Measurements of the matter power spectrum peak from eBOSS and DESI

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11th KIAS Workshop on Cosmology and Structure Formation
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DARK ENERGY SPECTROSCOPIC INSTRUMENT

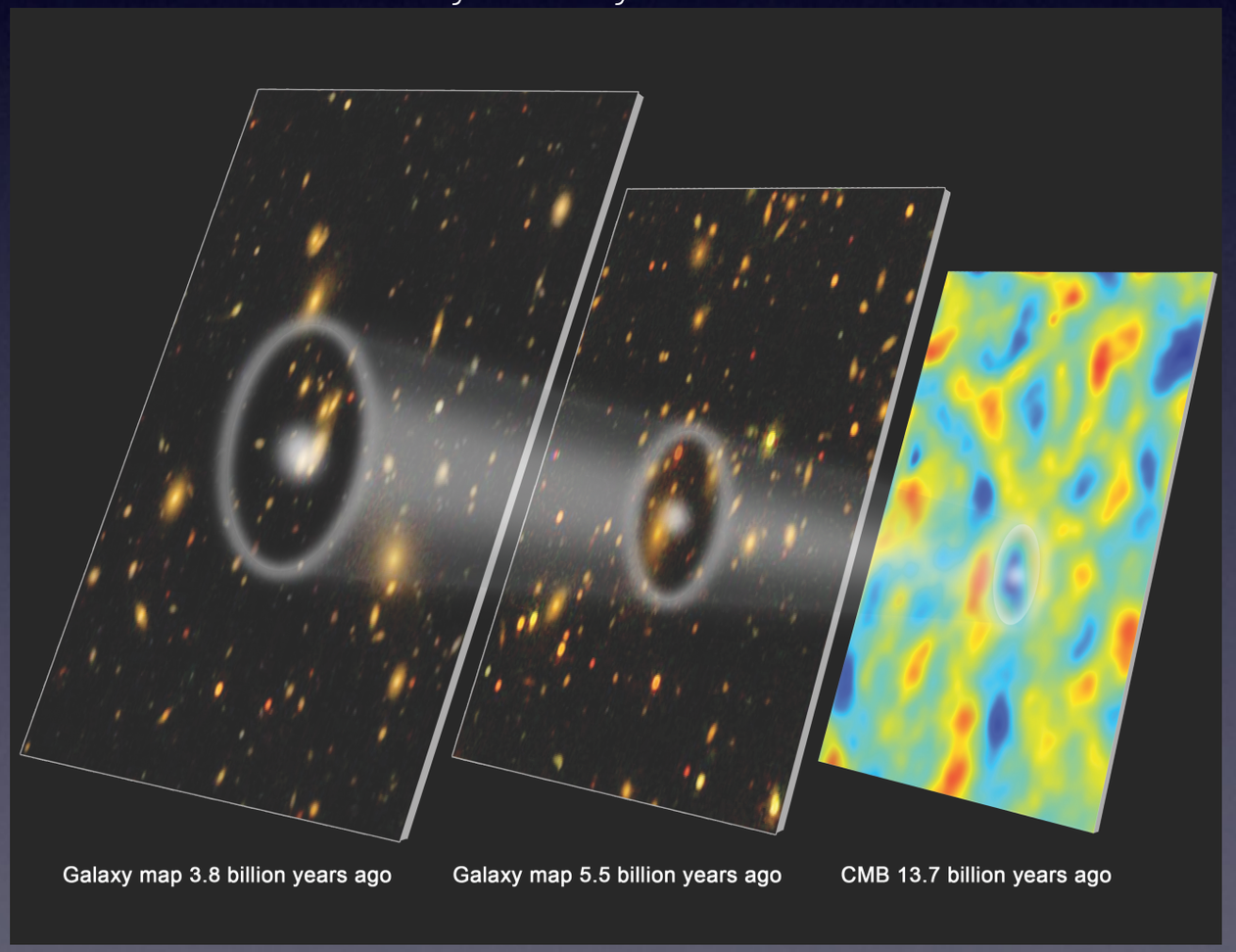
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A note about rulers

- 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 four 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

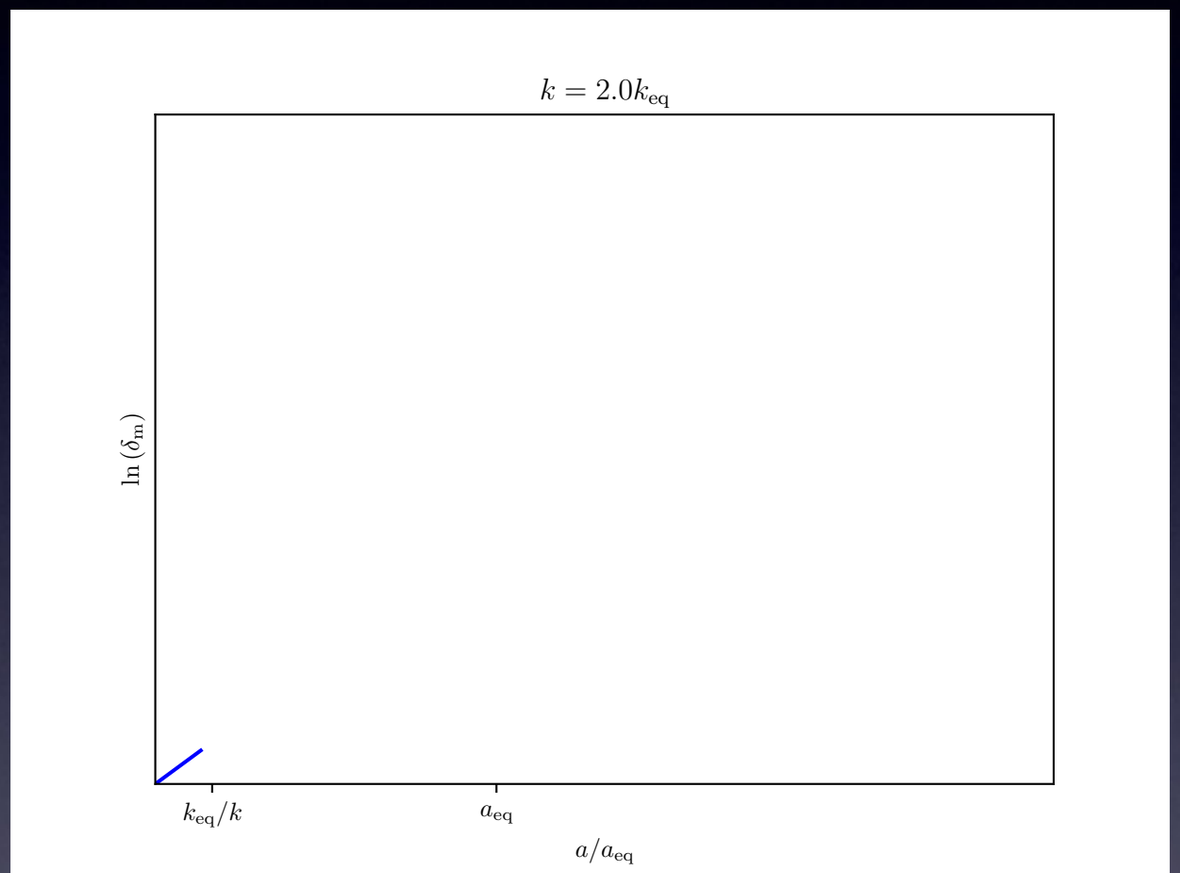
- The power spectrum peak is fixed by a physical scale: the matter-radiation equality scale
- Density fluctuations (after Inflation ends) grow at different rates depending on the details of the expansion (dominant component)
  - During Radiation Domination: Pressure stabilises sub-horizon perturbations, and they do not grow
  - During Matter Domination: Perturbations grow as $\delta_{\mathrm{m}} \propto a$
- 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

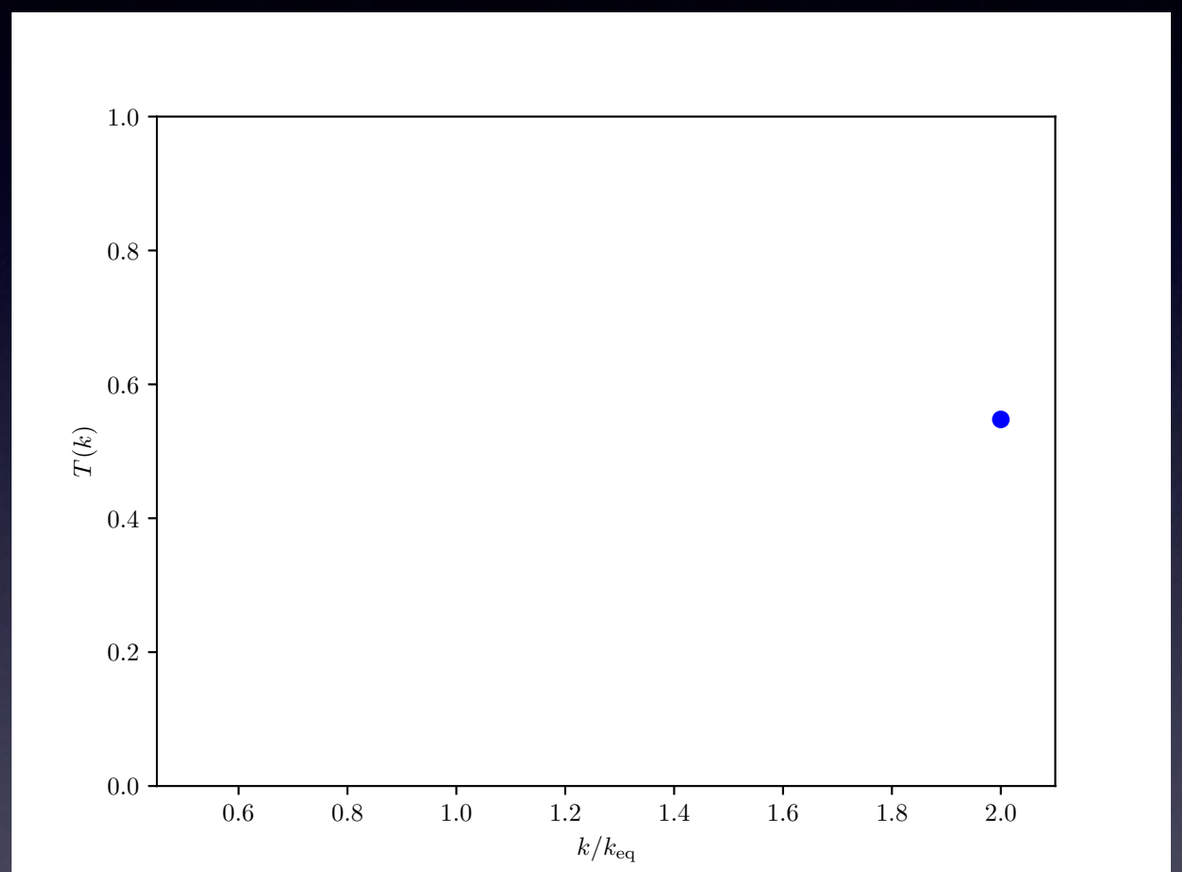
$$a_{\mathrm{eq}} = \rho_{\mathrm{rel}} / \rho_{\mathrm{mat}}$$

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

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

Radiation- vs Matter Domination





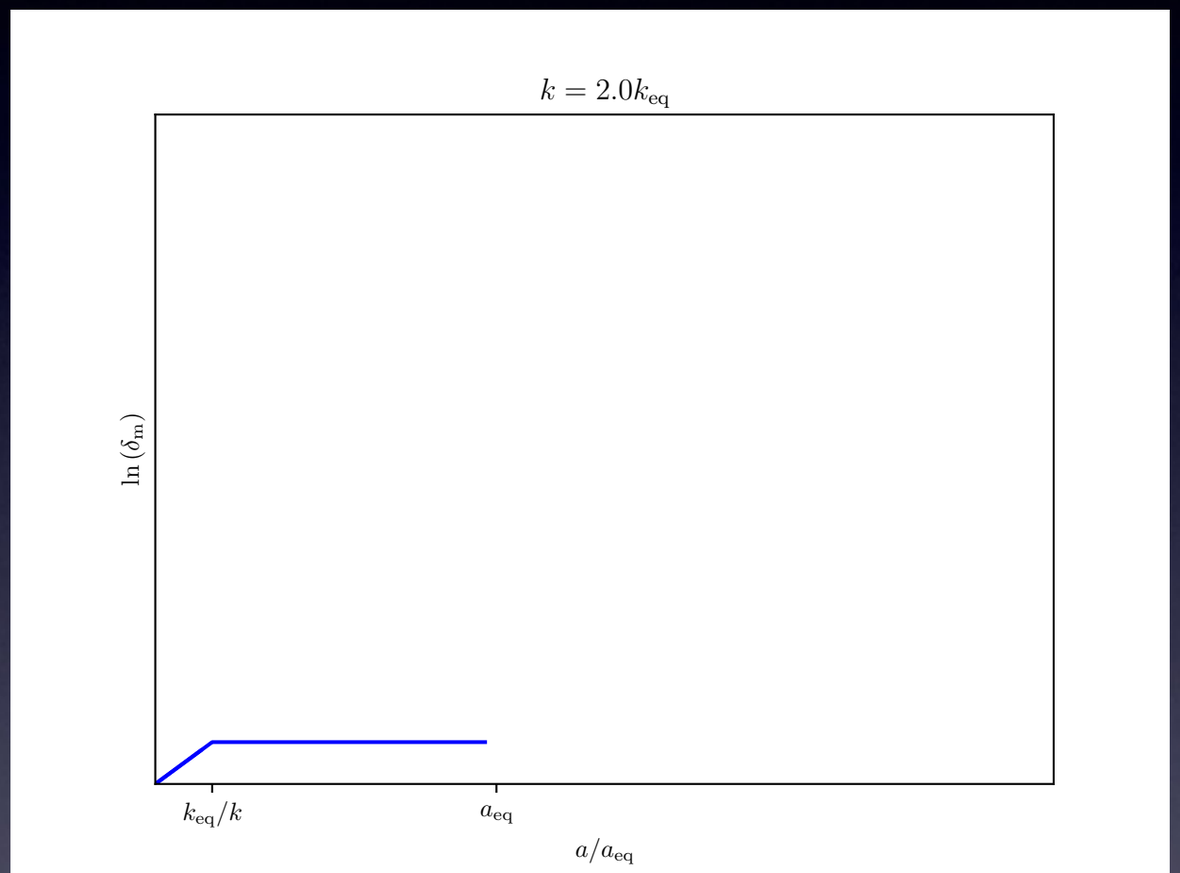
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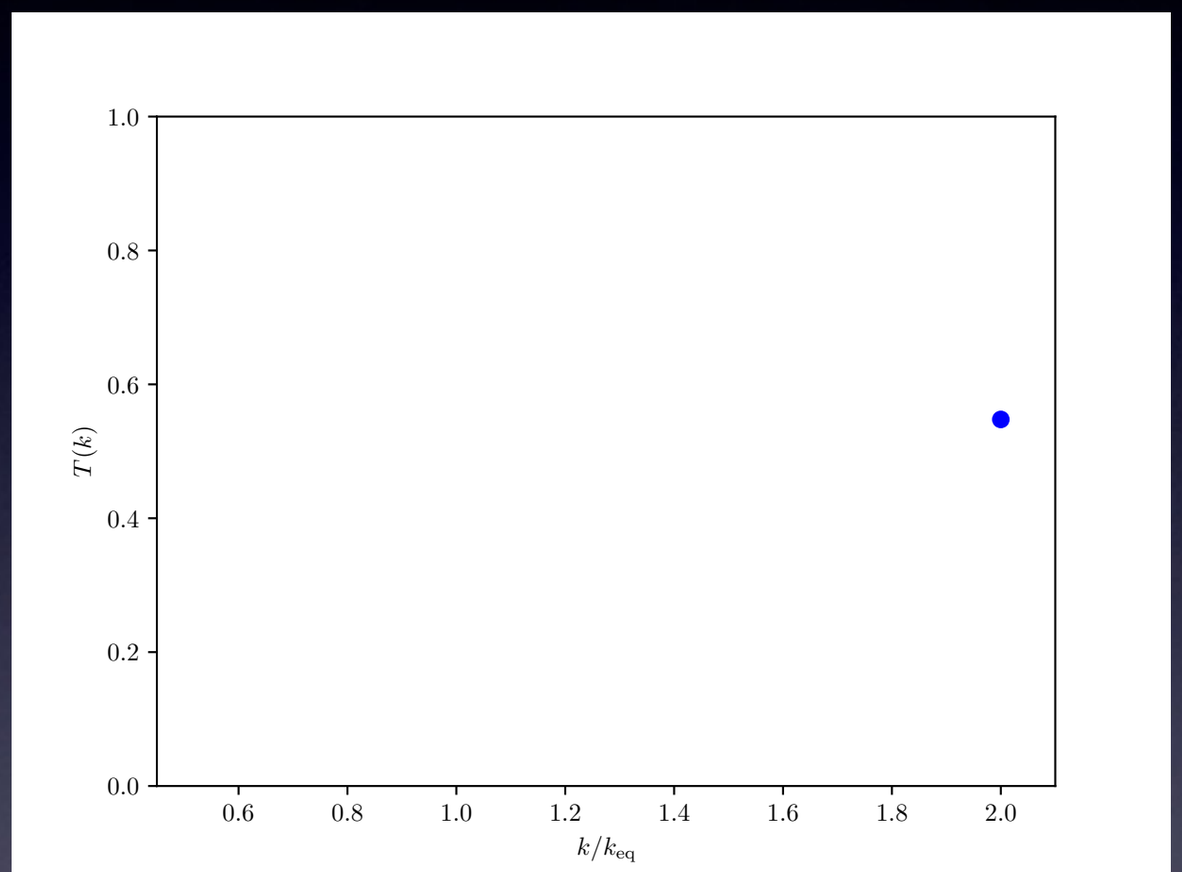
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Radiation- vs Matter Domination





