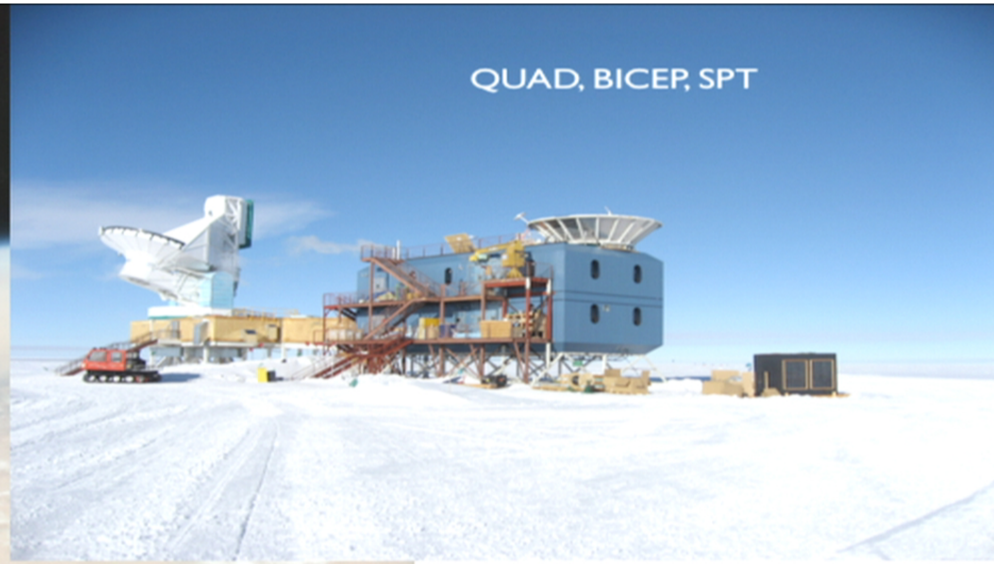
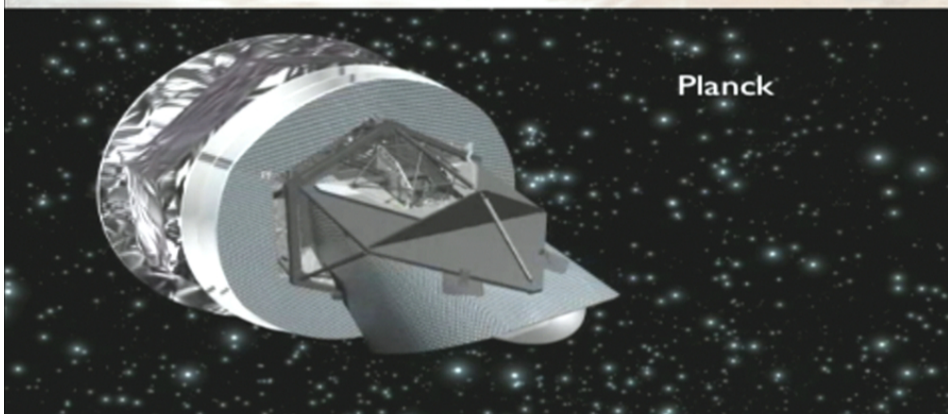
Title: On the Effective Field Theory of Inflation and on the Effective Field Theory of the Long Distance Universe

Date: Nov 30, 2011 11:00 AM

URL: http://pirsa.org/11110093

Abstract:





and many others

... LSST

What can we do with it?

- We are sensitive to non-linearities of the dynamics (interactions)
- Application of Effective Field Theory techniques to Cosmology
  - To explore the High Energy frontier
  - To gain control of current and next experiments (... LSST)
- This is what has happened in Particle Physics since the 80's.

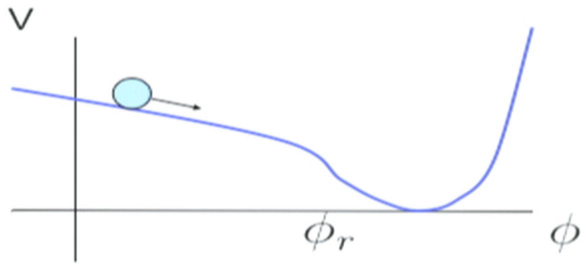
How do we probe Inflation?

How do we probe inflation?

- Simple Models

$$a \sim e^{Ht}$$

$$\dot\phi \sim \frac{V'}{H}$$



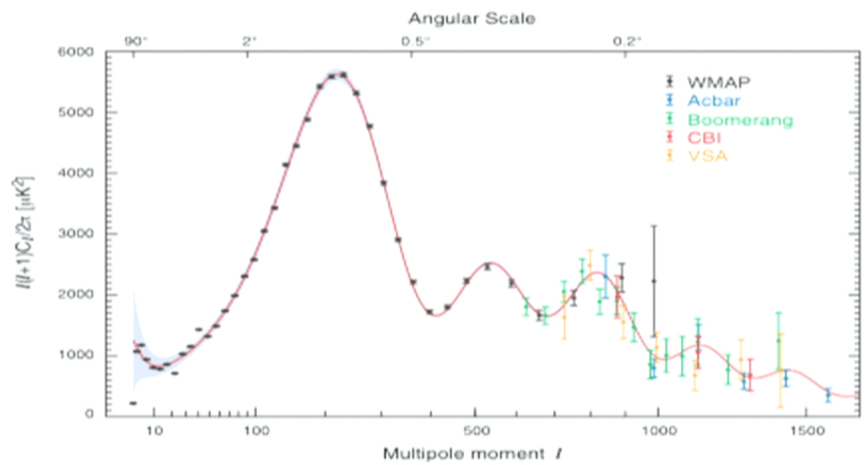
$$\epsilon \simeq \frac{\dot\phi^2}{V(\phi)} \ll 1$$

- Standard predictions

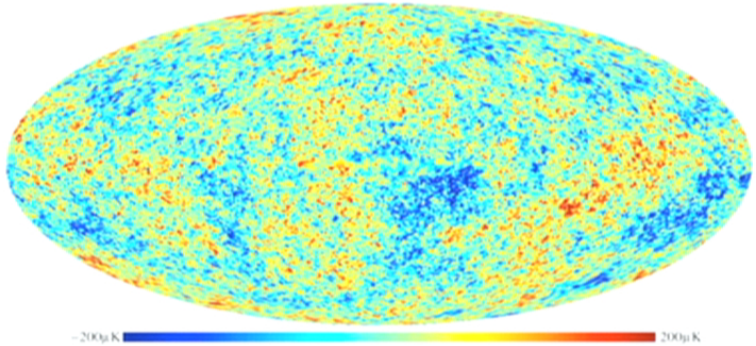
$$\zeta \sim \frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \qquad \zeta \simeq \frac{H}{\dot\phi}\delta\phi$$

$$\langle\zeta^2\rangle \sim \frac{1}{\epsilon}\frac{H^2}{M_{\rm Pl}^2}$$

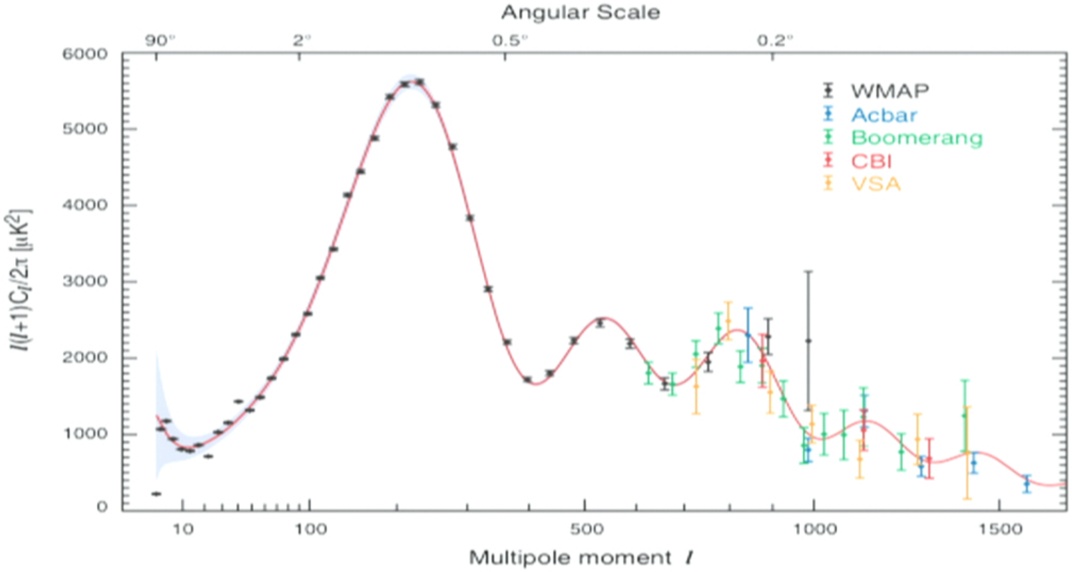
$$\langle\gamma^2\rangle \sim \frac{H^2}{M_{\rm Pl}^2}$$



What have we verified so far?



- The result of cosmological observations so far:



- A fantastic (percent) measurement of the cosmological parameters

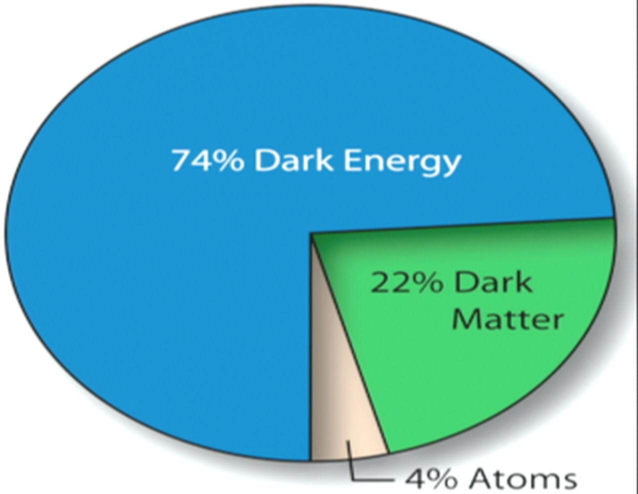
$$H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$\Omega_b = 0.0456$$

$$\Omega_c = 0.228$$

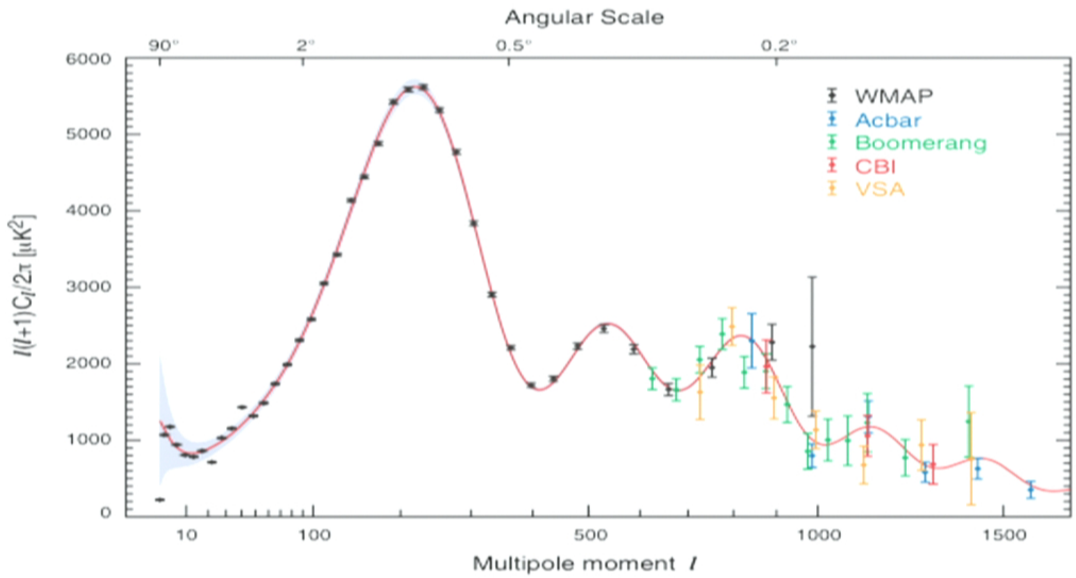
$$\Omega_\Lambda = 0.726$$

WMAP collaboration 7yr,
Komatsu et al.
Astr. J. Suppl. 180:330-376 2009



What have we verified so far about Inflation?

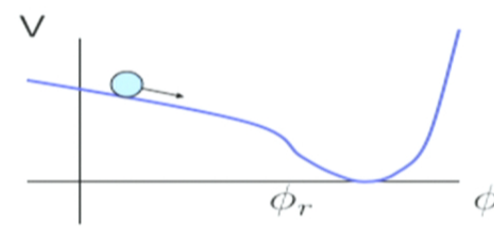
- Qualitative: all the modes are in phase, perturbations from superhubble scale
- Quantitative: Quasi-Scale Invariant Power Spectrum and its tilt:



$$\langle \zeta^2 \rangle \sim \frac{H^2}{\epsilon M_{\rm Pl}^2} \sim 10^{-10}$$

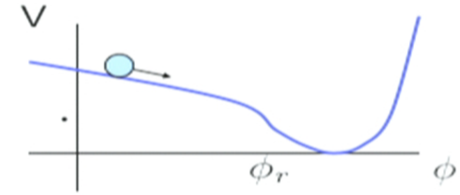
$$n_s - 1 = 2\eta - 6\epsilon \sim 10^{-2}$$

- Just 2 numbers ...



- But we have WMAP, Planck, ACT, BOSS, LSST is there something more to look for?

Statistics of the fluctuations

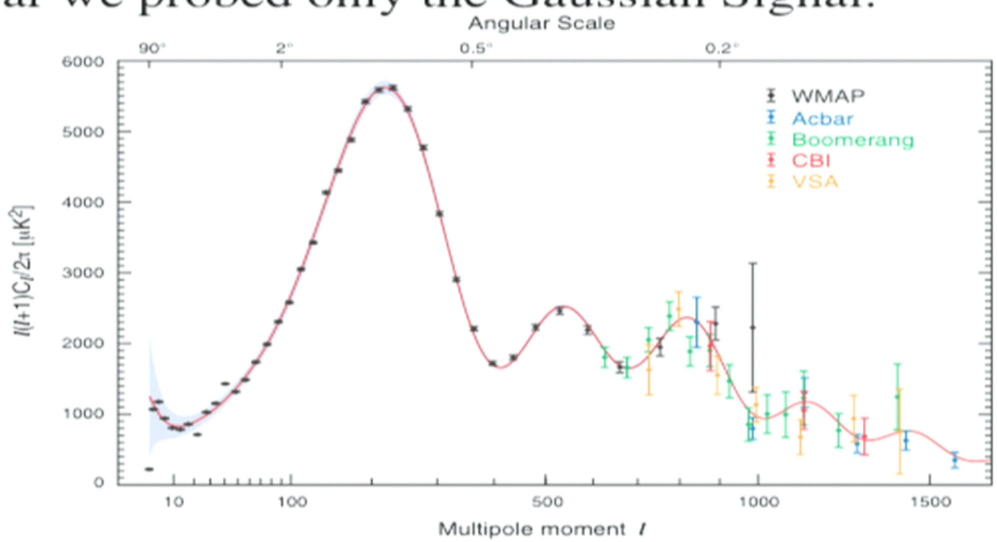


- We started from inflationary fluctuations, which induced $\zeta \simeq \frac{H}{\dot{\phi}} \delta\phi$
- The distribution is Gaussian

$$P(\{\zeta_{\vec{k}}\}) = N \text{ Exp}\left(-\sum_{\vec{k}_1} \frac{\zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}}{P(k_1)}\right) \quad \text{where} \quad P_k \sim \langle \zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle_{\text{vac}} \sim \frac{H^4}{\dot{\phi}^2}\langle \delta\phi_{\vec{k}}\delta\phi_{-\vec{k}}\rangle_{\text{vac}}$$

- Because we solved linear equations $\ddot{\delta\phi}_k + \frac{k^2}{a^2}\delta\phi_k = 0$
  (like QM harmonic oscillator $\hat{\delta\phi} \longrightarrow \hat{x}$)

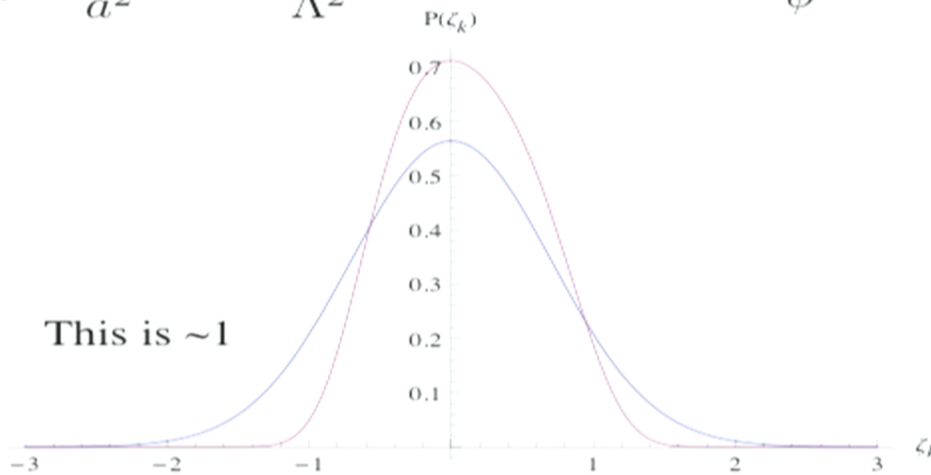
- So far we probed only the Gaussian Signal:



$$\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\rangle = \delta^3(\vec{k}_1 + \vec{k}_2) P_\zeta(k_1)$$

Non-Gaussianities

- The distribution can be non-Gaussian $P(\{\zeta_{\vec{k}}\}) = N \text{ Exp}\left(-\sum_{\vec{k}_i}\left(\frac{\zeta_{\vec{k}_1}\zeta_{-\vec{k}_1}}{P(k_1)} + \frac{\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{-\vec{k}_1-\vec{k}_2}}{C(k_1,k_2,|\vec{k}_1+\vec{k}_2|)} + \dots\right)\right)$
- This would have happened if we had solved $\ddot{\delta\phi}_k + \frac{k^2}{a^2}\delta\phi_k + \frac{1}{\Lambda^2}\dot{\delta\phi}^2 = 0$ $\qquad \zeta \simeq \frac{H}{\dot{\phi}}\delta\phi$
- This would come from interactions



- Non-Gaussian Signal:

$$\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)F(\vec{k}_1,\vec{k}_2,\vec{k}_3)$$

- So far: $\frac{\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle}{\langle\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle^{3/2}} \lesssim 10^{-2} \sim \frac{1}{N_{\text{pix}}^{1/2}}$

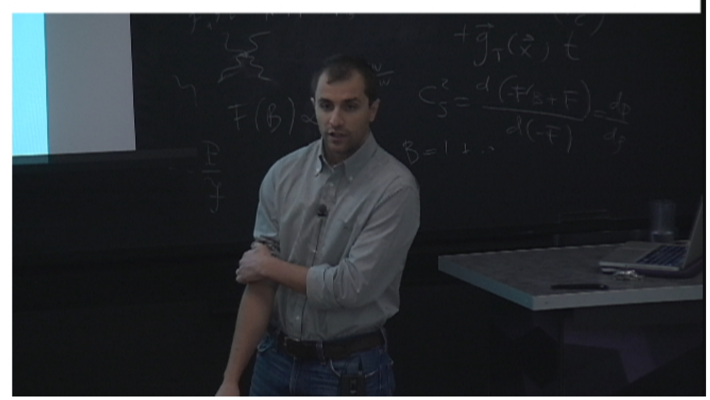
$$N_{\text{pix}}^{\text{WMAP}} \sim 10^5$$

- Free Field: Gaussian
- Interacting field: Non-Gaussian
- Interactions of Inflation!
- (beyond the Standard Model at very high energies)!
- Can we have them?

