Orbital Inflation

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Based on work with **Ana Achúcarro, Dong-Gang Wang, Gonzalo Palma**, Oksana Iarygina, Ed Copeland

arXiv: 1901.03657 (Achúcarro, Copeland, Iarygina, Palma, Wang, YW)
1907.02020 (Achúcarro, YW)
1907.02951
1908.06956 (Achúcarro, Palma, Wang, YW)

The success of single-field inflation

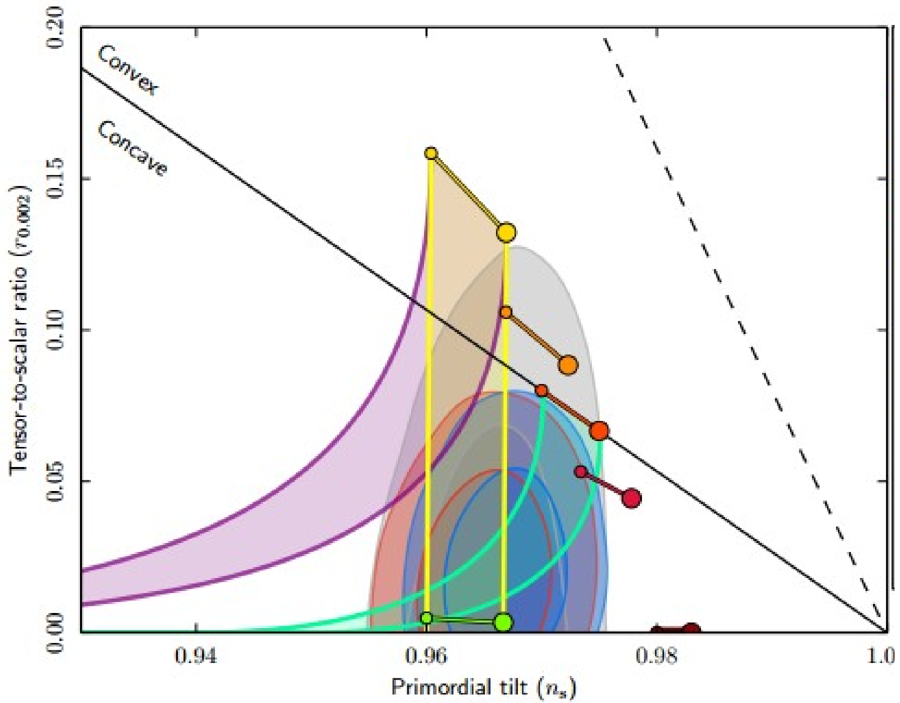
Solves horizon & flatness problem

Provides seeds for structure formation

(Guth, Linde, Starobinksy, Mukhanov)

Consistent with CMB data

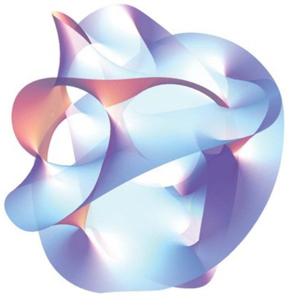
- Small but non-zero spectral tilt
- Small tensor-to-scalar ratio
- Small primordial non-Gaussianity
- Small isocurvature perturbations



(Planck collaboration, 2018)

Theoretical challenges

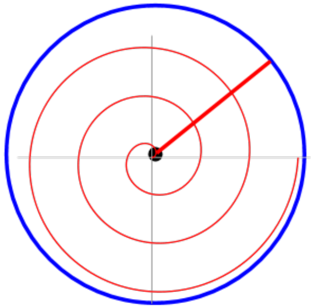
String embeddings of inflation typically contain multiple scalar fields living on a curved field space



→ they may interact with the inflaton (stabilize them all?)

Recent “swampland conjectures” suggest that inflation takes place in a small steep patch of field space (Ooguri & Vafa, 2007 Ooguri, Palti, Shiu & Vafa 2018)

→ curved trajectories (Achucarro & Palma, 2018) See Achúcarro’s talk!
+ posters by Wang, Chiovoloni



$$|\Delta\phi| \leq \mathcal{O}(1)M_p$$

A simple multi-field framework

It's desirable to have a **simple framework** that can deal with multi-field inflation with curved trajectories & curved field spaces

To address questions like

(1) What symmetries may protect the inflationary dynamics? (See also Achucarro's and Finelli's talk + poster by Wang)

(2) What's the role of the field space geometry? (See also talks by Achucarro, Sfakianakis, Turzynski + posters by Wang, Pinol, Christodoulis, Chiovoloni, Fumagelli)

(3) What are the signatures of new physics? (See also Pimentel's talk)

