CMB Observations:

Current Status and Implications for Theory

Anthony Lasenby

Astrophysics Group
Cavendish Laboratory
and Kavli Institute for Cosmology
University of Cambridge
a.n.lasenby@mrao.cam.ac.uk

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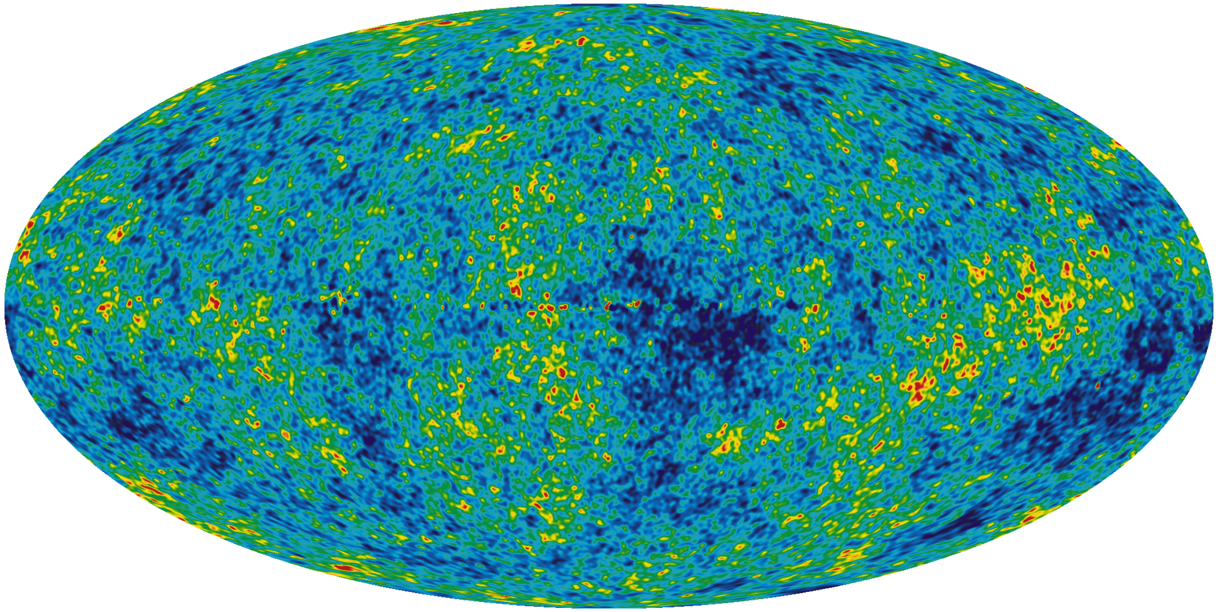
PLAN FOR TALK

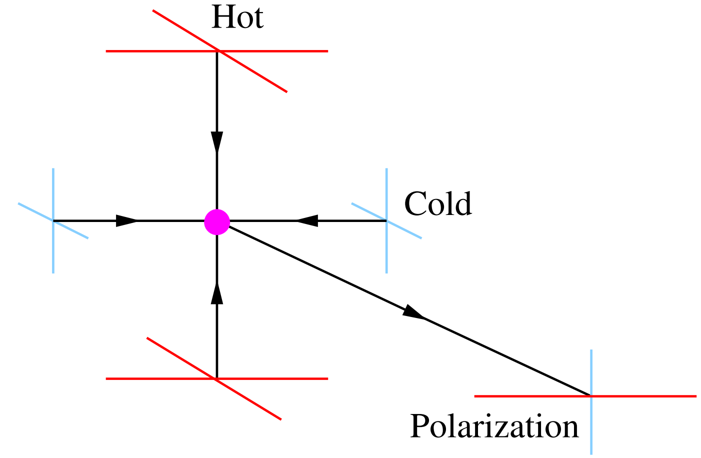
- Will give an overview of current state of CMB observations and scientific implications
- Want to emphasize the 'big questions' that the CMB can help address
- However, must also be said that we are in an 'interregnum' period as regards primordial CMB observations and results
- As regards ground-based experiments, not much new since last year
- In space have WMAP7 — should hear the details of that next
- And of course Planck is taking data!
- However, big progress with secondary anisotropy experiments — first 'blank field' Sunyaev-Zeldovich samples appearing, and new constraints on high-ℓ CMB power spectrum
- All may not be simple here! SZ amplitudes look systematically smaller than expected
- Will also include a more theoretical 'diversion'

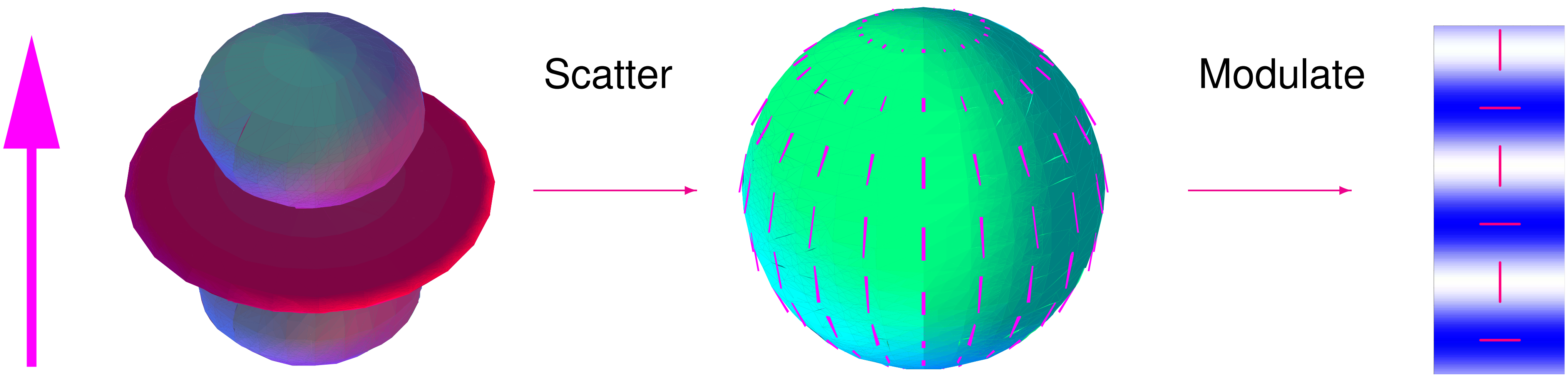
- The Cosmic Microwave Background (CMB), is a wonderful tool in modern cosmology
- A very significant fraction of all the information in cosmology over the last 10 to 15 years has come from it
- Has finally ushered us into an era of 'precision cosmology' (but also deep mysteries)
- The key modern frontiers are polarization and high resolution temperature power spectrum



Physics of CMB polarization

- Photon diffusion around recombination $\rightarrow$ local temperature quadrupole
  - Subsequent Thomson scattering generates (partial) linear polarization with r.m.s. $\sim 5\,\mu$K from density perturbations

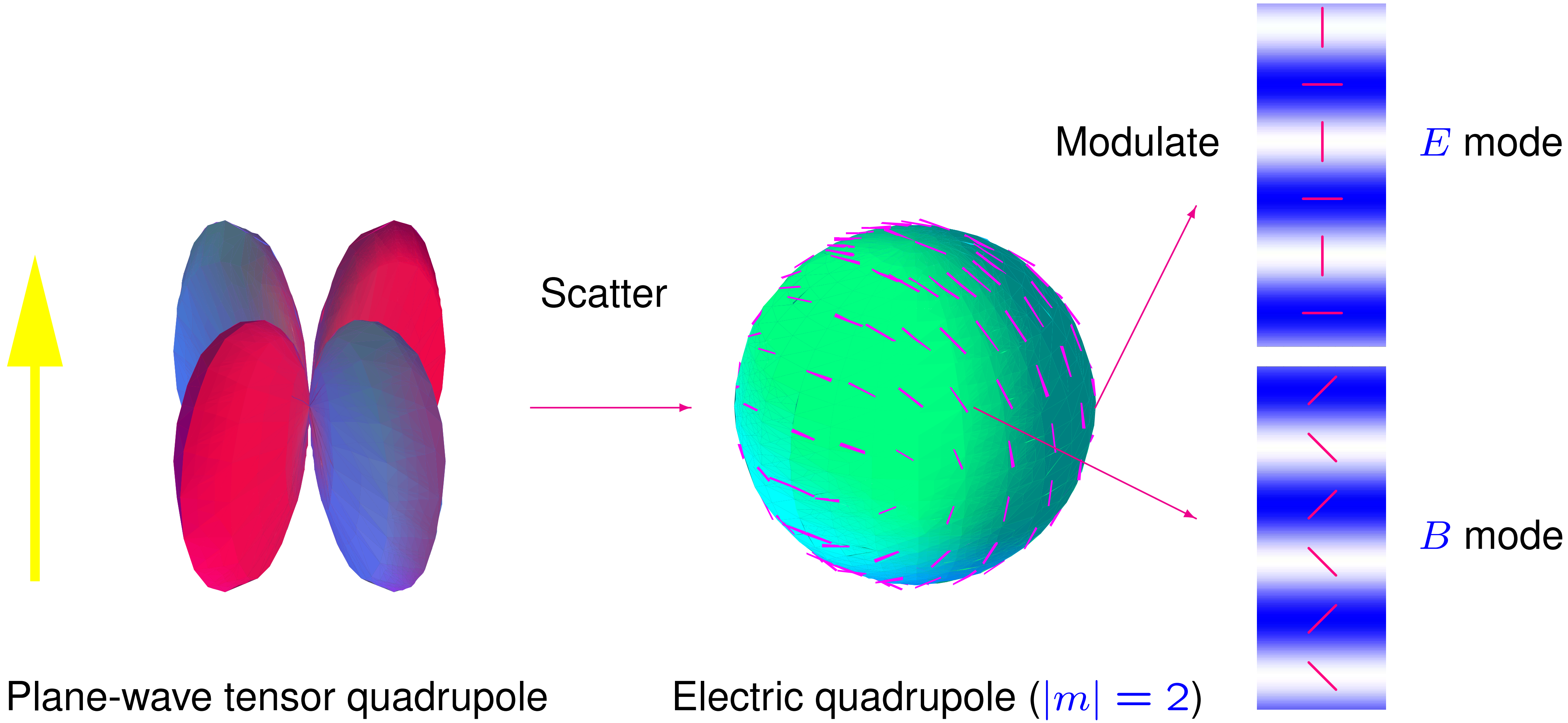




Plane-wave scalar quadrupole   Electric quadrupole ($m = 0$)   Pure E mode

- Linear scalar perturbations produce only E-mode polarization (Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997)

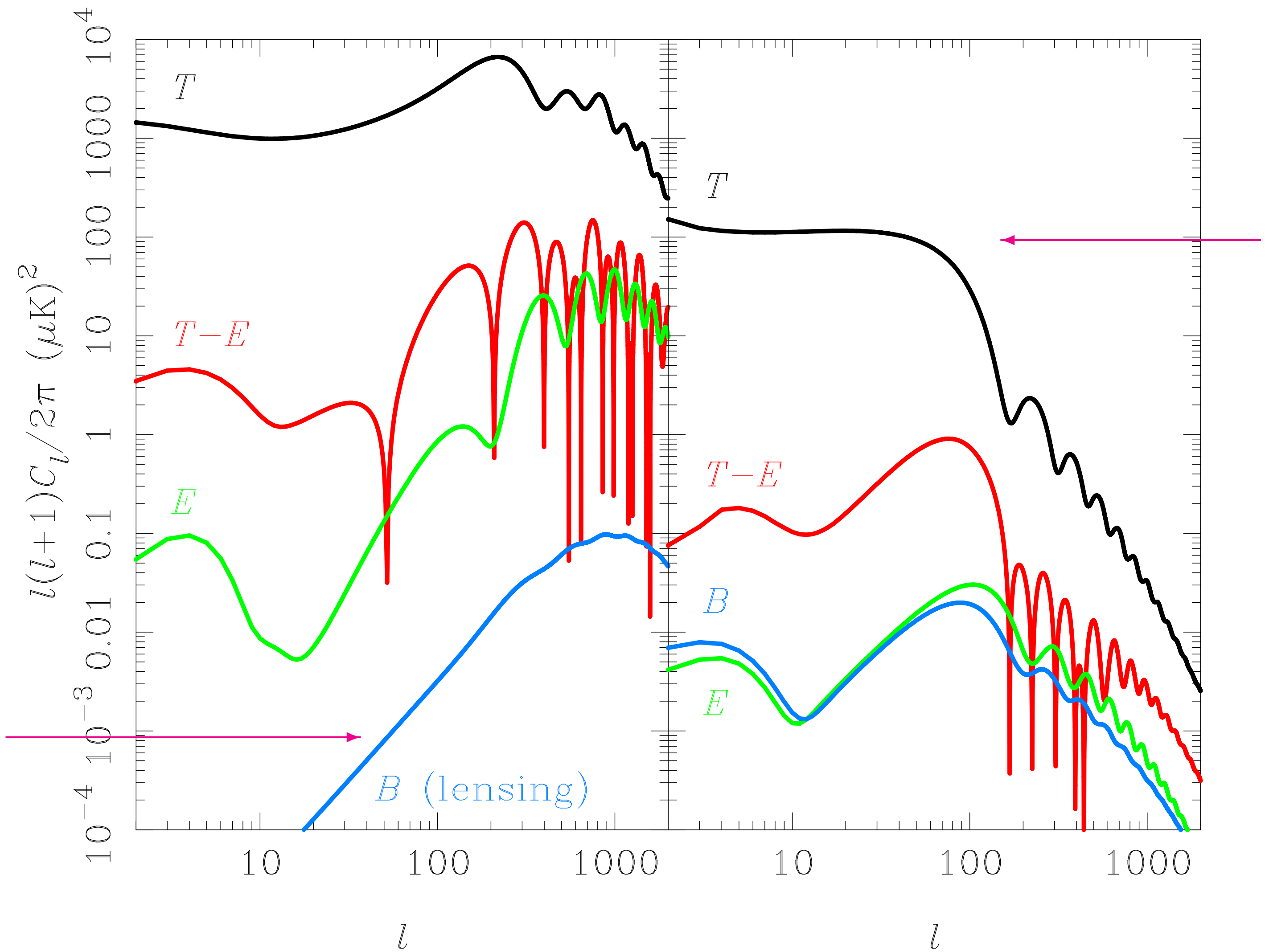
GRAVITY WAVES IN CMB POLARIZATION: PHYSICS



- Gravity waves produce both E- and B-mode polarization (latter have handedness)

POWER SPECTRA

Lens-induced B modes ($\sqrt{C_l^B} \approx 1.3\,\mathrm{nK}$)



Effects only on large scales since gravity waves damp inside horizon

What would a detection of primordial gravity waves tell us?

- Strong evidence that inflation happened
- The amplitude of the power spectrum $\mathcal{P}_{\rm grav}(k)$ is a model indepedent measure of the energy scale of inflation

$$\mathcal{P}_{\rm grav} = \frac{8}{M_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 = 1.92 \times 10^{-11}\left(\frac{E_{\rm inf}}{10^{16}\,{\rm GeV}}\right)^4$$

- Here H is the Hubble parameter through slow-roll (roughly constant)
- Define the tensor to scalar ratio r, via the ratio of the tensor to scalar power spectrum at some given k (typically a low value like $k = 0.001\,{\rm Mpc}^{-1}$ chosen)
- Find

$$r = 0.008\left(\frac{E_{\rm inf}}{10^{16}\,{\rm GeV}}\right)^4$$

- Thus detectable gravity waves ($r > 0.01$ say) would mean inflation occurred at the GUT scale
- We would then be accessing particle physics at a scale about at least 10^{12} higher than those achievable at LHC
- So where do things stand experimentally?

