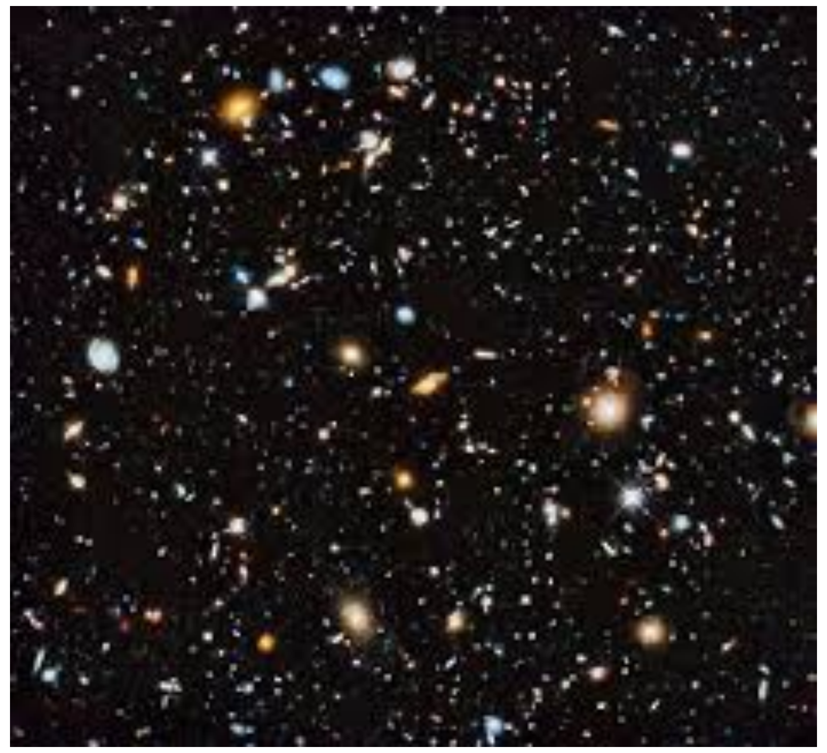
Precision cosmology from galaxy surveys

Marko Simonović (CERN)



	base $\nu\Lambda$CDM	
Parameter	FS	FS+BAO
ω_{cdm}	$0.1265^{+0.01}_{-0.01}$	$0.1259^{+0.009}_{-0.0093}$
n_s	$0.8791^{+0.081}_{-0.076}$	$0.9003^{+0.076}_{-0.071}$
H_0	$68.55^{+1.5}_{-1.5}$	$68.55^{+1.1}_{-1.1}$
σ_8	$0.7285^{+0.055}_{-0.053}$	$0.7492^{+0.053}_{-0.052}$
Ω_m	$0.3203^{+0.018}_{-0.019}$	$0.3189^{+0.015}_{-0.015}$

University of Florence
18 May 2022

Outline

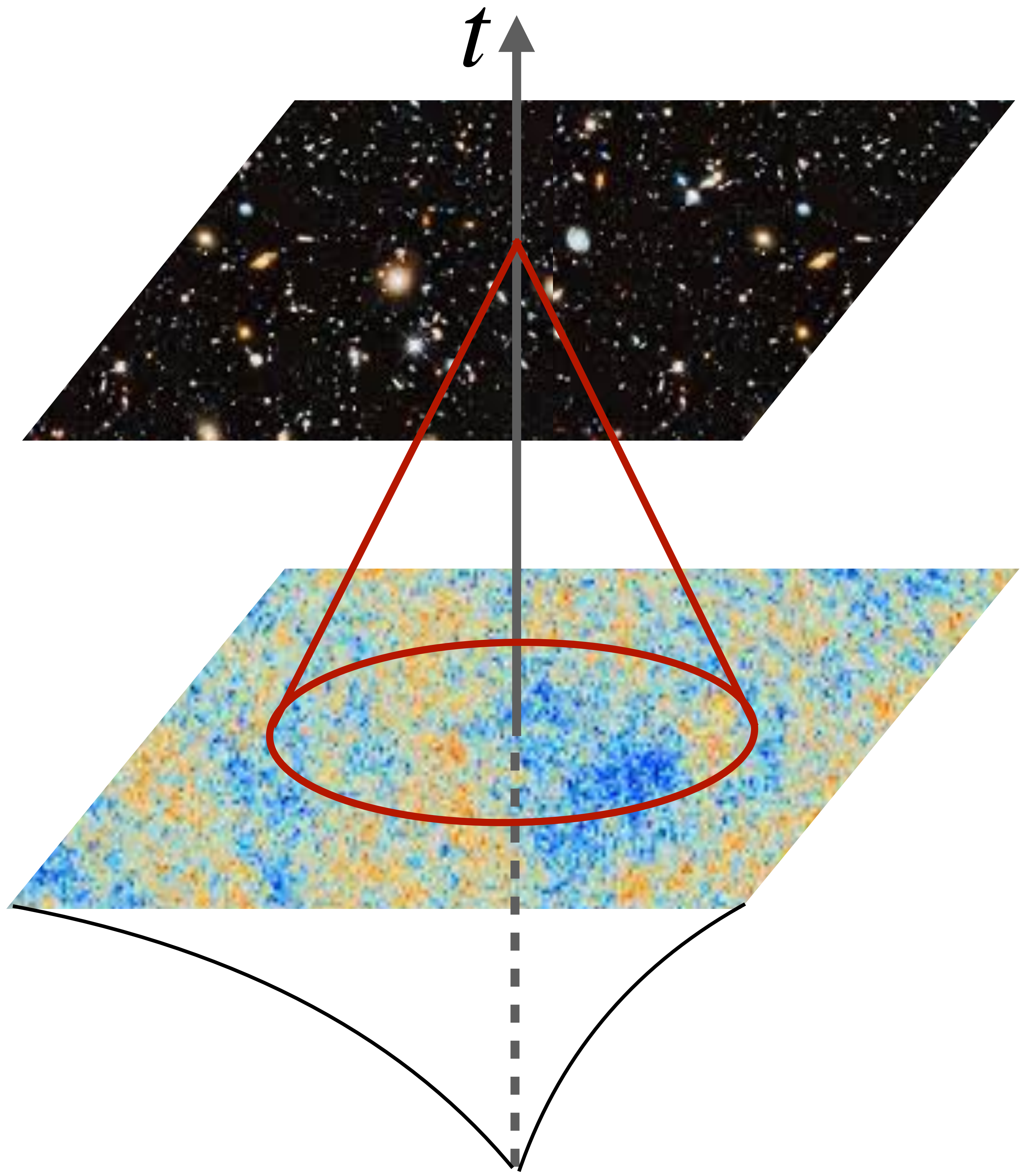
General motivation and context for spectroscopic galaxy surveys

Dynamics of large-scale structure as an EFT

Application to data and prospects for this decade

Motivation and context

Cosmology from density fluctuations



Initial conditions
(inflation)

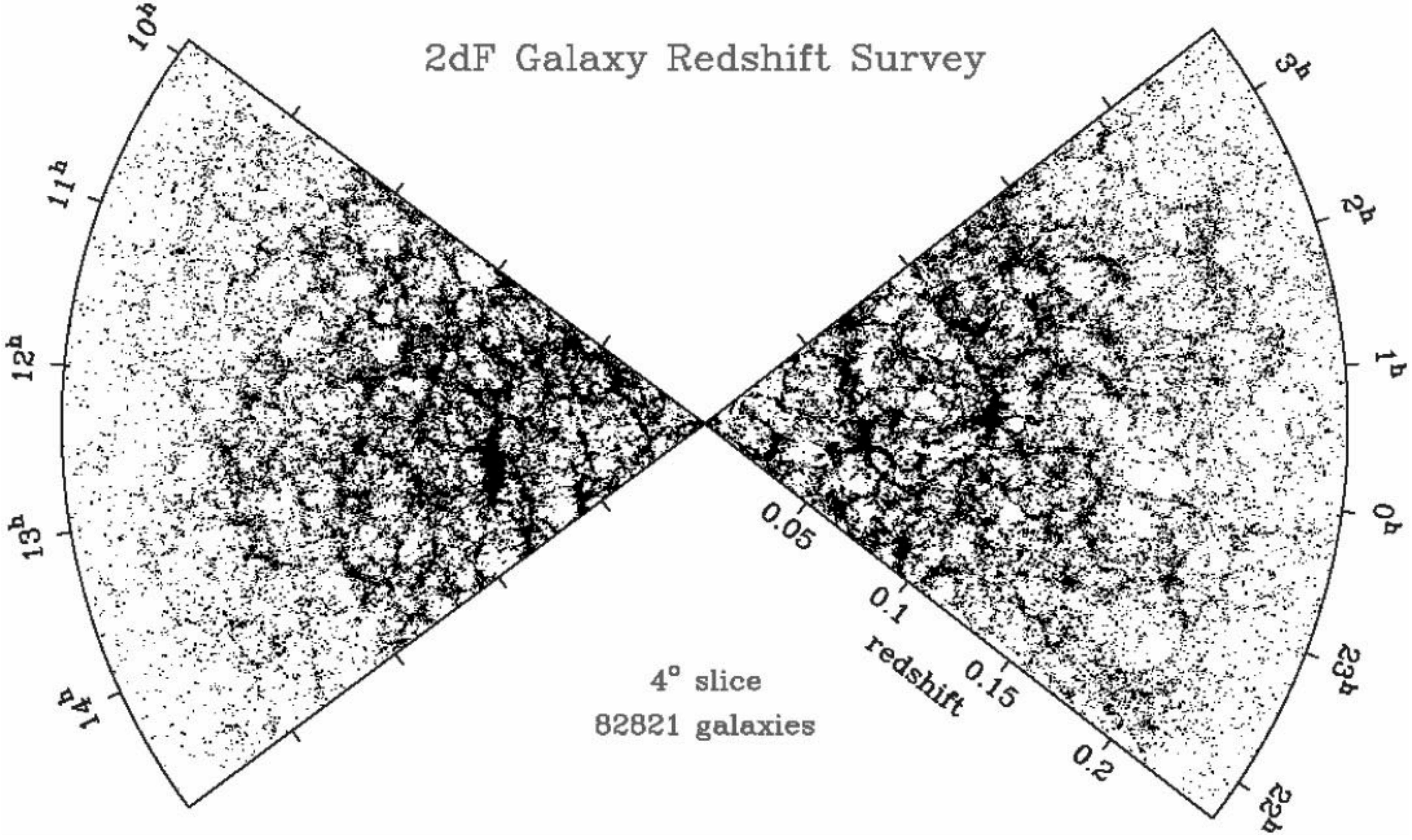
→ Can we learn more?

→ Dark matter
Dark energy
Inflation

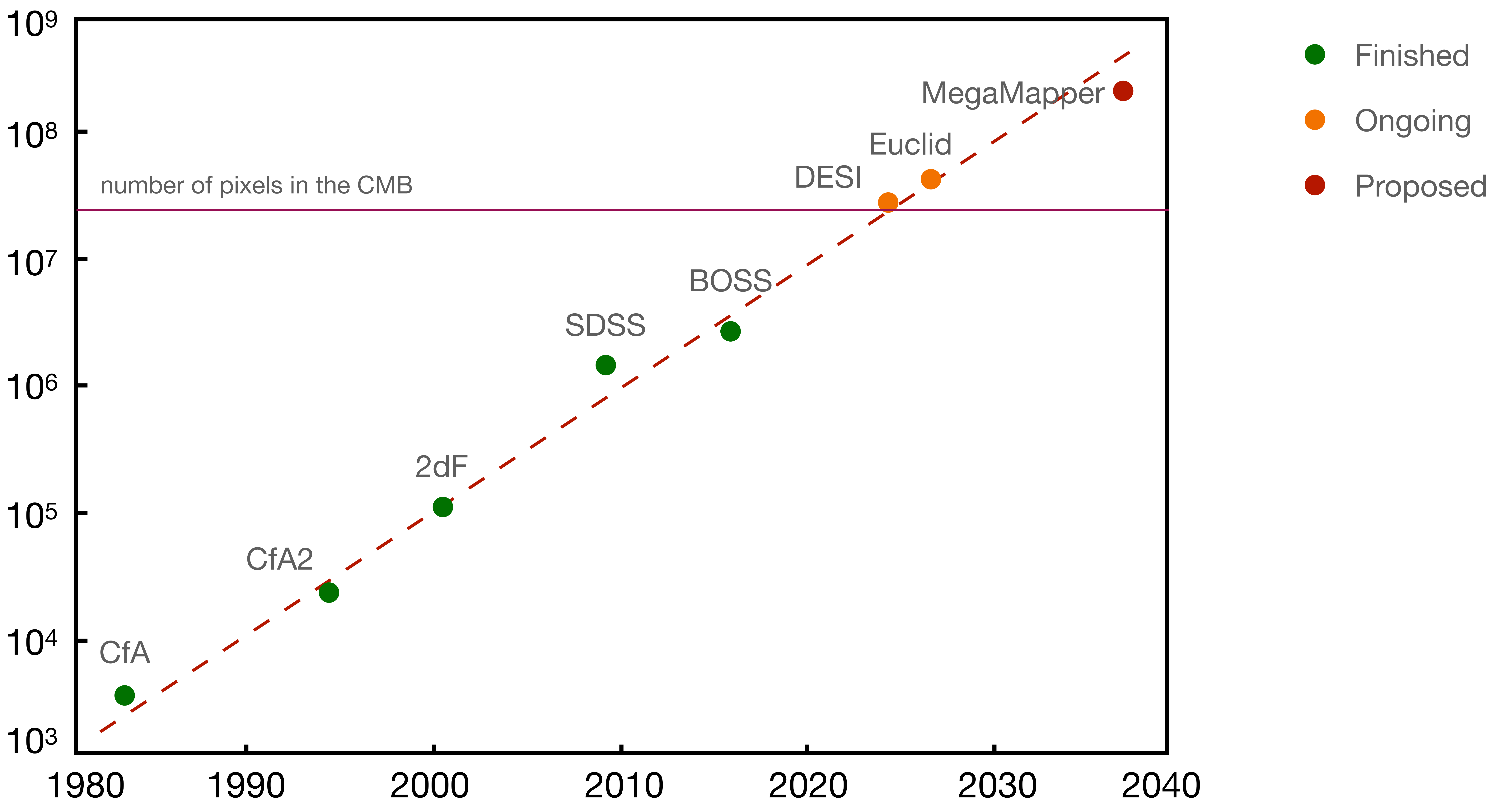
↓

Particle physics, string theory…

What are (spectroscopic) galaxy surveys?



Number of observed galaxy spectra as a function of time



Why are we doing it?

1) Distribution of galaxies remembers the initial conditions

Single “clock”? Speed of inflaton fluctuations less than 1?
“Spectroscopy” of massive/higher spin particles?
Primordial features in the power spectrum?

2) Everything gravitates

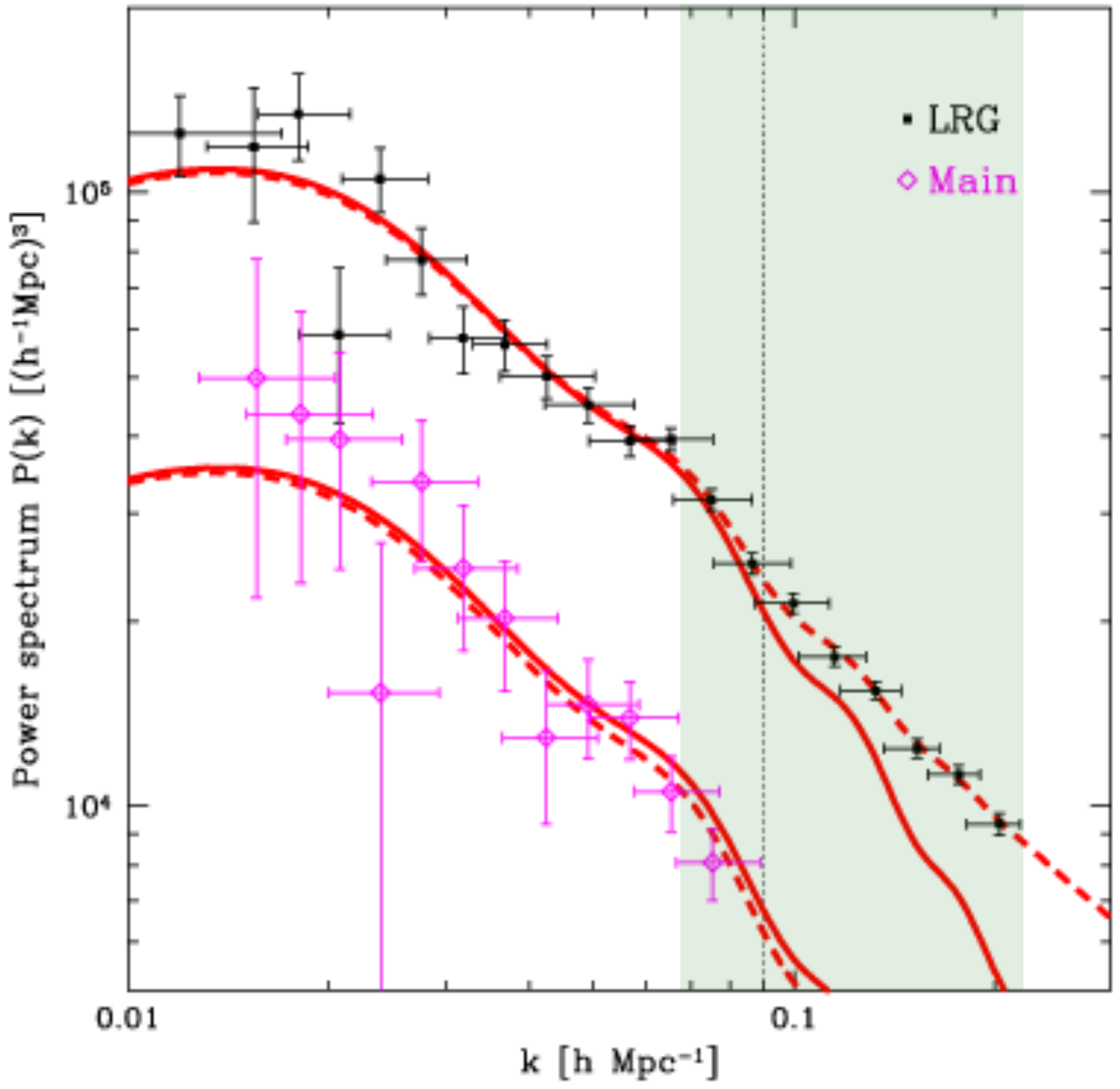
Sum of neutrino masses. Other massive (but light) relics? Ultralight axions?
Spatial curvature, dark energy?
New energy components in early or late universe?
Probing dark sector, new long-range interactions?

