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Measurement of the matter-radiation equality scale

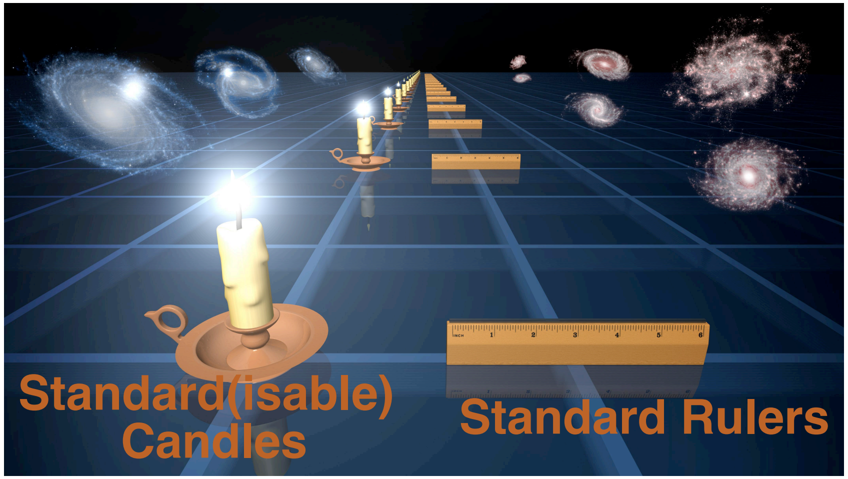
Special thanks to David Parkinson, Eva-Maria Mueller, Edmond Chaussidon, Arnaud de Mattia, Pigi Monaco, Guilhem Lavaux

Intro to Cosmology

The Universe is expanding

We call its expansion rate H_0

How do we know that?

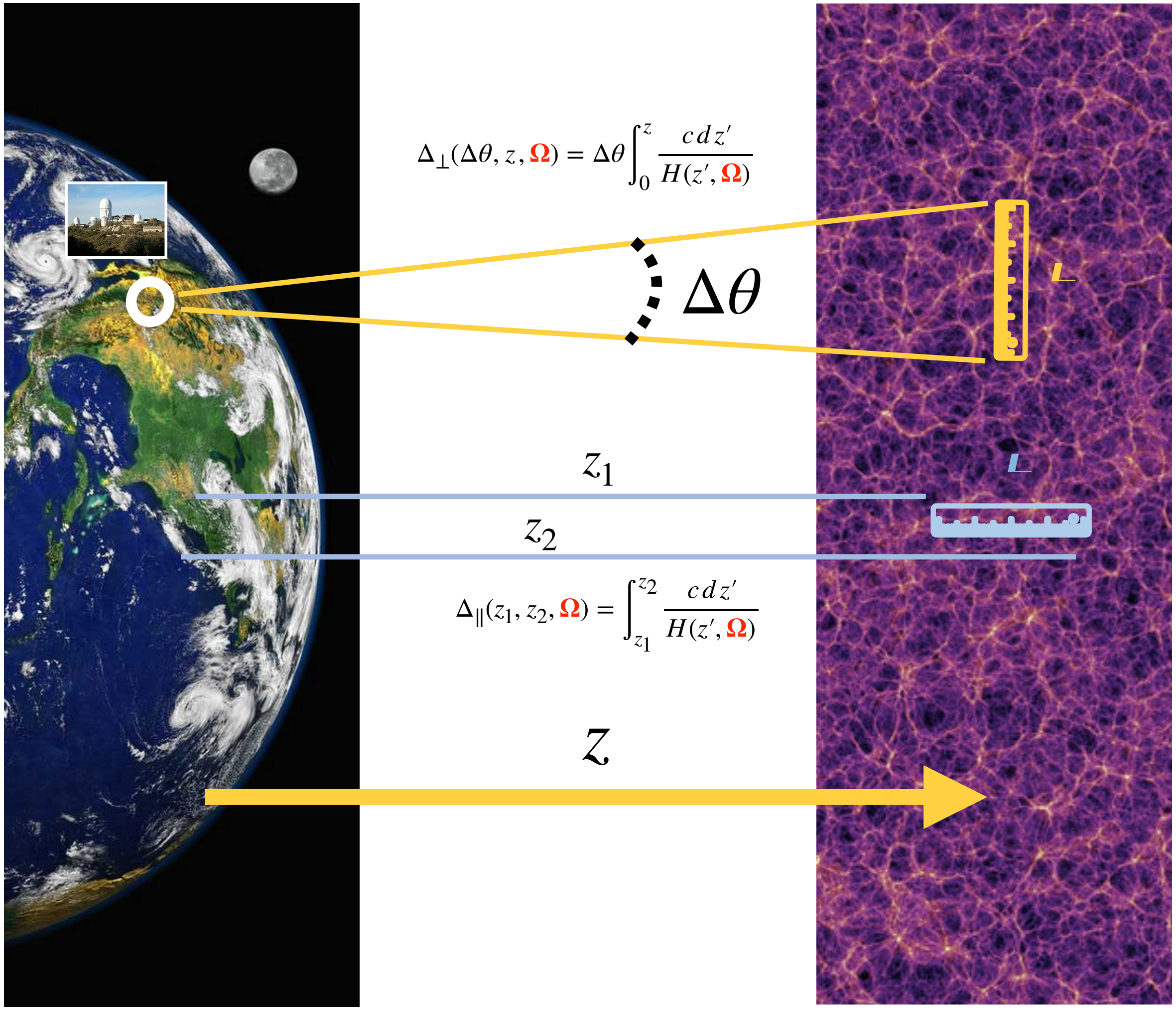


Credit: H. Gil-Marín

- Knowing intrinsic brightness of object, we know its distance by measuring its apparent brightness
- Redshift tells us how fast it moves away from us
- ⇒Obtain expansion rate of (local) Universe

- We know the physical size of a known feature
- Explained in further detail in following slides

Standard rulers?



$$\Delta_\perp(\Delta\theta, z, \boldsymbol{\Omega}) = \Delta\theta \int_0^z \frac{c\,dz'}{H(z', \boldsymbol{\Omega})} = \Delta\theta \int_0^z \frac{c\,dz'}{H_0 E(z', \Omega_m)}$$

$$\Delta_\parallel(z_1, z_2, \boldsymbol{\Omega}) = \int_{z_1}^{z_2} \frac{c\,dz'}{H(z', \boldsymbol{\Omega})} \simeq \frac{c\Delta z}{H_0 E(\bar{z}, \Omega_m)}$$

