The interplay of high energy theory and cosmology in the sky

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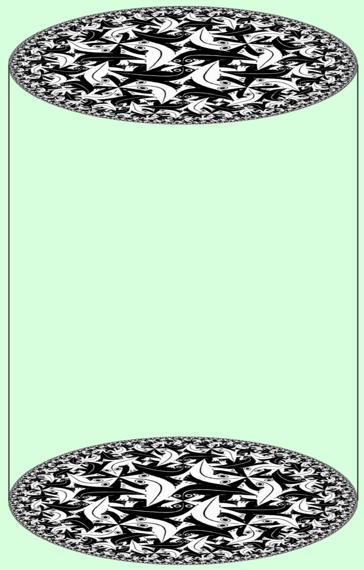
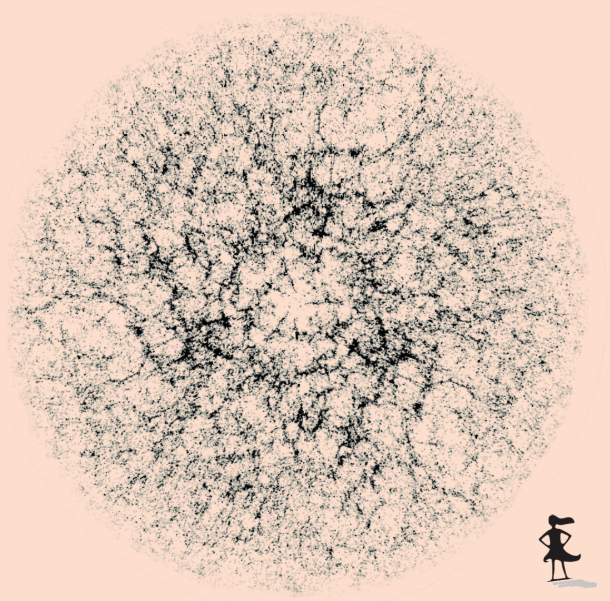
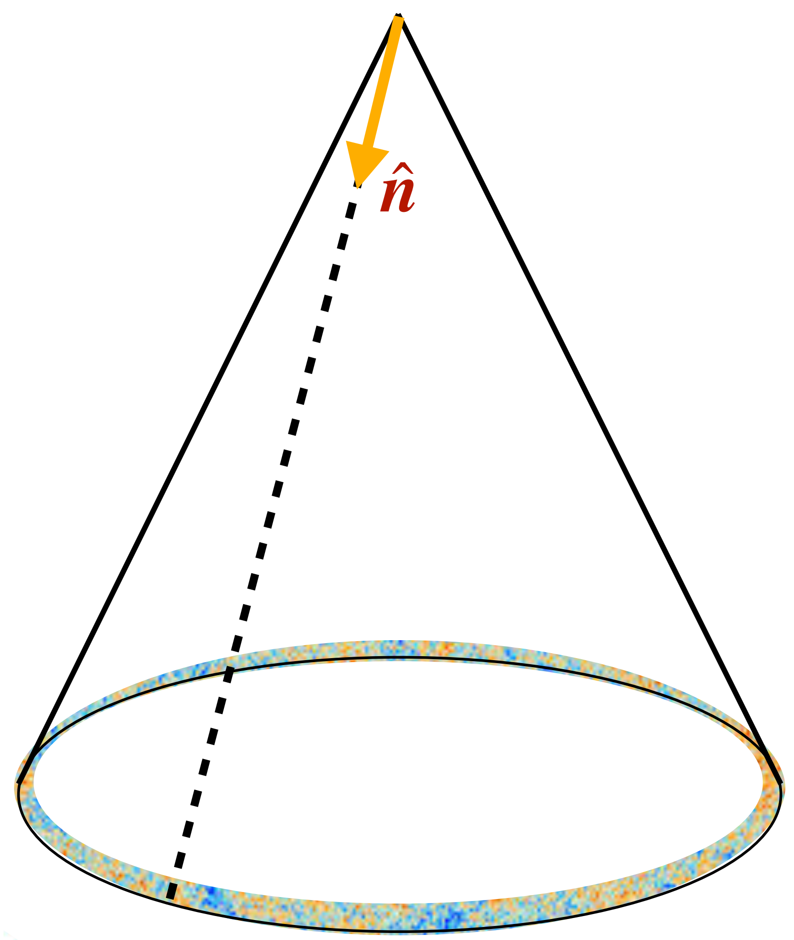




Petnica Summer Institute

Relevance of cosmology for HET



Dark matter

Dark energy

Inflation

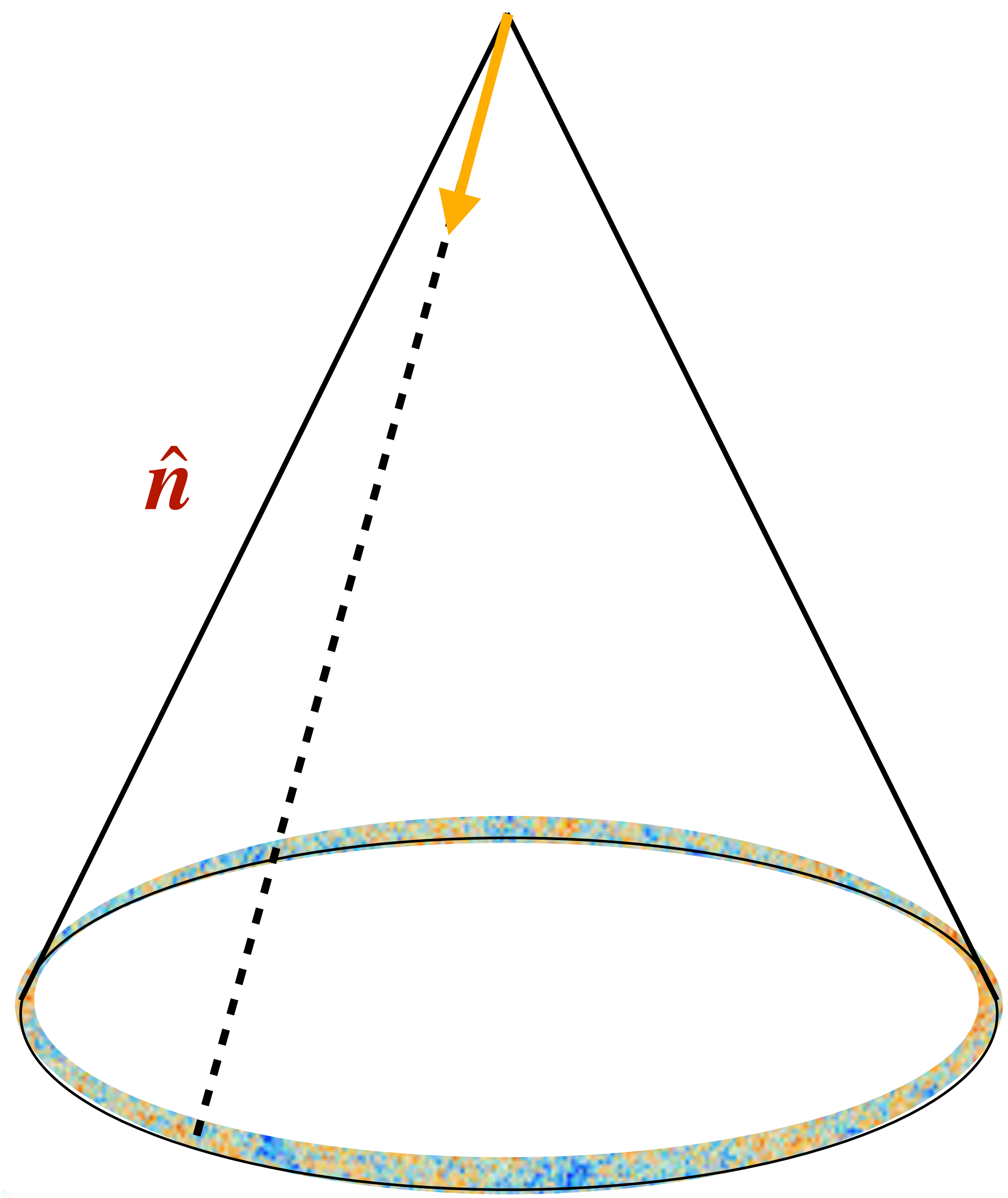
Particle physics, string theory…

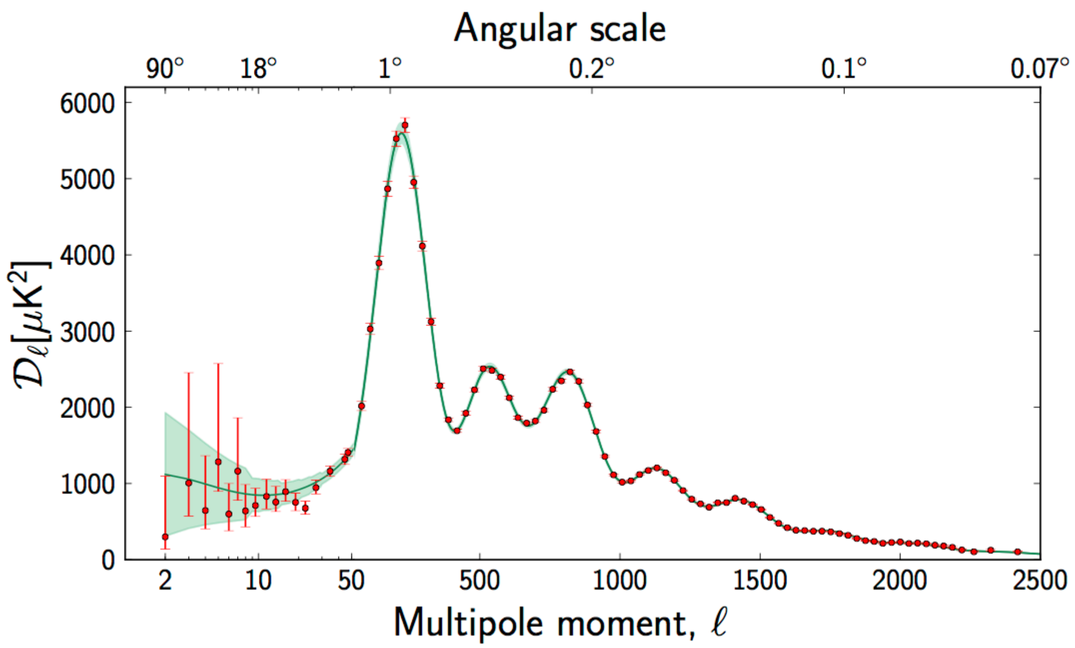
Relics from high energies + observations of large volumes