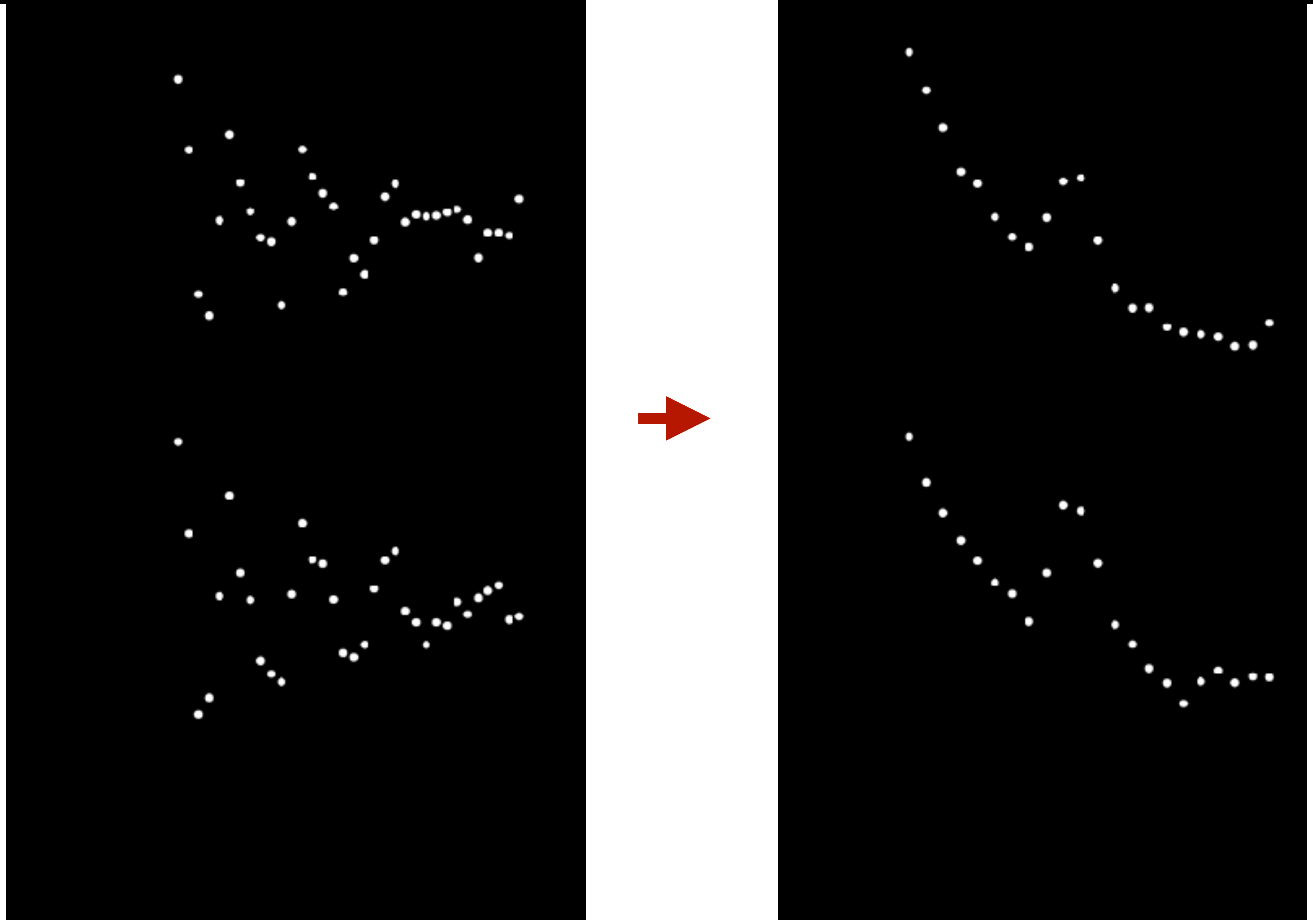
How are we going to do it?

$$\delta(\boldsymbol{x}) \equiv \frac{\rho(\boldsymbol{x}) - \bar{\rho}}{\bar{\rho}} \qquad \delta(\boldsymbol{x}) = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} \delta_{\boldsymbol{k}} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \qquad \langle \delta_{\boldsymbol{k}} \delta_{\boldsymbol{k}'} \rangle = (2\pi)^3 \delta^D(\boldsymbol{k} + \boldsymbol{k}') P(k)$$

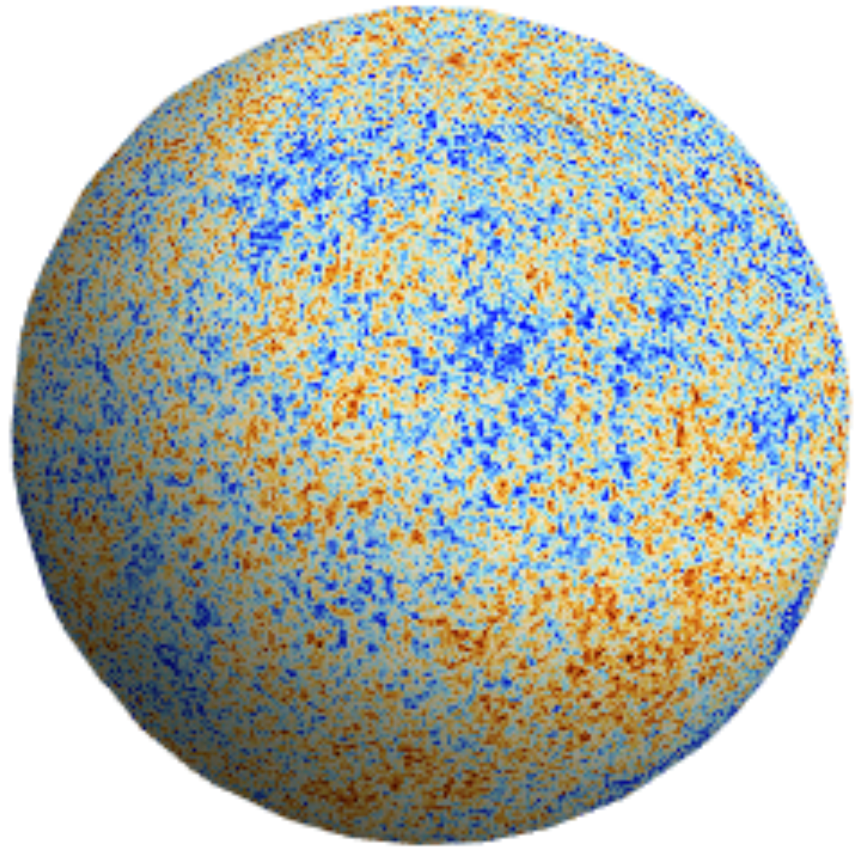
+n-point functions

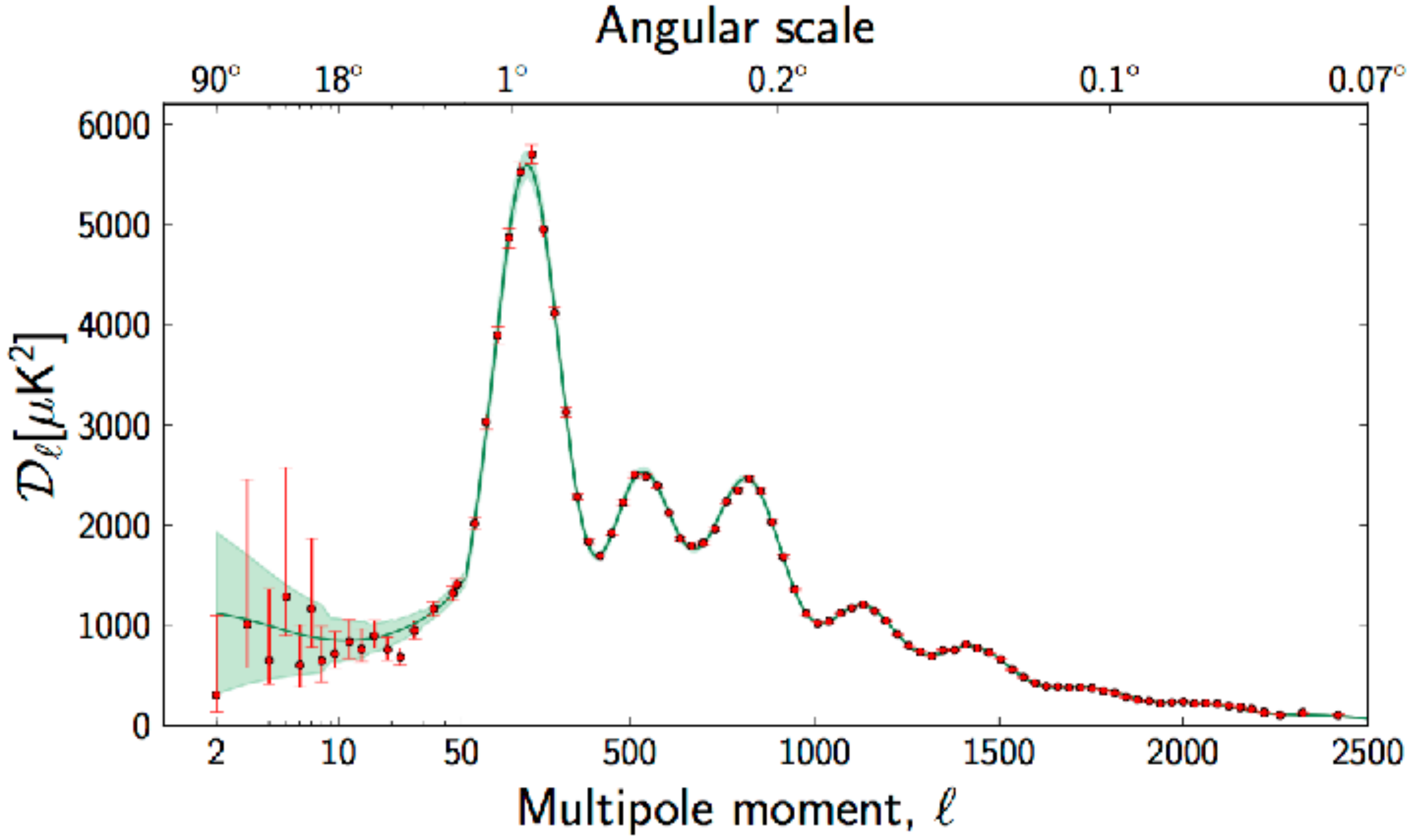
The power spectrum has a lot of features that carry information about cosmology





Isn’t the CMB good enough?





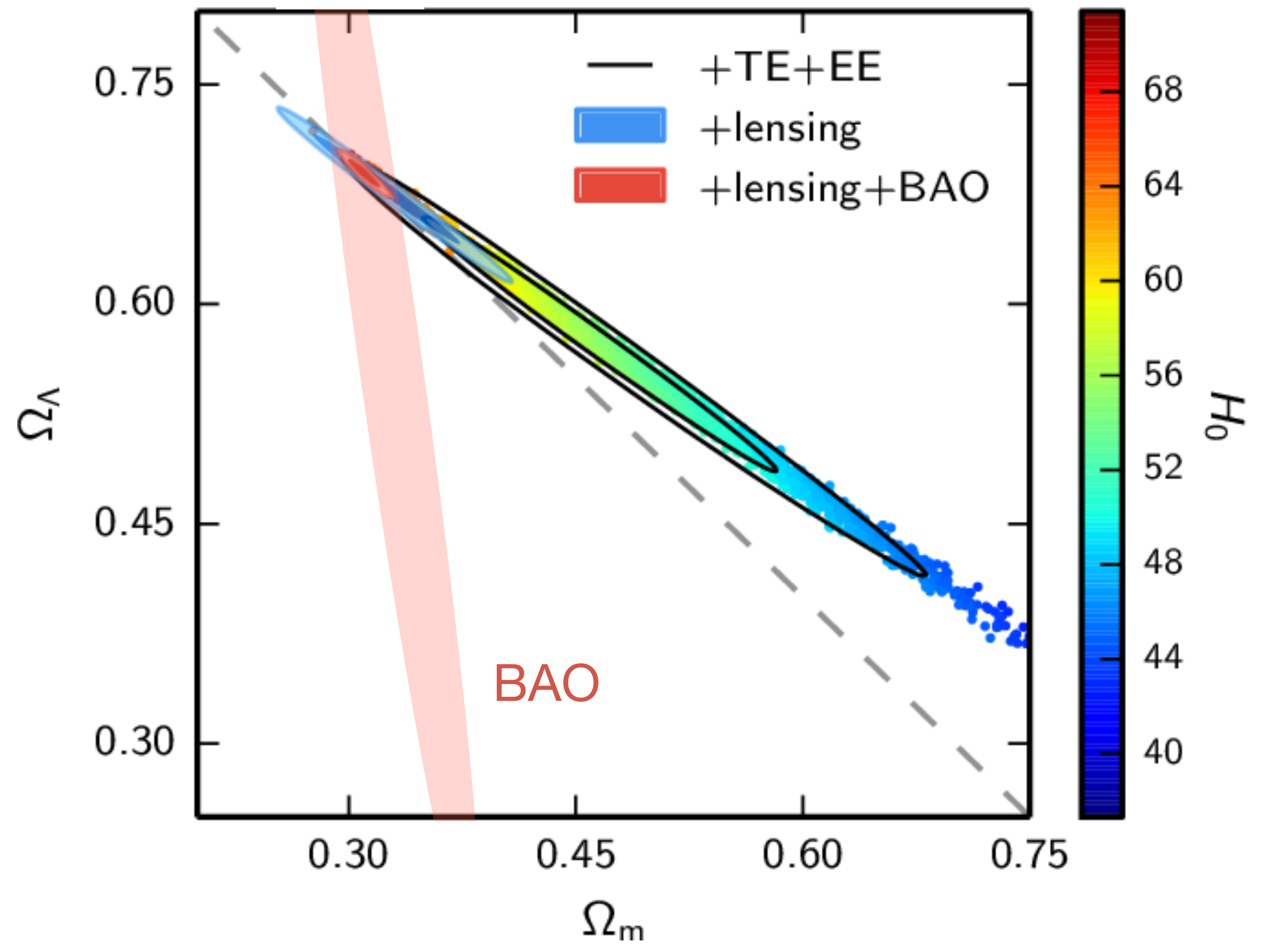
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10}A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54

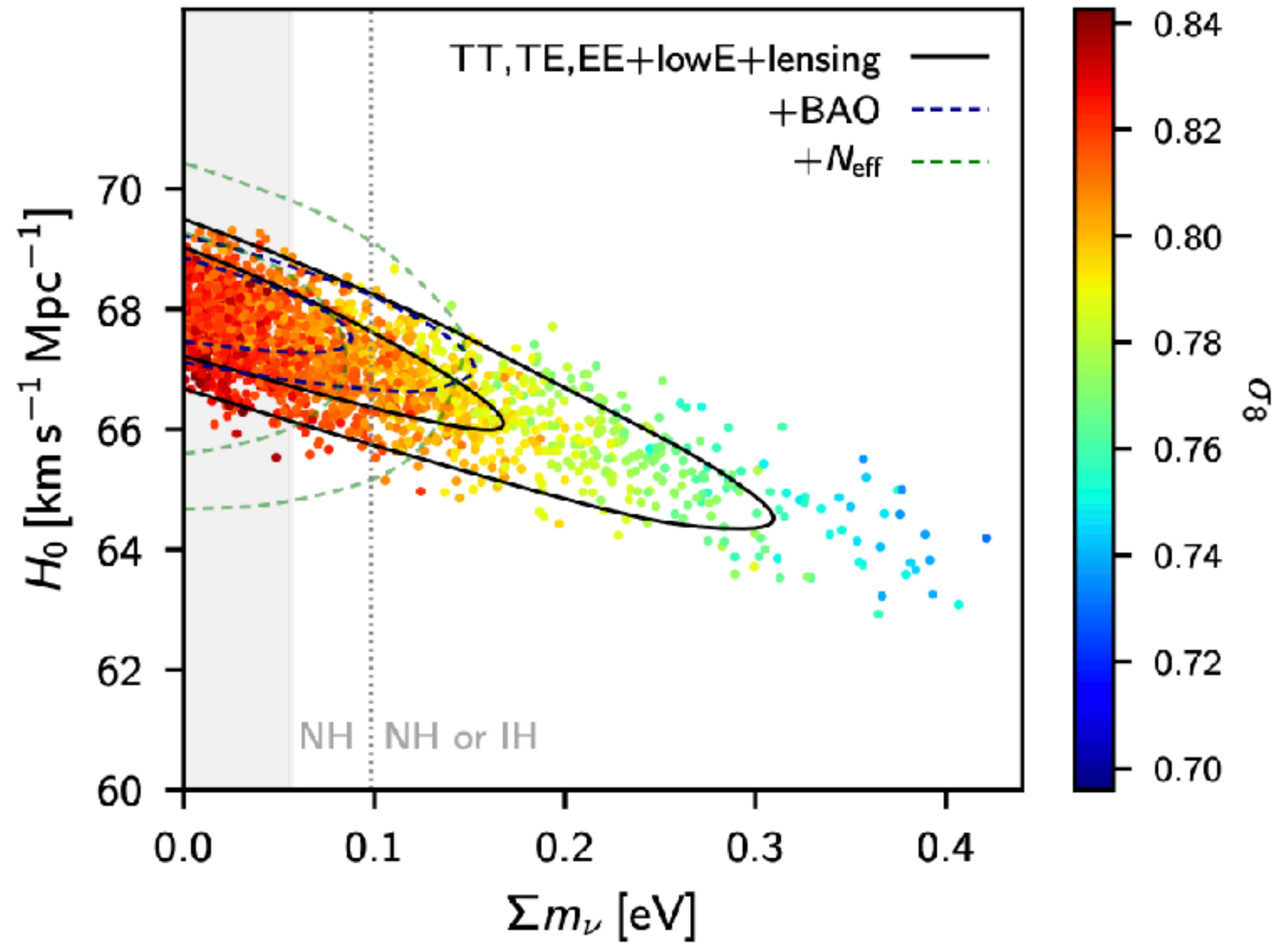
$r_s(\omega_{\rm cdm}, \omega_{\rm b})$ $\xrightarrow{\Lambda\text{CDM}}$ H_0

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

1) We are approaching the limit, given by the number of pixels on the sky: $N_{\rm pix.} \approx \ell^2_{\rm max.} \sim 10^7$

Isn't the CMB good enough?





