Ground-based and Balloon-borne CMB experiments of the future

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Cosmology Colloquium Ecole Chalonge, October 2006

Outline

- Status of CMB measurements
- CMB science of the future
- Foregrounds
- Future ground-based and balloon experiments
- Conclusion

Status of CMB measurements

CMB Power Spectra

Temperature

Polarization

Temperature power spectrum,
Lambda website, WMAP pictures

E-mode power spectrum

Temperature-Polarization correlation

~100 nK rms

Limits on B-modes with WMAP model for t=0.17 and r=0.1
Keating et al. 0607208

TE correlation

Status of CMB measurements
Blackbody spectrum

Precise measurements
by FIRAS, but little
constrained
at low frequencies

Kogut et al., astro-ph/0609373

CMB science of the future

- Temperature high l
  - inflationary physics
  - cluster physics/dark energy from Sunyaev Zel'dovich effect
  - …

- Polarization
  - primordial gravity waves
  - neutrino mass/dark energy parameters from lensing
  - cosmic strings
  - primordial magnetic fields

  …

- Frequency spectrum
  - dark matter decays in the early Universe
  - reionization

  …

Sunayev Zel'dovich effect (SZE)

Inverse Compton scattering of photons at hot electron gas in galactic clusters:

photons move to more energetic regions of blackbody spectrum

Measurements at different Frequencies recover distortion from CMB blackbody spectrum

Carlstrom, Holder, Reese, astro-ph/0208192

- Cluster physics
- Cosmology
  (combine with X-ray and optical data)

Cluster surveys
- redshift independence!
- constrain O_m,O_L, s_8, w …

Thermal
Kinetic
Total

SuZie measurements
Benson et al. astro-ph/0404391

Challenges of the future

High precision measurements of temperature and polarization power spectra

- High sensitivity

  receivers operate close to fundamental limits

  => large receiver arrays

- Exquisite foreground removal

  little is known about microwave (polarization) foregrounds

  => multiple frequencies for removal required

  => specific foreground studies crucial

- Unprecedented control of systematics

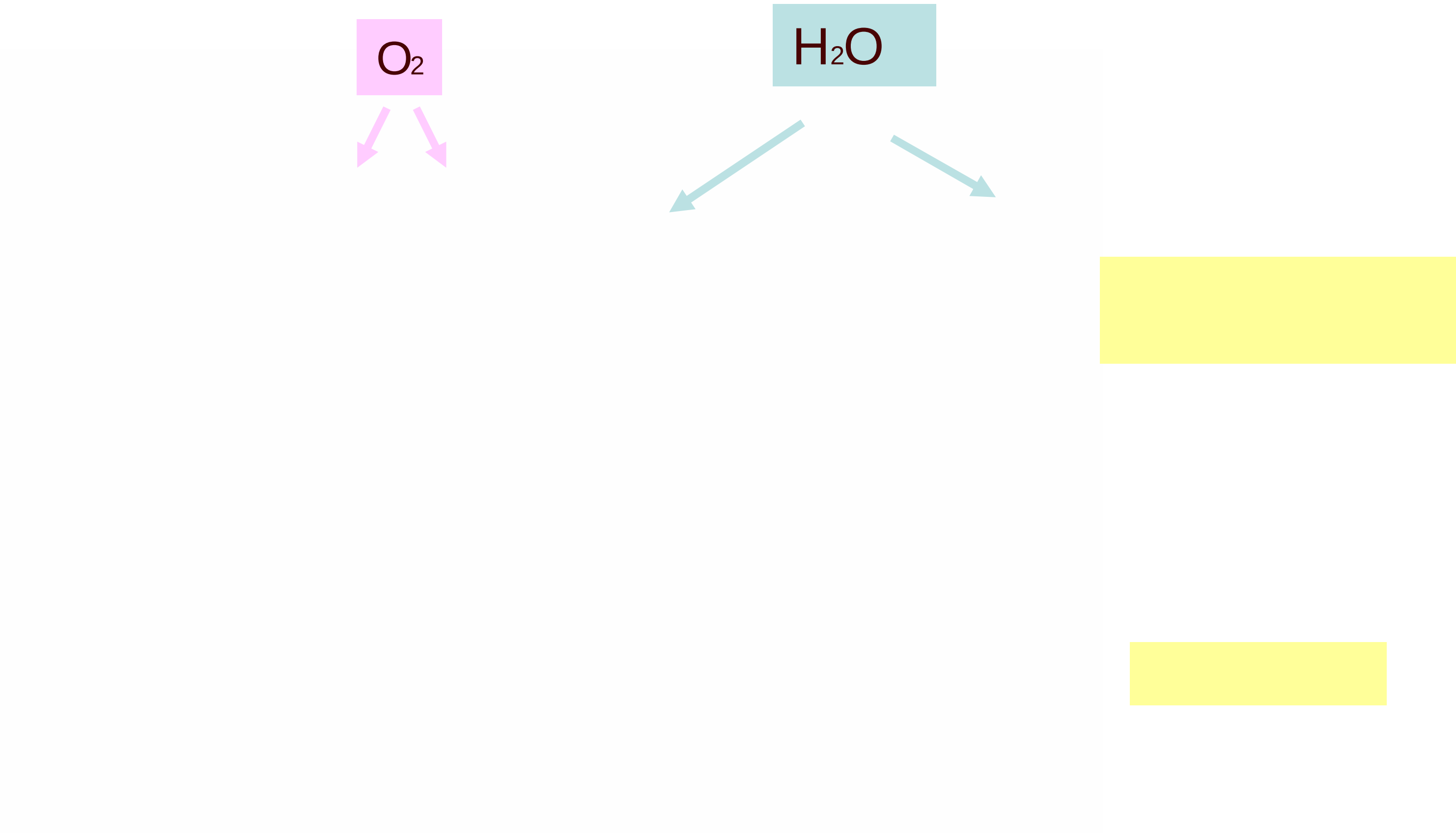
  => instrumental and environmental effects

  have to be minimized and well controlled

Access to the CMB from the ground/balloon

- Limited in frequency due to atmosphere

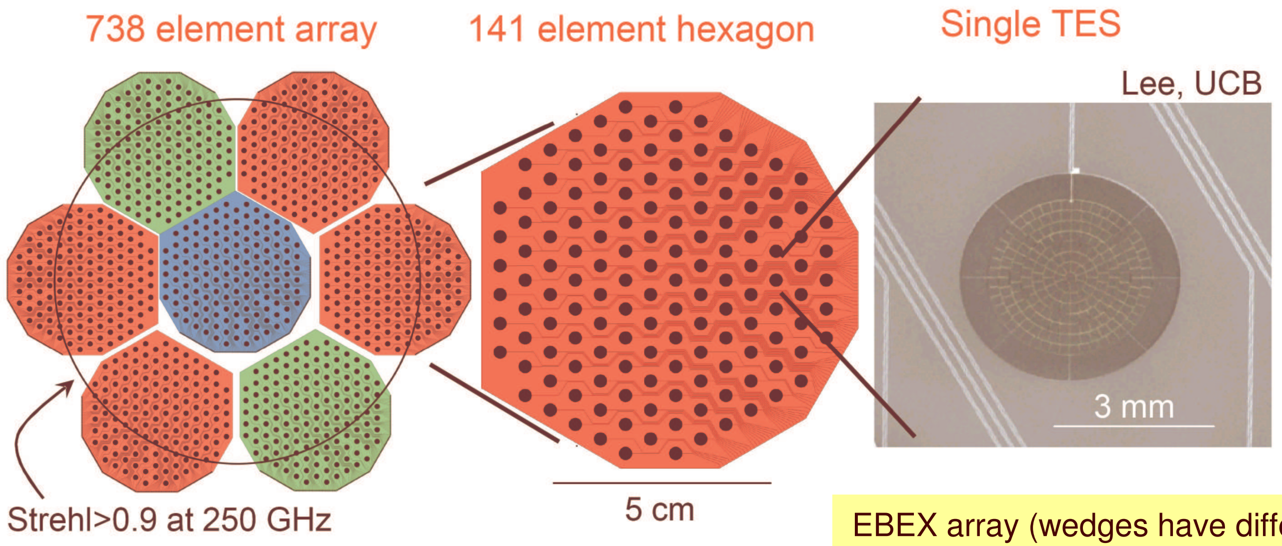
  => foreground removal options not necessarily optimal



Access to the CMB from the ground/balloon

- Large receiver arrays already underway
  (from 10s to 100s to 1000 of receivers!)
  => high sensitivity in sight

South Pole Telescope array
(wedges have different frequencies)



EBEX array (wedges have different frequencies)

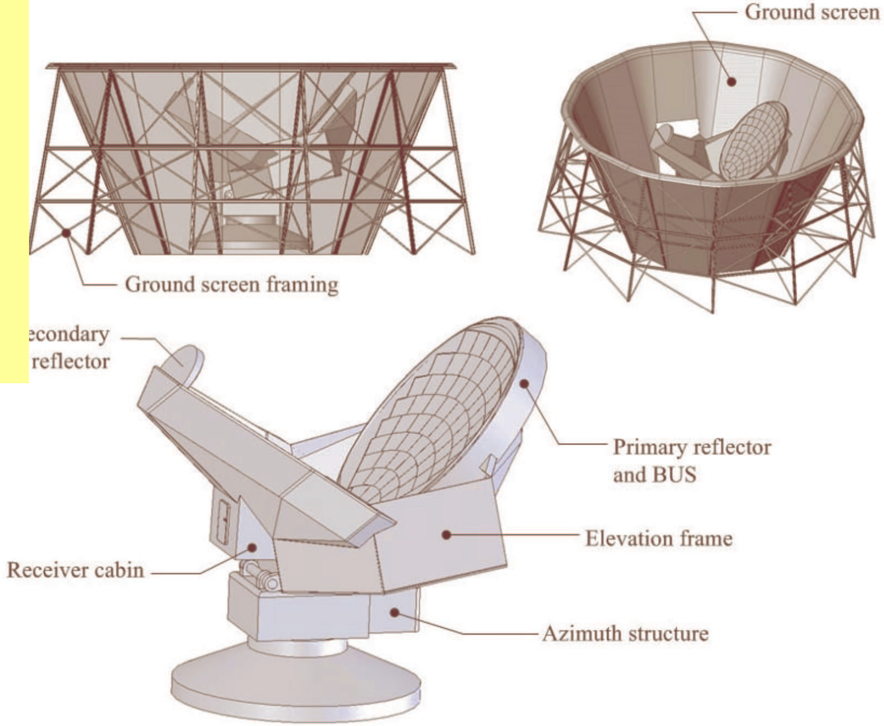
Access to the CMB from the ground/balloon