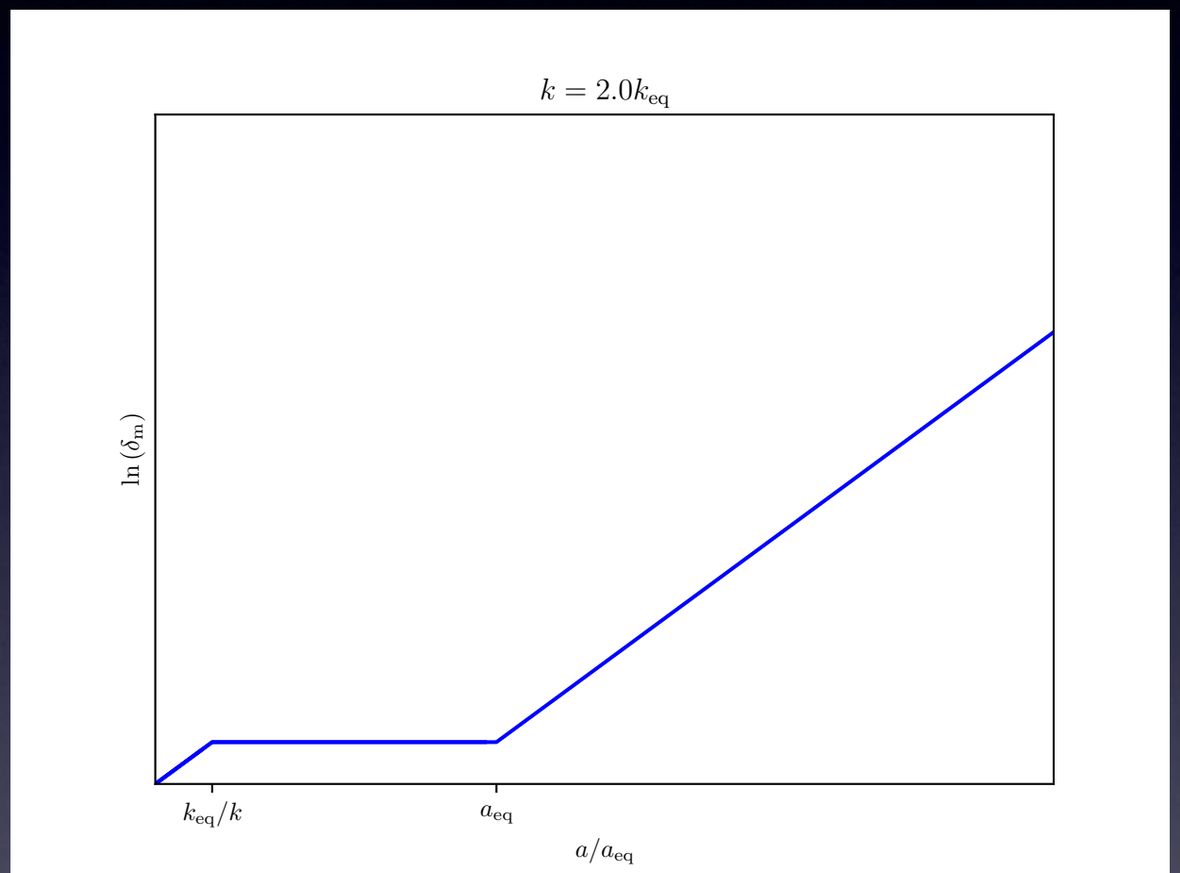
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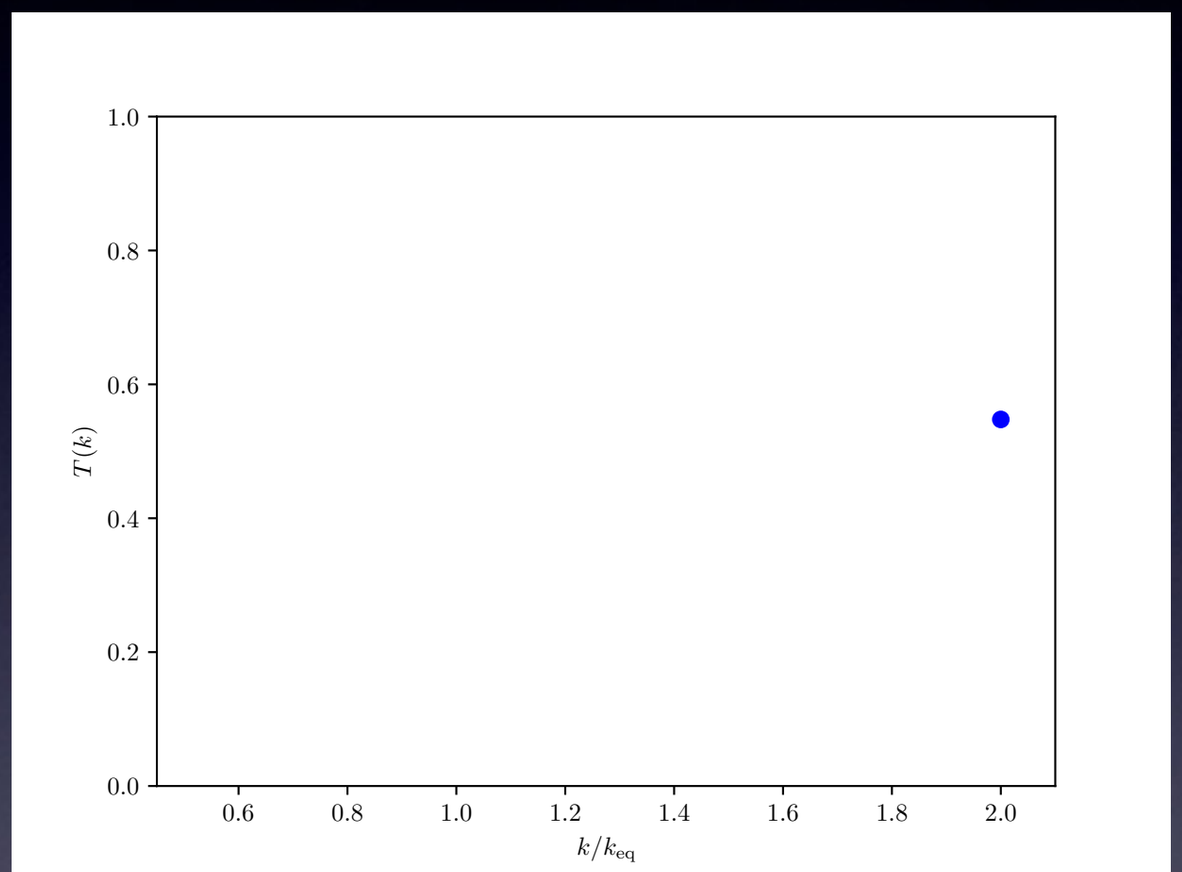
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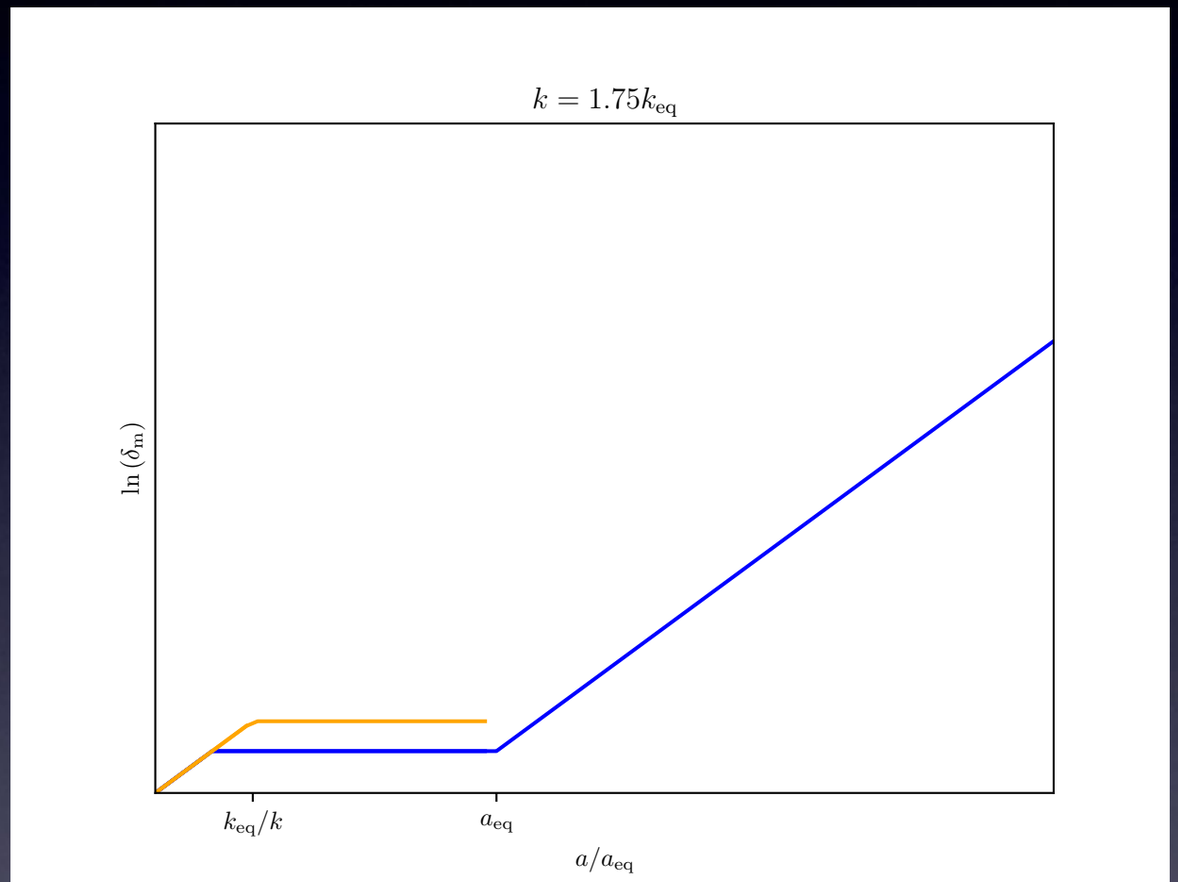
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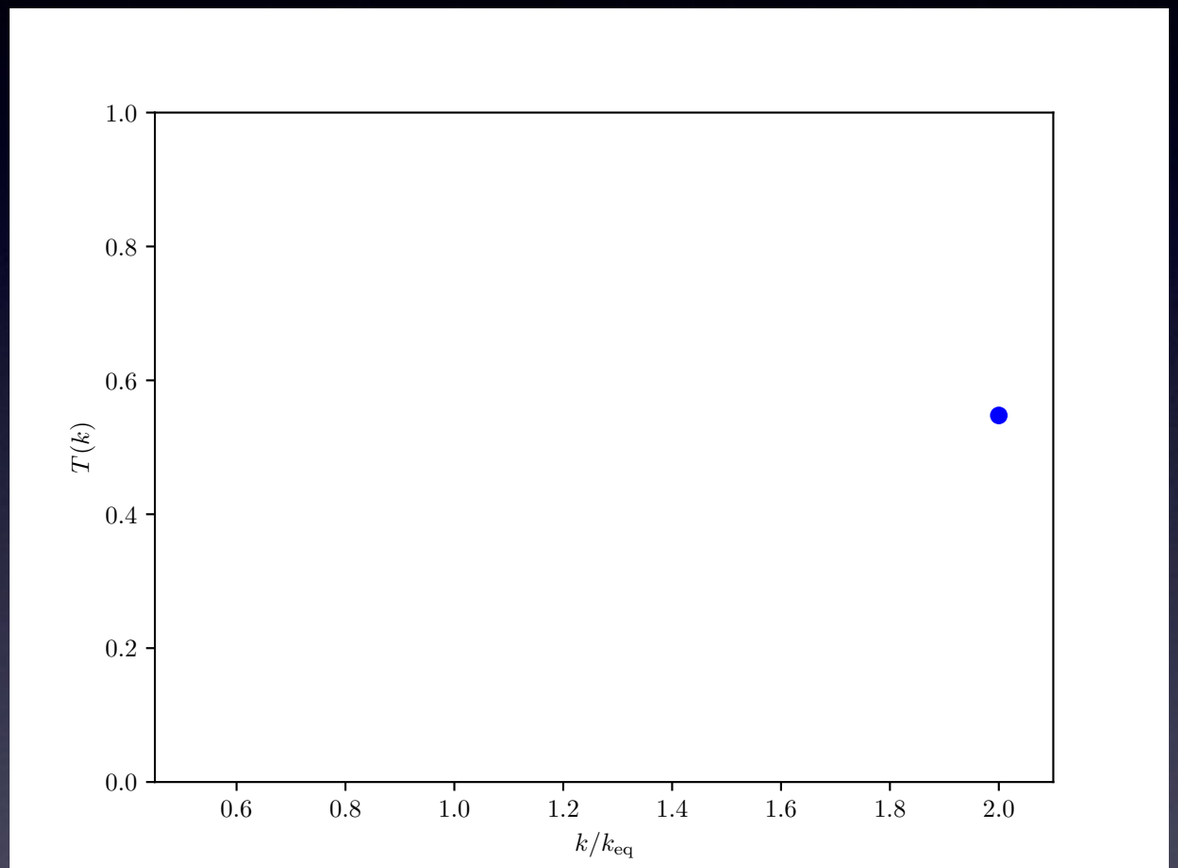
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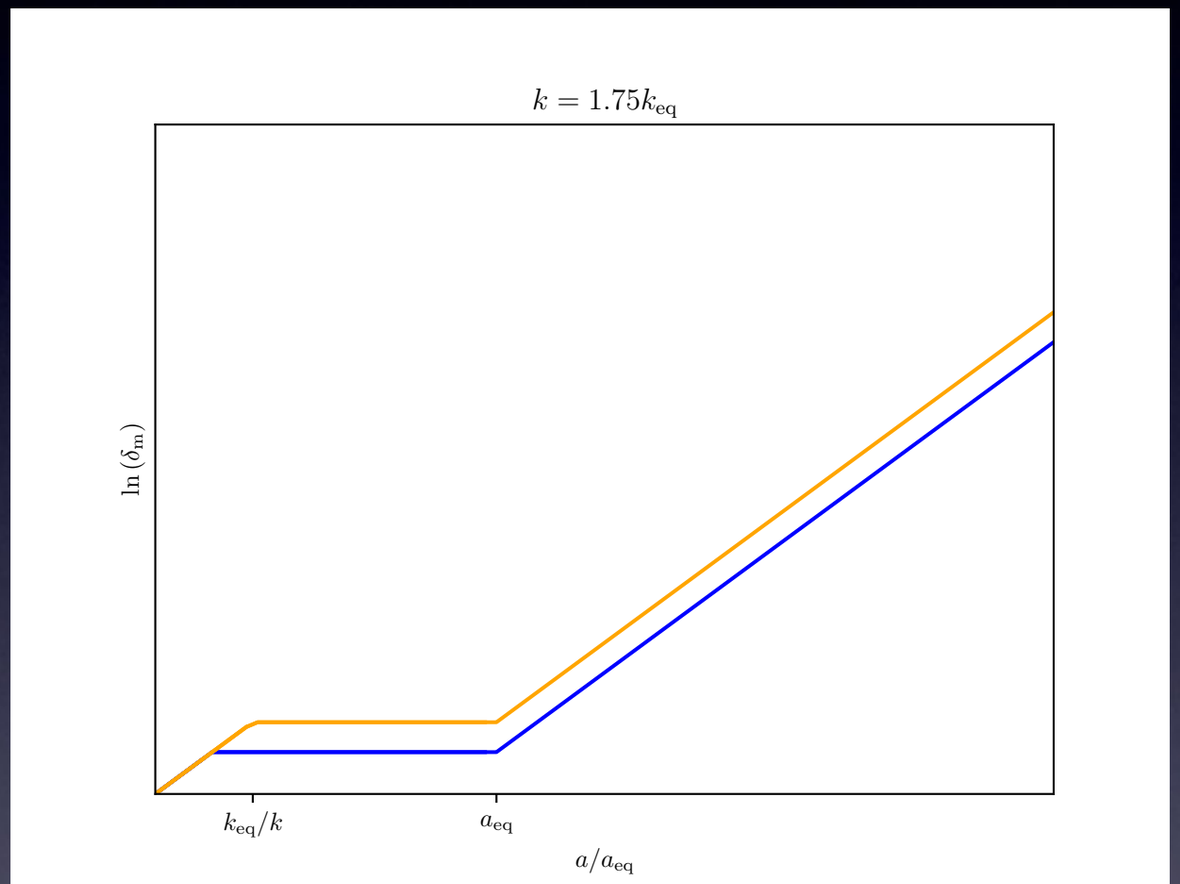
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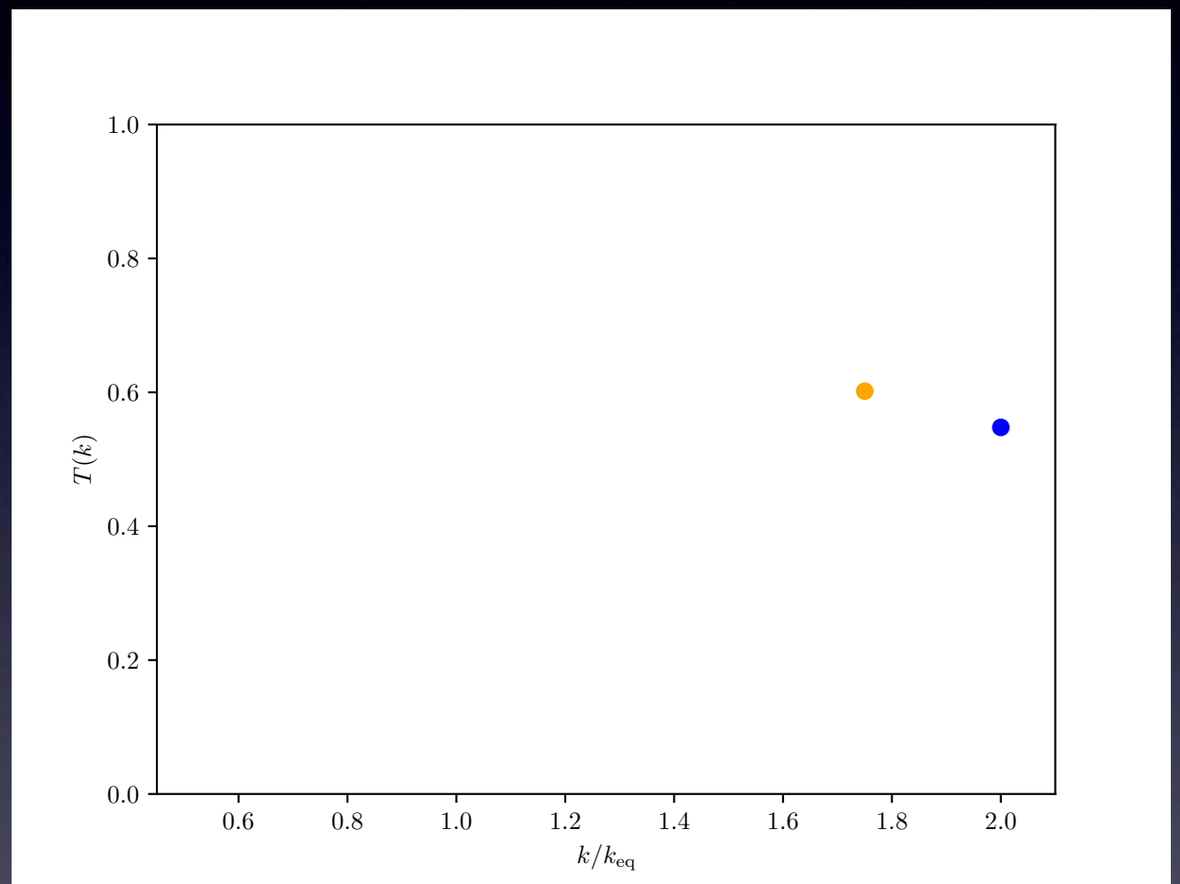
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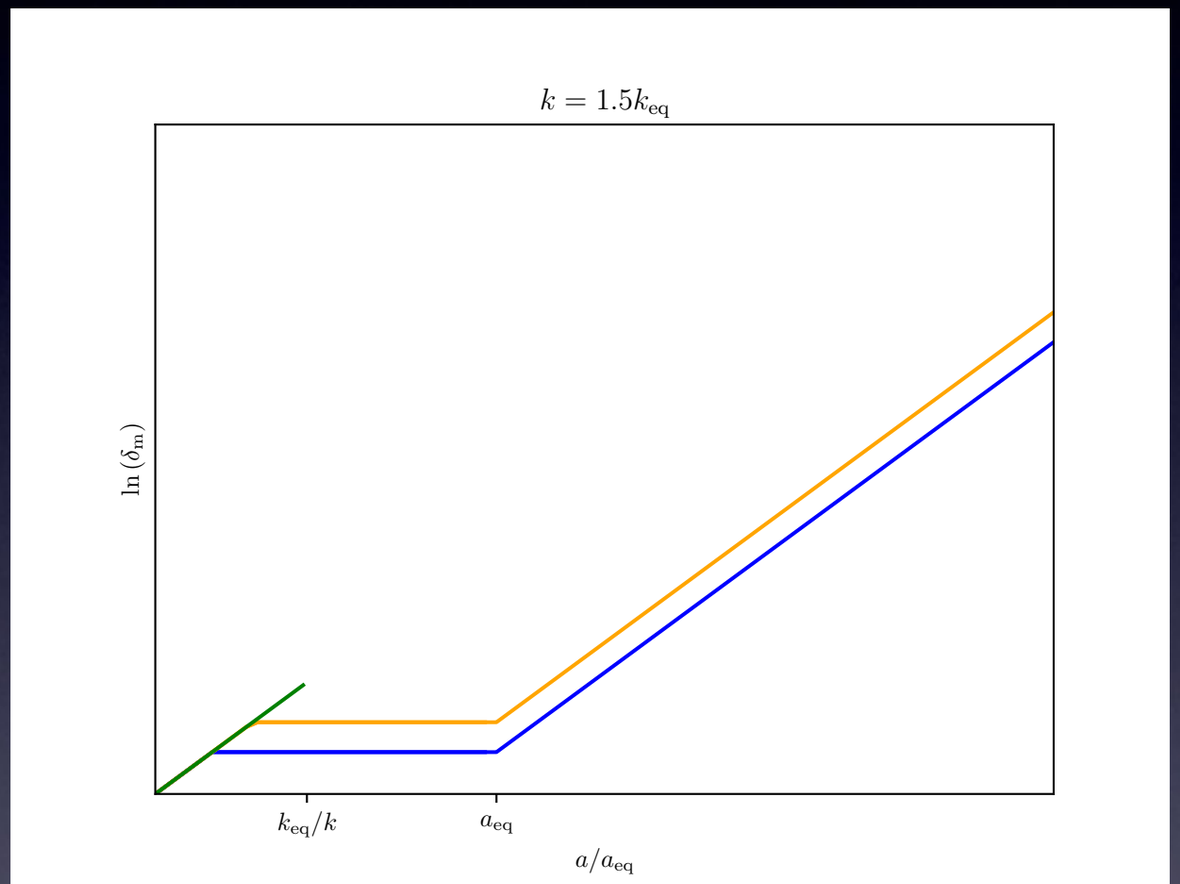
