How the Cosmic Microwave Background knows about dark radiation

Murali M. Saravanan

Based on: 2503.04671, accepted to JCAP

In collaboration with Marilena Loverde, Zachary J. Weiner, Thejs Brinckmann

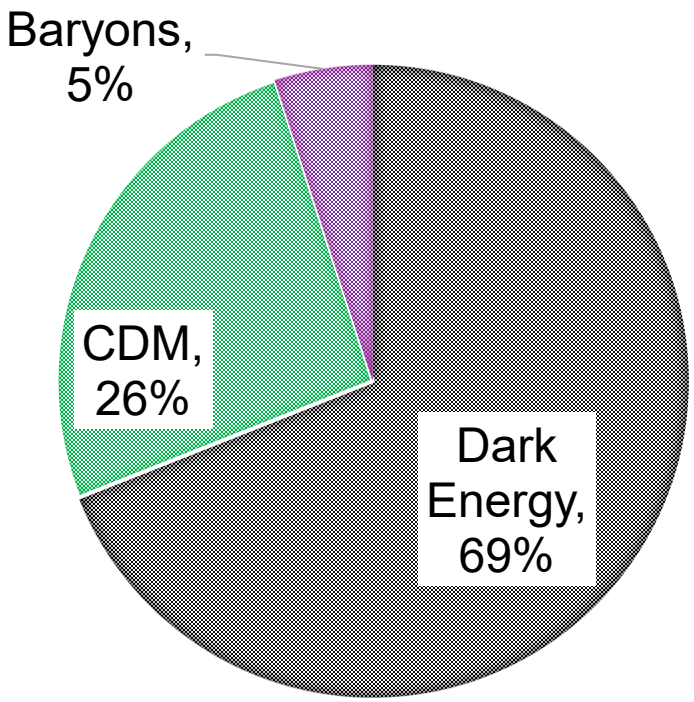
Outline

- **What is dark radiation?**
- How do we isolate the effect of dark radiation on the CMB?
- Constraints with data
- Conclusions

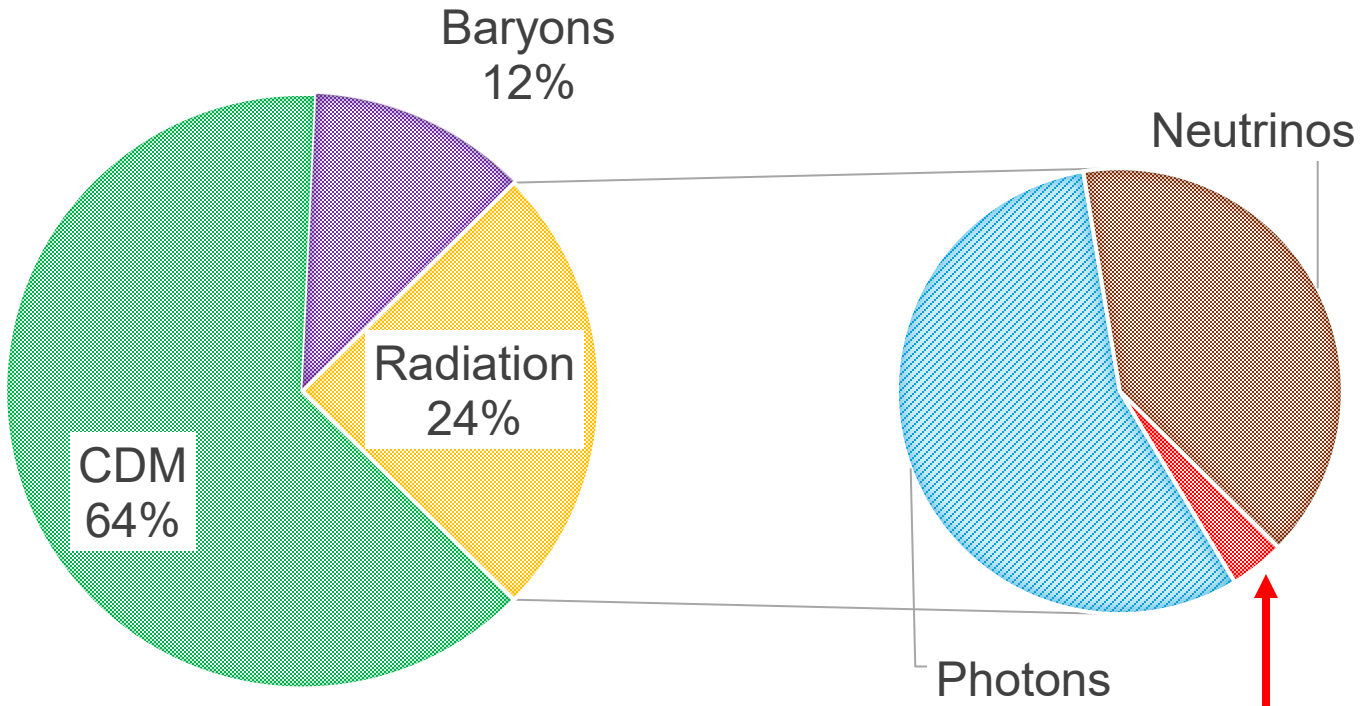
Please come talk to me if you want to know more! ☺

CMB as a probe of Beyond Standard Model

Time = Now



Time = CMB released



New Physics?

ΛCDM Radiation

$$C = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}$$

$$\omega_{\rm r} = \omega_\gamma + \omega_\nu = \omega_\gamma \left[1 + C \cdot N_{\rm fs}\right]$$

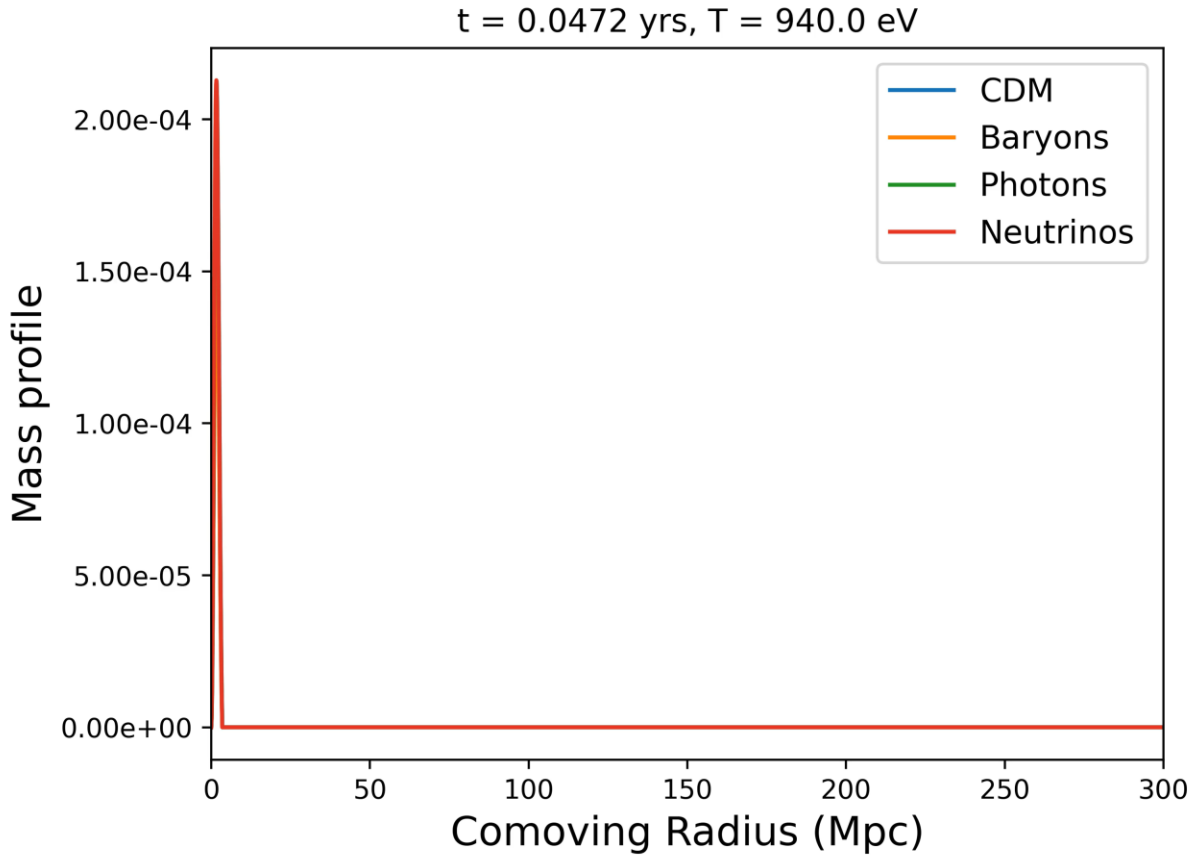
Theory: $N_{\rm fs} = 3.044$

Planck: $N_{\rm fs} = 3.08 \pm 0.17$

New Physics?

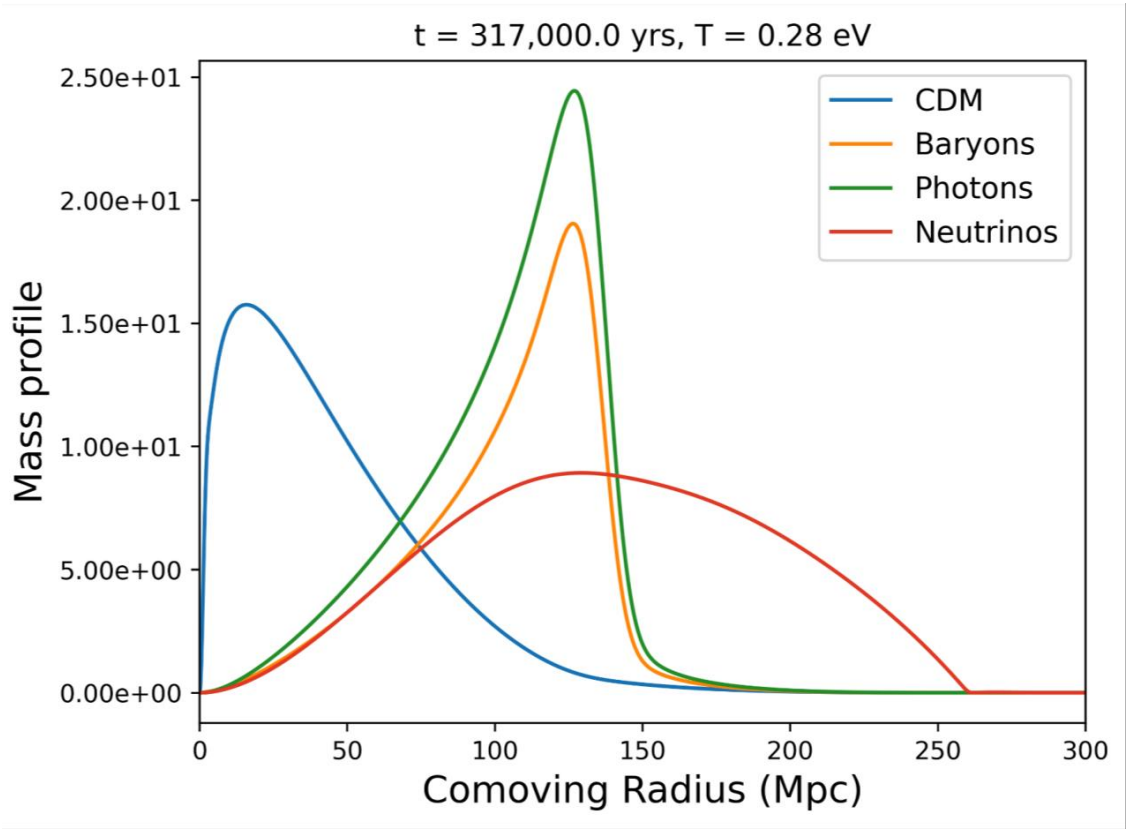
What is meant by free-streaming?

- Neutrinos have no self-interaction



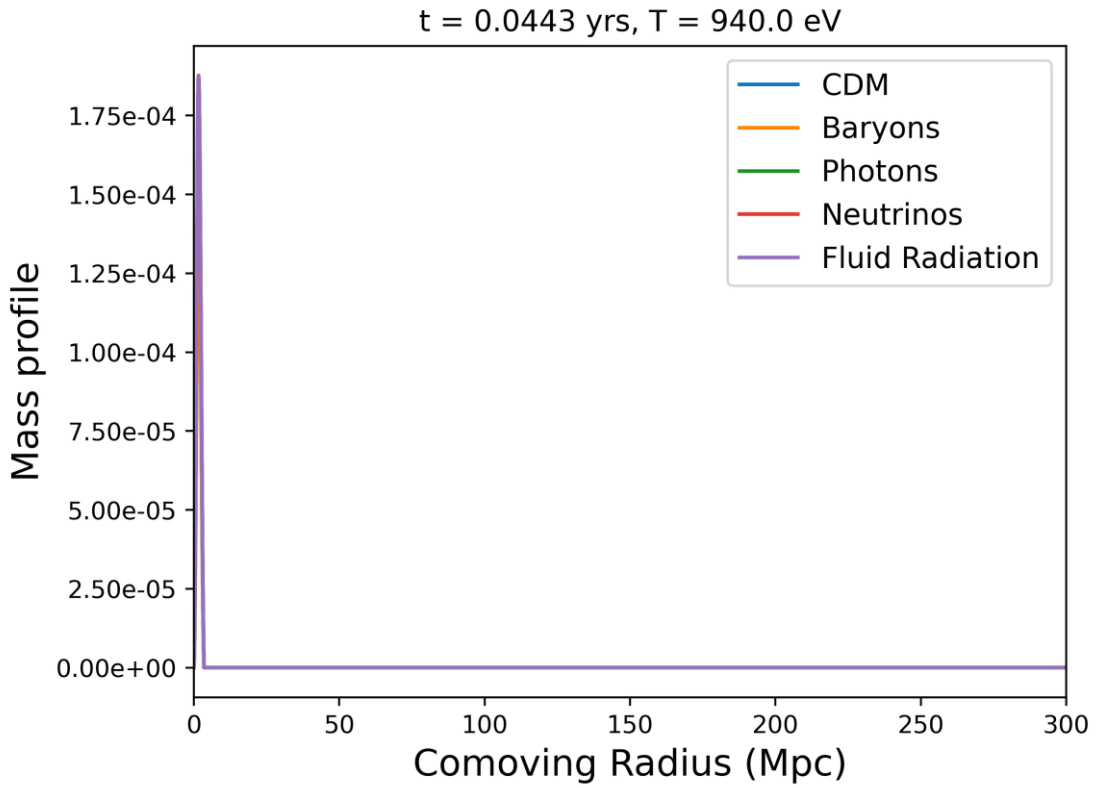
What is meant by free-streaming?

- Neutrinos have no self-interaction



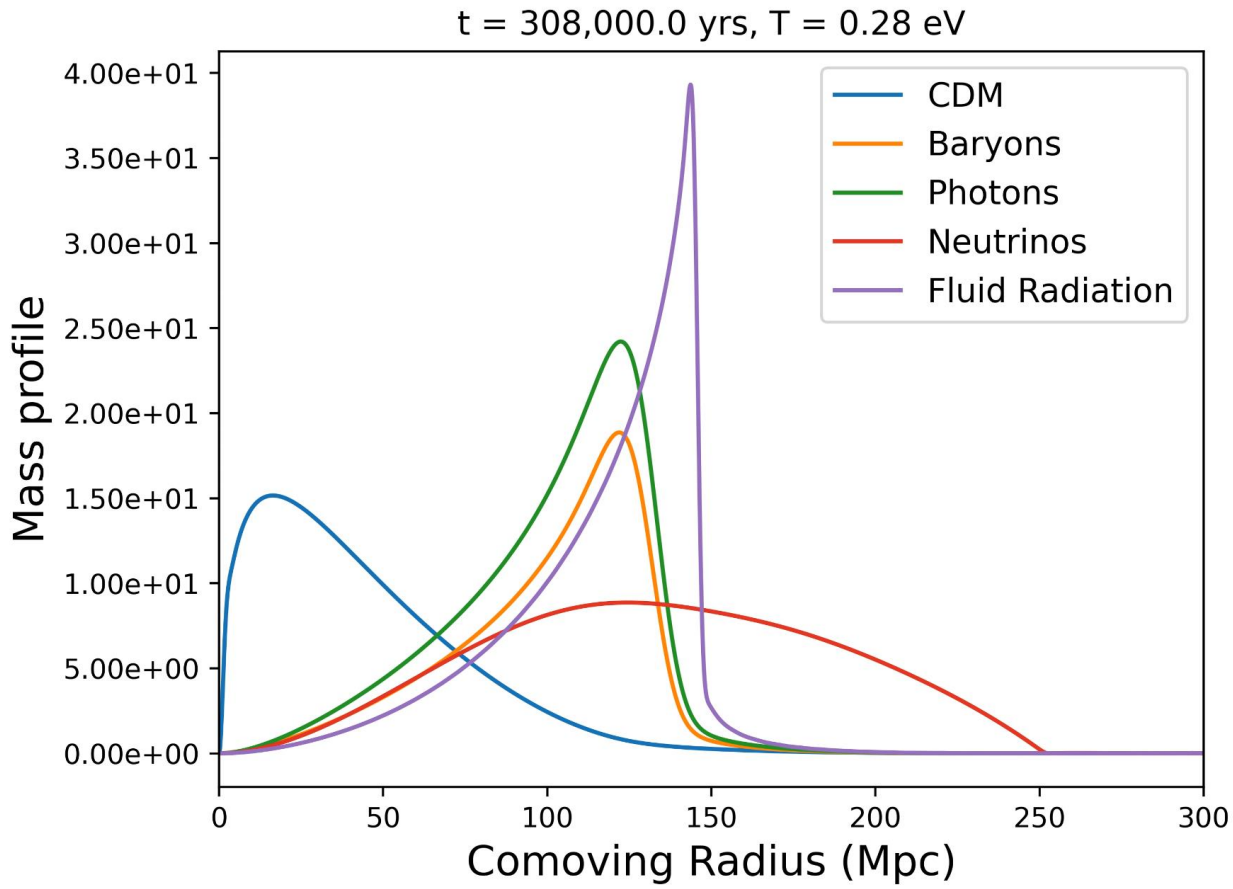
Fluidlike Radiation

- Tightly coupled radiation with sufficient self-interaction



Fluidlike Radiation

- Tightly coupled radiation with sufficient self-interaction



BSM Dark Radiation

$$C = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}$$

$$\omega_{\rm r} = \omega_\gamma + \omega_\nu + \omega_{\rm BSM} = \omega_\gamma \left[1 + C(N_{\rm fs} + \Delta N_{\rm fs} + \Delta N_{\rm fld})\right]$$

ΛCDM

$$N_{\rm tot} = N_{\rm fs} = 3.044$$
$$\Delta N_{\rm fs} = 0$$
$$\Delta N_{\rm fld} = 0$$

New Physics?

$$N_{\rm tot} = N_{\rm fs} + \Delta N_{\rm fs} + \Delta N_{\rm fld}$$

BSM Dark Radiation

$$C = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}$$

$$\omega_{\rm r} = \omega_\gamma + \omega_\nu + \omega_{\rm BSM} = \omega_\gamma \left[1 + C(N_{\rm fs} + \Delta N_{\rm fs} + \Delta N_{\rm fld})\right]$$

ΛCDM

$$N_{\rm tot} = N_{\rm fs} = 3.044$$
$$\Delta N_{\rm fs} = 0$$
$$\Delta N_{\rm fld} = 0$$

New Physics?

