$N_{\rm eff}$ and Σm_ν from cosmology:

the expected and the surprising

Lloyd Knox (UC Davis)

Neutrinos 2026

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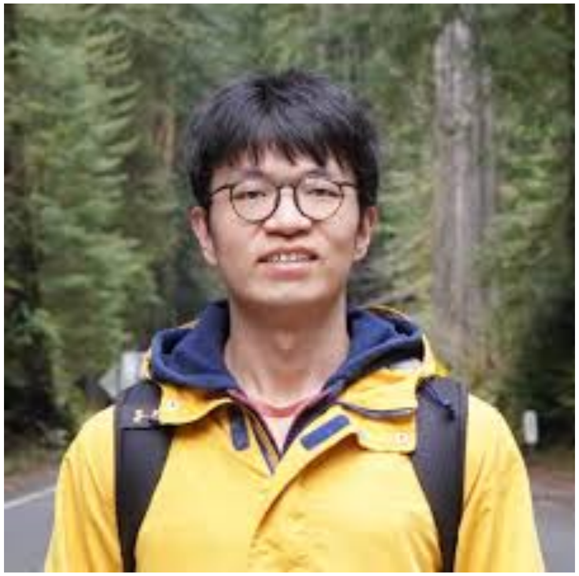


Fei Ge (Caltech)

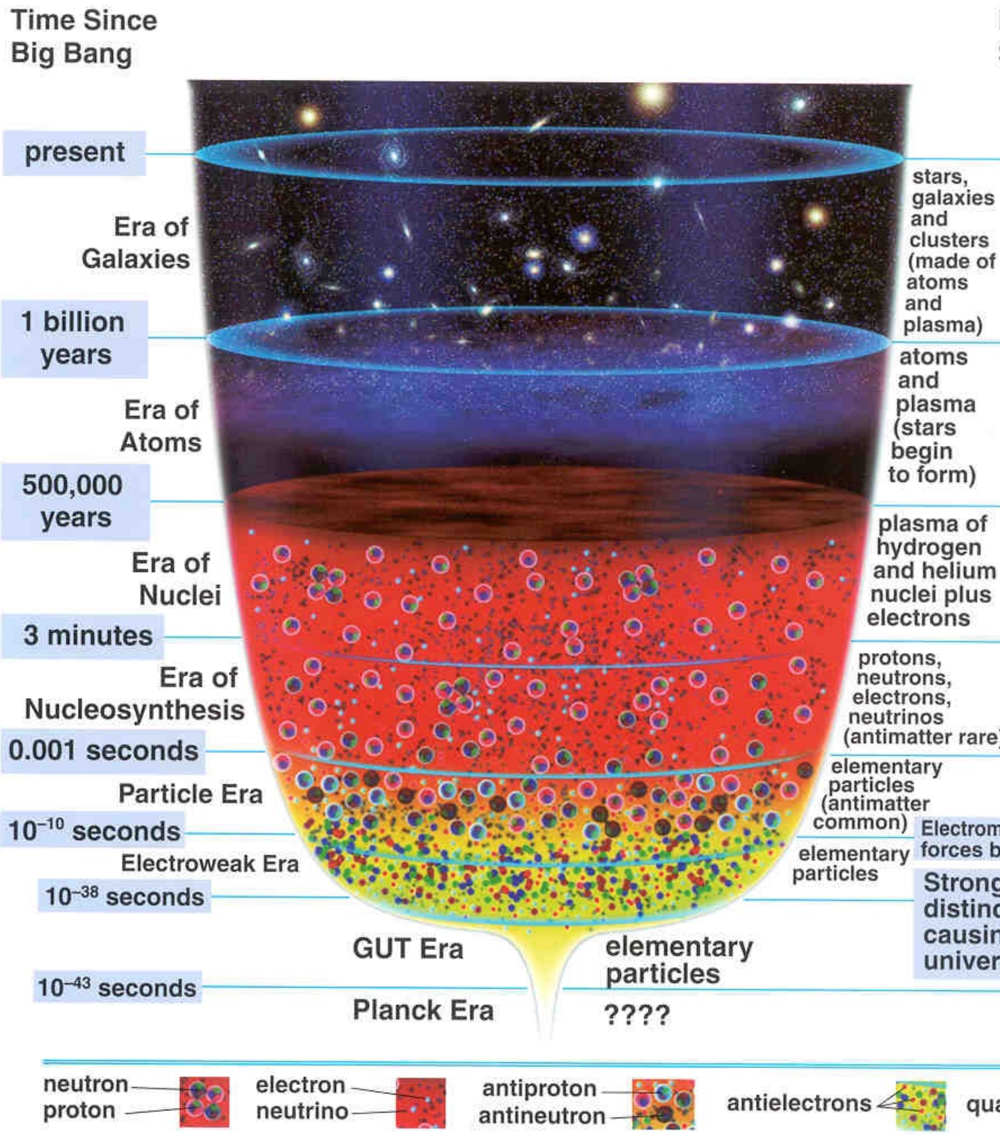
SPT Collaboration

Cosmological Neutrinos

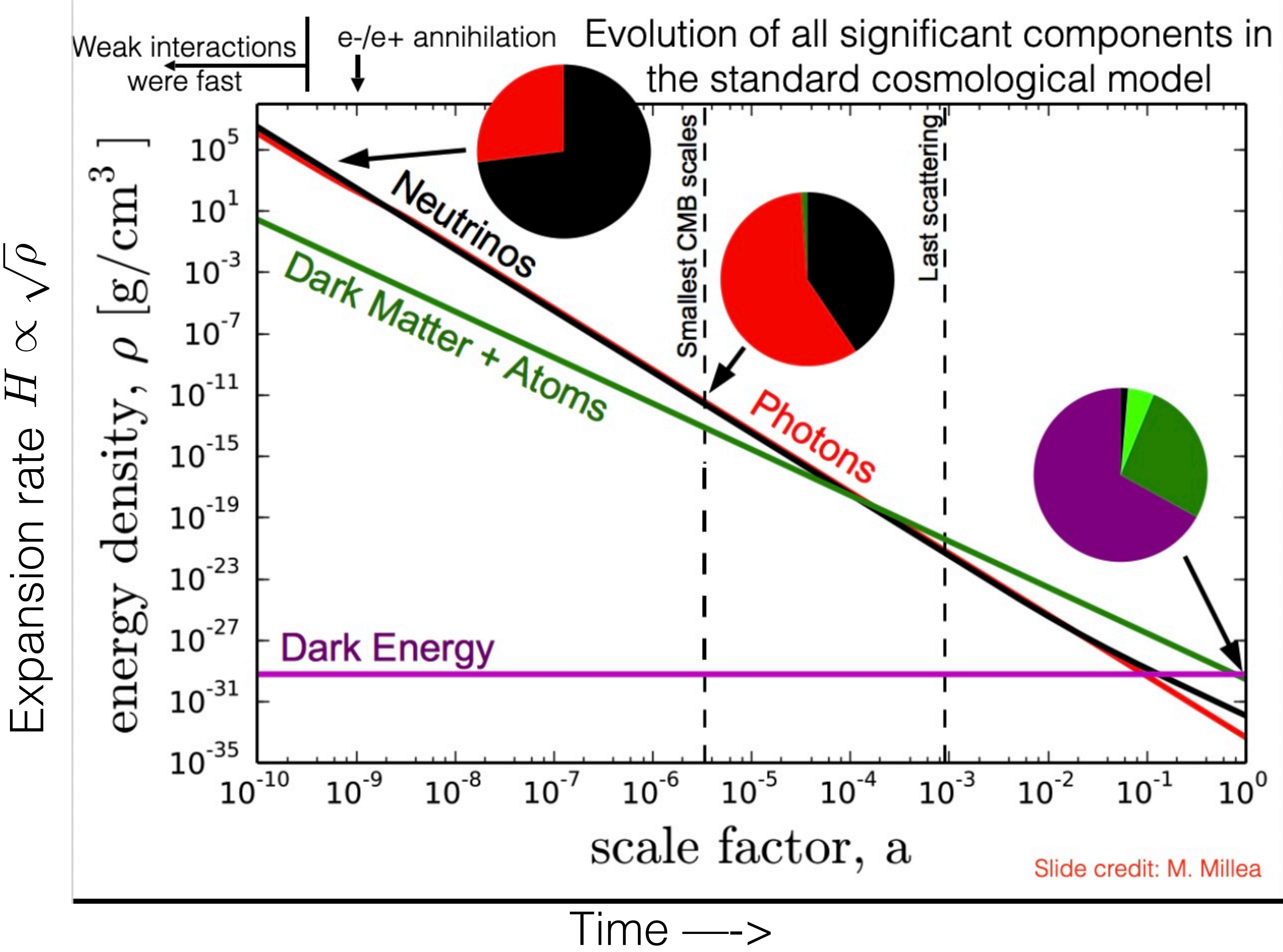
- The Big Bang is a prodigious neutrino factory: thermal production of all flavors and both neutrino and anti-neutrino.

- Neutrinos contribute significantly to the mean density at early times, and thus to the expansion rate (since it is proportional to the square root of the density).

- Almost all observable consequences, and therefore cosmological constraints, come from these contributions to the expansion rate.

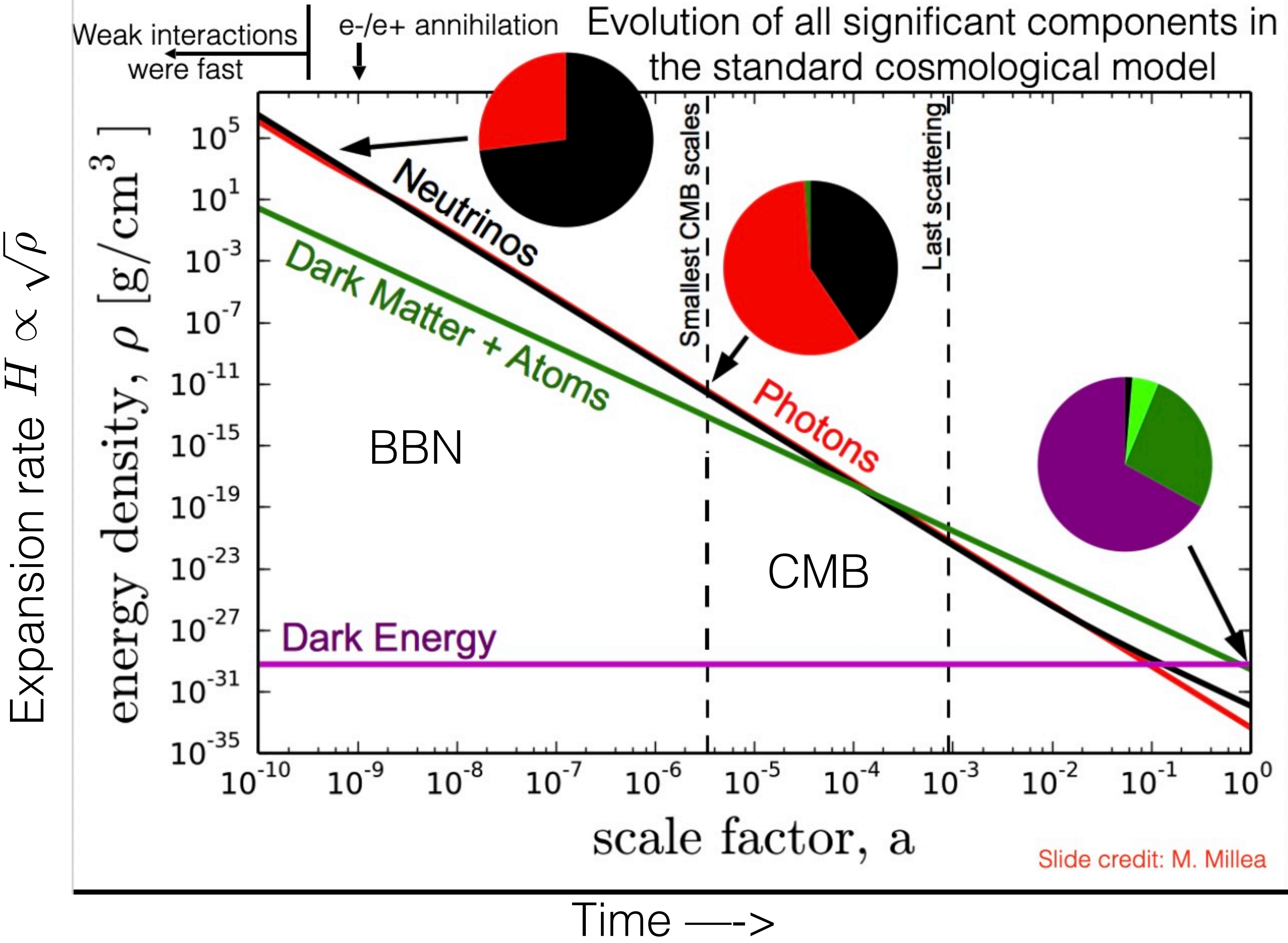


Credit: The Cosmic Perspective



Slide credit: M. Millea

Evolution of all significant components in the standard cosmological model



Slide credit: M. Millea

N_{eff} in a nutshell (the expected)

- Definition: N_{eff} is a measure of the energy density in dark and light particles, in units of the contribution from a single fully-thermalized neutrino species.

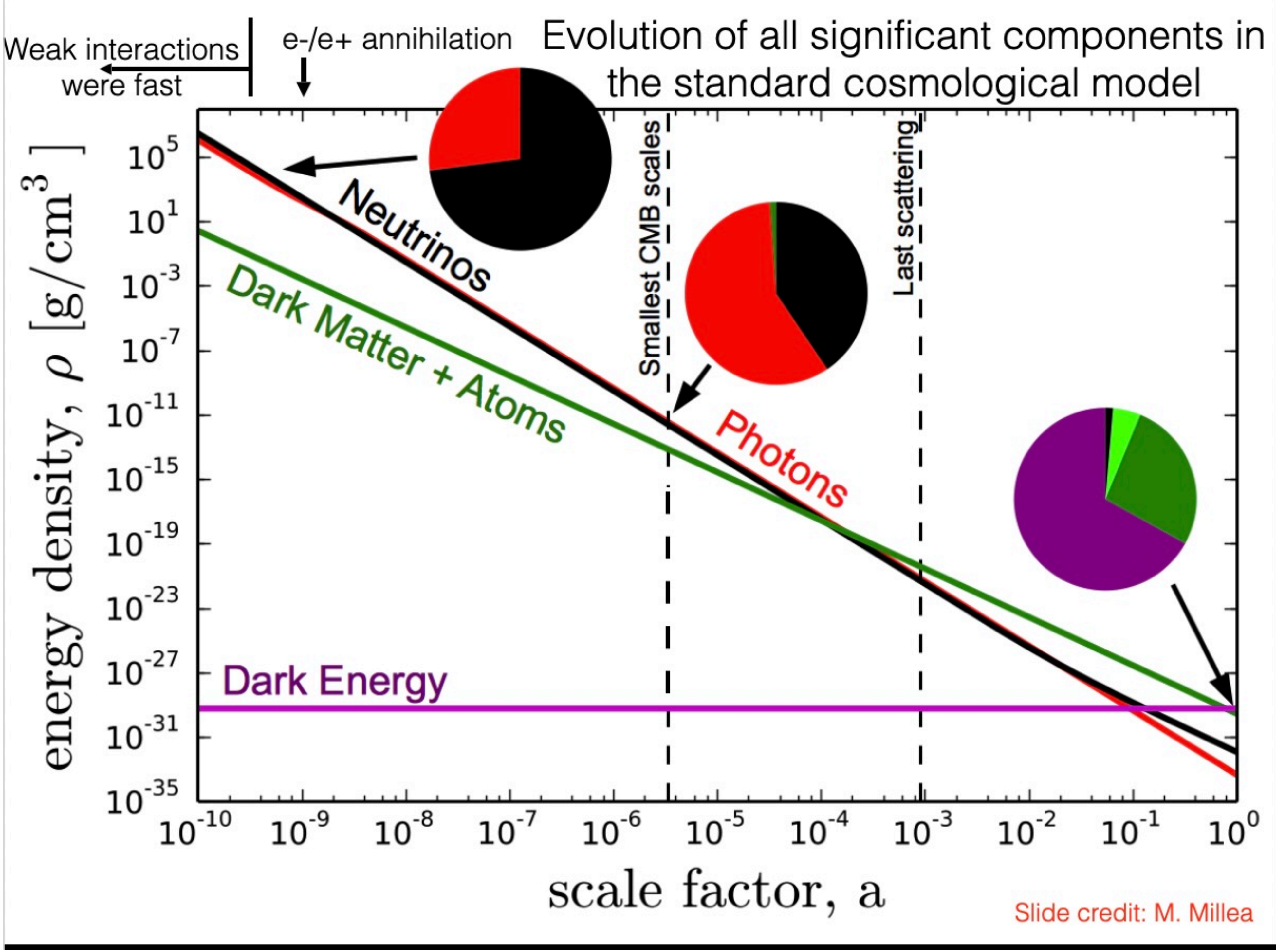
- Both BBN and CMB signals are sensitive to the neutrino contribution to the expansion rate when this is a dominant contribution. It's not a subtle effect.