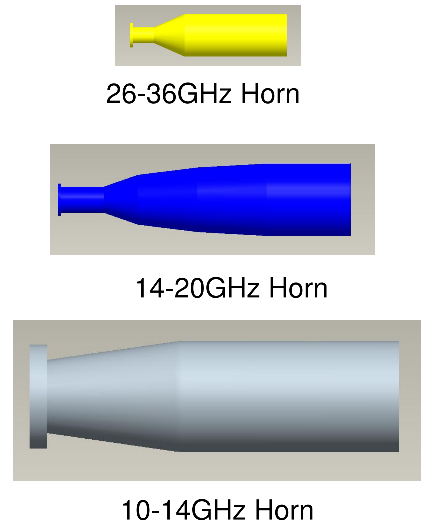
Some Current/Future CMB Polarisation Experiments

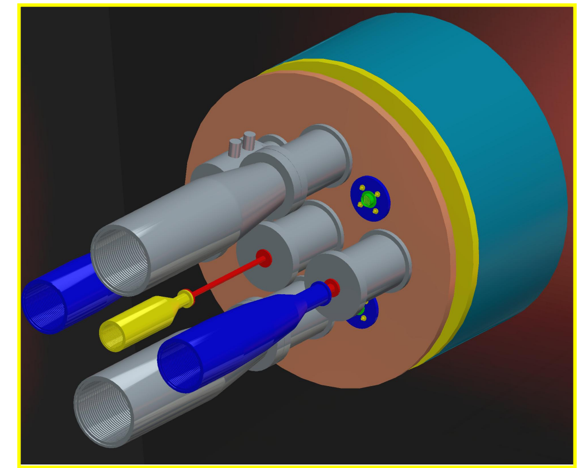
Name	Type	Detectors	ℓ range	r target	First Obs.
QUAD	ground	bolometer	$200 < \ell < 3000$		completed
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
QUIET	ground	MMIC	$\ell < 1000$	0.05	2008
CLOVER	ground	bolometer	$20 < \ell < 600$	0.01	Cancelled
EBEX	balloon	bolometer	$20 < \ell < 1000$	0.03	2011
SPIDER	balloon	bolometer	$\ell < 100$	0.025	2011
BPOL	space	bolometer	$\ell < 200$	1–5 $\times 10^{-3}$	??
QUIJOTE	ground	MMIC	$\ell < 80$	0.1/0.05	2010
POLARBEAR	ground	bolometer	$20 < \ell < 2000$	0.05	?

- EBEX — North American test flight was carried out 2009 — first Antarctica flight 2011 experiment
- SPIDER — First balloon flight will be 2011, Australia. First ULD flight 2012
- QUIET — Observations Oct. 2008 through May 2009 used a 19-element 40 GHz receiver on a 1.4 metre telescope. Observations with a 90-element 90 GHz instrument on the same telescope are ongoing

QUIJOTE

- Rafa Rebolo will give a lecture on this
- IAC (Tenerife)-Cambridge-Manchester-Santander collaboration
- With the demise of CLOVER, is probably now the premier ground-based European experiment
- Comes in stages:
  Phase 1: First Instrument: Horns and frequencies as in picture
  Phase 1: Second Instrument: 16×30 GHz horns substituted
- Will use spinning mount to achieve good sky coverage

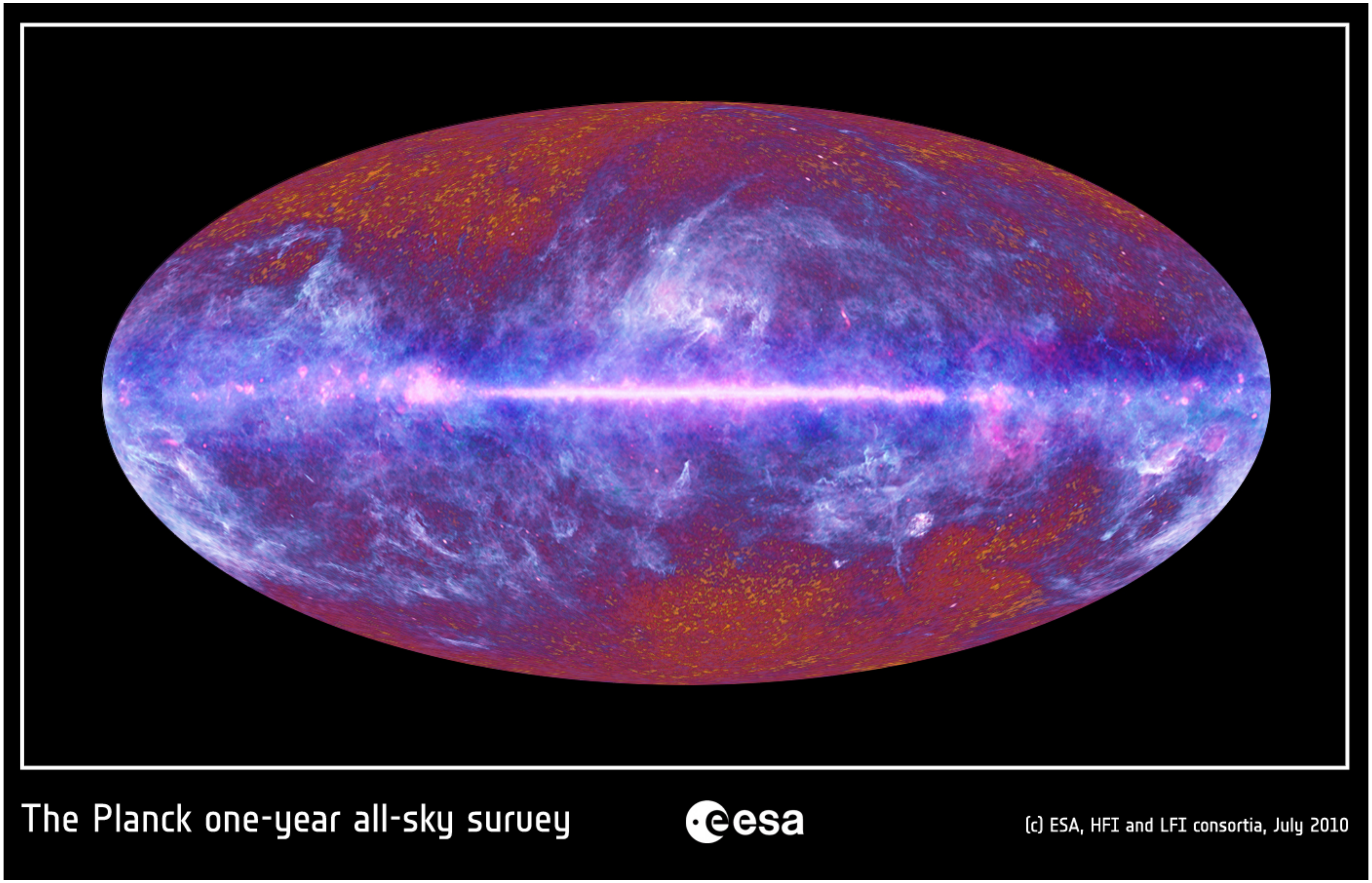




QUIJOTE 1 : Focal Plane Distribution

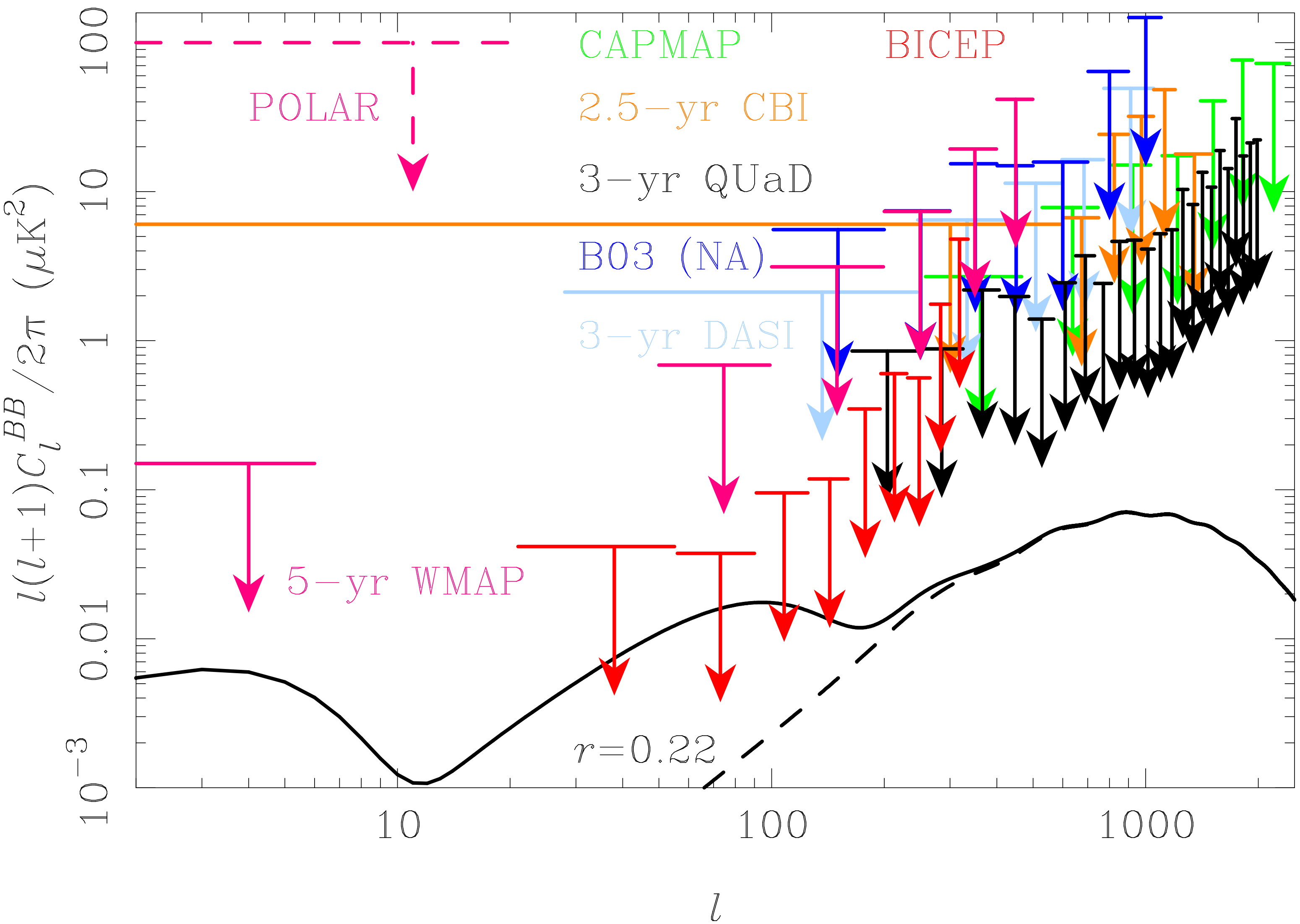
- Approx. 1 degree resolution
- Main aims: frequency coverage 10–36 GHz ideal for mapping and understanding properties of spinning dust and other foregrounds
- Also, could detect B-modes if large ($r \sim 0.1$)

PLANCK



- First two sky coverages were complete April/May
- Reno will be able to give us a full report

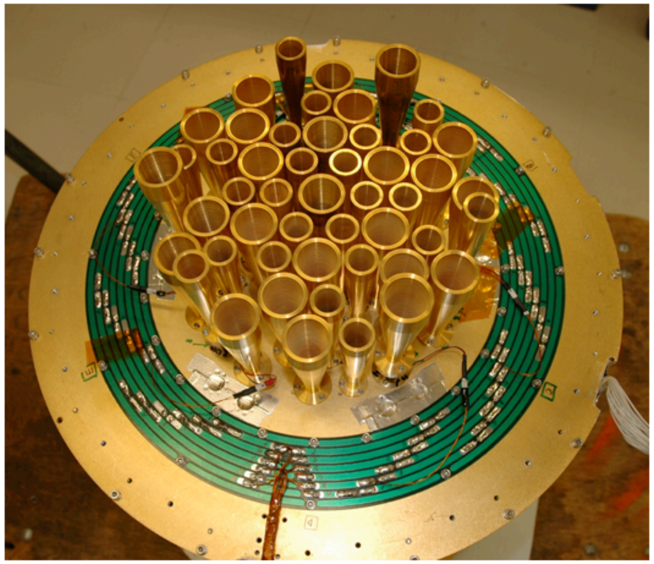
SUMMARY OF CONSTRAINTS ON BB

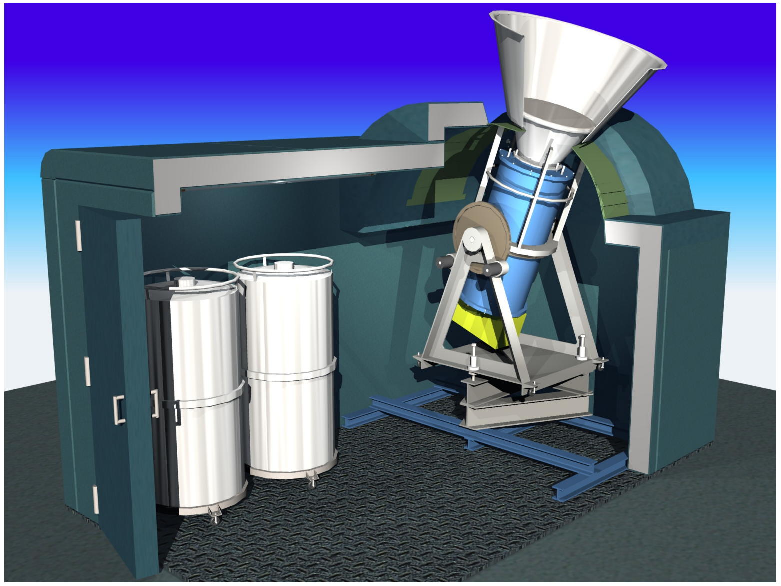


(2009 — only update is WMAP 7 year)

BICEP RESULTS

- BICEP Background Imaging of Cosmic Extragalactic Polarization
- Caltech, Princeton, JPL, Berkeley and others collaboration
- 100 and 150 GHz polarization sensitive bolometers, illuminated via a 2 lens system (so is a refractor!)
- At South Pole, in a mounting which maximises how much of telescope is easily accessible
- Going after polarisation anisotropy at larger scales than other ground-based designs so far
- Beams = 0.93° at 100 GHz and 0.60° at 150 GHz
- (Cf. QUAD, which has about 4 armin resolution)





BICEP RESULTS

- Their main (2009) result was a much improved limit on r of $r < 0.73$ (95% conf.)
- This may not look exciting compared to $r < 0.43$ (Dunkley et al. WMAP5 CMB only result) or $r < 0.33$ (QUAD CMB only result)
- However, this is by far most significant *direct* limit on r
- They said WMAP5 data analysed same way gives $r < 6$ (95% conf.)!
- In fact WMAP 7 year paper says $r < 4.7$ is proper 5 year limit just based on BB
- Same paper says $r < 2.1$ for 7 year, so a significant improvement
- Where do r limits leave inflation models?

