Challenges
present and future in the observation of the Cosmic Microwave Background

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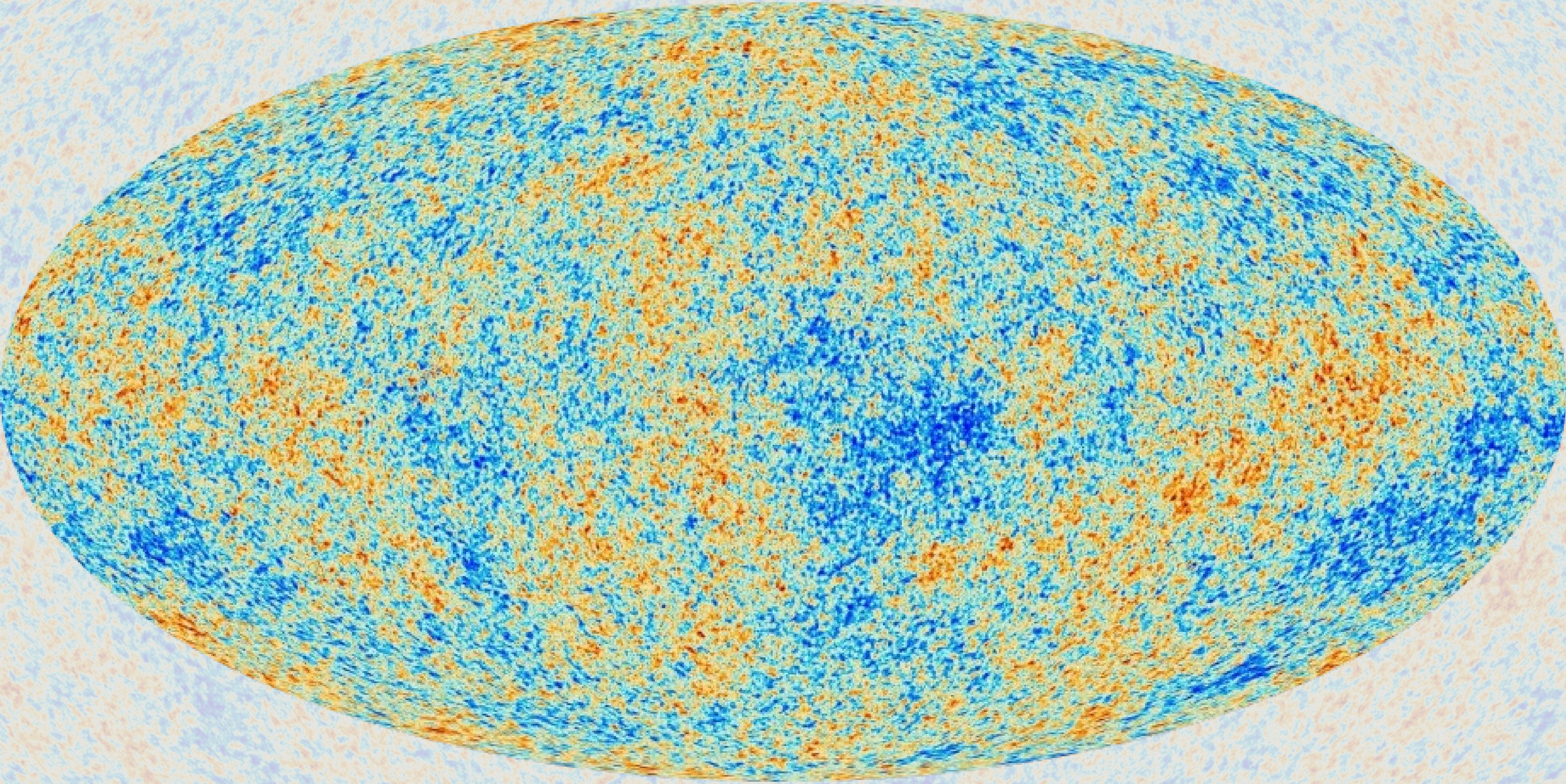
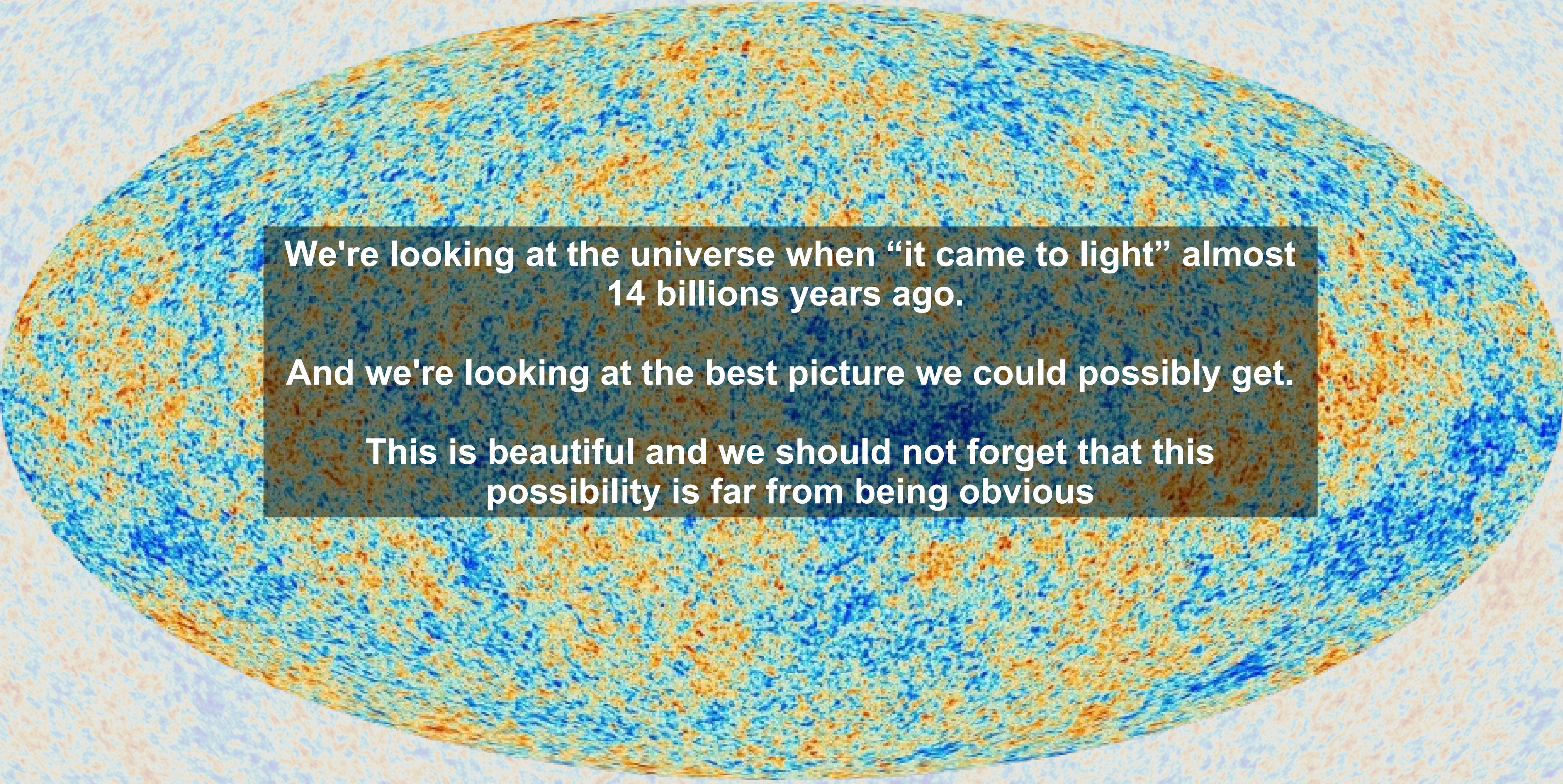
Dipartimento di Fisica

Today



Today

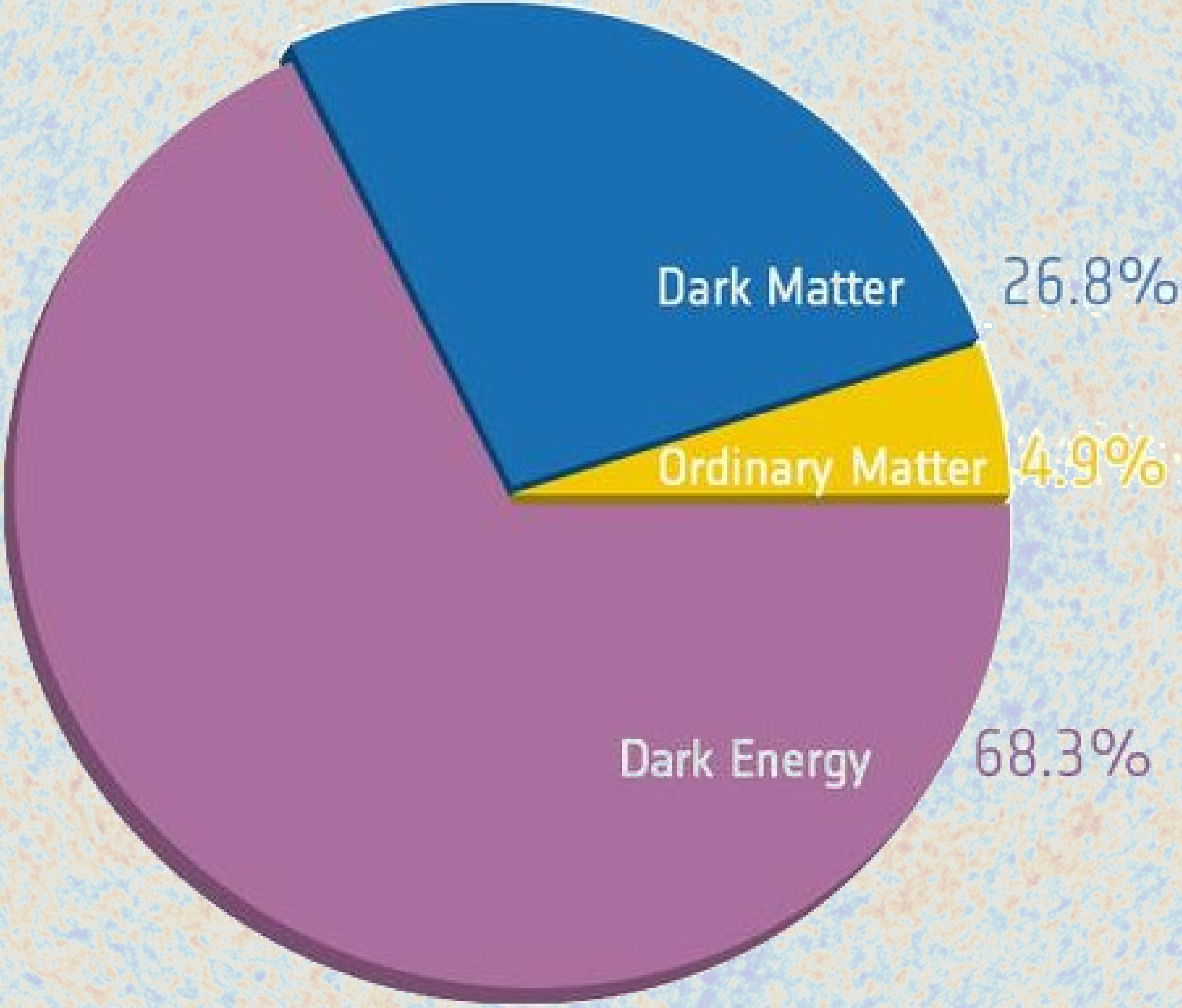


We're looking at the universe when “it came to light” almost 14 billions years ago.

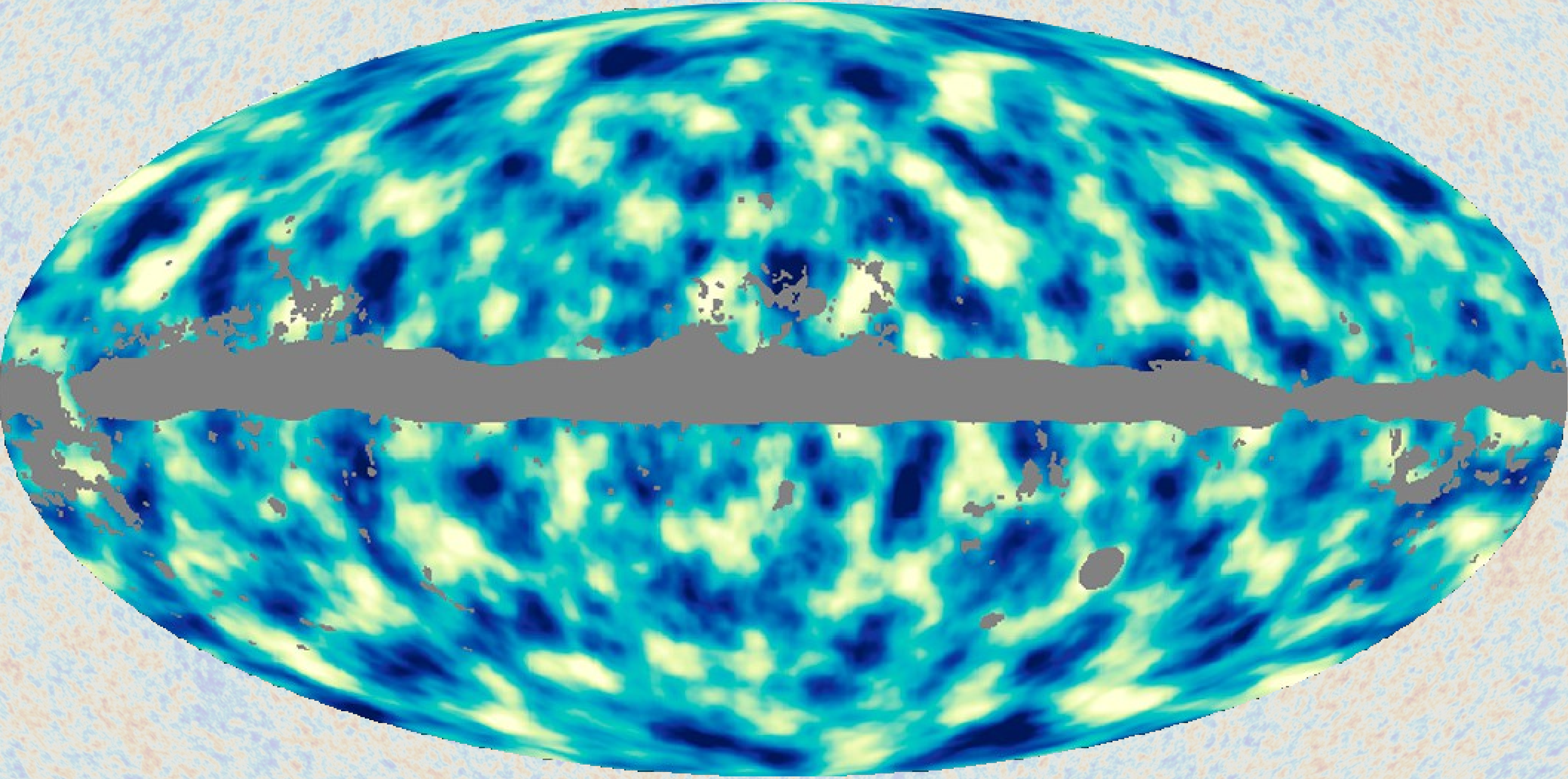
And we're looking at the best picture we could possibly get.

This is beautiful and we should not forget that this possibility is far from being obvious

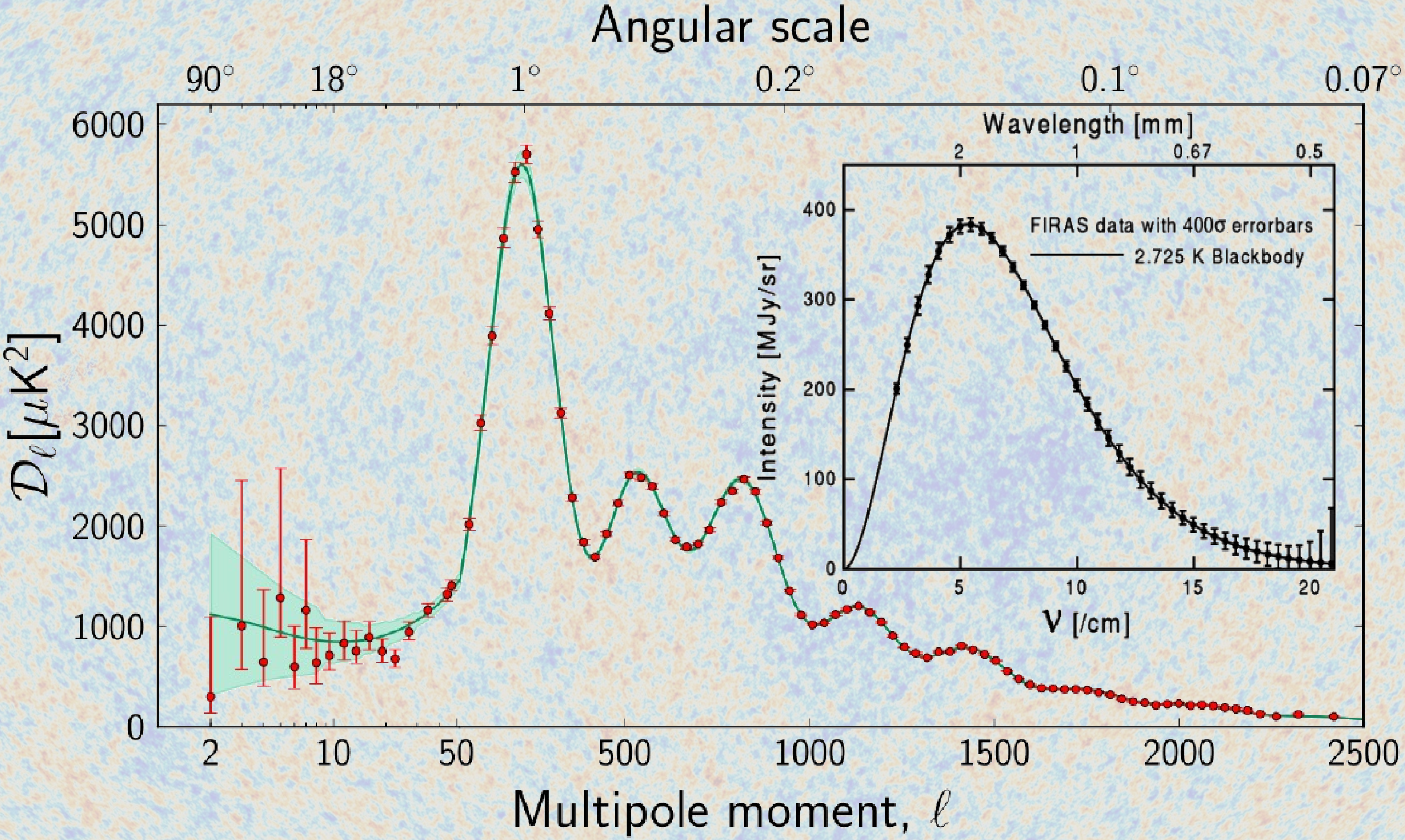
We know how much stuff there is in the universe



