EFT of large-scale structure

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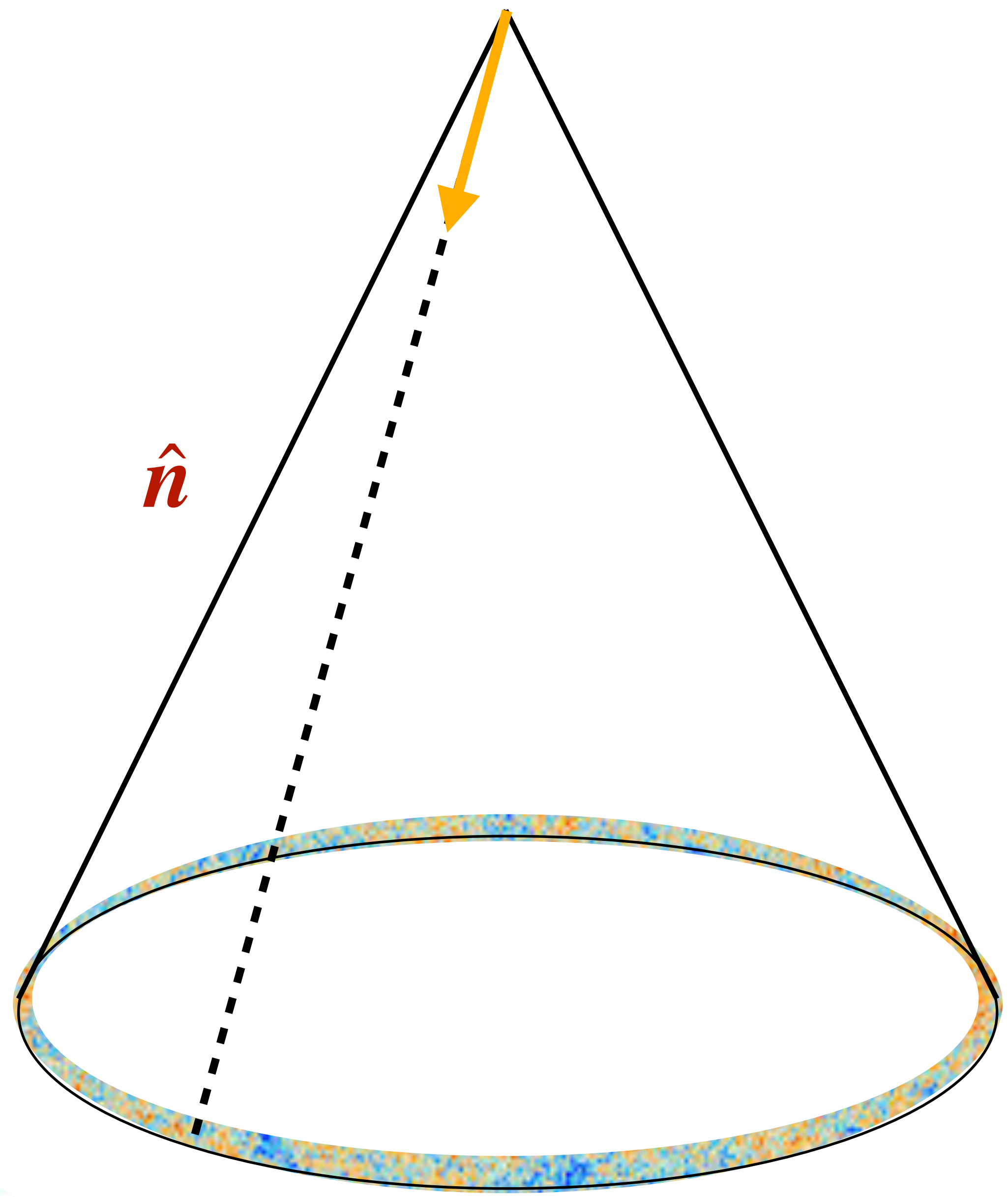
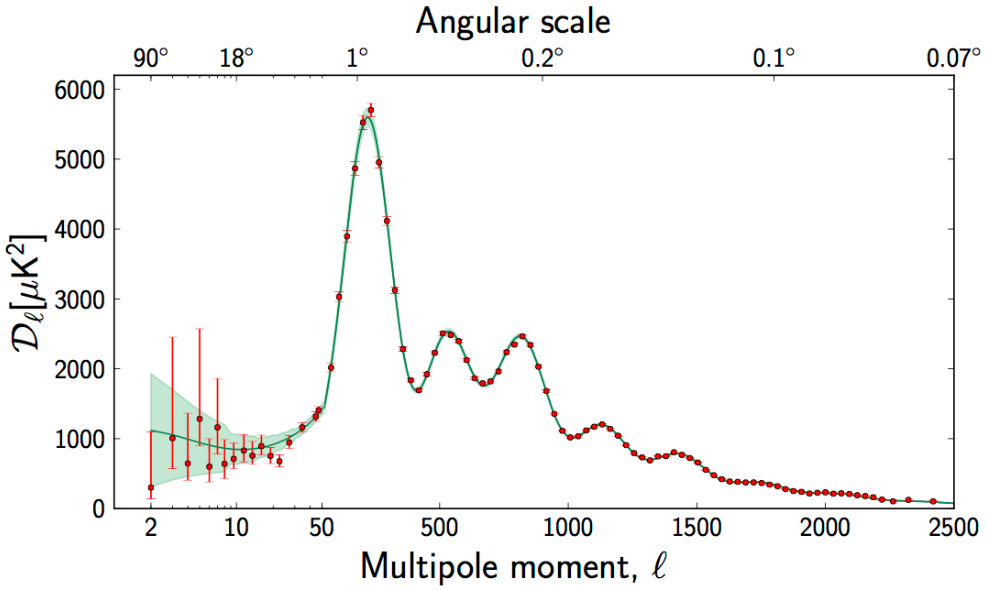
Higgs and Effective Field Theory, Bologna 2024

