CMB Observations:

Current Status and Implications for Theory

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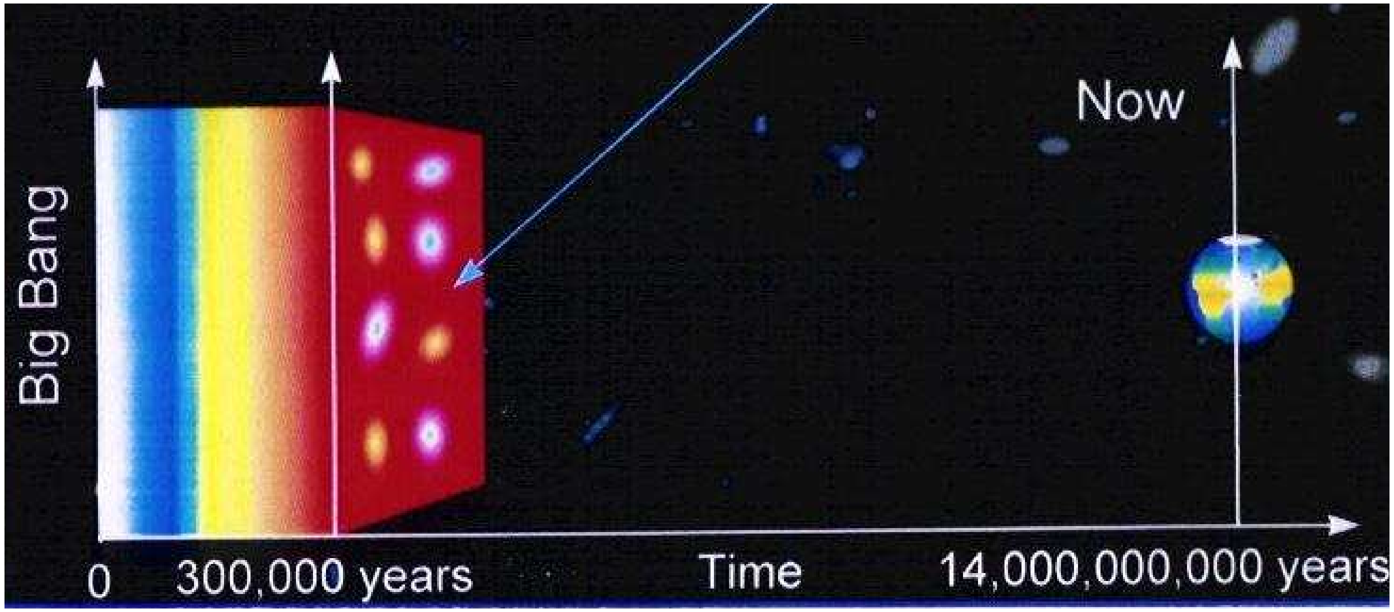
PLAN FOR TALK

- Will give an overview of current state of CMB observations and scientific implications
- This last year has been pretty exciting, mainly as regards high-ℓ CMB observations
- Plus Sunyaev-Zeldovich story continues to be very interesting, including first Planck results on this
- Will try to give a feel for theoretical context in which these results sit

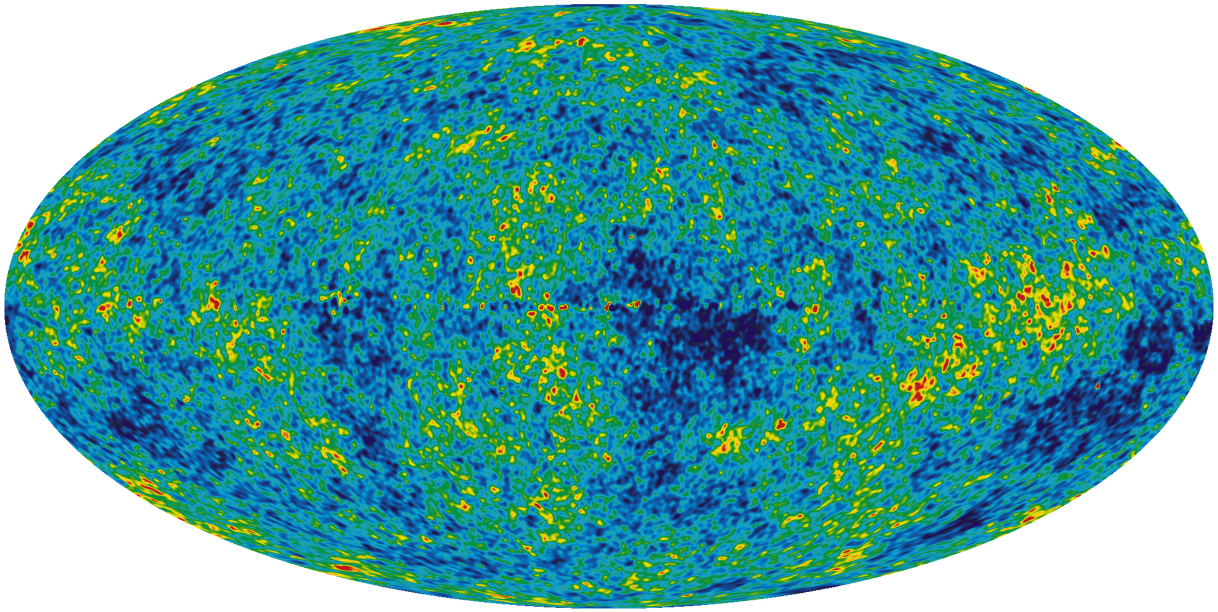
THE COSMIC MICROWAVE BACKGROUND



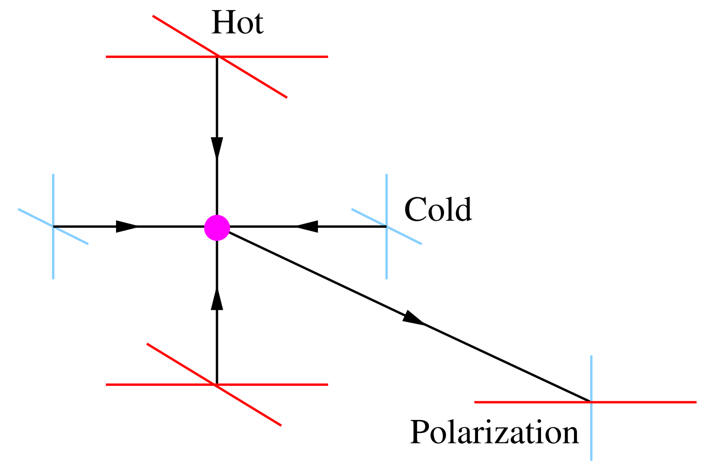
- The Cosmic Microwave Background (CMB) was emitted at about 300,000 years after the big bang and has been propagating to us ever since
- Think about 90% of the photons make it straight to us, telling us about the physics at the time of recombination
- Rest carry imprints of what has happened on the way
- But when emitted also has encoded in it information dating from about 10^{-36} seconds after the big bang

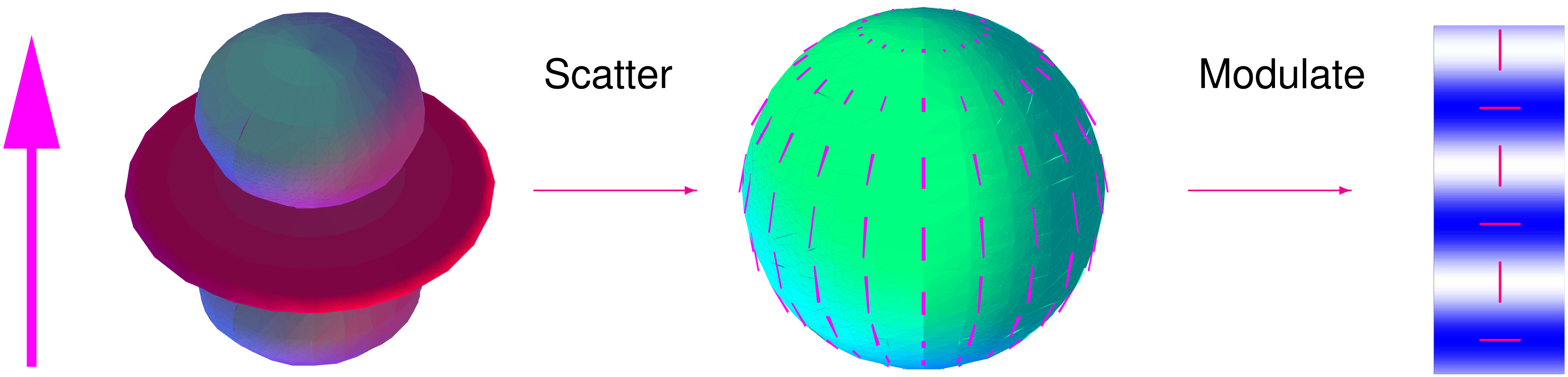
THE COSMIC MICROWAVE BACKGROUND (CONTD.)

- Huge advances in technology in past few years, are enabling us to measure all 3 of these aspects with rapidly increasing precision
- 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



