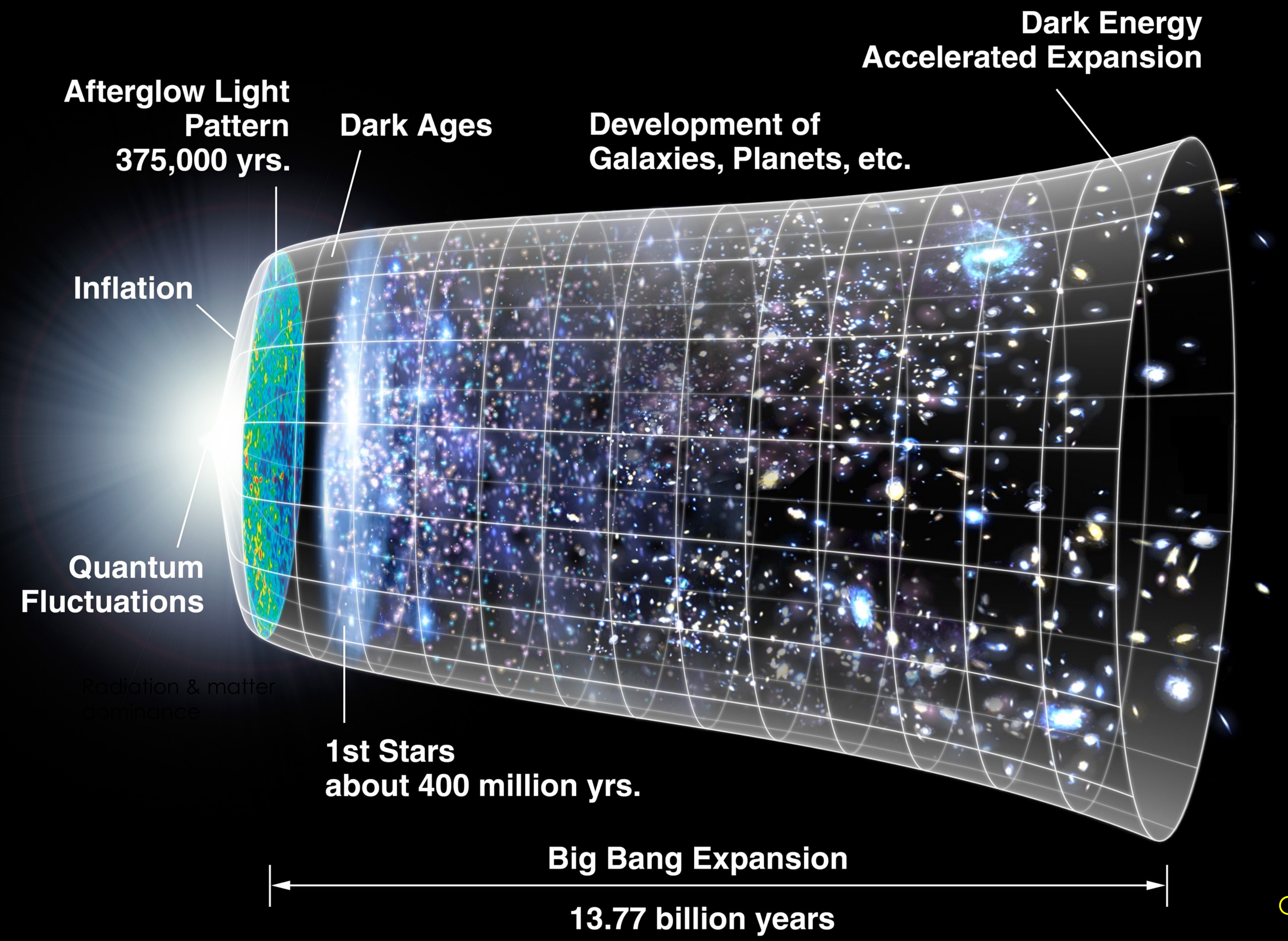
Non-Gaussianity in rapid-turn multi-field inflation

Oksana Iarygina

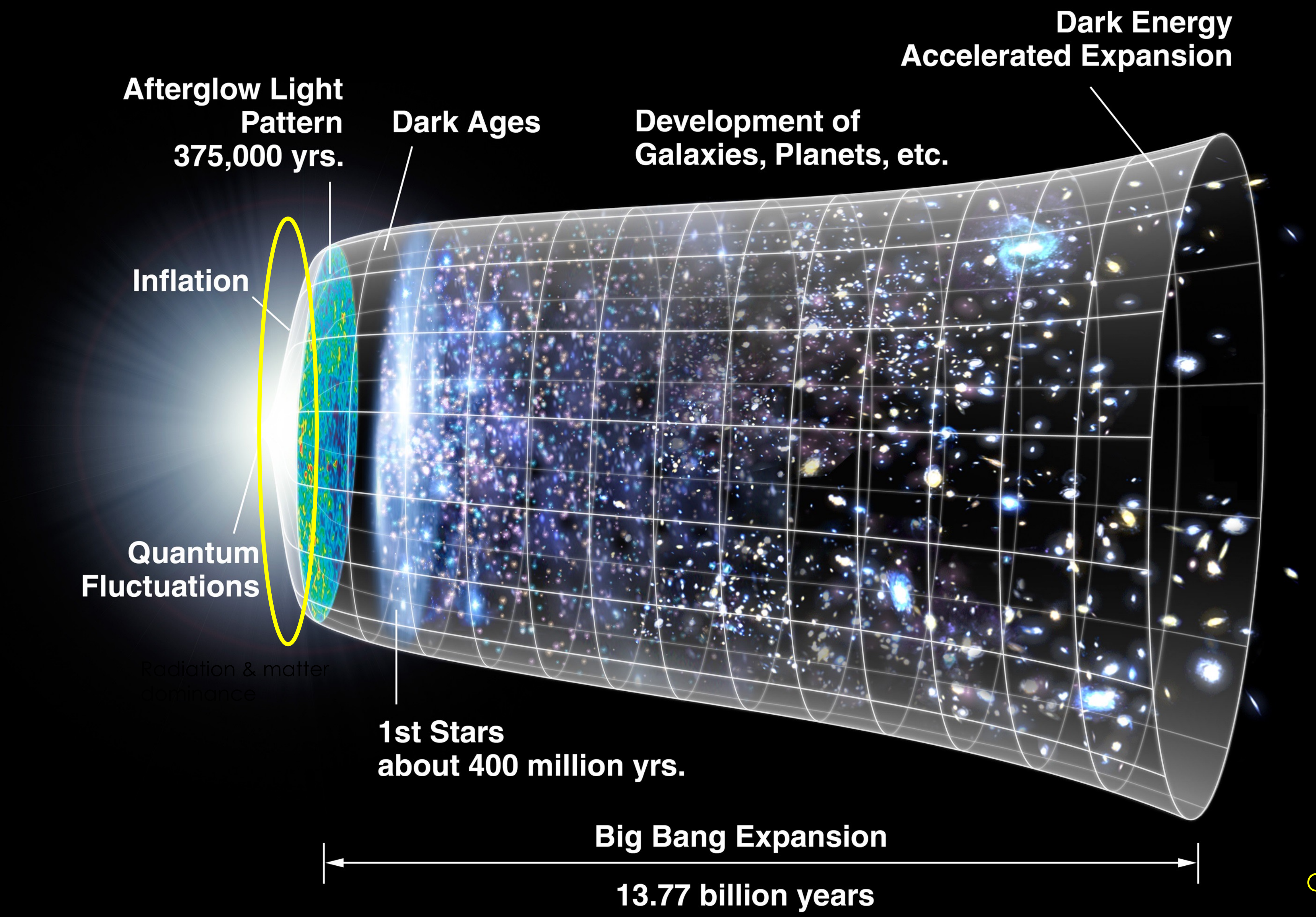
Cosmology from Home
July 2023

NORDITA
The Nordic Institute for Theoretical Physics

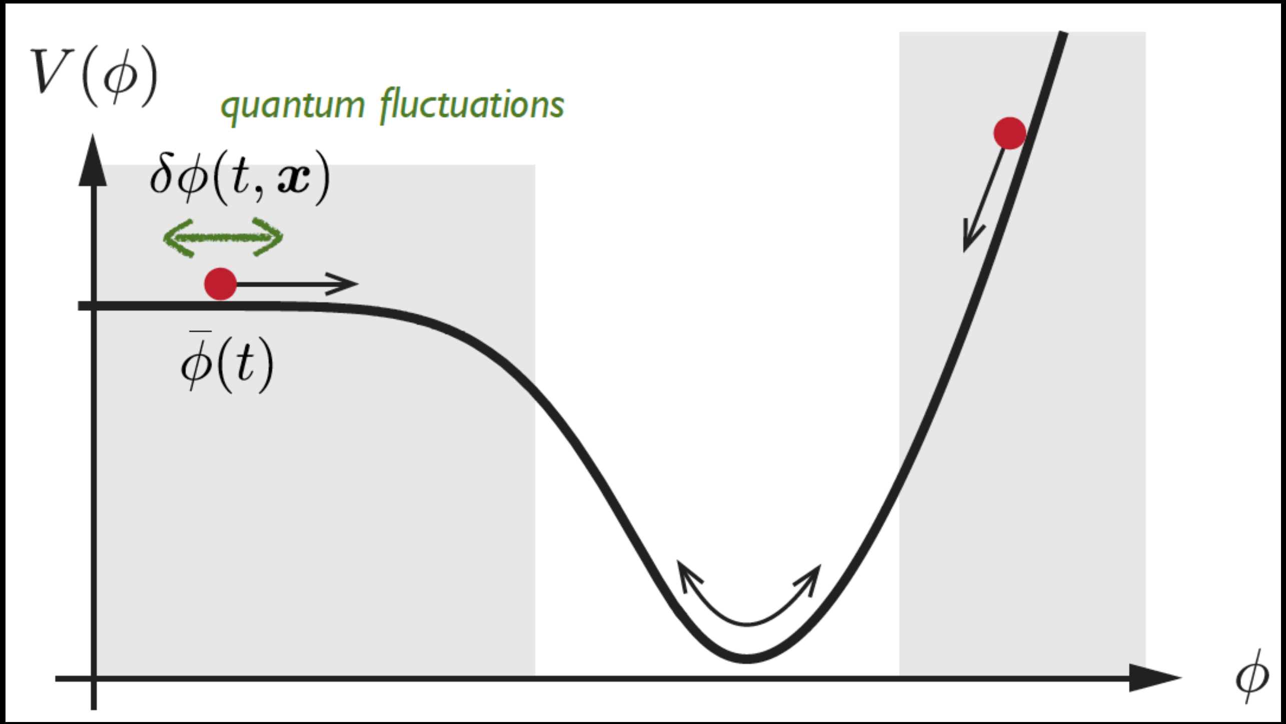
Early Universe cosmology



Early Universe cosmology



In the beginning, there was (probably) inflation



[Baumann]

