CMB Science Goals

Antony Lewis

http://cosmologist.info/

UNIVERSITY OF SUSSEX

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LCDM

- Higher precision parameters
  precision consistency tests

  probably not exciting unless ongoing inconsistency with other data (H0?)

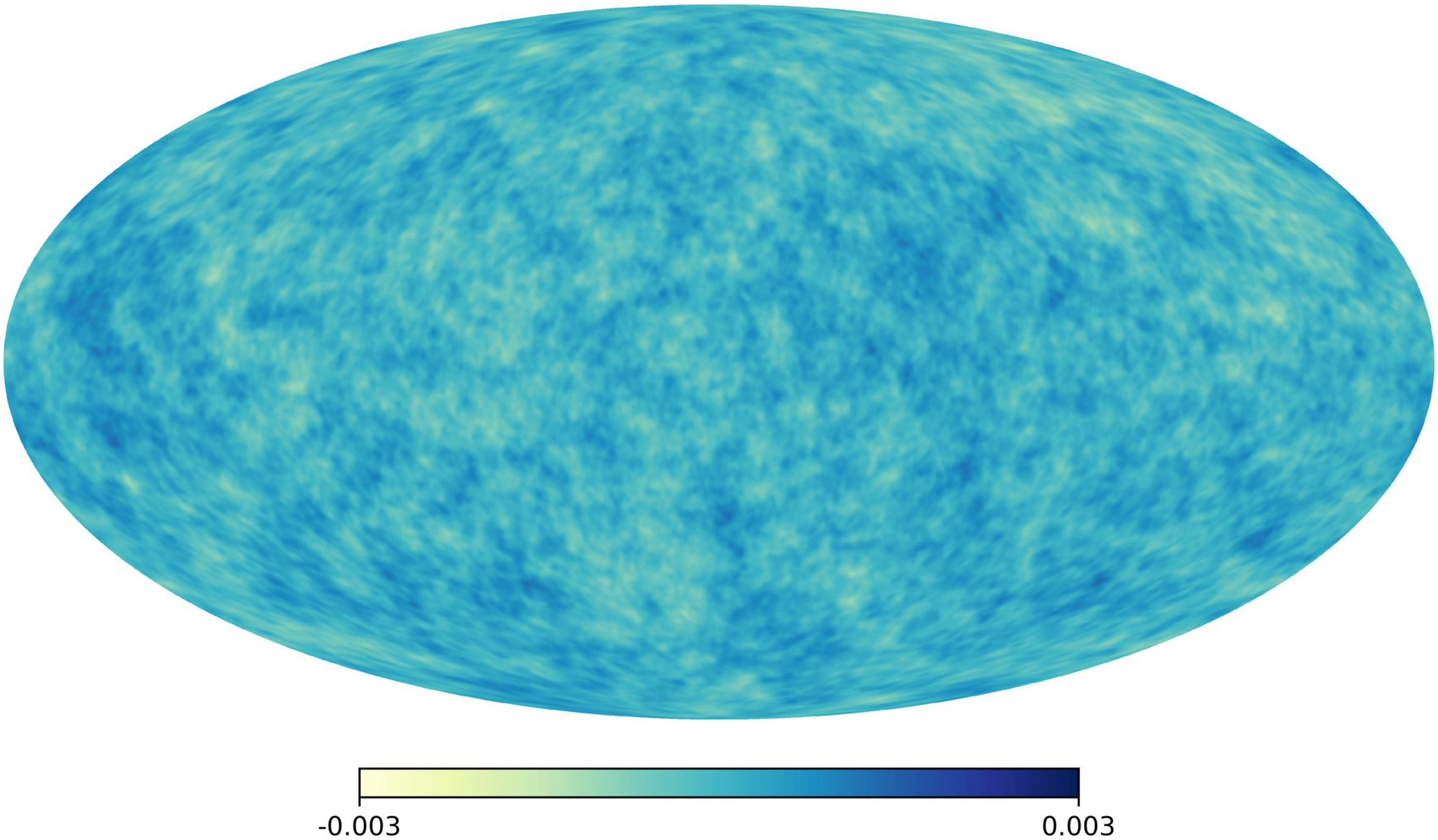
- Measure τ better: integrated constraint on reionization models + small amount of shape information from EE shape

- Precision SZ/kSZ: properties of hot gas and star formation, patchiness of reionization, cluster physics. Cluster catalogue at high redshift.

