“CoSyne: Cosmological Synergies in the upcoming decade”
December 2019, Paris

Lucas Pinol

With J. Fumagalli, S. Garcia-Saenz, S. Renaux-Petel, J. Ronayne

Institut d’Astrophysique de Paris (IAP)

OBSERVATIONAL SIGNATURES OF MULTIFIELD INFLATION WITH CURVED FIELD SPACE

BACKGROUND, LINEAR FLUCTUATIONS AND NON-GAUSSIANITIES

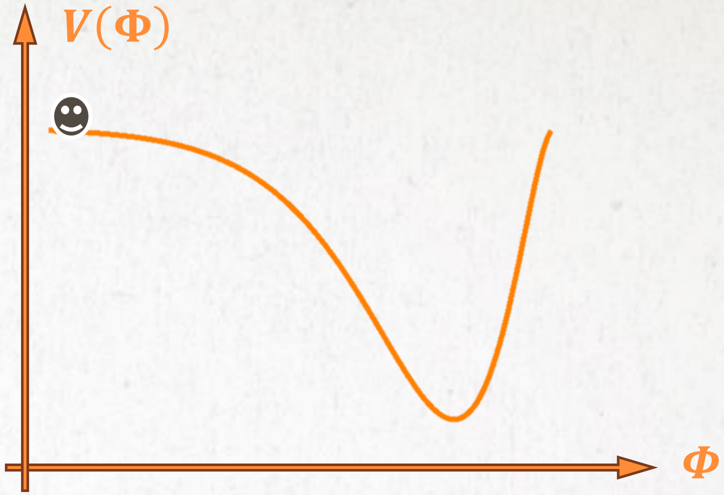
GEODESI

European Research Council
Established by the European Commission

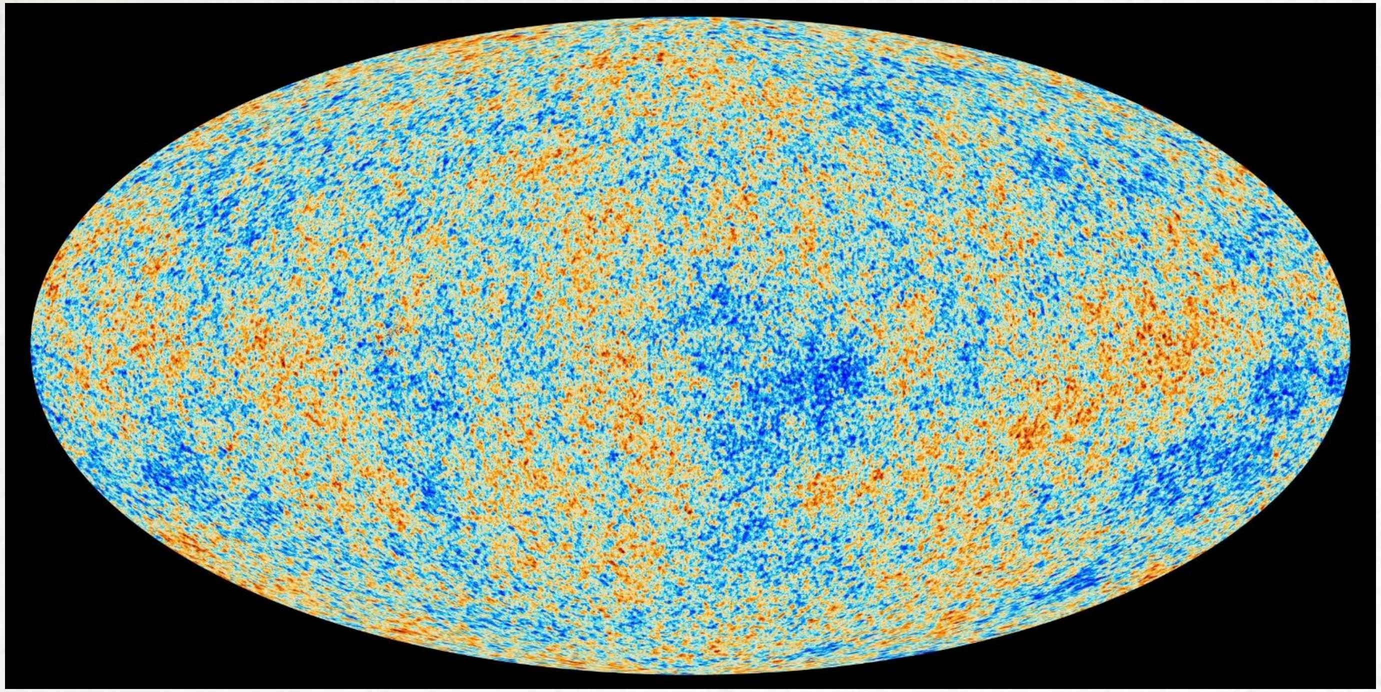
TABLE OF CONTENTS

I. USUAL PICTURE OF INFLATION

A CONSISTENT COSMOLOGICAL STORY



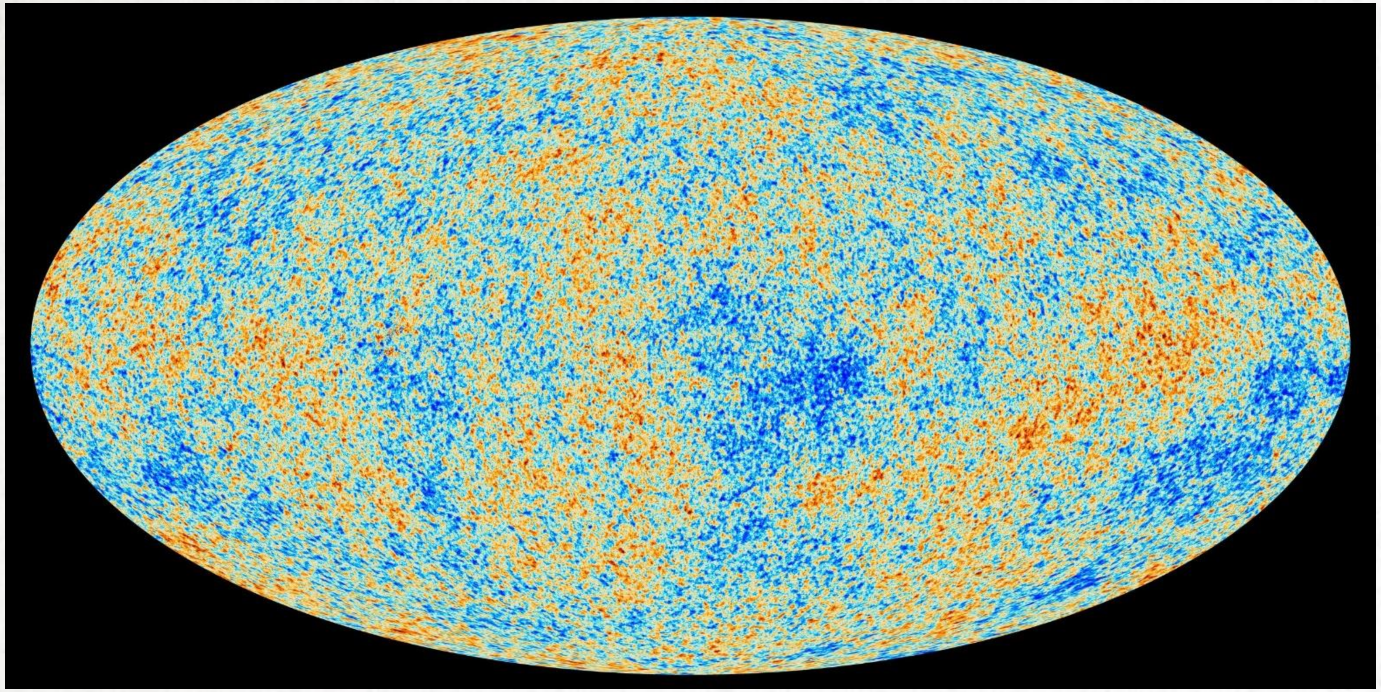
CMB OBSERVATION MOTIVATES INFLATION



$$T \sim 2.73K \; ; \; \frac{\delta T}{T} \sim 10^{-5} \; ; \; |\Omega_k| \ll 1$$

- How is the universe so homogeneous?
  Horizon problem
- Why is the universe so spatially flat?
  Flatness problem

CMB OBSERVATION MOTIVATES INFLATION



$$T \sim 2.73K \; ; \; \frac{\delta T}{T} \sim 10^{-5} \; ; \; |\Omega_k| \ll 1$$