2) There are degeneracies in the CMB that have to be broken by the external data

Motivation

CMB is great, but not sufficient to answer all open questions in cosmology

Galaxy surveys complementary, becoming competitive with the CMB

In combination, they become even more powerful

The key is robust theoretical description of galaxy clustering

Dynamics of LSS

Galaxy clustering from a physicist’s point of view

Dynamics

Perturbation theory

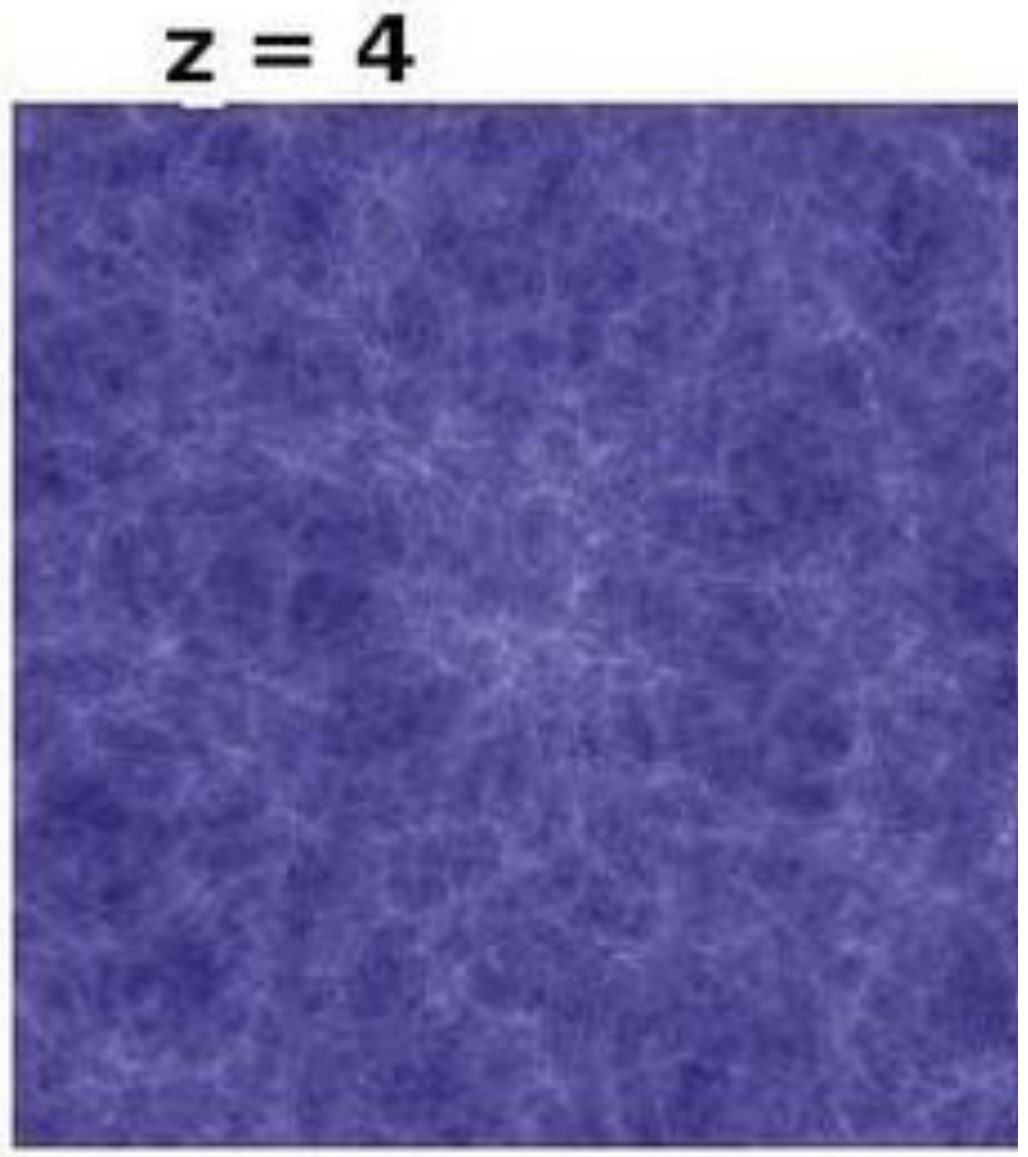
Effective Field Theory

Symmetries

Non-perturbative results

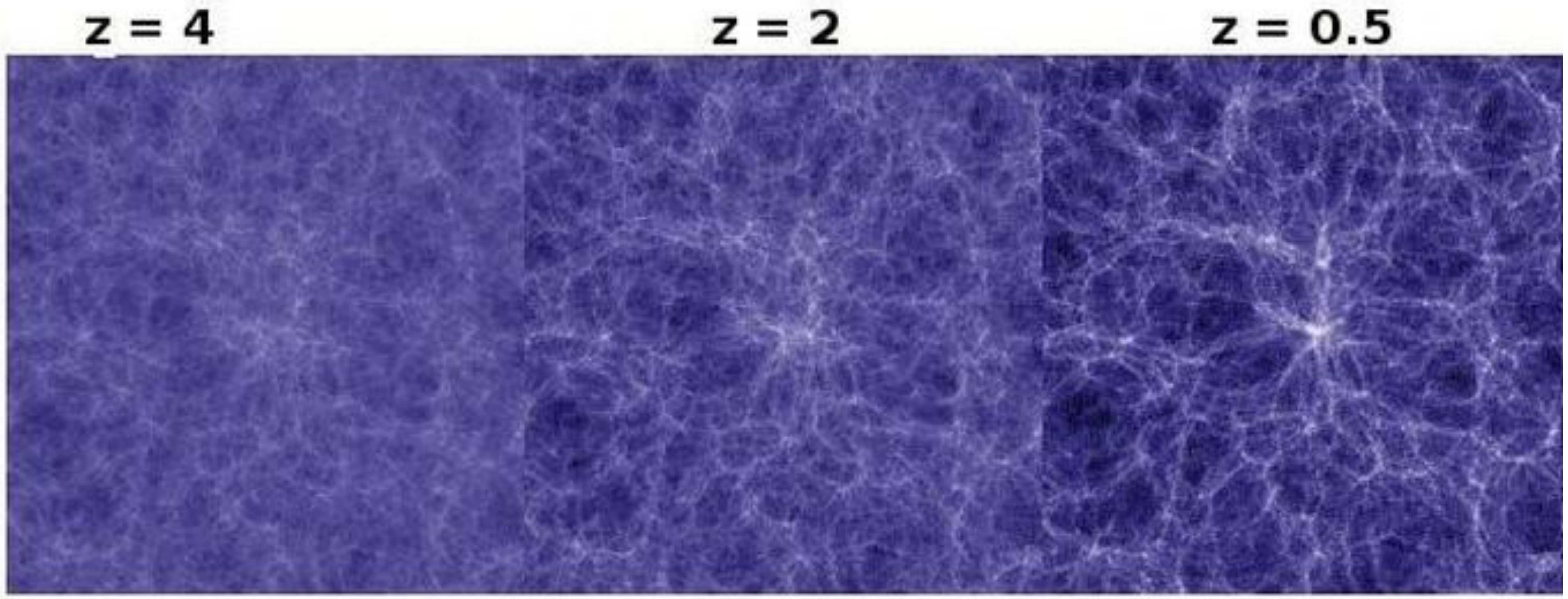
Soft theorems

The main nonlinearities in LSS



At early times fluctuations are very small and nearly gaussian

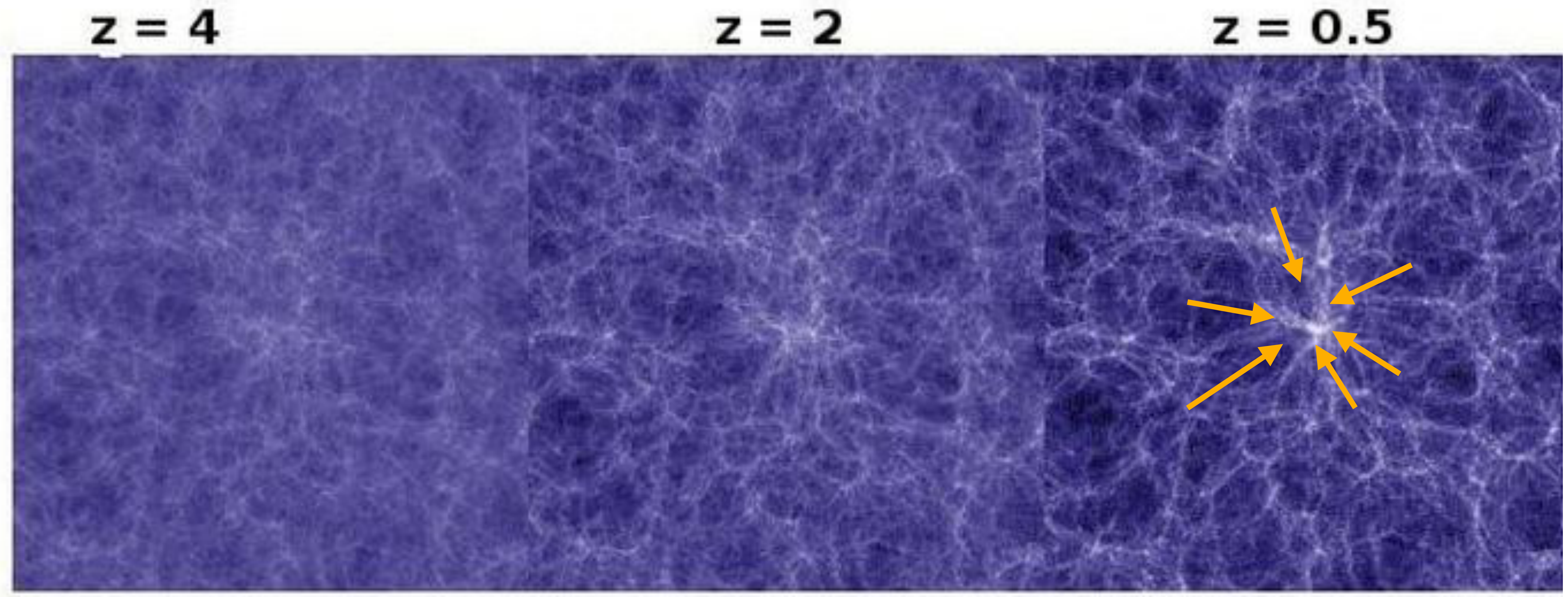
The main nonlinearities in LSS



Tides: $\partial_i \partial_j \Phi$ $\quad \sigma_R^2 \sim \frac{1}{2\pi^2} \int_0^{1/R} k^2 dk\, P_{\rm lin}(k) \sim 1$ for $R \sim$ few Mpc at low redshifts

The horizon scale $H_0^{-1} \sim 10^4$ Mpc number of pixels in LSS: $N_{\rm pix.} \approx (H_0 R_{\rm nl.})^{-3} \sim 10^9$

The main nonlinearities in LSS



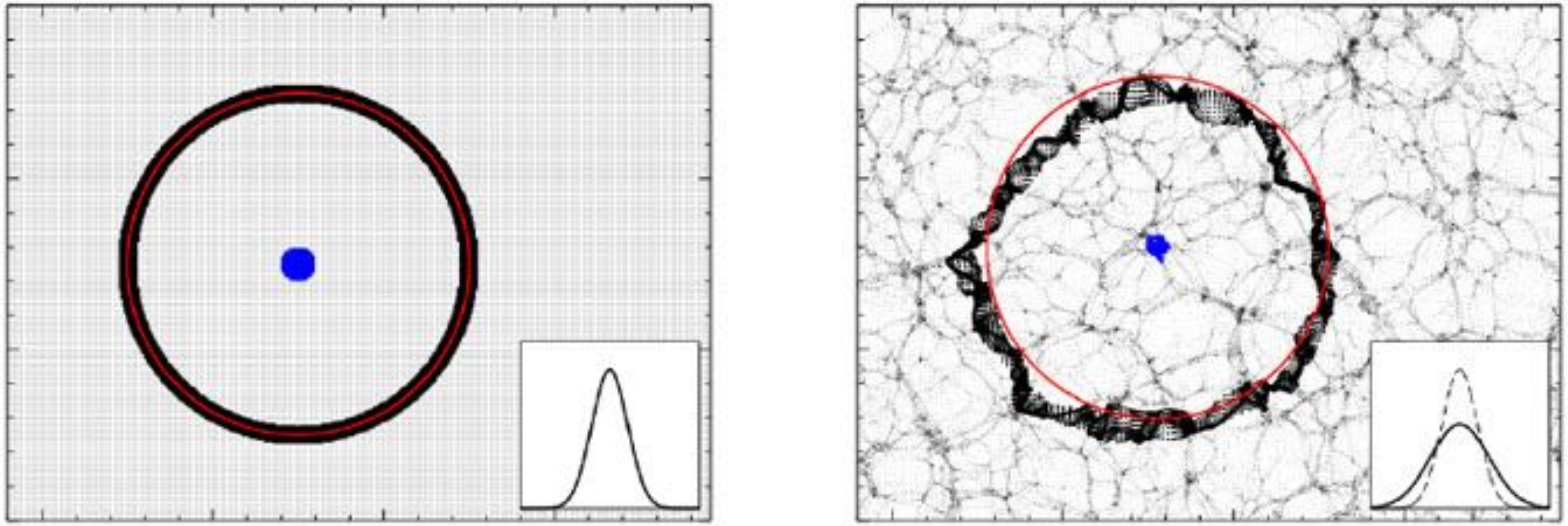
$$\boldsymbol{\psi} \sim \boldsymbol{\partial}\Phi \sim \frac{\boldsymbol{\partial}}{\partial^2}\delta$$

free fall in the potential produced by the long-wavelength fields

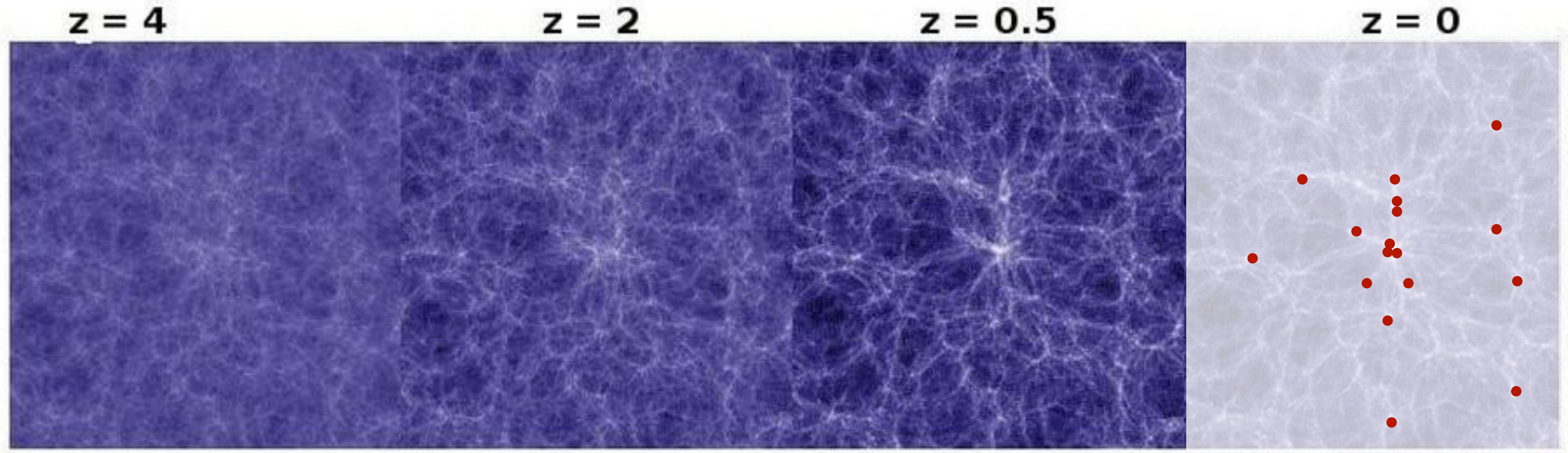
$$\sigma_v^2 = \frac{1}{6\pi^2}\int_0^{1/R} k^2 dk\, \frac{P_{\rm lin}(k)}{k^2} \approx 36\ {\rm Mpc}^2/h^2$$

typical displacements are $\mathcal{O}(10\ \mathrm{Mpc})$ at low redshifts

The main nonlinearities in LSS



The main nonlinearities in LSS

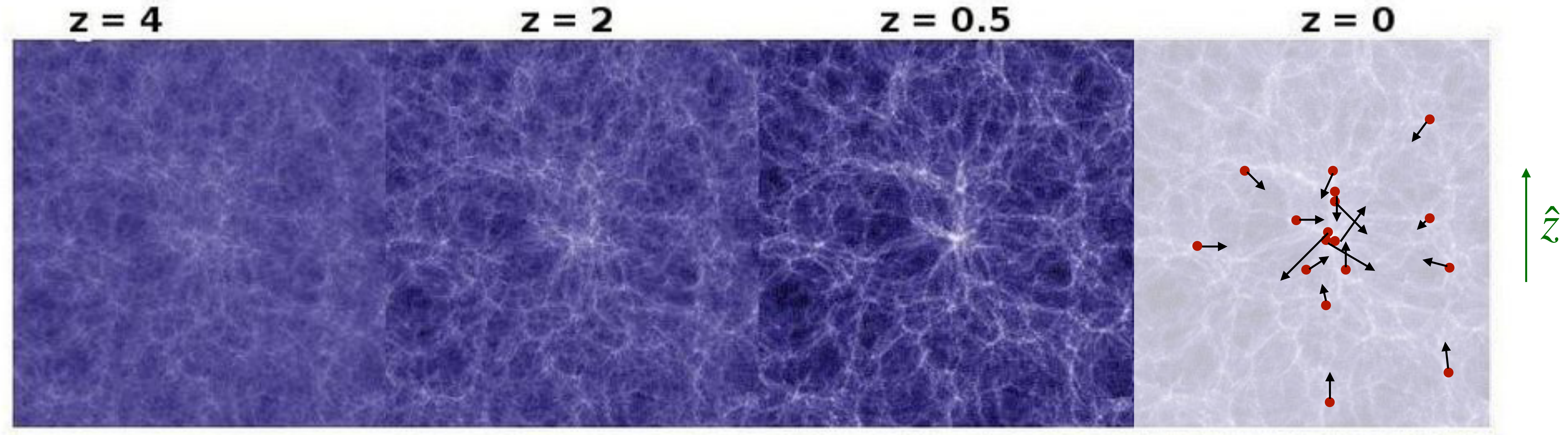


typical separation between galaxies is a few Mpc

Galaxies are discrete, biased tracers of the underlying DM field (no mass and momentum conservation)

Galaxy formation complicated, but local in space (nonlocal in time!)