Since we are probing very high energies surprises are possible

Cosmic Microwave Background

CMB extremely successful. Better polarization in the next ~10 yrs





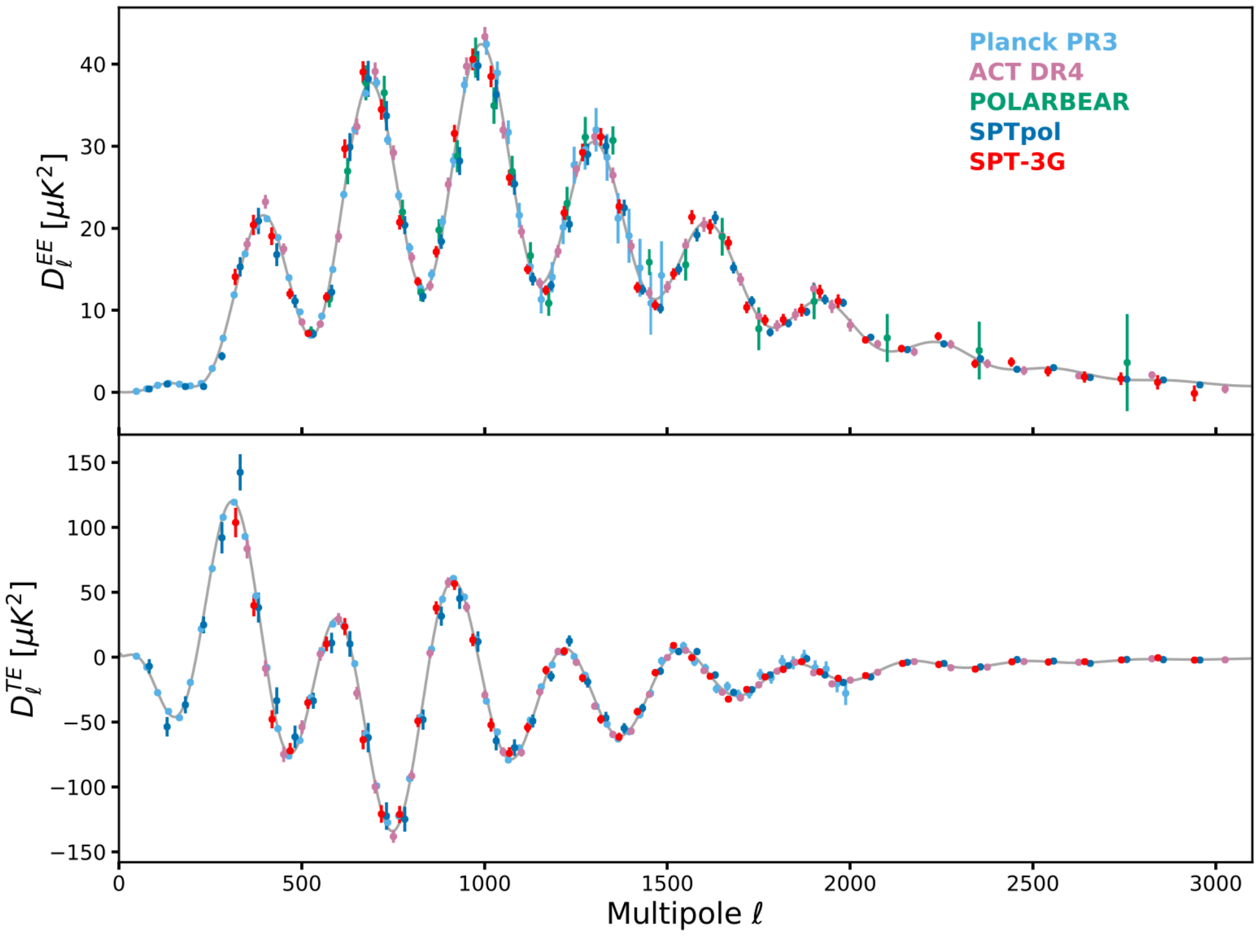
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54

Cosmic Microwave Background

The main focus on polarization — ACTPol, SPTpol

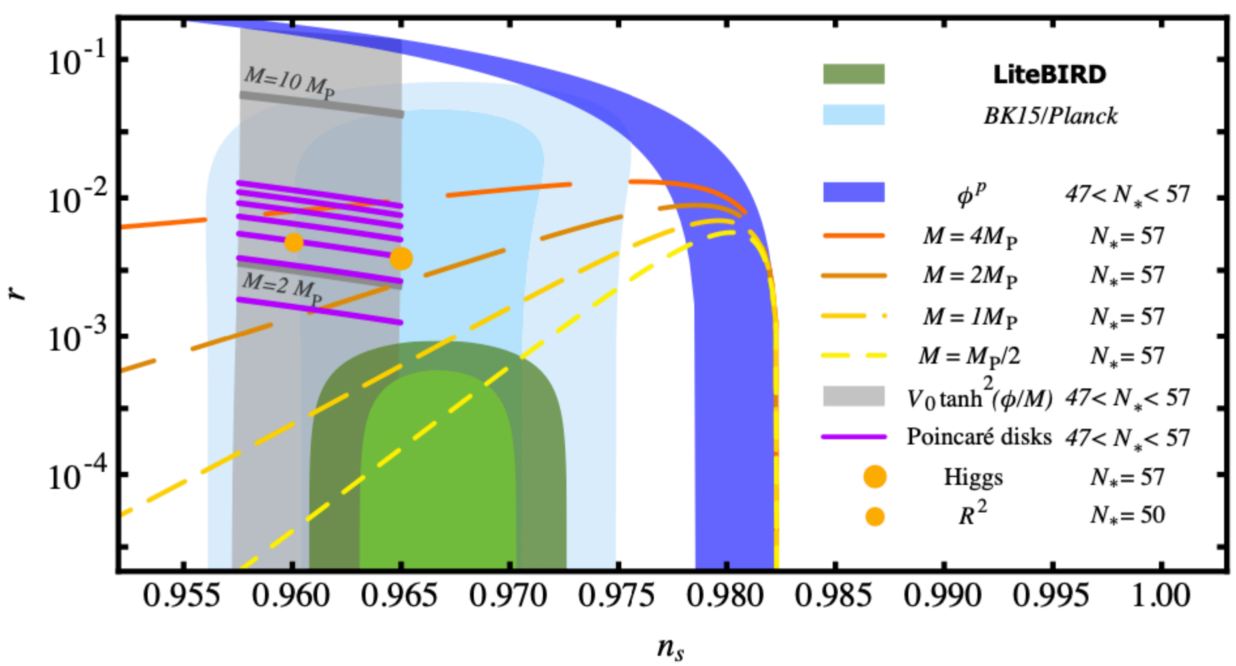
The big goal remains search for primordial B modes — BICEP

Simons Observatory, LiteBird, S4…



Direct measure of H during inflation

$$H \approx \sqrt{\frac{r}{0.001}} \cdot 10^{-6}\, M_{\rm pl}$$



Some open questions

Many scenarios predict $f_{\rm NL} \gtrsim 1$ and new "shapes" of PNG
(multi-field, warm inflation, ~~SUSY~~ at H, massive particles $m \sim H$)

Scalar fields in cosmology (inflaton, dark energy, axions…)

What if $\Omega_K \neq 0$? (current CMB-alone bound $|\Omega_K| < 0.01$)

Are there some primordial features on large or small scales?

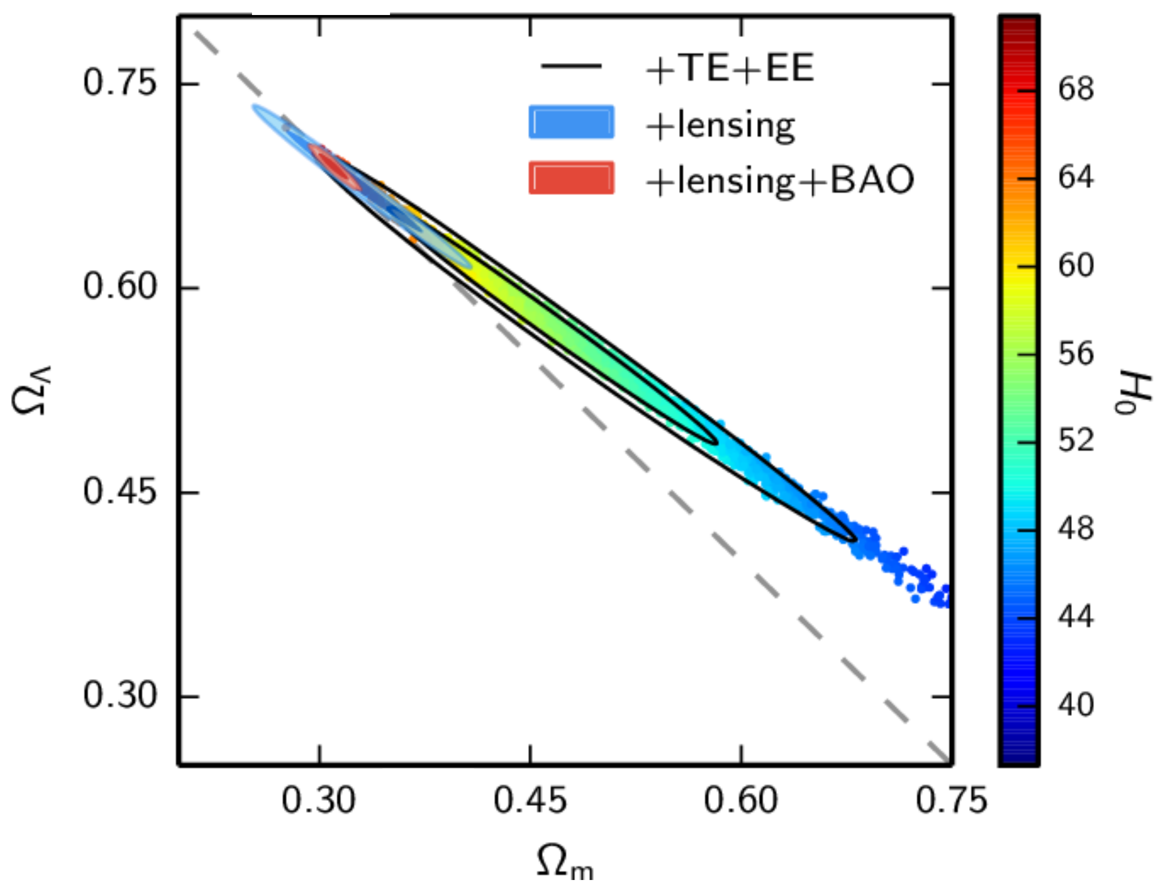
Is dark matter single component or not?

