Title: Planck and beyond

Date: Jul 10, 2013 10:50 AM

URL: http://pirsa.org/13070014

Abstract: After reviewing some of the highlights of the implications of the Planck results for cosmic inflation (presentation to be coordinated with Hiranya Peiris), I will discuss some recent developments
regarding future searches for B modes and other new science resulting from an ultra-precise
characterization of the microwave and far-infrared sky in polarization. I will outline ideas for
a recently proposed large-class European Space Agency mission called PRISM.

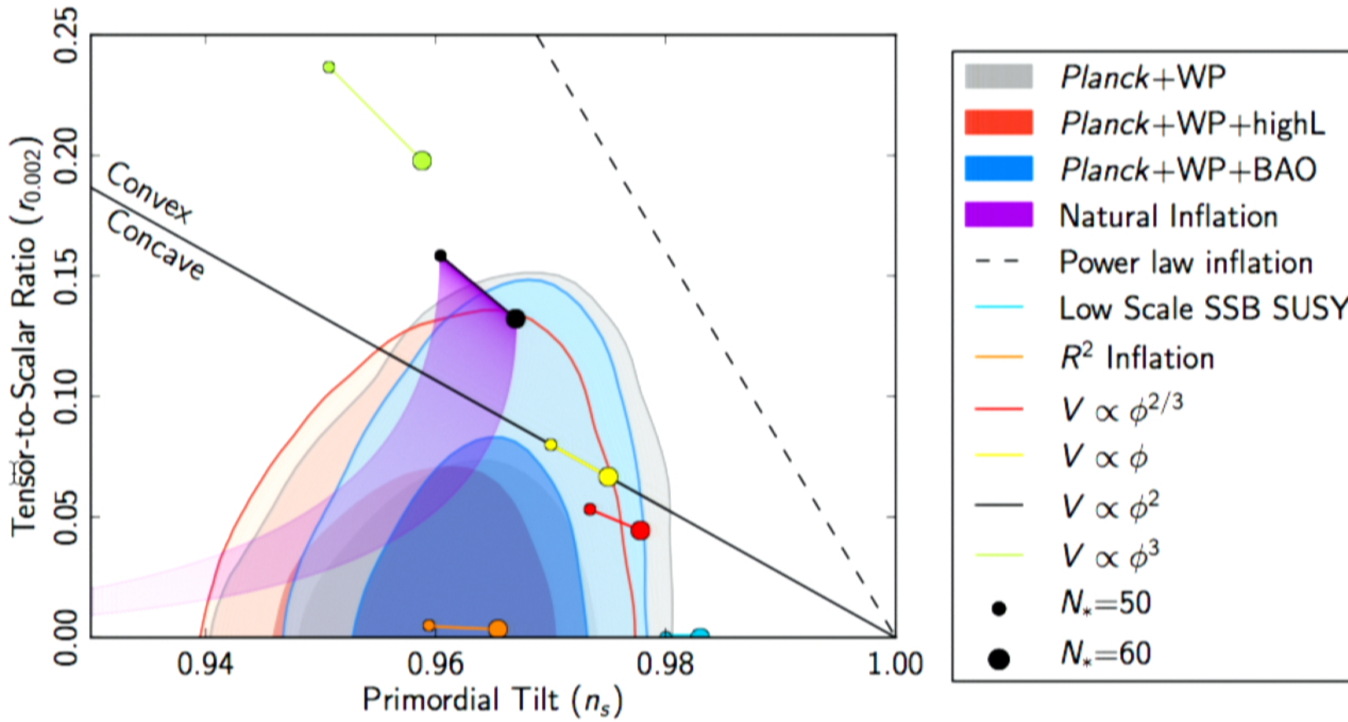
Outline

1. Selected results from Planck (very short)
2. Searching for B modes (mainly from space)
    2.1 COrE (a "medium cost" option)
    2.2 Other non-European initiatives
    2.3 PRISM (the near ultimate mission option)

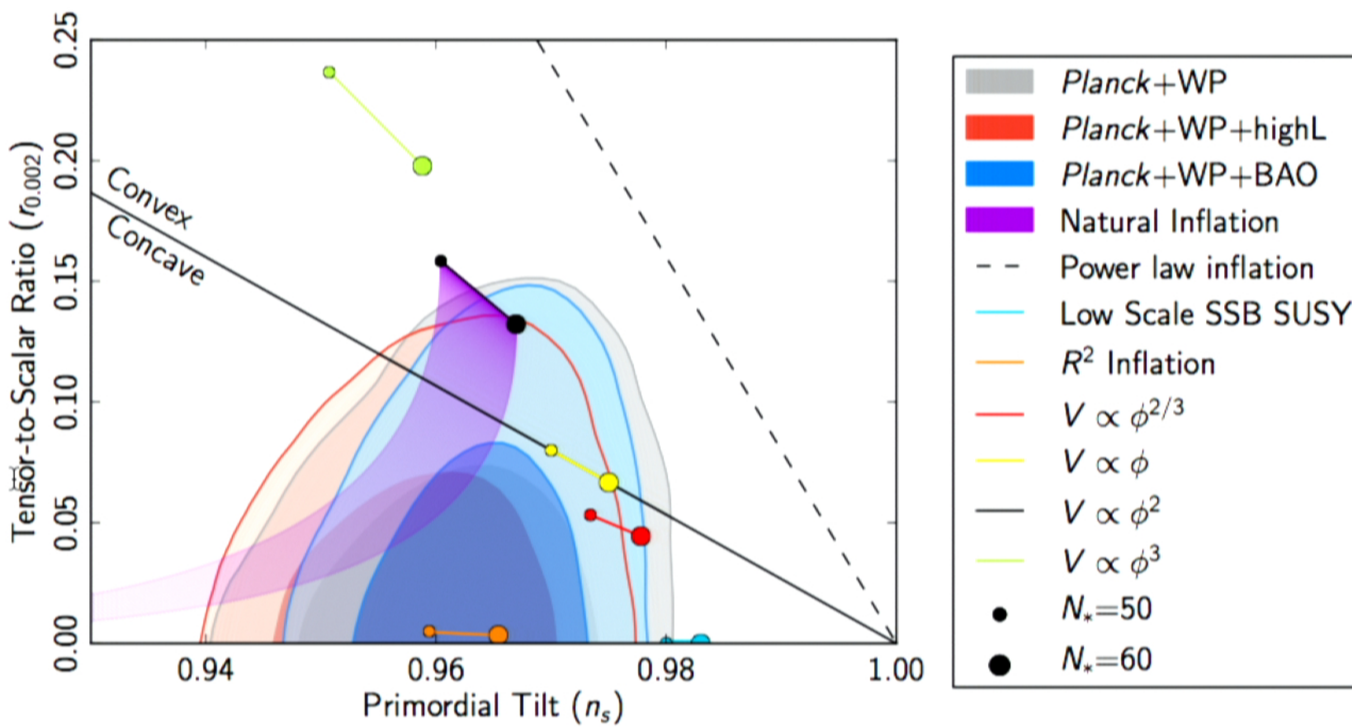
Outline

1. Selected results from Planck (very short)
2. Searching for B modes (mainly from space)
   2.1 COrE (a "medium cost" option)
   2.2 Other non-European initiatives
   2.3 PRISM (the near ultimate mission option)

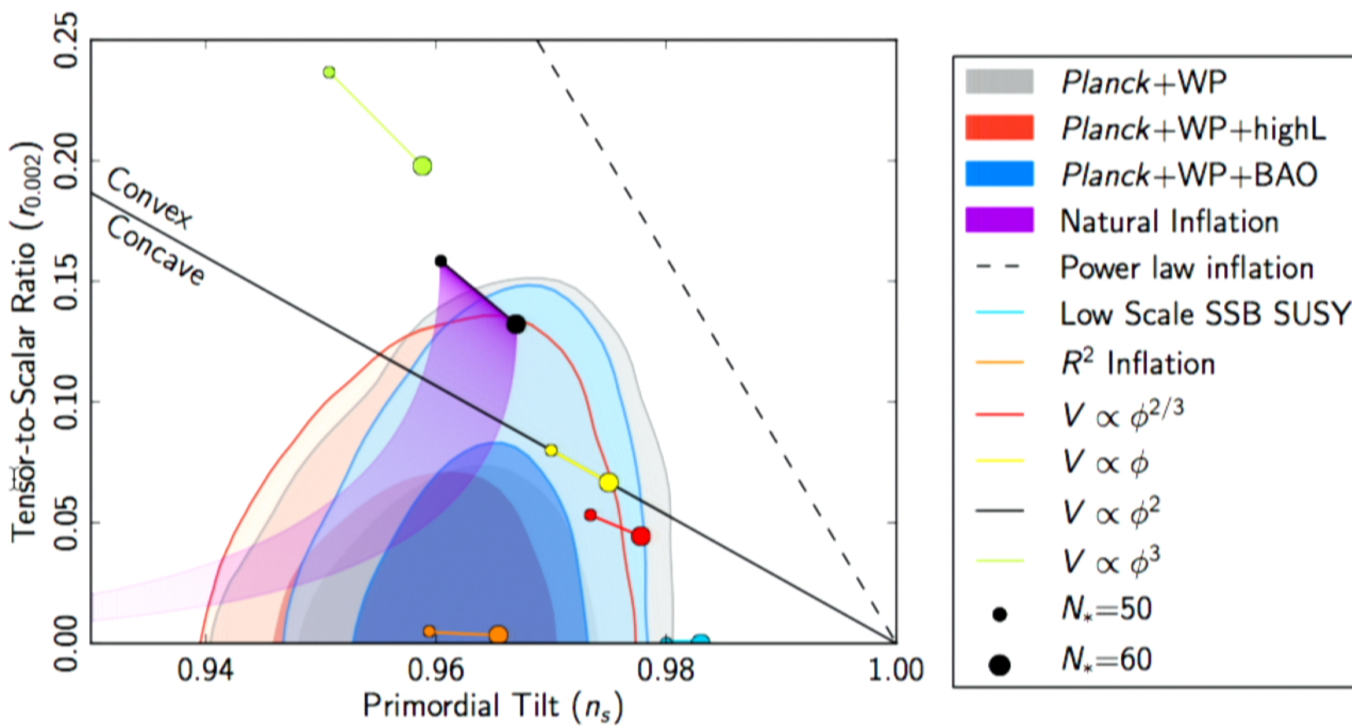
Implications for inflation—summary plot



Implications for inflation—summary plot



Implications for inflation—summary plot



Underlying question: conventional parameterization

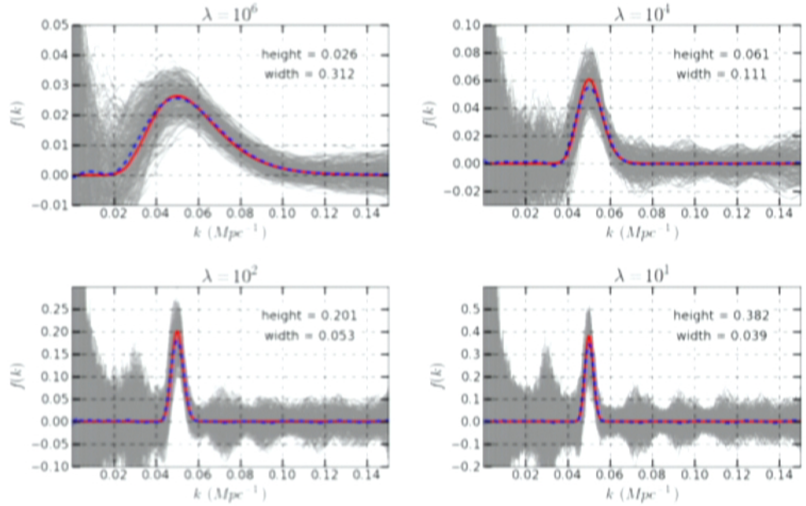
What is the primordial power spectrum?

- For lack of a fundamental theory, expand in powers of $\ln(k)$

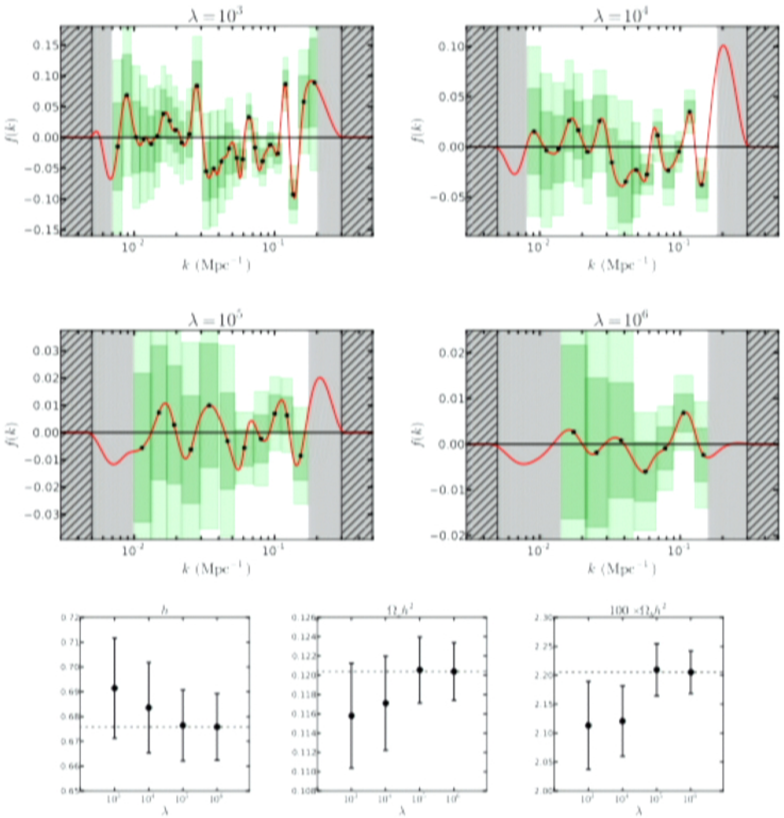
$$
\begin{aligned}
\ln\left(\mathcal{P}(\ln k)\right) &= \mathcal{P}_0 \left(\ln(k/k_{piv})\right)^0 + \mathcal{P}_1 \left(\ln(k/k_{piv})\right)^1 + \mathcal{P}_2 \left(\ln(k/k_{piv})\right)^2 + \dots \\
\mathcal{P}(k) &= A(k/k_{piv})^{(n_s-1)} \\
&\text{or} \\
\mathcal{P}(k) &= A(k/k_{piv})^{(n_s-1)+\alpha \ln(k/k_{piv})+\dots}
\end{aligned}
$$

- *Planck* seems to be telling us that the first two terms suffice, and using just the first term can be ruled out at a respectable statistical significance. $n_S \neq 1$ implies exact scale invariance needs to be downgraded to an approximate symmetry. No statistically significant evidence for running of the spectral index.