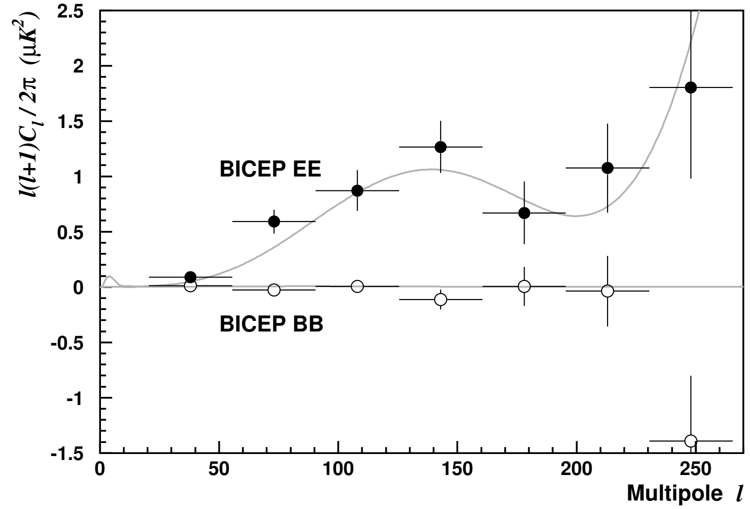
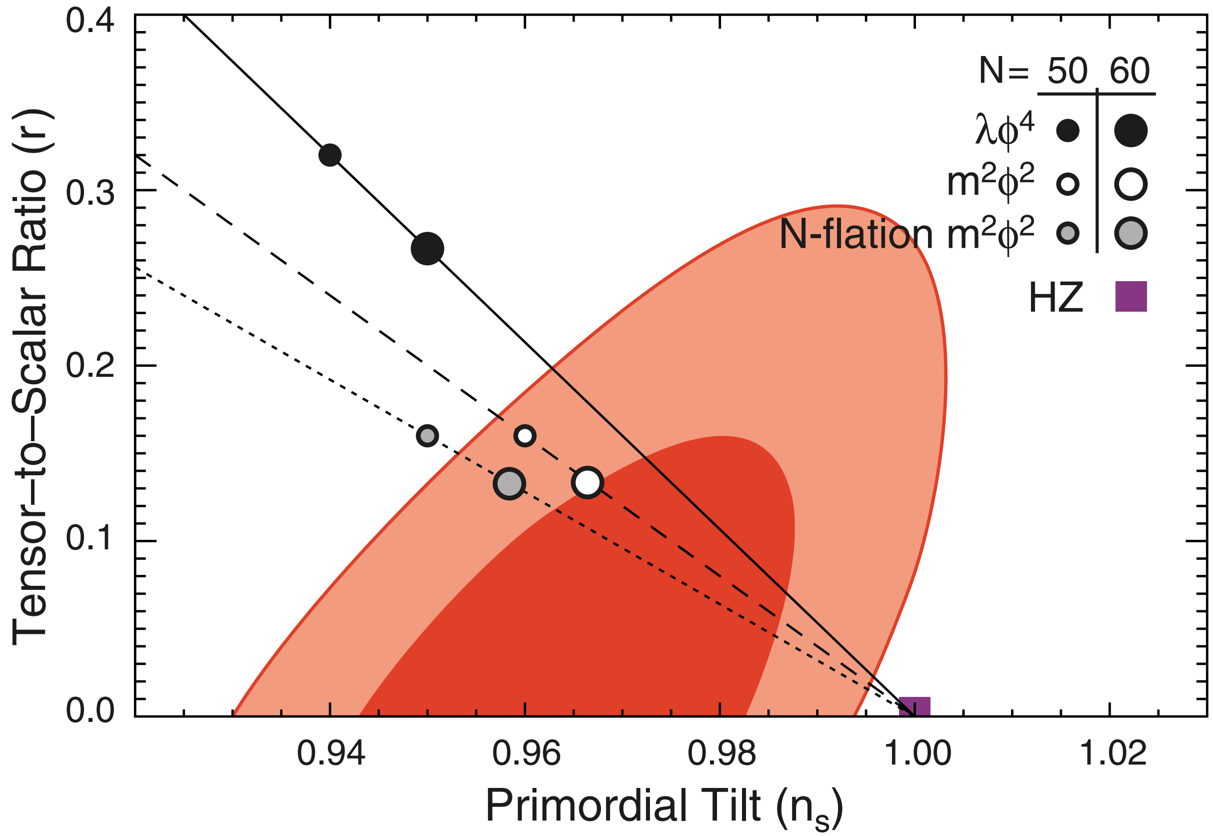


FIG. 12.— BICEP measures EE polarization (black points) with high signal-to-noise at degree angular scales. The BB spectrum (open circles) is overplotted and is consistent with zero. Theoretical ΛCDM spectra (with $r = 0.1$) are shown for comparison.



- Observational constraints shown are from WMAP7 (Komatsu et al., 2010)
- Basic results we need to understand this diagram are

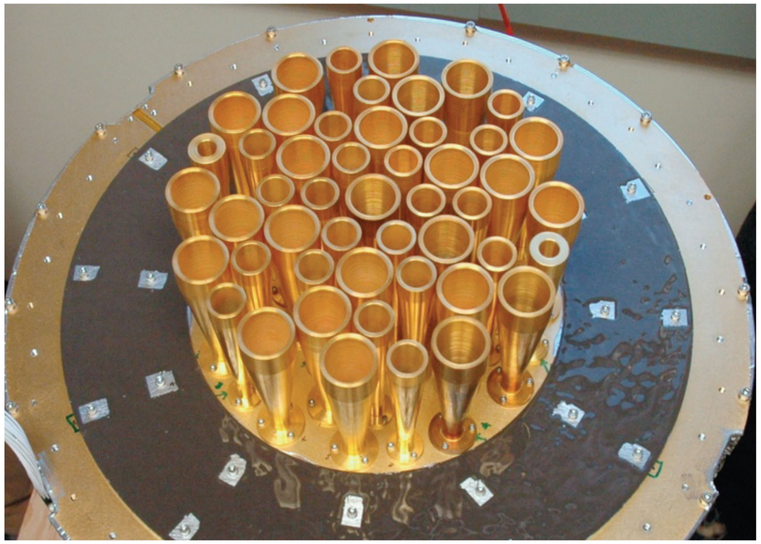
$$r = \frac{4\alpha}{N}, \qquad n_s = 1 - \frac{2+\alpha}{2N}$$

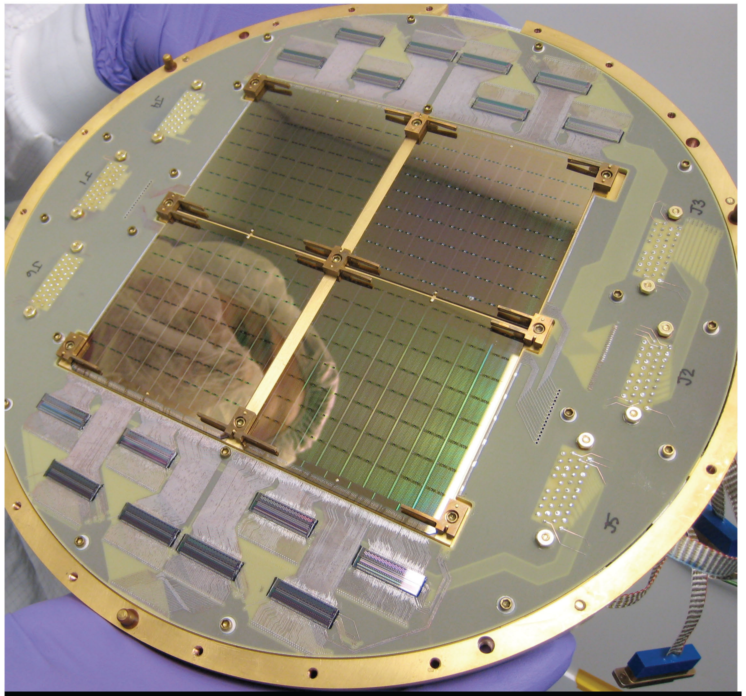
if $V(\phi) = \lambda\phi^{\alpha}$.

- However, if $V(\phi) = V_0(1 - (\phi/\phi_e)^p)$ then can get r as small as one wants

THE TRANSITION BICEP1 TO BICEP2 (SLIDE FROM J. KOVAC)

BICEP2: 10-fold increase in mapping speed:

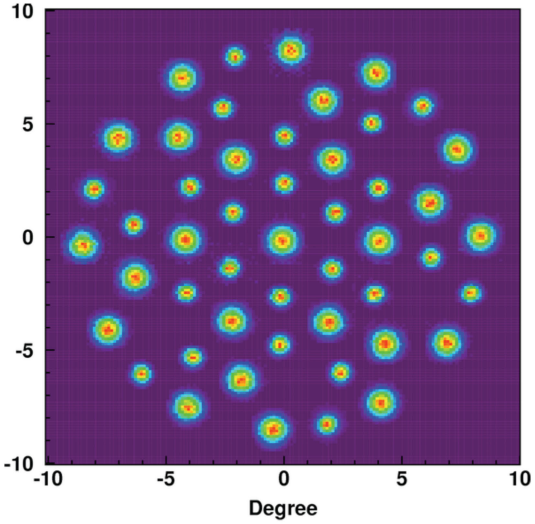


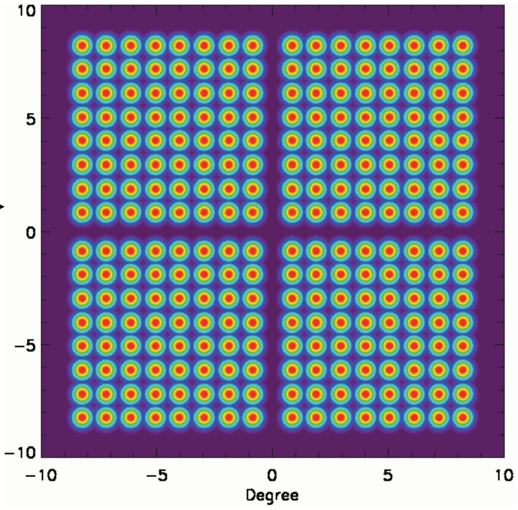


JPL : antenna-coupled TES arrays

BICEP1

48
150 GHz detectors



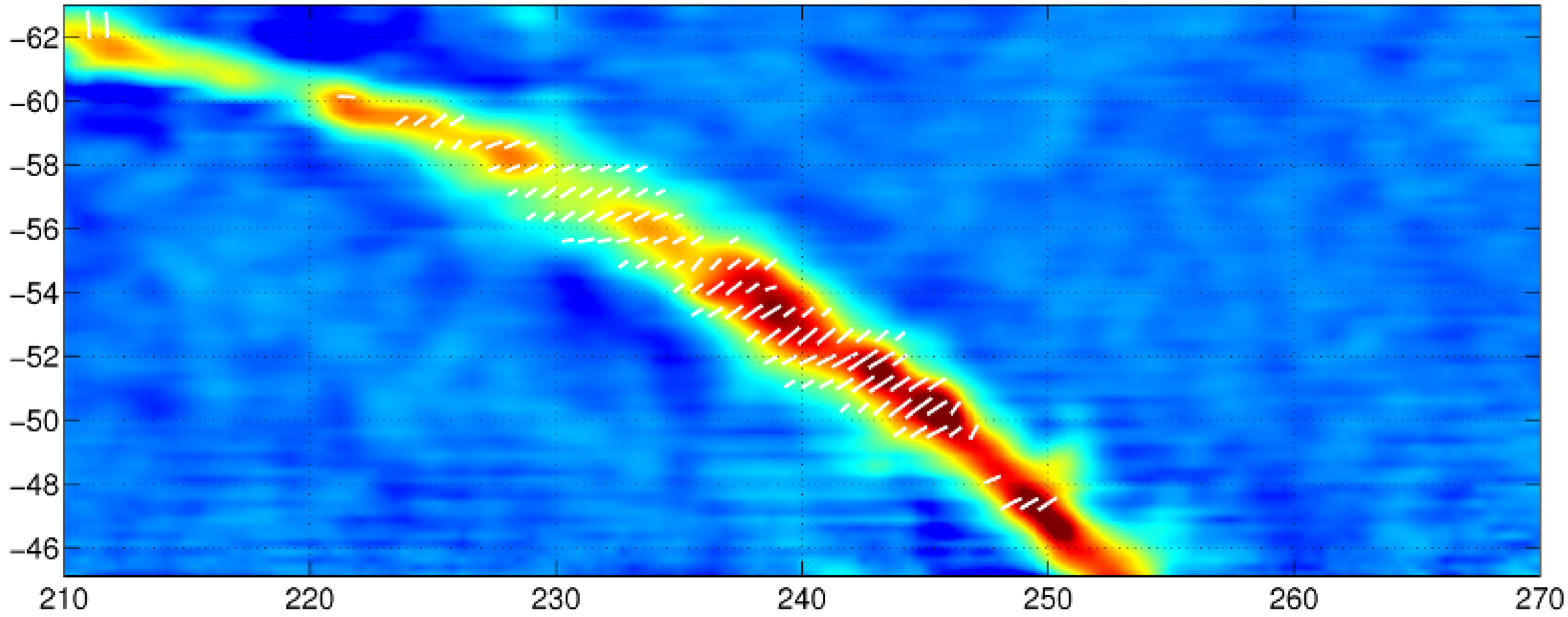


BICEP2

512
150 GHz detectors

BICEP PLANS

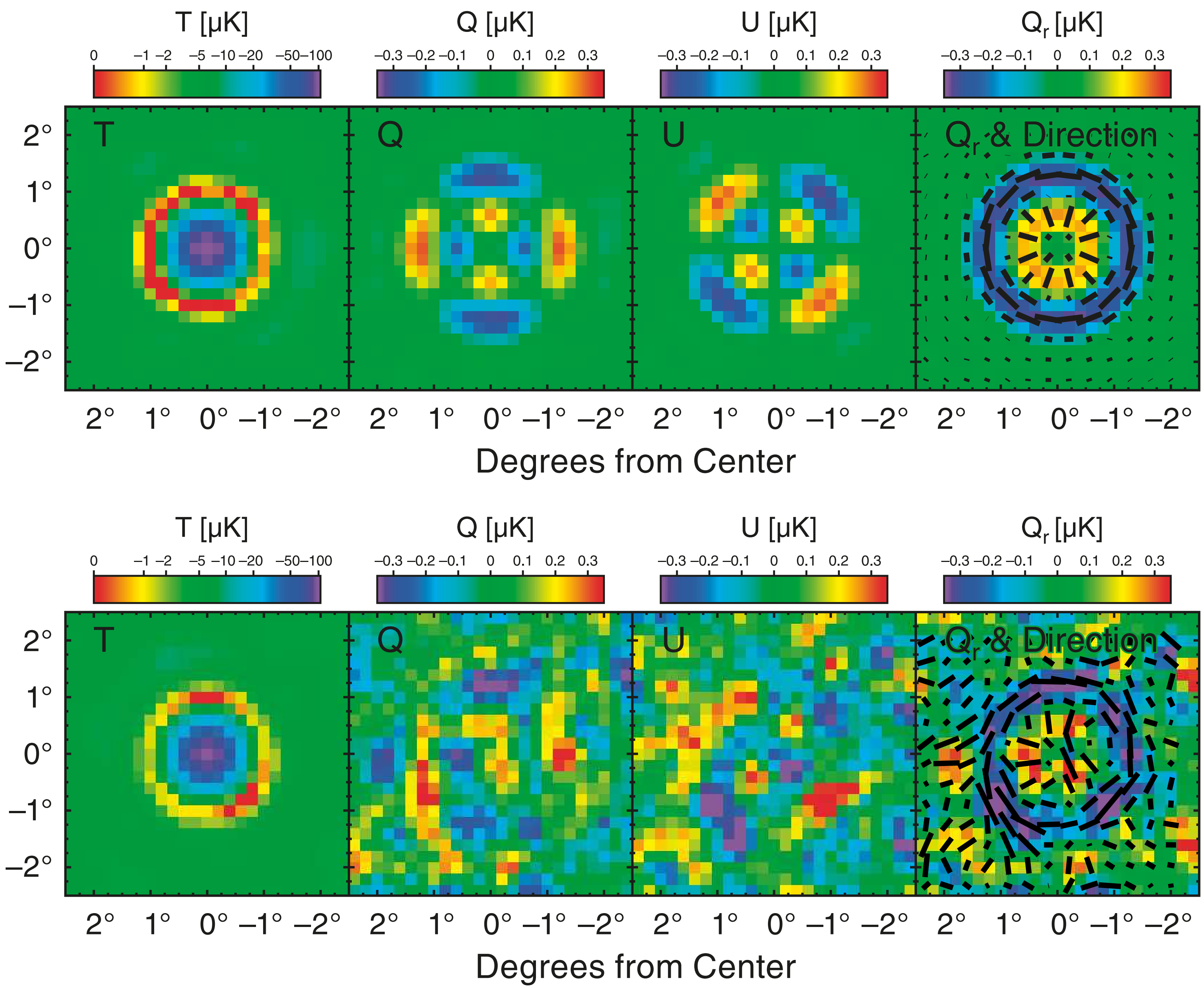
- BICEP2 was deployed to South Pole in November 2009
- 512 detectors at 150 GHz only
- 8 times the mapping speed of BICEP1 has been achieved (similar scales and ℓ-range aims)
- First (test) map now released - shows dust polarization (1-3% level) in plane of galaxy



