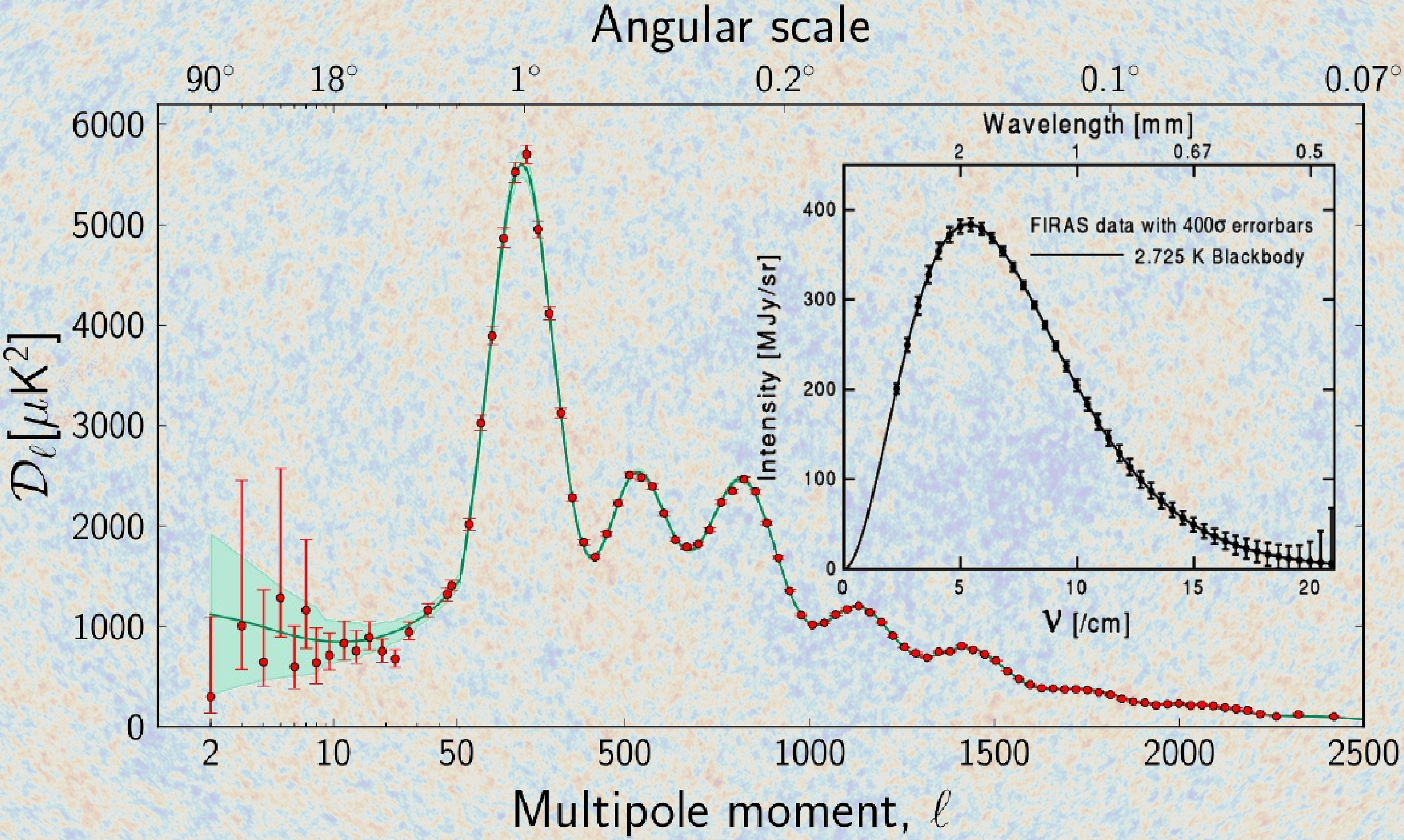
Challenges
present and future in the observation of the CMB from ground and stratosphere

Aniello (Daniele) Mennella

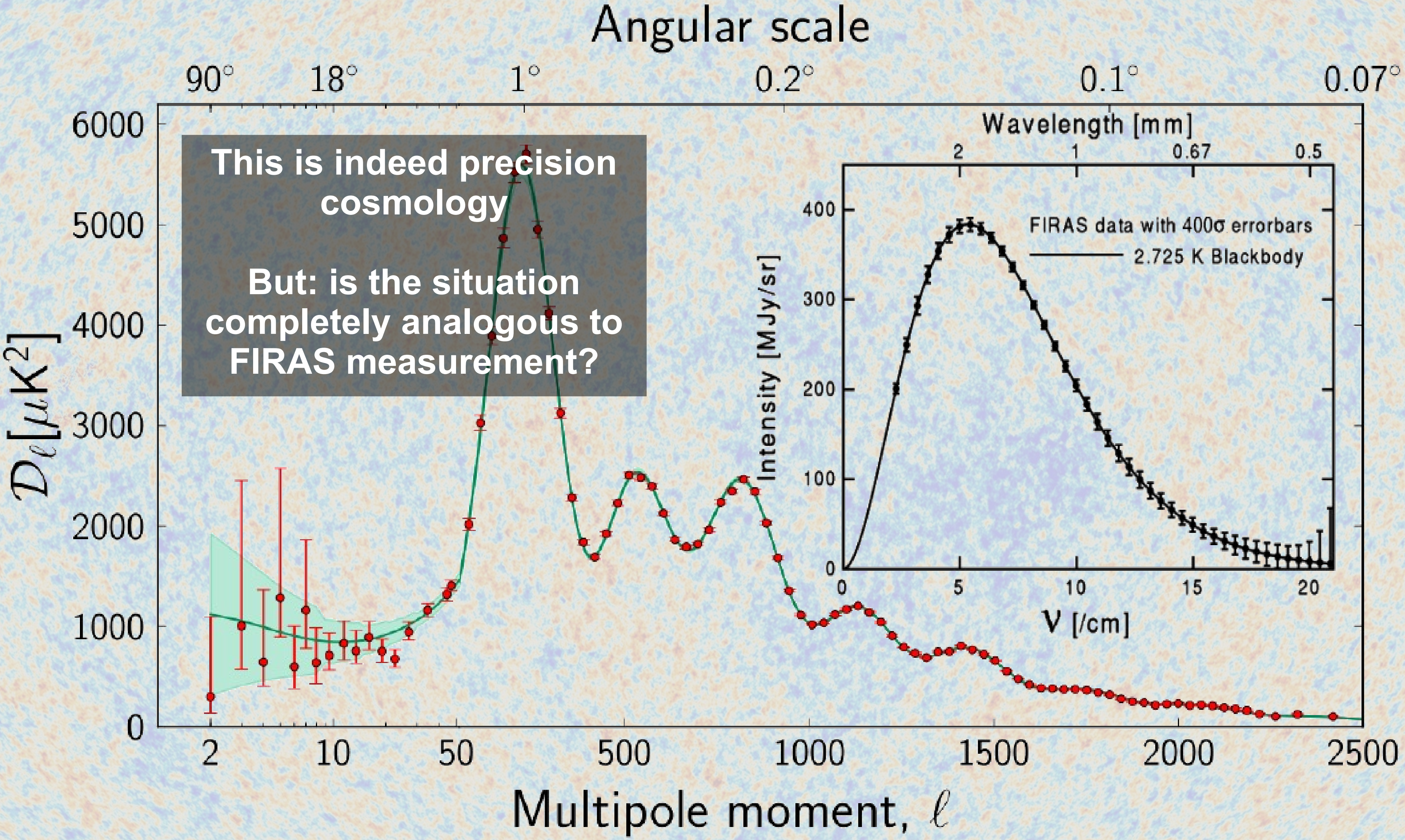
Università degli Studi di Milano –
Dipartimento di Fisica

Where I work and who I work with (+ many others...)

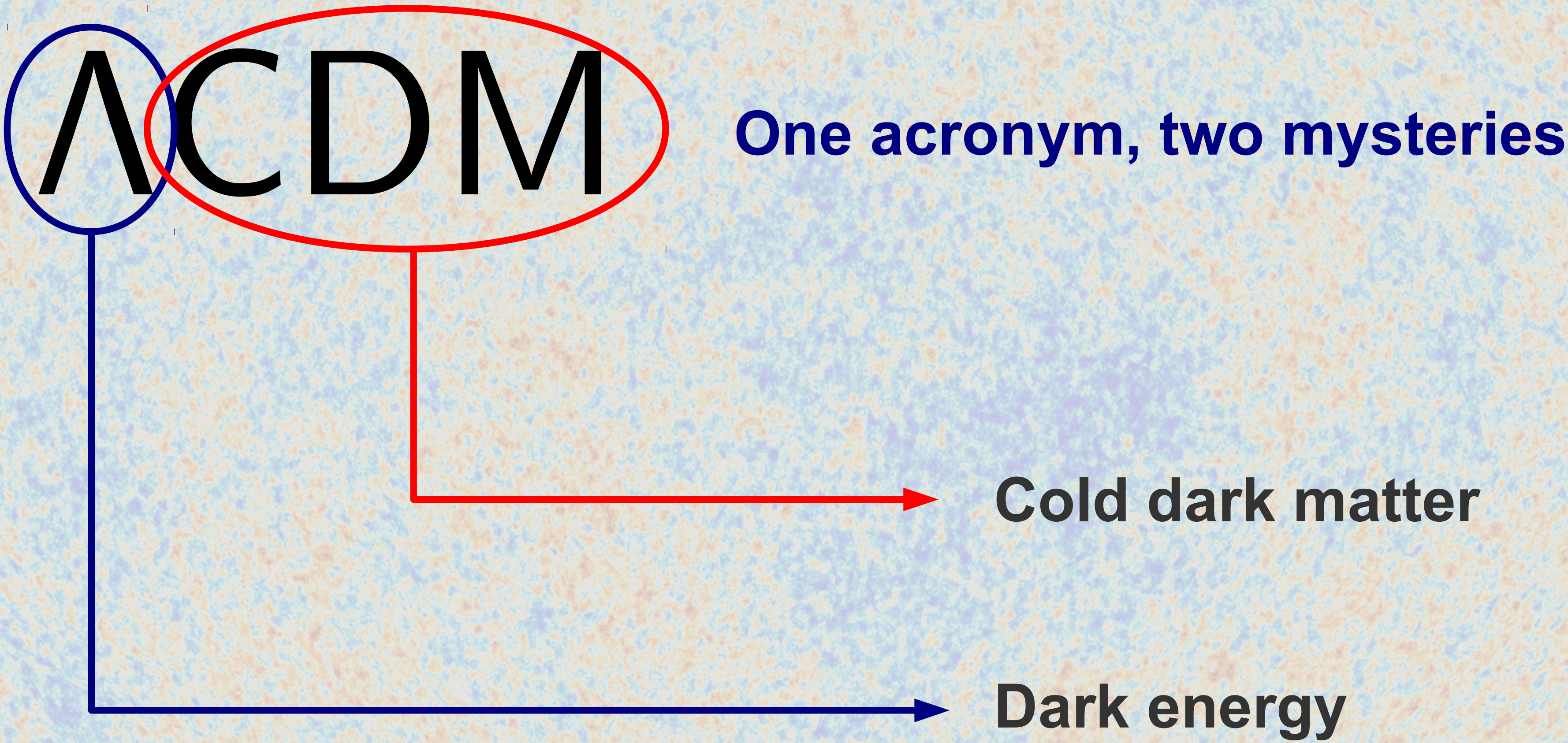
Remarkable agreement



Remarkable agreement



ΛCDM: a “mathematical miracle”? *(Tomasi, 2013)*



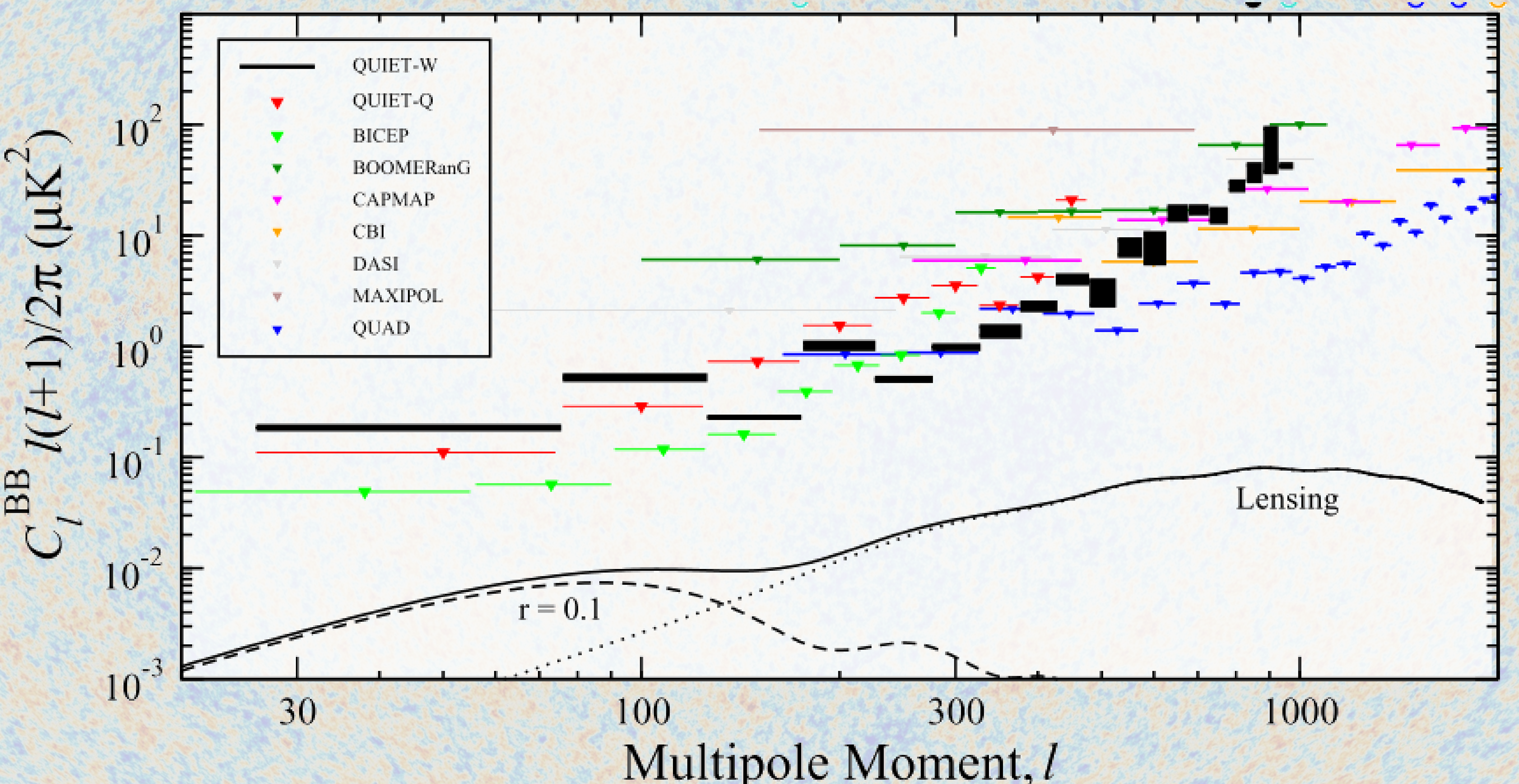
Wandering in “bright fog”
Today's BIG questions

- What is the nature of dark matter?
- Does dark energy exist, what is its nature? Is it constant or does it modify with time?
- Or is it necessary to invoke a modification of General Relativity at large scales? Or of its assumptions?
- Did inflation occur? *(it seems so)* – In which conditions?
- When did the first stars form and in which conditions?

These are big and deep questions, indeed. The CMB is still key to address many of them

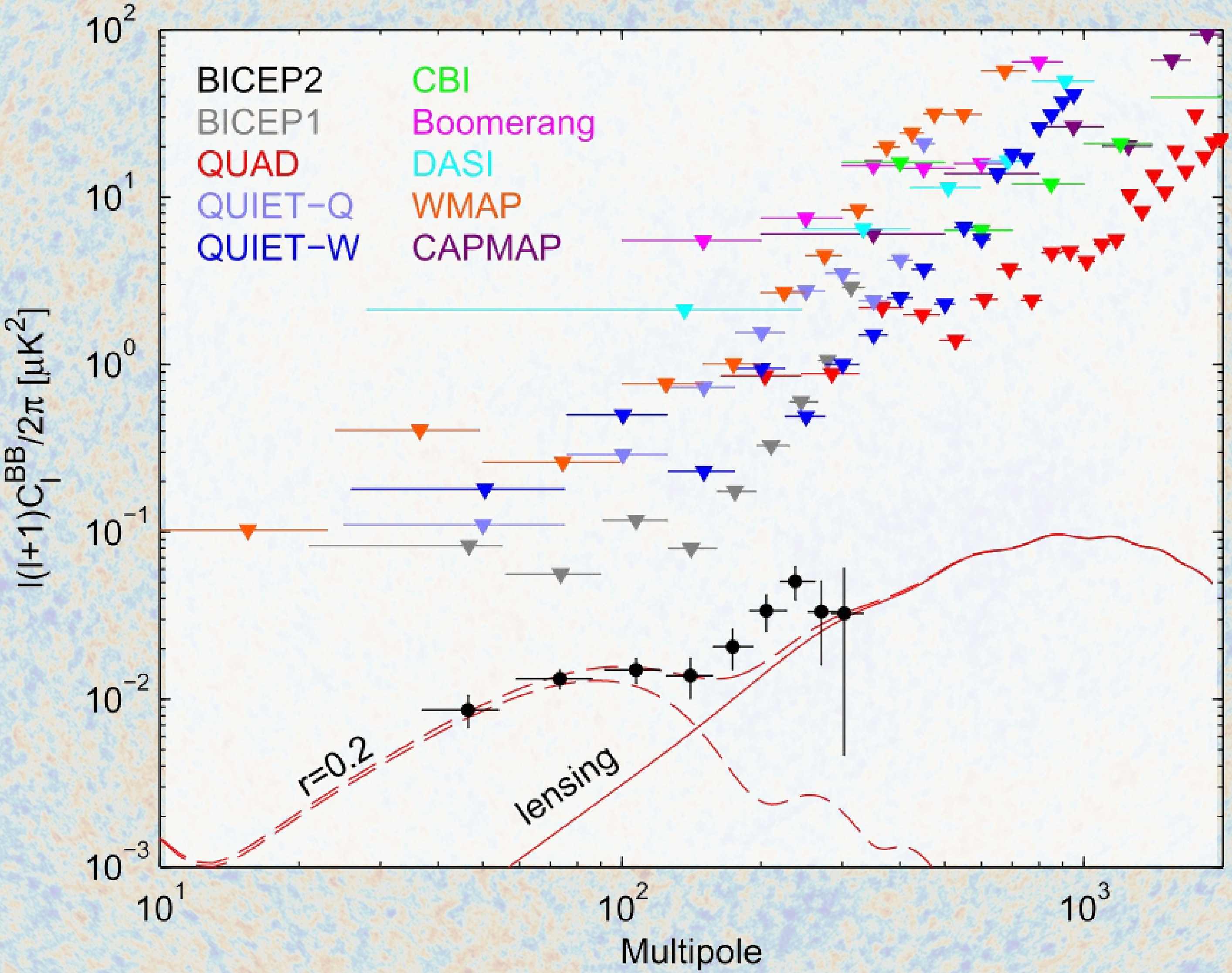
Just a bit more than one month ago

QUIET collaboration, ApJ 2012



17 March 2014

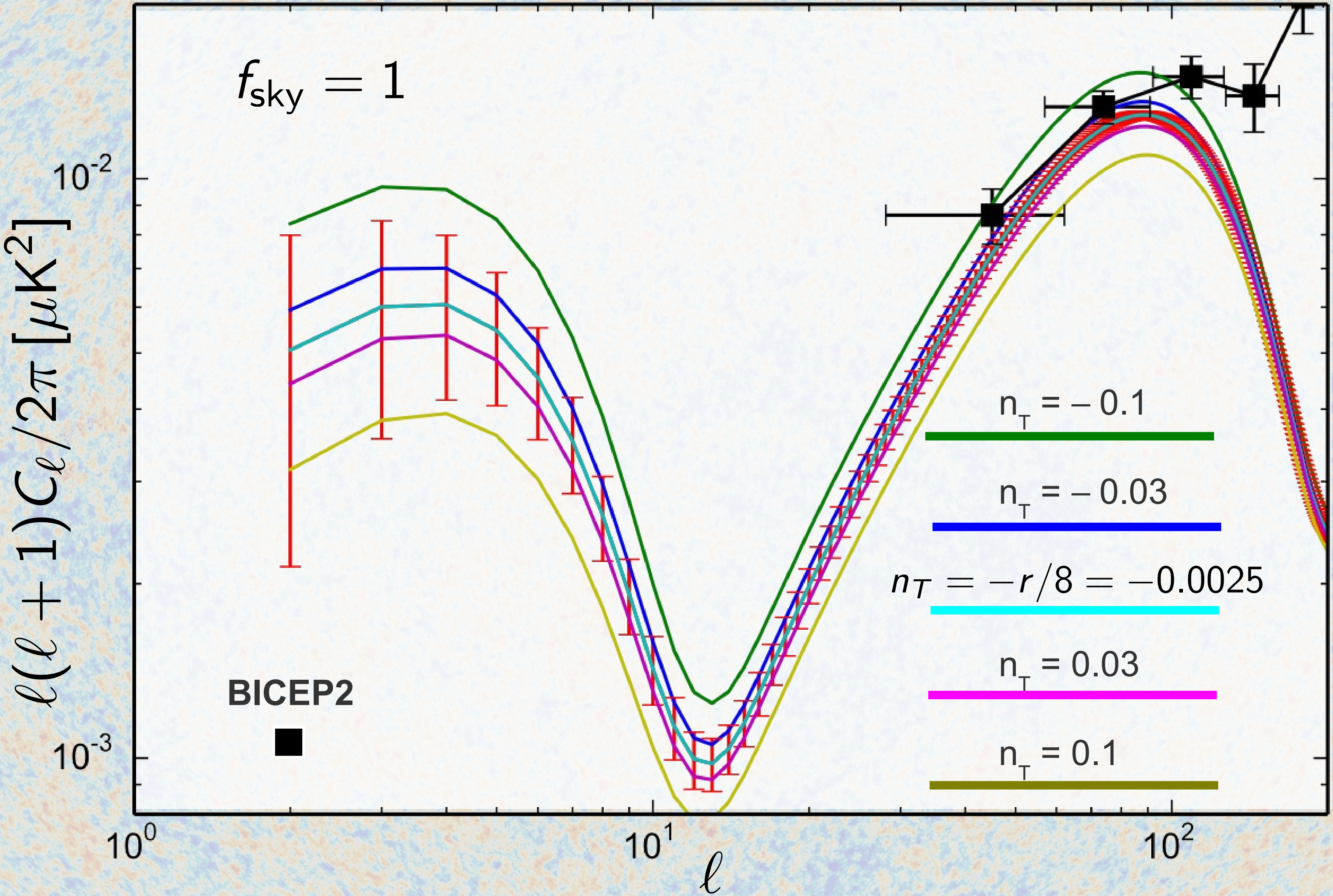
Signature of gravity waves (?)



