GReCO seminar, IAP
October 2022, 10th, Paris

Based on:

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

[Garcia-Saenz, LP, Renaux-Petel 2020]
J. High Energ. Phys. 2020, 73 (2020)

[LP 2020]
J. Cosm. & Astro. Phys. 04(2021)048

[LP, Aoki, Renaux-Petel, Yamaguchi 2021]
ArXiv:2112.05710

[Dimastrogiovanni, Fasiello, LP 2022]
JCAP 09 (2022) 031

[Garcia-Saenz, LP, Renaux-Petel, Werth 2022]
ArXiv: 2207.14267

Lucas Pinol
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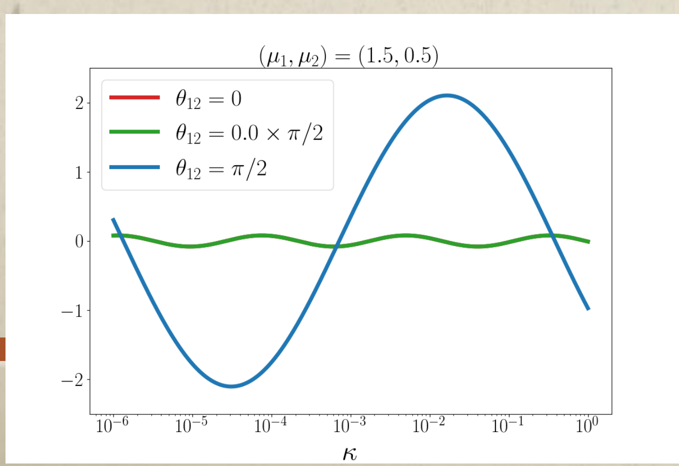
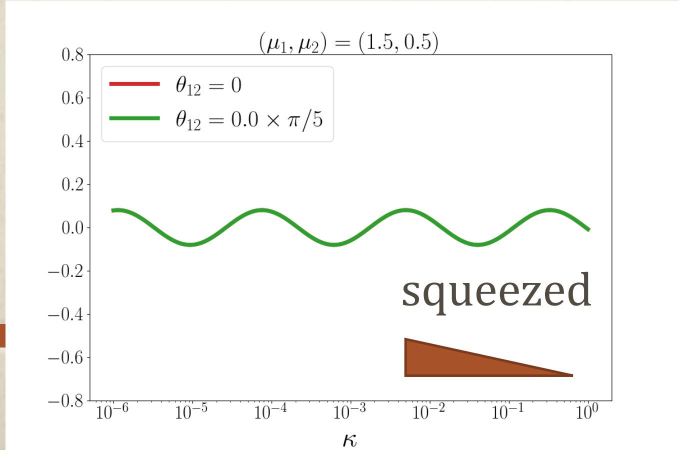
Madrid

THE NON-LINEAR UNIVERSE
AS A PARTICLE DETECTOR





Cosmic spectroscopy:

In the squeezed limit of the primordial scalar bispectrum, modulated oscillations depend on the masses and mixing angles of the inflationary theory

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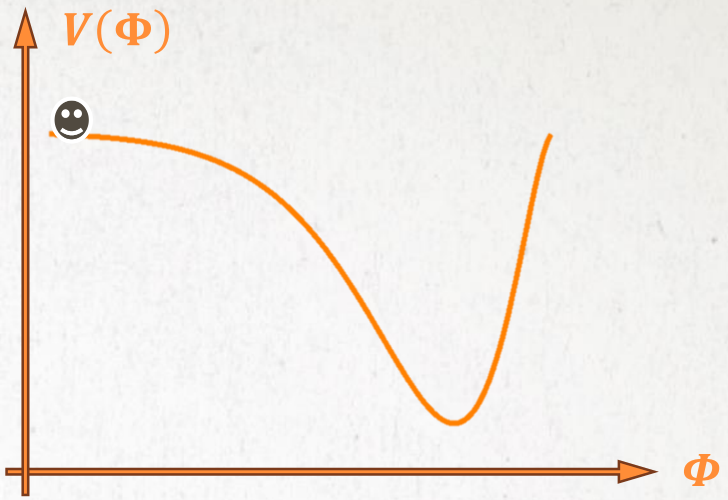
Cosmic spectroscopy:

In the squeezed limit of the primordial scalar bispectrum, modulated oscillations depend on the masses and mixing angles of the inflationary theory

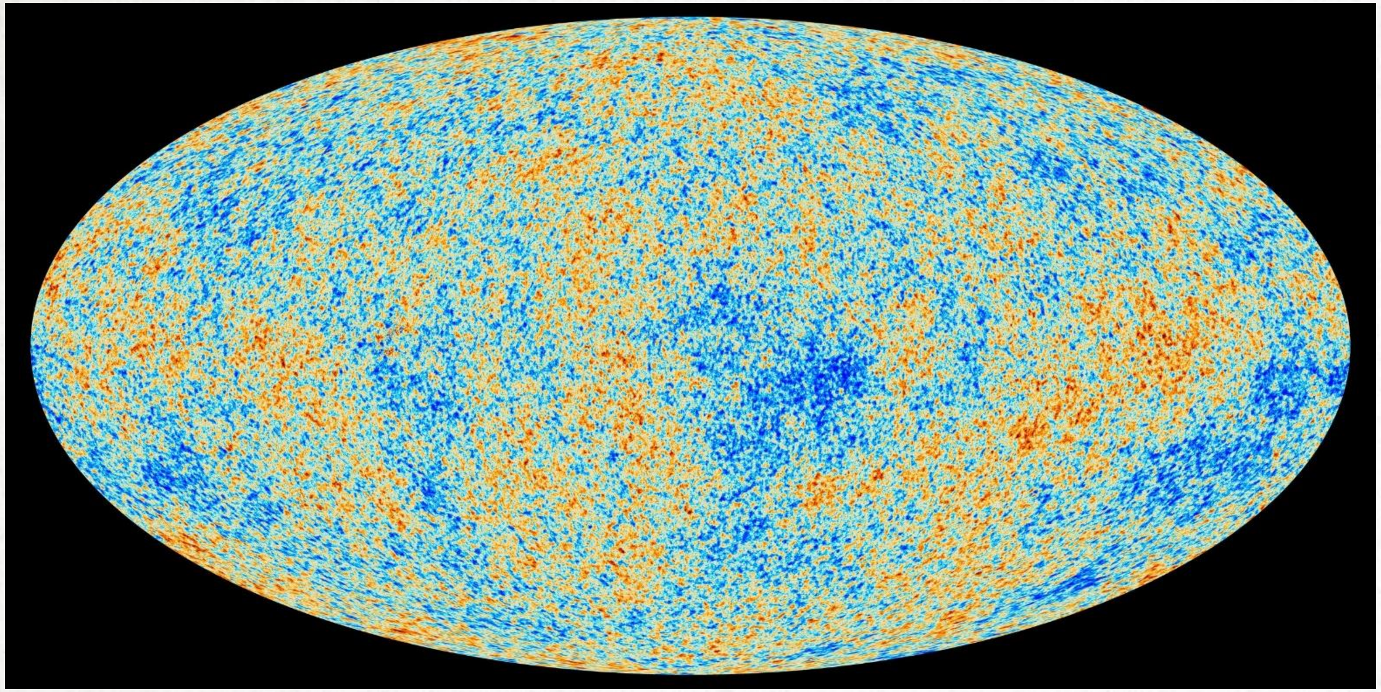
TABLE OF CONTENTS

I. INFLATION

Success story, missing evidence and future prospects



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

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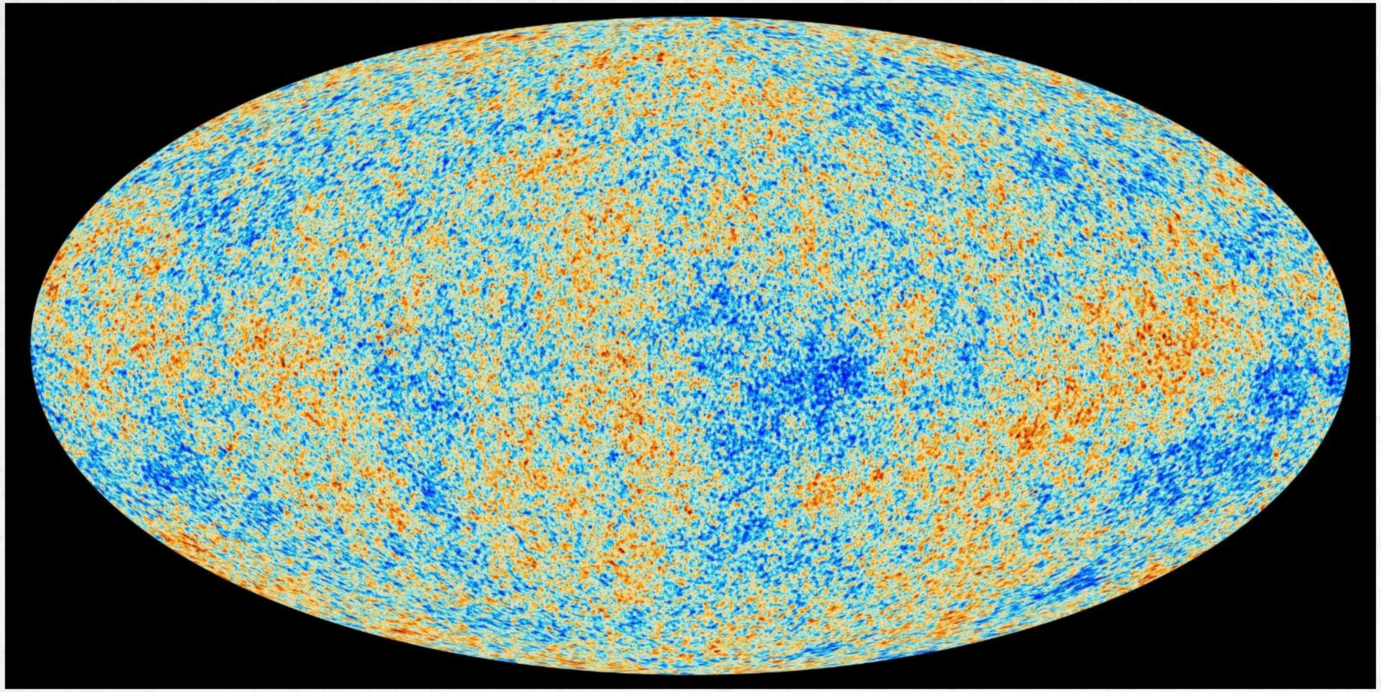

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- How is the universe so homogeneous?
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- Why is the universe so spatially flat?
  Flatness problem

Inflation, an era of accelerated expansion of the Universe, solves both the horizon and flatness problems

$$N_{\rm inf} = \ln\left(\frac{a_{\rm end}}{a_{\rm ini}}\right) \gtrsim 55$$

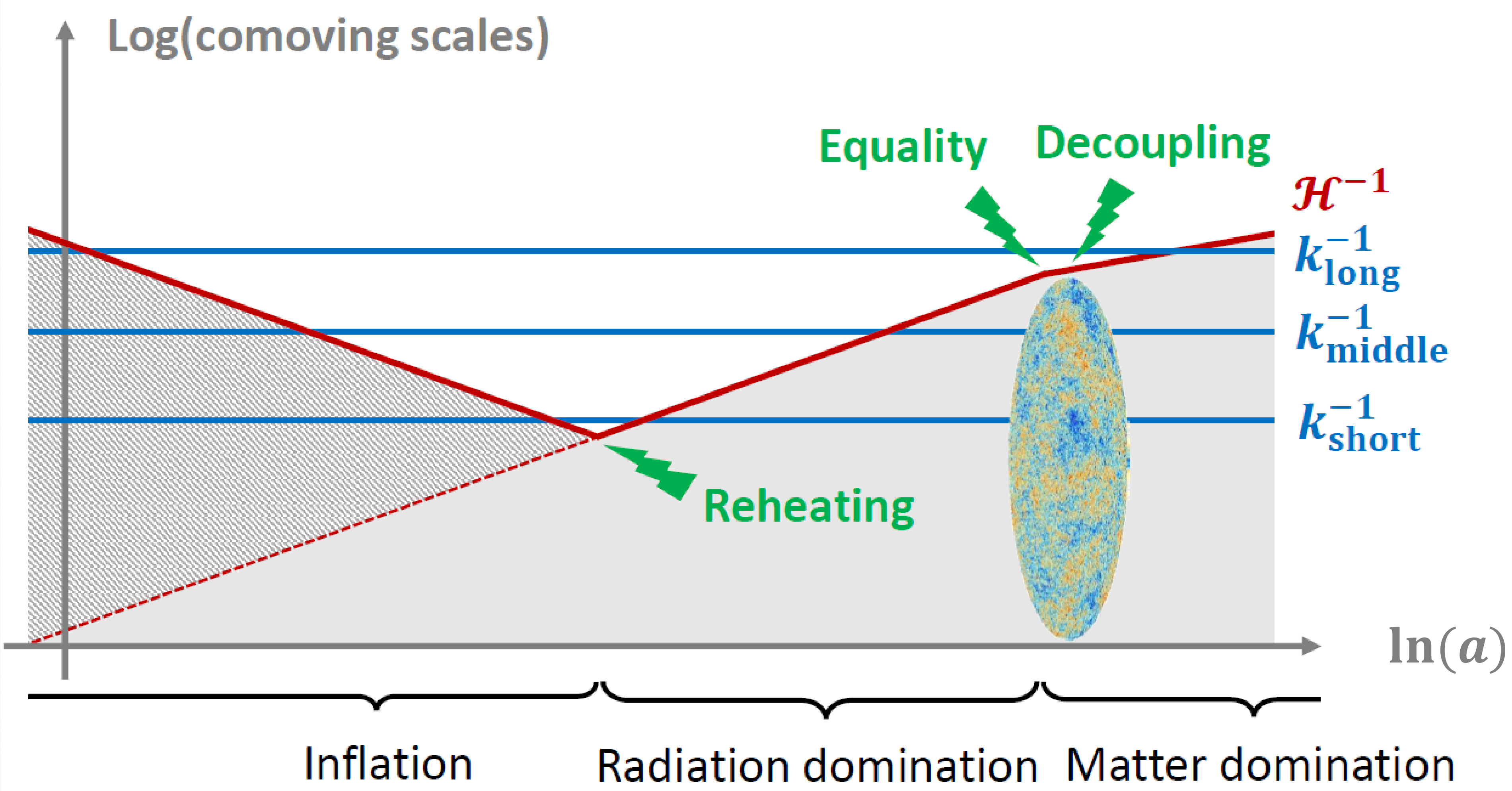
FLUCTUATIONS OF MICRO-PHYSICAL QUANTUM ORIGIN

$$\mathcal{H}^{-1} = (aH)^{-1}$$

Comoving Hubble radius

$$\tau = \int \mathrm{d}\ln a \;\, \mathcal{H}^{-1}$$

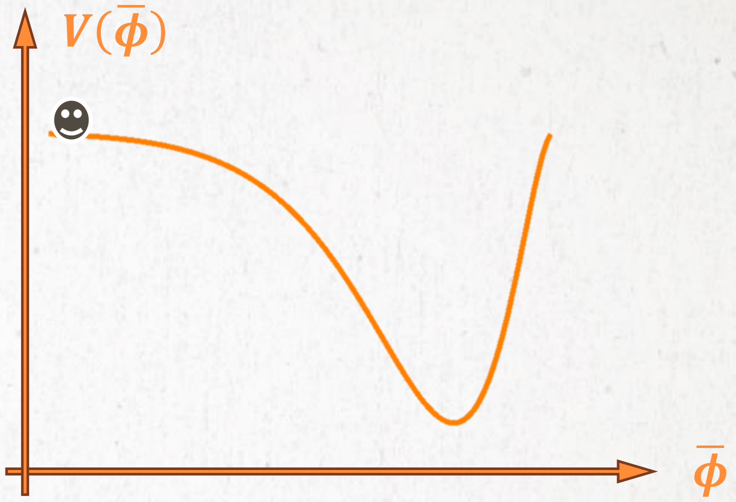
proper time
=
particle horizon



MECHANICS OF INFLATION: CURRENT PARADIGM

A single **scalar field** in slow roll does the job for both:

- The classical **background**…
- The quantum **fluctuations**…



$$\boldsymbol{\phi(\vec{x}, t) = \bar{\phi}(t) + Q(\vec{x}, t)}$$

MECHANICS OF INFLATION: CURRENT PARADIGM

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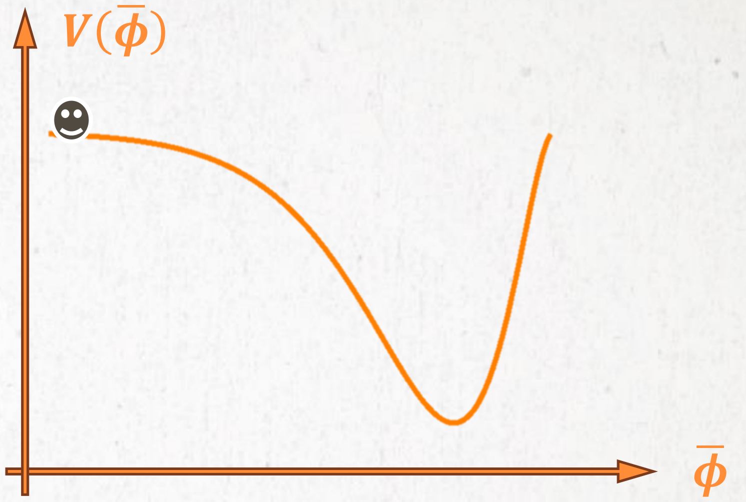
… provided the scalar potential is flat and inflation lasts long enough

- The quantum fluctuations…



$$\phi(\vec{x},t) = \bar{\boldsymbol{\phi}}(\boldsymbol{t}) + Q(\vec{x},t) \qquad \text{with } Q(\vec{x},t) \ll \bar{\phi}(t)$$

Homogeneous background, slow roll: $\dot{\boldsymbol{\phi}} \simeq -\frac{V_{,\phi}(\bar{\phi})}{3H}$; $H^2 \simeq \frac{V(\bar{\phi})}{3M_{\mathrm{Pl}}^2}$ **CLASSICAL**

MECHANICS OF INFLATION: CURRENT PARADIGM

A single scalar field in slow roll does the job for both:

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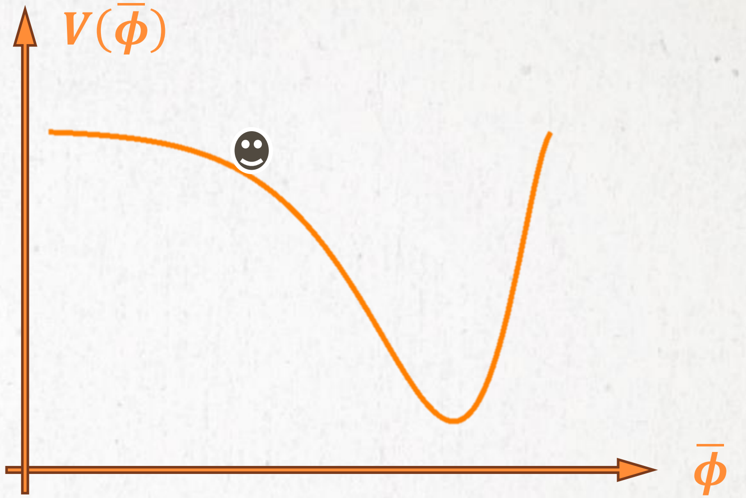
- The quantum **fluctuations**…

… if they emerge from the Bunch-Davies (BD) vacuum



Bunch-Davies: $Q_k(\tau) \simeq \frac{e^{-ik\tau}}{a\sqrt{2k}}\left(1 - \frac{i}{k\tau}\right) \rightarrow \zeta_k(\tau) \simeq \frac{H}{\dot{\phi}} Q_k(\tau)$

$$\phi(\vec{x}, t) = \bar{\phi}(t) + Q(\vec{x}, t)$$

QUANTUM

Homogeneous background, slow roll: $\dot{\phi} \simeq -\frac{V_{,\phi}(\bar{\phi})}{3H}$; $H^2 \simeq \frac{V(\bar{\phi})}{3M_{\rm Pl}^2}$ **CLASSICAL**

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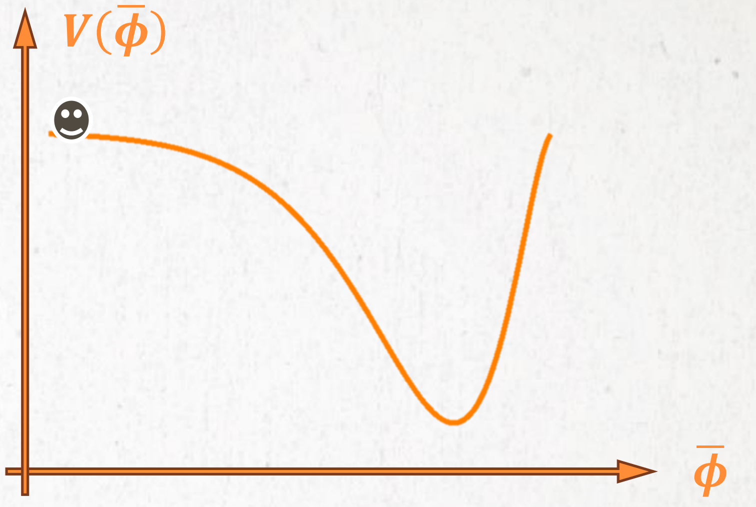


$$\phi(\vec{x},t) = \bar{\phi}(t) + Q(\vec{x},t)$$

$$\zeta_k(\tau) \simeq \frac{H}{\dot{\phi}} Q_k(\tau)$$

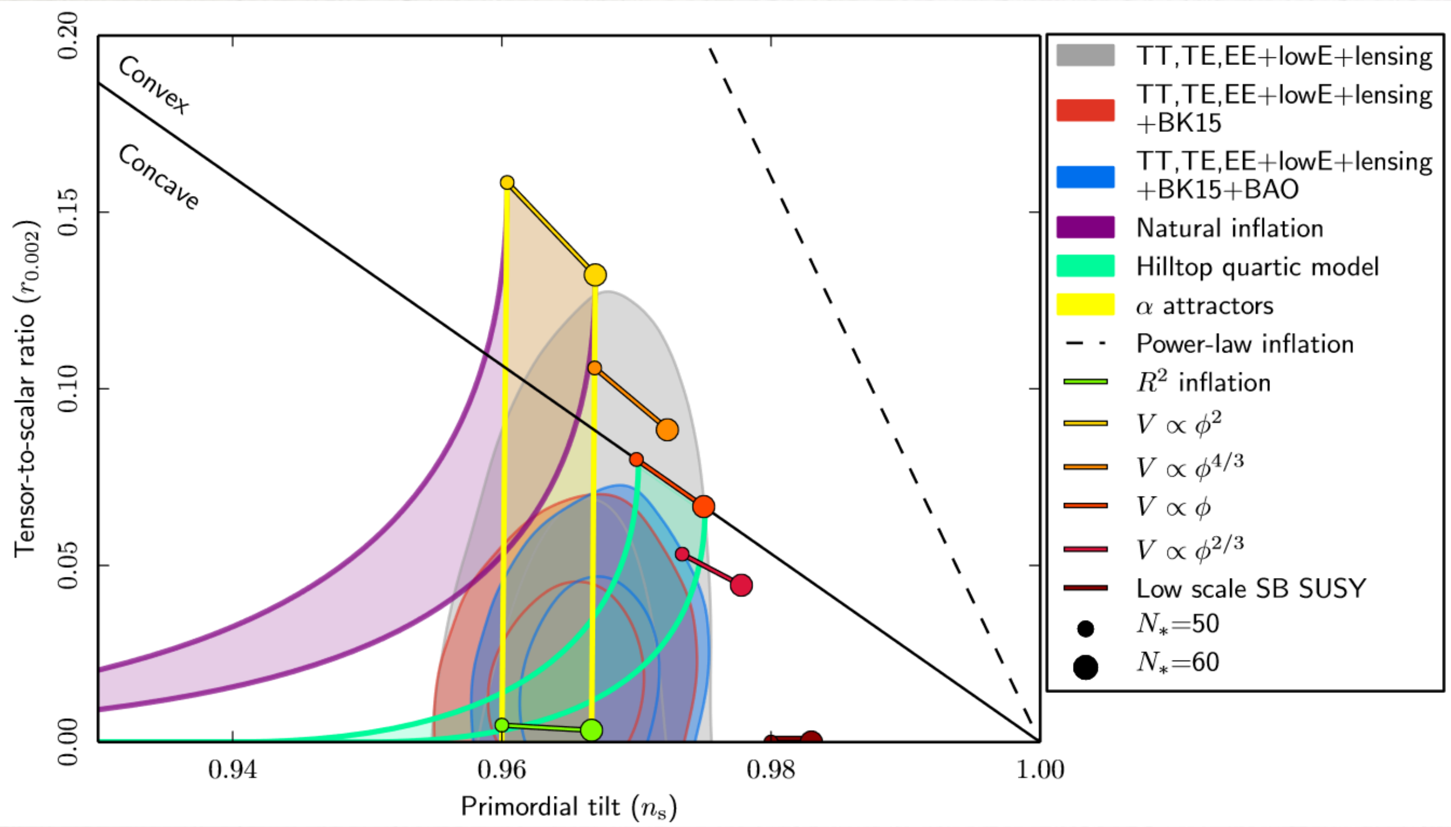
Homogeneous background, slow roll: $\dot{\phi} \simeq -\frac{V_{,\phi}(\bar{\phi})}{3H}$

Almost scale-invariant power spectrum: $n_s \simeq 1$

$$\mathcal{P}_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1}$$

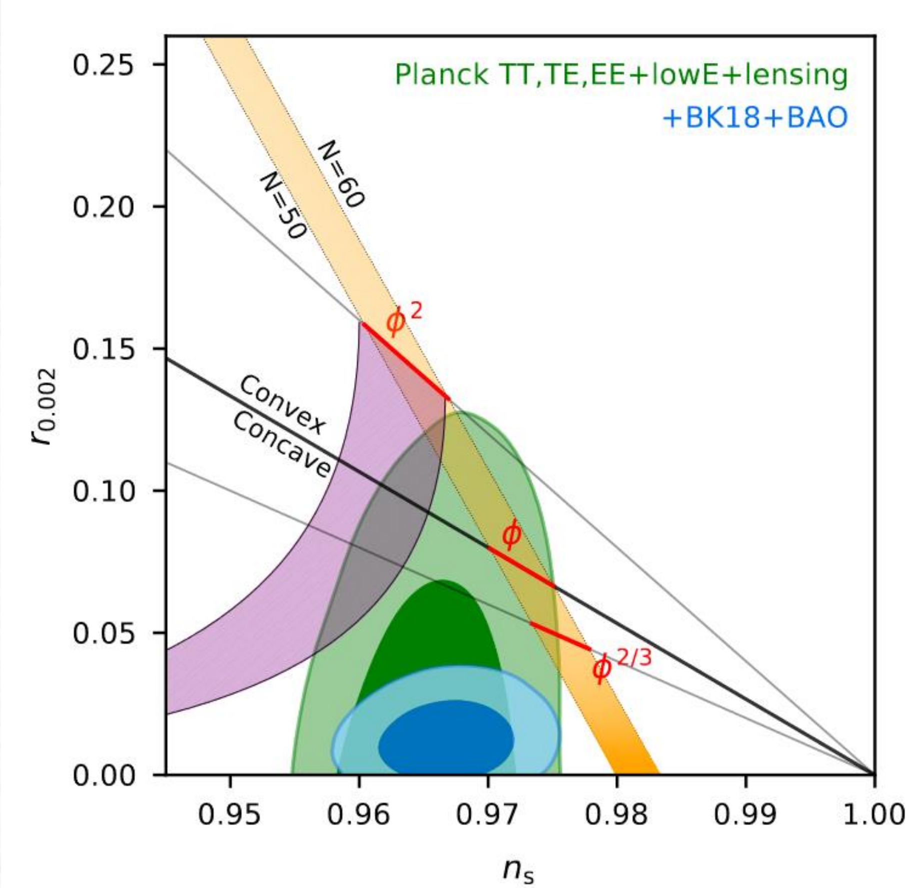
Also, $\mathcal{P}_\gamma(k) = rA_s \left(\frac{k}{k_*}\right)^{n_t}$, **with** $r \ll 1$

SINGLE-FIELD INFLATION: CONSTRAINTS



[Planck 2018]

$n_s = 0.9649 \pm 0.0042$



[BICEP-Keck 2022]

$r < 0.032$

MISSING EVIDENCE AND FUTURE PROSPECTS

- Primordial tensor modes of quantum-mechanical origin are expected *at some level*

Key prediction of inflation as a theory of gravity with quantized linear fluctuations + vacuum initial conditions