The Effective Field Theory of Inflation

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

JHEP 0803:014,2008



What is Inflation?

with C. Cheung, P. Creminelli, L. Fitzpatrick, J. Kaplan
JHEP 0803:014,2008

The Effective Field Theory

Inflation. Quasi dS phase with a privileged spacial slicing

Unitary gauge. This slicing coincide with time.

$$\delta\phi(\vec{x},t) = 0 \quad \left(\delta\phi(\vec{x},t) \to \delta\phi(\vec{x},t) - \dot{\phi}(t)\ \delta t(\vec{x},t) \right)$$

Most generic Lagrangian built by metric operators invariant only under $x^i \longrightarrow x^i + \xi^i(t,\vec{x})$

- Generic functions of time
- Upper 0 indices are ok. E.g. g^{00} R^{00}
- Geometric objects of the 3d spatial slices: e.g. extrinsic curvature K_{ij} and

covariant derivatives

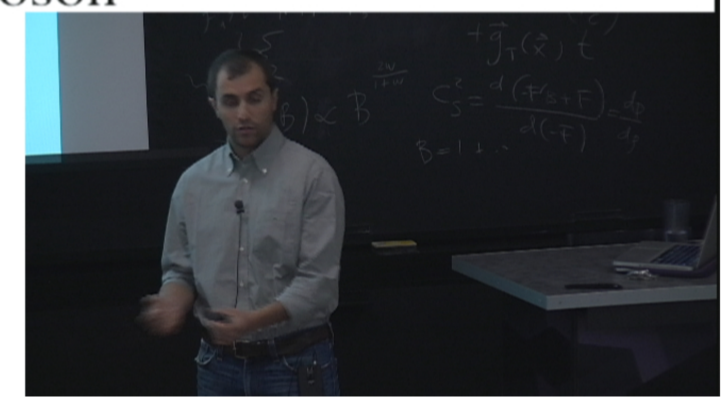
$$S = \int d^4x \sqrt{-g} \left[M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H}(-1+\delta g^{00}) - M_{\rm Pl}^2 (H^2+\dot{H}) + M_2^4(t)(\delta g^{00})^2 + M_3^4(t)(\delta g^{00})^3 \right.$$
$$\left. - \bar{M}_1^3(t)\delta g^{00}\delta K_i^i - \bar{M}_2^2(t)\delta K_i^{i\ 2} + \ldots \right]$$

A simplifying limit

$$S = \int d^4x \sqrt{-g} \Big[M_{\rm Pl}^2 R + M_{\rm Pl}^2 \dot{H}(-1 + \delta g^{00}) - M_{\rm Pl}^2 (H^2 + \dot{H}) + M_2^4(t)(\delta g^{00})^2 + M_3^4(t)(\delta g^{00})^3$$
$$- \bar{M}_1^3(t)\delta g^{00}\delta K_i^i - \bar{M}_2^2(t)\delta K_i^{i\ 2} + \dots \Big]$$

Spontaneously Broken Gauge Symmetry

Reintroduce the Goldstone boson



The Effective Field Theory

Reintroduce the Goldstone. $g^{00} \;\rightarrow\; g^{\mu\nu}\partial_\mu(t+\pi)\partial_\nu(t+\pi)$ $\qquad \pi \;\rightarrow\; \pi - \delta t$

Inflation: theory of the Goldstone:

Cosmological perturbations probe the theory at E ~ H

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

- Analogous of the (more important!) Chiral Lagrangian for the Pions S.Weinberg **PRL 17, 1966** $\quad \pi\sim\delta\phi$
- 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 **2011**
- What is forced by symmetries and large signatures are explicit:
  - The spatial kinetic term: pathologies for : $\dot H > 0$
  - Connection between c_s and Non-Gaussianities: $\dot\pi^2 - c_s^2(\partial_i\pi)^2$,

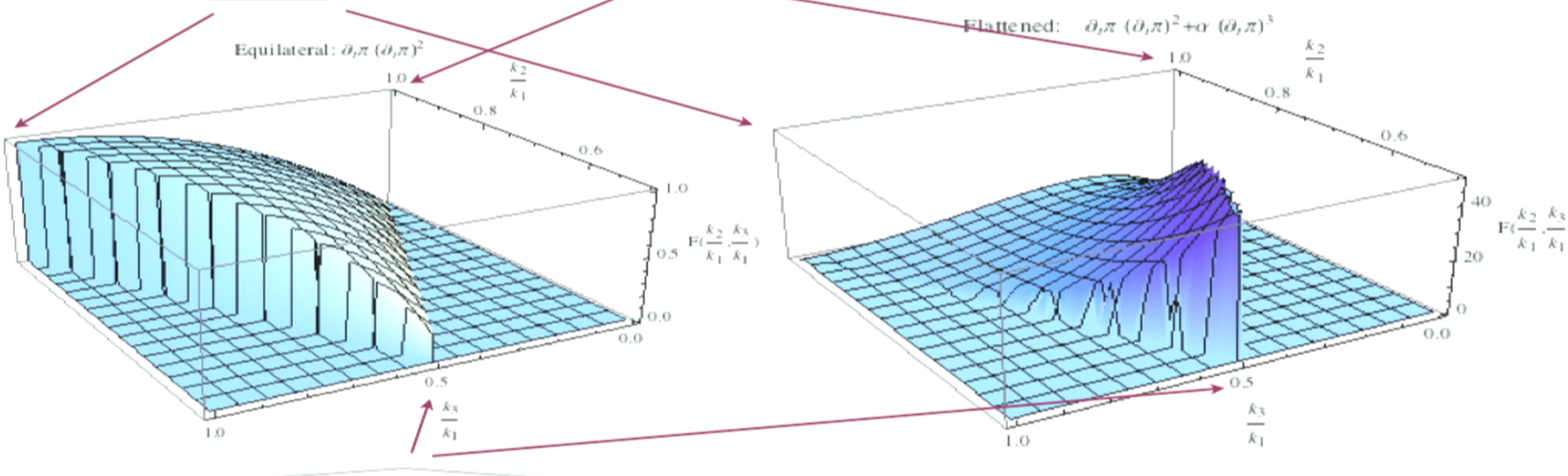
  NG: $f_{\rm NL}^{\rm non-loc.}\sim\frac{1}{c_s^2}$
- Large interactions are allowed $\Longrightarrow$ Large non-Gaussianities! $\quad \dot\pi(\nabla\pi)^2 \qquad \dot\pi^3$

Large non-Gaussianites

with Smith and Zaldarriaga,
JCAP1001:028,2010

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

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



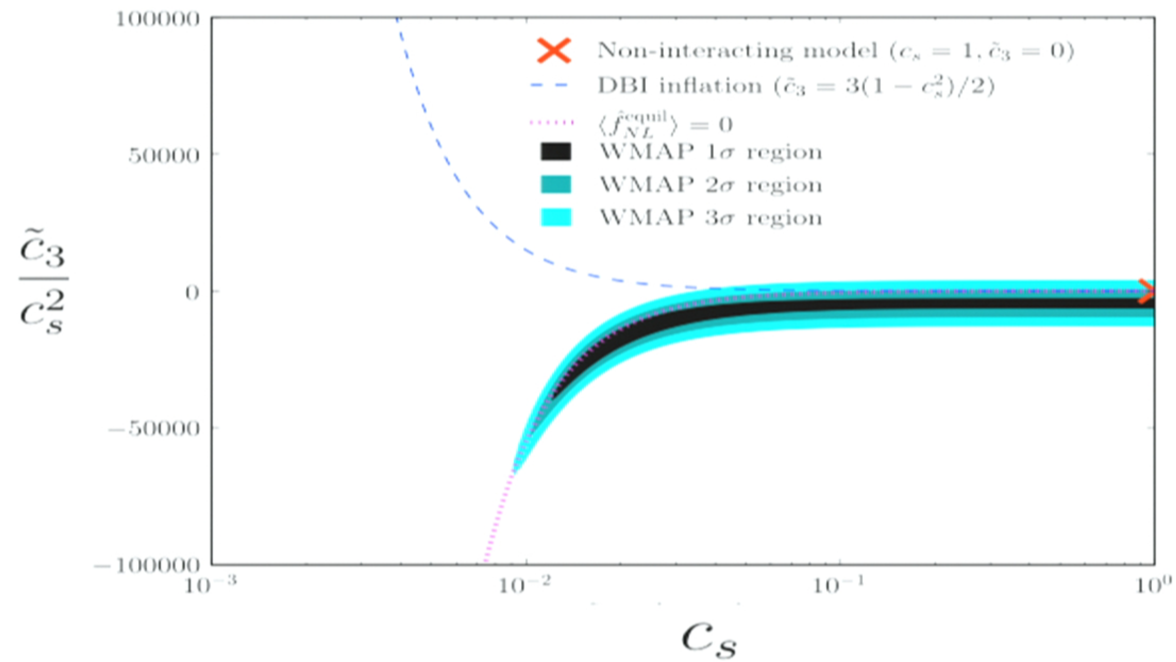
$$\frac{1}{c_s^2}\dot{\pi}(\partial_i\pi)^2 + \frac{\tilde{c}_3}{c_s^2}\dot{\pi}^3$$

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

(Optimal) Limits on the parameters of the Lagrangian

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

- 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**

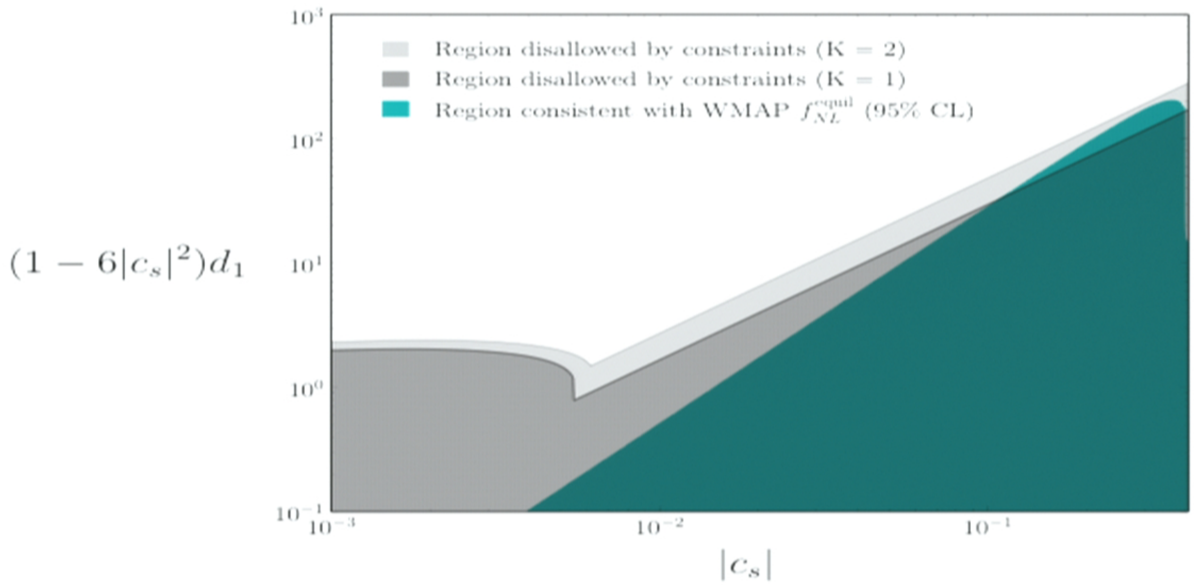
Very similar in spirit to Precision EW Test
Peskin and Takeuchi, **1992**
Barbieri, Pomarol, Rattazzi, Strumia, **2004**

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

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

(Optimal) Limits on the parameters of the Lagrangian

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



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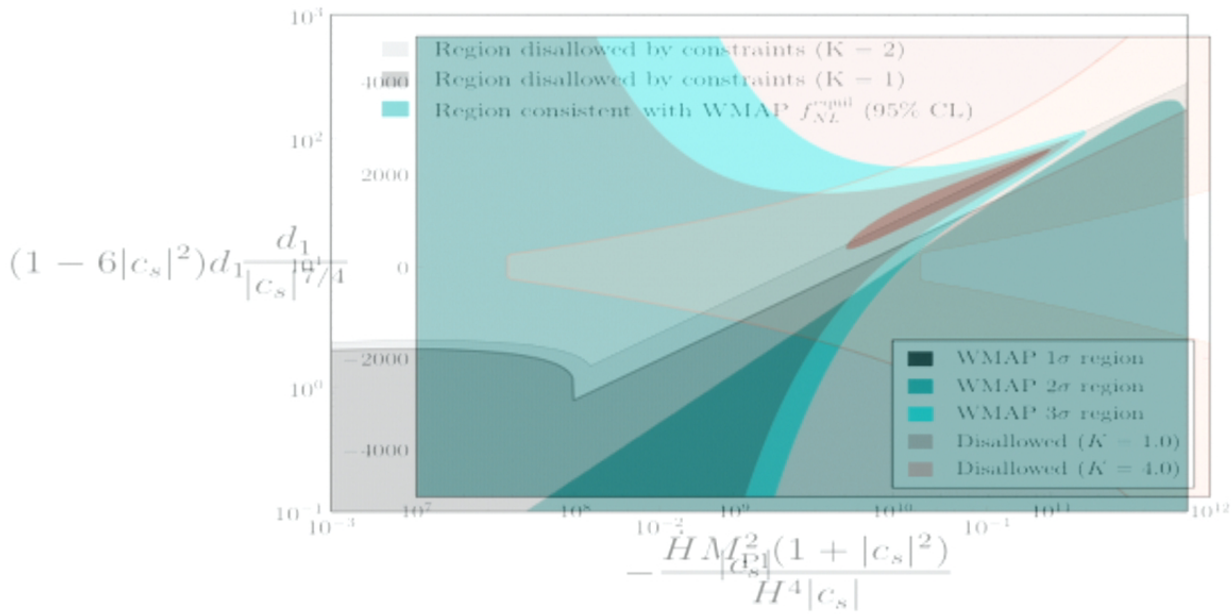
(Optimal) Limits on the parameters of the Lagrangian

- Close to de Sitter.
- Negative c_s^2 due to $\dot{H}_1 < 0$ $\quad \dot{H} c_s^2 M_{\rm Pl}^2 (\partial_i \pi)^2 \ll 1$
- Ruled out at 95% CL.