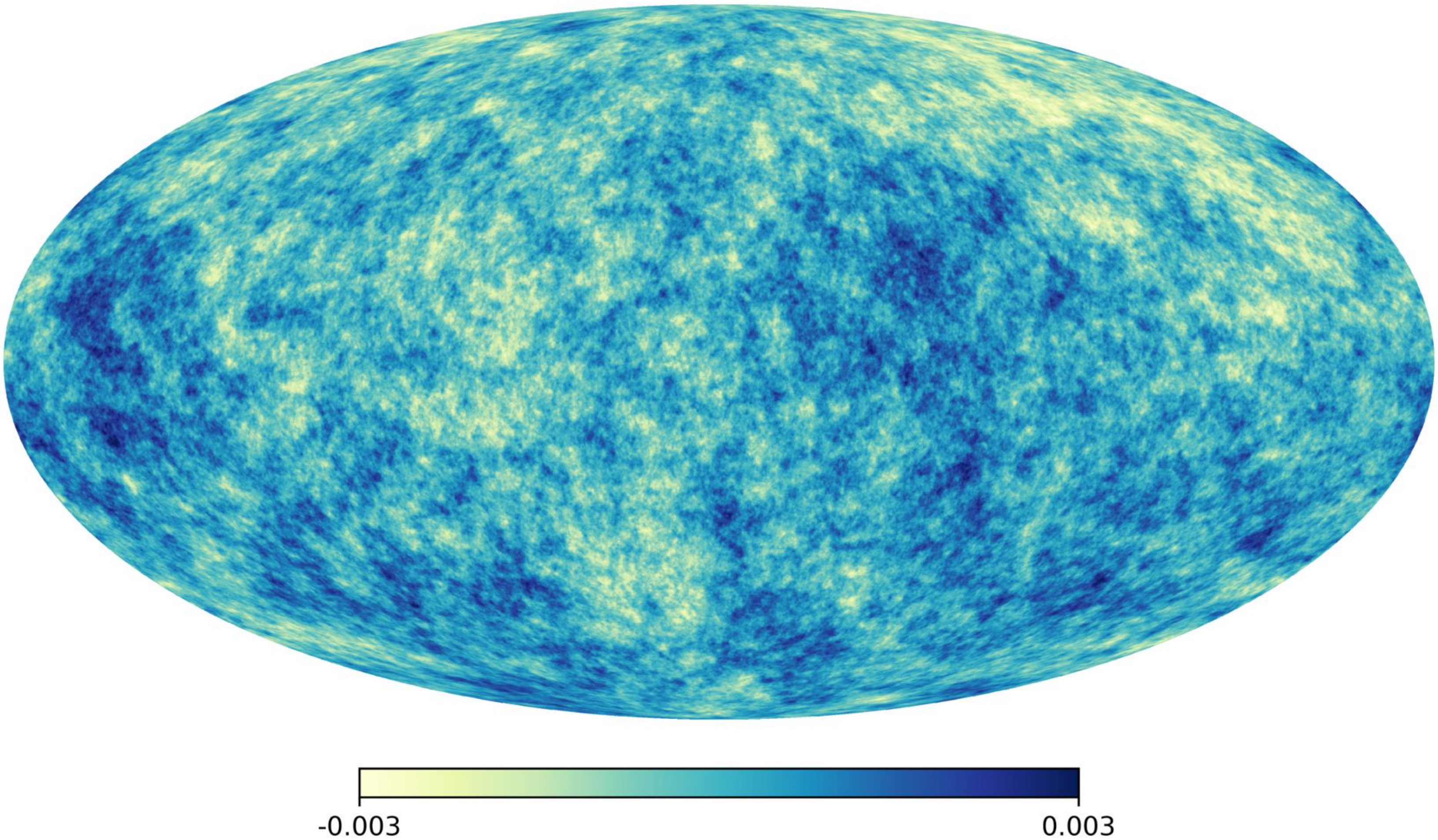
- Mapping. LOTS more clean nearly-linear modes.
  - E-modes to $\ell \gg 1000$
  - lensing resolved up to $L \sim 2000$
  - SZ

  Surely very good value compared to cost per clean mode in LSS/21cm.

Lensing deflection (E map): WF Planck sim



Lensing deflection (E map): Full signal sim



New signals in LCDM

- Spectral distortions in monopole:
  - $\mu \sim 10^{-8}$ from energy injection from damping of sound waves
    (challenging for $n_S \sim \text{const}$ with foregrounds)
  - Lines from recombination and metals
  - y distortion

- Spectral distortions in anisotropies
  - Rayleigh scattering from recombination
    (big signal if have $\nu \gg 300\ \text{Ghz}$, LiteBird, CCAT' ? ...)