Many upcoming experiments to be much more sensitive on B modes in the CMB:
Simons Observatory, LiteBIRD, CMB-S4 $\rightarrow \quad r < \mathcal{O}(10^{-3})$

- Primordial non-Gaussianities have the same status and have not been observed yet neither

Gravitational interactions always present + non-trivial multifield interactions give PNG *at some level*

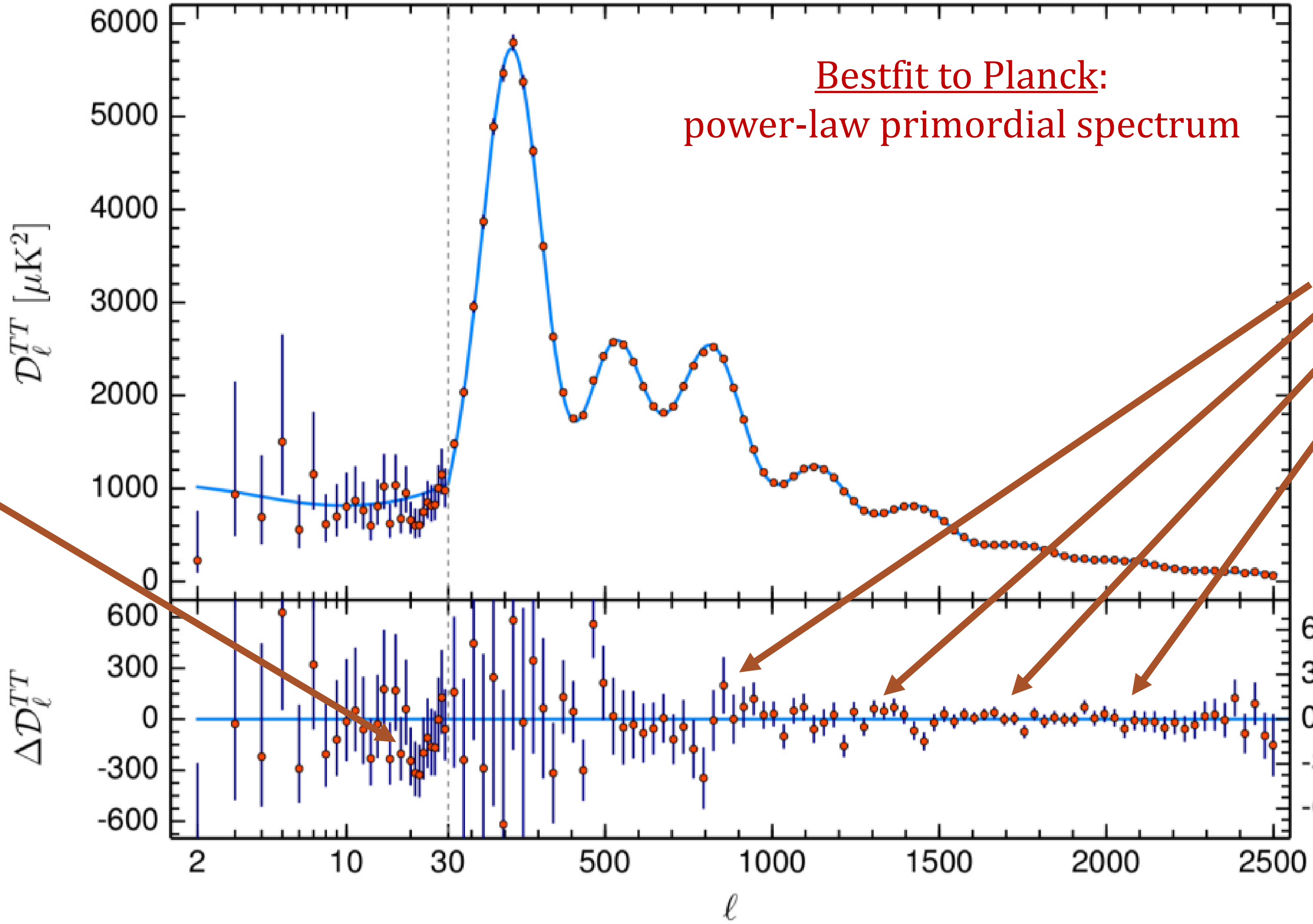
More challenging: CMB limited by cosmic variance. There is hope with LSS experiments:
DESI, Euclid, SPHEREx $\rightarrow \quad f_{\mathrm{NL}} < \mathcal{O}(1)$; *Brigthness temperature 21-cm maps* $\rightarrow f_{\mathrm{NL}} < \mathcal{O}(0.1)$

- Theoretical status: few theoretical motivation for single scalar field with a flat potential

Inflation with a shift-symmetry, with non-minimal coupling, multifield inflation, curved field space, etc.

ANOMALIES / RESIDUALS / BEYOND POWER LAW

CMB temperature and polarisation maps (TT, TE, EE) contain residuals not fitted by the standard picture



Low-ℓ anomaly:
lack of power on large scales

Not in TE nor EE maps but more significant

High-ℓ anomaly:
Residual oscillations

Also in TE and EE maps but less significant

ANOMALIES / RESIDUALS / BEYOND POWER LAW

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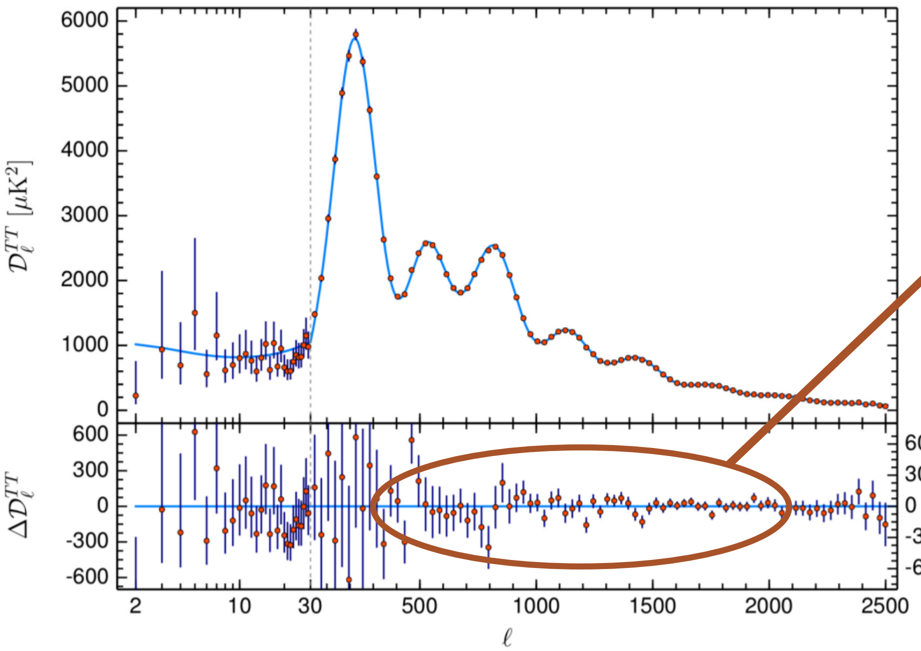

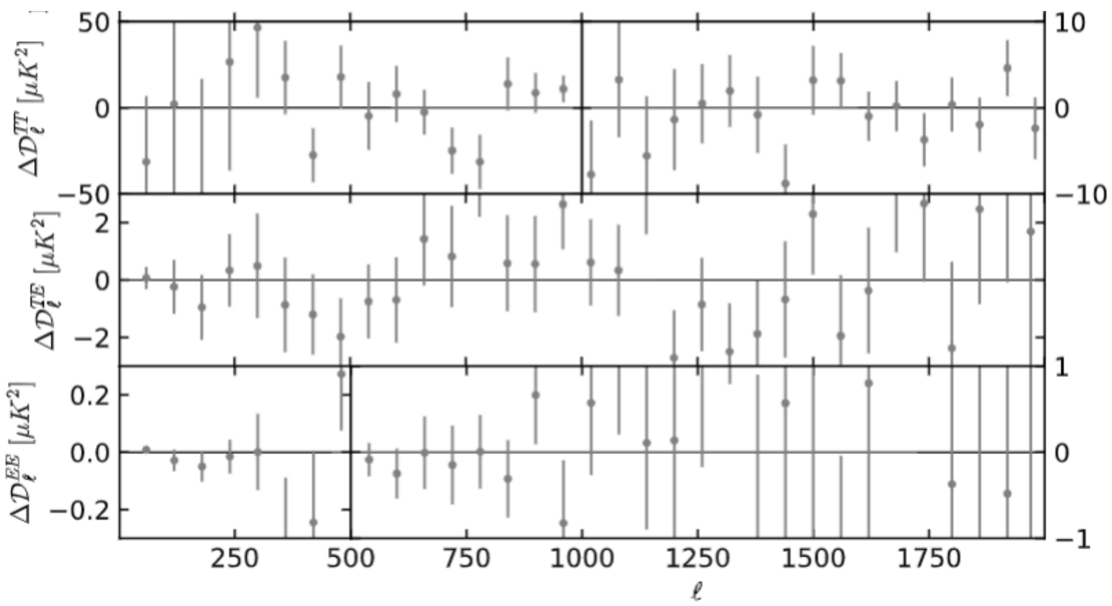

[Credits Matteo Braglia]

ANOMALIES / RESIDUALS / BEYOND POWER LAW

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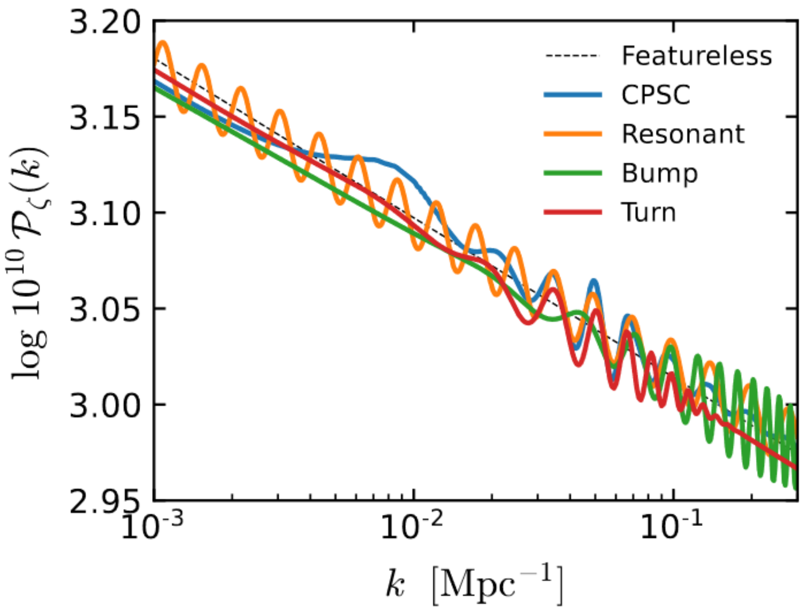
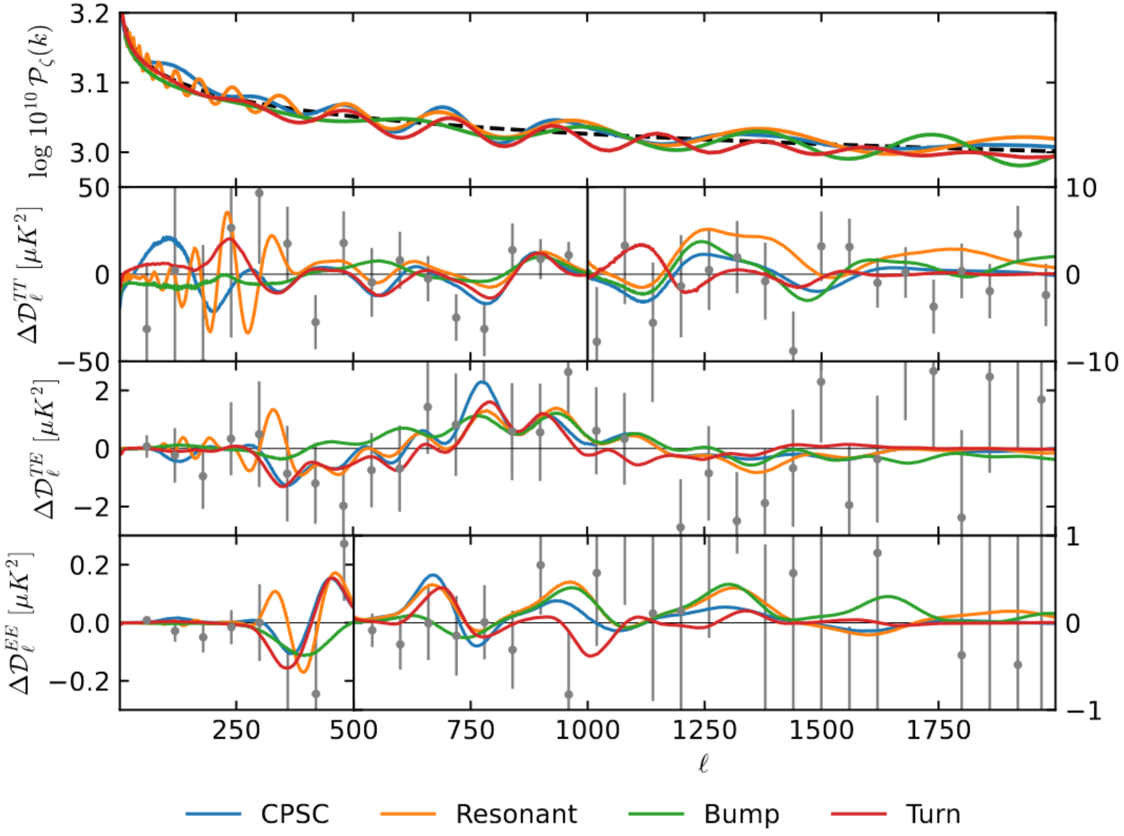
[PRELIMINARY RESULTS]





[Braglia, Chen, Hazra, Pinol *in prep.*]

	CPSC	Resonant	Bump	Turn
$\ln B$	-1.2 ± 0.36	-2.24 ± 0.38	-1.44 ± 0.36	-2.31 ± 0.36
$\Delta\chi^2$	13.4	10.9	8.9	8.6

→ Statistically slightly disfavored

→ Better fit

ANOMALIES / RESIDUALS / BEYOND POWER LAW

Future "B-modes" experiments (thanks to much better E-modes) like LiteBIRD, SO, CMB-S4 will tell!

- If the universe is featureless: current bestfits (turn, bump, CPSC, resonant, …) will all be ruled out

[PRELIMINARY RESULTS]

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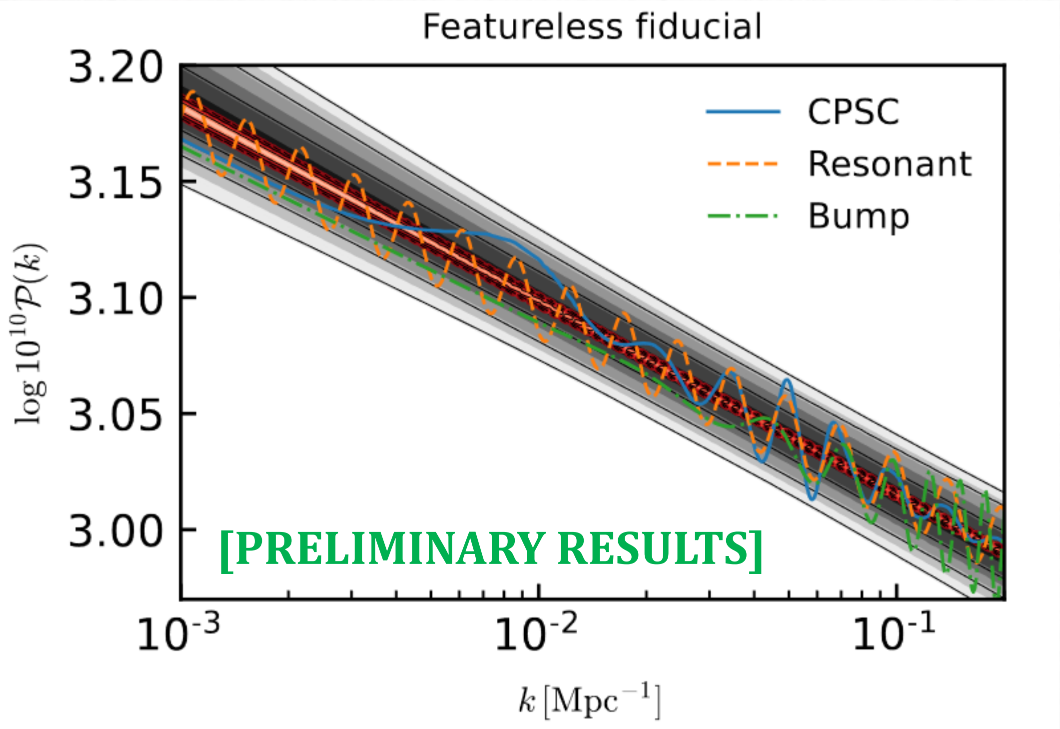

Grey: Planck error bars (data)

Red: PL+LB+S4 error bars (forecast)

[Braglia, Chen, Hazra, Pinol *in prep.*]

ANOMALIES / RESIDUALS / BEYOND POWER LAW

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- If one of the current feature bestfit indeed represents our universe:

  - The featureless universe will always be ruled out

    [PRELIMINARY RESULTS]

  - We will tell apart different feature models (often)

[Braglia, Chen, Hazra, Pinol *in prep.*]

ANOMALIES / RESIDUALS / BEYOND POWER LAW

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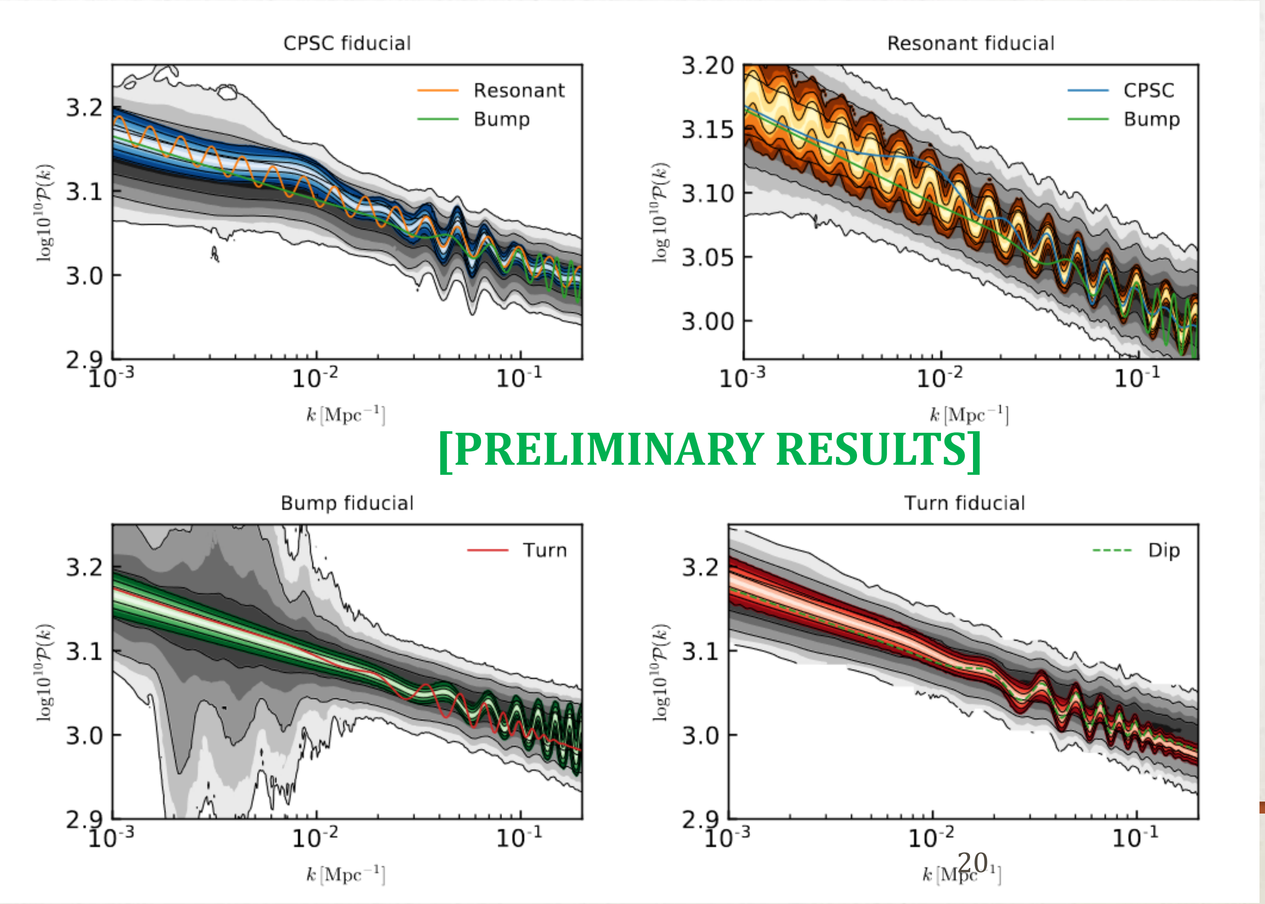
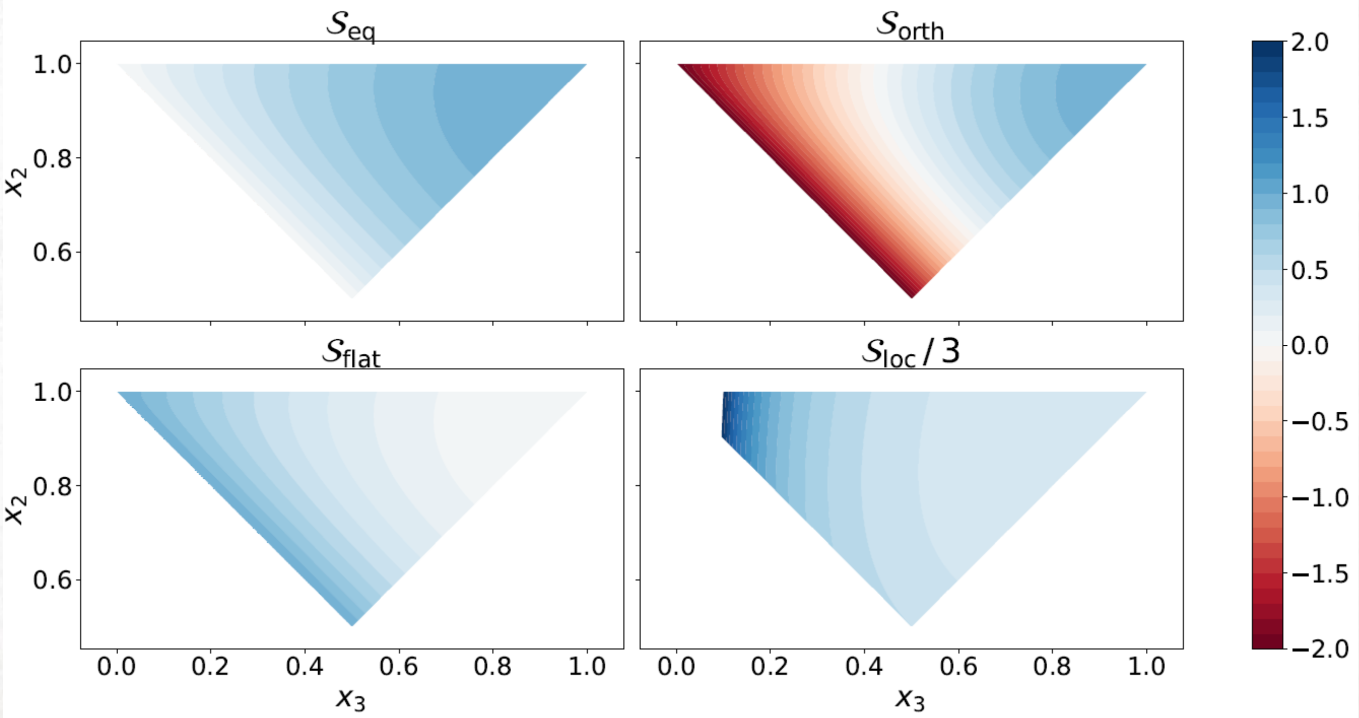


[Braglia, Chen, Hazra, Pinol *in prep.*]

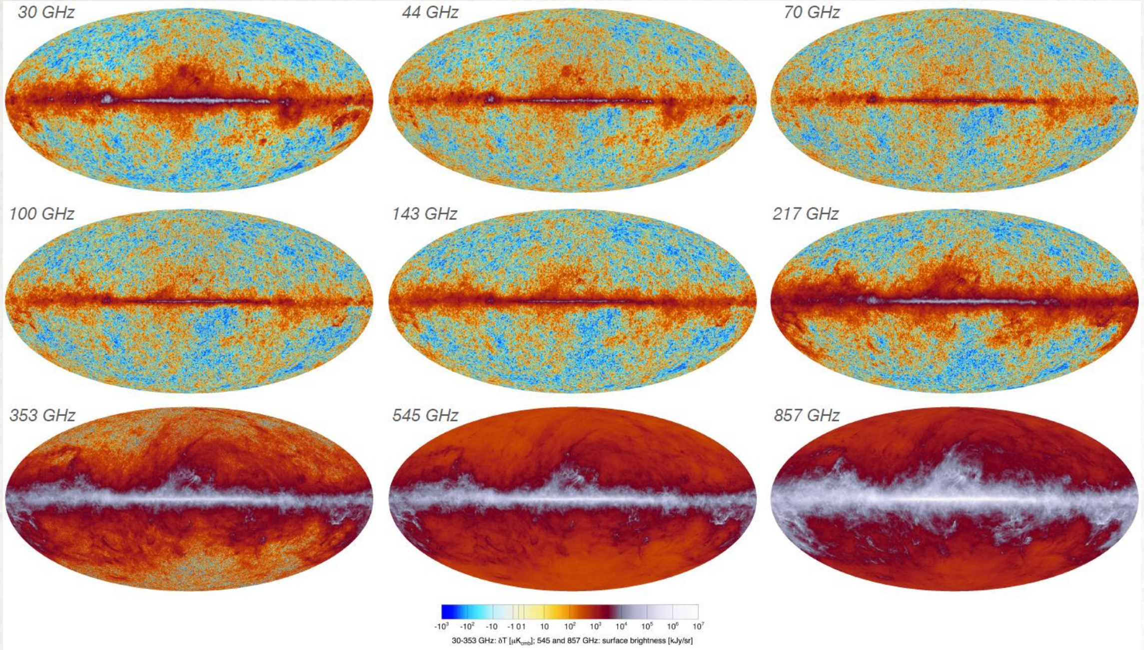
II. PRIMORDIAL NON-GAUSSIANITIES AS A PROBE OF THE SCALAR CONTENT

Single-field inflation
Multifield inflation
The cosmic spectroscopy



Single-field inflation (and definitions)

Non-linearities in the sky



Planck CMB intensity maps

Sources of non-Gaussianity:

- Foreground
- Late-time evolution: lensing, etc.
- Early-time evolution: gravity, interactions, etc.
- **Initial conditions:**

Primordial non-Gaussianities from inflation

$$\boldsymbol{T_{\mathrm{ini}}(\theta,\varphi) = T^{G}_{\mathrm{ini}}(\theta,\varphi) + f^{\mathrm{local}}_{\mathrm{NL}} \times \left[T^{G}_{\mathrm{ini}}(\theta,\varphi)\right]^2}$$

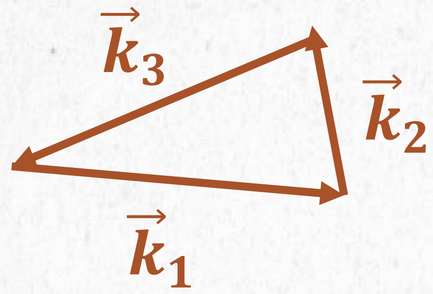
Gaussian *Non-Gaussian if* $f^{\mathrm{local}}_{\mathrm{NL}} \neq 0$

PRIMORDIAL BISPECTRUM

Power spectrum $= 2.10 \times 10^{-9}$

ζ the primordial curvature perturbation

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^7 \, \delta^{(3)}\left(\overrightarrow{k_1} + \overrightarrow{k_2} + \overrightarrow{k_3}\right) \frac{A_s^2}{(k_1 k_2 k_3)^2} \times S(k_1, k_2, k_3)$$



Shape function

PRIMORDIAL BISPECTRUM

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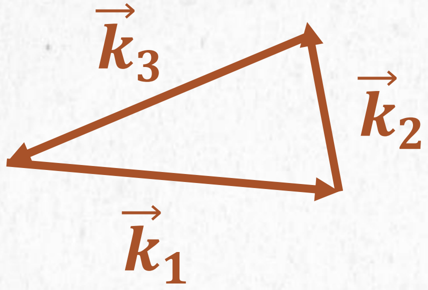