Validation of method

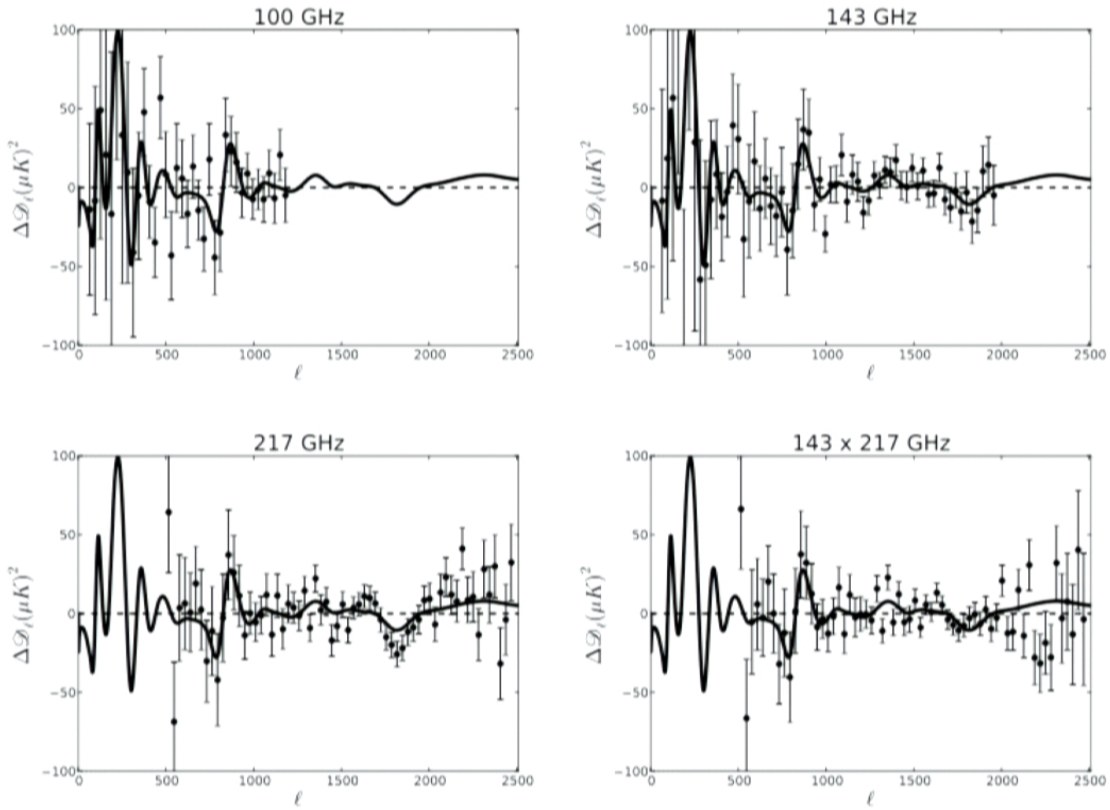


Results on Planck "Nominal mission" likeklihood

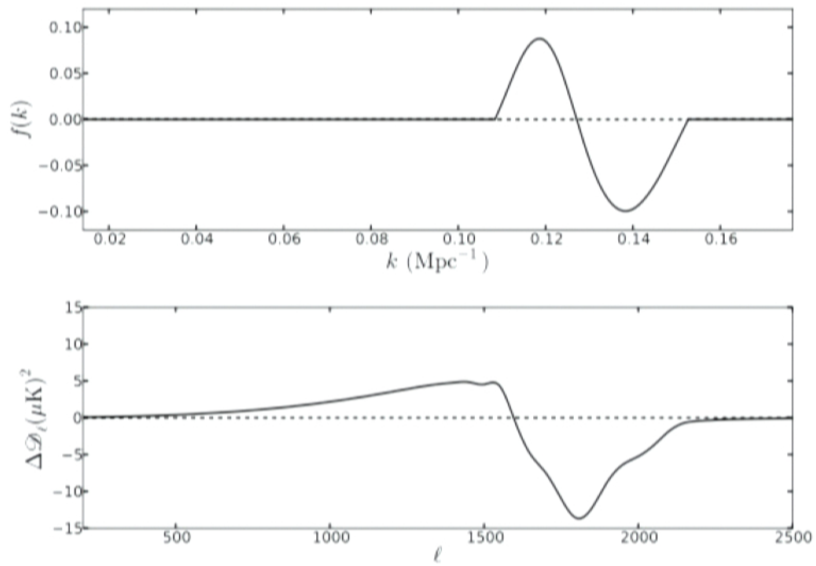


Maximum excursions locally 3.2σ and 3.9σ for $\lambda = 10^4$ and 10^3, respectively. After look-elsewhere-effect translates into $p = 1.74\%$ and $p = 0.21\%$, or 2.4σ and 3.1σ.

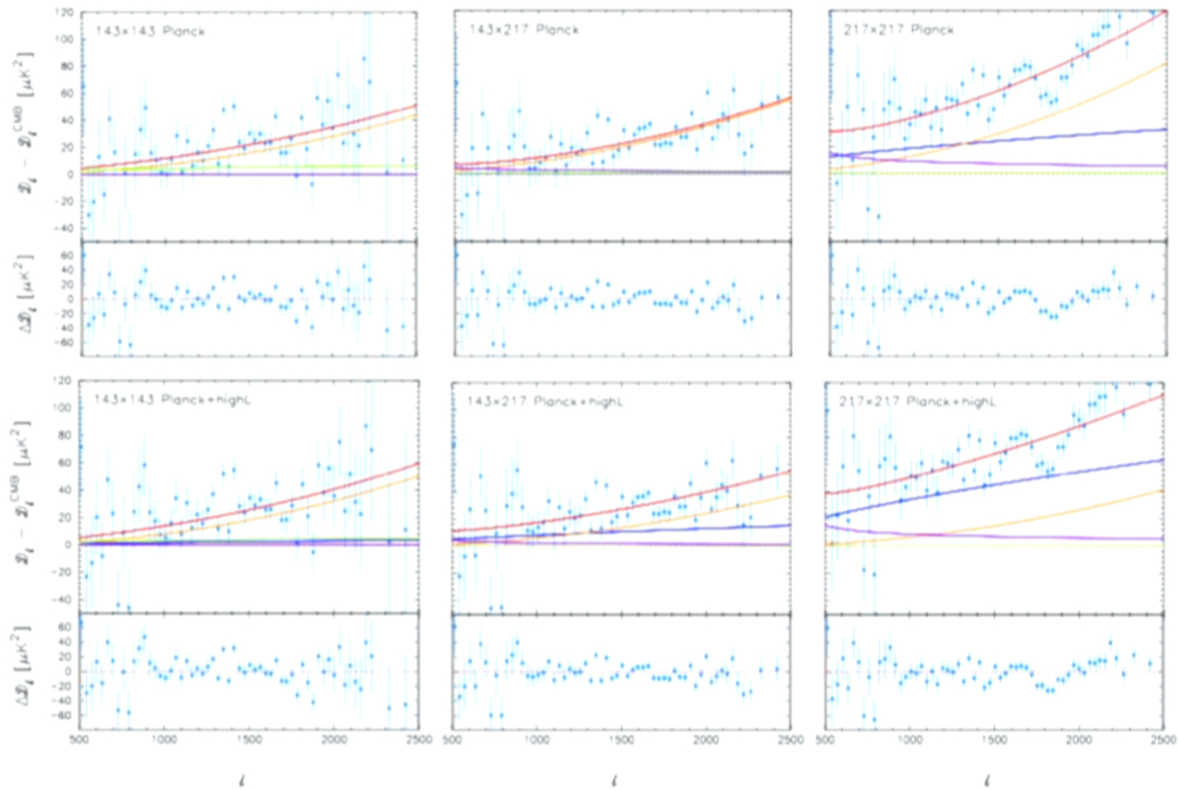
Where does this come from in the CMB multipole power spectrum?



Proof that signal is from around $\ell \approx 1800$



(Extract from parameters paper)



(Extract from parameters paper)

Table 6. Goodness-of-fit tests for the *Planck* spectra. The $\Delta\chi^2 = \chi^2 - N_\ell$ is the difference from the mean assuming the model is correct, and the last column expresses $\Delta\chi^2$ in units of the dispersion $\sqrt{2N_\ell}$.

Spectrum	$\ell_{\rm min}$	$\ell_{\rm max}$	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

Bayesian statistics – Sir Harold Jeffreys, FRS

Does the Jeffreys scale provide a reasonable standard of proof?

A value of $K > 1$ means that M_1 is more strongly supported by the data under consideration than M_2. Note that classical hypothesis testing gives one hypothesis (or model) preferred status (the 'null hypothesis'), and only considers evidence *against* it. Harold Jeffreys gave a scale for interpretation of K:[5]

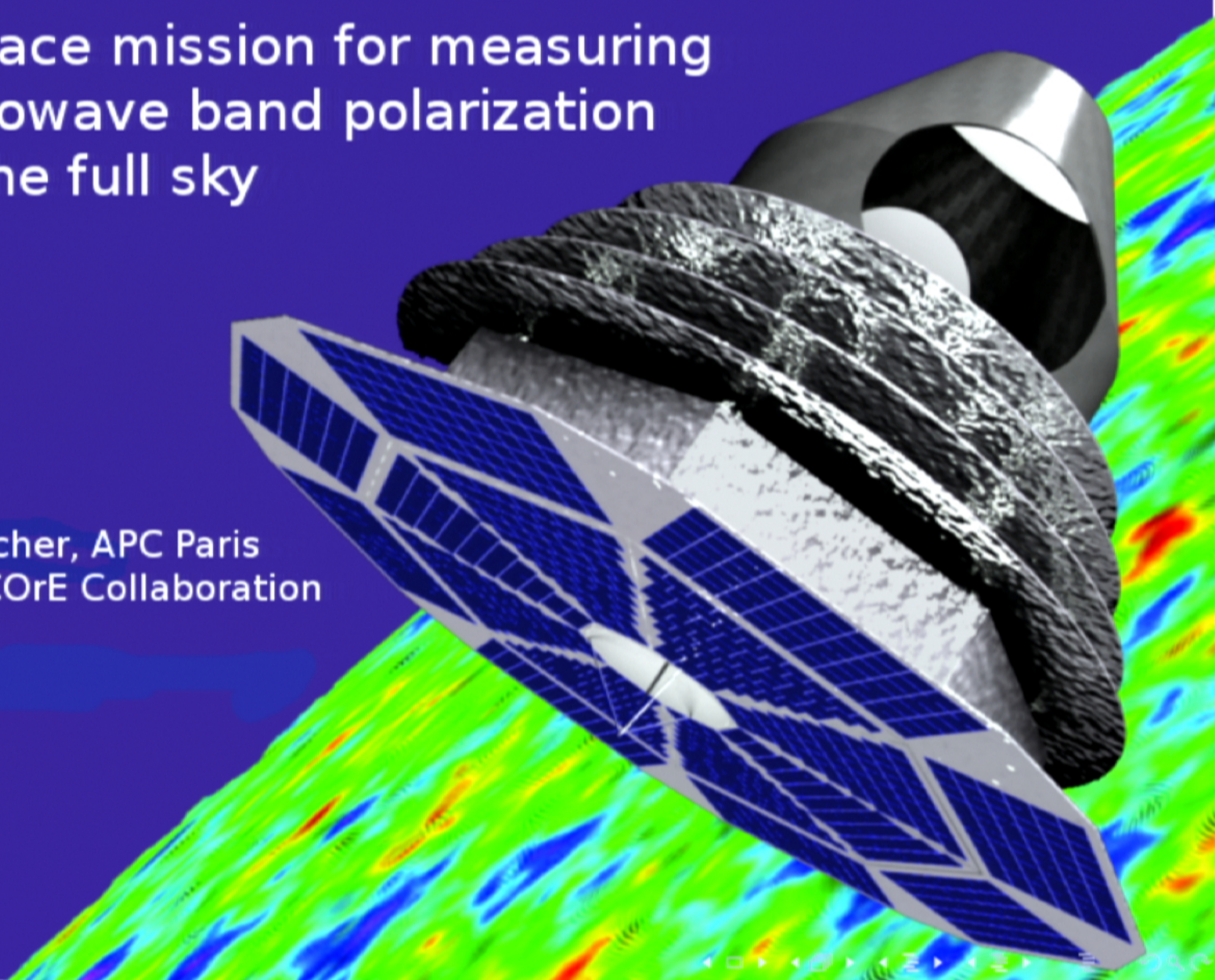
K	dB	bits	Strength of evidence
< 1:1	< 0		Negative (supports M_2)
1:1 to 3:1	0 to 5	0 to 1.6	Barely worth mentioning
3:1 to 10:1	5 to 10	1.6 to 3.3	Substantial
10:1 to 30:1	10 to 15	3.3 to 5.0	Strong
30:1 to 100:1	15 to 20	5.0 to 6.6	Very strong
> 100:1	> 20	> 6.6	Decisive

The second column gives the corresponding weights of evidence in decibans (tenths of a power of 10); bits are added in the third column for clarity. According to I. J. Good a change in a weight of evidence of 1 deciban or 1/3 of a bit (i.e. a change in an odds ratio from evens to about 5:4) is about as finely as humans can reasonably perceive their degree of belief in a hypothesis in everyday use.[6]

Everything beyond $\approx 3.0345\sigma$ has been "decisively" demonstrated.