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

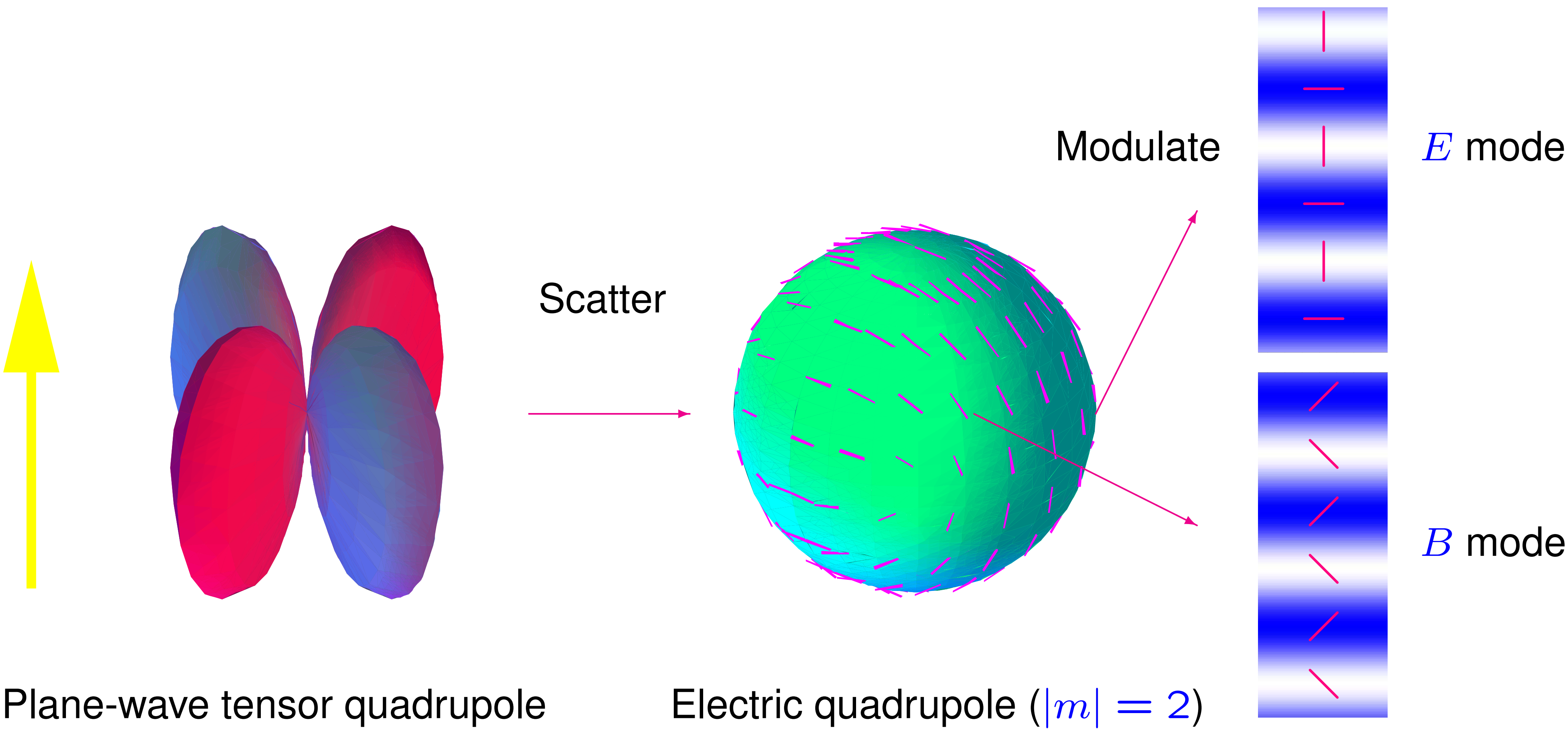




Plane-wave scalar quadrupole | Electric quadrupole ($m = 0$) | Pure E mode

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

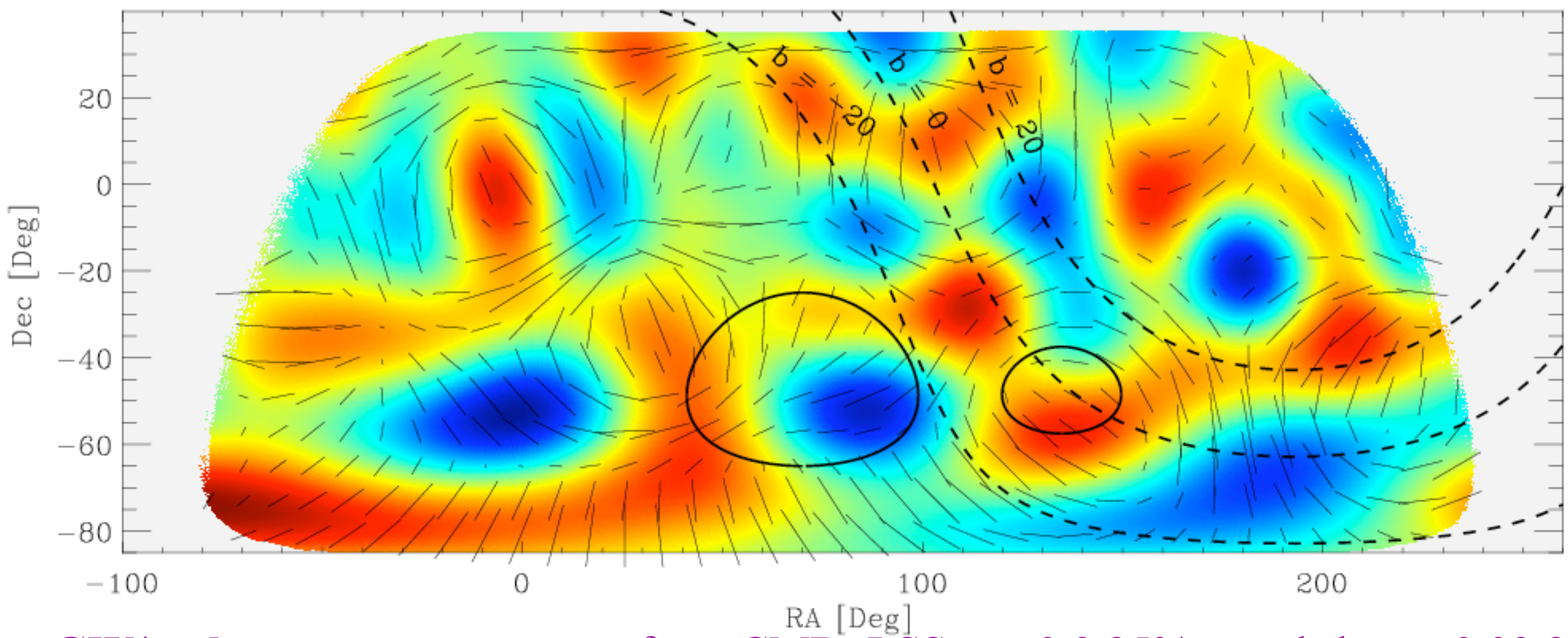
GRAVITY WAVES IN CMB POLARIZATION: PHYSICS



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

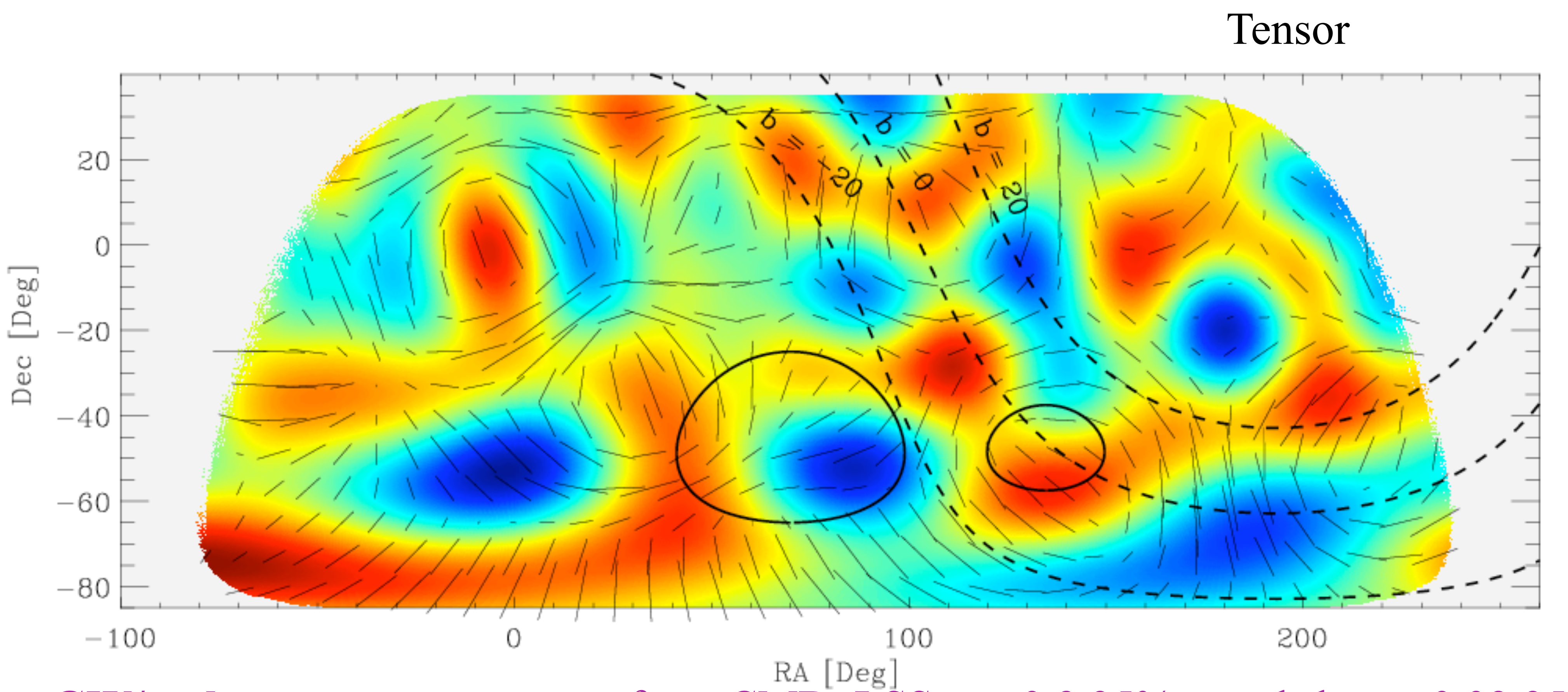
SKY WITH AND WITHOUT TENSORS

No Tensor



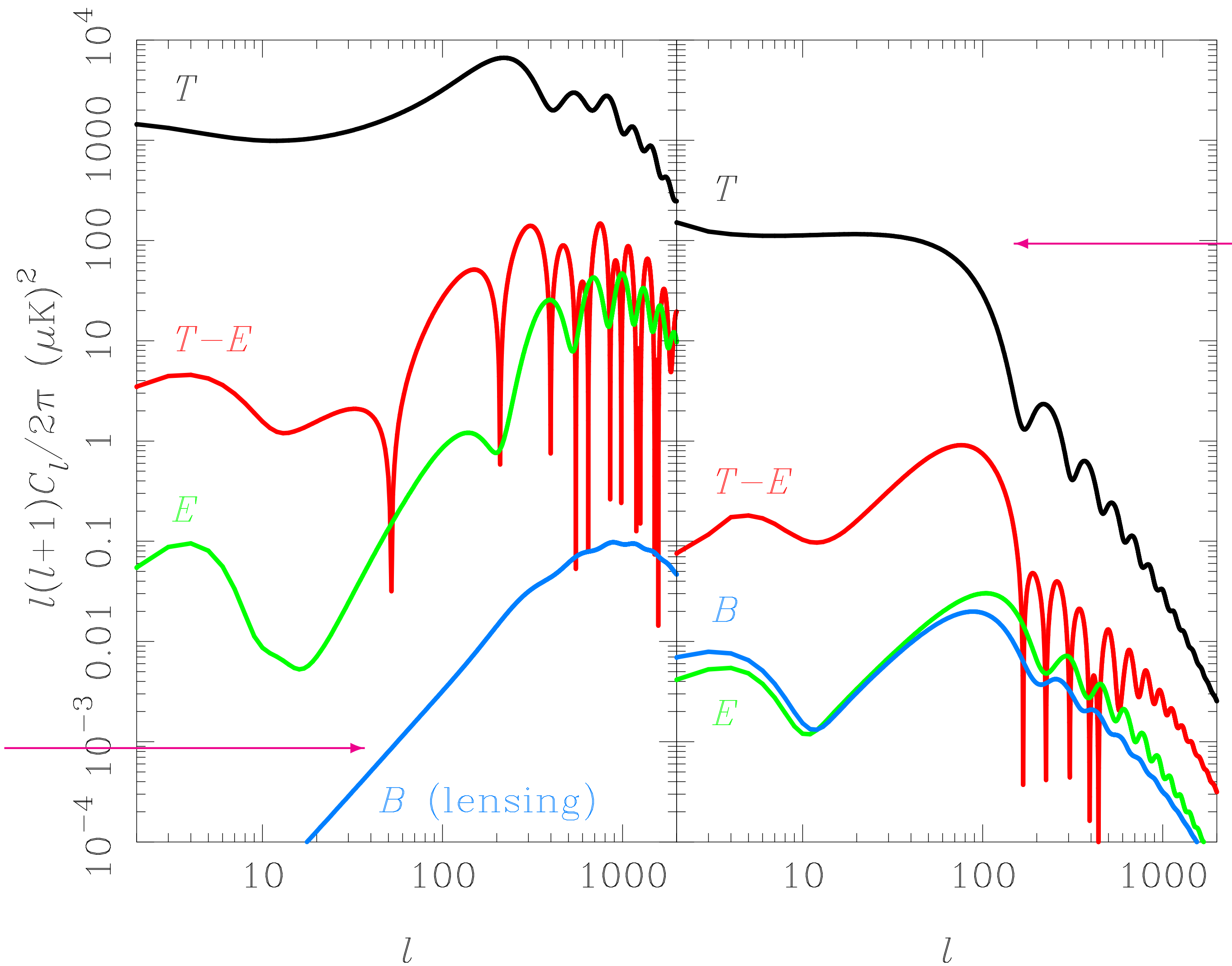
`http://www.astro.caltech.edu/~lgg/spider_front.htm`

Sky with and without tensors



http://www.astro.caltech.edu/~lgg/spider_front.htm

POWER SPECTRA

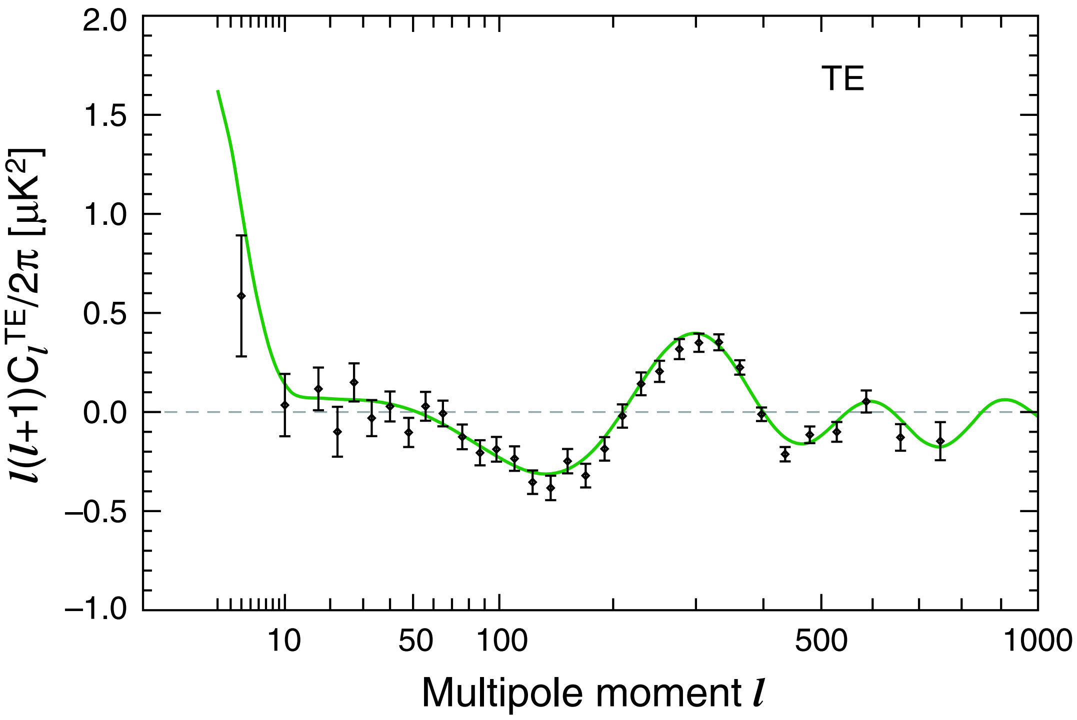


Lens-induced B modes ($\sqrt{C_l^B} \approx 1.3\,\text{nK}$)

Effects only on large scales since gravity waves damp inside horizon

Basic character of density perturbations

- We know amplitude is $\sim 10^{-5}$
- They are approximately scale-invariant
- They are Gaussian to high-accuracy
- They correspond (in simplest interpretation) to adiabatic mode
- They have to have gone through a period of existing on super-horizon scales
- Last two points can effectively be read off from TE spectrum (one shown is WMAP 7 year, Larson et al, arXiv:1001.4635)



