Leonardo Senatore
(Stanford University)

The Effective Field Theory of Inflation and Multifield Inflation

Large non-Gaussianities

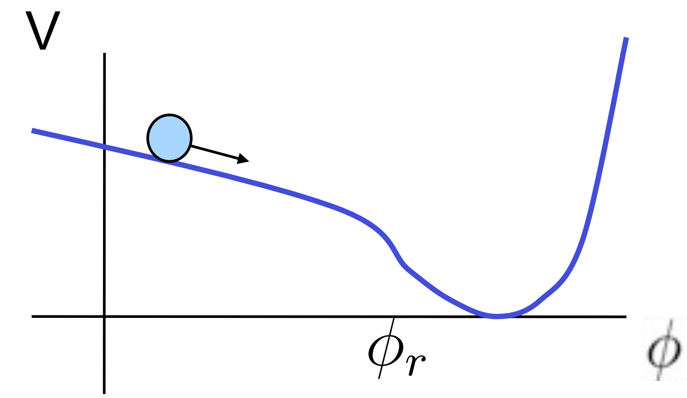
- Standard slow-roll infl.: very Gaussian

Maldacena, **JHEP,2003**
Acquaviva et al, **Nunl.Phys. B,2003**

$$\frac{\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle}{\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle^{3/2}} \simeq f_{\rm NL}\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle^{1/2} \sim 10^{-7}$$

$$f_{\rm NL} \sim 10^{-2}$$

So far undetectable

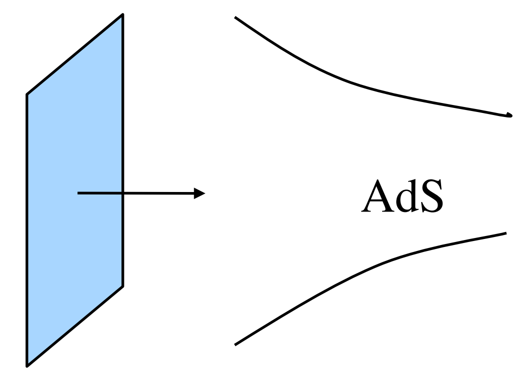


- DBI inflation

Alishahiha, Silverstein and Tong,
Phys.Rev.D70:123505,2004

$$\mathcal{L} = \phi^4\sqrt{1-\lambda\frac{\dot{\phi}^2}{\phi^4}}$$

Speed limit in AdS



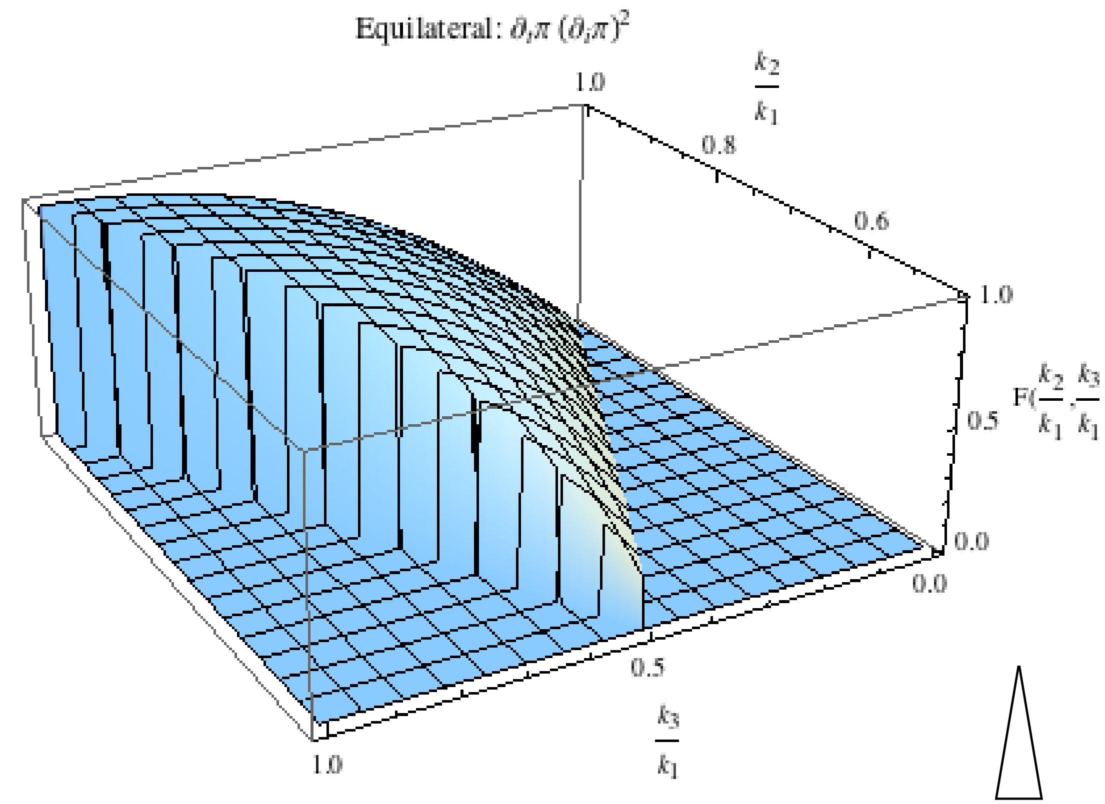
- Large non-Gaussianities

$$f_{\rm NL} \sim 10^2$$

Currently Detectable!

- Shape of non-Gaussianities

$$\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = (2\pi)^3\delta^{(3)}(\sum_i \vec{k}_i)F\left(\frac{k_2}{k_1},\frac{k_3}{k_1}\right)$$



- What are the generic signatures?

The Effective Field Theory of Inflation

with C. Cheung, P. Creminelli, L. Fitzpatrick, J. Kaplan

JHEP 0803:014,2008

The Effective Field Theory

Inflation: Quasi dS phase with a broken time-translation.

Inflation: theory of the Goldstone. $\pi \quad \rightarrow \quad \pi - \delta t$

$$S_\pi = \int d^4x \, \sqrt{-g} \left[M_{\rm Pl}^2 \dot{H} (\dot{\pi}^2 - (\partial_i \pi)^2) + M_2^4 \left(\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi} (\partial_i \pi)^2 \right) - M_3^4 \dot{\pi}^3 + \ldots \right]$$

- Analogous of the (more important!) Chiral Lagrangian for the Pions S.Weinberg **PRL 17, 1966** $\pi \sim \delta\phi$

- All single field models are unified (Ghost Inflation, DBI inflation, ...); prove theorems:
  - Theorem: In single clock models, only Inflation can produce more than 10 e-foldings of scale invariant fluct.

with Baumann and Zaldarriaga **1101:3320** [hep-th]

- What is forced by symmetries and large signatures are explicit:
  - The spatial kinetic term: pathologies for : $\dot{H} > 0$ add $\delta E^2 \quad \Rightarrow \quad \left(\partial_i^2 \pi\right)^2 \quad \Rightarrow \quad w < -1$

with Creminelli, Luty and Nicolis, **JHEP 0612**

  - Connection between c_s and Non-Gaussianities: $\dot{\pi}^2 - c_s^2 (\partial_i \pi)^2$,