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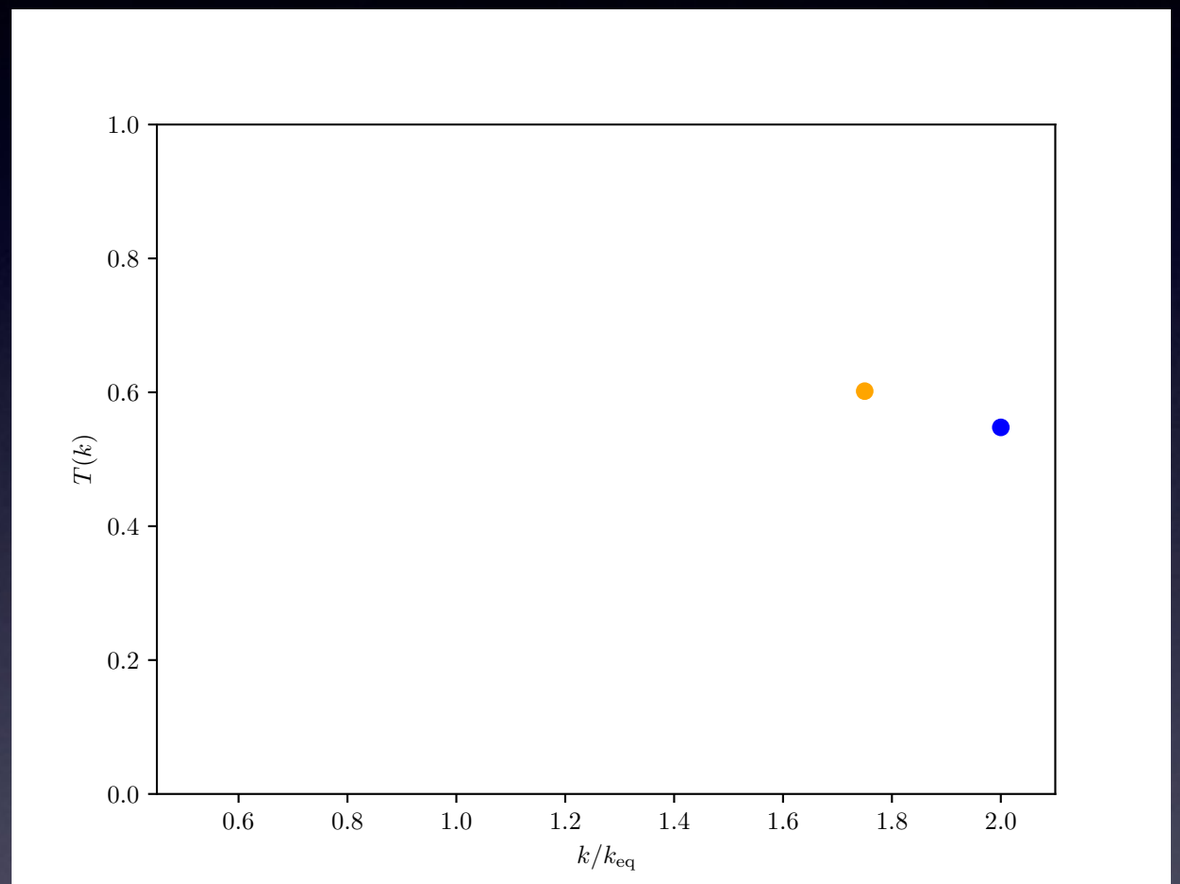
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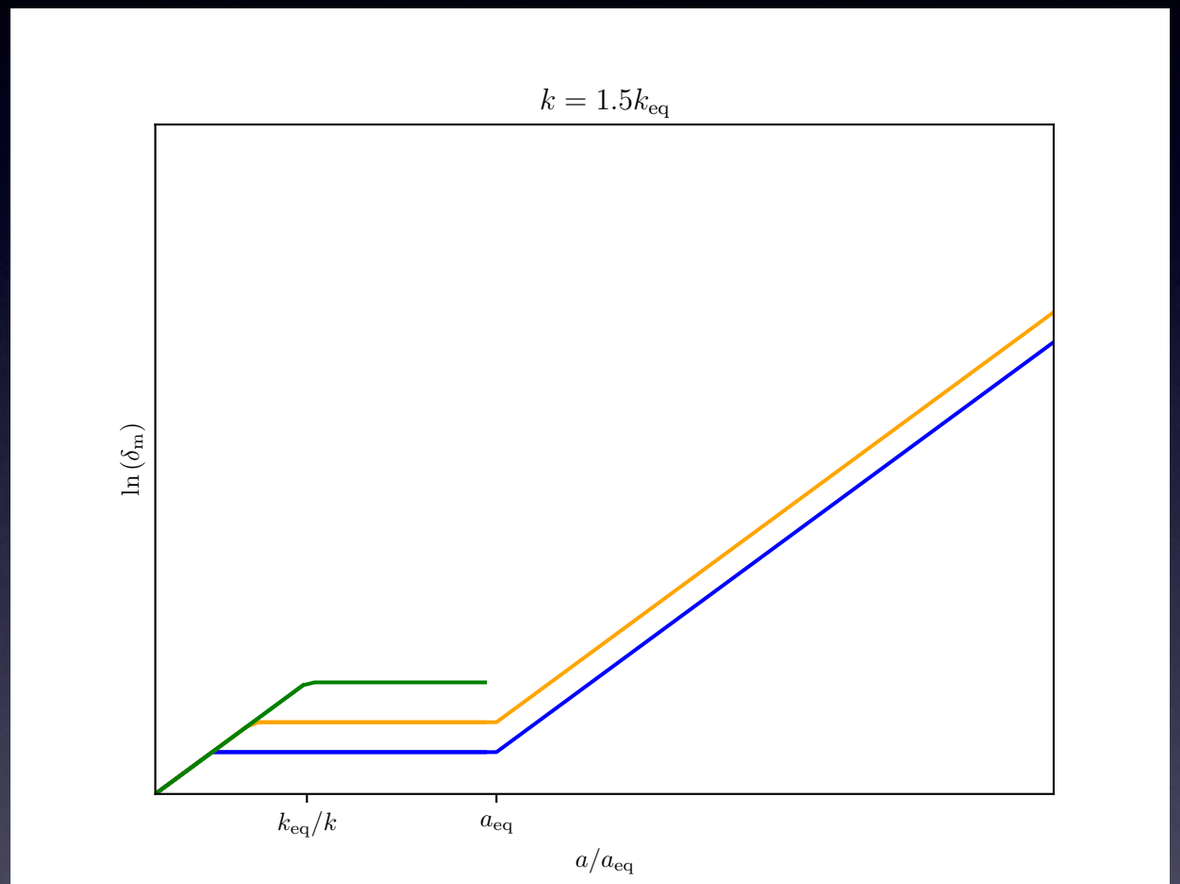
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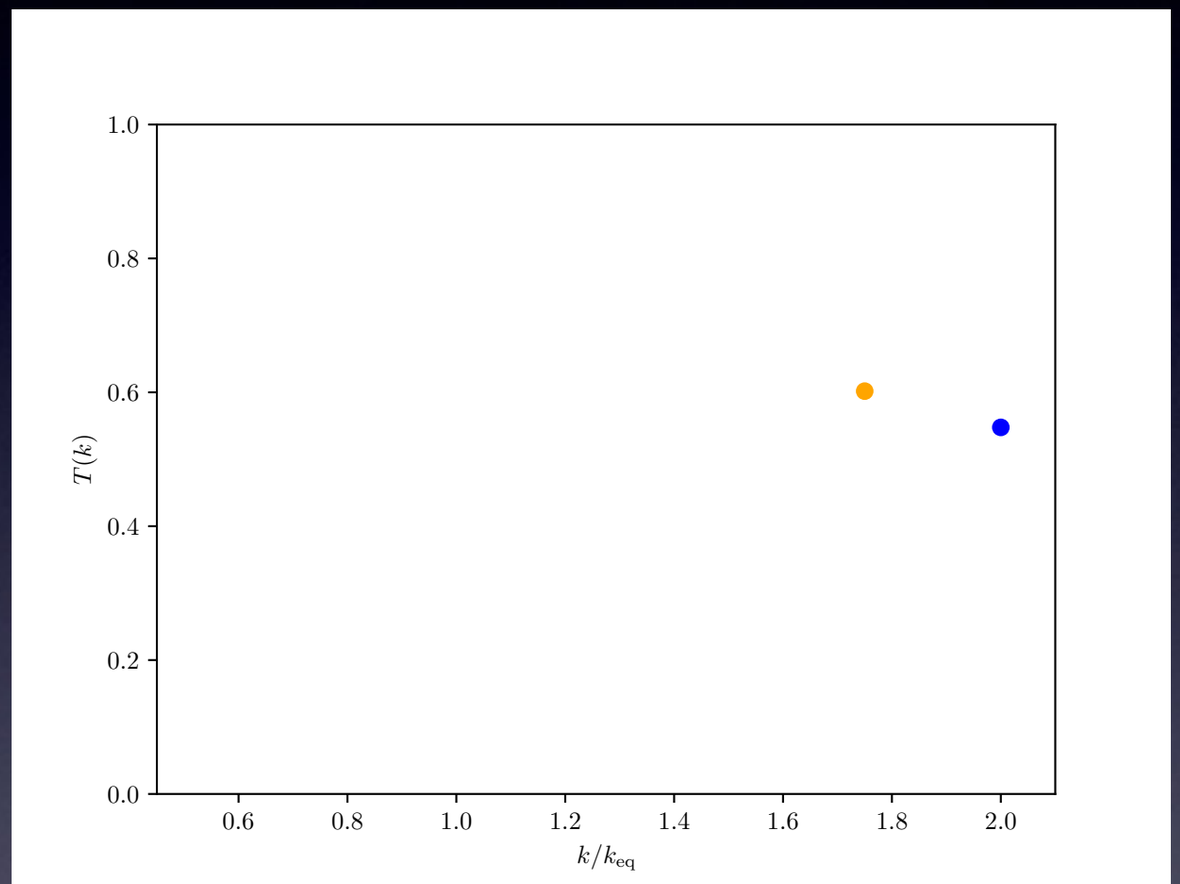
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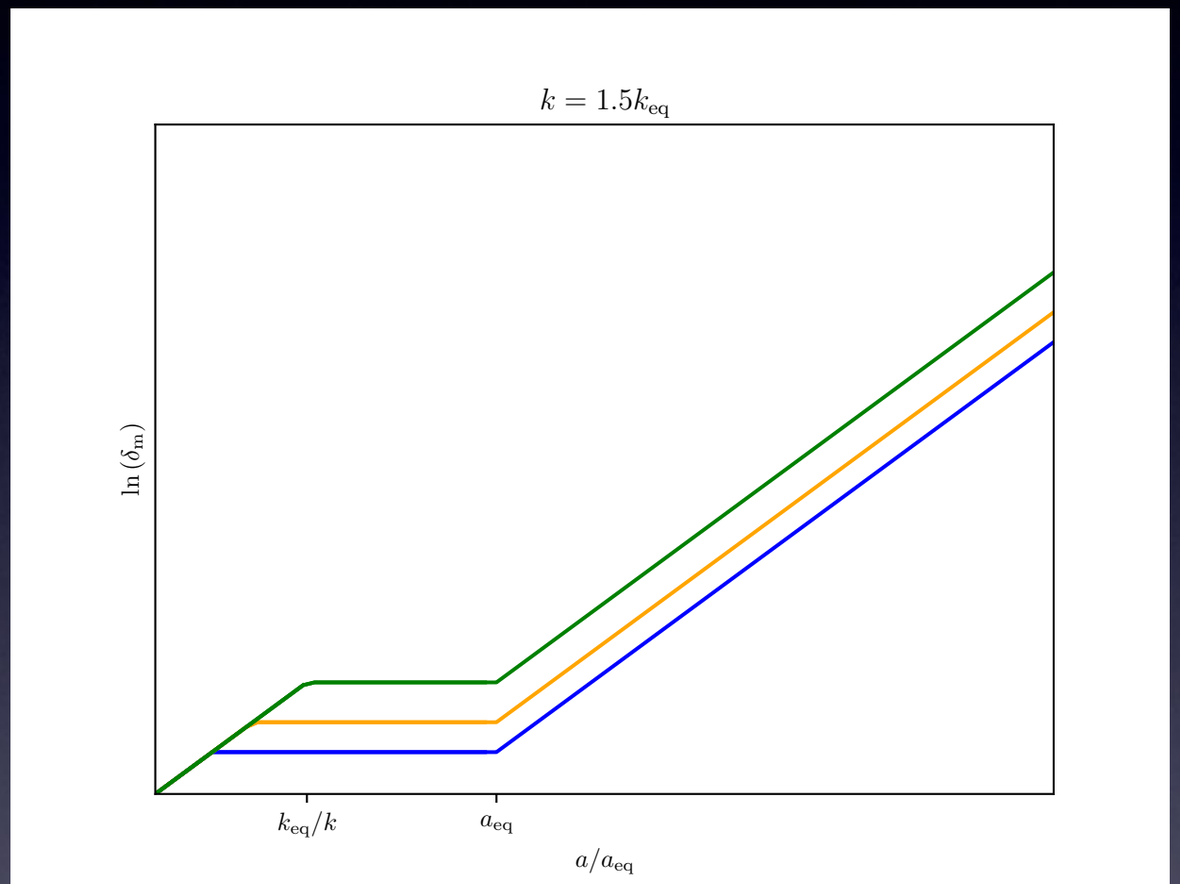
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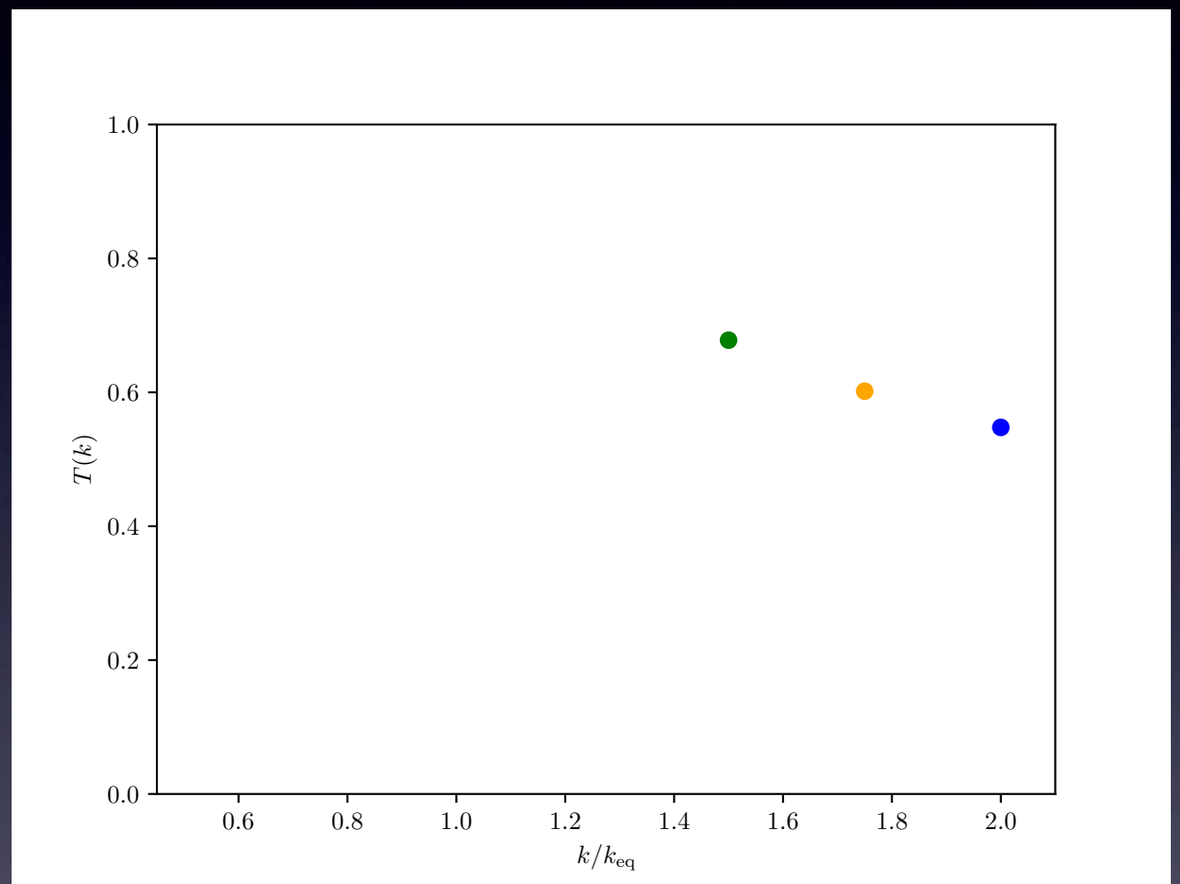
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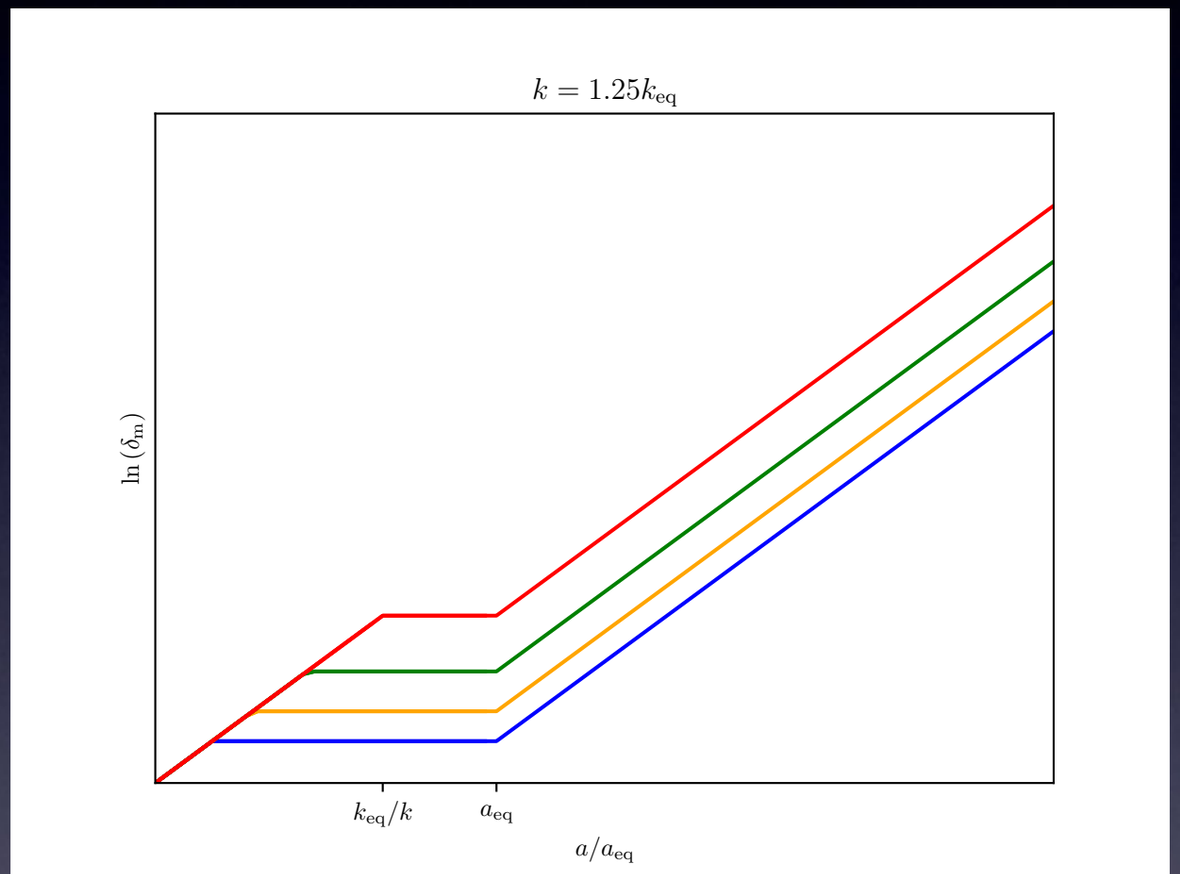
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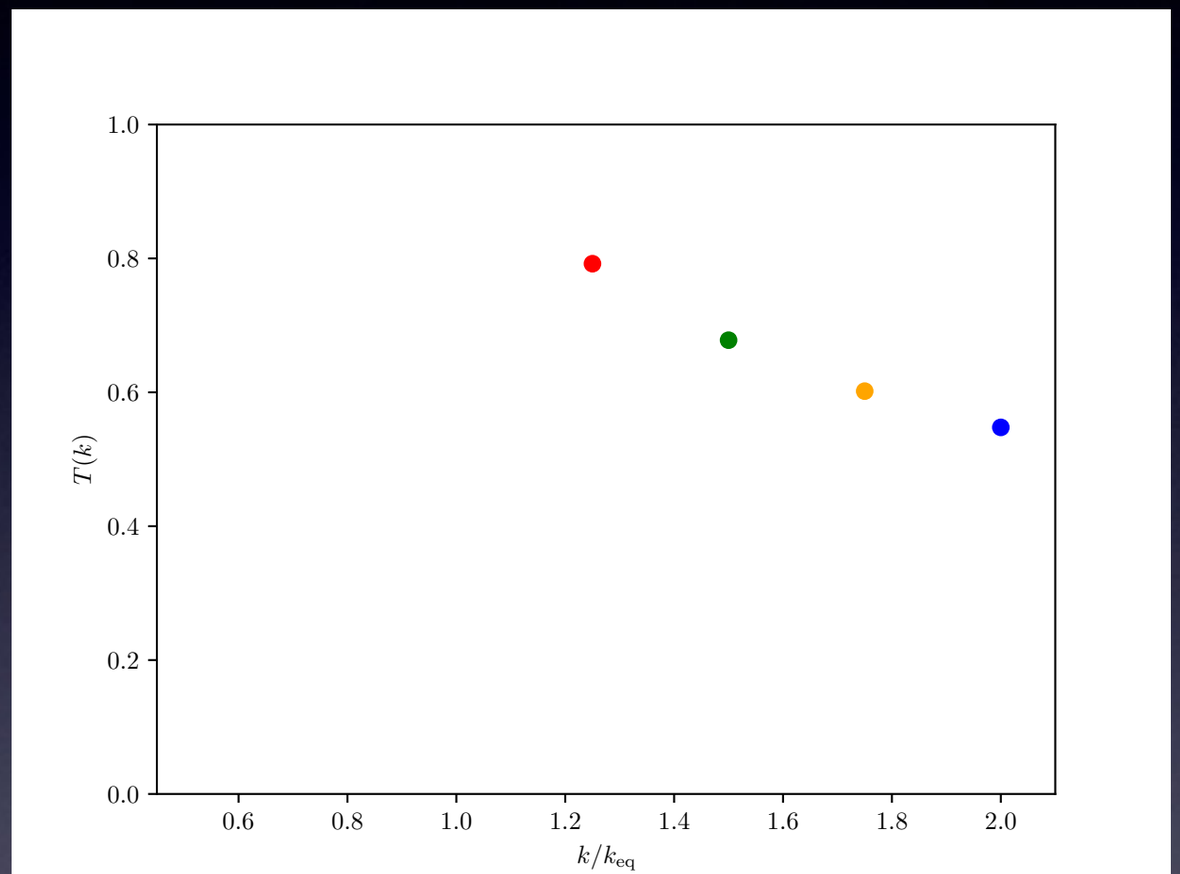
