Title: Beyond the CMB: The Effective Field Theory of Large Scale Structure

Date: Nov 17, 2015 11:00 AM

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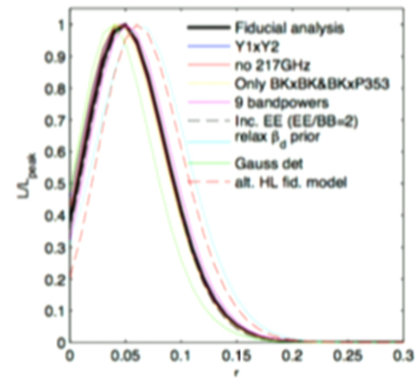
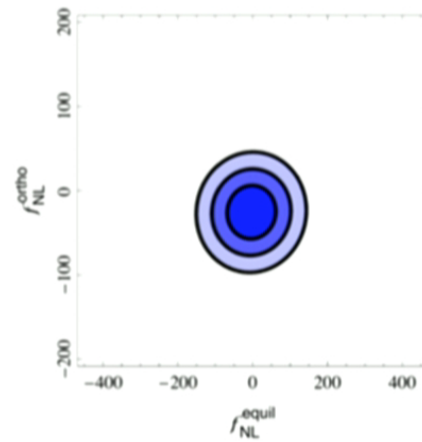
Abstract: <p>The next hope to constrain cosmological parameters observationally is in surveys of the large scale structure (LSS) of the universe. LSS has the potential to rival the CMB in cosmological constraints because the number of modes scales like the volume, but the nonlinear clustering due to gravity makes it more difficult to extract primordial parameters. In order to take full advantage of the constraining power of LSS, we must understand it in the quasi-nonlinear regime. The effective field theory (EFT) of LSS provides a consistent way to perturbatively predict the clustering of matter at large distances. In this talk, I will discuss the status of the EFT of LSS and present recent work describing the inclusion of baryons in the EFT approach, including comparisons to N-body simulations.</p>

testing inflation

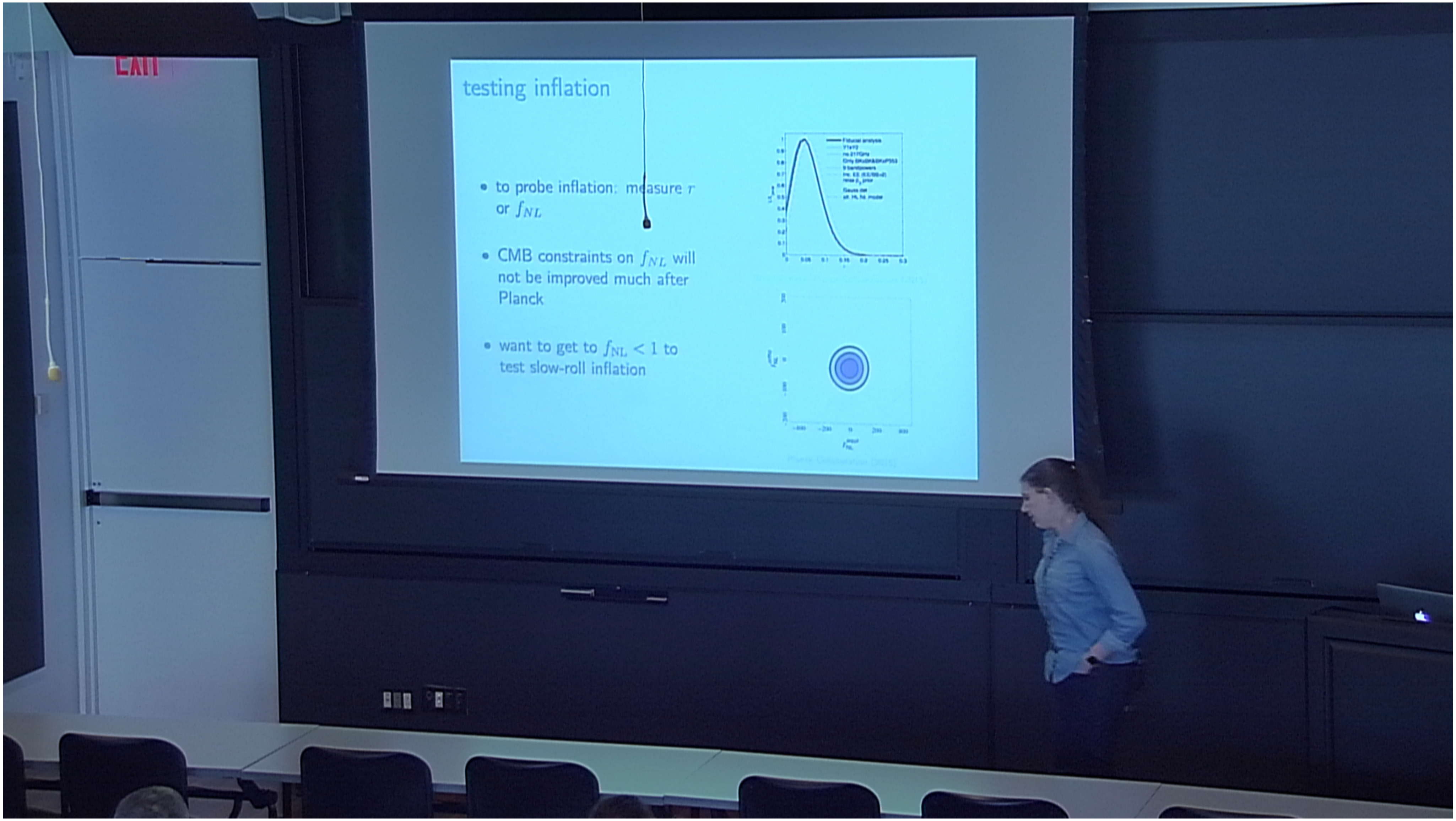
- to probe inflation: measure r or f_{NL}
- CMB constraints on f_{NL} will not be improved much after Planck
- want to get to $f_{\rm NL} < 1$ to test slow-roll inflation



