Planck and Cosmological Homogeneity

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Cosmology and Fundamental Physics with *Planck*
CERN, Geneva, Switzerland
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Based on:

JZ, A. Moss, and D. Scott, PRL **101**, 251303 (2008), arXiv:0809.3761;

A. Moss, JZ, and D. Scott, PRD **83**, 103515 (2011), arXiv:1007.3725;

Planck collaboration, arXiv:1303.5090;

JZ and A. Moss, arXiv:1306.xxxx

Outline

- Introduction
- LTB models for acceleration
- *Planck* vs LTB models
- Copernican Inhomogeneity
  - Statistical inhomogeneity
  - Isolated structures
- Conclusions

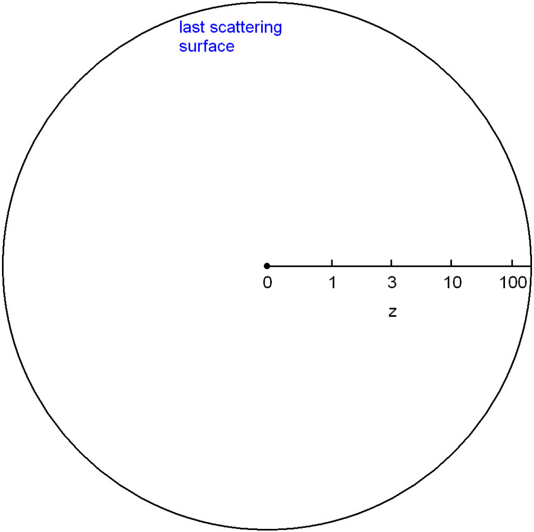
Cosmological Principle

- One of the foundations of cosmology

$$ds^2 = \underbrace{ds^2_{\text{FLRW}}}_{\text{homogeneity}} + \underbrace{ds^2_{\text{fluct}}}_{\substack{\text{statistical}\\ \text{homogeneity}}}$$

- Interested in largest scales $\Rightarrow$ line blurs between homogeneity and statistical homogeneity

What do we know about homogeneity?


last scattering
surface
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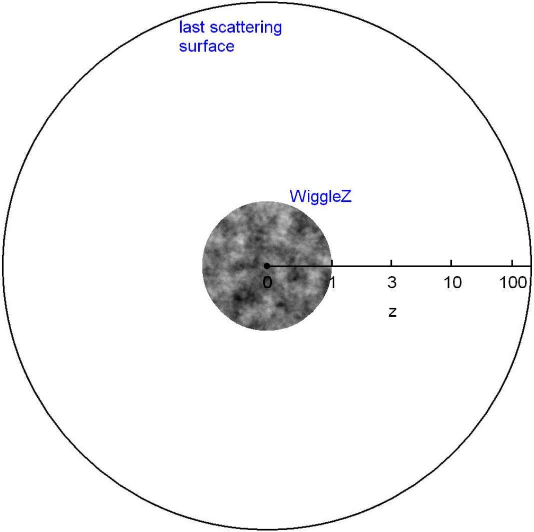
last scattering
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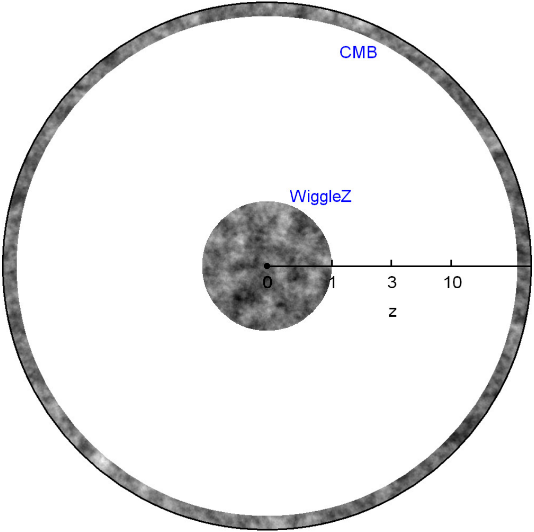
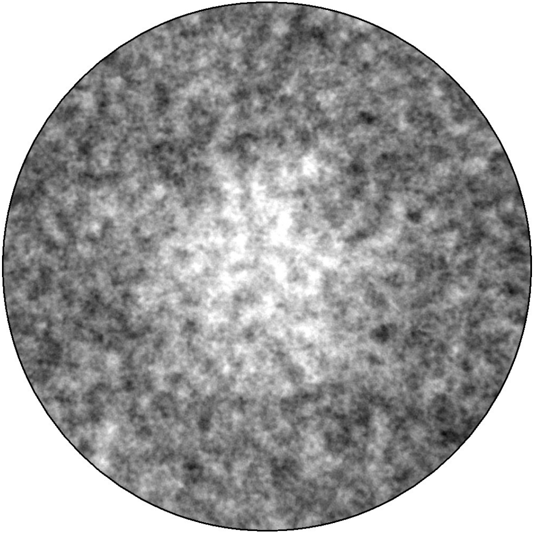

