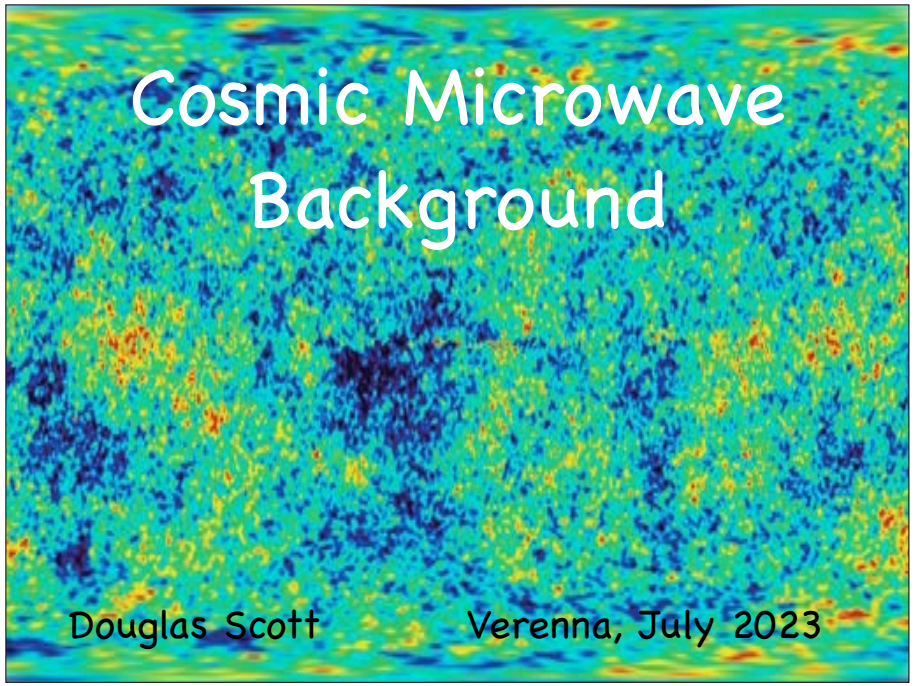
4 lectures:

1. CMB – back to basics
2. Cosmological parameters (a skeptical guide)
3. Leftover stuff about neutrinos

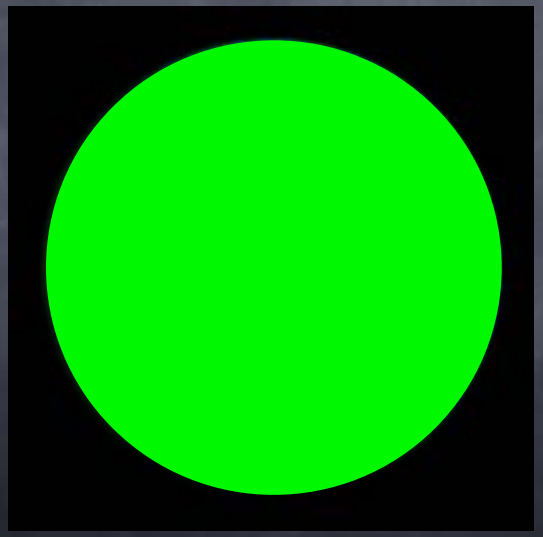
(There are 3 types of people in the world, those who can count and those who can't)

Cosmic Microwave Background



Douglas Scott Verenna, July 2023

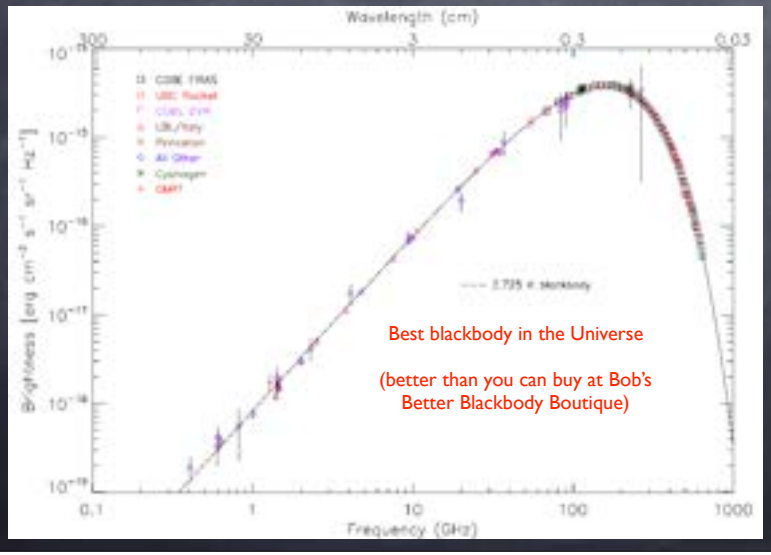
CMB Sky

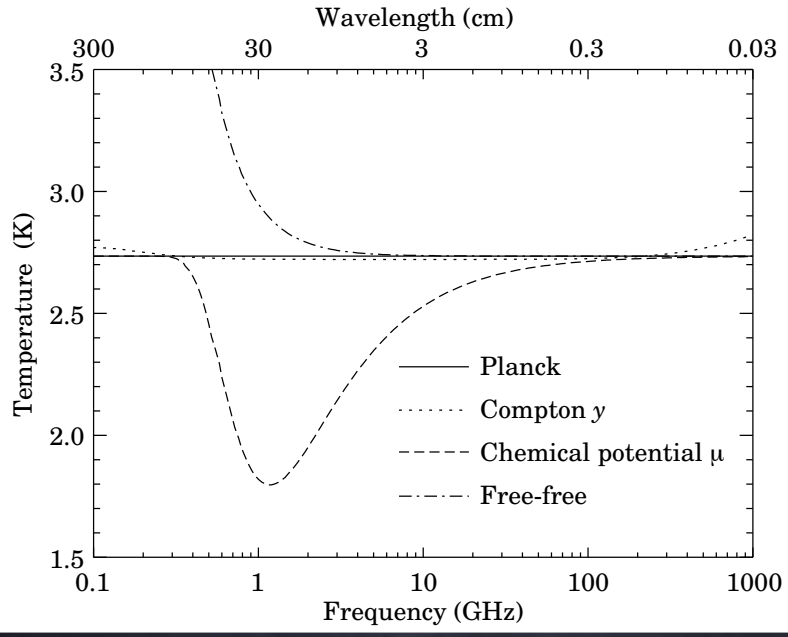


CMB Sky

- CMB "predicted" in 1940s
- Discovered by Penzias & Wilson 1965
- Spectrum measured 1970s
- Precisely blackbody by 1990
- Dipole measured 1970s
- Anisotropies predicted 1970s & 1980s
- Anistropies detected early 1990s
- Then lots of precision!

