Nu Physics in the LCDM Desert

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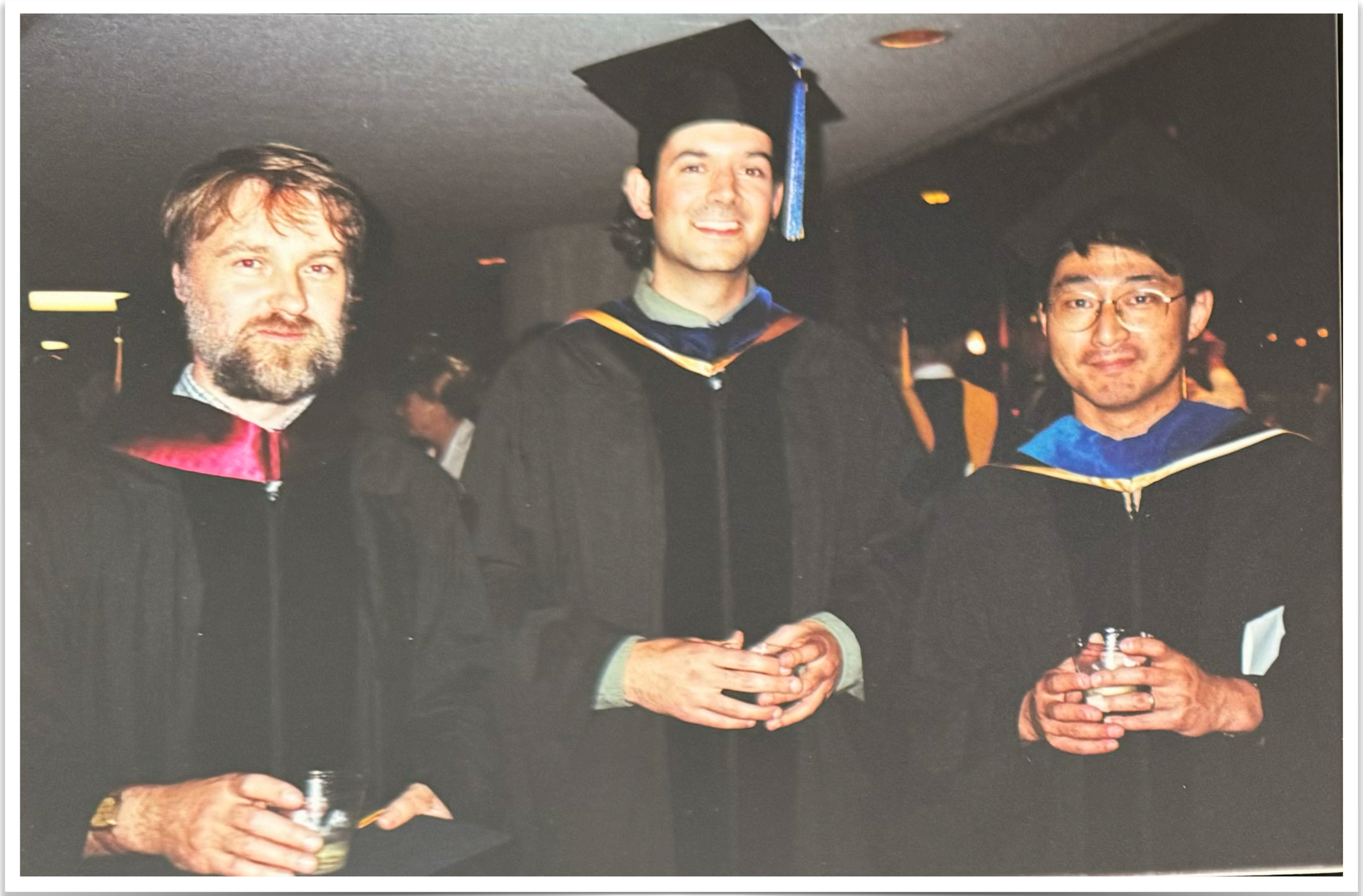
Sept 26, 2024

How did we even get here?



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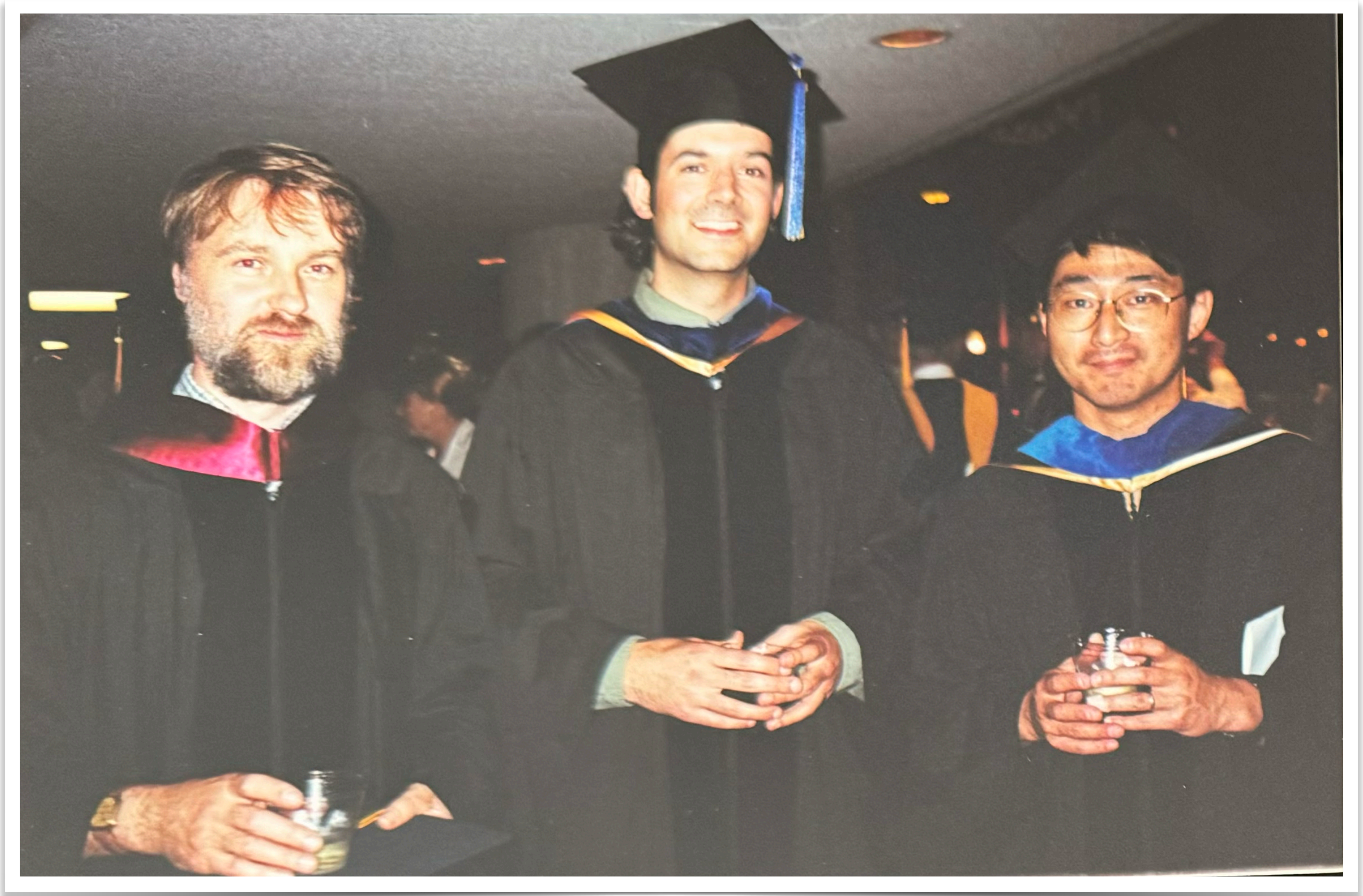
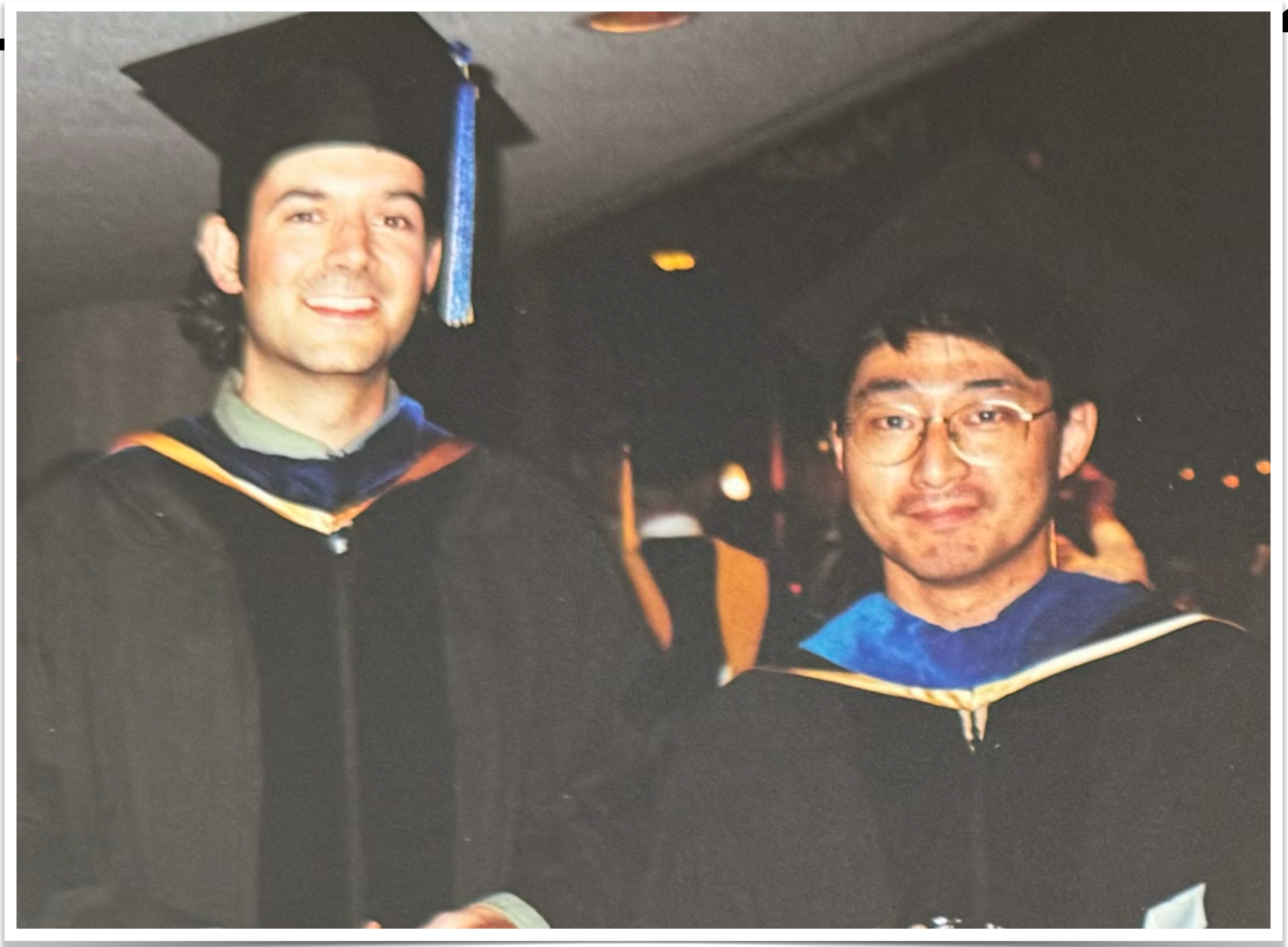


H ?



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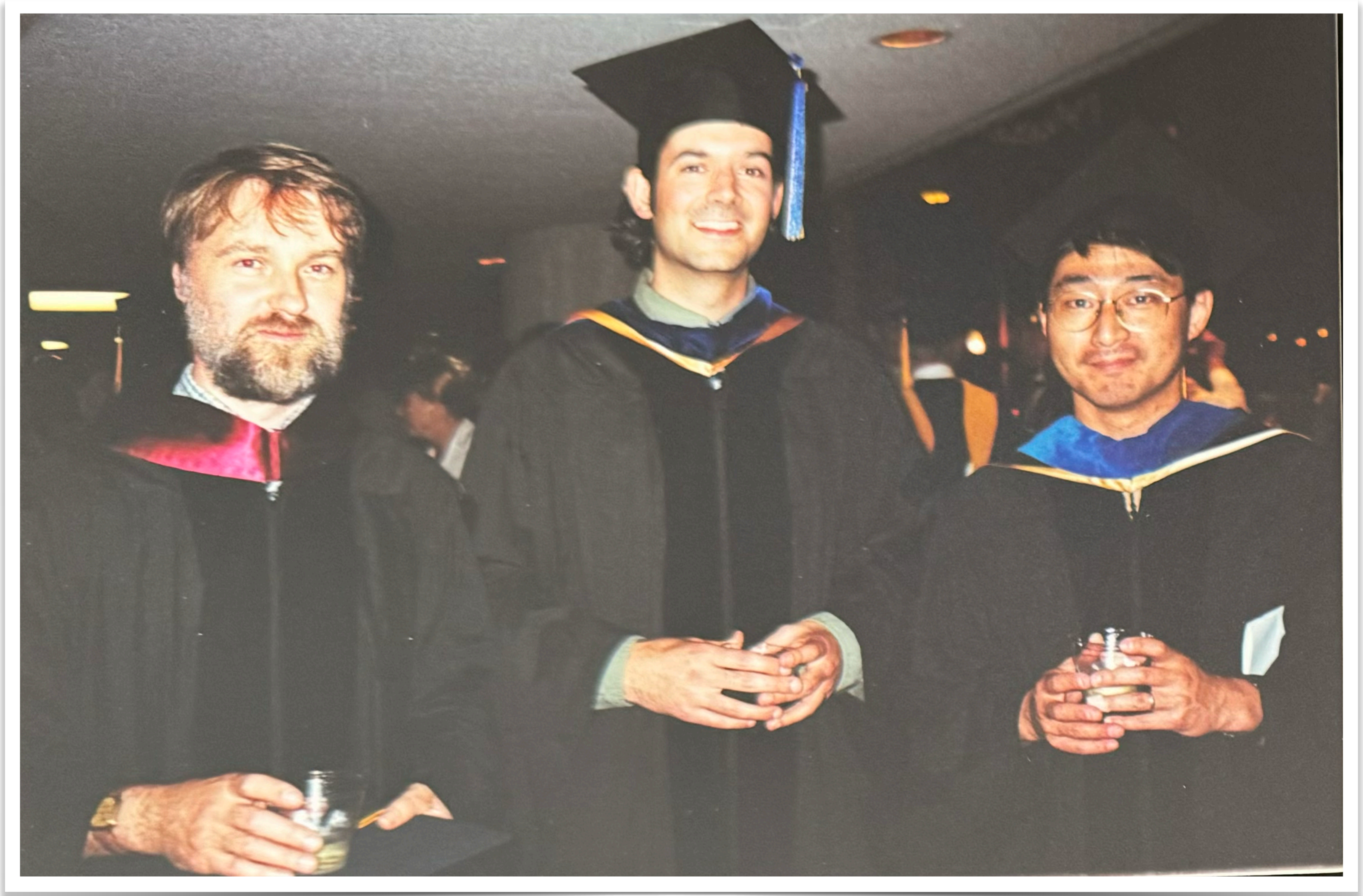
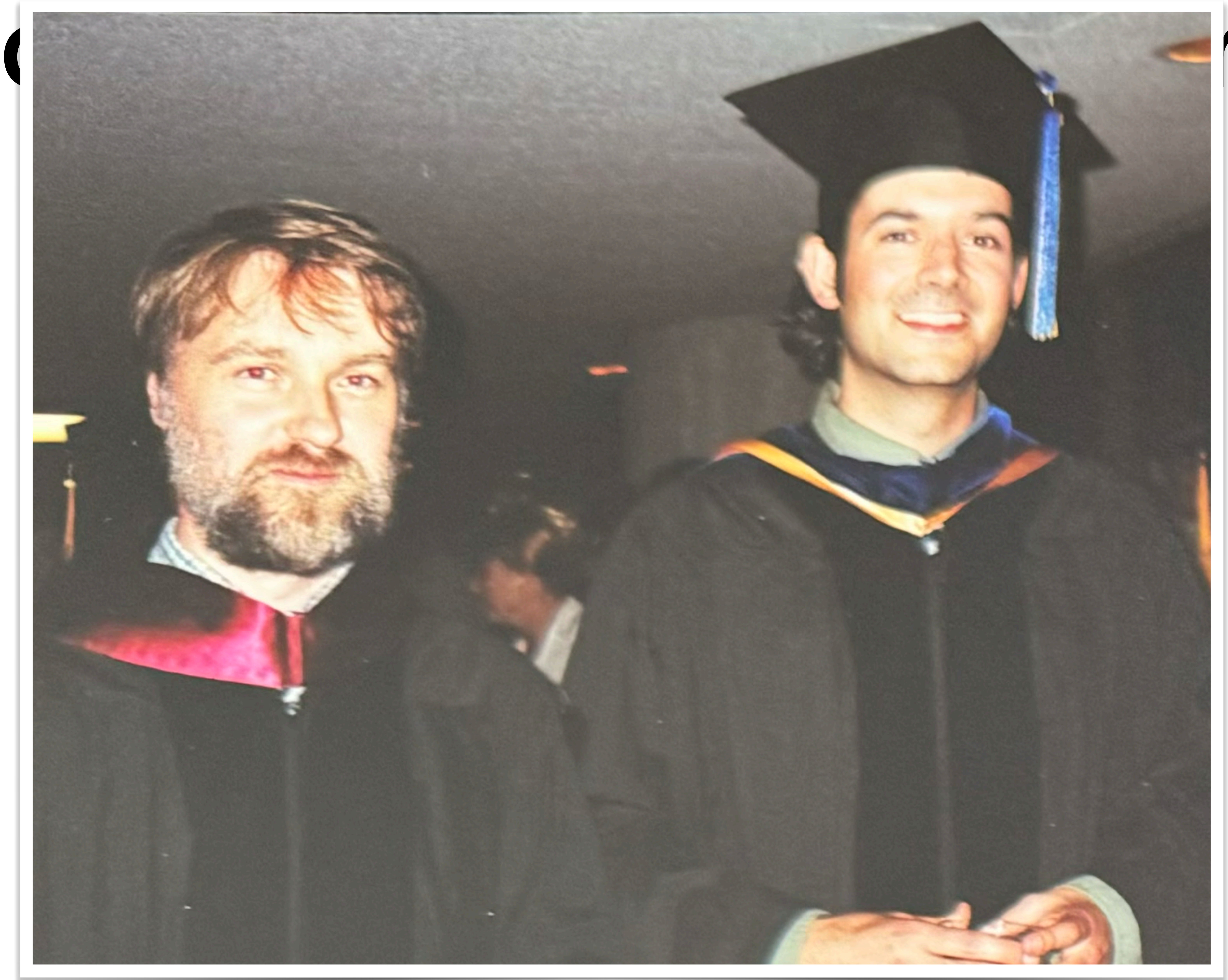


Ho… …re?