CMB
WiggleZ
0
1
3
10
z

Isotropy of CMB + Copernican principle $\Rightarrow$ homogeneity

Two "loopholes" allow for inhomogeneity, both could be consistent with galaxy surveys and primary CMB

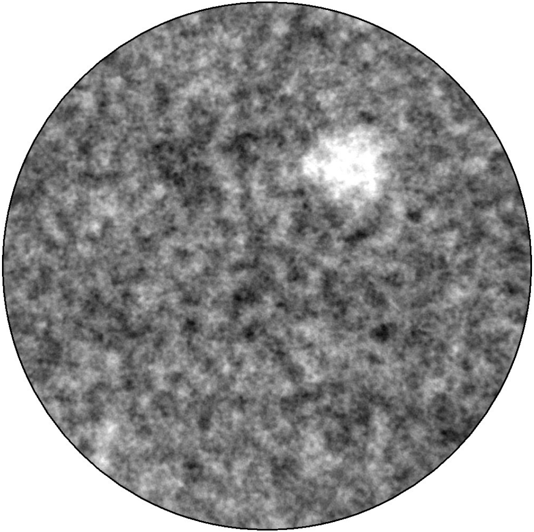
- Violate Copernican principle $\rightsquigarrow$ *radial* inhomogeneity

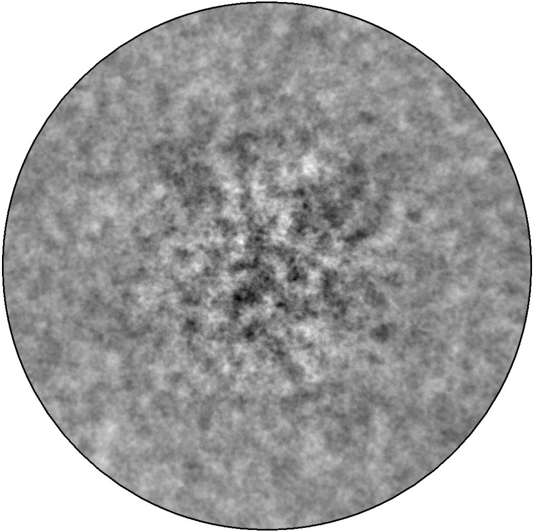


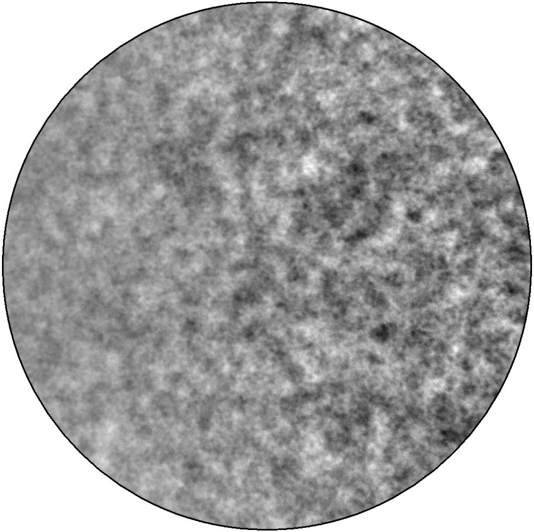
Isotropy of CMB + Copernican principle $\Rightarrow$ homogeneity

Two "loopholes" allow for inhomogeneity, both could be consistent with galaxy surveys and primary CMB

- Violate Copernican principle $\rightsquigarrow$ *radial* inhomogeneity
- CMB is *not* isotropic! How large inhomogeneities could "hide" in the CMB anisotropies?







