Measuring the matter-radiation equality scale

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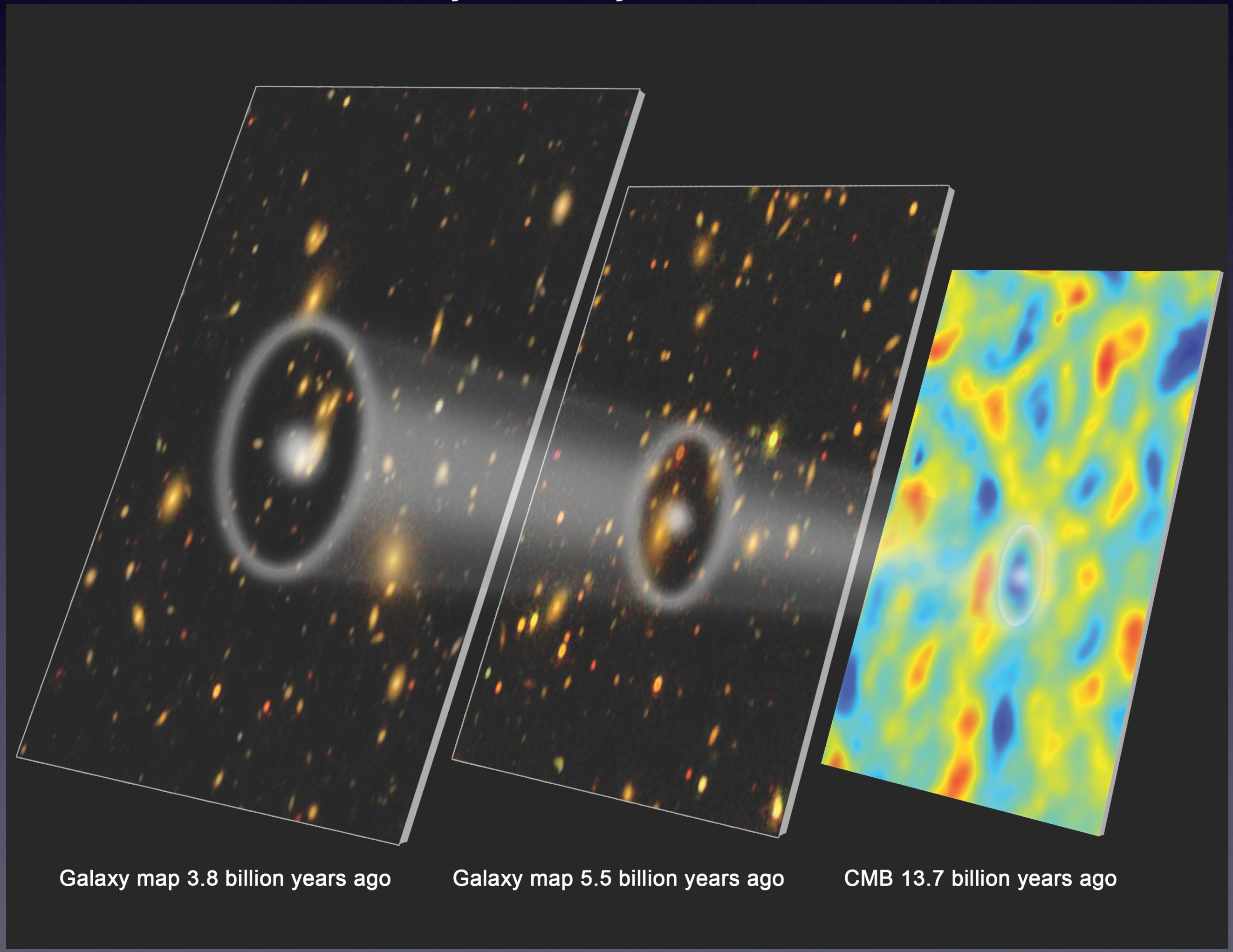
A note about rulers

- There are four physical quantities measured/relevant in cosmology:
  - Distance Earth to the Sun
  - Mass of the Earth/Sun
  - Monopole Temperature of the CMB
  - Recession velocity of galaxies
- Every other quantity in cosmology is either an angle, a number count (i.e. is there a galaxy or not), a ratio, or defined in terms of one of these three physical measures

- The physical scale of the BAO is fixed by the physics of the CMB, which relates to the CMB temperature, and the density of baryons



Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian.