BICEP2/Keck, Planck Collaborations (2015)



Planck Collaboration (2015)


testing inflation
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what can B modes tell us?

- B modes sensitive to tensor fluctuations during inflation
- "smoking gun" for inflation: can we make this more precise?
- inflation is the only single-field model that can produce scale-invariant scalar modes
- similar no-go theorem for tensors?

Baumann, Senatore, Zaldariagga (2011)

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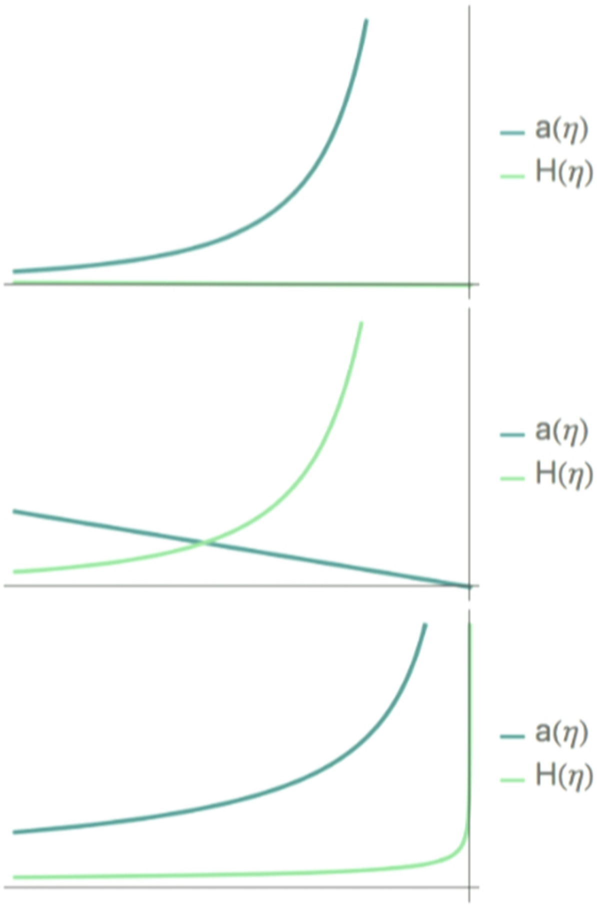
scaling solutions to the horizon problem

- "not-so-big bang": $\alpha > 1$
- contraction: $0 < \alpha < 1$
- "starting the universe": $\alpha < 0$
  Creminelli, Luty, Nicolis, Senatore



tensors in EFT of inflation

- epoch that pushes modes outside horizon ends to give normal expansion $\Rightarrow$ time diffs spontaneously broken
- EFT of inflation: most generic action consistent with symmetry
- keeping only terms fixed by background gives $\langle\gamma^2\rangle \sim H(t)^2/M_{\rm Pl}^2$
- with speed of sound, $\langle\gamma^2\rangle \sim H^2/c_\gamma M_{\rm Pl}^2 \Rightarrow$ can restore scale invariance

$$S = \int d^4x\sqrt{-g}\,\frac{1}{2}M_{\rm Pl}^2\left[R^{(4)} - 2(3H^2+\dot{H}) + 2\dot{H}\delta g^{00} - \left(1-\frac{1}{c_\gamma(t)^2}\right)\left(\delta K^\mu{}_\nu \delta K^\nu{}_\mu - \delta K^2\right)\right]$$

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rapidly varying speed of sound