A lightning review of multi-field effects

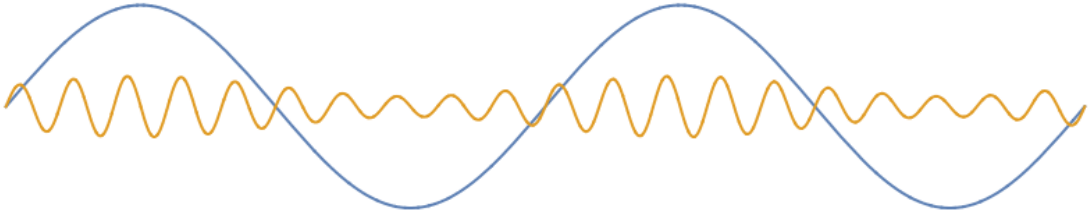
(1) Primordial non-Gaussianities

(2) Isocurvature perturbations

Primordial non-Gaussianities

Consider e.g. extra fields during inflation

Interactions = mode coupling

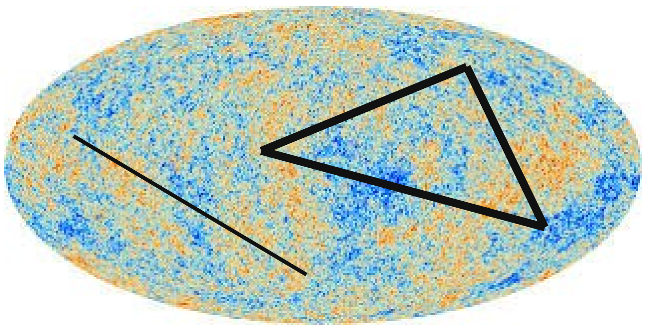


A long wave modulates the amplitude of a short wave

Correlation between different modes

$$\langle \mathcal{R}(k_1)\mathcal{R}(k_2)\mathcal{R}(k_3)\rangle \neq 0$$

non-zero **bispectrum** (non-Gaussian statistics)



Bispectrum = FT three-point correlation

Why do we care about primordial non-Gaussianities?

PNG is a smoking gun for single field

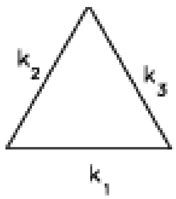
All canonical single field models of inflation can be ruled out by detecting a violation of the **single field consistency relation**

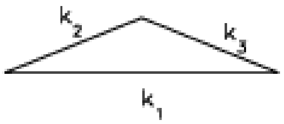
$$f_{\rm NL} = \frac{5}{12}(1 - n_s)$$

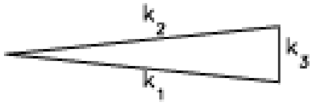
(Maldacena, 2002
Creminelli, Zaldarriaga, 2004)

PNG is a probe of fundamental physics

Derivative interactions / strong interactions with heavy fields / multiple light fields / cosmological collider physics / alternatives to inflation / ...





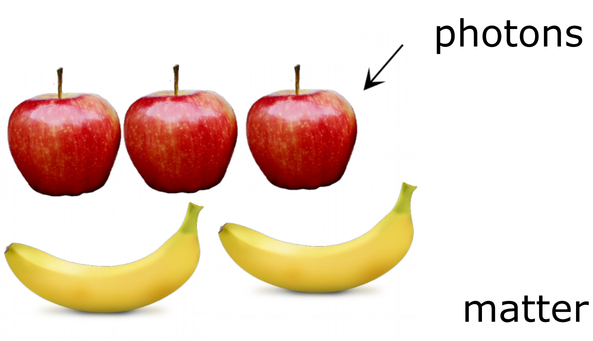


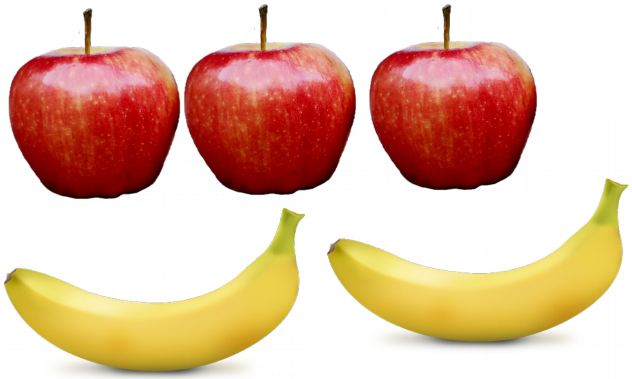
Isocurvature perturbations

Curvature = adiabatic perturbations

Local expansion of homogeneous background (time shift)

Composition universe the same, but overall *number density* varies





Single field inflation creates adiabatic perturbations that are conserved on SH scales

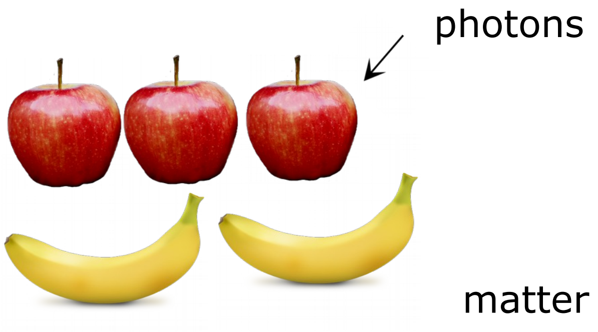
(Weinberg, 2003)