- Axions/Axion-like particles
- BSM Neutrino physics
- Non-Abelian Dark Sector
- Gravitational Waves
- Any light particle produced in the early Universe!
- Self-interacting = fluidlike
- No self-interactions = free-streaming

See: 1306.1536, 1501.04097, 1505.03542, 1708.09406, etc.

How do we compute (dark) radiation's effect on the CMB?

Abundance: $N_{\rm tot} = N_{\rm fs} + \Delta N_{\rm fs} + \Delta N_{\rm fld}$ } Background: Hubble

Composition: $f_{\rm fs} \equiv \omega_{\rm fs}/\omega_r$ } Perturbations (free-streaming fraction)

<u>ΛCDM</u>

$$N_{\rm tot} = N_{\rm fs} = 3.044$$

$$\Delta N_{\rm fs} = 0,\ \Delta N_{\rm fld} = 0$$

$$f_{\rm fs} \sim 0.41$$

Two sets of variables to think in

$$N_{\rm tot},\ f_{\rm fs} \quad \Longrightarrow \quad \Delta N_{\rm fs},\ \Delta N_{\rm fld}$$

Encodes Cosmology:
Abundance, composition

Encodes new physics:
changes both **abundance** and **composition**

Outline

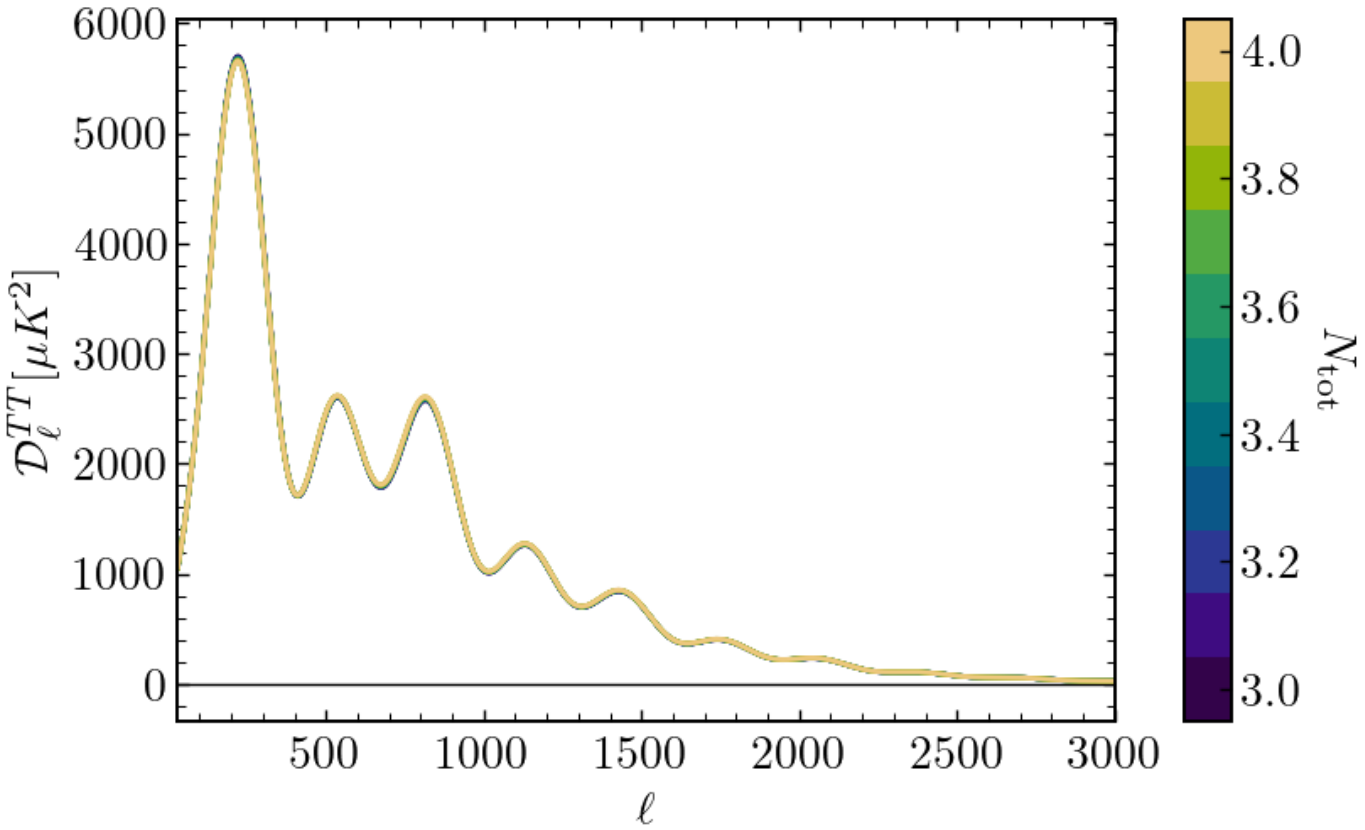
- Intro to the CMB
- What is dark radiation?
- **How do we isolate the effect of dark radiation on the CMB?**
  - **Effects of Abundance (background)**
  - Effects of Composition (perturbations)
  - Changing both
- Constraints with data
- Conclusions

Isolate effect of varying abundance

1. Fix the free-streaming fraction
2. Fix baryon density
3. Fix matter-radiation equality
4. Fix sound horizon
5. Fix damping scale

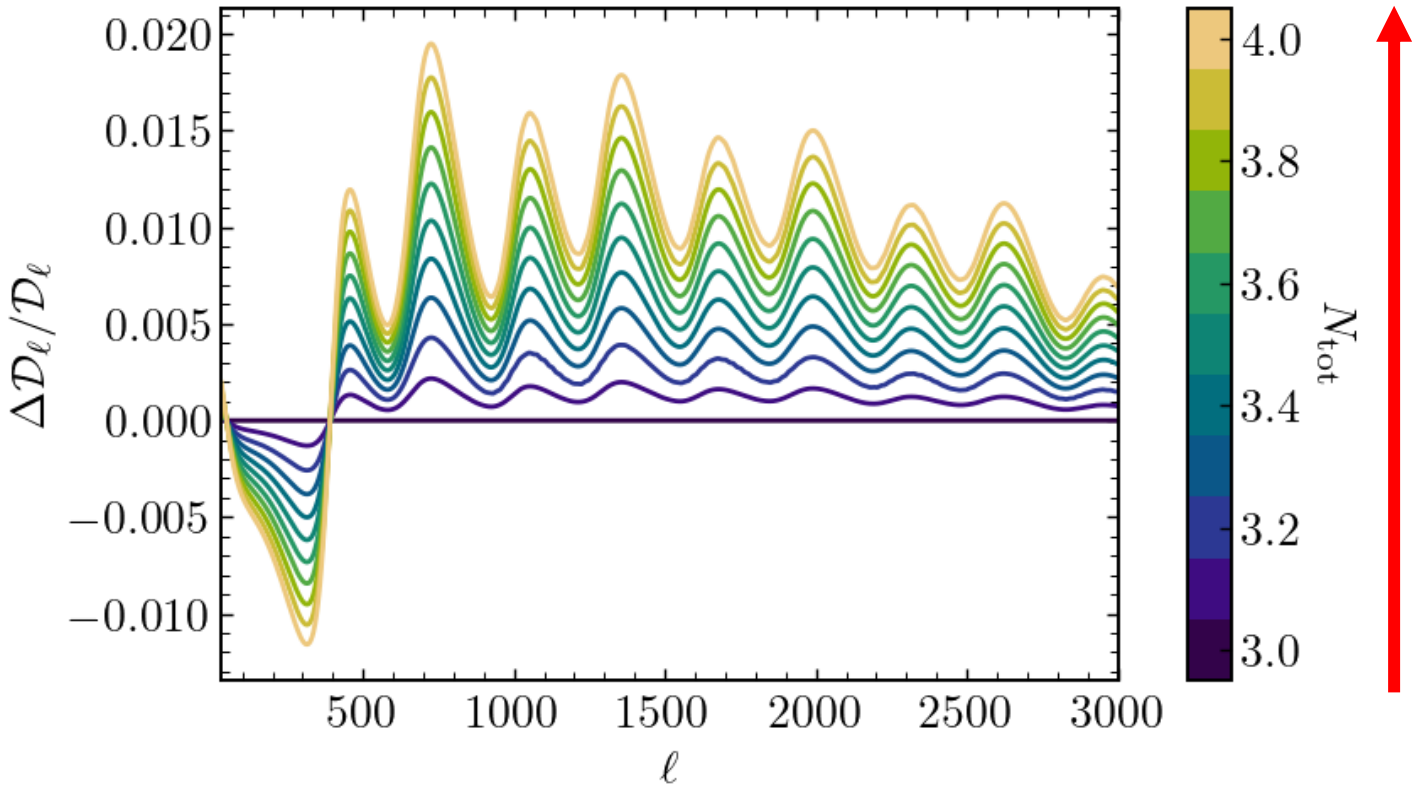
Isolate effect of varying abundance

1. Fix the free-streaming fraction
2. Fix baryon density
3. Fix matter-radiation equality
4. Fix sound horizon
5. Fix damping scale



Isolate effect of varying abundance

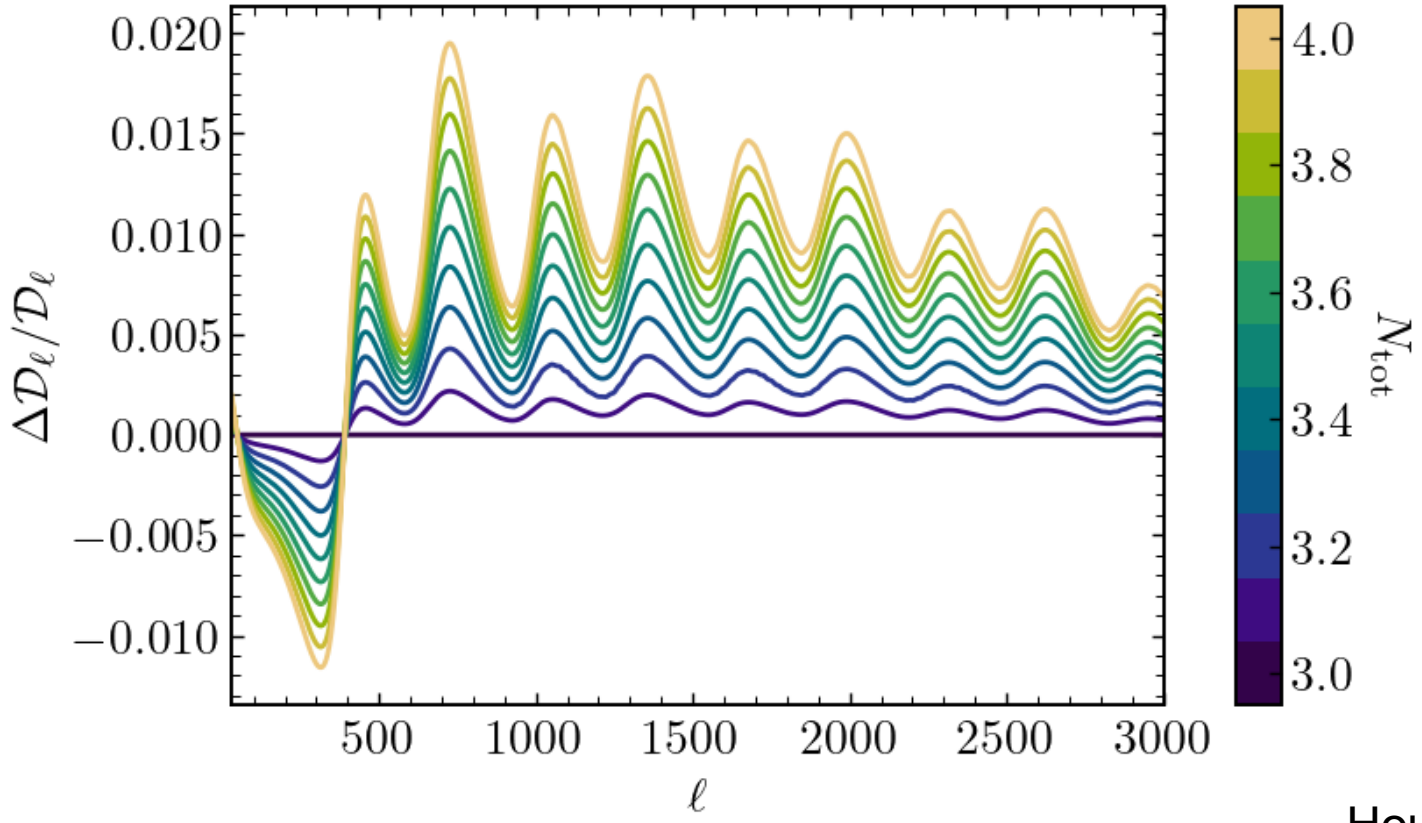
1. Fix the free-streaming fraction
2. Fix baryon density
3. Fix matter-radiation equality
4. Fix sound horizon
5. Fix damping scale



Decreasing ω_b/ω_{cb}

Pressure supported matter fraction ω_b/ω_{cb}

$$\psi \propto \omega_c \delta_c$$



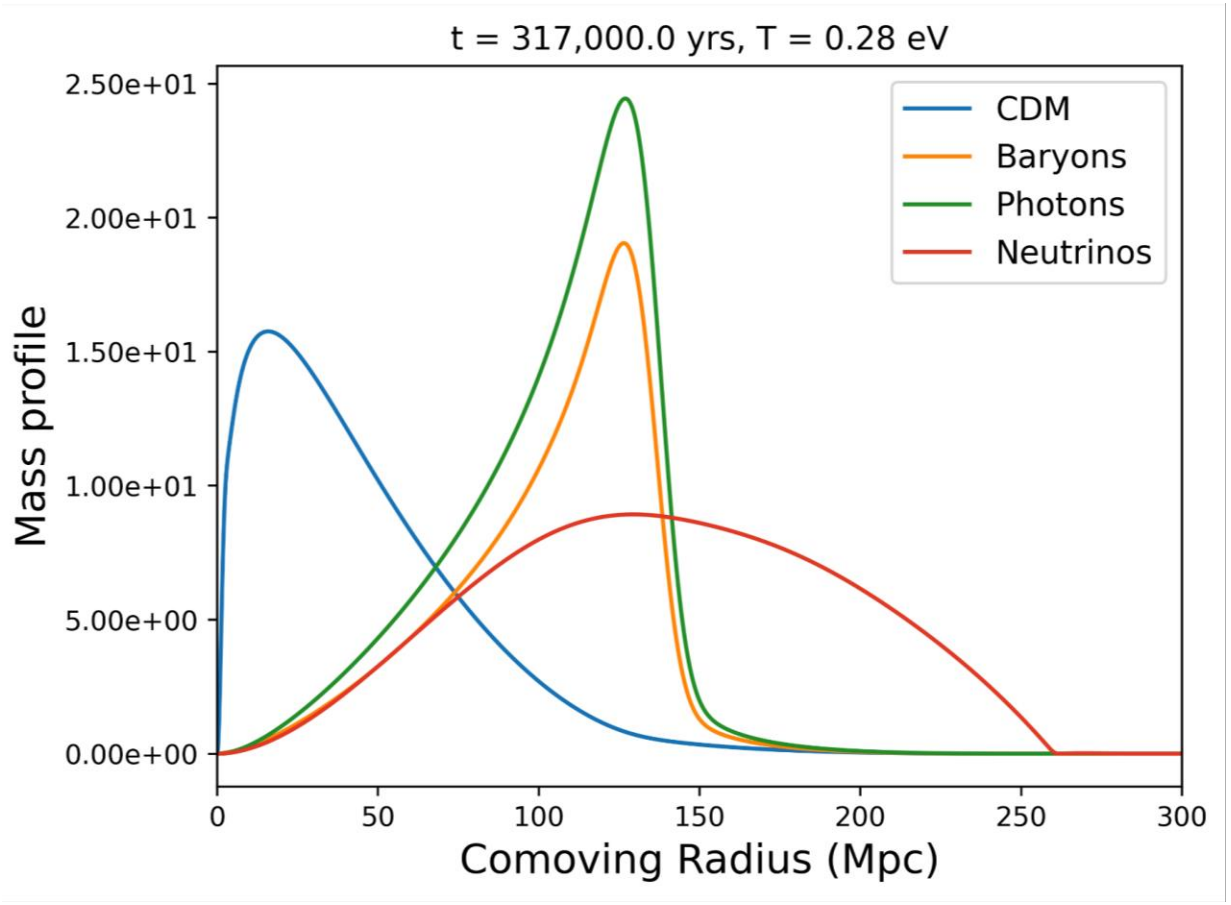
Fixed: $f_{\rm fs}$, θ_s, ω_b, $a_{\rm eq}$, r_D

Hou et al (2011),
Ge et al (2022)

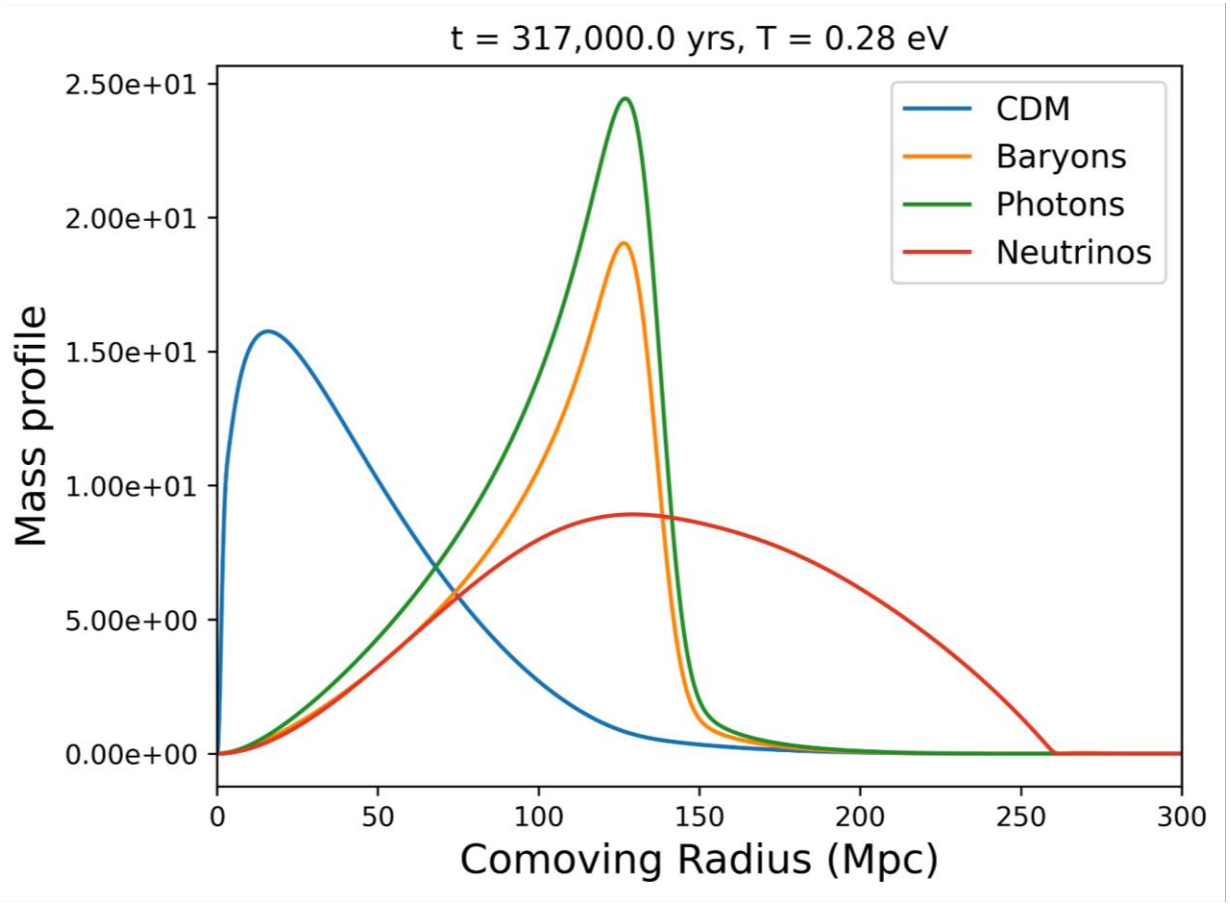
Outline

- Intro to the CMB
- What is dark radiation?
- How do we isolate the effect of dark radiation on the CMB?
  - Effects of Abundance (background)
  - **Effects of Composition (perturbations)**
  - Changing both
- Constraints with data
- Conclusions