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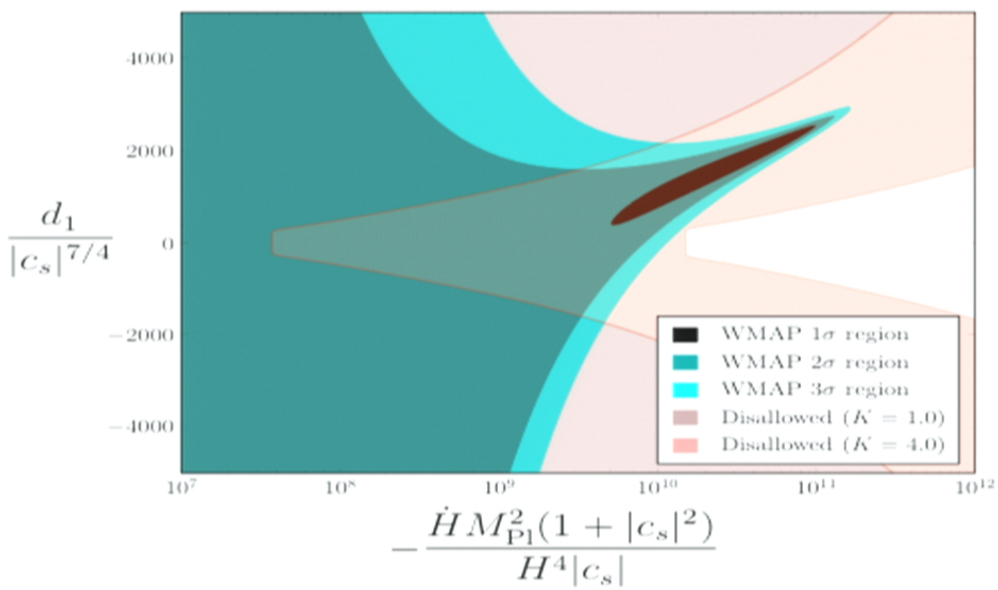

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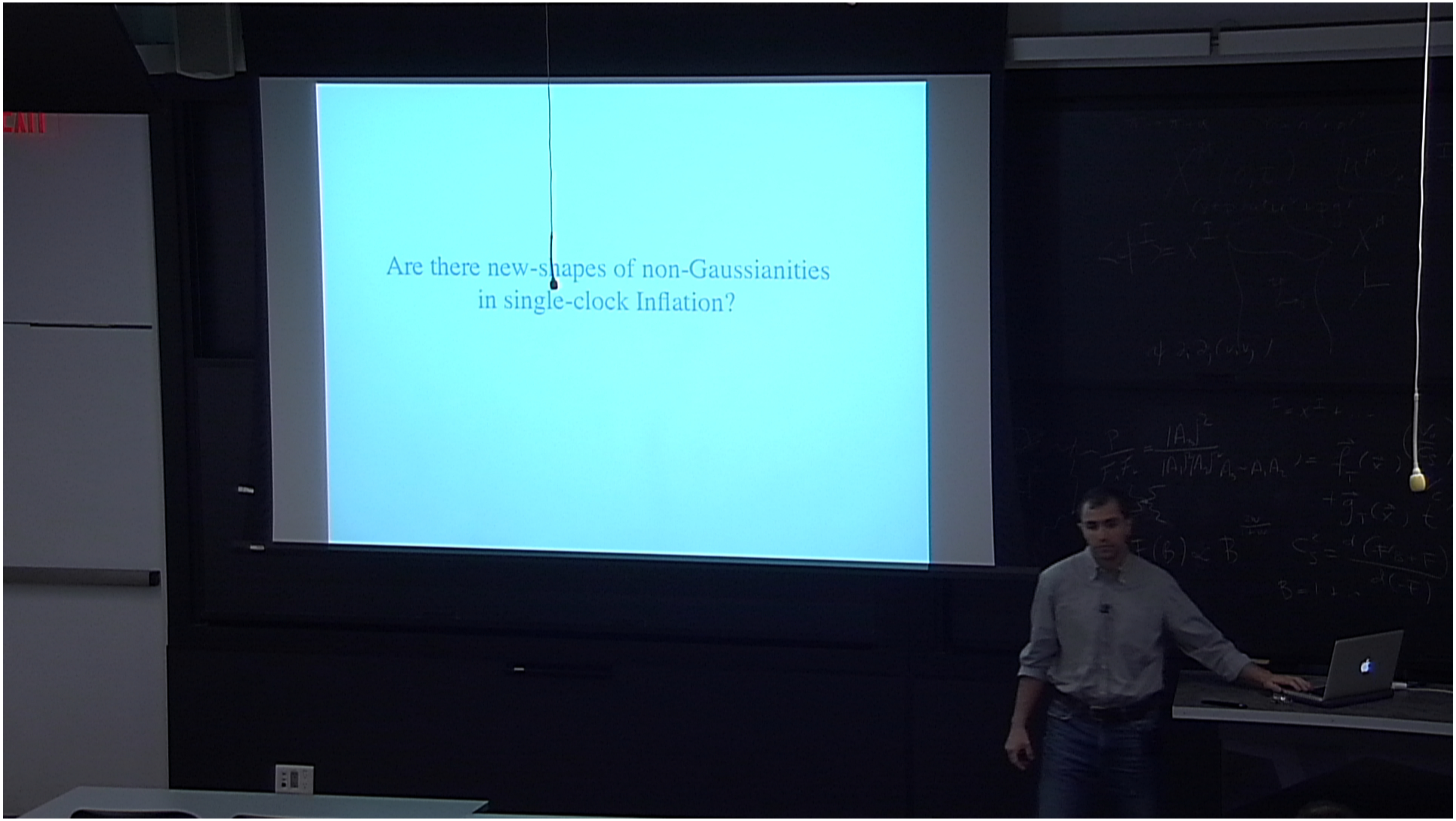

Are there new-shapes of non-Gaussianities
in single-clock Inflation?

Breaking the π Shift Symmetry

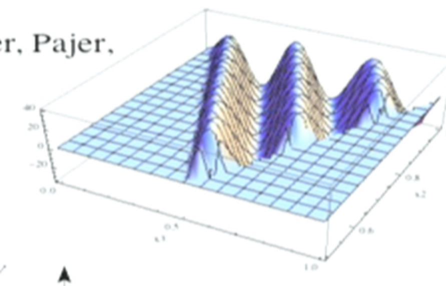
with Dymarsky, Behbahani, Mirbabayi
1111.3373

- Technically natural: break the continuous π shift symmetry $\quad \pi \longrightarrow \pi + C$

  discrete π shift symmetry $\quad \pi \longrightarrow \pi + C_0\, n$

- This is what happens in Axion Monodromy
- Predictions: Oscillations in Power Spectrum
- Oscillating non-Gaussianities

Lim, Easther, Chen **2008**
Silverstein, Westphal, McAllister, Flauger, Pajer, Leblond **2008, 2009, 2010**



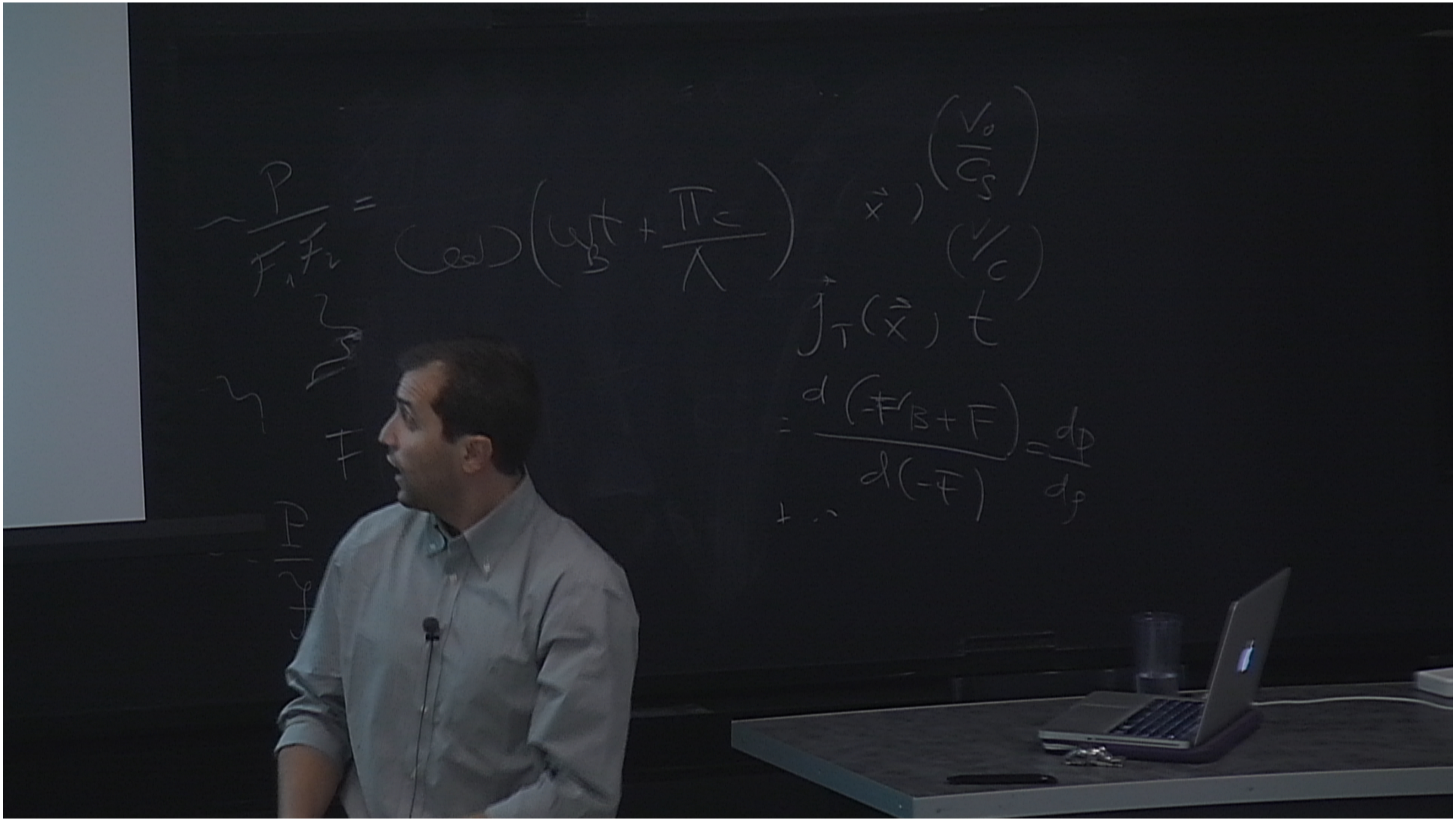
- Non-Gaussian signal more important than Gaussian? ... No

$$\mathcal{L}_{int} \sim \cos\left[\omega_B \left(t + \pi_c/\Lambda\right)\right] \quad \Rightarrow \quad \Lambda \sim \text{ cutoff}$$

- Background Oscillations $\Longrightarrow$ Modes resonate $\omega_{\rm phys}(t) \to \omega_B$

- NG $\sim \dfrac{\langle \zeta^n \rangle}{\langle \zeta^2 \rangle^{n/2}} \sim \dfrac{\mathcal{L}_n}{\mathcal{L}_2}\Big|_{\omega_{\rm res}} \sim \left(\dfrac{\pi_c}{\Lambda}\right)^n \sim \left(\dfrac{\omega_{\rm res}}{\Lambda}\right)^n$ very sensible

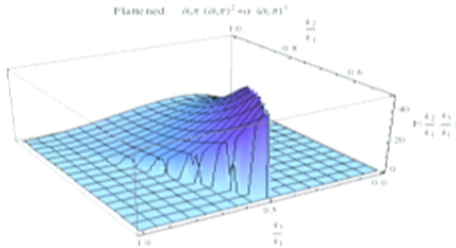
- n-point function > 2-point function when $\quad \omega_{\rm res} \gtrsim \Lambda \quad \to \quad NG \sim 1 \quad \Rightarrow \quad$ ruled out
- Much easier to see with EFT

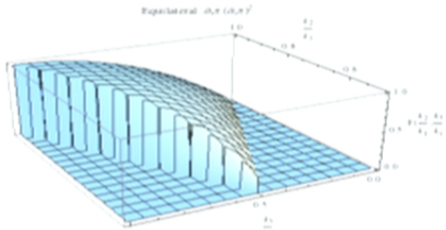


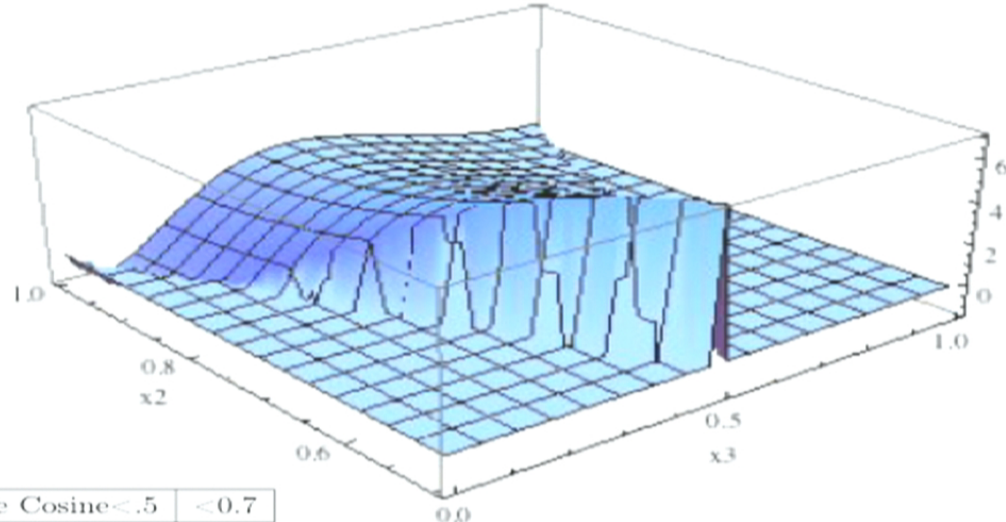
Higher Derivative Shapes

with Behbahani, Gruzinov, Mirbabayi, Zaldarriaga
in completion

- Is it possible to have $(\partial^4\pi)^3$ as the leading operator/shape?
- New symmetries
- A way to stop: $\dim[\mathcal{O}_{\pi^3}] = n \quad \Rightarrow \quad f_{NL}\zeta \sim \left(\frac{H}{\Lambda}\right)^n \quad \Rightarrow \quad \Lambda \to H \quad \text{as} \quad n \to \infty$



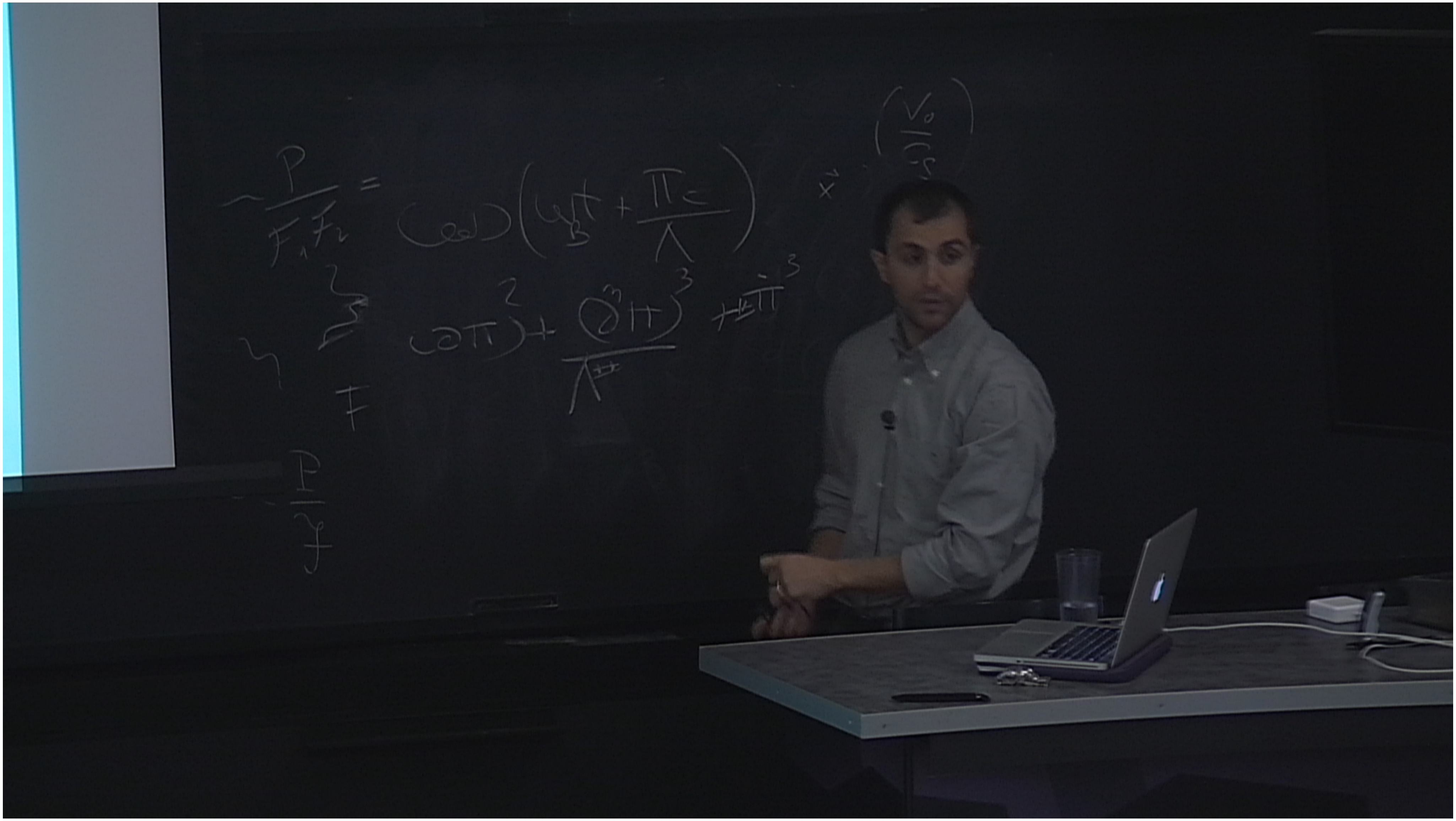




Combination	Percentage of parameter space where Cosine<.5	<0.7
$\dot\pi\pi_{,i}^2 + \dot\pi^3 + \dddot\pi_c\pi_{c,ijk}\pi_{c,ijk}$	0.28	0.95
$\ddot\pi\dot\pi_{,i}\pi_{,i} + \dot\pi^2\ddot\pi + \dot\pi^3$	0.06	0.13
$\ddot\pi_c^3 + \ddot\pi_c\dot\pi_{c,ij}\pi_{c,ij} + \dddot\pi_c\pi_{c,ijk}\pi_{c,ijk}$	0.14	0.62
$\ddot\pi_c^3 + \ddot\pi_c\dot\pi_{c,ij}\pi_{c,ij} + \dddot\pi_c\ddot\pi_{ci}\dot\pi_{ci}$	0.01	.09
$\dddot\pi_c\ddot\pi_{ci}\dot\pi_{ci} + \ddot\pi_c^3 + \dddot\pi_c\pi_{c,ijk}\pi_{c,ijk}$	0.07	0.67
5789	0.03	0.17
$\ddot\pi\dot\pi_{,i}\pi_{,i} + \dddot\pi_c\ddot\pi_{ci}\dot\pi_{ci} + \dddot\pi_c\pi_{c,ijk}\pi_{c,ijk}$	0.07	0.78