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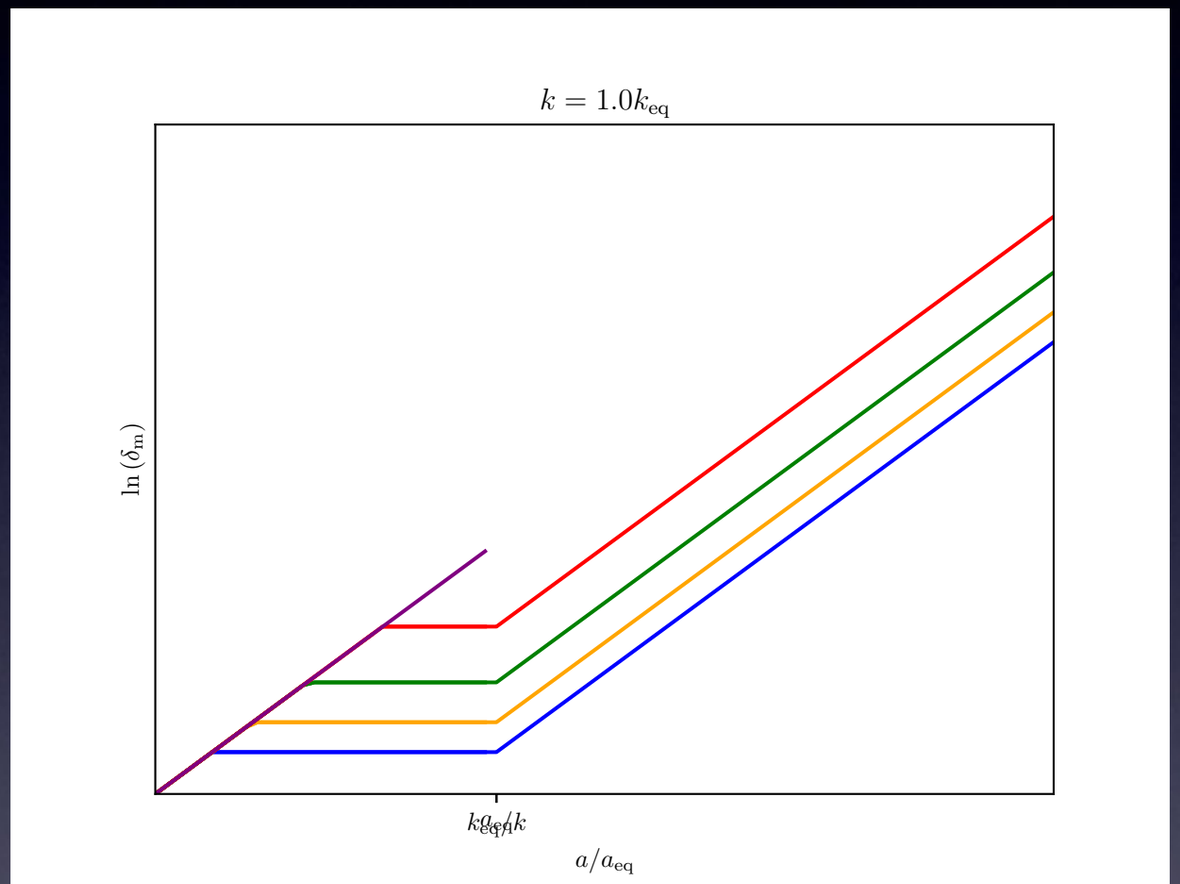
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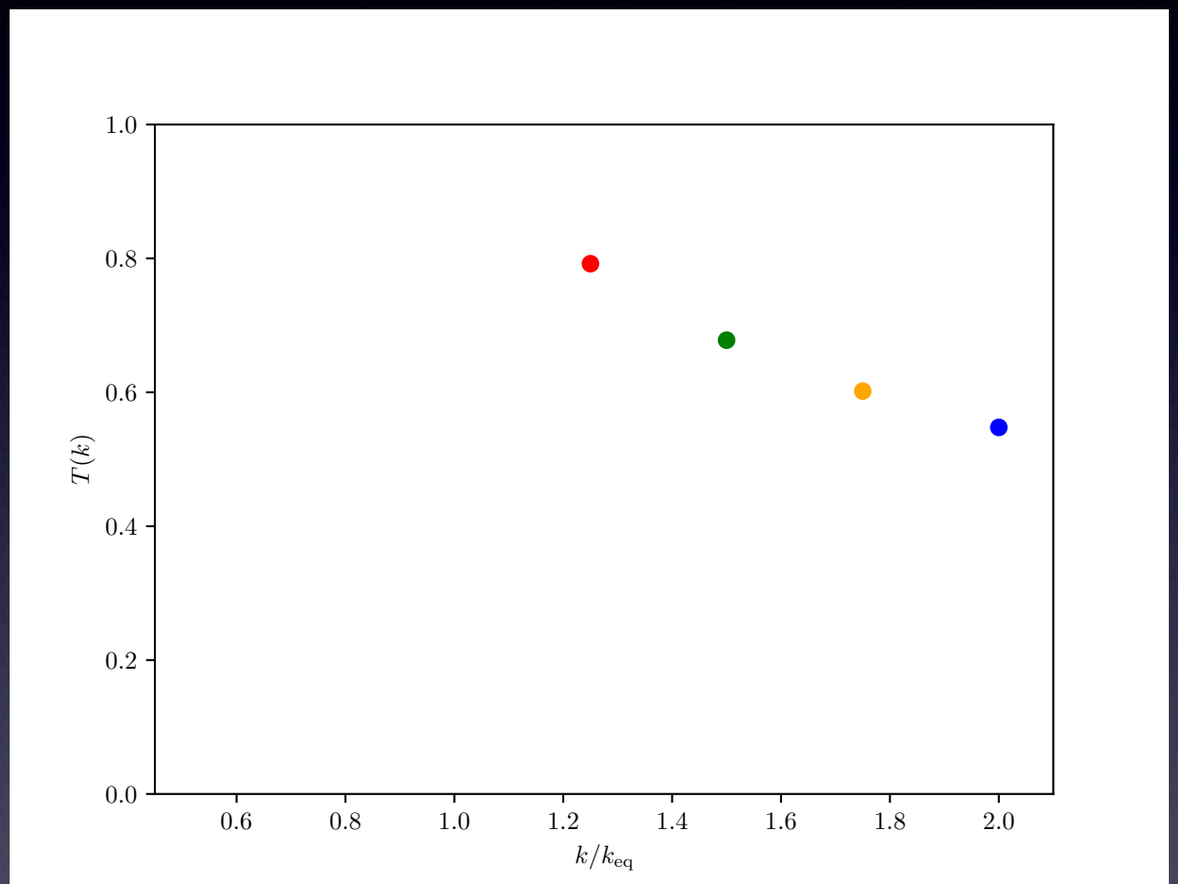
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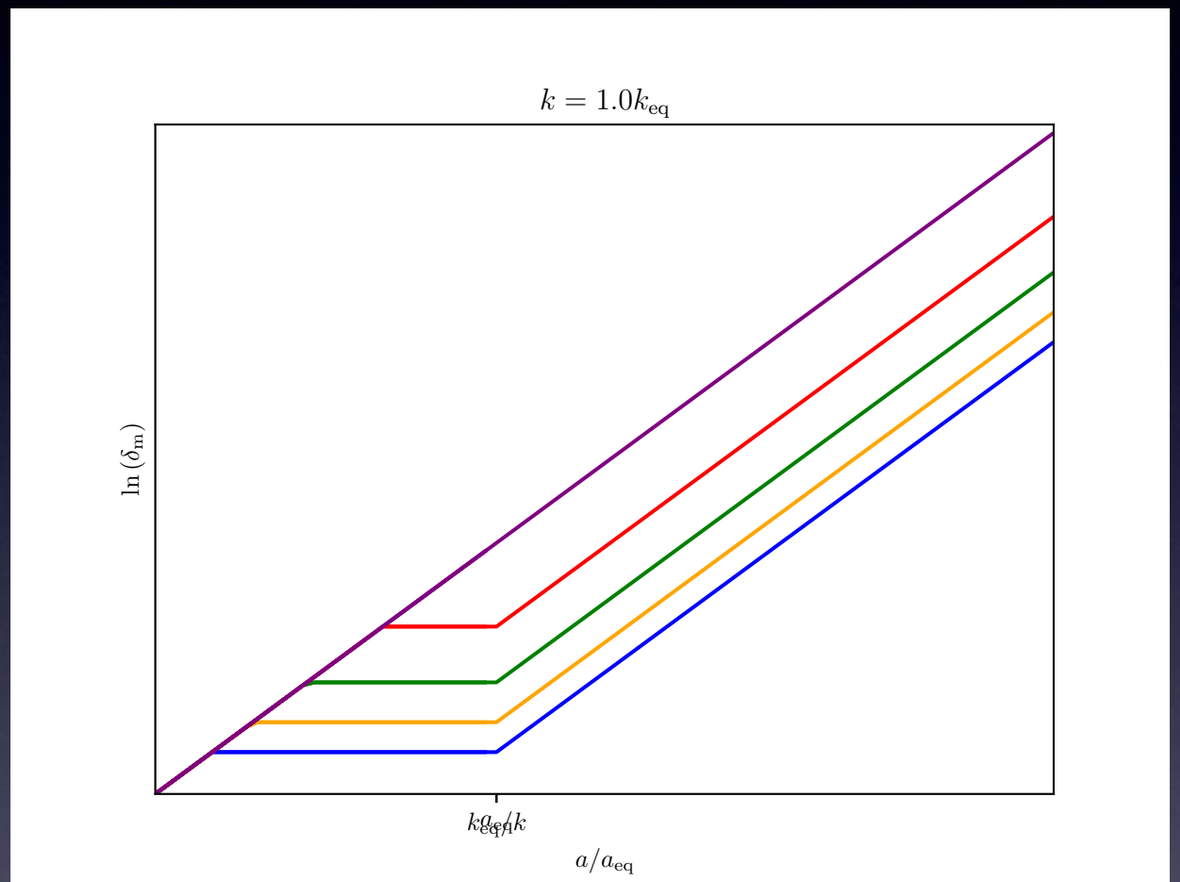
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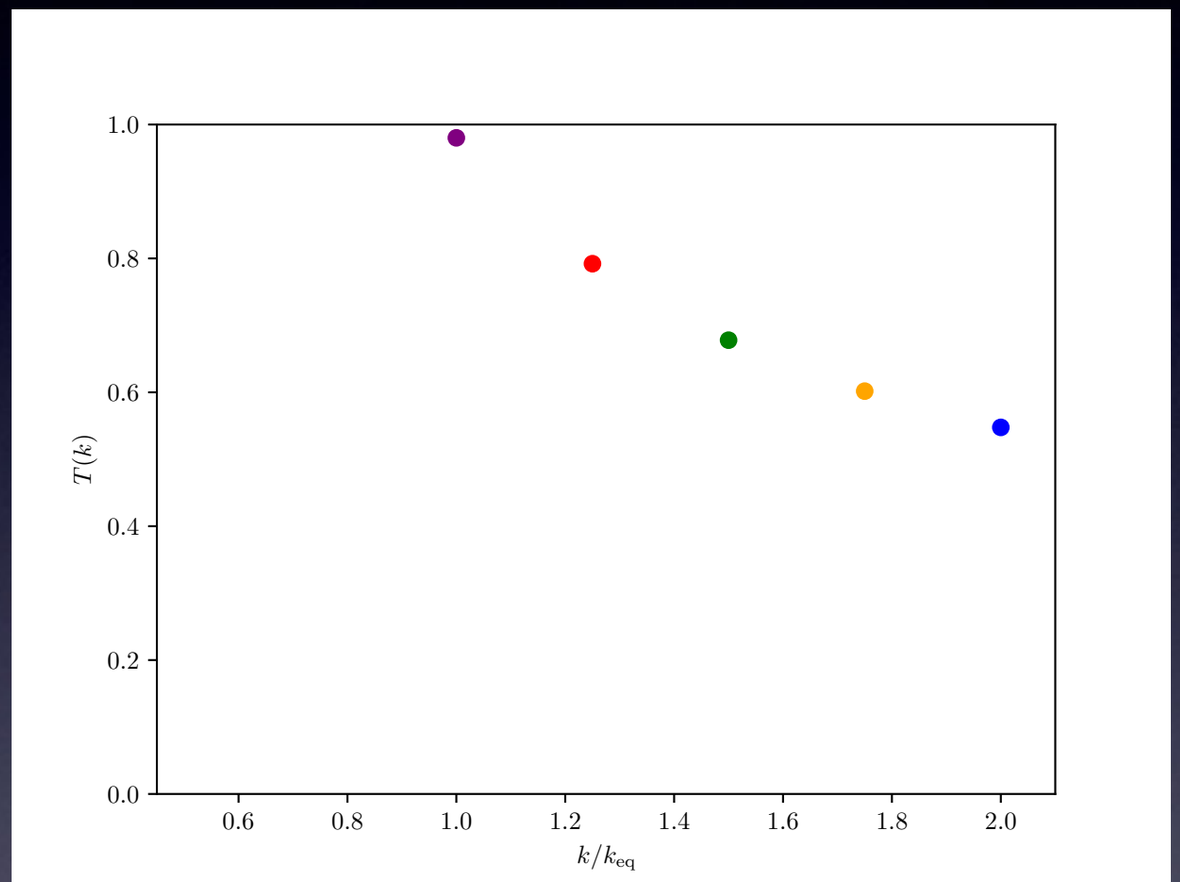
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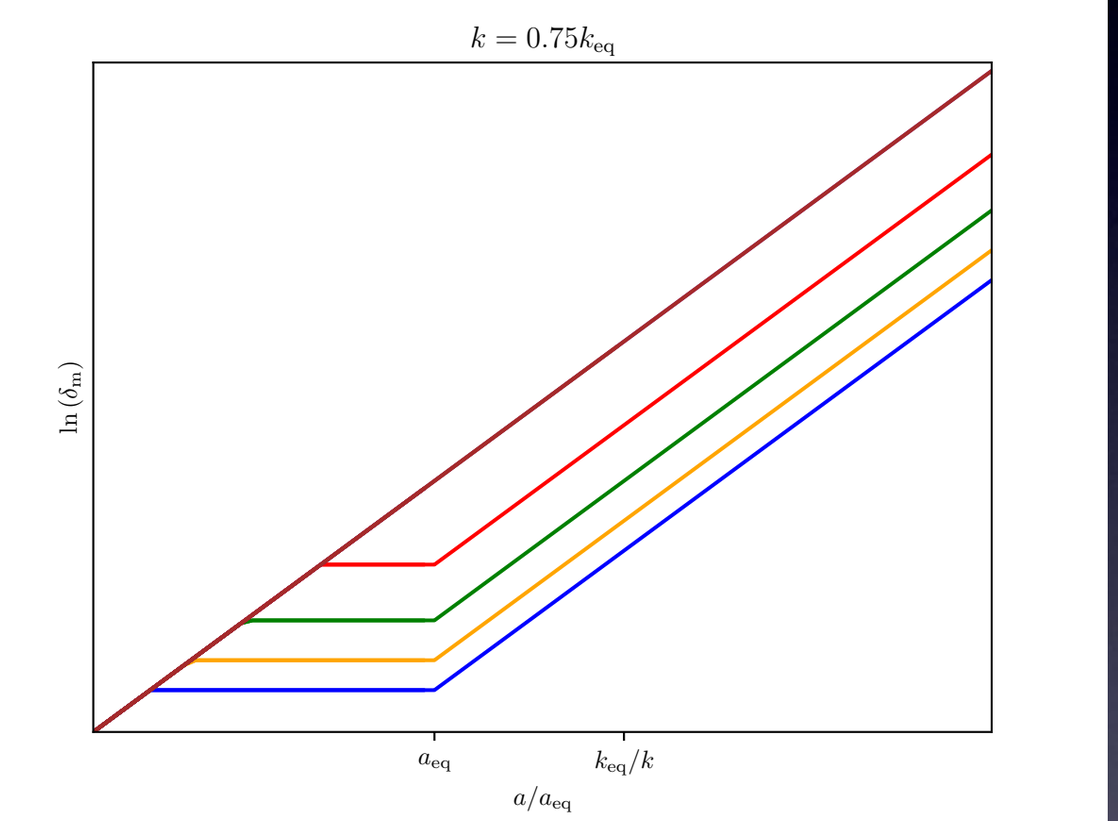
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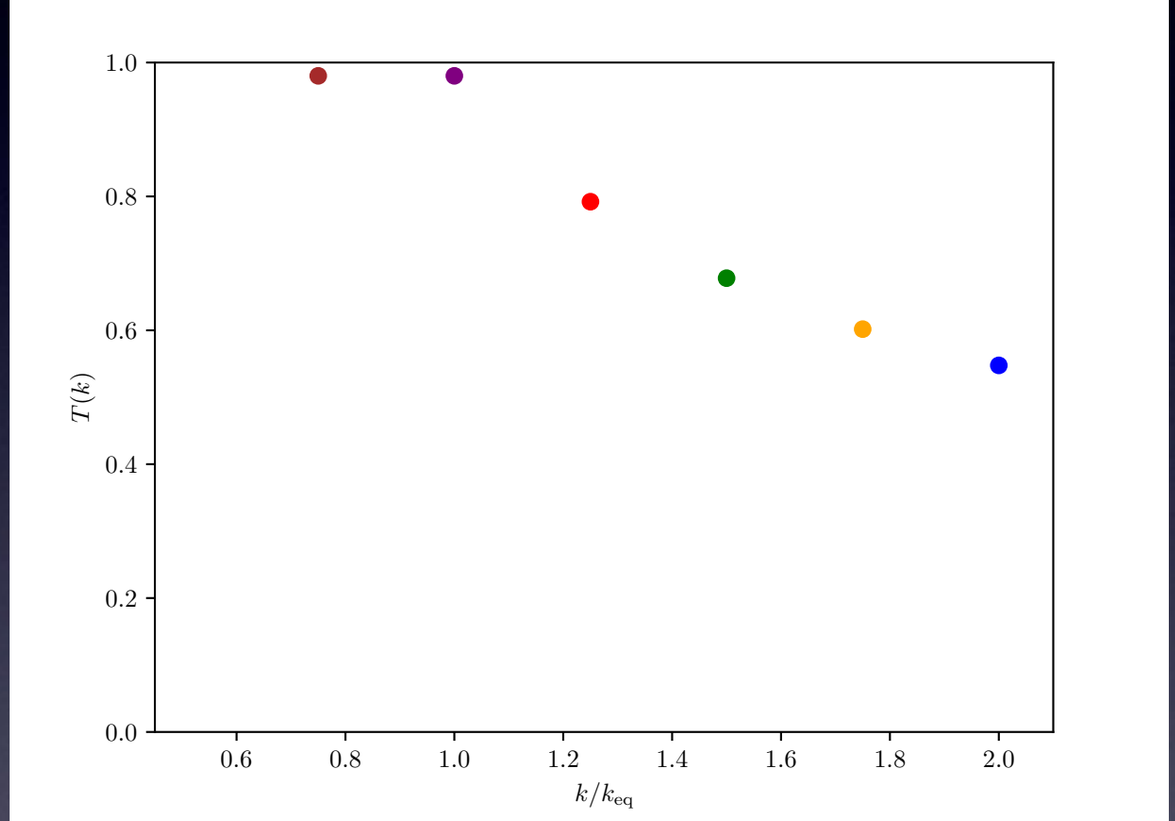
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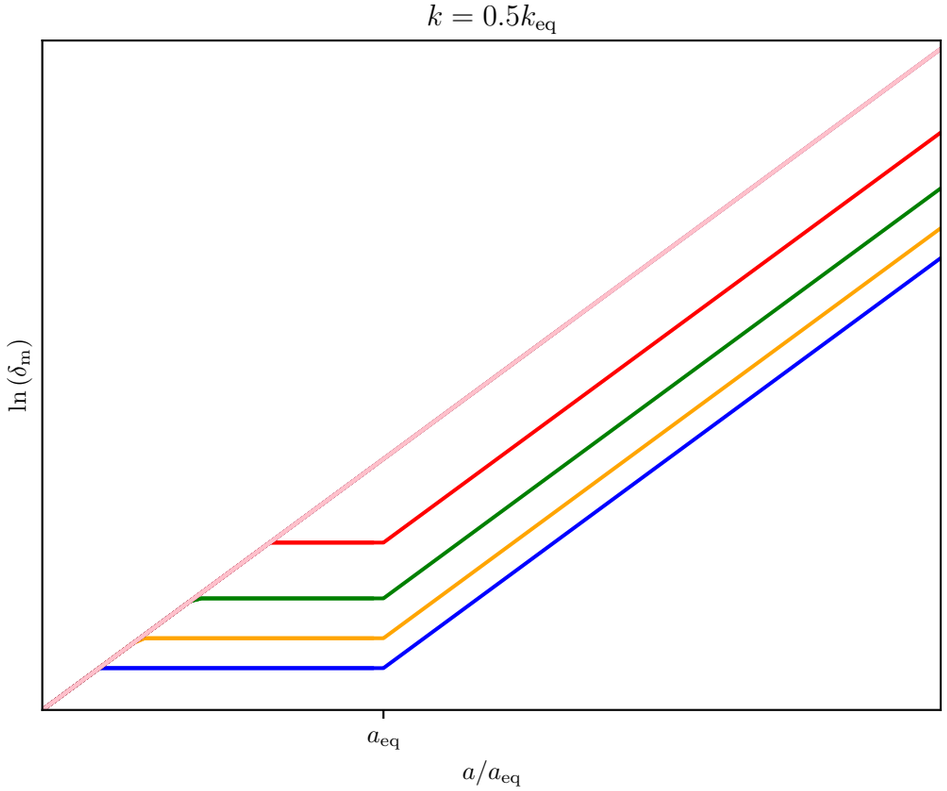
