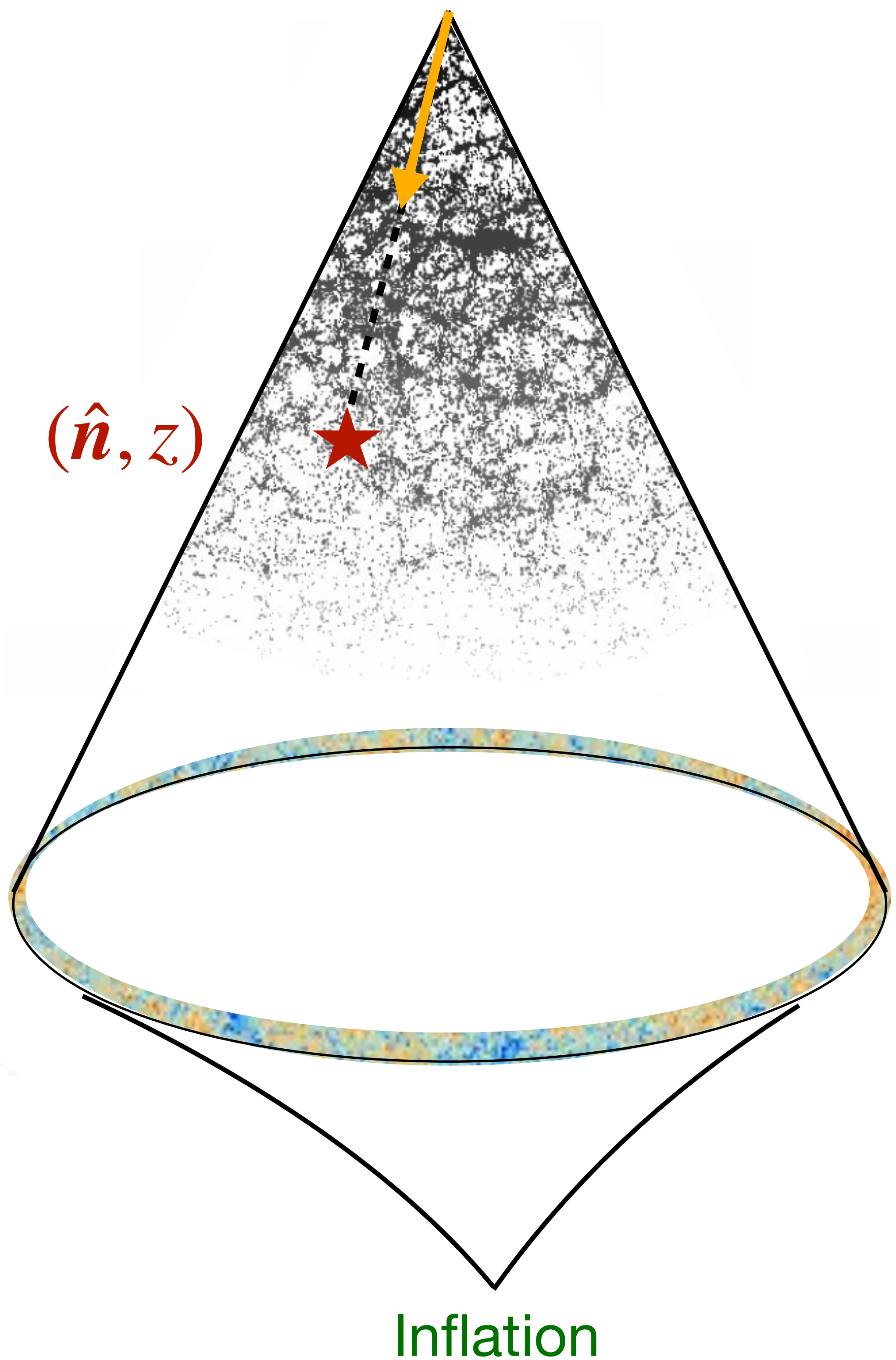
Cosmology from galaxy clustering: recent progress, current status and future prospects

Marko Simonović
University of Florence

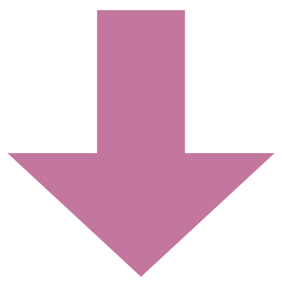
Big discoveries in cosmology



Dark matter

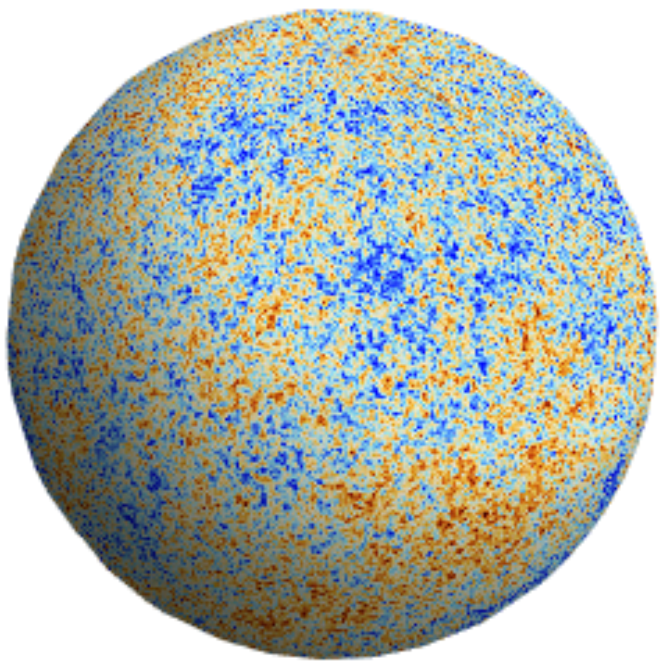
Dark energy

Inflation



astrophysics, particle physics, quantum gravity…

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

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

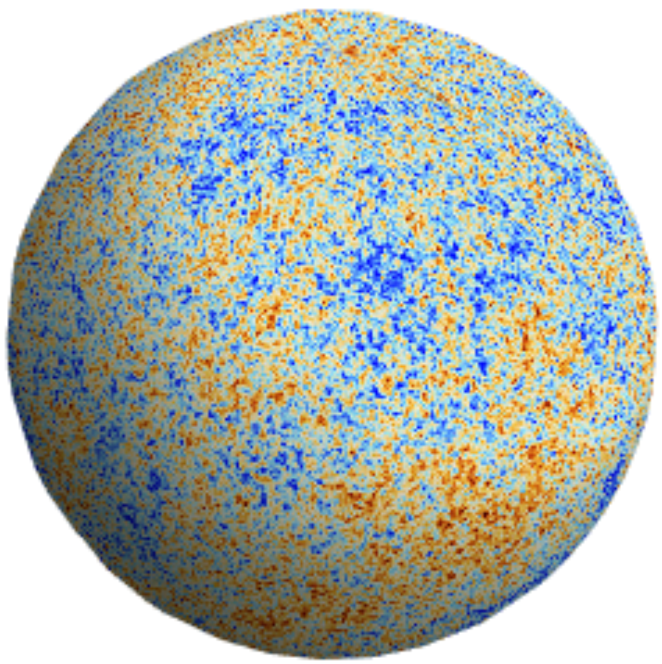
$$C_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$$

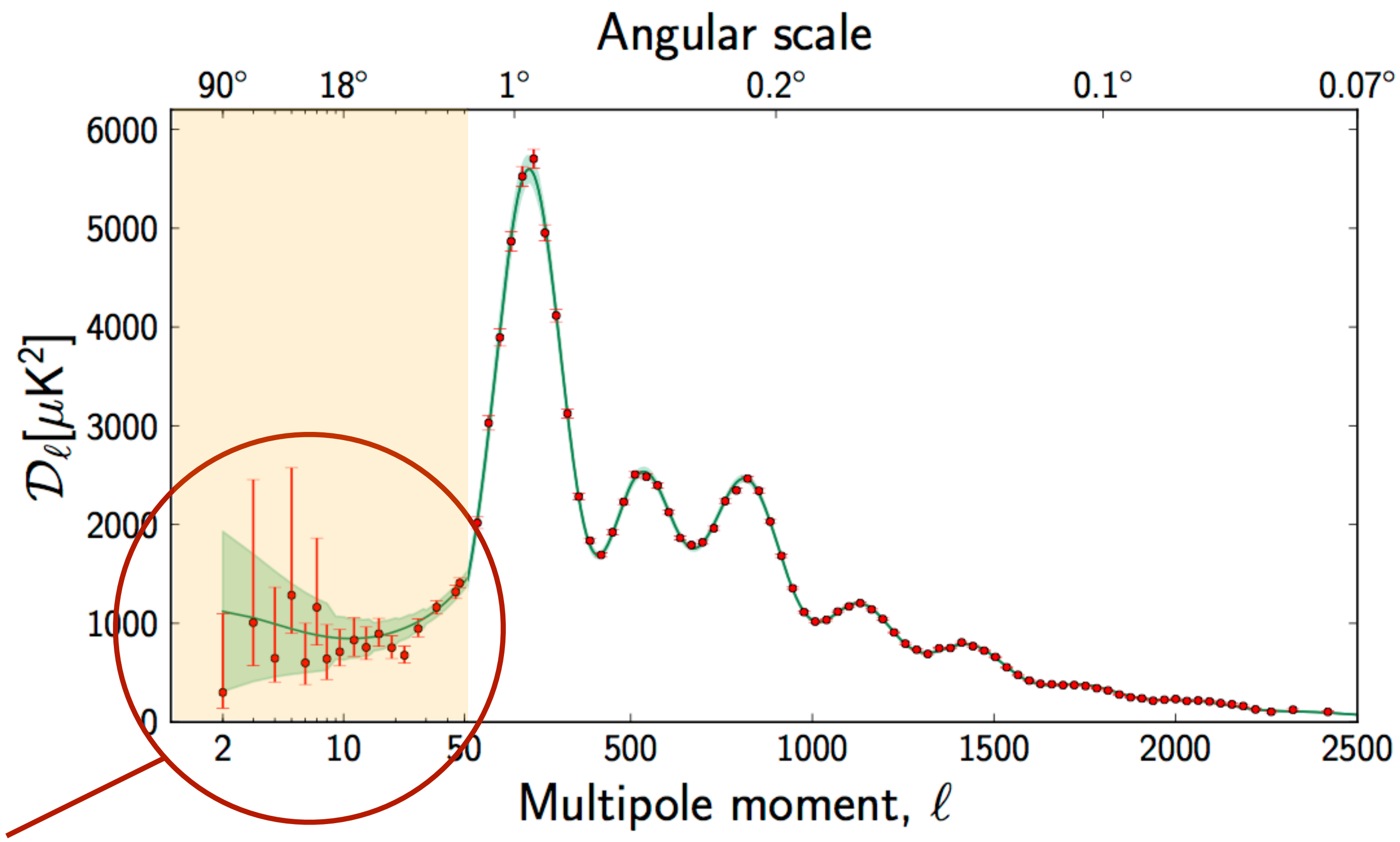
CMB power spectrum

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

variance of the temperature fluctuations

Cosmic Microwave Background

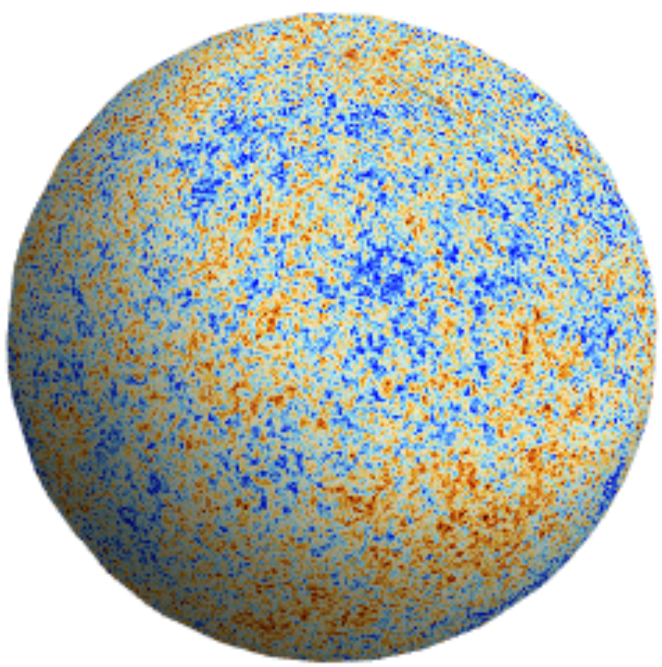


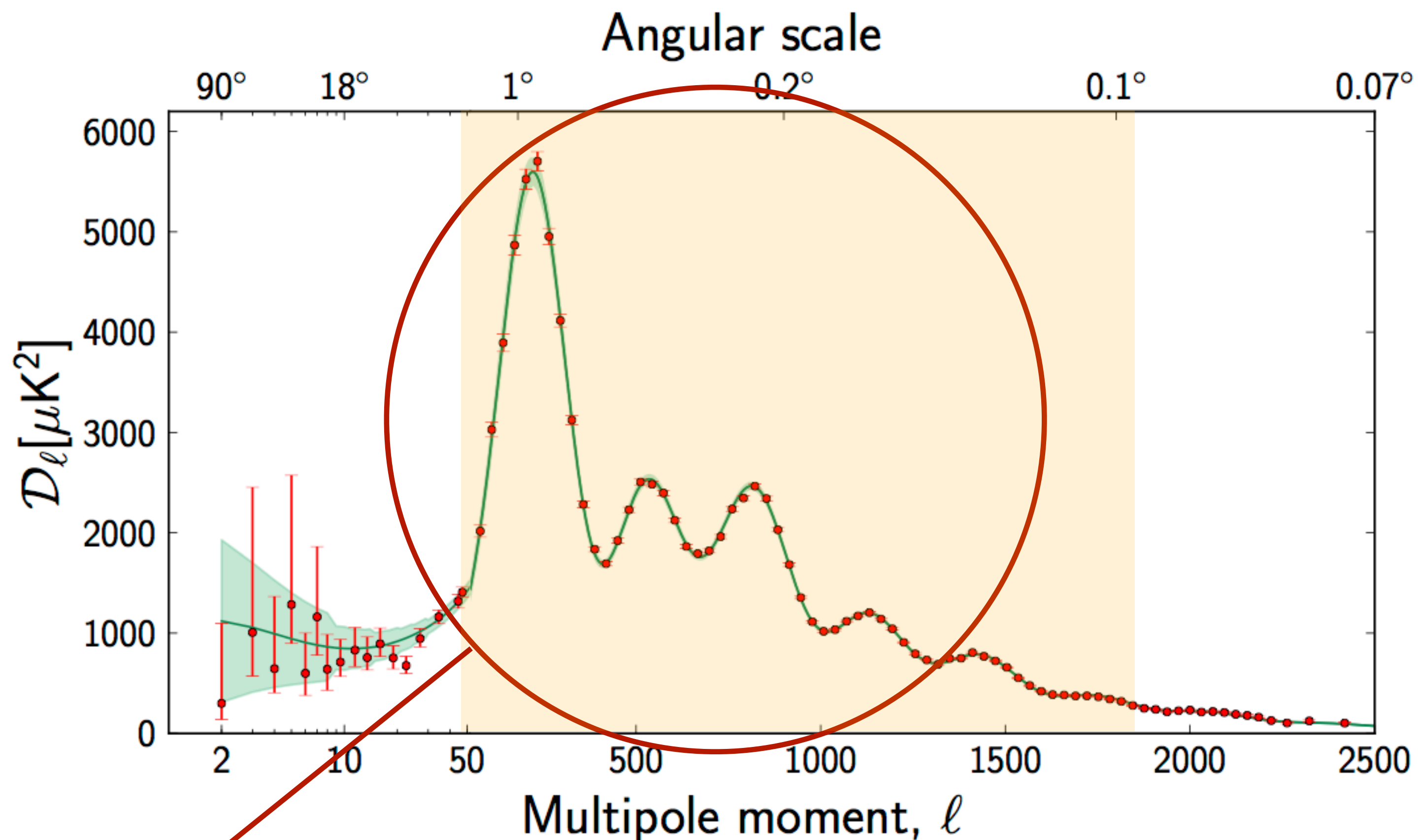


Scale-invariant power spectrum!