$$\delta\phi(x) \longrightarrow \delta\rho(x) \longrightarrow \delta T(x)$$

Quantum vacuum fluctuations around the inflaton vev

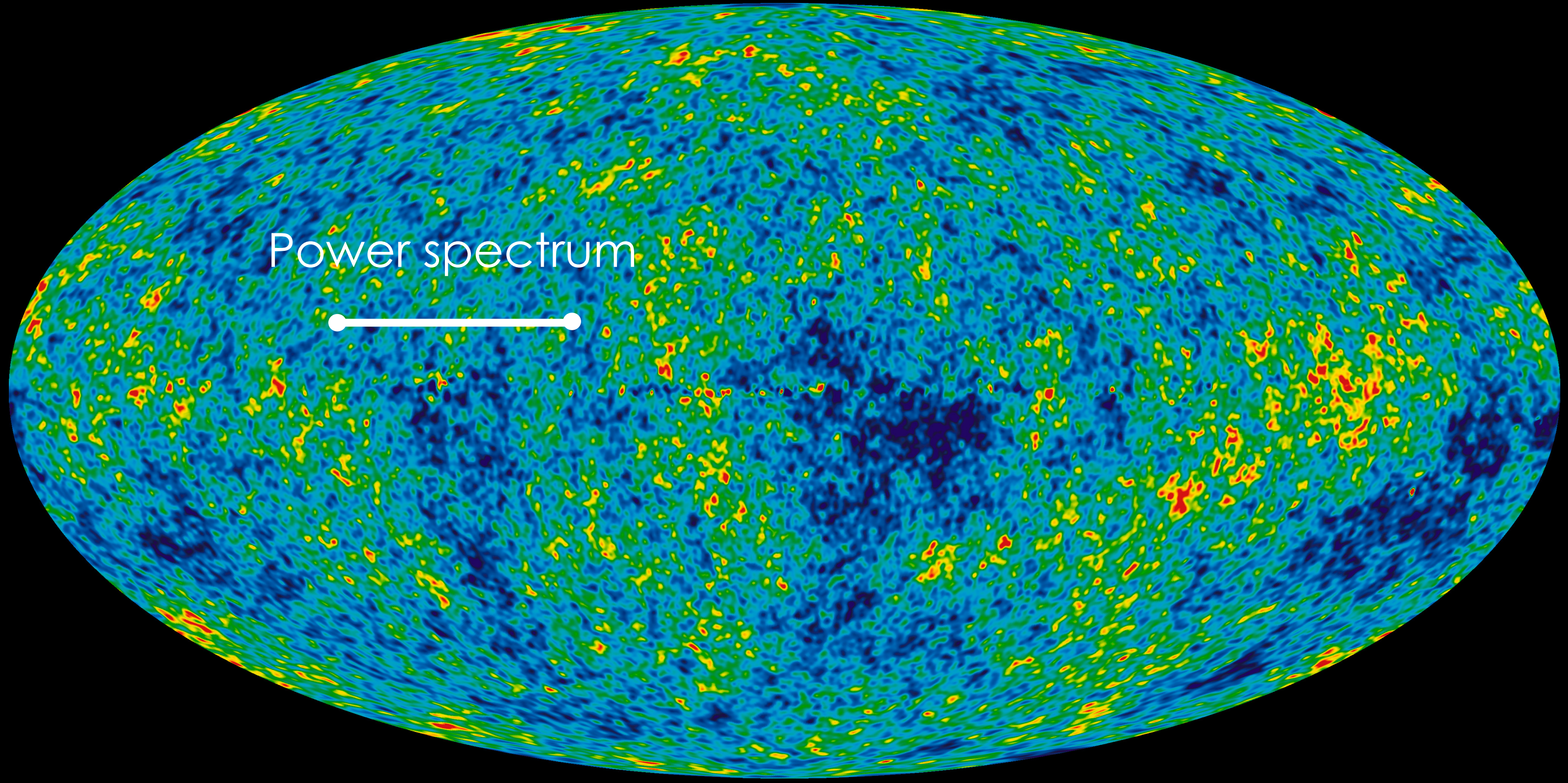
…translate into classical density fluctuations after inflation

…which become the CMB anisotropies.

CMB observations constrain the power spectra of primordial scalar and tensor perturbations

$$P_{\mathcal{R}}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 P_{\delta\phi}(k)$$

$$\langle \mathcal{R}_k \mathcal{R}_{k'} \rangle = (2\pi)^3 \delta^{(3)}(k+k') P_{\mathcal{R}}(k)$$



$$\Delta^2_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} P_{\mathcal{R}}(k) = A_s(k_*) \left(\frac{k}{k_*}\right)^{n_s-1}$$

amplitude of
the scalar power spectrum

$$n_s - 1 = \frac{d \ln \Delta^2_{\mathcal{R}}(k)}{d \ln k}$$

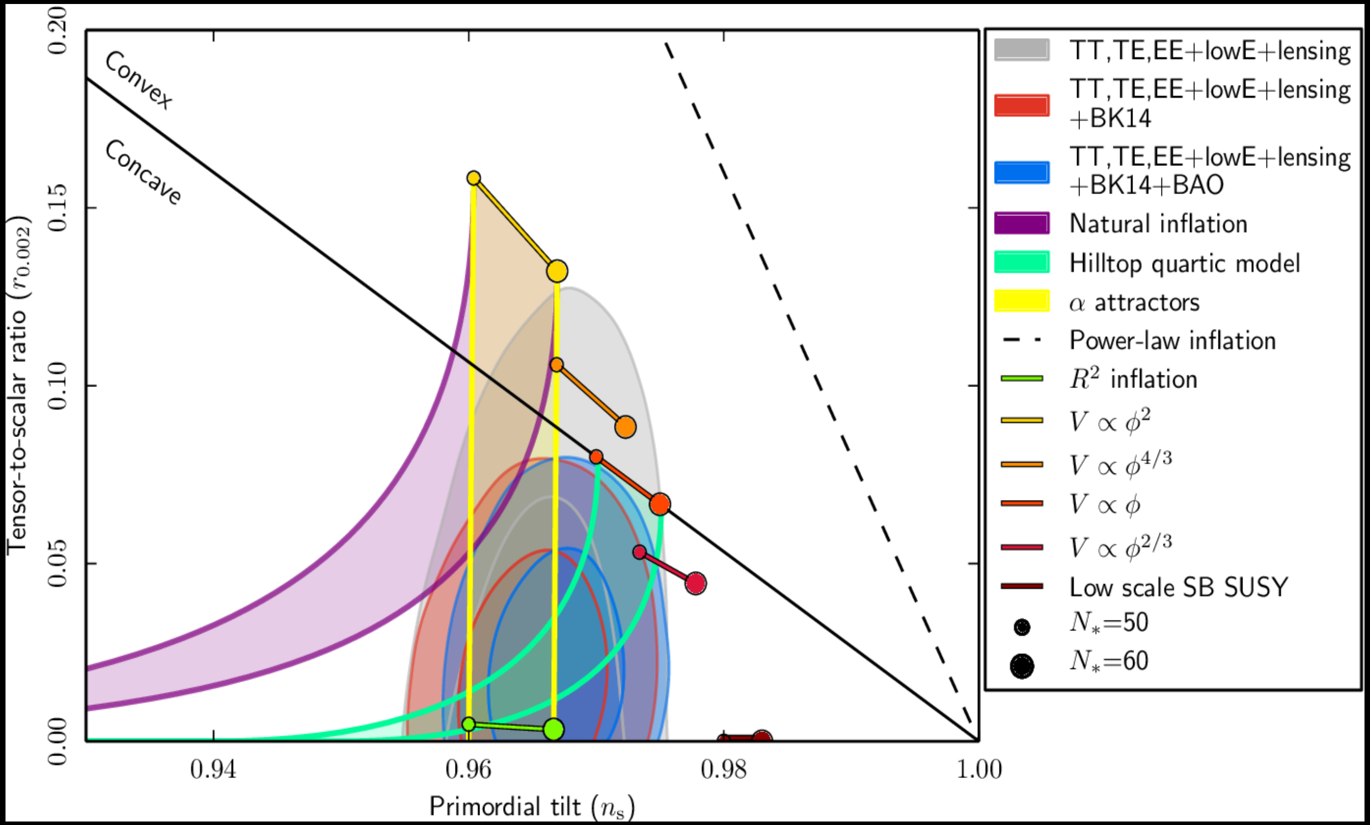
scalar spectral index

Current observational bounds from CMB

$$\boxed{n_s = 0.9603 \pm 0.0073, \quad r < 0.044}$$

$$r = \frac{A_t}{A_s}$$

tensor-to-scalar ratio



[Planck]