Effective Field Theory of Multifield Inflation

with M. Zaldarriaga
1009.2093 hep-th



The Effective Field Theory for Multifield Inflation

with M. Zaldarriaga
1009.2093 hep-th

In the same Unitary Gauge,
consider another massless scalar field σ
[Classification:
approximate shift symmetry:
- Abelian
- Non-Abelian
- Supersymmetry]

$$S_{\rm M.F.} = \int d^4x\, \sqrt{-g}\Big[\tilde M_1^2\ \delta g^{00}(g^{0\mu}\partial_\mu\sigma) + e_1\ (\partial_\mu\sigma)^2 + e_2\ (g^{0\mu}\partial_\mu\sigma)^2 + \\ + e_3^2\ \delta g^{00}(g^{0\mu}\partial_\mu\sigma)^2 + e_4^2\ \delta g^{00}(\partial_\mu\sigma)^2 + \tilde M_2^2\ (\delta g^{00})^2(g^{0\mu}\partial_\mu\sigma) \\ + \tilde M_3^{-2}\ (g^{0\mu}\partial_\mu\sigma)^3 + \tilde M_4^{-2}\ (g^{0\mu}\partial_\mu\sigma)(\partial_\mu\sigma)^2 + \ldots\Big]\ .$$

Then add conversion into curvature perturbations
(see Porto's talk when this is not the case)

The Effective Field Theory for Multifield Inflation

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1009.2093 hep-th

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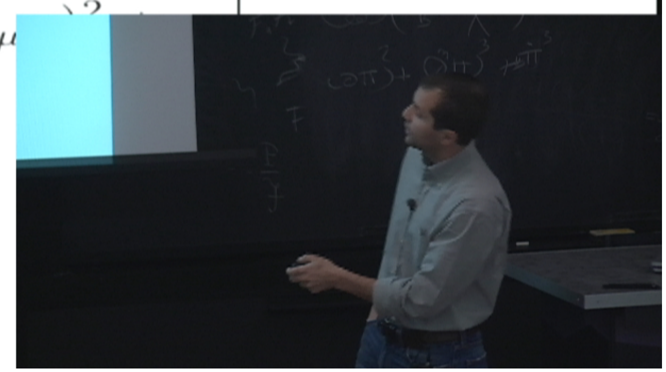
$$S_{\mathrm{M.F.}} = \int d^4x \, \sqrt{-g} \Big[\tilde{M}_1^2 \, \delta g^{00} (g^{0\mu}\partial_\mu\sigma) + e_1 \, (\partial_\mu\sigma)^2 + e_2 \, (g^{0\mu}\partial_\mu\sigma)^2 +$$
$$+ e_3^2 \, \delta g^{00} (g^{0\mu}\partial_\mu\sigma)^2 + e_4^2 \, \delta g^{00} (\partial_\mu\sigma)^2 + \tilde{M}_2^2 \, (\delta g^{00})^2 (g^{0\mu}\partial_\mu\sigma)$$
$$+ \tilde{M}_3^{-2} \, (g^{0\mu}\partial_\mu\sigma)^3 + \tilde{M}_4^{-2} \, (g^{0\mu}\partial_\mu\sigma)(\partial_\mu$$



Then add conversion into curvature perturbations
(see Porto's talk when this is not the case)

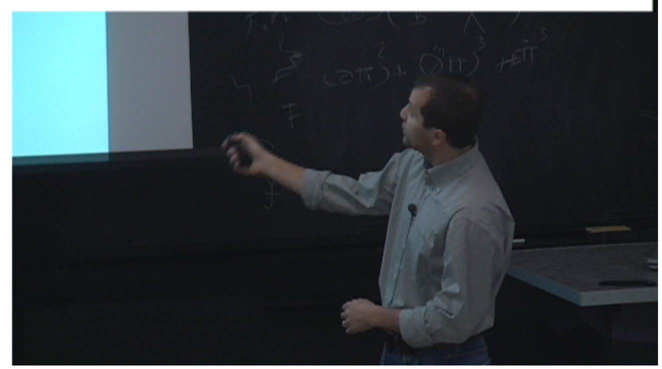
Reintroducing the Goldstone

with M. Zaldarriaga
1009.2093 hep-th

- Quadratic Lagrangian

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

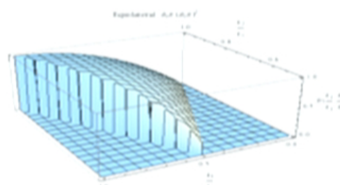
- Cubic Lagrangian ...
- Quartic Lagrangian ....
- Notice:
  - Small π speed of sound: Large coupling $M^4 \dot{\pi}^2 \quad \longrightarrow \quad M^4 \dot{\pi} (\partial_i \pi)^2$
  - Small σ speed of sound: Large coupling $(-e_1 + e_2) \, \dot{\sigma}^2 \quad \longrightarrow \quad e_2 \, (\partial_i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



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

with M. Zaldarriaga
1009.2093 hep-th

- In multifield inflation:
  - -Impose symm. $\sigma \longrightarrow -\sigma$
  - -Approximate Lorentz invariance $\Longrightarrow$ 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

with M. Zaldarriaga
1009.2093 hep-th

- 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:

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

- Mixed iso-adiabatic becomes large:

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

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

- A remarkable Signature
- Also SUSY implemented

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.$^\dagger_s$, non-Ab.$^\dagger_s$.	X
$\sigma^2\dot{\sigma}^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$^\star_s$.	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.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$.	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.$^\dagger_s$, non-Ab.$^\dagger_s$.	X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$, S.*	X
$\sigma(\partial\sigma)^3$	X		Iso.	non-Ab.$^\star_s$.	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.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$^{\dagger\star}_s$, non-Ab.$^{\dagger\star}_s$.	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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New Signatures: new 3-point and 4-point functions

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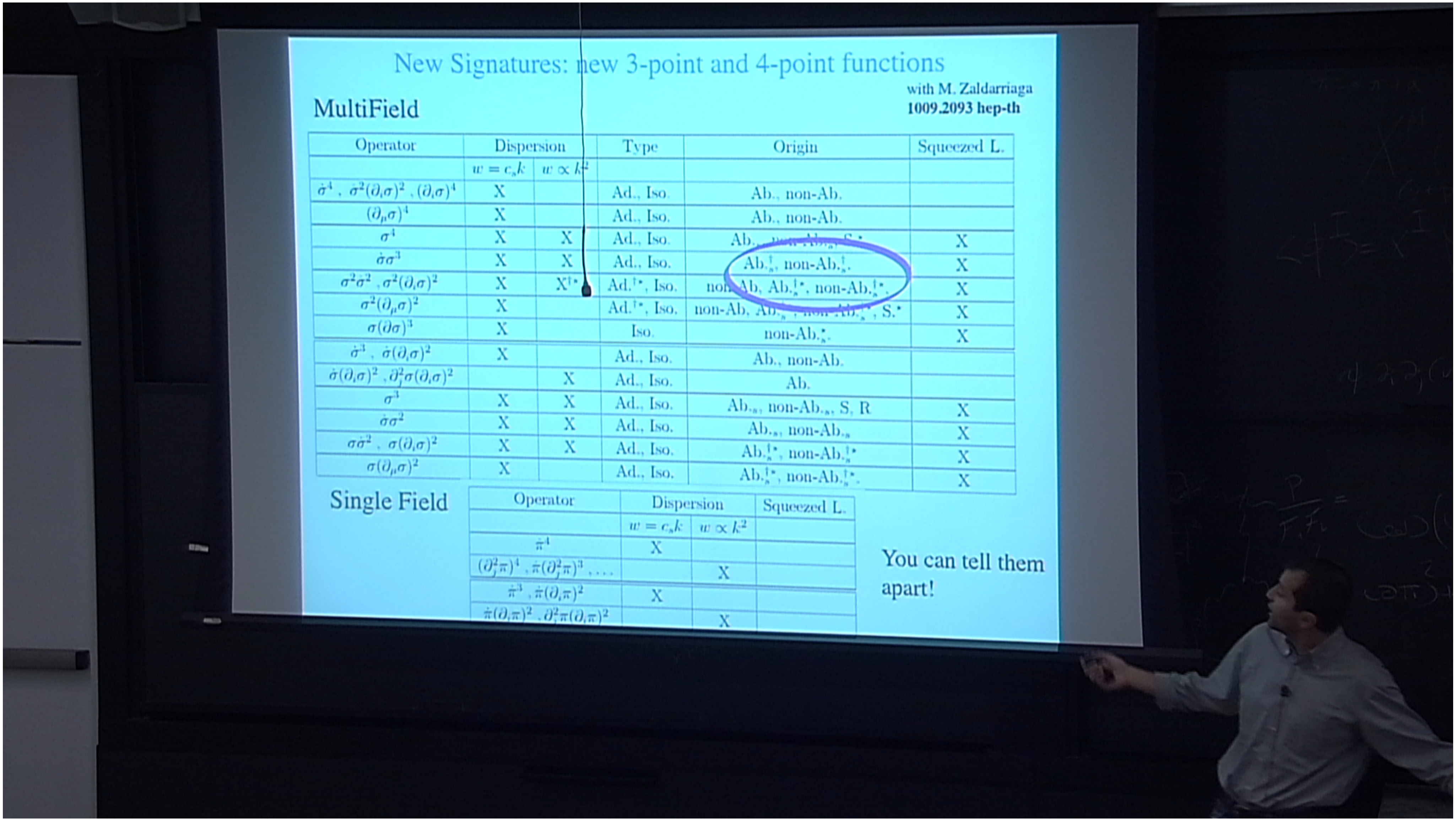
MultiField

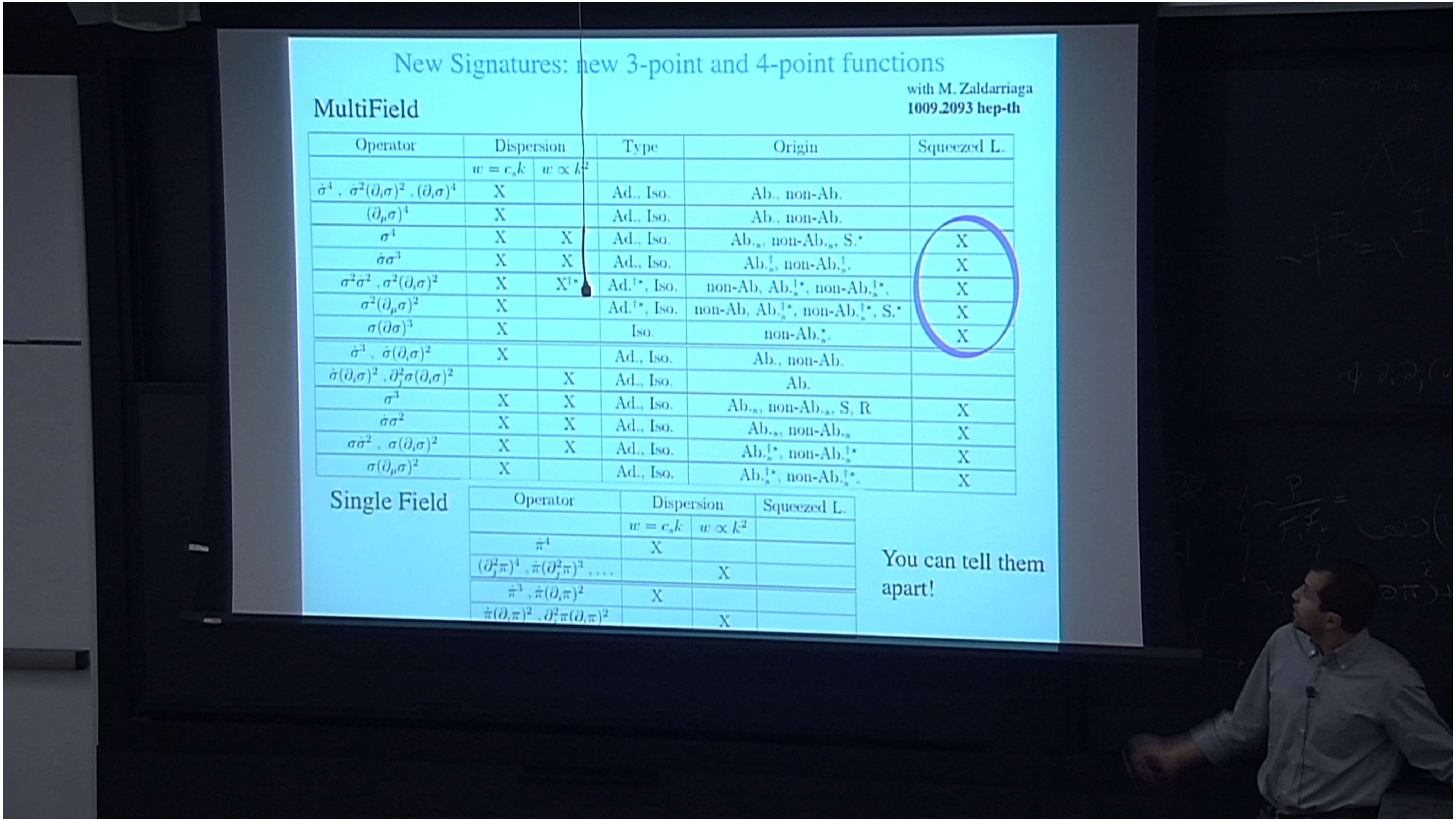
Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_s$, non-Ab.$_s$, S.*	X
$\dot\sigma\sigma^3$	X	X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

