

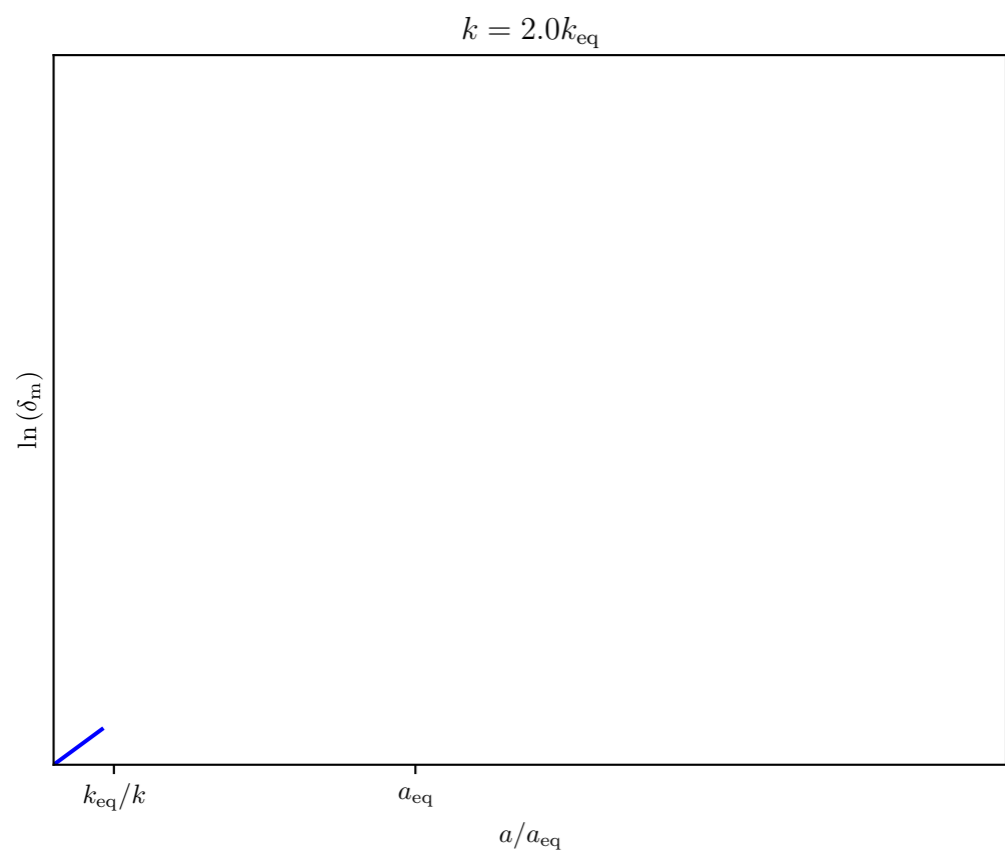
# The matter-radiation-equality scale: Robustness criterion on ultra-large scales and new insights into the Hubble tension

Benedict Bahr-Kalus  
IP2I Lyon, soon INAF Torino

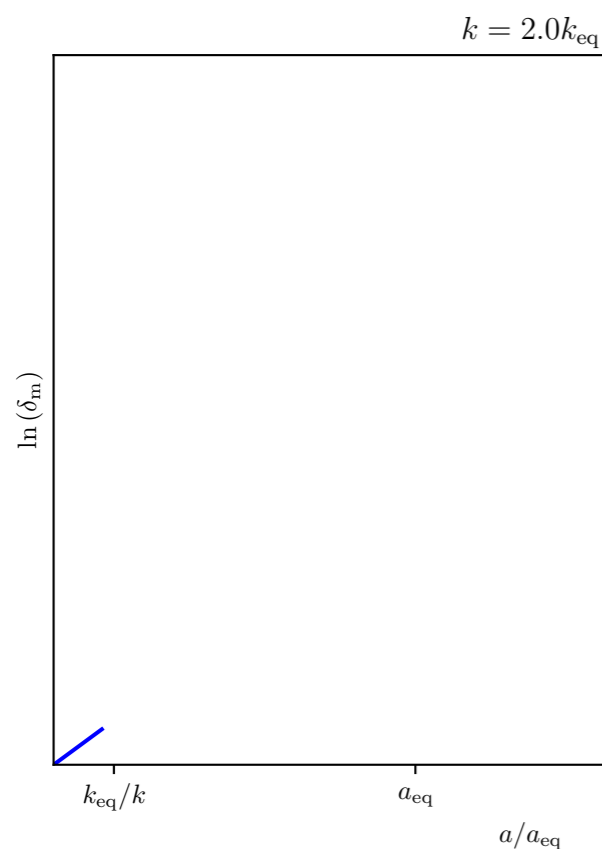
In collaboration with:  
David Parkinson (KASI) & Eva-Maria Mueller (University of Sussex)  
[arXiv:2302.07484](https://arxiv.org/abs/2302.07484)

With contributions from Edmond Chaussidon, Arnaud de Mattia, Pigi Monaco, Daniel Forero-Sanchez

# Radiation- vs Matter Domination



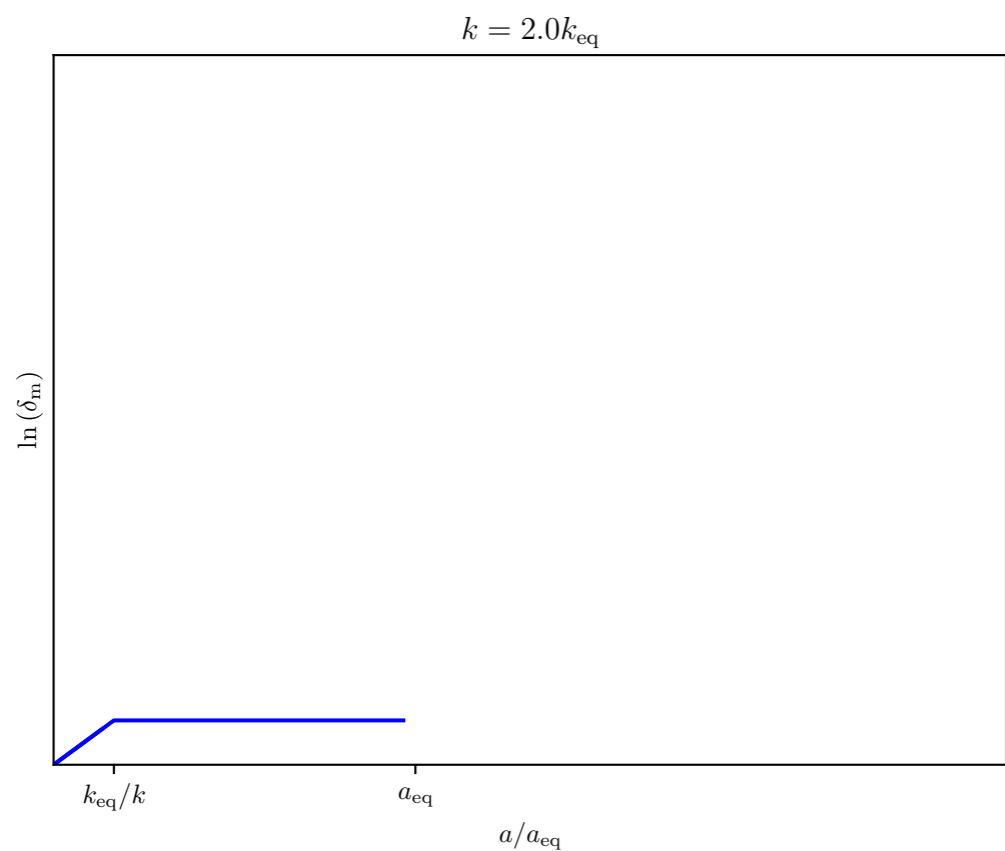
# Radiation- vs Matter Domination



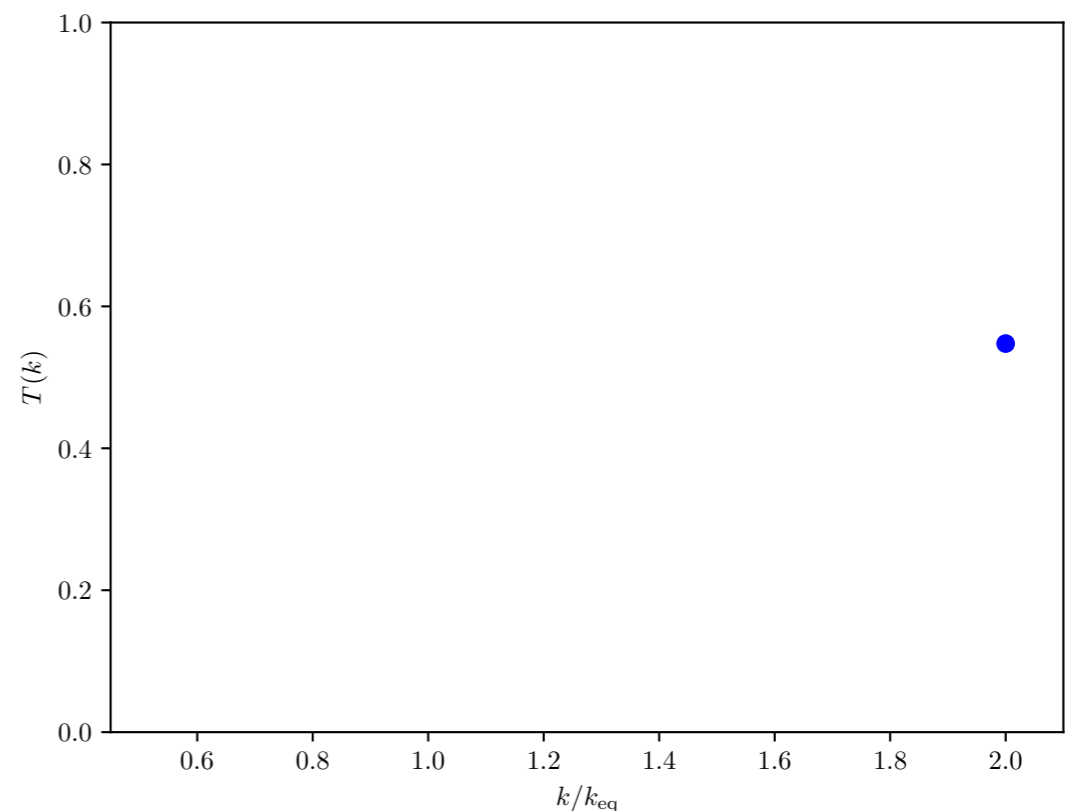
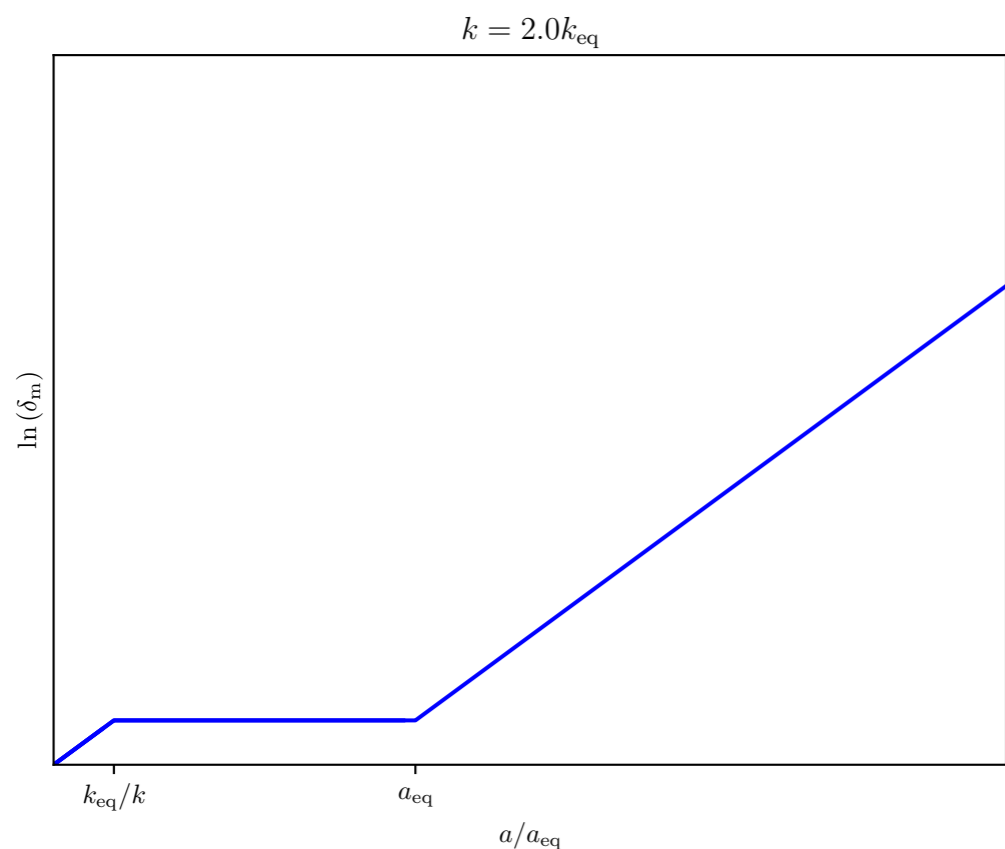
During Radiation Domination

- Pressure stabilises sub-horizon perturbations

# Radiation- vs Matter Domination



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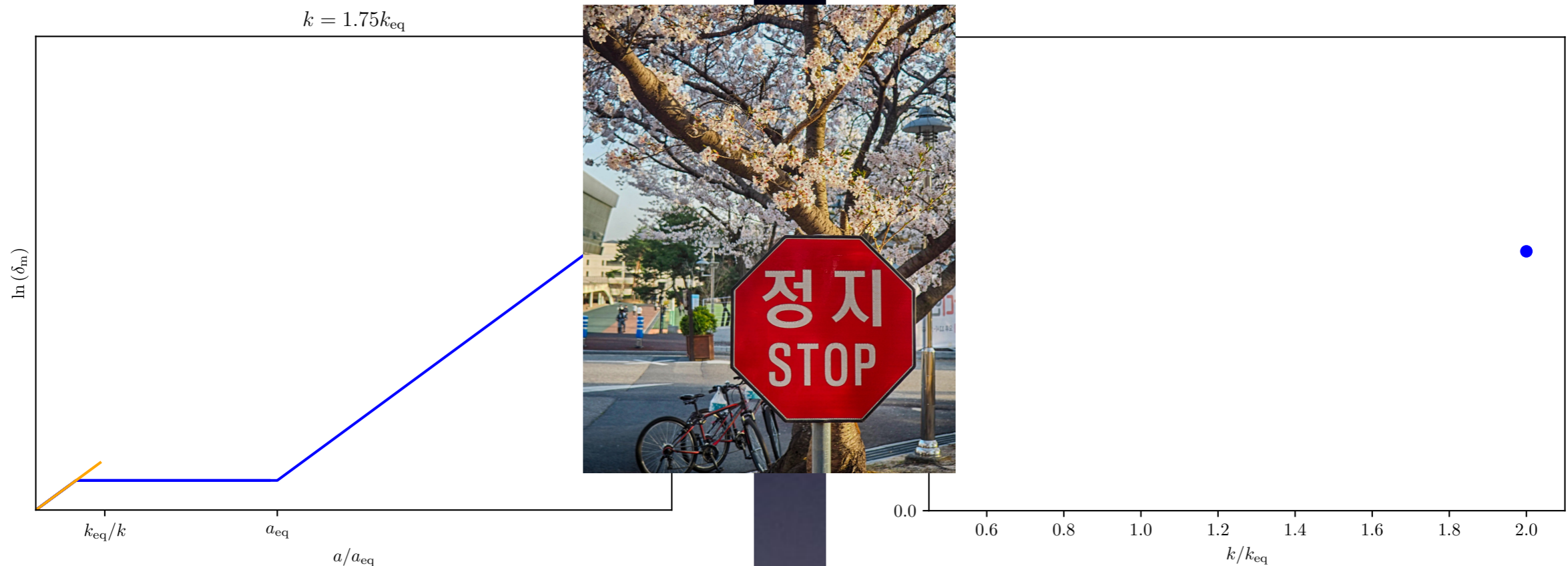