$$n_s - 1 = \frac{d \ln \Delta^2_{\mathcal{R}}(k)}{d \ln k}$$

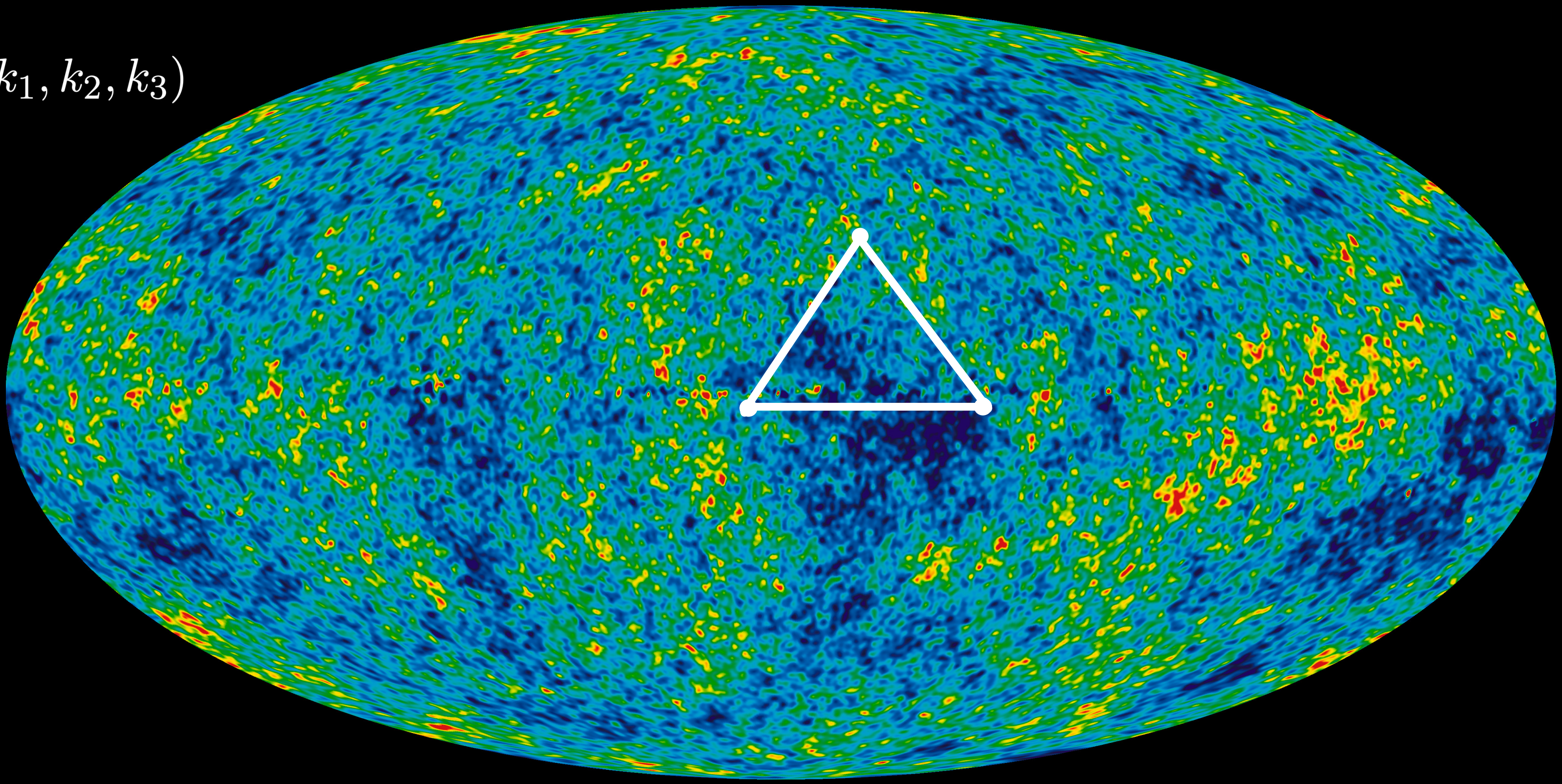
scalar spectral index

Non-Gaussianity

$$\left\langle \mathcal{R}_{\vec{k}_1}\mathcal{R}_{\vec{k}_2}\mathcal{R}_{\vec{k}_3}\right\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)B_{\mathcal{R}}(k_1,k_2,k_3)$$

Result of non-linear evolution of initially Gaussian fluctuations.

Bi-spectrum



Non-Gaussianity

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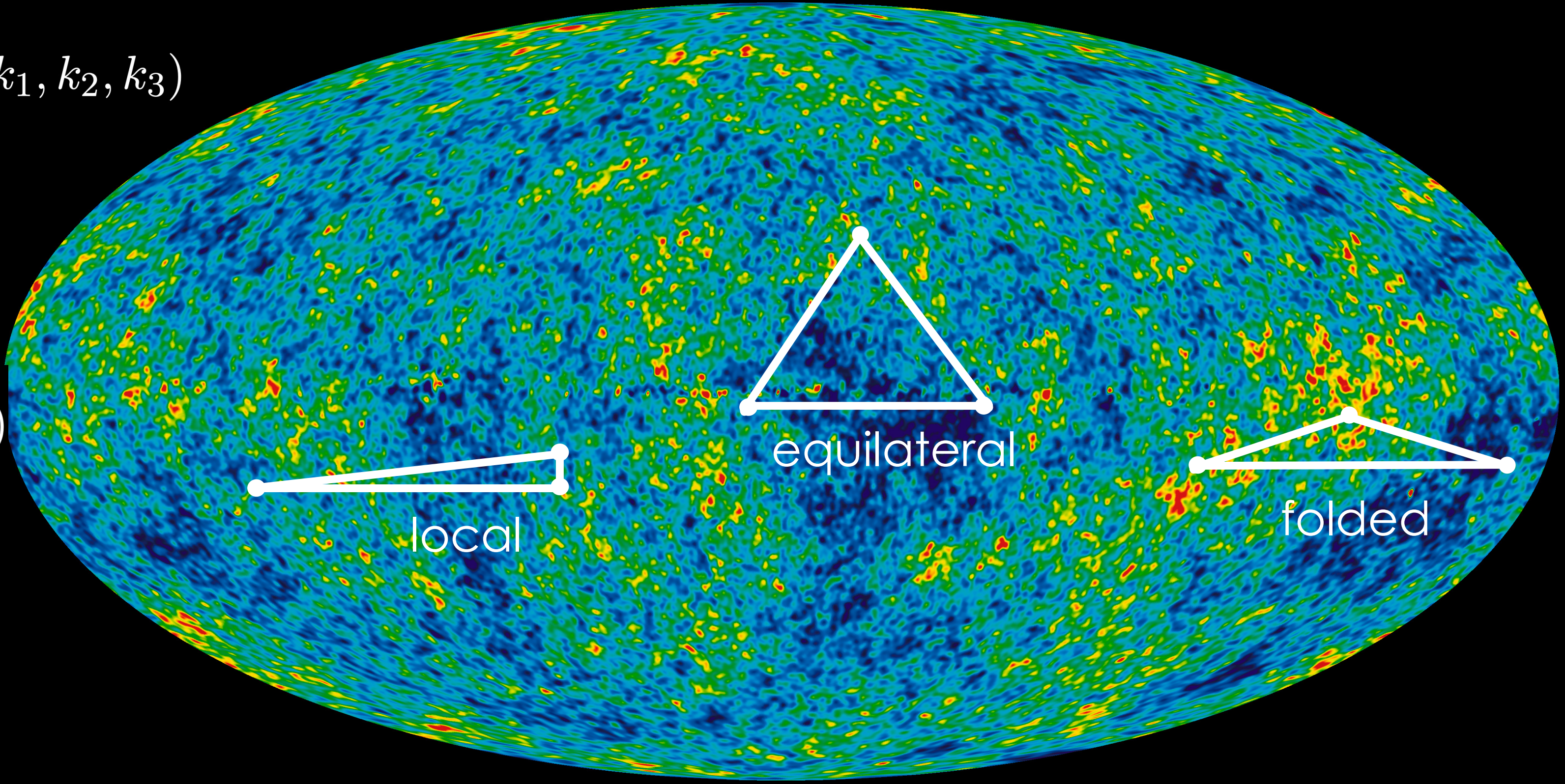
Result of non-linear evolution of initially Gaussian fluctuations.

$$B_{\mathcal{R}}(k_1,k_2,k_3) \propto \sum_{\text{type}} f_{\text{NL}}^{\text{type}} S_{\text{type}}(k_1,k_2,k_3)$$

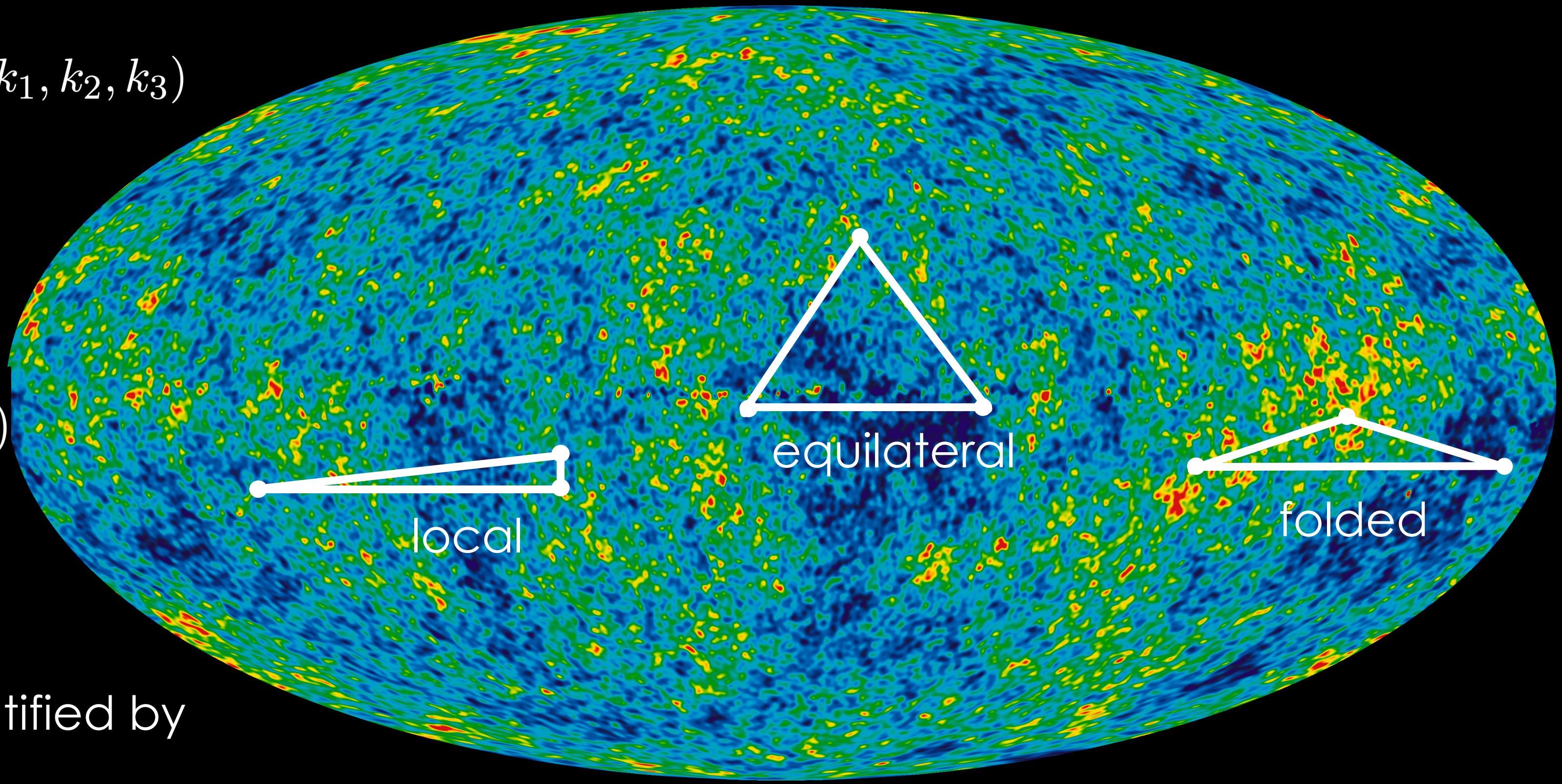
Bi-spectrum



Non-Gaussianity

$$\left\langle \mathcal{R}_{\vec{k}_1}\mathcal{R}_{\vec{k}_2}\mathcal{R}_{\vec{k}_3}\right\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)B_{\mathcal{R}}(k_1,k_2,k_3)$$

