Monopole fluctuations

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Overview

- CMB monopole fluctuations
- Current measurements of the monopole temperature
- New things we can do
  - Primordial mass spectrum
  - Peculiar velocities with quasar absorption lines

CMB monopole temperature

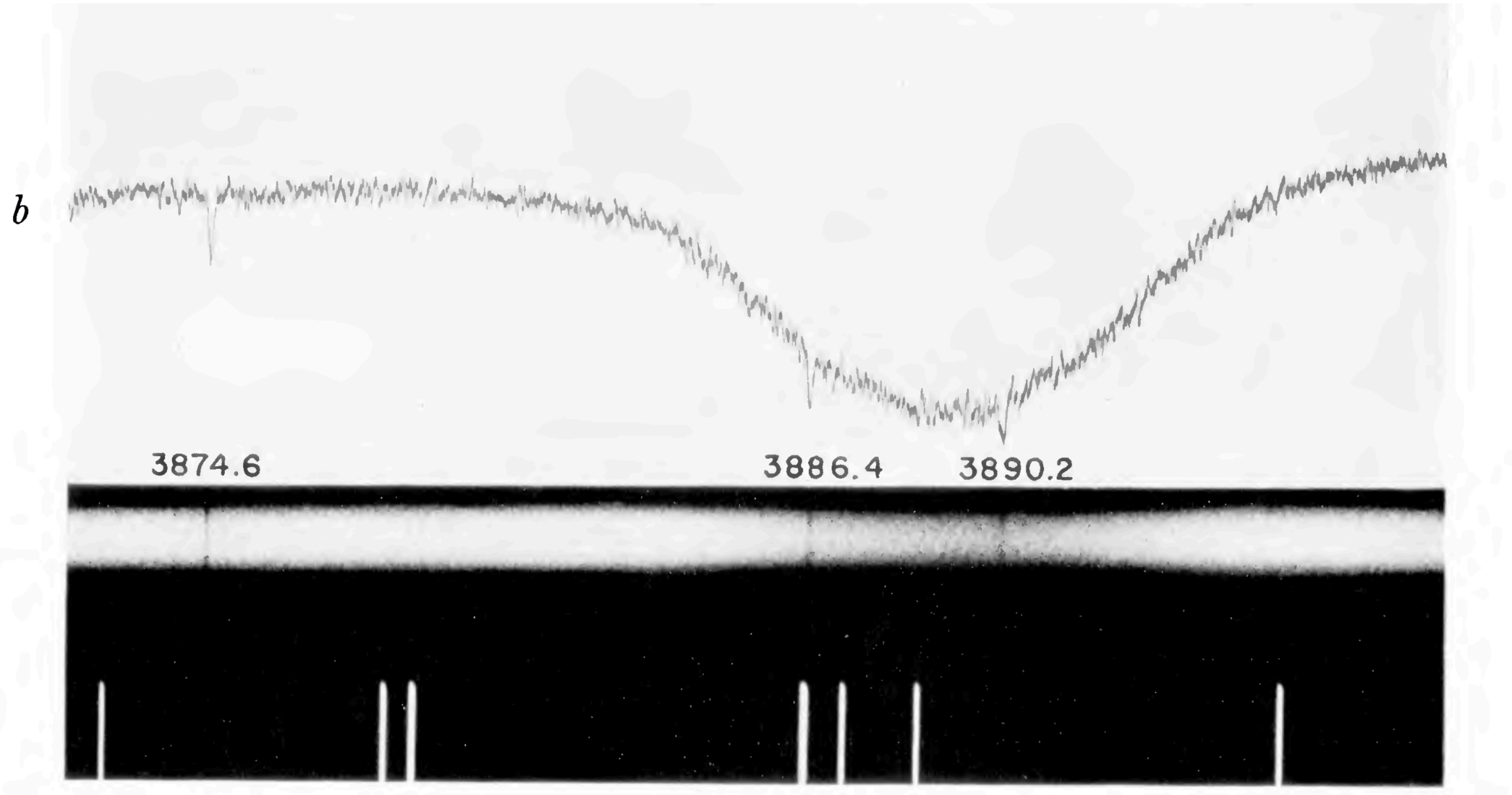
$$T_\gamma(\mathbf{x}) = \int \frac{d^2\mathbf{n}}{4\pi} T_\gamma(\mathbf{x}, \mathbf{n})$$

$$T_\gamma(\mathbf{x}) = \bar{T}_\gamma(1 + \Theta_0(\mathbf{x}))$$

- $\mathbf{x}$ is a position in the universe, $\mathbf{n}$ is a direction on the sky from that position

- **Penzias and Wilson** 1964 measured $T_\gamma(\mathbf{x}_{\text{Crawford Hill, NJ}}) = 3.5 \pm 1.0$ [K]

- **McKellar** 1941 measured $T_\gamma(\mathbf{x}_{\text{A distant molecular cloud}}) = 2.3$ [K]
  - Using CN stellar absorption lines of ζ Ophiuchi
  - The absorption depth depends on the spin temperature, for the right molecules this is CMB dominated



INTERSTELLAR LINES

~~a) α Cygni showing interstellar H and K superposed upon stellar lines~~; b) ζ Ophiuchi, positive reproduction of stellar and comparison spectra, with photometric tracings. Two lines of *CH* are shown, λ 3886 and λ 3890; also λ 3874.6 and a trace of λ 3874.0, both probably *CN*.