During Matter Domination

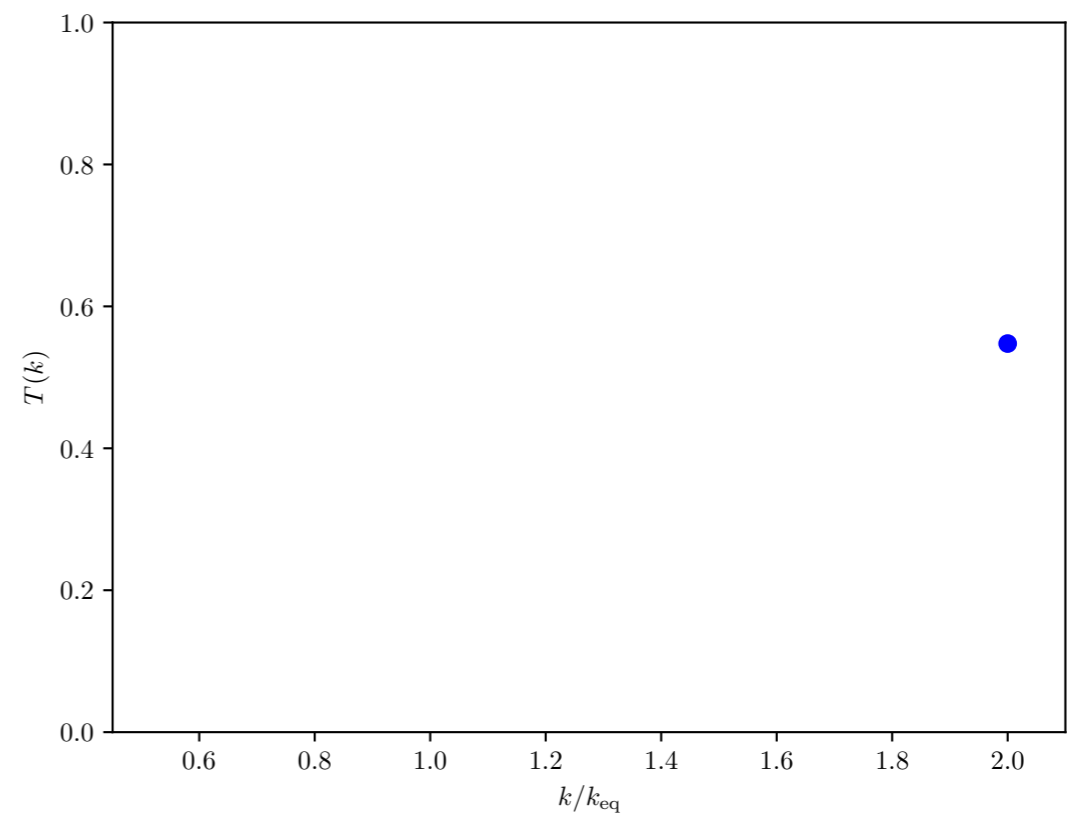
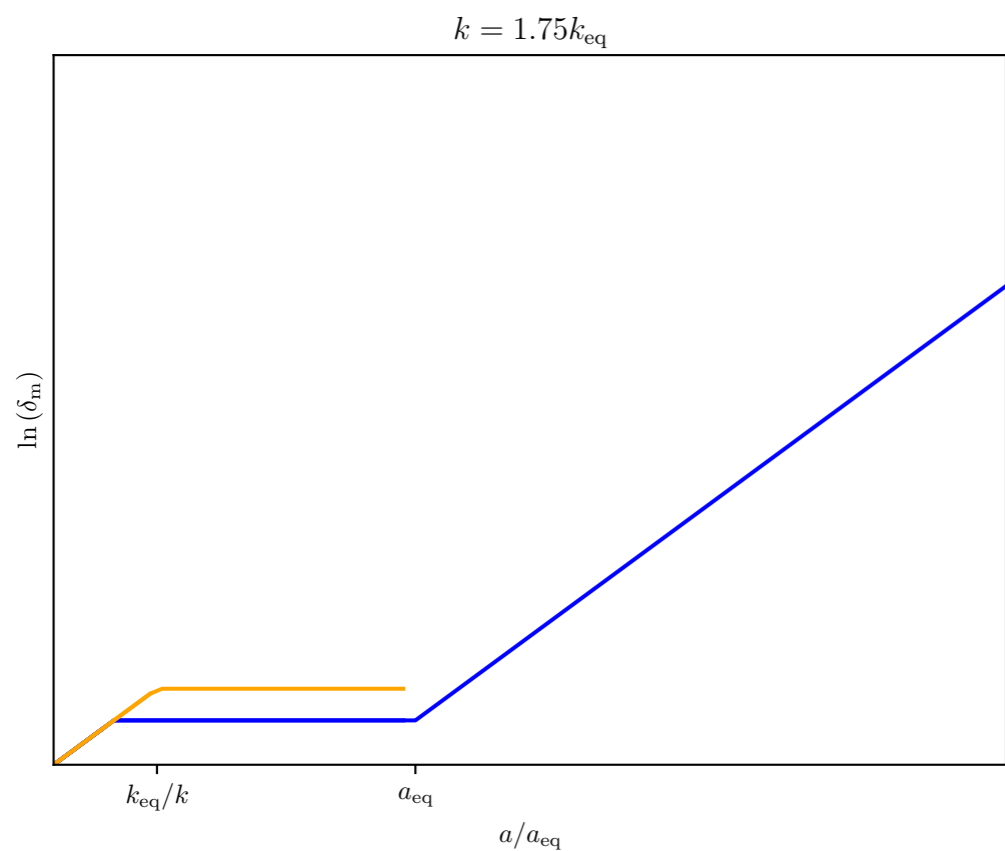
- Perturbations grow as

$$\delta_m \propto a$$

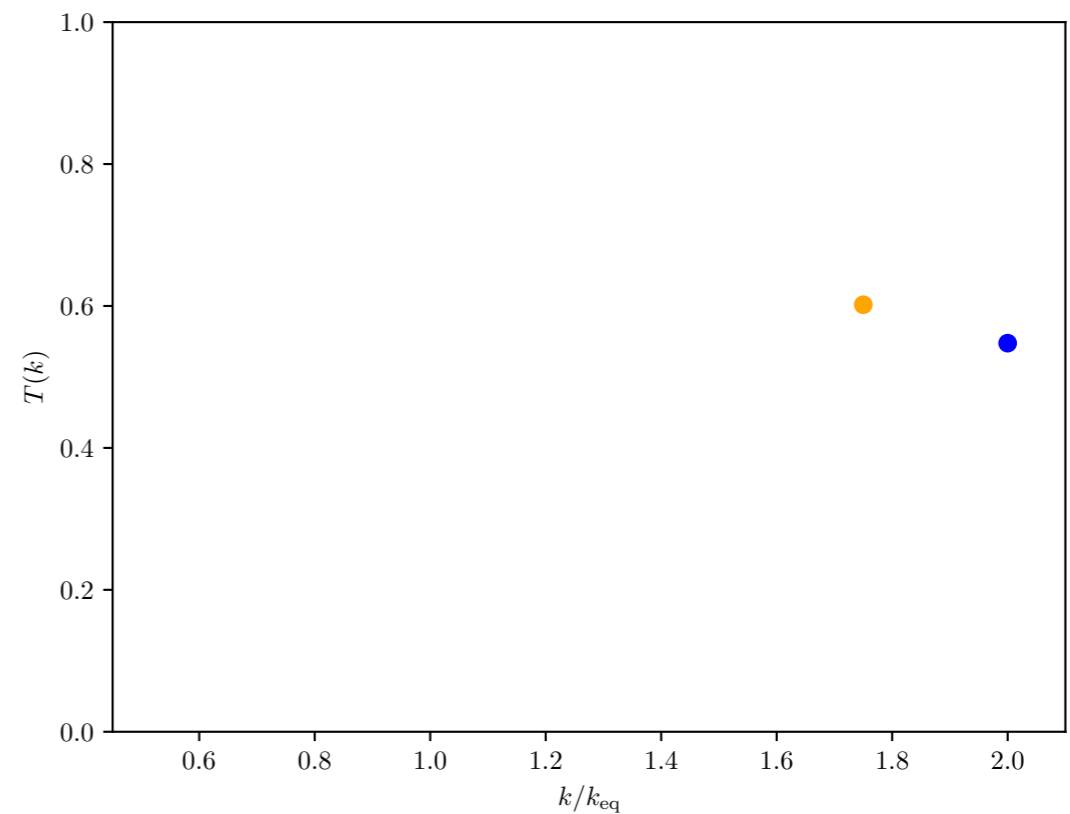
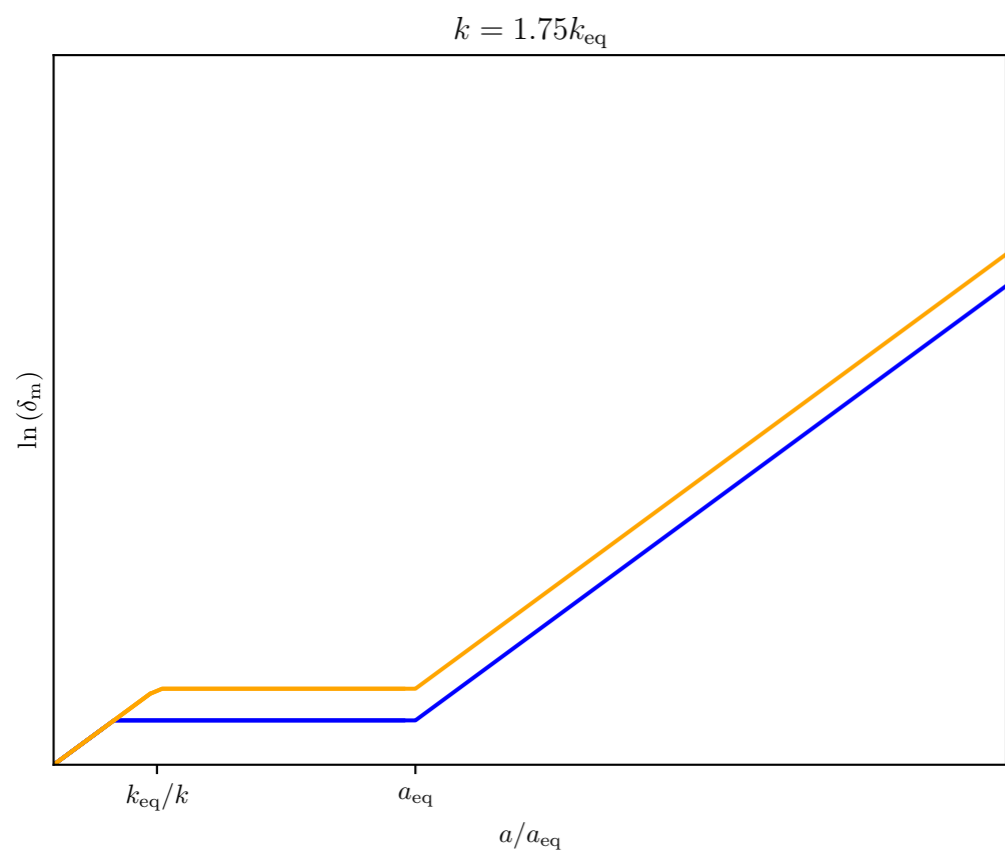
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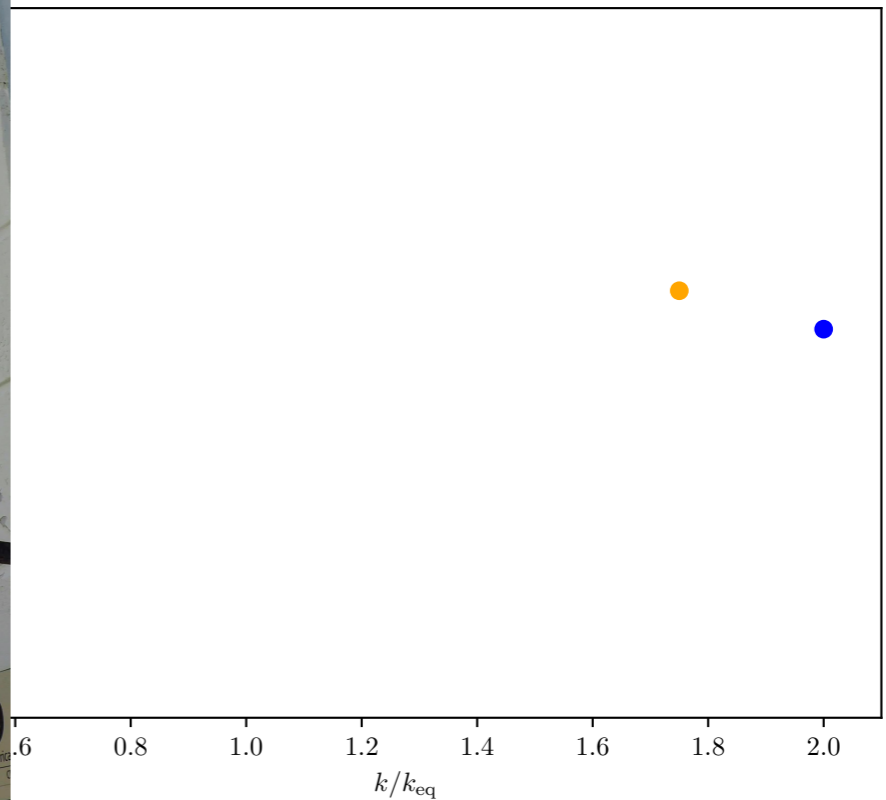
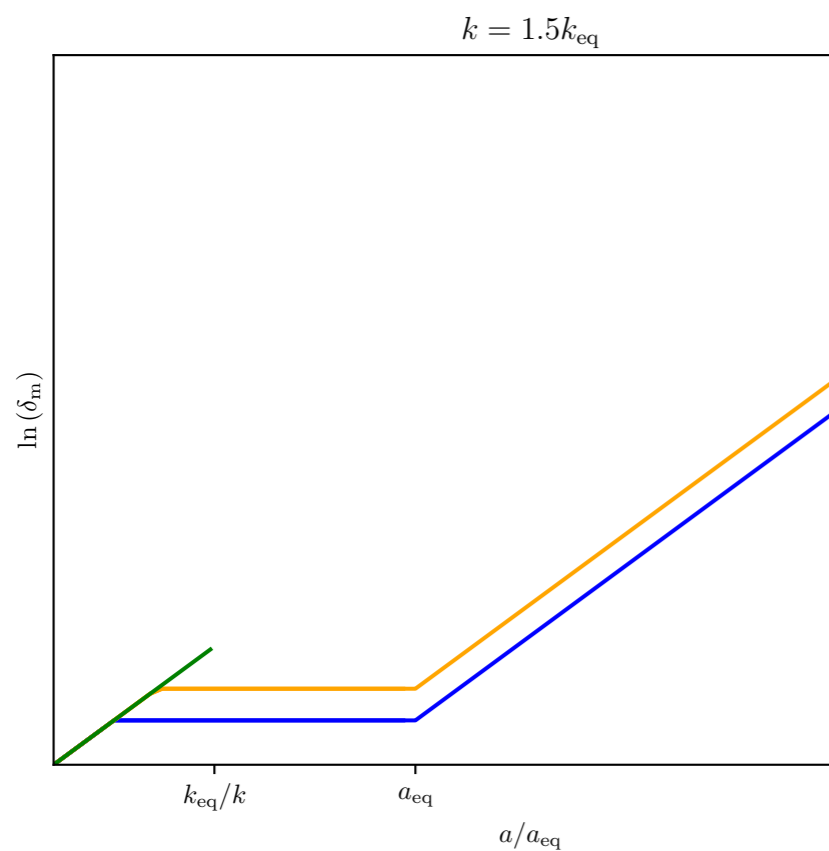