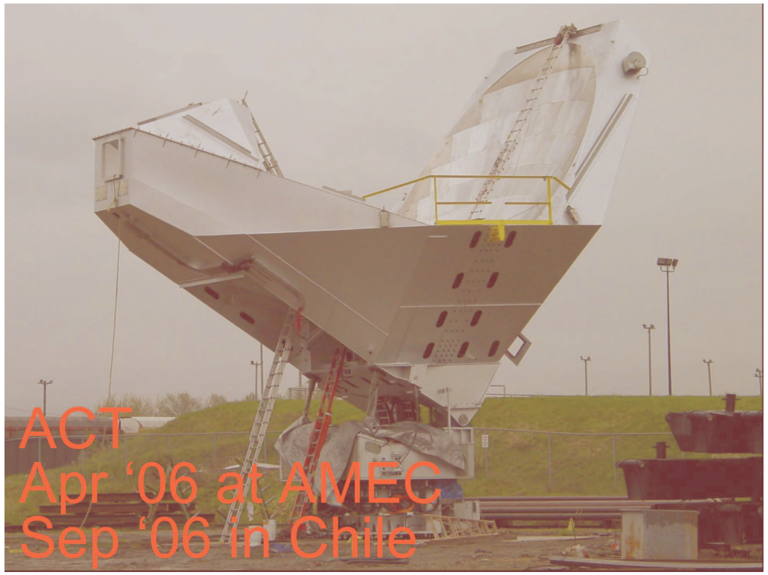
- Large telescopes
- Sensitivity focussed on small patch

  => high precision on high angular resolution
  => high S/N, beneficial for foreground removal

- Constant access to the instrument

  => flexible to possibly adjust to
  unforeseen systematics



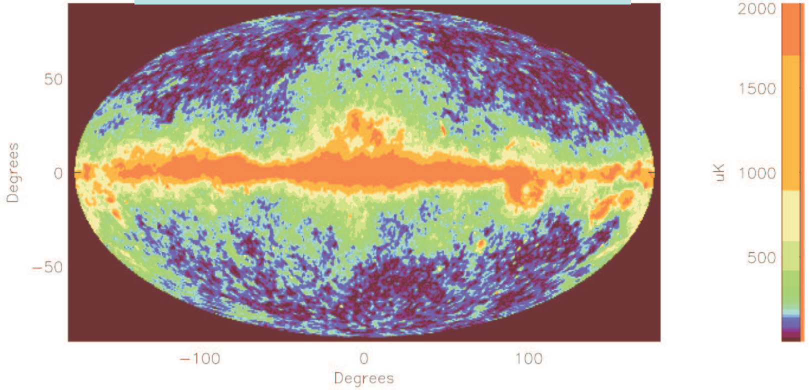


ACT telescope, 6m

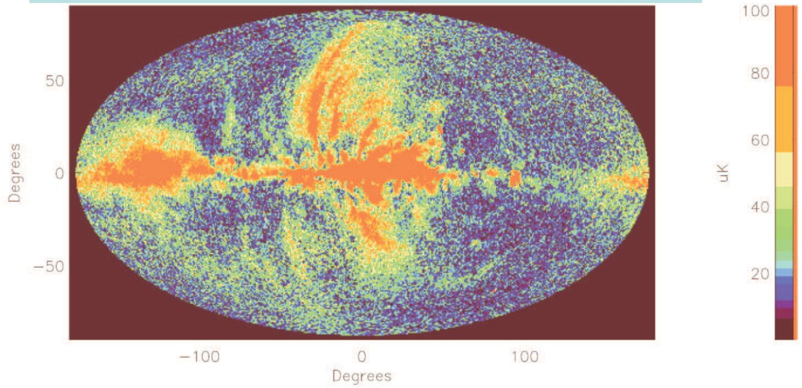
What do we know about foregrounds at microwave frequencies?

Looking for a few 10nK signal in maps of µK scales …

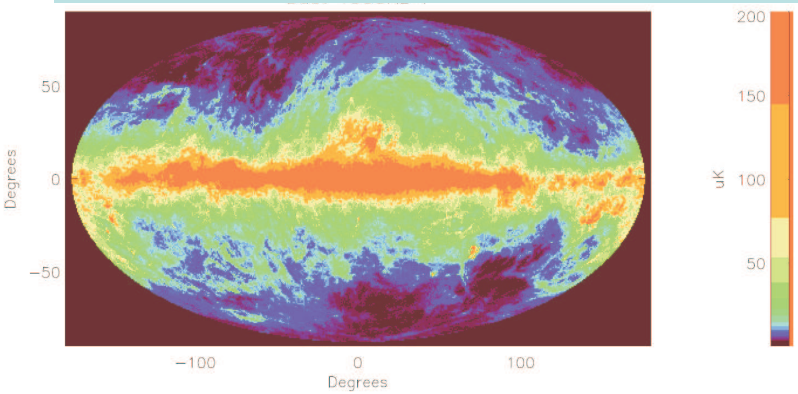
T at 23 GHz (WMAP)



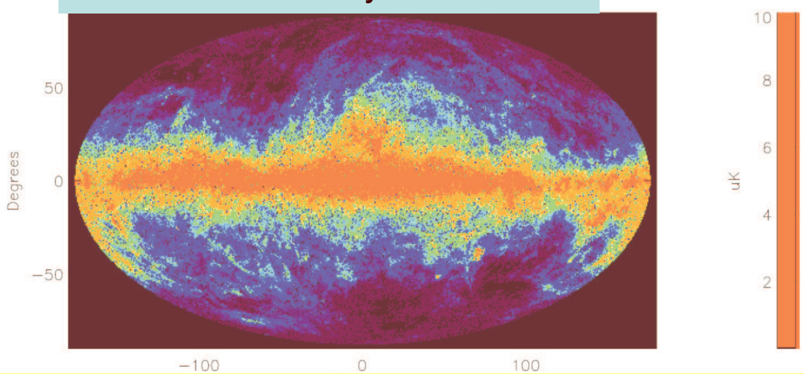
Polarized Intensity at 23 GHz (WMAP)



T at 150 GHz (extrapolation from 100 µm data)



Polarized Intensity at 150 GHz

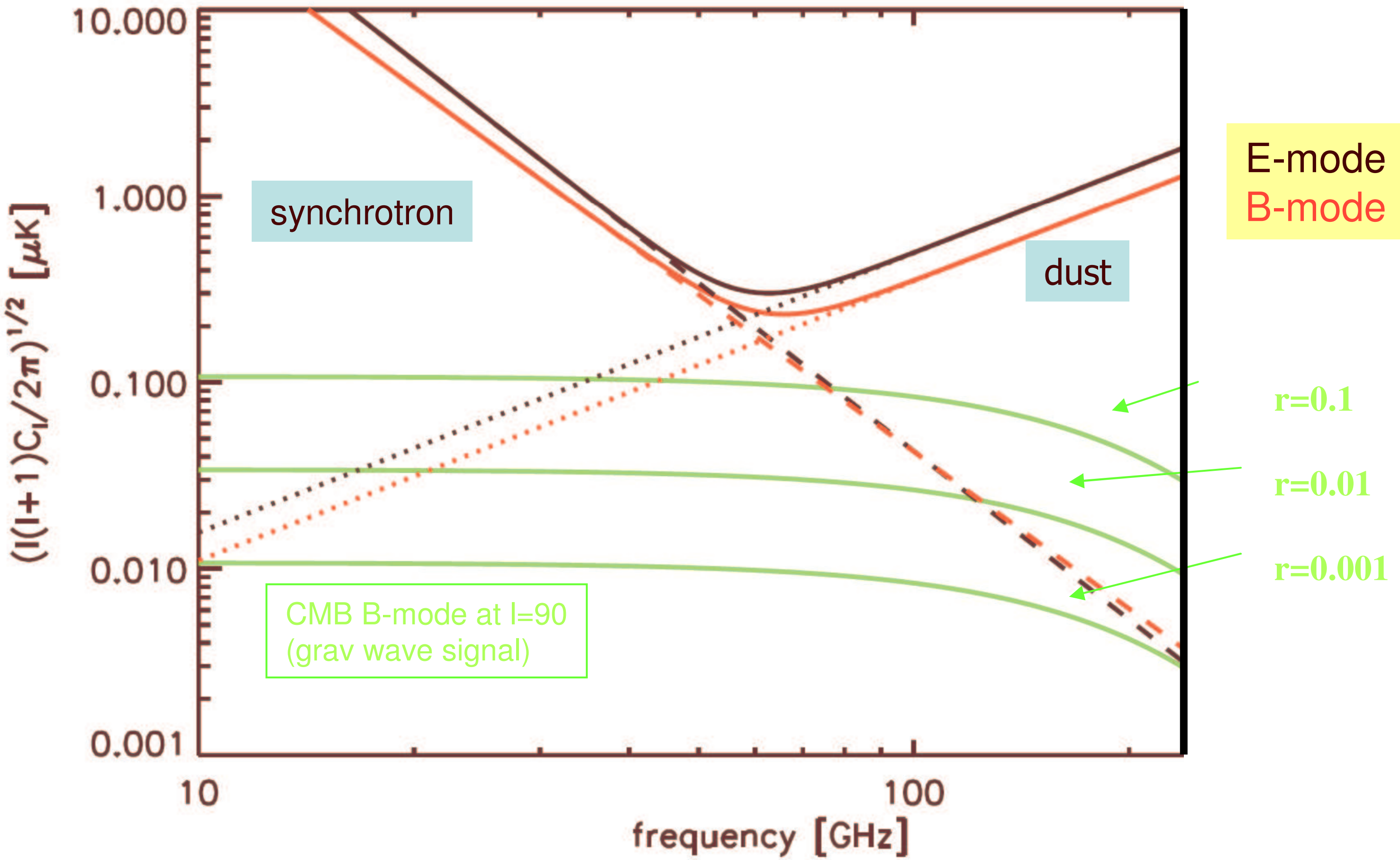


Pictures by K. Vanderlinde

Further extrapolation for polarization (just using Intensity scaled by 5%)!
(so far only large-scale measurements by Archeops on 30% of the sky at 12‘ FWHM)

Foreground fluctuations

WMAP estimates for l=90 (peak of grav wave signal)

