Observational prospects in cosmology in this decade

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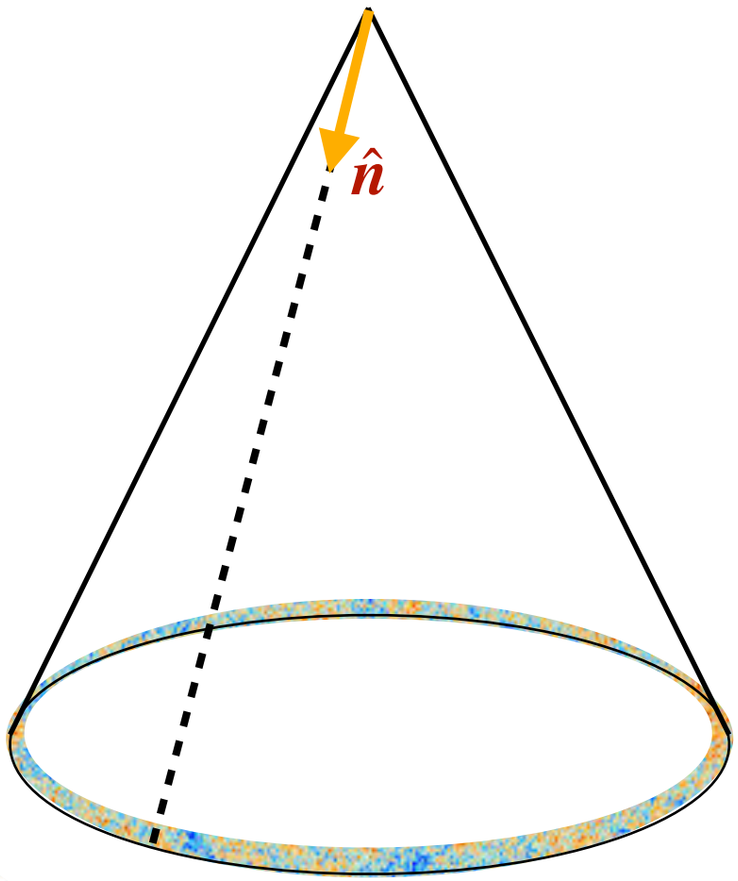
Strings 2024

Relevance of cosmology for HEP



Dark matter

Dark energy

Inflation

Particle physics, string theory…

Relics from high energies + observations of large volumes

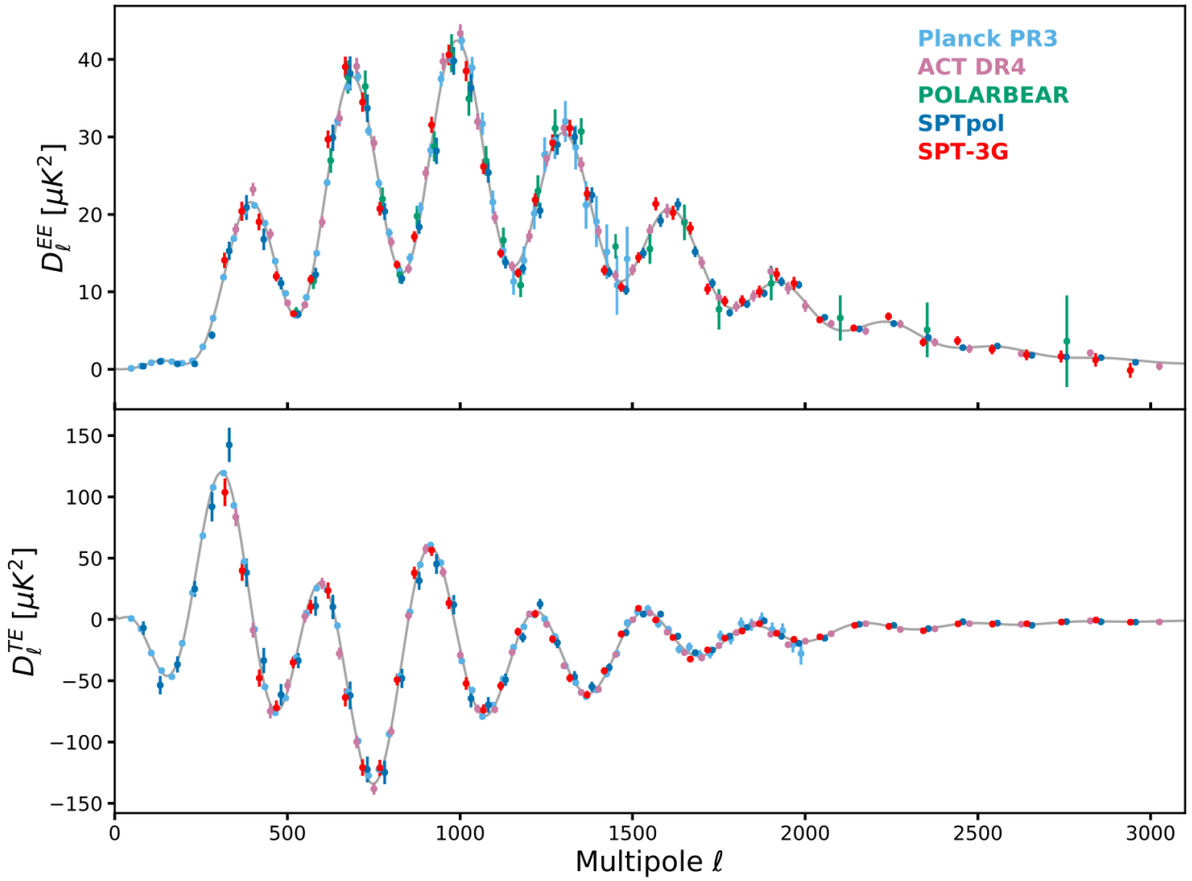
Since we are probing very high energies surprises are possible

CMB experiments

The main focus on polarization ACTPol, SPTpol

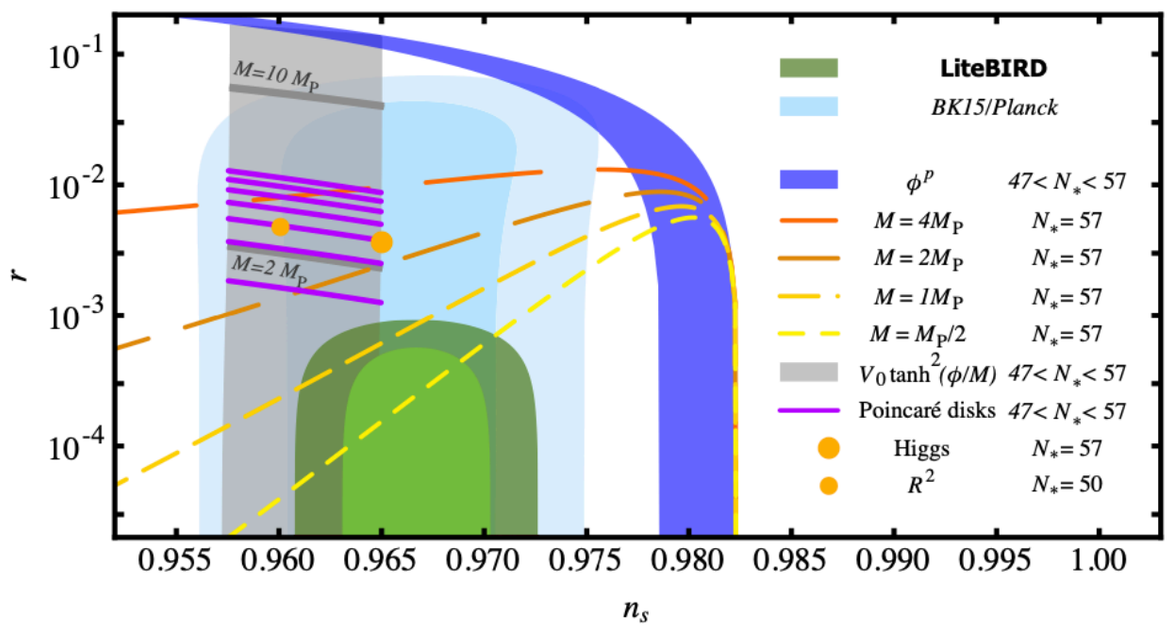
The big goal remains search for primordial B modes BICEP

Simons Observatory, LiteBird, S4…



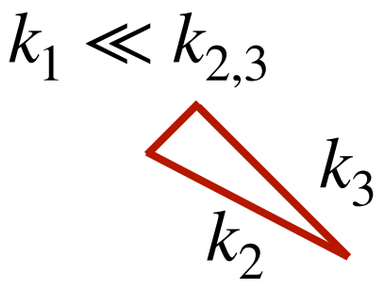
Direct measure of H during inflation

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

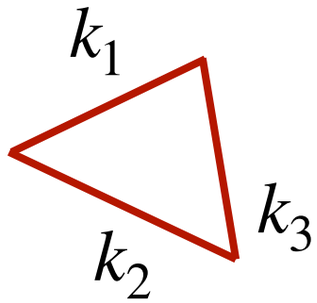


Primordial non-Gaussianities

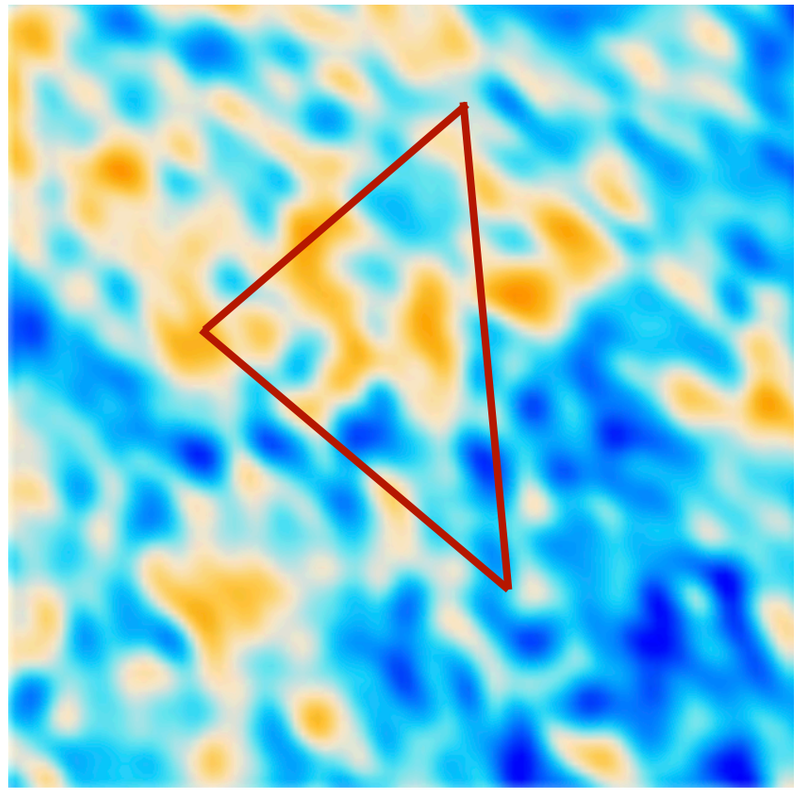
$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = (2\pi)^3 \delta^D(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3)\, B(k_1, k_2, k_3)$$



