Title: Signatures of Supersymmetry from the Early Universe

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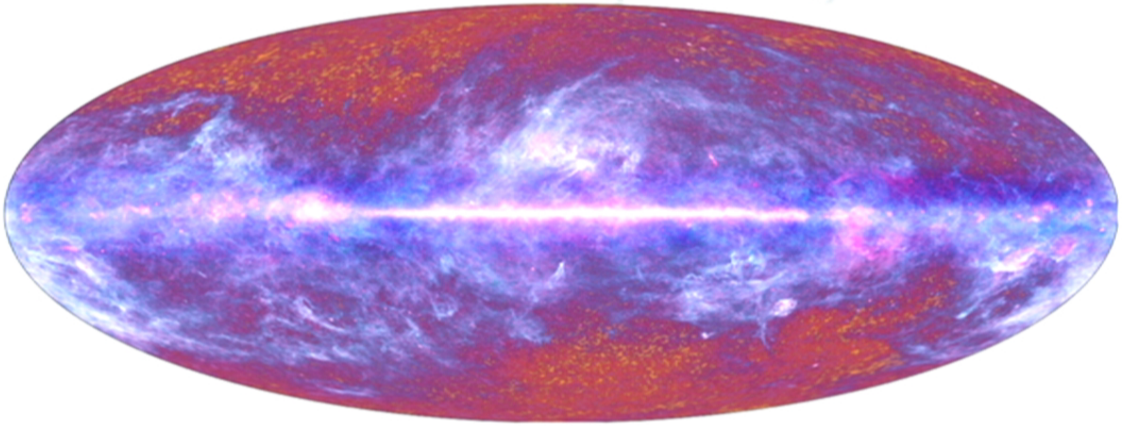
Abstract: Supersymmetry plays a fundamental role in the radiative stability of many inflationary models. I will explain how supersymmetry and naturalness require additional scalar degrees of freedom with masses on the order of the inflationary Hubble scale. These fields lead to distinctive non-gaussian signatures that may be observable in both the CMB and large scale structure.

Signatures of Supersymmetry



from the early universe

Daniel Green
IAS

Based on work with Daniel Baumann
arXiv: 1109.0292, 1109.0293

Outline

Introduction

Supersymmetry & Inflation

Quasi-Single Field Inflation

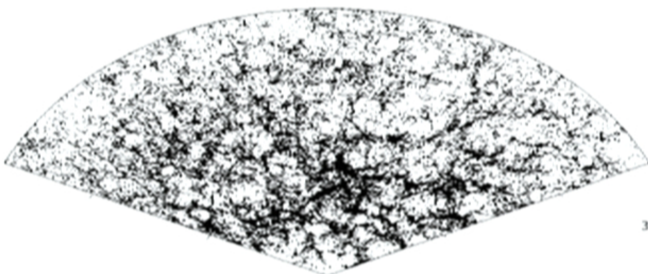
Signatures of SUSY

Inflation

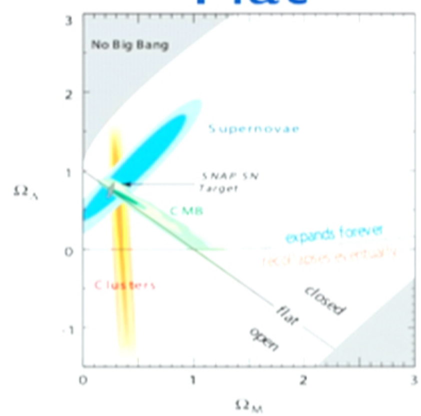
Explains observed features of cosmological data

Universe on largest scales:

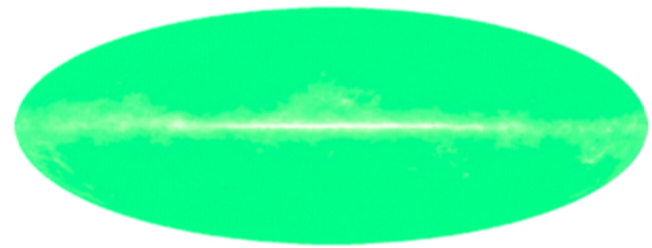
Homogeneous

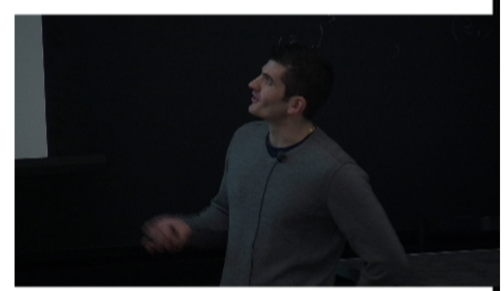


Flat



Isotropic



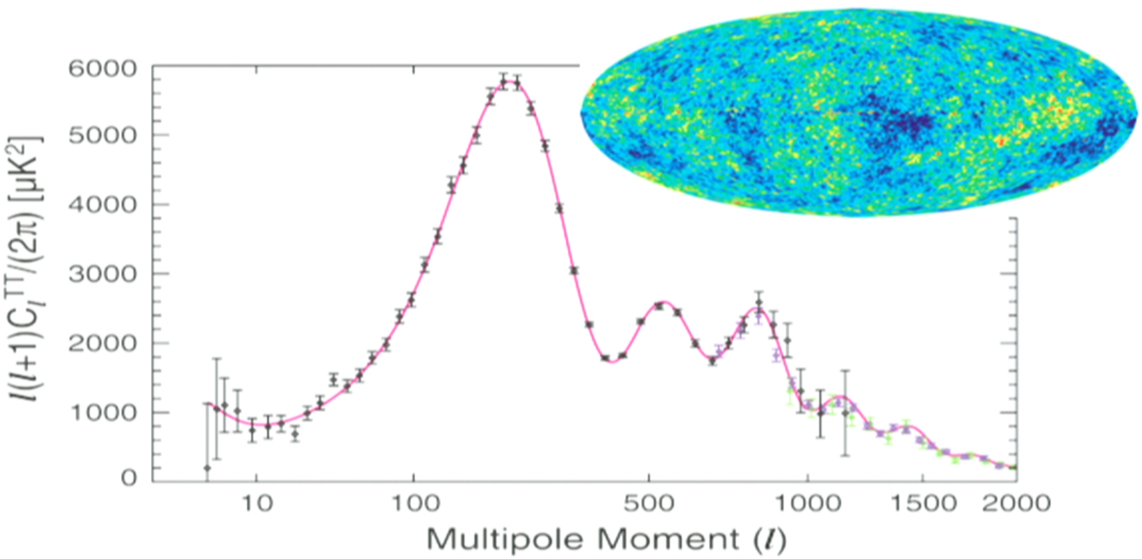


Inflation

Explains observed features of cosmological data

Fluctuations are:

- Scale Invariant
- Adiabatic
- Gaussian

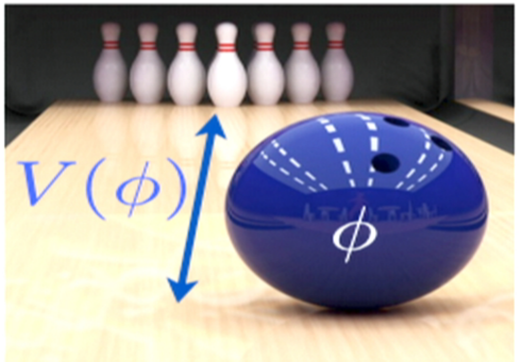


Inflation

A sufficient definition to explain data:

~60 e-folds of quasi de Sitter with $H^2 \gg |\dot{H}|$

e.g. Can be achieved via slow roll inflation



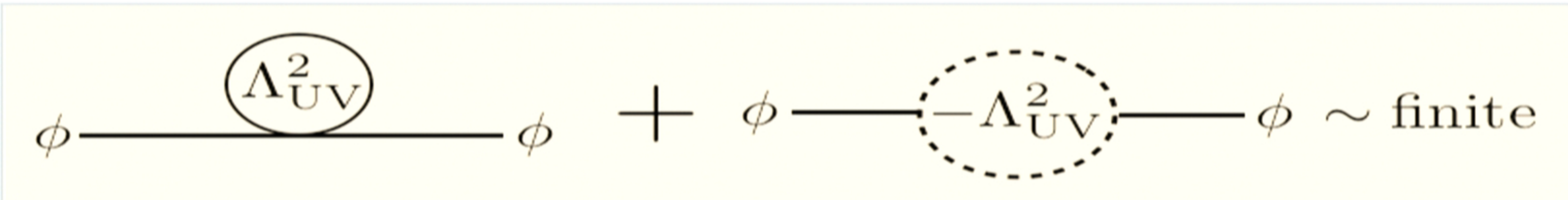
$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

$$\epsilon = M_{\rm pl}^2\left(\frac{V'}{V}\right)^2 \ll 1 \qquad \eta \simeq \frac{m_\phi^2}{H^2} \ll 1$$

What protects the flatness of the potential?

Supersymmetry

Protects inflaton potential



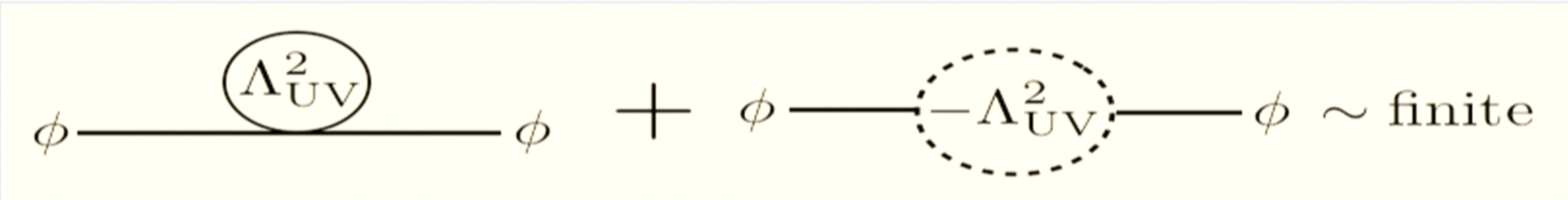
Without SUSY, models are typically baroque