One of the strongest evidence for inflation

Cosmic Microwave Background

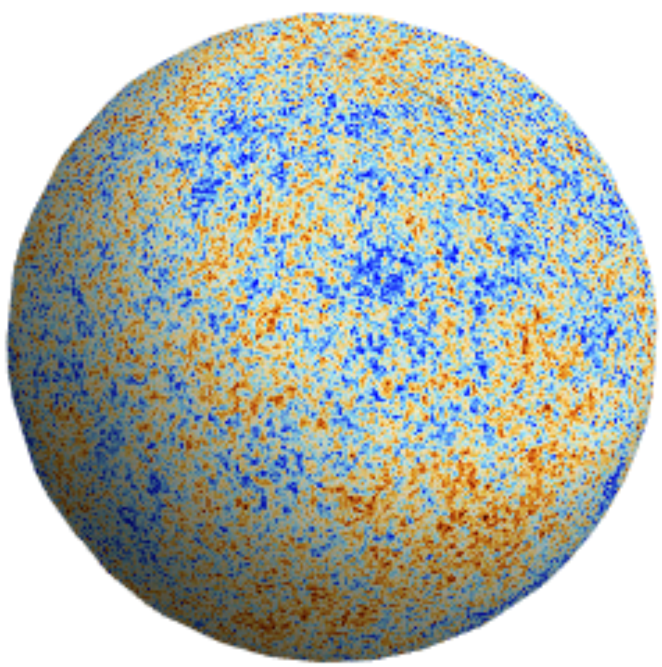


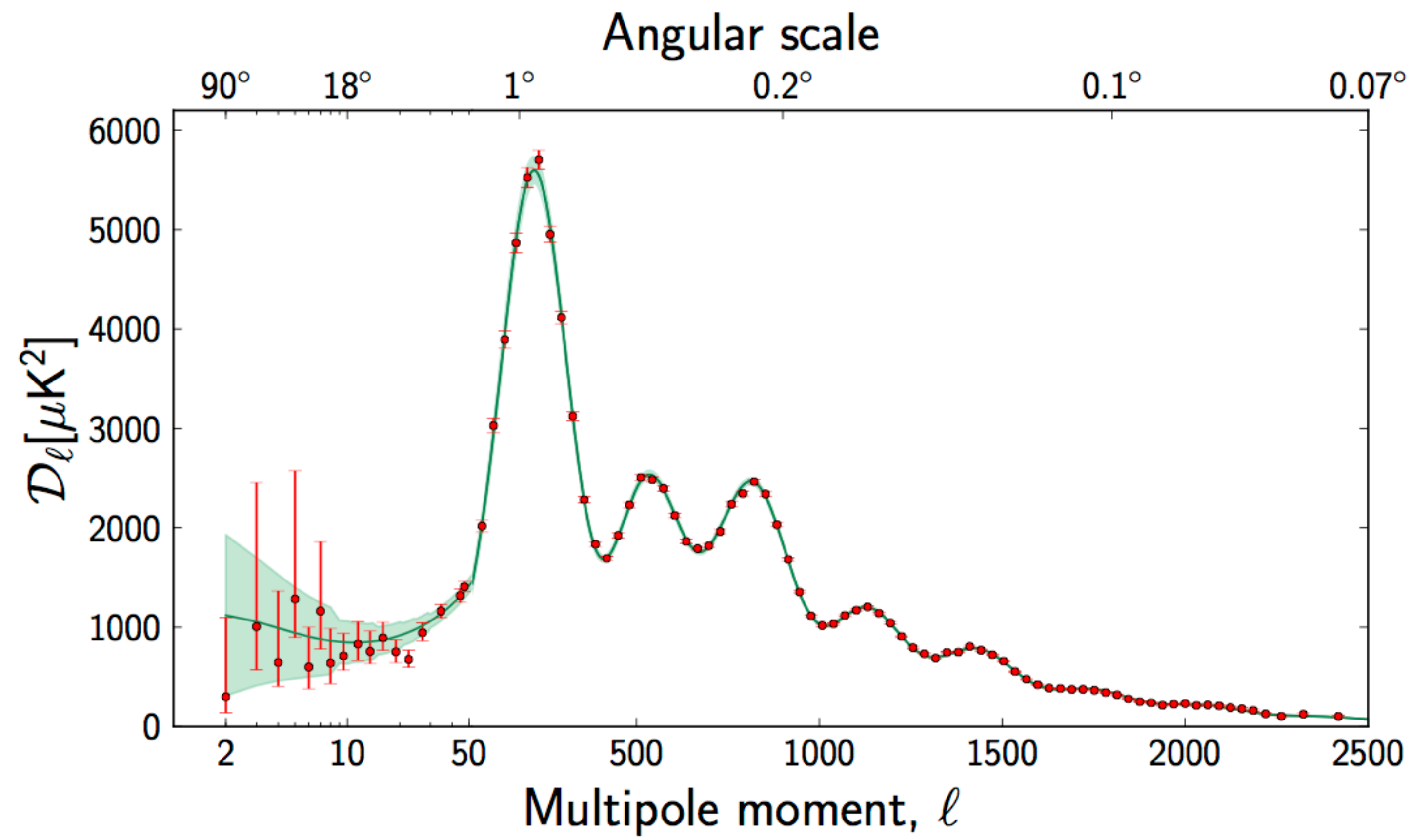


Features due the sound waves in primordial plasma

One of the strongest evidence for dark matter

Cosmic Microwave Background





Special ICs and matter content

ΛCDM cosmological model

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

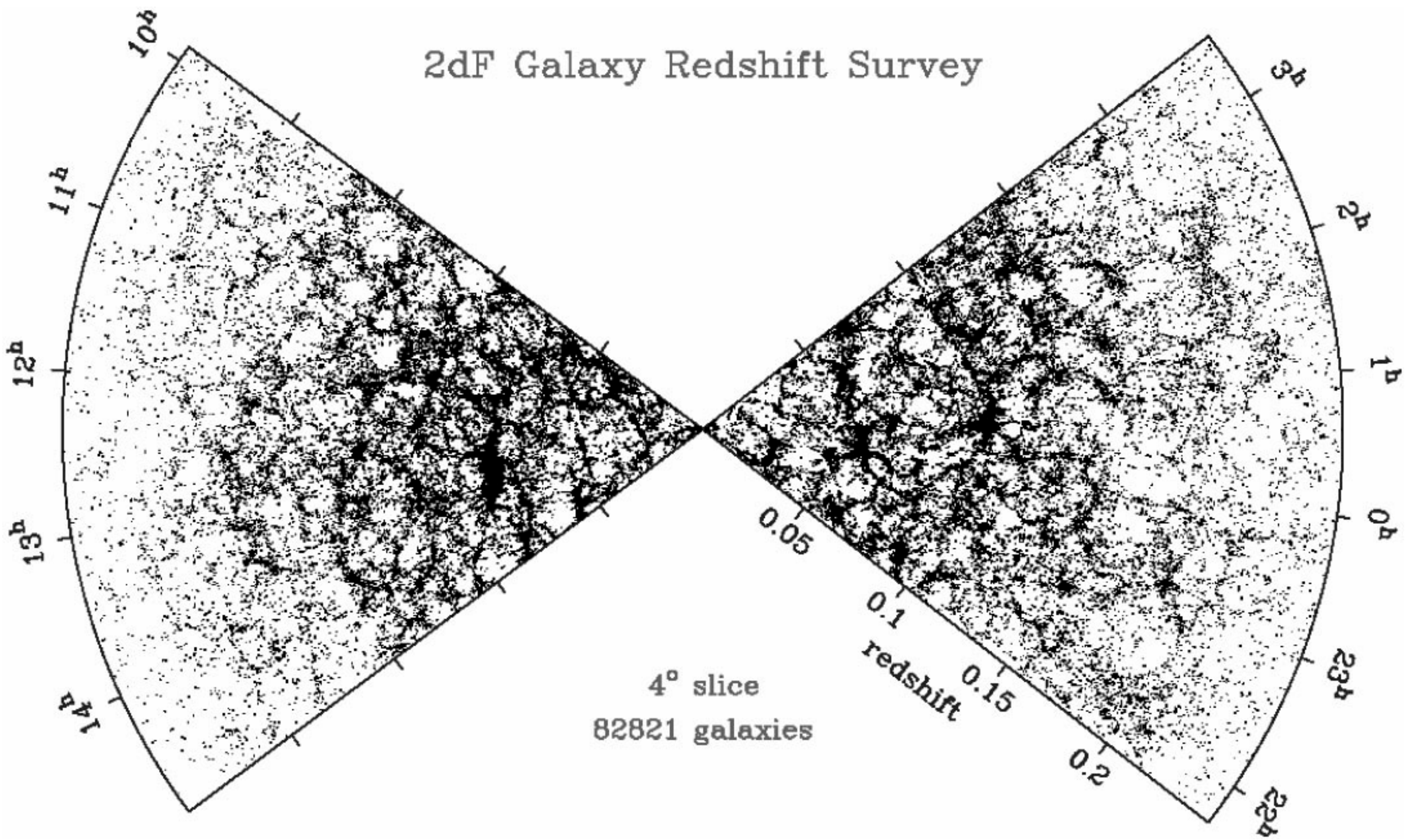
Single “clock”? Speed of inflaton fluctuations less than 1?
“Spectroscopy” of massive/higher spin particles?
Primordial features in the power spectrum?

2) Everything gravitates

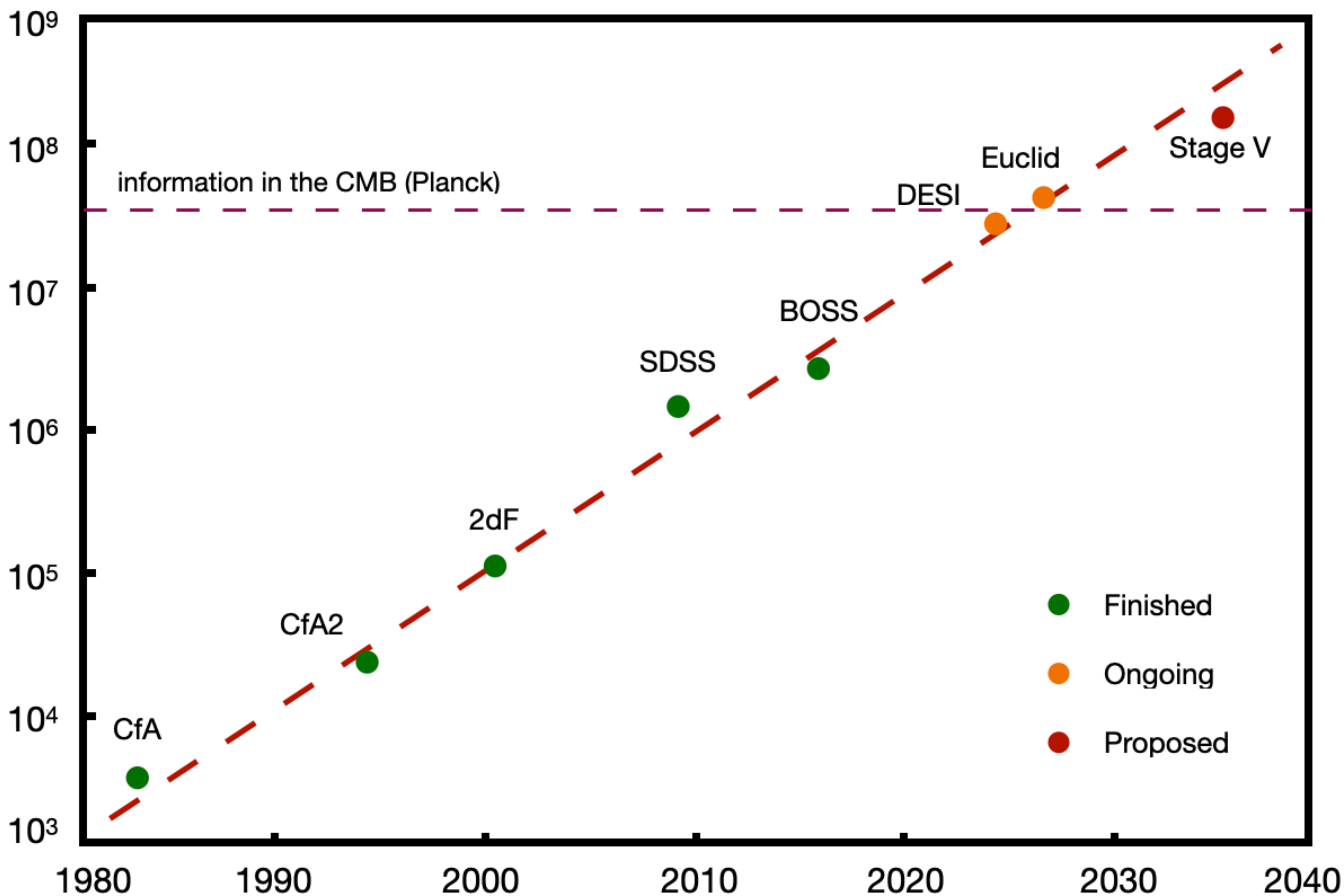
Sum of neutrino masses. Other massive (but light) relics?
Ultralight axions? Spatial curvature, dark energy?
New energy components in early or late universe?
Probing dark sector, new long-range interactions?