$f_{\rm NL}^{\rm loc}$



$f_{\rm NL}^{\rm eq}$



In simplest single-field inflation models $f_{\rm NL}^{\rm loc} = 0$ and $f_{\rm NL}^{\rm eq} \sim \epsilon$

multi-field

$c_s < 1$

Planck constraints: $\sigma(f_{\rm NL}^{\rm loc}) = 5$ $\sigma(f_{\rm NL}^{\rm eq}) \sim 50$

Some open questions

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

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…)

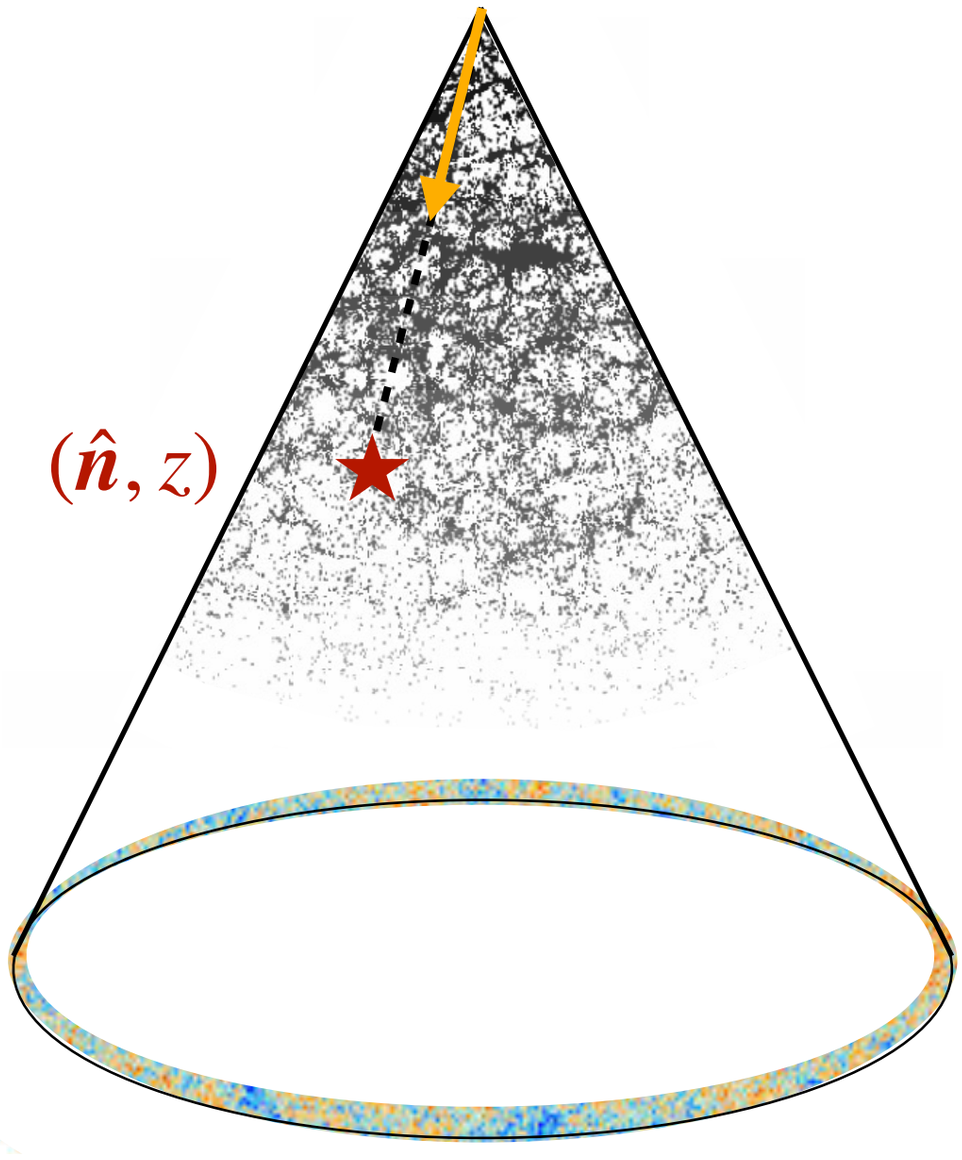
What if $\Omega_K \neq 0$? (current CMB-alone bound $|\Omega_K| < 0.01$)

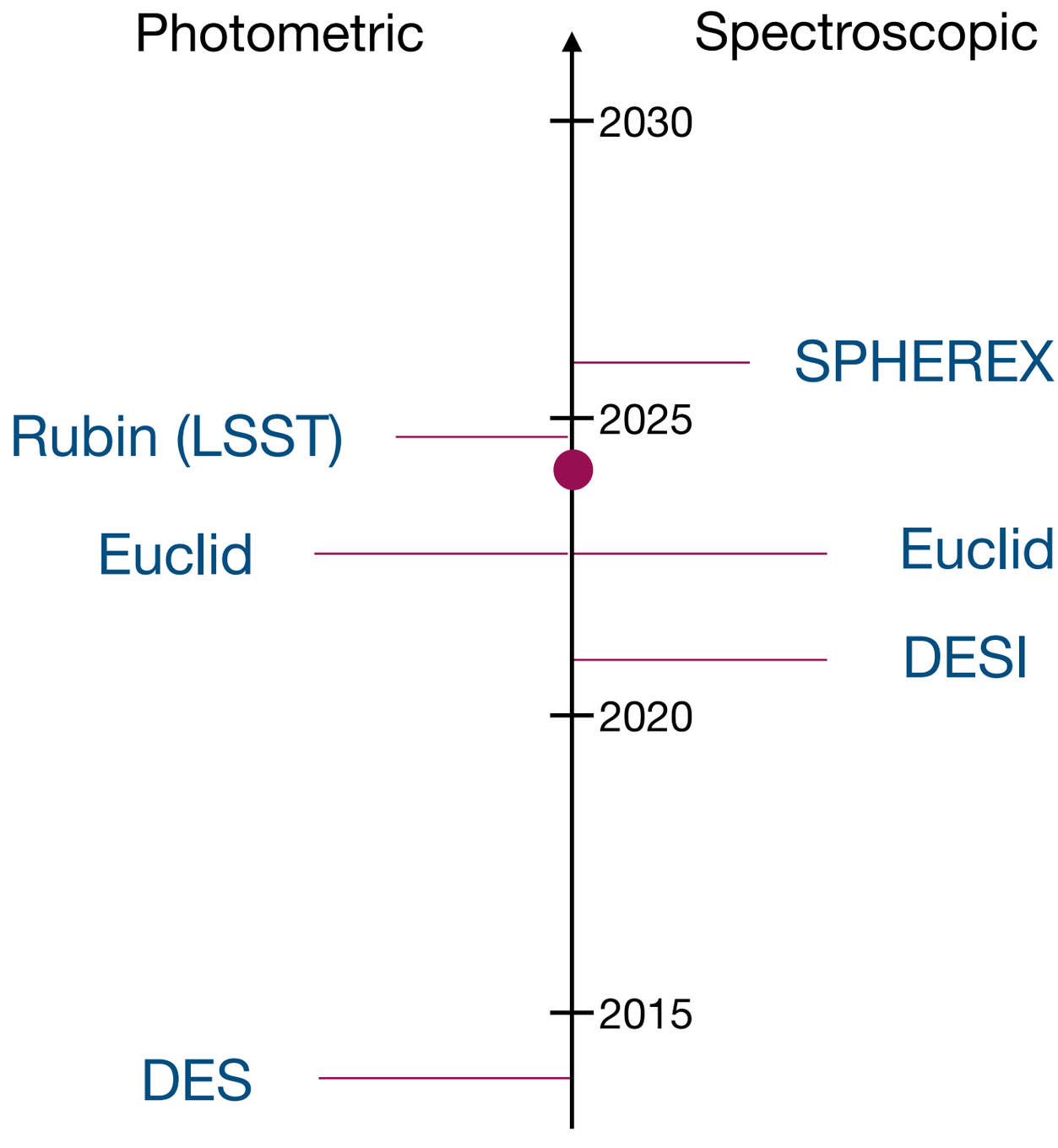
Are there some primordial features on large or small scales?