What if r = 0.2 for good?

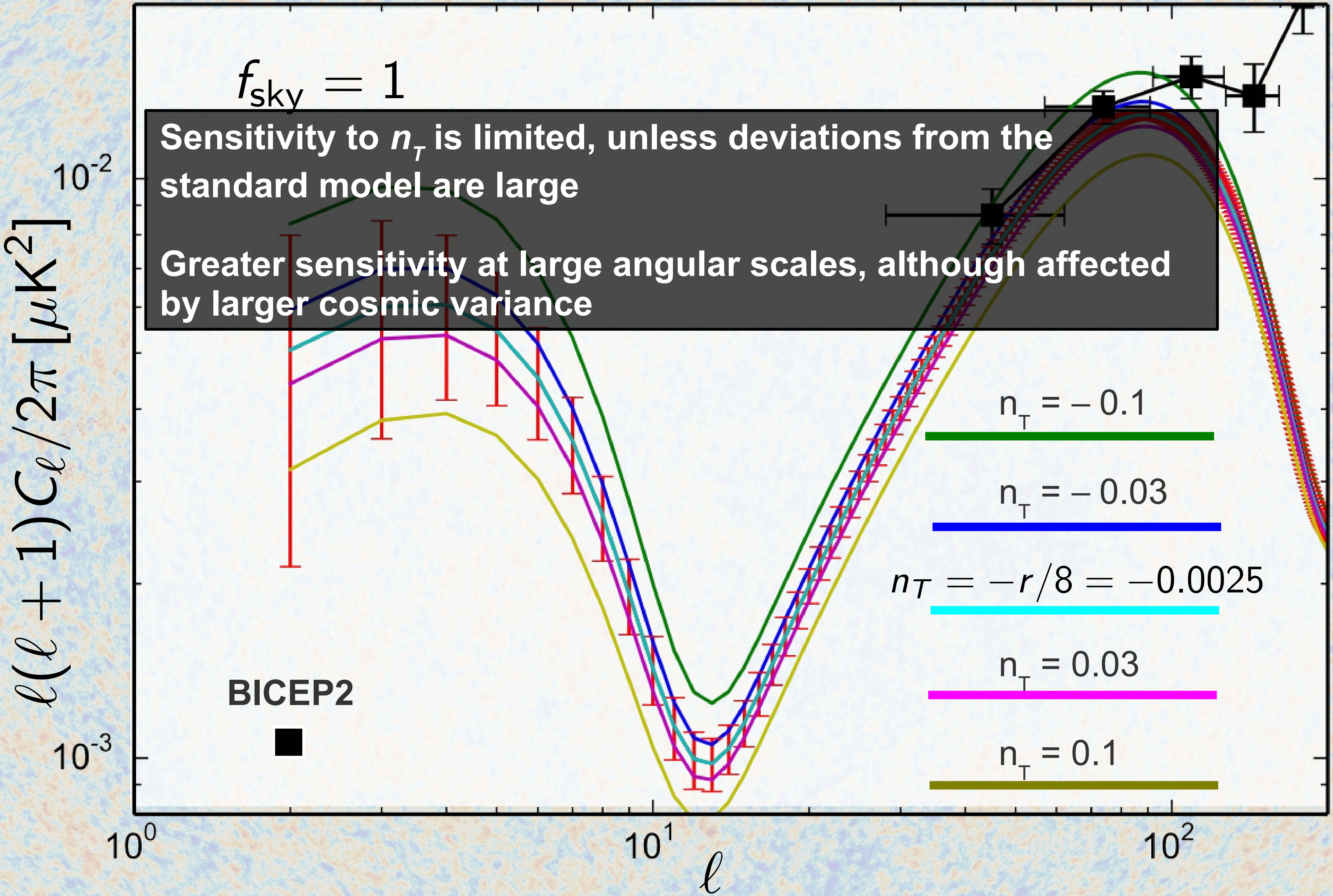
- Increasing sensitivity has been one of the main drivers of CMB polarisation instrument design to reach the lowest possible value of r
- Upcoming experiments (Planck, Spider) have the potential to provide evidence in favour or against the BICEP2 claim
- Confirmation will call for a re-scoping and re-thinking of future CMB polarisation experiments which will anyway face tough experimental challenges
- In a $r = 0.2$ scenario accurate test of the consistency relationship between n_T and r would be a natural aim of future experiments

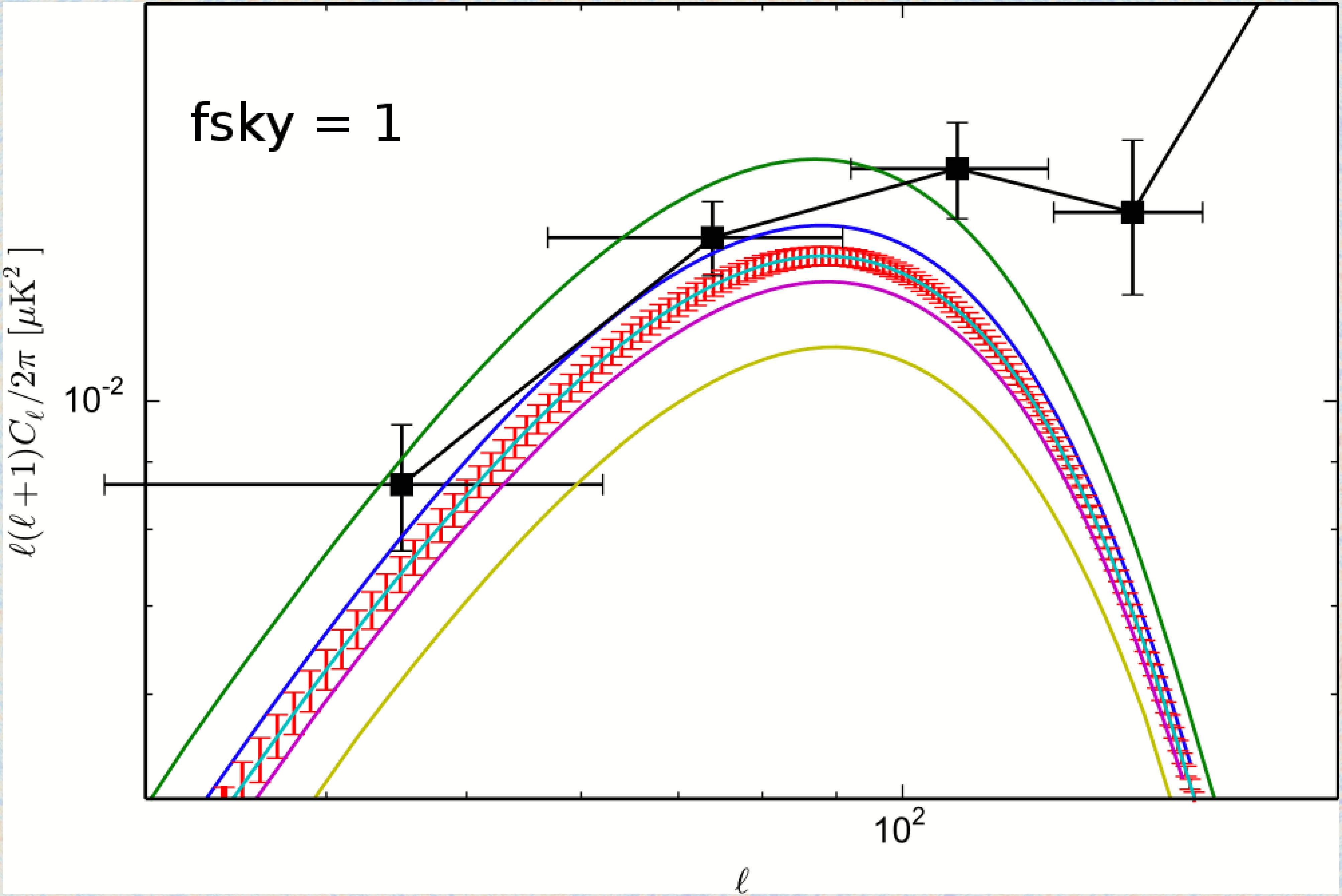
$r = 0.2$

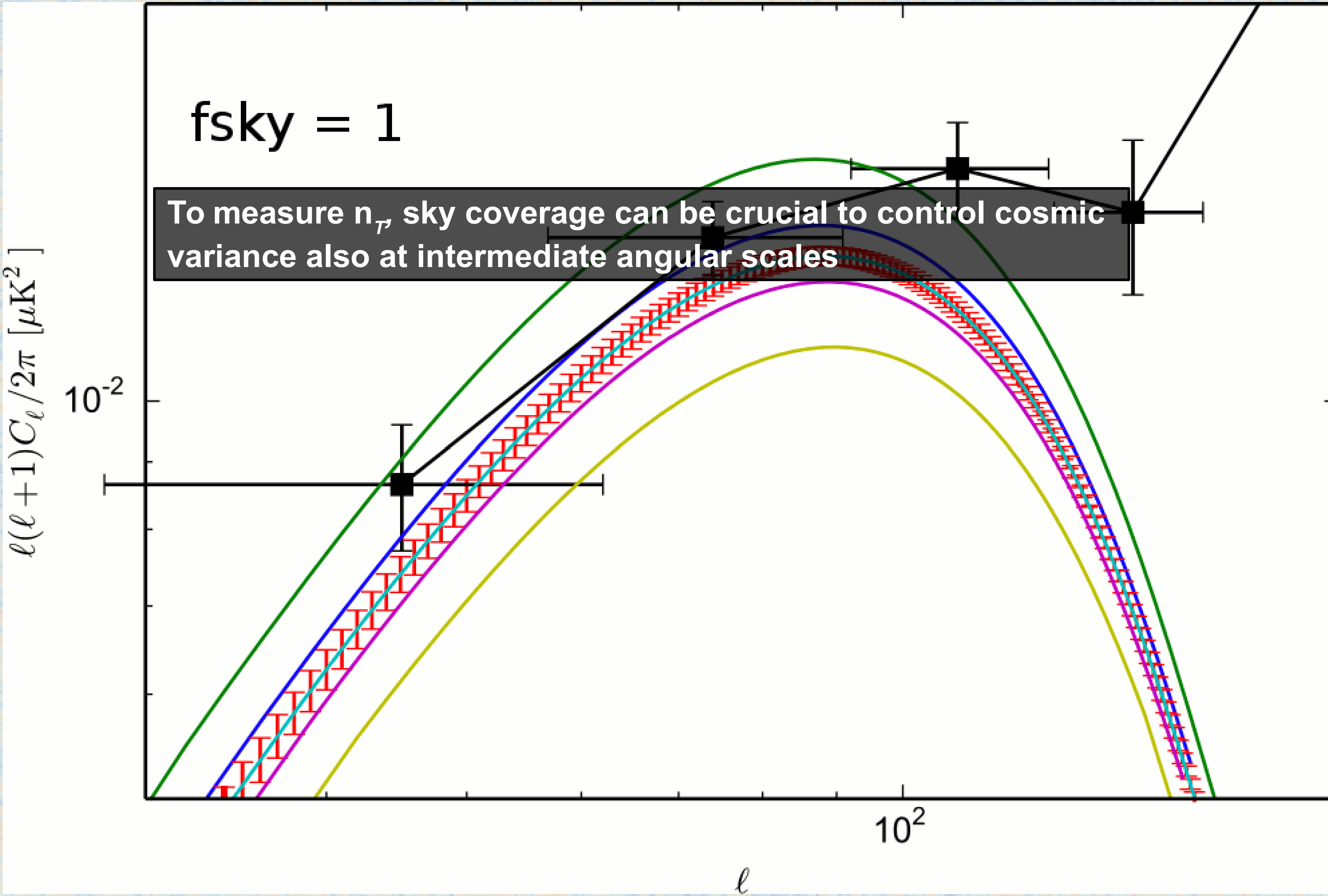


$f_{\rm sky} = 1$
10^{-2}
10^{-3}
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^0
10^1
10^2
ℓ
BICEP2
$n_T = -0.1$
$n_T = -0.03$
$n_T = -r/8 = -0.0025$
$n_T = 0.03$
$n_T = 0.1$

$r = 0.2$


$f_{sky} = 1$
Sensitivity to n_T is limited, unless deviations from the standard model are large
Greater sensitivity at large angular scales, although affected by larger cosmic variance
10^{-2}
10^{-3}
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^0
10^1
10^2
ℓ
BICEP2
$n_T = -0.1$
$n_T = -0.03$
$n_T = -r/8 = -0.0025$
$n_T = 0.03$
$n_T = 0.1$


fsky = 1
$\ell(\ell+1)C_\ell/2\pi$ [μK^2]
10^{-2}
10^{2}
ℓ

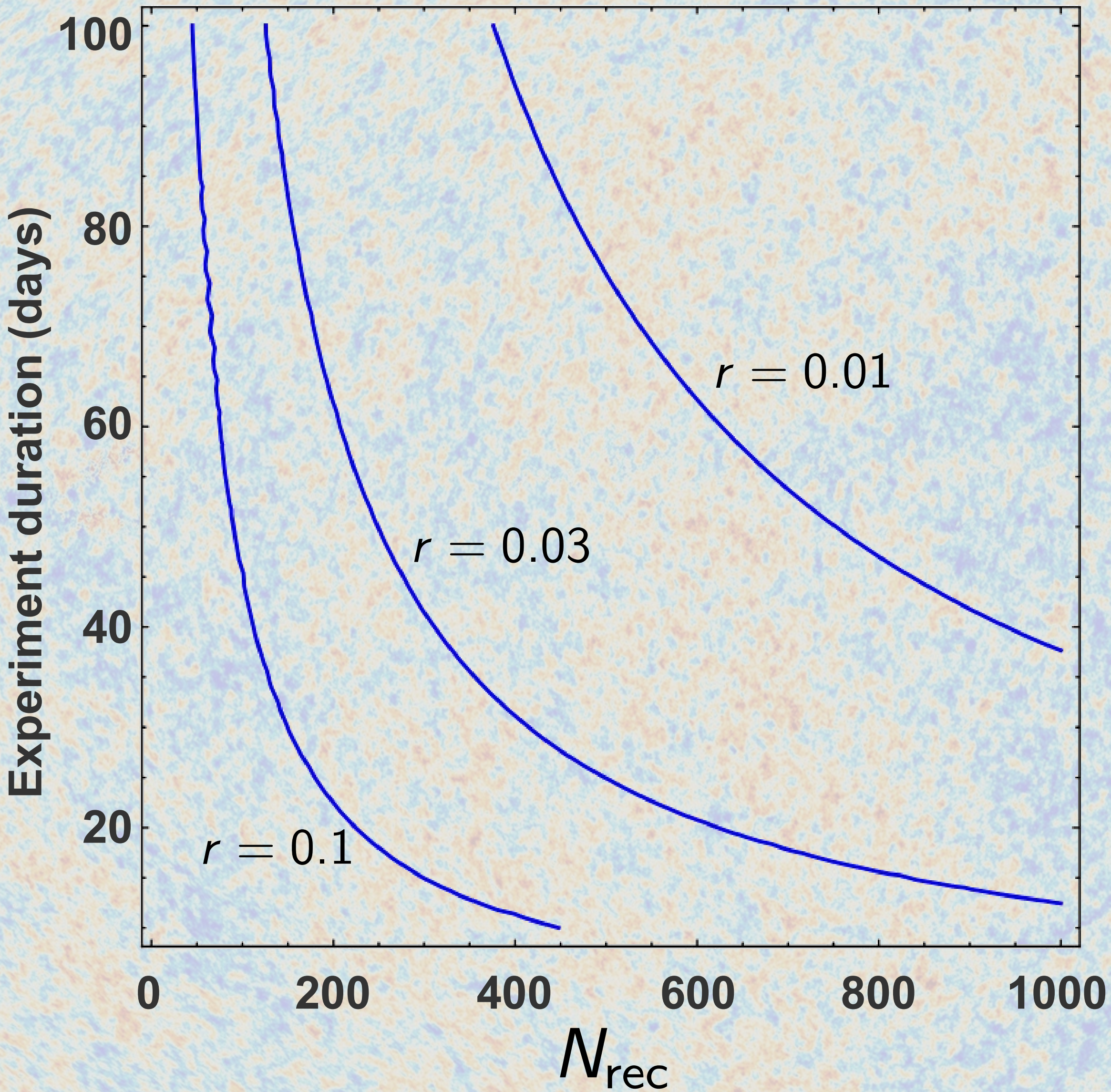

fsky = 1
To measure n_T, sky coverage can be crucial to control cosmic variance also at intermediate angular scales
10^{-2}
10^2
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ

BIG challenges

- Sensitivity to measure the B-mode precisely, in order to beat cosmic variance
- (Relatively) large sky coverage to control cosmic variance and be sensitive also to reionization bump
- Control of systematic effects at the sensitivity level
- Accurate calibration
- Control of polarized foregrounds