- We get light element abundances and CMB signals consistent with the expansion rate expected for 3 neutrino species (e.g., Camphuis + SPT 2025).

- We can even see a subtle effect due to neutrinos free streaming, long before photons can (actual faster-than-light neutrinos!). It's also consistent with 3 neutrino species (Follin, LK et al. 2015, Baumann et al. 2016, Montefalcone et al. 2025).

- By the way: the transfer of entropy from electrons and positrons to photons, after neutrino decoupling, leads to a big reduction in neutrino energy density relative to photon energy density. If it were absent, we would expect Neff = 11!

Expansion rate $H \propto \sqrt{\rho}$

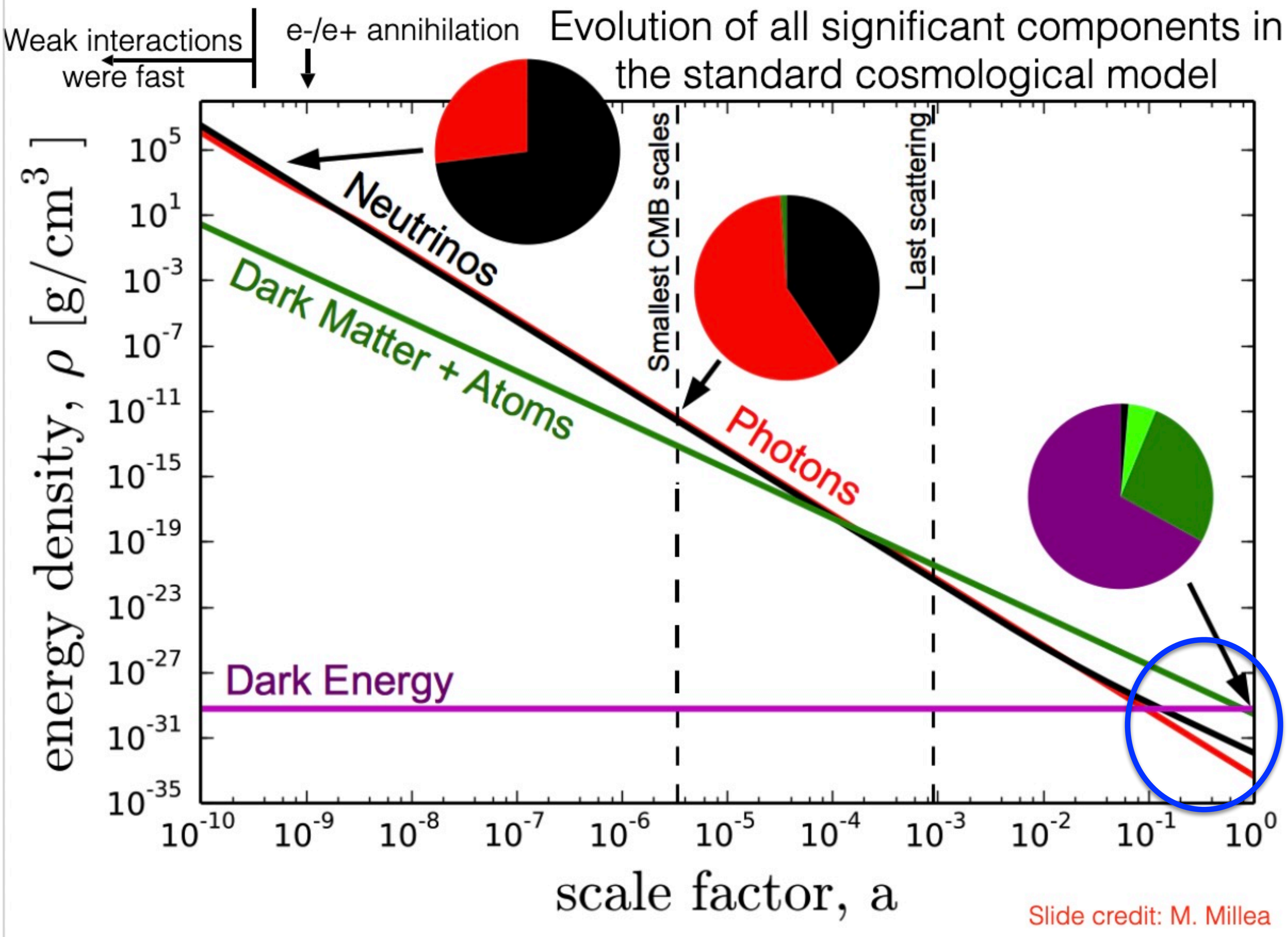


Evolution of all significant components in the standard cosmological model

Slide credit: M. Millea

Time —->

Expansion rate $H \propto \sqrt{\rho}$



Evolution of all significant components in the standard cosmological model

Slide credit: M. Millea

Time —->

Neutrino mass in a nutshell (the surprising)

- LCDM (by my definition) includes a sum of neutrino masses of 0.058 eV — the minimum expected given NO and neutrino oscillation observations.

- Increasing the sum of neutrino masses beyond that exacerbates three ‘anomalies’:

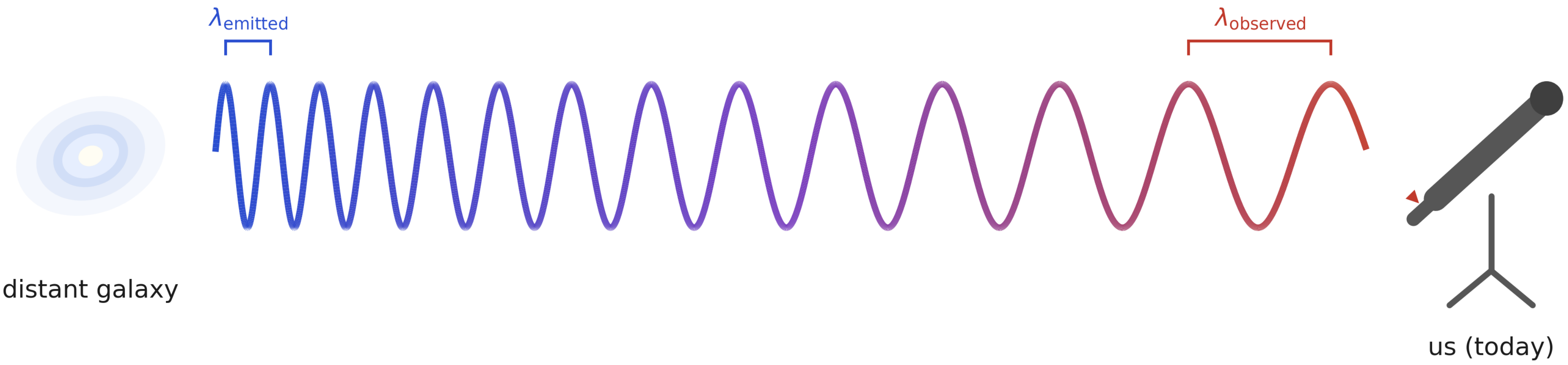
  - The Hubble anomaly: It decreases the prediction of H_0 from CMB data, slightly worsening the discrepancy with more direct measurements of H_0 — a highly significant discrepancy (Casertano et al. 2026; see also Freedman et al. 2025).

  - The matter density deficit anomaly: Baryon + CDM density today ($\omega_{\rm cb} \equiv \omega_{\rm c} + \omega_{\rm b}$) inferred from CMB data is ***less*** than the total non-relativistic matter density today ($\omega_{\rm m}$), inferred from BAO data.. (2 to 3 sigma)

  - The CMB lensing excess anomaly: LCDM predictions for CMB lensing, given CMB and BAO data, are for ***less*** lensing than observed — again, the opposite of what we’d expect from neutrinos. (2 to 3 sigma)

- We don’t know why.

Probing the expansion rate history H(z)



Space expands while the light is in transit, stretching its wavelength — cosmological redshift

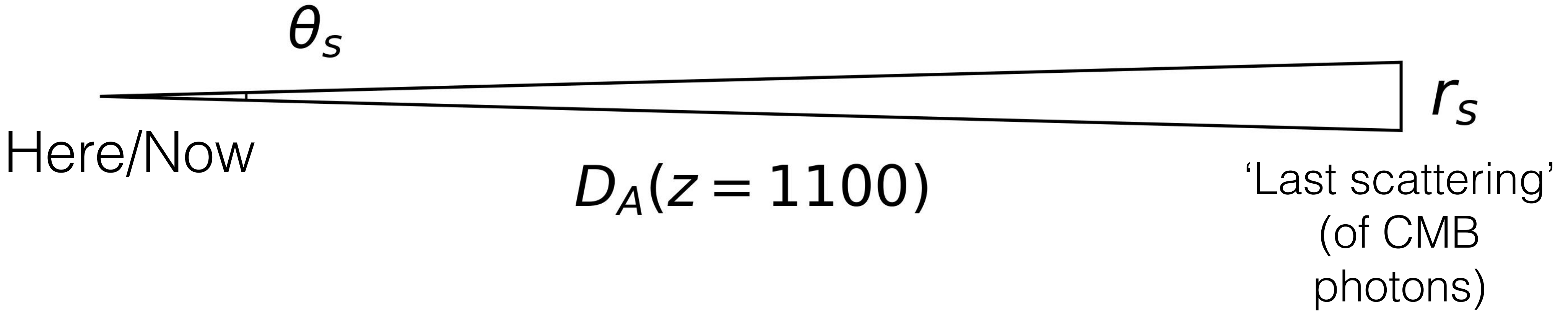
$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{a_{\text{today}}}{a_{\text{emitted}}}$$

Redshift, z, tells us how much Universe expanded since light left the object.

Distance is sensitive to history of expansion rate:

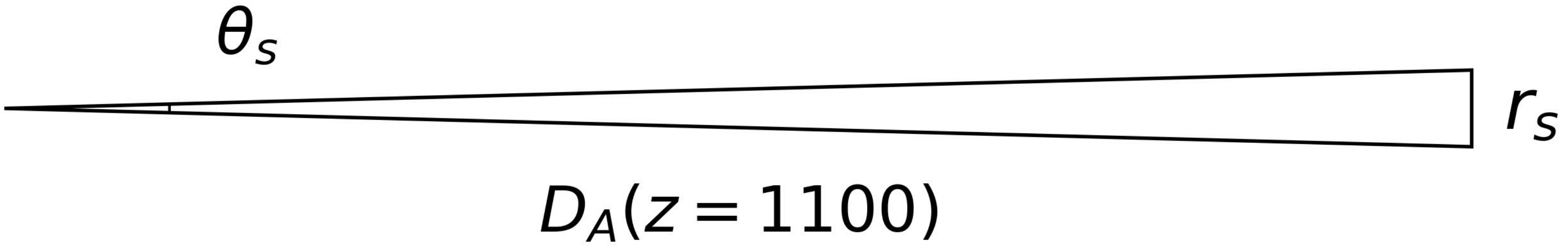
$$D_A(z) = \int_{\text{today}}^{\text{emitted}} dz'/H(z')$$

A standard ruler for measuring distances: the sound horizon



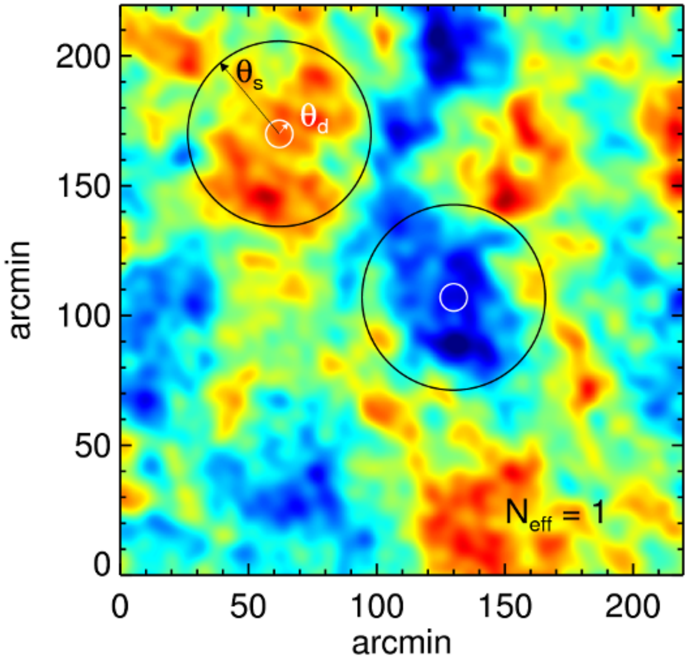
1) In the LCDM model we can use CMB data to calibrate this ruler.

A standard ruler for measuring distances: the sound horizon



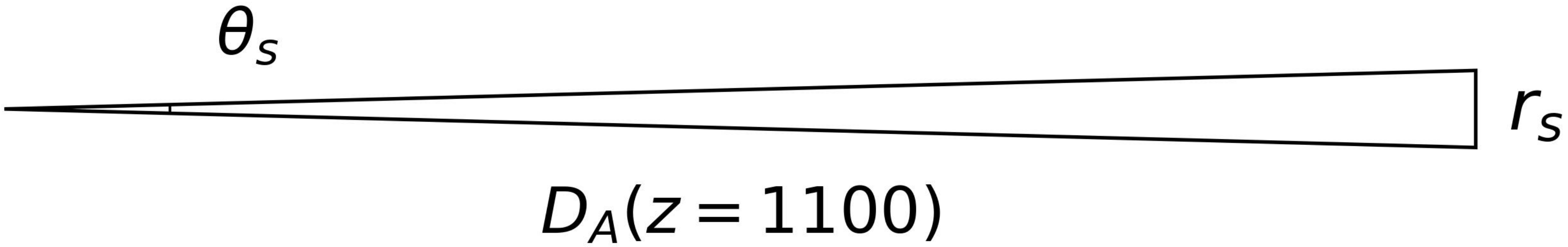
1) In the LCDM model we can use CMB data to calibrate this ruler.

2) We can measure the subtended angle.