CMB alone insufficient to answer these questions

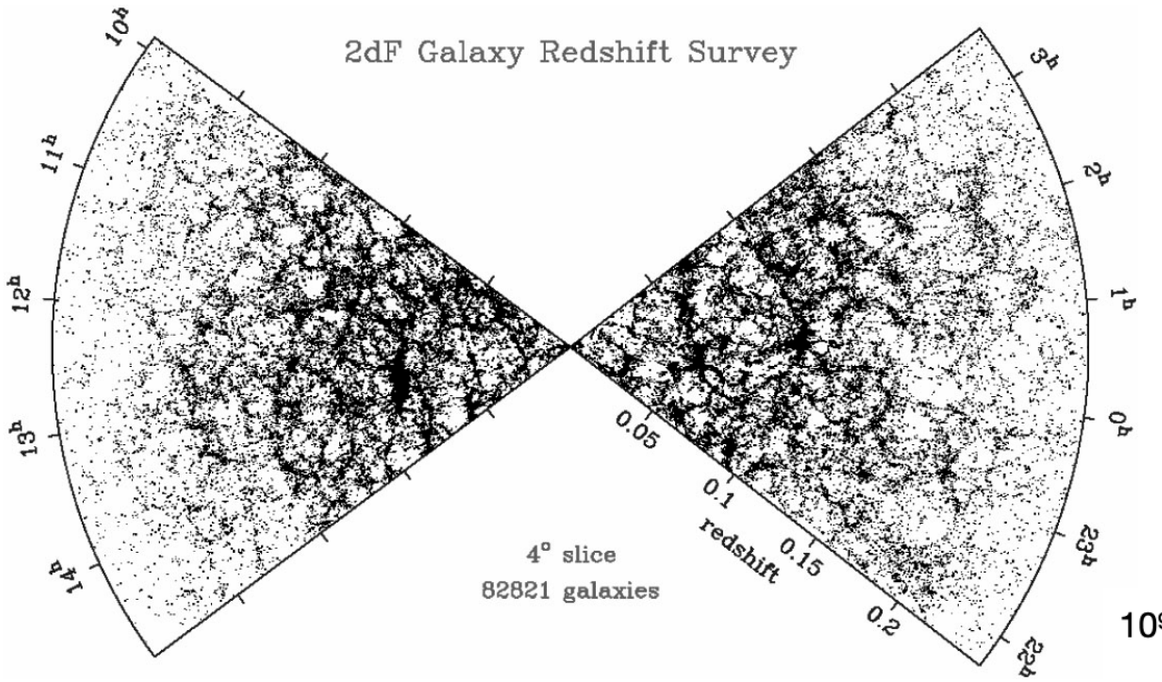
Observing the entire light-cone

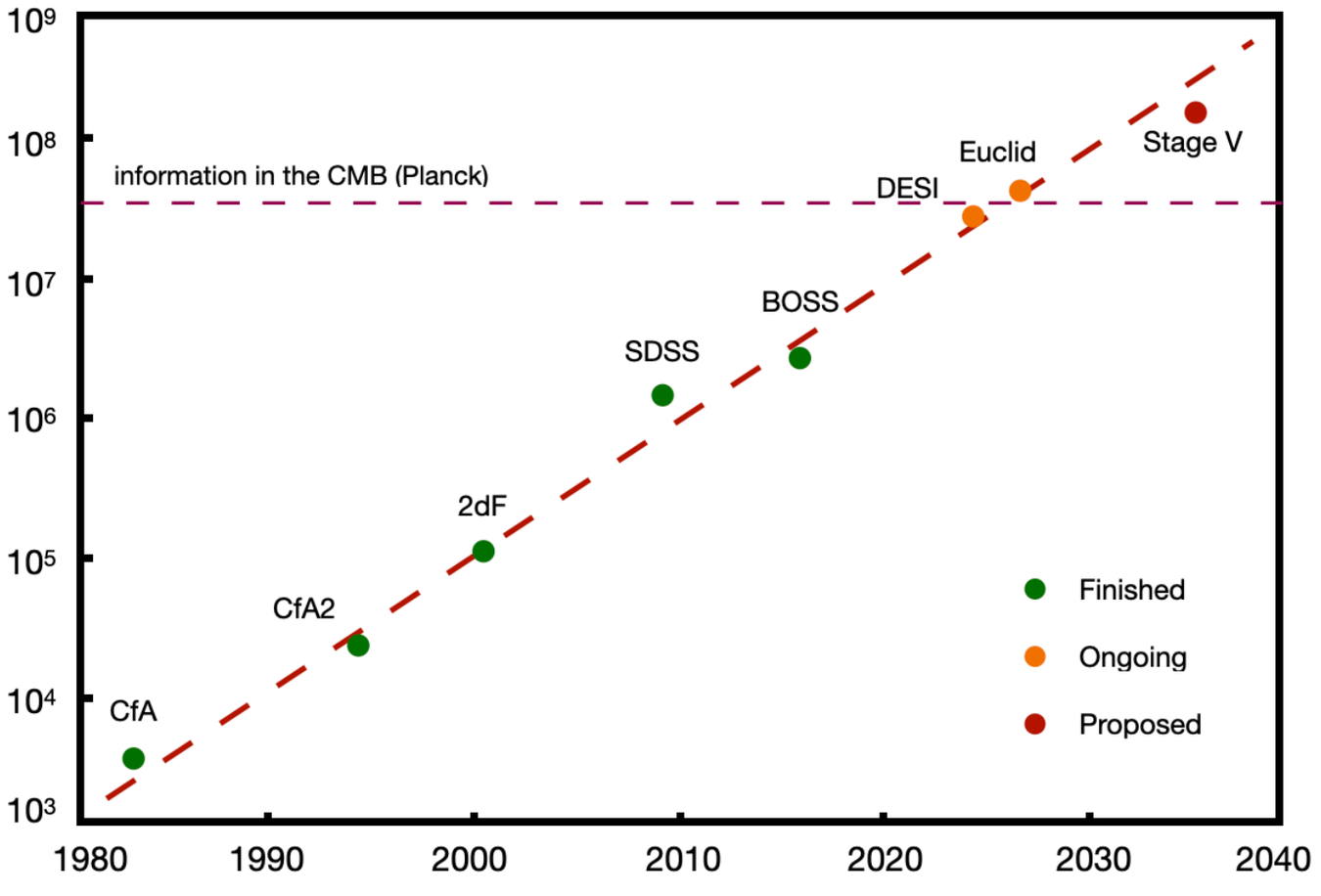
Image billions and take spectra of ~100 million of objects up to z<5