- result independent of α: all scalings of $a = (t/t_0)^\alpha$ allowed?
- c_γ term added in action also contributes higher order terms
- c_γ is very rapidly changing: if e^N modes go outside horizon, c_γ varies by:

$$\frac{c_{\gamma,f}}{c_{\gamma,in}} \sim \left(\frac{t_f}{t_{in}}\right)^{-2} \sim \left(\frac{a_f H_f}{a_{in} H_{in}}\right)^{2/(\alpha-1)} \sim e^{\frac{2N}{\alpha-1}}$$

- if c_γ always subluminal, then $c_\gamma \ll 1$ at some point

constraints from weak coupling

- cubic action is large when $c_\gamma \to 0$

$$\frac{L_{\gamma\gamma\zeta}}{L_{\zeta\zeta}} \sim \frac{M_{\rm Pl}^2 a^3 \zeta \dot\gamma_{ij}\dot\gamma^{ij} c_\gamma^{-2}}{M_{\rm Pl}^2 a^3 \dot\zeta^2} \sim \frac{1}{c_\gamma^{5/2}\sqrt{\alpha}} \langle \gamma^2 \rangle^{1/2}$$

- constrained by weak coupling

$$\frac{L_{\gamma\gamma\zeta}}{L_{\zeta\zeta}} \ll 1 \quad \Rightarrow \quad c_\gamma \gg 10^{-2}\left(\frac{r}{\alpha}\right)^{1/5}$$

constraints on tensor modes

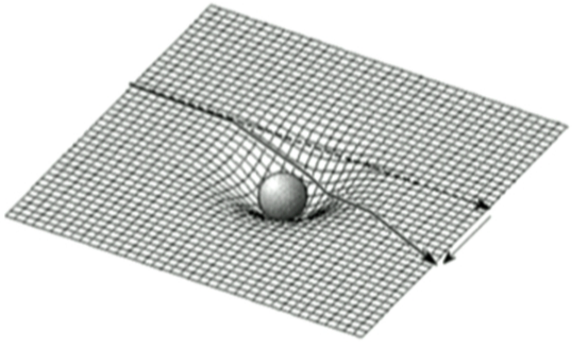
- get bound in terms of r and α

$$\frac{N}{|1-\alpha|} \ll 2 - \frac{1}{10} \log \frac{r}{\alpha}$$

- satisfied when $\alpha \to \infty$
- to have a large $\alpha \ll 1$, need non-perturbatively small r
- example: for $r > 10^{-6}$ and $N = 10$, need $\alpha \gtrsim 4$ ($\epsilon_{\rm sl} \lesssim 0.25$)
- these are inflation-like backgrounds

advantages of EFT

- approximation of high energy (UV) theory at low energies (IR) + perturbative corrections
- UV theory is known: integrate out to get simpler IR theory
- UV theory unknown: parameterize ignorance of UV effects in EFT parameters



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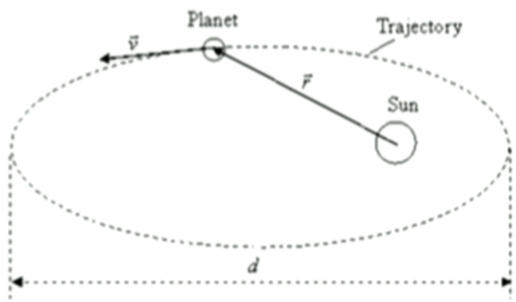
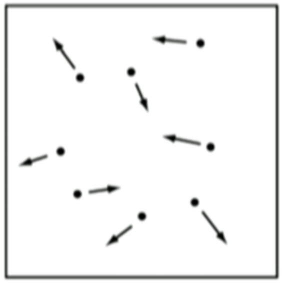


UV Construction for DM

- phase space density $f(\vec{x},\vec{p})d^3xd^3p$: probability that there is a particle in volume d^3xd^3p



- for particles, given by

$$f_n(\vec{x},\vec{p}) = \sum_n \delta^3(\vec{x}-\vec{x}_n)\delta^3(\vec{p}-ma\vec{v}_n)$$

- each particle obeys collisionless Bolzmann equation:

$$\frac{\partial f_n}{\partial t} + \frac{\vec{p}}{ma^2}\cdot\frac{\partial f_n}{\partial \vec{x}} - m\sum_{\tilde{n}\neq n}\frac{\partial \phi_{\tilde{n}}}{\partial \vec{x}}\cdot\frac{f_n}{\partial \vec{p}} = 0$$

integrate out UV modes

- apply window function that cuts off $k > \Lambda$ and expand $f(\vec{x}, \vec{p})$ in moments of $\vec{p} \Rightarrow$ fluid equations for δ and v^i

