Modeling the clustering of matter on large scales: progress and recent results

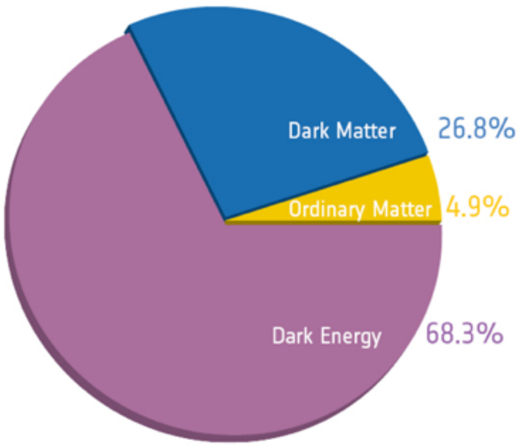
November 2020

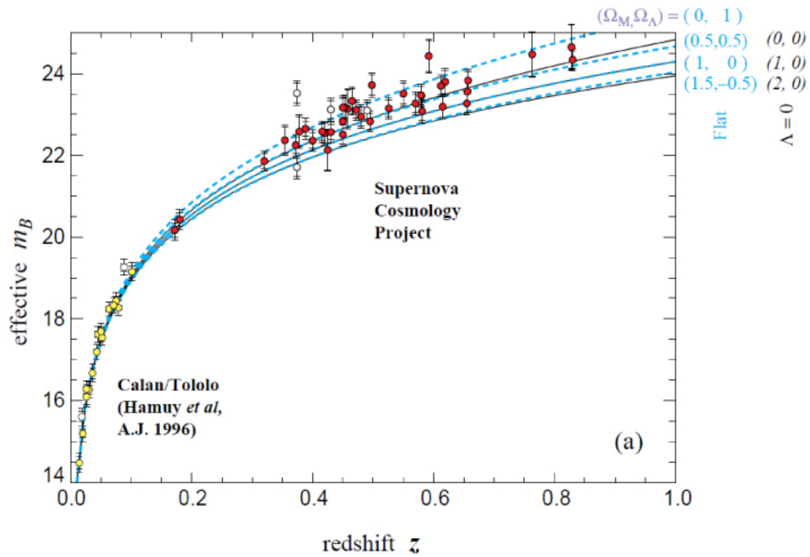
Outline

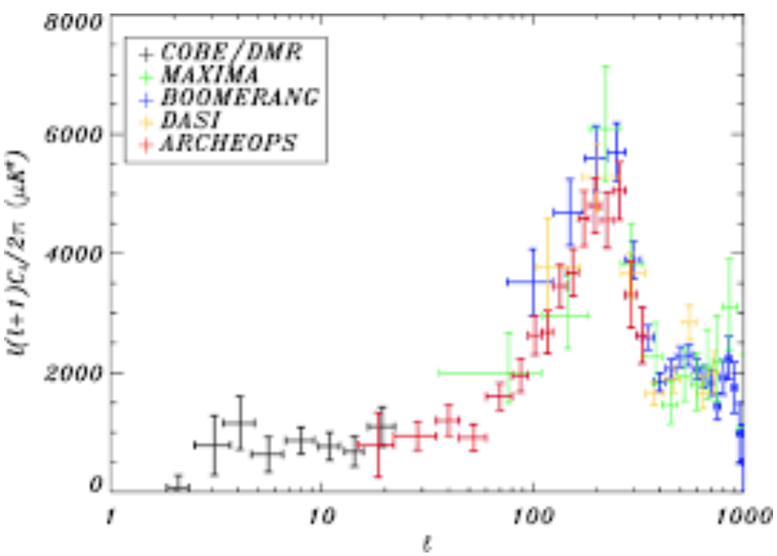
- Introduction: the current state of Cosmology
- Modeling LSS
- Our H0 measurement
- Prospects for the future

LCDM: The standard model for the last 20 years

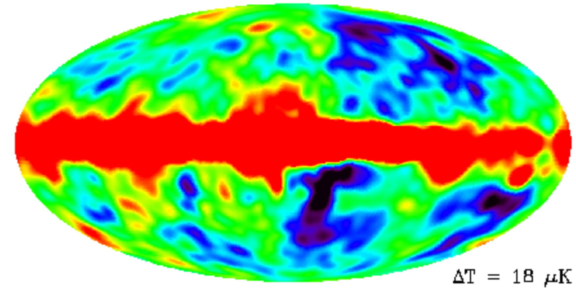
Composition

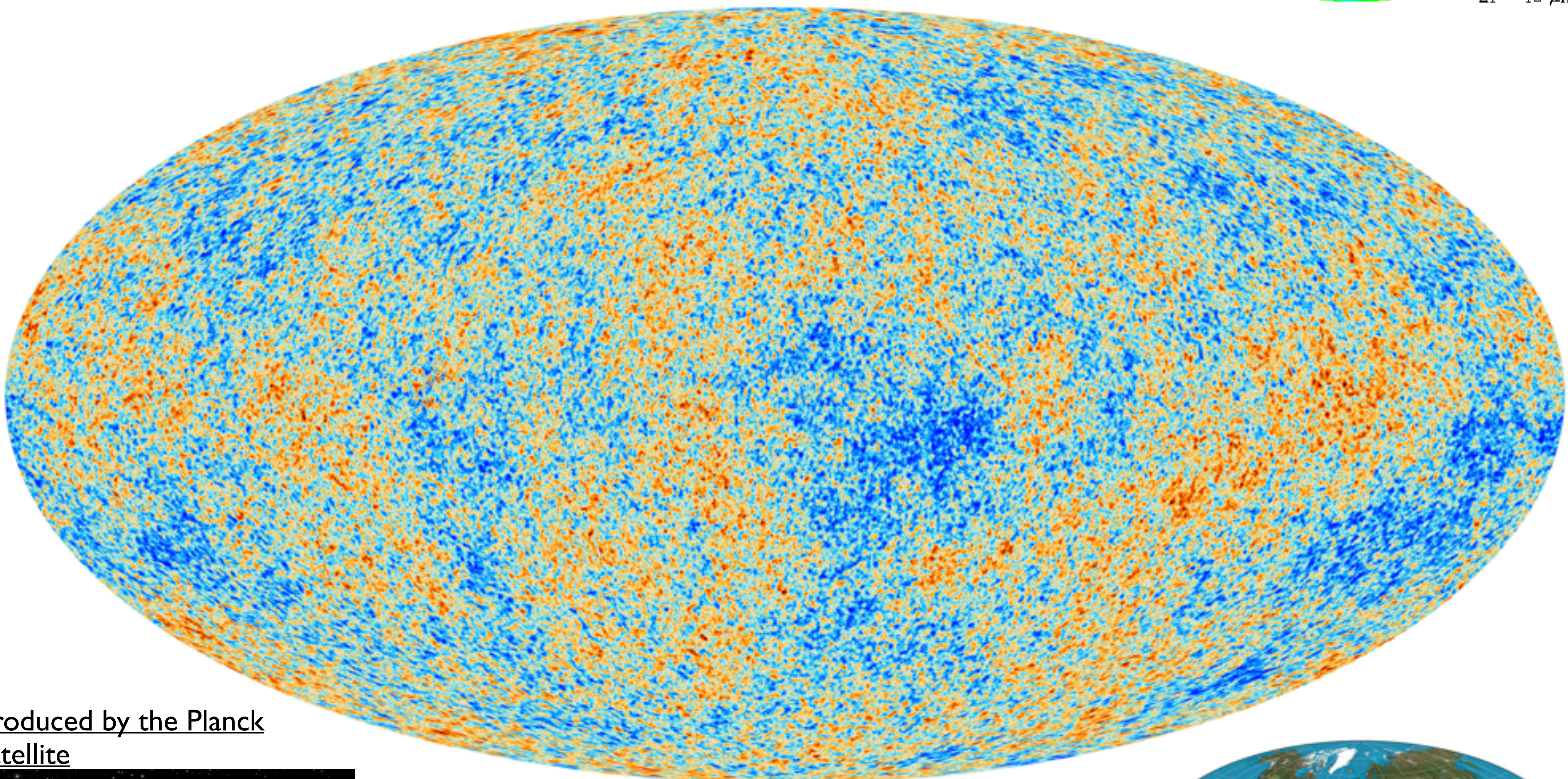




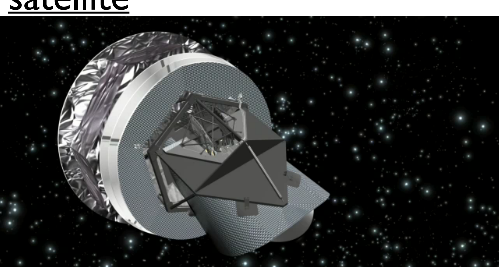


The early Universe as seen by Planck



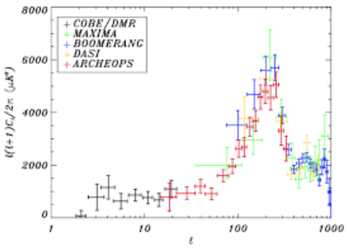


Produced by the Planck satellite

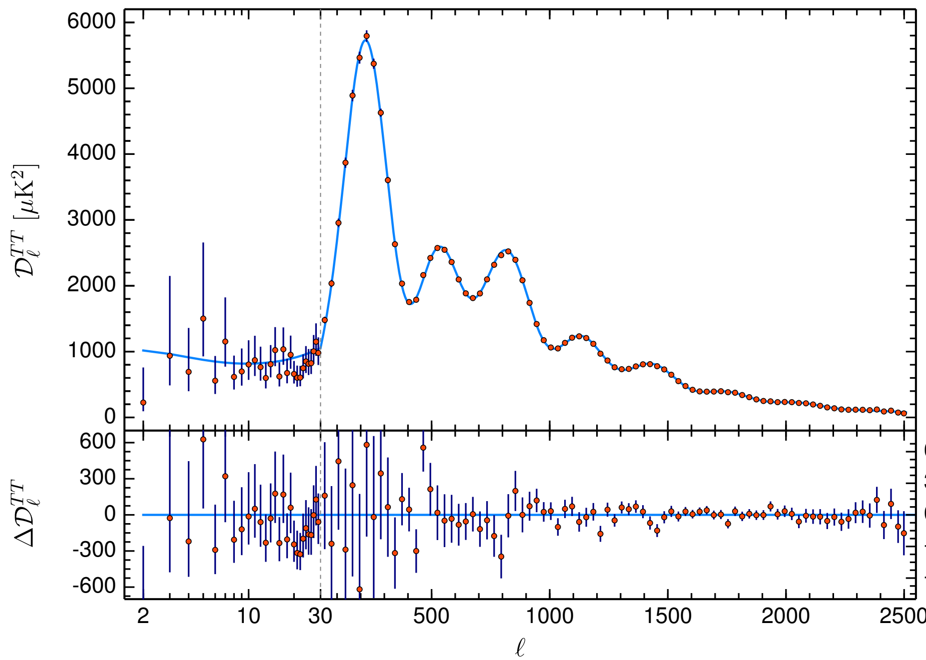


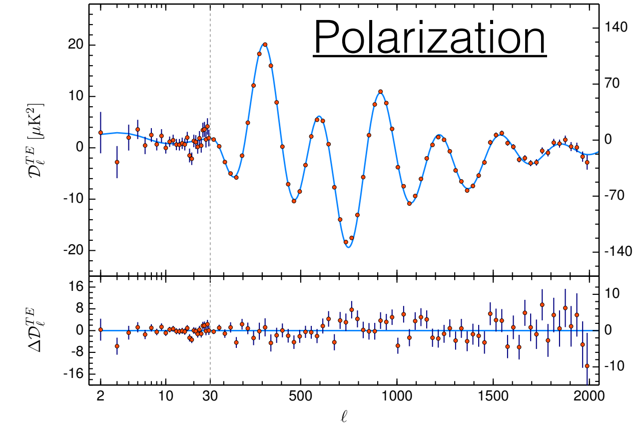
Earth in same projection

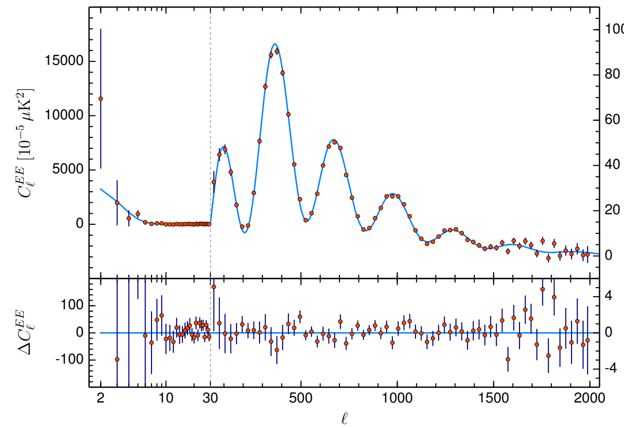
LCDM: Planck 2018



Temperature





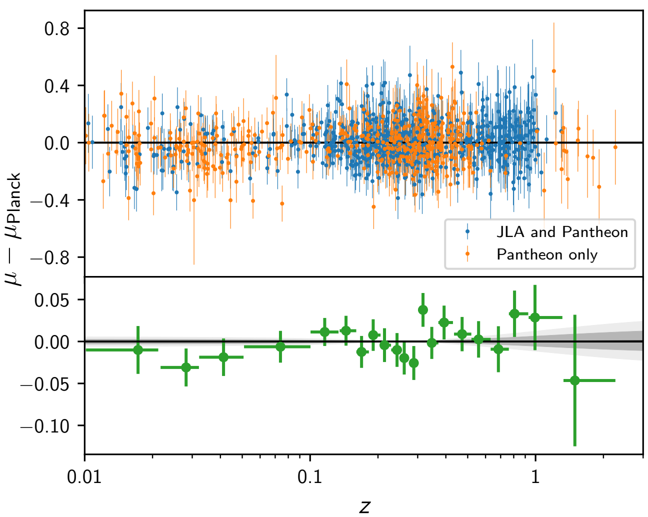


Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	-0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	-0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	-0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	-0.1	0.0540 ± 0.0074
$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	-0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	$+0.2$	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	-0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	$+0.1$	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	-0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	$+0.4$	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	-0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	-0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	-0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	-0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	$+0.6$	147.18 ± 0.29

