Model-Independent Measurement of the Matter-Radiation-Equality Scale

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In collaboration with:
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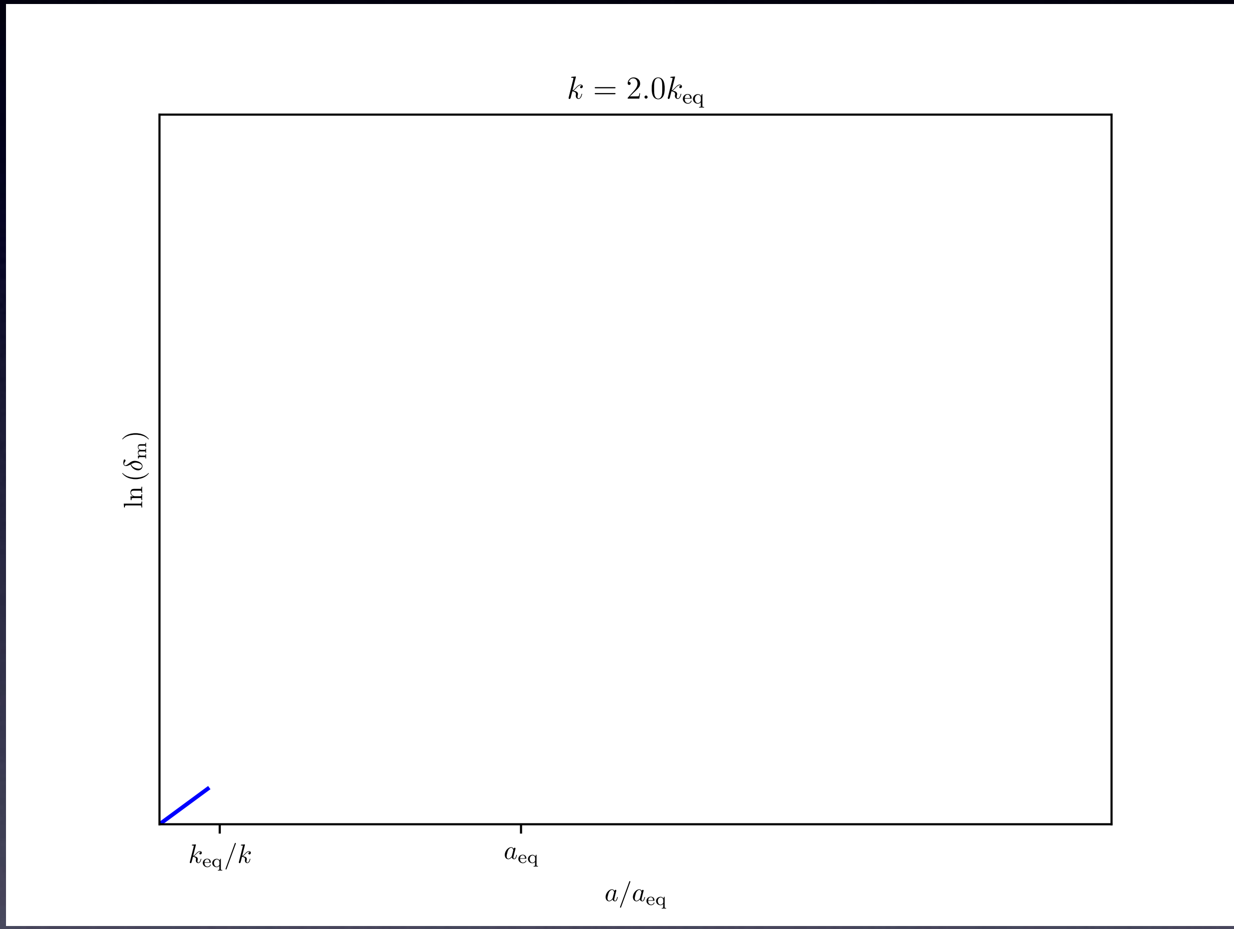
arXiv:2302.07484

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

Radiation- vs Matter Domination



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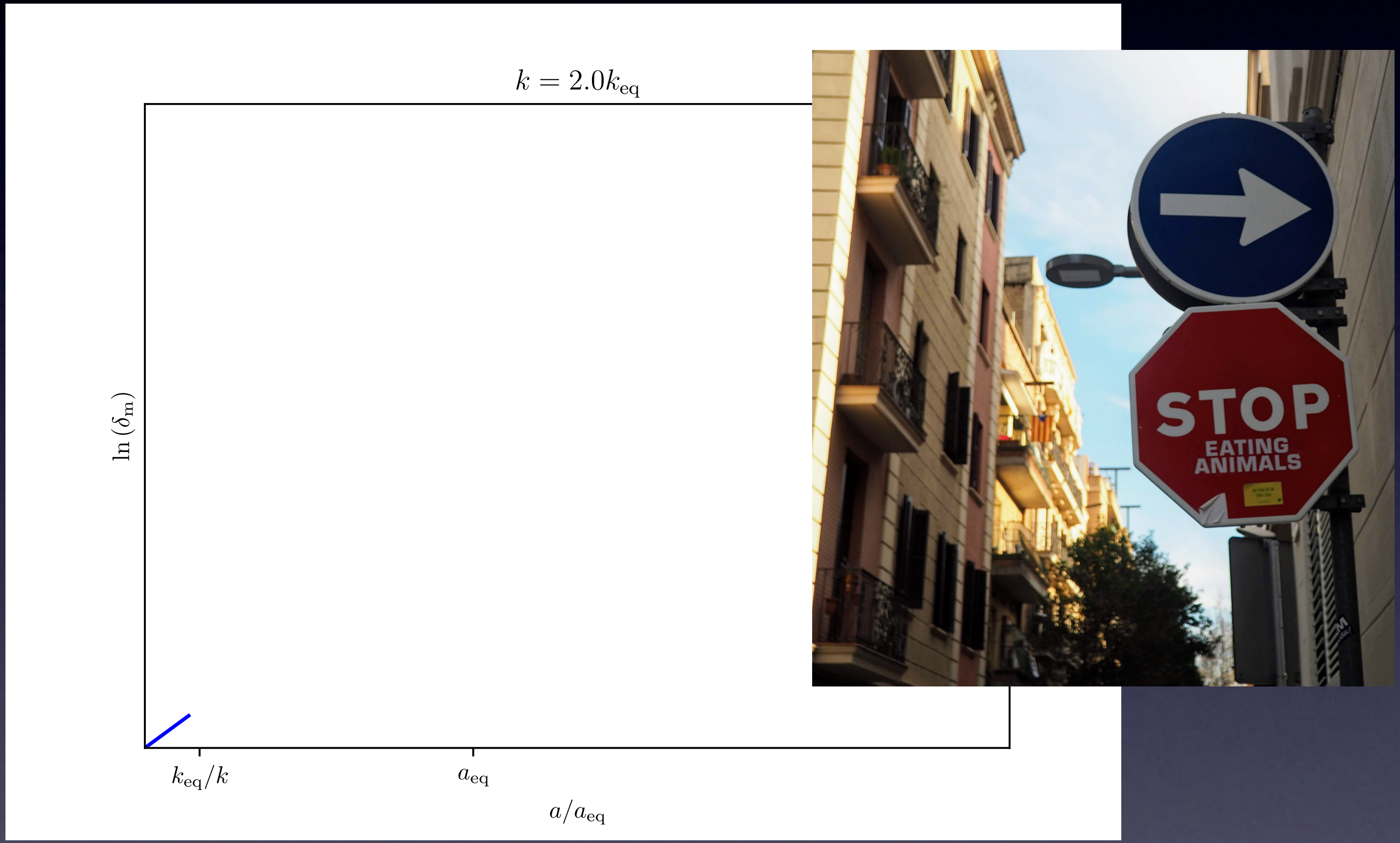

During Radiation Domination

- Pressure stabilises sub-horizon perturbations

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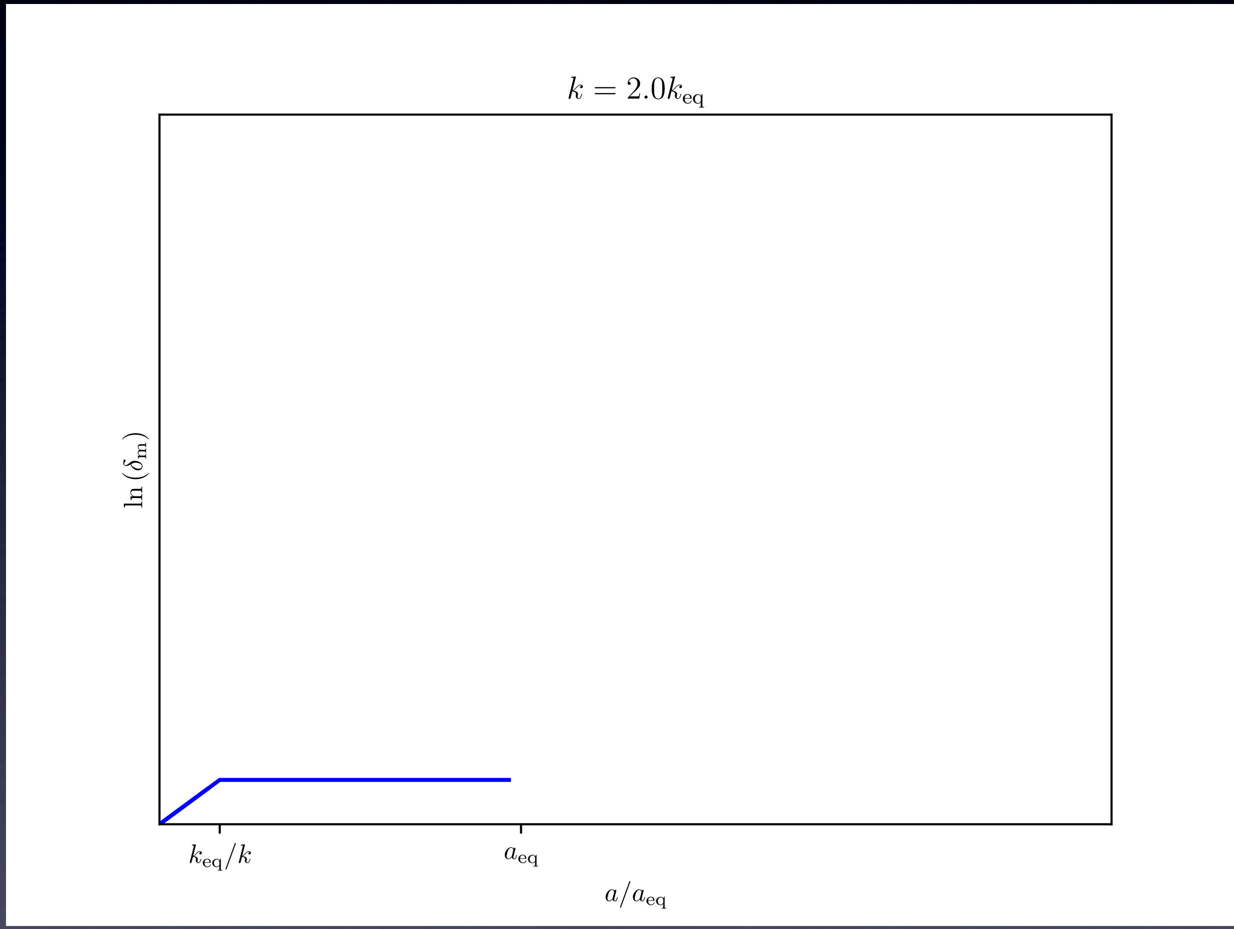

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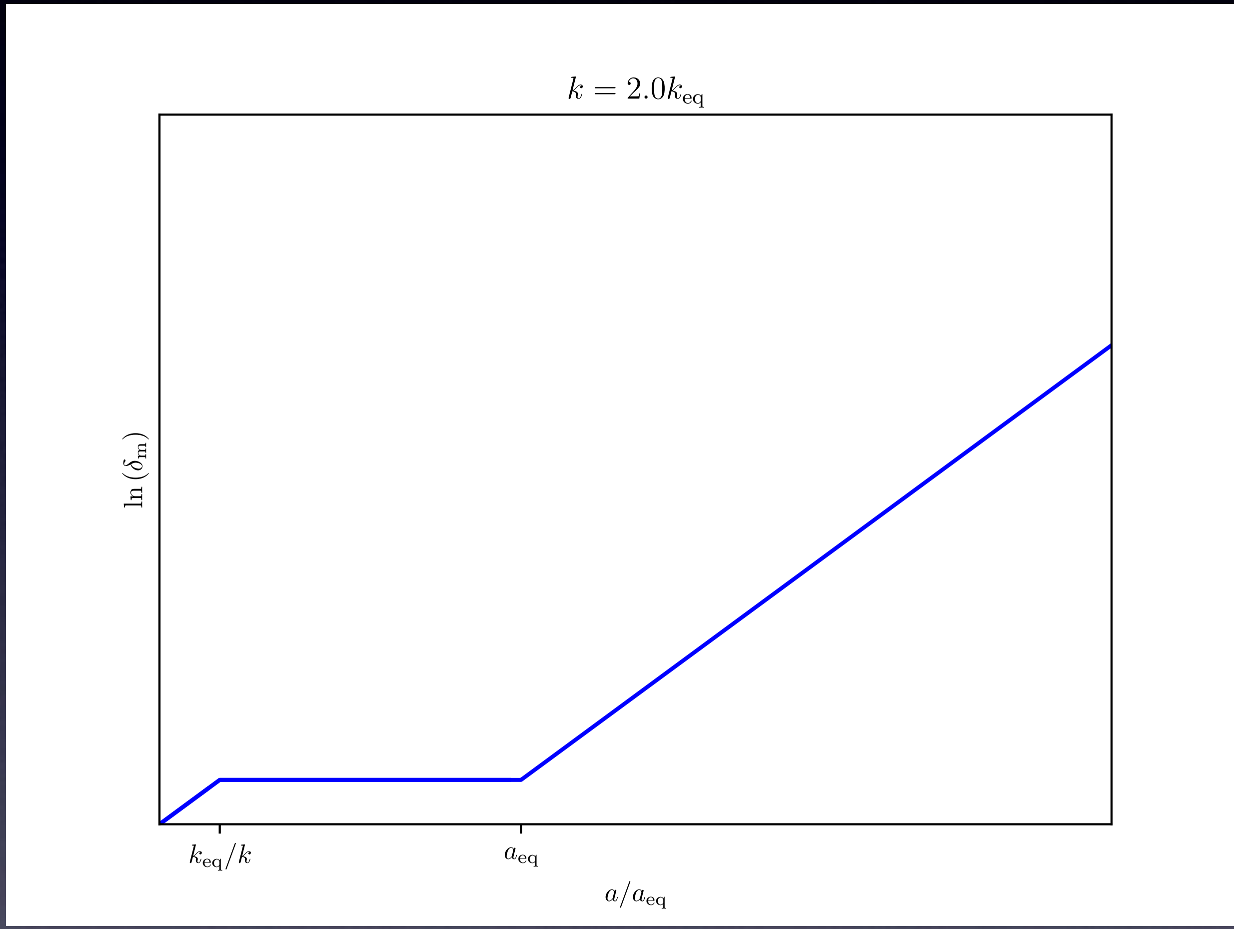
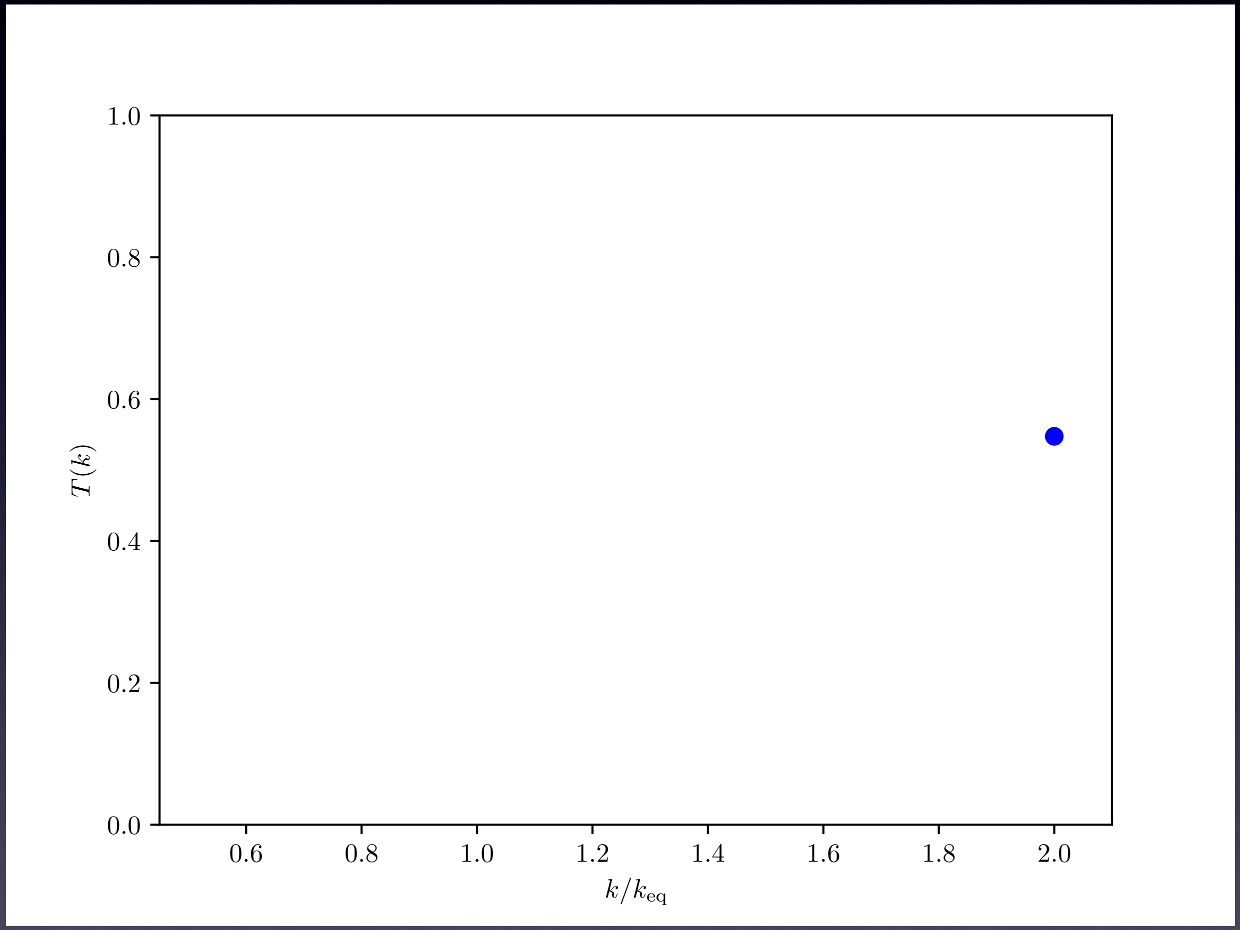
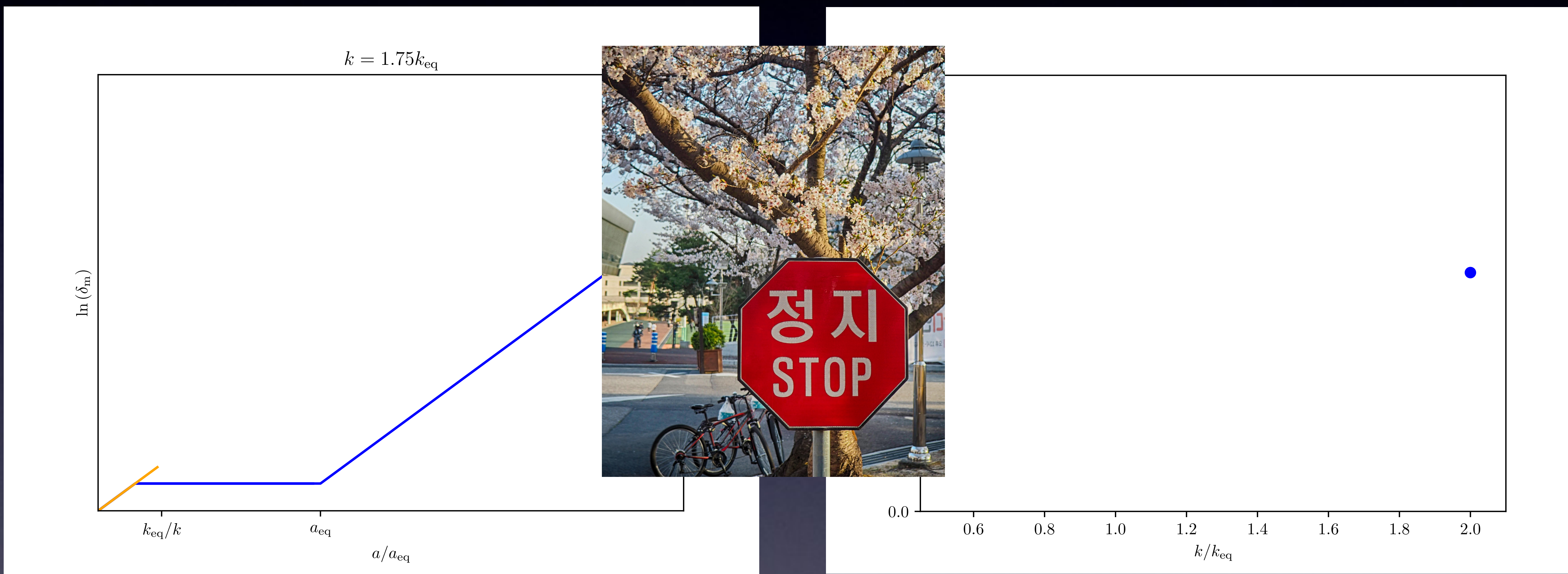