We see dark matter through CMB lensing



Remarkable agreement



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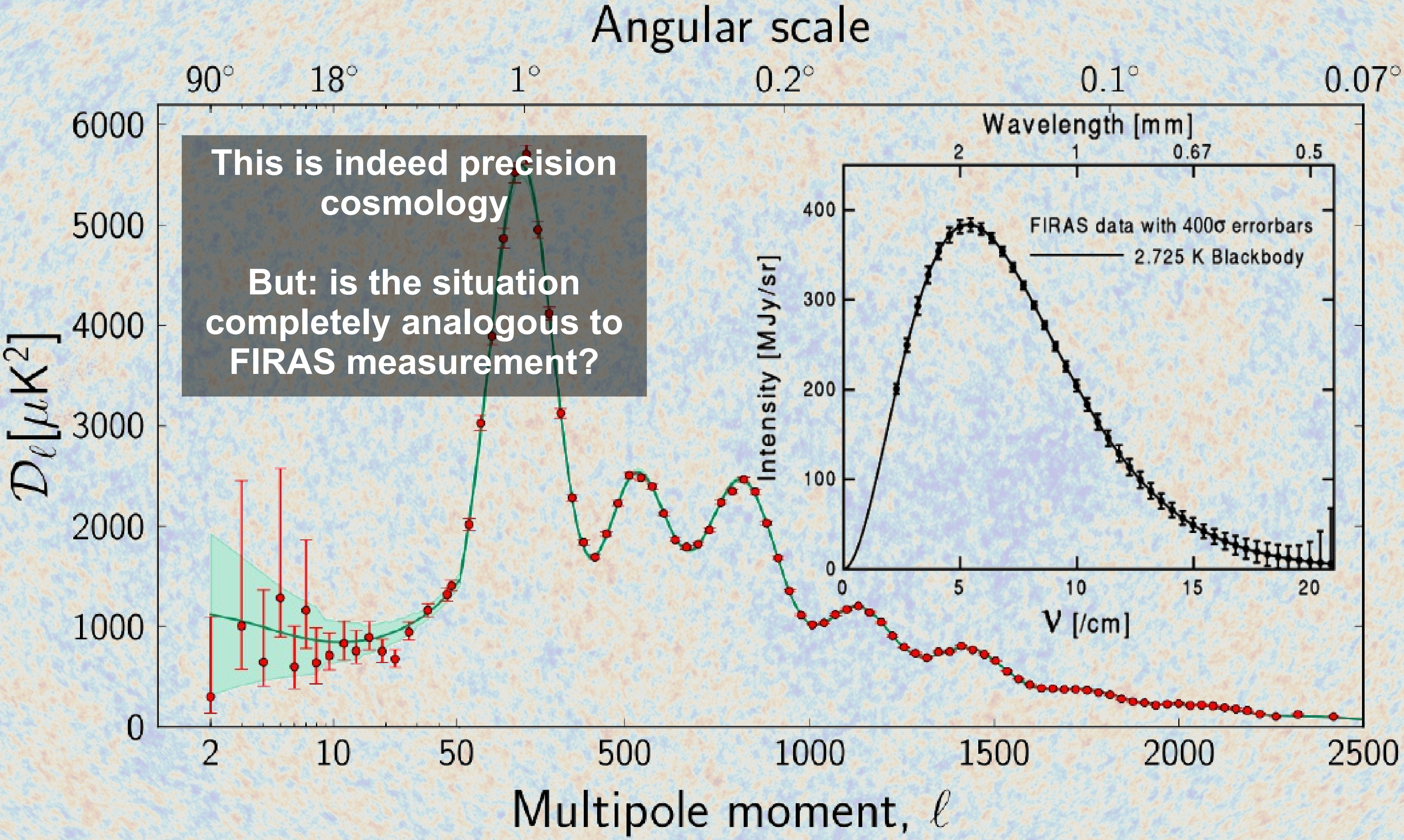
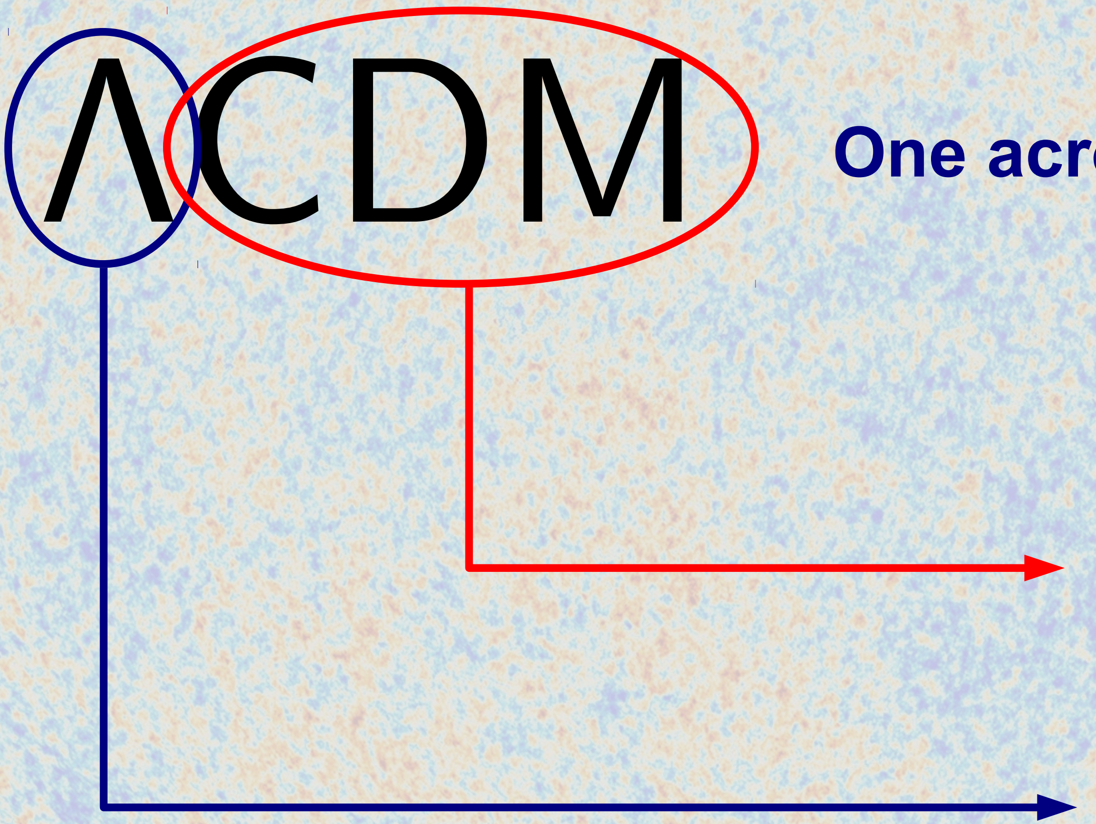


This is indeed precision cosmology

But: is the situation completely analogous to FIRAS measurement?

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

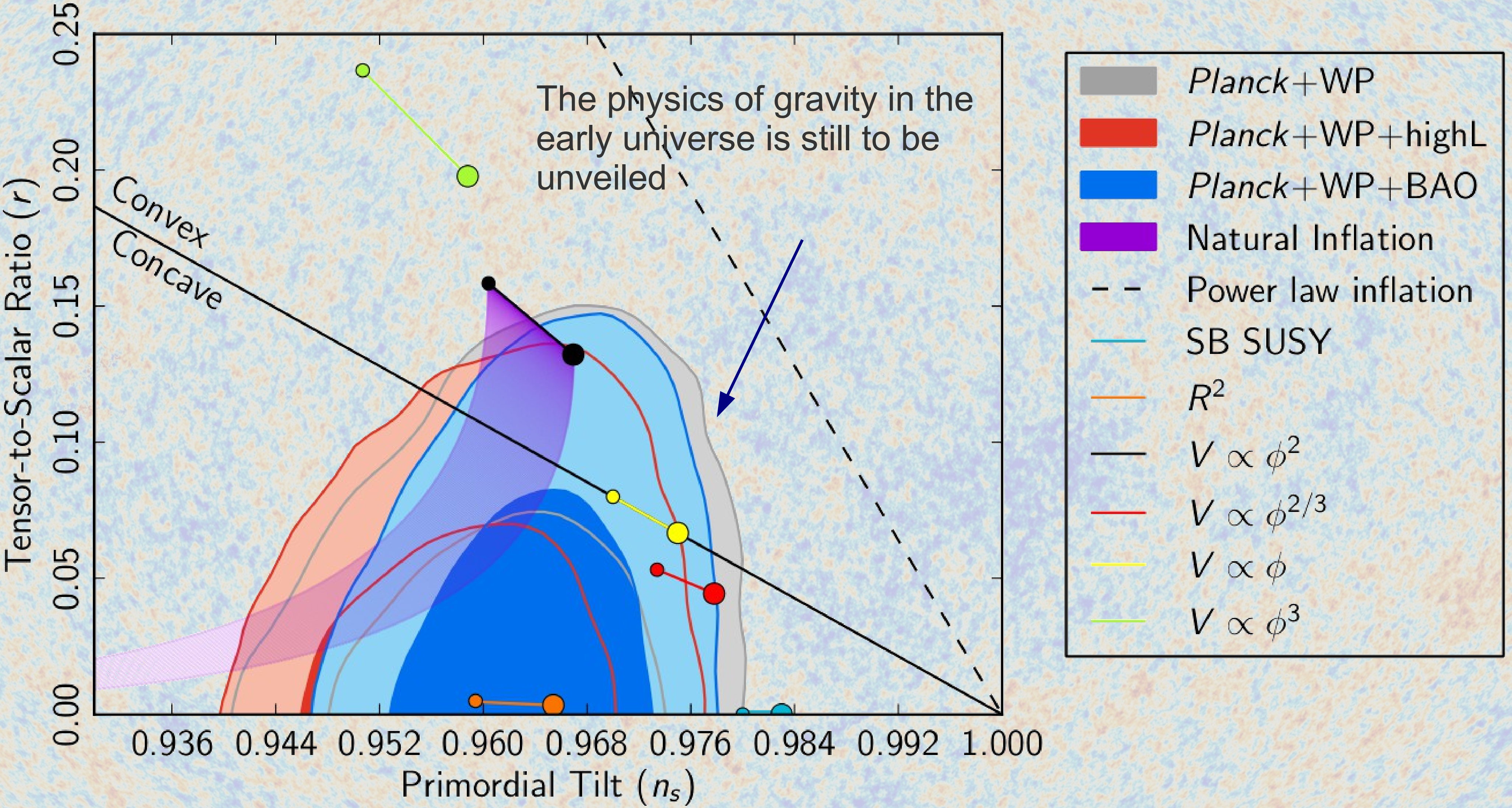
One acronym, two mysteries



Cold dark matter

Dark energy

The “tip of the iceberg”



Wandering in “bright fog”

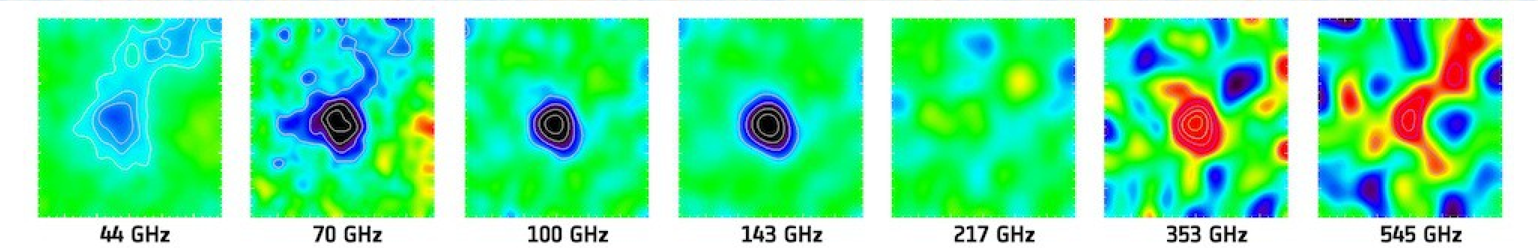
Today's BIG questions

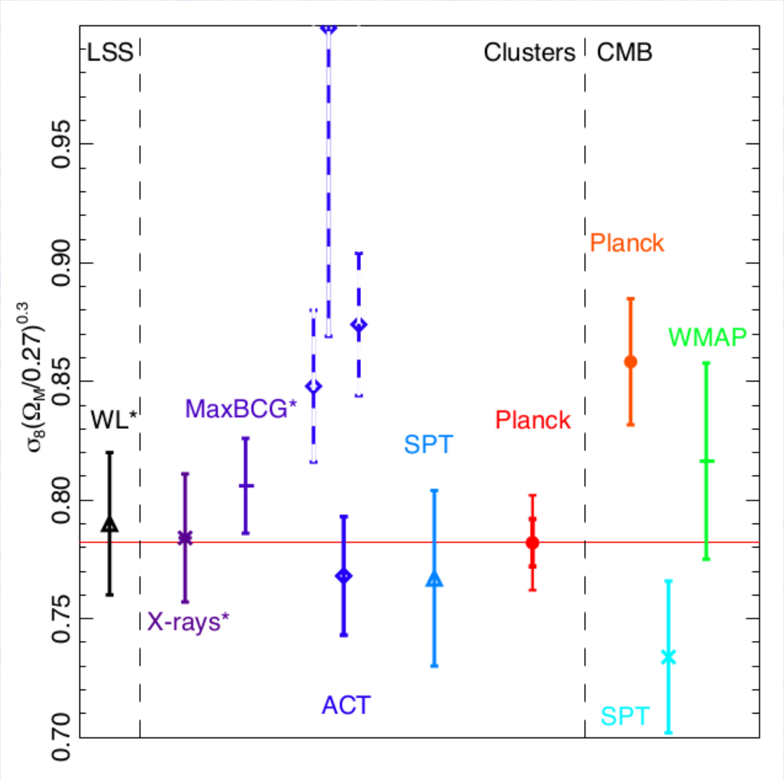
- What is the nature of dark matter?
- Does dark energy exist, what is its nature? Is it constant or does it modify with time?
- Or is it necessary to invoke a modification of General Relativity at large scales? Or of its assumptions?
- Did inflation occur? In which conditions?
- When did the first stars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

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

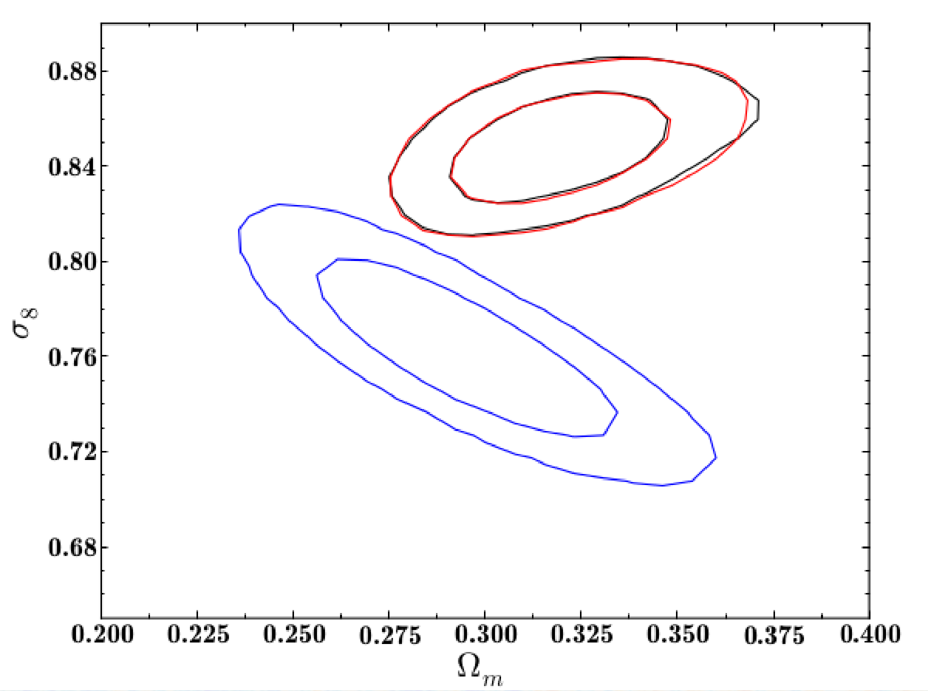
The shadow of the giants

Cosmology with the SZ effect





Planck 2013, XX.



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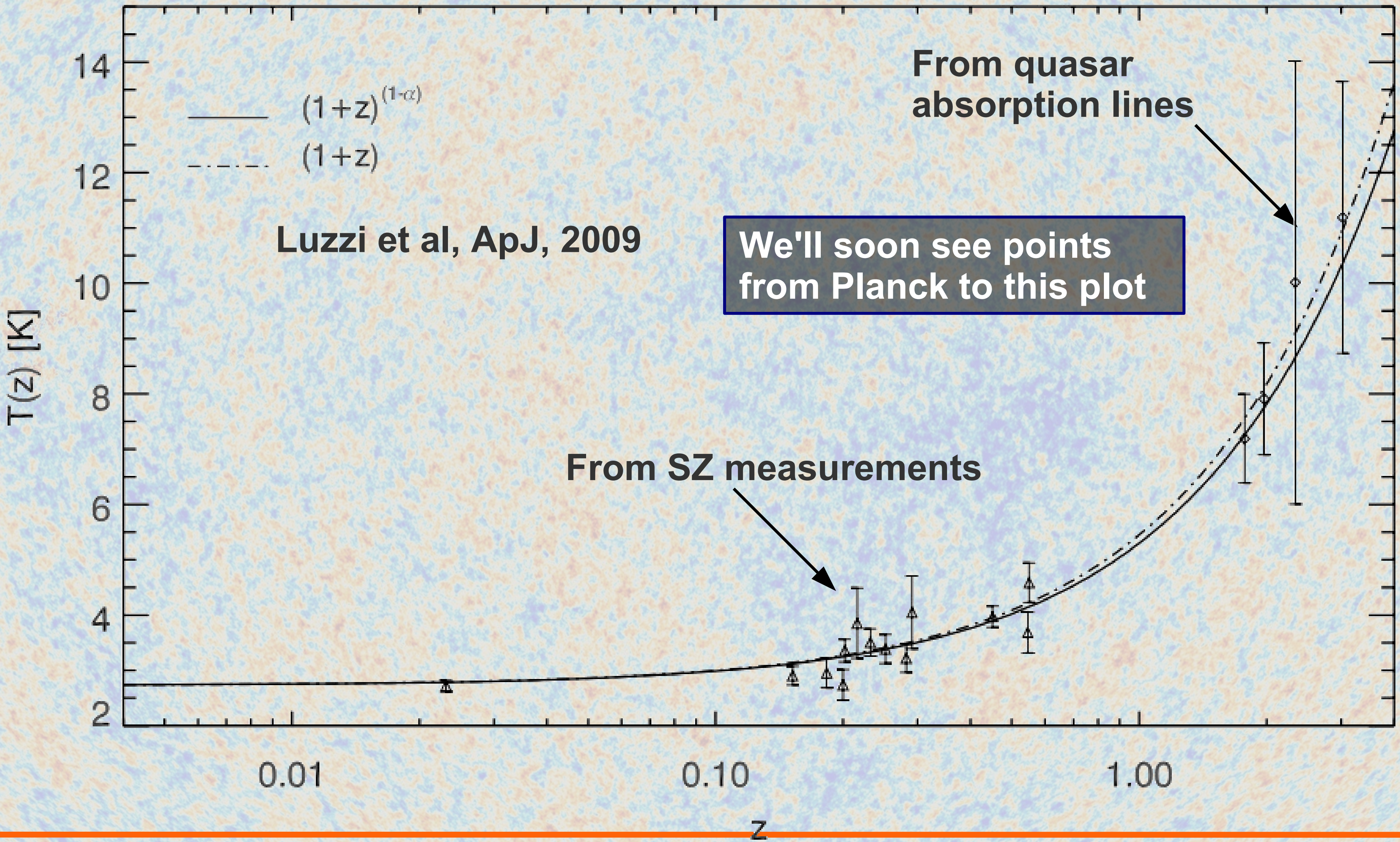
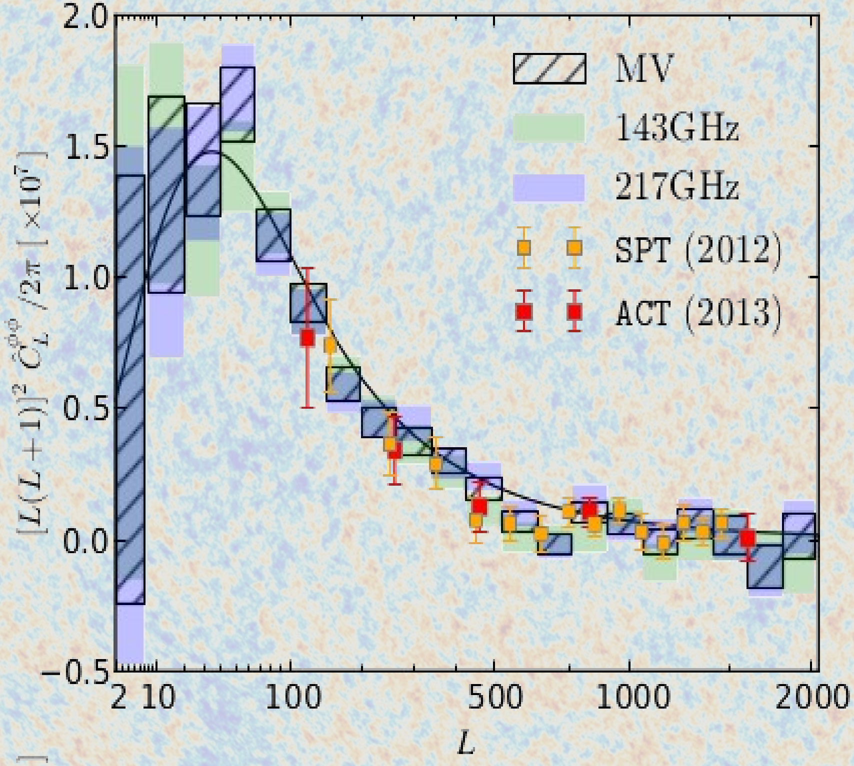