- How is the universe so homogeneous?
  Horizon problem
- Why is the universe so spatially flat?
  Flatness problem

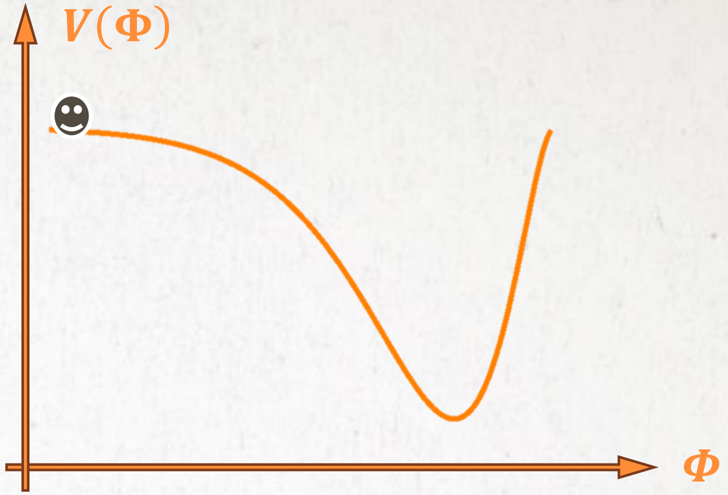
Inflation, an era of accelerated expansion of the Universe, solves both the horizon and flatness problems $\rightarrow$ $w < -1/3$

SLOW-ROLL SINGLE FIELD INFLATION

- Quasi de Sitter space: $\epsilon = -\frac{\dot{H}}{H^2} \ll 1\,; \eta = \frac{\dot{\epsilon}}{H\epsilon} \ll 1$

$$\Rightarrow \frac{M_p\, V'}{V} \ll 1\,; \frac{M_p^2 |V''|}{V} \ll 1$$

- Single-clock: only one scalar degree of freedom
- Canonical kinetic term

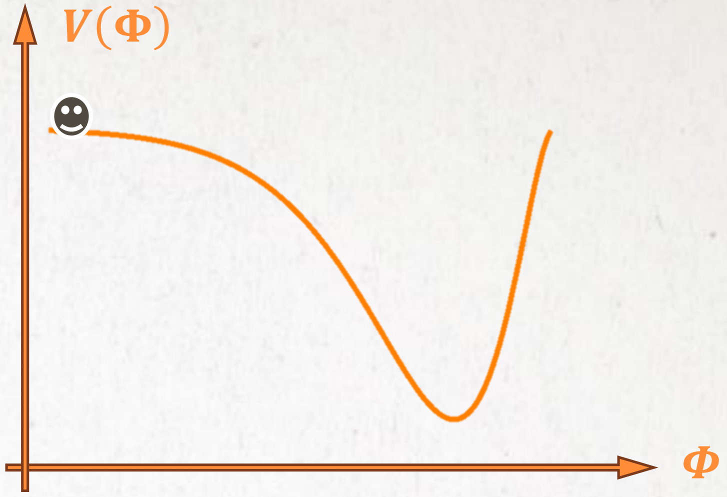


SLOW-ROLL SINGLE FIELD INFLATION

- Quasi de Sitter space: $\epsilon = -\frac{\dot{H}}{H^2} \ll 1\, ;\eta = \frac{\dot{\epsilon}}{H\epsilon} \ll 1$

$$\Rightarrow \frac{M_p\, V'}{V} \ll 1\, ;\ \boldsymbol{\frac{M_p^2 |V''|}{V} \ll 1}$$

- Single-clock: only one scalar degree of freedom
- Canonical kinetic term



Success and failure

✓ Enough expansion to solve the horizon and flatness problems

✓ Nearly scale-invariant scalar power spectrum

✓ Small tensor-to-scalar ratio
Small non-Gaussianities

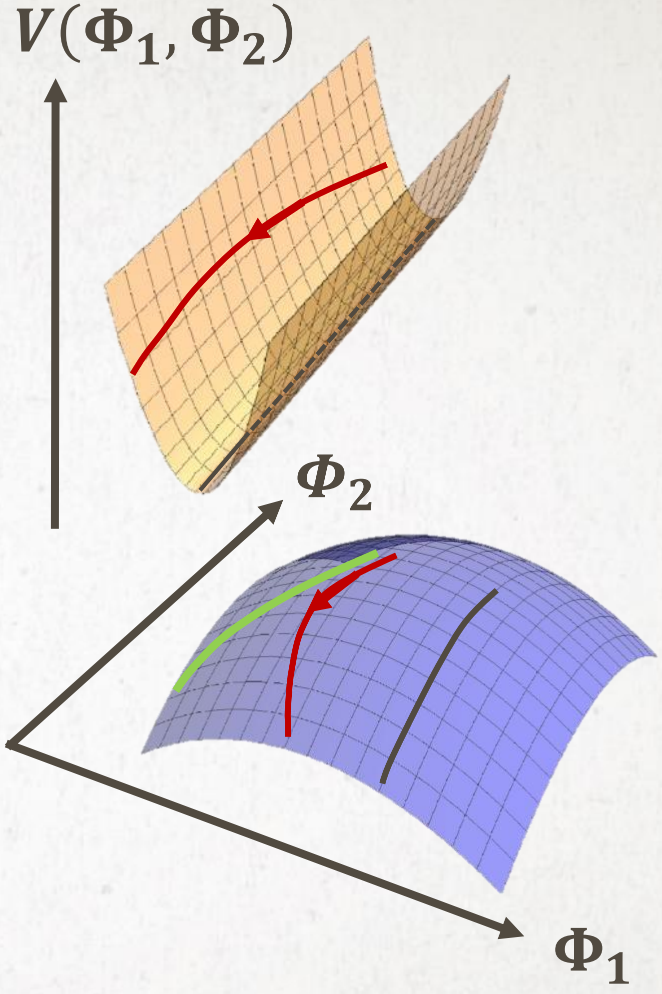
❖ Few theoretical motivation: realistic UV completions typically predict **several scalar fields with non-canonical kinetic terms**

❖ Sensitive to Planck scale suppressed operators, quantum loops renormalize the potential:

