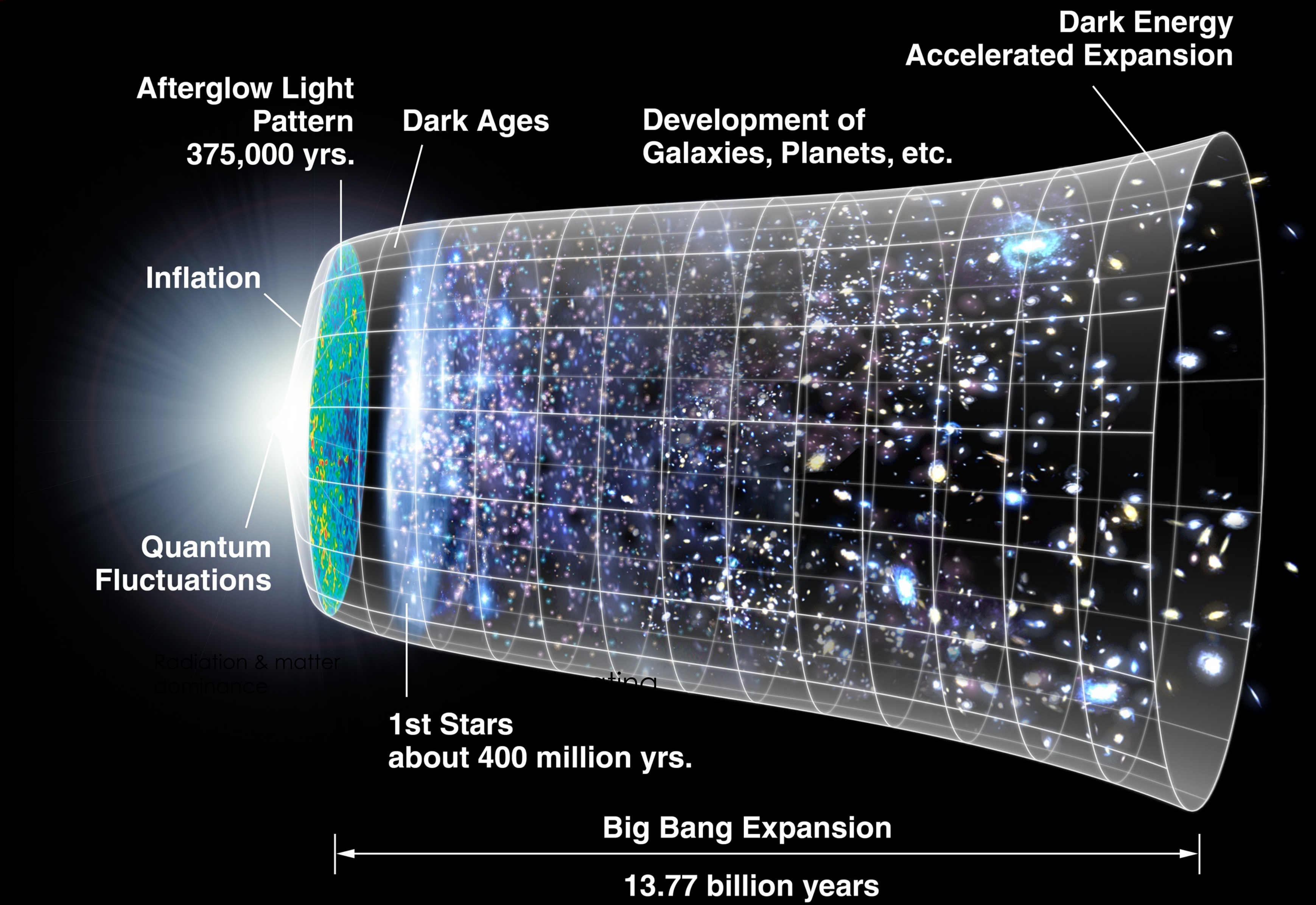
Non-Gaussianity in rapid-turn multi-field inflation

Oksana Iarygina

OKC @ 15, Stockholm
18 October 2023

NORDITA
The Nordic Institute for Theoretical Physics

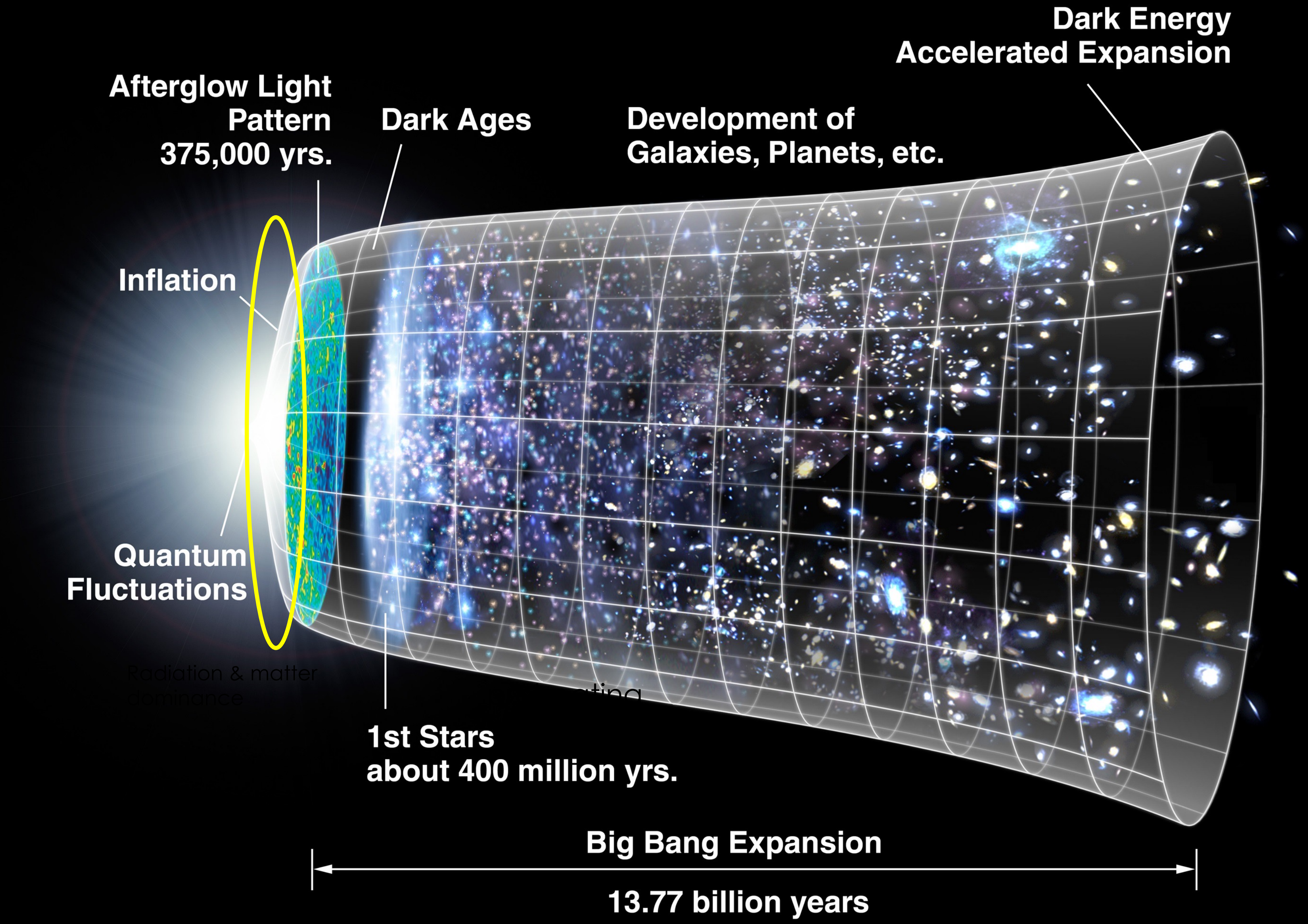
Early Universe cosmology



Radiation & matter
dominance

ating

Early Universe cosmology



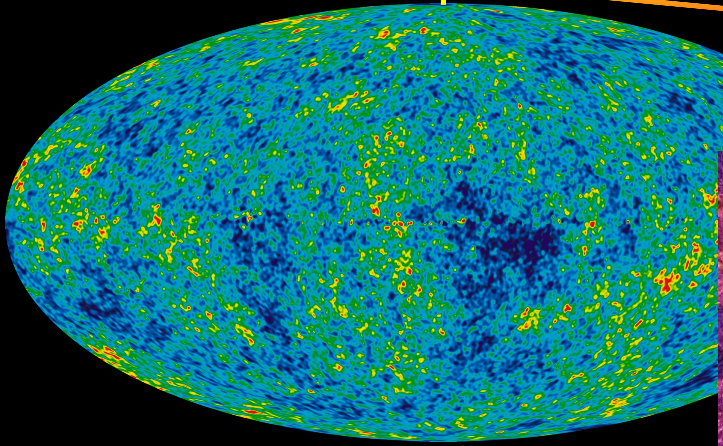
What is the origin of seeds for all structure?

?

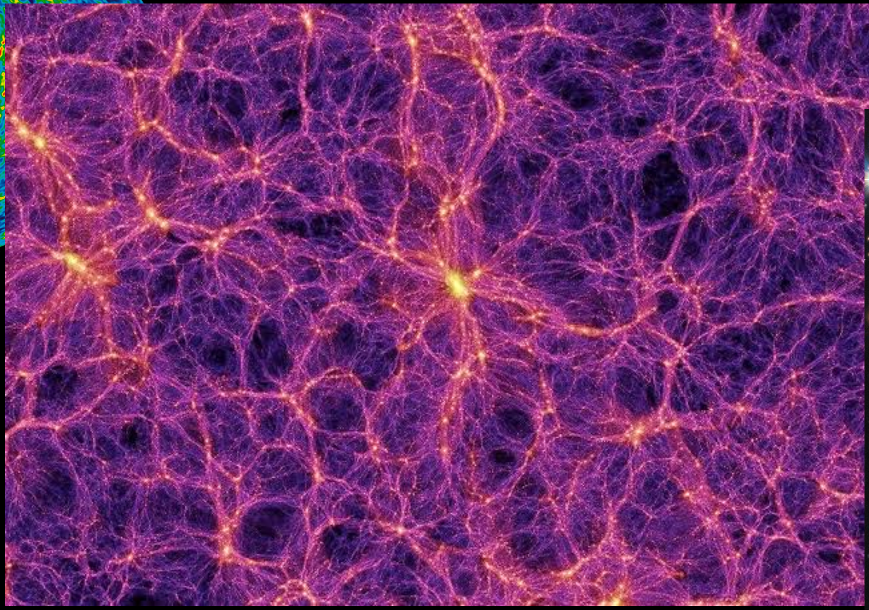
380,000 yrs.

10 billion yrs.