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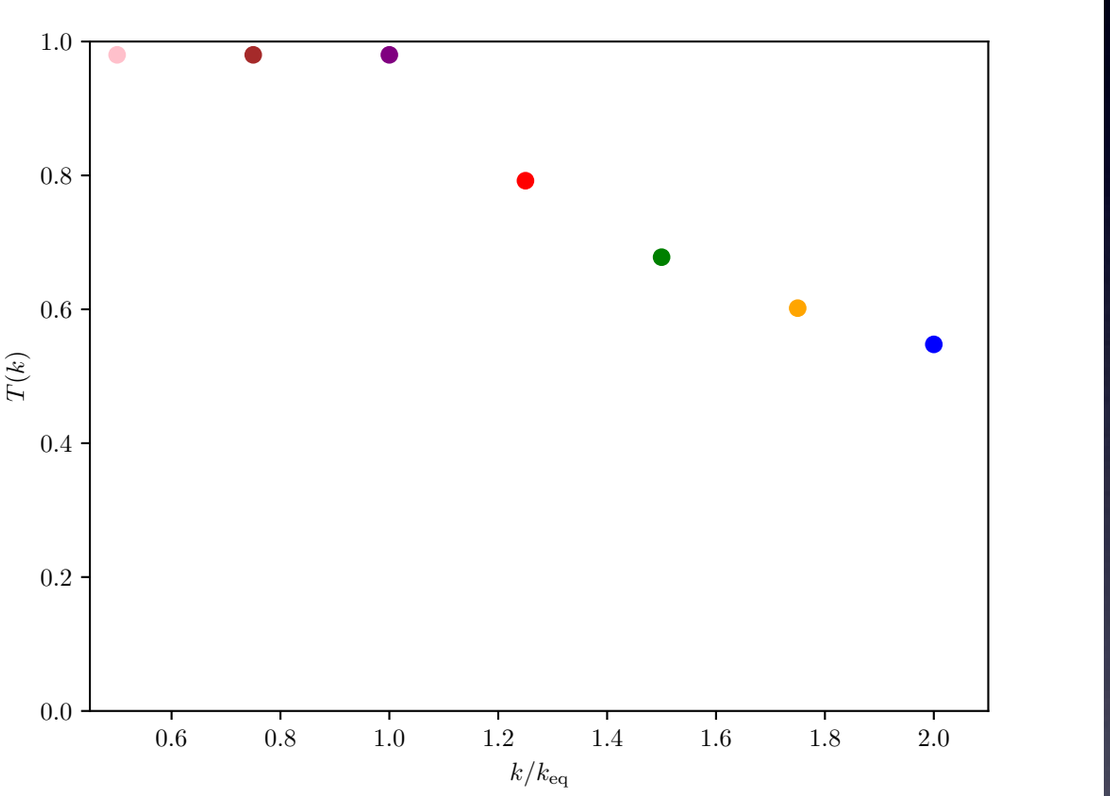
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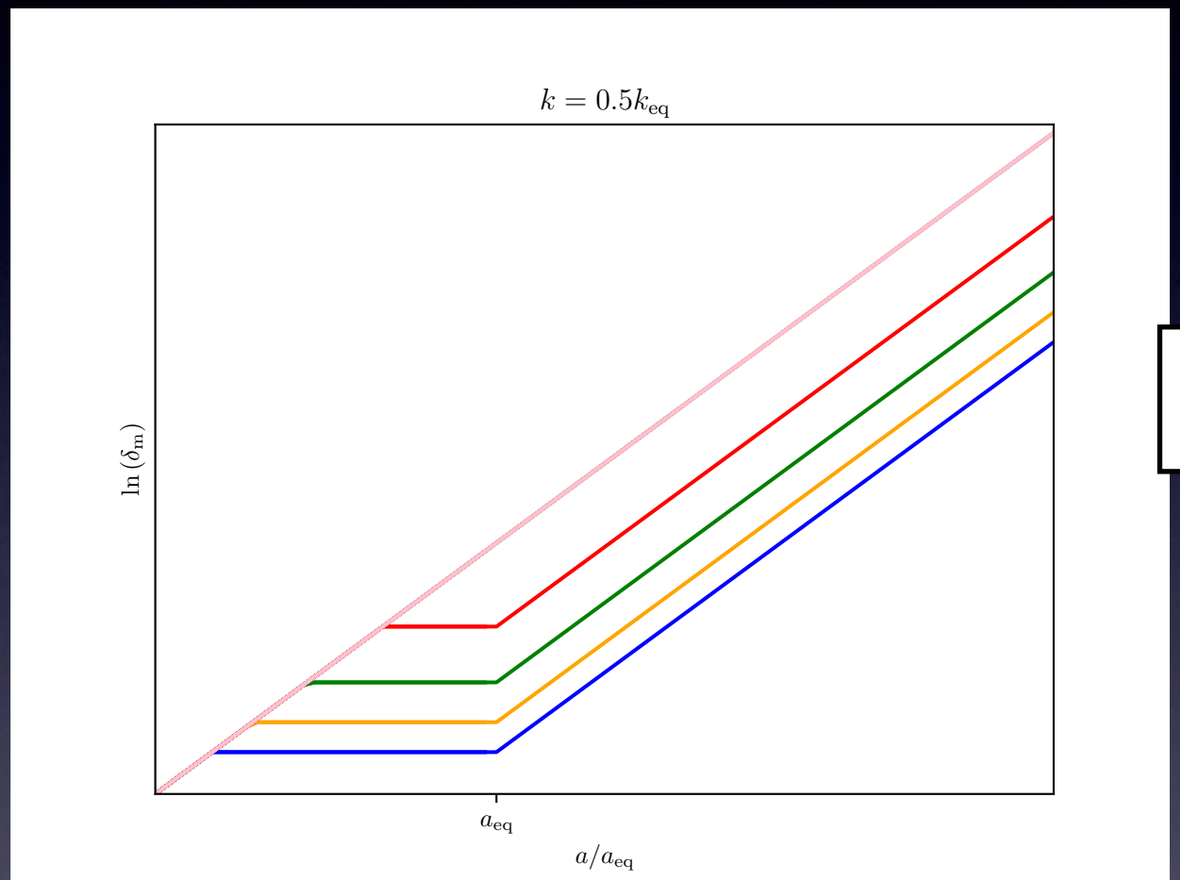
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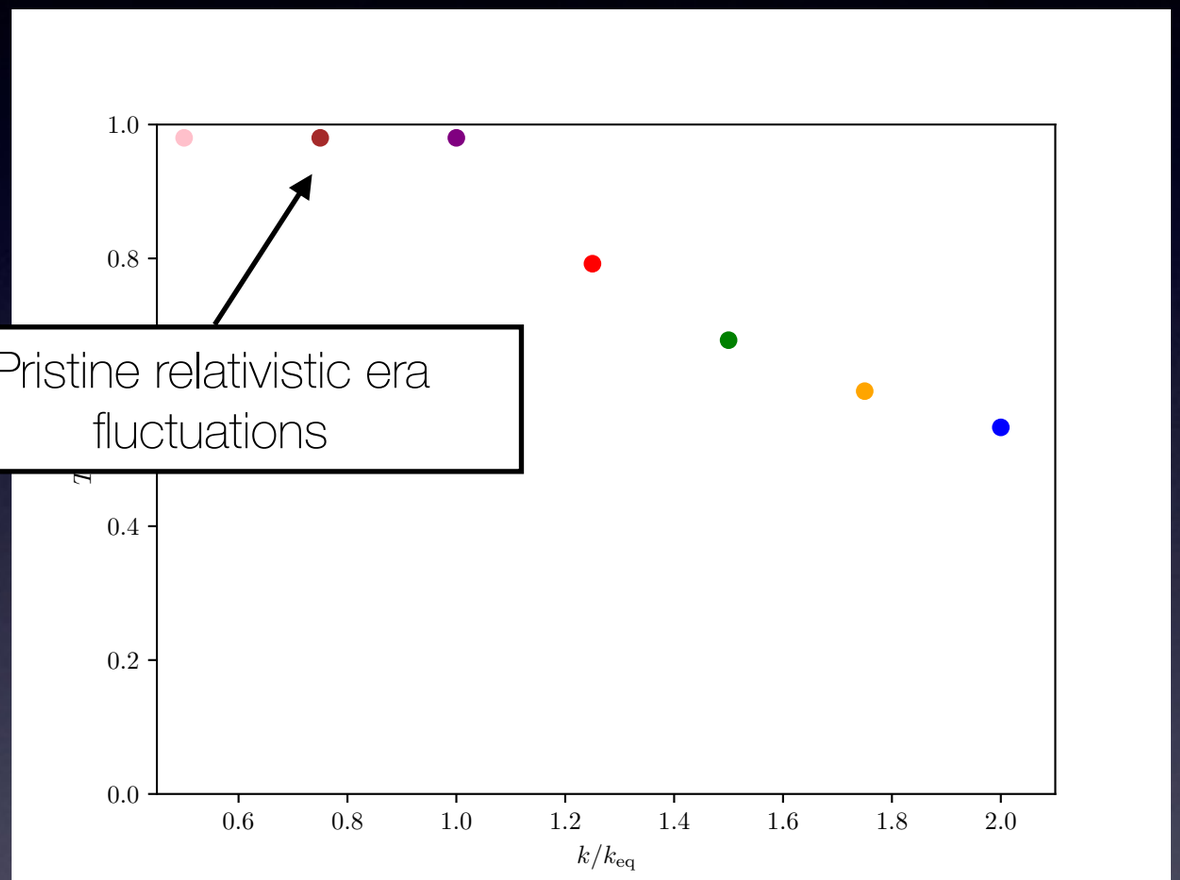
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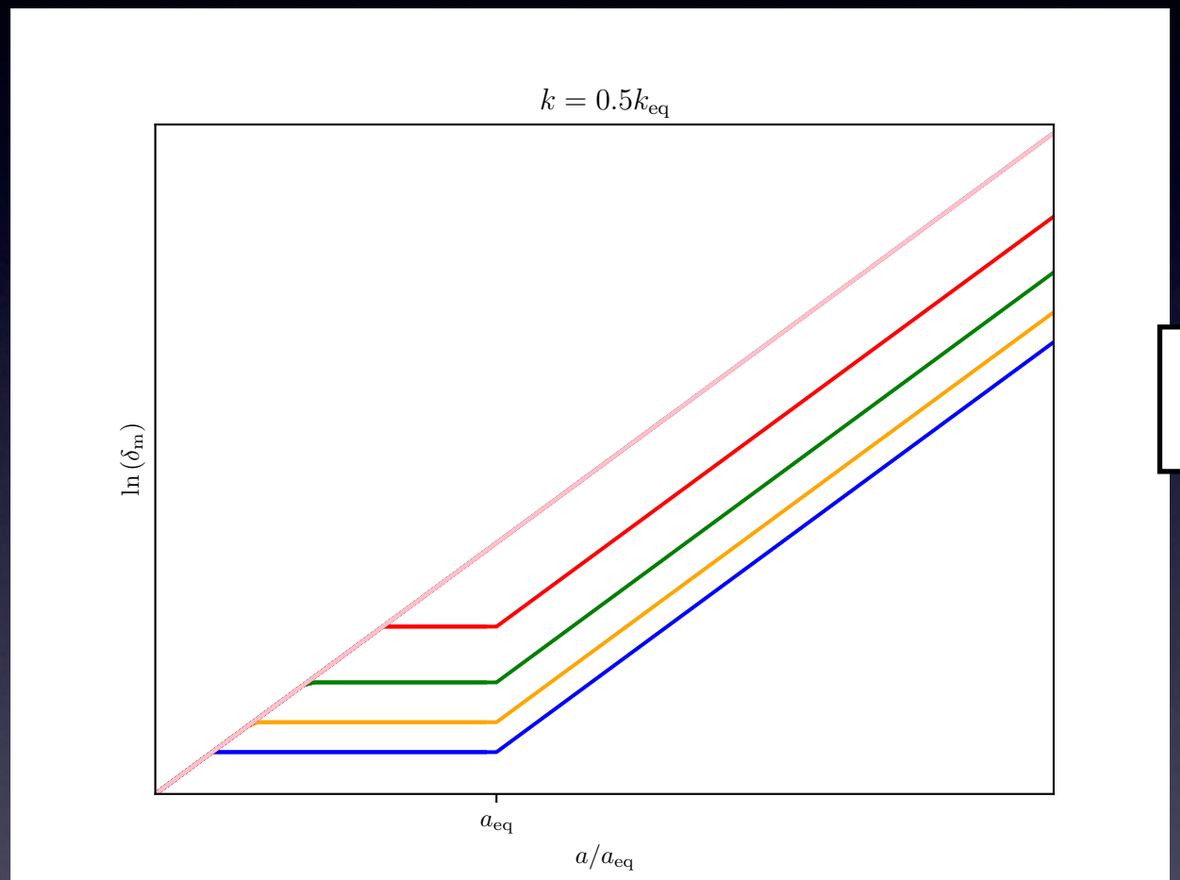
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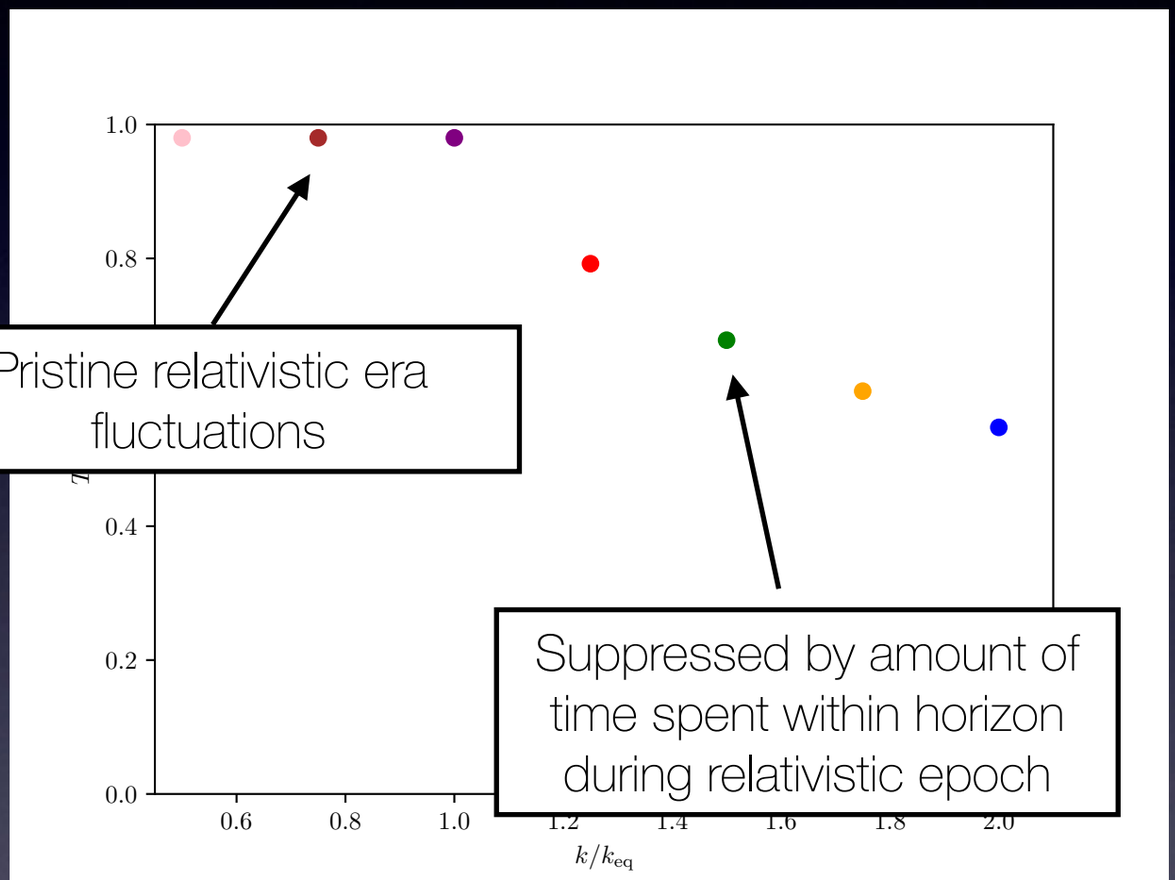
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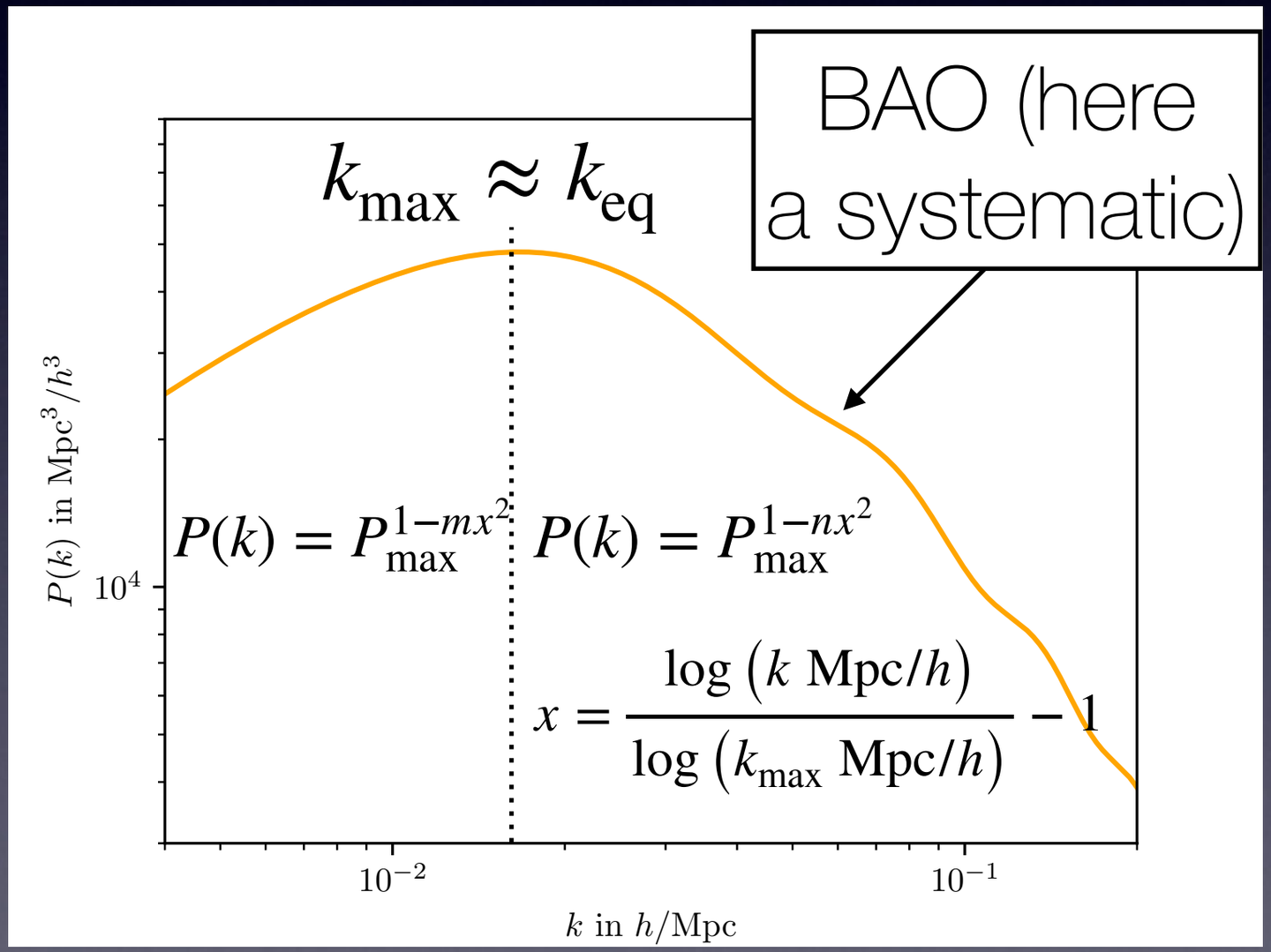
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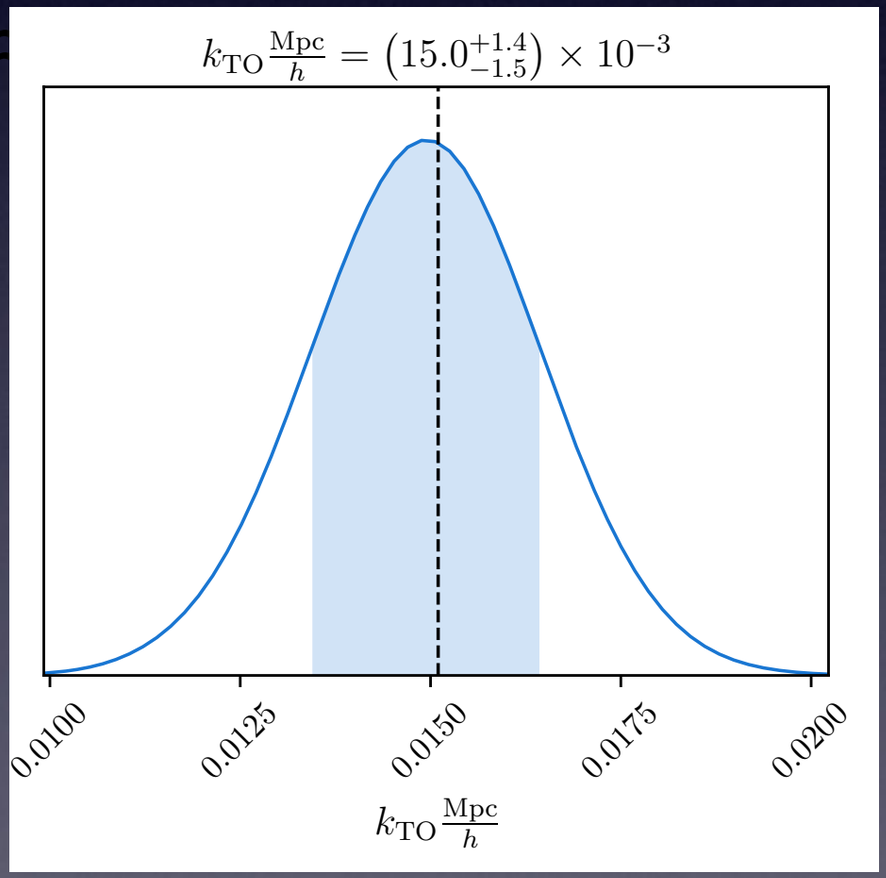
Alternative standard ruler