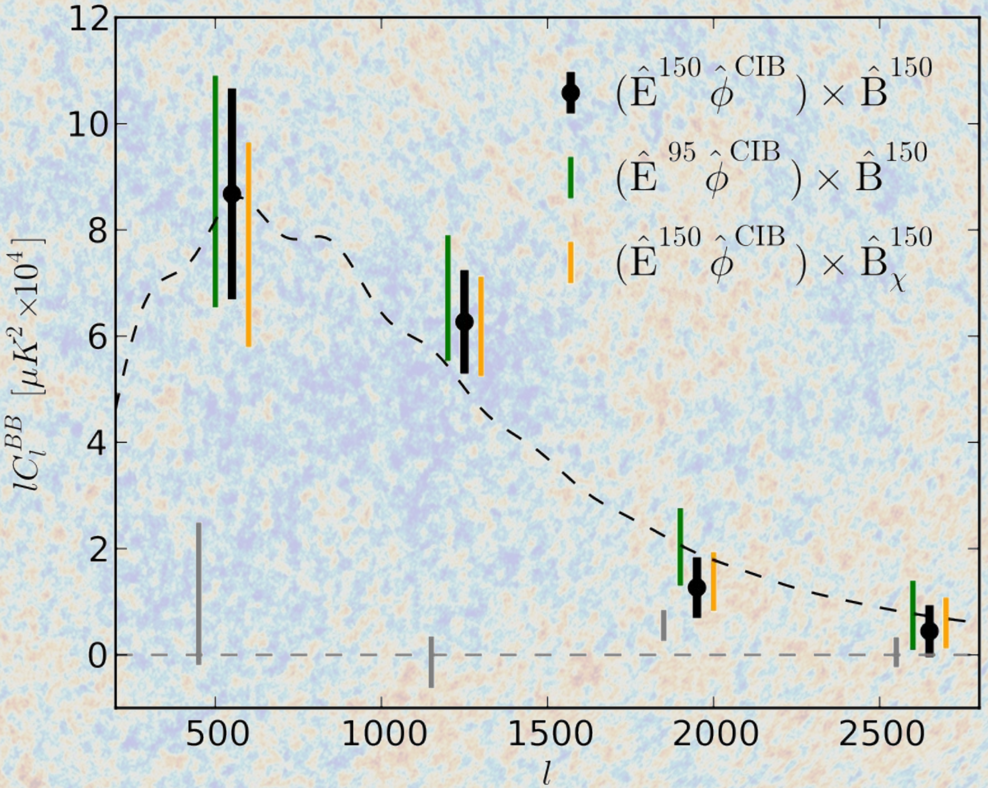
Cosmic glasses

Cosmic matter distribution through CMB lensing

Planck 2013, XVII

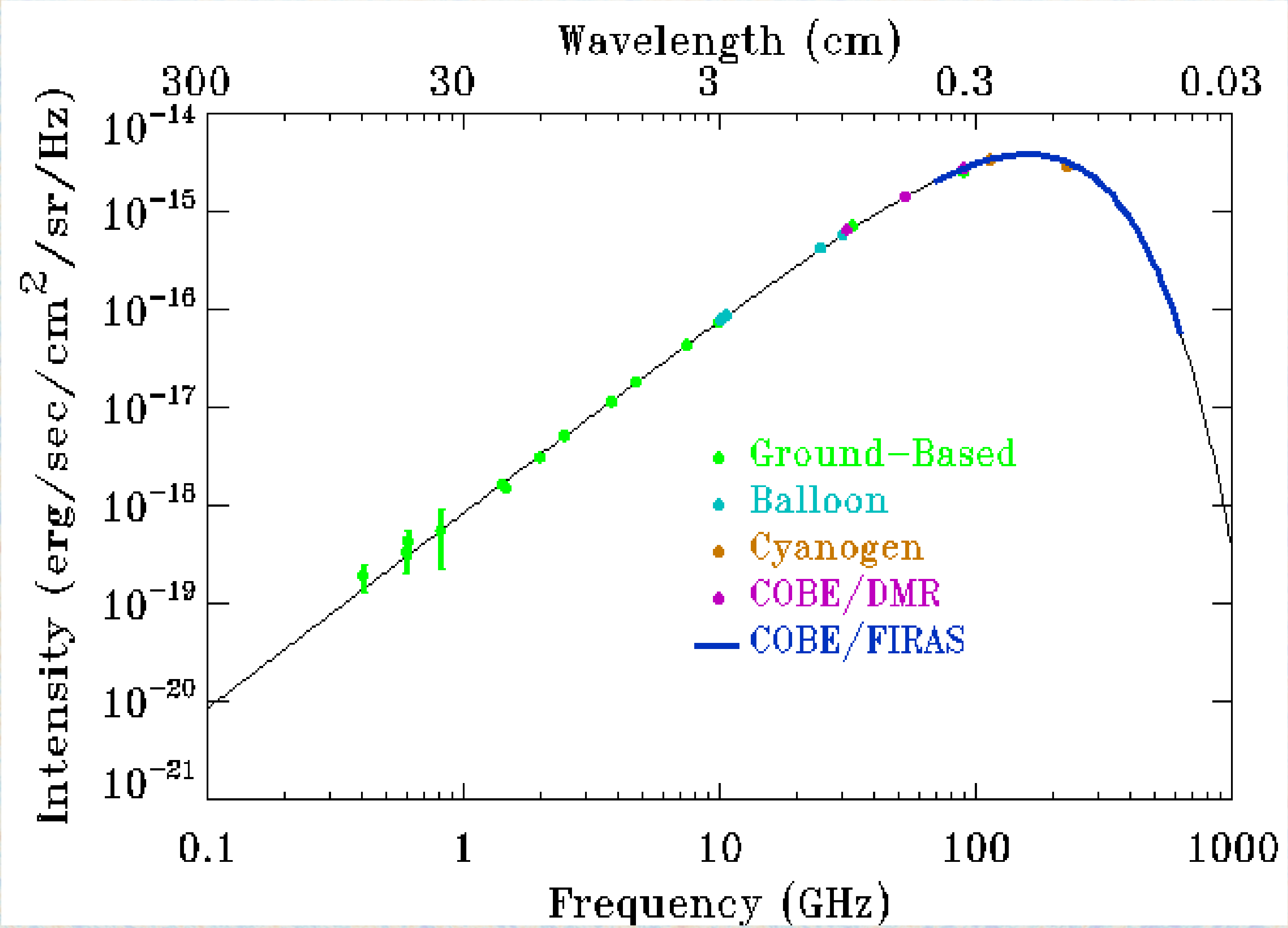


astro-ph > arXiv:1307.5830



Total blackness

The quest for distortions of the CMB spectrum

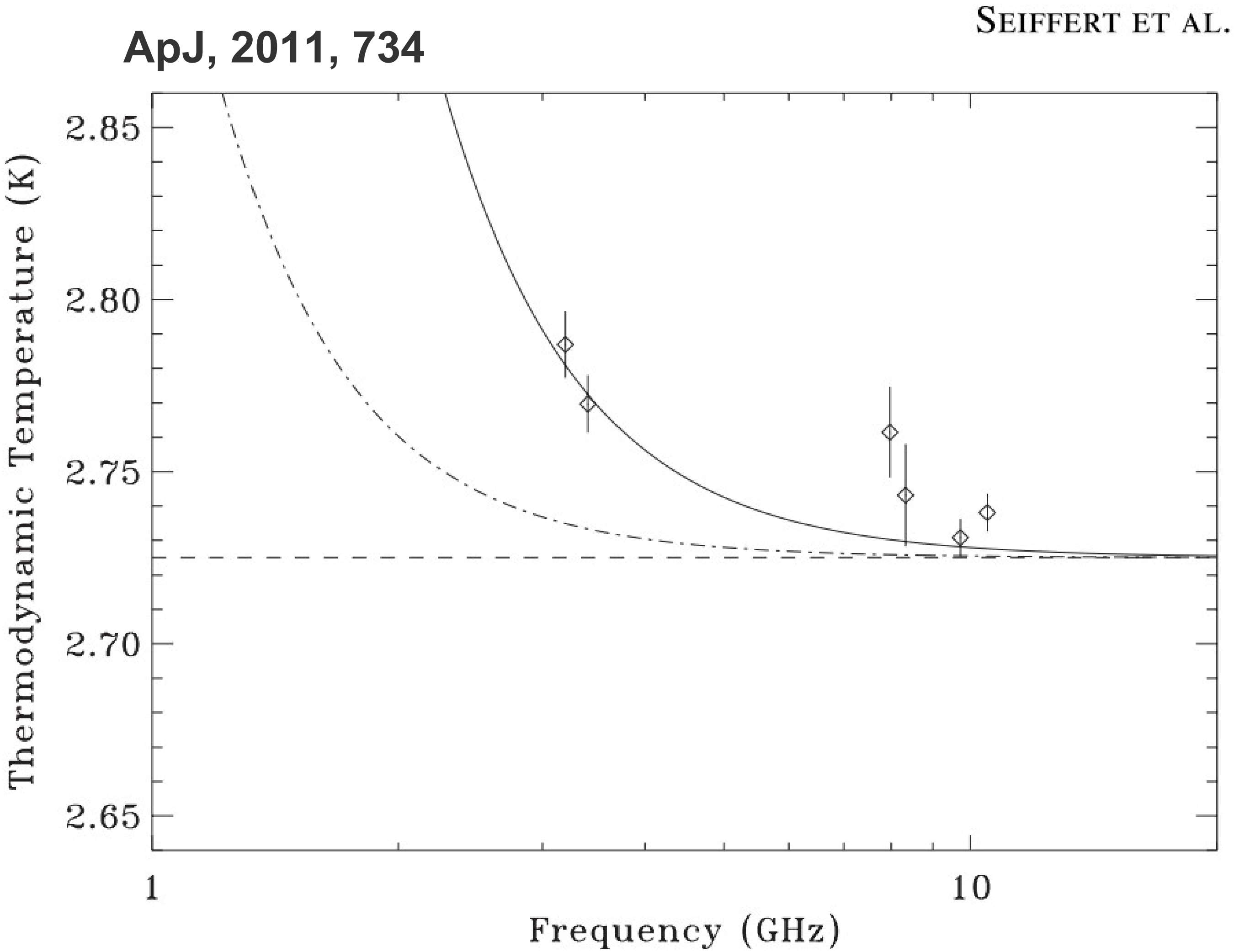


No distortions found over more than 3 decades in frequency

Total blackness

The quest for distortions of the CMB spectrum

ApJ, 2011, 734



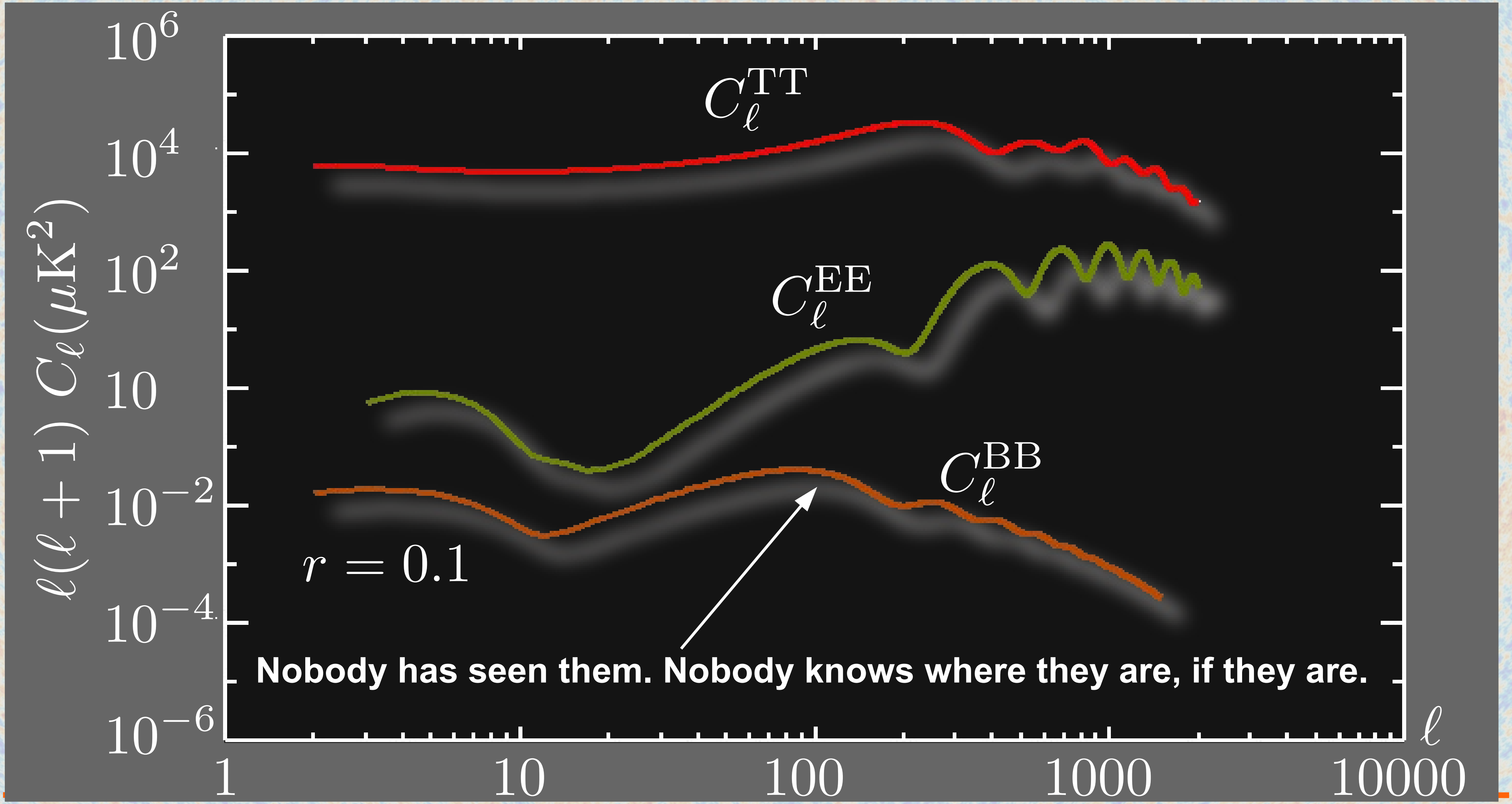
Last results from ARCADE 2, report low frequency excess NOT of cosmological origin

before the next one

The ultimate veil:

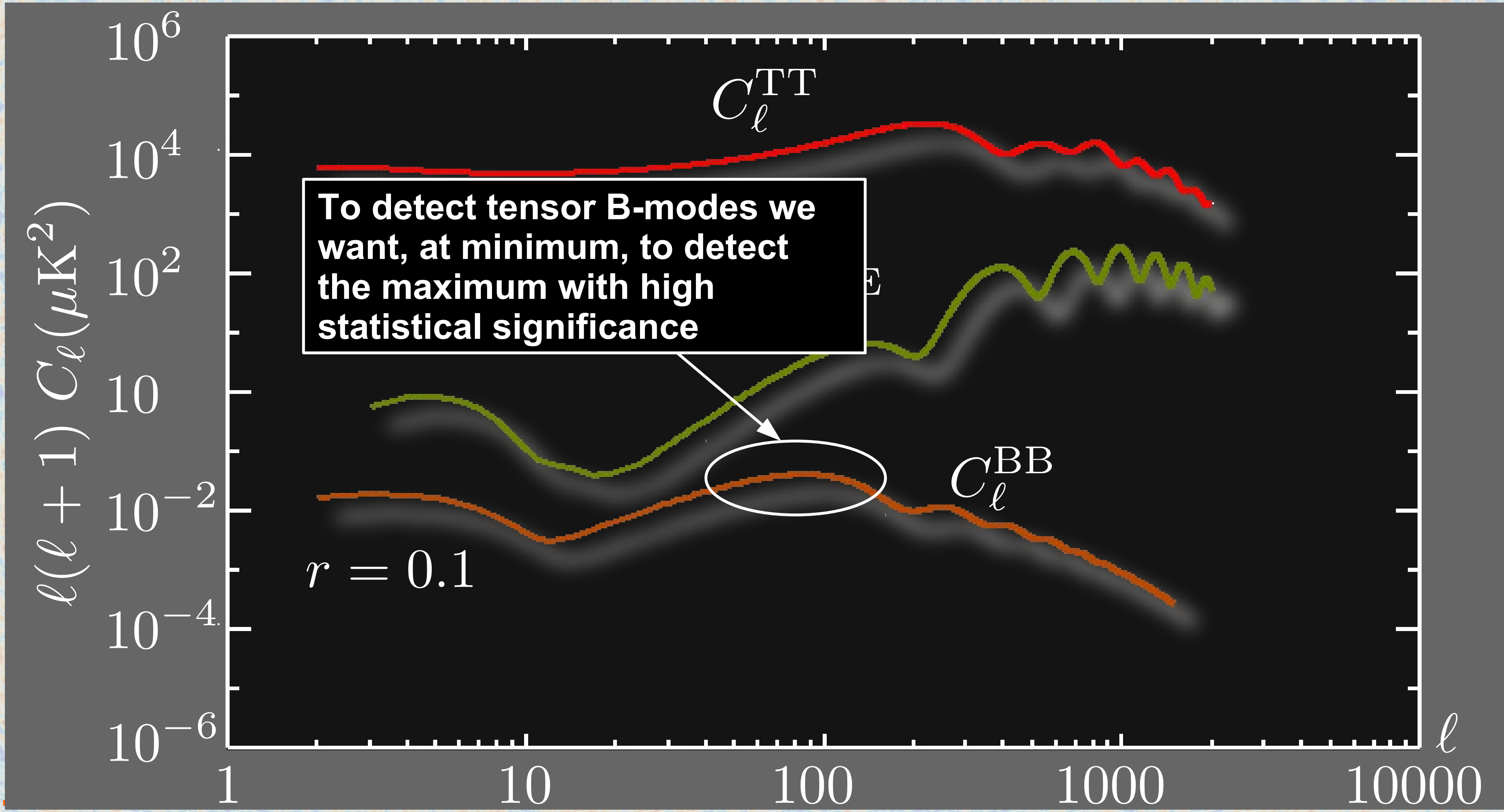
CMB polarisation

Tensor B-modes: a quest for the *Sacred Graal*

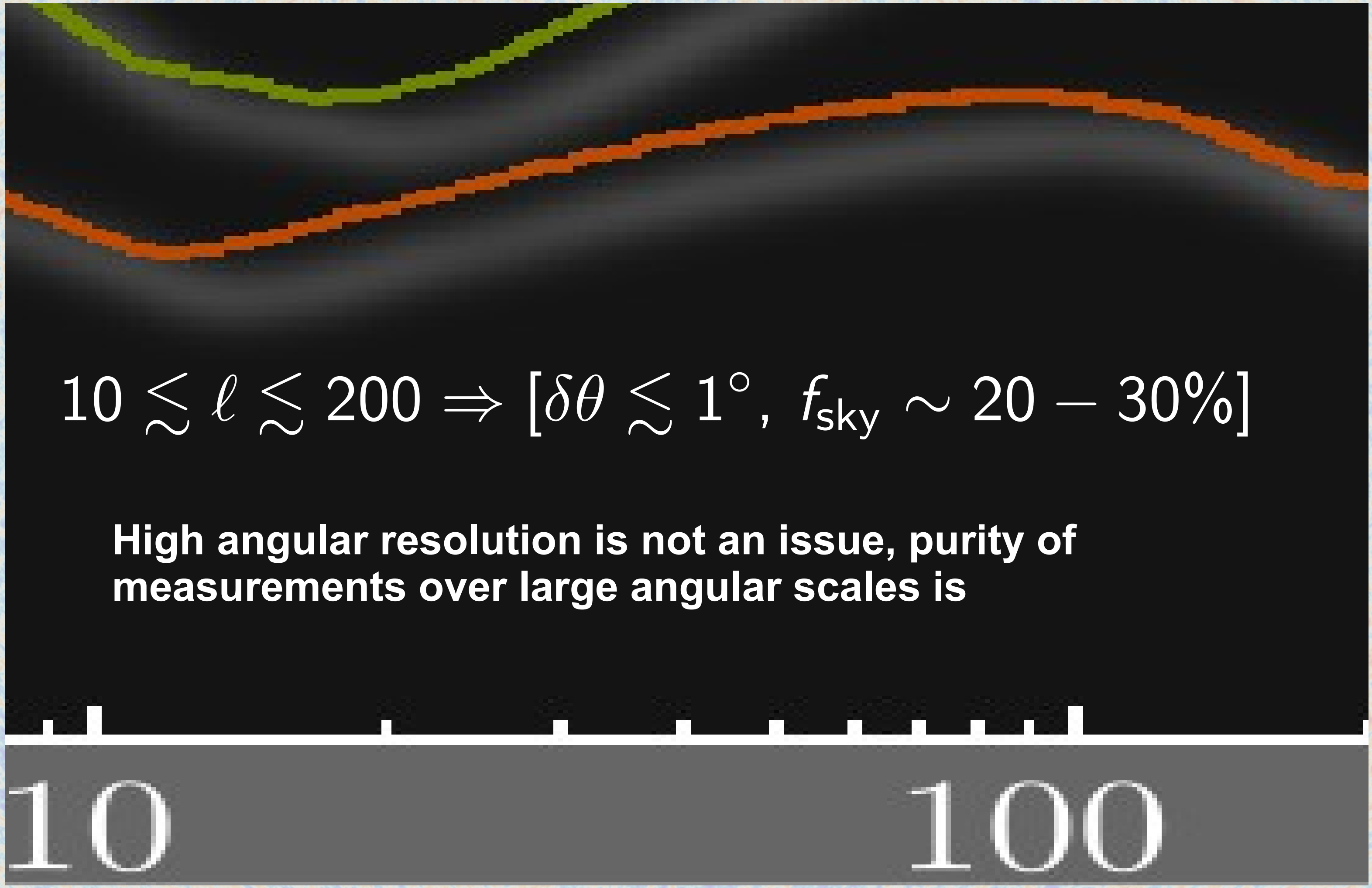


Aniello Mennella

Tensor B-modes: a quest for the *Sacred Graal*



Tensor B-modes: a quest for the *Sacred Graal*

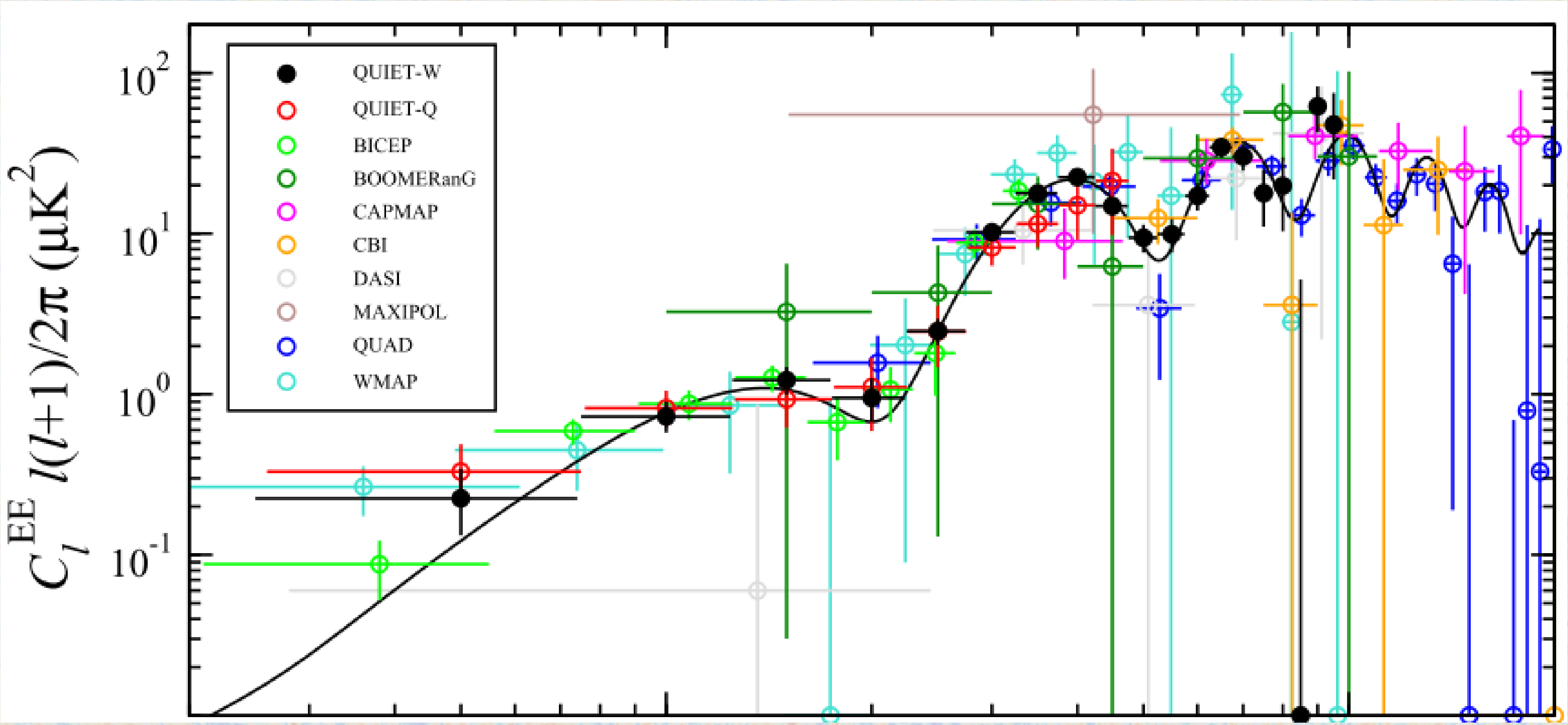


$$10 \lesssim \ell \lesssim 200 \Rightarrow [\delta\theta \lesssim 1^\circ,\ f_{\rm sky} \sim 20 - 30\%]$$

High angular resolution is not an issue, purity of measurements over large angular scales is

Latest results

QUIET collaboration, ApJ 2012



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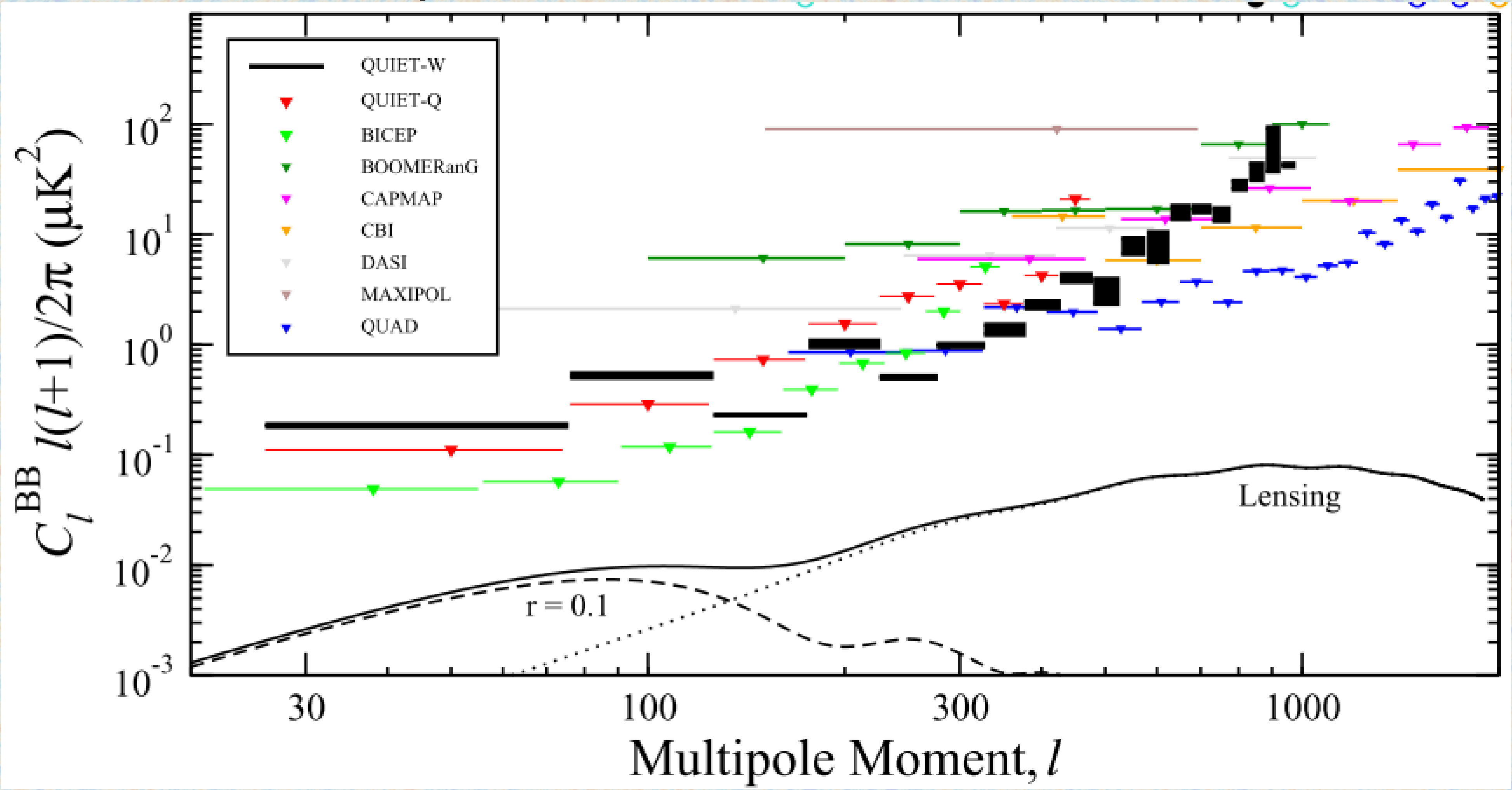
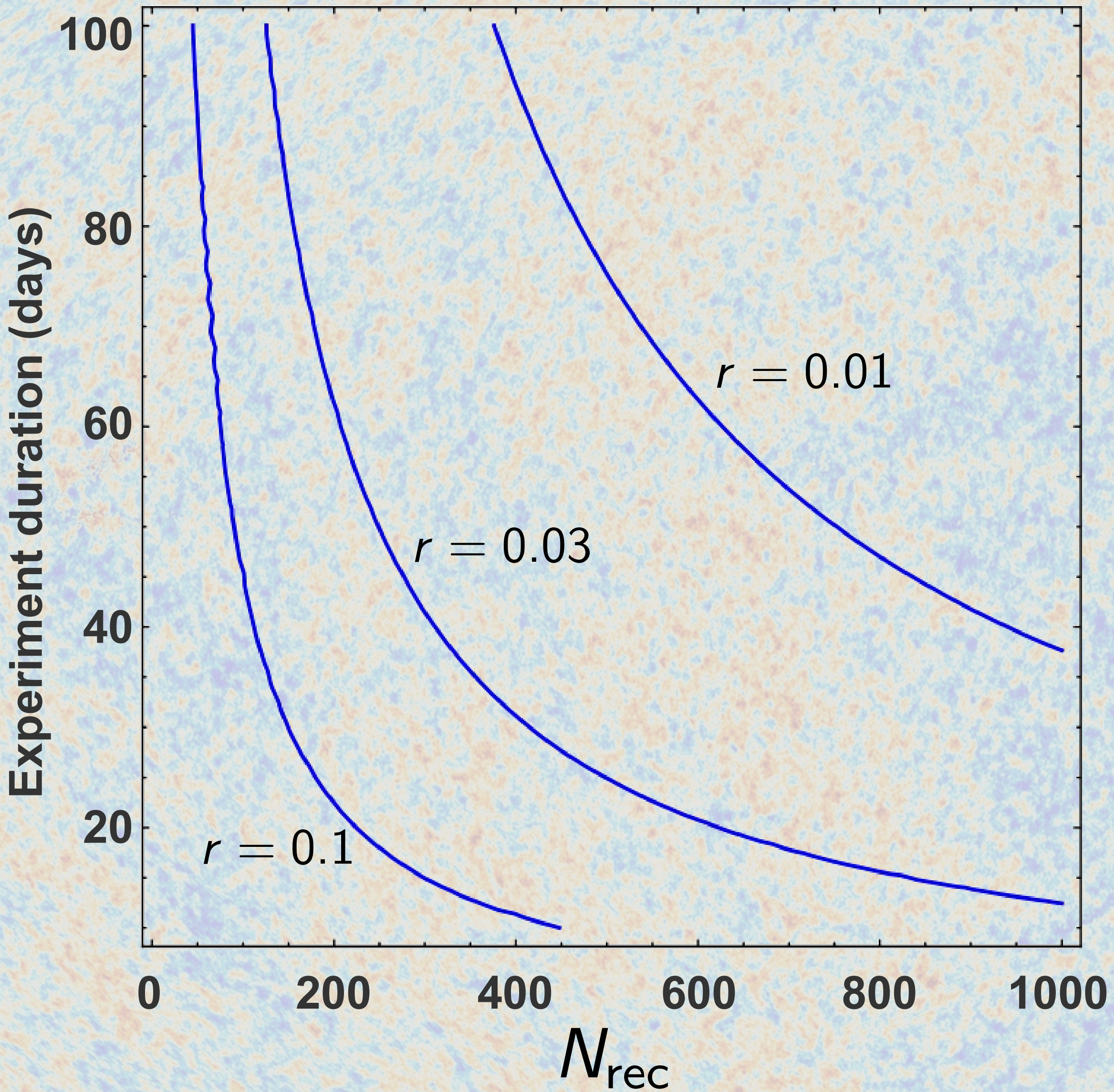


BIG challenges

- Sensitivity to hit the B-mode maximum at the lowest possible value of r
- (Relatively) large sky coverage
- Control of systematic effects at the sensitivity level
- Accurate calibration
- Control of polarized foregrounds

Challenge # 1
Meeting the sensitivity



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

- Photon noise limited detectors (Tnoise = 0)
- 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

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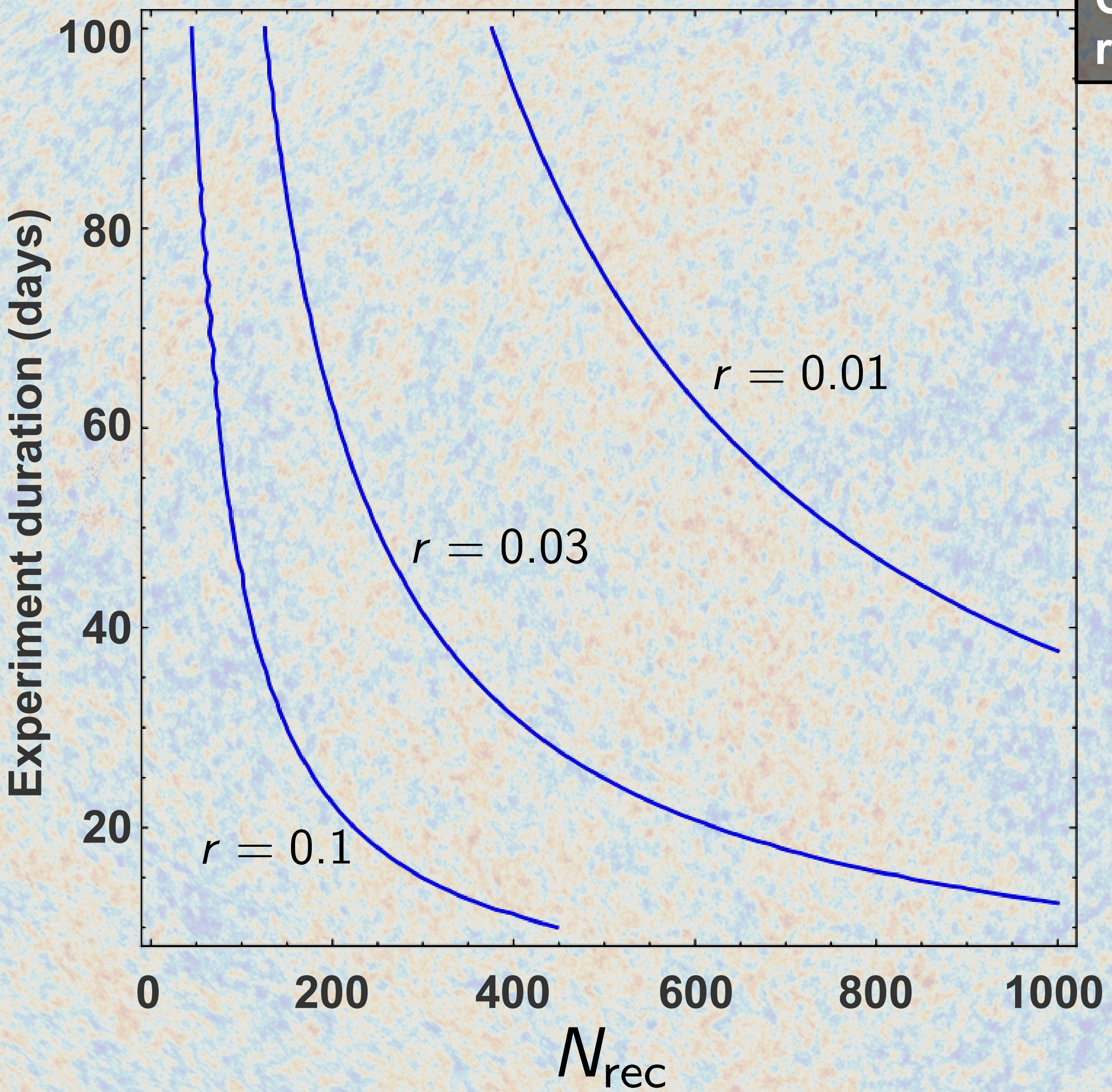

Constant ~ 1, dependent on receiver architecture

$$\Delta T_{rms} = K \frac{T_{sky} + T_{noise}}{\sqrt{\beta \tau N_{rec}}}$$

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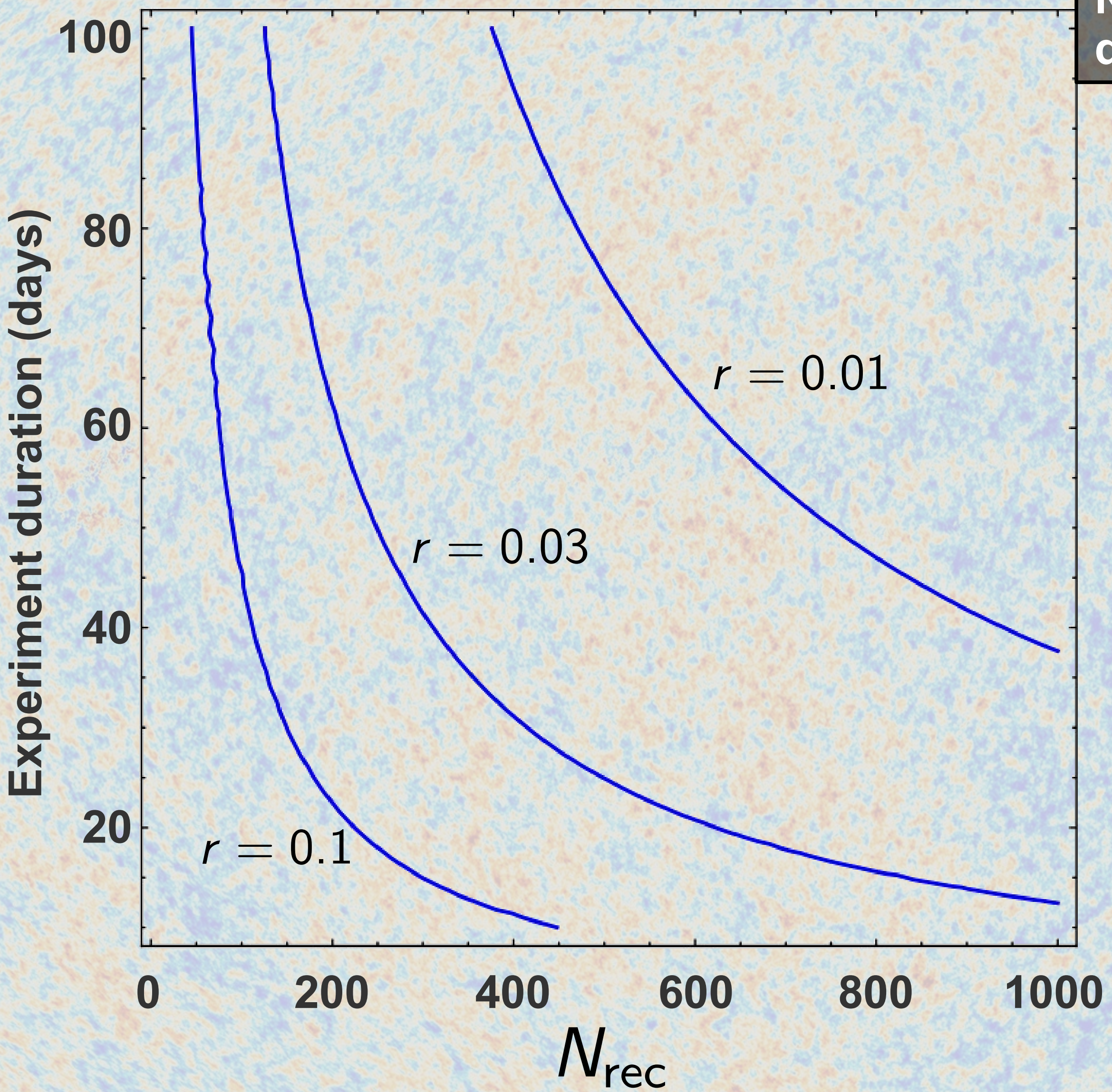