Shape function

$<$ **0.0035** (from $r < 0.056$)

[Maldacena 2003]

Ex: Single-field inflation (attractor)

$$S = \frac{5}{12}(1 - n_s) S_{\text{loc}} + \frac{\epsilon}{8} S_{\text{eq}} + \cdots = \textbf{VERY SMALL}$$

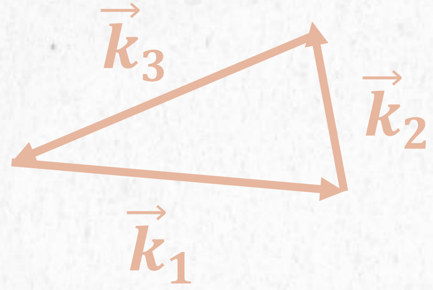
0.0015

PRIMORDIAL BISPECTRUM

ζ The curvature perturbation

Power spectrum $= 2.10 \times 10^{-9}$

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^7 \, \delta^{(3)}\left(\overrightarrow{k_1} + \overrightarrow{k_2} + \overrightarrow{k_3}\right) \frac{A_s^2}{(k_1 k_2 k_3)^2} \times S(k_1, k_2, k_3)$$



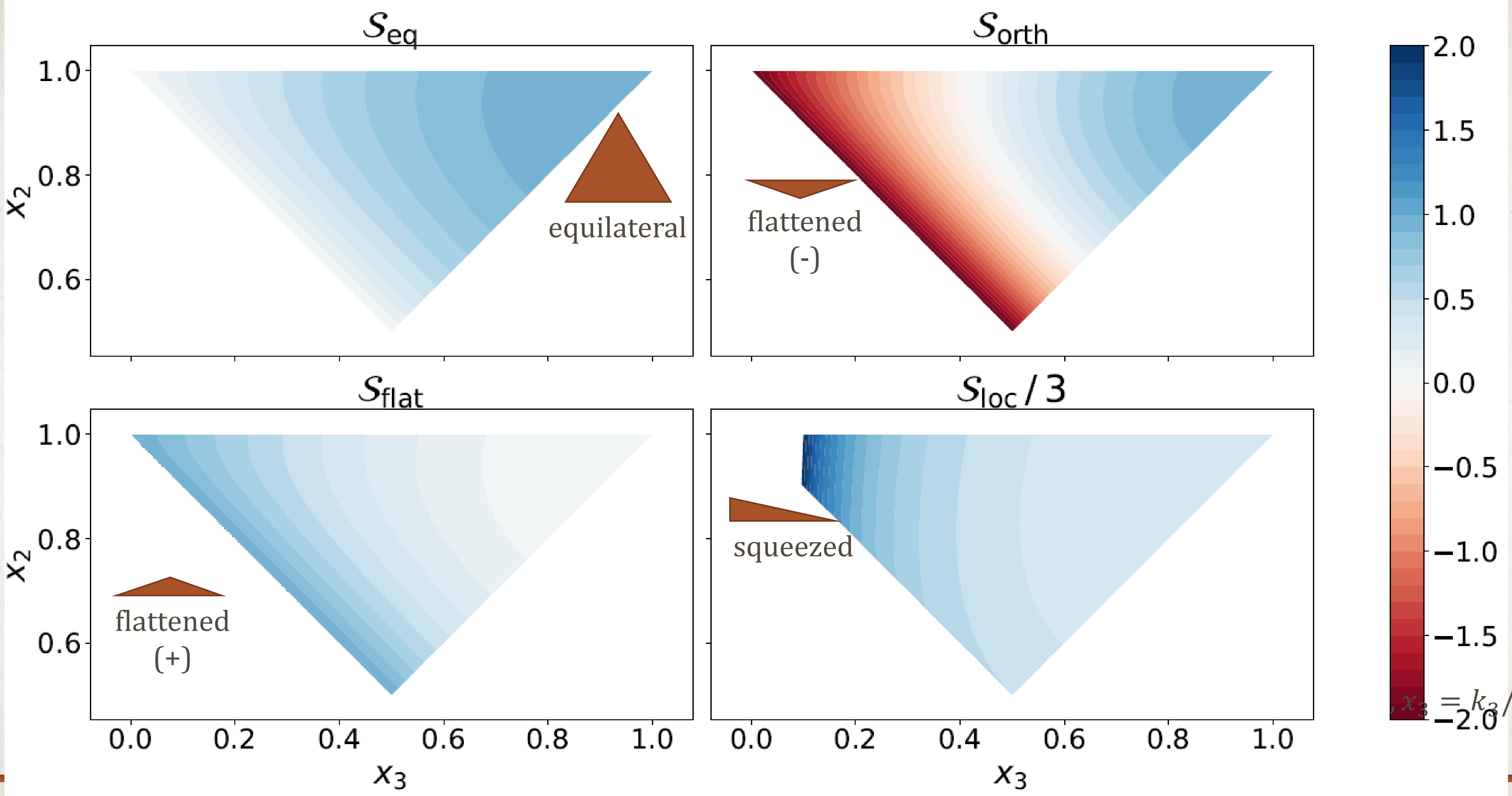
Shape function

Shape templates

Ex: Single-field inflation (attractor)

$$S = \frac{5}{12}(1 - n_s)\boldsymbol{S}_{\mathbf{loc}} + \frac{\epsilon}{8}\boldsymbol{S}_{\mathbf{eq}} + \cdots = \textbf{VERY SMALL}$$

$f_{\mathrm{NL}}^{\mathrm{loc}}$ $\quad$ $f_{\mathrm{NL}}^{\mathrm{eq}}$



k_1 fixed, $x_2 = k_2/k_1, x_3 = k_3/k_1$

OBSERVATIONAL CONSTRAINTS

$$\left.\begin{aligned} f_{\mathrm{NL}}^{\mathrm{local}} &= -0.9 \pm 5.1 \\ f_{\mathrm{NL}}^{\mathrm{eq}} &= -26 \pm 47 \\ f_{\mathrm{NL}}^{\mathrm{ortho}} &= -38 \pm 24 \end{aligned}\right\}$$ [Planck 2018]

Shape templates

Ex: Single-field inflation
(attractor)

$$S = \underbrace{\frac{5}{12}(1-n_s)}_{f_{\mathrm{NL}}^{\mathrm{loc}}} S_{\mathrm{loc}} + \underbrace{\frac{\epsilon}{8}}_{f_{\mathrm{NL}}^{\mathrm{eq}}} S_{\mathrm{eq}} + \cdots = \text{VERY SMALL}$$

SINGLE-FIELD EFFECTIVE THEORY OF INFLATIONARY FLUCTUATIONS

EFT of broken time-diffeomorphisms "beyond models":

$$S = \int \mathrm{d}^4 x \sqrt{-g} F\left(g^{\mu\nu}, g^{00}, R_{\mu\nu\sigma\rho}, K_{ij}, \nabla_\mu; t\right)$$

[Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore 2007]

Tadpole cancellation
Goldstone boson in the unitary gauge
Decoupling limit, neglecting higher-order derivatives

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

- c_s is the speed of sound
- A parameterizes the relative size of cubic derivative interactions

Non-linearly realized symmetry:
Same operator produces both quadratic and cubic interactions

Like a Wilson coefficient: naturally of order unity

SINGLE-FIELD EFFECTIVE THEORY OF INFLATIONARY FLUCTUATIONS

EFT of broken time-diffeomorphisms "beyond models":

$$\mathcal{P}_\zeta = \frac{H_\star^2}{8\pi^2 \epsilon_\star c_{s_\star} M_{\rm Pl}^2}$$

$$n_s - 1 = -2\epsilon_\star - \eta_\star - s_\star \quad \text{with } s = \dot{c}_s/(H c_s)$$

$$r = 16\epsilon_\star c_{s_\star}$$

$$S = \left(\frac{1}{c_s^2} - 1\right)\left[S_{\zeta'(\partial_i\zeta)^2} + \frac{A}{c_s^2} S_{\zeta'^3}\right]$$

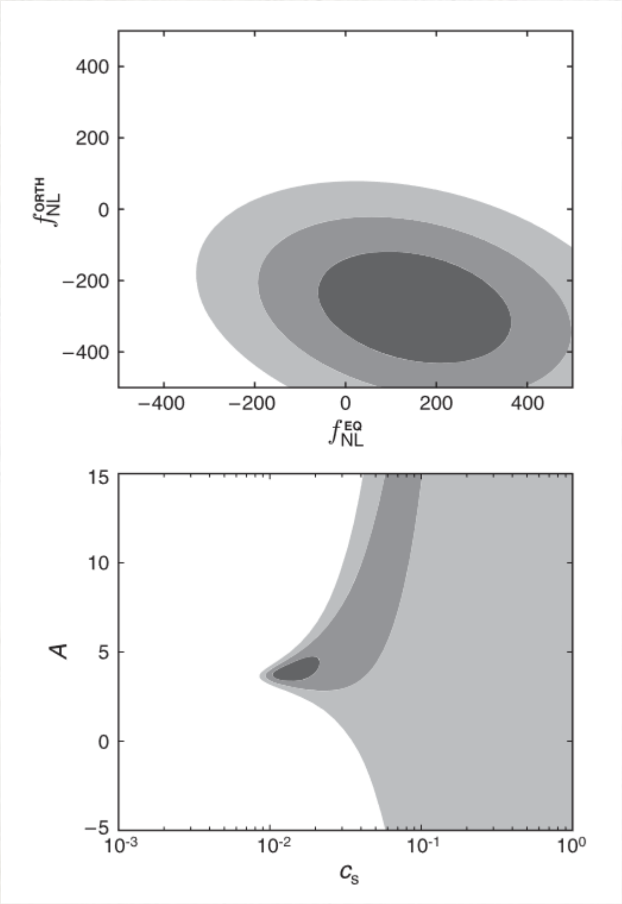
both shapes are ~equilateral but cancel each other for $A \simeq 4 \rightarrow$ *ortogonal shape*

$$f_{\rm NL}^{\rm eq} \simeq \frac{1}{18}\left(\frac{1}{c_s^2} - 1\right)\left(A - \frac{17}{4}\right)$$

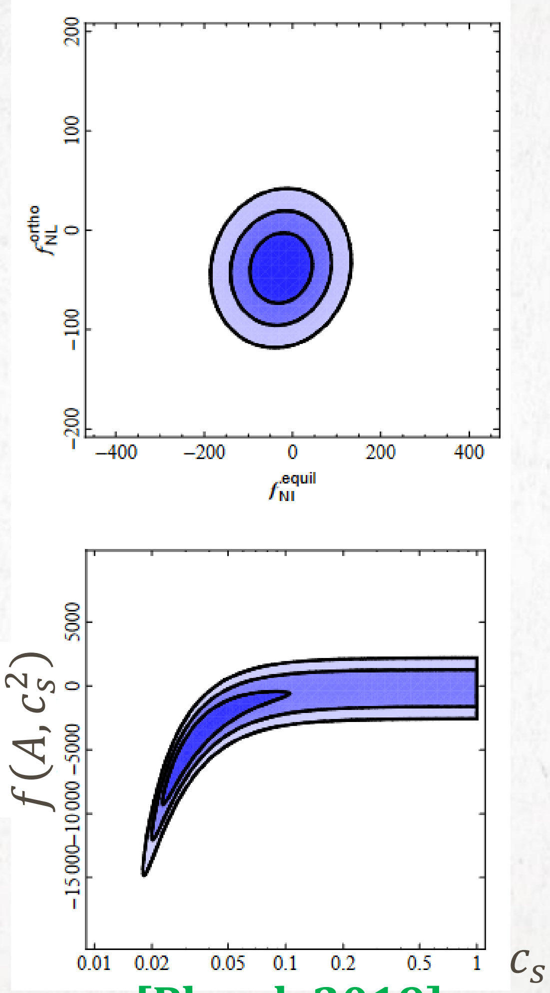
$$f_{\rm NL}^{\rm orth} \simeq -\frac{3}{64}\left(\frac{1}{c_s^2} - 1\right)(1 - A)$$

Large equilateral / ortogonal PNGs for small speed of sound!

SINGLE-FIELD EFFECTIVE THEORY OF INFLATIONARY FLUCTUATIONS



[WMAP 2012]



[Planck 2019]

Large equilateral / ortogonal PNGs for small speed of sound!

SINGLE-FIELD EFFECTIVE THEORY OF INFLATIONARY FLUCTUATIONS

UV-completions of the low-energy EFT:

- Single-field inflation with higher-order derivatives: P(X) inflation in slow-roll
  e.g. DBI inflation gives $c_s = 1/\gamma$ *"Lorentz factor" and* $A = -1$

- Multifield inflation
  e.g. 2-field inflation with one heavy fluctuation gives c_s*, but* A *not know before my work*
  N_{field}*-inflation but nor* c_s *nor* A *known before my work*

$$S_{2,3}^{\mathrm{EFT}}[\zeta] = \int \mathrm{d}\tau \mathrm{d}^3\vec{x}\; a^2 \epsilon M_{\mathrm{Pl}}^2 \left\{ \left(\frac{\zeta'^2}{c_s^2} - (\partial_i \zeta)^2 \right) + \frac{1}{\mathcal{H}} \left(\frac{1}{c_s^2} - 1 \right) \left(\zeta' (\partial_i \zeta)^2 + \frac{A}{c_s^2} \zeta'^3 \right) \right\}$$

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  N_{field}-inflation but nor c_s nor A known before my work

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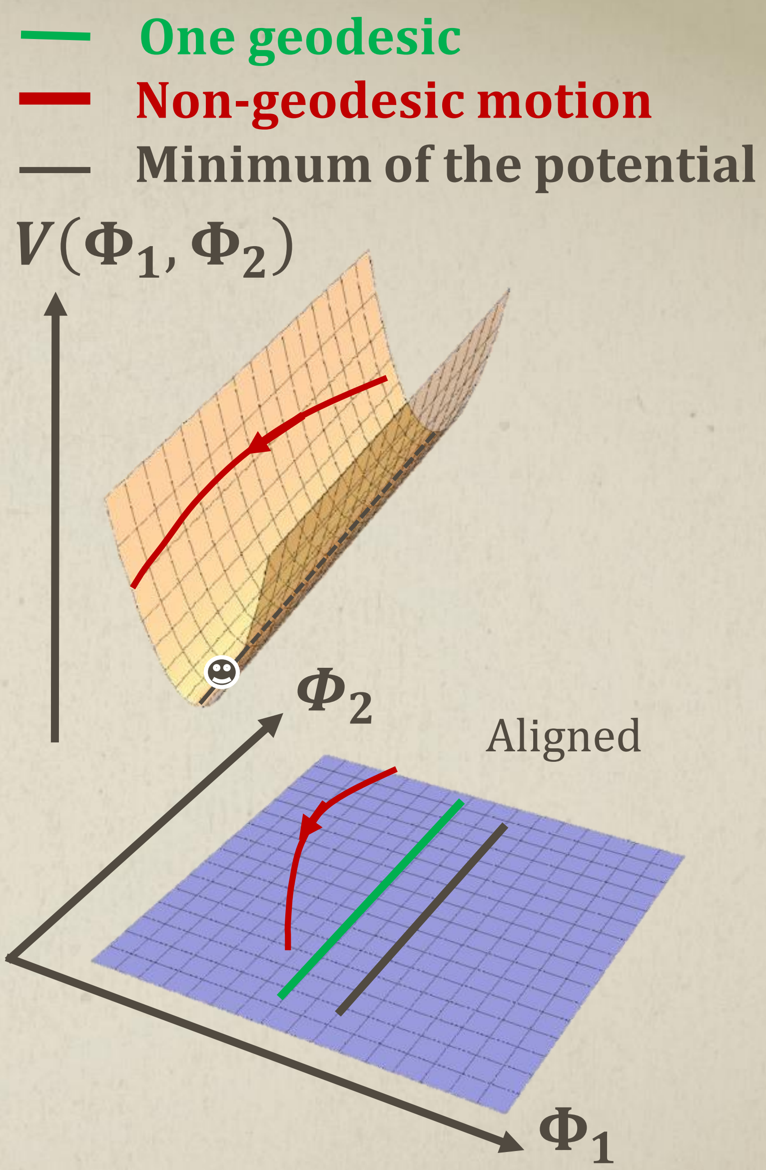
Multifield inflation

MULTIFIELD INFLATION

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

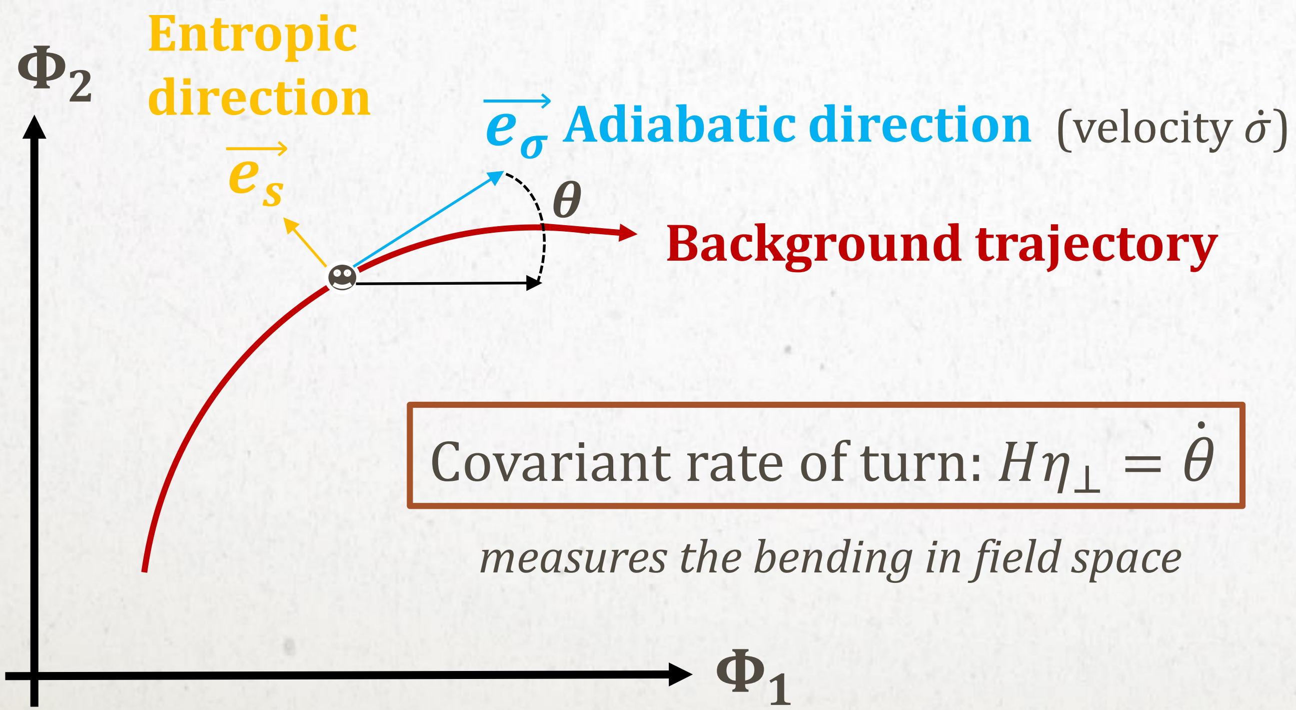


Flat field space

Vanishing curvature: $R_{fs} = 0$

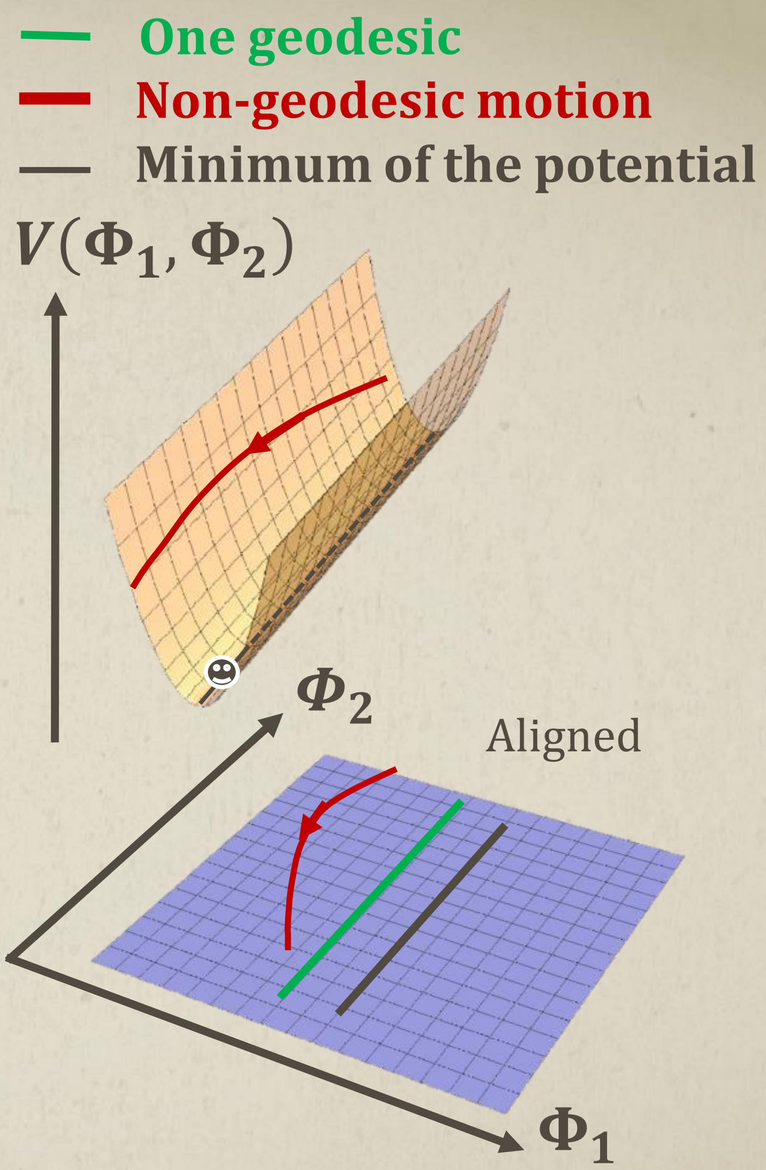
MULTIFIELD INFLATION

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



Covariant rate of turn: $H\eta_\perp = \dot{\theta}$

measures the bending in field space

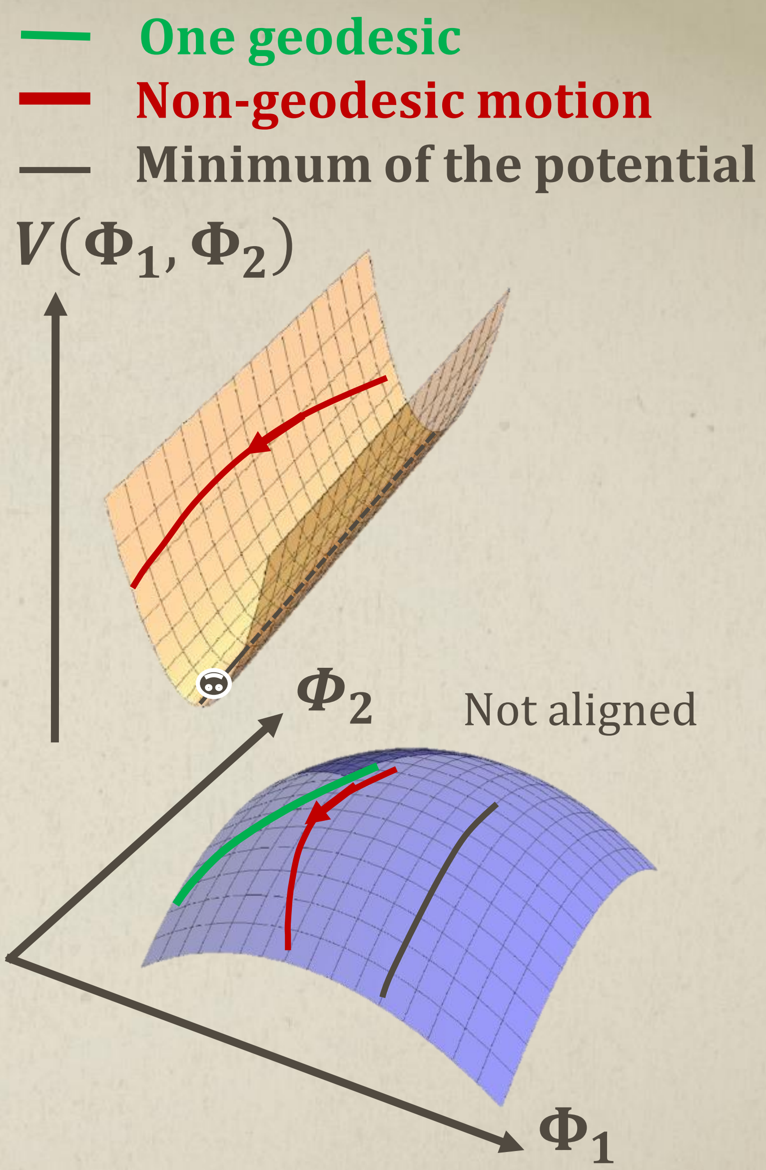


Flat field space

Vanishing curvature: $\mathrm{R_{fs}} = 0$

MULTIFIELD INFLATION WITH CURVED FIELD SPACE

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



Curved field space

Scalar curvature: $R_{fs} \neq 0$

MULTIFIELD INFLATION WITH CURVED FIELD SPACE

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

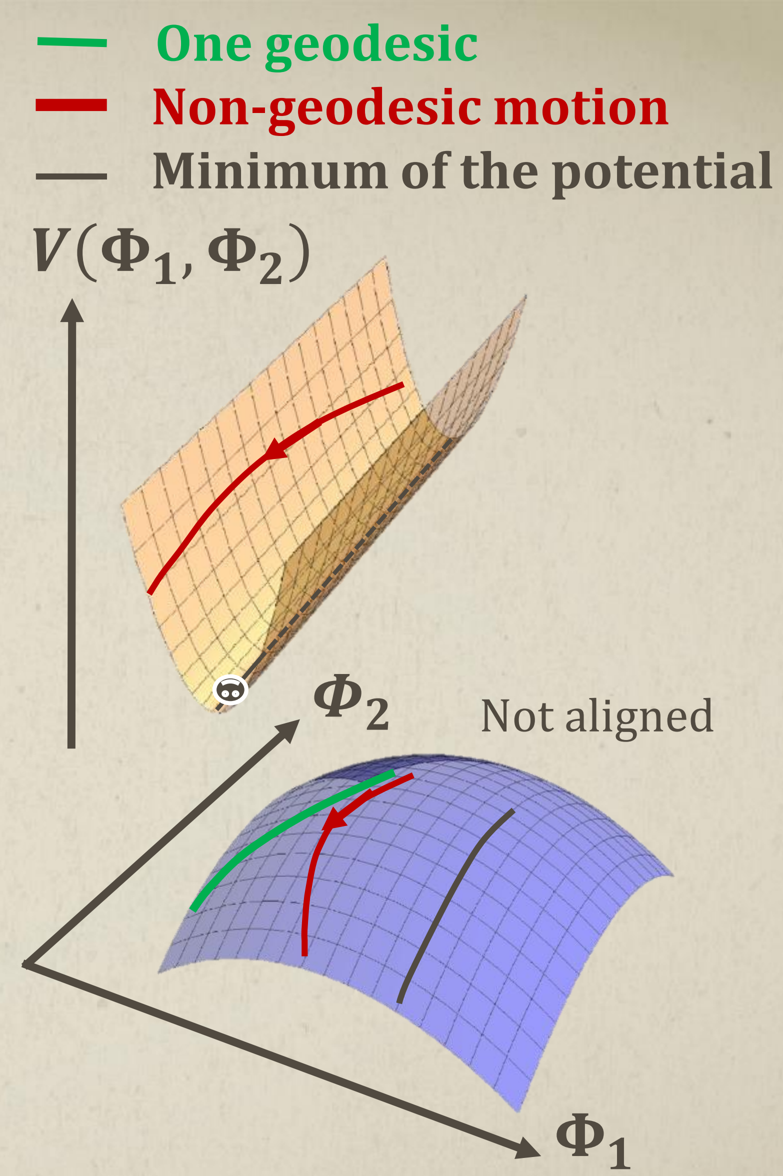
Covariant rate of turn: $H\eta_\perp = D_t e_\sigma^I / e_s^I$

measures deviation from a geodesic in field space

Local curvature in field space

Ricci scalar R_{fs} constructed from G

Geometry	Flat	Spherical	Hyperbolic
R_{fs}	0	> 0	< 0



Curved field space

Scalar curvature: $R_{\text{fs}} \neq 0$

$$\frac{\partial^2 \chi}{a^2} = \epsilon \dot{\zeta} + \frac{\dot{\sigma}}{M_{\rm Pl}^2} \eta_\perp \mathcal{F}$$