Changing the free-streaming fraction



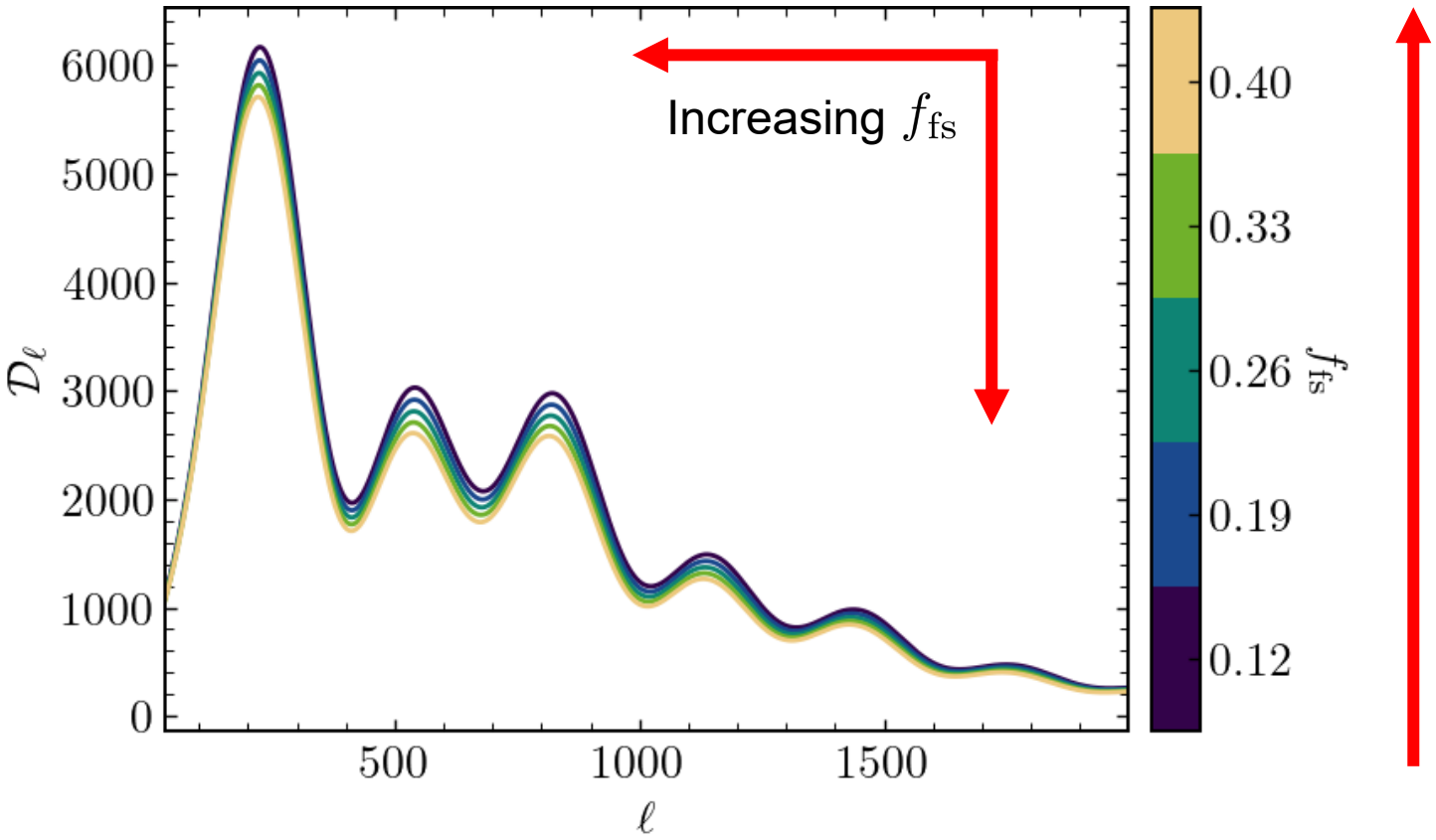
Changing the free-streaming fraction



Decrease amplitude

Move power to larger scales

Changing the free-streaming fraction



Decrease amplitude

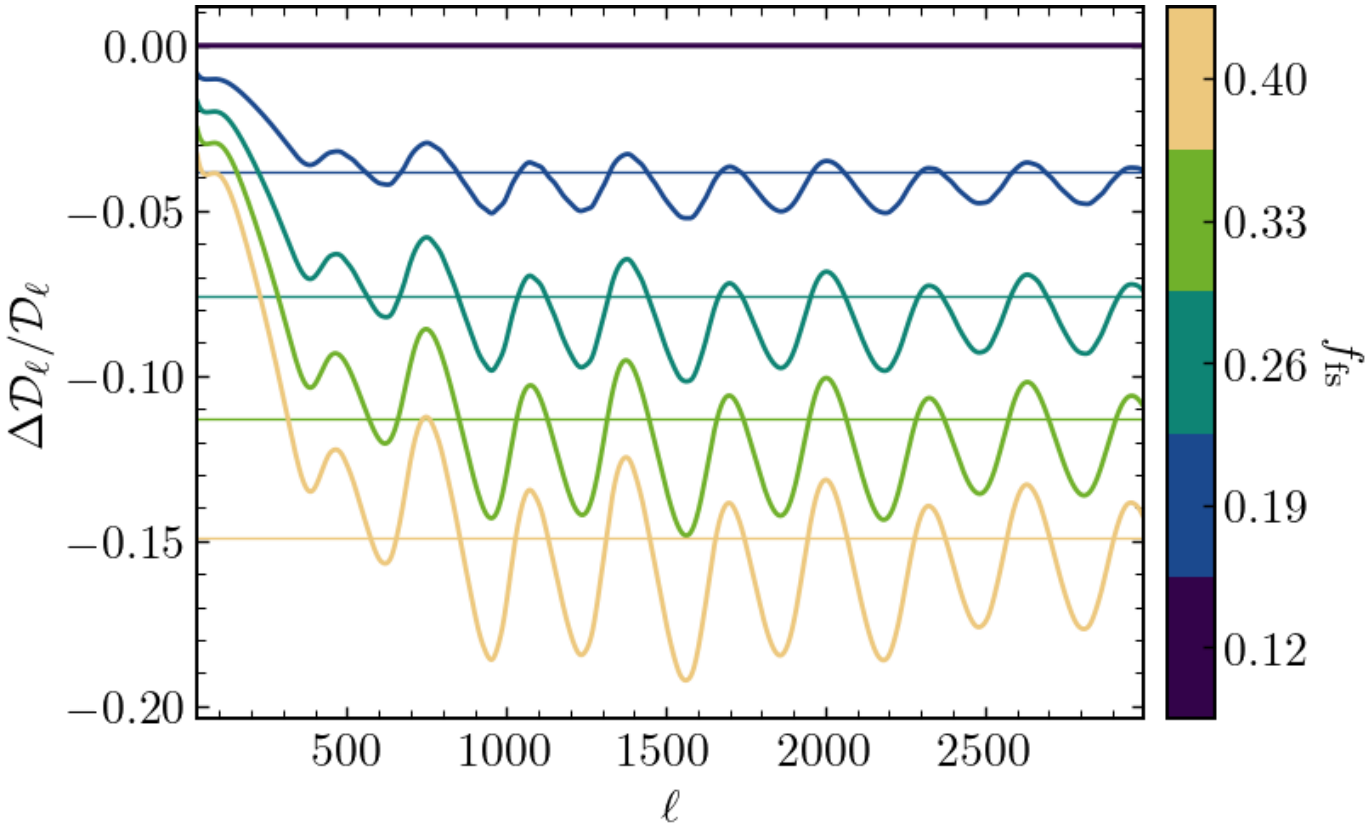
$$\frac{\Delta\mathcal{D}_\ell(f_{\rm fs})}{\mathcal{D}_\ell(f_{\rm fs})} = -0.246\frac{\Delta f_{\rm fs}}{f_{\rm fs}}$$

Move power to larger scales

$$\delta\ell \approx -0.19 f_{\rm fs}\Delta\ell$$

Uros and Seljak (2003),
Baumann et al (2016)

Changing the free-streaming fraction



Decrease amplitude

$$\frac{\Delta\mathcal{D}_\ell(f_{\rm fs})}{\mathcal{D}_\ell(f_{\rm fs})} = -0.246\frac{\Delta f_{\rm fs}}{f_{\rm fs}}$$

Phase Shift

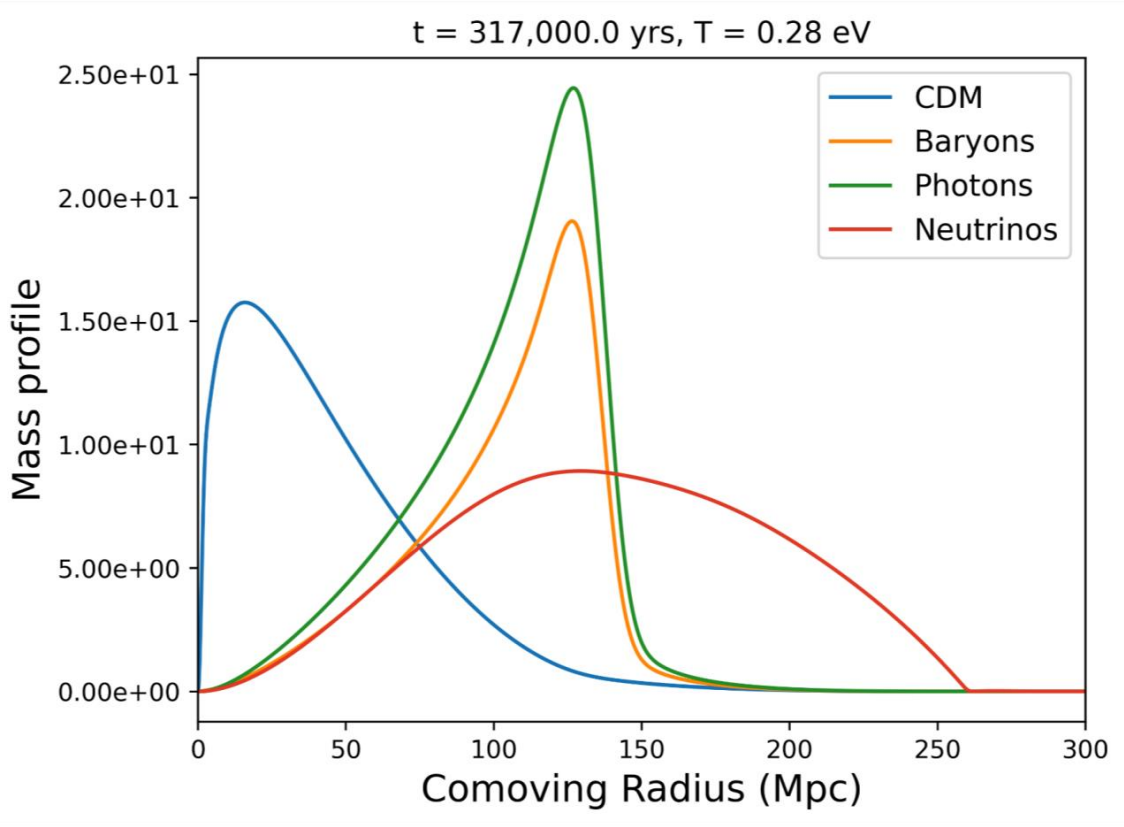
$$\delta\ell \approx -0.19 f_{\rm fs}\Delta\ell$$

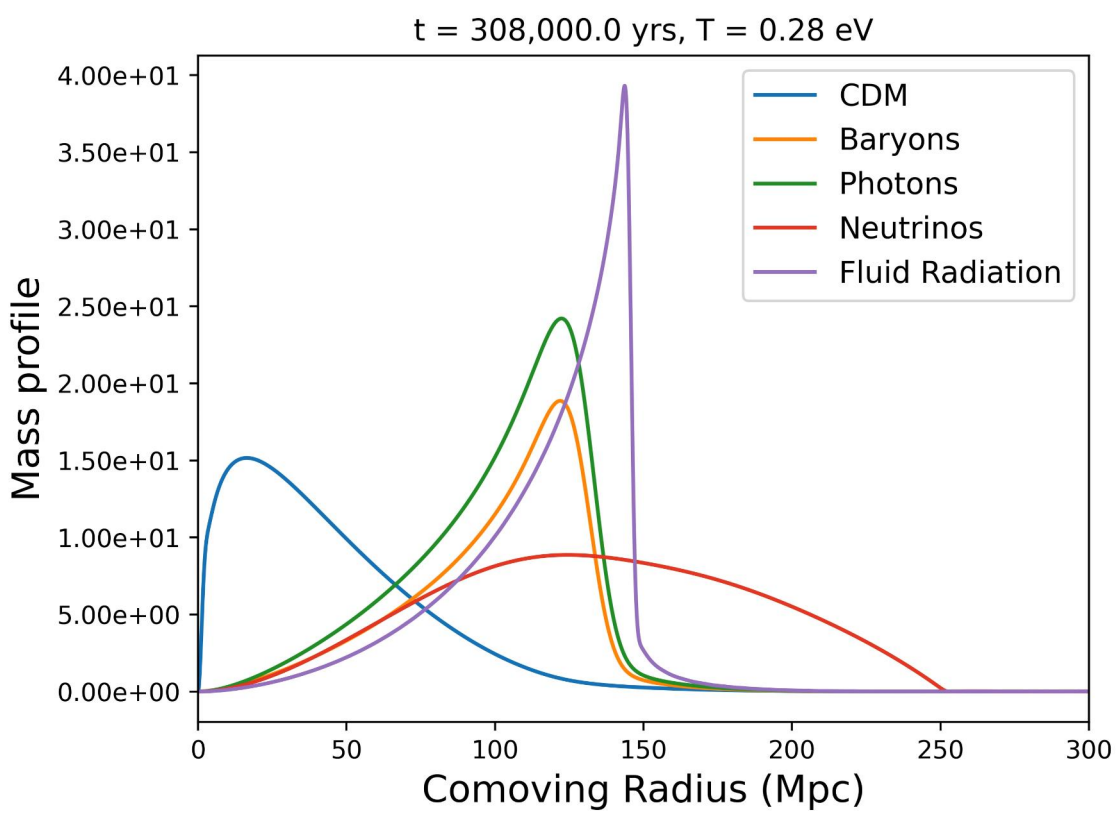
Bashinsky and Seljak (2003),
Baumann et al (2016)

Outline

- Intro to the CMB
- What is dark radiation?
- **How do we isolate the effect of dark radiation on the CMB?**
  - Effects of Abundance (background)
  - Effects of Composition (perturbations)
  - **Changing both**
- Constraints with data
- Future work
- Other work
- Conclusions

Free-streaming vs fluidlike radiation





Free-streaming vs fluidlike radiation

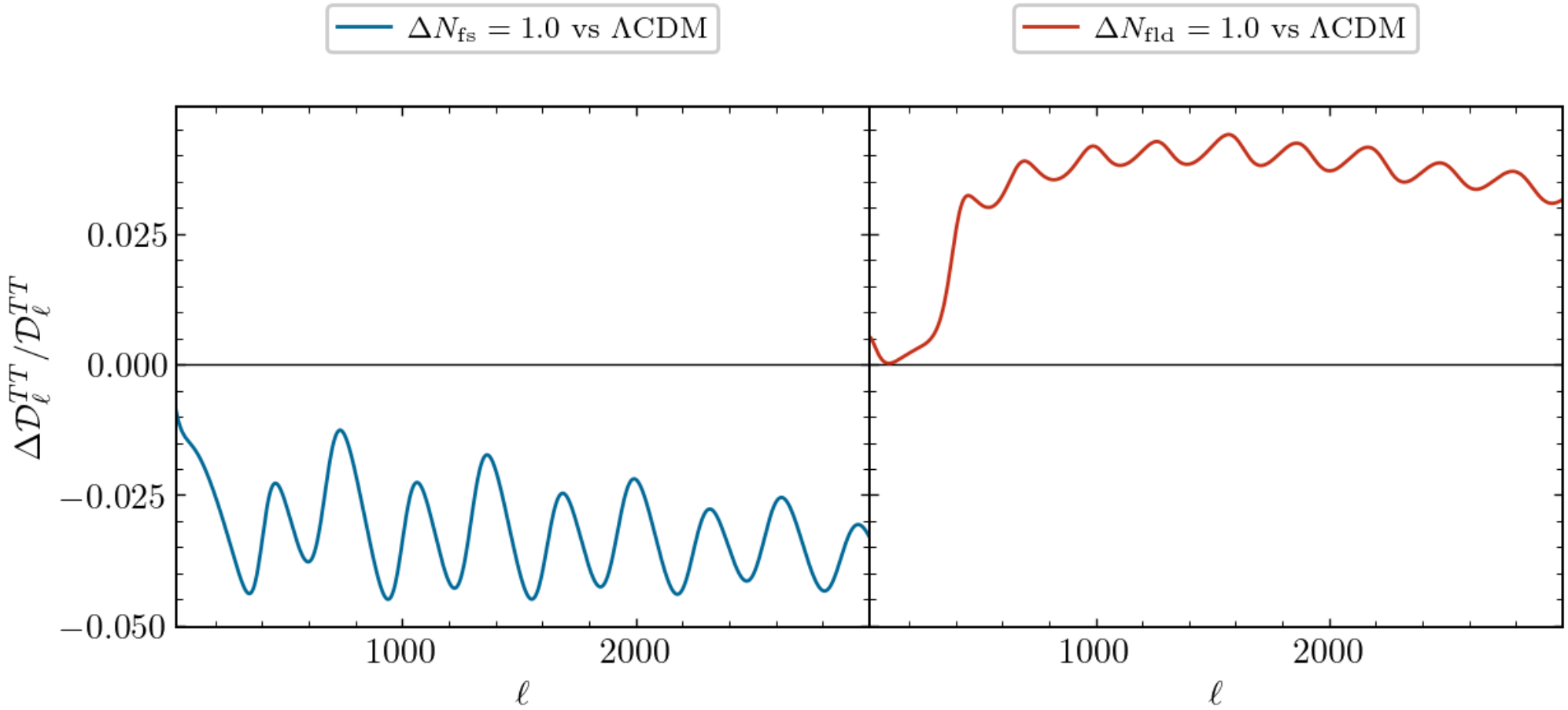
- Differential impact on free-streaming fraction