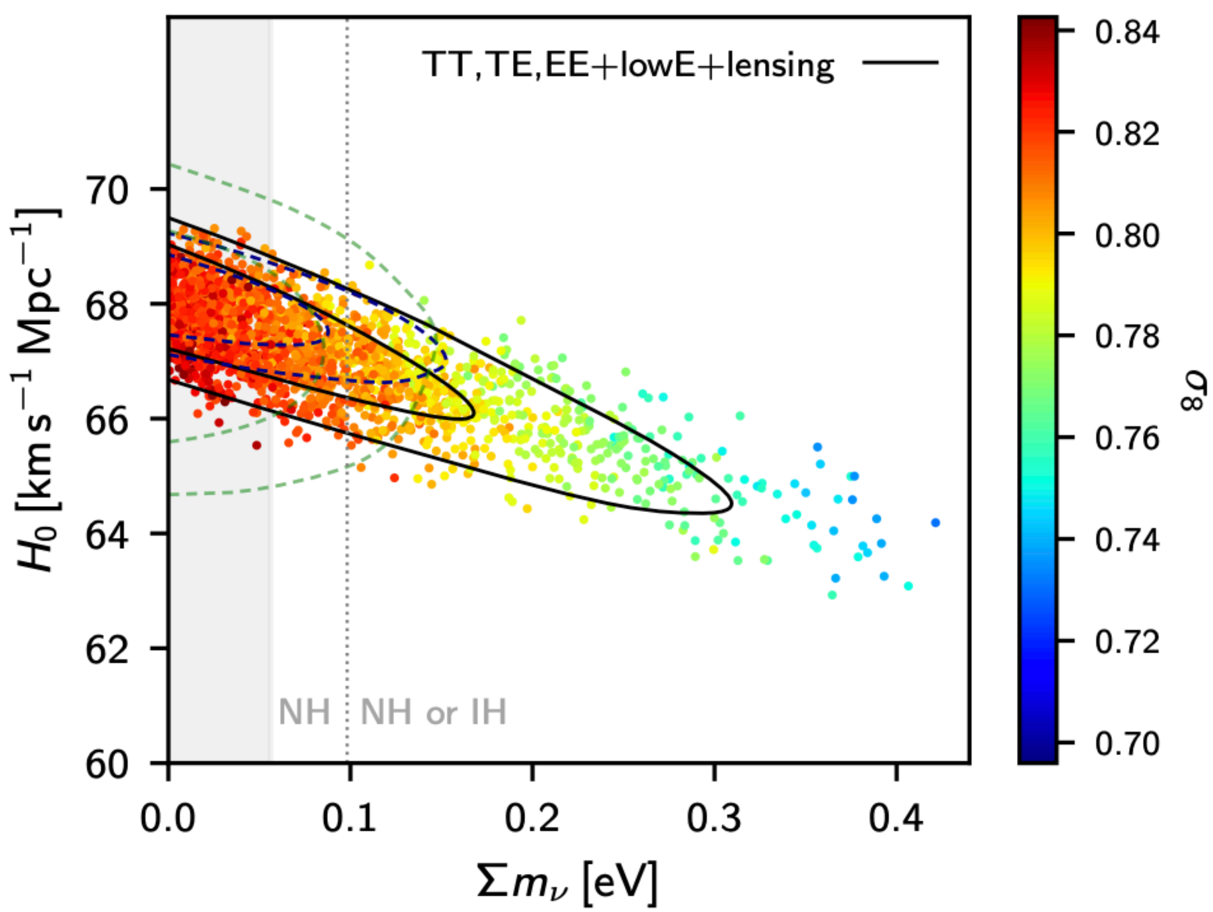
CMB alone insufficient to answer these questions

Why is the CMB insufficient?

With exception of r and $\Delta N_{\rm eff}$, CMB improvements ~2x

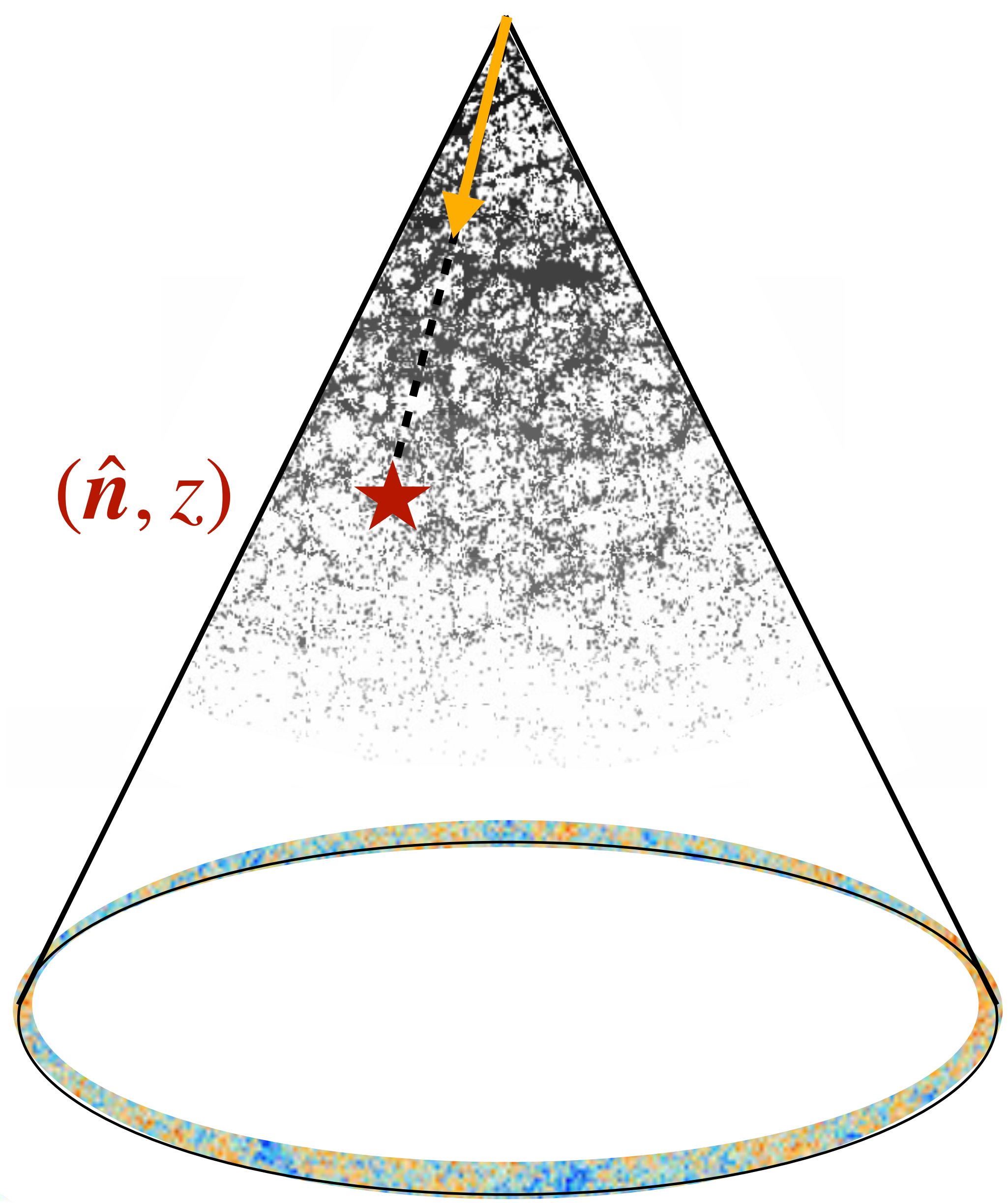
There are many degeneracies with more parameters