Bottom-up approach different from particle physics

More data in the late universe

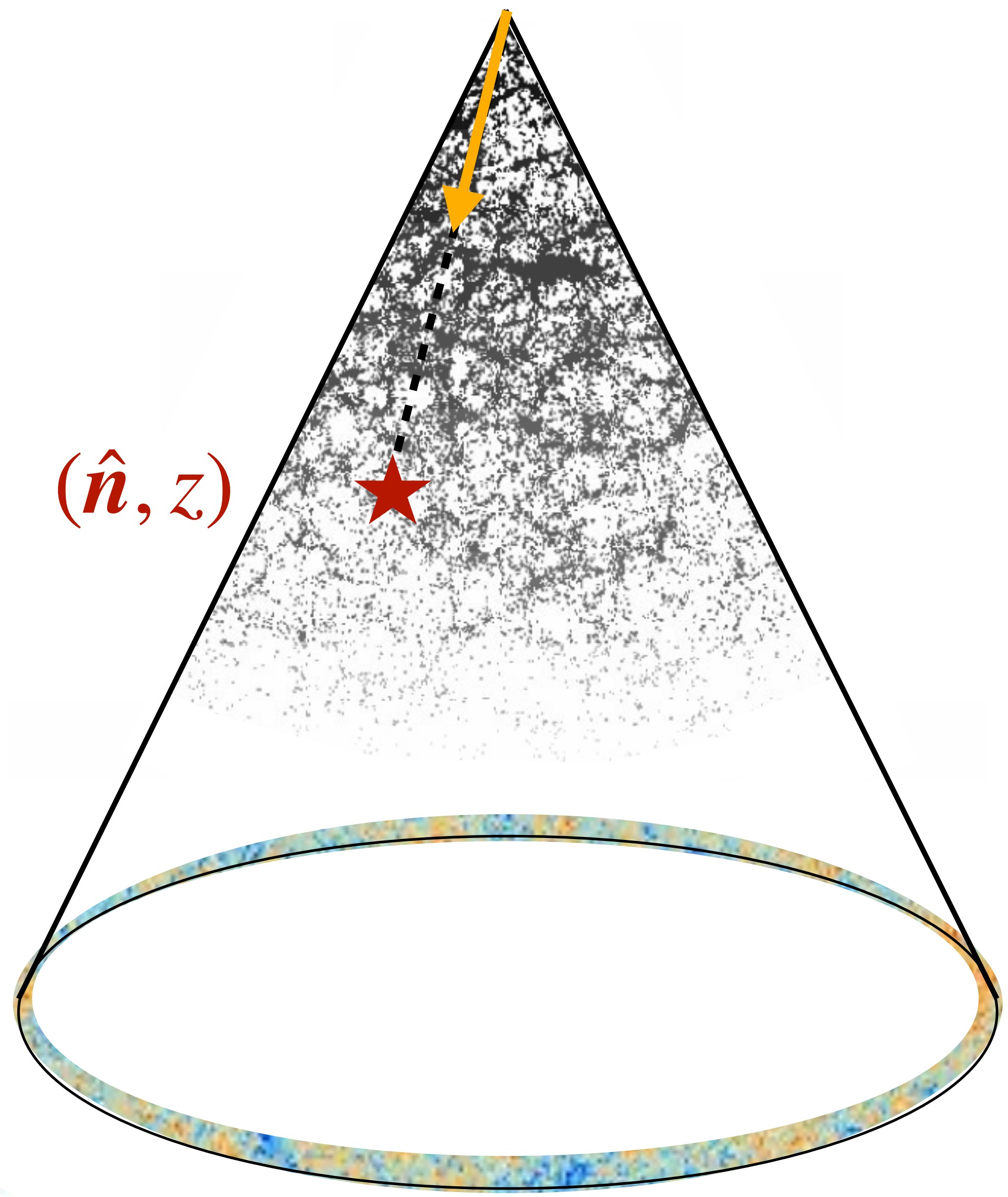


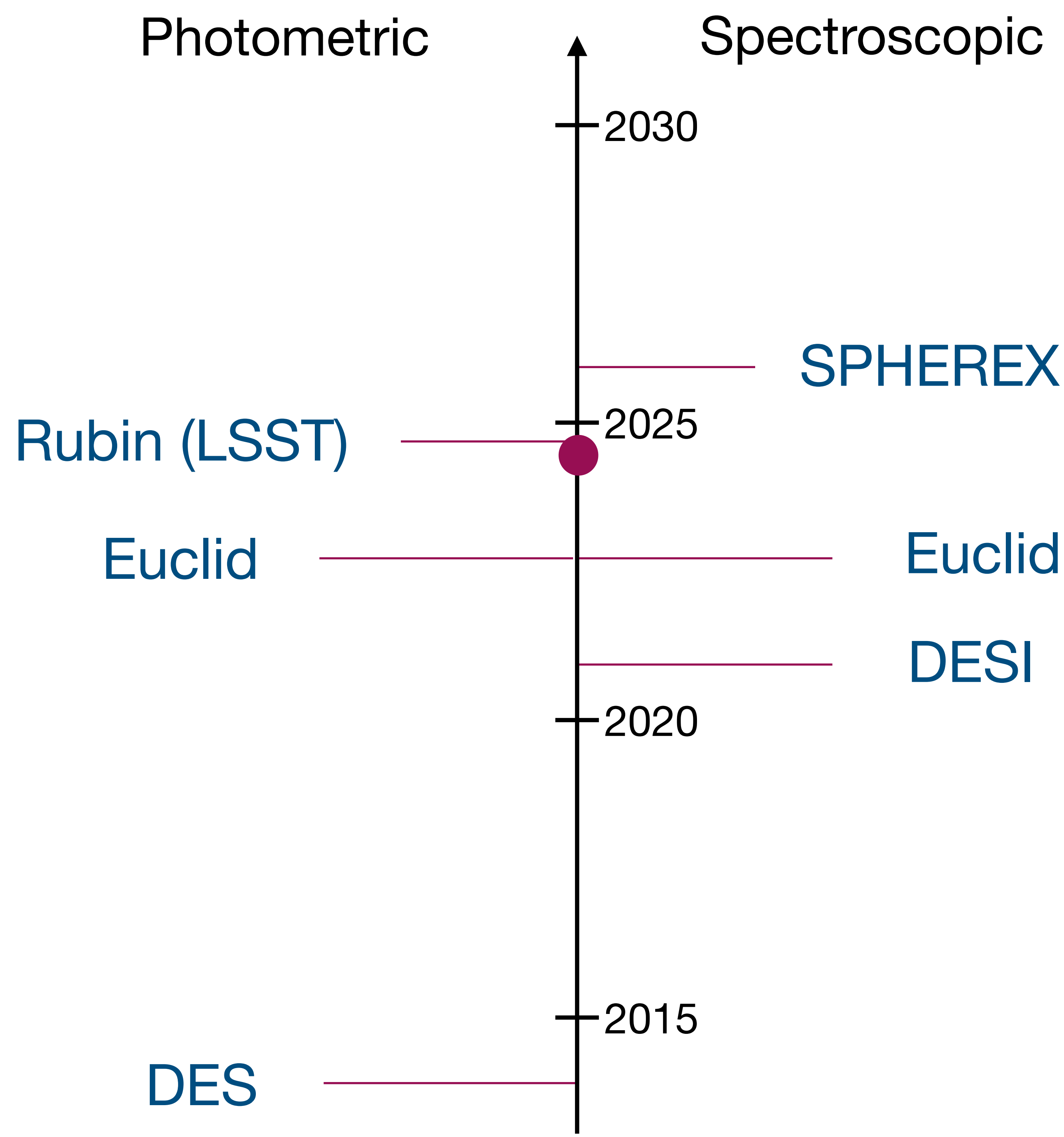
Spectroscopic galaxy surveys



Observing the entire light-cone

Image billions and take spectra of ~100 million of objects up to z~5

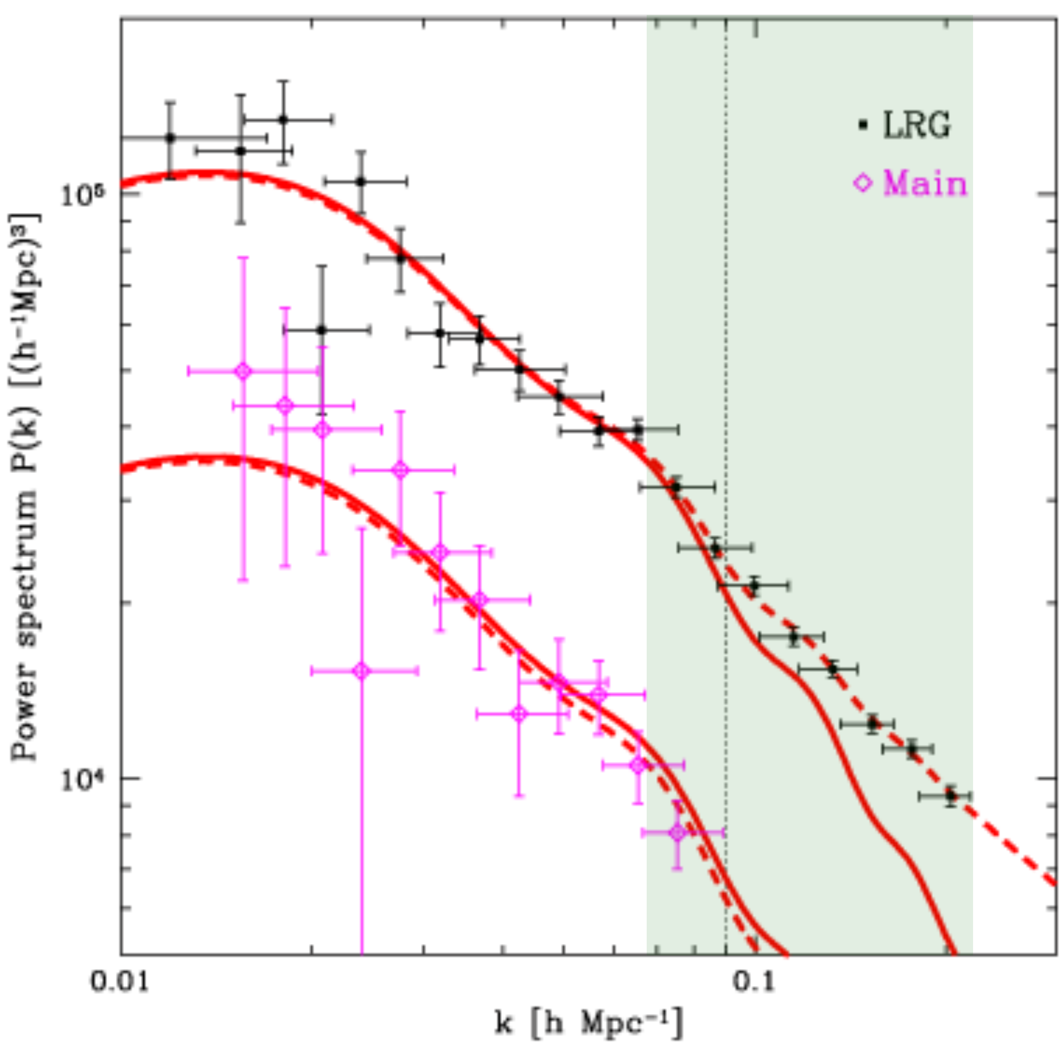




Galaxies remember ICs and history

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

The power spectrum has features that carry information about cosmology



Variance of the field

$$\sigma_R^2 = \frac{k^3}{2\pi^2} P(k) \Big|_{k\sim 1/R}$$

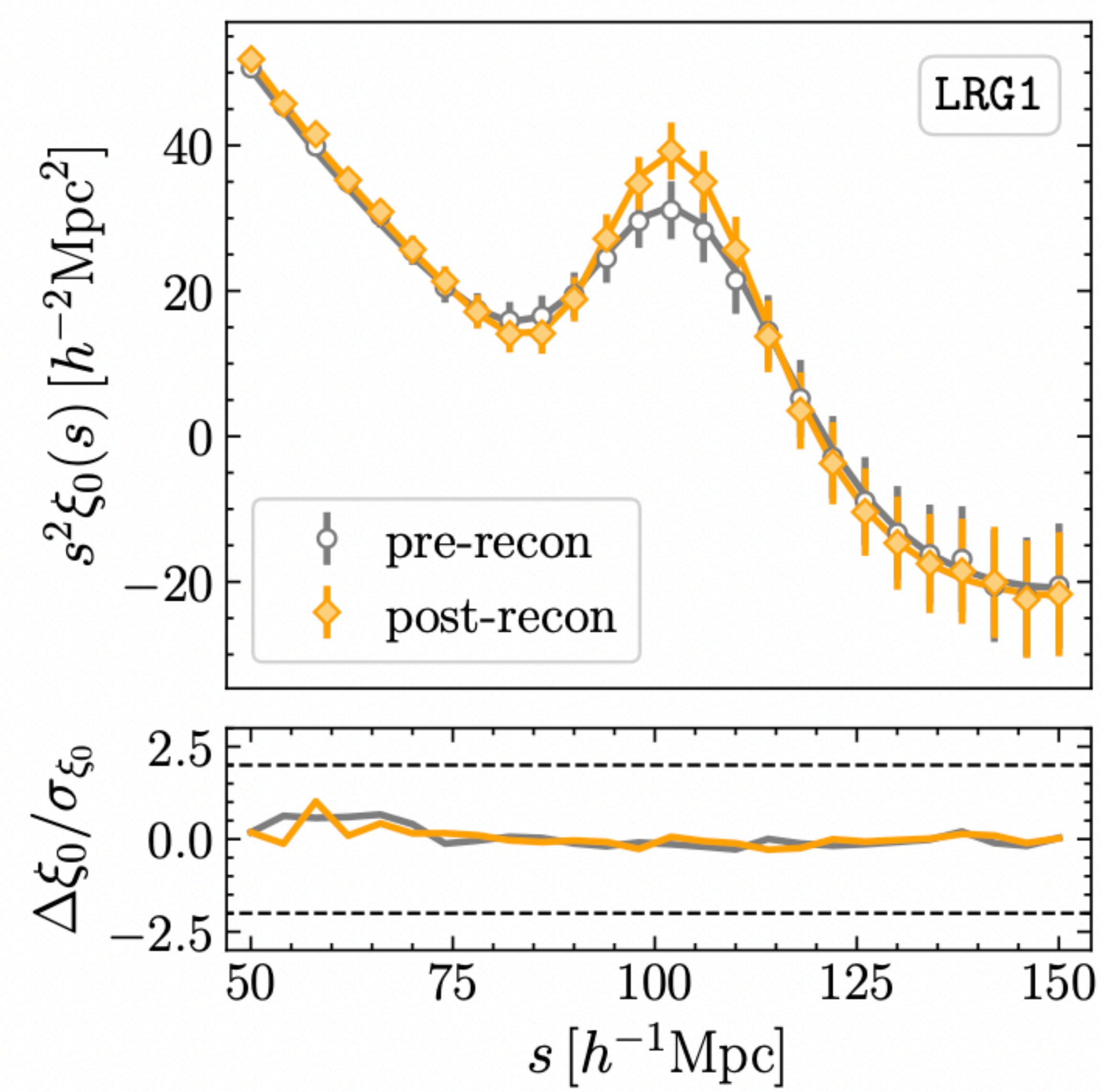
On large scales (>10Mpc) $\sigma^2 \ll 1$

The BAO peak

Features, such as the BAO peak, can be used as a standard ruler

(Fourier transform of a displaced Gaussian —> wiggles)

