The Effective Field Theory of Large-Scale Structure in Cosmology

Matthew Lewandowski

IPhT

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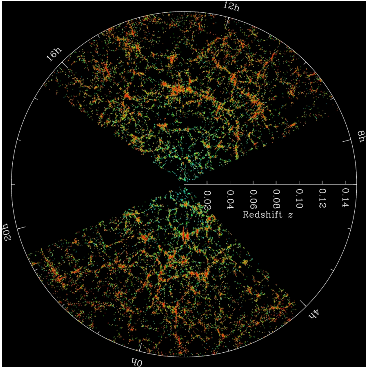
status

LSS measurements

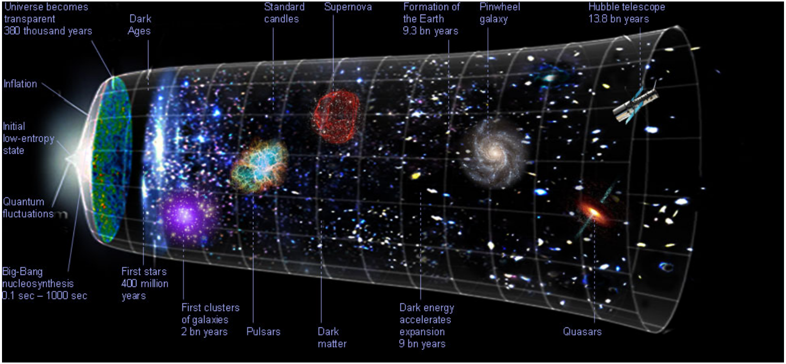


- locations of galaxies, create three dimensional map

[SDSS]

LSS measurements

- rewind this map using the knowledge that we have of the rest of univiverse



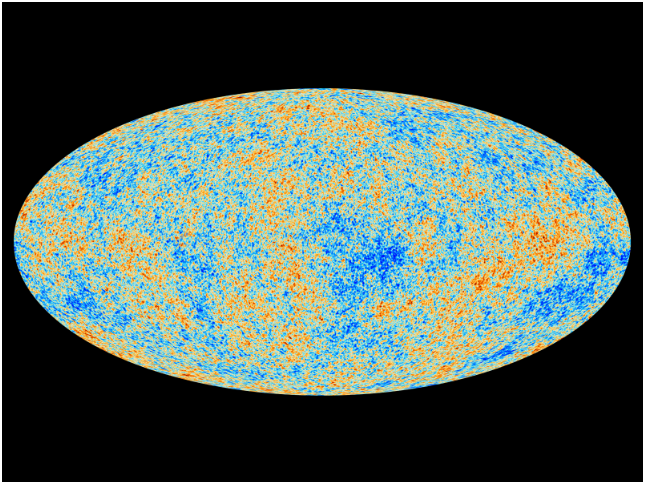
LSS measurements

- in order to do this accurately enough, need to understand lots of other things

LSS measurements

- in order to do this accurately enough, need to understand lots of other things
- dark matter evolution
- bias
- baryonic effects
- redshift-space distortions

cosmic microwave background [Planck 2015]



Planck: $-3 \lesssim f_{\mathrm{NL}} \lesssim 8$

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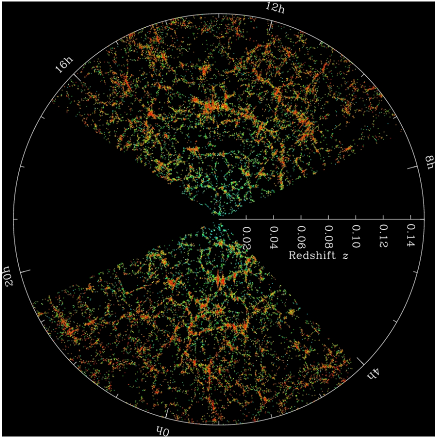
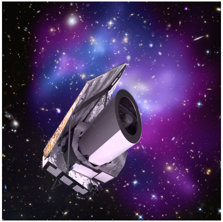
	$f_{\rm NL}^{loc} \lesssim 1$	$f_{\rm NL}^{loc} \gtrsim 1$
$f_{\rm NL}^{eq.,orthog.} \lesssim 1$	single field, slow roll	multi-field
$f_{\rm NL}^{eq.,orthog.} \gtrsim 1$	single field, not slow roll	multi-field

large-scale structure





- Euclid, LSST, ...
- number of modes $\sim \left(\frac{k_{max}}{k_{min}}\right)^3$
- k_{max} is limited by our understanding of the short distance physics
- EFToLSS increases k_{max}
- need percent level understanding of observables