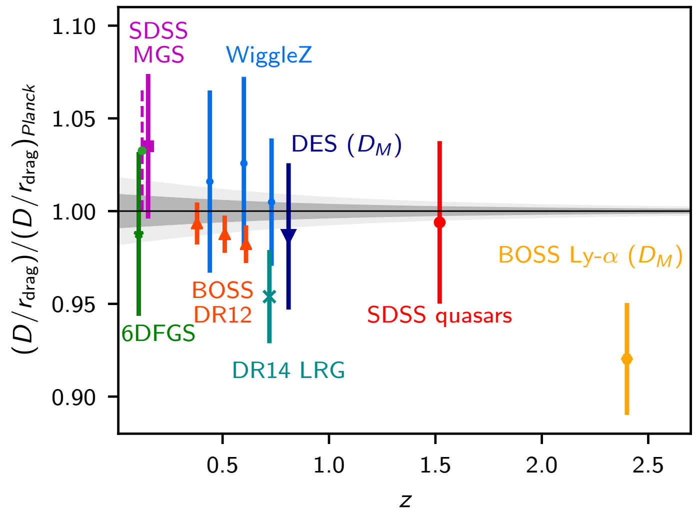
Percent and sub-percent error for many parameters

The standard cosmological model

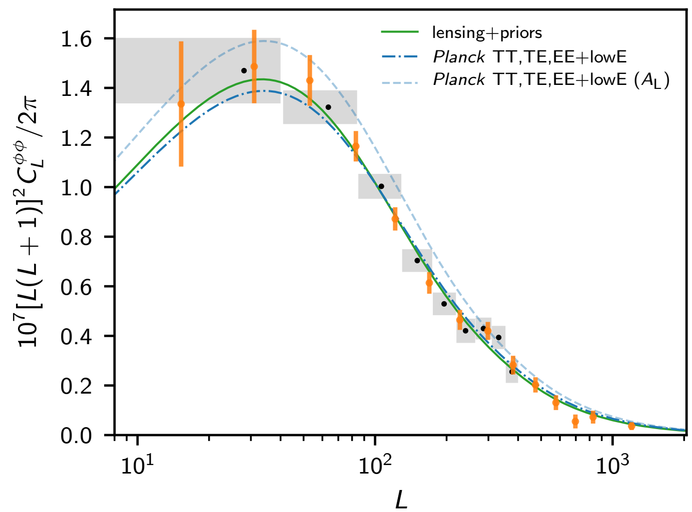
SN %-level



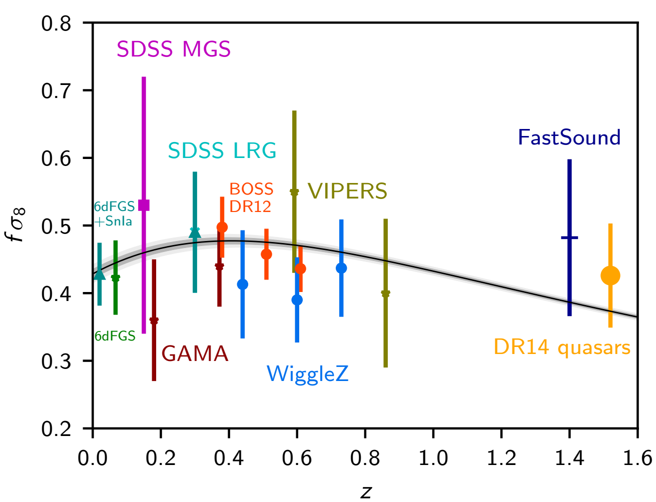
BAO scale %-level



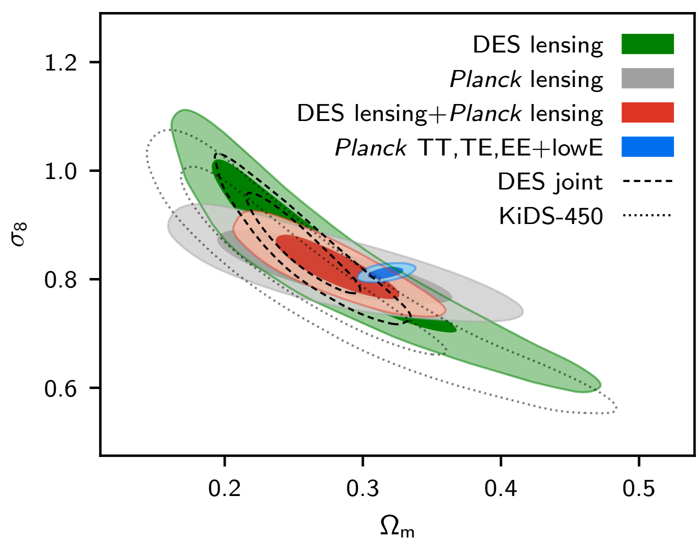
CMB lensing %-level



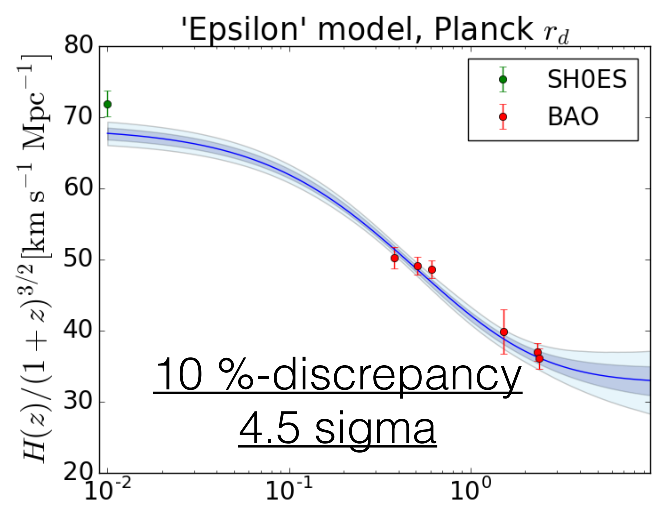
Growth of structure 10 %-level



Weak lensing 10 %-level



H0



LCDM: The standard model for the last 20 years

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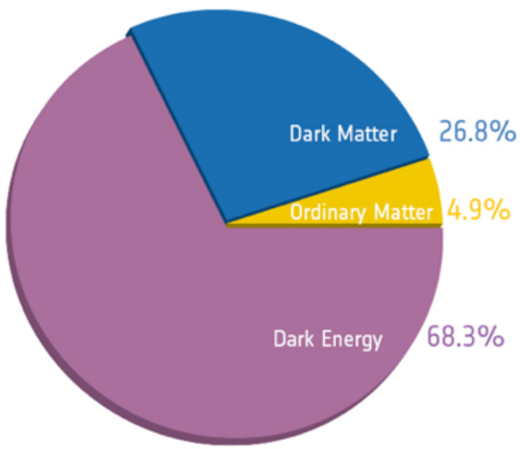
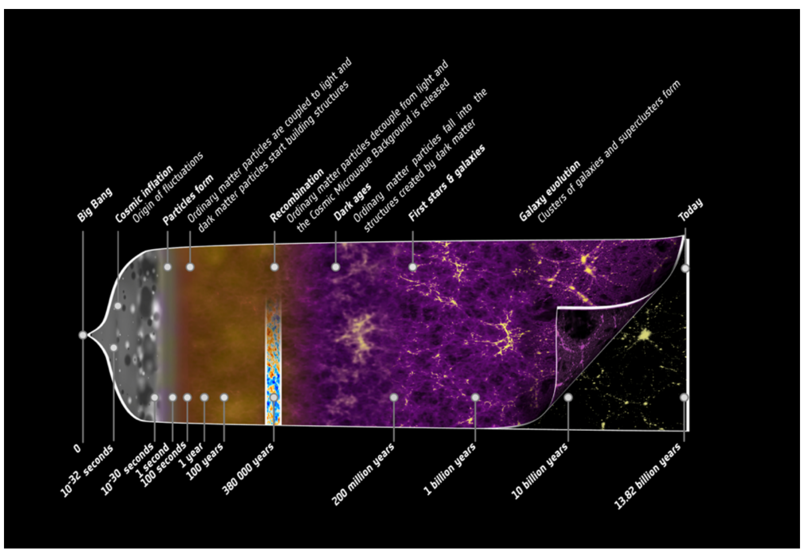


Initial conditions



- What are the properties of the DM and the DE Curvature
- How was the dark matter created?
- Baryogenesis
- Neutrino masses

The history of the Universe before the hot phase of the big bang

- How where the initial seeds created?
- Was anything else left from before the hot phase of the BB?

Astrophysical uncertainties

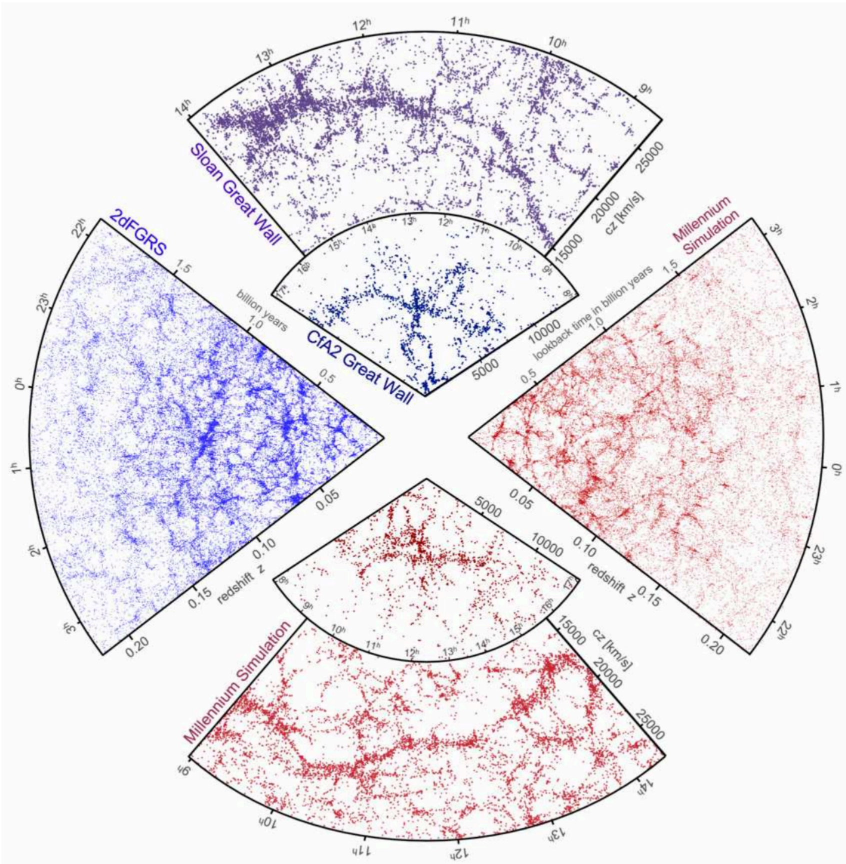
- First stars
- Galaxy formation
- SM black holes