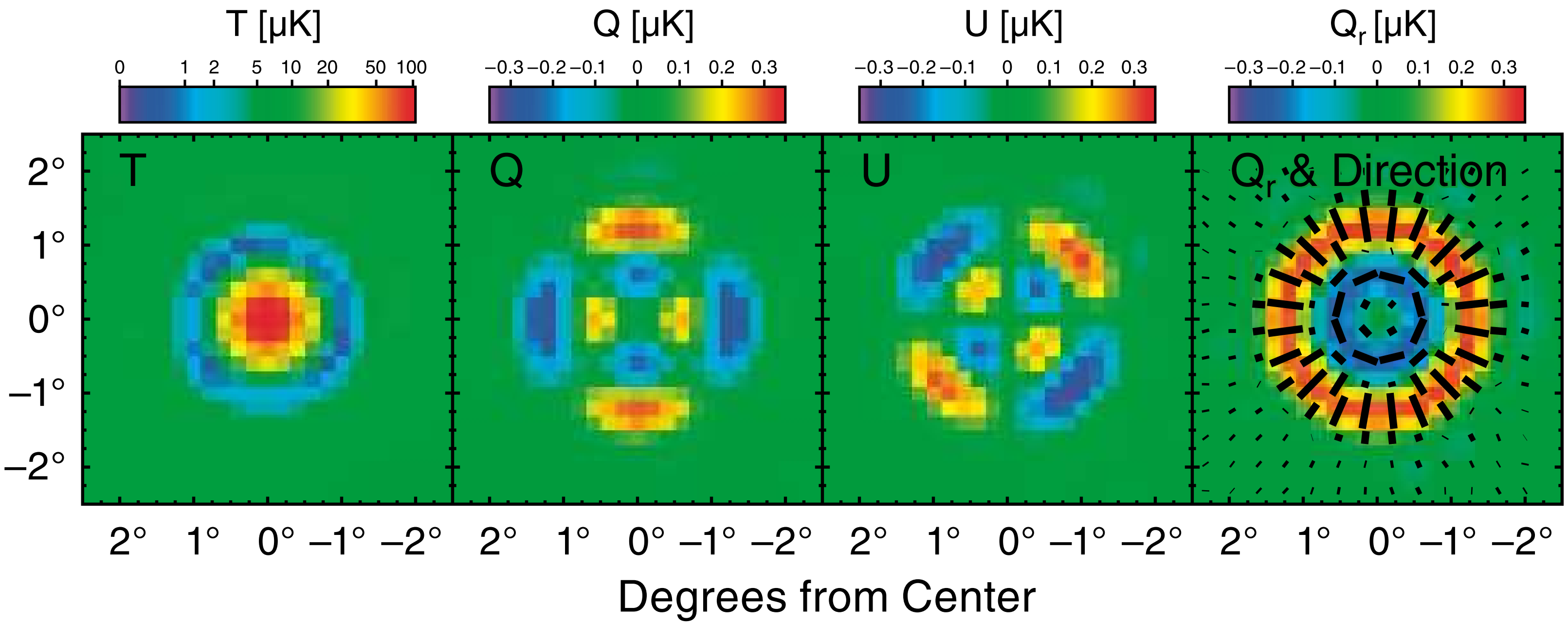
Other WMAP7 results

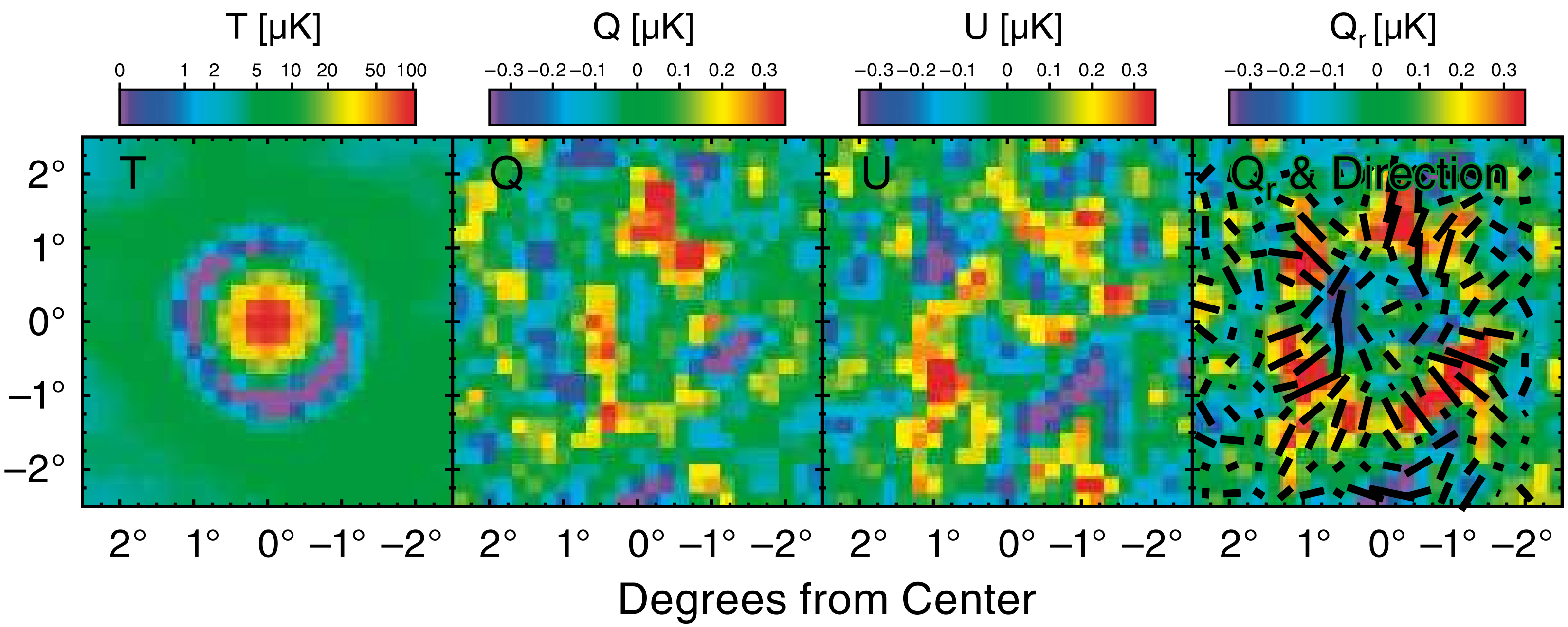
- WMAP7 results notable for extending analysis to new cosmological constraints
- E.g.
  - Neutrino mass constraints (and number of effective species)
  - Primordial gravitational wave density
  - Primordial helium abundance
- In addition new developments re Sunyaev-Zeldovich signal and high-ℓ CMB power spectrum
- Will talk about those later, but bottom line is that SZ power is smaller than expected, e.g. measured signal in SZ profiles in 1.5-2.0 times smaller then expected - (though even this is a smaller reduction than some previous claims)
- In addition will highlight two further areas here
- Polarization patterns of stacked hot and cold spots
- Curvature vs. w plot

WMAP7 Cold Spots



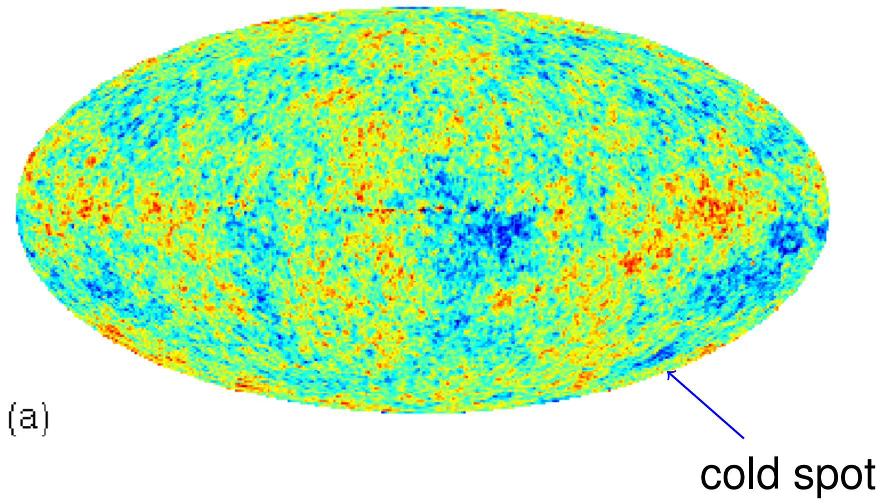
WMAP7 Hot Spots



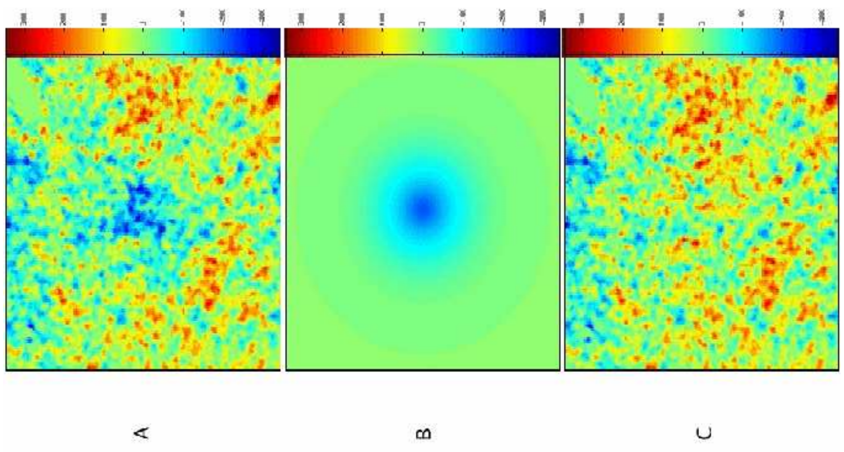


The Cold Spot

- There is a non-Gaussian spot found in Vielva et al. (astro-ph/0310273) and drawn further attention to in Cruz et al. (astro-ph/0405341)



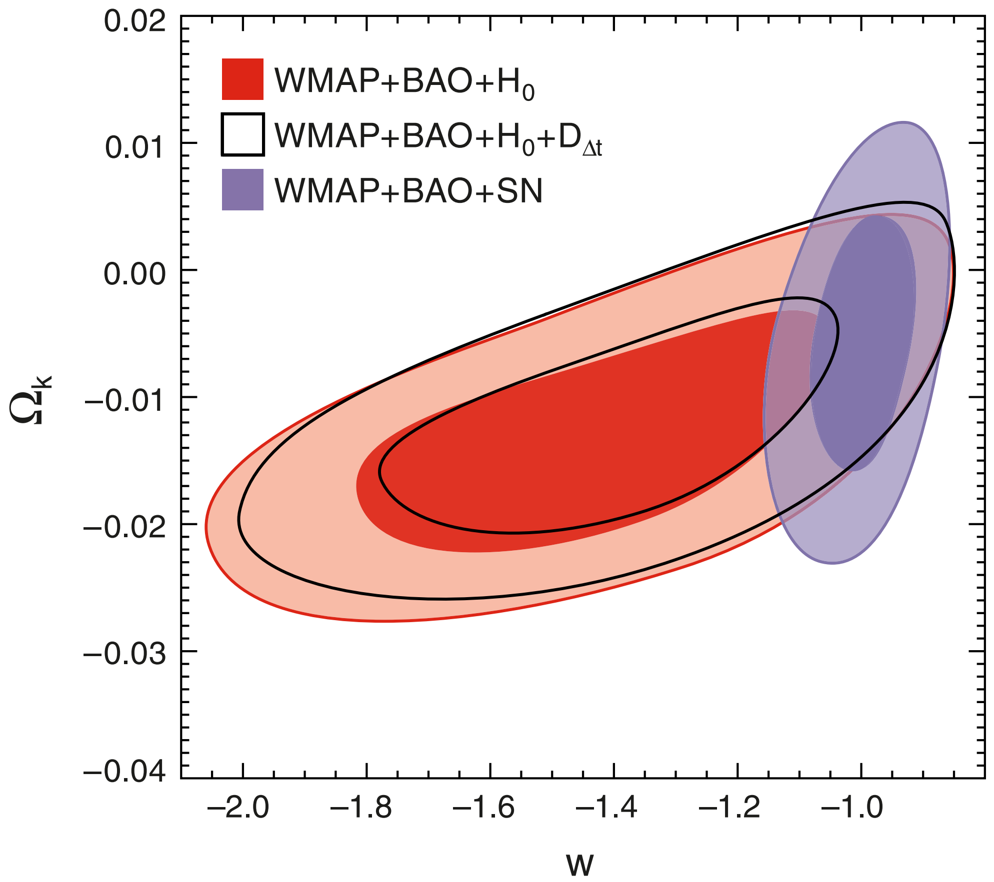
- Cruz et al (Science: astro-ph/0710.5737) suggested this corresponds to a texture
- Textures are 3d topological defects, coming from symmetry breaking in e.g. SU(2) gauge group
- One modelled here is for a global texture — these unwind gradually and can have late time effects



- A shows piece of actual CMB sky; B the texture model and C the CMB after model subtraction
- Crucial test of this will be polarization pattern — should be random if a texture rather than primordial CMB coldspot
- As with cosmic strings, detection would certainly be very important in gravitational and particle theory
- Fit to amplitude gives a symmetry-breaking scale of 8.7×10^{15} GeV