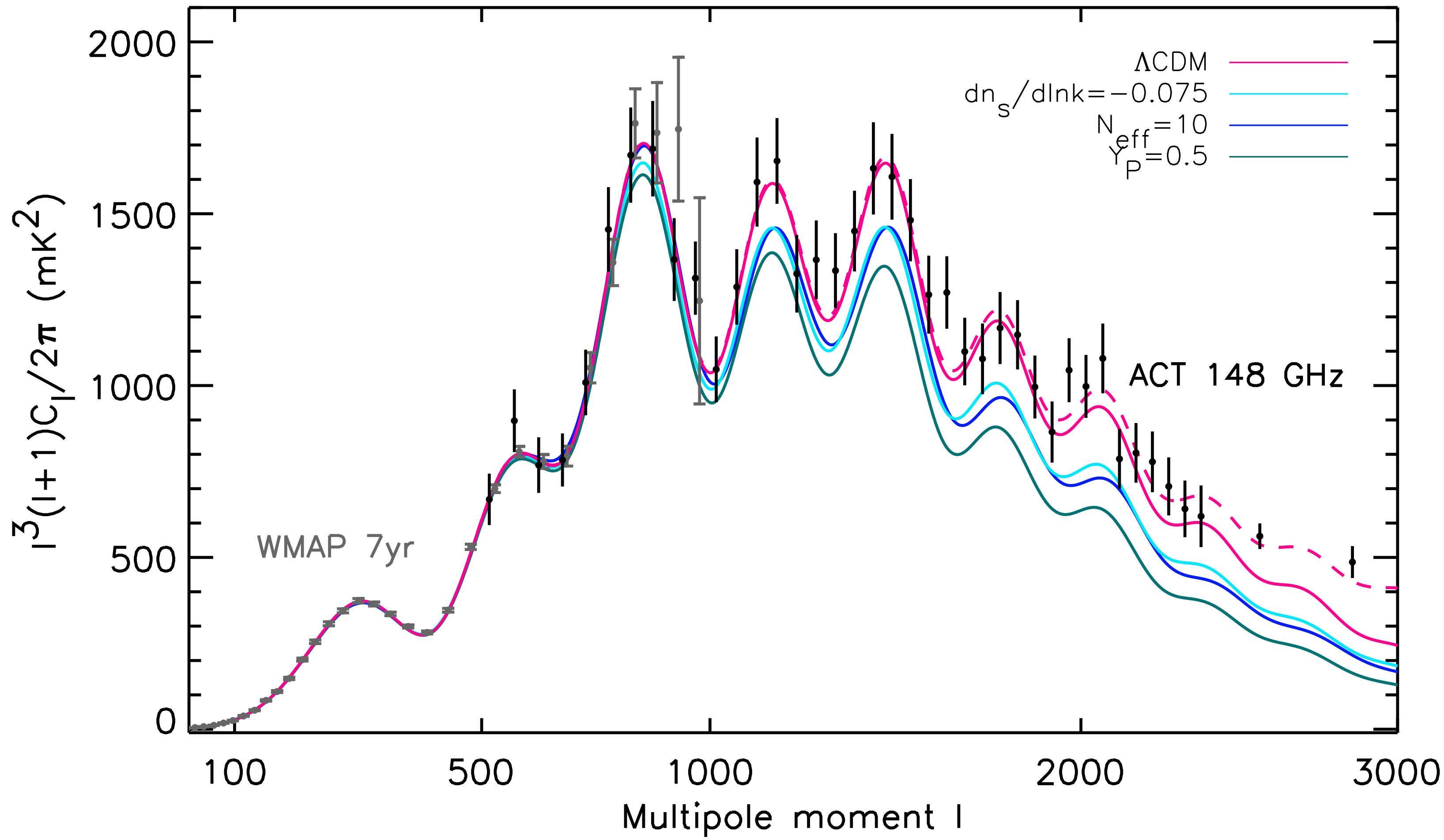
WHAT WOULD A DETECTION OF PRIMORDIAL GRAVITY WAVES TELL US?

- Strong evidence that inflation happened
- 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 $k = 0.001\,\mathrm{Mpc}^{-1}$ chosen)
- Find

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

- 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
- Combination of r and n_s (slope of scalar primordial power spectrum — $n_s = 1$ would be scale-invariant) is important in discriminating inflation theories

WHAT DO HIGH ℓ MEASUREMENTS TELL US?



- From arXiv:1009.0866 ‘ACT Cosmological parameters’ Dunkley et al
- Nice illustration of effects of varying (a) running of spectral index; (b) number of relativistic species during early expansion history; (c) helium abundance in nucleosynthesis

Some Current/Future CMB Polarisation Experiments

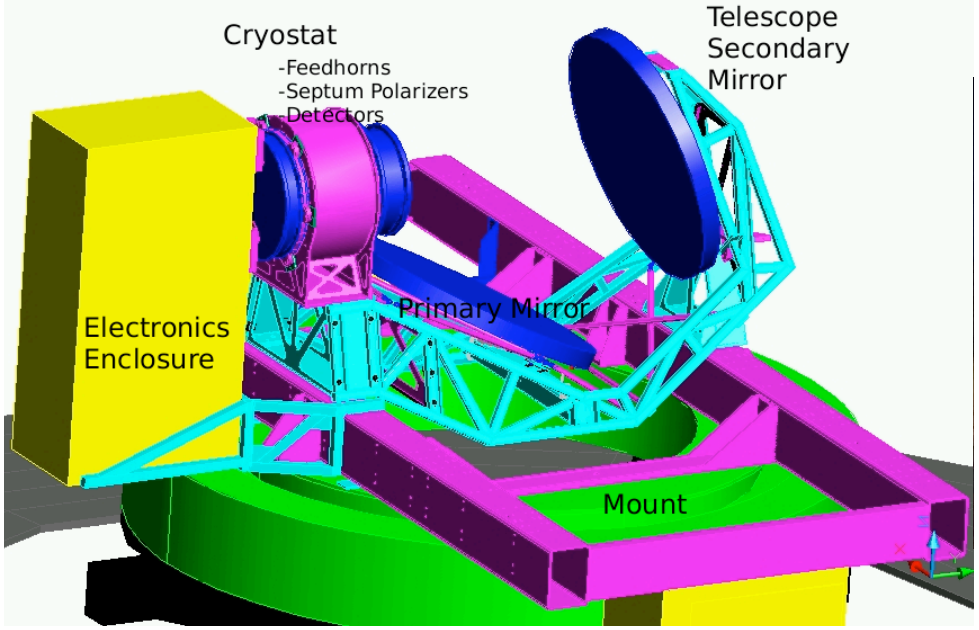
Partial list from 1 year ago

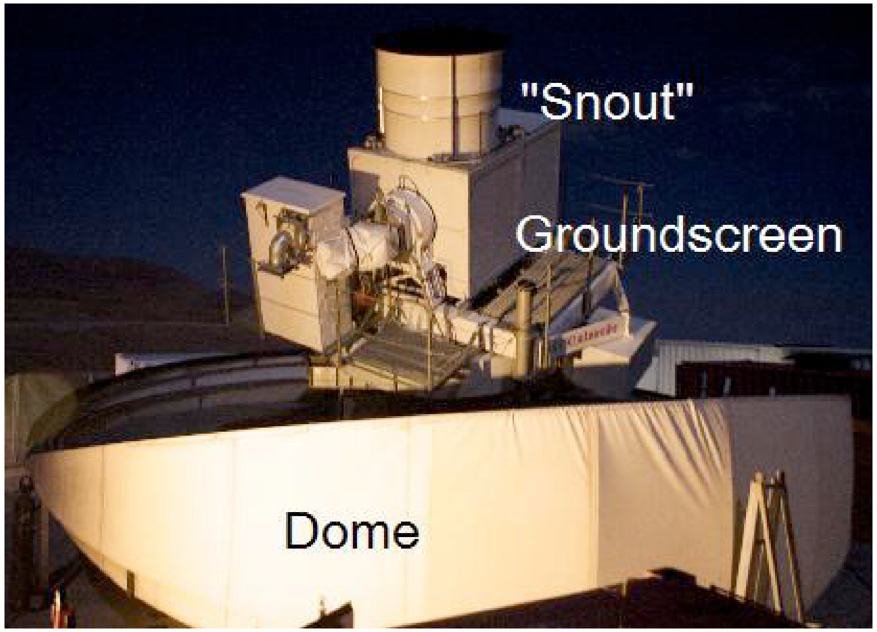
Name	Type	Detectors	ℓ range	r target	First Obs.
QUAD	ground	bolometer	$200 < \ell < 3000$		completed
BICEP	ground	bolometer	$50 < \ell < 300$	0.1	2007
QUIET	ground	MMIC	$\ell < 1000$	0.05	2008
CLOVER	ground	bolometer	$20 < \ell < 600$	0.01	Cancelled
EBEX	balloon	bolometer	$20 < \ell < 1000$	0.03	2011
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	?

New since then

- SPIDER — Spider first flight now expected next year (Australia)
- QUIET — Results from first season at 40 GHz now available (lowest B-mode systematics claimed for this)

QUIET



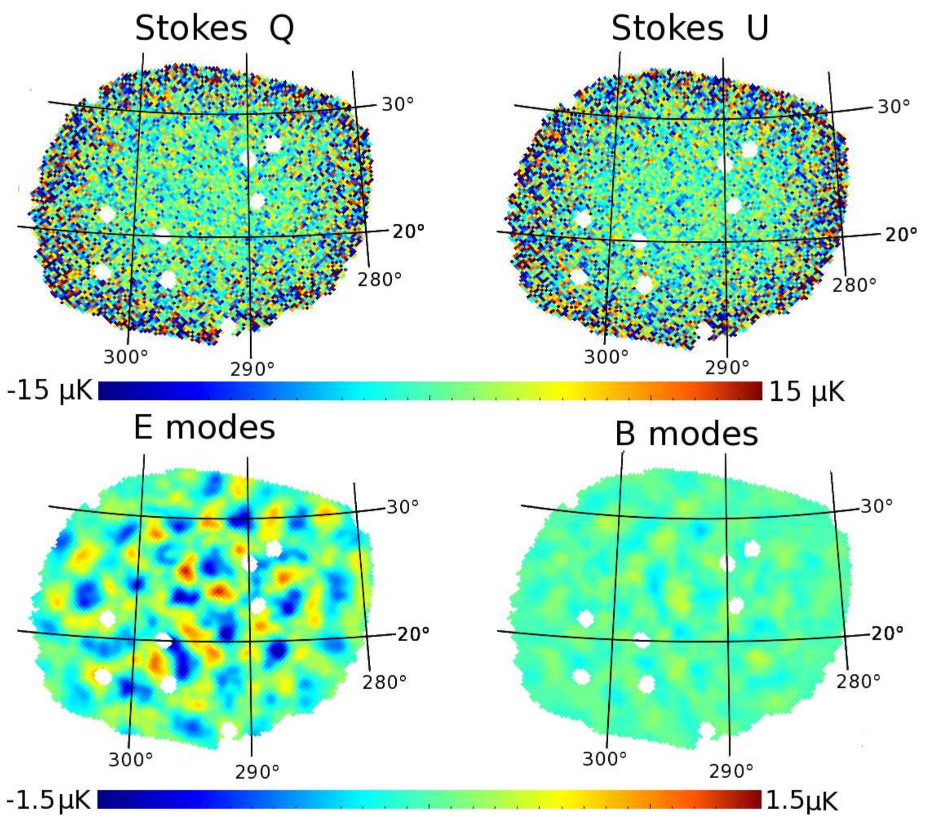


- Unlike most other current experiments uses coherent rather than bolometric techniques
- Feeds look at a 1.4 m primary — whole is mounted on old CBI mount in Chile
- Most of the visible exterior consists of groundscreens