Spectroscopic galaxy surveys





The 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

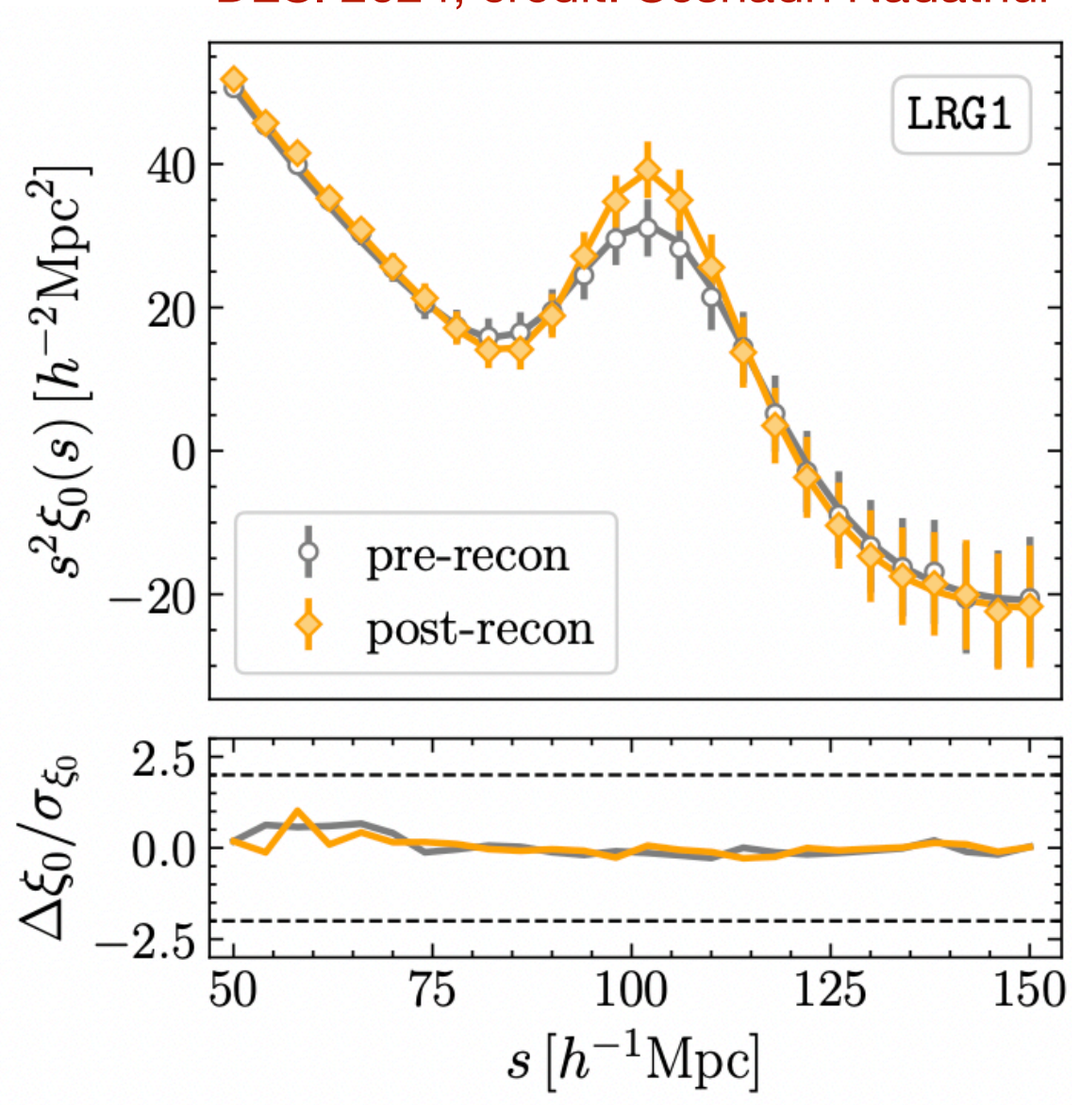
Easy to measure

Easy to model

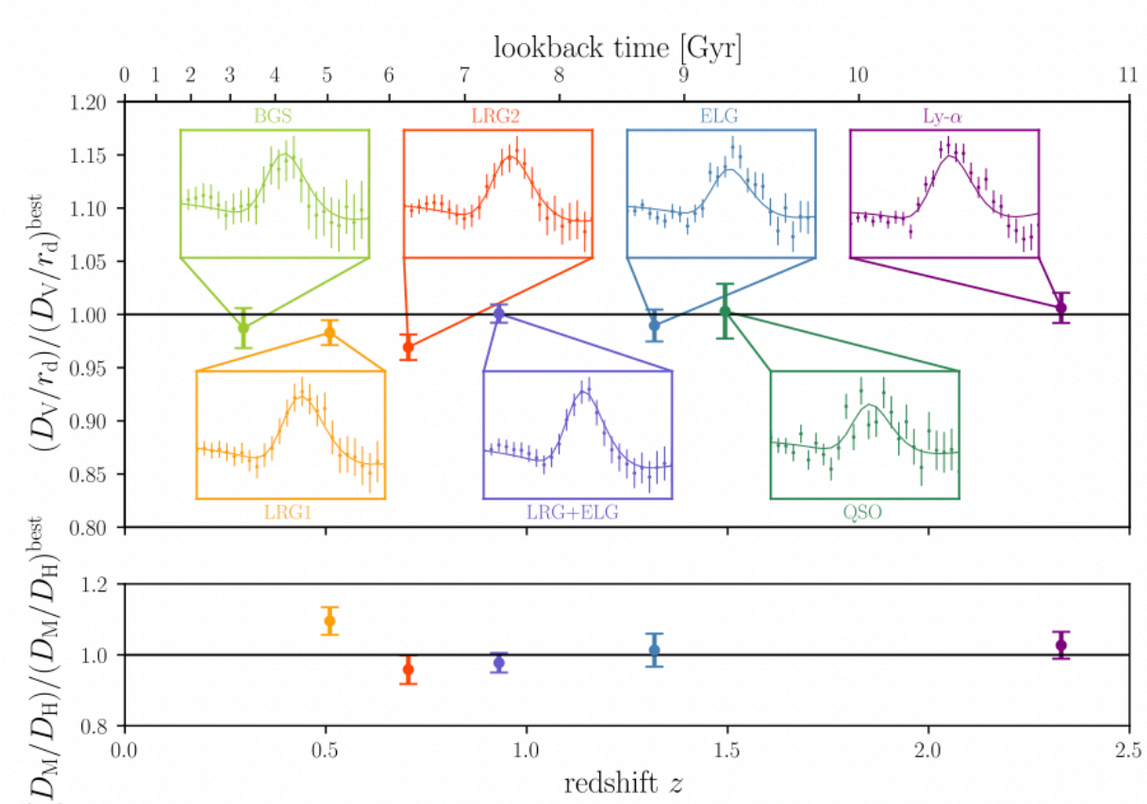
$$\text{angle} = \frac{r_d}{d_A} = \frac{H_0 r_d}{F(\Omega_m, z)}$$