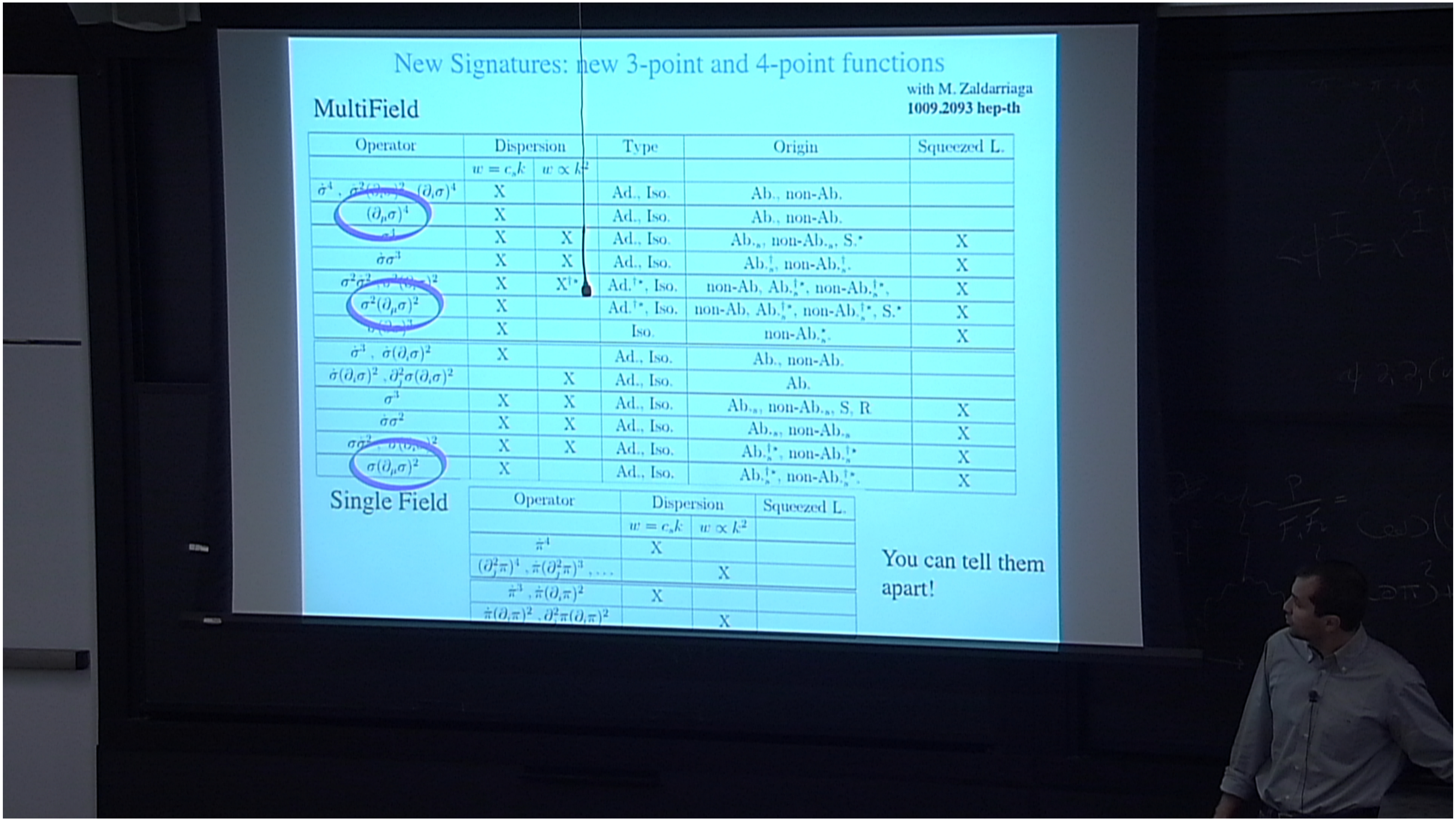
Single Field

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. | X
$\dot\sigma\sigma^3$ | X | X | Ad., Iso. | X
$\sigma^2\dot\sigma^2$, $\sigma^2(\partial_i\sigma)^2$ | X | Ad., Iso. | X
$\sigma^2(\partial_\mu\sigma)^2$ | X | Iso. | X
$\sigma(\partial\sigma)^3$ | X | Iso. | 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. | X
$\dot\sigma\sigma^2$ | X | X | Ad., Iso. | X
$\sigma\dot\sigma^2$, $\sigma(\partial_i\sigma)^2$ | X | X | Ad., Iso. | X
$\sigma(\partial_\mu\sigma)^2$ | X | Ad., Iso. | 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 |
You can tell them apart!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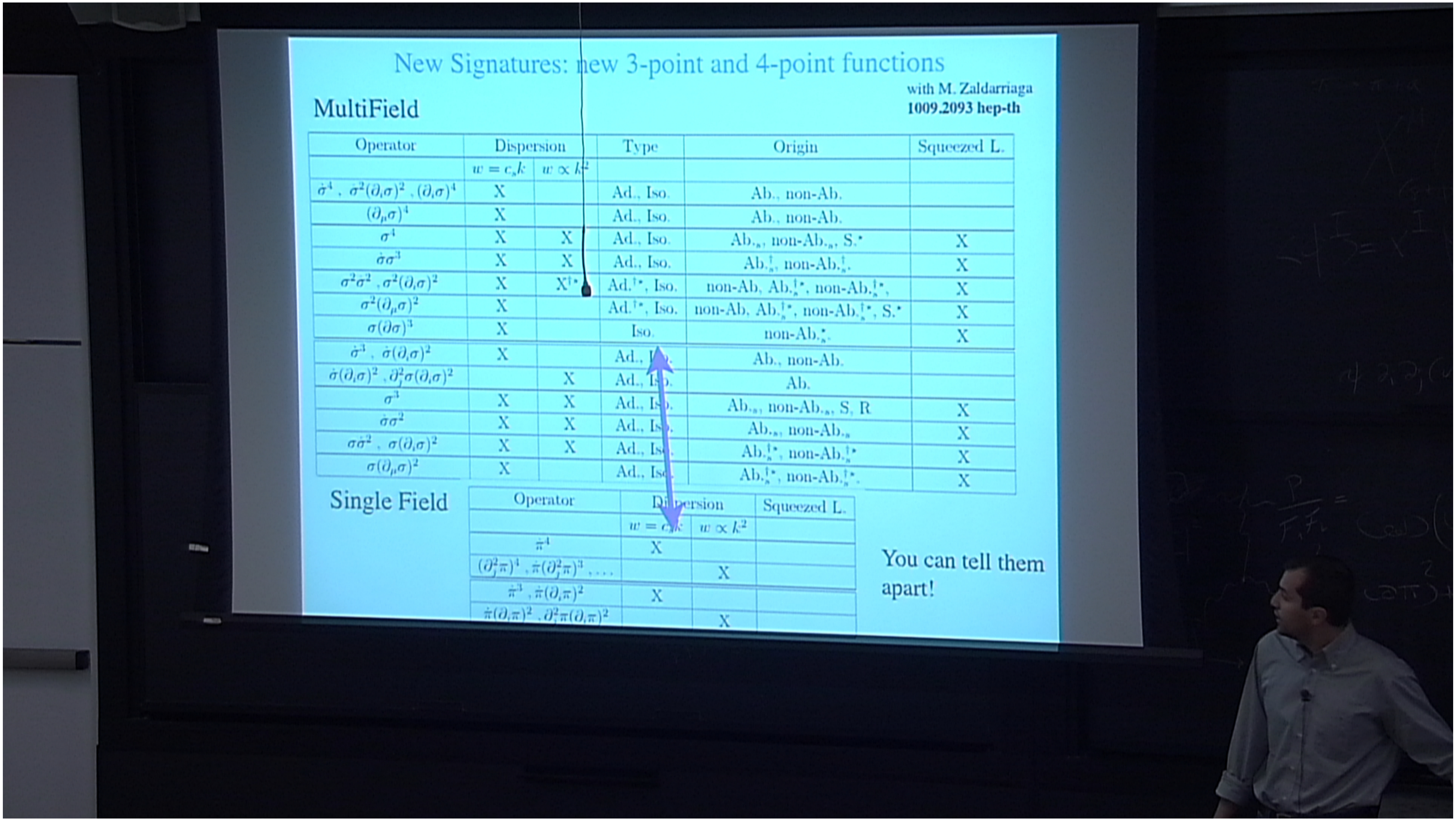
MultiField

Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, … $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
	X	X	Ad., Iso.	Ab.$_{,s}$, non-Ab.$_{,s}$, S.*	X
$\dot\sigma\sigma^3$	X	X	Ad., Iso.	Ab.$^\dagger_{,s}$, non-Ab.$^\dagger_{,s}$.	X
$\sigma^2\dot\sigma^2$ …	X	X†*	Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_{,s}$, non-Ab.$^{\dagger\star}_{,s}$,	X
$\sigma^2(\partial_\mu\sigma)^2$	X		Ad.†*, Iso.	non-Ab, Ab.$^{\dagger\star}_{,s}$, non-Ab.$^{\dagger\star}_{,s}$, S.*	X
	X		Iso.	non-Ab.$^\star_{,s}$.	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
$\sigma\dot\sigma^2$ …	X	X	Ad., Iso.	Ab.$^{\dagger\star}_{,s}$, non-Ab.$^{\dagger\star}_{,s}$	X
$\sigma(\partial_\mu\sigma)^2$	X		Ad., Iso.	Ab.$^{\dagger\star}_{,s}$, non-Ab.$^{\dagger\star}_{,s}$.	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

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1009.2093 hep-th

MultiField

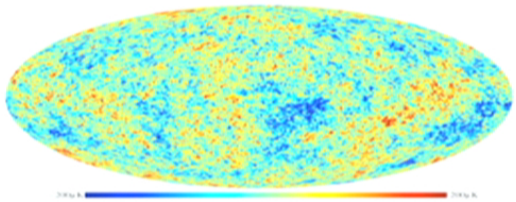
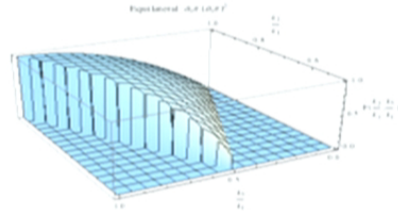
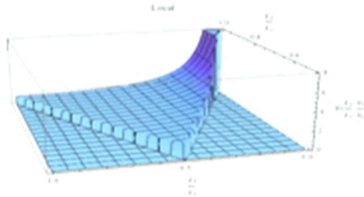
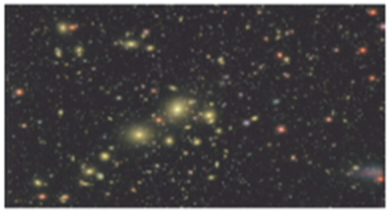
Operator	Dispersion		Type	Origin	Squeezed L.
	$w = c_s k$	$w \propto k^2$			
$\dot\sigma^4$, $\dot\sigma^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
$(\partial_\mu\sigma)^4$	X		Ad., Iso.	Ab., non-Ab.	
σ^4	X	X	Ad., Iso.	Ab.$_{,s}$, non-Ab.$_{,s}$, S.*	X
$\dot\sigma\sigma^3$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

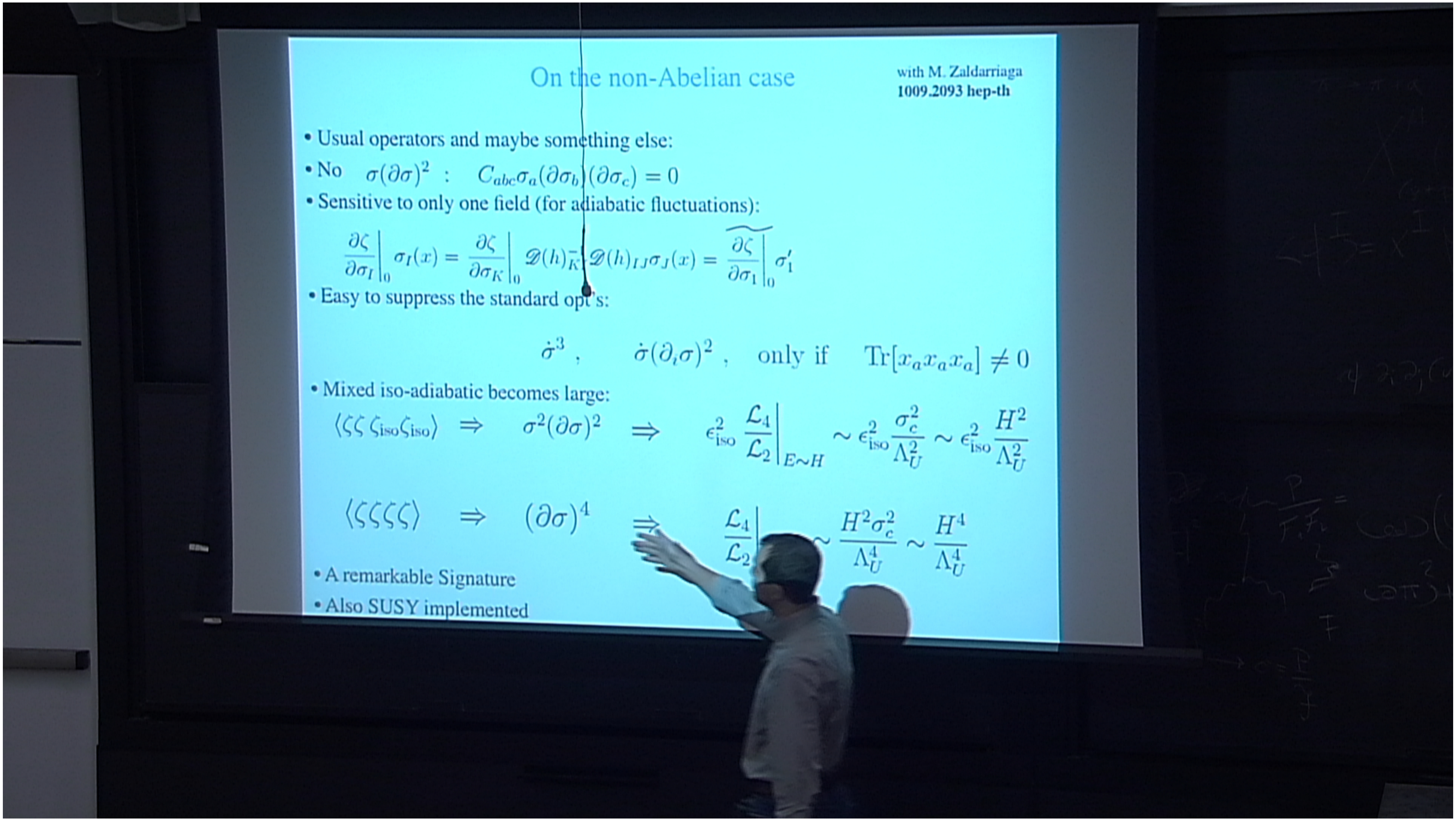
Developing the Phenomenology of Inflation

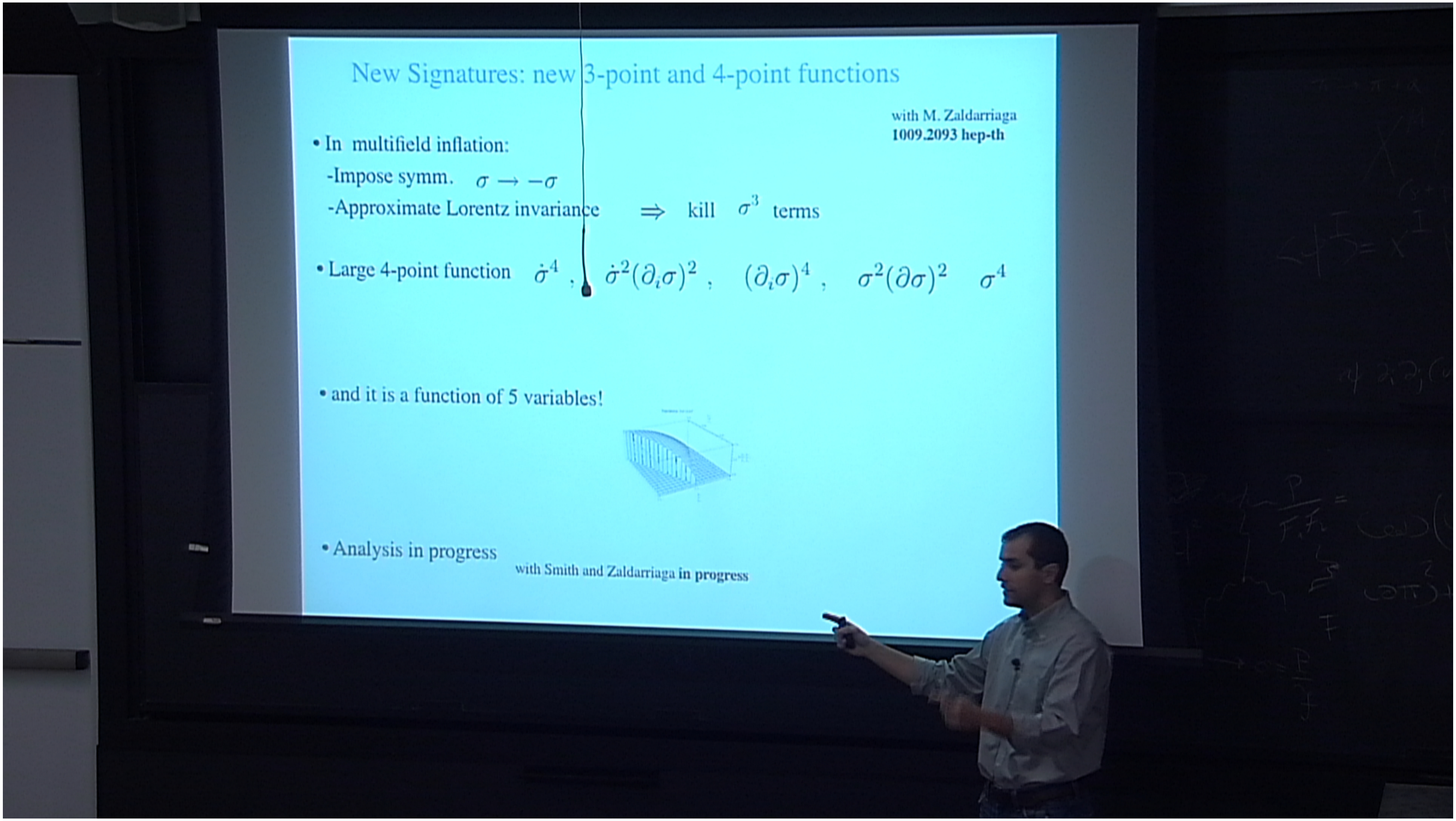
   

- The Effective Field Theory of Multifield Inflation — with M. Zaldarriaga **1009**
- Higher derivative interactions, ex: $(\partial^4\pi)^3$ — with Behbahani, Mirbabayi **in progress**; Riotto et al **0808, 0908** D'Amico et al **1011**
- Relaxing the shift-symmetry of π — with Behbahani, Mirbabayi **1111**
- Dissipative Effects in Inflation — with Nacir, Porto, and Zaldarriaga **1109**
- Additional Massive Fields... — Baumann and Green, **1109** with Villadoro, **in progress**

Impact

- Workshops on Effective Field Theory in Inflation — Michigan, Leiden (Organizer)
- Other groups joining in (Princeton, Cambridge, CERN, UCSD, Padova, ...)
- Already thought in Summer Schools and Graduate Classes at Harvard, Stanford (Arkani-Hamed, Silverstein, Zaldarriaga ...)


On the non-Abelian case
with M. Zaldarriaga
1009.2093 hep-th
• 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:
$\dot\sigma^3$, $\dot\sigma(\partial_i\sigma)^2$, only if $\mathrm{Tr}[x_a x_a x_a] \neq 0$
• Mixed iso-adiabatic becomes large:
$\langle\zeta\zeta\,\zeta_{\rm iso}\zeta_{\rm iso}\rangle \Rightarrow \sigma^2(\partial\sigma)^2 \Rightarrow \epsilon^2_{\rm iso}\left.\frac{\mathcal{L}_4}{\mathcal{L}_2}\right|_{E\sim H} \sim \epsilon^2_{\rm iso}\frac{\sigma_c^2}{\Lambda_U^2} \sim \epsilon^2_{\rm iso}\frac{H^2}{\Lambda_U^2}$
$\langle\zeta\zeta\zeta\zeta\rangle \Rightarrow (\partial\sigma)^4 \Rightarrow \frac{\mathcal{L}_4}{\mathcal{L}_2} \sim \frac{H^2\sigma_c^2}{\Lambda_U^4} \sim \frac{H^4}{\Lambda_U^4}$
• A remarkable Signature
• Also SUSY implemented


New Signatures: new 3-point and 4-point functions
with M. Zaldarriaga
1009.2093 hep-th
• In multifield inflation:
-Impose symm. $\sigma \rightarrow -\sigma$
-Approximate Lorentz invariance $\Rightarrow$ kill σ^3 terms
• Large 4-point function $\dot{\sigma}^4$, $\dot{\sigma}^2(\partial_i\sigma)^2$, $(\partial_i\sigma)^4$, $\sigma^2(\partial\sigma)^2$ σ^4
• and it is a function of 5 variables!
• Analysis in progress
with Smith and Zaldarriaga in progress

Leonardo Senatore (Stanford)

The Effective Theory of the Long Distance Universe

Cosmological non-Linearities as an Effective Fluid with Baumann, Nicolis and Zaldarriaga, **1004.2488** [astro-ph.CO]

Measuring the Parameters of the Cosmic Fluid with Carrasco, Hertzberg, Wechsler, **in progress**

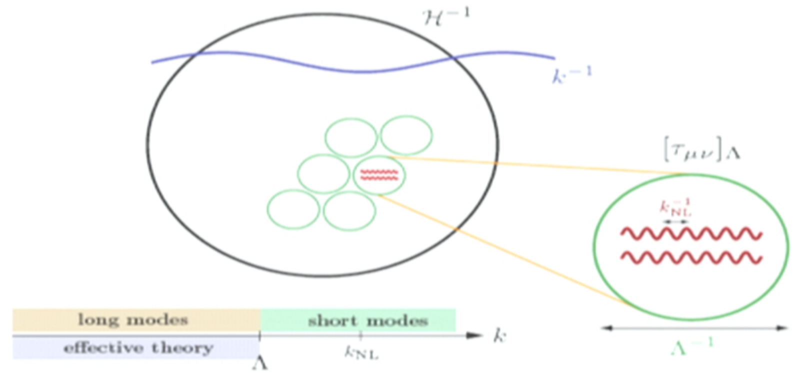
Outline:
When Cosmology Becomes non-Linear