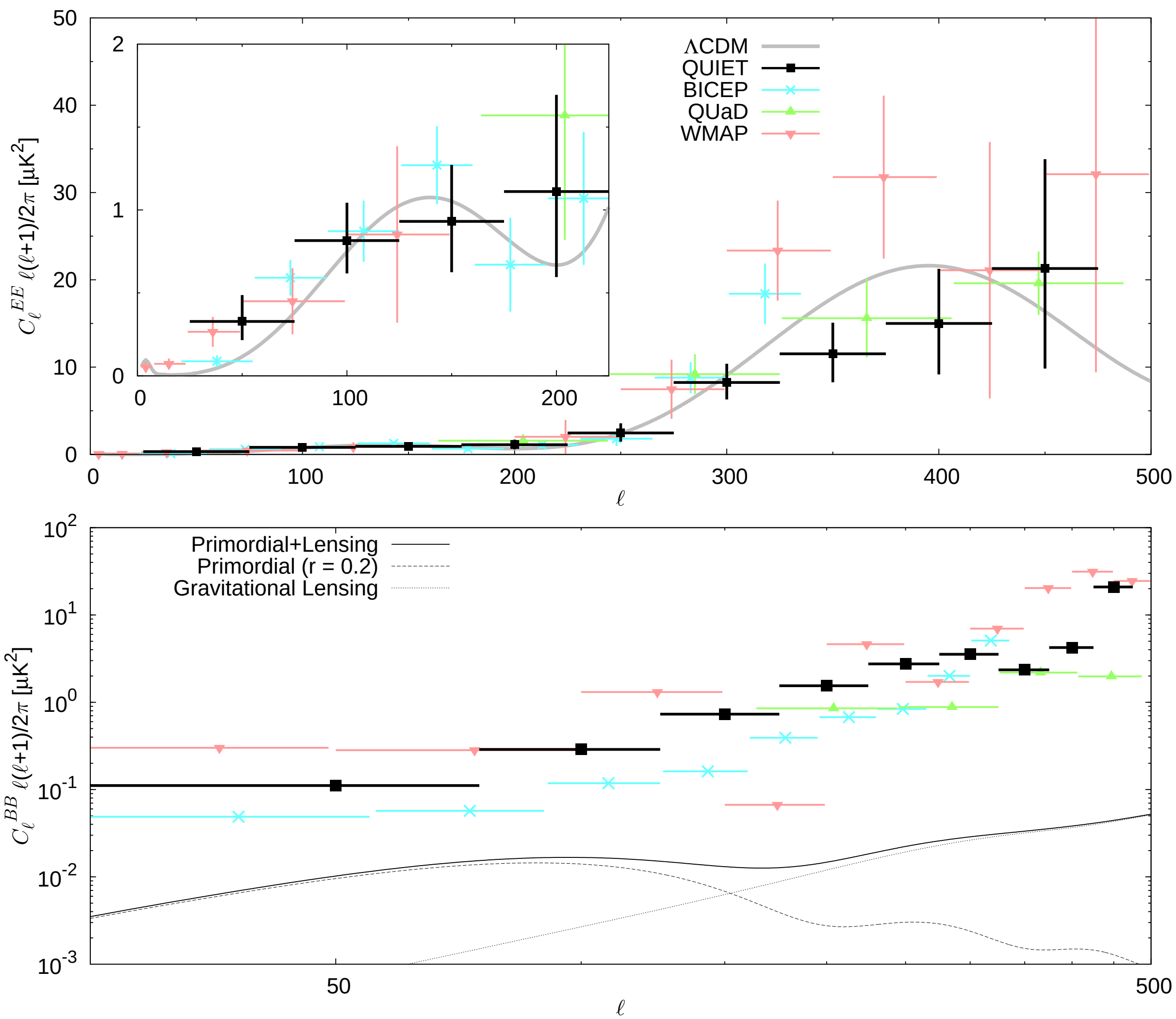
QUIET (FURTHER VIEW)

Some QUIET maps

- Top Q and U maps of a QUIET region
- Bottom, processed to E and B
- Very striking how the transformed Q and U accumulate into E
- Note foregrounds would be expected to be equal mixtures of each
- They do detect clear EE foreground in one region (removed via WMAP data)
- If BB were same, and if extrapolate to expected foreground minimum of 95 GHz (where next observations have been carried out), would correspond to $r = 0.02$



LATEST QUIET RESULTS



- From arXiv:1012.3191 Bischoff et al.
- So they confirm the 'first peak' in EE first seen by BICEP

WHERE DO WE STAND ON r RESULTS?

- BICEP's main result (Chiang et al 2010) was a much improved limit on r of $r < 0.73$ (95% conf.)
- This may not look exciting compared to $r < 0.36$ (Larson et al. WMAP7 CMB only result) or $r < 0.33$ (QUAD CMB only result)
- However, this is by far most significant *direct* limit on r
- (QUIET gives $r < 0.9$, but they stress systematic error of ~ 0.1 is smallest yet.)
- Shortly look at where r limits leave inflation models
- First, what is BICEP doing next?

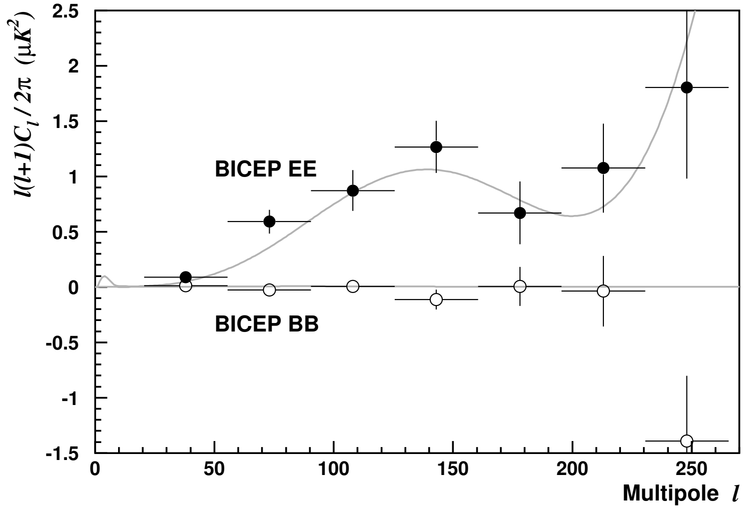
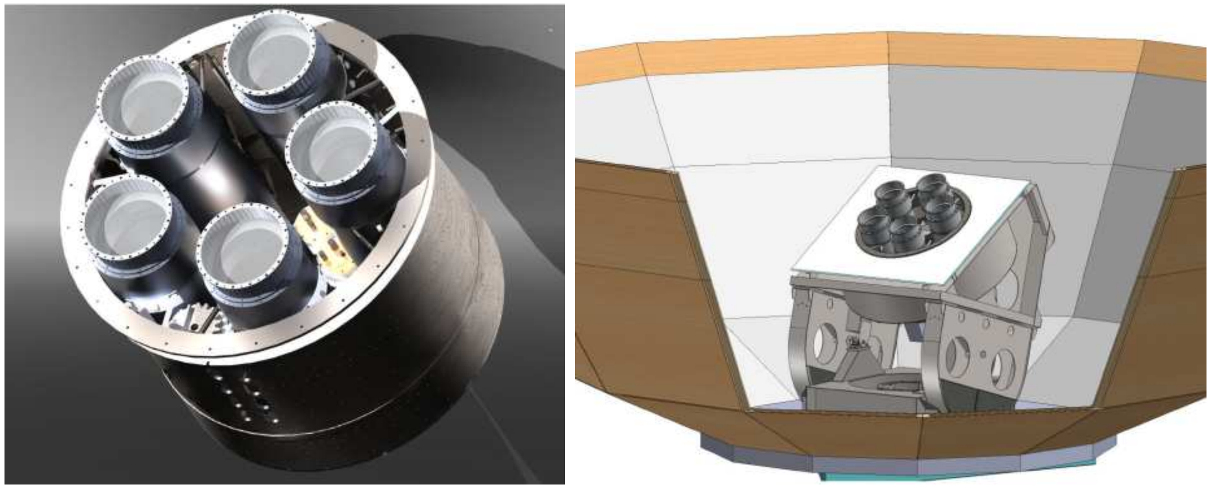


FIG. 12.— BICEP measures *EE* polarization (black points) with high signal-to-noise at degree angular scales. The *BB* spectrum (open circles) is overplotted and is consistent with zero. Theoretical ΛCDM spectra (with $r = 0.1$) are shown for comparison.

THE TRANSITION BICEP2 TO KECK



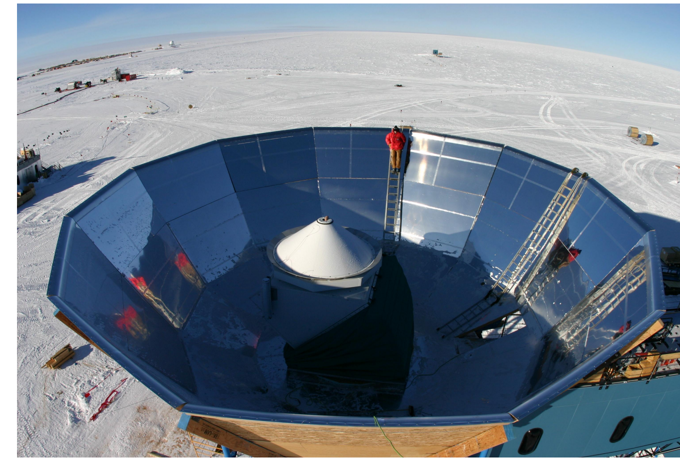
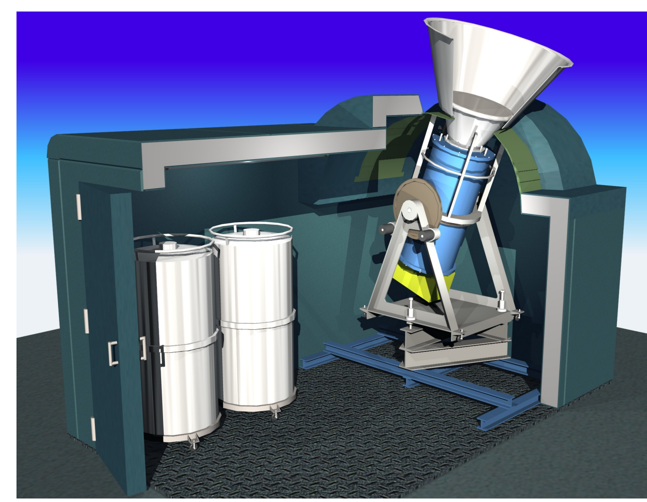
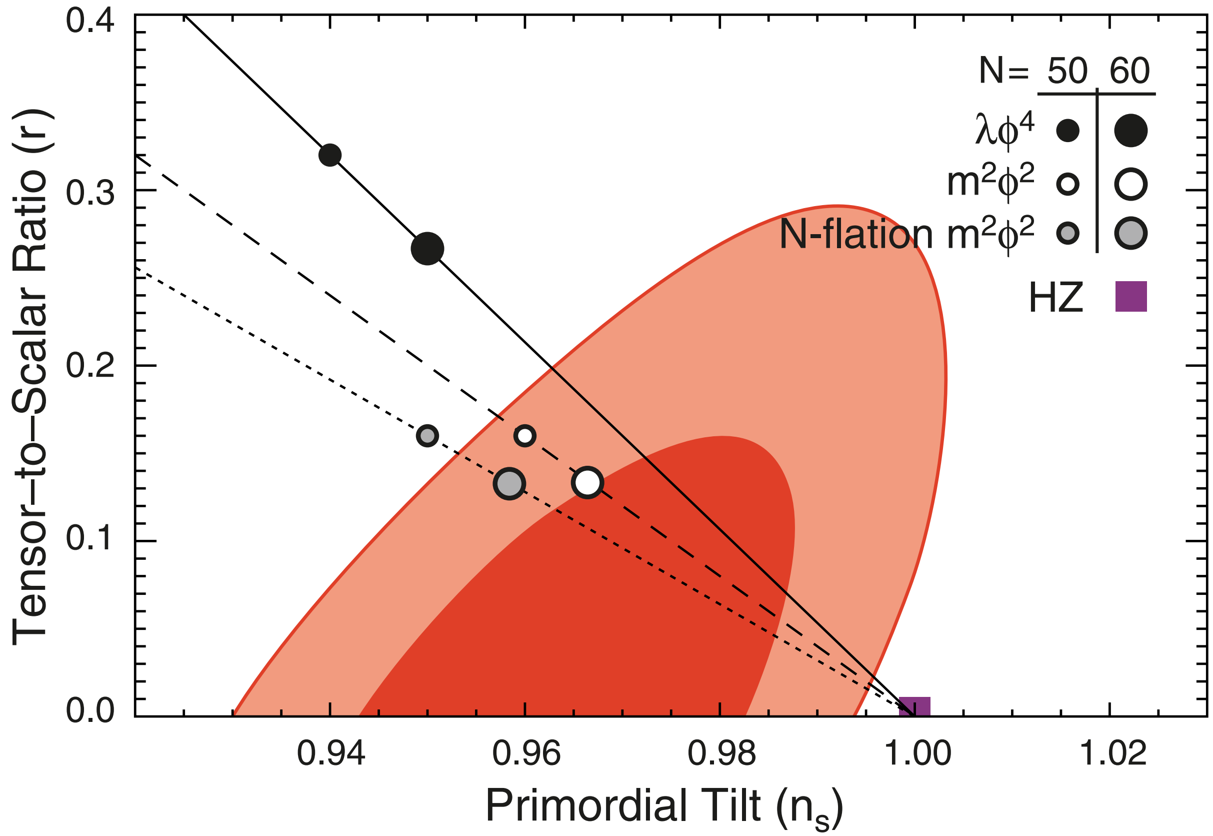


Figure 1. Left: CAD rendering of the modified drum of the DASI mount with 5 Keck cryostats installed. Right: Keck cryostats installed in the DASI mount and ground shield (cutaway).

- 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)
- Now KECK array being deployed - effectively 5 x BICEP2 cryostats



- 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 two years ago (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?
- A new ‘theme’ emerging is that of models predicting a fairly flat potential, $V(\phi) \propto \phi^p$, with $p < 1$.