WMAP7 CURVATURE VERSUS EQUATION OF STATE

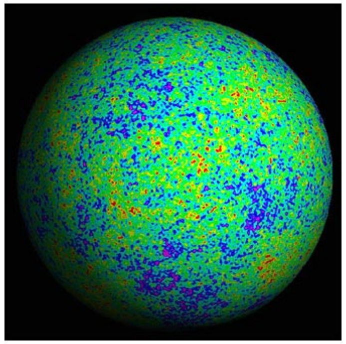
- Plots shows WMAP7 results for curvature versus equation of state parameter w
- Can see Supernovae make a dramatic improvement to this
- (Will see something similar in a plot later from the South Pole Telescope.)
- Point would like to make here is that a slightly closed universe with acceleration due to a simple cosmological constant still looks fine

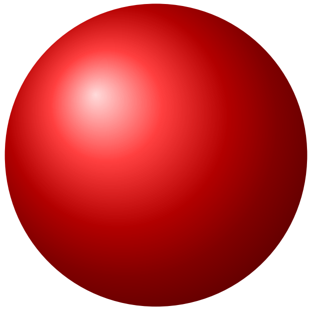


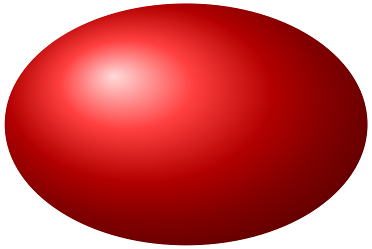
Bianchi Models

- Homogeneous but anisotropic – generalise FRW
- Homogeneity generated by the 3-parameter Lie groups
- Bianchi IX (closed) vs Bianchi VII_h (open)
- Early-time (effects laid down during inflation) vs late-time (since recombination)
- Bianchi IX group is $SO(3)$ and group manifold is S^3
- Consider biaxially symmetric Bianchi IX so universe essentially a squashed 3-sphere

$$ds^2 = dt^2 - \frac{1}{4}R_1^2(\omega^1)^2 - \frac{1}{4}R_2^2\left[(\omega^2)^2 + (\omega^3)^2\right]$$







Bianchi IX dynamics

- Perfect fluid in Bianchi IX thought to generically lead to an oscillatory singularity (going back in time)
- The three axes tend to zero in a chaotic fashion (Mixmaster behaviour). (Evolution approximated by infinite sequence of successive Kasner epochs (Bianchi I solution).)

We worked with a setup including a scalar field

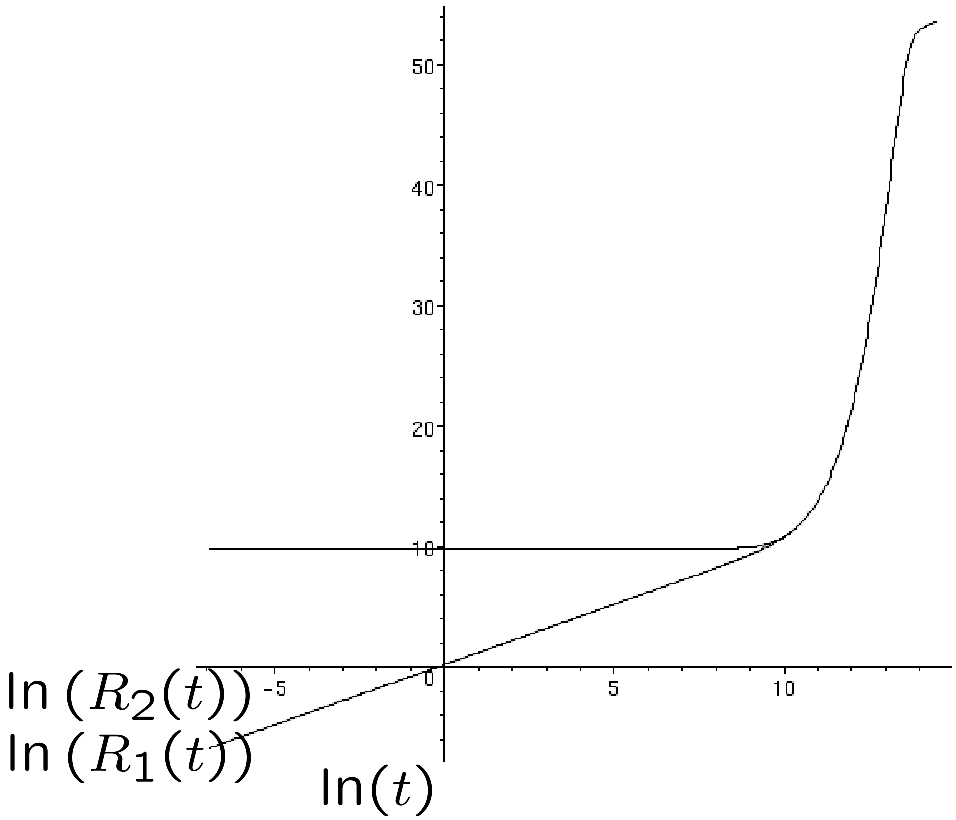
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa}(R+2\Lambda) - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + V(\phi)\right]$$

and with the assumption of biaxiality found two solutions (of definite parity) that have very simple dynamics — see Dechant et al. Phys. Rev. D 79, 043524 (2009) for details

- One odd-parity, pancaking solution
- One even-parity, bouncing solution

THE PANCAKING SOLUTION

$R_1 \propto t$, $R_2 = R_3 \propto$ const, $\phi =$ const through the 'Big Bang' at $t = 0$



$$R_1(t) = t\left(a_0 + a_2 t^2 + a_4 t^4 + \ldots\right)$$

$$R_2(t) = R_3(t) = b_0 + b_2 t^2 + b_4 t^4 + \ldots \quad ,$$

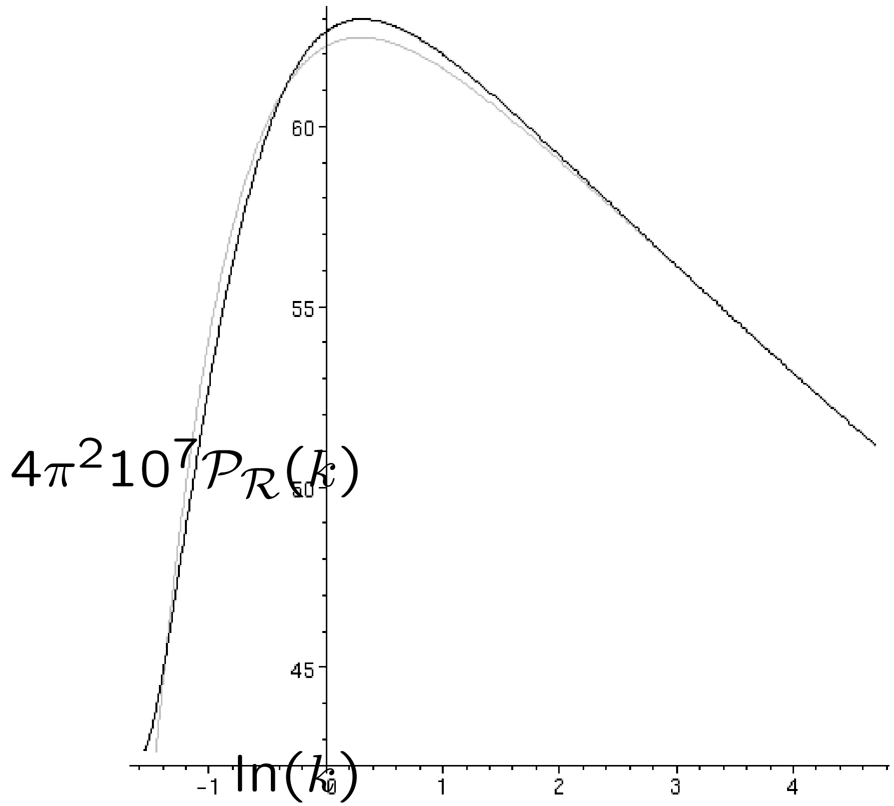
$$\phi(t) = f_0 + f_2 t^2 + f_4 t^4 + \ldots$$

This solution has odd parity – it extends smoothly ($R_1 \sim t$) through the pancaking with a parity inversion and no singularities in any physical quantities. Late-time slope is $R \sim t^{2/3}$ as befits non-relativistic dust.

CONSEQUENCES OF EARLY OBLATENESS

- Isotropisation and Inflation overlap
- Universe is just oblate (at $\sim 0.2\%$ level) when perturbations on the scale of the current Hubble radius left the horizon
- Structure on the largest scales could stem from a time where the universe was still significantly oblate
- Could generate large-scale asymmetries and phase correlations?
- Isotropisation and Inflation make sure universe is close to isotropy and flatness at late times

THE POWER SPECTRUM



- Other features very similar to closed FRW case discussed in Lasenby & Doran (2005) — more generally low-k dip due to period of kinetic dominance, and this applies here equally as in cases with actual initial singularity
- Spectral index $n_s \sim 0.975$
- Tensor-to-scalar ratio $r \sim 0.15$
- low-ℓ dip: CMB power spectrum suppressed for low multipoles (exponential cutoff) due to low-k cutoff
- The grey line is the fit to an exponential cutoff proposed by Efstathiou (2003) on phenomenological grounds

FURTHER POINTS

- Also wish to look at link with horizon-scale velocity perturbations, e.g. see Dark Flow (Kashlinsky et al (2008, 2009, 2010); Feldman, Hudson, Watkins (2008, 2009))
- Also, probably of more interest to relativists than cosmologists!, there is a connection with Taub-NUT space
- Paper on this accepted by CQG, now on archive (arXiv:1007.1662), by Dechant, Lasenby & Hobson ('Cracking the Taub-NUT')

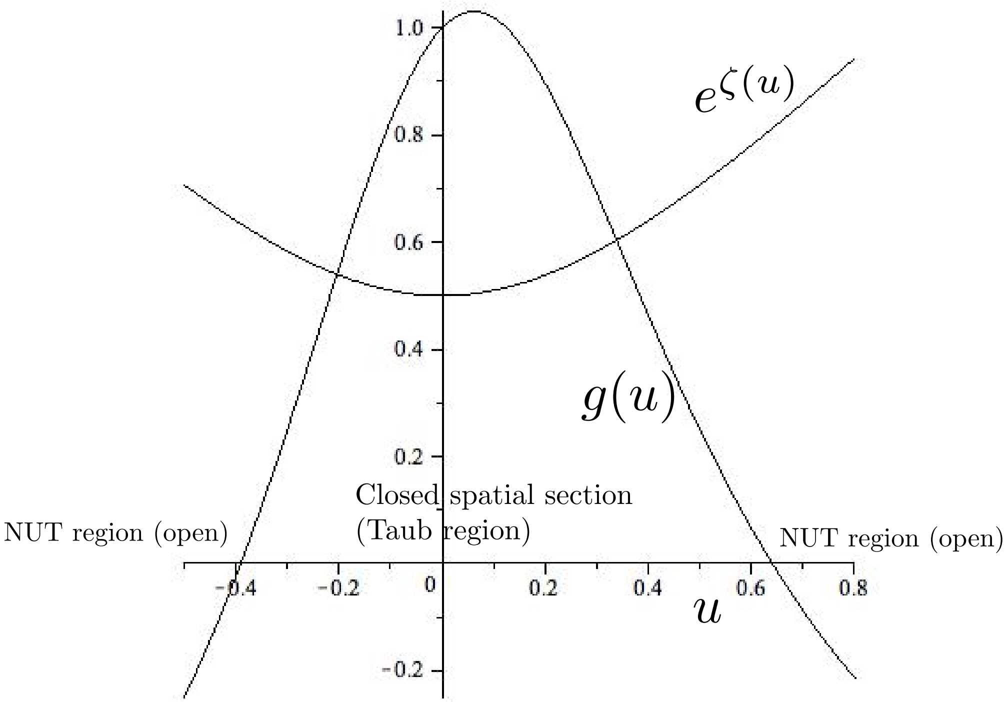
LINK WITH TAUB-NUT

- Taub solution (Ann.Math., **53**, 472 (1951)) — Empty Space-Times Admitting a Three Parameter Group of Motions, was one of first Bianchi type solutions to be introduced into cosmology

- Taub's motivation, coming out of Mach's principle, was to see whether non-singular vacua have to be flat

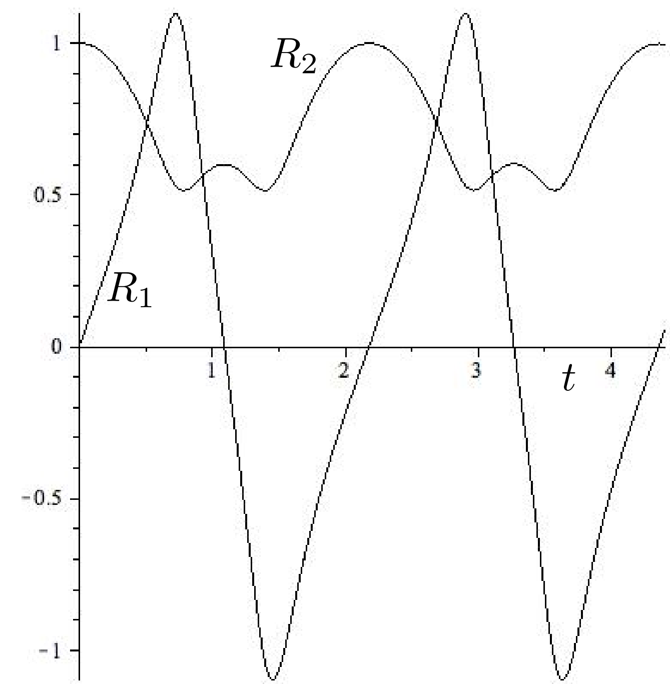
- Found a spacetime controlled by two functions (with simple analytic forms), $g(u)$ and $\zeta(u)$

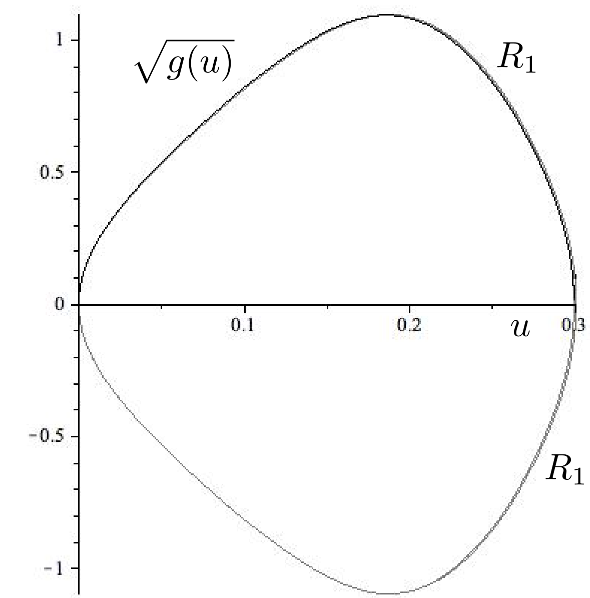
- $g(u)$ is effectively a radius^2 in a pancaking direction