- equations for higher moments suppressed by mean free path

- DM moves slowly compared to $H \Rightarrow$ effective mean free path $v/H \sim 1/k_{NL}$, so fluid description valid

smoothed overdensity

smoothed fluid velocity

$$\dot{\delta} + \frac{1}{a}\partial_i((1+\delta)\, v^i\,) = 0$$

$$\dot{v}^i + Hv^i + \frac{1}{a}v^j\partial_j v^i + \frac{1}{a}\,\partial_i\phi \;= -\frac{1}{a\bar{\rho}}\,\partial_j[\tau^{ij}]_\Lambda$$

$\partial_i\partial^i\phi \sim \Omega_m\delta$

effective stress tensor

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effective stress tensor

induced stress tensor

- smoothed effective stress tensor $[\tau^{ij}]_\Lambda$ is a function of long modes
- expansion in perturbations and k/k_{NL} (constrained by symmetry)

bulk viscosity

shear viscosity

speed of sound

stochastic stress

$$\tau^{ij} = \bar{p}\delta^{ij} + \bar{\rho}\left(c_1\delta + \frac{c_2}{aH}\,\partial_k v^k \right)\delta^{ij} + \bar{\rho}\,\frac{c_3}{aH}\,\partial^{(i}v^{j)} + \Delta\tau^{ij} + \dots$$

- parameters encode expectation values of short modes in the presence of long modes

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bulk viscosity

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loops + counterterms

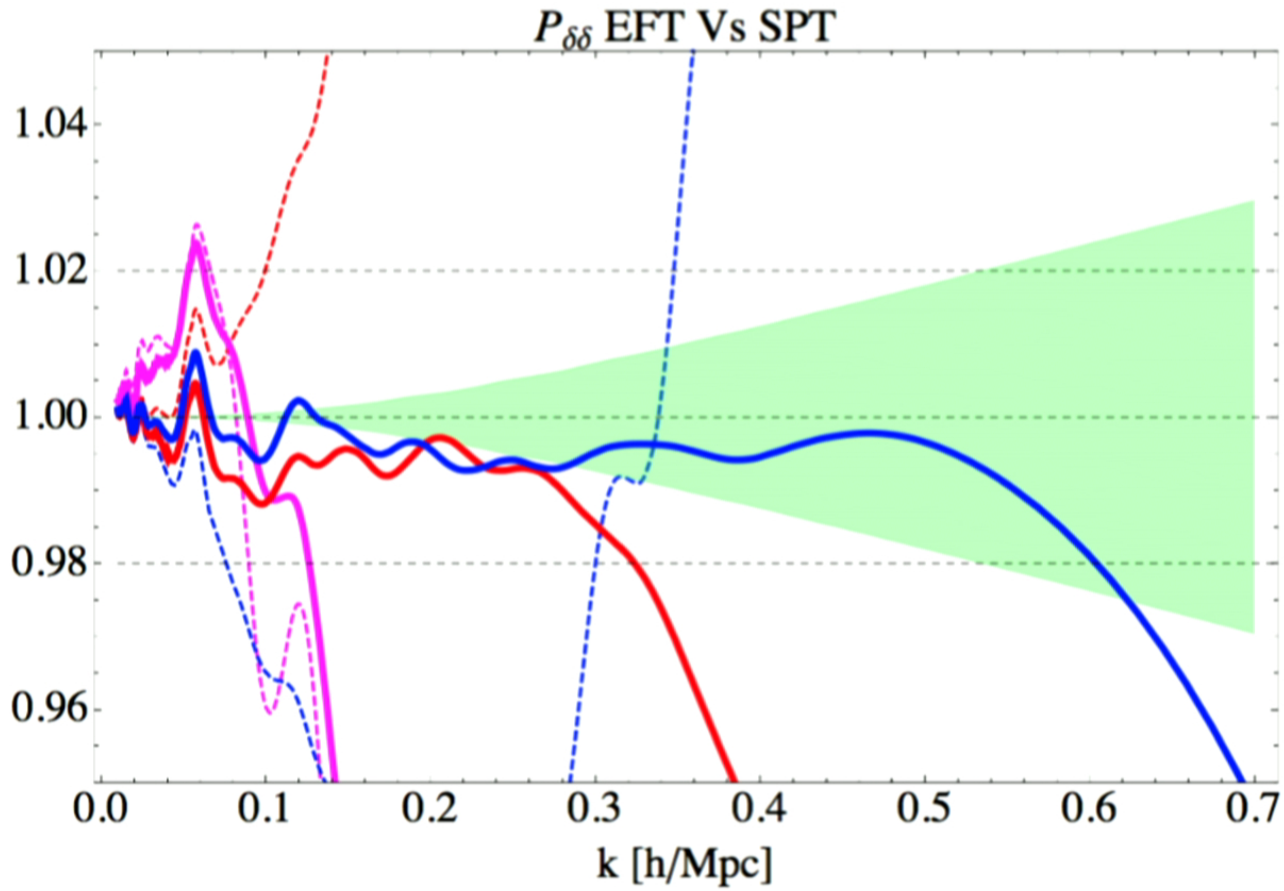
- $\langle\delta\delta\rangle = \langle\delta^{(1)}\delta^{(1)}\rangle + \langle\delta^{(2)}\delta^{(2)}\rangle + \langle\delta^{(1)}\delta^{(3)}\rangle + 2\langle\delta^{(1)}\delta^{(\mathrm{ct})}\rangle$