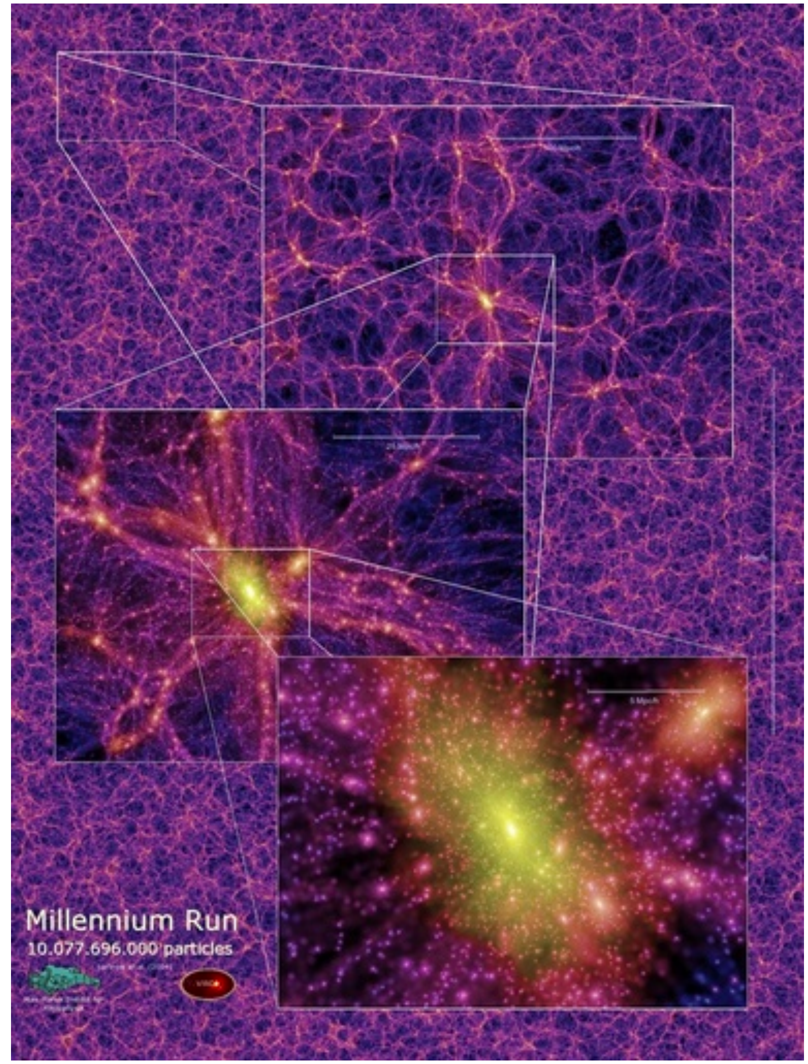
Potential for new physics

Looking towards the future

- There are many questions still open on Cosmology, eg. the origin of the primordial seeds, neutrino masses, the evolution of the dark energy.
- We expect to get answers to some of these questions from the studies of the clustering of matter on large scales. These are scales where the dynamics is simple, linear theory captures it very well but there are small corrections. Those corrections however are larger than the observational errors and cannot be calculated from first principles.
- What is the theory that describes the dynamics on very large scales? What is needed to compute these small corrections both consistently and accurately?
- The fact that on small scales the dynamics is complicated, modifies in fundamental ways the theory that describe the evolution on large scales. Although this field has a long history, only recently have consistent calculations of this small corrections become available.

Large Scale Structure

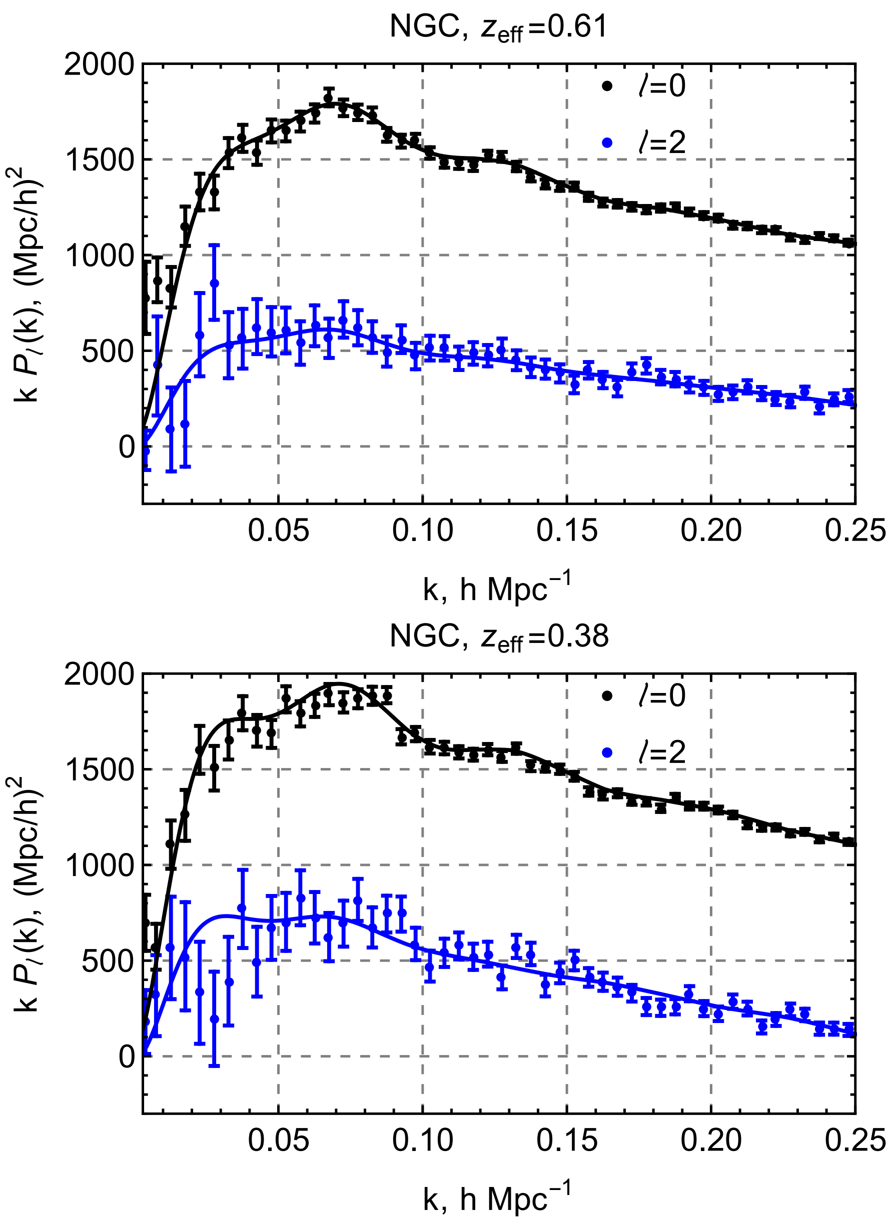




The distribution of matter on large scales encodes interesting information about Cosmology. There are several complications: 1. On small scales the dynamics is complicated and 2. we use discrete objects to trace the distribution of matter 3. Clustering appears anisotropic as peculiar velocities distort the apparent radial position of objects. 4. **We cannot predict the small scales from first principles.**

The BOSS survey

Baryon Oscillation Spectroscopic Survey. Map luminous red galaxies. Primary objective BAO. Observations 2009-2014 Latest papers DR12 2016



Spectra we used. Selection of samples slightly different from chuck to chunk so we allow different bias parameters.

Covariance from patchy mocks, results independent of details of covariance (analytic covariance from Scoccimarro or Gaussian covariance give same results)

Data	$V_{\rm eff}$ $[({\rm Gpc}/h)^3]$	V $[({\rm Gpc}/h)^3]$
low-z NGC	0.84	1.46
low-z SGC	0.31	0.53
high-z NGC	0.93	2.8
high-z SGC	0.34	1.03

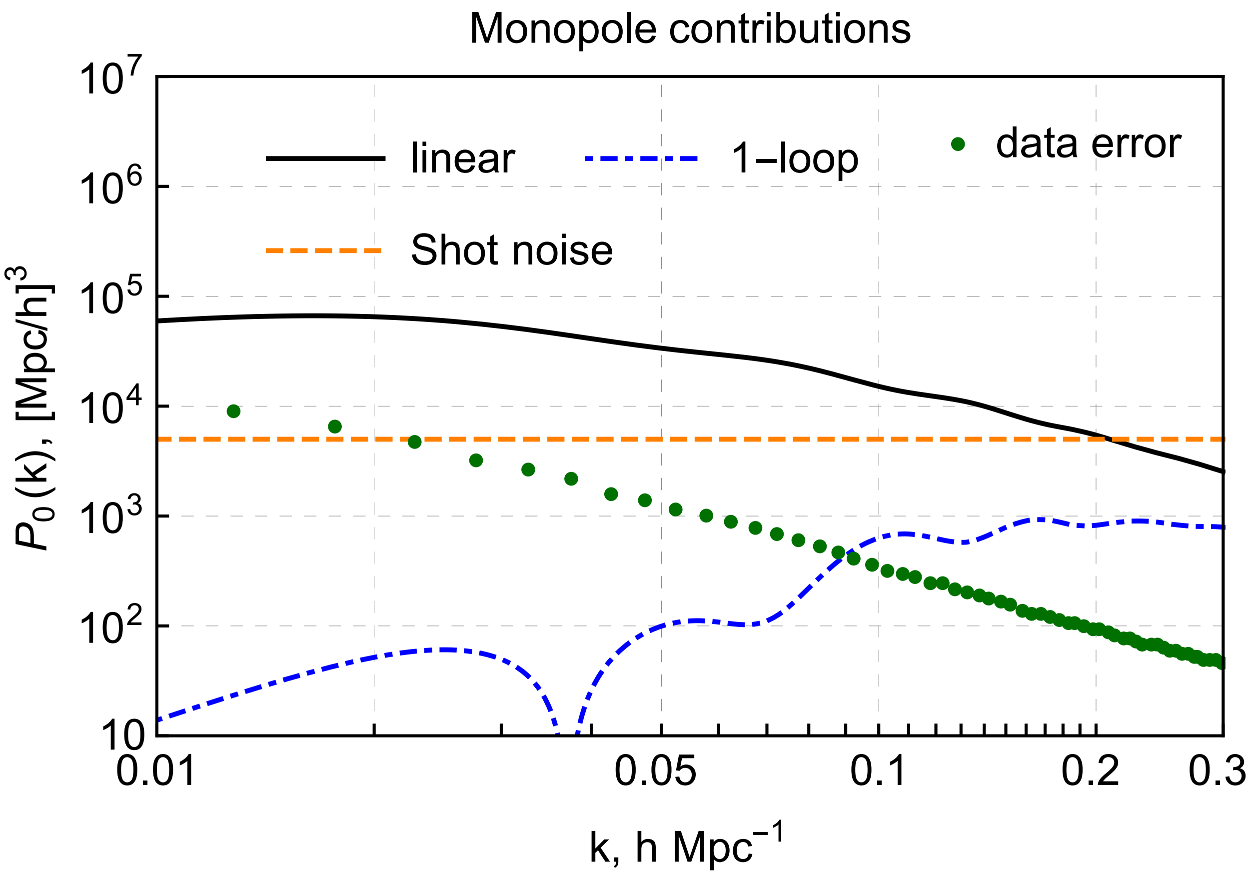
Our results are in 1909.05277, 1912. 08208 and 2002.04035

Ingredients needed to model LSS data

- Non-linear model for the dark matter evolution [PT or N-body]
- Relation between dark matter and galaxies (this depends on small scale physics we cannot yet simulate from first principles or have measured in the necessary detail. Details of this relation also depend on how the galaxies are selected.) [Biasing model or Hydro-simulation + subgrid].
- Noise from the fact measurements are discrete points. Typically one galaxy per 10 Mpc size cube [Poisson + corrections].

All these ingredients are important to make the predictions. As you go towards smaller scales the model are less and less under control.

Size of selected contributions



We are operating in a regime where the non-linear corrections are small but larger than the error bars which are very small.

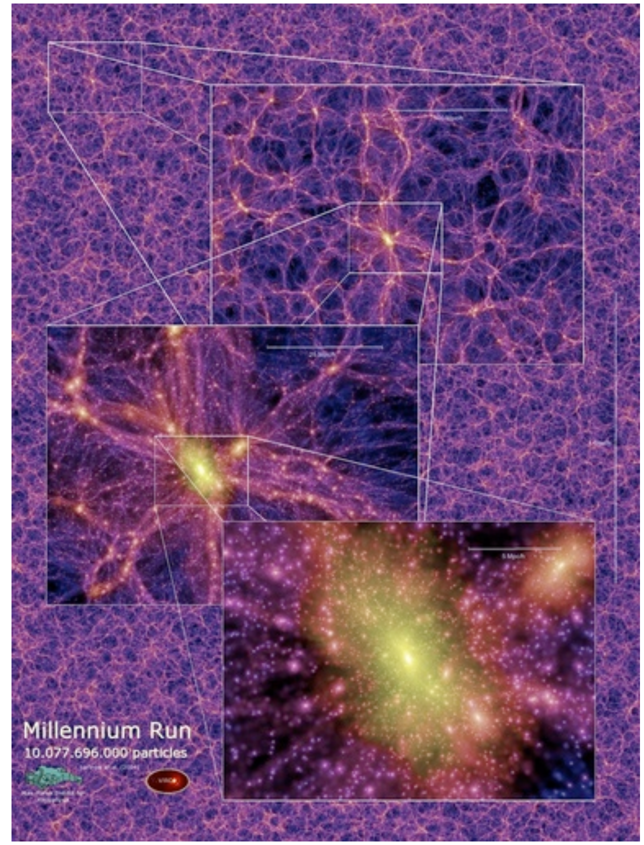
This regime is perfectly suitable for perturbative type approaches which has several advantages.

Future surveys will operate in a similar regime.

What theory describes the dynamics on large scales?

As you go to large scales the Universe becomes more homogeneous.

If we restrict to large scales we should be able to have a very accurate description.



density **velocity**

$$\partial_\tau \delta + \partial_i[(1+\delta)v^i] = 0$$

$$\partial_\tau v^i + \mathcal{H}v^i + \partial^i\phi + v^j\partial_j v^i = -\frac{1}{a\rho}\partial_j\tau^{ij}$$

$$\triangle\phi = \frac{3}{2}\mathcal{H}^2\Omega_{\rm m}\delta\ .$$

Mass and momentum conservation

Gravitational interactions

$$\delta = \delta_{(1)} + \delta_{(2)} + \delta_{(3)} + \delta_{(4)} + \delta_{(5)} + \cdots$$

Describe the dynamics on large scales, after integrating out the short scale modes (EFT of LSS).