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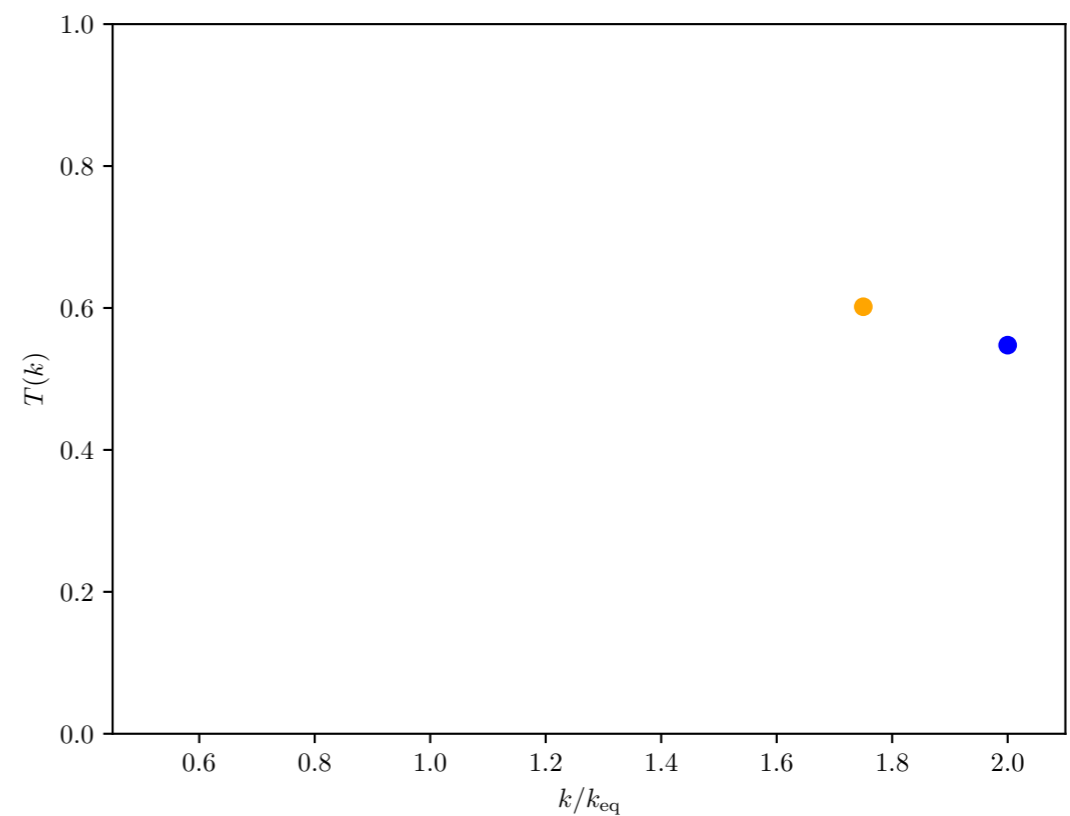
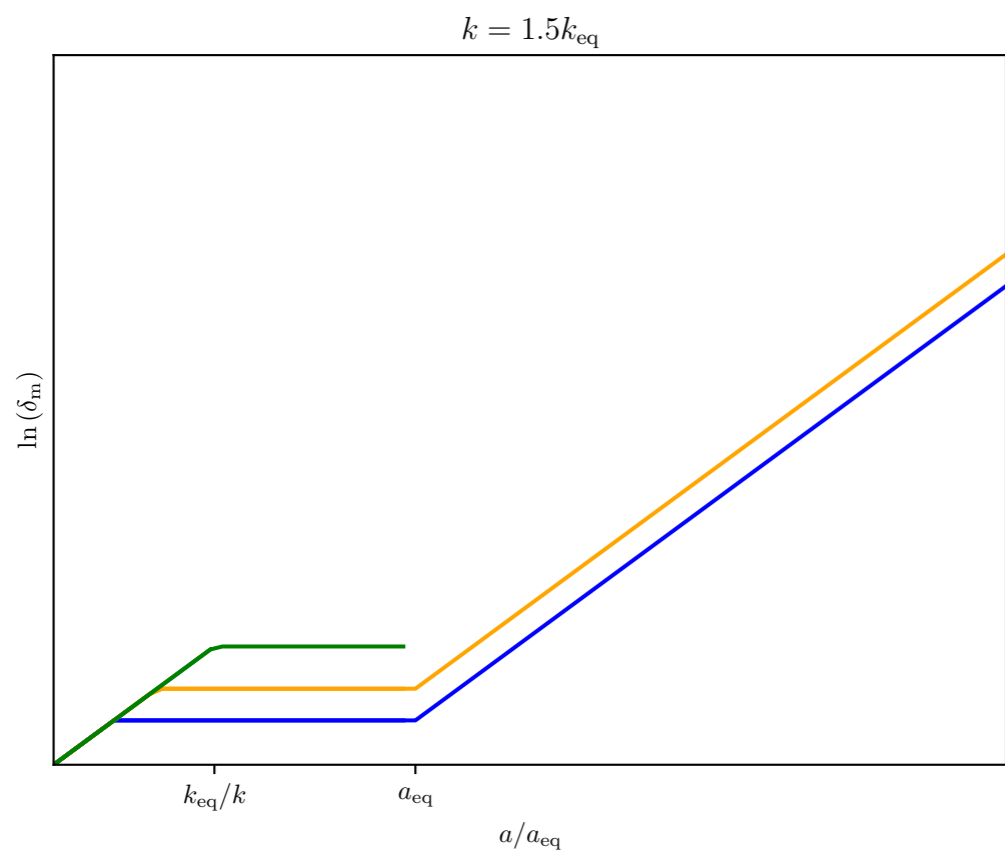