GENERALIZING MALDACENA'S CALCULATION

USING INTEGRATION BY PARTS AND LINEAR EQUATIONS OF MOTION

Resulting Lagrangian, after $O(40)$ integrations by parts and $O(10)$ uses of equations of motion:

$$\mathcal{L}(\zeta, \mathcal{F}) = \mathcal{L}^{(2)}(\zeta, \mathcal{F}) + \mathcal{L}^{(3)}_{\mathbf{Maldacena}}(\zeta, \chi) + \mathcal{L}^{(3)}_{\mathrm{new}}(\zeta, \mathcal{F}) + \mathcal{D}$$

There are two gauge-invariant scalar fluctuating degrees of freedom:

- ζ the adiabatic curvature perturbation
- $\mathcal{F}$ the entropic perturbation

$$\frac{\partial^2 \chi}{a^2} = \epsilon\dot{\zeta} + \frac{\dot{\sigma}}{M_{\rm Pl}^2}\eta_\perp \mathcal{F}$$

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$$\mathcal{L}^{(2)}(\zeta,\mathcal{F}) = \frac{a^3}{2}\left(2\epsilon M_{\rm Pl}^2\left(\dot{\zeta}^2 - \frac{(\partial\zeta)^2}{a^2}\right) + \dot{\mathcal{F}}^2 - \frac{(\partial\mathcal{F})^2}{a^2} - \underbrace{m_s^2}\mathcal{F}^2 + 4\dot{\sigma}\eta_\perp\mathcal{F}\dot{\zeta}\right)$$

$$\boxed{m_s^2 = V_{;ss} - H^2\eta_\perp^2 + \epsilon R_{\rm fs} H^2 M_{\rm Pl}^2}$$

Mixing via the bending

Hessian of the potential

Bending of the trajectory

Field-space curvature

$$\frac{\partial^2\chi}{a^2} = \epsilon\dot{\zeta} + \frac{\dot{\sigma}}{M_{\mathrm{Pl}}^2}\eta_\perp\mathcal{F}$$

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$$\mathcal{L}^{(3)}_{\mathrm{Maldacena}}(\zeta,\chi) = a^3 M_{\mathrm{Pl}}^2\left[\epsilon(\epsilon-\eta)\dot{\zeta}^2\zeta + \epsilon(\epsilon+\eta)\zeta\frac{(\partial\zeta)^2}{a^2} + \left(\frac{\epsilon}{2}-2\right)\frac{1}{a^4}(\partial\zeta)(\partial\chi)\partial^2\chi + \frac{\epsilon}{4a^4}\partial^2\zeta(\partial\chi)^2\right]$$

[J. Maldacena 2003]

GENERALIZING MALDACENA'S CALCULATION

USING INTEGRATION BY PARTS AND LINEAR EQUATIONS OF MOTION

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New interactions

Boundary terms:
Total time derivatives
contribute to 3-pt functions
[C. Burrage, R. Ribeiro, D. Seery 2011]
[F. Arroja, T. Tanaka 2011]

NEW INTERACTIONS

$$\lambda_\perp = \frac{\dot{\eta}_\perp}{H\eta_\perp} \quad ; \quad \mu_s = \frac{\dot{m}_s}{H m_s}$$

$$\frac{\partial^2 \chi}{a^2} = \epsilon\dot{\zeta} + \frac{\dot{\sigma}}{M_{\mathrm{Pl}}^2}\eta_\perp \mathcal{F}$$

$$\mathcal{L}^{(3)}_{\mathbf{new}}(\zeta, \mathcal{F}) = \frac{1}{2} m_s^2 \zeta \mathcal{F}\left((\epsilon + \mu_s)\mathcal{F} + (2\epsilon - \eta - 2\lambda_\perp)\frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}\right) + \frac{\dot{\sigma}\eta_\perp}{a^2 H}\mathcal{F}[(\partial\zeta)^2 - \dot{\zeta}^2]$$
$$- \frac{1}{H}(H^2\eta_\perp^2 - \epsilon H^2 M_{\mathrm{Pl}}^2 R_{fs})\dot{\zeta}\mathcal{F}^2 - \frac{1}{6}(V_{;sss} - 2\dot{\sigma}H\eta_\perp R_{fs} + \epsilon H^2 M_{\mathrm{Pl}}^2 R_{fs,s})\mathcal{F}^3$$
$$+ \frac{1}{2}\epsilon\zeta\left(\dot{\mathcal{F}}^2 + \frac{(\partial\mathcal{F})^2}{a^2}\right) - \frac{1}{a^2}\dot{\mathcal{F}}(\partial\mathcal{F})(\partial\chi)$$

Check: ζ is well massless at any order as it should (Weinberg adiabatic mode)

$$\mathcal{D} = \frac{M_{\mathrm{Pl}}^2}{2}\frac{\mathbf{d}}{\mathbf{d}t}[\ldots]$$

[Garcia-Saenz, Pinol, Renaux-Petel]
J. High Energ. Phys. **2020,** 73 (2020)

INTEGRATING OUT HEAVY ENTROPIC FLUCTUATIONS

AN EFFECTIVE THEORY FOR THE OBSERVABLE CURVATURE PERTURBATION

$$S[\zeta,\mathcal{F}] \xrightarrow{\mathcal{F}_{\text{heavy}}(\zeta)} S_{\text{EFT}}[\zeta] = S[\zeta,\mathcal{F}_{\text{heavy}}(\zeta)]$$

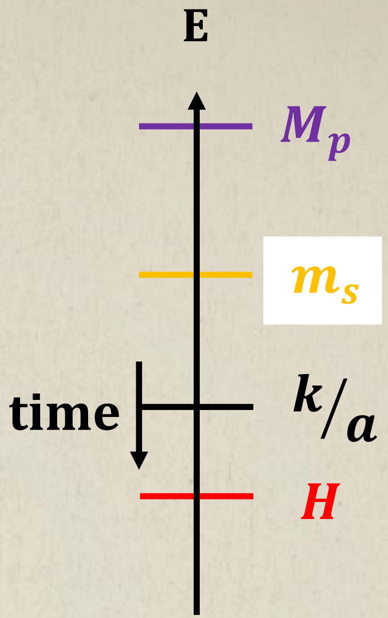
A HIERARCHY OF SCALES

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

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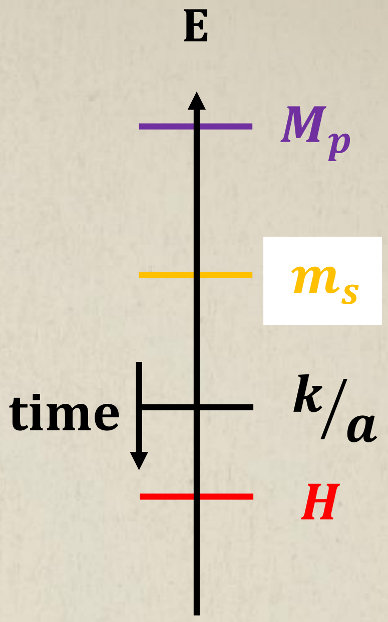
$$\cancel{\ddot{\mathcal{F}}} + \cancel{3H\dot{\mathcal{F}}} + \left(m_s^2 + \cancel{\frac{k^2}{a^2}}\right)\mathcal{F} = 2\dot{\sigma}\eta_\perp\dot{\zeta}$$

When $\mathcal{F}$ is heavy $\boxed{\mathcal{F}_{\text{heavy}}^{\text{LO}} = \frac{2\dot{\sigma}\eta_\perp}{m_s^2}\dot{\zeta}}$ $\boldsymbol{\omega^2, \omega H, \frac{k^2}{a^2} \ll m_s^2}$

Hierarchy of scales



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A HIERARCHY OF SCALES

THE QUADRATIC EFFECTIVE ACTION

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

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

When $\mathcal{F}$ is heavy

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

⇩

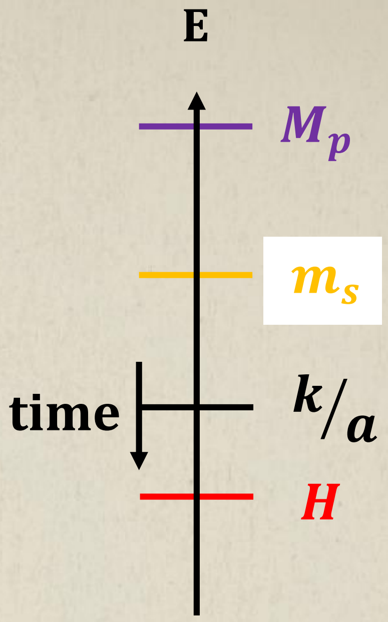
Effective single-field action for the curvature perturbation

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

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

$s = \dot{c}_s/Hc_s$

THE CUBIC EFFECTIVE ACTION

FULL RESULT

P(X) cubic lagrangian:

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

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 $\sim \boldsymbol{O(\epsilon, \eta)}$

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

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

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

THE CUBIC EFFECTIVE ACTION

RECOVERING THE EFT OF INFLATION

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

Slow-varying result:

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

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

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

THE EFT OF INFLATION

REVISITED…

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

$$\text{with } \boldsymbol{A} = \underbrace{-\frac{1}{2}(1 + c_s^2)}_{\textbf{Previously known}} + \cdots$$

THE EFT OF INFLATION
REVISITED...

Bending radius of the trajectory: $\boldsymbol{\kappa = \frac{\sqrt{2\epsilon}M_p}{\eta_\perp}}$

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

$$\text{with } \boldsymbol{A} = -\frac{1}{2}(1+c_s^2) - \underbrace{\frac{1}{6}(1-c_s^2)\frac{\kappa V_{;sss}}{m_s^2}}_{} + \cdots$$

3rd derivative of the potential (expected)

Self-coupling of entropic fluctuations

THE EFT OF INFLATION
REVISITED...

Bending radius of the trajectory: $\boldsymbol{\kappa = \frac{\sqrt{2\epsilon}M_p}{\eta_\perp}}$

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$$\text{with } \boldsymbol{A} = -\frac{1}{2}(1+c_s^2) - \frac{1}{6}(1-c_s^2)\frac{\kappa V_{;sss}}{m_s^2} + \underbrace{\frac{2}{3}(1+2c_s^2)\frac{\epsilon R_{\mathrm{fs}} H^2 M_{\mathrm{Pl}}^2}{m_s^2}}_{\text{Scalar curvature of the field space}} + \cdots$$

THE EFT OF INFLATION

REVISITED...

Bending radius of the trajectory: $\boldsymbol{\kappa = \frac{\sqrt{2\epsilon}M_p}{\eta_\perp}}$

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

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Derivative of the scalar curvature

THE EFT OF INFLATION
REVISITED...

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

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

Then you can use the result of the EFToI:

Equilateral shape with:

[Garcia-Saenz, Pinol, Renaux-Petel]
J. High Energ. Phys. **2020,** 73 (2020)

THE EFT OF INFLATION

REVISITED…

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$$f_{\mathrm{NL}}^{\mathrm{eq}} \simeq \frac{1}{18}\left(\frac{1}{c_s^2} - 1\right)\left(\boldsymbol{A} - \frac{17}{4}\right)$$

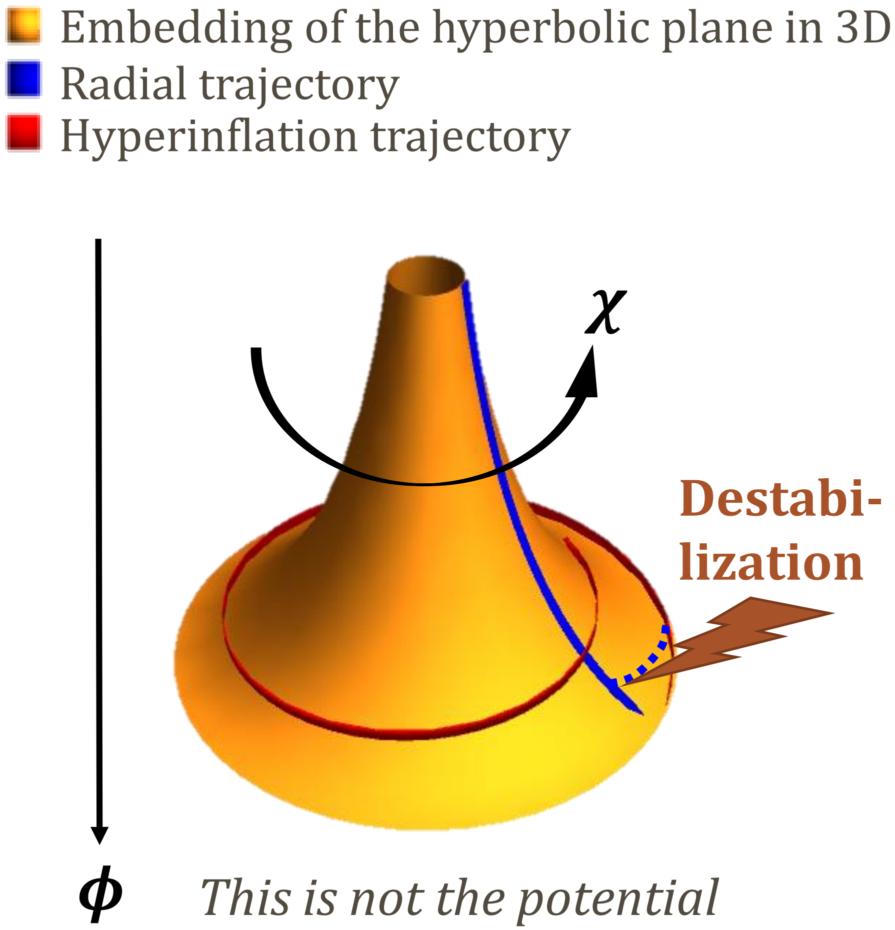
All contributions matter, none is a priori negligible

THE EFT OF INFLATION

HYPERINFLATION

An exotic case where conditions to integrate out are fulfilled

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



This is not the potential

Hyperbolic field space

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

THE EFT OF INFLATION
HYPERINFLATION

[Fumagalli, Garcia-Saenz, Pinol, Renaux-Petel, Ronayne 2019]
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An exotic case where conditions to integrate out are fulfilled

- Our new formula enables to **compute**

0 without the geometric $\propto R_{\mathrm{fs}}$ contribution

$$c_s^2 \simeq -1 \qquad\qquad A \simeq -0.33$$

THE EFT OF INFLATION
HYPERINFLATION

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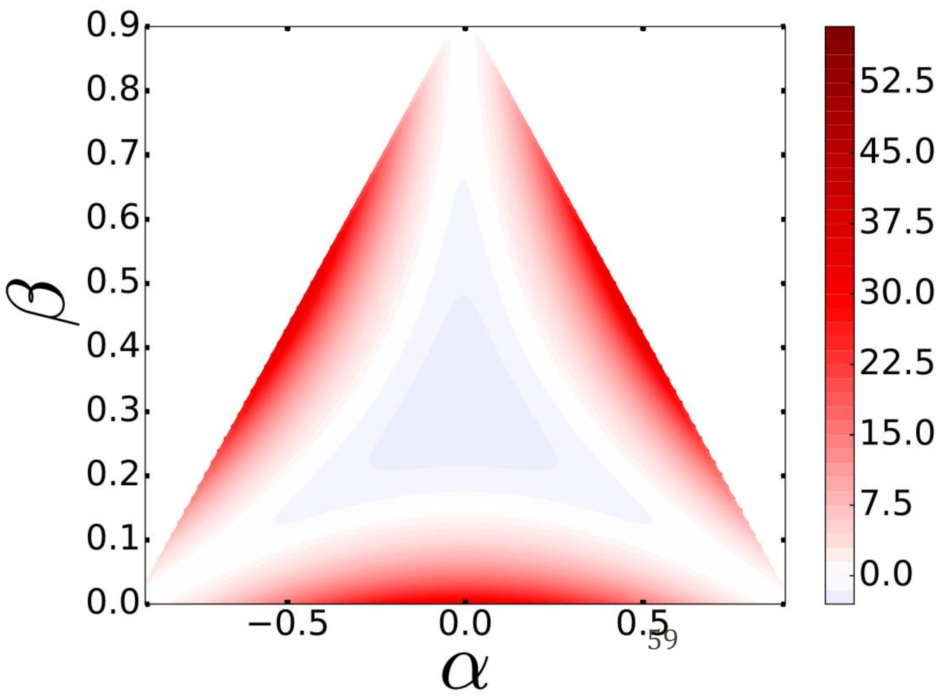
- Analytical prediction for the whole shape of the bispectrum:



vs. numerical resolution for the full multified model?

THE EFT OF INFLATION

HYPERINFLATION

[Fumagalli, Garcia-Saenz, Pinol, Renaux-Petel, Ronayne 2019]
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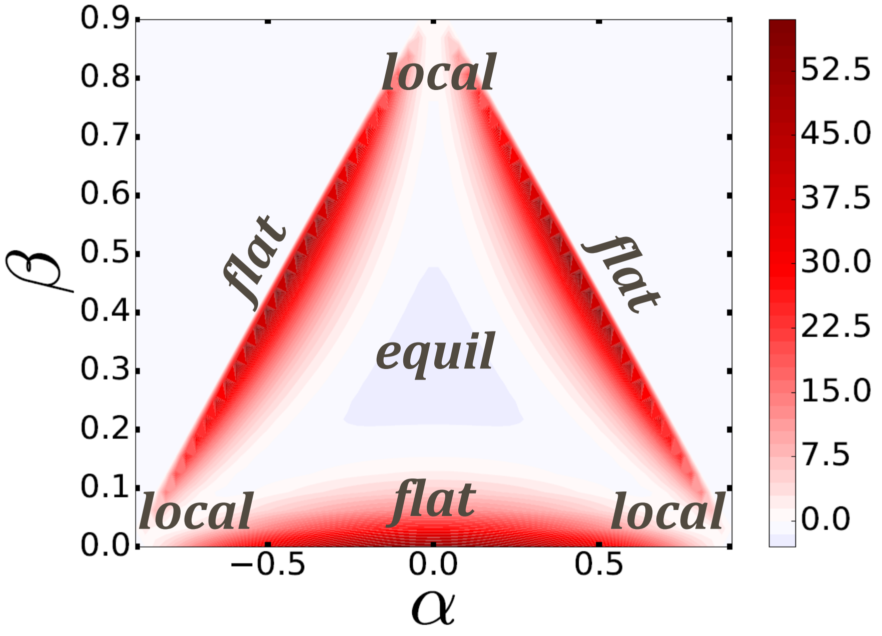

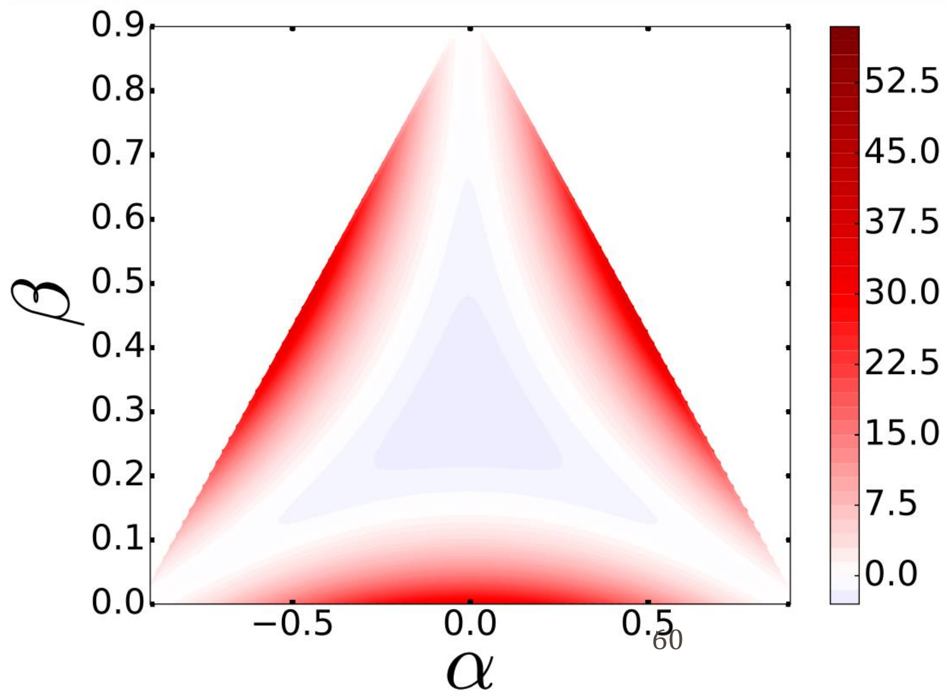

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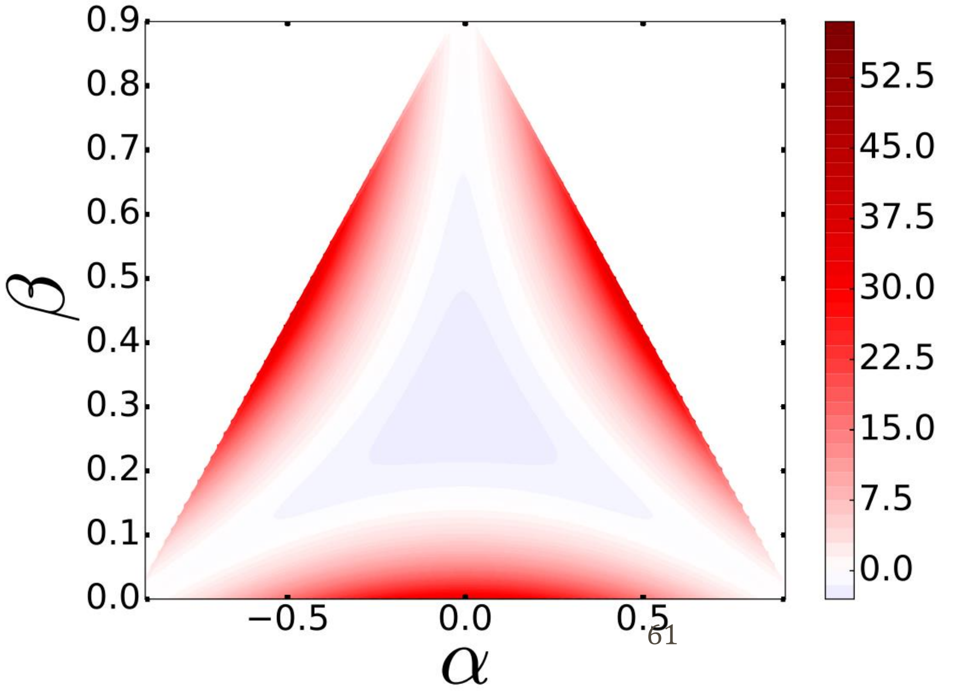
Perfect fit to numerics!



FROM 2 FIELDS TO N FIELDS

TOWARDS A MORE GENERAL UNDERSTANDING

[Pinol 2020]

J. Cosm. & Astro. Phys. 04(2021)048

Resulting Lagrangian, after $O(40)$ integrations by parts and $O(10)$ uses of equations of motion:

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Purely entropic mixing via the torsion matrix

$$\mathcal{L}^{(2)}(\zeta, \mathcal{F}^\alpha) = \frac{a^3}{2}\left(2\epsilon M_{\mathrm{Pl}}^2\left(\dot{\zeta}^2 - \frac{(\partial\zeta)^2}{a^2}\right) + 4\sqrt{2\epsilon}M_{\mathrm{Pl}}\omega_1\mathcal{F}^1\dot{\zeta} + \dot{\mathcal{F}}^{\alpha\,2} - \frac{(\partial\mathcal{F}^\alpha)^2}{a^2} - \underbrace{m^2_{\alpha\beta}}\mathcal{F}^\alpha\mathcal{F}^\beta + \Omega_{\alpha\beta}\dot{\mathcal{F}}^\alpha\mathcal{F}^\beta\right)$$

Adiabatic-entropic mixing via the bending

$$\boxed{m^2_{\alpha\beta} = V_{;\alpha\beta} - \delta_{\alpha 1}\delta_{\beta 1}\omega_1^2 + (\Omega^2)_{\alpha\beta} + 2\epsilon H^2 M_{\mathrm{Pl}}^2 R_{\alpha\sigma\beta\sigma}}$$

Covariant hessian of the potential

Bending / torsion of the trajectory

Field-space curvature

FROM 2 FIELDS TO N FIELDS

TOWARDS A MORE GENERAL UNDERSTANDING

[Pinol 2020]

J. Cosm. & Astro. Phys. 04(2021)048

$$
\begin{aligned}
\mathcal{L}^{(3)} = M_p^2 a^3 \Bigg[& \epsilon(\epsilon-\eta)\dot{\zeta}^2\zeta + \epsilon(\epsilon+\eta)\zeta\frac{(\partial\zeta)^2}{a^2} + \left(\frac{\epsilon}{2}-2\right)\frac{1}{a^4}(\partial\zeta)(\partial\chi)\partial^2\chi + \frac{\epsilon}{4a^4}\partial^2\zeta(\partial\chi)^2\Bigg] \\
& + a^3\Bigg\{\sqrt{2\epsilon}\,\omega_1 M_{\rm Pl}\left[\frac{\mathcal{F}^1}{H}\left(\frac{(\partial\zeta)^2}{a^2} - \dot{\zeta}^2 - \dot{\zeta}\zeta H\left(\eta+2u_1\right)\right) + 2\frac{\Omega_{1\alpha}}{H}\dot{\zeta}\zeta\mathcal{F}^\alpha\right] \\
& + \left[\frac{\epsilon}{2}m^2_{\alpha\beta} + \frac{\dot{\left(m^2_{\alpha\beta}\right)}}{2H} + \Omega_{\gamma\beta}\left(\epsilon\Omega^\gamma{}_\alpha + \frac{\dot{\Omega}^\gamma{}_\alpha}{H} - \frac{m^2_{\gamma\alpha}}{H}\right)\right]\zeta\mathcal{F}^\alpha\mathcal{F}^\beta + \epsilon\Omega_{\alpha\beta}\zeta\dot{\mathcal{F}}^\alpha\mathcal{F}^\beta \\
& + \left(2\epsilon H^2 M_{\rm Pl}^2 R_{\alpha\sigma\beta\sigma} - \omega_1^2\delta_{\alpha1}\delta_{\beta1}\right)\frac{\dot{\zeta}}{H}\mathcal{F}^\alpha\mathcal{F}^\beta + \frac{1}{2}\epsilon\zeta\left(\left(\dot{\mathcal{F}}^\alpha\right)^2 + \frac{(\partial\mathcal{F}^\alpha)^2}{a^2}\right) \qquad (3.10) \\
& - \frac{1}{a^2}\left(\partial\mathcal{F}^\alpha\right)\left(\partial\chi\right)\left(\dot{\mathcal{F}}^\alpha + \Omega_{\alpha\beta}\mathcal{F}^\beta\right) + \frac{2}{3}\sqrt{2\epsilon}\,H M_{\rm Pl} R_{\alpha\beta\gamma\sigma}\dot{\mathcal{F}}^\alpha\mathcal{F}^\beta\mathcal{F}^\gamma \\
& - \frac{1}{6}\left(V_{;\alpha\beta\gamma} - 4\sqrt{2\epsilon}\,H M_{\rm Pl}\left(\omega_1\delta_{\alpha1}R_{\beta\sigma\gamma\sigma} + \Omega^\delta{}_\alpha R_{\delta\beta\gamma\sigma}\right) + 2\epsilon H^2 M_{\rm Pl}^2 R_{\alpha\sigma\beta\sigma;\gamma}\right)\mathcal{F}^\alpha\mathcal{F}^\beta\mathcal{F}^\gamma\Bigg\} \\
& + \mathcal{D},
\end{aligned}
$$

$$\mathcal{L}^{(3)}_{\rm new}(\zeta, \mathcal{F}^\alpha)$$

APPLICATIONS

[Pinol 2020]
J. Cosm. & Astro. Phys. 04(2021)048

➢ Single-field EFT from N_{field} inflation as a realistic UV completion:

$$\boxed{\frac{1}{c_s^2} = 1 + 4\omega_1^2 (m^{-2})_{11}}$$

Bending to deviate from $c_s^2 = 1$

Inverse squared mass matrix

$$A = -\frac{1}{2}(1+c_s^2) + \frac{4}{3}(1+2c_s^2)\epsilon H^2 M_p^2 \left(m^{-2}\right)_{11} R_{m\sigma m\sigma}$$
$$-\frac{\kappa}{6}(1-c_s^2)\left(m^{-2}\right)_{11}\left[V_{;mmm} + 2\epsilon H^2 M_p^2 R_{m\sigma m\sigma;m}\right.$$
$$\left. +4\sqrt{2\epsilon}\, H M_p \left(\Omega^\alpha{}_m + \frac{1}{\left(m^{-2}\right)_{11}} \frac{\mathrm{d}\left(m^{-2}\right)^\alpha{}_1}{\mathrm{d}t}\right) R_{m\alpha m\sigma}\right],$$

<ins>Ex</ins>: $R_{m\sigma m\sigma} = \frac{(m^{-2})_{1\alpha}(m^{-2})_{1\beta}}{[(m^{-2})_{11}]^2} R_{\alpha\sigma\beta\sigma}$

The whole mass matrix of entropic fields matters! (not just m_{11}^2)
The whole geometry of the non-linear sigma model matters! (not just the Ricci scalar R_{fs})

➢ Cosmological collider with N_{field}-1 entropic fields: what is the bispectrum in the squeezed limit?