If L = L then

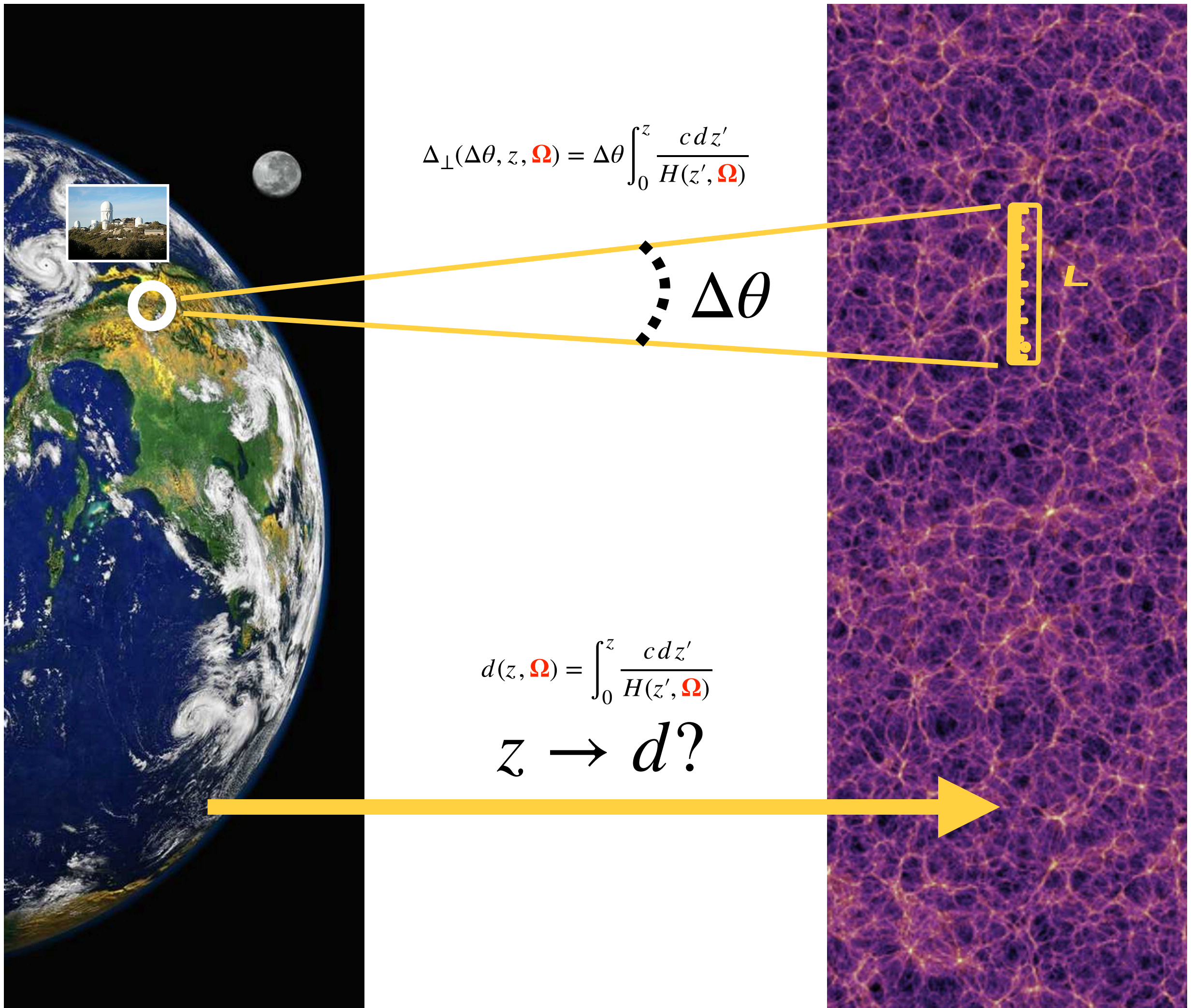
$$\frac{c\Delta z}{\cancel{H_0} E(\bar{z}, \boldsymbol{\Omega})} = \Delta\theta \int_0^z \frac{c\,dz'}{\cancel{H_0} E(z', \boldsymbol{\Omega})}$$

We can weigh Universe
With this so-called
Alcock-Paczyński effect

$$E(z, \boldsymbol{\Omega}) \rightarrow \Omega$$

Credit: H. Gil-Marín

Standard rulers?



If L is not known, we can establish the following relation,

$$L = \Delta\theta \int_0^z \frac{c\,dz'}{H(z', \mathbf{\Omega})} = \Delta\theta \int_0^z \frac{c\,dz'}{H_0 E(z', \mathbf{\Omega})}$$

$$H_0 L = \Delta\theta \int_0^z \frac{c\,dz'}{E(z', \mathbf{\Omega})}$$

Having established measurement of $E(z, \Omega)$ on previous slide, we can infer expansion rate, but it is degenerate with length of standard ruler L

Gold standard ruler:
BAO

BAO not visible with the naked eye. In practice, we measure it statistically through the 2-point correlation function $\xi(r)$ or its Fourier counterpart, the power spectrum $P(k)$:

1. We need to assume a *fiducial* value for $\boldsymbol{\Omega_m^{fid}}$ for transforming z into *d*
2. We also need to assume a *template/fiducial* cosmology (whose $\boldsymbol{r_d^{fid}}$) for a reference

All scales (including BAO) along/across the LOS are

$$r^{\rm true}_{\parallel,\perp} = \frac{D^{\rm true}_{\parallel,\perp}}{D^{\rm fid}_{\parallel,\perp}} r^{\rm obs.}_{\parallel,\perp}$$

$$D_\perp(z) = \Delta\theta \int_0^z \frac{c\,dz'}{H(z',\boldsymbol{\Omega})} \sim D_M(z) \qquad D_\parallel(\bar{z},\Delta z) \simeq \frac{c\Delta z}{H(\bar{z},\Omega)} \sim D_H(z)$$

We measure the relative displacement $\alpha_{\parallel,\perp}$ of the scales with respect to a template,

- caused by inaccurate choice of $\boldsymbol{\Omega_m^{fid}}$
- caused by the inaccurate choice of $\boldsymbol{r_d^{fid}}$

$$[D_H(z)/r_d]^{\rm true} = \alpha_\parallel \cdot [D_H/r_d]^{\rm fid} \qquad [D_H(z)/r_d]^{\rm true} = \alpha_\perp \cdot [D_H/r_d]^{\rm fid}$$