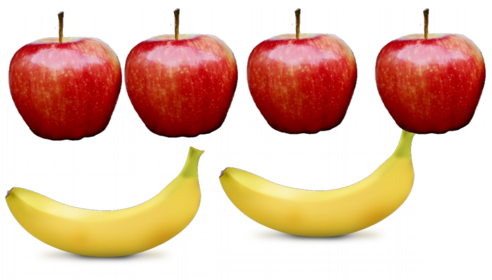
Isocurvature perturbations

Isocurvature = non-adiabatic perturbations

NOT-adiabatic

Composition universe is *not* the same, *relative ratio of species varies*





Multi-field inflation is generically expected to produce large isocurvature pt* and $f_{NL} \sim O(1)$ primordial non-Gaussianities

(Alvarez et al, 2014)

*Except when reheating washes it out completely

Inflation with light coupled scalars

BAD because:

- They source curvature perturbations → **large non-Gaussianities**
- Light scalars don't decay → **isocurvature pt**

Inflation with light coupled scalars

GOOD because:

- They **efficiently** source curvature perturbations → **smaller nG**
- Light scalars don't decay → **dynamically suppressed**

These systems are as multi-field as can be
But look a lot like single field !

Simplest extension of the single field EFT

$$S^{(2)} = \frac{1}{2}\int d^4x a^3 \left[2\epsilon\dot{\mathcal{R}}^2 - 2\epsilon\frac{(\partial_i\mathcal{R})^2}{a^2}\right]$$ (Single field)

(Two field) ↓

Curvature perturbation

Isocurvature perturbation

$$S^{(2)} = \frac{1}{2}\int d^4x a^3 M_p^2 \left[2\epsilon\left(\dot{\mathcal{R}} - \omega\sigma\right)^2 - 2\epsilon\frac{(\partial_i\mathcal{R})^2}{a^2} + \dot{\sigma}^2 - \mu^2\sigma^2 - \frac{(\partial_i\sigma)^2}{a^2}\right]$$

Efficiency of interaction

Isocurvature mass

Simplest extension of the single field EFT

$$S^{(2)} = \frac{1}{2}\int d^4x a^3 \left[2\epsilon\dot{\mathcal{R}}^2 - 2\epsilon\frac{(\partial_i\mathcal{R})^2}{a^2}\right]$$

(Single field)

(Two field) ↓

Bottom up simplest: static coefficients

$$S^{(2)} = \frac{1}{2}\int d^4x a^3 M_p^2 \left[2\epsilon\left(\dot{\mathcal{R}} - \omega\sigma\right)^2 - 2\epsilon\frac{(\partial_i\mathcal{R})^2}{a^2} + \dot{\sigma}^2 - \mu^2\sigma^2 - \frac{(\partial_i\sigma)^2}{a^2}\right]$$

Efficient coupling

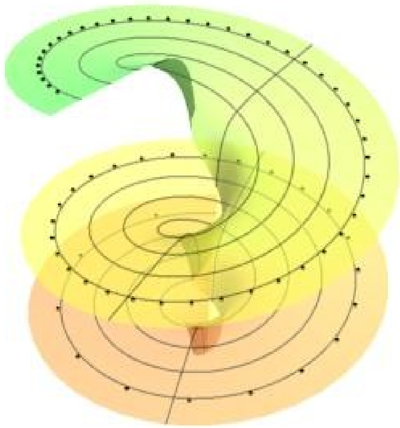
Small mass

How to realize this explicitly?
Phenomenology?
What are the symmetries protecting the coefficients?

Main obstacle: no potential gradient flow

Inflationary trajectories generically do not follow the potential gradient flow

$$\dot{\phi}^a \not\propto -\nabla^a V$$



→ **The potential does not reflect the symmetries of the perturbations**

Orbital Inflation

(Achúcarro, Copeland, Iarygina, Palma, Wang, YW, 1901.03657)
(Achúcarro, YW, 1907.02020)

Idea: consider inflationary models that attract to the Hubble gradient flow

$$\dot{\phi}^a = -2M_p^2 G^{ab} H_{,b}$$

(Generalization of single-field Hamilton-Jacobi, Salopek & Bond 1990)

+ align this with an isometry of field space, e.g. 'angular' θ direction

$$\sqrt{-g}^{-1}\mathcal{L} = \frac{1}{2}\left[e^{2\rho/R_0}(\partial\theta)^2 + (\partial\rho)^2\right] - V(\rho,\theta)$$

$$\dot{\rho} = 0 \quad \text{and} \quad \dot{\theta} \neq 0$$

This gives a set of possible Hubble parameters → family of potentials that admit a constant coupling ω

$$V = 3H^2 - 2G^{ab}H_{,a}H_{,b}$$

Exact solution

(Achúcarro, Copeland, Iarygina, Palma, Wang, YW, 1901.03657)
(Achúcarro, YW, 1907.02020)

Remarkably, the background attractor is an exact solution

$$\dot{\phi}^a = -2M_p^2 G^{ab} H_{,b}$$

The Hubble parameter also determines the properties of the perturbations

e.g. if $\dot{\rho} = 0 \quad \text{and} \quad \dot{\theta} \neq 0$

$$H(\theta, \rho) = W(\theta) X(\rho)$$

Determines ε, η, ..