LSS and cosmology

effective field theory of large-scale structure

status

standard perturbation theory

$$\delta \equiv \delta\rho/\rho, \qquad v^i, \qquad \theta \equiv \partial_i v^i$$

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$$\nabla^2 \phi = \frac{3}{2} H_0^2 \frac{a_0^3}{a} \delta$$

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

$$a\dot{\theta} + aH\theta + \partial_i(v^j \partial_j v^i) + \nabla^2 \phi = 0$$

Fourier space

$$a\mathcal{H}\delta' + \theta = -\int \frac{d^3\vec{q}}{(2\pi)^3}\,\alpha(\vec{q},\vec{k})\delta(\vec{k}-\vec{q})\theta(\vec{q})$$

$$a\mathcal{H}\theta' + \mathcal{H}\theta + \frac{3}{2}\frac{\mathcal{H}_0^2\Omega_m}{a}\delta = -\int \frac{d^3\vec{q}}{(2\pi)^3}\beta(\vec{q},\vec{k})\theta(\vec{k}-\vec{q})\theta(\vec{q})$$

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$$\delta = \delta^{(1)} + \delta^{(2)} + \delta^{(3)} + \dots$$

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$$\langle \delta^{(1)}(\vec{k},a_0)\delta^{(1)}(\vec{k}',a_0)\rangle = (2\pi)^3\delta(\vec{k}-\vec{k}')P_{11}(k)$$

loops

$$\langle\delta\delta\rangle = \langle\delta^{(1)}\delta^{(1)}\rangle + \langle\delta^{(2)}\delta^{(2)}\rangle + 2\langle\delta^{(1)}\delta^{(3)}\rangle + \cdots$$

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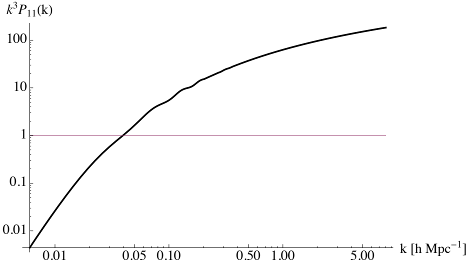
$$\delta^{(2)} \sim \int_0^\infty \frac{d^3\vec{q'}}{(2\pi)^3} G\,\delta^{(1)}\delta^{(1)}$$

$$\delta^{(3)} \sim \int_0^\infty \frac{d^3\vec{q'}}{(2\pi)^3} G\,\delta^{(1)}\delta^{(2)}$$

loops

$$P_{13}(k) = \frac{k^3 P_{11}(k)}{1008\pi^2} \int_0^\infty dr P_{11}(kr) \left(100r^2 + \frac{12}{r^2} + \frac{3}{r^3} \left(r^2 - 1\right)^3 \left(7r^2 + 2\right) \log \left| \frac{r+1}{1-r} \right| - 42r^4 - 158 \right)$$