Observing a slice of the light-cone

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



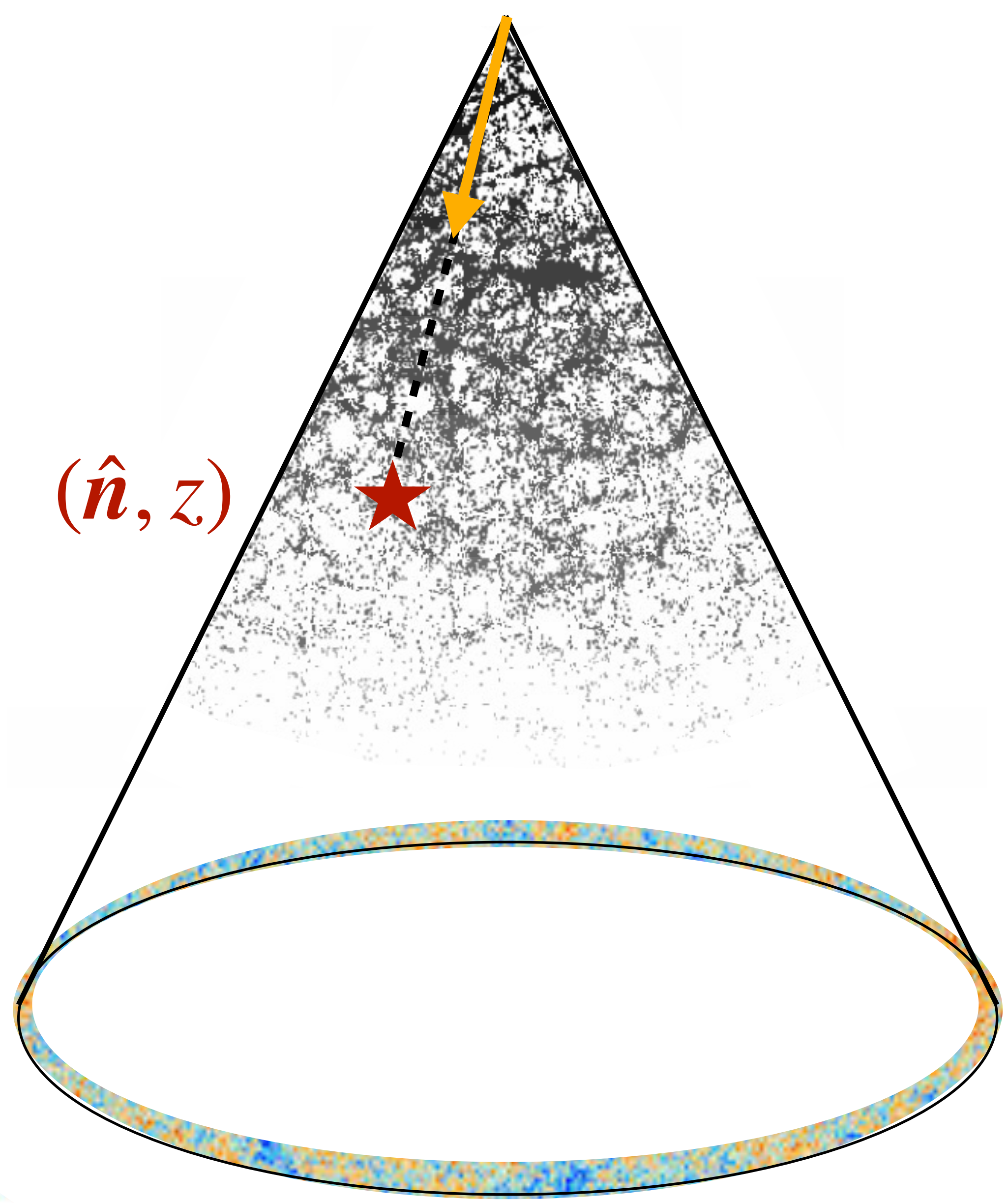


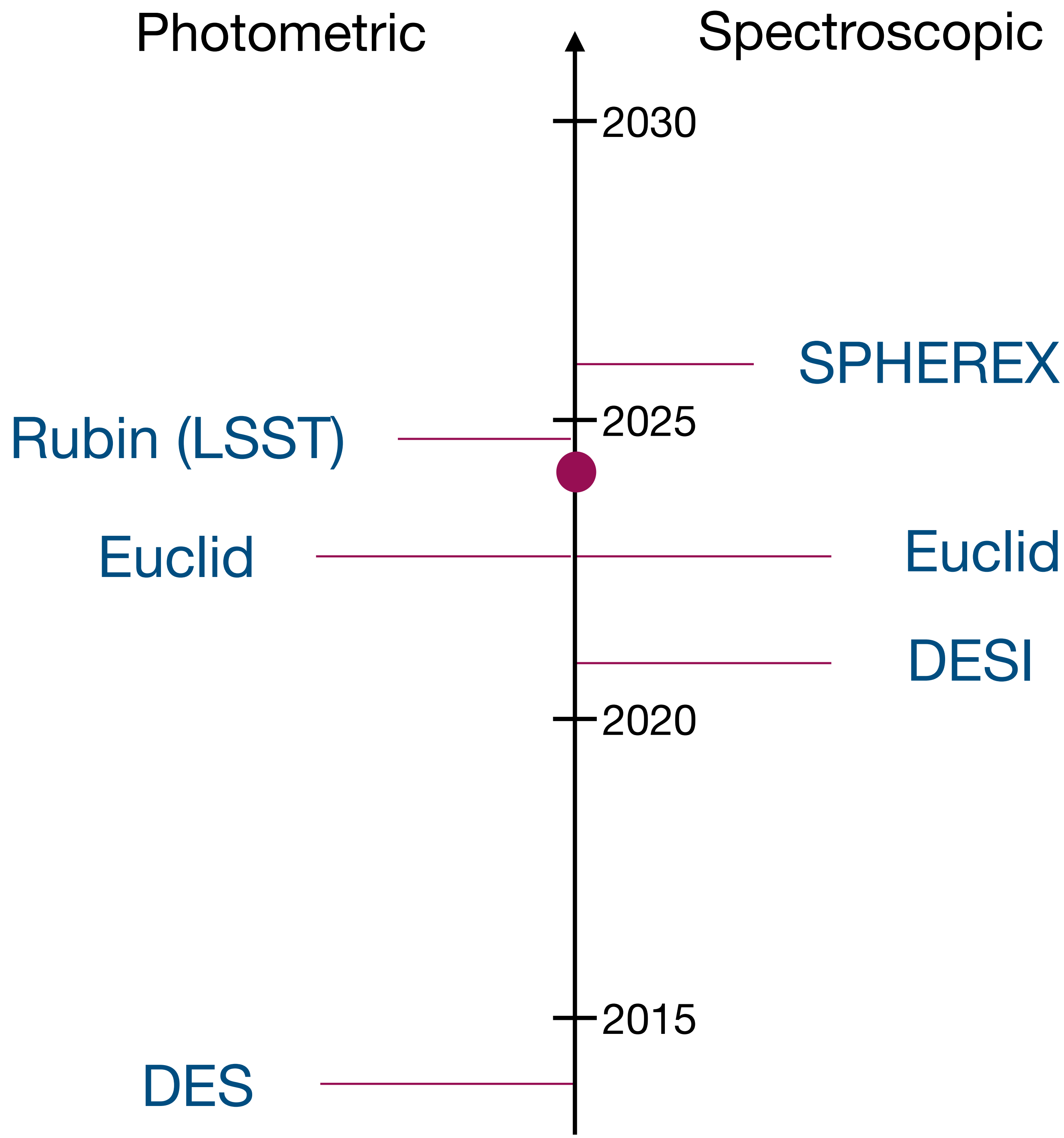
Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54

Many open questions that CMB alone cannot answer!