CMB Spectrum





CMB Spectrum

- mild scattering (τ<1) gives y-distortion:
  τ x BB(T_1) + (1-τ) x BB(T_2)
  → particular analytic shape
  decrement in RJ, increment in Wien
  $y = \tau \times k\,(T_1 - T_2)/mc^2$
  (with $\tau = \int \sigma\, n\, dx$, Thomson optical depth)
  y<1 for z<10^5 (in LCDM)
  → "Compton distortion" or SZ effect
- multiple scatterings gives μ-distortion:
  τ>>1 for z>10^5
  CMB reaches new equilibrium
  with wrong number of γs for the T
  Spectrum ∝ 1/{exp(x+μ)-1},
  with x=hν/kT and μ the chemical potential
  It turns out that $\mu \approx 1.4\,\Delta E/E$
  → "Bose-Einstein" or "chem. pot." distortion
  At z>10^7, double Compton etc. give BB again

CMB Spectrum

$T_\gamma = 2.728 \pm 0.002$ K (now 2.7255±0.0006K)

$n_\gamma = (2\zeta(3)/\pi^2) T_\gamma^3 \simeq 413\,\mathrm{cm}^{-3}$

$\rho_\gamma = (\pi^2/15) T_\gamma^4 \simeq 4.68 \times 10^{-34}\,\mathrm{g\,cm}^{-3} \simeq 0.262\,\mathrm{eV\,cm}^{-3}$

$|y| < 1.2 \times 10^{-5}$ (95% CL)

$|\mu_0| < 9 \times 10^{-5}$ (95% CL)

$|Y_{ff}| < 1.9 \times 10^{-5}$ (95% CL)

tight constraints on distortions

but expected distortions smaller still

Spectral distorions

- y-distortion from average amount of inverse-Compton scattering
- Expect recombination lines (have to be there, but may not tell us much new)
- Dissipation of primordial adiabatic modes (i.e. damping) - could increase lever arm in k for constraining inflation
- Structure formation and feedback effects
- Possible effects from decaying or annihilating particles
- Other effects of reionization

CMB history (eh)

Andrew McKellar

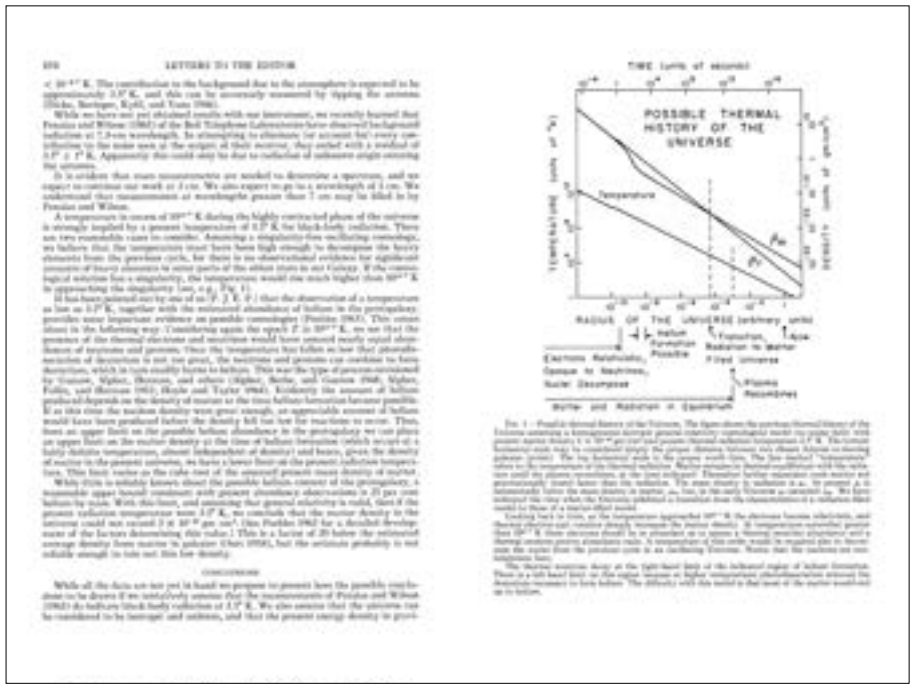
CN measurements at DAO (1940, 1941) ⇒ rotational temp ≈ 2.3K

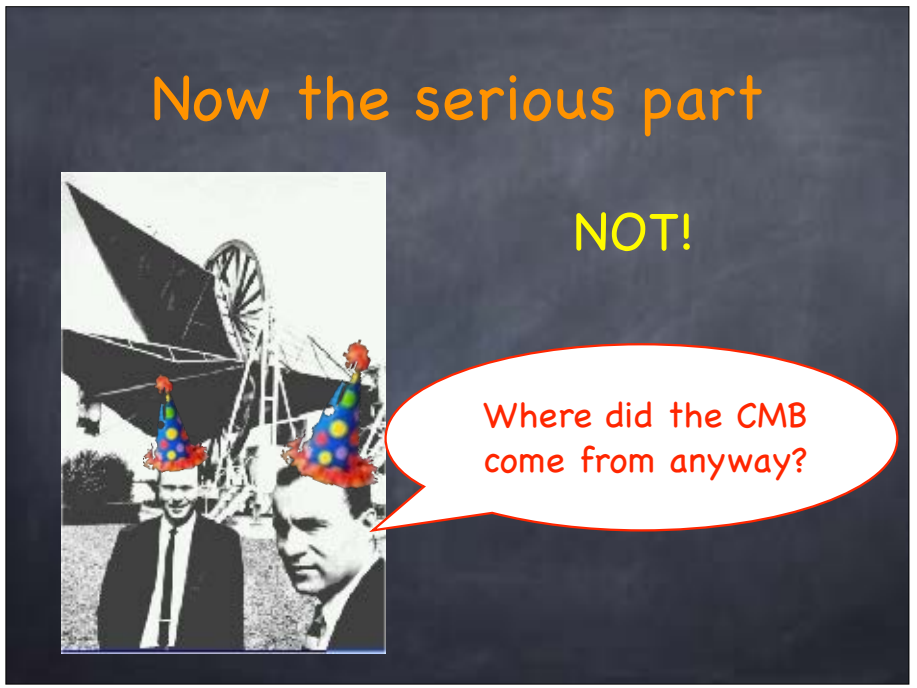
Herzberg (1950): "...only a very restricted meaning"

THE ASTROPHYSICAL JOURNAL

JULY 1, 1965

SPECTRAL AND PHOTOMETRIC MEASUREMENTS OF SOLAR X-RAY EMISSION BELOW 60 Å




Now the serious part
NOT!
Where did the CMB come from anyway?

Where did the CMB temperature come from?