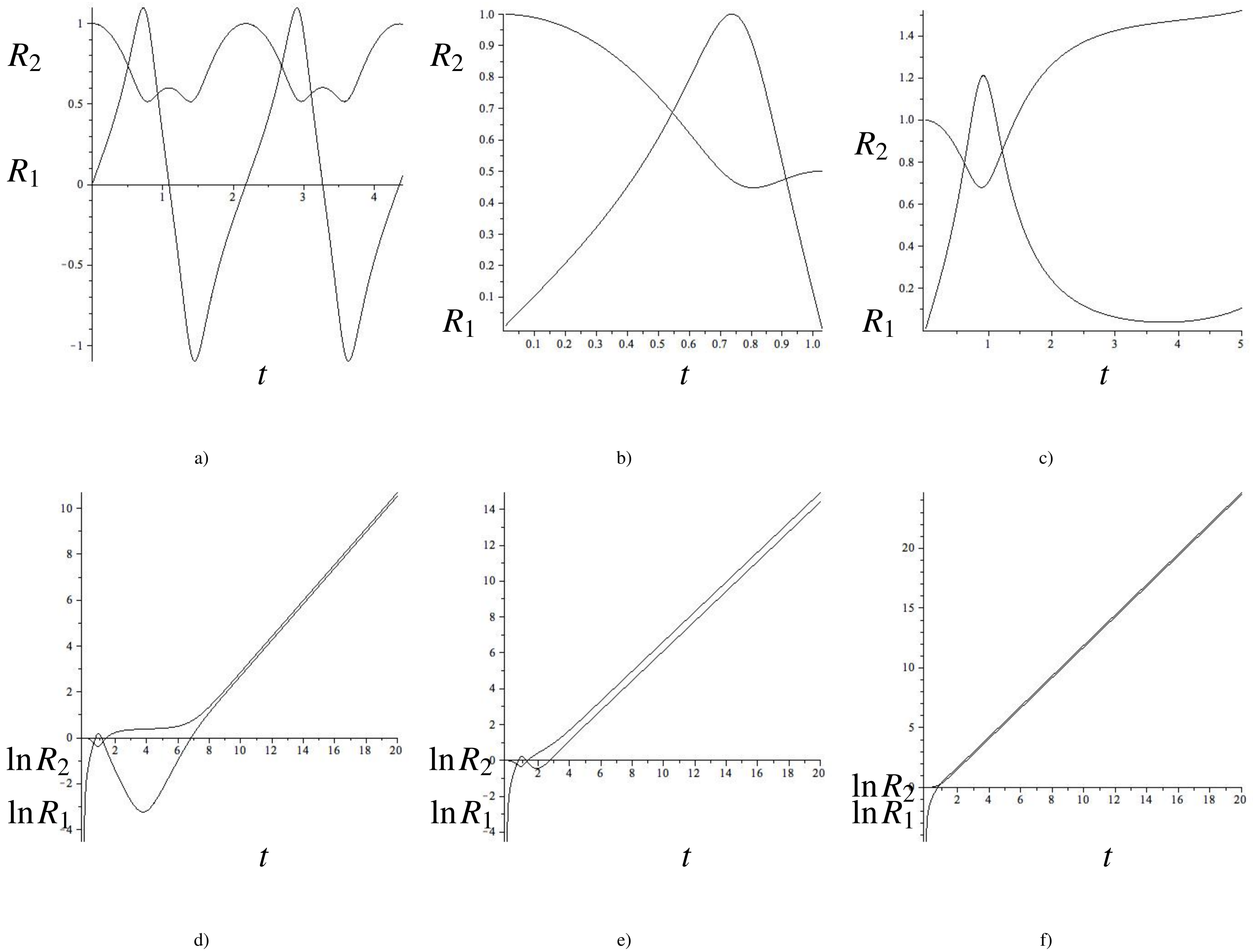
- $g(u)$ passes through 0, leading to transitions to regions called 'NUT' regions (after Newman, Tamburino & Unti, who discovered them)

- Given similar pancaking behaviour and biaxiality, we were interested in the vacuum limit of our Bianchi IX model
- Discovered that it consisted of an infinite, periodic succession of pancakings, with alternate periods of expansion and contraction
- Very striking behaviour for a vacuum!
- Next page shows behaviour as one gradually re-introduces scalar field into this
- Eventually periodicity destroyed, and one recovers our previous inflationary solution
- Can relate vacuum case to Taub-NUT via the coordinate transform $u == \int_0^t \frac{1}{2} R_1(t')dt'$
- Surprise is how this maps onto an infinitely traversed loop in the Taub-NUT coordinates





GRADUALLY INTRODUCING A SCALAR FIELD



Summary on Taub-NUT: we believe our picture is the more physical one!

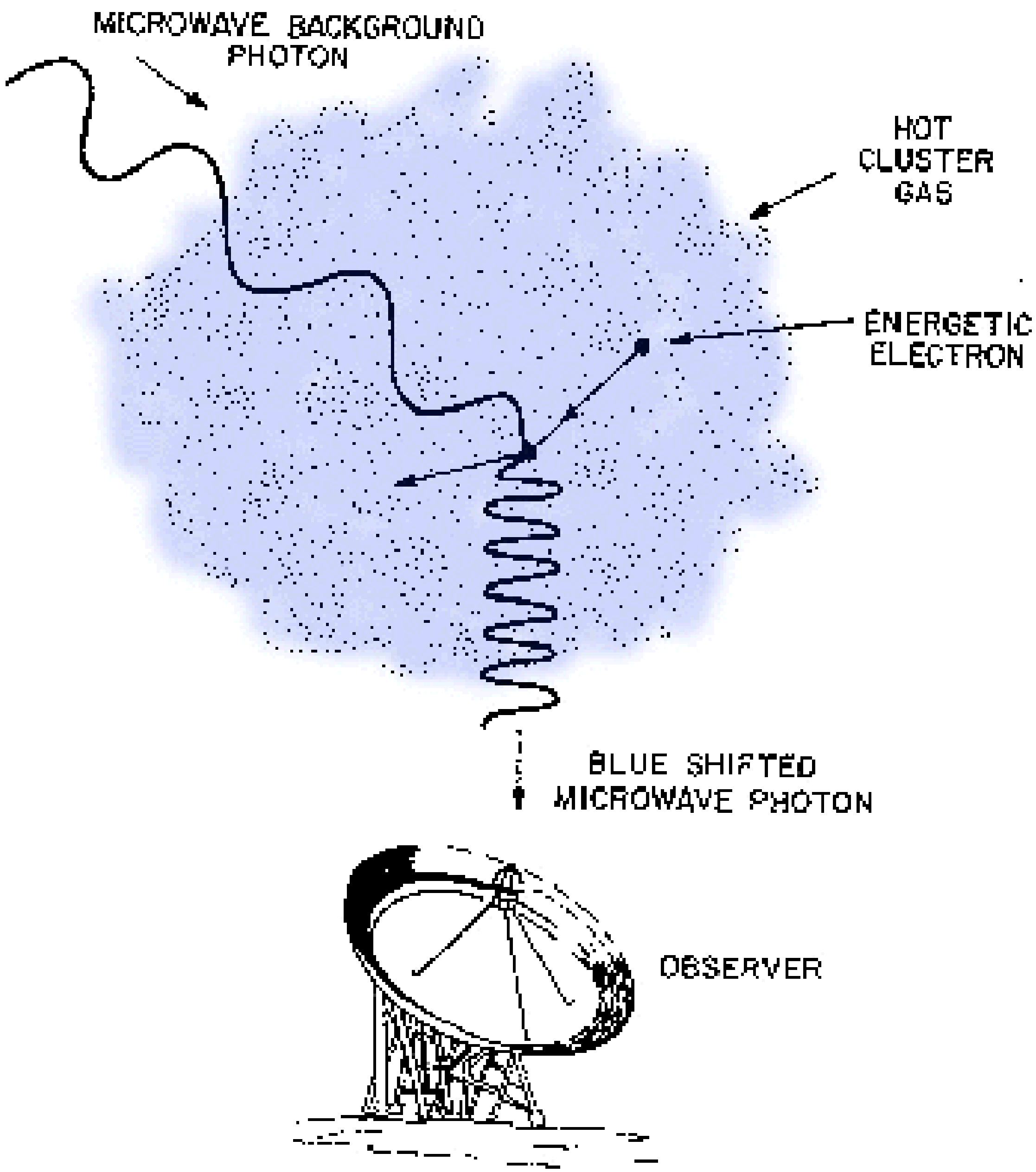
INFLATION AND STRING THEORY

- Mentioned this last year, and not very much to update
- In canonical single field models, Lyth (1997) showed

$$r = \frac{8}{M_{\mathrm{Pl}}^2}\left(\frac{d\phi}{dN}\right)^2$$

- Thus field evolution of 50–60 e-folds implies $\Delta\phi \sim (r/0.002)^{1/2}$
- Detectable gravity waves means inflaton evolved through a super-Plankian distance
- There may be geometrical effects in string theory moduli which makes this difficult
- Also now believed that having a smooth potential over $\Delta\phi > M_{\mathrm{Pl}}$ problematic for effective field theory with a cutoff $\Lambda < M_{\mathrm{Pl}}$ unless shift symmetry removes higher order corrections
- First ‘stringy’ models incorporating this (with axion-like potentials) appeared last year (e.g. Flauger et al. hep-th/0907.2916 - Axion Monodromy model)
- These may lead to a broad ϕ^2 type potential, but with superposed oscillations — observable effects in CMB?
- Daniel Baumann now has an alternative in which inflaton is coupled to a conformal sector, (see e.g. hep-th/1004.3801) — claims this is more generic and natural — no specific predictions as yet

THE SUNYAEV-ZELDOVICH EFFECT



(From astro.uchicago.edu.)

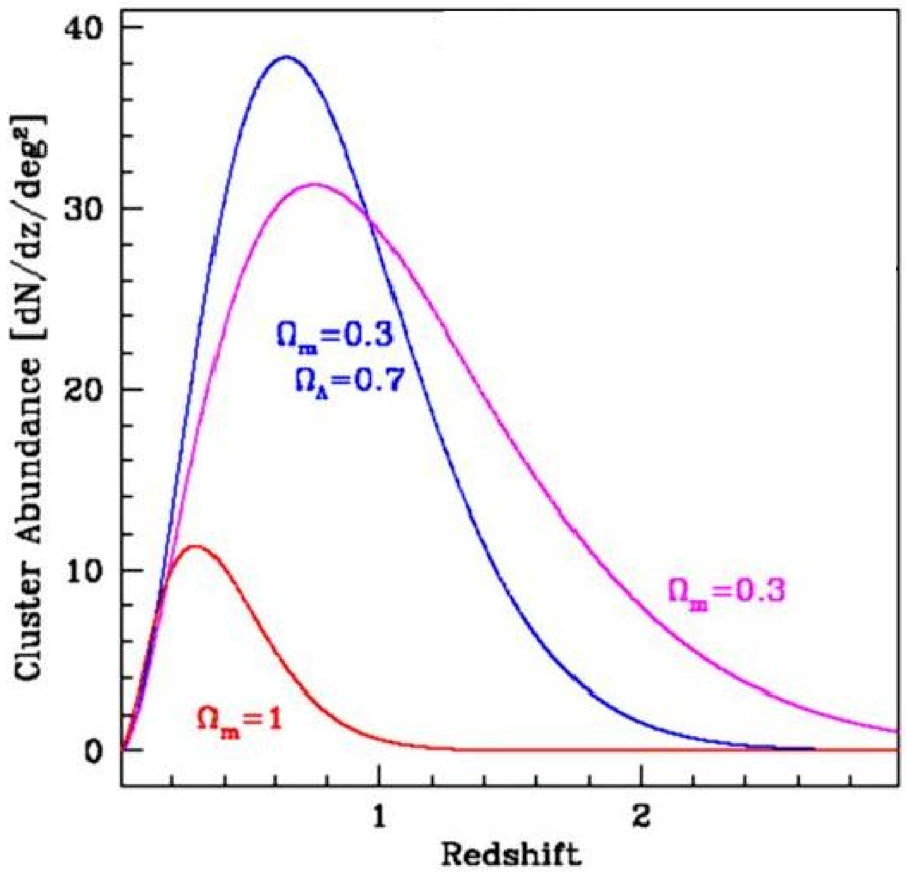
AMI

- The AMI Small Array
- Ten 3.7 m dishes
- Has been working fully for 3 year

- The AMI Large Array
- The Eight 13 m dishes of the old Ryle Telescope
- Reconfigured to make a compact array for source subtration for Small Array SZ surveys
- Key for measuring radio source contamination

CLUSTER NUMBER COUNTS

- Measure $\frac{\mathrm{d}n(M,z)}{\mathrm{d}z}$ to constrain cosmology
- Probes volume-redshift relation
- Probes abundance evolution
- Cluster structure and evolution



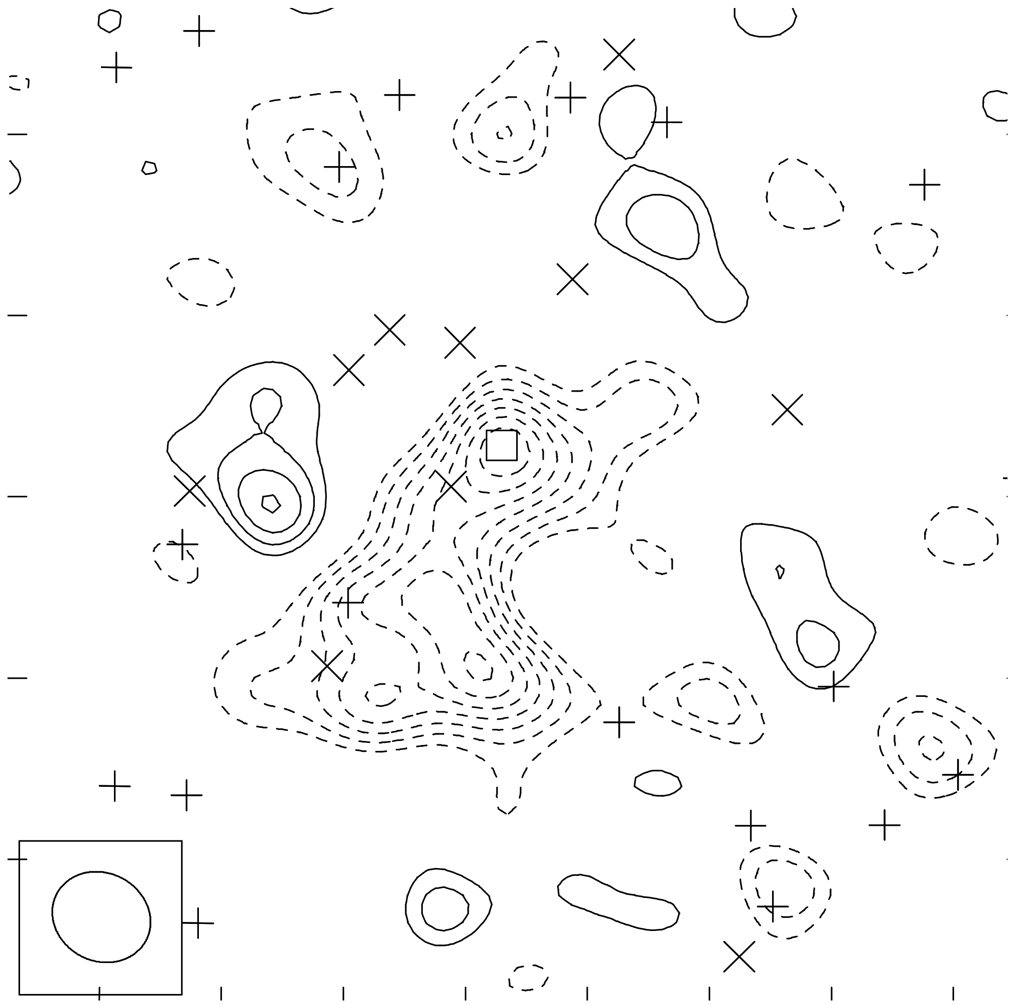
(Anna Scaife)

Current use of AMI

- Pointed observations of over 100 SZ clusters have now been carried out with the SA and LA source observations have now gradually caught up
- Therefore now ready to start publishing SZ results in addition to the several results already published on Galactic objects and spinning dust
- Also 10 x (1 square degree) fields now fully surveyed with both instruments (will show a first result from this shortly)
- With other blank field surveys now coming on line, a prime role for AMI can emerge in terms of follow up and validation
- AMI inherently sensitive (probably better mass limits than other current SZ telescopes):
  - For clusters with $M > 3.0 \times 10^{14} M_{\odot}$, and at $z > 0.1$, an 8 hour observation with both arrays will give a detection at about the 7σ level — good for validation
  - For follow-up purposes about 32 hours with both arrays would be suitable. On rich clusters this will give well resolved $\sim 20\,\sigma$ detections, including the outer regions of the cluster gas

CURRENT USE OF AMI (CONTD.)