- from equations of motion: counterterm proportional to linear field, $\delta^{(\mathrm{ct})} \sim \left(\frac{k}{k_{NL}}\right)^2 \delta^{(1)}$

- Smoothed fields δ and v^i depend on smoothing scale Λ

- Λ-dependence in loops canceled by Λ-dependence of counter-term c_s

dark matter results at two loops



Carrasco, Foreman, Green, Senatore (2013)

the problem with baryons: astrophysical processes

- various baryon processes modify the matter power spectrum by $> 1\%$ on relevant scales

- baryon effects include: star formation, SN feedback, AGN feedback

van Daalen, Schaye, Booth, and Dalla Vecchia (2011)

a simple modification of EFT

- generalize to 2 particle species interacting only via gravity with relative densities $w_b = \Omega_{\rm baryon}/\Omega_{\rm m}$, $w_c = \Omega_{CDM}/\Omega_{\rm m}$

$$\dot\delta_{\mathbf{c}} = -\frac{1}{a}\partial_i((1+\delta_{\mathbf{c}}){v_{\mathbf{c}}}^i)$$

$$\dot\delta_{\mathbf{b}} = -\frac{1}{a}\partial_i((1+\delta_{\mathbf{b}}){v_{\mathbf{b}}}^i)$$

$$\partial_i\dot v^i_{\mathbf{b}} + H\partial_i v^i_{\mathbf{b}} + \frac{1}{a}\partial_i(v^j_{\mathbf{b}}\partial_j v^i_{\mathbf{b}}) + \frac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_{\mathbf{b}}{}^i + \frac{1}{a}\partial_i(\gamma)_{\mathbf{b}}{}^i$$

$$\partial_i\dot v^i_{\mathbf{c}} + H\partial_i v^i_{\mathbf{c}} + \frac{1}{a}\partial_i(v^j_{\mathbf{c}}\partial_j v^i_{\mathbf{c}}) + \tfrac{1}{a}\partial^2\phi = -\frac{1}{a}\partial_i\left(\partial\tau_\rho\right)_{\mathbf{c}}{}^i + \frac{1}{a}\partial_i(\gamma)_{\mathbf{c}}{}^i$$

$\partial^2\phi \sim \omega_b\delta_b + \omega_c\delta_c$

effective stress tensor

momentum exchange part, only affects stochastic term

counter-terms

- at one loop, four possible parameters:

response to velocity gradients and star-formation physics

gravitationally induced speed of sound

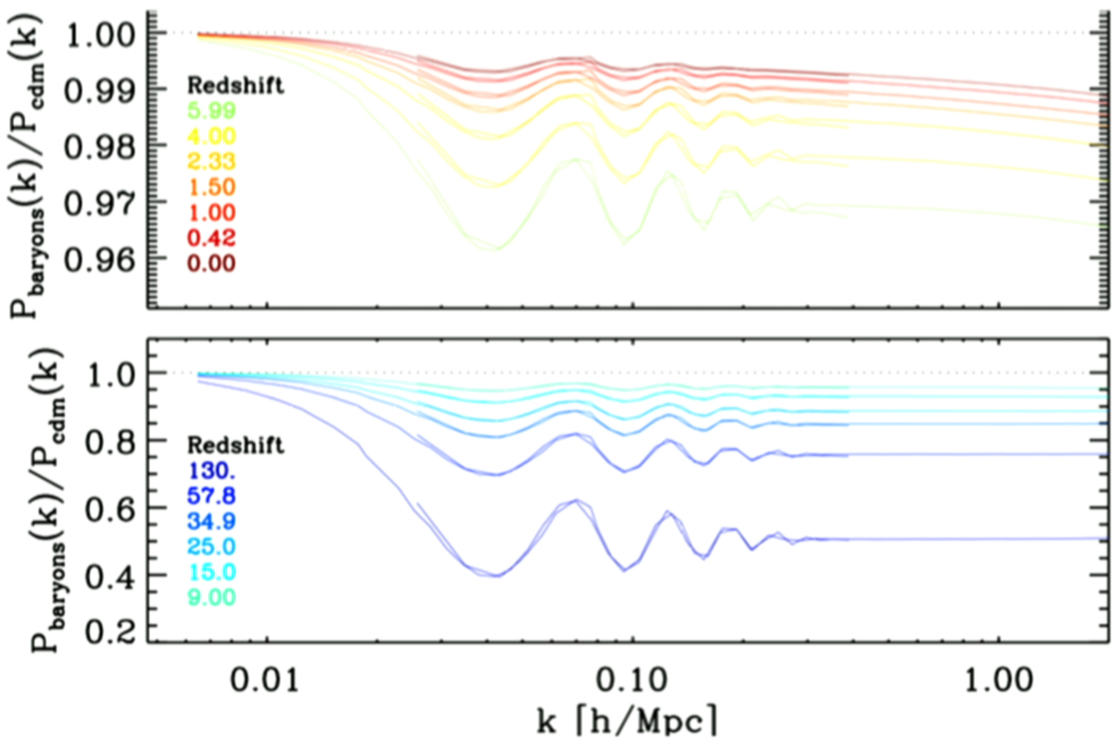
$$\partial_i \left(\partial\tau_\rho\right)^i_{\mathbf{b}} - \partial_i(\gamma)^i_{\mathbf{b}} \sim c^2_{\mathbf{b},g}\left(w_{\mathbf{c}}\partial^2\delta_{\mathbf{c}} + w_{\mathbf{b}}\partial^2\delta_{\mathbf{b}}\right) + c^2_{\mathbf{b},v}\,\partial^2\delta_{\mathbf{b}}$$