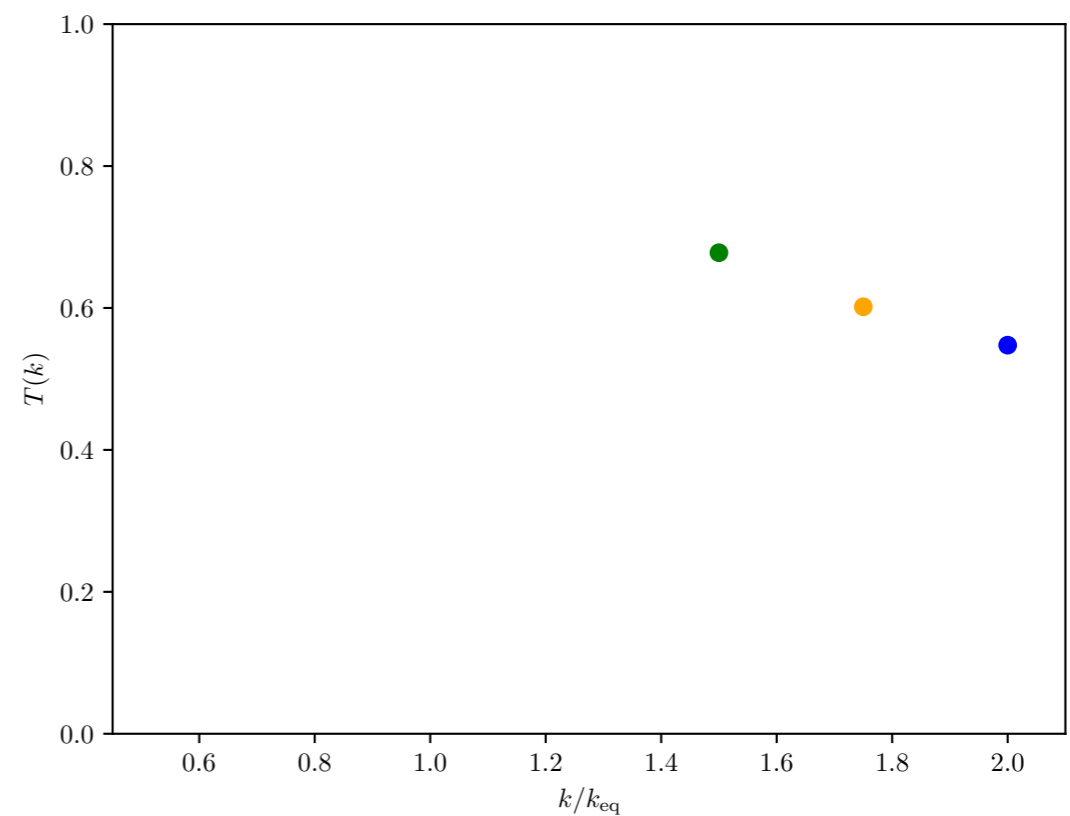
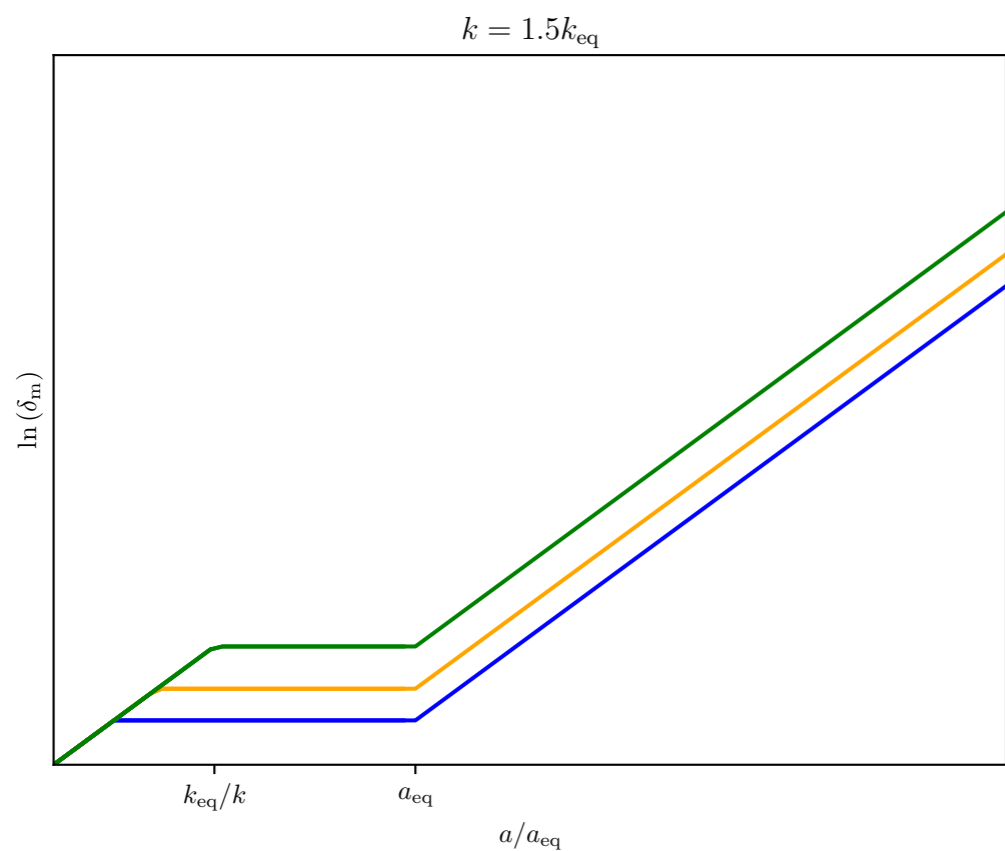
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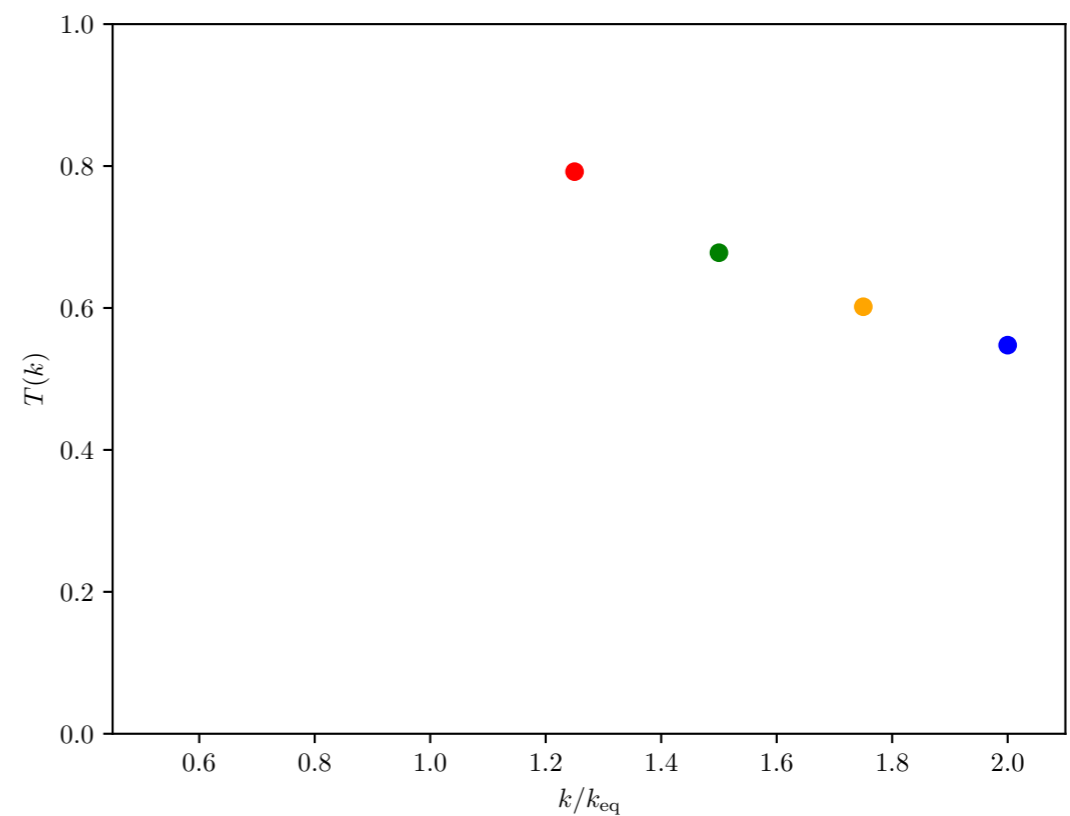
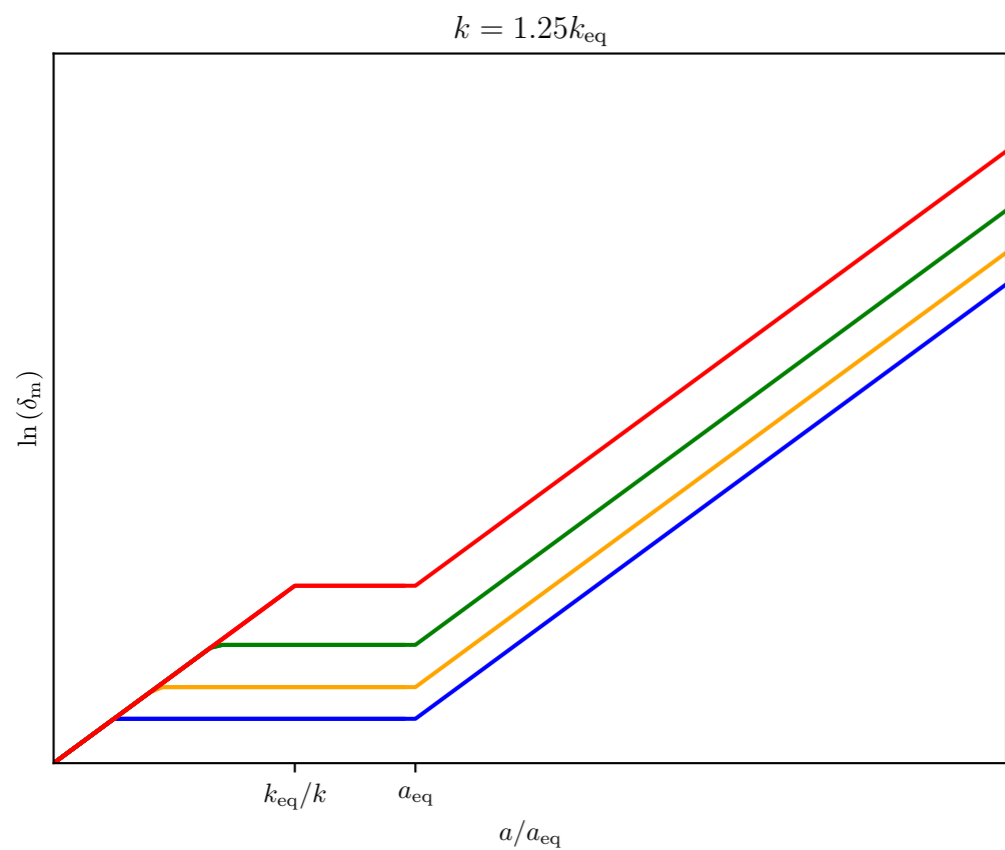
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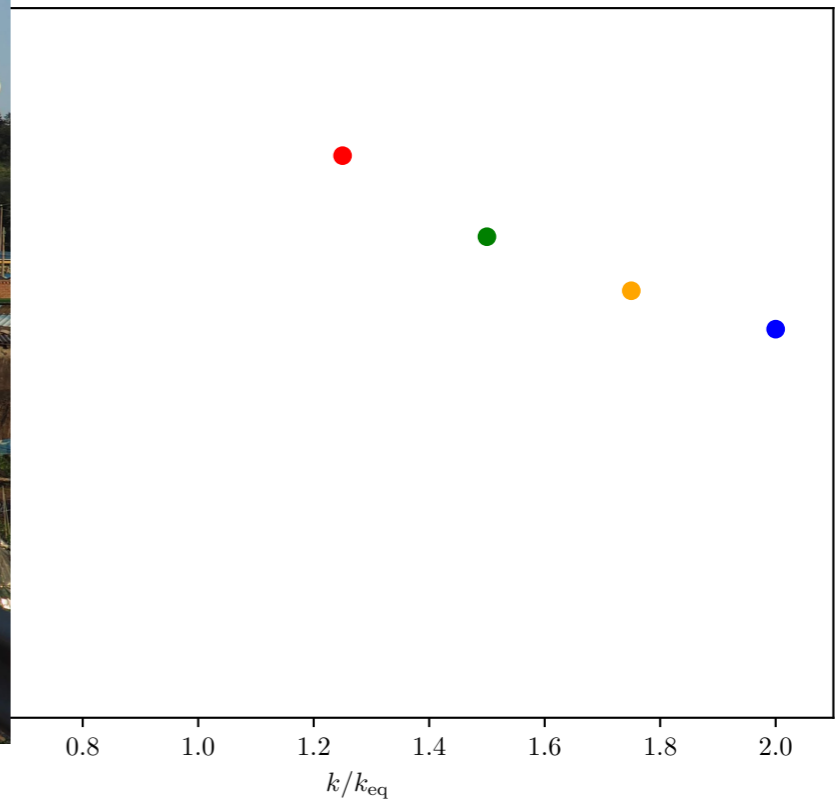
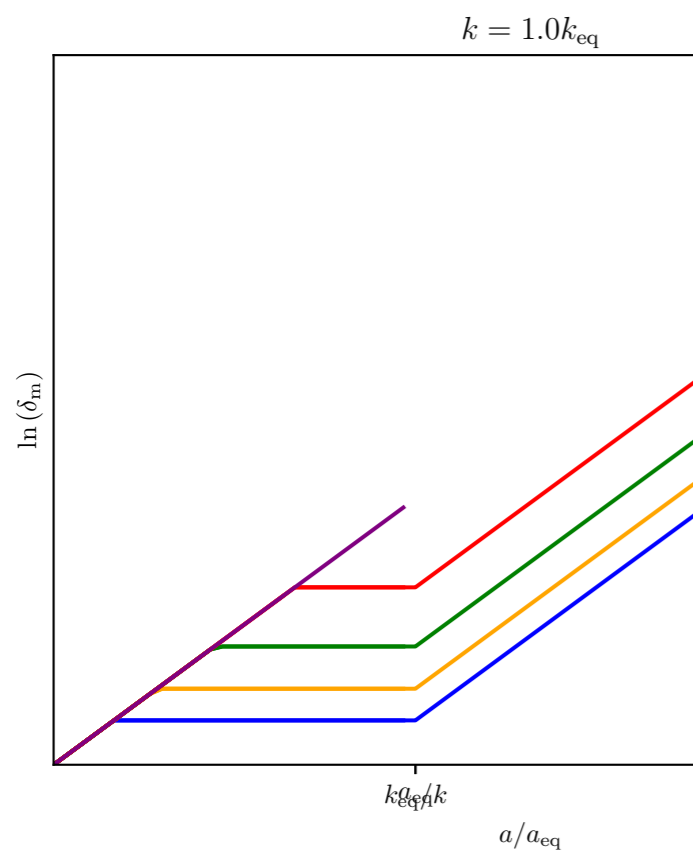
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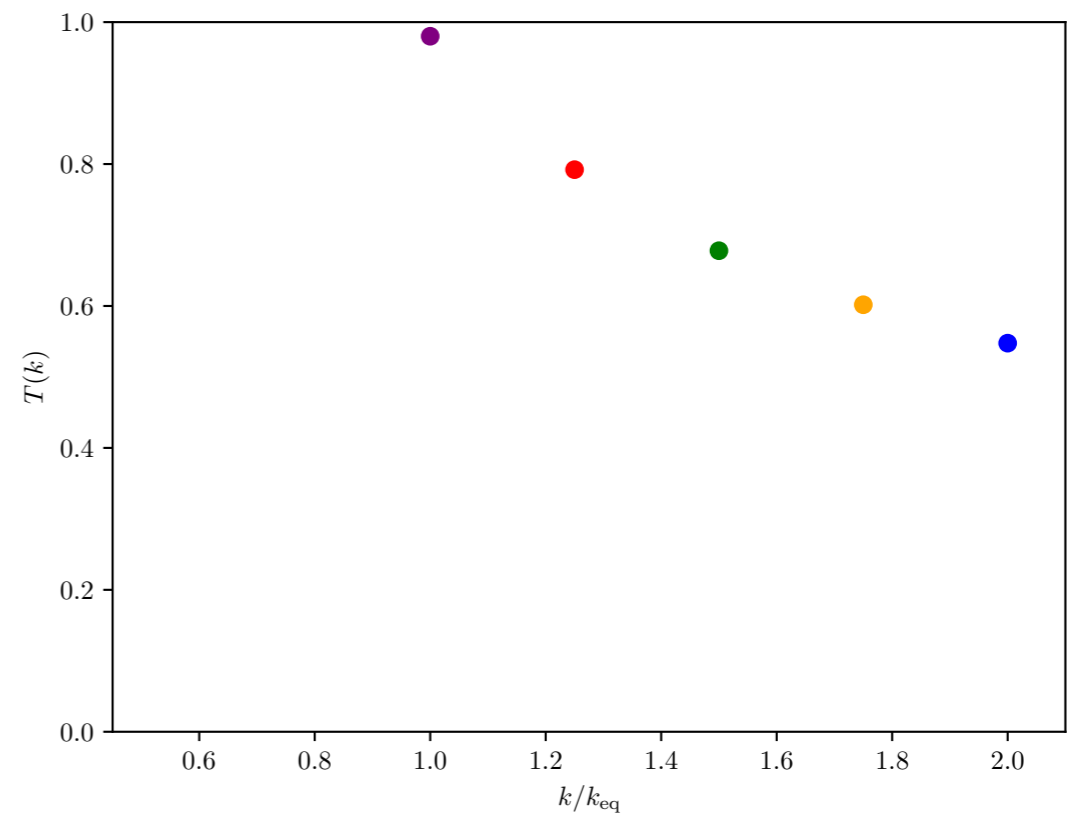
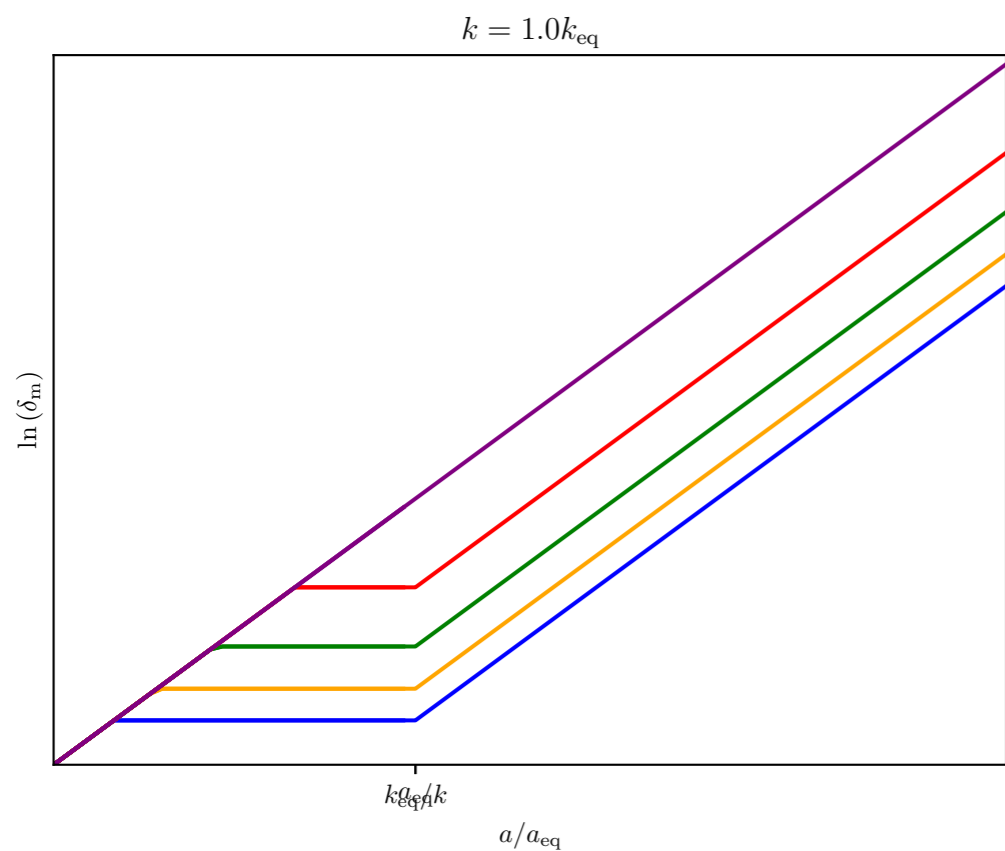
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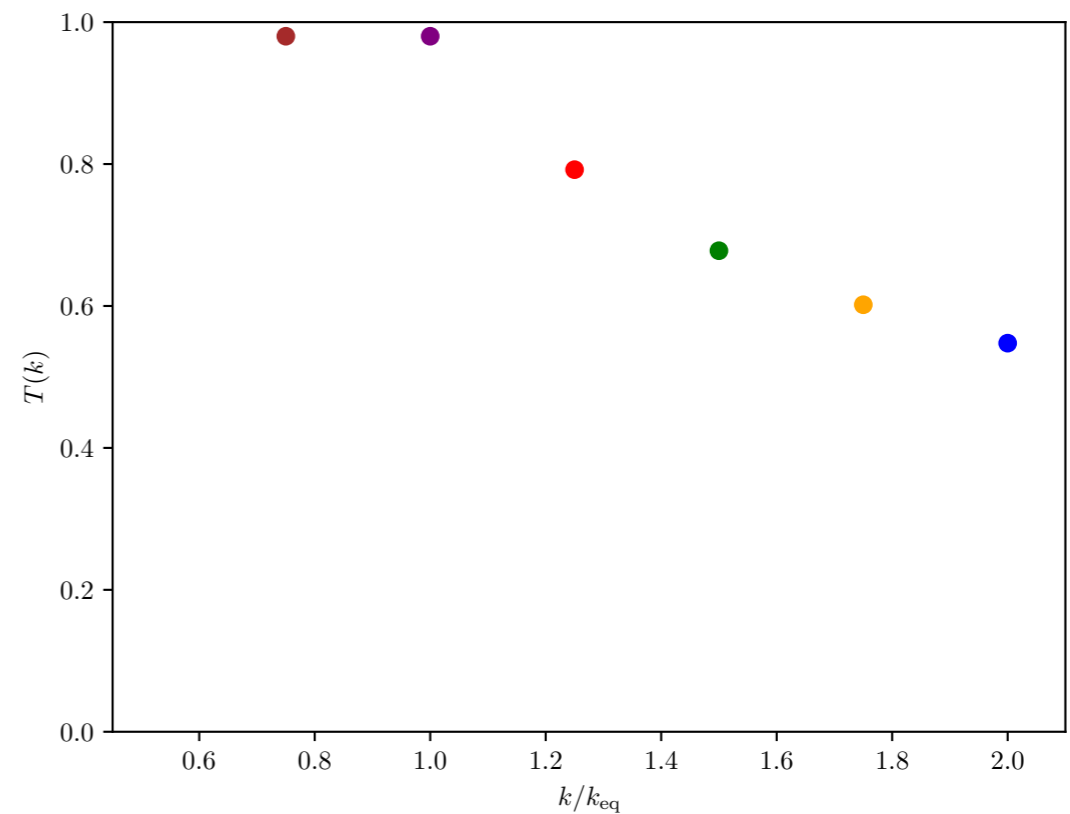
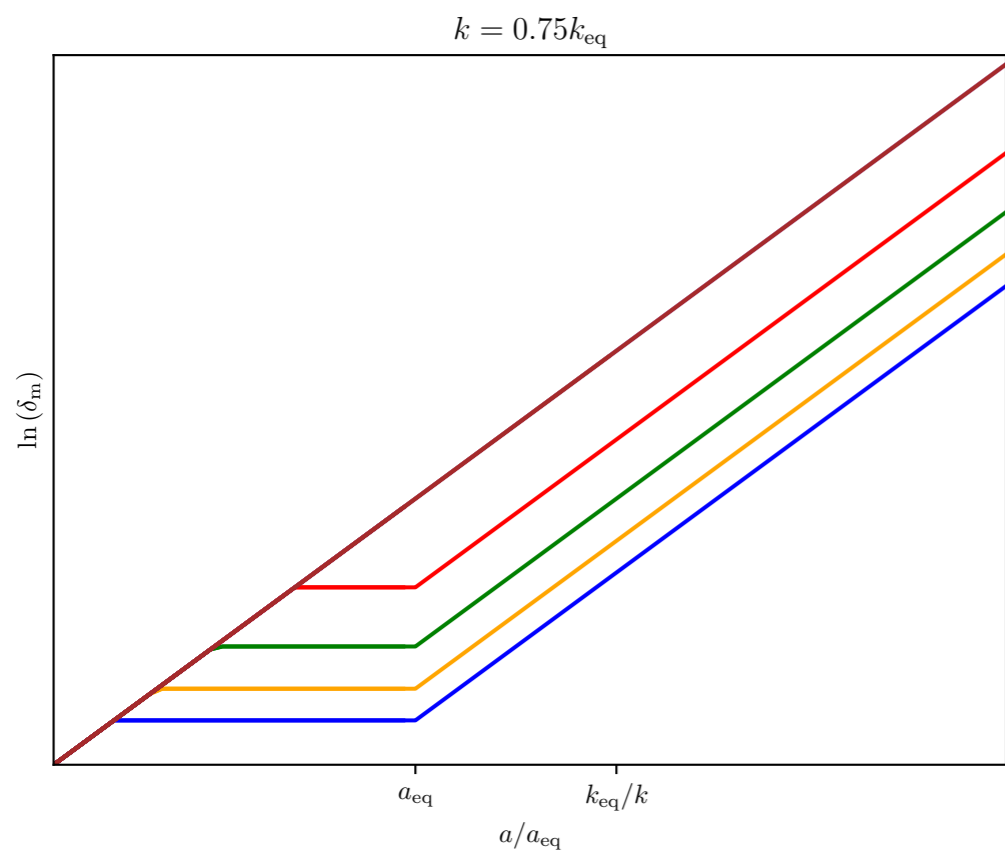
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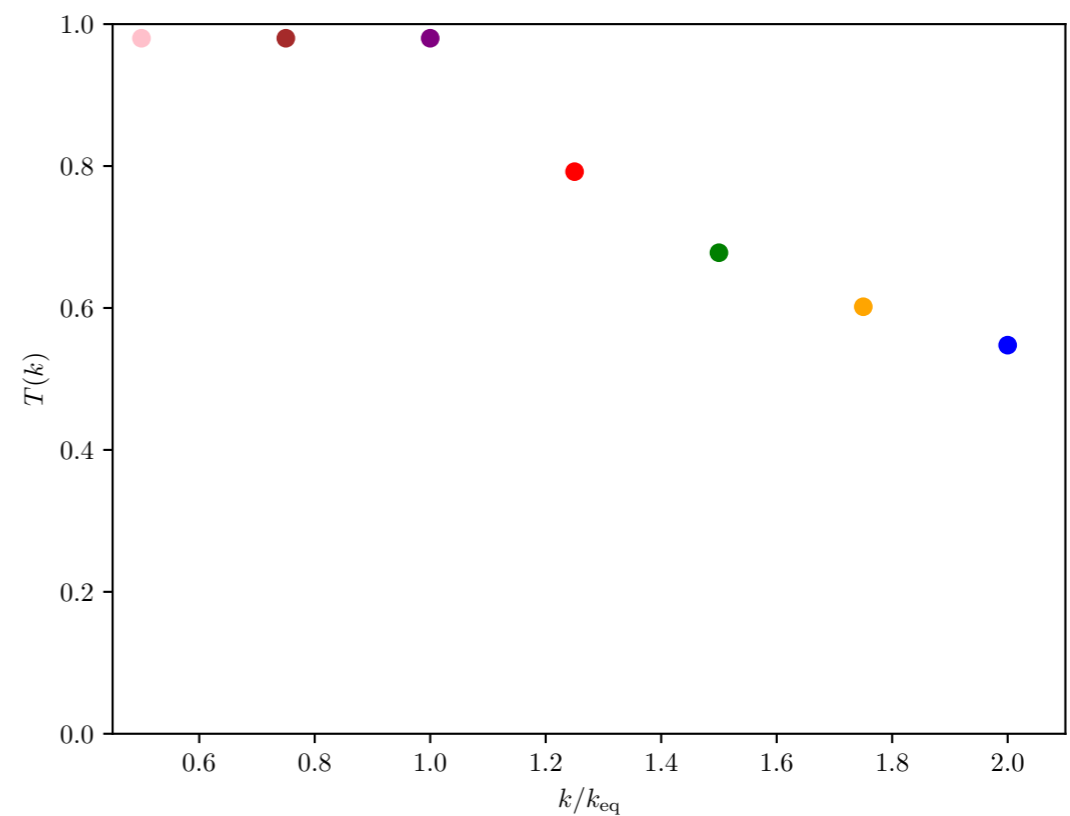
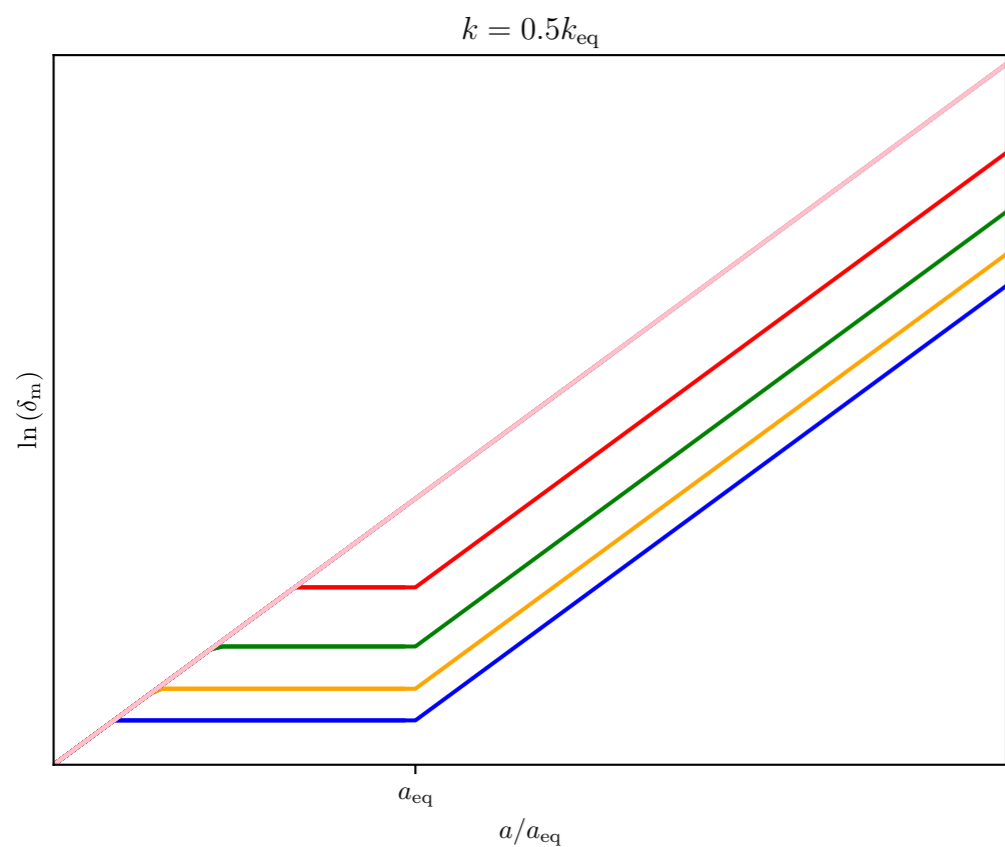
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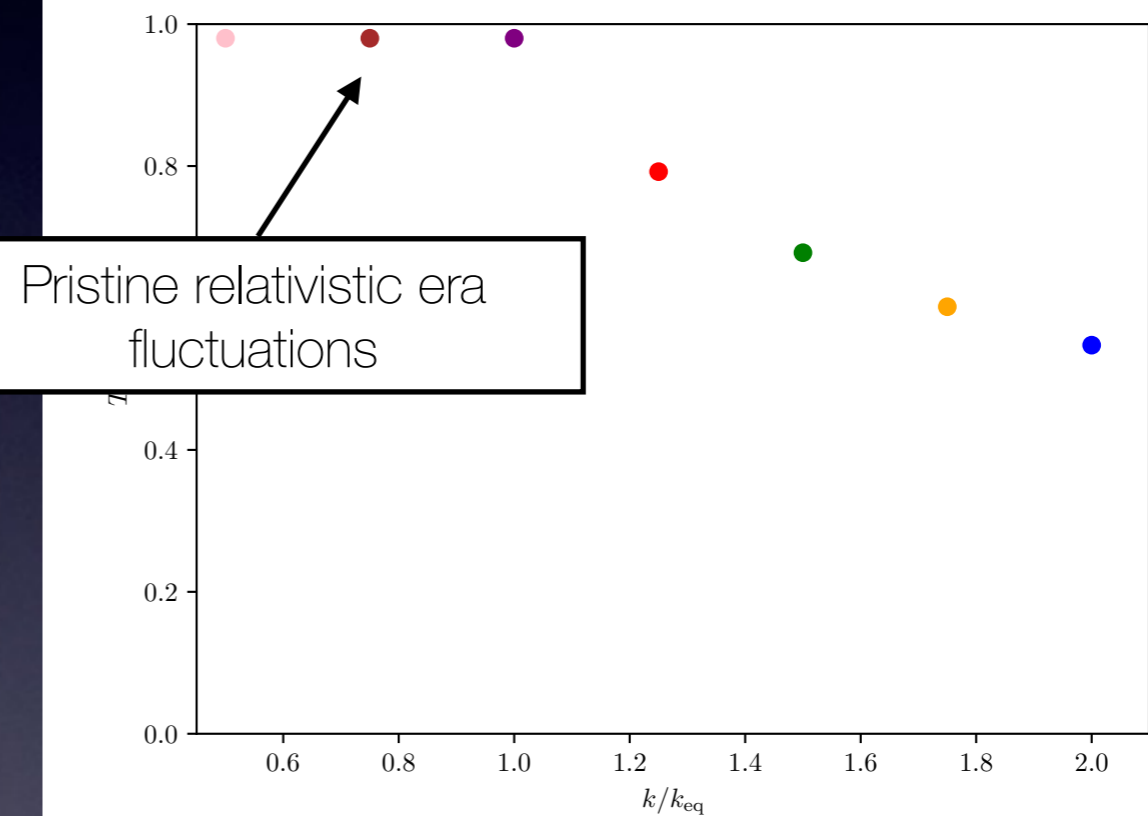
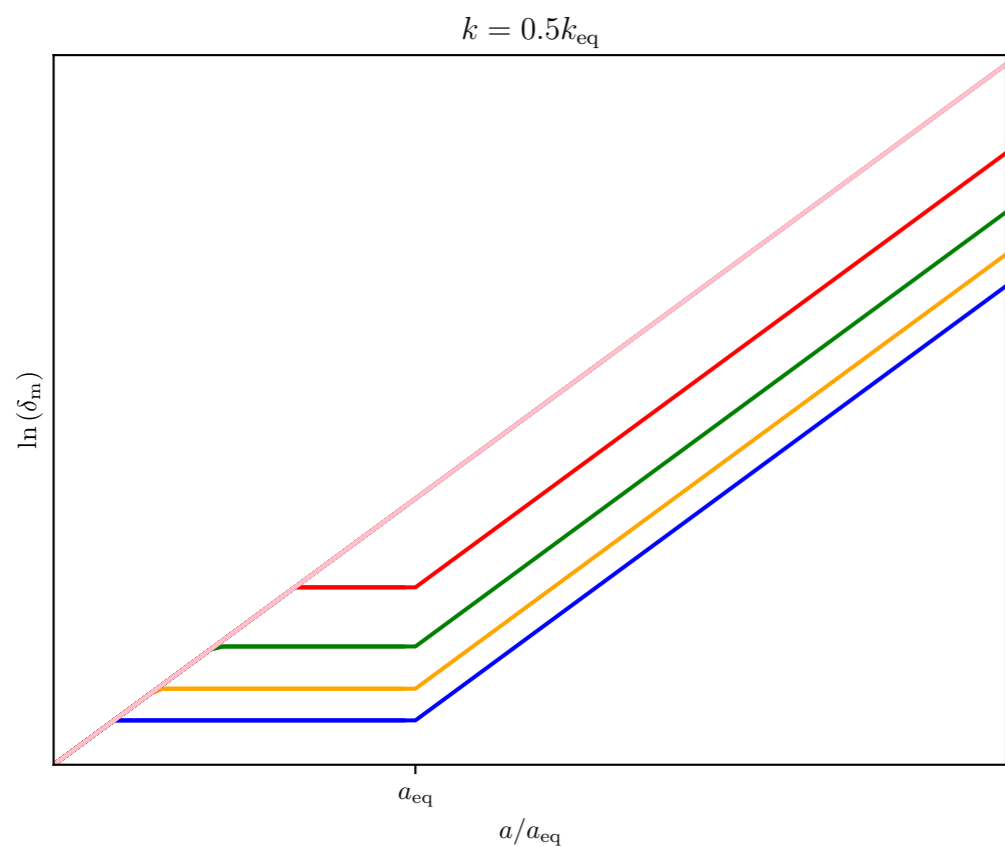