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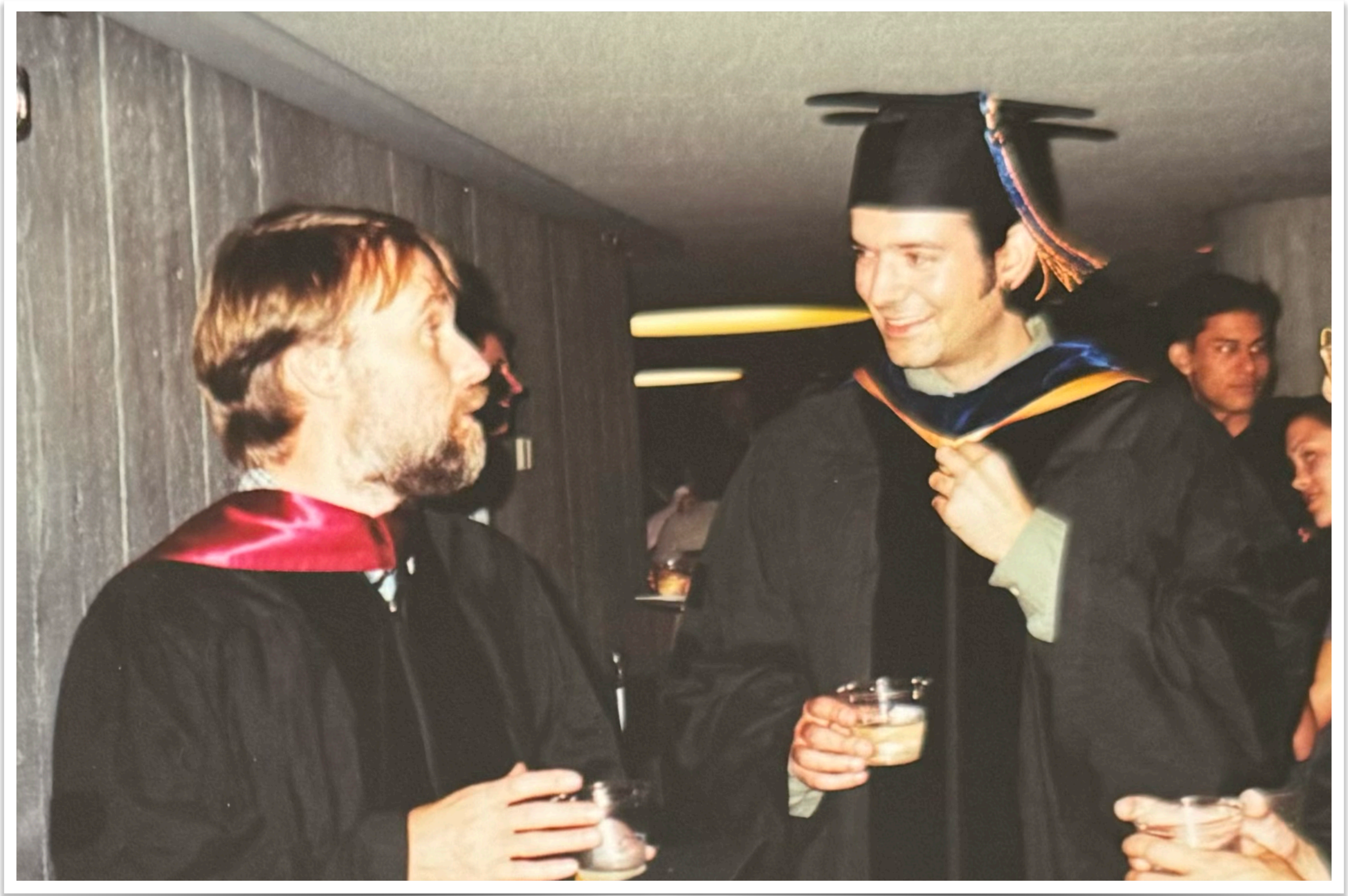


Grad student topics

- CP violation in EFTs
- Flavor symmetries
- Neutrino oscillations
- Neutrino masses (including anarchy!)
- Extra dimensions
- Supersymmetry
- Dark matter

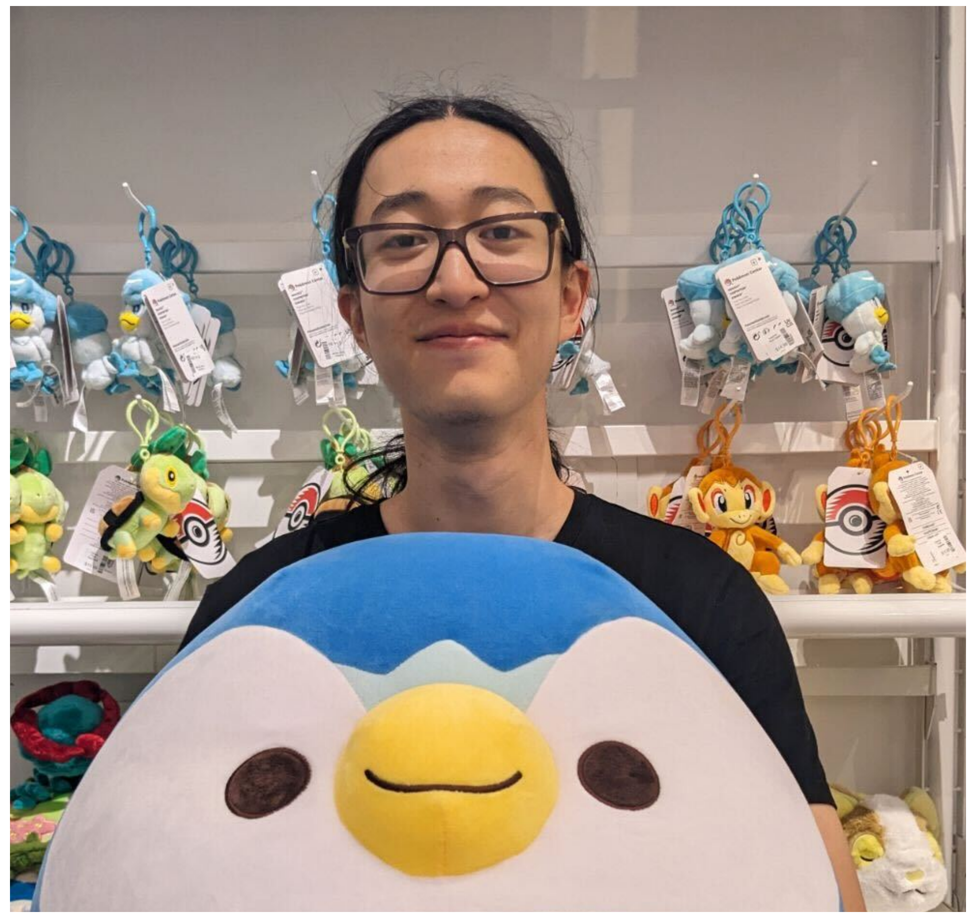
Follow the data; don’t underestimate what a fresh perspective can bring

Signals of the desert

Melissa Joseph,
BU GS -> Utah PD

Daniel Aloni,
Harvard/BU PD

Cara Giovanetti
NYU GS



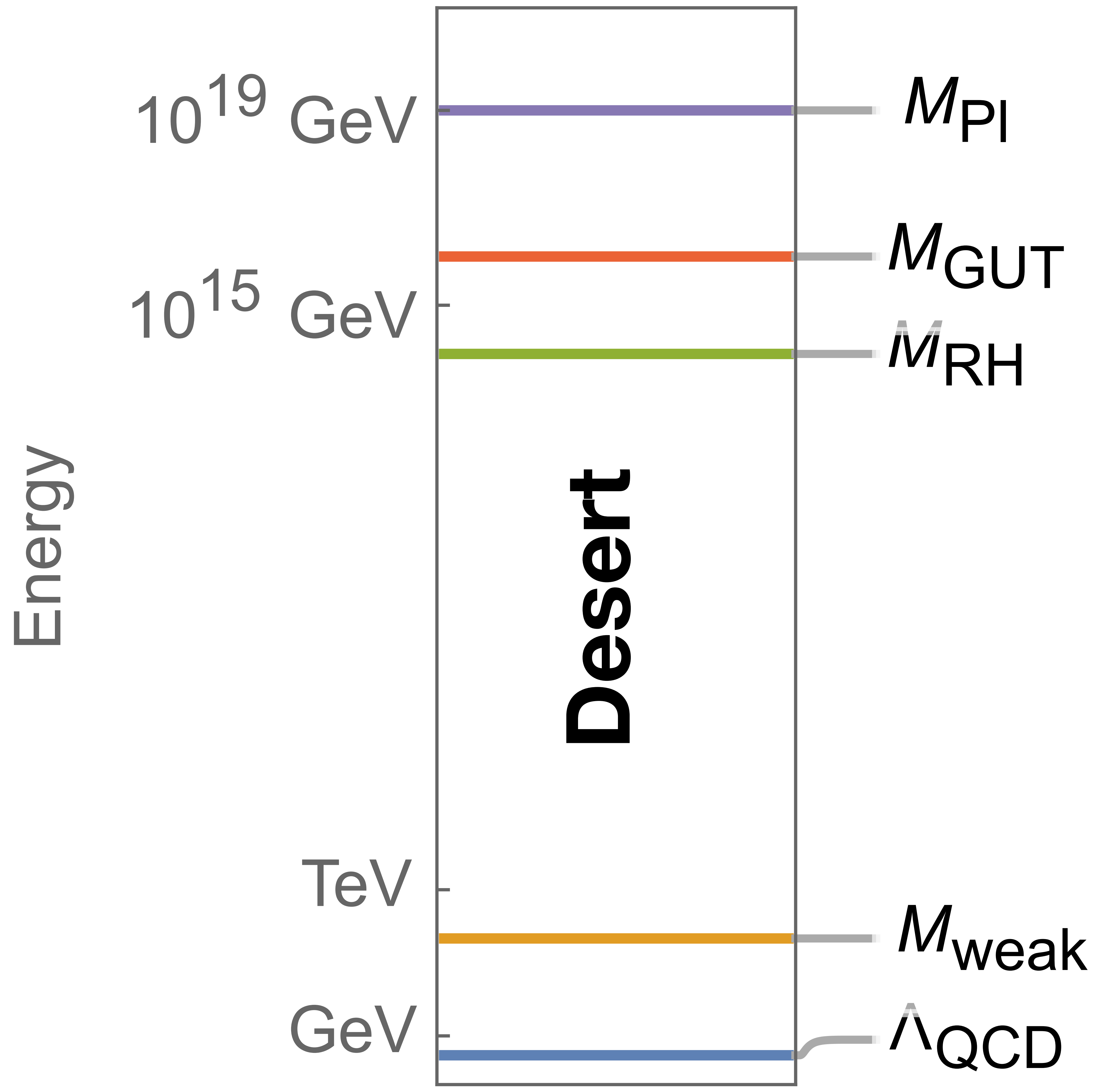
Tony Zhou
NYU GS

Eashwar Sivarajan,
BU GS

Asher Berlin,
Fermilab JF

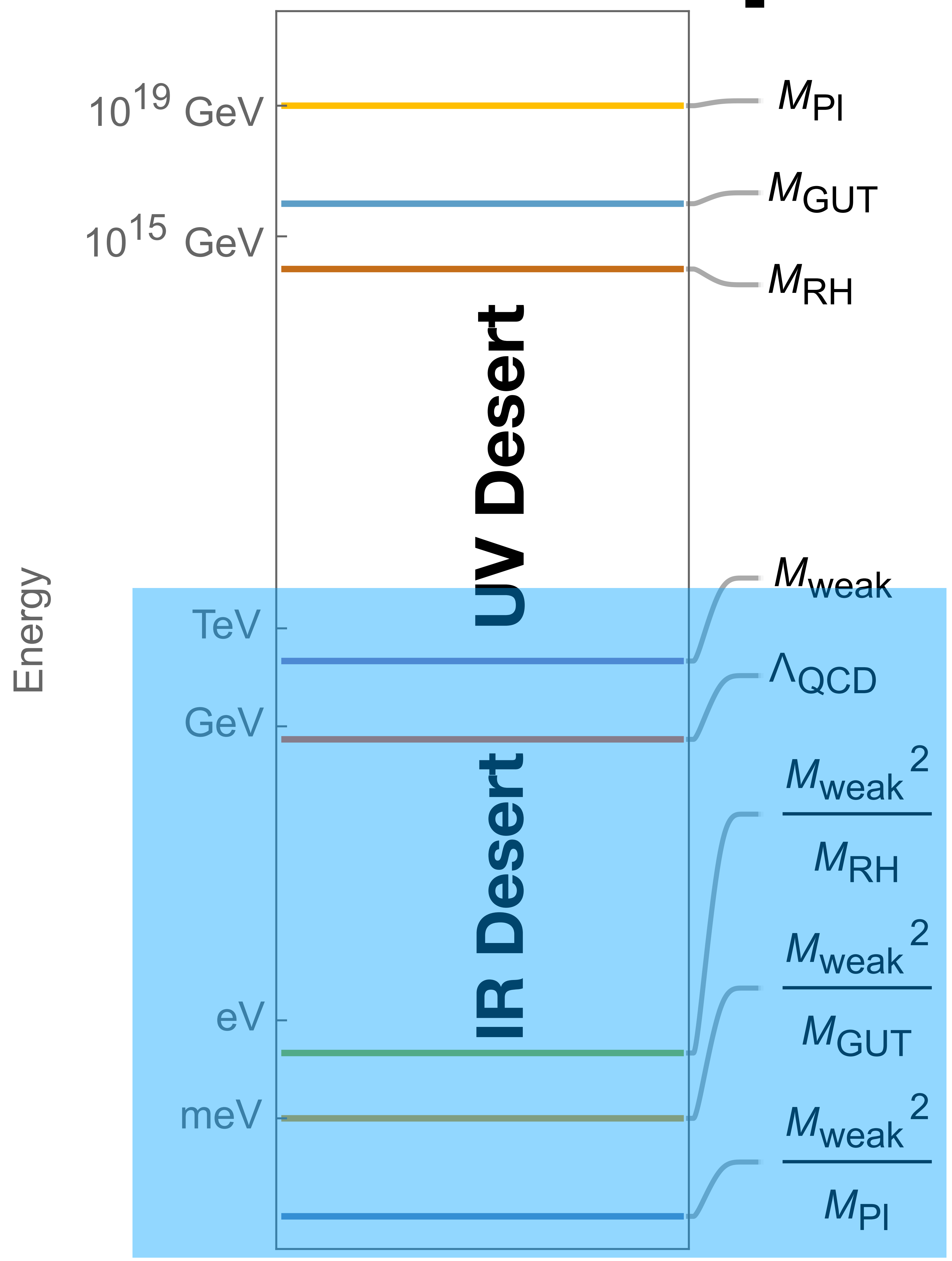
Martin Schmaltz,
BU SF

The desert

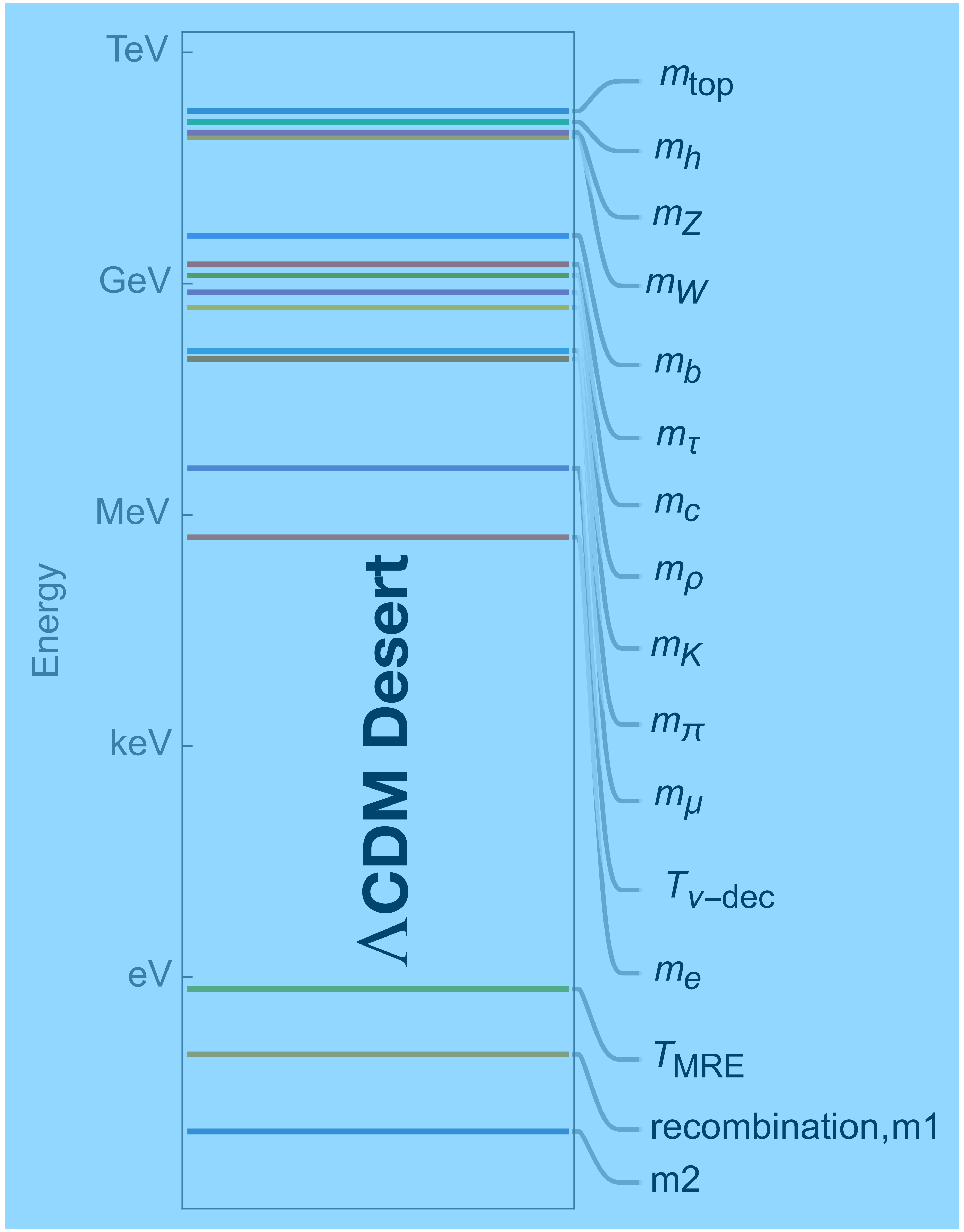


Energy
10^{19} GeV
10^{15} GeV
TeV
GeV
Desert
M_{Pl}
M_{GUT}
M_{RH}
M_{weak}
Λ_{QCD}