- Non-Gaussianity from patchy reionization

- Lensing curl

- etc…

Gravitational waves: B-modes

- Lyth bound – large $\Delta\phi$ – symmetries
  - conservatively $r > 0.01 \Rightarrow \Delta\phi > M_P$
- $r \sim O(0.001)$ target: test if $r \sim O\left(\frac{1}{N^2}\right)$
  - *need delensing*
- Test specific predictive models (R^2 ...)
- Testing consistency relation difficult

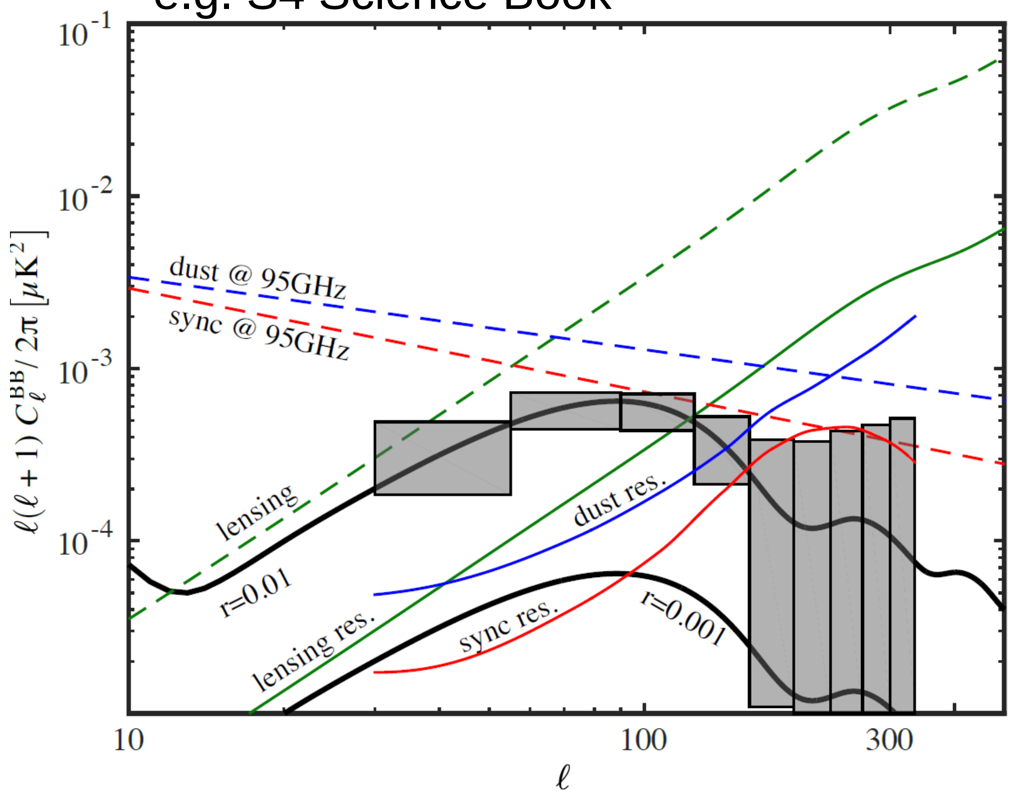
Limits on delensing

Optimal internal reconstruction in principle only limited by noise down to $r \sim 10^{-4} - 10^{-6}$

But: residual foregrounds in B may limit nearer $r \sim 10^{-3}$ depending on frequencies etc.

Lensing B still important source of noise for $r \sim 10^{-3}$: delensing required