T_0=2.7255±0.0006K (Fixsen 2009)

$e\,\mathrm{Kelvin} (= 2.718\,\mathrm{K})$

$\sqrt{15/2}\,\mathrm{Kelvin} (= 2.739\,\mathrm{K})$

$30/11\,\mathrm{Kelvin} (= 2.727\,\mathrm{K})$

$-\ln(9\alpha)\,\mathrm{Kelvin} (= 2.723\,\mathrm{K})$

Triple point of water $\div\, 100 (= 2.7315\,\mathrm{K})$

$(2\alpha/\pi)^4 m_e c^2/k\ (= 2.762\,\mathrm{K})$

$(2/5)(\alpha_G m_e/2\pi m_p)^{1/4} m_p c^2/k\ (= 2.719\,\mathrm{K})$

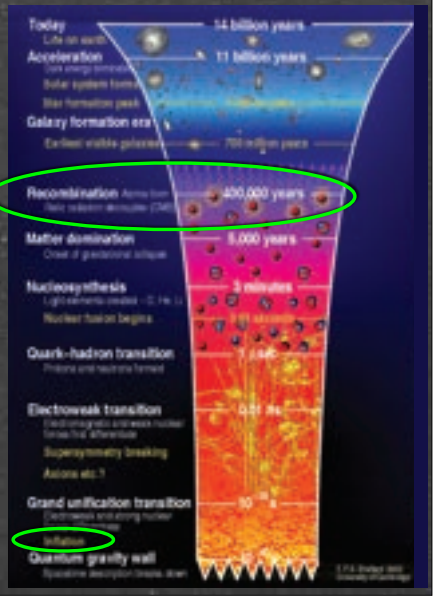
$[\alpha_G \equiv G m_e^2/c\hbar]$ $\quad 16\sqrt{2}\pi\alpha_G^{1/4} m_e c^2/k\ (= 2.727\,\mathrm{K})$

$(hc/k)\ \mu\mathrm{Leagues}^{-1} (= 2.98\,\mathrm{K})$

$[\pi e^{\pi} \simeq 73]$ $\quad e^{-73} T_{\mathrm{Pl}}\ (= 2.805\,\mathrm{K})$

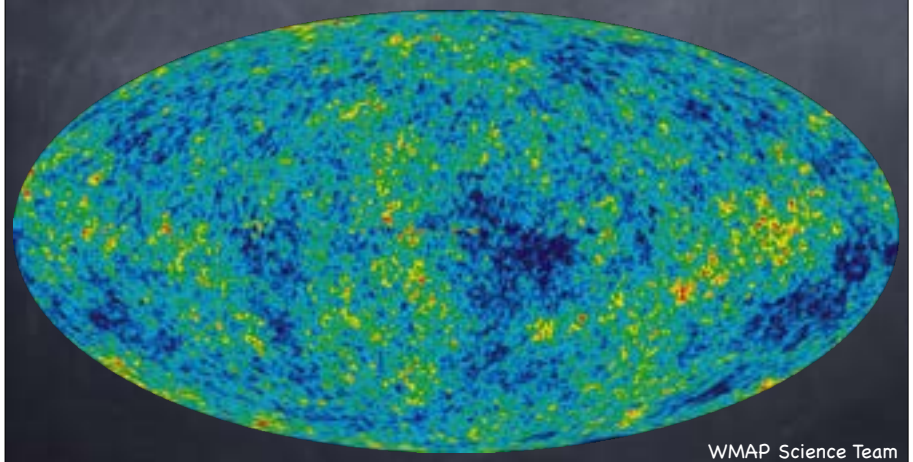
Hot Big Bang picture

Where did the CMB really come from?

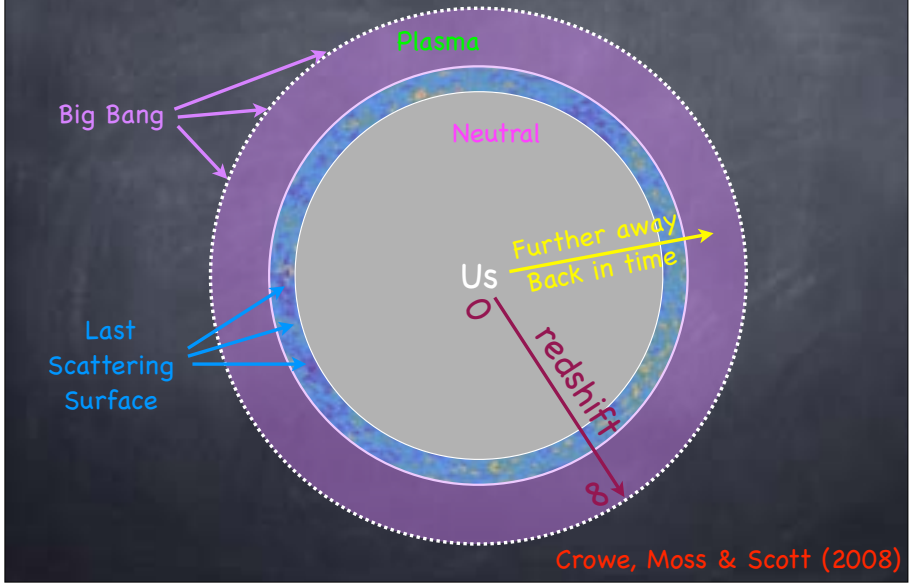


The CMB Sky

Temperature anisotropies at ~400,000 years



The Universe is an inside-out star!



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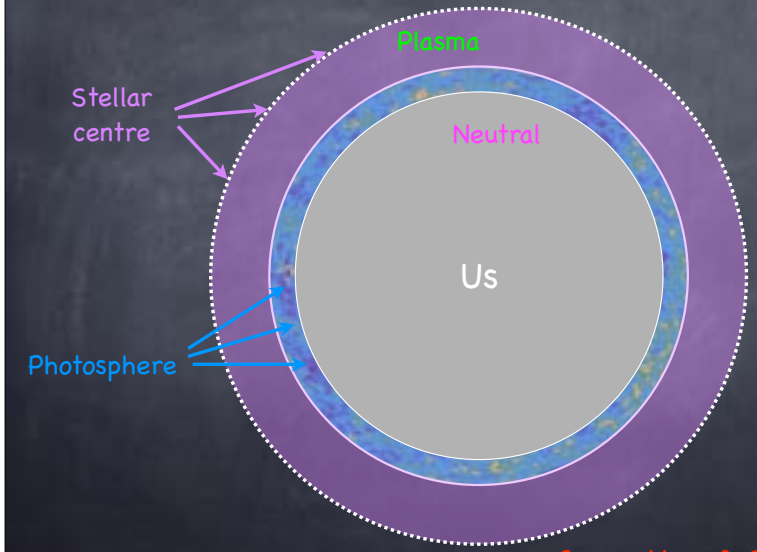
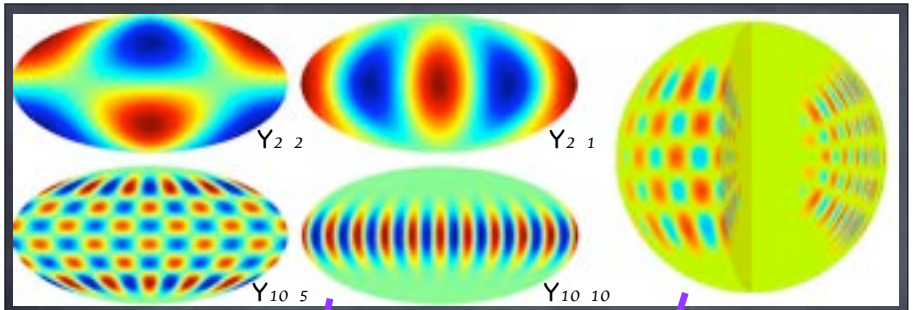
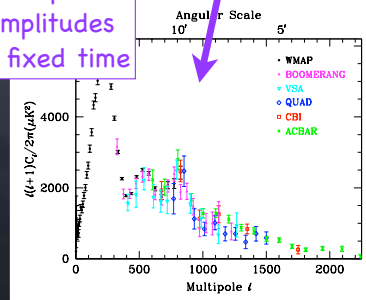


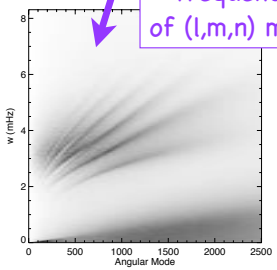
Crowe, Moss & Scott (2008)



Use squared amplitudes at fixed time



Use temporal frequencies of (l,m,n) modes



The Universe is an inside-out star!