During Matter Domination

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

Radiation- vs Matter Domination



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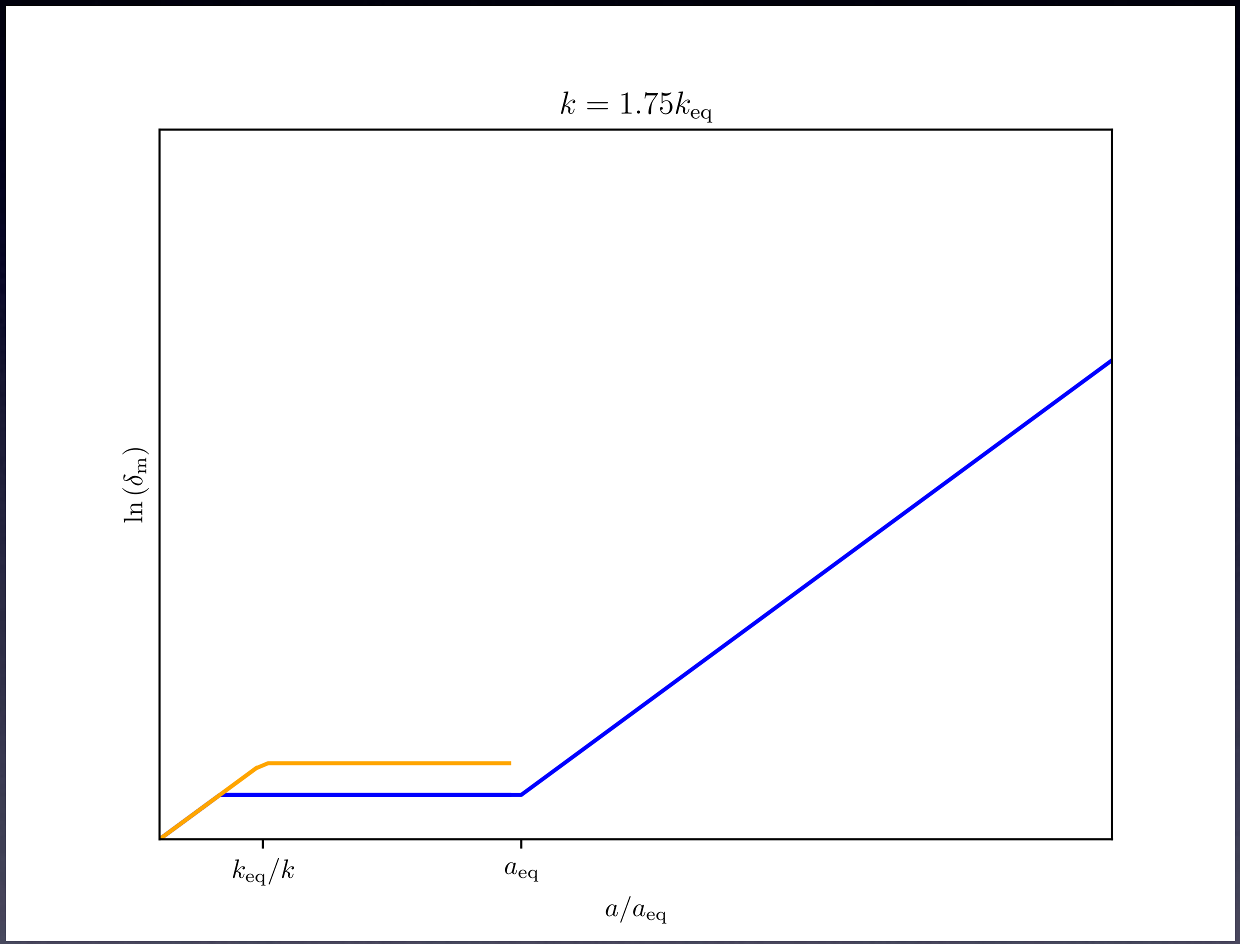

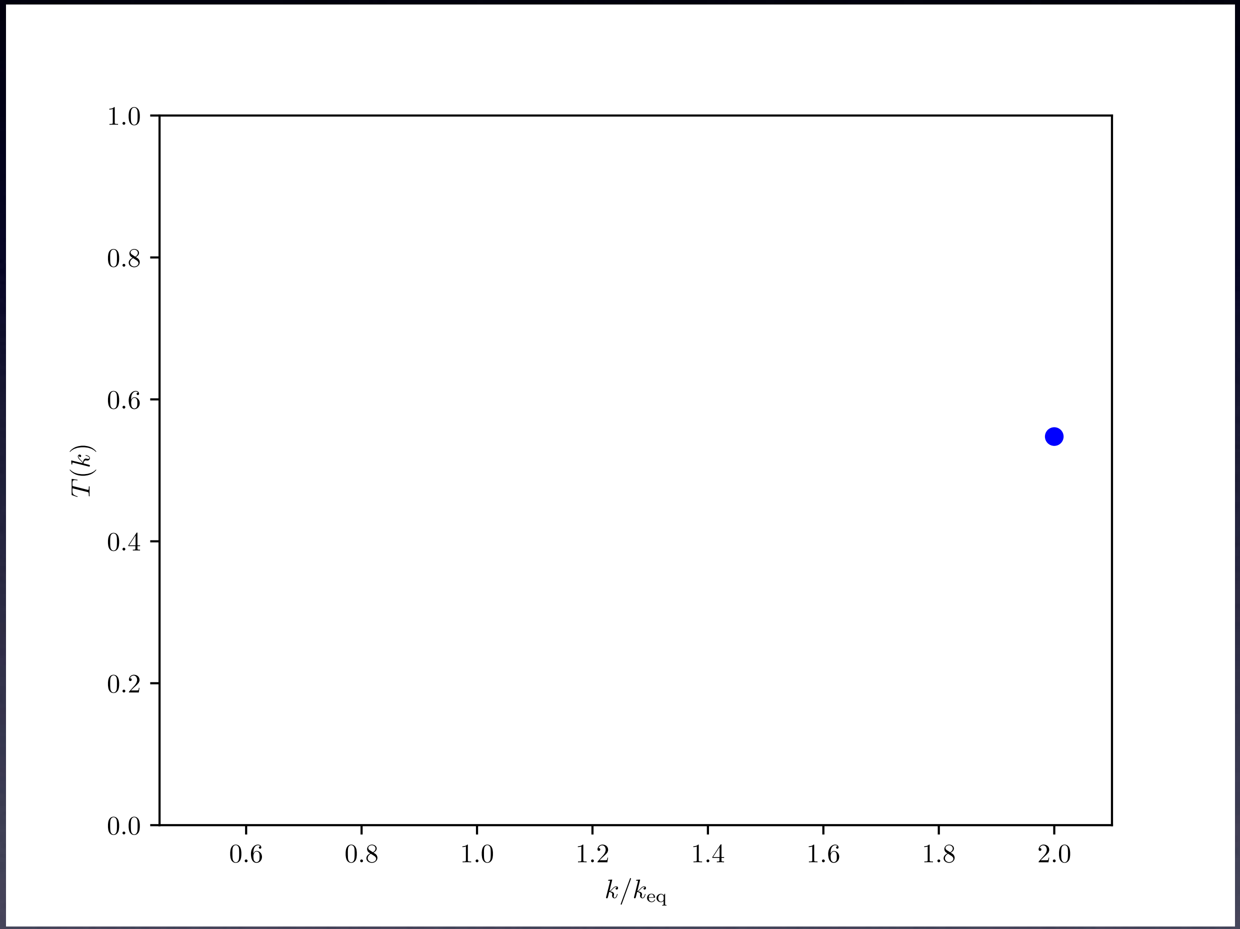

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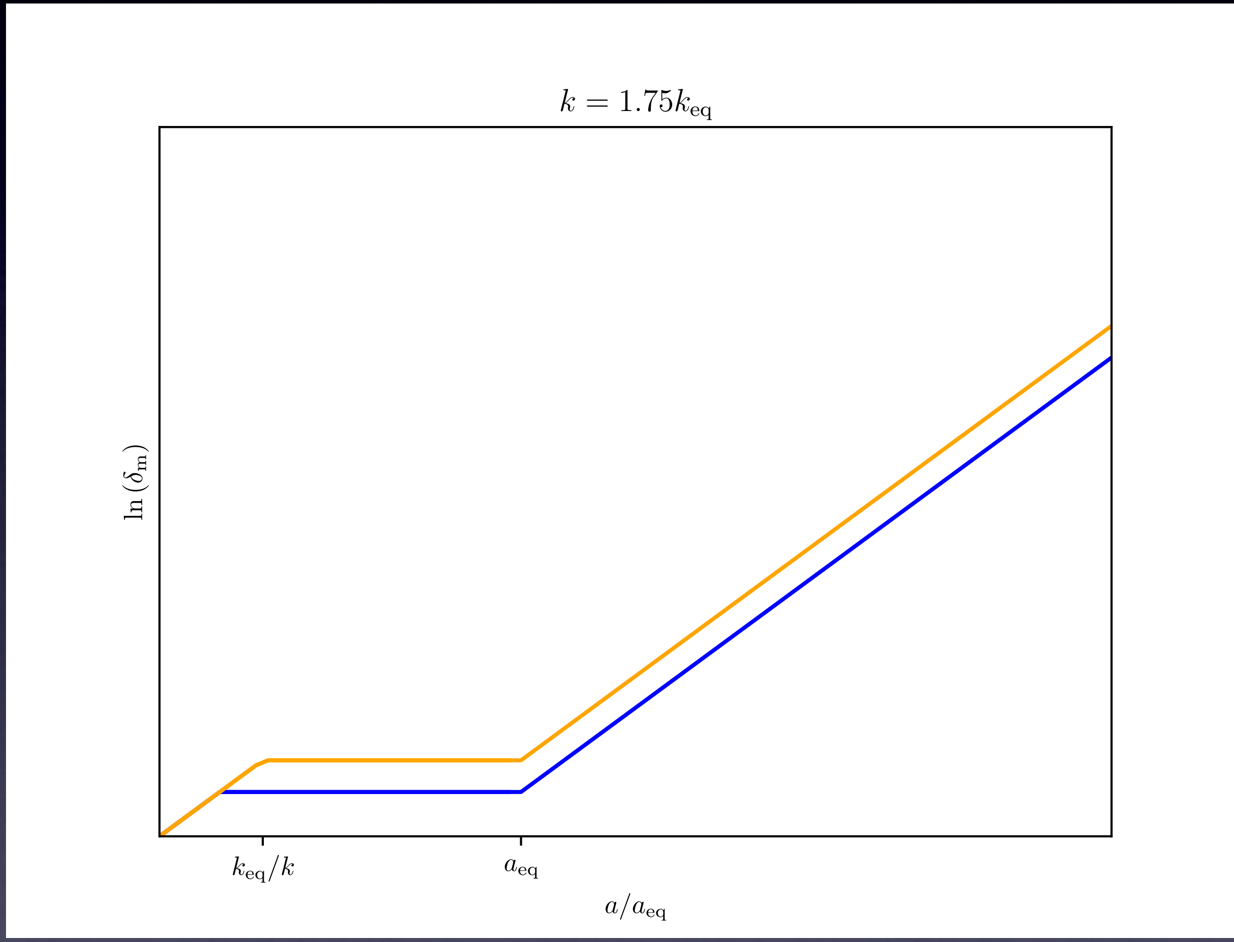

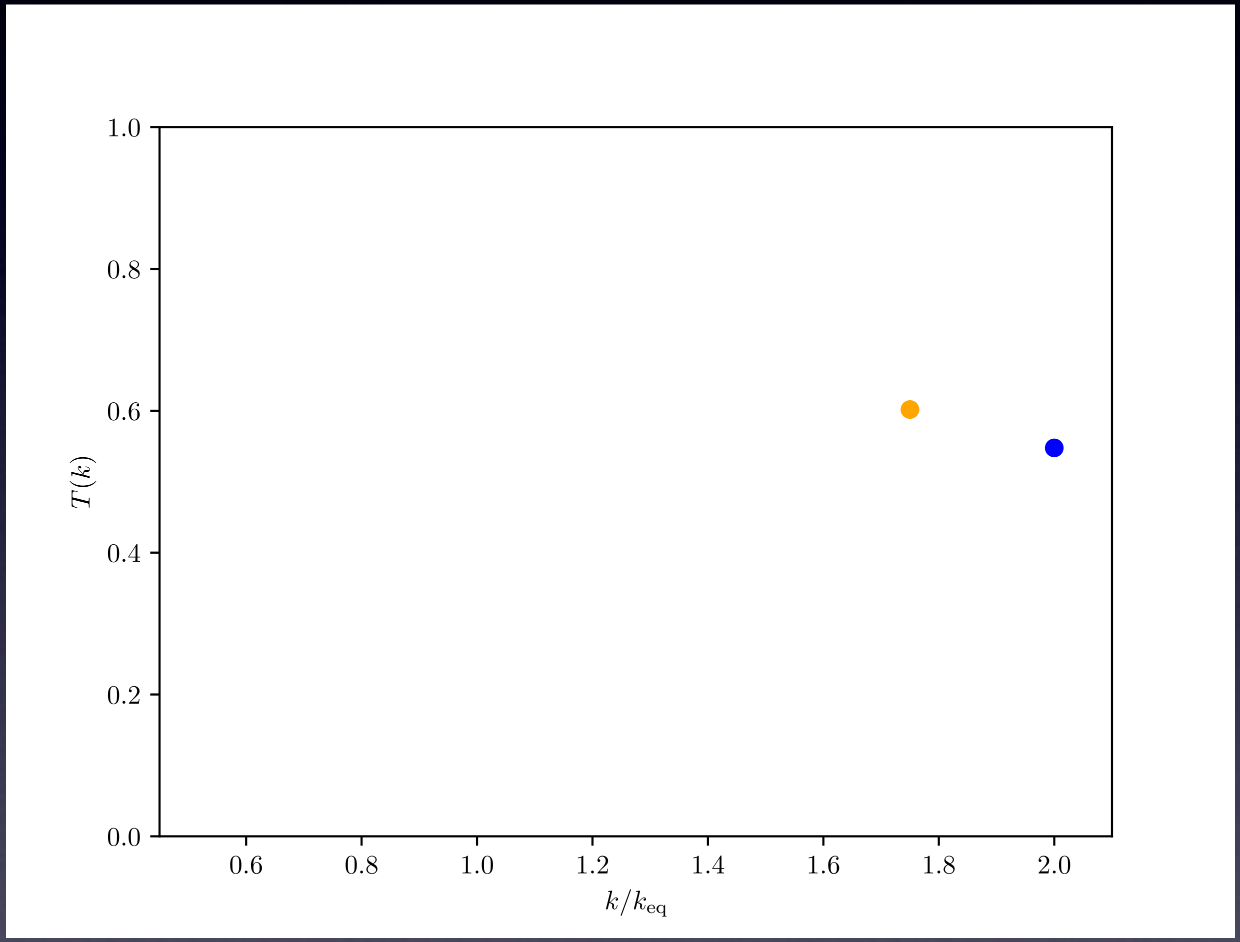

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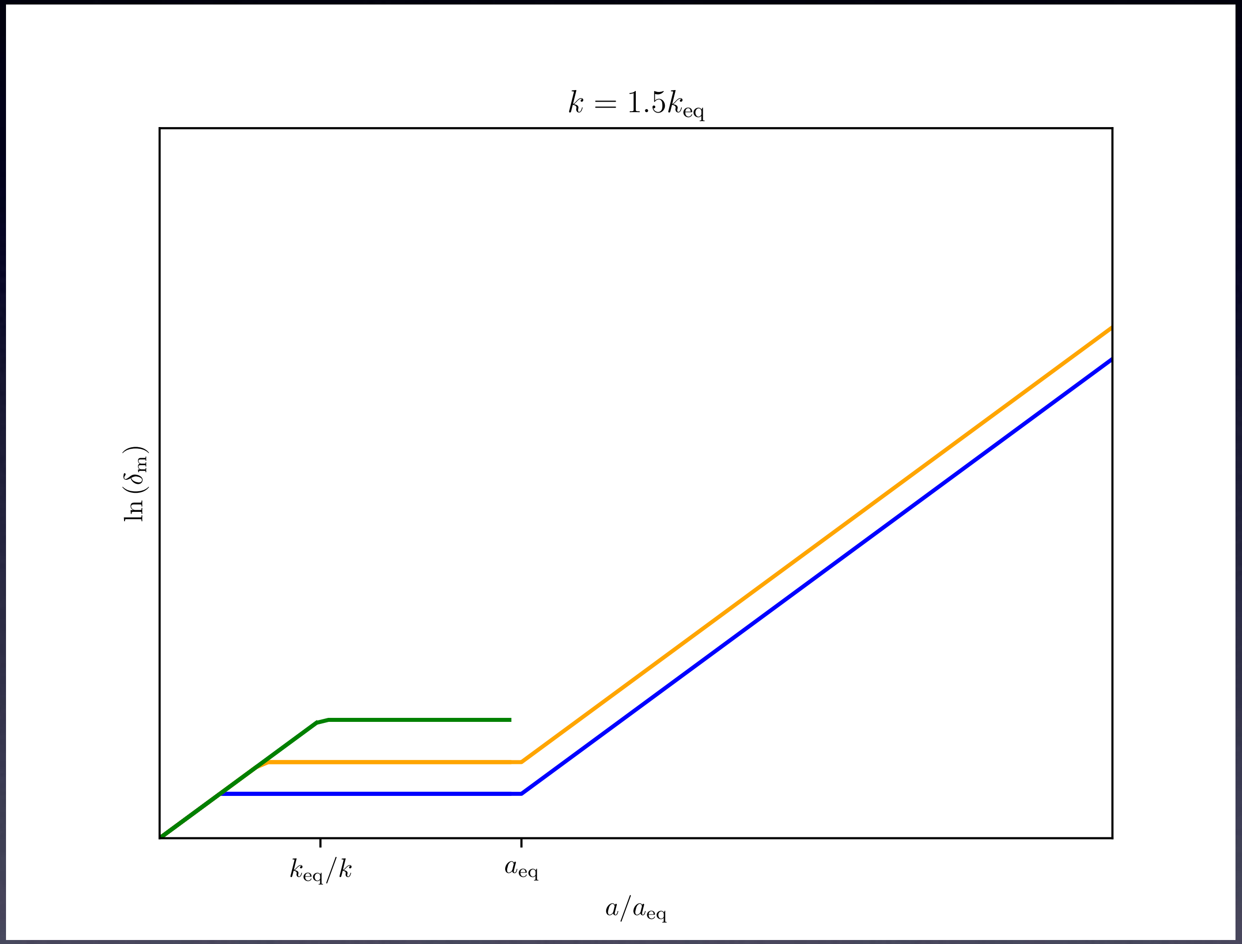