$$\partial_i \left(\partial\tau_\rho\right)^i_{\mathbf{c}} - \partial_i(\gamma)^i_{\mathbf{c}} \sim c^2_{\mathbf{c},g}\left(w_{\mathbf{c}}\partial^2\delta_{\mathbf{c}} + w_{\mathbf{b}}\partial^2\delta_{\mathbf{b}}\right) + c^2_{\mathbf{c},v}\,\partial^2\delta_{\mathbf{c}}$$

perturbation theory

- basis of adiabatic (total matter) $\delta_A = w_{\mathbf{c}}\delta_{\mathbf{c}} + w_{\mathbf{b}}\delta_{\mathbf{b}}$ and isocurvature modes: $\delta_I = \delta_{\mathbf{c}} - \delta_{\mathbf{b}}$
- from linear equations, $\delta_I^{(1)} \sim$ const and $\delta_A^{(1)}(k,a) \sim D(a)$, linear growth factor for total matter
- at $z = 0$, $\delta_I/\delta_A \sim 10^{-2} \rightarrow$ isocurvature mode suppressed, can neglect in loops
- because isocurvature loops neglected, counterterms needed for only adiabatic diagrams, so only two c_s parameters come in

isocurvature mode

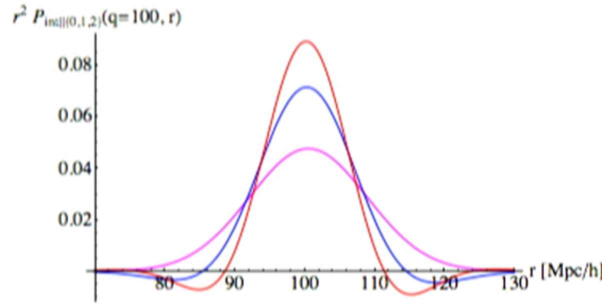


Angulo, Hahn, Abel (2013)

IR resummation: hybrid approach

- Lagrangian approach: probability to be displaced from $\vec{q}$ to $\vec{r}$:

$$P \sim \int d^3k \; e^{-i\vec{k}\cdot(\vec{q}-\vec{r})} e^{-(\vec{k}\cdot\Delta\vec{s}_1)^2}$$



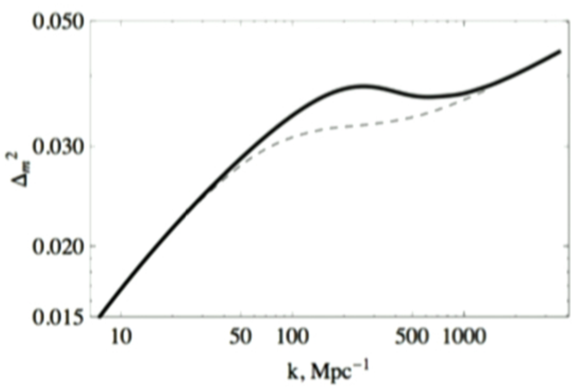
- resum leading effect of large displacements by convolving Eulerian correlator with this probability

$$\xi^{(N)}_{\rm resum}(\vec{r}, t_1, t_2) = \sum_{j=0}^{N} \int d^3q \; P_{N-j}(\vec{r}|\vec{q}, t_1, t_2)\,\xi^{(j)}_{\rm Euler}(\vec{q}, t_1, t_2)$$