Motivates SUSY at energy scale of inflation

No less motivated if SUSY is absent at the weak scale

Supersymmetry

Protects inflaton potential



SUSY is broken (at least) at the Hubble scale

SUSY η problem : $m_\phi^2 \sim H^2$

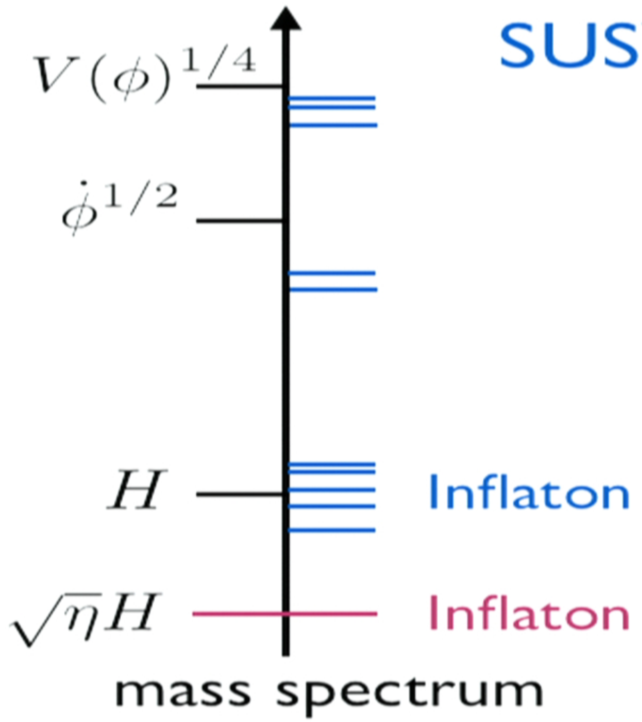
need fine tuning
or more symmetry

SUSY drastically simplifies the problem
(but does not solve it)

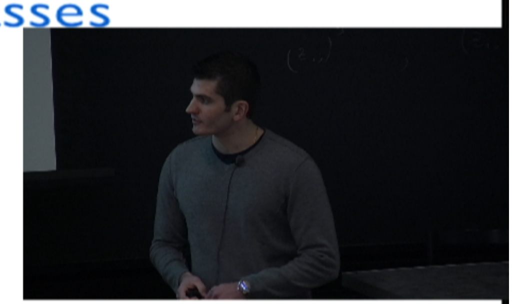
Supersymmetry

Inflaton is a *REAL* scalar

SUSY uses *complex* scalars



SUSY "predicts" at least one extra light(ish) scalar



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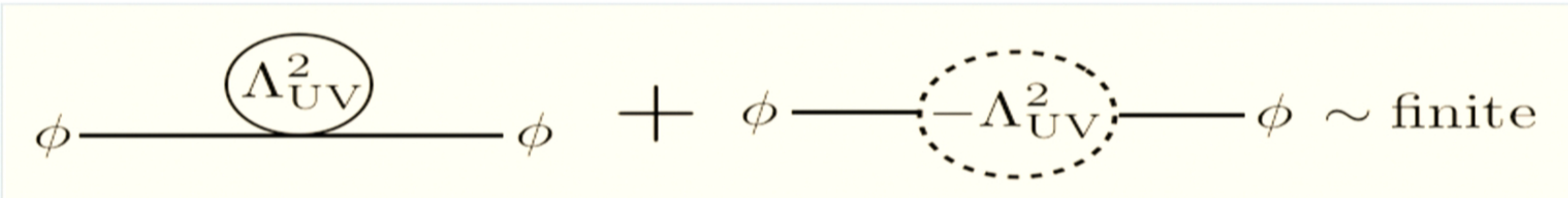

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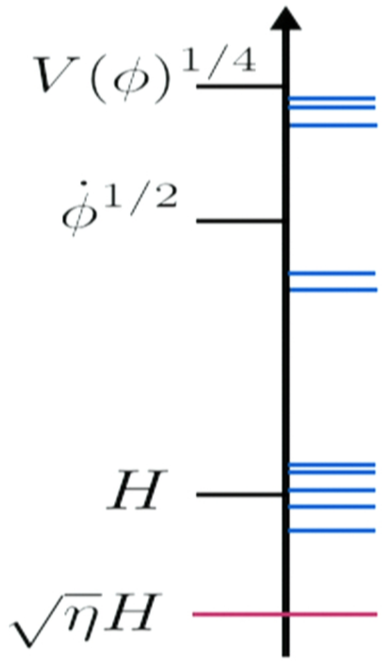

Inflaton partner / gravity mediated masses

Inflaton

mass spectrum

SUSY "predicts" at least one extra light(ish) scalar

Can we “detect” these extra species?

Non-Gaussianity

N-point functions contain lots of information

E.g. : 3-point function of curvature perturbation ζ

Rotation + Translation Invariance

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = (2\pi)^3 B_\zeta(k_1, k_2, k_3) \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

Scale Invariance

$$B_\zeta(k_1, k_2, k_3) = \frac{1}{k_3^6} B_\zeta(x_1, x_2, 1) \ ; \quad x_{1,2} = \frac{k_{1,2}}{k_3}$$

Function of 2 variables

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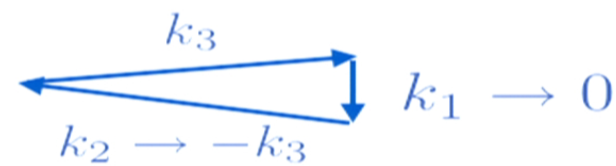
Function of 2 variables

Squeezed Limit

Three point function sensitive to # of fields

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle |_{k_1 \to 0}$$



In single field inflation $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle |_{k_1 \to 0} \propto \frac{1}{k_1}$ Creminelli et al.