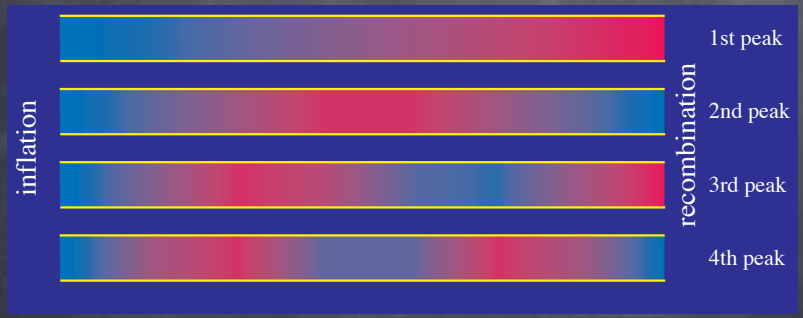
The Sun	The Universe
6000K	3000K
Photosphere 0.1% thick	Photosphere 10% thick
Complicated opacity	Thomson scattering
< billionth photons per atom	~billion photons per atom
Helioseismology	CMBology
Rotation defines m=0	No special directions
Fundamental mode in radius	Fundamental mode in time
Info from frequencies	Info from power spectra
Stochastic excitation	Synchronized init. conds.
Variability ~5mins	Variability ~Gyrs

Discovered in pre-history

Discovered in 1965

Crowe, Moss & Scott (2008)

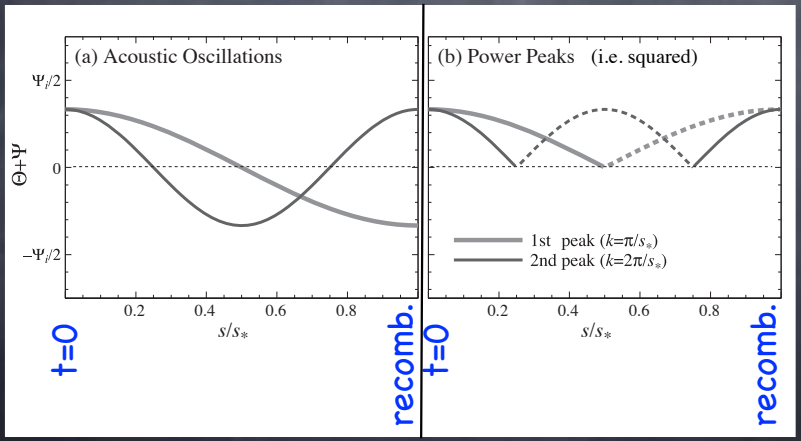
Acoustics



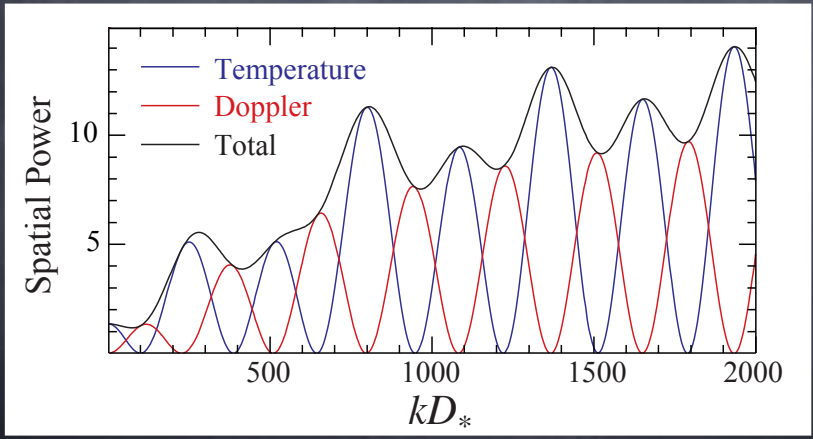
Cosmological perturbations are like standing waves, with a node at t=0, and observed as a snapshot at recombination

Wayne Hu

Origin of acoustic peaks



Temperature effect plus sub-dominant out-of-phase Doppler effect



Multiplied by damping envelope

Simplified explanation of acoustics:
Scott & White, "Echoes of Gravity"
arXiv.org/abs/astro-ph/9505102

CMB mini-review in RPP/PDG
by Scott & Smoot
pdg.lbl.gov/2022/reviews/contents_sports.html

For more description
see Wayne Hu's web-pages:
background.uchicago.edu/~whu/

A bit more technical

- Write distribution function f for each fluid: f(p,θ,φ,x)
- Boltzmann equations
- Perform linear
- Expand in k
- →co… in equations
- S… independent) k
- Ev…
- Inte… over k and integrate through… ight for power spectra

DONE!
Linear theory + well understood physics (gravity-driven sound waves)

e.g. camb (now cobaya) or class

Statistical description of anisotropies

Expand sky in spherical harmonics

$$T(\theta,\phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

Monopole is T$_0$ ($=a_{00}$)

Dipole is our "absolute motion"

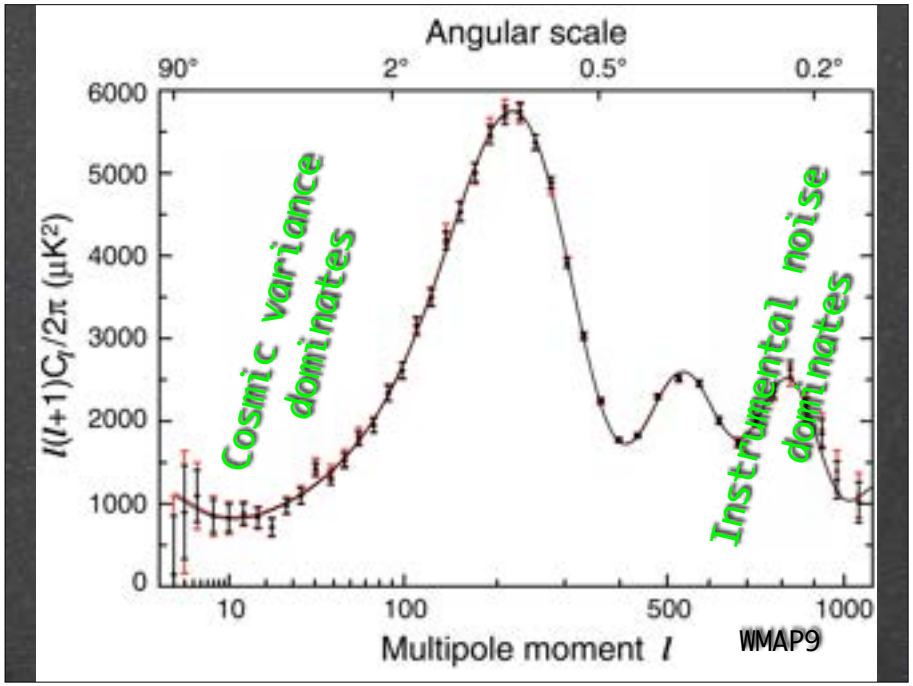
$\ell \geq 2$ modes give info on perturbations