Simulated CMB map

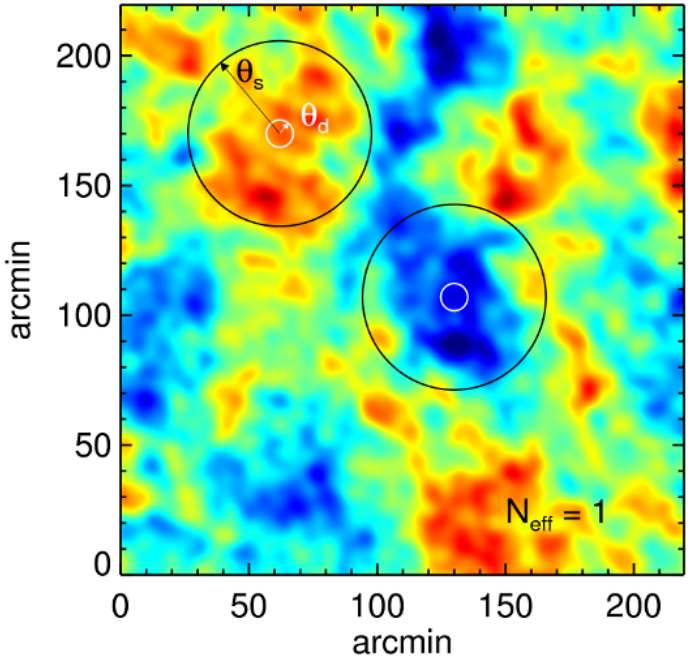
A standard ruler for measuring distances: the sound horizon



1) In the LCDM model we can use CMB data to calibrate this ruler.

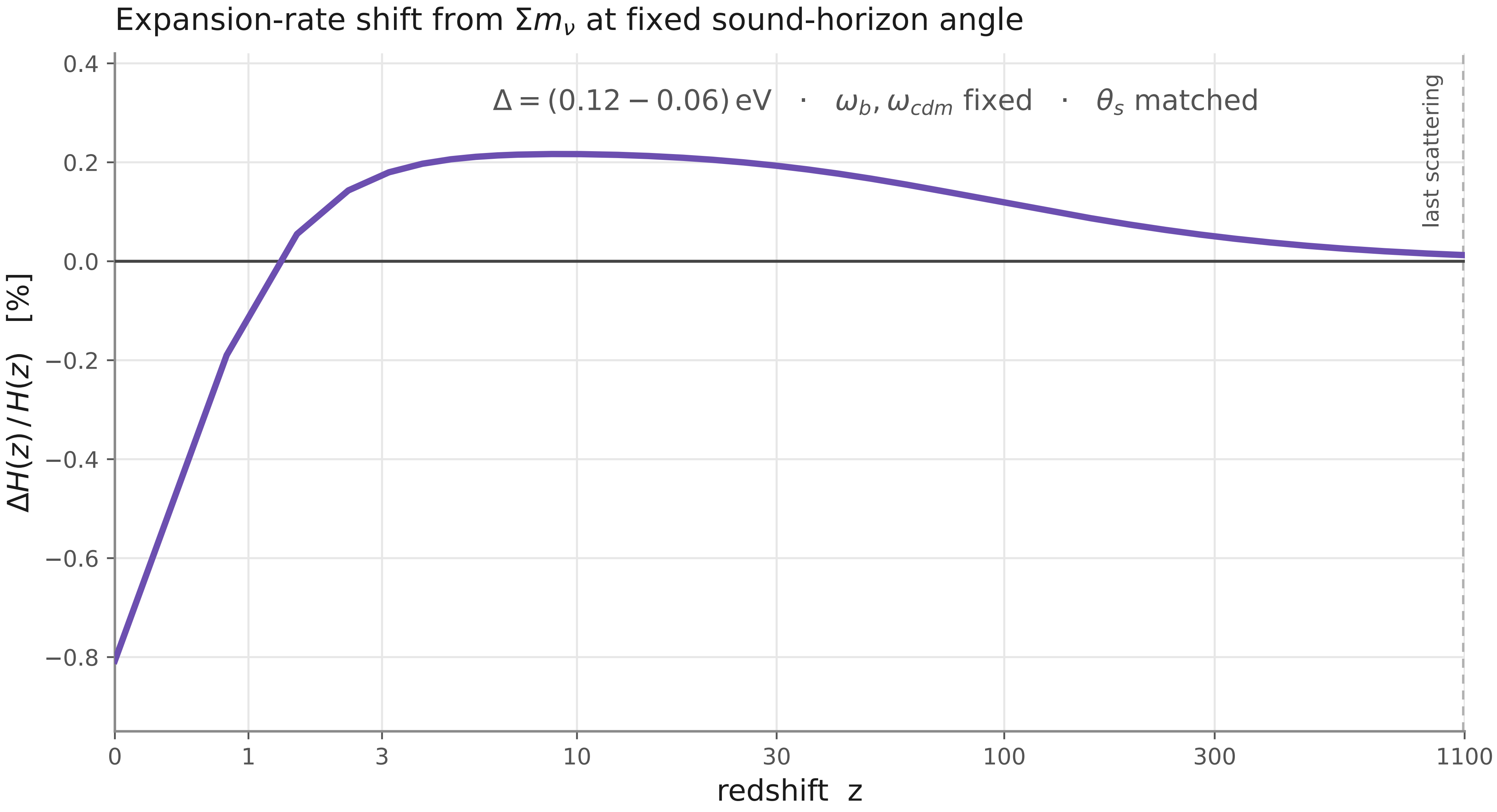
2) We can measure the subtended angle.

3) and thereby determine the distance $D_A(z=1100)$.

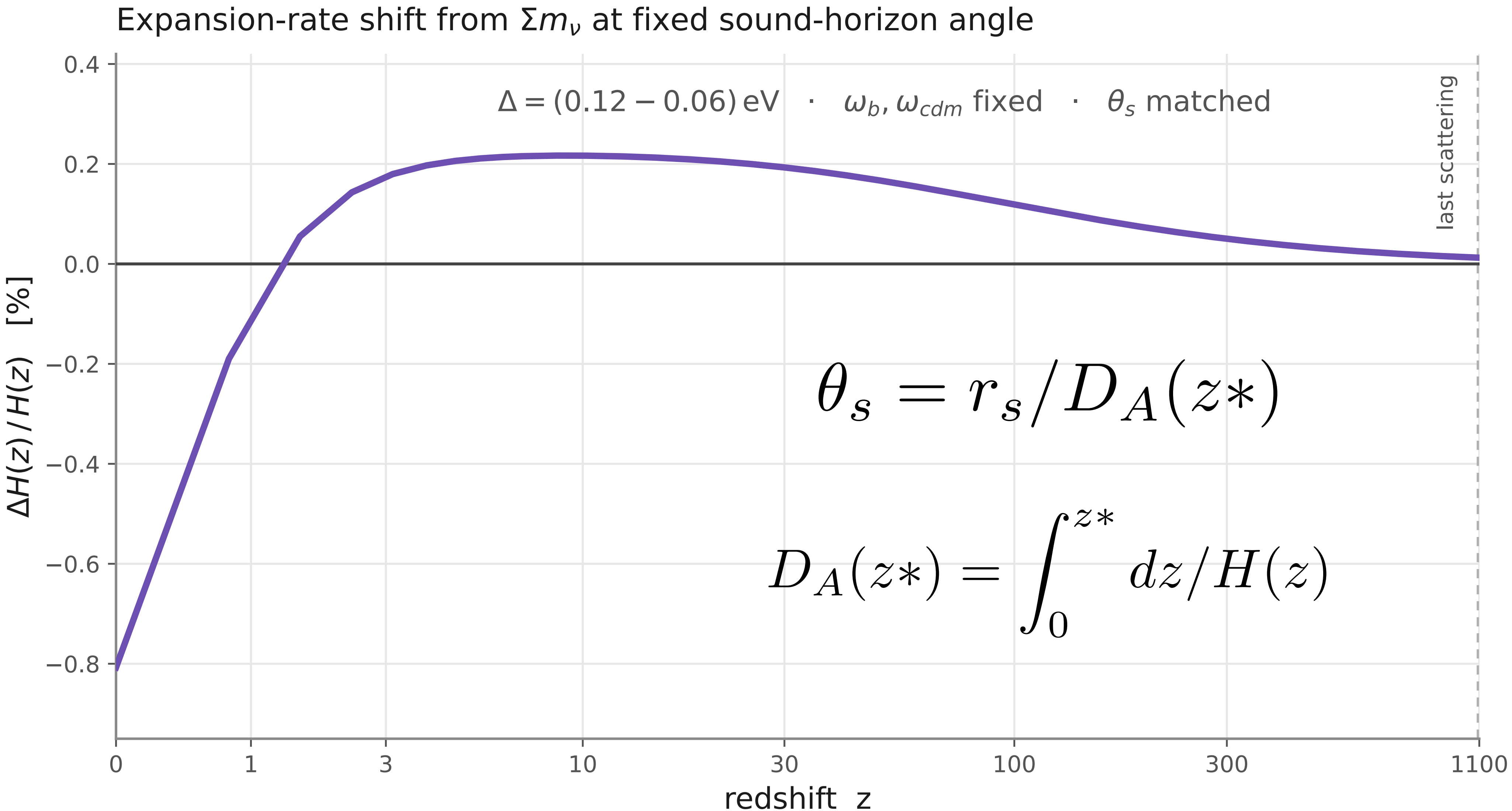


Simulated CMB map

Impact of increased neutrino mass on the expansion rate



Impact of increased neutrino mass on the expansion rate

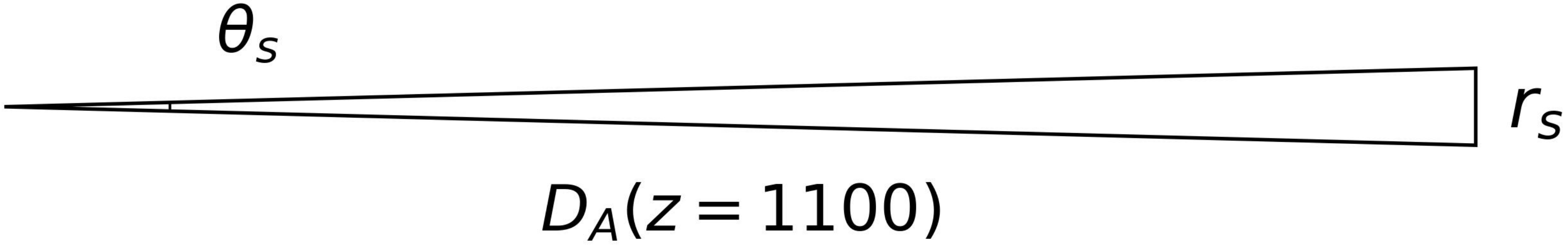


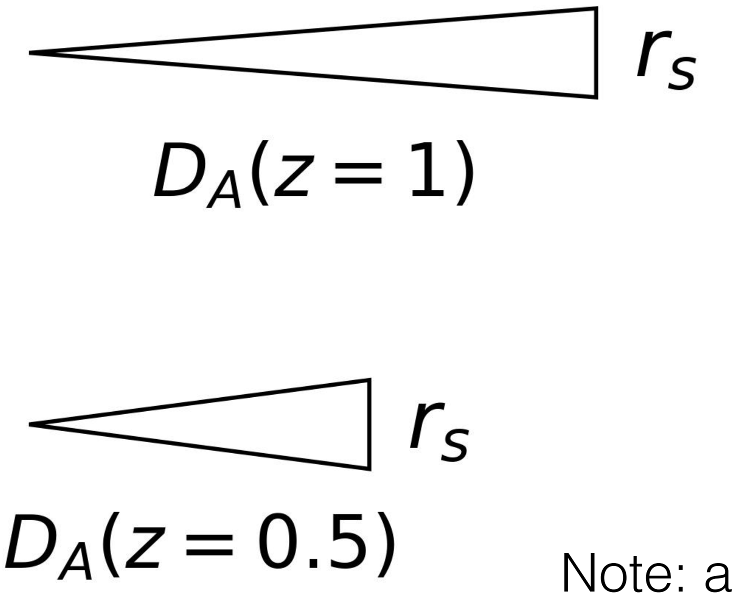
$$\theta_s = r_s / D_A(z*)$$

$$D_A(z*) = \int_0^{z*} dz / H(z)$$

$$z* \simeq 1100$$

Baryon Acoustic Oscillations (BAO)





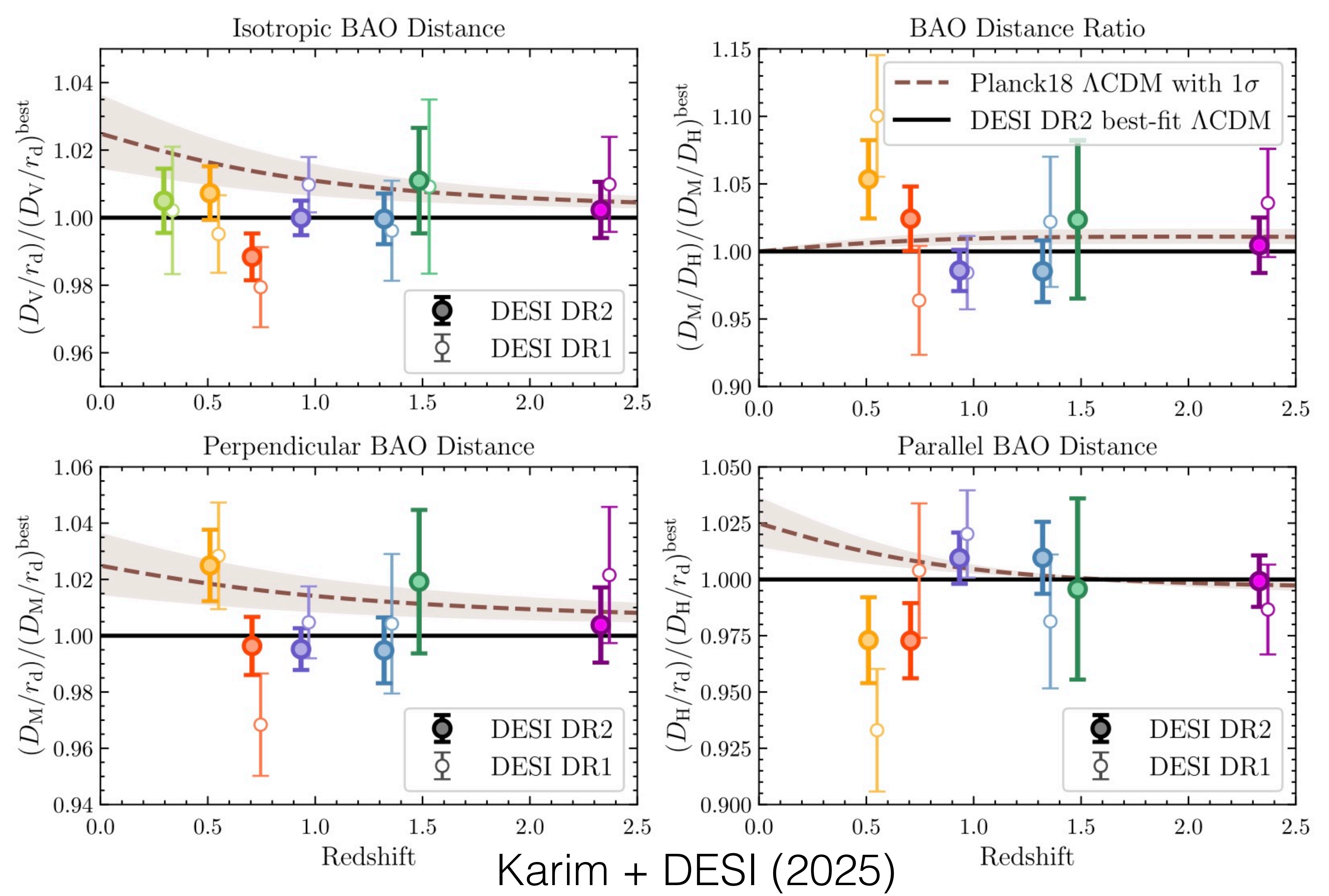
The sound horizon at last scattering also imprints itself in the galaxy distribution. From galaxy surveys we can measure the angle it subtends from different redshifts (for example, z=1 and z=0.5).