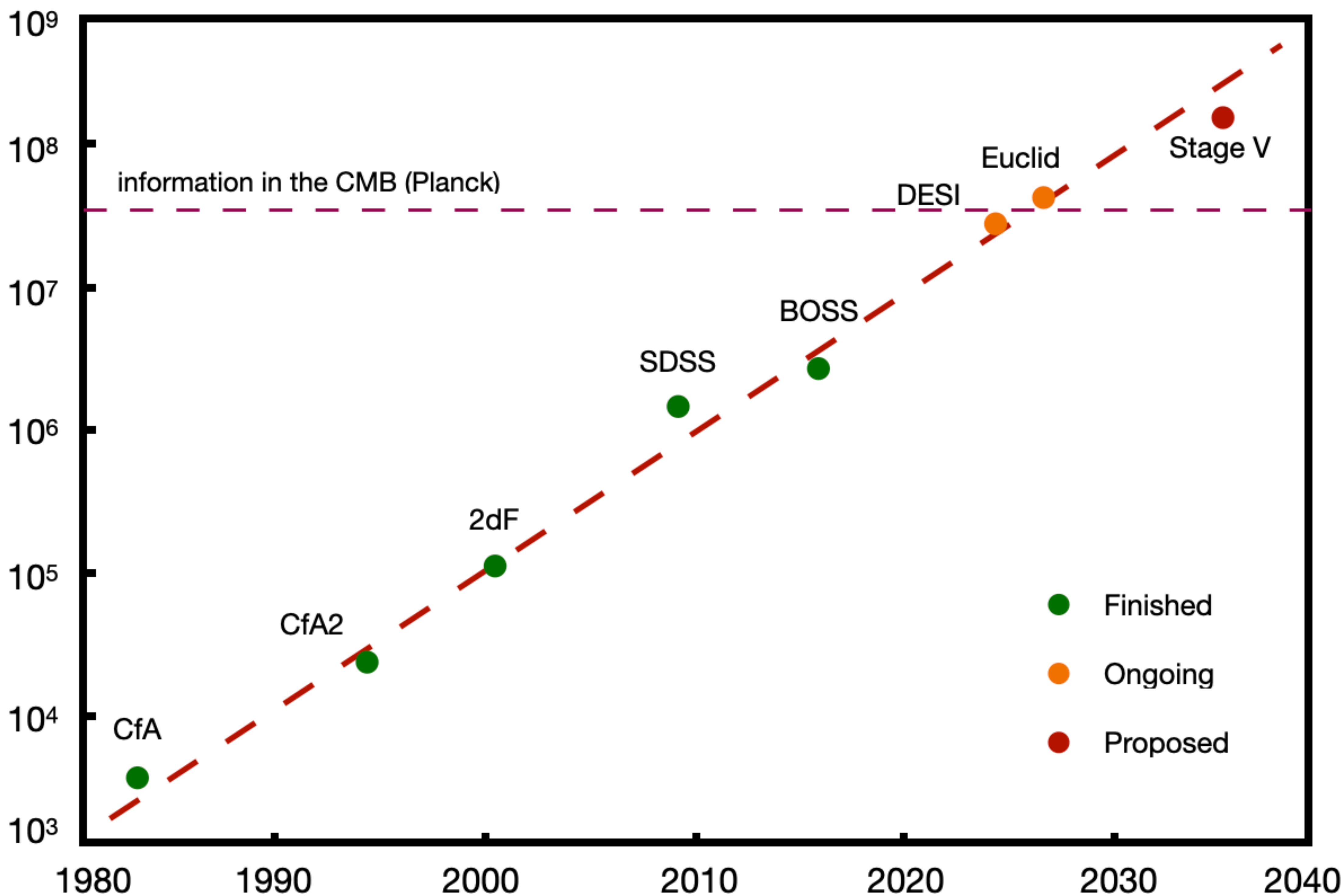
Observing the entire light-cone

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



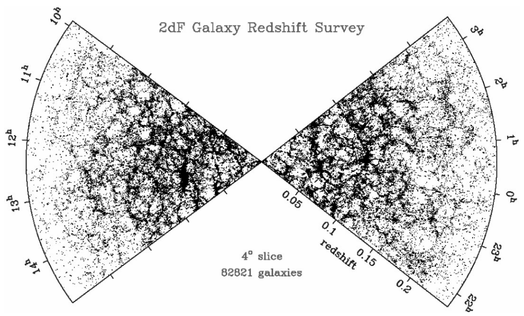


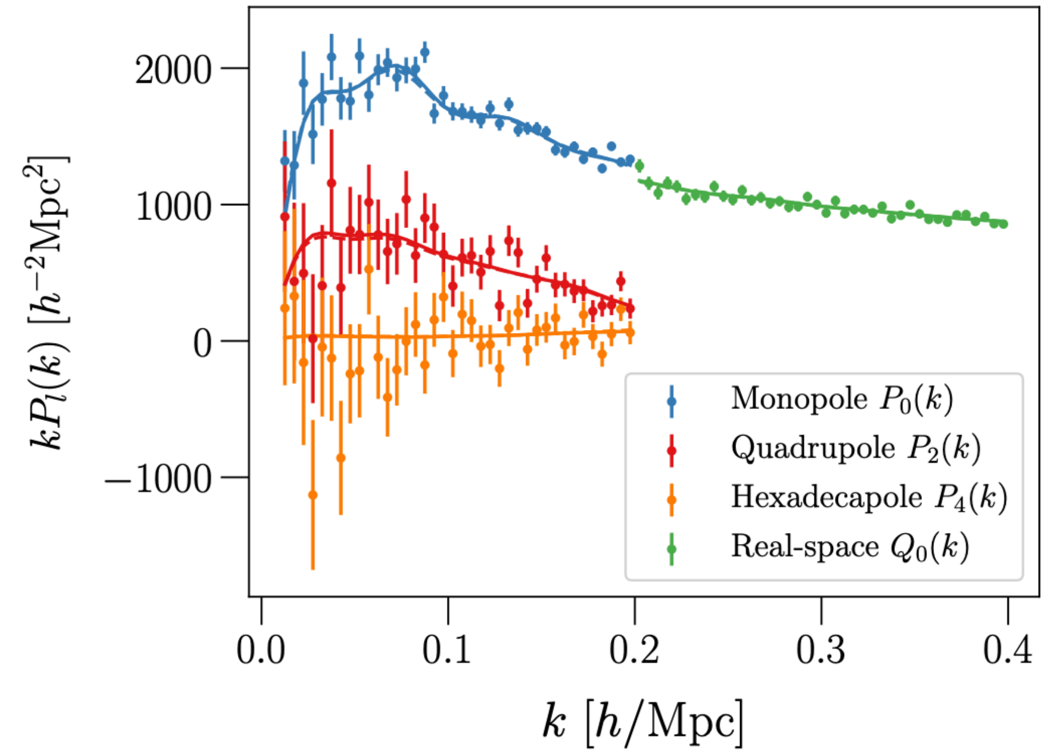
Spectroscopic galaxy surveys



Spectroscopic galaxy surveys

galaxy map





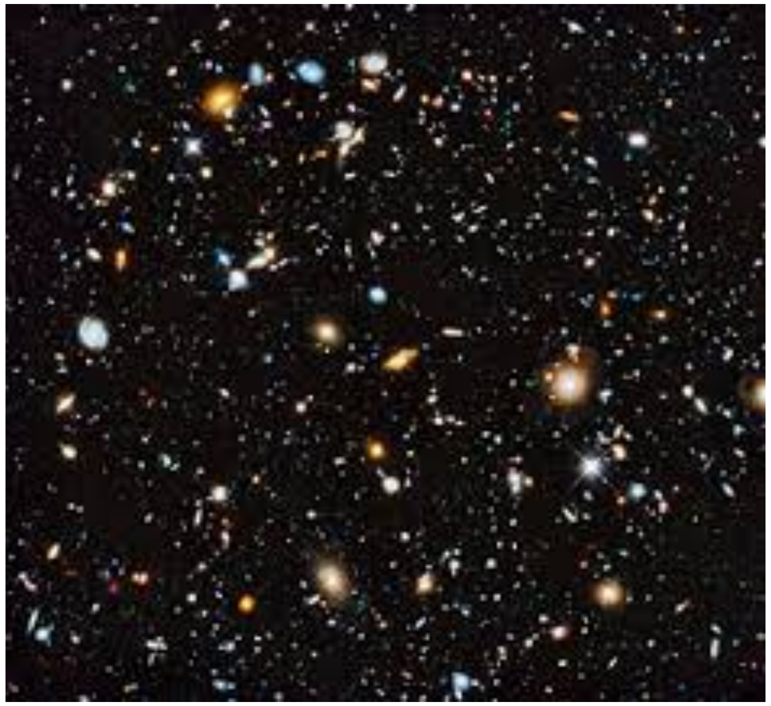
Full-shape analysis

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?

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

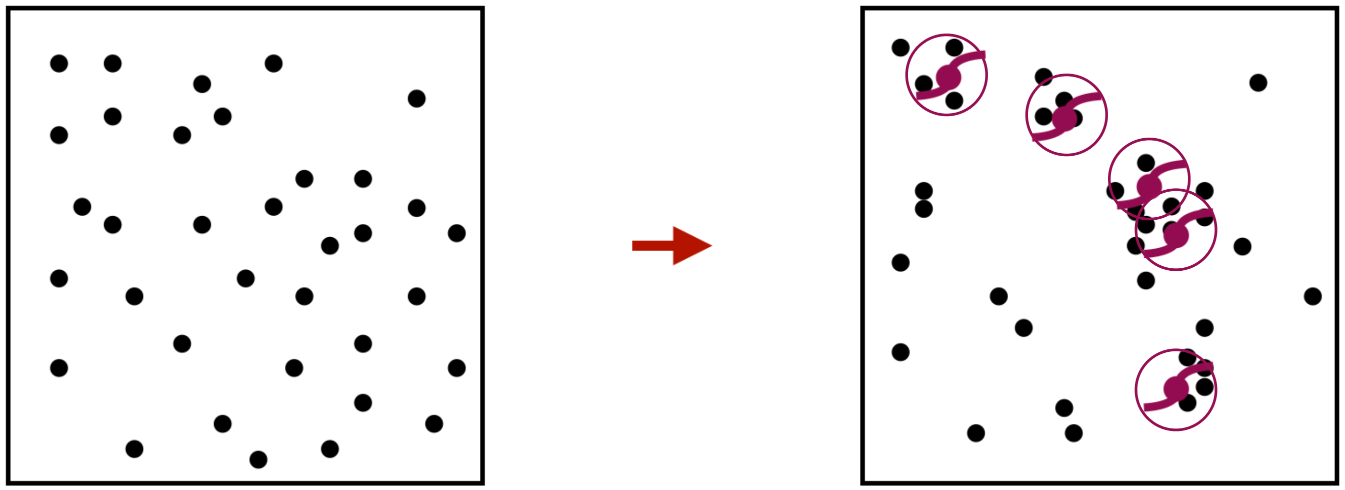
Expansion parameters: δ_g, ∂/k_{NL}

All "UV" dependence is in a handful of free parameters

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

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

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

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

Small-scale nonlinear DM physics encoded in c_s^2

Is this useful in practice?

