Beyond Λ-CDM

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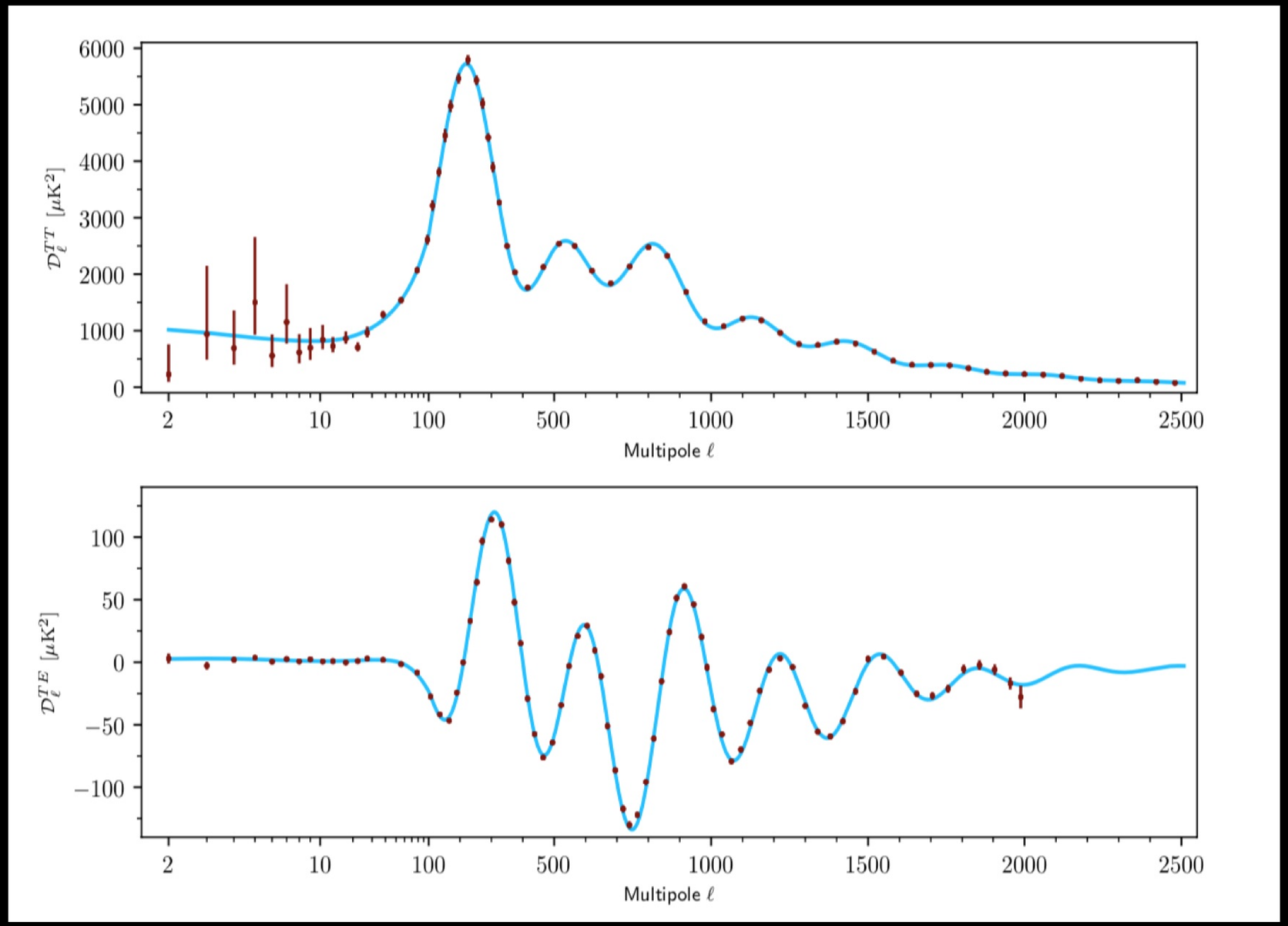
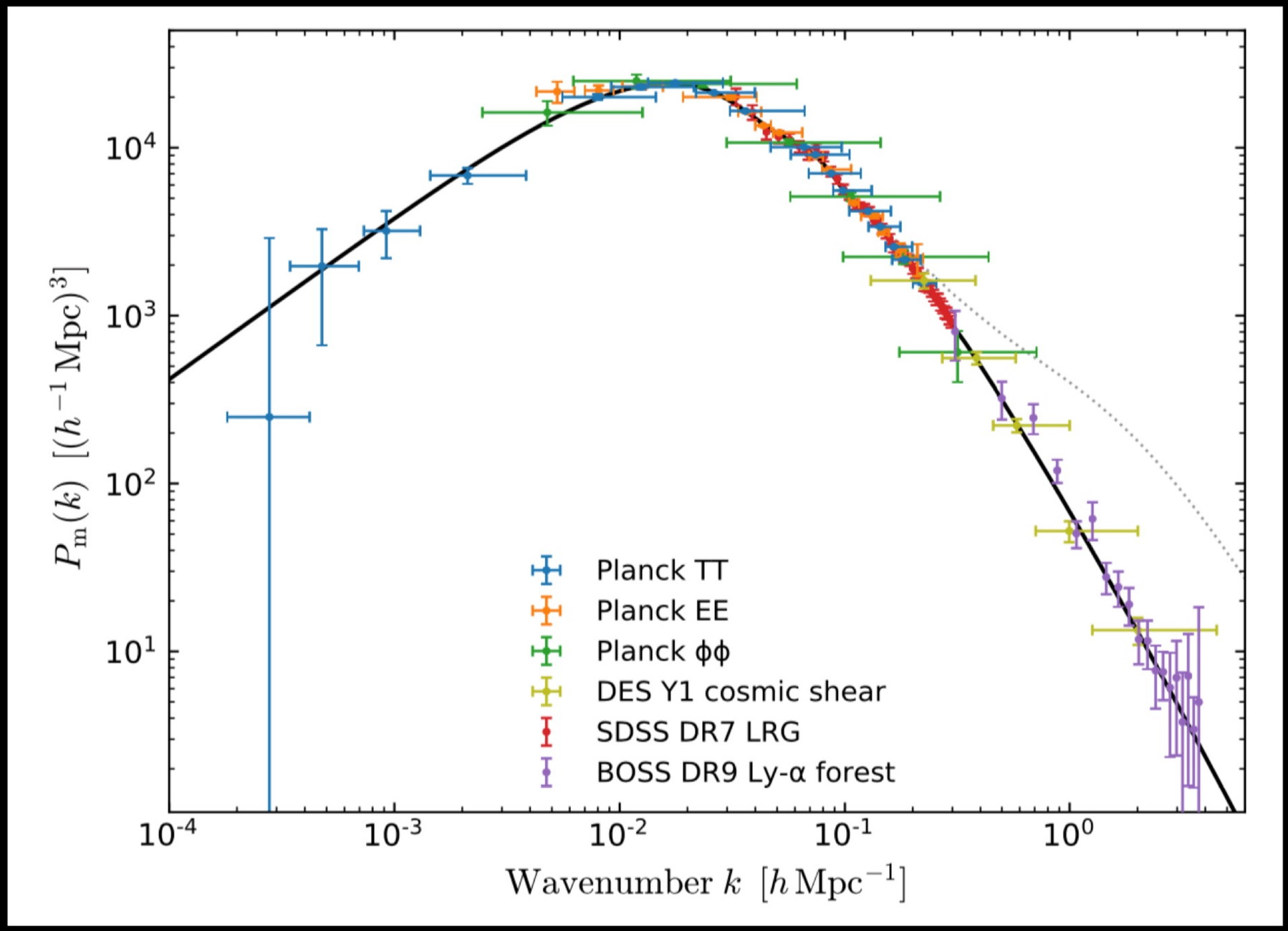
ΛCDM : CMB



Planck 2018 (1807.06209)

ΛCDM : P(k)



Planck 2018 (1807.06209)

ΛCDM : theory

Einstein Field Equations

cosmological constant

$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta} - \Lambda g_{\alpha\beta}$$

Energy momentum tensor

(radiation, baryons, dark matter)

Homogeneity ↓ Isotropy

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

where $ds^2 = -dt^2 + a^2(dr^2)^2$ is the metric.