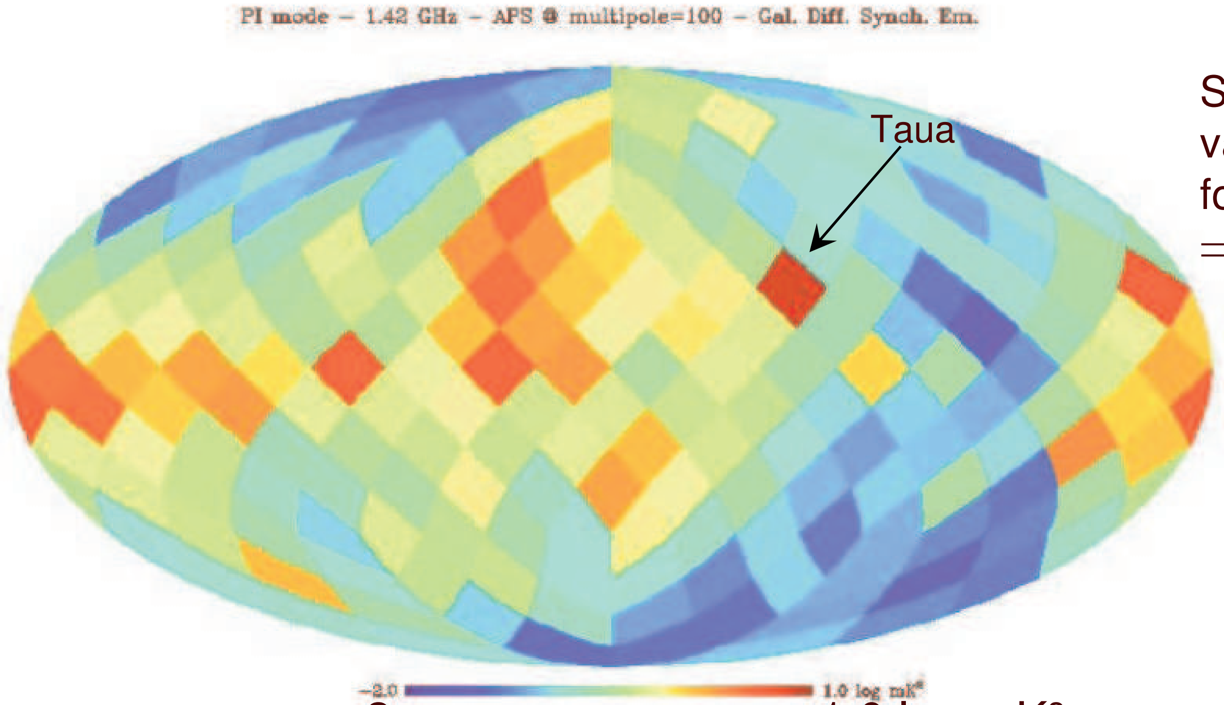


Synchrotron and dust fluctuations show minimum around 70 GHz
ALWAYS LARGER THAN B-MODE SIGNAL!

Improvement using small patches?

Using synchrotron maps at 1.4 GHz:
APS value at l=100

Analysis by Burigana/La Porta



-2 1.0 log mK²

Size of Fluctuations varies significantly for different patches
⇒ Wise choice of clean patches can help ground-based experiments!

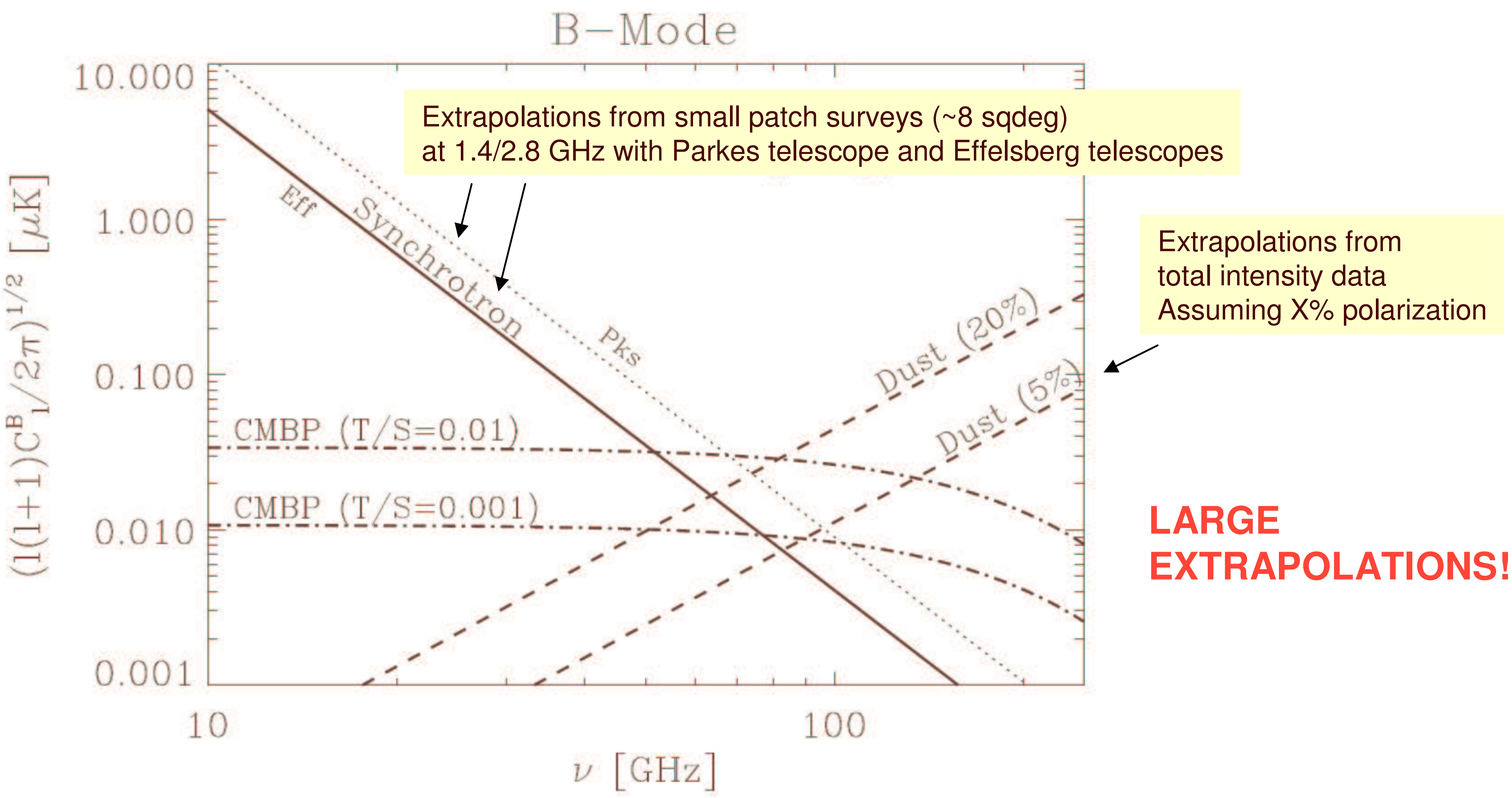
Minimum of 0.01 mK² will give at 70 GHz for the power spectrum:
$0.01\ l(l+1)/2\pi\ (70/1.4)^{-2\beta} = 0.001\ (2.5)\ \mu K^2$ for $\beta=3(2)$!
(RJ conversion adds another factor of 1.1^2)

B-mode signal for
r=0.01 ~0.001 μK²

LARGE EXTRAPOLATION!

Foreground fluctuations

Estimates for l=90 (peak of grav wave signal) from surveys on small patches



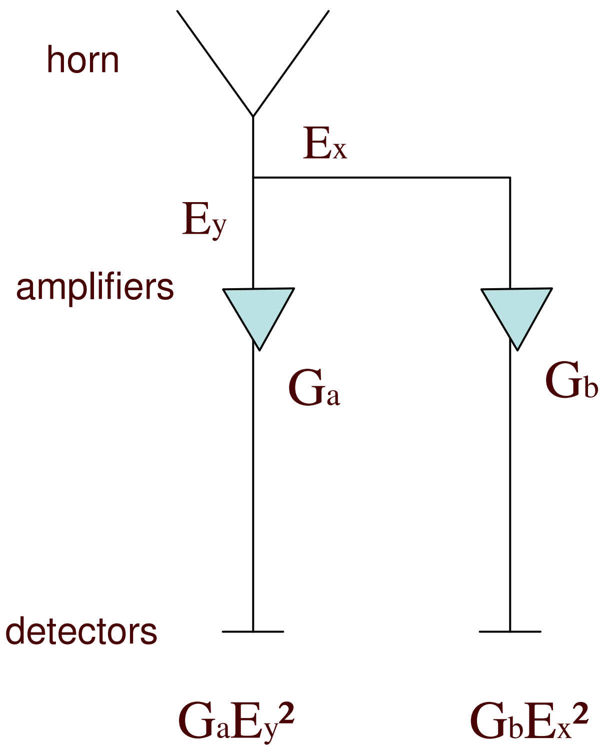
LARGE EXTRAPOLATIONS!

Carretti et al.

Future Experiments

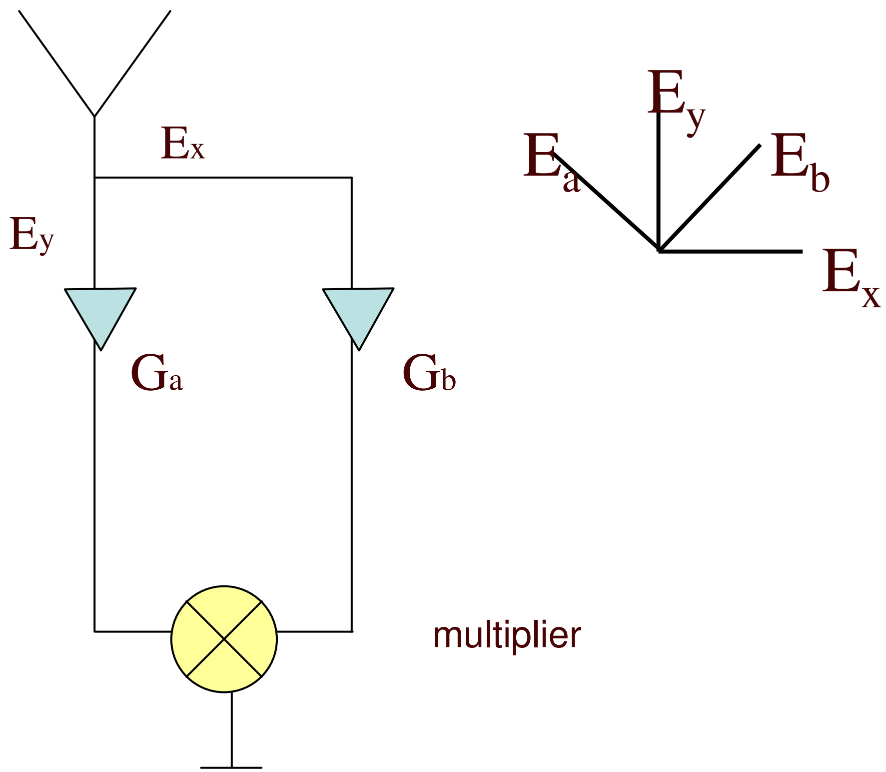
Different receiver types

Incoherent Receivers



Signal from detector differencing
Gain differences will introduce fake signal

Coherent Receivers



$$G_a G_b\, E_x E_y = G_a G_b\, (E_a^2 - E_b^2)$$

Gain differences can not fake a signal!
Phase switch used to eliminate slow drifts

Systematics

Tiny signal can be affected/faked by various effects:

- Elliptical beamsizes
- Pointing differences
- Bandwidth differences
- Gain fluctuations
- Instrumental Polarization
- Ground pickup
- E/B mixing in finite sky patches
- …..