DESI 2024, credit: Seshadri Nadathur



Set in the early universe

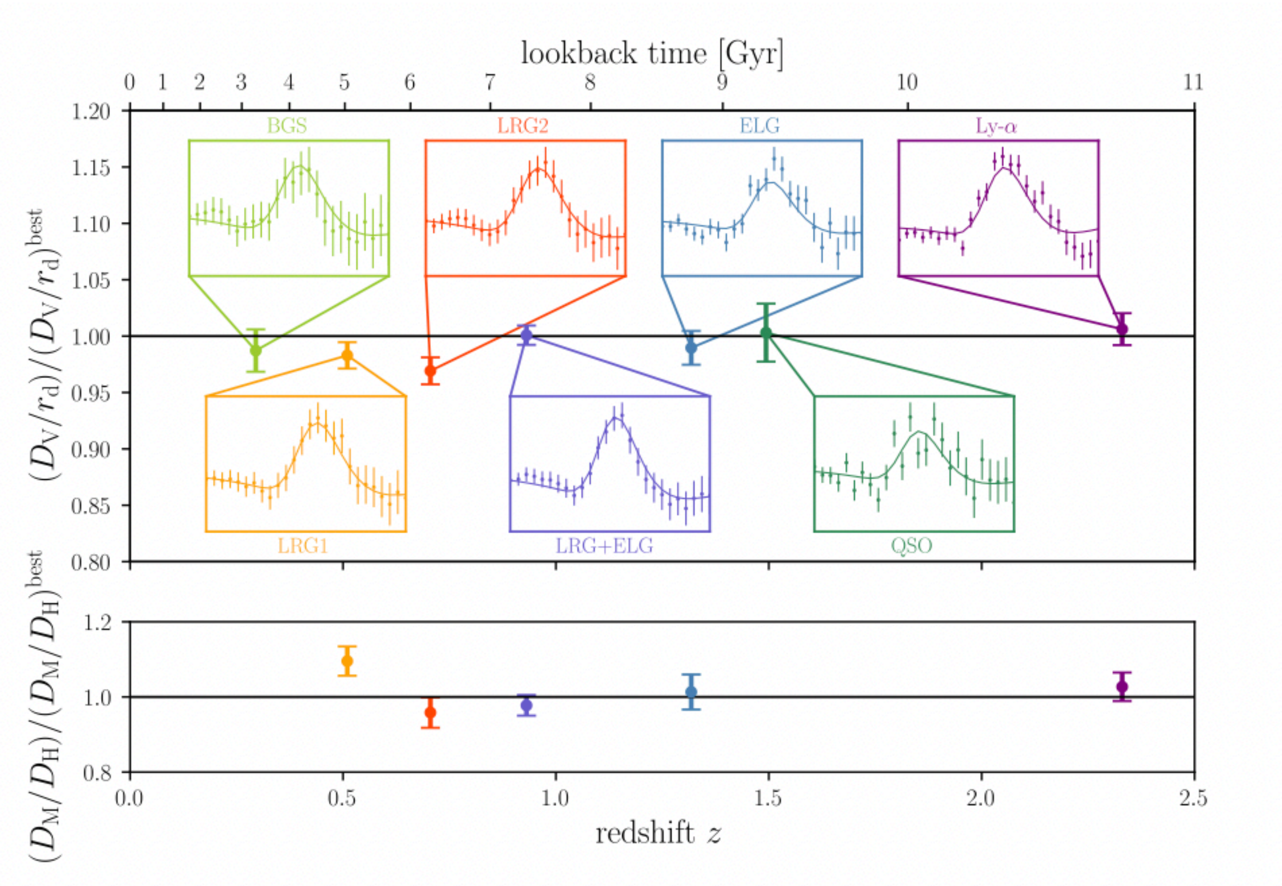
Easy to measure

Easy to model

$$\text{angle} = \frac{r_d}{d_A} = \frac{H_0 r_d}{F(\Omega_m, z)}$$

$$d_A \propto \frac{1}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + (1-\Omega_m)}}$$

The BAO peak

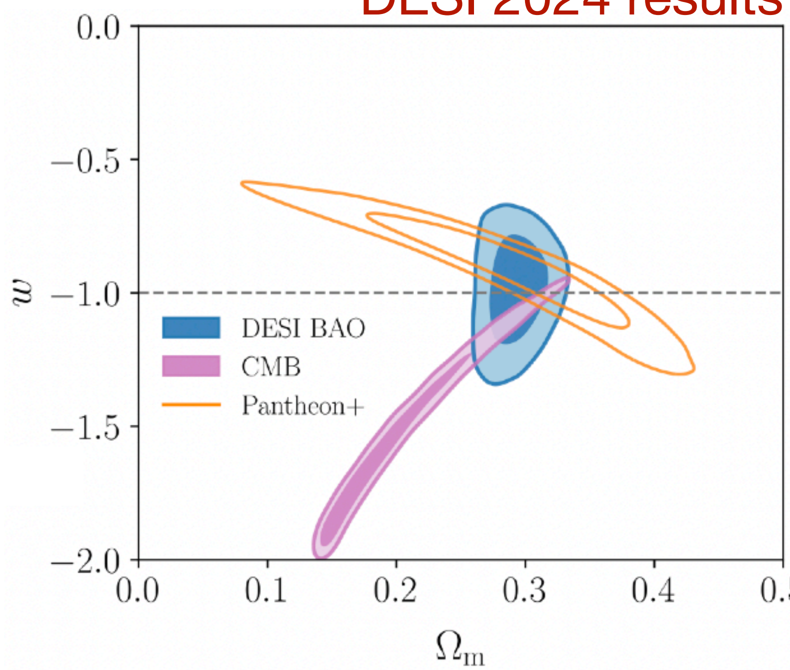


credit: Arnaud de Mattia

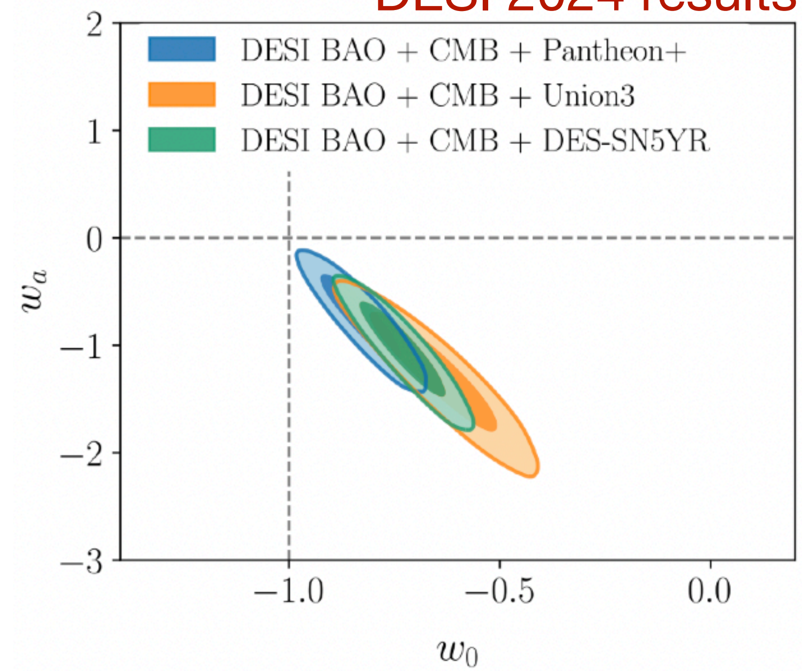
Use $F(\Omega_m, \Omega_K, w_0, w_a, \ldots, z)$ to test ΛCDM

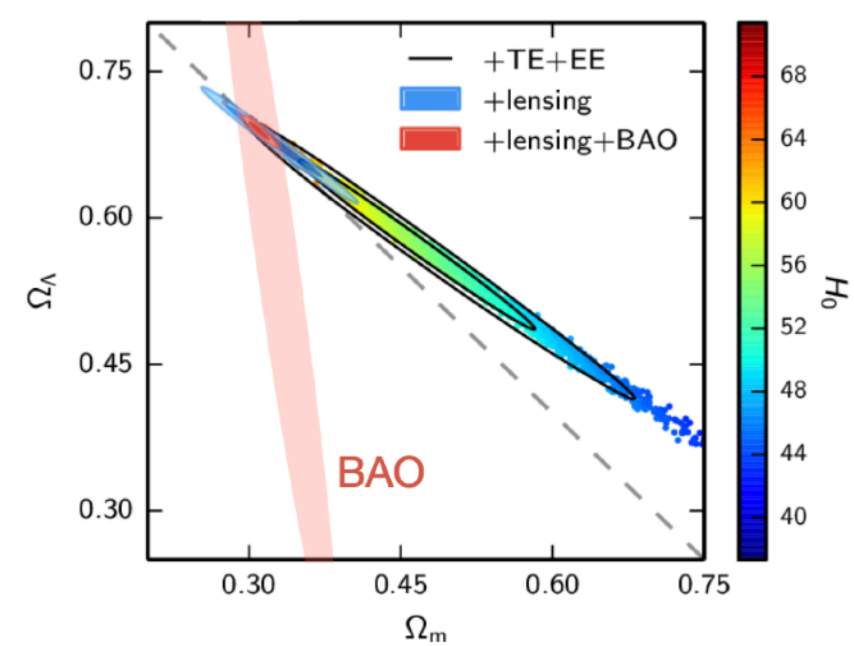
$|\Omega_K| < 0.002$

DESI 2024 results



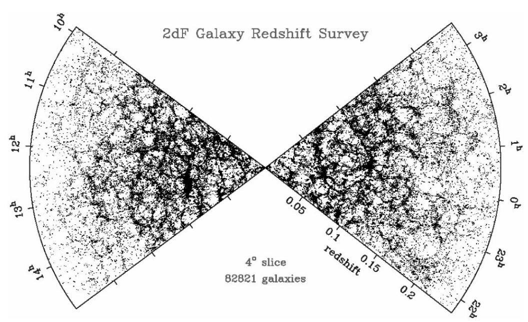
DESI 2024 results

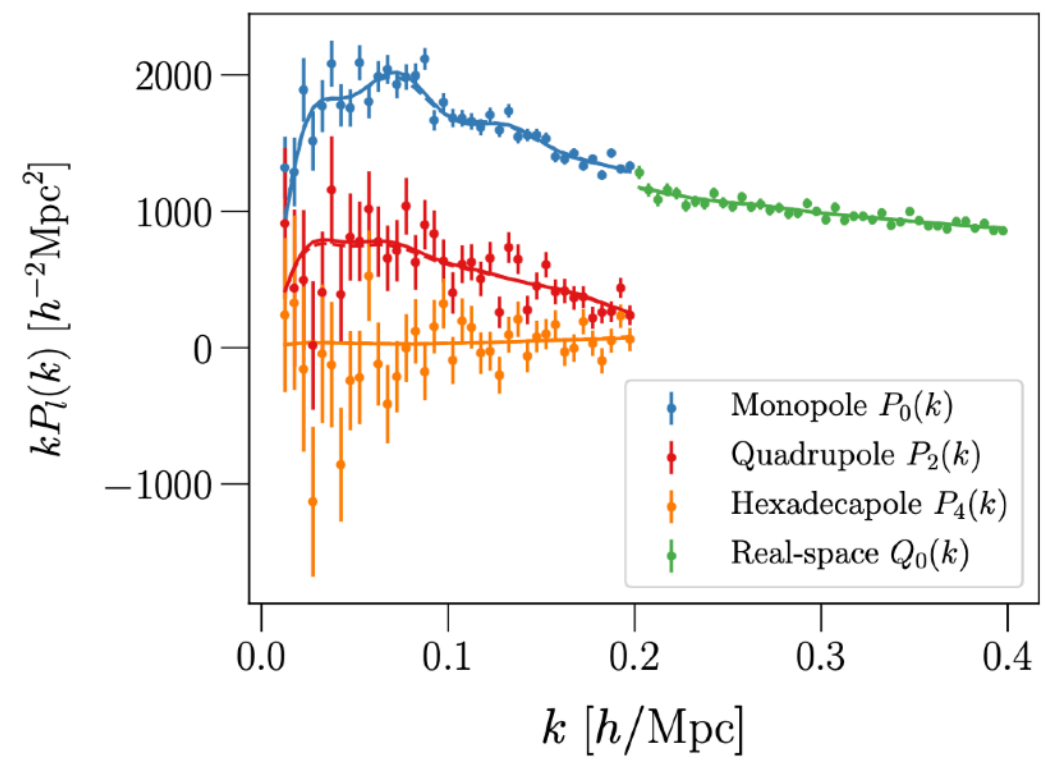




We would like to use all features

galaxy map





Full-shape analysis

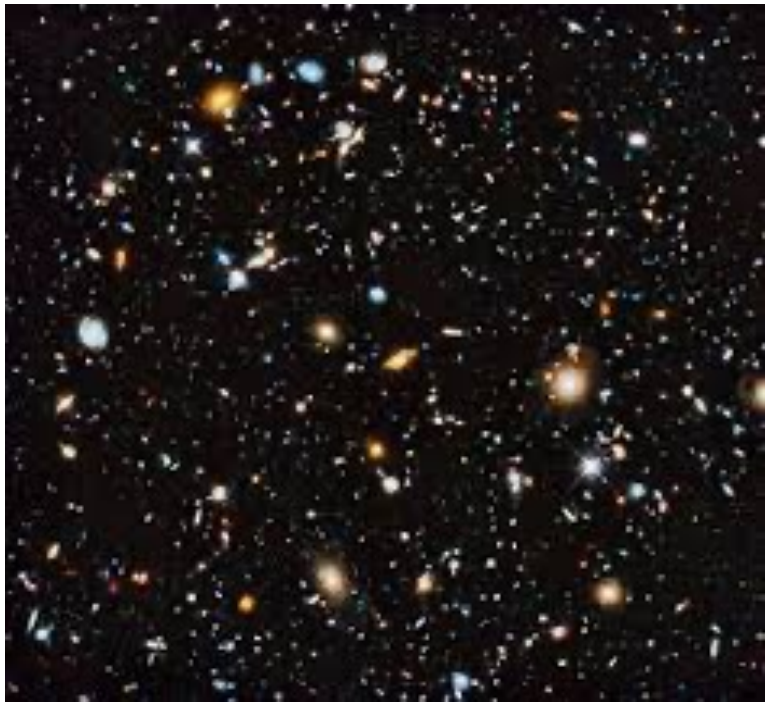
Similar to CMB, directly measures “shape” parameters

↓

all cosmological parameters
no CMB input needed

How do we formulate a theory of density fluctuations in the late universe?

How to make theoretical predictions?



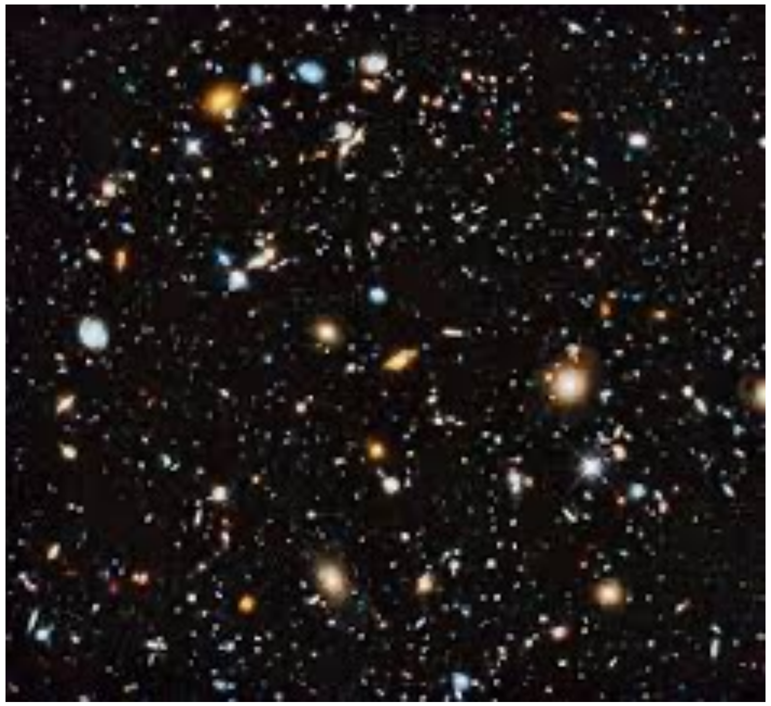
Use simulations? But this requires detailed knowledge of galaxy formation…

Even if we had precise hydro simulations, can we run many of them fast?