We need to check homogeneity! Violations could have important implications:

- Large-scale inhomogeneities could be sign of pre-inflationary remnants or other non-standard inflationary artifacts
- Biases in cosmological parameter estimation

Outline

• Soon after SN evidence for acceleration, it was noticed that effect on d_L-z relation could be *mimicked* with a very large void in EdS

• Inhomogeneity replaces dark energy or modified gravity

$\rightsquigarrow$ *Motivation:* In "age of precision cosmology" it should be possible to rule these models out!

• To fit supernova data, clearly require nonlinear void out to $z \sim 1$, i.e. $\delta\rho/\rho \sim 1$ on Gpc scales!

• I.e., void models are zeroth order departures from ΛCDM!

• No parameter smoothly takes you from void models to ΛCDM

$\rightsquigarrow$ *More motivation:* Unlike many DE/MG models, we *can* rule these models out!

Exact solution to GR + dust under spherical symmetry:

- Found by Lemaître, Tolman, and Bondi: LTB

Radial and transverse expansion rates: $H_R = \frac{\dot{Y}'}{Y'}, \qquad H_T = \frac{\dot{Y}}{Y}$

- Define local density parameter, $\Omega_m^{\rm loc}(z) \equiv \frac{24\pi G\rho}{\theta^2}$
- Radial geodesic equations: $\frac{dt}{dr} = \frac{-Y'}{\sqrt{1-K}}$
- For redshift between times t_E and t_R, have exact expression:

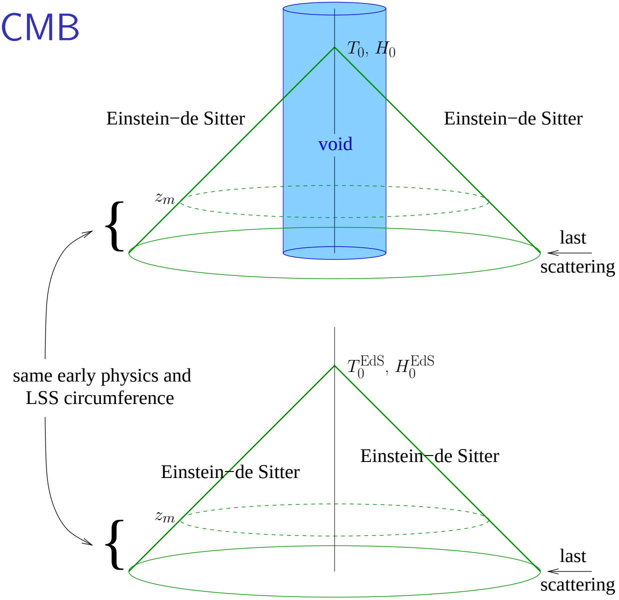
$$z(t_E, t_R) = \exp\left(\int_{t_E}^{t_R} H_R dt\right) - 1$$

- Luminosity distance: $d_L(z) = (1+z)^2 Y(z)$

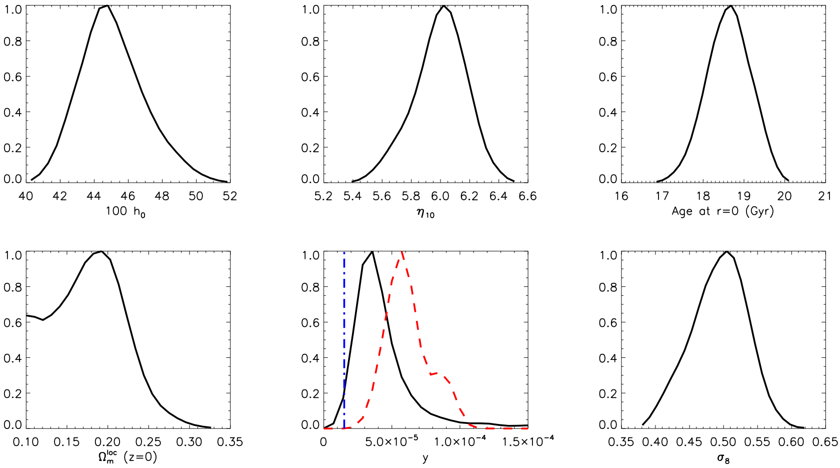
Calculating the CMB

LTB Model:

Effective EdS Model: same *primary* CMB



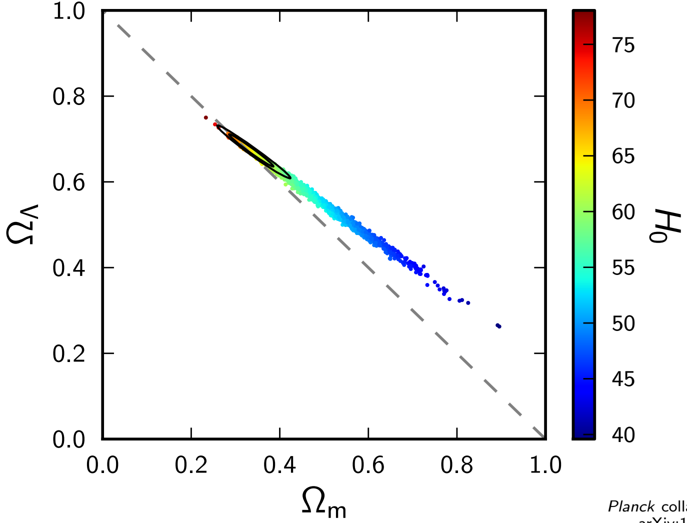
Marginalized likelihoods, using CMB+SNe:



Strongest, most robust result is from CMB+SNe:

- We find $h_0 = 0.45 \pm 0.02$
- Can't fit CMB with *any* H_0 unless void is in closed background or surrounded by huge overdense shell!

Geometrical degeneracy in FLRW models—these models share the same physics and circumference of LSS:



Planck collaboration
arXiv:1303.5076

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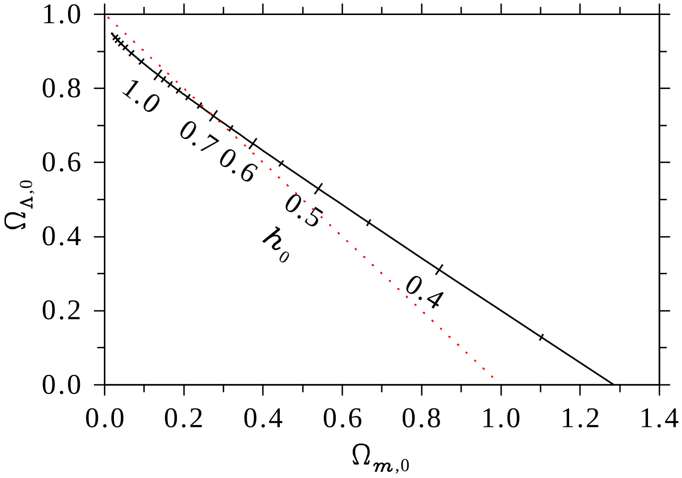
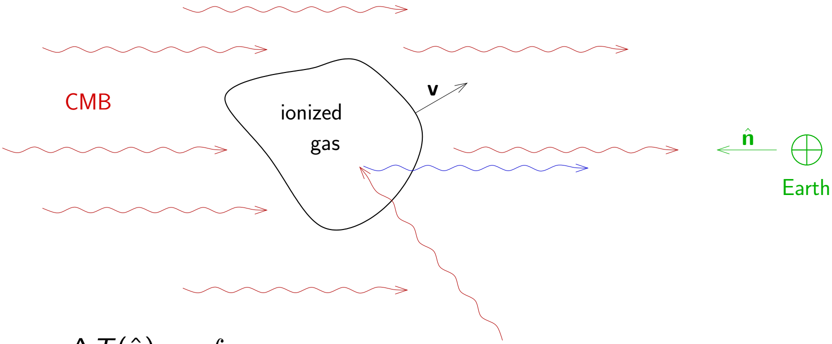


Closed, $\Omega_\Lambda = 0$ model fits primary CMB, but requires $h_0 = 0.32$

Outline

Important to confirm CMB+SN result with an independent approach...