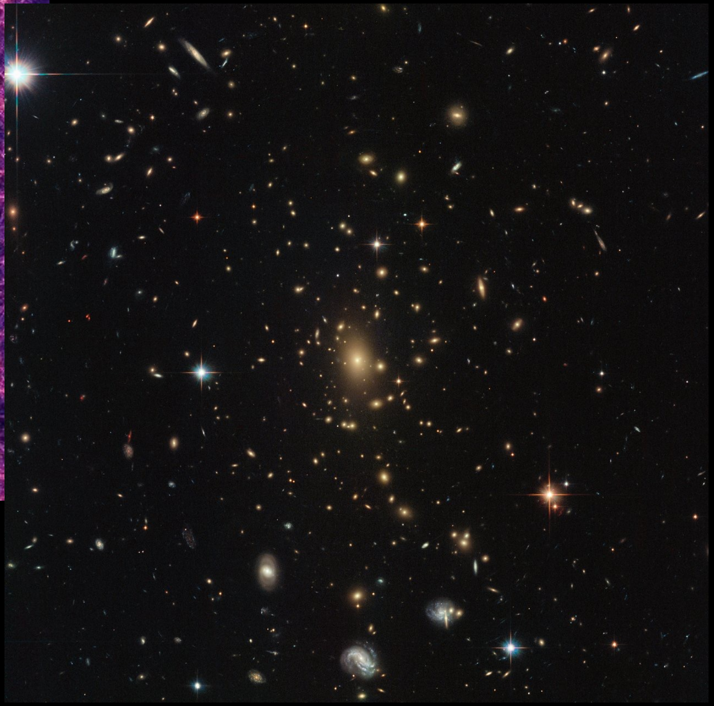
13.7 billion yrs.



[Planck]

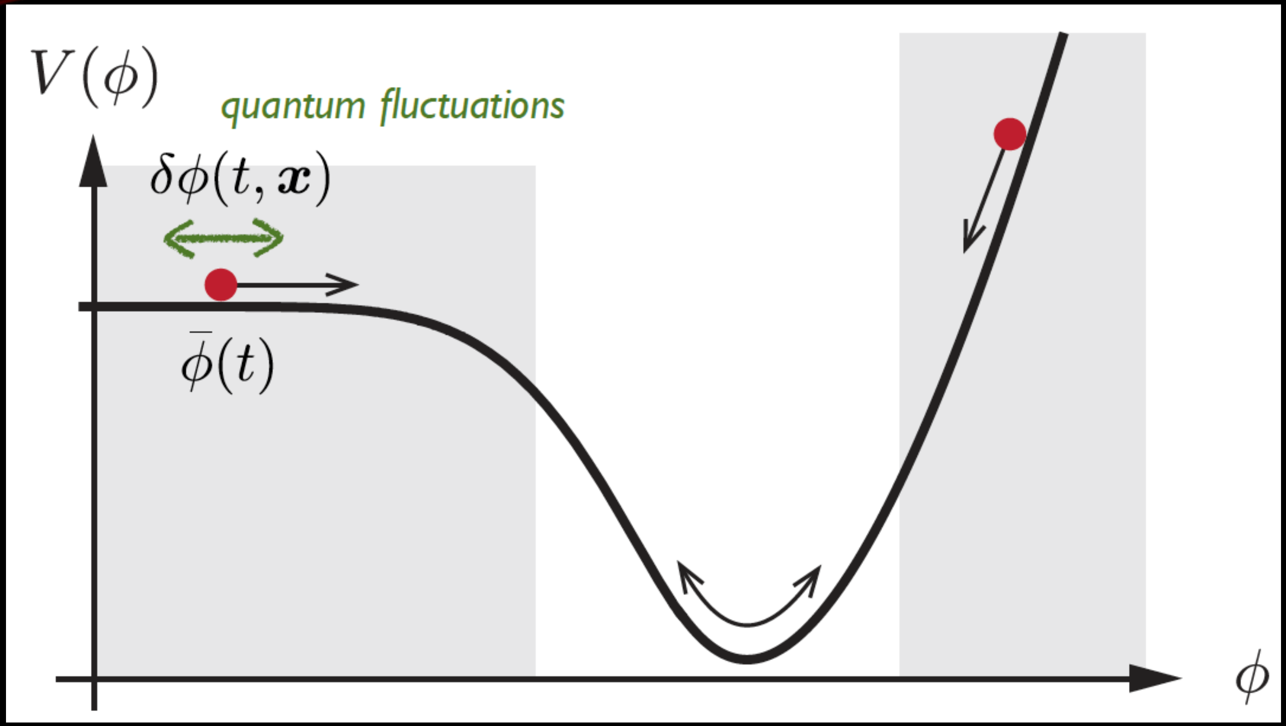


[Max Planck Inst. for Astrophysics]



[ESA/Hubble & NASA]

Seeds for all structure from quantum fluctuations!



[Baumann]

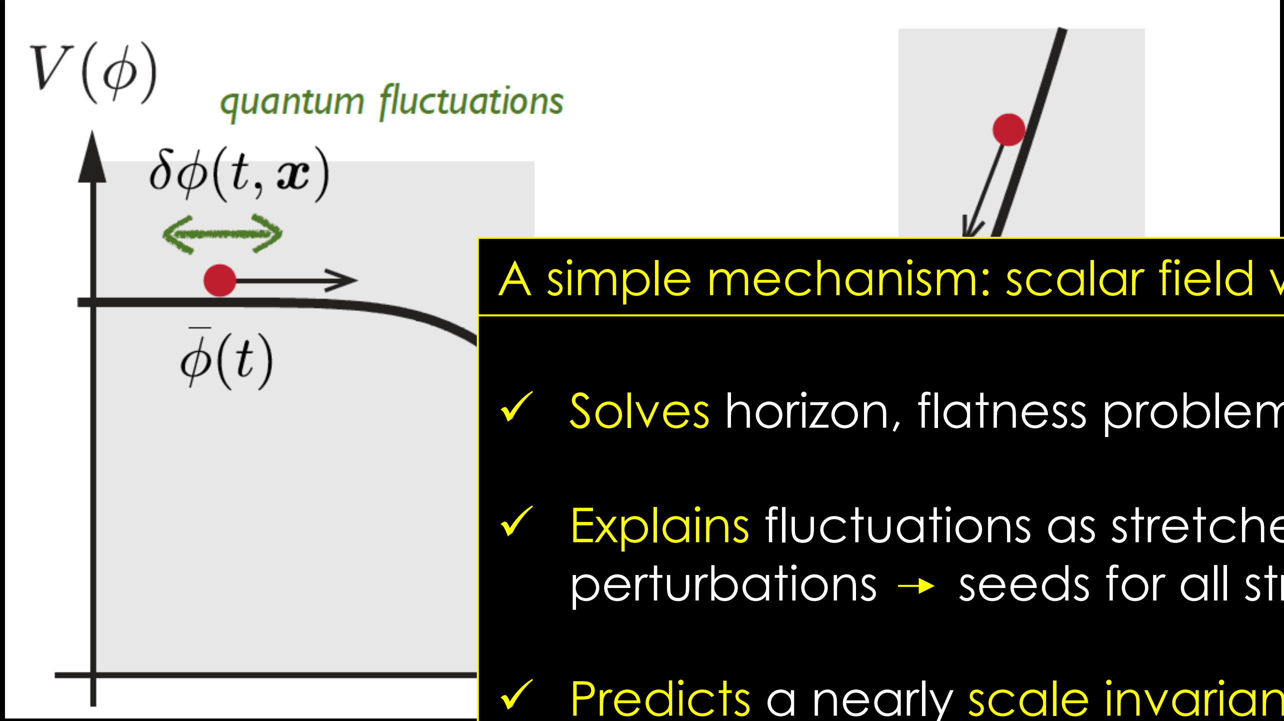
$$\delta\phi(x) \longrightarrow \delta\rho(x) \longrightarrow \delta T(x)$$

Quantum vacuum fluctuations around the inflaton vev

…translate into classical density fluctuations after inflation

…which become the CMB anisotropies.

In the beginning, there was (probably) inflation



A simple mechanism: scalar field with a flat potential.

- ✓ Solves horizon, flatness problems
- ✓ Explains fluctuations as stretched quantum perturbations → seeds for all structure
- ✓ Predicts a nearly scale invariant spectrum together with Gaussian perturbations

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

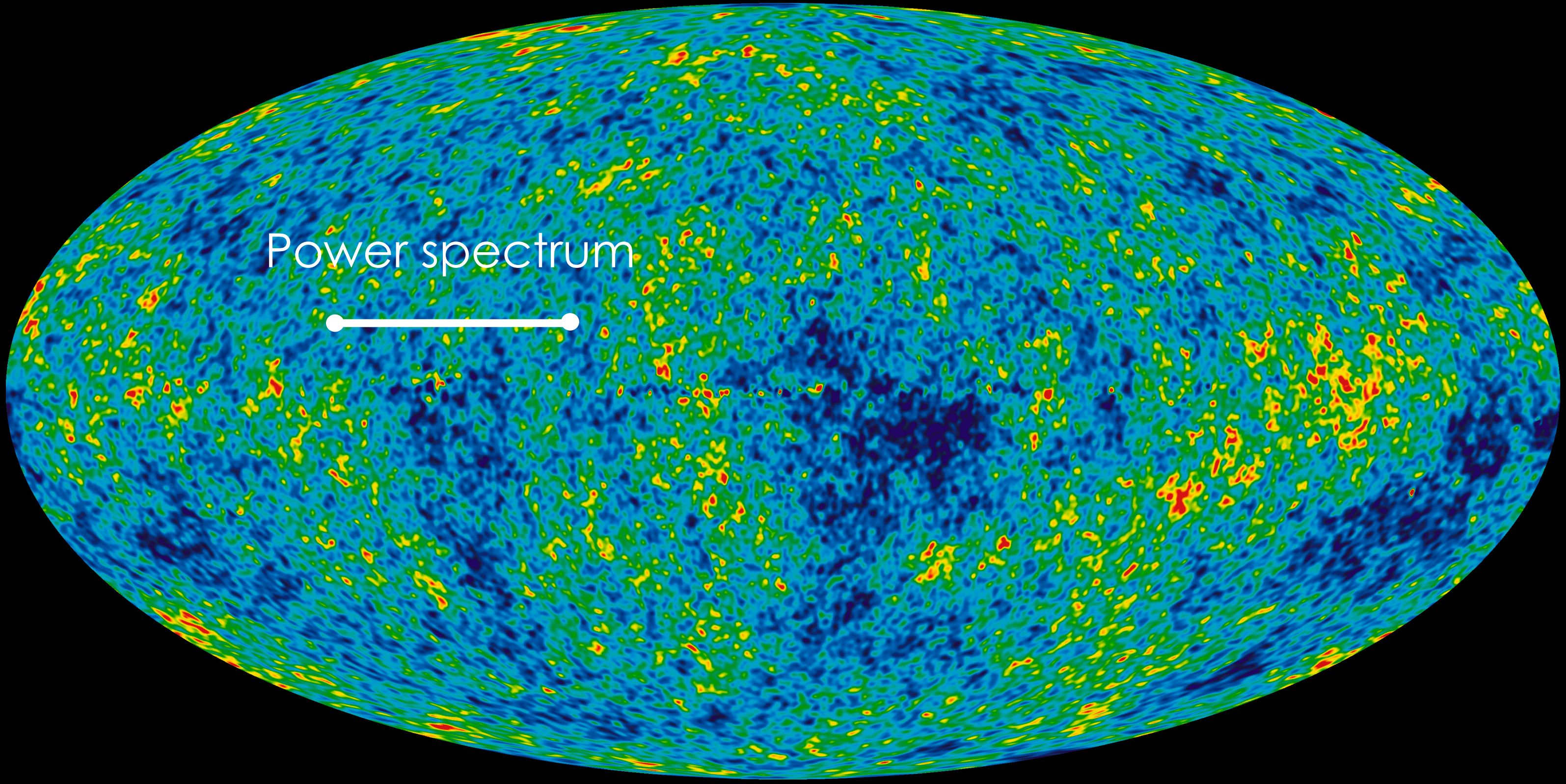
Quantum vacuum fluctuations around the inflaton vev

…translate into classical density fluctuations after inflation

…which become the CMB anisotropies.