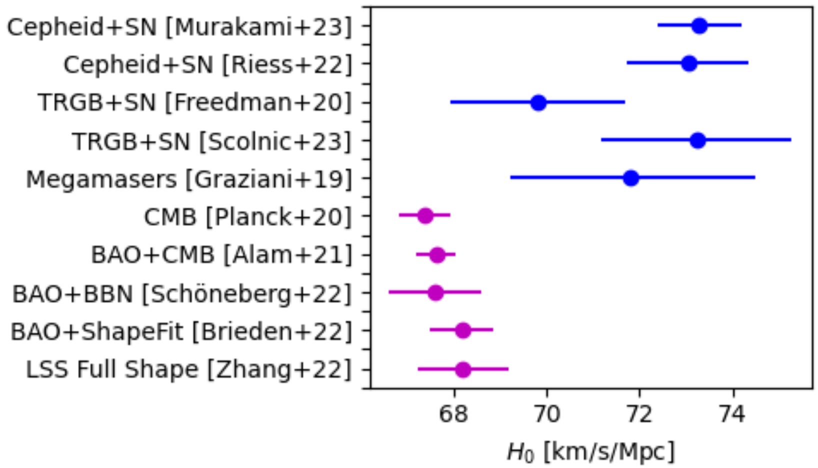
$$\xi^{\rm obs}(r_\parallel, r_\perp) = \xi^{\rm fid}(\alpha_\parallel r_\parallel, \alpha_\perp r_\perp) \qquad P^{\rm obs}(k_\parallel, k_\perp) = P^{\rm fid}(k_\parallel/\alpha_\parallel, k_\perp/\alpha_\perp)$$

Hubble tension

H_0 from standard candles (blue) discrepant with CMB/LSS constraints (magenta)

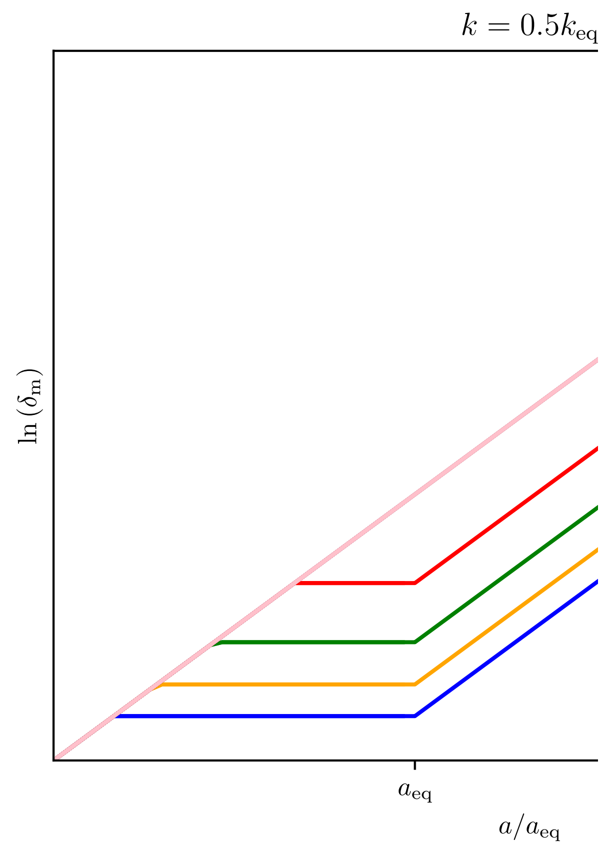
What might be going on?

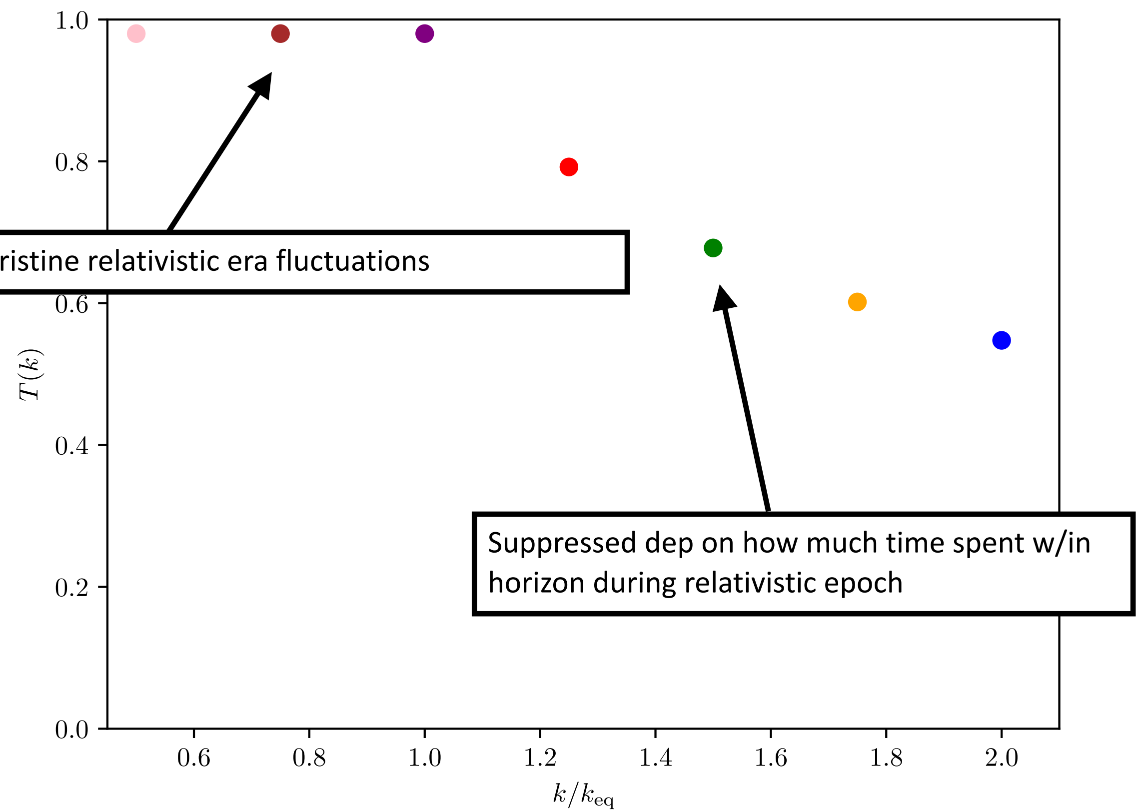
- Systematics
- ΛCDM is wrong
  - If so, is our BAO standard ruler really 147 Mpc long?
  - Is there an alternative standard ruler?