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

DESI 2024, credit: Seshadri Nadathur



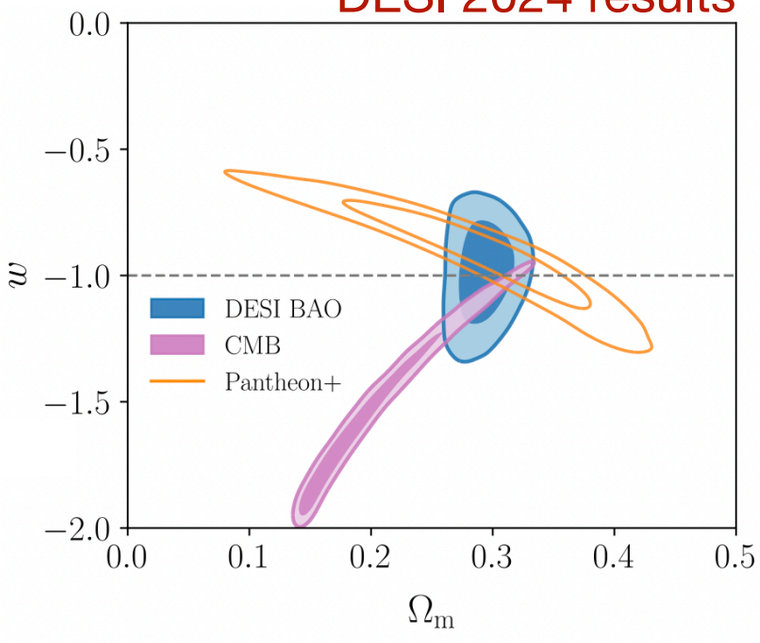
The BAO peak



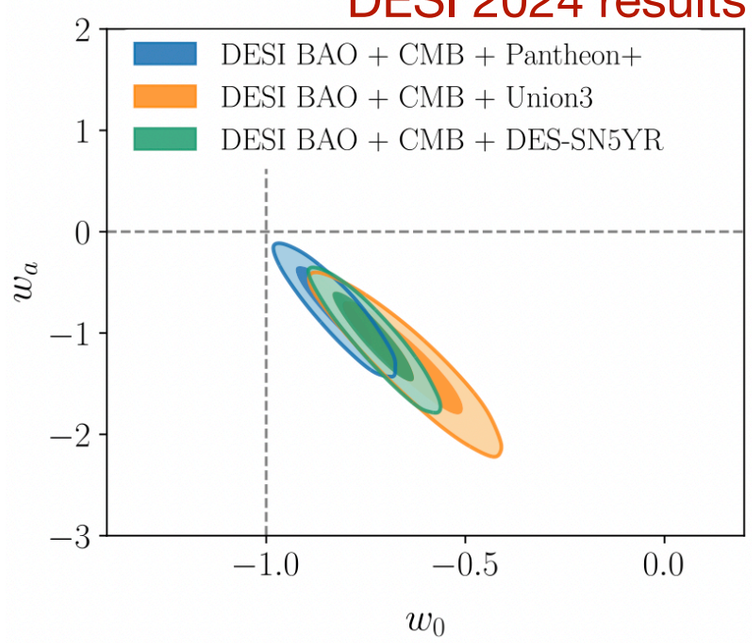
credit: Arnaud de Mattia

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

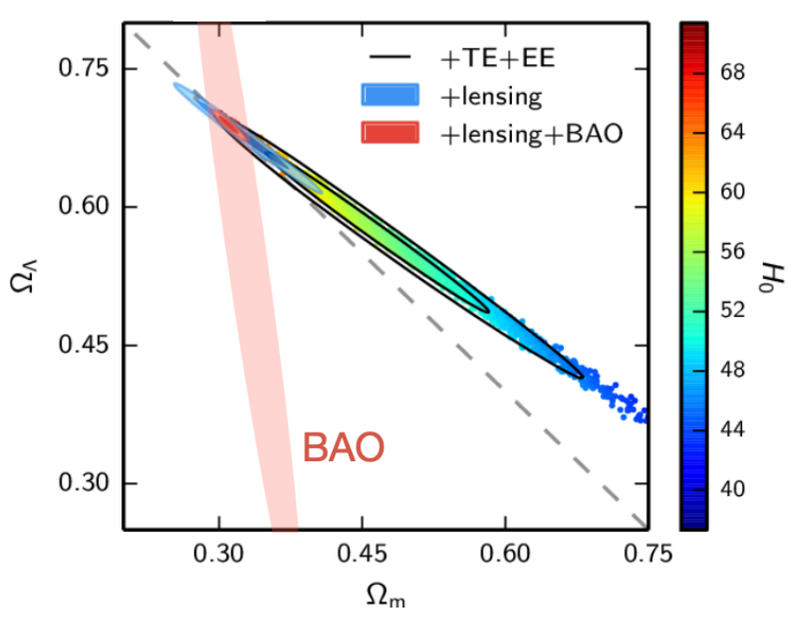
DESI 2024 results



DESI 2024 results

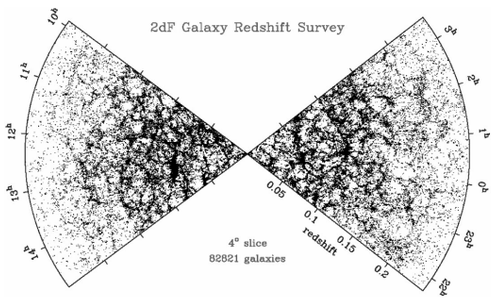


$|\Omega_K| < 0.002$

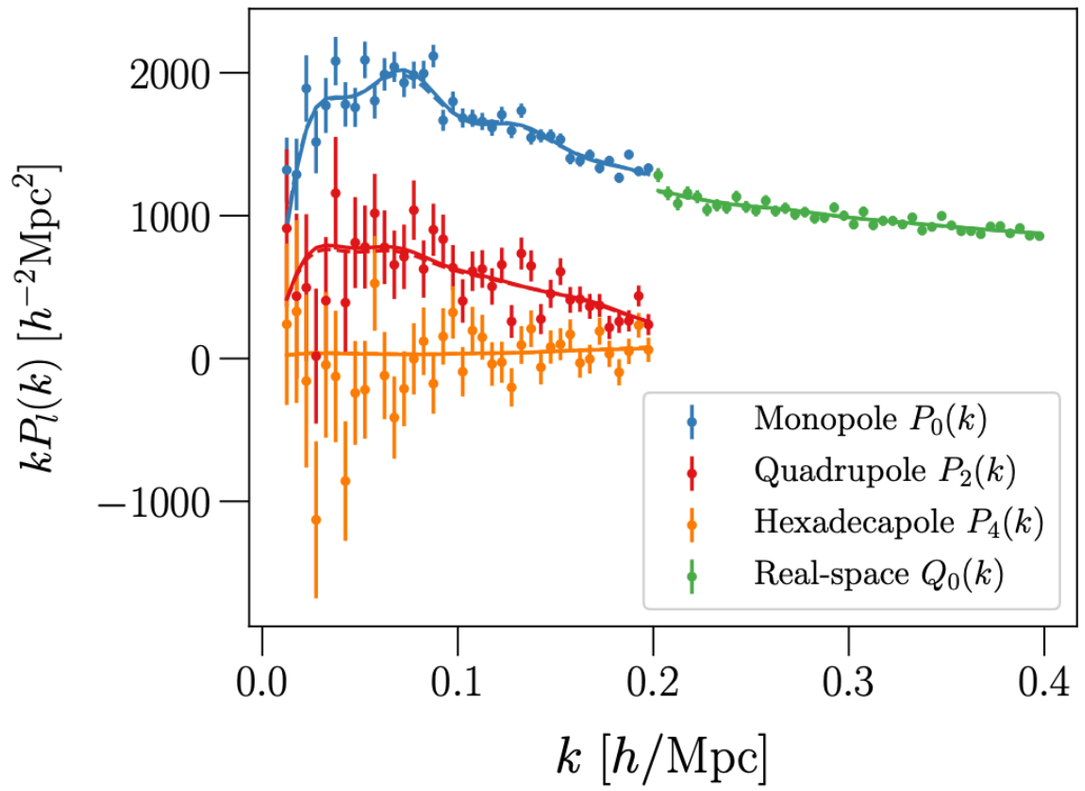


Beyond the BAO peak

galaxy map



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

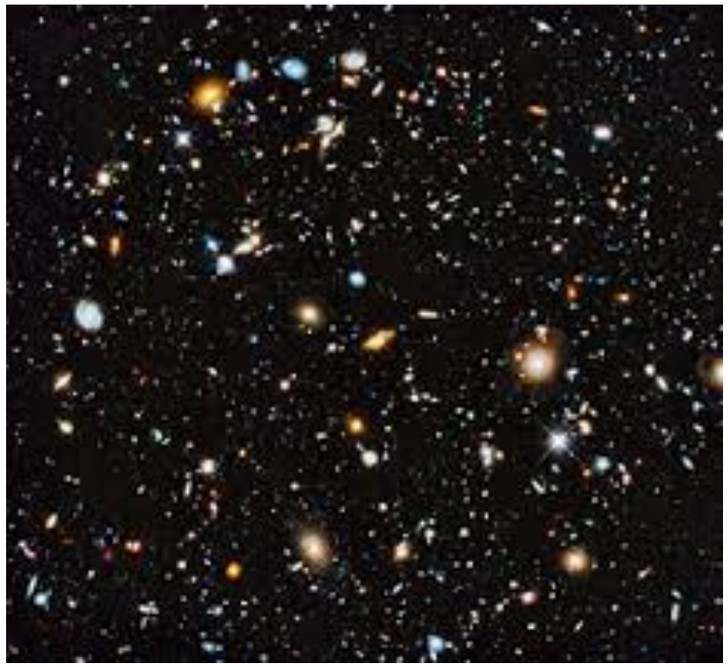


Full-shape analysis

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, $\partial/k_{\rm NL}$

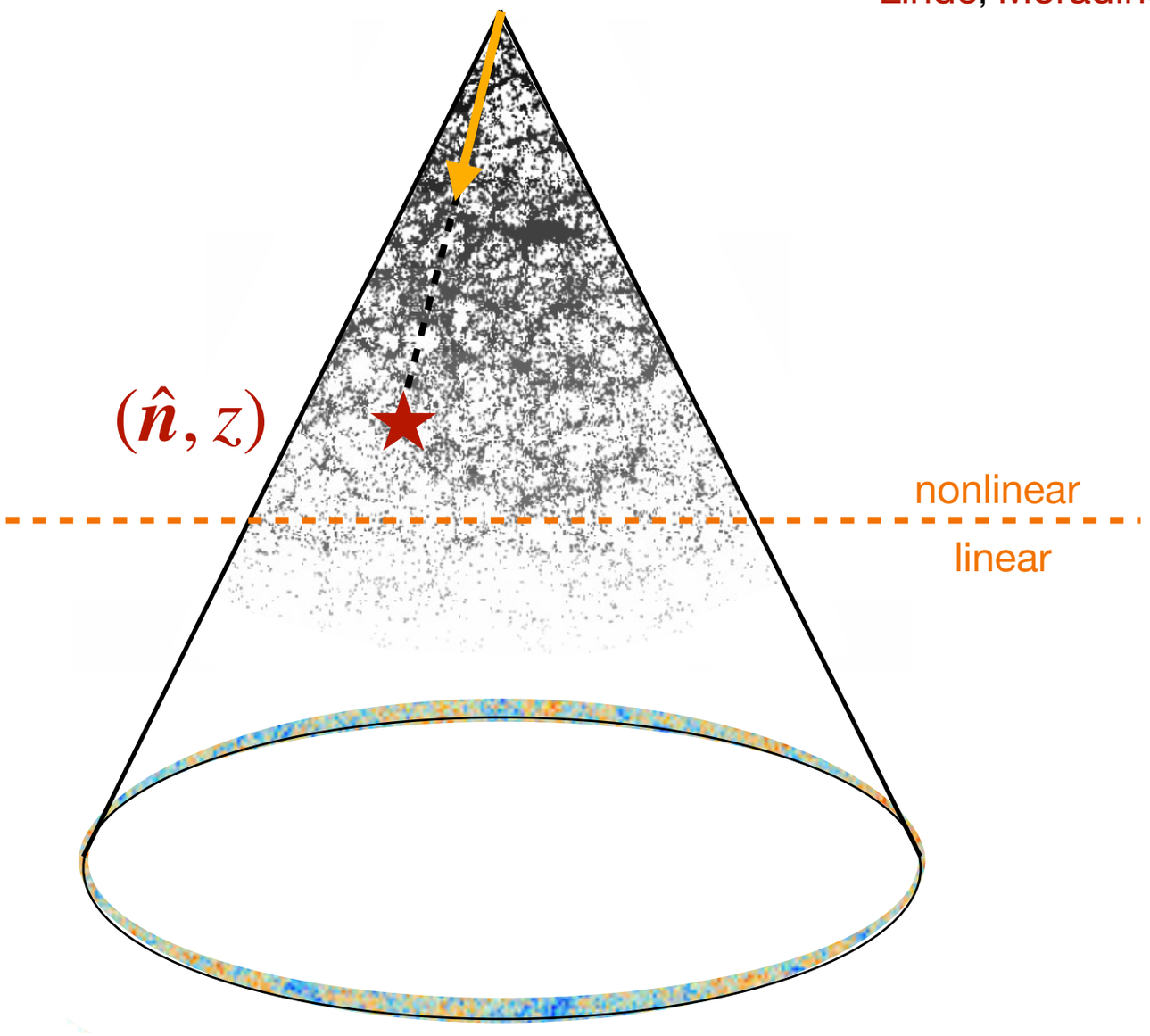
All “UV” dependence is in a handful of free parameters

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

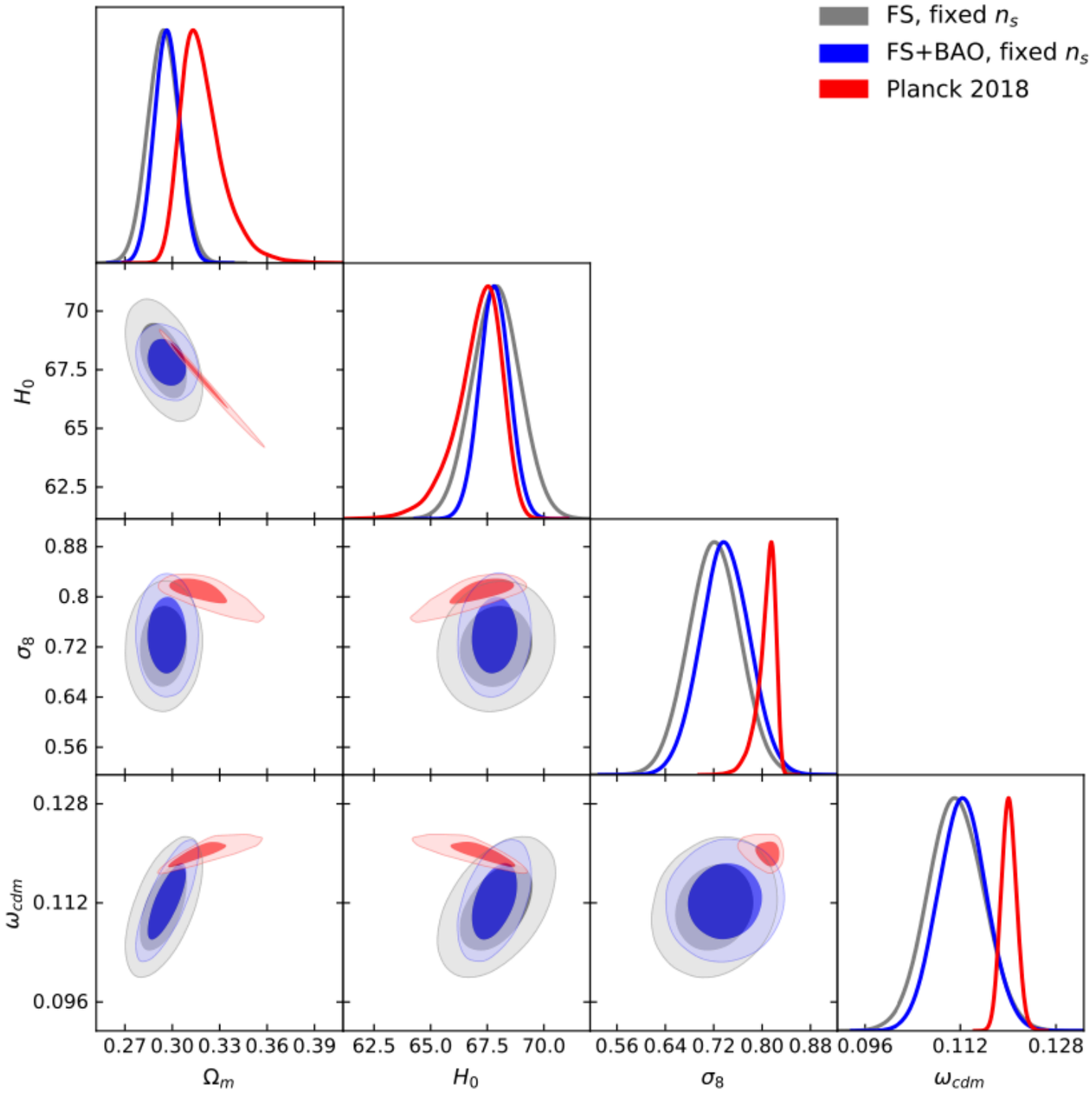
Evolution of the vacuum state from inflation to redshift zero