The main nonlinearities in LSS



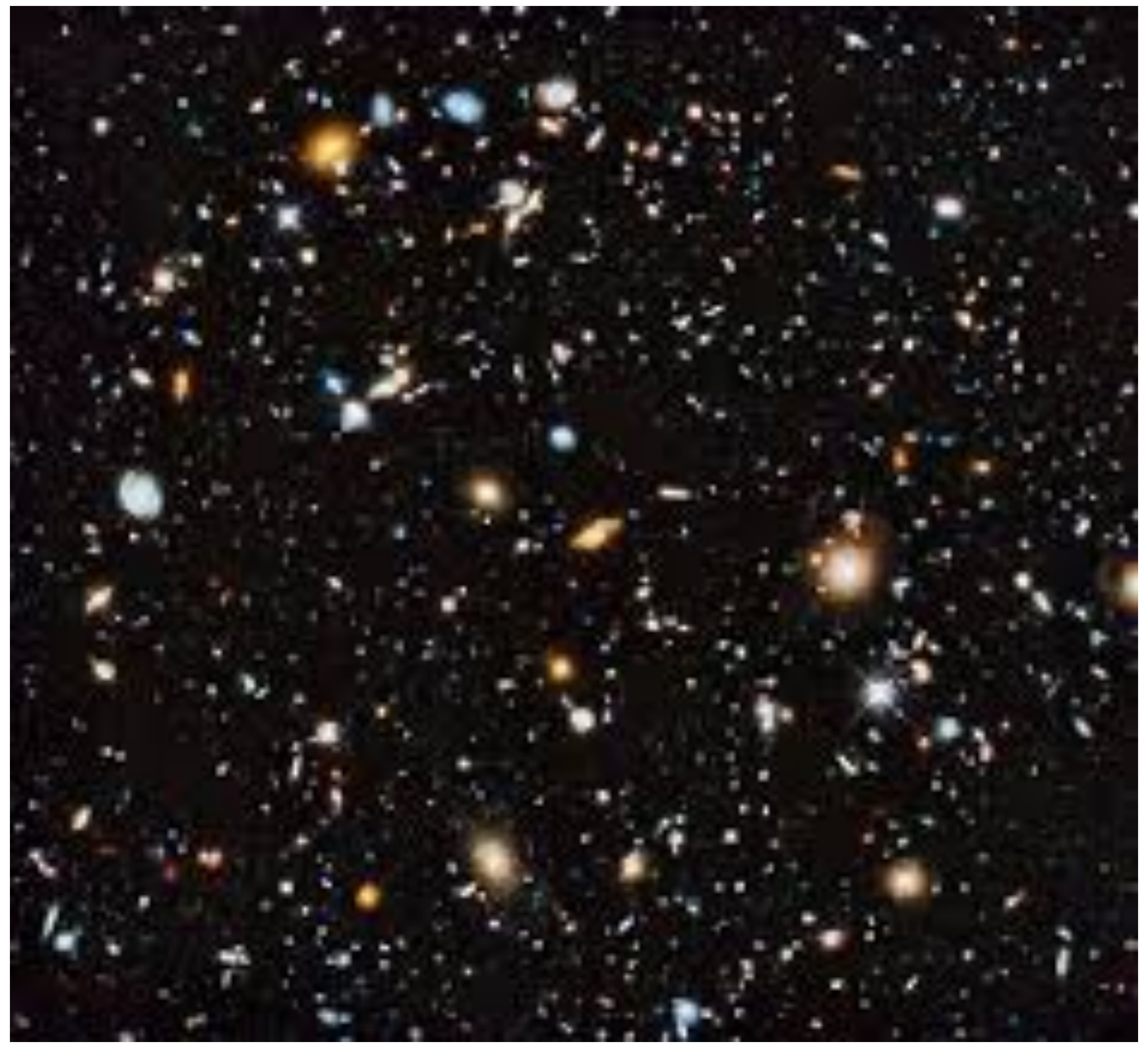
Peculiar velocities introduce redshift-space distortions

$$\vec{s} = \vec{x} + \frac{v_z}{\mathcal{H}}\hat{z}$$ velocity dependent change of coordinates

The power spectrum becomes anisotropic — multipole expansion $P_0(k)$, $P_2(k)$ …

Effective field theory of large-scale structure

Baumann, Nicolis, Senatore, Zaldarriaga (2010)
Carrasco, Hertzberg, Senatore (2012)
...



Galaxy field is a material that fills the expanding universe

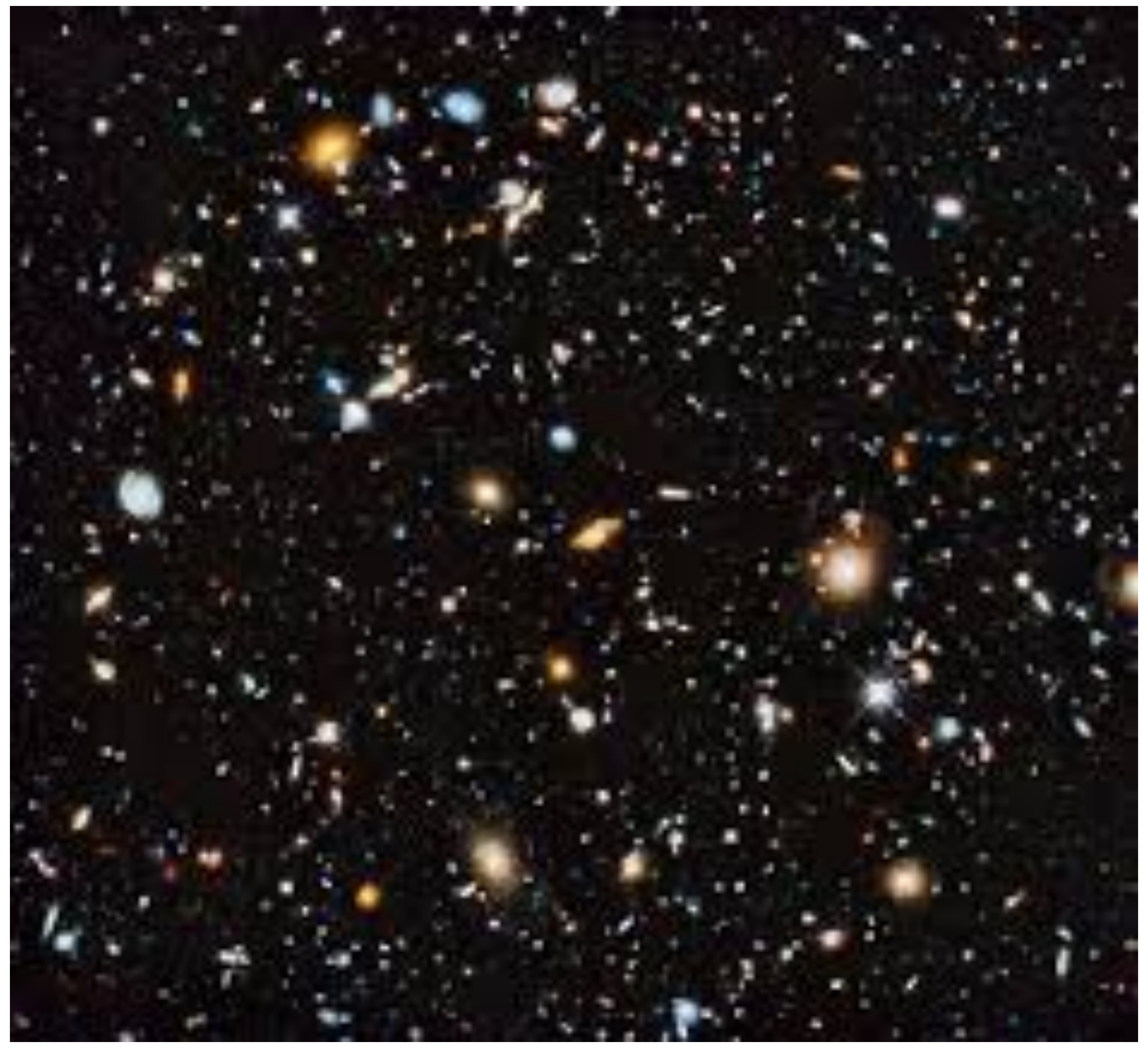
Unknown microphysics, the only long-range force is gravity

Formation of galaxies is local in space

It is ok, we do not have to know anything on small scales in order to do large-distance physics

Effective field theory of large-scale structure

Baumann, Nicolis, Senatore, Zaldarriaga (2010)
Carrasco, Hertzberg, Senatore (2012)
…



Large distance dof: δ_g

EoM are fluid-like, including gravity

Symmetries, Equivalence Principle

Expansion parameters: δ_g, $\partial / k_{\rm NL}$

All “UV” dependence is in a handful of free parameters

On scales larger than $1/k_{\rm NL}$ this is the universal description of galaxy clustering

The simplest case — dark matter

Baumann, Nicolis, Senatore, Zaldarriaga (2010)
Carrasco, Hertzberg, Senatore (2012)

Collisionless Boltzmann equation + gravity

average over “short” fluctuations →

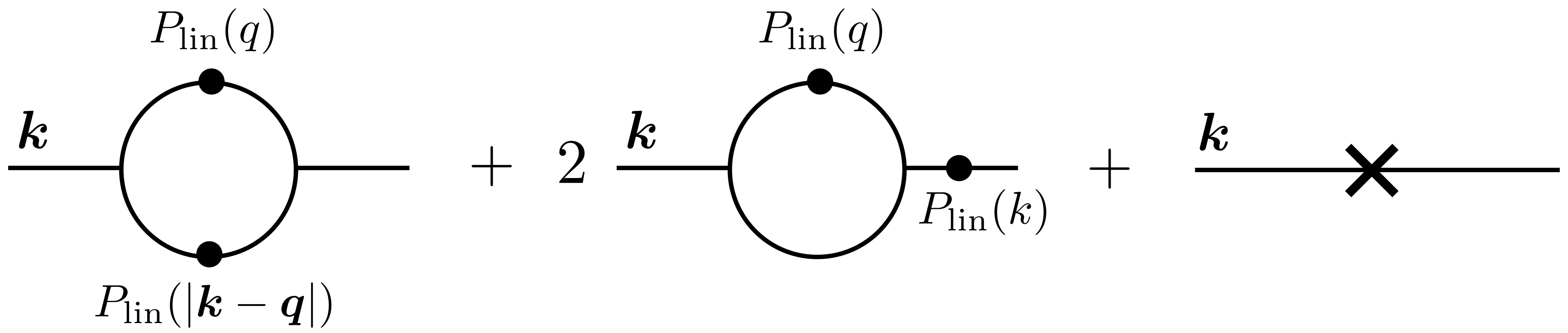
$$\partial_\tau \delta + \nabla[(1+\delta)\boldsymbol{v}] = 0$$
$$\partial_\tau \boldsymbol{v} + \mathcal{H}\boldsymbol{v} + \nabla\Phi + \boldsymbol{v}\cdot\nabla\boldsymbol{v} = \boxed{-c_s^2 \nabla\delta + \cdots}$$
$$\nabla^2\Phi = \frac{3}{2}\mathcal{H}^2\Omega_m\delta$$

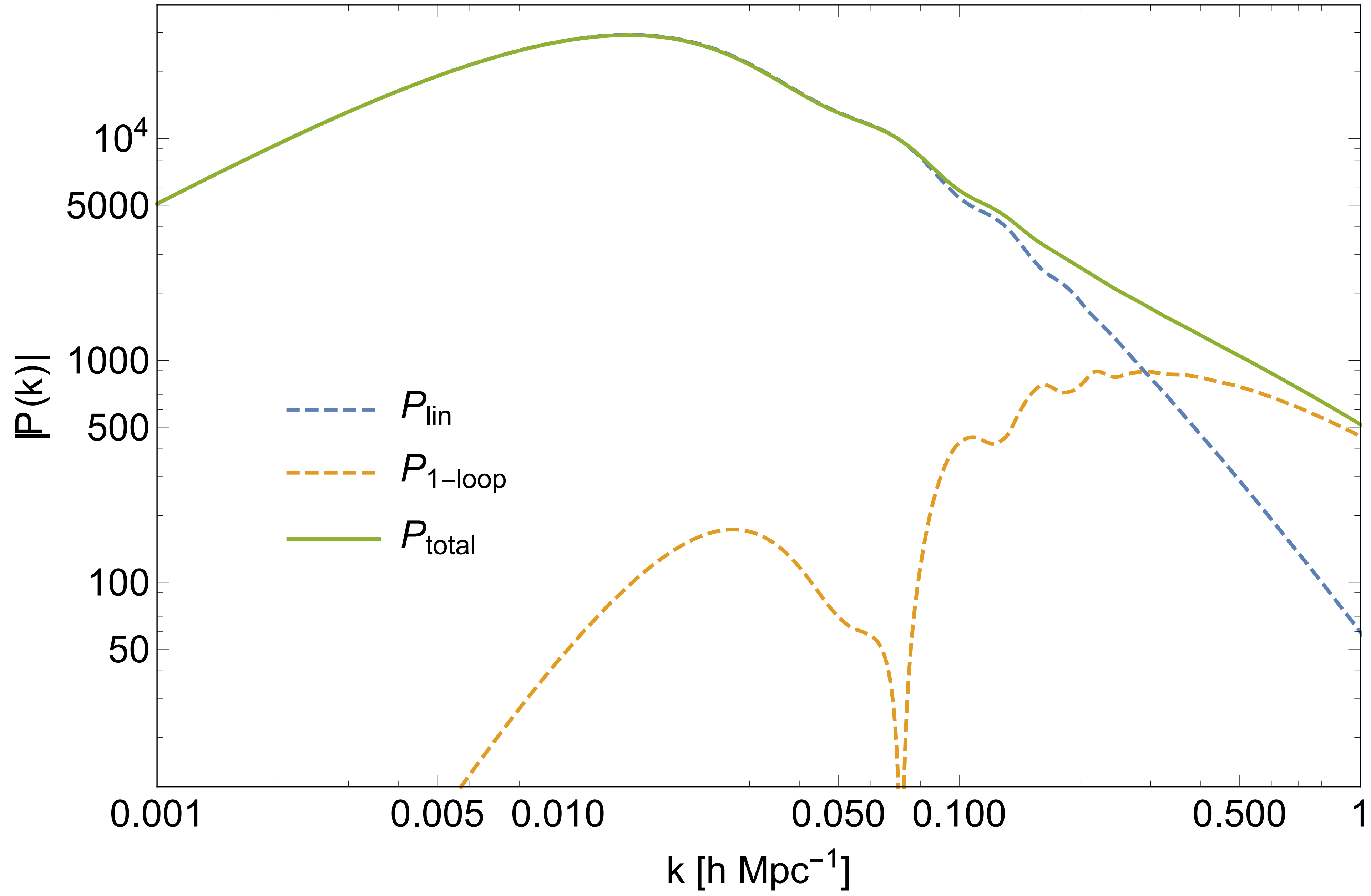
Unique long-distance description of a self-gravitating collisionless system
(the same EoM for DM and axion-like particle)

The one-loop power spectrum of dark matter

Carrasco, Hertzberg, Senatore (2012)

$$\langle \delta_{\boldsymbol{k}} \delta_{-\boldsymbol{k}} \rangle = \langle \delta^{(1)}_{\boldsymbol{k}} \delta^{(1)}_{-\boldsymbol{k}} \rangle + \langle \delta^{(2)}_{\boldsymbol{k}} \delta^{(2)}_{-\boldsymbol{k}} \rangle + \langle \delta^{(1)}_{\boldsymbol{k}} \delta^{(3)}_{-\boldsymbol{k}} \rangle + \langle \delta^{(3)}_{\boldsymbol{k}} \delta^{(1)}_{-\boldsymbol{k}} \rangle + \cdots$$

$P_{1-\mathrm{loop}}(k) =$ 



$$P_{1-\mathrm{loop}}(k) = P_{22}(k) + P_{13}(k) + 2R^2k^2P_{\mathrm{lin}}(k)$$

The counterterm R cancels the leading UV sensitivity of the loop integral: $P_{13}^{\mathrm{UV}}(k) = -\frac{61}{630\pi^2} P_{\mathrm{lin}}(k) k^2 \int_0^\infty dq P_{\mathrm{lin}}(q)$

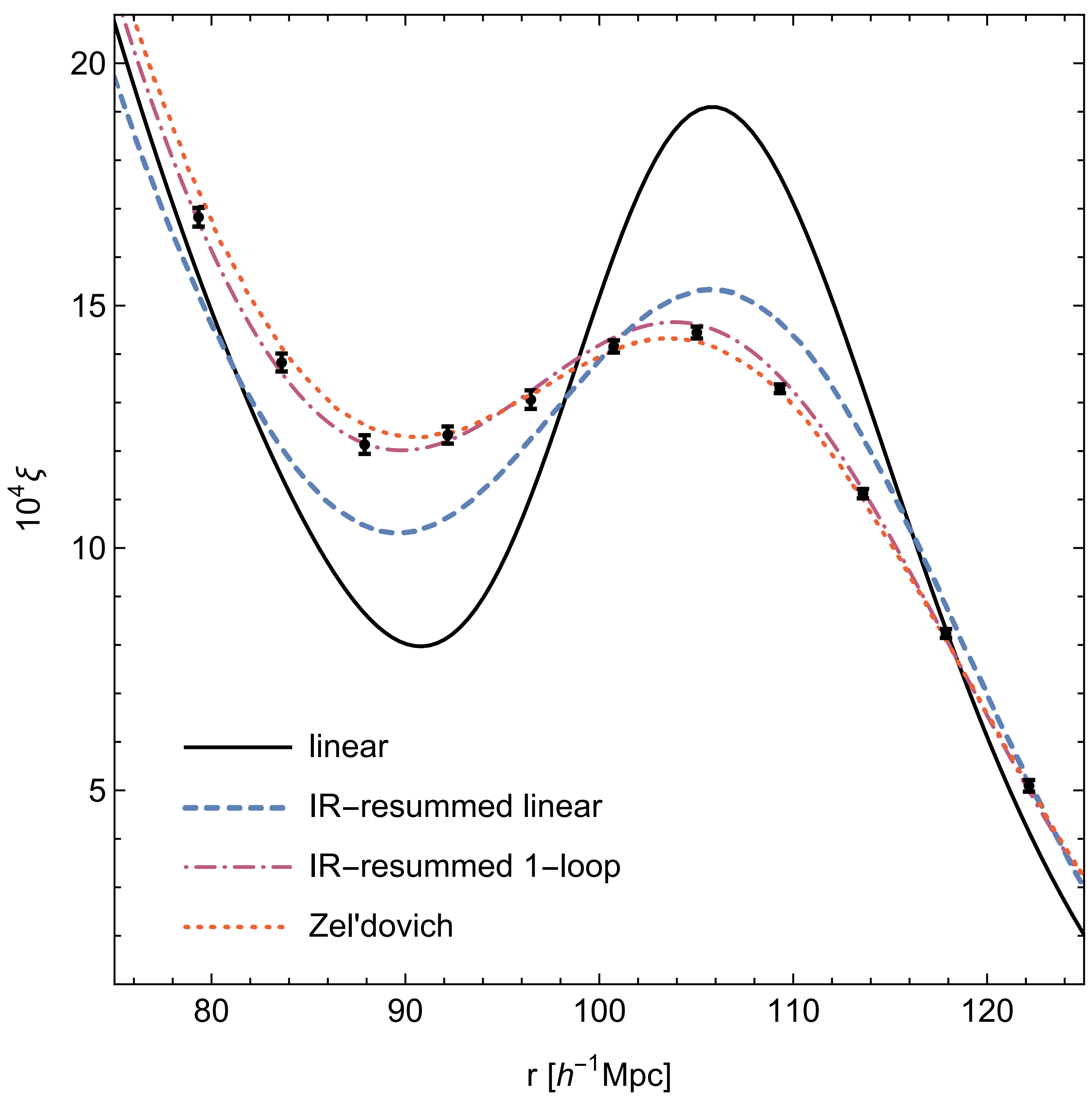
Infrared resummation

Senatore, Zaldarriaga (2014)
Baldauf, Mirbabayi, MS, Zaldarriaga (2015)
Vlah, Seljak, Chu, Feng (2015)
Blas, Garny, Ivanov, Sibiryakov (2016)
Senatore, Trevisan (2017)