Idea: $ds^2 = -dt^2 + a(t)^2 e^{2\zeta} dx_i^2 = -dt^2 + a(t)^2 d\tilde{x}_i^2$

Constant ζ is not physical

Physical Quantities $\dot{\zeta}, \nabla^2 \zeta \propto k^2 \zeta$

Squeezed Limit

Three point function sensitive to # of fields

$$\langle \zeta^3 \rangle_{k \to 0} \propto \frac{1}{k^\alpha}$$

$\alpha > 1$: *Multiple light scalars*

What more might we learn?

Symmetries ⟷ Interactions
Senatore & Zaldarriaga

Measure detailed "shape": requires high signal to noise

What do we learn from the scaling itself?

Quasi-Single Field Inflation

Chen & Wang

Hubble mass fields lead to unique signatures

e.g. $\mathcal{L} \supset \rho^2 \dot{\zeta} \sigma + m^2 \sigma^2 + \mu \sigma^3$

$$\langle \zeta^3 \rangle_{k_1 \to 0} \propto \frac{1}{k_1^{\alpha}} \qquad \alpha = \frac{3}{2} + \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Squeezed limit measures the mass!

$1 < \alpha < 3$ is natural in SUSY

The Supersymmetric EFT of Inflation

SUSY and Inflation

Basic Ingredients

1. Inflation requires positive vacuum energy

Positive vacuum energy breaks SUSY

2. Inflation breaks time translations

Creminelli et al. ; Cheung et al.

Inflation must end so we need a clock

Goldstone boson = local fluctuations of clock

Goldstone is eaten $\zeta = -H\pi$

SUSY and Inflation

Basic Ingredients

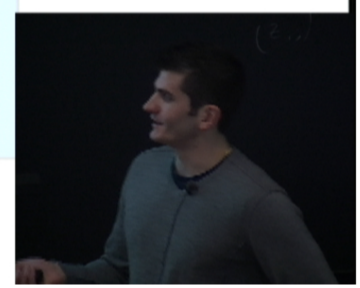
Inflation requires positive vacuum energy

$V(\phi)$ F-term breaking: $|F_X|^2 = 3M_{\rm pl}^2 H^2$

$X = x + \theta\psi_x + \theta^2 F_X$ x is typically heavy

Integrate out x : $X = \dfrac{\psi^2}{F_X} + \theta\psi + \theta^2 F_X$

$$\int d^4\theta X^\dagger X + \left[\int d^2\theta(\sqrt{3}M_{\rm pl}H)X + \text{h.c.}\right]$$



SUSY and Inflation

Basic Ingredients

Inflation breaks time translations

~~Time Translations~~ $\xrightarrow{\{Q,\bar{Q}\} = 2iP_\mu}$ ~~SUSY~~

Lorentz breaking: $\Phi = \ldots\theta\sigma^\mu\bar{\theta}\partial_\mu\phi \longrightarrow \theta\sigma^0\bar{\theta}\dot{\phi}(t)$

Write this in general as

$$\Phi \supset \theta\sigma^\mu\bar{\theta}M_{\rm pl}|\dot{H}|^{1/2}\partial_\mu t \longrightarrow \theta\sigma^0\bar{\theta}M_{\rm pl}|\dot{H}|^{1/2}$$

e.g. for slow roll $\sqrt{2}M_{\rm pl}\dot{H}^{1/2} = \dot{\phi}$

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SUSY and Inflation

Basic Ingredients

Inflation *spontaneously* breaks time translations

Include goldstone of time translation breaking $\pi \simeq \frac{\delta\phi}{\dot{\phi}}$

Always appears as $\varphi = t + \pi$ Cheung et al.

$$t \longrightarrow t + \xi(t, x)$$
$$\pi \longrightarrow \pi - \xi(t, x)$$

$\longrightarrow$ φ is invariant !

e.g. : $\Phi = \sigma + i\phi(t + \pi) + i\bar{\theta}\sigma^\mu\theta\partial_\mu\Big(\sigma + i\phi(t + \pi)\Big) + \ldots$

σ is our extra scalar!

Scalar Masses

Mass for σ generated by SUSY breaking

In Field Theory - Self-interactions generate small mass

$$m^2\sigma^2 \sim \frac{\dot{\phi}^2}{\Lambda^2}\sigma^2 \qquad \Lambda^2 \lesssim M_{\rm pl}^2 \to m^2 \sim \dot{H} \ll H^2$$

Coupled to Gravity - Curvature of space-time breaks SUSY

$$m^2\sigma^2 \sim (a\mathcal{R} + b\frac{V(\phi)}{M_{\rm pl}^2})\sigma^2 \sim H^2\sigma^2$$

Curvature Perturbations

During Inflation - Goldstone "eaten"