Bi-spectrum



$$B_{\mathcal{R}}(k_1,k_2,k_3) \propto \sum_{\text{type}} f_{\rm NL}^{\text{type}} S_{\text{type}}(k_1,k_2,k_3)$$

The amount of non-Gaussianity is quantified by the parameter

$$-\frac{6}{5}f_{\rm NL} = \frac{B_{\mathcal{R}}(k_1,k_2,k_3)}{P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2) + (\vec{k}\text{ cyclic perms})}$$

Non-Gaussianity in single-field inflation

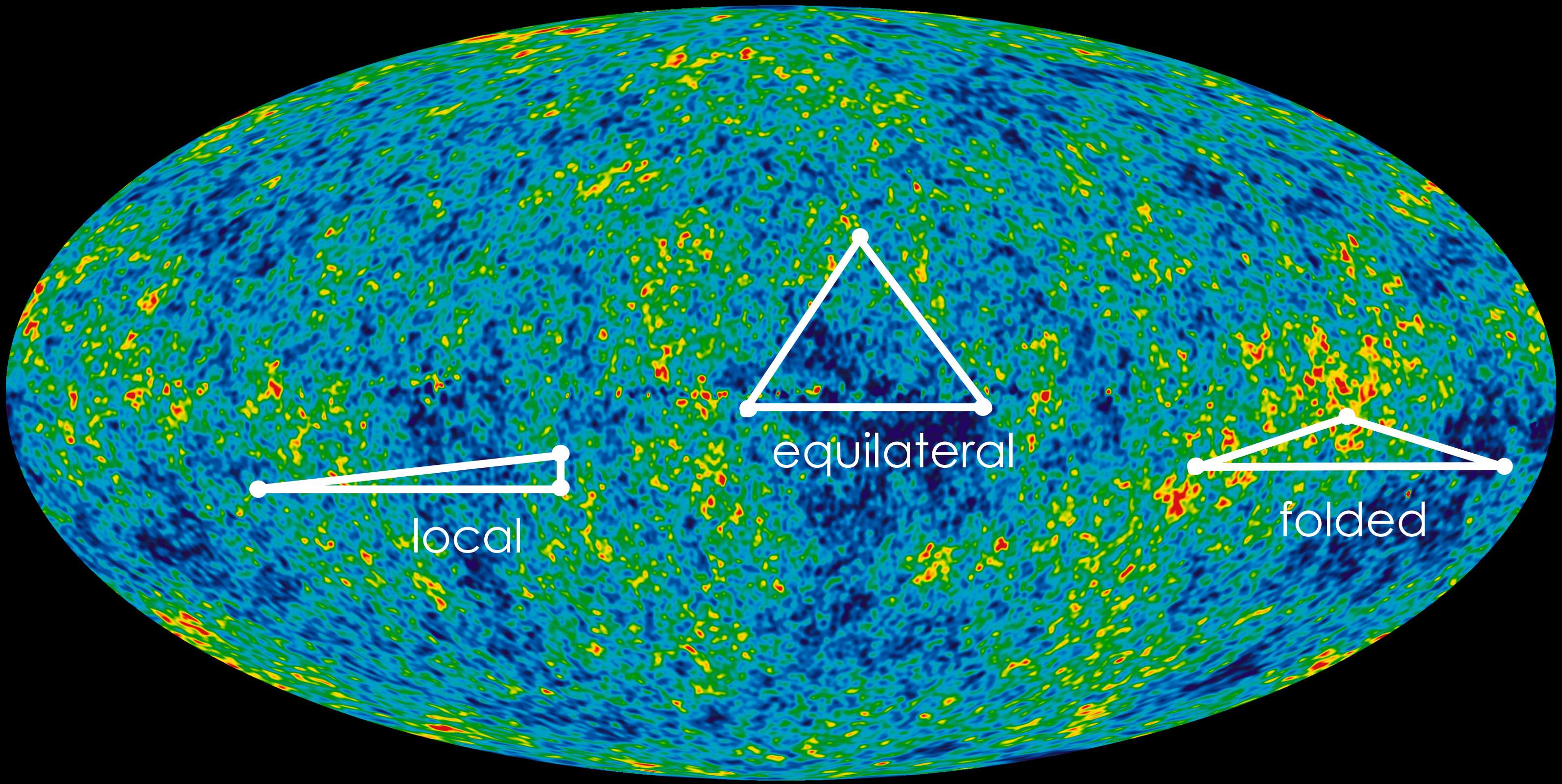
$$f_{\rm NL}^{\rm type} \simeq \mathcal{O}(\epsilon, \eta)$$

[Maldacena, 2002]

$$f_{\rm NL}^{\rm loc} = 0$$

[Tanaka & Urakawa, 2011]
[Pajer, Schmidt, Zaldarriaga, 2013]

Bi-spectrum



Single-field models of inflation most strongly couple momenta of similar wavelengths and result in bispectra that are highly suppressed in the 'squeezed limit' where one long-wavelength-mode couple to two short-wavelength-modes.

Non-Gaussianity in single-field inflation

$$f_{\rm NL}^{\rm type} \simeq \mathcal{O}(\epsilon, \eta)$$

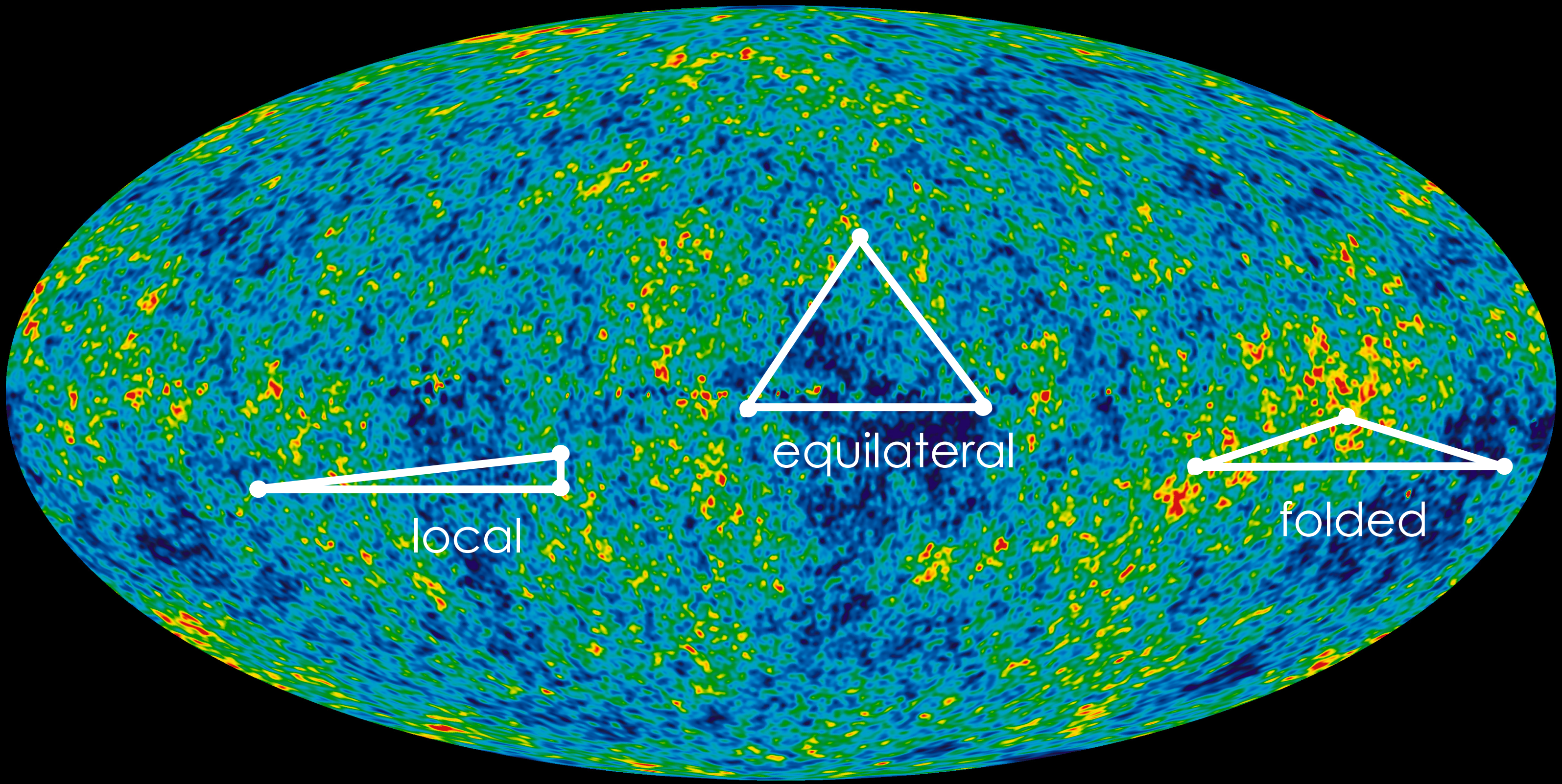
[Maldacena, 2002]

$$f_{\rm NL}^{\rm loc} = 0$$

[Tanaka & Urakawa, 2011]
[Pajer, Schmidt, Zaldarriaga, 2013]

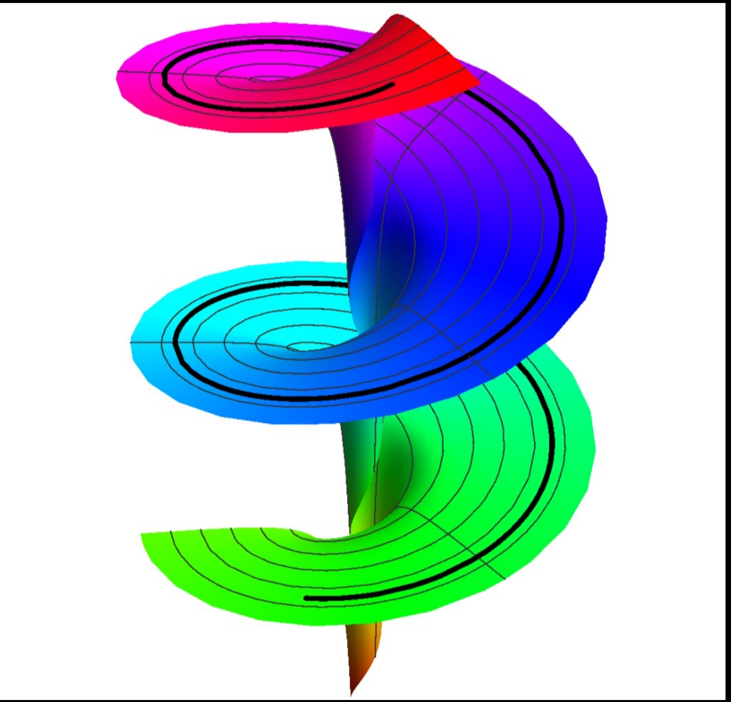
CMB constraint: $f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$