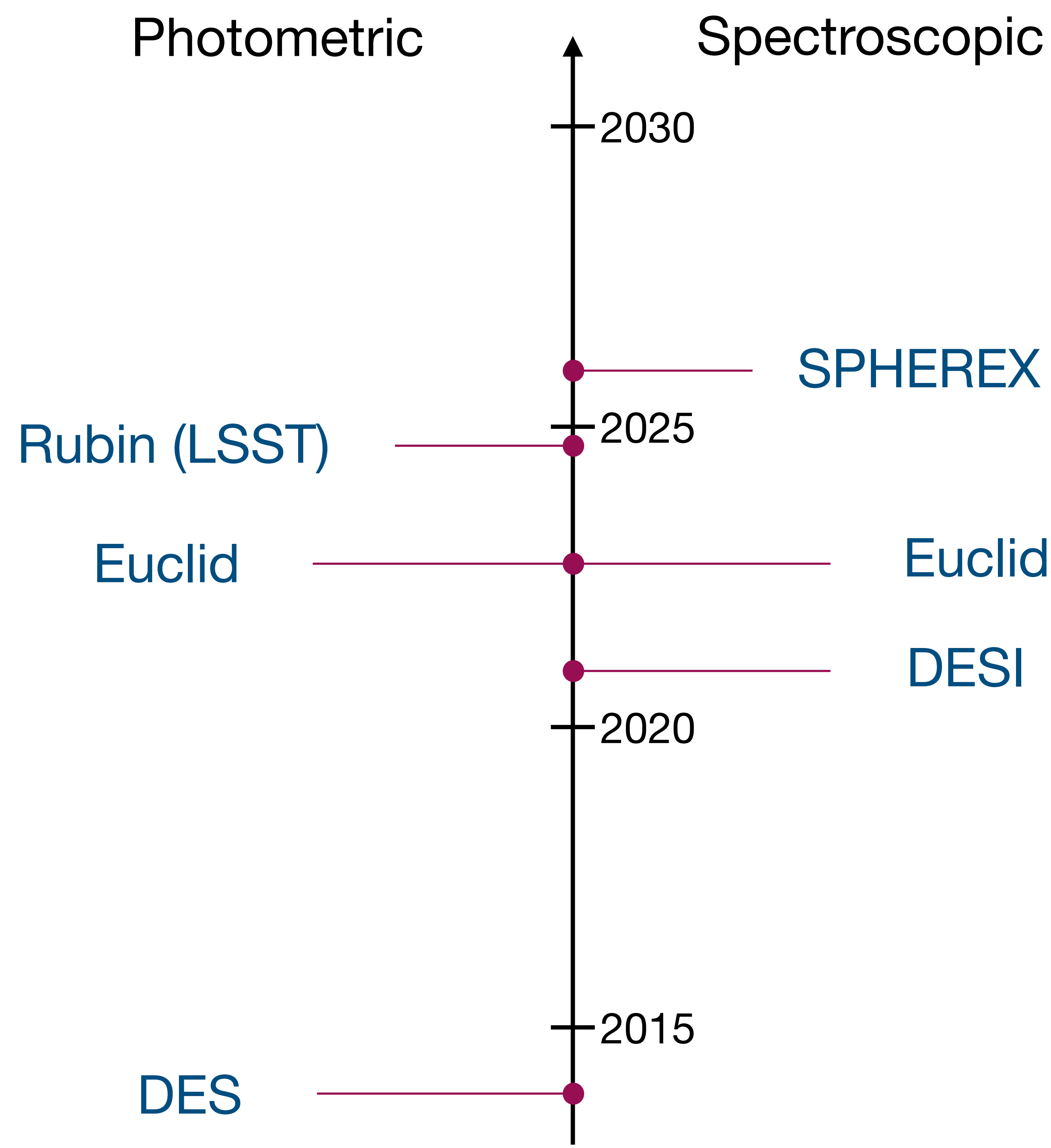




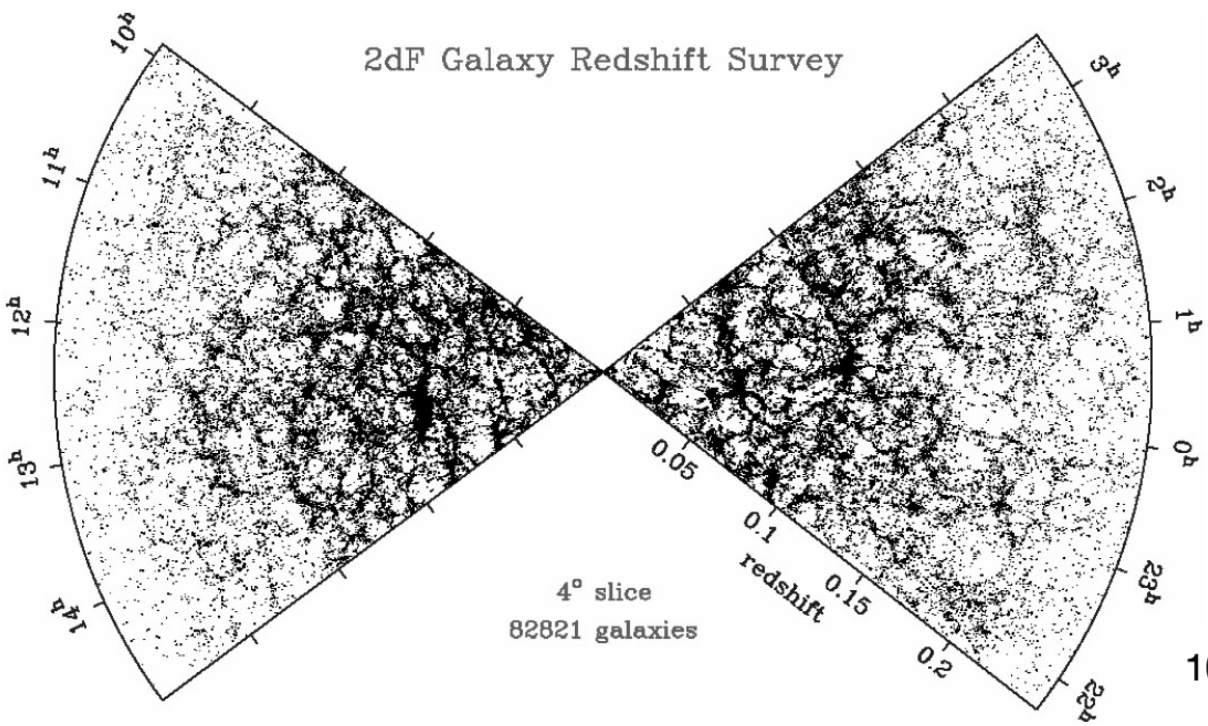
Observing the entire light-cone

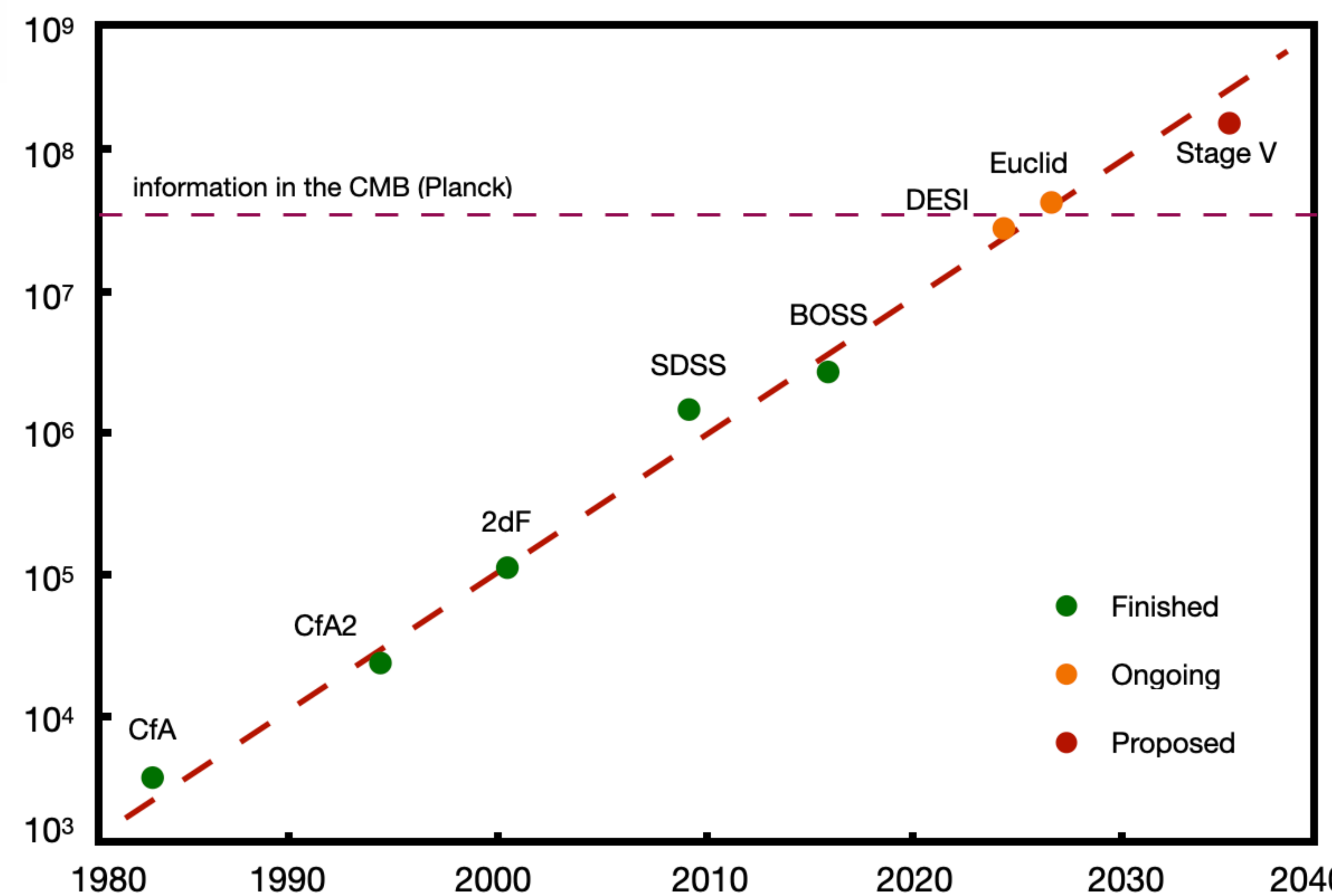
Image billions and take spectra of ~100 million of objects up to z<5