$$\Delta N_{\rm fs}\colon N_{\rm tot}\uparrow \quad f_{\rm fs}\uparrow$$

$$\Delta N_{\rm fld}\colon N_{\rm tot}\uparrow \quad f_{\rm fs}\downarrow$$

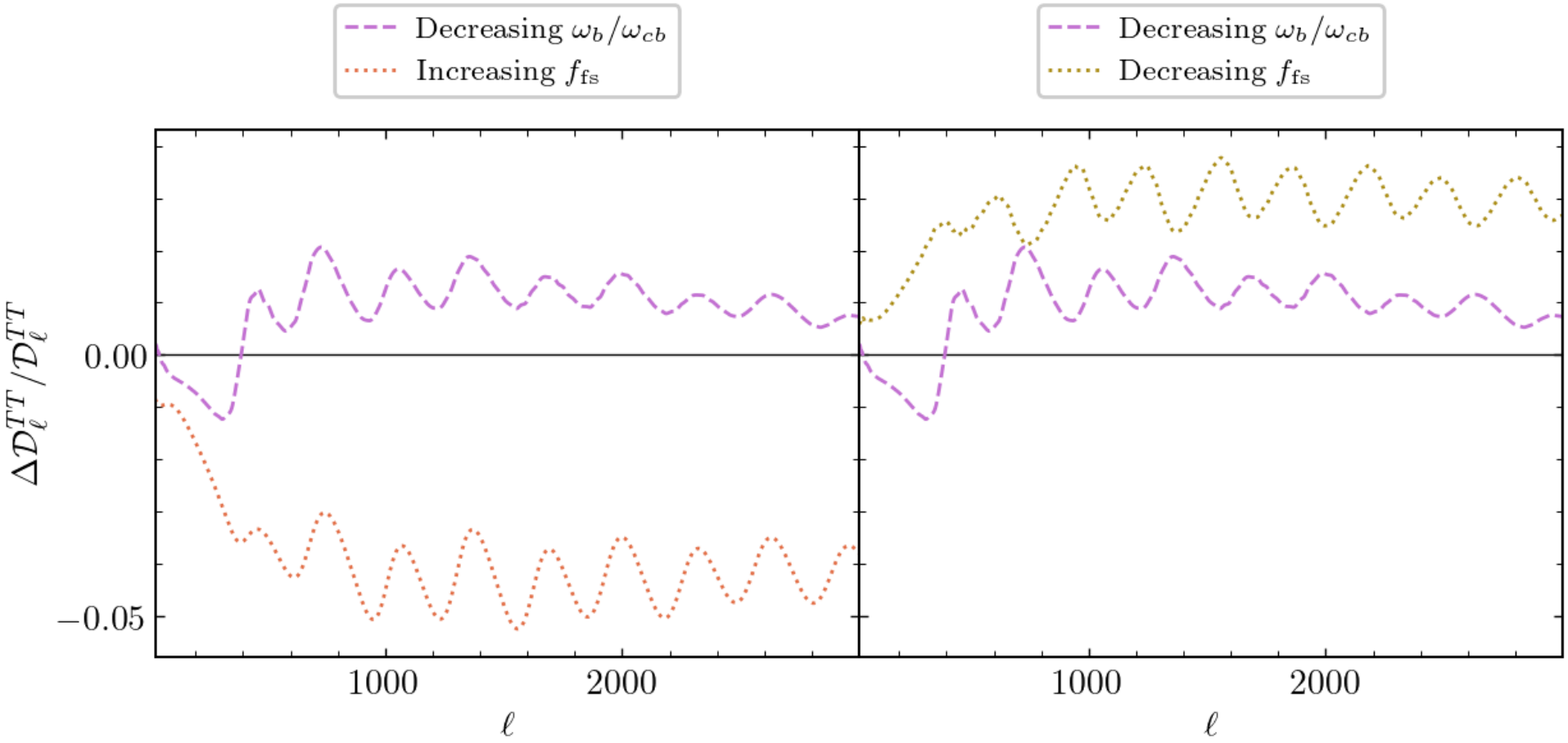
- What is the physical effect in the CMB?

Free-streaming vs fluidlike radiation



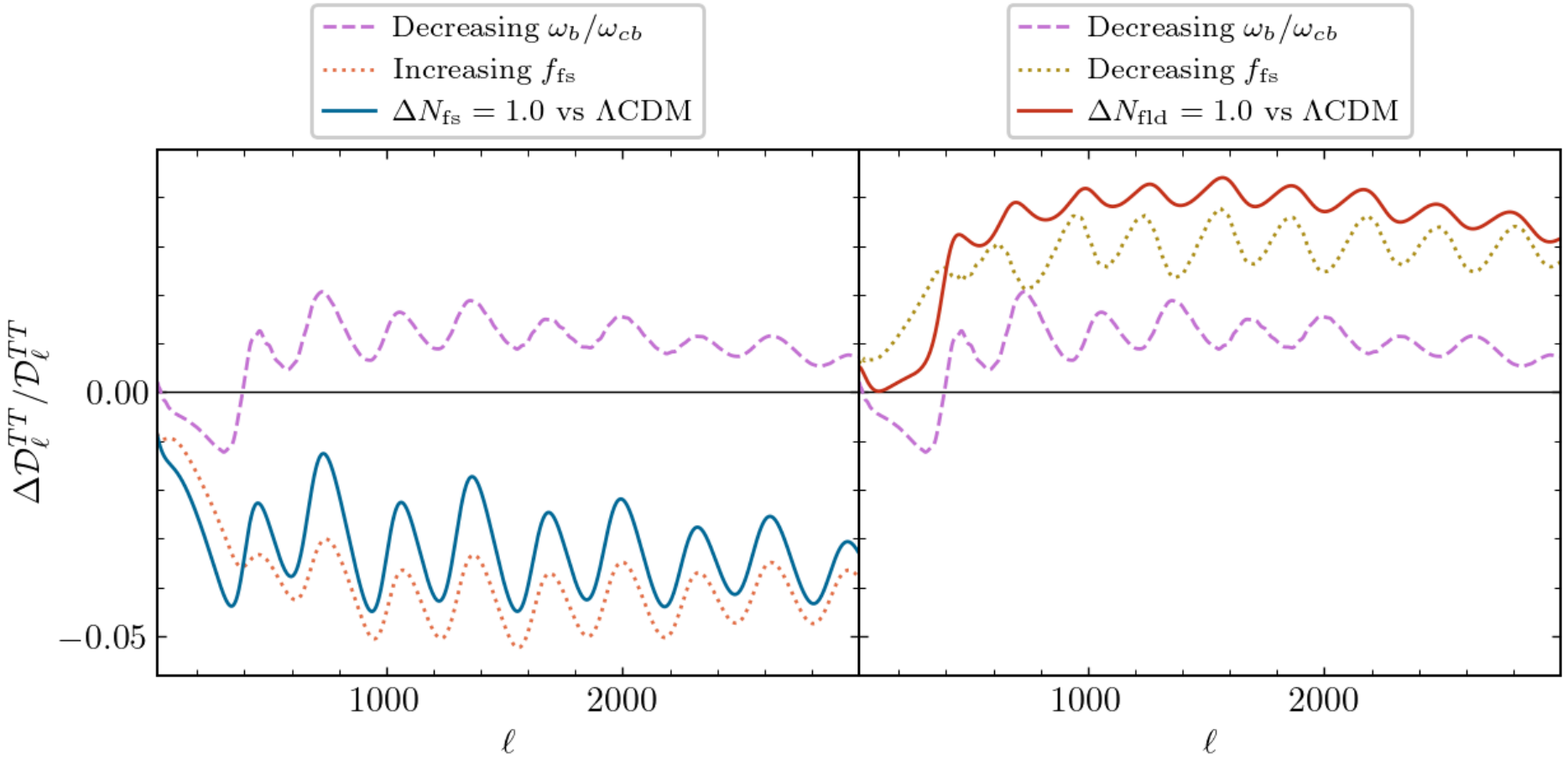
Fixed: θ_s, ω_b, $a_{\rm eq}$, r_D

Pressure supported matter fraction and free-streaming fraction



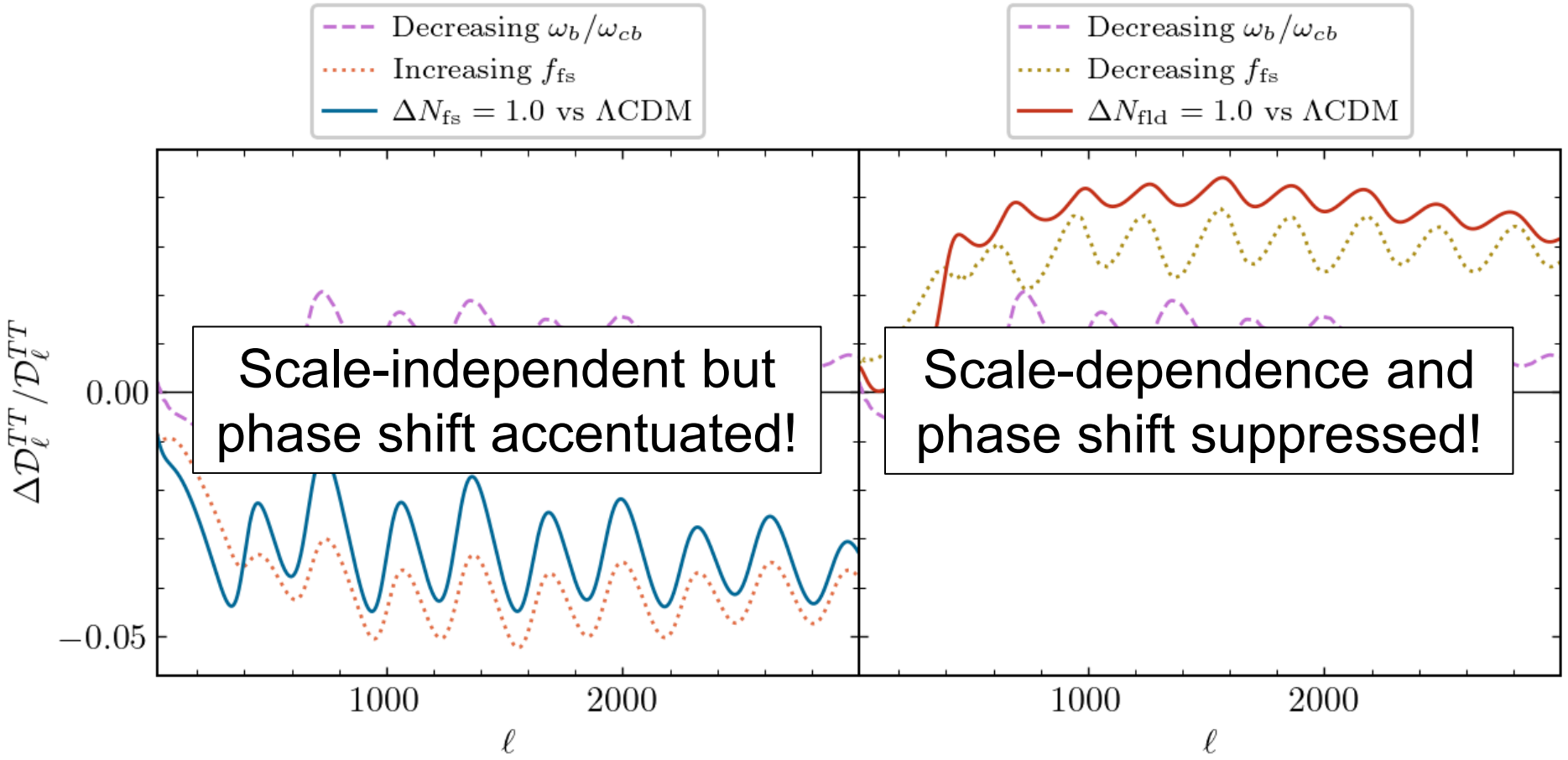
Fixed: θ_s, ω_b, $a_{\rm eq}$, r_D

Effects combine
Roughly: solid = dashed + dotted



Fixed: θ_s, ω_b, $a_{\rm eq}$, r_D

Effects combine
Roughly: solid = dashed + dotted



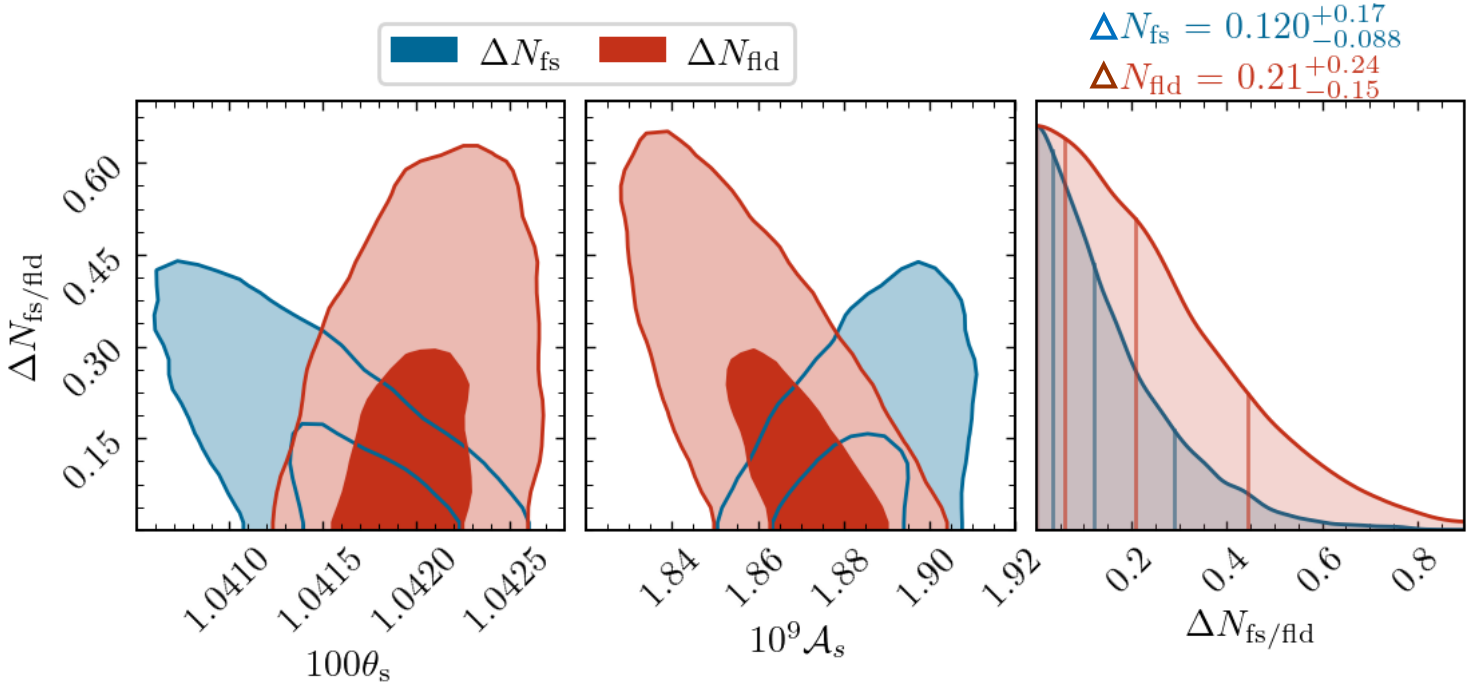
Fixed: θ_s, ω_b, $a_{\rm eq}$, r_D

Outline

- Intro to the CMB
- What is dark radiation?
- How do we isolate the effect of dark radiation on the CMB?
- **Constraints with data**
  - **CMB only**
  - BAO Data
- Conclusions

Free-streaming vs fluid radiation

- Place upper bounds on contribution to energy budget
- Planck PR4 data
- $Y_{\rm He}$ free



MMS, Loverde, Brinckmann, Weiner (2025)

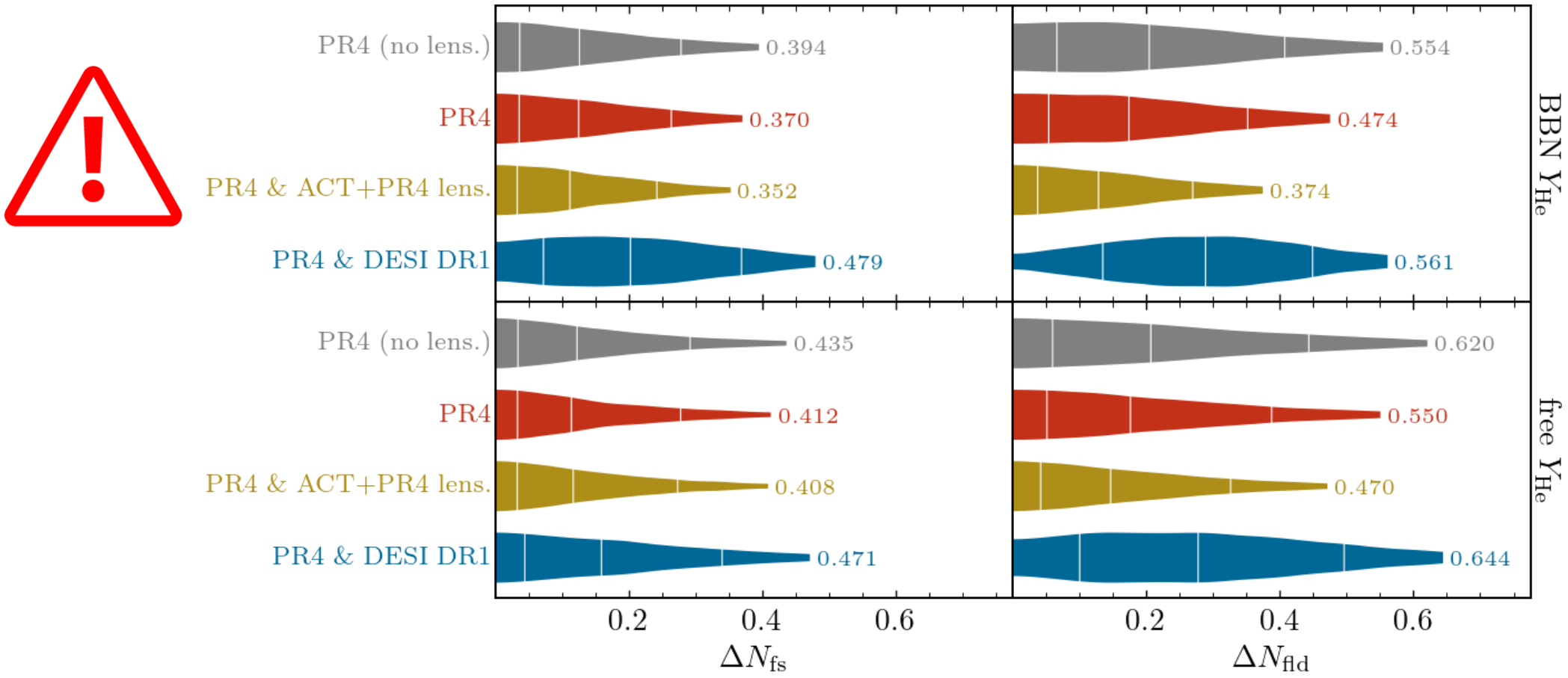
Free-streaming vs fluid radiation

- Constraints on free-streaming radiation are tighter than fluidlike radiation
- Interpretation: the phase shift induced by changes to **both** free-streaming fraction and pressure-supported matter fraction are incompatible with the data
- Other parameters are compensating for scale dependent feature of fluidlike radiation

Outline

- Intro to the CMB
- What is dark radiation?
- How do we isolate the effect of dark radiation on the CMB?
- **Constraints with data**
  - CMB only
  - **BAO Data**
- Future work
- Conclusions

Constraints with BAO data



MMS, Loverde, Brinckmann, Weiner (2025)

