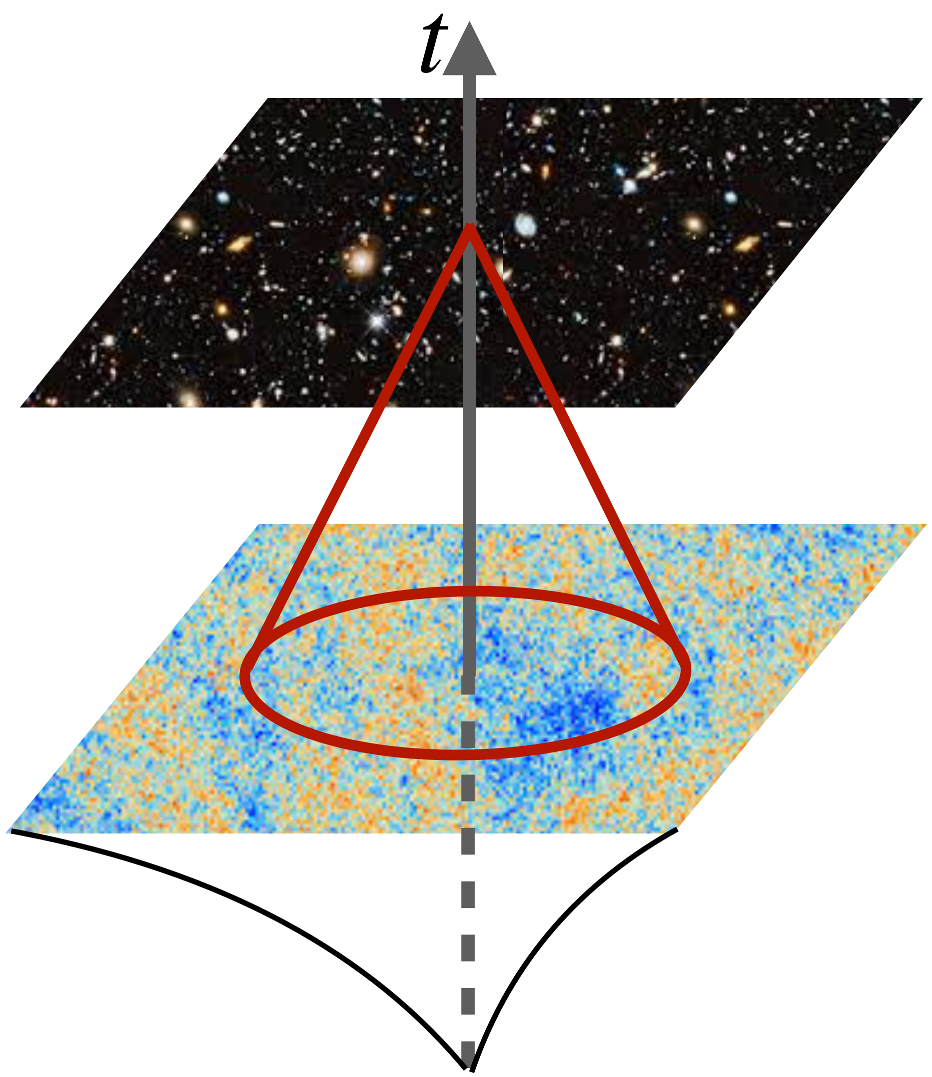
Studying history of the Universe through galaxy clustering

Marko Simonović
University of Florence

Introduction and context

Big discoveries in cosmology

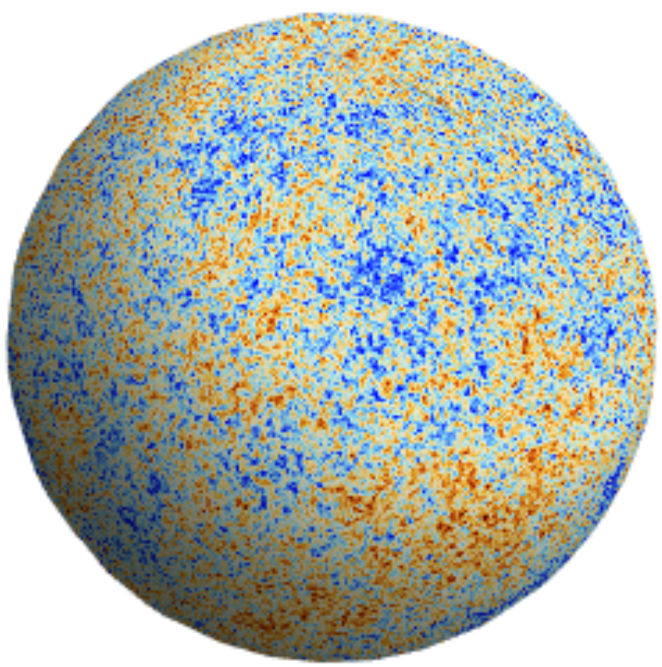


Initial conditions
(inflation)

Dark matter
Dark energy
Inflation

Particle physics, string theory…

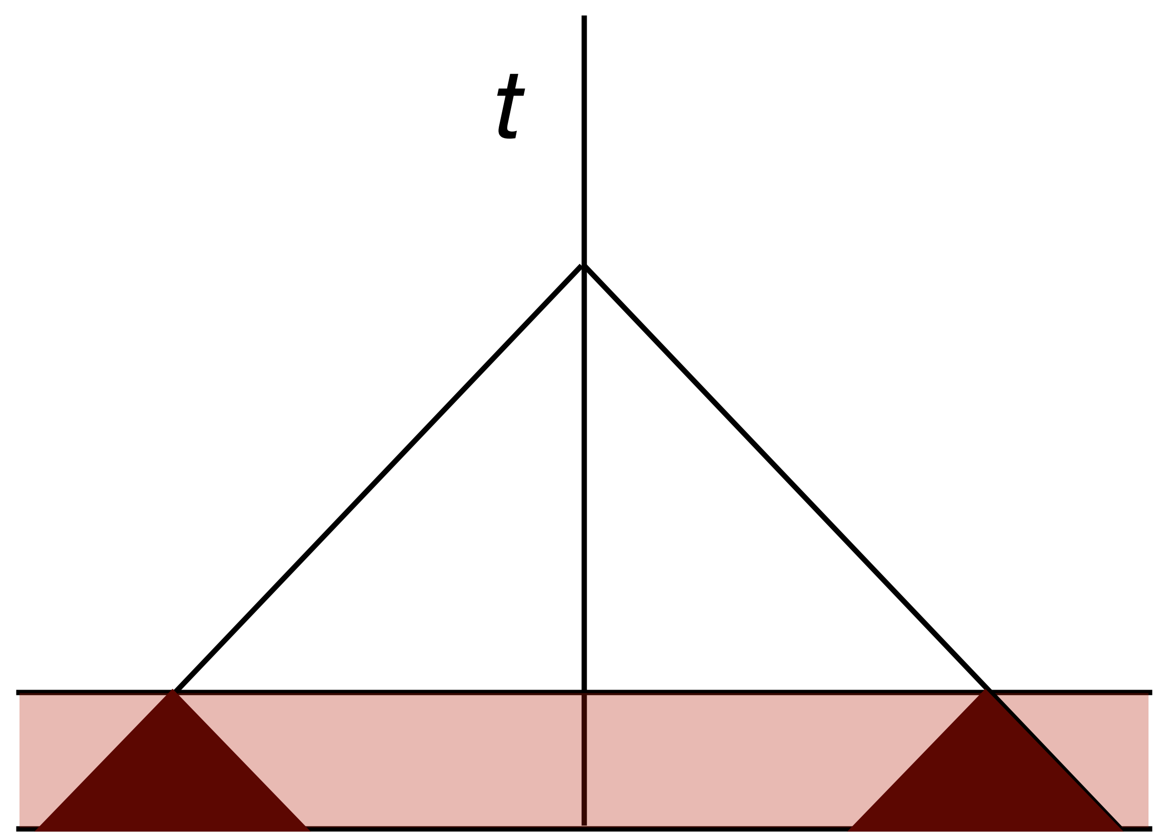
Cosmic Microwave Background



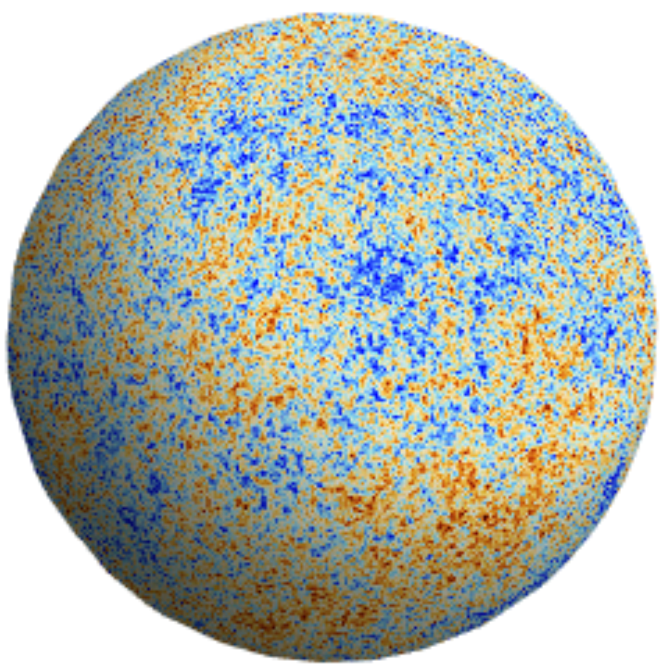
Leftover radiation from the time when the universe becomes transparent

What do we learn from it?

The horizon problem



Cosmic Microwave Background



$$\delta_T(\hat{\boldsymbol{n}}) \equiv \frac{\delta T(\hat{\boldsymbol{n}})}{T} = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{\boldsymbol{n}})$$

For Gaussian fluctuations only the two-point function matters

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle \equiv \delta^K_{\ell \ell'} \delta^K_{m m'} \, C_\ell$$

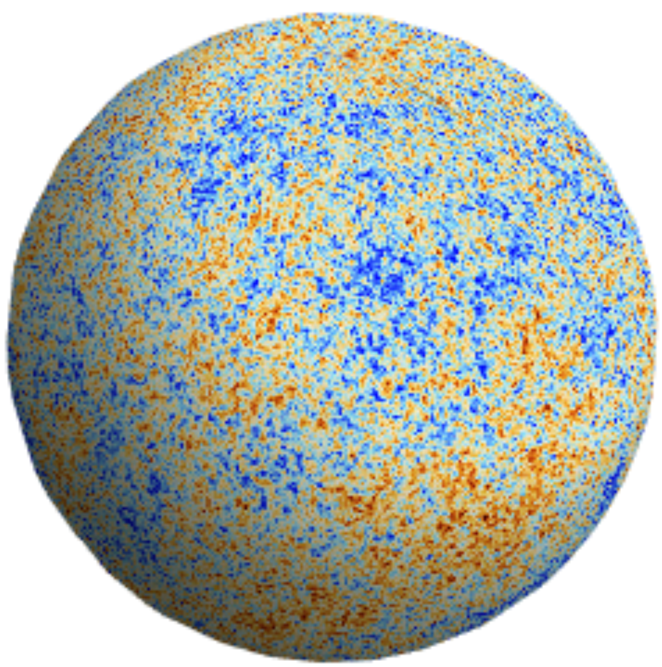
$$C_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