The Turnover

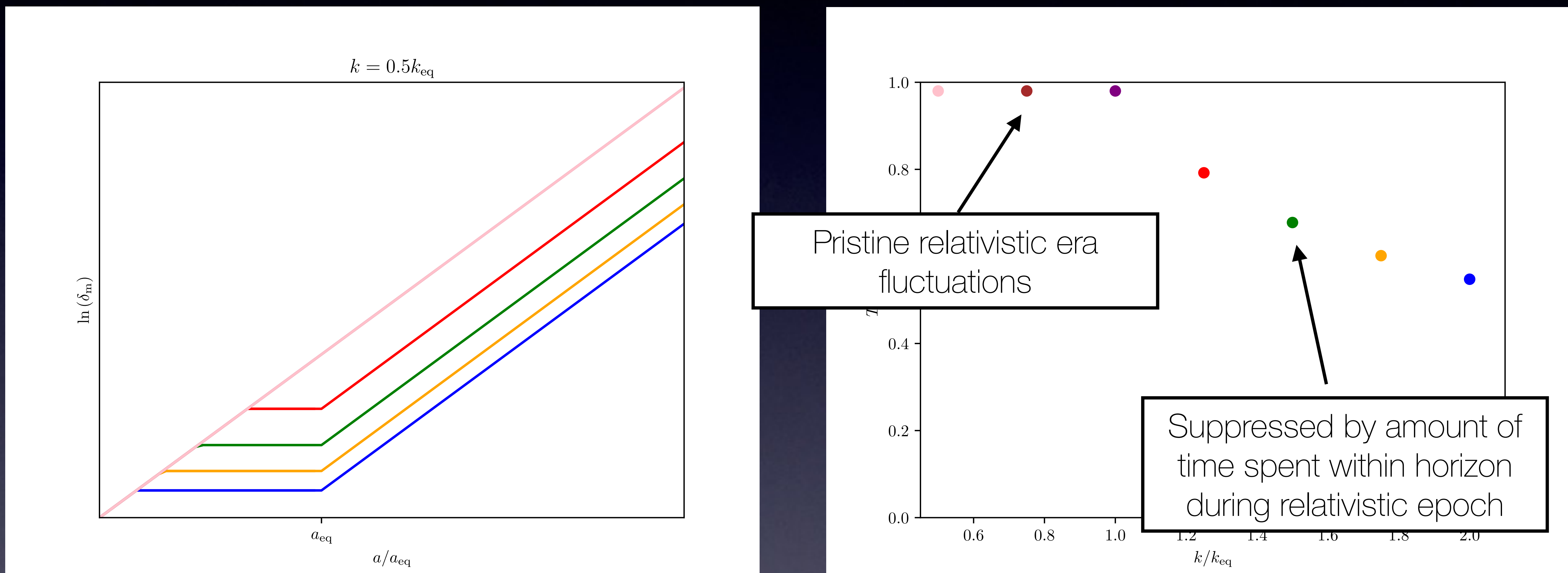
- The power spectrum peak is fixed by a physical scale: the matter-radiation equality scale
- Density fluctuations (after Inflation ends) grow at different rates depending on the details of the expansion (dominant component)
  - During Radiation Domination: Pressure stabilises sub-horizon perturbations, and they do not grow
  - During Matter Domination: Perturbations grow as $\delta_{\rm m} \propto a$
- This change over from radiation to matter domination is imprinted in the distribution of fluctuation amplitudes
- If we can measure the position of the power spectrum peak, we can use it as a standard ruler, similar to the BAO

$$a_{\rm eq} = \rho_{\rm rel} / \rho_{\rm mat}$$

$$r_{\rm H} = \frac{2c\left(\sqrt{2}-1\right)\sqrt{a_{\rm eq}}}{H_0\sqrt{\Omega_m}}$$