e.g. S4 Science Book



Note: testing slow-roll from expected level of n_s running is very difficult

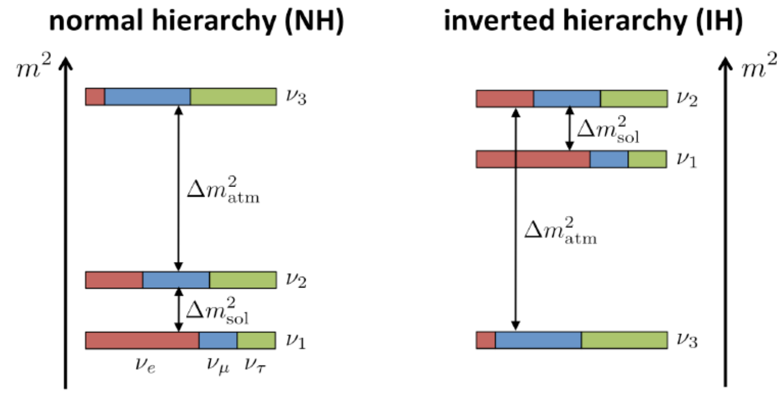
Neutrino mass

S4 Science Book

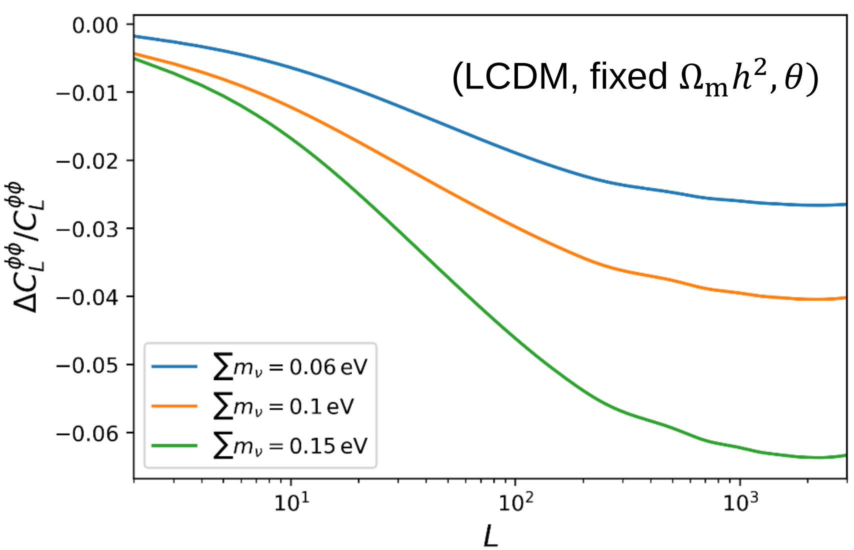
Measure $\sum m_\nu$

Inverted or normal hierarchy?
(inverted already disfavoured ($2-3\sigma$) by
oscillations (NoVA/SuperK. e.g. 1804.09678))

(+ lepton numbers/CP violation..)