W.S. Adams 1941 (Coudé spectrograph of the Mount Wilson Observatory)

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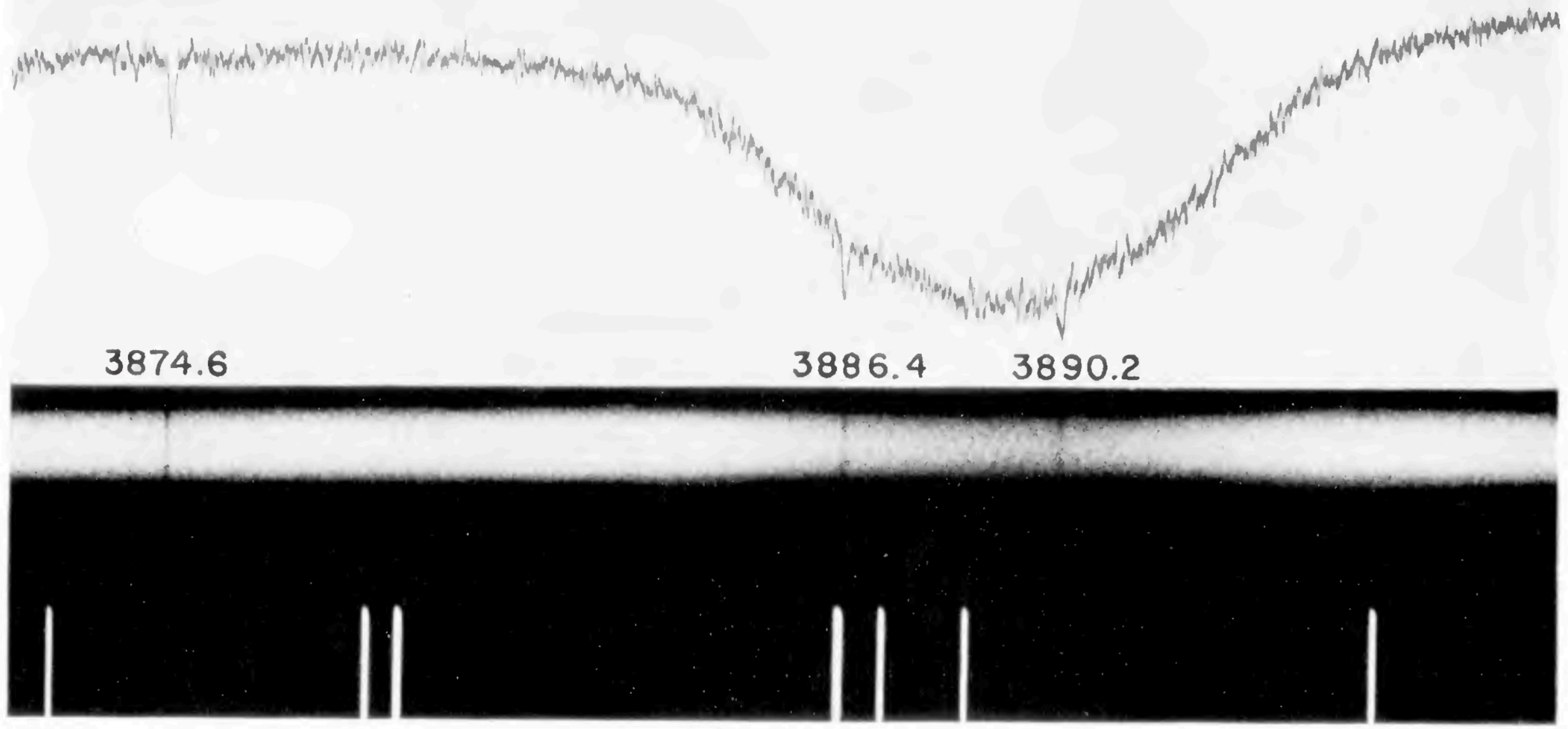
- $\bar{T}_\gamma$ is the **average temperature** of the universe over **all positions**
- Often **monopole fluctuations** are called unobservable due to having only one measure of the monopole, this is not true we have many measurements so they are **observable**!

b



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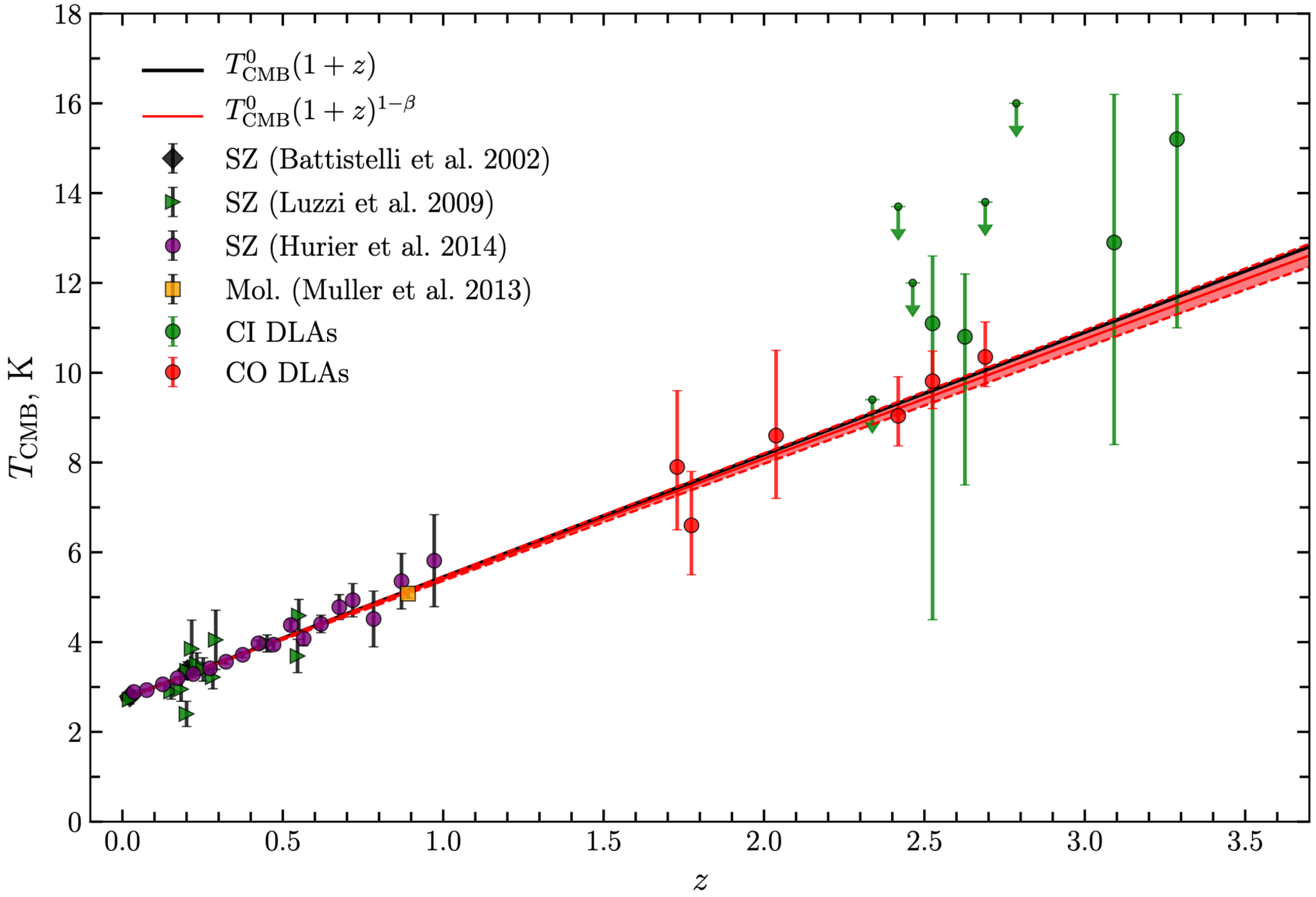
Current measurements $\bar{T}_\gamma(z) = \bar{T}_{\gamma,0}(1+z)$