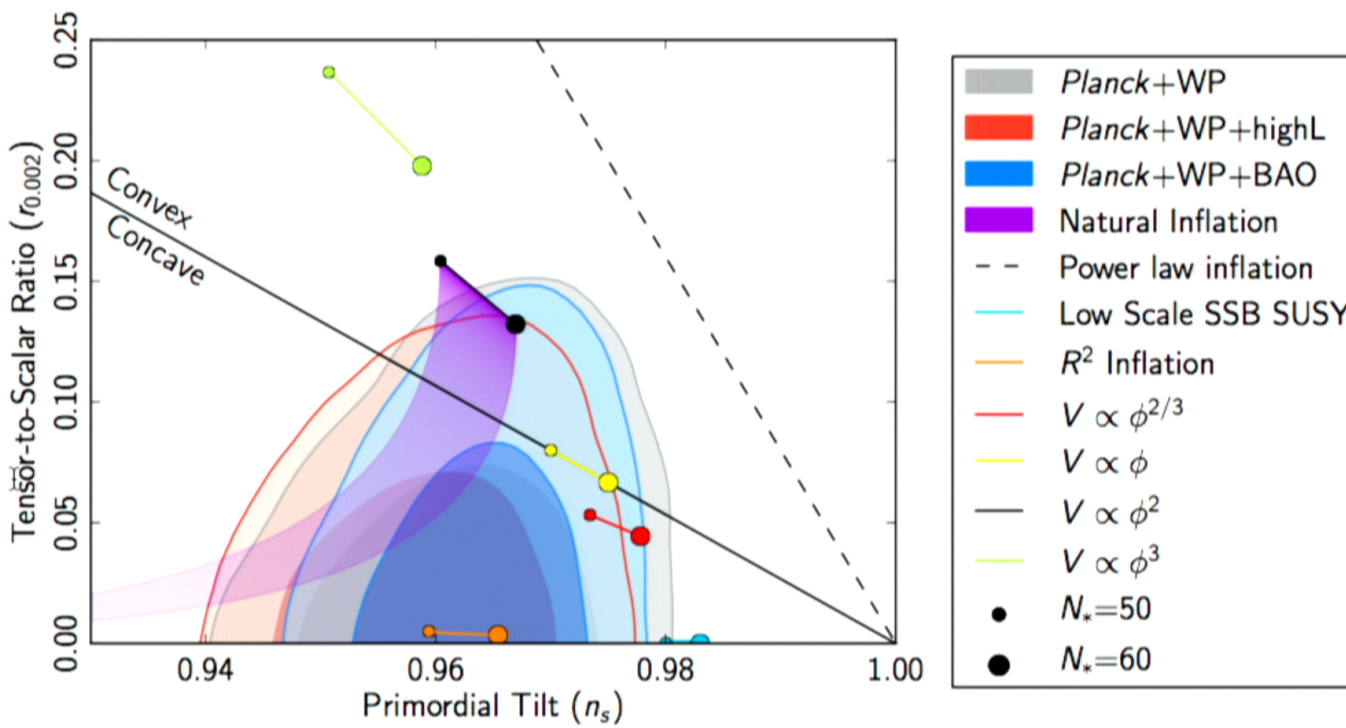
COrE : Cosmic Origins Explorer

A space mission for measuring microwave band polarization on the full sky

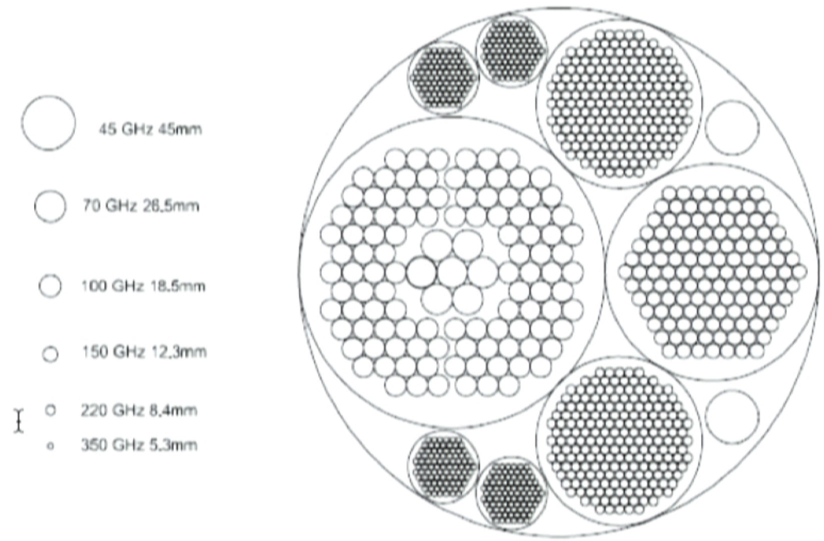


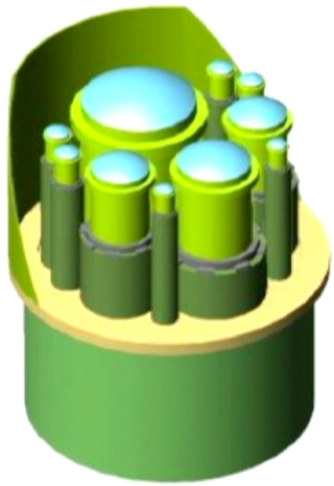
Martin Bucher, APC Paris
for the COrE Collaboration

Implications for inflation—summary plot



B-Pol (2007)


45 GHz 45mm
70 GHz 26.5mm
100 GHz 18.5mm
150 GHz 12.3mm
220 GHz 8.4mm
350 GHz 5.3mm



COrE: Cosmic Origins Explorer

Proposed to ESA in December 2012 as a Cosmic Vision M3 Mission for ≈ 2020
http://www.core-mission.org
White paper available (90 pages) (astro-ph/1102.2181)
Answers to AWG Questions (available on website)

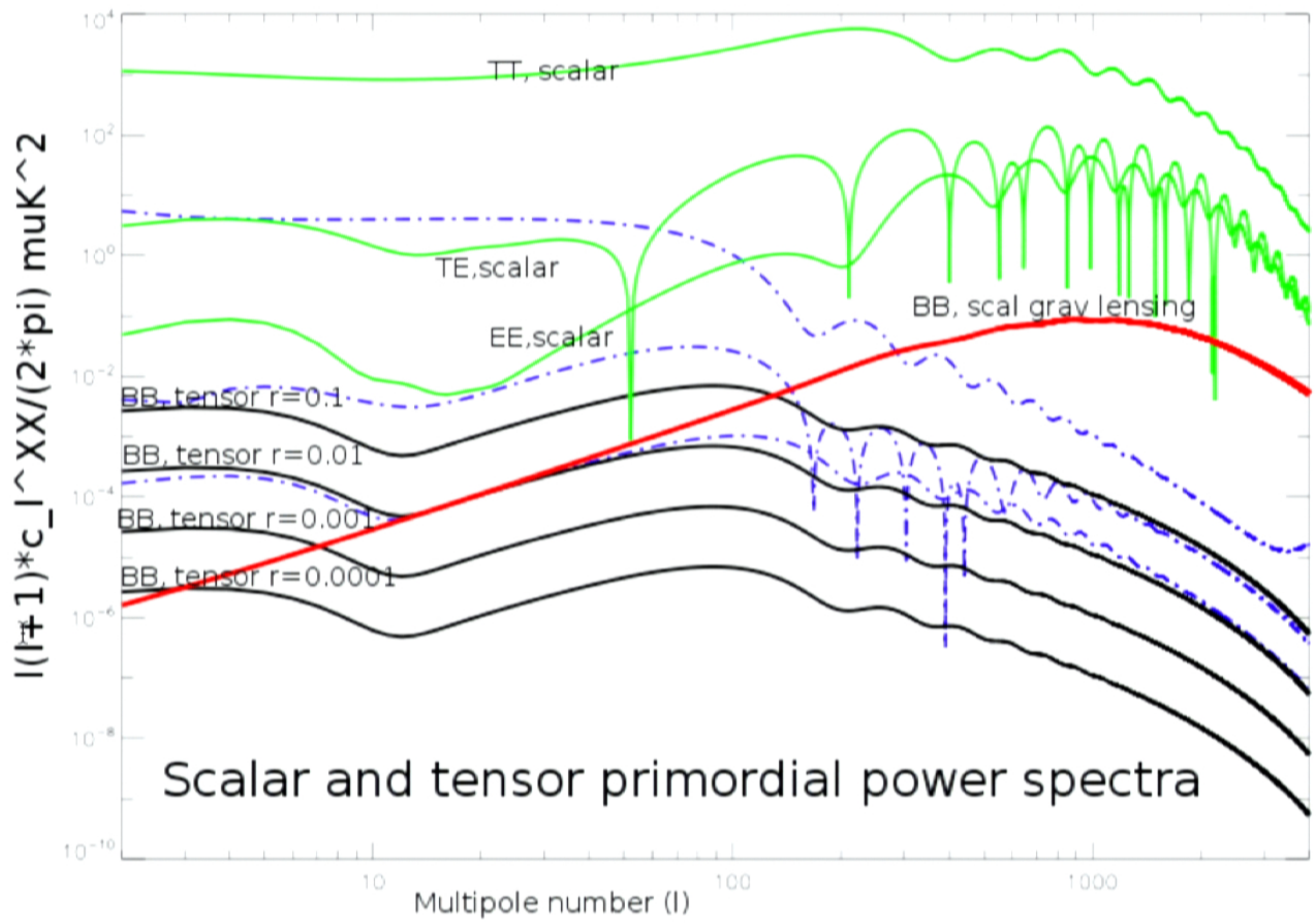
Mission and programmatics working group: F. R. Bouchet, P. de Bernardis, B. Maffei, P. Natoli, M. Piat, N. Ponthieu, R. Stompor

Instrument working group: B. Maffei, M. Bersanelli, P. Bielewicz, P. Camus, P. de Bernardis, M. De Petris, P. Mauskopf, S. Masi, F. Nati, T. Peacocke, F. Piacentini, L. Piccirillo, M. Piat, G. Pisano, M. Salatino, R. Stompor, S. Withington,

Science working group: M. Bucher, M. Avilles, D. Barbosa, N. Bartolo, R. Battye, J.-P. Bernard, F. Boulanger, A. Challinor, S. Chongchitnan, S. Colafrancesco, T. Ensslin, J. Fergusson, P. Ferreira, K. Ferriere, F. Finelli, J. Garcia-Bellido, S. Galli, C. Gauthier, M. Haverkorn, M. Hindmarsh, A. Jaffe, M. Kunz, J. Lesgourgues, A. Liddle, M. Liguori, P. Marchegiani, S. Matarrese, A. Melchiorri, P. Mukherjee, L. Pagano, D. Paoletti, H. Peiris, L. Perroto, C. Rath, J. Rubino Martin, C. Rath, P. Shellard, J. Urrestilla, B. Van Tent, L. Verde, B. Wandelt

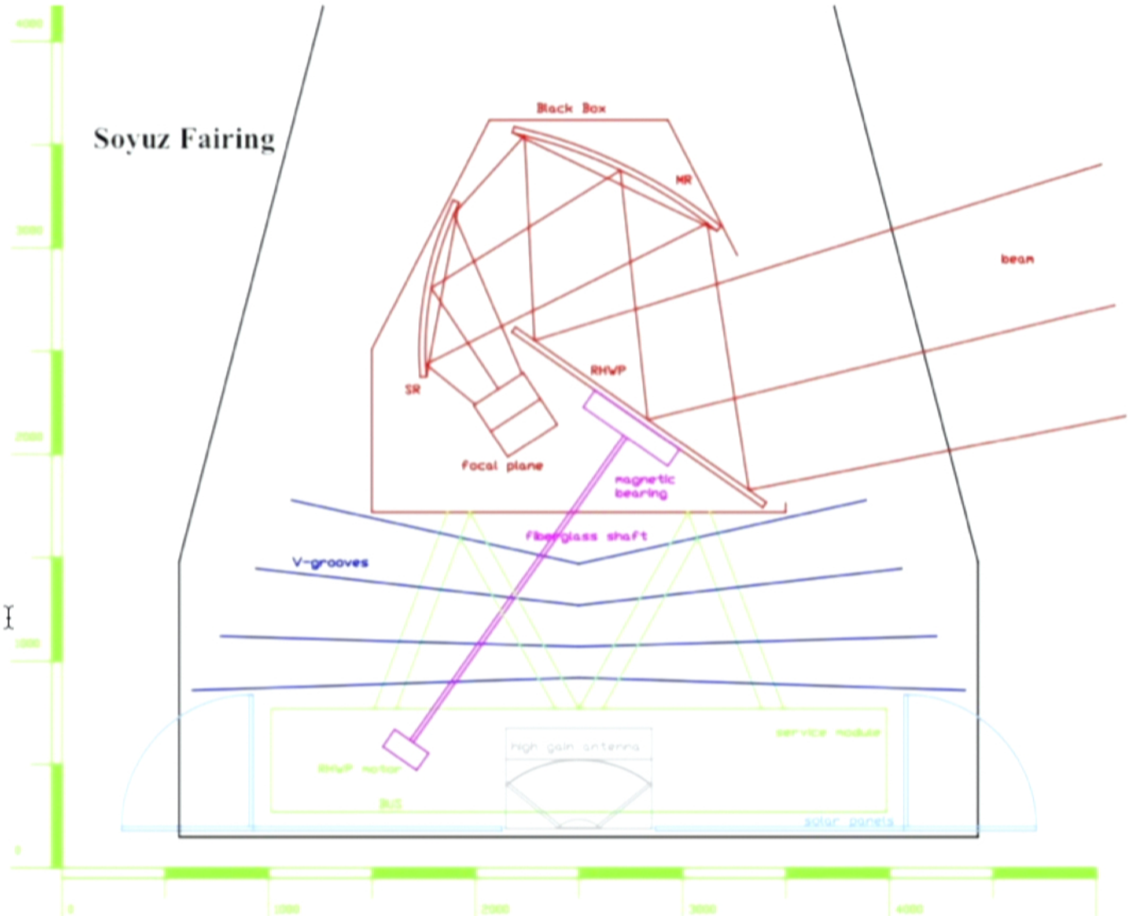
Foregrounds working group: C. Burigana, J. Delabrouille, C. Armitage-Caplan, A. Banday, S. Basak, A. Bonaldi, D. Clements, G. De Zotti, C. Dickinson, J. Dunkley, M. Lopez-Caniego, E. Martinez-Gonzalez, M. Negrello, S. Ricciardi, L. Toffolatti