eta problem: $\boldsymbol{\frac{M_p^2 |V''|}{V} > 1}$

II. MULTIFIELD INFLATION WITH CURVED FIELD SPACE

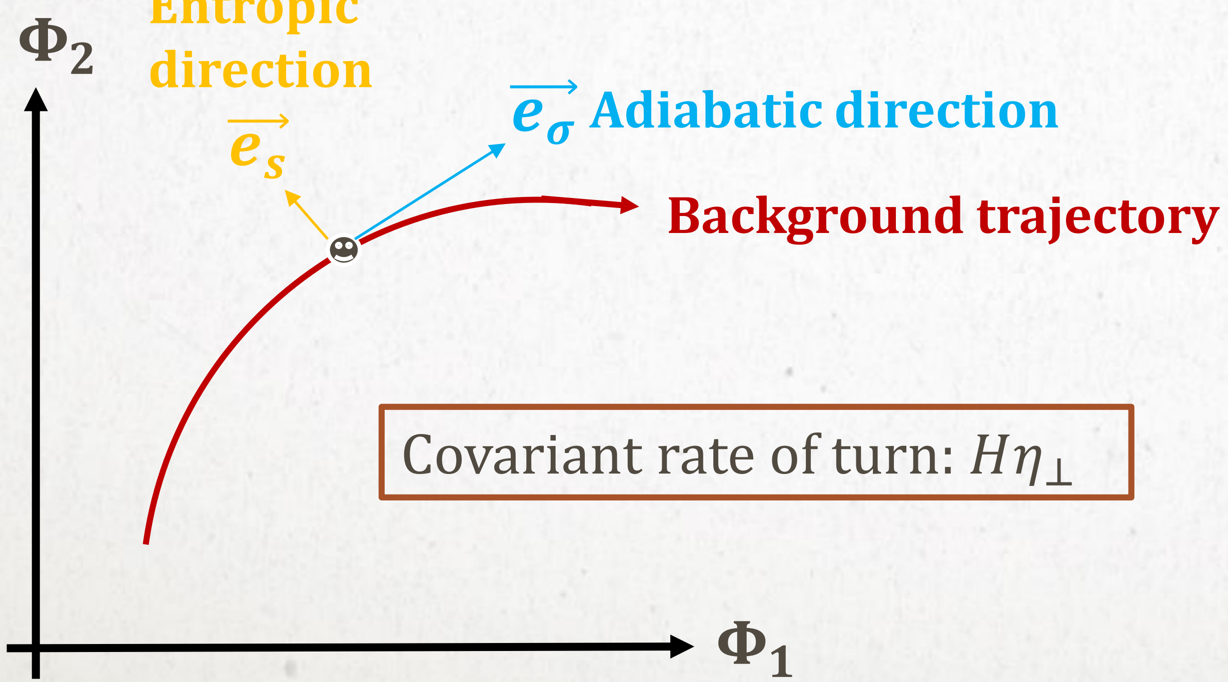
GEOMETRICAL EFFECTS UNVEILED



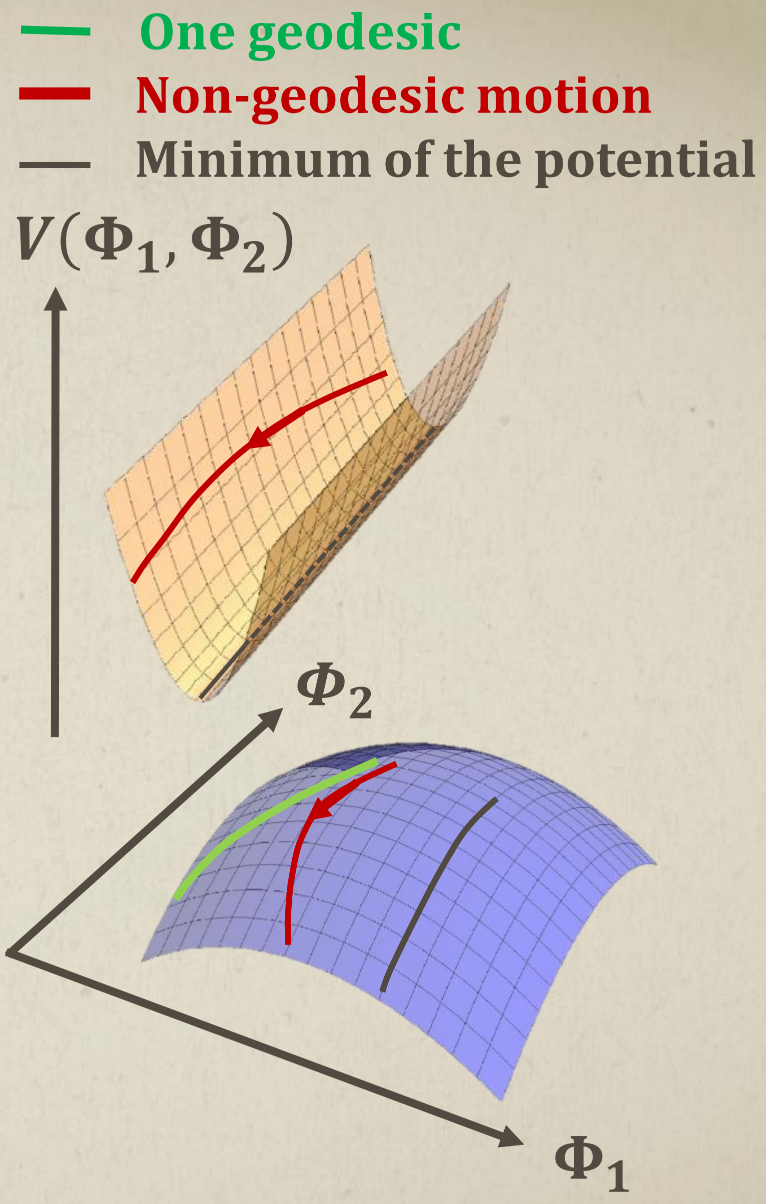
Curved field space

MULTIFIELD INFLATION WITH CURVED FIELD SPACE

$$S = \int \sqrt{-g} \left(\frac{R}{2} - \sum_{a,b} g^{\mu\nu} \boldsymbol{G_{ab}(\phi^c)} \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi^c) \right)$$

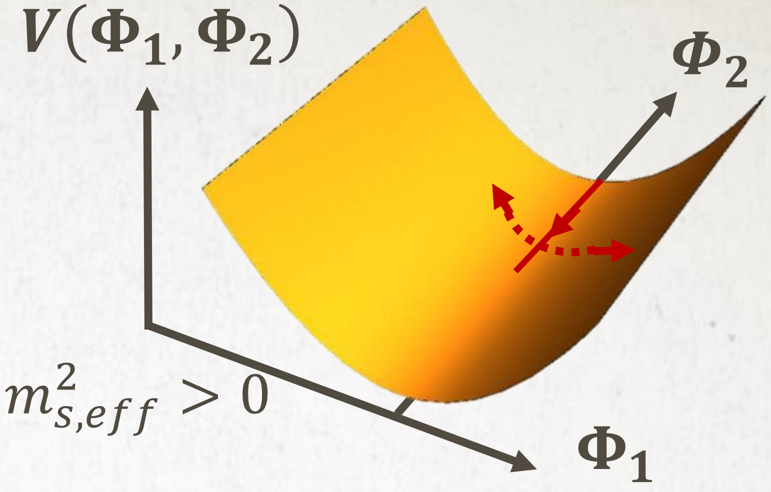


Covariant rate of turn: $H\eta_\perp$



Curved field space

STABILITY OF BACKGROUND TRAJECTORIES

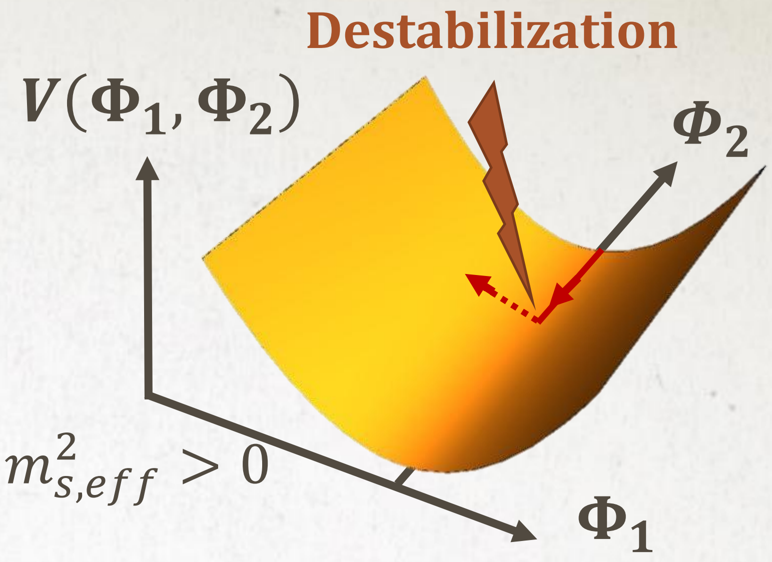


GEOMETRICAL DESTABILIZATION OF INFLATION

- A stable trajectory requires ⊥ long wavelength modes to be stable: $m_{s,eff}^2 > 0$

STABILITY OF BACKGROUND TRAJECTORIES

GEOMETRICAL DESTABILIZATION OF INFLATION



- A stable trajectory requires ⊥ long wavelength modes to be stable: $m^2_{s,eff} > 0$

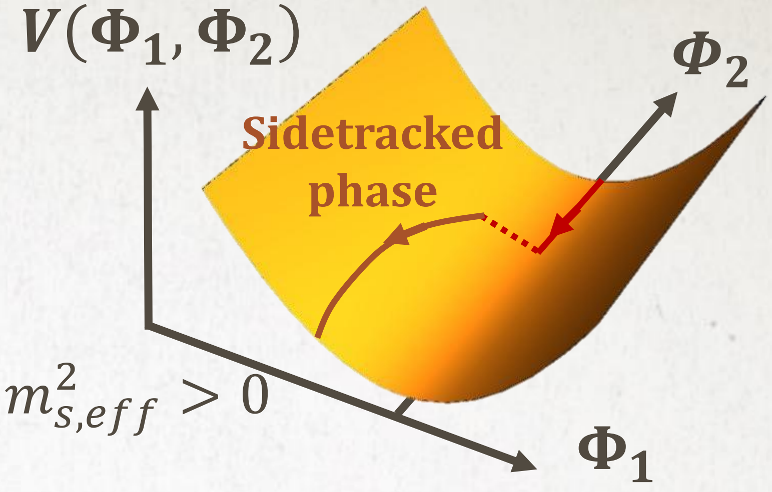
Hessian of the potential   Bending   Geometry of field-space

- Geometrical destabilization of inflation: $\frac{m^2_{s,eff}}{H^2} = \underbrace{\frac{V_{;ss}}{H^2} + 3\eta_\perp^2}_{>0} + \underbrace{\epsilon R_{\mathrm{fs}} M_p^2}_{<0 \text{ for hyperbolic field spaces}} < 0$