Note: also measure it in the z direction, $\Delta z_s = H(z) r_s$

CMB-BAO Tension

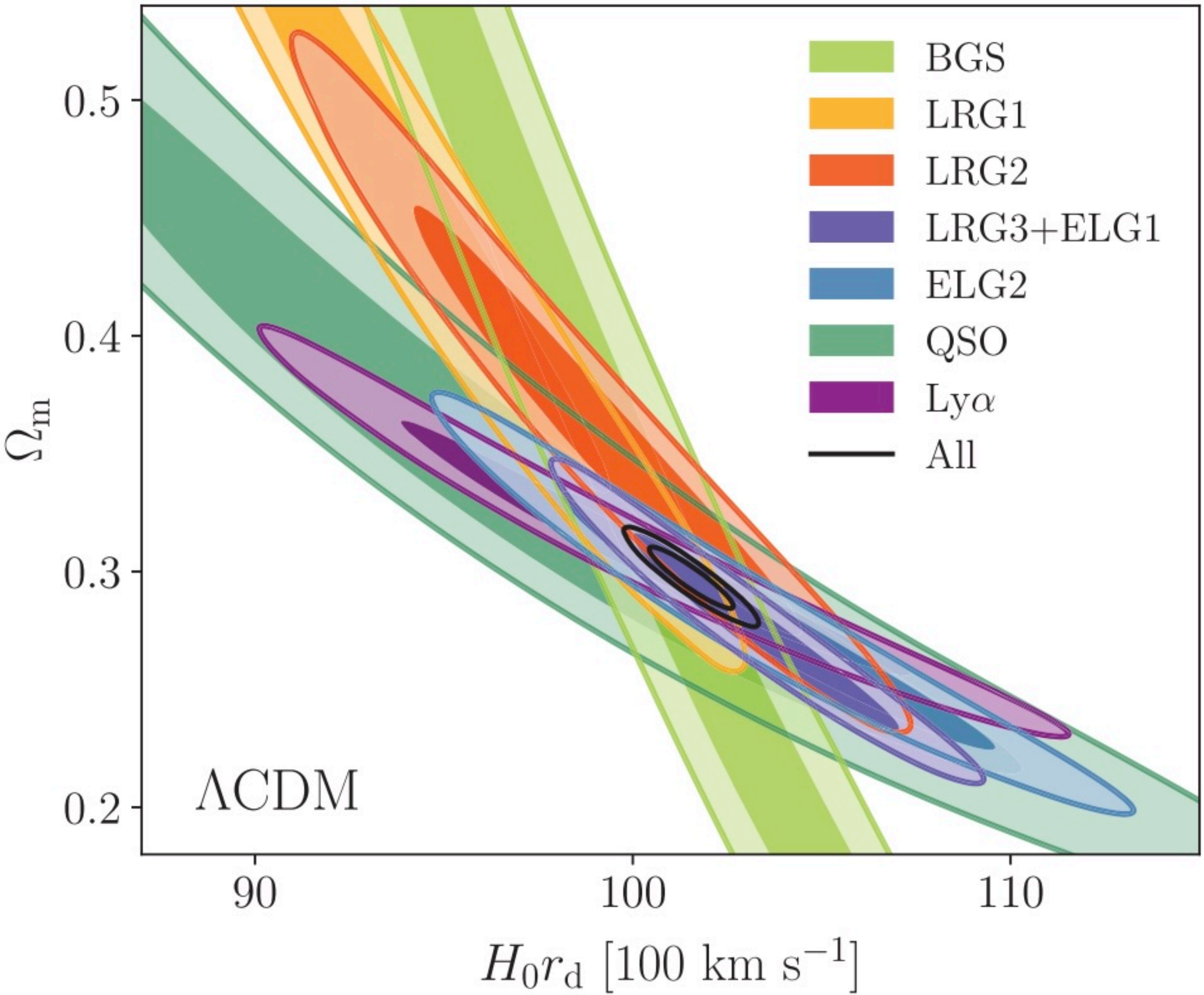
- BAO alone is well-fit by LCDM.
- CMB alone is well-fit by LCDM.
- There are two distinct but related tensions, when these data are jointly analyzed assuming LCDM
- Together they are statistically weak: 2 to 3 sigma
- We are calling these a “matter density deficit” and a “CMB lensing excess.” (Lynch and LK 2025)

BAO data well-fit by LCDM $\chi^2/(\mathrm{d.o.f.}) = 10.2/11$



Karim + DESI (2025)

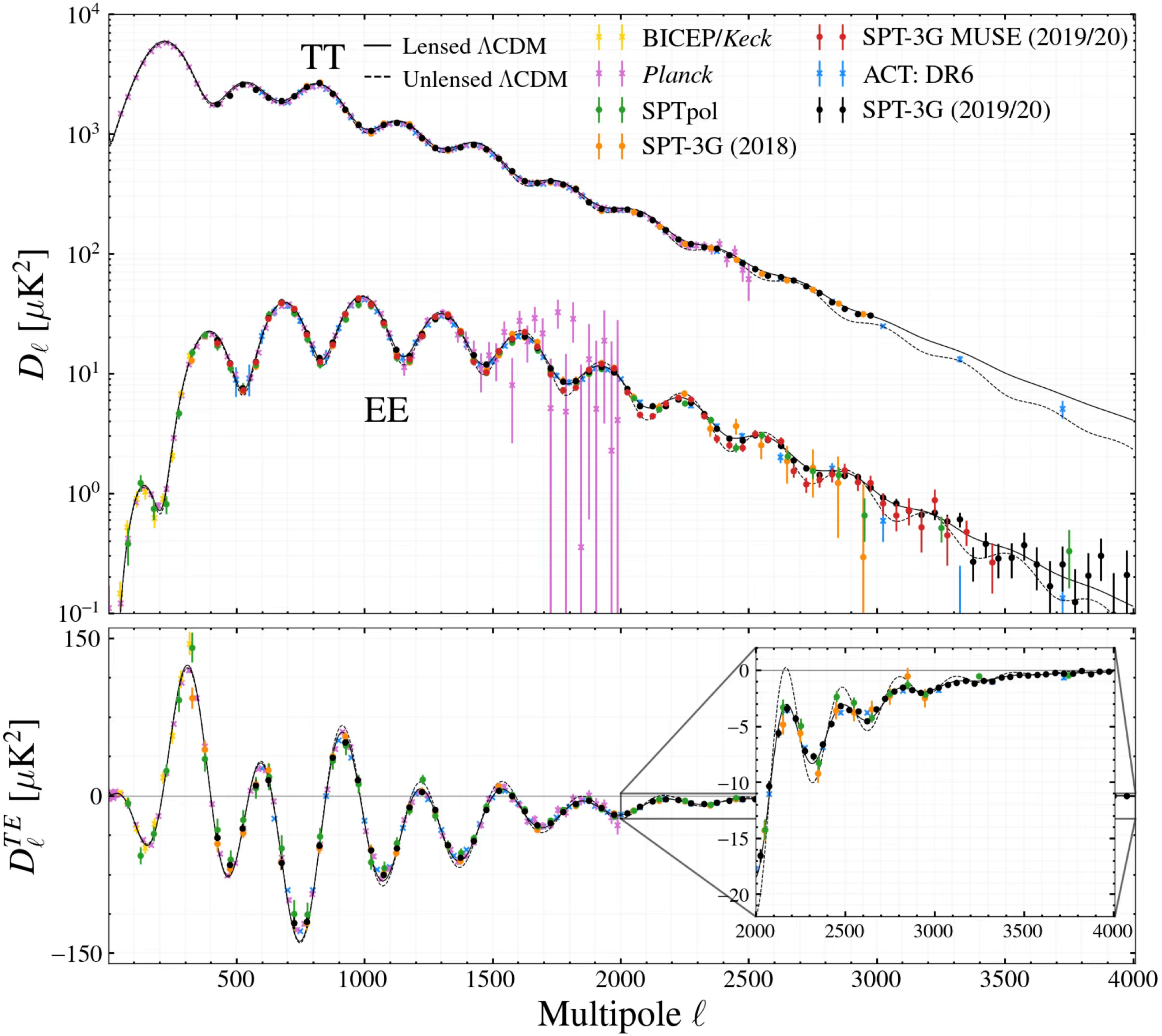
Can losslessly compress BAO data in LCDM to Ω_m and $H_0 r_\mathrm{d}$



Note: r_d and r_s are interchangeable for our purposes

Karim + DESI (2025)

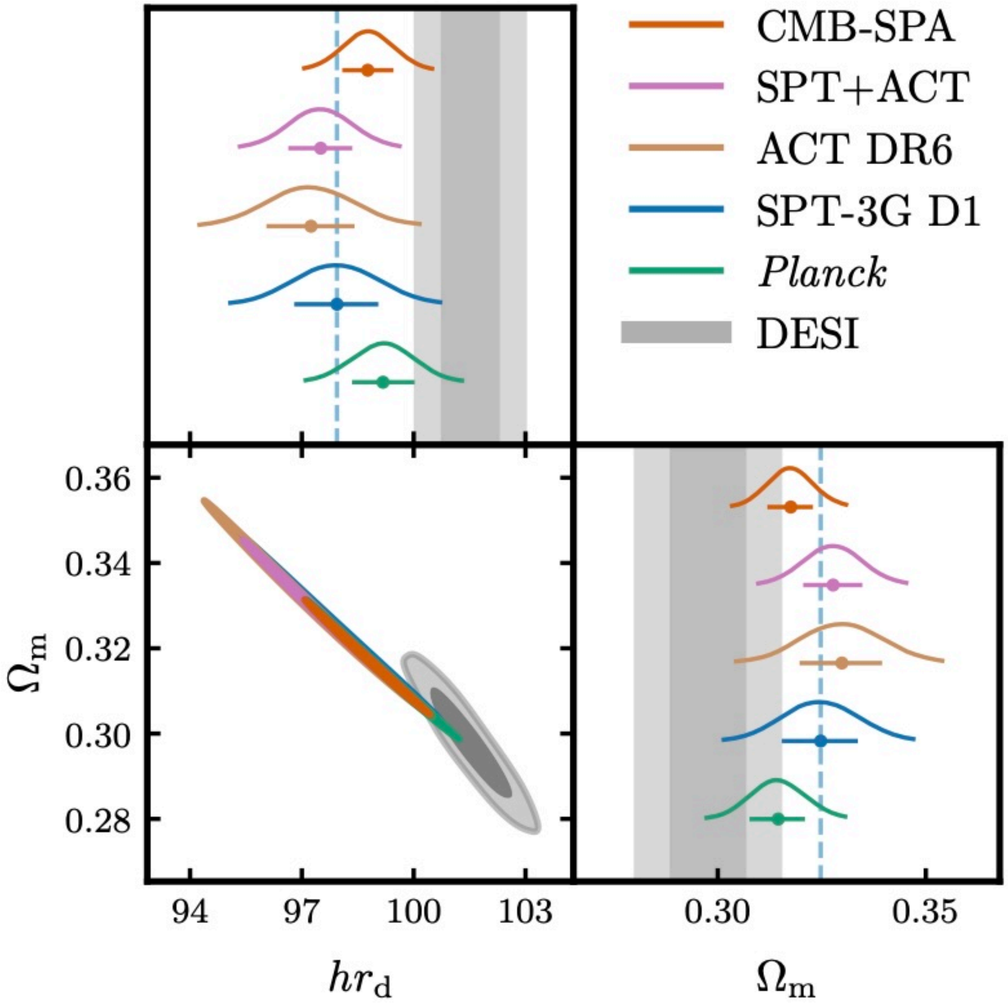
Current CMB Measurements

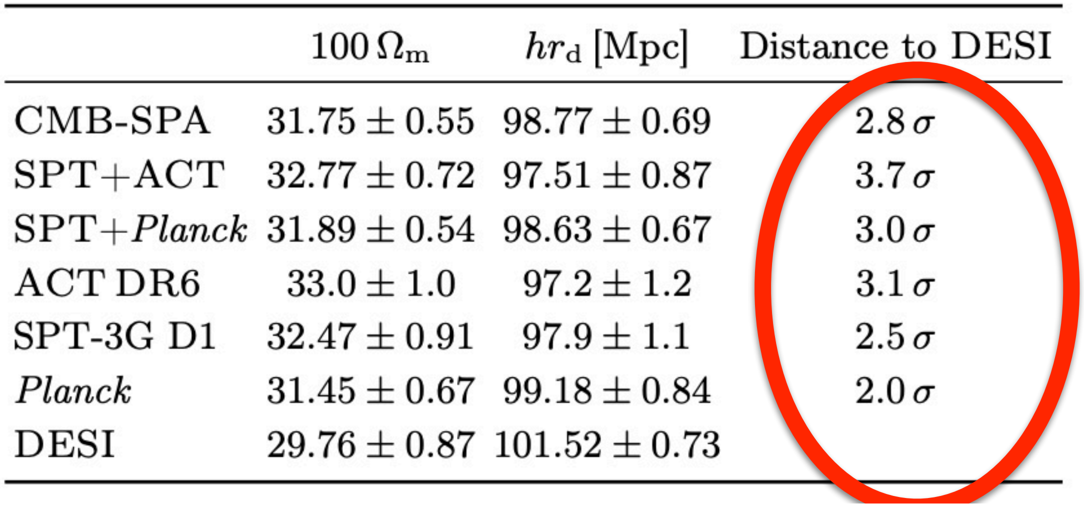


CMB-BAO Tension

BAO data losslessly compress to Ω_m and $H_0 r_\mathrm{d}$

$$h \equiv \frac{H_0}{100\ \mathrm{km/sec/Mpc}}$$





	$100\,\Omega_\mathrm{m}$	hr_d [Mpc]	Distance to DESI
CMB-SPA	31.75 ± 0.55	98.77 ± 0.69	$2.8\,\sigma$
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	$3.7\,\sigma$
SPT+*Planck*	31.89 ± 0.54	98.63 ± 0.67	$3.0\,\sigma$
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	$3.1\,\sigma$
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	$2.5\,\sigma$
Planck	31.45 ± 0.67	99.18 ± 0.84	$2.0\,\sigma$
DESI	29.76 ± 0.87	101.52 ± 0.73	

Camphuis + SPT 2025

If you can compress to

$$\Omega_m \text{ and } hr_d$$

You can also compress to

$$\Omega_m \text{ and } \Omega_m (hr_d)^2 = \omega_m r_d^2$$

One can determine $\omega_{\rm m} r_d^2$ very precisely from BAO + $\theta_s(z*)$