$$k_{\rm eq} = \left(4 - 2\sqrt{2}\right) r_{\rm H}^{-1}$$

Radiation- vs Matter Domination



During Radiation Domination

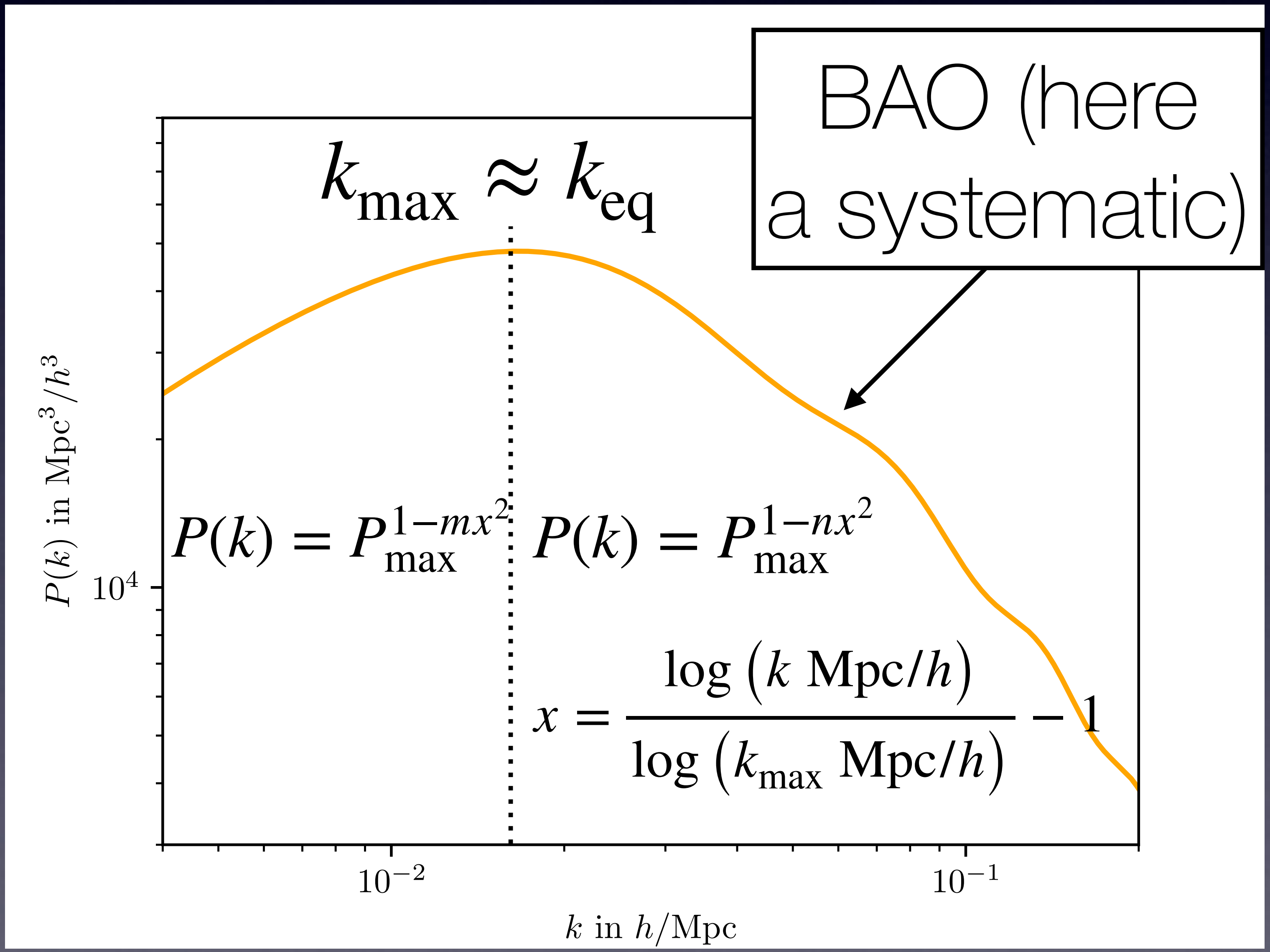
- Pressure stabilises sub-horizon perturbations

During Matter Domination

- Perturbations grow as $\delta_{\rm m} \propto a$

Alternative standard ruler

- Alternative to Full Shape: Localising Turnover scale similar to BAO method
- Parameterisation following [Poole *et al.* 2011]:
  - two slopes (m, n)
  - One amplitude $P_{\rm max}$
  - One turn-over scale $k_{\rm max}$
  - $k_{\rm max,fid} = 0.0166 h/{\rm Mpc}$
- Probability of $m > 0$ gives turn-over detection probability