Challenge # 1

Meeting the sensitivity

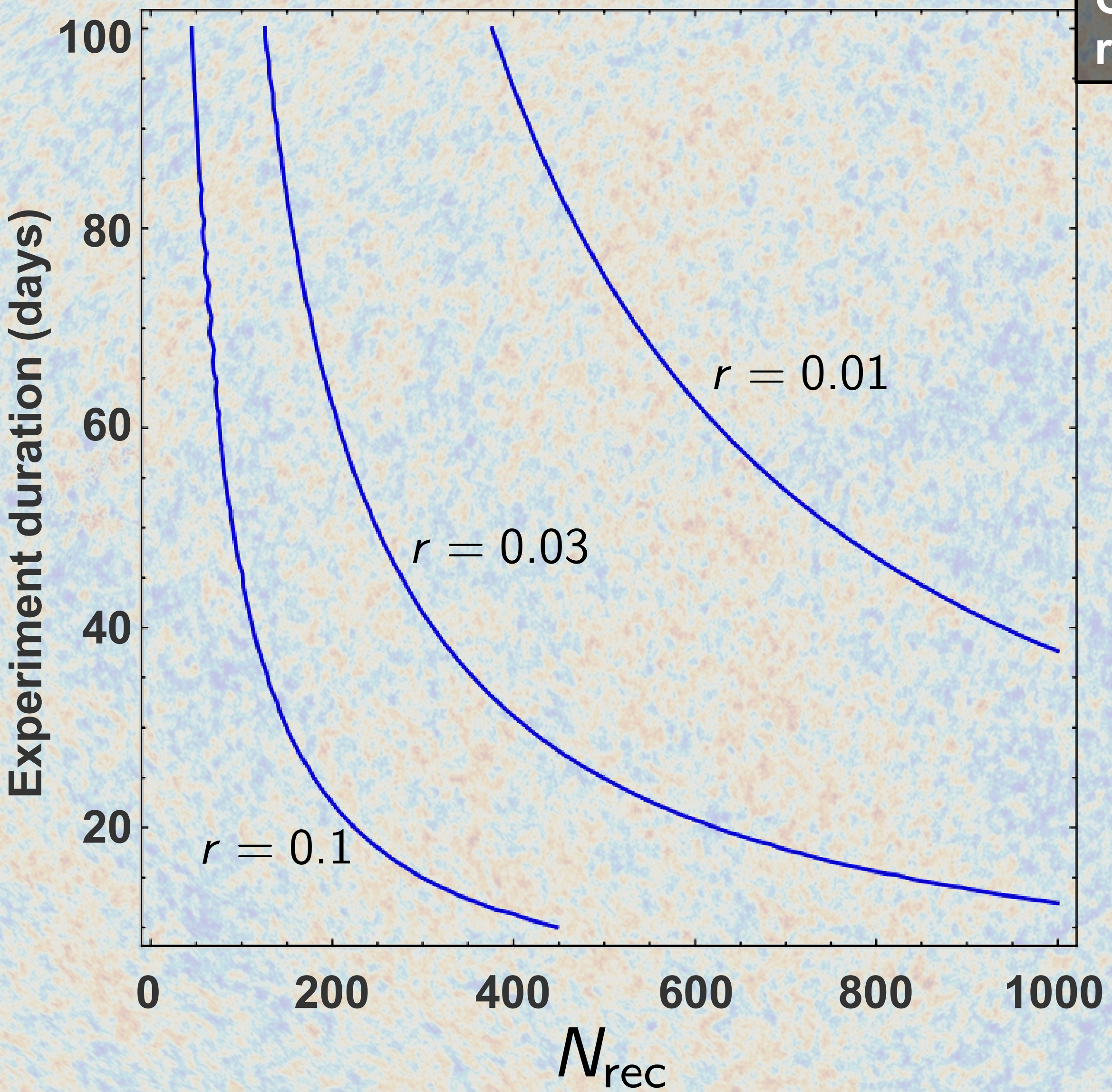


$$\Delta T_{rms} = K \frac{T_{sys}}{\sqrt{\beta \tau N_{rec}}}$$

- Photon noise limited detectors
- fsky = 30 %
- S/N = 1
- Bandwidth = 20 GHz
- $\ell(\ell+1) C_\ell = 0.05 \mu K^2$ for $\ell = 200$ and $r = 0.1$
- Duty cycle = 1

Challenge # 1

Meeting the sensitivity



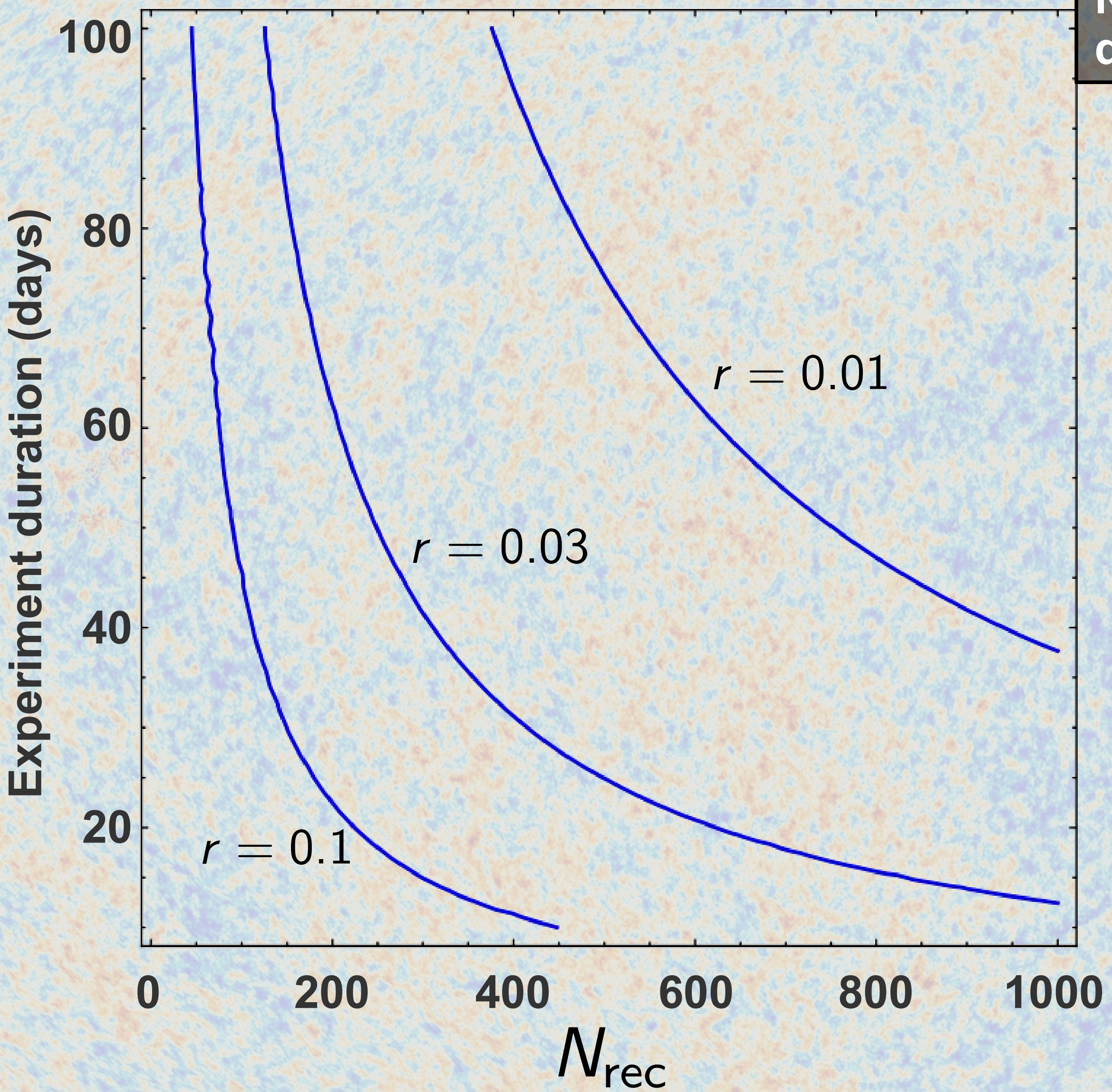
Constant ~ 1, dependent on receiver architecture

$$\Delta T_{rms} = K \frac{T_{sys}}{\sqrt{\beta \, \tau \, N_{rec}}}$$

- Photon noise limited detectors
- fsky = 30 %
- S/N = 1
- Bandwidth = 20 GHz
- $\ell(\ell+1)C_\ell = 0.05 \mu K^2$ for $\ell = 200$ and $r = 0.1$
- Duty cycle = 1

Challenge # 1

Meeting the sensitivity



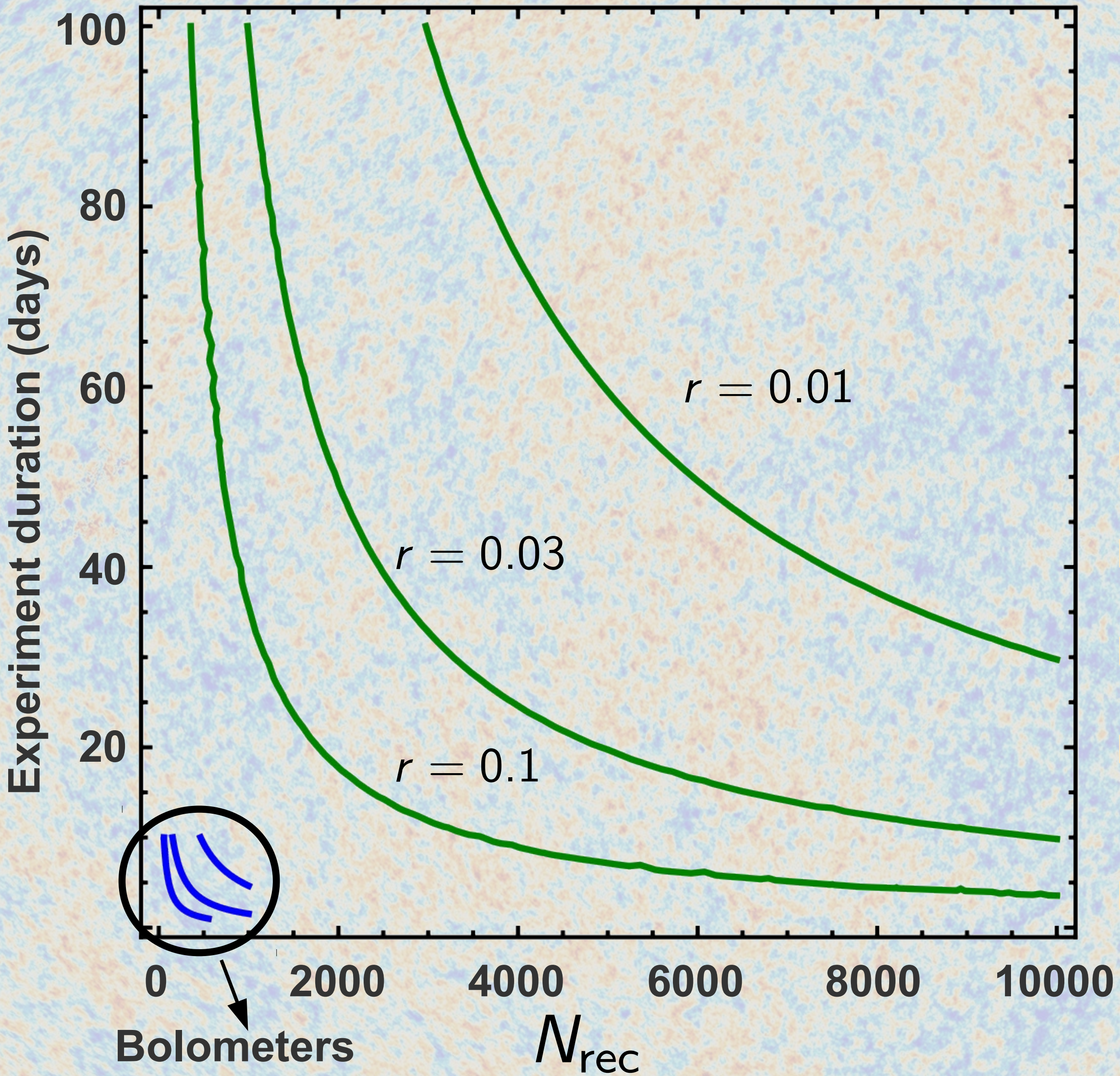
Number of receiver units detecting Q and U

$$\Delta T_{rms} = K \frac{T_{sys}}{\sqrt{\beta\, \tau\, N_{rec}}}$$

- Photon noise limited detectors
- fsky = 30 %
- S/N = 1
- Bandwidth = 20 GHz
- $\ell(\ell+1)C_\ell = 0.05 \mu K^2$ for $\ell = 200$ and $r = 0.1$
- Duty cycle = 1

Challenge # 1

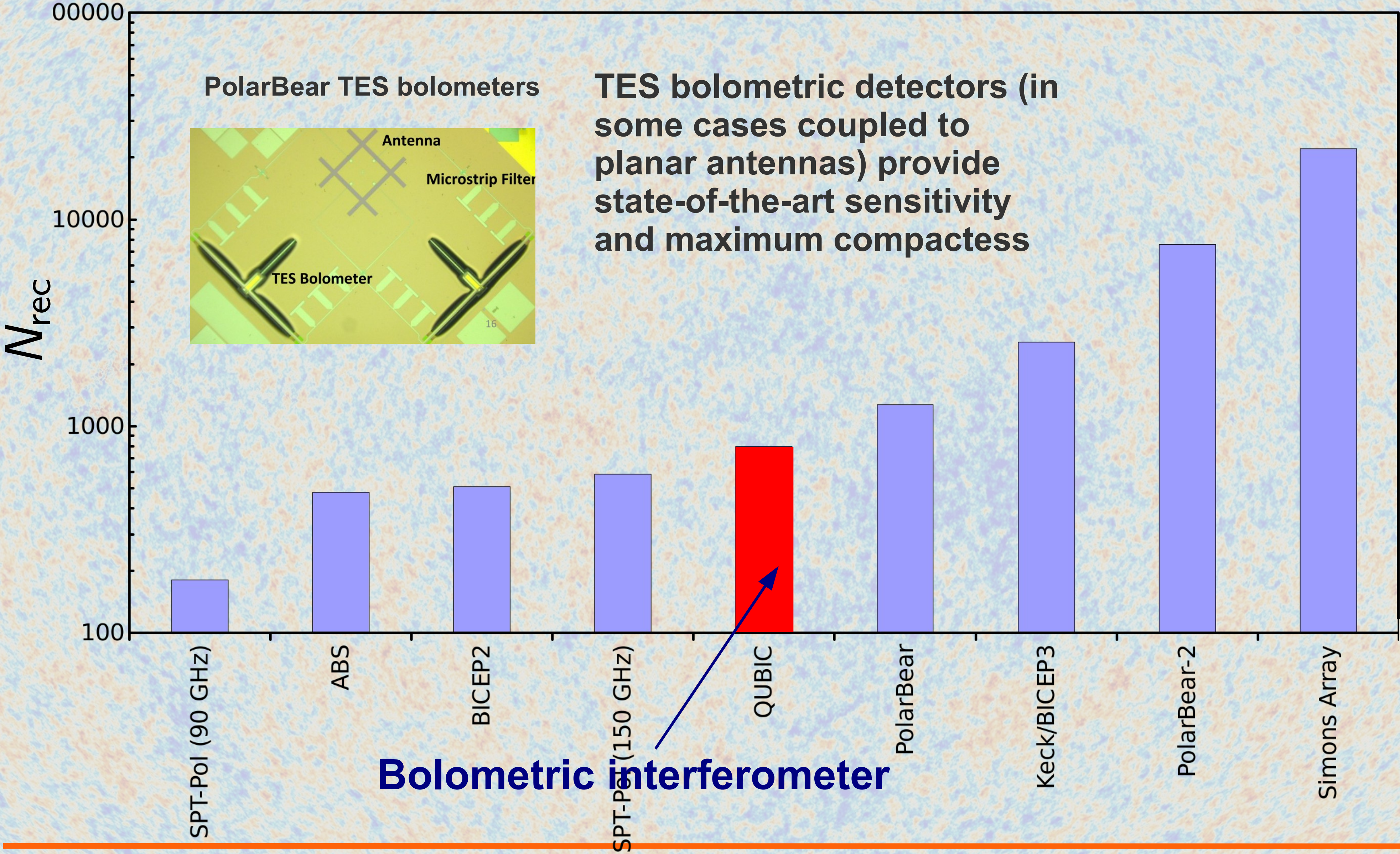
Meeting the sensitivity



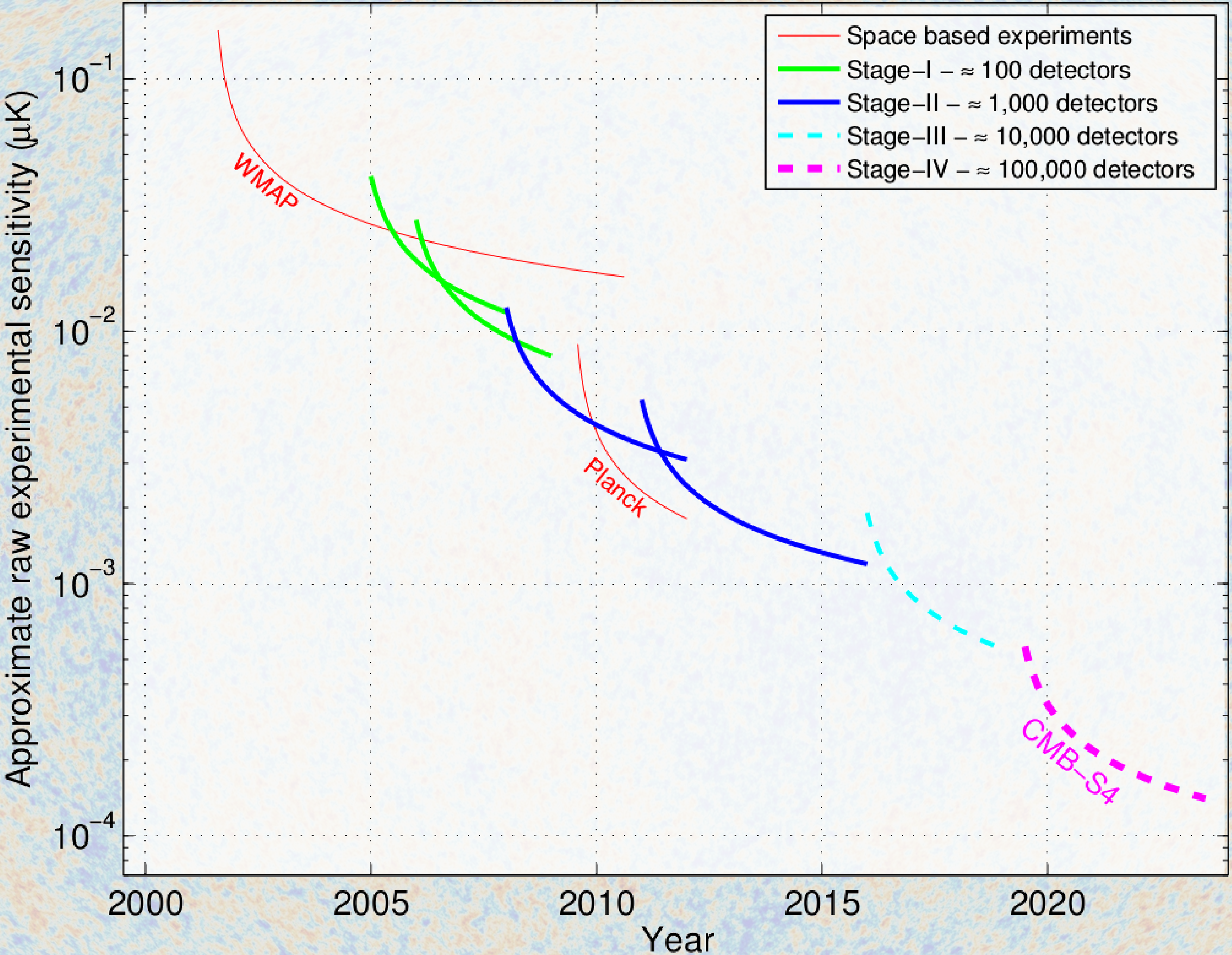
$$\Delta T_{\rm rms} = K \frac{T_{\rm sys}}{\sqrt{\beta\, \tau\, N_{\rm rec}}}$$

- W-band HEMT detectors (Tsys = 40K)
- fsky = 30 %
- S/N = 1
- Bandwidth = 20 GHz
- $\ell(\ell+1)C_\ell = 0.05\mu\mathrm{K}^2$ for $\ell = 200$ and $r = 0.1$
- Duty cycle = 1