Kinetic Sunyaev-Zeldovich (kSZ) effect due to Thomson scattering of CMB from free electrons:



$$\frac{\Delta T(\hat{\mathbf{n}})}{T} = \int v_{\parallel}(\hat{\mathbf{n}}, z)\, d\tau \qquad (v_{\parallel}(\hat{\mathbf{n}}, z) \equiv \mathbf{v}(\hat{\mathbf{n}}, z) \cdot \hat{\mathbf{n}})$$

- LTB models expected to produce very large kSZ monopole signal:

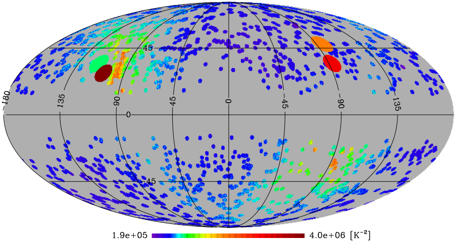
$$\bar{\mathbf{v}}(\hat{\mathbf{n}}, z) = \hat{\mathbf{n}}\bar{v}_{\|}(z)$$

$$\text{i.e.} \quad \frac{\Delta T(\hat{\mathbf{n}})}{T} = \int \bar{v}_{\|}(z)\delta_e(\hat{\mathbf{n}}, z)d\bar{\tau} \qquad \text{monopole}$$

- Constrained by kSZ upper limits at a few clusters (García-Bellido and Haugboelle, 2008).

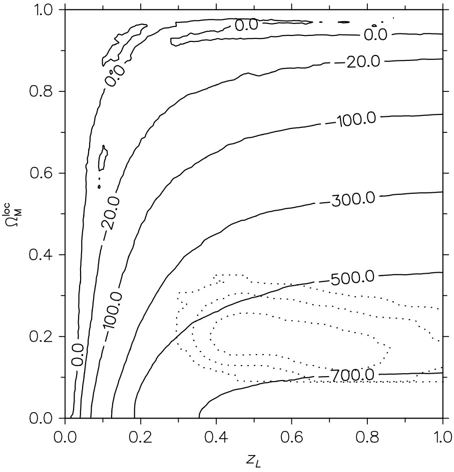
- *Planck* provides a large sample of kSZ measurements at cluster positions

- Used Meta Catalogue of X-ray detected Clusters, with $\simeq 1400$ clusters:



"*Planck* intermediate results. XIII. Constraints on peculiar velocities," arXiv:1303.5090

Parametrize void by width (z_L) and depth (Ω_m^{loc}):



Solid contours: $\log_{10}(\mathcal{L}/\mathcal{L}_{\mathrm{hom}})$
Dotted contours: 1, 2, 3σ Union2 SN CL's

Conclusion: Voids which fit the SN data are ruled out at *extremely* high confidence by the *Planck* cluster kSZ measurements.

Outline

Over what distances and scales do various observations tell us about fluctuations?

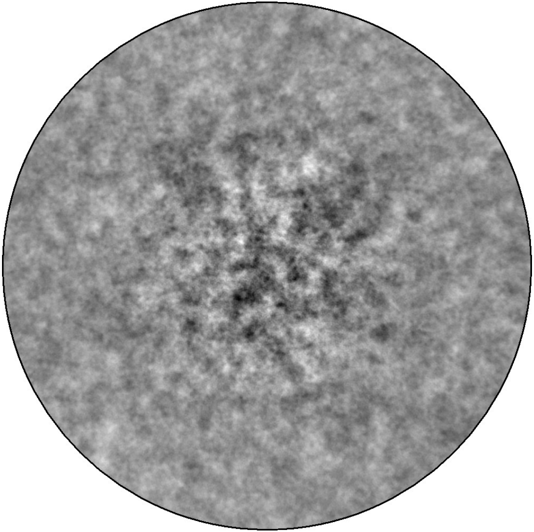
- ISW, CMB lensing potential, and galaxy lensing convergence power spectra in the Limber approximation:

$$C_\ell^{\rm ISW} \propto \frac{1}{\ell^3}\int_0^{r_{\rm LS}} dr\, r g'^2(r)\mathcal{P}_{\mathcal{R}}\left(k(\ell,r)\right) T^2\left(k(\ell,r)\right)$$