Radiation- vs Matter Domination

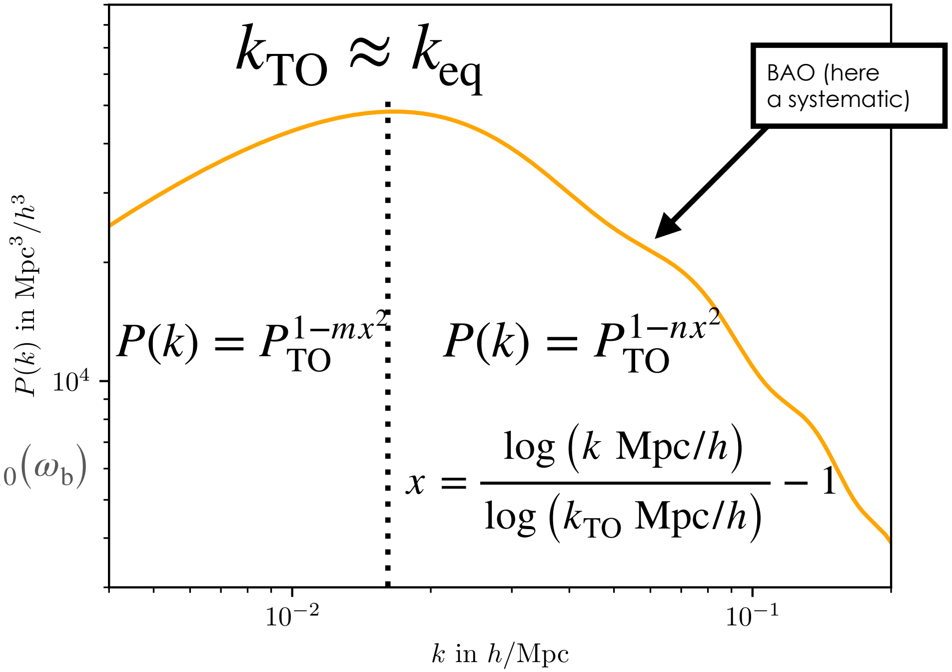
The effect of sub-horizon ra





Model-independent approach

- Alternative to full-shape modelling: Localising Turnover scale similar to what we do with BAO
- Parameterisation following [Poole *et al.* 2011]:
  - two slopes (m, n)
  - One amplitude $P_{\rm TO}$
  - One turn-over scale $k_{\rm TO}$
  - $k_{\rm TO,fid} = 16.6h/{\rm Gpc}$
  - $k_{\rm TO} = \frac{0.194}{\omega_{\rm b}^{0.321}} k_{\rm eq}^{0.685-0.121\log_{10}(\omega_{\rm b})}$ [Prada+11]
- Probability of $m > 0$ gives turn-over detection probability



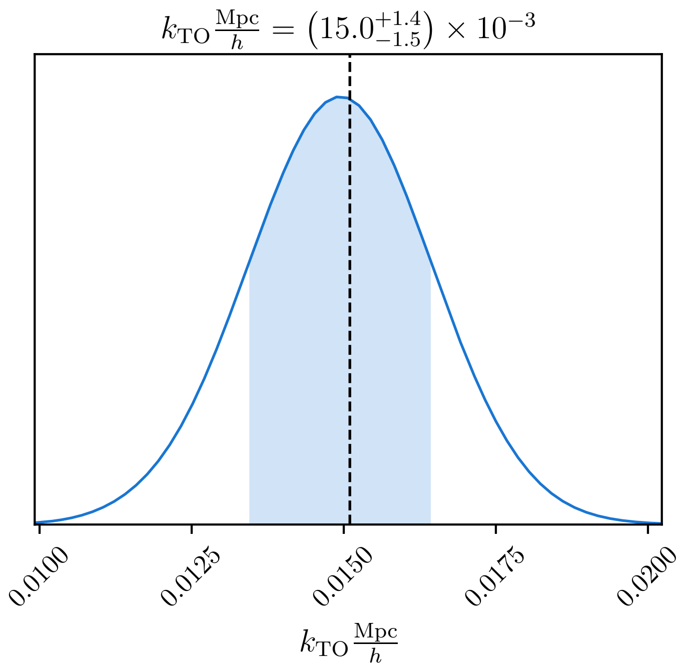
Model-independent approach

- Analogous to BAO measurements:
  - $P^{\mathrm{obs}}(k) = P^{\mathrm{fid}}(k/\alpha_{\mathrm{TO}})$
  - $[D_V(z)/r_H]^{\mathrm{true}} = \alpha_{\mathrm{eq}} \cdot [D_V/r_H]^{\mathrm{fid}}$
  - $\alpha_{\mathrm{TO}} \approx \alpha_{\mathrm{eq}}^{0.685-0.121\log_{10}(\omega_{\mathrm{b,fid}})}$
- No model assumptions needed to measure α_{TO}
- Need model to interpret α_{TO}-measurement cosmologically:
  1. Horizon size at equality: $r_{\mathrm{H}} = c \int_0^{a_{\mathrm{eq}}} \frac{\mathrm{d}\,a}{a^2 H(a)}$
  2. Scale factor at equality: $a_{\mathrm{eq}} = \Omega_{\mathrm{r}}/\Omega_{\mathrm{m}}$
  3. Angular diameter distance: $D_{\mathrm{A}}(z) = \frac{c}{(1+z)} \int_0^z \frac{\mathrm{d}\,z'}{H(z')}$
  4. 3D dilation measure: $D_{\mathrm{V}}(z) = \sqrt[3]{(1+z)^2 D_{\mathrm{A}}^2(z) \frac{cz}{H(z)}}$
- Only need to model $H(a)$ during relativistic epoch, $H(z)$ since redshift of tracers, (and probably Ω_{r})