NG: $f_{\rm NL}^{\rm non-loc.} \sim \frac{1}{c_s^2}$

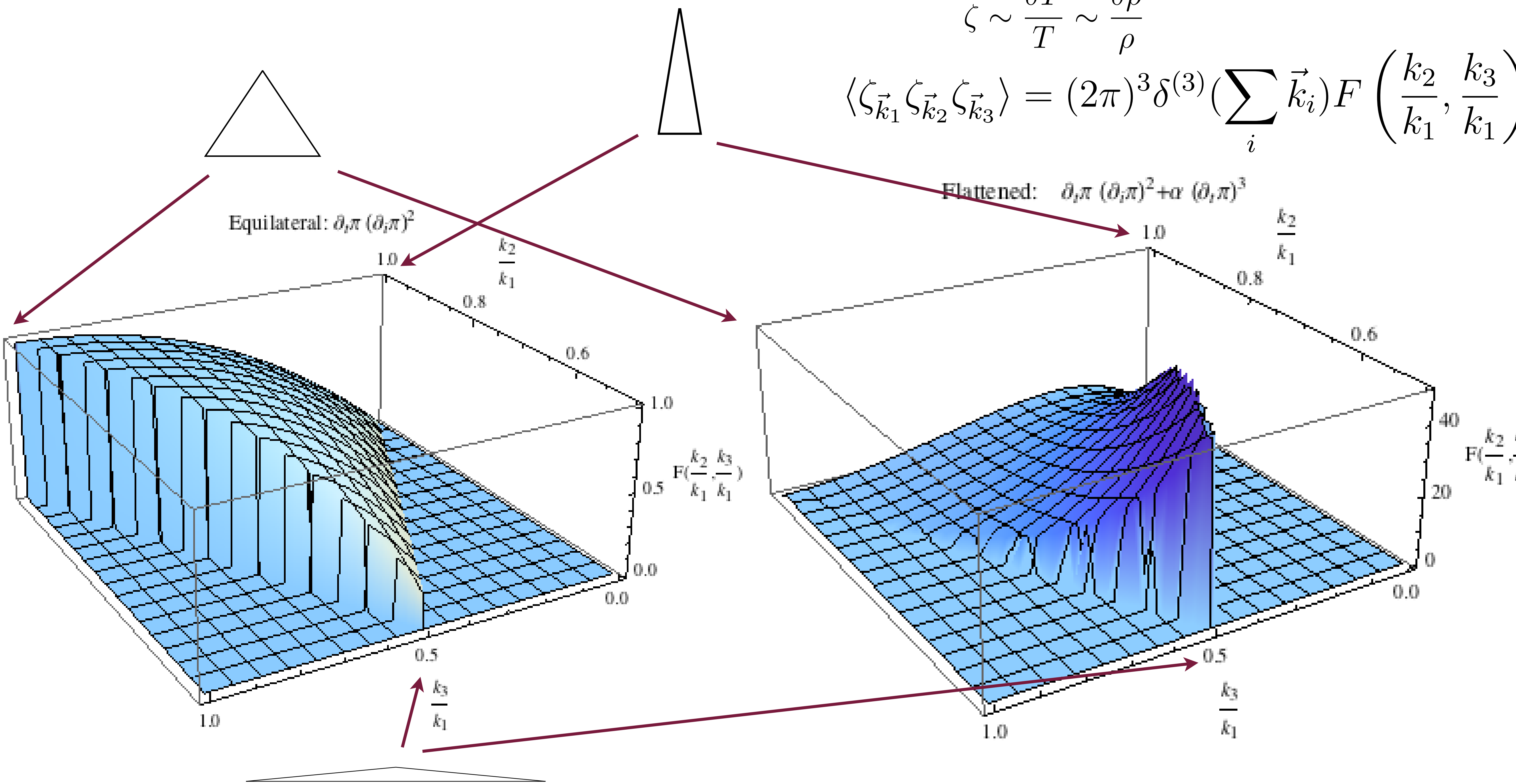
- Large interactions are allowed $\Longrightarrow$ Large non-Gaussianities! $\dot{\pi}(\nabla\pi)^2 \qquad \dot{\pi}^3$

Large non-Gaussianites

with Smith and Zaldarriaga,
JCAP1001:028,2010

$$\zeta \sim \frac{\delta T}{T} \sim \frac{\delta \rho}{\rho}$$

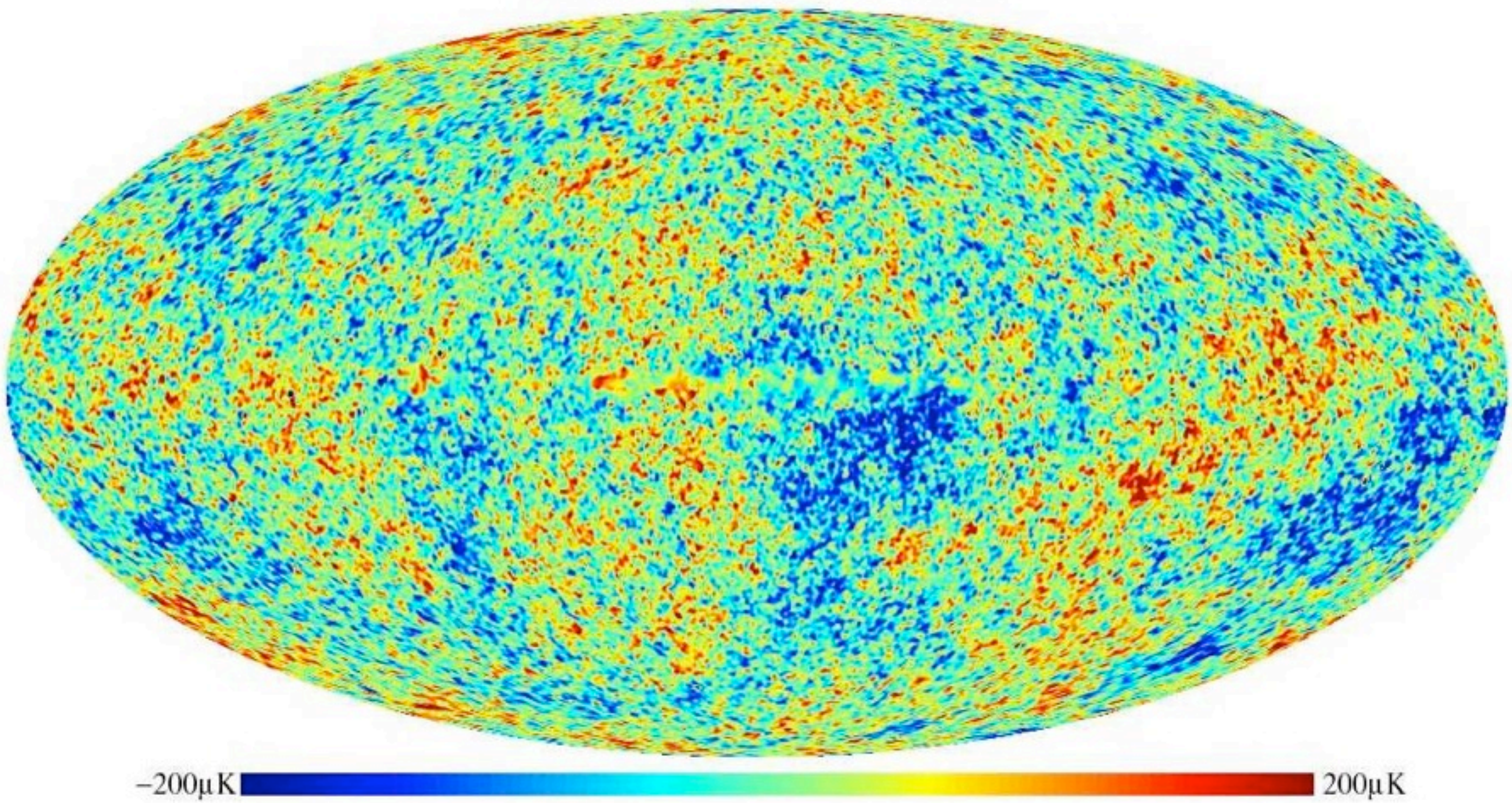
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = (2\pi)^3 \delta^{(3)}(\sum_i \vec{k}_i) F\left(\frac{k_2}{k_1}, \frac{k_3}{k_1}\right)$$



$$\frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 + \frac{\tilde{c}_3}{c_s^2}\dot{\pi}^3$$

A function of two variables: we are measuring the interactions!
(and the coefficient of the Lagrangian!)

Let’s look at the data



☹ ~No detection ☹

With Smith and Zaldarriaga,
JCAP0909:006,2009
JCAP1001:028,2010

Optimal analysis of WMAP data (foreground template corrections) are ~ compatible with Gaussianity

Optimal limits on NG

$-10 < f_{NL}^{local} < 74$ at 95% C.L.

Komatsu *et al*. **WMAP 7yr**

$(-5 < f_{NL}^{local} < 59$ at 95% C.L.)