$$\sigma_R^2 \sim \frac{1}{2\pi^2}\int_0^{1/R} k^2 dk\; P_{\rm lin}(k) \sim 1$$

for $R \sim$ few Mpc at low redshifts

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

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

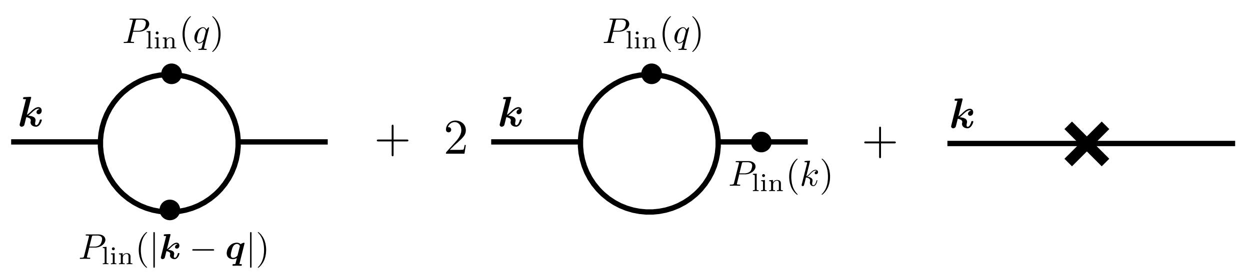
$$N_{\rm pix.}^{\rm LSS} \gg N_{\rm pix.}^{\rm CMB}$$

EFT of large-scale structure

Correlation functions computed using perturbation theory

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

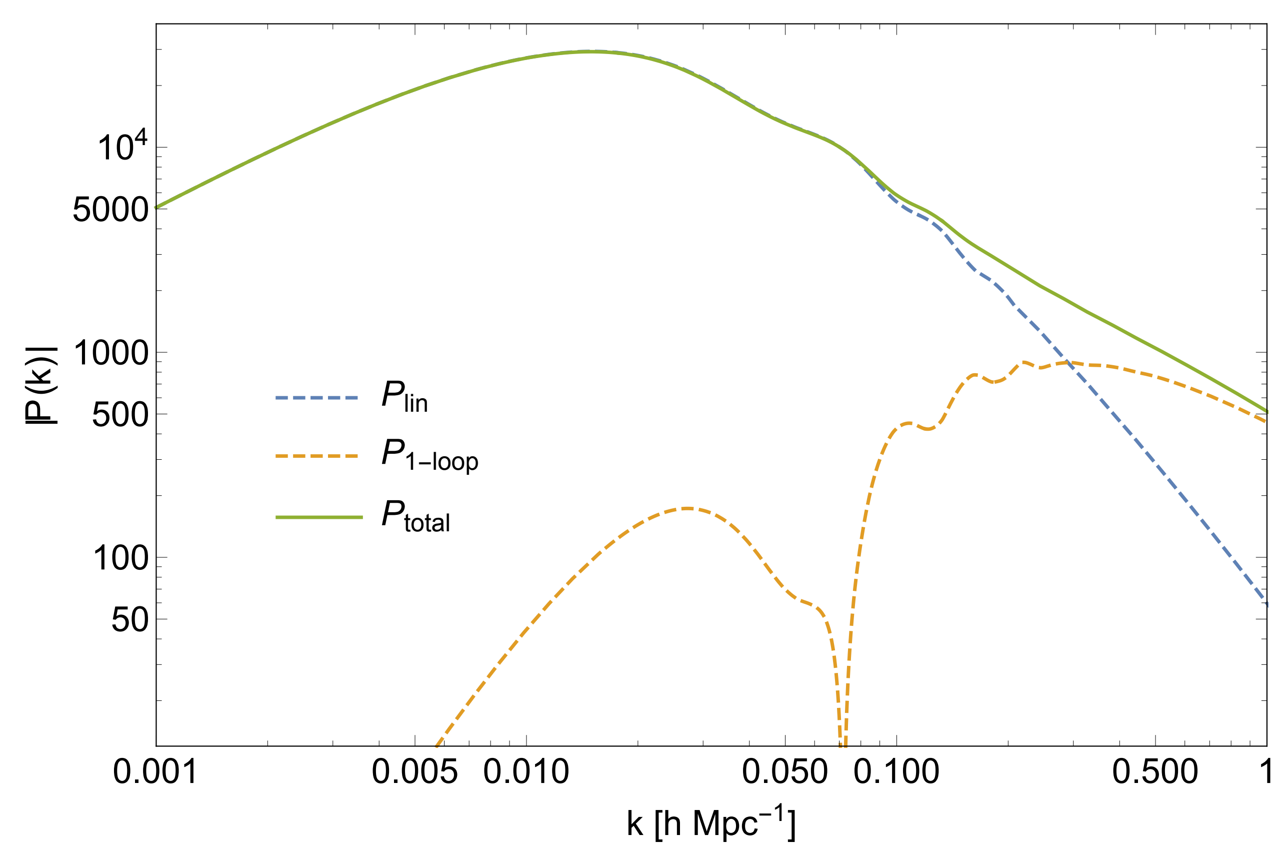
$P_{1-\mathrm{loop}}(k) =$



Carrasco, Hertzberg, Senatore (2012)

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

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



Renormalization

IR resummation

…

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

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

Infrared resummation

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

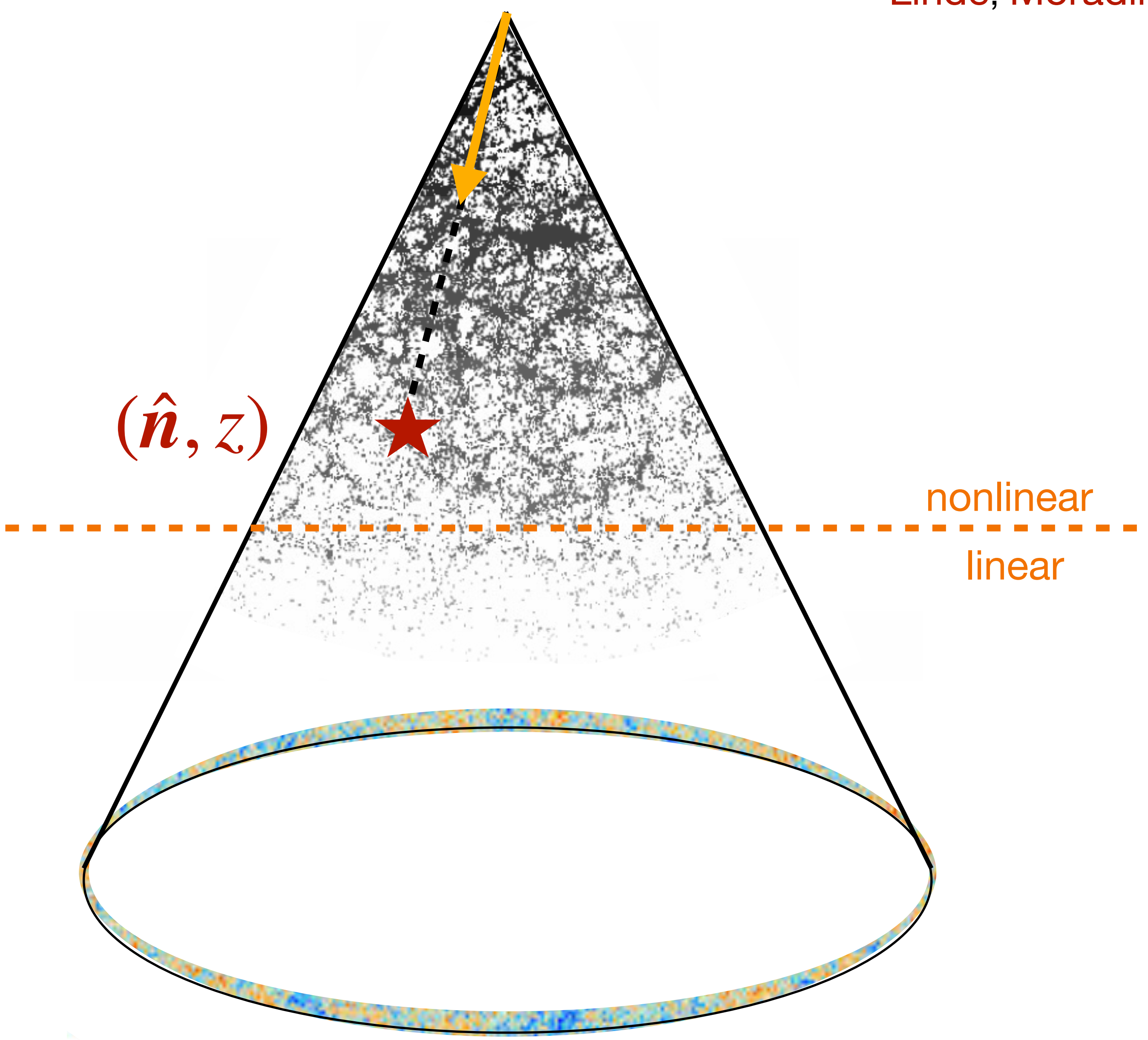
$$\Sigma^2_{\rm tot}(z,\mu) = (1 + f(z)\mu^2(2+f(z)))\Sigma^2(z) + f^2(z)\mu^2(\mu^2-1)\delta\Sigma^2(z)$$