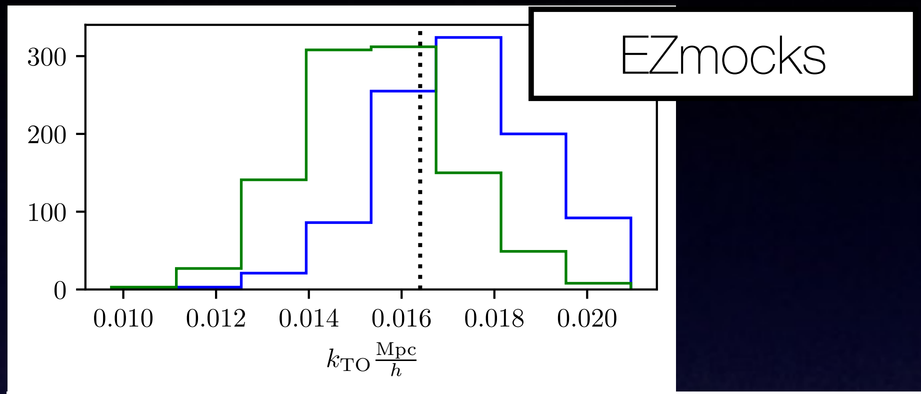


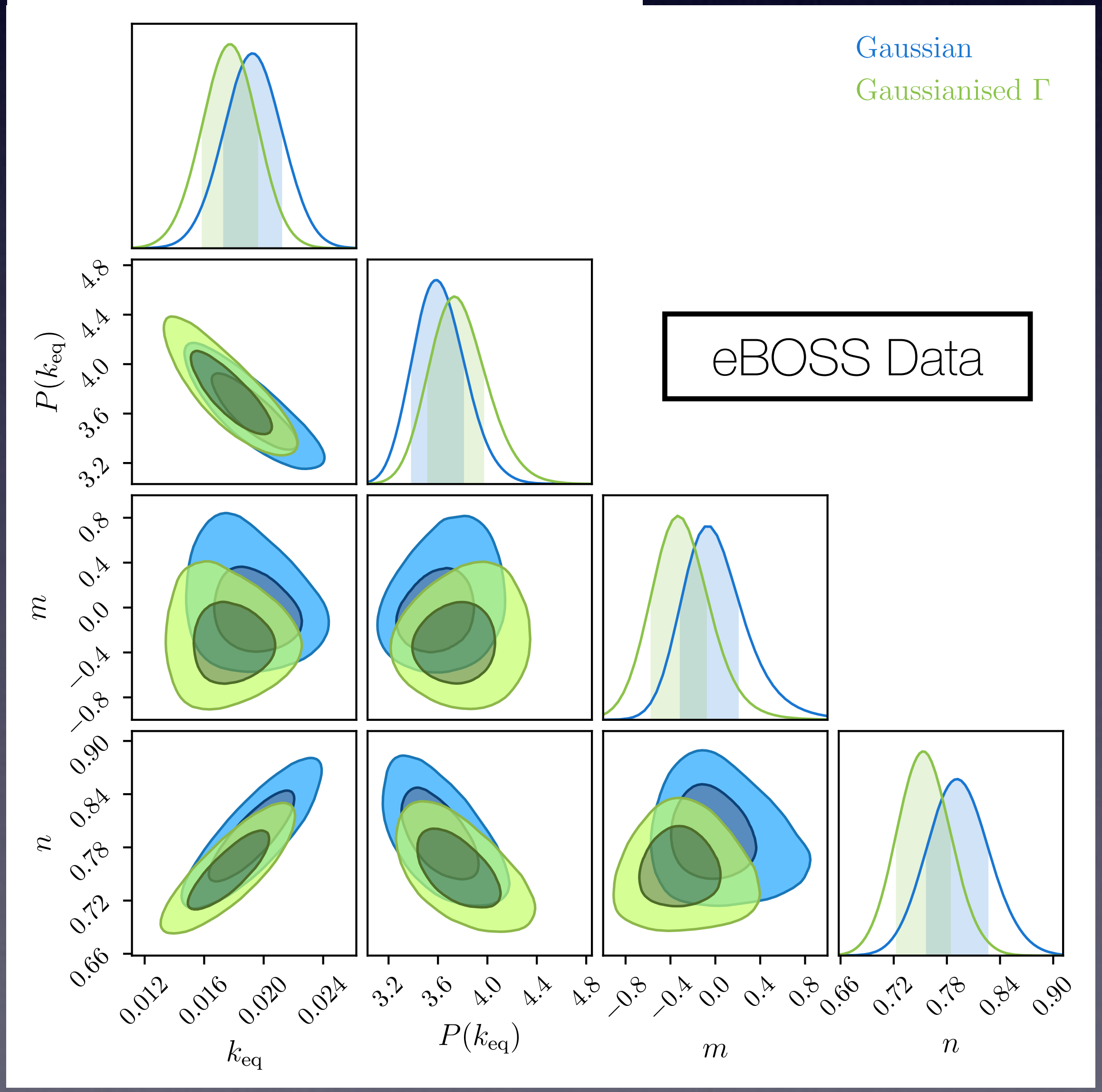
Application to eBOSS

- Most redshift surveys don't probe enough volume to probe scales $k < k_{\mathrm{TO,fid}} = 0.0166h/\mathrm{Mpc}$
- Largest pre-DESI spectroscopic data: eBOSS QSO
  - 343 708 Quasars, $0.8 < z < 2.2$, $4699\mathrm{deg}^2$
  - Mean redshift of sample $z = 1.48$
  - We use Rezaie *et al.* (2021)'s $P(k)$ measurement and randoms with systematic weights optimised for eBOSS DR16 f_{NL} measurement [Mueller *et al.* 2021]

Results

- Unfortunately, no evidence for $m > 0$
- However, we do find inflection point at the expected scale
  - Fiducial value: $k_{\mathrm{TO,fid}} = 16.6 \times 10^{-3} h/\mathrm{Mpc}$
  - With Gaussianised Γ-distributed $P(k)$ [Wang et al. 2019]: $k_{\mathrm{TO}} = \left(17.6^{+1.9}_{-1.8}\right) \times 10^{-3} h/\mathrm{Mpc}$