Large displacements can be resummed, this is exact for galaxies too

$$\tilde{P}(k) = P^{nw}_{\rm lin}(k) + P^{nw}_{\rm 1-loop}(k) + e^{-\Sigma^2_{\epsilon k} k^2}(1+\Sigma^2_{\epsilon k}k^2)P^{w}_{\rm lin}(k) + e^{-\Sigma^2_{\epsilon k} k^2} P^{w}_{\rm 1-loop}(k)$$

$$\Sigma^2_\Lambda \approx \frac{1}{6\pi^2}\int_0^\Lambda {\rm d}q P_{\rm lin}(q)[1 - j_0(q\ell_{\rm BAO}) + 2 j_2(q\ell_{\rm BAO})]$$



One of the applications of cosmological soft theorems

Creminelli, Vernizzi, MS (2013)
Baldauf, Mirbabayi, MS, Zaldarriaga (2015)

$$\langle \delta_{\boldsymbol{q}}(\eta)\delta_{\boldsymbol{k}_1}(\eta_1)\cdots\delta_{\boldsymbol{k}_n}(\eta_n)\rangle'_{q\ll k} = -P_{\rm lin}(q,\eta)\sum_a \frac{D(\eta_q)}{D(\eta)}\frac{\boldsymbol{q}\cdot\boldsymbol{k}}{q^2}\langle\cdots\delta_{\boldsymbol{k}_a+\boldsymbol{q}}\cdots\rangle$$

Galaxies in redshift space

The nonlinear model including galaxy bias and redshift-space distortions

$$P_{\text{gg,RSD}}(z,k,\mu) = Z_1^2(\mathbf{k})P_{\text{lin}}(z,k) + 2\int_{\mathbf{q}} Z_2^2(\mathbf{q},\mathbf{k}-\mathbf{q})P_{\text{lin}}(z,|\mathbf{k}-\mathbf{q}|)P_{\text{lin}}(z,q)$$
$$+ 6Z_1(\mathbf{k})P_{\text{lin}}(z,k)\int_{\mathbf{q}} Z_3(\mathbf{q},-\mathbf{q},\mathbf{k})P_{\text{lin}}(z,q)$$
$$+ P_{\text{ctr,RSD}}(z,k,\mu) + P_{\epsilon\epsilon,\text{RSD}}(z,k,\mu)\,,$$

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

contain galaxy formation physics (b_2, $b_{\mathcal{G}_2}$, b_1)

Infrared resummation

$$\Sigma^2(z) \equiv \frac{1}{6\pi^2}\int_0^{k_S} dq\, P_{\text{nw}}(z,q)\left[1 - j_0\left(\frac{q}{k_{osc}}\right) + 2j_2\left(\frac{q}{k_{osc}}\right)\right]$$

$$\delta\Sigma^2(z) \equiv \frac{1}{2\pi^2}\int_0^{k_S} dq\, P_{\text{nw}}(z,q)j_2\left(\frac{q}{k_{osc}}\right)$$

$$\Sigma^2_{\text{tot}}(z,\mu) = (1 + f(z)\mu^2(2+f(z)))\Sigma^2(z) + f^2(z)\mu^2(\mu^2-1)\delta\Sigma^2(z)$$

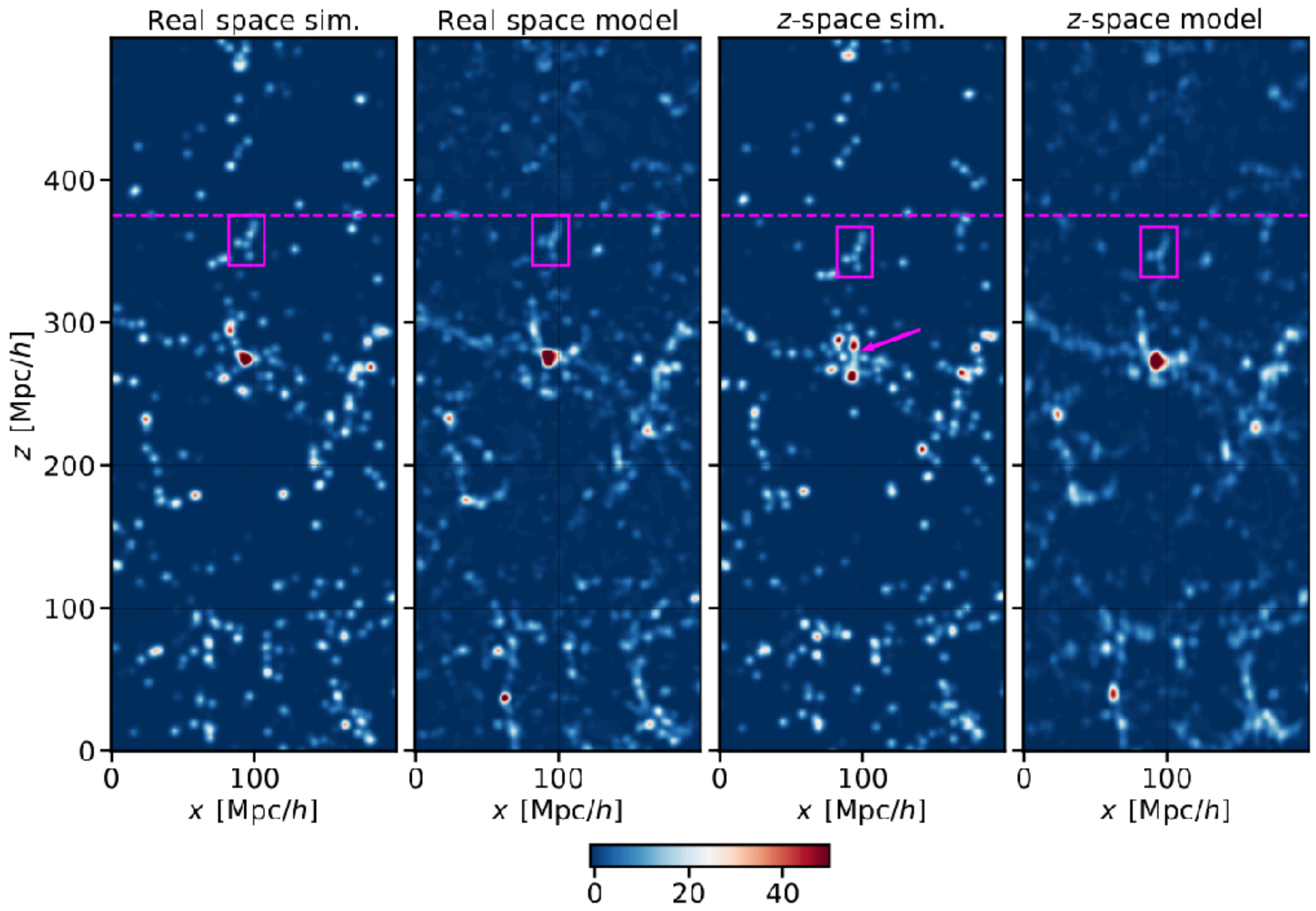
$$P_{\text{gg}}(z,k,\mu) = (b_1(z) + f(z)\mu^2)^2\left(P_{\text{nw}}(z,k) + \mathrm{e}^{-k^2\Sigma^2_{\text{tot}}(z,\mu)}P_{\text{w}}(z,k)(1+k^2\Sigma^2_{\text{tot}}(z,\mu))\right)$$
$$+ P_{\text{gg, nw, RSD, 1-loop}}(z,k,\mu) + \mathrm{e}^{-k^2\Sigma^2_{\text{tot}}(z,\mu)}P_{\text{gg, w, RSD, 1-loop}}(z,k,\mu)\,.$$

Parameters: $(\omega_b, \omega_{cdm}, h, A^{1/2}, n_s, m_\nu) \times (b_1A^{1/2}, b_2A^{1/2}, b_{\mathcal{G}_2}A^{1/2}, P_{shot}, c_0^2, c_2^2, \tilde{c})$

How well does PT work?

Schmittfull, MS, Ivanov, Philcox, Zaldarriaga (2020)

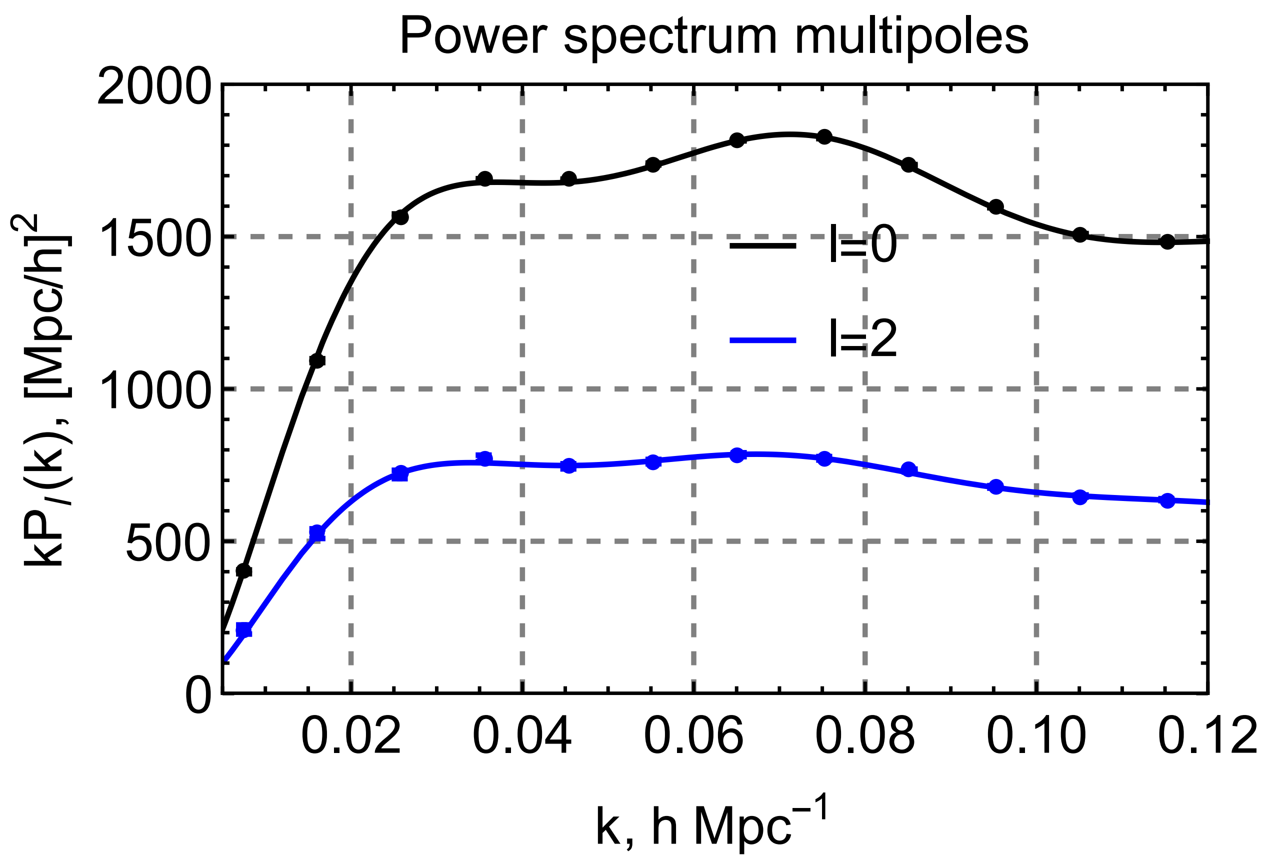
The most stringent test are on the map level, differences to the truth compatible with the shot noise

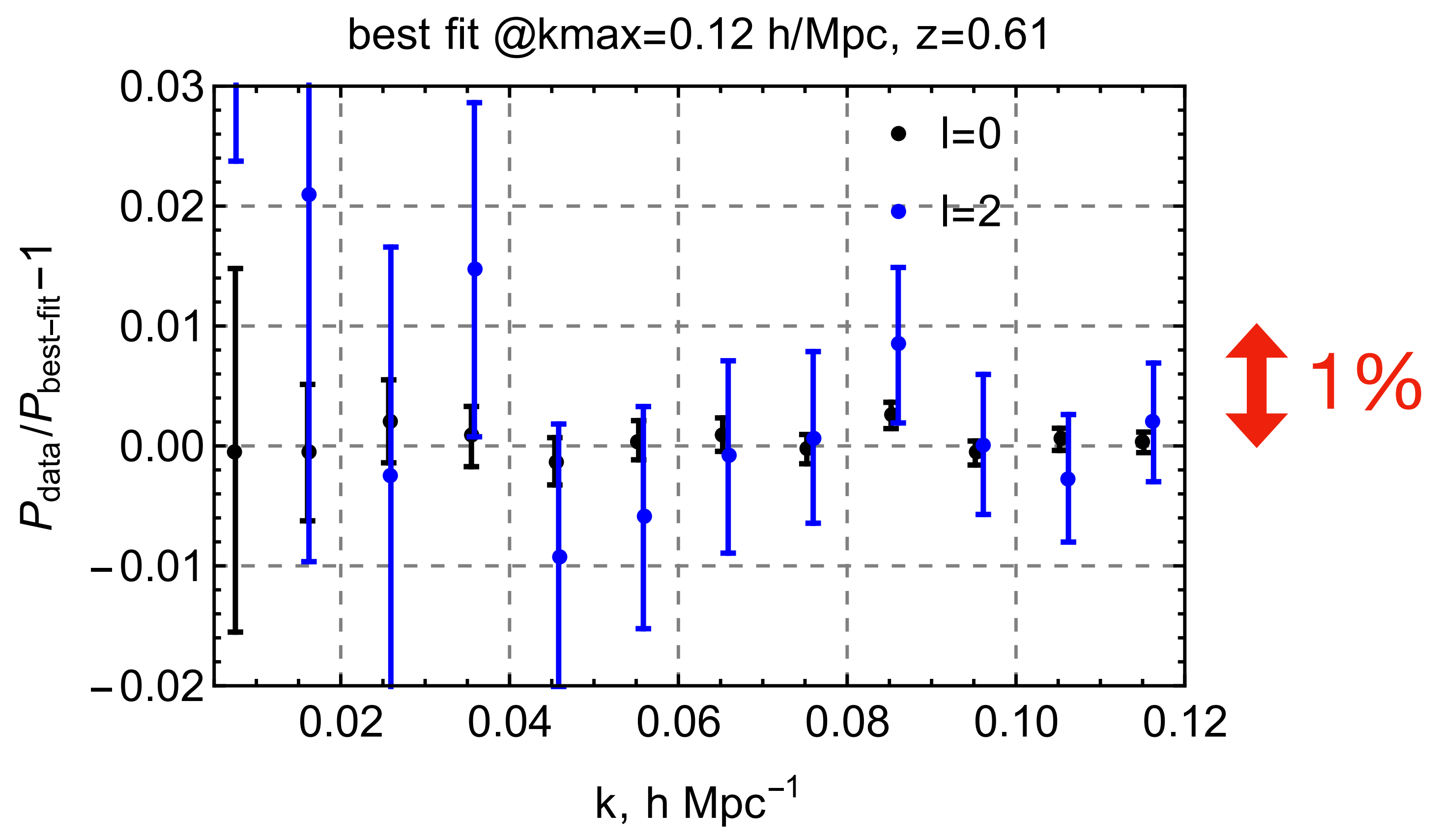


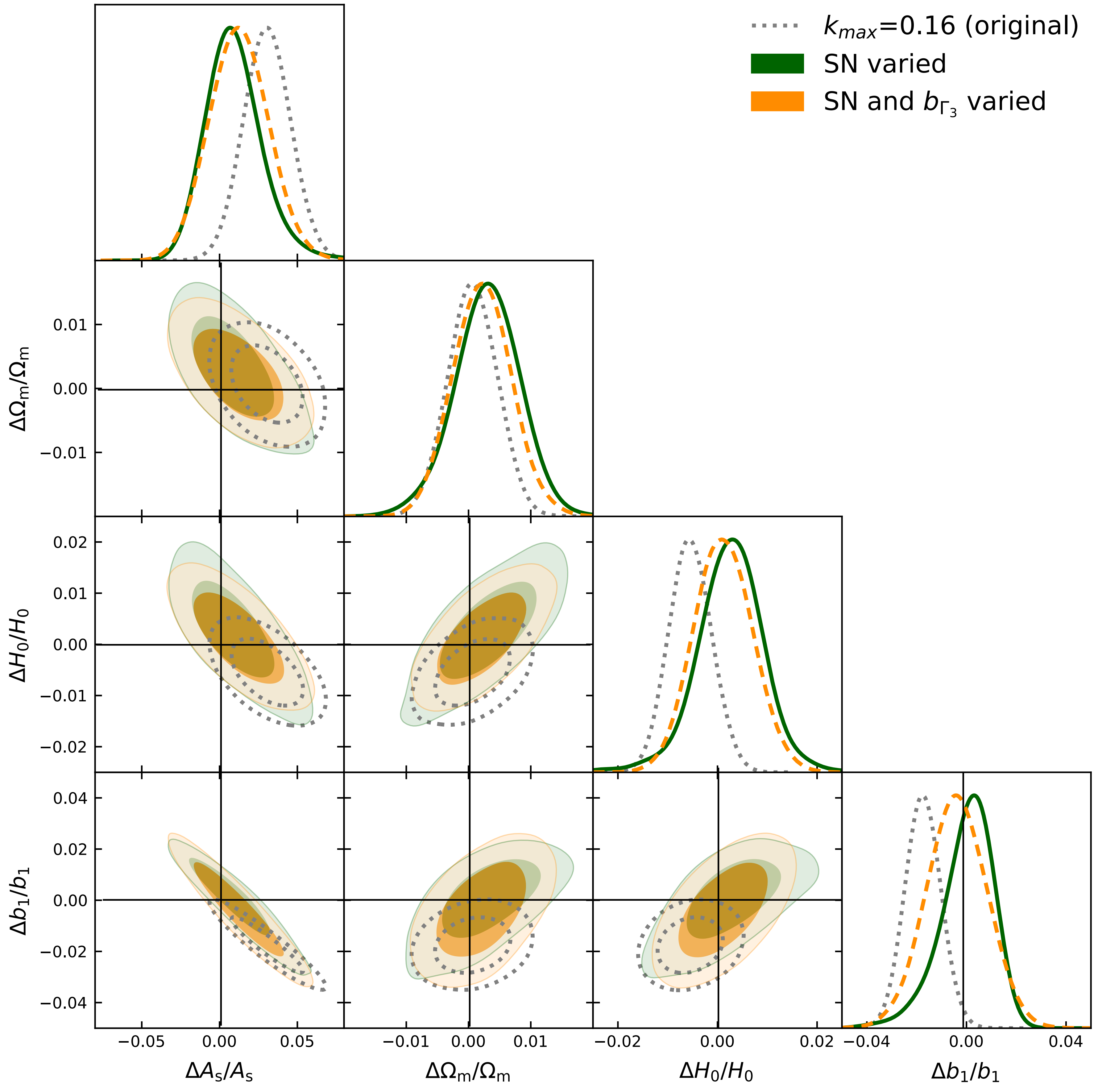
How well does PT work?