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

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

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

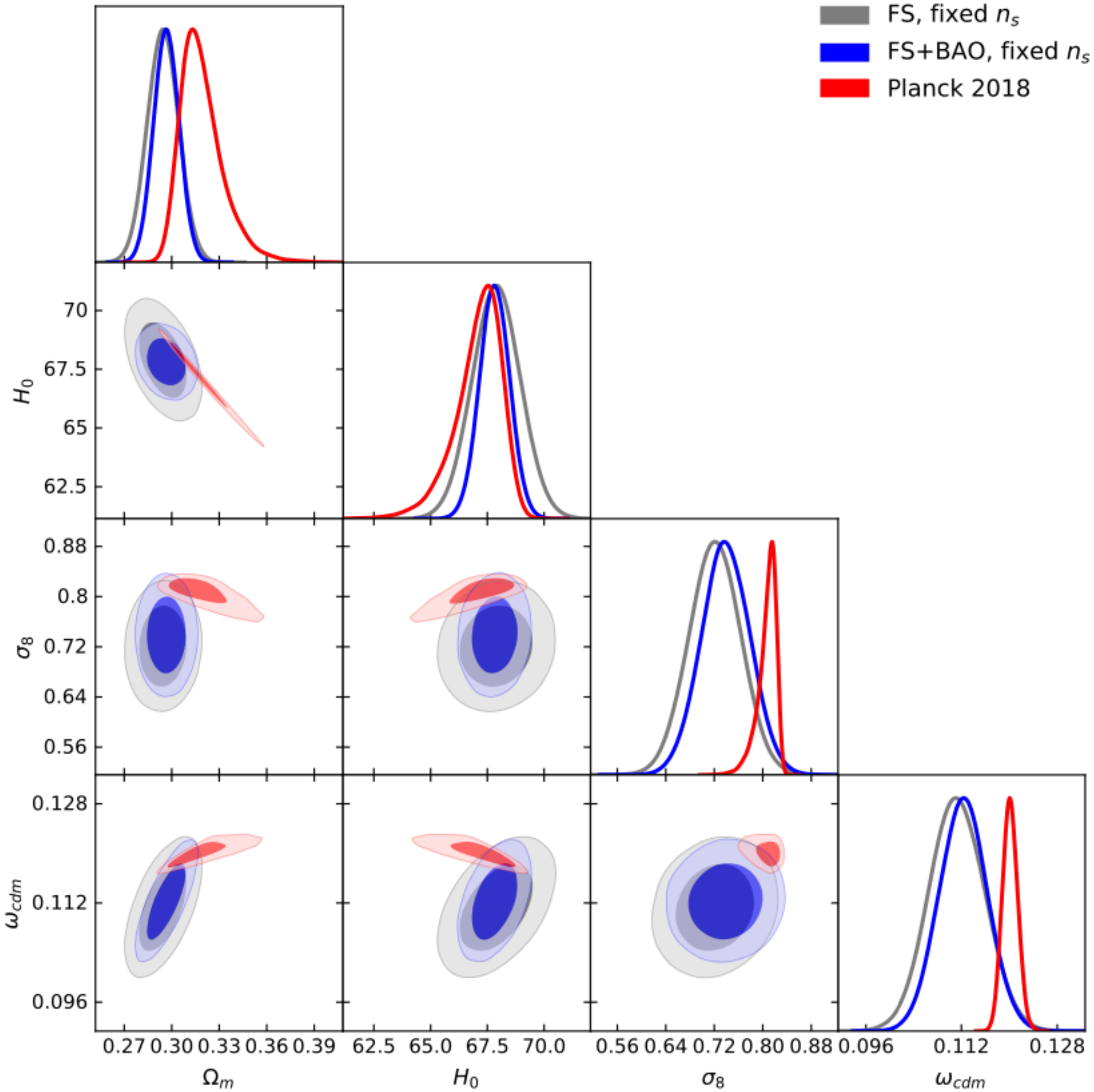
Evolution of the vacuum state from inflation to redshift zero

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

$$H_0 = 67.8 \pm 0.7 \text{ km/s/Mpc}$$

Naive rescaling to DESI Y1

$$\Delta H_0 \approx 0.4 \text{ km/s/Mpc}$$

Beyond ΛCDM

If you are interested ask me about:

Neutrinos and other light relics

Non-CDM subcomponents of dark matter

Hubble tension

Dark energy

Spatial curvature

Primordial non-Gaussianities

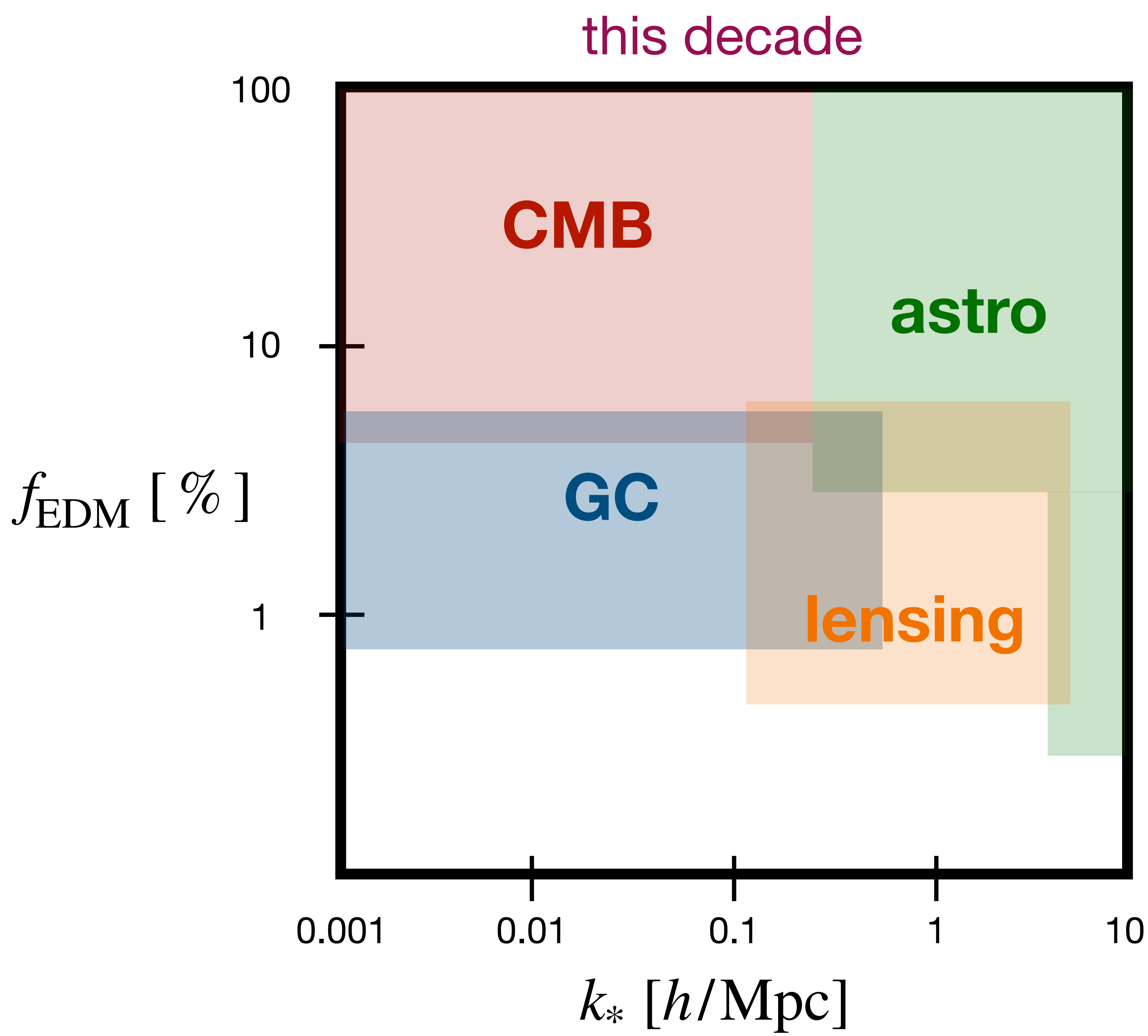
Beyond ΛCDM - exotic dark matter

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

Imprints a characteristic scale k_* on the matter power spectrum

ULA
Baryon-DM interactions
LiMRs (thermal QCD axion)
Long-range forces
SIDM
…

What are the odds?