Interpreting BAO Data

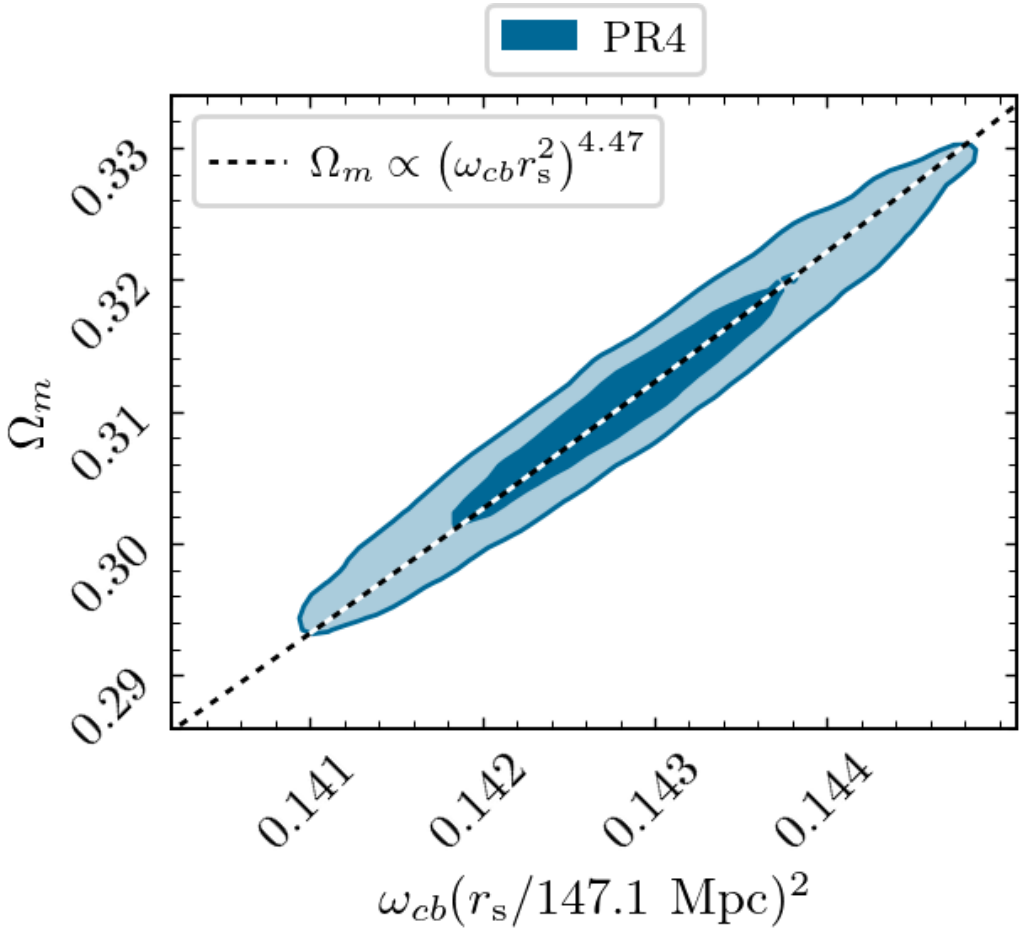
- The precision of the measurement of the angular sound horizon requires:

$$\Omega_m|_{\theta_s} \propto \left(\omega_{cb} r_s^2\right)^5$$

Interpreting BAO Data

- The precision of the measurement of the angular sound horizon requires:

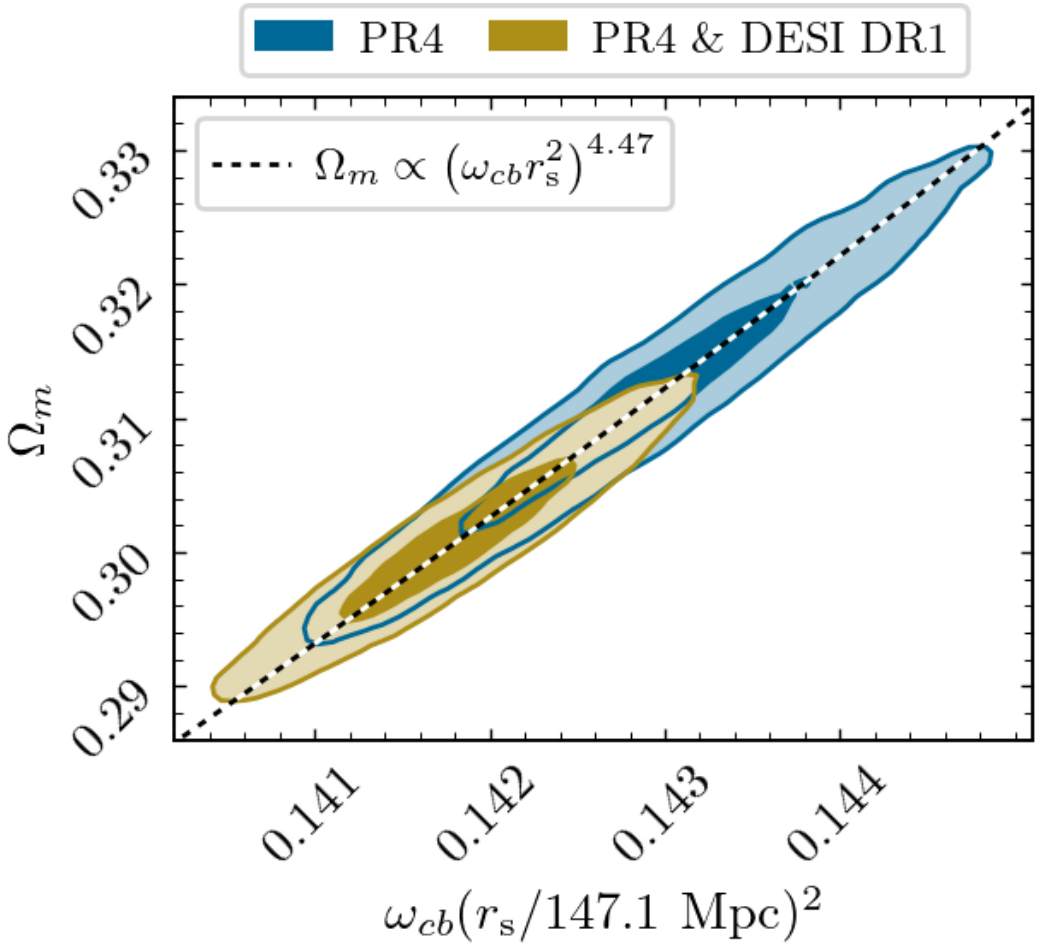
$$\Omega_m|_{\theta_s} \propto \left(\omega_{cb} r_s^2\right)^5$$



Interpreting BAO Data

- The precision of the measurement of the angular sound horizon requires:

$$\Omega_m|_{\theta_s} \propto \left(\omega_{cb} r_s^2\right)^5$$

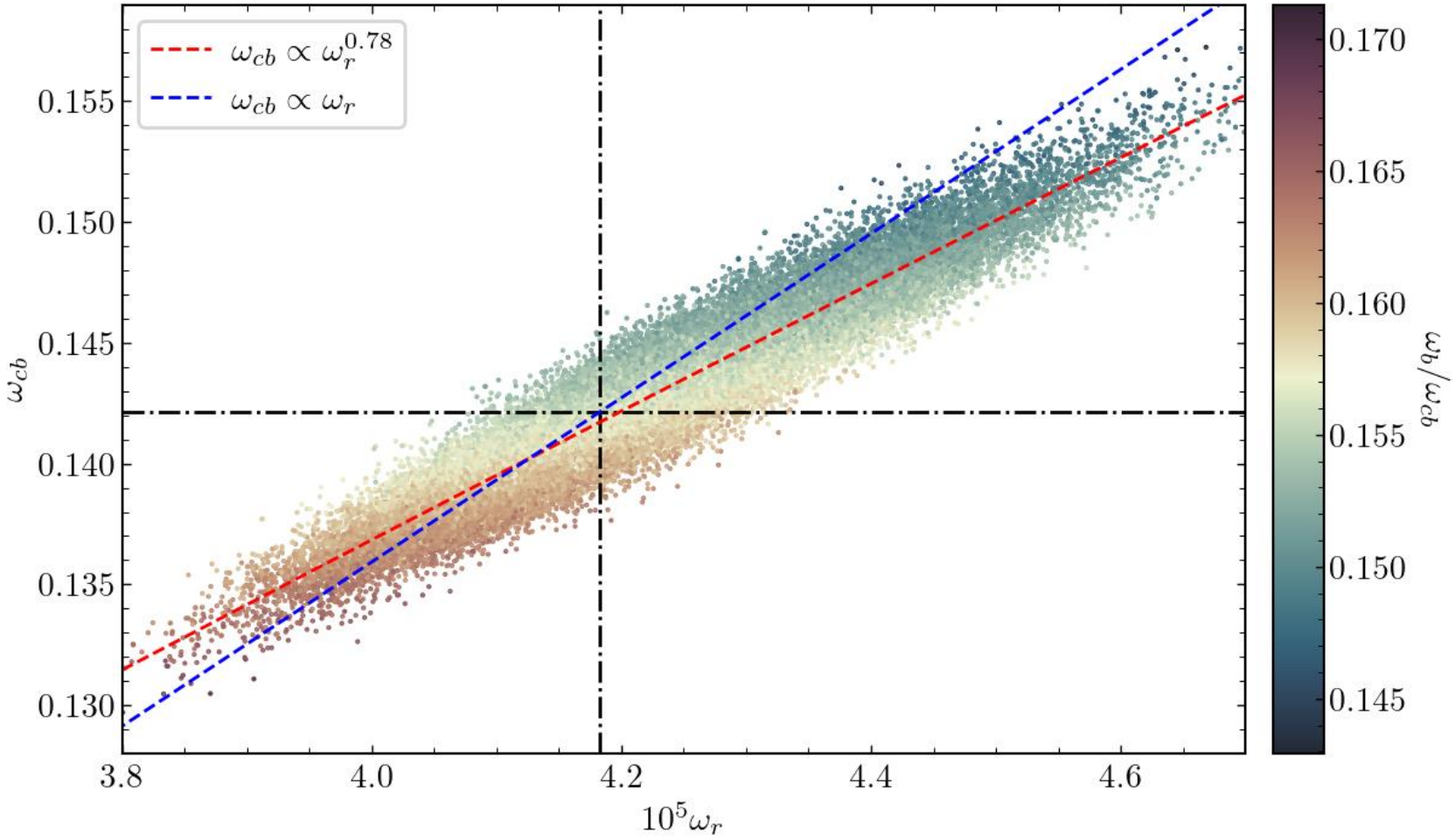


Why does increasing radiation move along the degeneracy direction?

- Fixing equality requires: $\omega_{cb} \propto \omega_r$
- Fixing θ_s requires: $r_s \propto 1/\sqrt{\omega_r}$

$$\Omega_m|_{\theta_s} \propto \left(\omega_{cb} r_s^2\right)^5$$

Fixing equality vs fixing the pressure-supported matter fraction

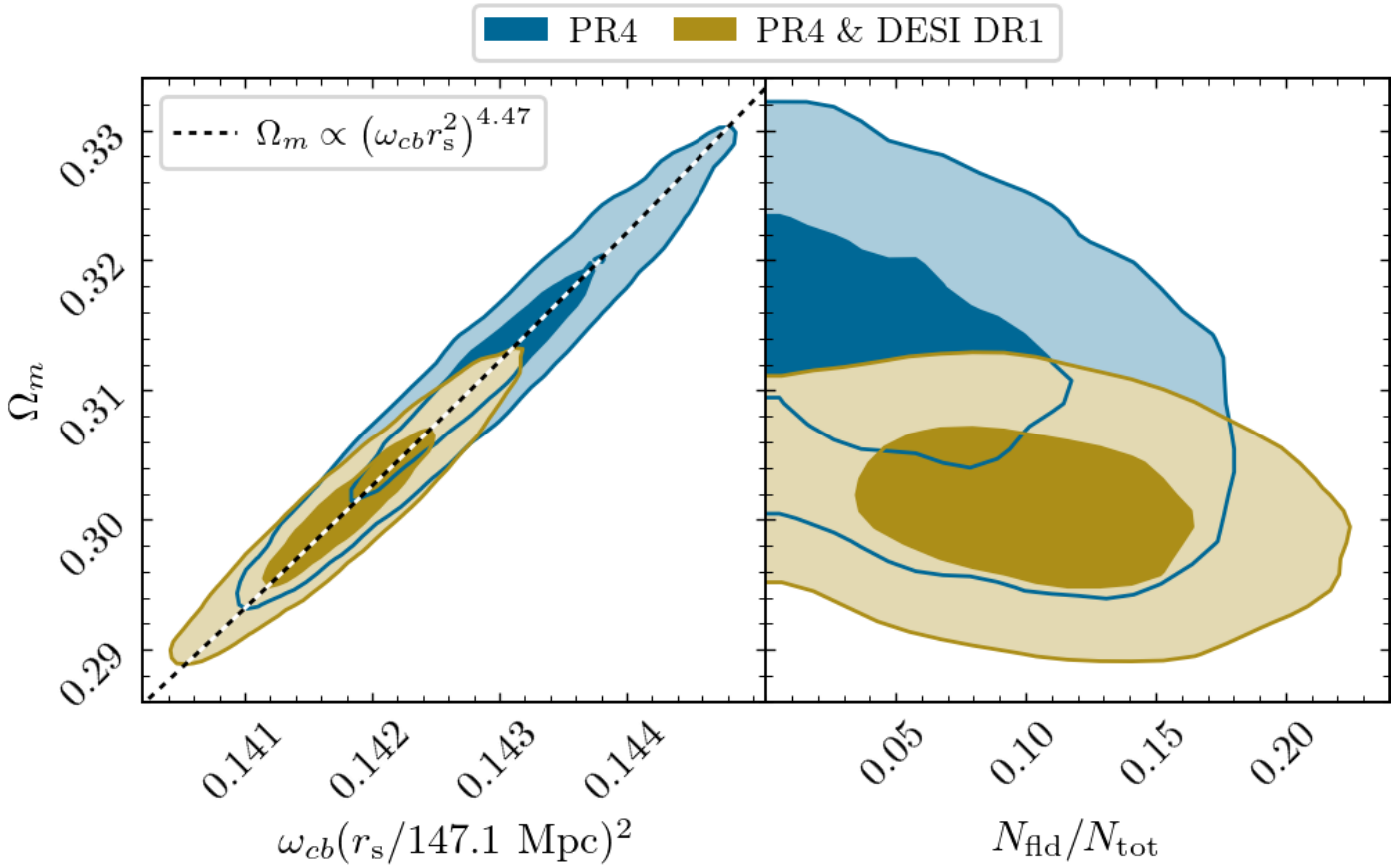


$$\omega_{cb} \propto \omega_r^{0.78}$$

$$r_s \propto 1/\sqrt{\omega_r}$$

$$\Omega_m|_{\theta_s} \propto \left(\omega_{cb} r_s^2\right)^5$$

Interpreting BAO Data



Easier to add fluid radiation!

Also in the paper

- Numerical degeneracy with LCDM parameters
- Breaking degeneracies with large scale structure data
- Differences between 2018 and 2020 analysis of Planck data
- Interplay with inflationary parameters (running of the tilt)
- Impact of CMB lensing and SDSS BAO data
- Constraints from different multipole ranges
- ~~S4 forecasts~~

Outline

- Intro to the CMB
- What is dark radiation?
- How do we isolate the effect of dark radiation on the CMB?
- Constraints with data
  - CMB only
  - BAO Data
- **Conclusions**

Conclusions

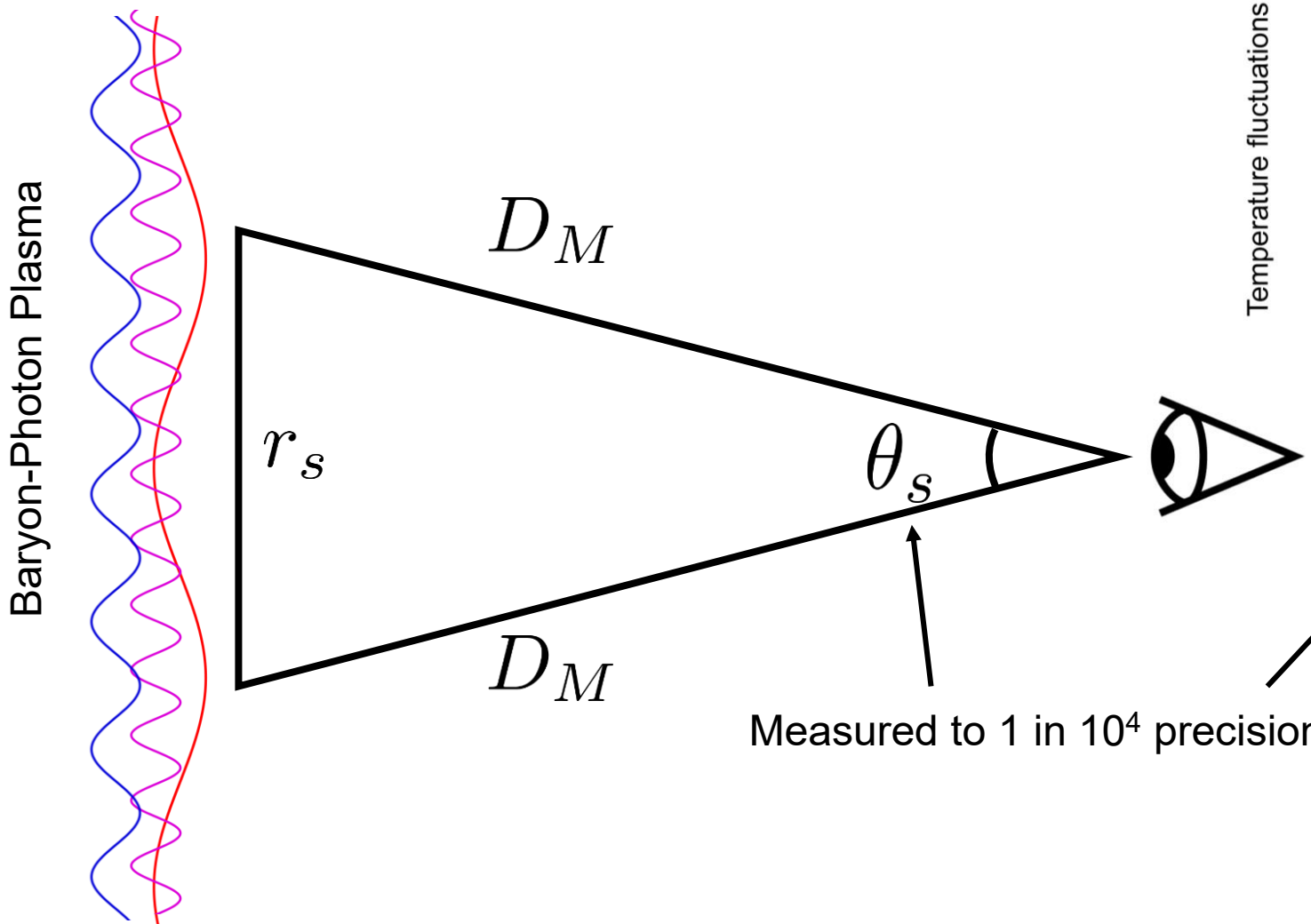
- CMB constraints on fluidlike radiation are weaker. The data is incompatible with the phase shift induced by free-streaming radiation.
  - Phase shift induced by **both** free-streaming fraction and pressure-supported matter fraction effects
- DESI BAO data prefers more radiation due to a preference for lower matter fraction

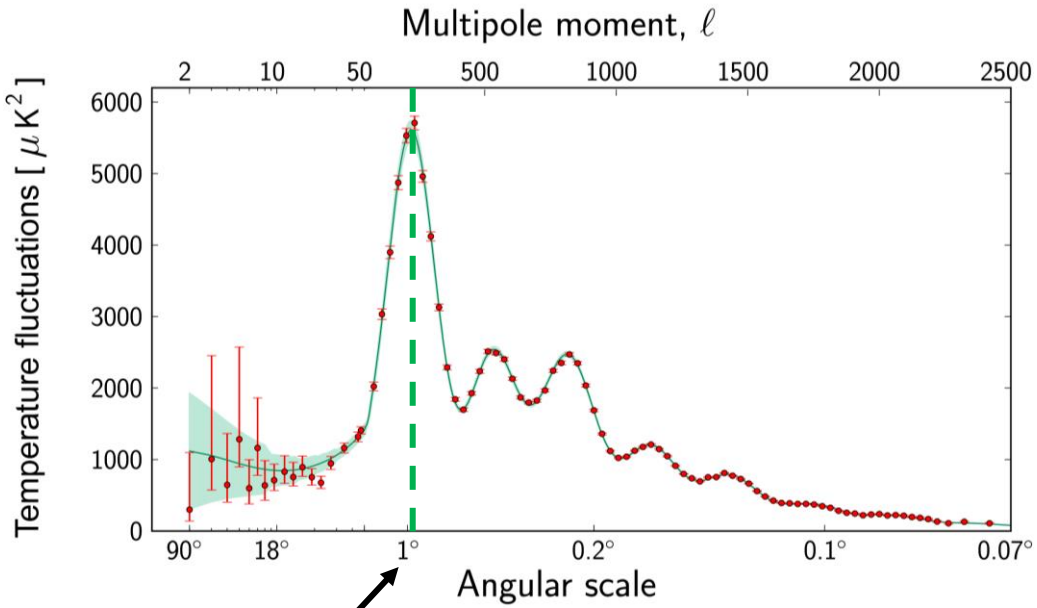
Conclusions (contd.)