Higgs mechanism - $\zeta \sim -H\pi + \ldots$

In single field, ζ is conserved outside the horizon

After Inflation - Multi-field effects

$$\zeta \sim aH\pi + b\sigma(x) + c\sigma^2(x) + \ldots$$

Non-conservation of ζ is local in real space

Senatore & Zaldarriaga

Quasi-Single Field Inflation

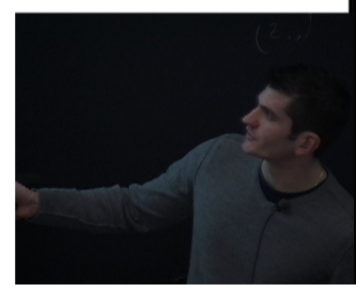
Chen & Wang

$$\mathcal{L} = M_{\rm pl}^2 \dot{H} \partial_\mu \pi \partial^\mu \pi + \tfrac{1}{2} \partial_\mu \sigma \partial^\mu \sigma + \tilde{m}^3 \dot{\pi} \sigma + m^2 \sigma^2 + \mu \sigma^3$$

mixing term

$$\rho \dot{\pi}_c \sigma \qquad \rho = \frac{\tilde{m}^3}{M_{\rm pl} \dot{H}^{1/2}} \ll H$$

treat mixing perturbatively



Quasi-Single Field Inflation

Chen & Wang

Basic Idea

Massless field

$$\pi \sim \frac{\delta\phi}{\dot{\phi}}$$

Mixing term

Massive field

$$\sigma$$

Only derivative interactions

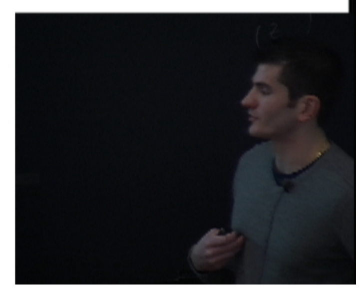
e.g. $\mathcal{L}_{\rm int} = M^4 \dot{\pi}^3$

Interactions unconstrained

e.g. $\mathcal{L}_{\rm int} = \mu \sigma^3$

Massive fluctuations converted into curvature!

$$\sigma \longrightarrow H\pi = \zeta$$



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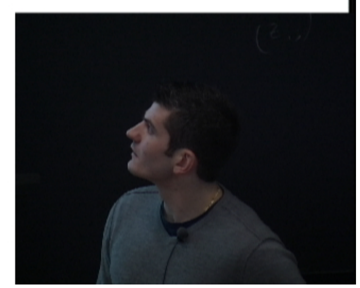

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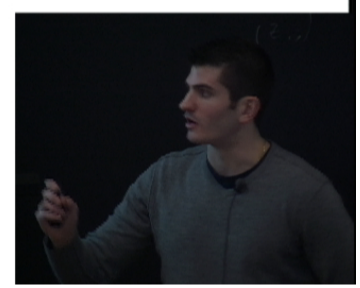
mass term

$$\sigma_k \sim H k^{-\nu} (-\tau)^{-\nu + 3/2} \qquad \nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

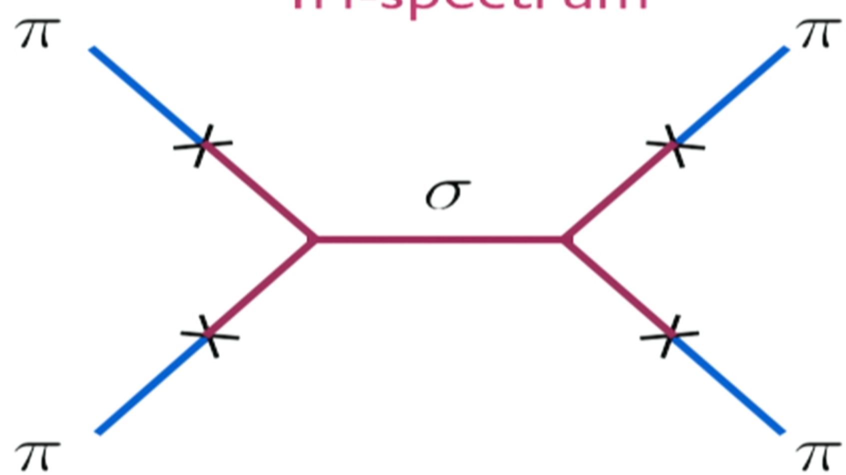
Fluctuations decay outside the horizon



Quasi-Single Field Inflation

Chen & Wang

Tri-spectrum



$$\tau_{\rm NL} \sim \left(\frac{\rho}{H}\right)^4 \frac{\mu^2}{H^2} \Delta_\zeta^{-1} \sim \frac{H^2}{\rho^2} f_{\rm NL}^2 \gg f_{\rm NL}^2$$

Four point function enhanced

Quasi-Single Field Inflation

Chen & Wang

$$\mathcal{L} = M_{\rm pl}^2 \dot{H} \partial_\mu \pi \partial^\mu \pi + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma + \tilde{m}^3 \dot{\pi} \sigma + m^2 \sigma^2 + \mu \sigma^3$$

Why scale invariant?