What about beyond ΛCDM?

The data is already here!

EFT of large-scale structure



Baumann, Nicolis, Senatore, Zaldarriaga (2010)
Carrasco, Hertzberg, Senatore (2012)
Senatore, Zaldarriaga (2014)
Senatore (2014)
Mirbabayi, Schmidt, Zaldarriaga (2014)
Baldauf, Mirbabay, MS, Zaldarriaga (2015)
...

Large distance dof: δ_g

EoM are fluid-like, including gravity

Symmetries, Equivalence Principle

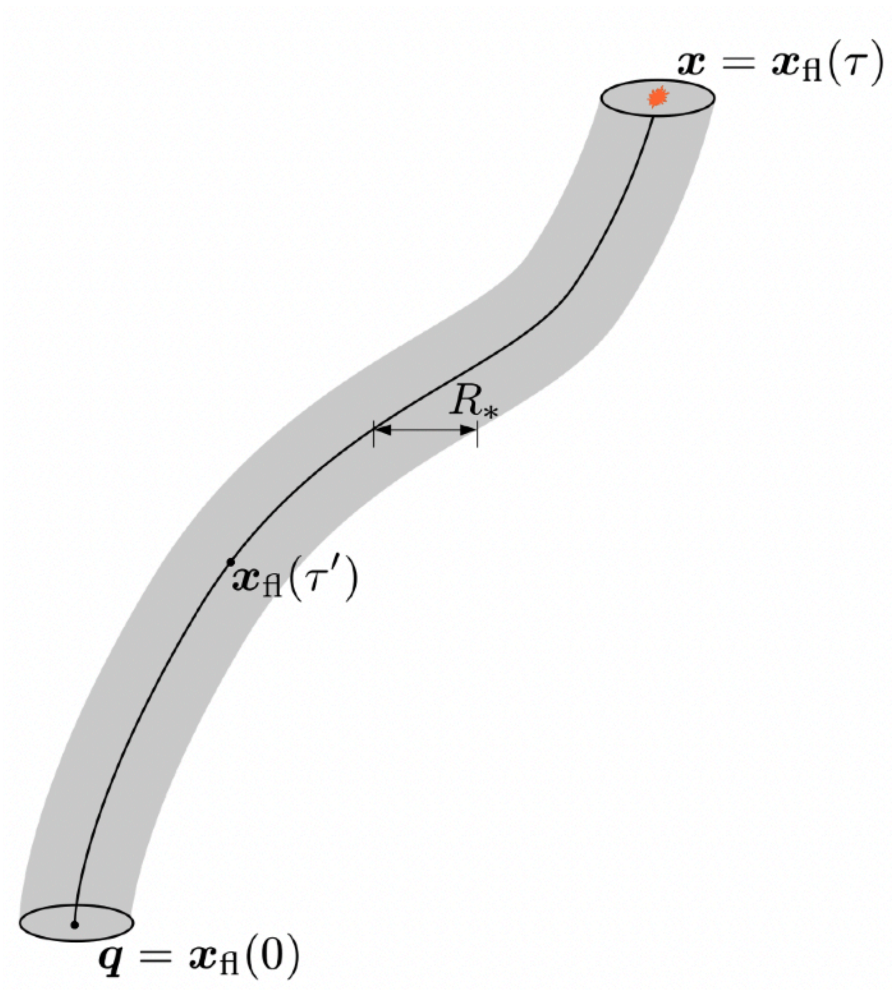
Expansion parameters: δ_g, $\partial/k_{\rm NL}$

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

EFT of large-scale structure

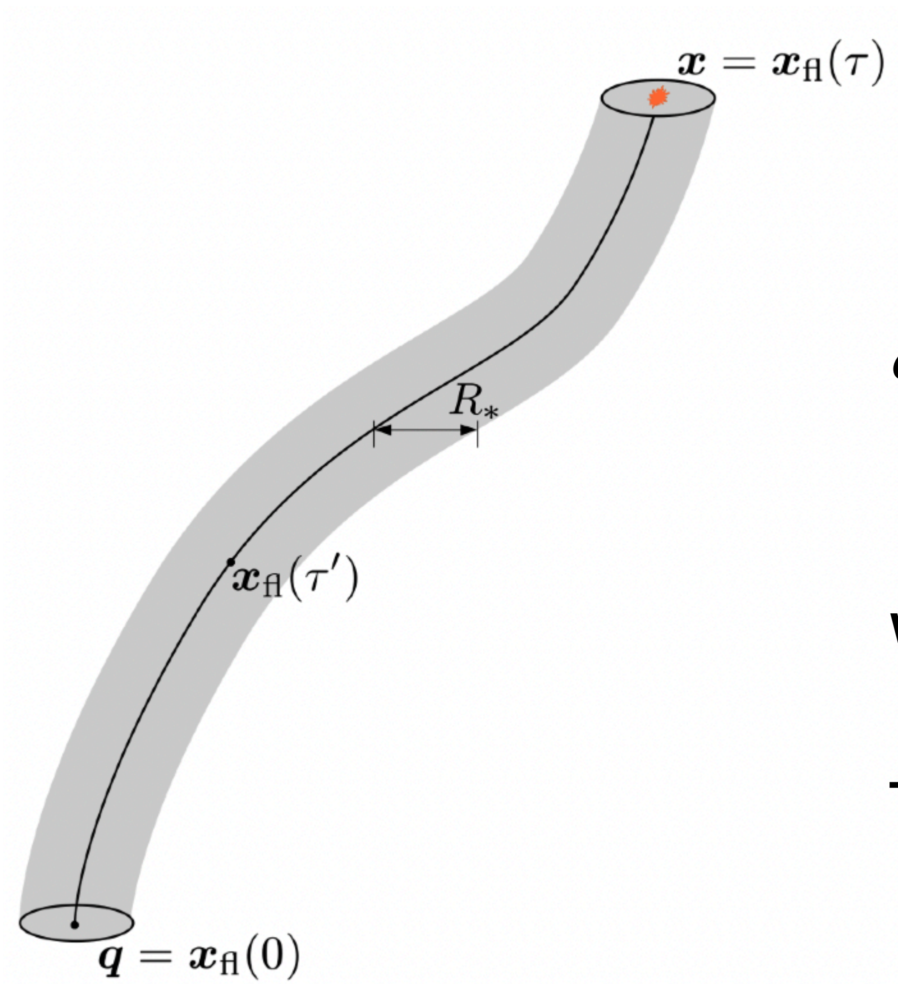
$$\delta_g(\boldsymbol{x},\tau) = \int_0^\tau d\tau' F[\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau'), \mathrm{ICs}, \Omega_b, H_0, \ldots, \mathrm{SFR}(\tau,\tau'),\ \mathrm{AGN}(\tau,\tau'), \ldots]$$



EFT of large-scale structure

$$\delta_g(\boldsymbol{x},\tau) = \int_0^\tau d\tau' F[\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau'), \text{ICs}, \Omega_b, H_0, \ldots, \text{SFR}(\tau,\tau'),\ \text{AGN}(\tau,\tau'), \ldots]$$

assume to be
local in space!



$$\delta_{g,l}(\boldsymbol{x},\tau) = \sum_n \int_0^\tau d\tau' c_n(\tau,\tau')\mathcal{O}_n[\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau')] + \epsilon(\tau)$$

We can perturbatively solve for $\partial_i\partial_j\Phi(\boldsymbol{x}_{\rm fl}(\tau'),\tau')$

The noise $\epsilon(\tau)$ is also assumed to be local

EFT of large-scale structure

Along the fluid element:

$$\mathcal{O}(\boldsymbol{x}_{\text{fl}}(\tau'), \tau') = \mathcal{O}(\boldsymbol{x}, \tau) + (\tau' - \tau)\frac{D}{D\tau}\mathcal{O}(\boldsymbol{x}, \tau) + \cdots \qquad \frac{D}{D\tau} \equiv \frac{\partial}{\partial \tau} + v^i \nabla_i$$

This allows us to integrate in time

$$\delta_{g,l}(\boldsymbol{x}, \tau) = b_1(\tau)\delta(\tau) + \frac{b_2(\tau)}{2}\delta^2(\tau) + b_t(\tau)(\partial_i\partial_j\Phi(\tau))^2 + \cdots + P_{\text{shot}}$$

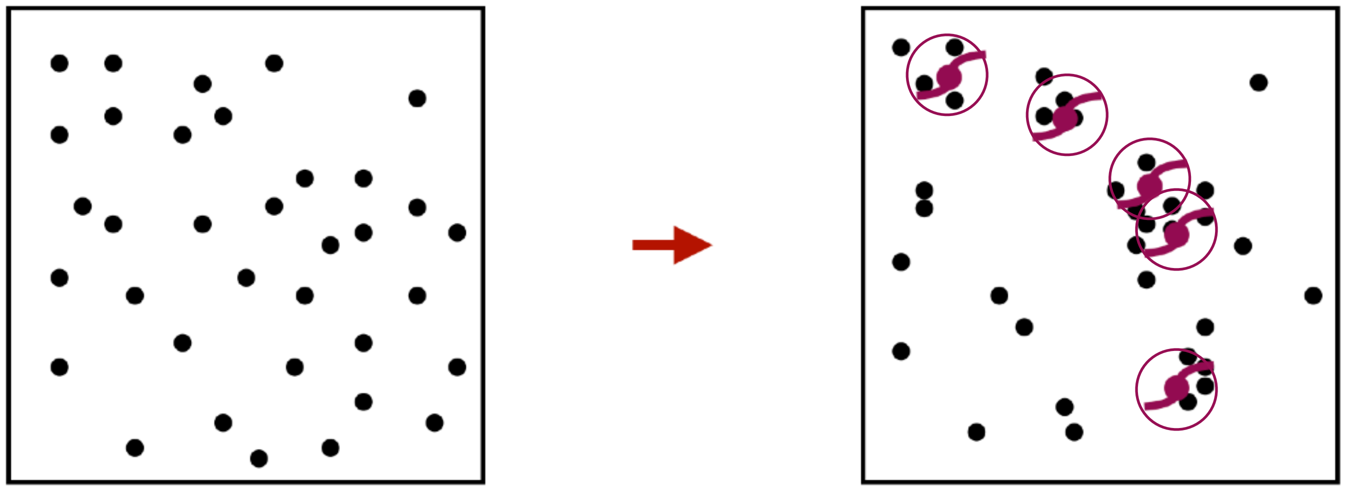
Bias parameters $b_i(\tau)$ encode all small scale physics of galaxy formation!

On large scales P_{shot} is approximately constant and given by $P_{\text{shot}} \approx \frac{1}{n}$

We need to focus on matter

EFT of large-scale structure

Just DM particles in an expanding universe



UV description: collisionless Boltzmann eq. $\frac{d}{dt} f(\boldsymbol{x}, \boldsymbol{p}, t) = 0$

gravity $\nabla^2 \Phi \propto \int d^3\boldsymbol{p}\, f(\boldsymbol{x}, \boldsymbol{p}, t)$

From far away we only see fluctuations in number density of particles

What is the IR description in terms of $\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$?

EFT of large-scale structure

Naively fluid, but collisionless and gravity is unscreened long-range force…

Mean free path effectively set by the age of the universe (DM particles are slow)

Gravity helps by "gluing" DM particles which form DM halos

This allows to consistently truncate the Boltzmann hierarchy

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

← new nonlinear terms with free coefficients

Baumann, Nicolis, Senatore, Zaldarriaga (2010)

Carrasco, Hertzberg, Senatore (2012)

These eom can be derived bottom-up too, using symmetries

EFT of large-scale structure

Classical EFT with the usual features, can be solved perturbatively

Small-scale nonlinear DM physics encoded in c_s^2

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

$$k_{\rm NL} \sim 1/R_{\rm halo}$$

Variance of the field

$$\sigma_R^2 = \frac{k^3}{2\pi^2} P(k) \Big|_{k\sim 1/R}$$

$\sigma_R^2 \sim 1$ for $R \sim$ few Mpc at low redshifts

Is this useful in practice?

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

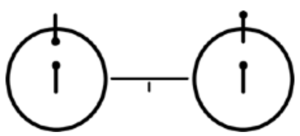
number of pixels in LSS: $N_{\rm pix.} \approx (H_0 R_{\rm nl.})^{-3} \sim 10^9$

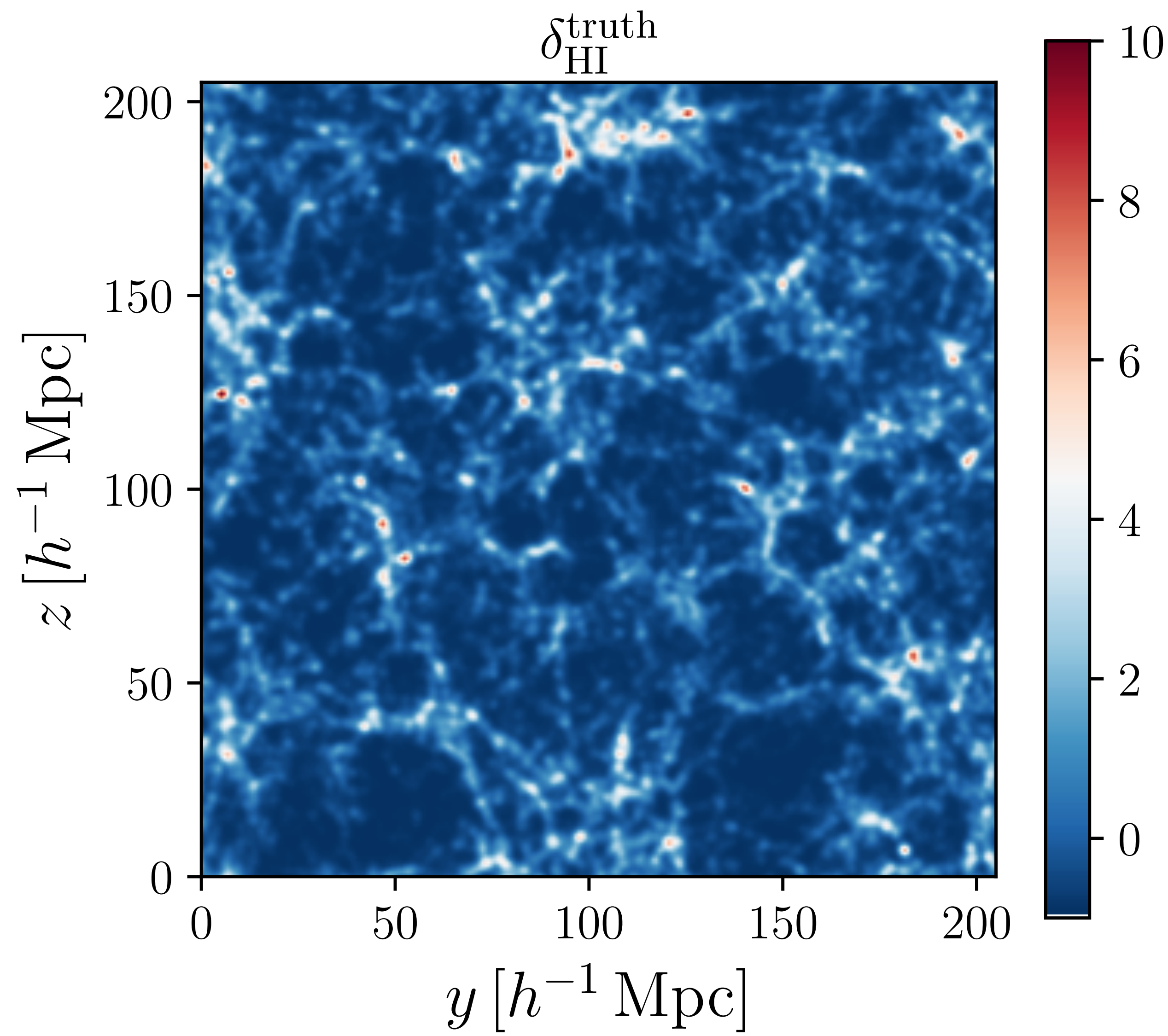
$$N_{\rm pix.}^{\rm LSS} \gg N_{\rm pix.}^{\rm CMB}$$

How well does EFT work?