LSS perturbation theory



- no clear expansion parameter, $k^3 P_{11}(k)$ becomes large at small scales
- loops contain integrals of $P_{11}(k)$ over *all* k, even UV
- clearly, need to deal with UV
- EFT allows us to systematically parametrize UV effects in $k/k_{\rm NL}$

fluid-like equations

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$$a\dot{\theta} + aH\theta + \partial_i(v^j\partial_j v^i) + \nabla^2\phi = 0$$

smoothed/long wavelength fields

$$\mathcal{O}_l(\vec{x},t) \equiv \int d^3x' W_\Lambda(x - x') \mathcal{O}(x',t)$$

$$\mathcal{O}(\vec{x},t) = \mathcal{O}_l(\vec{x},t) + \mathcal{O}_s(\vec{x},t)$$

fluid-like equations

$$\delta \equiv \delta\rho/\rho, \qquad v^i, \qquad \theta \equiv \partial_i v^i$$

$$\nabla^2 \phi_l = \frac{3}{2} H_0^2 \frac{a_0^3}{a} \delta_l$$

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

$$\pi_l^i = [(1+\delta) v^i]_l$$

$$v_l^i = \pi_l^i / (1 + \delta_l)$$

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$$v_l^i = \pi_l^i / (1 + \delta_l)$$

$$a\dot{\theta}_l + aH\theta_l + \partial_i (v_l^j \partial_j v_l^i) + \nabla^2 \phi_l \sim -\partial_i (v_s^j \partial_j v_l^i) - \partial_i (v_l^j \partial_j v_s^i) = -\partial_i \left(\partial_j \tau_s^{ij} / \rho \right)$$

stress tensor

$$\tau_s^{ij} \to \langle \tau_s^{ij} \rangle_{\delta_l}$$

stress tensor

$$\tau_s^{ij} \to \langle \tau_s^{ij} \rangle_{\delta_l} \approx \langle \tau_s^{ij} \rangle_0 + \left. \frac{\partial \langle \tau_s^{ij} \rangle_{\delta_l}}{\partial \delta_l} \right|_0 \delta_l + \cdots$$

stress tensor

$$\tau_s^{ij} \to \langle \tau_s^{ij} \rangle_{\delta_l} \approx \langle \tau_s^{ij} \rangle_0 + \frac{\partial \langle \tau_s^{ij} \rangle_{\delta_l}}{\partial \delta_l}\bigg|_0 \delta_l + \cdots$$

$$\approx \bar{p}\, \delta^{ij} + \bar{\rho} \left[c_s^2\, \delta^{ij} \delta_l - \frac{c_v^2}{aH} \delta^{(ij} \partial_k v_l^{k)} + \ldots \right] + \Delta\tau^{ij}$$

stress tensor

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$$\partial_i \left(\partial_j \tau_s^{ij} / \rho \right) \to c_s^2\, H^2 \left(\frac{k}{k_{\rm NL}} \right)^2 \delta_l$$

Fourier space

$$a\mathcal{H}\delta' + \theta = -\int \frac{d^3\vec{q}}{(2\pi)^3}\,\alpha(\vec{q},\vec{k})\delta(\vec{k}-\vec{q})\theta(\vec{q})$$

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$$\langle\delta\delta\rangle = \langle\delta^{(1)}\delta^{(1)}\rangle + \langle\delta^{(2)}\delta^{(2)}\rangle + 2\langle\delta^{(1)}\delta^{(3)}\rangle + 2\langle\delta^{(1)}\delta^{(c.t.)}\rangle + \cdots$$

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$$P(k) = P_{11}(k) + P_{22}(k,\Lambda) + P_{13}(k,\Lambda) - c_s^2(\Lambda)\left(\frac{k}{k_{NL}}\right)^2 P_{11}(k)$$

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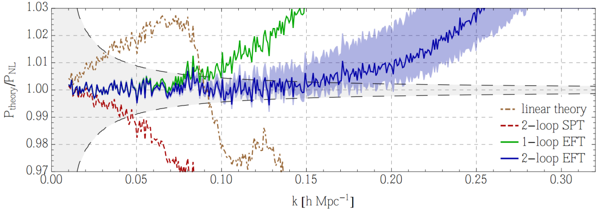
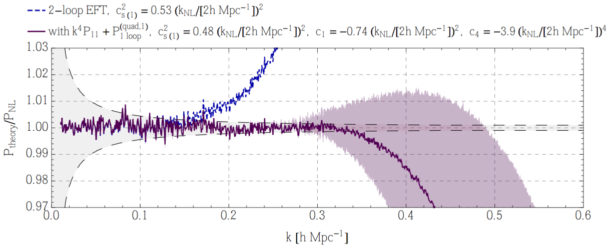
$$\delta^{(2)} \sim \int^{\Lambda} \frac{d^3\vec{q'}}{(2\pi)^3} G\,\delta^{(1)}\delta^{(1)} \qquad \delta^{(c.t.)} \sim c_s^2(\Lambda)\left(\frac{k}{k_{NL}}\right)^2 \delta^{(1)}$$