One can determine $\omega_{\rm cb} r_d^2$ and r_d^2 from CMB data

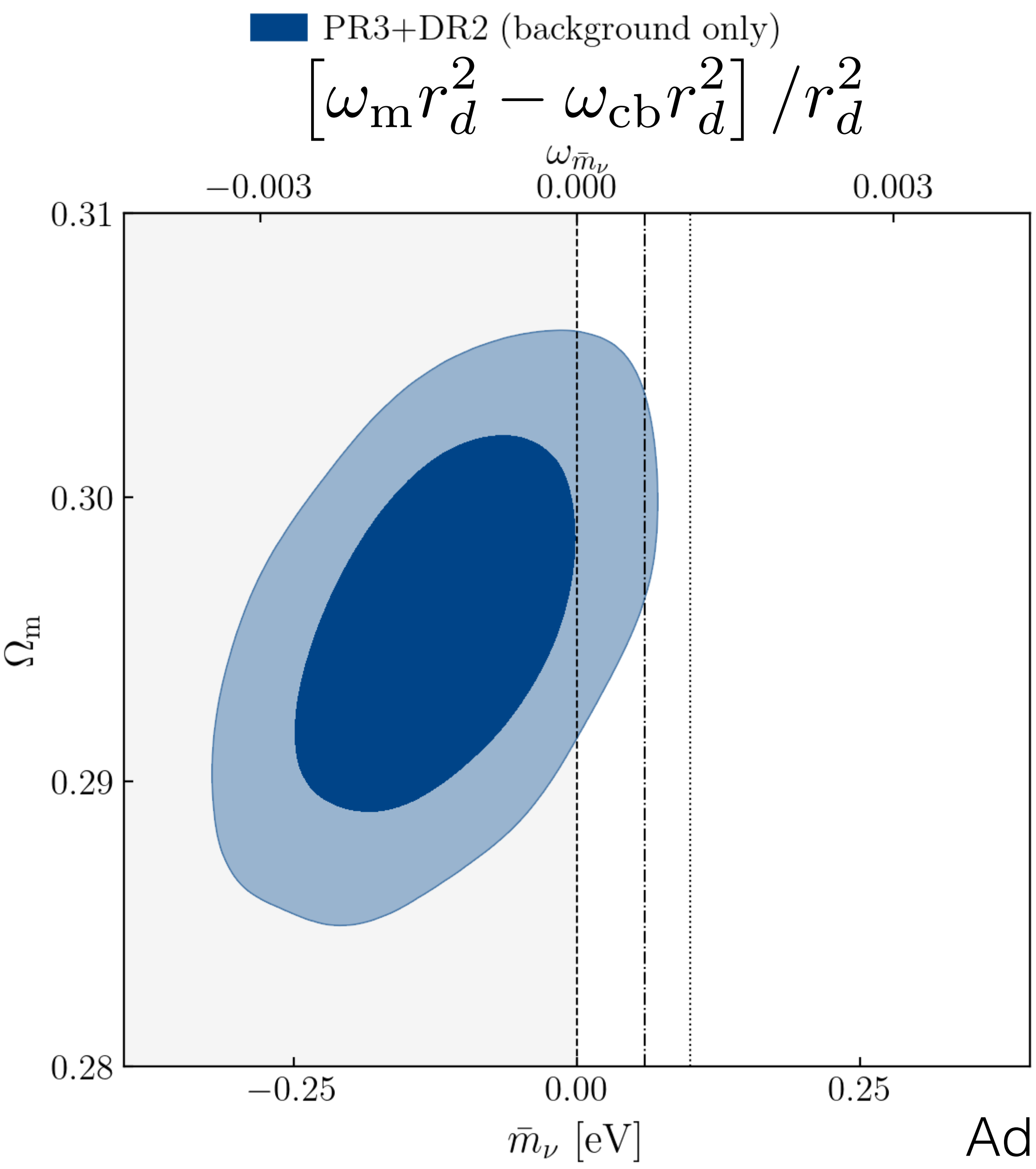
If $\omega_{\rm m} = \omega_{\rm cb} + \omega_\nu$ then

one can estimate $\omega_\nu = \left[\omega_{\rm m} r_d^2 - \omega_{\rm cb} r_d^2\right] / r_d^2$

and $\Sigma m_\nu = 91.4 \text{ eV} \times \omega_\nu$

Loverde & Weiner (2024), Lynch & LK (2025)

Matter density deficit



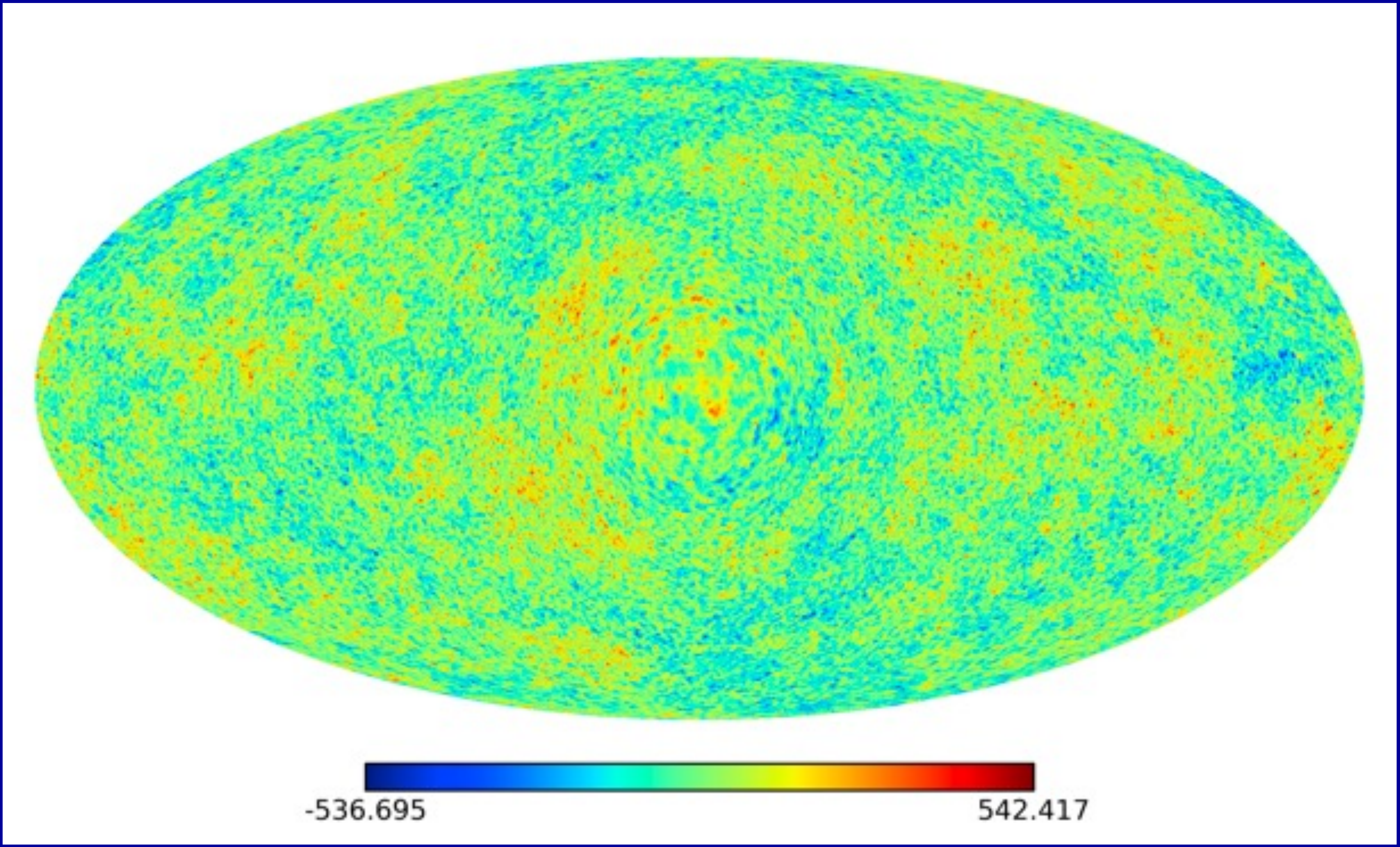
Constraints from Planck (PR3) and DESI BAO (DR2) in a model space with a neutrino-mass-like parameter that can be negative.

Adapted from Lynch & LK (2025)

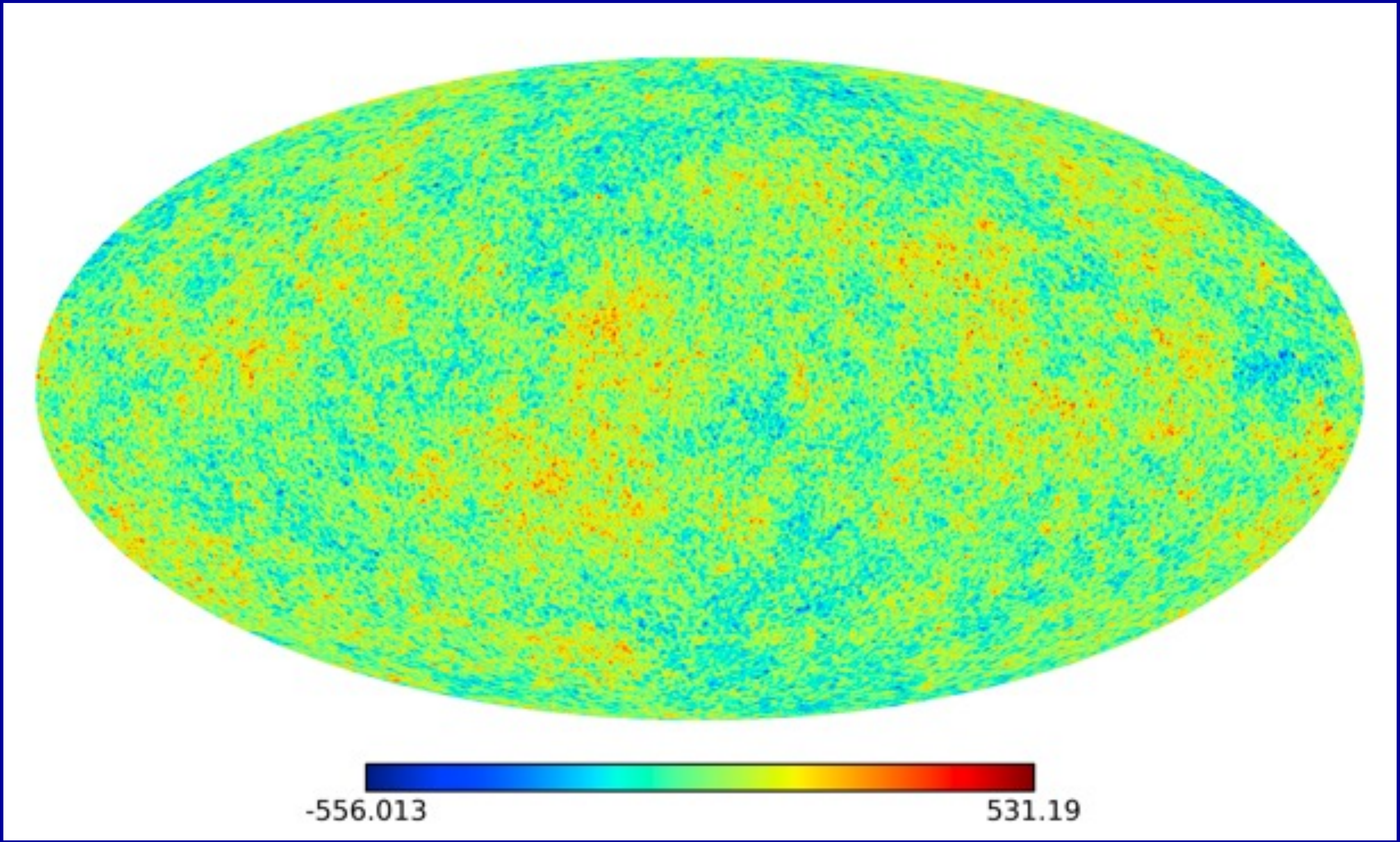
That’s the matter density deficit. Now for the CMB lensing excess.

(Artificially Large Distortion)

Gravitational Lensing



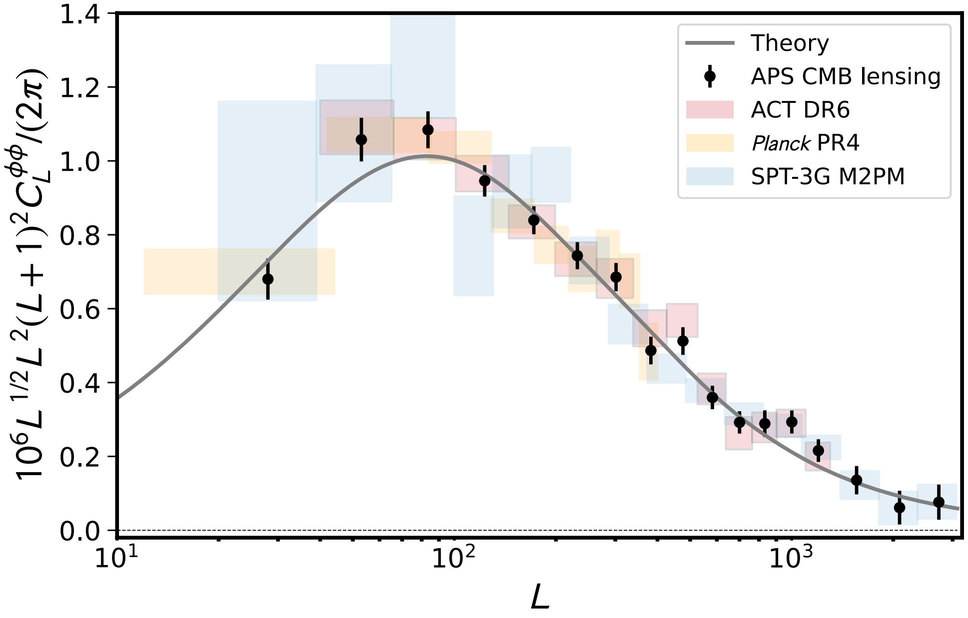
Gravitational Lensing



Gravitational Lensing

- Creates detectable departures from statistical isotropy that can be exploited to ‘reconstruct’ maps of lensing deflections.
- Smears out peaks and troughs of the CMB power spectra