- COBE/FIRAS $T_{0,\gamma}(\mathbf{x}) = 2.72548 \pm 0.00057$ [K]
- In an adiabatic universe, the temperature has a very simple relation with redshift
    - The universe cools down (Tolman 1934)
- Decaying dark energy would change this (Lima et al. 2000)
    - Would mean $\beta \neq 0$
    - $\beta = 0.010 \pm 0.013$ (Klimenko et al. 2020)
- SZ + molecules gives an independent measure of the monopole temperature!
    - $\bar{T}_{0,\gamma} = 2.719 \pm 0.009$ [K] (Klimenko et al. 2020)
- On the order of 100s of SZ clusters and 10s molecular absorption systems (Saro et al. 2014 Planck clusters, Muller et al. 2013 CN, Li et al. 2021 ACT clusters, and many others)



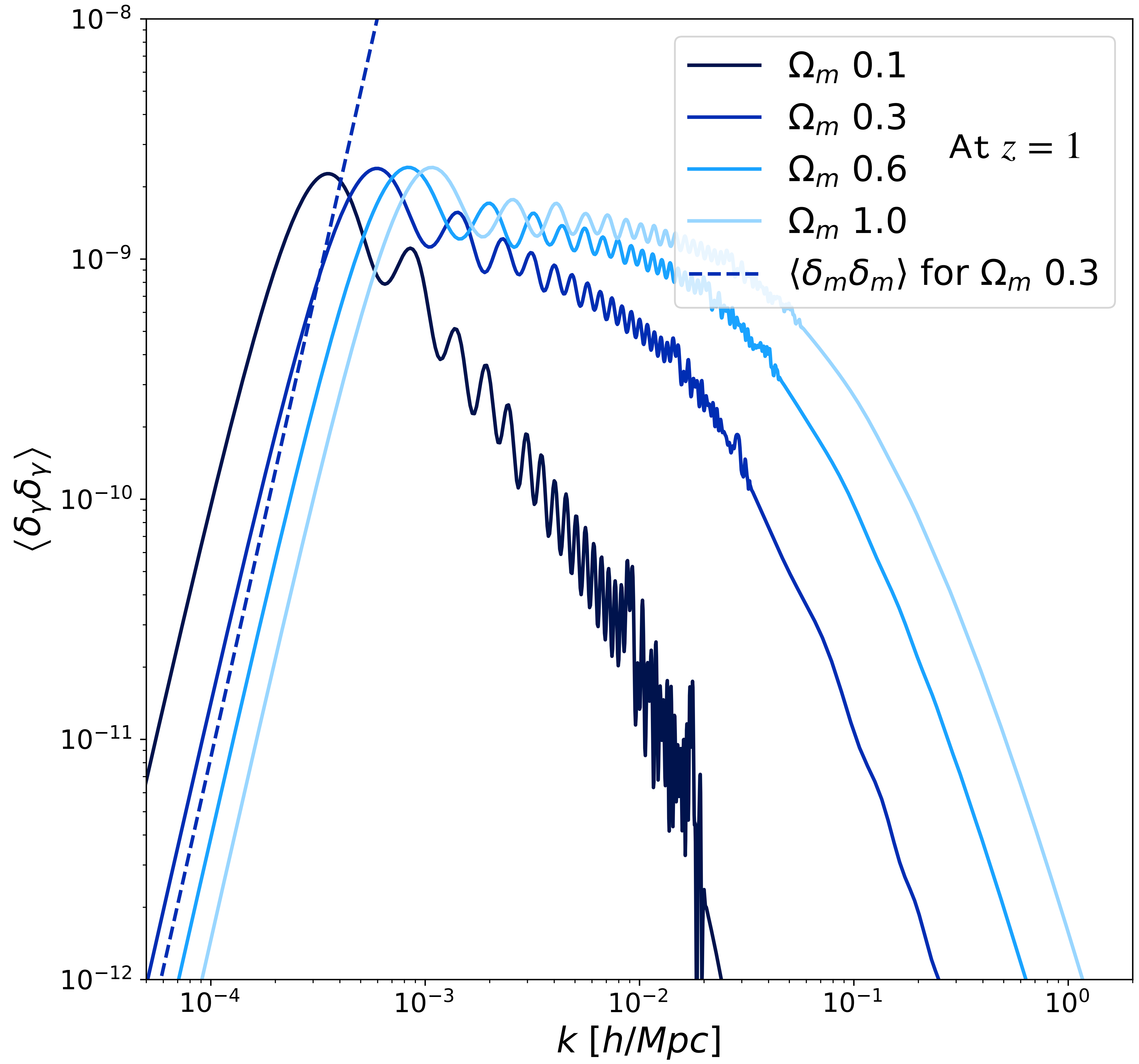
Klimenko et al. 2020

Photon energy density fluctuations

- We can measure the CMB temperature elsewhere
    - Therefore we can measure the photon energy density elsewhere
- Sensitive to the spectrum of primordial density perturbations therefore gives **new** cosmological information
- For gauge issues see:
    - Zibin & Scott 2008
    - Baumgartner & Yoo 2021