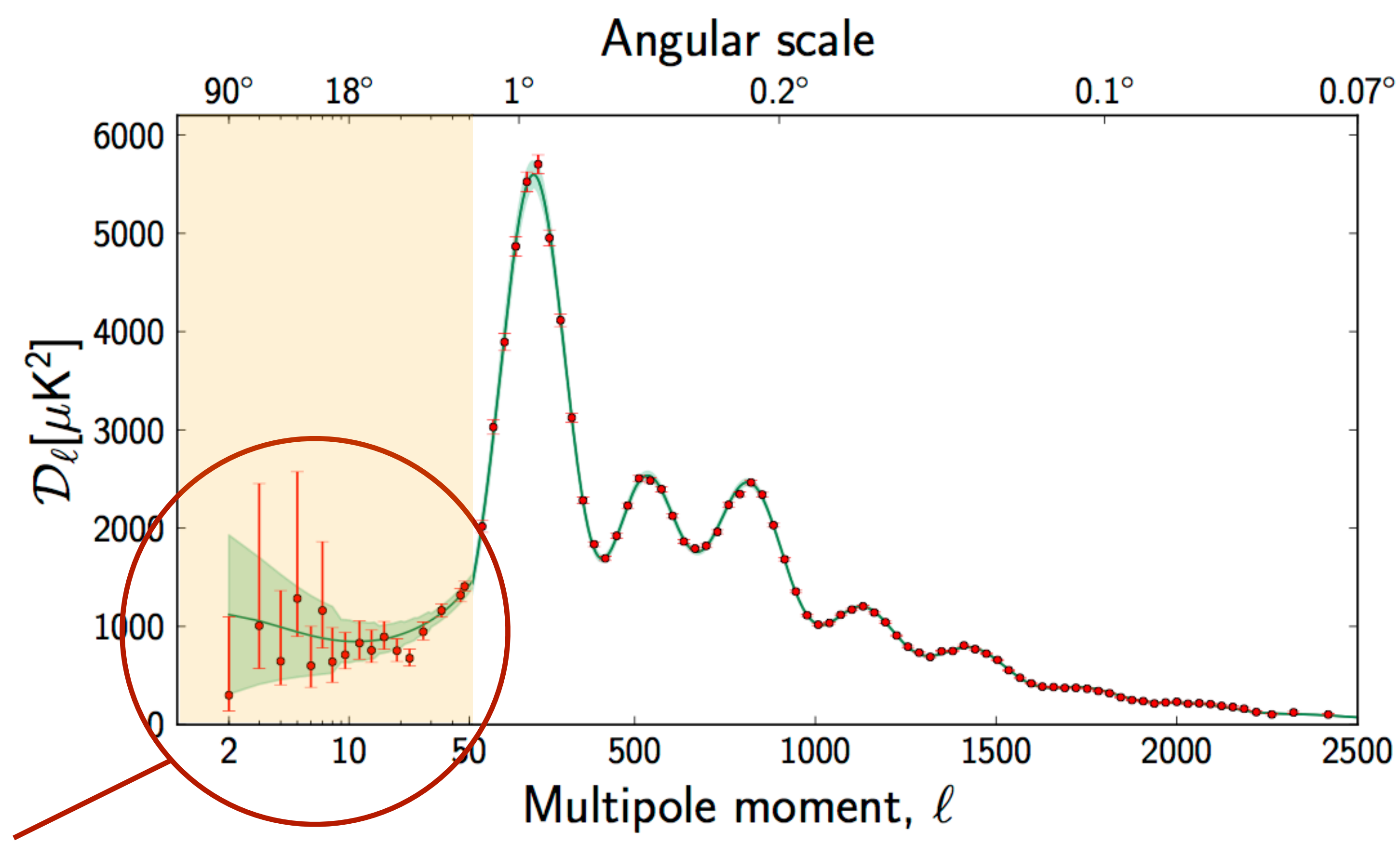
CMB power spectrum

$$D_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$

variance of the temperature fluctuations

Cosmic Microwave Background

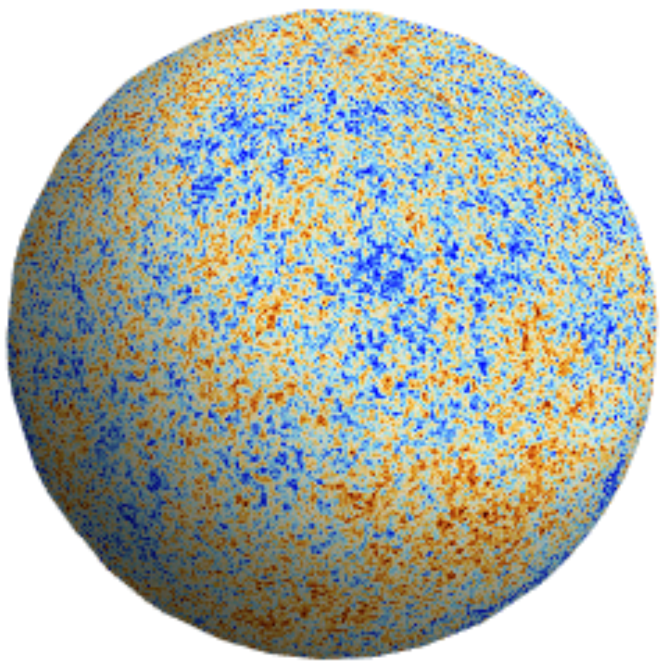


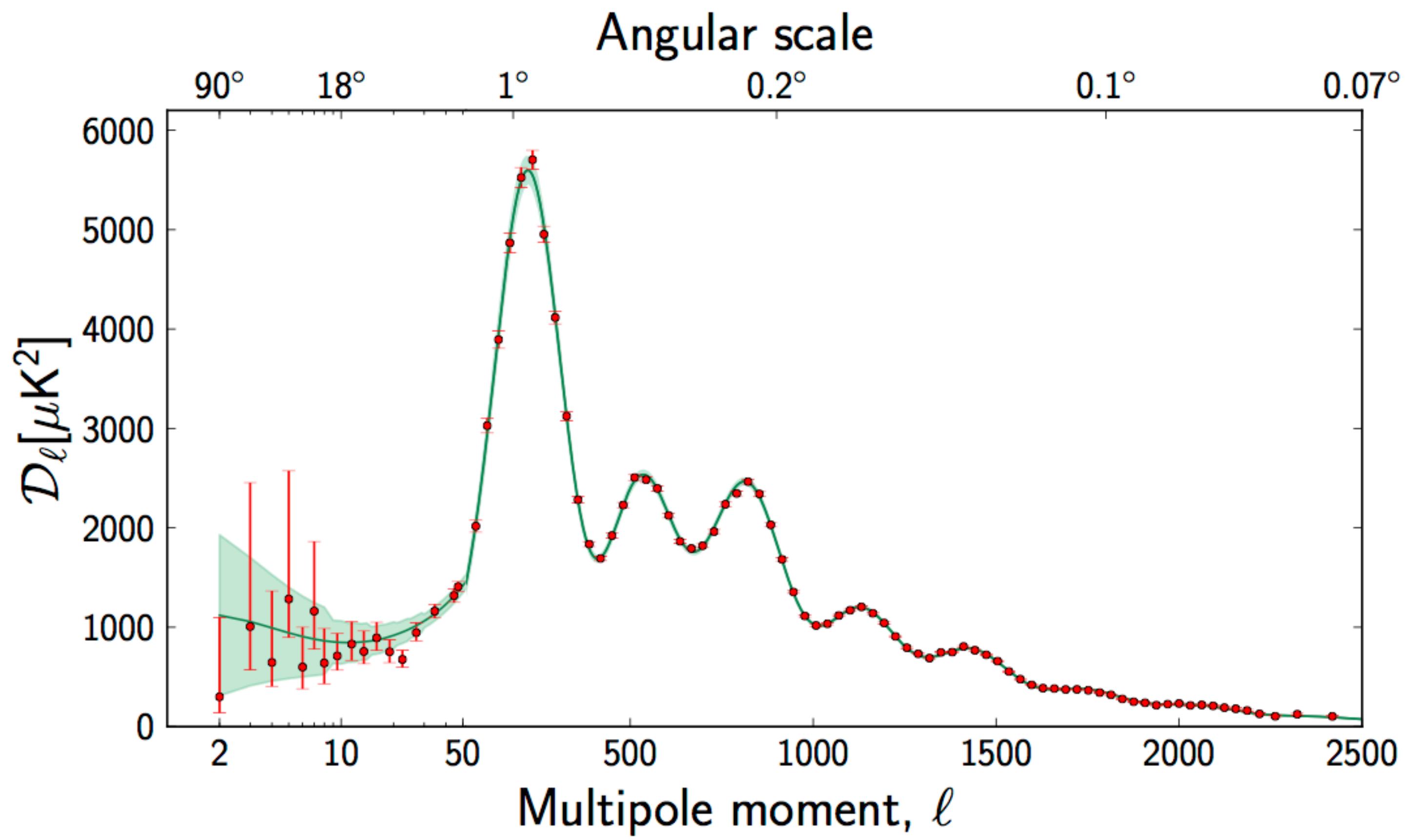


Scale-invariant power spectrum!

One of the strongest evidence for inflation

Cosmic Microwave Background



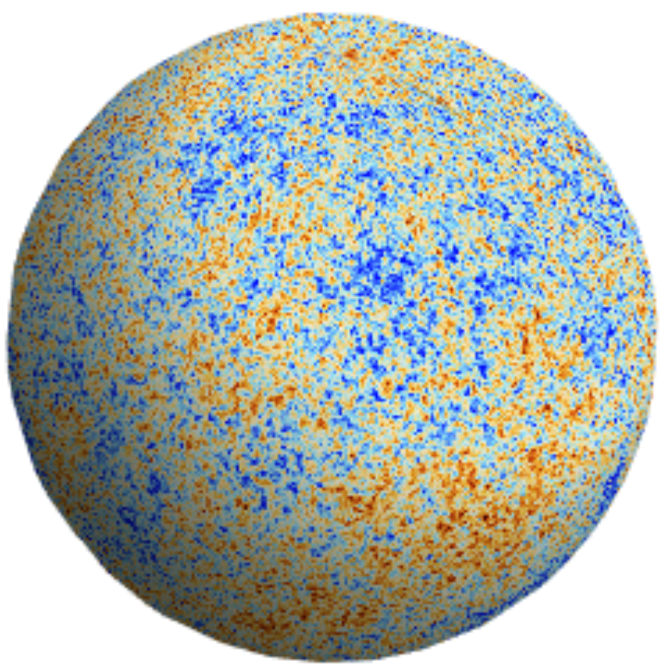


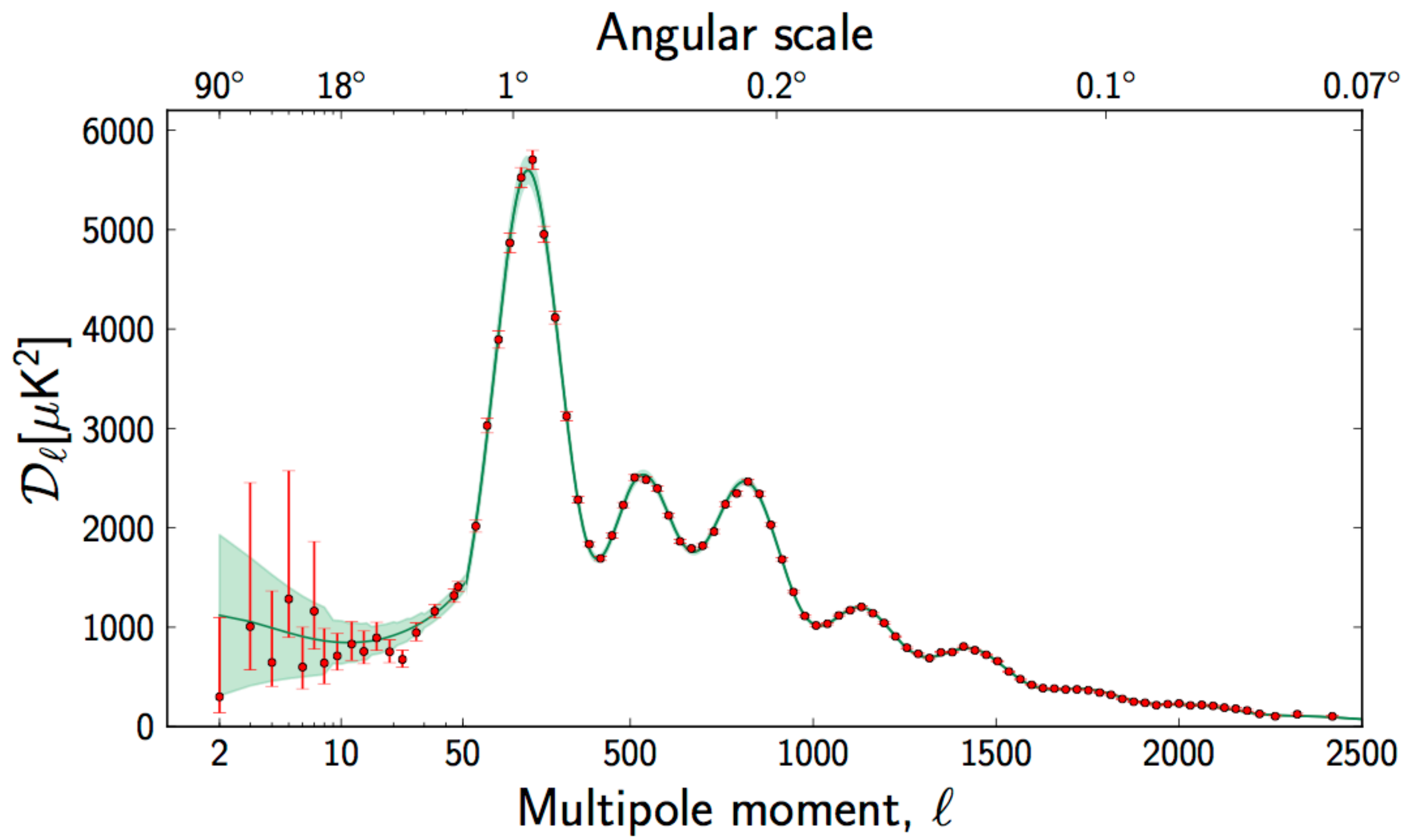
In general, the whole shape of the power spectrum is special

It requires special initial conditions and matter content

Emergence of the ΛCDM cosmological model

Cosmic Microwave Background





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

Open questions

1) Properties of the initial conditions

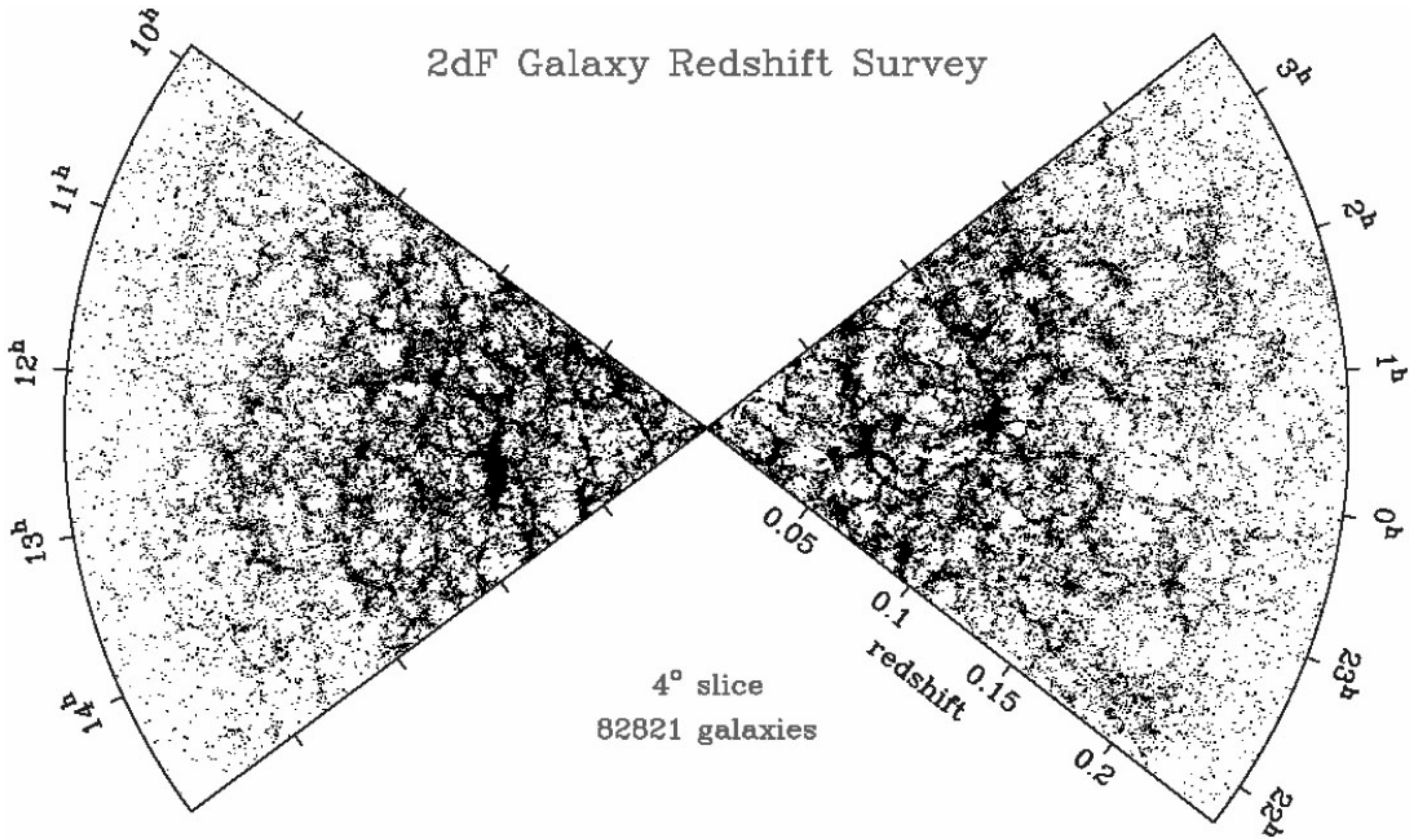
Single “clock”? Speed of inflaton fluctuations less than 1?
“Spectroscopy” of massive/higher spin particles?
Primordial features in the power spectrum?

2) Everything gravitates

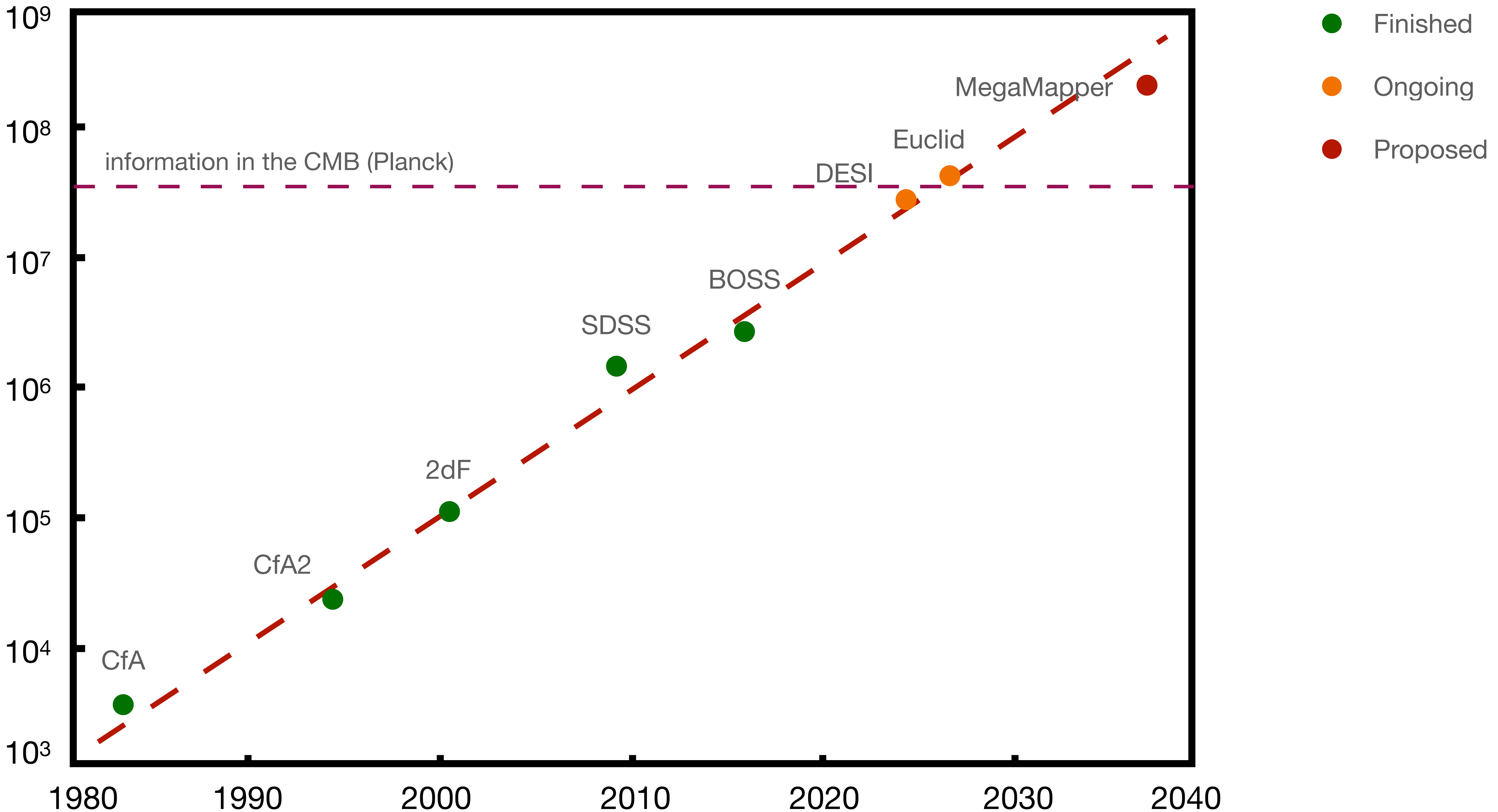
Sum of neutrino masses. Other massive (but light) relics? Ultralight axions?
Spatial curvature, dark energy?
New energy components in early or late universe?
Probing dark sector, new long-range interactions?

What is the way forward?