CMB Lensing Power Spectrum

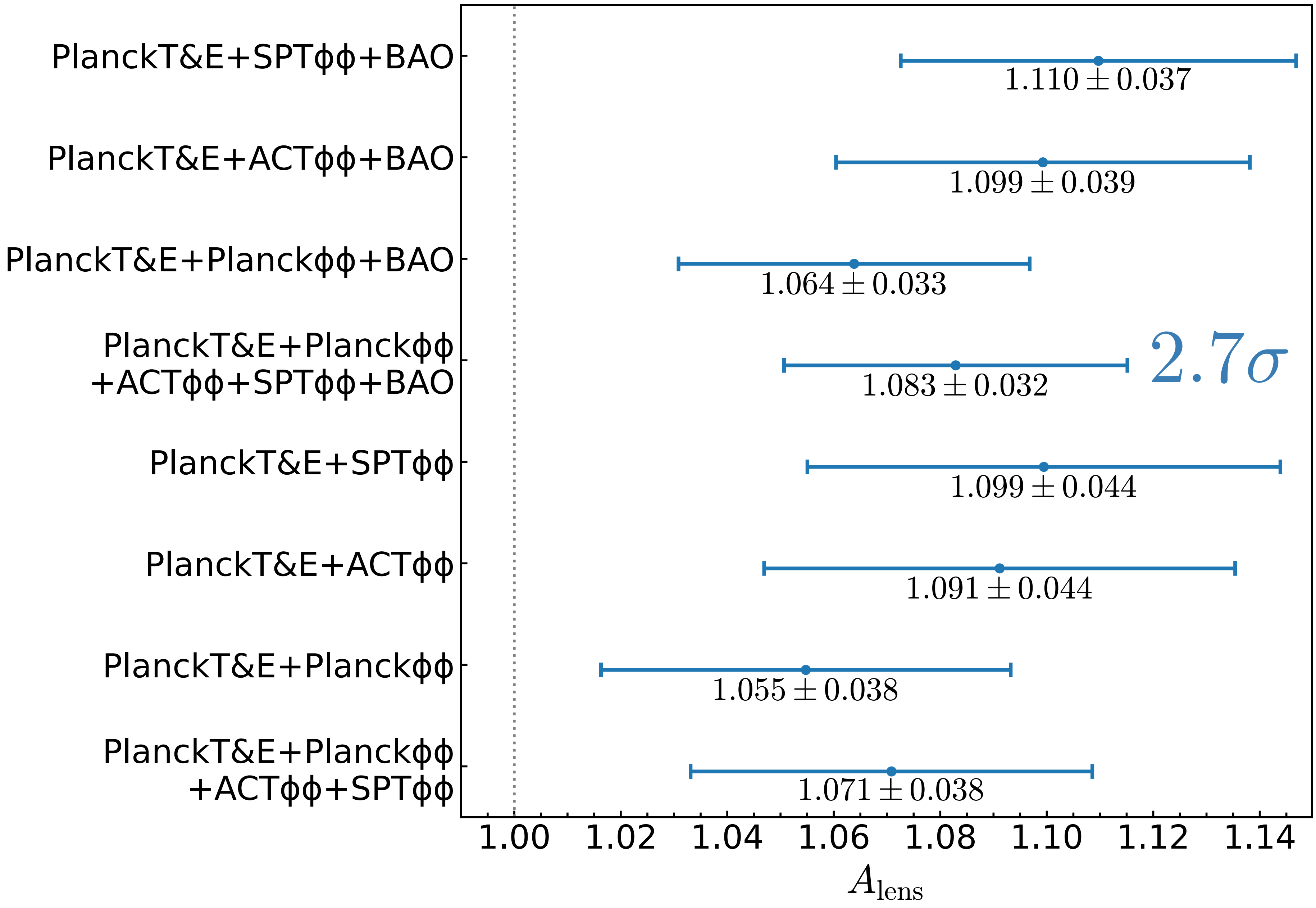


Qu + Ge + ACT + SPT 2025

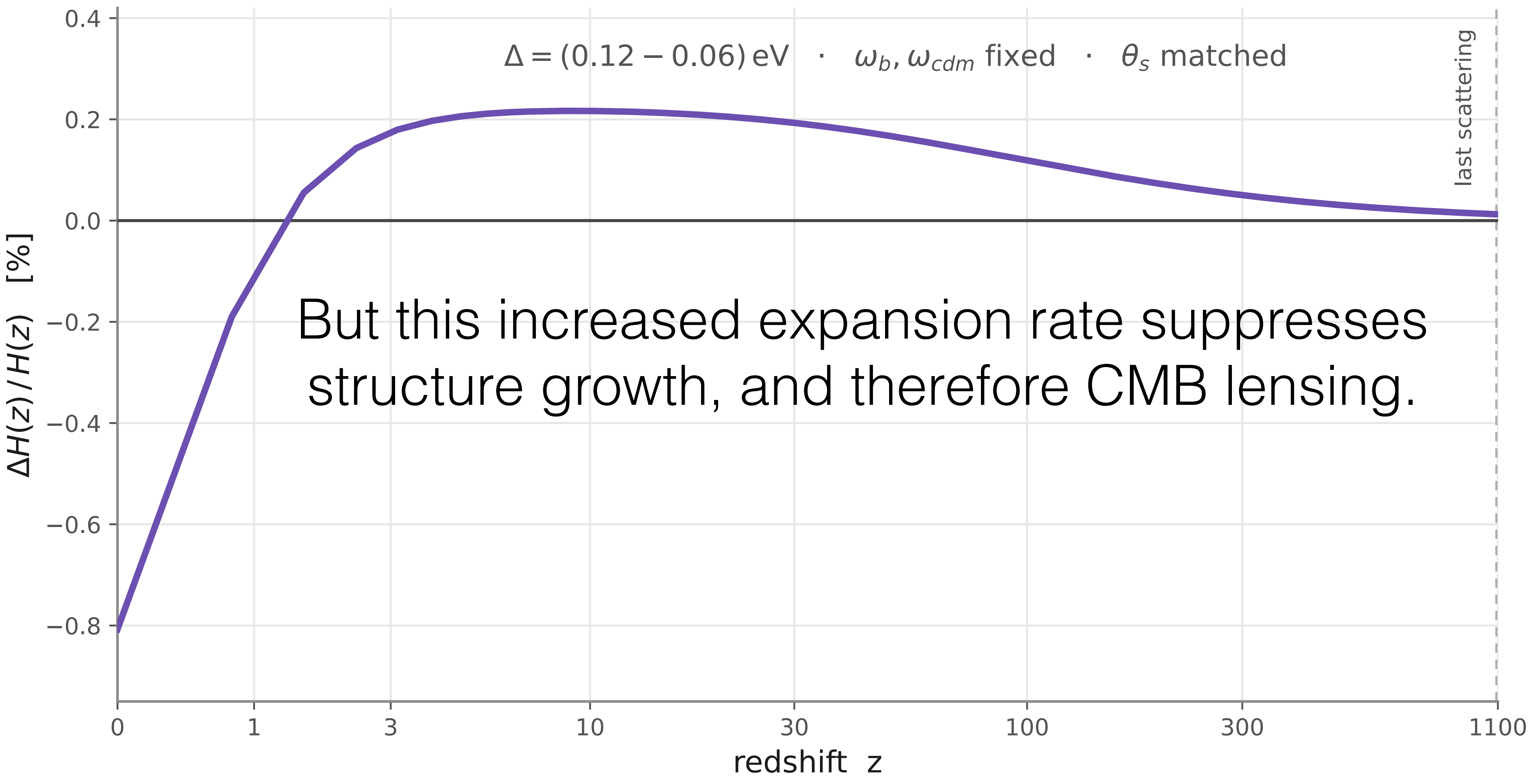
$\Lambda\mathrm{CDM} + A_{\mathrm{lens}}$

Excess lensing power

Ge + SPT (2025)



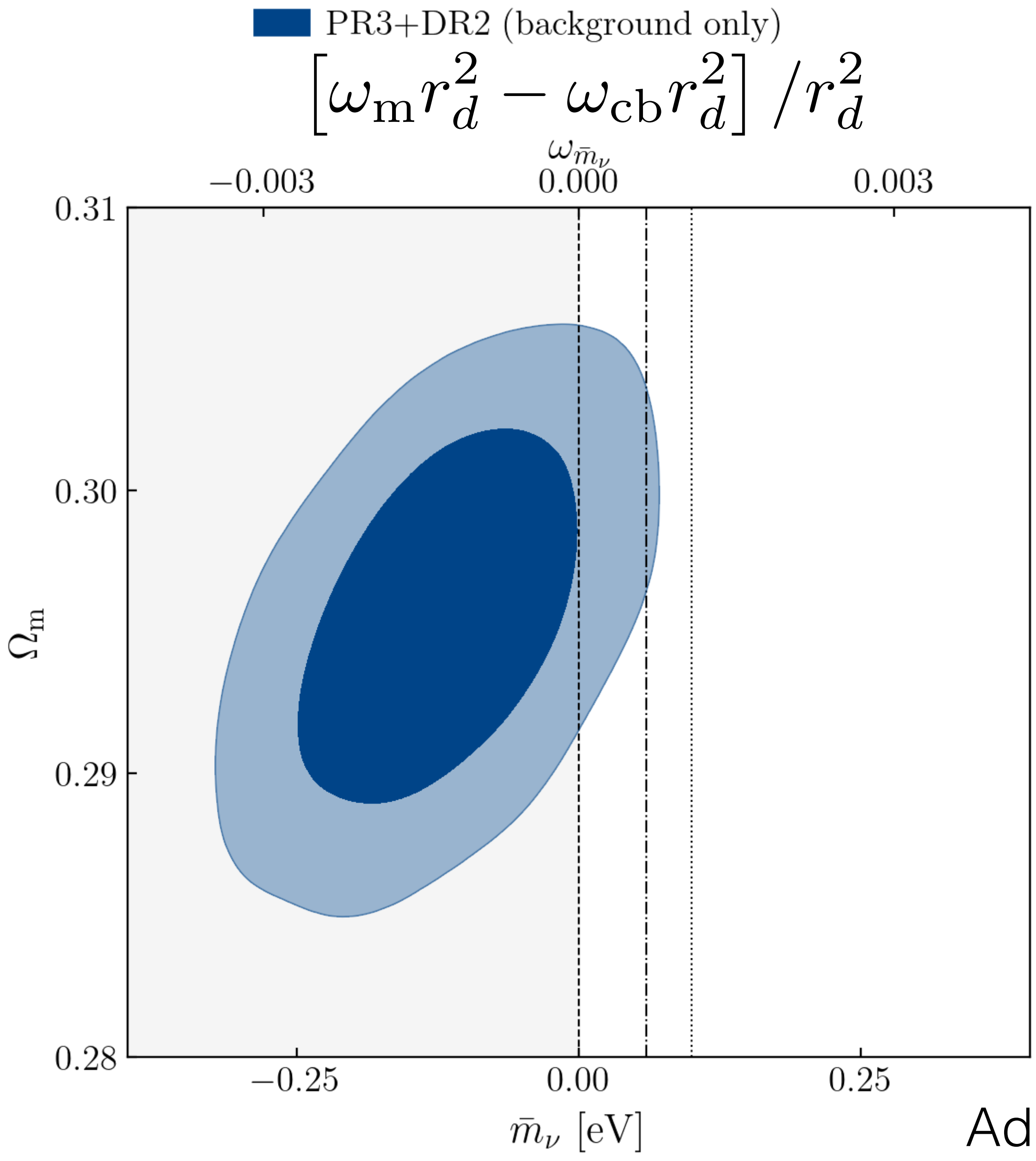
Impact of increased neutrino mass on the expansion rate



Expansion-rate shift from Σm_ν at fixed sound-horizon angle

But this increased expansion rate suppresses structure growth, and therefore CMB lensing.

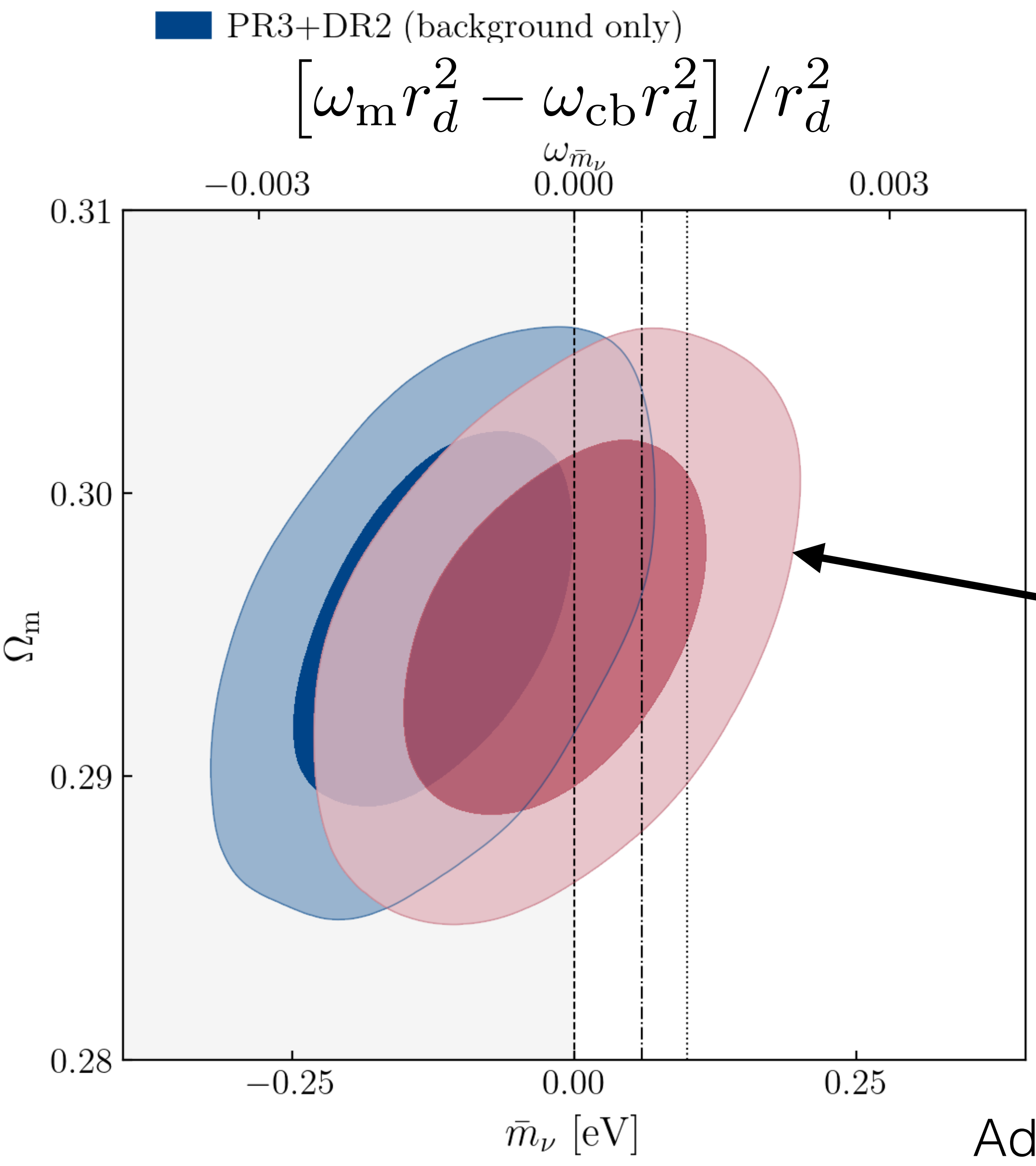
Matter density deficit



Constraints from Planck (PR3) and DESI BAO (DR2) in a model space with a neutrino-mass-like parameter that can be negative

Adapted from Lynch & LK (2025)

Matter density deficit



Constraints from Planck (PR3) and DESI BAO (DR2) in a model space with a neutrino-mass-like parameter that can be negative

With CMB lensing information removed.

Adapted from Lynch & LK (2025)

Possible sources of these (mild) discrepancies:

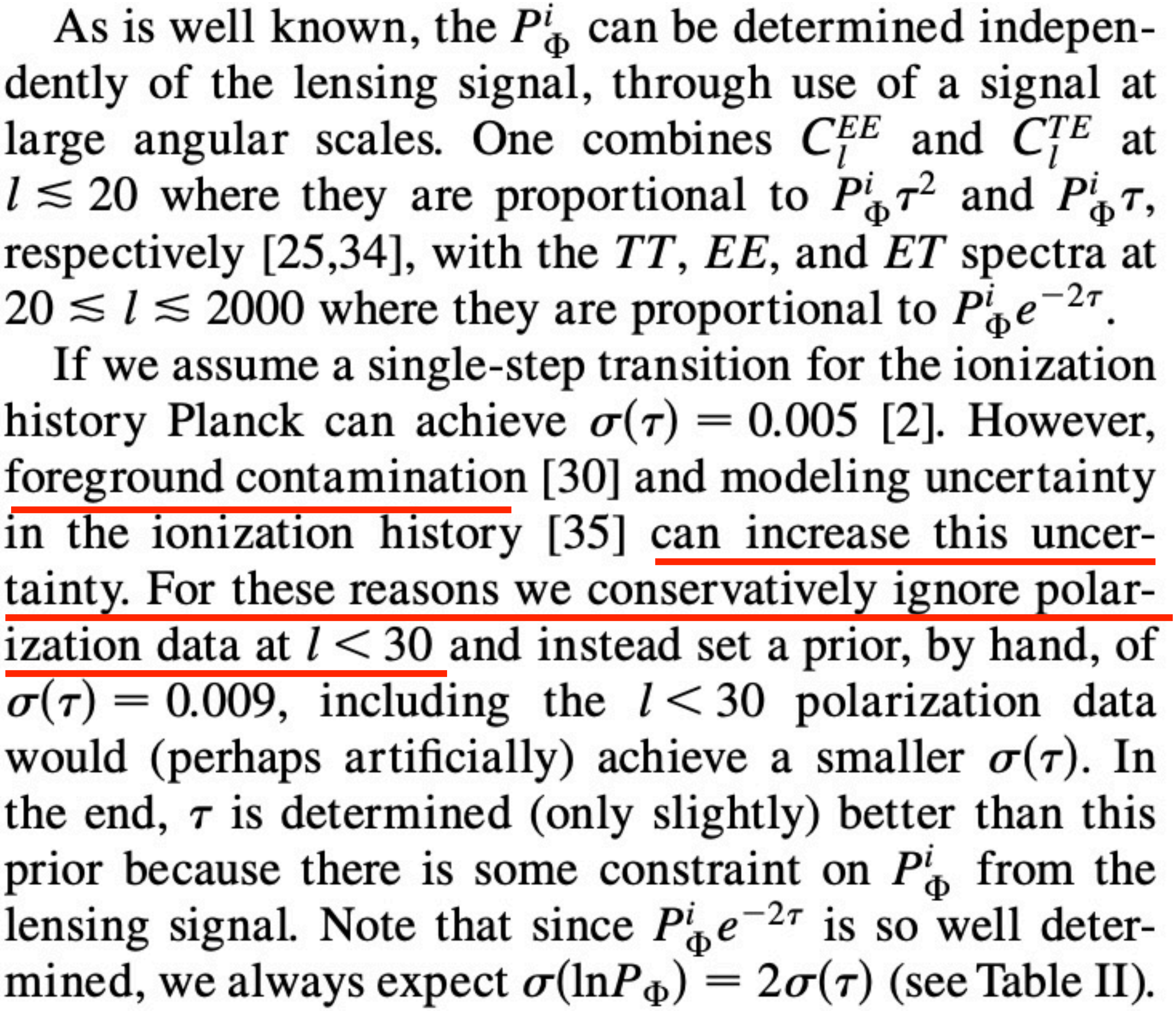
1. **Alter late time evolution**
    1. Dark energy is not a cosmological constant.
    2. Dark matter and dark energy interact with each other.
2. **Alter CMB inferences of** $\omega_{\rm cb} r_d^2$
    1. Modifications to recombination (perhaps from primordial magnetic fields)
    2. Early dark energy
3. **Boost CMB lensing model expectations**
    1. High optical depth (switching acoustic scale tension for ‘tau tension’) [Saylor et al. 2026, Jhaveri et al. 2026]

Type 2 solutions also boost H_0. Let’s consider Type 3.