TES detectors (ground)



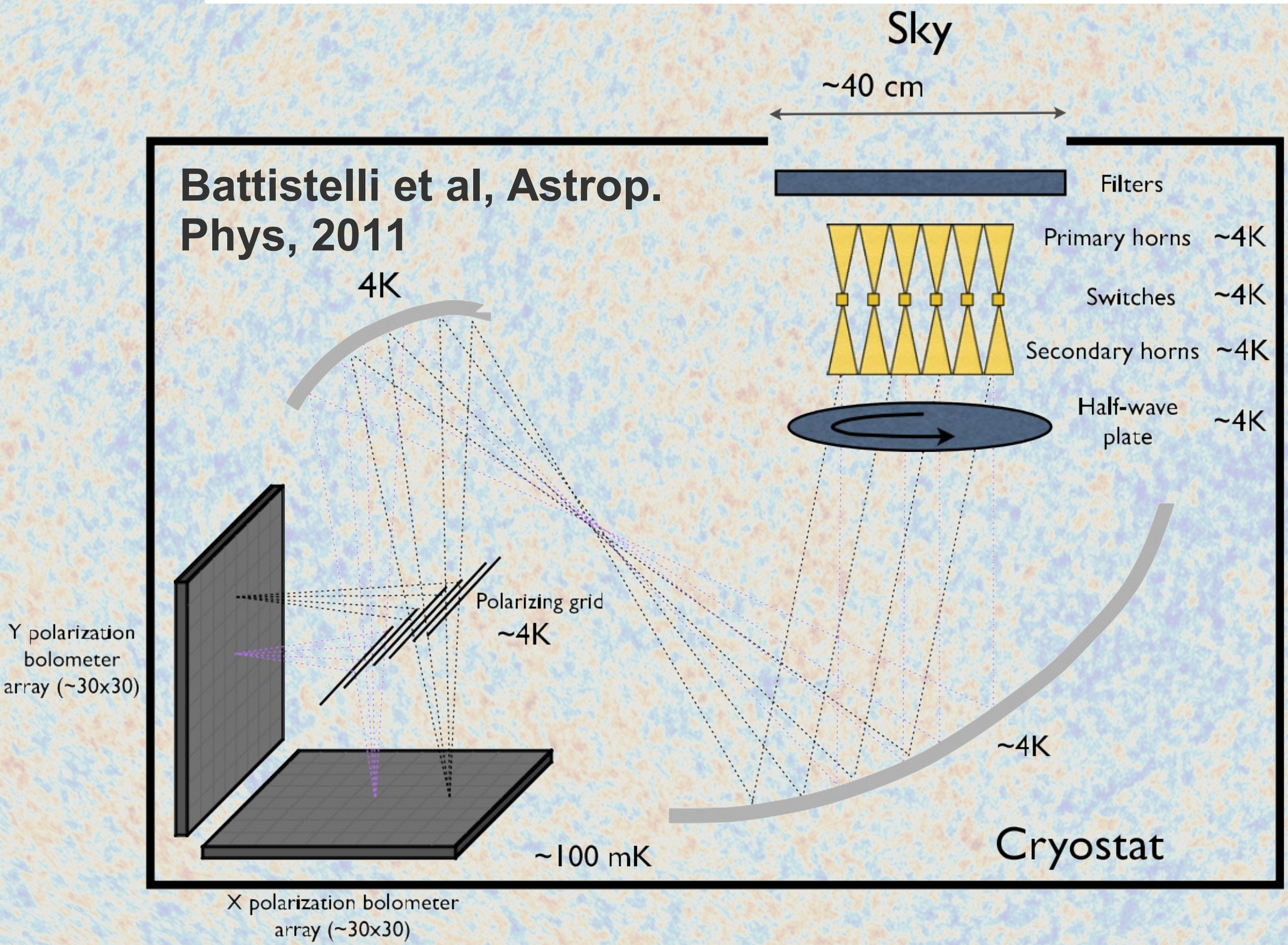
TES bolometric detectors (in some cases coupled to planar antennas) provide state-of-the-art sensitivity and maximum compactess



Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Approximate raw experimental sensitivity (μK)
2000
2005
2010
2015
2020
Year

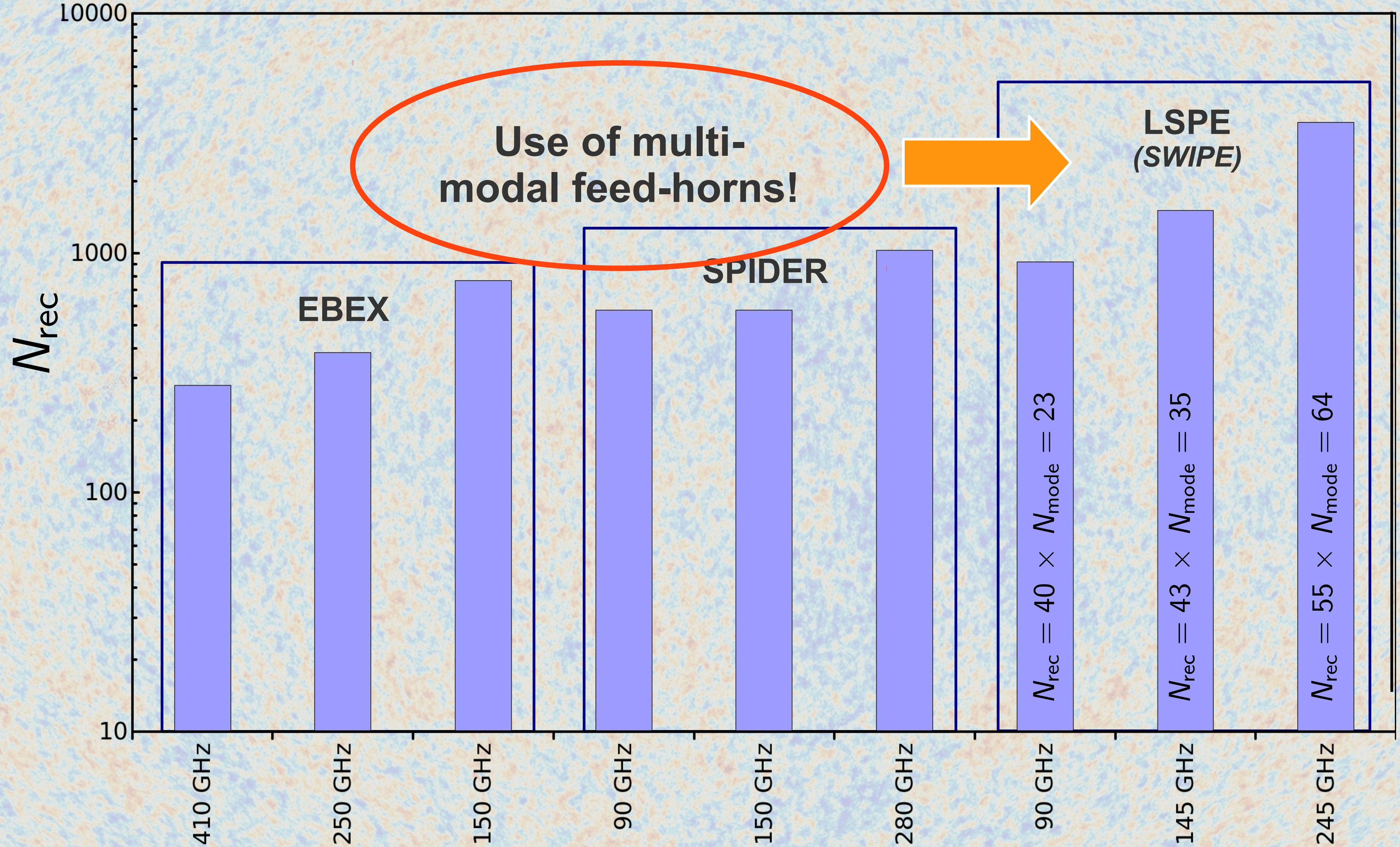
QUBIC

a Q&U Bolometric Interferometer for Cosmology

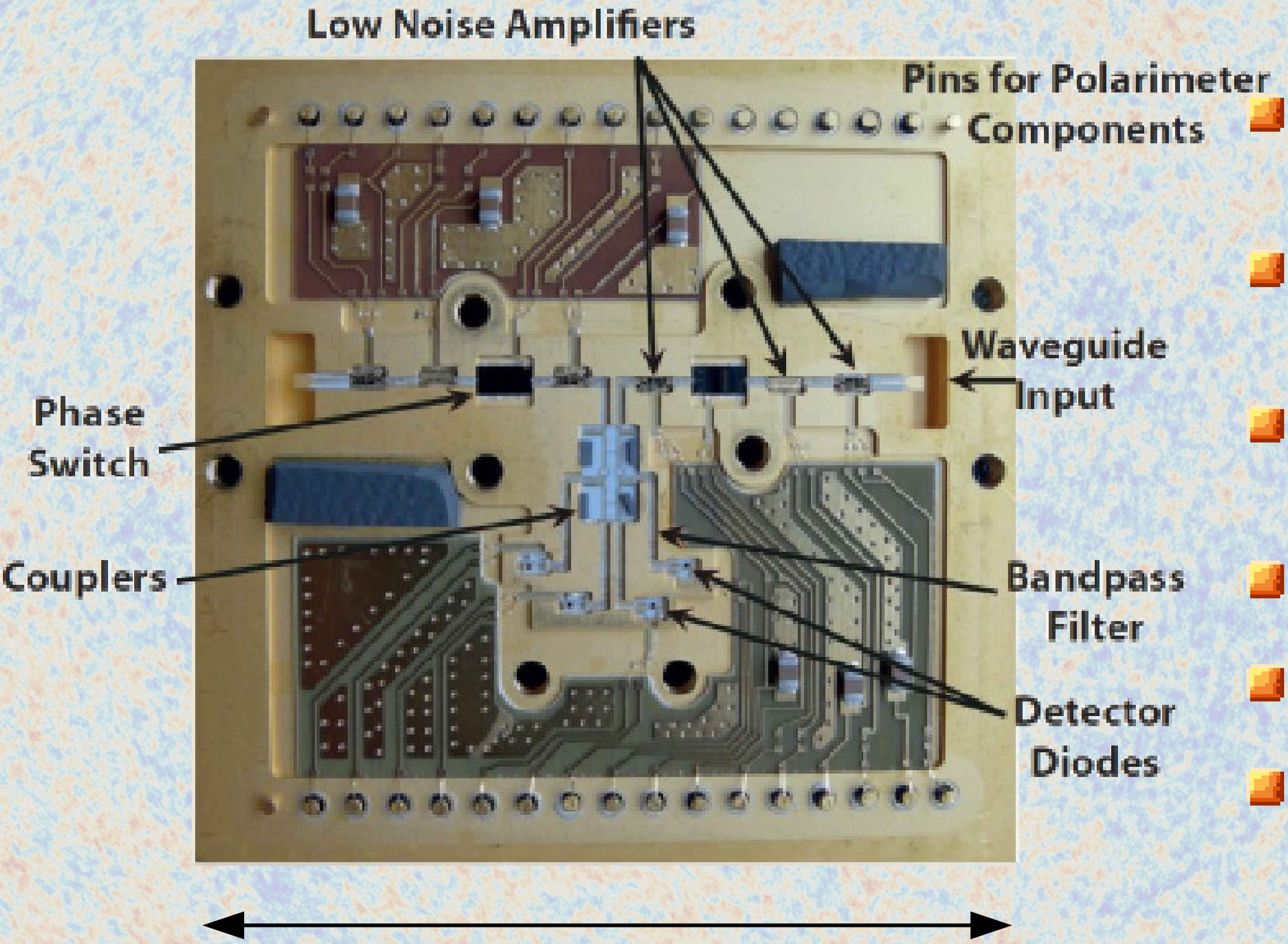


- New tecnique applied to bolometric CMB measurements
- Planned for observations from DOME-C
- Potential advantages in systematic effects control and calibration

TES detectors (balloon)



HEMT detectors

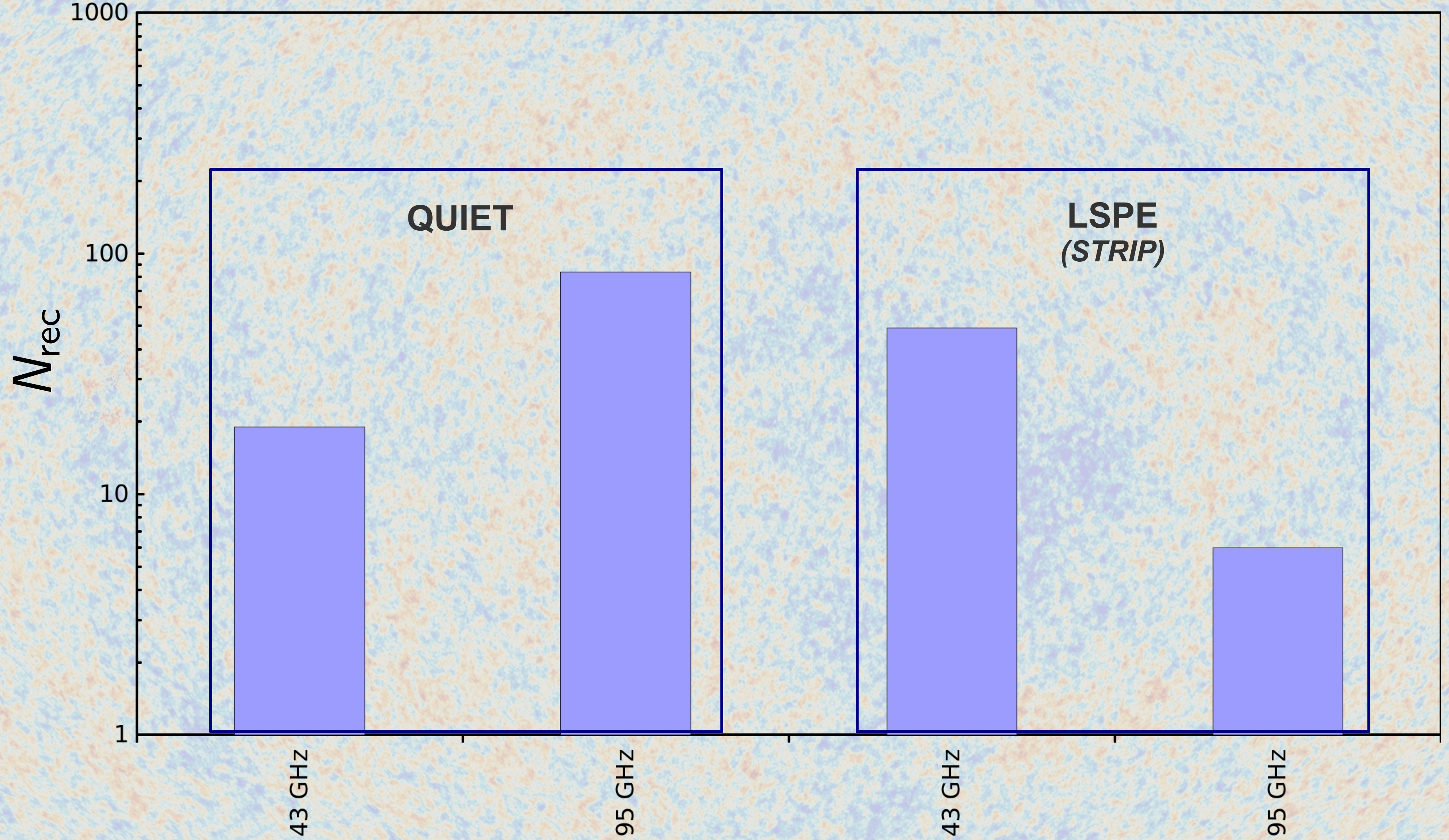


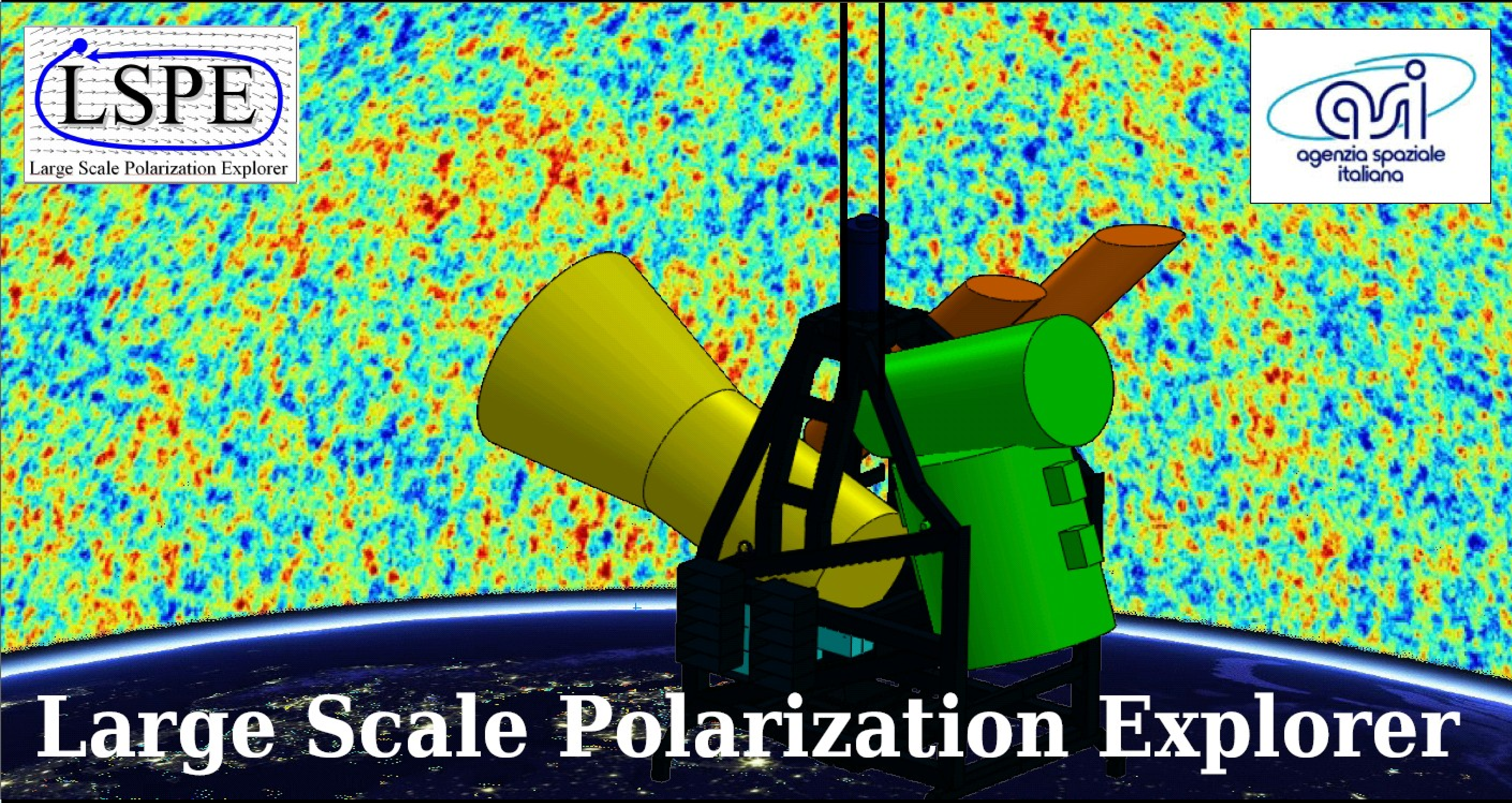
~ 5 cm @ 43 GHz, ~ 2.5 cm @ 95 GHz

QUIET design

- Developed at JPL (Todd Gaier et al)
- Compact, on-chip receiver design
- Pseudo correlation polarimetry (detects Q/U simultaneously)
- Applied in QUIET and LSPE
- Benign to systematic effects
- Significant noise improvements with last generation InP devices (35 nm gate technology, not implemented yet)