Spectroscopic galaxy surveys



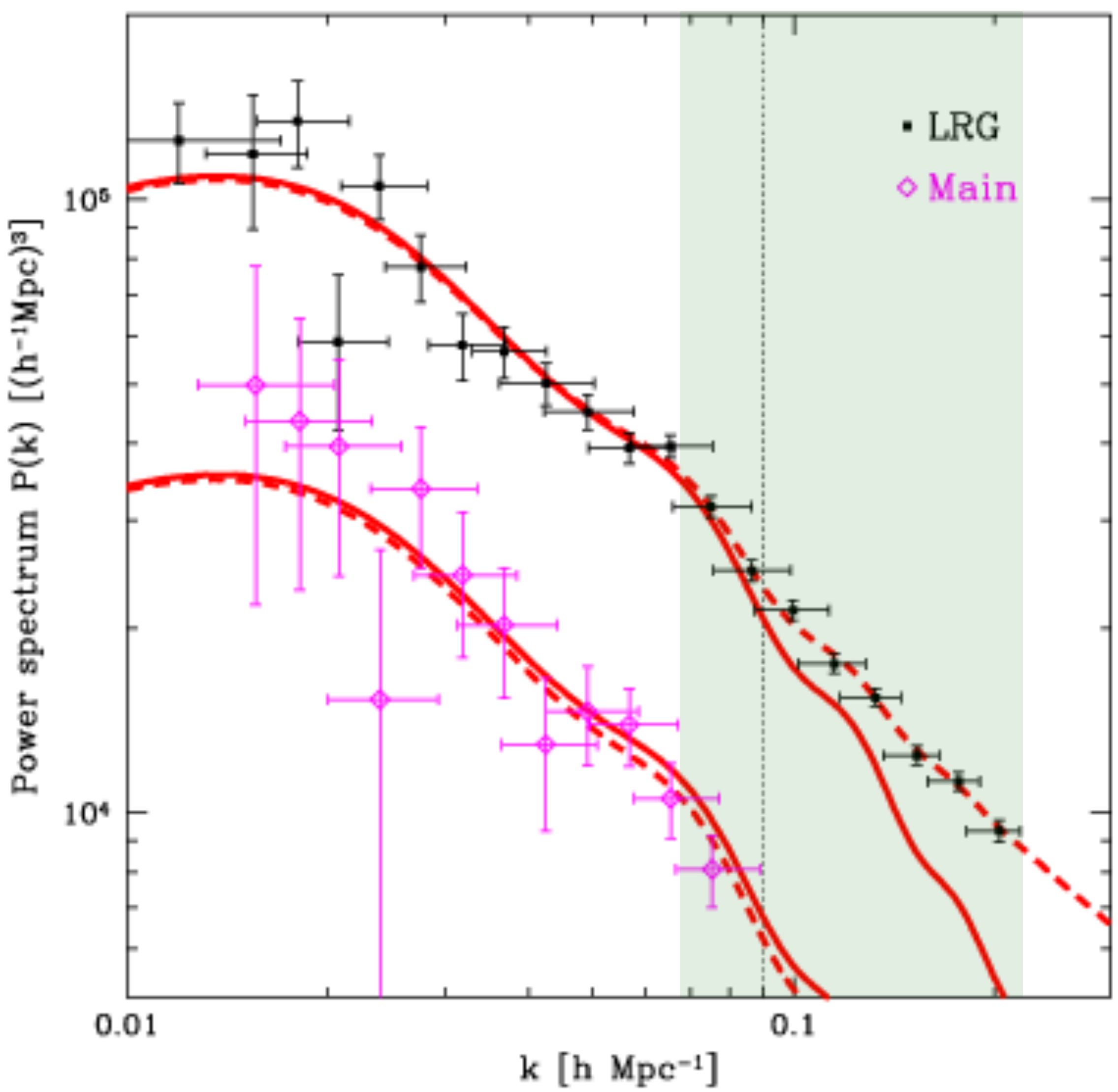
Spectroscopic galaxy surveys



Power spectrum

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

The power spectrum has features that carry information about cosmology



Nonlinear evolution is a challenge

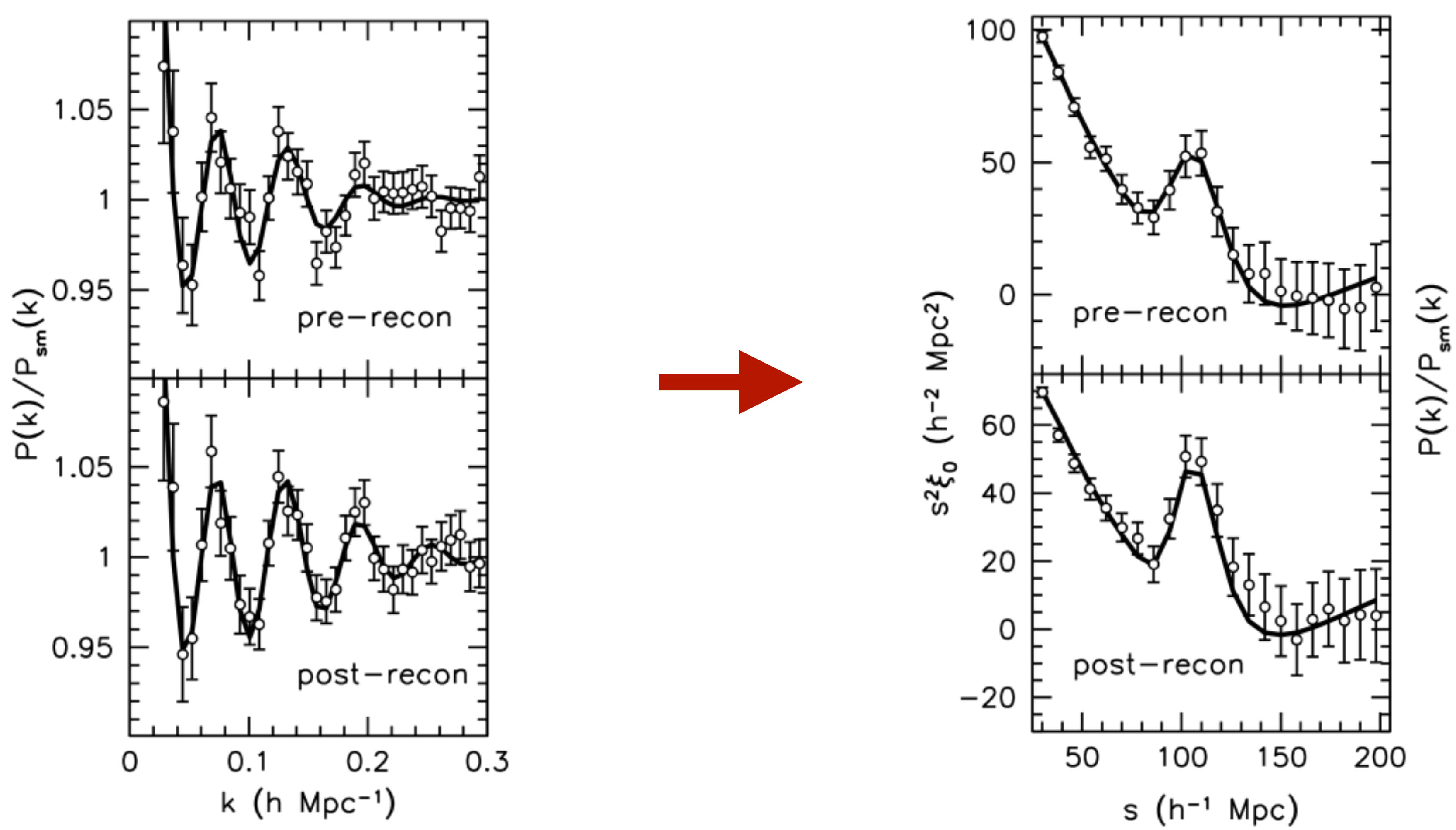
BUT

$$N_{\text{pix.}} \sim V k_{\text{max.}}^3$$

Correlation function and the BAO peak

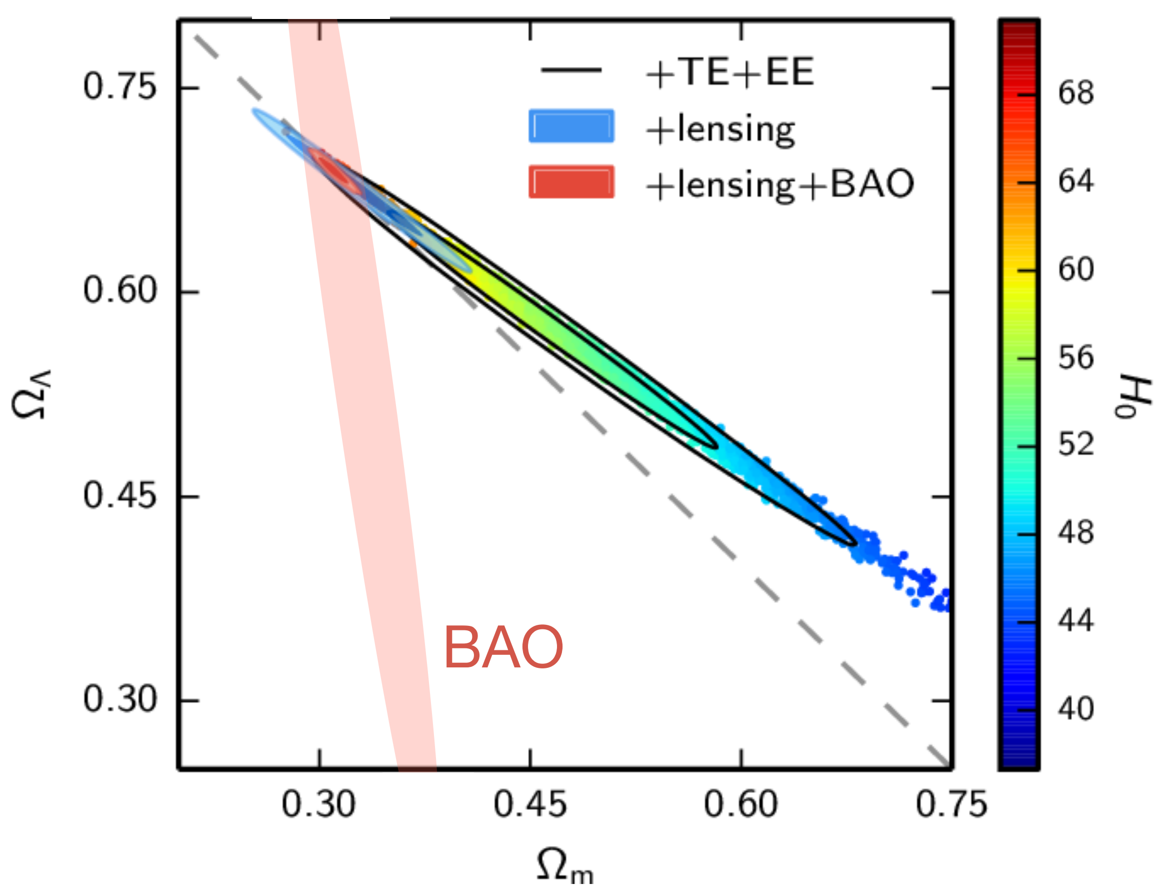
The feature is set in the early universe

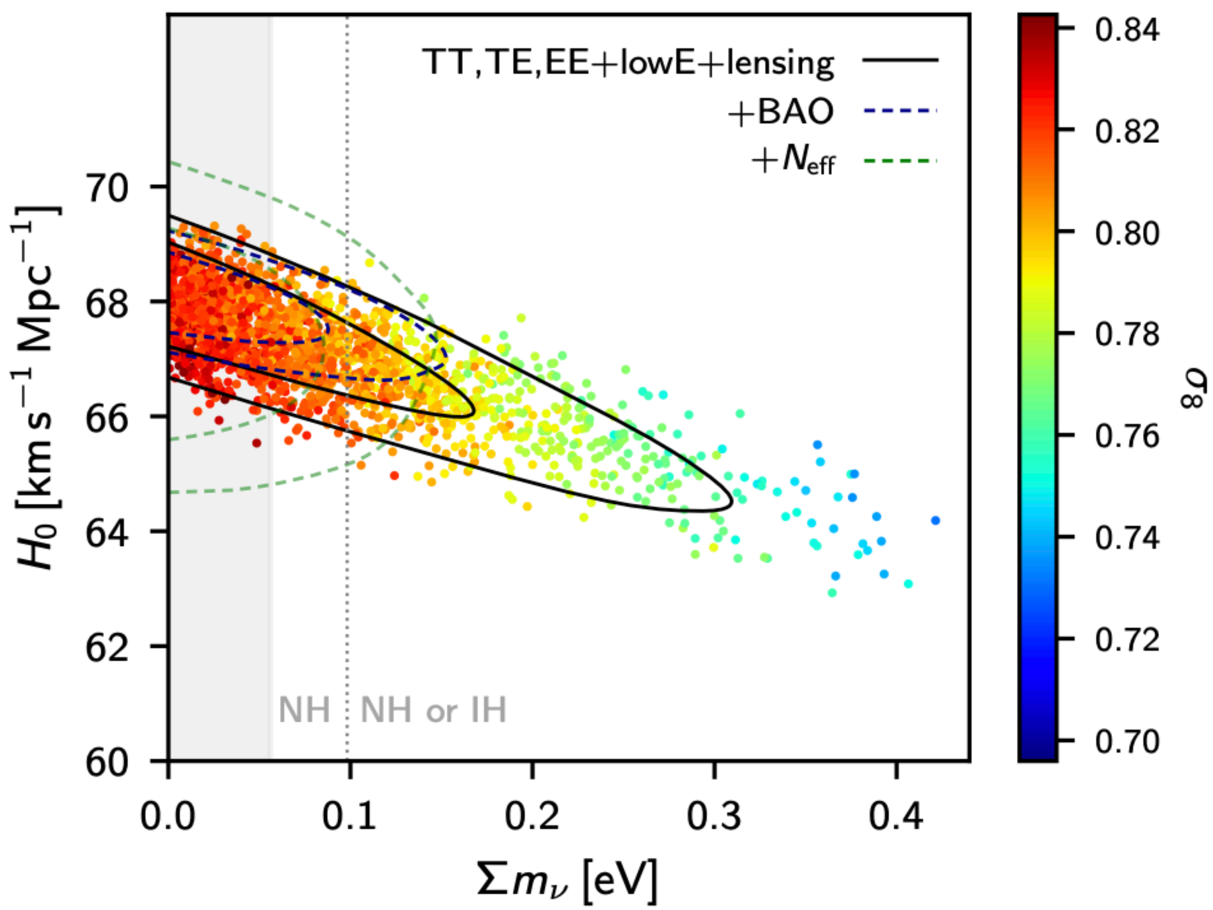
Very robust against nonlinear evolution and galaxy formation



Correlation function and the BAO peak

BAO has been extremely useful in combination with the CMB





Can we do even better than this?

Beyond the BAO peak

BAO has been bread and butter of galaxy clustering so far

Spectroscopic galaxy surveys contain much more information

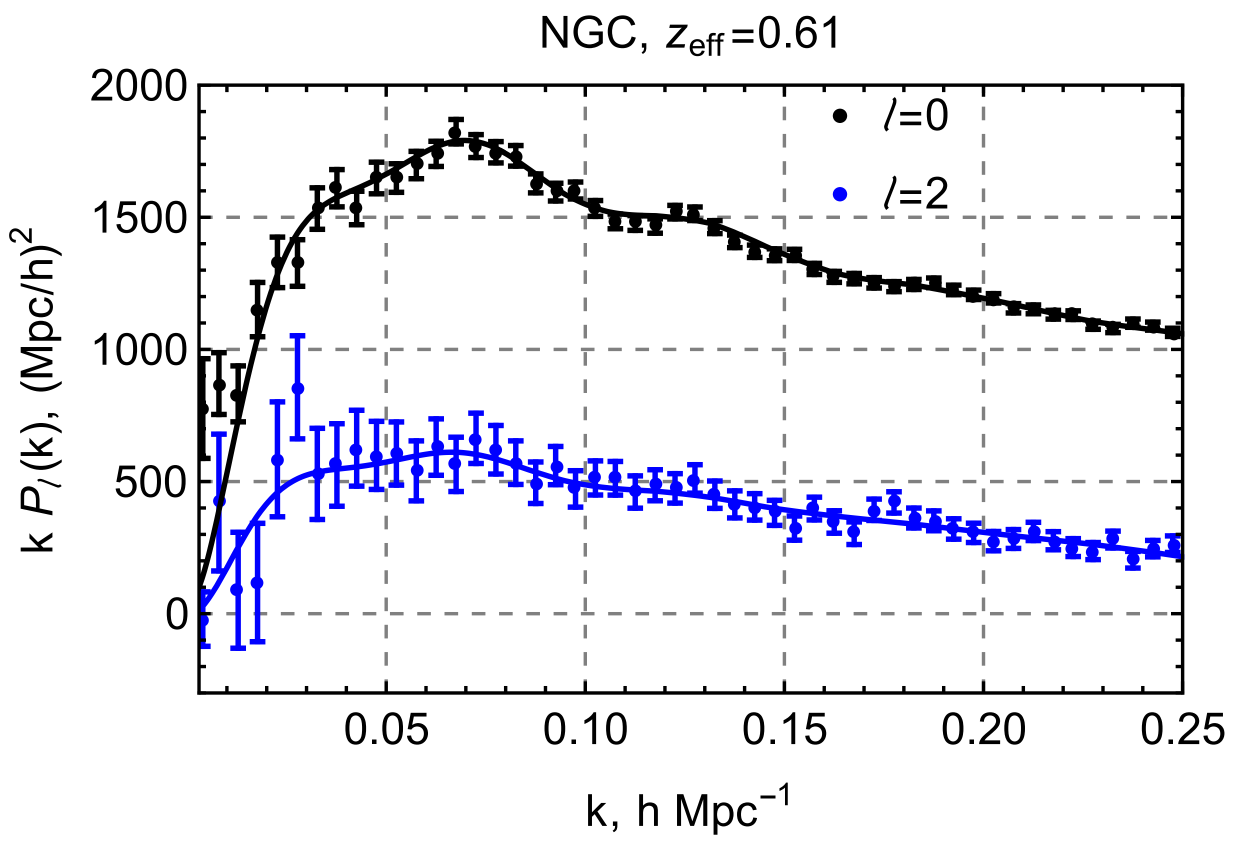
Like in the CMB, use the whole field and summary statistics