The ionized intergalactic medium and CMB lensing model expectations

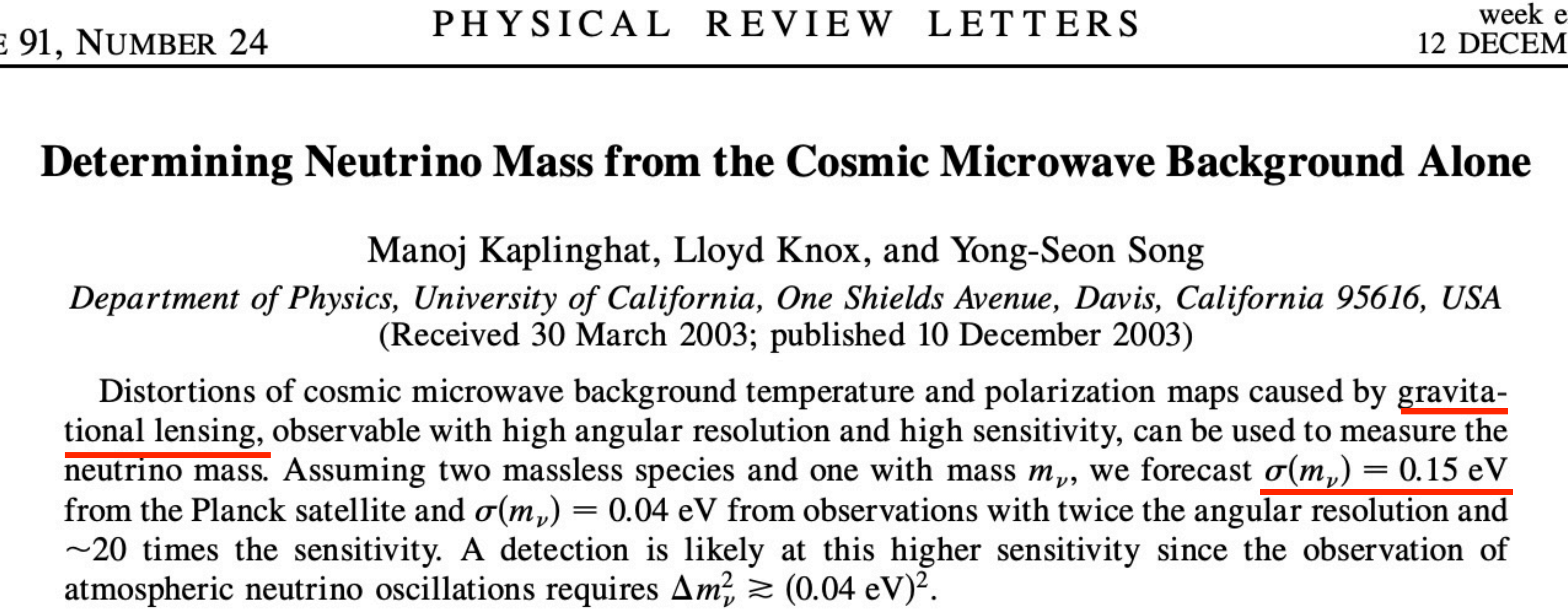
- About 6% of CMB photons that we see, last scatter off of free electrons, not out at z=1100 on the edge of the observable universe, but more recently. We say “tau (optical depth) = 0.06.”
- Like a fog spreading out the light on a sunny day, this late-time scattering suppresses CMB anisotropies
- It therefore impacts our estimate of the amplitude of primordial fluctuations, and therefore of the CMB lensing power spectrum.

From Kaplinghat et al. (2003): constraints on tau (from low-ell polarization data) identified as a weak link in the inference chain:



As is well known, the P^i_Φ can be determined independently of the lensing signal, through use of a signal at large angular scales. One combines C_l^{EE} and C_l^{TE} at $l \lesssim 20$ where they are proportional to $P^i_\Phi \tau^2$ and $P^i_\Phi \tau$, respectively [25,34], with the TT, EE, and ET spectra at $20 \lesssim l \lesssim 2000$ where they are proportional to $P^i_\Phi e^{-2\tau}$.

If we assume a single-step transition for the ionization history Planck can achieve $\sigma(\tau) = 0.005$ [2]. However, foreground contamination [30] and modeling uncertainty in the ionization history [35] can increase this uncertainty. For these reasons we conservatively ignore polarization data at $l < 30$ and instead set a prior, by hand, of $\sigma(\tau) = 0.009$, including the $l < 30$ polarization data would (perhaps artificially) achieve a smaller $\sigma(\tau)$. In the end, τ is determined (only slightly) better than this prior because there is some constraint on P^i_Φ from the lensing signal. Note that since $P^i_\Phi e^{-2\tau}$ is so well determined, we always expect $\sigma(\ln P_\Phi) = 2\sigma(\tau)$ (see Table II).



91, NUMBER 24 PHYSICAL REVIEW LETTERS week e
12 DECEM

Determining Neutrino Mass from the Cosmic Microwave Background Alone

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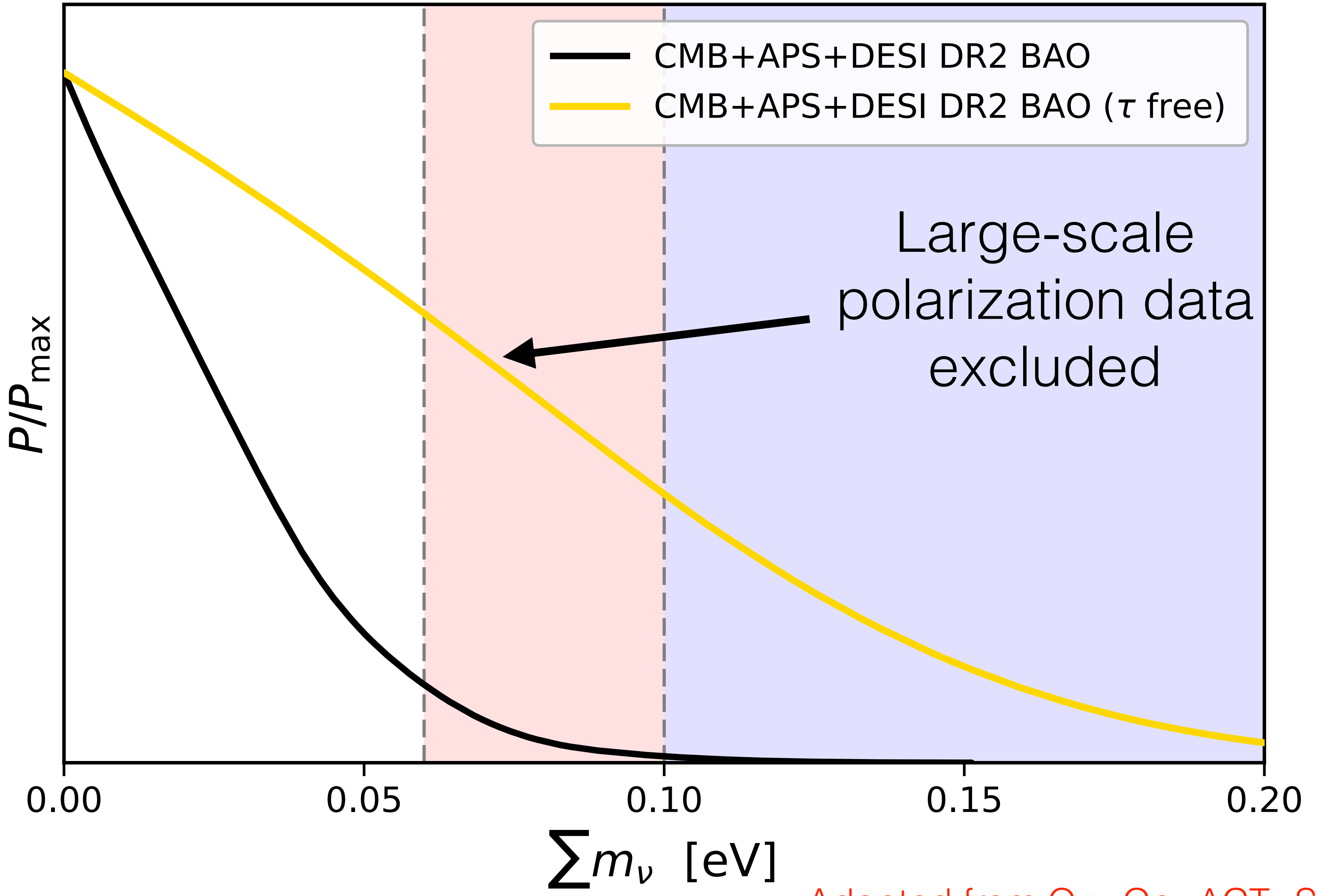
(Received 30 March 2003; published 10 December 2003)

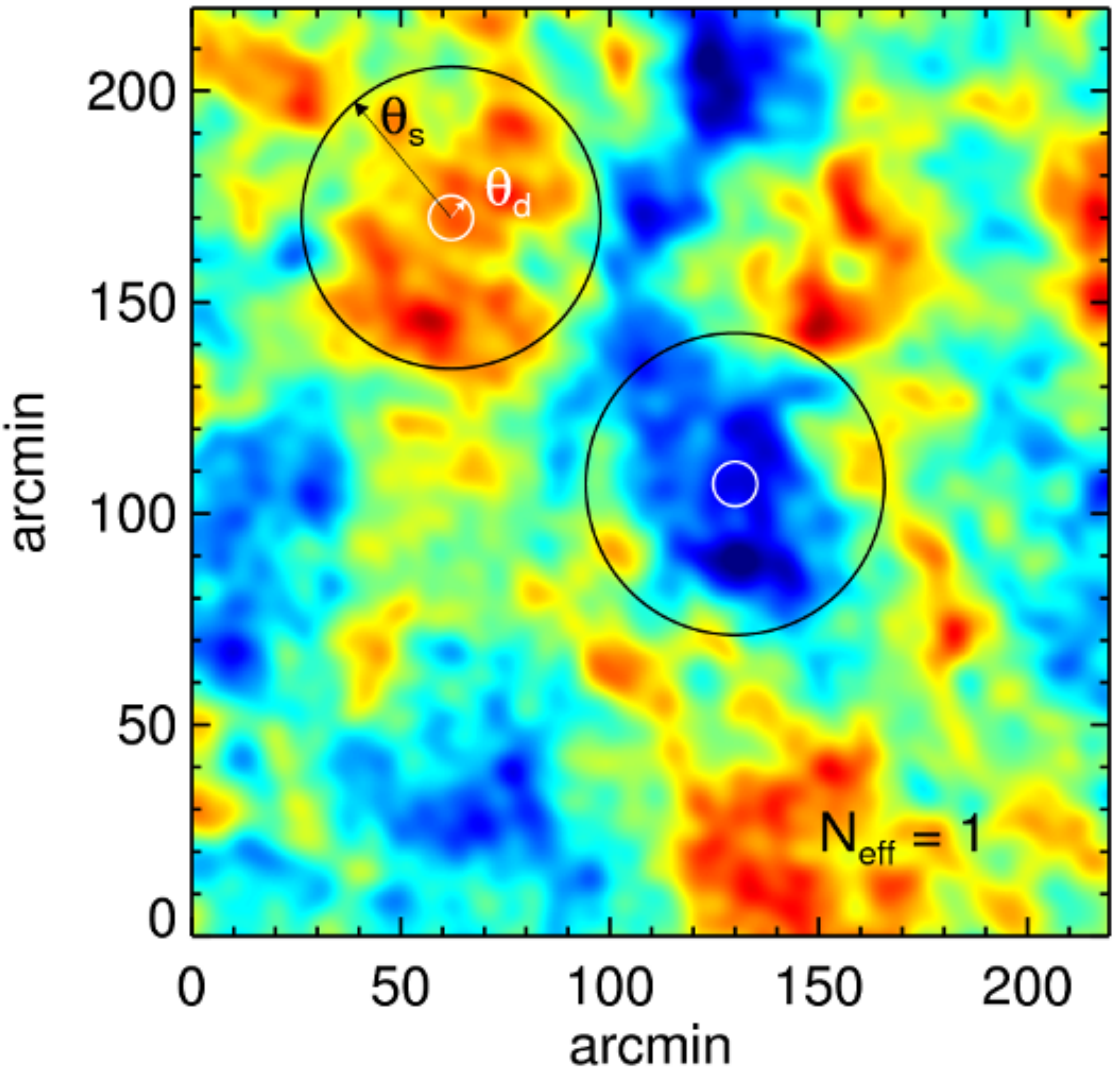
Distortions of cosmic microwave background temperature and polarization maps caused by gravitational lensing, observable with high angular resolution and high sensitivity, can be used to measure the neutrino mass. Assuming two massless species and one with mass m_ν, we forecast $\sigma(m_\nu) = 0.15$ eV from the Planck satellite and $\sigma(m_\nu) = 0.04$ eV from observations with twice the angular resolution and $\sim$20 times the sensitivity. A detection is likely at this higher sensitivity since the observation of atmospheric neutrino oscillations requires $\Delta m_\nu^2 \gtrsim (0.04 \text{ eV})^2$.