HEMT detectors



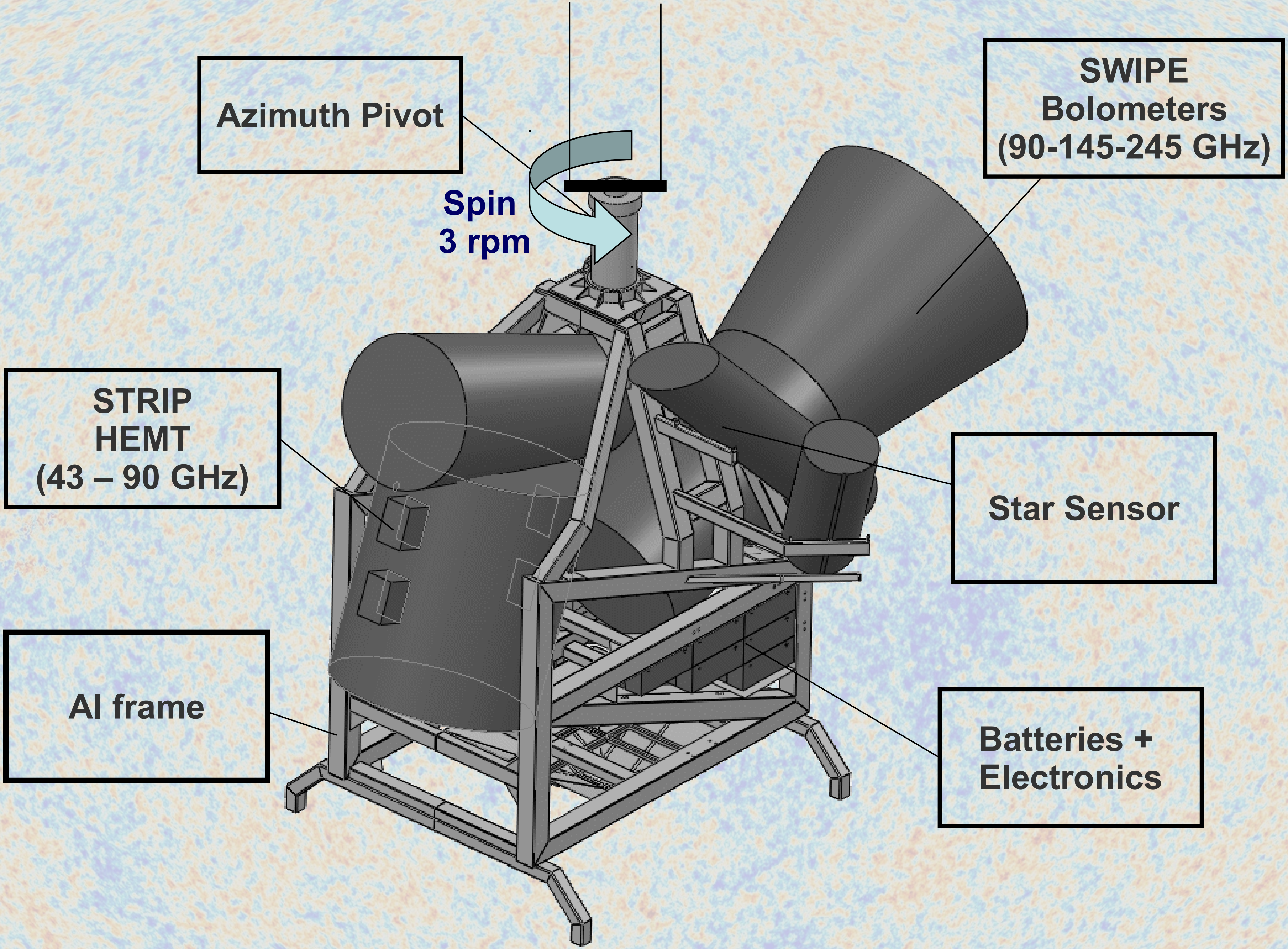


Large Scale Polarization Explorer

LSPE
Large Scale Polarization Explorer

agenzia spaziale italiana

SAPIENZA UNIVERSITÀ DI ROMA
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
IASF bo
IEIIT
IFAC
UNIVERSITY OF CAMBRIDGE
MANCHESTER 1824

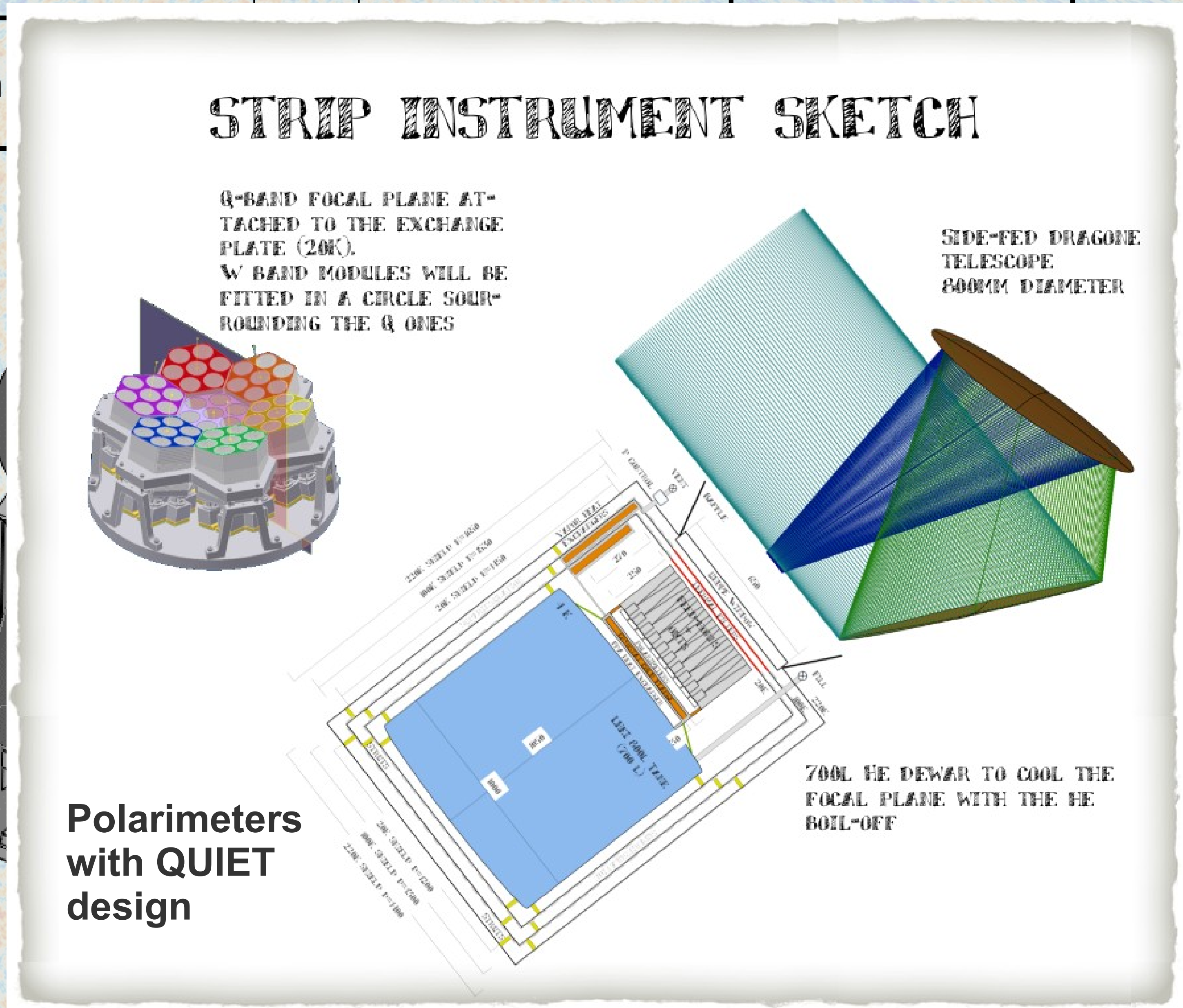


The height of the gondola for this configuration is about 4.5 m

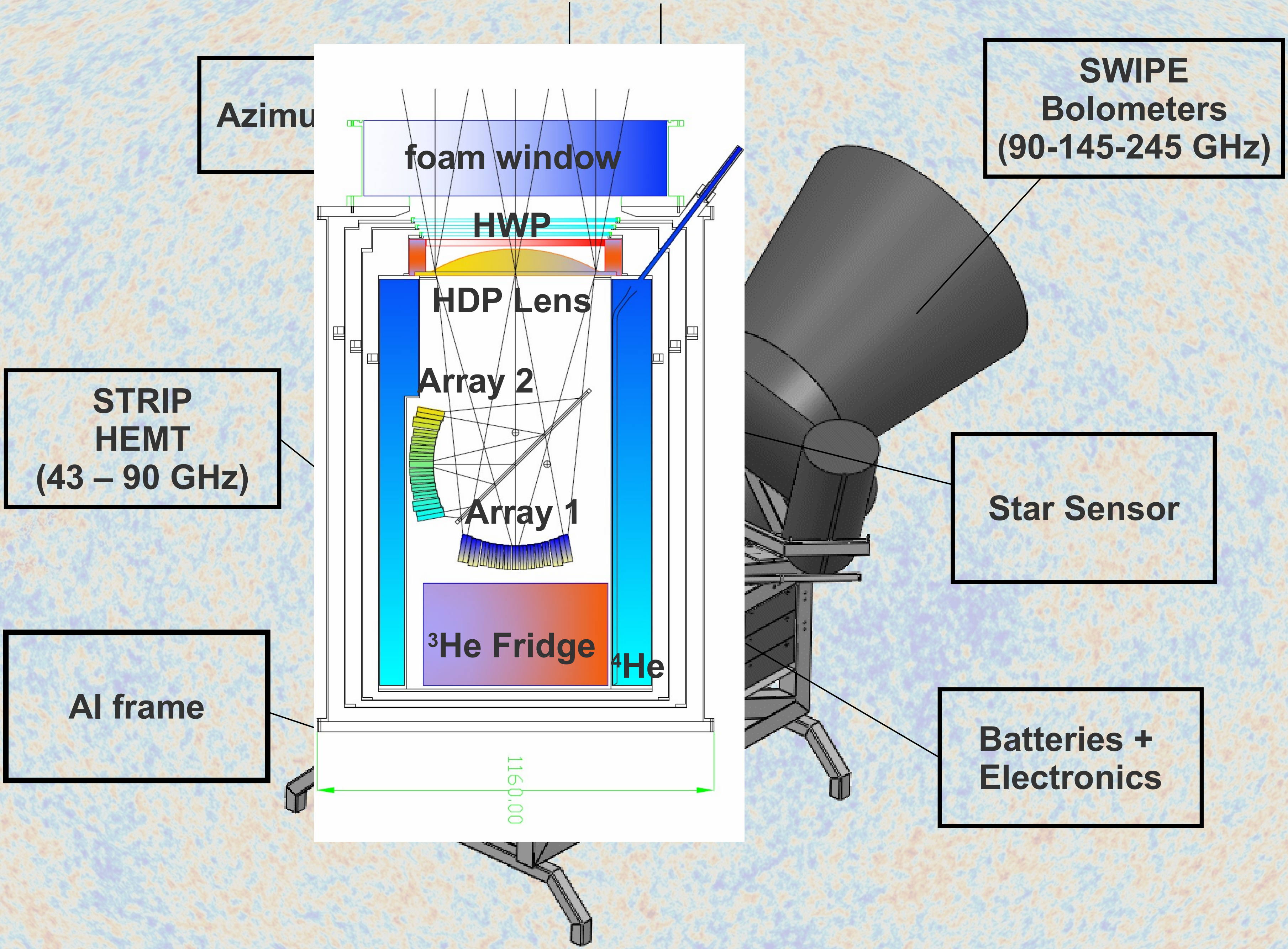
Azimuth

STRIP HEMT (43 – 90 GHz)

Al frame



The height of the gondola for this configuration is about 4.5 m

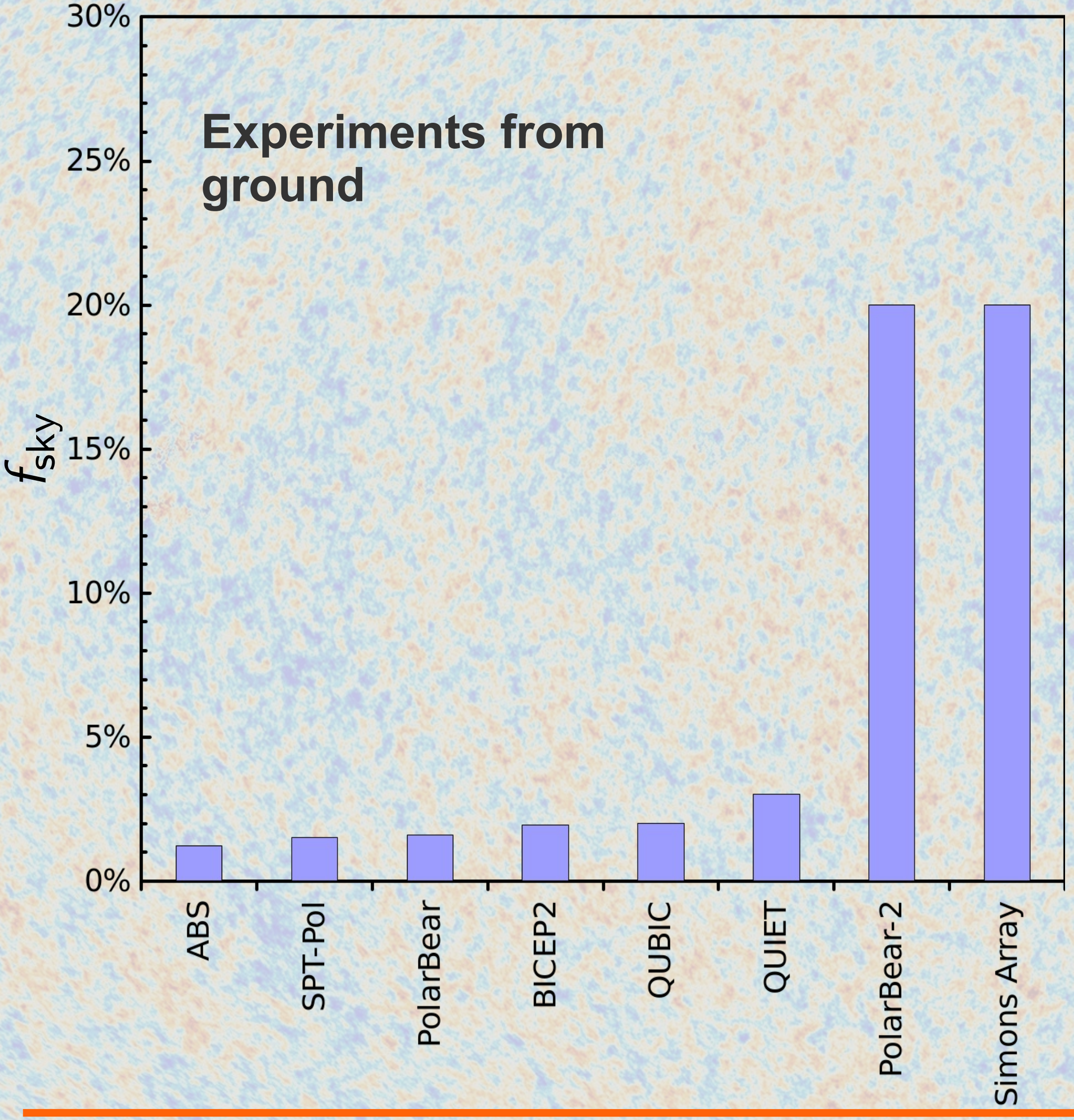


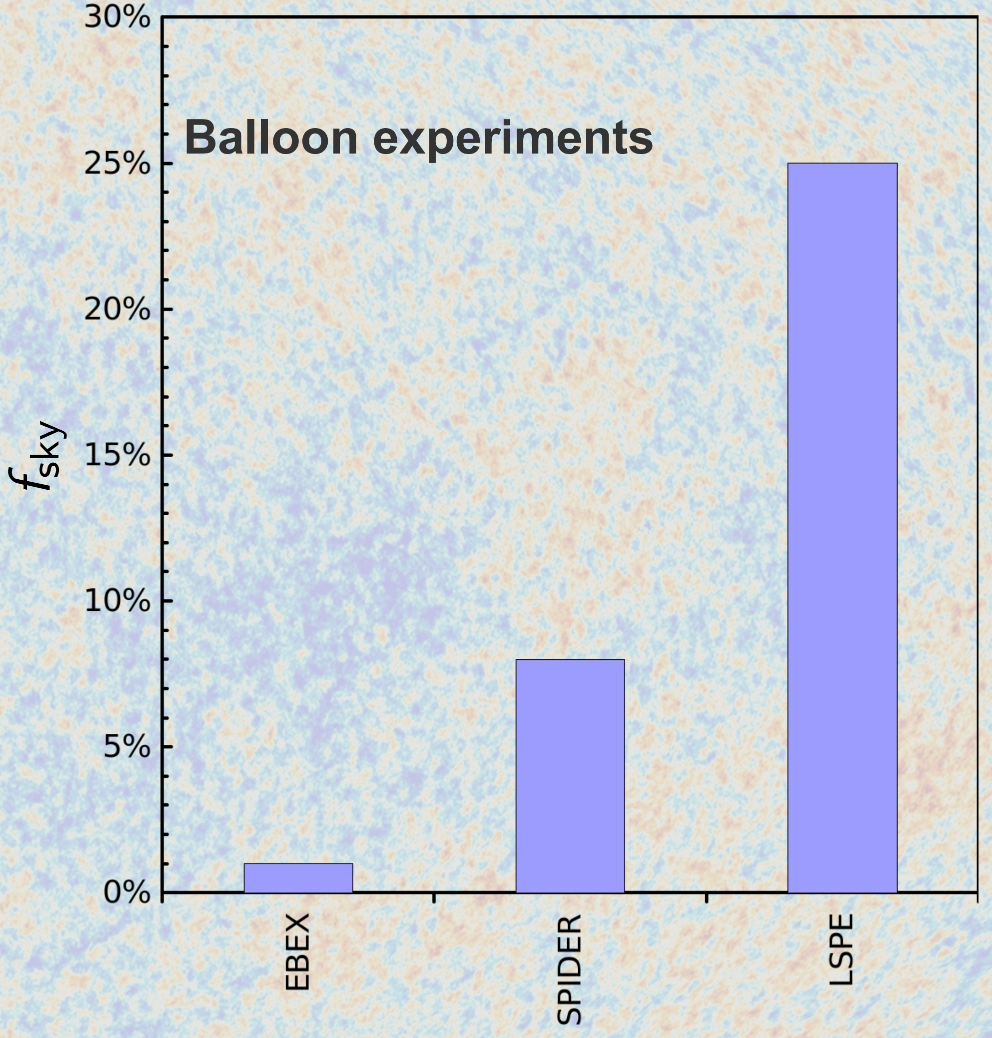
The height of the gondola for this configuration is about 4.5 m

Challenge # 1
Meeting the sensitivity

- Larger arrays being designed and developed
- TES and InP technology improvements allow manufacturing of large focal planes
- Use of multi-modal horns can be explored to further increase array sensitivity
- Challenge is tough, but roads lay ahead