- 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 $k_{\rm max}$
  - $k_{\rm max,fid} = 0.0166h/{\rm Mpc}$
- Probability of $m > 0$ gives turn-over detection probability



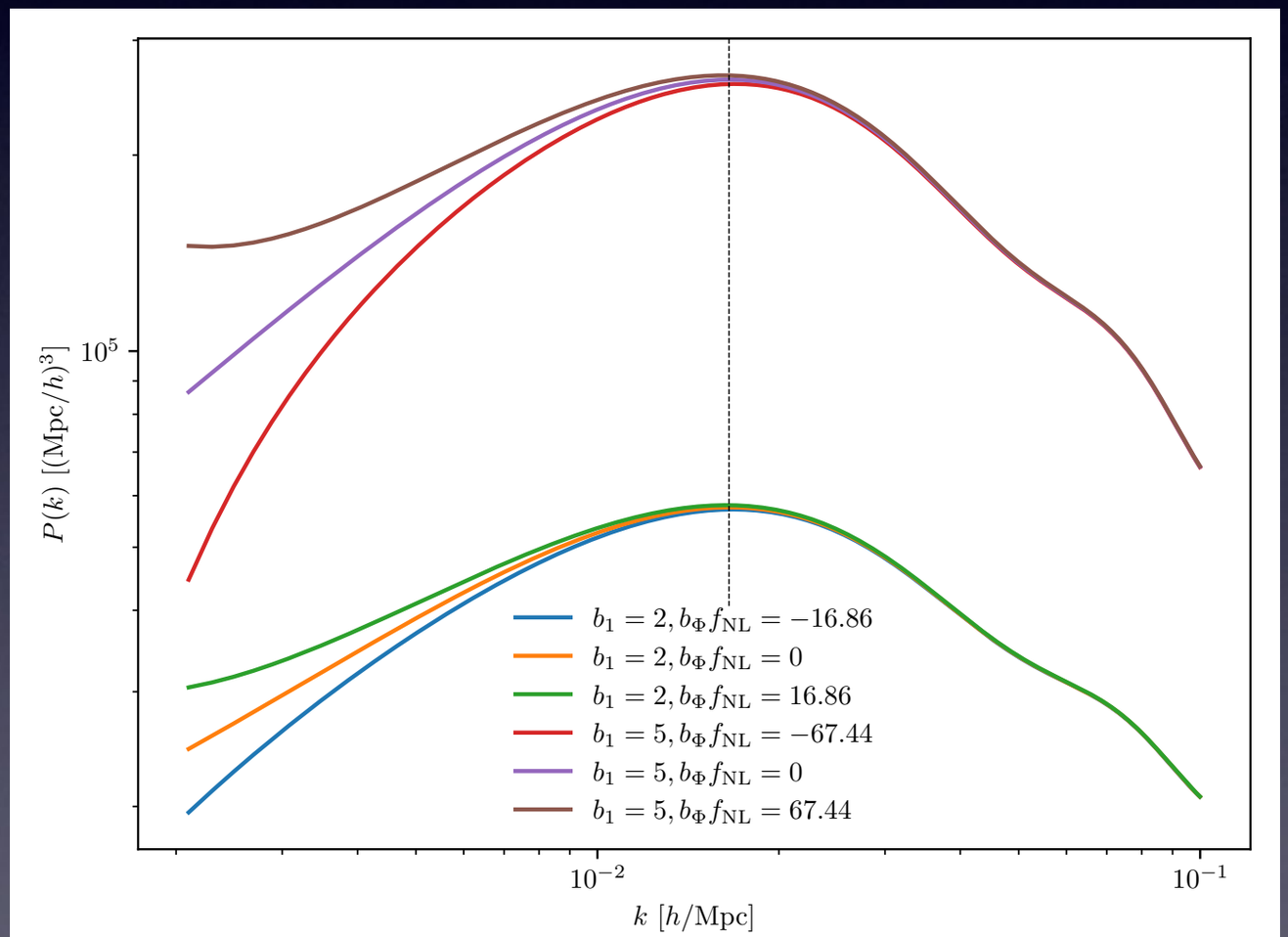
Model-independent approach: Deprojecting modelling systematics