Bi-spectrum

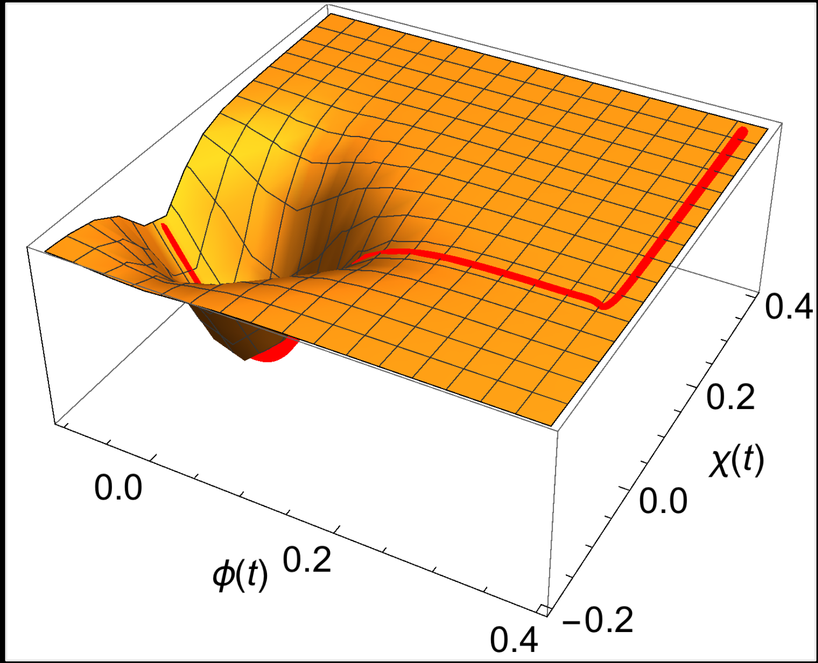


Detection of $f_{\rm NL}^{\rm loc} \simeq \mathcal{O}\left(1\right)$ would rule out all attractor models of single-field inflation!

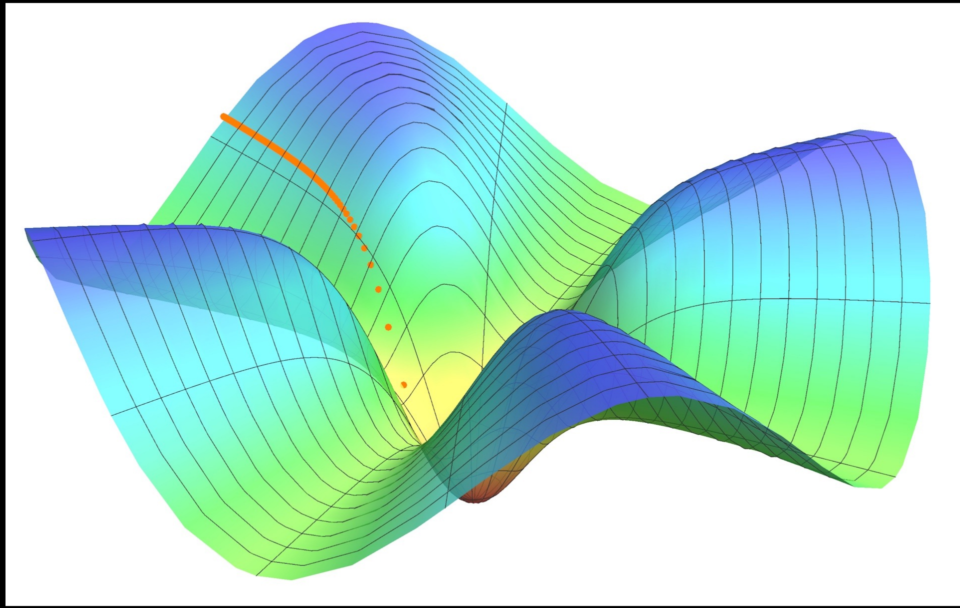
Multi-field inflation



[A. Achucarro, E. Copeland, O.I. et al]



[O.I., E. Sfakianakis, D.-G.Wang, A. Achucarro]



[A. Achucarro, R. Kallosh, A. Linde et al]

Multi-field inflation and turning trajectory

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm pl}^2}{2} R - \frac{1}{2} g^{\mu\nu} G_{ab}(\phi) \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi^a) \right]$$

field-space metric

multi-field potential

Multi-field inflation and turning trajectory

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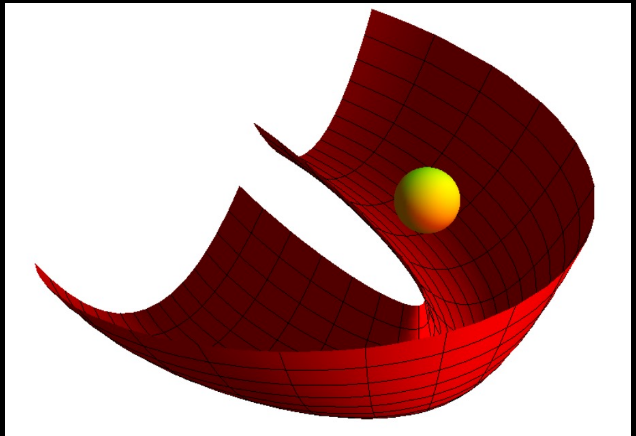
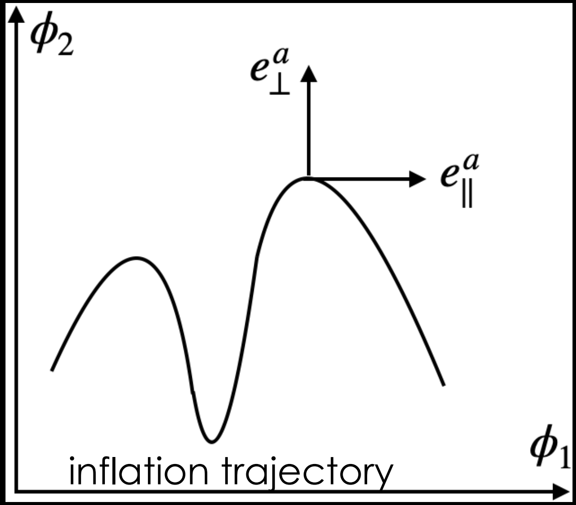


[D.-G. Wang]



Turn-rate:

$$D_N e_\parallel^a = \eta_\perp e_\perp^a$$

Trajectory turns couple the fluctuations and modify their dispersion relations and correlators.

Multi-field inflation and turning trajectory

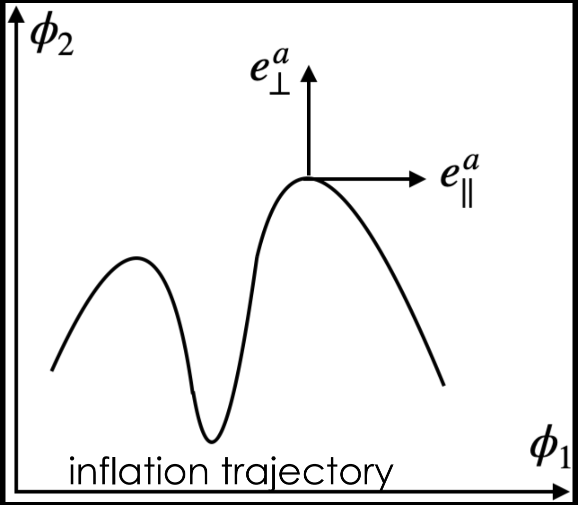
$$S = \int d^4x \sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}G_{ab}(\phi)\partial_\mu\phi^a\partial_\nu\phi^b - V(\phi^a)\right]$$

field-space metric

multi-field potential

Two types of field perturbations:

- Adiabatic (curvature) → along trajectory $\mathcal{R}$
- Non-Adiabatic (isocurvature) → orthogonal to trajectory $\mathcal{S}$



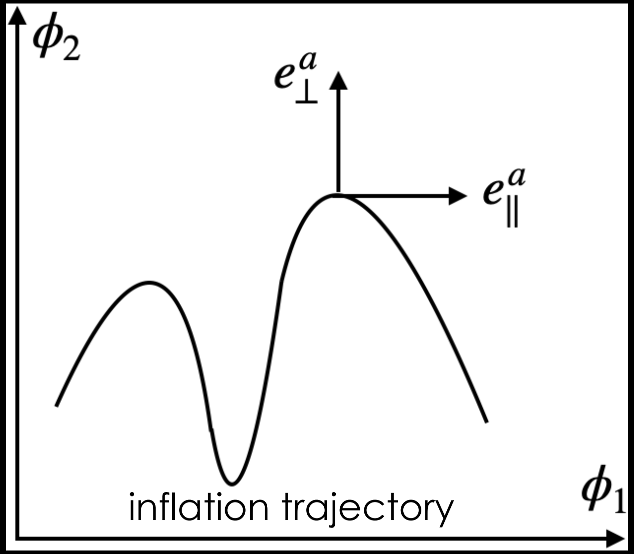
Turn-rate:

$$D_N e_\parallel^a = \eta_\perp e_\perp^a$$

Classification of perturbations

[D. Wands, K.Malik, D. Lyth, A. Liddle, 2000]
[L. Amendola, C. Gordon, D. Wands, M. Sasaki, 2002]
[D. Wands, N. Bartolo, S. Matarrese, A. Riotto,2002]

$$\begin{cases} \dot{\mathcal{R}} & \simeq \alpha H \mathcal{S} \\ \dot{\mathcal{S}} & \simeq \beta H \mathcal{S} \end{cases}$$



$$\alpha = 2\,\eta_\perp$$

$$\beta = -2\epsilon - \frac{\mathcal{M}_{\perp\perp}}{V} + \frac{\mathcal{M}_{\parallel\parallel}}{V} - \frac{4}{3}\,(\eta_\perp)^2$$

$$\mathcal{M}^a{}_b = G^{ac}\nabla_b\nabla_c V - R^a_{dfb}\dot\phi^d\dot\phi^f$$

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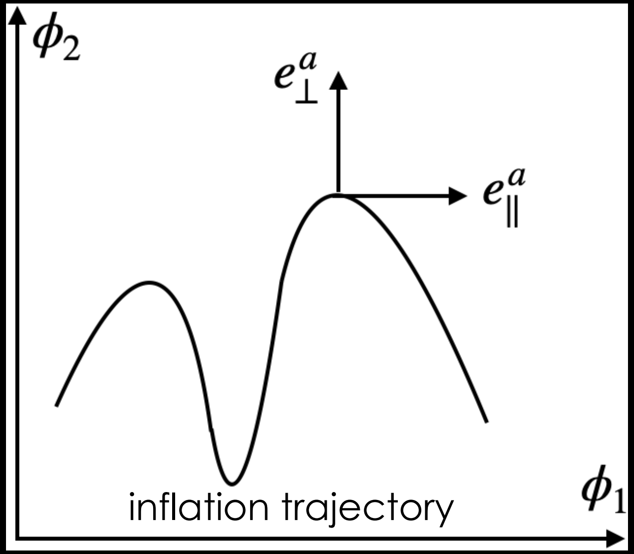

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The sourcing of curvature perturbations by isocurvature perturbations is proportional to the turn-rate!