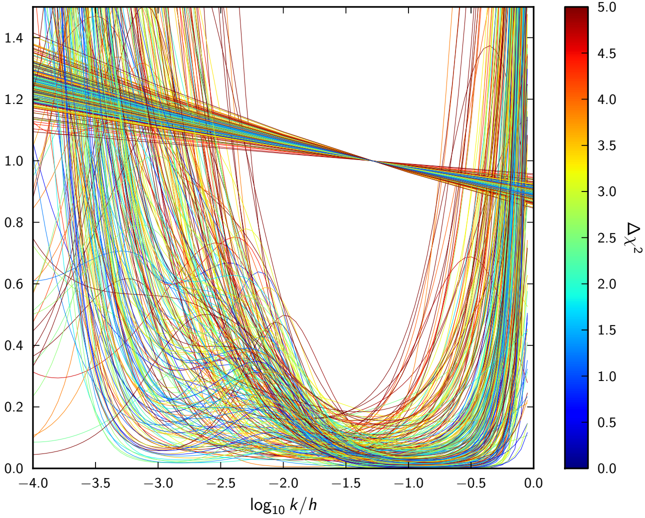
$$C_\ell^{\phi\phi} \propto \frac{1}{\ell^3}\int_0^{r_{\rm LS}} dr\, r\left(\frac{r_{\rm LS}-r}{r_{\rm LS} r}\right)^2 g^2(r)\mathcal{P}_{\mathcal{R}}\left(k(\ell,r)\right) T^2\left(k(\ell,r)\right)$$

$$C_\ell^{\kappa\kappa} \propto \frac{1}{\ell}\int_0^{r_{\rm max}} dr\, r\left(\frac{r_{\rm max}-r}{r_{\rm max} r}\right)^2 g^2(r)\mathcal{P}_{\mathcal{R}}\left(k(\ell,r)\right) T^2\left(k(\ell,r)\right)$$

$$k(\ell,r) = \frac{\ell}{r}$$

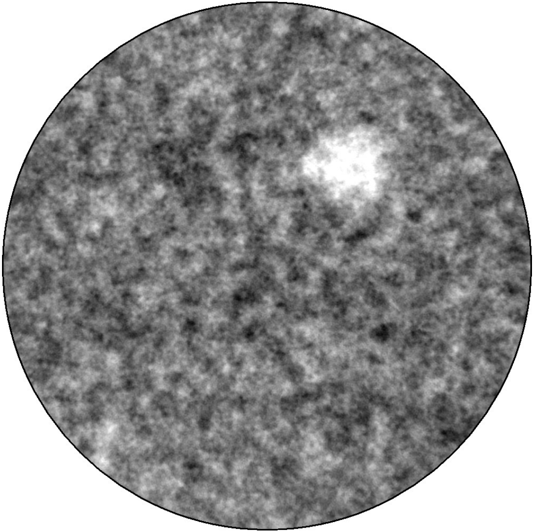


Result: $\mathcal{P}_{\mathcal{R}}^{\rm mod}(k)/\mathcal{P}_{\mathcal{R}}^{\Lambda\rm CDM}(k)$ using $C_\ell^{\rm TT}$ (*Planck*), $C_\ell^{\phi\phi}$ (*Planck* + SPT)



Isolated structures

- Goal is to find *model independent* limits on amplitudes of spherical structures vs. width and distance
- I.e., how large amplitude structures can be "hiding" in the CMB, as a function of width and distance?
- Distinct from searches for particular structures (e.g., textures, multi-stream inflation defects, bubble collision scars)



• Spherical structure in dust + Λ FLRW background can be described exactly in GR with ΛLTB solution:

$$ds^2 = -dt^2 + \frac{Y'^2}{1-K}dr^2 + Y^2 d\Omega^2$$

• Can calculate SW, RS, ISW, lensing effects by propagating null geodesics:

$$\frac{dt}{d\lambda} = \gamma \ , \qquad \frac{dr}{d\lambda} = \frac{\gamma n_r}{Y'}, \qquad \frac{d\theta}{d\lambda} = \frac{L}{Y^2},$$
$$\frac{dn_r}{d\lambda} = \frac{1}{2}\gamma \left(n_r^2 - 1\right)\left(3\Sigma n_r - \frac{2}{Y}\right)$$

• Then find amplitude of structure which gives

$$(S/N)^2 = \sum_{\ell m} \frac{|a_{\ell m}|^2}{C_\ell} = 1$$

($a_{\ell m}$ are the multipoles due to the structure)

Conclusions

- Homogeneity needs to be checked, rather than assumed!
- Very large radial inhomogeneity ruled out as source of apparent acceleration, using both CMB+SNe and *Planck* kSZ measurements
- We have vastly extended the range of scales and redshifts accessible to surveys to test homogeneity over most of our observable volume, using ISW/RS/SW and CMB and galaxy lensing, finding results consistent with homogeneity
- This solidifies the foundations of our picture of cosmology: flat FLRW + adiabatic, near-scale-invariant fluctuations