[S. Renaux-Petel, K. Turzynski 2015]

STABILITY OF BACKGROUND TRAJECTORIES

GEOMETRICAL DESTABILIZATION OF INFLATION



- A stable trajectory requires ⊥ long wavelength modes to be stable: $m_{s,eff}^2 > 0$

- Geometrical destabilization of inflation: $$\frac{m_{s,eff}^2}{H^2} = \underbrace{\overbrace{\frac{V_{;ss}}{H^2}}^{\text{Hessian of the potential}} + \overbrace{3\eta_\perp^2}^{\text{Bending}}}_{>0} + \underbrace{\overbrace{\epsilon R_{\text{fs}} M_p^2}^{\text{Geometry of field-space}}}_{<0 \text{ for hyperbolic field spaces}} < 0$$

[S. Renaux-Petel, K. Turzynski 2015]

→ Second, sidetracked phase of inflation

[O. Grocholski, M. Kalinowski, M. Kolanowski, S. Renaux-Petel, K.Turzynski, V. Vennin 2019]

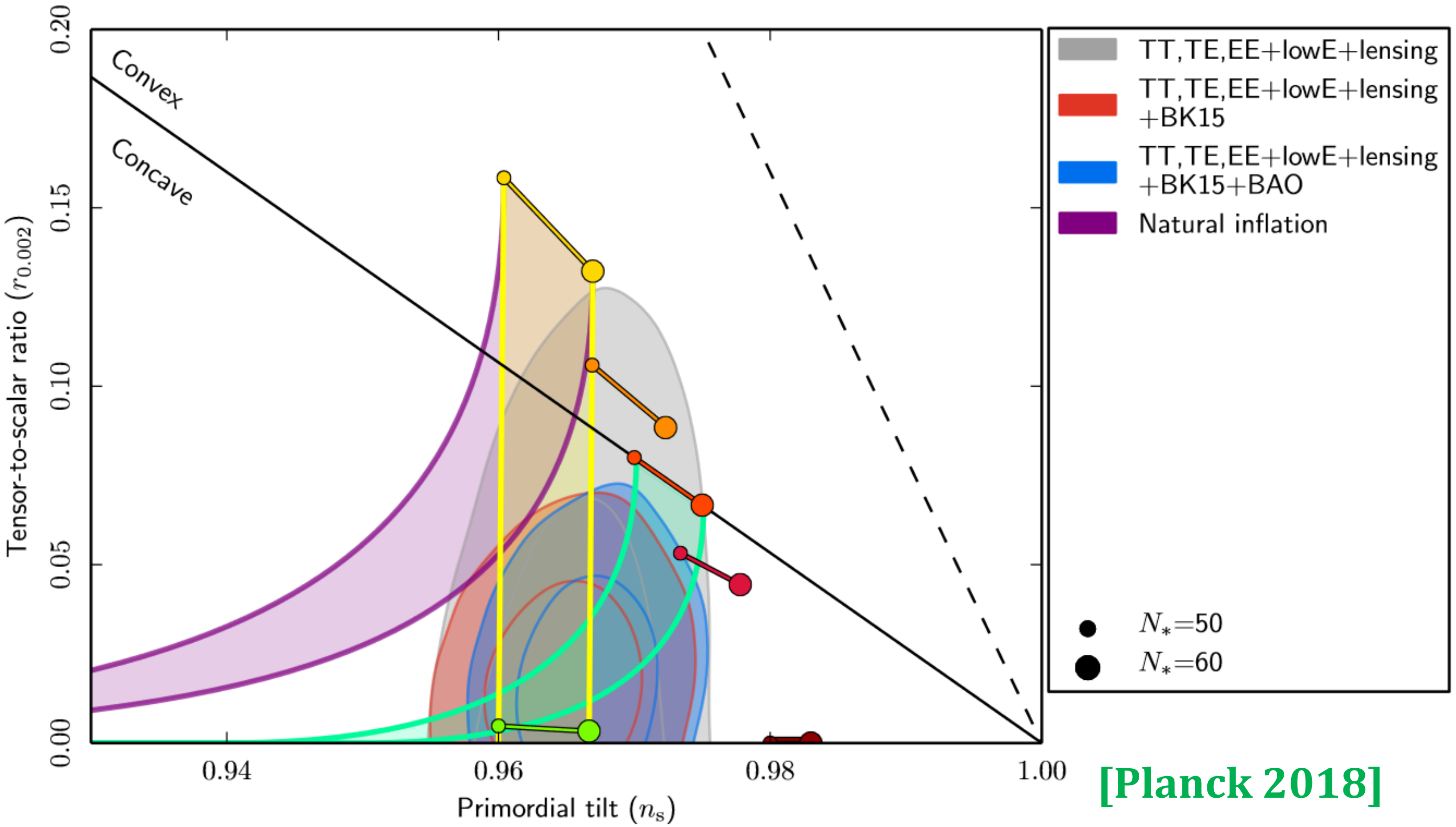
All observables $(N_{\text{inflation}}, n_s, r, f_{\text{nl}} \ldots)$ affected

PHYSICS OF LINEAR FLUCTUATIONS

RESURRECTING NATURAL INFLATION?

$$V(\phi) = \Lambda^4\left(1 + \cos\left(\frac{\phi}{f}\right)\right)$$

Discrete shift symmetry protecting potential from quantum corrections



[Planck 2018]

PHYSICS OF LINEAR FLUCTUATIONS

RESURRECTING NATURAL INFLATION?

$$V(\phi,\chi) = \Lambda^4\left(1+\cos\left(\frac{\phi}{f}\right)\right)+\frac{1}{2}m^2\chi^2$$

Negatively curved field spaces

Toy models (so far)

PHYSICS OF LINEAR FLUCTUATIONS

RESURRECTING NATURAL INFLATION?

$$V(\phi,\chi) = \Lambda^4\left(1+\cos\left(\frac{\phi}{f}\right)\right)+\frac{1}{2}m^2\chi^2$$

Negatively curved field spaces

Toy models (so far)

[Garcia-Saenz, Renaux-Petel, Ronayne 2018]

- Minimal metric:

$$d\sigma^2 = \left(1+\frac{\boldsymbol{2\chi^2}}{\boldsymbol{M^2}}\right)d\phi^2 + d\chi^2$$

$$R_{\mathrm{fs}} = -\frac{4}{M^2(1+2\chi^2/M^2)^2}$$

PHYSICS OF LINEAR FLUCTUATIONS

RESURRECTING NATURAL INFLATION?

$$V(\phi,\chi) = \Lambda^4 \left(1 + \cos\left(\frac{\phi}{f}\right)\right) + \frac{1}{2} m^2 \chi^2$$

Negatively curved field spaces

Toy models (so far)

[Garcia-Saenz, Renaux-Petel, Ronayne 2018]

- Minimal metric:

$$d\sigma^2 = \left(1 + \frac{2\chi^2}{M^2}\right) d\phi^2 + d\chi^2$$

$$R_{\mathrm{fs}} = -\frac{4}{M^2(1 + 2\chi^2/M^2)^2}$$

- Hyperbolic metric:

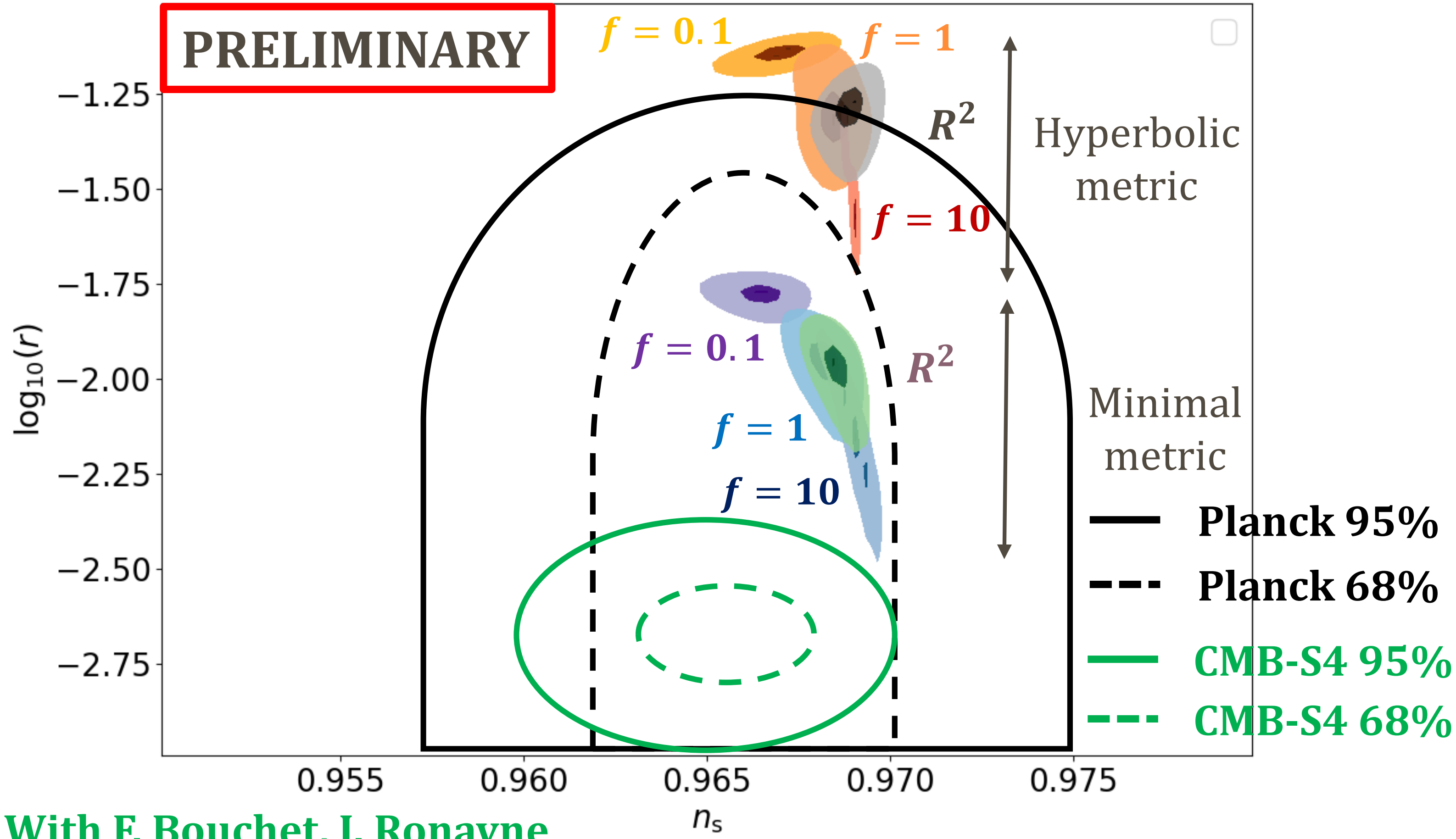
$$d\sigma^2 = \left(1 + \frac{\boldsymbol{2\chi^2}}{\boldsymbol{M^2}}\right) d\phi^2 + \frac{\boldsymbol{2\sqrt{2}\,\chi}}{\boldsymbol{M}} \boldsymbol{d\phi d\chi} + d\chi^2$$

$$R_{\mathrm{fs}} = -\frac{4}{M^2}$$

PHYSICS OF LINEAR FLUCTUATIONS

RESURRECTING NATURAL INFLATION?

$$V(\phi,\chi) = \Lambda^4\left(1+\cos\left(\frac{\phi}{f}\right)\right) + \frac{1}{2}m^2\chi^2$$



With F. Bouchet, J. Ronayne

Negatively curved field spaces

Toy models (so far)

- Minimal metric:

$$d\sigma^2 = \left(1+\frac{2\chi^2}{M^2}\right)d\phi^2 + d\chi^2$$

$$R_{\rm fs} = -\frac{4}{M^2(1+2\chi^2/M^2)^2}$$

- Hyperbolic metric:

$$d\sigma^2 = \left(1+\frac{2\chi^2}{M^2}\right)d\phi^2 + \frac{2\sqrt{2}\,\chi}{M}d\phi d\chi + d\chi^2$$

$$R_{\rm fs} = -\frac{4}{M^2}$$

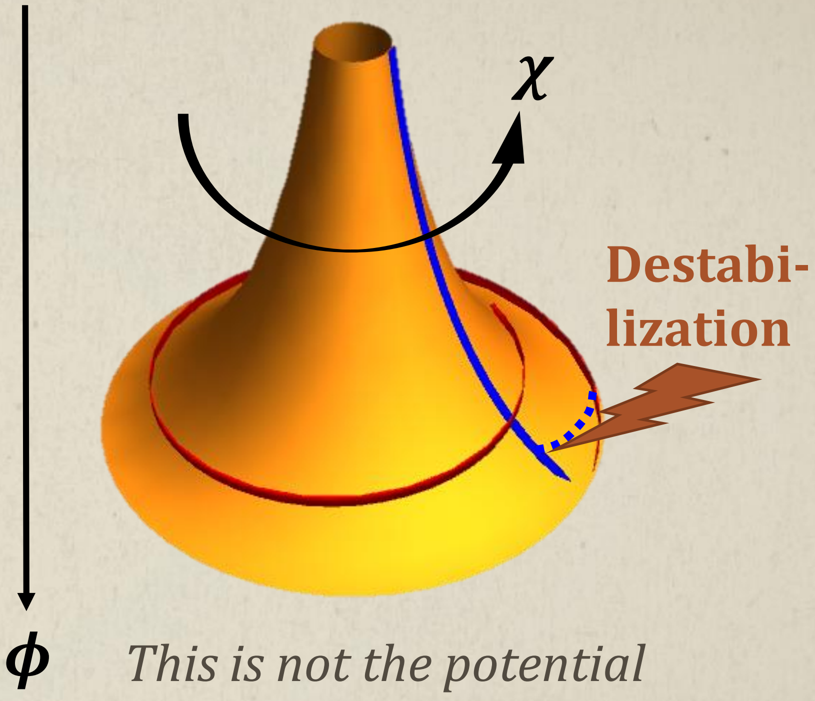
NON-GAUSSIANITIES
HYPERINFLATION

[Fumagalli, Garcia-Saenz, Pinol, Renaux-Petel, Ronayne 2019]
Phys. Rev. Lett. 123, 201302

Setup radial angular

The scalar fields ϕ , χ live on an internal hyperbolic plane

Embedding of the hyperbolic plane in 3D
Radial trajectory
Hyperinflation trajectory



This is not the potential

Hyperbolic field space

$$R_{\mathrm{fs}} = -\frac{4}{M^2}, \qquad M \ll M_p$$

NON-GAUSSIANITIES

HYPERINFLATION

[Fumagalli, Garcia-Saenz, Pinol, Renaux-Petel, Ronayne 2019]
Phys. Rev. Lett. 123, 201302

Setup radial angular

The scalar fields ϕ , χ live on an internal hyperbolic plane

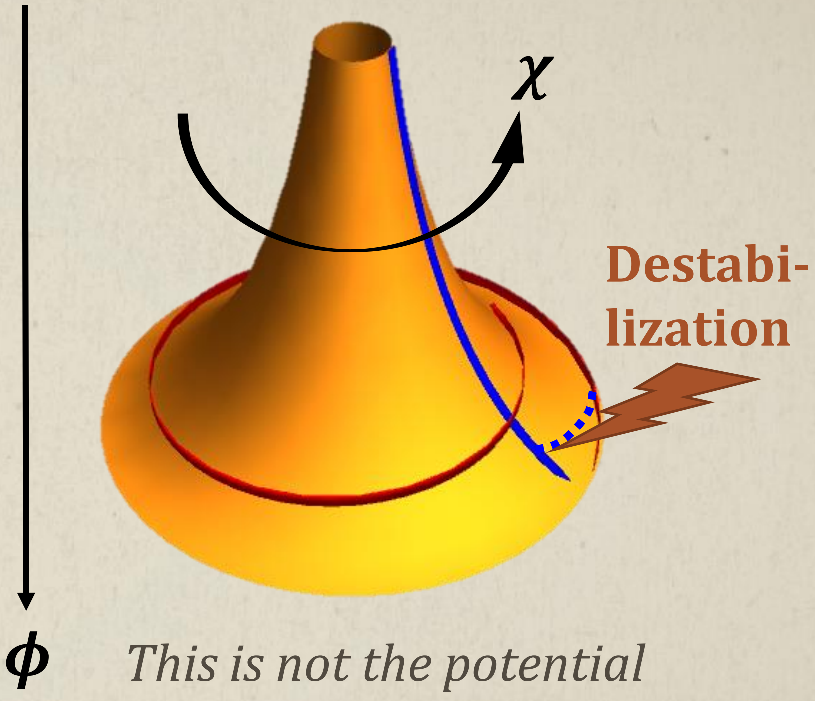
Interesting observational signatures: large non-Gaussianities in exotic flattened configurations

$$\boxed{f_{\mathbf{nl}}^{\mathbf{eq}} = \mathcal{O}(\mathbf{1});\ f_{\mathbf{nl}}^{\mathbf{flat}} = \mathcal{O}(\mathbf{50})}$$