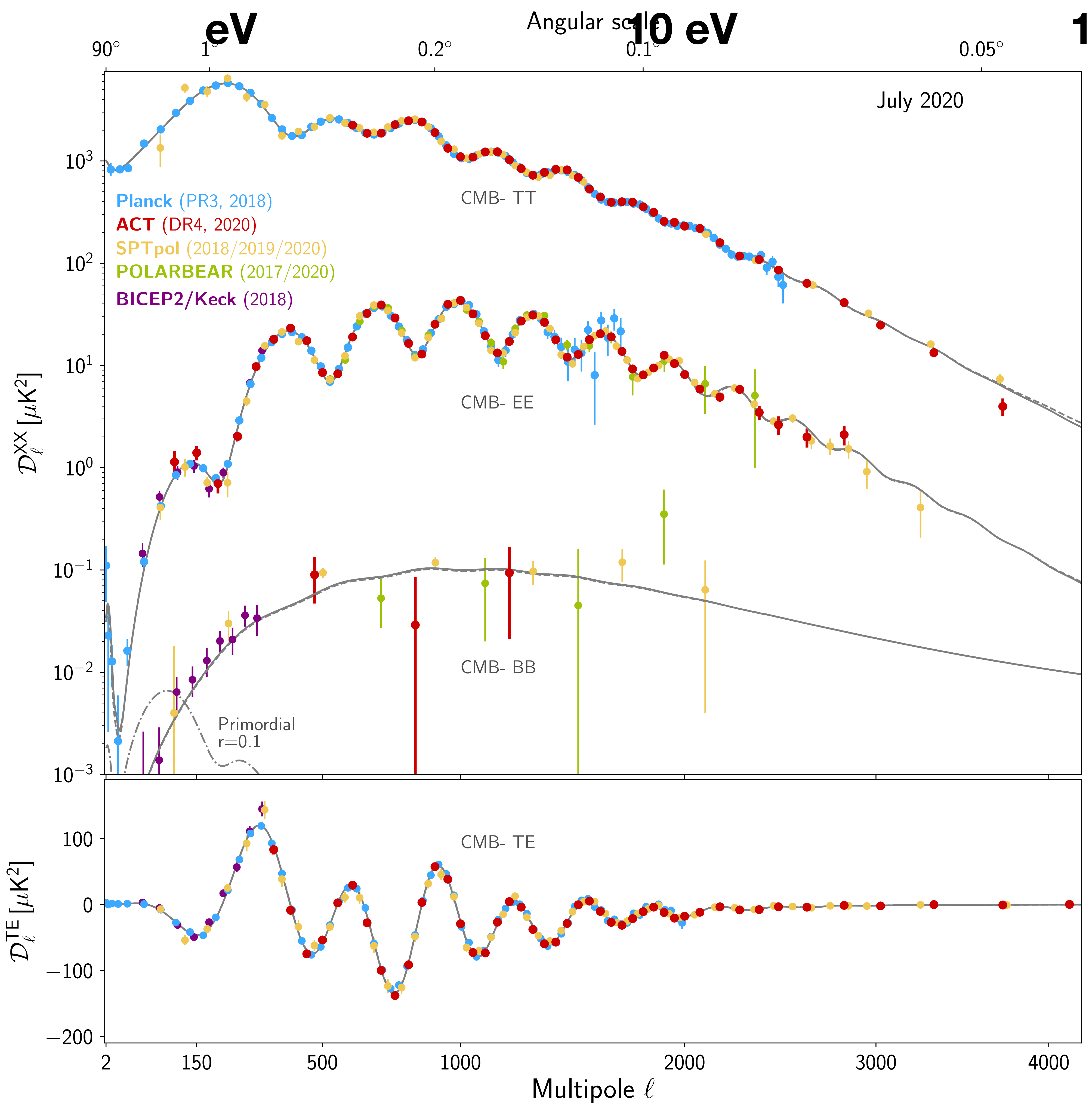
The desert correspondence

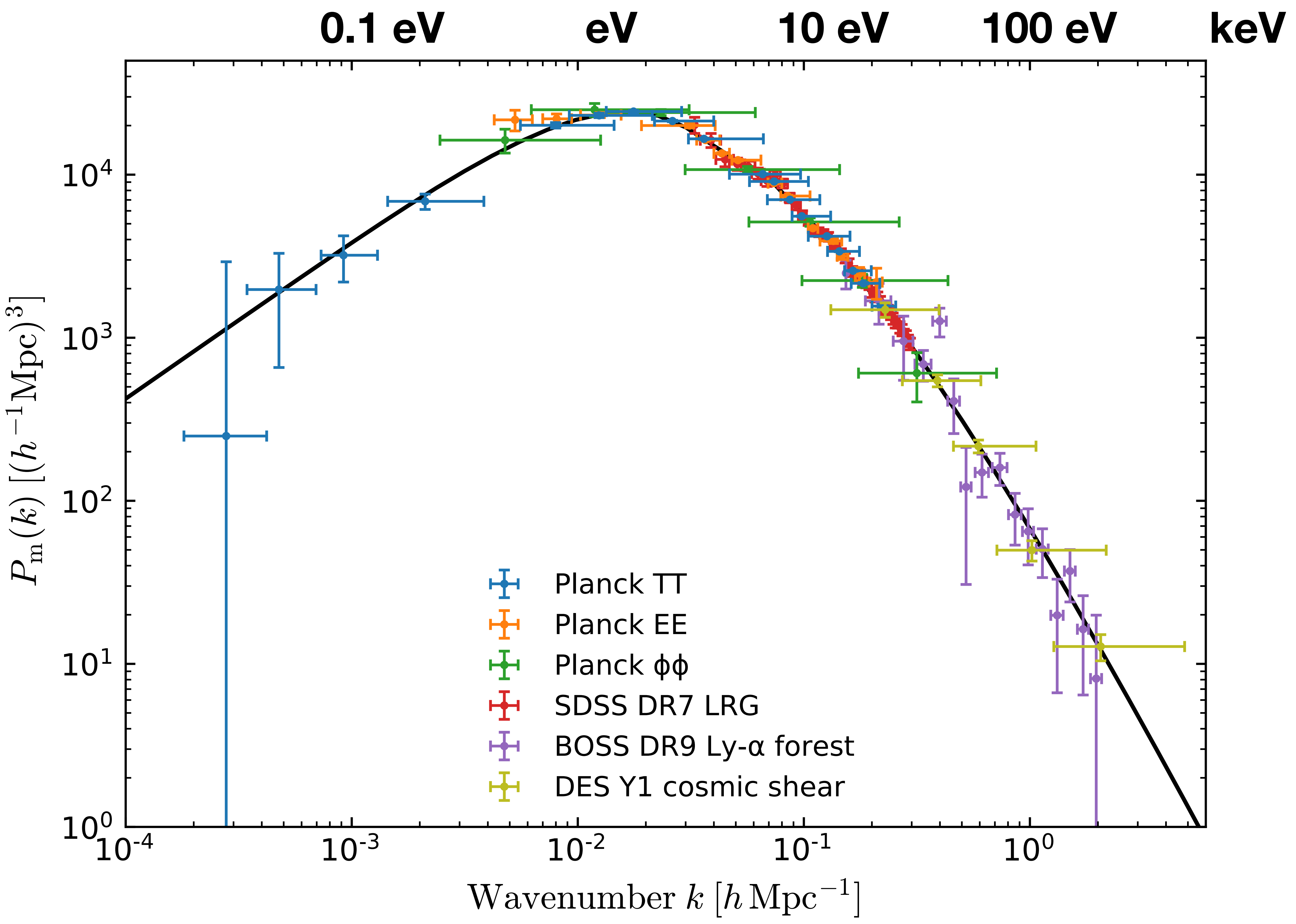


The LCDM desert

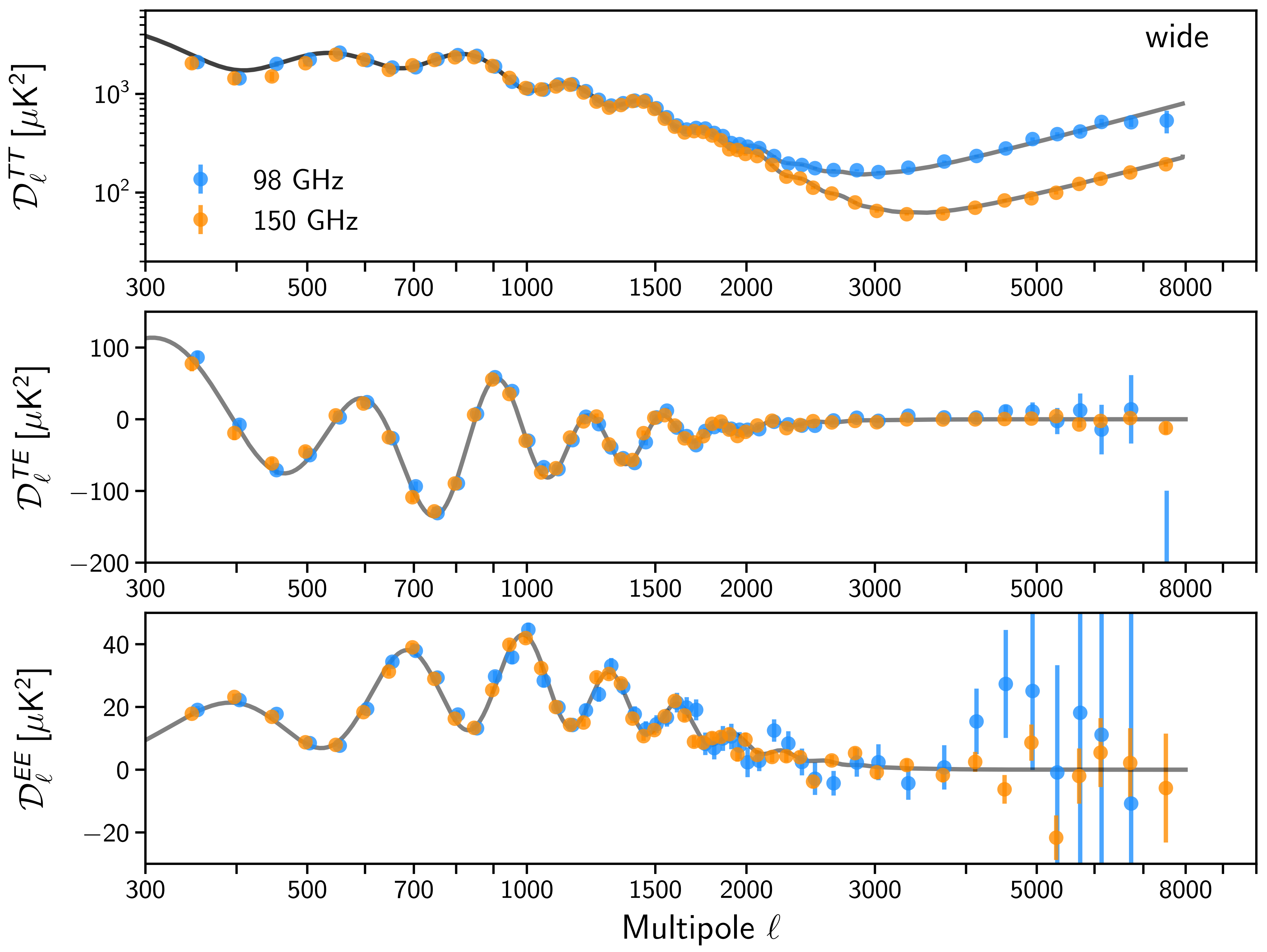


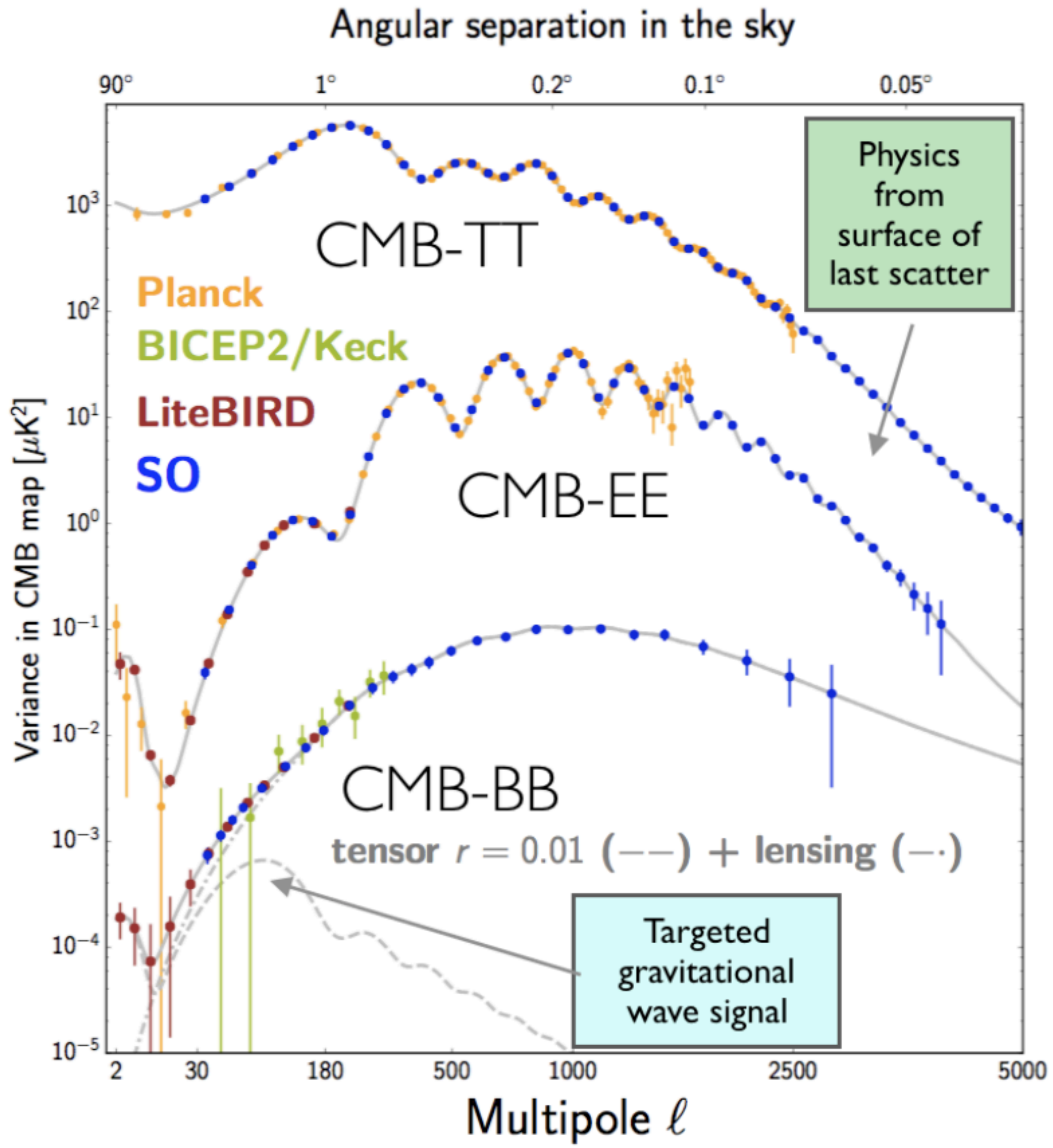
What's in the desert: data

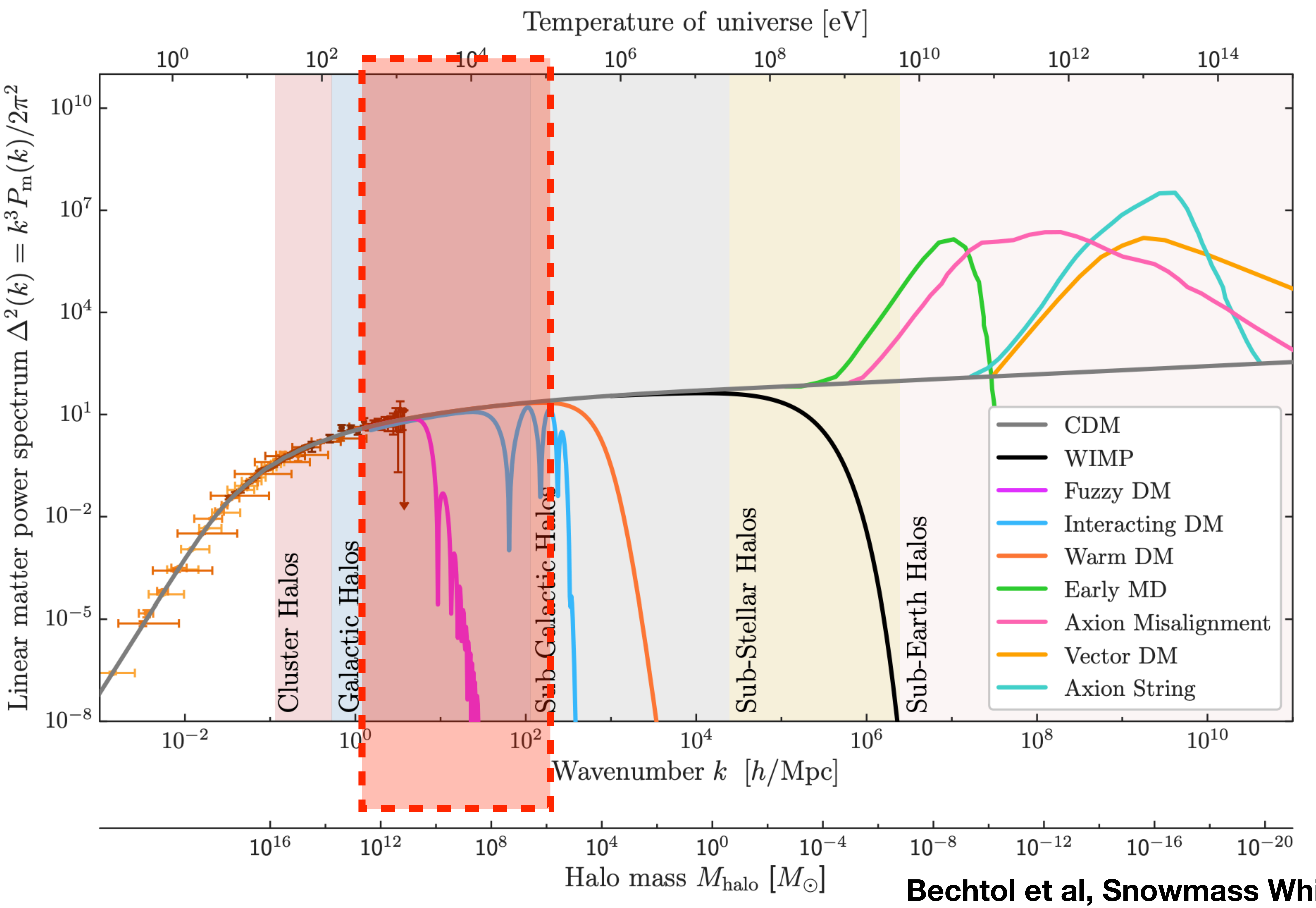




What's in the desert: more data







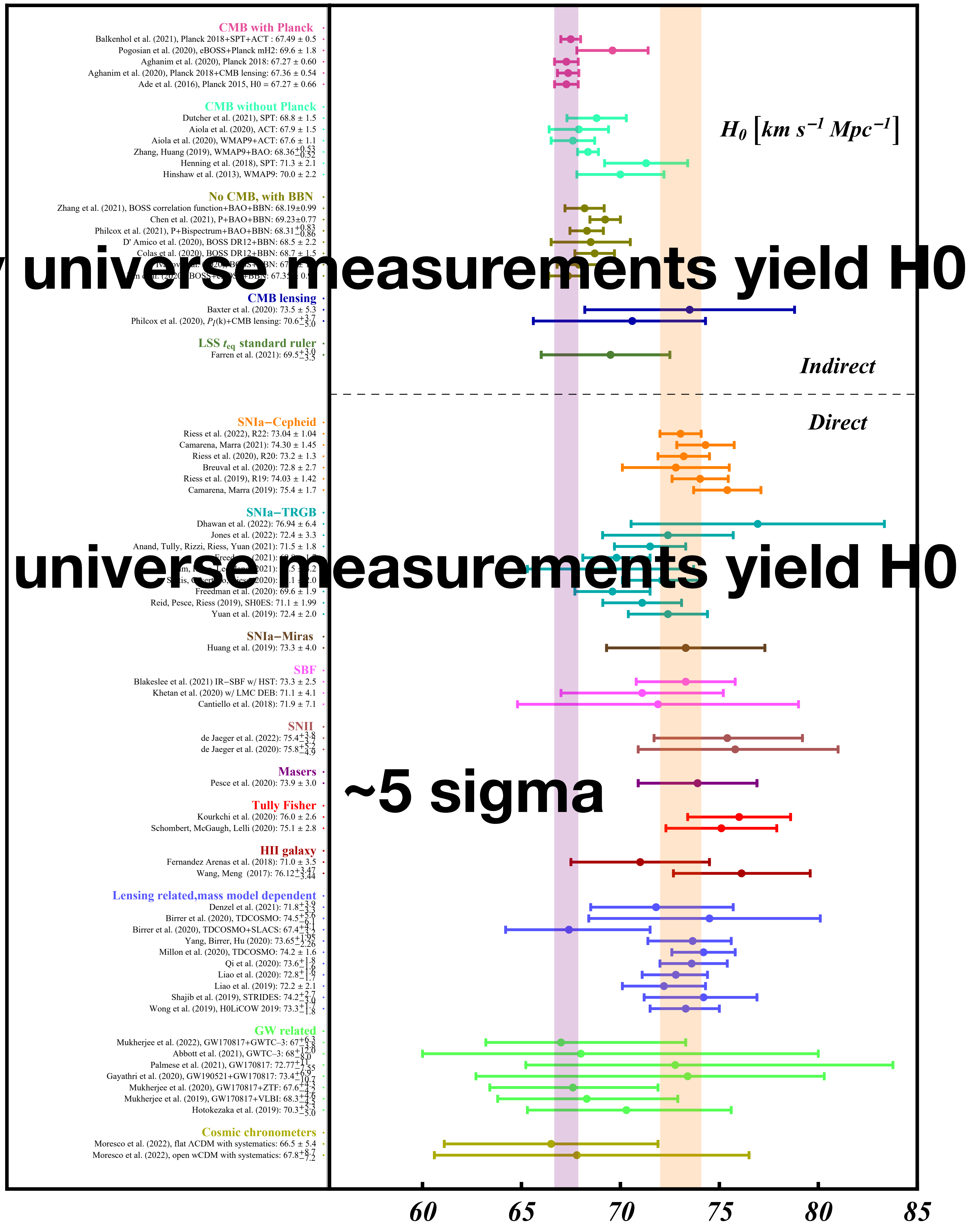
Bechtol et al, Snowmass White Paper 2023