Determines the couplings with the isocurvature perturbations

Applications of Orbital Inflation

(1) Playground for Quasi-Single-Field Inflation (Chen, Wang, 2010)

(2) We can exactly solve the phenomenology of Orbital Inflation in the limit of small isocurvature mass and a small radius of curvature

(3) We gain new insights on the symmetries that protect the inflationary dynamics

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An exact model of QSF inflation

(Chen, Wang, 2010)
(YW, 1907.02951)

Lagrangian

$$\mathcal{L} = \frac{1}{2}\rho^2(\partial\theta)^2 + \frac{1}{2}(\partial\rho)^2 - V(\rho,\theta)$$

Potential

$$V(\theta,\rho) = 3\left(W^2(\theta) - \frac{2W_\theta^2(\theta)}{3\rho^2}\right) \times \left(1 + \frac{\lambda}{2}(\rho-\rho_0)^2 + \frac{\alpha}{6}(\rho-\rho_0)^3 + \dots\right)^2$$

Determines ε, η, ..

Determines the couplings with the isocurvature perturbations

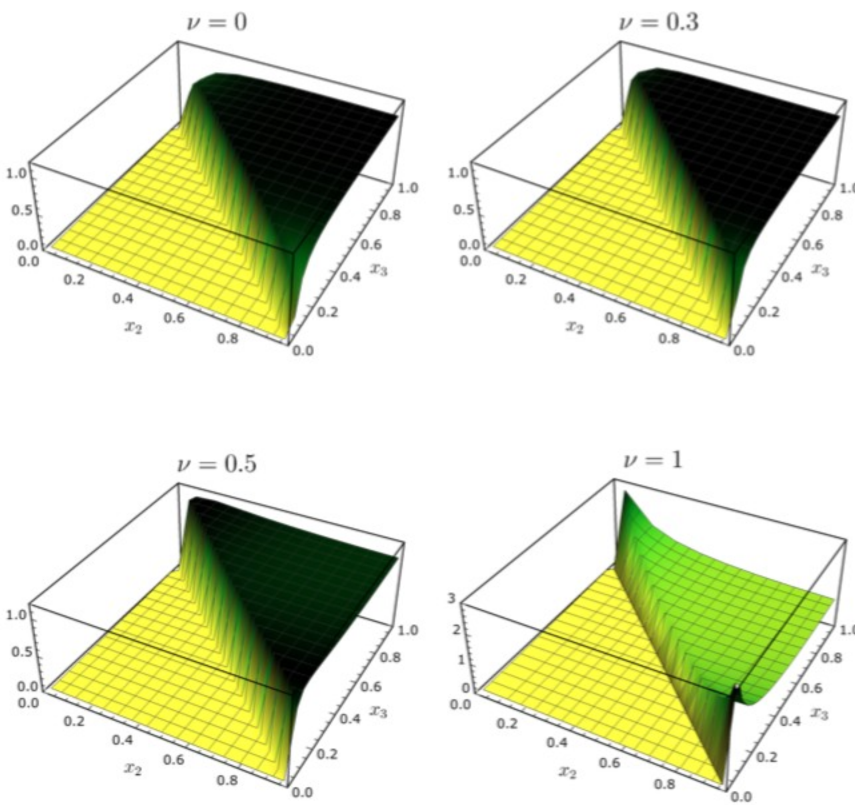
$$\mu^2/H^2 = 6\lambda + \mathcal{O}(\epsilon) \qquad \omega/H \sim 1/\rho_0$$

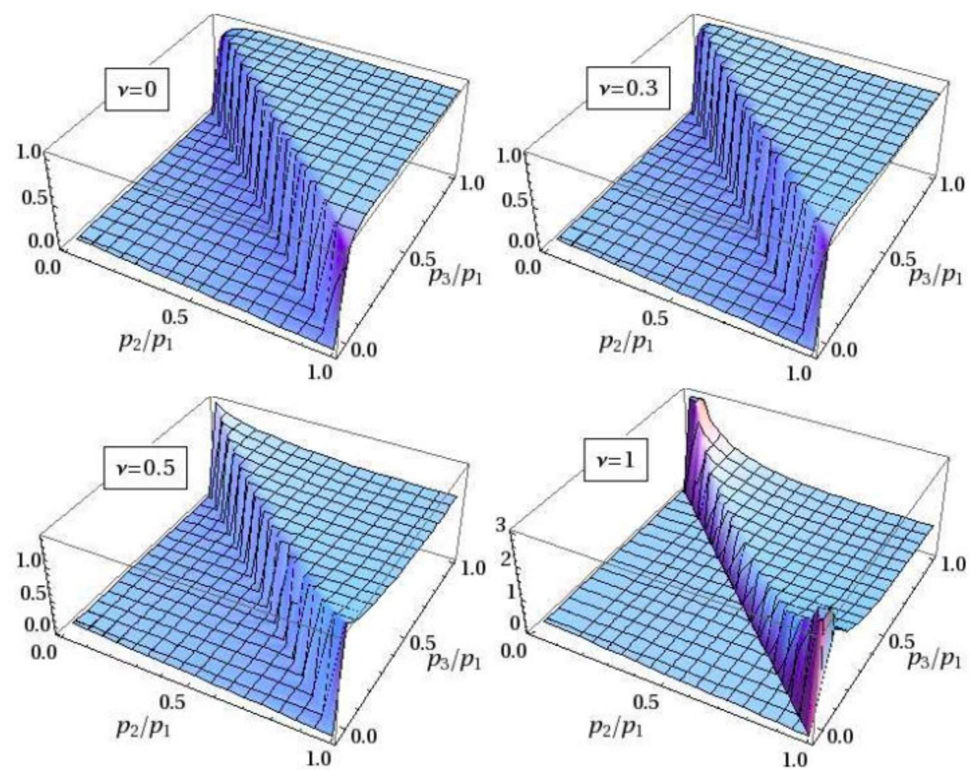
$$V_{\rho\rho\rho} = 6\alpha + \mathcal{O}(\epsilon)$$