Scale invariance is about shift symmetry: $t \longrightarrow t + c$
(or equivalently $\pi \longrightarrow \pi + c$)

Action preserves this symmetry

Symmetry also broken at the end of inflation $\eta = \eta_{\rm end}$

$\sigma \longrightarrow \pi$ conversion happens during inflation

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Quasi-Single Field Inflation

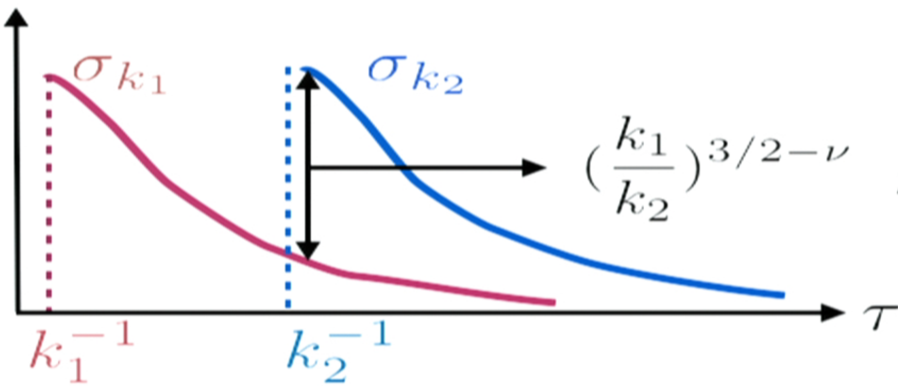
Squeezed Limit

Chen & Wang

$$\langle \zeta^3 \rangle_{k_1 \to 0} \sim \frac{1}{k_1^3 k_2^3} \left(\frac{k_1}{k_2}\right)^{\frac{3}{2} - \nu} \sim \frac{1}{k_1^{3/2+\nu}}$$

Local shape

$$\sigma_{k_1}(k_2^{-1}) = \sigma_{k_1}(k_1^{-1}) \left(\frac{k_1}{k_2}\right)^{3/2-\nu}$$



$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Signatures of SUSY

Supersymmetric QSFI

$$\int d^4\theta \tfrac{1}{2}(\Phi + \Phi^\dagger)^2 + \frac{1}{\Lambda_1}(\Phi + \Phi^\dagger)^3 + \frac{1}{\Lambda_2^3}(\Phi + \Phi^\dagger)^5$$

$$m^2 \sim H^2 \qquad \rho = \frac{\dot\phi}{\Lambda_1} \qquad \mu = \frac{\dot\phi^2}{\Lambda_2^3}$$

Generates $\rho\dot\pi_c\sigma$

Includes interactions $\frac{1}{\Lambda_1}(\sigma\partial_\mu\pi_c\partial^\mu\pi_c + \sigma\partial_\mu\sigma\partial^\mu\sigma)$

These interactions generate $f_{\rm NL} < 1$

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Variations on QSFI

Include extra chiral field

$$\mathcal{L}_{\Sigma\Phi} = \int d^4\theta \frac{1}{\tilde{\Lambda}} (\Phi + \Phi^\dagger)^2 (\Sigma + \Sigma^\dagger) + \frac{1}{\Lambda_1} (\Sigma + \Sigma^\dagger) \Sigma \Sigma^\dagger$$

$$\frac{\dot{\phi}^2}{\tilde{\Lambda}} \partial_\mu (t + \pi) \partial^\mu (t + \pi) \tilde{\sigma} \rightarrow \rho \dot{\pi}_c \tilde{\sigma}$$

Mixing term

Variations on QSFI

e.g. - Include extra chiral field

$$\mathcal{L}_{\Sigma\Phi} = \int d^4\theta \frac{1}{\tilde{\Lambda}}(\Phi + \Phi^\dagger)^2(\Sigma + \Sigma^\dagger) + \frac{1}{\Lambda_1}(\Sigma + \Sigma^\dagger)\Sigma\Sigma^\dagger$$

$$\frac{1}{\Lambda_1}\tilde{\sigma}\partial_\mu\tilde{\sigma}\partial^\mu\tilde{\sigma} \longrightarrow f_{\rm NL} \sim \frac{\rho^3}{H^3}\frac{H}{\Lambda_1}\Delta_\zeta^{-1/2}$$

Squeezed limit unchanged

$$\sigma_L(x)\partial_\mu\sigma_S(x)\partial^\mu\sigma_S(x)$$

Still have local coupling to long mode

Variations on QSFI

Other possibilities?