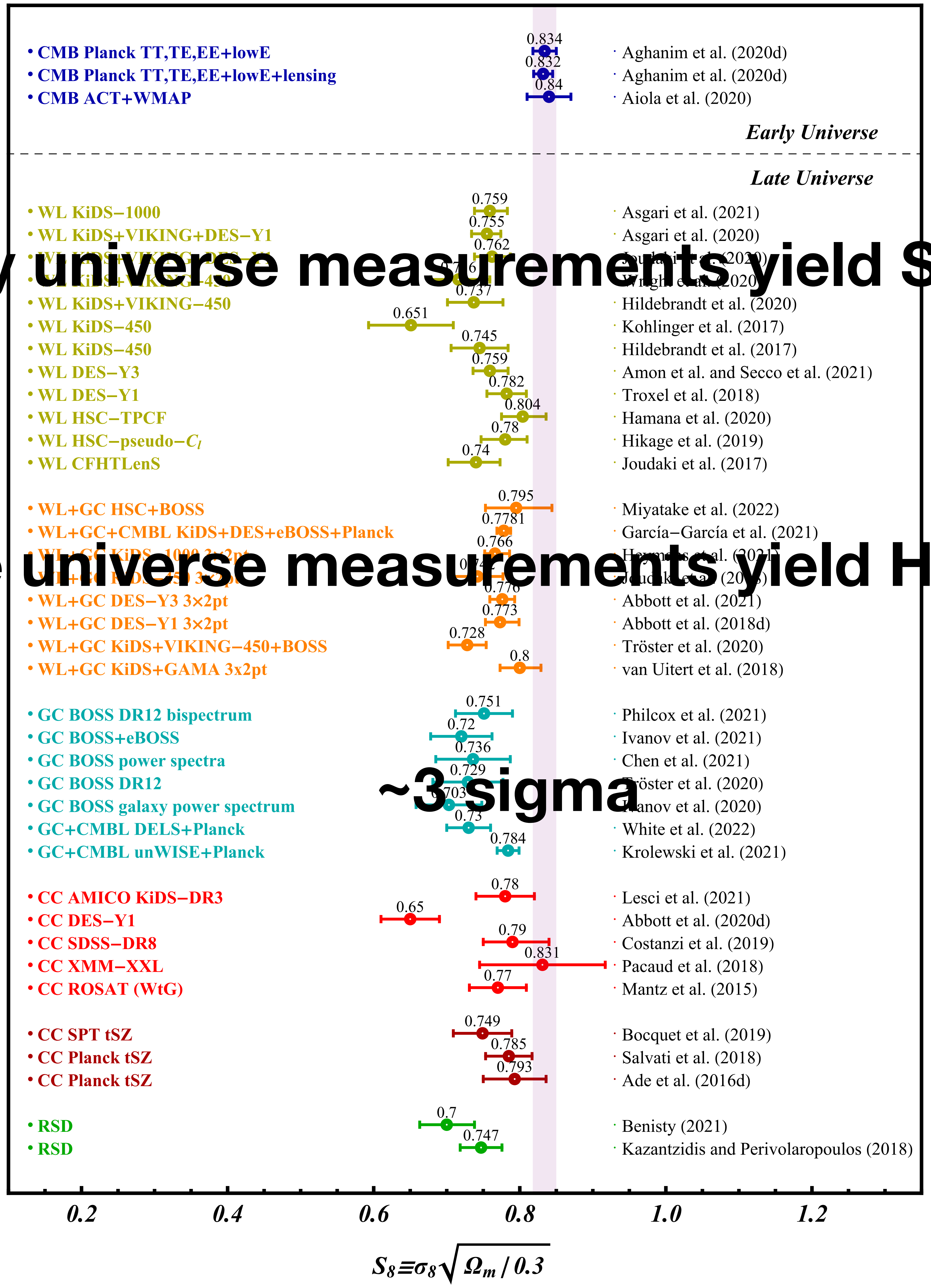
This is the era of the desert

- These decades (WMAP/SDSS/Planck/BOSS -> Today -> Rubin/EUCLID/Roman/SO/CMB-S4) will explore these energies/temperatures by seeing objects directly sensitive to those eras

“Cosmology, Schmosmology”

What’s in the desert: anomalies





Early universe measurements yield H0 ~67

Early universe measurements yield S8 ~0.83

Late universe measurements yield H0 ~73

Late universe measurements yield H0 ~0.77

~5 sigma

~3 sigma

The desert is exciting

- Irrespective of anything else, there’s a tremendous opportunity to constrain or discover new physics below the MeV scale
- Anomalies, make concrete targets especially interesting
- Provides motivation for models to consider as we approach new data

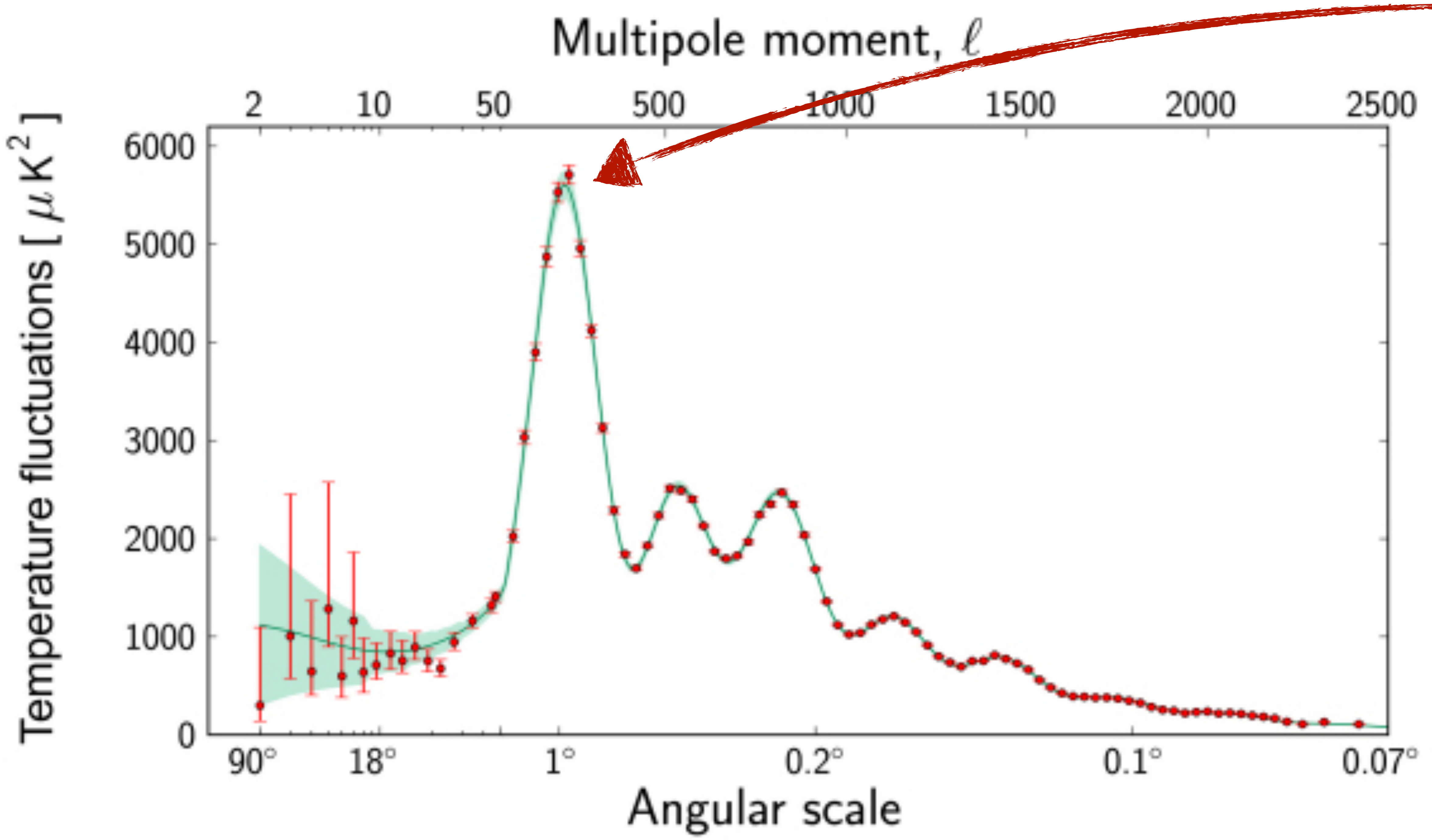
Hubble and dark radiation

The Hubble tension

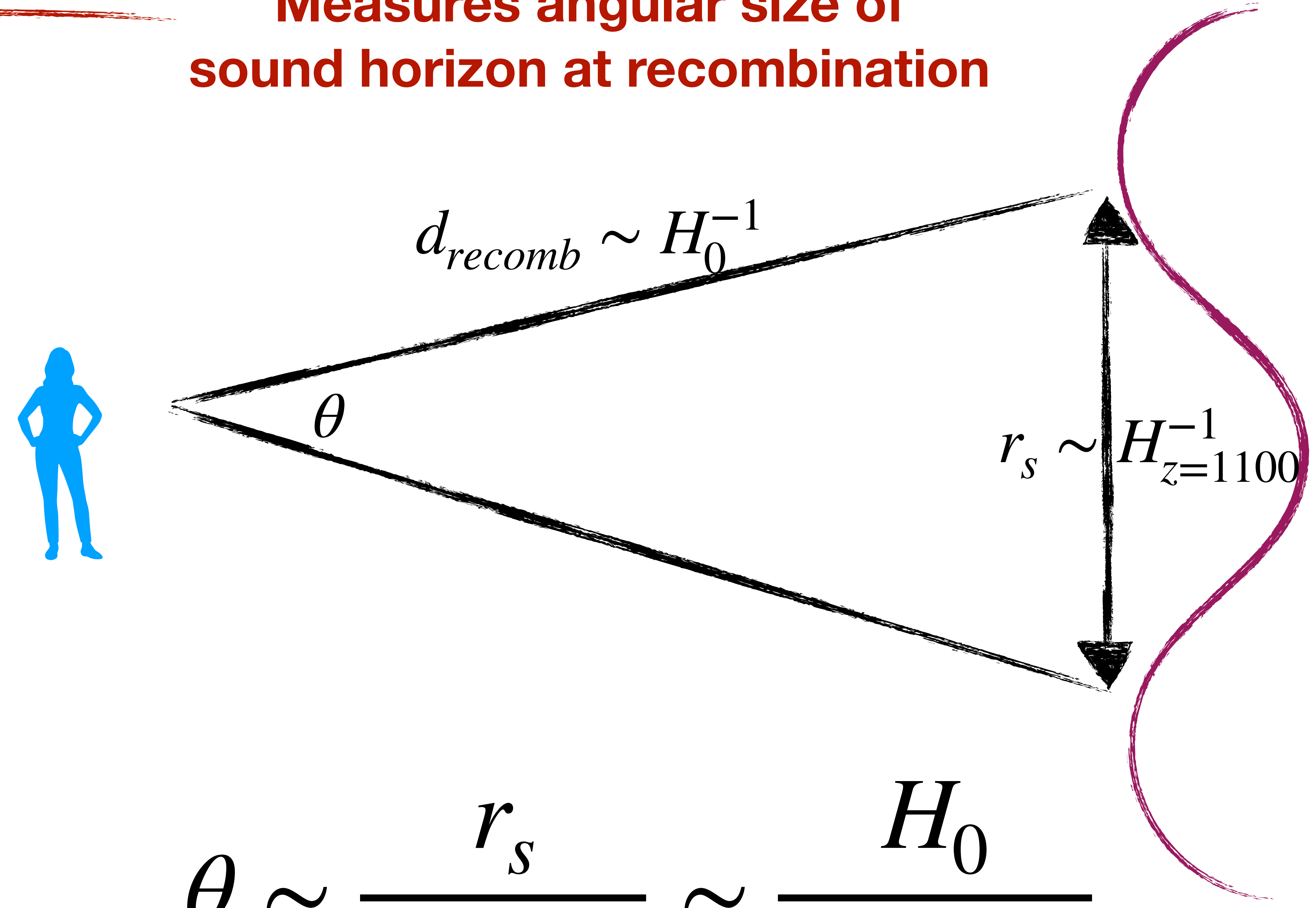
- The Hubble tension is the disagreement between late-universe measurements of the expansion rate versus values inferred assuming LCDM using the CMB and other cosmological data
- CMB+: $H0 \approx 67$
- SH0ES: $H0 \approx 73$

A horizon problem?

“Sounds Discordant” Aylor et al 2019



Measures angular size of sound horizon at recombination



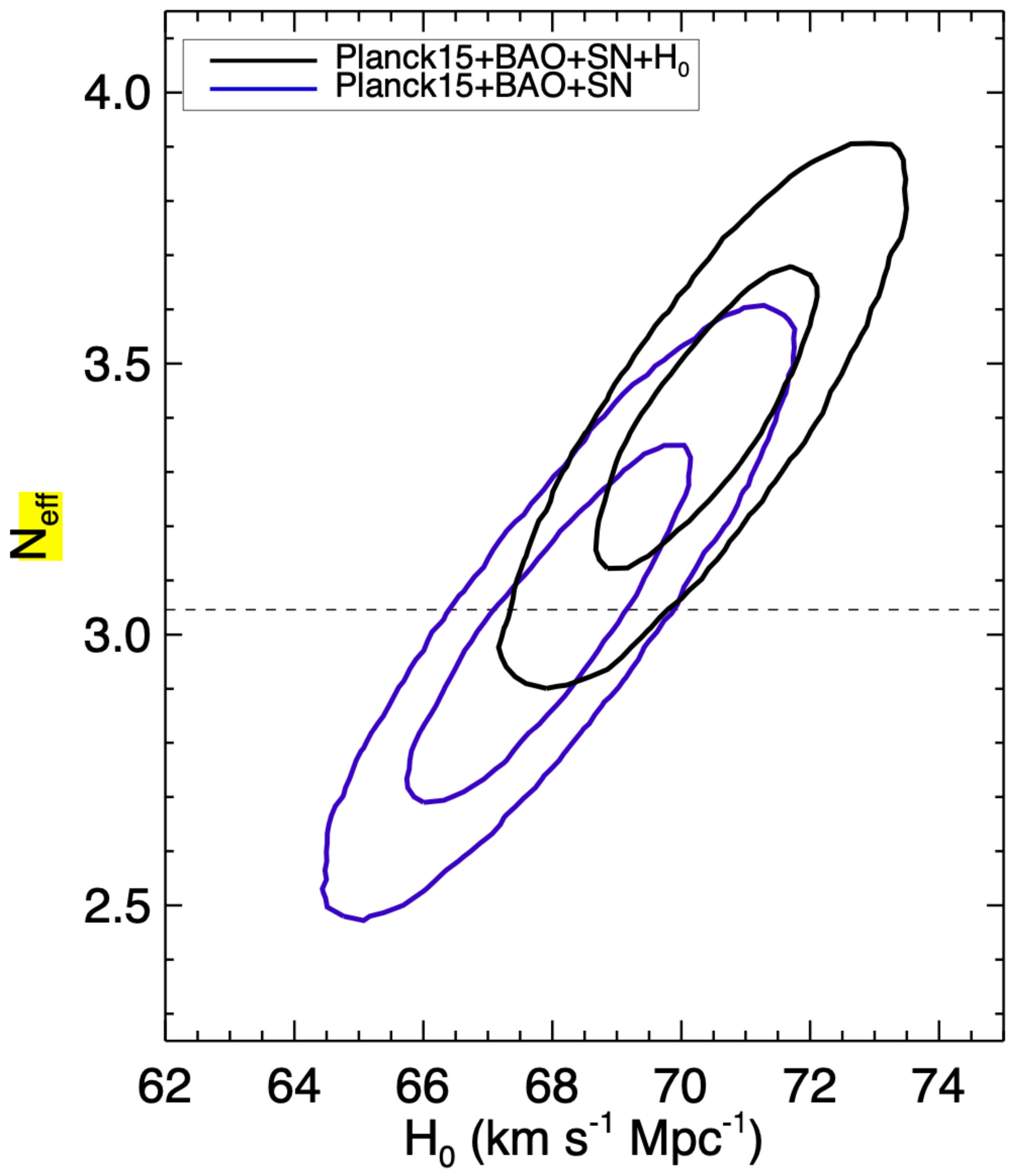
$$\theta \sim \frac{r_s}{d_{recomb}} \sim \frac{H_0}{H_{z=1100}}$$

A horizon problem?