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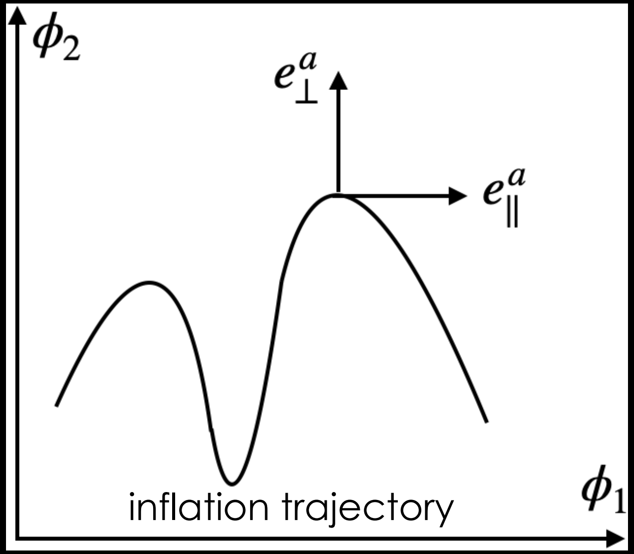

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$$\mathcal{M}^a{}_b = G^{ac}\nabla_b\nabla_c V - R^a_{dfb}\dot{\phi}^d\dot{\phi}^f$$

Determined by potential & geometry of field-space.

Classification of perturbations

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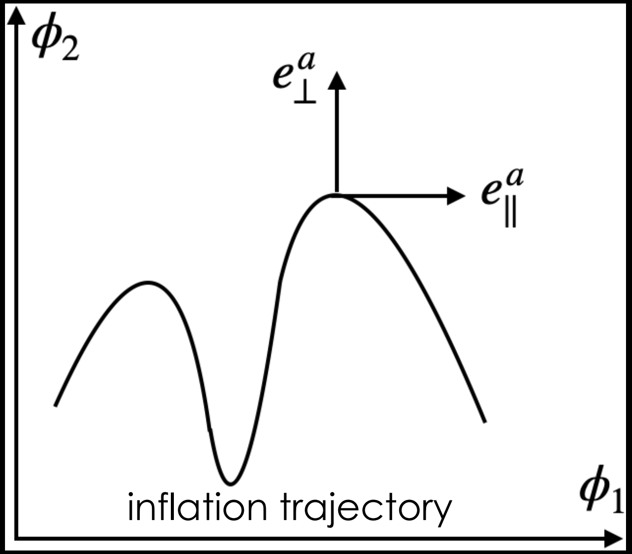

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$$\alpha = 2\,\eta_\perp$$

$$\beta = -2\epsilon - \frac{\mathcal{M}_{\perp\perp}}{V} + \frac{\mathcal{M}_{\|\|}}{V} - \frac{4}{3}\,(\eta_\perp)^2$$

$$\langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \rangle = \frac{1}{2\epsilon} \langle \delta\phi_{\| \vec{k}_1} \delta\phi_{\| \vec{k}_2} \rangle \;\Rightarrow\; P_{\mathcal{R}}$$
Power spectrum of curvature perturbations,

$$\langle \mathcal{R}_{\vec{k}_1} \mathcal{S}_{\vec{k}_2} \rangle = \frac{1}{2\epsilon} \langle \delta\phi_{\| \vec{k}_1} \delta\phi_{\perp \vec{k}_2} \rangle \;\Rightarrow\; C_{\mathcal{R}\mathcal{S}}$$
cross-correlation,

$$\langle \mathcal{S}_{\vec{k}_1} \mathcal{S}_{\vec{k}_2} \rangle = \frac{1}{2\epsilon} \langle \delta\phi_{\perp \vec{k}_1} \delta\phi_{\perp \vec{k}_2} \rangle \;\Rightarrow\; P_{\mathcal{S}}$$
isocurvature perturbations.

Slow-turn vs rapid-turn inflation

[C. Peterson, M. Tegmark, 2011]

Slow-turn: $\eta_\perp \ll 1$

$$f_{\rm NL}^{\rm loc} \supset \frac{5}{6}\sqrt{\frac{r}{8}}\left(\frac{T_{\mathcal{RS}}}{\sqrt{1+T_{\mathcal{RS}}^2}}\right)^3 \partial_{\perp *} \ln T_{\mathcal{RS}}$$

$$\begin{pmatrix} \mathcal{R} \\ \mathcal{S} \end{pmatrix} = \begin{pmatrix} 1 & T_{\mathcal{RS}} \\ 0 & T_{\mathcal{SS}} \end{pmatrix} \begin{pmatrix} \mathcal{R}_* \\ \mathcal{S}_* \end{pmatrix}$$

Slow-turn vs rapid-turn inflation

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What is different in the rapid-turn regime? $\eta_\perp \gg 1$

M.C. David Marsh

Gustavo Salinas

[arXiv:2303.14156]

Non-Gaussianity in rapid-turn multi-field inflation

Oksana Iarygina[1,2], M.C. David Marsh[2], Gustavo Salinas[2*]

[1] *Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvéns väg 12, SE-106 91 Stockholm, Sweden*

[2] *The Oskar Klein Centre, Department of Physics, Stockholm University, Stockholm 106 91, Sweden*

δN -formalism

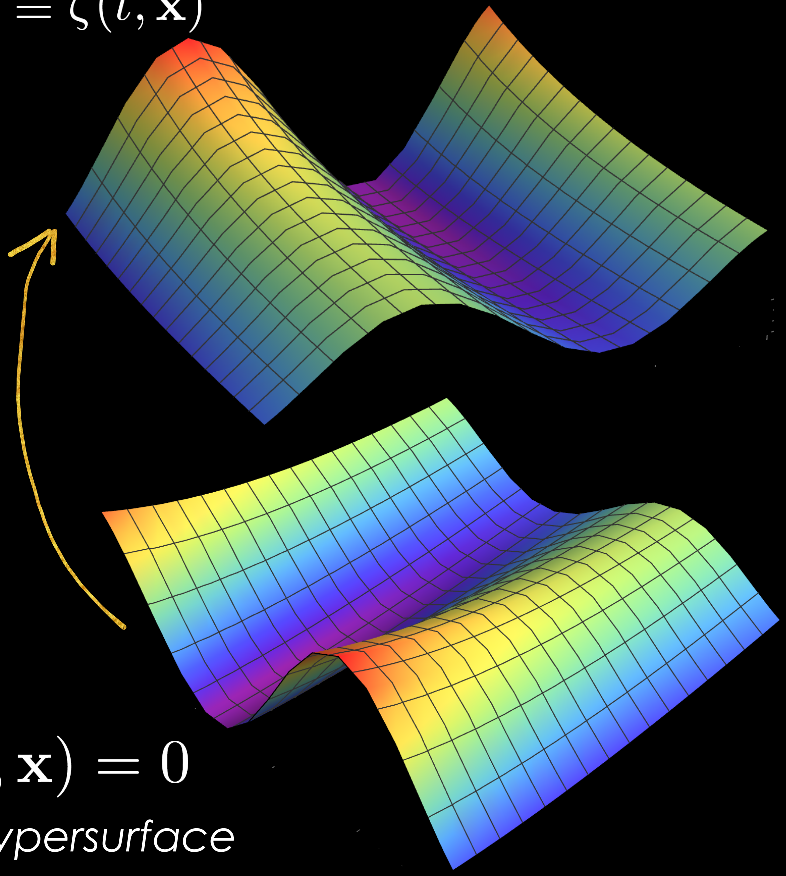
[Sasaki and Stewart,(1996)]
[Wands, Malik, Lyth, Liddle (2000)]

$$g_{ij} = a^2(t)\gamma_{ij}\, \mathrm{e}^{2\psi(t,\mathbf{x})}$$

$$\zeta(t,\mathbf{x}) = \delta N = N(t,\mathbf{x}) - N_0(t)$$

uniform density hypersurface

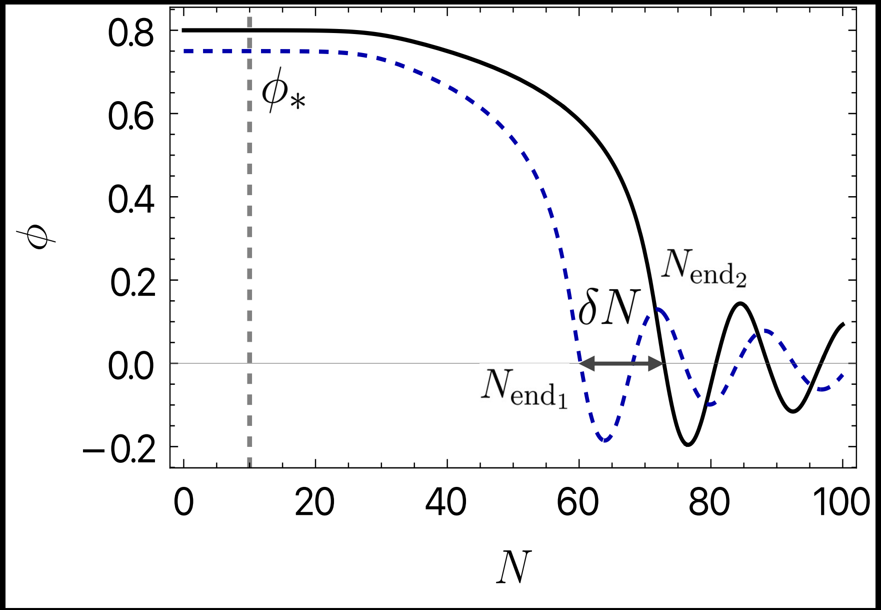
$$\psi_{\mathrm{UD}}(t,\mathbf{x}) \equiv \zeta(t,\mathbf{x})$$



$$\psi_{\mathrm{flat}}(t,\mathbf{x}) = 0$$

initial flat hypersurface

$$\delta N = N_a \delta\phi_*^a + \frac{1}{2} N_{ab}\delta\phi_*^a \delta\phi_*^b + \ldots$$