Number of receiver units detecting Q and U

$$\Delta T_{rms} = K \frac{T_{sky} + T_{noise}}{\sqrt{\beta \tau N_{rec}}}$$

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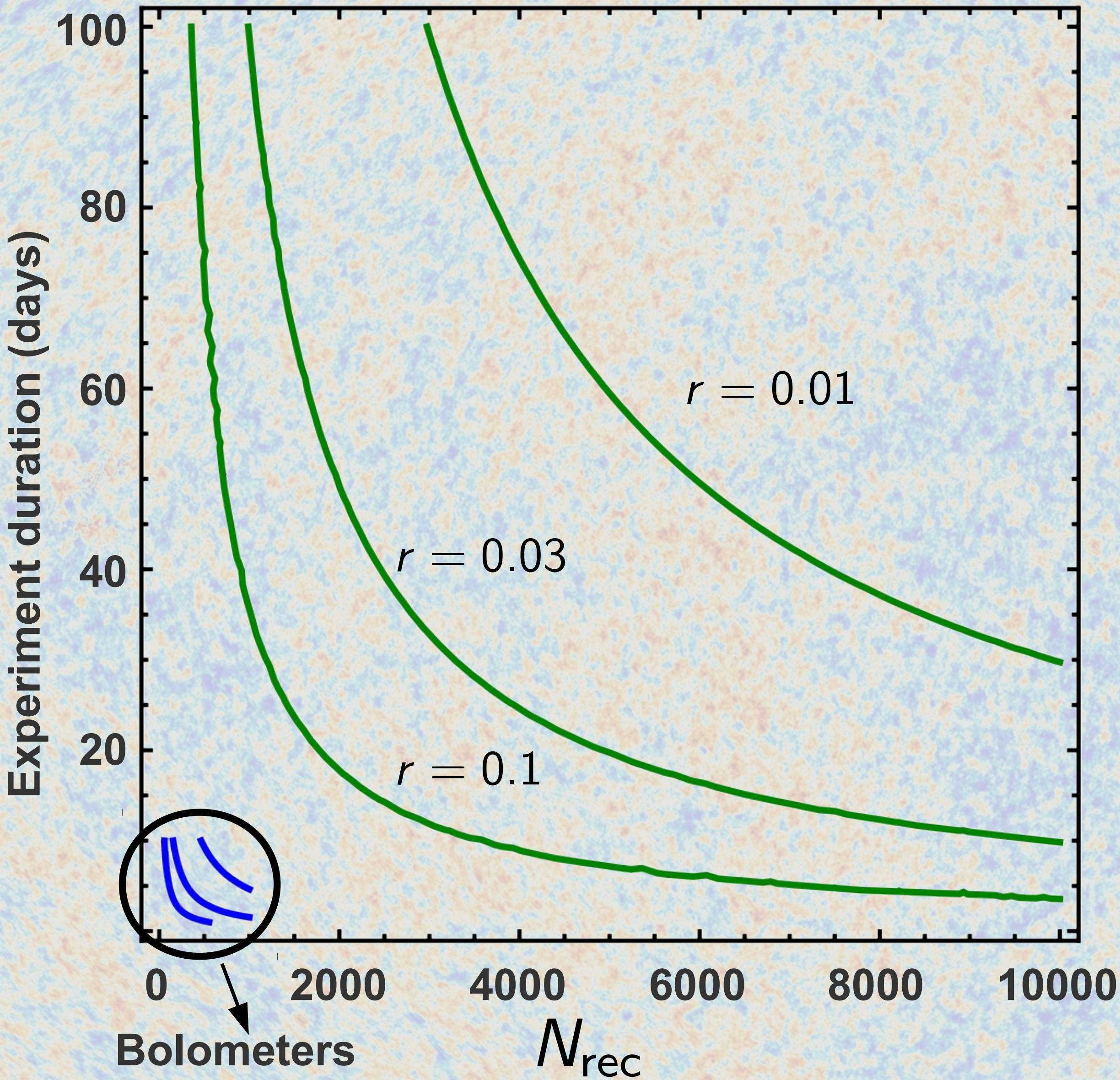
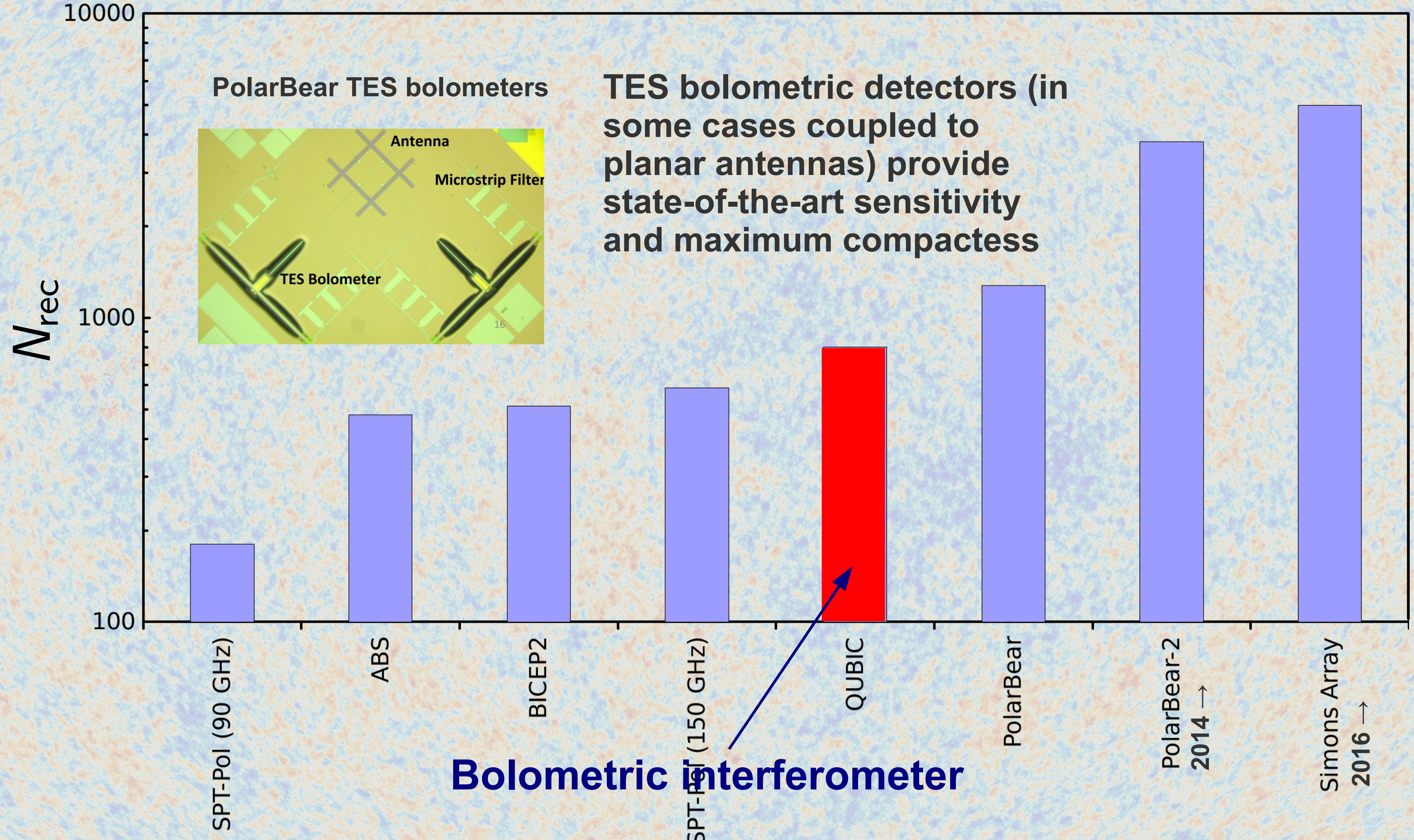


$$\Delta T_{rms} = K \frac{T_{sky} + T_{noise}}{\sqrt{\beta\,\tau\,N_{rec}}}$$

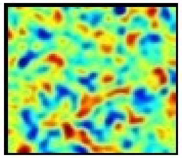
- Wband HEMT detectors (Tsky + Tnoise = 40K)
- fsky = 30 %
- S/N = 1
- Bandwidth = 20 GHz
- $\ell(\ell+1)C_\ell = 0.05\mu\mathrm{K}^2$ for $\ell = 200$ and $r = 0.1$
- Duty cycle = 1

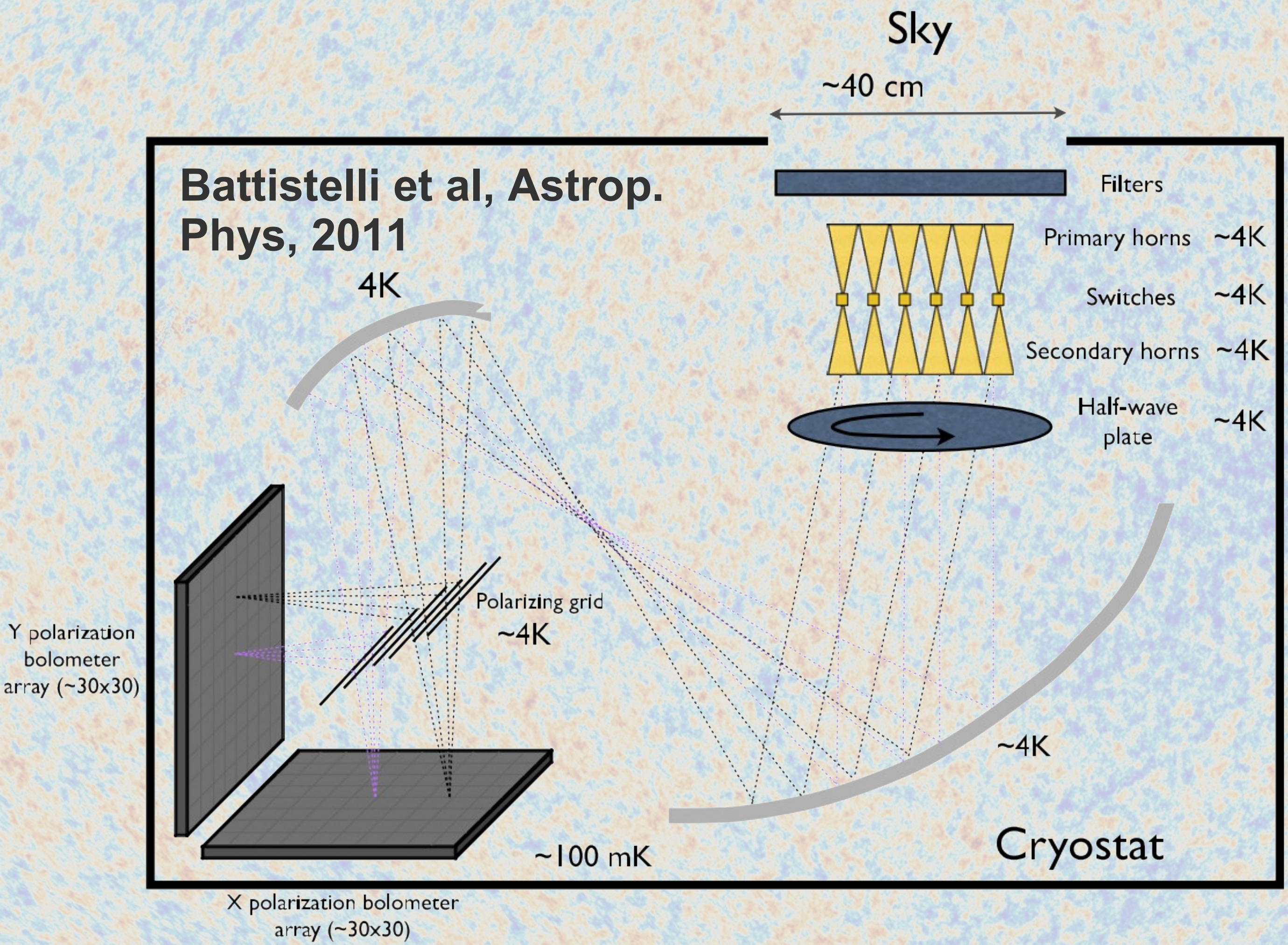
TES detectors (ground)



QUBIC

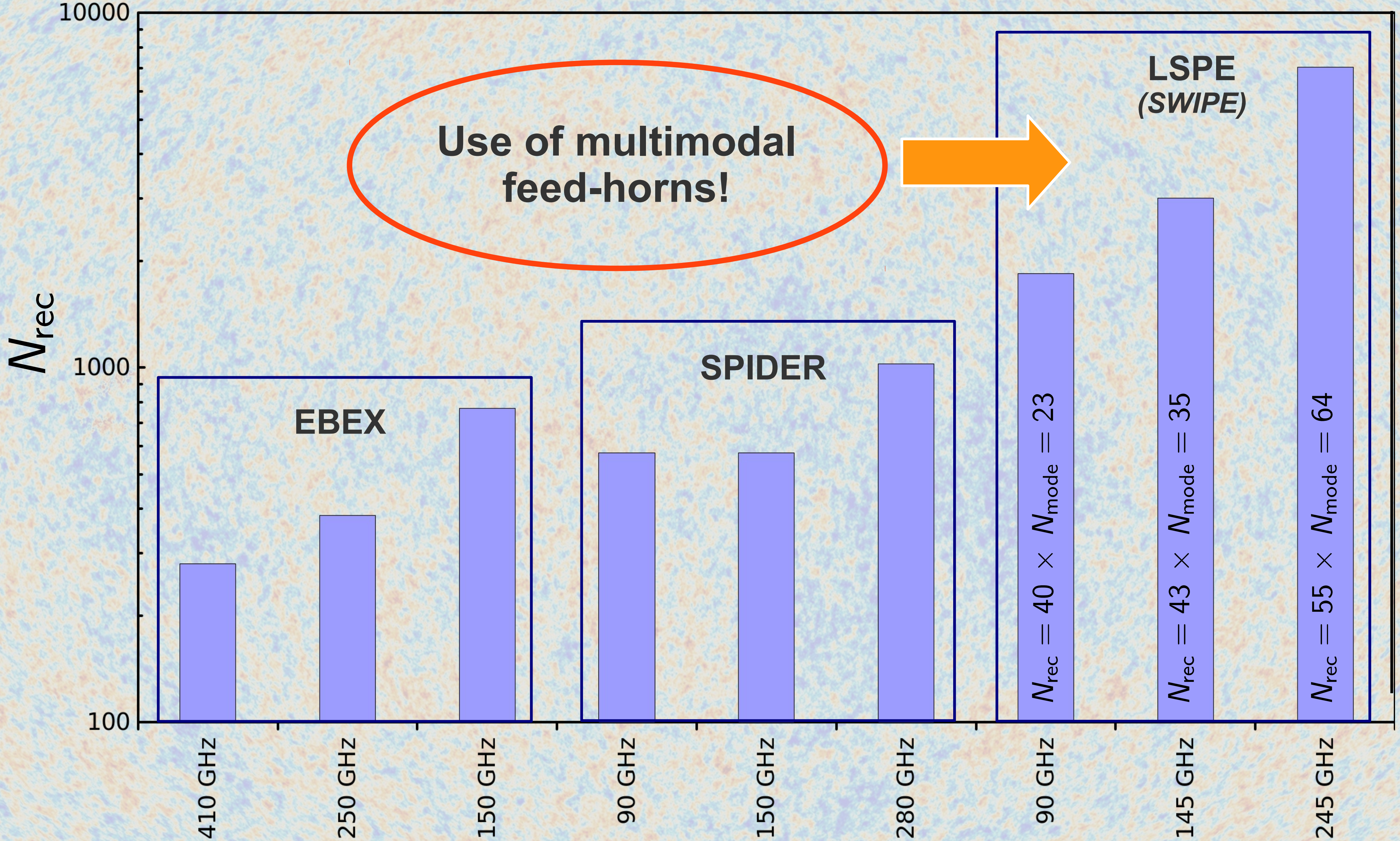
a Q&U Bolometric Interferometer for Cosmology



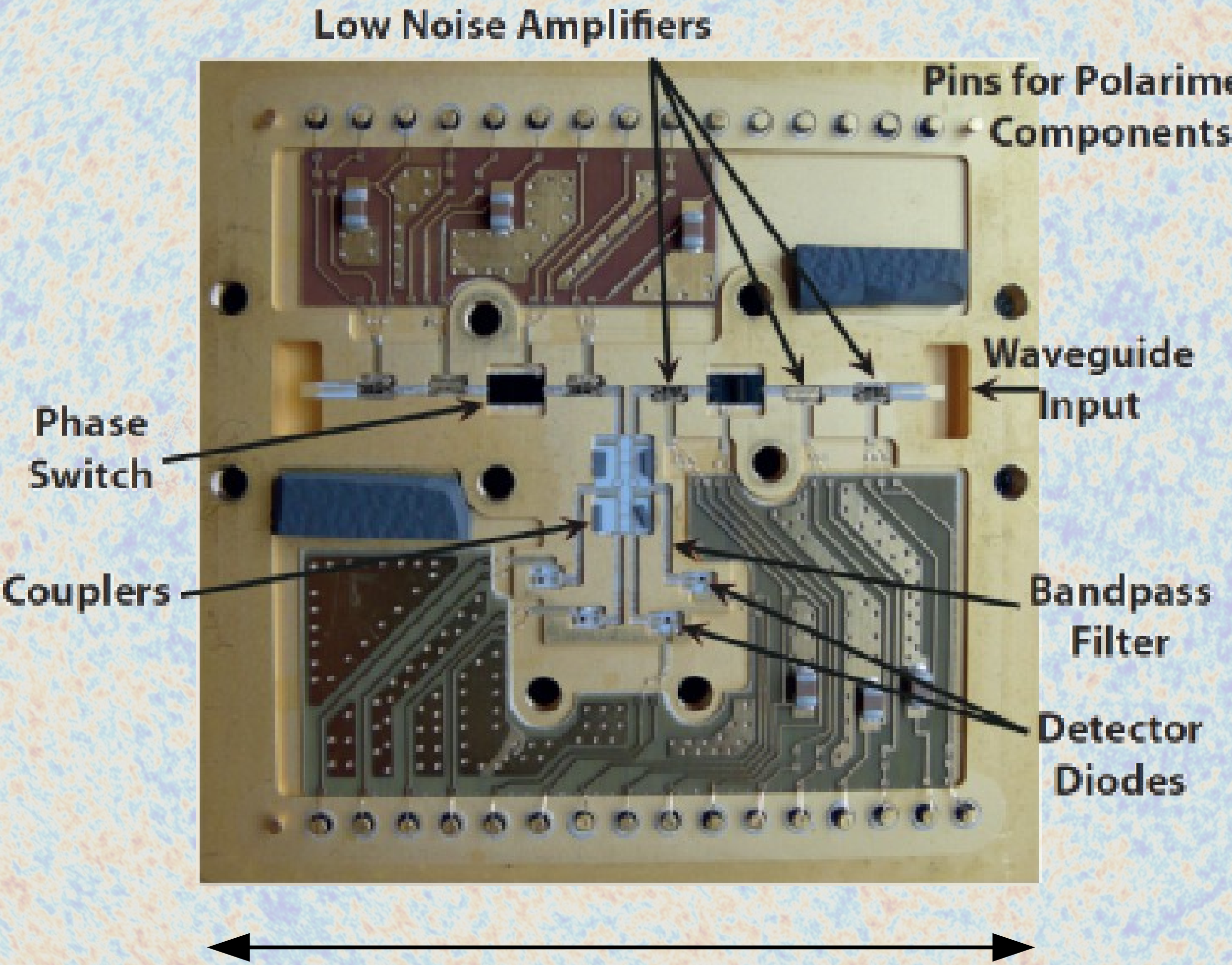


- New tecnique applied to bolometric CMB measurements
- Planned for observations from DOME-C
- Potential advantages in systematic effects control and calibration