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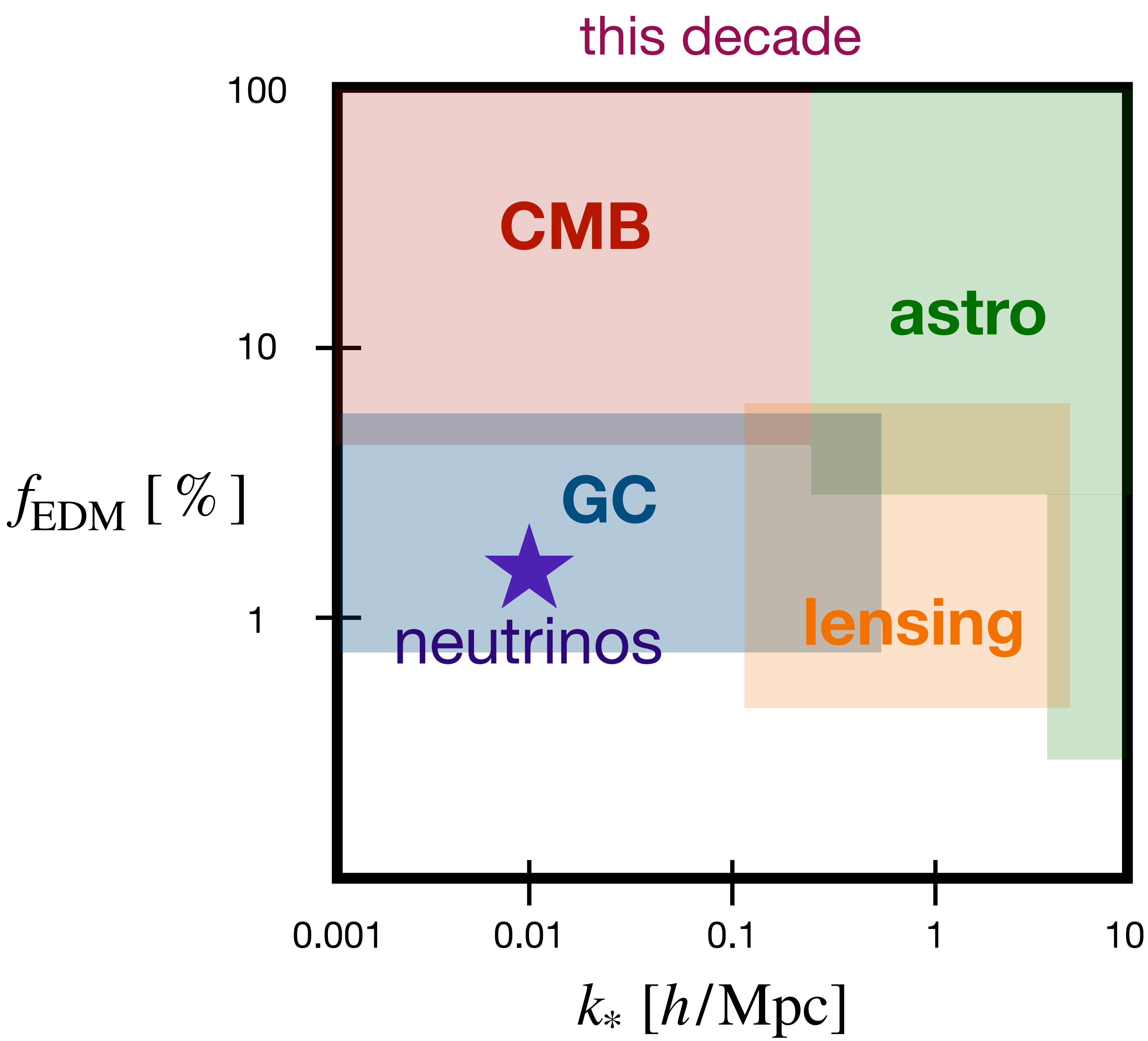


Beyond ΛCDM - ultralight axions

Fuzzy dark matter

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

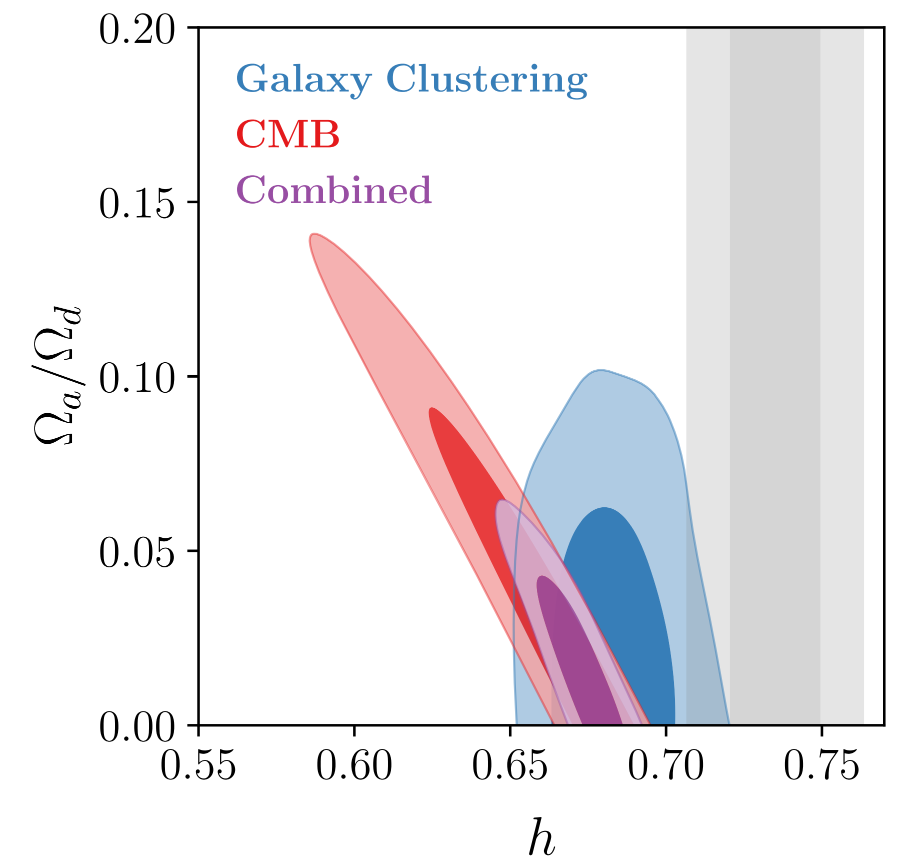
$$\frac{\Omega_a}{\Omega_d} \sim 0.01 \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m_a}{10^{-26}\,\mathrm{eV}}\right)^{1/2}$$

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

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

In the range $10^{-32} - 10^{-25}\,\mathrm{eV}$ ULA can be a fraction of DM and LSS probe those scales!