$$\delta^{(3)} \sim \int^{\Lambda} \frac{d^3\vec{q'}}{(2\pi)^3} G\,\delta^{(1)}\delta^{(2)}$$

plots





[Foreman, Perrier, Senatore]

LSS and cosmology

effective field theory of large-scale structure

status

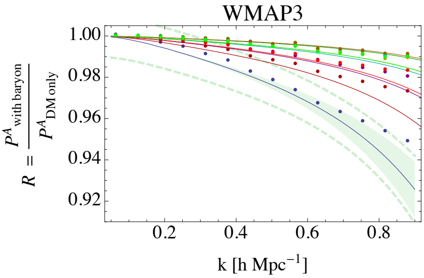
baryons, challenges

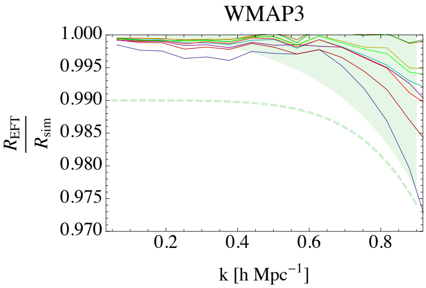
- not a pressureless, collisionless, fluid (even less so than dark matter)
- baryons heat up, re-ionize, form supernova, active galactic nuclei, etc.
- simulations are difficult, require many scales, don't know complexities of UV
- relative bulk velocity

baryons in the EFT

- treat as a fluid on large scales
- the two species can exchange momentum
- at one-loop, c_c^2 and c_b^2
- the difference between them measures the effect of star formation physics

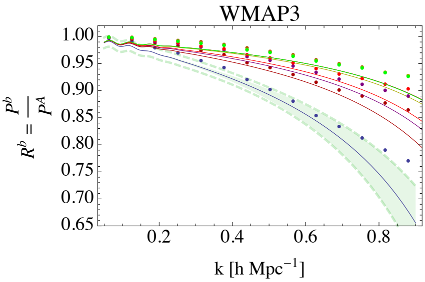
total power spectrum

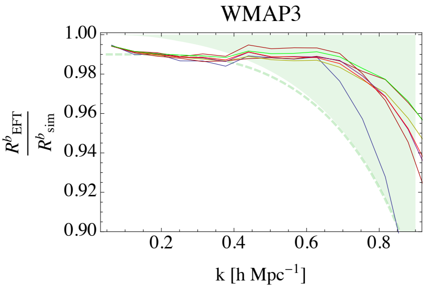




[ML, Perko, Senatore]

baryon power spectrum





[ML, Perko, Senatore]

$$c_c^2 = 0.41$$
$$c_b^2 = 0.44$$

effect of star formation physics ($c_\star^2$) is small compared to effect of gravitational non-linearities

redshift-space distortions

- we measure $(z_{\text{obs}}, \theta, \phi)$ and then we convert to $(s(z_{\text{obs}}), \theta, \phi)$ using

$$s(z_{\text{obs}}) = \int_0^{z_{\text{obs}}} \frac{dz'}{H(z')}$$

  but in these variables, the distribution of galaxies is not isotropic because of peculiar velocities adding to the redshift
- it *is* isotropic in $s(z)$, the redshift related to the Hubble flow
- $z_{\text{obs}} \approx z + a^{-1} \hat{s} \cdot \vec{v}$
- $\Rightarrow \vec{x}_r(z) \equiv \vec{x}(z_{\text{obs}}(z)) \approx \vec{x}(z) + \frac{\hat{s}\cdot\vec{v}}{aH} \hat{s}$