The cosmic spectroscopy (beyond single-field EFT)

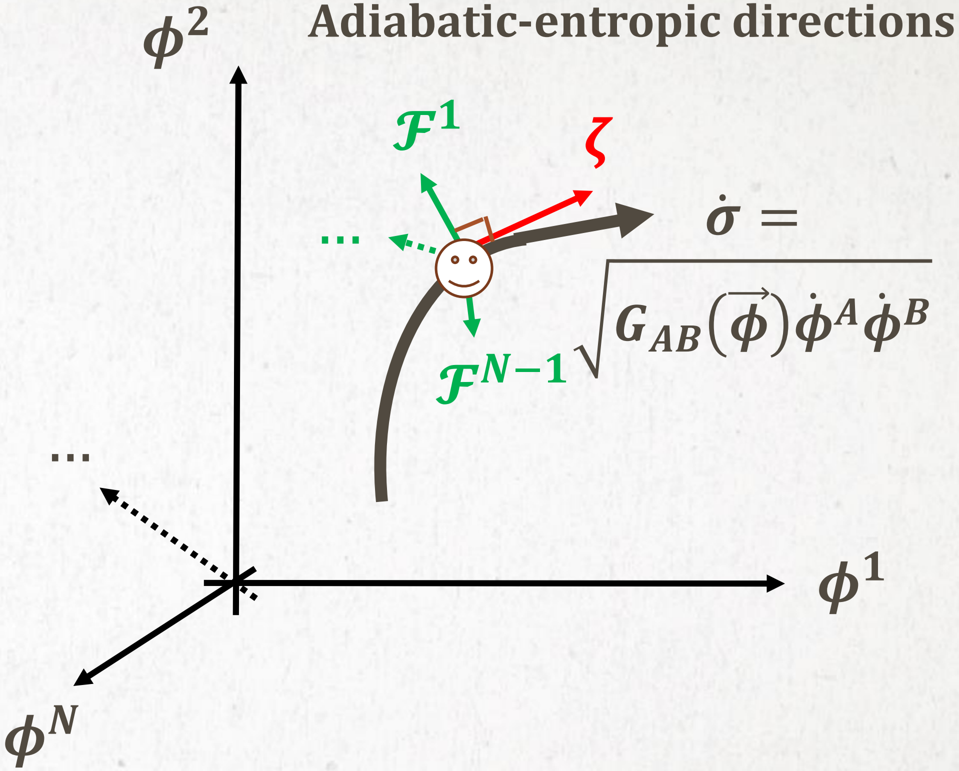
INFLATIONARY FLAVOR AND MASS BASES

[Lucas Pinol 2020]
J. Cosm. & Astro. Phys. 04(2021)048

Quadratic action for the extra fluctuations:
(Also the cubic action is computed)

ζ	The curvature perturbation
$\mathcal{F}^1, \dots, \mathcal{F}^{N-1}$	The entropic/isocurvature perturbations

Adiabatic-entropic directions



INFLATIONARY FLAVOR AND MASS BASES

[Lucas Pinol 2020]

J. Cosm. & Astro. Phys. 04(2021)048

Quadratic action for the extra fluctuations:

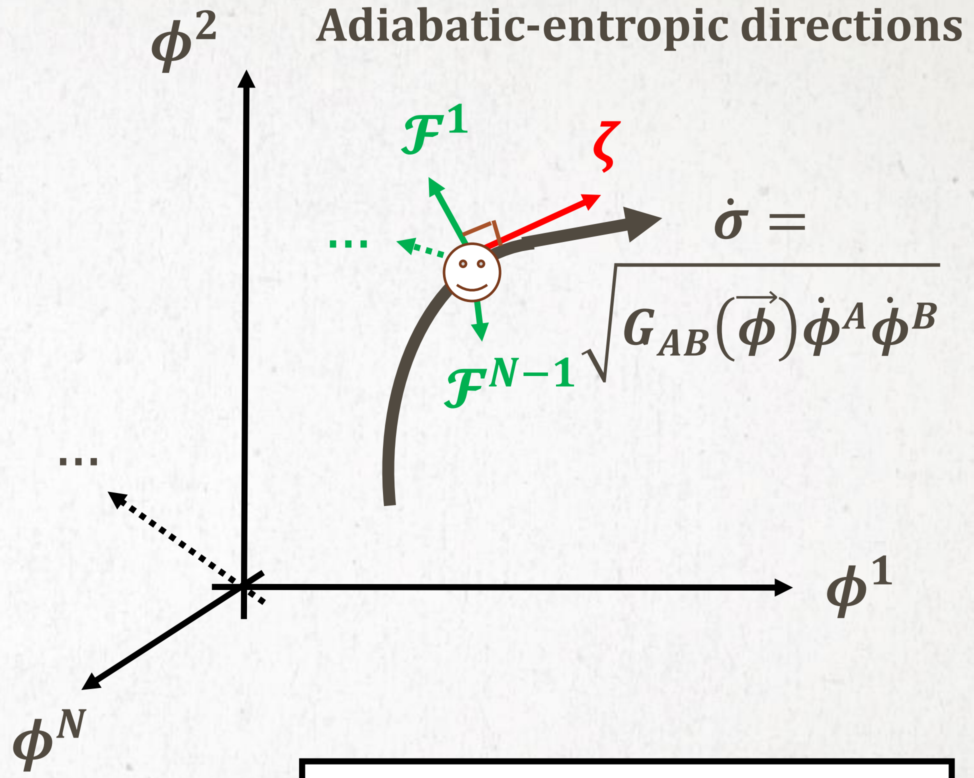
$$\mathcal{L}^{(2)}_{\text{flavor}} = \frac{a^3}{2}\left[\delta_{\alpha\beta}\left(\dot{\mathcal{F}}^\alpha\dot{\mathcal{F}}^\beta - \frac{\partial\mathcal{F}^\alpha\partial\mathcal{F}^\beta}{a^2}\right) - \underline{M^2_{\alpha\beta}\mathcal{F}^\alpha\mathcal{F}^\beta}\right]$$

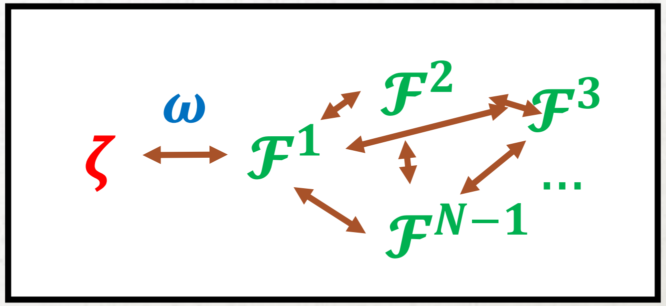
$$+ 4\sqrt{2\epsilon}M_{\text{Pl}}\, \underline{\boldsymbol{\omega\delta_{\alpha 1}}\mathcal{F}^\alpha\dot{\zeta}}$$

- Non-trivial mass matrix mixing

- Only the first extra field $\mathcal{F}^1$ is coupled to ζ:

  portal field + sterile sector





Flavor basis: the one in which interactions are specified

Diagonalization: $M_{\alpha\beta} = \left(OmO^T\right)_{\alpha\beta}$ **and** $\mathcal{F}^\alpha = O^\alpha{}_i\,\sigma^i$

INFLATIONARY FLAVOR AND MASS BASES

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]

ArXiv:2112.05710

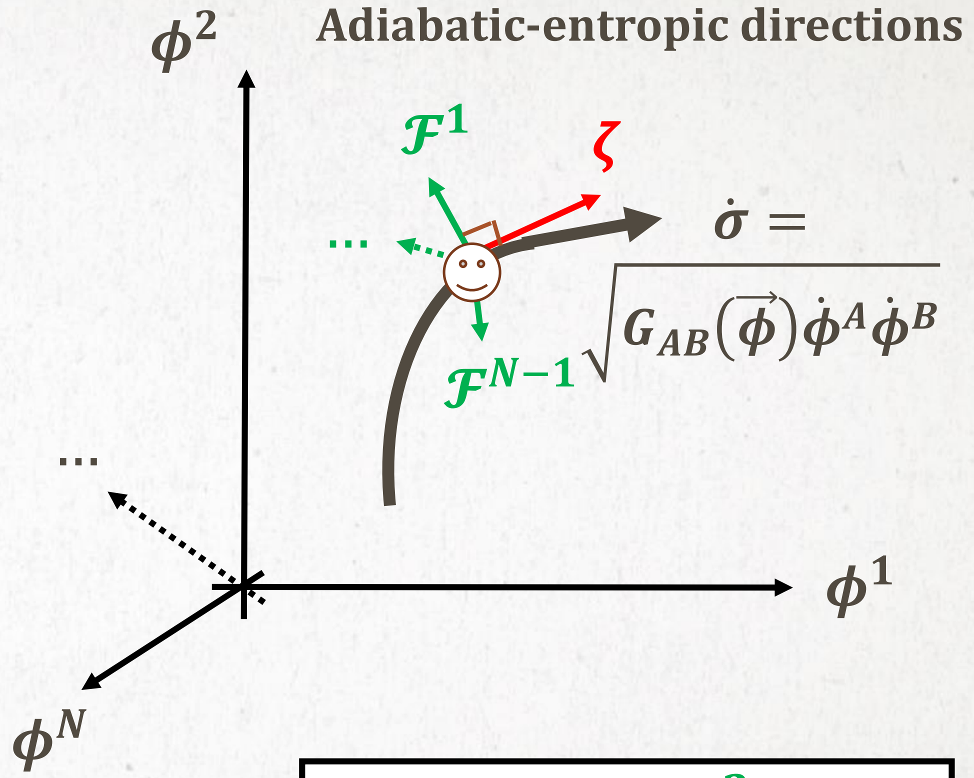
Quadratic action for the extra fluctuations:

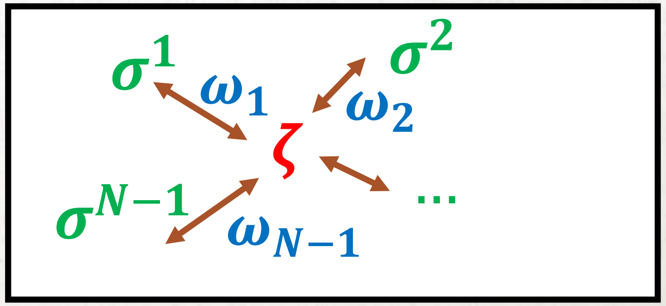
$$\mathcal{L}^{(2)}_{\text{mass}} = \frac{a^3}{2}\left[\delta_{ij}\left(\dot{\sigma}^i\dot{\sigma}^j - \frac{\partial\sigma^i\partial\sigma^j}{a^2}\right) - \sum_i \underline{m_i^2\sigma_i^2}\right]$$

$$+ 4\sqrt{2\epsilon}M_{\text{Pl}}\, \underline{\boldsymbol{\omega O^1}_{\boldsymbol{i}}\, \sigma^i\dot{\zeta}}$$

- **Well-defined masses**
- **All mass eigenstates are coupled to ζ with:**

$$\boldsymbol{\omega_i = \omega O^1{}_i \text{ with } \mathcal{F}^1 = O^1{}_i\sigma^i}$$

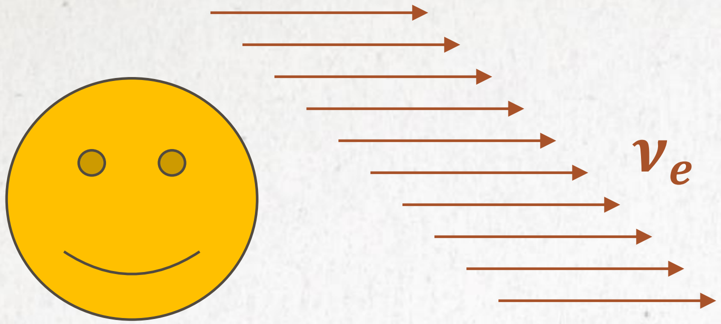




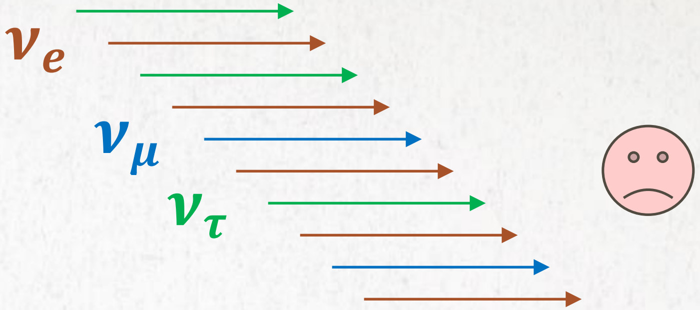
Mass basis: the one in which masses are specified

Diagonalization: $M_{\alpha\beta} = \left(OmO^T\right)_{\alpha\beta}$ **and** $\mathcal{F}^\alpha = O^\alpha{}_i\,\sigma^i$

ANALOGY WITH NEUTRINO OSCILLATIONS



NO INTERACTIONS



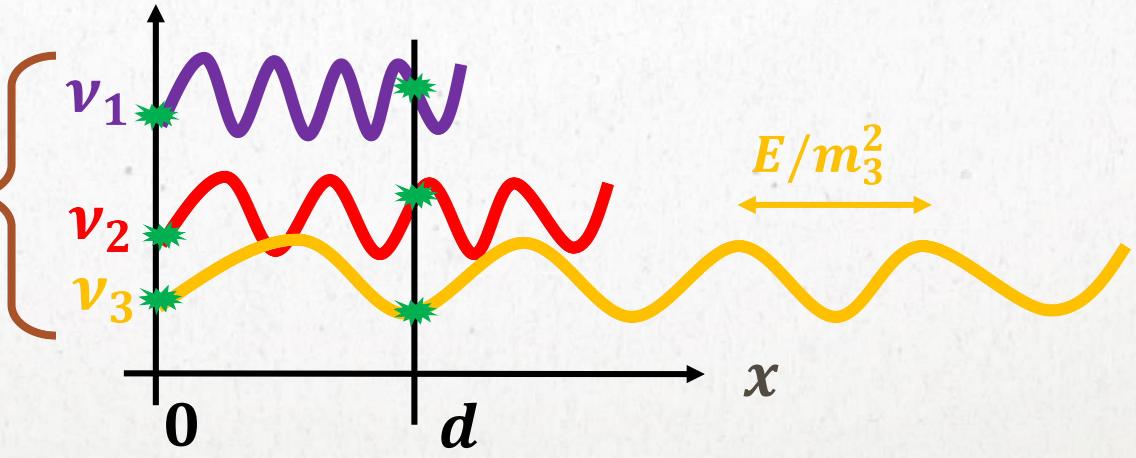
This is the Sun

This is me

It is emitting electronic neutrinos*

I am seeing many less electronic neutrinos

$$\nu_e = \sum_i U_{ei}\, \nu_i$$

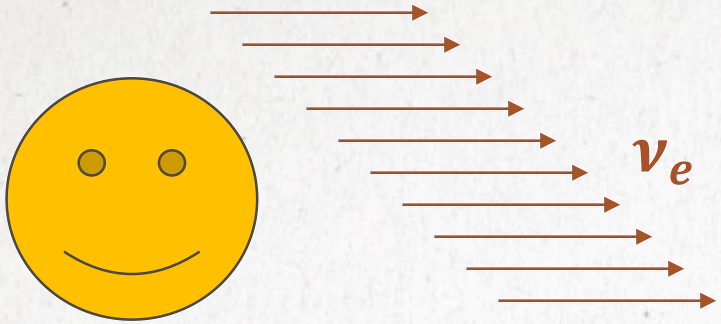


Entries of the PMNS matrix: mixing angles

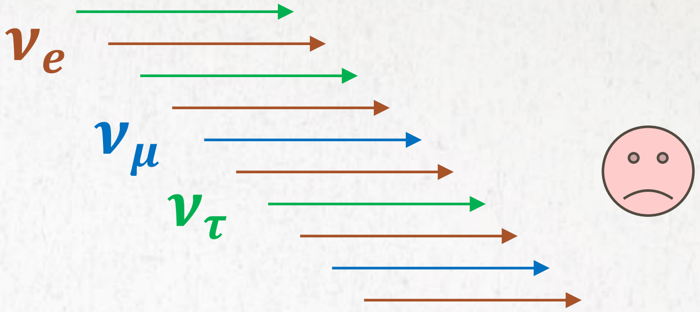
*also some ν_τ from MSW

PMNS stands for Pontecorvo-Maki-Nakagawa-Sakata: try to pronounce it ten times in a row

ANALOGY WITH NEUTRINO OSCILLATIONS



NO INTERACTIONS



This is the Sun

It is emitting electronic neutrinos

This is me

I am seeing many less electronic neutrinos

For us, $\mathcal{F}^\alpha$ are the flavor eigenstates and σ_i the free fields: the mass eigenstates.

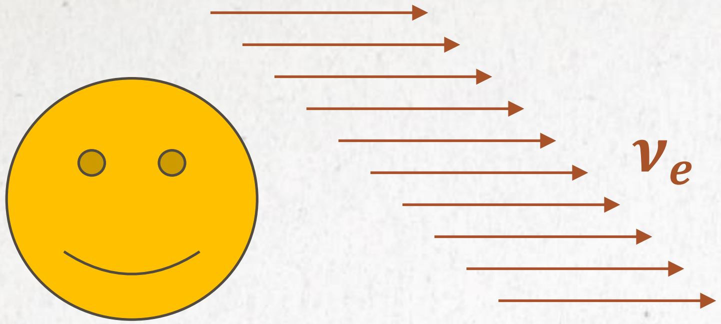
In particular: $\mathcal{F}^1 = \sum_i O^1{}_i \, \sigma_i$ with $O^1{}_i = [\cos(\theta_{12})\cos(\theta_{13}), \sin(\theta_{12})\cos(\theta_{13}), \sin(\theta_{13})]_i \;, \quad (3)$

if $N_{\text{flavor}} = 3$

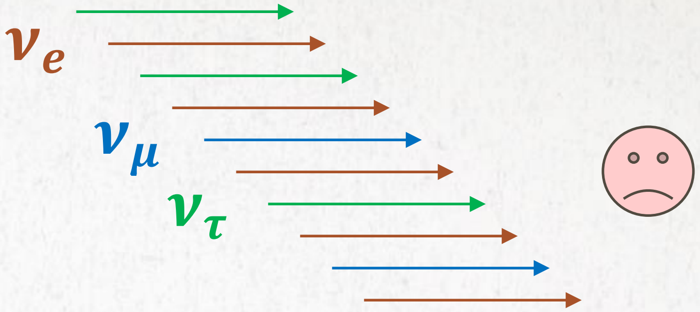
Mixing angles

Maybe called the FARY matrix one day?

ANALOGY WITH NEUTRINO OSCILLATIONS



NO INTERACTIONS



This is the Sun

It is emitting electronic neutrinos

This is me

I am seeing many less electronic neutrinos

What process equivalent to the missing solar neutrinos may hint towards inflationary flavor oscillations?

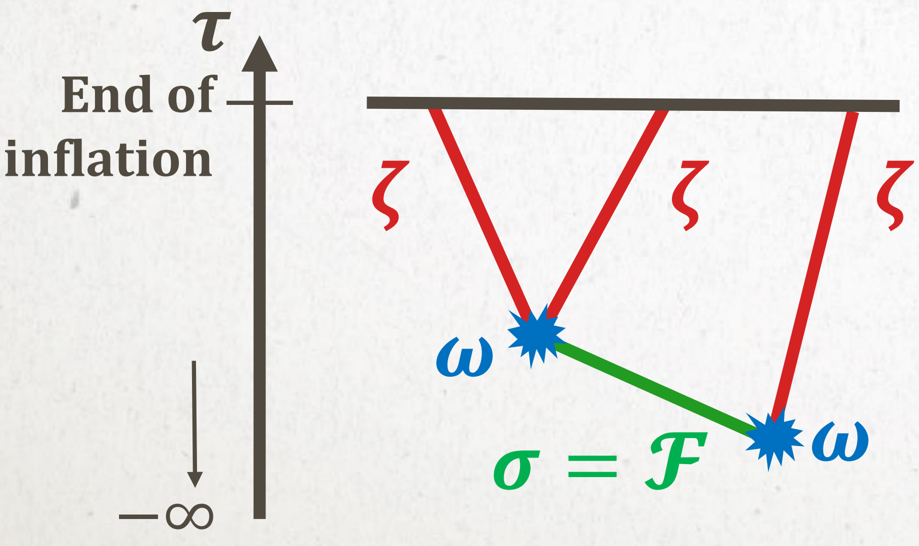
BISPECTRUM IN MULTIFIELD INFLATION

The squeezed limit as a cosmological collider

Single-field result: $\boxed{f_{\mathrm{NL}}^{\mathrm{squeezed}} \propto 1 - n_s \ll 1}$ **consistency relation** **[Maldacena 2003]**

Two-field result: Usual curvature perturbation ζ + one heavy field $\sigma = \mathcal{F}$ (no flavor oscillation)

[Chen, Wang 2009]
[Noumi, Yamaguchi, Yokoyama 2013]
[Arkani-Hamed, Maldacena 2015]



$$f_{\mathrm{NL}}^{\mathrm{squeezed}} \sim \left(\frac{\omega}{H}\right)^2 e^{-\pi\mu} \cos\left[\boldsymbol{\mu} \log\left(\frac{k_l}{k_s}\right) + \varphi(\boldsymbol{\mu})\right]$$

Oscillatory pattern: massive particle

$\boldsymbol{\mu} = \sqrt{\frac{m_\sigma^2}{H^2} - \frac{9}{4}}$ **the reduced mass**

BISPECTRUM IN MULTIFIELD INFLATION

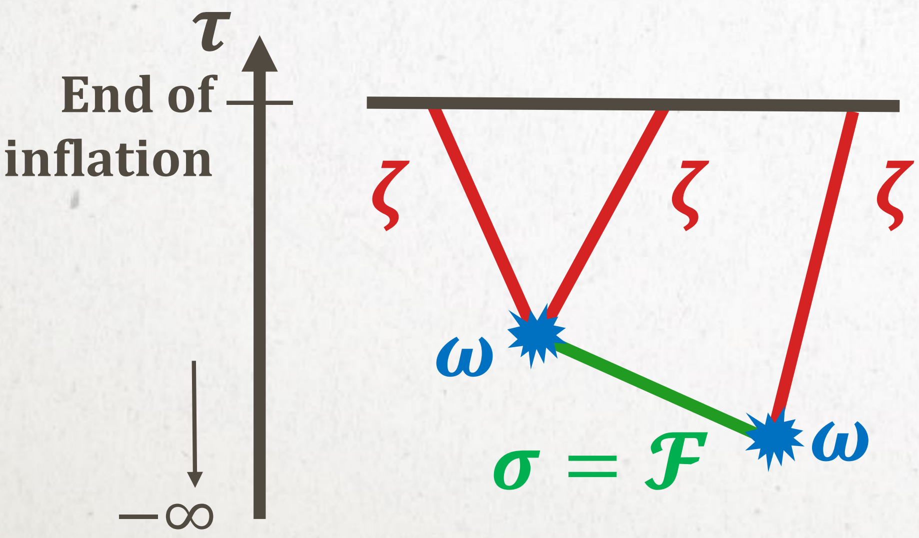
The squeezed limit as a cosmological collider

Single-field result:

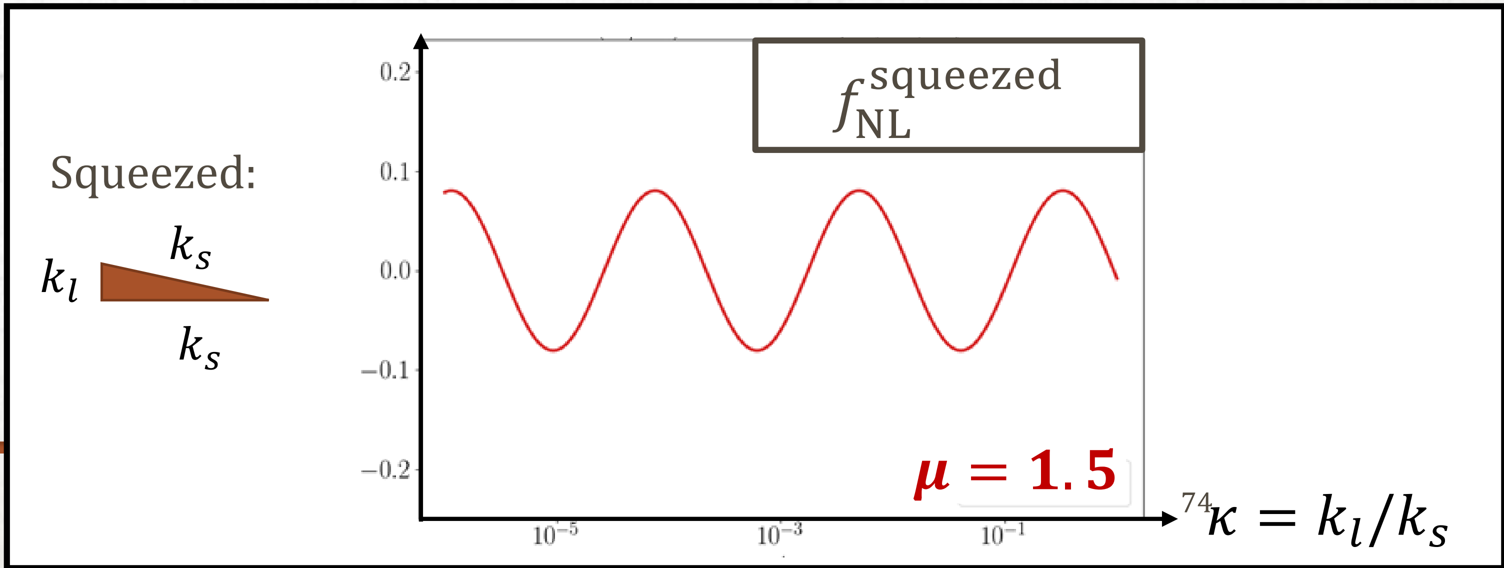
$$\boxed{f_{\mathrm{NL}}^{\mathrm{squeezed}} \propto 1 - n_s \ll 1}$$

consistency relation

Two-field result: Usual curvature perturbation ζ + one heavy field $\sigma = \mathcal{F}$ (**no flavor oscillation**)



Super-Hubble oscillations of a massive scalar field

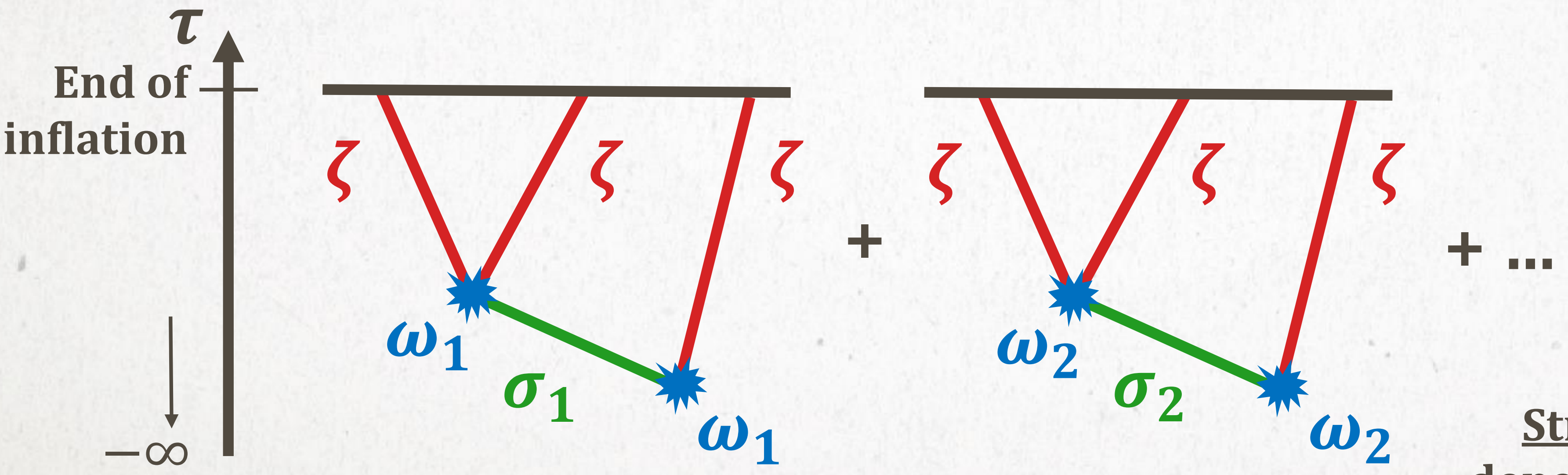


BISPECTRUM IN MULTIFIELD INFLATION

The squeezed limit as a cosmological collider

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]
ArXiv:2112.05710

N-field result: … this work!