Obuljen, MS, Schneider, Feldmann (2022)

Differences wrt the truth compatible with the shot noise



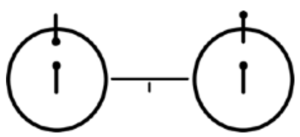


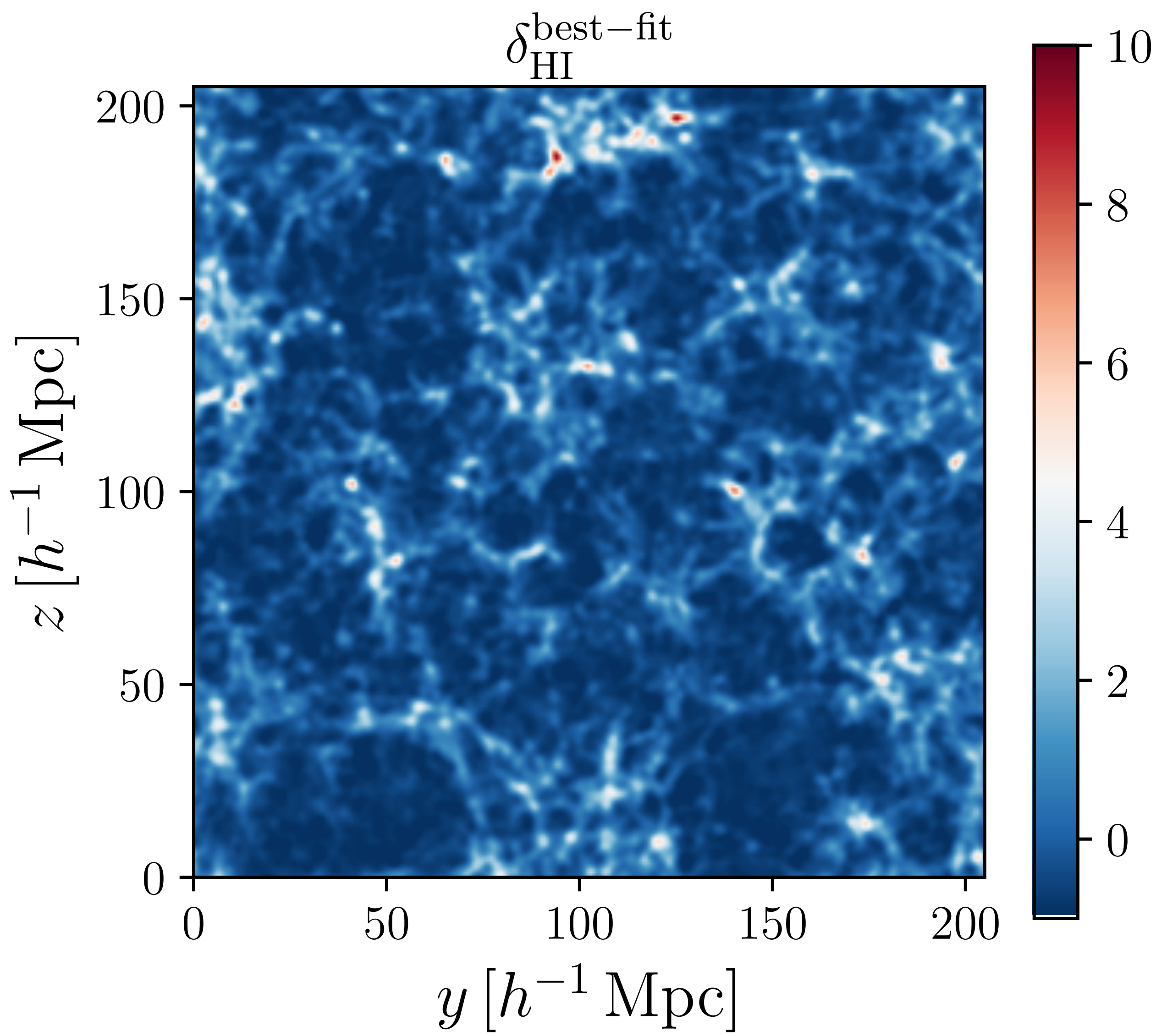
Hydro code

How well does EFT work?

Obuljen, MS, Schneider, Feldmann (2022)

Differences wrt the truth compatible with the shot noise



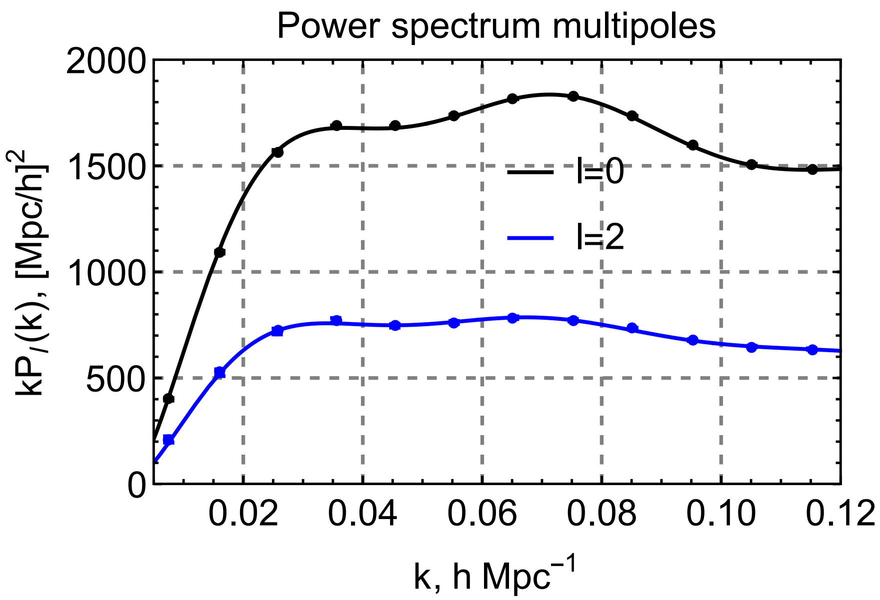


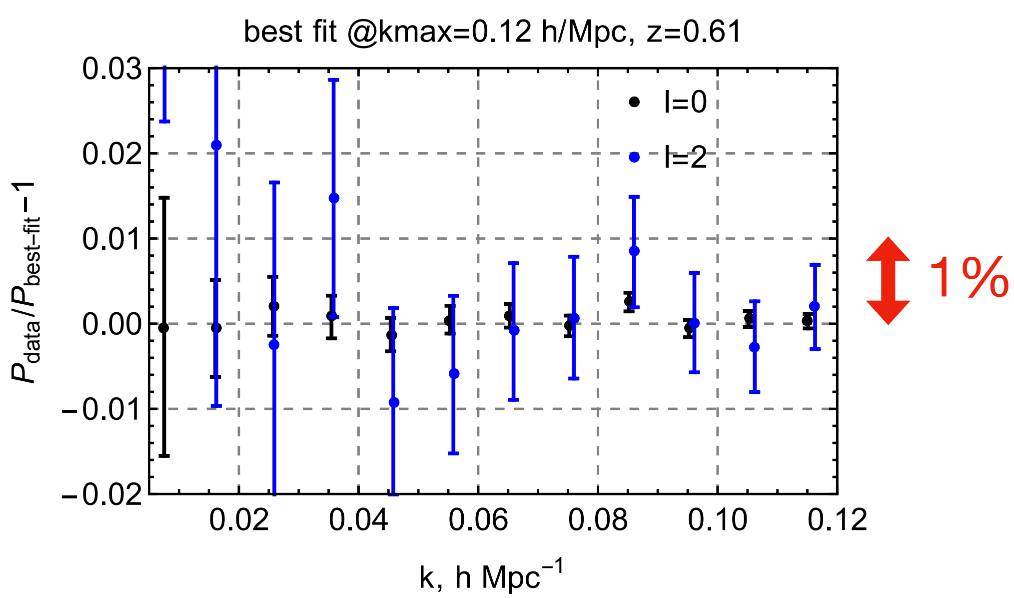
PT map

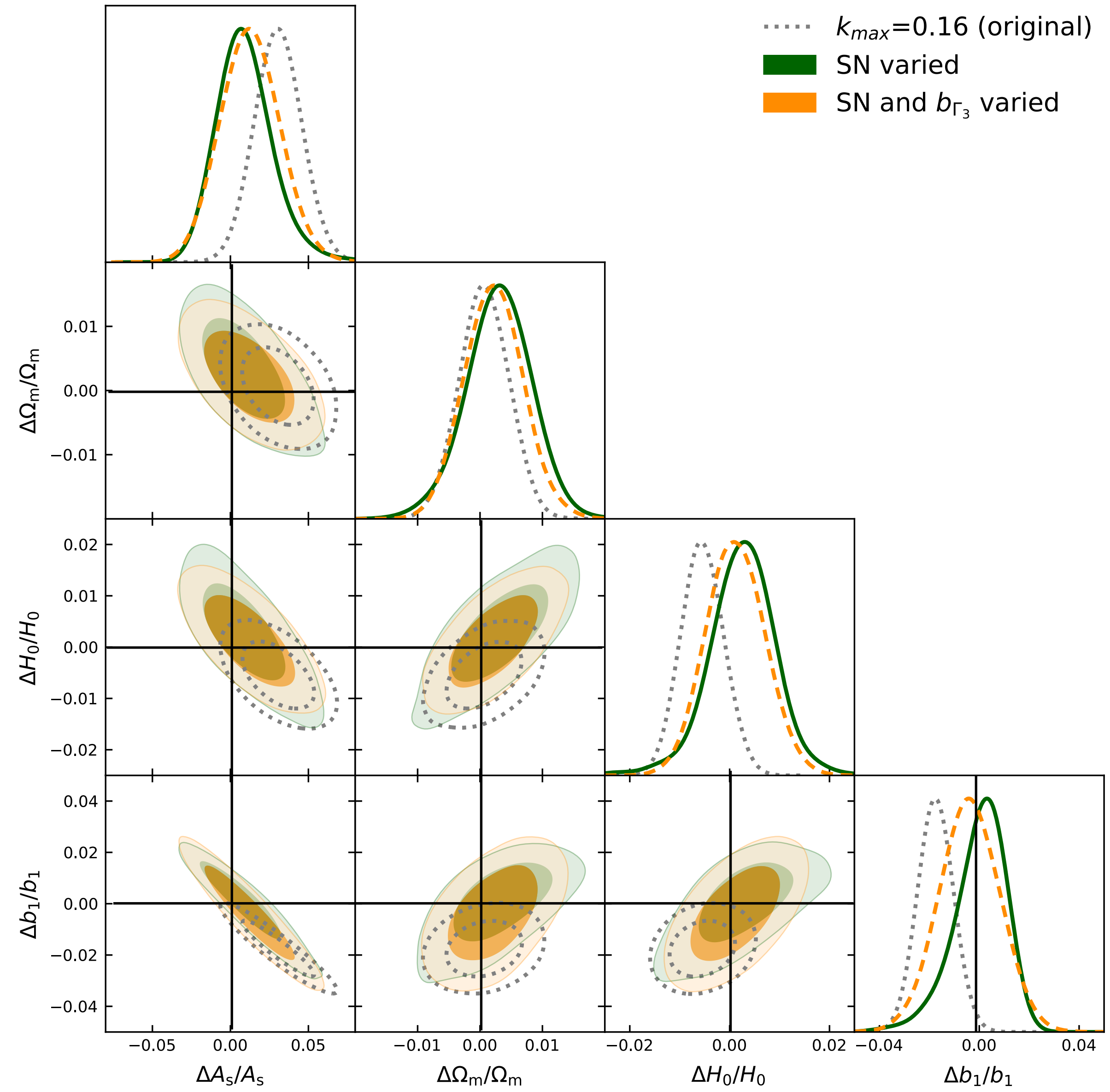
How well does EFT work?