$C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$ i.e. average over ms

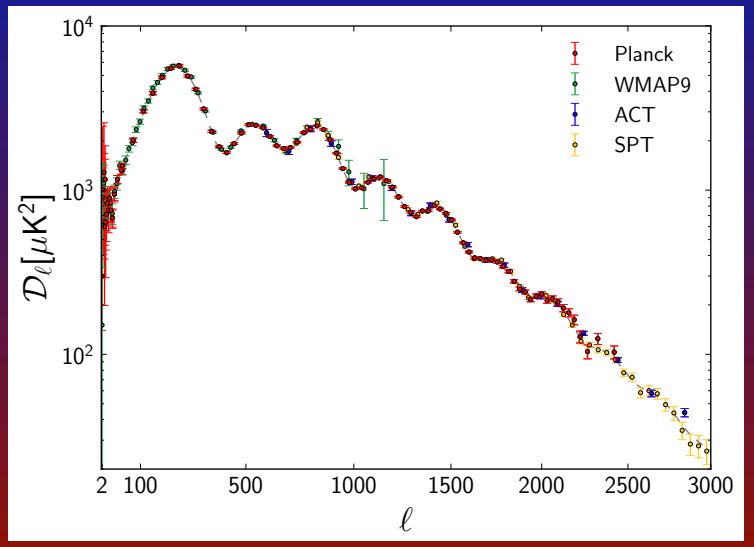
$(2\ell+1)C_\ell/4\pi$ is power at each ℓ

Statistical description of anisotropies

- Remember: we are measuring variance
- Variance of variance is:
  $\{2/(2\ell+1)\}C_\ell^2$
- This is "Cosmic variance"
- Gives "theory uncertainty" at low ℓ
  ("Precision" for our realization
  vs "accuracy" for underlying theory)
- Enhanced for partial sky coverage



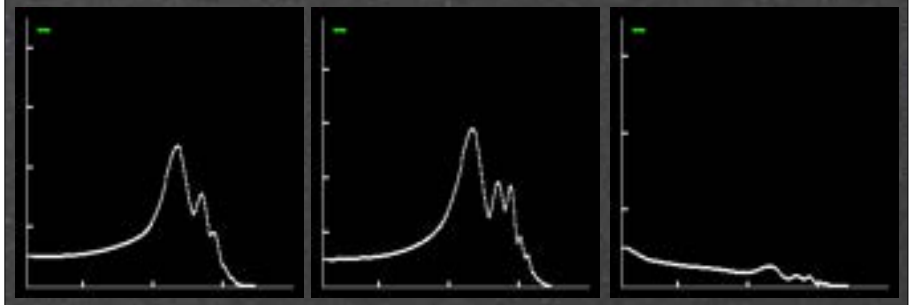
Acoustic peaks easy to see
(8 or 9 here, ~40 peaks and troughs in all power spectra)



- Individual hot/cold spots are just the particular realisation of our sky
- Actually anisotropies look very Gaussian (i.e. maximally random)
- This is what is expected from inflation
- Gaussian ⇒ all info. in variance (or power spectrum)
- Shape of power spectrum varies with cosmological parameters

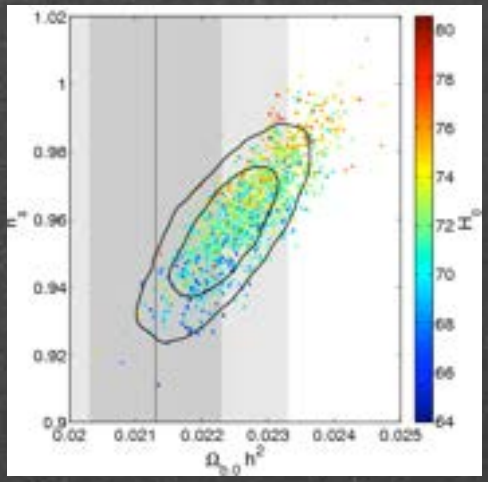
Parameters affect peak structure in different ways

Baryons | Dark Energy | "Tilt" of ICs



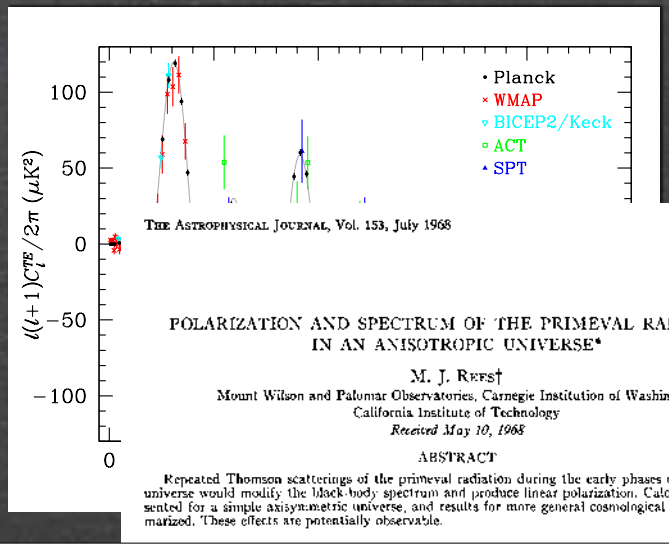
Movies from Martin White

Markov chain Monte Carlo



e.g. cosmomc

CMB Polarization



THE ASTROPHYSICAL JOURNAL, Vol. 153, July 1968

POLARIZATION AND SPECTRUM OF THE PRIMEVAL RADIATION IN AN ANISOTROPIC UNIVERSE*

M. J. REES†
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington
California Institute of Technology
Received May 10, 1968

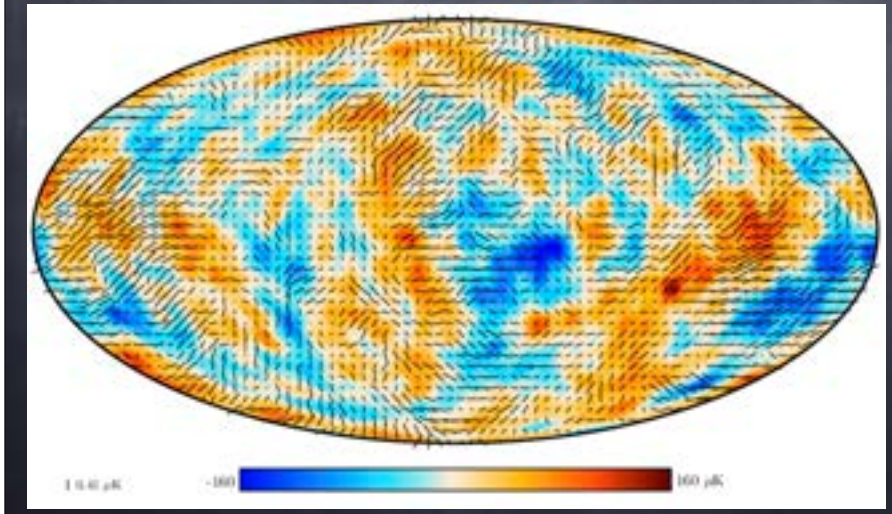
ABSTRACT

Repeated Thomson scatterings of the primeval radiation during the early phases of an anisotropic universe would modify the black-body spectrum and produce linear polarization. Calculations are presented for a simple axisymmetric universe, and results for more general cosmological models are summarized. These effects are potentially observable.