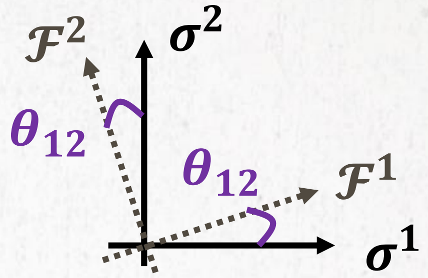
Strength of interactions depend on the mixing angles

$$\omega_i = O^1{}_i \times \omega$$

BISPECTRUM IN MULTIFIELD INFLATION

❖ Three fields: ζ and 2 flavors $(\mathcal{F}^1, \mathcal{F}^2)$

→ Only one **mixing angle $\boldsymbol{\theta_{12}}$**



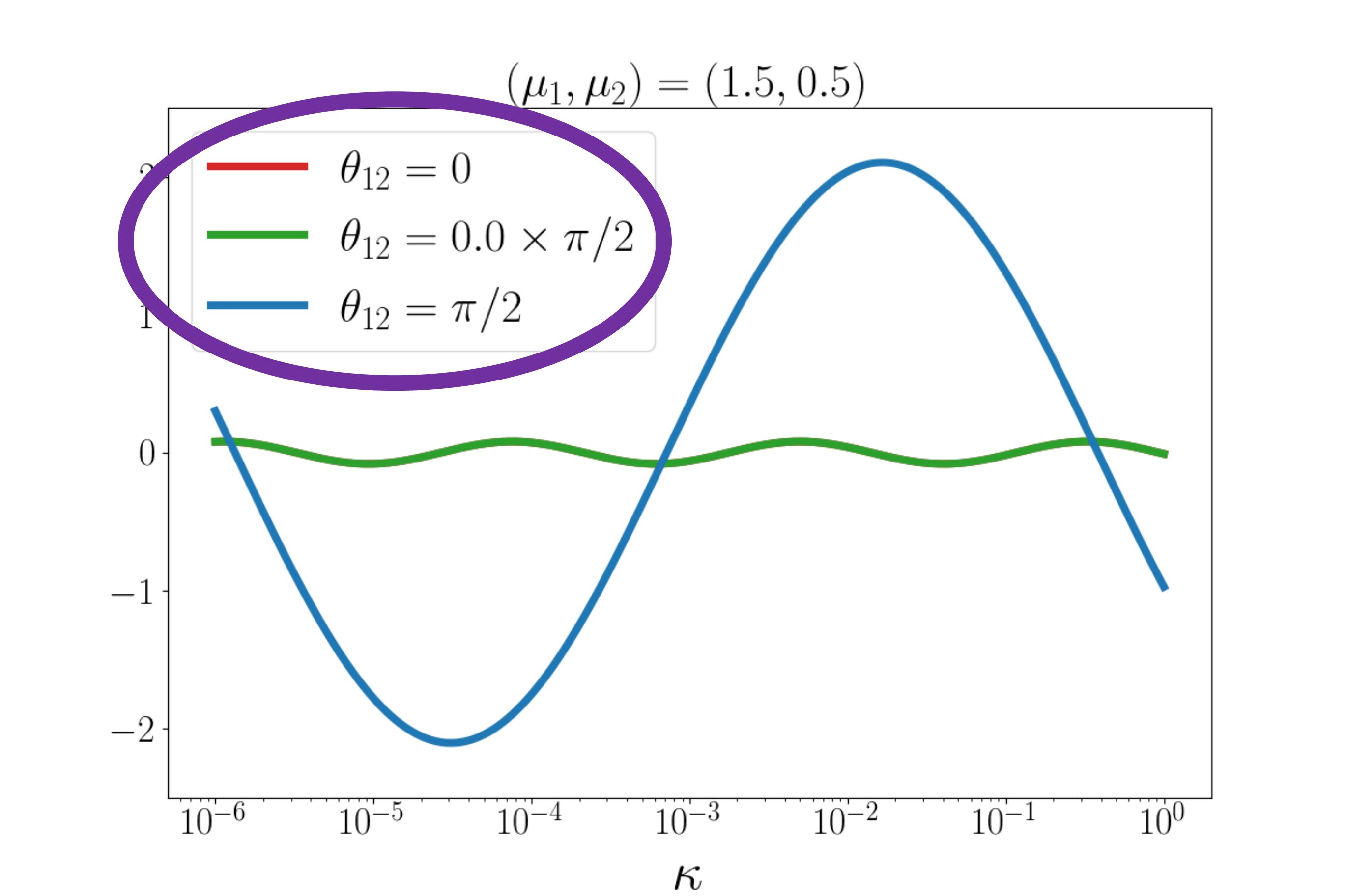
❖ If $\theta_{12} \in \{0, \pi/2\}$: no mixing

❖ If $0 < \theta_{12} < \pi/2$: mixing

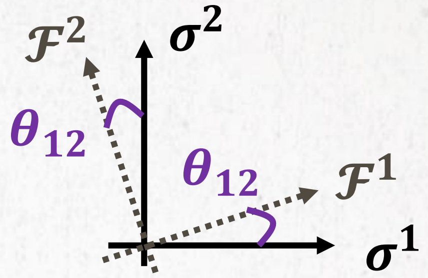
[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]
ArXiv:2112.05710

BISPECTRUM IN MULTIFIELD INFLATION

For heavy mass eigenstates σ_1, σ_2



- Three fields: ζ and 2 flavors $(\mathcal{F}^1, \mathcal{F}^2)$
  - Only one **mixing angle θ_{12}**



- If $\theta_{12} \in \{0, \pi/2\}$: no mixing
  - **Oscillations** with frequency $\mu_{1,2}$
- If $0 < \theta_{12} < \pi/2$: mixing
  - **Modulated oscillations** with frequencies $\dfrac{\mu_1 \pm \mu_2}{2}$

[Lucas Pinol, Aoki, Renaux-Petel, Yamaguchi 2021]
ArXiv:2112.05710

See the paper for all cases and any N

BISPECTRUM IN MULTIFIELD INFLATION

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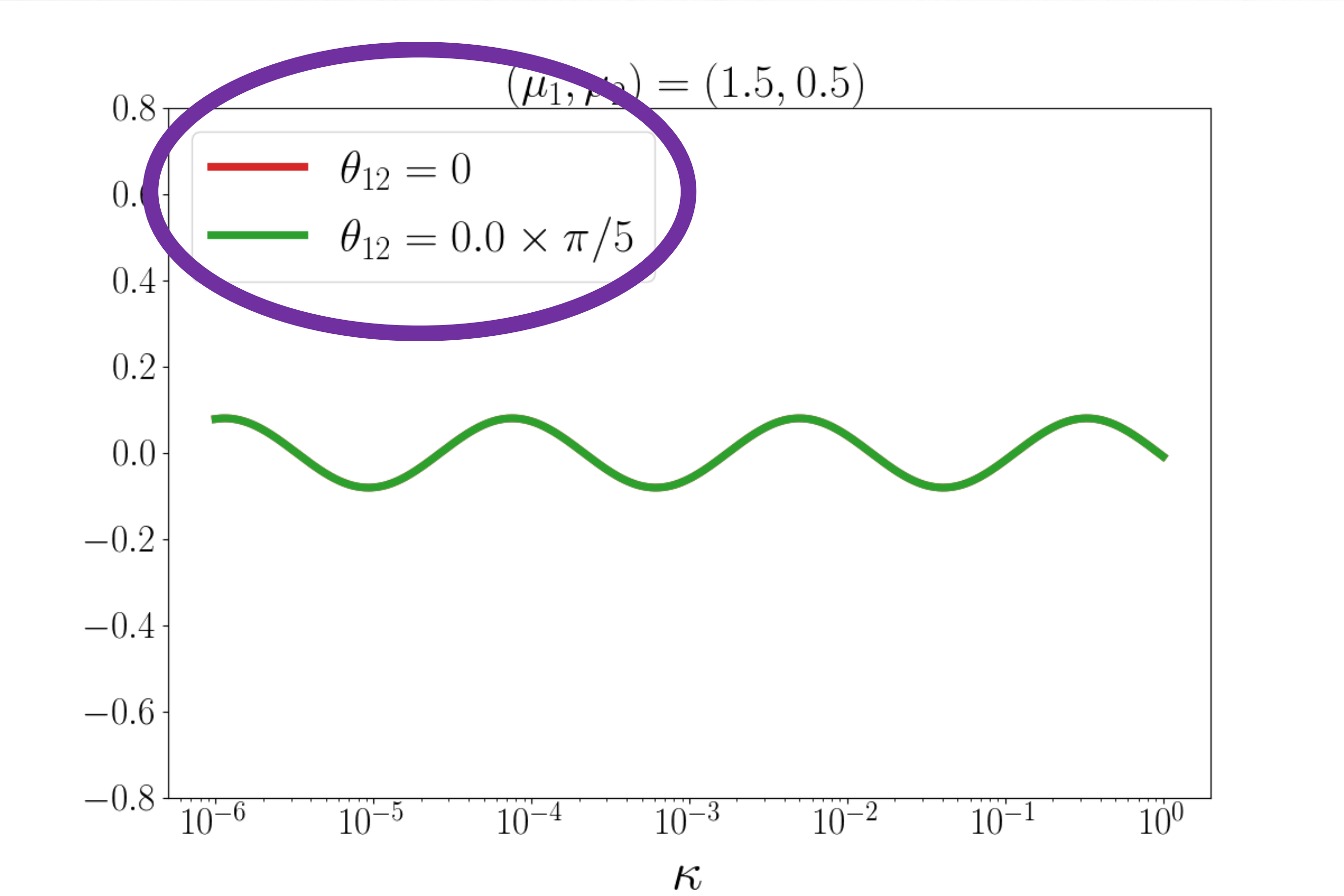

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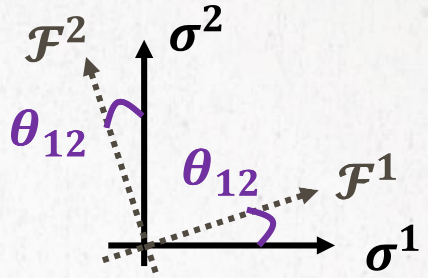

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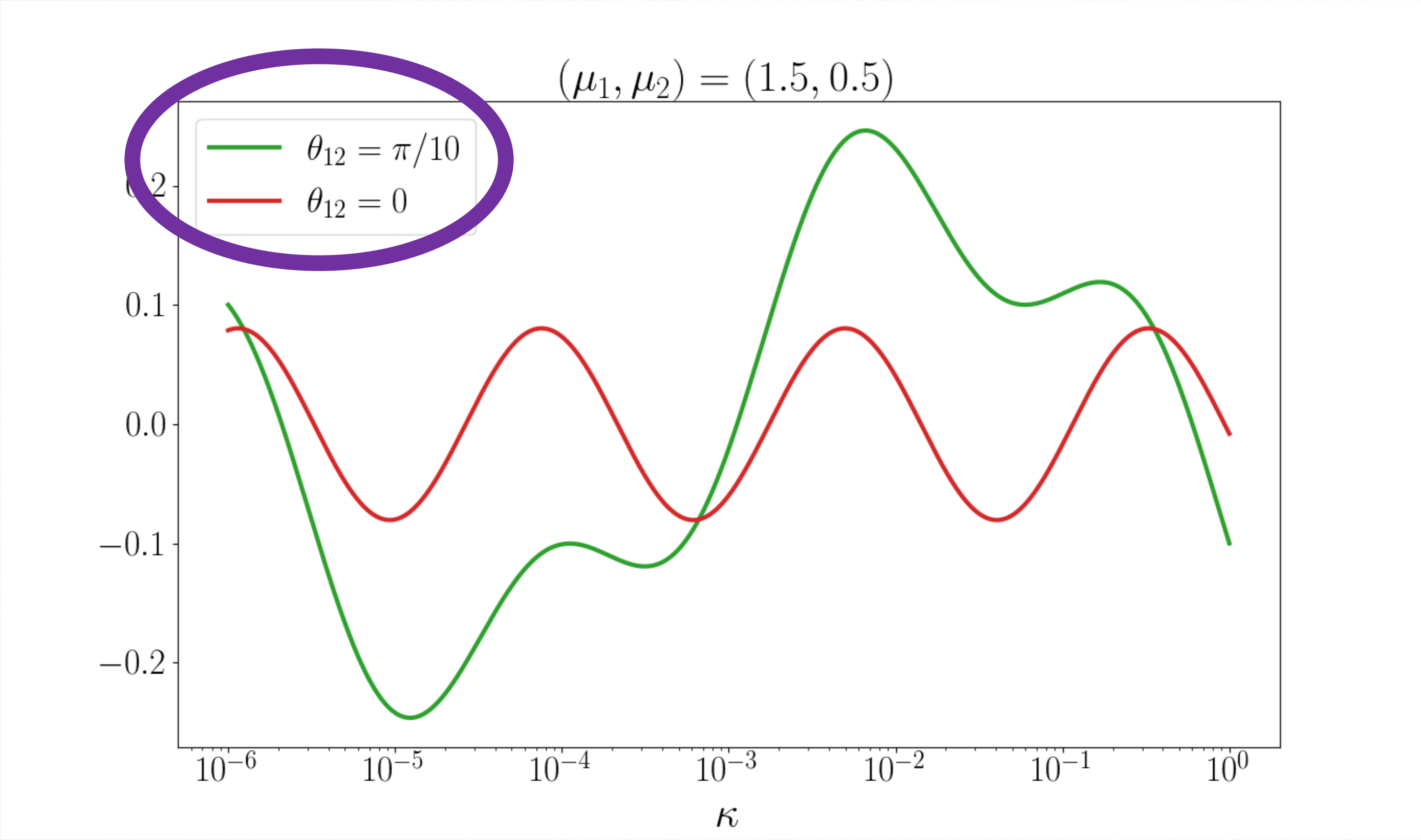

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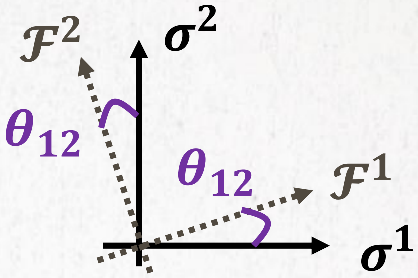
  - Only one **mixing angle θ_{12}**



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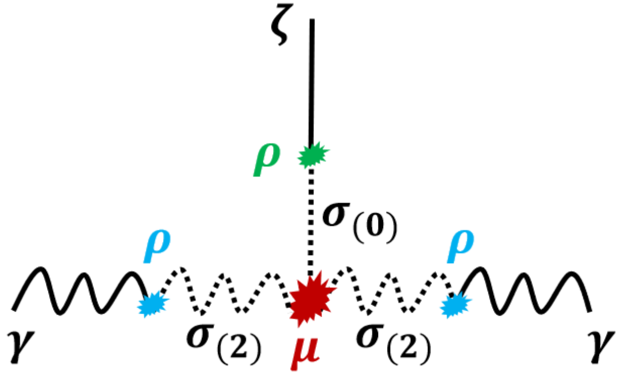
ArXiv:2112.05710

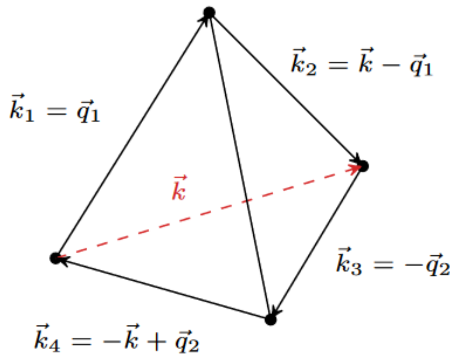
See the paper for all cases and any N

III. PNG AND GW: AN INTERTWINED STORY

GW anisotropies of primordial origin
Scalar-trispectrum-induced GW: a no-go theorem



Mixed bispectrum (scalar-tensor-tensor) inducing GW anisotropies



Tetrahedron shape for the scalar trispectrum inducing GW

OTHER KINDS OF PNG

Trispectrum

- Higher-order correlation functions:

SSSS $\left\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\zeta_{\vec{k}_4} \right\rangle_c = (2\pi)^3\,\delta^{(3)}\left(\overrightarrow{k_1}+\overrightarrow{k_2}+\overrightarrow{k_3}+\overrightarrow{k_4}\right)\times T_\zeta\left(\overrightarrow{k_1},\overrightarrow{k_2},\overrightarrow{k_3},\overrightarrow{k_4}\right)$

etc.

- Tensor and mixed scalar-tensor PNG

SST $\left\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\gamma_{\vec{k}_3} \right\rangle = (2\pi)^3\,\delta^{(3)}\left(\overrightarrow{k_1}+\overrightarrow{k_2}+\overrightarrow{k_3}\right)\times B_{\zeta\zeta\gamma}(k_1,k_2,k_3)$

STT $\left\langle \zeta_{\vec{k}_1}\gamma_{\vec{k}_2}\gamma_{\vec{k}_3} \right\rangle = (2\pi)^3\,\delta^{(3)}\left(\overrightarrow{k_1}+\overrightarrow{k_2}+\overrightarrow{k_3}\right)\times B_{\zeta\gamma\gamma}(k_1,k_2,k_3)$

TTT $\left\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}\gamma_{\vec{k}_3} \right\rangle = (2\pi)^3\,\delta^{(3)}\left(\overrightarrow{k_1}+\overrightarrow{k_2}+\overrightarrow{k_3}\right)\times B_{\gamma\gamma\gamma}(k_1,k_2,k_3)$

All these correlators are observable and contain information about high-energy physics and inflation

OTHER KINDS OF PNG: CONSTRAINTS

Bounds at CMB scales

- Higher-order correlation functions:

$$\text{SSSS} \xrightarrow{\text{squeezed}} g_{\rm NL} = (-5.8 \pm 6.5)10^4$$ **[Planck 2018]**

$$\text{SSSS} \xrightarrow{\text{collapsed}} \tau_{\rm NL} = 400 \pm 1300$$ **[Marzouk, Lewis, Carron 2022]**

from theory…

$$\tau_{\rm NL} \geq \left(\frac{6}{5} f_{\rm NL}^{\rm loc}\right)^2$$ **(= in single-field only)**

[Suyama, Yamaguchi 2007]
[Smith, LoVerde, Zaldarriaga 2011]

- Tensor and mixed scalar-tensor PNG

$$\text{SST} \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\zeta\zeta\gamma} = -48 \pm 28$$ **[Shiraishi, Liguori, Fergusson 2017]**

$$\text{STT} \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\zeta\gamma\gamma} = \;???$$

$$\text{TTT} \xrightarrow{\text{squeezed}} f_{\rm NL,loc}^{\gamma\gamma\gamma} = 220 \pm 170$$ **[WMAP 2013]**

… and nothing else…

Please tell me if these are outdated

OTHER KINDS OF PNG: CONSTRAINTS

- Higher-order correlation functions:

$$\text{SSSS} \xrightarrow{\text{squeezed}} g_{\text{NL}} = (-5.8 \pm 6.5)10^4$$ **[Planck 2018]**

[Marzouk, Lewis, Carron 2022]

$$\text{SSSS} \xrightarrow{\text{collapsed}} \tau_{\text{NL}} = 400 \pm 1300$$

END OF THIS TALK

- Tensor and mixed scalar-tensor PNG

$$\text{SST} \xrightarrow{\text{squeezed}} f_{\text{NL,loc}}^{\zeta\zeta\gamma} = -48 \pm 28$$ **[Shiraishi, Liguori, Fergusson 2017]**

$$\text{STT} \xrightarrow{\text{squeezed}} f_{\text{NL,loc}}^{\zeta\gamma\gamma} = \ ???$$

$$\text{TTT} \xrightarrow{\text{squeezed}} f_{\text{NL,loc}}^{\gamma\gamma\gamma} = 220 \pm 170$$ **[WMAP 2013]**

GW anisotropies of primordial origin

THE STOCHASTIC GRAVITATIONAL WAVE BACKGROUND

Primordial gravitational waves constitute a key prediction from inflation!

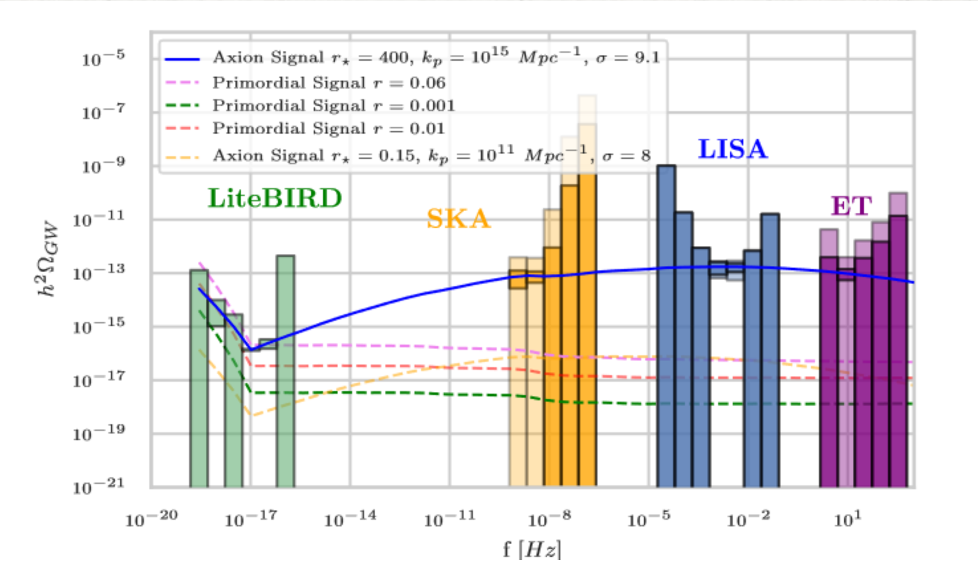
But…

Many sources! Astrophysical, cosmological… How to disentangle them?

DISTINCTIVE FEATURES OF THE SGWB

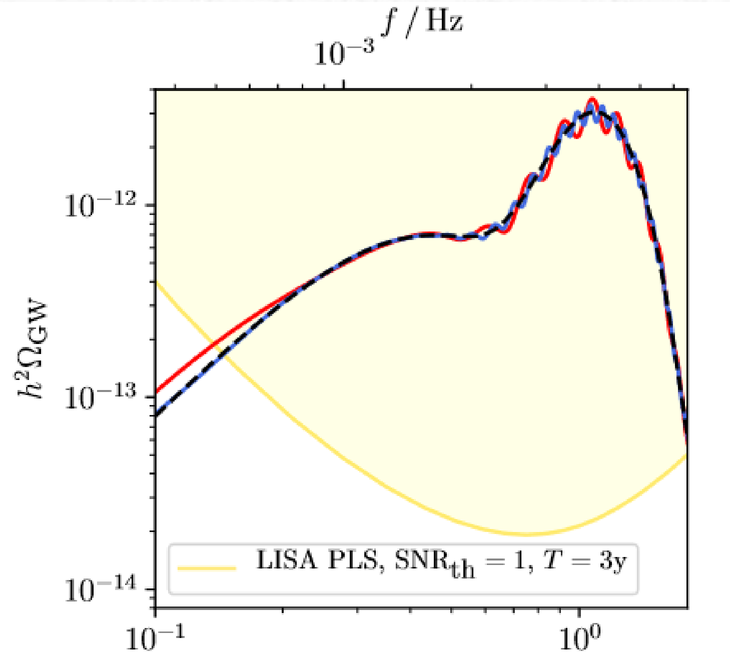
Frequency profile

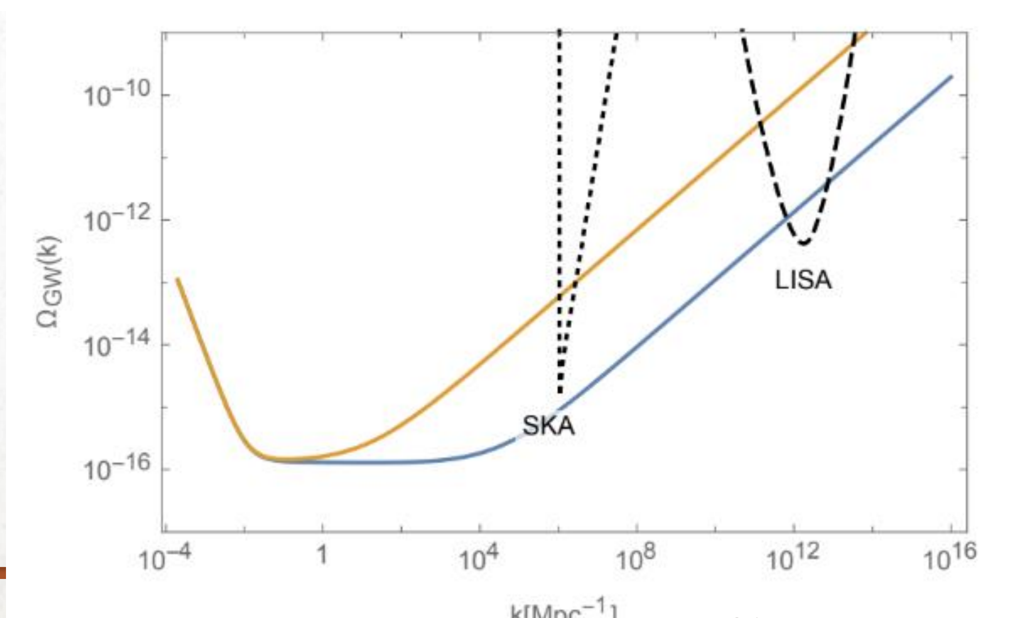
$$\bar{\Omega}_{GW}(f) = \Omega_0 \left(\frac{f}{f_*}\right)^{n_{\mathrm{GW}}(f)}$$



Having access to several orders of magnitude in frequency can help

[Auclair *et al.*, LISA CWG 2022]





[Many many works, sorry for not showing yours]

DISTINCTIVE FEATURES OF THE SGWB

Chirality

Often in the context of a Cherns-Simon term

- Gauge fields: $g(\chi)F^{a\mu\nu}\,\tilde{F}^{a}_{\mu\nu} \in \mathcal{L}$

[Anber, Sorbo 2010, 2011]
[Barnaby, Peloso 2011]
[Dimastrogiovanni, Peloso 2013]
[Adshead, Martinec, Wyman 2013]
[Dimastrogiovanni, Fasiello, Fujita 2016]
[Watanabe, Komatsu 2020]

- Beyond GR: $g(\chi)R^{\mu\nu}\,\tilde{R}_{\mu\nu} \in \mathcal{L}$

[Bartolo, Orlando 2017, 2018]

Unstable polarisation that sources **chiral** GWs:

$$\gamma_L \gg \gamma_R$$

Chirality $\chi = \frac{|P^L_\gamma - P^R_\gamma|}{P^{\rm tot}_\gamma}$ can be measured

