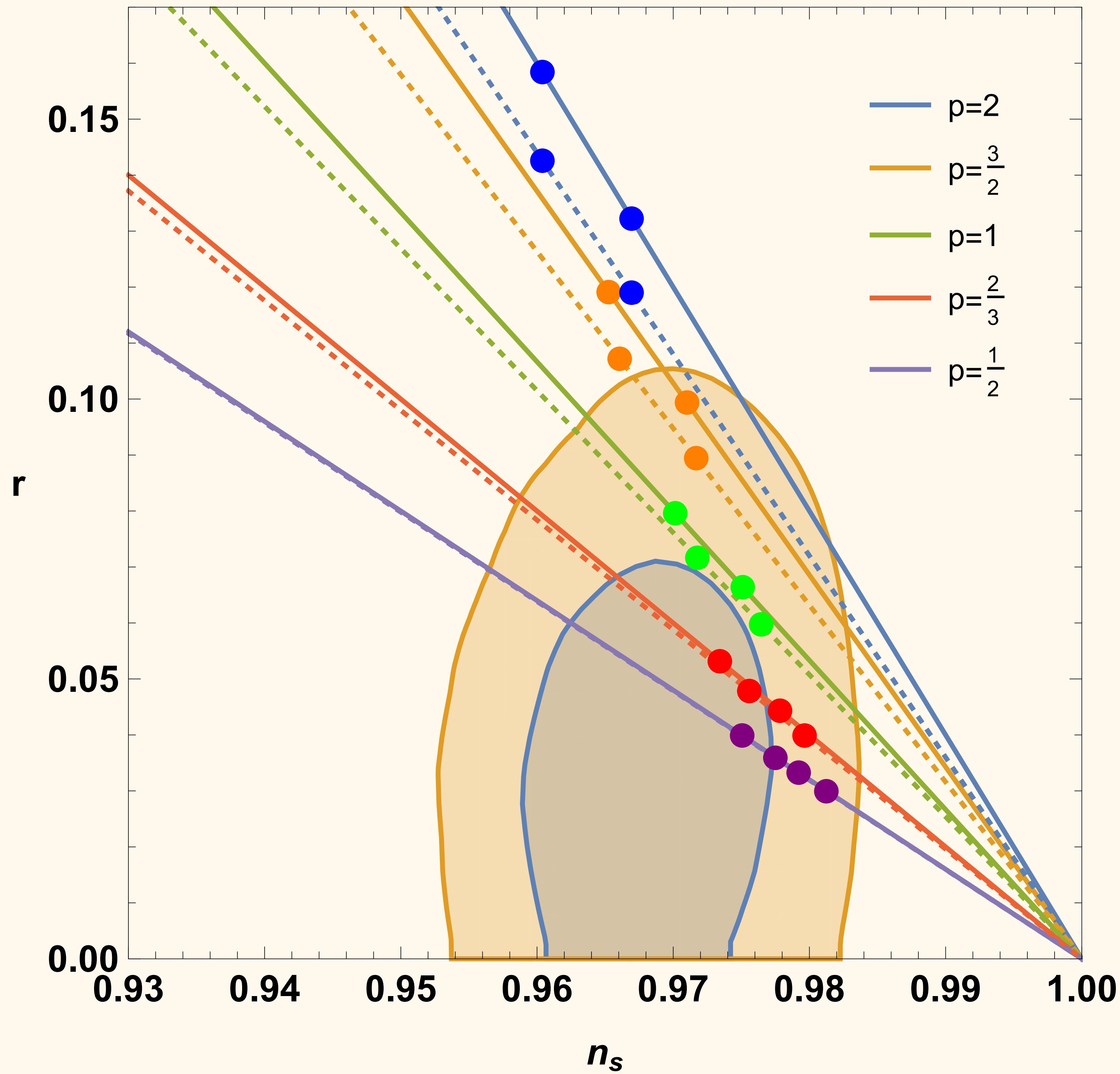




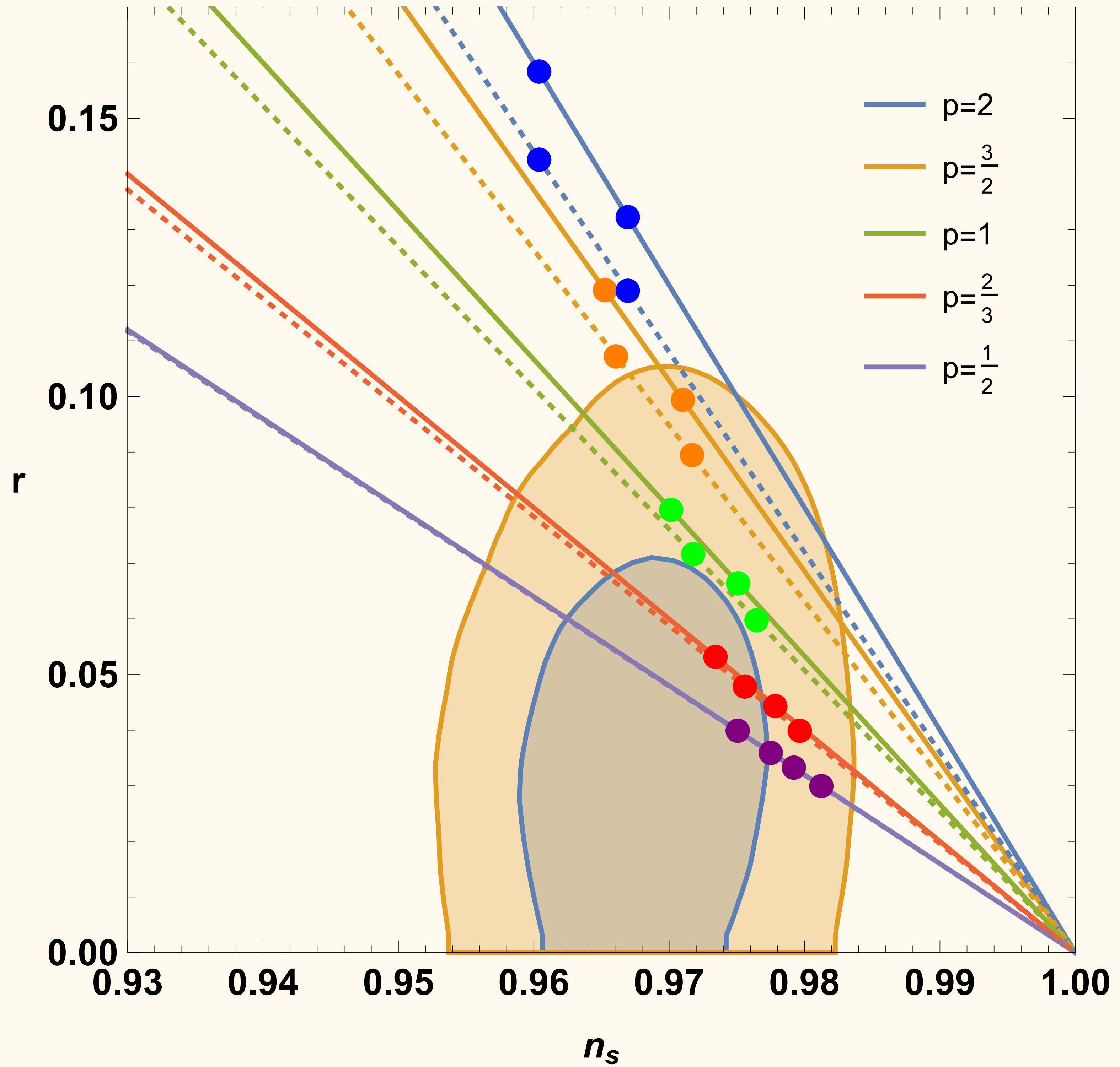
r vs f_{NL}



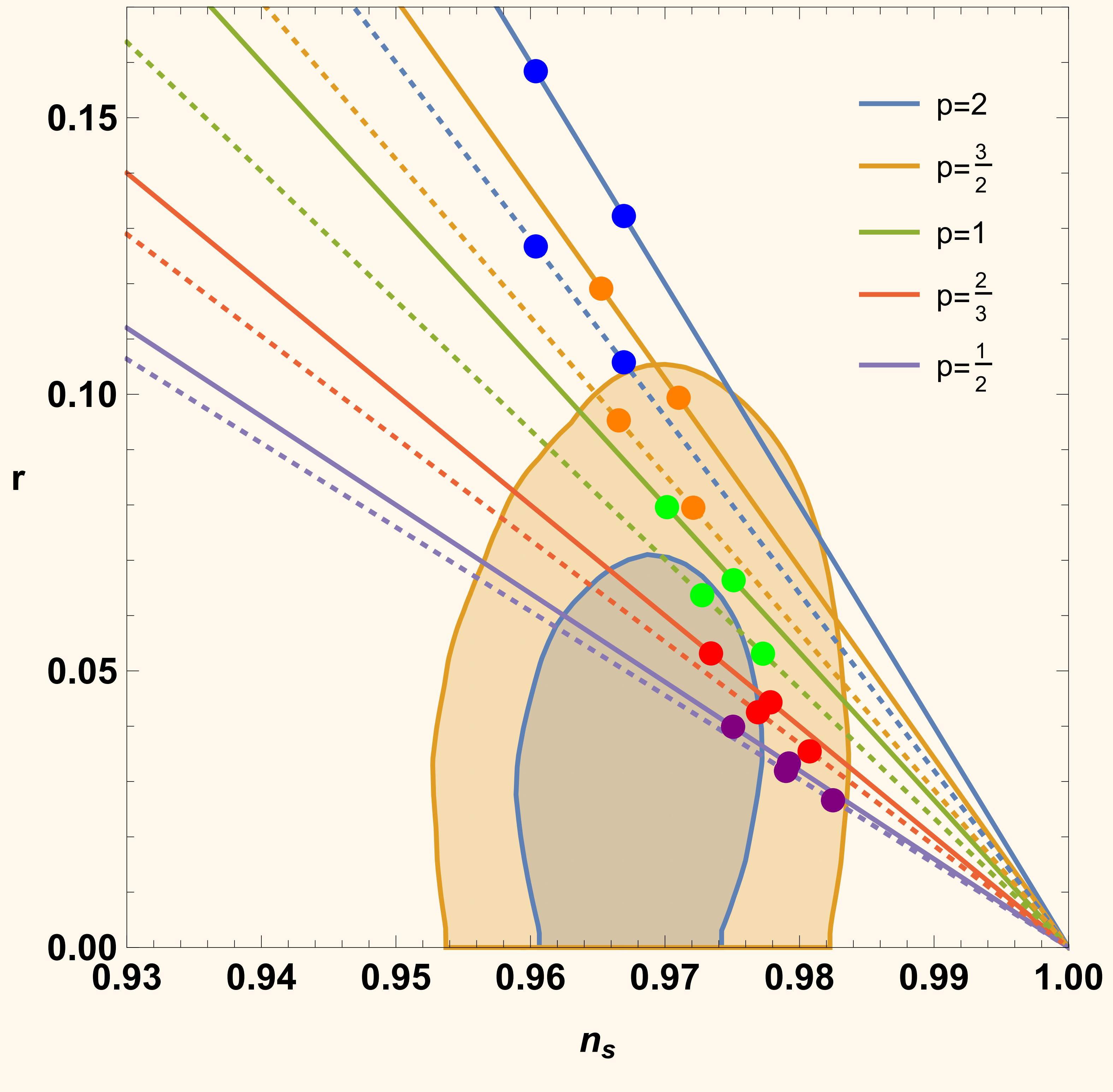
Quadratic observables, c_s=0.9



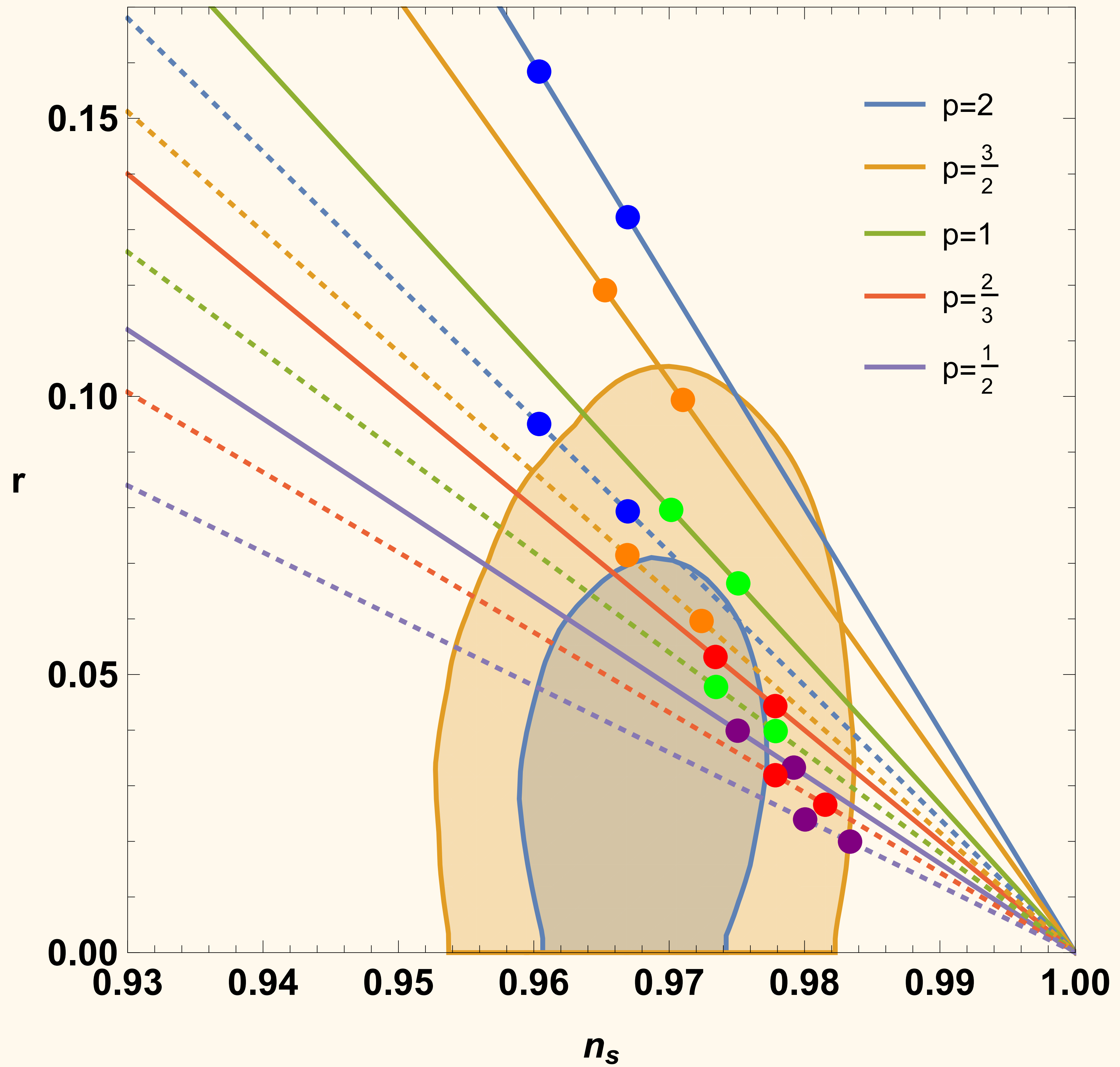