- 4-parameter power spectrum good approximation around turnover, but fails at smaller scales k_{max}
- 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 $\mathbf{f}^{\mathrm{BAO}}_k = P_{\mathrm{fid}}(k) - P^{1-n_{\mathrm{BF}}x^2}_{\mathrm{eq,BF}}$
- Method does not bias k_{TO}-measurement



Turnover scale vs PNG

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



TO as standard ruler

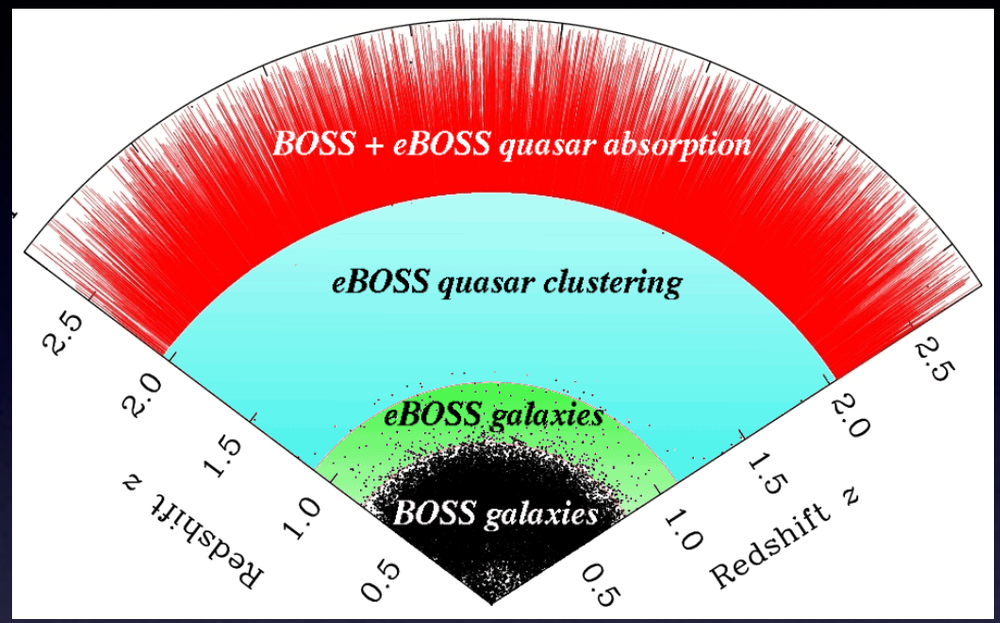
- Analogous to BAO, define $r_{\rm d}$-independent standard ruler

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

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

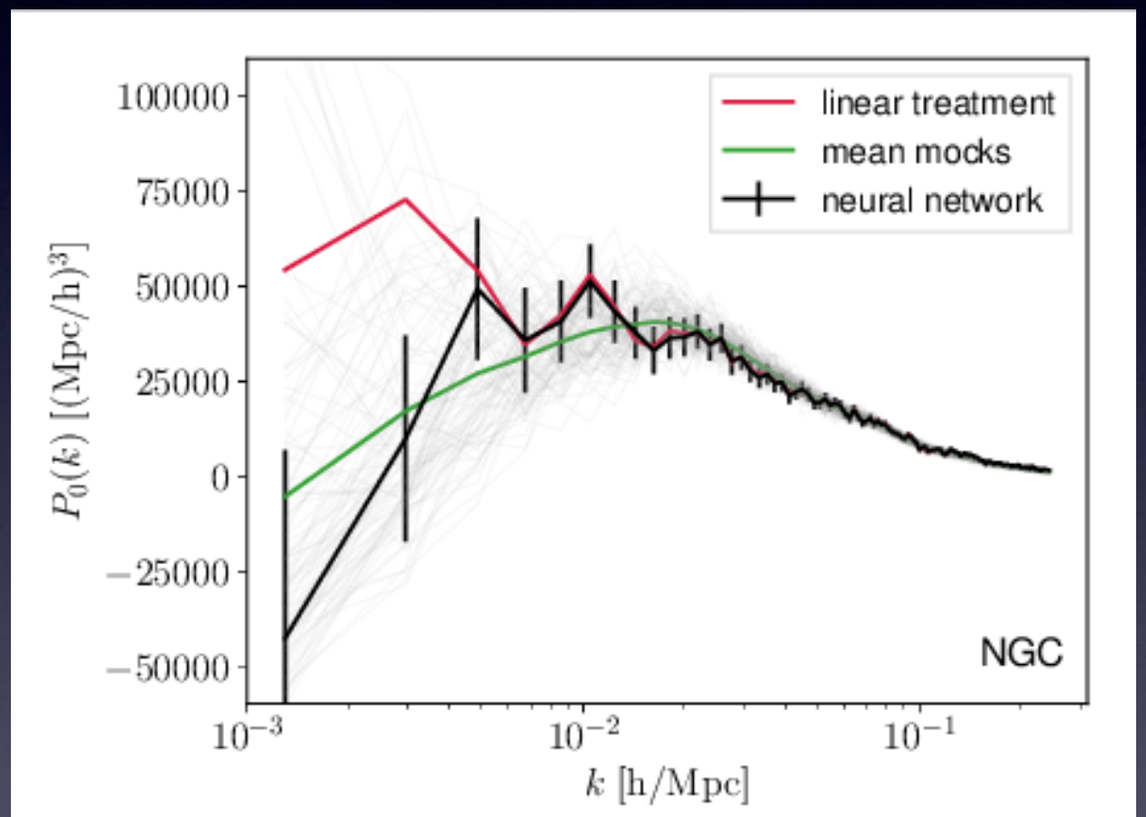
- Test of Universe at z = 3400 rather than z = 1100, Early Dark Energy? Alternatively, test neutrino sector

Application to eBOSS



- Most redshift surveys 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]

eBOSS ultra-large-scale systematic treatment

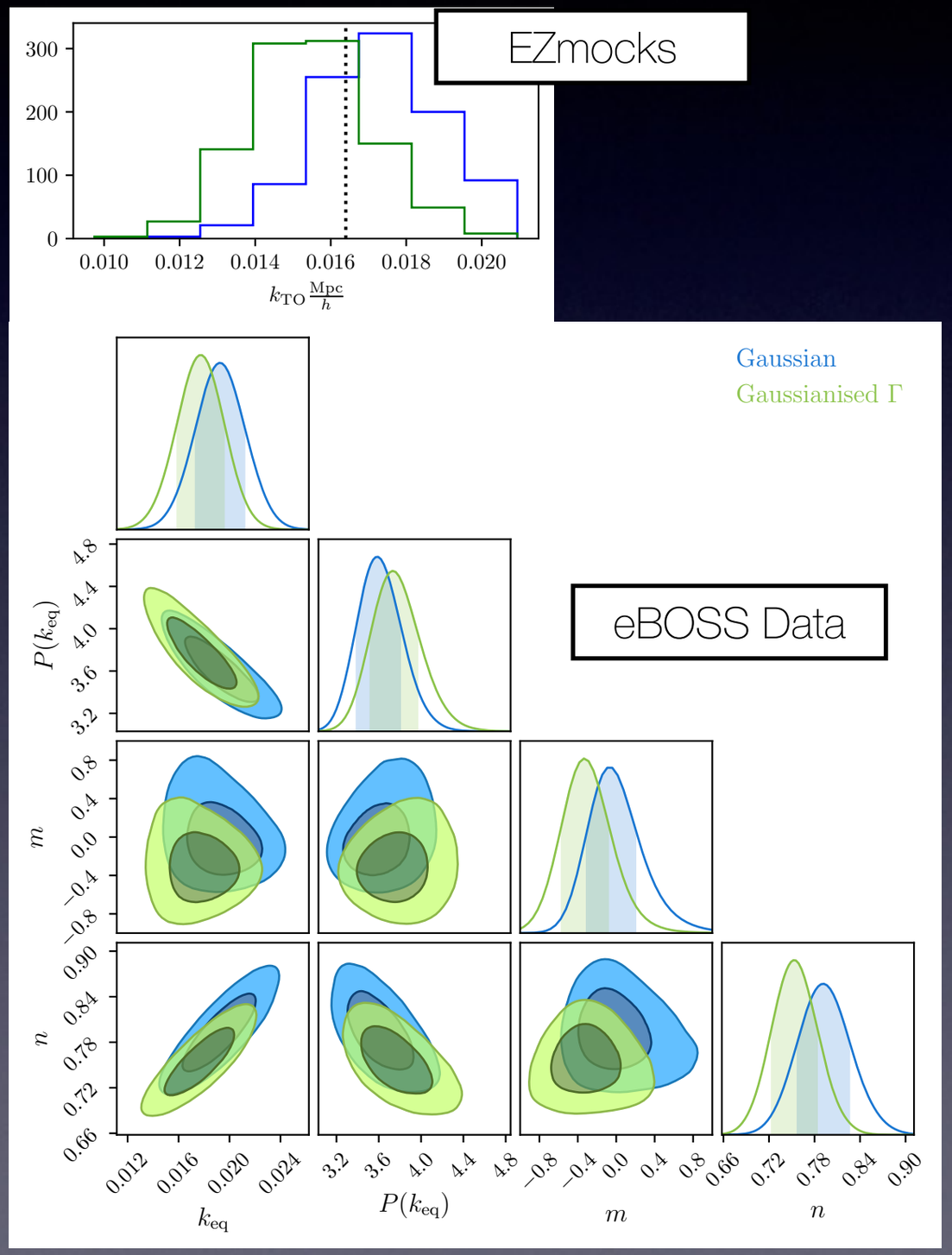


eBOSS QSO DR16 [Mueller et al. 2021]

- 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

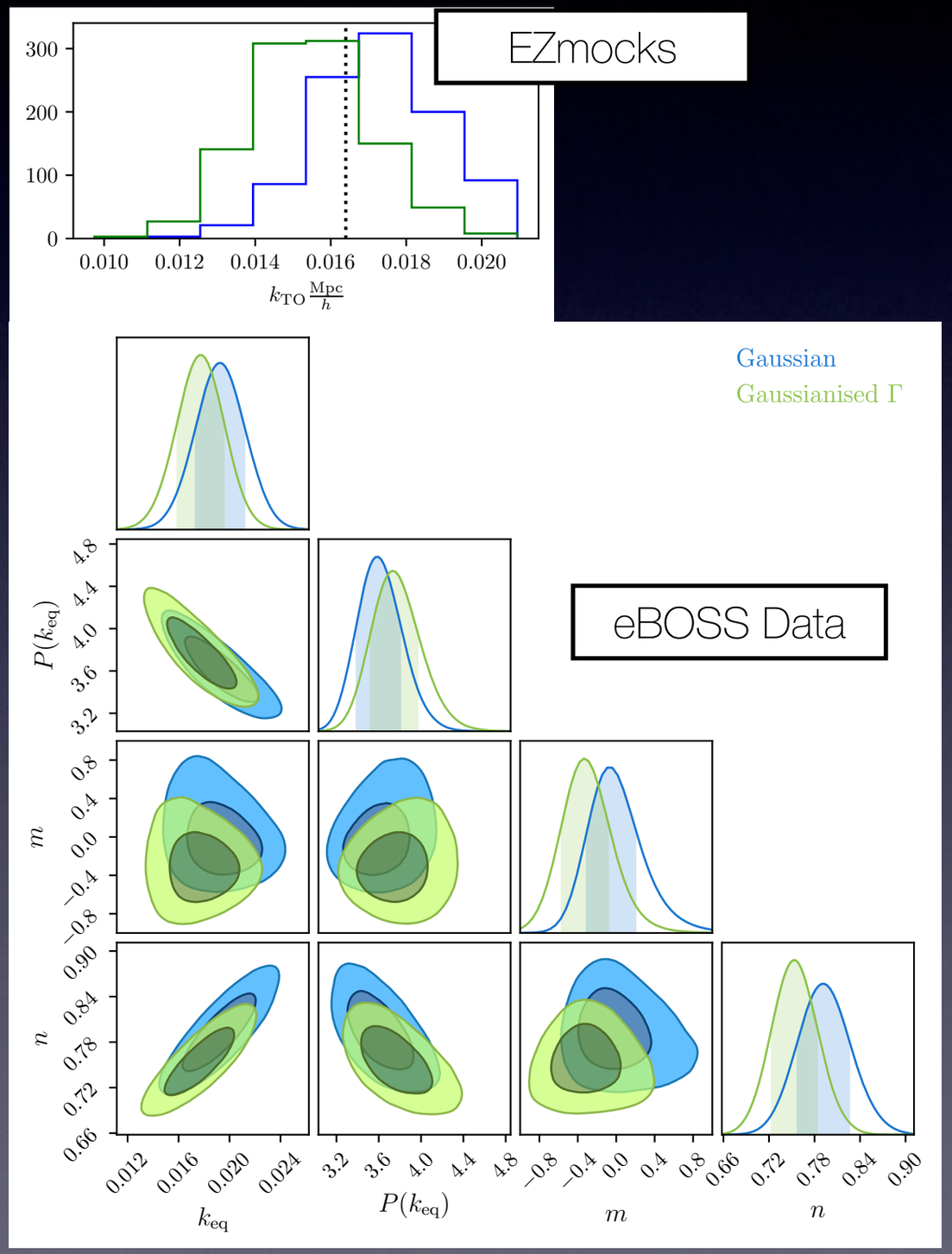
eBOSS results

- At largest scales: Gaussian assumption on power spectrum likelihood breaks down
- Windowed $P(k)$ hypo-exponentially distributed [Peacock & Nicholson 91]
- Well-approximated by Gamma-distribution [Wang+19]
- Gaussianisation through Box-Cox transformation $Z = \left[P(k)\right]^{\nu}$