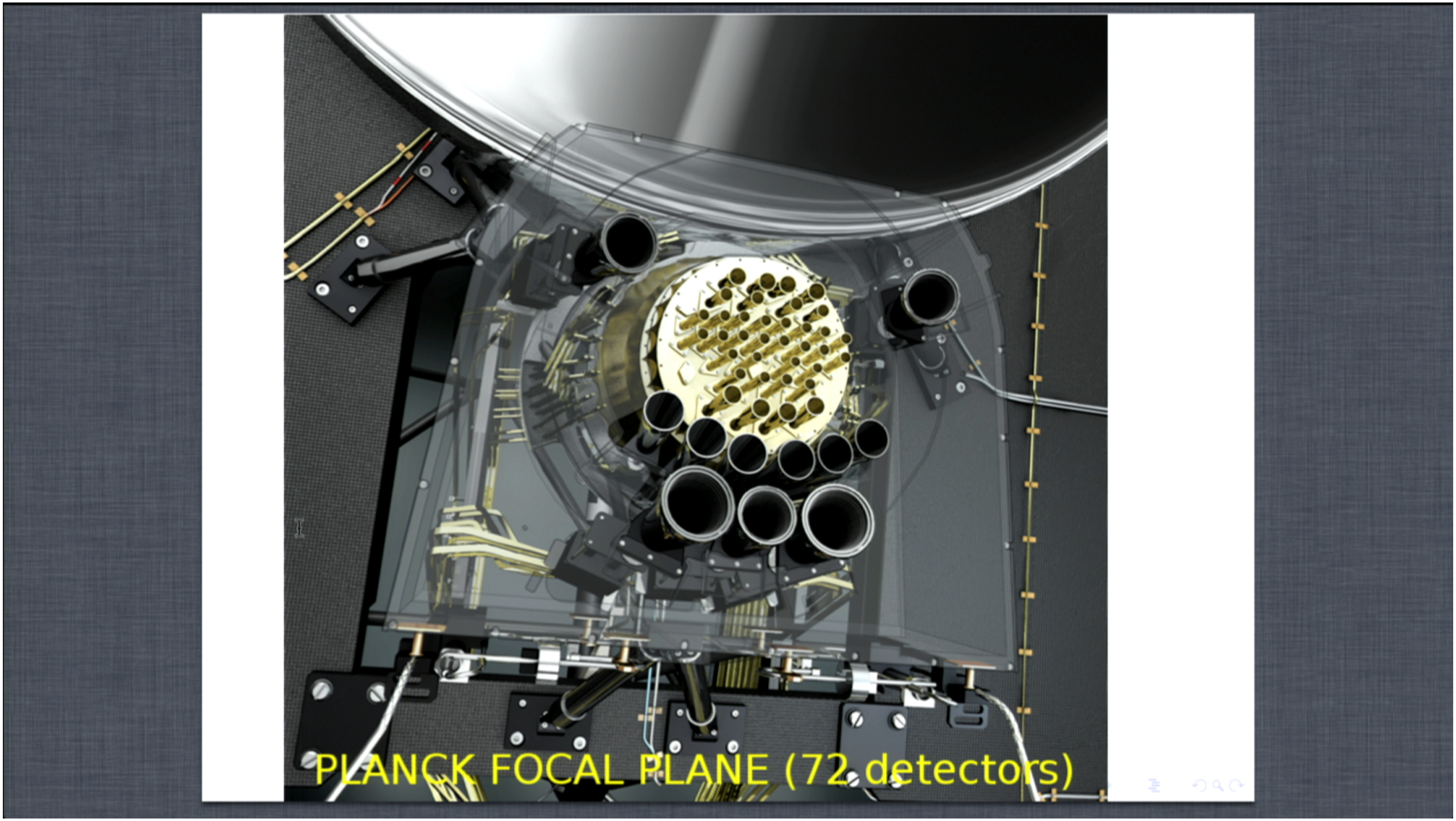
Page 18 of 68



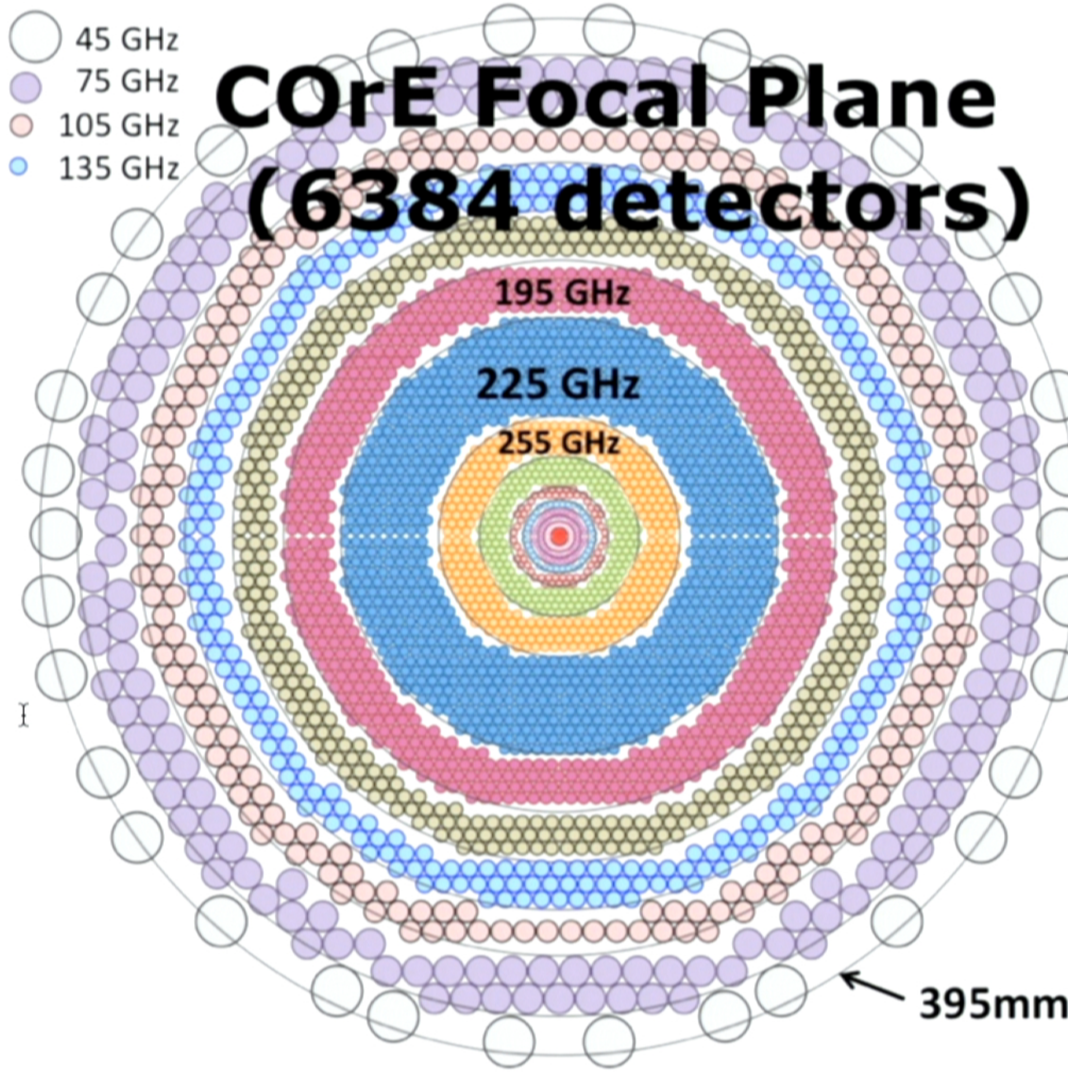
TT, scalar
TE,scalar
EE,scalar
BB, scal grav lensing
BB, tensor r=0.1
BB, tensor r=0.01
BB, tensor r=0.001
BB, tensor r=0.0001
Scalar and tensor primordial power spectra
l(l+1)*c_l^XX/(2*pi) muK^2
Multipole number (l)
10
100
1000

COrE schematic

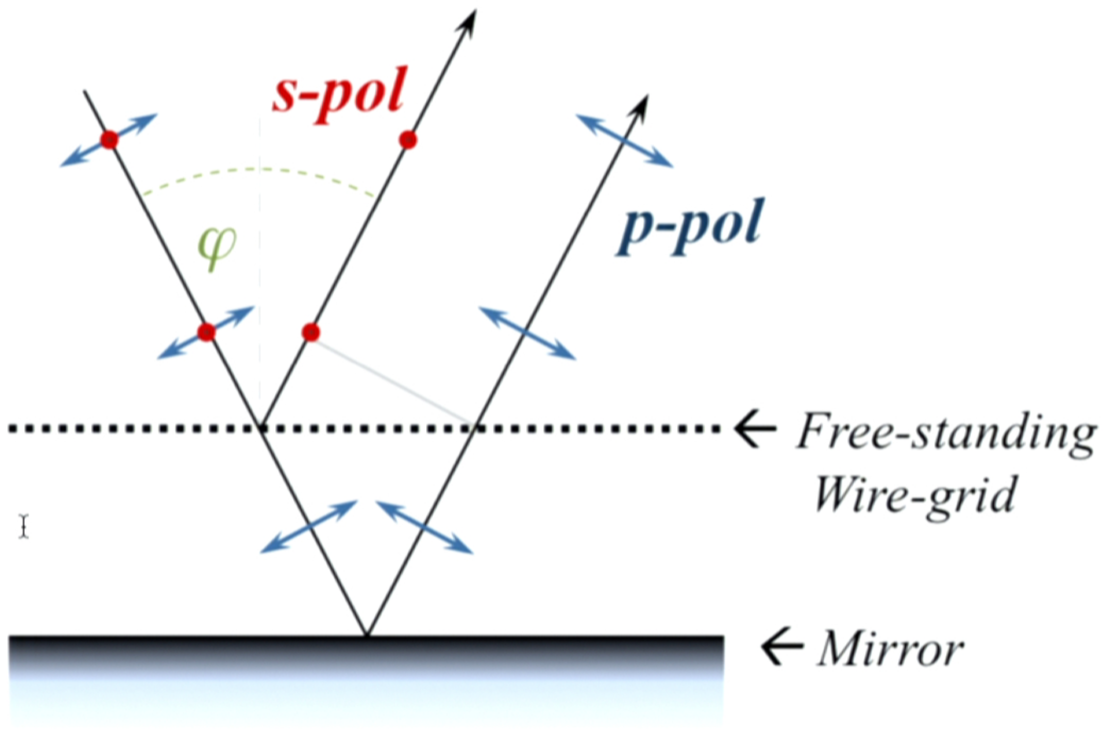



PLANCK FOCAL PLANE (72 detectors)

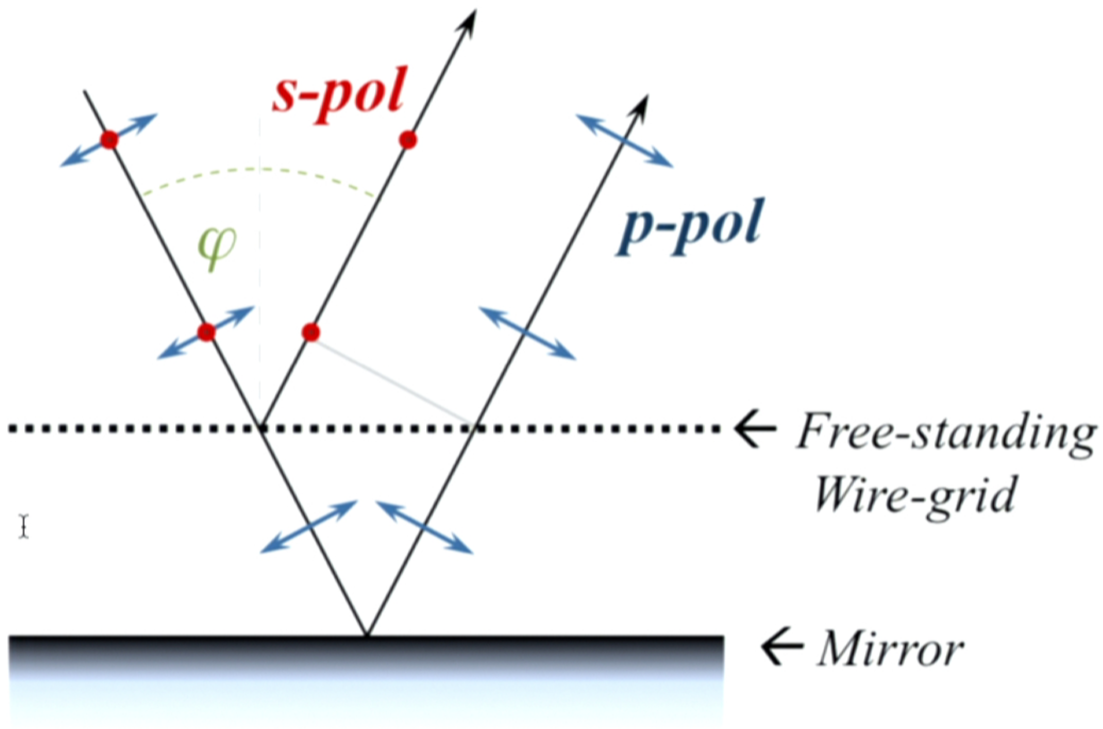
COrE Focal Plane (6384 detectors)



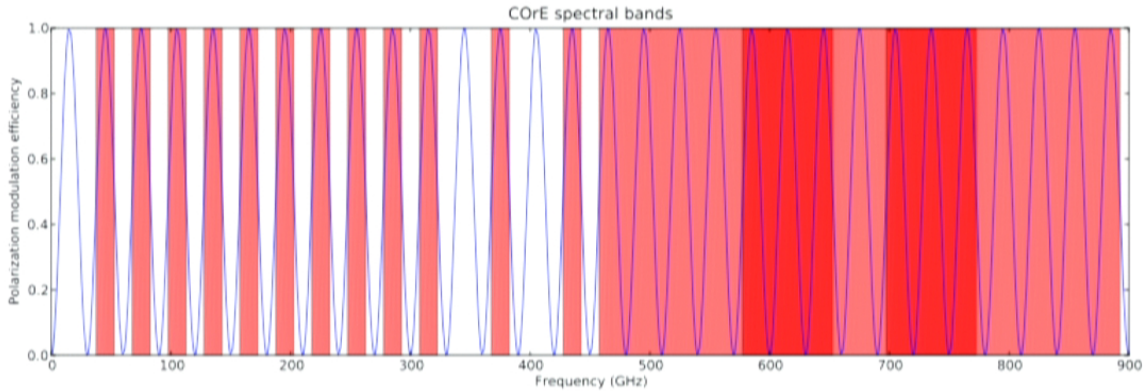
Polarization Modulation—Rotating Half-Wave Plate