Information in the CMB

- CMB partially polarized
- 2 numbers for each pixel (as well as T)
  → call these "E" and "B"
- 4 correlations to measure: TT, TE, EE, BB
  → 4 different power spectra
- (TB and EB are zero)
- plus "non-Gaussian" signatures

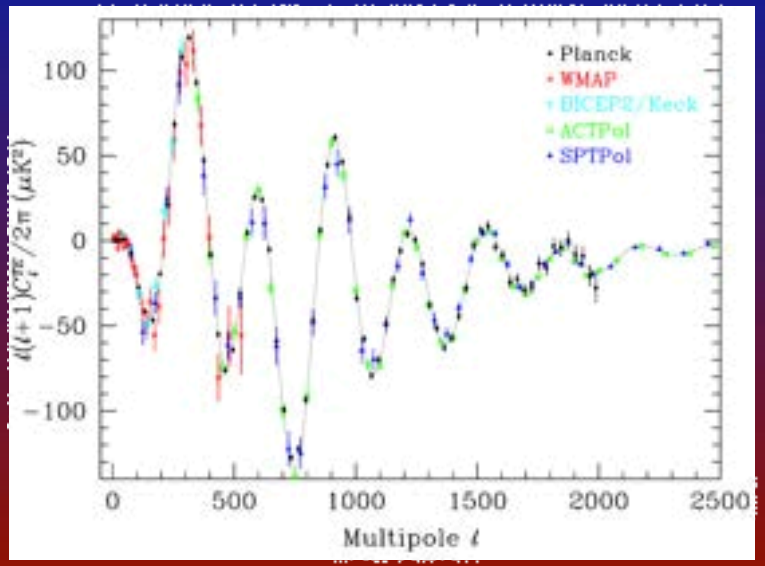
All-sky Cosmic Polarization (from Planck)



Polarization Observables

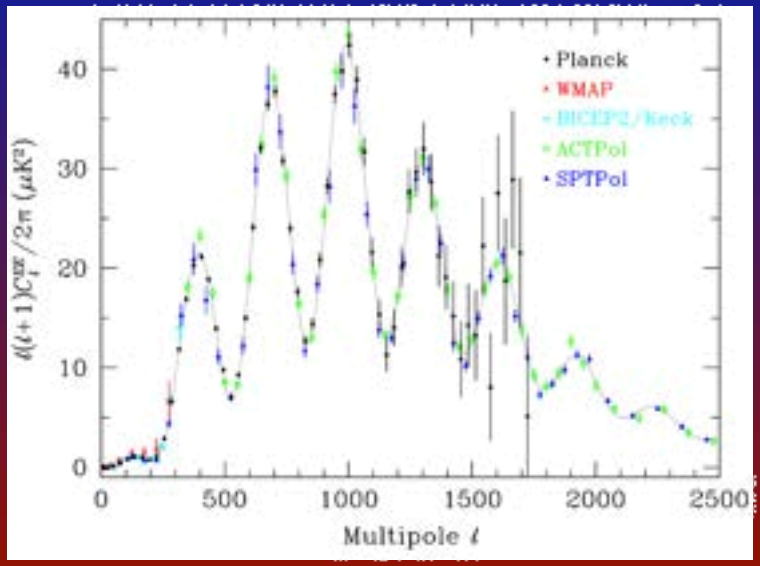
- Linear polarization expected only
- Measure x and y E-fields
- Convert to Q and U Stokes parameters
- Or use pseudo-vectors with $P^2=(Q^2+U^2)$ and $\tan 2\theta = U/Q$
- Or use coordinate-free geometric pair, "E" and "B"

TE



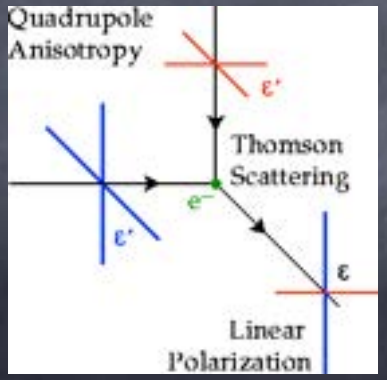
Scott & Smoot 2022 RPP

EE



Scott & Smoot 2022 RPP

Scattering of anisotropies generates polarization

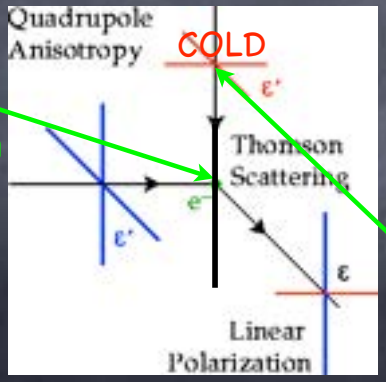


Hu & White 1997

Scattering of anisotropies generates polarization

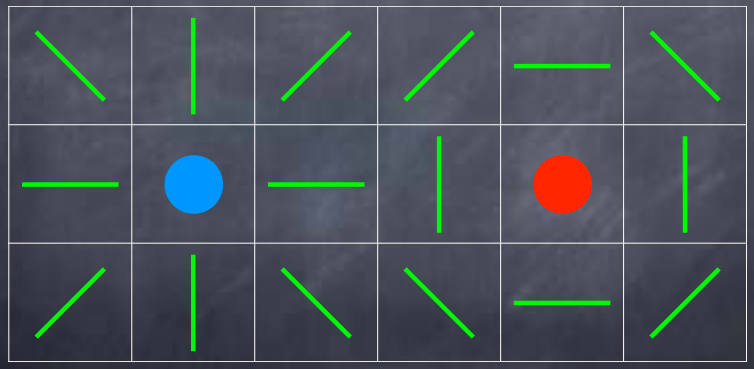
And so you observe a polarization pseudo-vector radial to the cold spot

For nearby scatterers, like this one, the polarization is like the black line (and that's true all around the cold spot)