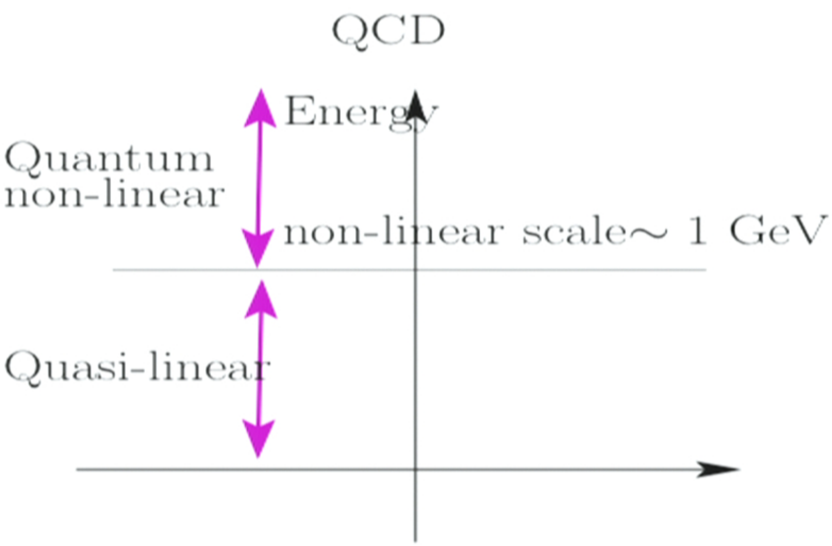
- Cosmological non-Linearities as an Effective Fluid
  - Short-scale non-linearities and large-scale linearities
  - Construction of the effective fluid theory
  - Properties
  - Applications

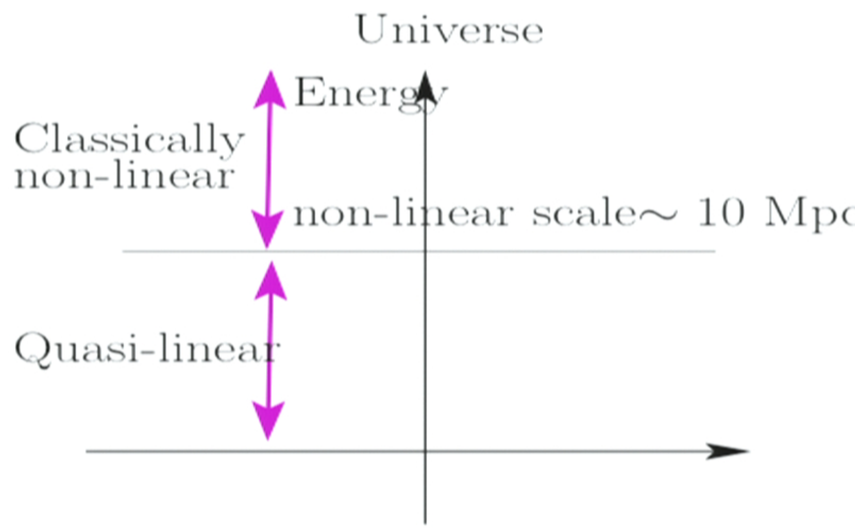
Our universe

- What is the effective theory at long-wavelength?
- Non-linear on short scales $\lambda_{NL} \sim 10 - 100 \text{ Mpc}$ $\delta\rho/\rho \gg 1$
- Linear on large-scales

$H^{-1} \sim 14000 \text{ Mpc}$ $\delta\rho/\rho \ll 1$

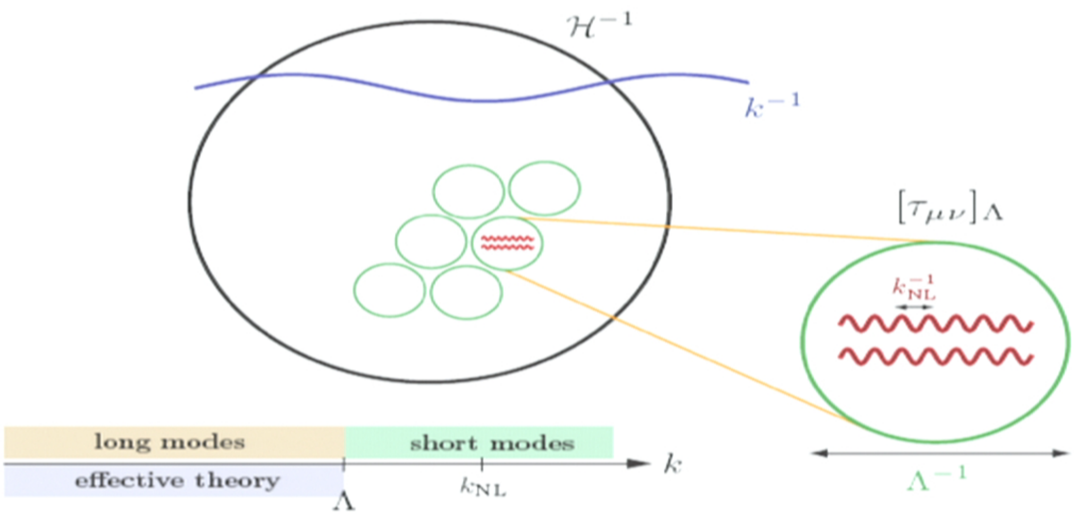






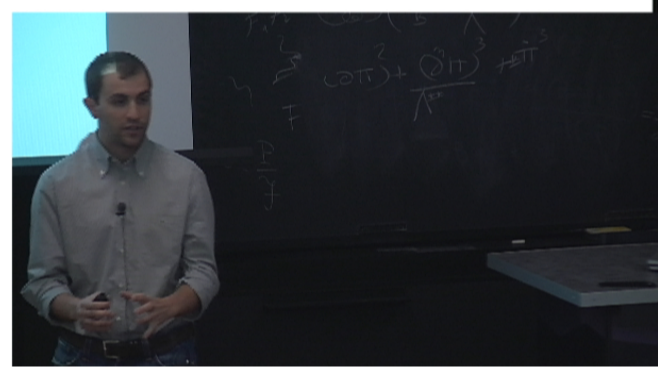
Our universe

- Short scale non-linearities $\lambda_{NL} \sim 10 - 100$ Mpc $\delta\rho/\rho \gg 1$
- Large scale linear $H^{-1} \sim 14000$ Mpc $\delta\rho/\rho \ll 1$
- Why the universe is FRW on large scales?
- Is there some back-reaction from small scales?
- What is the effective theory for the long-distance universe?
- The answer will be small, but why? It is a bit tricky



1) No large back-reaction effects

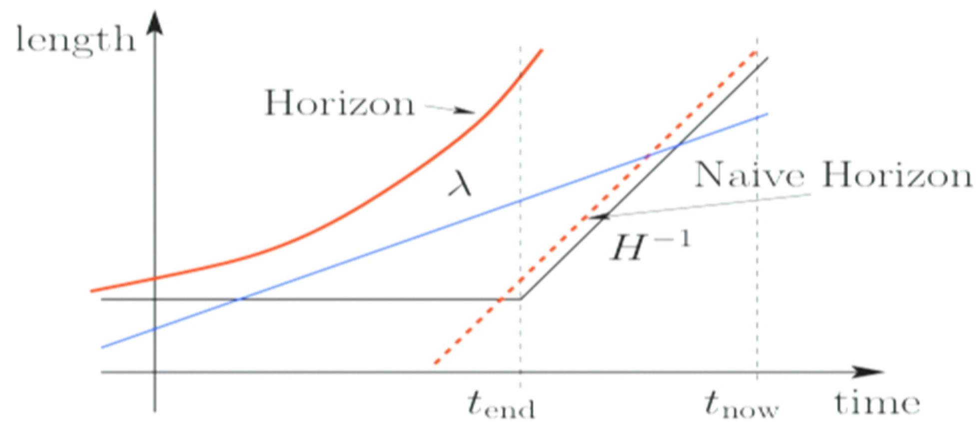
- Does structure formation induce an acceleration without dark energy?
  - E. W. Kolb, S. Matarrese and A. Riotto **astro-ph/0506534**
  - S. Rasanen **Cosmo 2009, Plenary talk**
  - ....
- We believe we are able to answer: no.



2) Understanding evolution of curvature out of horizon

- L. Boubekeur et al **JCAP 2008** found that $\dot{\zeta} \neq 0$ at non-linear level when there are modes inside the horizon
- Crucial for predictivity of inflation

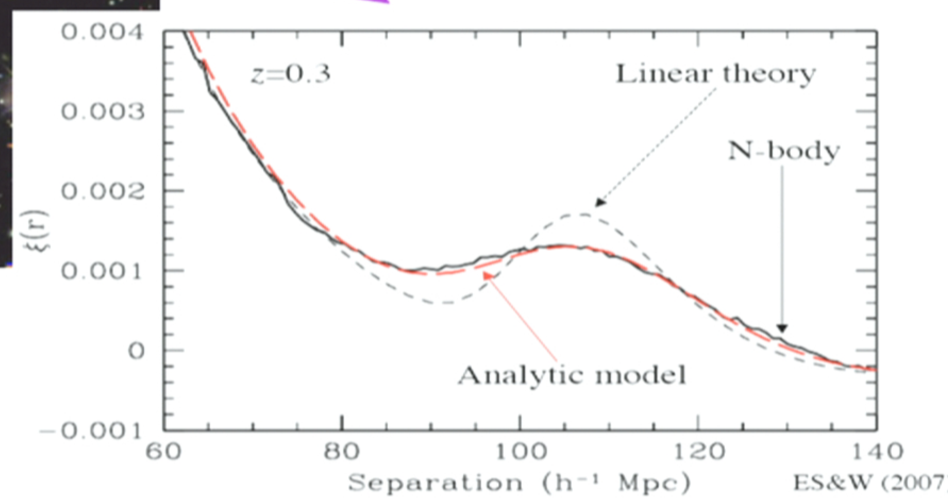
$$ds^2 = -dt^2 + e^{2\zeta(x)} a^2(t) dx_i dx^i$$



- Former proofs (with C. Cheung, L. Fitzpatrick, J. Kaplan **JHEP 2008**, generalization of Maldacena **JHEP, 2003**) assumed all modes outside of the horizon.
- We will find that it is just a redefinition of the background (same conclusion as from quantum-loop effects (with M. Zaldarriaga **JHEP 2010**))

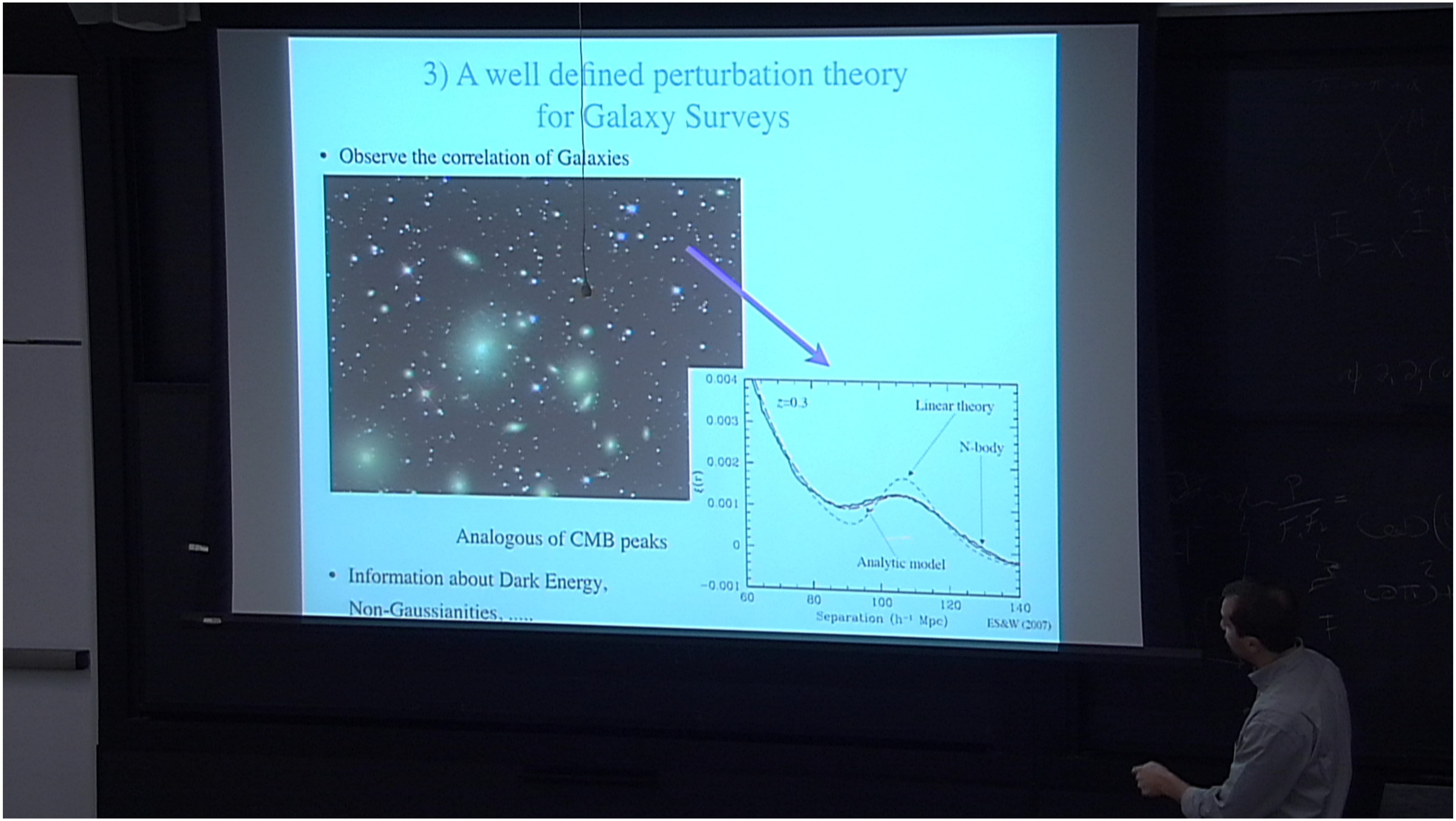
3) A well defined perturbation theory for Galaxy Surveys

- Observe the correlation of Galaxies



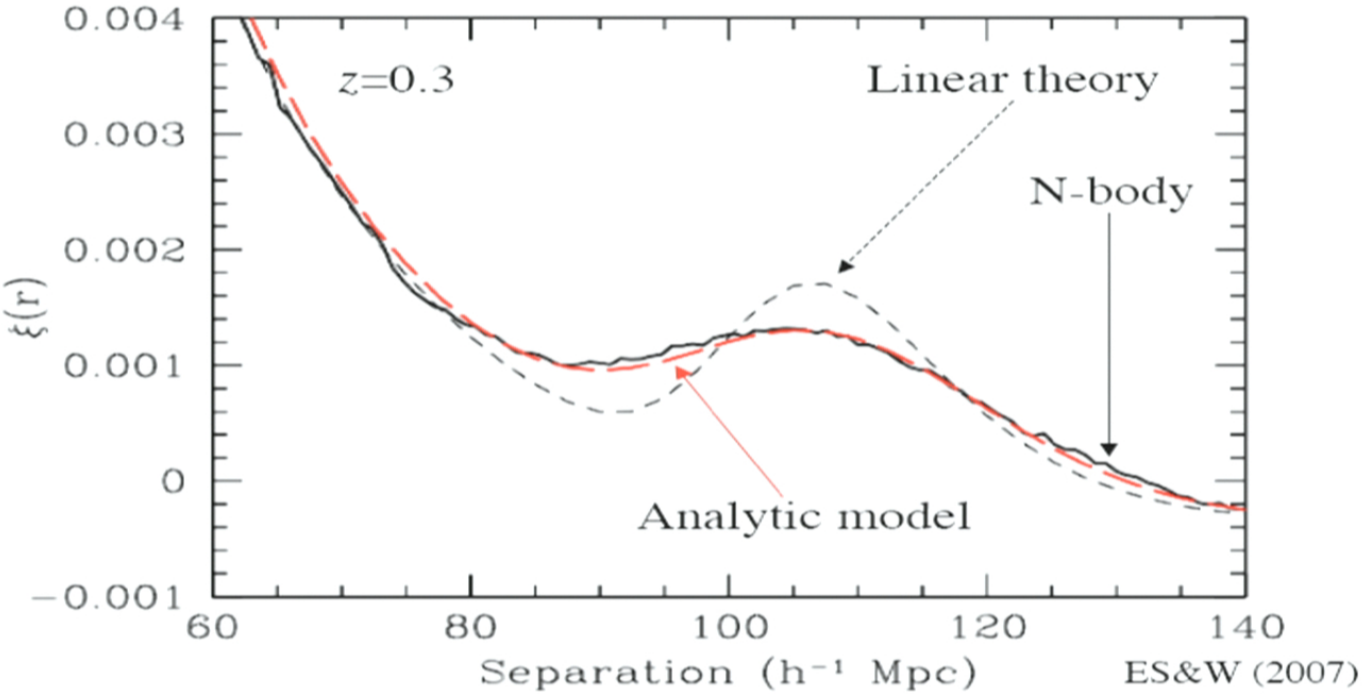
Analogous of CMB peaks

- Information about Dark Energy, Non-Gaussianities, ...