Application 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

Primordial features and PNG

Various types of primordial “features” will be constrain up to 2-10x better

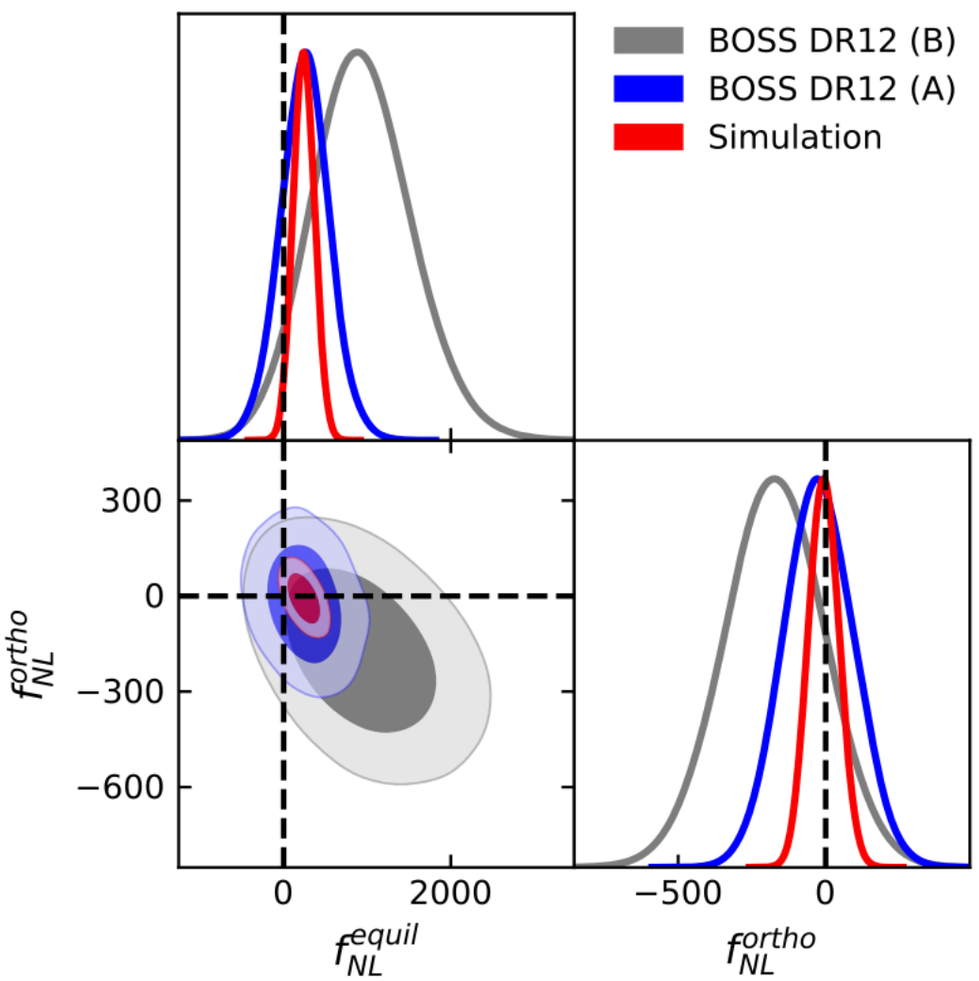
SPHEREX and other surveys can reach the target of $\sigma(f_{\rm NL}^{\rm loc.}) < 1$

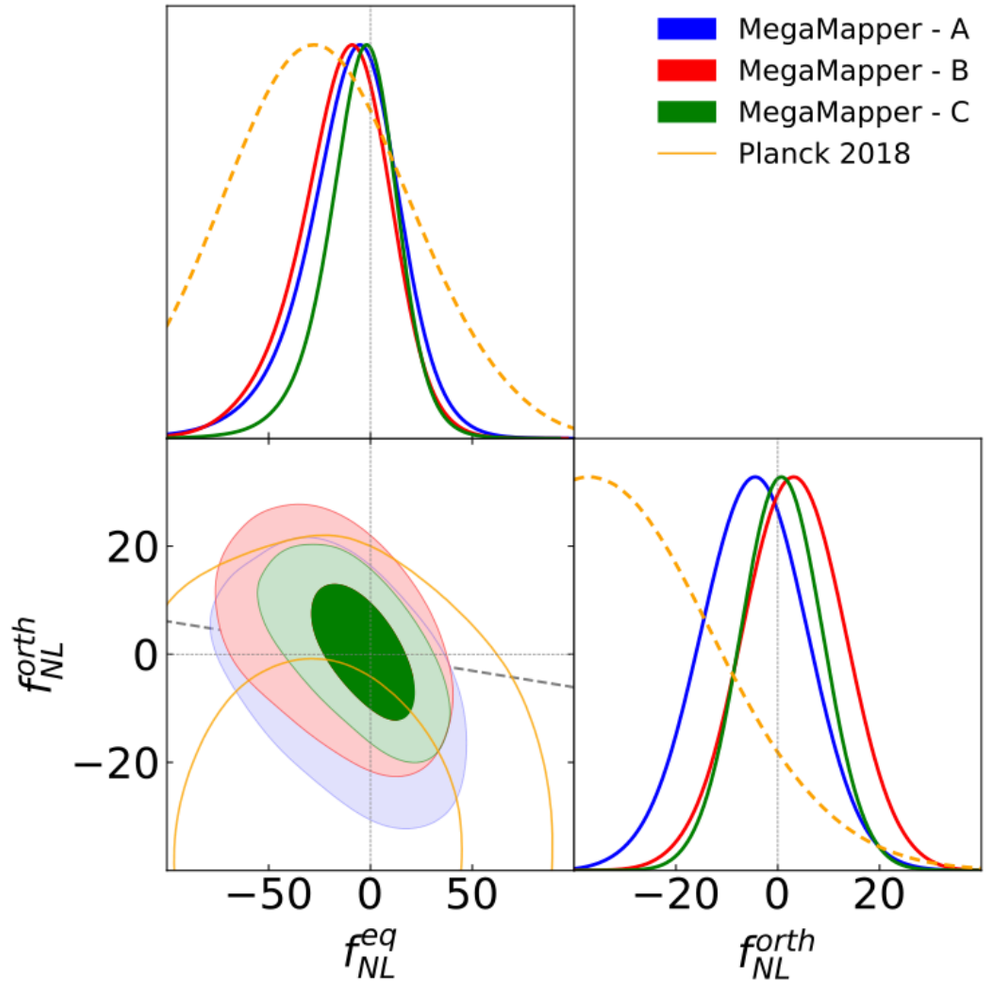
Other types of PNG better than in the CMB, $\sigma(f_{\rm NL}^{\rm eq.}) \sim 1$ remains hard

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

D’Amico, Lewandowski, Senatore, Zhang (2022)

Stage V spectroscopic survey





Dark energy and spatial curvature

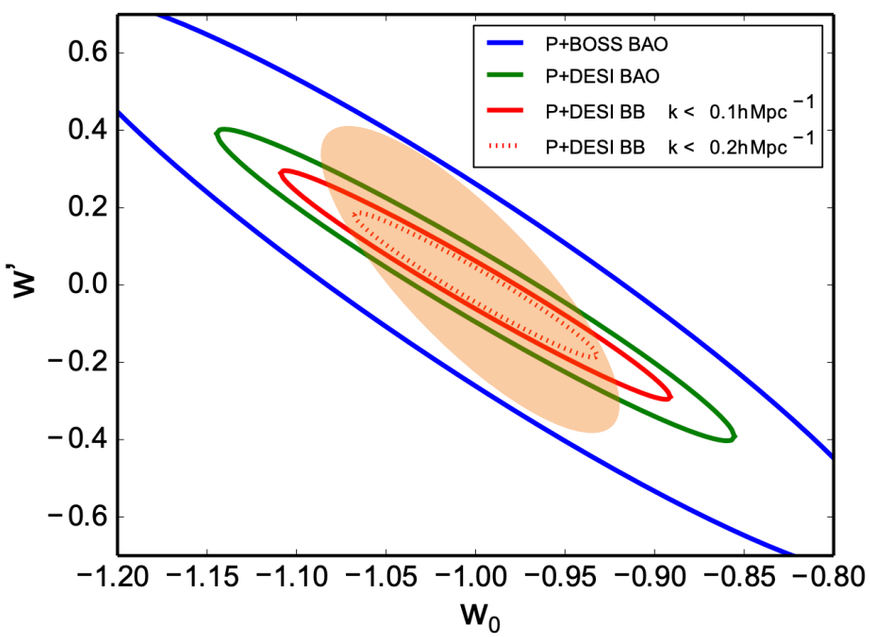
$$\rho \sim a^{-3(1+w)}$$

$$w = w_0 + w_a(1-a)$$

Imagine a scalar field with the potential V

$$3(1+w) = \left(\frac{V'}{V}\right)^2$$

Full DESI-only forecast,
credit: Patrick McDonald



Rough current errors
BAO+CMB+SNIa

Do we have any interesting target for V'/V ?

Galaxy surveys will constrain $V'/V \lesssim 0.05$

(remember inflation where we can reach $V'/V \lesssim 0.01$)

The spatial curvature will be constrained better: $\sigma(\Omega_K) < 10^{-4} - 10^{-3}$

Any measurement of $|\Omega_K| > 10^{-4}$ will have large implications for inflation

Ultralight axions

Cosmology can constrain other
light scalar fields

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

Rogers et. al. (2023)

Fuzzy dark matter

Hui, Ostriker, Tremaine, Witten (2016)