Blind analysis, very large volume, realistic galaxies

Nishimichi et al. (2020)

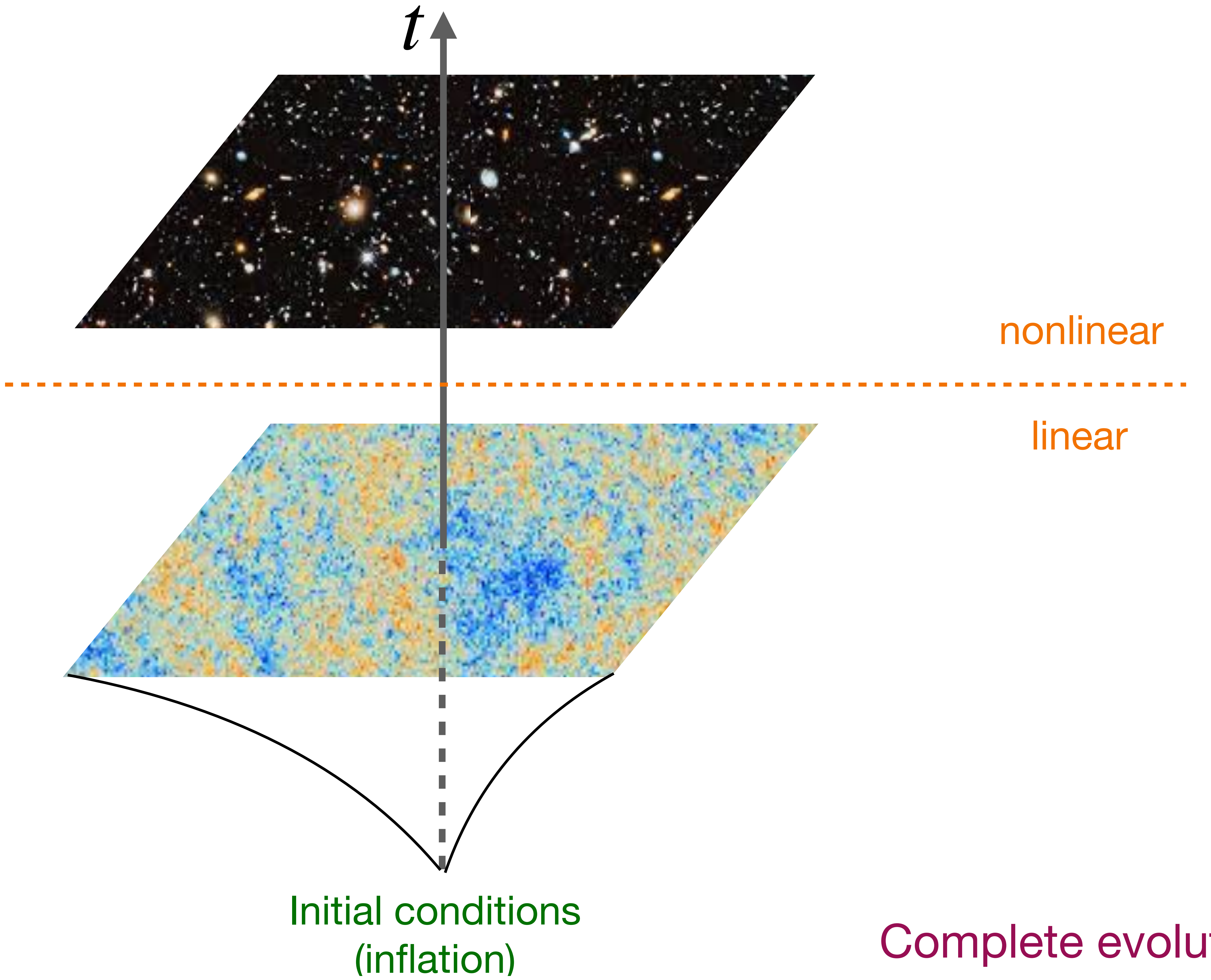






A new era in cosmology

Chudaykin, Ivanov, Philcox, MS (2019)
D'Amico, Senatore, Zhang (2019)
Chen, Vlah, Castorina, White (2020)



CLASS-PT
PyBird
velocileptors

MCMC made possible

CMBFAST
CAMB
CLASS

MCMC done routinely

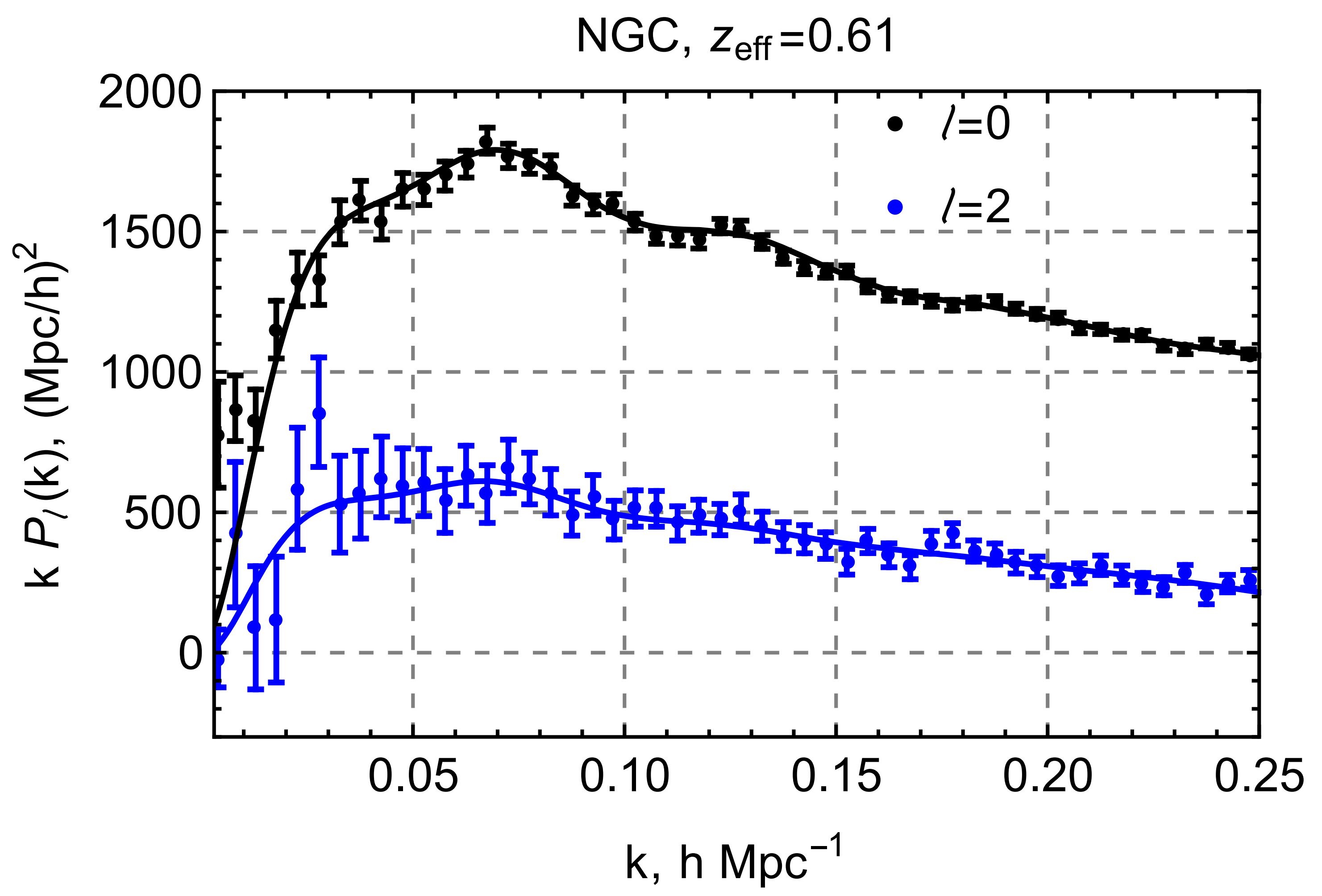
Complete evolution of the vacuum state from inflation to redshift zero

Snowmass White Paper: EFTs in Cosmology
Cabass, Ivanov, Lewandowski, Mirbabayi, MS

Applications

Application to BOSS data

Galaxy map

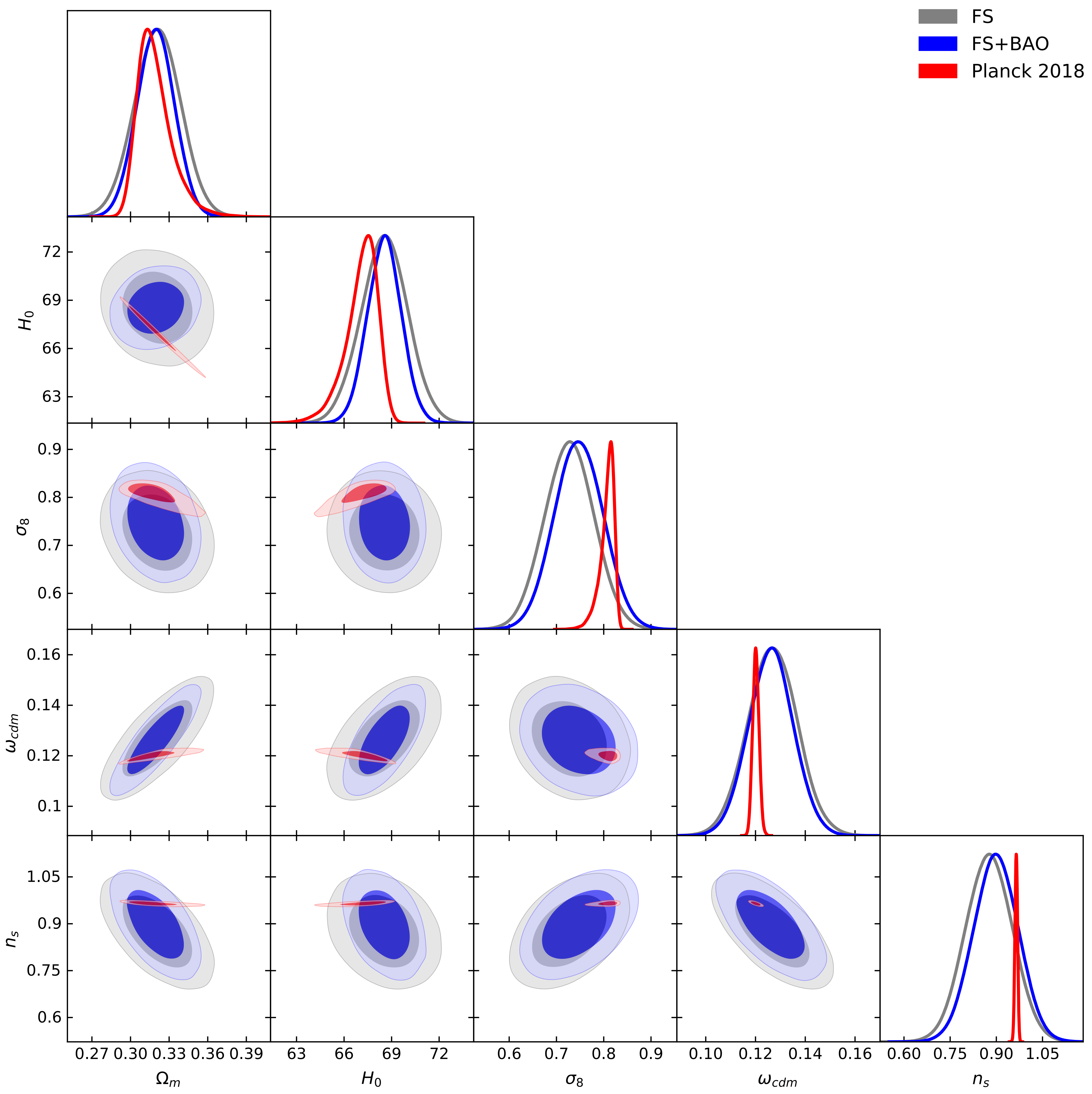


Full-shape analysis

Similar to CMB, directly measures “shape” parameters

all cosmological parameters
no CMB input needed

Application to BOSS data



Ivanov, MS, Zaldarriaga (2019)

d'Amico, Gleyzes, Kokron, Markovic, Senatore, Zhang, Beutler, Gil Marin (2019)

Philcox, Ivanov, MS, Zaldarriaga (2020)

Here we use the BBN prior on ω_b

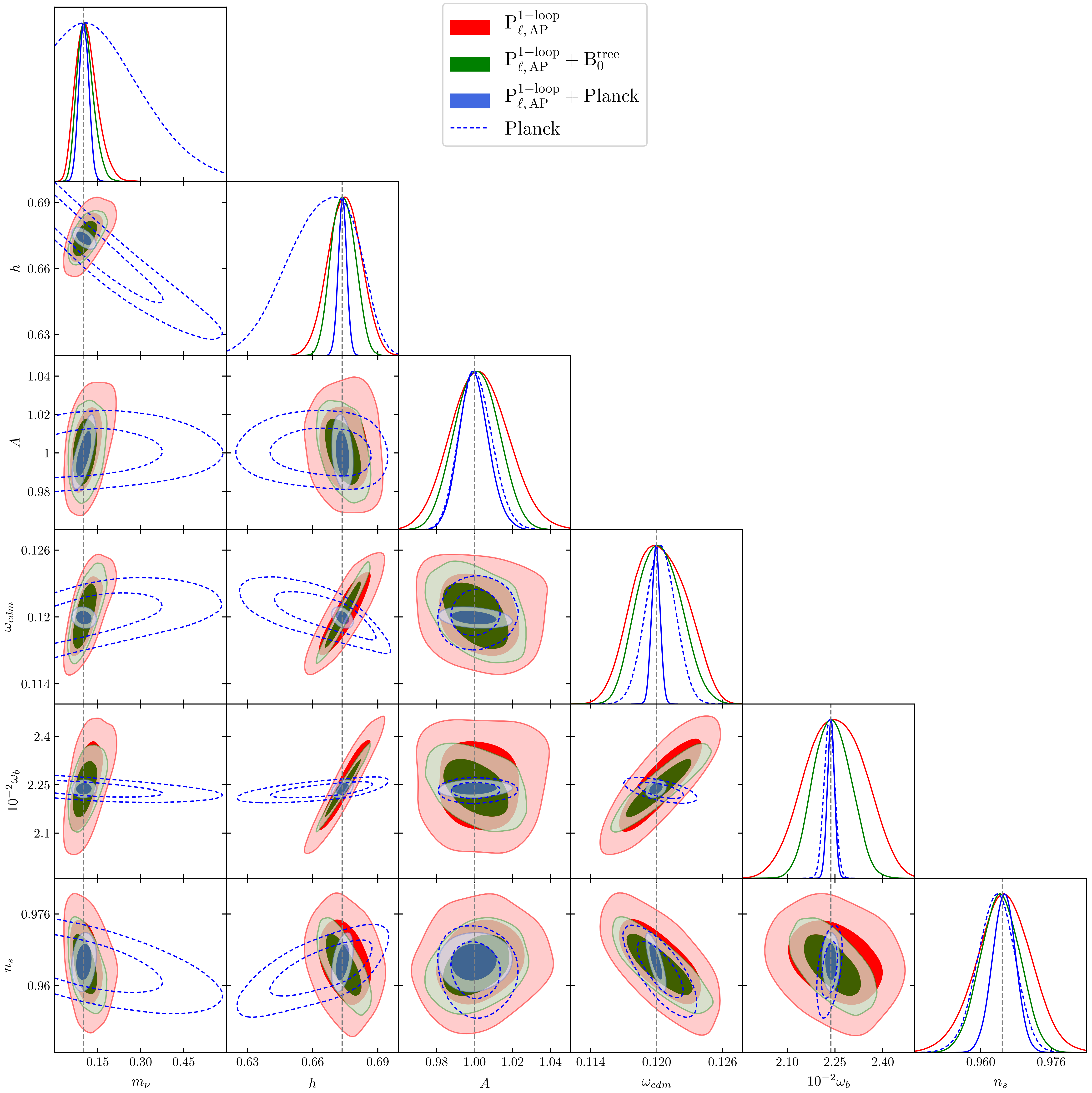
$$H_0 = 68.6 \pm 1.1 \text{ km/s/Mpc}$$

$$H_0 = 67.8 \pm 0.7 \text{ km/s/Mpc}$$ (fixing the tilt)

1) Datasets are consistent

2) BOSS errors on H0 and Ω_m comparable to Planck

Forecast for a Euclid/DESI-like survey



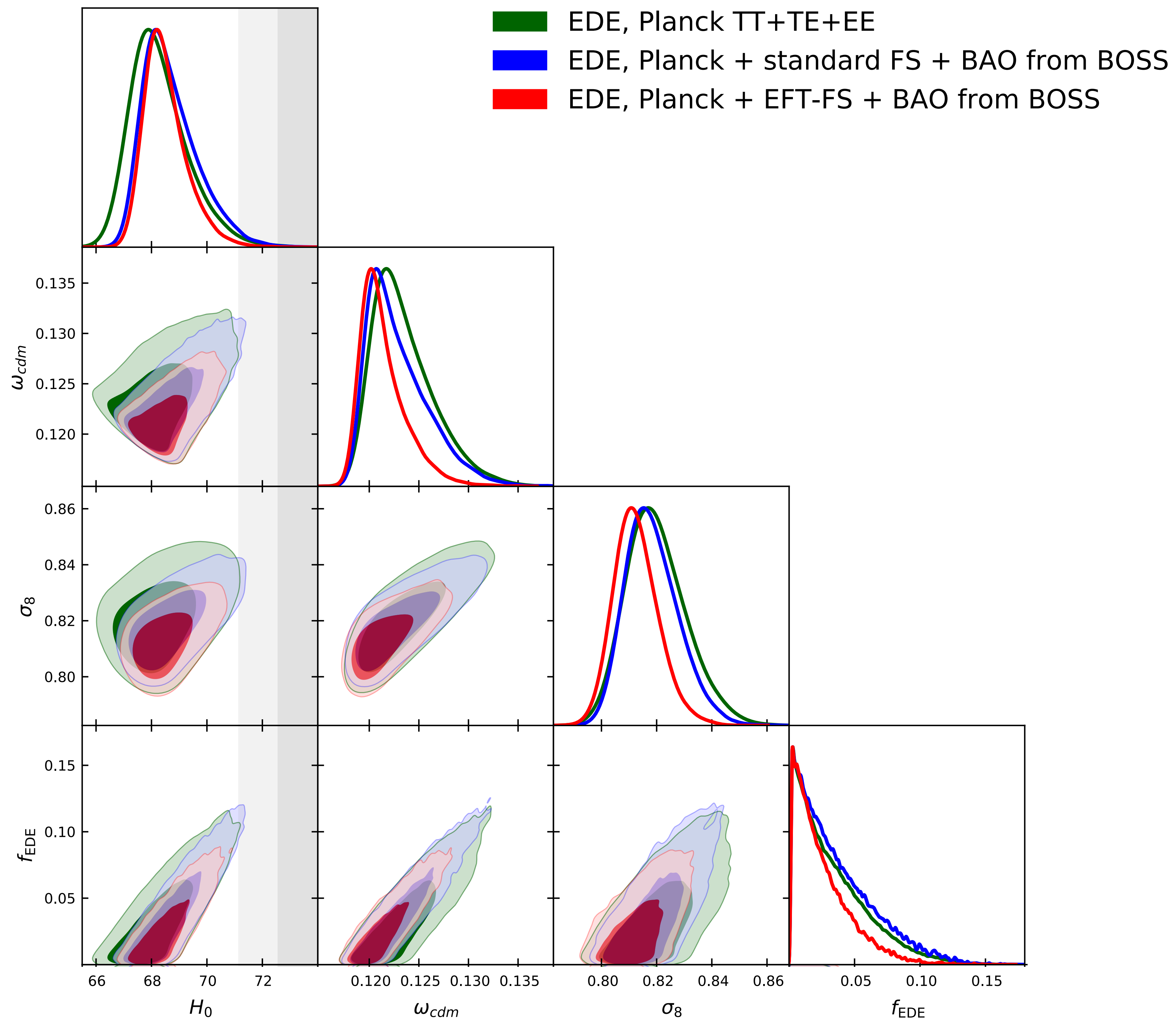
Chudaykin, Ivanov (2019)