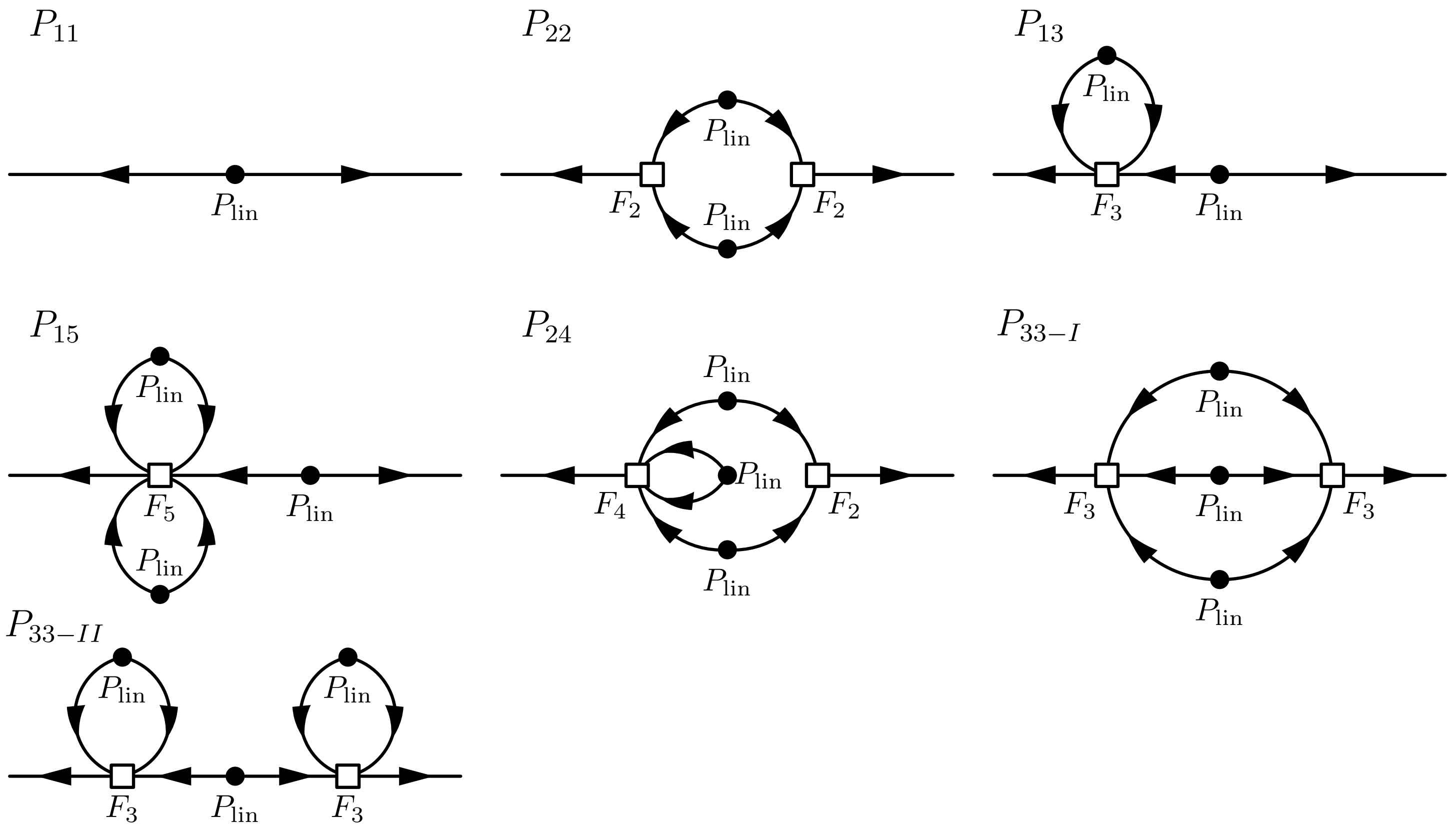


FIG. 1. Diagrams for the tree level, one- and two-loop expressions of the SPT power spectrum.

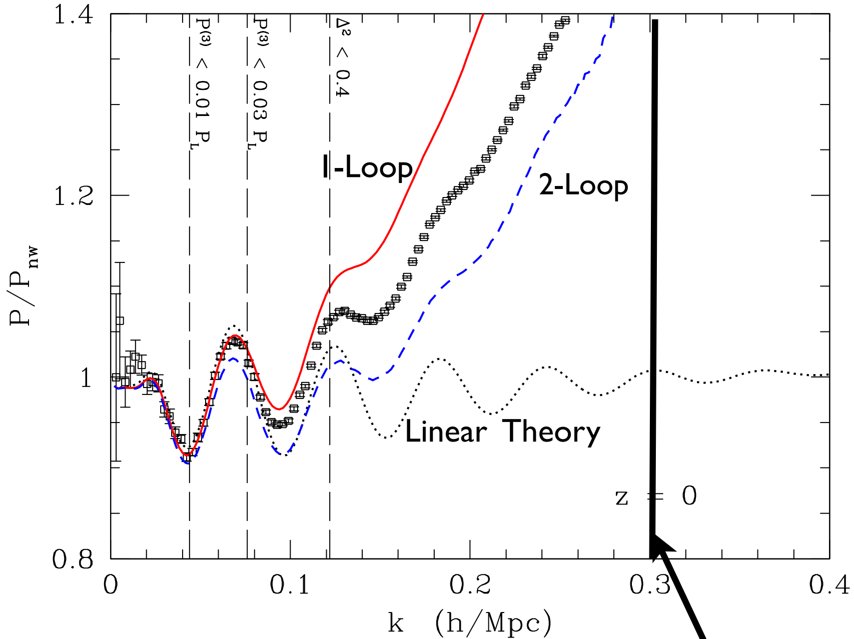
Solve equations for density and velocity in powers of the over density then compute N-point function.

Solutions for various statistics like the power spectrum is a series in powers of the initial power spectrum.

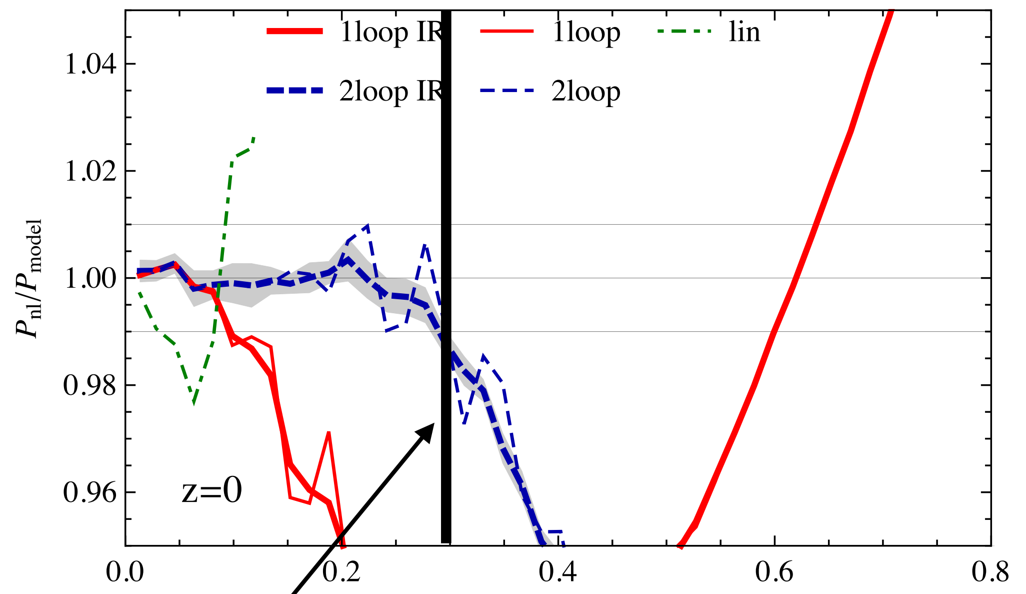
Standard Perturbation Theory

EFT of LSS

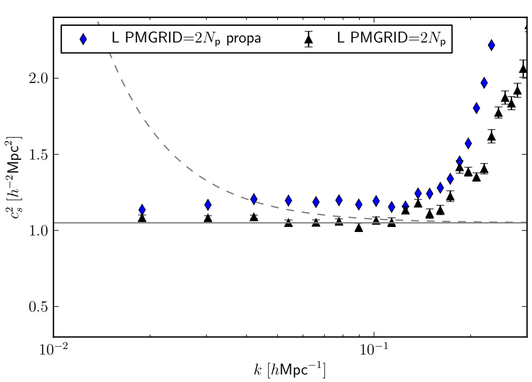
Carlson et al 0905.0479



Baldauf, Mercolli & MZ



At this scale the 2-loop EFT is good to 1 %



Lowest order counter term

$$\delta^{ct(1)}(\boldsymbol{k}) = l_1^2 \boldsymbol{k}^2 \delta_0(\boldsymbol{k}) + l_1^2 \int_p \frac{\boldsymbol{k}\cdot\boldsymbol{p}_1}{\boldsymbol{p}_1^2}\frac{\boldsymbol{k}\cdot\boldsymbol{p}_2}{\boldsymbol{p}_2^2}\boldsymbol{p}_1^2 \delta_0(\boldsymbol{p}_1)\delta_0(\boldsymbol{p}_2)$$

Amplitude determined at
k=0.02,

Biased tracers

$$\delta_g = \sum_{\mathcal{O}} b_{\mathcal{O}} \mathcal{O} = b_1 \delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + \cdots$$

We know how to construct a list of all the relevant terms needed to get to a desired precision. Eg. Two point function (power spectrum)

$$P_g(k,z) = A^4 \left[b_{\mathcal{G}_2}\left(b_{\mathcal{G}_2} - \frac{5}{7}b_2\right) I_{\mathcal{G}_2\mathcal{G}_2}(k,z) + 2b_1\left(b_{\mathcal{G}_2} + \frac{2}{5}b_{\Gamma_3}\right) F_{\mathcal{G}_2}(k,z) + 4b_2^2 I_{\delta_2\delta_2}(k,z) + 4b_1\left(b_2 - \frac{2}{5}b_{\mathcal{G}_2}\right) I_{\delta_2}(k,z)\right] + b_1^2 P_{\rm NL}(k,z) + s_p(z)$$

- One needs to add free parameters to describe the relation between galaxies and the large-scale field.
- N-point functions can be expressed as a sum of functions one can calculate times unknown coefficients.
- One has to go to fairly large order to get things right.
- Error comes from PT calculation of density and from connection between density and galaxies.

Our BOSS analysis

$$P_g(k,\mu) = Z_1^2(\mathbf{k})P_{\rm lin}(k) + 2\int_{\mathbf{q}} Z_2^2(\mathbf{q},\mathbf{k}-\mathbf{q})P_{\rm lin}(|\mathbf{k}-\mathbf{q}|)P_{\rm lin}(q)$$
$$+ 6Z_1(\mathbf{k})P_{\rm lin}(k)\int_{\mathbf{q}} Z_3(\mathbf{q},-\mathbf{q},\mathbf{k})P_{\rm lin}(q)$$
$$- 2\tilde{c}_0 k^2 P_{\rm lin}(k) - 2\tilde{c}_2 f\mu^2 k^2 P_{\rm lin}(k) - 2\tilde{c}_4 f^2\mu^4 k^2 P_{\rm lin}(k)\,,$$
$$- \tilde{c} f^4\mu^4 k^4 (b_1 + f\mu)^2 P_{\rm lin}(k) + P_{\rm shot}\,,$$

$$Z_1(\mathbf{k}) = b_1 + f\mu^2\,,$$
$$Z_2(\mathbf{k}_1,\mathbf{k}_2) = \frac{b_2}{2} + b_{\mathcal{G}_2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - 1\right) + b_1F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu^2 G_2(\mathbf{k}_1,\mathbf{k}_2)$$
$$+ \frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}(b_1 + f\mu_2^2) + \frac{\mu_2}{k_2}(b_1 + f\mu_1^2)\right)\,,$$

$$Z_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2b_{\Gamma_3}\left[\frac{(\mathbf{k}_1\cdot(\mathbf{k}_2+\mathbf{k}_3))^2}{k_1^2(\mathbf{k}_2+\mathbf{k}_3)^2} - 1\right]\left[F_2(\mathbf{k}_2,\mathbf{k}_3) - G_2(\mathbf{k}_2,\mathbf{k}_3)\right]$$
$$+ b_1F_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + f\mu^2 G_3(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) + \frac{(f\mu k)^2}{2}(b_1 + f\mu_1^2)\frac{\mu_2}{k_2}\frac{\mu_3}{k_3}$$
$$+ f\mu k\frac{\mu_3}{k_3}\left[b_1F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu_{12}^2 G_2(\mathbf{k}_1,\mathbf{k}_2)\right] + f\mu k(b_1 + f\mu_1^2)\frac{\mu_{23}}{k_{23}}G_2(\mathbf{k}_2,\mathbf{k}_3)$$
$$+ b_2F_2(\mathbf{k}_1,\mathbf{k}_2) + 2b_{\mathcal{G}_2}\left[\frac{(\mathbf{k}_1\cdot(\mathbf{k}_2+\mathbf{k}_3))^2}{k_1^2(\mathbf{k}_2+\mathbf{k}_3)^2} - 1\right]F_2(\mathbf{k}_2,\mathbf{k}_3) + \frac{b_2 f\mu k}{2}\frac{\mu_1}{k_1}$$
$$+ b_{\mathcal{G}_2} f\mu k\frac{\mu_1}{k_1}\left[\frac{(\mathbf{k}_2\cdot\mathbf{k}_3)^2}{k_2^2k_3^2} - 1\right]\,,$$

The EFT model:

One loop 5 cosmo pars

7 nuisance parameters, loop counter terms, bias parameters including shot noise.