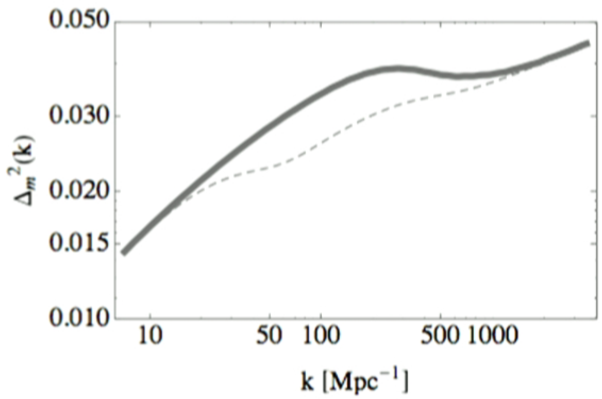
- remaining effect of large displacements is perturbative

effect of relative velocity on BAO peak

- modify IR resummation to include baryons: large effect in cross-correlation
- relative velocity effect large at $z \sim 40$ and leads to a breaking of perturbation theory
- EFT provides a consistent perturbative scheme, with higher order corrections



Tseliakhovich and Hirata (2010)



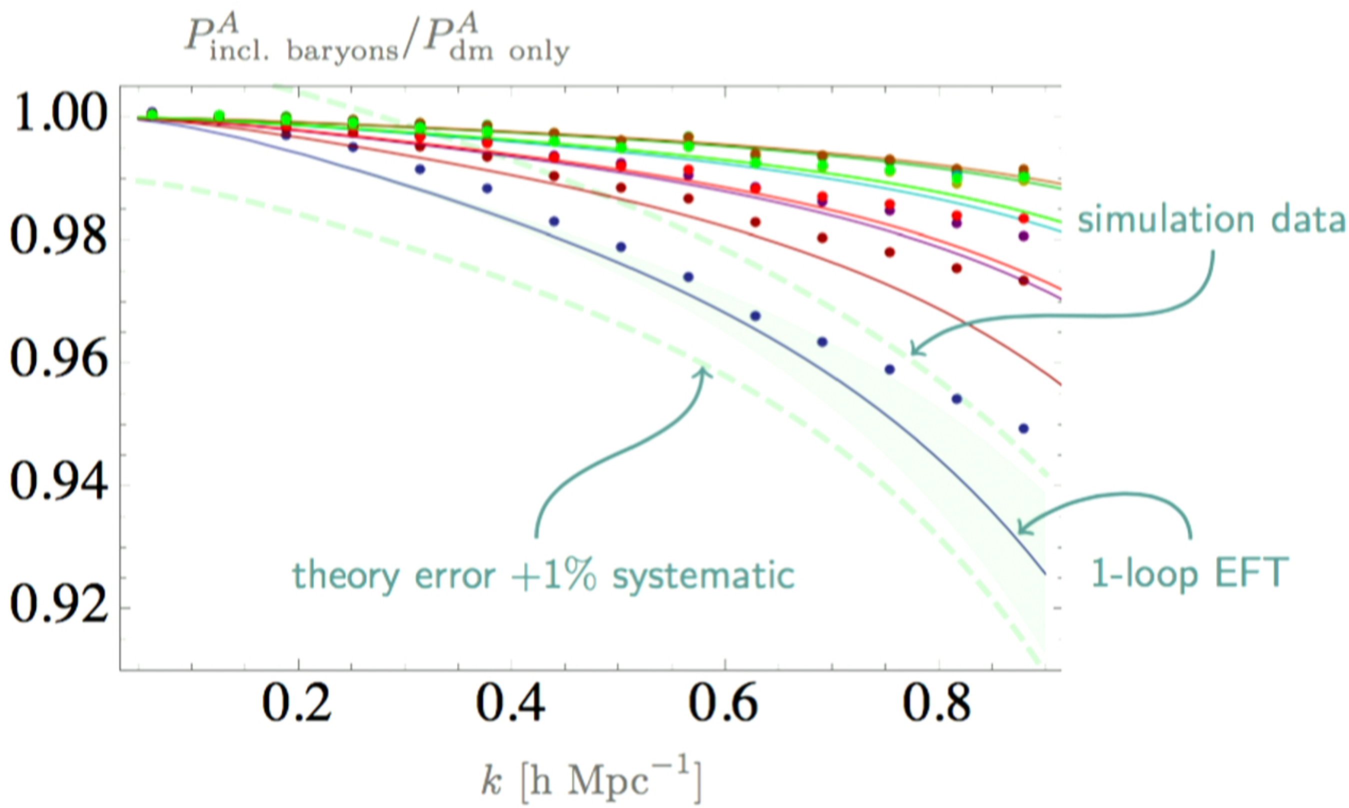
Lewandowski, AP, Senatore (2014)

comparison to simulations

$$P^{\mathbf{c}}(k) = P^{\mathbf{c}}{}_{11}(k) + P^A_{1-\text{loop}}(k) - 2(2\pi)\left(\bar{c}^2_A(a_0) + w_{\mathbf{b}}\bar{c}^2_I(a_0)\right) k^2 P^A_{11}(k)$$
$$P^{\mathbf{b}}(k) = P^{\mathbf{b}}{}_{11}(k) + P^A_{1-\text{loop}}(k) - 2(2\pi)\left(\bar{c}^2_A(a_0) - w_{\mathbf{c}}\bar{c}^2_I(a_0)\right) k^2 P^A_{11}(k)$$