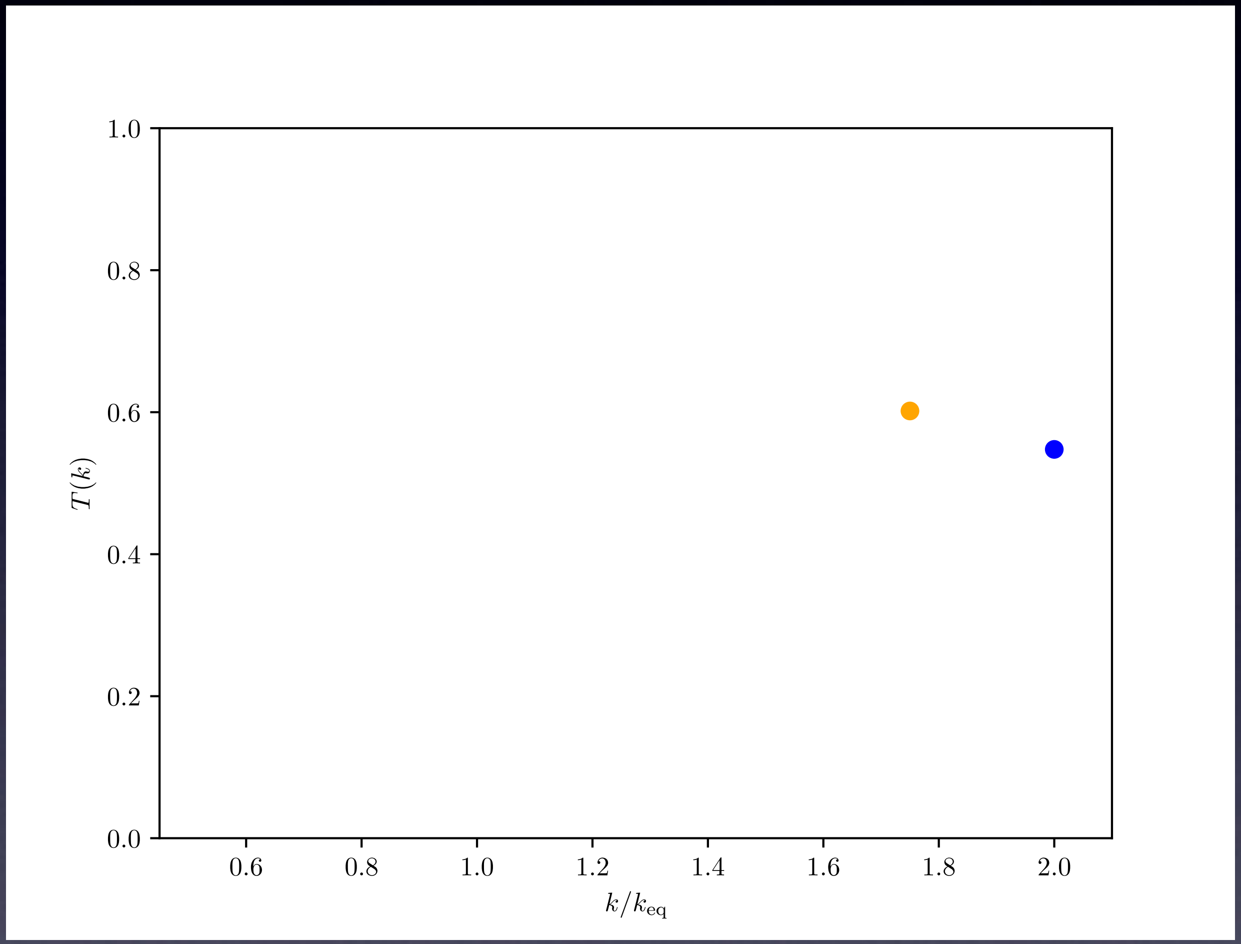

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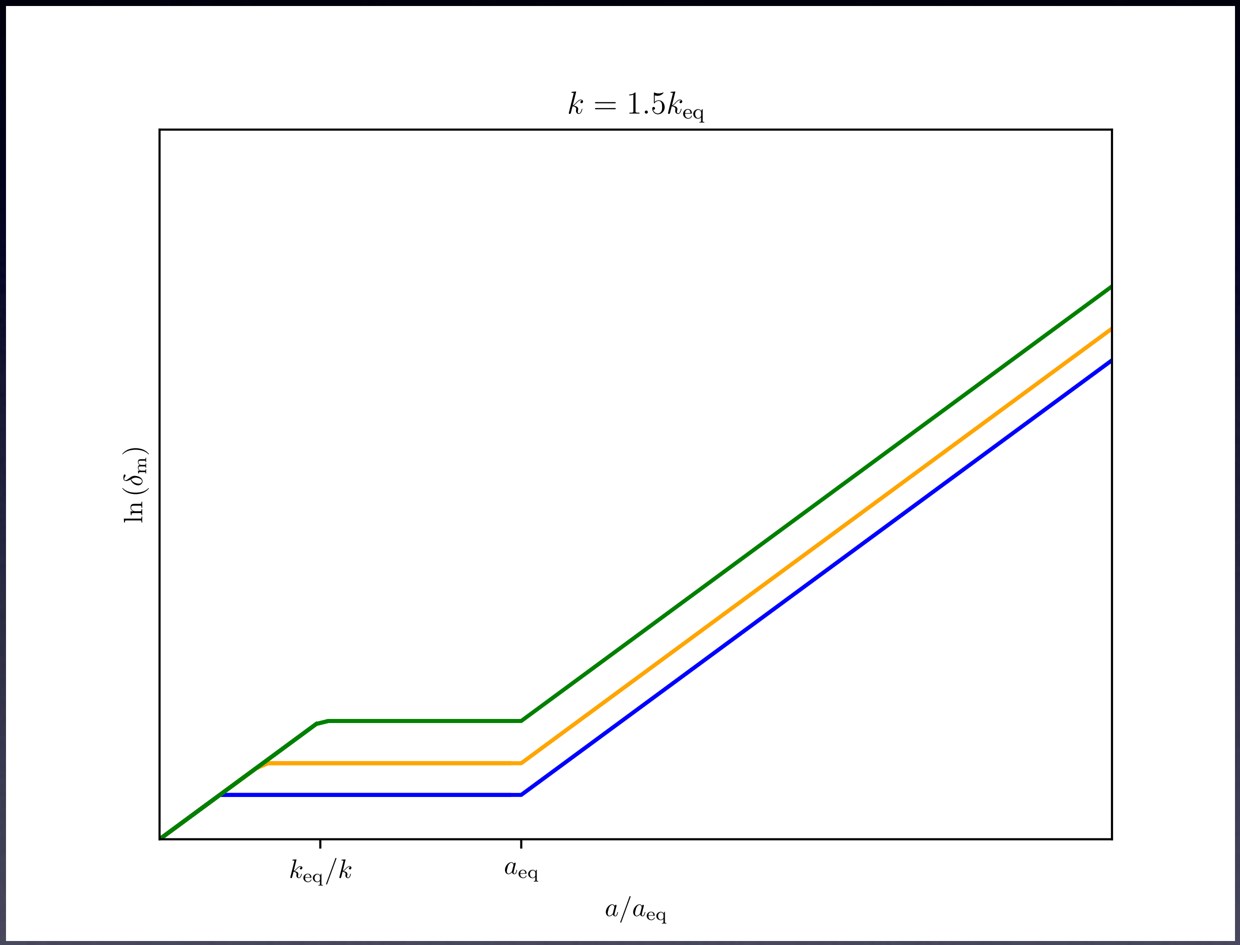

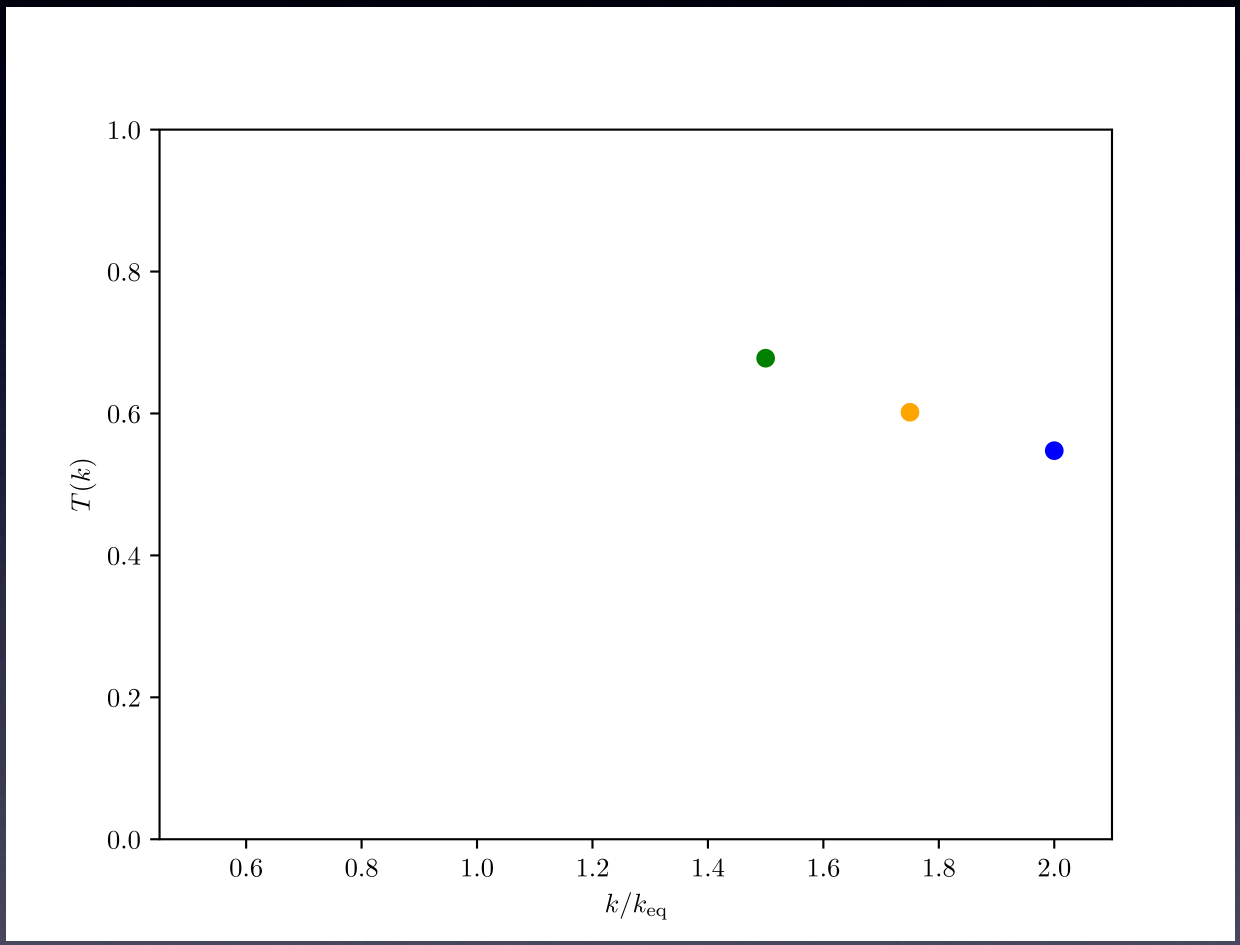

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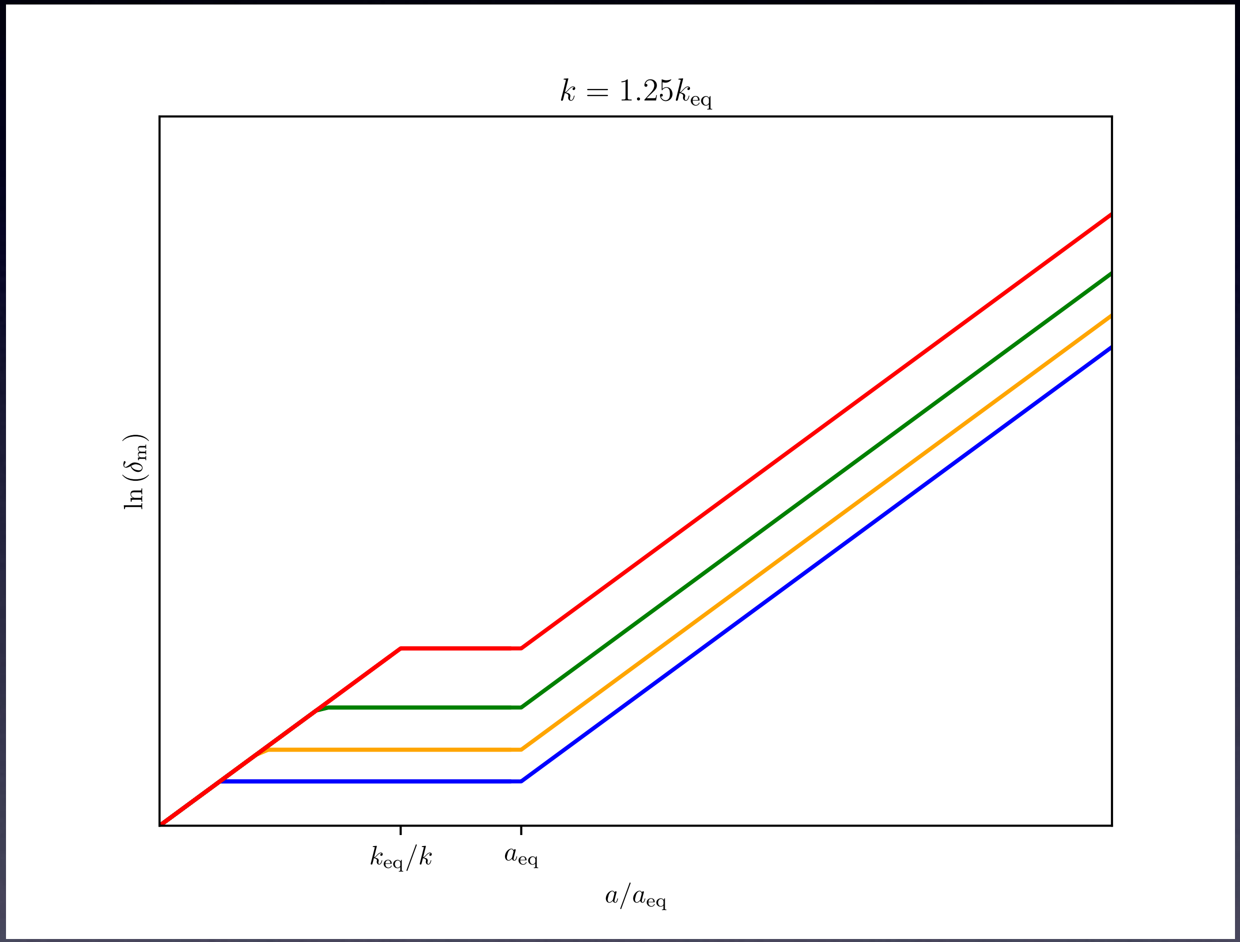