redshift-space distortions

$$\delta_r(\vec{k}) \simeq \delta(\vec{k}) - i\frac{k\mu}{aH}v_s(\vec{k}) + \frac{i^2}{2}\left(\frac{k\mu}{aH}\right)^2 [v_s^2]_{\vec{k}} - \frac{i^3}{3!}\left(\frac{k\mu}{aH}\right)^3 [v_s^3]_{\vec{k}} - i\frac{k\mu}{aH}[v_s\delta]_{\vec{k}} + \frac{i^2}{2}\left(\frac{k\mu}{aH}\right)^2 [v_s^2\delta]_{\vec{k}}$$

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$$- i\frac{k\mu}{aH}[v_s\delta]_{\vec{k}} + \frac{i^2}{2}\left(\frac{k\mu}{aH}\right)^2 [v_s^2\delta]_{\vec{k}}$$

$$[v_s^3]_{R,\vec{k}} = \hat{s}^i\hat{s}^j\hat{s}^l \left\{ [v_i v_j v_l]_{\vec{k}} + \left(\frac{aH}{k^r_{\rm NL}}\right)^2 c_{21}\left(\delta_{ij}v_l + \delta_{il}v_j + \delta_{jl}v_i\right) \right\}$$
$$= [v_s^3]_{\vec{k}} + 3\left(\frac{aH}{k^r_{\rm NL}}\right)^2 c_{21} v_s(\vec{k})$$

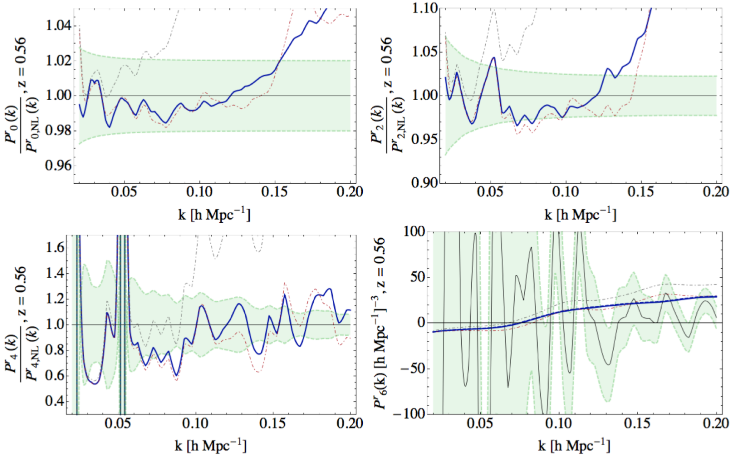
redshift-space distortions

$$P^r_{||_{\text{1-loop}}}(k,\mu,a) = D^2\, P^r_{11}(k,\mu) + D^4\, P^r_{\text{1-loop, SPT}}(k,\mu)$$
$$-(2\pi)D^2\Big[2c_s^2 + \mu^2\left(4\,c_s^2\,f + 2\,\frac{d\,c_s^2}{d\log a}\right) + 2\,\mu^4\left(c_s^2\,f^2 + \frac{d\,c_s^2}{d\log a}\,f\right)$$
$$+\left(1+f\mu^2\right)\left(\bar{c}_1^2\mu^2 + \bar{c}_2^2\mu^4\right)\Big]\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}(k)$$

- two new counter terms
- need time dependence of c_s^2

[Senatore, Zaldarriaga]

redshift-space distortions



even more

even more

- primordial non-Gaussianities

even more

- primordial non-Gaussianities
- biased tracers

even more

- primordial non-Gaussianities
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- bispectrum

even more

- primordial non-Gaussianities
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- redshift dependence and lensing

even more

- primordial non-Gaussianities
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- vorticity

even more

- primordial non-Gaussianities
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- biased tracers in redshift space

even more

- primordial non-Gaussianities
- biased tracers
- bispectrum
- redshift dependence and lensing
- vorticity
- biased tracers in redshift space
- codes: http://web.stanford.edu/~senatore/

THANK YOU