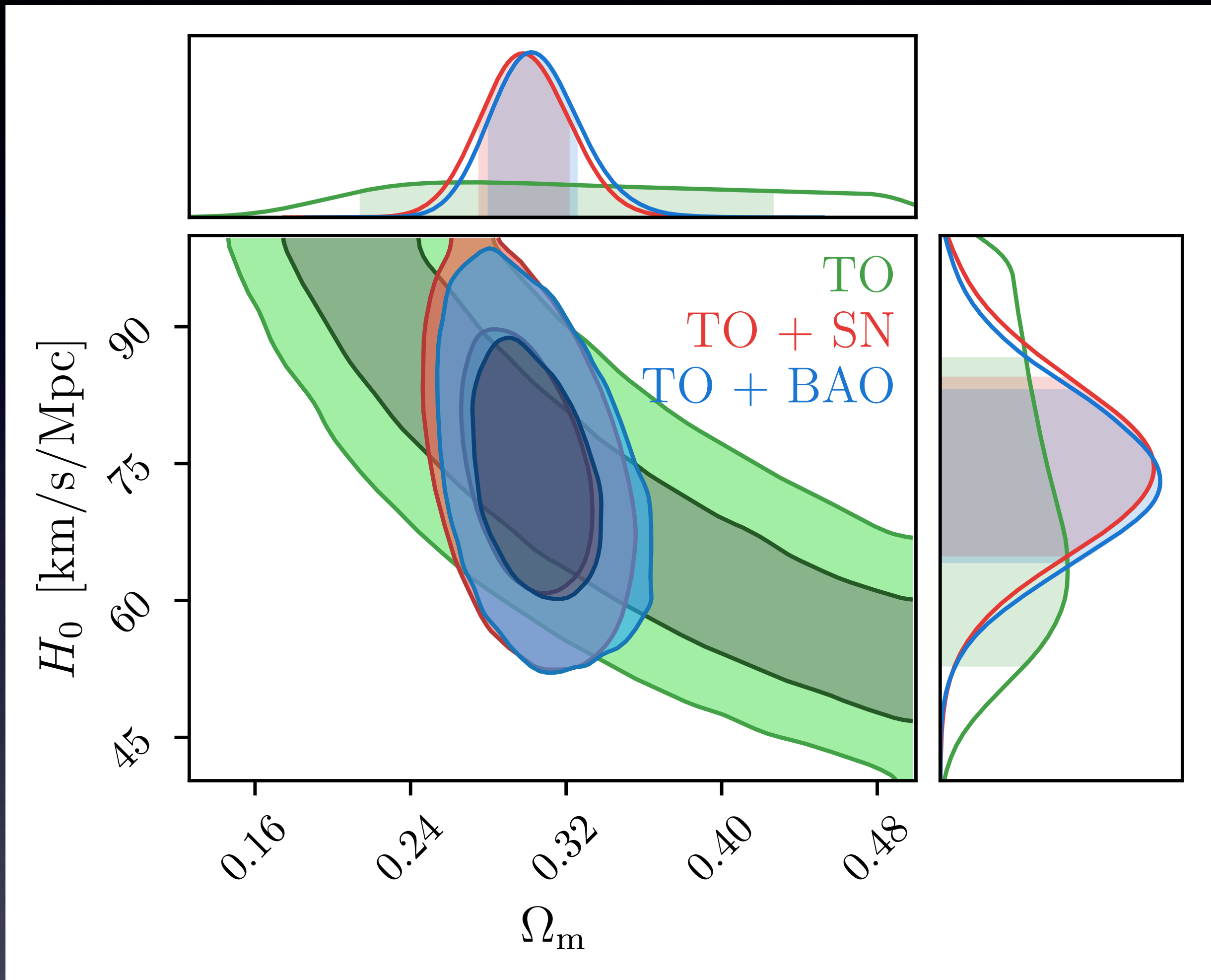


Results

- Though we cannot be completely certain that the inflection point we detected is the turnover, we can still use the position to make some inferences
- Define r_d-independent standard ruler $\alpha_\mathrm{eq} = \dfrac{D_\mathrm{V}}{D_\mathrm{V}^\mathrm{fid}} \dfrac{r_\mathrm{H}^\mathrm{fid}}{r_\mathrm{H}}$
    - $\alpha_\mathrm{eq} = 1.07^{+0.12}_{-0.13}$
    - cf. $\alpha_\mathrm{bao} = 1.025 \pm 0.020$ [Neveux et al. 2020]
- Assuming 3 standard neutrino species, direct measurement of $\Omega_\mathrm{m} h^2 = 0.159^{+0.041}_{-0.037}$

Turnover and H_0