Parameter	Prior
Cosmology	
n_s (not varied)	$n_s = 0.9649$
ω_b	different for each analysis
$A^{1/2}$	$\mathrm{flat}(0.02, 2)$
h	$\mathrm{flat}(0.4, 1)$
ω_{cdm}	$\mathrm{flat}(0.05, 0.2)$
m_ν	$\mathrm{flat}(0.06, 0.18)$ eV
Biases and shot noise	
$b_1 \times A^{1/2}$	$\mathrm{flat}(1, 4)$
$b_2 \times A^{1/2}$	$\mathrm{flat}(-4, 2)$
$b_{\mathcal{G}_2} \times A^{1/2}$	$\mathrm{flat}(-3, 3)$
b_{Γ_3} (not varied)	$b_{\Gamma_3} = 0$
$P_{\rm shot}$	$\mathrm{flat}(0, 10^4)$ Mpc^3/h^3
Counterterms	
c_0^2, c_2^2	$\mathrm{flat}(-\infty, \infty)$ Mpc^2/h^2
$\tilde{c}$	$\mathrm{flat}(-\infty, \infty)$ Mpc^4/h^4

Fast evaluation of loop integrals

$$\bar{P}_{\rm lin}(k_n) = \sum_{m=-N/2}^{m=N/2} c_m \, k_n^{\nu+i\eta_m} \ ,$$

One loop matter

$$\bar{P}_{22}(k) = 2 \sum_{m_1,m_2} c_{m_1} c_{m_2} \sum_{n_1,n_2} f_{22}(n_1,n_2)\, k^{-2(n_1+n_2)} \int_{\boldsymbol{q}} \frac{1}{q^{2\nu_1-2n_1} |\boldsymbol{k}-\boldsymbol{q}|^{2\nu_2-2n_2}} \ .$$

$$\bar{P}_{22}(k) = k^3 \sum_{m_1,m_2} c_{m_1} k^{-2\nu_1} \cdot M_{22}(\nu_1,\nu_2) \cdot c_{m_2} k^{-2\nu_2}$$

$$M_{22}(\nu_1,\nu_2) = \frac{(\frac{3}{2}-\nu_{12})(\frac{1}{2}-\nu_{12})[\nu_1\nu_2(98\nu_{12}^2-14\nu_{12}+36)-91\nu_{12}^2+3\nu_{12}+58]}{196\,\nu_1(1+\nu_1)(\frac{1}{2}-\nu_1)\,\nu_2(1+\nu_2)(\frac{1}{2}-\nu_2)} \mathsf{I}(\nu_1,\nu_2).$$

$$\mathsf{I}(\nu_1,\nu_2) = \frac{1}{8\pi^{3/2}} \frac{\Gamma(\frac{3}{2}-\nu_1)\Gamma(\frac{3}{2}-\nu_2)\Gamma(\nu_{12}-\frac{3}{2})}{\Gamma(\nu_1)\Gamma(\nu_2)\Gamma(3-\nu_{12})}$$

$$\bar{P}_{13}(k) = 6 P_{\rm lin}(k) \sum_{m_1} c_{m_1} \sum_{n_1,n_2} f_{13}(n_1,n_2)\, k^{-2(n_1+n_2)} \int_{\boldsymbol{q}} \frac{1}{q^{2\nu_1-2n_1} |\boldsymbol{k}-\boldsymbol{q}|^{-2n_2}}$$

$$\bar{P}_{13}(k) = k^3 P_{\rm lin}(k) \sum_{m_1} c_{m_1} k^{-2\nu_1} \cdot M_{13}(\nu_1)$$

$$M_{13}(\nu_1) = \frac{1+9\nu_1}{4} \frac{\tan(\nu_1\pi)}{28\pi(\nu_1+1)\nu_1(\nu_1-1)(\nu_1-2)(\nu_1-3)}$$

Biased tracers

$$\delta_h = b_1\delta + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + \frac{b_3}{6}\delta^3 + b_{\mathcal{G}_3}\mathcal{G}_3 + b_{(\mathcal{G}_2\delta)}\mathcal{G}_2\delta + b_{\Gamma_3}\Gamma_3$$

$$M_{\mathcal{I}_{\delta^2}}(\nu_1,\nu_2) = \frac{(3-2\nu_{12})(4-7\nu_{12})}{17\nu_1\nu_2} \,\mathsf{I}(\nu_1,\nu_2)\,,$$

$$M_{\mathcal{I}_{\mathcal{G}_2}}(\nu_1,\nu_2) = -\frac{(3-2\nu_{12})(1-2\nu_{12})(6+7\nu_{12})}{28\nu_1(1+\nu_1)\nu_2(1+\nu_2)} \,\mathsf{I}(\nu_1,\nu_2)\,,$$

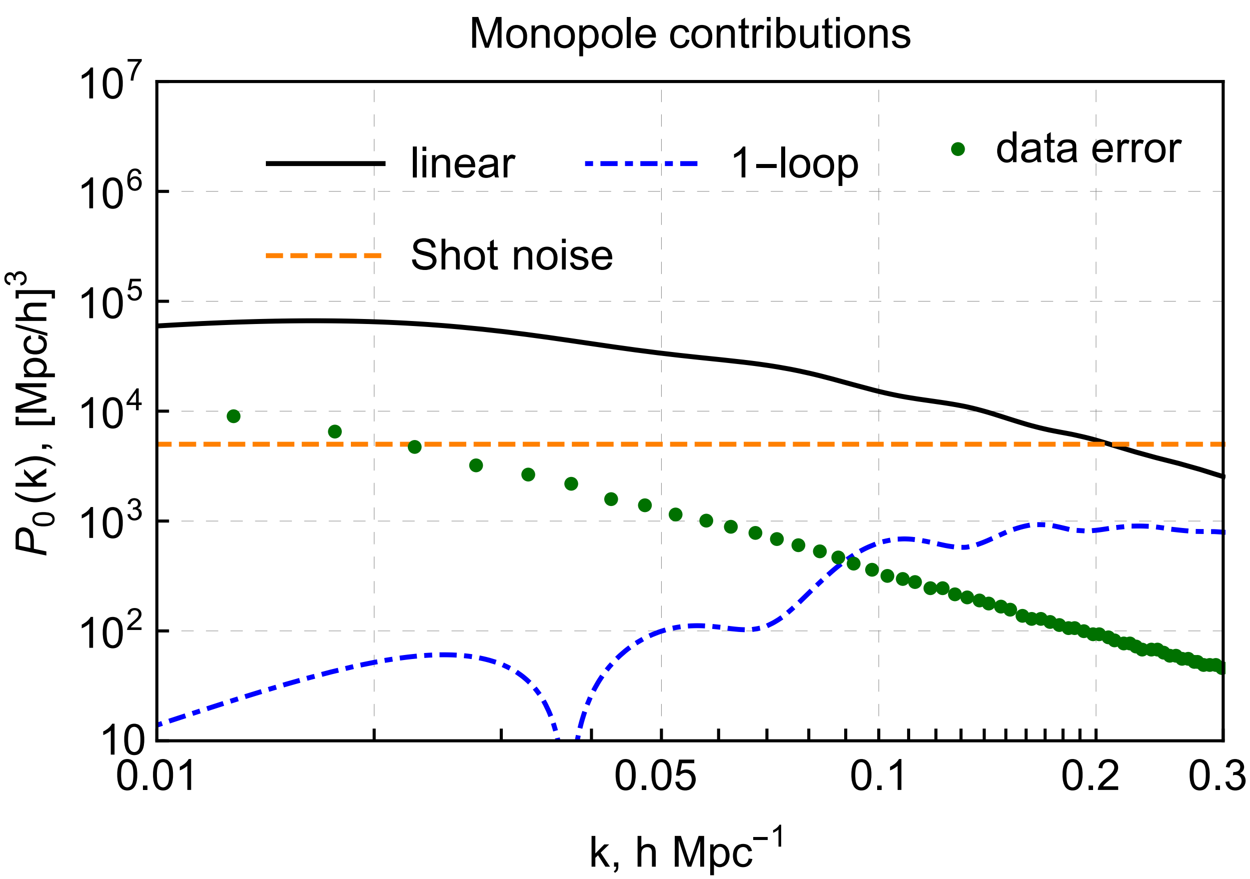
$$M_{\mathcal{F}_{\mathcal{G}_2}}(\nu_1) = -\frac{15\tan(\nu_1\pi)}{28\pi(\nu_1+1)\nu_1(\nu_1-1)(\nu_1-2)(\nu_1-3)}\,,$$

$$M_{\mathcal{I}_{\delta^2\delta^2}}(\nu_1,\nu_2) = 2\mathsf{I}(\nu_1,\nu_2)\,,$$

$$M_{\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}}(\nu_1,\nu_2) = \frac{(3-2\nu_{12})(1-2\nu_{12})}{\nu_1(1+\nu_1)\nu_2(1+\nu_2)} \,\mathsf{I}(\nu_1,\nu_2)\,,$$

$$M_{\mathcal{I}_{\delta^2\mathcal{G}_2}}(\nu_1,\nu_2) = \frac{3-2\nu_{12}}{\nu_1\nu_2} \,\mathsf{I}(\nu_1,\nu_2)\,.$$

Size of selected contributions



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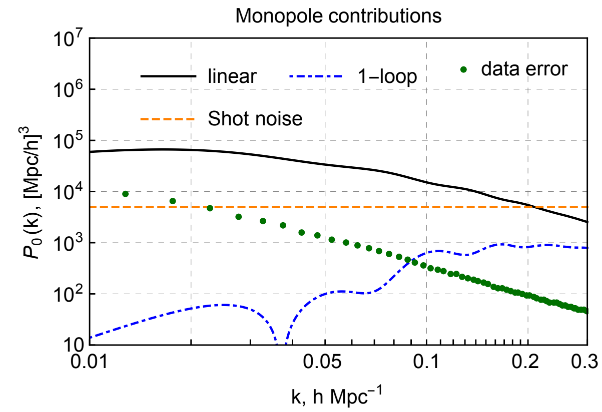
Future surveys will operate in a similar regime.

The EFT of Large Scale Structure



- It describes the clustering on large scales.
- It gives you a systematic counting of how many terms you need to calculate to have a given precision. No need to go to very high order.
- It has free parameters but it is not a fitting function. It is a consistent expansion and provides both analytic formulas to predict observables as well as an estimate of the errors as a function of scale.
- It leads to unbiased measurements of cosmological parameters of interest and consistent marginalization over the uncertain small scale physics. Challenging because errors are so small.
- Constraints one gets for cosmological parameters are significantly degraded by having to fit the nuisance parameters.

The EFT of Large Scale Structure

Perturbation theory is an old school approach.