Polarization Modulation—Rotating Half-Wave Plate



COrE's 15 Spectral Bands



Note that 3 highest bands overlap

- In order to carry out foreground subtraction and provide redundancy for cross-checks 15 bands are required, minus a few. [3 synchrotron-amp.+spect-ind+running, 1 CMB, 2 free-free, 6 dust (2 BBs A+temp+emmis. index)+1 th.sz=13+2(safety)]

ν GHz	n_{unpol}	n_{pol}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
30	4	4	32.7	198.5	203.2	280.7	287.4
44	6	6	27.9	228.0	239.6	322.4	338.9
70	12	12	13.0	186.5	211.2	263.7	298.7
100	8	8	9.9	23.9	31.3	33.9	44.2
143	11	8	7.2	11.9	20.1	19.7	33.3
217	12	8	4.9	9.4	28.5	16.3	49.4
353	12	8	4.7	7.6	107.0	13.2	185.3
545	3	0	4.7	6.8	1.1×10^3	—	—
857	3	0	4.4	2.9	8.3×10^4	—	—

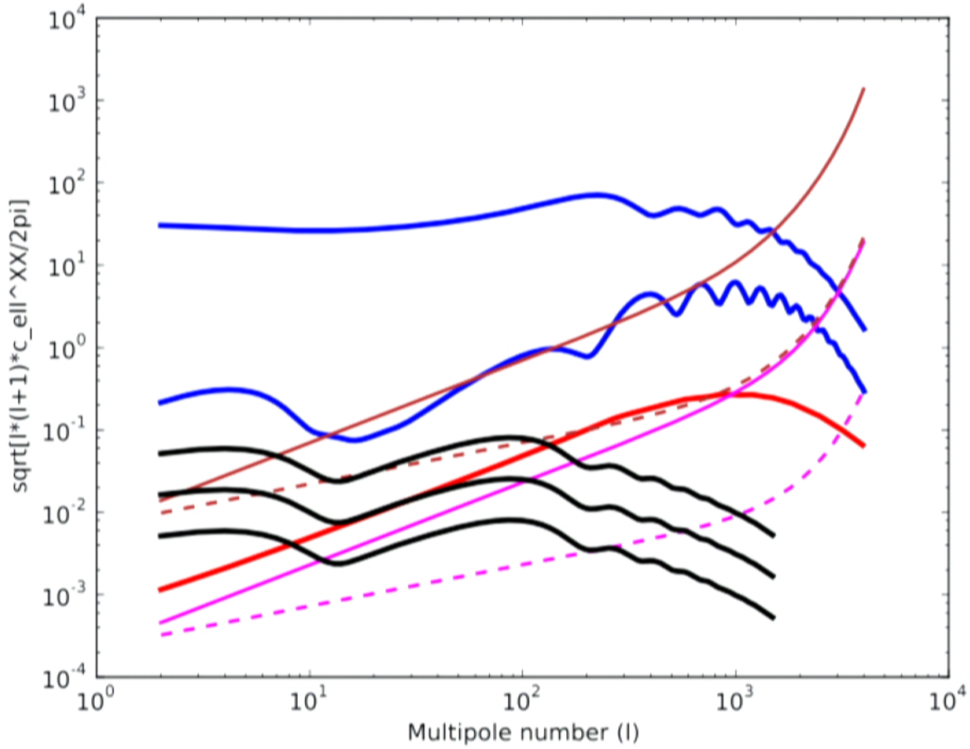
PLANCK (30 month mission)

ν *GHz*	$(\Delta\nu)$ *GHz*	n_{det}	θ_{fwhm} arcmin	Temp (I) $\mu K\cdot$arcmin RJ	Temp (I) $\mu K\cdot$arcmin CMB	Pol (Q,U) $\mu K\cdot$arcmin RJ	Pol (Q,U) $\mu K\cdot$arcmin CMB
45	15	64	23.3	4.98	5.25	8.61	9.07
75	15	300	14.0	2.36	2.73	4.09	4.72
105	15	400	10.0	2.03	2.68	3.50	4.63
135	15	550	7.8	1.68	2.63	2.90	4.55
165	15	750	6.4	1.38	2.67	2.38	4.61
195	15	1150	5.4	1.07	2.63	1.84	4.54
225	15	1800	4.7	0.82	2.64	1.42	4.57
255	15	575	4.1	1.40	6.08	2.43	10.5
285	15	375	3.7	1.70	10.1	2.94	17.4
315	15	100	3.3	3.25	26.9	5.62	46.6
375	15	64	2.8	4.05	68.6	7.01	119
435	15	64	2.4	4.12	149	7.12	258
555	195	64	1.9	1.23	227	3.39	626
675	195	64	1.6	1.28	1320	3.52	3640
795	195	64	1.3	1.31	8070	3.60	22200

COrE summary (4 year mission)

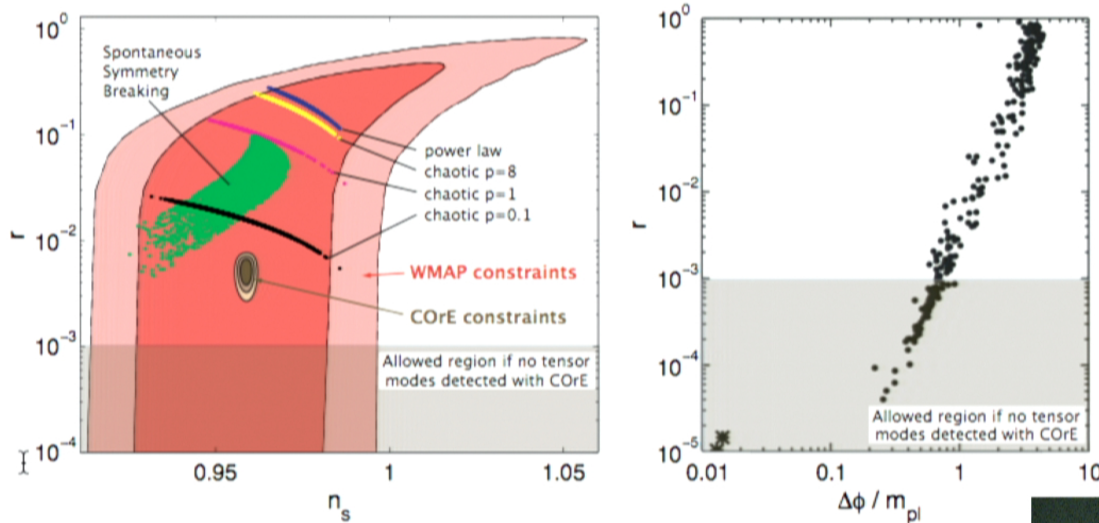
Table: **COrE performance compared to WMAP and PLANCK.**

COrE Planck Sensitivities vs. Expected signal



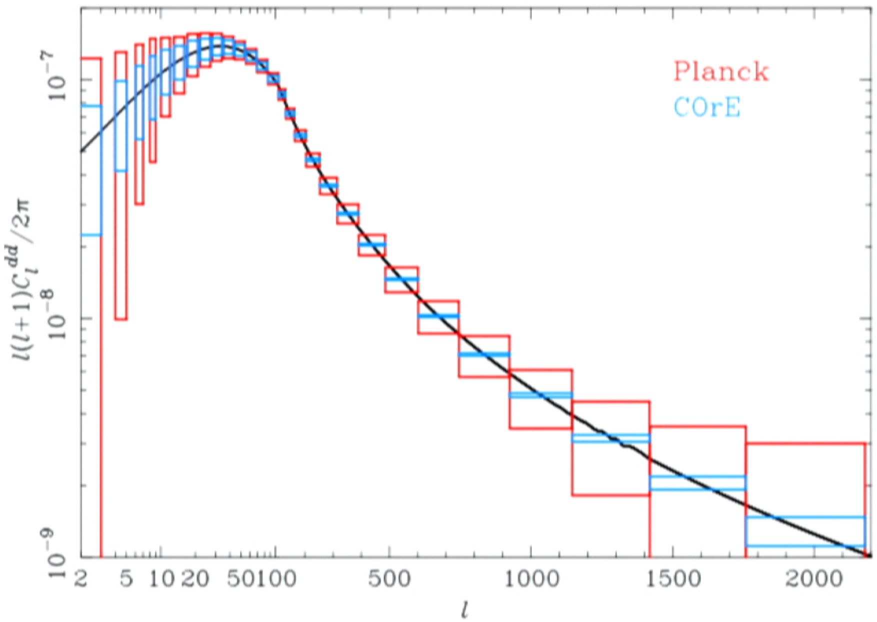
brown=planck; magenta=COrE; dashed = broad binning $\Delta\ell \approx \ell$, black=BB, ten for $r = 10^{-1}$, $r = 10^{-2}$, and $r = 10^{-3}$

Constraining inflation with COrE

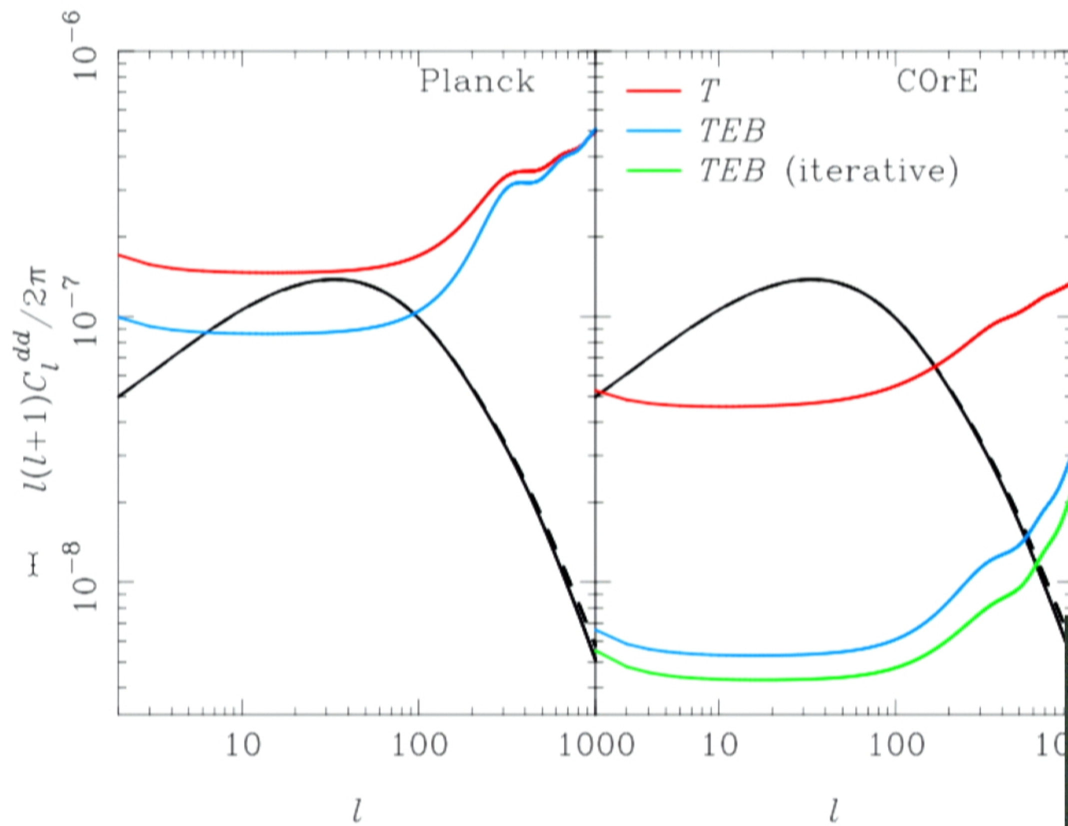


$r = 10^{-3}$ at 3σ at least.

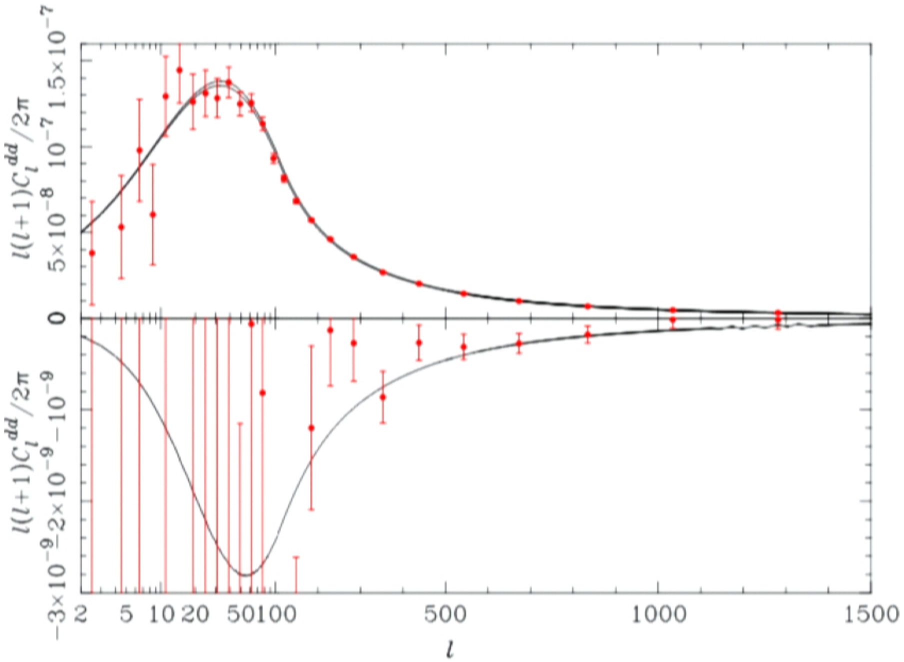
Lensing science with COrE—Measuring the Lensing Deflection Power Spectrum