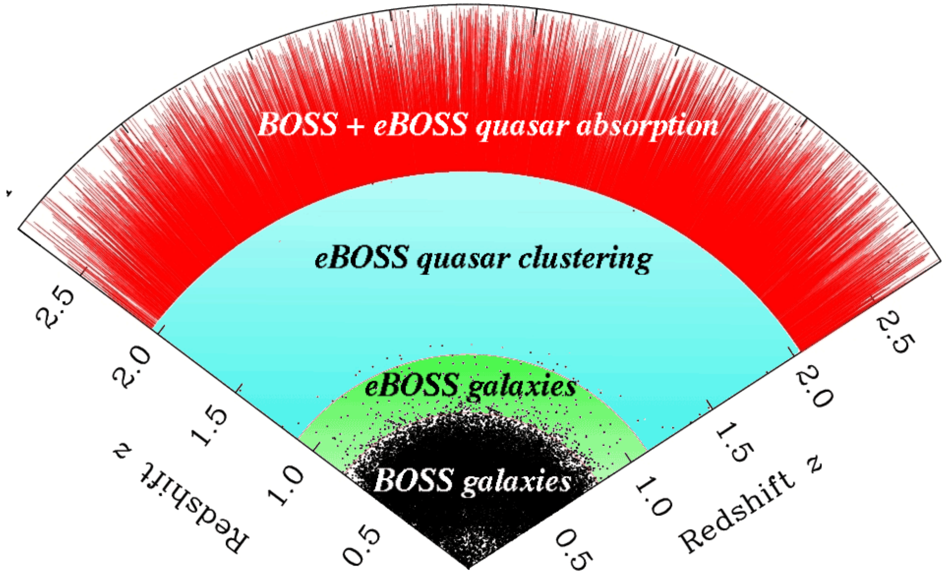
Model-independent approach

Deprojecting modelling systematics

- 4-parameter power spectrum good approximation around turnover, but fails at smaller scales
- Scale cuts remove important broad-band information
- Increase covariance matrix $\tilde{\mathbf{C}} = \mathbf{C} + \lim_{\tau \to \infty} \tau \mathbf{f}^{\mathrm{BAO}} \mathbf{f}^{\mathrm{BAO}\dagger}$ by expected inaccuracy of model $\mathbf{f}_k^{\mathrm{BAO}} = P_{\mathrm{fid}}(k) - P_{\mathrm{eq,BF}}^{1-n_{\mathrm{BF}}x^2}$
- Method does not bias k_{TO} -measurement

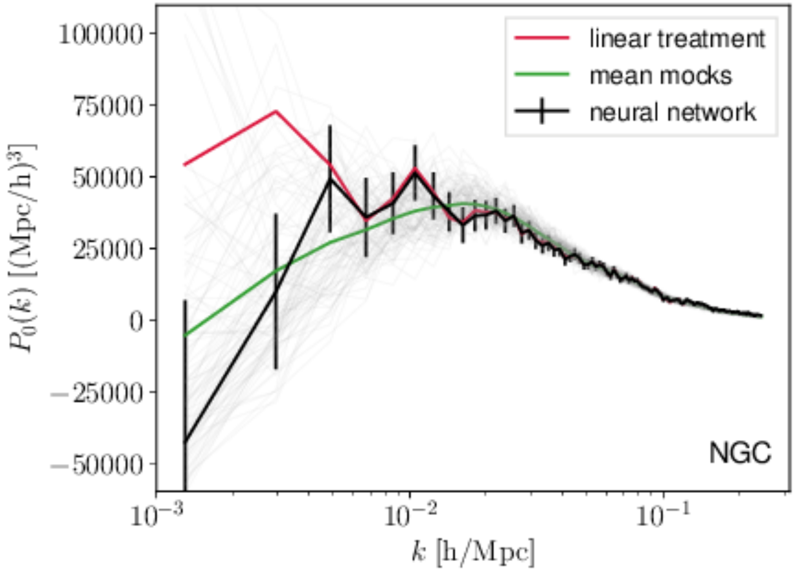


eBOSS



- Largest stage-3 spectroscopic data volume: eBOSS QSO
  - 343 708 Quasars, $0.8 < z < 2.2$, $4699\mathrm{deg}^2$
  - Comes with Rezaie *et al.* (2021)'s systematic weights optimised for eBOSS DR16 f_{NL} measurement [Mueller *et al.* 2021]

eBOSS ultra-large-scale systematic treatment



eBOSS QSO DR16 [Mueller et al. 2021]

Train neural network on 60% of the sky, validate on 20%, test on remaining 20% (SYSNet [Rezaie et al. 2021])

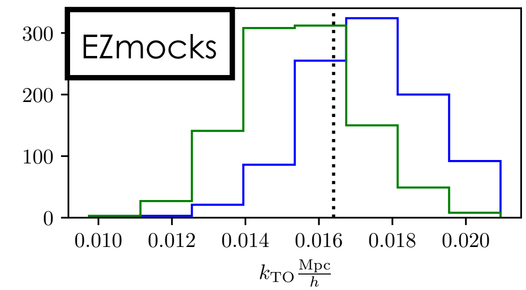
Great flexibility for response shape (though overfitting is a problem)