An exact model of QSF inflation

Numerical verification of the analytical ansatz of **dimensionless bispectrum QSF**

$$\nu \equiv \sqrt{9/4 - \mu^2/H^2}, \qquad \alpha = 1000, \qquad \rho_0 = 2$$





(YW, 1907.02951)
Numerical computations done with PyTransport

(Chen, Wang, 2010)

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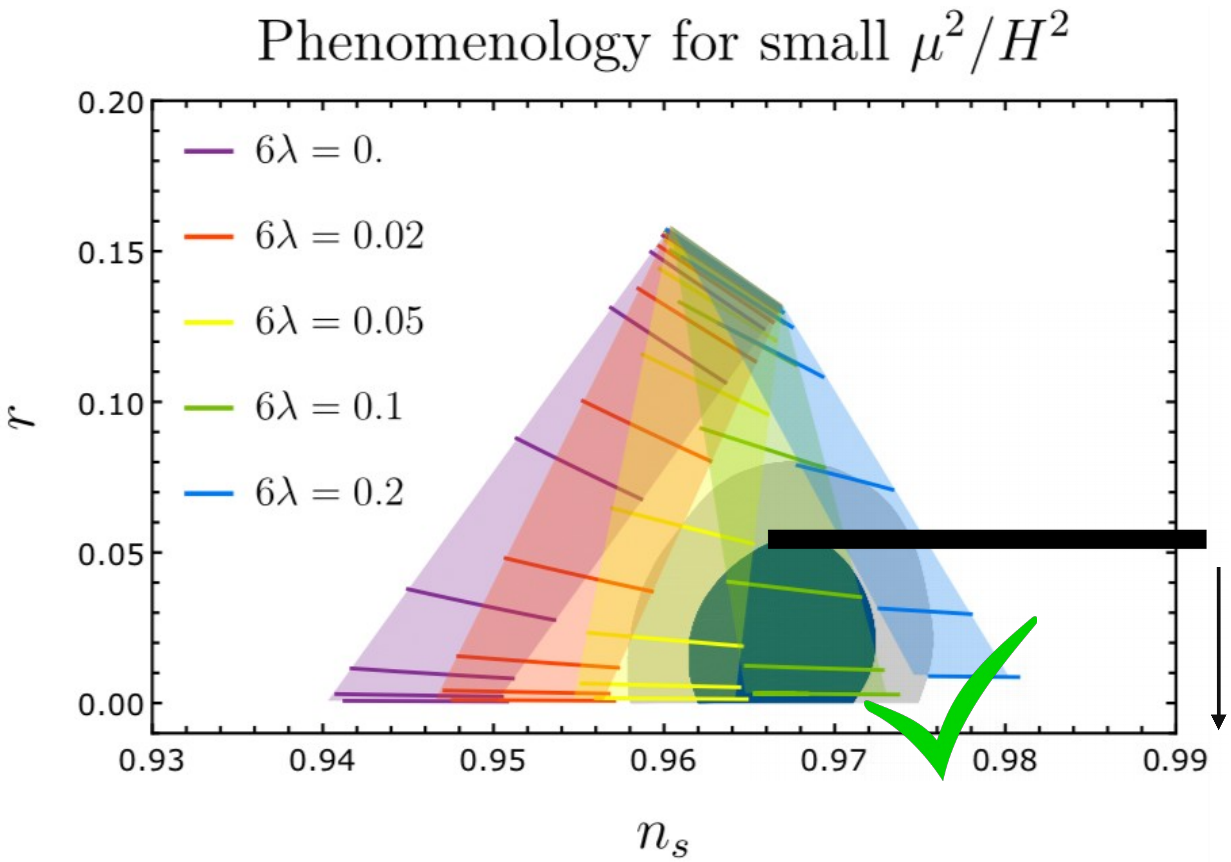
Phenomenology for small isocurvature mass