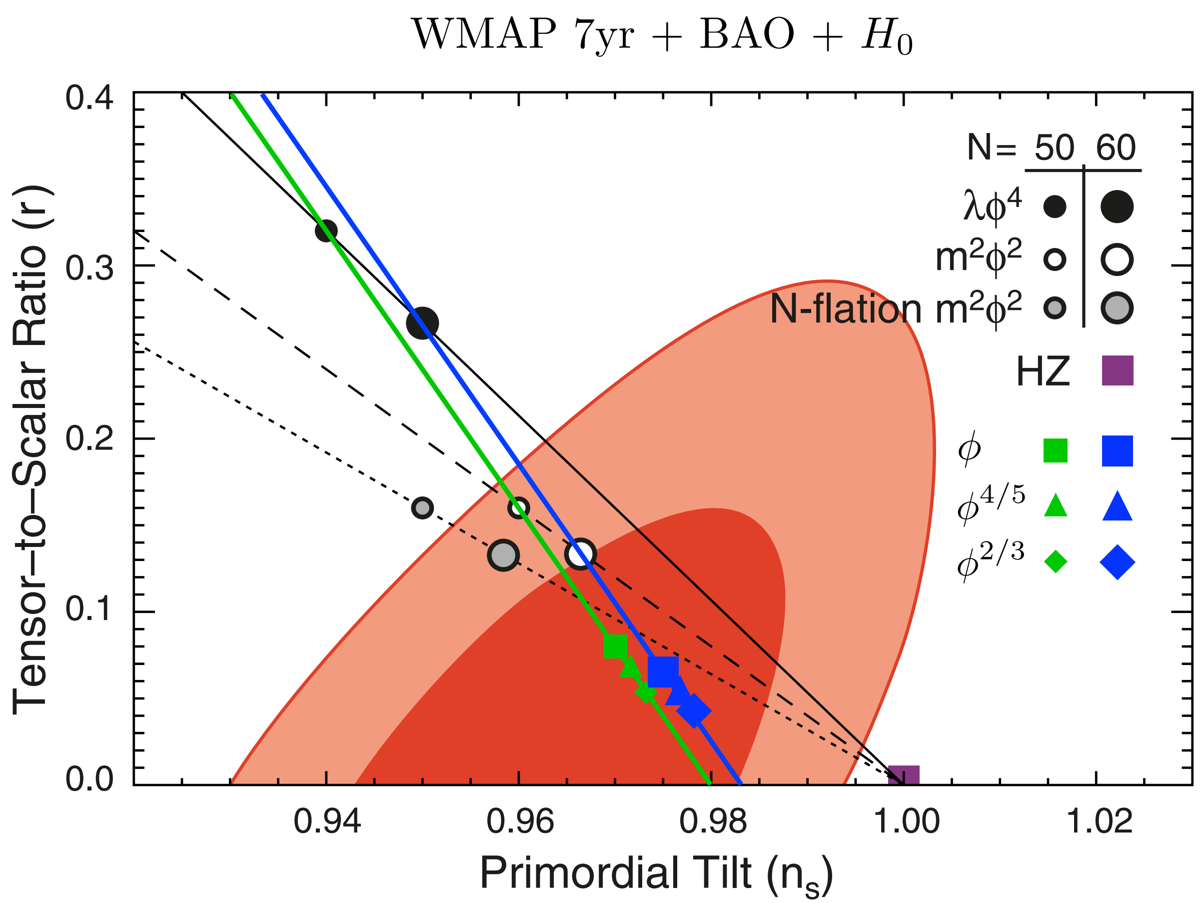
- Observational constraints shown are from WMAP7 (Komatsu et al., 2010)
- Basic results we need to understand this diagram are

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

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

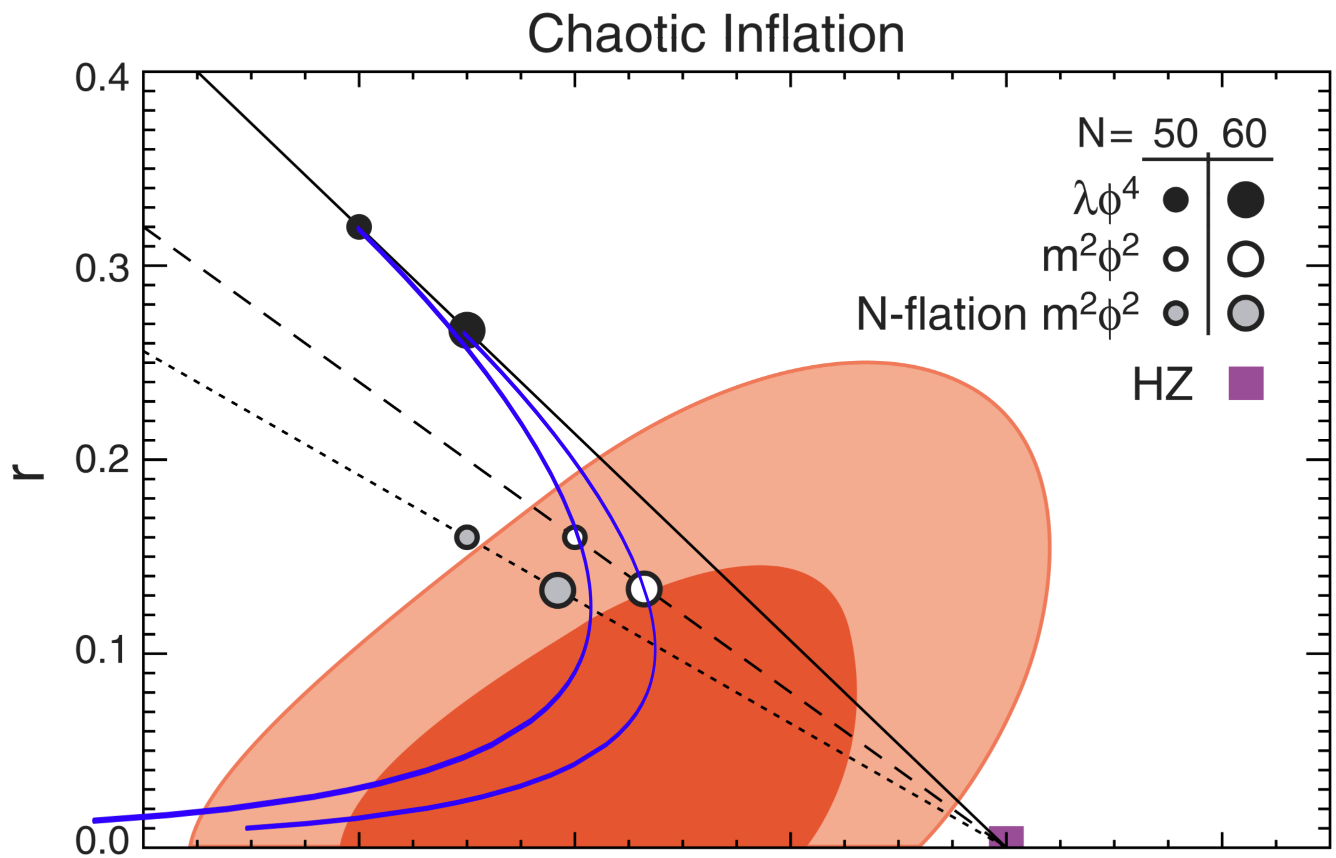
- (Note, if $V(\phi) = V_0(1 - (\phi/\phi_e)^p)$ then can get r as small as one wants.)

INFLATION PHENOMONOLOGY (CONTD.)



- From arXiv:1011.4521 'Simple exercises to flatten your potential' Dong, Horn, Silverstein & Westphal
- IIB linear axion monodromy from 5-branes (squares; $\propto \phi$), IIA moving 4-brane monodromy (diamonds; $\propto \phi^{3/2}$), and a candidate example of IIB flux axion monodromy (triangles; $\propto \phi^{4/5}$).

Inflation phenomonology (contd.)

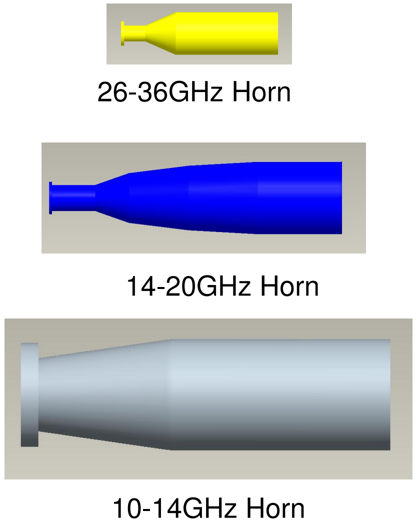


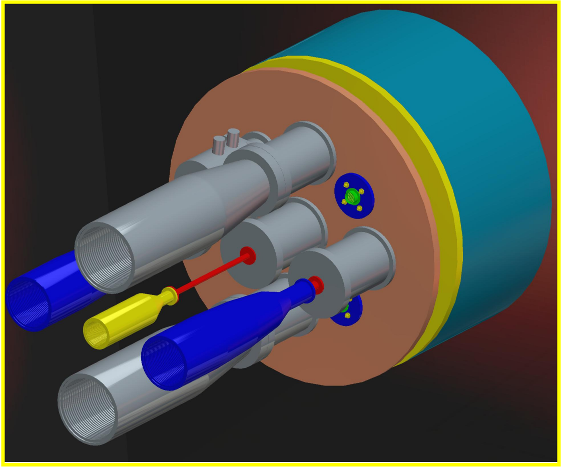
Blue lines – chaotic inflation with the simplest spontaneous symmetry breaking potential $-m^2\phi^2 + \lambda\phi^4$ for N = 50 and N = 60

- Or can have mixtures of other potentials (from talk at Pascos 2011 by A. Linde)

QUIJOTE

- 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





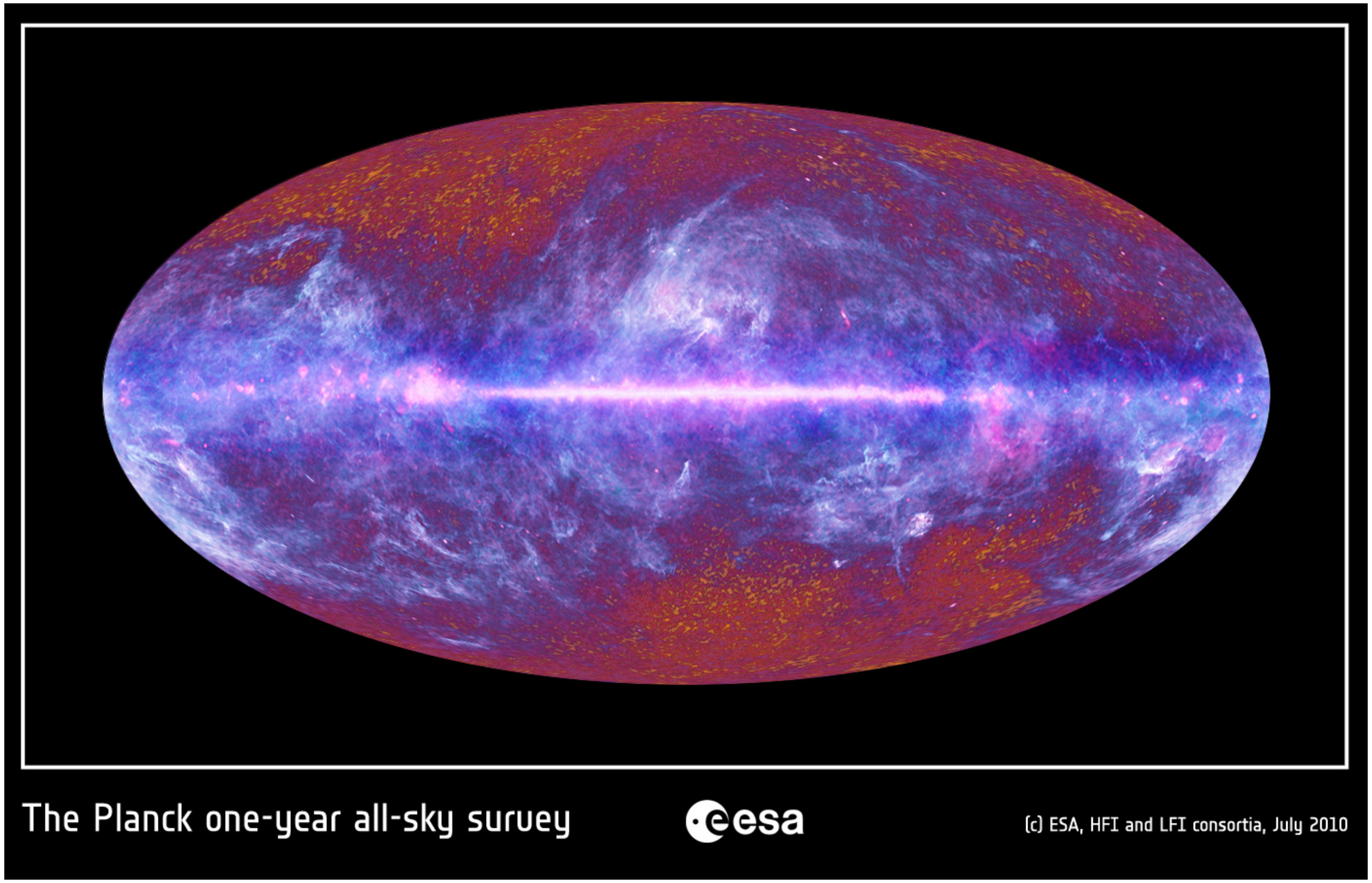
QUIJOTE 1 : Focal Plane Distribution

- 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 ($r \sim 0.1$)