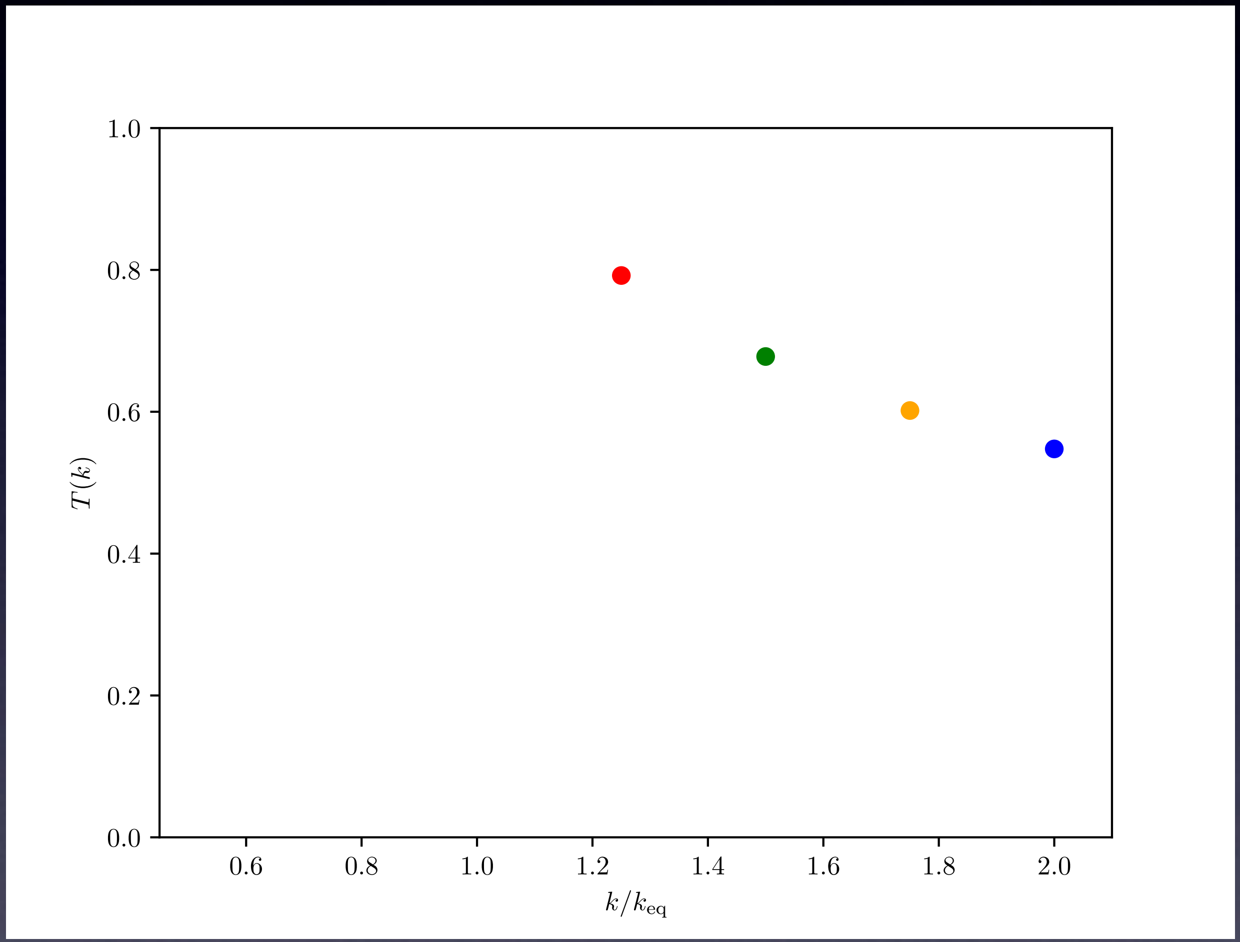

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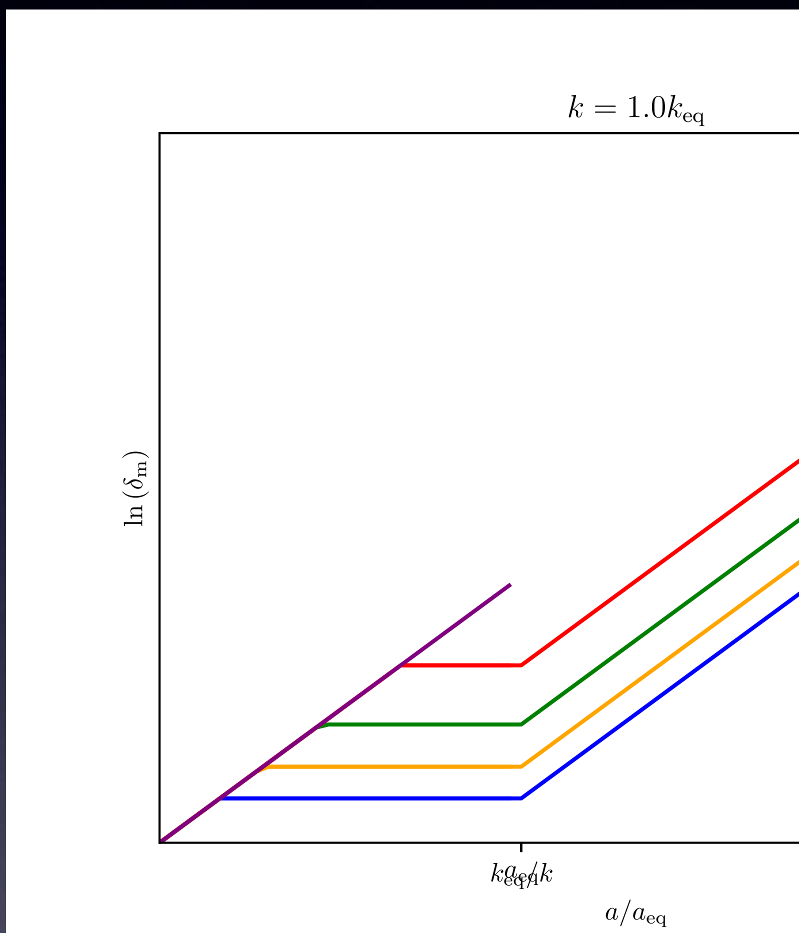

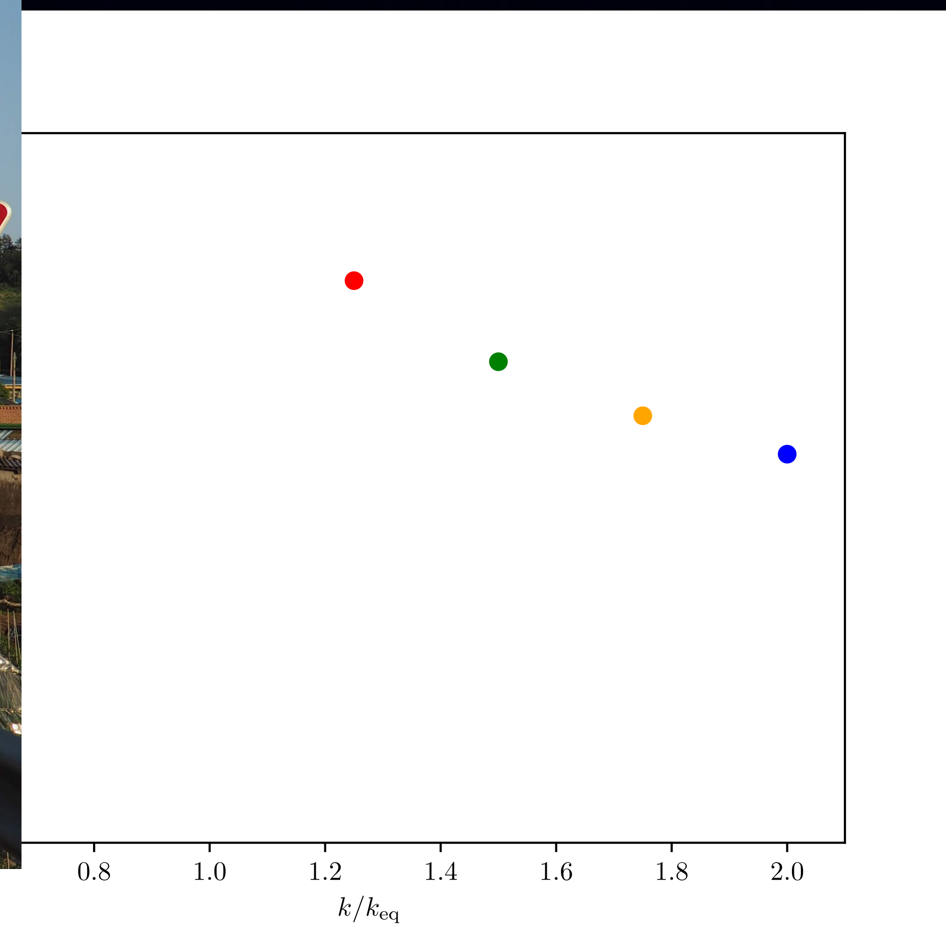

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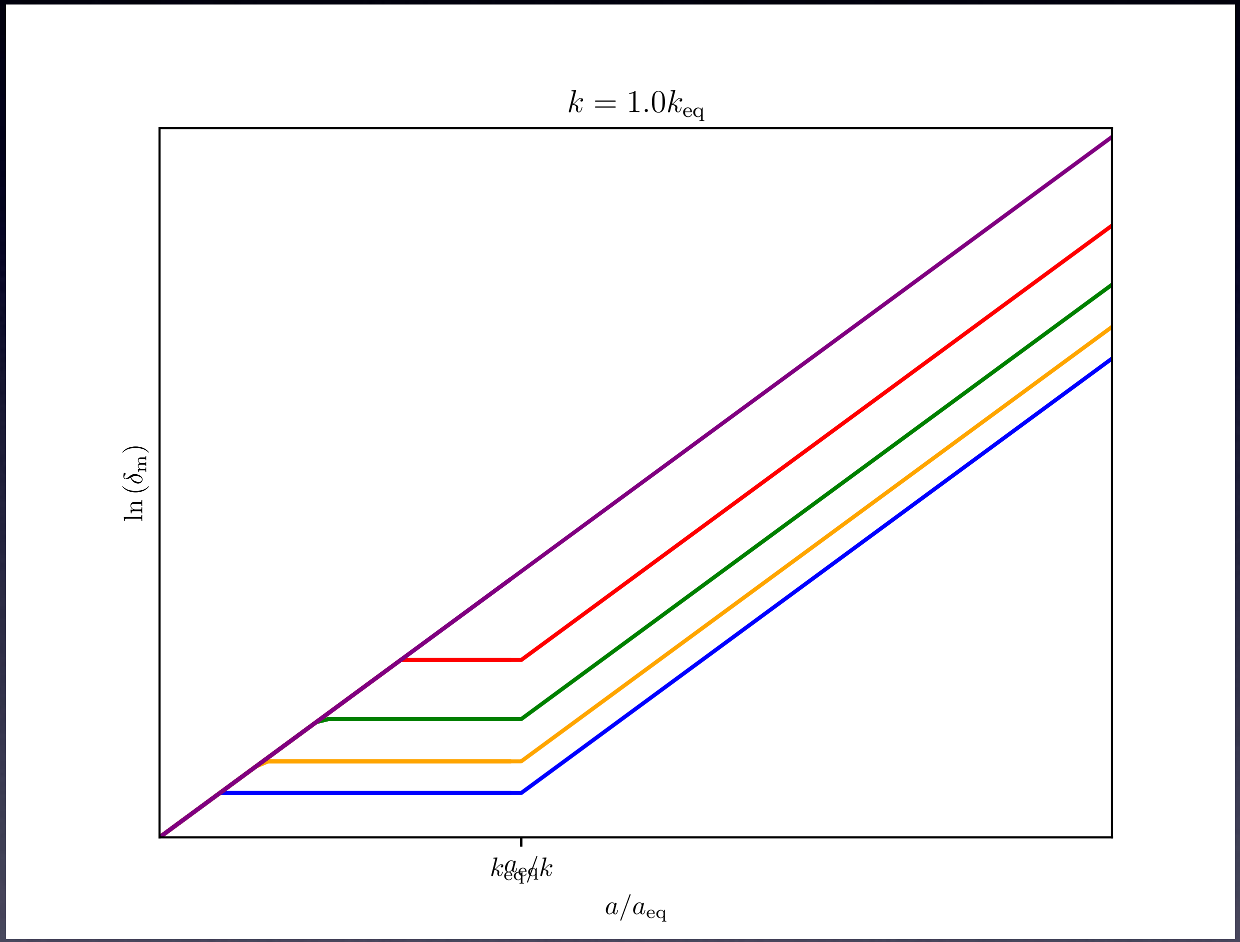

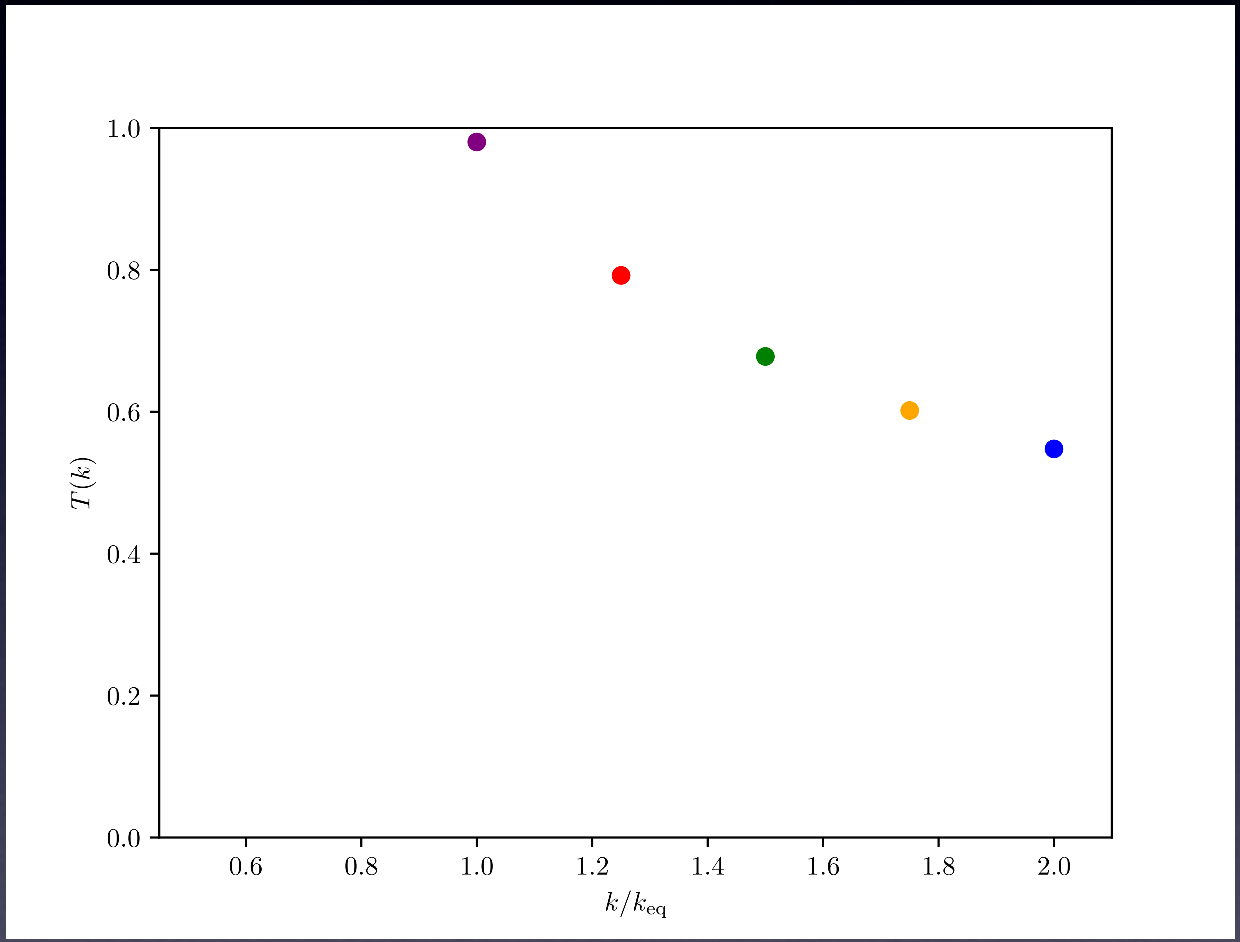

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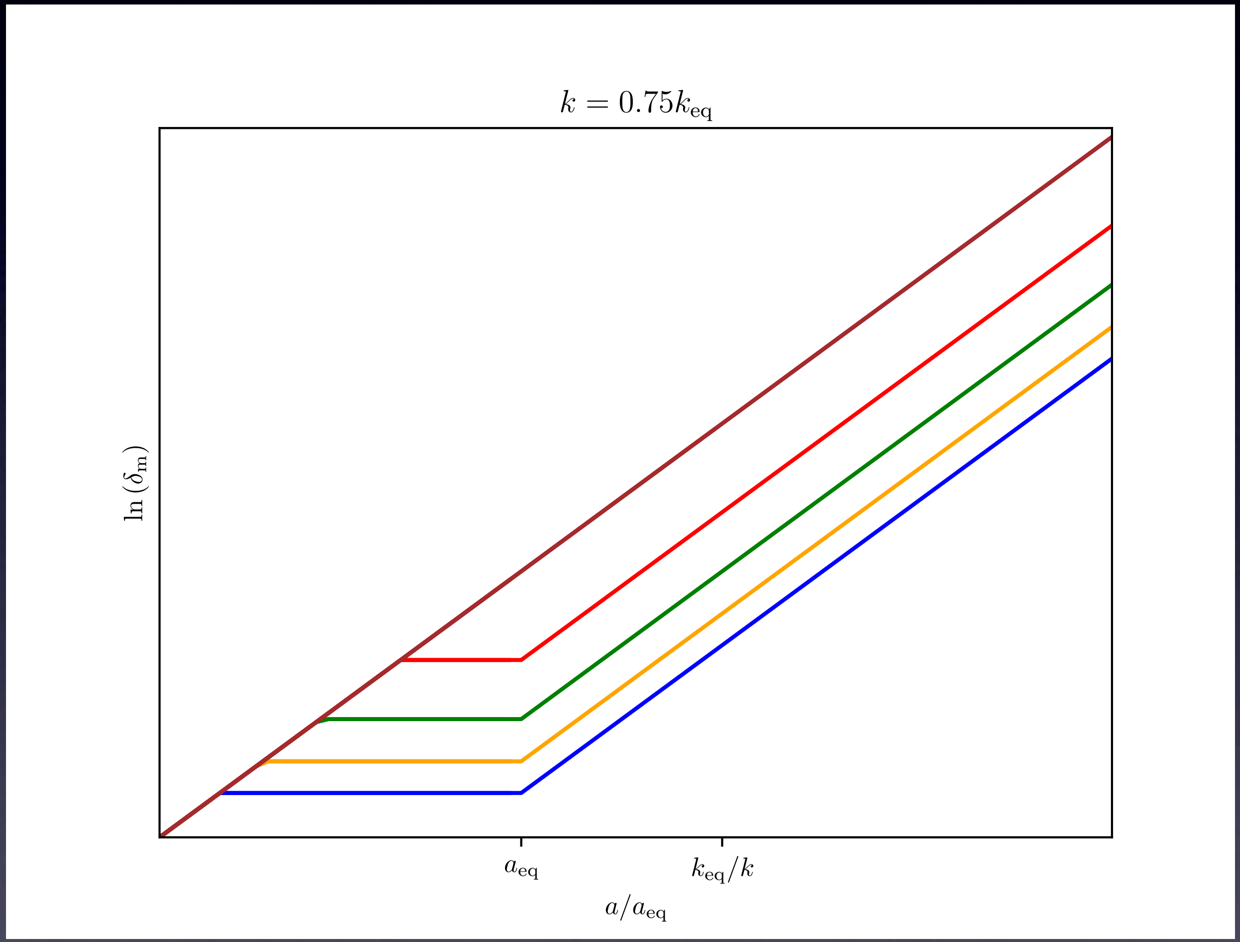