TES detectors (balloon)



HEMT detectors

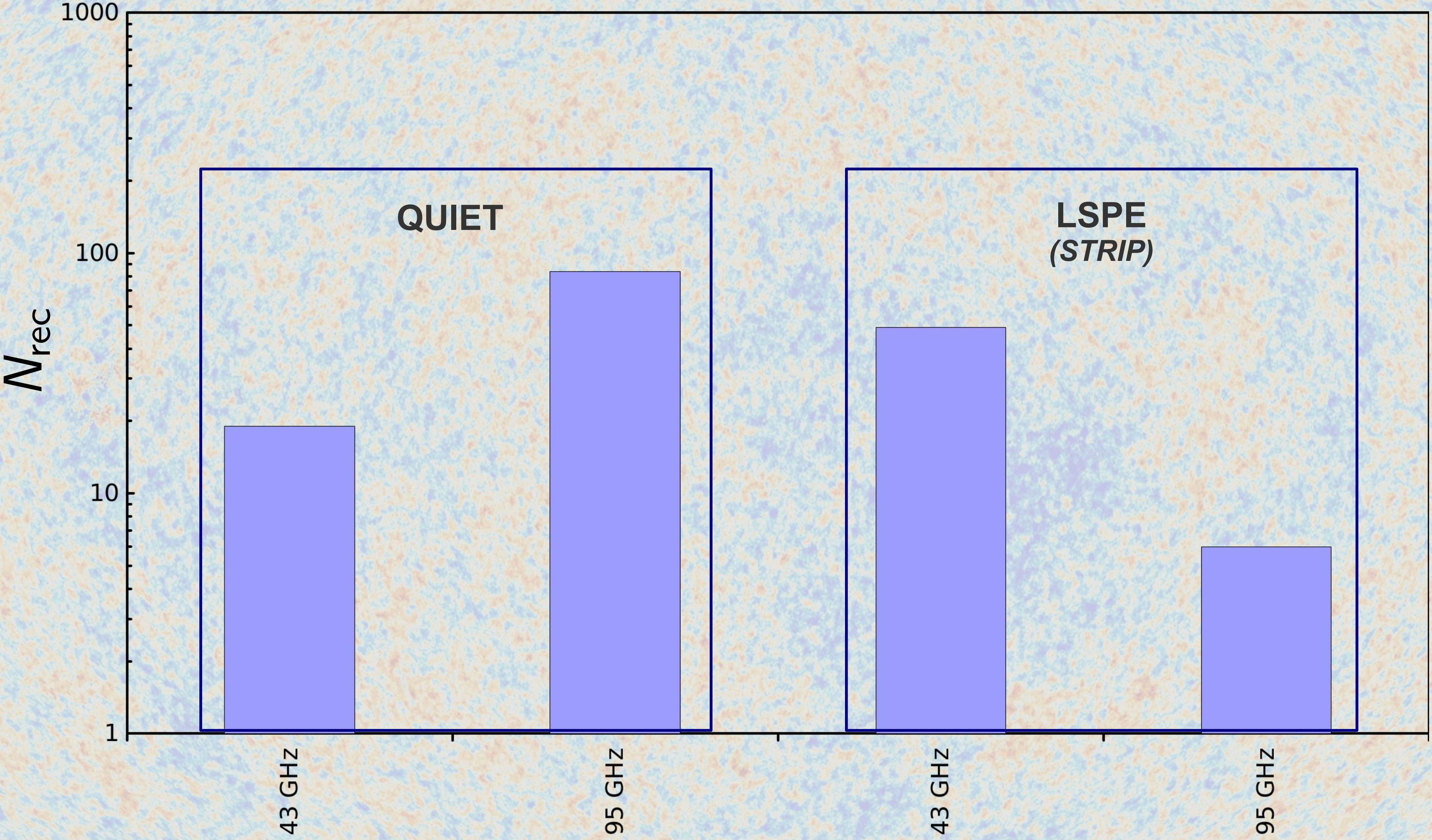


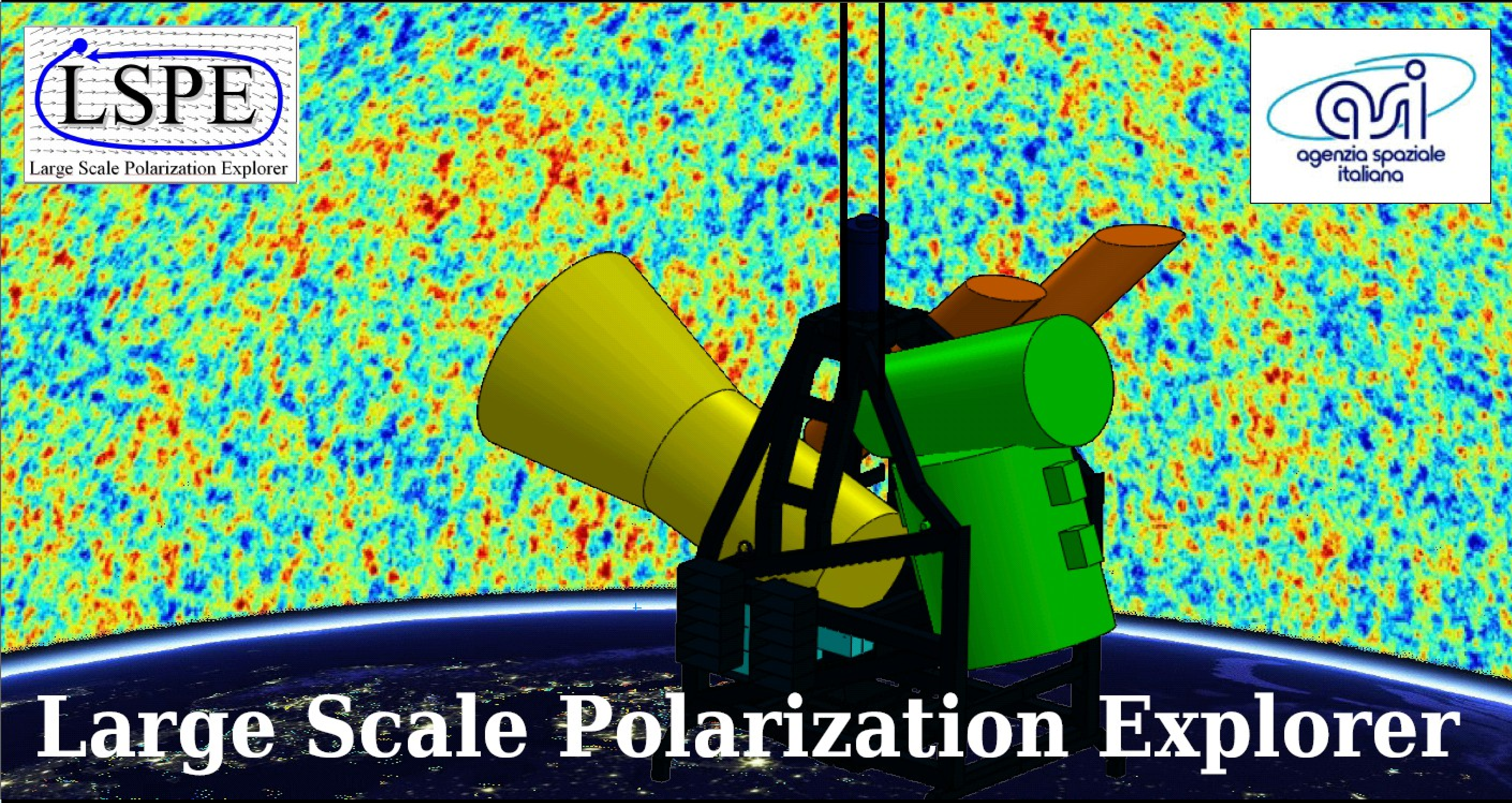
~ 5 cm @ 43 GHz, ~ 2.5 cm @ 95 GHz

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





SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

IASF bo INAF IASF BOLOGNA

IEIIT

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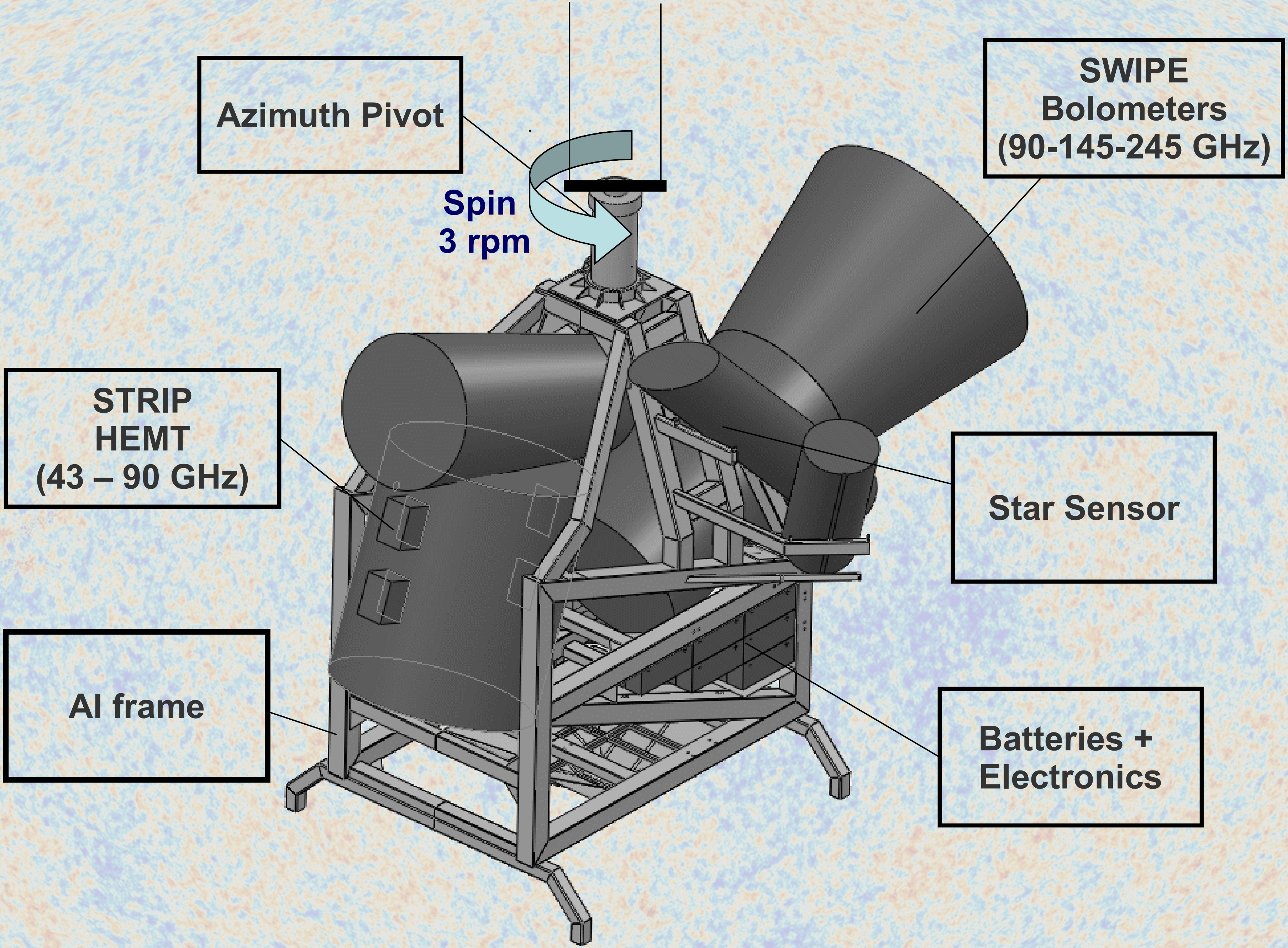
UNIVERSITY OF CAMBRIDGE

MANCHESTER 1824

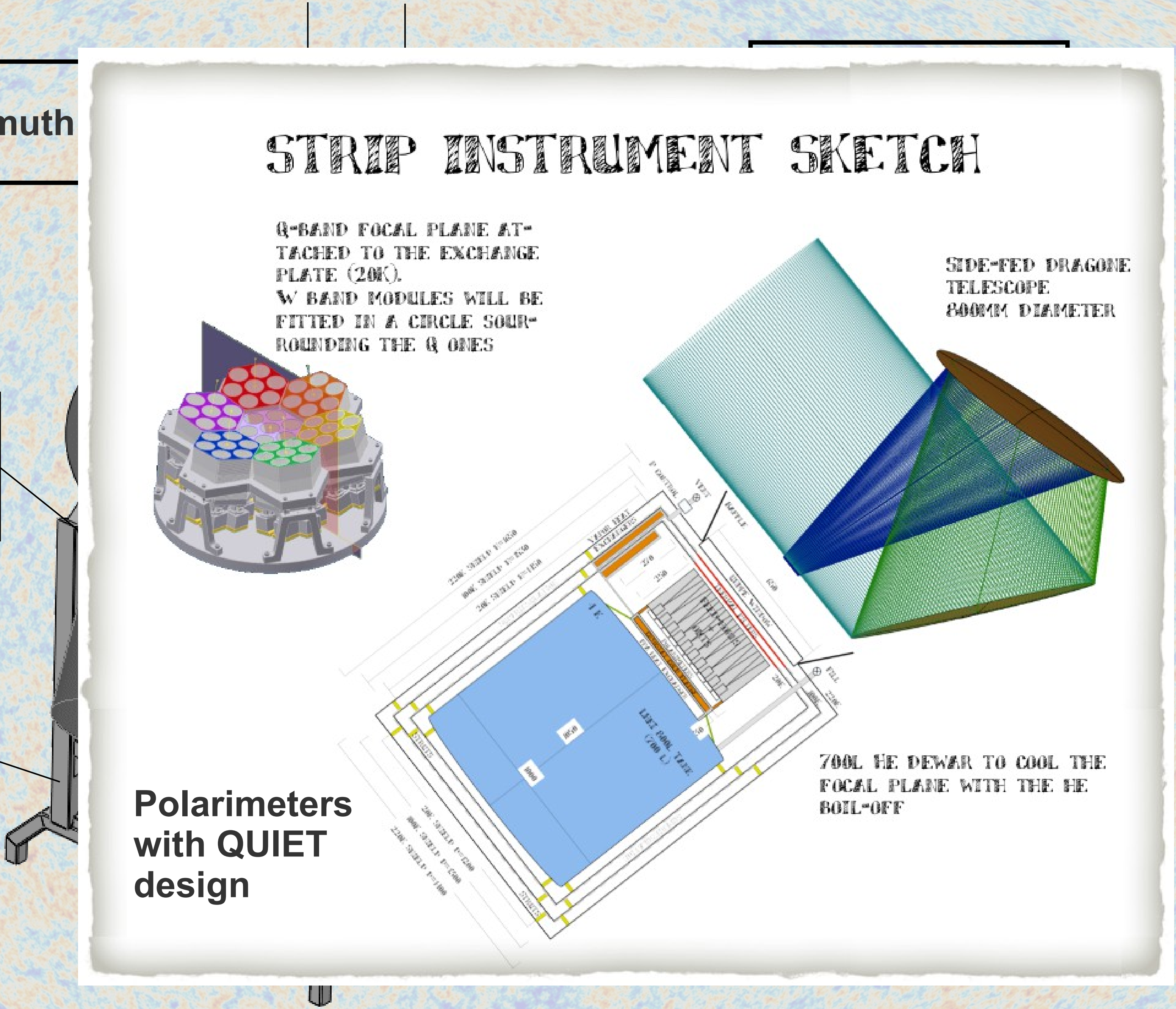


The height of the gondola for this configuration is about 4.5 m

Azimuth

STRIP
HEMT
(43 – 90 GHz)

Al frame



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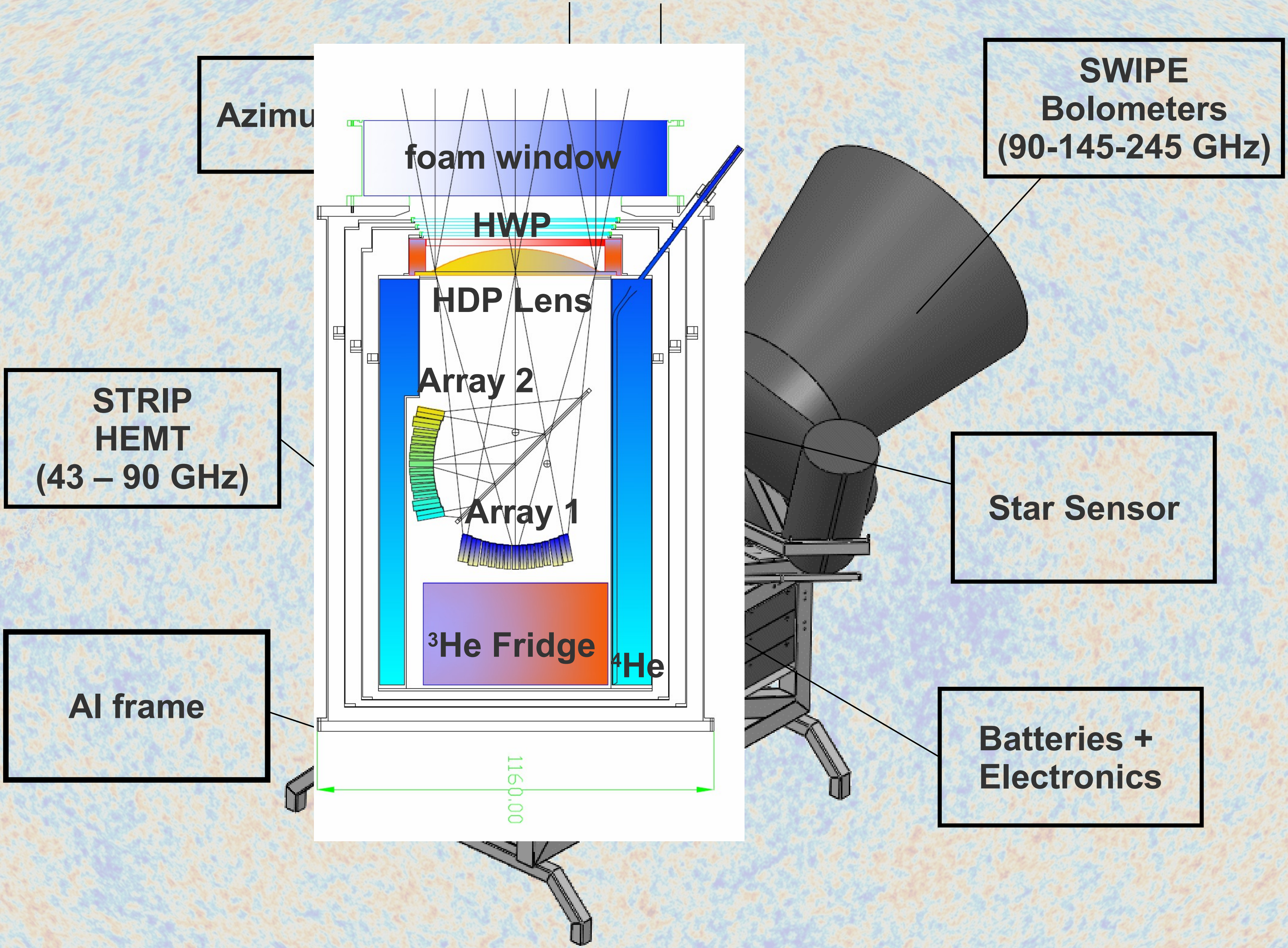
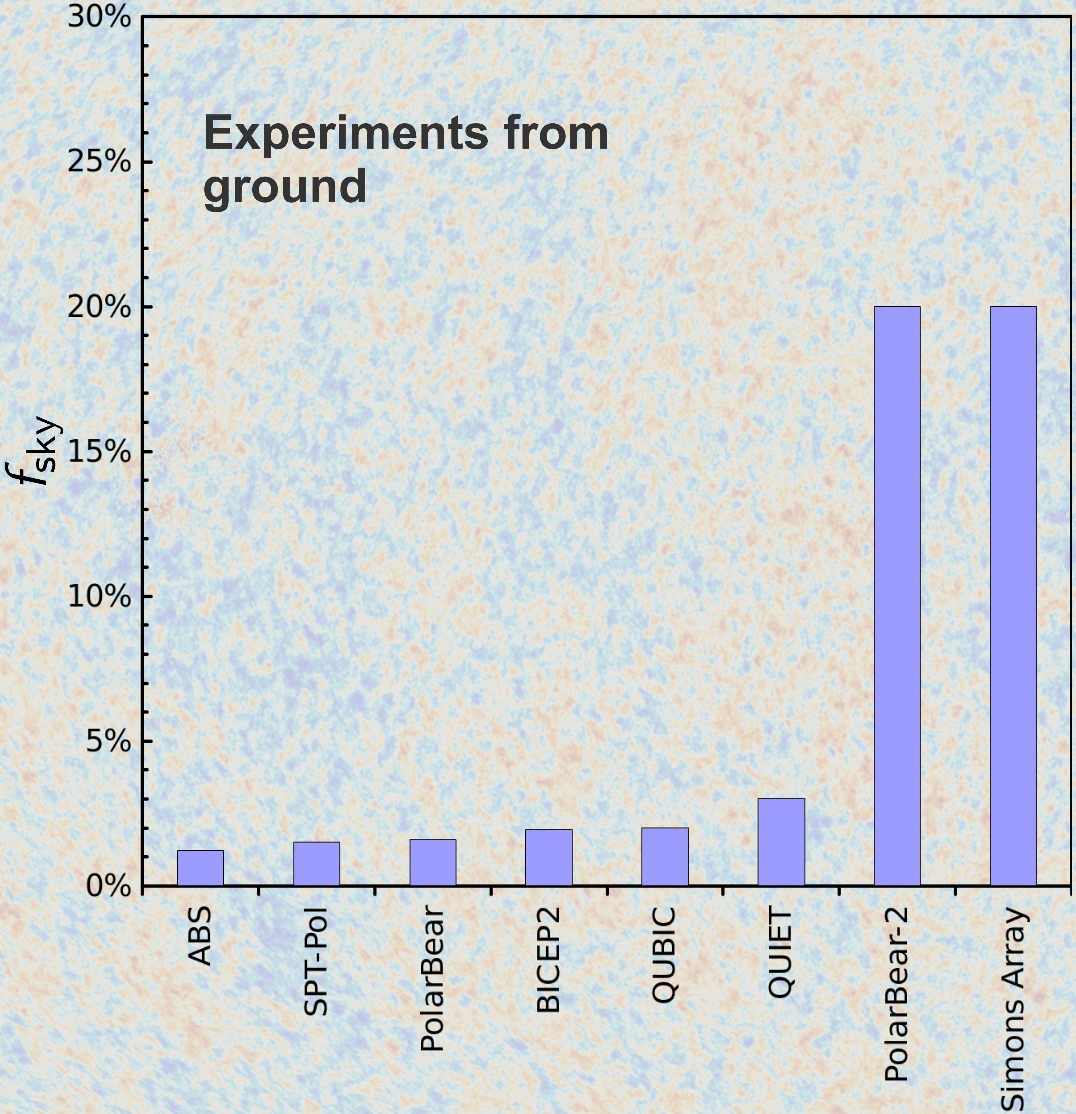