Lensing reconstruction noise: PLANCK vs COrE



Detecting inverted absolute neutrino mass hierarchy

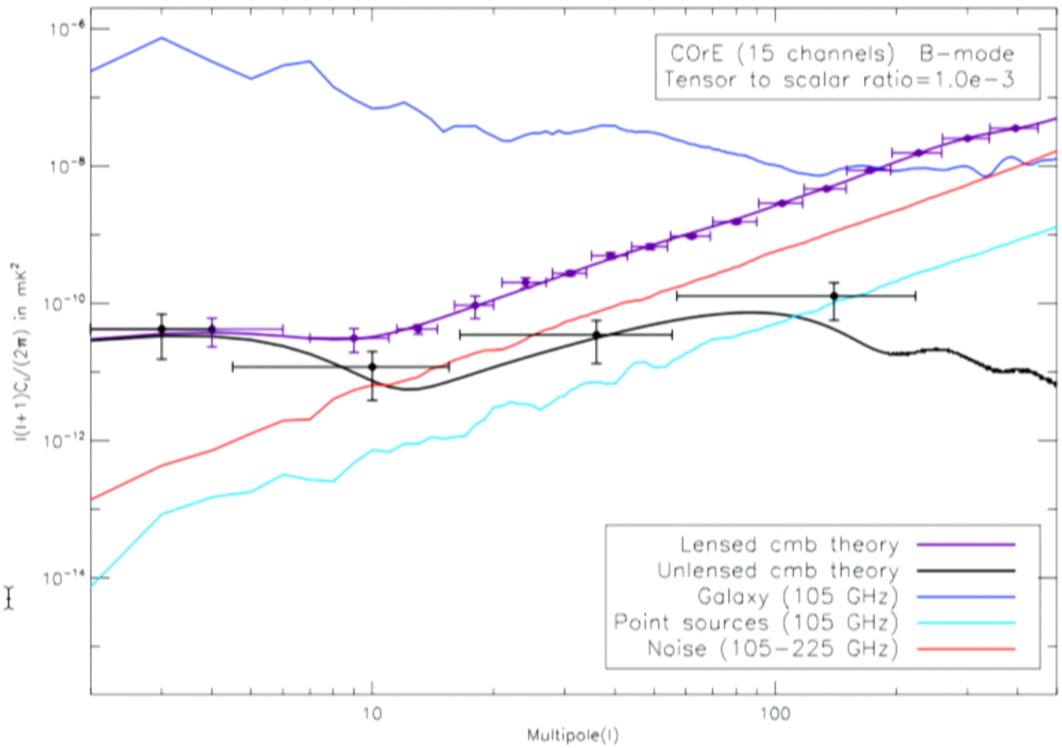


Here we plot $m_\nu^i = 0$ vs. $m_1 = m_2 = 0.05$ eV, $m_3 = 0$

$\sigma(\sum m_\nu^i)$=0.03 eV (COrE with all parameters other parameters determined by COrE), 0.012 eV (with other parameters fixed)
For comparison, KATRIN projection is $\sigma \approx 0.1eV$ on electron neutrino mass.

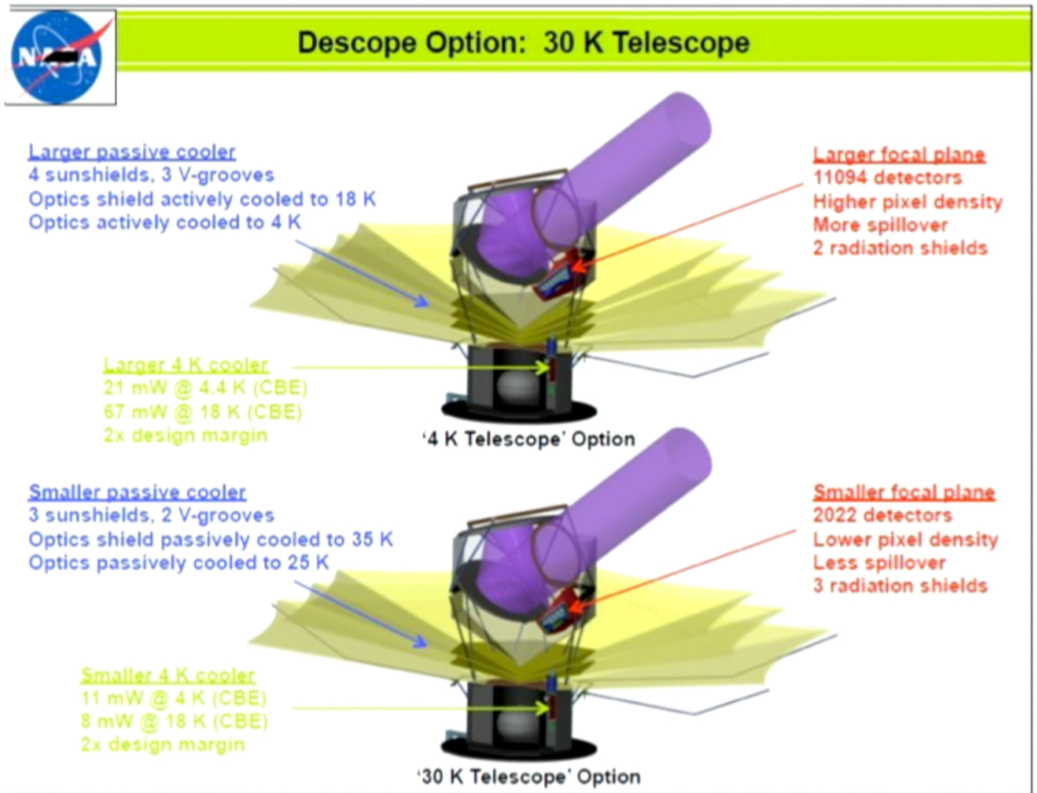
Galactic science with COrE

- The low-frequency data (especially the 45 GHz map) will be 30 times more sensitive than PLANCK LFI and will provide a full-sky view of the synchrotron polarization virtually free of Faraday rotation, which in conjunction with lower frequency data from the ground (eg QUIJOTE ....) can be used to map the galactic magnetic field.
- Above 353 GHz PLANCK has no polarization sensitive bolometers and the resolution is not diffraction limited (4.4 arcmin vs 1.3 arcmin) in highest frequency channel. This will allow high-resolution mapping of the polarized dust emission in diffuse regions not accessible and allow mapping the magnetic field in regions of star formation.
- Numerous new point sources (both polarized and unpolarized) will be discovered across the full sky.



Basak & Delabrouille; similar results from Bonaldi & Ricciardi

US Proposal: EPIC



Page 42 of 68

Prepared for submission to JCAP

arXiv:1105.2044v1 [astro-ph.CO] 10 May 2011

The Primordial Inflation Explorer (PIXIE): A Nulling Polarimeter for Cosmic Microwave Background Observations

A. Kogut[1] D.J. Fixsen[1,2] D.T. Chuss[1] J. Dotson[3] E. Dwek[1] M. Halpern[4] G.F. Hinshaw[4] S.M. Meyer[5] S.H. Moseley[1] M.D. Seiffert[6] D.N. Spergel[7] and E.J. Wollack[1]

[1]Code 665, Goddard Space Flight Center, Greenbelt, MD 20771 USA
[2]University of Maryland, College Park, MD 20742 USA
[3]MS 245-6, Ames Research Center, Moffett Field, CS 94035 USA
[4]University of British Columbia, Vancouver, BC V67 1Z1 Canada
[5]University of Chicago, 5801 South Ellis Ave, Chicago, IL 60637 USA
[6]M/S 169-506, Jet Propulsion Laboratory, Pasadena, CA 91109 USA

E-mail: Alan.J.Kogut@nasa.gov

Abstract. The Primordial Inflation Explorer (PIXIE) is an Explorer-class mission to measure the gravity-wave signature of primordial inflation through its distinctive imprint on the linear polarization of the cosmic microwave background. The instrument consists of a polarizing Michelson interferometer configured as a nulling polarimeter to measure the difference spectrum between orthogonal linear polarizations from two co-aligned beams. Either input can view the sky or a temperature-controlled absolute reference blackbody calibrator. PIXIE will map the absolute intensity and linear polarization (Stokes I, Q, and U parameters) over the full sky in 400 spectral channels spanning 2.5 decades in frequency from 30 GHz to 6 THz (1 cm to 50 μm wavelength). Multi-moded optics provide background-limited sensitivity using only 4 detectors, while the highly symmetric design and multiple signal modulations provide robust rejection of potential systematic errors. The principal science goal is the detection and characterization of linear polarization from an inflationary epoch in the early universe, with tensor-to-scalar ratio $r < 10^{-3}$ at 5 standard deviations. The rich PIXIE data set will also constrain physical processes ranging from Big Bang cosmology to the nature of the first stars to physical conditions within the interstellar medium of the Galaxy.

Keywords: CMBR experiments, CMBR polarisation, inflation, reionization

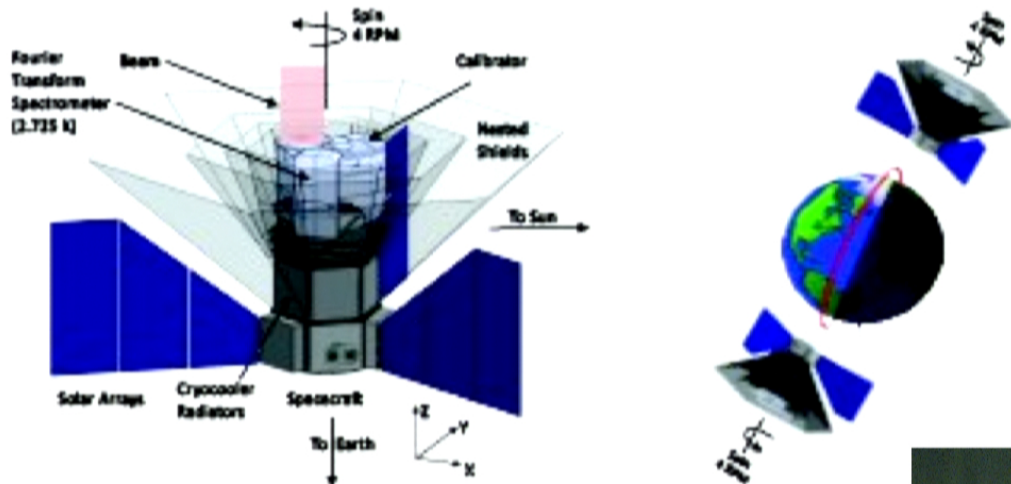
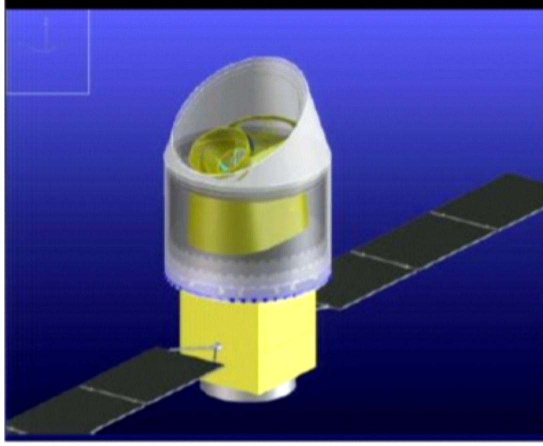


Figure 4. PIXIE observatory and mission concept. The instrument is maintained at 2.725
surrounded by shields to block radiation from the Sun or Earth. It observes from a 660 km p
synchronous terminator orbit. The rapid spin and interferometer stroke efficiently separate
Q, and U parameters independently within each pixel to provide a nearly diagonal covarianc

ビッグバン以前の宇宙を探るLiteBIRD衛星

Lite (light) Satellite for the studies of **B**-mode polarization and **I**nflation from cosmic background **R**adiation **D**etection

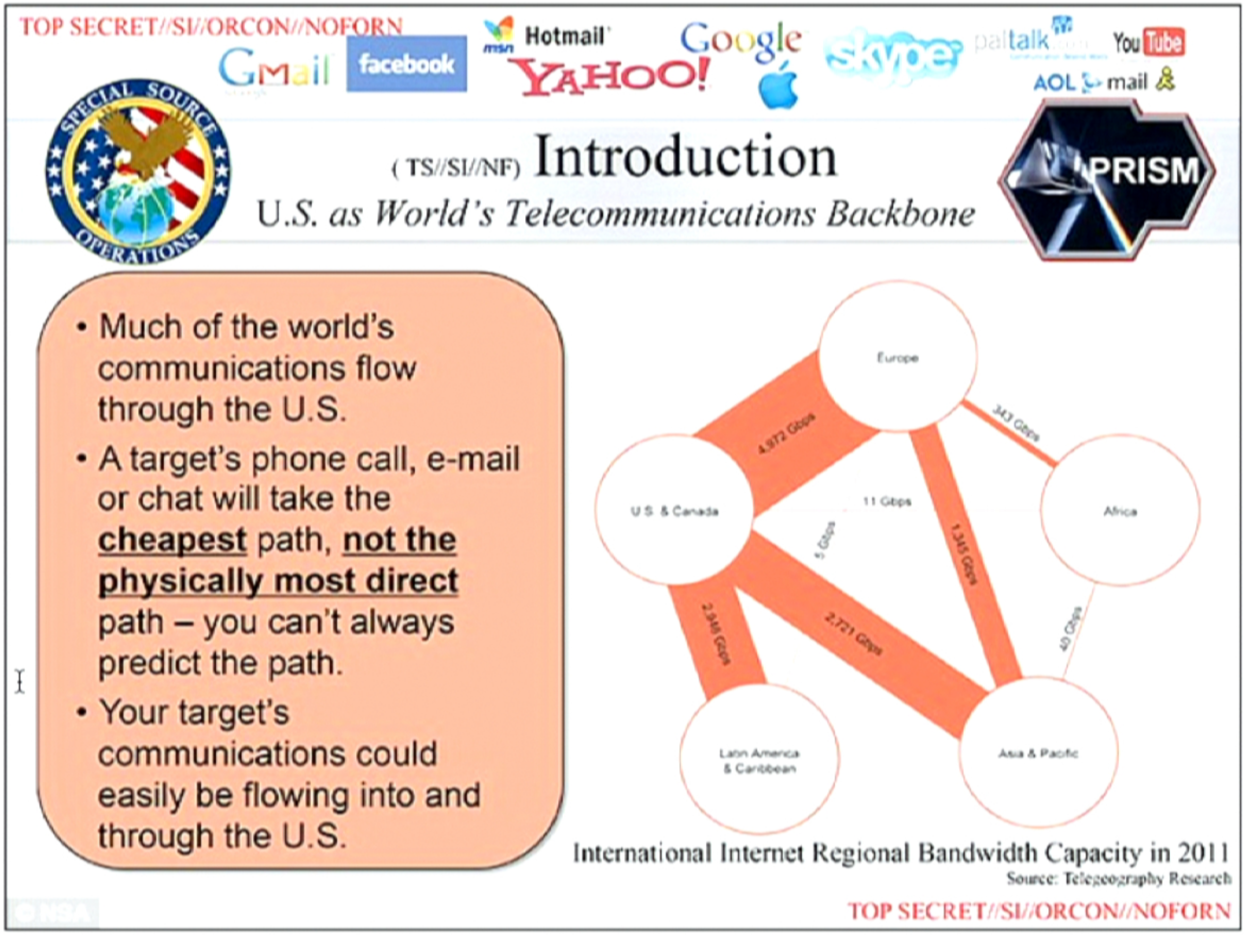


高エネルギー加速器研究機構(KEK)
素粒子原子核研究所
宇宙背景放射(CMB)実験グループ
羽澄昌史(はずみまさし)
for the LiteBIRD Working Group