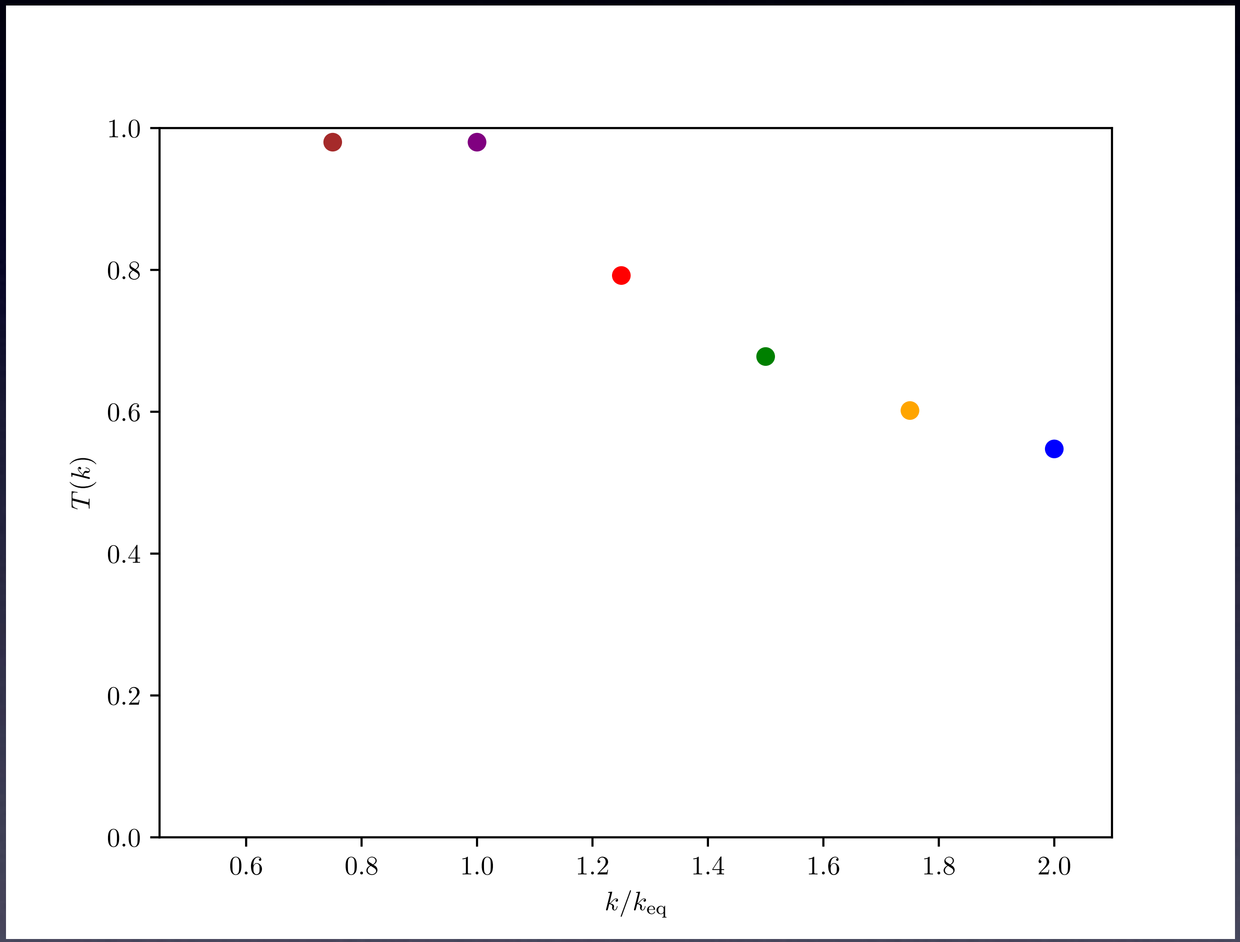

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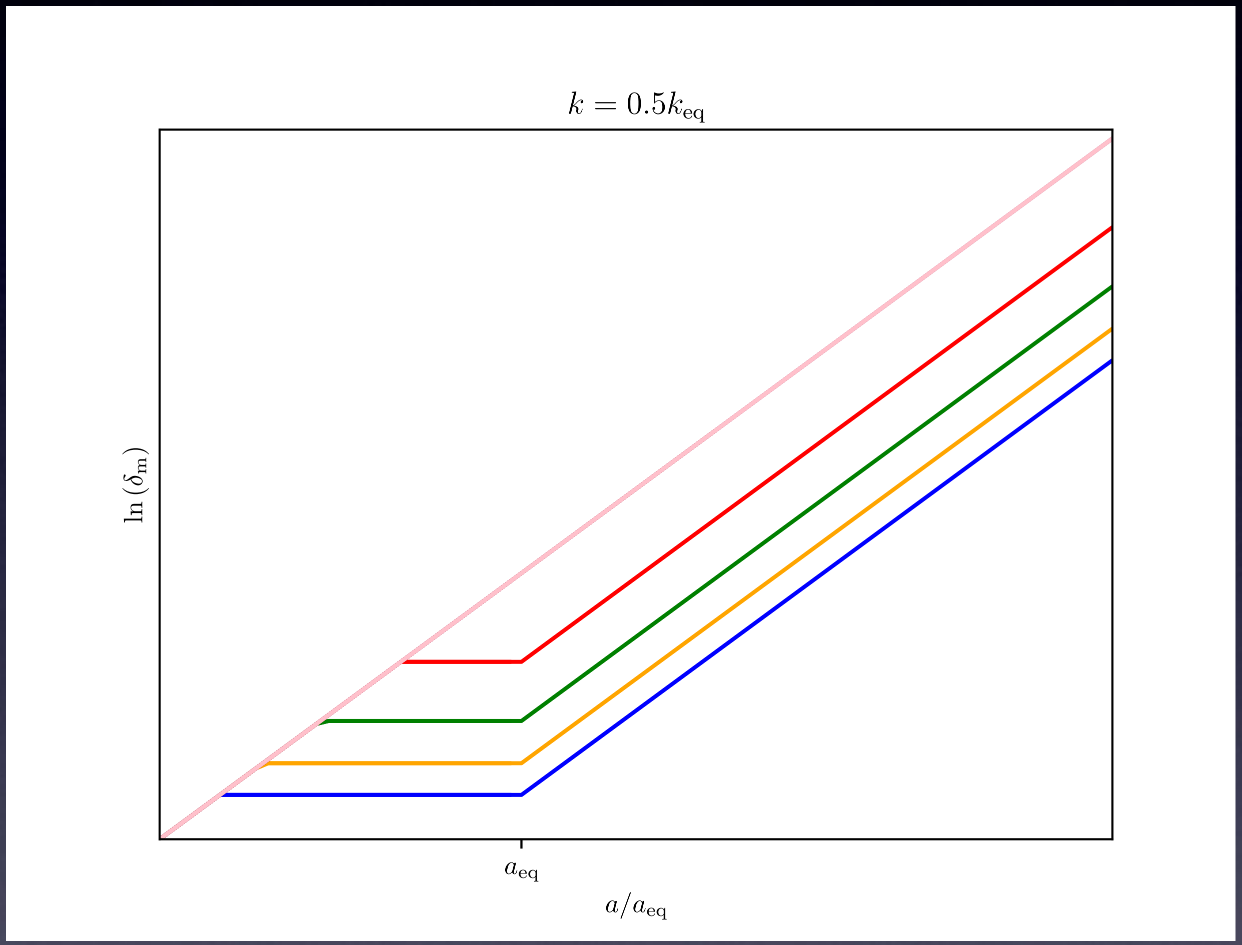

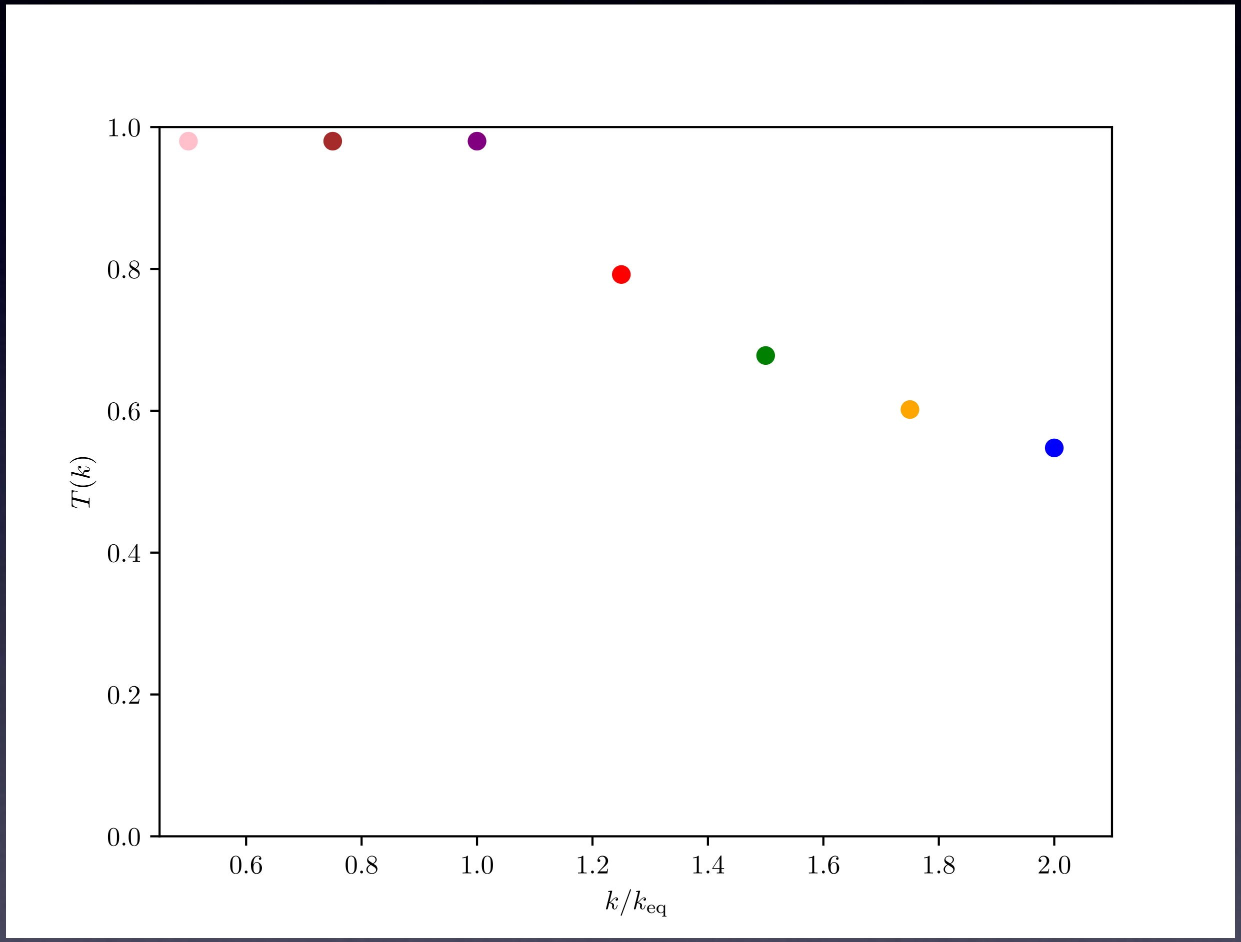

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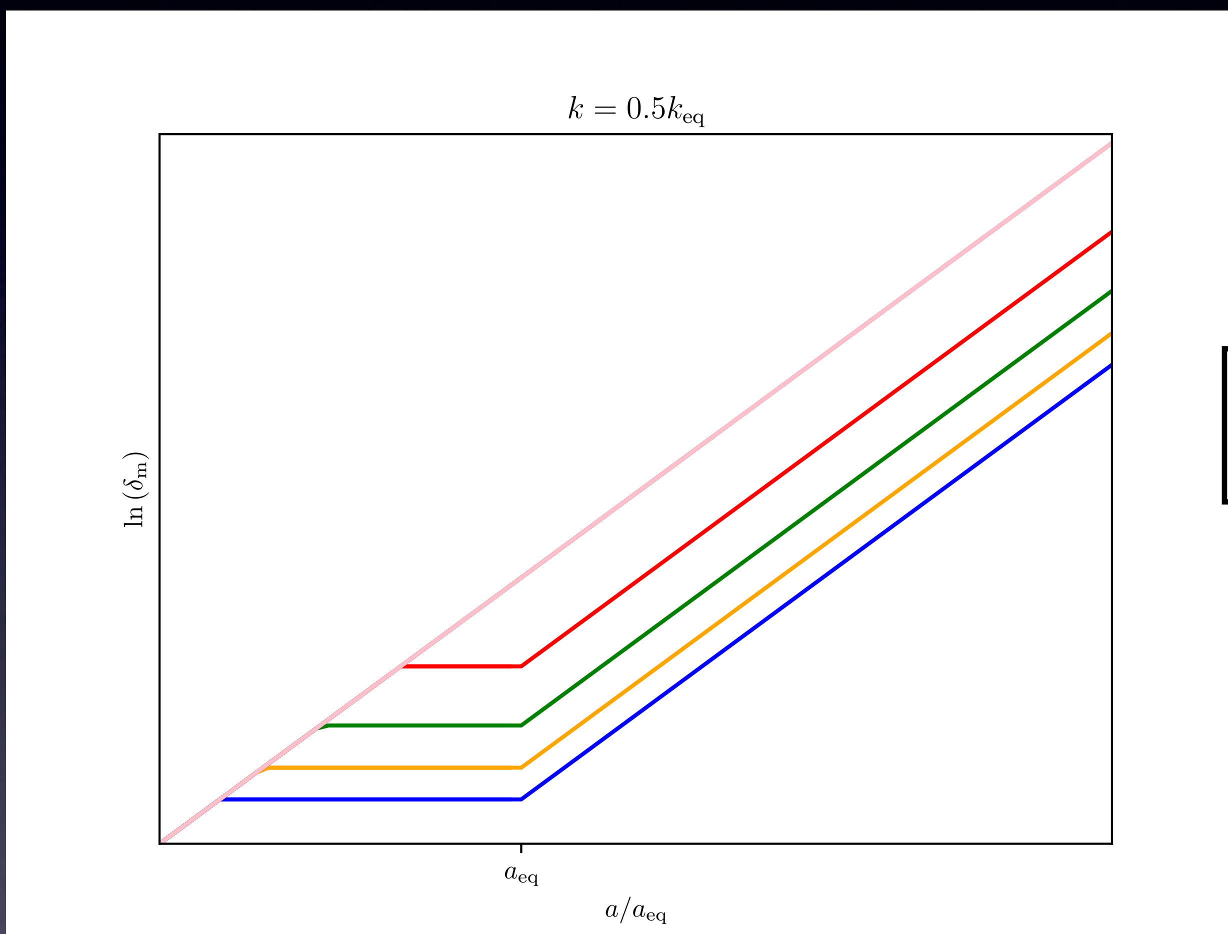