$\sum m_\nu > 0.058$ eV $\sum m_\nu > 0.1$ eV

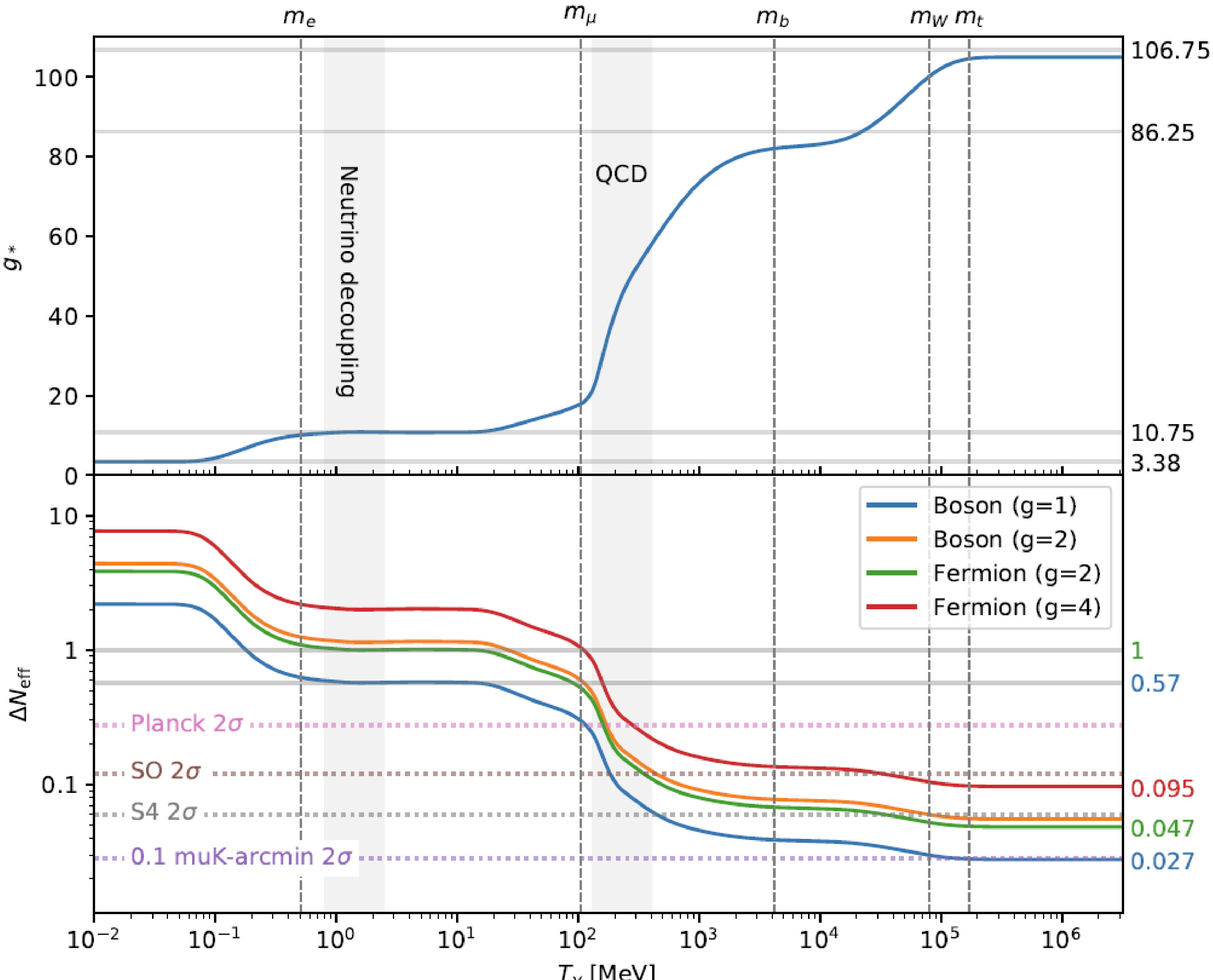


Most modes on small scales

Amplitude relative to TT/TE/EE partly degenerate with τ

+ Clusters   Can also be done by galaxy surveys, but very different systematics

Right sterile relics: constraints on $N_{\rm eff}$

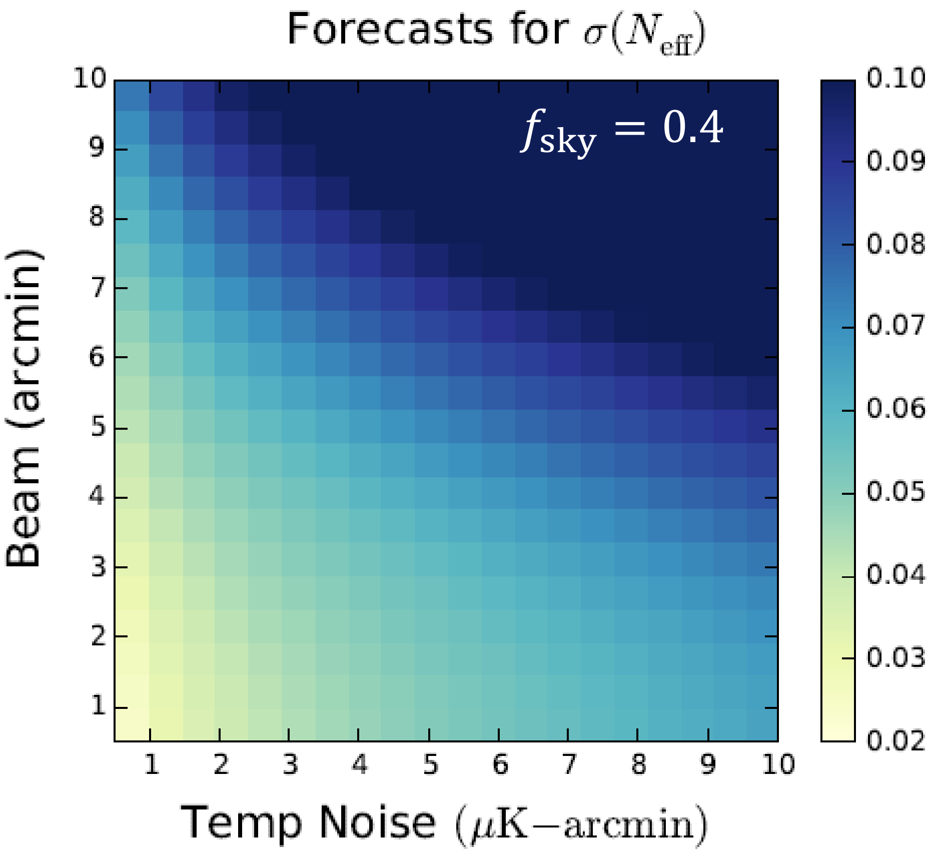


Possible specific targets:
(want $\sigma(N_{\rm eff}) > 2\Delta N_{\rm eff}$)

Axions: $\Delta N_{\rm eff} = 0.027\ N_a$

Gravitino: $\Delta N_{\rm eff} = 0.047 - 0.057$
(rule out all low-scale SUSY?)

S4 Science Book



Need large $f_{\rm sky}$ to beat down cosmic variance

Note: Y_p degeneracy and BBN uncertaintiy of ~0.001 (bottle/beam τ_n difference) is about $\Delta N_{\rm eff} \sim 0.01$