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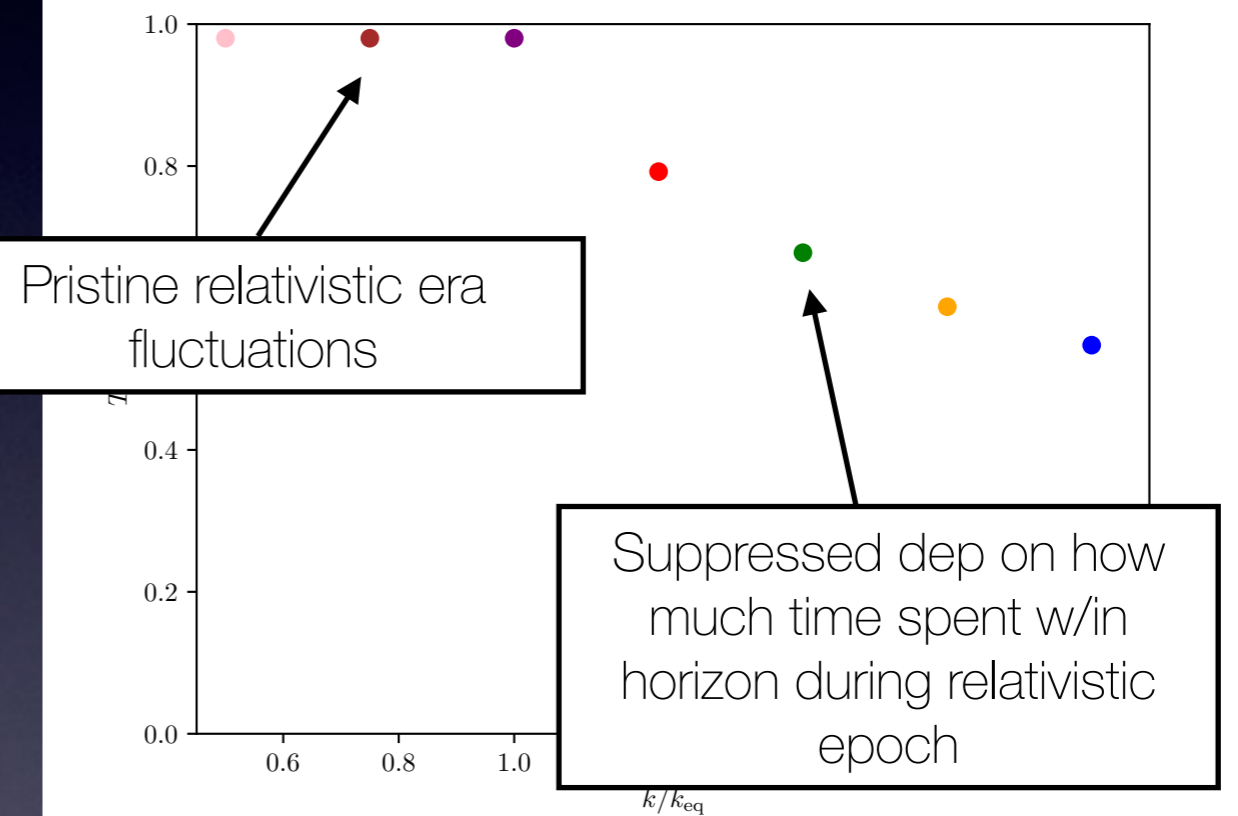
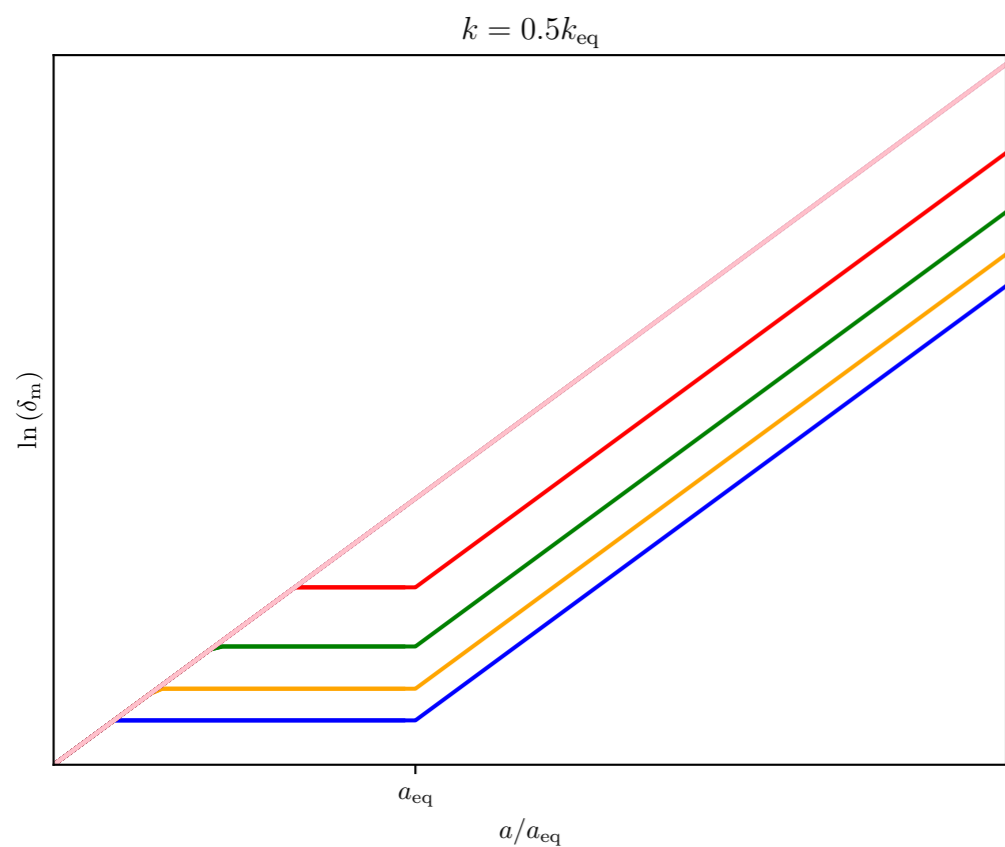