3) A well defined perturbation theory
for Galaxy Surveys
• Observe the correlation of Galaxies
Analogous of CMB peaks
• Information about Dark Energy,
Non-Gaussianities, ...
z=0.3
Linear theory
N-body
Analytic model
ξ(r)
Separation (h⁻¹ Mpc)
ES&W (2007)

3) A well defined perturbation theory

- Baryon Acoustic Oscillations scale is close to non-linear scale (factor of ~10)

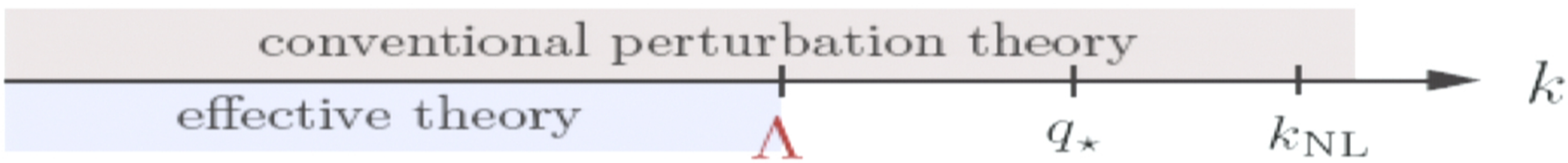


- It is very unclear if current perturbation theory is well defined (at 1% level ?!)
- Fitted with damping and stochasticity

$$P_{\rm obs}(k) = e^{-\frac{1}{2}k^2\Sigma^2} P_{\rm L}(k) + P_{\rm mc}(k)$$

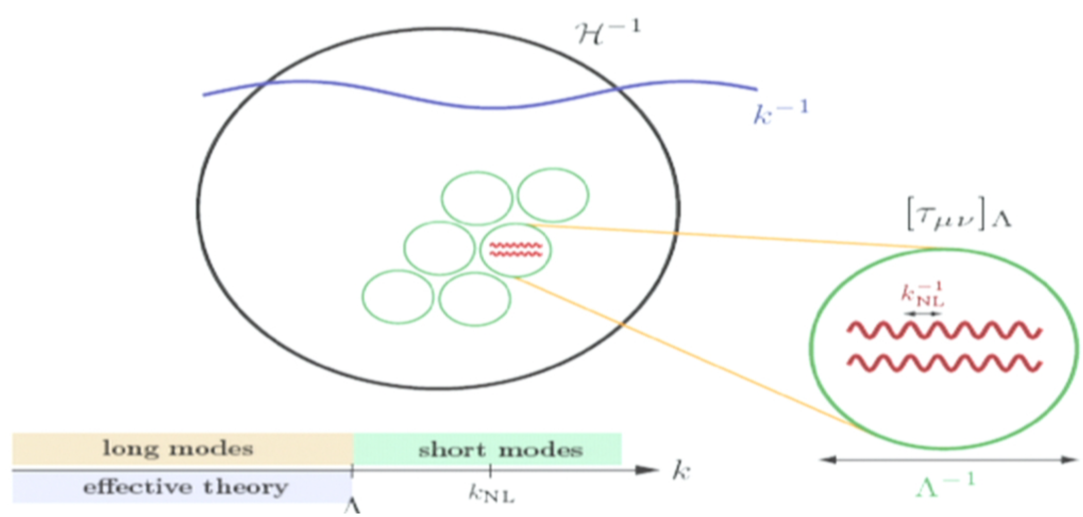
3) A well defined perturbation theory

- BAO scale is close to non-linear scale (factor of ~10)
- It is unclear if current perturbation theory is well defined
- We will define a manifestly convergent perturbation theory



– where the ingredient is an imperfect stochastic fluid with

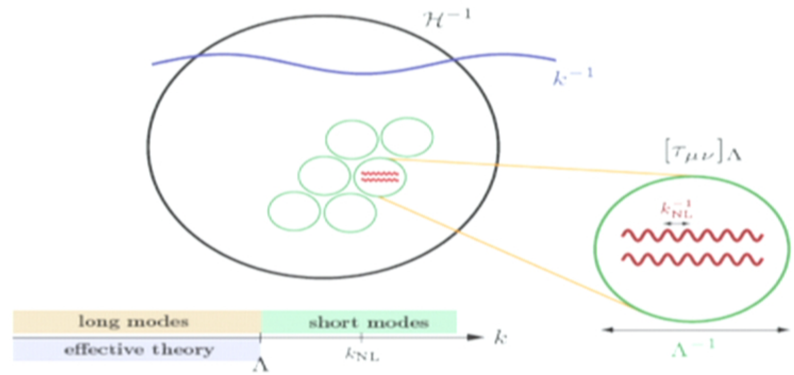
$$\delta_\ell, v_\ell, \Phi_\ell \ll 1$$



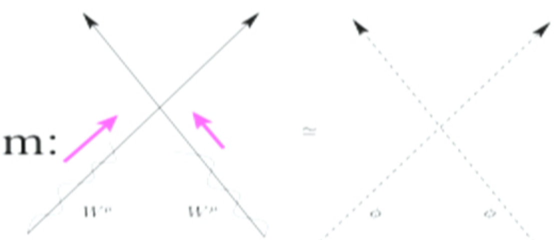
Our universe

- What is the effective theory at long-wavelength?
- Non-linear on short scales $\lambda_{NL} \sim 10 - 100\ \mathrm{Mpc}$
- Linear on large-scales $\delta\rho/\rho \gg 1$

  $H^{-1} \sim 14000\ \mathrm{Mpc}$ $\delta\rho/\rho \ll 1$

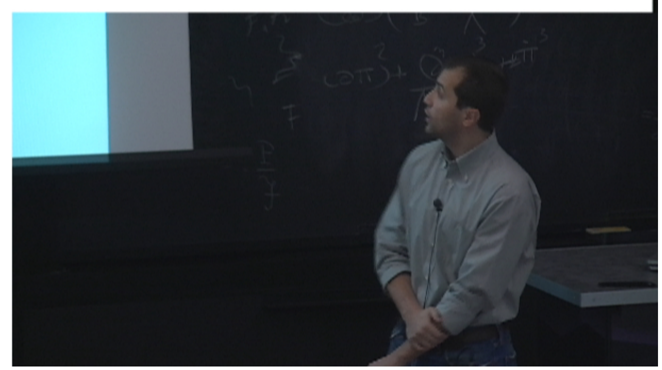


- To describe the problem: two kinds of expansions:
  - Relativistic on large scales $\delta\rho/\rho \sim \delta v \sim \Phi\ , \quad k \lesssim H$
  - Newtonian approximation on small scales $\Phi \sim \delta v^2 \ll \delta\rho/\rho \quad k \gtrsim H$
    - On large scale: Gauge ambiguities
    - On small scales: there are good gauges: it is matter that is becoming non-linear
      - not the spacetime!
        - » Take a gauge with matter non-zero fluctuations.
        - » Analogous to Goldstone bosons equivalence theorem: at high energies do not go to unitary gauge!



Short-Scale Stress-Tensor
Newtonian derivation

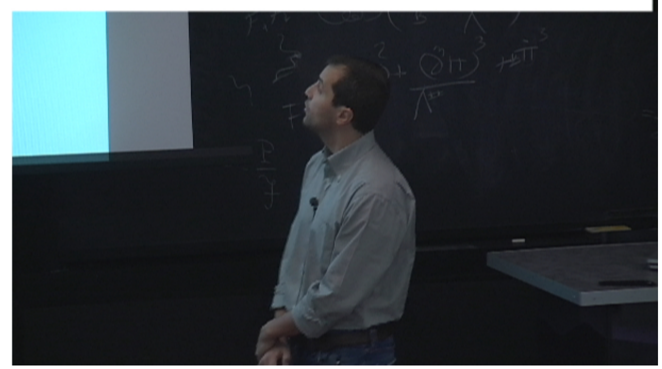
- Let us find effect of short modes on long modes
- Short scale non-linearities: apply Newtonian approximation
- Matter moves in flat space, and its $\tau_{\mu\nu}$ is conserved $\partial_\mu \tau^{\mu\nu} = 0$
- This sources gravity on the long-distance
- Let us find $\tau_{\mu\nu}$ in Newtonian approximation $\Phi \sim \delta v^2 \ll \delta\rho/\rho \quad k \gtrsim H$
- and just use GR concepts
- Three different ways



Short-Scale Stress-Tensor
Newtonian derivation

- Use Newtonian equation, and GR concepts
- FRW metric $ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$
- Go to Fermi-Coordinates $t_c = t - \frac{1}{2}H(t)\boldsymbol{x}^2$, $\boldsymbol{x}_c = \frac{\boldsymbol{x}}{a(t)}[1 + \frac{1}{4}H^2(t)\boldsymbol{x}^2]$
- $\mathrm{d}s^2_{\mathrm{FRW}} \simeq -\left[1 - (\dot{H} + H^2)\boldsymbol{x}^2\right]\mathrm{d}t^2 + \left[1 - \frac{1}{2}H^2\boldsymbol{x}^2\right]\mathrm{d}\boldsymbol{x}^2 = \left(\eta_{\mu\nu} + h^{\mathrm{FRW}}_{\mu\nu}\right)\mathrm{d}x^\mu \mathrm{d}x^\nu$
- $\Phi_{\mathrm{FRW}} = -\frac{1}{2}(\dot{H} + H^2)\boldsymbol{x}^2$, $v_{\mathrm{FRW}} = H\boldsymbol{x}$
- Newtonian approximation is valid for $Hx \ll 1$, for all times.
- Take equations and find $\tau_{\mu\nu}$ and let us take a pressureless fluid as an example.

$$\begin{aligned} \dot{\rho}_m + \boldsymbol{\nabla}\cdot(\rho_m \boldsymbol{v}) &= 0\,, \\ \dot{\boldsymbol{v}} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} &= -\boldsymbol{\nabla}\Phi\,, \\ \nabla^2\Phi &= 4\pi G\,\rho_m\,. \end{aligned}$$



Short-Scale Stress-Tensor Newtonian derivation

$$\begin{aligned} \dot{\rho}_m + \boldsymbol{\nabla} \cdot (\rho_m \boldsymbol{v}) &= 0\,, \\ \dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} &= -\boldsymbol{\nabla} \Phi\,, \\ \nabla^2 \Phi &= 4\pi G\, \rho_m\,. \end{aligned}$$

- Postulate $\tau^{0i} = \rho_m v^i$
- Write Momentum equation as a divergency:

$$\begin{aligned} 0 = \partial_\mu \tau^{\mu i} &= \dot{\rho}_m v^i + \rho_m \dot{v}^i + \partial_j \tau^{ji} \\ &= -\partial_j (\rho_m\, v^i v^j) - \rho_m \partial_i \Phi + \partial_j \tau^{ji}\,, \end{aligned}$$

$$\rho_m\, \partial_i \Phi = \frac{1}{4\pi G} \nabla^2 \Phi\, \partial_i \Phi = \frac{1}{4\pi G} \partial_j \left[\partial_i \Phi \partial_j \Phi - \frac{1}{2} \delta_{ij} (\nabla \Phi)^2 \right]$$

- Space-Space part: $\tau^{ij} = \rho_m v^i v^j + \frac{1}{8\pi G} \left[2\partial_i \Phi \partial_j \Phi - \delta_{ij} (\nabla \Phi)^2 \right]$
- Time-Time part: include Gravitational Energy: $\tau^{00} = \rho_m + \frac{1}{2} \rho_m v^2 - \frac{1}{8\pi G} (\nabla \Phi)^2$
- Notice that this was a bit ambiguous, we could have taken matter conservation:
  - . $\tilde{\tau}^{00} = \rho_m$: mass is conserved in Newtonian limit: educated guess
- We have an effective pressure starting from zero pressure.

Short-Scale Stress-Tensor Newtonian derivation

- $$\tau^{0i} = \rho_m v^i$$
$$\tau^{00} = \rho_m + \frac{1}{2}\rho_m v^2 - \frac{1}{8\pi G}(\nabla\Phi)^2$$
$$\tau^{ij} = \rho_m v^i v^j + \frac{1}{8\pi G}\left[2\partial_i\Phi\partial_j\Phi - \delta_{ij}(\nabla\Phi)^2\right]$$

$$\begin{aligned} \dot\rho_m + \boldsymbol{\nabla}\cdot(\rho_m \boldsymbol{v}) &= 0\,, \\ \dot{\boldsymbol{v}} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} &= -\boldsymbol{\nabla}\Phi\,, \\ \nabla^2\Phi &= 4\pi G\,\rho_m\,. \end{aligned}$$

- This stress-tensor is the source of perturbative gravity

S. Weinberg **Phys.Rev. 135 (1964)**
Phys.Rev. 138 (1965)

- Describe only short scales with Newtonian dynamics:
  - Apply smoothing filter
  - Define $X_\ell \equiv [X]_\Lambda(\boldsymbol{x}) = \int d^3\boldsymbol{x}'\, W_\Lambda(|\boldsymbol{x}-\boldsymbol{x}'|)X(\boldsymbol{x}')$ where $X \equiv \{\rho_m, \Phi, \rho_m \boldsymbol{v}\}$
  - Take long wavelength part to study dynamics of long modes:

$$[\tau^0{}_0]^s = -[\rho v_s^k v_s^k]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda - 4[\phi^s\phi^s_{,kk}]_\Lambda}{8\pi G a^2}\,,$$

$$[\tau^i{}_j]^s = [\rho v_i^s v_j^s]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda\delta^i_j - 2[\phi^s_{,i}\phi^s_{,j}]_\Lambda}{8\pi G a^2}\,.$$

  - This is the stress-tensor that sources long-distance gravity:
    - it is different than the original stress-tensor

Even more intuitively

$$\begin{aligned} \dot{\rho}_m + \boldsymbol{\nabla} \cdot (\rho_m \boldsymbol{v}) &= 0 \,, \\ \dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} &= -\boldsymbol{\nabla} \Phi \,, \\ \nabla^2 \Phi &= 4\pi G \, \rho_m \,. \end{aligned}$$

- Smooth equations

$$\int d^3\boldsymbol{x}' \; W_\Lambda(|\boldsymbol{x} - \boldsymbol{x}'|) \cdot \{ \; \rho_m \left[\dot{v}^i + v^j \nabla_j v^i \right] + \rho \nabla_i \Phi \; \} = 0$$

- Define: $X_\ell \equiv [X]_\Lambda(\boldsymbol{x}) = \int d^3\boldsymbol{x}' \, W_\Lambda(|\boldsymbol{x} - \boldsymbol{x}'|) X(\boldsymbol{x}')$, where $X \equiv \{\rho_m, \Phi, \rho_m \boldsymbol{v}\}$
- After some algebra:

$$\rho_\ell \left[\dot{v}^i_\ell + v^j_\ell \nabla_j v^i_\ell \right] + \rho_\ell \nabla_i \Phi_\ell = -\nabla_j \left[\tau^j{}_i \right]^s ,$$

- with

$$\left[\tau_{ij} \right]^s \equiv \left[\rho_m v^s_i v^s_j \right]_\Lambda + \frac{1}{8\pi G} \left[2 \partial_i \Phi_s \partial_j \Phi_s - \delta_{ij} (\nabla \Phi_s)^2 \right]_\Lambda$$

- Again we learn: the short-distance physics acts as a modified stress tensor for the long-distance fluid.

Integrating out Small-Scales

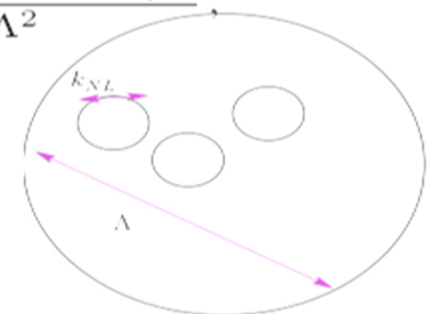
- Smoothing: • *short-wavelength non-linearities*

$$[\tau^0{}_0]^s = -[\rho v^k_s v^k_s]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda - 4[\phi^s\phi^s_{,kk}]_\Lambda}{8\pi G a^2}\,,$$

$$[\tau^i{}_j]^s = [\rho v^s_i v^s_j]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda\delta^i_j - 2[\phi^s_{,i}\phi^s_{,j}]_\Lambda}{8\pi G a^2}\,.$$

  • *higher-derivative terms*

$$[\tau^0{}_0]^{\partial^2} = -\rho_\ell\frac{\nabla v^k_\ell\cdot\nabla v^k_\ell}{\Lambda^2} - \frac{\nabla\phi^\ell_{,k}\cdot\nabla\phi^\ell_{,k} - 4\nabla\phi^\ell\cdot\nabla\phi^\ell_{,kk}}{8\pi G a^2\cdot\Lambda^2}\,,$$



- Integrate out short modes: i.e. solve equations of motion
- This is true realization by realization
- Good approximation:
  - In considering the effect on large scales $\Lambda \ll k_{NL}$, take first two moments: $\langle[\tau^{\mu\nu}_s]_\Lambda\rangle_{\phi_\ell}$
    - $\langle[\tau_{\mu\nu}]_\Lambda\rangle(x)$ space-dependence coming from presence of background long-mode
    - $\mathrm{Var}([\tau_{\mu\nu}]_\Lambda) \equiv \langle[\tau_{\mu\nu}]^2_\Lambda\rangle - \langle[\tau_{\mu\nu}]_\Lambda\rangle^2$: random statistical fluctuations (check later)

Effects on Background

- Take expectation value without long mode: $\langle [\tau_s^{\mu\nu}]_\Lambda \rangle$ versus $\langle [\tau_s^{\mu\nu}]_\Lambda \rangle_{\phi_\ell}$
- Effective stress tensor from short-scale

$$[\tau^0{}_0]^s = -[\rho v_s^k v_s^k]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda - 4[\phi^s \phi^s_{,kk}]_\Lambda}{8\pi G a^2}$$

$$[\tau^i{}_j]^s = [\rho v_i^s v_j^s]_\Lambda - \frac{[\phi^s_{,k}\phi^s_{,k}]_\Lambda \delta^i_j - 2[\phi^s_{,i}\phi^s_{,j}]_\Lambda}{8\pi G a^2}$$

- Let us take the expectation value

$$\kappa_{ij} \sim \langle (1+\delta) v_s^2 \rangle \delta_{ij}$$
$$\omega_{ij} \sim \langle \delta_s \phi_s \rangle \delta_{ij}$$

- Effective density and pressure:

$$\bar\rho_{\rm eff} = \bar\rho_m (1 + \kappa + \omega)$$

$$\bar w_{\rm eff} \equiv \frac{\bar p_{\rm eff}}{\bar\rho_{\rm eff}} = \frac{1}{3}(2\kappa + \omega)$$

- Virialized objects decouple! (each term is large)
- This means that there no large backreaction. The acceleration is due to the cc.
  - Small difference in equation of state $w_{\rm eff} = \frac{\bar p_{\rm eff}}{\bar\rho_{\rm eff}} \sim \langle \delta\Phi \rangle \sim +\mathcal{O}(\Phi \sim 10^{-5})$