Interaction	$f_{\rm NL}^{(1)}$	$f_{\rm NL}^{(2)}$	Large NG	S.L.	SUSY	Natural
$\mathcal{L}_{1a} = m_a^3(\partial_\mu\pi)^2\sigma$	$(\frac{\rho}{H})^2$	$\alpha\,\frac{\rho}{H}$		✓	✓	
$\mathcal{L}_{1b} = m_b^3(\dot\pi)^2\sigma$	$(\frac{\rho}{H})^2$	$\alpha\,\frac{\rho}{H}$		✓	✓	
$\mathcal{L}_2 = \bar m^2(\partial_\mu\pi)^2\dot\sigma$	$\frac{\rho}{H}\,\alpha$	α^2				
$\mathcal{L}_3 = \bar m^2\dot\pi\sigma^2$	$(\frac{\rho}{H})^2\,(\frac{\bar m}{H})^2$	$\alpha^2\,(\frac{\bar m}{H})^2$		✓		
$\mathcal{L}_{4a} = m_a\partial_\mu\pi\partial^\mu\sigma\sigma$	$(\frac{\rho}{H})^2\,\frac{m_a}{H}$	$\alpha^2\,\frac{m_a}{H}$		✓	✓	
$\mathcal{L}_{4b} = m_b\dot\pi\dot\sigma\sigma$	$(\frac{\rho}{H})^2\,\frac{m_b}{H}$	$\alpha^2\,\frac{m_b}{H}$		✓		
$\mathcal{L}_{5a} = \lambda_a\dot\pi(\partial_\mu\sigma)^2$	$(\frac{\rho}{H})^2\,\lambda_a$	$\alpha^2\,\lambda_a$				
$\mathcal{L}_{5b} = \lambda_b\partial_\mu\pi\partial^\mu\sigma\dot\sigma$	$(\frac{\rho}{H})^2\,\lambda_b$	$\alpha^2\,\lambda_b$				
$\mathcal{L}_{5c} = \lambda_c\dot\pi\dot\sigma^2$	$(\frac{\rho}{H})^2\,\lambda_c$	$\alpha^2\,\lambda_c$				
$\mathcal{L}_6 = \mu\sigma^3$	$(\frac{\rho}{H})^3\,\frac{\mu}{H}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{\mu}{H}\,\Delta_\zeta^{-1}$	✓	✓	✓	✓
$\mathcal{L}_7 = \lambda\dot\sigma\sigma^2$	$(\frac{\rho}{H})^3\,\lambda\,\Delta_\zeta^{-1}$	$\alpha^3\,\lambda\,\Delta_\zeta^{-1}$	✓	✓		(?)
$\mathcal{L}_{8a} = \Lambda_1^{-1}(\partial_\mu\sigma)^2\sigma$	$(\frac{\rho}{H})^3\,\frac{H}{\Lambda_1}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{H}{\Lambda_1}\,\Delta_\zeta^{-1}$	✓	✓	✓	✓
$\mathcal{L}_{8b} = \Lambda_2^{-1}\dot\sigma^2\sigma$	$(\frac{\rho}{H})^3\,\frac{H}{\Lambda_2}\,\Delta_\zeta^{-1}$	$\alpha^3\,\frac{H}{\Lambda_2}\,\Delta_\zeta^{-1}$	✓	✓		(?)
$\mathcal{L}_{9a} = \Lambda_3^{-2}\dot\sigma(\partial_\mu\sigma)^2$	$(\frac{\rho}{H})^3\,(\frac{H}{\Lambda_3})^2\,\Delta_\zeta^{-1}$	$\alpha^3\,(\frac{H}{\Lambda_3})^2\,\Delta_\zeta^{-1}$	✓			✓
$\mathcal{L}_{9b} = \Lambda_4^{-2}\dot\sigma^3$	$(\frac{\rho}{H})^3\,(\frac{H}{\Lambda_4})^2\,\Delta_\zeta^{-1}$	$\alpha^3\,(\frac{H}{\Lambda_4})^2\,\Delta_\zeta^{-1}$	✓			✓

Requirements:

Naturally large NG

Squeezed limit

Only interactions with both:

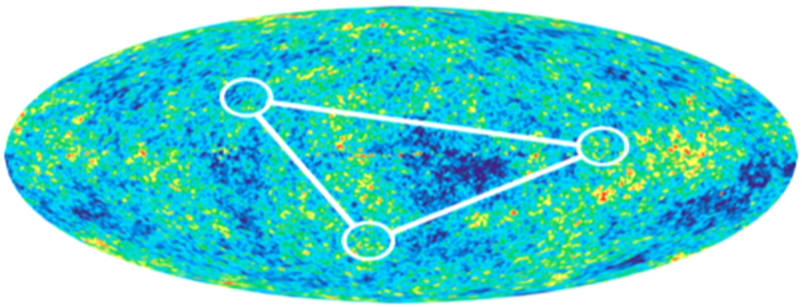
σ^3 and

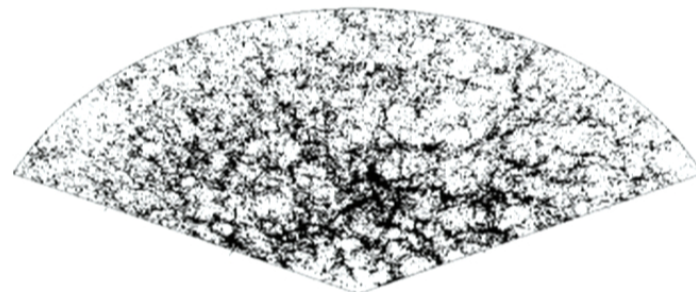
$\sigma\partial_\mu\sigma\partial^\mu\sigma$

Observations

Non-Gaussianity

Two complimentary approaches





CMB

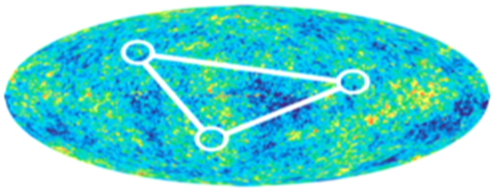
WMAP

Planck

Large scale structure

SDSS

BOSS, DES, LSST, ...