Modulation of signal helps to extract tiny signal from large ‘offset‘
- phase switches in correlation receivers
- half-wave-plate modulation in bolometric receivers
- scanning across the sky, sky rotation => cross-correlating
- …

The effects need to be controlled at unprecedented levels well below a percent

Interferometers have been used for previous
CMB (polarization) measurements (DASI, CBI, VSA …)

PRO
- direct view onto the Fourier sky (power spectrum)
- receiver gain fluctuations and sky emission do not correlate
- no sub-K cryogenics

CONS
- not directly scalable (N*(N-1) correlators!)
- no direct maps of the sky (good for foreground removal)

(Pseudo-)Correlation receivers have been used for previous
CMB measurements (WMAP, CAPMAP)

PRO
- gain fluctuations do NOT introduce fake polarization signal
- no sub-K cryogenics

CON
- low noise only at frequencies <100 GHz

Bolometric receivers have been used in CMB temperature experiments, proven on Boomerang for polarization measurements (ACBAR, Archeops, Boomerang)

PRO
- high sensitivity, large bandwidth
- scalable

CON
- not yet proven for high sensitivity at low frequencies
- gain fluctuations can introduce fake polarization
- sub-K cryogenics

Future ground-based/balloon experiments

- Bolometric arrays
  ACT, APEX, BICEP, ClOVER, EBEX, *OLIMPO,* PAPPA, Polarbear, QUAD, Spider, *SPT*
- Pseudocorrelation receivers
  QUIEt, Bar-Sport
- Interferometers
  AMI, AMIBA, SZA, VSA
- Bolometric interferometers
  MBI, BRAIN
- *Radiometers*
  7 receivers 3-90 GHz ARCADE

Already taking data
Funded and under development
Funding pending
Italics: SZ

This overview is based on presentations of experiments at recent 'CMB' conferences. There are e.g. SZ-surveys underway of which I know little (AzTEC, Gemini-SZ, OCRA …)

Future ground-based/balloon experiments

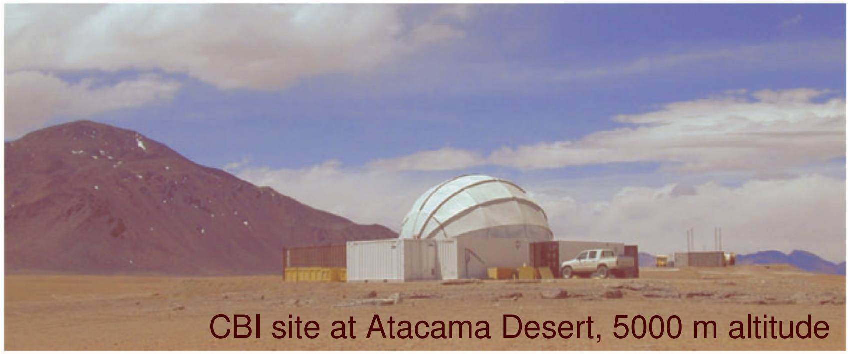
- Bolometric arrays
  ACT, APEX, BICEP, CIOVER, EBEX, *OLIMPO,* PAPPA, Polarbear, QUAD, Spider, *SPT*

- Pseudocorrelation receiver
  QUIEt, Bar-Sport

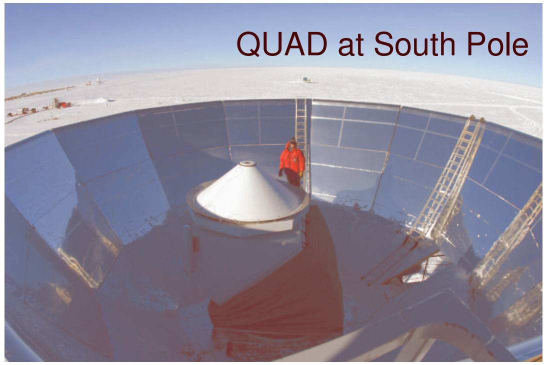
- Interferometers
  AMI, AMIBA, SZA, VSA

- Bolometric interferometers
  MBI, BRAIN

- *Regular receivers*
  7 receivers 3-90 GHz ARCADE



Atacama Desert Chile
South Pole/Dome C
Balloon



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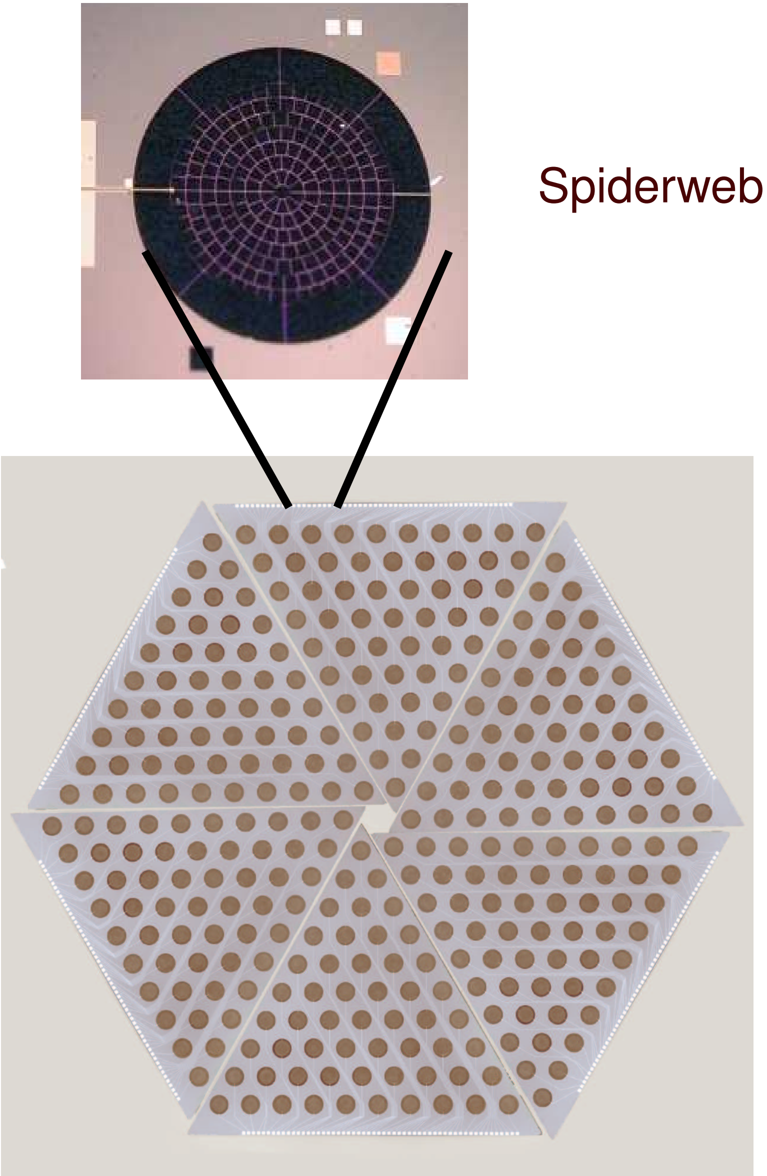
Bolometer arrays



Spiderweb bolometers

Polarization sensitive bolometers were successfully used for CMB measurements by Boomerang, will also be used by Planck HFI

Transition Edge Sensitive (TES) Bolometers highly sensitive, allow multiplexed SQUID readout and easy mass production (photolithography)

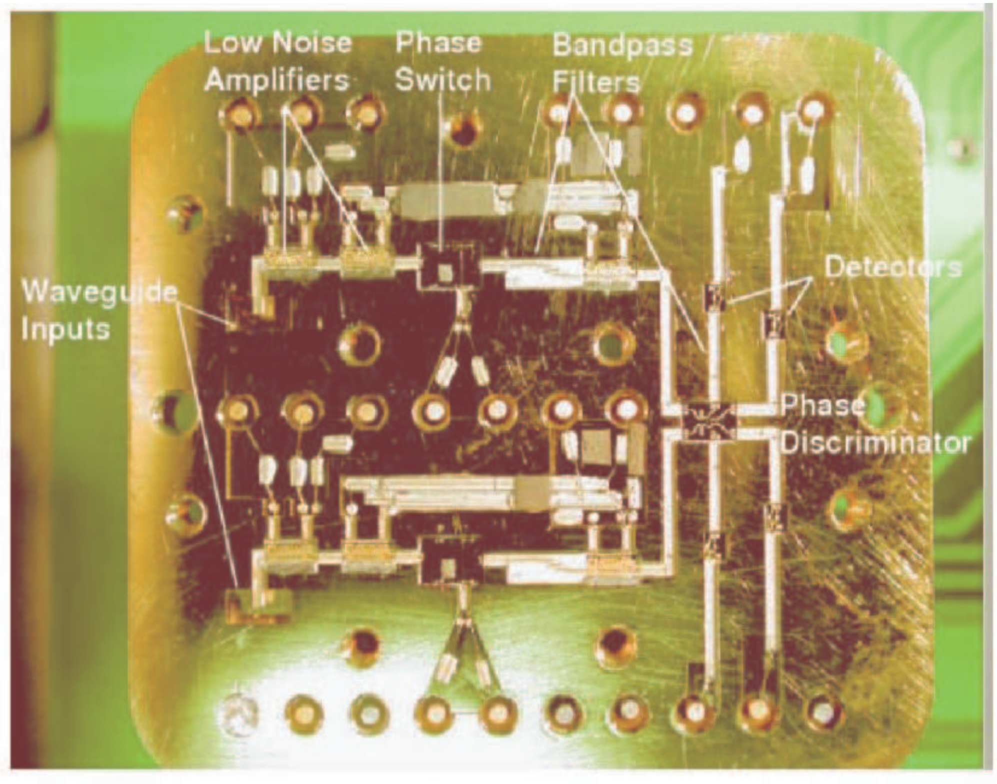
Antenna coupled TES bolometers will enable easily scalable arrays without feedhorns (Spider, Polarbear)