- We can combine the turnover position with uncalibrated BAO or SN-Ia
  - Without Cepheids (SN-Ia) or the CMB (BAO) these distances are insensitive to H0 and only measure the density parameters, such as Ω_m
- We find:
  - $H_0 = (74.7 \pm 9.6)$ km/s/Mpc (with Pantheon) and
  - $H_0 = (72.9^{+10.0}_{-8.6})$ km/s/Mpc (with eBOSS LRG and Lyα BAO)
- Results seem to prefer higher value of H0 than Planck+BAO results, more in line with SH0ES Cepheid+SN-Ia results



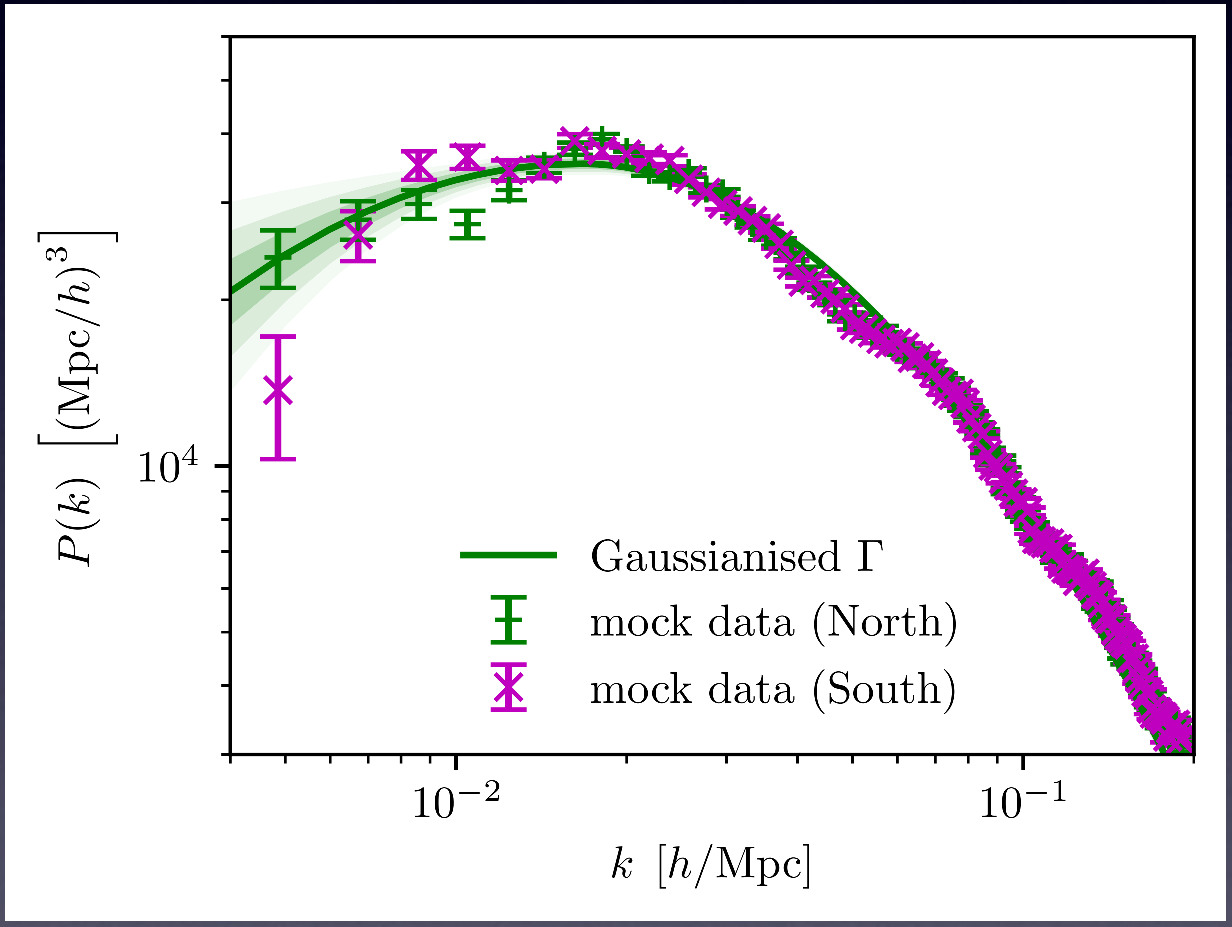
No sound horizon information included (marginalise over $\Omega_b h^2$ w/o prior, and parameter is poorly constrained)