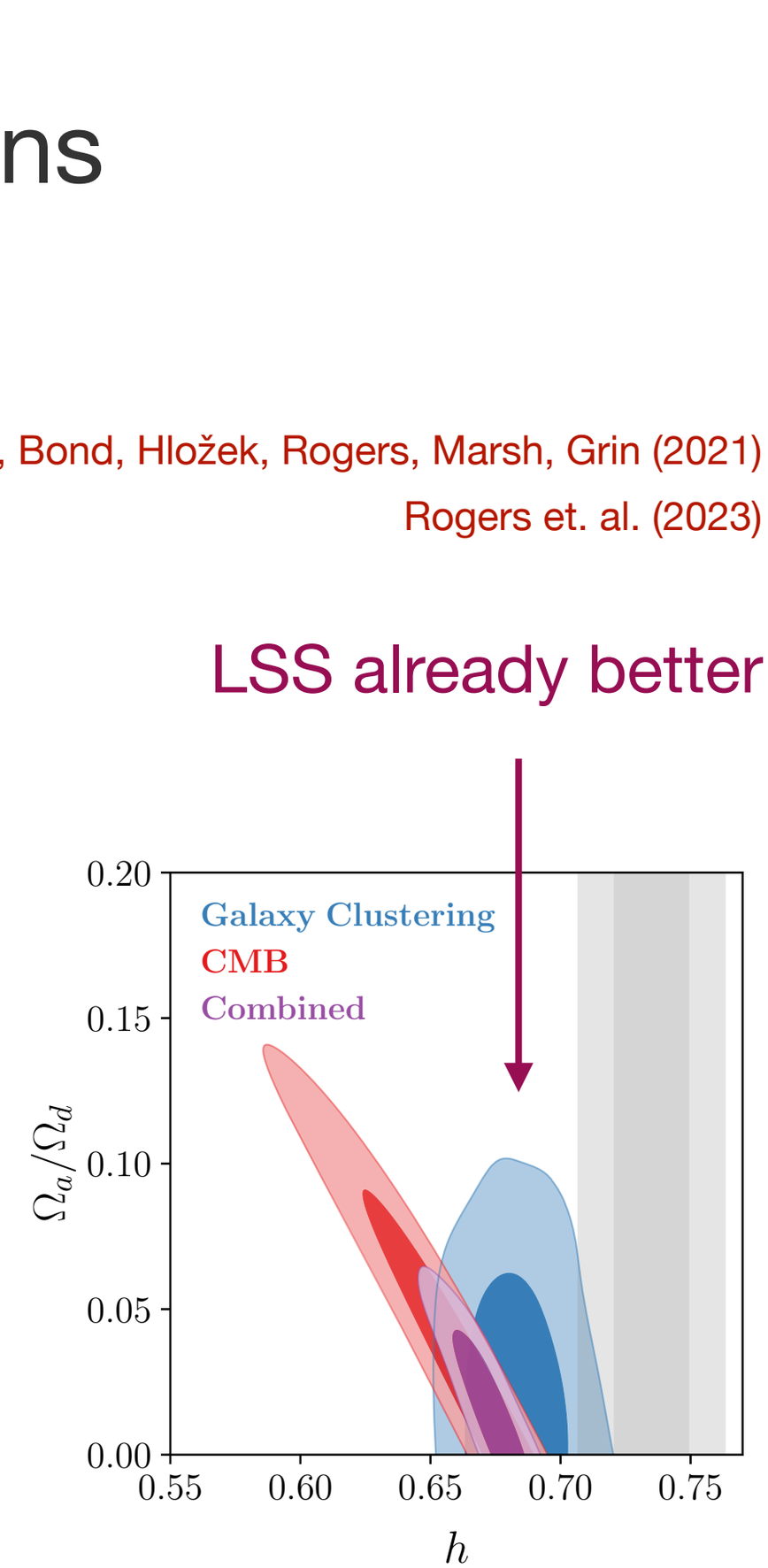
$$\Omega_a \sim 0.1 \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

For the whole of DM to be ULA, $m_a > 10^{-19}\,\mathrm{eV}$

In the mass range $10^{-32} - 10^{-25}\,\mathrm{eV}$
ULA can be a fraction of DM

These constraints will further improve by ~10x

LSS already better



Conclusions

A big amount of new data in this decade

Novel approaches to theory and data analyses

Many factors-of-10 improvements

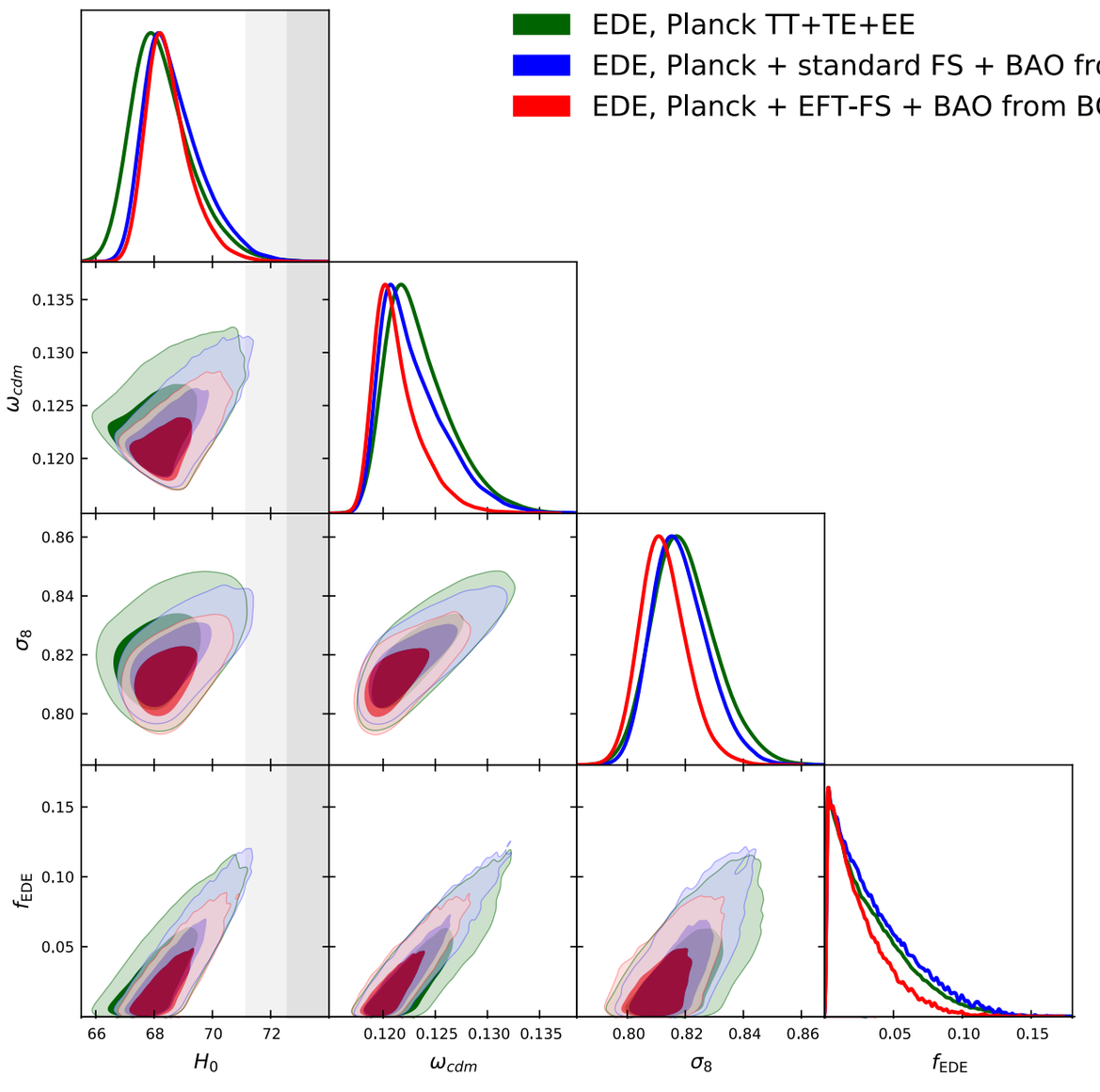
It may be that there is nothing beyond ΛCDM…

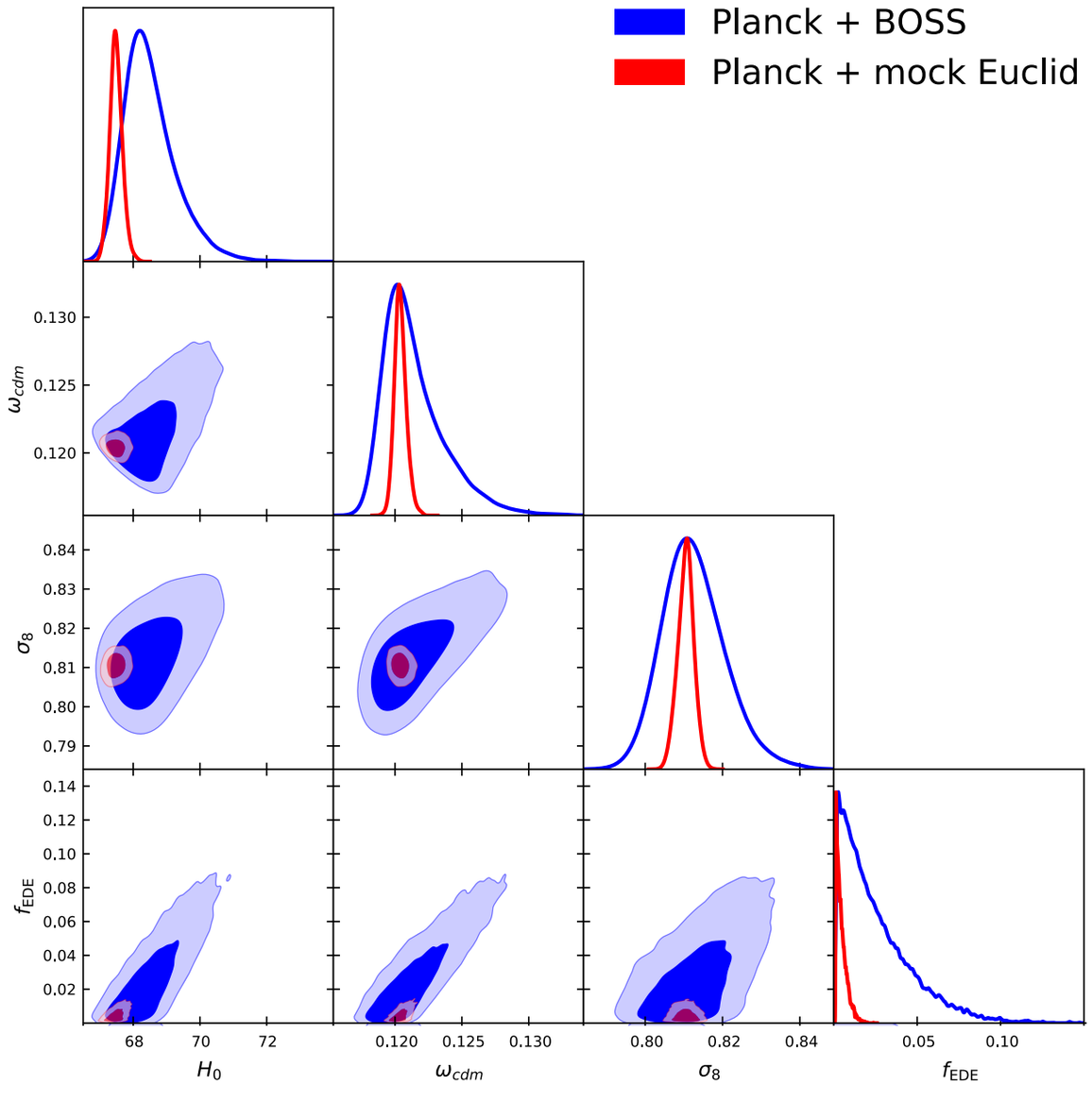
… but surprises are possible and now is the time to pay attention