Also the possibility of other modes in the GWs

DISTINCTIVE FEATURES OF THE SGWB

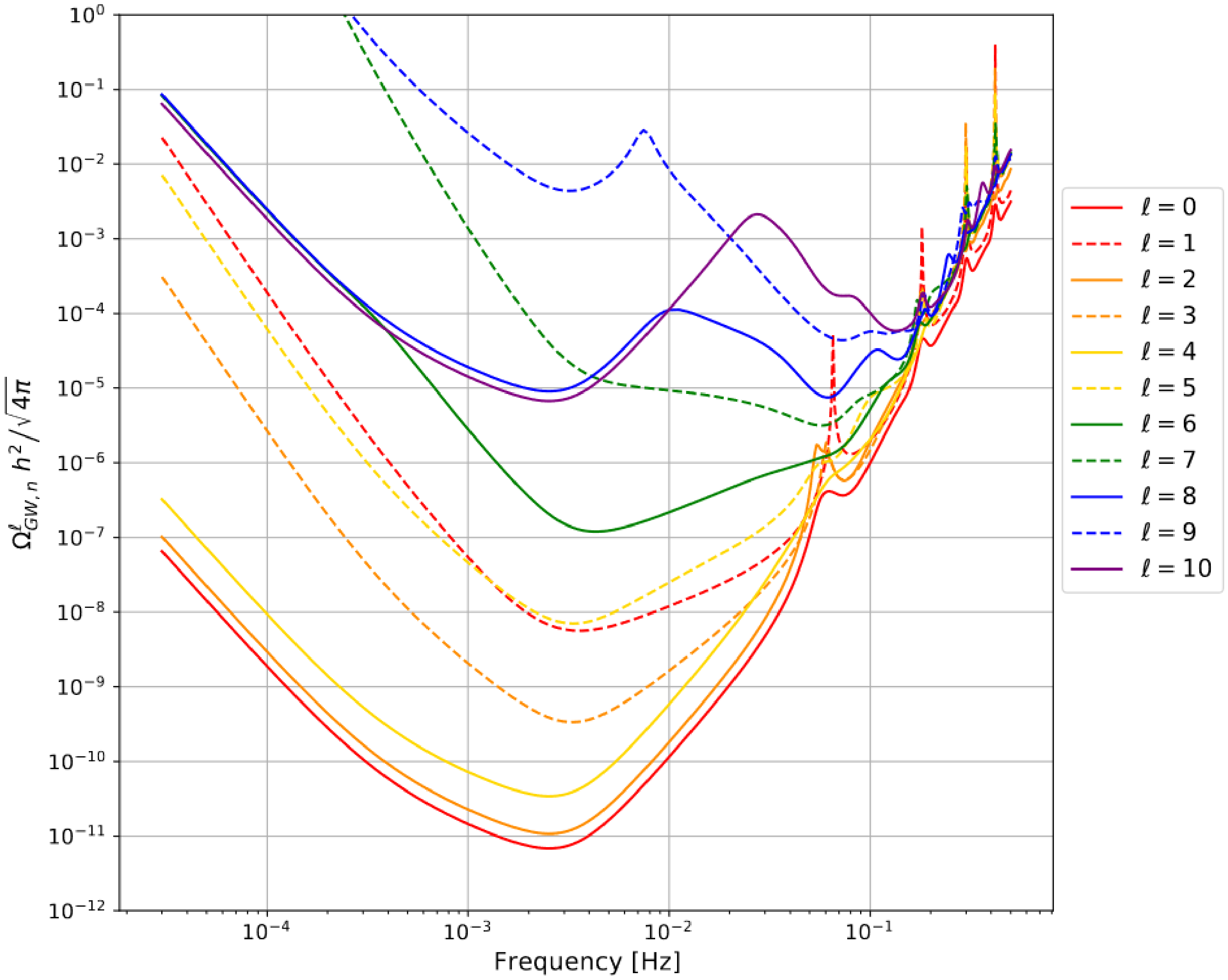
Anisotropies:

$$\Omega_{GW}(f,\hat{n}) = \bar{\Omega}_{GW}(f)\left(1 + \boldsymbol{\delta_{GW}(f,\hat{n})}\right)$$

$$\boldsymbol{a_{\ell,m}} = \int \mathrm{d}\Omega \; Y_{\ell,m}(\hat{n})\boldsymbol{\delta_{GW}(\hat{n})}$$

$$\boldsymbol{C_\ell} = \frac{1}{2\ell+1}\sum_m \boldsymbol{a^*_{\ell,m} a_{\ell,m}}$$

Different sources give different anisotropies



[Bartolo *et al.*, LISA Cosmology Working Group 2022]

SEVERAL SOURCES OF ANISOTROPIES

- GWs signal from astrophysical sources expected to be anisotropic

  [Cusin *et al*. 2017, 2018, 2019]

  [Bertacca *et al*. 2019]

  [Bellomo *et al*. 2021]

- Cosmological background propagates through structures → anisotropic

  [Alba, Maldacena 2015]

  [Contaldi *et al*. 2016]

  [Bartolo *et al*. 2018, 2019] *These anisotropies inherit a non-Gaussian statistics from propagation*

  [Domcke, Jinno, Rubira 2020]

- Primordial NGs also induce anisotropies:

  [Jeong, Kamionkowski 2012] *Anisotropies of the LSS from the same effect*

  [Brahma, Nelson, Chandera 2013]

  [Dimastrogiovanni *et al*. 2014, 2015, 2021]

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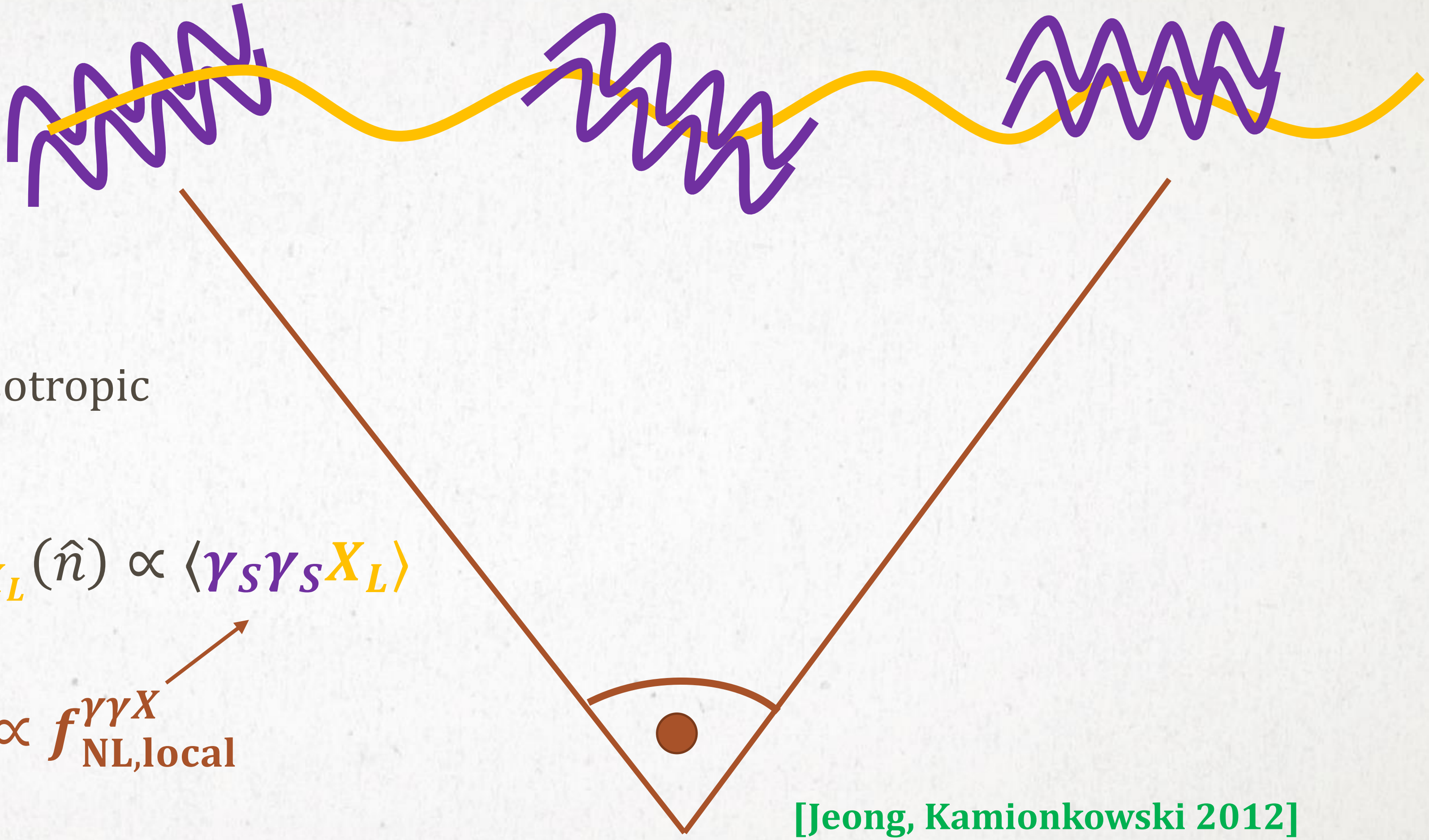
PNG-INDUCED ANISOTROPIES IN THE SGWB

- The idea:



Consider the modulation of
two short modes by a **long one**:
seen from far away the signal is anisotropic

$$\langle \gamma_S \gamma_S \rangle \to \delta_{\mathrm{GW}}(\hat{n}, f_s) \propto \langle \gamma_S \gamma_S \rangle_{X_L}(\hat{n}) \propto \langle \gamma_S \gamma_S X_L \rangle$$

$$\frac{\Omega_{\mathrm{GW}}(\hat{n}, f)}{\bar{\Omega}_{\mathrm{GW}}(f)} - 1 \qquad \propto f_{\mathrm{NL,local}}^{\gamma\gamma X}$$

[Jeong, Kamionkowski 2012]

Here γ_s is a tensor (anisotropies of the SGWB) but first introduced for scalars (anisotropies of LSS)

Also X_L can be ζ_L (modulation by a soft scalar mode) or γ_L (modulation by a soft tensor mode)

INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

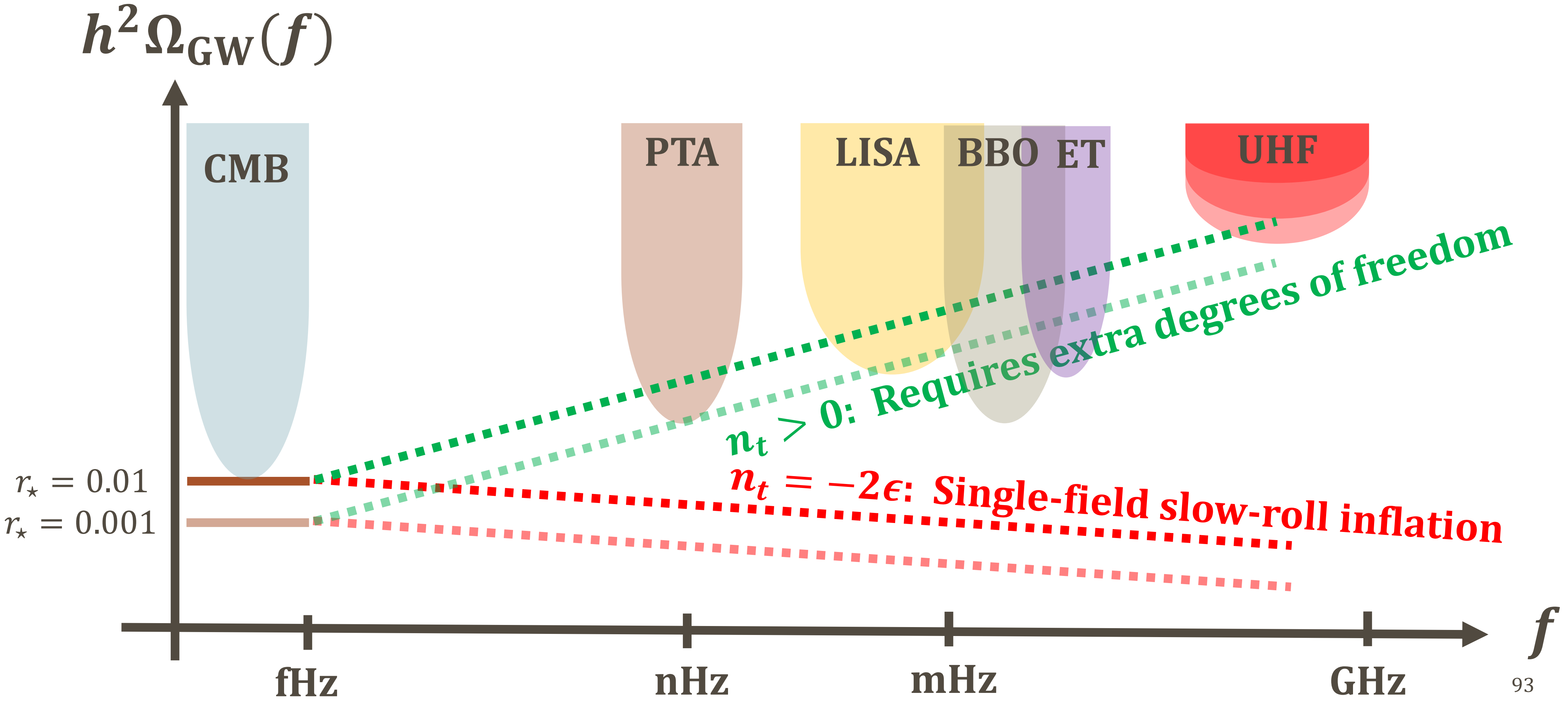
of primordial origin!

- Having an observable monopole signal

INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

of primordial origin!

- Having an observable monopole signal → smaller scales, requires a blue tilt: $n_t > 0$



INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

of primordial origin!

- Having an observable monopole signal: $n_t > 0$

- Having large STT or TTT bispectra in the (ultra) squeezed limit

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- Having an observable monopole signal: $n_t > 0$

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$$\left\langle \gamma_{\vec{k}_1}^{\lambda_1} \gamma_{\vec{k}_2}^{\lambda_2} \right\rangle_{\gamma_{\vec{q}_L}} = \sum_{\lambda_3} \int_{|\vec{q}|<q_L} d^3q\, \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{q}) \gamma_{\mathbf{q}}^{*\lambda_3} \frac{B_\gamma^{\lambda_1\lambda_2\lambda_3}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{q})}{P_\gamma^{\lambda_3}(q)}$$

"heuristic" formula of the literature

[Ricciardone, Tasinato 2017]

[Dimastrogiovanni, Fasiello, Tasinato 2019]

INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

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- Having large STT or TTT bispectra in the (ultra) squeezed limit: $f_{\rm NL,sq}^{\zeta\gamma\gamma},\ f_{\rm NL,sq}^{\gamma\gamma\gamma} \gg 1$

- That this squeezed limit is not due to spurious residual gauge artifacts

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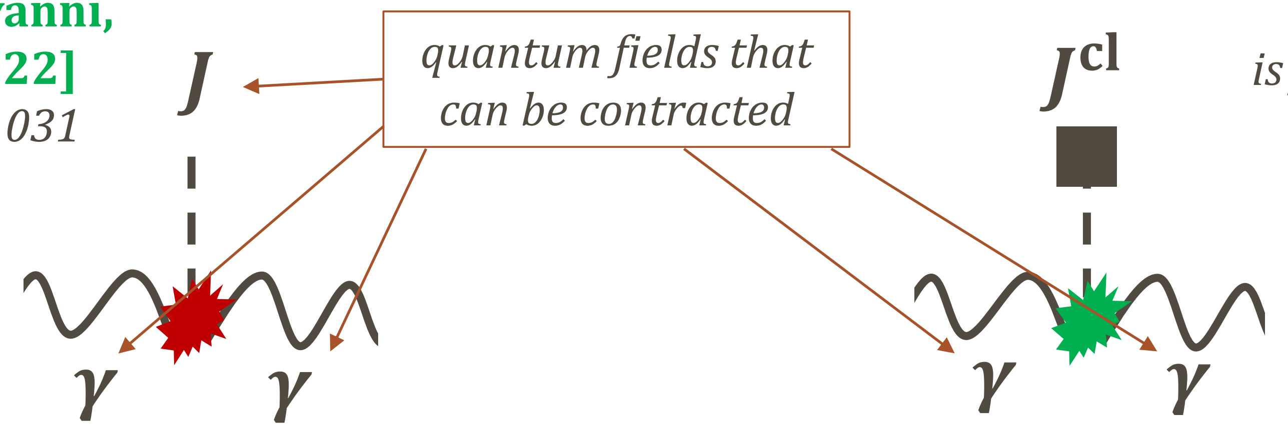
This work: ❖ Go beyond the heuristic approach and **compute** the two-point function with a classical source

[Dimastrogiovanni, Fasiello, LP 2022]
JCAP 09 (2022) 031



classical field that is factored out of vevs

For a QED example see
[Peskin, Schroeder 1995]

INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

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[Dimastrogiovanni, Fasiello, LP 2022]
JCAP 09 (2022) 031

This work: ❖ Go beyond the heuristic approach and **compute** the two-point function with a classical source

$$\boxed{\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}\rangle_{J^{\mathrm{cl}}} \underset{|\vec{k}_1+\vec{k}_2| \ll k_{1,2}}{=} \int \mathrm{d}^3\vec{q}\ \delta^{(3)}(\vec{q}+\vec{k}_1+\vec{k}_2)P_\gamma(k_1)\boldsymbol{f}_{\mathbf{NL,sq}}^{\boldsymbol{J\gamma\gamma}}(\vec{k}_1,\vec{k}_2,\vec{q})\boldsymbol{J}^{\mathbf{cl}}(\vec{\boldsymbol{q}})}$$

Non-diagonal part, $\vec{k}_1+\vec{k}_2 \neq \vec{0}$, of the 2-pt function does not vanish → anisotropies

$\boldsymbol{J}^{\mathbf{cl}}(\vec{\boldsymbol{q}})$ is a statistical quantity → so is $\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}\rangle_{J^{\mathrm{cl}}}$ → $\langle \delta(\hat{n}_1)\delta(\hat{n}_2)\rangle \propto \langle J^{\mathrm{cl}}(\vec{q})J^{\mathrm{cl}}(\vec{q}\,')\rangle \neq 0$

INGREDIENTS FOR OBSERVABLE GW ANISOTROPIES

of primordial origin!

- Having an observable monopole signal: $\boldsymbol{n_t > 0}$ **1**

- Having large STT or TTT bispectra in the (ultra) squeezed limit: $\boldsymbol{f^{\zeta\gamma\gamma}_{\mathrm{NL,sq}},\ f^{\gamma\gamma\gamma}_{\mathrm{NL,sq}} \gg 1}$ **2**

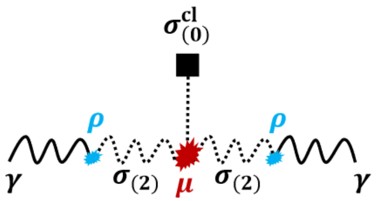
- That this **squeezed limit is not due to spurious residual gauge artifacts** **3**

[Dimastrogiovanni, Fasiello, LP 2022]
JCAP 09 (2022) 031

This work:
- Go beyond the heuristic approach and compute the two-point function with a classical source
- Prove that some already existing inflationary models verify **all 3 requirements above**

Example 1: EFT of spin-2 field
[Bordin *et al.* 2018]

$$\sigma_{ij} = \partial_i\partial_j\sigma^{(0)} + \sigma^{(2)}_{ij}$$

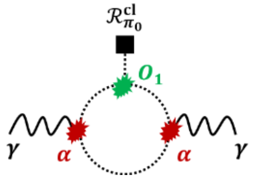


Example 2: Supersolid inflation
[Celoria *et al.* 2021]

Two scalars (ζ_n, R_{π_0})

adiabatic

entropic



$$\boldsymbol{\delta_{\mathrm{GW}}(\hat{n}) \geq 10\%}$$

Scalar-trispectrum-induced GW: a no-go theorem

SCALAR-INDUCED GW

- At horizon re-entry in the radiation era:

$$\gamma_k'' + 2\mathcal{H}\gamma_k' + k^2\gamma_k = \mathcal{S}_k \left\{ \begin{array}{l} \text{Source term including scalar perturbations at quadratic order} \\ \\ \propto \int \mathrm{d}^3\vec{q}\ (\ldots)\zeta_{\vec{q}}\zeta_{\vec{k}-\vec{q}} \end{array} \right.$$

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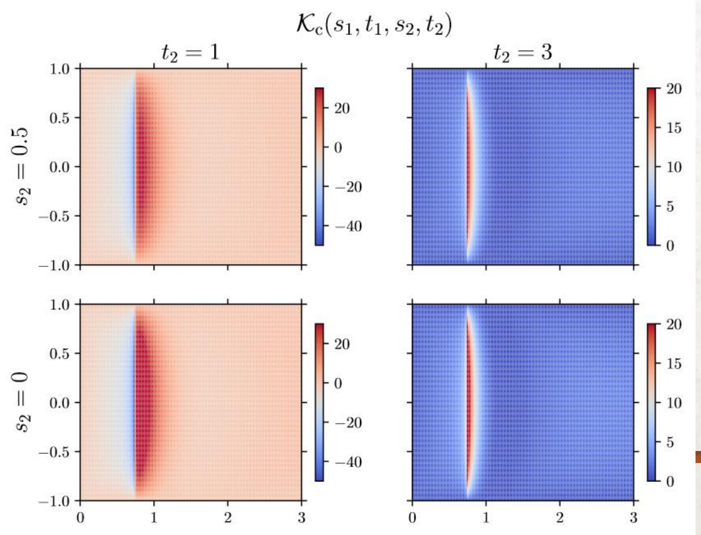
- The tensor two-point function is proportional to the scalar four-point function:

$$P_\gamma(k) = \int \mathrm{d}^3\vec{q}_1 \int \mathrm{d}^3\vec{q}_2\ \mathcal{K}(\vec{q}_1, \vec{q}_2) \times \langle \zeta_{\vec{q}_1}\zeta_{\vec{k}-\vec{q}_1}\zeta_{-\vec{q}_2}\zeta_{-\vec{k}+\vec{q}_2} \rangle$$

general kernel

[Adshead, Lozanov, Weiner 2021]
[Garcia-Saenz, LP, Renaux-Petel, Werth 2022]
ArXiv: 2207.14267



we discuss its symmetries etc.

SCALAR-INDUCED GW

- At horizon re-entry in the radiation era:

$$\gamma_k'' + 2\mathcal{H}\gamma_k' + k^2\gamma_k = \mathcal{S}_k \left\{ \begin{array}{l} \text{Source term including scalar perturbations at quadratic order} \\ \\ \propto \int \mathrm{d}^3\vec{q}\ \ (\dots)\zeta_{\vec{q}}\zeta_{\vec{k}-\vec{q}} \end{array} \right.$$

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Disconnected (Gaussian) piece:

$$(2\pi)^3\delta^{(3)}(\vec{q}_1 - \vec{q}_2)P_\zeta(q_1)P_\zeta\left(\left|\vec{k} - \vec{q}_1\right|\right)$$

$+$ perm.

[Many works]

Connected (non-Gaussian) piece:

$$T_\zeta\left(\vec{q}_1, \vec{k} - \vec{q}_1, -\vec{q}_2, -\vec{k} + \vec{q}_2\right)$$

[Garcia-Saenz, LP, Renaux-Petel, Werth 2022]
ArXiv: 2207.14267

SCALAR-TRISPECTRUM-INDUCED GW

- ❖ Only a few recent works working out *some* scalar trispectrum effects:

[Garcia-Bellido, Peloso, Unal 2017]
[Unal 2018]
[Atal, Domenech 2021]
[Adshead, Lozanov, Weiner 2021]

- ❖ But *all* limited themselves to **local non-linearities:** $\zeta = \zeta_G + f_{\rm NL}^{\rm loc}\zeta_G^2$

renormalizes the power spectrum: $P_\zeta = P_{\zeta_G} + 3 f_{\rm NL}^2 \left(P_{\zeta_G}\right)^2$

induces NGs: $\langle \zeta^4 \rangle_{\rm connected} \propto f_{\rm NL}^2 P_{\zeta_G}^3 + \mathcal{O}\left(f_{\rm NL}^3\right)$

… and did not check perturbative control → large effects from NGs

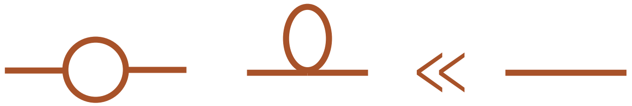
NO-GO THEOREM FOR SCALAR-TRISPECTRUM-INDUCED GW

Lemma. Given real symmetric matrices $\boldsymbol{A}$ and $\boldsymbol{B}$, with $\boldsymbol{A}$ positive definite, then $\boldsymbol{C} \equiv \boldsymbol{AB}$ is diagonalizable (over the complex numbers) and has real eigenvalues.

<u>This work</u>:

[Garcia-Saenz, LP, Renaux-Petel, Werth 2022]
ArXiv: 2207.14267

- ❖ we investigate motivated scalar trispectrum shapes
- ❖ **AND** we check perturbative control $\longrightarrow$ **small loops:**



	Shape	$\Omega^{\rm GW}_{\rm connected}/\Omega^{\rm GW}_{\rm disconnected}$	Perturbativity bound
Local shapes	$g_{\rm NL}$	0	...
	$\tau_{\rm NL}$	$\mathbf{4} \times \tau_{\rm NL}\mathcal{P}_\zeta \log(kL)$	$\tau_{\rm NL}\mathcal{P}_\zeta \log(kL) \ll 1$
"Equilateral" shapes: interactions from EFToI	$t_{\rm NL}^{\dot\zeta^4}, t_{\rm NL}^{\dot\zeta^2(\partial\zeta)^2}, t_{\rm NL}^{(\partial\zeta)^4}$	0 or negligible	...
	$t_{\rm NL}^{[\dot\zeta^3]^2}, t_{\rm NL}^{[\dot\zeta(\partial\zeta)^2]^2}, t_{\rm NL}^{\dot\zeta^3\times\dot\zeta(\partial\zeta)^2}$	$\boldsymbol{\mathcal{O}(10^{-1})} \times (H/\Lambda_\star)^4$ **Numerically computed coefficient**	$H/\Lambda_\star \ll 1$
"Cosmo. collider" shapes: exchange of massive and spinning fields	$\tau_{\rm NL}^{\rm exchange}(\Delta, S)$	$\mathbf{4\boldsymbol{f}(\Delta,S)} \times \tau_{\rm NL}\mathcal{P}_\zeta \log(kL)$	?

$\boldsymbol{f(\Delta,S) < 1}$

***L* is the size of the Universe (IR cutoff)**

$\Lambda_\star$ is the smallest strong coupling scale

CONCLUSION…

- Primordial NGs contain much more information than a single number $f_{\mathrm{NL}}^{\mathrm{local}}$

- Depending on the mass spectrum, mixing angles and interactions of primordial field content, scalar and tensor PNGs are of different **amplitudes** and **shapes**

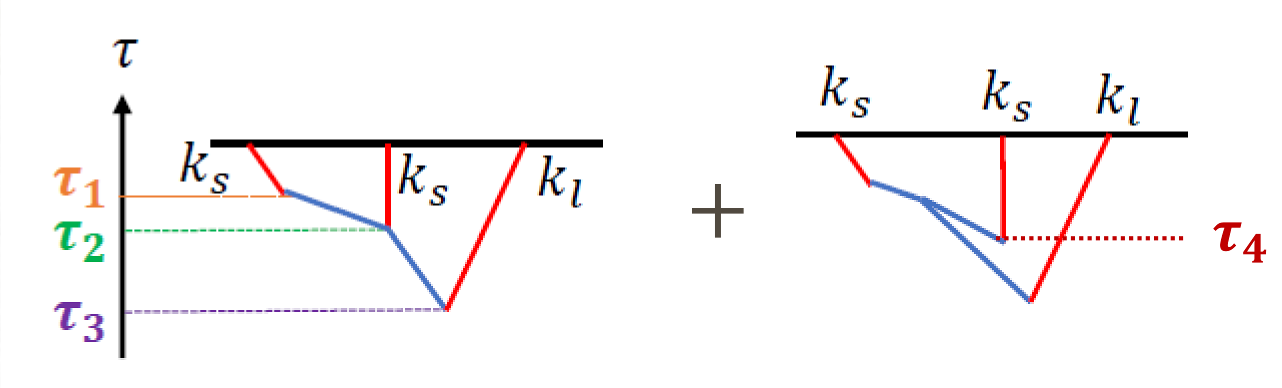
- Small-scale ultra-squeezed STT and TTT PNGs survive in the form of induced anisotropies in the SGWB

- The scalar trispectrum sources GWs at horizon re-entry but its relative contribution must remain small IN SCALE-INVARIANT MODELS

  → **Warning for scale-dependent models: compute perturbativity bounds!**

→ **Formidable opportunity to use the non-linear Universe as a particle detector**

… AND PROSPECTS

- Cosmic spectroscopy computed for:
  - Single-exchange diagram. What about  ?

    What about exchange of spinning fields?
  - Quadratic coupling ω treated perturbatively. What about large mixing?

    → **[Werth, Pinol, Renaux-Petel *in prep.*]**

  - Observational constraints and forecast. What are the current constraints? How better will we do with LSS?