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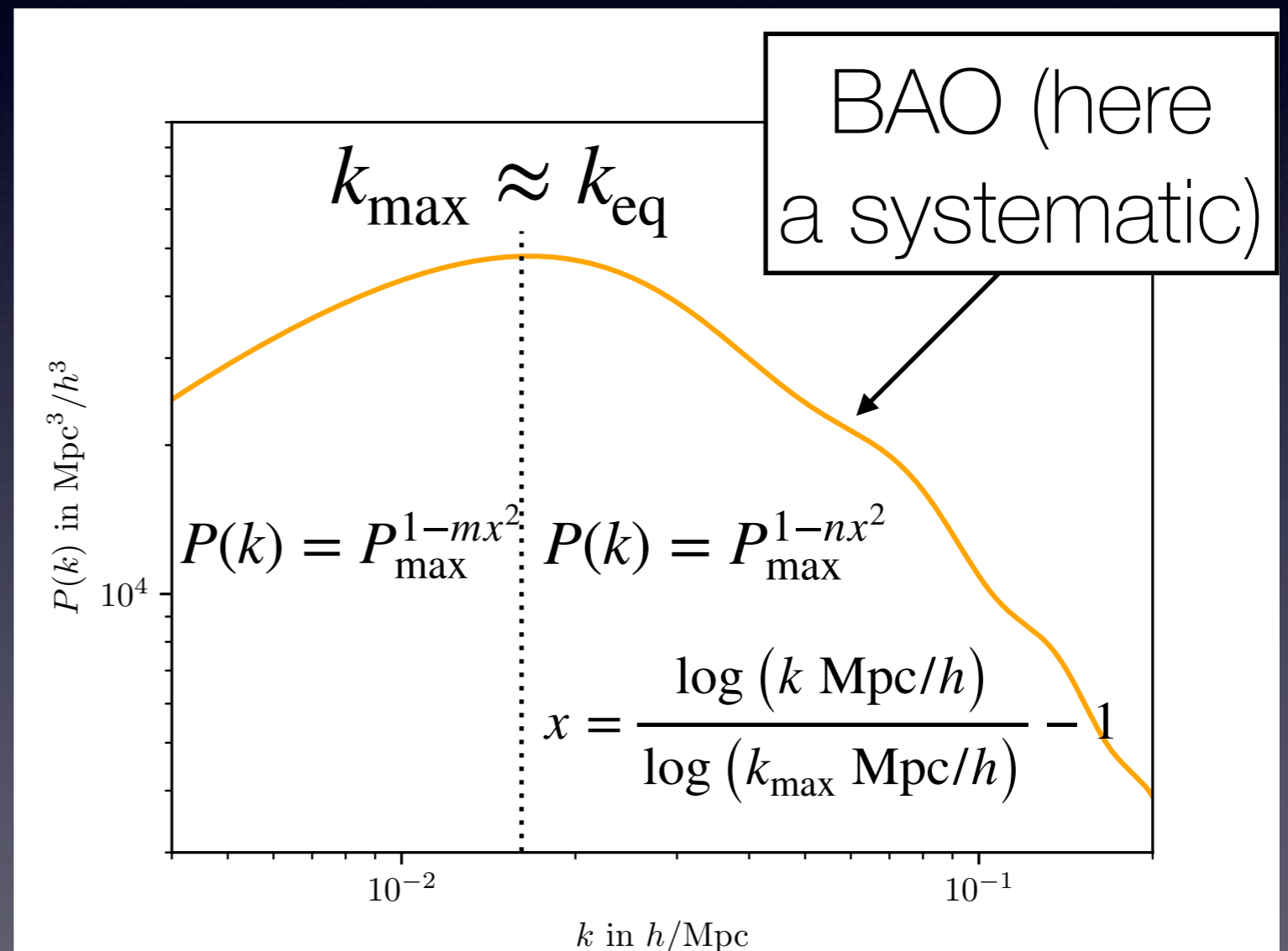


# Radiation- vs Matter Domination



# Model-independent approach

- Alternative to Full Modelling: Localising Turnover scale similar to what we do with BAO (compressed analysis)
- Parameterisation following [Poole *et al.* 2011]:
  - two slopes ( $m, n$ )
  - One amplitude  $P_{\max}$
  - One turn-over scale  $k_{\max}$
  - $k_{\max, \text{fid}} = 0.0166h/\text{Mpc}$
- Probability of  $m > 0$  gives turn-over detection probability
- Note  $m, n$  different to ShapeFit parameters (but highly correlated)

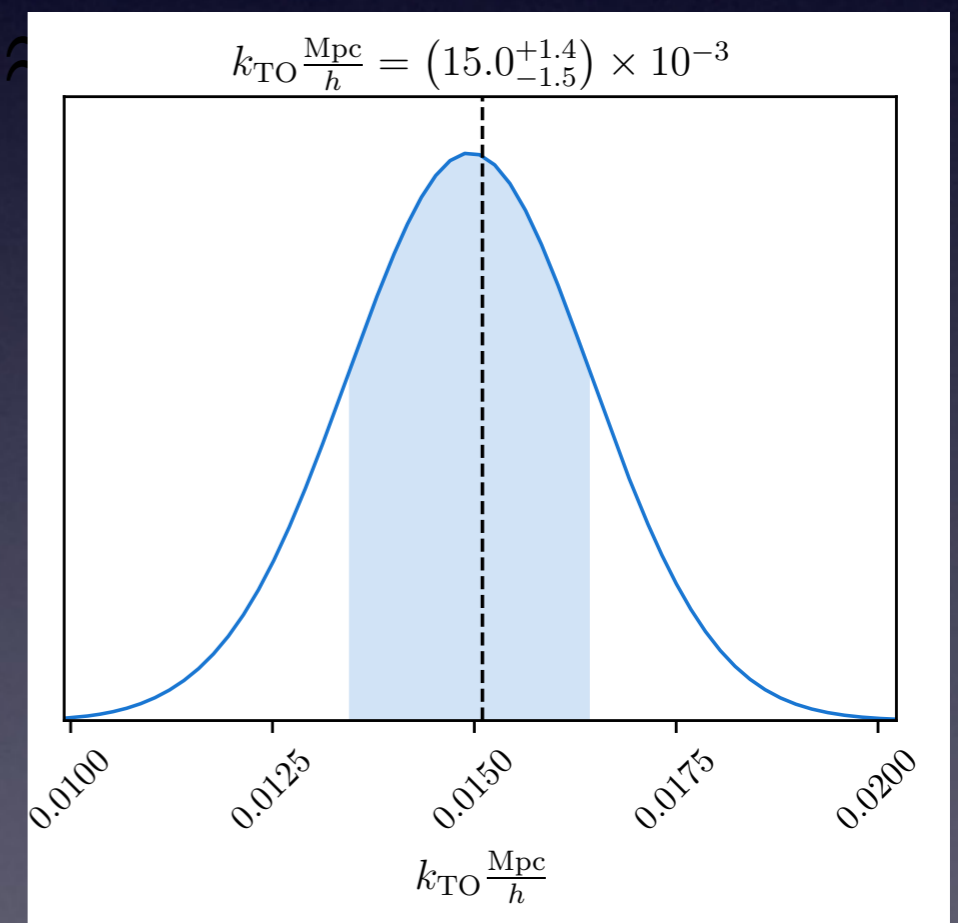


# Model-independent approach: Deprojecting modelling systematics

- 4-parameter power spectrum good approximation around turnover, but fails at smaller scales
- Scale cuts remove important broad-band information
- Increase covariance matrix  $\tilde{\mathbf{C}} = \mathbf{C} + \lim_{\tau \rightarrow \infty} \tau \mathbf{f}^{\text{BAO}} \mathbf{f}^{\text{BAO}\dagger}$  by expected inaccuracy of model
- Method does not bias  $k_{\text{TO}}$ -measurement

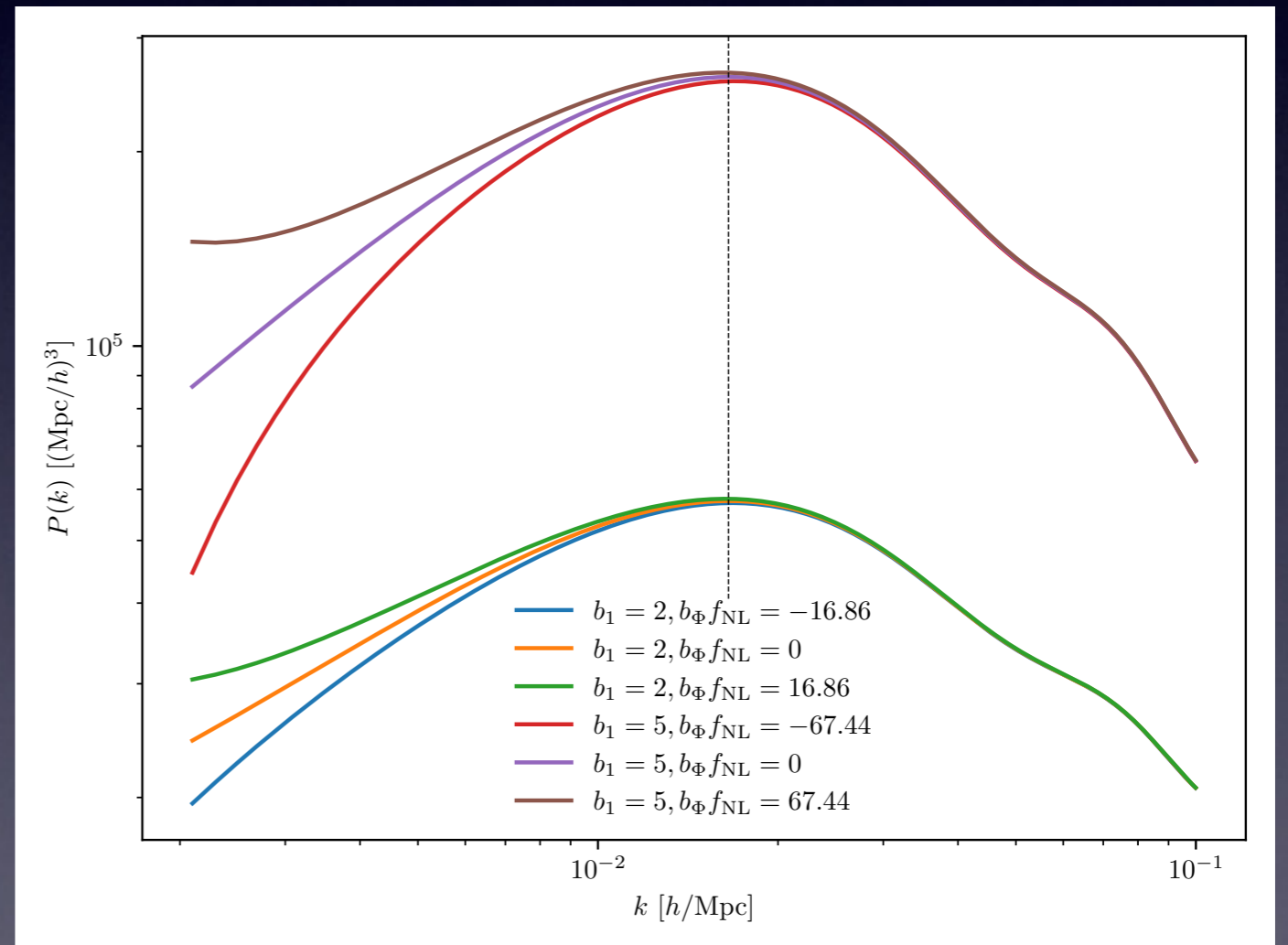
$$\mathbf{f}_k^{\text{BAO}} = P_{\text{fid}}(k) - P_{\text{eq,BF}}^{1-n_{\text{BF}}x^2}$$

$k_{\text{max}}$



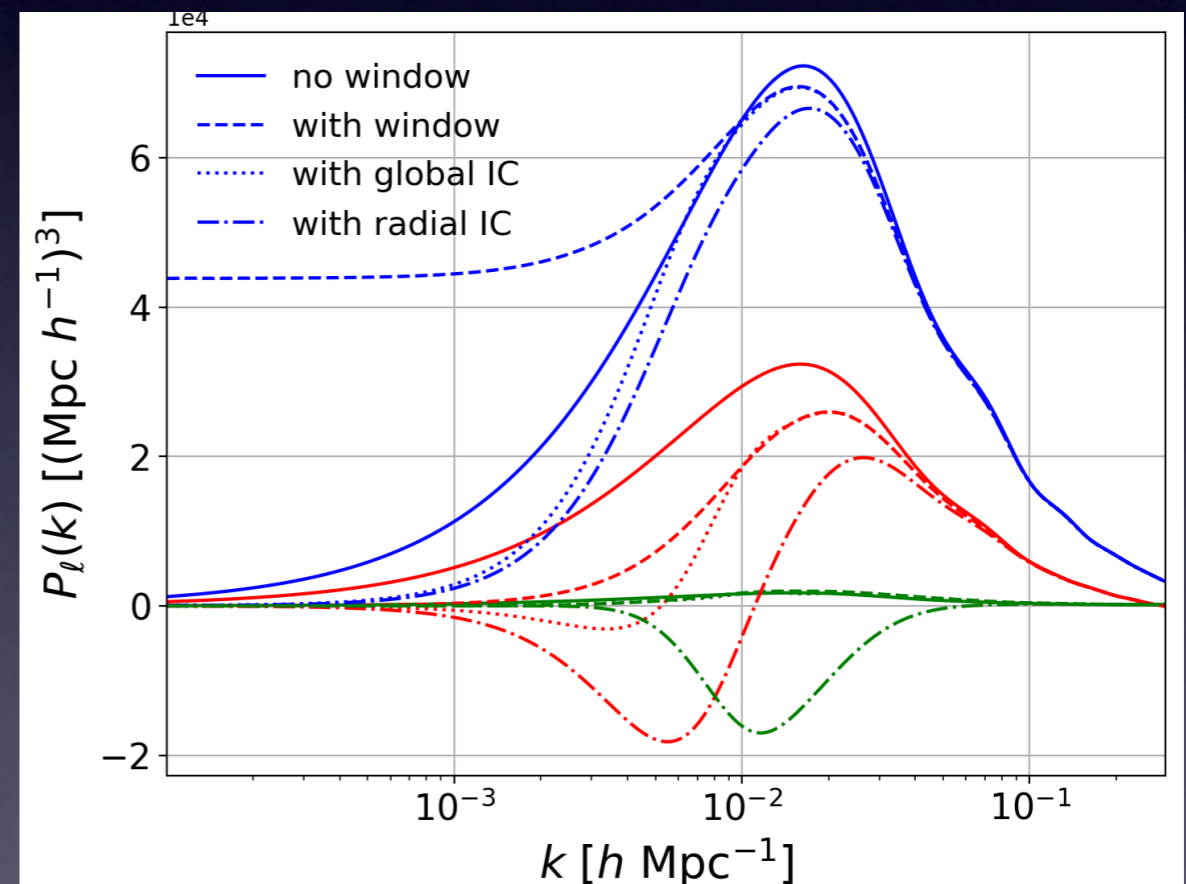
# Turnover scale as robustness criterion