For example, the whole “shape” of the galaxy power spectrum

Full-shape analysis

Beyond the BAO peak

Galaxy map



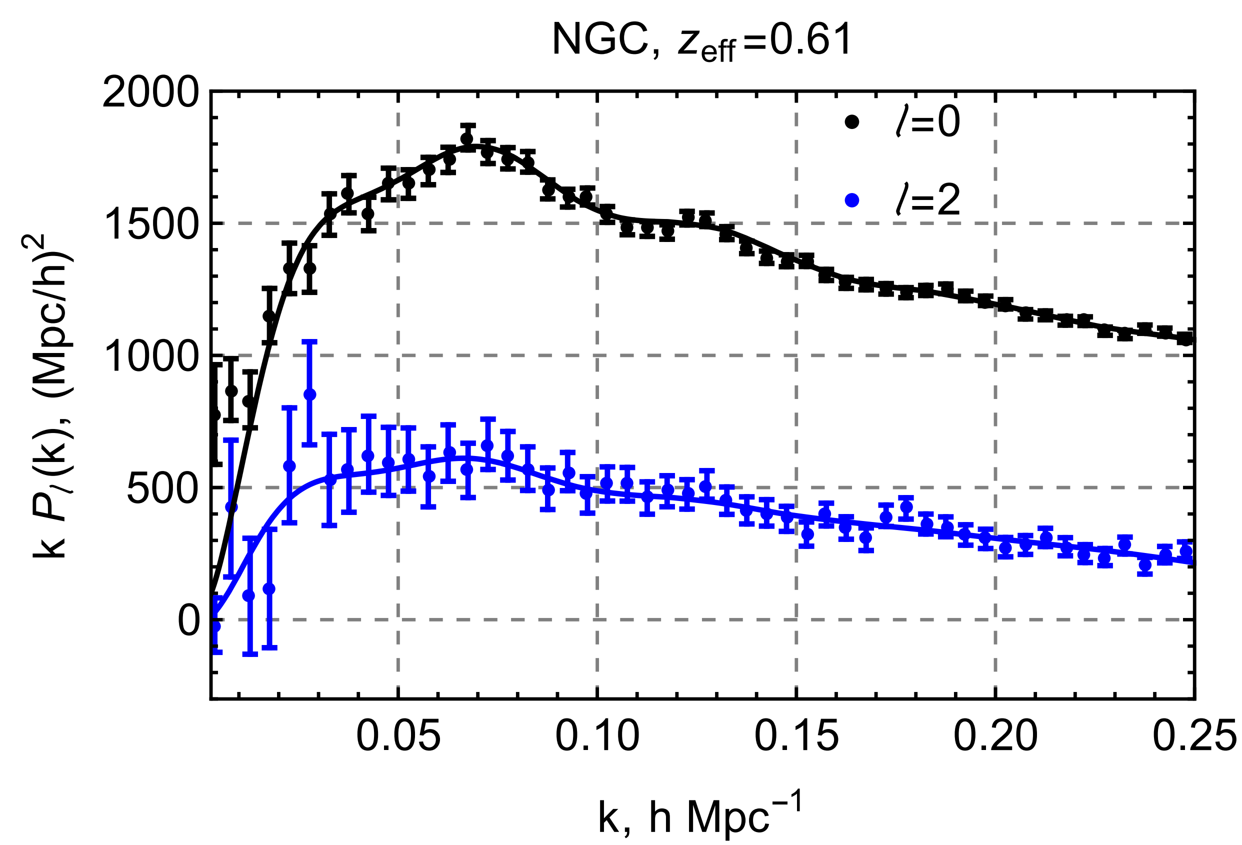
Full-shape analysis

Similar to CMB, directly measures “shape” parameters

all cosmological parameters
no CMB input needed

Beyond the BAO peak

Galaxy map



A key ingredient is a robust, flexible and accurate theoretical model

What is the theory of fluctuations in galaxy density on large scales?

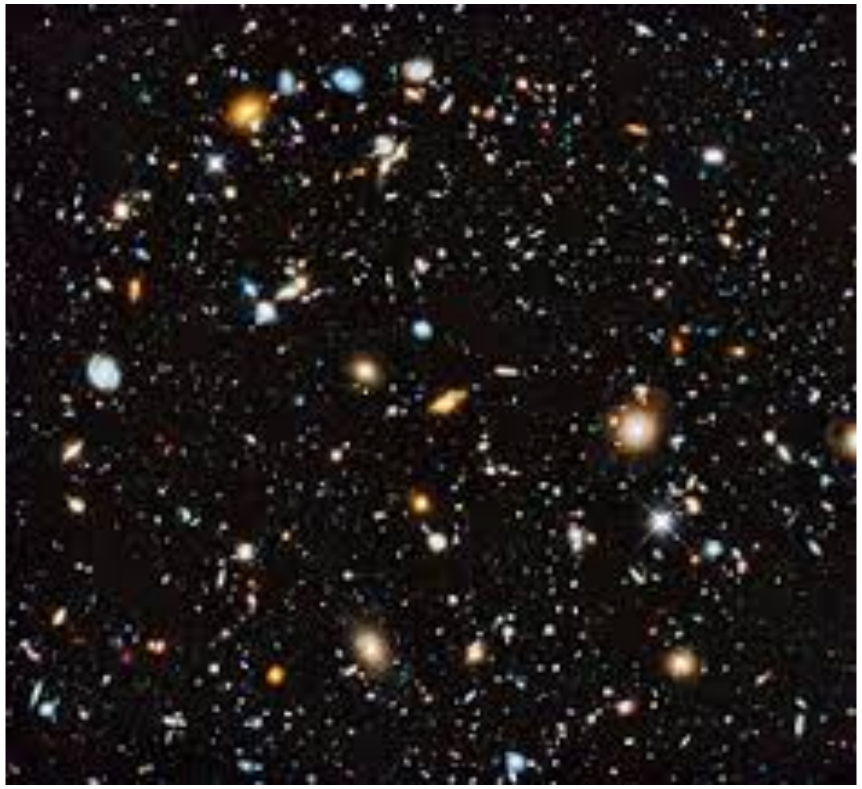
Theory of galaxy fluctuations

Effective Field Theory of Large-scale Structure

Baumann, Nicolis, Senatore, Zaldarriaga (2010)

Carrasco, Hertzberg, Senatore (2012)

...



What is a consistent theoretical framework to describe galaxy density field on large scales?

DM particles do not move far away

Galaxy formation is to a good approximation local in space

Effective Field Theory of Large-scale Structure

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

Effective Field Theory of Large-scale Structure

What do we gain?

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

The horizon scale $H_0^{-1} \sim 10^4\ \text{Mpc}$

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

$$N_{\rm pix.}^{\rm LSS} \gg N_{\rm pix.}^{\rm CMB}$$

1-loop galaxy power spectrum

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

contain galaxy formation physics

$$Z_1(\mathbf{k}) = b_1 + f\mu^2\,,$$
$$Z_2(\mathbf{k}_1,\mathbf{k}_2) = \frac{b_2}{2} + b_{\mathcal{G}_2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2k_2^2} - 1\right) + b_1 F_2(\mathbf{k}_1,\mathbf{k}_2) + f\mu^2 G_2(\mathbf{k}_1,\mathbf{k}_2)$$
$$+ \frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}(b_1 + f\mu_2^2) + \frac{\mu_2}{k_2}(b_1 + f\mu_1^2)\right)\,,$$

Infrared resummation

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

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

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

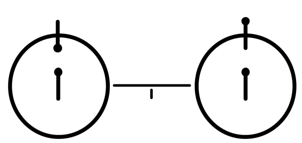
$$P_{\rm gg}(z,k,\mu) = (b_1(z) + f(z)\mu^2)^2\left(P_{\rm nw}(z,k) + {\rm e}^{-k^2\Sigma^2_{\rm tot}(z,\mu)}P_{\rm w}(z,k)(1 + k^2\Sigma^2_{\rm tot}(z,\mu))\right)$$
$$+ P_{\rm gg,\ nw,\ RSD,\ 1\text{-}loop}(z,k,\mu) + {\rm e}^{-k^2\Sigma^2_{\rm tot}(z,\mu)}P_{\rm gg,\ w,\ RSD,\ 1\text{-}loop}(z,k,\mu)\,.$$

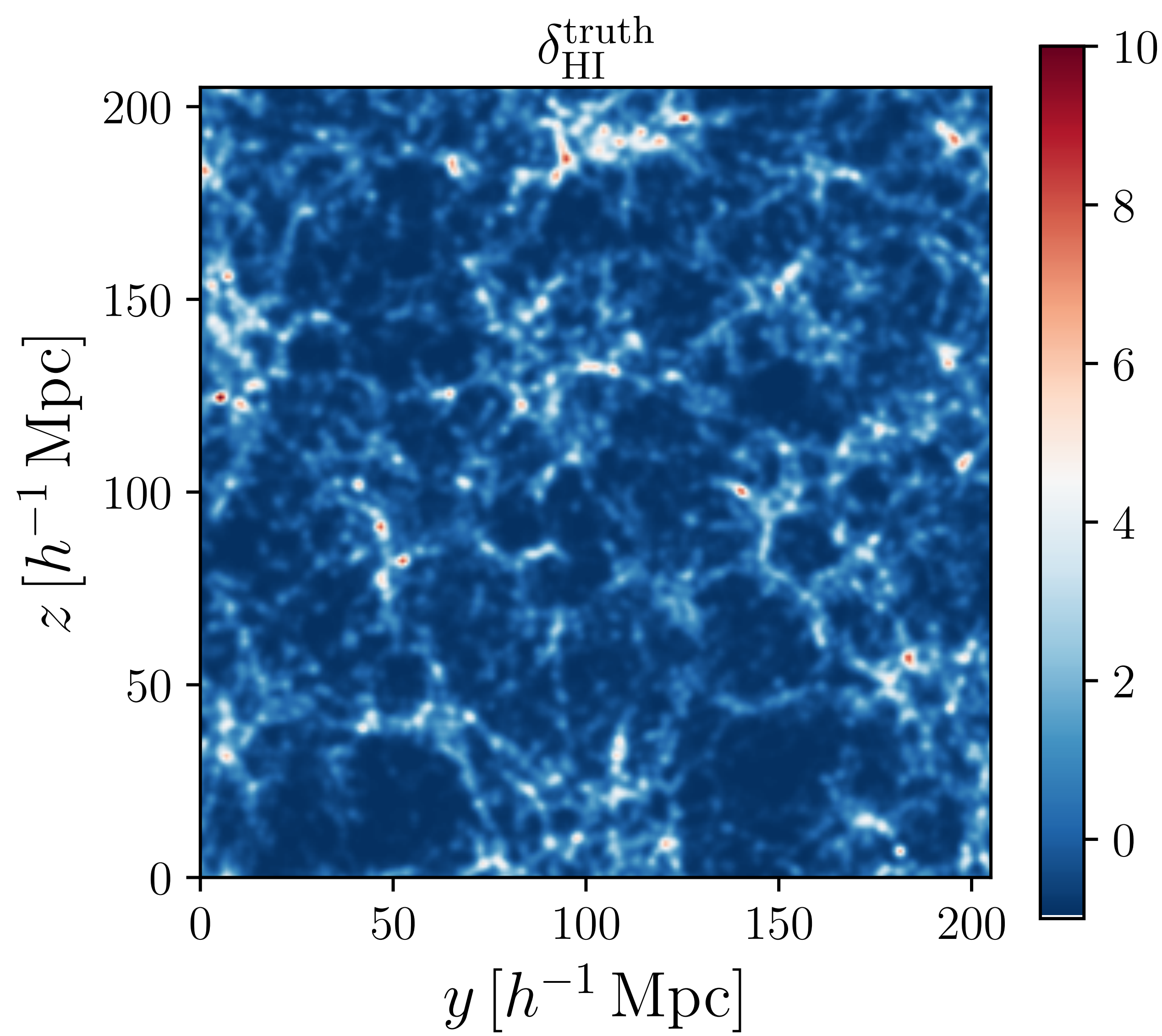
Parameters: $(\omega_{\rm b}, \omega_{\rm cdm}, h, A^{1/2}, n_s, m_\nu) \times (b_1A^{1/2}, b_2A^{1/2}, b_{\mathcal{G}_2}A^{1/2}, P_{\rm shot}, c_0^2, c_2^2, \tilde{c})$

How well does PT work?

Obuljen, MS, Schneider, Feldmann (2022)

Differences wrt the truth compatible with the shot noise



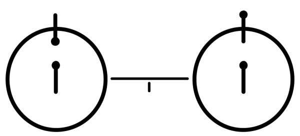


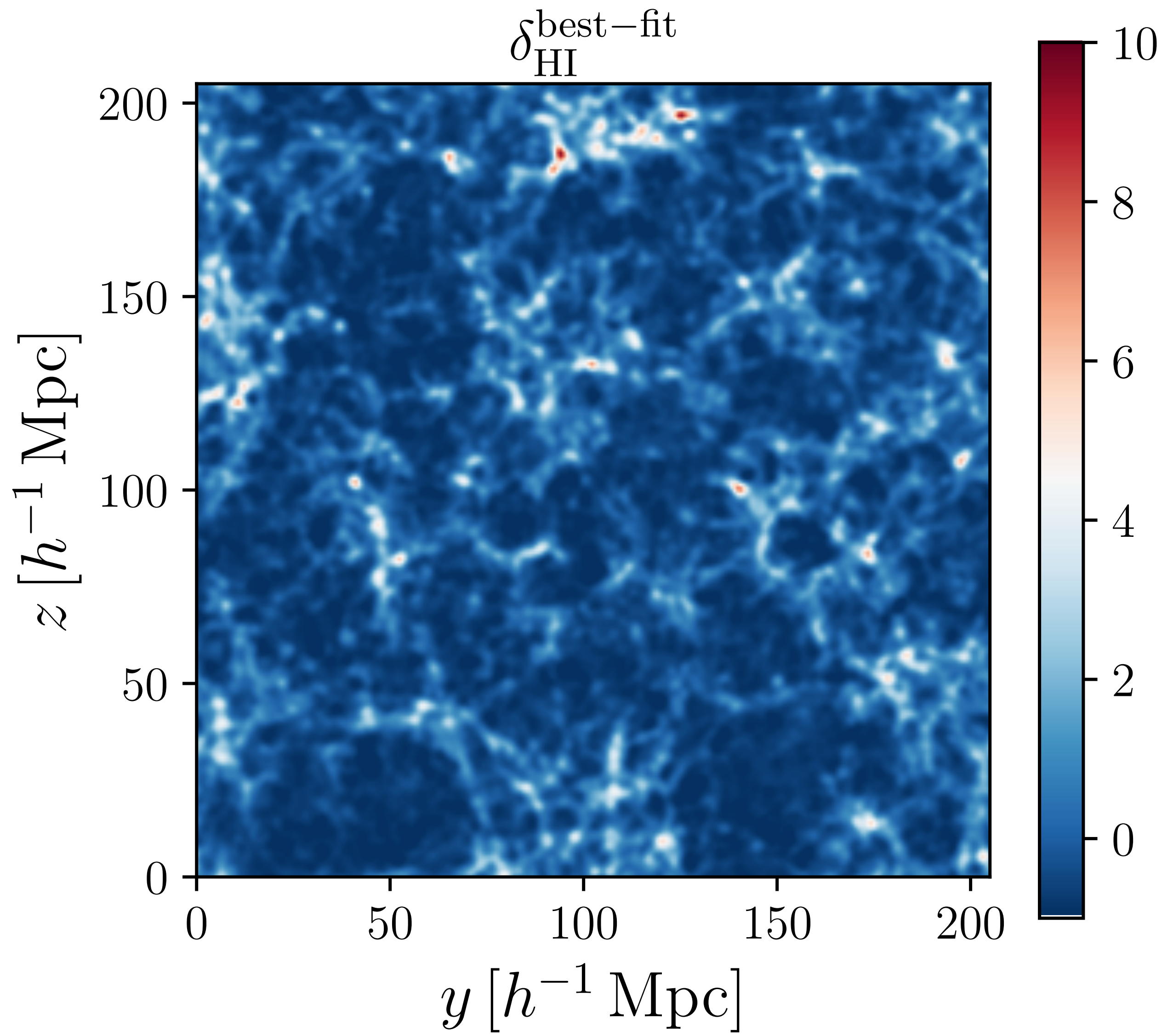
Hydro code

How well does PT work?