Beyond ΛCDM

What does it mean?

Break one or more parts of the model

Modify GR

Add exotic form of matter

Replace Λ by something else ($V(\phi)$?)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

Violate homogeneity

Beyond ΛCDM – quintessence

Replace Λ by $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$

If $V(\phi)$ dominates then $\frac{\Lambda}{3} \sim \frac{8\pi G}{3} V(\phi)$

But not exactly like Λ.

Characterized in terms of equation of state

$$w \equiv \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi} + V(\phi)} \neq -1 .$$

Note: Goal is then to characterize $w(z)$

Beyond ΛCDM : fuzzy dark matter

Replace particle like dark matter ($P=0$) & CDM by coherent, massive scalar field (axion).

$$\Box\phi + m^2\phi = 0 \longrightarrow \rho_\phi \sim 1/a^3$$

if m sufficiently large.

but $c_s^2 \neq 0$

↑ sound speed.

Note: other possibilities → Warm Dark Matter, etc...

Beyond ΛCDM : void model.

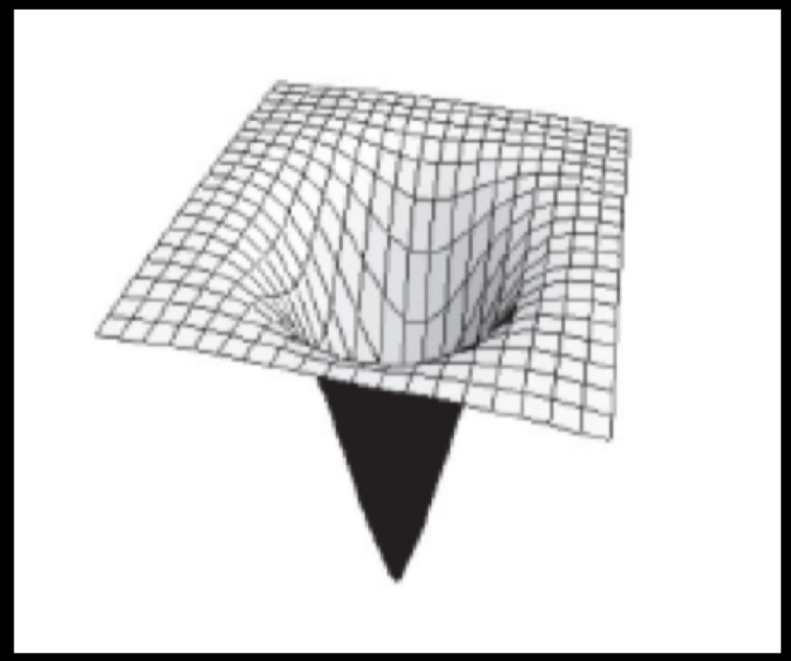
We live in an underdensity $\sim$ 100 Mpc $\rightarrow$ Gpc

$$ds^2 \neq -dt^2 + a^2(d\vec{r})^2$$

but now

radial dependence

$$ds^2 = -dt^2 + \frac{a^2(t,r)}{1-k(r)\,r^2}dr^2 + b^2(t,r)\,r^2 d\Omega^2$$



Beyond ΛCDM ⟶ non Λ / non acceleration?

- SN results

- Large scale anomalies

Beyond ΛCDM → Beyond GR

- Why GR ?
- Why not GR?
- What do theories look like?
- Gravitational Screening
- Large scale Structure
- Large scale constraints
- Galactic constraints