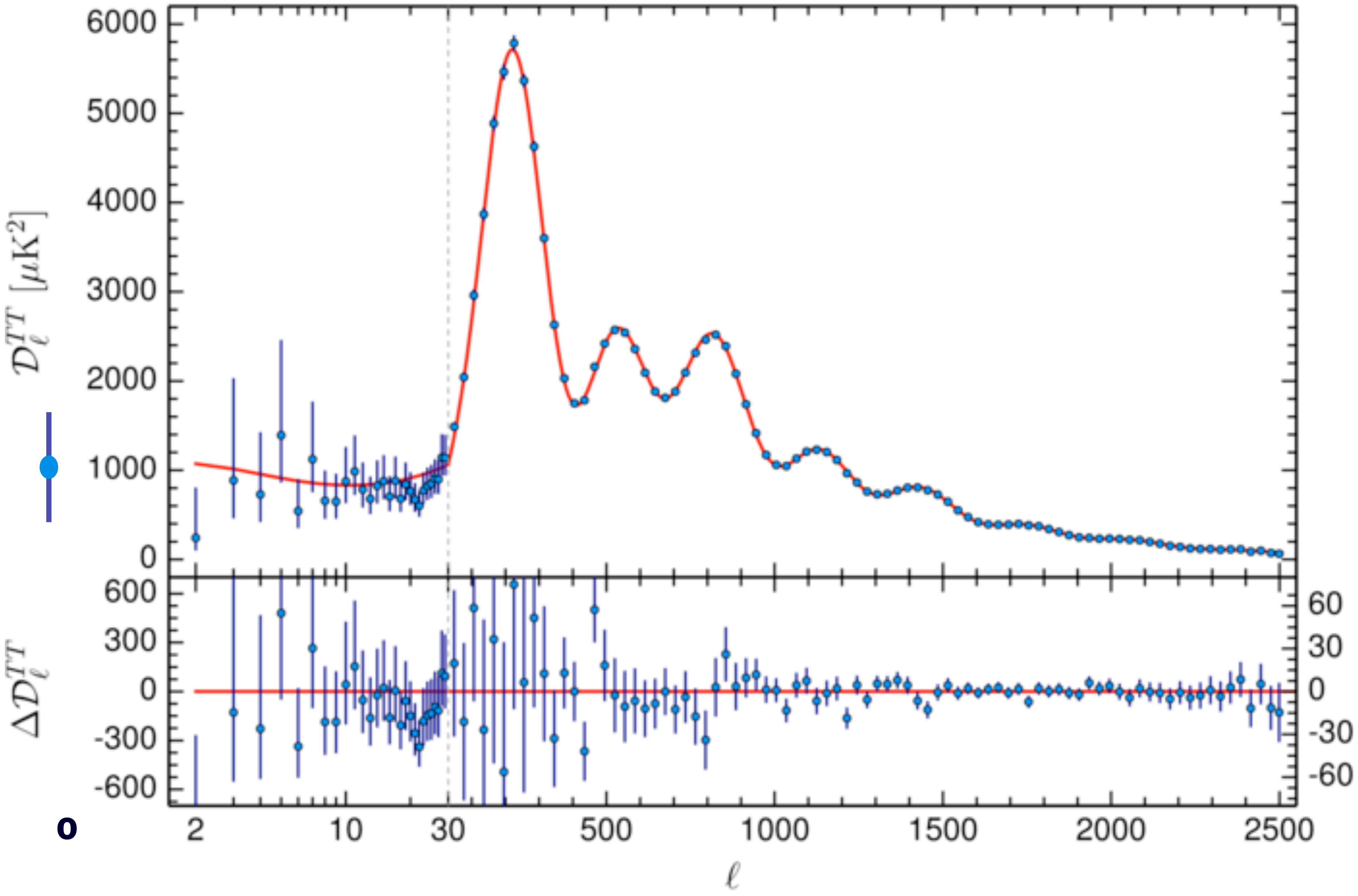
$$T_\gamma(\mathbf{x}) = \bar{T}_\gamma(1 + \Theta_0(\mathbf{x})) \qquad \rho_\gamma = aT_\gamma^4$$

$$\delta_\gamma(\mathbf{x}) = \frac{\rho_\gamma(\mathbf{x})}{\bar{\rho}_\gamma} - 1 \approx 4\Theta_0(\mathbf{x})$$