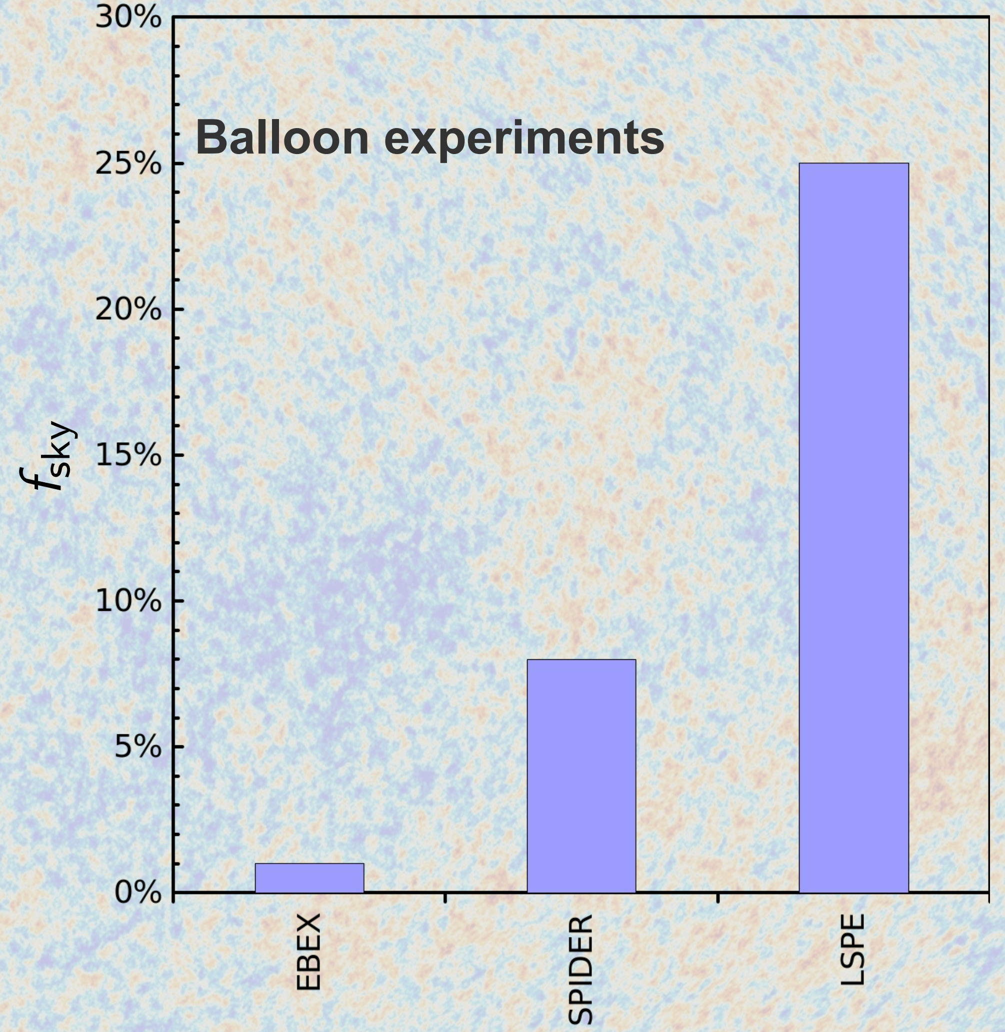
The height of the gondola for this configuration is about 4.5 m

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

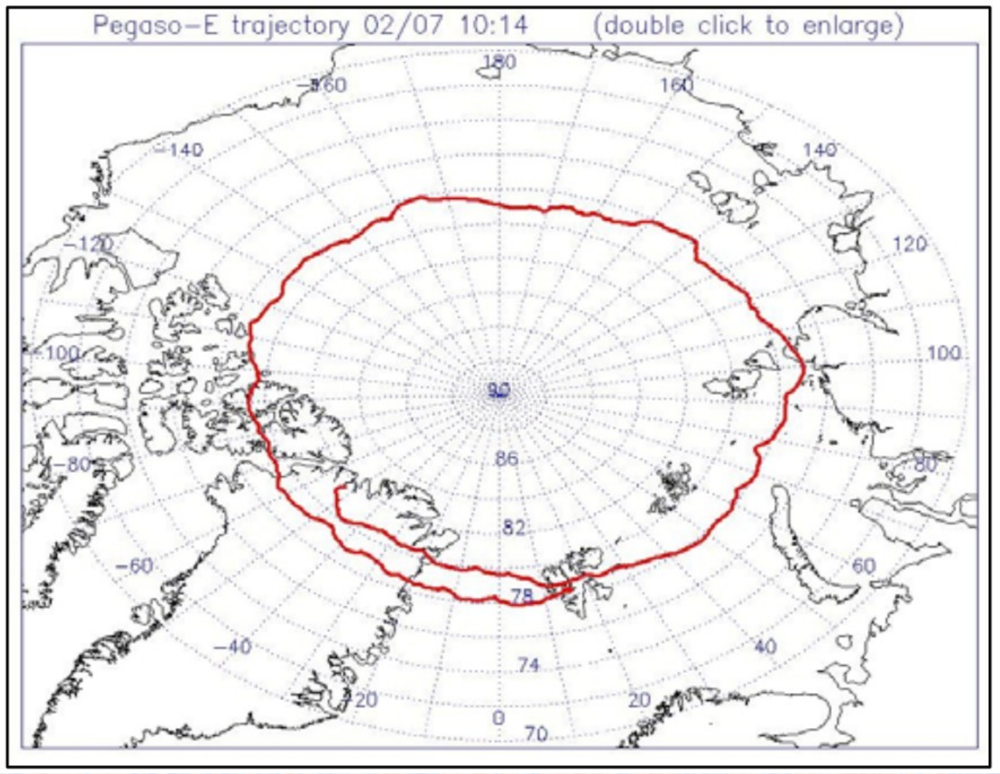




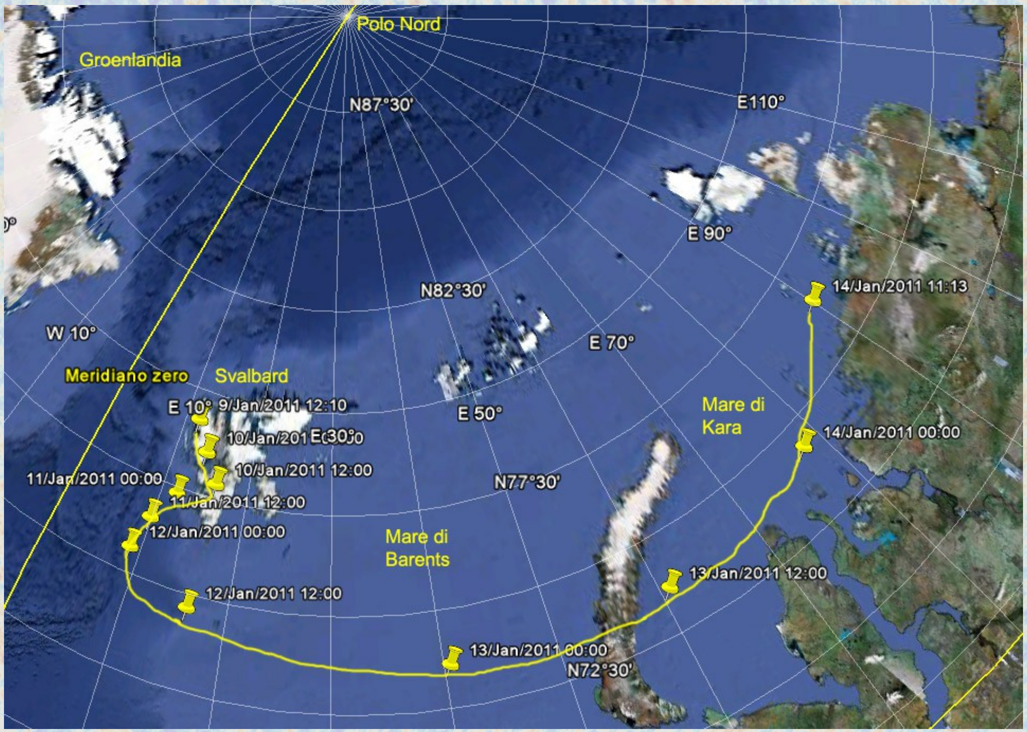
LDB flights in the Arctic night

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

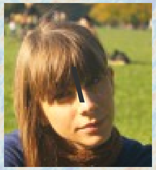


Test flight #2 – Winter 2011

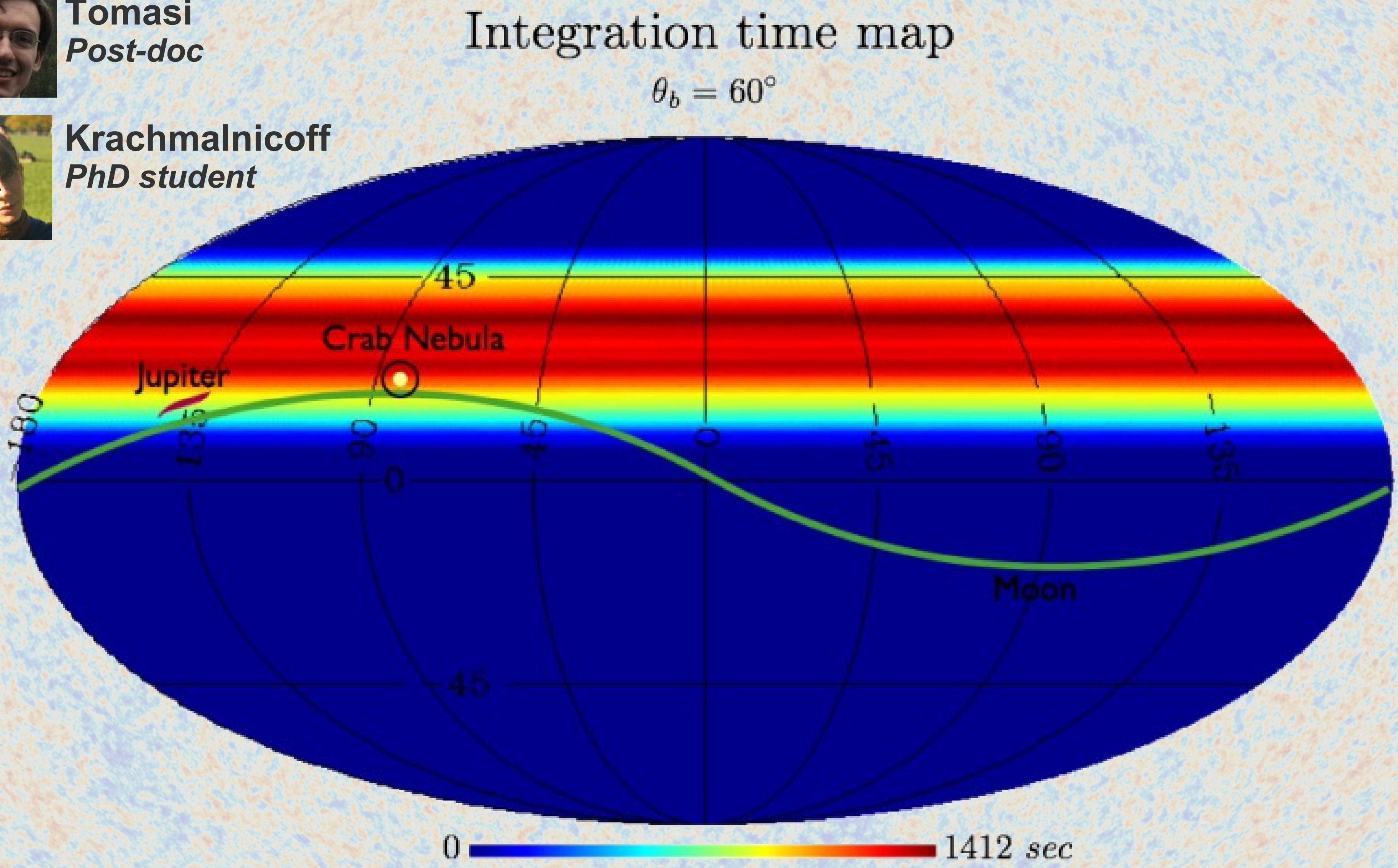


LSPE Sky coverage

Tomasi
Post-doc



Krachmalnicoff
PhD student



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

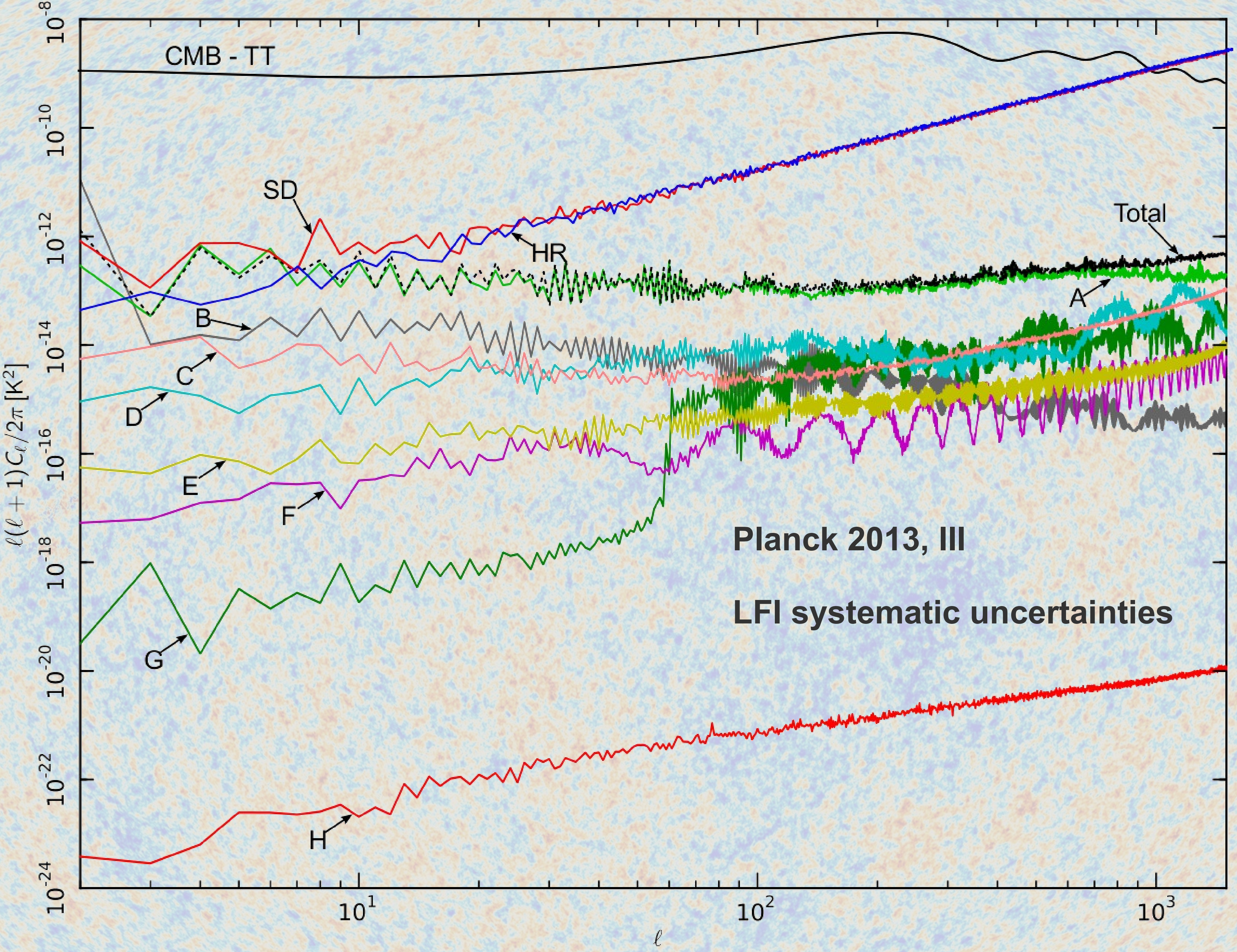
  - *Telescope arrays: coordinate and harmonize measurements from different telescope / sites*