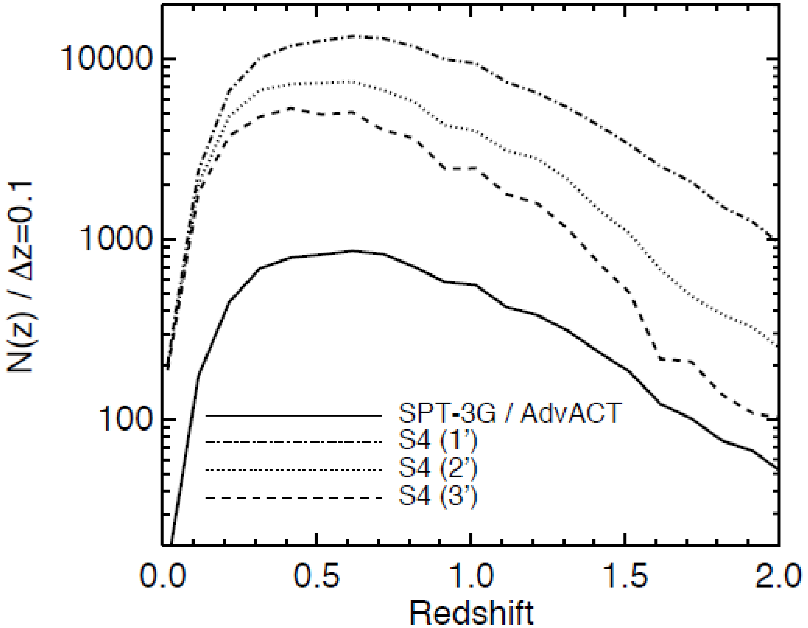
Dark energy

Very weak from CMB power spectrum.
Weak from CMB lensing, but can improve joint constraints.

SZ Clusters:
$N(M)$: probe of cosmology, NG, and dark energy

SZ good probe at $z > 1$, complementary to DES, LSST etc.

Want small beam



CMB lensing for mass calibration of high-z clusters

e.g. high-sensitivity, high-resolution CMB can calibrate mass of 1000 stacked clusters to a few percent

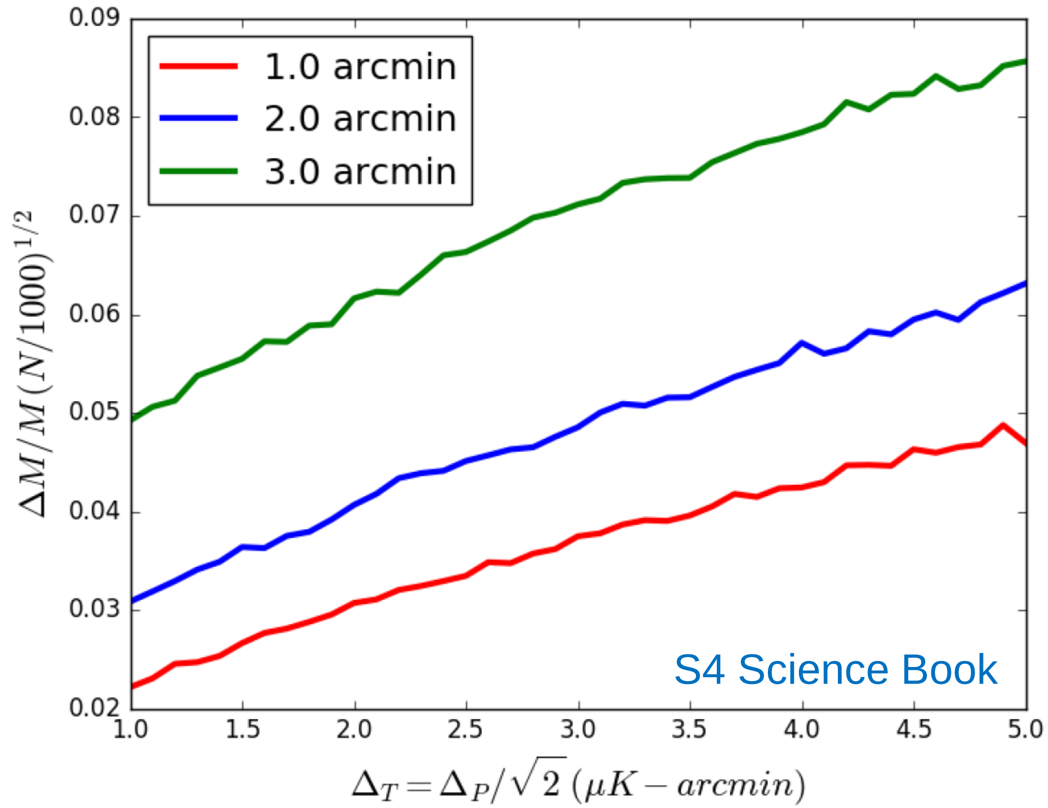


Figure 53. *Mass uncertainty from CMB halo lensing measurements stacking 10^3 halos of mass $M_{180\rho_{m0}} \approx 5 \times 10^{14} M_\odot$, as a function of instrumental noise and varying instrumental resolution.*

Other models…

- Dark matter-baryon scattering
- Axions (ultra-light, cold, fluctuating in inflation,…)
- Strings, magnetic fields..