Obuljen, MS, Schneider, Feldmann (2022)

Differences wrt the truth compatible with the shot noise



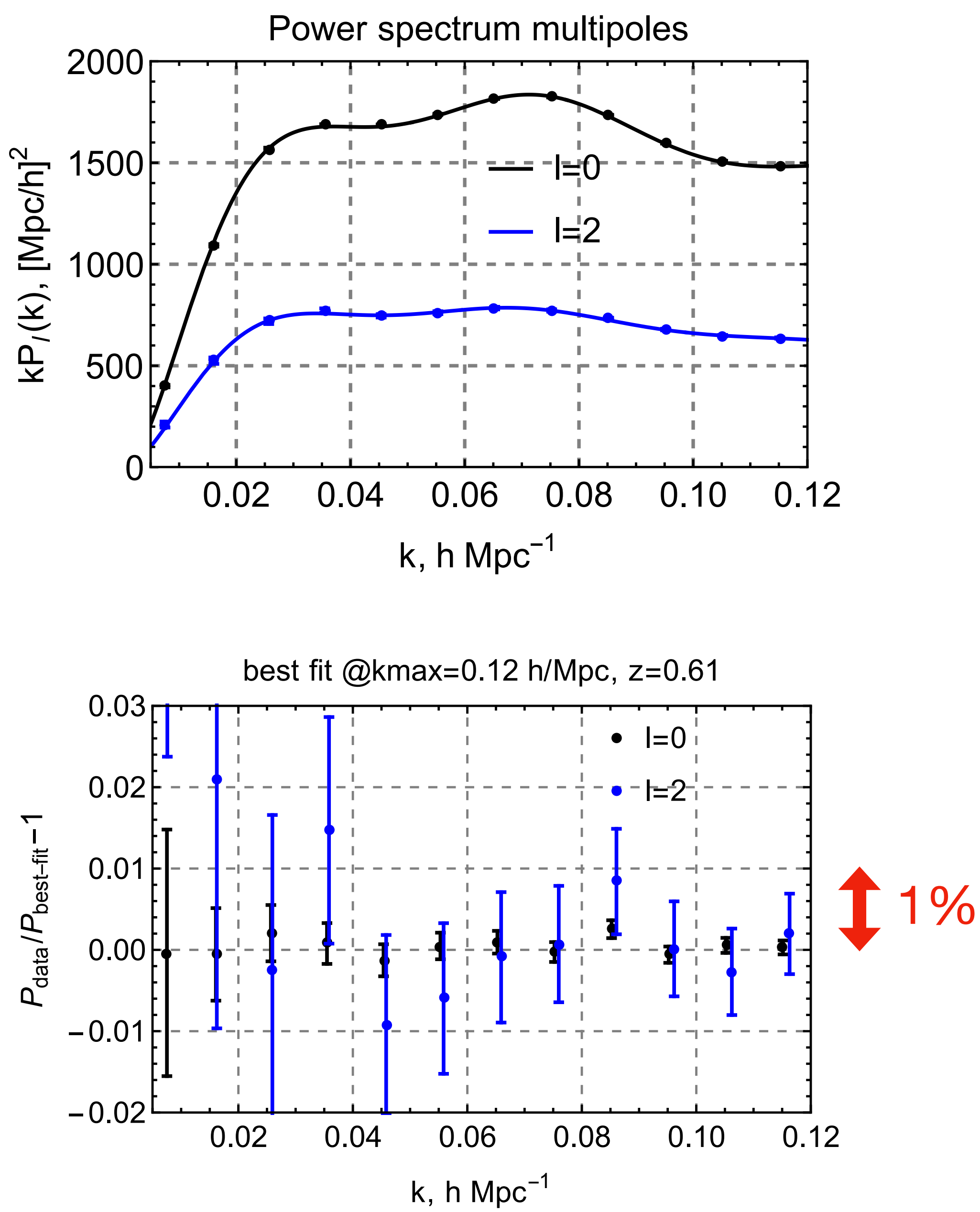


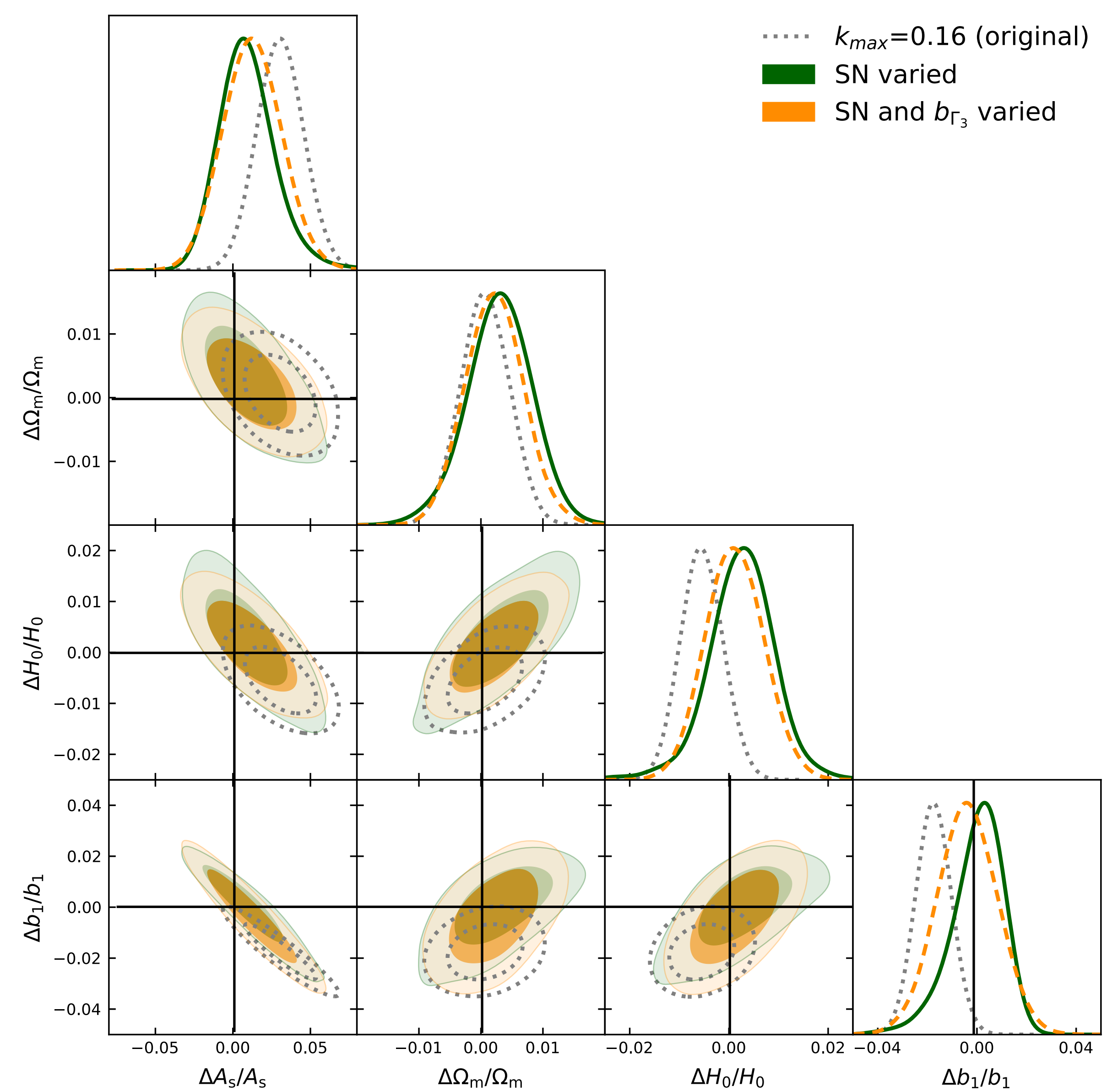
PT map

How well does PT work?

Nishimichi et al. (2020)

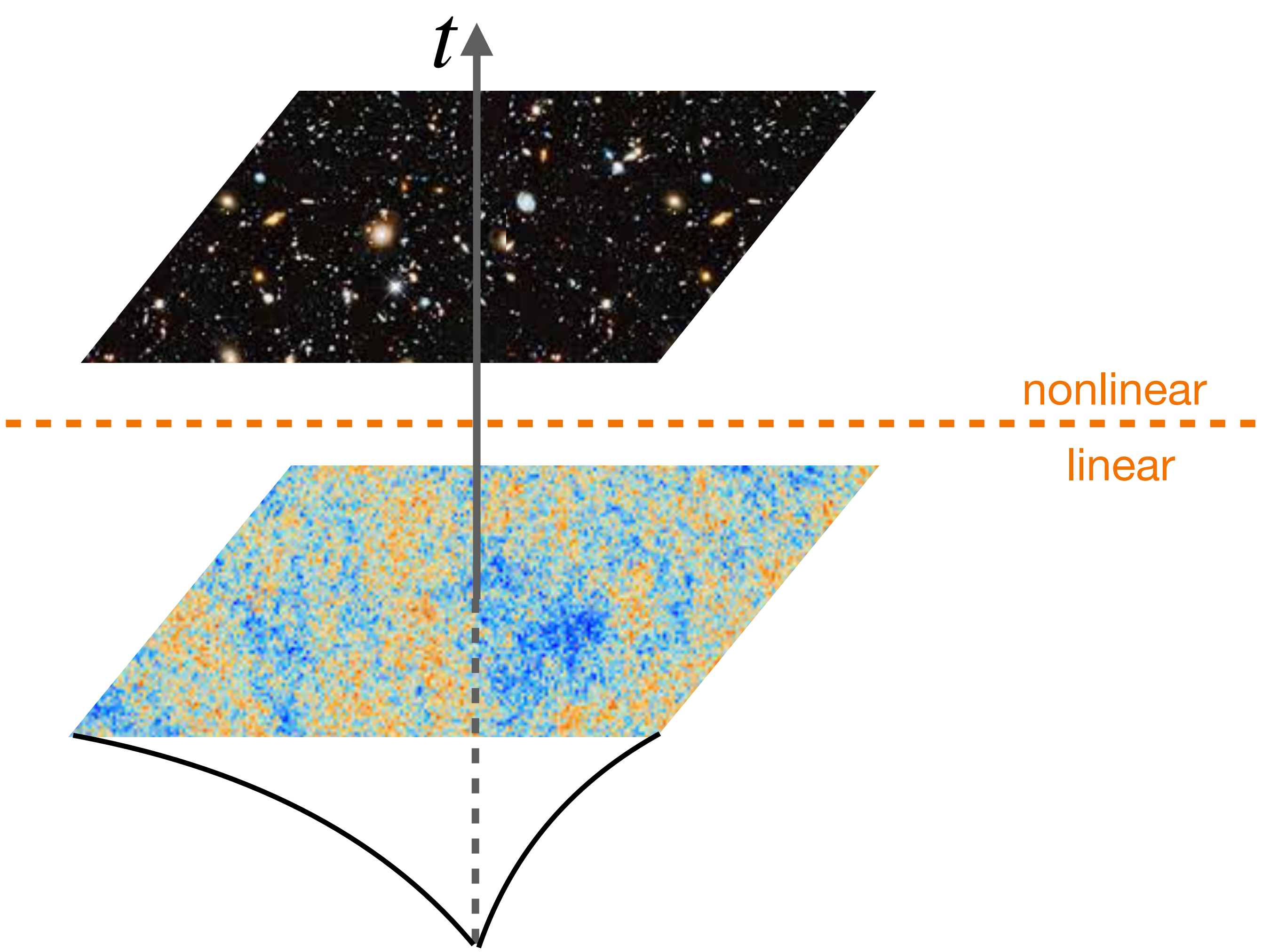
Blind analysis, very large volume ~ 600 (Gpc/h)³), realistic galaxies





A new era in cosmology

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



Initial conditions
(inflation)

CLASS-PT
PyBird
velocileptors

MCMC made possible

CMBFAST
CAMB
CLASS

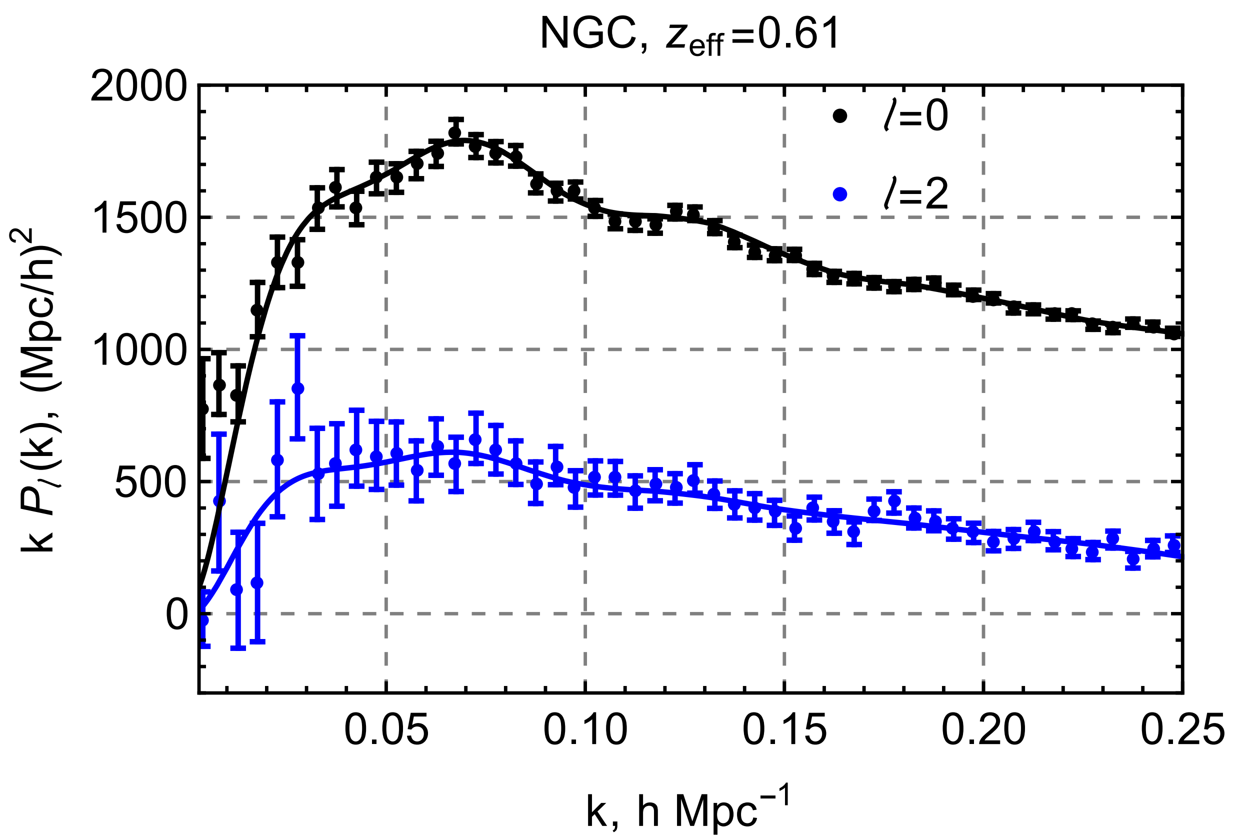
MCMC done routinely

Evolution of the vacuum state from inflation to redshift zero

Application to BOSS data

Galaxy map

BOSS data
~ few x 10^6 galaxies
~ 6 (Gpc/h)^3



Full-shape analysis

Similar to CMB, directly measures “shape” parameters

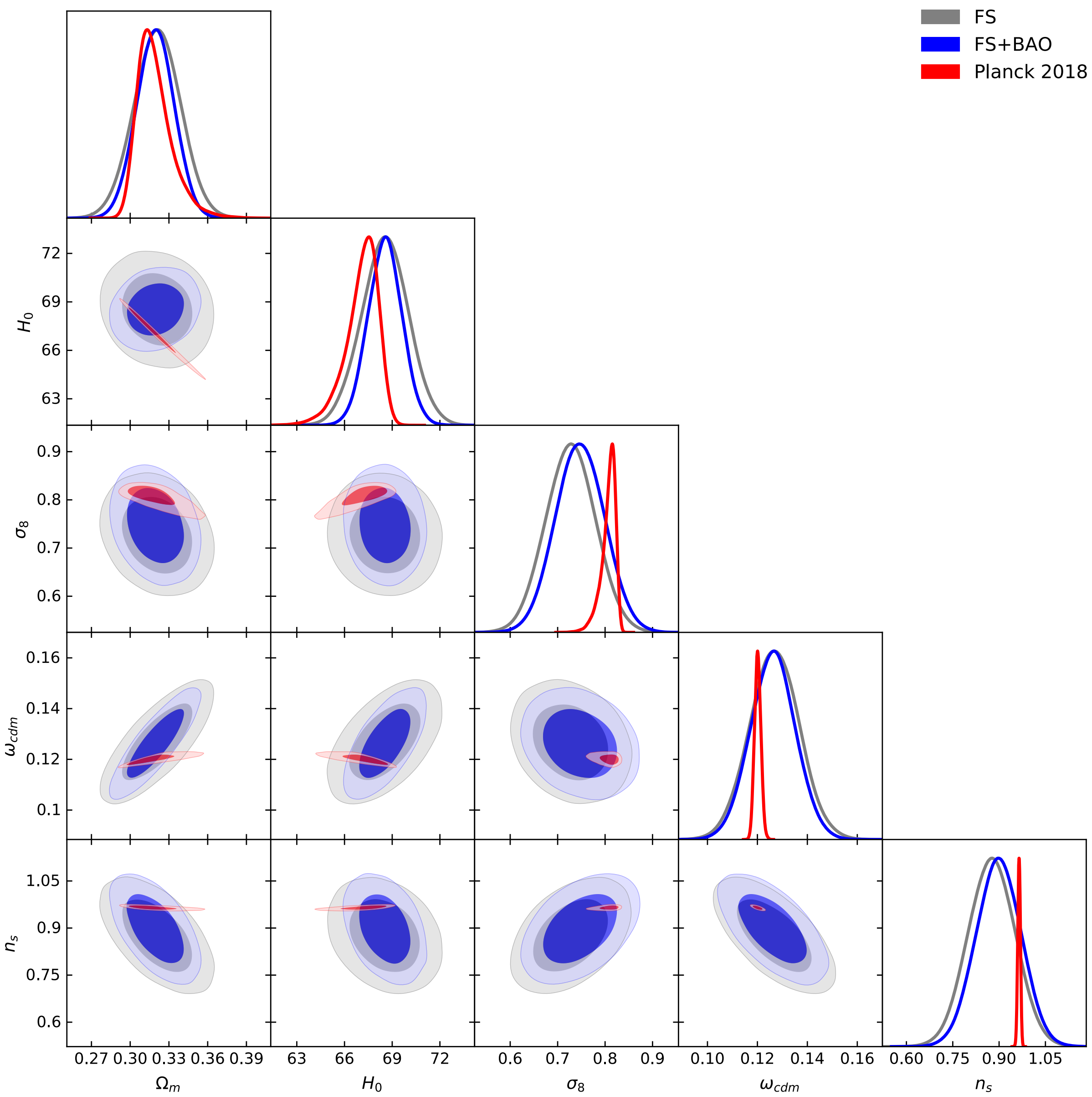
all cosmological parameters
no CMB input needed

Application to BOSS data

Ivanov, MS, Zaldarriaga (2019)

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

Philcox, Ivanov, MS, Zaldarriaga (2020)



Using 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)

Application to BOSS data

Many additional analyses including new estimators, data compression, higher-order statistics etc.