Spectroscopic galaxy surveys





The baryon acoustic oscillation (BAO) peak

LSS "remembers" the initial conditions and the entire history

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

Set in the early universe

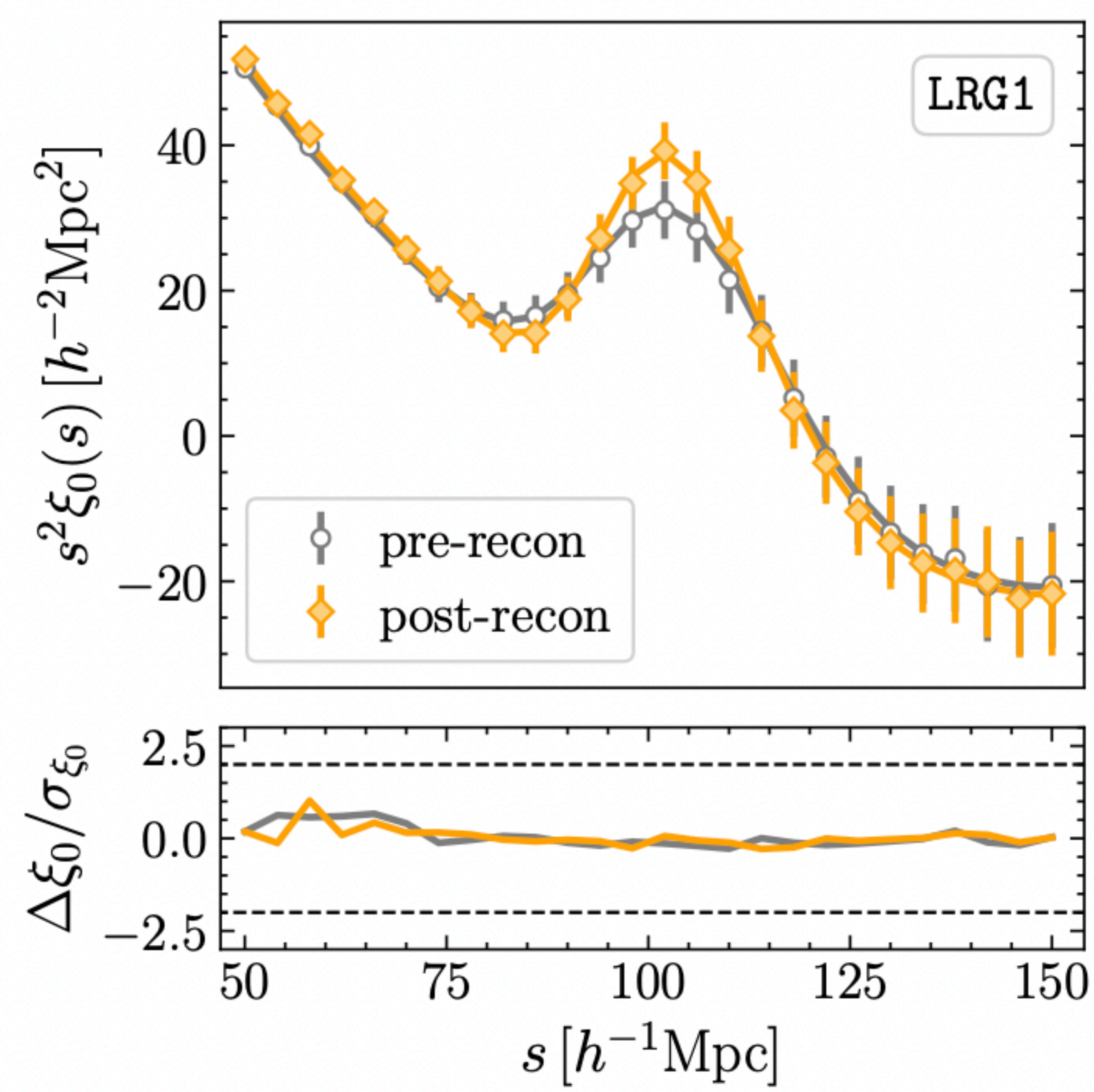
Easy to measure

Easy to model

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

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

DESI 2024, credit: Seshadri Nadathur



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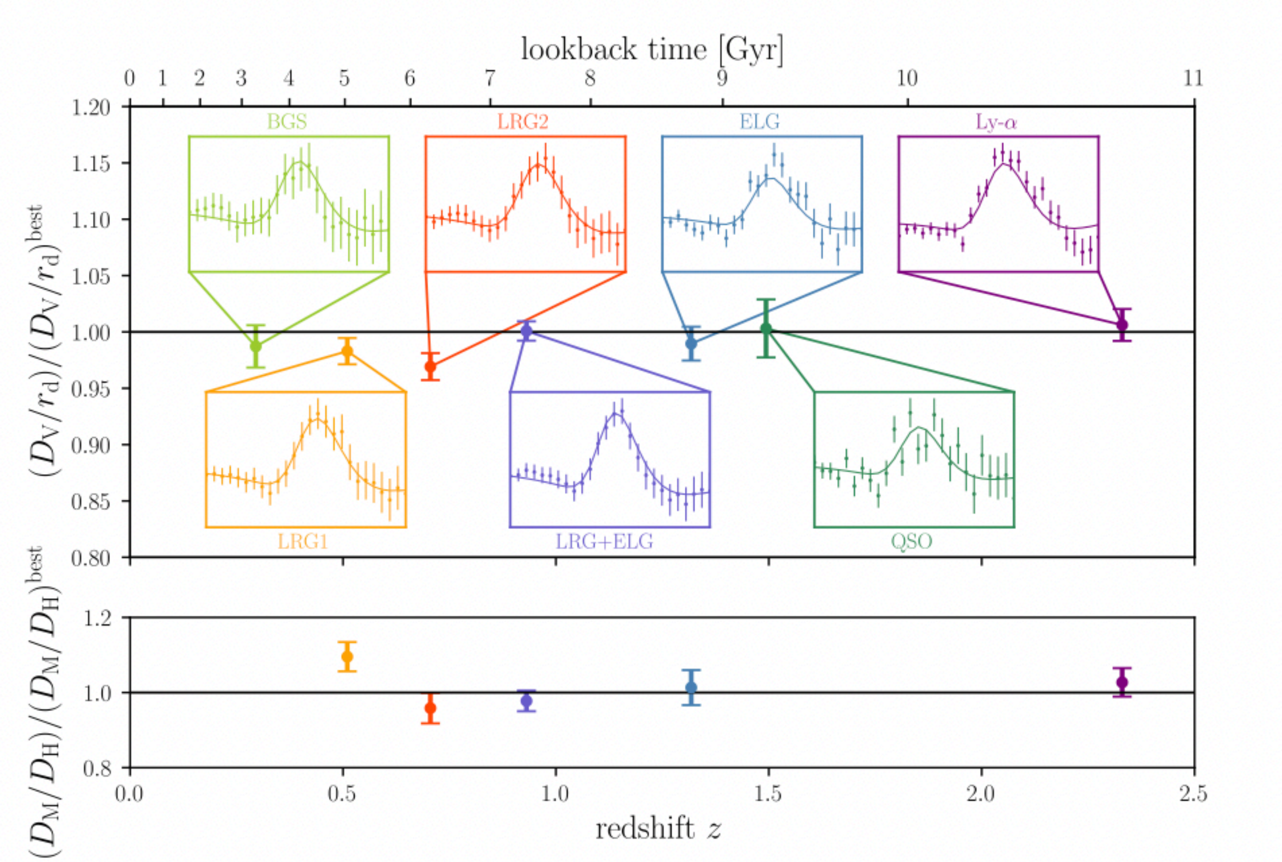
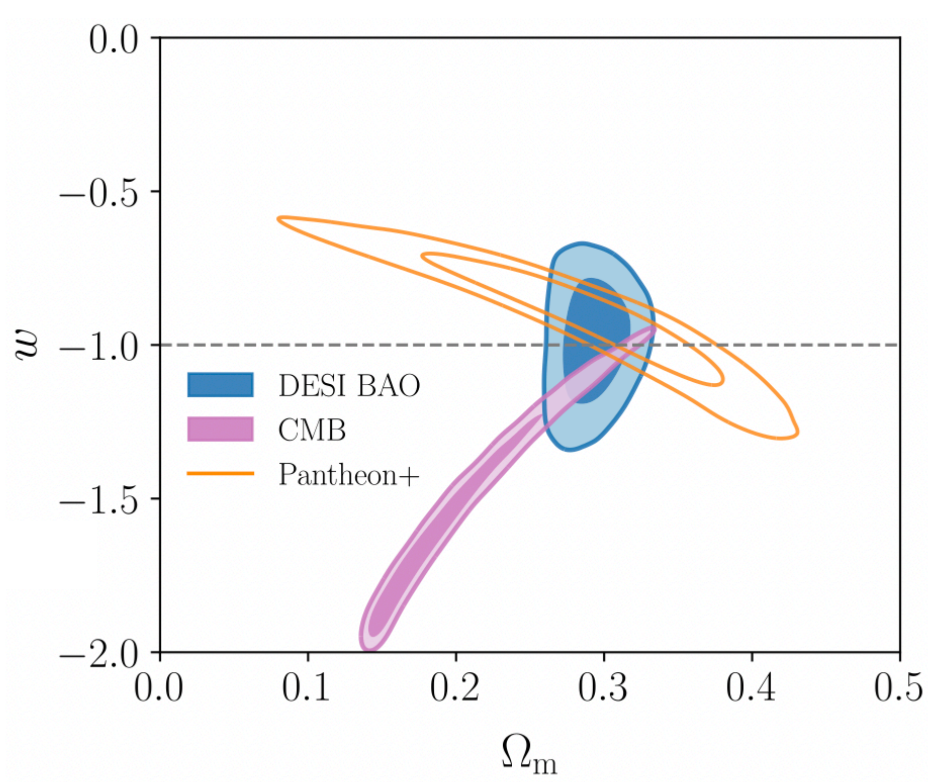
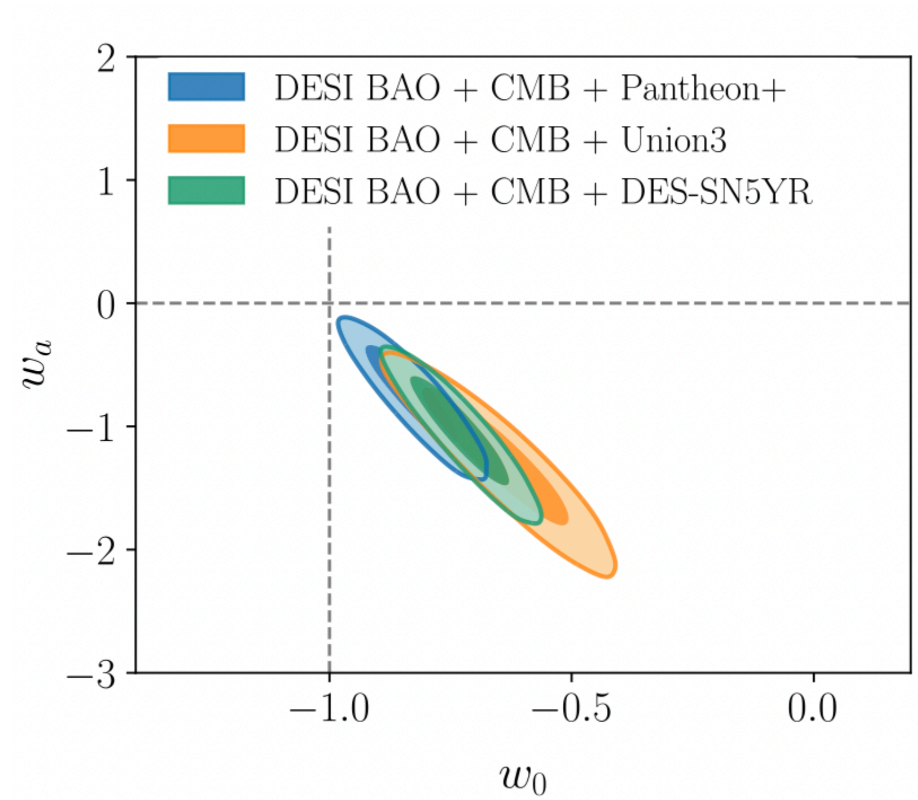