- PNGs and GWs:
  - Realistic trispectrum shape for models with small-scale enhancement and GWs contribution.
  - Anisotropies from other soft limits of higher-order correlation functions

BACK UP SLIDES

ANISOTROPIES

SEVERAL SOURCES OF ANISOTROPIES

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PNG-INDUCED ANISOTROPIES

[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

- Formal derivations with the in-in formalism:
  - We look for interactions between small and large scales → $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\gamma}$ and $f^{\mathrm{sq}}_{\mathrm{NL},\gamma\gamma\zeta}$
  - A long-wavelength mode J_L can be treated classicaly and has negligible derivatives:

$$\hat{J}_L = J_L(\tau)\hat{a}_{\vec{k}} + J_L^*(\tau)\hat{a}^\dagger_{-\vec{k}} \rightarrow J_L^{\mathrm{cl}}(\tau)\underbrace{\left(\hat{a}_{\vec{k}} + \hat{a}^\dagger_{-\vec{k}}\right)}_{\boldsymbol{b}_{\vec{k}}} \quad ; \quad \left(\partial_i J_L^{\mathrm{cl}}, \partial_t J_L^{\mathrm{cl}}\right) \text{ are negligible}$$

$$\left[\hat{a}_{\vec{k}}, \hat{a}^\dagger_{\vec{k}'}\right] = (2\pi)^3\delta^{(3)}(\vec{k}-\vec{k}') \qquad \left[b_{\vec{k}}, b^\dagger_{\vec{k}'}\right] = 0$$

<u>Ex</u>: massless scalar perturbation $\quad Q_k(\tau) = \dfrac{e^{-ik\tau}}{\sqrt{2k^3}}(1+ik\tau) \underset{-k\tau\rightarrow 0}{\rightarrow} \dfrac{1}{\sqrt{2k^3}}$ purely real

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[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

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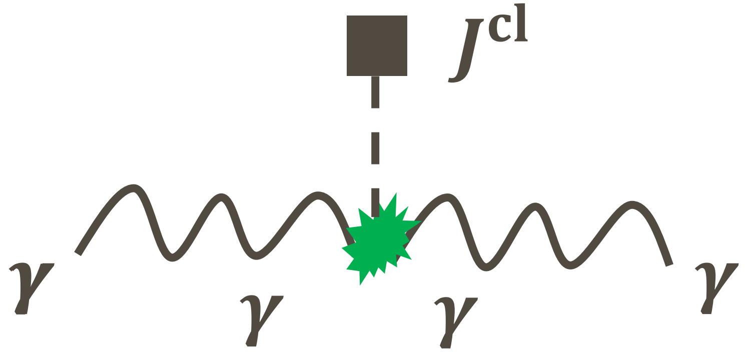
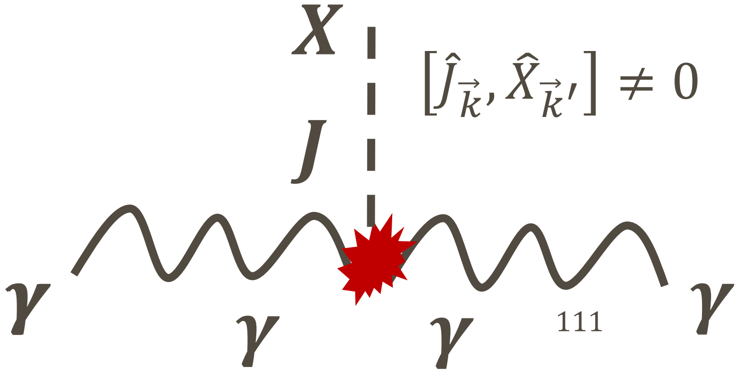
  - ❖ A **3-pt interaction** involving J_L becomes a **2-pt interaction** times a classical source $J_L^{\rm cl}$
  - ❖ 2-pt functions in the presence of a classical source are now defined:

$$<\gamma_{\vec{k}_1}\gamma_{\vec{k}_2}>_{J^{\rm cl}}$$

$$\langle\gamma_{\vec{k}_1}\gamma_{\vec{k}_2}X_{\vec{k}_3}\rangle = (2\pi)^3\,\delta^3\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)B^{\gamma\gamma X}$$





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$$\hat{J}_L = J_L(\tau)\hat{a}_{\vec{k}} + J_L^*(\tau)\hat{a}^\dagger_{-\vec{k}} \to J_L^{\rm cl}(\tau)\left(\hat{a}_{\vec{k}} + \hat{a}^\dagger_{-\vec{k}}\right) \quad ; \quad \left(\partial_i J_L^{\rm cl}, \partial_t J_L^{\rm cl}\right) \text{ are negligible}$$

  - A **3-pt interaction** involving J_L becomes a **2-pt interaction** times a classical source $J_L^{\rm cl}$
  - 2-pt functions in the presence of a classical source are now defined
  - We compute both diagrams with the in-in formalism and are therefore able to relate them:

$$\boxed{\langle \gamma_{\vec{k}_1}\gamma_{\vec{k}_2}\rangle_{X^{\rm cl}} \underset{|\vec{k}_1+\vec{k}_2| \ll k_{1,2}}{=} \int {\rm d}^3\vec{q}\ \delta^{(3)}(\vec{q}+\vec{k}_1+\vec{k}_2)P_\gamma(k_1) f^{\gamma\gamma X}_{\rm NL,sq}(\vec{k}_1,\vec{k}_2,\vec{q})X^{\rm cl}(\vec{q})}$$

Derivation makes clear that the non-diagonal part of the 2-pt function does not vanish → anisotropies

J can be X (the formula reduces then to the one in the literature), or not but you need $[\hat{J},\hat{X}] \neq 0$

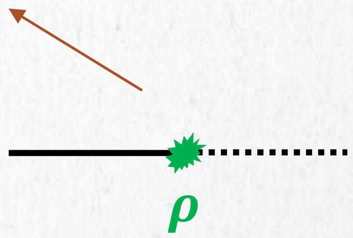
MULTIFIELD MODELS WITH LARGE ANISOTROPIES

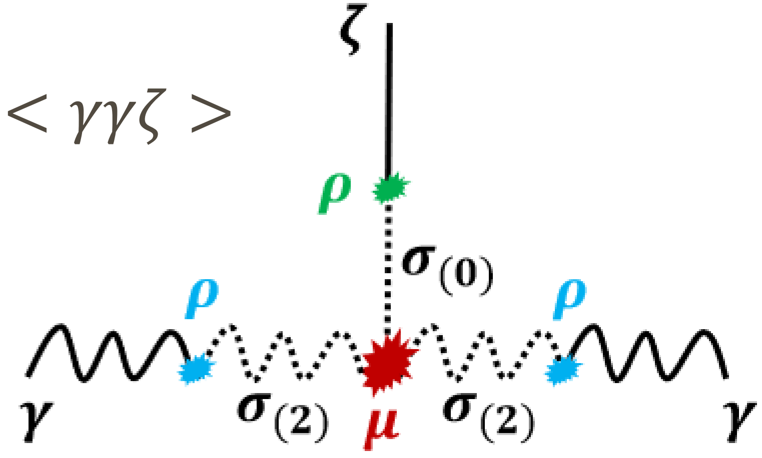
- Spin-2 EFT of inflation: $\sigma_{ij} = \partial_i \partial_j \sigma^{(0)} + \sigma_{ij}^{(2)}$ **[Bordin *et al.* 2018]**

$\rightarrow$ $\sigma^{(2)}$ couples linearly to γ and can enhance the tensor power spectrum: $A_t / \frac{2H^2}{M_{Pl}^2} \sim \frac{\rho^2}{c_2^3}$

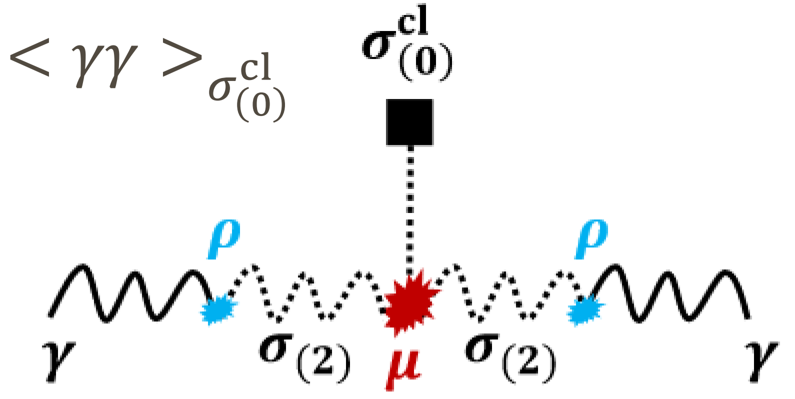
make the tilt blue: $n_t \sim -3\, \partial_t c_2 / (H\, c_2)$

We compute anisotropies explicitly and find: $\sqrt{< \delta_{GW}^2(k_S, \hat{n}) >} \sim \frac{< \gamma\gamma\zeta > (k_S, k_S, k_L)}{P_\gamma(k_S) P_{\zeta\sigma^{(0)}}(k_L)} \sqrt{\mathcal{P}_{\sigma^{(0)}}(k_L)}$





(a) Mixed scalar-tensor-tensor bispectrum.



(b) Tensor two-point function in the presence of a classical scalar source.

[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

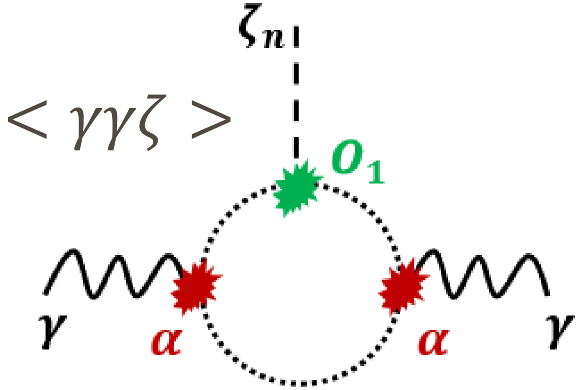
MULTIFIELD MODELS WITH LARGE ANISOTROPIES

- Supersolid inflation: two fundamental scalar fluctuations $(\overset{\text{adiabatic}}{\zeta_n}, \overset{\text{entropic}}{R_{\pi_0}})$ **[Celoria *et al.* 2021]**

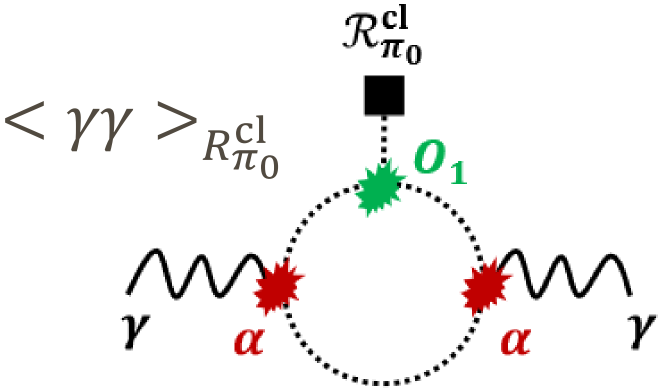
→ R_{π_0} couples **quadratically** to γ and can enhance the tensor power spectrum: $A_t / \frac{2H^2}{M_{Pl}^2} > 1$

make the tilt blue: $n_t = 2(n_s^{\text{en}} - 1) > 0$

We compute anisotropies explicitly and find: $\sqrt{< \delta^2_{GW}(k_S, \hat{n}) >} \sim \underbrace{f_{\text{NL,sq}}^{\gamma\gamma\zeta_n}(k_S, k_S, k_L)}_{\gg 1} \underbrace{\left(\sqrt{\frac{\mathcal{P}_{\zeta_n}\mathcal{P}_{R_{\pi_0}}}{\mathcal{P}_{\zeta_n R_{\pi_0}}}}\right)_{k_L}}_{\mathcal{O}(1)} \underbrace{A_s^{1/2}}_{4\times 10^{-5}}$



(b) One-loop scalar-tensor-tensor bispectrum



(c) One-loop tensor two-point function in the presence of a classical scalar source.

[Dimastrogiovanni, Fasiello, LP 2022]
ArXiv:2203.17192

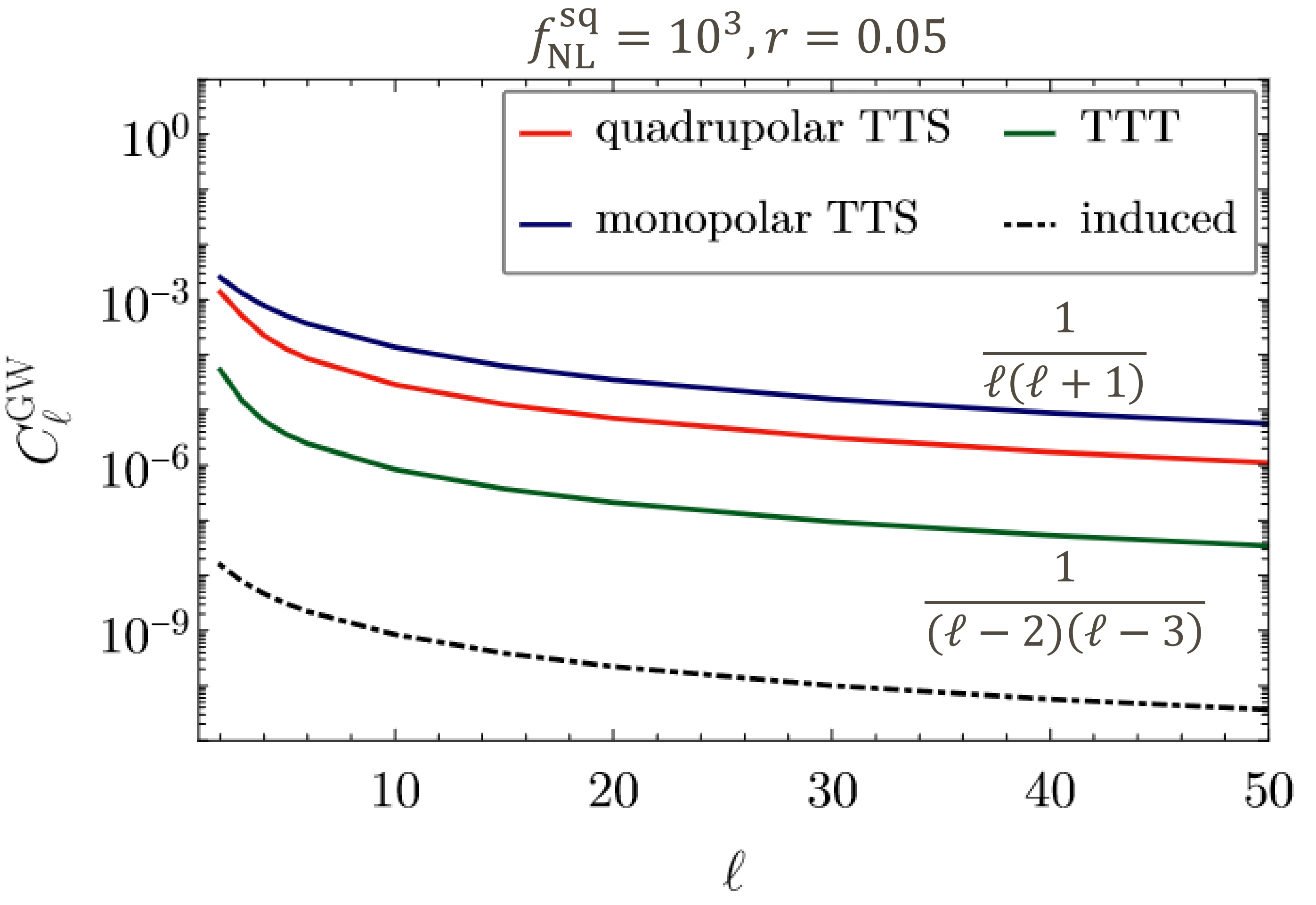
ℓ-DEPENDENCE

Anisotropies:

$$\Omega_{GW}(f,\hat{n}) = \bar{\Omega}_{GW}(f)\left(1 + \boldsymbol{\delta_{GW}(f,\hat{n})}\right)$$

$$\boldsymbol{a_{\ell,m}} = \int \mathrm{d}\Omega\ Y_{\ell,m}(\hat{n})\boldsymbol{\delta_{GW}(\hat{n})}$$

$$\boldsymbol{C_\ell} = \frac{1}{2\ell+1}\sum_m \boldsymbol{a^*_{\ell,m} a_{\ell,m}}$$

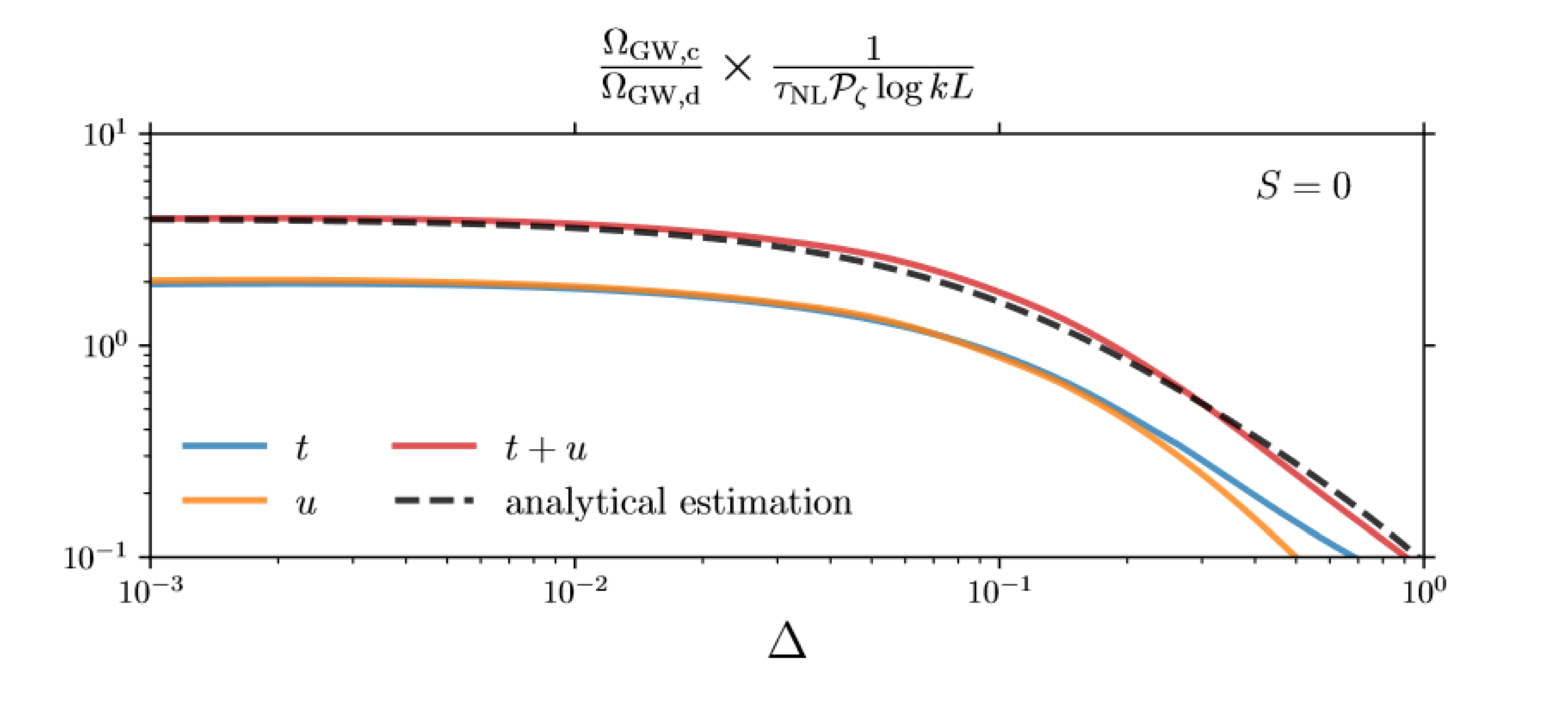


[Dimastrogiovanni *et al.* 2021]

BACK UP SLIDES

TRISPECTRUM INDUCED

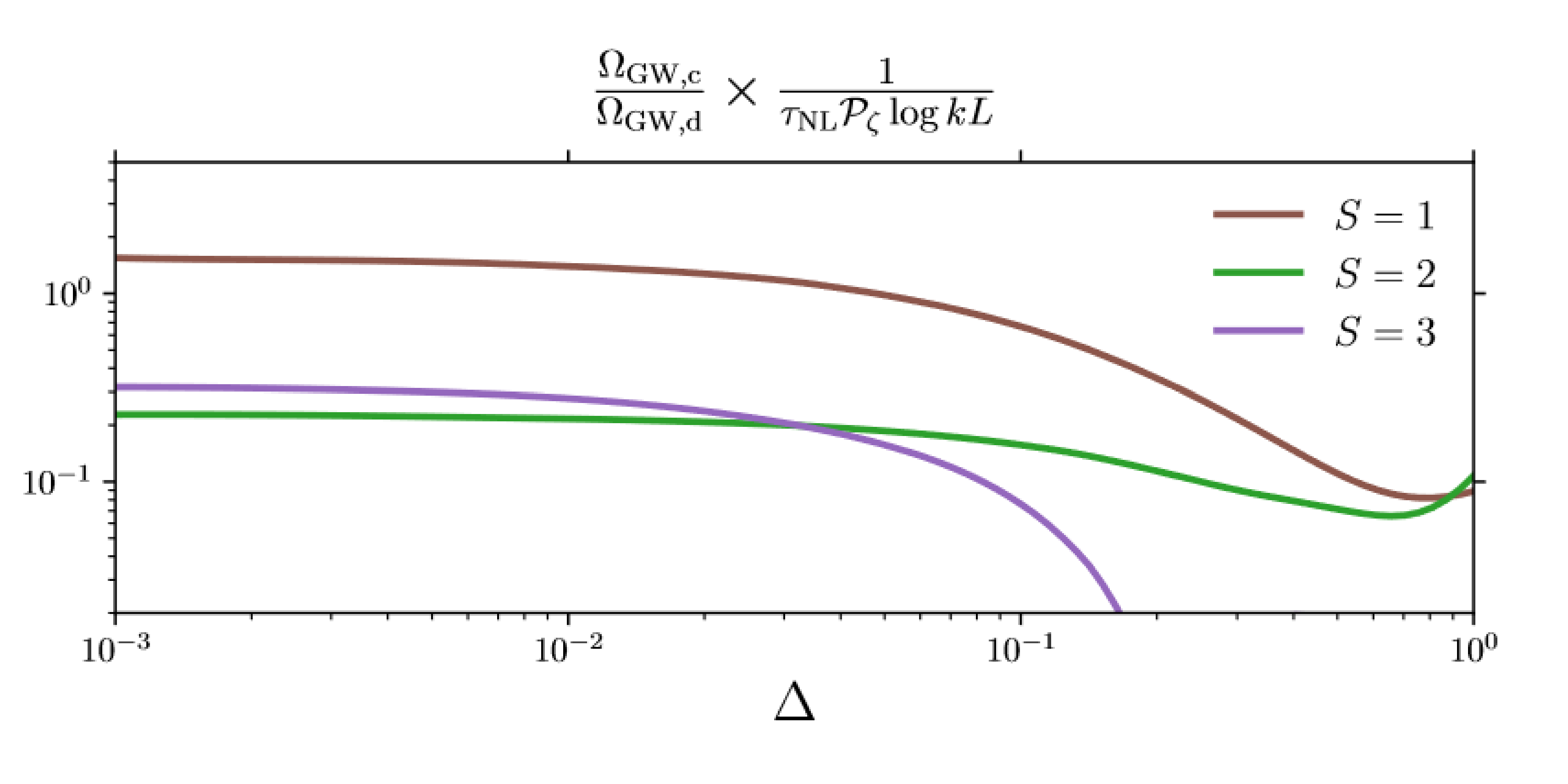
EXCHANGE OF A MASSIVE SCALAR FIELD



Analytical estimation:

$$\frac{\Omega_{\mathrm{GW,c}}}{\Omega_{\mathrm{GW,d}}} \simeq 4\,\tau_{\mathrm{NL}} \mathcal{P}_\zeta \,\frac{\alpha^{2\Delta}}{2\Delta}\left[1 - e^{-2\Delta \log kL}\right]$$

EXCHANGE OF A MASSIVE SPINNING FIELD



BACK UP SLIDES

SCALAR PNG

BISPECTRUM IN MULTIFIELD INFLATION

The squeezed limit as a cosmological collider

Remember the single-field result: $\boxed{\begin{array}{c} f_{\rm NL}^{\rm squeezed} \propto n_s - 1 \ll 1 \\ \textit{universal relation} \end{array}}$

Two-field result:

[Chen, Wang 2009]

[Noumi, Yamaguchi, Yokoyama 2013] (one extra heavy field $m_s > 3H/2$, perturbatively coupled)

[Arkani-Hamed, Maldacena 2015]

[Arkani-Hamed, Baumann, Lee, Pimentel 2018]

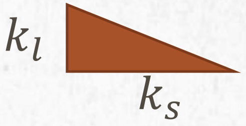
BISPECTRUM IN MULTIFIELD INFLATION

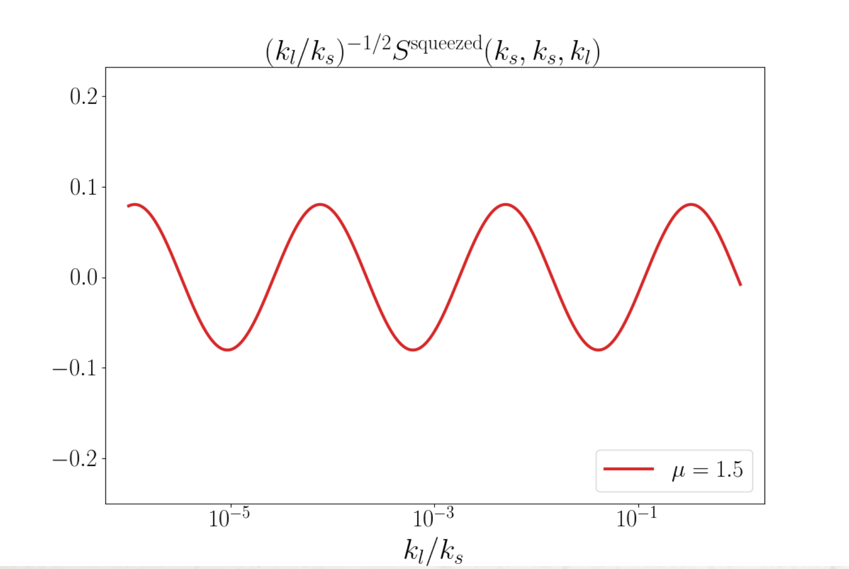
The squeezed limit as a cosmological collider

[Noumi, Yamaguchi, Yokoyama 2013]

Small coupling between the two fields : $\eta_\perp \ll 1$

Two-field result: $$f_{\mathrm{NL}}^{\text{squeezed}} \underset{k_l \ll k_s}{\simeq} \eta_\perp^2 e^{-\pi\mu} \cos\left[\mu \log\left(\frac{k_l}{k_s}\right)\right]$$





Oscillatory pattern: massive particle

$\mu = \sqrt{\frac{m_s^2}{H^2} - \frac{9}{4}}$ **the reduced mass**

Boltzmann suppression for heavy particles

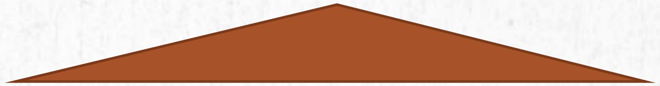
$H/2\pi \sim T$ so $\mathrm{e}^{-\pi\mu} \sim e^{-\frac{m_s}{T}}$

BISPECTRUM IN MULTIFIELD INFLATION

Probing other regimes

- Large coupling, $\eta_\perp \gg 1 \rightarrow$ Multifield instability $\rightarrow$ Large flattened NGs:

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

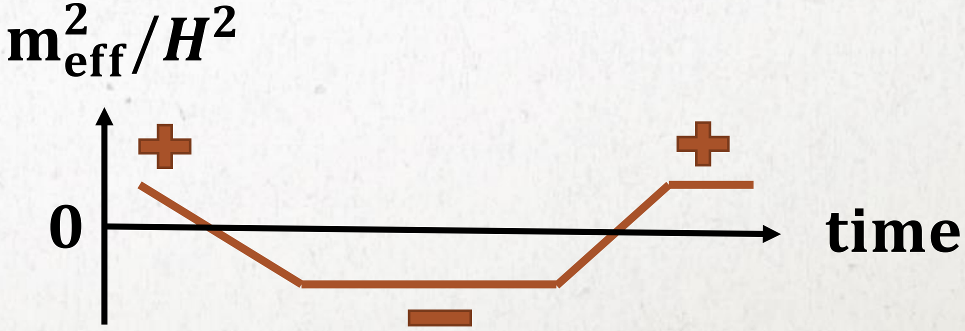


$f_{\mathrm{NL}}^{\mathrm{flat}} = \mathcal{O}(50)$

Higher-order correlation functions are boosted in similar configurations

$g_{\mathrm{NL}}^{\mathrm{flat}} = \mathcal{O}(10^5)$ etc.

Clear sign of transiently unstable degrees of freedom:



BISPECTRUM IN MULTIFIELD INFLATION

Probing other regimes

- Large mass, $|m_s^2| \gg H^2 \;\rightarrow$ Single-field effective theory for ζ

  (including the instability with $m_s^2 < 0$*)*

$$f_{\mathrm{nl}}^{\mathrm{eq}} \simeq \left(\frac{1}{c_s^2} - 1\right)\left(-\frac{85}{324} + \frac{15}{243}\boldsymbol{A}\right)$$

Speed of sound:
Dictated by the bilinear coupling $\eta_\perp$

[Achucarro, Gong, Hardeman, Palma, Patil 2012]

Single-field effective interactions
Dictated by the multifield cubic interactions

[Garcia-Saenz, Lucas Pinol, Renaux-Petel 2019]
J. High Energ. Phys. **2020,** 73 (2020)

Later extended to any number of heavy fields: **[Lucas Pinol 2020]** *J. Cosm. & Astro. Phys.* 04(**2021**)048