- Must look for new physics in **sufficient generality**
- Even a simple model has many complex, nuanced features! Rich interplay between the ‘old’ and ‘new’ physics
- Need to **interpret** constraints carefully in the data space.

Thanks! Questions?

The sound horizon





Measured to 1 in 10^4 precision!

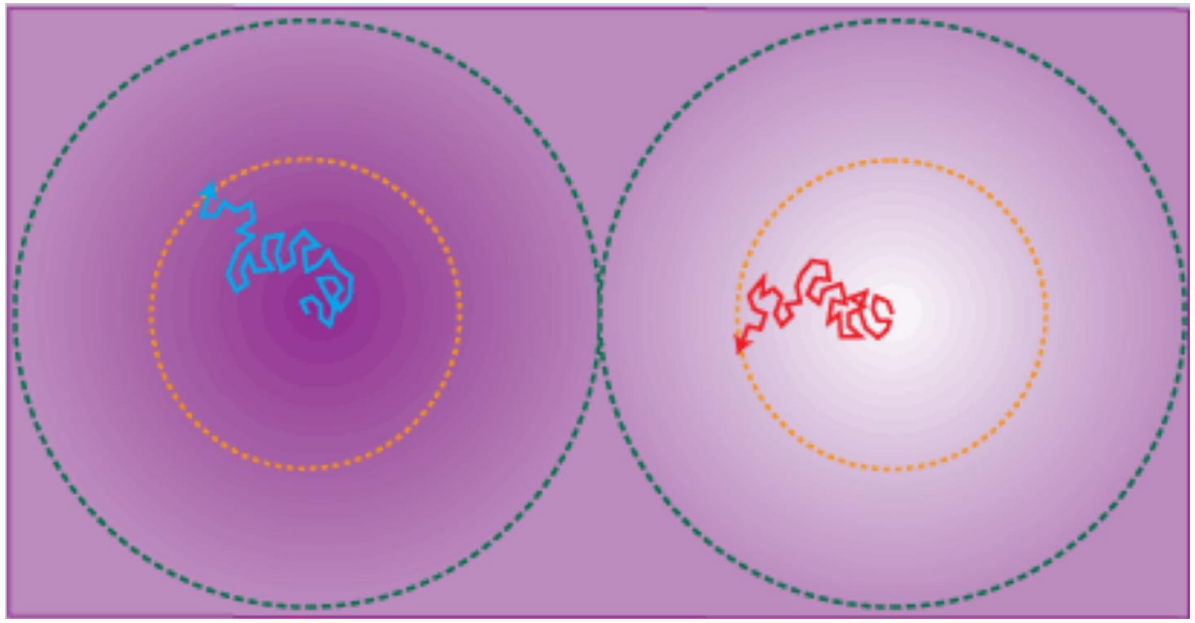
$$\theta_s \propto 1/\ell_0$$

Determined by peak locations

FYI: Moon is 0.5°

Diffusion Damping

- Anisotropies with size below the mean free path of photons are damped



Credit: Wayne Hu

$$r_D^2 \propto \frac{H}{n_e \sigma_T} \propto \frac{H}{(1-Y_{\rm He})\sigma_T}$$

n_e Free electron number density

σ_T Thompson cross-section

$Y_{\rm He}$ Fraction of baryonic mass in Helium

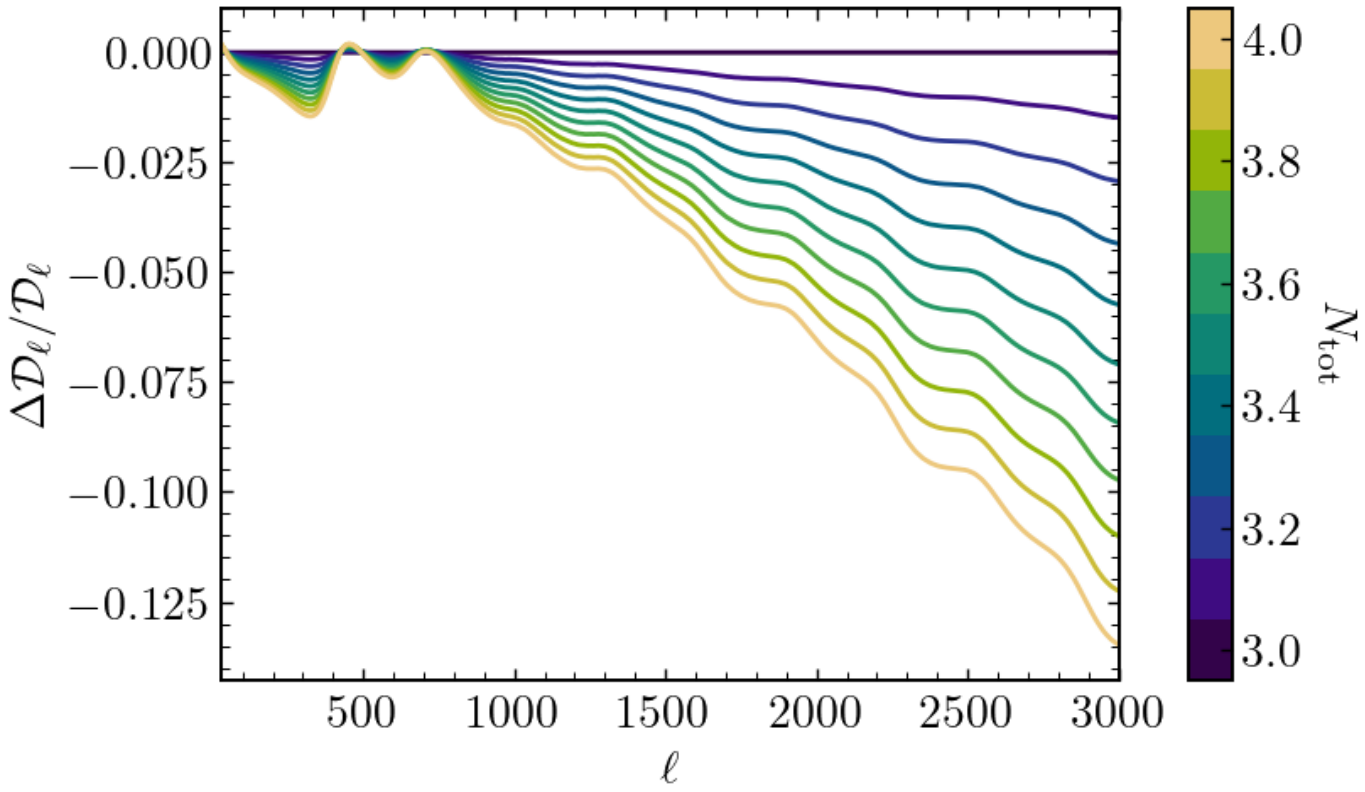
Fixing $\theta_s \Longrightarrow H \propto \sqrt{\omega_r}$

Isolate effect of varying abundance

1. Fix the free-streaming fraction
2. Fix baryon density
3. Fix matter-radiation equality
4. Fix sound horizon

Varying radiation density causes more diffusion damping!

$$r_D/r_s \propto \frac{\omega_r^{0.134}}{(1-Y_{\rm He})^{0.238}}$$

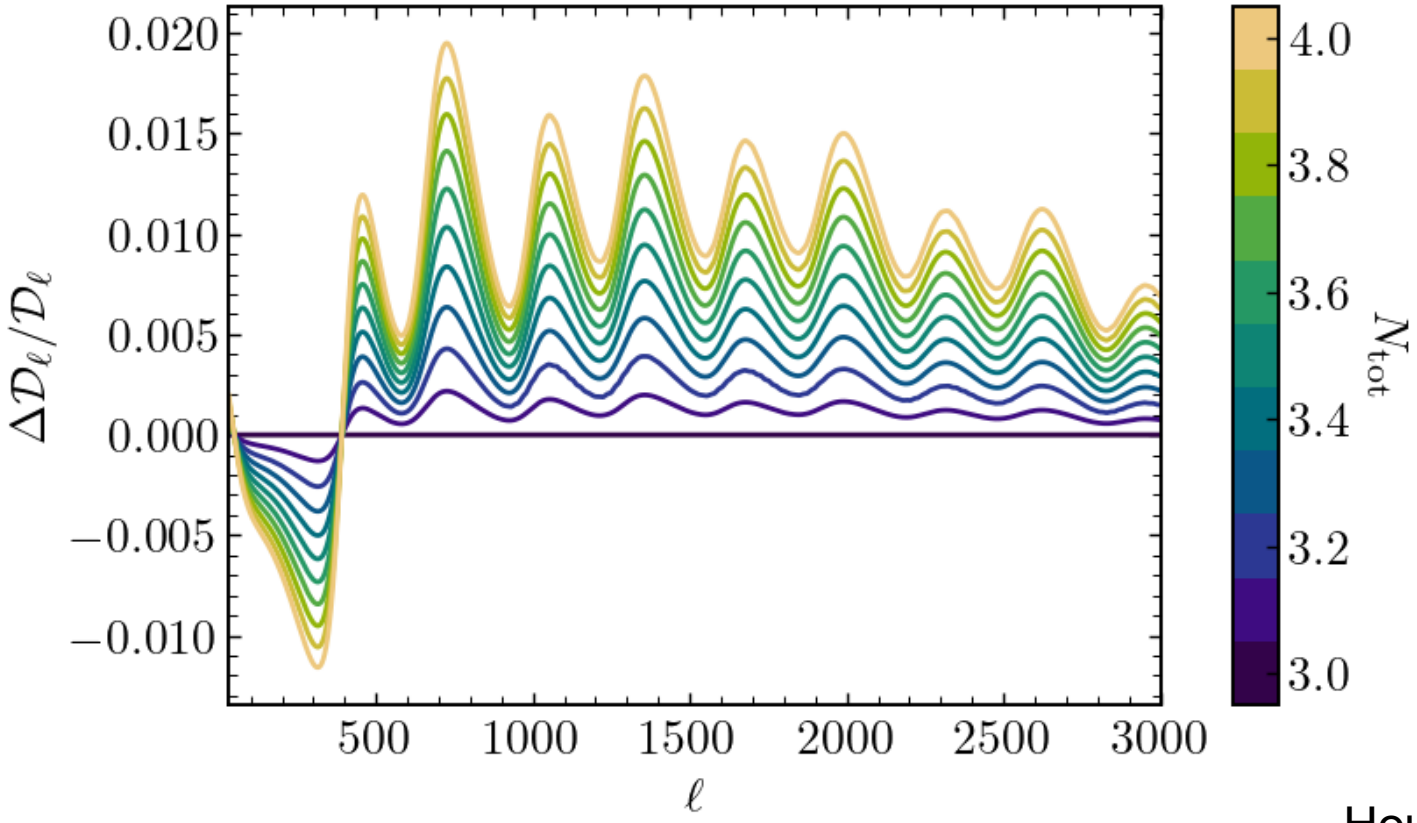


Pressure supported matter fraction ω_b/ω_{cb}

$$\psi \propto \omega_c \delta_c$$

Large Scales

Less radiation driving



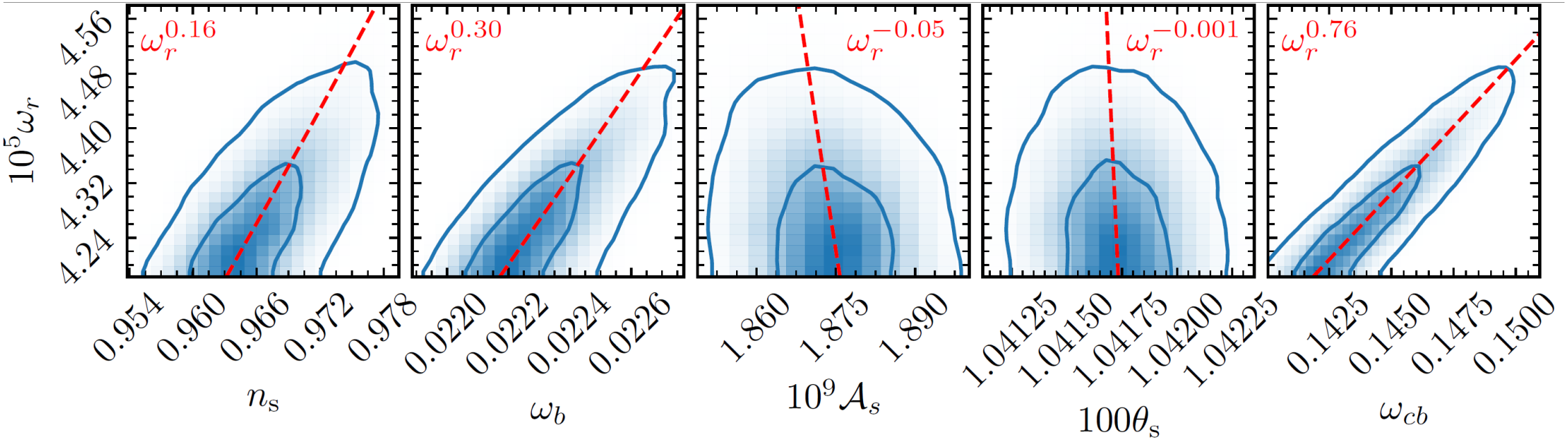
Small Scales

Deeper potential wells

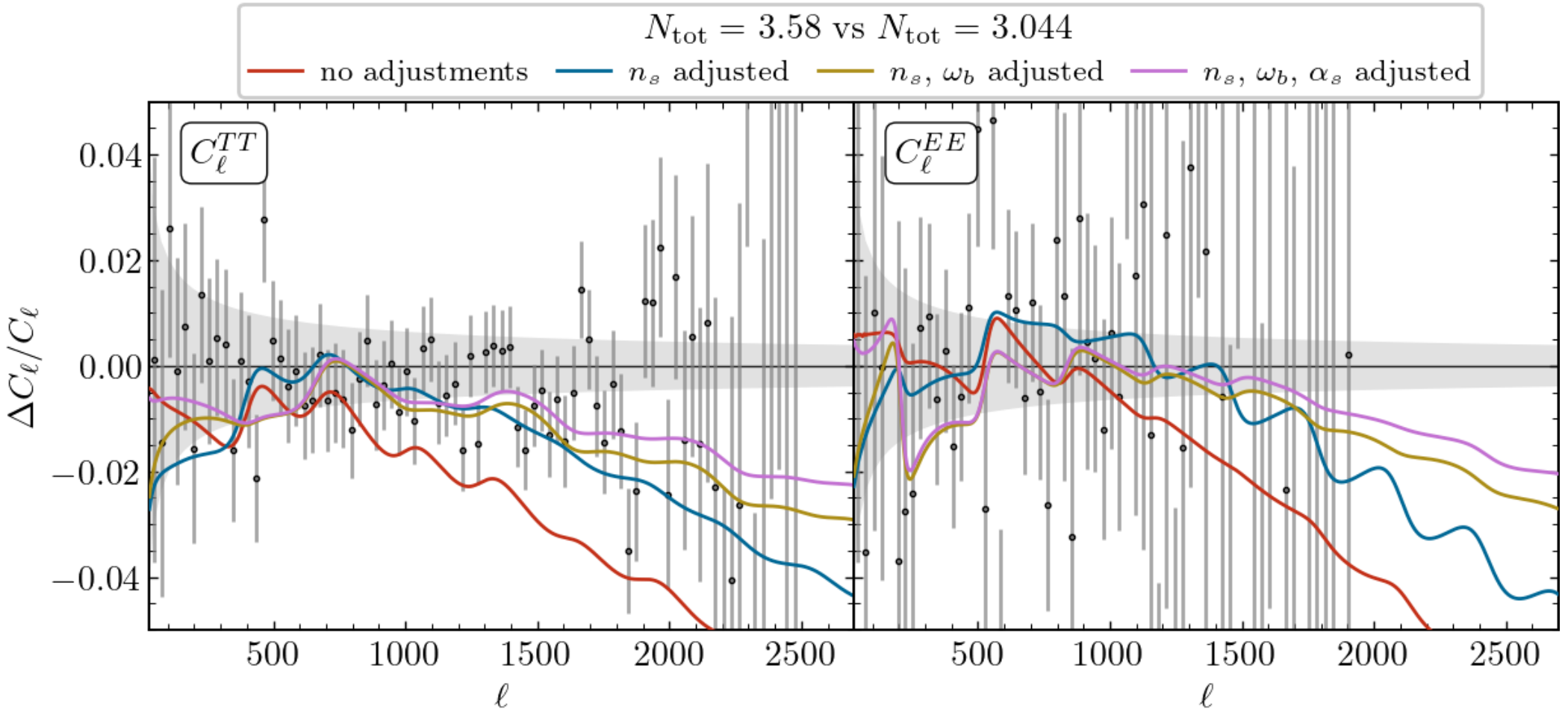
Fixed: $f_{\rm fs}$, θ_s, ω_b, $a_{\rm eq}$, r_D

Hou et al (2011), Ge et al (2022)