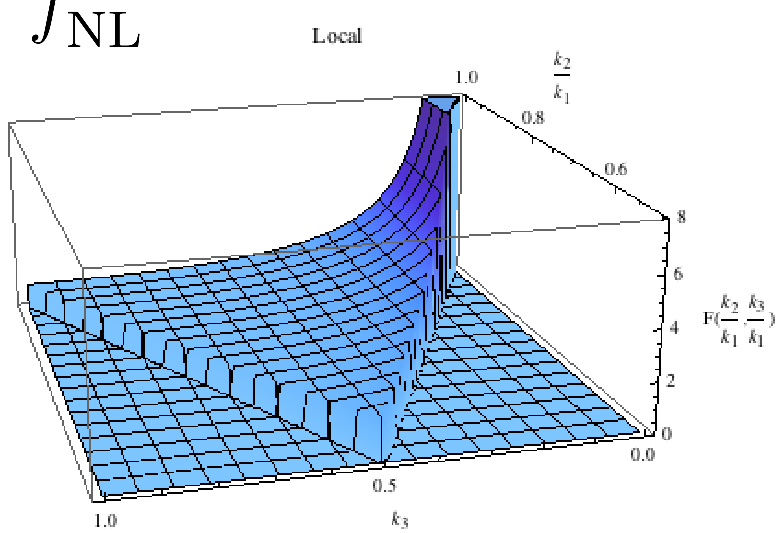
after combining with LSS
Slosar *et al*. **JCAP 0808:031, 2008**

$-214 < f_{NL}^{equil.} < 266$ at 95% C.L.

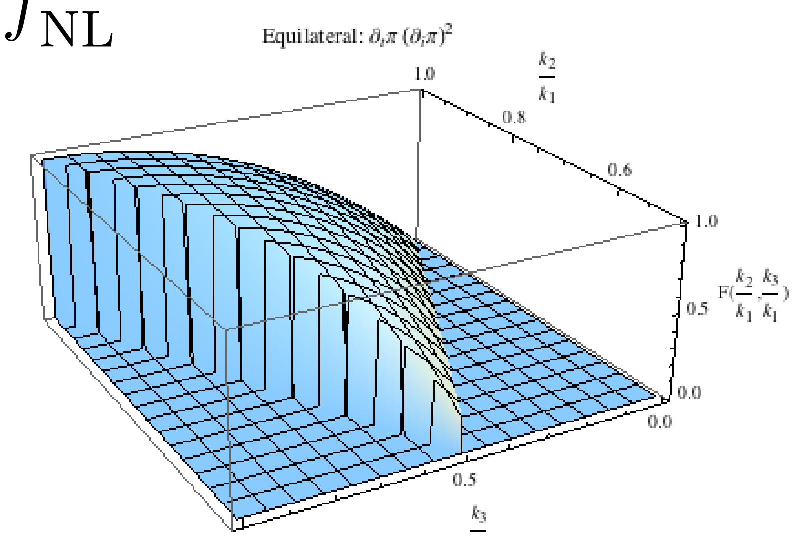
$-410 < f_{NL}^{orthog.} < 6$ at 95% C.L.

Komatsu *et al*. **WMAP 7yr**

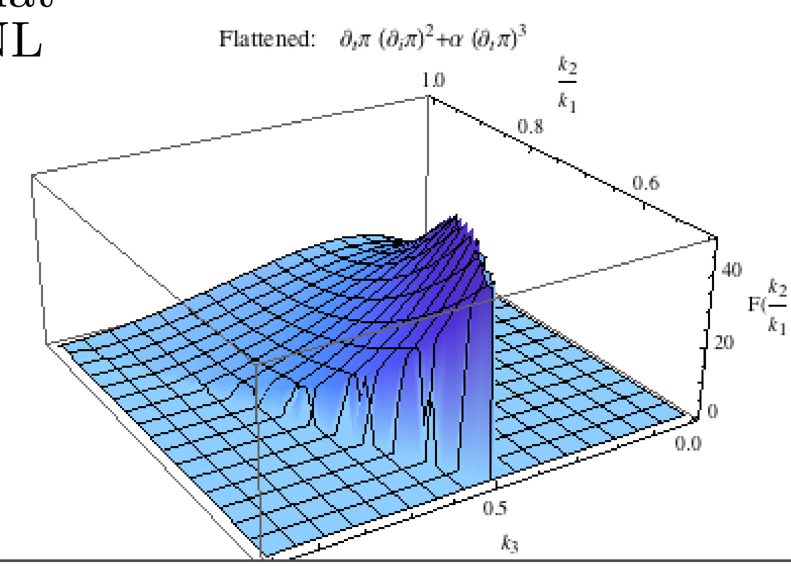
$f_{NL}^{loc.}$



$f_{NL}^{equil.}$



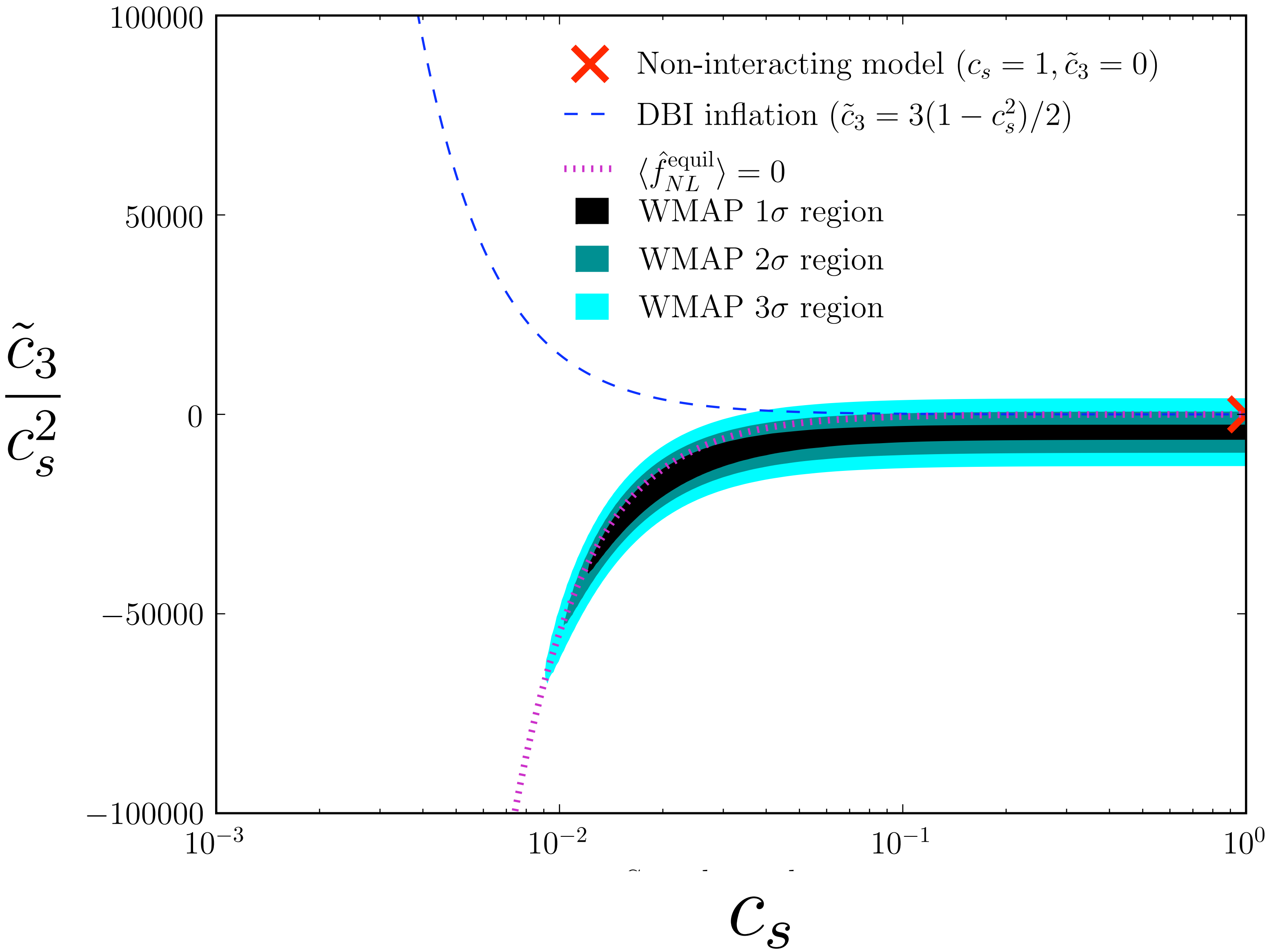
f_{NL}^{flat}



(Optimal) Limits on the parameters of the Lagrangian

$$S_\pi = \int d^4x\,\sqrt{-g}\left[M_{\rm Pl}^2\dot H(\dot\pi^2-(\partial_i\pi)^2)+M_2^4\left(\dot\pi^2+\dot\pi^3-\dot\pi(\partial_i\pi)^2\right)-M_3^4\dot\pi^3+\dots\right]$$