Effective Theory for Fluctuations: the Very-Imperfect Fluid

- In fact, plugging back in fluid equation $$\dot{\theta}_\ell + \mathcal{H}\theta_\ell + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_\ell = -\frac{1}{\rho_\ell}\nabla_i \nabla_j \langle \tau_{ij} \rangle$$
- Isotropic part $$\frac{k_i k_j}{k^2}\frac{\langle \tau_{ij} \rangle}{\bar{\rho}} = c_s^2\, \delta_\ell - c_{\rm vis}^2 \frac{\theta_\ell}{\mathcal{H}}$$ $$\theta_\ell \equiv \nabla \cdot \boldsymbol{v}_\ell .$$
- Shear and Bulk viscosity $$c_{\rm vis}^2 \equiv \left(\frac{2}{3}\eta + \zeta\right)\frac{\mathcal{H}}{\bar{\rho}} .$$
- Notice that $c_s^2 \sim c_{\rm vis}^2 \sim \langle v_s^2 \rangle$
- Outside of the horizon, viscous terms negligible
- Inside of the horizon: $\theta_\ell/\mathcal{H} \sim \dot{\delta}_\ell/\mathcal{H} \sim \delta_\ell .$ comparable!
  - It had to be so: no oscillations
  - But still a fluid (there is an hierarchy), an incredibly viscous one though.
    - Why did we truncate the Boltzmann hierarchy?
    - In a standard fluid, higher moments are suppressed by $k v_{\rm p} \tau_c$, fluid valid for $k v_{\rm p} \tau_c \ll 1$
    - Here scaling is $k v_{\rm p} \mathcal{H}^{-1} \lesssim \frac{k}{k_{\rm NL}}$:
      - there is a finite time for the particles to travel, and since they are non-relativistic, we have a derivative expansion inside the horizon!
- We generate vorticity (contrary to standard perturbation theory)

The Effective Theory: generalization

- Since $\dot{\theta}_\ell + \mathcal{H}\theta_\ell + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_\ell = -\frac{1}{\rho_\ell}\nabla_i \nabla_j \langle \tau_{ij} \rangle$
- In general, define

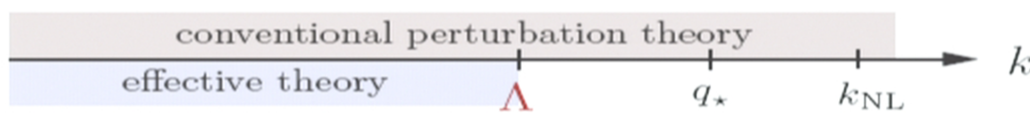
$$\langle \tau_{ij} \rangle = \rho \left[c_1 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)_{ij} + c_2 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)^2_{ij} + \cdots \right] \phi_\ell + $$
$$+ \rho \left[\left(d_1^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right) + d_2^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right)^2 + \cdots \right) \left\{ v_\ell^2 , \delta_\ell \phi_\ell , \cdots \right\} \right]_{ij}$$

- Match the coefficients with simulations:

$$- \mathcal{A} \equiv \frac{k_i k_j}{k^2} \frac{\langle \tau_{ij} \rangle}{\bar{\rho}} = c_s^2 \delta_\ell - c_{\rm vis}^2 \Theta_\ell .$$
$$A_\delta \equiv \langle \delta_\ell \mathcal{A} \rangle = c_s^2 P_{\delta\delta} - c_{\rm vis}^2 P_{\delta\theta}$$
$$A_\theta \equiv \langle \Theta_\ell \mathcal{A} \rangle = c_s^2 P_{\delta\theta} - c_{\rm vis}^2 P_{\theta\theta}$$
$$\Longrightarrow$$
$$c_s^2 = \frac{P_{\theta\theta} A_\delta - P_{\delta\theta} A_\theta}{P_{\delta\delta} P_{\theta\theta} - P_{\delta\theta}^2} ,$$
$$c_{\rm vis}^2 = \frac{P_{\delta\theta} A_\delta - P_{\delta\delta} A_\theta}{P_{\delta\delta} P_{\theta\theta} - P_{\delta\theta}^2} .$$

- Add statistical fluctuations $p_{\rm eff} = \bar{p}_{\rm eff} + \delta p_{\rm eff}^\ell + \delta p_{\rm eff}^{\rm stat}$ $\quad {\rm Var}([\tau_{\mu\nu}]_\Lambda) \equiv \langle [\tau_{\mu\nu}]_\Lambda^2 \rangle - \langle [\tau_{\mu\nu}]_\Lambda \rangle^2$
  - . $\delta p_{\rm eff}^{\rm stat} = \alpha \, \bar{p}_{\rm eff}$ where the power is estimated as $\Delta_\alpha^2 \equiv \frac{\Lambda^3}{q_\star^3}$ (check) and
- This effective theory converges! $\delta_\ell, v_\ell, \Phi_\ell \ll 1$

$q_\star \sim$ matter − radiation equality



The Effective Theory: generalization

- Since $\dot{\theta}_\ell + \mathcal{H}\theta_\ell + \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_\ell = -\frac{1}{\rho_\ell}\nabla_i \nabla_j \langle \tau_{ij} \rangle$
- In general, define

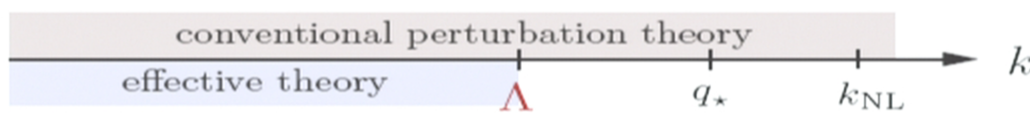
$$\langle \tau_{ij} \rangle = \rho \left[c_1 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)_{ij} + c_2 \left(\frac{\langle v_s^2 \rangle \partial^2}{\mathcal{H}^2} \right)^2_{ij} + \cdots \right] \phi_\ell + $$
$$+ \rho \left[\left(d_1^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right) + d_2^{(n)} \left(\frac{\partial^2}{\Lambda^2} \right)^2 + \cdots \right) \left\{ v_\ell^2 , \delta_\ell \phi_\ell , \cdots \right\} \right]_{ij}$$

- Match the coefficients with simulations:

$$- \mathcal{A} \equiv \frac{k_i k_j}{k^2} \frac{\langle \tau_{ij} \rangle}{\bar{\rho}} = c_s^2 \delta_\ell - c_{\rm vis}^2 \Theta_\ell .$$
$$A_\delta \equiv \langle \delta_\ell \mathcal{A} \rangle = c_s^2 P_{\delta\delta} - c_{\rm vis}^2 P_{\delta\theta}$$
$$A_\theta \equiv \langle \Theta_\ell \mathcal{A} \rangle = c_s^2 P_{\delta\theta} - c_{\rm vis}^2 P_{\theta\theta}$$
$$\Longrightarrow$$
$$c_s^2 = \frac{P_{\theta\theta}\, A_\delta - P_{\delta\theta}\, A_\theta}{P_{\delta\delta} P_{\theta\theta} - P_{\delta\theta}^2} ,$$
$$c_{\rm vis}^2 = \frac{P_{\delta\theta}\, A_\delta - P_{\delta\delta}\, A_\theta}{P_{\delta\delta} P_{\theta\theta} - P_{\delta\theta}^2} .$$

- Add statistical fluctuations $p_{\rm eff} = \bar{p}_{\rm eff} + \delta p_{\rm eff}^\ell + \delta p_{\rm eff}^{\rm stat}$ $\quad \mathrm{Var}([\tau_{\mu\nu}]_\Lambda) \equiv \langle [\tau_{\mu\nu}]_\Lambda^2 \rangle - \langle [\tau_{\mu\nu}]_\Lambda \rangle^2$
  - . $\delta p_{\rm eff}^{\rm stat} = \alpha\, \bar{p}_{\rm eff}$ where the power is estimated as $\Delta_\alpha^2 \equiv \frac{\Lambda^3}{q_\star^3}$ (check) and
- This effective theory converges! $\delta_\ell, v_\ell, \Phi_\ell \ll 1$

$q_\star \sim$ matter $-$ radiation equality

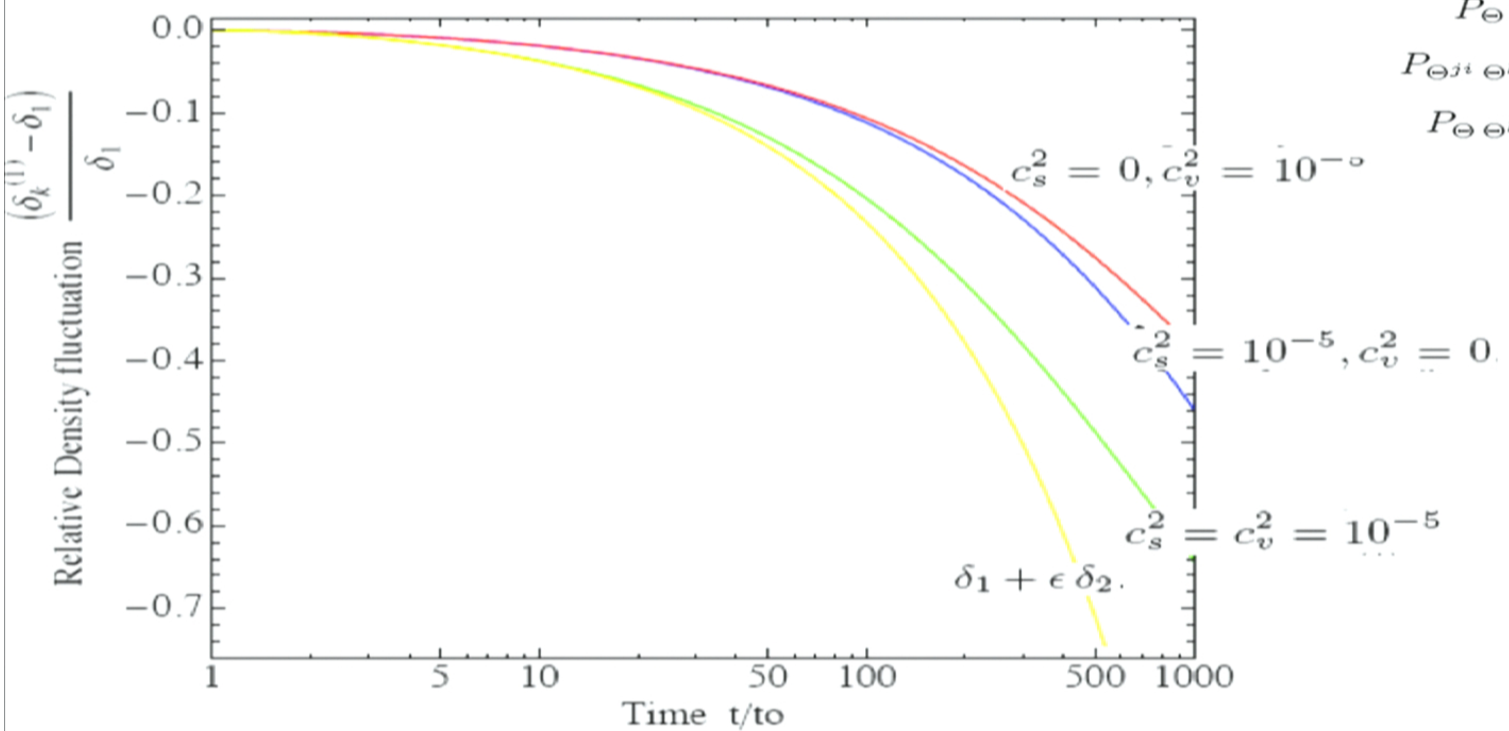


Apply it to the data

with Carrasco, Hertzberg, Wechsler, **in progress**

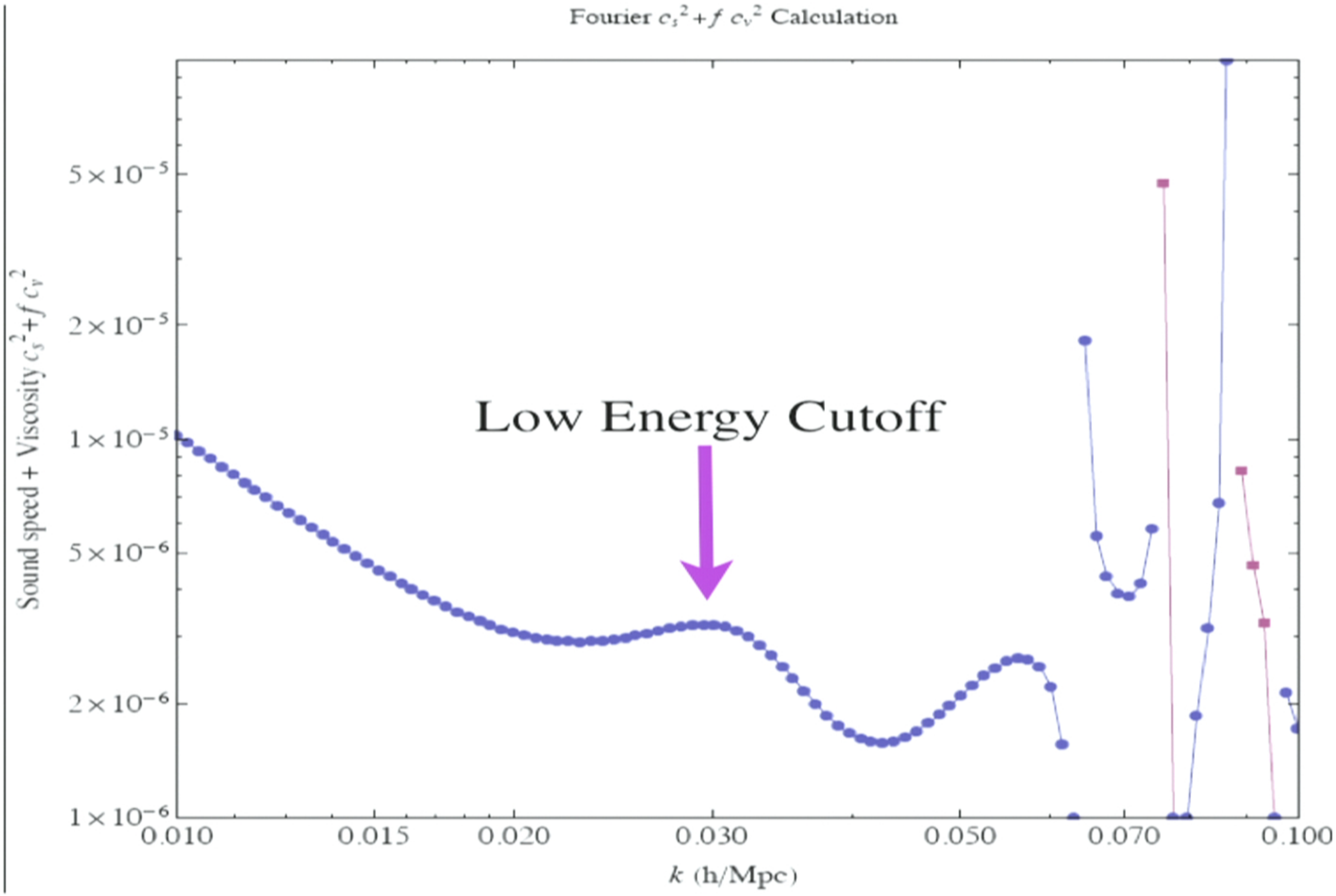
- UV fluid is Boltzmann equation
- Match using numerical N-body simulations
- Apply perturbation Theory

$$P_{A\,\delta}(x) \equiv \langle A_l(\mathbf{x}+\mathbf{x}')\,\delta_l(\mathbf{x}')\rangle$$
$$P_{A\,\Theta}(x) \equiv \langle A_l(\mathbf{x}+\mathbf{x}')\,\Theta_l(\mathbf{x}')\rangle$$
$$P_{A^{ki}\,\Theta^{ki}}(x) \equiv \langle A_l^{ki}(\mathbf{x}+\mathbf{x}')\,\Theta_l^{ki}(\mathbf{x}')\rangle$$
$$P_{A\,\Theta^{ki}}(x) \equiv \langle A_l(\mathbf{x}+\mathbf{x}')\,\Theta_l^{ki}(\mathbf{x}')\rangle$$
$$P_{B\,\Theta}(x) \equiv \langle B_l(\mathbf{x}+\mathbf{x}')\,\Theta_l(\mathbf{x}')\rangle$$
$$P_{\delta\,\delta}(x) \equiv \langle \delta_l(\mathbf{x}+\mathbf{x}')\,\delta_l(\mathbf{x}')\rangle$$
$$P_{\delta\,\Theta}(x) \equiv \langle \delta_l(\mathbf{x}+\mathbf{x}')\,\Theta_l(\mathbf{x}')\rangle$$
$$P_{\Theta\,\Theta}(x) \equiv \langle \Theta_l(\mathbf{x}+\mathbf{x}')\,\Theta_l(\mathbf{x}')\rangle$$
$$P_{\Theta^{ji}\,\Theta^{ki}}(x) \equiv \left\langle \Theta_l^{ji}(\mathbf{x}+\mathbf{x}')\,\Theta_l^{ki}(\mathbf{x}')\right\rangle$$
$$P_{\Theta\,\Theta^{ki}}(x) \equiv \left\langle \Theta_l(\mathbf{x}+\mathbf{x}')\,\Theta_l^{ki}(\mathbf{x}')\right\rangle$$



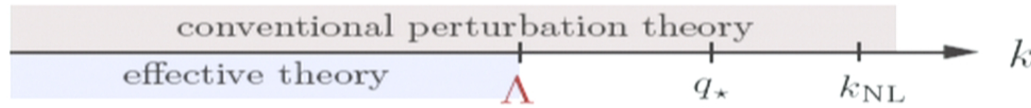
Work in Progress

- Matching to
- N-body simulations



Applications & Summary

- An alternative to perturbation theory
  - an effective fluid with
    - pressure, anisotropic stress, and random fluctuations
  - coeff. to be measured from simulation



- Beginning to be applied Baryon Acoustic Oscillations $P_{\rm obs}(k) = e^{-\frac{1}{2}k^2\Sigma^2} P_{\rm L}(k) + P_{\rm mc}(k)$

- Background cosmology:
  - There is NO large backreaction
  - There is NO real evolution of ζ out of the horizon
    - No $\lim_{k \ll \mathcal{H}} \dot{\zeta}_\ell \approx \frac{\mathcal{H}}{\bar{\rho}} \bar{p}_{\rm eff}$ once you renormalize the backgr
      - It would have been a disaster for inflation