Tilt Degeneracy

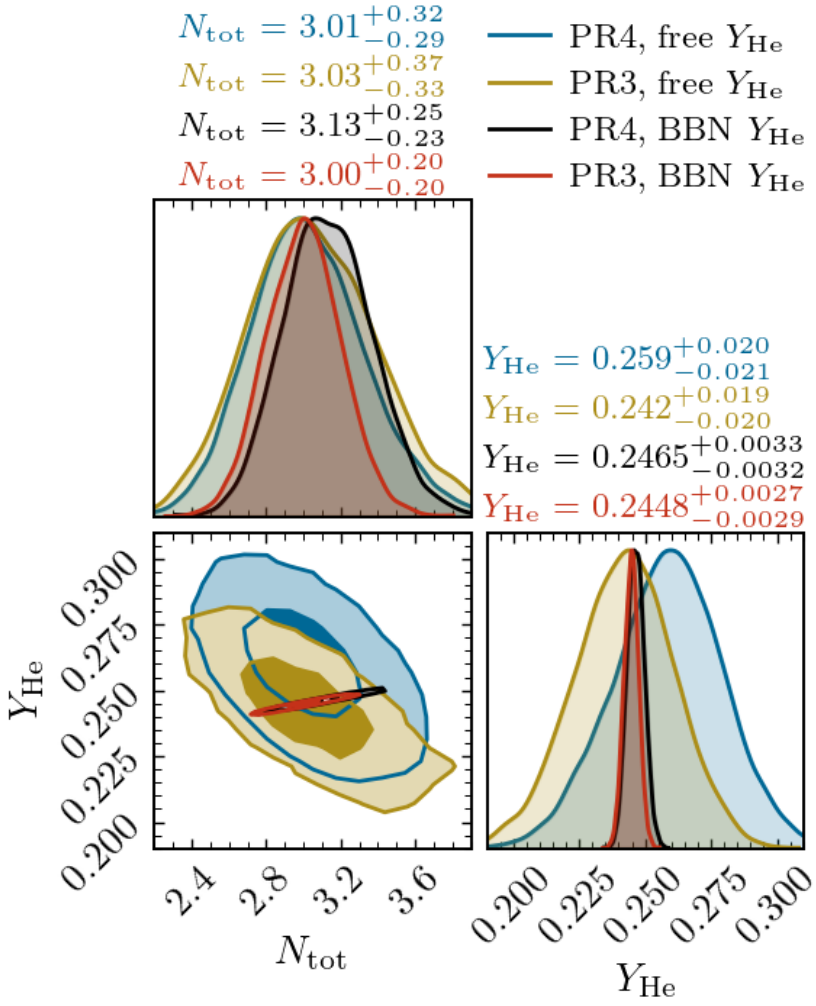


Tilt Degeneracy

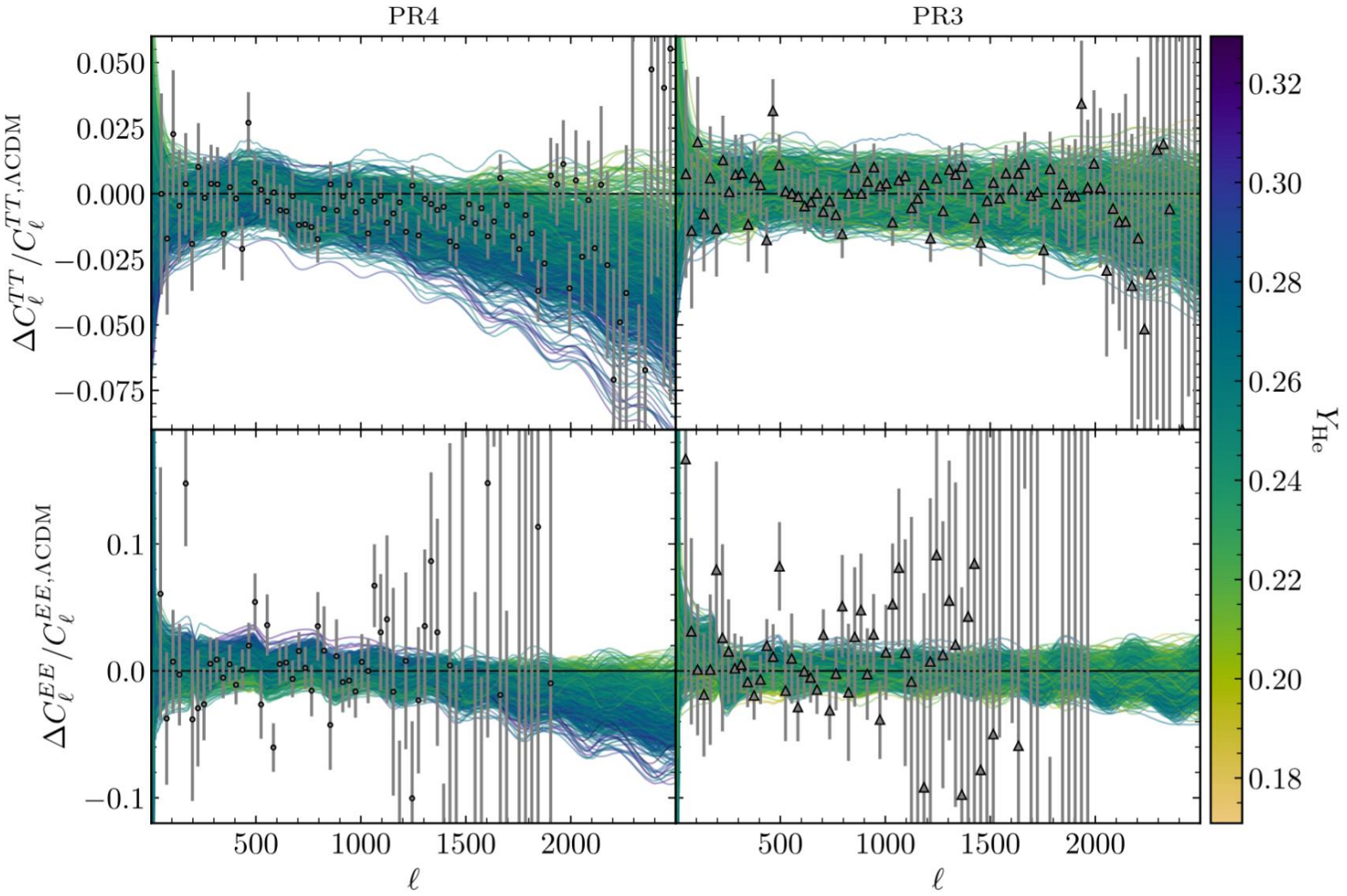


PR4 vs PR3

- Think in ω_r, $f_{\rm fs}$ space



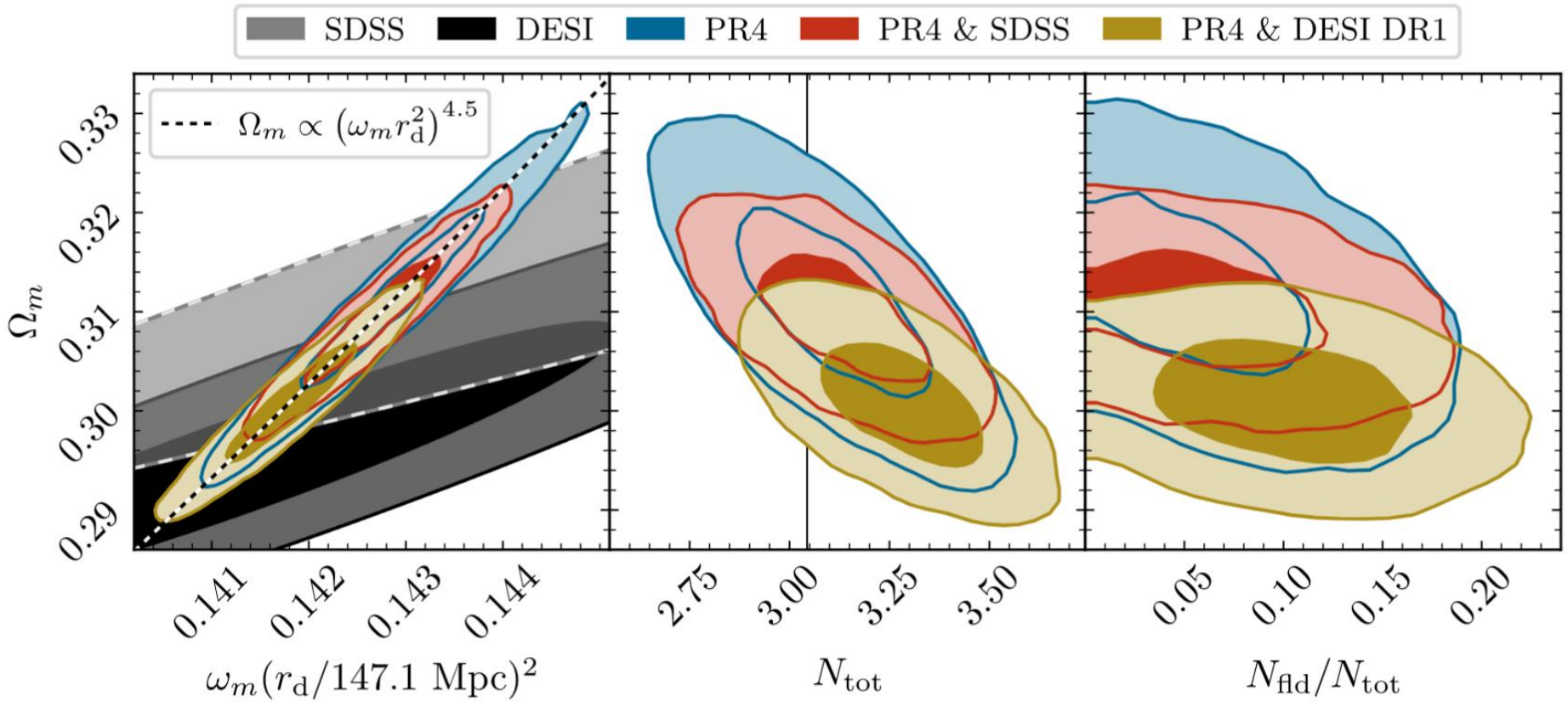
PR4 vs PR3



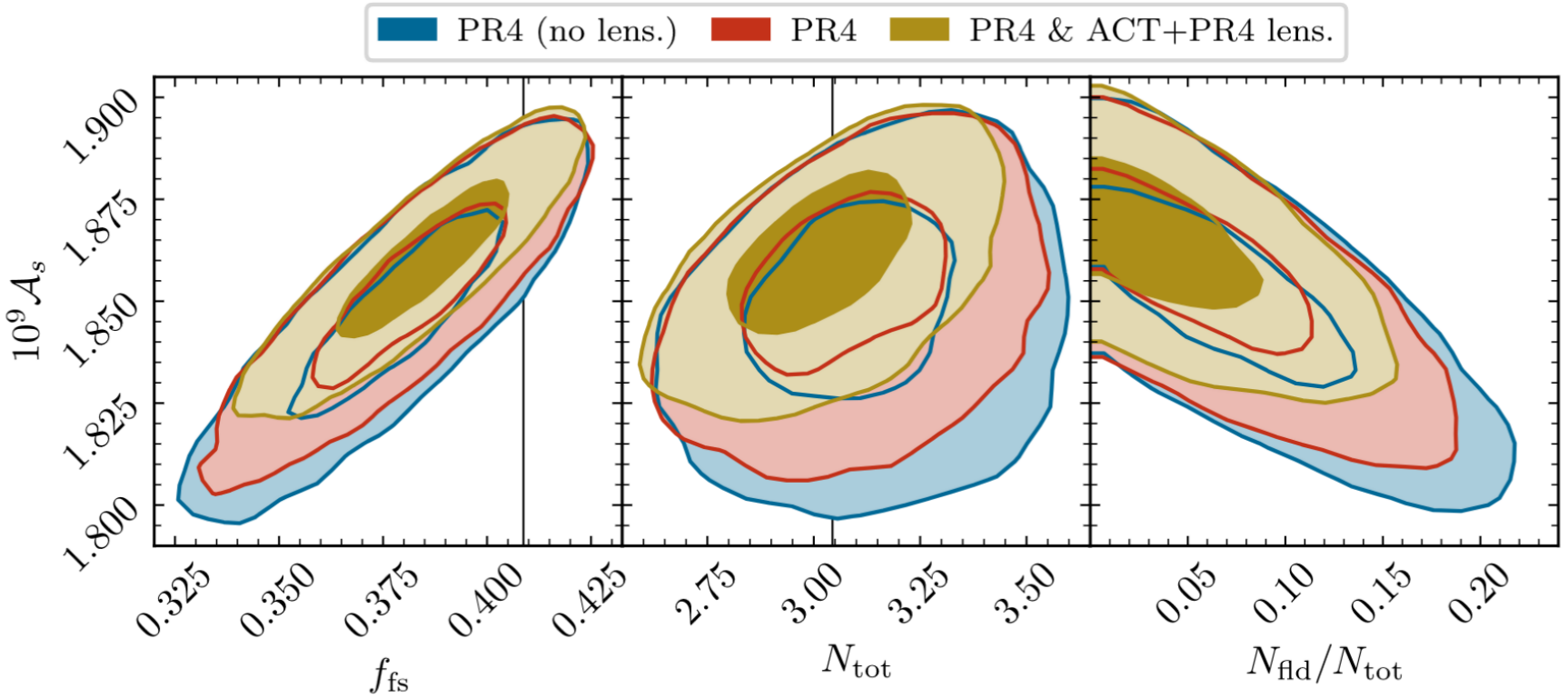
Increasing the number density of electrons prolongs recombination, generating more polarization

Also incurs more damping

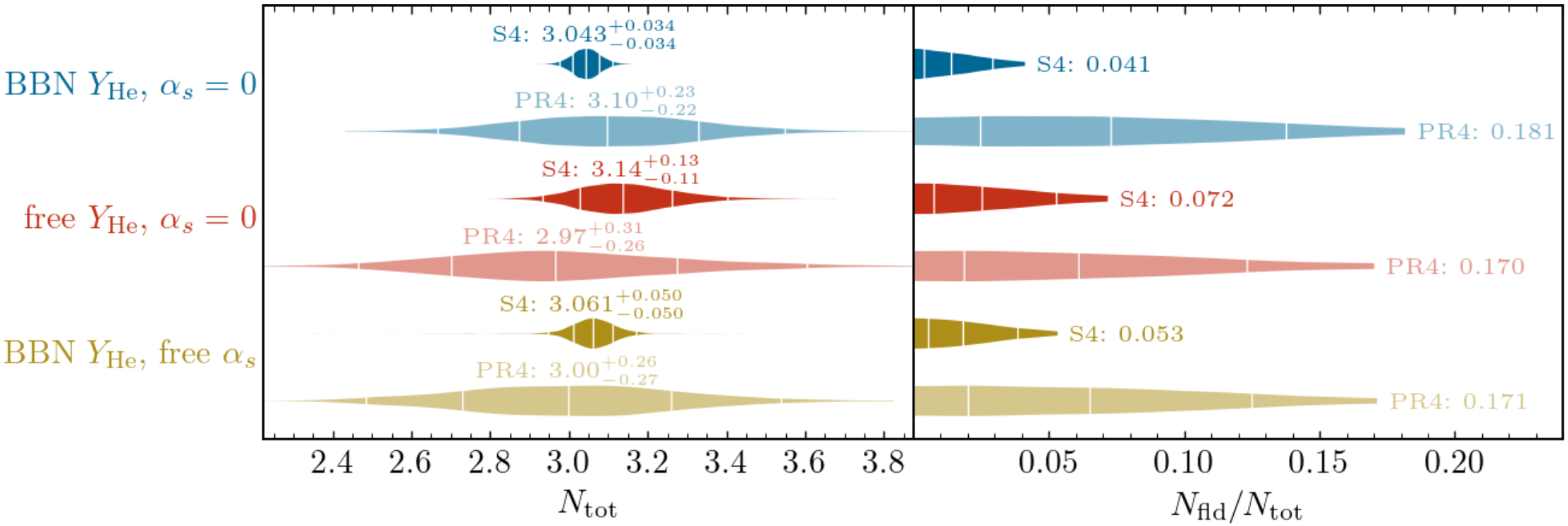
BAO Plot


SDSS
DESI
PR4
PR4 & SDSS
PR4 & DESI DR1
$\Omega_m \propto (\omega_m r_{\rm d}^2)^{4.5}$
Ω_m
0.33
0.32
0.31
0.30
0.29
0.141
0.142
0.143
0.144
$\omega_m(r_{\rm d}/147.1\ {\rm Mpc})^2$
2.75
3.00
3.25
3.50
$N_{\rm tot}$
0.05
0.10
0.15
0.20
$N_{\rm fld}/N_{\rm tot}$