- Limits on f_{NL}'s get translated into limits on the parameters
- For models not-very-close to de Sitter (like DBI): c_s , $\tilde c_3$



With Smith and Zaldarriaga,
JCAP1001:028,2010

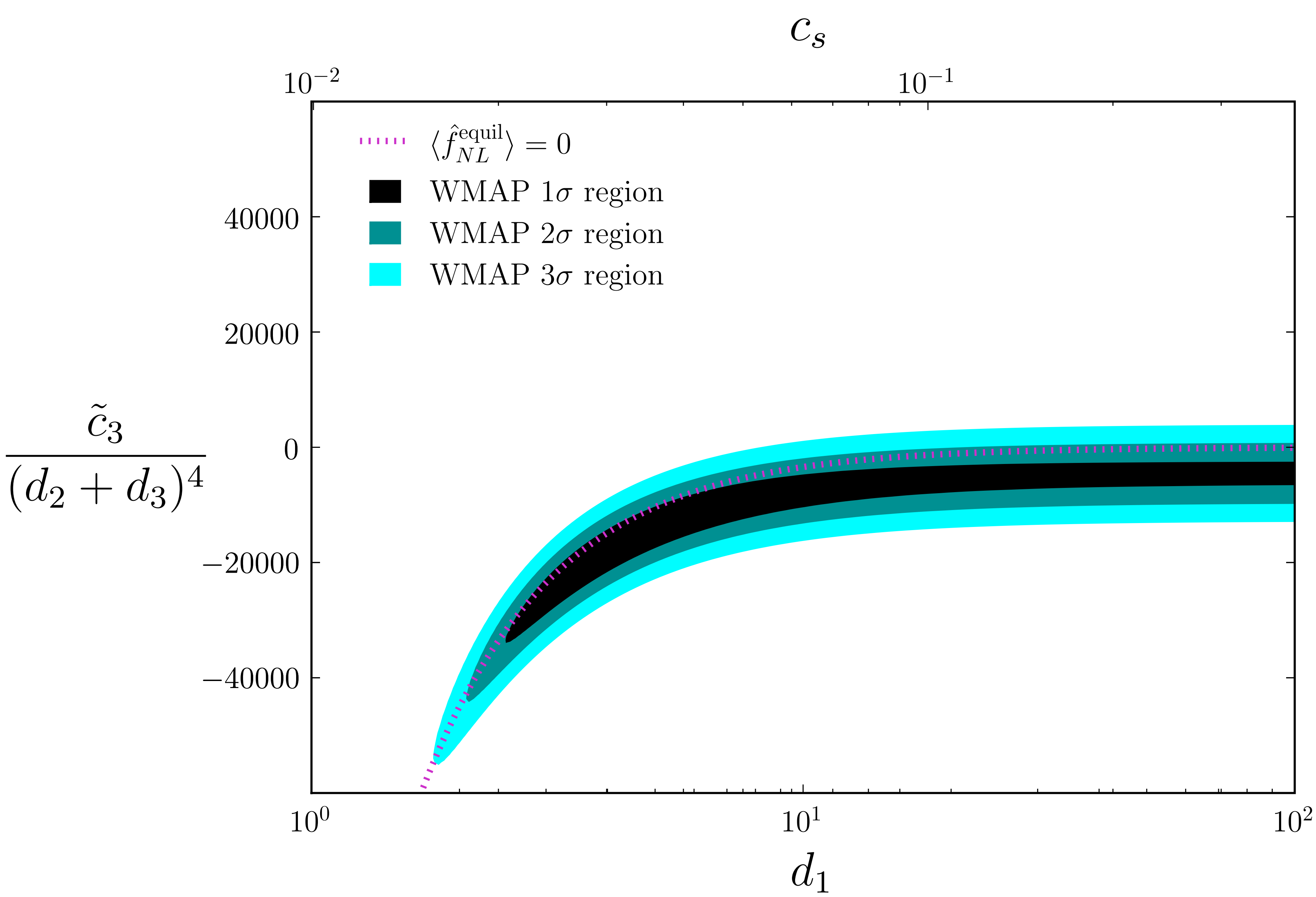
Very similar in spirit to
Peskin and Takeuchi
PRD46:381,1992

$$\frac{1}{c_s^2}\dot\pi(\partial_i\pi)^2+\frac{\tilde c_3}{c_s^2}\dot\pi^3$$

- Limit on the speed of sound: $c_s \gtrsim 0.011$!

(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter. $d_1\, \delta g^{00} \delta K_i^i$
- Dispertion relation: $\omega^2 = c_s^2 k^2 \qquad c_s^2 = d_1 \dfrac{H}{M} \ll 1$



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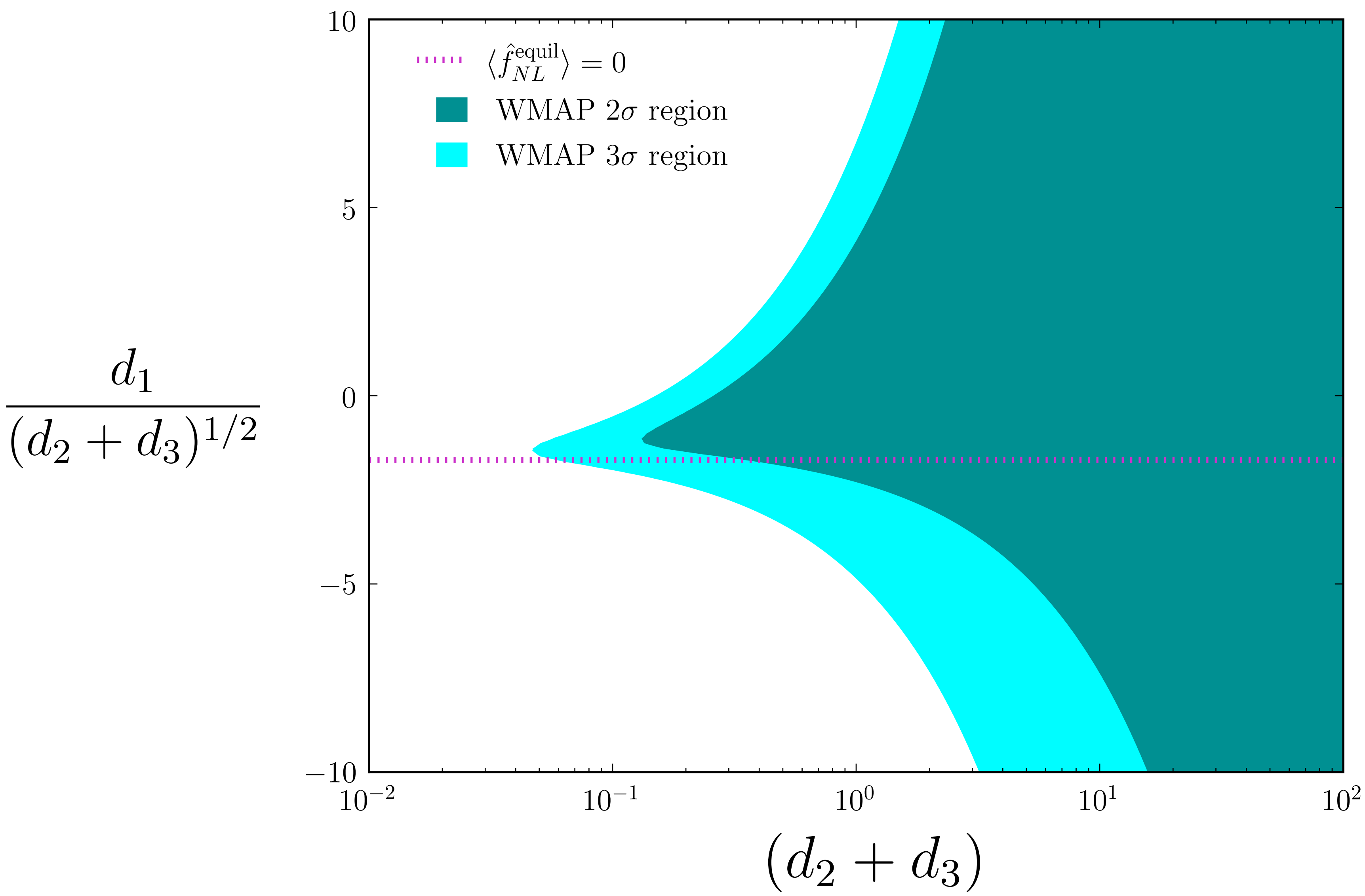