- Changing the horizon, by adding extra energy density (e.g., dark radiation) can shift $H_{z=1100}$ and thus the inferred value of H_0

$$\theta \sim \frac{H_0}{H_{z=1100}}$$

Riess et al 2016



- But it doesn't really work (anymore)

Quick aside on BBN

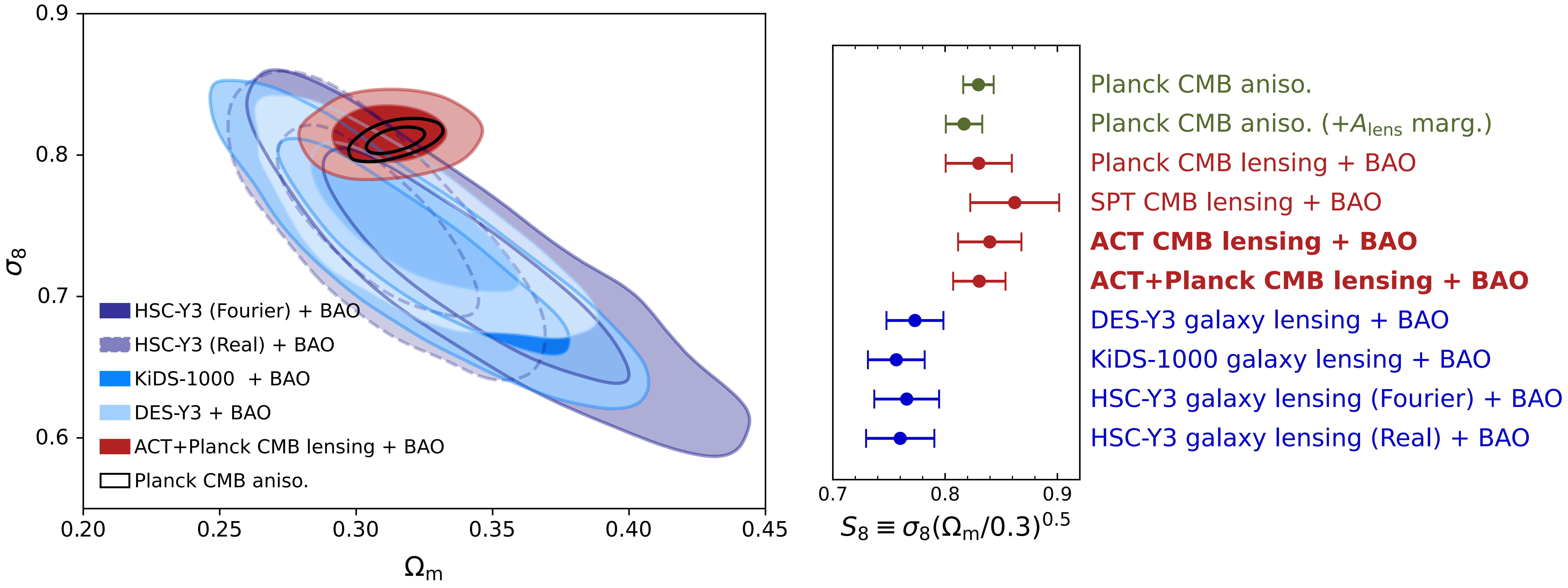
- Historically, when people add dark radiation they also assume it was there during BBN, and take the resulting increase in primordial Helium for CMB calculations

- Even without the BBN data, this hurts the CMB fit, because Helium leads to additional damping at high-l

- If a light sector came into equilibrium post BBN, this would not apply

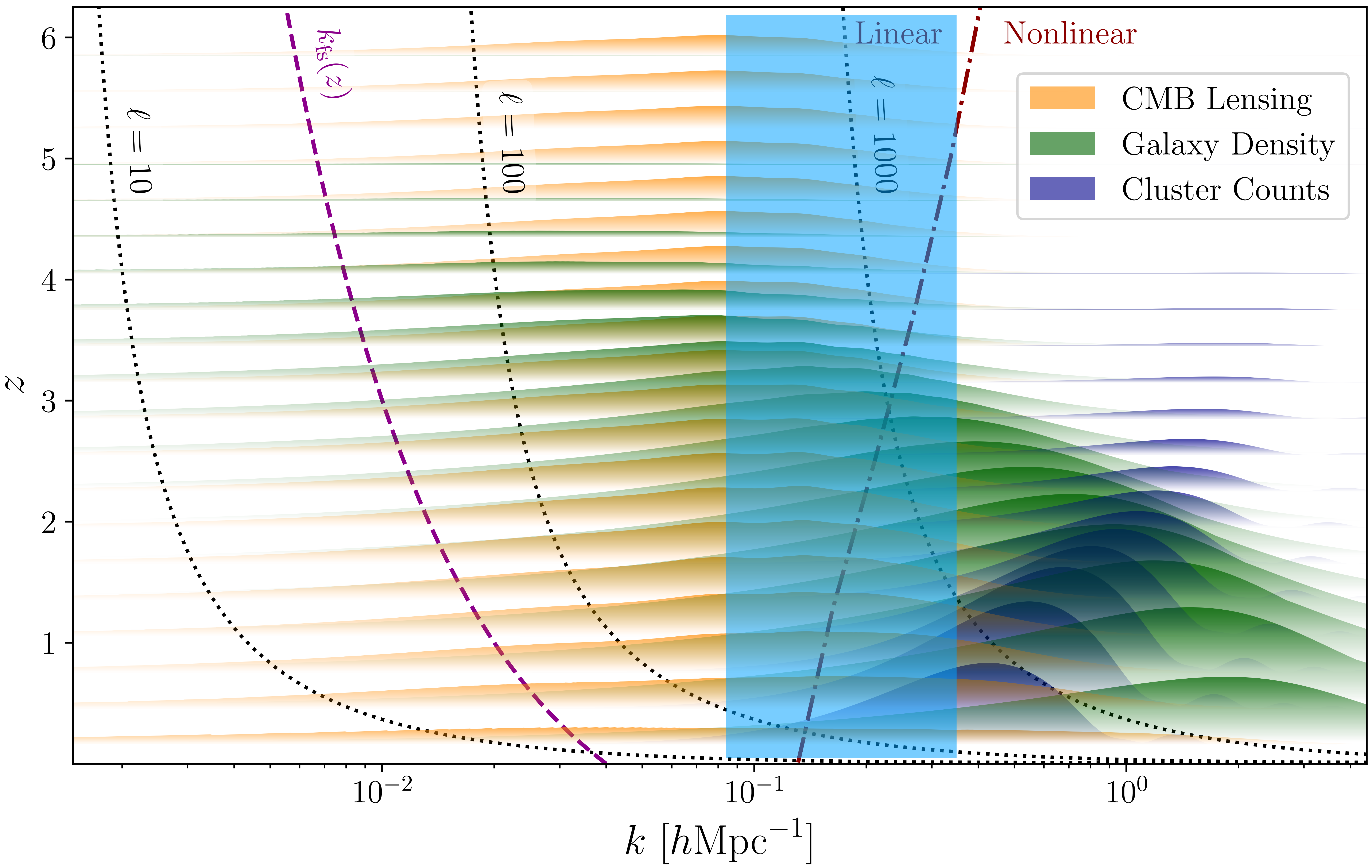
What about S_8?

A late universe measurement of S8?



Madhavacheril, Qu, Sherwin, MacCrann, Li et al. (ACT collaboration) 2023

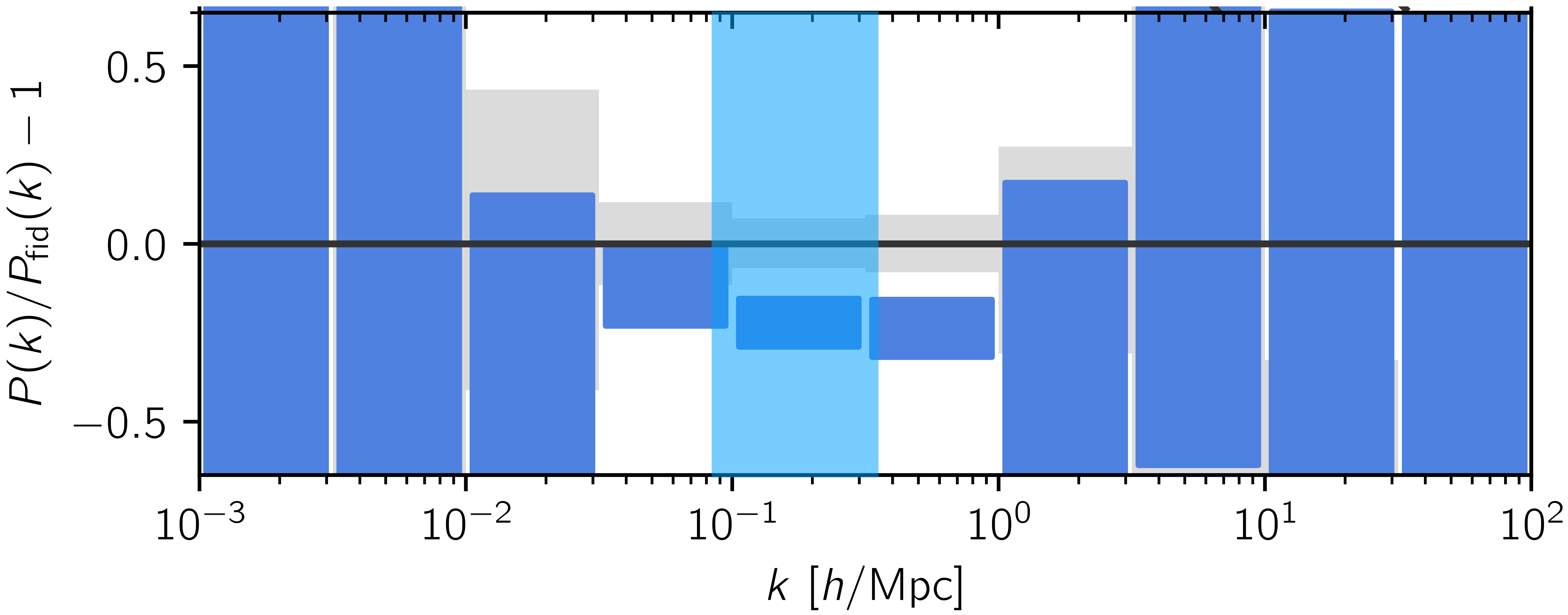
Apples to apples



We should not be fitting one number!

Gerbino et al 2022

DES8

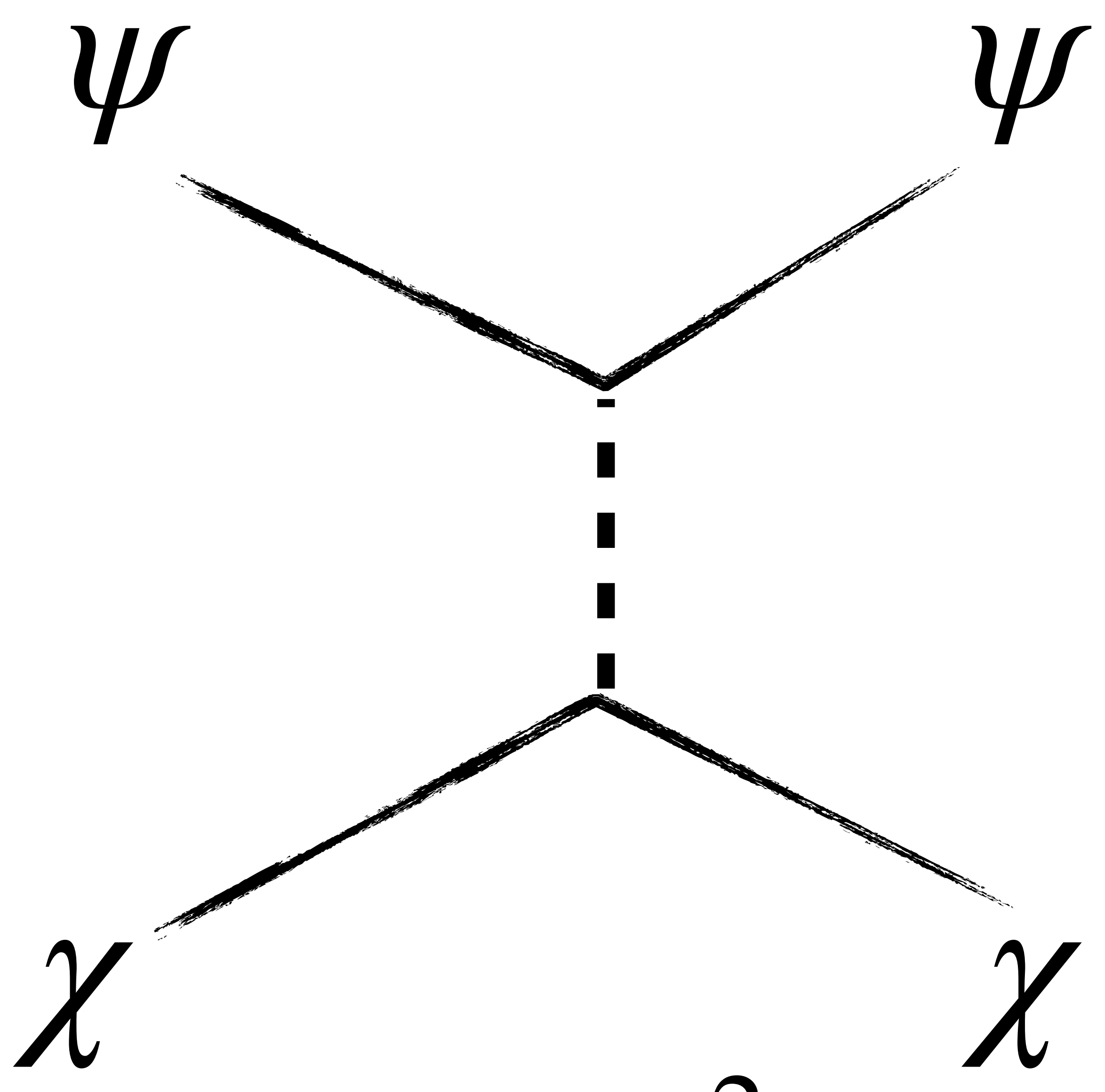


Doux et al 2022

DM - DR Interactions and S8

- Gentle DM-DR interactions (WZDR+) can suppress power in scale dependent fashion - may be relevant for S8 (Buen-Abad, Marques-Tavares, Schmaltz, 2015)

- Generally suppresses power too much at the largest scales

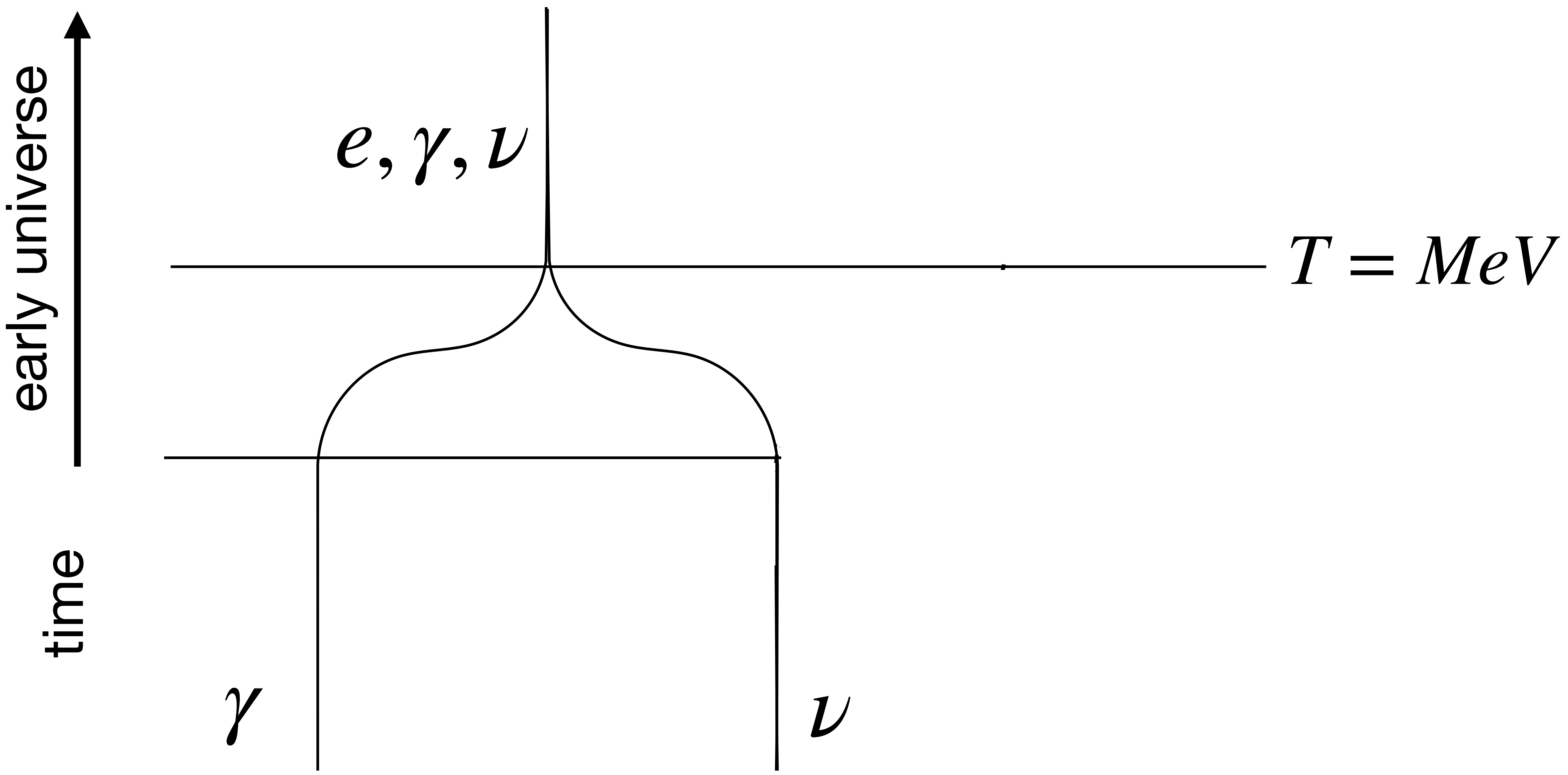


$$\Gamma \sim \frac{T^2}{M_\chi}$$

A cosmological history

- Can we have a scenario where at late times (post MeV) the system comes into equilibration with the SM
- Rich dynamics in this dark sector relevant for cosmological observables

A cosmological history



Can have rich dynamics of interactions and mass thresholds at late times

Phenomena to consider

- Late equlibration -> Generate radiation for H0
- Mass thresholds
  - Heat up the fluid -> Affects CMB
  - Turn off interactions -> Affects S8
- Dark matter scattering -> Affects S8

Thermalizing via the neutrino portal

cf Dodelson & Widrow

Neutrinos can mix with dark fermions (aka sterile neutrinos)

Neutrinos are produced in the SM, then oscillate into a superposition of Dark and SM states

If scattering is present, after t~MFP/c, the states decohere and the state either is sterile or SM

$$\nu_{SM} \xrightarrow{\text{Oscillate}} \cos\theta\nu_{SM} + \sin\theta\nu_d \xrightarrow{\text{Scatter}} \begin{pmatrix} \sin^2\theta & 0 \\ 0 & \cos^2\theta \end{pmatrix}$$

Repeat

$$\Gamma_{\nu_{SM}->\nu_d} = \frac{1}{4}\sin^2 2\theta_m \Gamma_{scatter}$$

In general, scattering is higher at high T, mixing is lower at high T

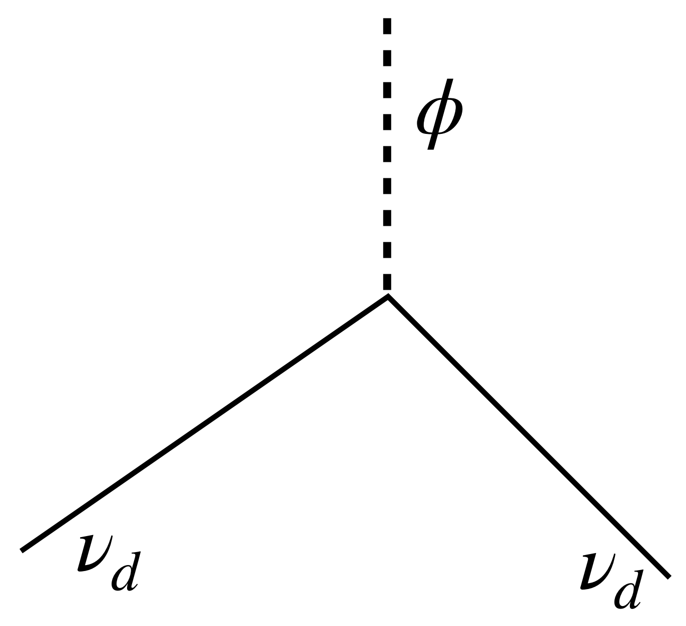
=>

mixing wins

production *increases* as temperature drops until some scale

Beyond minimal sterile neutrinos

$$\mathscr{L} \supset m_{dark}\nu_d\nu_d + m_{mix}\nu_d\nu_{SM} + \lambda\phi\nu_d\nu_d$$