Most of the work done for the standard cosmological model

These were large steps forward

What do we expect in the near future?

Future prospects

Beyond ΛCDM

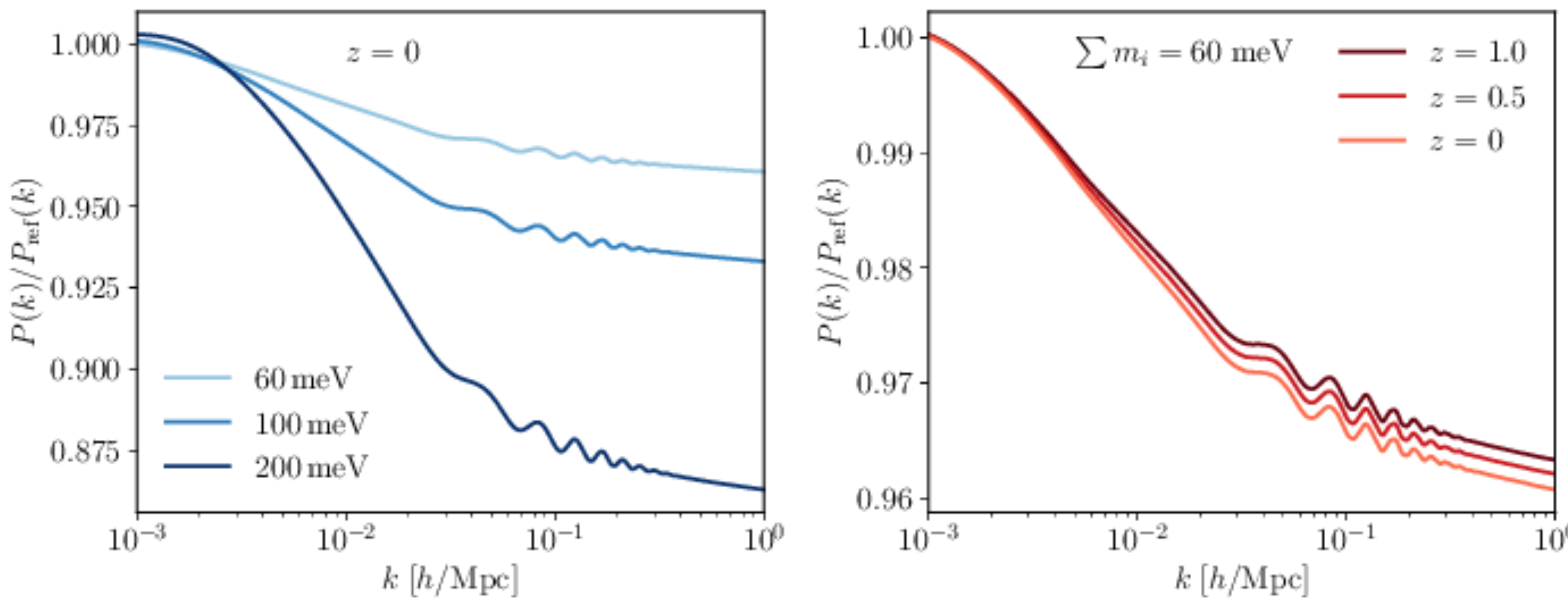
Many extensions of the standard model are interesting to explore

DESI/Euclid + CMB has huge constraining power

There is a unique potential for discoveries in the next ~5 yr

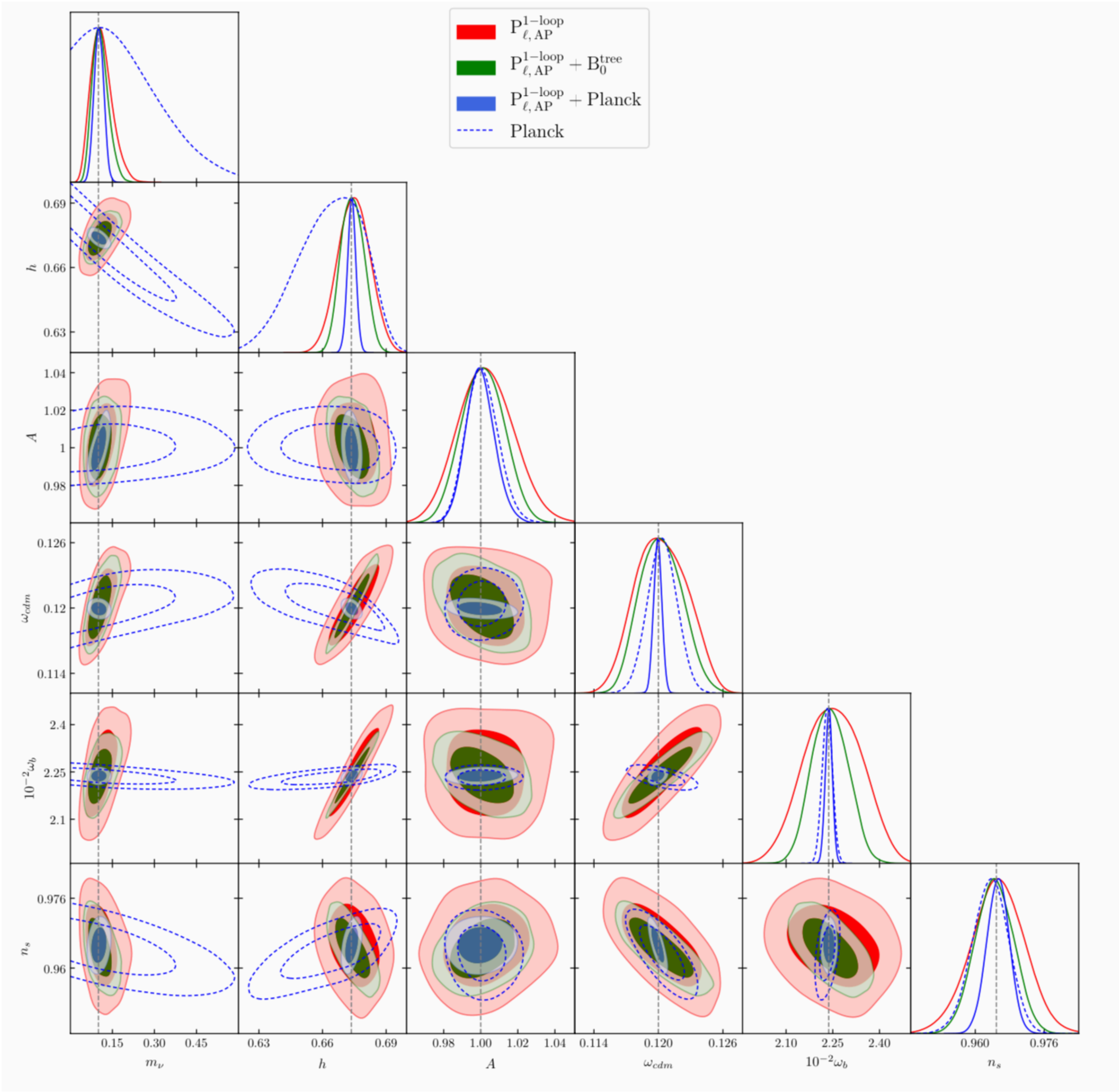
Beyond ΛCDM - neutrinos

Free-streaming neutrinos cause scale-dependent suppression of structure



Beyond ΛCDM - neutrinos

Chudaykin, Ivanov (2019)



for a Euclid-like survey

Beyond ΛCDM

Other neutrino-like light but massive relics in the dark sector

Spatial curvature of the universe

Various proposed models to resolve Hubble tension

Small fractions of dark matter being ultralight axions

Long range forces in the dark sector

Physics of inflation and primordial non-Gaussianities

~ 5-10 times better constraints with LSS

Conclusions

Great success in the past, large amount of data in the near future

There is no guaranteed discovery, many options to explore

A bulk of relevant data will be collected in the next 5 years

An order of magnitude improvements in all directions

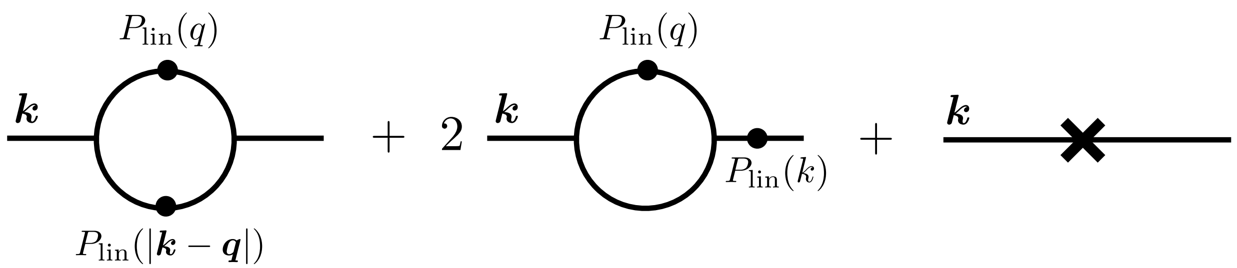
A lot of work to be done in theory and data analysis

Additional slides

Leading nonlinear corrections

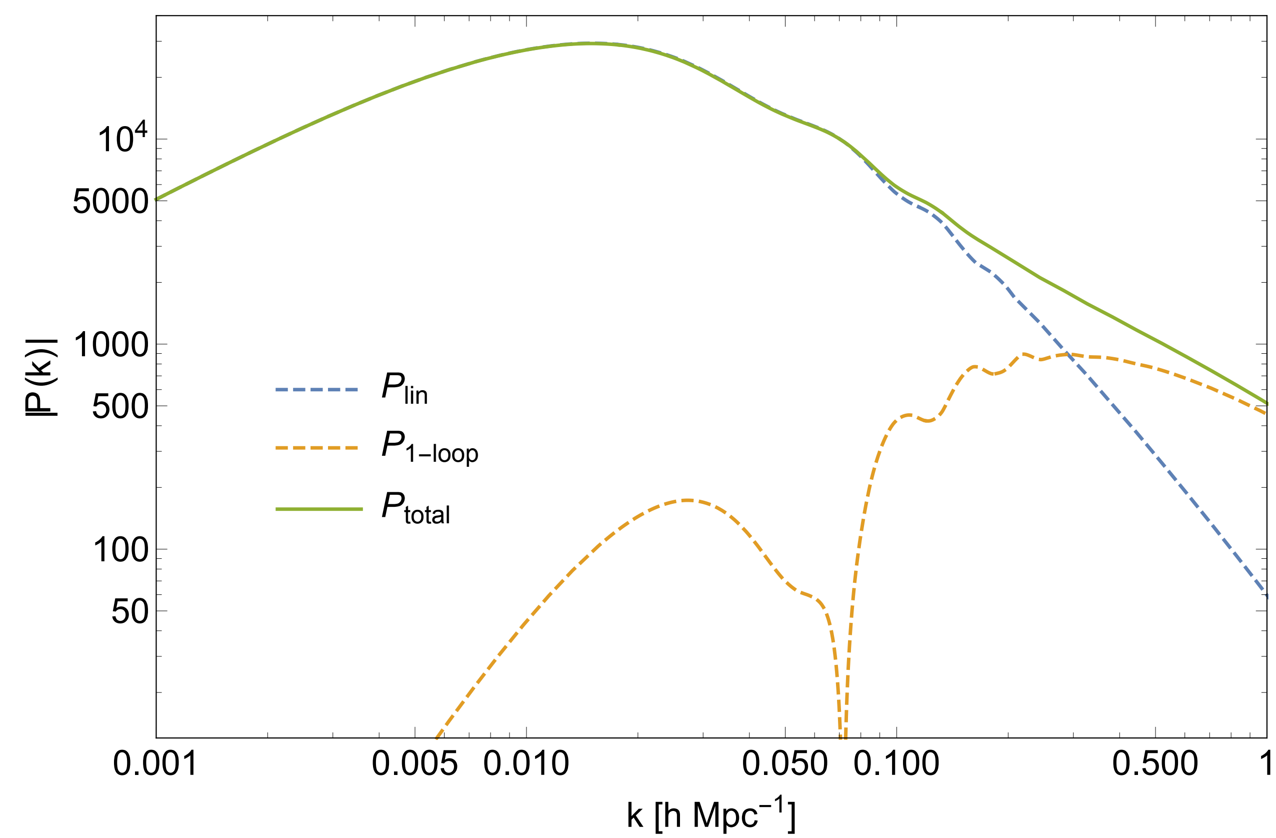
$$\langle \delta_{\boldsymbol{k}} \delta_{-\boldsymbol{k}} \rangle = \langle \delta^{(1)}_{\boldsymbol{k}} \delta^{(1)}_{-\boldsymbol{k}} \rangle + \langle \delta^{(2)}_{\boldsymbol{k}} \delta^{(2)}_{-\boldsymbol{k}} \rangle + \langle \delta^{(1)}_{\boldsymbol{k}} \delta^{(3)}_{-\boldsymbol{k}} \rangle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

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



$$P_{13}^{\mathrm{UV}}(k) = -\frac{61}{630\pi^2} P_{\mathrm{lin}}(k) k^2 \int_0^\infty dq P_{\mathrm{lin}}(q)$$

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

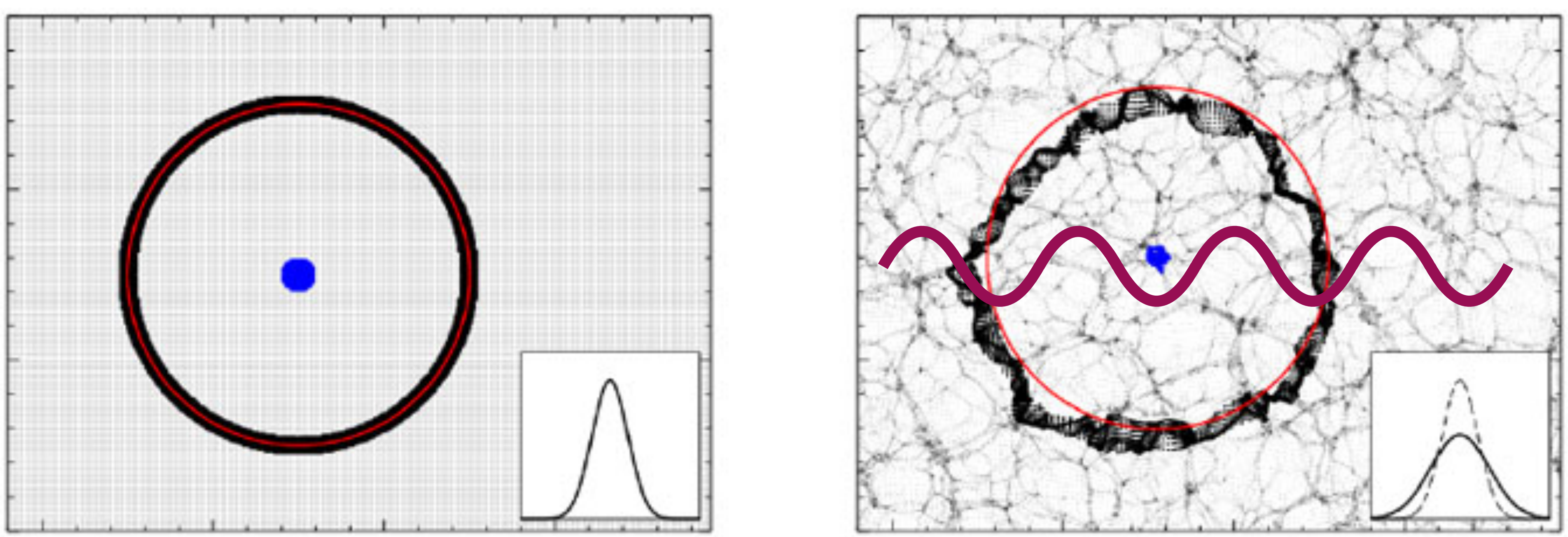


Infrared resummation

$$\boldsymbol{\psi} \sim \boldsymbol{\partial}\Phi \sim \frac{\boldsymbol{\partial}}{\partial^2}\delta \quad \rightarrow \quad \Sigma_\Lambda^2 \approx \frac{1}{6\pi^2}\int_0^\Lambda \mathrm{d}q P_{\rm lin}(q)[1-j_0(q\ell_{\rm BAO})+2j_2(q\ell_{\rm BAO})]$$

new parameter

Displacements can be large compared to the nonlinear scale



$$2\pi/\ell_{\rm BAO} < q \ll 2\pi/\sigma$$

Infrared resummation

Senatore, Zaldarriaga (2014)

Baldauf, Mirbabayi, MS, Zaldarriaga (2015)

Vlah, Seljak, Chu, Feng (2015)