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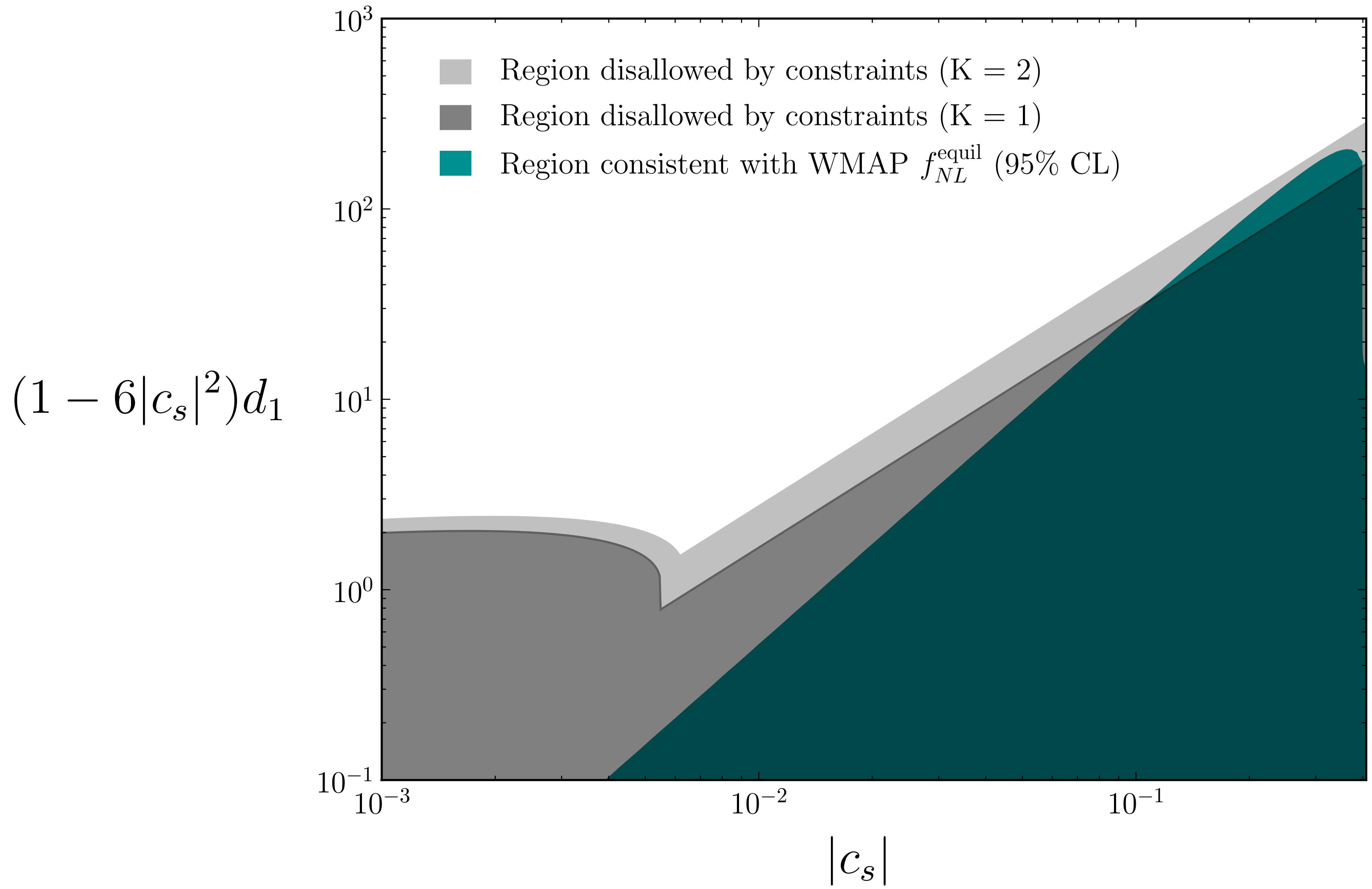
(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter.
- Negative c_s^2 due to $d_1 < 0$ $\qquad c_s^2 = d_1 \frac{H}{M} \ll 1$
- Ruled out at 95% CL.



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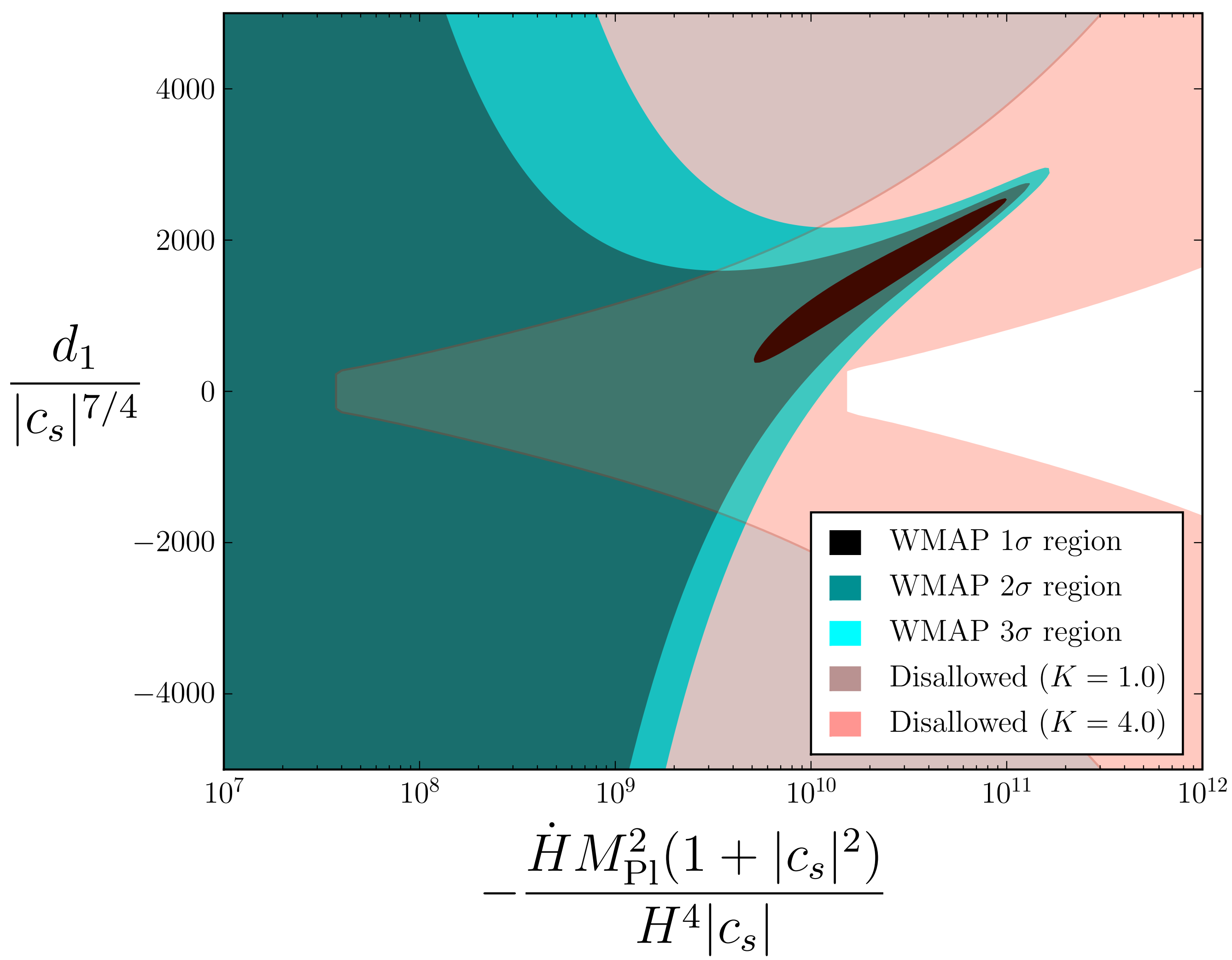
(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter.
- Negative c_s^2 due to $\dot{H} > 0$ $\qquad \dot{H} M_{\rm Pl}^2 (\partial_i \pi)^2$
- Ruled out at 95% CL.