- Turnover scale at scales often plagued by ULS systematics
  - e.g. large enough volume in BOSS CMASS and eBOSS ELGs but no TO
- However, TO shifts by less than 1% for reasonable values of  $f_{\text{NL}}$  [Cunnington 2022]
- Finding TO in the right spot thus provides confidence for potential detections of PNG



# Radial integral constraint

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



[de Mattia&RuhImann-Kleider19]

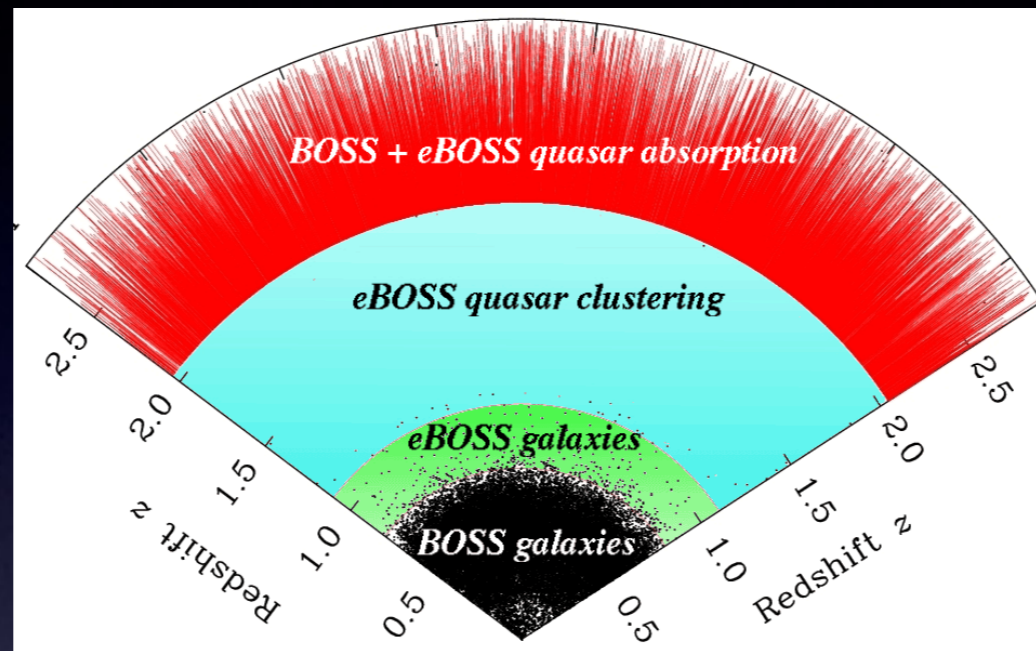
# TO as standard ruler

- Analogous to BAO (cf. Hector's talk), define  $r_d$ -independent standard ruler

$$\alpha_{\text{TO}} = \frac{D_V^{\text{fid}} r_H}{D_V r_H^{\text{fid}}}$$

- $r_H \propto (\Omega_m h^2)^{-2}$ , so we can measure  $H_0$  independent of  $r_d$  and BBN when combining with  $\Omega_m$  from, e.g., BAO
- Test of Universe at  $z = 3400$  rather than  $z = 1100$ , Early Dark Energy?  
Alternatively, test neutrino sector
- Independent of BAO, only mildly correlated with ShapeFit parameter  $m_{\text{SF}}$  and  $f\sigma_8$
- Can we get tighter cosmology constraints w/out full modeling by combining BAO+SF+TO ?

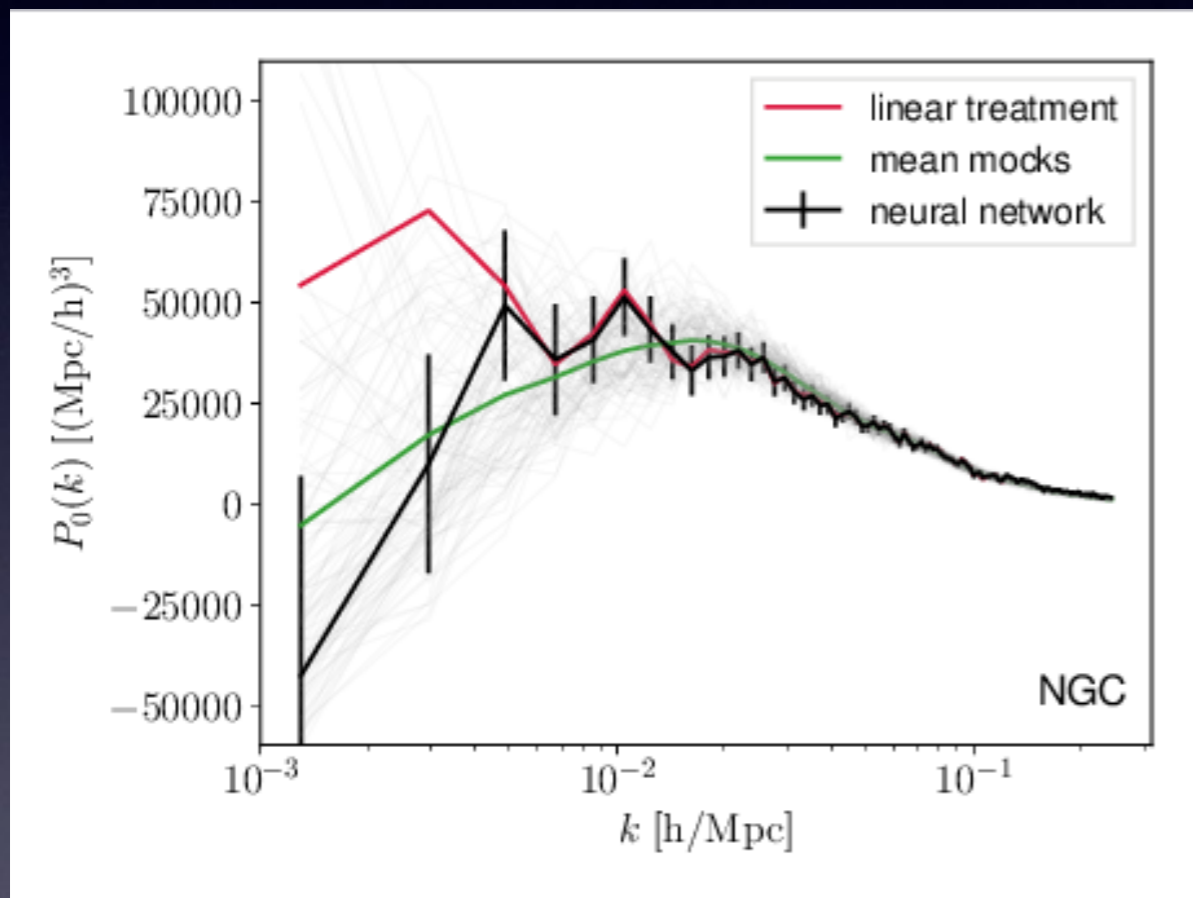
# Application to eBOSS



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

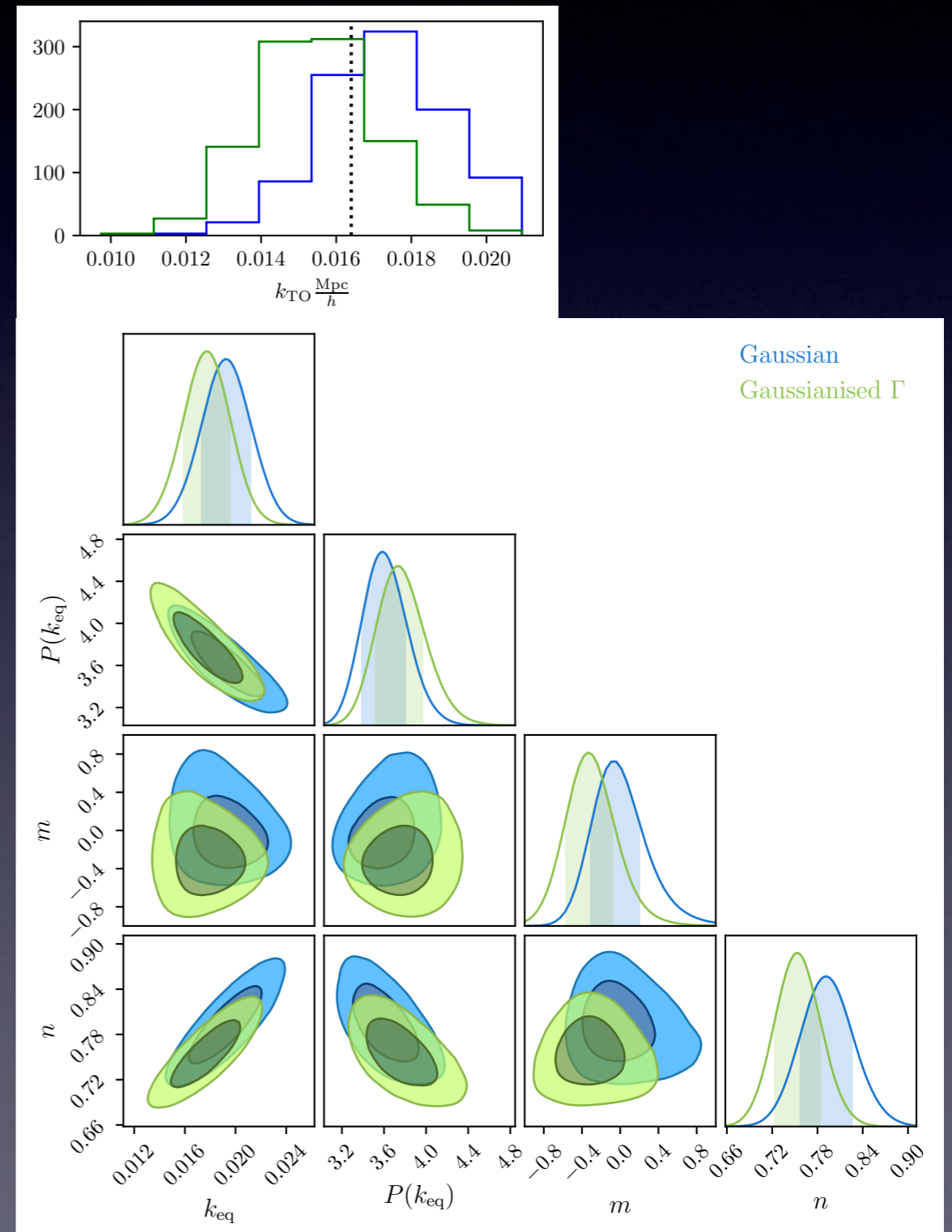
17 systematic maps (stars, dust, imaging depth, airmass, etc.)