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]:
  $k_{\mathrm{TO}} = \left(17.6^{+1.9}_{-1.8}\right) \times 10^{-3} h/\mathrm{Mpc}$

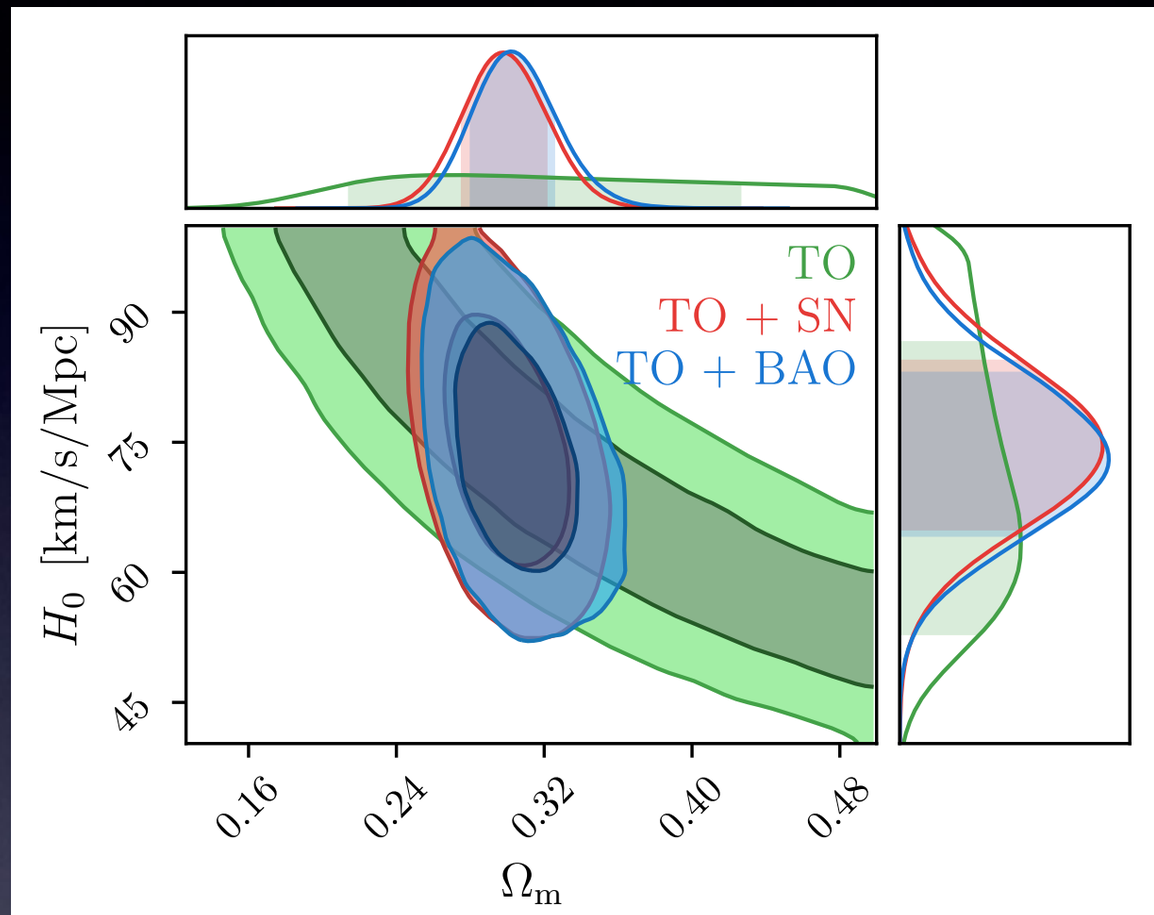


eBOSS Results

- 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 $r_{\rm d}$-independent standard ruler $\alpha_{\rm eq} = \dfrac{D_{\rm V}}{D_{\rm V}^{\rm fid}} \dfrac{r_{\rm H}^{\rm fid}}{r_{\rm H}}$
  - $\alpha_{\rm eq} = 1.07^{+0.12}_{-0.13}$
  - cf. $\alpha_{\rm bao} = 1.025 \pm 0.020$ [Neveux et al. 2020]
- Assuming 3 standard neutrino species, direct measurement of $\Omega_{\rm m} h^2 = 0.159^{+0.041}_{-0.037}$, consistent with Planck ($\Omega_{\rm m} h^2 = 0.1430 \pm 0.0011$)

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 H_0 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)

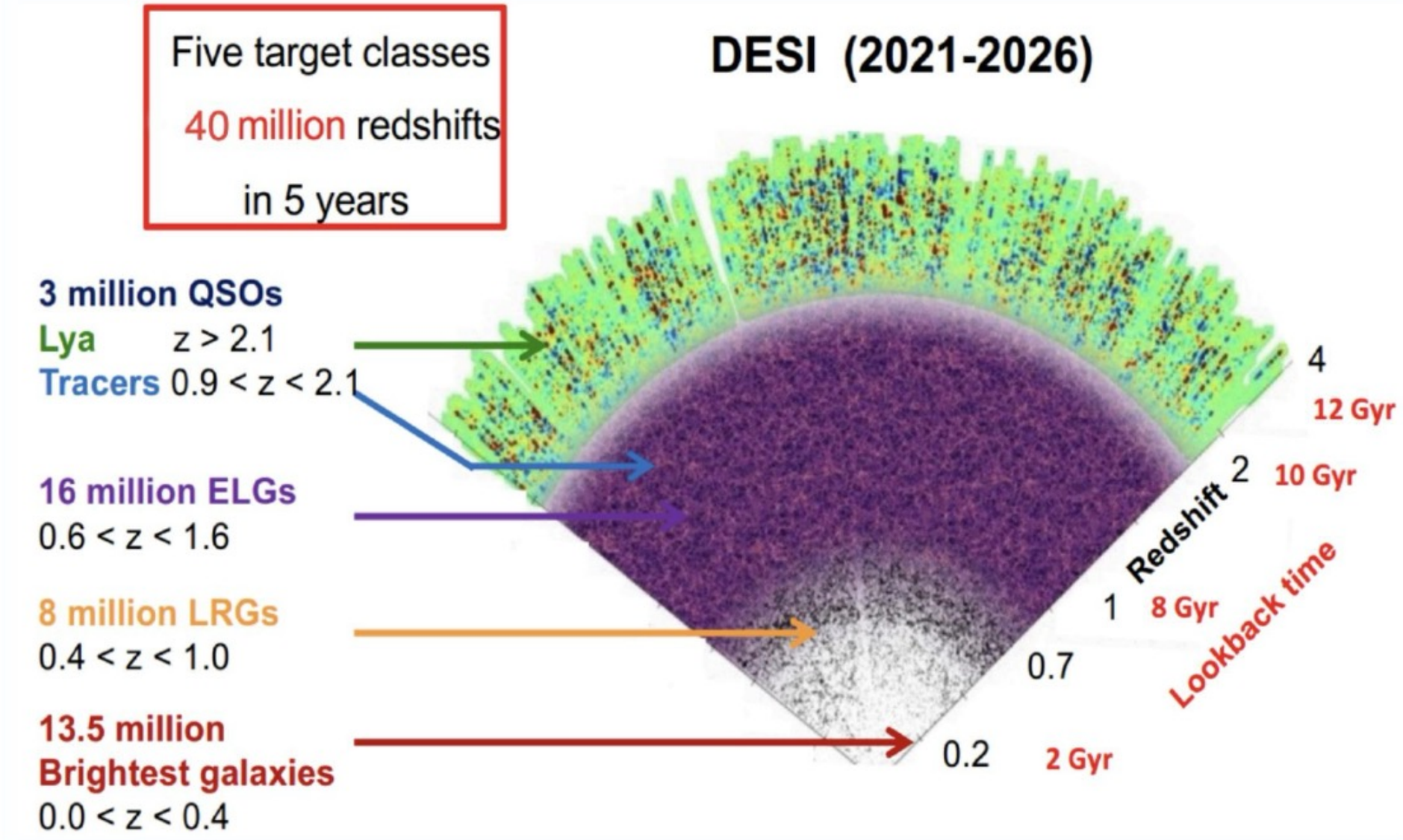
Comparison Table

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

DARK ENERGY SPECTROSCOPIC INSTRUMENT

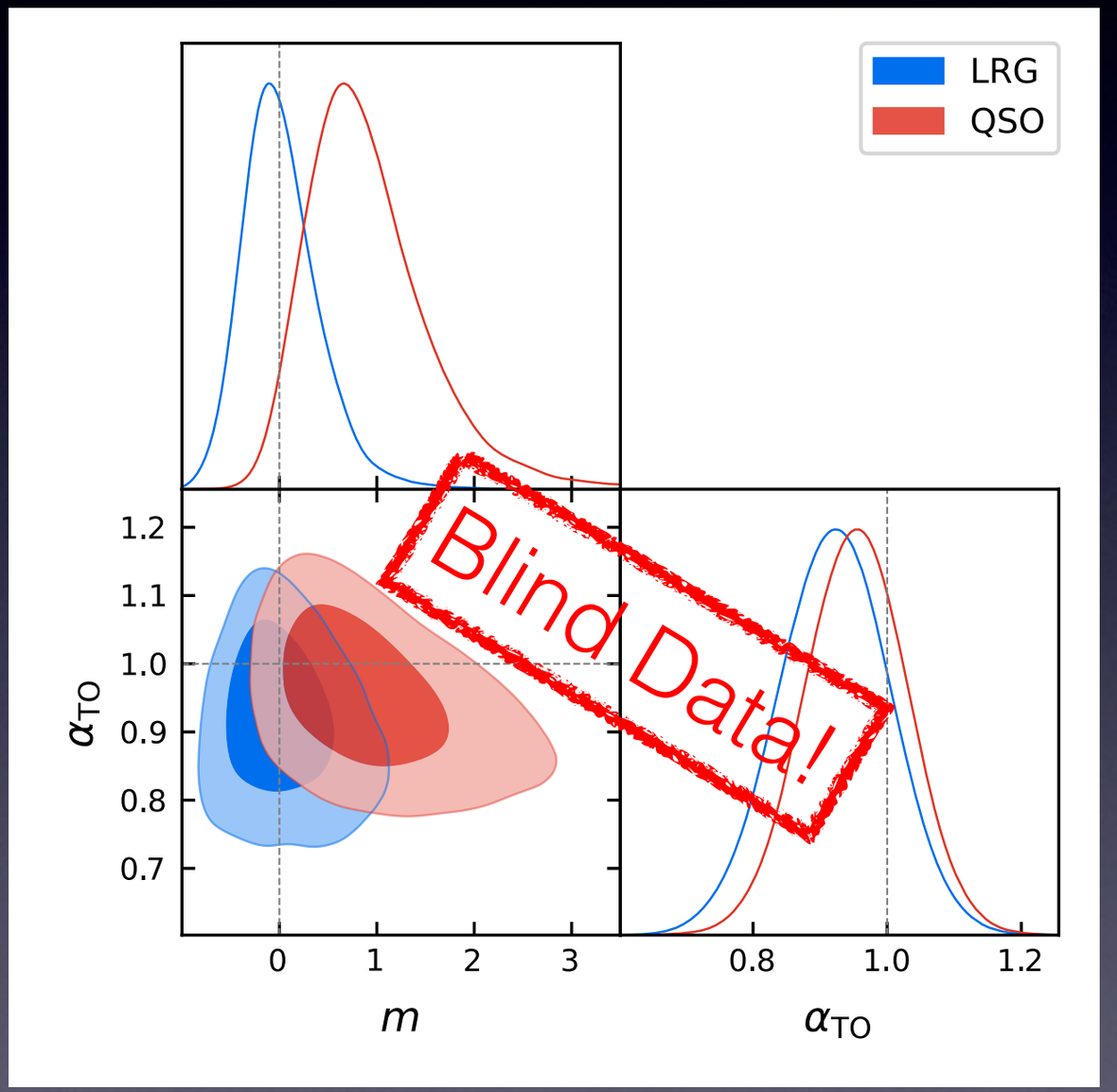
U.S. Department of Energy Office of Science

Tracers of the matter distribution



Blind DESI results

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



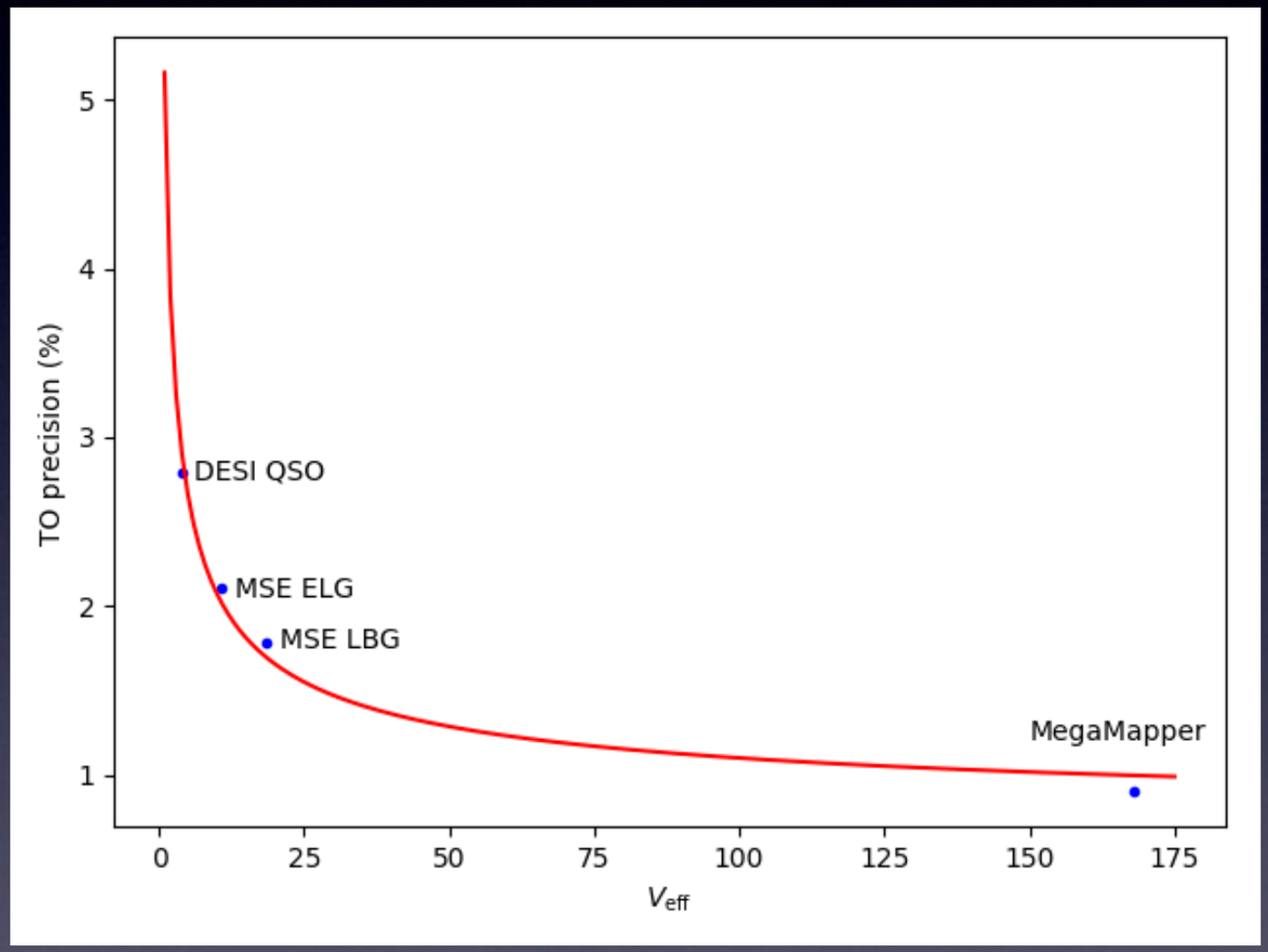
Beyond DESI

- 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
  $H_0 = \left(74.7 \pm 9.6\right)$ 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)
- DESI QSO and LRG will establish evidence for the turnover at >90 percent 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



Photo by Tim Schilstra