Adding the monopole

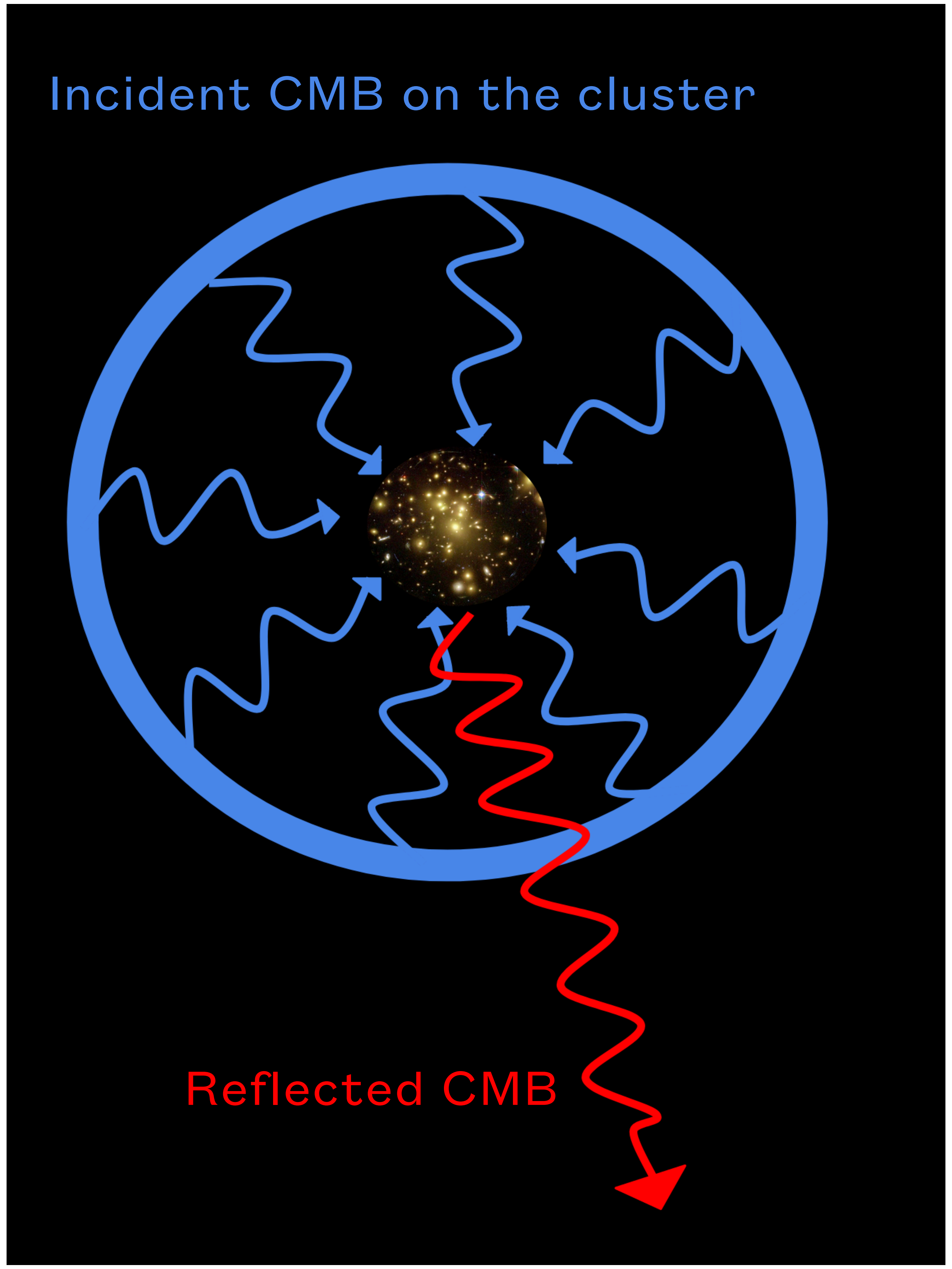
- CMB low multipoles are dominated by cosmic variance
  - We can not measure the monopole fluctuations with normal analyses
- The rms of the monopole fluctuations is $\sqrt{\Theta_0^2} \approx 1.15 \cdot 10^{-5}$ assuming Planck 2018 ΛCDM (Baumgartner & Yoo 2021, although they don't understand that it is directly measurable)
- Although this $\mathscr{D}_\ell$ is defined so that the monopole variance is zero....