LSS constraints will further improve ~ 10x



Conclusions

A big amount of new data in this decade

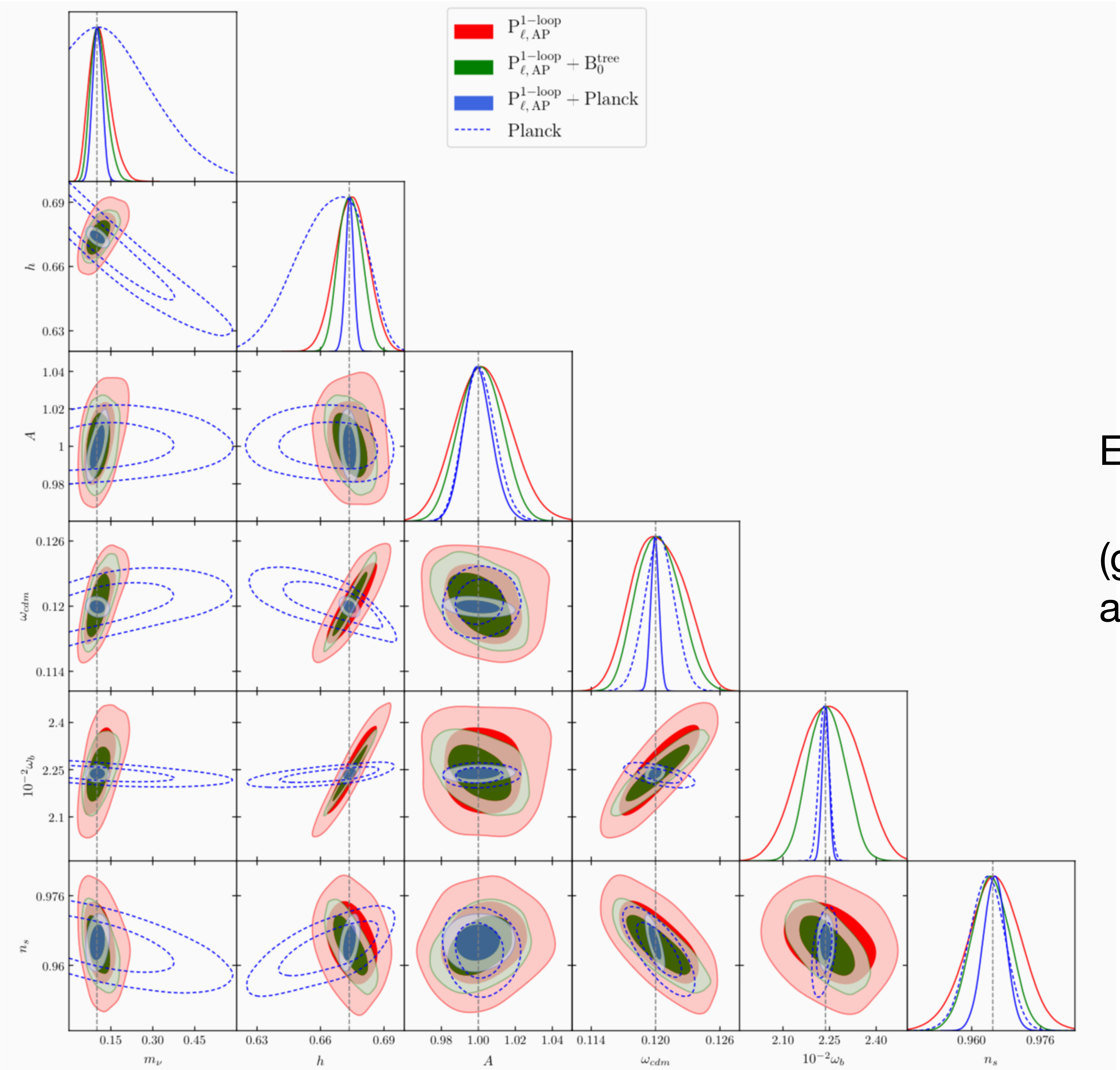
Novel approaches to theory and data analyses

Many possible factors-of-10 improvements

It may be that there is nothing beyond ΛCDM…

… but in cosmology surprises are possible and we should be excited

Beyond ΛCDM - neutrinos



Chudaykin, Ivanov (2019)

Euclid/DESI-like survey

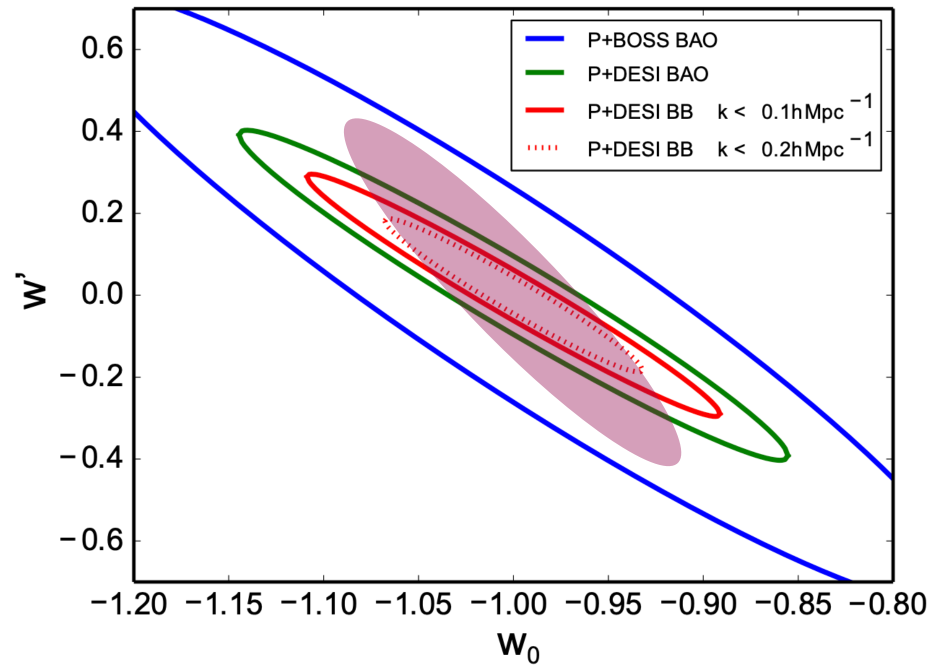
(galaxies only, no Lya and quasars)

Beyond ΛCDM - DE and spatial curvature

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

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

DESI Fisher forecast,
credit: Patrick McDonald



Rough current errors
BAO+CMB+SNIa

Imagine a scalar field with the potential V

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

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

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

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

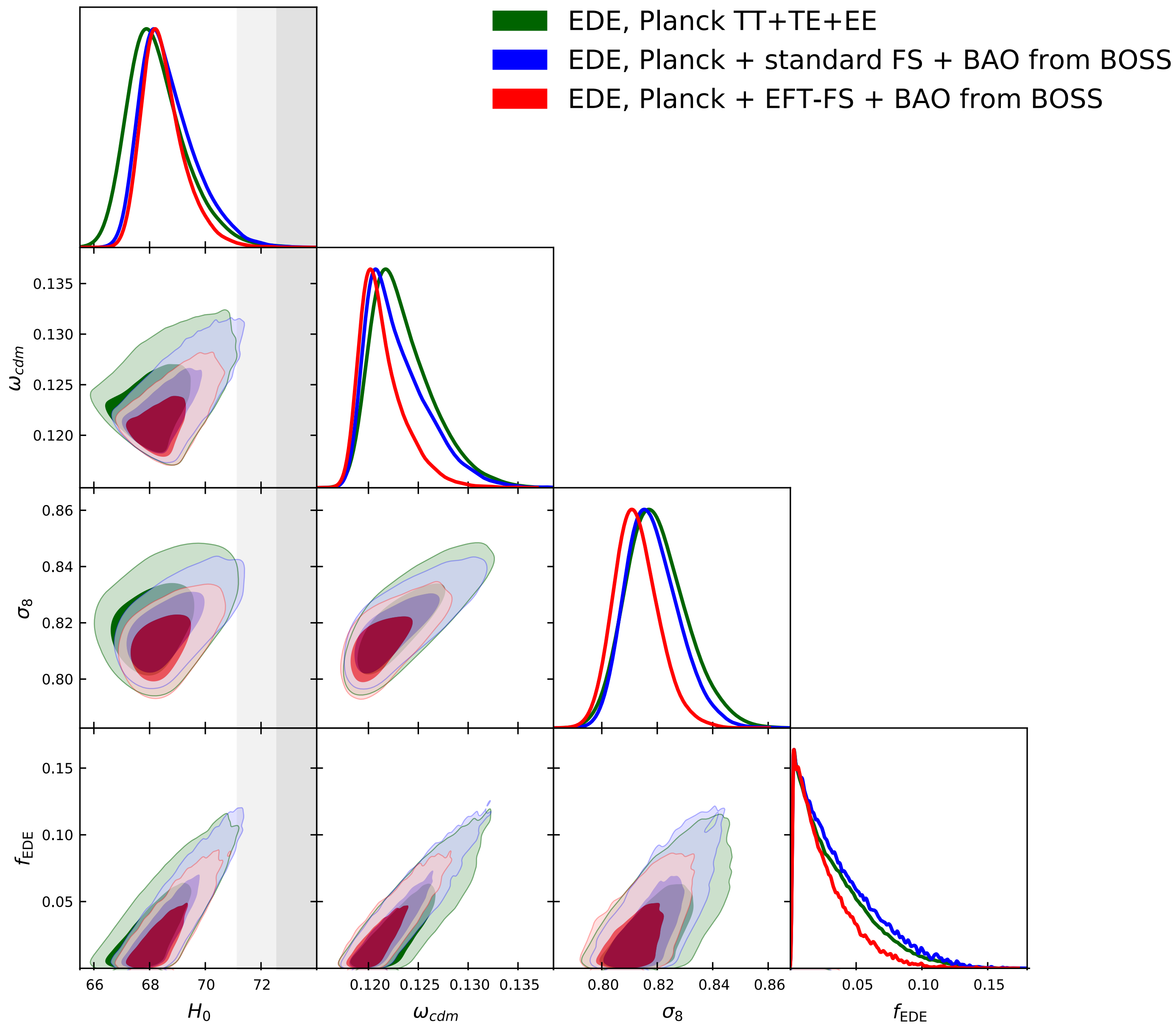
The spatial curvature will be constrained better: $\sigma(\Omega_K) < 5 \times 10^{-4} - 10^{-3}$