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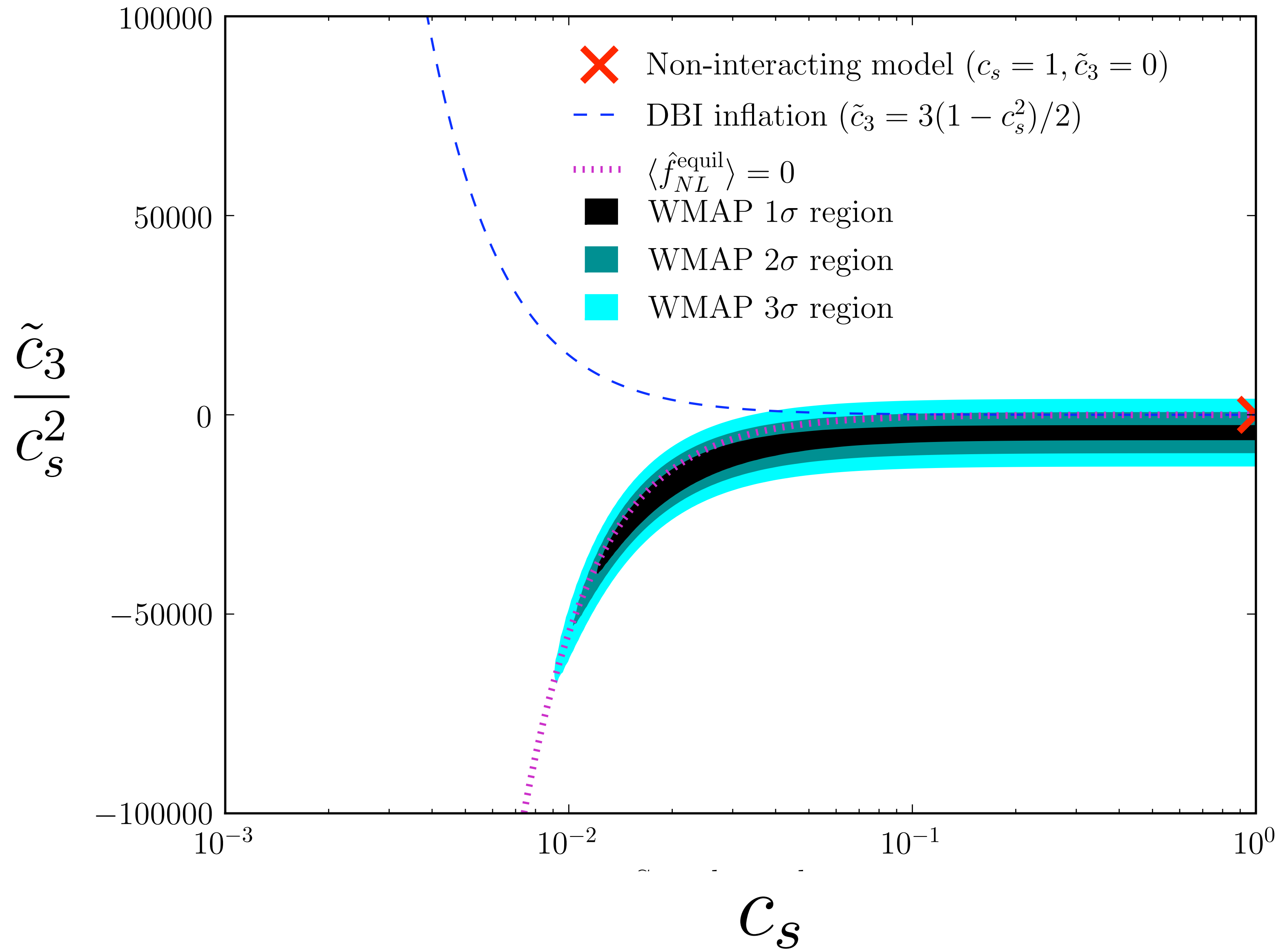
- Thanks to the EFT: A qualitatively new (and superior) way to use the cosmological data



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$$\frac{1}{c_s^2}\dot\pi(\partial_i\pi)^2 + \frac{\tilde c_3}{c_s^2}\dot\pi^3$$

This was about 3-point function.
What about 4-point function?

with M. Zaldarriaga
JCAP 2011 [hep-th]

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JCAP 2011

Another New Signature:
A large 4-point function without a larger 3-point function

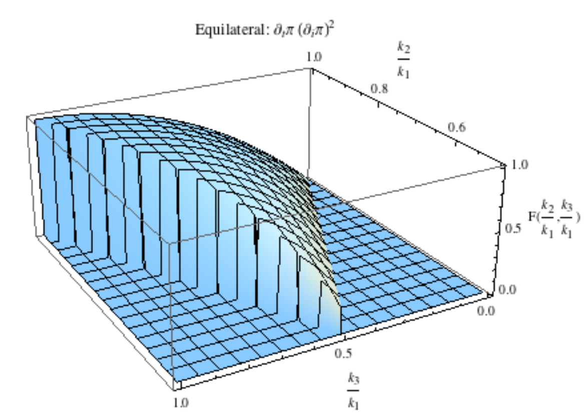
- Large 4-point: Symmetries forces to have a leading 3-point function but for one case:

$$\dot{\pi}^4$$

- Protected by a approximate symmetry $\Rightarrow \quad \pi \longrightarrow -\pi$

- Huge amount of information: function of 5 variables
- Looking it in the data

with Smith and Zaldarriaga **in progress**



Effective Field Theory of Multifield Inflation

with M. Zaldarriaga
1009.2093 hep-th

The Effective Field Theory for Multifield Inflation

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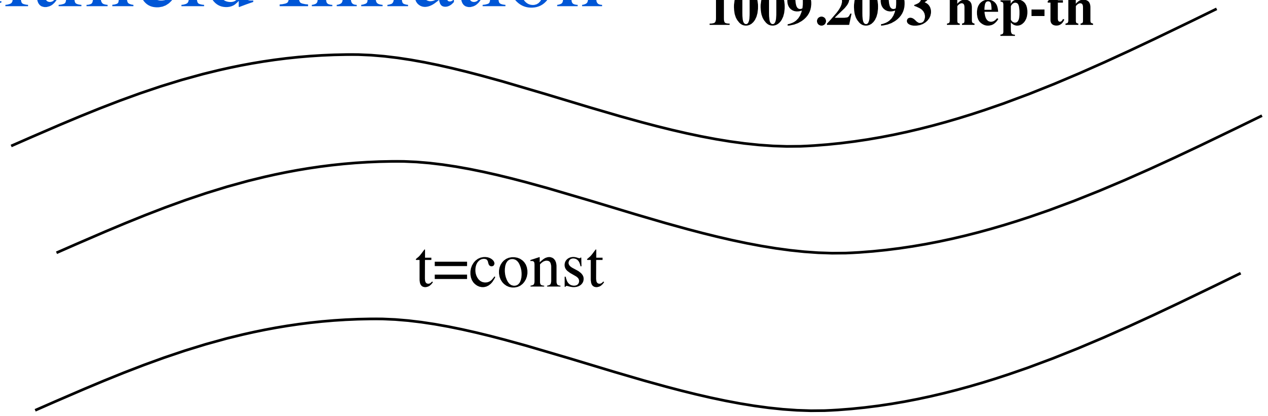

In the same Unitary Gauge,

consider another massless scalar field σ

[Classification:

approximate shift symmetry:

- Abelian
- Non-Abelian
- Supersymmetry]