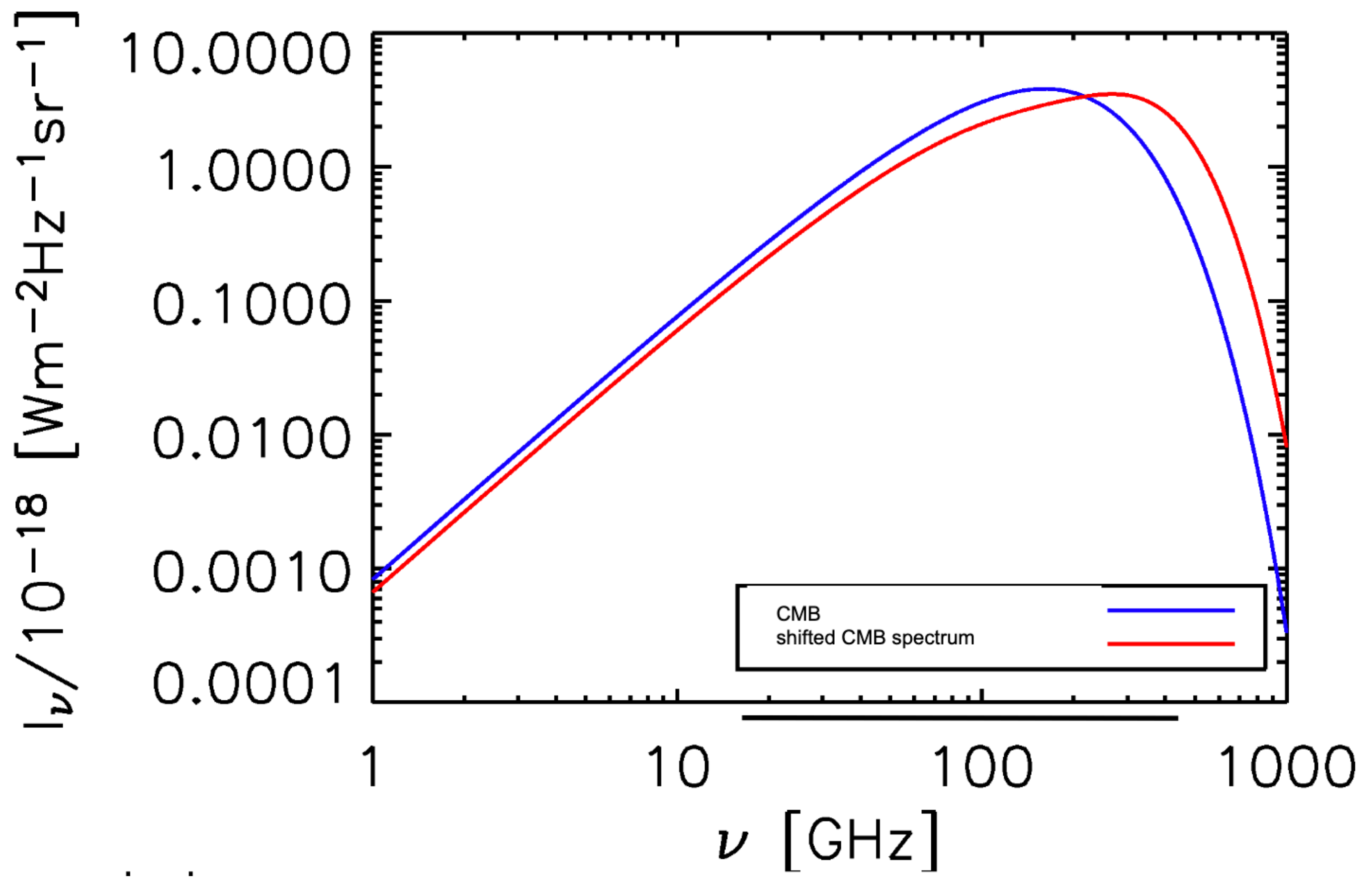


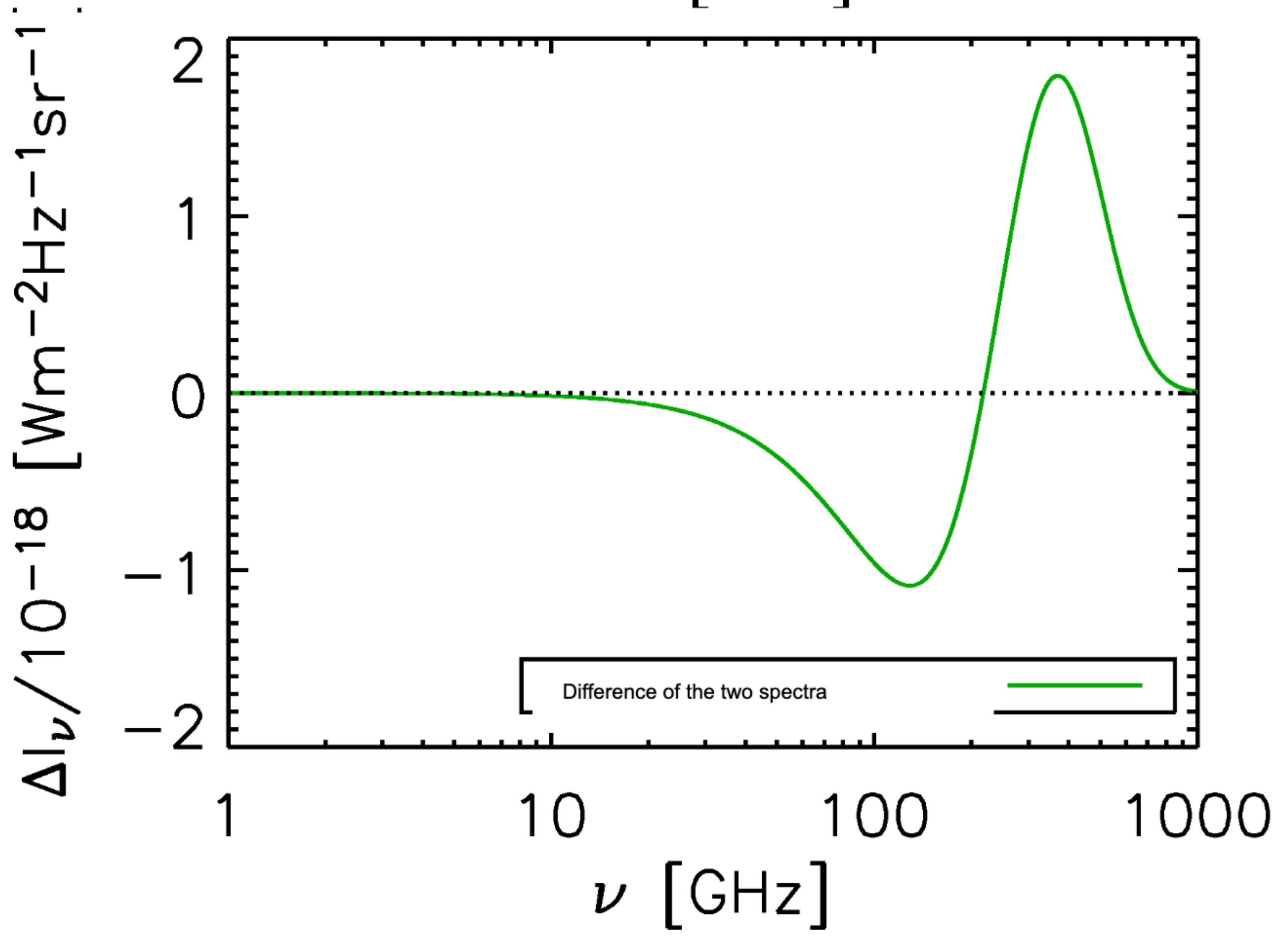
Planck 2018

Sunyaev-Zel'dovich effect

- The thermal SZ is the **spectral distortion** of the CMB as they are reflected by the hot electron gas inside galaxy clusters
- The **reflected spectrum** depends on the CMB temperature!
- Unlike the absorption lines, the SZ signal is sensitive to redshifted temperature $T_{\gamma,0,cluster}$ not the absolute CMB temperature
  - Therefore **no peculiar velocity effects**
  - Except doppler beaming but that's order $\sim 10^{-6}$