Primordial non-Gaussianity

- Standard shapes only shrink sigma by 2-3
  - limited by cosmic variance on large modes
  - modes smaller than recombination width are line-of-sight averaged (i.e. Gaussianised)

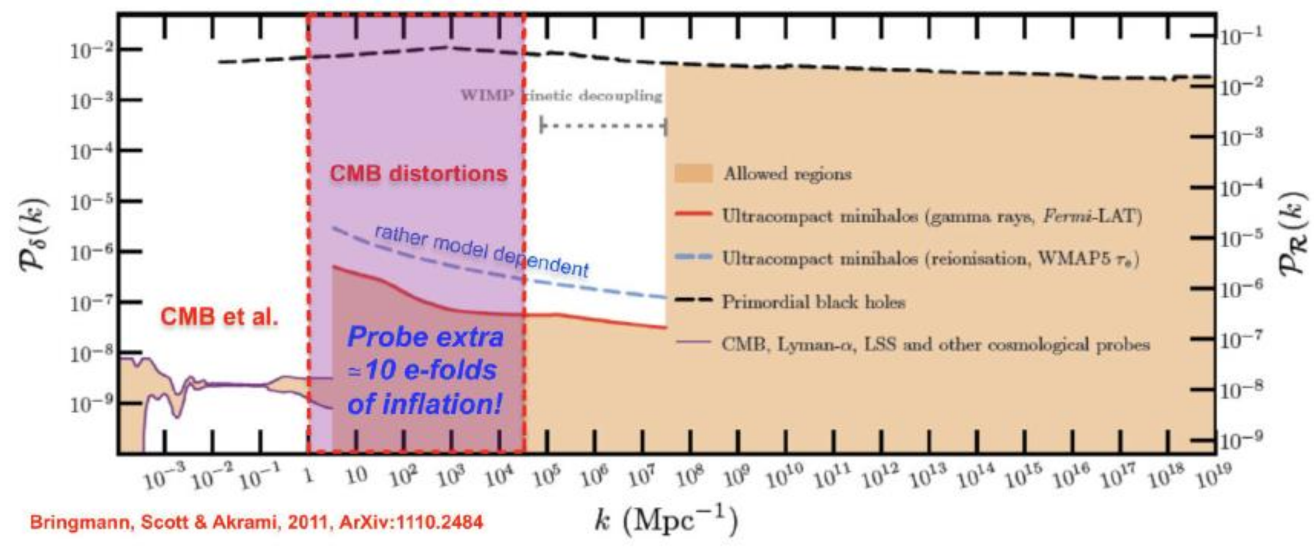
- Worth having, no obvious targets possible at high significance
  (though any detection of local $f_{NL} \neq 0$ would rule out almost all single field inflation models)

- Could test non-standard scale dependence/extended shapes

- Can also look for tensor non-Gaussianity (but no motivated target in reach)

New physics from distortions

- Probe unconstrained scales: $50\mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$
  - test slow-roll inflation



- New decays, annihilations, primordial black holes, etc…

- Non-Gaussianity from spatial variation in μ (hard)

Indirect science case

- Using CMB, CMB lensing and clusters to improve joint constraints with other data

  - cross-correlations
  - measuring bias
  - reducing systematics
  - cross-calibration

CMB lensing to calibrate shear for galaxy lensing

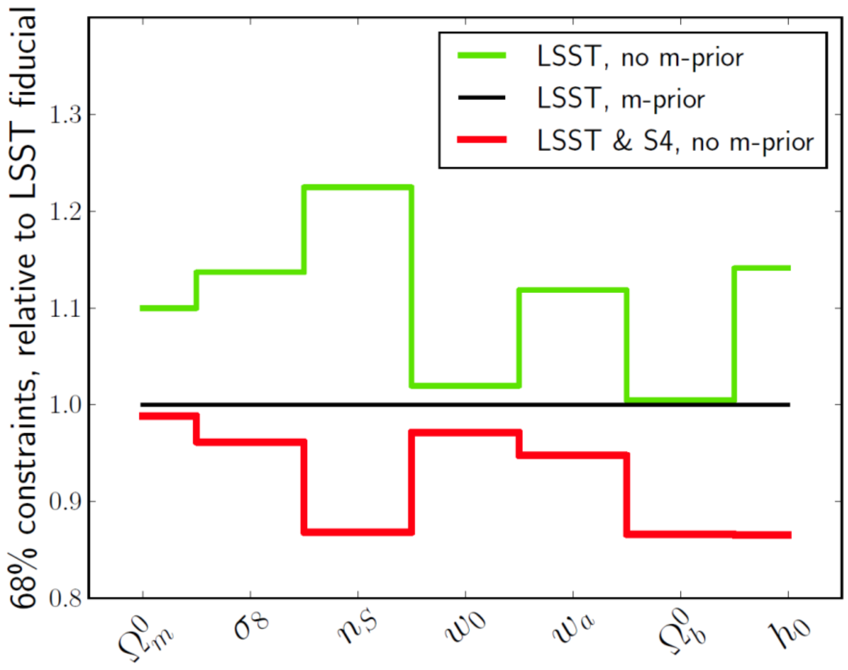
Galaxy lensing surveys measure (roughly) galaxy ellipticity e_g.
Hard to relate directly to lensing shear γ_{lens}.

$$e_{\text{g}} \sim (1+m)\gamma_{\text{lens}}$$

m could mimic different dark energy models.