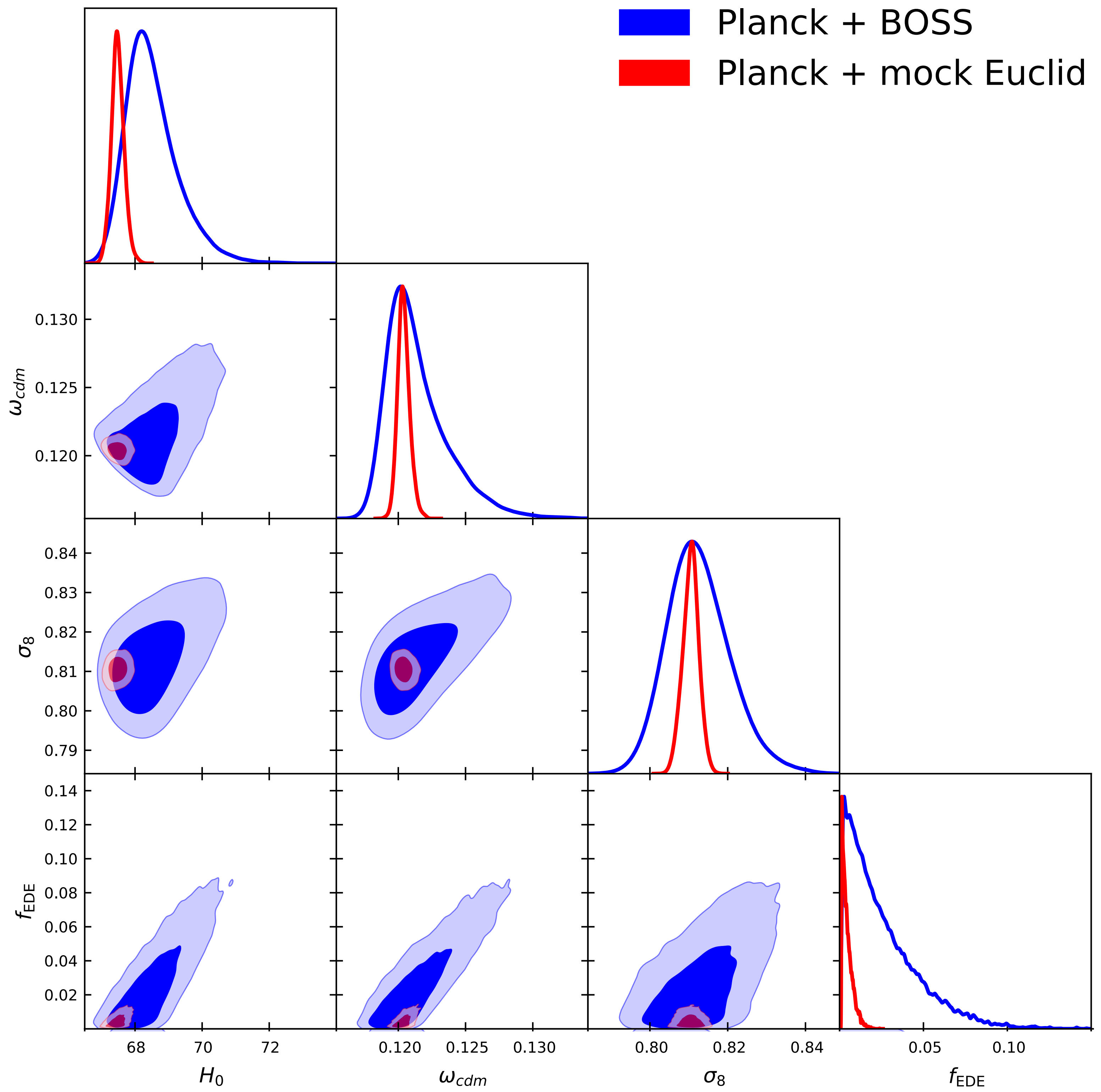
1) Euclid/DESI ~ Planck

2) much better in combination

Early dark energy example

Ivanov et al. (2020)





This is a general lesson, extensions constrained much better than with the CMB alone

Summary

We are in a new era in which galaxy surveys become comparable to the CMB

EFT approach to galaxy clustering has proven to be very successful and fruitful

Now we can routinely use galaxy clustering data to constrain LCDM and extensions

Many more things I didn't have time to talk about…

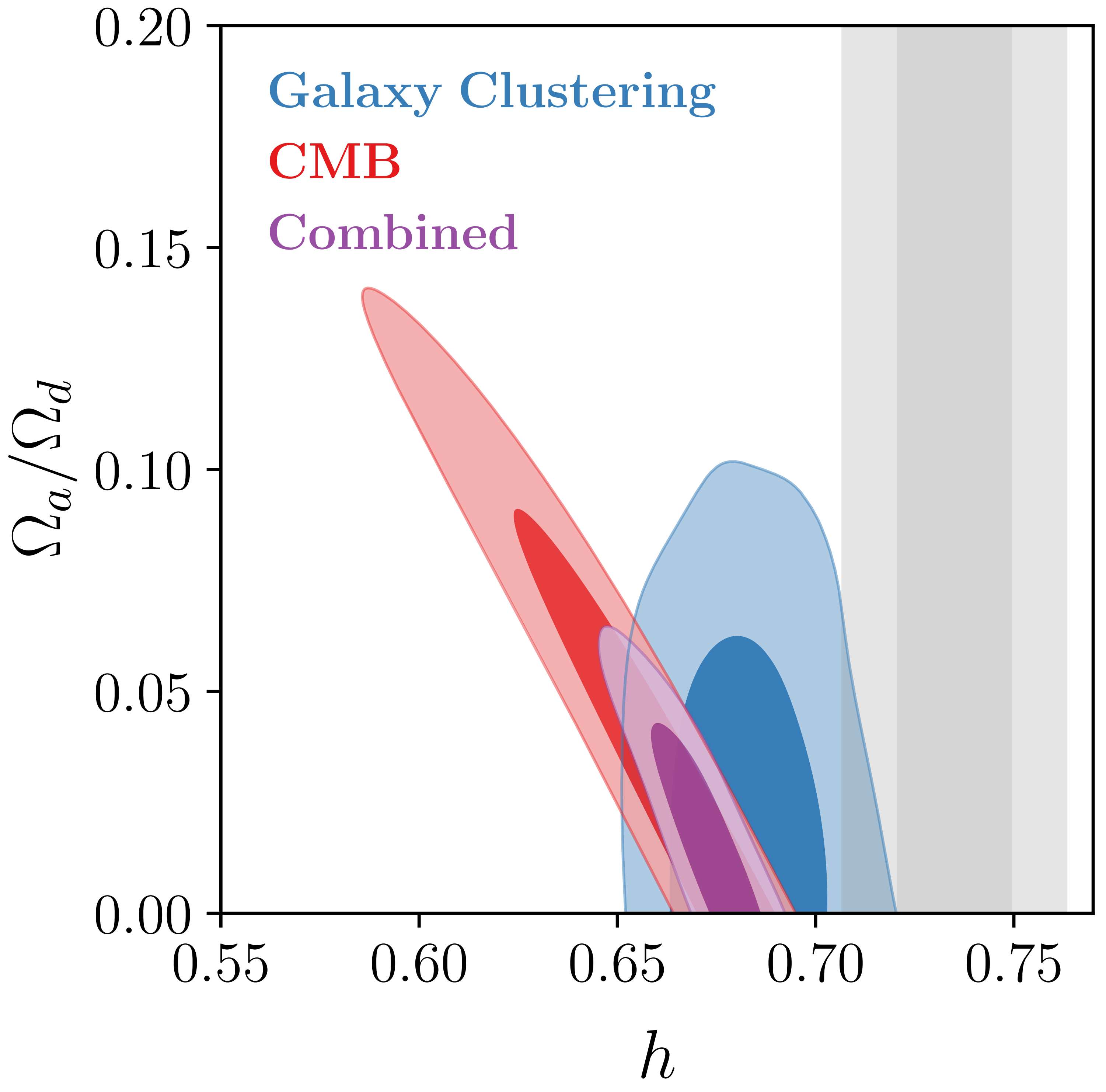
(bispectrum and first PNG constraints, perturbative forward modeling vs. n-point functions, novel data compression techniques to simplify covariance matrix estimates, new observables to mitigate RSD issues, new estimators to include the effects of the window functions exactly, perturbative models for the BAO reconstruction, efficient evaluation of higher order loops in PT and higher order n-point functions…)

Additional slides

Beyond LCDM

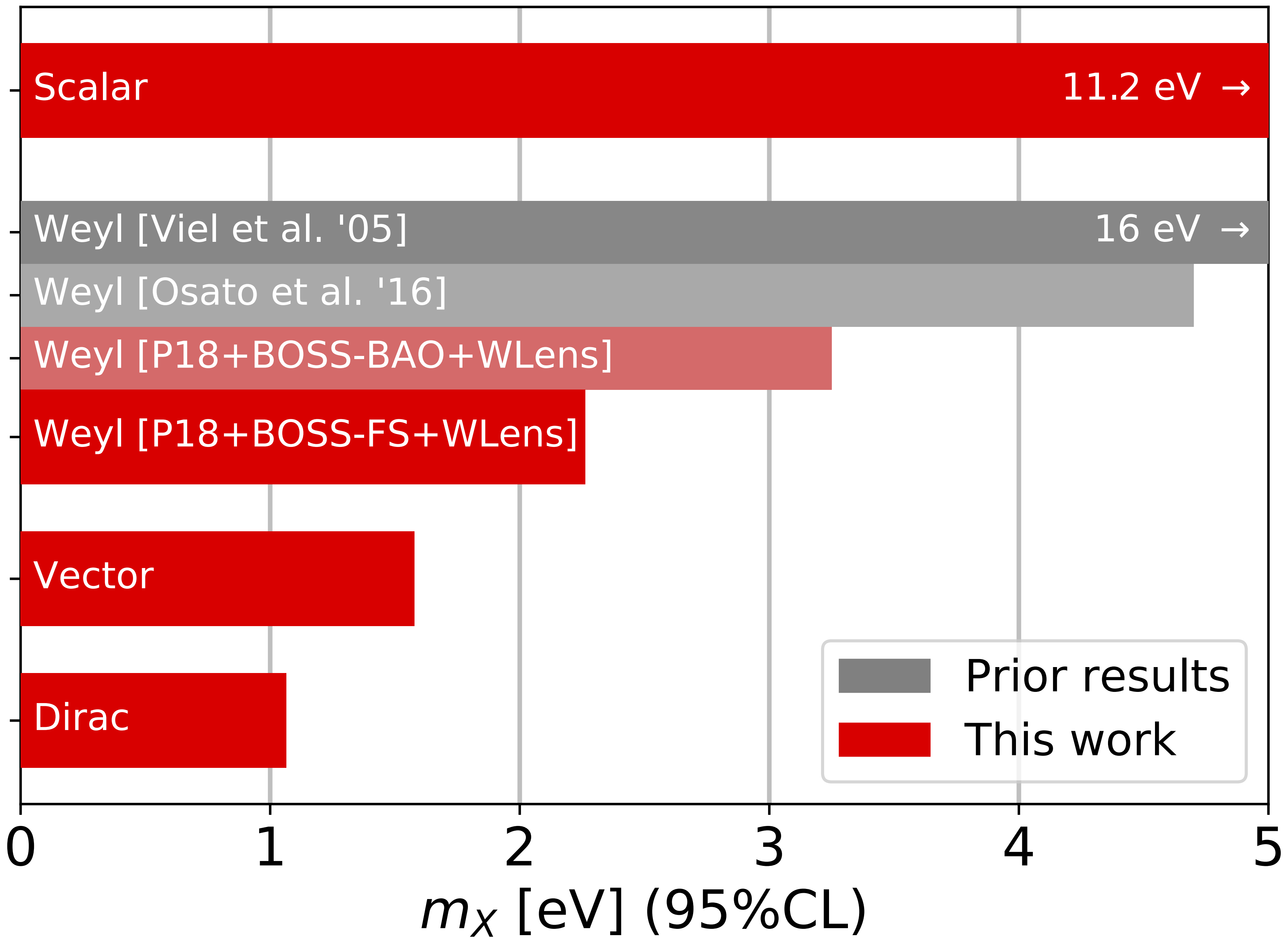
Laguë, Bond, Hložek, Rogers, Marsh, Grin (2021)

Ultralight axions

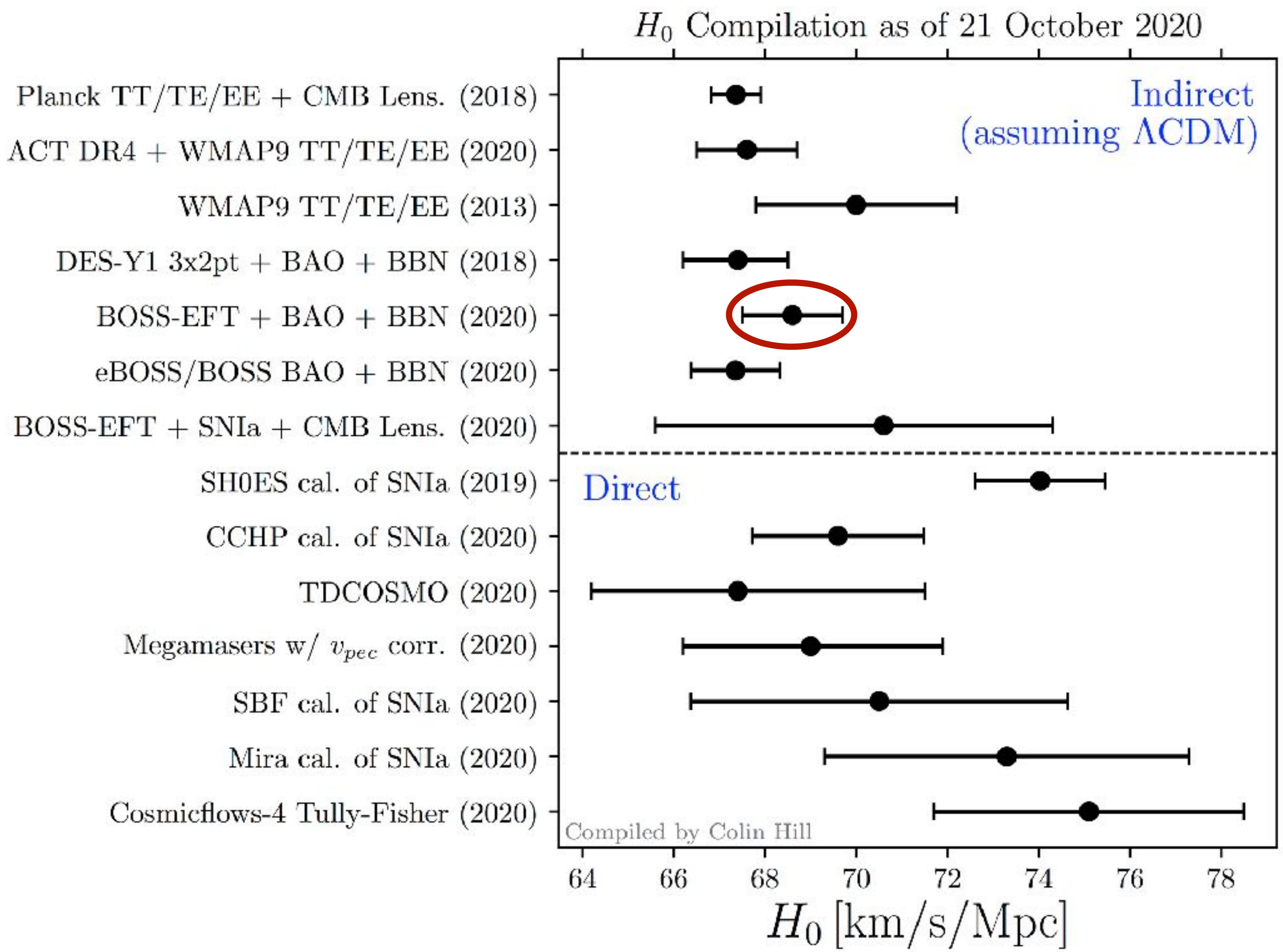


Xu, Muñoz, Dvorkin (2021)

Light (but Massive) Relics — LiMRs



H0 tension



credit: Colin Hill

Milestones towards the optimal analysis

1) Do the optimal bispectrum analysis and make it “easy”

2) Complete the $P_{2\text{-loop}} + B_{1\text{-loop}} + T_{\text{tree}}$ calculation and implement it in the nonlinear codes

3) Include relativistic effects, go to the light cone and full sky

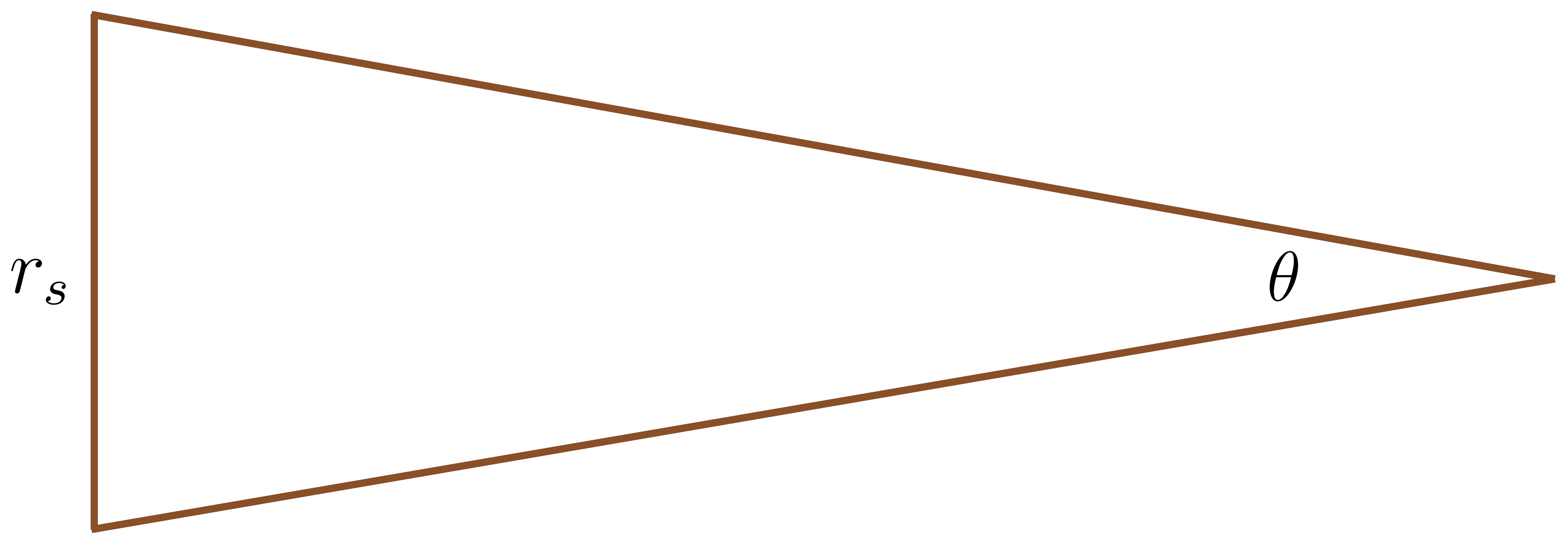
classification of all relevant nonlinearities,
efficient evaluation of loops, explore new “simpler” observables

new methods for data analysis,
compression, new observables

	tree	1-loop	2-loop
P			
B			
T			

How are we going to do it?