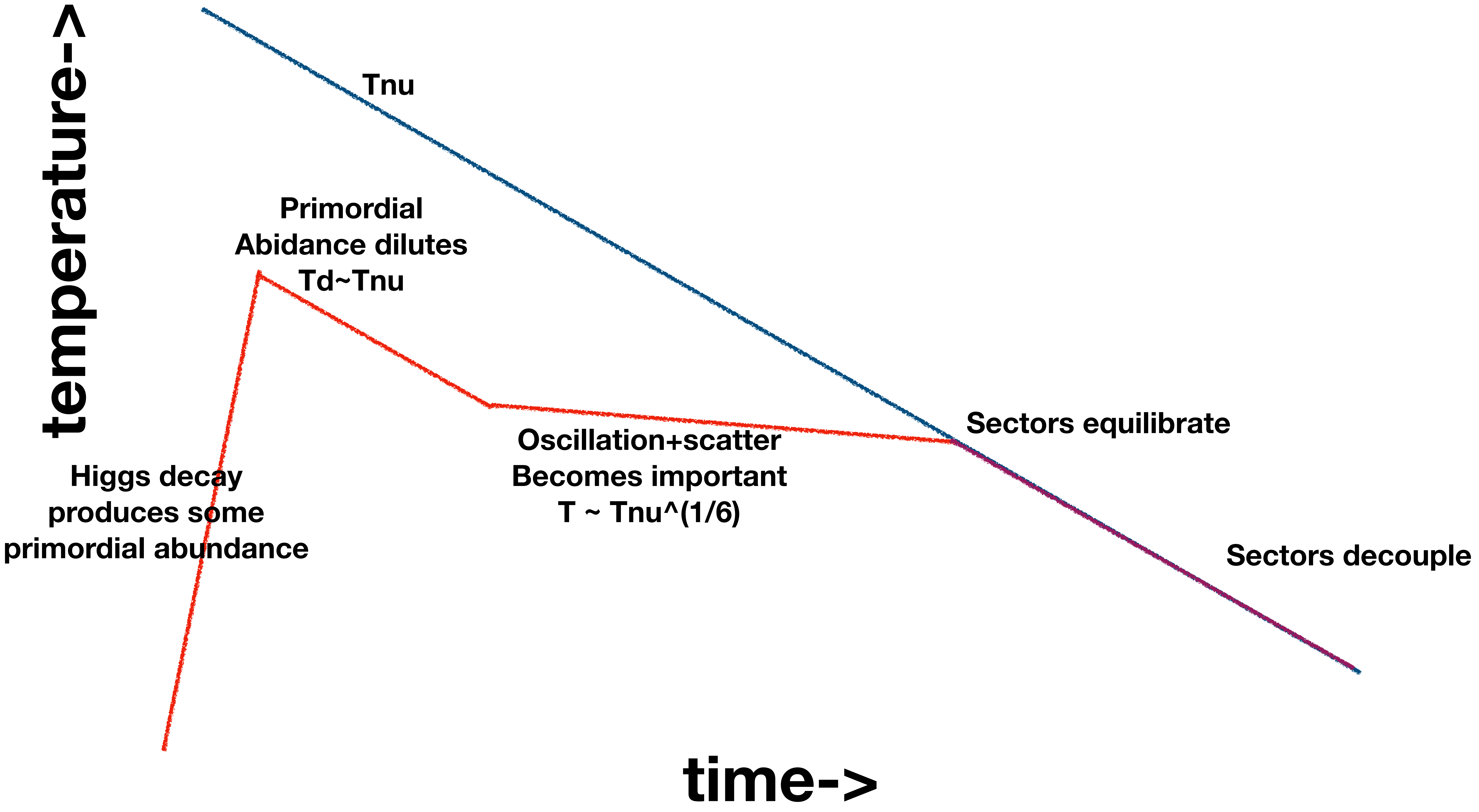


Finite (dark) temp effects

New dark effects
Can enhance scattering
(Bringmann et al)

$$\Gamma_{\nu_{SM} -> \nu_d} = \frac{1}{4} \sin^2 2\theta_m \Gamma_{scatter}$$

New dark effects
Can suppress mixing
(Dasgupta + Kopp)

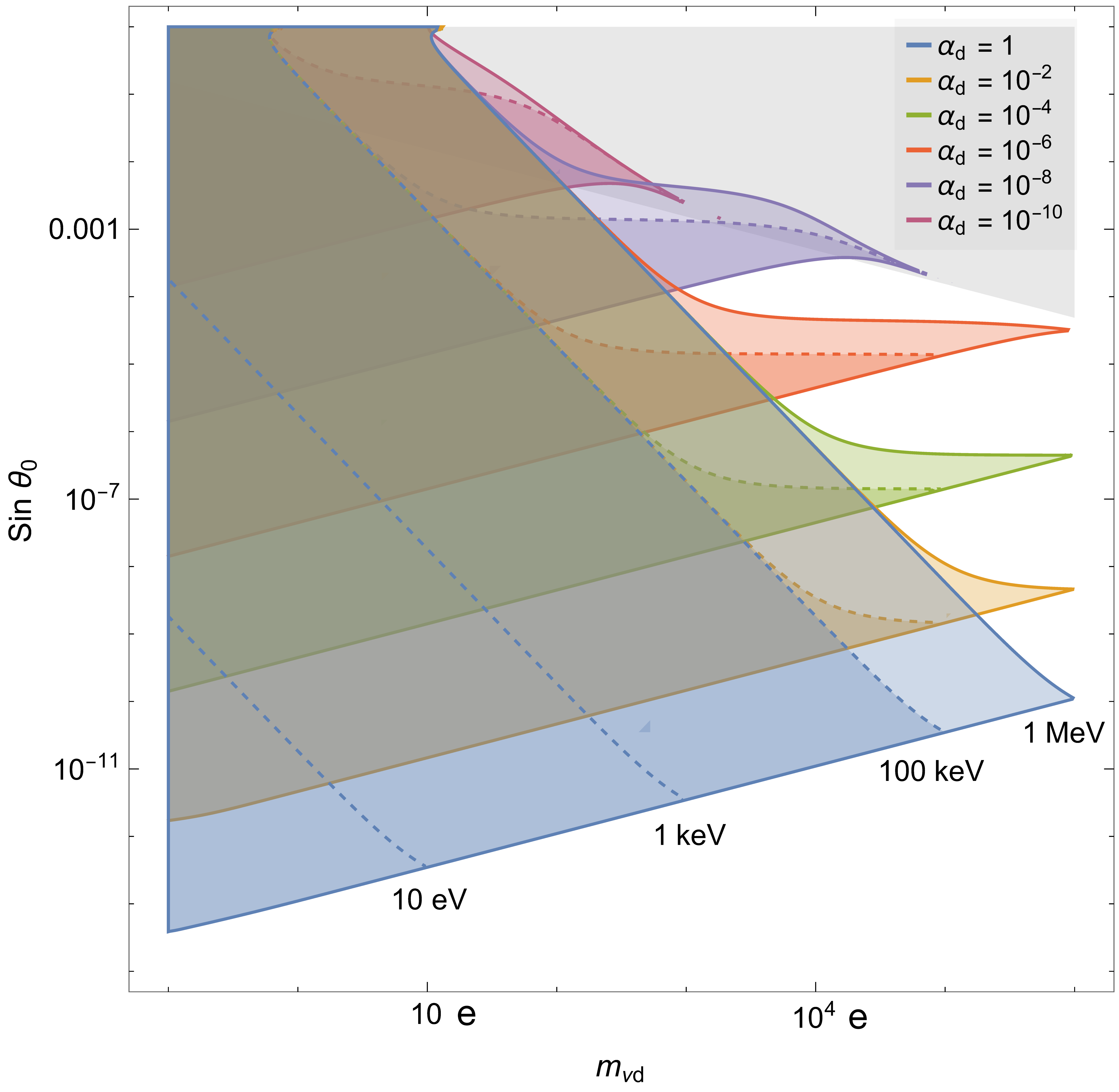

temperature->
Tnu
Primordial
Abidance dilutes
Td~Tnu
Higgs decay
produces some
primordial abundance
Oscillation+scatter
Becomes important
T ~ Tnu^(1/6)
Sectors equilibrate
Sectors decouple
time->

$$\langle\Gamma\rangle = \frac{\frac{1}{4}\sin^2 2\theta_0 (3c_\Gamma T_\nu^5 G_F^2 + \alpha_d^2 \frac{T_d^2}{T_\nu})}{\left(\cos 2\theta_0 + \alpha_d \frac{T_d^2}{m_{\nu d}^2} + 18 c_V \frac{G_F^2 T_\nu^6}{m_{\nu d}^2}\right)^2 + \sin^2 2\theta_0}$$

$$1 \simeq \frac{\langle\Gamma\rangle}{H} \simeq \frac{\theta_0^2 \alpha_d^2 T_\nu}{(1 + \alpha_d \frac{T_\nu^2}{m_{\nu d}^2})^2} \frac{M_{Pl}}{T_\nu^2} \simeq \theta_0^2 \frac{M_{Pl}}{m_{\nu d}} \frac{m_{\nu d}^5}{T_\nu^5}$$

$$T_{\text{equil}} = m_{\nu d} (\theta_0^2 M_{Pl}/m_{\nu d})^{1/5}$$

If there are dark states below an MeV they will naturally thermalize “near” their mass



A light dark state with self interactions, will naturally thermalize at late time - even with very small mixing

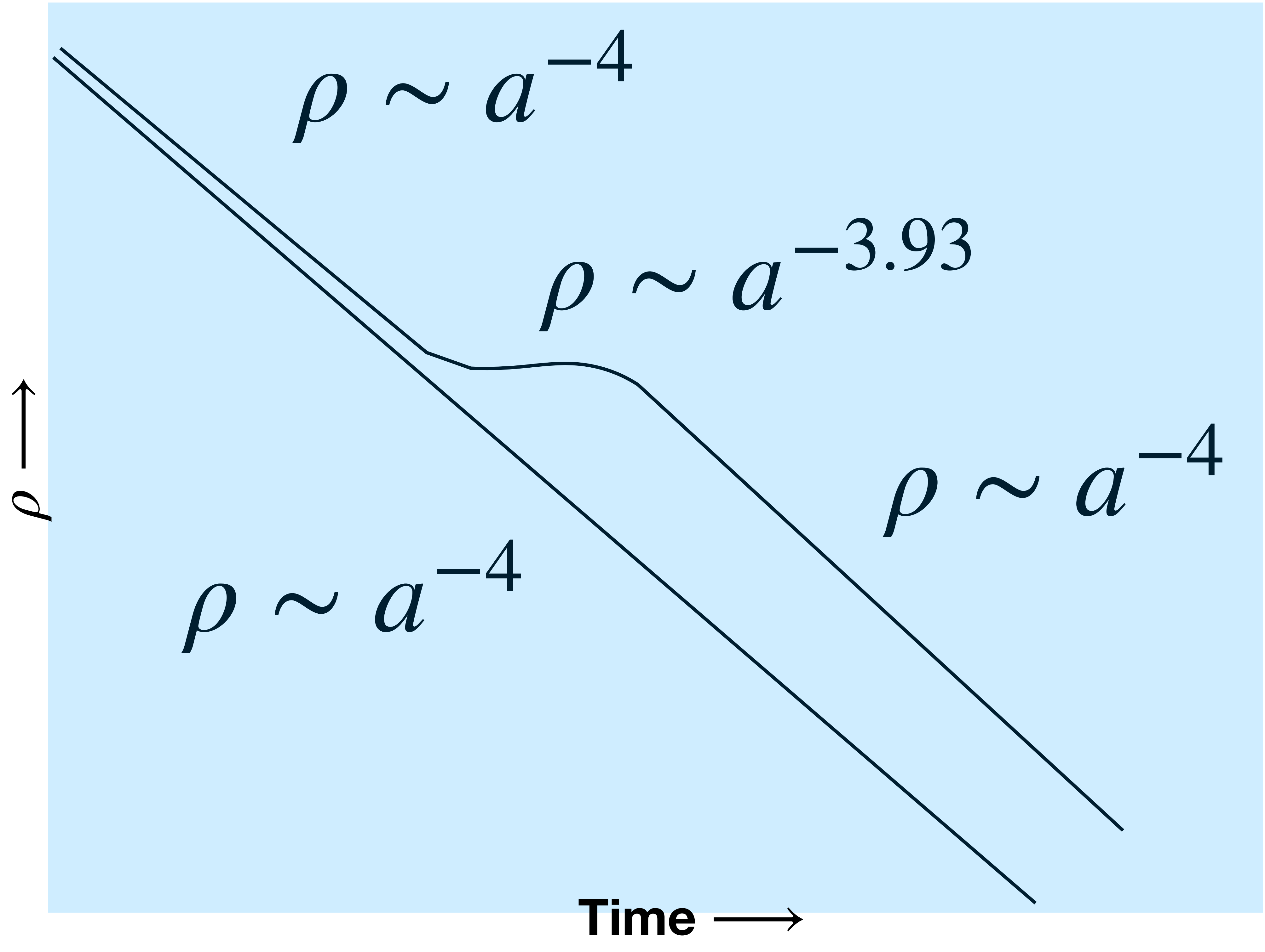
Steps in the dark sector

- When a particle becomes non-relativistic, it deposits its entropy in the remaining light particles

- This heats up the light particles, raising their temperature

- It also redshifts slightly more slowly that radiation during the transition

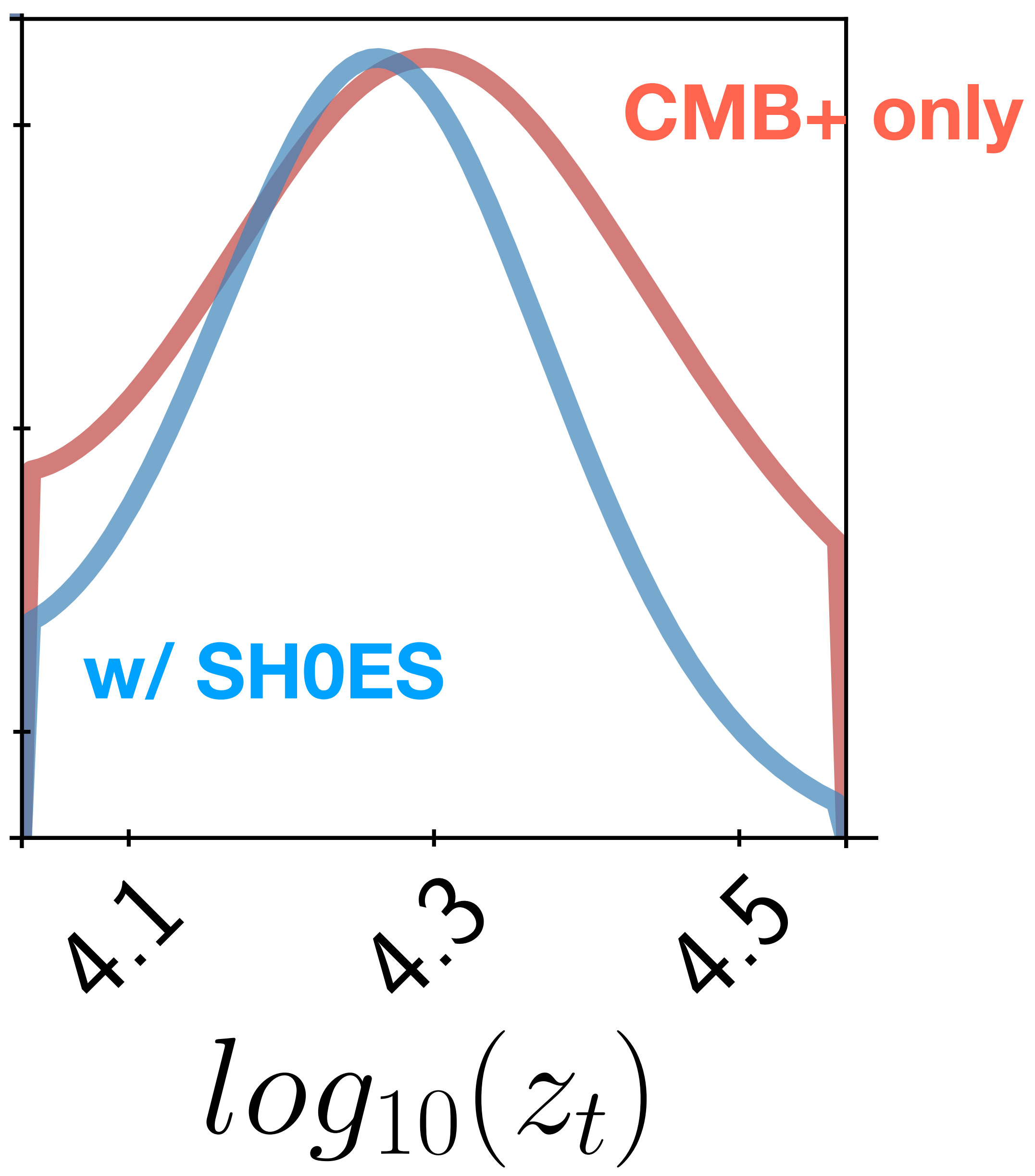
- This means N_{eff} (the amount of dark radiation) is naturally time-dependent with a mass threshold



$$\frac{\rho}{\rho_{a^{-4}}} = \left(\frac{g_{before}}{g_{after}} \right)^{1/3}$$

An ~eV step

- What if dark radiation has a "step" (changes Neff) during the CMB era?