The add conversion into curvature perturbations

The Effective Field Theory for Multifield Inflation

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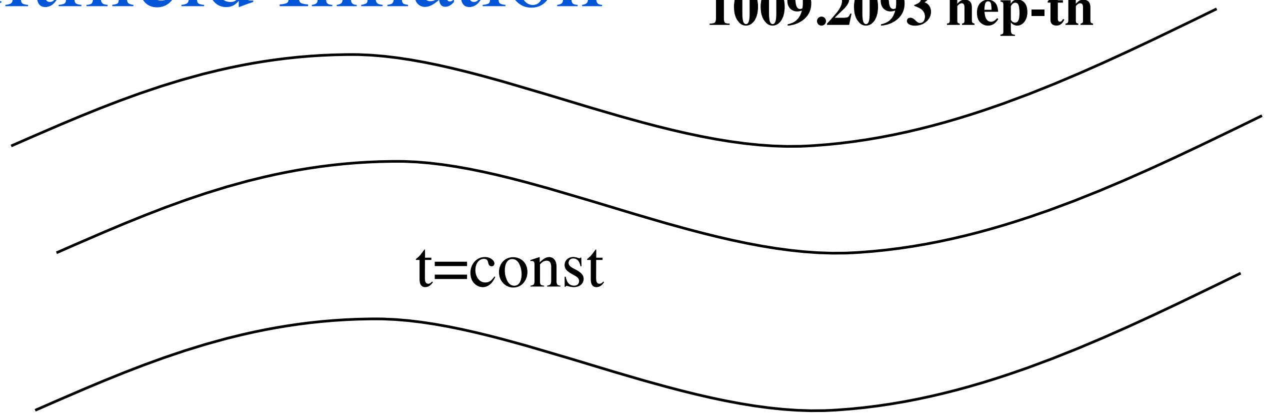

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Reintroducing the Goldstone

with M. Zaldarriaga
1009.2093 hep-th

- Quadratic Lagrangian

$$S^{(2)} = \int d^4x\sqrt{-g}\left[(2M_2^4 - M_{\rm Pl}^2\dot{H})\dot{\pi}^2 + M_{\rm Pl}^2\dot{H}\frac{(\partial_i\pi)^2}{a^2} + 2\tilde{M}_1^2\ \dot{\pi}\dot{\sigma} + (-e_1+e_2)\ \dot{\sigma}^2 + e_1\ \frac{(\partial_i\sigma)^2}{a^2} + ...\right]$$

- Cubic Lagrangian ...
- Quartic Lagrangian ....
- Notice:
  - Small π speed of sound: Large coupling $M^4\dot{\pi}^2 \quad \rightarrow \quad M^4\dot{\pi}(\partial_i\pi)^2$
  - Small σ speed of sound: Large coupling $(-e_1+e_2)\ \dot{\sigma}^2 \quad \rightarrow \quad e_2\ (\partial_i\pi\partial_i\sigma)\dot{\sigma}$
  - Time-kinetic mixing σ - π .

Reintroducing the Goldstone

with M. Zaldarriaga
1009.2093 hep-th

- Quadratic Lagrangian

$$S^{(2)} = \int d^4x\sqrt{-g}\left[(2M_2^4 - M_{\rm Pl}^2\dot{H})\dot{\pi}^2 + M_{\rm Pl}^2\dot{H}\frac{(\partial_i\pi)^2}{a^2} + 2\tilde{M}_1^2\,\dot{\pi}\dot{\sigma} + (-e_1+e_2)\,\dot{\sigma}^2 + e_1\,\frac{(\partial_i\sigma)^2}{a^2} + ...\right]$$

- Cubic Lagrangian ...
- Quartic Lagrangian ....
- Notice:
  - Small π speed of sound: Large coupling $M^4\dot{\pi}^2 \quad \rightarrow \quad M^4\dot{\pi}(\partial_i\pi)^2$
  - Small σ speed of sound: Large coupling $(-e_1+e_2)\,\dot{\sigma}^2 \quad \rightarrow \quad e_2\,(\partial_i\pi\partial_i\sigma)\dot{\sigma}$
  - Time-kinetic mixing σ - π .

New Signatures: new 3-point and 4-point functions

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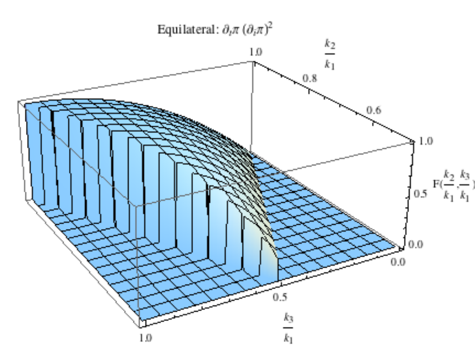
- In multifield inflation:
  - -Impose symm. $\sigma \longrightarrow -\sigma$
  - -Approximate Lorentz invariance $\Rightarrow$ kill σ^3 terms

- Large 4-point function $\dot\sigma^4\ ,\quad \dot\sigma^2(\partial_i\sigma)^2\ ,\quad (\partial_i\sigma)^4\ ,\quad \sigma^2(\partial\sigma)^2\quad \sigma^4$

- and it is a function of 5 variables!



- Analysis in progress

with Smith and Zaldarriaga **in progress**

On the non-Abelian case

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- Not exactly a shift symmetry: $\sigma^2(\partial\sigma)^2$
- Building Blocks:

$$[t_i, t_j] = iC_{ijk}t_k$$

$$[t_i, x_a] = iC_{iab}x_b$$

$$[x_a, x_b] = iC_{abi}t_i + iC_{abc}x_c$$

- .

$$D_{a\mu} = \partial_\mu\sigma_a + \frac{1}{2}C_{abc}\sigma_b\partial_\mu\sigma_c + \frac{1}{6}\left(C_{cde}C_{bea} + C_{cdi}C_{bia}\right)\sigma_b\sigma_c\partial_\mu\sigma_d + \mathcal{O}(\sigma^3\partial_\mu\sigma)$$

- Good Transformation Properties:

$$D_\mu \equiv D_{a\mu}x_a$$

$$D'_\mu = h\left(\sigma(x), g)\right) D_\mu h\left(\sigma(x), g)\right)^{-1}$$

- Lagrangian:

$$S_{\pi\sigma} = \int d^4x\sqrt{-g} \quad \mathrm{Tr}\left[F_1^2 D_\mu D^\mu + F_2^2 D^0 D^0 + 2F_2^2\partial_\mu\pi D^\mu D^0 - 2F_3^3\dot{\pi}D^0 + F_3^3(\partial_\mu\pi)^2 D^0\right.$$
$$\left. -2F_4^2\dot{\pi}D_\mu D^\mu - 2F_5^2\dot{\pi}D^0D^0 + \bar{F}_1 D_\mu D^\mu D^0 + \bar{F}_2 D^0D^0D^0 + \ldots\right]$$

On the non-Abelian case

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- Usual operators and maybe something else:
- No $\sigma(\partial\sigma)^2$: $C_{abc}\sigma_a(\partial\sigma_b)(\partial\sigma_c) = 0$
- Sensitive to only one field (for adiabatic fluctuations):

$$\left.\frac{\partial\zeta}{\partial\sigma_I}\right|_0 \sigma_I(x) = \left.\frac{\partial\zeta}{\partial\sigma_K}\right|_0 \mathscr{D}(h)^{-1}_{KI}\mathscr{D}(h)_{IJ}\sigma_J(x) = \widetilde{\left.\frac{\partial\zeta}{\partial\sigma_1}\right|_0}\sigma'_1$$

- Easy to suppress the standard opt's:

$$\dot\sigma^3\ , \qquad \dot\sigma(\partial_i\sigma)^2\ , \quad \text{only if} \quad \text{Tr}[x_a x_a x_a] \neq 0$$

- Mixed iso-adiabatic becomes large:

$$\langle\zeta\zeta\,\zeta_{\rm iso}\zeta_{\rm iso}\rangle \quad \Rightarrow \quad \sigma^2(\partial\sigma)^2 \quad \Rightarrow \quad \epsilon^2_{\rm iso}\left.\frac{\mathcal{L}_4}{\mathcal{L}_2}\right|_{E\sim H} \sim \epsilon^2_{\rm iso}\frac{\sigma_c^2}{\Lambda_U^2} \sim \epsilon^2_{\rm iso}\frac{H^2}{\Lambda_U^2}$$

$$\langle\zeta\zeta\zeta\zeta\rangle \quad \Rightarrow \quad (\partial\sigma)^4 \quad \Rightarrow \quad \left.\frac{\mathcal{L}_4}{\mathcal{L}_2}\right|_{E\sim H} \sim \frac{H^2\sigma_c^2}{\Lambda_U^4} \sim \frac{H^4}{\Lambda_U^4}$$

- A remarkable Signature

SuperSymmetric case

with M. Zaldarriaga
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- Chiral Multiplet $\Sigma \supset \sigma,\ \psi_\sigma$, with shift symmetry $K = (\Sigma + \Sigma^\dagger)^2$
- In dS, propagator modified at $E \lesssim H$

- Because of week coupling, radiative corrections stop at $E \sim \lambda\, H$ with $W = \lambda \Sigma^3$
- no relevant mass is generated
- Leading interaction $\lambda^2 \mathrm{Im}(\sigma)^4$ with no $\mathrm{Im}(\sigma)^3$

- Another way to get detectable τ_{NL}^{loc} and no f_{NL}^{loc}

New Signatures: new 3-point and 4-point functions

with M. Zaldarriaga
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MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

You can tell them apart!