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

Allows to include cross-correlations between foregrounds

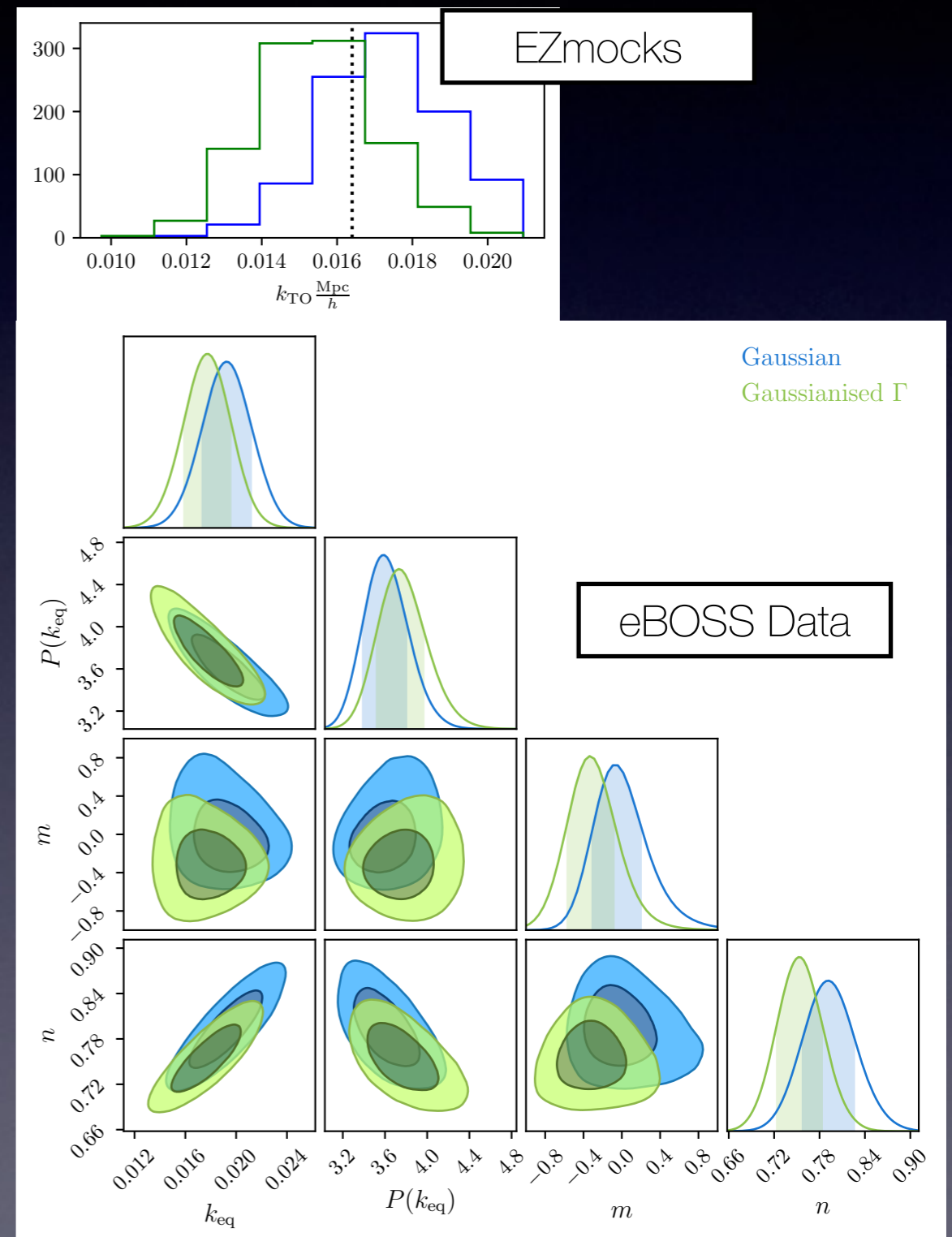
# eBOSS results

- 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  $Z = [P(k)]^\nu$



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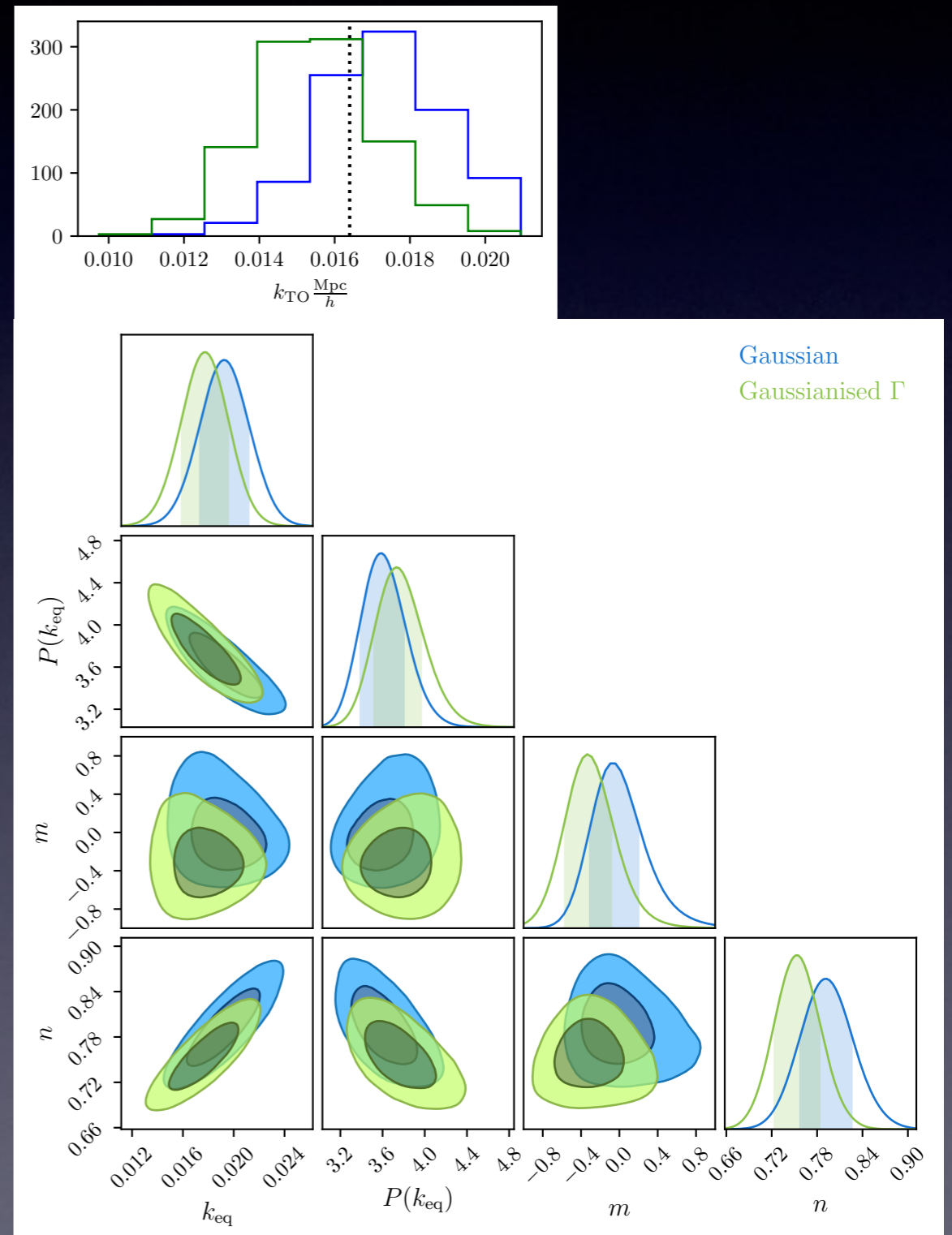


# eBOSS results

- Unfortunately, no evidence for  $m > 0$
- However, we do find inflection point at the expected scale
- Fiducial value:  

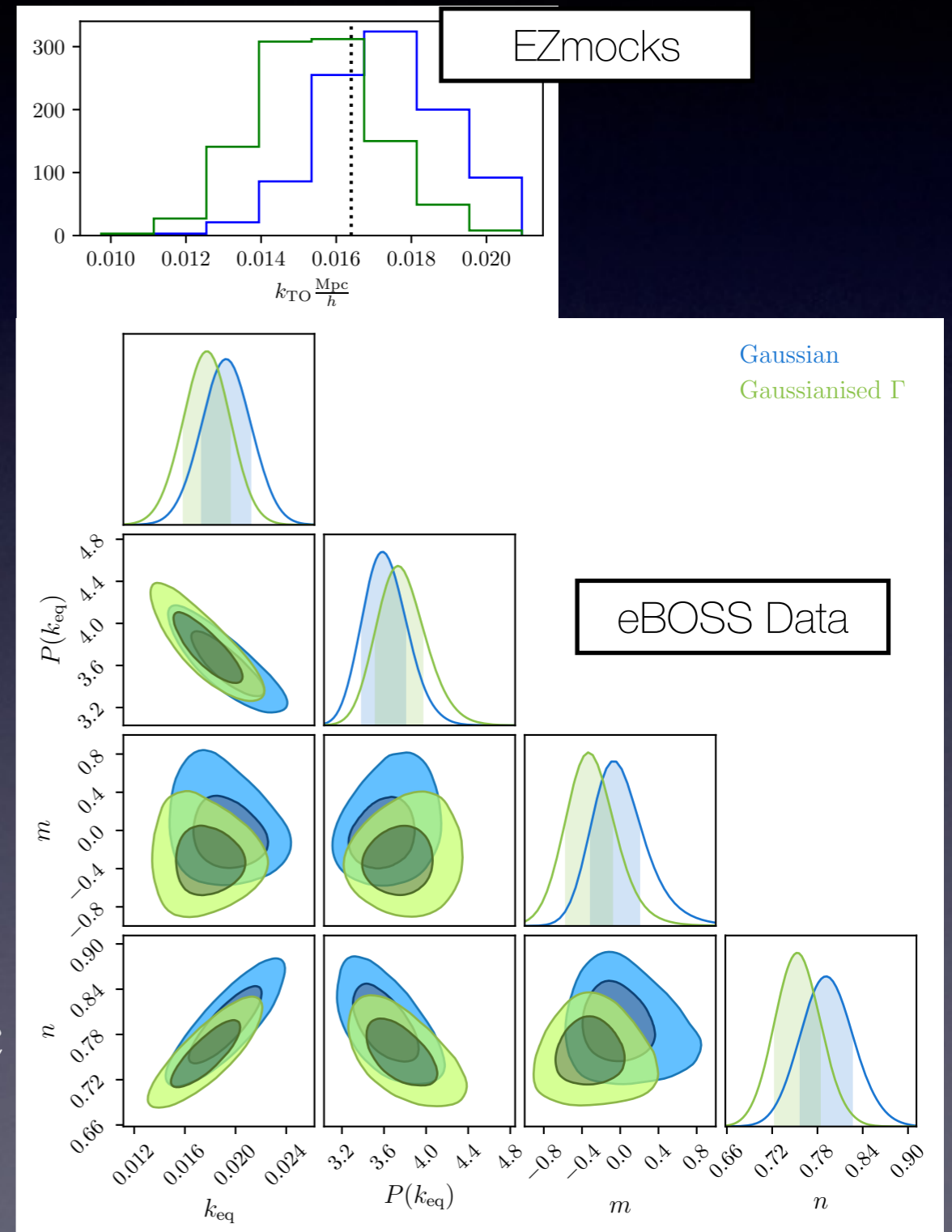
$$k_{\text{TO, fid}} = 16.6 \times 10^{-3} h/\text{Mpc}$$
- With Gaussianised  $\Gamma$ -distributed  $P(k)$  [Wang et al. 2019]:  

$$k_{\text{TO}} = (17.6^{+1.9}_{-1.8}) \times 10^{-3} h/\text{Mpc}$$



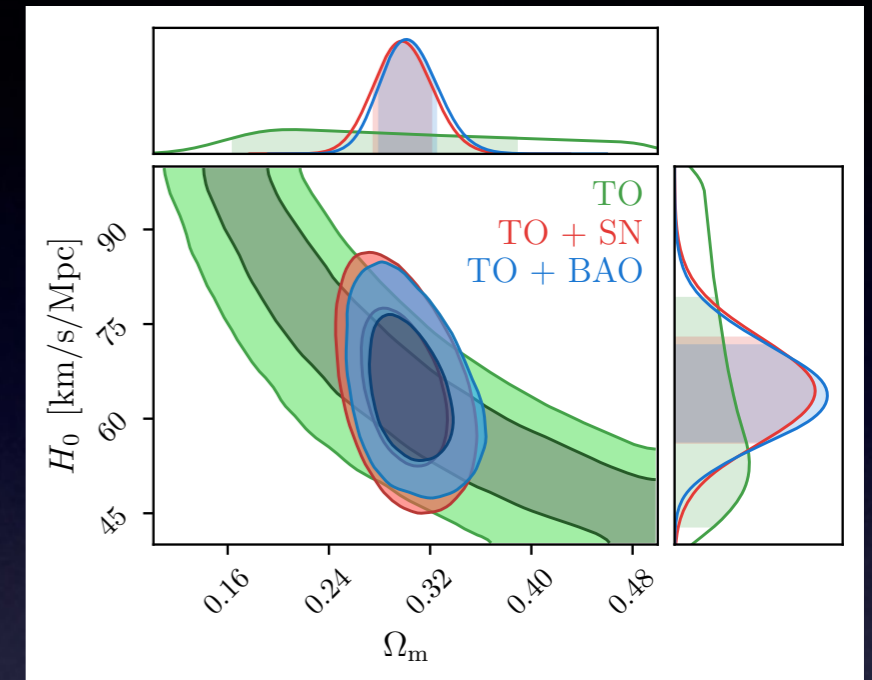
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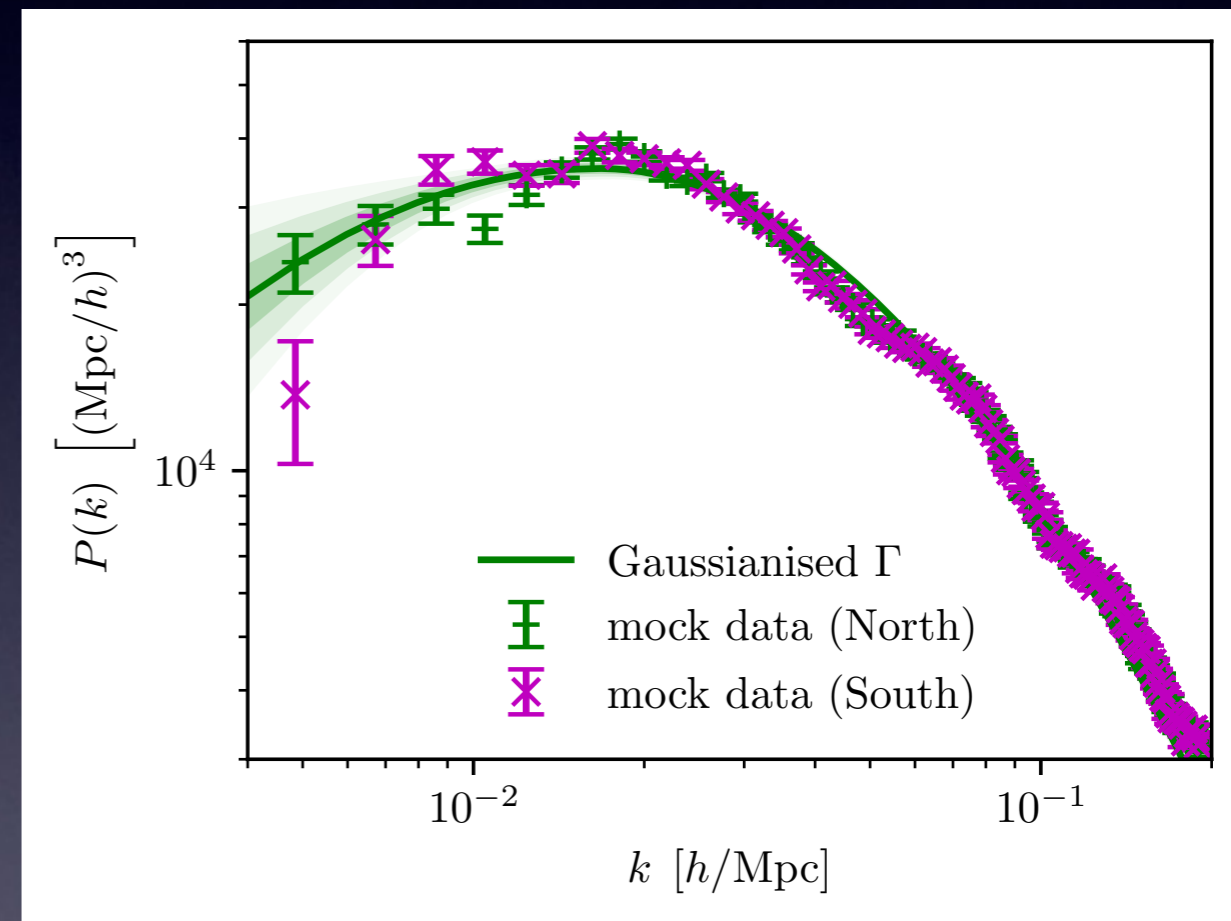
# eBOSS results

- Assume inflection point is turnover
- $\alpha_{\text{TO}} = 1.06 \pm 0.11$
- cf.  $\alpha_{\text{bao}} = 1.025 \pm 0.020$  [Neveux et al. 2020]
- Assuming 3 standard massless neutrino species, direct measurement of  $\Omega_m h^2 = 0.159^{+0.041}_{-0.037}$ , consistent with Planck ( $\Omega_m h^2 = 0.1430 \pm 0.0011$ )
- In combination with  $\Omega_m$  from BAO or SNe, we get  
 $H_0 = (74.7 \pm 9.6) \text{ km/s/Mpc}$  (with Pantheon) and  
 $H_0 = (72.9^{+10.0}_{-8.6}) \text{ km/s/Mpc}$  (with eBOSS LRG and Ly $\alpha$  BAO) without any sound horizon information

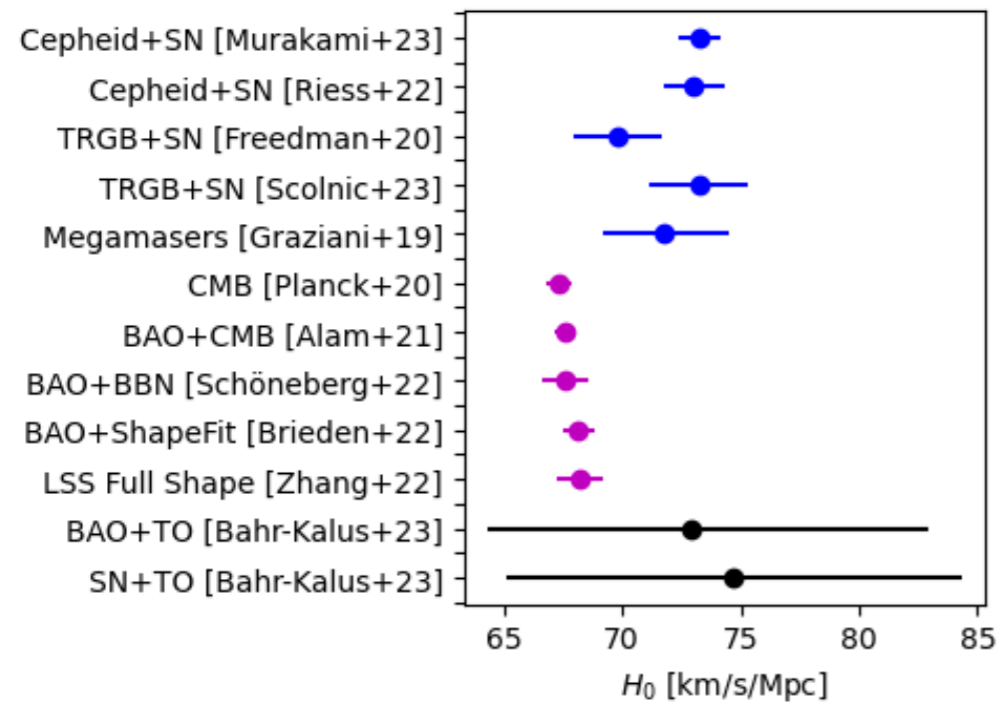


# Stage IV forecasts

- DESI QSO similarly deep as eBOSS QSO sample  
-> no access to new scales, but 3 times the area
- $V_{\text{eff}} \sim 8$  times larger (at TO scale)
- $\mathcal{P}(m > 0) = 0.96$
- $\alpha_{\text{eq}} = 0.973^{+0.028}_{-0.029}$
- Already twice as many QSOs observed in DESI Y1 than by eBOSS
- LRGs promising, challenges with ELGs (see Rongpu's talk)
- Year 1 forecasts from Euclid Large Mocks (thanks Figi) comparable with DESI Y1
- Will Euclid photo-z add information?



# 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
- More than 1-sigma turnover signal with DESI and Euclid Y1