QUIJOTE TELESCOPE

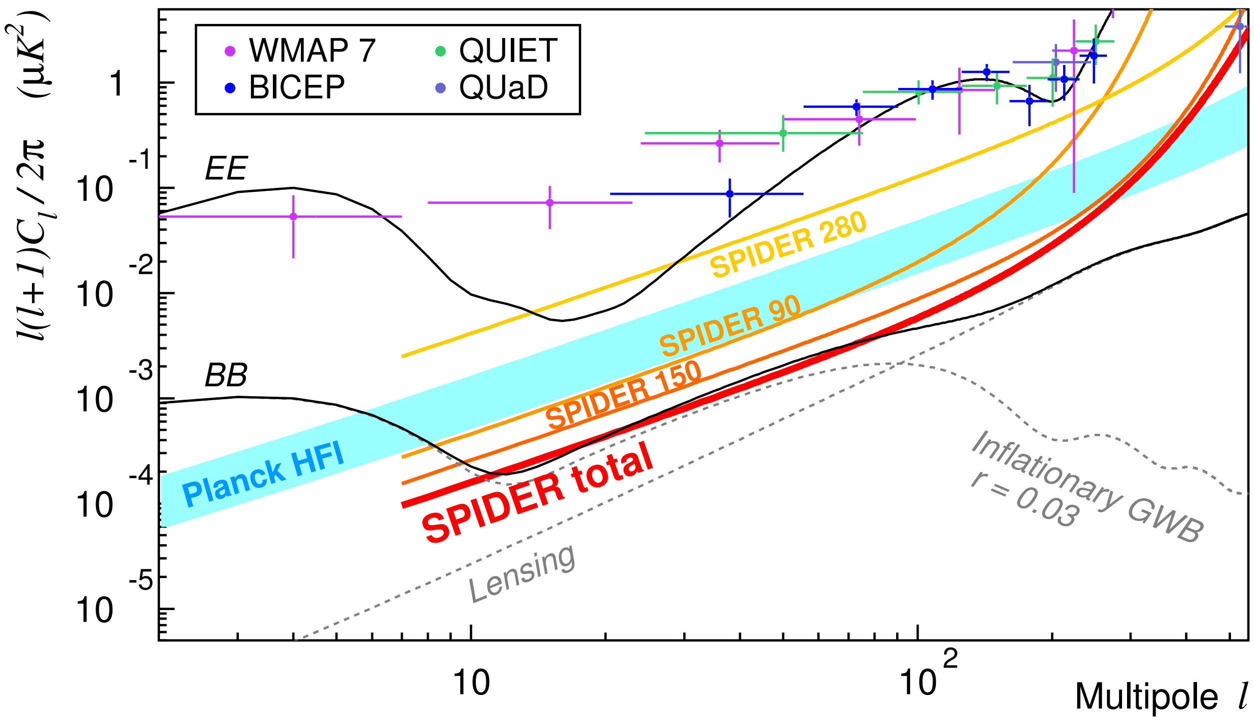
- Final tests on electronics on telescope being carried out this coming week
- Science commissioning will start very shortly!

PLANCK



- 4 sky coverages nearly complete
- Carlo Burigana/Reno Mandolesi will be able to give us a full report
- 26 scientific papers on results now submitted/in press
- Below will talk about some aspects of the Sunyaev-Zeldovich cluster work

Planck vs. SPIDER



Summary of general information on the Spider mission

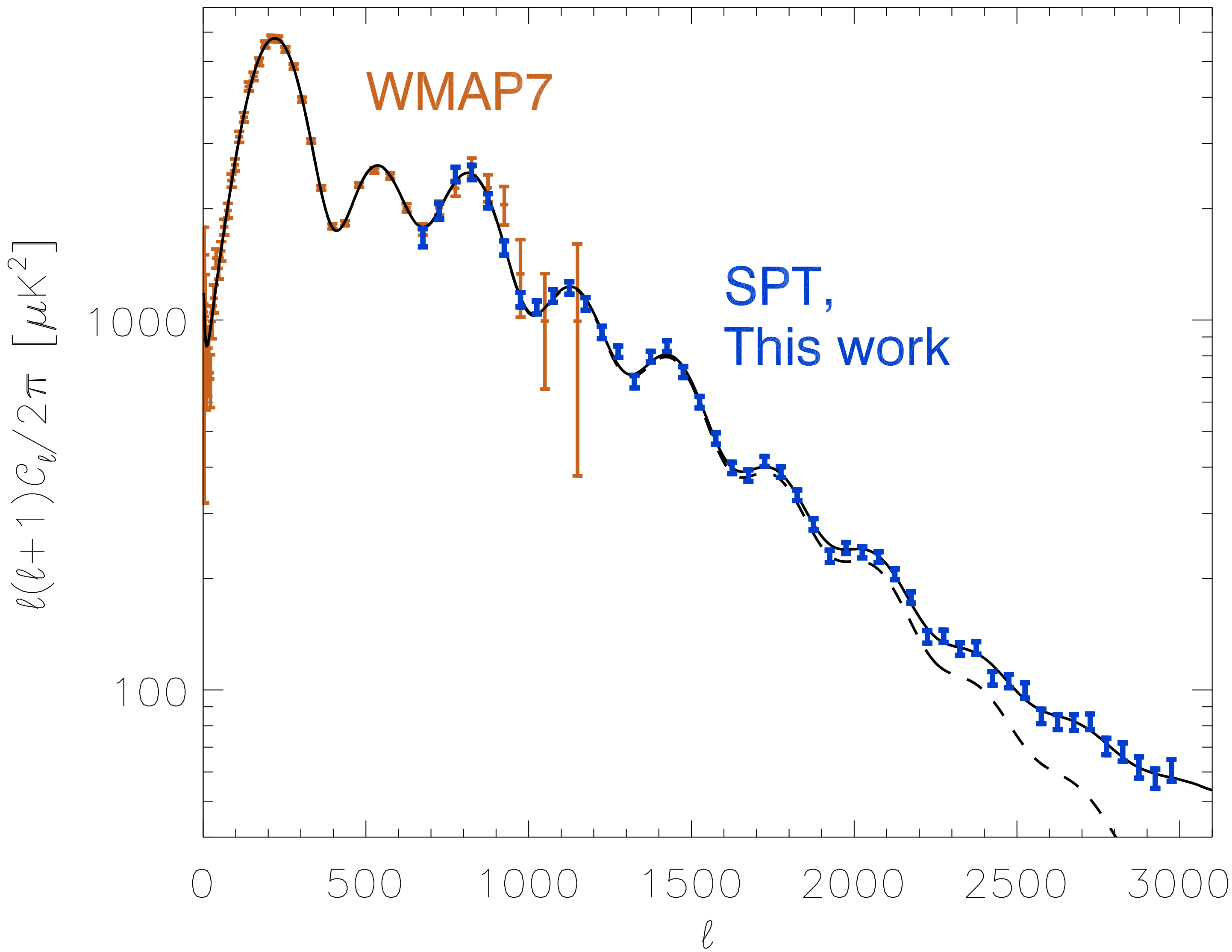
Launch Location	McMurdo Station, Antarctica
Launch Date	12/2012 (Flight 1), 12/2014 (Flight 2)
Flight Duration (target)	20 days per flight
Altitude (target)	36,000 m
Flight Path	Circumpolar, typically 73°S $<$ latitude $<$ 82°S
Sky Coverage	$f_{\rm sky} \sim 0.1$, $10 \lesssim \ell \lesssim 300$

Note. — The flight schedule provided in this table is consistent with the state of hardware development as of June 2011.

- With ability to use Planck 217 GHz channel to separate polarized dust emission, belief is SPIDER can reach $r \approx 0.03$ (Fraisse et al, arXiv:1106.3087)

- An interesting new feature is that some of the ‘lever arm’ effect that comes from using data related to the matter power spectrum (e.g. Lyman-α, LSS etc.) can now be supplied by small-scale CMB data
- Jo Dunkley will be talking about ACT results, so I’ll concentrate here on the South Pole Telescope results
- Very impressive recent paper from Keisler et al (arXiv:1105.318)
- Uses 790 square degrees of sky measured at 150 GHz

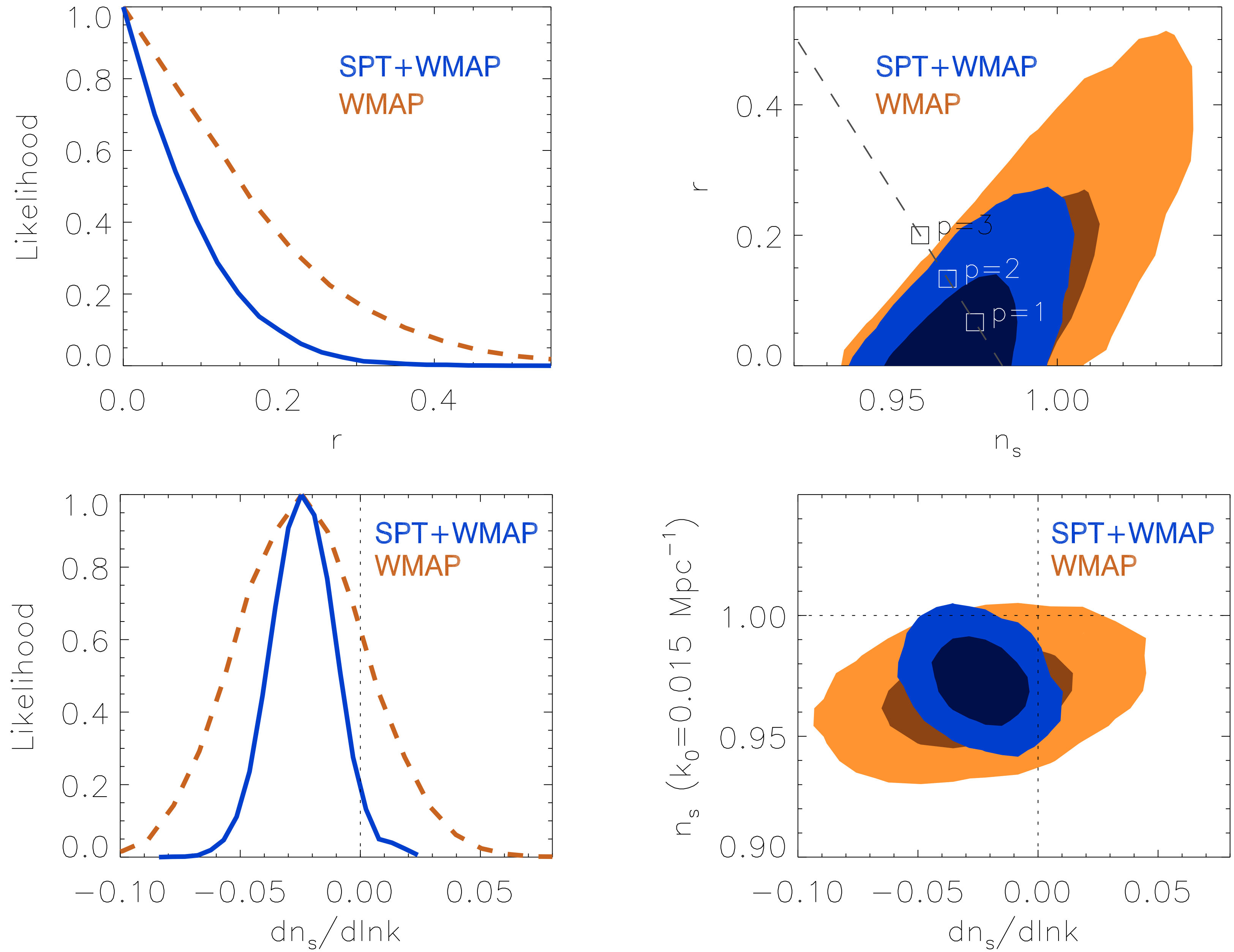
Basic SPT Power Spectrum Result



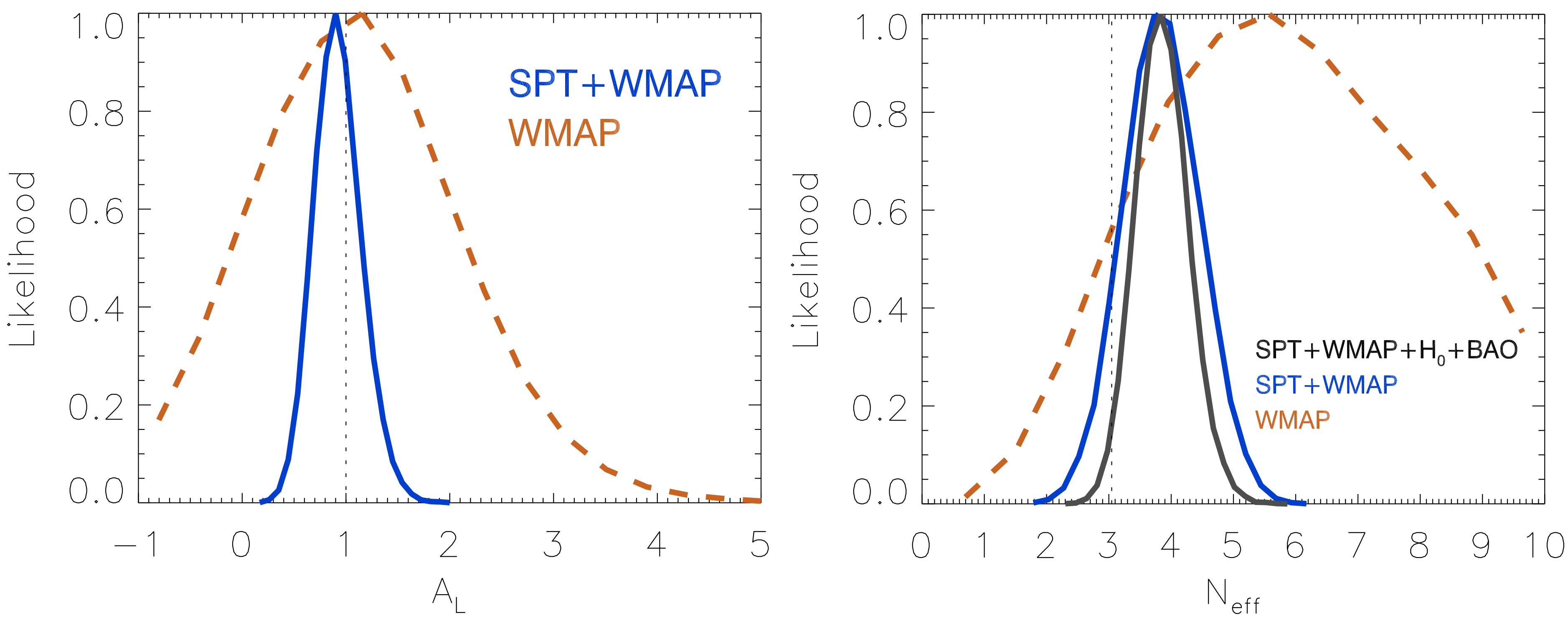
Keisler et al (arXiv:1105.318)

- Think one could now reasonably claim that 9 peaks have been measured in the CMB power spectrum!