Target for upcoming LSS experiments

cf. talks by D. Meerburg, O. Doré

Embedding of the hyperbolic plane in 3D
Radial trajectory
Hyperinflation trajectory



This is not the potential

Hyperbolic field space

$$R_{\rm fs} = -\frac{4}{M^2}, \qquad M \ll M_p$$

III. REVISITING PRIMORDIAL NON-GAUSSIANITIES

GENERALIZING MALDACENA'S CALCULATION TO CURVED FIELD SPACE

[J. Maldacena 2003]

$$\mathcal{L}(\zeta,\mathcal{F}) = \underbrace{\mathcal{L}^{(2)}(\zeta,\mathcal{F})}_{\text{Dictating the power spectrum: 2-point function}} + \underbrace{\mathcal{L}^{(3)}_{\text{Maldacena}}(\zeta) + \mathcal{L}^{(3)}_{\text{new}}(\zeta,\mathcal{F}) + \mathcal{D}^{(3)}}_{\text{Dictating the bispectrum: 3-point function}}$$

[arXiv:1907.10403 Garcia-Saenz, Pinol, Renaux-Petel]

NEW INTERACTIONS

<u>Applications</u>: *quasi-single field, cosmological collider physics, single-field effective theory*

$$\mathcal{L}^{(3)}_{\mathbf{new}}(\zeta,\mathcal{F}) = \frac{1}{2}m_s^2\zeta\mathcal{F}\left((\epsilon+\mu_s)\mathcal{F} + (2\epsilon-\eta-2\lambda_\perp)\frac{2\dot\sigma\eta_\perp}{m_s^2}\dot\zeta\right) + \frac{\dot\sigma\eta_\perp}{a^2H}\mathcal{F}(\partial\zeta)^2$$

$$-\frac{\dot\sigma\eta_\perp}{H}\dot\zeta^2\mathcal{F} - \frac{1}{H}\left(H^2\eta_\perp^2 - \epsilon H^2M_p^2R_{fs}\right)\dot\zeta\mathcal{F}^2 - \frac{1}{6}\left(V_{;sss} - 2\dot\sigma H\eta_\perp R_{fs} + \epsilon H^2M_p^2R_{fs,s}\right)\mathcal{F}^3$$

$$+\frac{1}{2}\epsilon\zeta\left(\dot{\mathcal{F}}^2 + \frac{(\partial\mathcal{F})^2}{a^2}\right) - \frac{1}{a^2}\dot{\mathcal{F}}(\partial\mathcal{F})(\partial\chi)$$

$$\mathcal{D}^{(3)} = \frac{M_p^2}{2}\frac{\mathbf{d}}{\mathbf{dt}}\left\{\begin{array}{l} -\frac{1}{3aH^3}\zeta\left[\left(\partial_i\partial_j\zeta\right)^2 - (\partial^2\zeta)^2\right] + \frac{a}{H}\left[2(1-\epsilon)\zeta(\partial\zeta)^2 - \frac{1}{M_p^2}\zeta(\partial\mathcal{F})^2\right] - a^3\left[18H\,\zeta^3 + \frac{1}{M_p^2H}(m_s^2+4H^2\eta_\perp^2)\zeta\mathcal{F}^2\right] \\ +\boldsymbol{\partial^2\chi}\frac{a}{H}\left[-2\dot\zeta\zeta + \frac{\dot\sigma\eta_\perp}{M_p^2\epsilon}\zeta\mathcal{F} + \frac{1}{a^2}\left((\partial\zeta)^2 - \partial^{-2}\,\partial_i\partial_j\left(\partial_i\zeta\partial_j\zeta\right)\right) - \frac{1}{a^2}\left(\partial_i\zeta\partial_i\chi - \partial^{-2}\,\partial_i\partial_j\left(\partial_i\zeta\partial_j\chi\right)\right)\right] - \frac{a^3}{M_p^2H}\zeta\dot{\boldsymbol{\mathcal{F}}}^2 \end{array}\right\}$$

[arXiv:1907.10403 Garcia-Saenz, Pinol, Renaux-Petel]

INTEGRATING OUT HEAVY ENTROPIC FLUCTUATIONS

A SINGLE-FIELD EFFECTIVE THEORY: $S[\zeta,\mathcal{F}] \xrightarrow{\mathcal{F}_{\text{heavy}}(\zeta)} S_{\text{EFT}}[\zeta] = S[\zeta,\mathcal{F}_{\text{heavy}}(\zeta)]$

Decoupling limit (slow-roll leading-order) of the EFT of inflation:

$$S_3^{\text{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{\mathcal{H}}\left(\frac{1}{c_s^2}-1\right)\left(\zeta'(\partial_i\zeta)^2 + \frac{\boldsymbol{A}}{c_s^2}\zeta'^3\right)$$

INTEGRATING OUT HEAVY ENTROPIC FLUCTUATIONS

A SINGLE-FIELD EFFECTIVE THEORY: $S[\zeta, \mathcal{F}] \xrightarrow{\mathcal{F}_{\text{heavy}}(\zeta)} S_{\text{EFT}}[\zeta] = S[\zeta, \mathcal{F}_{\text{heavy}}(\zeta)]$

Decoupling limit (slow-roll leading-order) of the EFT of inflation: $f_{\text{nl}}^{\text{eq}} \simeq \left(\frac{1}{c_s^2} - 1\right)\left(-\frac{85}{324} + \frac{15}{243}\boldsymbol{A}\right)$

$$S_3^{\text{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{\mathcal{H}}\left(\frac{1}{c_s^2} - 1\right)\left(\zeta'(\partial_i\zeta)^2 + \frac{\boldsymbol{A}}{c_s^2}\zeta'^3\right)$$

with $\boldsymbol{A} =$

INTEGRATING OUT HEAVY ENTROPIC FLUCTUATIONS

A SINGLE-FIELD EFFECTIVE THEORY: $S[\zeta,\mathcal{F}] \xrightarrow{\mathcal{F}_{\mathrm{heavy}}(\zeta)} S_{\mathrm{EFT}}[\zeta] = S[\zeta,\mathcal{F}_{\mathrm{heavy}}(\zeta)]$

Decoupling limit (slow-roll leading-order) of the EFT of inflation: $f_{\mathrm{nl}}^{\mathrm{eq}} \simeq \left(\frac{1}{c_s^2}-1\right)\left(-\frac{85}{324}+\frac{15}{243}\boldsymbol{A}\right)$

$$S_3^{\mathrm{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{\mathcal{H}}\left(\frac{1}{c_s^2}-1\right)\left(\zeta'(\partial_i\zeta)^2+\frac{\boldsymbol{A}}{c_s^2}\zeta'^3\right)$$

$$\text{with } \boldsymbol{A} = \underbrace{-\frac{1}{2}(1+c_s^2)}_{\text{Previously known}} + \underbrace{\frac{2}{3}(1+c_s^2)\frac{\epsilon R_{\mathrm{fs}} H^2 M_p^2}{m_s^2}}_{\text{Scalar curvature of the field space}} - \frac{1}{6}(1-c_s^2)\left(\underbrace{\frac{\kappa V_{;sss}}{m_s^2}}_{\text{3^{rd} derivative of the potential}} + \underbrace{\frac{\kappa\epsilon H^2 M_p^2 R_{\mathrm{fs},s}}{m_s^2}}_{\text{Derivative of the scalar curvature}}\right)$$

CONCLUSION

- Slow-roll single-field inflation challenged: theory or model?

- Multifield inflation with curved field space is more generic and motivated by UV completions (string theory compactifications, supergravity…)

- Internal geometry plays a crucial role already at the background level: GEOmetrical DEStabilization of Inflation (ERC working group « GEODESI » led by S. Renaux-Petel at IAP)

- It crucially affects the physics of linear fluctuations and can shift (n_s, r) predictions by a lot

- Non-Gaussianities can be enhanced, thus providing exotic detectable signatures

- Step towards the general understanding of Non-Gaussianities of such models:

  Extending Maldacena's calculation

  Single-field effective theory: explicit geometry-dependent f_{nl}

THANKS FOR YOUR ATTENTION!