Now imagine you're looking around a cold spot here

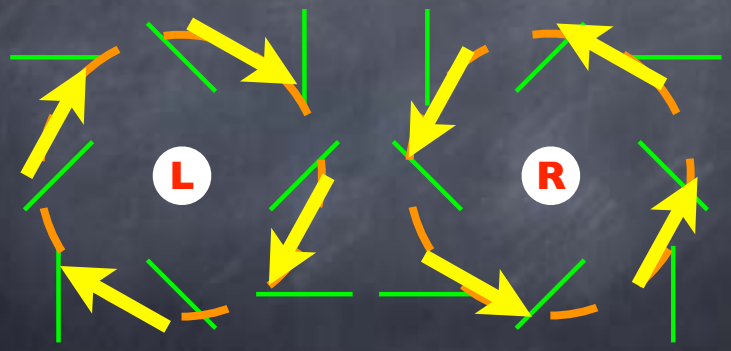
Polarization patterns



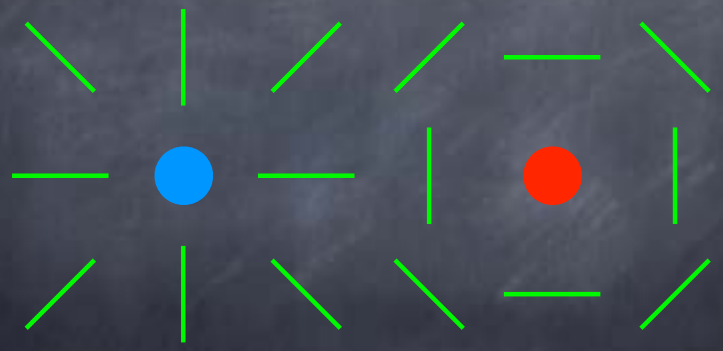
Cold spot

Hot spot

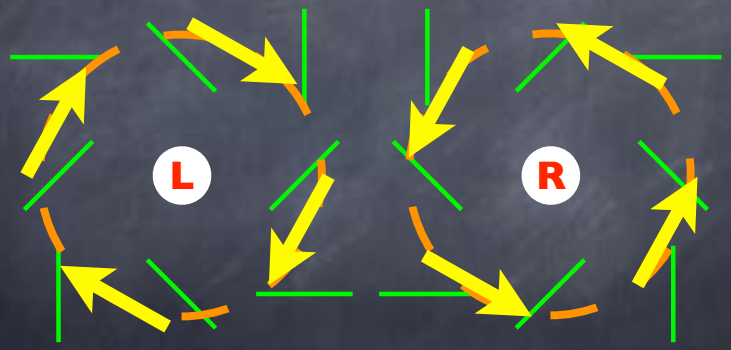
Rotate by 45°



"E modes"

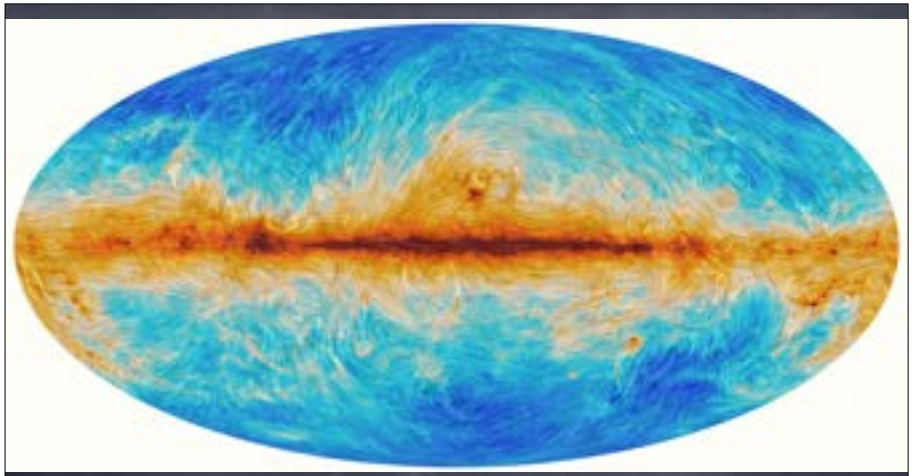


"B modes"



B-modes

- Require source with handedness
  ⇒ Gravity waves (not density perts.)
- Gravity waves generated during inflation
  Amplitude ∝ inflationary energy scale
  ⇒probe of 10^{16} GeV physics!
- Lots of experiments planned -
  Hard!



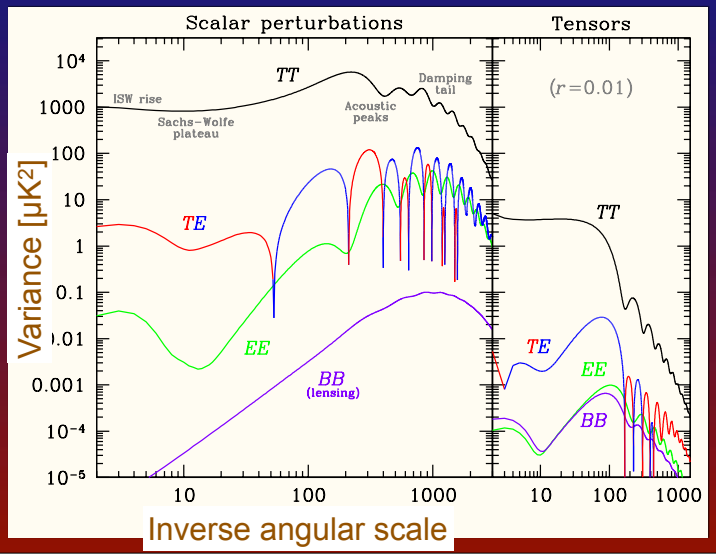
But...

polarized foregrounds are complicated and MUCH brighter!

Information in the CMB

- CMB partially polarized
- 2 numbers for each pixel (as well as T)
  → call these "E" and "B"
- 4 correlations to measure: TT, TE, EE, BB
  → 4 different power spectra
- (TB and EB are zero)
- plus "non-Gaussian" signatures

Can precisely calculate 4 power spectra (given a set of parameters)



Scott & Smoot 2022 RPP

Polarization: why bother?

- Check CMB is polarized as expected for Thomson scattering at z=1100
- Out of phase with Temp., confirming adiabatic modes + signature of super-horizon fluctuations at large angles
- Reionization signature for lowest multipoles
- Breaks some parameter degeneracies
- Go to higher ℓ because no foregrounds
- Can we detect inflationary B-modes?

B-modes

- Require source with handedness
  ⇒ Gravity waves (not density perts.)
- Gravity waves generated during inflation
  Amplitude ∝ inflationary energy scale
  ⇒ probe of 10^{16} GeV physics!
- Lots of experiments planned –
  But HARD!
- If $V=m^2\varphi^2$ and $n\approx0.95$, then $r\equiv T/S\approx0.15$
  ⇒ ruled out!
- New target is "large field excursion models", where $r>0.001$ expected

CMB future

- ACT-Pol, SPT-3G, BICEP, …
- Simons Observatory
- Litebird
- CMB-S4
- Spectral distortions?