- An MoU has now been formally agreed between AMI and Planck for validation and follow-up of samples of the Planck SZ cluster candidates
- Will highlight here two results (unrelated to Planck!)
  - A candidate cluster detection in one of our own blank fields (therefore a blind SZ detection)
  - Pointed observations of an interesting new version of the 'bullet cluster'



AMI blank field cluster detection

Approx. 7σ detection

19 point sources have been measured and removed

BLANK FIELD CLUSTER PHYSICAL PARAMETERS

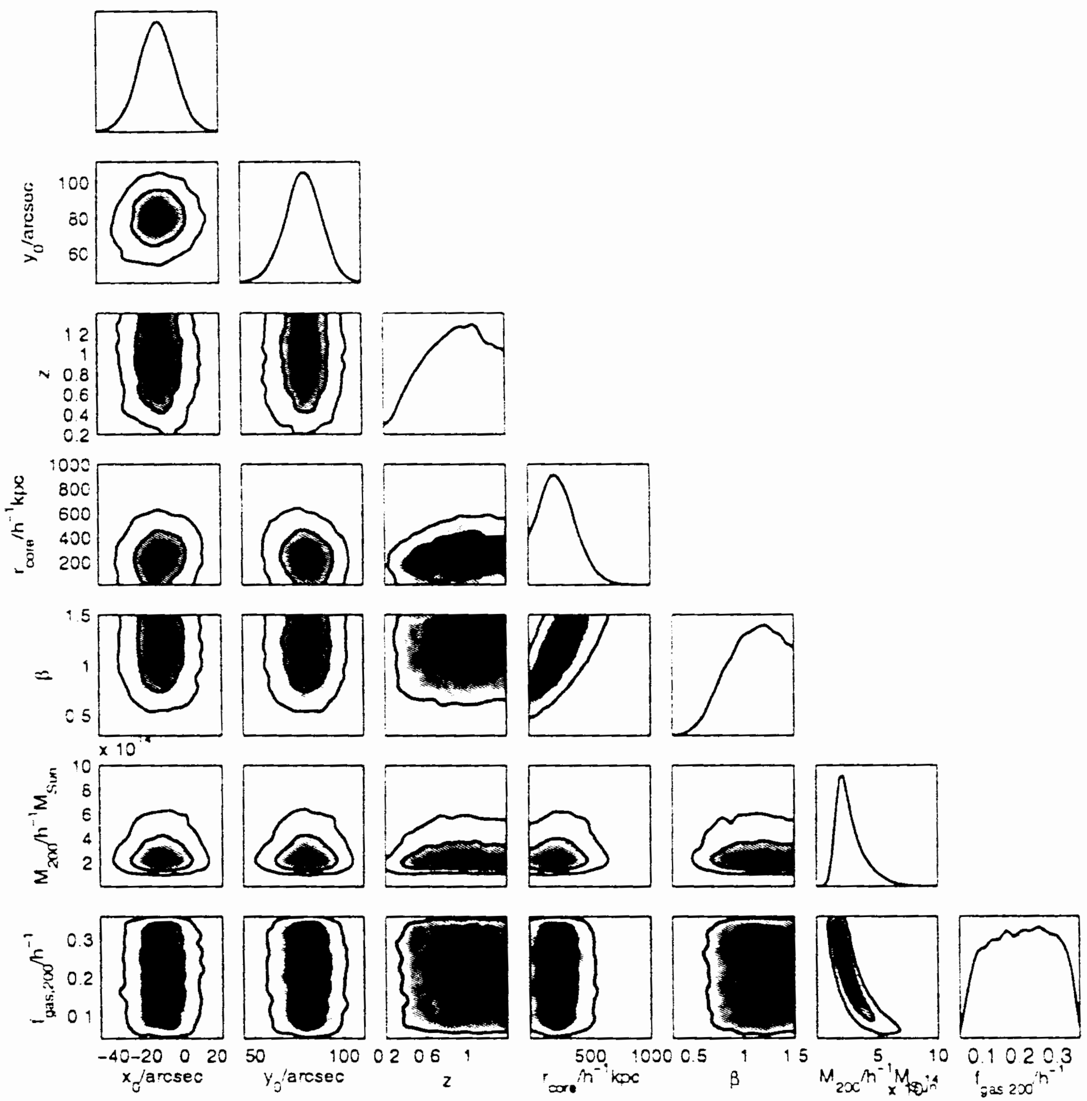
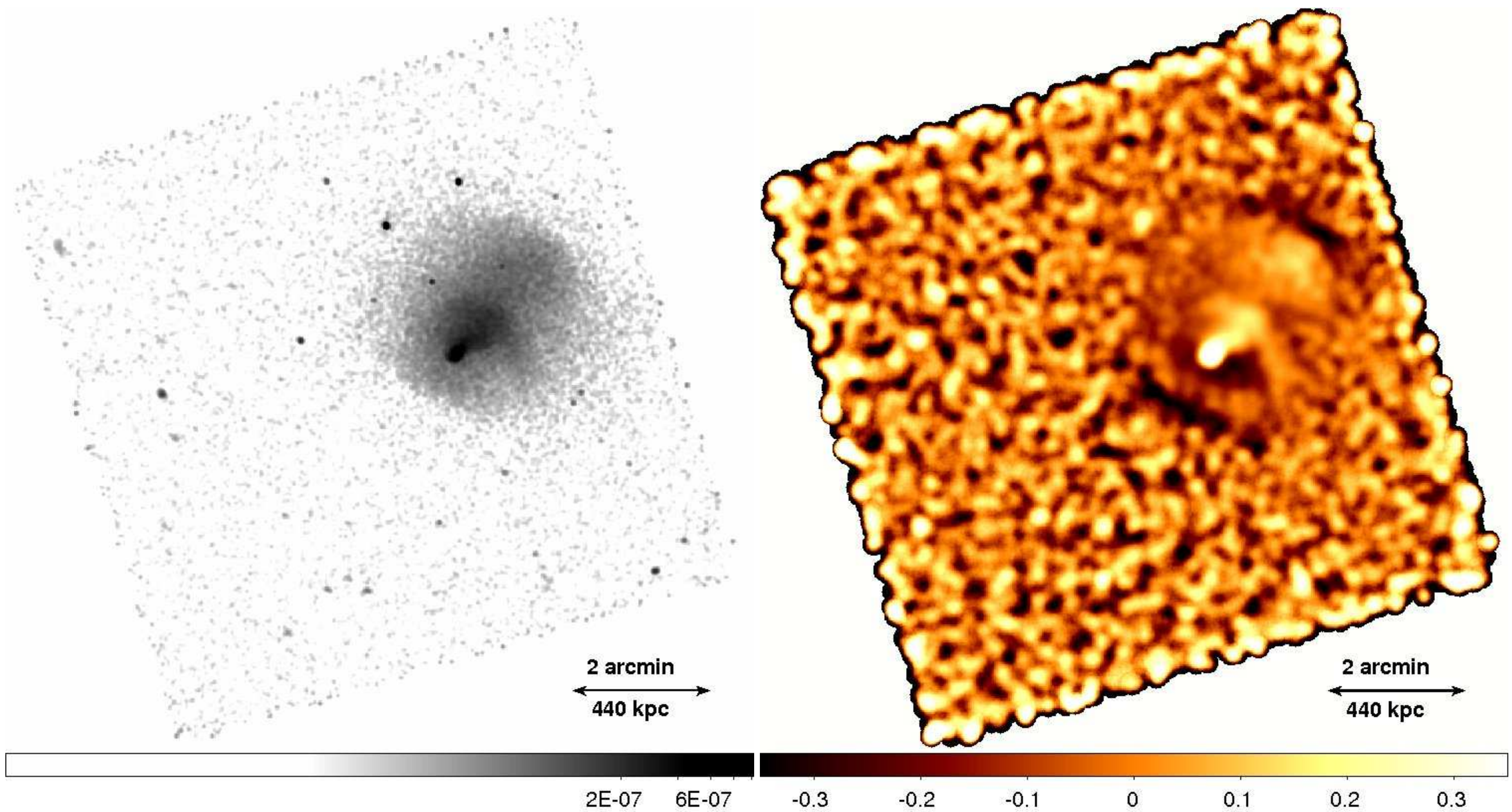


Figure 7. Derived cluster parameters from the pointed observation towards the cluster candidate .

A2146 — ANOTHER BULLET CLUSTER

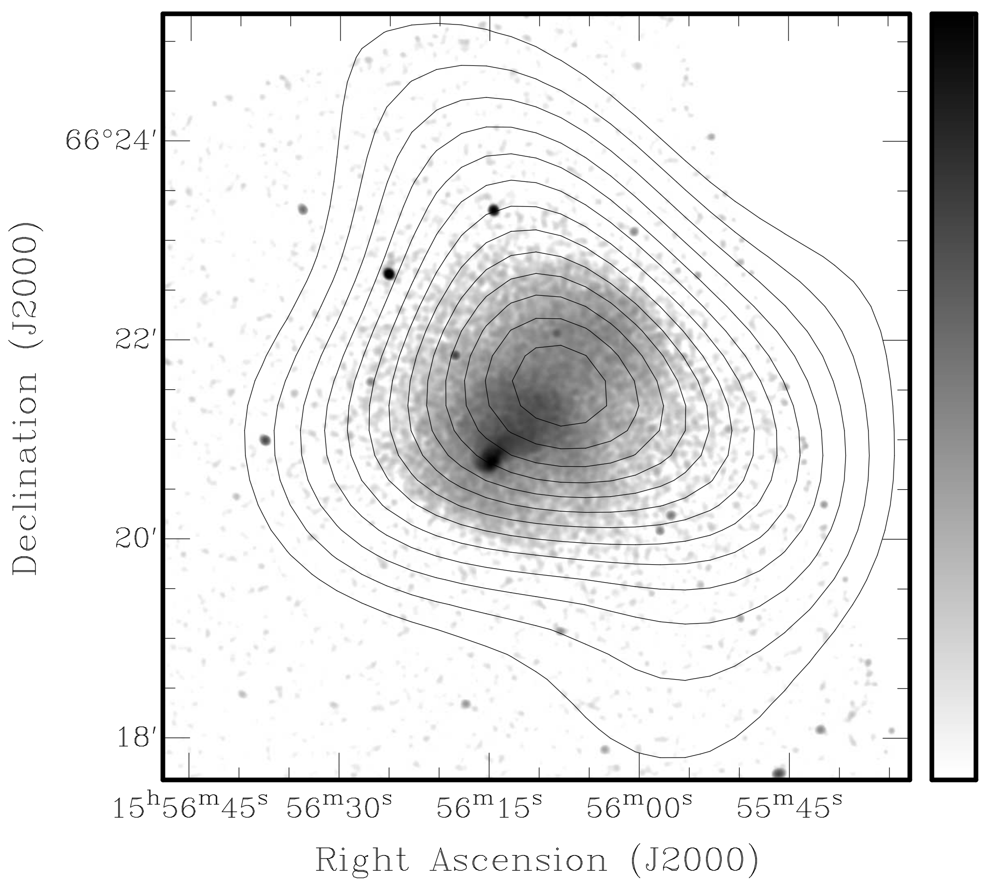


Chandra observations from Russell et al. (2010) (arXiv:1004.1559)

Left: X-ray map; Right: Unsharp mask version

Idea is that we are seeing shock fronts due to flows in NW/SE direction

AMI Results on A2146

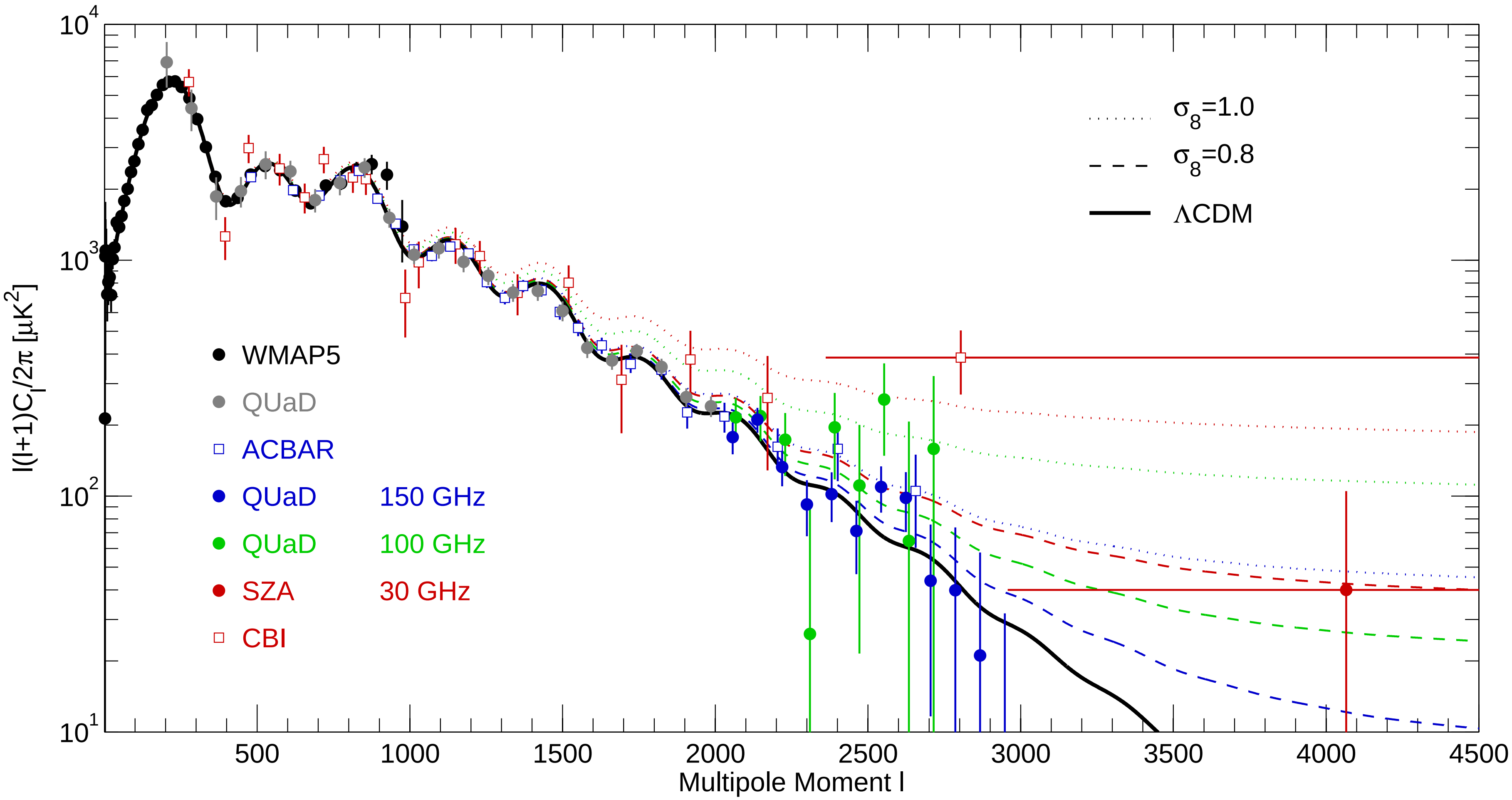


- Cluster is bright enough that we get 13σ detection in just 9 hours observation
- Clear offset between peaks of X-ray and SZ emission, and moreover extensions seem to be orthognal
- Ties in with idea of complex bulk flow motions
- Can also see this from fact that purely hydrostatic equilibrium model does not work for modelling SZ profile ($f_{\rm gas}$ comes out much too low)

Damping tail and CBI excess

- Photon diffusion suppresses photon density fluctuations below $\sim 3\,\mathrm{Mpc}$ at last scattering; $80\,\mathrm{Mpc}$ width of last scattering surface further washes out projection to ΔT
- Predicted exponential decline seen by CBI (30 GHz) and ACBAR (150 GHz) but ...
  - CBI and BIMA see excess emission at $l > 2000$: interpreted as SZ gives $\sigma_8 \approx 1.0$

DAMPING TAIL AND CBI EXCESS — QUAD RESULTS FROM LAST YEAR



Taken from Friedman et al. (2009) (astro-ph/0901.4334).