Quadratic observables, c_s=0.9



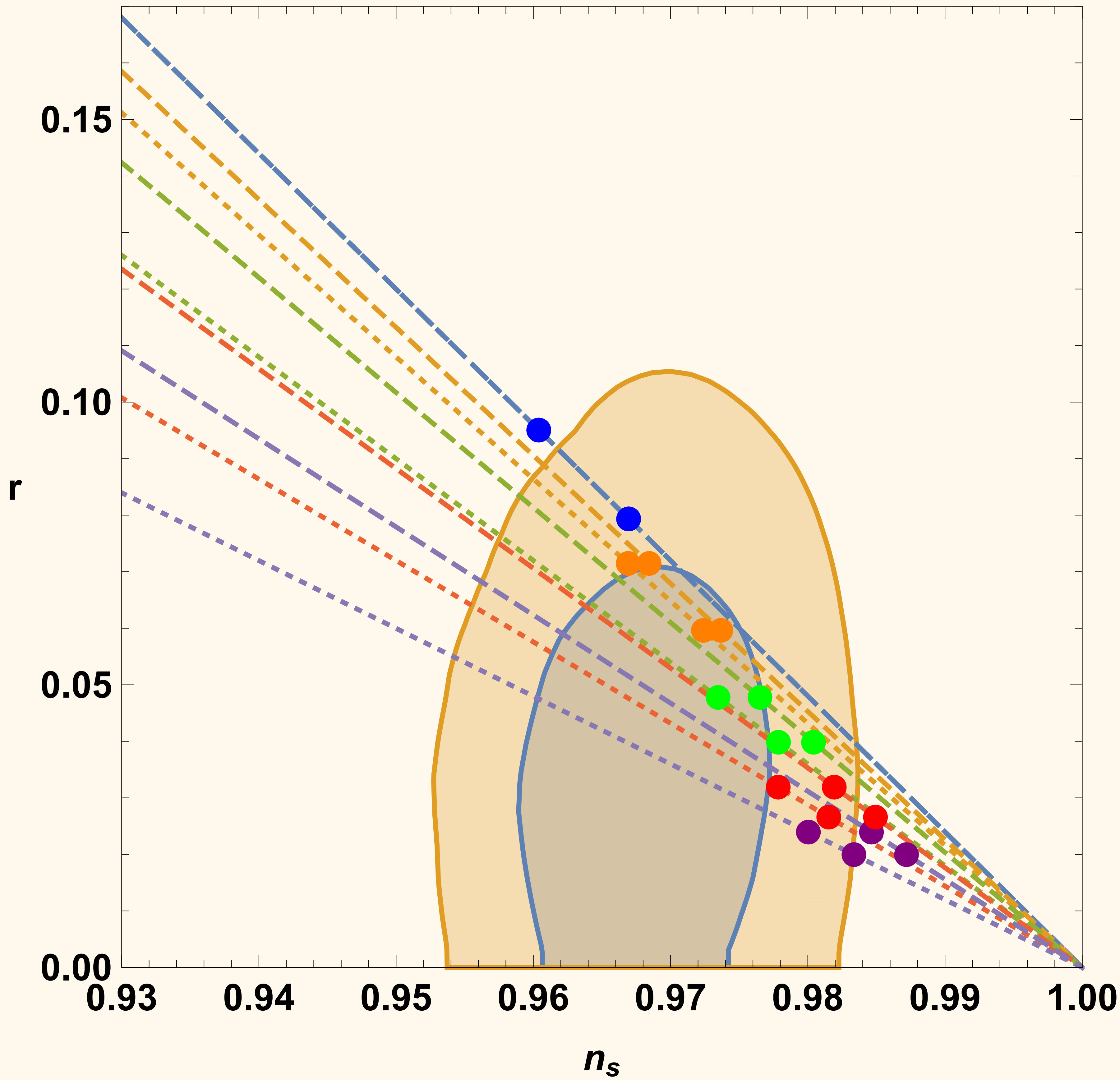
Quadratic observables, c_s=0.8



Quadratic observables, c_s=0.6



Comparing models, DBI vs $X+X^2$



Summary and Outlook

- Monodromy QFT accommodates the issue of UV sensitivity of inflation nicely
- Hidden gauge symmetries: a key controlling mechanism behind monodromy QFT.
  They protect EFT from itself, and from gravity.
- Gauge symmetries also explain why the large field vevs are fine: they are dual gauge field strengths which count the sources!
  Large field = many sources
- UV constructions: needed to understand the origin of the mass gap, analogous to BCS theory vs massive gauge theory
- The ideas are predictive: experiments already constrain the theory.
  In a natural theory, we will see either tensors or NGs in the next round of CMB experiments. If not the theory is tuned/unnatural.

Thank you!