Challenge # 2
Meeting the sky coverage

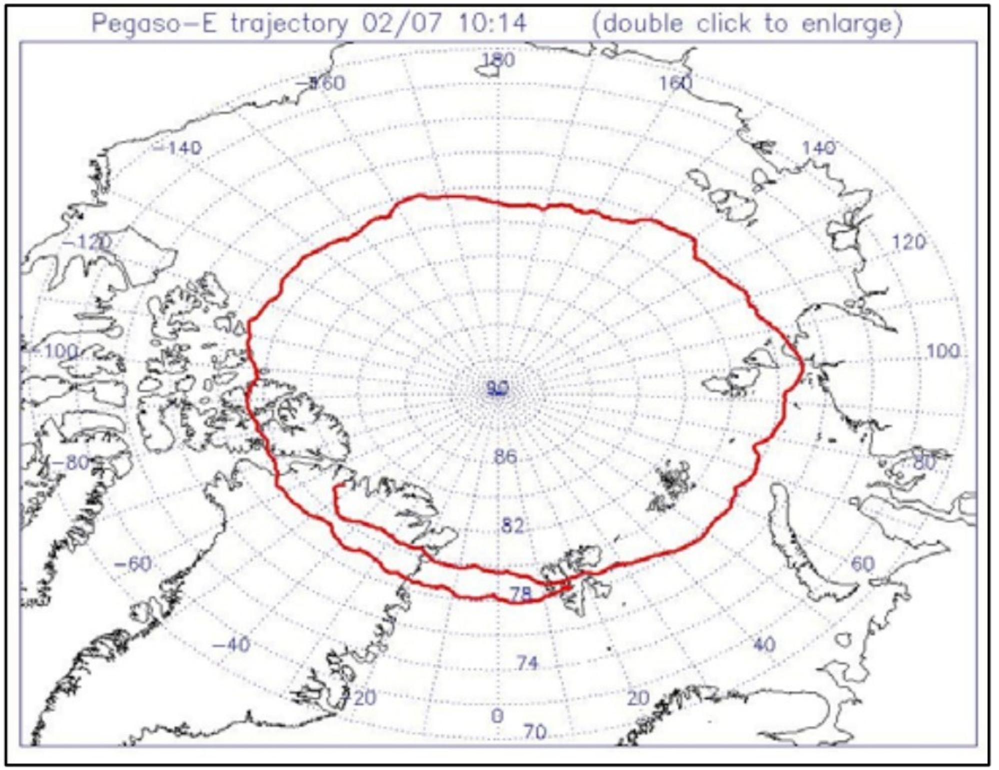




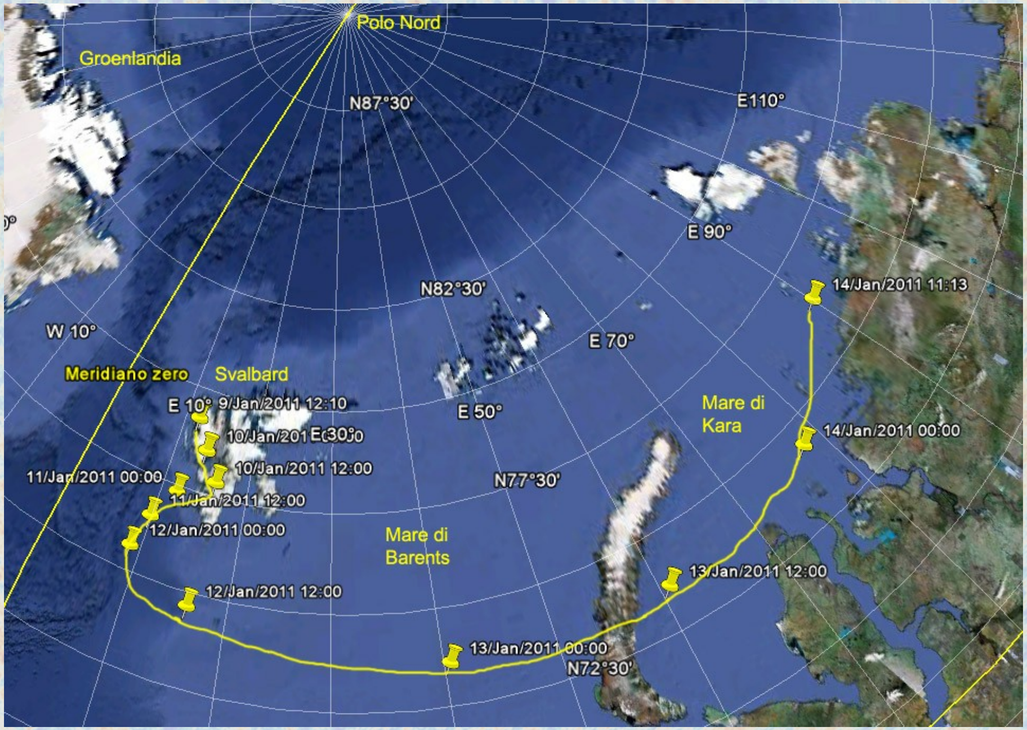
LDB flights in the Arctic night

Svalbard islands provide a very good opportunity to launch long duration balloons during the Arctic night. OLIMPO (launch in summer 2014) will be the first ballon to perform a complete circle around the North Pole

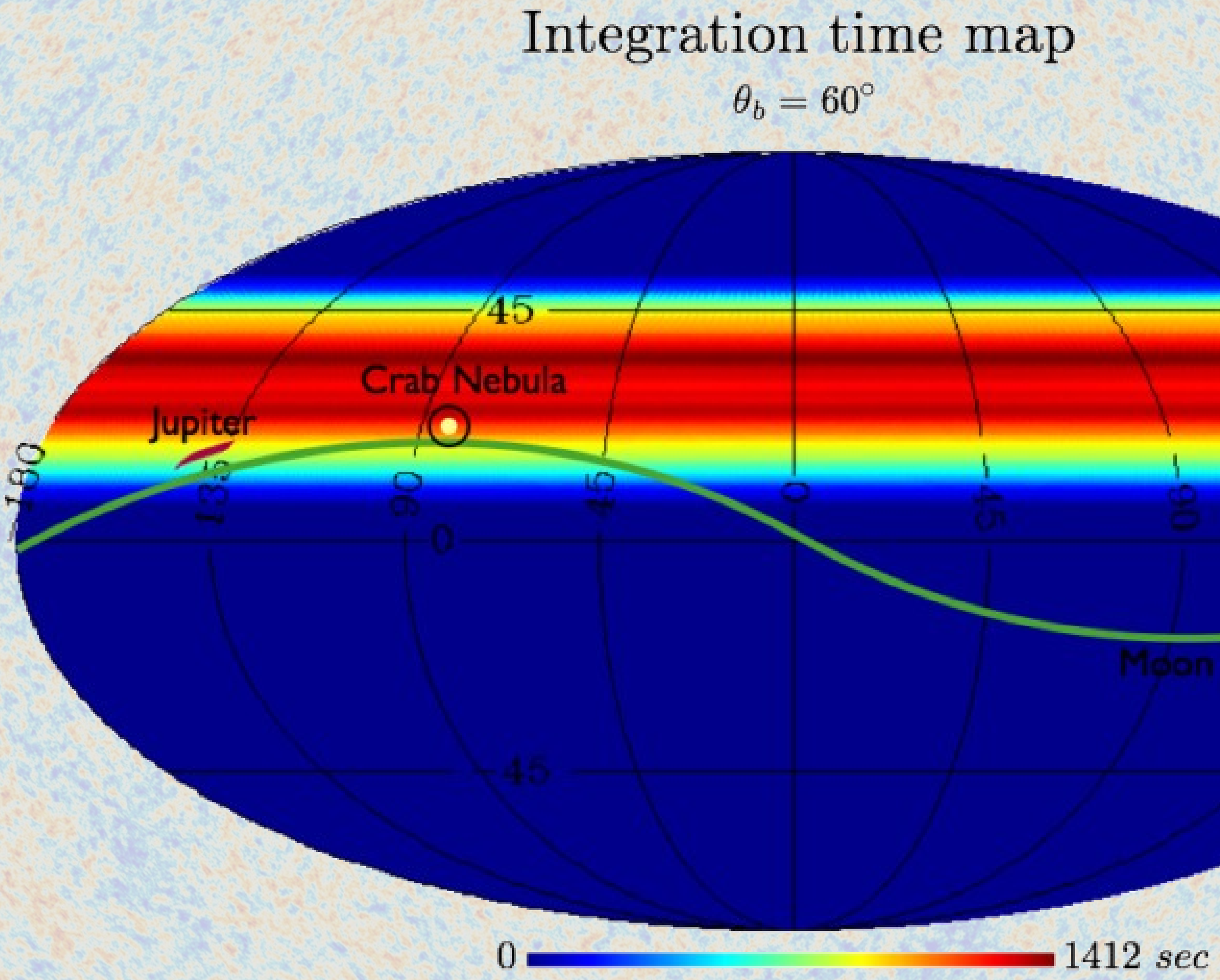
Test flight #1 – Summer 2007



Test flight #2 – Winter 2011



LSPE Sky coverage



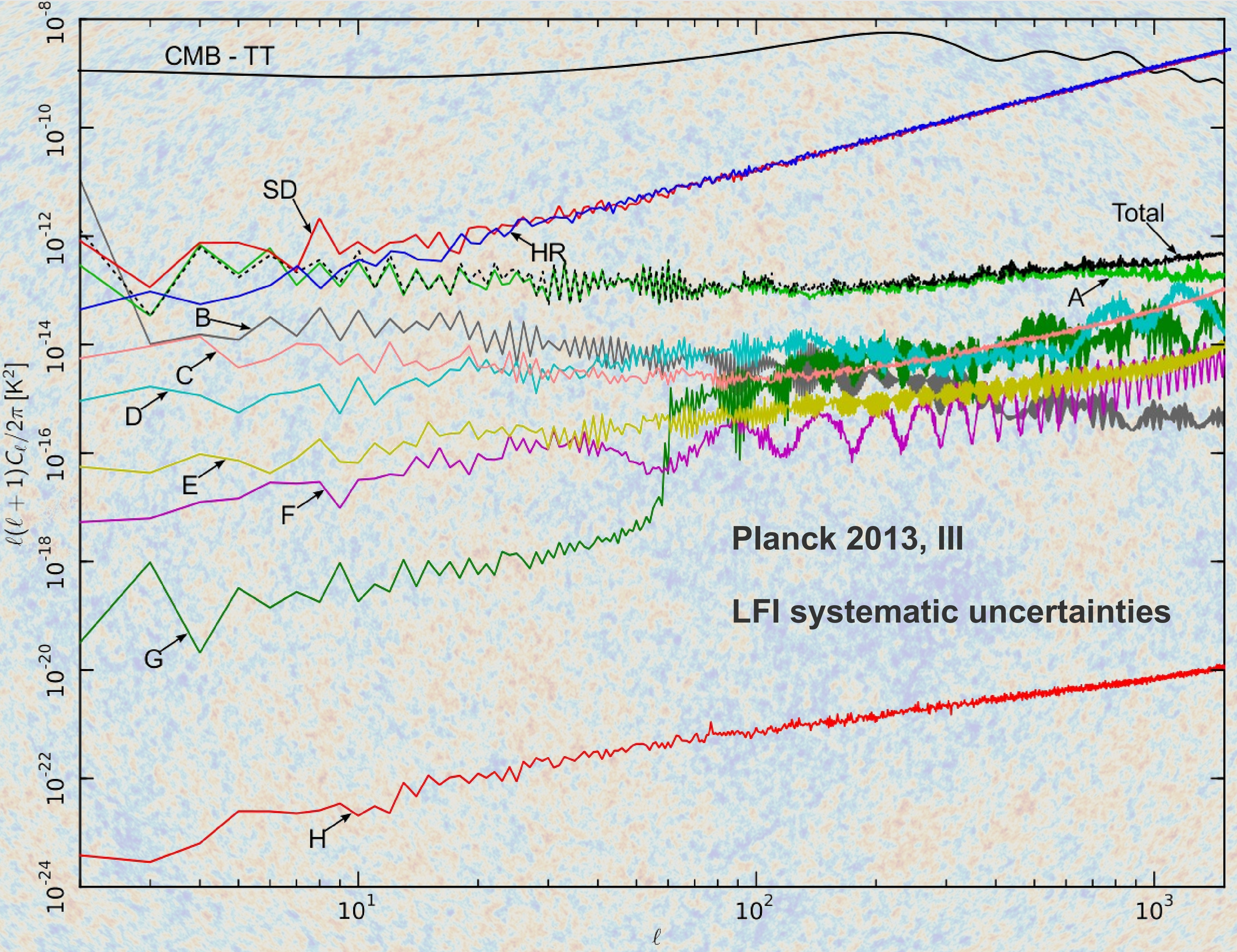
Challenge # 2

Meeting the sky coverage

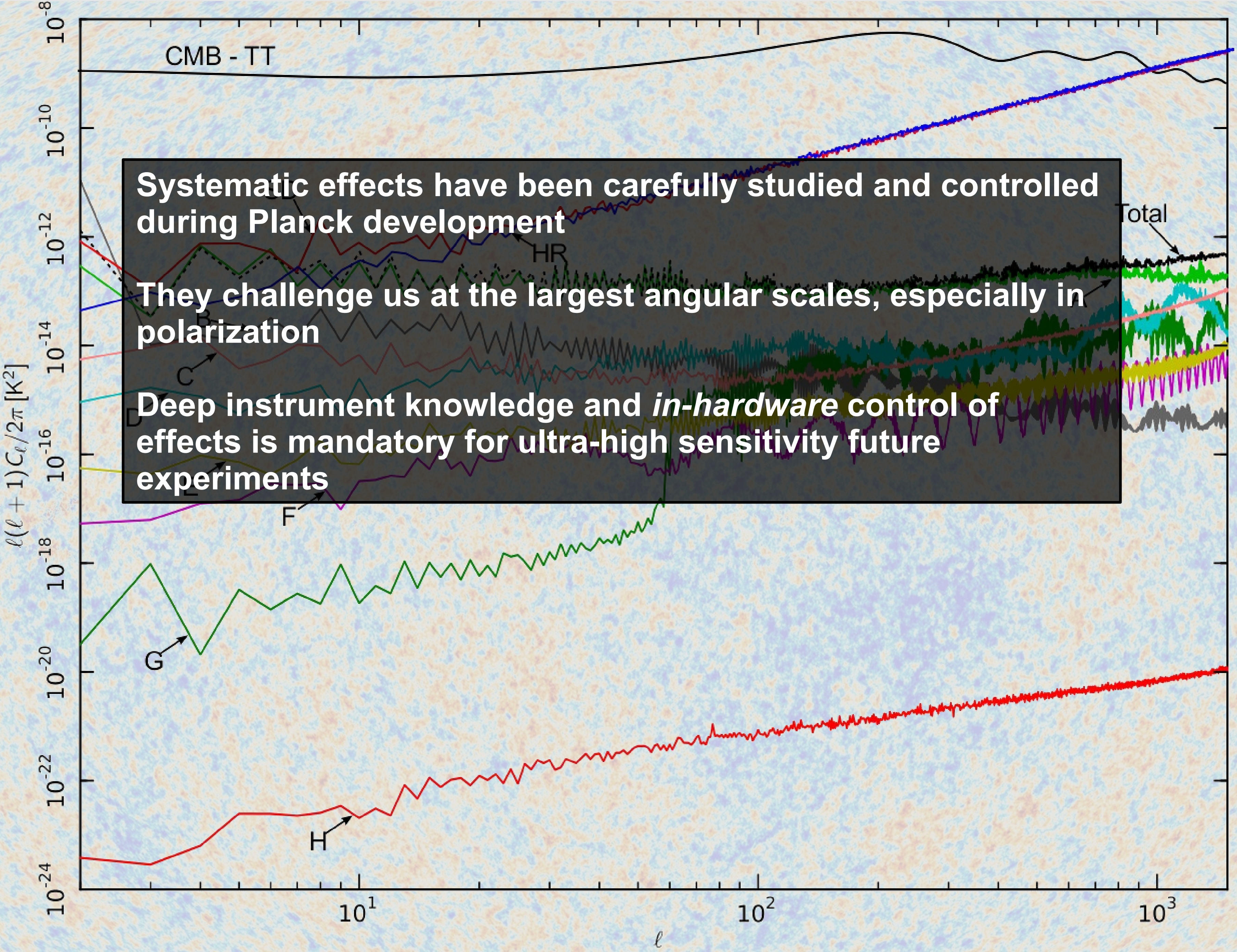
- Telescope arrays from ground and long duration flights during polar nights are most promising short term solutions
- Main challenges are
  - *Telescope arrays: coordinate and harmonize measurements from different telescope / sites*
  - *LDB flights in polar night: stratospheric currents around North Pole less known than around South Pole*
- Space is the ultimate challenge for total sky coverage

Challenge # 3

Meeting the systematic effects control



CMB - TT
SD
HR
Total
A
B
C
D
E
F
G
H
Planck 2013, III
LFI systematic uncertainties
$\ell(\ell+1)C_\ell/2\pi\,[K^2]$
ℓ
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^1
10^2
10^3



Systematic effects have been carefully studied and controlled during Planck development

They challenge us at the largest angular scales, especially in polarization

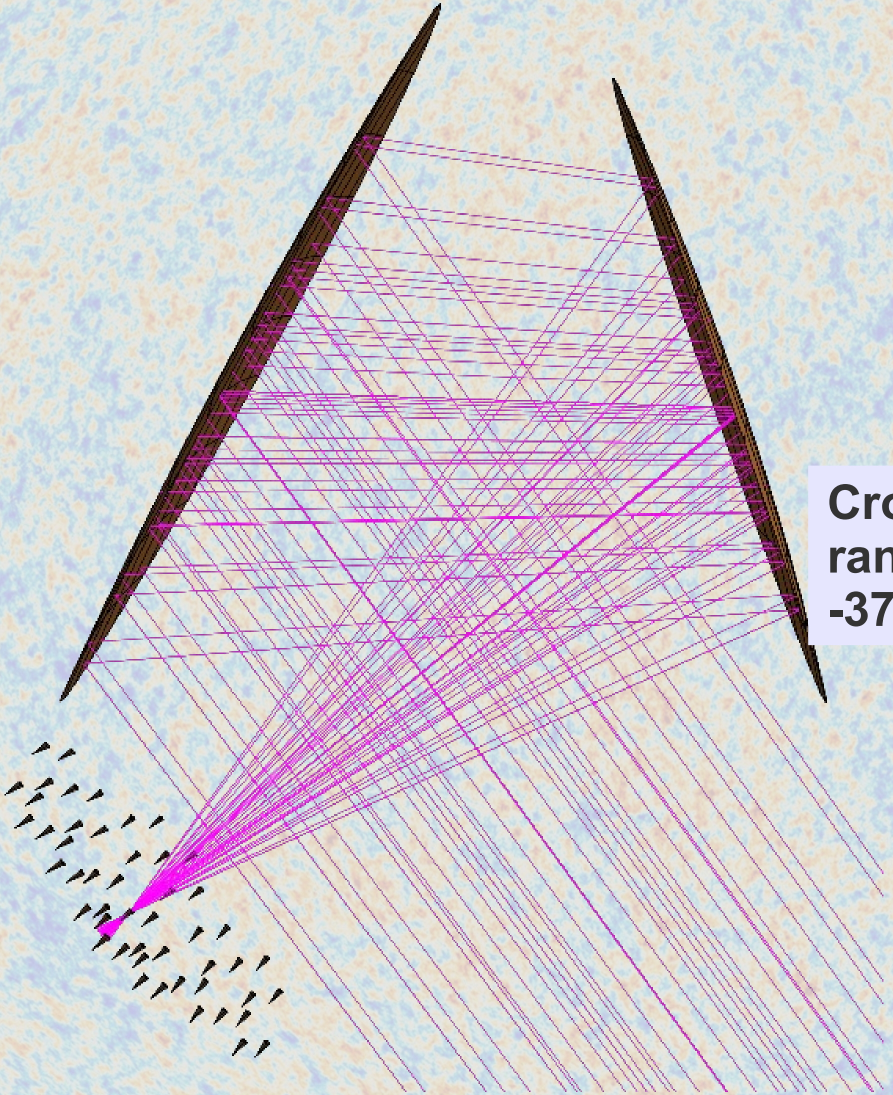
Deep instrument knowledge and *in-hardware* control of effects is mandatory for ultra-high sensitivity future experiments

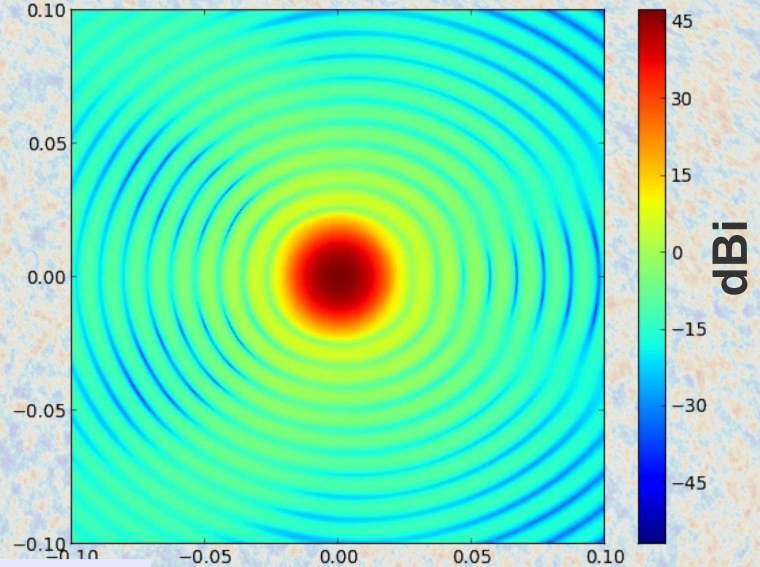
Optical	*Beam ellipticity / cross polarization* *Sidelobes (Earth, Sky pickup)*
Polarization	*I → Q/U leakage* *Q → U leakage*
Noise and stability	*1/f noise* *Thermal stability* *Cosmic ray hits* *Time constants*
Pointing	*Pointing uncertainties*
Electronics	*ADC non linearities* *DC spurious signals*