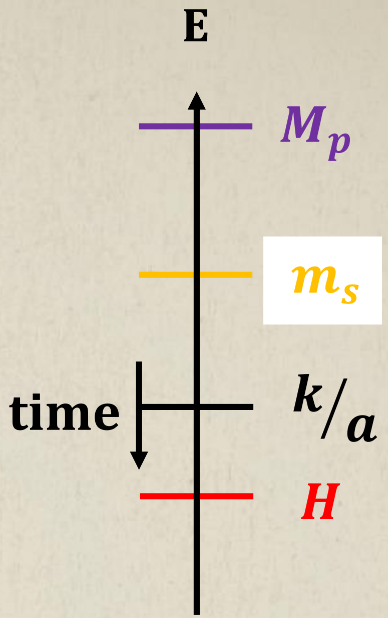
A HIERARCHY OF SCALES

WHEN ENTROPIC FLUCTUATIONS ARE HEAVY

- Equation of motion for $\mathcal{F}$:

$$\ddot{\mathcal{F}} + 3H\dot{\mathcal{F}} + \left(m_s^2 + \frac{k^2}{a^2}\right)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$$

Hierarchy of scales



Energy of the "experiment"

$$H \ll m_s$$

Integrate out the heavy perturbation

Like in the Fermi theory:
Integrate out the heavy W, Z bosons and consider contact interactions for fermions

A HIERARCHY OF SCALES

WHEN ENTROPIC FLUCTUATIONS ARE HEAVY

- Equation of motion for $\mathcal{F}$:

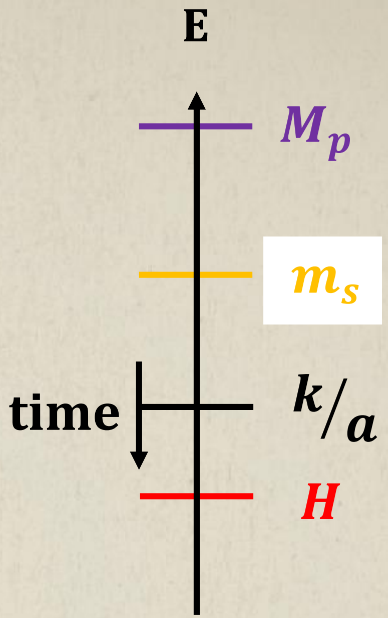
$$\cancel{\ddot{\mathcal{F}}} + 3\cancel{H\dot{\mathcal{F}}} + \left(m_s^2 + \cancel{\frac{k^2}{a^2}}\right)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$$

When $\mathcal{F}$ is heavy

$$\boxed{\mathcal{F}_{\text{heavy}}^{\text{LO}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}}$$

$$\omega^2, \omega H, \frac{k^2}{a^2} \ll m_s^2$$

Hierarchy of scales



Energy of the "experiment"

$$H \ll m_s$$

Integrate out the heavy perturbation

Like in the Fermi theory:
Integrate out the heavy W, Z bosons and consider contact interactions for fermions

A HIERARCHY OF SCALES

THE QUADRATIC EFFECTIVE ACTION

- Equation of motion for $\mathcal{F}$:

$$\cancel{\ddot{\mathcal{F}}} + 3\cancel{H\dot{\mathcal{F}}} + \left(m_s^2 + \cancel{\frac{k^2}{a^2}}\right)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$$

When $\mathcal{F}$ is heavy $\boxed{\mathcal{F}_{\text{heavy}}^{\text{LO}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}}$

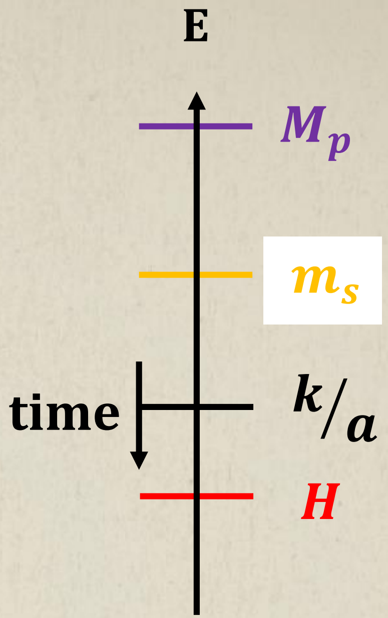
$$\Downarrow$$

Effective single-field action for the curvature perturbation

$$S_2^{\text{EFT}}[\zeta] = \int d\tau d^3x a^2\epsilon\left(\frac{\zeta'^2}{c_s^2} - (\partial_i\zeta)^2\right)$$

With a speed of sound c_s: $\boxed{\frac{1}{c_s^2} = 1 + \frac{4H^2\eta_\perp^2}{m_s^2}}$

Hierarchy of scales



Energy of the "experiment"

$H \ll m_s$

Integrate out the heavy perturbation

Like in the Fermi theory:
Integrate out the heavy W, Z bosons and consider contact interactions for fermions

$s = \dot{c}_s / H c_s$

THE CUBIC EFFECTIVE ACTION

FULL RESULT

$$S_3^{\mathrm{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{c_s^2} \begin{pmatrix} \frac{g_1}{\mathcal{H}} \zeta'^3 + \\ g_2 \zeta'^2 \zeta + \\ g_3 c_s^2 \zeta (\partial_i \zeta)^2 + \\ \frac{\tilde{g}_3 c_s^2}{\mathcal{H}} \zeta' (\partial_i \zeta)^2 + \\ g_4 \zeta' \partial_i \partial^{-2} \zeta' \partial_i \zeta + \\ g_5 \partial^2 \zeta (\partial_i \partial^{-2} \zeta')^2 \end{pmatrix} \text{ with } \begin{cases} g_1 = \left(\frac{1}{c_s^2} - 1 \right) \boldsymbol{A} \\ g_2 = \epsilon - \eta + 2s \\ g_3 = \epsilon + \eta \\ \tilde{g}_3 = \frac{1}{c_s^2} - 1 \\ g_4 = \frac{-2\epsilon}{c_s^2} \left(1 - \frac{\epsilon}{4} \right) \\ g_5 = \frac{\epsilon^2}{4 c_s^2} \end{cases}$$

The only new parameter is **A**, and depends on the UV physics

THE CUBIC EFFECTIVE ACTION

RECOVERING CANONICAL SINGLE-FIELD LIMIT

Maldacena's result:
Non-Gaussianities $\sim \boldsymbol{O(\epsilon, \eta)}$

$\boldsymbol{c_s^2 \to 1}$

$$S_3^{\text{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{c_s^2} \begin{pmatrix} \cancel{\frac{g_1}{\mathcal{H}}\zeta'^3} + \\ g_2 \zeta'^2 \zeta + \\ g_3 \zeta (\partial_i \zeta)^2 + \\ \cancel{\frac{g_3}{\mathcal{H}}\zeta'}(\partial_i \zeta)^2 + \\ g_4 \zeta' \partial_i \partial^{-2} \zeta' \partial_i \zeta + \\ g_5 \partial^2 \zeta (\partial_i \partial^{-2} \zeta')^2 \end{pmatrix} \text{ with } \begin{cases} g_2 = \epsilon + \eta \\ g_3 = \epsilon - \eta \\ g_4 = -2\epsilon \left(1 - \frac{\epsilon}{4}\right) \\ g_5 = \frac{\epsilon^2}{4} \end{cases}$$

~~The only new parameter is **A**, and depends on the UV physics~~

THE CUBIC EFFECTIVE ACTION

RECOVERING THE EFT OF INFLATION

Decoupling limit result:

Non-Gaussianities $\sim \frac{1}{c_s^2} - 1$

$\epsilon, \eta, s \to 0$

$$S_3^{\mathrm{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{c_s^2} \left(\begin{array}{c} \frac{g_1}{\mathcal{H}} \zeta'^3 + \\ \cancel{g_2 \zeta'^2 \zeta} + \\ \cancel{g_3 c_s^2 \zeta (\partial_i \zeta)^2} + \\ \frac{\tilde{g}_3 c_s^2}{\mathcal{H}} \zeta' (\partial_i \zeta)^2 + \\ \cancel{g_4 \zeta' \partial_i \partial^{-2} \zeta' \partial_i \zeta} + \\ \cancel{g_5 \partial^2 \zeta (\partial_i \partial^{-2} \zeta')^2} \end{array} \right) \text{ with } \begin{cases} g_1 = \left(\frac{1}{c_s^2} - 1 \right) \boldsymbol{A} \\ \tilde{g}_3 = \frac{1}{c_s^2} - 1 \end{cases}$$