Model	$\Delta\chi^2$	$N_{\text{eff,IR}}$	H_0 (km/s/Mpc)
ΛCDM	0.0	3.04	68.2 [67.5, 68.9]
$\Lambda\text{CDM} + N_{\text{eff}}$	-5.7	3.37 [3.20, 3.63]	70.0 [68.9, 71.6]
SIDR	-10.6	3.51 [3.31, 3.77]	71.0 [69.6, 72.6]
WZDR	-15.1	3.63 [3.37, 3.92]	71.4 [69.7, 73.0]

Relaxing the BBN->Helium assumption improves fit for Neff,

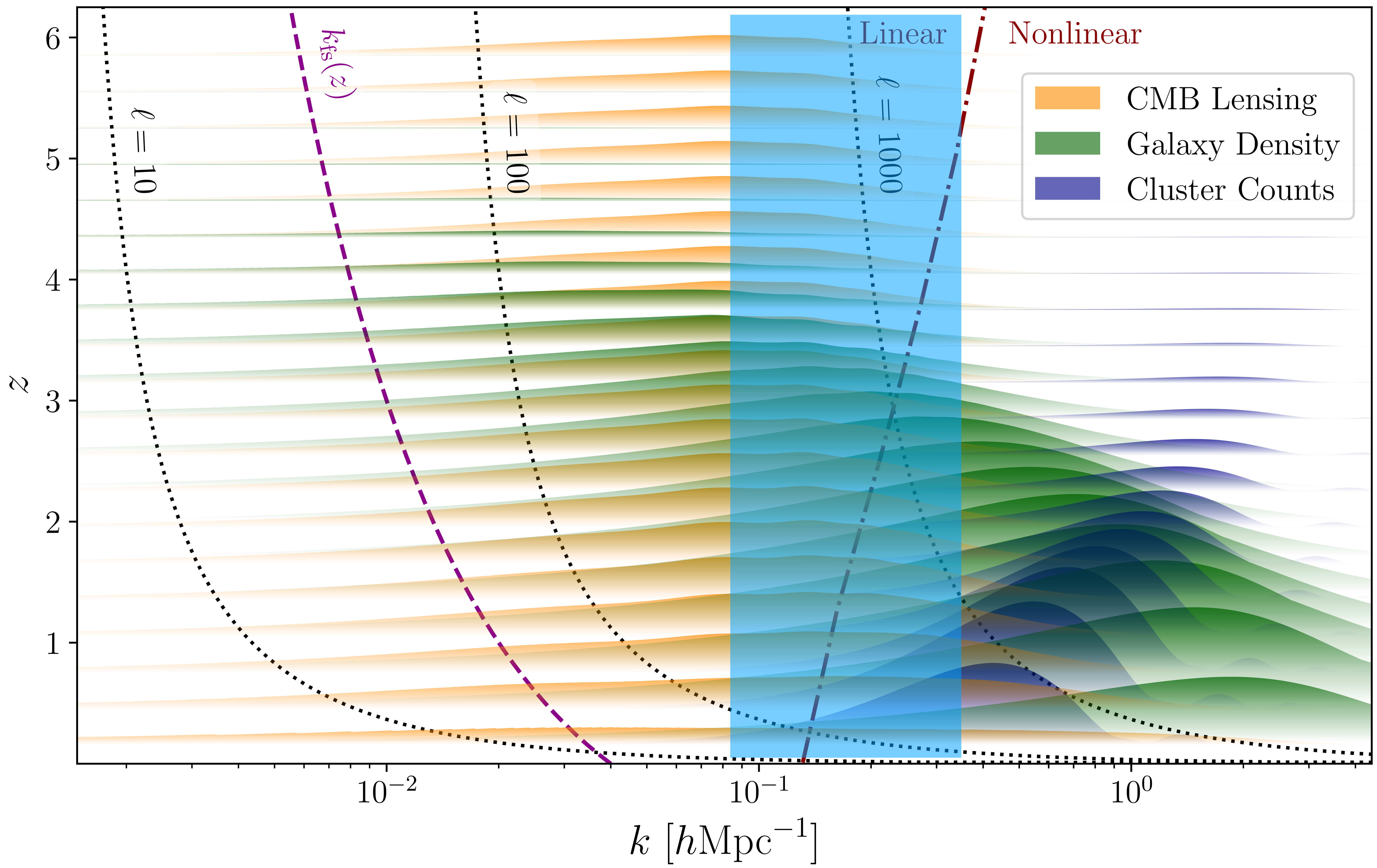
interactions improve fit more,

step improves fit more

Does **not** "solve" the Hubble tension (see later)

What about S8?

Apples to apples



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Gerbino et al 2022

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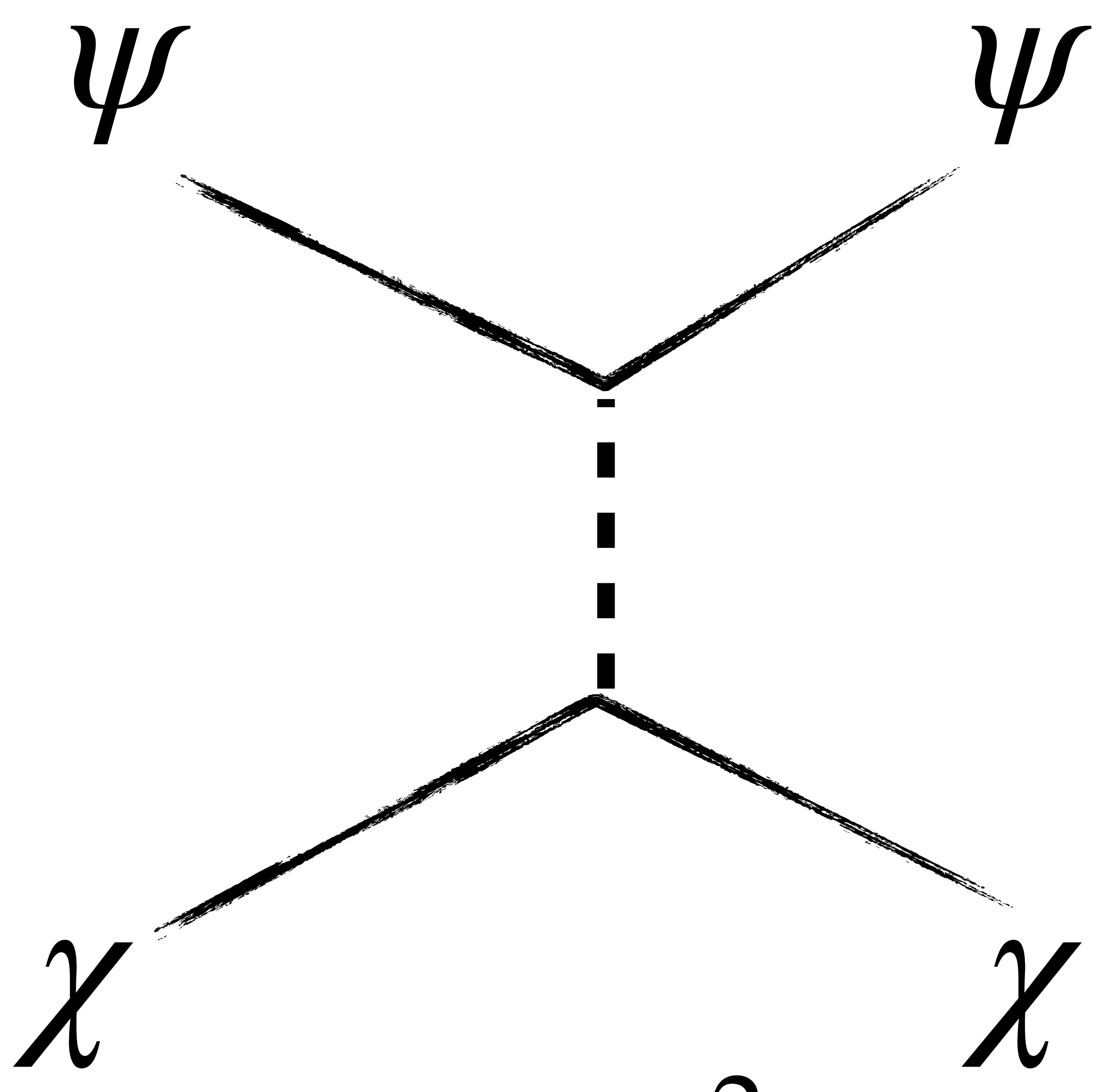


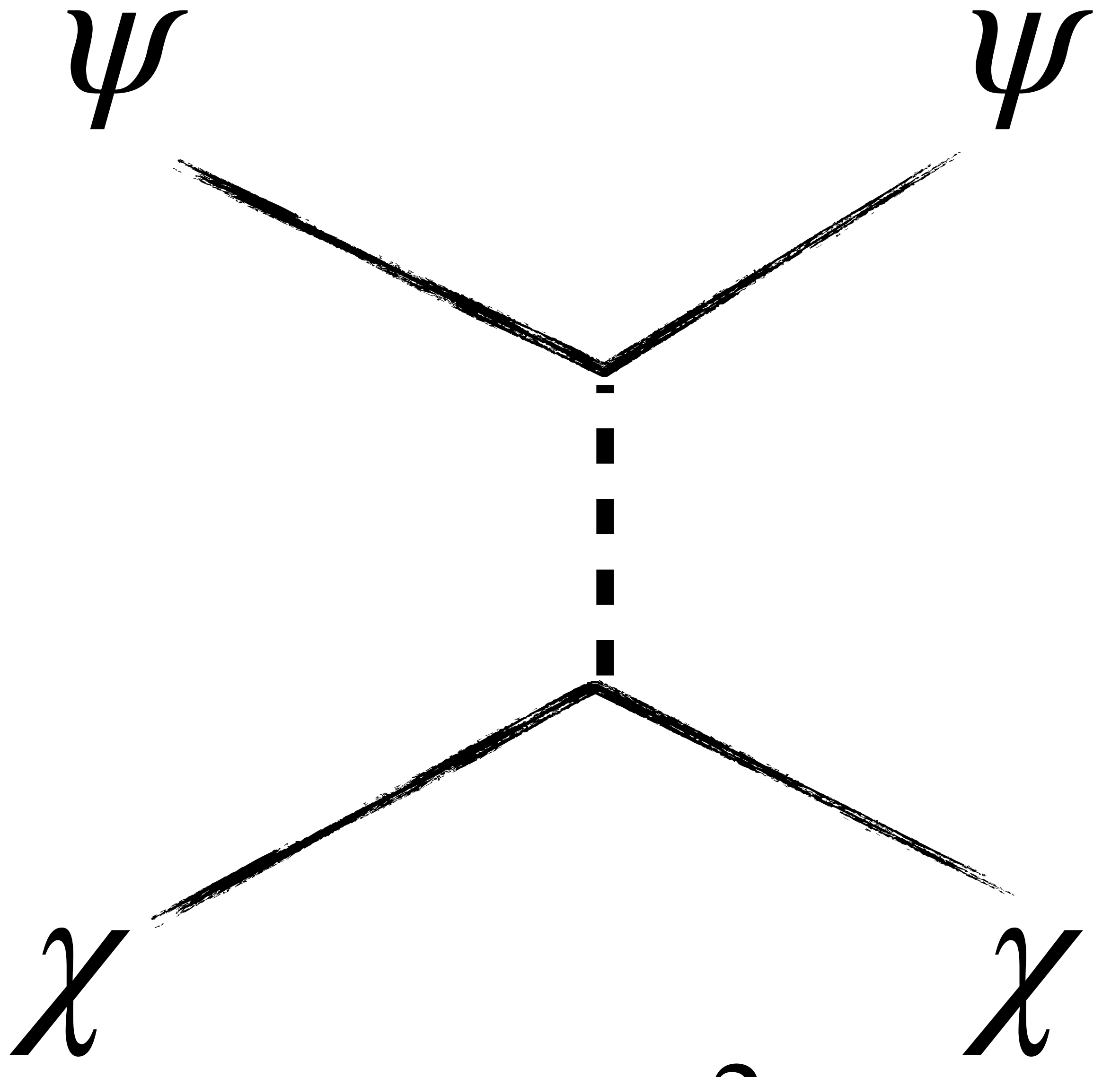
$$\Gamma \sim \frac{T^2}{M_\chi}$$

A step in DM-DR interactions

Aloni et al 2022

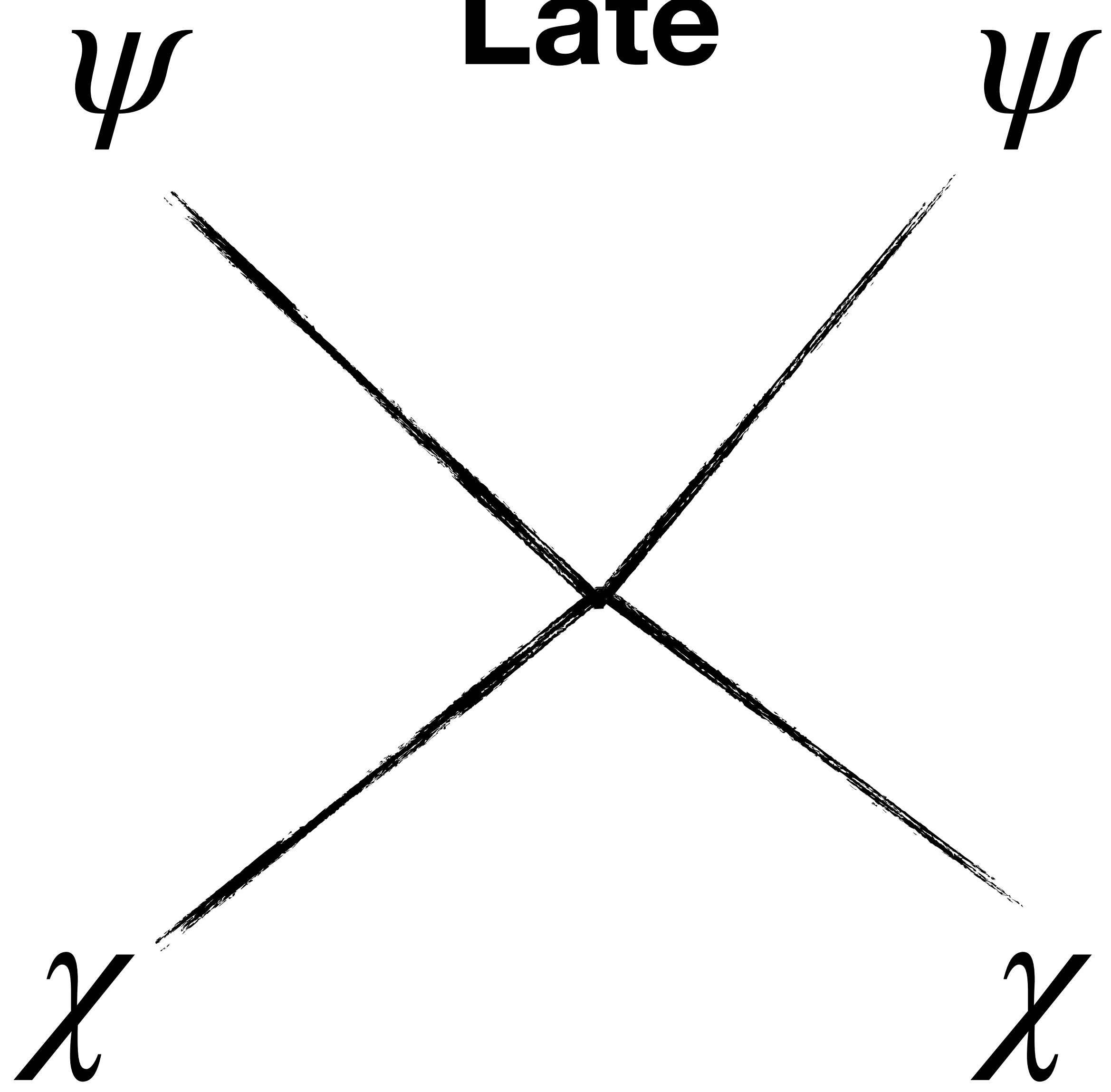
- The same mass threshold in the dark sector can also help “turn off” DM-DR interactions