Nishimichi et al. (2020)

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

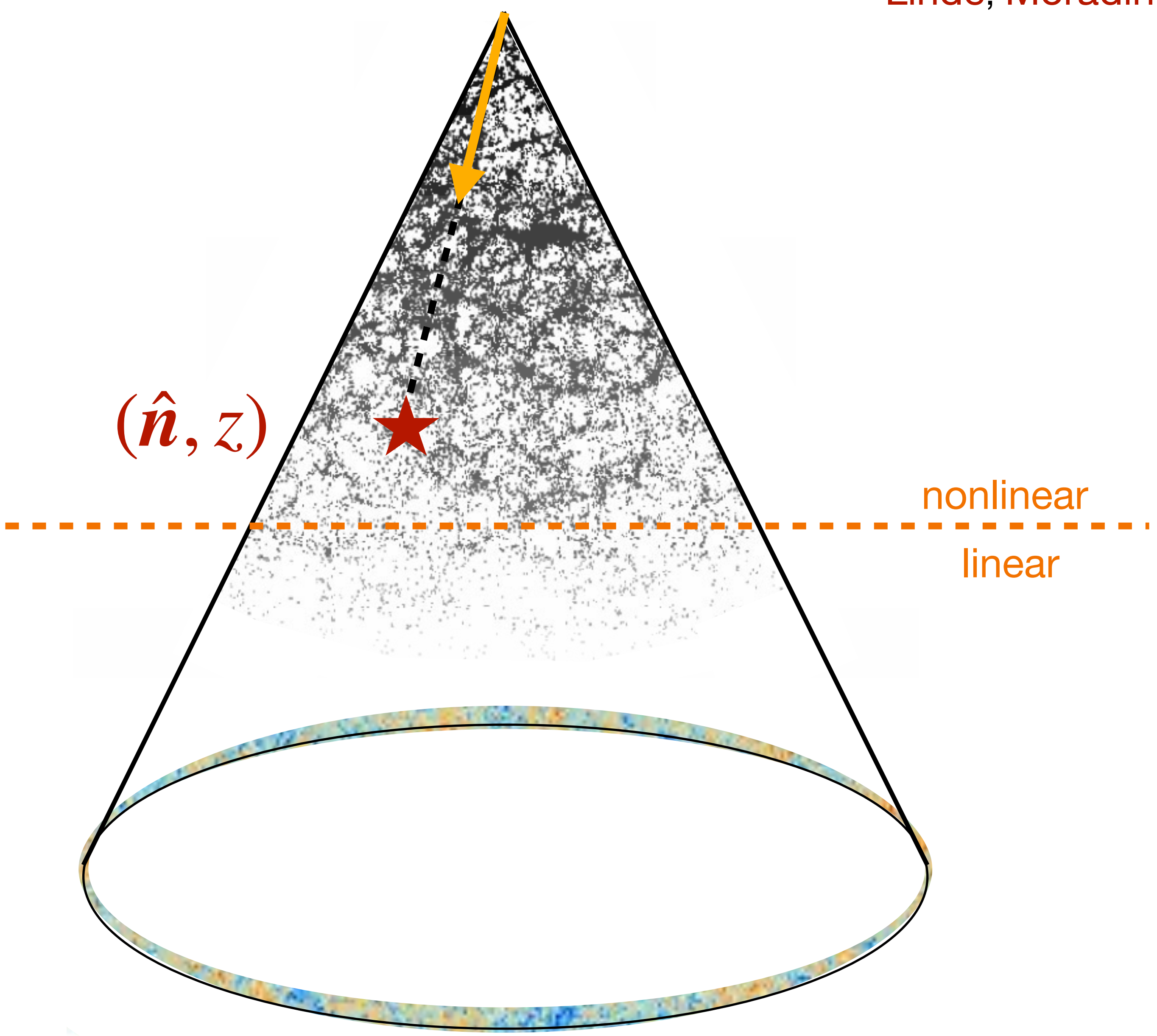






A new era in cosmology

Chudaykin, Ivanov, Philcox, MS (2019)
D'Amico, Senatore, Zhang (2019)
Chen, Vlah, Castorina, White (2020)
Linde, Moradinezhad Dizgah, Radermacher, Casas, Lesgourgues (2024)



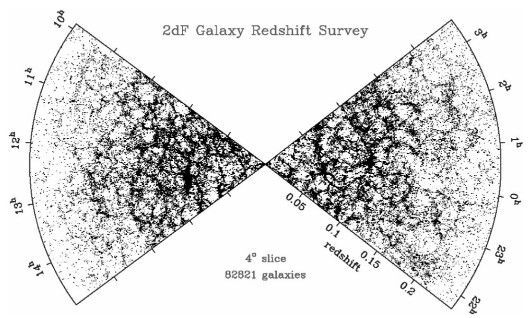
CLASS-PT
PyBird
velocileptors
CLASS-OneLoop

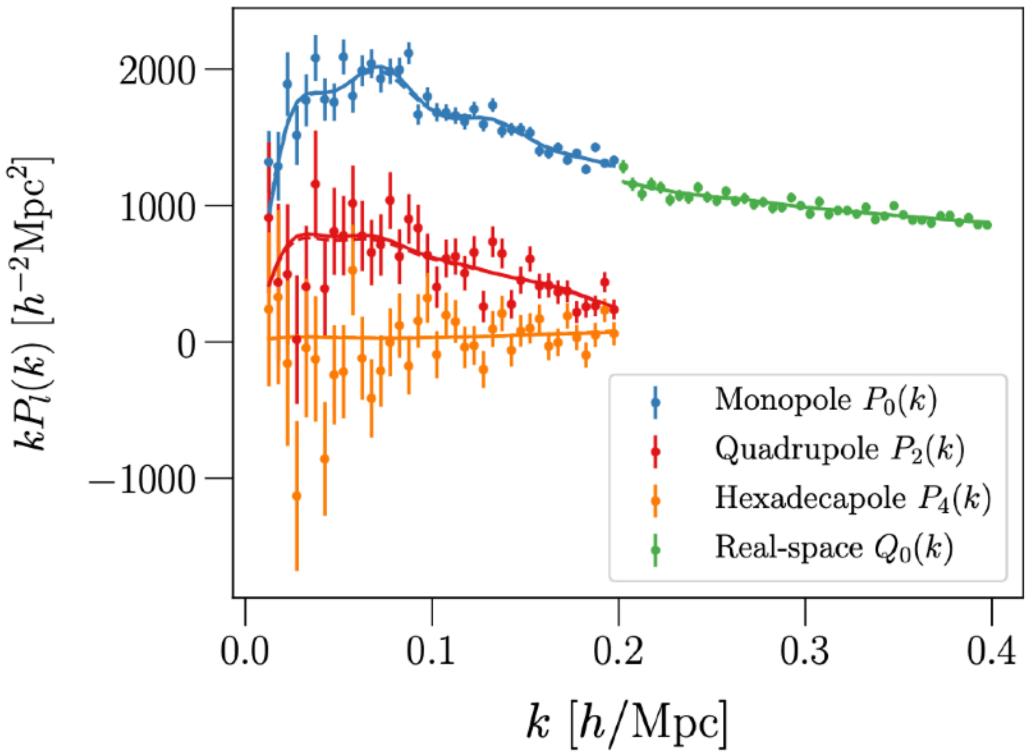
CMBFAST
CAMB
CLASS

Evolution of the vacuum state from inflation to redshift zero

Now we can use all features!

galaxy map





Full-shape analysis

Similar to CMB, directly measures "shape" parameters

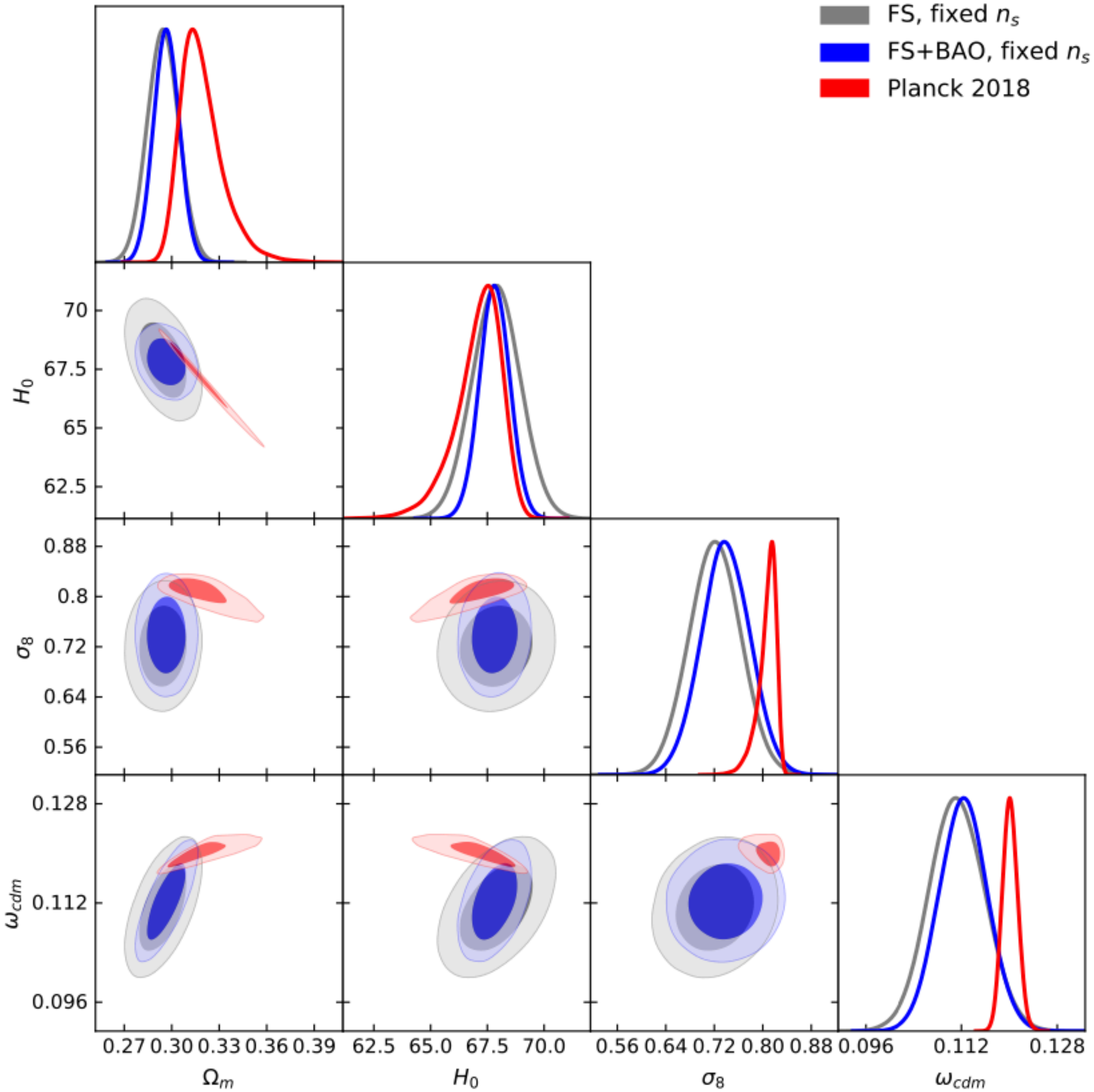
all cosmological parameters
no CMB input needed

Application to BOSS data

Ivanov, MS, Zaldarriaga (2019)

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

Philcox, Ivanov, MS, Zaldarriaga (2020)