Comparison Table

Data set combination	H_0 constraints (km/s/Mpc)	Calibrator
Cepheid+SN-Ia	73.04 ± 1.04	Parallax
CMB+BAO	67.66 ± 0.42	CMB Physics
Turnover+SN-Ia	74.7 ± 9.6	Equality scale
Turnover+BAO	72.9+10/-8.6	Equality scale

DESI forecasts

- DESI QSO similarly deep as eBOSS QSO sample -> no access to new scales, but 3 times the area
  - V_{eff} ~ 8 times larger (at TO scale)
  - $\mathscr{P}(m > 0) = 0.96$
  - $\alpha_{\mathrm{eq}} = 0.973^{+0.028}_{-0.029}$
  - $H_0 = \left(63.0^{+7.5}_{-2.8}\right)\ \mathrm{km/s/Mpc}$
- Making similar forecasts for DESI BGS, LRG and ELG surveys
- Constraints will not be competitive with BAO+CMB, but will provide an independent cross-check/confirmation



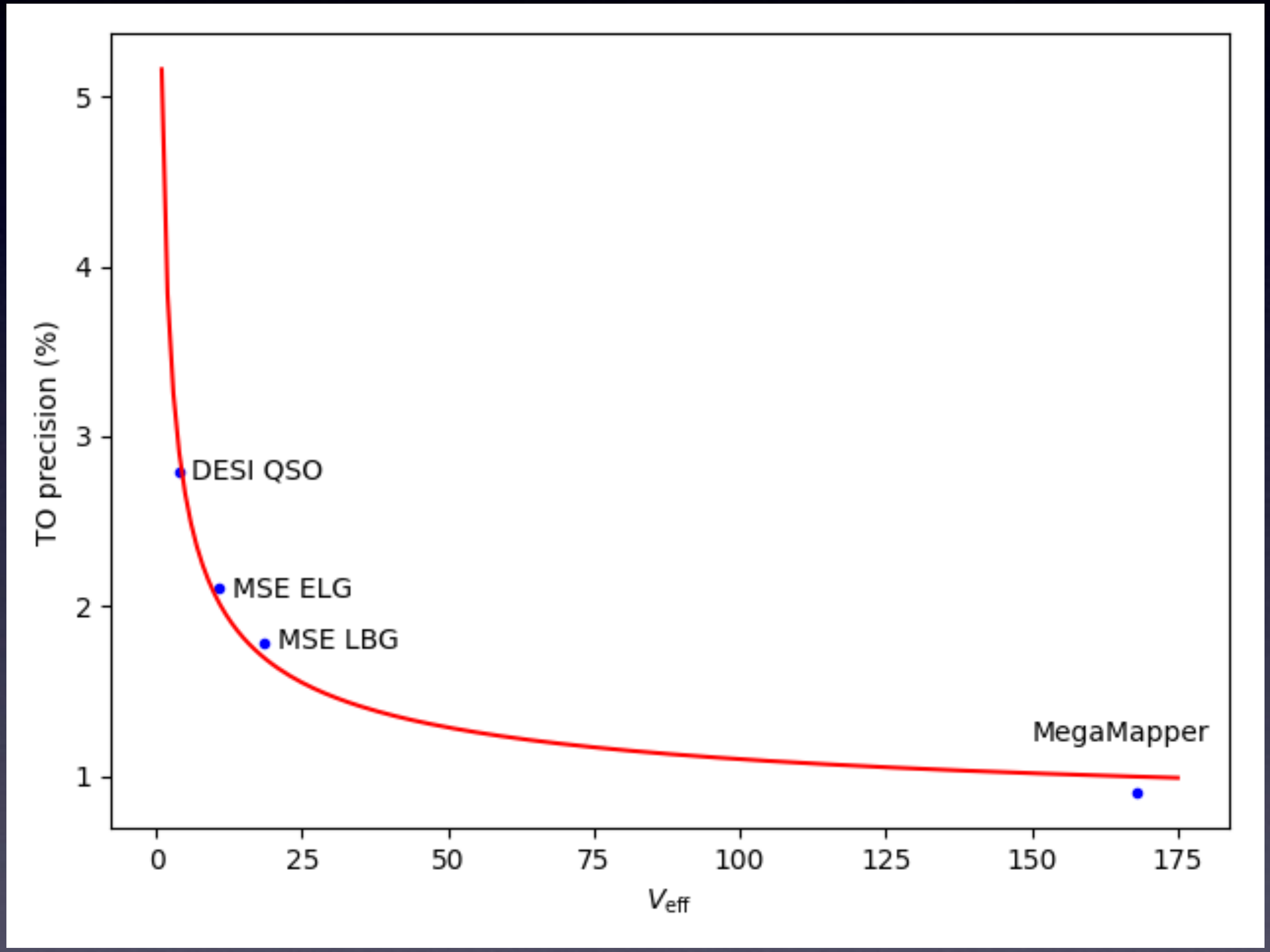
Beyond DESI

- We forecast for DESI, MSE and MegaMapper, as baseline future surveys
  - MegaMapper will provide an α_{eq} constraint that is tighter than the isotropic α_{BAO} from eBOSS QSO
- With a set of equality scale measurements and a Hubble parameter at z=0, we can also inverse the ladder, to measure $\Omega_{rel}h^2$

Sample	$\Omega_m h^2$	H_0
DESI QSO	0.135 +0.03/-0.013	66.3 +7.2/-2.9
MSE ELG	0.139 +0.026/-0.010	67.0 +6.3/-2.3
MSE LBG	0.01385 +0.0228/-0.0077	66.8 +5.4/-1.7
MegaMapper	0.1367 +0.00177/-0.0046	66.4 +4.2/-1.0

Survey parameters

- Volume is key
  - Modes are linear, so redshift makes less of a difference than volume