Main beams

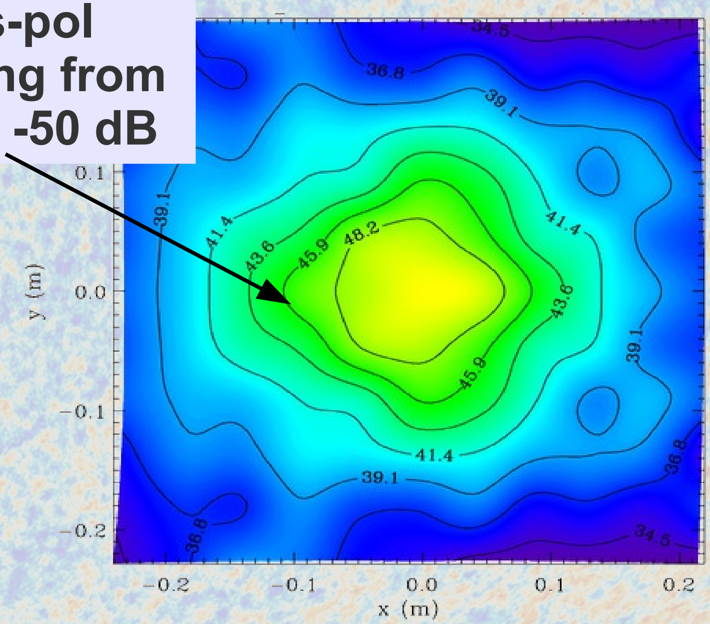
- Symmetrical beams are required to minimize cross polarization
- Possible solutions: (1) on-axis lenses (like, e.g. BICEP2, SPIDER, LSPE-SWIPE), (2) off-axis reflectors (like Crossed-Dragone configurations used by QUIET, ABS, LSPE-STRIP)
- Simulation of impact of beam asymmetries recommended

STRIP crossed Dragone





Cross-pol ranging from -37 to -50 dB



Assessing impact of beam asymmetries

Instrumental polarization pattern:

Carretti et al. 2004

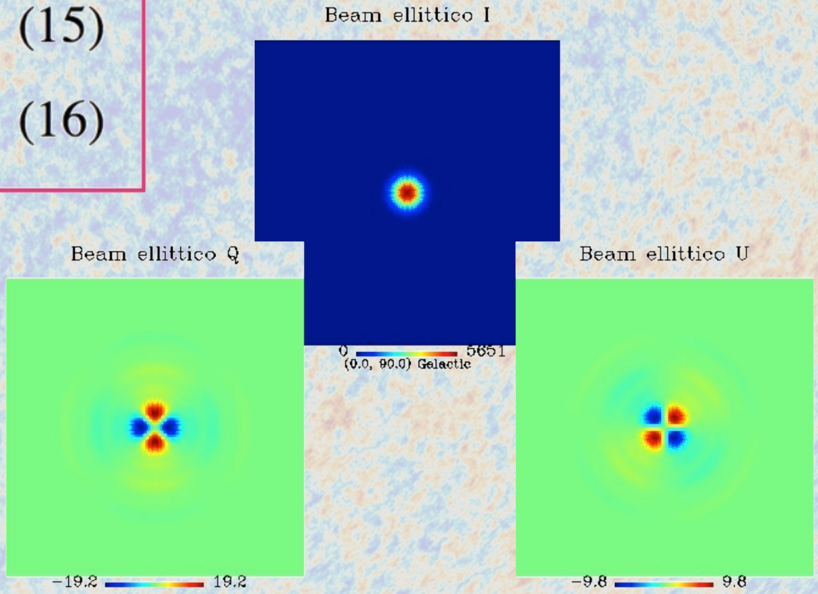
$$\Pi(\theta', \phi') = \Pi_Q(\theta', \phi') + j\, \Pi_U(\theta', \phi') \quad (14)$$

with

$$\Pi_Q = \frac{|g_x|^2 + |\chi_x|^2 - |g_y|^2 - |\chi_y|^2}{2}, \quad (15)$$

$$\Pi_U = \Re\,(g_x\chi_y^* + g_y\chi_x^*). \quad (16)$$

$$g_x(\theta, \phi) = g(\theta, \phi)$$
$$g_y(\theta, \phi) = g(\theta, \phi - \pi/2)$$
$$\chi_x(\theta, \phi) = \chi(\theta, \phi)$$
$$\chi_y(\theta, \phi) = -\chi(\theta, \phi - \pi/2)$$



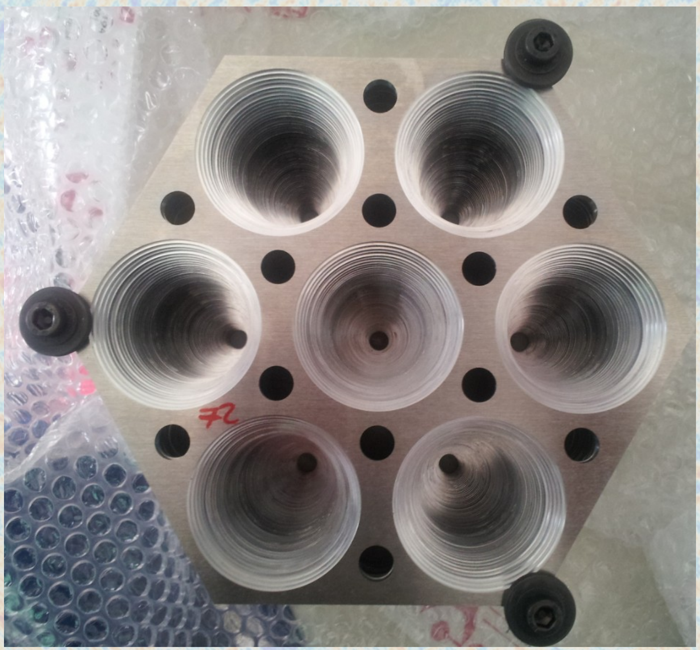
Sidelobes

- Pickup of polarized sky or earth signals by beam sidelobes can introduce a large systematic uncertainties
- Typical requirements for LSPE are ~ -70 dB (tough !)
- Simple reflective baffles can be not enough (sidelobes are redirected towards the sky) – evaluating possibility of a warm stop
- Corrugated feed horns are still the best choice for best optical performance

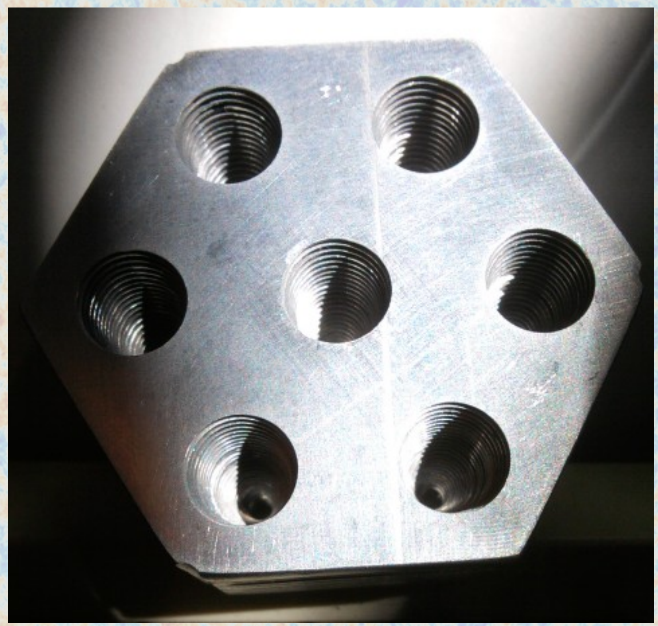
Platelet corrugated feeds

Patelet feeds can be manufactured in series with much lower costs compared to other techniques (e.g. electroforming) – already implemented, e.g., in QUIET

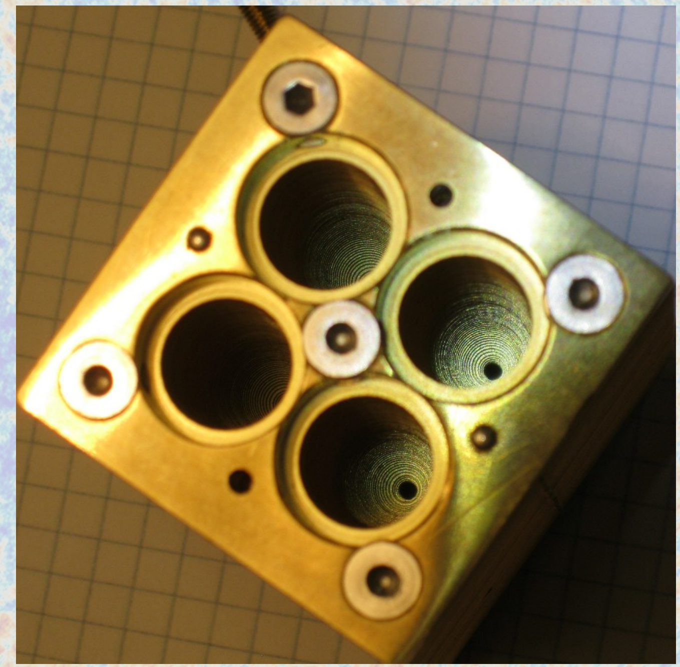
43 GHz – LSPE-STRIP



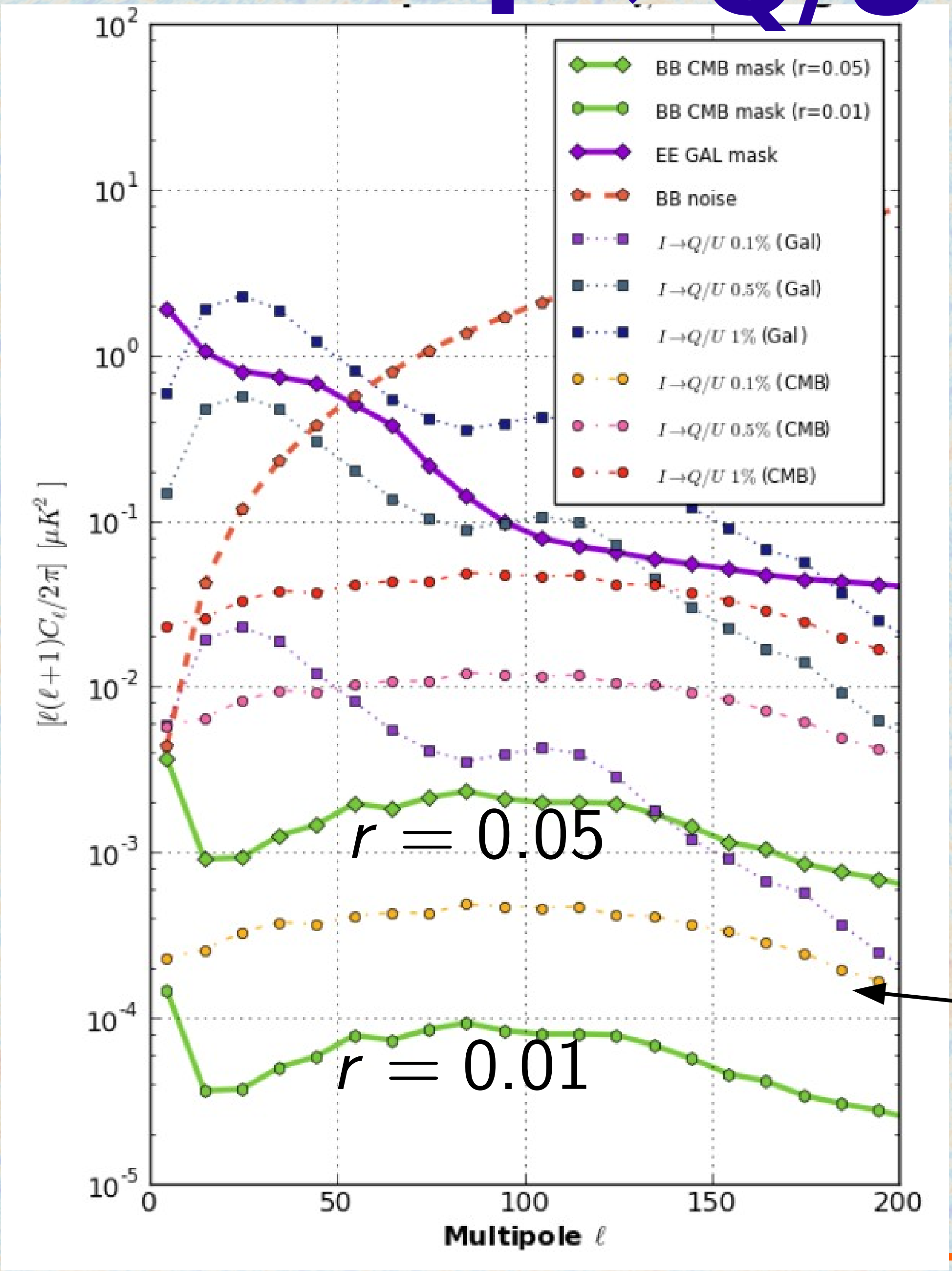
95 GHz – prototype study



150 GHz – QUBIC prototype



I → Q/U leakage

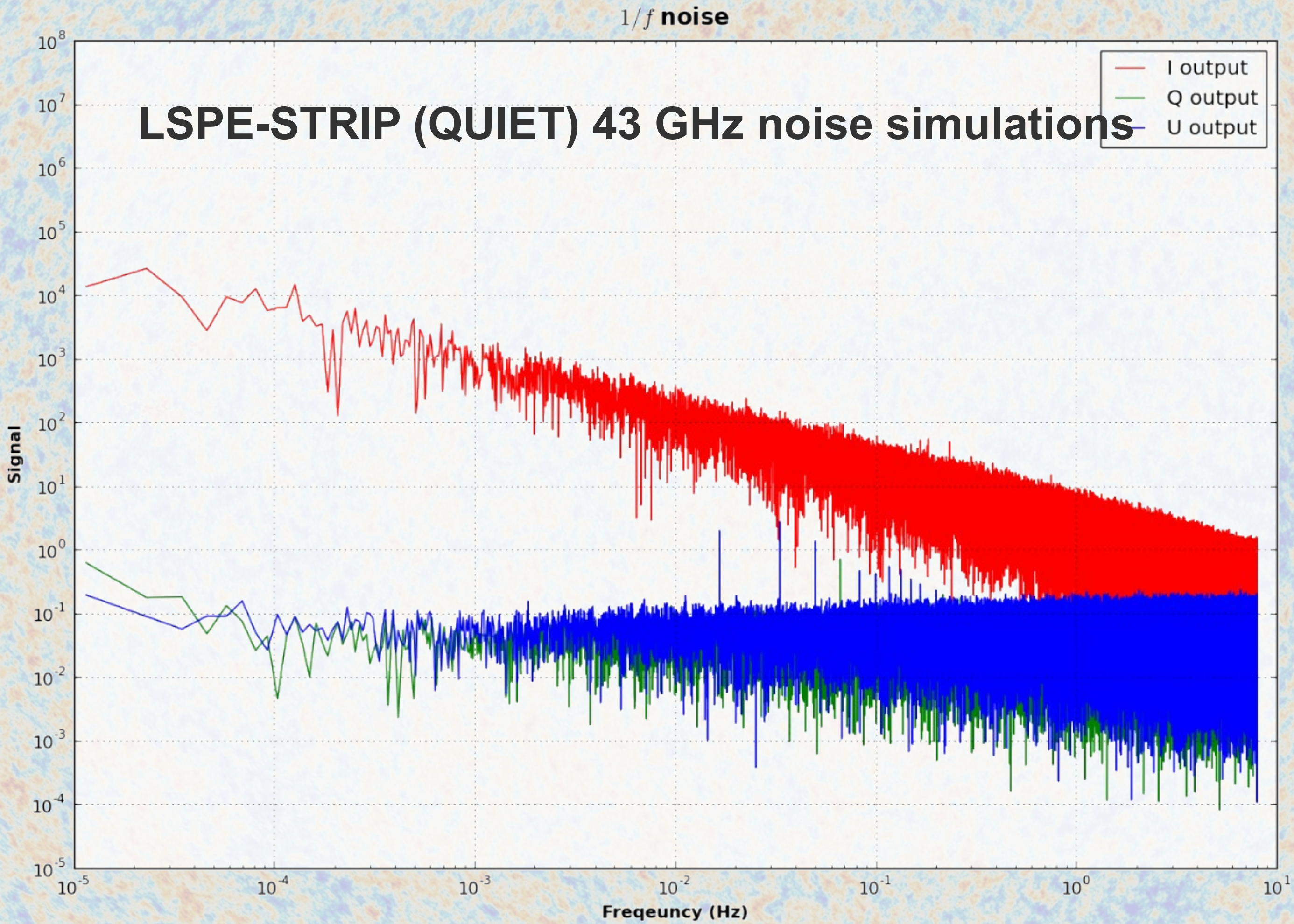


- One of the most critical effects
- Can arise because of various depending on the instrument (e.g. bandpass mismatches, OMT or polarizer non idealities)
- Needs be kept below 0.1%

$I \to Q/U = 0.5\%$

Krachmalnicoff, 2013

Noise and stability



- Large angular scale experiments require high level of stability
- Aggressive filtering impacts signal on large angular scales
- Knee frequencies of order of mHz or less are required
- Coherent polarimeters offer an advantage

Challenge # 3

Meeting the systematic effect control

- **Very tough challenge.**
- Current level of systematic effects in polarization experiments can still be marginal for robust B-mode detections, especially at low-ell.
- Optics, polarization leakage, sidelobes control are critical.
- Simulations and in-hardware control (as much as possible) are key

Challenge # 4

Meeting the calibration accuracy

Planck 2013, V

Table 8. Accuracy in the calibration of LFI data.