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

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



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

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

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

amplitude of
the scalar power spectrum

scalar spectral index

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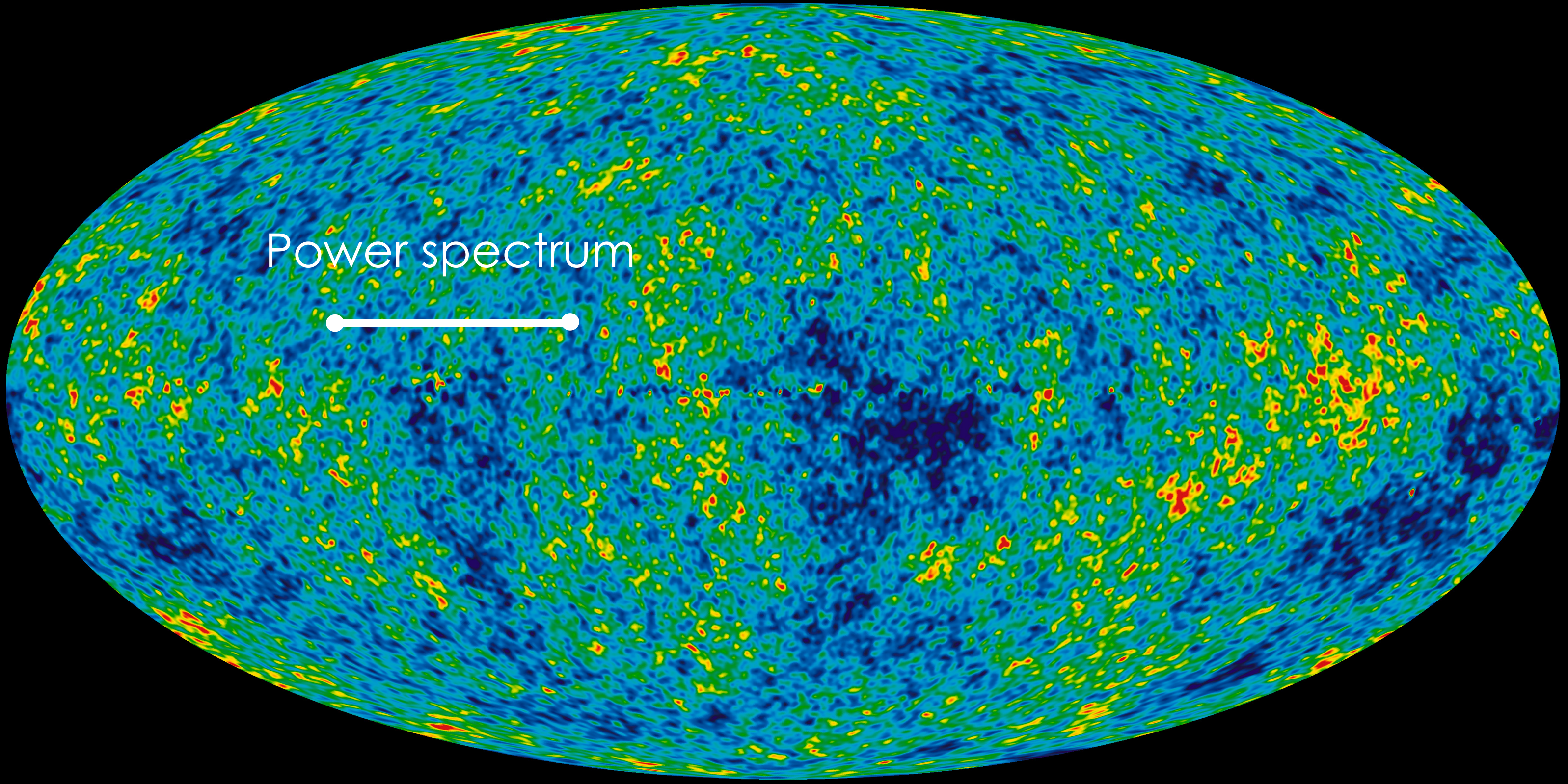

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amplitude of
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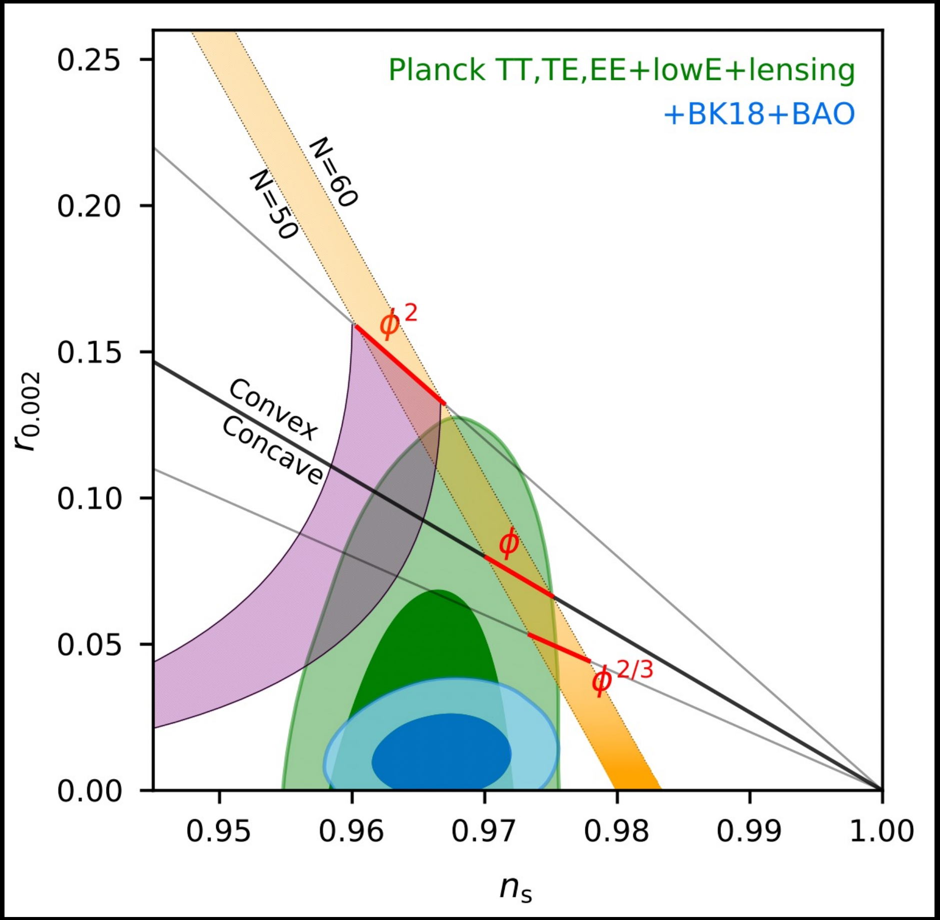
$$n_s - 1 = \frac{d \ln \Delta^2_{\mathcal{R}}(k)}{d \ln k}$$

scalar spectral index

Current observational bounds from CMB

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

tensor-to-scalar ratio



[BICEP/Keck]