early



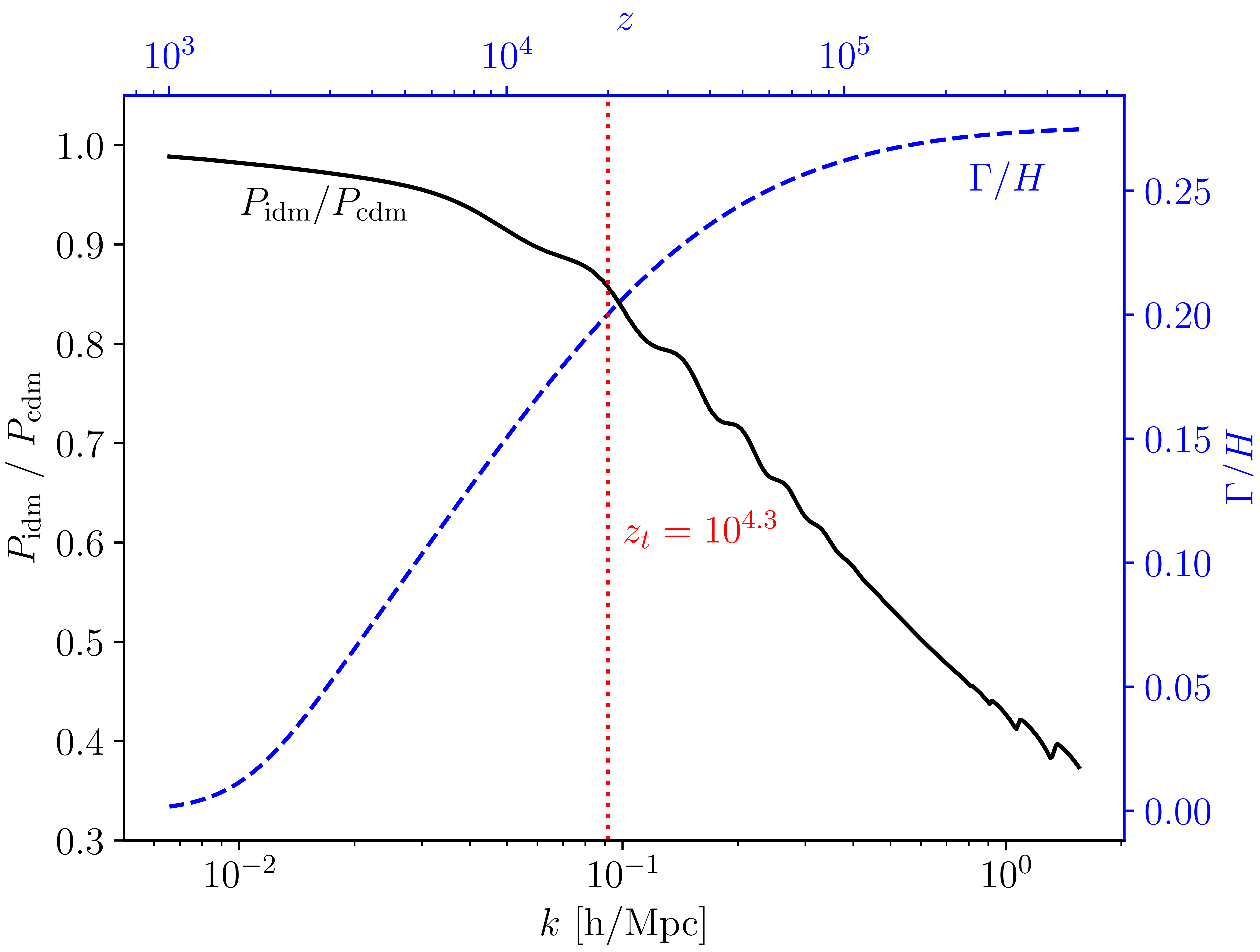
$$\Gamma \sim \frac{T^2}{M_\chi}$$

Late



$$\Gamma \sim \frac{T^2}{M_\chi} \times \left(\frac{T}{M_\chi}\right)^2$$

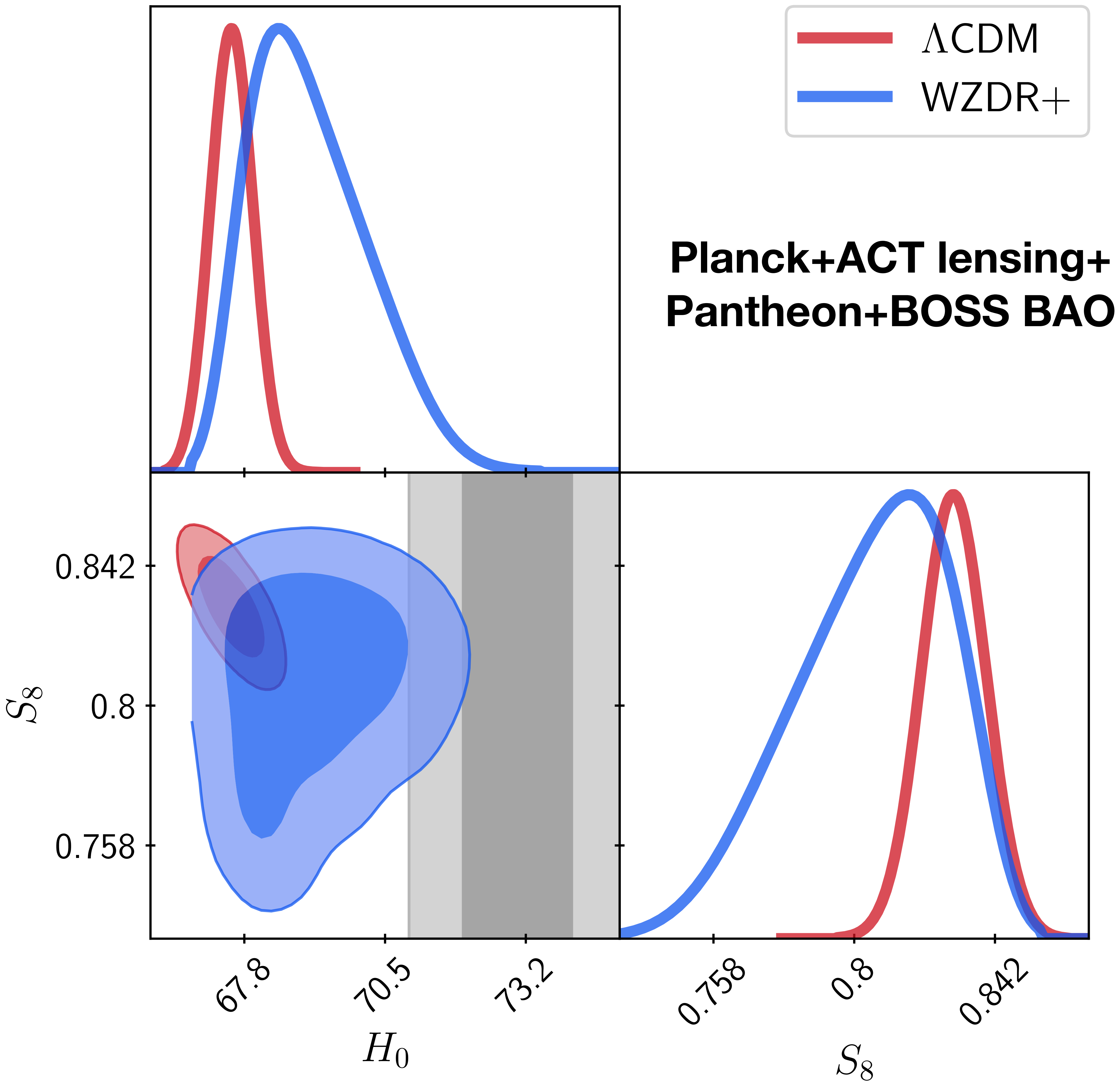
Scale dependent structure suppression



Study this

- Baseline dataset: Planck CMB, Pantheon, BOSS BAO, ACT DR 6 CMB lensing (**D**)
- Additional datasets: DES power spectrum (**DES**)
- ACT DR4 + SPT 3G (**ACT+SPT**)

DM-DR scattering + lensing

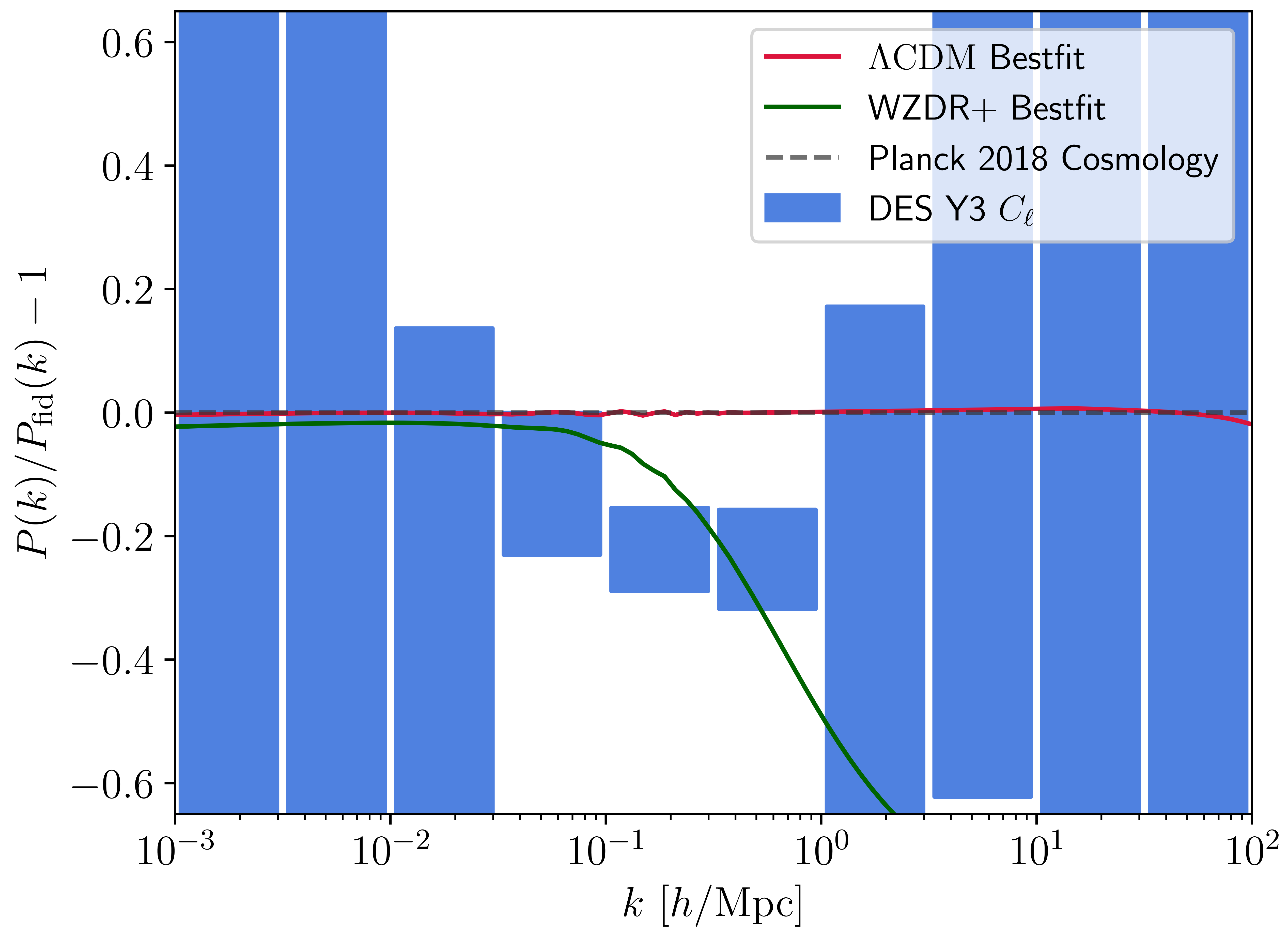


Zhou, NW 2409.06771

Planck+ACT lensing+ Pantheon+BOSS BAO

In a model with DM-DR scattering, there is a preference for a lower value of S8 even with ACT lensing

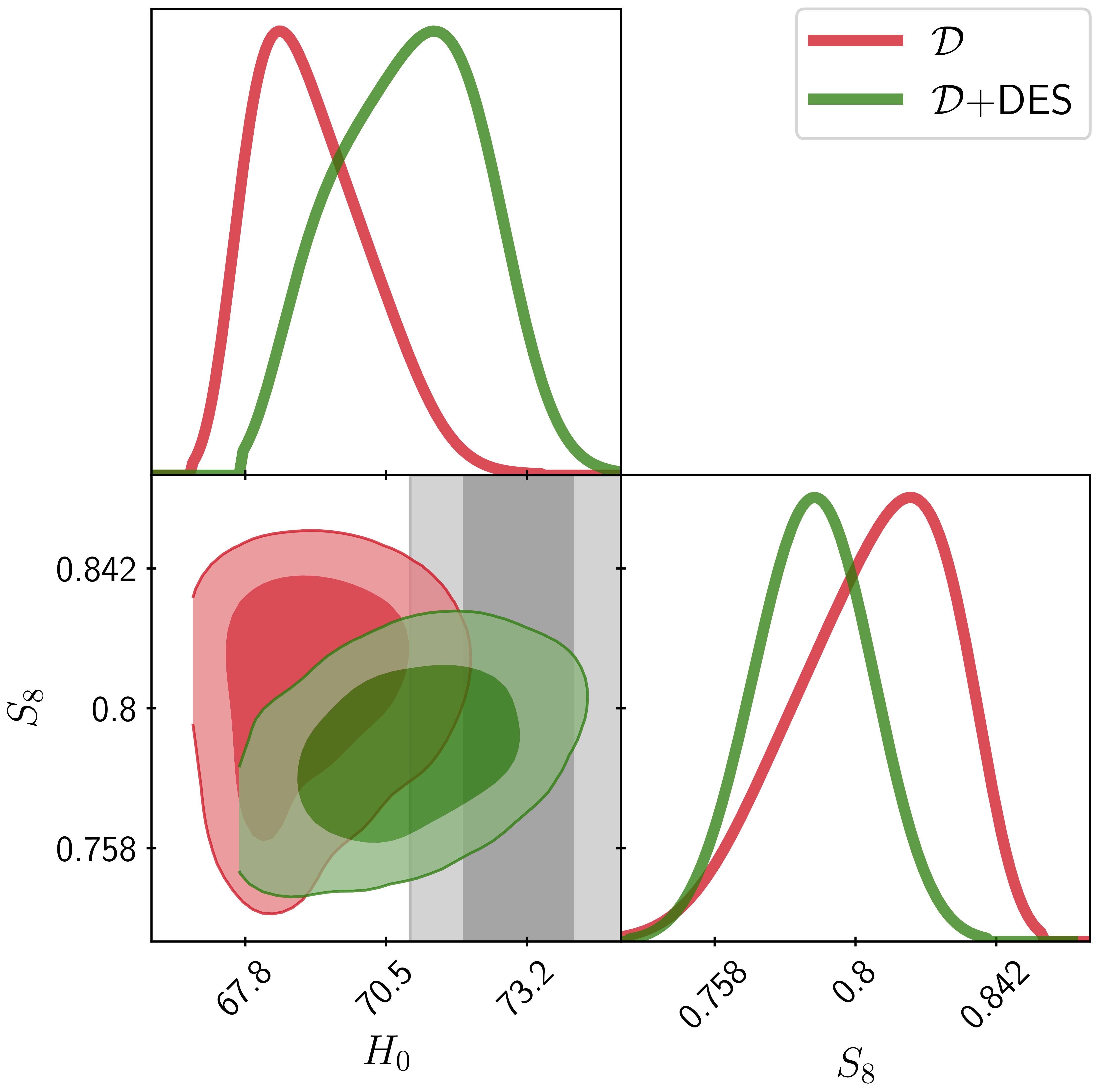
DES



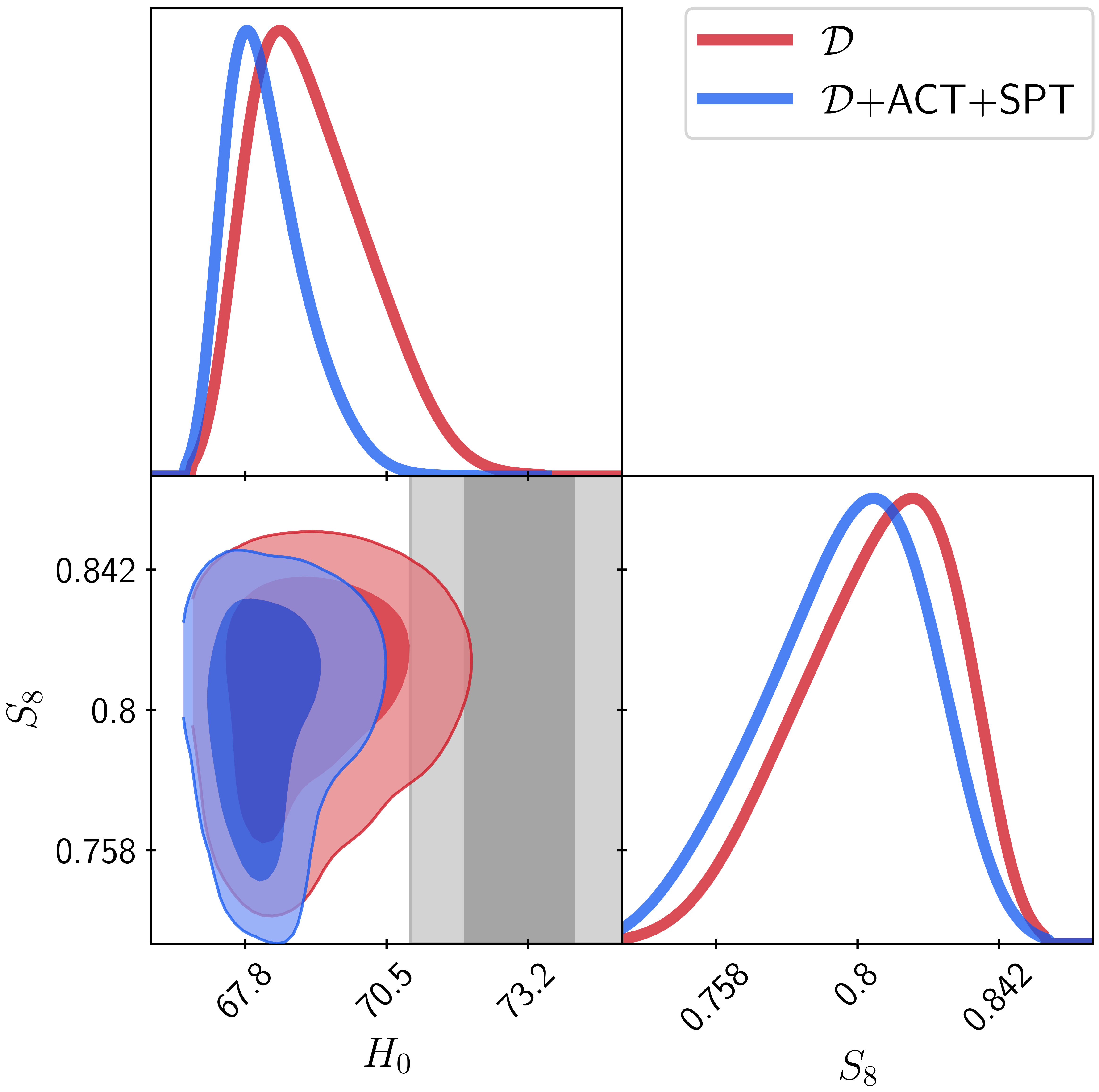
“Best fit” naturally gives power suppression w/o DES

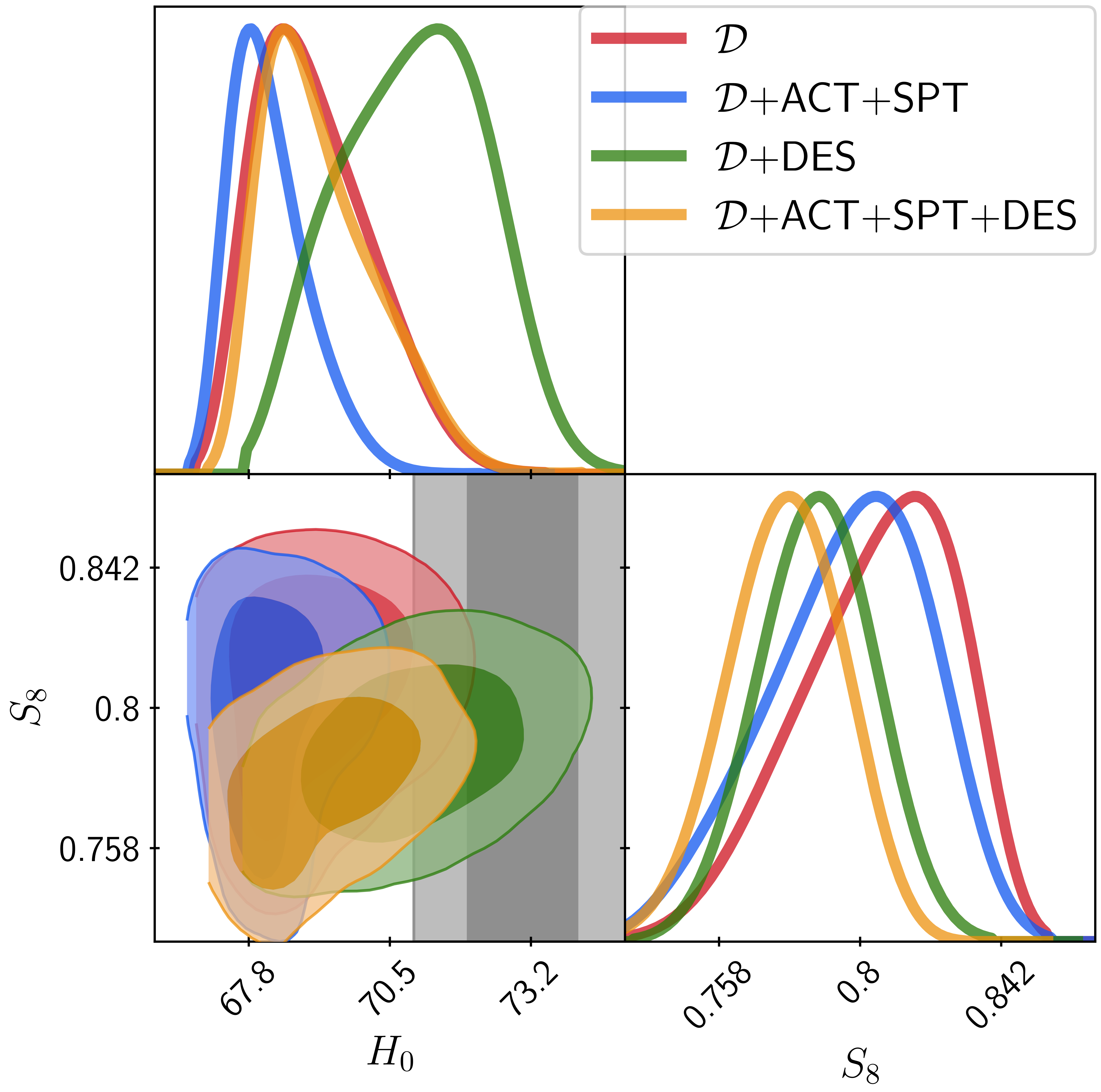
So what happens if we include more data

- Dataset:
    - Planck
    - BOSS BAO
    - Pantheon
    - ACT DR6 Lensing
- DES



- Dataset:
    - Planck
    - BOSS BAO
    - Pantheon
    - ACT DR6 Lensing
- ACT DR4 + SPT 3G





Different data pull in different directions

Is Late Equlibration of Dark Radiation the answer to the Hubble and S8 tensions?!!??!?

- It doesn’t matter!
- Well, it does matter, but it’s not really the point
- The point is there’s a tremendous amount of freedom of what can happen in the eV-MeV era
- And this will be constrained by future data
- And being excited about that is what I learned from Lawrence and Hitoshi


Thank you (Lawrence and Hitoshi!) very much!