Adrian Lee, Berkeley

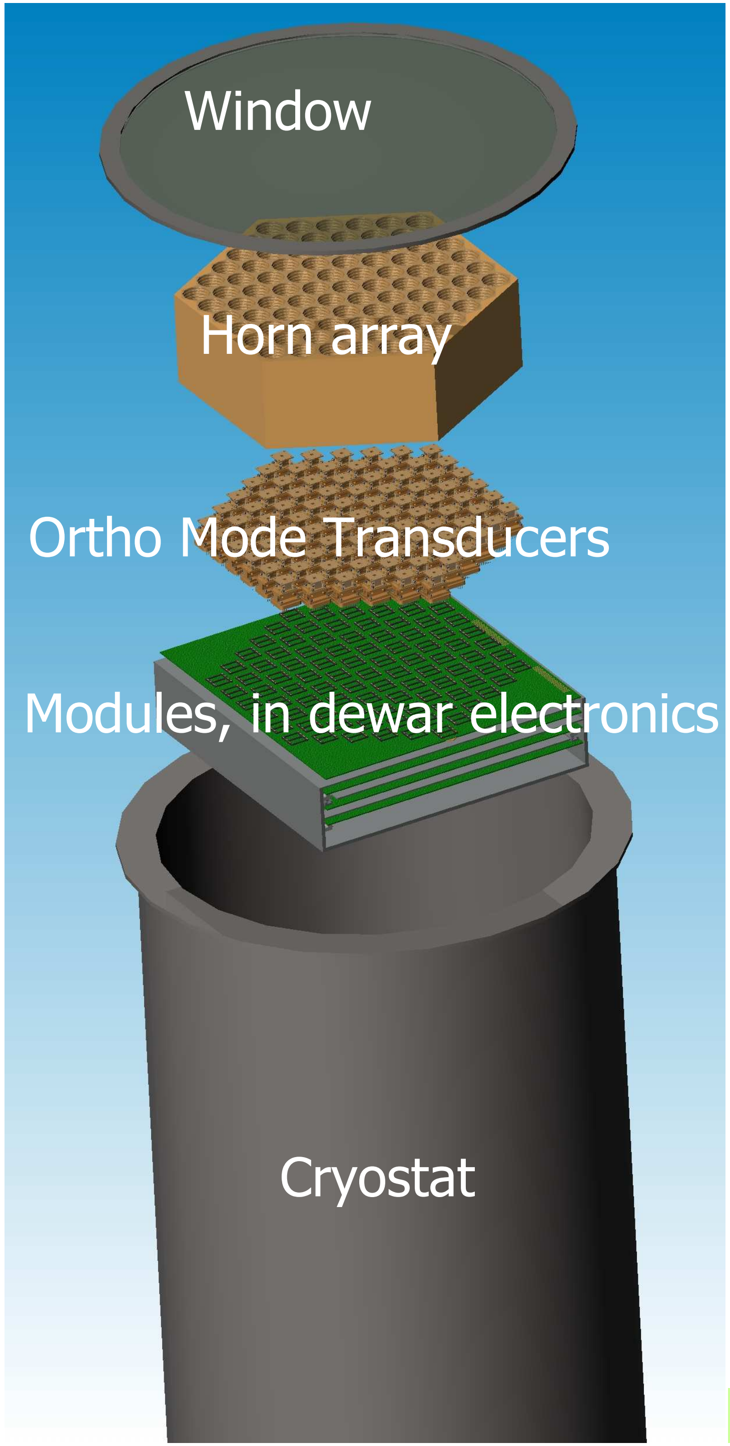
Q/U Imaging ExperimenT (QUIET)

Collaboration by: Berkeley, Bonn, Caltech, Chicago, Columbia, GSFC, Harvard Smithsonian, JPL, Miami, Oxford, Princeton

- Radiometer on a chip
- Automated assembly and optimization
- Large array of correlation polarimeters



~1 inch



Plans for QUIET

- Install up to four new 1.4m telescopes on CBI platform
- Move 7m telescope to Chile

91 W band elements
19 Q band elements

Phase I, in Chile 2007

2x397 W band elements
2x91 Q band elements

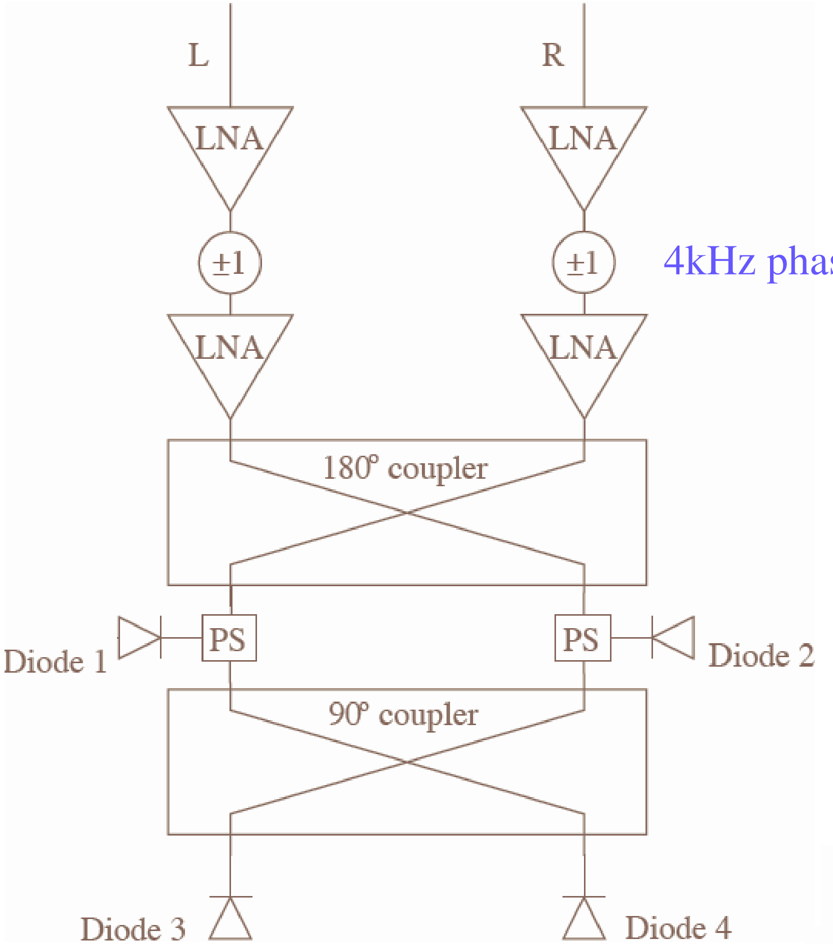
Phase II

Observations at small and large scales!

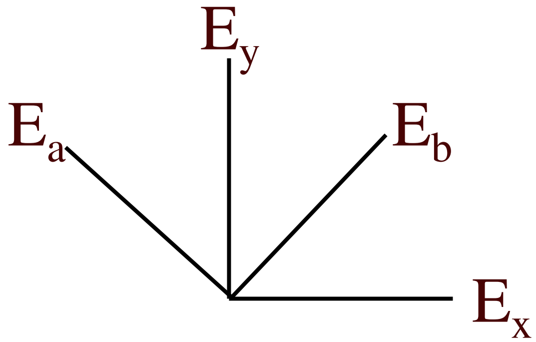
7m telescope at Crawford Hill, NJ

CBI platform, Atacama Desert, Chile

QUIET L/R Correlator: Simultaneous Q/U measurements



4kHz phase switching



$$|L \pm R|^2 = \left|(E_x + iE_y) \pm (E_x - iE_y)\right|^2 = \underline{4E_x^2, 4E_y^2}$$

Q

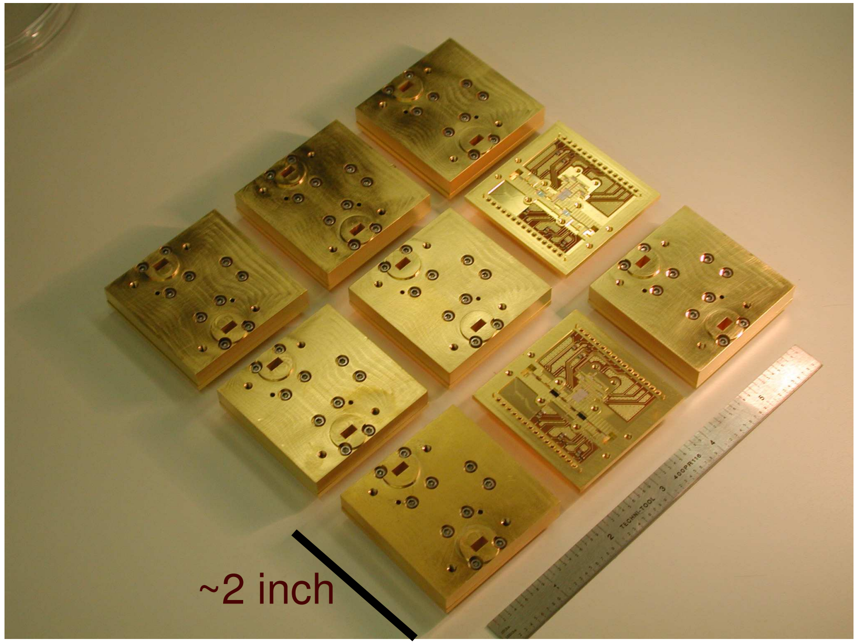
$$\left|(L \pm R) + i(L \mp R)\right|^2 = |L \mp iR|^2 = |L|^2 + |R|^2 \mp 2\,\mathrm{Im}(RL^*)$$

$$\mathrm{Im}(RL^*) = \mathrm{Im}(E_x + iE_y)^2 = 2E_xE_y = \underline{E_a^2 - E_b^2}$$