credit: Arnaud de Mattia

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



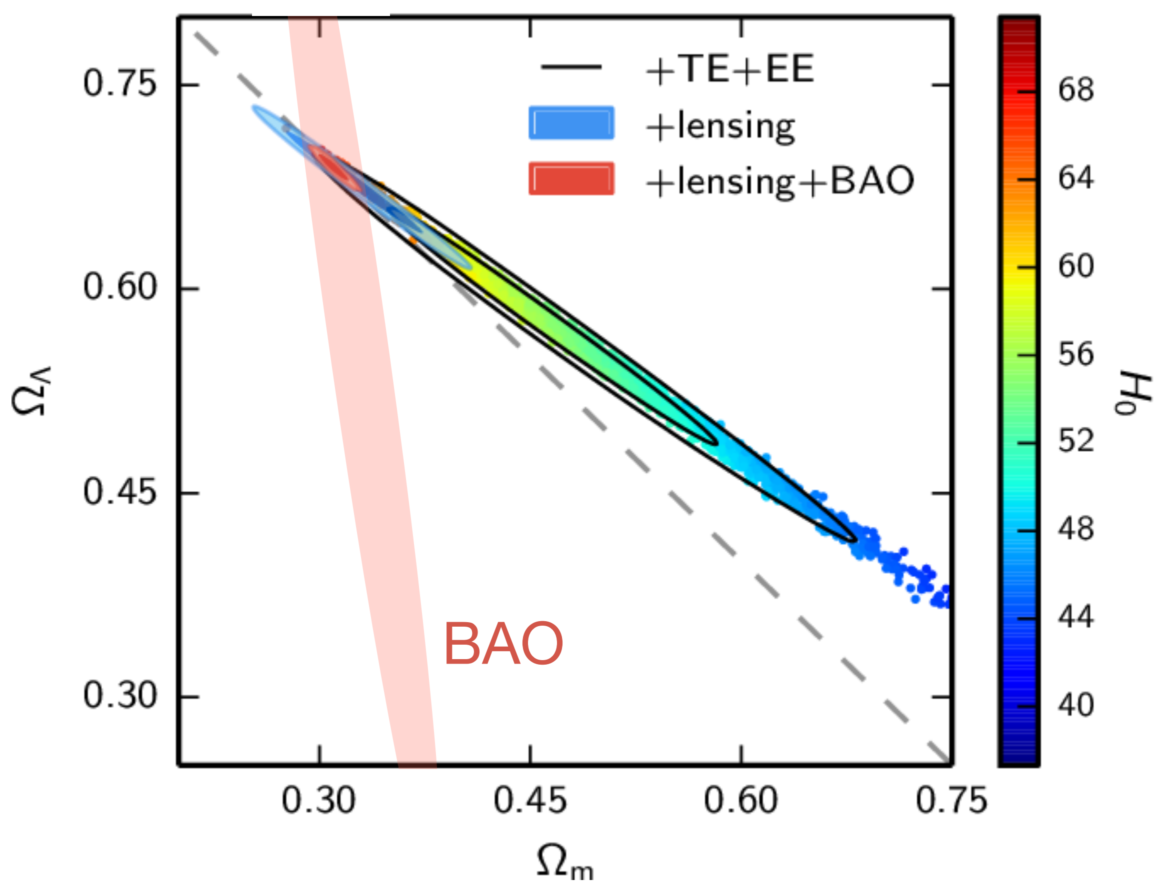


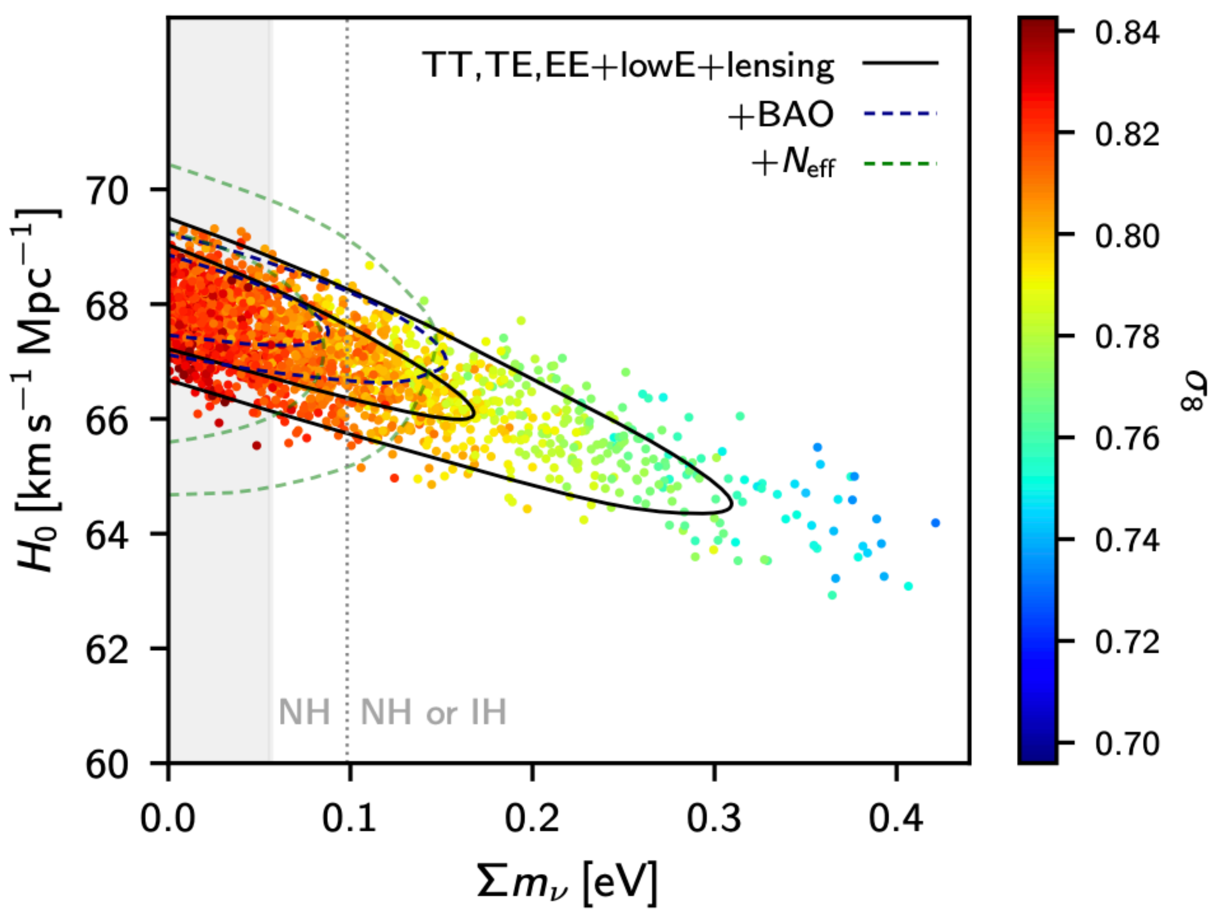
DESI 2024 results

The baryon acoustic oscillation (BAO) peak

The BAO breaks degeneracies and it is already very important

$$|\Omega_K| < 0.01 \quad \rightarrow \quad |\Omega_K| < 0.002$$

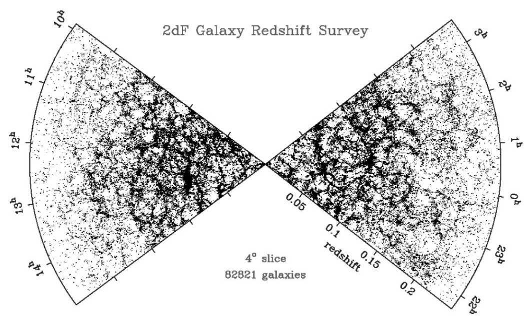




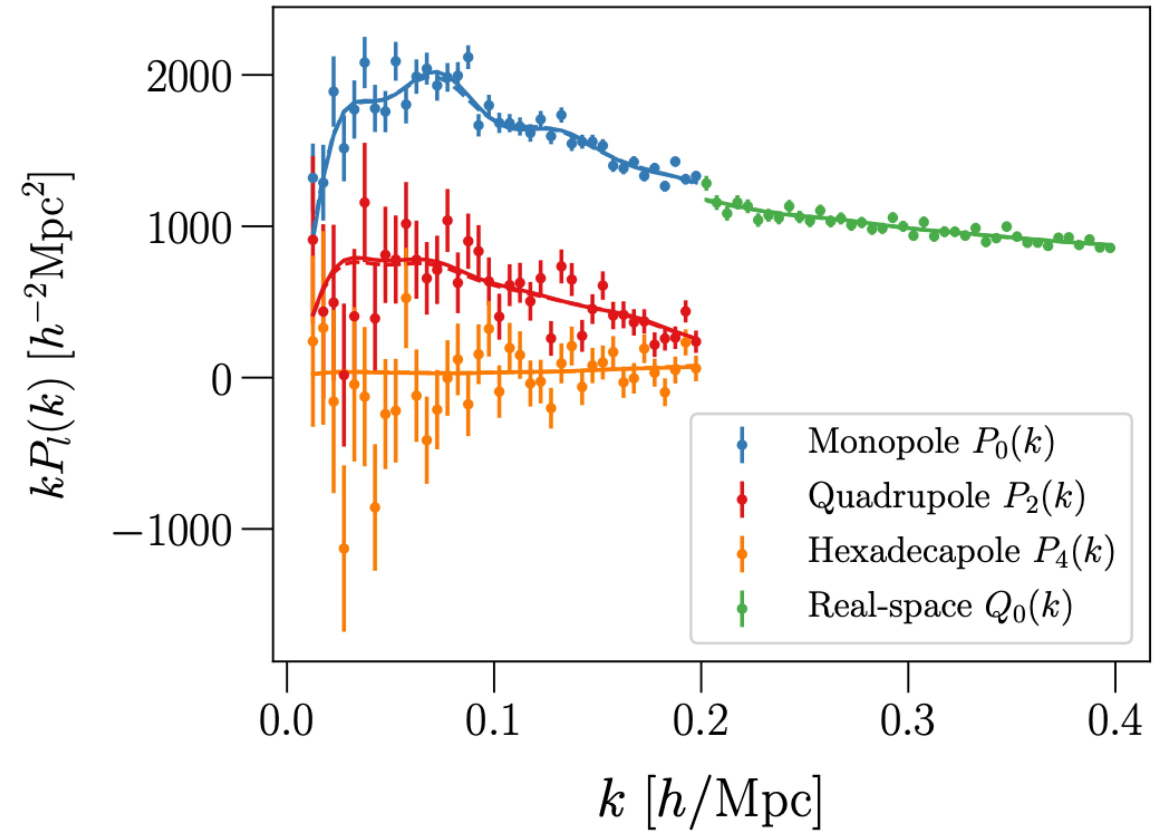
Can we do even better than this?

Beyond the BAO peak

galaxy map



BOSS data
LRGs, 0.2<z<1
~ few x 10^6 galaxies
~ 6 (Gpc/h)^3

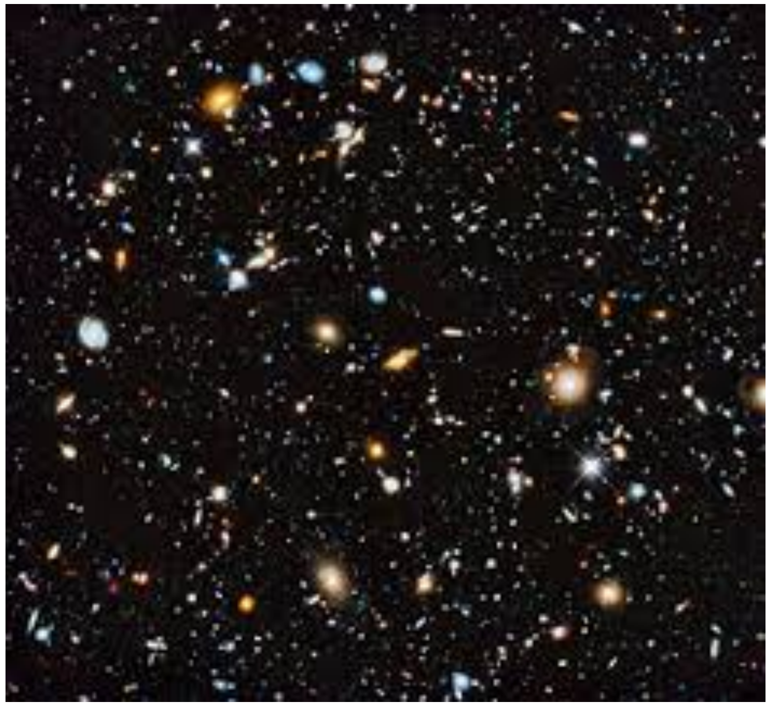


Full-shape analysis

Similar to CMB, directly measures “shape” parameters

all cosmological parameters
no CMB input needed

Effective Field Theory of LSS



Large distance dof: δ_g

EoM are fluid-like, including gravity

Symmetries, Equivalence Principle

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

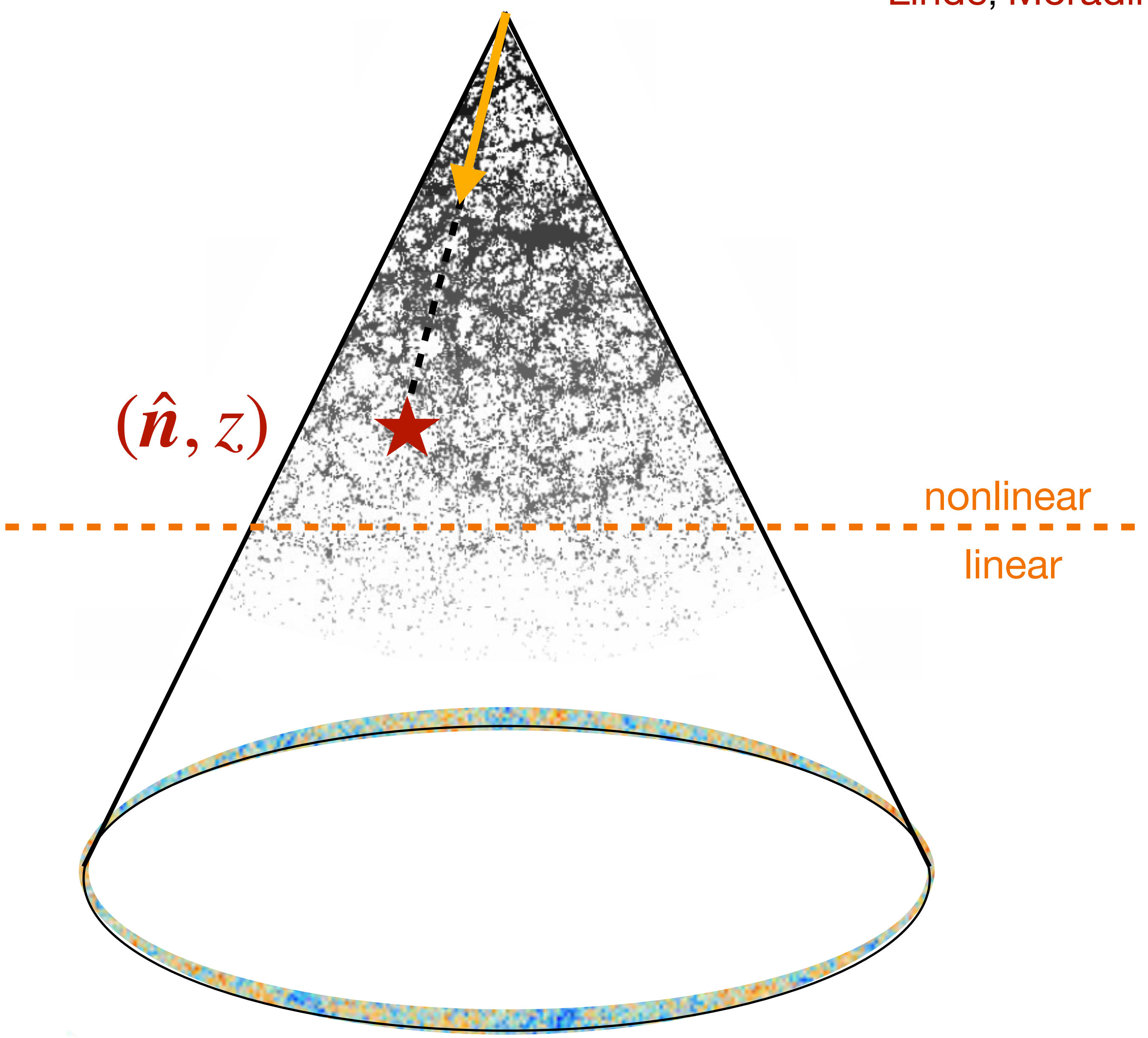
All “UV” dependence is in a handful of free parameters