Type of uncertainty	Applies to	30 GHz	44 GHz	70 GHz
Absolute				
Standard[a]	All sky	0.25 %	0.25 %	0.25 %
Zero level [μK_{CMB}]	All sky	-300.84 ± 2.23	-22.83 ± 0.78	-28.09 ± 0.64
Beam uncertainty	All sky	0.5 %	0.1 %	0.3 %
Sidelobe convolution effect	All sky	0.2 %	0.2 %	0.2 %
Colour corrections	Galactic areas	$\lvert\alpha - 2\rvert$ 0.1 %	$\lvert\alpha - 2\rvert$ 0.3 %	$\lvert\alpha - 2\rvert$ 0.2 %
Relative				
Statistical/algorithmical errors[b] [μK_{CMB} pixel^{-1}] .	All sky	4.3	4.7	6.5
Known systematics[c]	All sky	0.1 %	0.1 %	0.1 %
Unknown systematics[d] [μK_{CMB} pixel^{-1}]	CMB areas	[illegible]	[illegible]	< 9.5
	Galactic region	< 17.0	[illegible]	< 13.1
Unknown systematics[e] ($50 < \ell < 250$)	All sky	0.2 %	0.2 %	0.1 %
Total				
CMB areas[f] [μK_{CMB} pixel^{-1}]		< 8.5	< 7.1	< 8.2
Galactic region[f] [μK_{CMB} pixel^{-1}]		< 18.5	< 13.7	< 16.8
Sum of absolute and relative errors[g]	All sky	0.82 %	0.55 %	0.62 %

Planck photometric calibration for temperature data is < 1 % and will have to be improved for next release

Accurate calibration in polarimetry

- **Internal calibrators:** useful, may be difficult in balloon experiments (Boomerang achieved 0.1% with internal calibration lamp)
- **Few well known natural polarized calibrators** (Crab nebula). No well know diffuse calibrators, unfortunately!
- **Polarization angle**: needs be know better than 1°
- **Main beams**: needs be measured in flight to ~ – 20 dB to ensure window function reconstruction

QUIET calibration schedule

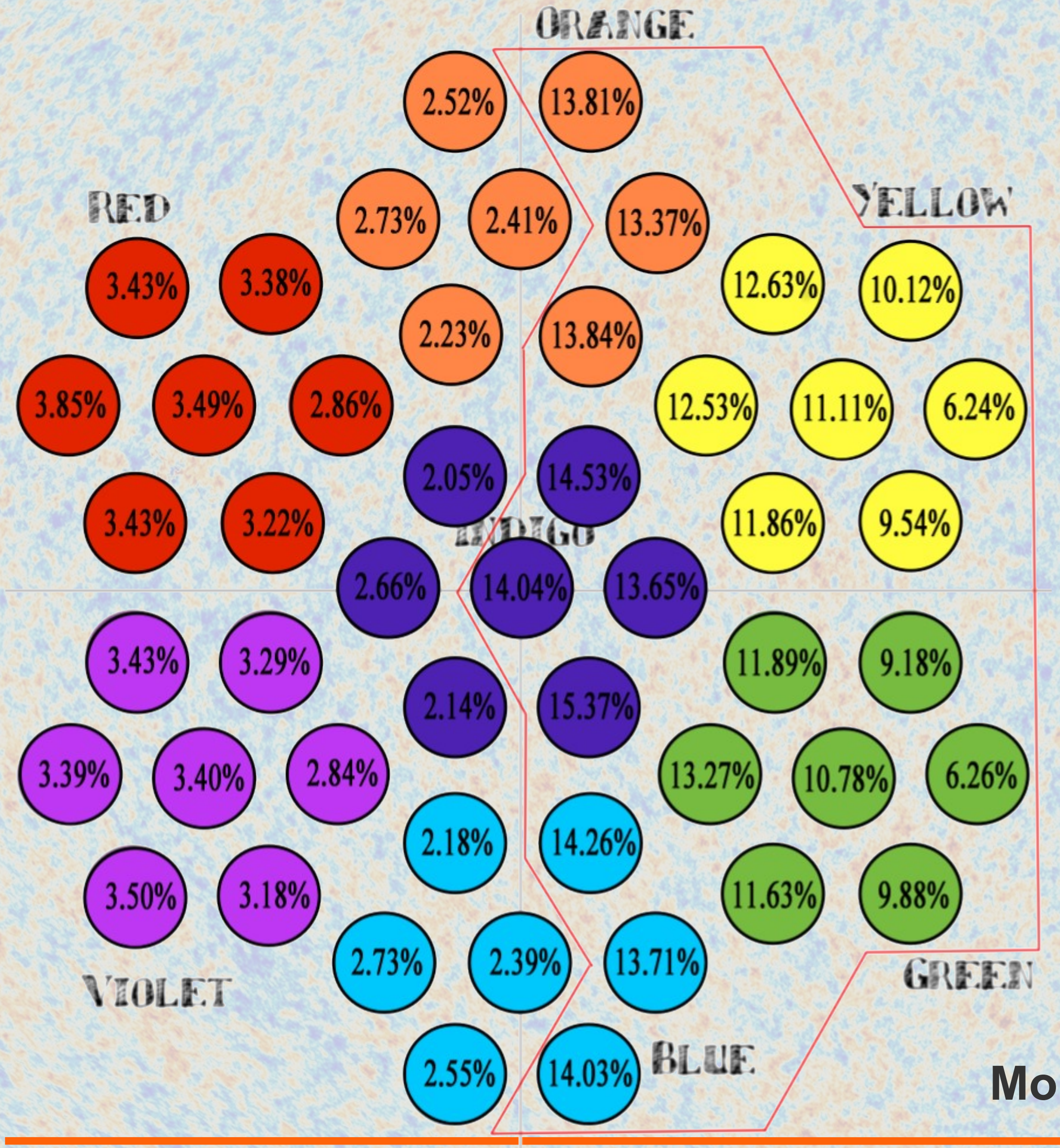
QUIET collaboration, ApJ, 2011

Source	Frequency of observation	TT/polarization	absolute/relative
Jupiter	weekly	TT	absolute
RCW38	weekly	TT	absolute
Venus	every second week	TT	absolute
Tau A	every 1-2 days	polarization	absolute
Moon	weekly	TT/polarization	relative
wire-grid	once; end-of-season	polarization	relative
skydips	$\sim$ every 1.5 hours	TT/polarization	relative

Table 1. Summary of QUIET calibration sources

Overall calibration accuracy ~ 6%

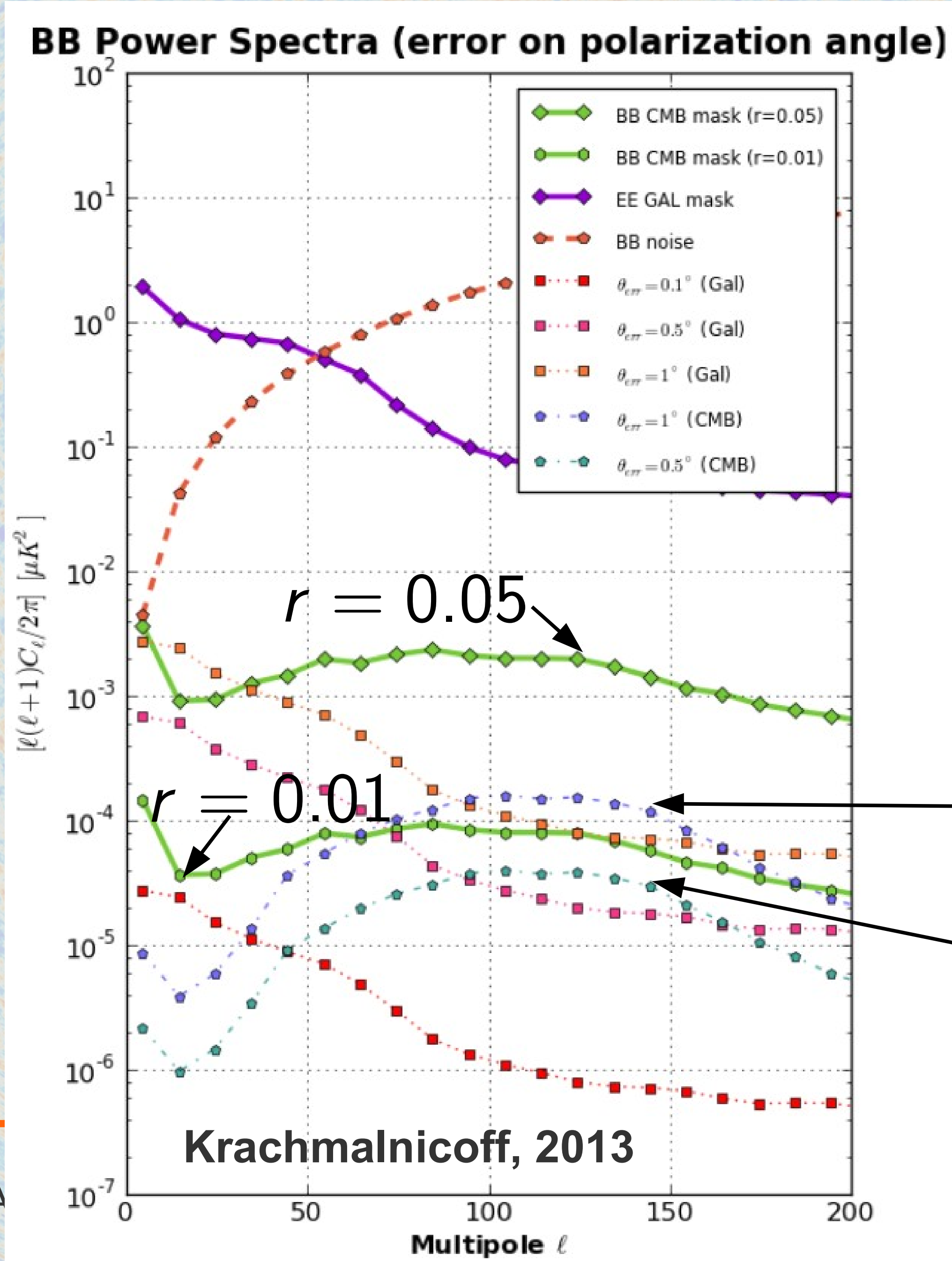
LSPE-STRIP preliminary calibration assessment



- Crab visited during dedicated low-elevation scans
- Accuracy determined by S/N ratio
- Need to optimize scanning strategy to uniform calibration accuracy

Montresor, 2013

Effect of polarization angle



- Polarization angle can be measured on Crab and Moon
- 1° accuracy can be achievable, but better is required to go below r = 0.03

1° error on polarization angle

0.5° error on polarization angle

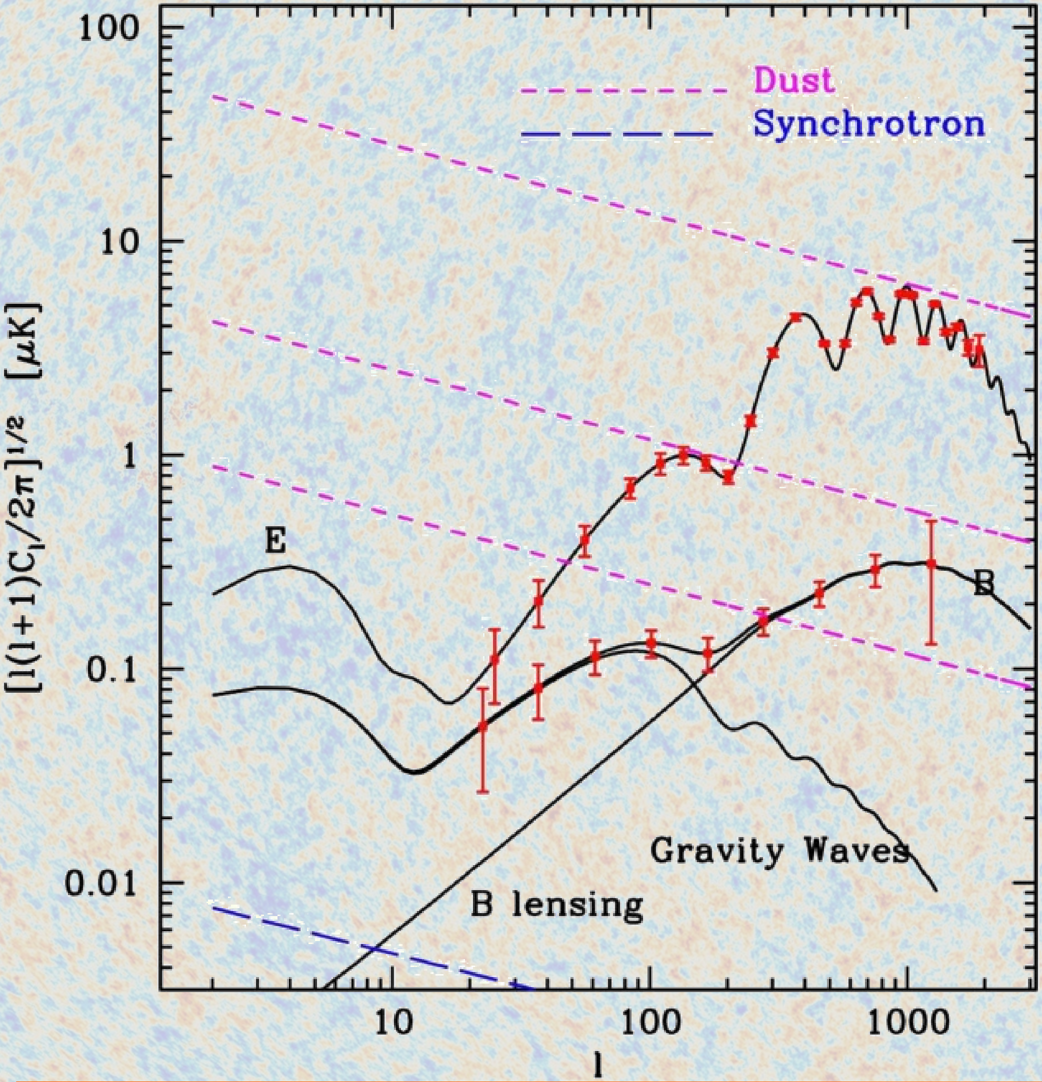
Challenge # 4
Meeting the calibration accuracy

- **Very tough challenge.**
- Photometric calibration accuracy < 1% → *optimize scanning strategy, artificial calibrators*
- Polarization angle better than 0.5° → *optimize scanning strategy, observe various sources, artificial calibrators*
- Beam reconstruction down to –20 dB → *can be critical for complex beams*

Challenge # 5

Meeting the foregrounds control

EBEX, Reichborn et al 2011

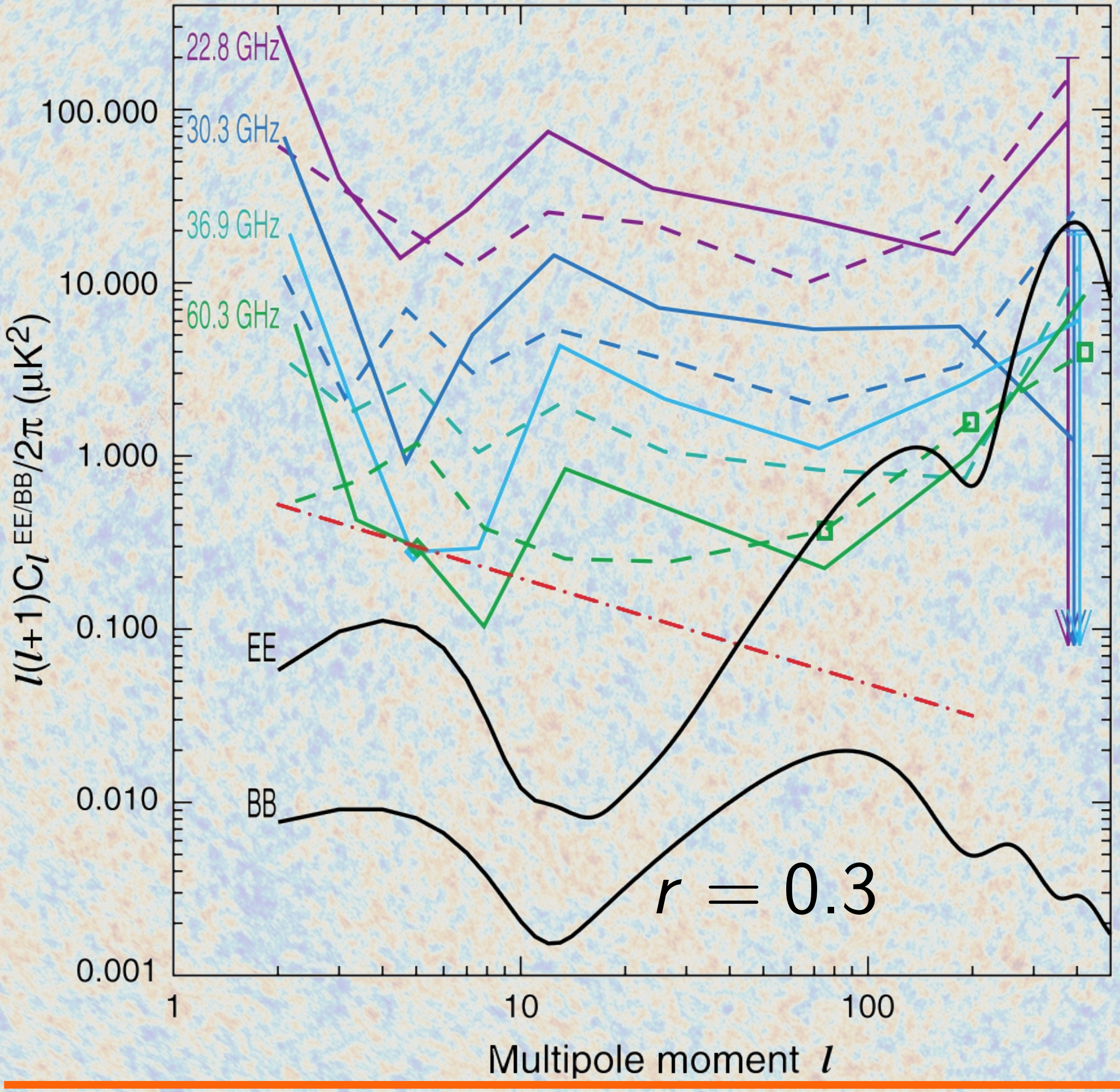


- On selected sky patches it is possible to find *relatively* foreground clean regions
- Here we have that synctrotron is sub-dominant, but dust remain important

Challenge # 5

Meeting the foregrounds control

WMAP, Page et al 2007



- On large angular scales foregrounds dominate
- Foregrounds are **the key issue** for accurate CMB polarization measurements at large angular scales
- Sensitive measurements for synchrotron polarized emission control are crucial

Challenge # 5

Meeting the foregrounds control

- **Extremely tough challenge.**
- At large angular scales the polarized CMB is foreground-dominated
- Wide frequency measurements with high sensitivity are necessary to control synchrotron and dust
- Combination of data from different instruments can be an important mitigation factor

Conclusions

- **Precision polarization measurements are extremely hard**
- Several advances in detector technology available thanks to latest ground and balloon efforts
- Systematic effects and foregrounds are key for large scales measurements
- In Feb 2014 I stated:

It is possible that a tensor B-mode detection will come in the next years, but certainly it is not at hand

- Last famous words? The next months will be key to hear what the universe is really telling us

And finally...

A real dream

The *CNB*

The Cosmic Neutrino Background

... maybe the Universe will look much different than we think

Dedicated to Professor Apolodor Aristotel Răduţă's 70^{th} Anniversary

SEARCH FOR THE COSMIC NEUTRINO BACKGROUND AND KATRIN

AMAND FAESSLER[1], RASTISLAV HODAK[2], SERGEY KOVALENKO[3], FEDOR ŠIMKOVIC[4]

[1]Institute für Theoretische Physik der Universität Tübingen,
D-72076 Tübingen, Germany
E-mail: faessler@uni-tuebingen.de
[2]Institute of Experimental and Applied Physics, Czech Tecnical University, Horská 3a/22, 12800 Prague, Czech Republic
[3]Departamento de Fisica, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
[4]JINR, 141980 Dubna, Moscow Region, Russia
and Comenius University, Physics Dept., SK-842 15 Bratislava, Slovakia

Received April 22, 2013

The Cosmic Microwave Background (CMB) has been detected in 1964 by Penzias and Wilson. It shows today a remarkable constant temperature of $T_{0\gamma} \approx 2.7$ K independent of the direction. Present density is about 370 photons per cm^3. The size of the hot spots, which deviates only in the fifth decimal of the temperature from the average value, tells us, that the universe is flat. About 300 000 years after the Big Bang at a temperature of $T_{0\gamma} = 3000$ K already in the matter dominated era the electrons combine with the protons and the ^{4}He and the photons move freely in the neutral universe. So the temperature and distribution of the photons give us information of the universe 300 000 years after the Big Bang. Information about earlier times can, in principle, be derived from the Cosmic Neutrino Background ($C\nu B$). The neutrinos decouple already 1 second after the Big Bang at a temperature of about 10^{10} K. Today their temperature is ~ 1.95 K and the average density is 56 electron-neutrinos per cm^3. Registration of these neutrinos is an extremely challenging experimental problem which

1230 Amand Faessler *et al.* 10

- With the average relic neutrino number density of $< n_{\nu,e} >= 56\ \text{cm}^{-3}$ KATRIN could measure only every 240 000 years a count. So the hope is with the local overdensity due to gravitational clustering of the neutrinos in our galaxy. Estimates for this overdensity $n_{\nu,e}/ < n_{\nu,e} >$ vary widely from about 10^2 to 10^6. With the optimistic estimate of a local overdensity of 10^6 one obtains with KATRIN 4 counts per year. If one could increase the mass of the tritium source from 50 microgram to 5 milligram, this optimistic estimate of the overdensity would mean 400 counts per year.