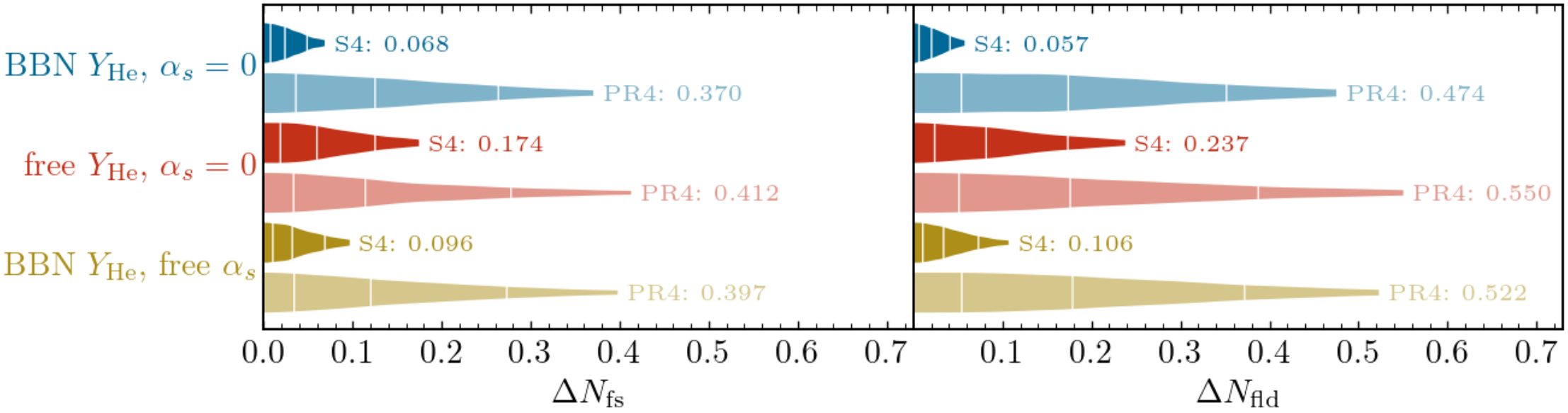
Lensing Plot



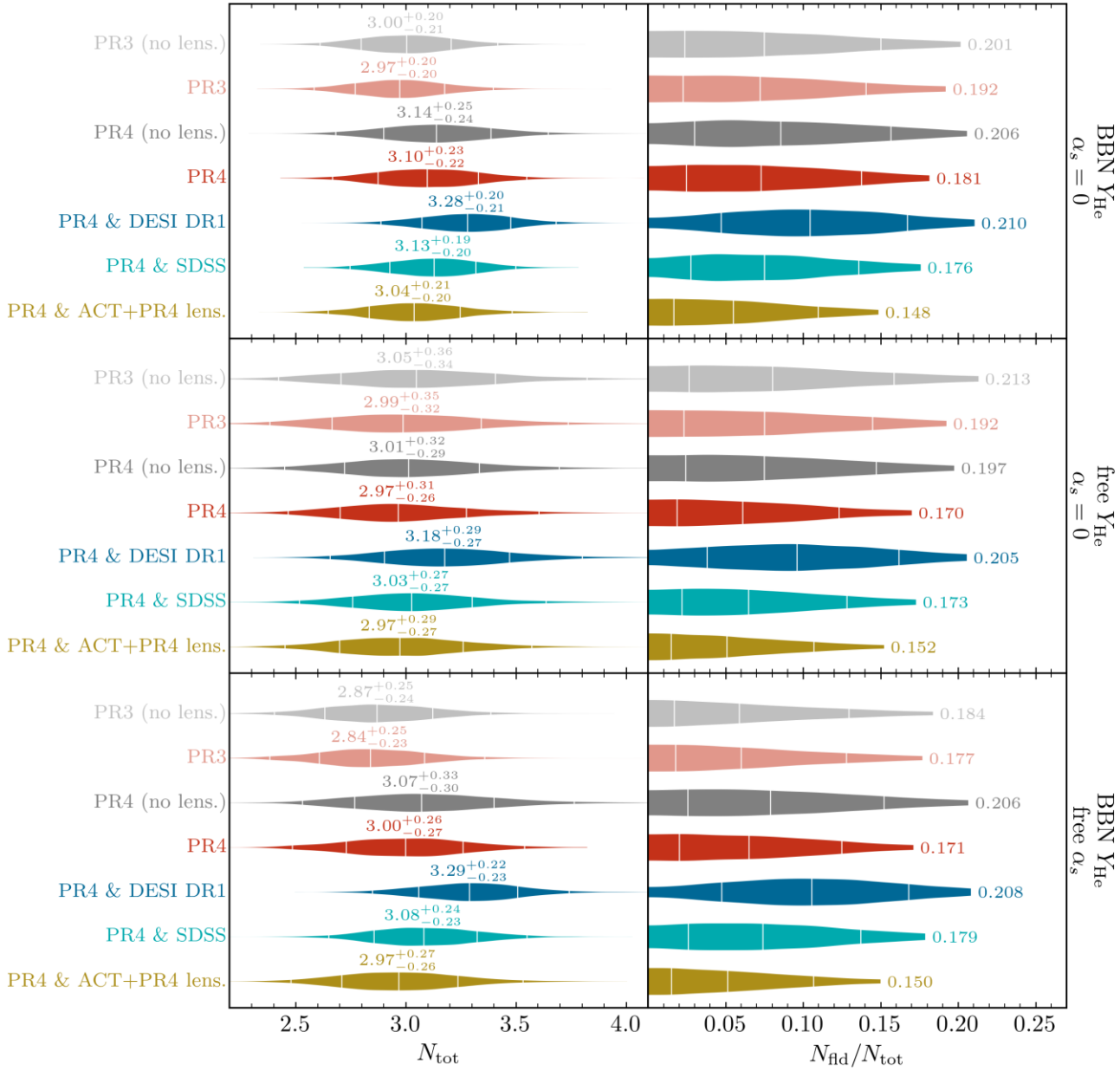
CMB-S4 Forecasts



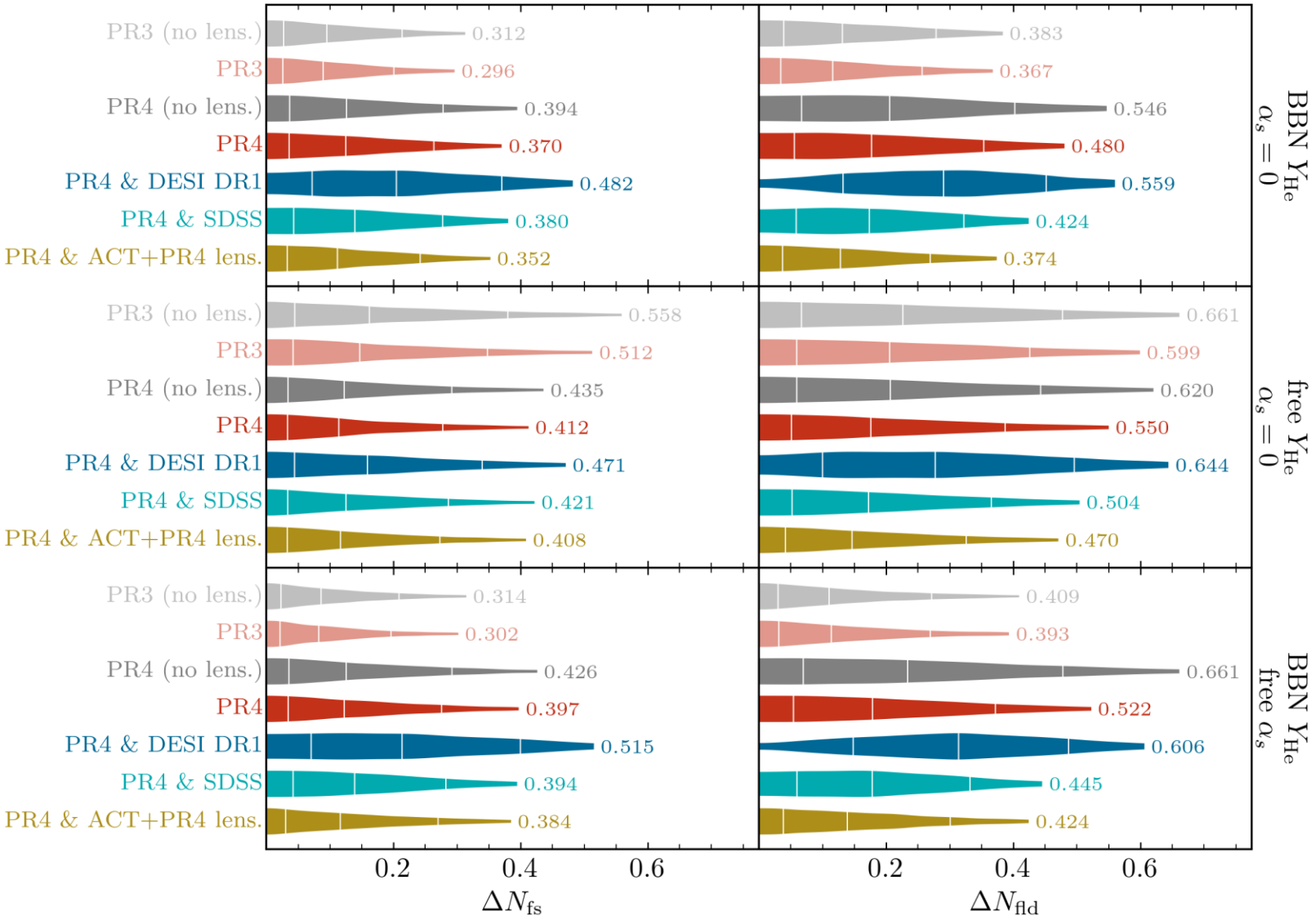
CMB-S4 Forecasts



Full Constraints



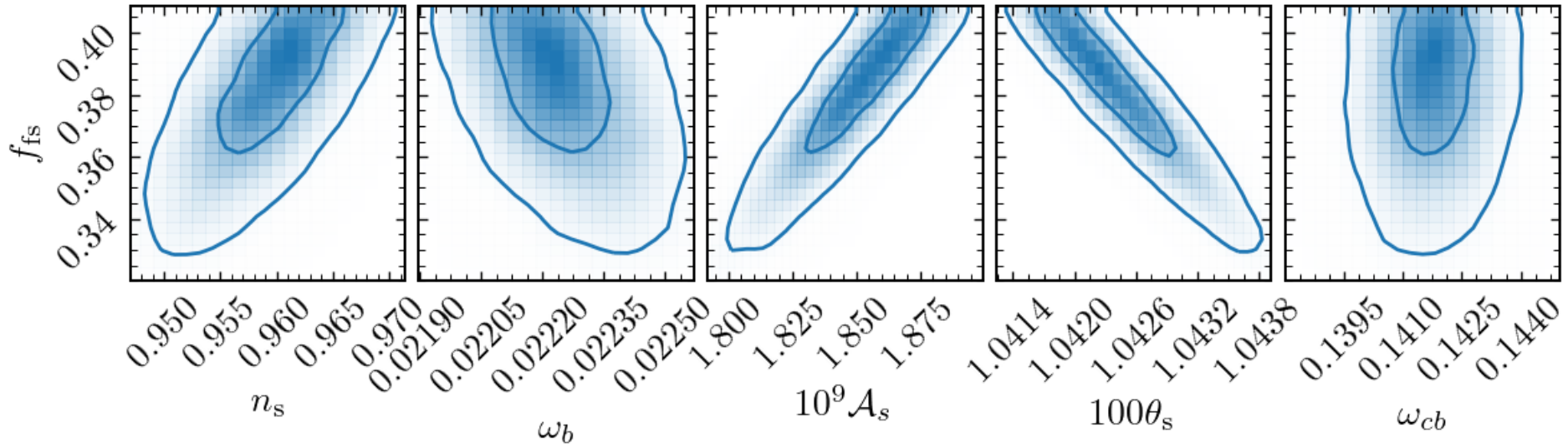
Full Constraints



Parameter degeneracy with $f_{\rm fs}$

- What parameters are degenerate with the free-streaming fraction? And why?
- Fit a model where the composition varies at fixed abundance
- BSM (ignoring SM neutrino physics)

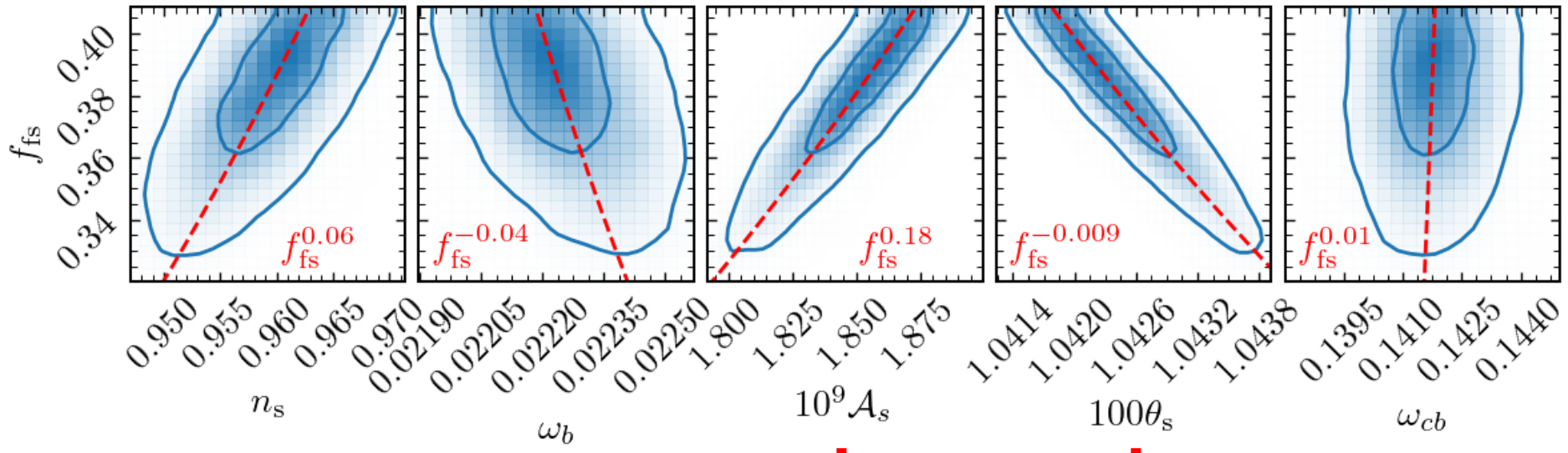
Latest “PR4” reanalysis of Planck data



Shift degeneracy

- Degeneracy with other LCDM parameters
- Study at fixed $N_{\rm tot}$

Latest “PR4” reanalysis of Planck data

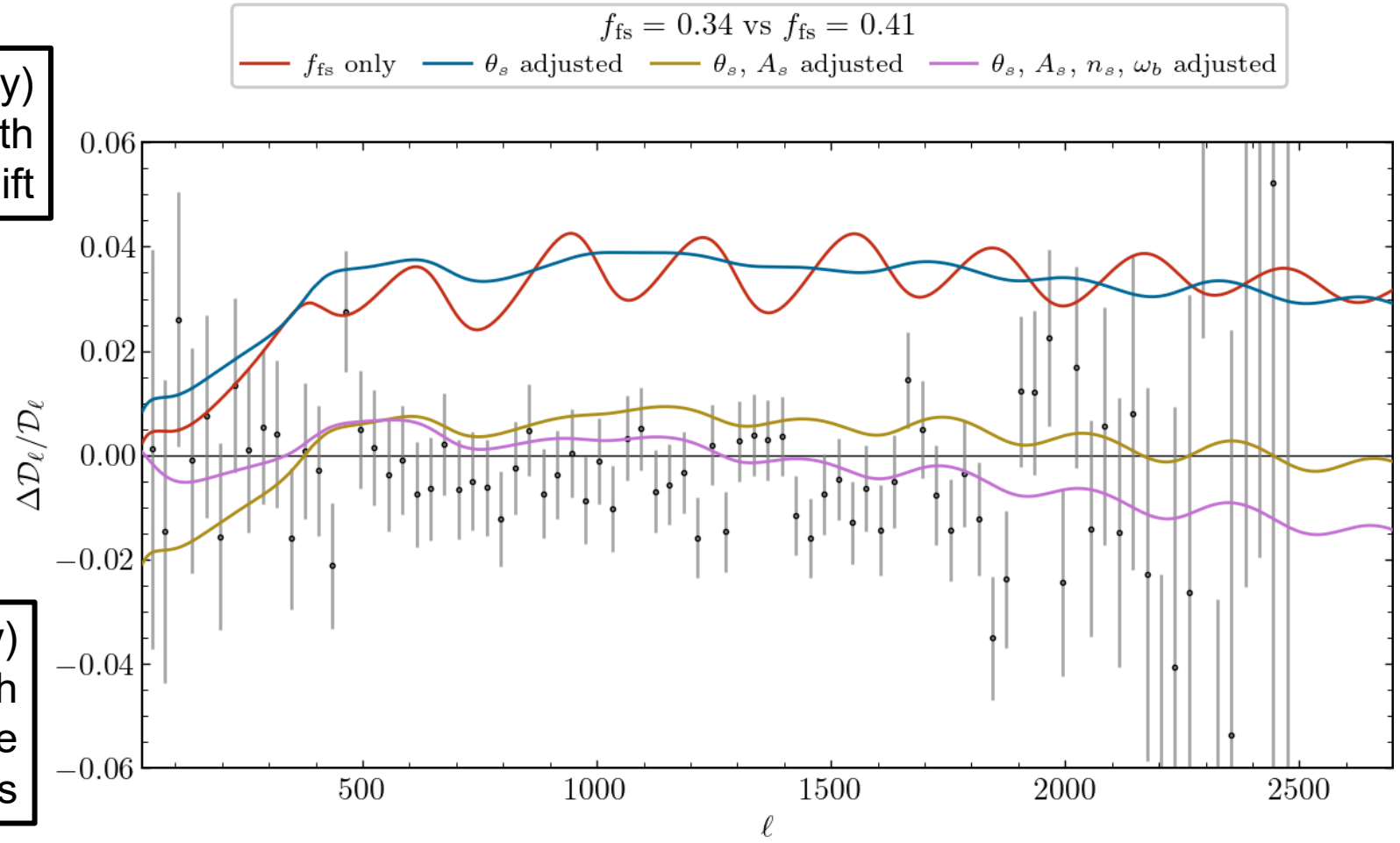


Amplitude

Peak locations

Shift Degeneracy

θ_s is (partly) degenerate with phase shift



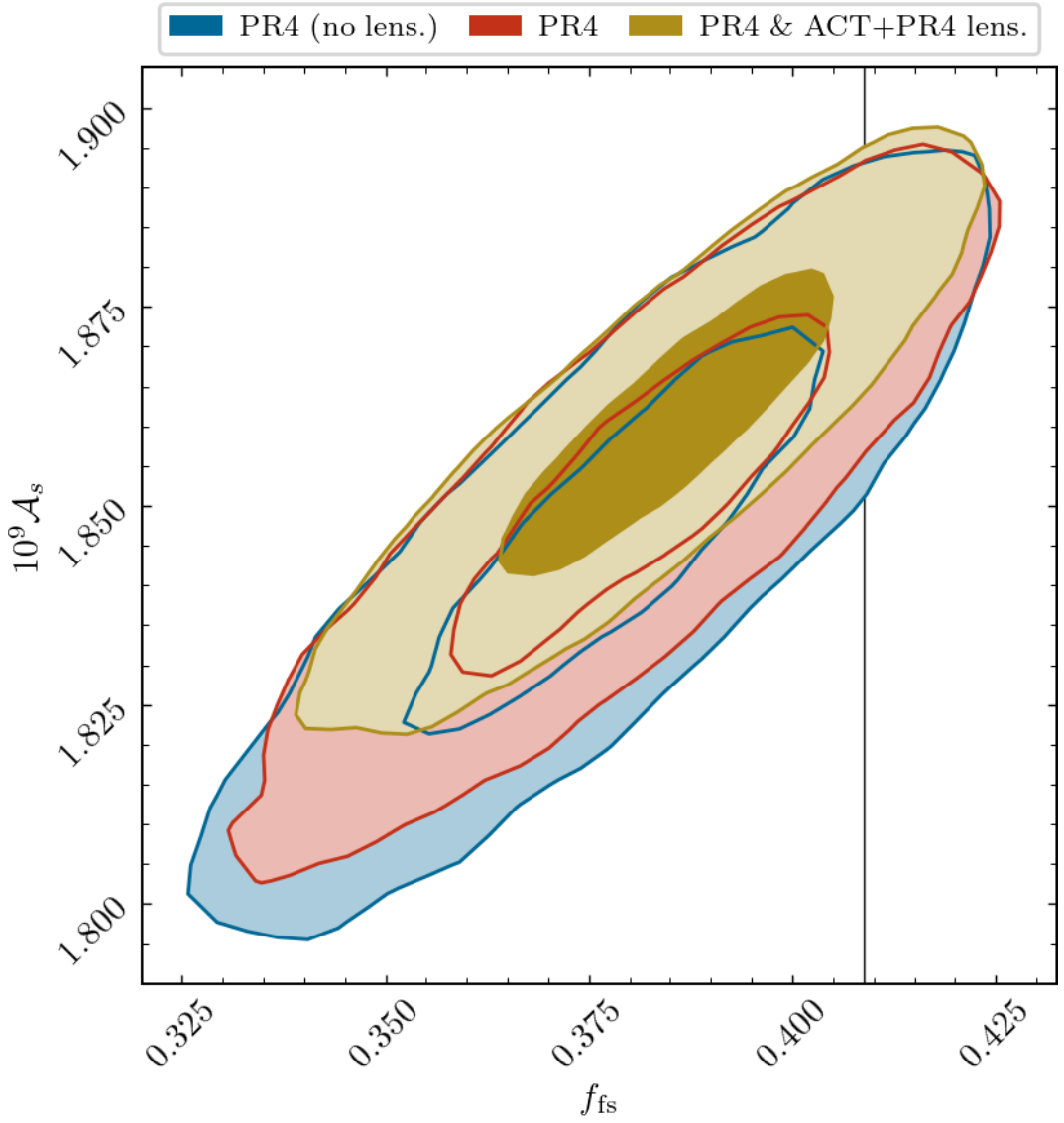
A_s is (partly) degenerate with amplitude changes

n_s, ω_b can (partly) compensate for remaining differences at large scales

Shift Degeneracy – So what?

- Interplay between parameters will affect constraints
- Isolate which parameters care about each other and why at the level of the **data**

Interpreting Lensing Data



- Lensing requires higher values of A_s, which disfavors lower values of $f_{\rm fs}$
- Lensing Anomaly