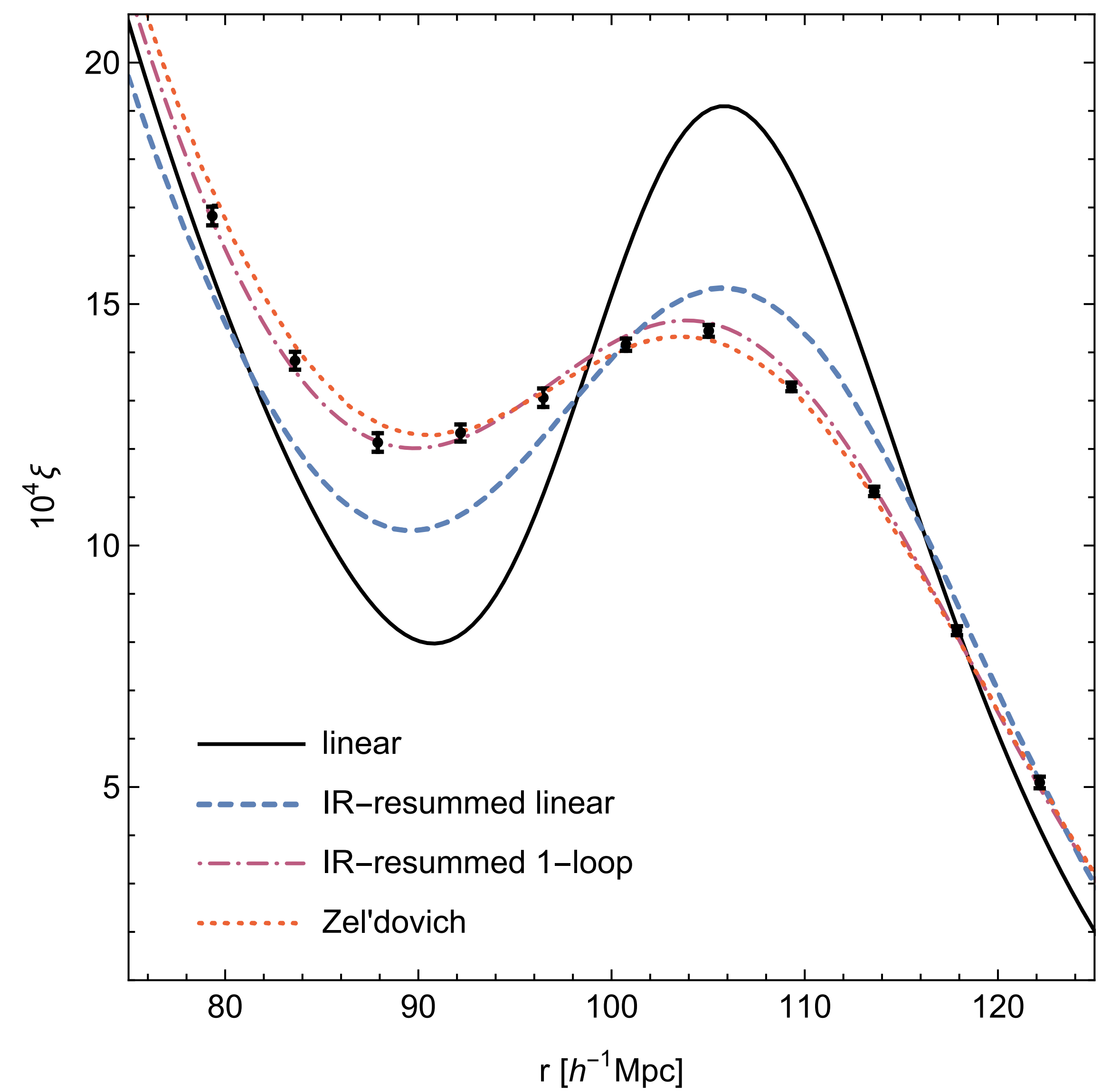
Blas, Garny, Ivanov, Sibiryakov (2016)

Senatore, Trevisan (2017)

Large displacements can be resummed, for galaxies as well

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

PT in tidal fields, nonperturbative in displacements

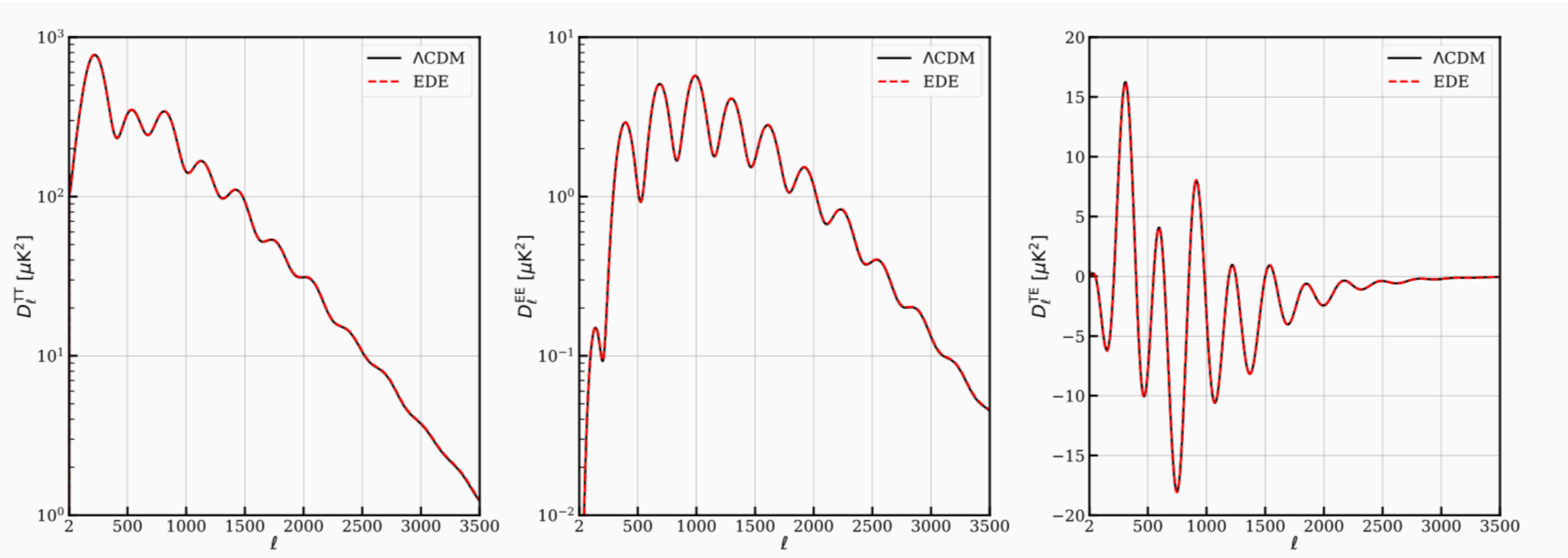


Beyond ΛCDM - Hubble tension

Populin, Smith, Karwal, Kamionkowski (2018)

New energy component in the early universe that accelerates the expansion and changes the sound horizon can change *H0*

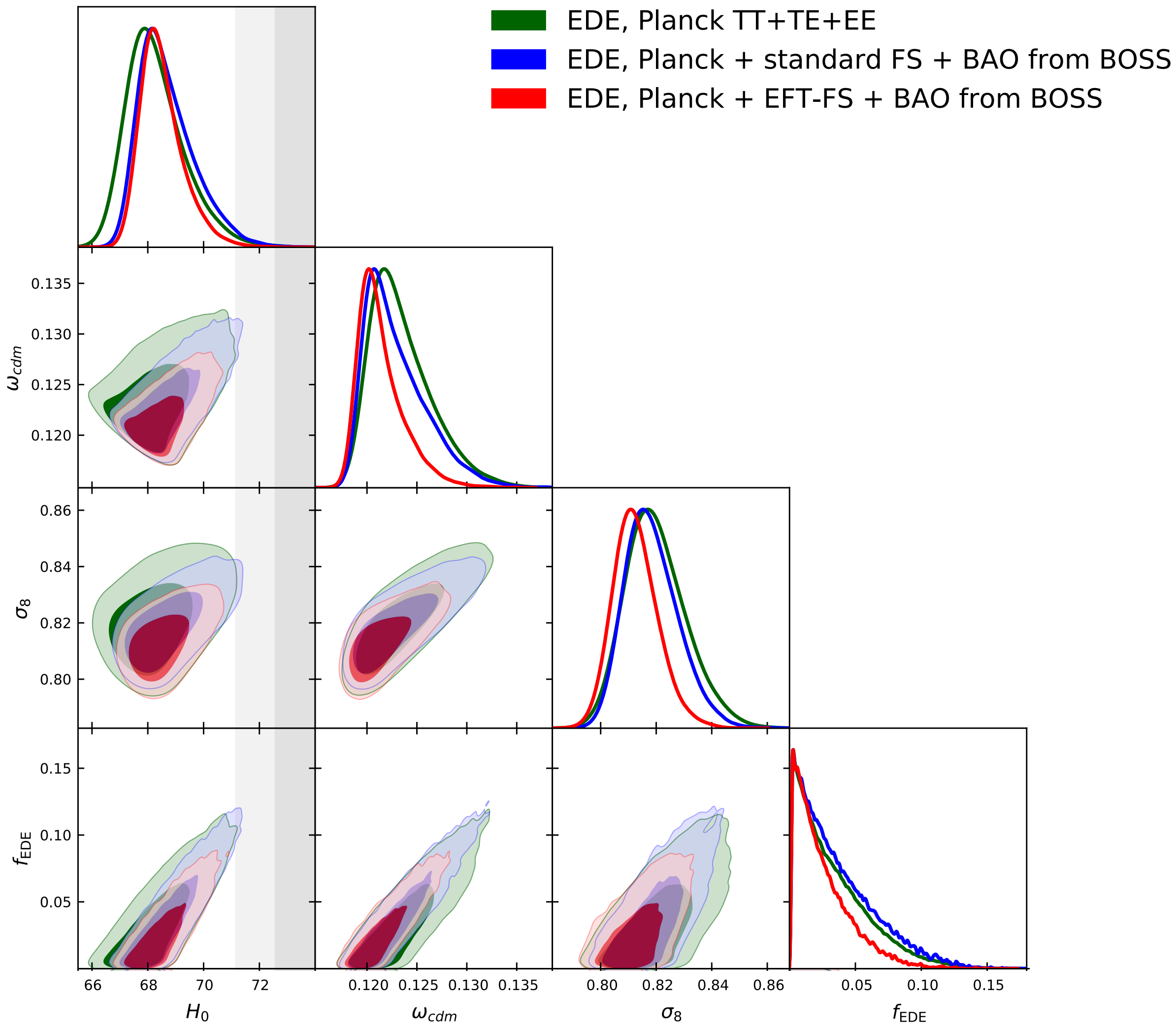
Early dark energy

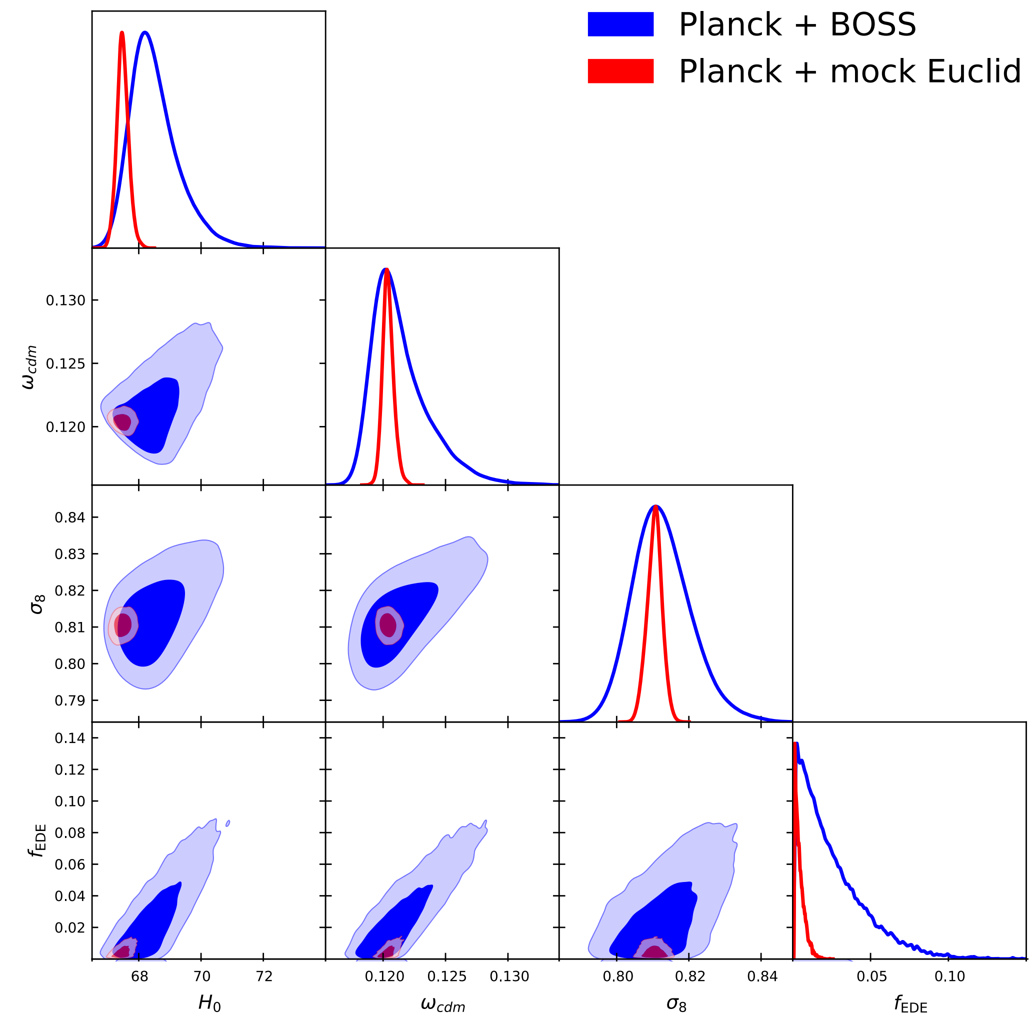


Beyond ΛCDM - Hubble tension

Ivanov et al. (2020)