SPT CONSTRAINTS ON r AND SPECTRAL INDEX

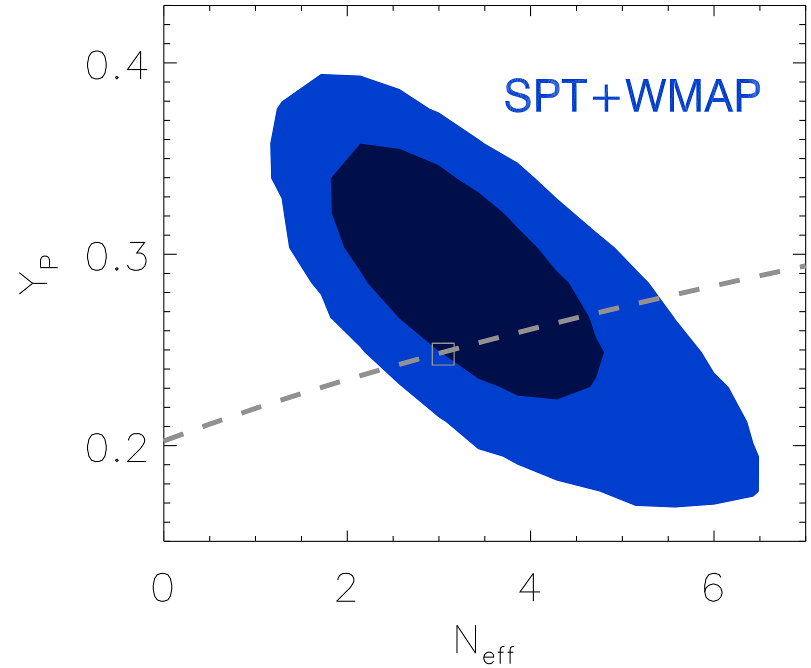


SPT constraints on lensing and $N_{\rm eff}$



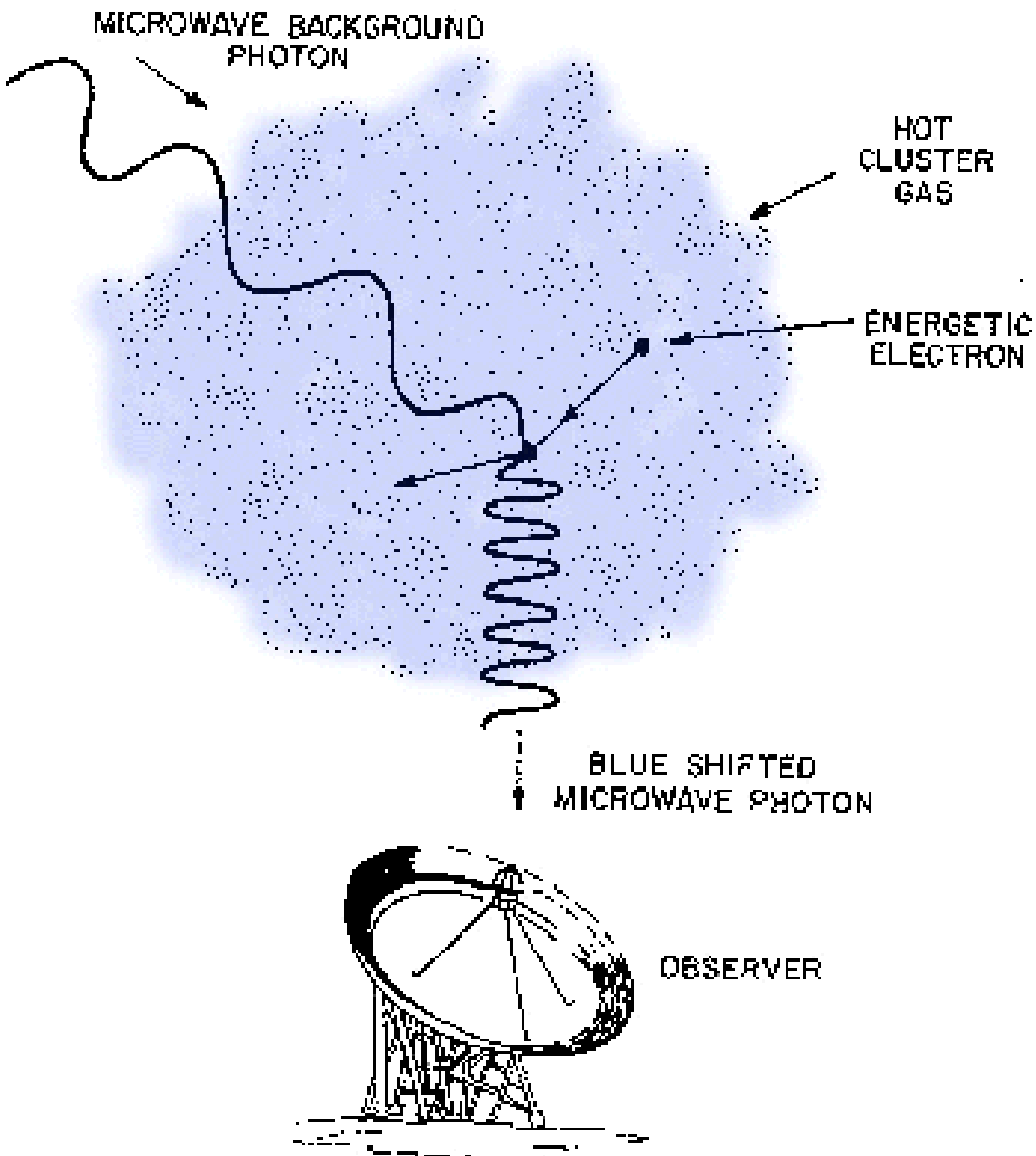
- Some beautiful results. ACT comparable. Note n_s departure from 1 now over 3σ
- Plot on left shows lensing results now reaching amplitude expected (first ones from ACBAR were coming out too high)
- The $N_{\rm eff}$ results particularly interesting in context of possible sterile neutrinos
- If these have thermal abundances at decoupling, then starting to be pretty difficult to have two extra species (which some models like)

SPT JOINT CONSTRAINTS ON N_{eff} AND Y



- Basically what's happening with each of N_{eff}, Y and n_{run}, is that there is a preference from the data for more damping at small scales
- Hence degeneracy in above figure, though can still discriminate against non-zero values of each
- This would lead to higher σ_8 (≈ 0.87) and SPT paper suggest this is ruled out by current local cluster results (e.g. Viklihin et al (2010))
- In any case appears to be some tension here

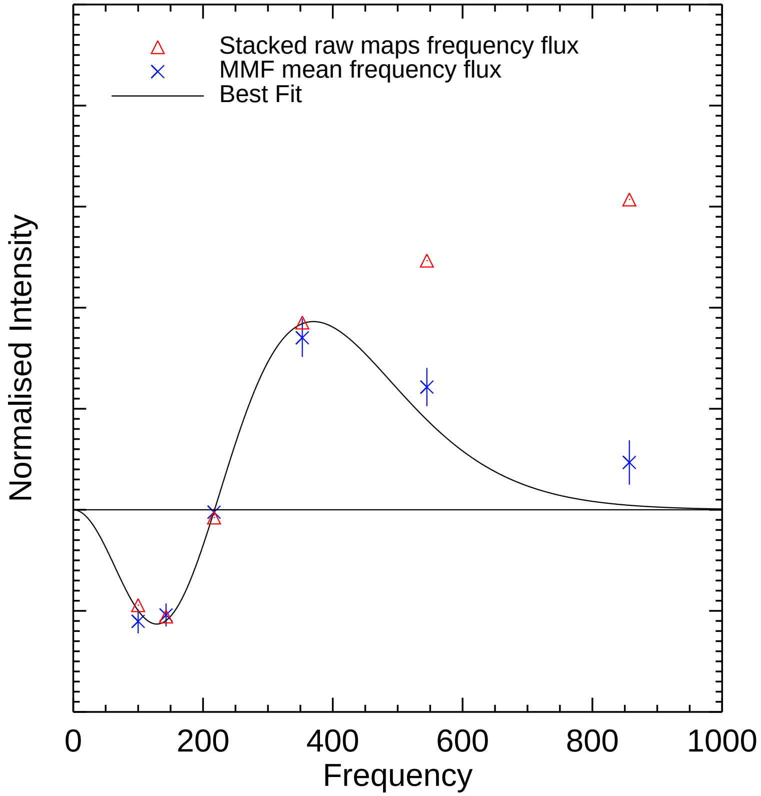
The Sunyaev-Zeldovich Effect



(From astro.uchicago.edu.)

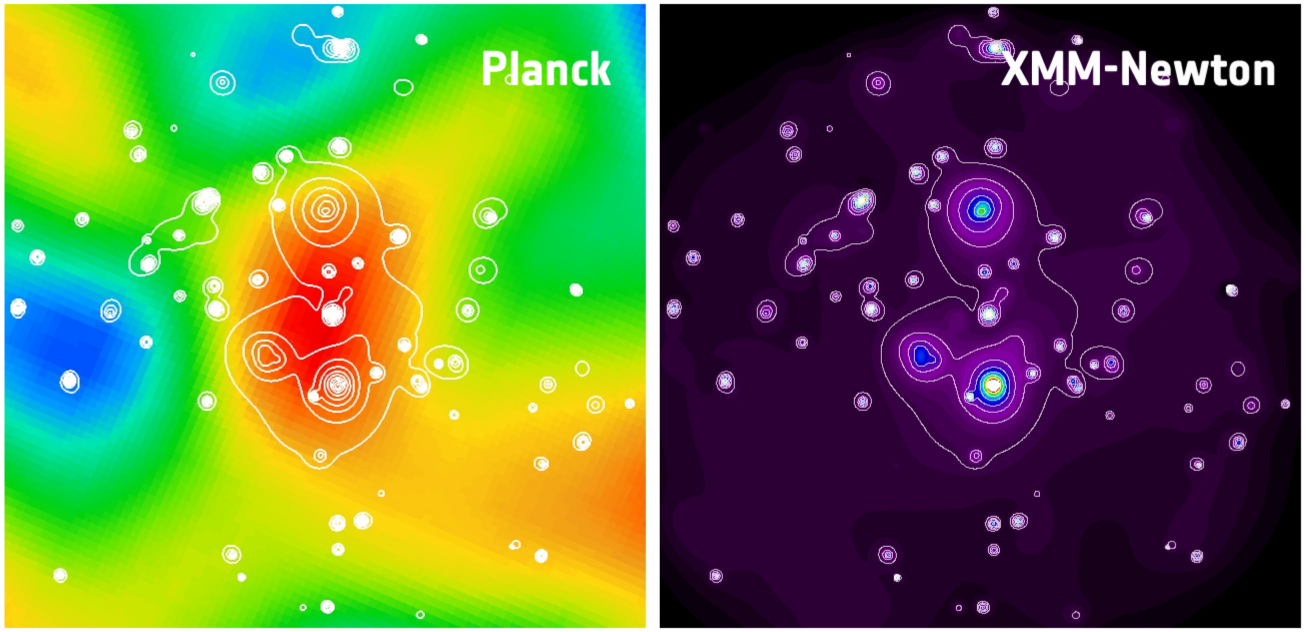
PLANCK AND THE SZ EFFECT

- Planck has been doing very well on the SZ effect
- Resolution (best $\sim 5'$) is lower than for most ground-based observations, but compensated by all-sky coverage, plus good frequency discrimination
- The figure and table are from arXiv:1101.2024 'Planck Early Results VIII: The all-sky early SZ sample'



Selection		SZ Candidates	Rejected
	S/N ≥ 6 and good quality flag on SZ spectrum	201	
	Detected by one method only		11
	Bad quality flag from visual inspection		1
ESZ sample		189	
Known clusters		169	
	X-ray only	30	
	Optical only	5	
	NEDSimbad only	1	
	X-ray + Optical	128	
	X-ray + SZ	1	
	SZ + Optical	1	
	X-ray + Optical +SZ	3	
New *Planck* clusters		20	
	XMM confirmed	11	
	AMI confirmed	1	
	Candidate new clusters	8	