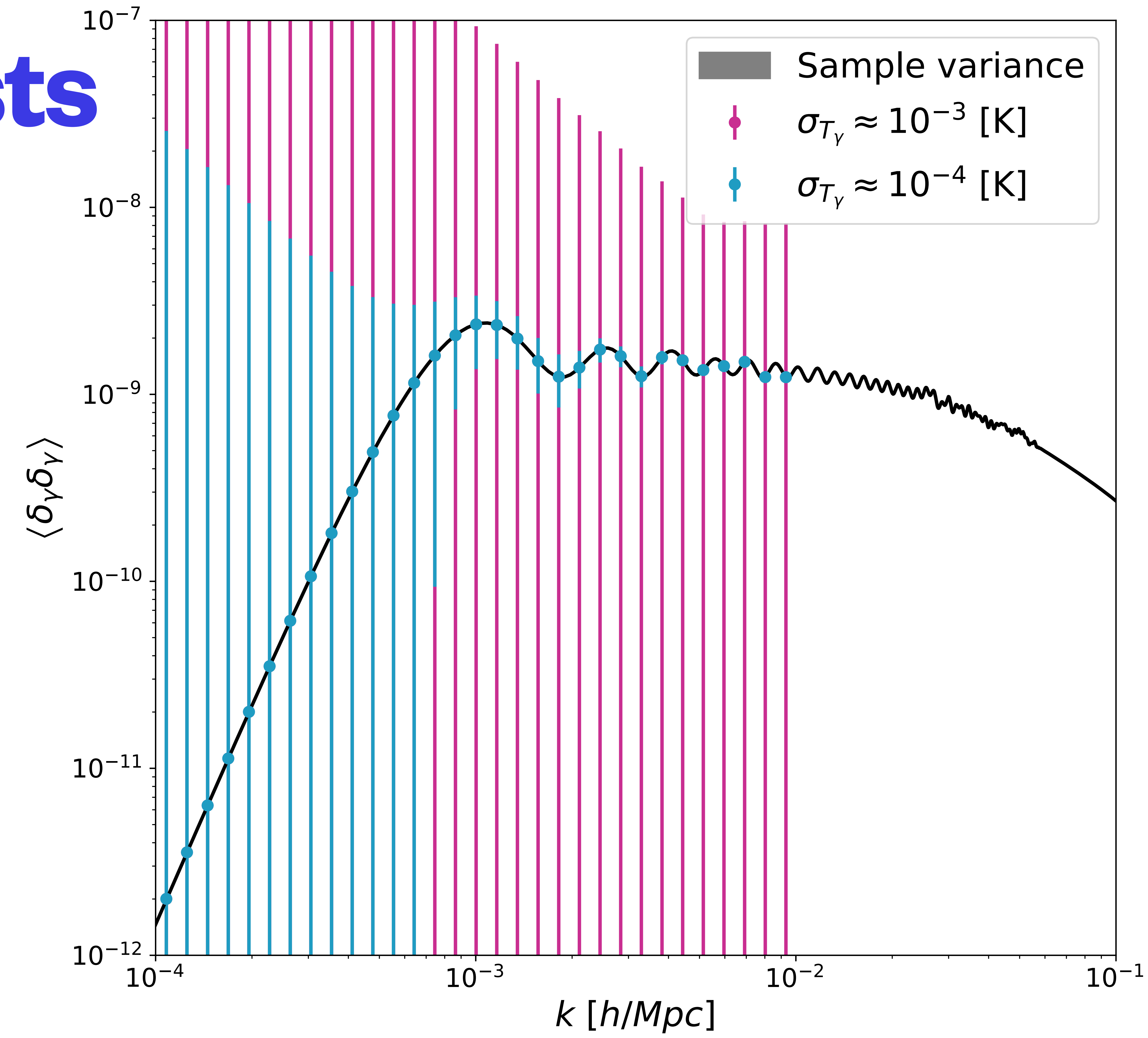






Preliminary $P(k)$ forecasts

- We can estimate the precision at which the photon energy density power spectrum may be reconstructed
  - $\Delta P(k) = \frac{1}{\sqrt{N_k}}\left(P(k) + \sigma^2_{\delta_\gamma}\right)$
  - $N_k \sim 2\pi k^2 \Delta k V$ is the number of independent modes measurable for each k mode, where V is the survey volume
  - $\sigma^2_{\delta_\gamma}$ is the measurement variance
- Consider a cluster survey which extends to a **redshift z = 2** with 100,000 galaxy clusters
- Unable to access small scales due to the sparse sampling of the survey volume
- We need a precision on the remote CMB monopole of $< 10^{-3}$ to make power spectrum measurements