Non-Gaussianity

3 Point Function

$$\langle \Delta T(\theta_1) \Delta T(\theta_2) \Delta T(\theta_3) \rangle \longrightarrow \langle \zeta(k_1)\zeta(k_2)\zeta(k_3) \rangle$$

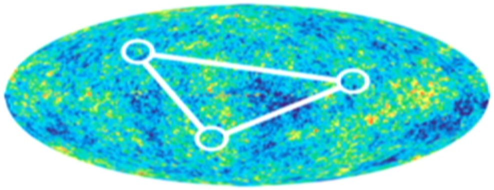
Measure — Infer — Primordial

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = (2\pi)^3 B_\zeta(k_1, k_2, k_3) \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

S/N enhance by projecting data onto templates

$$S(x_1, x_2) \equiv B_\zeta(x_1, x_2, 1) x_1^2 x_2^2 \qquad x_{1,2} = \frac{k_{1,2}}{k_3}$$

Peaks where S/N is concentrated



Non-Gaussianity

Squeezed Limit

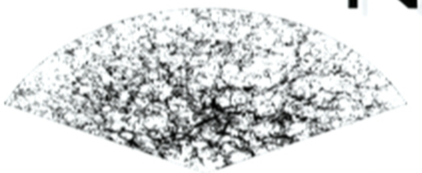
$$k_1 \longrightarrow 0 \equiv x_1 \longrightarrow 0, x_2 \longrightarrow 1$$

QSFI : $B(k_1, k_2, k_3) \longrightarrow \frac{1}{k_1^{\alpha}}$ **as** $k_1 \longrightarrow 0$

Squeezed "shape" : $S(x_1, x_2) \longrightarrow \frac{1}{x_1^{\alpha - 2}}$ as $x_1 \longrightarrow 0$

Dominates S/N:	$2 < \alpha$
Interesting range:	$1 < \alpha$

Non-Gaussianity in LSS



Galaxy Clustering

Local Non-Gaussianity $\alpha = 3$

$$\Phi = \Phi_g(x) + f_{\rm NL}\Phi_g^2(x)$$

Matter power spectrum

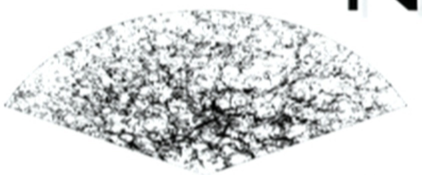
$$\delta_{k_s} \sim \delta_{k_s(g)}(1 + f_{\rm NL}\Phi_{k_L})$$

$$\langle\delta_{k_s}^2(x)\rangle \sim f\Phi_{k_{\rm NL}}\bar{\sigma}_8 \sim \frac{f_{\rm NL}}{k_L^2}\bar{\sigma}_8$$

Scale dependent bias $\delta_{\rm halo} \sim bf_{\rm NL}\Phi \sim \frac{bf_{\rm NL}}{k^2}\delta$

Dalal et al.

Non-Gaussianity in LSS



Galaxy Clustering

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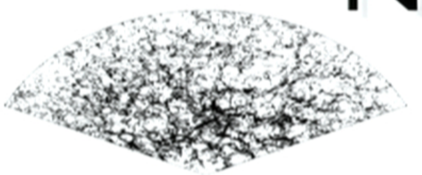
Scale dependent bias
Dalal et al.

$$\delta_{\rm halo} \sim bf_{\rm NL}\Phi \sim \frac{bf_{\rm NL}}{k^2}\delta$$

Non-Gaussianity in LSS



Galaxy Clustering

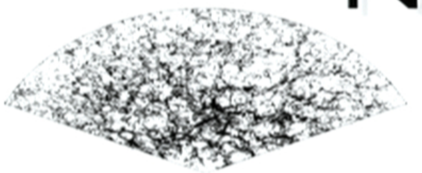
Probes the squeezed limit

$$\langle \zeta(k_1)\zeta_((k_2)\zeta(k_3)\rangle \longrightarrow \frac{1}{k_1^{\alpha}} \quad \textbf{as} \quad k_1 \longrightarrow 0$$

$$\langle \delta_{\rm halo}(k)\delta(-k)\rangle \longrightarrow \frac{b f_{\rm NL}}{k^{\alpha-1}}\langle \delta(k)\delta(-k)\rangle \quad \textbf{as} \quad k \longrightarrow 0$$

Measurable for interesting range : $\alpha > 1$

Non-Gaussianity in LSS



Galaxy Clustering

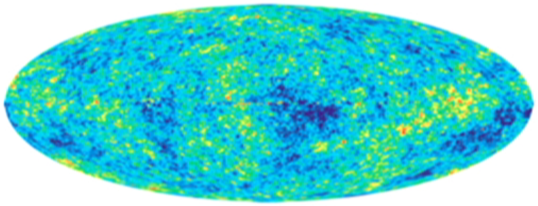
Probes the squeezed limit

$$\langle \zeta(k_1)\zeta_(k_2)\zeta(k_3)\rangle \longrightarrow \frac{1}{k_1^\alpha} \quad \textbf{as} \quad k_1 \longrightarrow 0$$

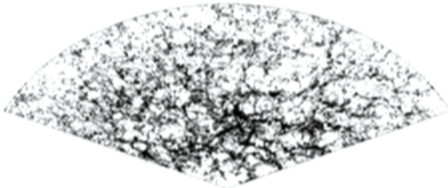
$$\langle \delta_{\rm halo}(k)\delta(-k)\rangle \longrightarrow \frac{bf_{\rm NL}}{k^{\alpha-1}}\langle \delta(k)\delta(-k)\rangle \quad \textbf{as} \quad k \longrightarrow 0$$

Measurable for interesting range : $\alpha > 1$

Summary



CMB + LSS will measure squeezed limit(s)



Scaling in squeezed limit determines mass of extra fields

Hubble mass particles are a generic feature of SUSY inflation

Quasi-local N.G. arises naturally