Non-Gaussianity from the δN -formalism

[D.H. Lyth and Y. Rodriguez,(2005)]

$$\left\langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \mathcal{R}_{\vec{k}_3} \right\rangle = N_a N_b N_c \left\langle \delta\phi^a_{*\vec{k}_1} \delta\phi^b_{*\vec{k}_2} \delta\phi^c_{*\vec{k}_3} \right\rangle$$

$$+\frac{1}{2} N_a N_b N_{cd} \left\langle \delta\phi^a_{*\vec{k}_1} \delta\phi^b_{*\vec{k}_2} \left(\delta\phi^c_* * \delta\phi^d_* \right)_{\vec{k}_3} \right\rangle + (\vec{k} \text{ cyclic perms}) \; + \cdots$$

$$-\frac{6}{5} f_{\rm NL} \approx -\frac{6}{5} f^{(3)}_{\rm NL} - \frac{6}{5} f^{(4)}_{\rm NL}$$

horizon crossing contribution

super-horizon evolution

Non-Gaussianity in rapid-turn inflation

Slow-turn: $\eta_\perp \ll 1$

$$\langle \delta\phi^a_{*\vec{k}_1} \delta\phi^b_{*\vec{k}_2} \rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P^*_\phi(k_1) \delta^{ab}$$

Non-Gaussianity in rapid-turn inflation

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$$P_{\mathcal{R}*} = P_{\mathcal{S}*}, \quad C_{\mathcal{RS}*} = 0$$

Non-Gaussianity in rapid-turn inflation

[OI, D. Marsh, G. Salinas, 2023]

Slow-turn: $\eta_\perp \ll 1$

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$$P_{\mathcal{R}*} = P_{\mathcal{S}*}, \quad C_{\mathcal{R}\mathcal{S}*} = 0$$

Rapid-turn: $\eta_\perp \gg 1$

$$\langle \delta\phi^a_{*\vec{k}_1} \delta\phi^b_{*\vec{k}_2} \rangle = (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P^{*ab}_\phi(k_1)$$

$$P_{\mathcal{R}*} \neq P_{\mathcal{S}*} \neq C_{\mathcal{R}\mathcal{S}*} \neq 0$$

Non-Gaussianity in rapid-turn inflation

[OI, D. Marsh, G. Salinas, 2023]

Slow-turn: $\eta_\perp \ll 1$

$$-\frac{6}{5} f_{\rm NL}^{(4)} = \frac{N_a N_b N^{ab}}{(N_c N^c)^2}$$

Rapid-turn: $\eta_\perp \gg 1$

$$-\frac{6}{5} f_{\rm NL}^{(4)} = \frac{N_a N_b N_{cd} \left[P_\phi^{*ac}(k_1)\, P_\phi^{*bd}(k_2) + (\vec{k} \text{ cyclic perms}) \right]}{N_e N_f N_g N_h \left[P_\phi^{*ef}(k_1) P_\phi^{*gh}(k_2) + (\vec{k} \text{ cyclic perms}) \right]}$$

Non-Gaussianity in rapid-turn inflation

Rapid-turn: $\eta_\perp \gg 1$

[OI, D. Marsh, G. Salinas, 2023]

$$-\frac{6}{5} f_{\rm NL}^{(4)}(k_1, k_2, k_3) = \sum_{I,J\,=\,\mathcal{R},\mathcal{C}} f_{\rm NL}^{IJ} \frac{\tilde{\mathcal{P}}^I(k_1)\tilde{\mathcal{P}}^J(k_2) + (\vec{k}\text{ cyclic perms})}{P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2) + (\vec{k}\text{ cyclic perms})}$$

$$\downarrow$$

$$f_{\rm NL}^{\mathcal{R}\mathcal{R}},\, f_{\rm NL}^{\mathcal{R}\mathcal{C}},\, f_{\rm NL}^{\mathcal{C}\mathcal{R}},\, f_{\rm NL}^{\mathcal{C}\mathcal{C}}$$

$$\tilde{\mathcal{P}}^{\mathcal{R}}(k) = P_{\mathcal{R}}(k)\ ,\ \tilde{\mathcal{P}}^{\mathcal{C}}(k) = C_{\mathcal{R}\mathcal{S}}(k)$$

Non-Gaussianity in rapid-turn inflation

Rapid-turn: $\eta_\perp \gg 1$

[OI, D. Marsh, G. Salinas, 2023]

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$$\downarrow$$

$$f_{\rm NL}^{\mathcal{RR}},\ \underline{f_{\rm NL}^{\mathcal{RC}},\ f_{\rm NL}^{\mathcal{CR}},\ f_{\rm NL}^{\mathcal{CC}}}$$

$$\tilde{\mathcal{P}}^{\mathcal{R}}(k) = P_{\mathcal{R}}(k)\ ,\ \tilde{\mathcal{P}}^{\mathcal{C}}(k) = C_{\mathcal{RS}}(k)$$

Scale dependence and new shape functions!

Non-Gaussianity in rapid-turn inflation

Rapid-turn: $\eta_\perp \gg 1$

[OI, D. Marsh, G. Salinas, 2023]

Assuming the scale-invariant power spectrum, it reduces to:

$$f_{\rm NL}^{(4)} \supset \eta_\perp\, I_4 + \tilde{M}_{\perp\perp *}\, I_5 + \tilde{M}_{\perp || *}\, I_6$$

$$I_i = I_i \left(T_{\mathcal{RS}}, \mathcal{C}_{\mathcal{RS}}, P_{\mathcal{S}}/P_{\mathcal{R}}\right)$$

New model-independent potentially large contributions to the non-Gaussianity parameter!

Example: Angular inflation model

[P. Christodoulidis, D. Roest, E. I. Sfakianakis, 2019]

$$V(\phi,\chi) = \frac{\tilde{\alpha}}{2}\left(m_\phi^2\phi^2 + m_\chi^2\chi^2\right)$$

$$G_{ab} = \frac{6\tilde{\alpha}}{\left(1-\phi^2-\chi^2\right)^2}\delta_{ab}$$

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[OI, D. Marsh, G. Salinas, 2023]

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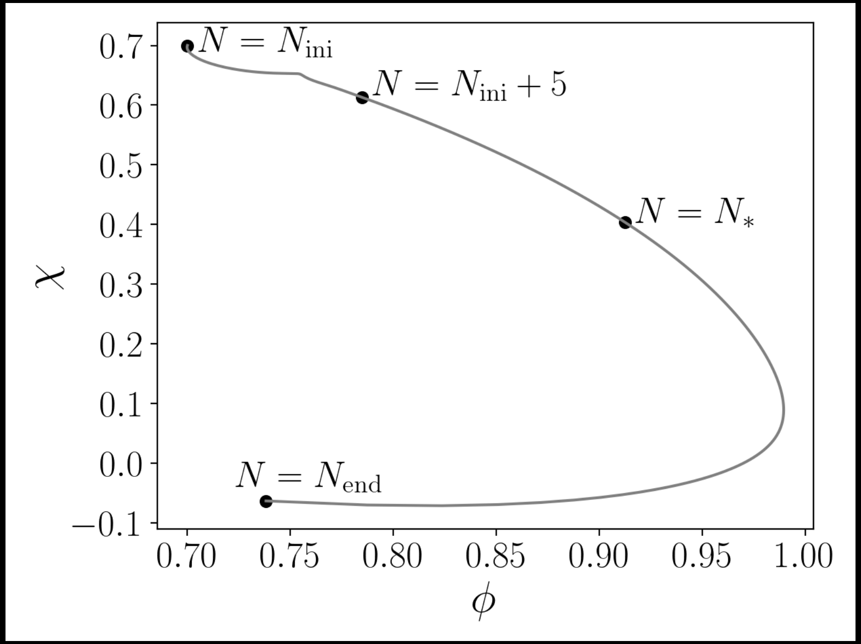
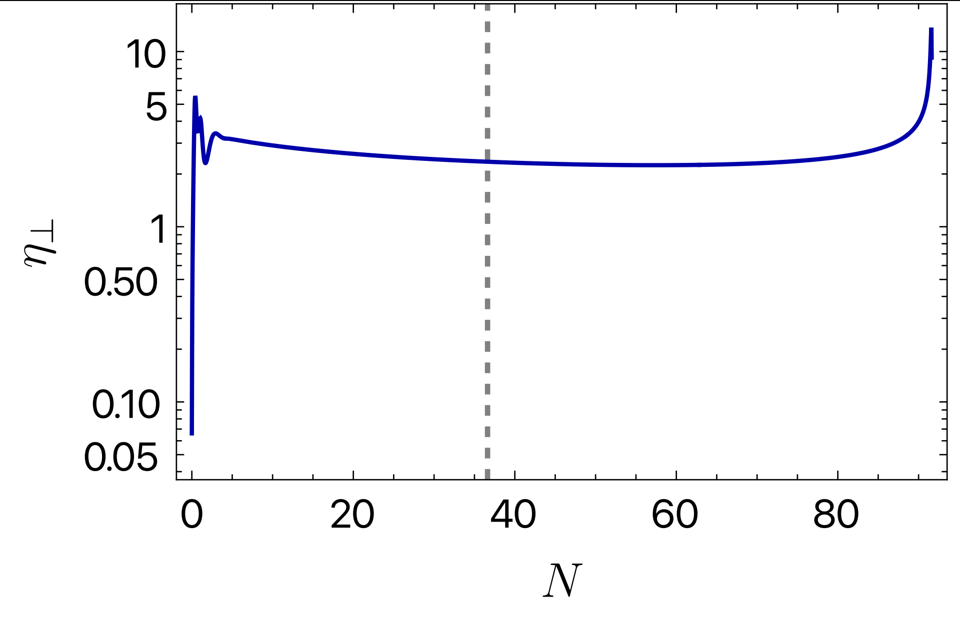
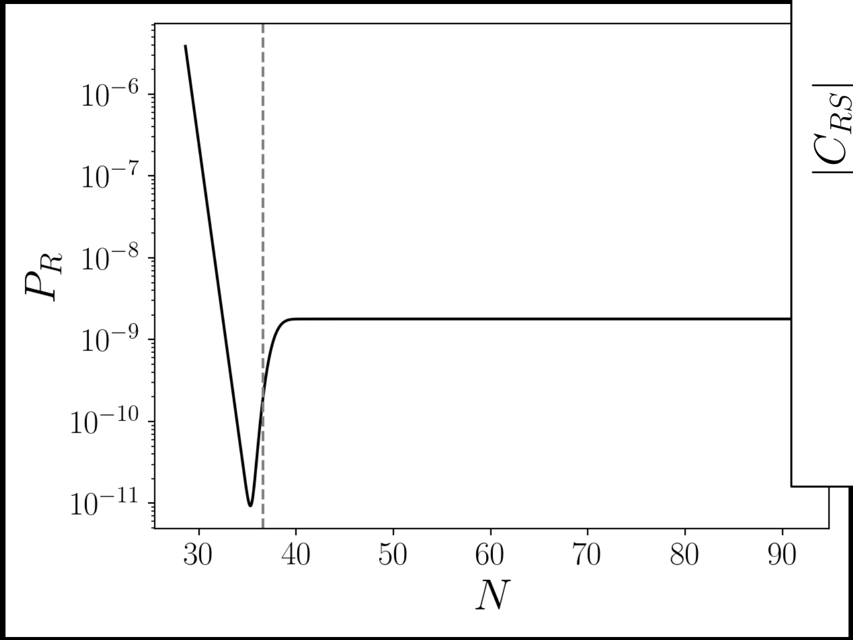