$$r < 0.036$$

$$n_s = 0.9603 \pm 0.0073$$

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

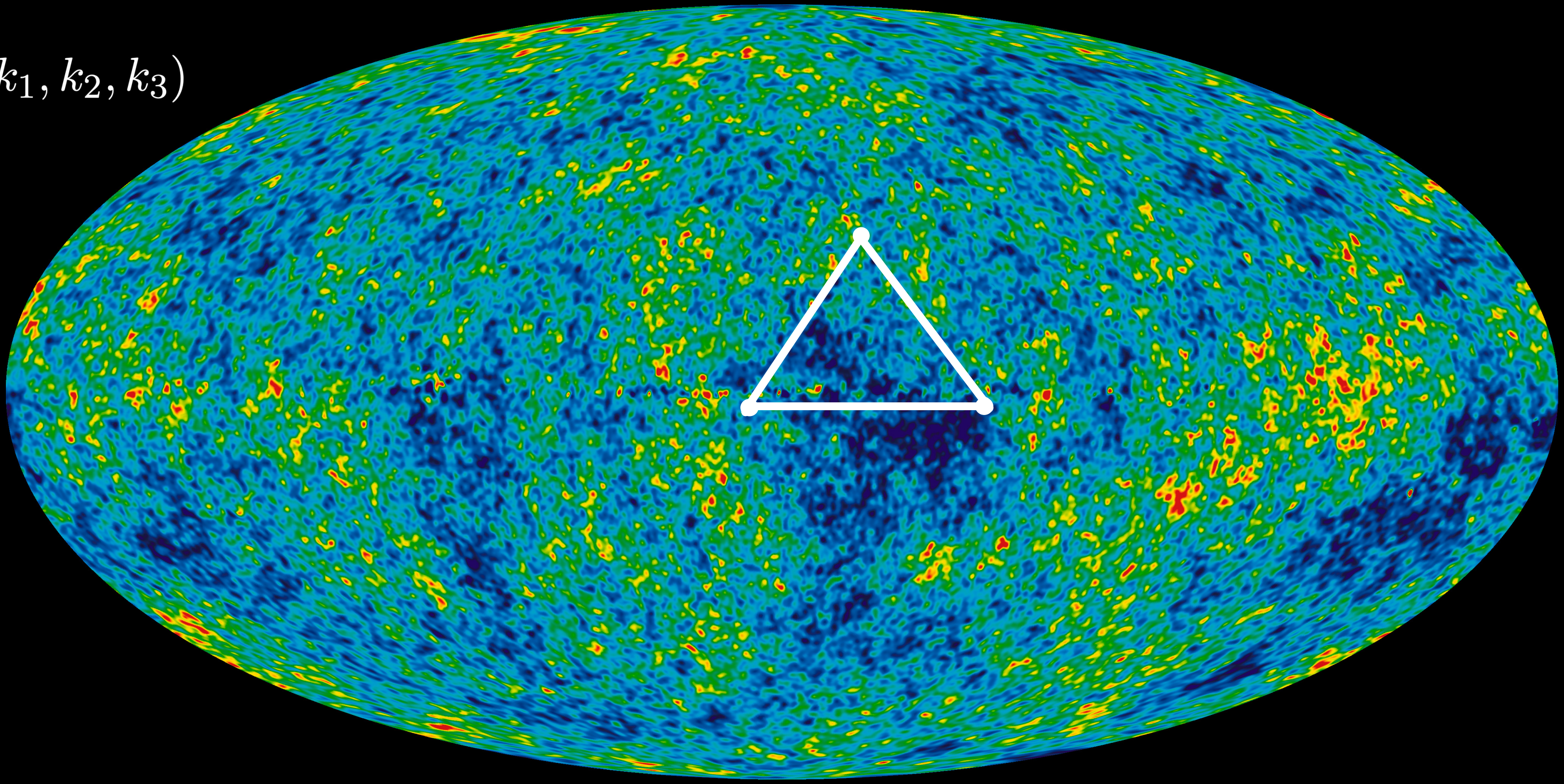
scalar spectral index

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



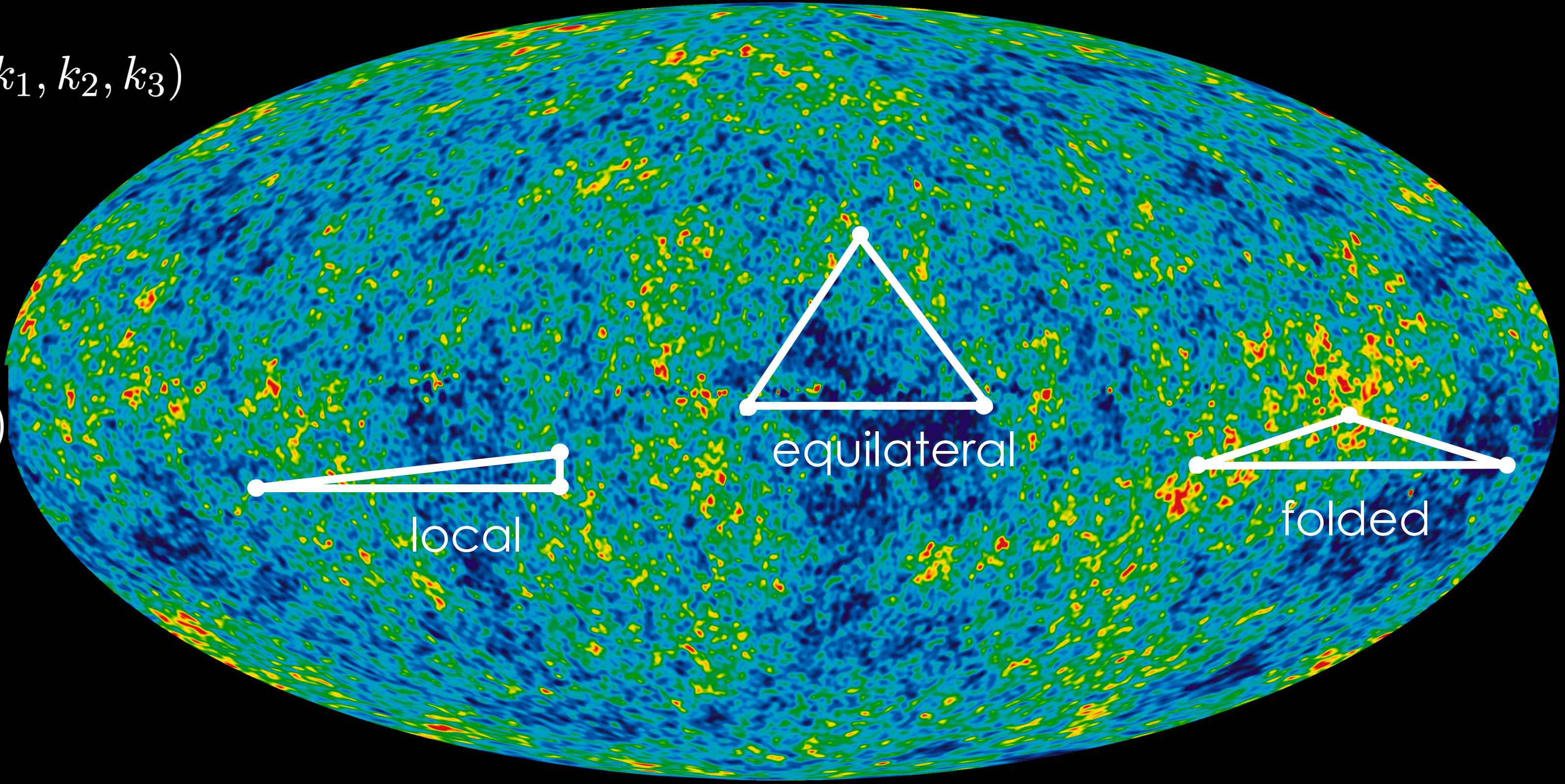
Non-Gaussianity

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

Result of non-linear evolution of initially Gaussian fluctuations.

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

Bi-spectrum



Non-Gaussianity

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

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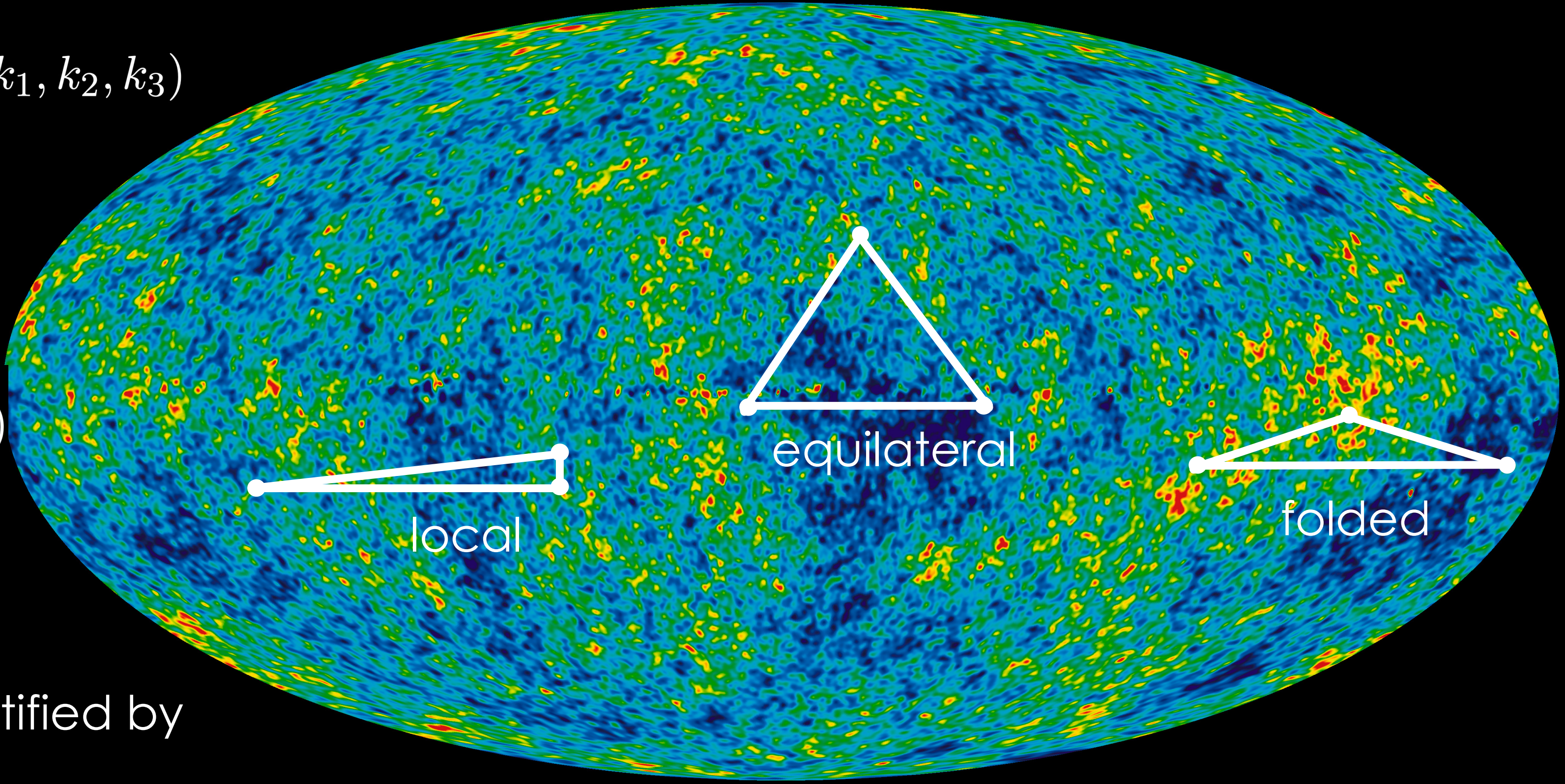