(Achúcarro, YW, 1907.02020)



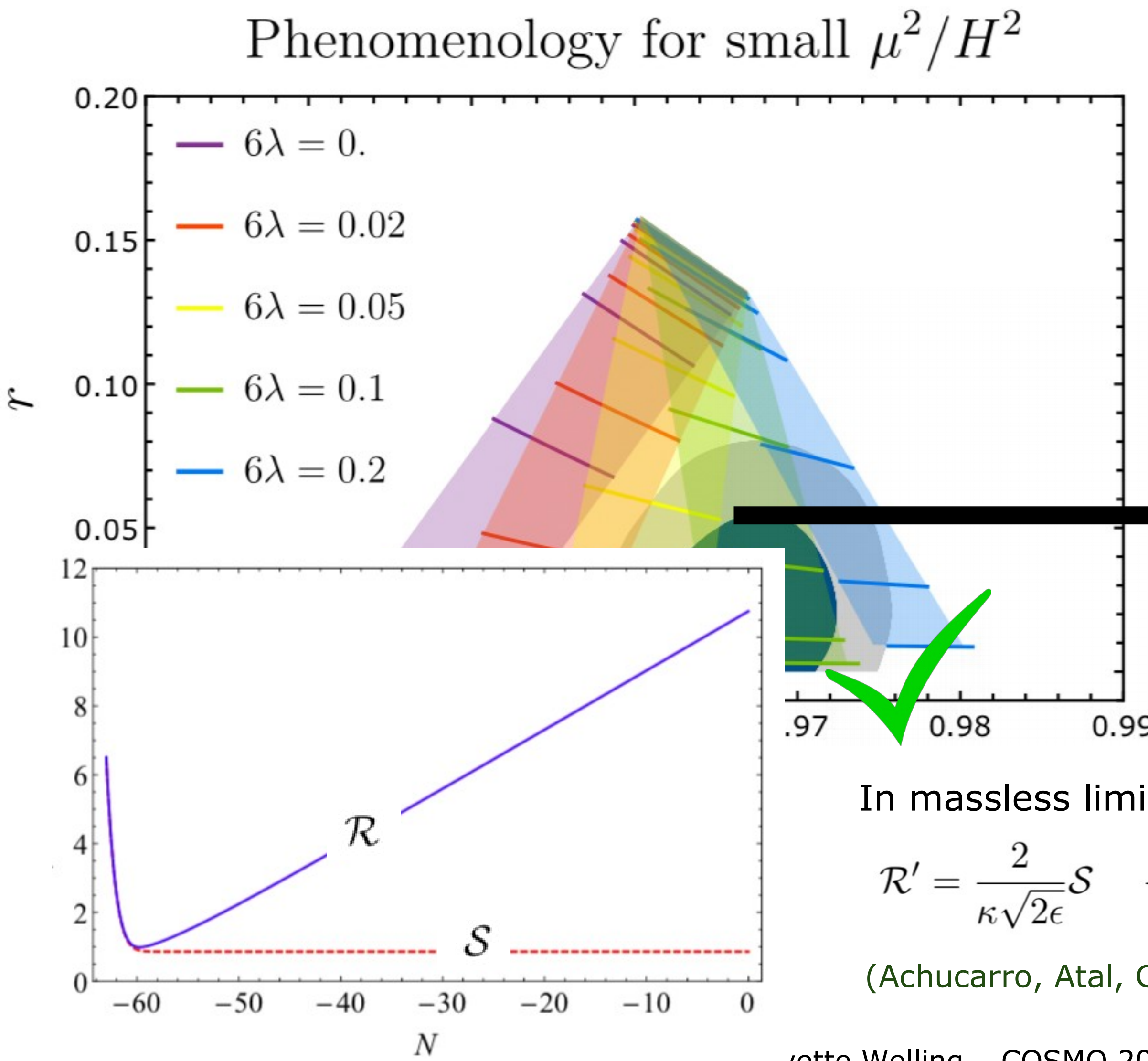
ε: starting point

λ: sets mass. Angle in which it vans out in (ns, r) plane

κ^{-1}: sets efficiency interaction. Reduction r

Phenomenology for small isocurvature mass

(Achúcarro, YW, 1907.02020)



ε: starting point
λ: sets mass. Angle in which it vans out in (ns, r) plane
κ^{-1}: sets efficiency interaction. Reduction r

“Single field” regime
isocurvature pt suppressed
but consistency relation violated!