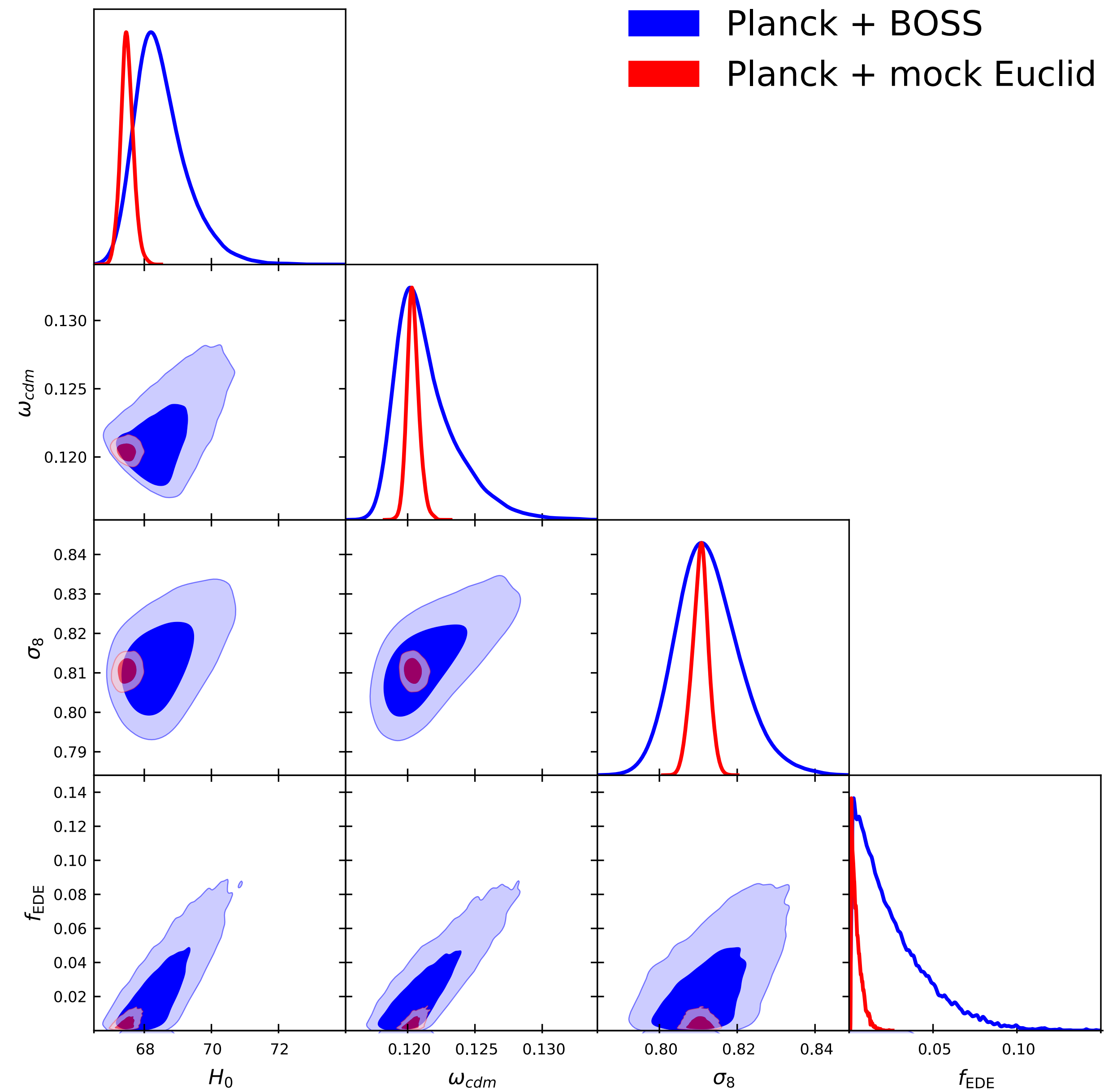
Any measurement of $|\Omega_K| > 10^{-4}$ will have large implications for inflation

Beyond ΛCDM - Hubble tension

Ivanov et al. (2020)

Early dark energy





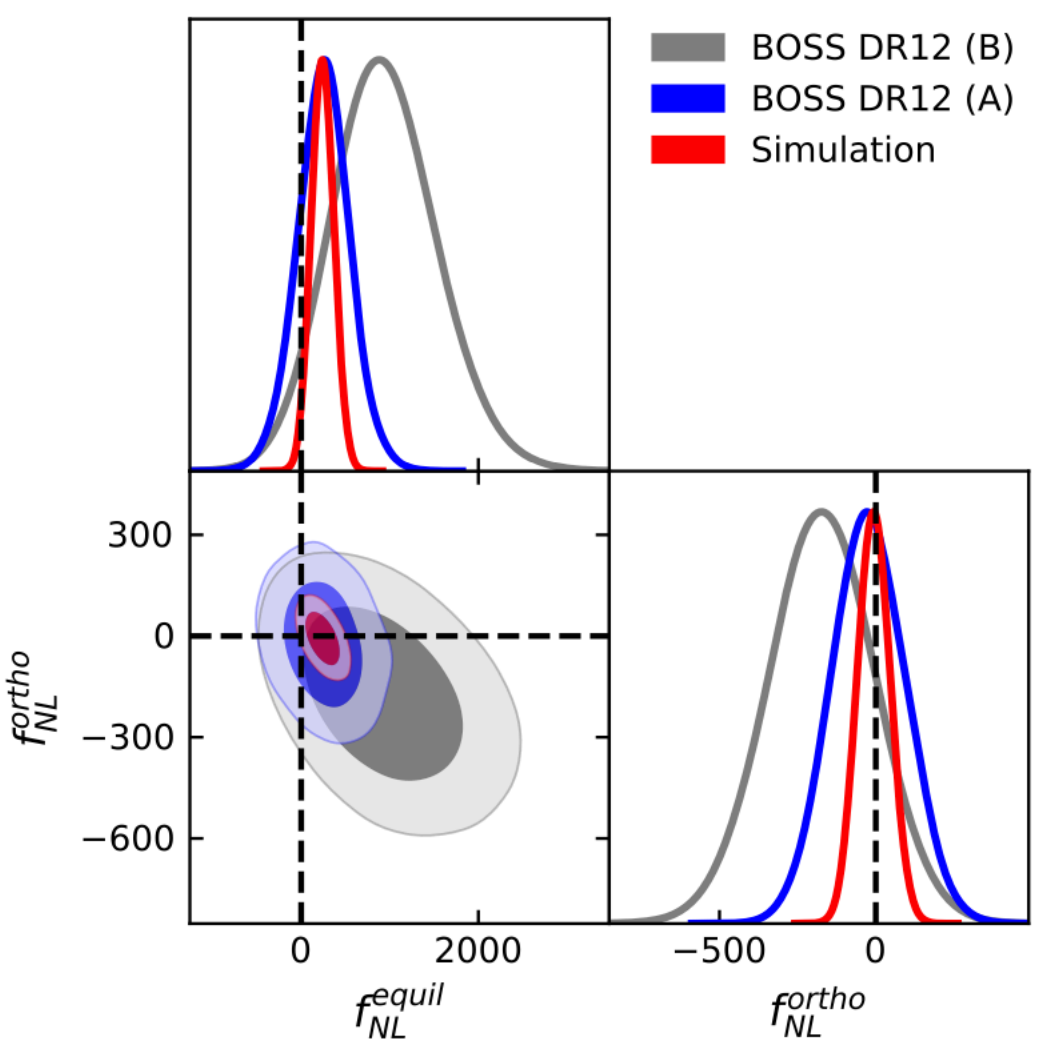
Beyond ΛCDM - primordial NG

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