The amount of non-Gaussianity is quantified by the parameter

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

Non-Gaussianity in single-field inflation

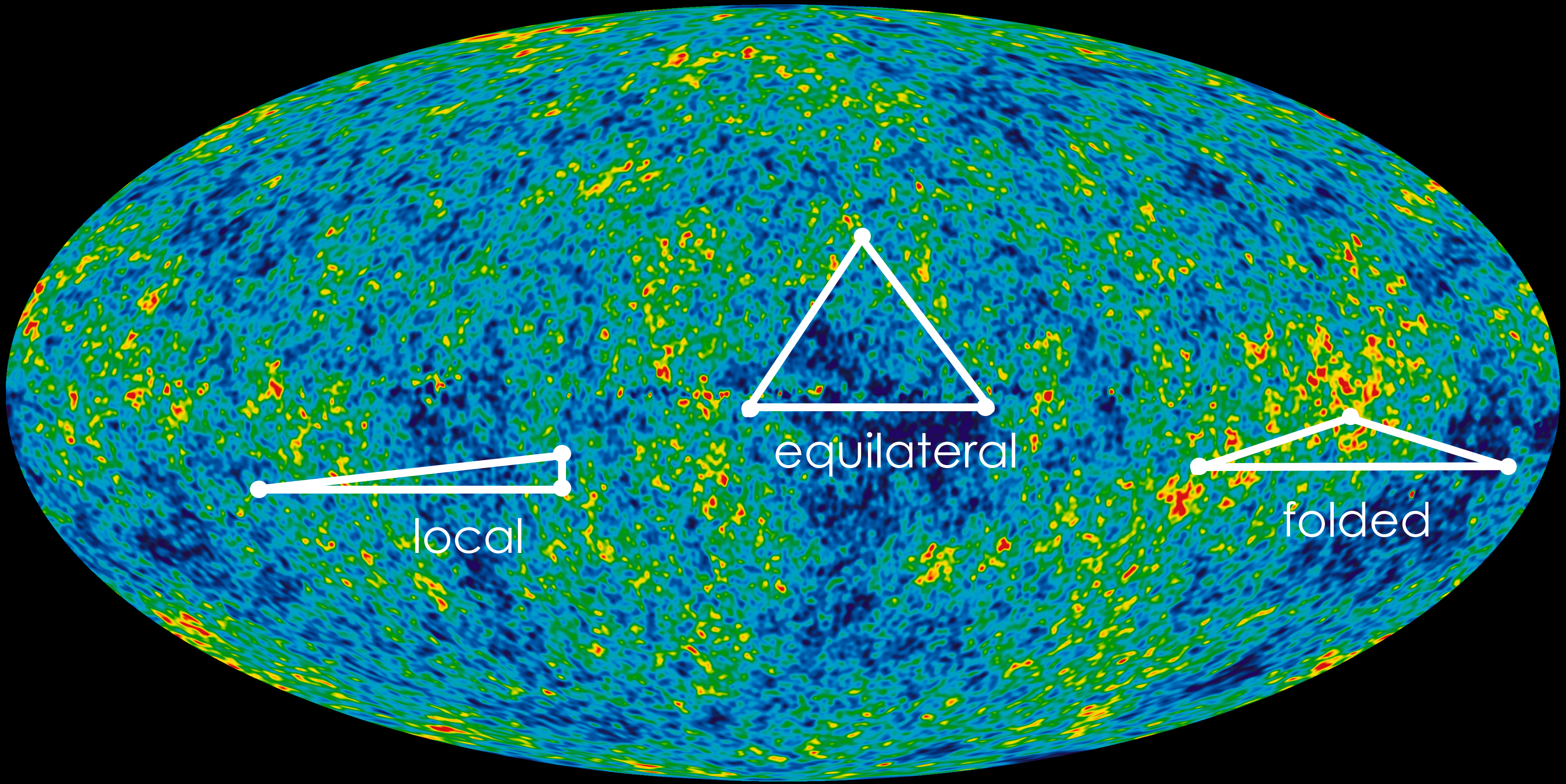
$$f_{\rm NL}^{\rm type} \simeq \mathcal{O}(\epsilon, \eta)$$

[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

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

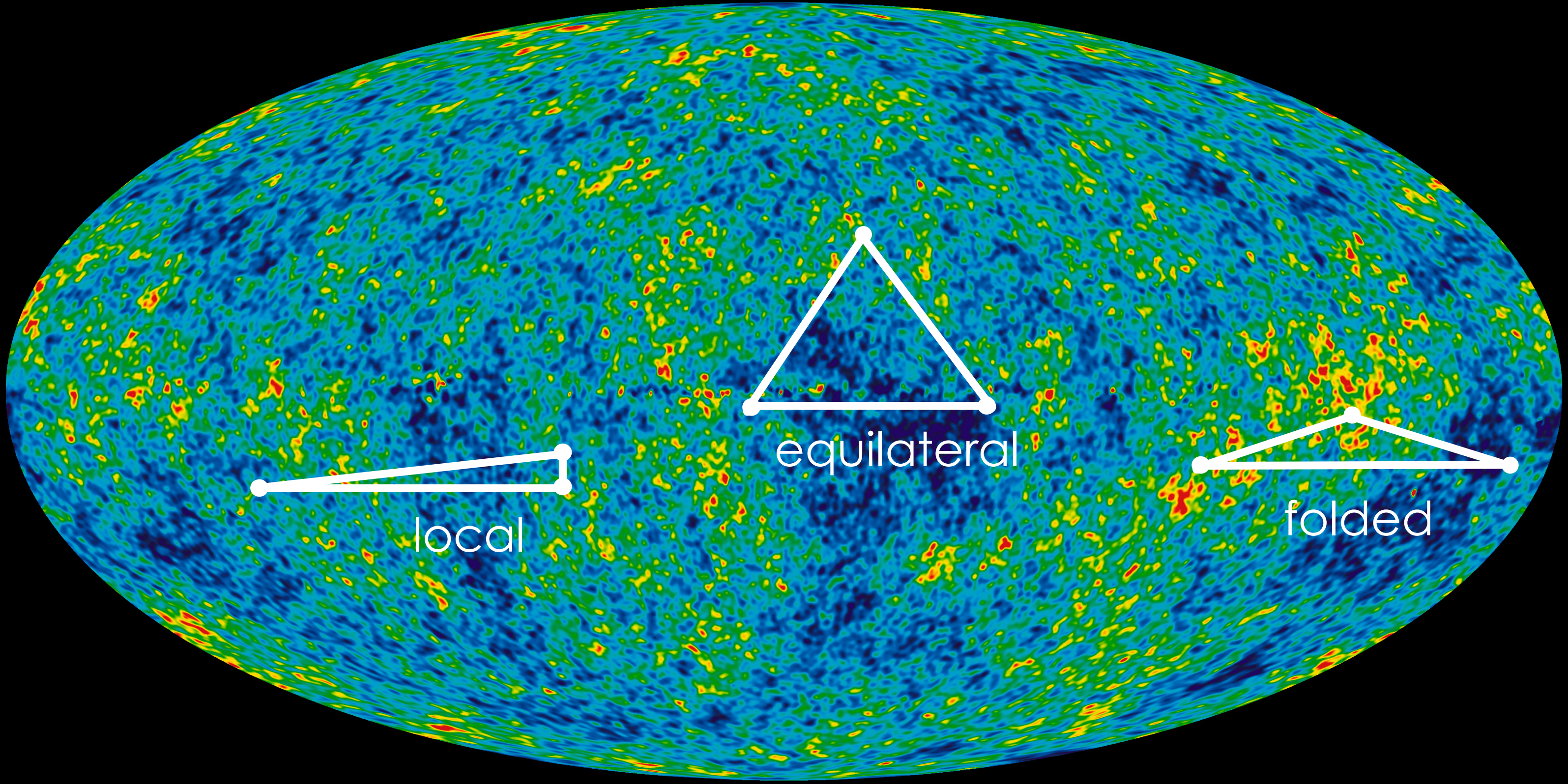
[Maldacena, 2002]

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

[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 and turning trajectory

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

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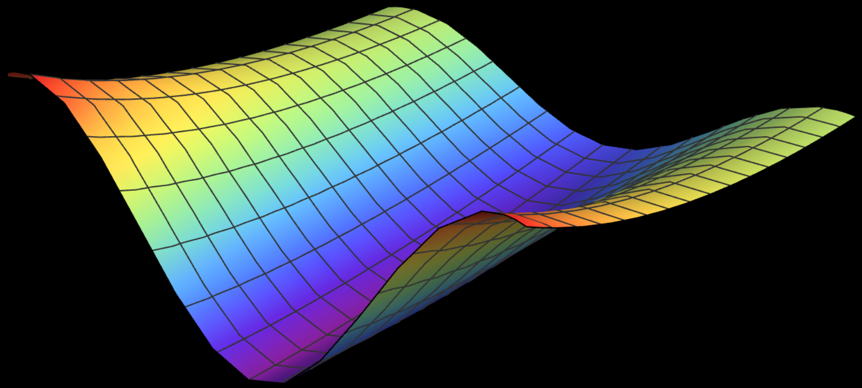

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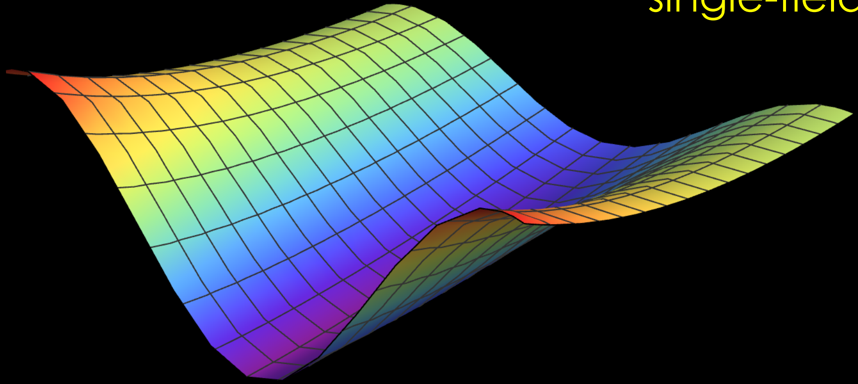
field-space metric

multi-field potential

single-field inflation



$$\epsilon_H = \epsilon_V \ll 1$$

$$\epsilon_H = -\frac{\dot{H}}{H^2}$$

$$\epsilon_V = \frac{M_{\rm pl}^2}{2} \left(\frac{\partial_\phi V}{V} \right)^2$$

Multi-field inflation and turning trajectory

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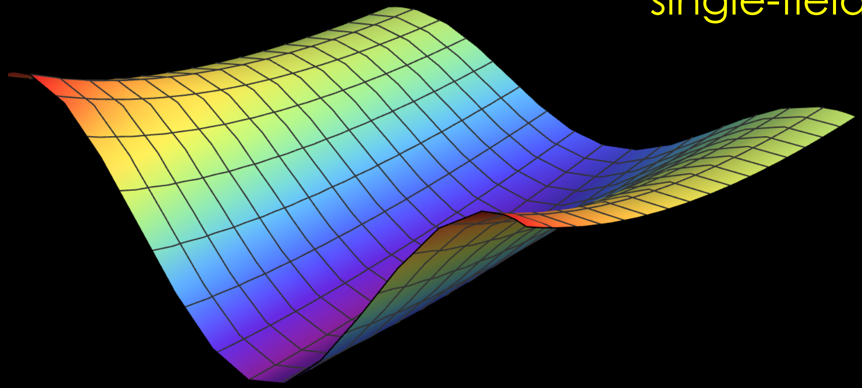


single-field inflation

$\epsilon_H = \epsilon_V \ll 1$

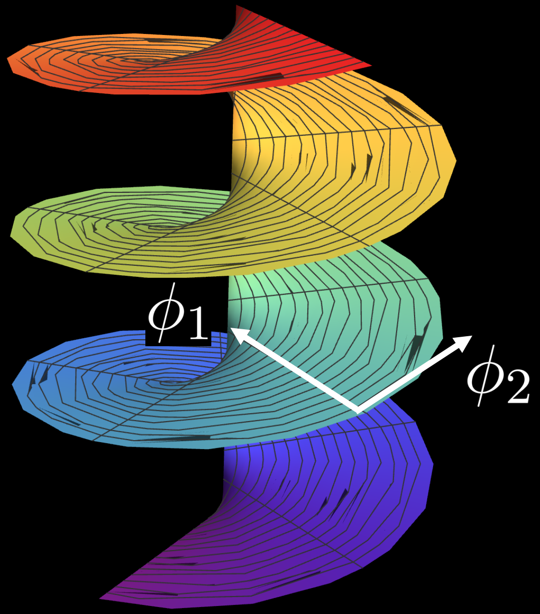
generic potentials: $\epsilon_V \sim \mathcal{O}(1)$