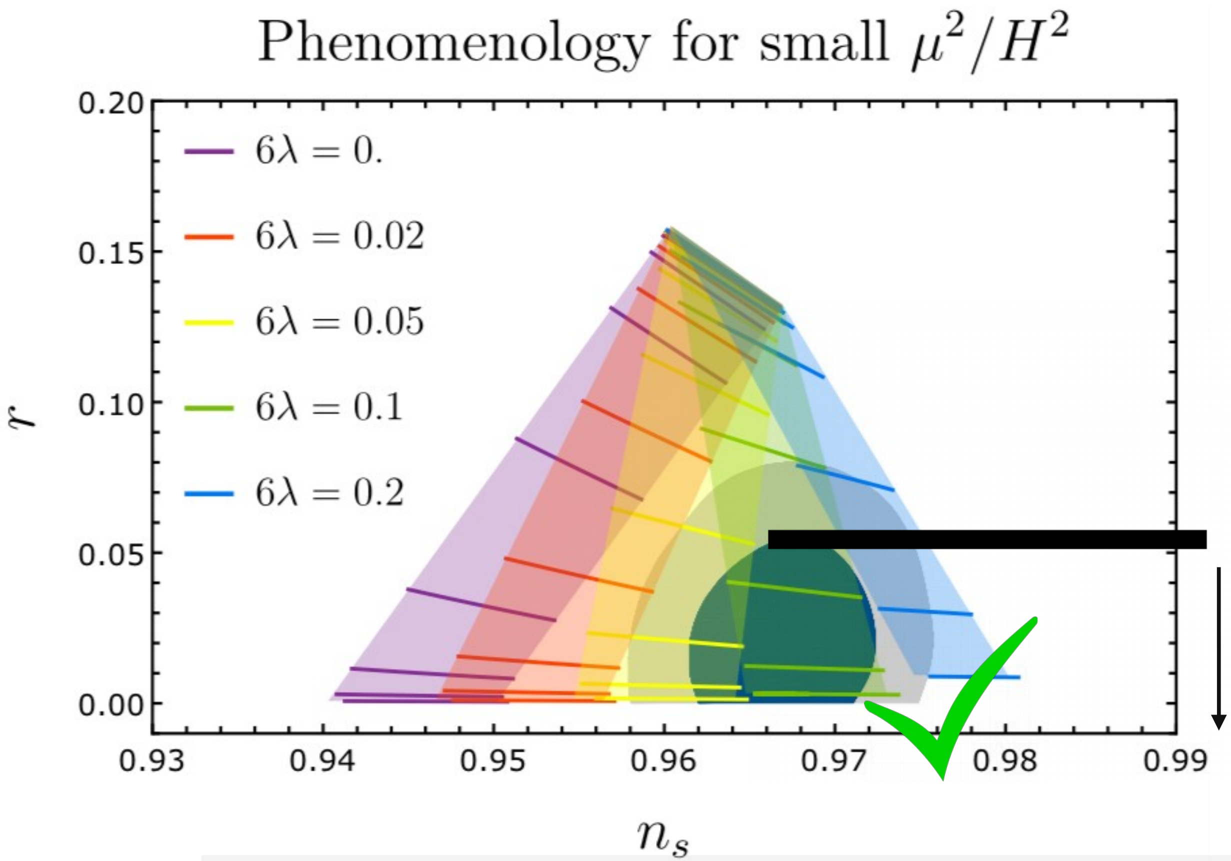
In massless limit λ = 0

$$\mathcal{R}' = \frac{2}{\kappa\sqrt{2\epsilon}}\mathcal{S} \longrightarrow \mathcal{R}_{\rm end} \approx \frac{2\Delta N}{\kappa\sqrt{2\epsilon}}\sigma_* \longrightarrow P_{\mathcal{R}} \gg P_{\mathcal{S}}$$

(Achucarro, Atal, Germani, Palma)

Phenomenology for small isocurvature mass

(Achúcarro, YW, 1907.02020)



ε: starting point

λ: sets mass. Angle in which it vans out in (ns, r) plane

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"Single clock" regime
isocurvature pt suppressed
but consistency relation violated!

$$f_{\rm NL} = -\frac{5}{12}\left(\alpha\kappa + \lambda\frac{10 - \mathbb{R}\kappa^2}{2}\right) + \frac{5}{N_\rho}\frac{2 - \mathbb{R}\kappa^2}{12\kappa}$$

$$N_\rho = \frac{1}{\kappa\lambda}\left(1 - e^{-2\lambda\Delta N}\right)$$

Small if λ, α are suppressed!

Applications of Orbital Inflation

(1) Playground for Quasi-Single-Field Inflation

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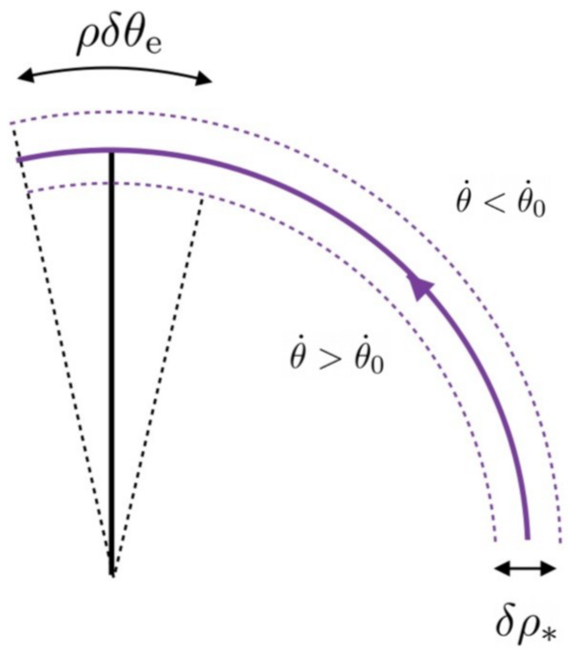
Scaling similarity ↔ massless fields