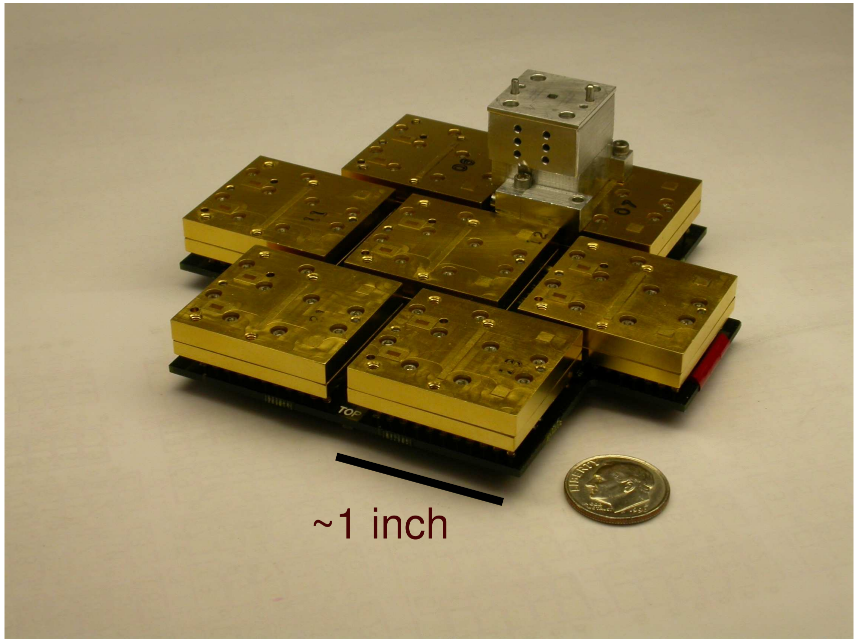
U

Prototype arrays

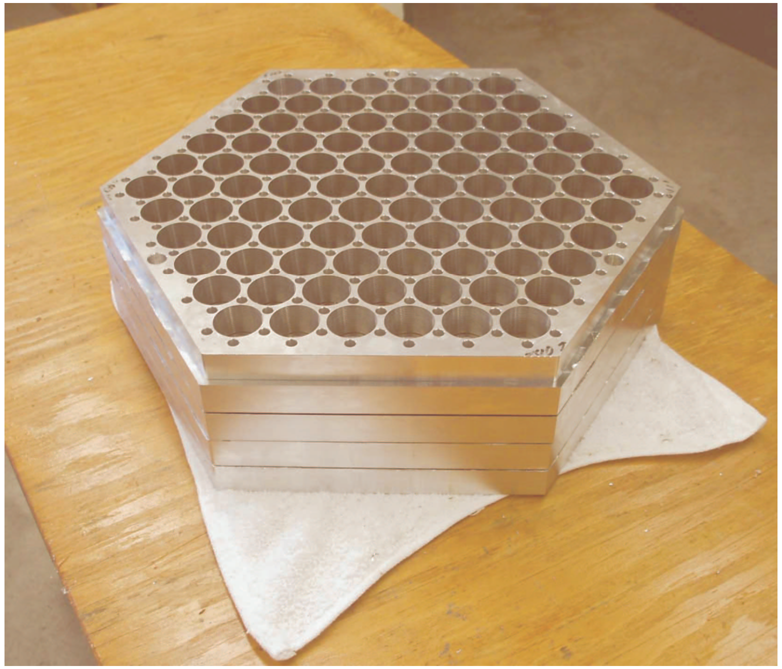
Q-Band (44 GHz)

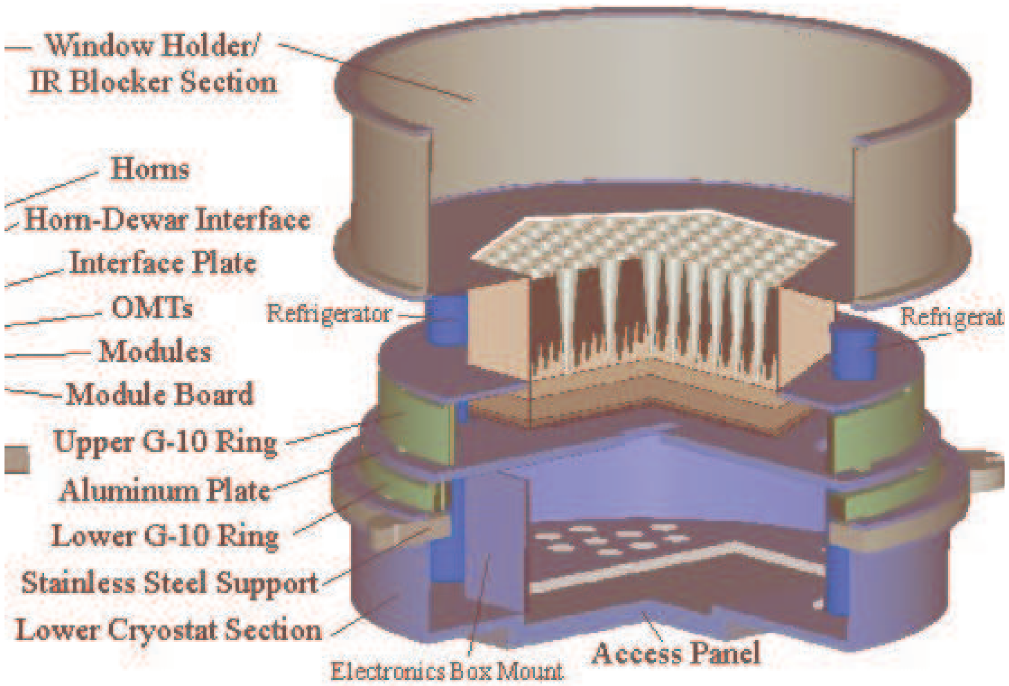


W-Band (90 GHz)



Horn array and cryostat



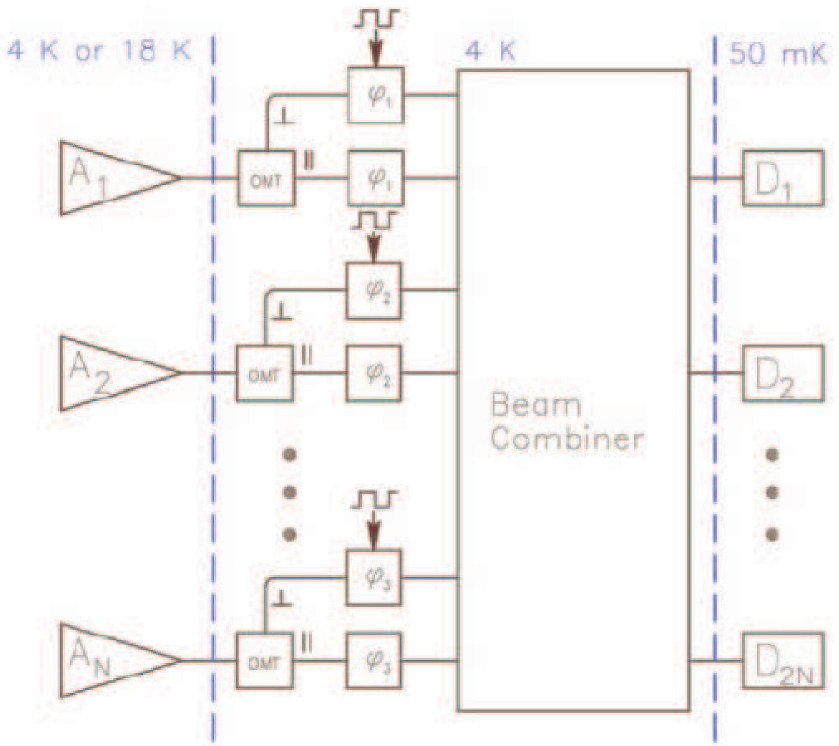


New: Interferometric Bolometry

Combine the benefits of interferometers with the sensitivity of bolometers:

Principle of adding interferometer:

Measure $(A+B)^2$ and $(A-B)^2$ => difference gives correlation AB



MBI prototype in lab, going to
Pine Bluff Observatory
64 elements planned at 90 GHz

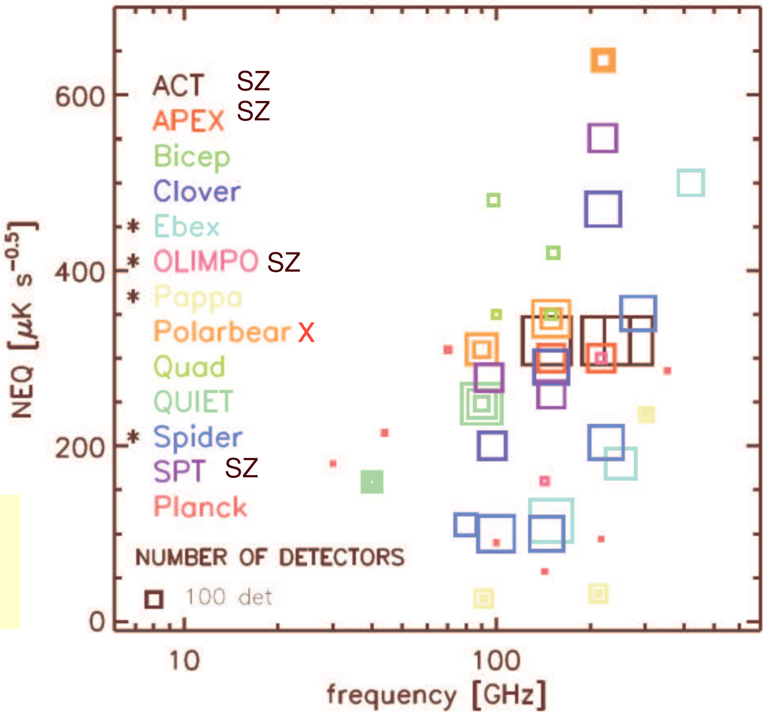
Brown, Cardiff, LLNL, Northwestern, UC San Diego, Richmond, Wisconsin

BRAIN pathfinder at Dome C
2x256 elements planned at 90 and 150 GHz

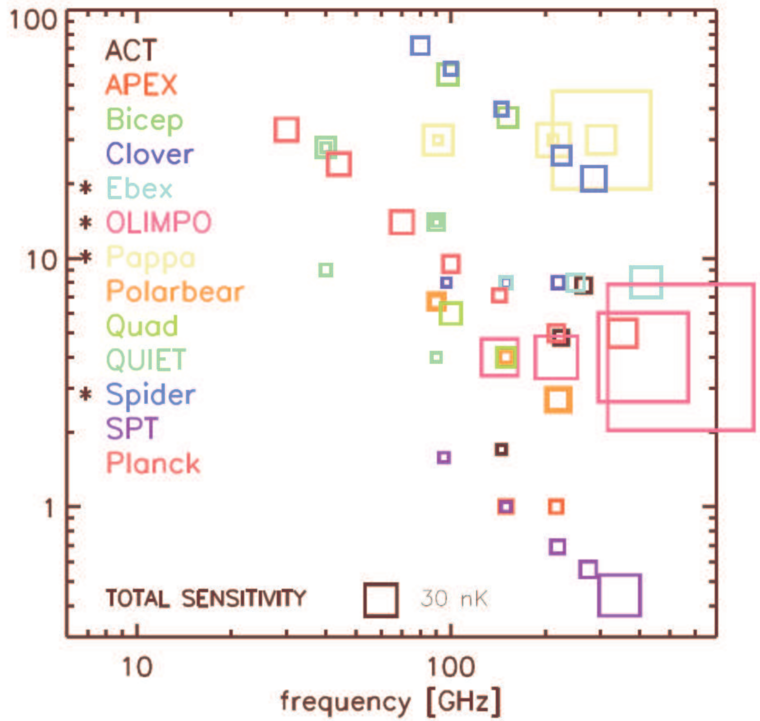
Rome, Milano, Cardiff, APC Paris, CESR Toulouse, CSNSM Orsay, IAS Orsay