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$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
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σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
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$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

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$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

You can tell them apart!

New Signatures: new 3-point and 4-point functions

with M. Zaldarriaga
1009.2093 hep-th

MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

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Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
	$w = c_s k$	$w \propto k^2$	
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, $\ldots$		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

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Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

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$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

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MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$_s^\dagger$, non-Ab.$_s^\dagger$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$_s^\star$.	X
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$	X		Ad., Iso.	Ab., non-Ab.	
$\dot\sigma(\partial_i\sigma)^2$, $\partial_j^2\sigma(\partial_i\sigma)^2$		X	Ad., Iso.	Ab.	
σ^3	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S, R	X
$\dot\sigma\sigma^2$	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$	X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$	X	X	Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$_s^{\dagger\star}$, non-Ab.$_s^{\dagger\star}$.	X

Single Field

Operator	Dispersion		Squeezed L.
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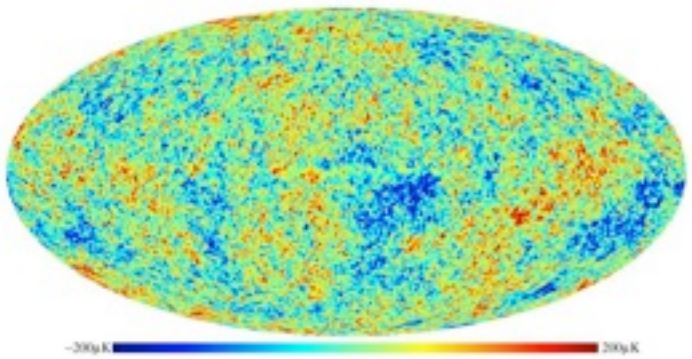
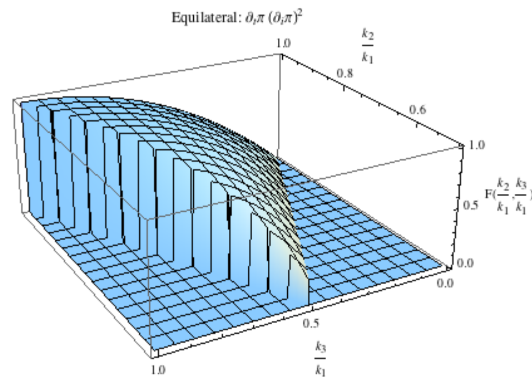
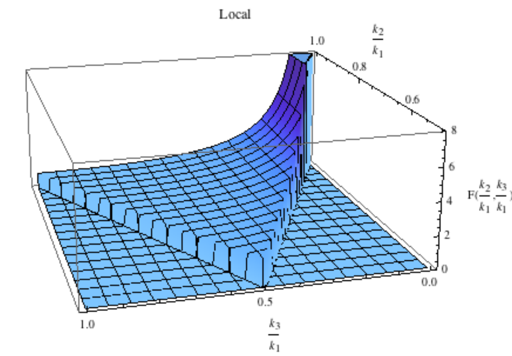
$\dot\pi^4$	X		
$(\partial_j^2\pi)^4$, $\dot\pi(\partial_j^2\pi)^3$, ...		X	
$\dot\pi^3$, $\dot\pi(\partial_i\pi)^2$	X		
$\dot\pi(\partial_i\pi)^2$, $\partial_j^2\pi(\partial_i\pi)^2$		X	

You can tell them apart!



What is next?





Theory

- Adding Gauge Bosons and Fermions

- Higher derivative interactions in π , ex: $(\partial^4\pi)^3$

  Bartolo, Fasiello, Matarrese, Riotto **2010, 2010**
  Creminelli, D'Amico, Norena, Trincherini **2010**
  with Behbahani, Mirbabayi **in progress**

- Relaxing the shift-symmetry of π

  with Dimarsky, Behbahani, Mirbabayi **in progress**

- Backreaction from additional Fields on π , EFT for thermal and trapped Inflat.

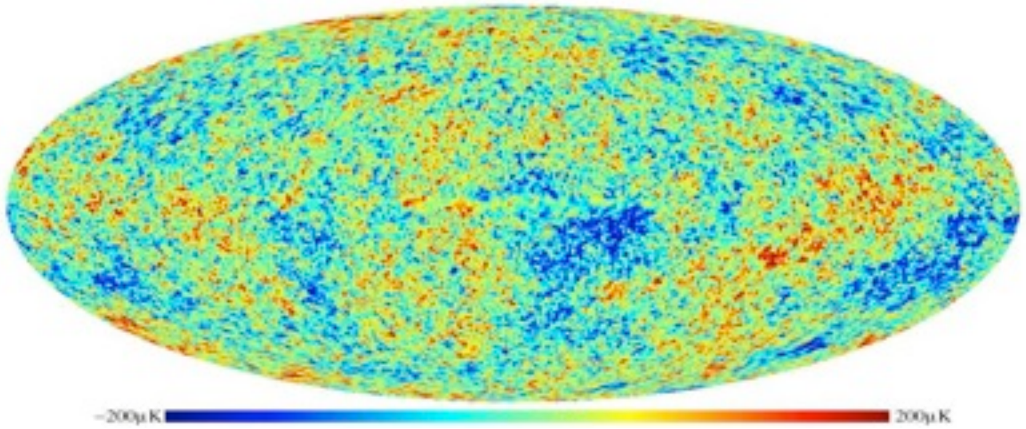
$$S_{\rm int} = -\int d^4x \mathcal{O}(x)\pi(x),$$

with Nacir, Porto, and Zaldarriaga **in progress**

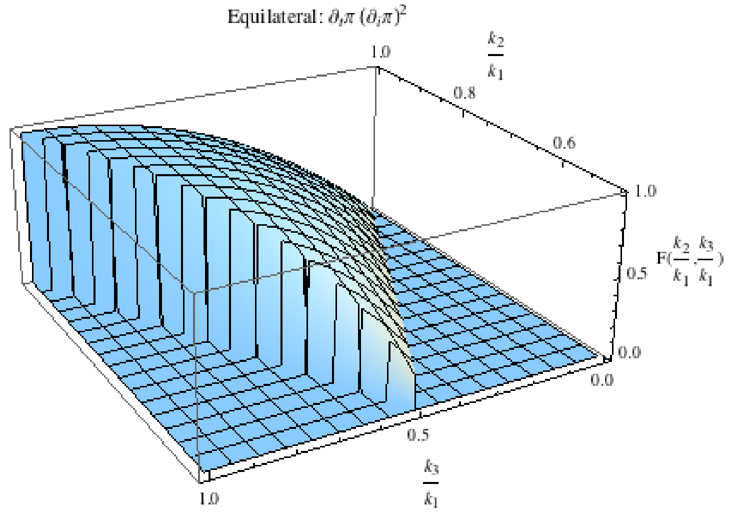
Conclusions

Inflation: Exploring the beginning of the Universe

- Many observational data, and many more to come



- Power Spectra: scalar and gravity waves
- Non-Gaussianities: Richness of information
  - Smoking Gun
  - Interactions



Fundamental Theory

- Learning about the origin of the Universe and the high energy physics

$$S_\pi = \int d^4x\,\sqrt{-g}\left[M_{\rm Pl}^2\dot{H}(\dot{\pi}^2-(\partial_i\pi)^2)+M_2^4\left(\dot{\pi}^2+\dot{\pi}^3-\dot{\pi}(\partial_i\pi)^2\right)-M_3^4\dot{\pi}^3+\dots\right]$$