In the last several years many improvements:

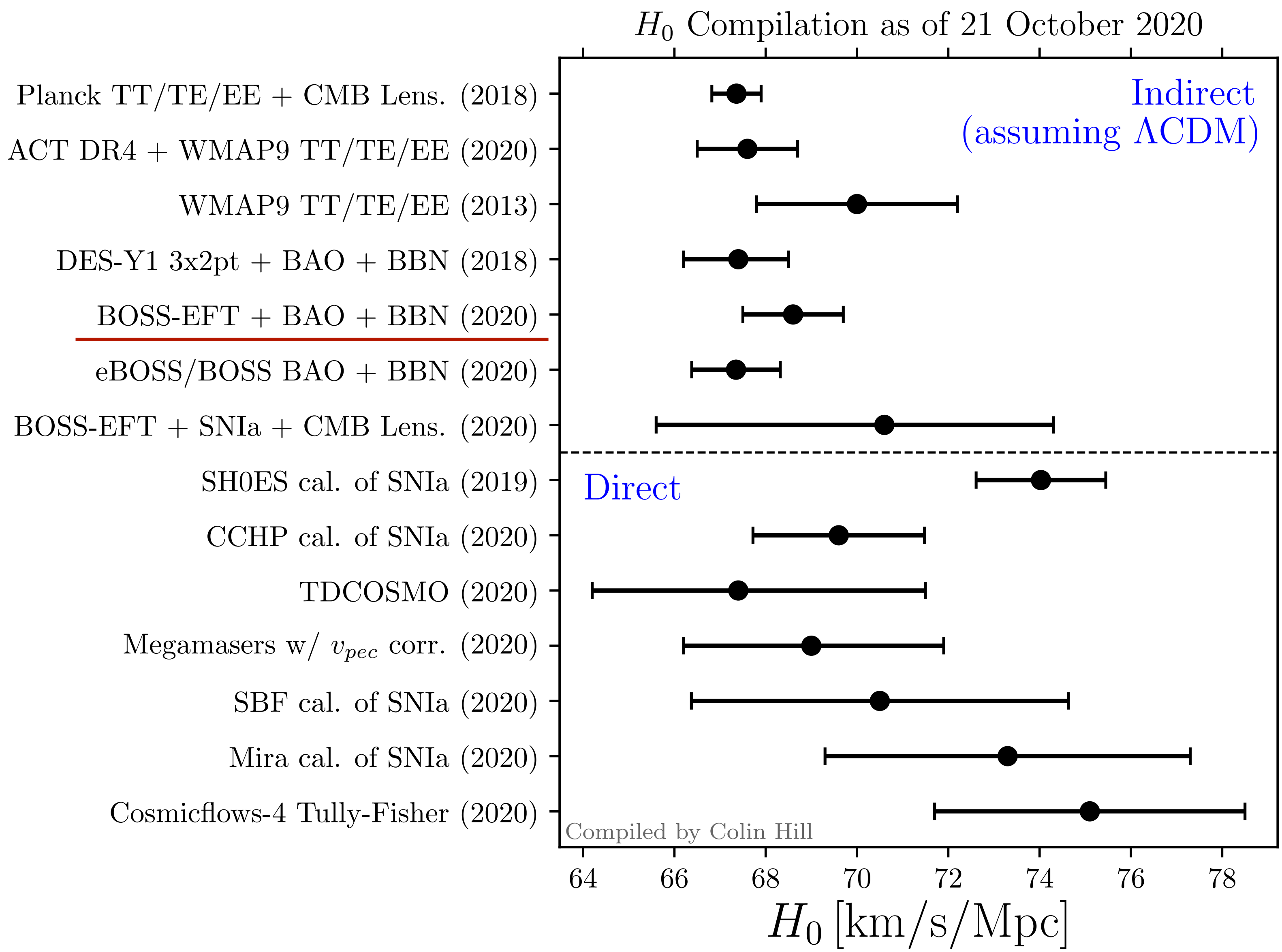
- Recognize that there are multiple expansion parameters, resum some IR effects (peculiar motions)
- Recognize the need for counter terms and developed the needed machinery to characterize them, including RSD. Write all terms consistent with symmetries: Mass & momentum conservation, equivalence principle
- Systematic characterization of bias parameters, non-locality in time etc.
- Quantitative understanding of range of validity vs loop order
- Develop computational techniques to evaluate loops fast.

A 1% CMB independent constraint on H0

Marco Simonovic *Mikhail Ivanov* *Oliver Philcox*

Based on 1909.05277, 1912. 08208 and 2002.04035

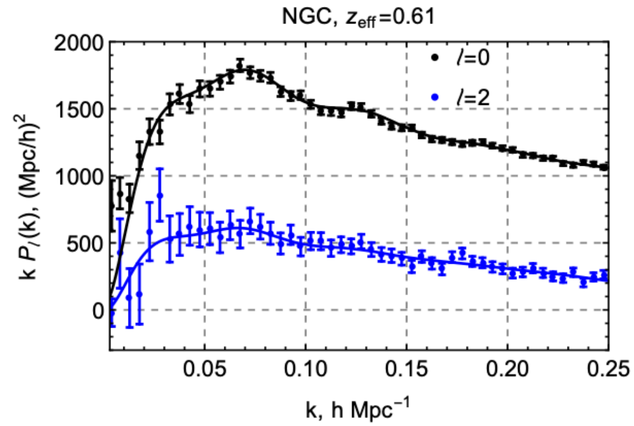
Current State of H0 measurements

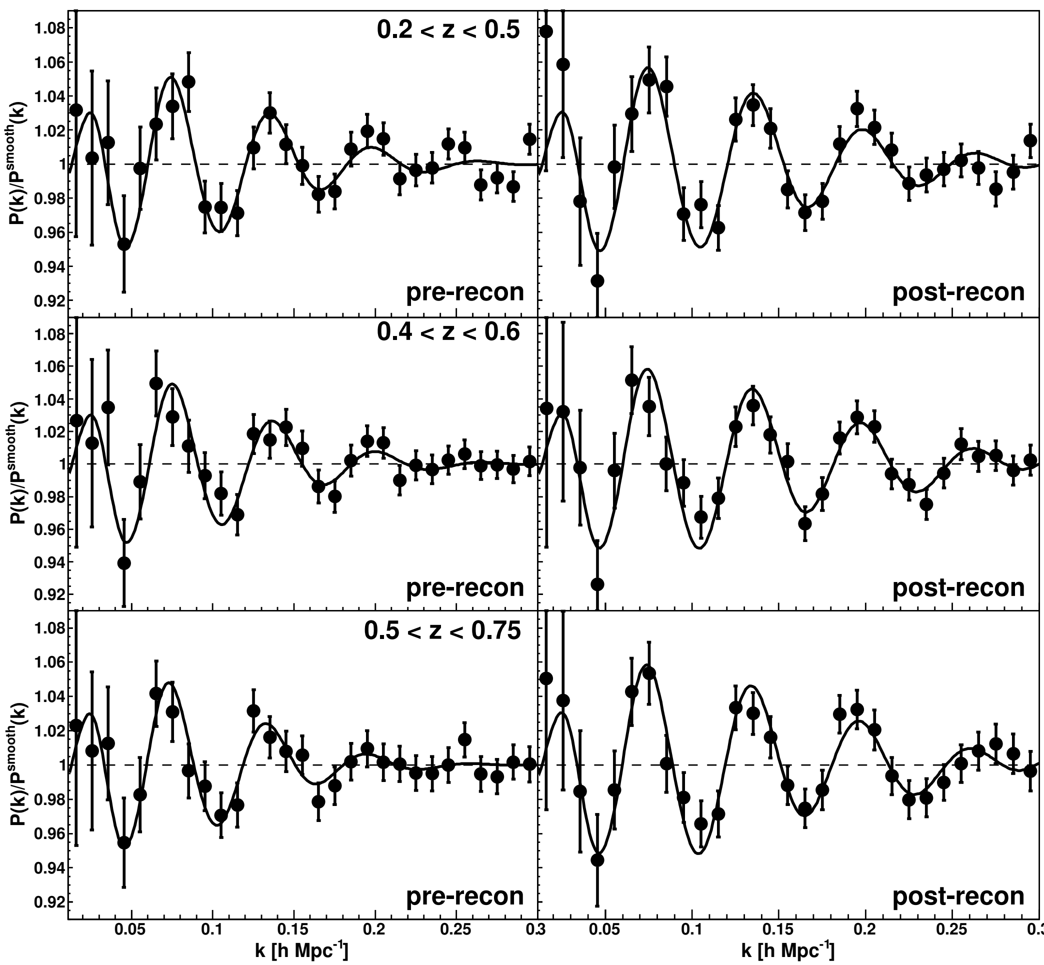


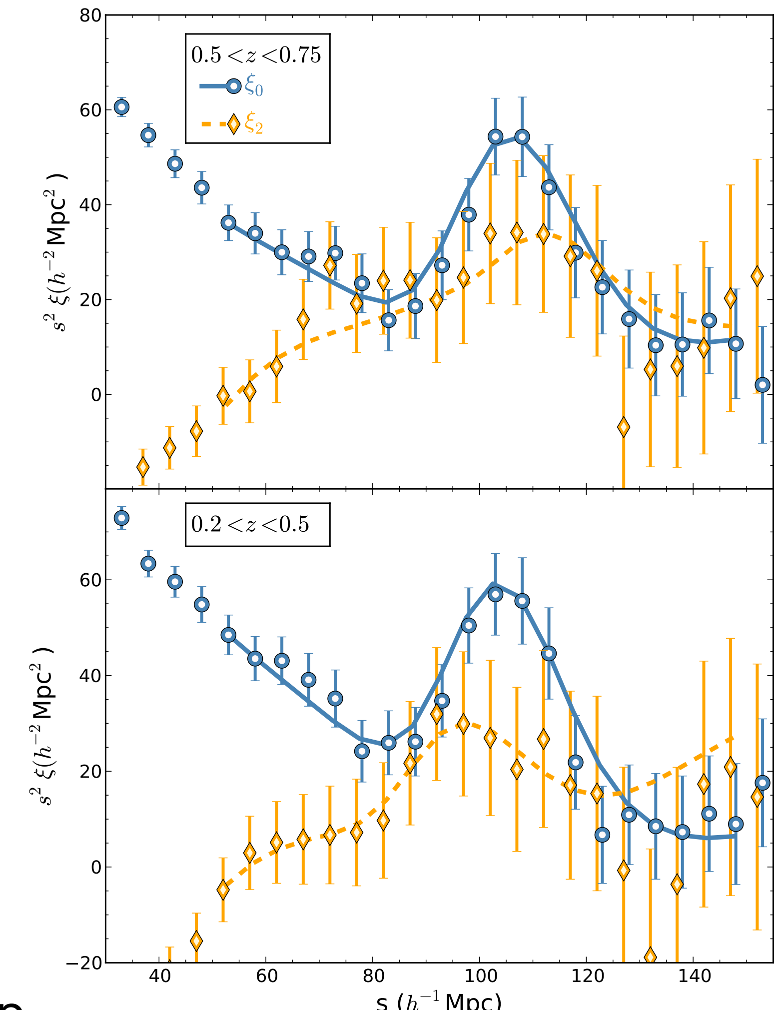
Compiled by Colin Hill

The BOSS Survey

BAO standard ruler set by CMB, one of the best ways to infer the late expansion history of the Universe. Currently 1% errors.

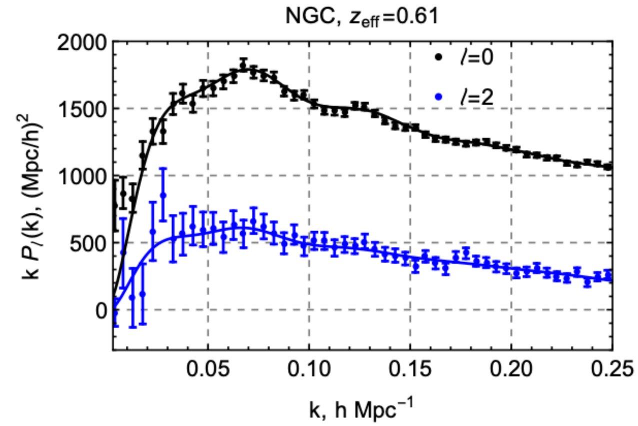






http://www.sdss3.org/science/boss_publications.php

Information in LSS data



Sources of information:

- Distance free information, shape of the spectrum

- $\omega_b = \Omega_b h^2$; $\omega_m = \Omega_m h^2$ Set the sound horizon $r_d(\omega_b, \omega_m)$

- Distance information

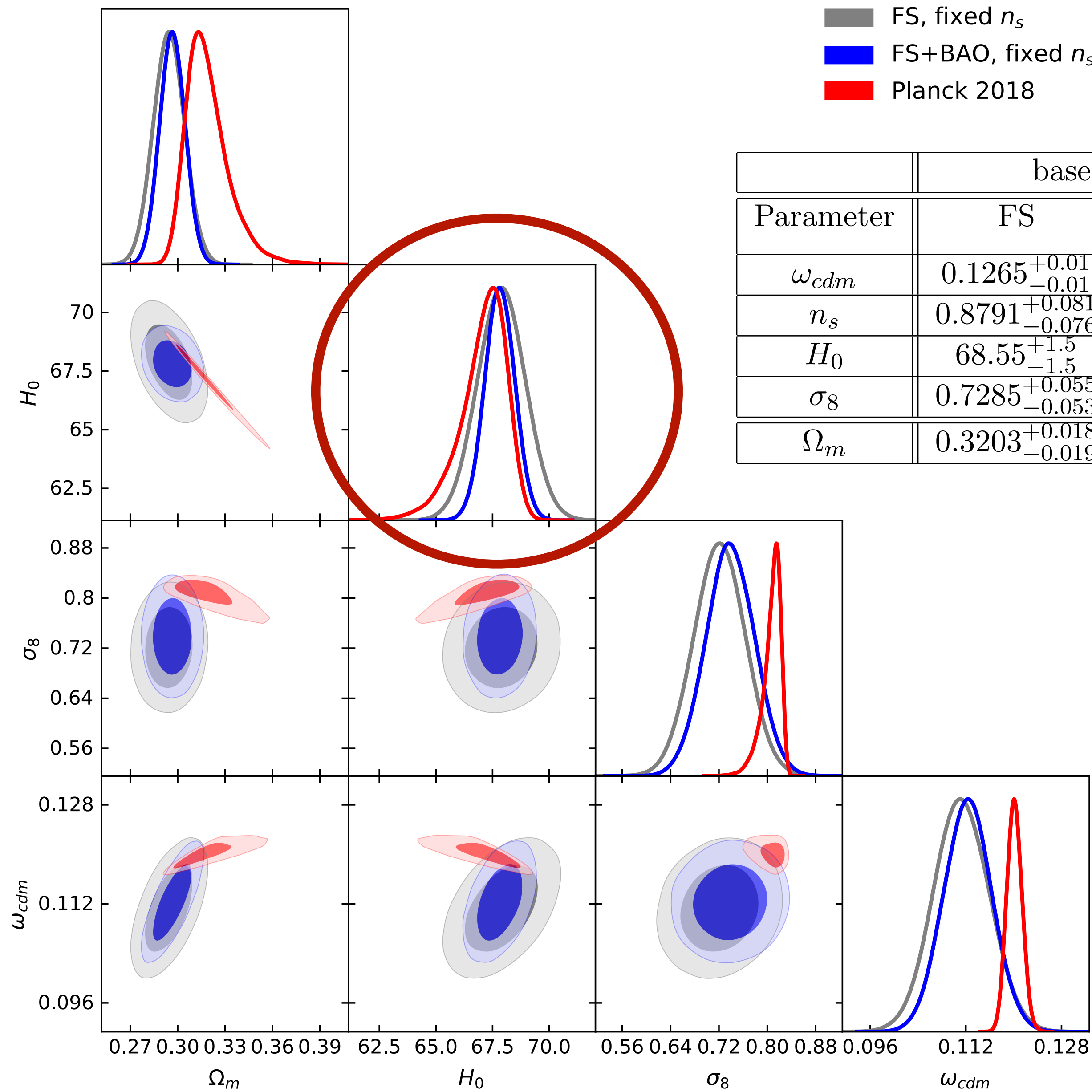
$$D_V(z) \equiv ((1+z)^2 D_A^2(z) z / H(z))^{1/3}$$