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

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

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

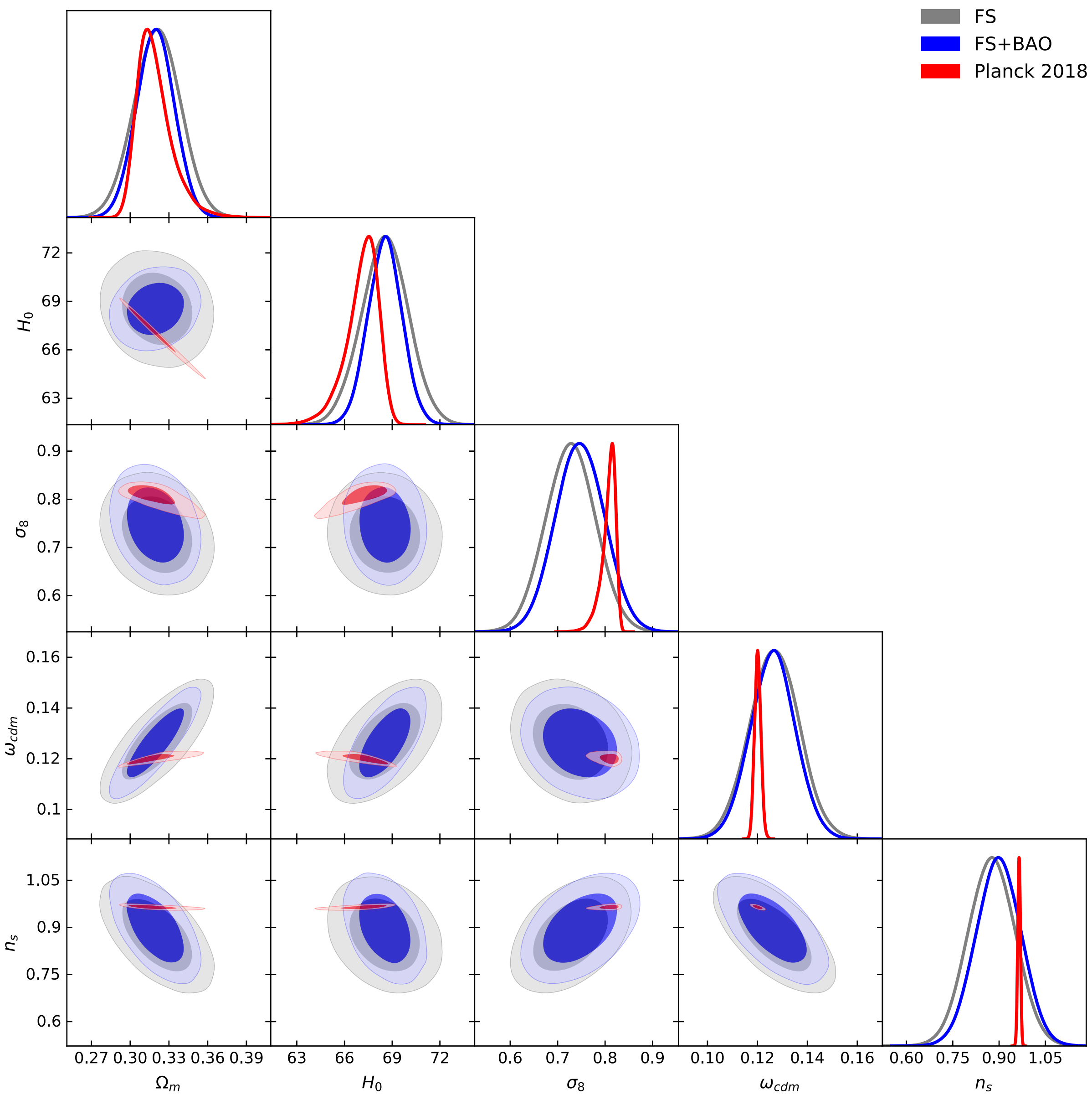
Evolution of the vacuum state from inflation to redshift zero

Application of FS analysis 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

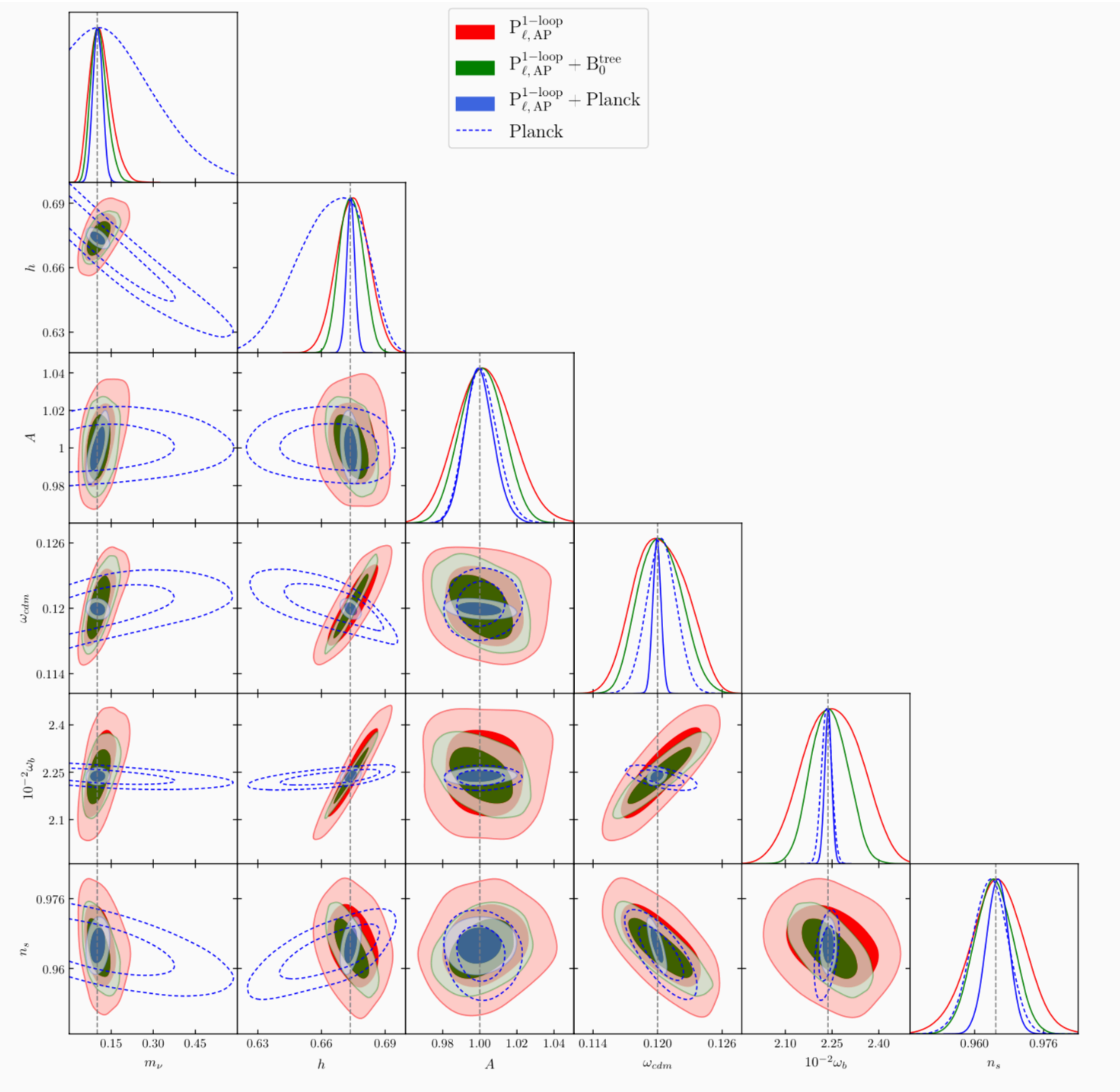
$H_0 = 68.6 \pm 1.1$ km/s/Mpc

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

Naive rescaling to DESI Y1

$\Delta H_0 \approx 0.6(0.4)$ km/s/Mpc

Application of FS analysis to BOSS data



Chudaykin, Ivanov (2019)

Euclid/DESI-like survey

(galaxies only, no Lya and quasars)