Cross-correlation with CMB lensing can measure m

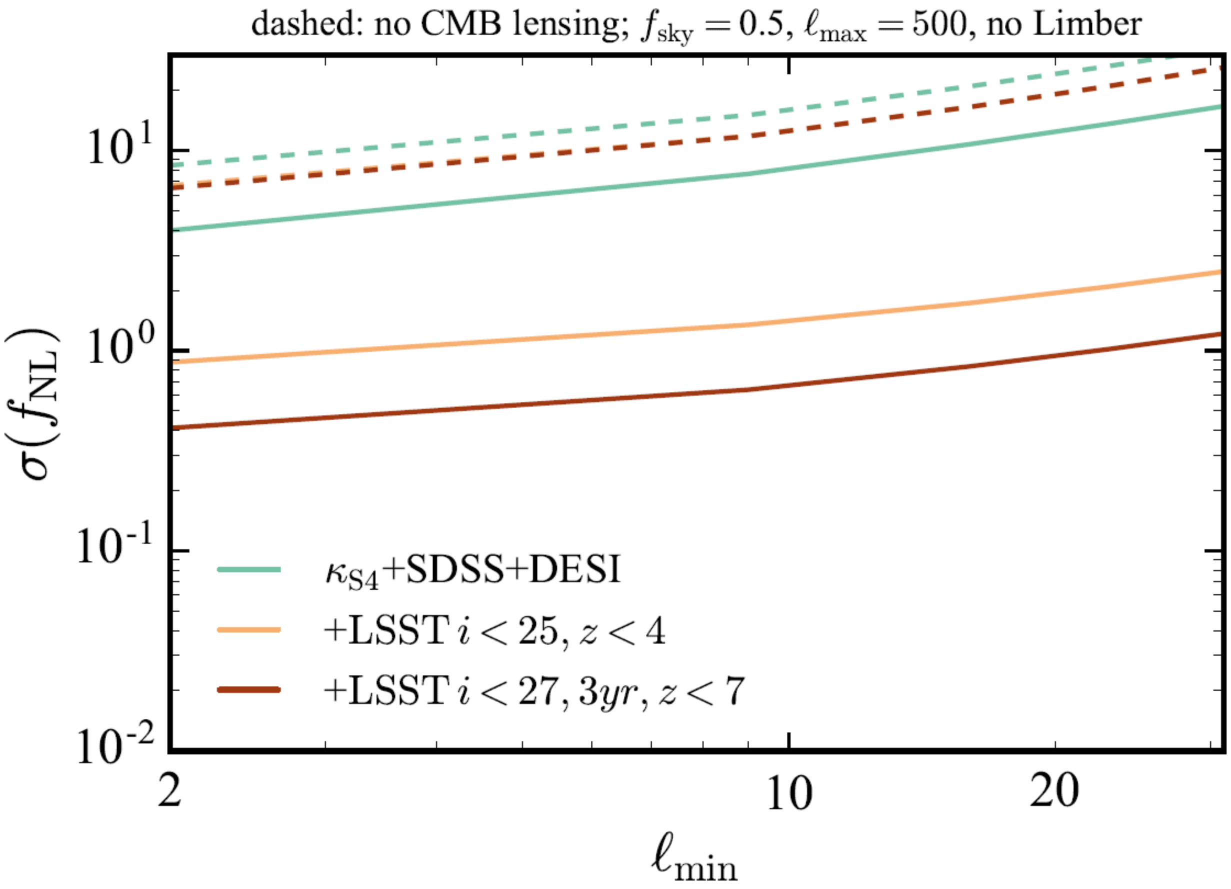
e.g. S4 to calibrate LSST



Valuable for EUCLID, WFIRST, LSST, etc.
- more robust prior-independent constraints on dark energy

Schaan et al. arXiv: 1607.01761

CMB lensing + LSS for f_{NL} from scale-dependent bias



Schmittfull & Seljak :1710.09465

Summary

- Lots of new nearly-linear modes easily accessible
  - map polarization at recombination and integrated matter of the universe
- Good targets for r-modes
  - separate qualitative classes of inflation
- Motivated targets hard to reach at high significance for many other parameters ($N_{\rm eff}, m_\nu,\ \mu$) but may be doable
- Some new sure-fire signals are in reach: kSZ/SZ/Rayleigh
- Distortions probe wide-open parameter space
- Lots of scope for clever joint analyses