$$D_A(z) \equiv \frac{1}{1+z} \int_0^z \frac{dz'}{H(z')} .$$

Set the angle and redshift we observe the features in the spectrum

- Amplitude information, mainly from RSD (growth, neutrino masses) $f\sigma_8$

A CMB independent measurement of Ho



	base $\nu\Lambda$CDM		base $\nu\Lambda$CDM + fixed n_s	
Parameter	FS	FS+BAO	FS	FS+BAO
ω_{cdm}	$0.1265^{+0.01}_{-0.01}$	$0.1259^{+0.009}_{-0.0093}$	$0.1113^{+0.0047}_{-0.0048}$	$0.1121^{+0.0041}_{-0.0041}$
n_s	$0.8791^{+0.081}_{-0.076}$	$0.9003^{+0.076}_{-0.071}$	–	–
H_0	$68.55^{+1.5}_{-1.5}$	$68.55^{+1.1}_{-1.1}$	$67.90^{+1.1}_{-1.1}$	$67.81^{+0.68}_{-0.69}$
σ_8	$0.7285^{+0.055}_{-0.053}$	$0.7492^{+0.053}_{-0.052}$	$0.7215^{+0.044}_{-0.044}$	$0.7393^{+0.04}_{-0.041}$
Ω_m	$0.3203^{+0.018}_{-0.019}$	$0.3189^{+0.015}_{-0.015}$	$0.2945^{+0.01}_{-0.01}$	$0.2962^{+0.0082}_{-0.008}$

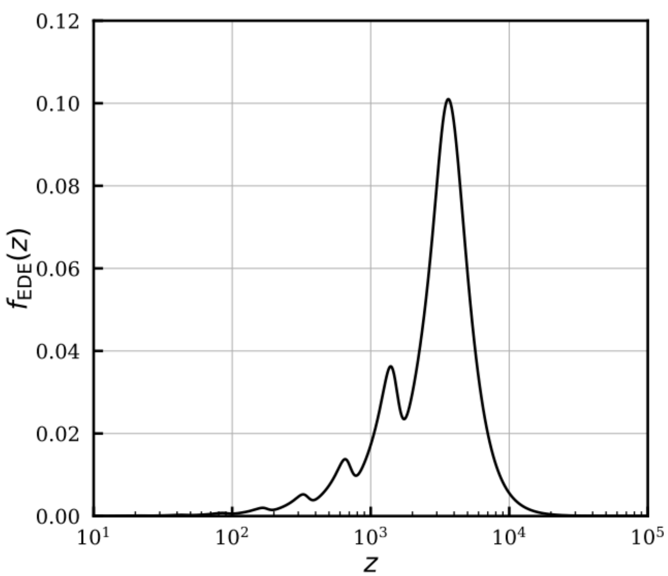
It is still dependent on the physics at decoupling being "standard". Will present an example where this is relaxed at the end.

2002.04035

\+ Evan McDonough, Colin Hill, Michael Toomey, Stephon Alexander

2006.11235

Early Dark Energy



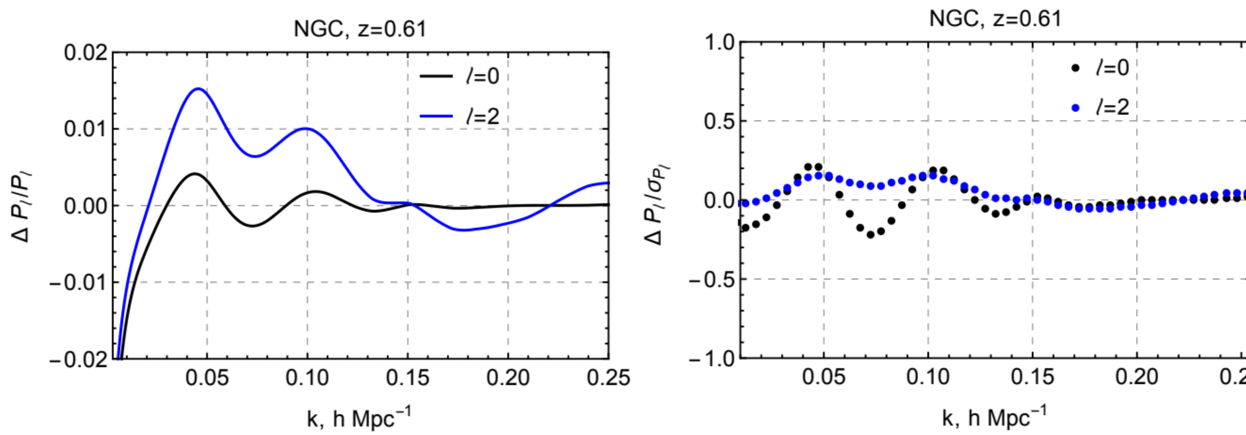


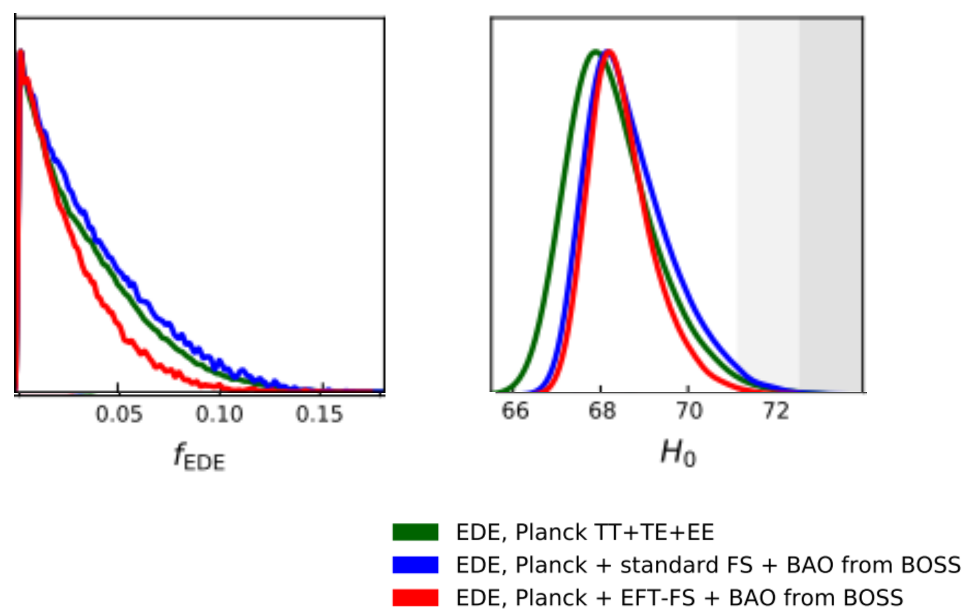
FIG. 4. Multipoles of the galaxy power spectrum at $z = 0.61$, after marginalizing over nuisance parameters as in the right panel of Fig. 3. *Left panel*: Fractional difference between ΛCDM and EDE: $\Delta P/P \equiv (P^{\rm EDE} - P^{\Lambda\rm CDM})/P^{\Lambda\rm CDM}$. The monopole features a 0.3% pattern produced by the mismatch in the shape of the BAO wiggles between the two models, whereas the quadrupole exhibits a $\mathcal{O}(2\%)$ fractional difference at low k. *Right panel*: Fractional difference in units of the BOSS data error bar for every wavenumber bin: $\Delta P/\sigma_P$. (Note that the neighboring k bins are correlated). The biggest discrepancy is observed in the shape and position of the BAO wiggles in the monopole; see the main text for details.

EDE

$$
\begin{aligned}
H_0 &= 71.15\,\text{km/s/Mpc}, & 100\omega_b &= 2.286 \qquad (7)\\
\omega_{\rm cdm} &= 0.12999, & \ln 10^{10}A_s &= 3.058,\\
n_s &= 0.9847, & \tau_{\rm reio} &= 0.0511\\
f_{\rm EDE} &= 0.105 \quad \log_{10}(z_c) = 3.59 & \theta_i &= 2.71\,,\\
\Omega_m &= 0.303 \quad \sigma_8 = 0.8322 & S_8 &= 0.8366,\\
f\sigma_8|_{z=0.38} &= 0.482 & f\sigma_8|_{z=0.61} &= 0.477\,.
\end{aligned}
$$

LCDM

$$
\begin{aligned}
H_0 &= 68.07\,\text{km/s/Mpc} & 100\omega_b &= 2.249, \qquad (8)\\
\omega_{\rm cdm} &= 0.11855 & \ln 10^{10}A_s &= 3.047,\\
n_s &= 0.9686 & \tau_{\rm reio} &= 0.0566,\\
\Omega_m &= 0.306 \quad \sigma_8 = 0.808 & S_8 &= 0.816,\\
f\sigma_8|_{z=0.38} &= 0.47 & f\sigma_8|_{z=0.61} &= 0.464\,.
\end{aligned}
$$



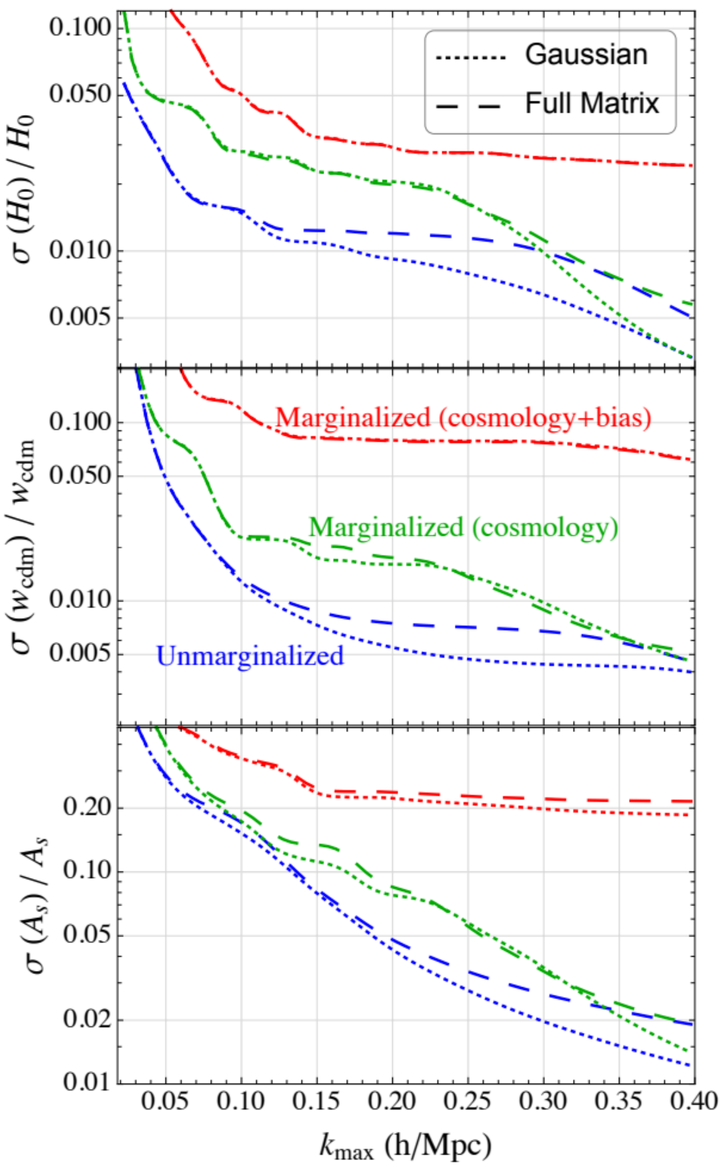
Implications H0 measurement

- Tension not a result of systematics in the CMB data
- Independent measurement with similar error bar as Planck but consistent with it
- Discrepancy can only be fixed by changing assumed physics during recombination but and LSS data has very small error bars and no hint of any discrepancy.

Prospects for the future

- We now understand what the theory for large scale clustering is and how accurate it is.
- It is agnostic about the small scale dynamics which is encoded in a handful of free parameters which are derived on the basis of symmetries.
- We still need to compute predictions for higher order moments and perhaps improve the predictions for the two point function by going to higher loop order.
- The limiting factor in our ability to extract cosmological information is the uncertainty coming from the small scale physics. What would it take to improve on this?