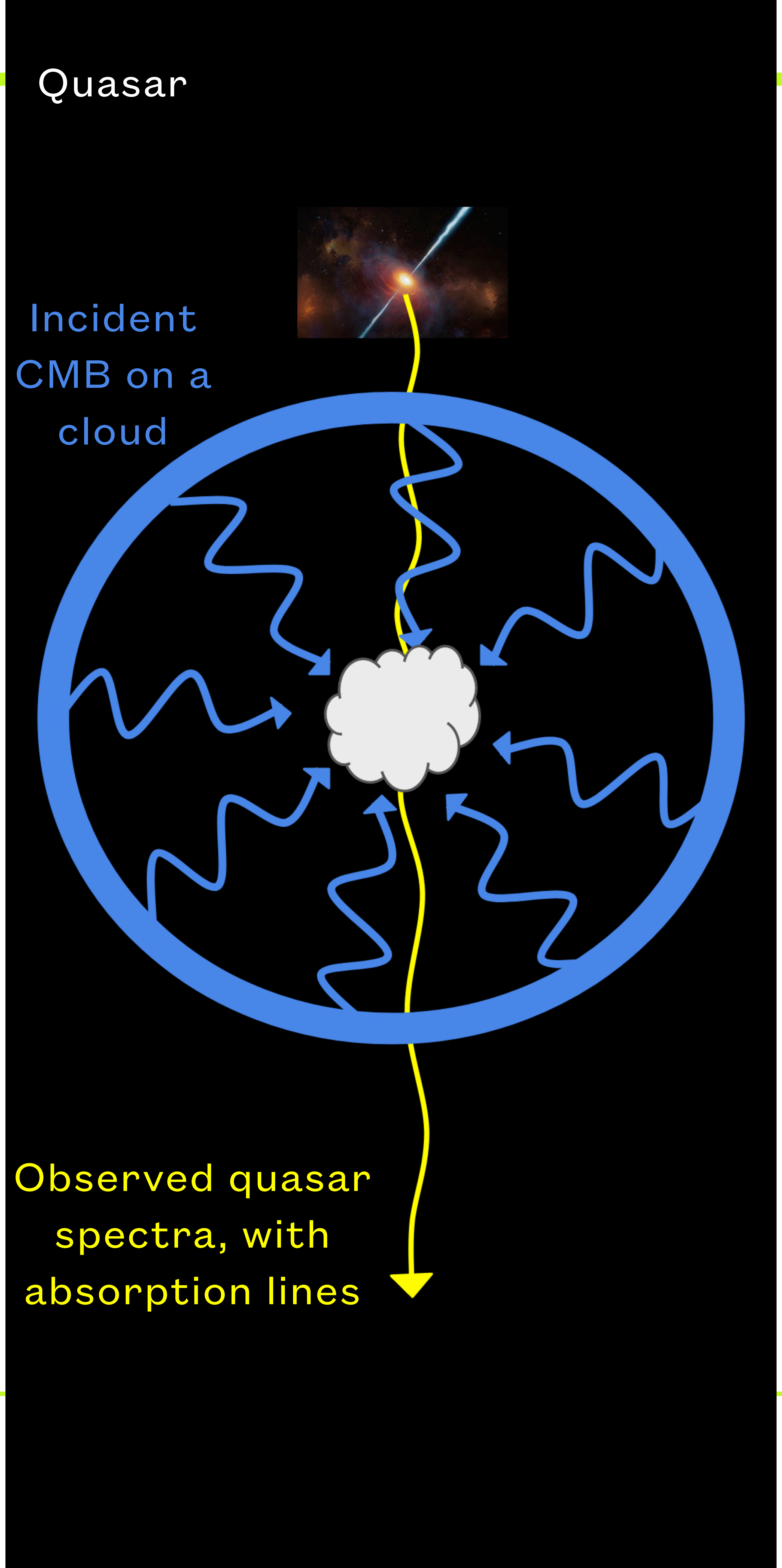


Quasar absorption lines

- Considering a molecular cloud in interstellar space
- An incident radiation field (the CMB, which is dominant for certain transitions) will excite molecules to higher energy states
- Lines are redshifted but the **proportion of molecules** in each state will depend on the **CMB temperature**

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-(E_u - E_l)/k_b T_\gamma}$$

- Various molecules can be used CO, CN CI,... (J. Bahcall and R. Wolf 1968 provide a detailed overview)



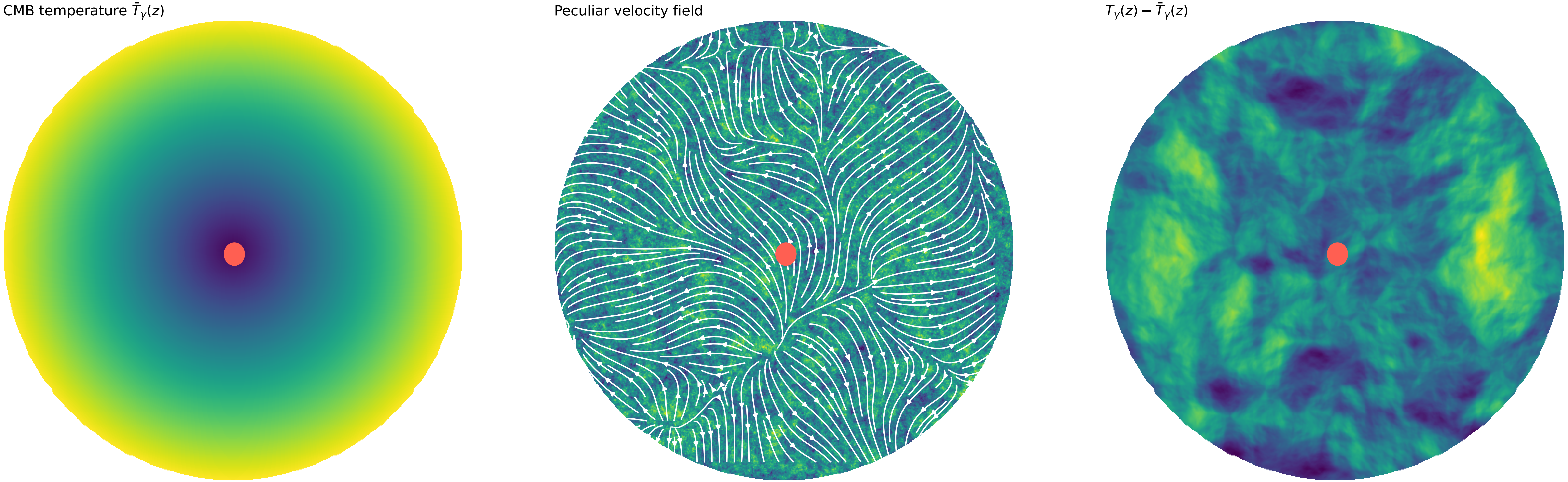
Peculiar velocity effects

$$\bar{T}_\gamma(z) = \bar{T}_{\gamma,0}(1+z)$$

$$T_\gamma(\mathbf{s}) = T_\gamma(\mathbf{x}) + \delta z E(z)\bar{T}_{\gamma,0}$$

- Consider the observed position of a source $\mathbf{s}$,
  - $\mathbf{s} = \mathbf{x} + \frac{c}{H}\delta z \mathbf{n}$
- Where $\mathbf{x}$ is the unperturbed position, $\mathbf{n}$ is the unit vector pointing to the source and δz is the redshift perturbation
- For peculiar velocities, $\delta z \approx \frac{1}{a}\frac{v_\parallel}{c}$, with scale factor a and line-of-sight velocity $v_\parallel$

● The observer



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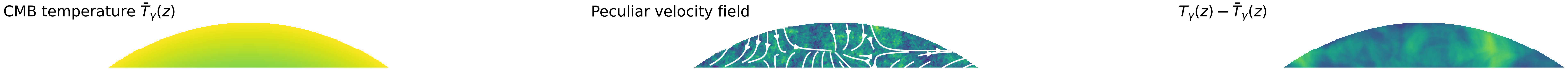
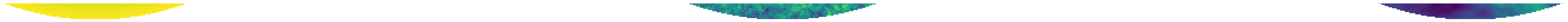


$$\left\langle \Theta_0(k,z)\Theta_0(k',z) \right\rangle = \frac{1}{16}\left\langle \delta_\gamma \delta_\gamma \right\rangle + \frac{\mathscr{A}}{2}\frac{\left\langle \delta_m \delta_\gamma \right\rangle}{k^2}(\vec{k}\cdot\vec{n}) + \mathscr{A}^2 \frac{\left\langle \delta_m \delta_m \right\rangle}{k^4}(\vec{k}\cdot\vec{n})(\vec{k'}\cdot\vec{n'})$$

where $\mathscr{A} = -iHf(z)E(z)$



Conclusions

- CMB monopole fluctuations are measurable (but very small) and could constrain the primordial density field
- Preliminary forecast using an SZ survey
- Molecular cloud measurements allow peculiar velocity measurements