Dropping large-scale (low-ell) polarization data restores consistency

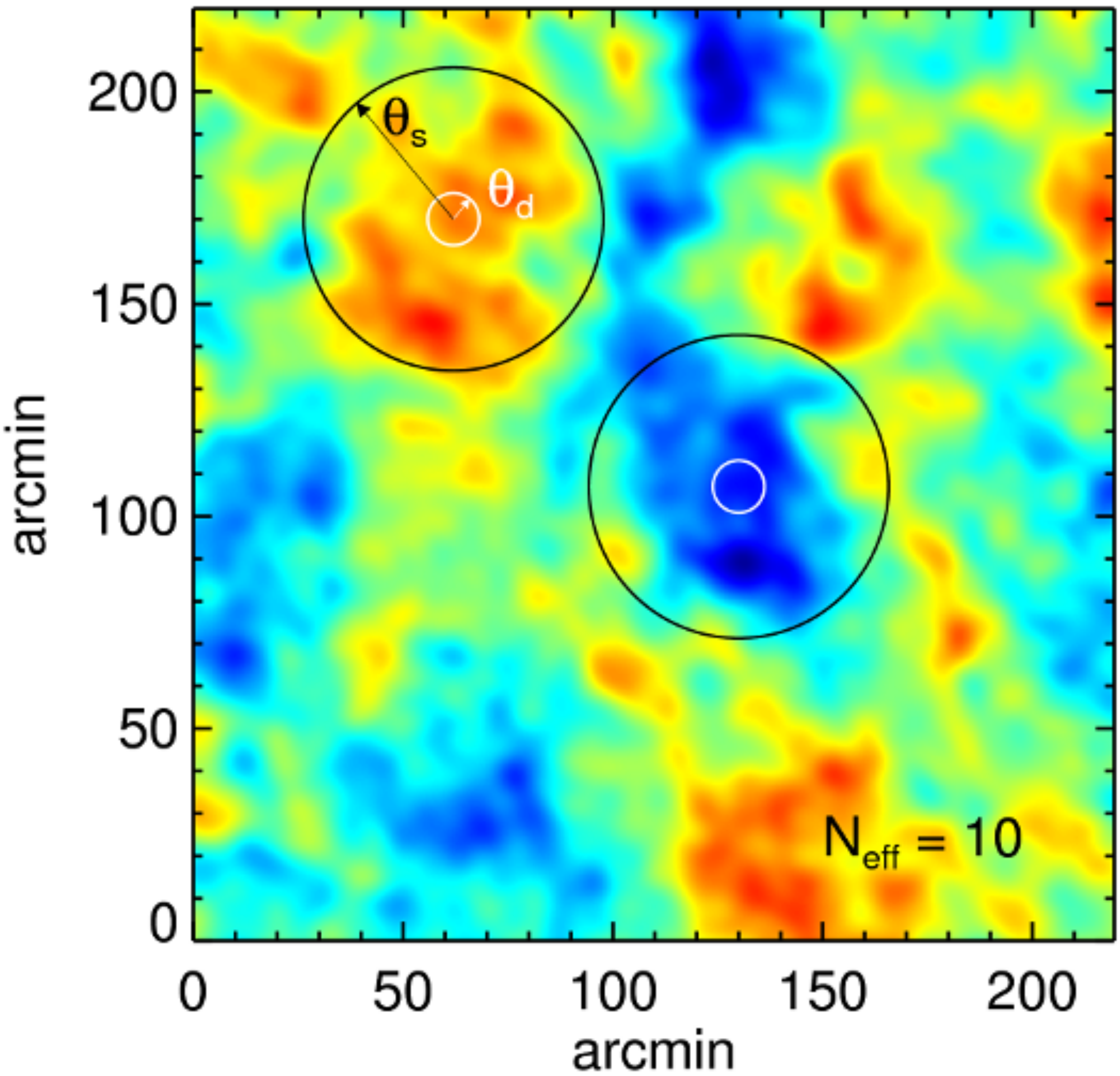


Large-scale polarization data excluded

Adapted from Qu+Ge+ACT+SPT 2025

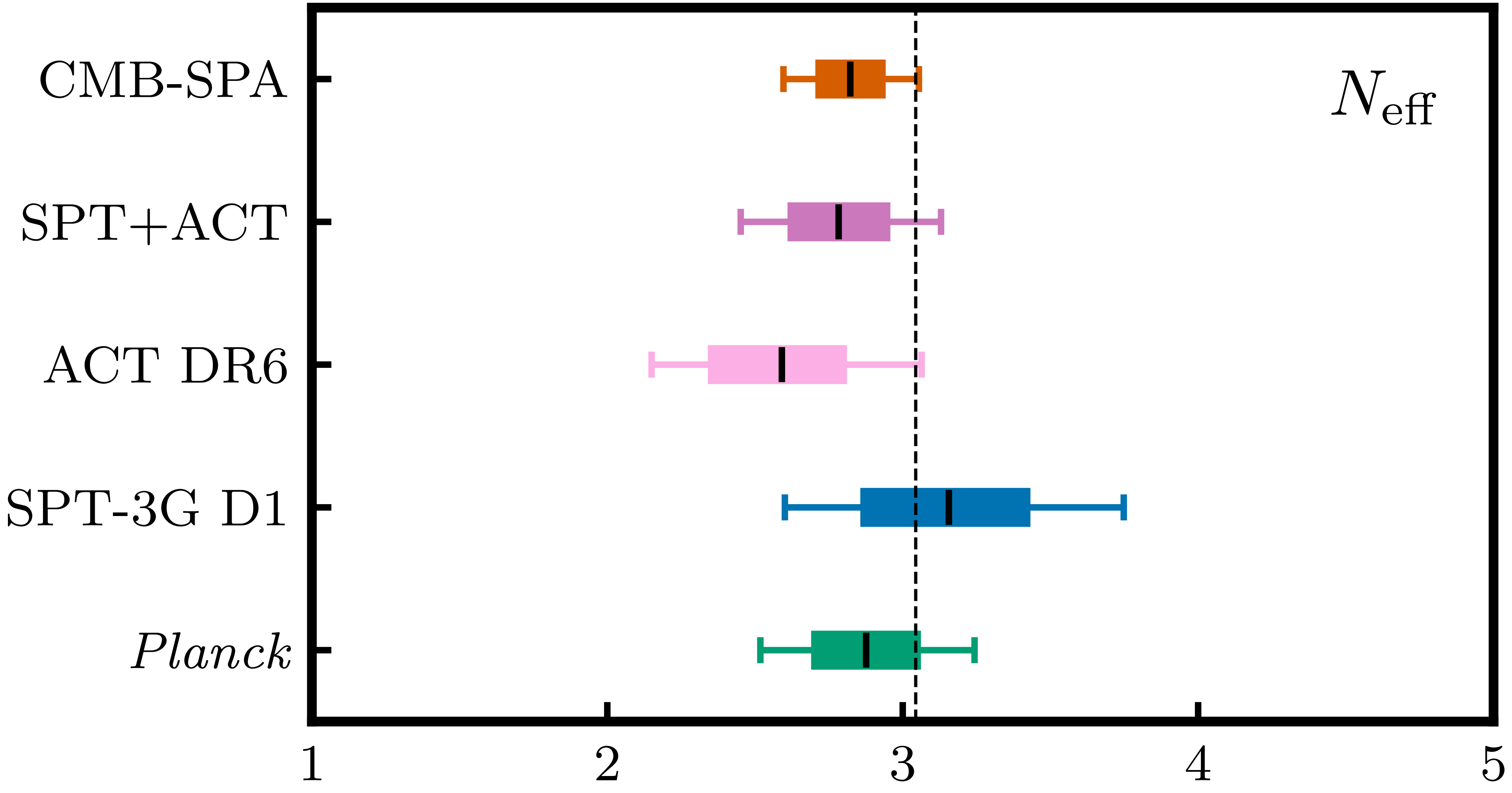


θ_s
θ_d
N_eff = 1
arcmin
arcmin
0
50
100
150
200
0
50
100
150
200



θ_s
θ_d
N_eff = 10
0
50
100
150
200
arcmin
0
50
100
150
200
arcmin

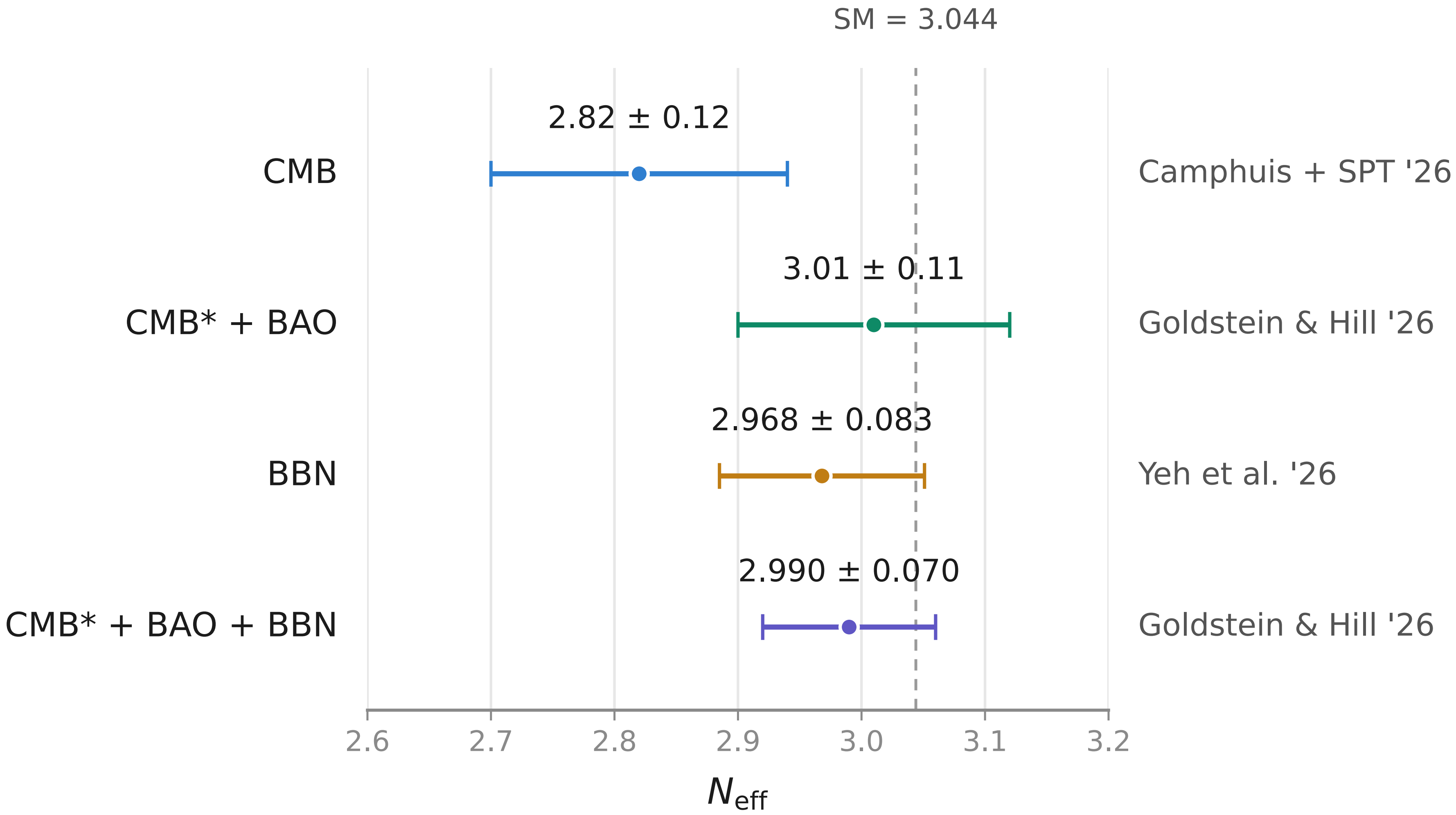
N_{eff} from CMB



N_{eff}

"SPA" = SPT+Planck+ACT

N_{eff} from CMB, BAO, BBN



Key

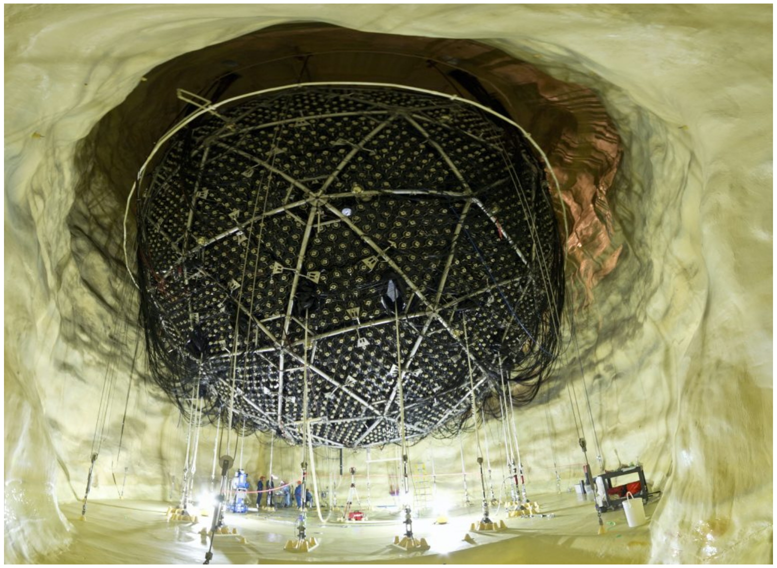
CMB = CMB-SPA

BBN = helium and deuterium

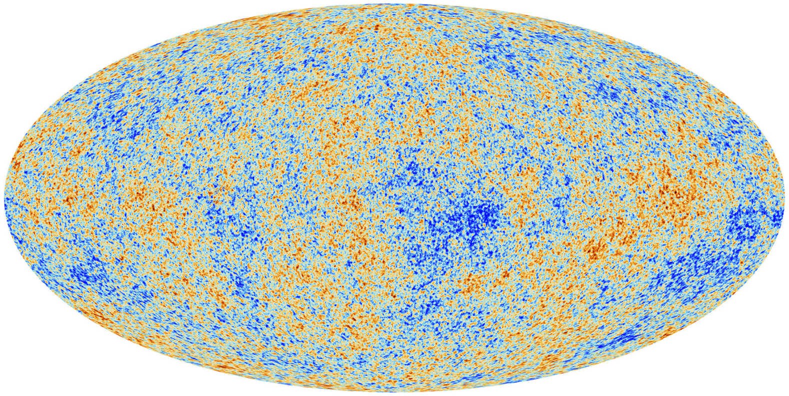
CMB* = CMB-SPA w/o low-ℓ EE

BAO = DESI DR2

Laboratory Experiments



Neutrino Observatories



Cosmological Observables

Complementary Probes of Nature

Summary

- Big bang copiously produced neutrinos. They have a huge impact on observables while relativistic, and subtler (but measurable) influence when non-relativistic.

- **Neutrino mass**: BAO + CMB sensitive to neutrino mass via H(z) and therefore D(z) and CMB lensing suppression.

    - Sensitivity is at the scale where we expect to detect the smallest mass total consistent with atmospheric and solar neutrino oscillation standard interpretations (0.058 eV), and possibly rule out IO in favor of NO.

    - Current data favor NO over IO.

    - In danger of ruling out 0.058 eV! (The surprise — moderate statistical significance)

    - Could be a breakdown of LCDM (e.g., evolving dark energy), or systematic errors (underestimated uncertainty in the optical depth to Thomson scattering).

    - Model dependence of inferences of neutrino properties from cosmology is on full display.

- **Light relics**: CMB, BBN, BAO are all consistent under LCDM + Neff with joint constraint Neff = 3.004 +/- 0.071 (Goldstein & Hill 2026). (The expected)

- **Complementarity, or model dependence as a strength**: You are doing neutrino physics for all the great reasons you are doing neutrino physics *and* via cosmology, you can contribute to discoveries that potentially have nothing to do with neutrino physics.

Acknowledgments

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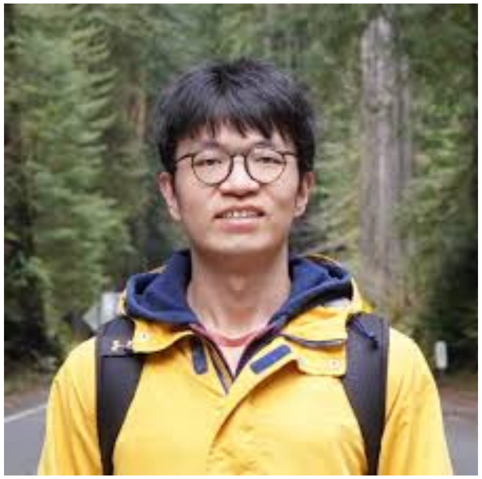
Gabe Lynch (UCD)



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