QUAD disagreed with CBI

Consistent with $\sigma_8 = 0.8$ rather than 1

Is CBI estimated source correction underestimated?

THE SOUTH POLE TELESCOPE

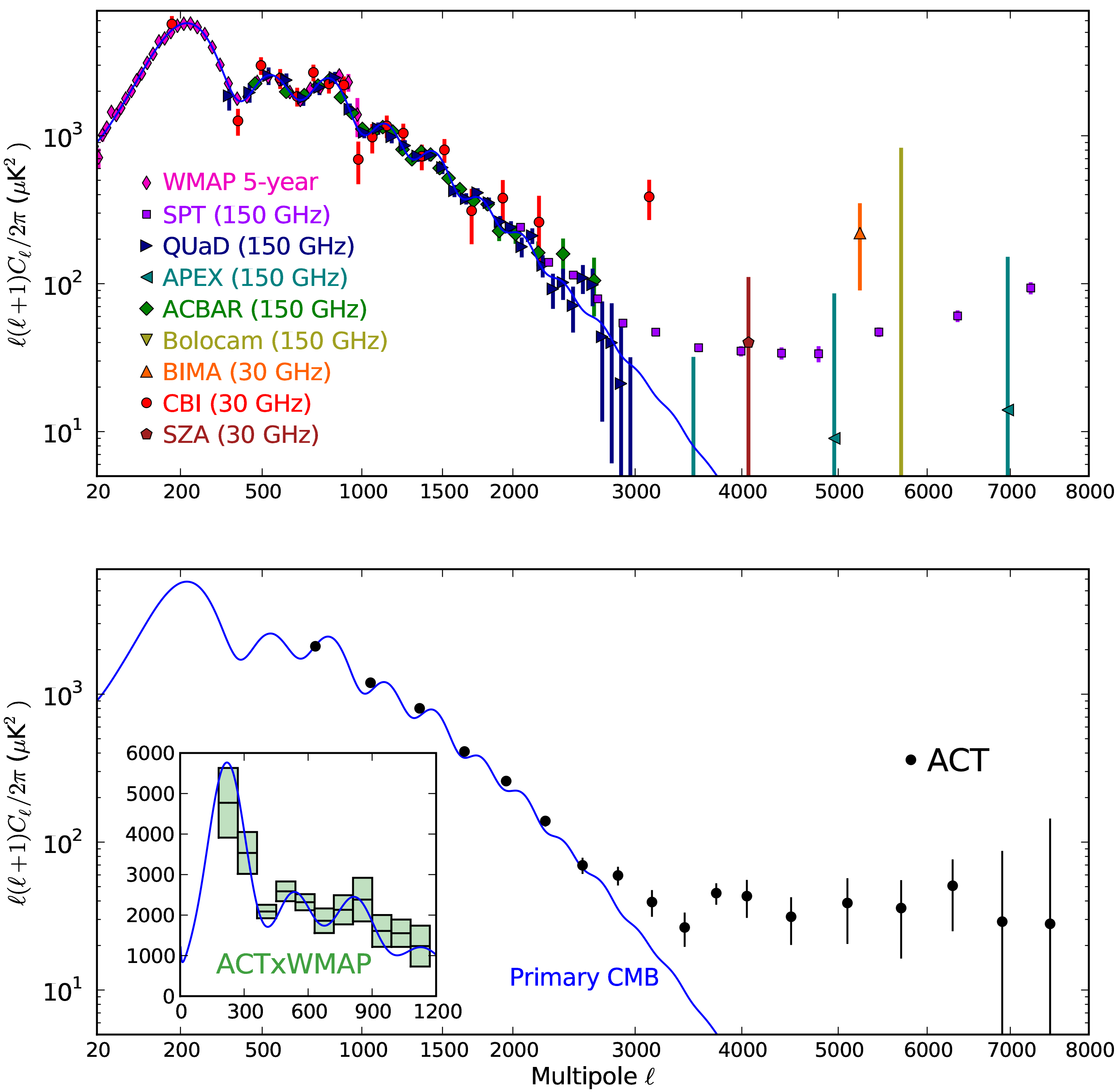
- South Pole Telescope (10m) has been carrying out first surveys
- These are at 150 and 220 GHz, covering two 100 deg^2 fields — there have been some problems with 90 GHz channel
- Have now had the following sequence from SPT
  - Measurements of Secondary CMB Anisotropies with the South Pole Telescope, Lueker et al., arXiv:0912.4317

SPT (CONTD.) AND ATACAMA COSMOLOGY TELESCOPE

- Galaxy Clusters selected with the SZ effect from 2008 SPT observations, Vanderlinde et al., arXiv:1003.0003
- X-ray properties of the first SZE-selected galaxy cluster sample from the SPT, Andersson et al., arXiv:1006.3068
- In addition the Atacama Cosmology Telescope (in Chile) has been reporting results for the high-ℓ CMB power spectrum (Fowler et al., arXiv:1001.2934) and the X-ray properties of its first blank field SZ results (Menateau et al., arXiv:1006.5126)
- Things are hotting up!

- The ACT (with ground screens removed)
- 6 metre, off-axis Gregorian telescope
- Main results come from 148 GHz
- Beamsize about 1.4 arcmin

The Atacama Cosmology Telescope high-ℓ results



The South Pole Telescope — Results from SZ cluster sample

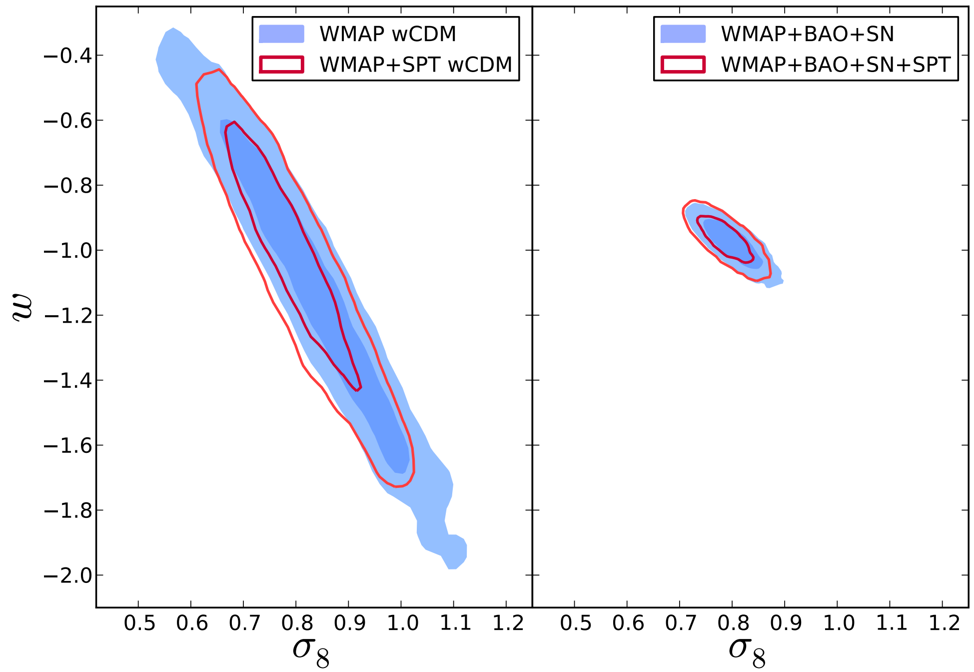
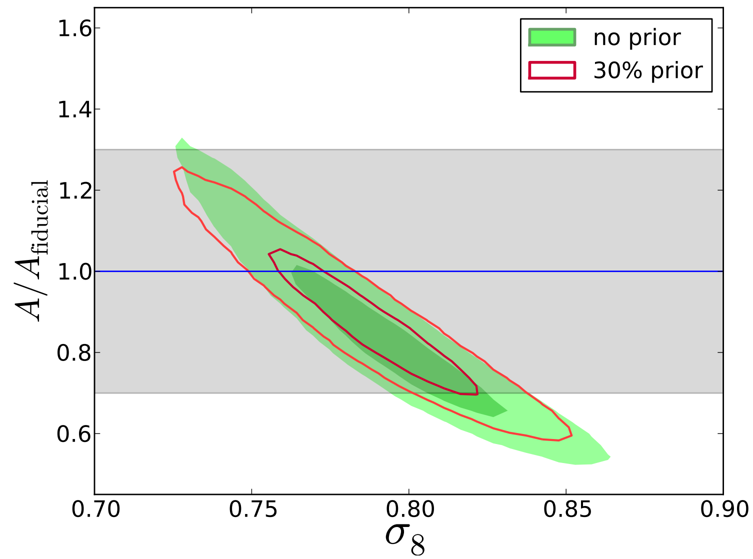
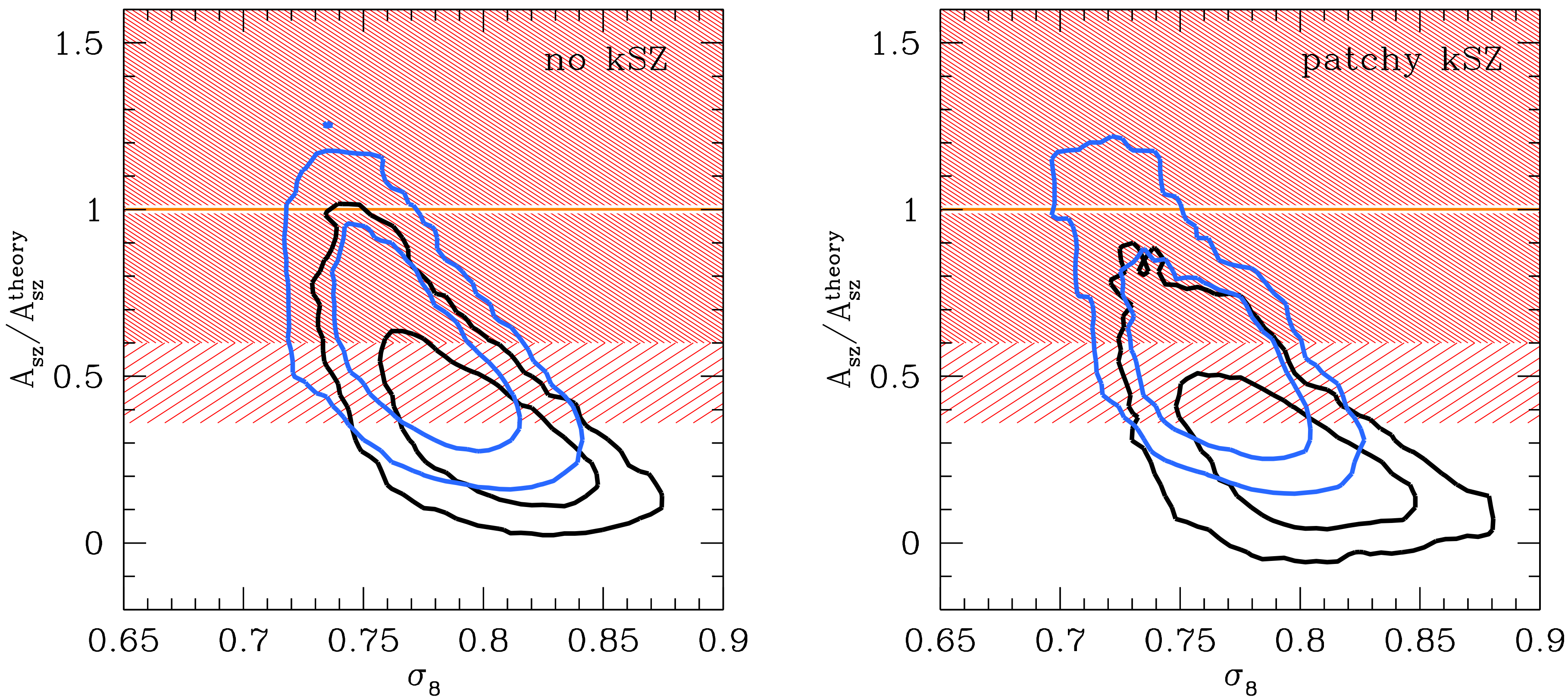


Fig. 5.— Likelihood contour plot of w versus σ_8 showing $1\,\sigma$ and $2\,\sigma$ contours for several data sets. The left panel shows the constraints from WMAP7 alone (blue) and with the SPT cluster catalog included (red). The right panel shows show the full cosmological data set of WMAP7+SN+BAO (blue), and this plus the SPT catalog (red). The ability to constrain cosmological parameters is severely impacted by the uncertainties in the mass scaling relation, though some increase in precision is still evident.



- This is from the Vanderlinde et al. paper
- Illustrates again the current importance of SN data in constraining w
- Other figure shows how SZ amplitude is coming out smaller than expected from X-ray-inferred values



- Things are even more extreme in the high-ℓ CMB spectrum results
- The red contours are when a prior on $A_{\mathrm{SZ}}^{\mathrm{theory}}$ is introduced
- Basically, either σ_8 has been overestimated (note $C_\ell^{\mathrm{SZ}} \propto \sigma_8^{11}$ in this region!)
- Or SZ contribution expected in power spectrum is overestimated for some reason (cf. WMAP results)

SUMMARY

- CMB still providing essential information
- On primordial side only new results WMAP7 — results from Planck eagerly expected
- BICEP2 promises to be interesting
- Secondaries are moving ahead rapidly, and are currently providing some puzzles w.r.t. SZ power
- Again Planck will be extremely important for this