Allows to include cross-correlations between foregrounds

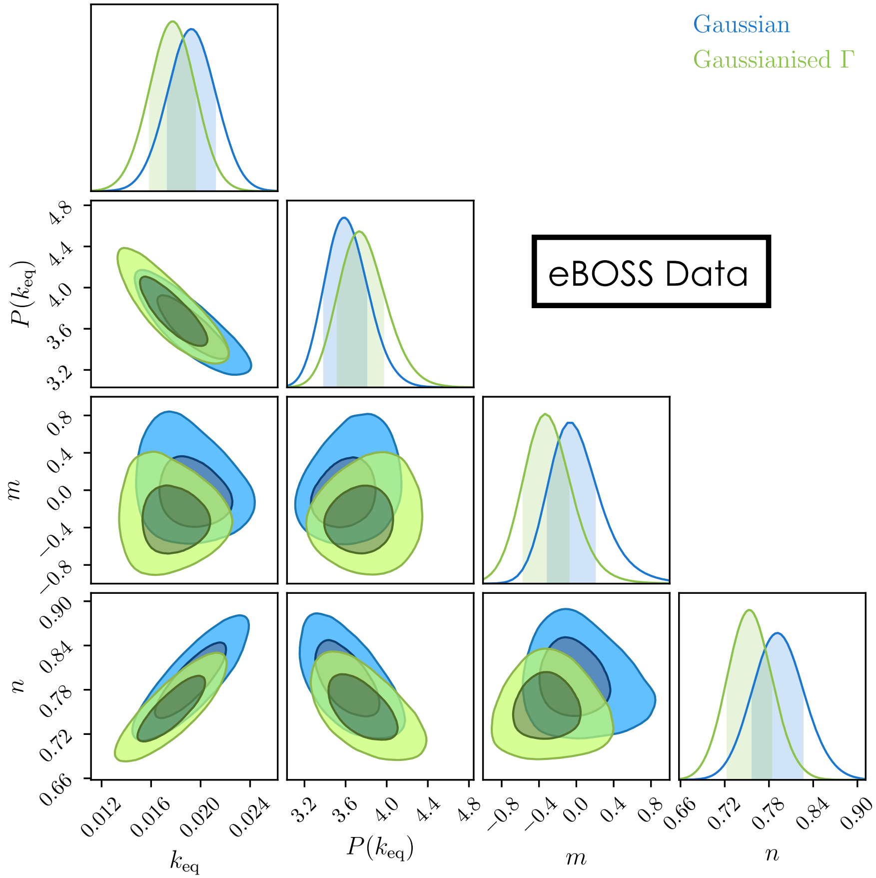
Shown to work great for eBOSS QSO

Two-point estimates may be biased

eBOSS Quasar Results

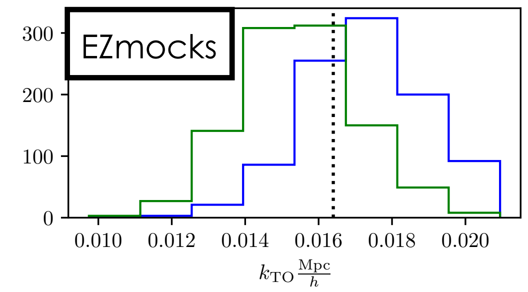


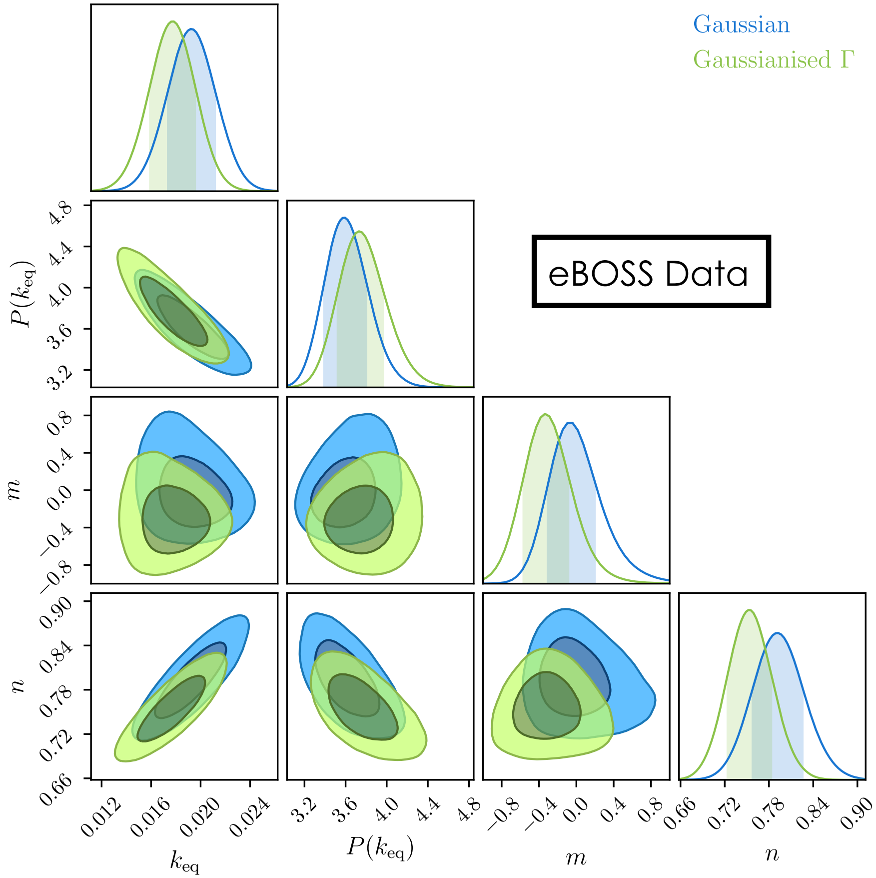
- At largest scales: Gaussian assumption on power spectrum likelihood breaks down
- Windowed $P(k)$ hypo-exponentially distributed [Peacock&Nicholson91]
- Well-approximated by Gamma-distribution [Wang+19]
- Gaussianisation through Box-Cox transformation $Z = \left[P(k)\right]^{\nu}$



eBOSS Quasar Results

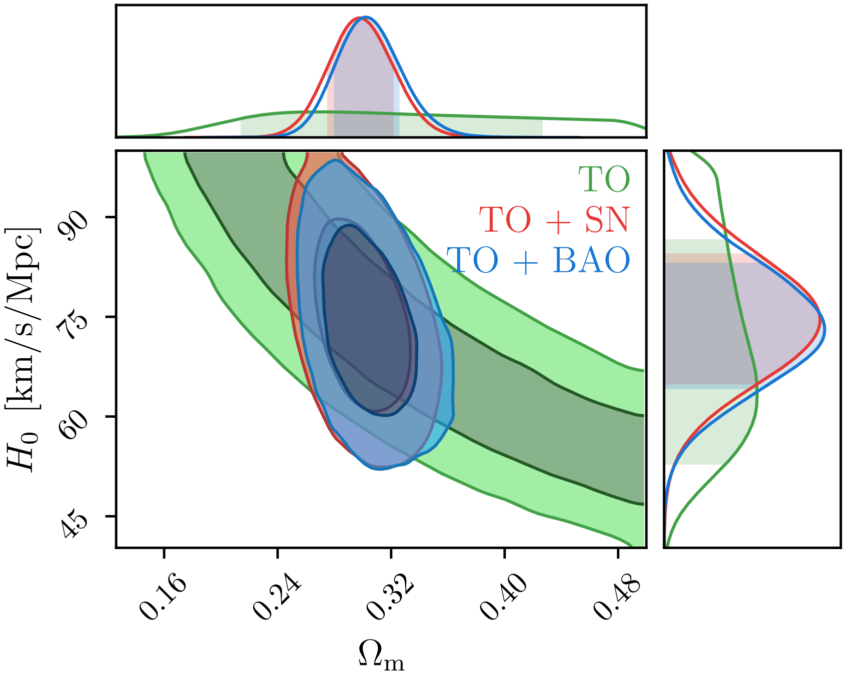
- Fiducial value: $k_{\mathrm{TO,fid}} = 16.6h/\mathrm{Gpc}$
- With Gaussianised Γ-distributed $P(k)$ [Wang et al. 2019]: $k_{\mathrm{TO}} = \left(17.6^{+1.9}_{-1.8}\right) h/\mathrm{Gpc}$
- Biased result with Gaussian likelihood
- No evidence for $m > 0$
- However, we do find inflection point at the expected scale