Multi-field inflation and turning trajectory

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

field-space metric

multi-field potential



In multi-field inflation

$\epsilon_H \ll 1$

$\epsilon_V \sim \mathcal{O}(1)$

can coexist when $\eta_\perp \gg 1$

$$\boxed{\epsilon_V = \epsilon_H\left(1 + \eta_\perp^2/9\right)}$$

[Achucarro at al, arXiv: 1807.04390]

Multi-field inflation and turning trajectory

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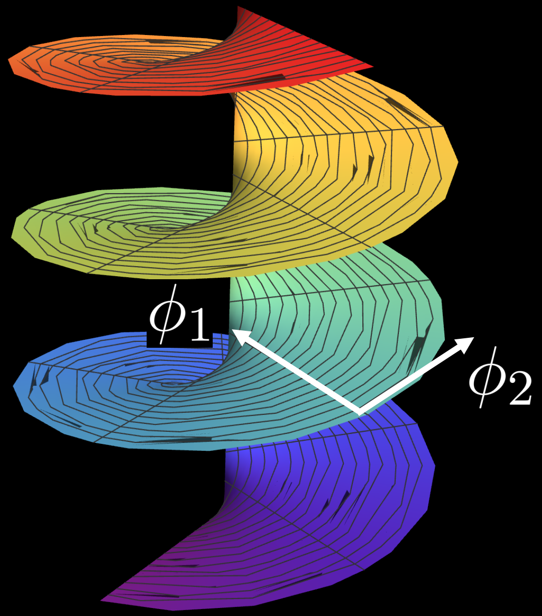

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Rapid-turn inflation!

Multi-field inflation and turning trajectory

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

field-space metric

multi-field potential

Turn-rate: $\eta_\perp$

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

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

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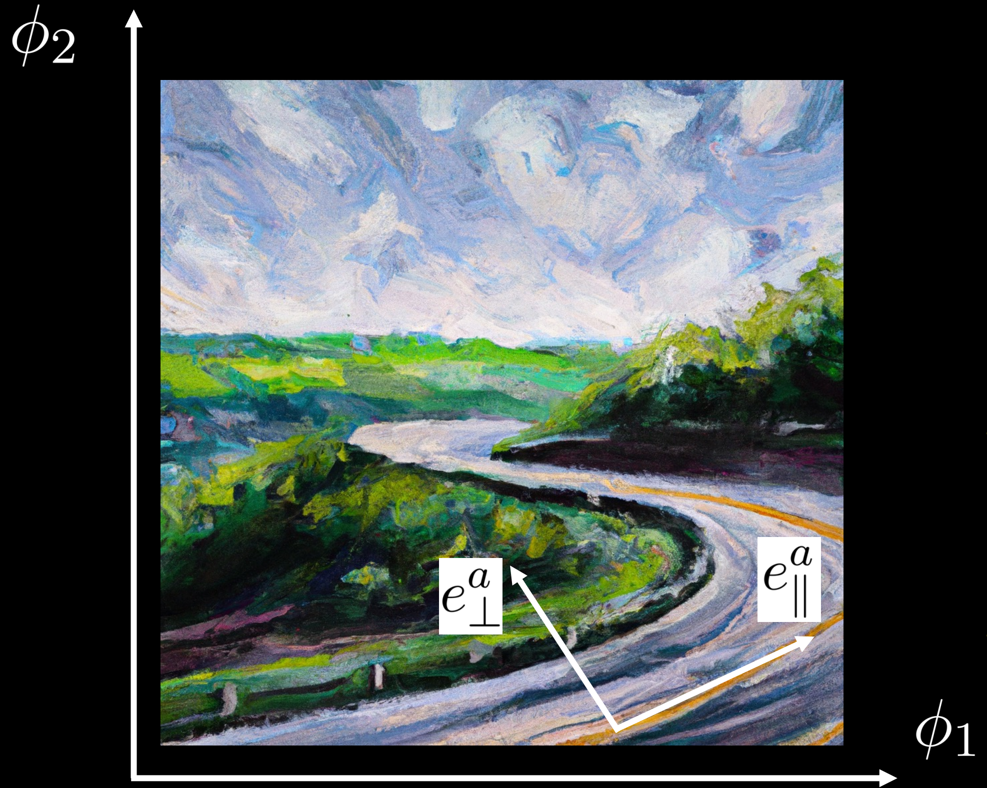

Two types of field perturbations:

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

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]

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

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

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

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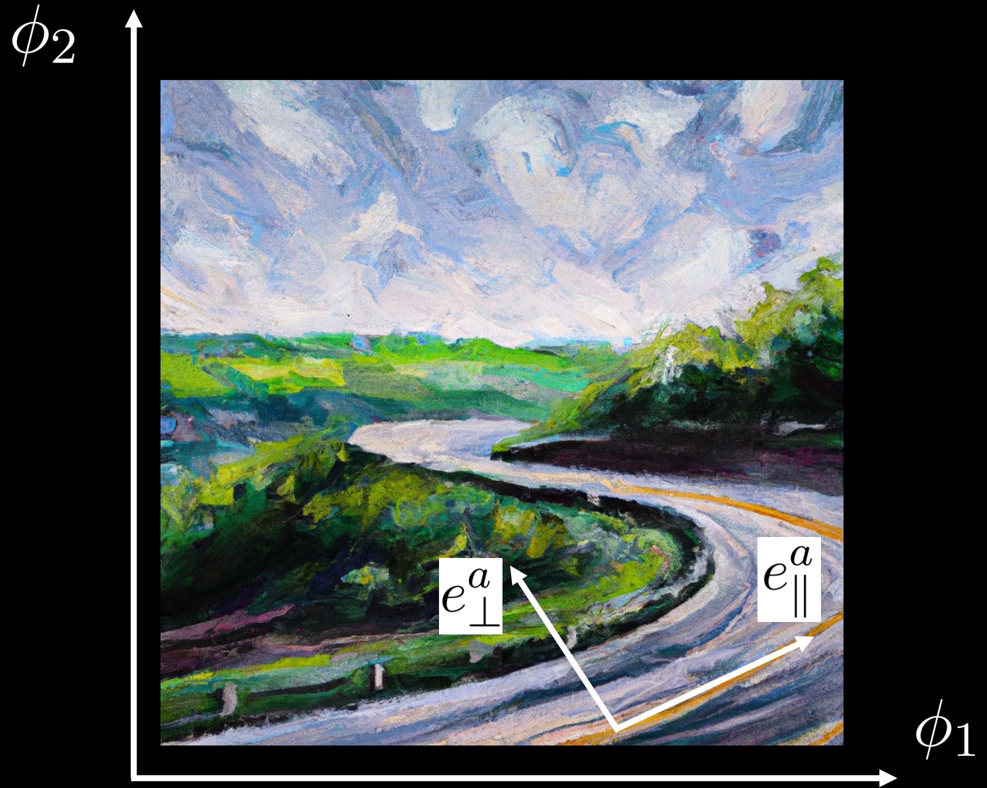

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The sourcing of curvature perturbations by isocurvature perturbations is proportional to the turn-rate!

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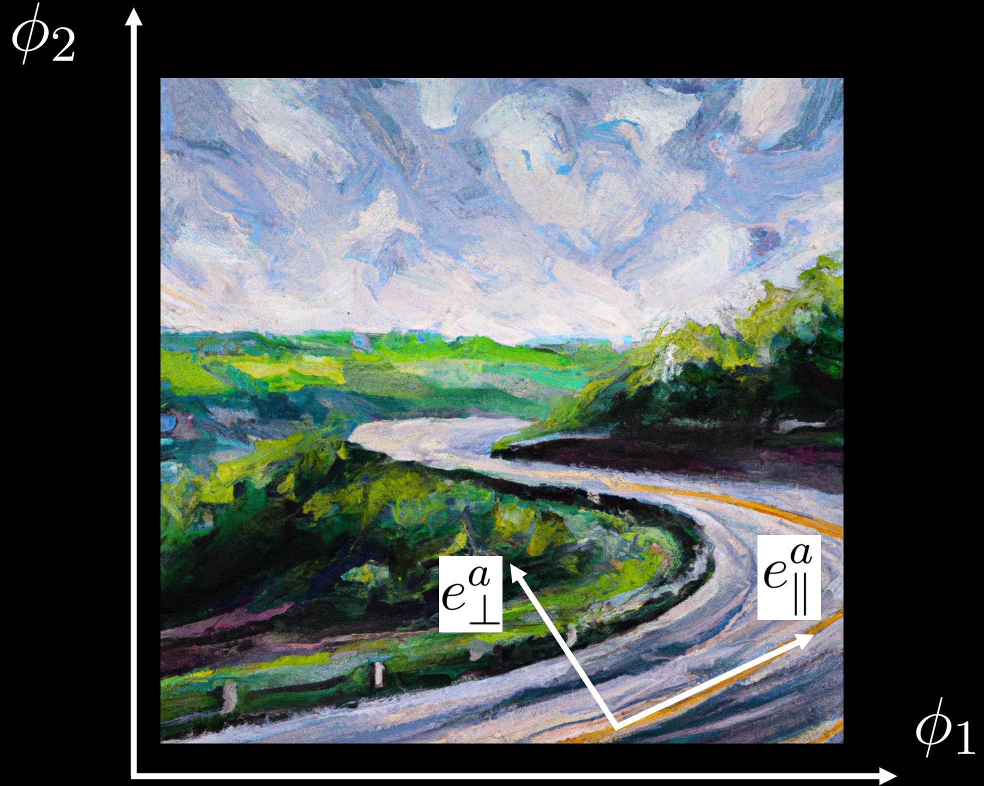

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$$\mathcal{M}^a{}_b = G^{ac}\nabla_b\nabla_c V - R^a_{dfb}\dot{\phi}^d\dot{\phi}^f$$

Determined by potential & geometry of field-space.

Classification of perturbations

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

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

$$\langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \rangle = \frac{1}{2\epsilon} \langle \delta\phi_{\parallel\vec{k}_1} \delta\phi_{\parallel\vec{k}_2} \rangle \;\Rightarrow\; P_{\mathcal{R}}$$

Power spectrum of curvature perturbations,

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

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.