Future CMB experiments

(no interferometers)



*: Balloon
X :Funding pending



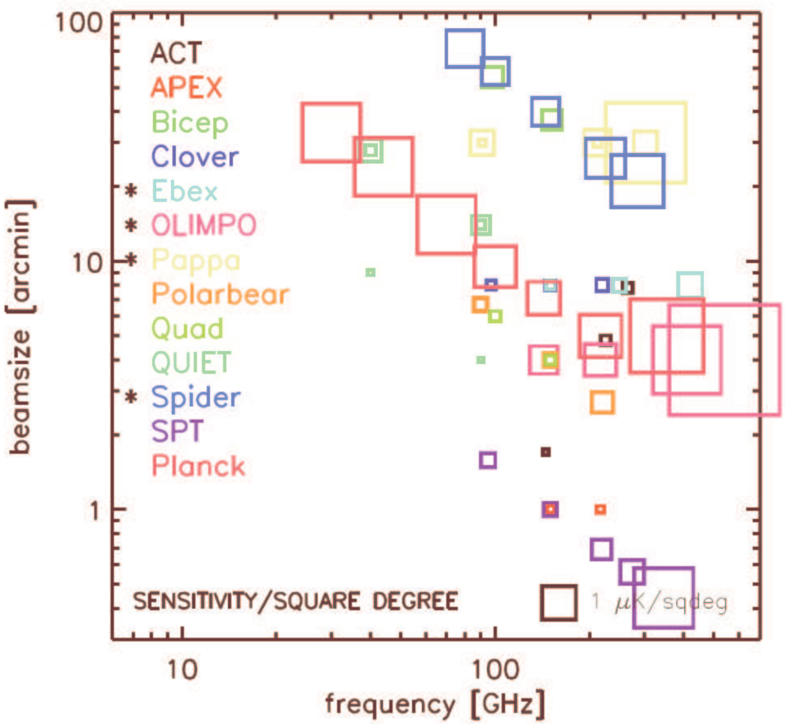
Beware: sqrt(2)s …
Plotted: NEQ with NET=NEQ (Q=(Tx-Ty)/2)

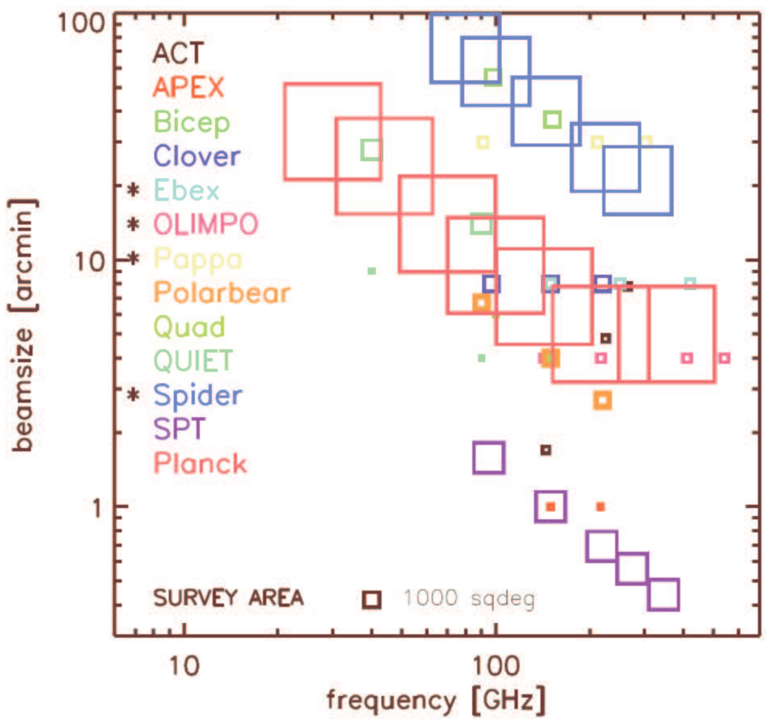
Very few low frequency experiments underway!

These are goals/current plans **BUT**: some experiments are not yet (completely) funded and future technologies are not yet fully established, don‘t take the numbers too literally!
Also: SYSTEMATICS/FOREGROUNDS not taken into account in these numbers

Future CMB experiments

(no interferometers)





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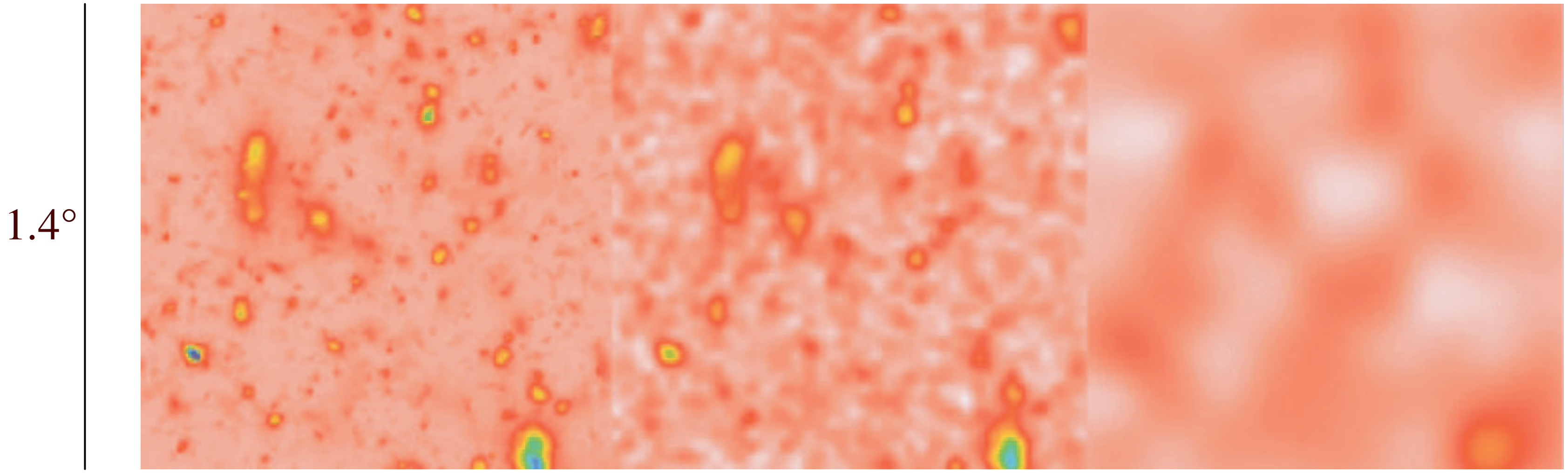
SZ resolution



SZ simulation
150 GHz simulation

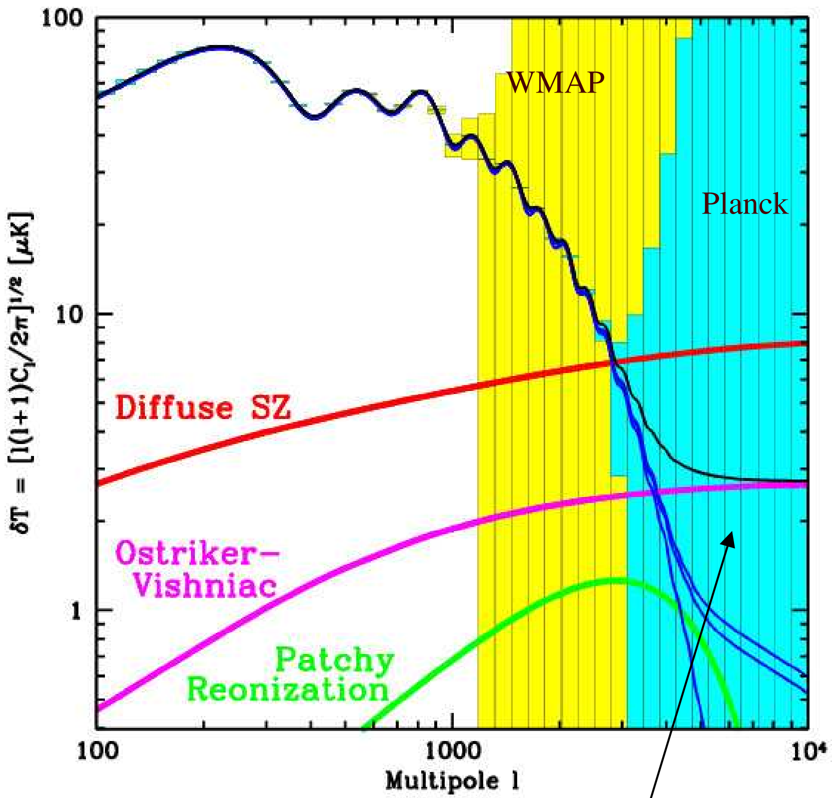
ACT
1.7‘ beam

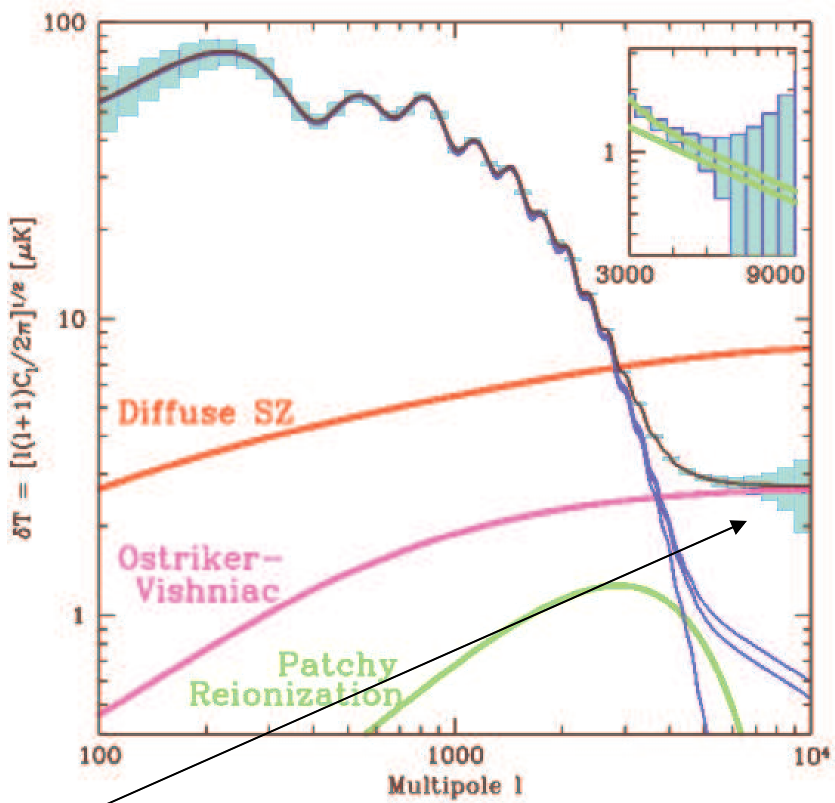
Planck

Burwell/Seljak 2000

Planck will cover all sky but only be able to see highly massive clusters
Ground-based experiments cover small fractions of sky but resolve with a much finer resolution