The only new parameter is **A**, and depends on the UV physics

$$X = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

RECOVERING P(X) THEORY

Redundancy of operators

$$S_3^{\mathrm{EFT}}[\zeta] = \int d\tau d^3x a^2 M_p^2 \frac{\epsilon}{c_s^2}\left(\begin{array}{c} \frac{g_1}{\mathcal{H}}\zeta'^3 + \\ g_2\zeta'^2\zeta + \\ g_3 c_s^2\zeta(\partial_i\zeta)^2 + \\ \cancel{\frac{\tilde{g}_3 c_s^2}{\mathcal{H}}\zeta'(\partial_i\zeta)^2} + \\ g_4\zeta'\partial_i\partial^{-2}\zeta'\partial_i\zeta + \\ g_5\partial^2\zeta(\partial_i\partial^{-2}\zeta')^2 \end{array}\right) \text{ with }$$

P(X) cubic lagrangian:

$$\begin{cases} g_1 = \left(\frac{1}{c_s^2} - 1\right)(1 + 2A) \\ g_2 = \frac{1}{c_s^2}\left(3(c_s^2 - 1) + \epsilon - \eta\right) \\ g_3 = \frac{1}{c_s^2}\left(-(c_s^2 - 1) + \epsilon + \eta - 2s\right) \\ g_4 = \frac{-2\epsilon}{c_s^2}\left(1 - \frac{\epsilon}{4}\right) \\ g_5 = \frac{\epsilon^2}{4c_s^2} \end{cases}$$

Direct mapping with P(X):

$$\frac{2\lambda}{\Sigma} = -\left(\frac{1}{c_s^2} - 1\right)A \quad \text{with}$$

$$\Sigma = XP_{,X} + 2X^2P_{,XX}$$

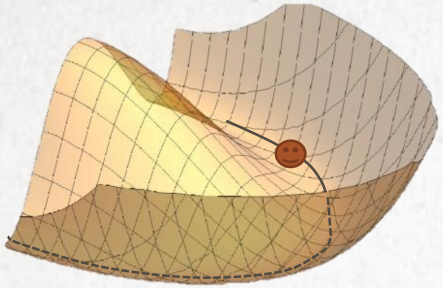
$$\lambda = X^2P_{,XX} + \frac{2}{3}X^3P_{,XXX}$$

[X. Chen, M. Huang, S. Kachru, G. Shiu 2008]

[C. Burrage, R. Ribeiro, D. Seery 2011]

THE GELATON CHECK

The gelaton scenario



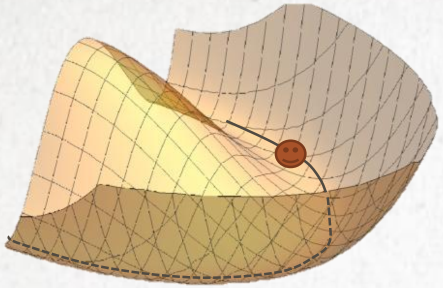
- 2 fields (ϕ, ψ), curved field-space
- ψ is very heavy and adiabatically follows the min of its effective potential
- The full field ψ can be integrated out, giving a single-field P(X) theory

Our procedure

- Keeping $\bar{\psi}$ at the level of the background
- Integrating out heavy entropic fluctuations
- Get P(X)-like cubic Lagrangian

THE GELATON CHECK

The gelaton scenario



- 2 fields (ϕ, ψ), curved field-space
- ψ is very heavy and adiabatically follows the min of its effective potential
- The full field ψ can be integrated out, giving a single-field P(X) theory

Our procedure

- Keeping $\bar{\psi}$ at the level of the background
- Integrating out heavy entropic fluctuations
- Get P(X)-like cubic Lagrangian

Same P(X) theory!

REGIME OF VALIDITY OF THE EFT

MAKING ASSUMPTIONS MORE PRECISE

$$\mathcal{F}_{\text{heavy}}^{\text{LO}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}$$

- A more formal solution to $(m_s^2 - \Box)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$ is $\mathcal{F}_{\text{heavy}} = \frac{1}{m_s^2}\sum_{i=0}^{\infty}\left(\frac{\Box}{m_s^2}\right)^i 2\dot{\sigma}\eta_\perp\dot{\zeta}$

For consistency, NLO (i=1) correction must be neglible compared to LO (i=0) in the expansion

$$\Box\left(2\dot{\sigma}\eta_\perp\dot{\zeta}\right) \ll m_s^2(2\dot{\sigma}\eta_\perp\dot{\zeta})$$

REGIME OF VALIDITY OF THE EFT

MAKING ASSUMPTIONS MORE PRECISE

$$\mathcal{F}^{\mathrm{LO}}_{\mathrm{heavy}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}$$

- A more formal solution to $(m_s^2 - \Box)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$ is $\mathcal{F}_{\mathrm{heavy}} = \frac{1}{m_s^2}\sum_{i=0}^{\infty}\left(\frac{\Box}{m_s^2}\right)^i 2\dot{\sigma}\eta_\perp\dot{\zeta}$

For consistency, NLO (i=1) correction must be neglible compared to LO (i=0) in the expansion

$$\Box\left(2\dot{\sigma}\eta_\perp\dot{\zeta}\right) \ll m_s^2\left(2\dot{\sigma}\eta_\perp\dot{\zeta}\right)$$

- This is verified as soon as: $\frac{k^2 c_s^2}{a^2} \ll m_s^2 \frac{c_s^2}{1-c_s^2}$ and

[D. Baumann, D. Green 2011] ω^2_{new}

REGIME OF VALIDITY OF THE EFT

MAKING ASSUMPTIONS MORE PRECISE

$$\mathcal{F}^{\mathrm{LO}}_{\mathrm{heavy}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}$$

- A more formal solution to $(m_s^2 - \Box)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$ is $\mathcal{F}_{\mathrm{heavy}} = \frac{1}{m_s^2}\sum_{i=0}^{\infty}\left(\frac{\Box}{m_s^2}\right)^i 2\dot{\sigma}\eta_\perp\dot{\zeta}$

For consistency, NLO (i=1) correction must be neglible compared to LO (i=0) in the expansion

$$\Box(2\dot{\sigma}\eta_\perp\dot{\zeta}) \ll m_s^2(2\dot{\sigma}\eta_\perp\dot{\zeta})$$

- This is verified as soon as: $\frac{k^2 c_s^2}{a^2} \ll m_s^2 \frac{c_s^2}{1-c_s^2}$ and

[D. Baumann, D. Green 2011] ω^2_{new}

[S. Céspedes, V. Atal, G. Palma 2012]

Adiabaticy conditions

$$\left(\frac{\dot{\eta}_\perp}{\eta_\perp m_s}\right)^2 \ll 1 \quad ; \quad \left(\frac{\dot{c}_s}{c_s m_s}\right)^2 \ll 1$$

$$\frac{\ddot{\eta}_\perp}{\eta_\perp m_s^2} \ll 1 \quad ; \quad \frac{\ddot{c}_s}{c_s m_s^2} \ll 1$$

REGIME OF VALIDITY OF THE EFT

MAKING ASSUMPTIONS MORE PRECISE

$$\mathcal{F}^{\mathrm{LO}}_{\mathrm{heavy}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}$$

- A more formal solution to $(m_s^2 - \Box)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$ is $\mathcal{F}_{\mathrm{heavy}} = \frac{1}{m_s^2}\sum_{i=0}^{\infty}\left(\frac{\Box}{m_s^2}\right)^i 2\dot{\sigma}\eta_\perp\dot{\zeta}$

For consistency, NLO (i=1) correction must be neglible compared to LO (i=0) in the expansion

$$\Box(2\dot{\sigma}\eta_\perp\dot{\zeta}) \ll m_s^2(2\dot{\sigma}\eta_\perp\dot{\zeta})$$

[S. Céspedes, V. Atal, G. Palma 2012]

- This is verified as soon as: $\frac{k^2 c_s^2}{a^2} \ll m_s^2\frac{c_s^2}{1-c_s^2}$ and

[D. Baumann, D. Green 2011] ω^2_{new}

- The EFT is useful only if it is well valid at sound

horizon crossing: $\boxed{\frac{H^2}{m_s^2}\left(\frac{1}{c_s^2}-1\right) \ll 1}$

<u>Adiabaticy conditions</u>

$$\left(\frac{\dot{\eta}_\perp}{\eta_\perp m_s}\right)^2 \ll 1 \quad ; \quad \left(\frac{\dot{c}_s}{c_s m_s}\right)^2 \ll 1$$

$$\frac{\ddot{\eta}_\perp}{\eta_\perp m_s^2} \ll 1 \quad ; \quad \frac{\ddot{c}_s}{c_s m_s^2} \ll 1$$