Non-Gaussianity in slow-turn vs rapid-turn inflation

[C. Peterson, M. Tegmark, 2011]

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

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

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

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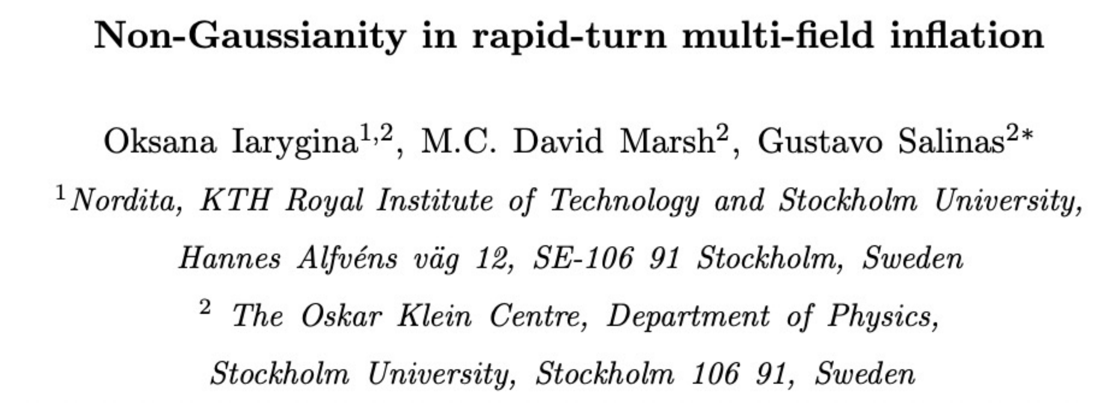
What is different in the rapid-turn regime? $\eta_\perp \gg 1$

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*]

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Hannes Alfvéns väg 12, SE-106 91 Stockholm, Sweden

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

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

Non-Gaussianity in rapid-turn inflation

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

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

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

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

δN -formalism

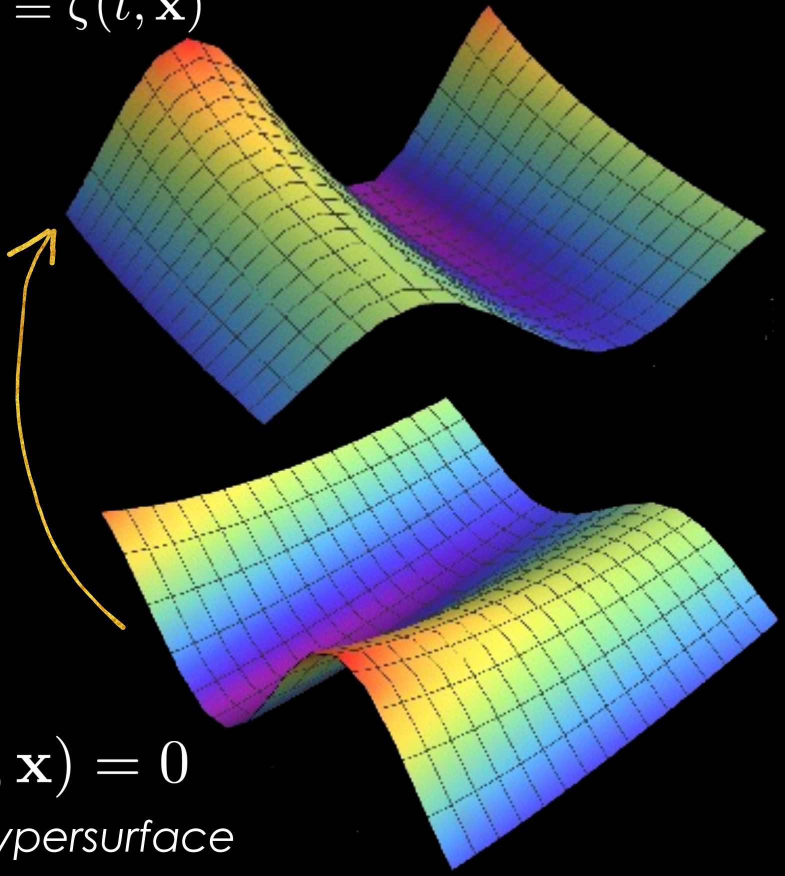
[Sasaki and Stewart,(1996)]
[Wands, Malik, Lyth, Liddle (2000)]

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

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

uniform density hypersurface

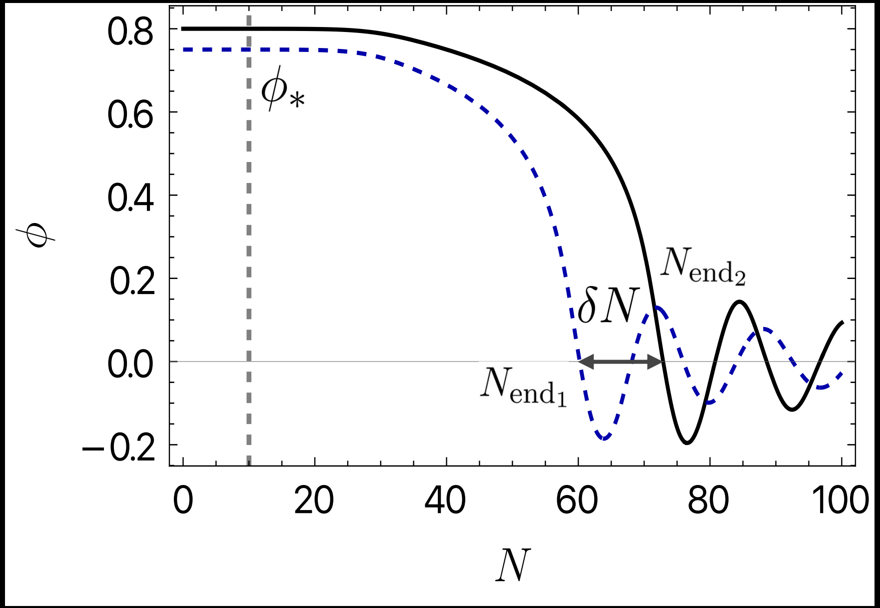
$$\psi_{\mathrm{UD}}(t,\mathbf{x}) \equiv \zeta(t,\mathbf{x})$$



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

initial flat hypersurface

$$\delta N = N_a\delta\phi^a_* + \frac{1}{2}N_{ab}\delta\phi^a_*\delta\phi^b_* + \ldots$$



Non-Gaussianity in rapid-turn inflation

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

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

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

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

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

Non-Gaussianity in rapid-turn inflation

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

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

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

$$\downarrow$$

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

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

Non-Gaussianity in rapid-turn inflation

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$$\Big\downarrow$$

$$f_{\mathrm{NL}}^{\mathcal{R}\mathcal{R}}, \underline{f_{\mathrm{NL}}^{\mathcal{R}\mathcal{C}}, f_{\mathrm{NL}}^{\mathcal{C}\mathcal{R}}, f_{\mathrm{NL}}^{\mathcal{C}\mathcal{C}}}$$

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

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:

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

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

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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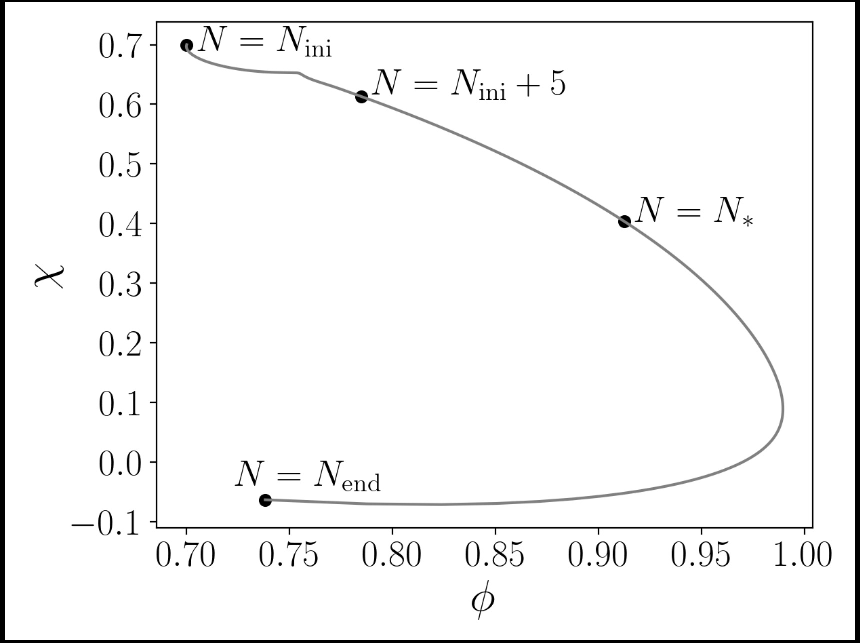
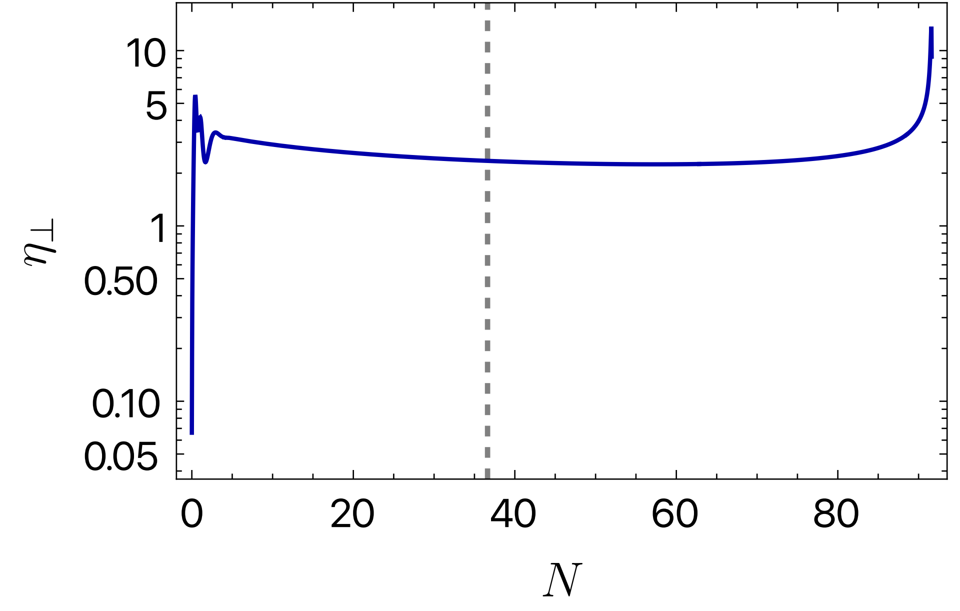
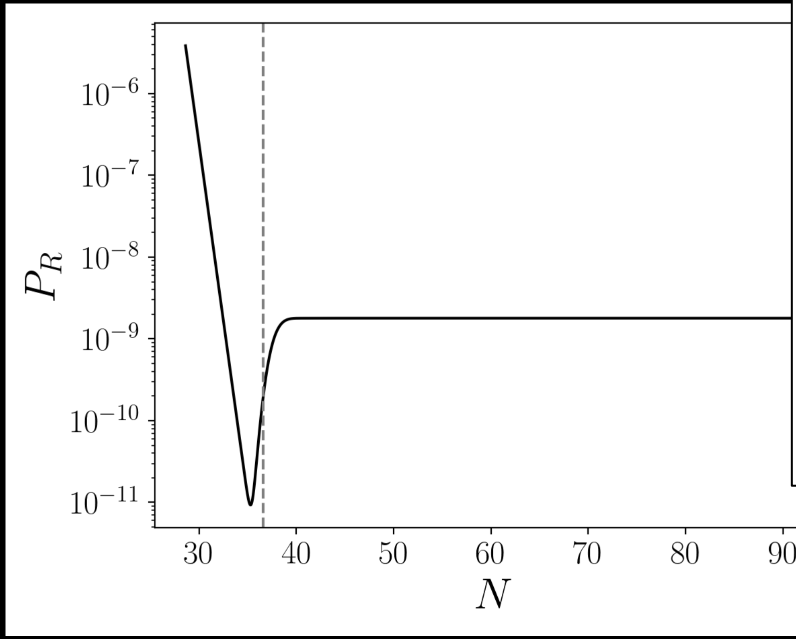