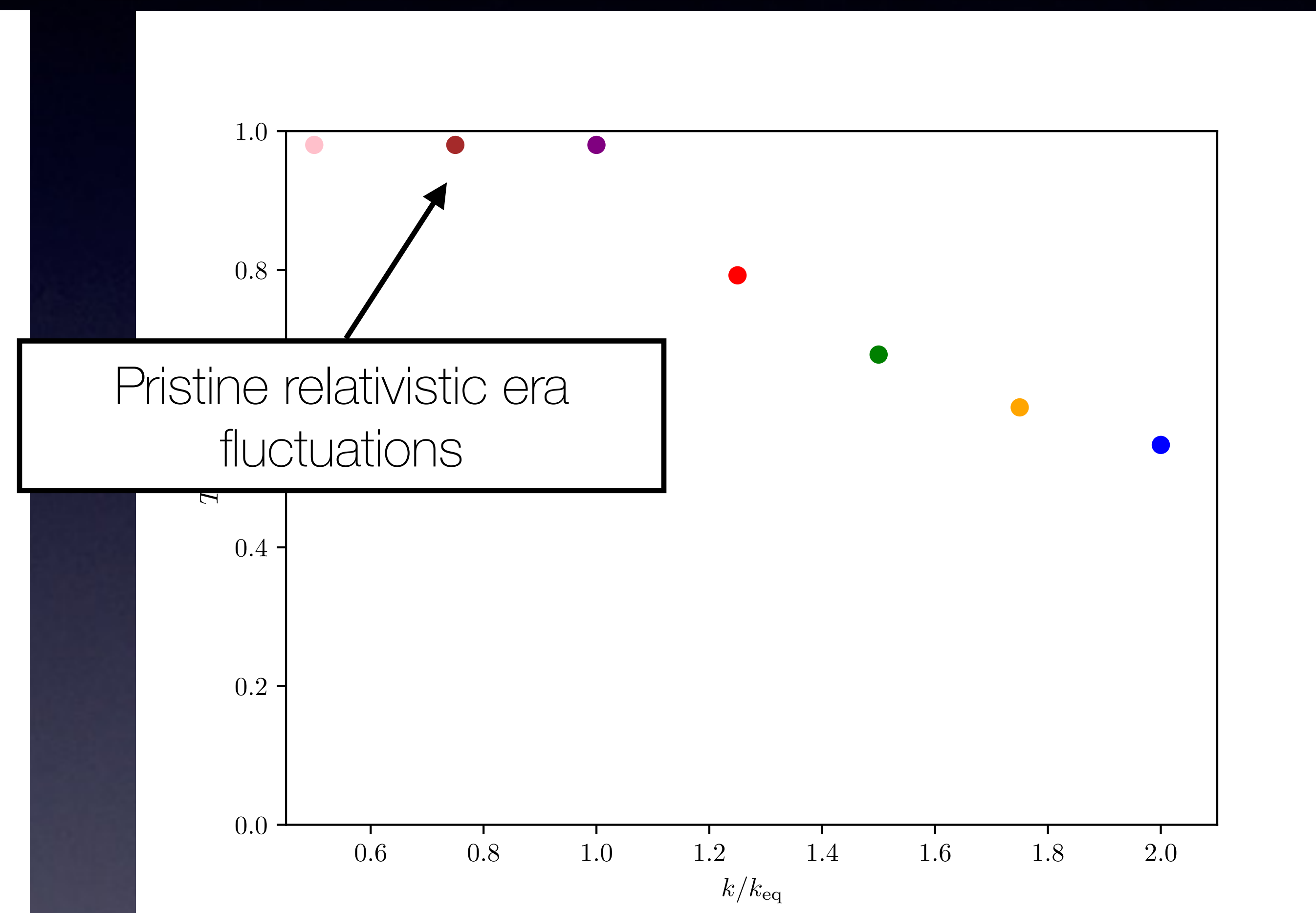

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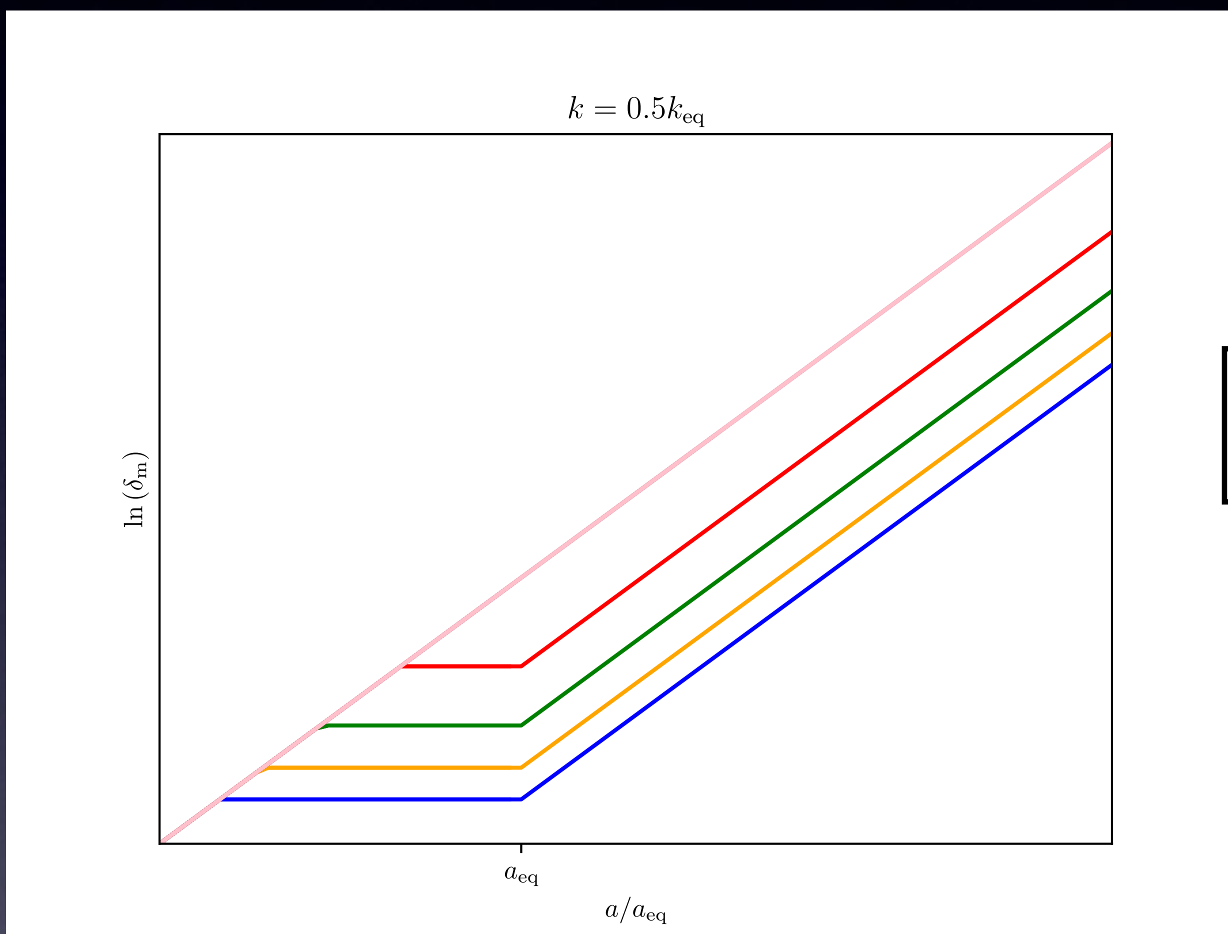

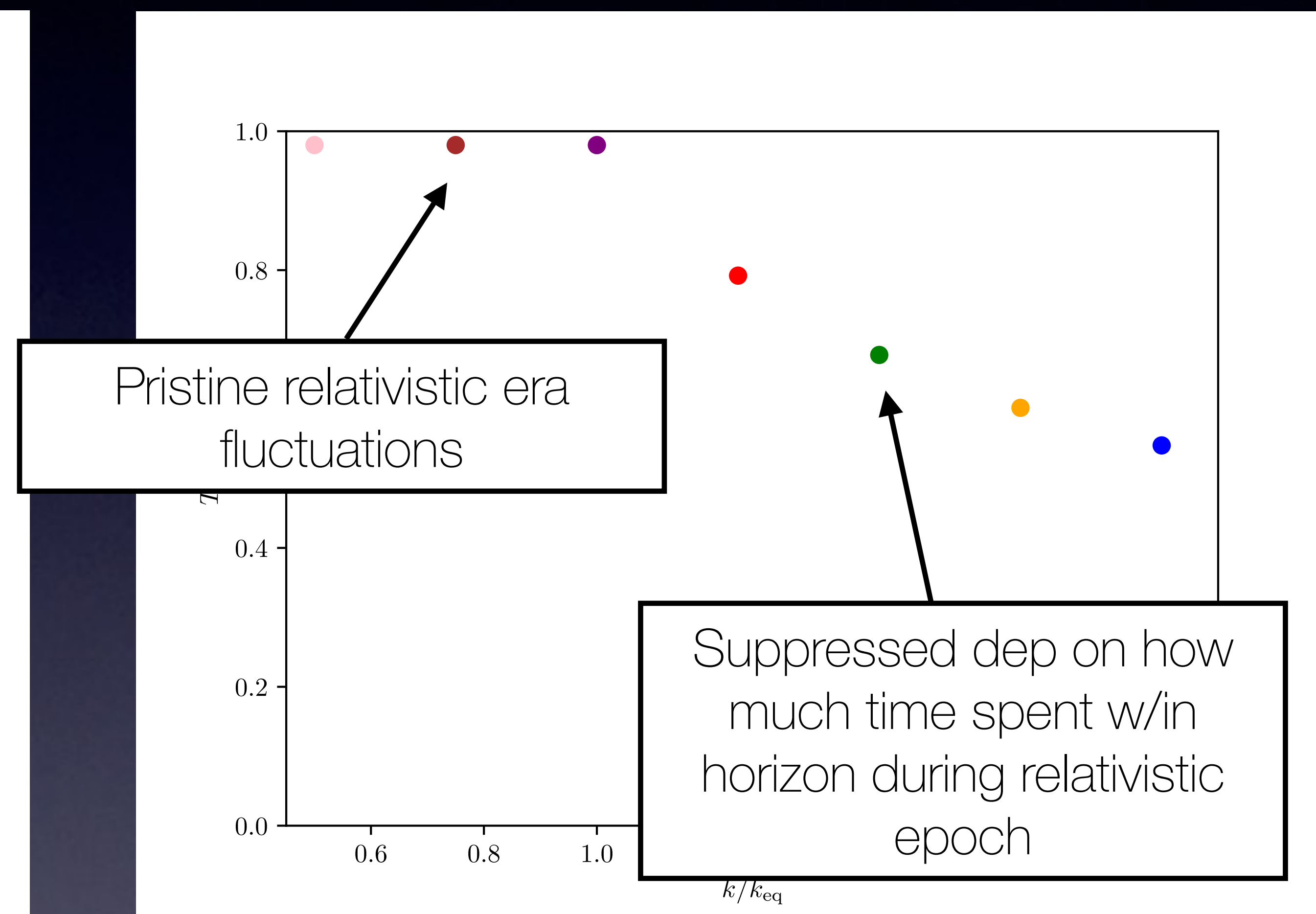

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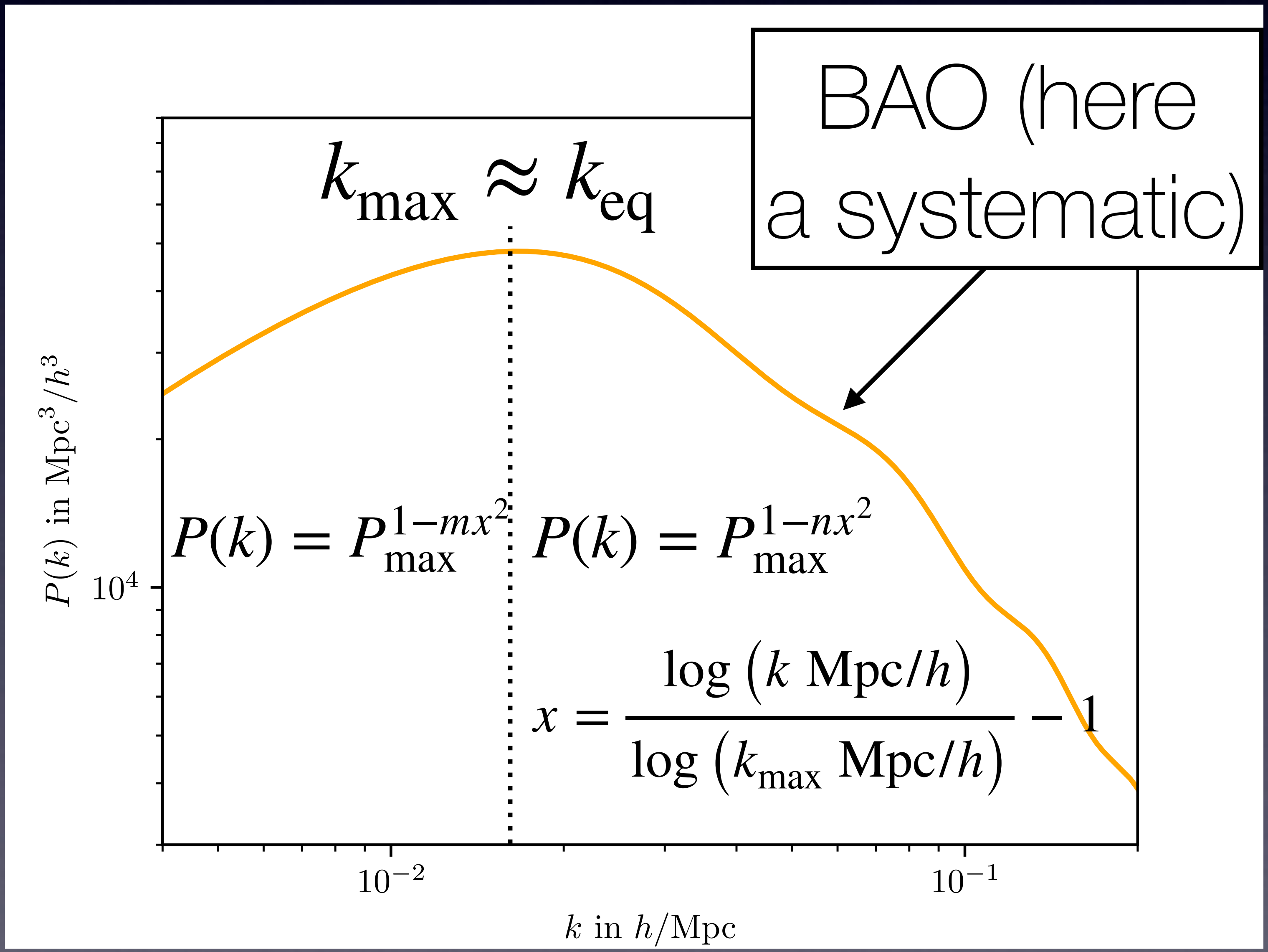
Model-independent approach

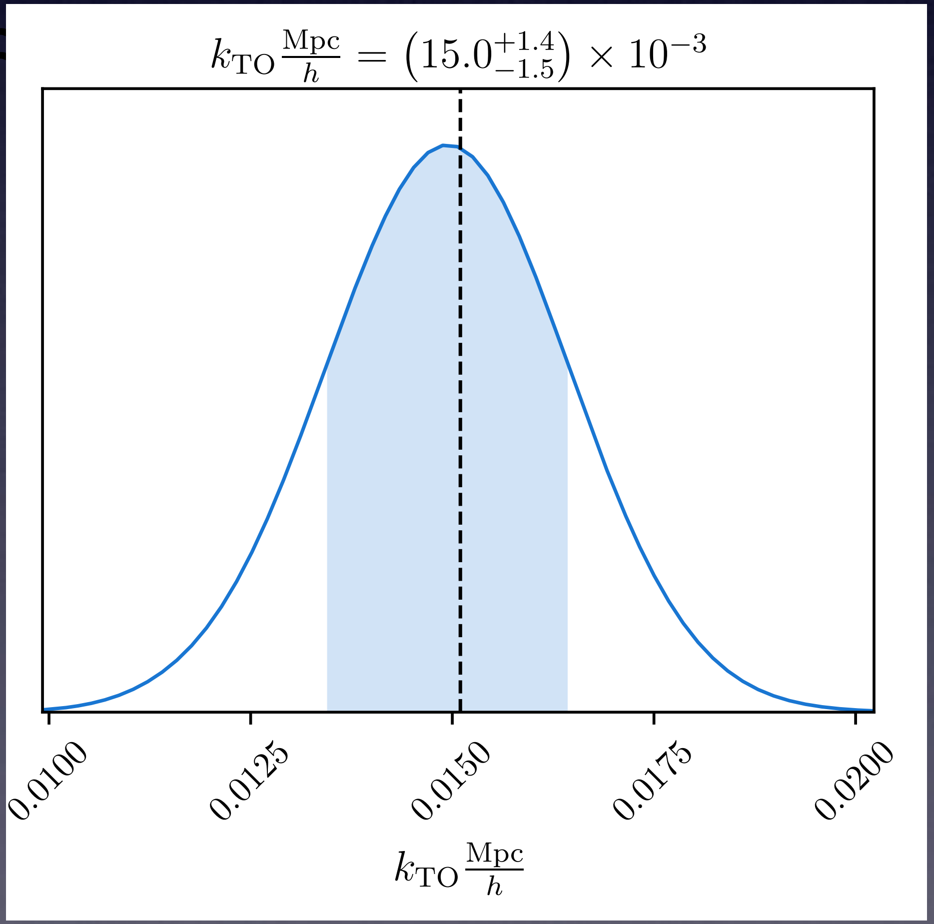
- Alternative to Full Modelling: Localising Turnover scale similar to what we do with BAO (compressed analysis)
- Parameterisation following [Poole *et al.* 2011]:
  - two slopes (m, n)
  - One amplitude $P_{\rm max}$
  - One turn-over scale $k_{\rm max}$
  - $k_{\rm max,fid} = 0.0166 h/{\rm Mpc}$
-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



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

k_{max} ≈



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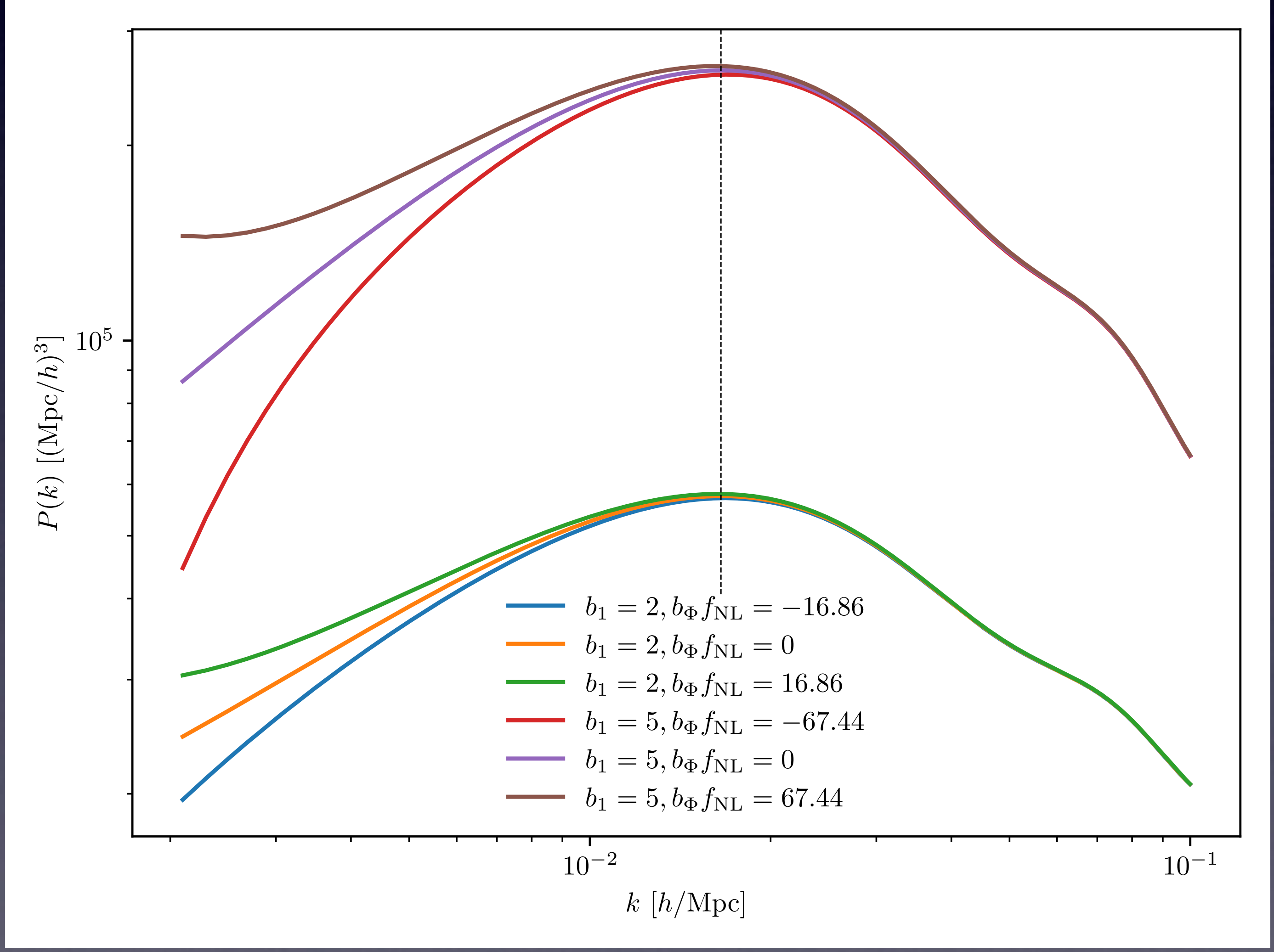
Turnover scale vs PNG

- TO shifts by less than 1% for reasonable values of $f_{\rm NL}^{\rm loc}$ [Cunnington 2022]
- Finding TO in the right spot thus provides confidence for potential detections of PNG
- But, DESI has $f_{\rm NL}^{\rm loc}$ blinding with potentially stronger PNG