  - Number density is less of an issue, as sample/cosmic variance dominates, but high V_{eff} helps
- Need something like MegaMapper to reach sub-percent level



Summary

- Power spectrum turnover provides alternative standard ruler independent of BAO, calibrated purely in terms of relativistic energy density
- eBOSS QSO power spectrum not precise enough to determine gradient on scales larger than the turnover, but scale of turnover in agreement with expectation
- Using turnover scale as standard ruler, we find $D_{\rm V}(z_{\rm eff} = 1.48) = \left(36.2^{+4.1}_{-4.4}\right) r_{\rm H}$
- 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
  $H_0 = \left(74.7 \pm 9.6\right)\ {\rm km/s/Mpc}$ (with Pantheon) and
  $H_0 = \left(72.9^{+10.0}_{-8.6}\right)\ {\rm km/s/Mpc}$ (with eBOSS LRG and Lyα BAO)
- Full DESI QSO will establish evidence for the turnover at 96 per cent confidence level
- Future spectroscopic surveys will measure the turnover scale accurately enough to constrain H_0 at the 5% level, independently of any other calibrator

Extra slide - correlation

- The feature is extracted in such a way to minimise the effect of BAO on the recovery of the scale (mode de-projection), there may still be some covariance between the turnover and BAO scale
- We use DESI mocks to check for correlation between the dilation parameter **α** for the BAO and a measurement of the turnover, finding it to be <10%