(Achúcarro, Palma, Wang, YW, 1908.06956)

Inspecting the massless case H = H(θ) in more detail

$$S_\phi = -\frac{1}{2}\int d^4x\sqrt{-g}\left((\partial\rho)^2 + e^{2\rho/R_0}(\partial\theta)^2 + \Lambda\left(\theta^2 - \frac{2p}{3e^{2\rho/R_0}}\right)\right)$$

It has a scaling similarity !



Relating BG solutions

$$\rho(x) \to \rho'(x') = \rho(x) + \Lambda c$$
$$\theta(x) \to \theta'(x') = e^{-c\Lambda/R_0}\theta(x)$$
$$x^\mu \to x'^\mu = e^c x^\mu$$

$$S \to S' = e^{2c}S$$

Perturbations

$$\rho(x) = \bar\rho(t+\pi(x)) + \mathcal{S}(x)$$
$$\theta(x) = e^{-\mathcal{S}(x)/R_0}\bar\theta(t+\pi(x))$$

Massless isocurvature pt

Scaling similarity ↔ massless fields

(Achúcarro, Palma, Wang, YW, 1908.06956)

We can generalize this to the family of potentials

$$S_\phi = -\frac{1}{2}\int d^4x\sqrt{-g}\left((\partial\rho)^2 + e^{2\rho/R_0}(\partial\theta)^2 + \sum_m c_m \theta^{2n-2m} e^{-2m\rho/R_0}\right)$$

Same scaling similarity → massless perturbation AND small self-interactions

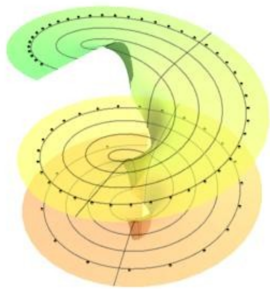
$$f_{\rm NL} \approx \frac{5}{12}\left(\frac{2\epsilon}{n} + \eta - \frac{2\dot\rho}{R_0 H}\right)$$

(If the radial field has a sufficiently small velocity)

In multi-field set-ups f_{NL} becomes slow-roll suppressed if:

- The isocurvature pt are responsible for the final curvature pt
- The isocurvature self interactions are small

Conclusions



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(YW, 1907.02951)

Orbital Inflation: a class of exact multi-field attractors in curved field spaces and with curved trajectories (that contain QSF)

In the limit of small isocurvature self interactions and a small radius of curvature Orbital Inflation **mimics the phenomenology of single-field inflation**

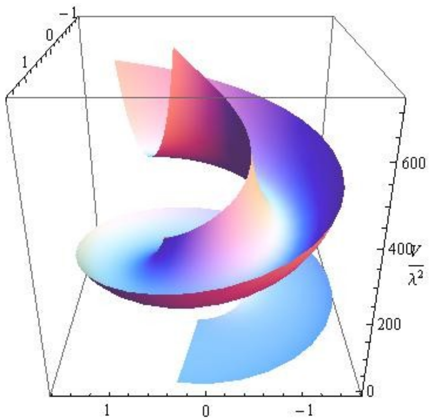
A **scaling similarity** can explain the above properties

Successful inflation doesn't necessarily require to get rid of all light fields!!

Thank you!

Old slides

Derivative interactions



Example: a potential which forces the inflaton to turn at constant radius

$$\mathcal{L} = \frac{1}{2}\rho^2\dot{\theta}^2 + \frac{1}{2}\dot{\rho}^2 - V(\rho,\theta) + \ldots$$

Expand around bg: derivative coupling proportional to turn rate

$$\mathcal{L} = \frac{1}{2}(\rho_0 + \delta\rho)^2(\dot{\theta}_0 + \delta\dot{\theta})^2 + \frac{1}{2}\delta\dot{\rho}^2 - V(\rho,\theta) + \ldots$$

$$\supset 2\rho_0\dot{\theta}_0\underline{\delta\rho\delta\dot{\theta}}$$

This happens whenever background trajectory $\neq$ geodesic

Derivative interactions

General quadratic action:

$\mathcal{R}$: curvature pt

σ : isocurvature pt

$$S^{(2)} = \frac{1}{2}\int d^4x a^3 M_p^2 \left[2\epsilon\left(\dot{\mathcal{R}} - \omega\sigma\right)^2 - 2\epsilon\frac{(\partial_i\mathcal{R})^2}{a^2} + \dot{\sigma}^2 - \mu^2\sigma^2 - \frac{(\partial_i\sigma)^2}{a^2}\right]$$

The coupling constant is proportional to the turn rate ω

The effective mass μ is given by $\mu^2 = V_{NN} + \epsilon M_p^2 H^2 \mathbb{R} + 3\omega^2$