CONFIRMATIONS



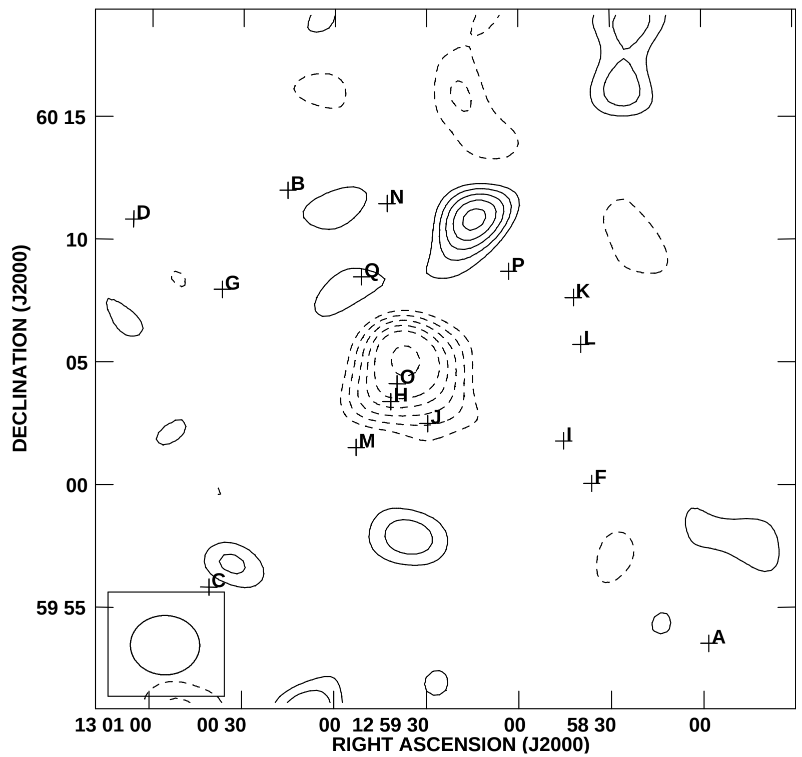
- First supercluster to be detected via ‘blank field’ SZ effect!
- Also 5 clusters in southern hemisphere have now been confirmed by SPT (arXiv:1102.2189 Story et al)
- And AMI (declinations $\gtrsim 20^\circ$) has confirmed a further ESZ candidate (following the one in ESZ paper itself)

AMI

- The AMI Small Array
- Ten 3.7 m dishes
- Many papers now appearing on SZ (e.g. first blank field detection, several SZ samples and a northern hemisphere 'bullet cluster') as well as Galactic astronomy (e.g. 'spinning dust' emission)

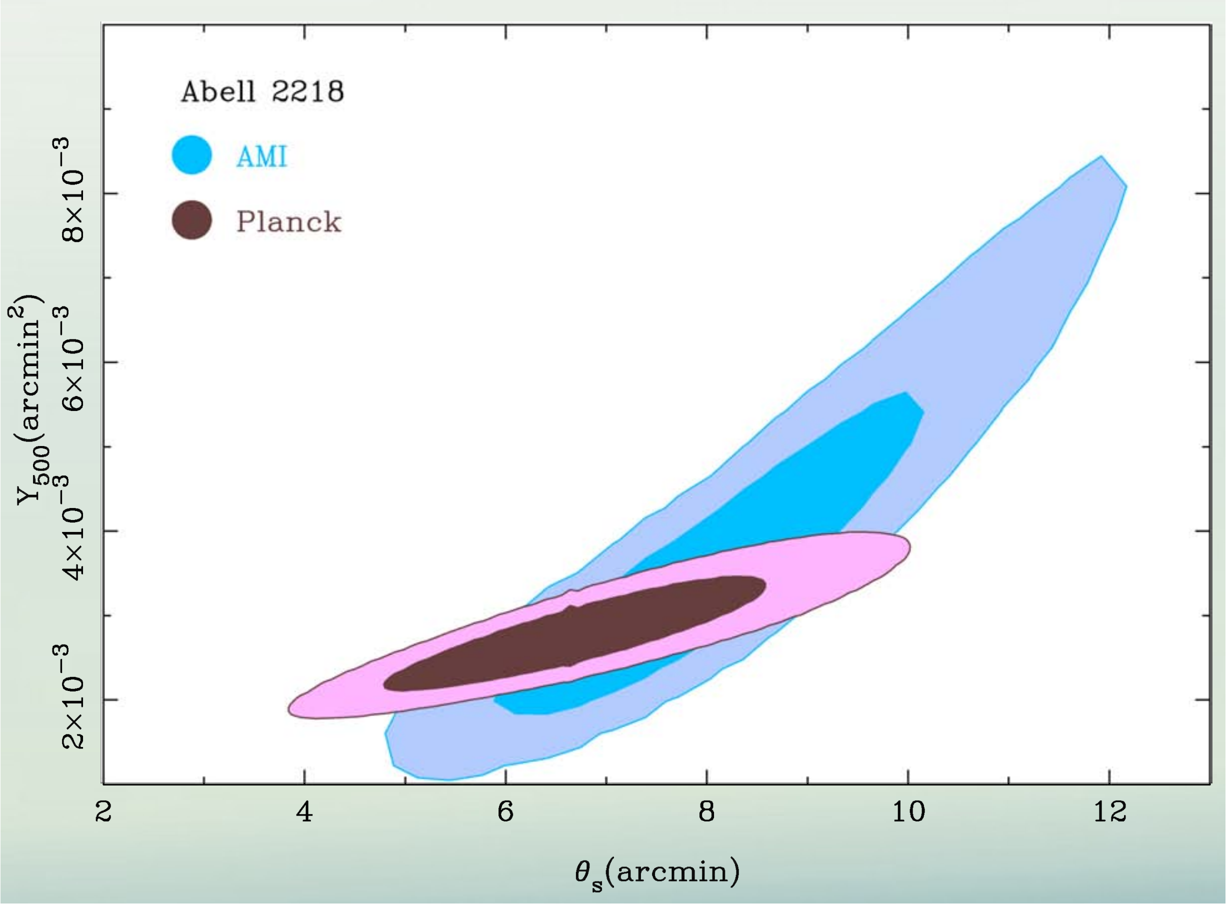
- The AMI Large Array
- The Eight 13 m dishes of the old Ryle Telescope
- Reconfigured to make a compact array for source subtration for Small Array SZ surveys
- Key for measuring radio source contamination

AMI PLANCK CONFIRMATION



- AMI confirmation for the Planck candidate PLCKESZG121.11+57.01
- Letters mark position of radio sources removed via Large Array observations
- Taken from arXiv:1103.0947 — approx 13σ confirmation (in 40 hours observation) plus refined position
- New position allows identification with a z=0.33 cluster in SDSS catalogue (Wen et al, 2009)
- Few X-ray photons in this position

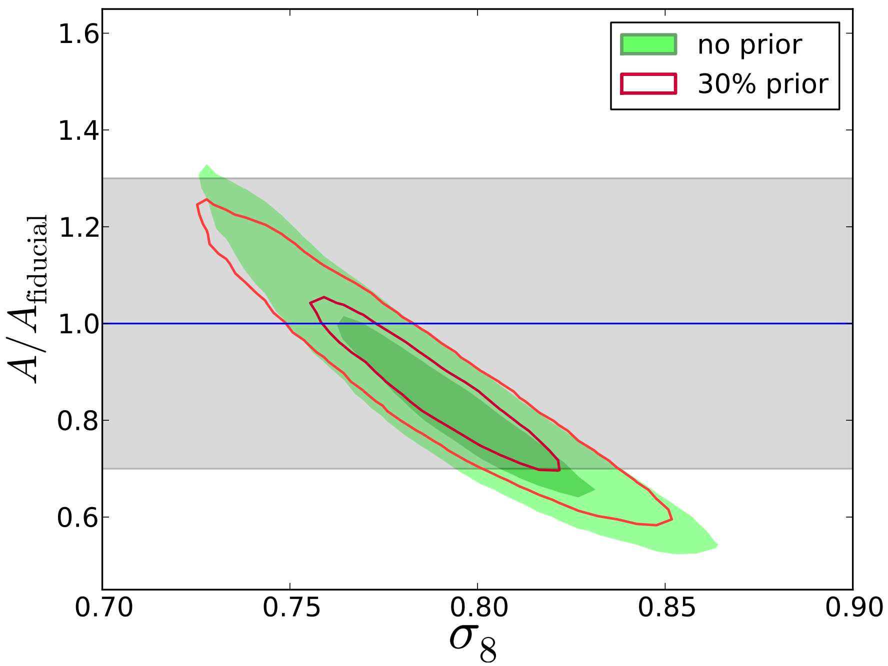
AMI PLANCK COMPARISON FOR A KNOWN CLUSTER



- Comparison of Planck and AMI data for a known cluster — A2218
- Shown are likelihood contours in plane of total Compton distortion parameter versus angular scale
- Illustrates 'degeneracy problem' as discussed in the EZ paper arXiv:1101.2024, plus how observations by complementary instruments may help overcome this

A KEY SCIENCE IMPLICATION OF PLANCK EARLY SZ RESULTS

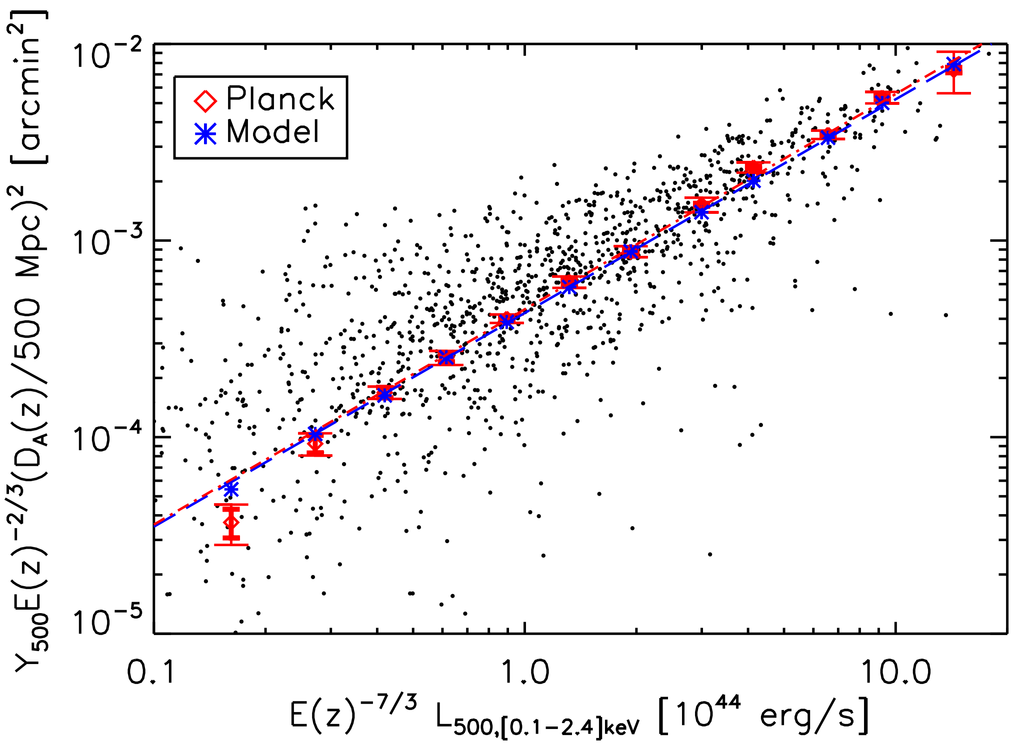
- Last year at this time a key debate was over the amplitude of SZ signals found in e.g. WMAP7 and SPT results
- Komatsu et al (arXiv:1001.4538) found a deficit of about 0.5 to 0.7 compared to what's expected from known X-ray measurements and current cluster models using the Arnaud et al 'Universal Pressure profile'
- Also said division into 'relaxed' versus 'non-relaxed' clusters was very important, and could partially explain discrepency



- From Vanderlinde et al., arXiv:1003.0003, illustrating similar effect for SPT cluster results

A KEY SCIENCE IMPLICATION OF PLANCK EARLY SZ RESULTS (CONTD.)

- Now Planck is able to look at this
- Result shown is Planck ESZ scaling relation between total Y and X-ray luminosity (from Planck Early Results paper: 'Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters' (arXiv:1101.2043)
- Moreover, when analysis redone assuming pressure profiles corresponding to 'cool cores' or 'morphologically disturbed' (respectively) then results still robust to this (max deviations from 8% (low L) to 1% (high L))



- Quoting from abstract: There is no evidence for a deficit in SZ signal strength in Planck data relative to expectations from the X-ray properties of clusters, underlining the robustness and consistency of our overall view of intra-cluster medium properties.

Summary

- CMB still providing essential information
- On primordial polarization side new results from QUIET
- BICEP2 then KECK promise to be interesting
- Spectacular results now starting to come from high-ℓ damping tail of CMB spectrum
- Secondaries are moving ahead rapidly — Planck has made an impressive start on SZ clusters
- An advertisement: Lasenby & Doran model (Phys.Rev.D, **71**, (2005) 063502) of a slightly closed universe with non-trivial constraint on total elapsed conformal time (which translates to a constraint on the cosmological constant via $\Lambda \sim \exp(-6N)$ in natural units, where N is the number of e-folds during inflation), still doing well. See recent Vazquez, Lasenby & Hobson, arXiv:1103.4619