BBN prior on ω_b, fixed tilt

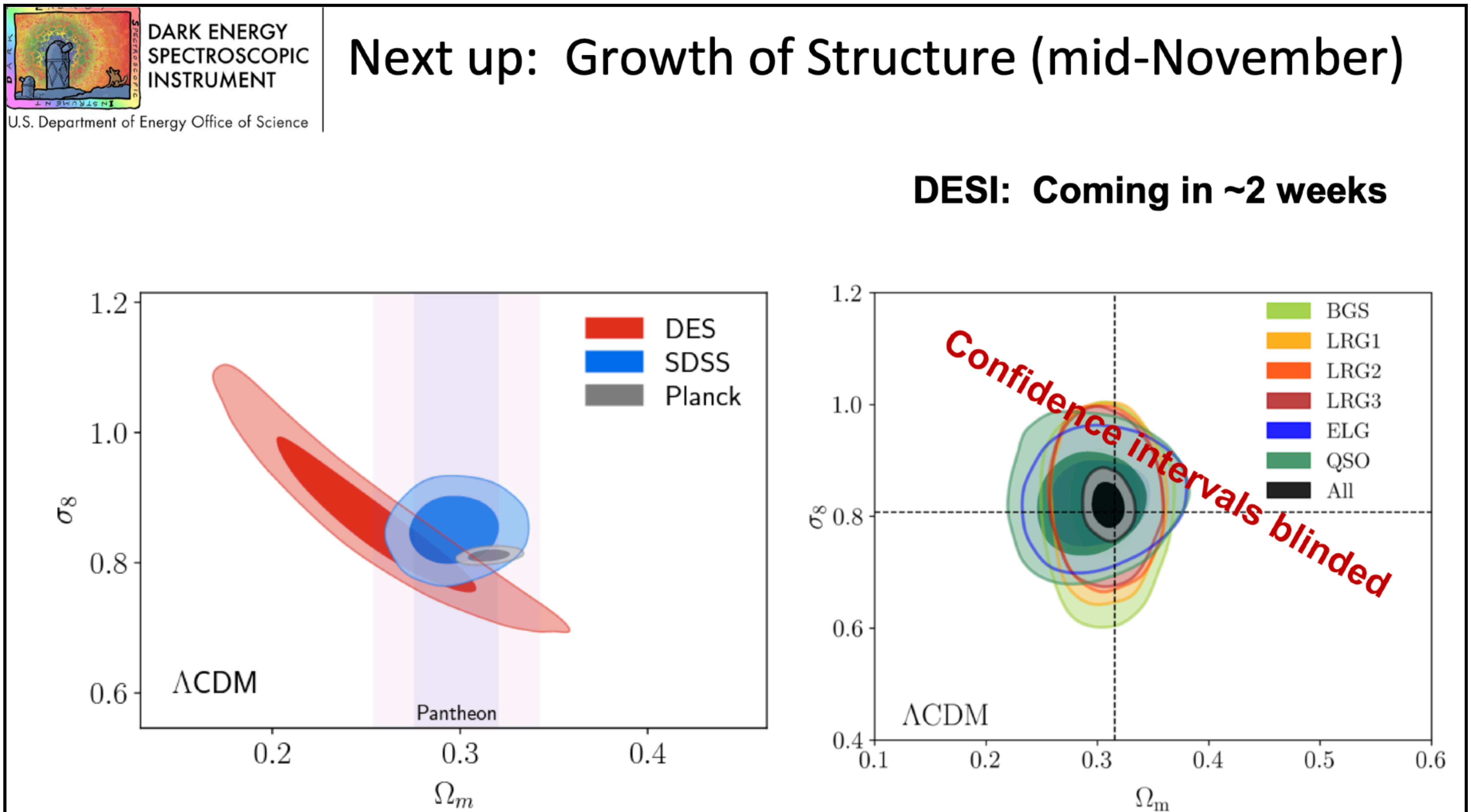
$H_0 = 67.8 \pm 0.7$ km/s/Mpc

Naive rescaling to DESI Y1

$\Delta H_0 \approx 0.4$ km/s/Mpc

Upcoming DESI results

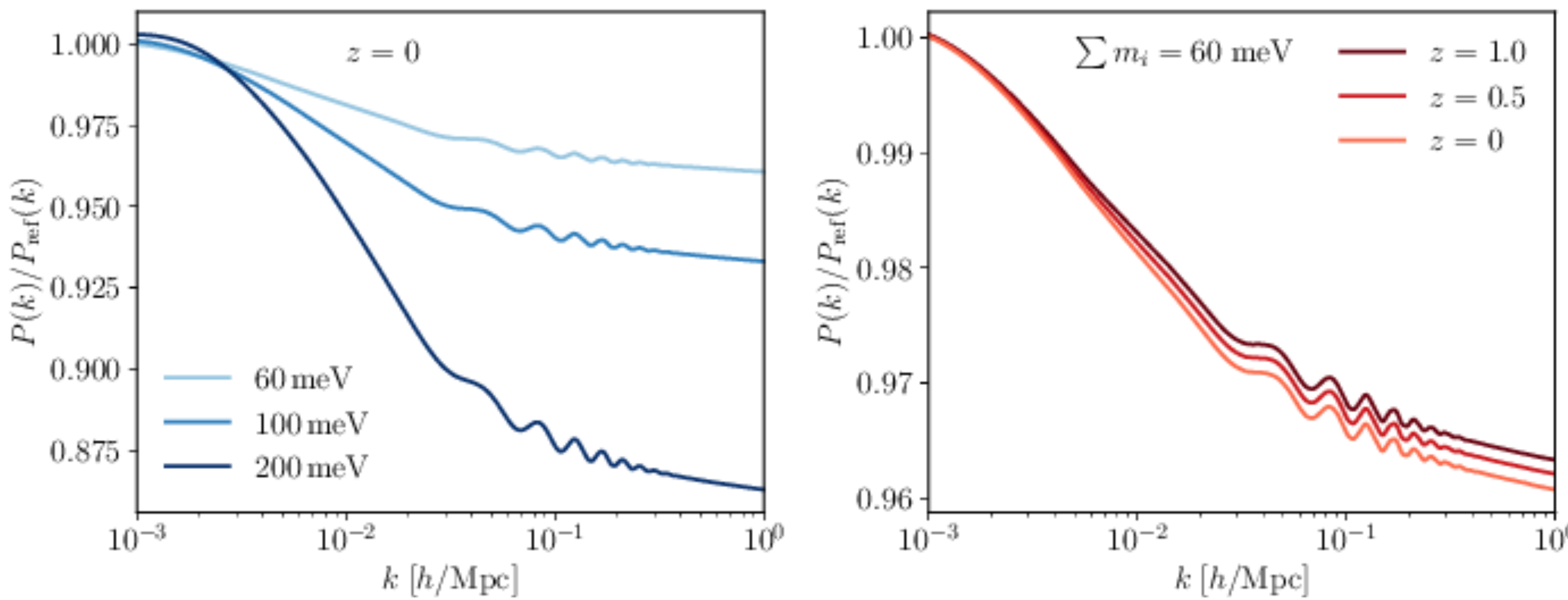
A slide from Kyle Dawson’s presentation



Beyond ΛCDM - neutrinos

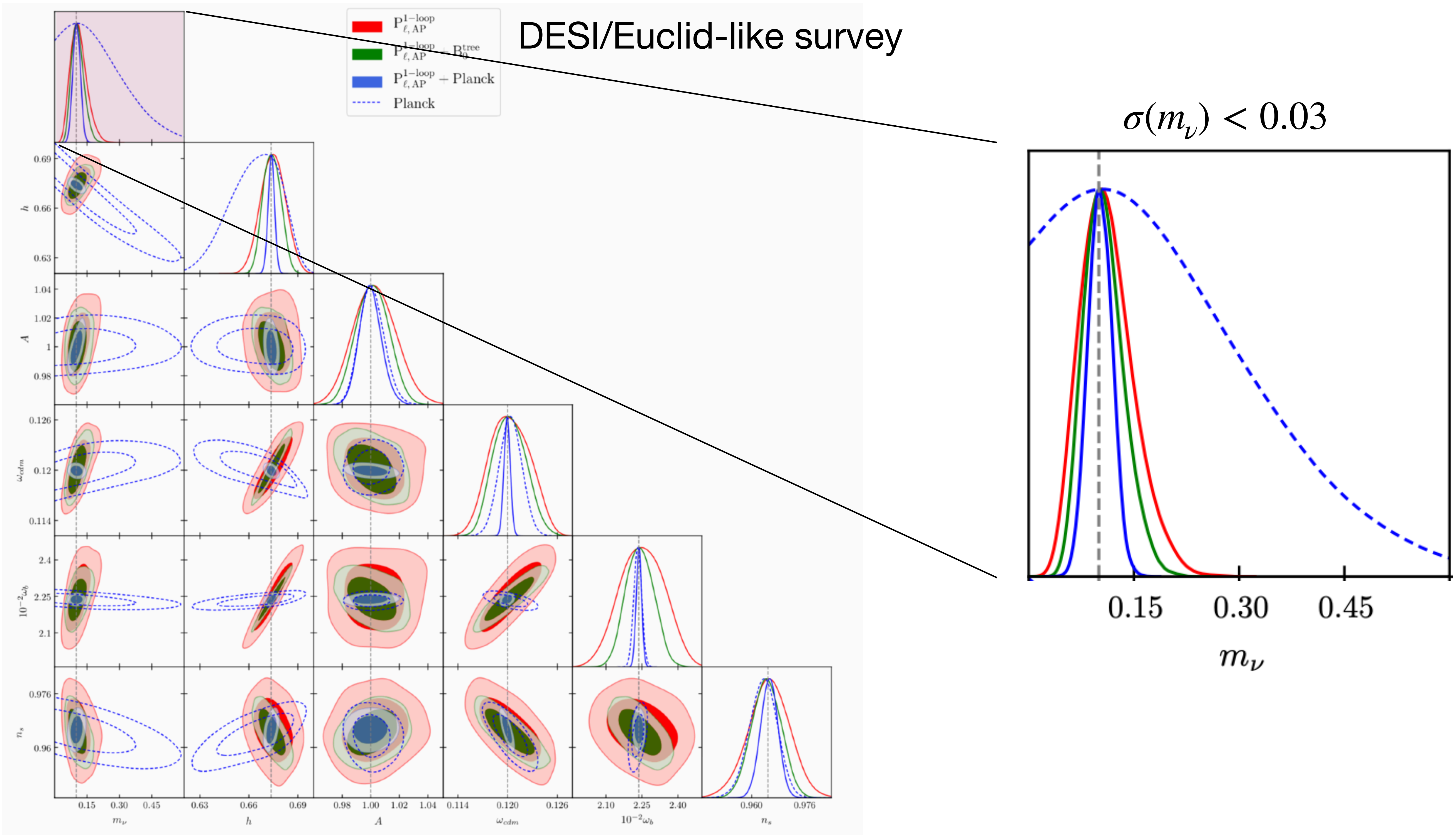
Neutrinos thermally produced in the early universe

Free-streaming causes scale-dependent suppression of structure



Beyond ΛCDM - neutrinos

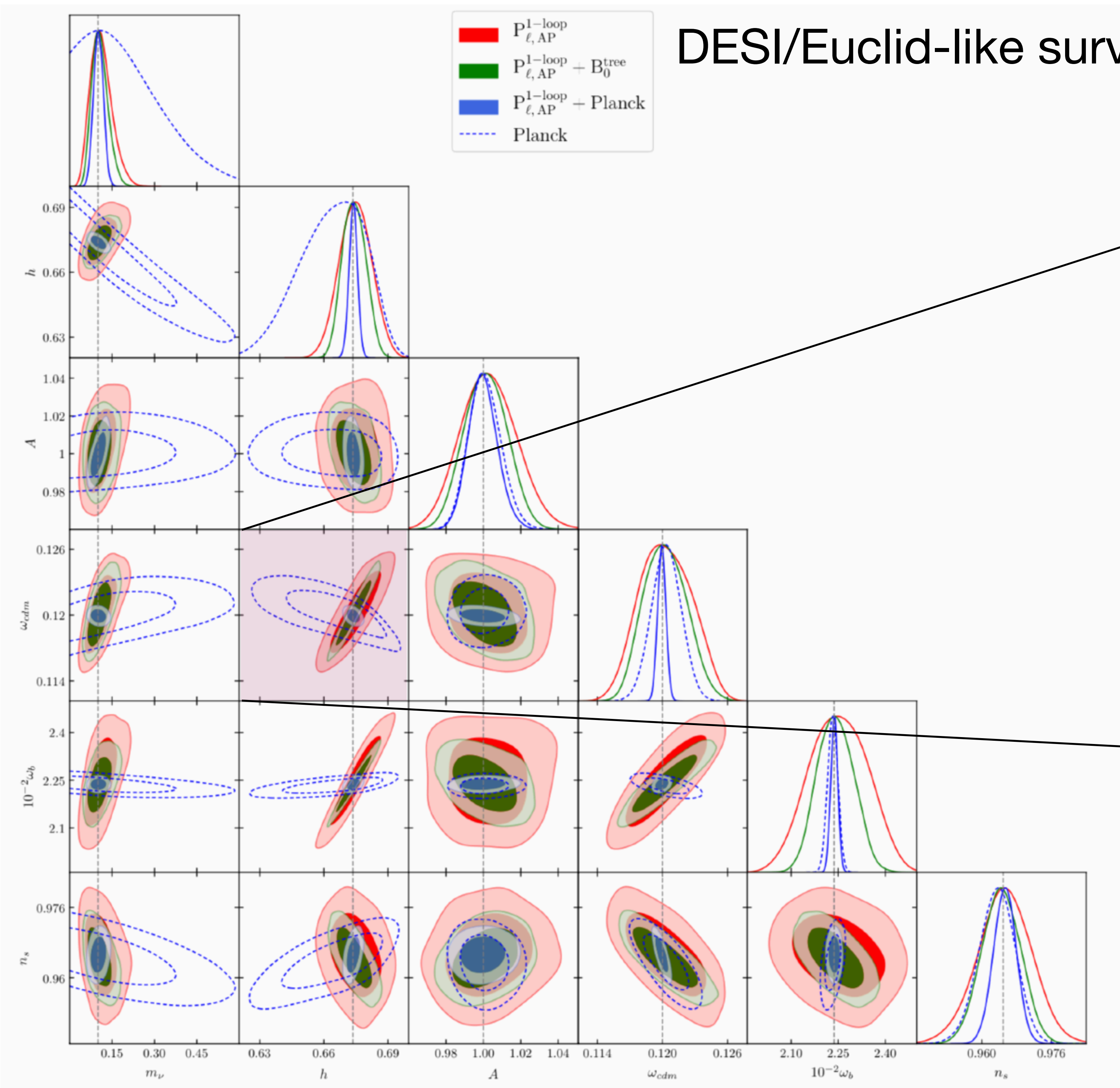
Chudaykin, Ivanov (2019)

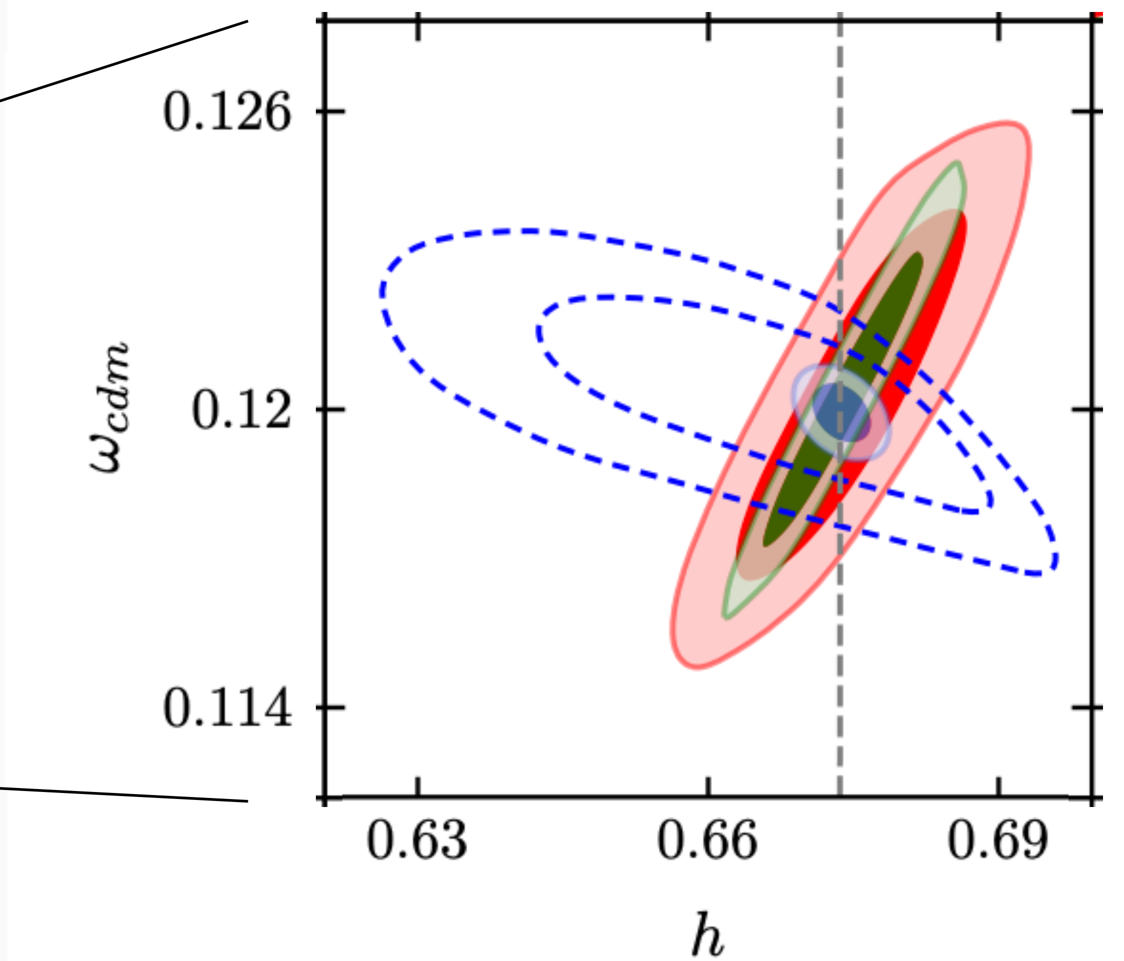


Beyond ΛCDM - neutrinos

Chudaykin, Ivanov (2019)

DESI/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

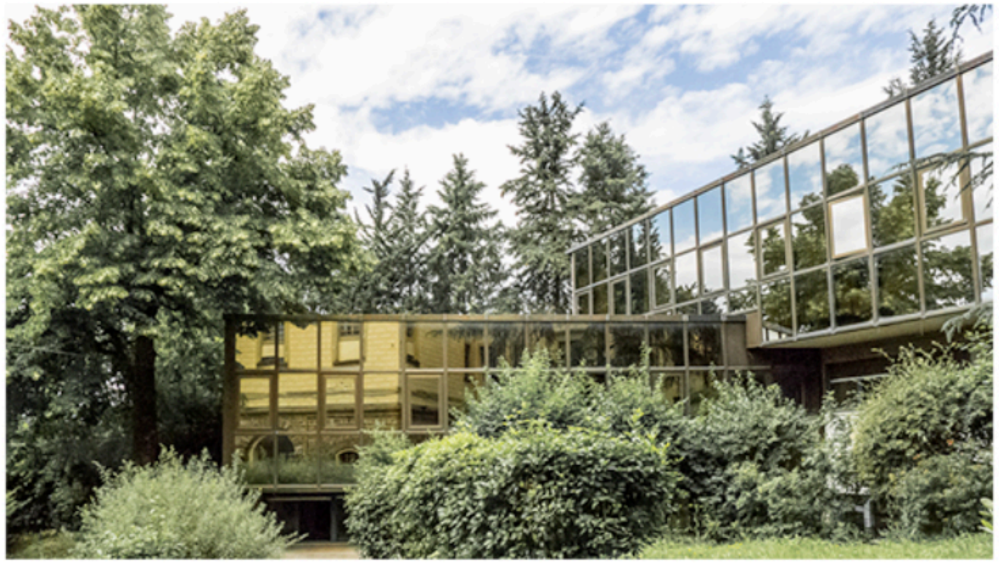
https://www.ggi.infn.it/workshops.html

deadline: May 31, 2025

The Galileo Galilei Institute For Theoretical Physics

Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare

Arcetri, Firenze



Home > Workshops

Workshops at Galileo Galilei Institute

Aug 25, 2025 - Oct 03, 2025

New Physics from Galaxy Clustering at GGI

- **Training Week** (Aug 25, 2025 - Aug 29, 2025)
- **Focus Week** (Sep 15, 2025 - Sep 19, 2025)
- **Conference** (Sep 29, 2025 - Oct 03, 2025)

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