Reach at the temperature power spectrum



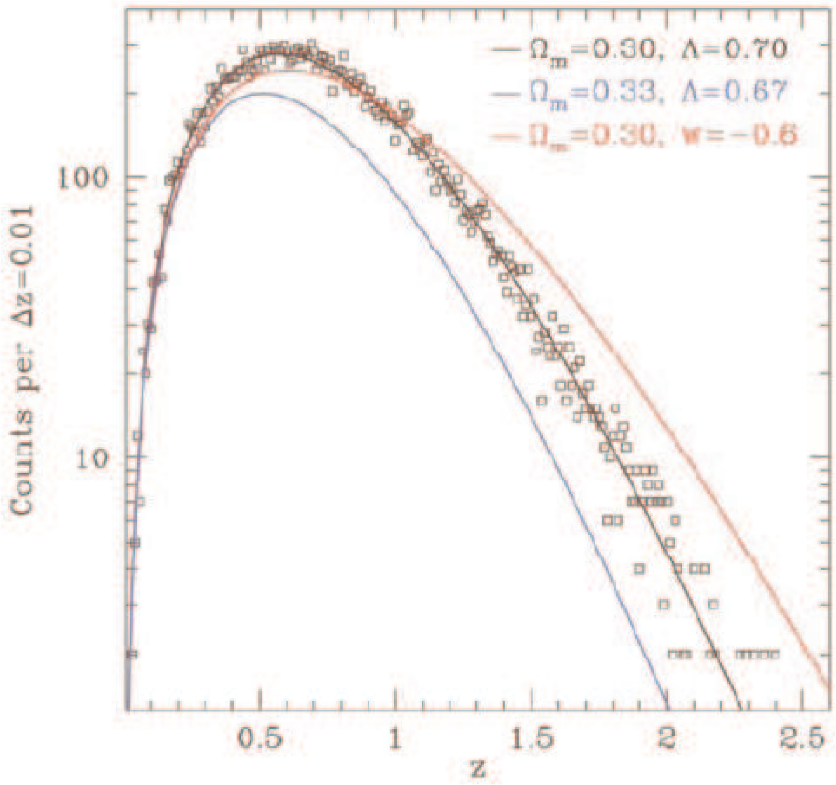


Estimates for Planck and ACT

Statistical uncertainties only! Results will differ!

De Oliveira-Costa

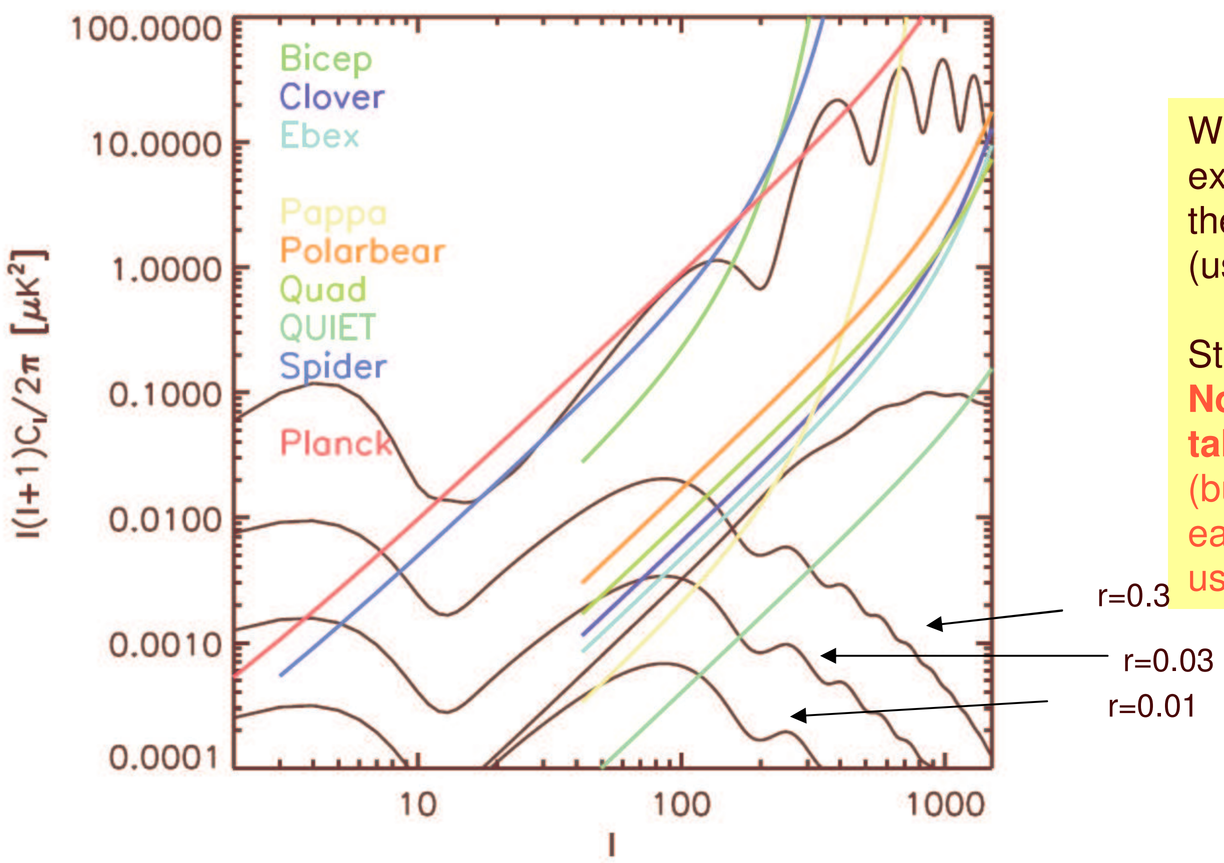
Cluster counts



Simulated cluster survey from SPT

Cluster counts sensitive to cosmological parameters

Do we get to interesting levels of T/S from the ground?



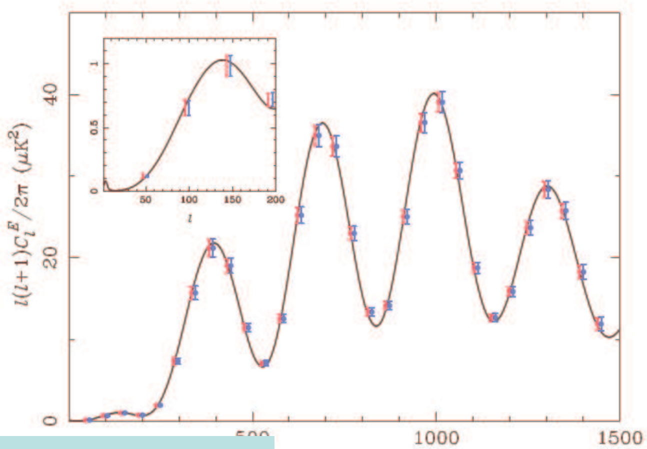
White noise level of the different experiments in comparison to the CMB power spectrum (using most sensitive CMB frequency)

Statistical uncertainty only,
No impact of foregrounds/systematics taken into account!
(but: only one frequency used from each experiment, others can be used for foreground removal)

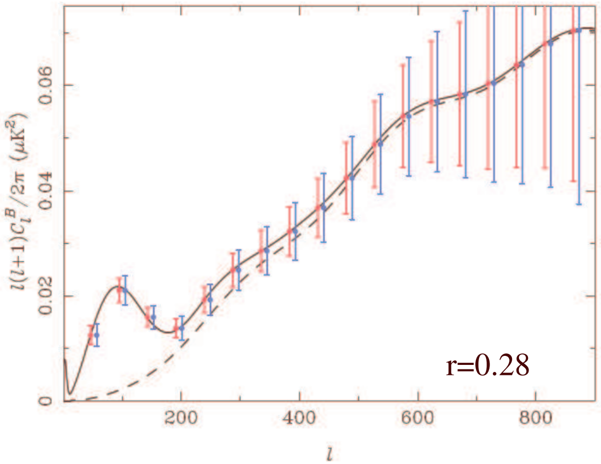
Better S/N for the ground-based efforts (compared to Planck)

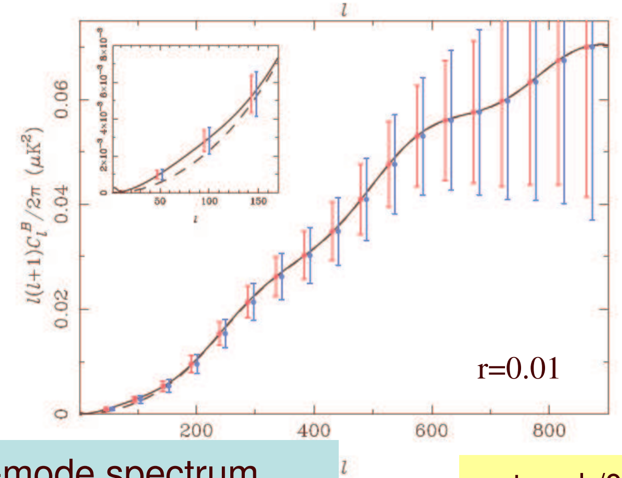
Power spectra

Expected reach of Clover
(Fisher matrix calculation, no systematics!)
Magenta errors ignore effects from E/B mixing



E-mode spectrum





Predictions use sensitivity of only
one of 3 frequencies to account for
sensitivity loss through foreground removal

B-mode spectrum
(grav wave + lensing)

astro-ph/0610716

Access to $r=10^{-2}$ already with ground-based efforts possible!

Conclusion

Many ground-based efforts are underway, aiming at measurements of high-l temperature spectrum, polarization spectra and frequency spectrum

- Excellent sensitivity reached with large receiver arrays

- Multifrequency measurements used in order to control/measure foregrounds

- Different techniques are being exploited, crucial to enable control of systematics at the required level

Ground based experiments will significantly advance CMB science and improve our understanding of foregrounds