Beyond ΛCDM - Hubble tension

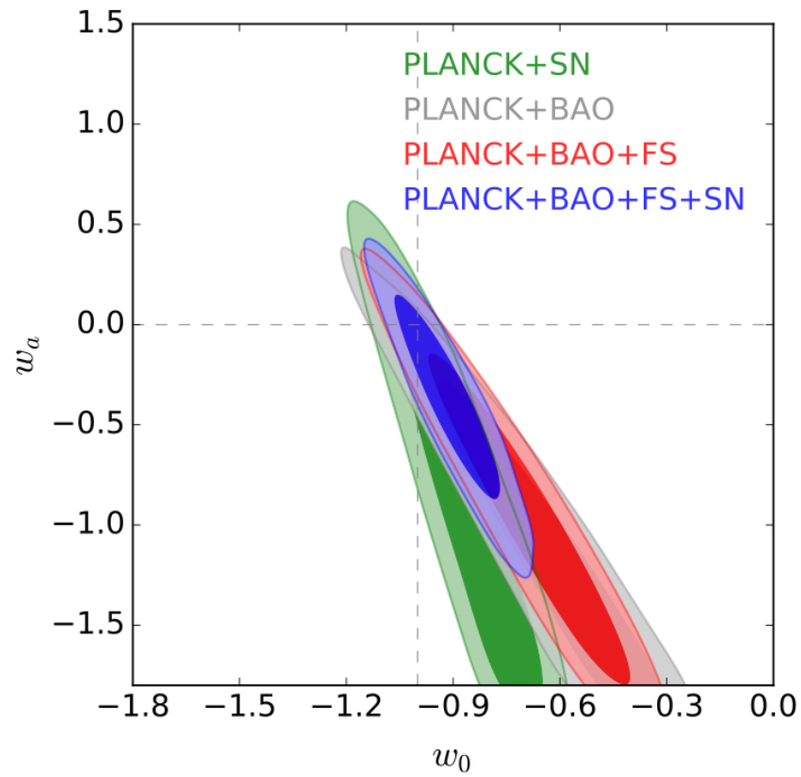
Ivanov et al. (2020)

Early dark energy

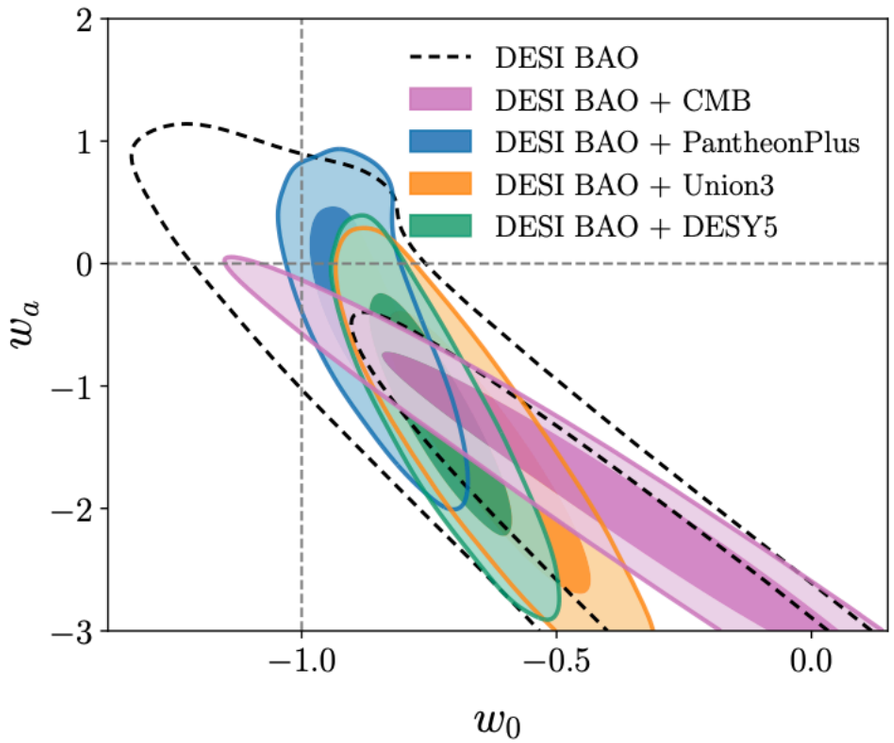


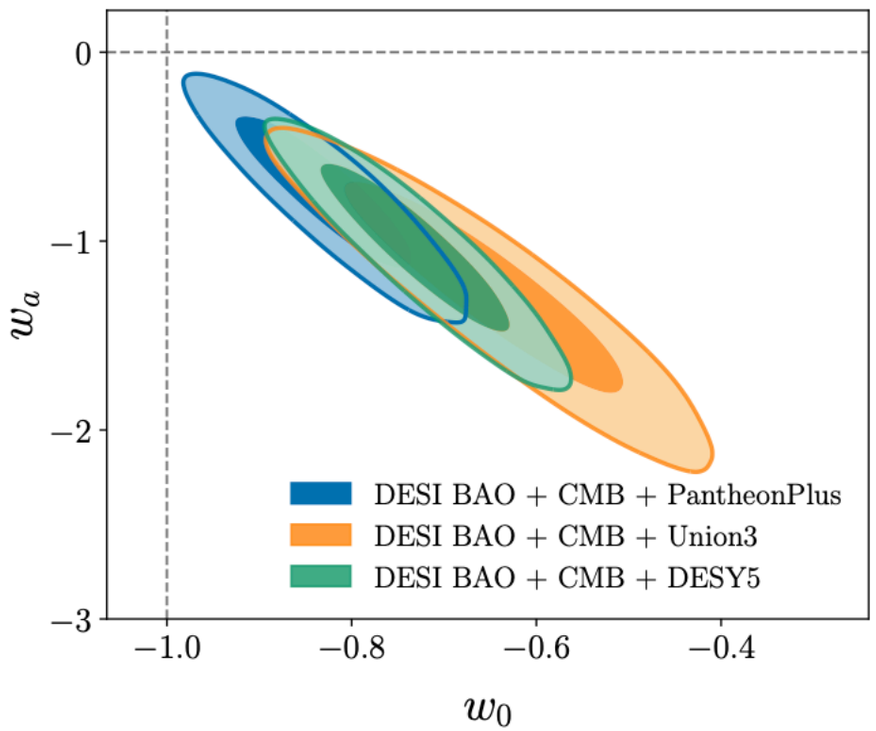


Beyond ΛCDM - dark energy



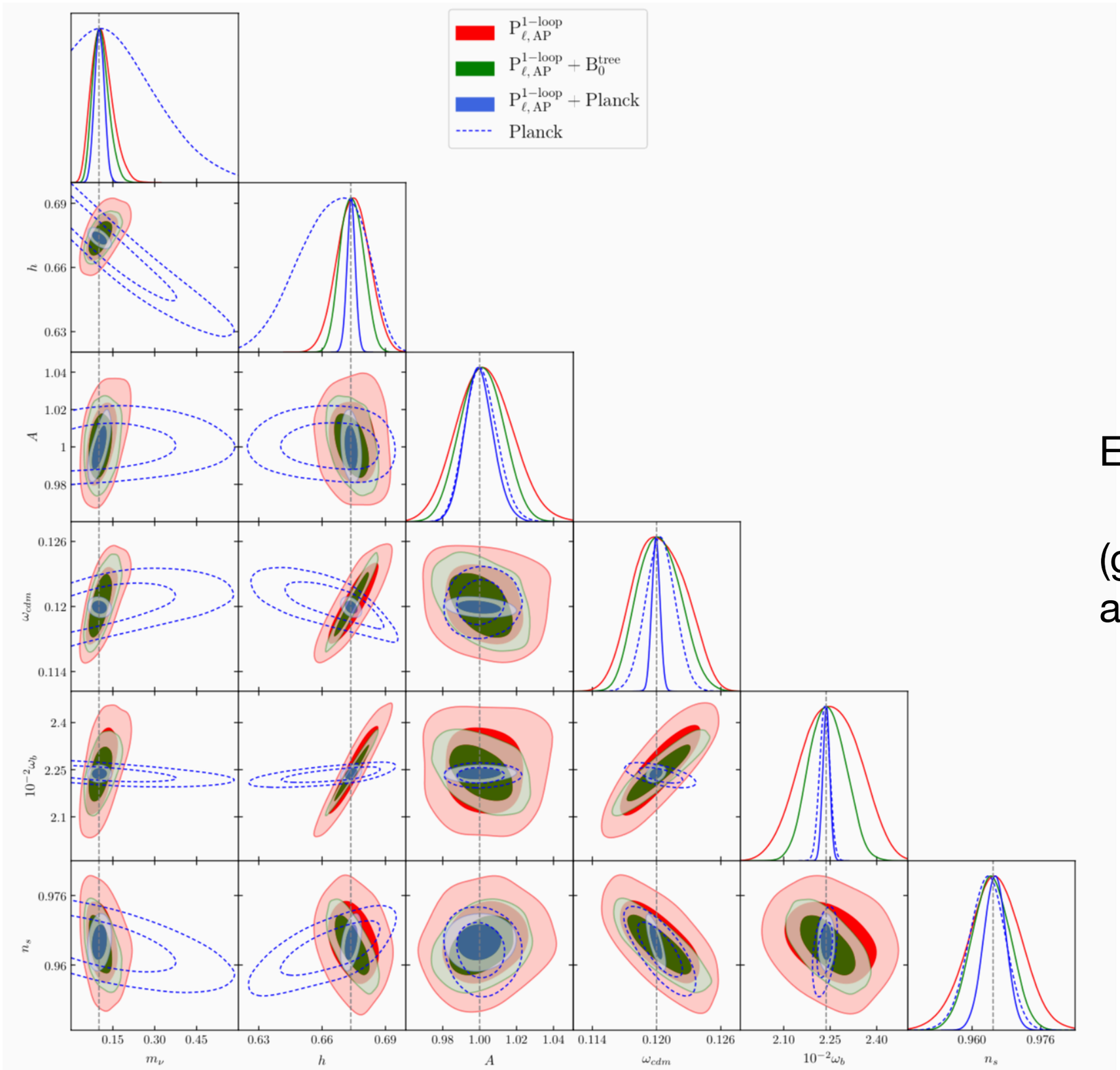
BOSS 2016 results





DESI 2024 results

Beyond ΛCDM - neutrinos



Chudaykin, Ivanov (2019)

Euclid/DESI-like survey

(galaxies only, no Lya and quasars)