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TO as standard ruler

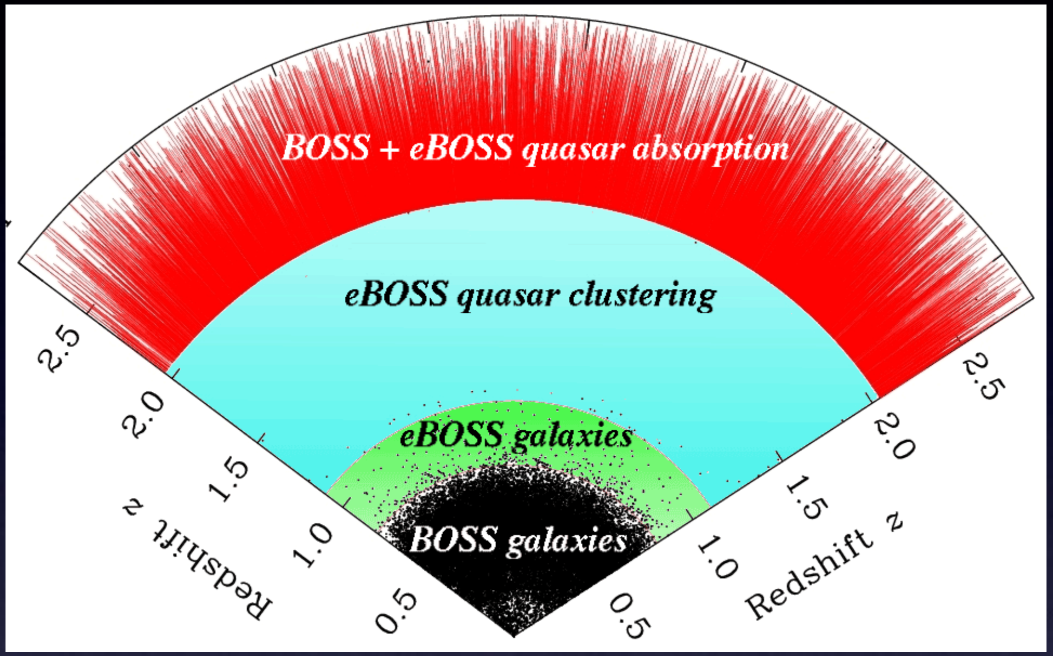
- Analogous to BAO, define $r_{\rm d}$-independent standard ruler

$$\alpha_{\rm TO} = \frac{D_{\rm V}^{\rm fid}}{D_{\rm V}} \frac{r_{\rm H}}{r_{\rm H}^{\rm fid}}$$

- $r_{\rm H} \propto \left(\Omega_{\rm m} h^2\right)^{-2}$, so we can measure H_0 independent of $r_{\rm d}$ and BBN when combining with $\Omega_{\rm m}$ from, e.g., BAO

- Test of Universe at z = 3400 rather than z = 1100, Early Dark Energy? Alternatively, test neutrino sector

Application to eBOSS



- Most redshift surveys in the past didn't probe enough volume to probe scales $k < k_{\mathrm{TO,fid}} = 0.0166h/\mathrm{Mpc}$
- Largest volume Stage III spectroscopic data set: eBOSS QSO
  - 343 708 Quasars, $0.8 < z < 2.2$, $4699\mathrm{deg}^2$
  - 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]

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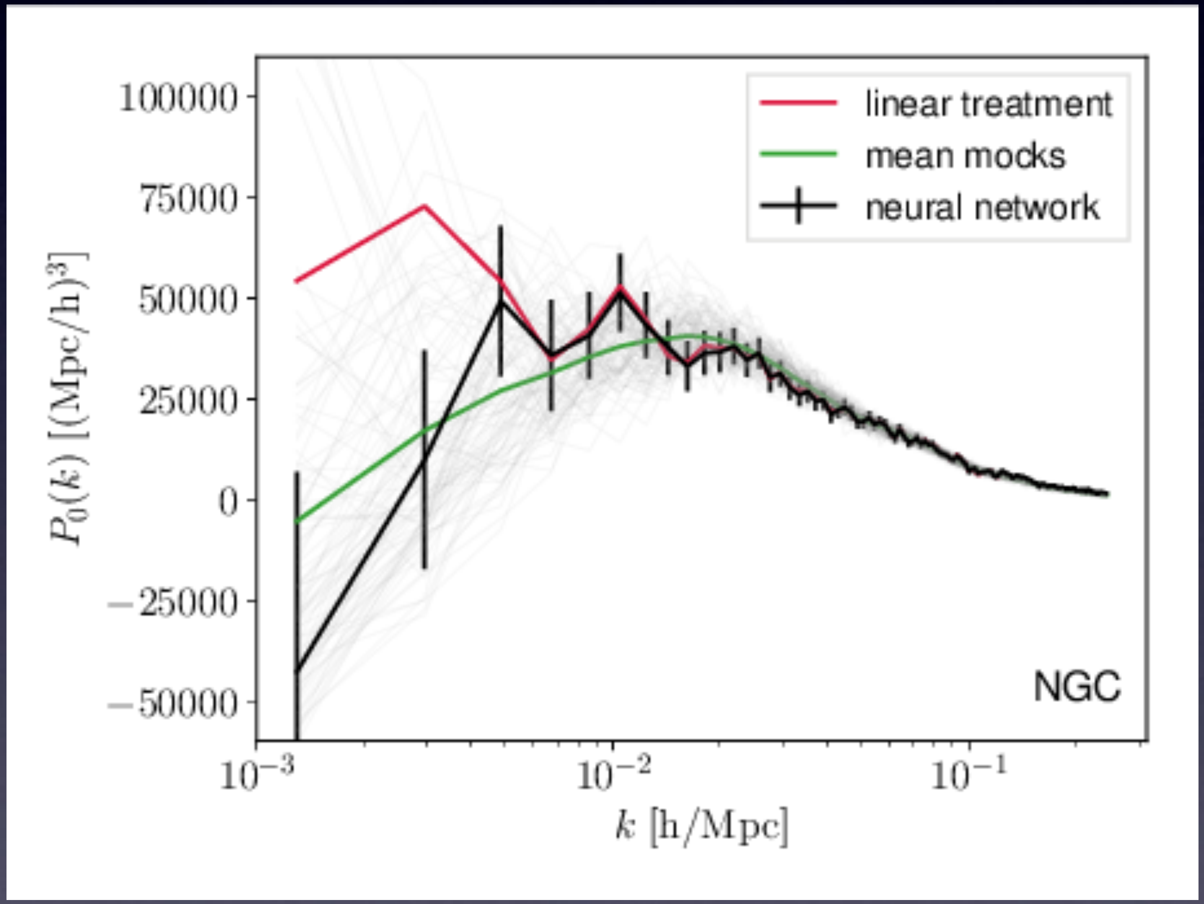
eBOSS ultra-large-scale systematic treatment



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

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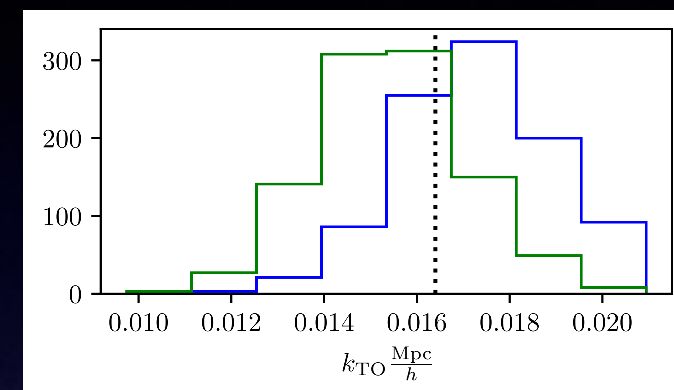
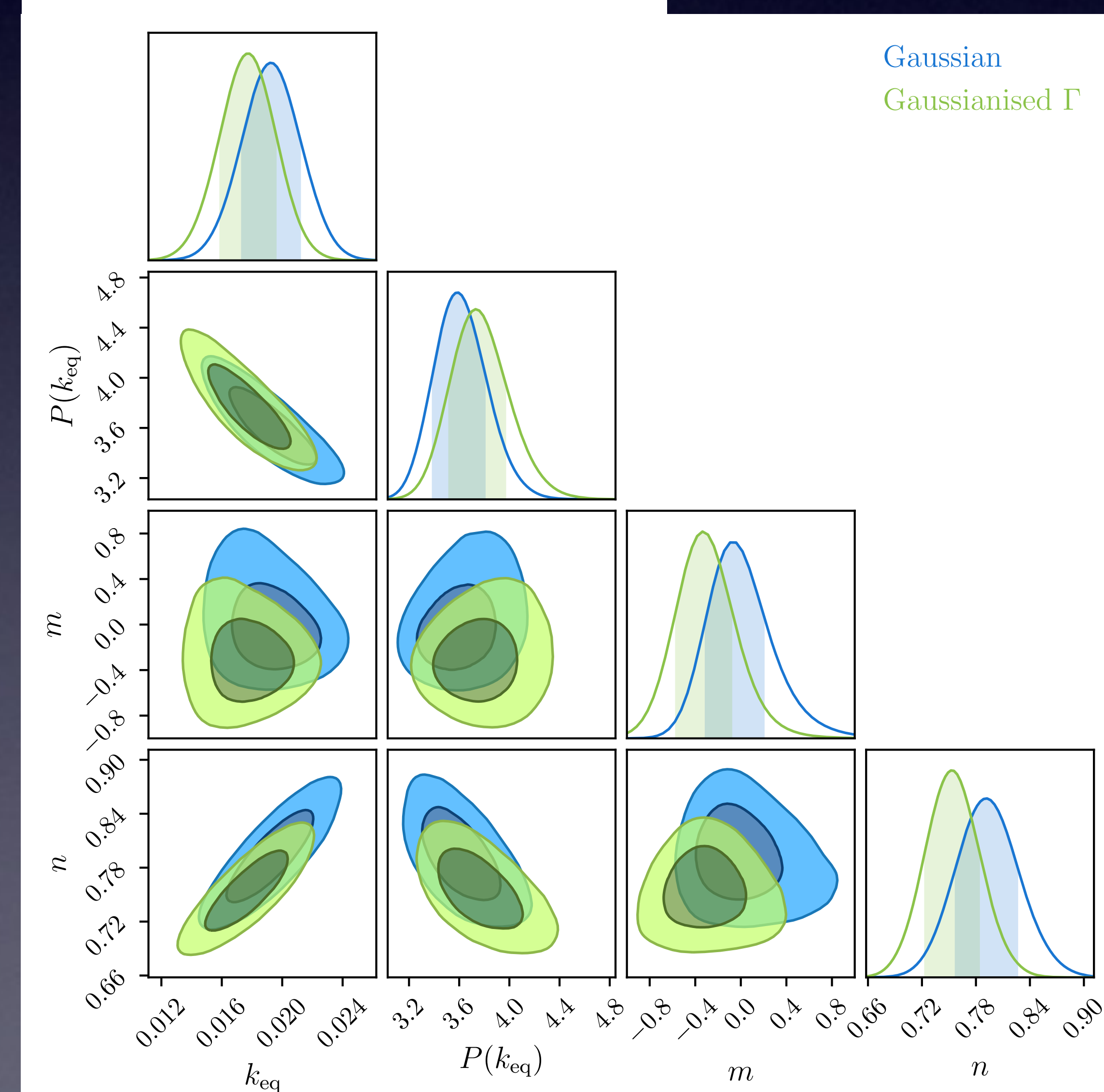
eBOSS results

- 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 $Z = \left[P(k)\right]^{\nu}$





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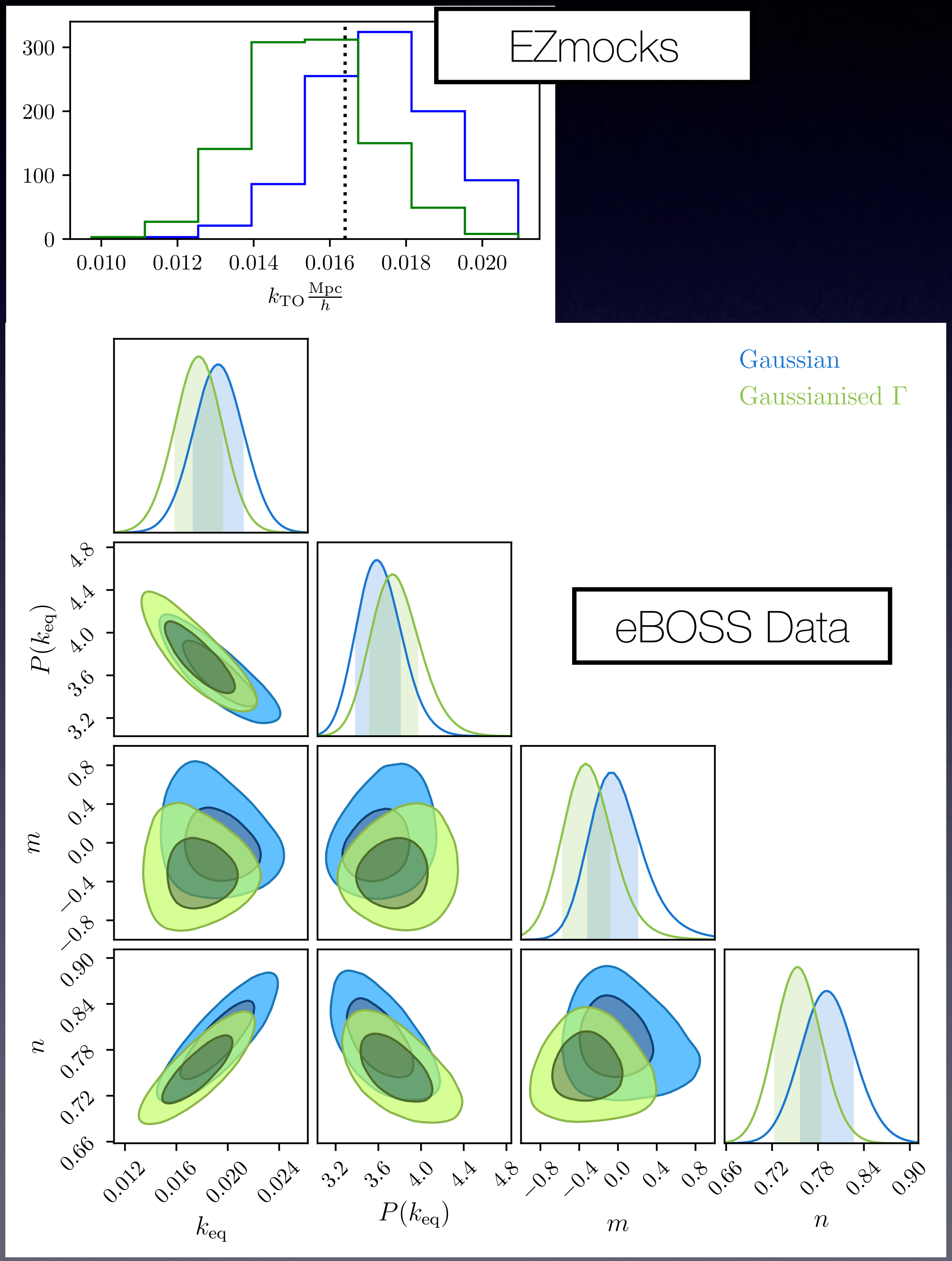

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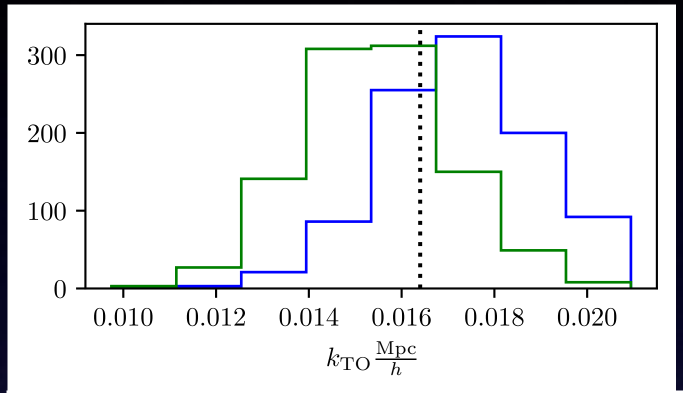
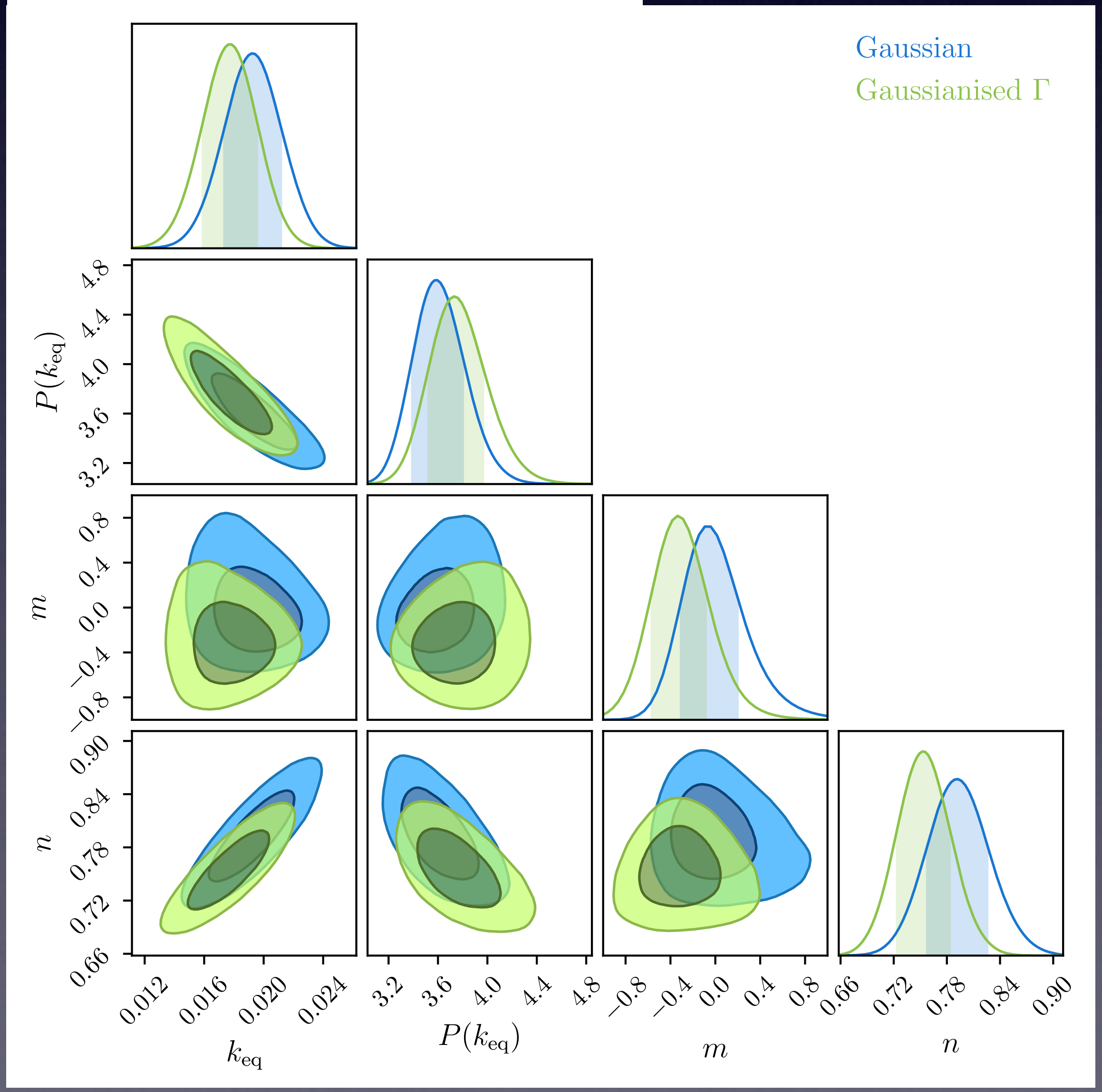
eBOSS results