Early dark energy

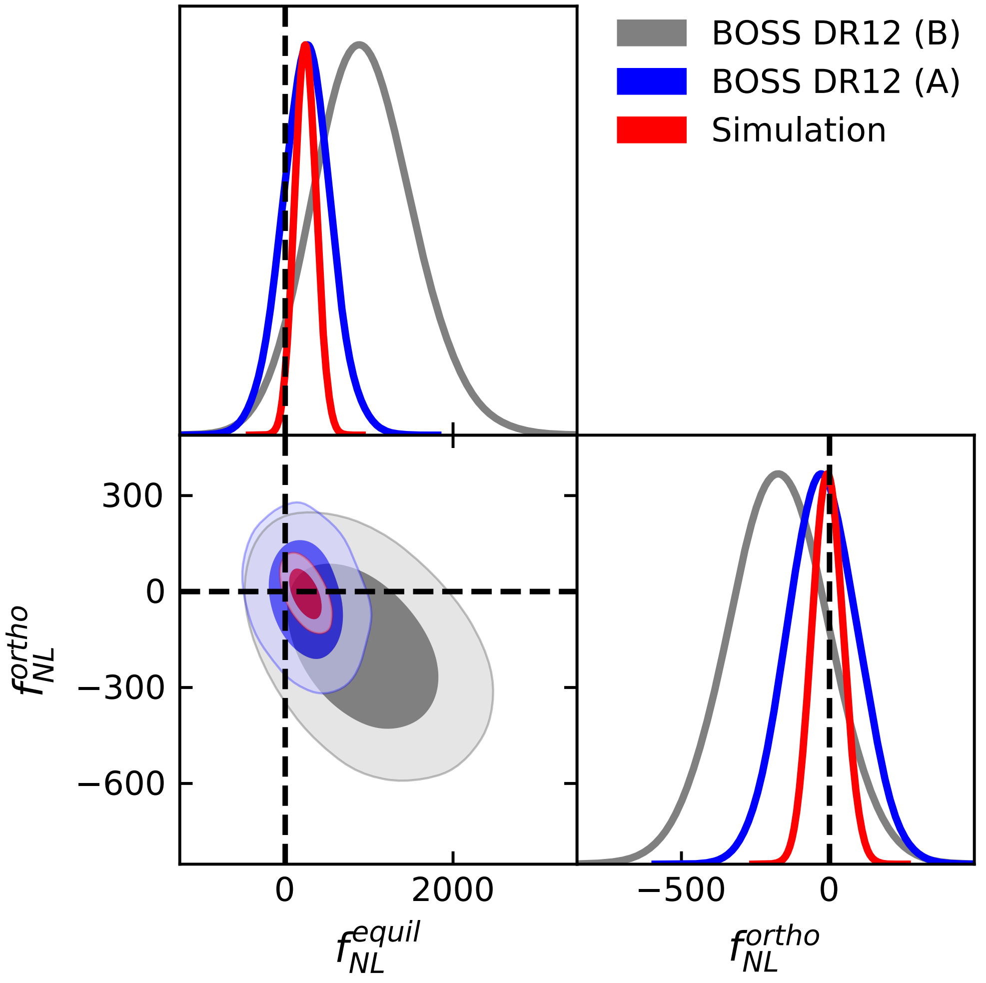


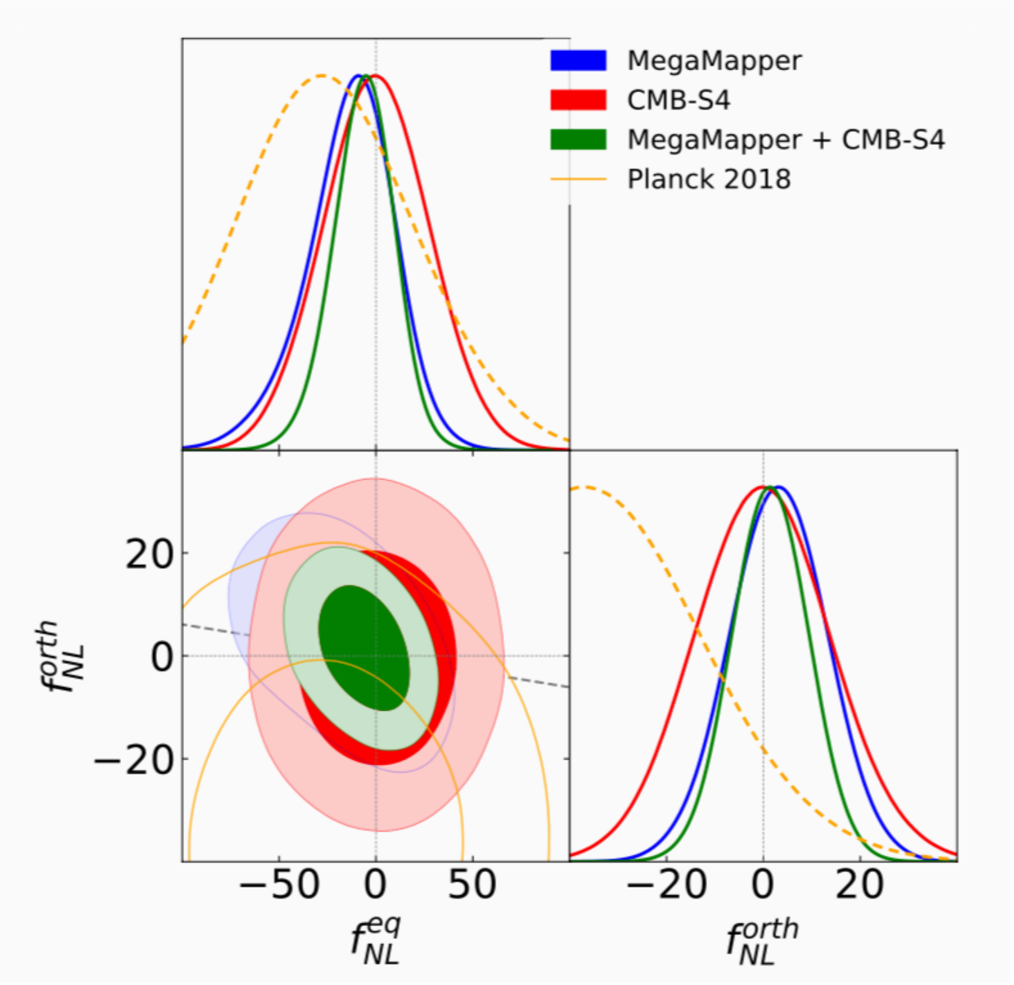


Beyond ΛCDM - PNG

Cabass, Ivanov, Philcox, MS, Zaldarriaga (2022)

PNG in single-field inflation





Beyond ΛCDM - exploring DM

A fraction of DM is exotic

ULA

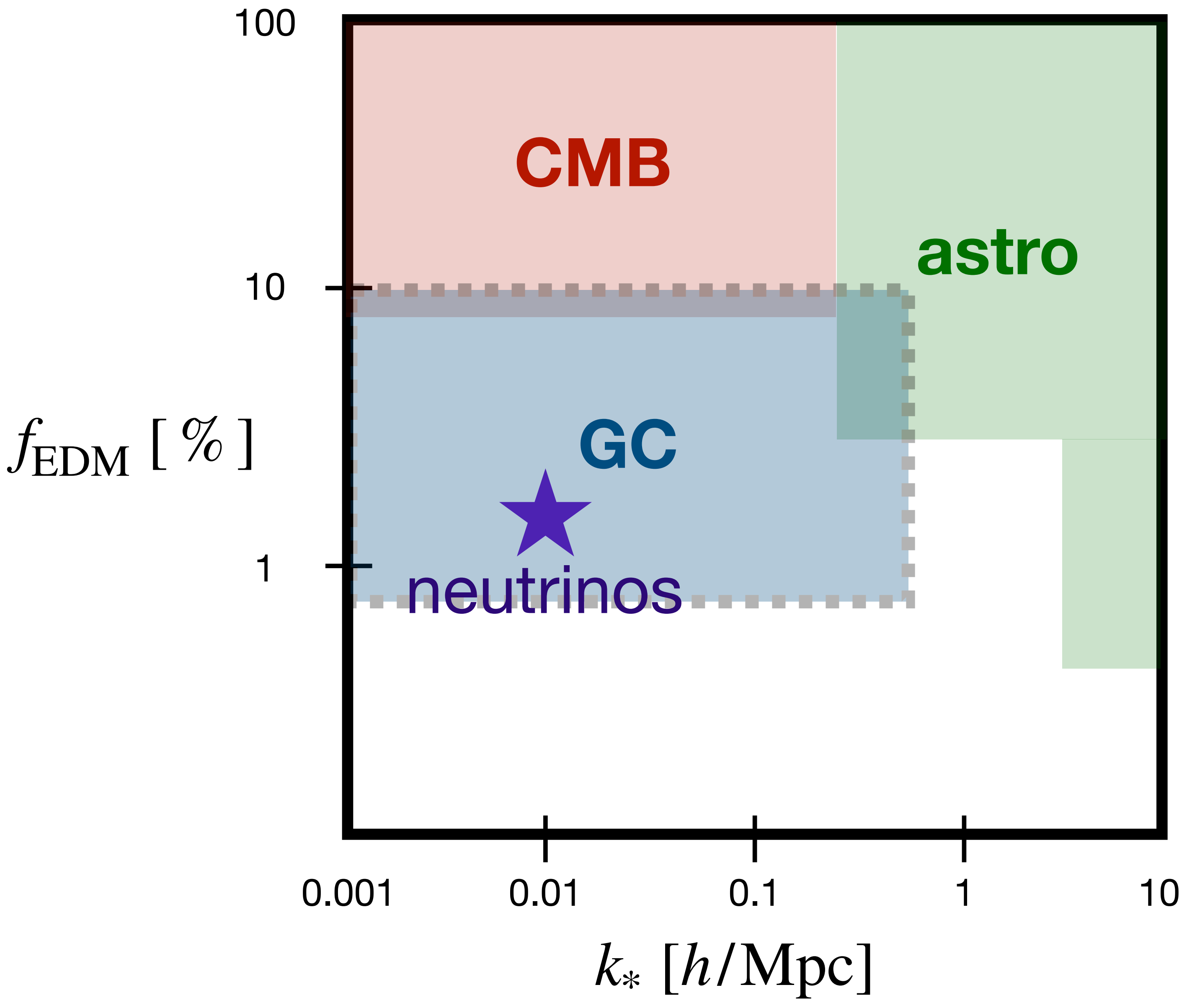
Baryon-DM interactions

LiMRs

Long-range forces

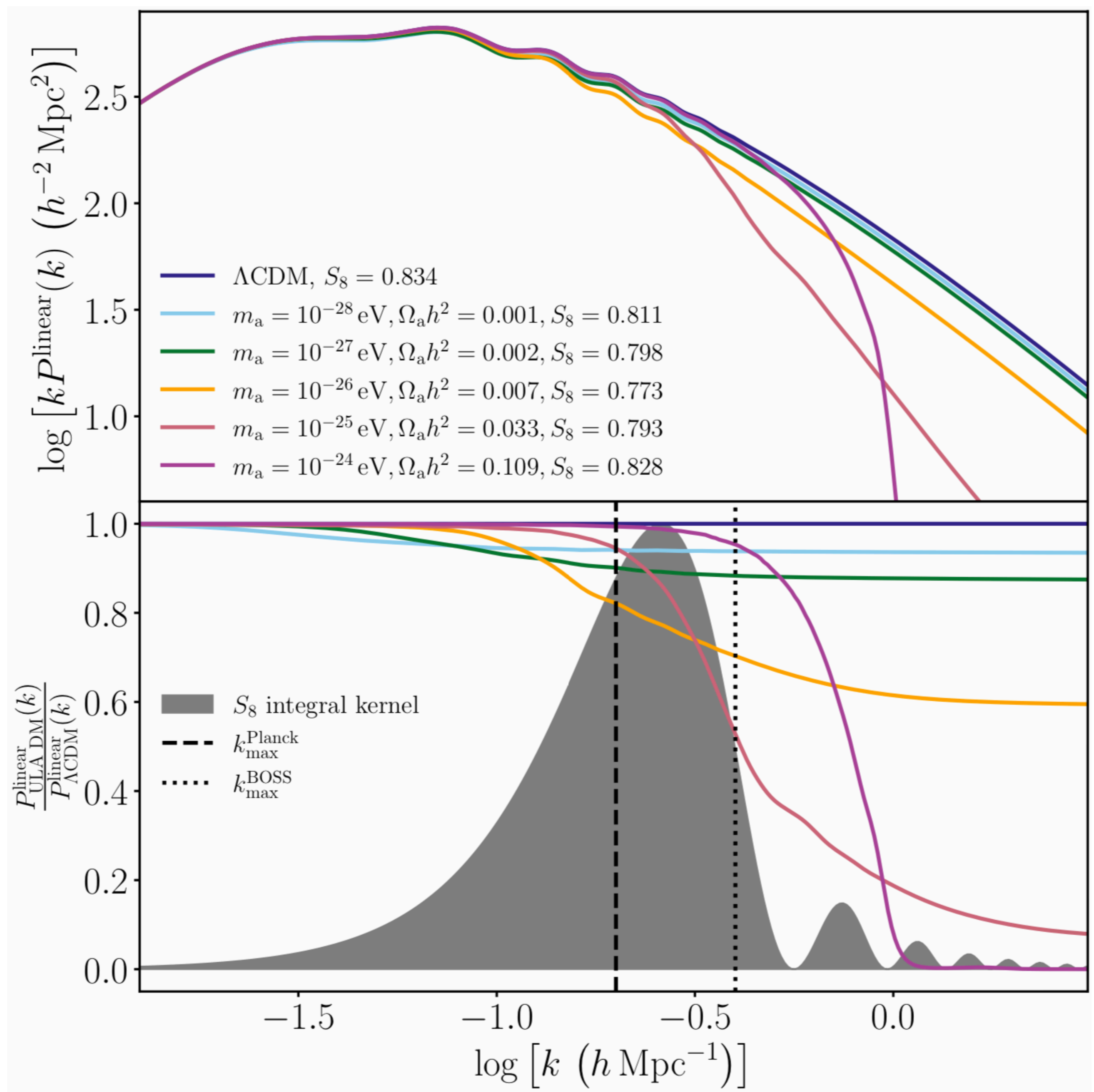
SIDM

…



Beyond ΛCDM - ULA

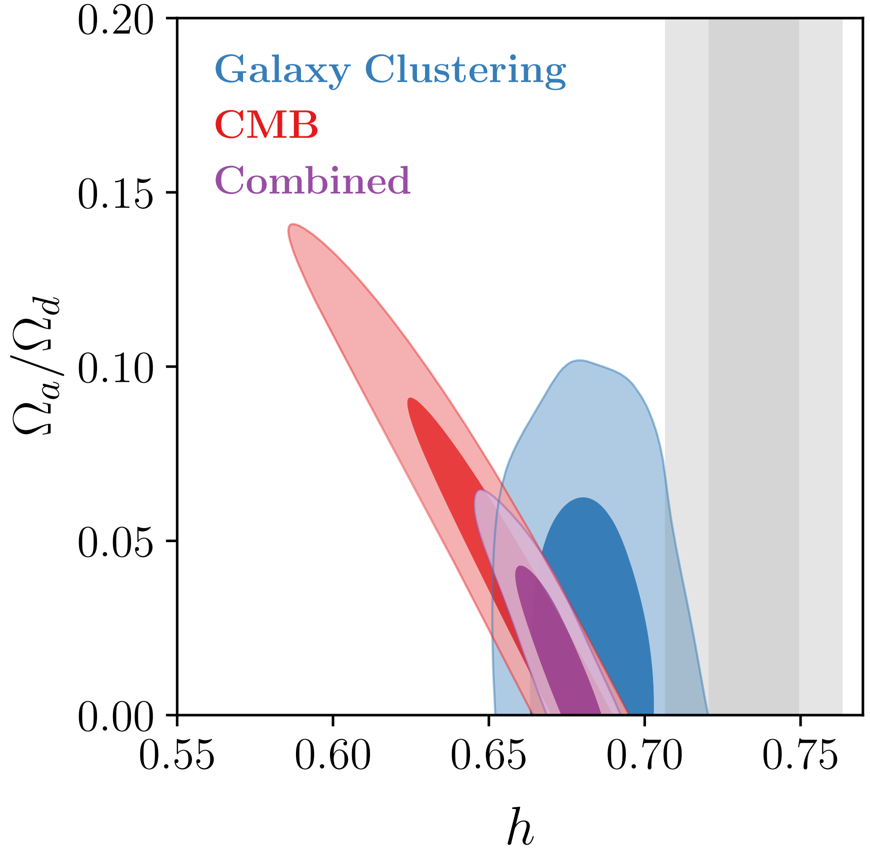
On scales smaller than de Broglie wavelength, axion DM does not cluster

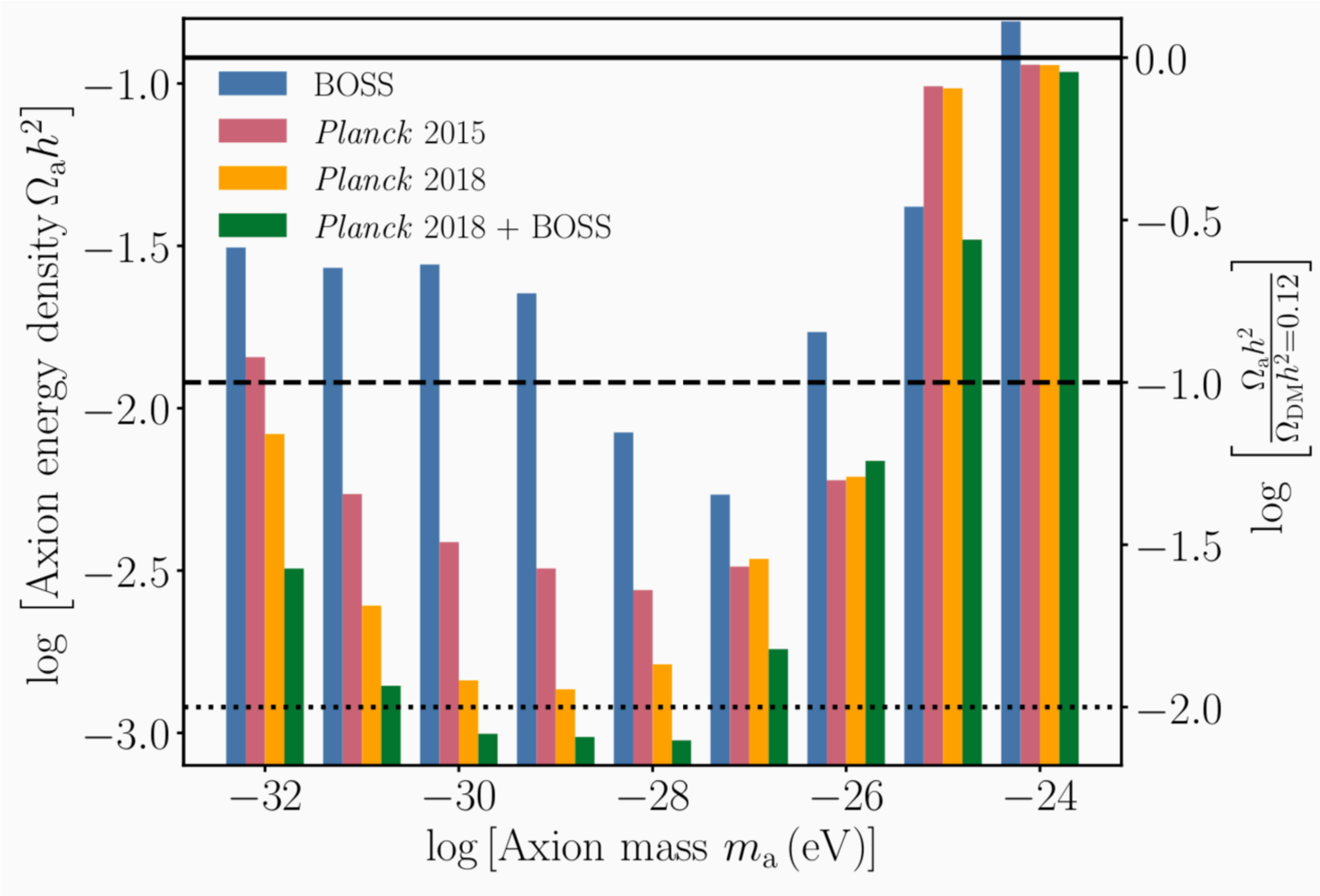


Beyond ΛCDM - ULA

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

Rogers et. al. (2023)





Beyond ΛCDM - DM long range force

Bottaro, Castorina, Costa, Redigolo, Salvioni (2023)

Additional long-range force mediated by a massless scalar

Appears as “modified gravity” for DM