第1回小型科学衛星シンポジウム
2011年3月1日

This talk is dedicated to Bruce Win

PRISM



Key source: PRISM has been described by NSA officials 'as the most prolific contributor to the president's Daily Brief,' providing analysts with a wealth of 'raw material'

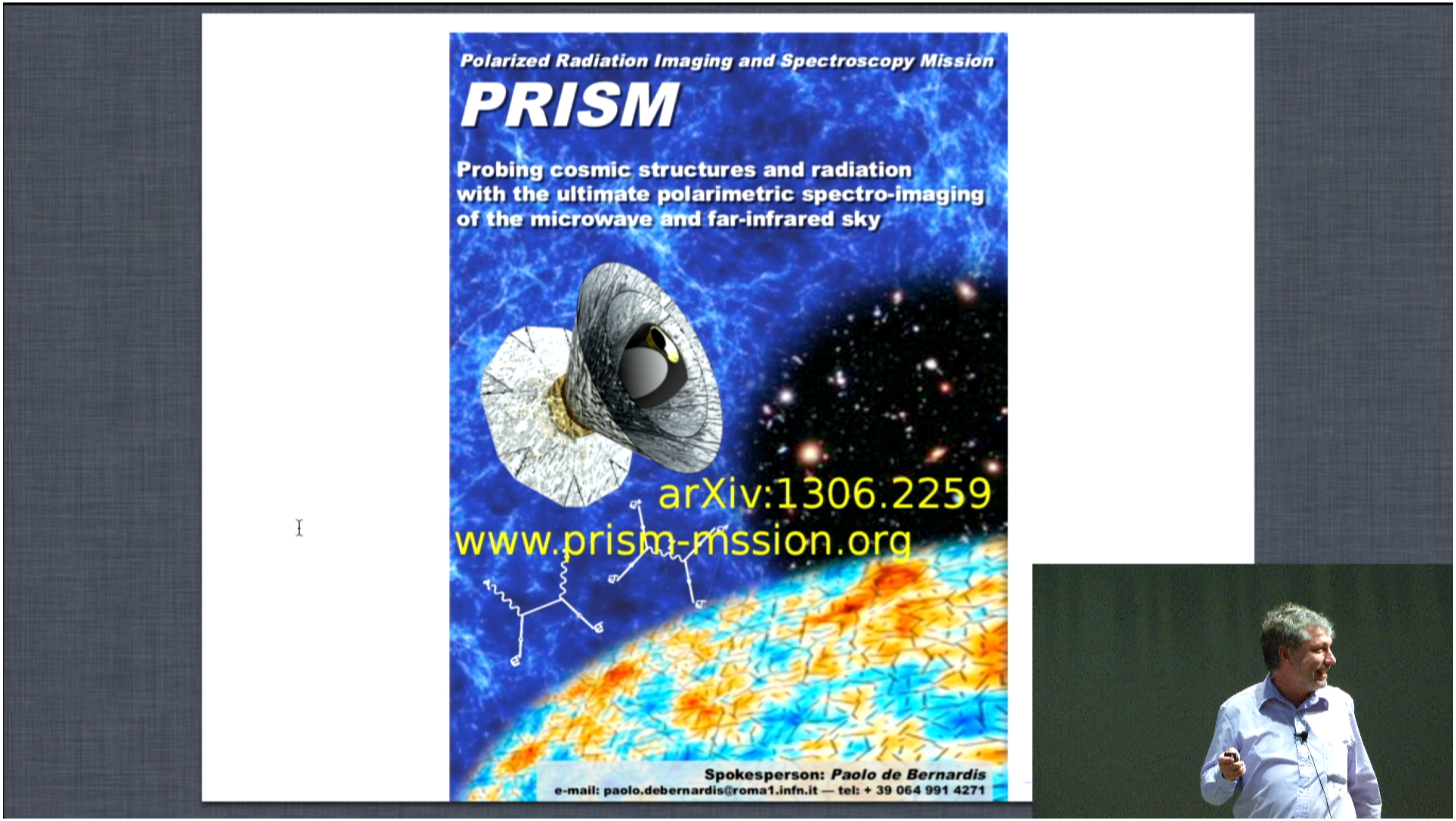
European support for NSA PRISM

UK gathering secret intelligence via covert NSA operation

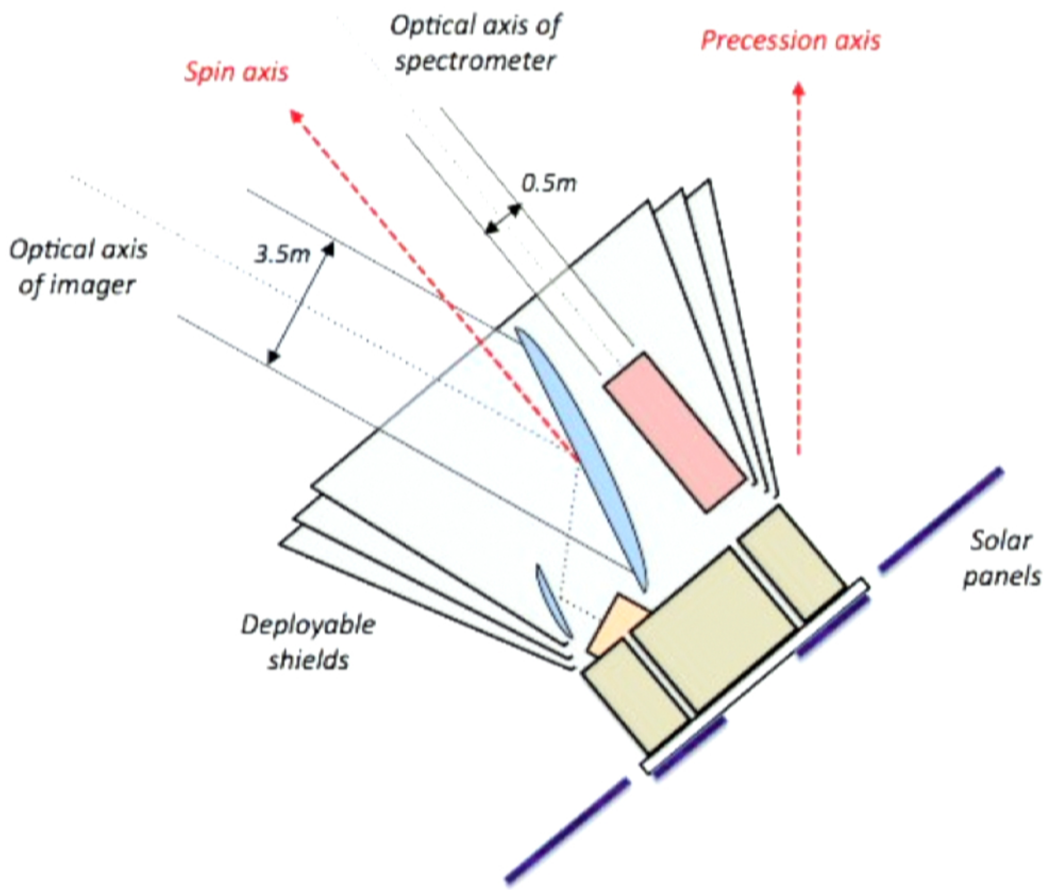
Exclusive: UK security agency GCHQ gaining information from world's biggest internet firms through US-run Prism programme

Nick Hopkins
guardian.co.uk, Friday 7 June 2013 14.27 BST

Documents show GCHQ (above) has had access to the NSA's Prism programme since at least June 2010. Photograph: David Goddard/Getty Images

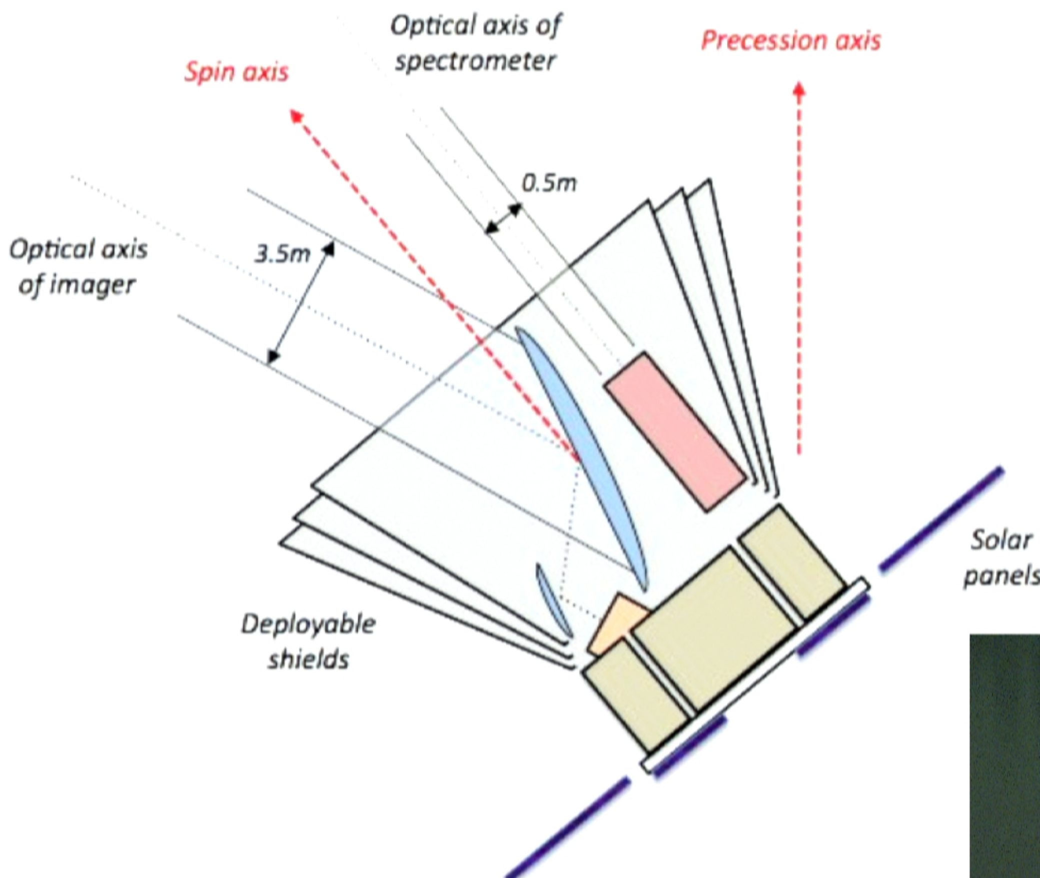

Polarized Radiation Imaging and Spectroscopy Mission
PRISM
Probing cosmic structures and radiation
with the ultimate polarimetric spectro-imaging
of the microwave and far-infrared sky
arXiv:1306.2259
www.prism-mssion.org
Spokesperson: Paolo de Bernardis
e-mail: paolo.debernardis@roma1.infn.it — tel: + 39 064 991 4271

PRISM "Strawman" instrument concept



PRISM spacecraft with its two instru-

PRISM "Strawman" instrument concept



PRISM spacecraft with its two in

PRISM instrument highlights

Two instruments working in tandem:

1. A Polarimeteric Imager
   - 3.5 mirror (cooled to $\approx 4K$) (to be compared with Planck mirror 1.5m not including underilumination)
   - Approximately 7000 detectors deployed at frequencies ranging from 30 GHz to 6 THz (details to be optimized). A small number of detectors with split bands for enhanced spectral sensitivity and targetting galactic emission lines.
   - Elaborate scanning strategy mitigates systematic effects
2. FTS (Fourier Transform Spectrometer)
   - Basic idea is to measure the absolute spectrum with an Martin-Pupplet FTS instrument (like COBE FIRAS but over three orders of magnitude better and similar to PIXIE)
   - Splitting bands with dichroics increases sensitivity
   - Combining with imager (having high angular resolution) provides important synergies