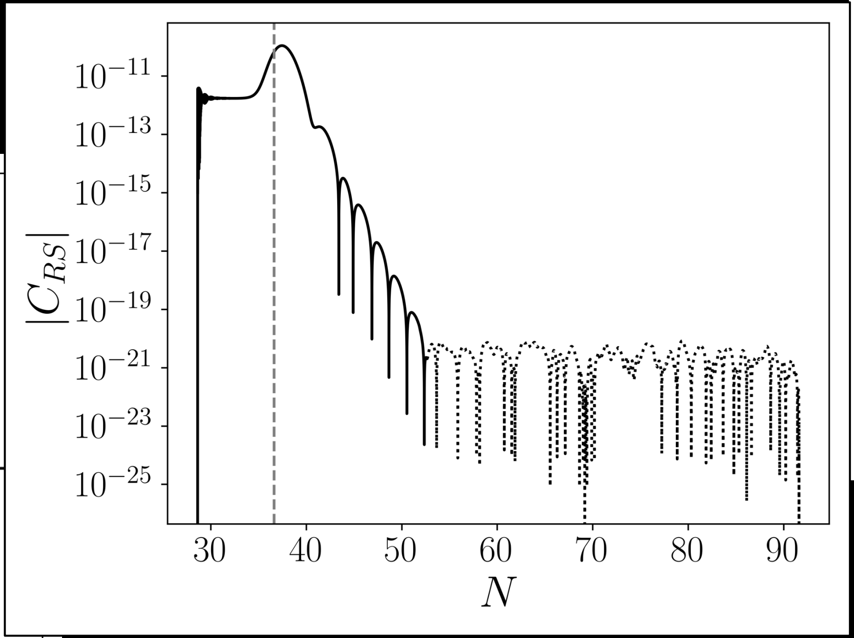


Example: Angular inflation model

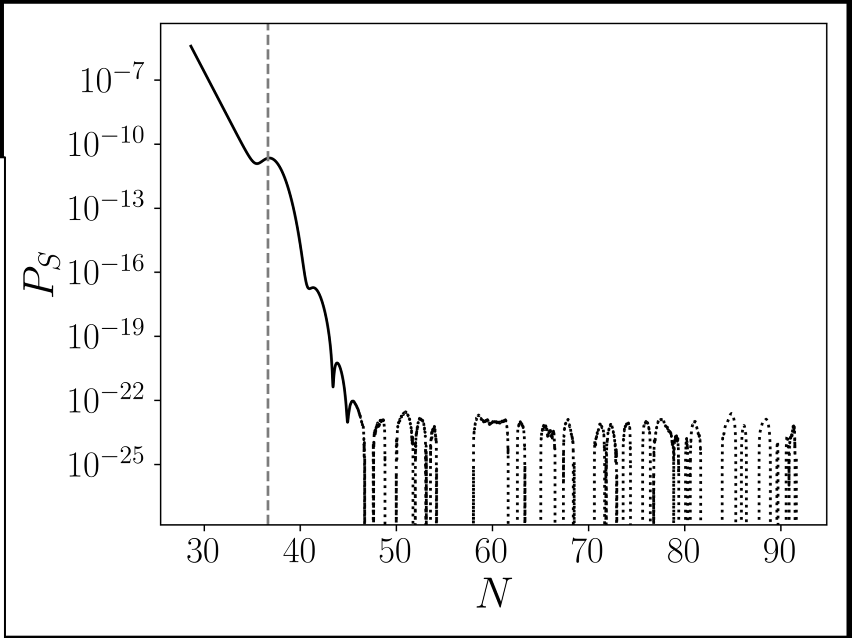
[OI, D. Marsh, G. Salinas, 2023]



Power spectrum of curvature perturbations,



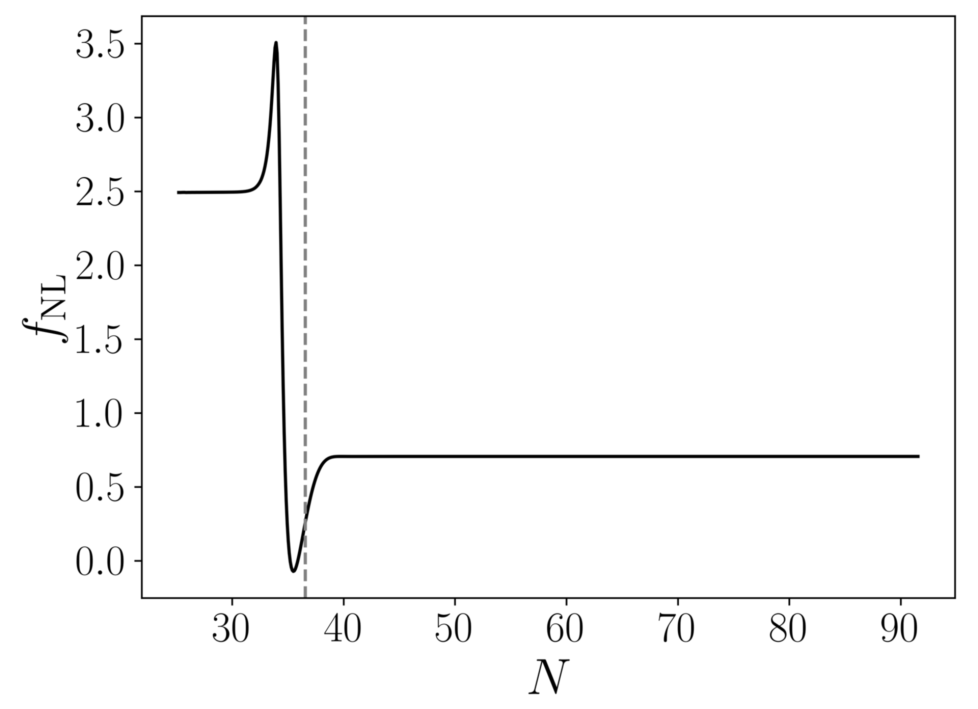
cross-correlation,



isocurvature perturbations.

Example: Angular inflation model

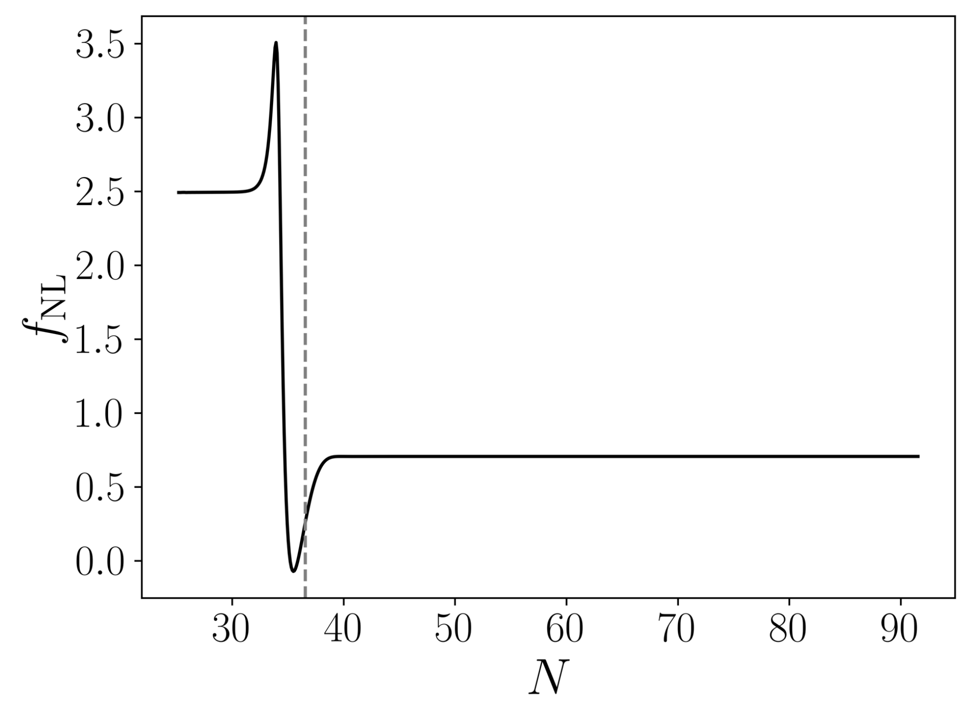
[OI, D. Marsh, G. Salinas, 2023]



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

Example: Angular inflation model

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



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

$$\boxed{f_{\rm NL} = 0.93 \simeq \mathcal{O}\left(1\right)}$$

Conclusions

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

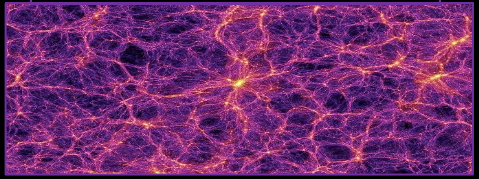
2. Identified new model-independent potentially large contributions to the non-Gaussianity parameter.

3. Detection of Non-Gaussianity $f_{\rm NL}^{\rm loc} \simeq \mathcal{O}\left(1\right)$ 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



Conclusions

Thank you!

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

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

3. Detection of Non-Gaussianity $f_{\mathrm{NL}}^{\mathrm{loc}} \simeq \mathcal{O}\left(1\right)$ signals:

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CMB-S4
Next Generation CMB Experiment

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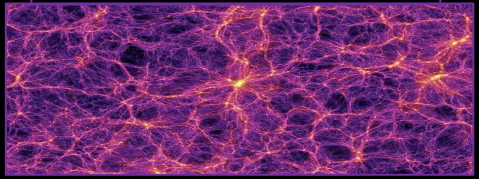

Back up slides

The effective mass of isocurvature perturbation:

$$\mu^2 = e^a_\perp e^b_\perp \nabla_a \nabla_b V + \epsilon H^2 \mathbb{R} + 3H^2 \eta^2_\perp,$$

Non-Gaussianity from the δN -formalism

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

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

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

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

horizon crossing contribution

super-horizon evolution

The end