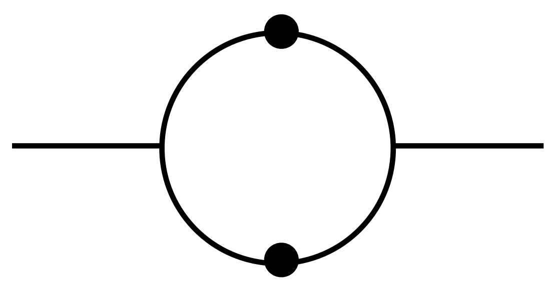
$$D_A = \frac{r_s}{\theta} \qquad D_A(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')} \qquad H \equiv \frac{\dot{a}}{a} \qquad H^2(z) = H_0^2(\Omega_m(1+z)^3 + \Omega_\Lambda)$$



H_0^{-1} gives the size and the age of the universe

Loop integrals and massless QFT

MS, Baldauf, Zaldarriaga, Carrasco, Kollmeier (2017)



$$P_{22}(k) = 2\int_{\boldsymbol{q}} F_2^2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}) P_{\rm lin}(q) P_{\rm lin}(|\boldsymbol{k}-\boldsymbol{q}|)$$

$$F_2(\boldsymbol{q}_1, \boldsymbol{q}_2) = \frac{5}{7} + \frac{1}{2}\frac{\boldsymbol{q}_1\cdot\boldsymbol{q}_2}{q_1 q_2}\left(\frac{q_1}{q_2}+\frac{q_2}{q_1}\right) + \frac{2}{7}\left(\frac{\boldsymbol{q}_1\cdot\boldsymbol{q}_2}{q_1 q_2}\right)^2$$

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

using FFT Log

all cosmology dependence in coefficients

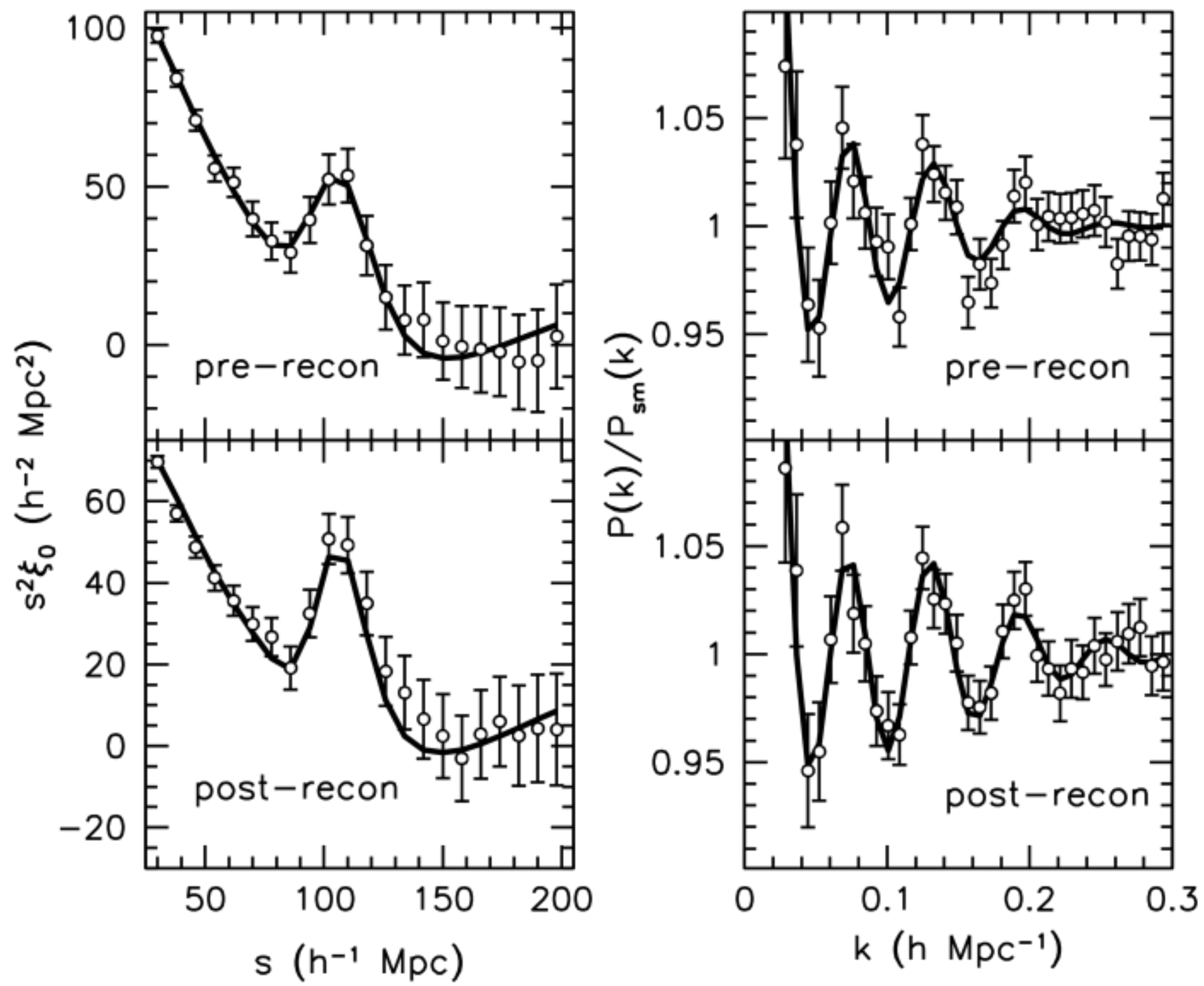
$$\int_{\boldsymbol{q}} \frac{1}{q^{2\nu_1}|\boldsymbol{k}-\boldsymbol{q}|^{2\nu_2}} \equiv k^{3-2\nu_{12}}\, I(\nu_1,\nu_2)$$

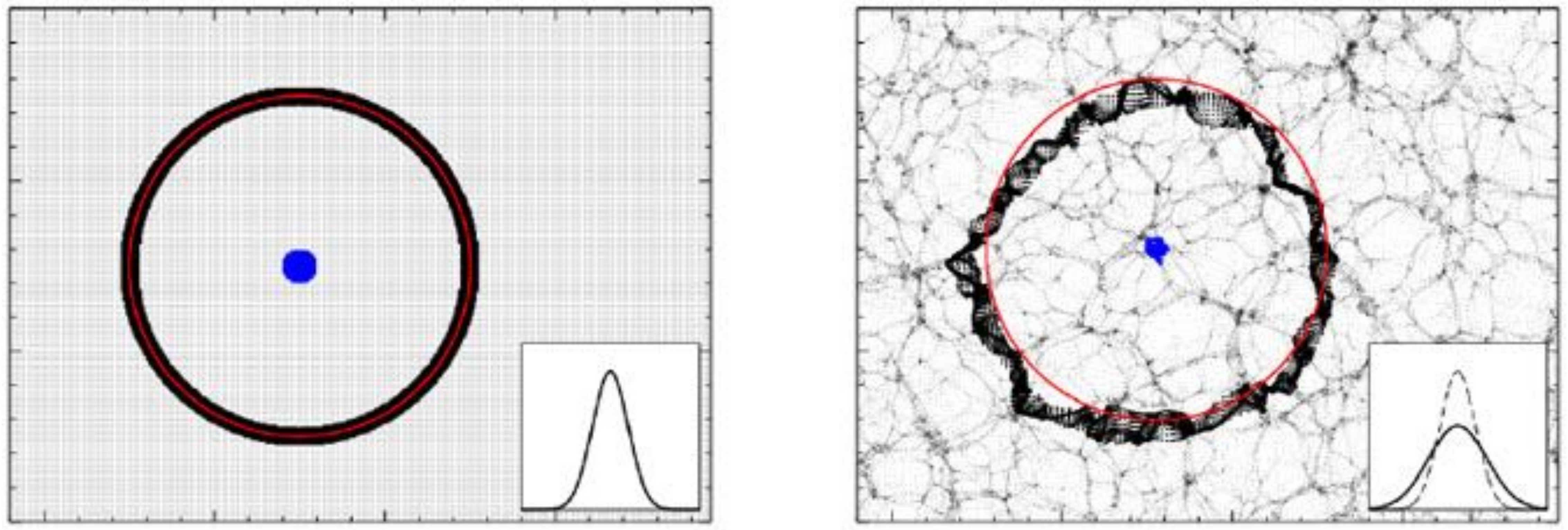
$$\int_{\boldsymbol{q}} \frac{1}{q^{2\nu_1}|\boldsymbol{k}_1-\boldsymbol{q}|^{2\nu_2}|\boldsymbol{k}_2+\boldsymbol{q}|^{2\nu_3}} \equiv k_1^{3-2\nu_{123}}\, J(\nu_1,\nu_2,\nu_3;x,y) \qquad x\equiv k_3^2/k_1^2 \qquad y\equiv k_2^2/k_1^2$$

$$\int_{\boldsymbol{q}} \frac{1}{q^{2\nu_4}|\boldsymbol{k}-\boldsymbol{q}|^{2\nu_5}} \int_{\boldsymbol{p}} \frac{1}{p^{2\nu_1}|\boldsymbol{k}-\boldsymbol{p}|^{2\nu_2}|\boldsymbol{q}-\boldsymbol{p}|^{2\nu_3}} \equiv k^{6-2\nu_{12345}}\, K(\nu_1,\ldots,\nu_5)$$

Very useful in practice, it speeds up evaluation of loop integrals by orders of magnitude

Infrared resummation





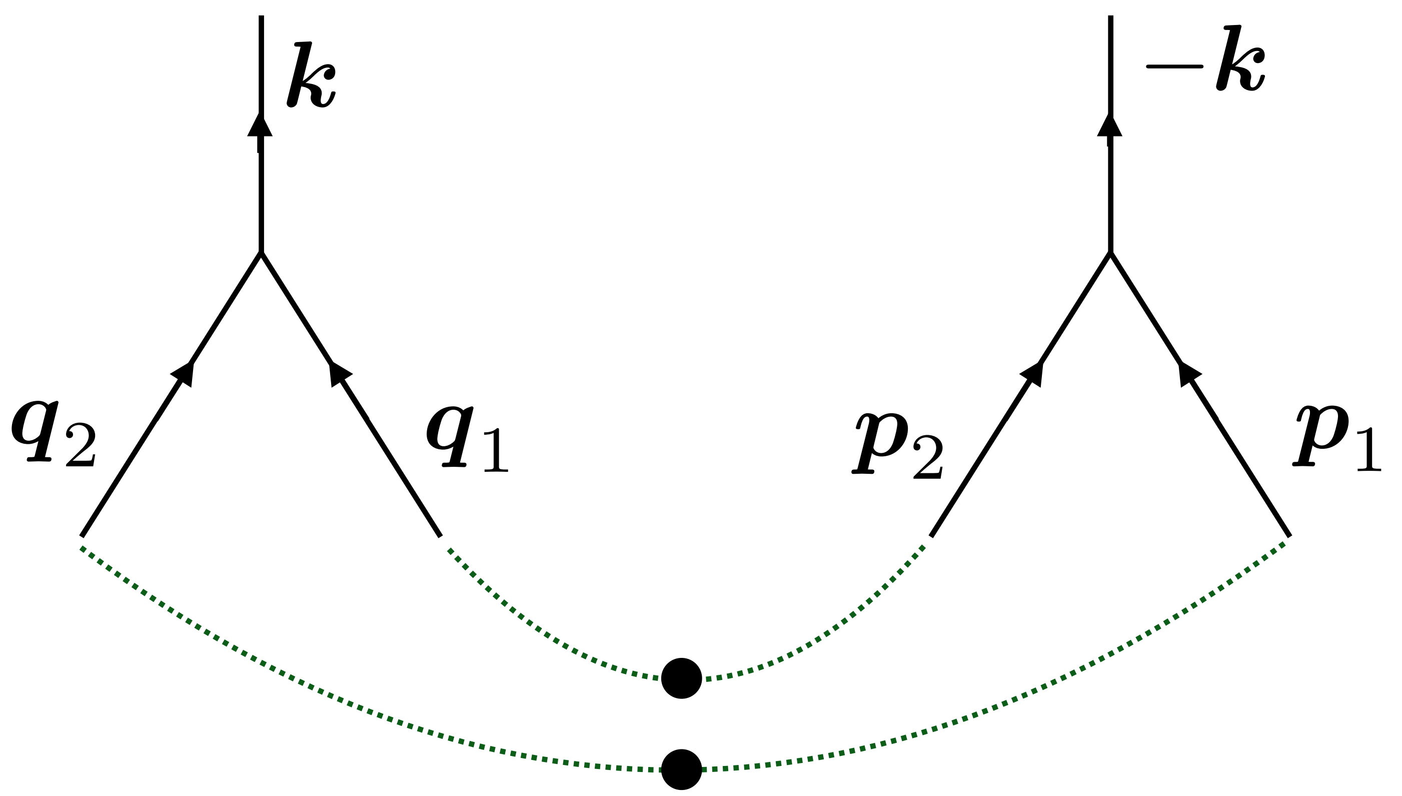
The simplest case — dark matter

These equations of motion can be solved perturbatively

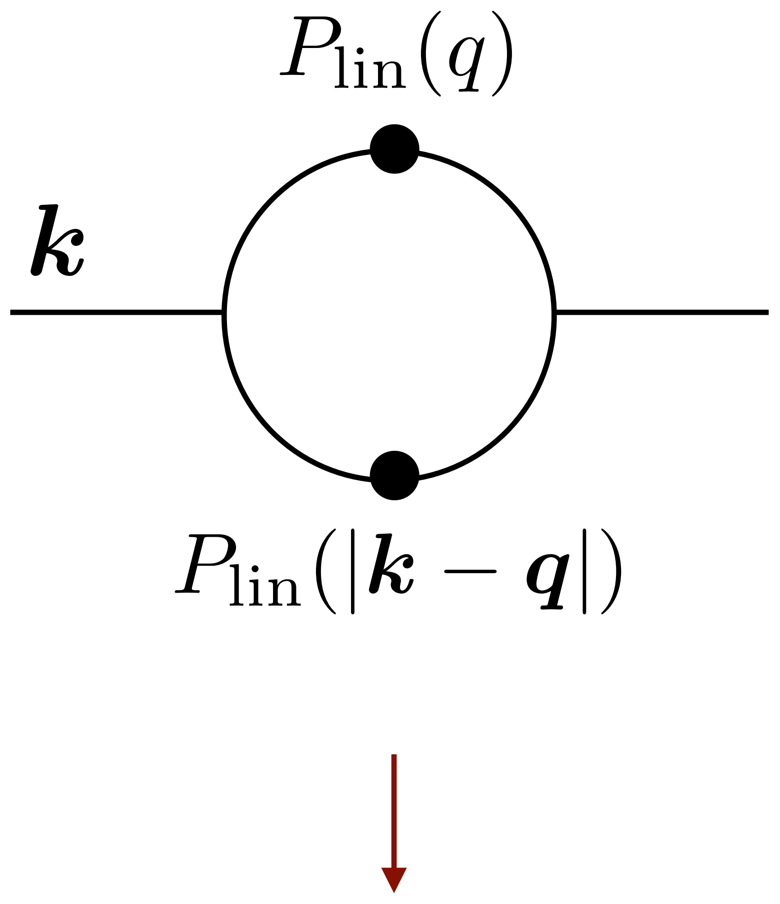
$$\delta_{\boldsymbol{k}}^{(2)}(\eta) = D^2(\eta) \int_{\boldsymbol{q}_1} \int_{\boldsymbol{q}_2} F_2(\boldsymbol{q}_1, \boldsymbol{q}_2) \delta^0_{\boldsymbol{q}_1} \delta^0_{\boldsymbol{q}_2} (2\pi)^3 \delta^D(\boldsymbol{k} - \boldsymbol{q}_1 - \boldsymbol{q}_2)$$

Scoccimarro, Frieman (1996)

$$F_2(\boldsymbol{q}_1, \boldsymbol{q}_2) = \frac{5}{7} + \frac{1}{2} \frac{\boldsymbol{q}_1 \cdot \boldsymbol{q}_2}{q_1 q_2} \left(\frac{q_1}{q_2} + \frac{q_2}{q_1} \right) + \frac{2}{7} \left(\frac{\boldsymbol{q}_1 \cdot \boldsymbol{q}_2}{q_1 q_2} \right)^2$$



Average over initial conditions



$$P_{22}(k) = 2 \int_{\boldsymbol{q}} F_2^2(\boldsymbol{q}, \boldsymbol{k} - \boldsymbol{q}) P_{\rm lin}(q) P_{\rm lin}(|\boldsymbol{k} - \boldsymbol{q}|)$$