- $\bar{c}^2_A = c^2_{\text{no baryon}} + w_b \Delta\bar{c}^2_A$
- $\Delta\bar{c}^2_A$: effect of baryons on total matter speed of sound, determine by matching to $P^A/P^A_{\text{dm only}}$
- $\bar{c}^2_I$: effect of having 2 species, determine by matching to P^b/P^A

EFT results at one loop: determining $\Delta \bar{c}_A^2$



$$\Delta \bar{c}_A^2 = -.3 \text{ to } -3\ k_{NL}^{-2},\ k_{NL} = 4.0\ \text{Mpc}^{-1}$$

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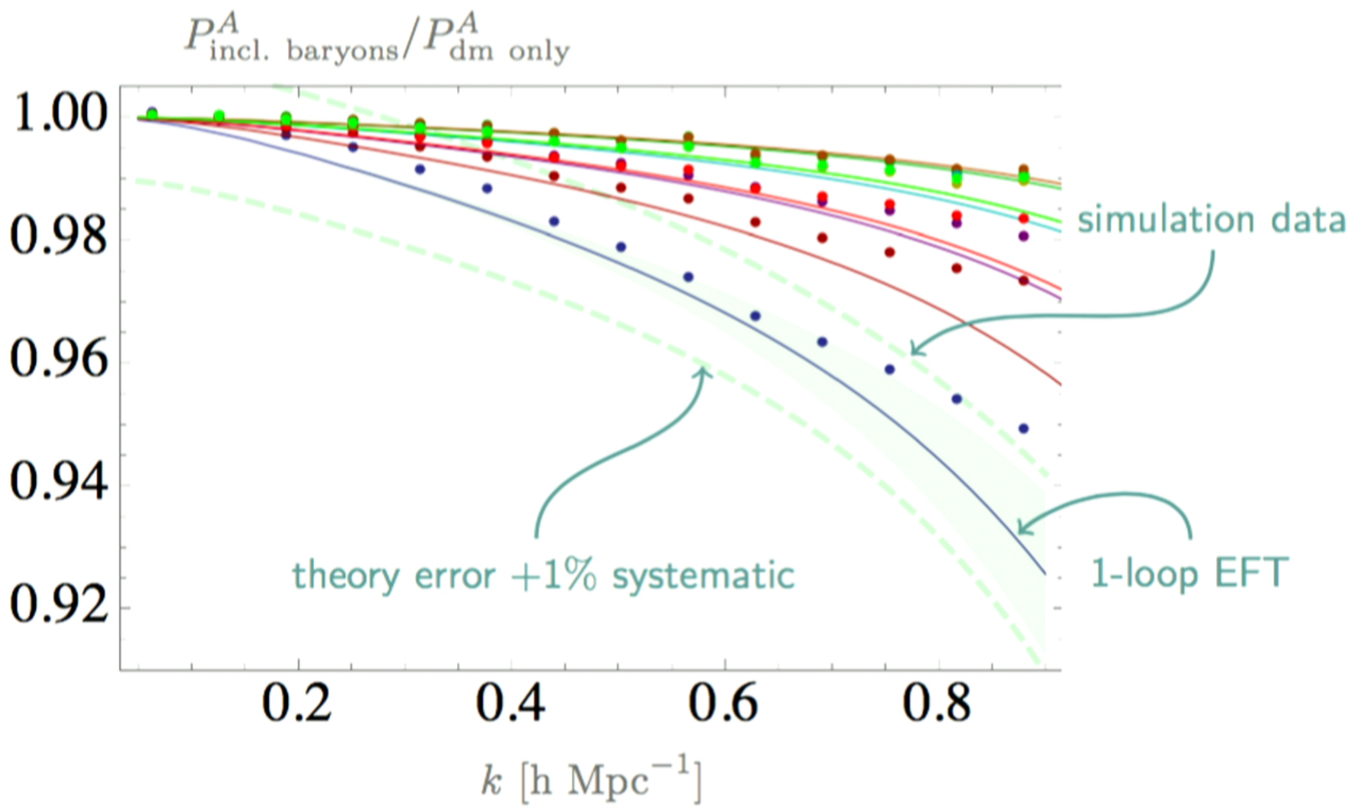

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