Nuisance parameters



Wadekar, Ivanov and Scoccimarro 2009.00822

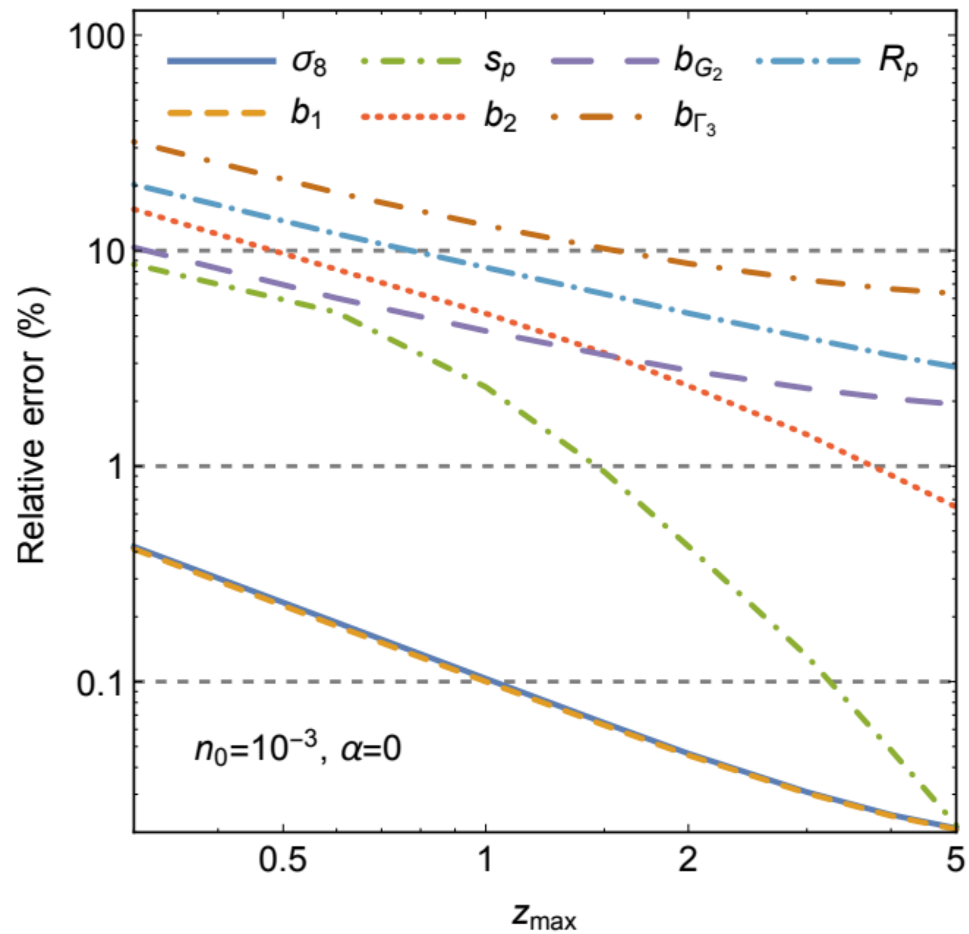
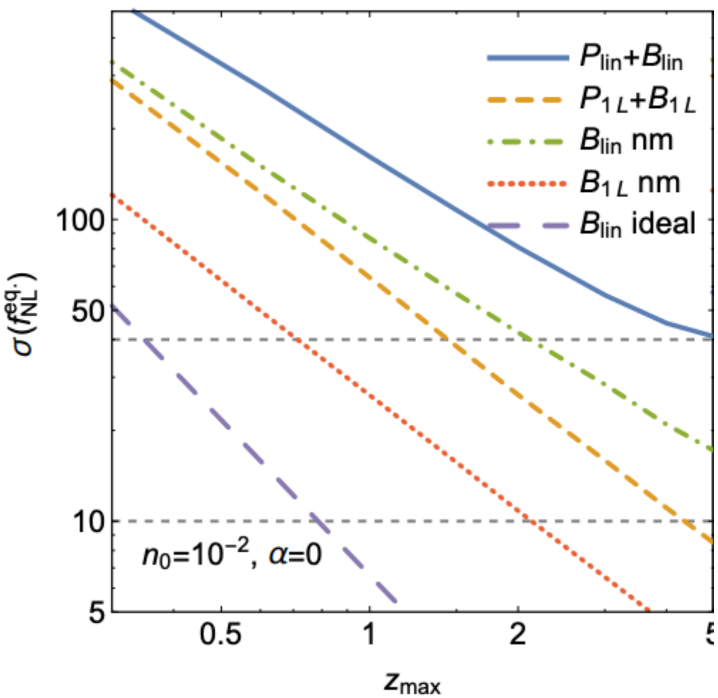


FIG. 5: Unmarginalized relative errors of different parameters as a function of maximal redshift $z_{\max}$.

Baldauf, Mirbabayi, Simonović, Zaldarriaga 1602.00674

Primordial non-Gaussianity: Theoretical errors



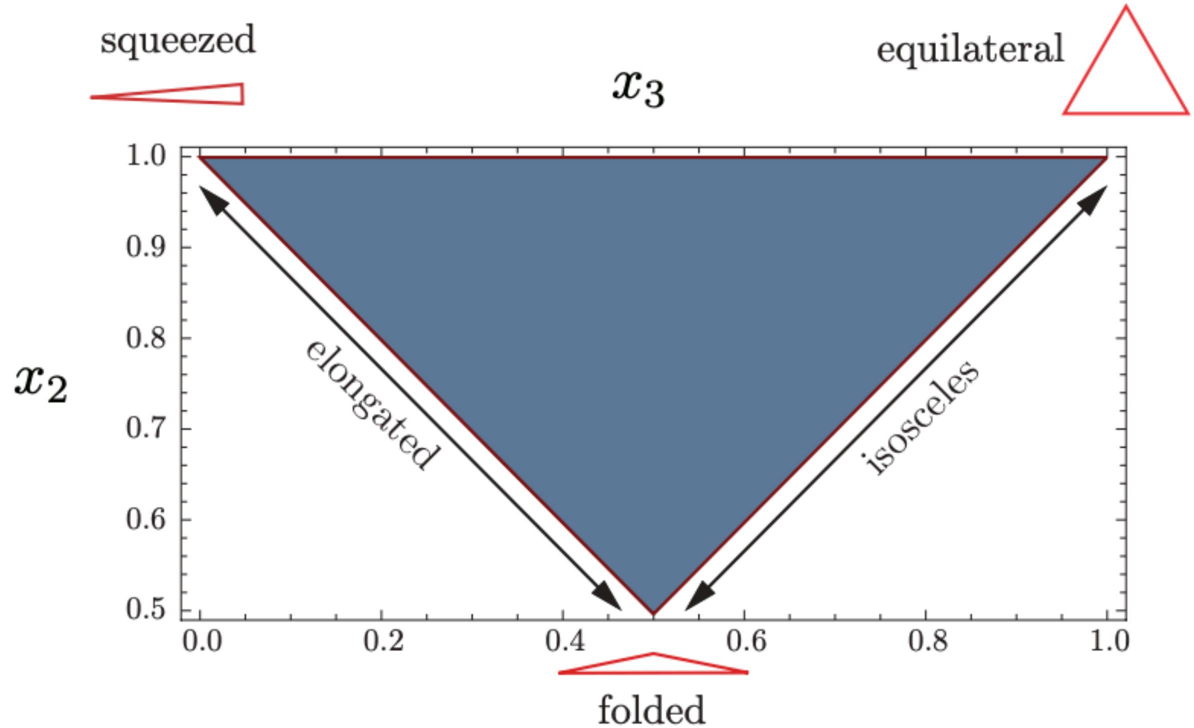


Figure 5.1: *Momentum configurations of the bispectrum.*

FIG. 6: One sigma error bar on $f_{NL}^{eq.}$ as a function of the maximal redshift z_{max}. Two horizontal lines correspond to $f_{NL}^{eq.} = 40$ (the current strongest bound from the CMB) and $f_{NL}^{eq.} = 10$. Each panel shows the constraints with and without marginalization over the EFT and bias parameters. Different lines correspond to different combinations of the tree-level and the one-loop power spectrum and bispectrum. As a reference we also plot a line for the ideal case with no theoretical error and no marginalization.

Baldauf, Mirbabayi, Simonović, Zaldarriaga 1602.00674

To improve on Planck we need to detect sub percent effects and have the theory under control at that level!.

Theoretical errors

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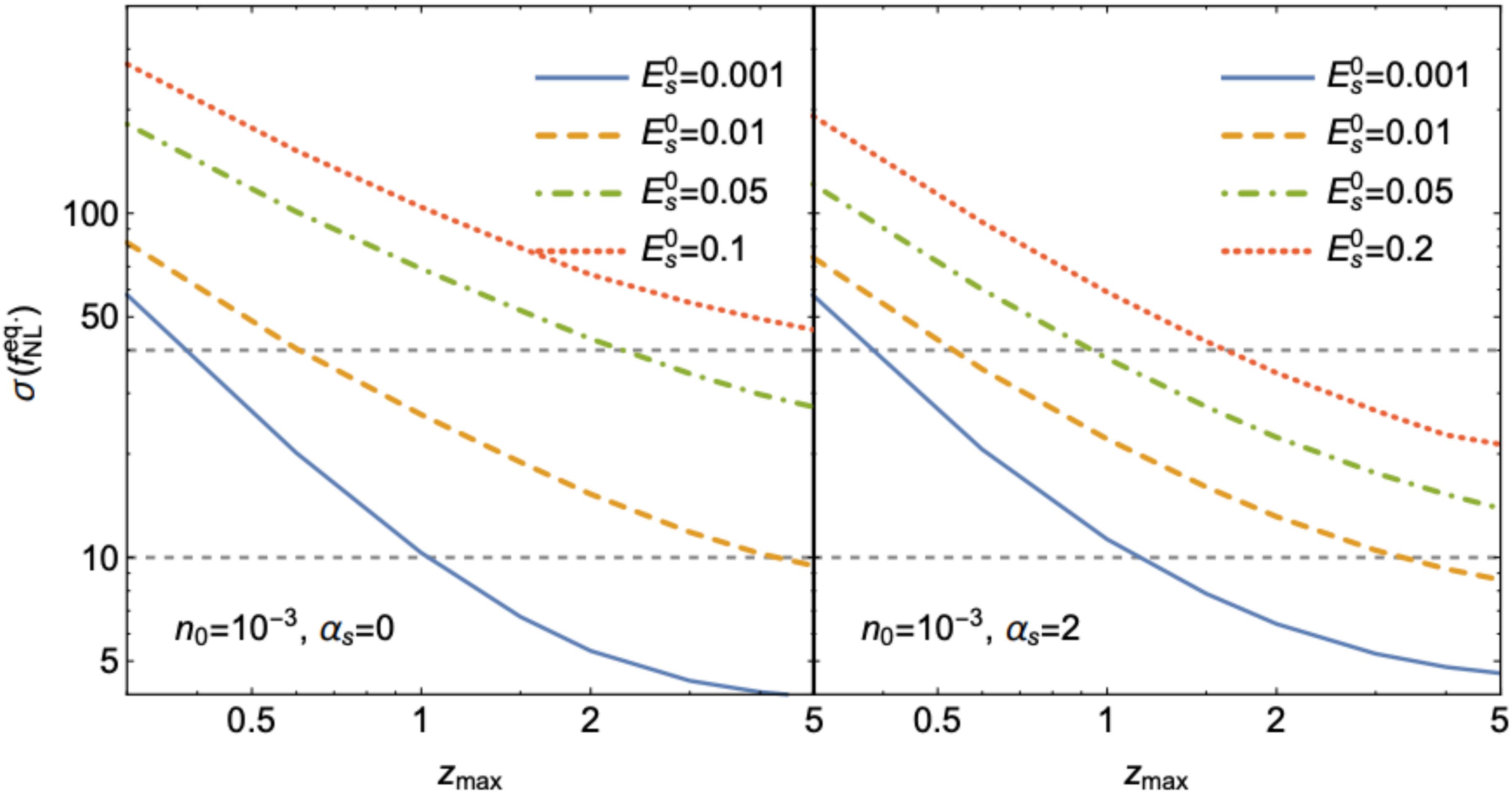

In order to improve over CMB constraints one needs to be able to predict the large scale 3 point function with percent or better precision after accounting for any nuisance parameters (which could be fixed on the basis of other observations).

Summary

- There are many questions still open on Cosmology, eg. the origin of the primordial seeds, neutrino masses, the evolution of the dark energy.
- We expect to get answers to some of these questions from the studies of the clustering of matter on large scales. These are scales where the dynamics is simple, linear theory captures it very well but there are small corrections. Those corrections however are larger than the observational errors.
- The EFT of Large Scale Structure is the theory that describes the dynamics on very large scales. We understand what is needed to compute these small corrections both consistently and accurately.
- The fact that on small scales the dynamics is complicated, modifies in fundamental but controllable ways the theory that describe the evolution on large scales. Although these effects are small and are encoded in a handful of free parameters marginalizing over the corresponding uncertainties degrades constraints substantially. There is significant room for progress.