Prog. Theor. Exp. Phys. 2015, 00000 (156 pages)
DOI: 10.1093/ptep/0000000000

Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey

LiteBIRD Collaboration*
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CMB-S4 Science Book, First Edition

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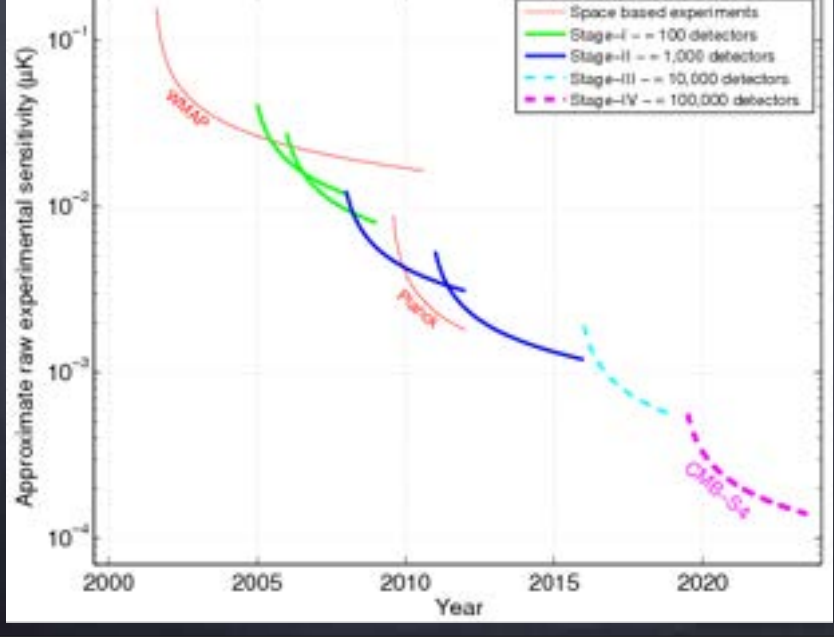
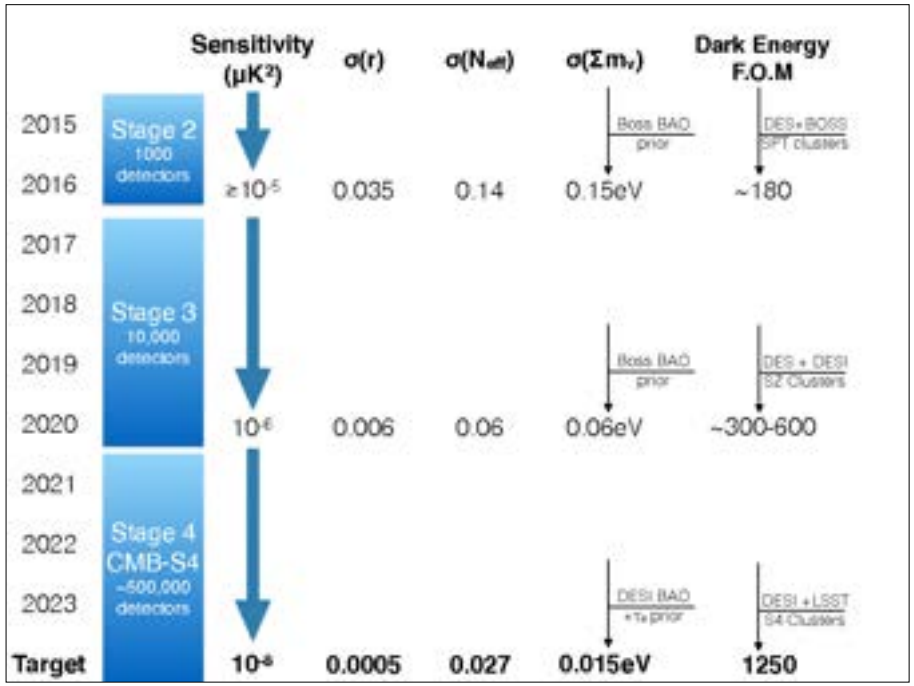
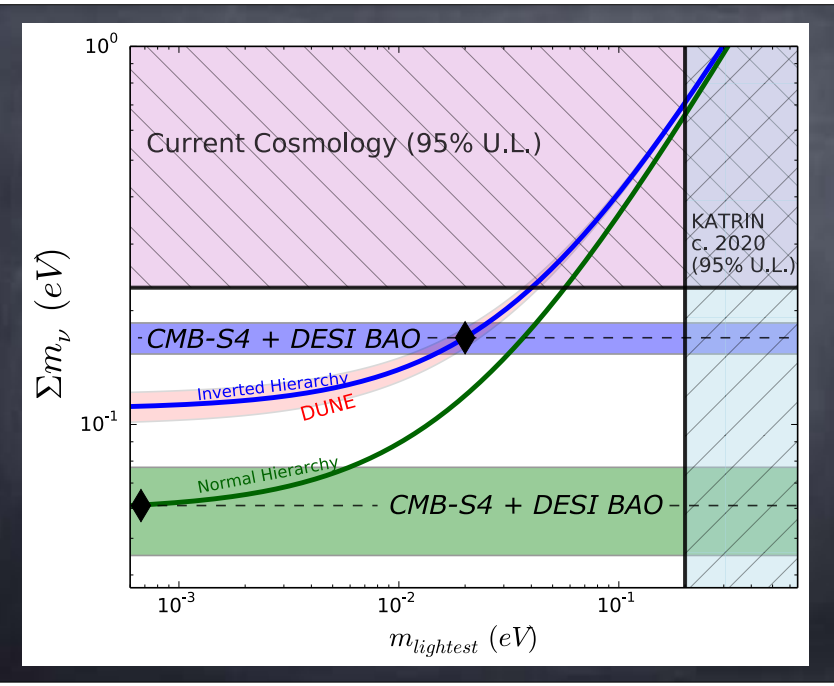
Abstract (arXiv)
This book lays out the scientific goals to be addressed by the next-generation ground-based cosmic microwave background experiment, CMB-S4, envisioned to consist of dedicated telescopes at the South Pole, the high Chilean Atacama plateau and possibly a northern hemisphere site, all equipped with new superconducting cameras. CMB-S4 will dramatically advance cosmological studies by crossing critical thresholds in the search for the B-mode polarization signature of primordial gravitational waves, in the determination of the number and masses of the neutrinos, in the search for evidence of new light relics, in constraining the nature of dark energy, and in testing general relativity on large scales.

Keyword(s): INSPIRE: gravitational radiation: primordial | neutrino: mass | cosmic background radiation | general relativity | superconductivity | cosmic background radiation: polarization | dark energy | B-mode







And lastly for something completely different...

Stayed tuned for more

Extra

Map-making

One detector: $d_t = \mathcal{A}_{tp} m_p + n_t$

time index, pixel index

DATA VECTOR, POINTING MATRIX, MAP, NOISE

Maximum Likelihood Solution:

$$m_p = \left(\mathcal{A}^{\mathrm{T}} \mathcal{N}^{-1} \mathcal{A}^{\mathrm{T}}\right)^{-1} \mathcal{A}^{\mathrm{T}} \mathcal{N}^{-1} d_t$$

with: $\mathcal{N}_{tt'} = \langle n_t n_{t'}^{\mathrm{T}} \rangle$

NOISE CORRELATION MATRIX

PIXEL-PIXEL CORRELATION MATRIX

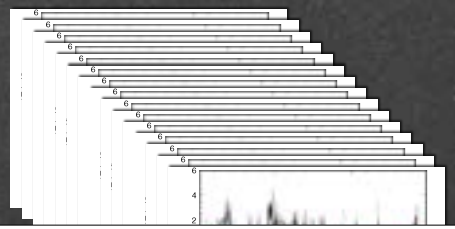
Map-making

But $N_{\mathrm{times}} \sim 10^8$

And $N_{\mathrm{pixels}} \sim 10^6$

⇒ age of Universe to invert!

So use: iterative techniques
Fourier space speed-ups
covariance through Monte Carlo
+ any other tricks you can think of!



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