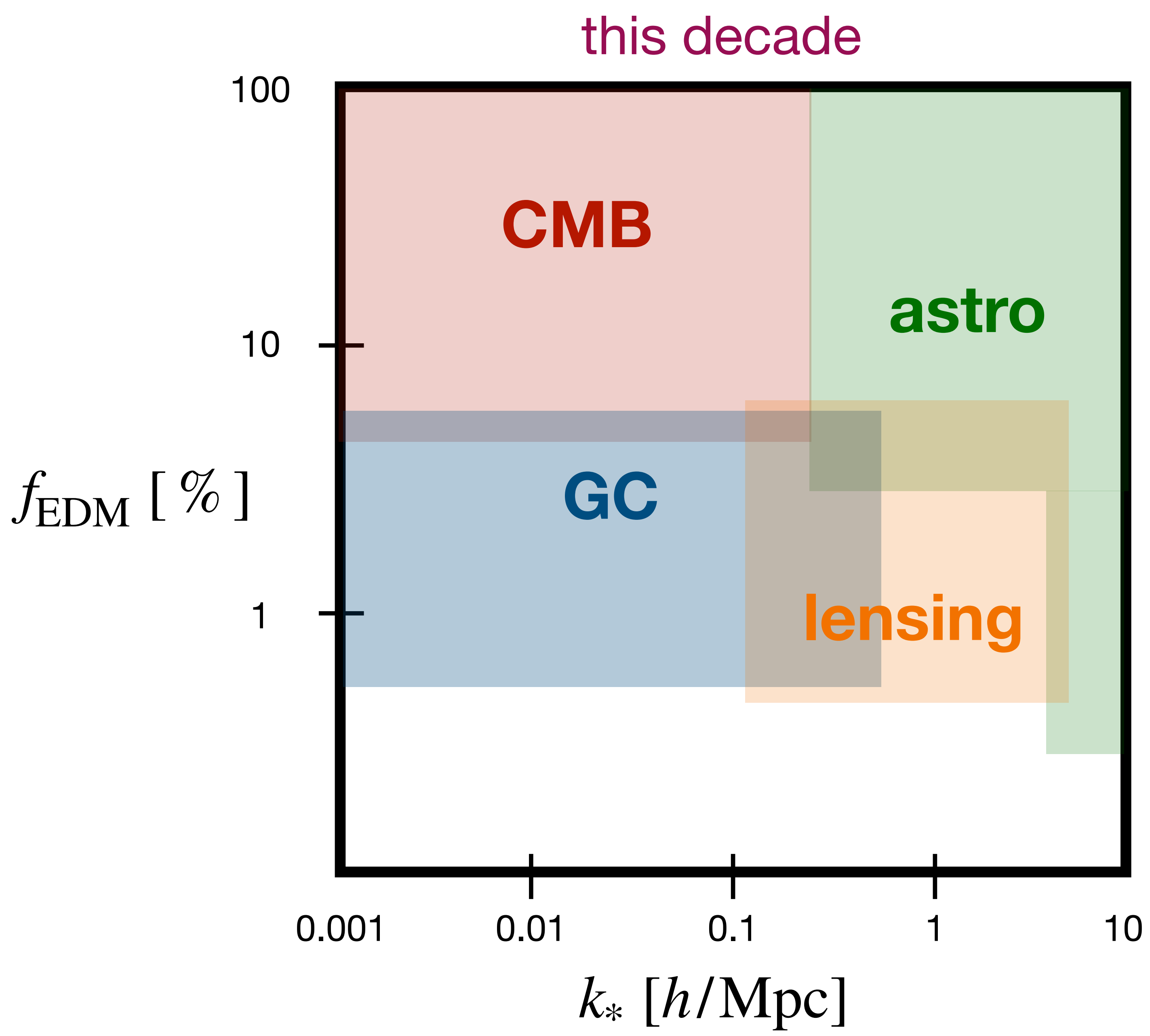
Beyond ΛCDM - exotic dark matter

A fraction of DM is exotic: $f_{\rm EDM} = \Omega_{\rm EDM}/\Omega_d$

Imprints a characteristic scale k_* on the matter power spectrum

Use gravity only!

ULA
Baryon-DM interactions
LiMRs
Long-range forces
SIDM
…



What are the odds?

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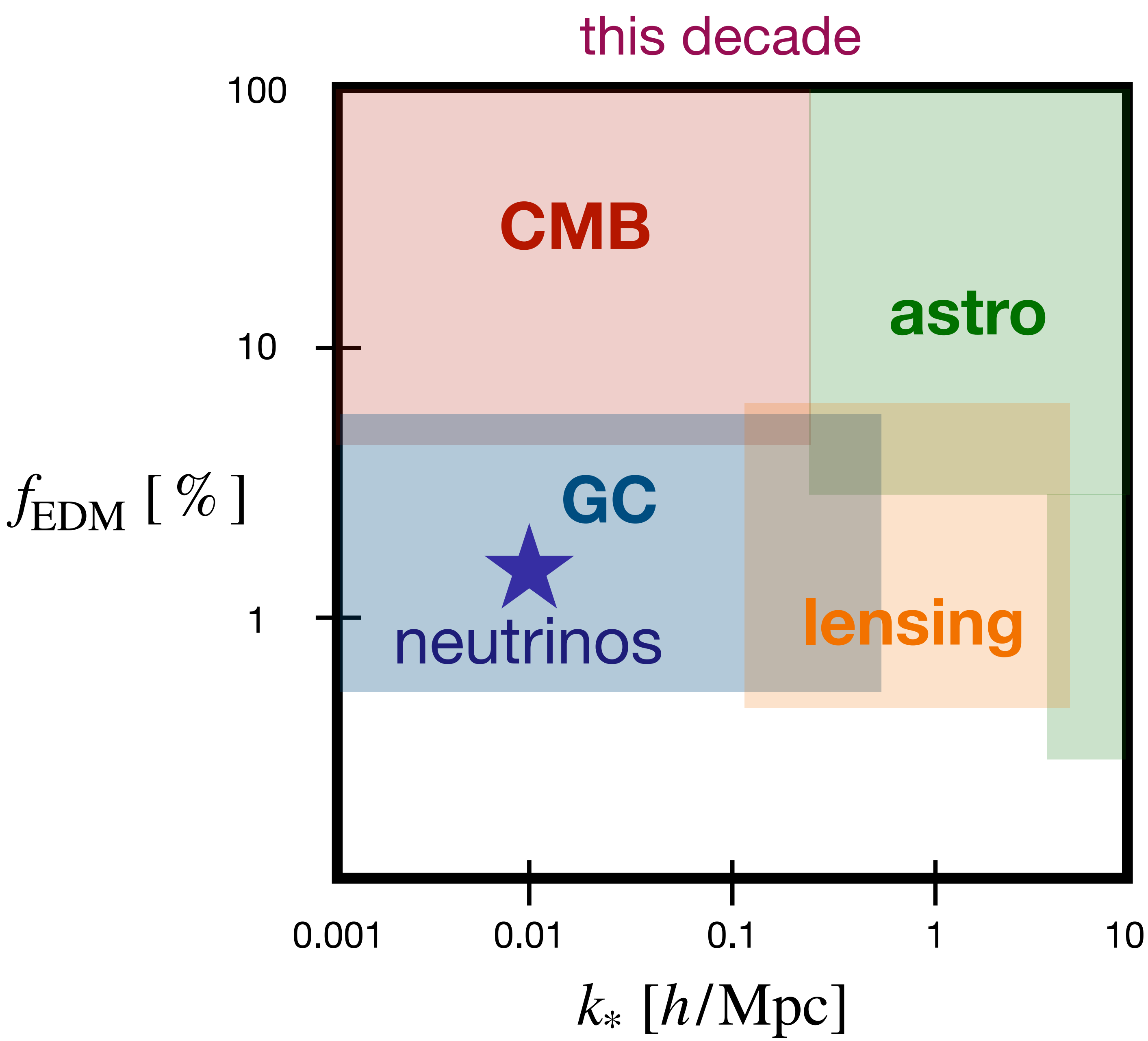


What are the odds?

Beyond ΛCDM - ultralight ALP

Fuzzy dark matter

Hu, Barkana, Gruzinov (2000)
Hui, Ostriker, Tremaine, Witten (2016)

$$\sim \frac{\hbar}{m_a v} \longrightarrow k_* \sim m_a v$$

$$\Delta x \cdot \Delta(m_a v) = \hbar/2$$

The whole of DM ULA, $m_a > 10^{-19}\,\mathrm{eV}$

Galaxy clustering probes $10^{-32} - 10^{-24}\,\mathrm{eV}$
where ULA can be just a fraction of DM

Beyond ΛCDM - ultralight ALP

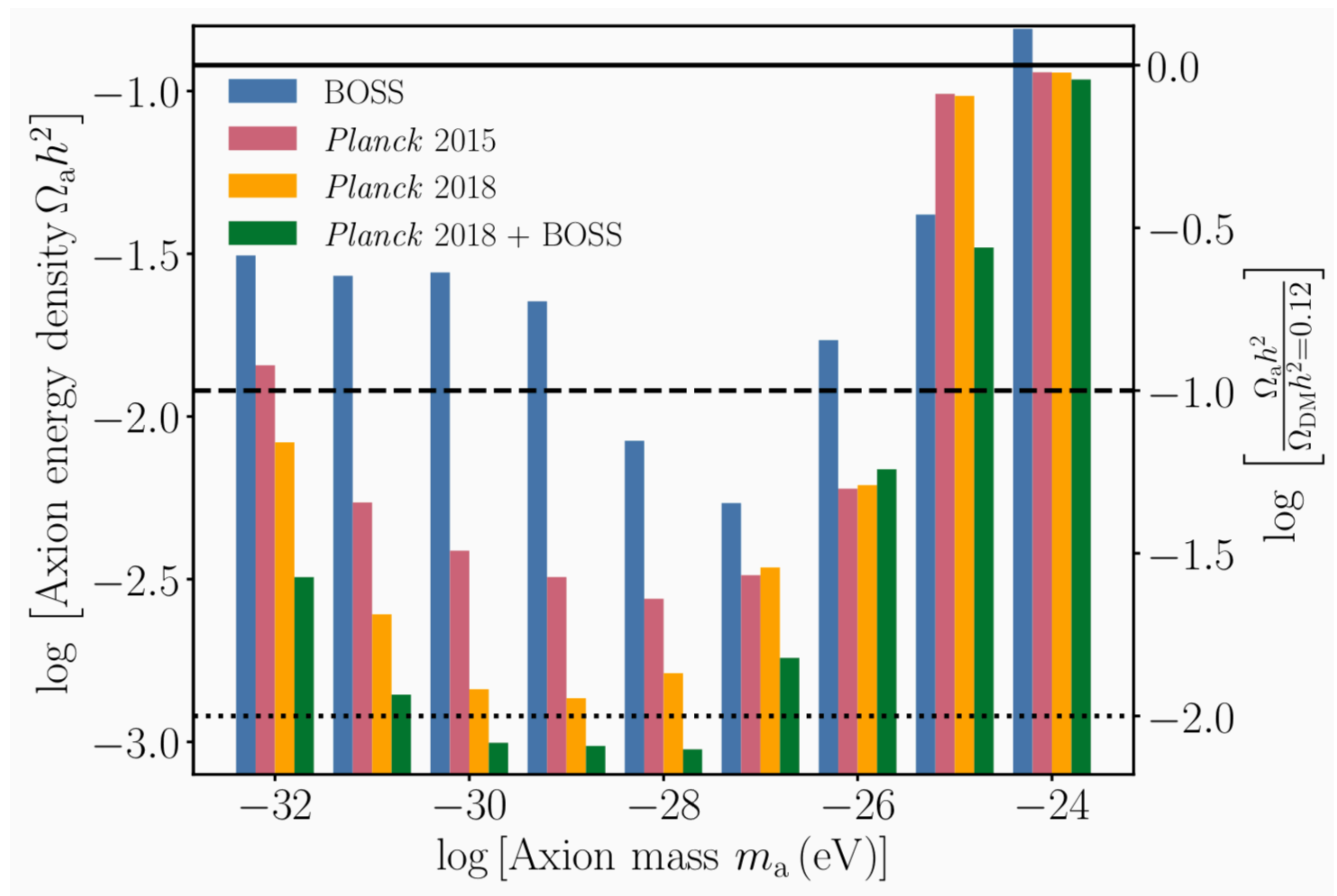
Fuzzy dark matter

Hu, Barkana, Gruzinov (2000)
Hui, Ostriker, Tremaine, Witten (2016)

String-theory “inspired” target:

$$\frac{\Omega_a}{\Omega_d} \sim 0.1 \left(\frac{F}{M_{\rm pl}}\right)^2 \left(\frac{m_a}{10^{-28}\,{\rm eV}}\right)^{1/2}$$

Laguë, Bond, Hložek, Rogers, Marsh, Grin (2021)
Rogers et. al. (2023)



LSS constraints will improve ~ 5x

Conclusions

A big amount of new data in this decade

Novel approaches to theory and data analyses

Many factors-of-10 improvements

It may be that there is nothing beyond ΛCDM…

… but surprises are possible and you should be excited about it!