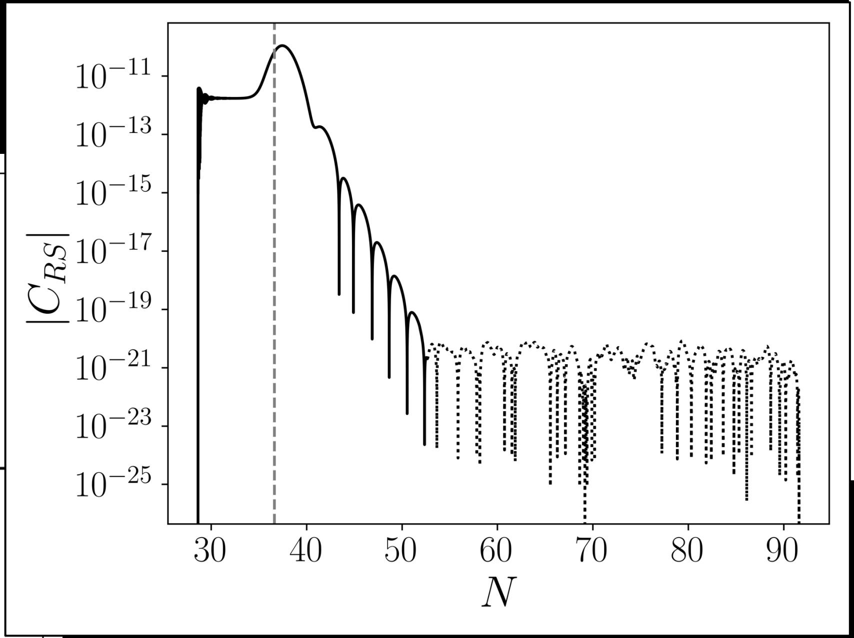


Example: Angular inflation model

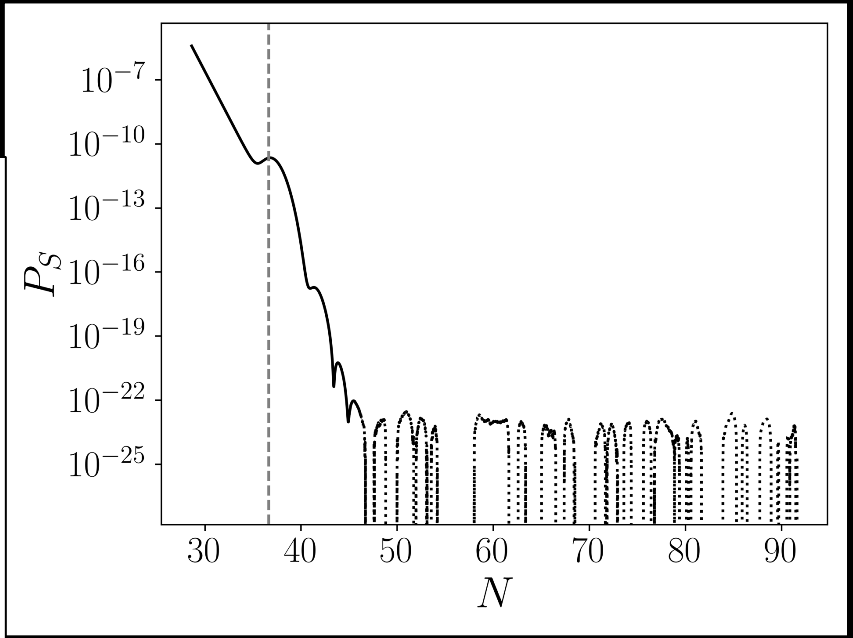
[OI, D. Marsh, G. Salinas, 2023]



Power spectrum of curvature perturbations,



cross-correlation,



isocurvature perturbations.

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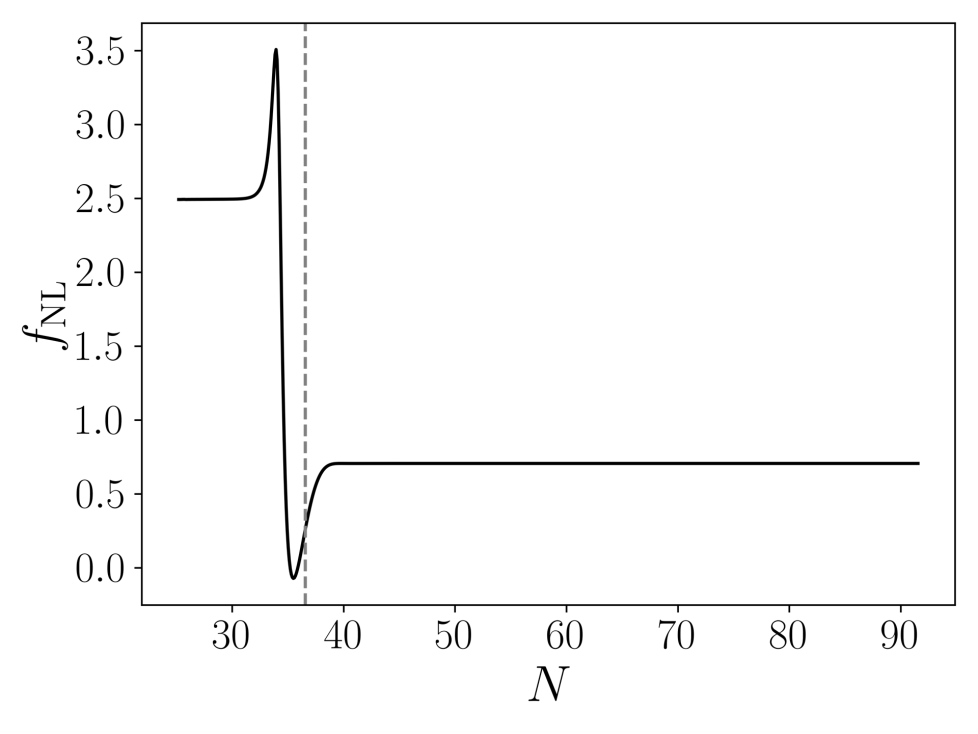

$$f_{\mathrm{NL}}^{\mathrm{loc}} = -\frac{5}{6}\left(0.006\, I_{1*} + 1.89\, I_{2*} + 0.004\, I_{3*} - 2.35\, I_{4*} - 0.015\, I_{5*} + 2.3\, I_{6*}\right)$$

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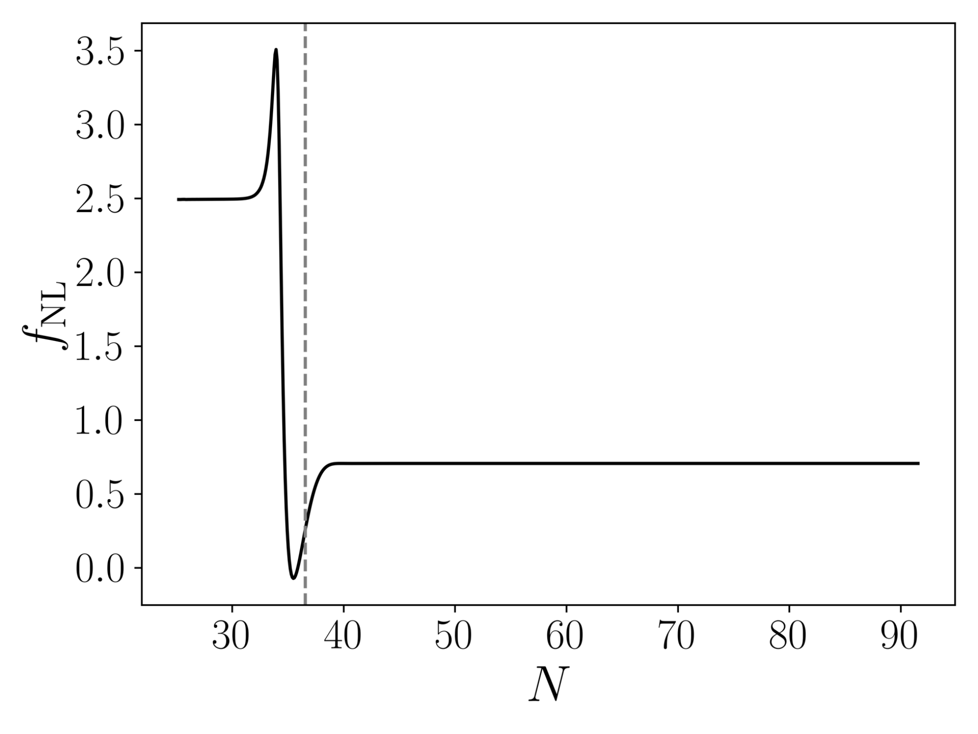

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$$\boxed{f_{\rm NL}^{\rm loc} = 0.705 \simeq \mathcal{O}\left(1\right)}$$

Conclusions

1. Extended the δN -formalism to rapid-turn inflation.

2. Identified new model-independent potentially large contributions to the non-Gaussianity parameter.

3. The resulting bispectrum in general is not of the local shape.

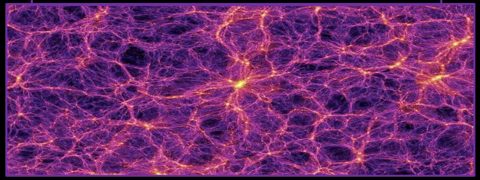
4. Detection of Non-Gaussianity $f_{\rm NL}^{\rm loc} \simeq \mathcal{O}\,(1)$ signals:

- New particles → inflation with more than one field, curved field-space, steep potentials, UV competions…

- *OR non-inflationary perturbations?*

CMB-S4
Next Generation CMB Experiment

LSS experiments



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CMB-S4 Next Generation CMB Experiment

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Thank you!