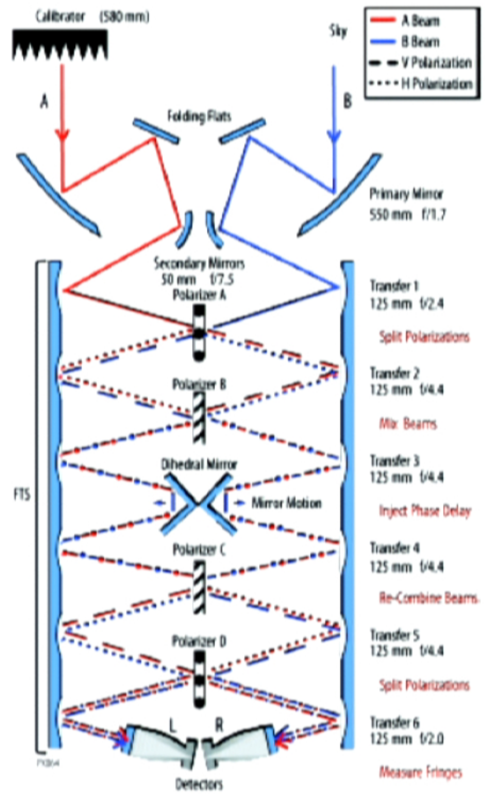
Polarimetric imager—CMBchannels

ν_0 GHz	Range GHz	$\Delta\nu/\nu$	n_{det}	$\theta_{\rm fwhm}$	σ_I per det 1 arcmin		$\sigma_{(Q,U)}$ per det 1 arcmin		Main molec. & atomic lines
					μK$_{\rm RJ}$	μK$_{\rm CMB}$	μK$_{\rm RJ}$	μK$_{\rm CMB}$	
30	26-34	.25	50	17'	61.9	63.4	87.6	89.7	
36	31-41	.25	100	14'	57.8	59.7	81.7	84.5	
43	38-48	.25	100	12'	53.9	56.5	76.2	79.9	
51	45-59	.25	150	10'	50.2	53.7	71.0	75.9	
62	54-70	.25	150	8.2'	46.1	50.8	65.2	71.9	
75	65-85	.25	150	6.8'	42.0	48.5	59.4	68.6	
90	78-100	.25	200	5.7'	38.0	46.7	53.8	66.0	HCN & HCO^+ at 89 GHz
105	95-120	.25	250	4.8'	34.5	45.6	48.8	64.4	CO at 110-115 GHz
135	120-150	.25	300	3.8'	28.6	44.9	40.4	63.4	
160	135-175	.25	350	3.2'	24.4	45.5	34.5	64.3	
185	165-210	.25	350	2.8'	20.8	47.1	29.4	66.6	HCN & HCO^+ at 177 GHz
200	180-220	.20	350	2.5'	18.9	48.5	26.7	68.6	
220	195-250	.25	350	2.3'	16.5	50.9	23.4	71.9	CO at 220-230 GHz
265	235-300	.25	350	1.9'	12.2	58.5	17.3	82.8	HCN & HCO^+ at 266 GHz
300	270-330	.20	350	1.7'	9.6	67.1	13.6	94.9	
320	280-360	.25	350	1.6'	8.4	73.2	11.8	103	CO, HCN & HCO^+
395	360-435	.20	350	1.3'	4.9	107	7.0	151	
460	405-520	.25	350	1.1'	3.1	156	4.4	221	CO, HCN & HCO^+
555	485-625	.25	300	55"	1.6	297	2.3	420	C-I, HCN, HCO^+, H_2O, CO
660	580-750	.25	300	46"	0.85	700	1.2	990	CO, HCN & HCO^+

Polarimetric imager—high-frequency channels

					nK_{RJ}	kJy/sr	nK_{RJ}	kJy/sr	
800	700-900	.25	200	38"	483	9.5	683	13.4	
960	840-1080	.25	200	32"	390	11.0	552	15.6	
1150	1000-1300	.25	200	27"	361	14.6	510	20.7	
1380	1200-1550	.25	200	22"	331	19.4	468	27.4	N-II at 1461 GHz
1660	1470-1860	.25	200	18"	290	24.5	410	34.7	
1990	1740-2240	.25	200	15"	241	29.3	341	41.5	C-II at 1900 GHz
2400	2100-2700	.25	200	13"	188	33.3	266	47.1	N-II at 2460 GHz
2850	2500-3200	.25	200	11"	146	36.4	206	51.4	
3450	3000-3900	.25	200	8.8"	113	41.4	160	58.5	O-III at 3393 GHz
4100	3600-4600	.25	200	7.4"	98	50.8	139	71.8	
5000	4350-5550	.25	200	6.1"	91	70.1	129	99.1	O-I at 4765 GHz
6000	5200-6800	.25	200	5.1"	87	96.7	124	136	O-III at 5786 GHz

Martin-Pupplet FTS spectrometer–basic concept



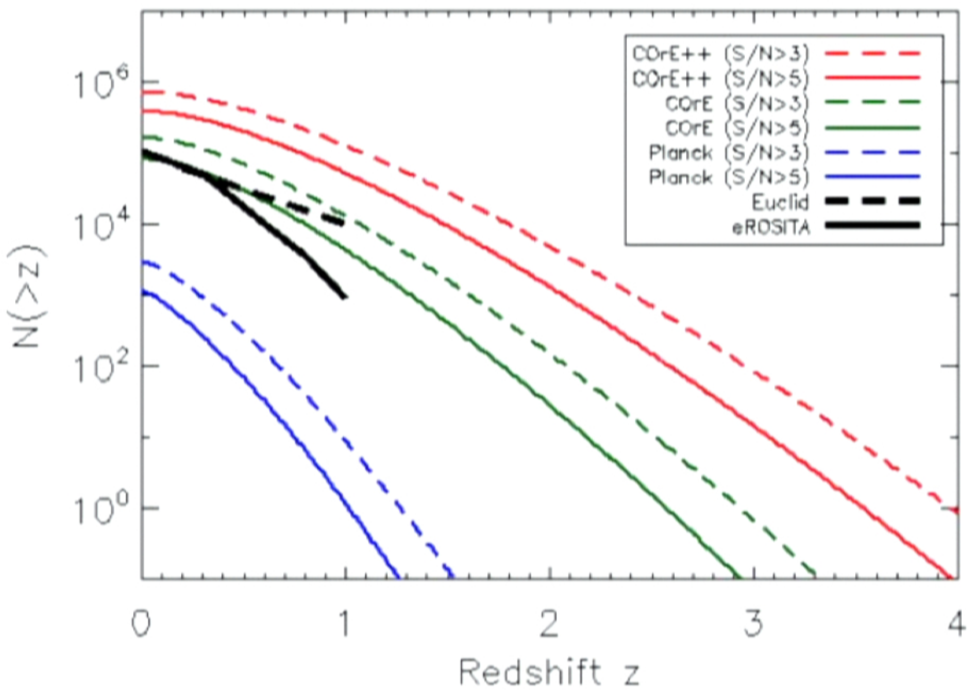
Courtesy of PIXIE collaboration–arXiv:1105.2044

Qualitatively new science made possible by PRISM

- The ultimate cluster survey 10^6 clusters including many at $z > 1$ Significantly surpasses eRosita, which will be the state-of-the-art when PRISM flies. Temperature will be measured based on relativistic corrections to the SZ spectral template and peculiar velocities from kSZ.
- Understanding the origin of the CIB (dusty IR galaxies) where most of the star formation in the universe took place
- Detect distortions to the perfect blackbody spectrum (cannot be done with convential CMB experiments that are sensitive only to angular variations and lack an absolute calibration)
- Map the galactic magnetic field both in the hot gas and the diffuse cold regions where star formation takes place.
- Probe B modes from primordial gravitational wave generated during inflation much better than any other experiment even if foregrounds are very messy and probe gravitational lensing.

Expected cluster counts

(Plot courtesy of Jean-Baptiste MELIN)



Relativistic Sunyaev-Zeldovich Effect

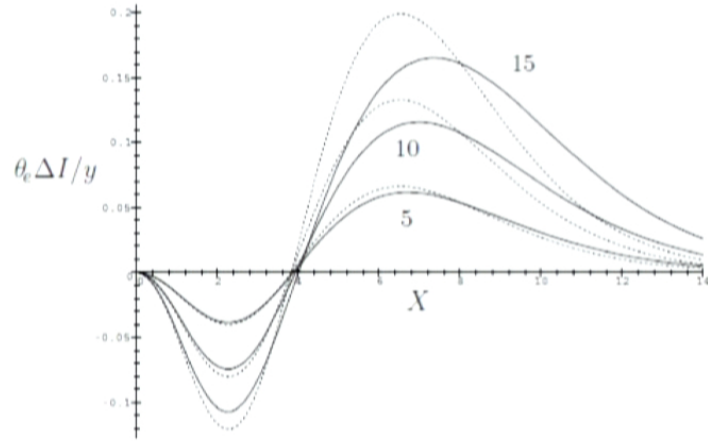
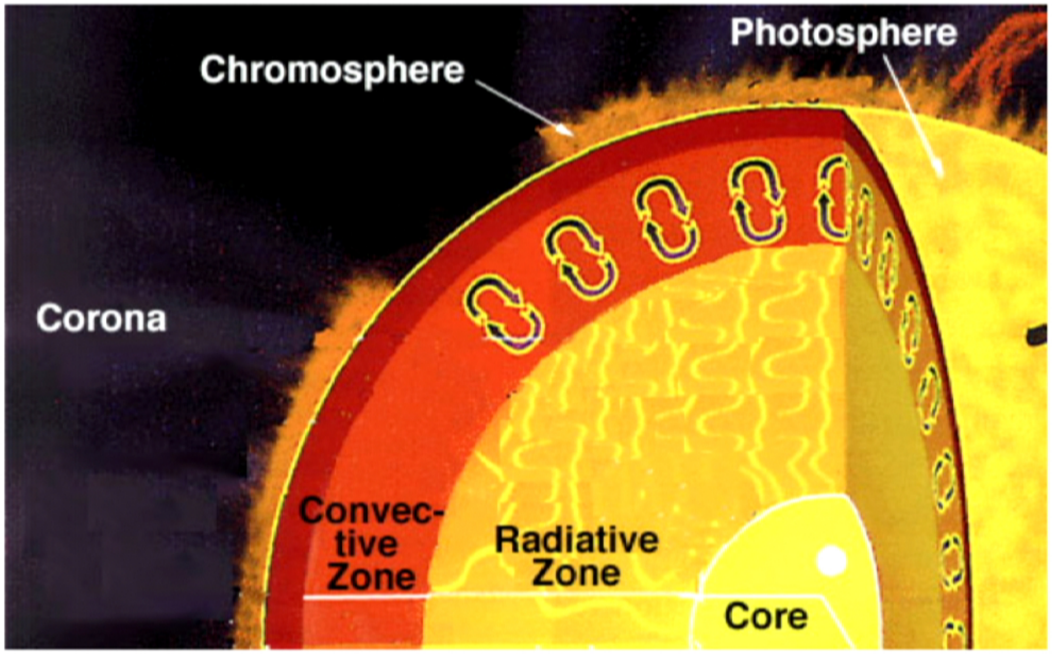


Fig. 1.— *The intensity change $\theta_e \Delta I/y$ (in units of $2(k_B T_0)^3/(hc)^2$) plotted against X for three values of $k_B T_e$ (in keV). The solid curves are calculated using the first-order correction to the Kompaneets equation, while the dashed lines are calculated from the usual Kompaneets expression.*

Allows independent measurement of gas temperature

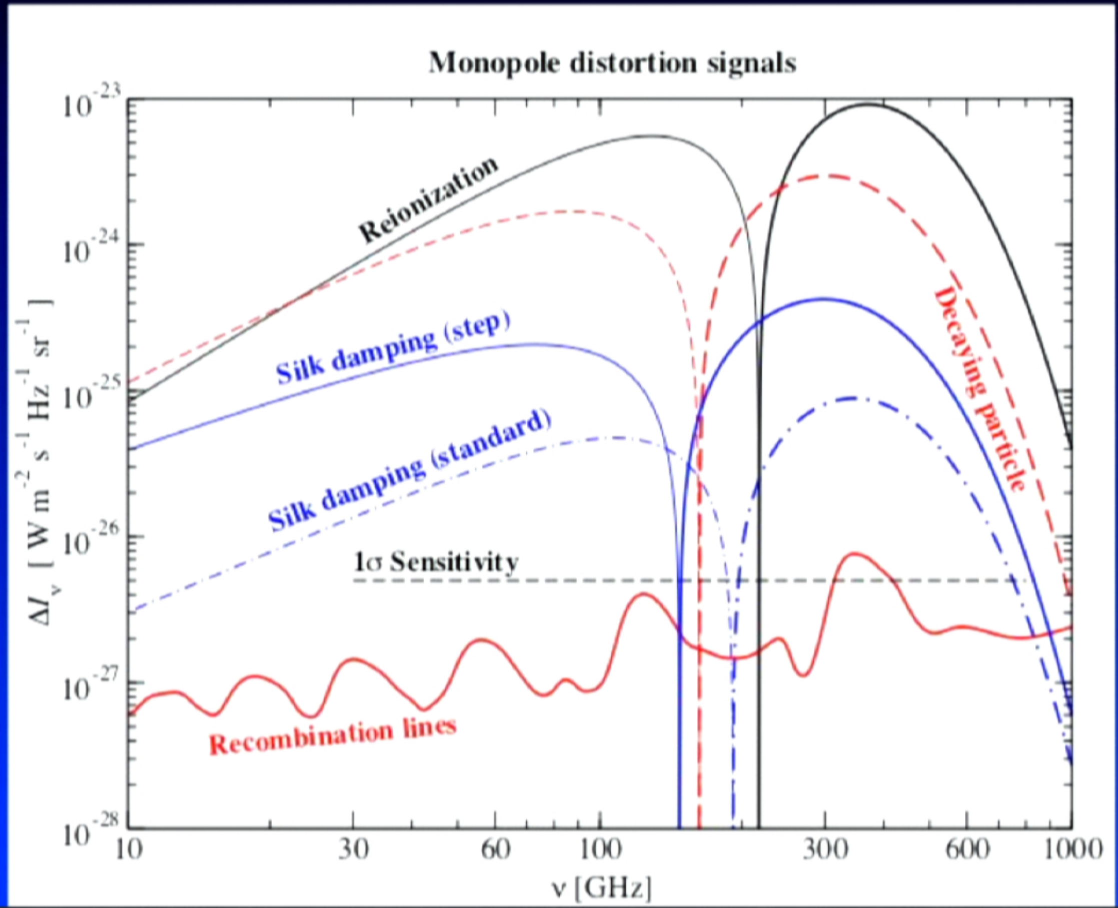
(From Challinor and Lasenby, astro-ph/9711161)

What is the depth of the CMB "photosphere"?



Defined in the same way as for the Sun. How deep can you see?

Average CMB spectral distortions



NSA PRISM vs ESA PRISM

James Clapper, PI NSA Prism

Paolo de Bernardis, ESA Prism Spokeperson

- The NSA wants wants to find out everything about you.
- We want to find out everything about the Universe between 30GHz and 6THz capturing all available signals.

Conclusion:

Help us find out everything there is to know about the universe with PRISM.

Please sign up as a supporter:

www.prism-mission.org

and sign up on email list to receive updates

http://listserv.in2p3.fr/cgi-bin/wa?A0=BPOL-ALL-L