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





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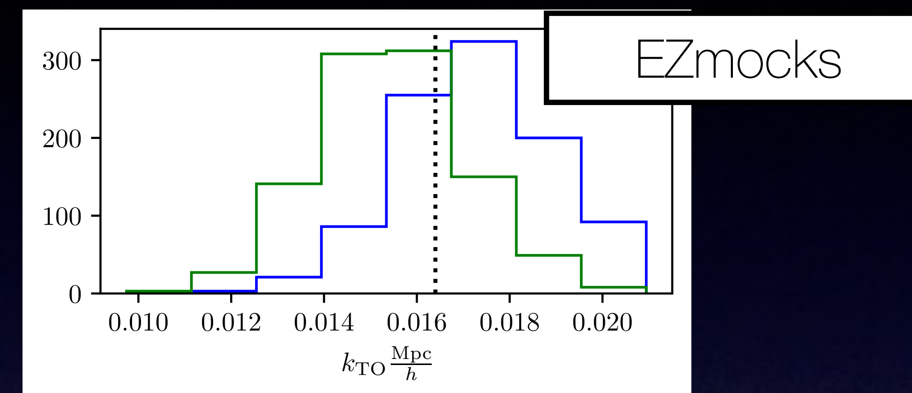

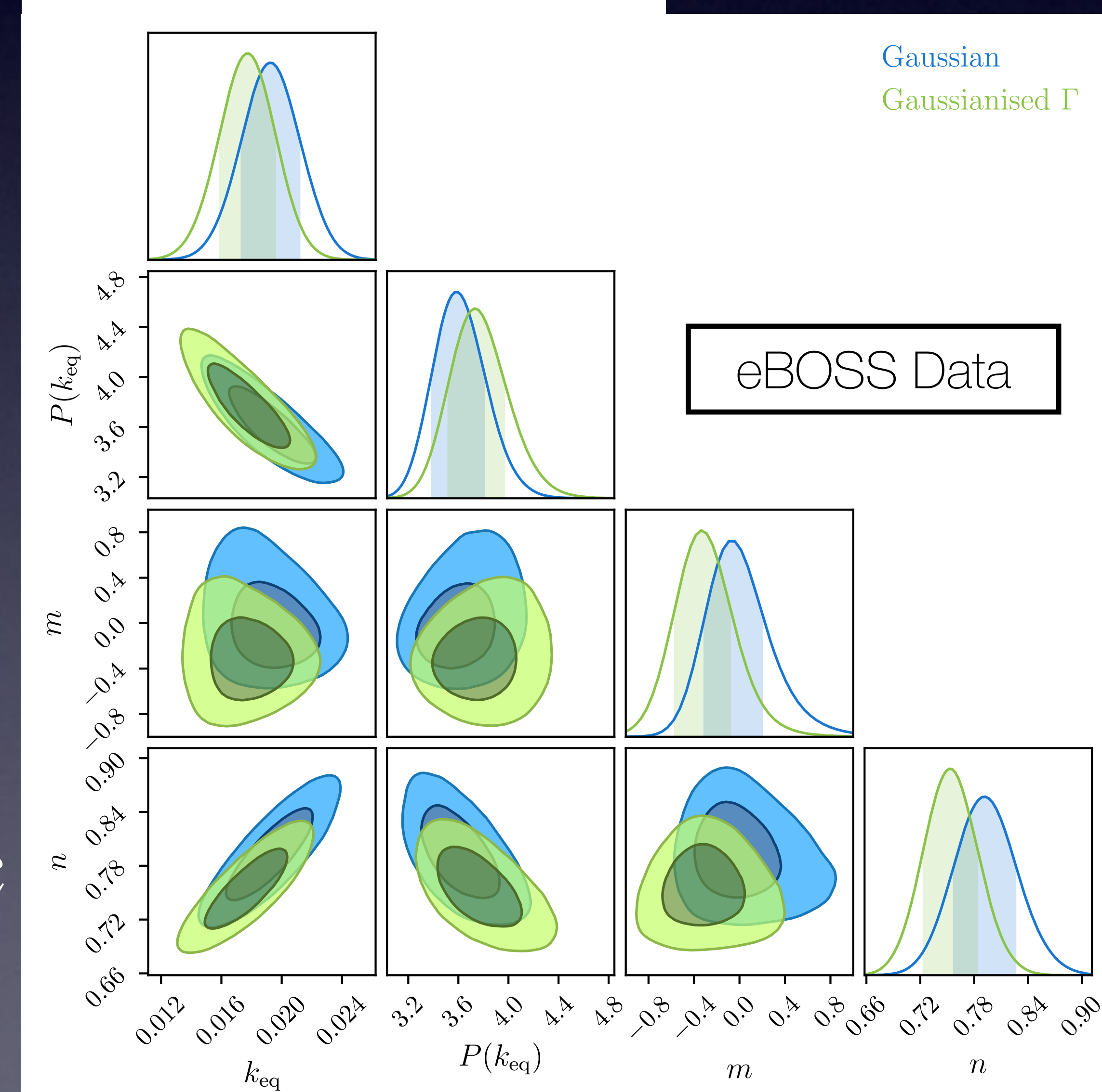

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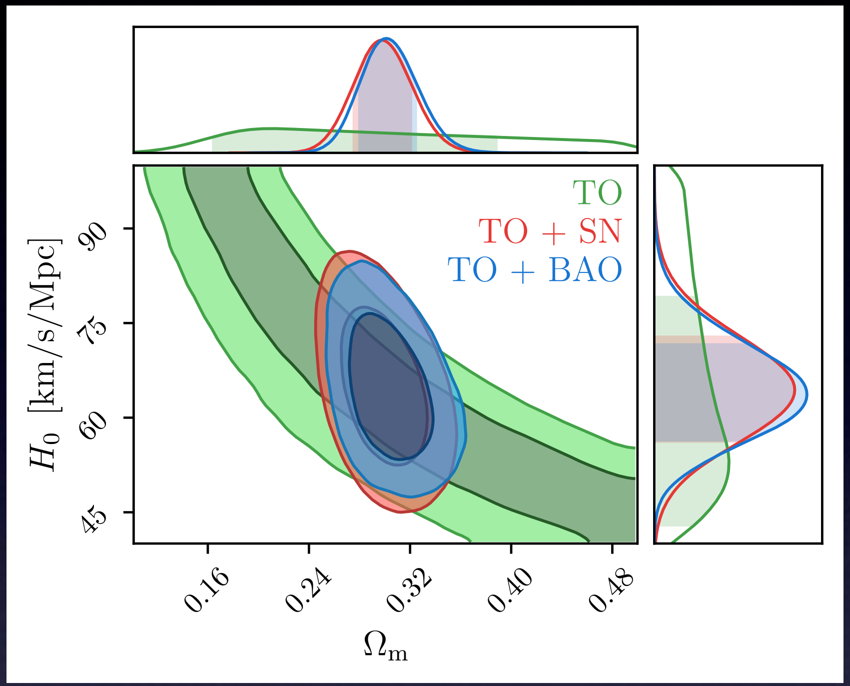
eBOSS results

- Assume inflection point is turnover
- $\alpha_{\mathrm{TO}} = 1.06 \pm 0.11$
- cf. $\alpha_{\mathrm{bao}} = 1.025 \pm 0.020$ [Neveux et al. 2020]



- Assuming 3 standard massless neutrino species, direct measurement of $\Omega_\mathrm{m} h^2 = 0.159^{+0.041}_{-0.037}$, consistent with Planck ($\Omega_\mathrm{m} h^2 = 0.1430 \pm 0.0011$)
- In combination with Ω_m from BAO or SNe, we get $H_0 = \left(74.7 \pm 9.6\right)$ km/s/Mpc (with Pantheon) and $H_0 = \left(72.9^{+10.0}_{-8.6}\right)$ km/s/Mpc (with eBOSS LRG and Lyα BAO) without any sound horizon information

Euclid Hα 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
- $M_p = 1.5 \cdot 10^{10}$ $M_\odot/h$, 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

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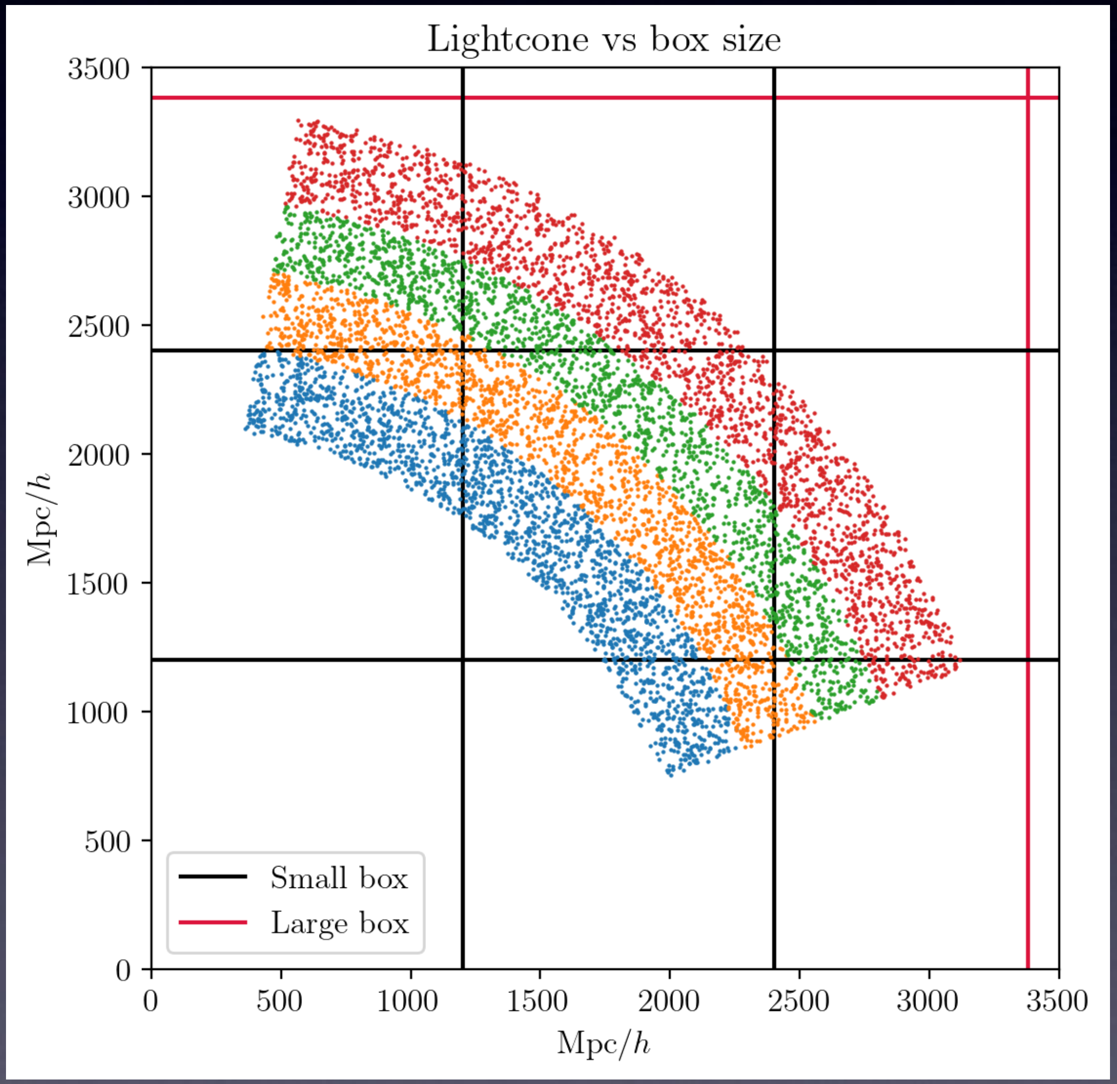
Euclid Hα forecasts

Constraints on mock mean

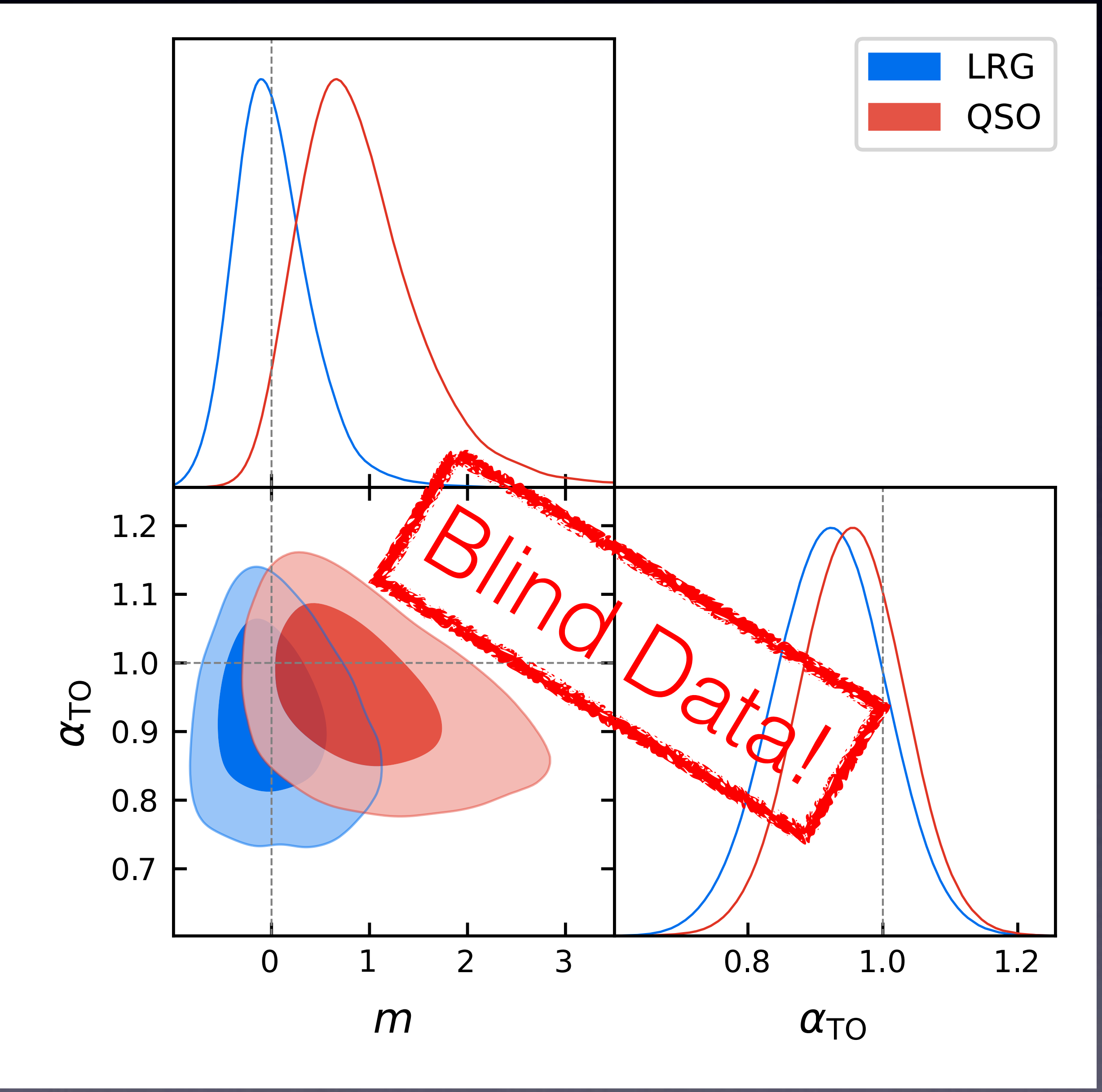
- Allow for different P(k) amplitude in redshift bins
- Other 3 parameters kept equal at all redshifts
- $\alpha_{\rm TO} = 0.981^{+0.028}_{-0.026}$, errors 4 times smaller as eBOSS errors
- Detection probability ($m > 0$): 85%



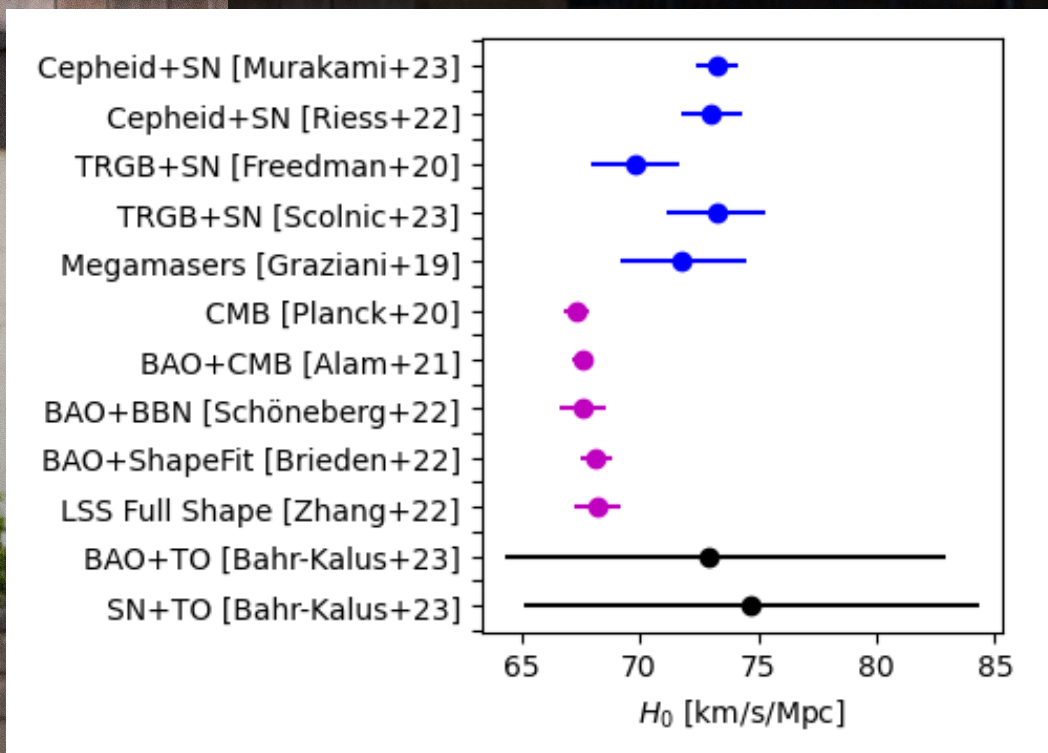
Credits: J. Salvalaggio

Blind DESI results

- Already twice as many QSOs observed in DESI Y1 than by eBOSS
- Are DESI LRGs a contender?
- $\mathscr{P}\left(m > 0\right) = 0.96$, $\sigma\left(\alpha_{\mathrm{TO}}\right) = 0.077$ with blind QSO
- $\mathscr{P}\left(m > 0\right) = 0.48$, $\sigma\left(\alpha_{\mathrm{TO}}\right) = 0.083$ with blind LRG
- Note that DESI-blinding strategy changes detection probability



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 blind DESI Y1 QSOs and forecast Euclid Y1

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