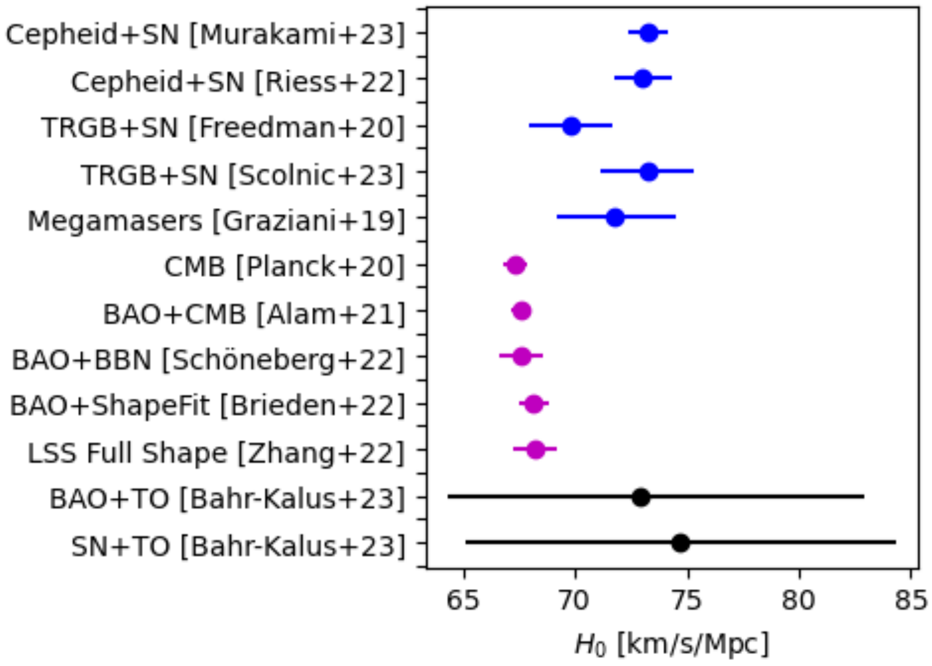


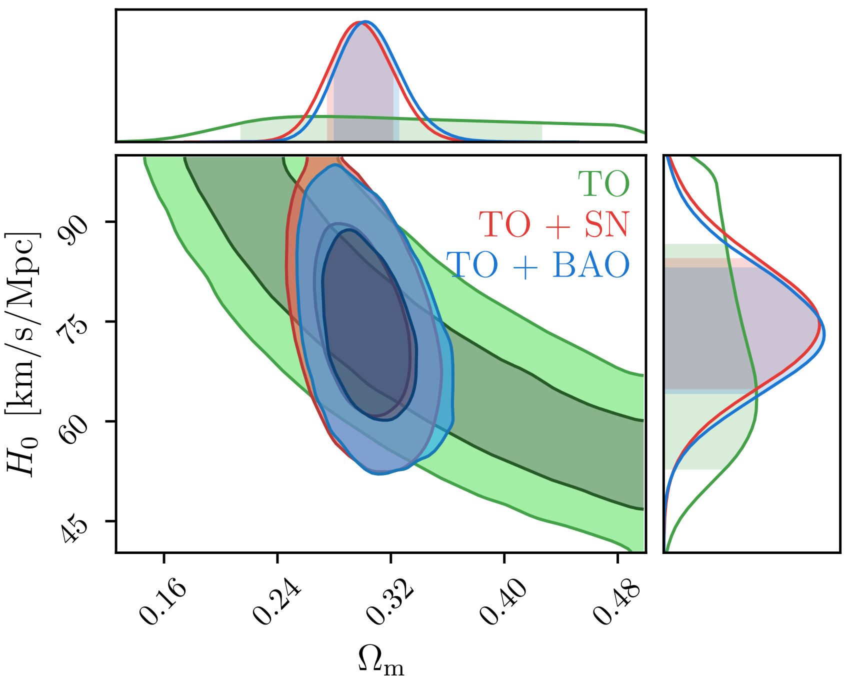
eBOSS Quasar Results

- Assume inflexion point is turnover
- Define r_d-independent standard ruler
  $$\alpha_{\rm eq} = \frac{D_{\rm V}^{\rm fid}}{D_{\rm V}} \frac{r_{\rm H}}{r_{\rm H}^{\rm fid}}$$
- $\alpha_{\rm eq} = 1.07^{+0.12}_{-0.13}$
- cf. $\alpha_{\rm bao} = 1.025 \pm 0.020$ [Neveux et al. 2020]
- $$\Omega_{\rm r} = \frac{8\pi G}{3H_0^2} \frac{4\sigma_{\rm B} T_{\rm CMB}^4}{c^3} (1 + 0.2271 N_{\rm eff})$$
- Assuming 3 standard neutrino species, direct measurement of $\Omega_{\rm m} h^2 = 0.159^{+0.041}_{-0.037}$
- In combination with $\Omega_{\rm m}$ from BAO or SNe, we get $H_0 = (74.7 \pm 9.6)\ \rm km/s/Mpc$ (with Pantheon) and $H_0 = (72.9^{+10.0}_{-8.6})\ \rm km/s/Mpc$ (with eBOSS LRG and Lyα BAO) without any sound horizon information



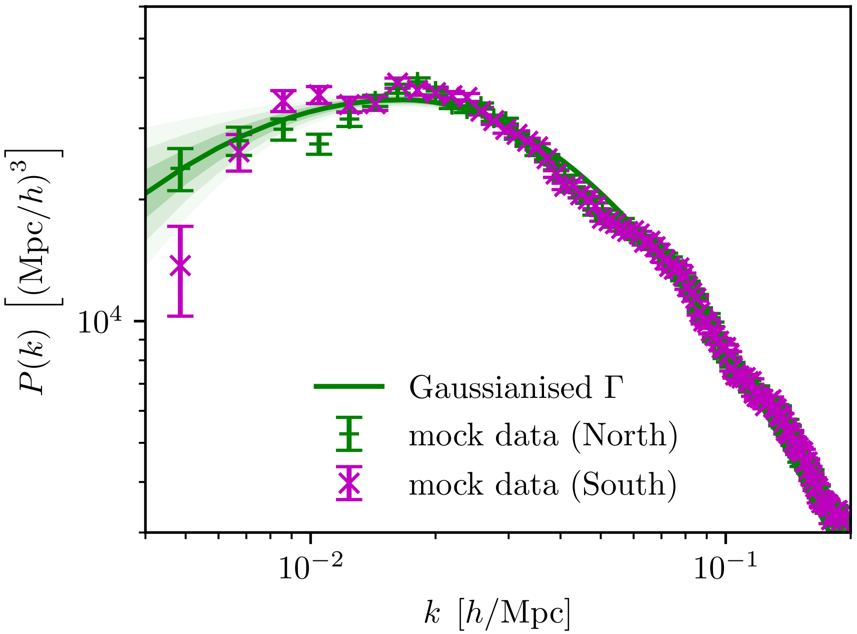
eBOSS Quasar Results





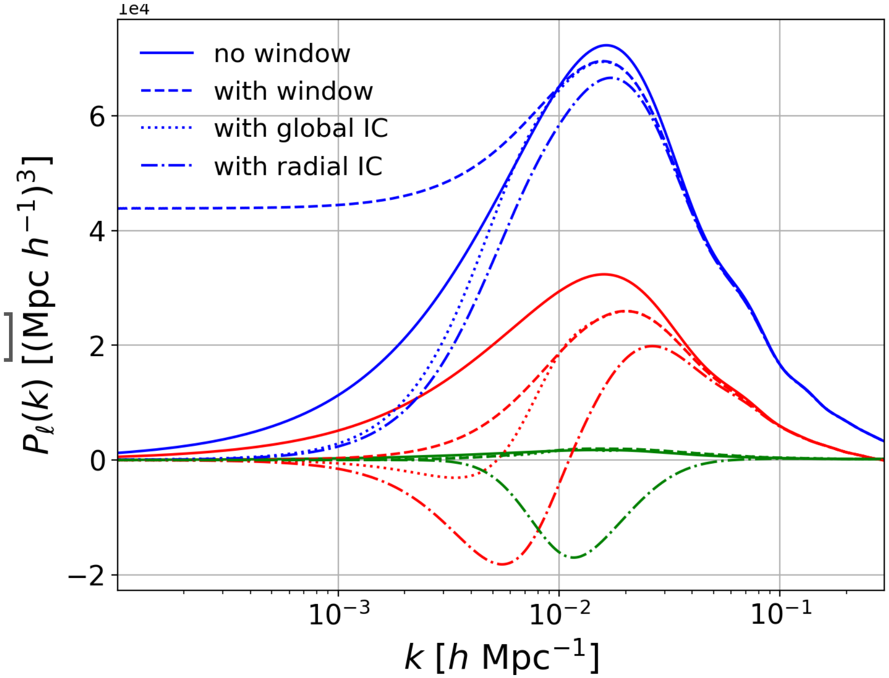
DESI forecasts

- DESI QSO similarly deep as eBOSS QSO sample -> no access to new scales, but 3 times the area
- $V_{\rm eff} \sim$ 8 times larger (at TO scale)
- $\mathscr{P}(m > 0) = 0.97$
- $\alpha_{\rm eq} = 1.018^{+0.032}_{-0.029}$
- $H_0 = \left(66.3^{+7.2}_{-2.9}\right)$ km/s/Mpc
- Blinded preliminary Y1 QSO results indicate we are on a good way



Radial integral constraint

- Radial selection function of random catalogue calibrated on radial distribution of data
- Nulling of radial modes [de Mattia&Ruhlmann-Kleider19]
- Radial integral constraint crucial for DESI LRG ultra-large-scale measurements
- Preserves position of DESI LRG turnover



[de Mattia&Ruhlmann-Kleider19]

Euclid forecasts

Euclid Large Mocks from Pinocchio lightcones (credit: Pigi Monaco)

Simulations performed with PINOCCHIO v4.1.3 and (mostly) v5:

- ΛCDM cosmology similar to Flagship 1
- $M_p=1.5\cdot10^{10}\ M_\odot/h$, smallest halo has 10 particles
- outputs at z=1, 0 + lightcone + histories
- periodic boxes available on request

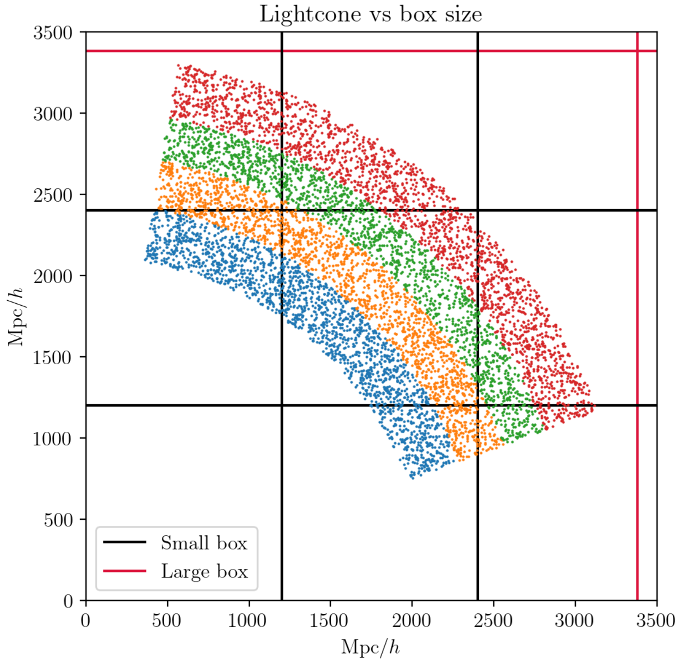
CREDITS:

- computing time provided by **INFN**, CINECA (ISCRA-B), INAF (Pleiadi)
- post-processing time provided by SGS
- storage provided by SGS and INAF IA2 archives

Euclid forecasts

Constraints on mock mean

- Measurement in 3 lowest redshift bins
- Allow for different P(k) amplitude
- Other 3 parameters kept equal at all redshifts
- $\alpha_{\mathrm{TO}} = 0.981^{+0.028}_{-0.026}$, errors 4 times smaller as eBOSS errors
- Detection probability $(m > 0)$: 85%



Credits: J. Salvalaggio

Conclusions

- Power spectrum turnover provides alternative standard ruler independent of BAO
- eBOSS QSO power spectrum not precise enough to determine gradient on scales larger than the turnover
- Scale of turnover in agreement expectation
- Euclid Y1 will establish evidence for the turnover at 85 per cent confidence level
- 97 per cent with full DESI QSO sample