  - *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}
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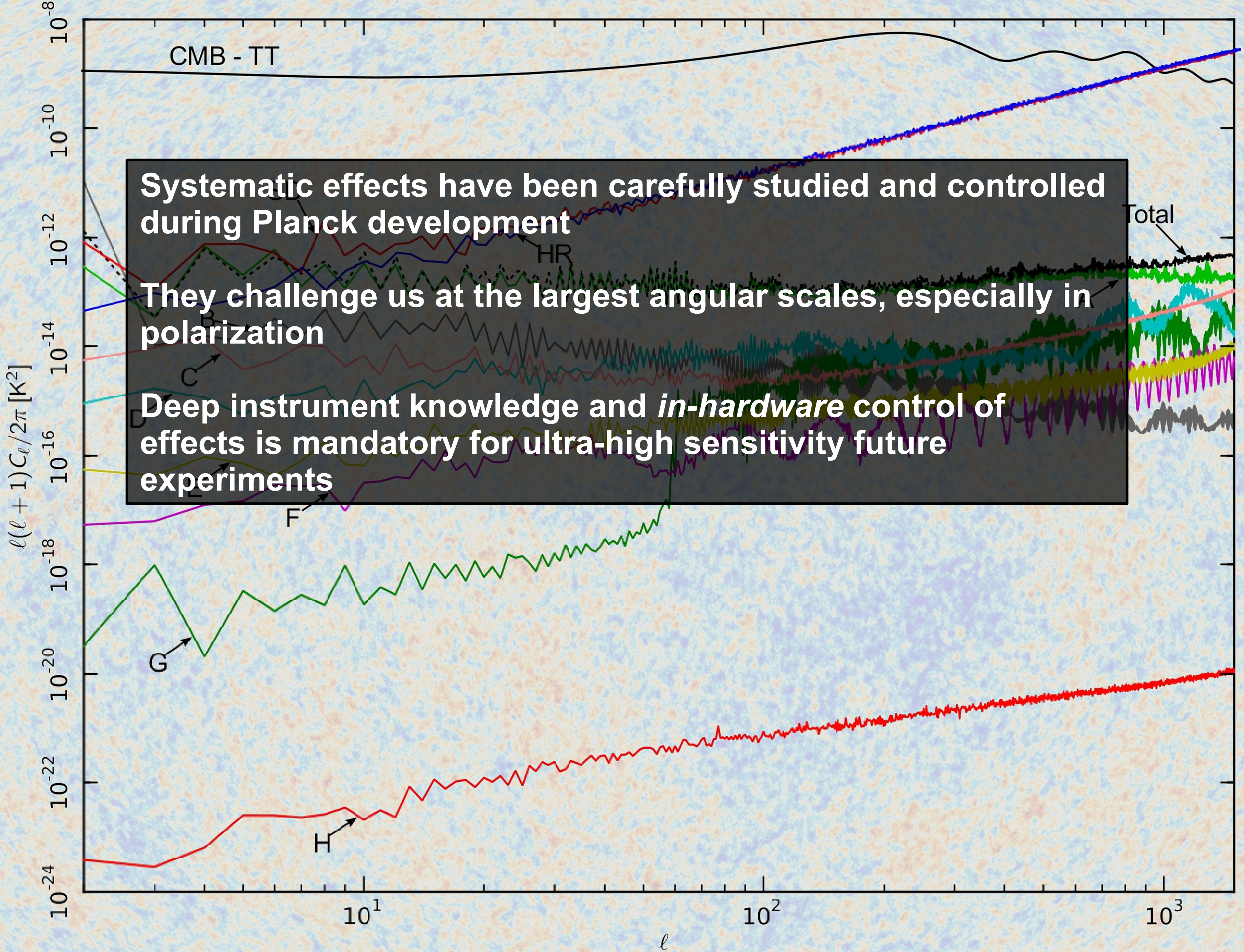
10^{1}
10^{2}
10^{3}



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

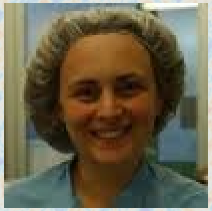
Optical	*Beam ellipticity / cross polarization* *Sidelobes (Earth, Sky pickup)*
Polarization	*$I \rightarrow Q/U$ leakage* *$Q \rightarrow U$ leakage*
Noise and stability	*1/f noise* *Thermal stability* *Cosmic ray hits* *Time constants*
Pointing	*Pointing uncertainties*
Electronics	*ADC non linearities*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

Main beams

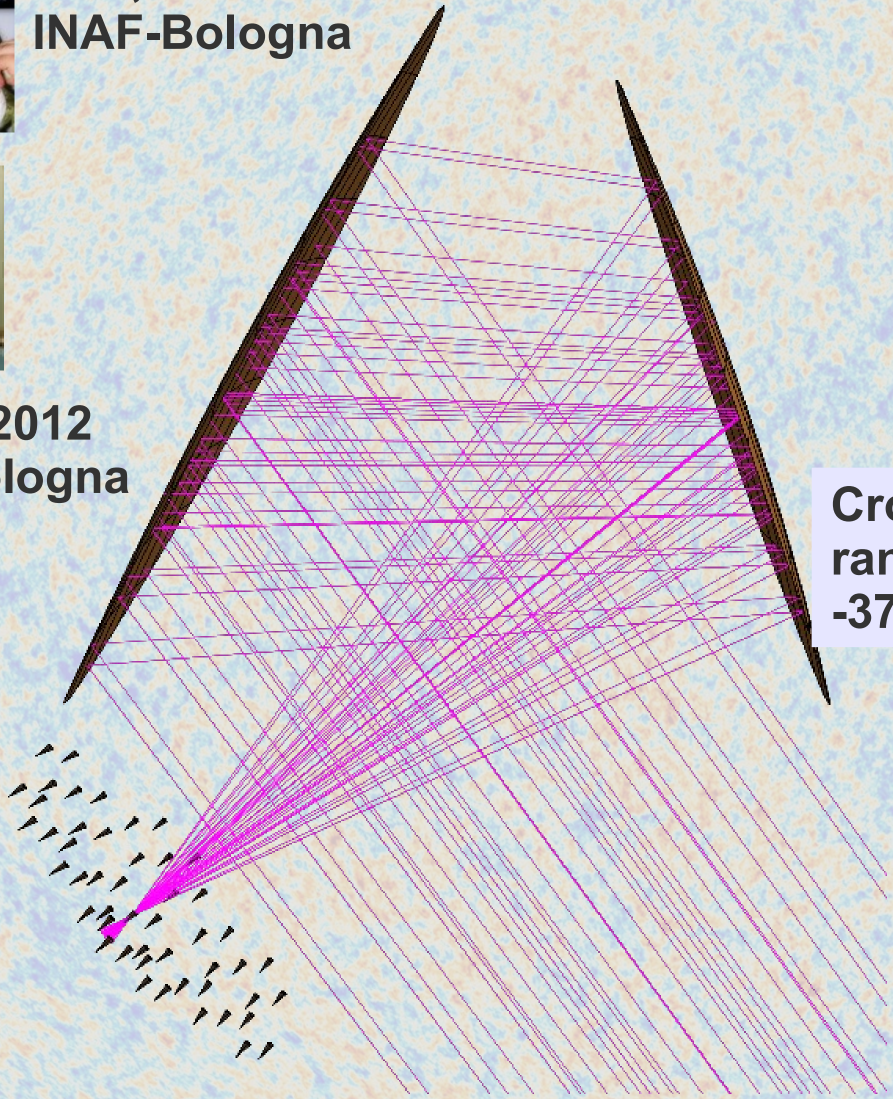
- Symmetrical beams are required to minimize cross polarization
- Possible solutions: (1) on-axis lenses (like, e.g. SPIDER, LSPE-SWIPE), (2) off-axis reflectors (like Crossed-Dragone configurations used by QUIET, ABS, LSPE-STRIP)
- Simulation of impact of beam asymmetries recommended

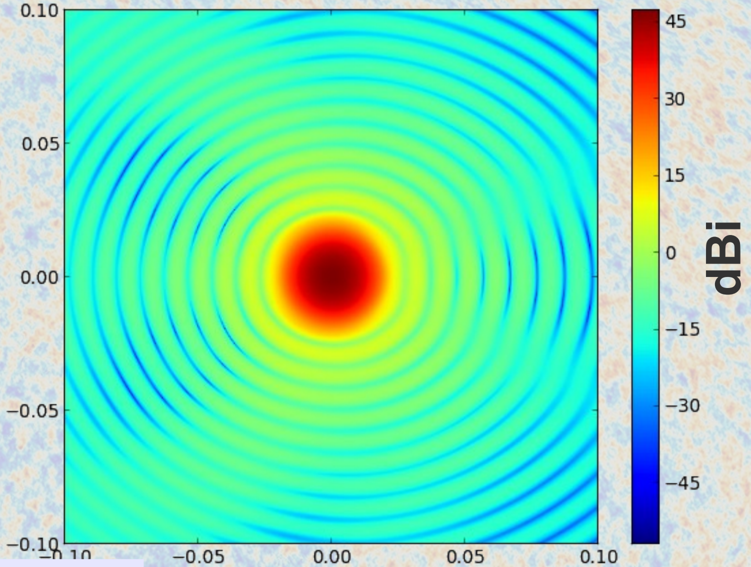
STRIP crossed Dragone

Villa, 2012
INAF-Bologna

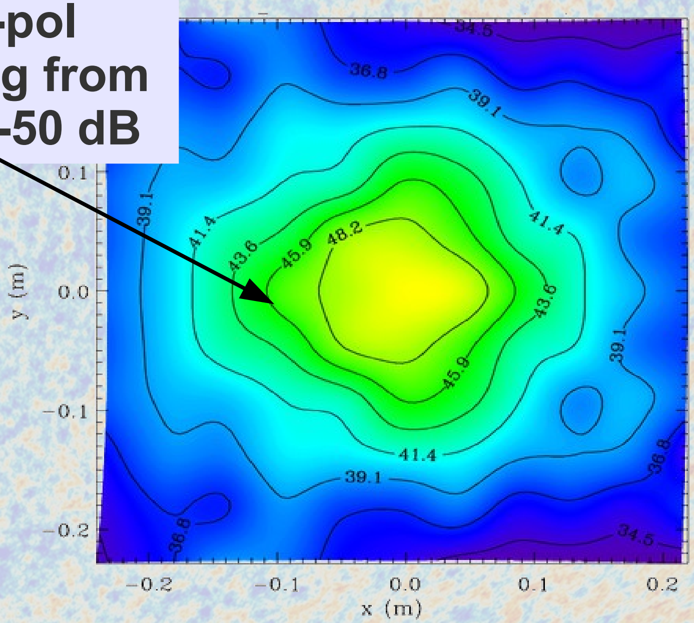


Sandri, 2012
INAF-Bologna





Cross-pol ranging from -37 to -50 dB



Assessing impact of beam asymmetries

Instrumental polarization pattern:

Carretti et al. 2004

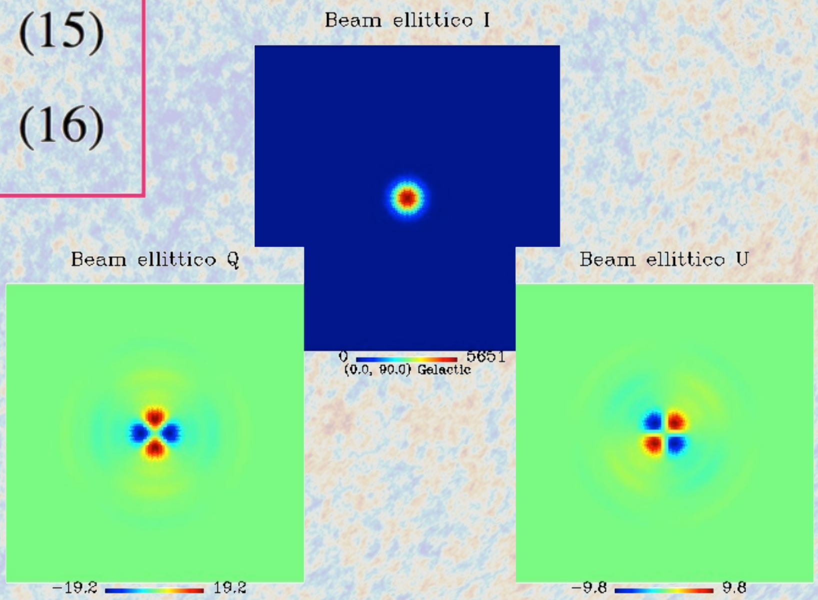
$$\Pi(\theta', \phi') = \Pi_Q(\theta', \phi') + j\, \Pi_U(\theta', \phi') \quad (14)$$

with

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

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

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



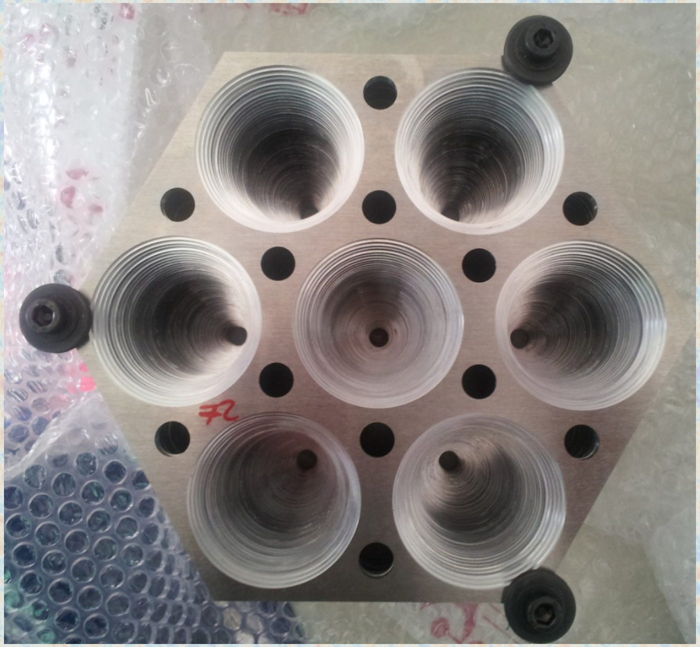
Sidelobes

- 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

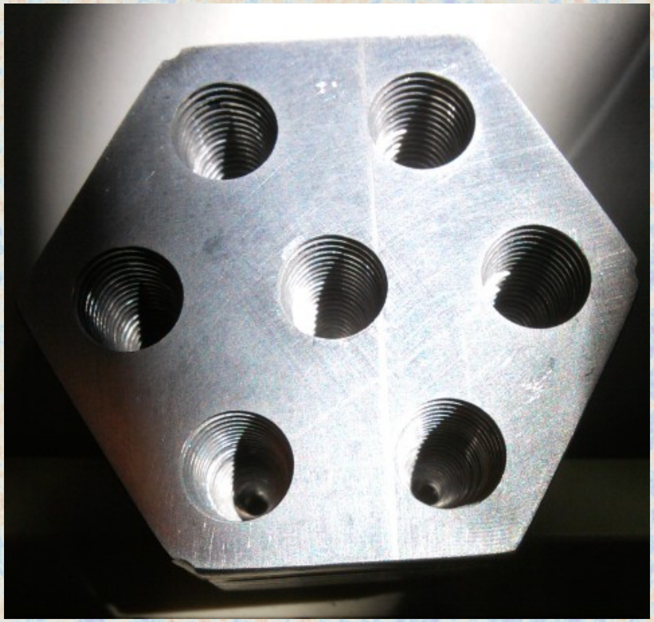
Platelet corrugated feeds

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

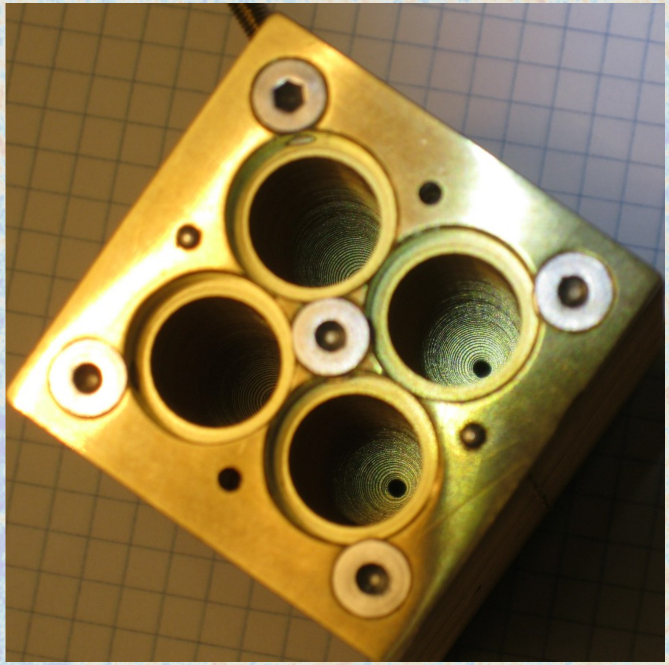
43 GHz – LSPE-STRIP

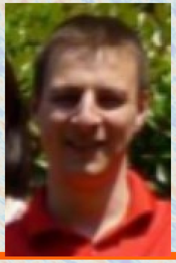


95 GHz – prototype study

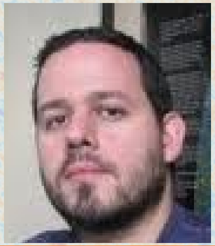


150 GHz – QUBIC prototype

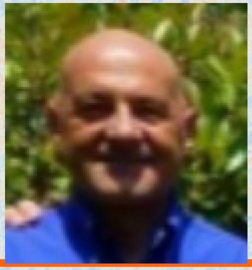




Del Torto
Post-doc

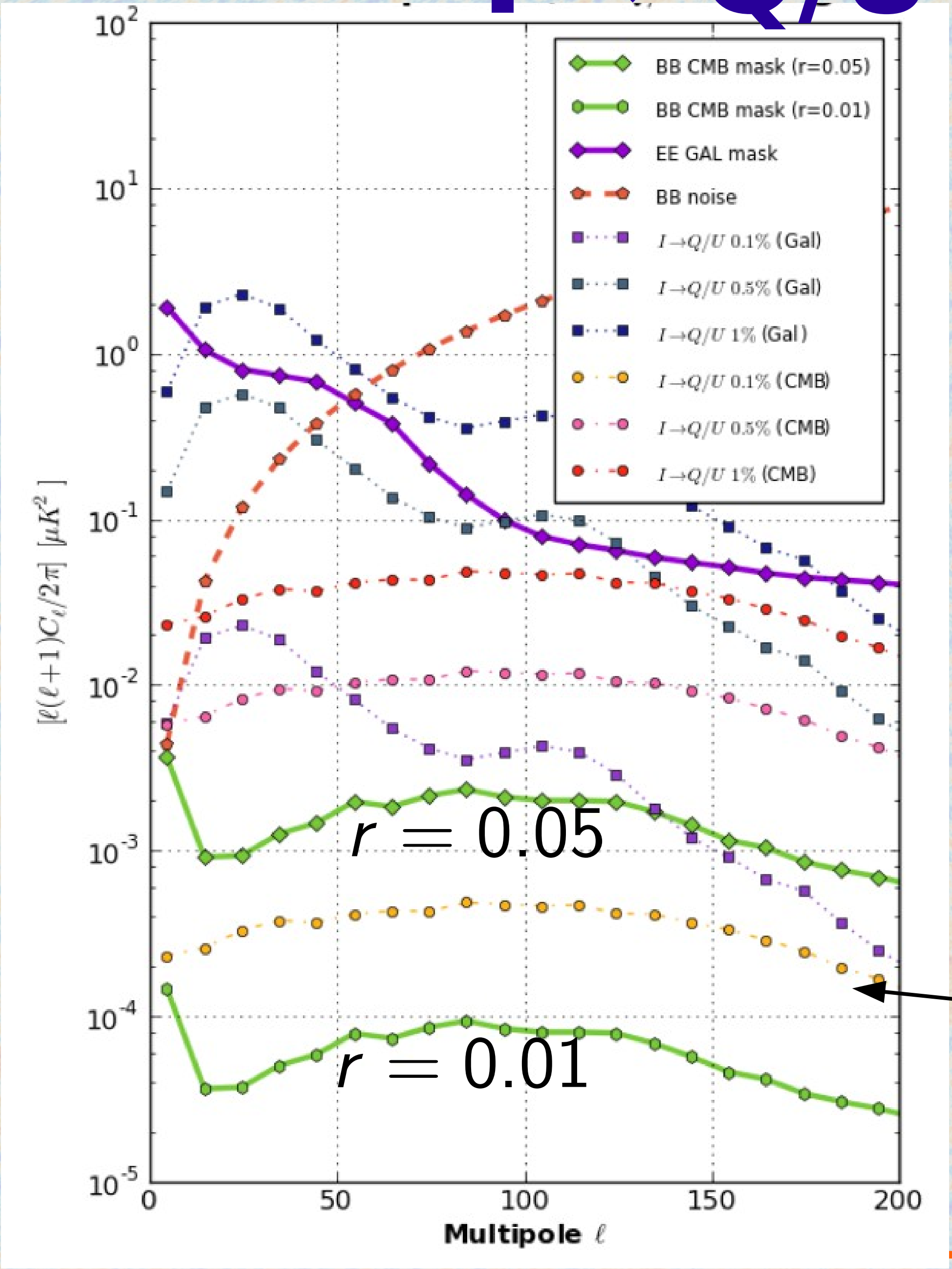


Franceschet
PhD student



Cavaliere
Head of mechanical shop

I → Q/U leakage

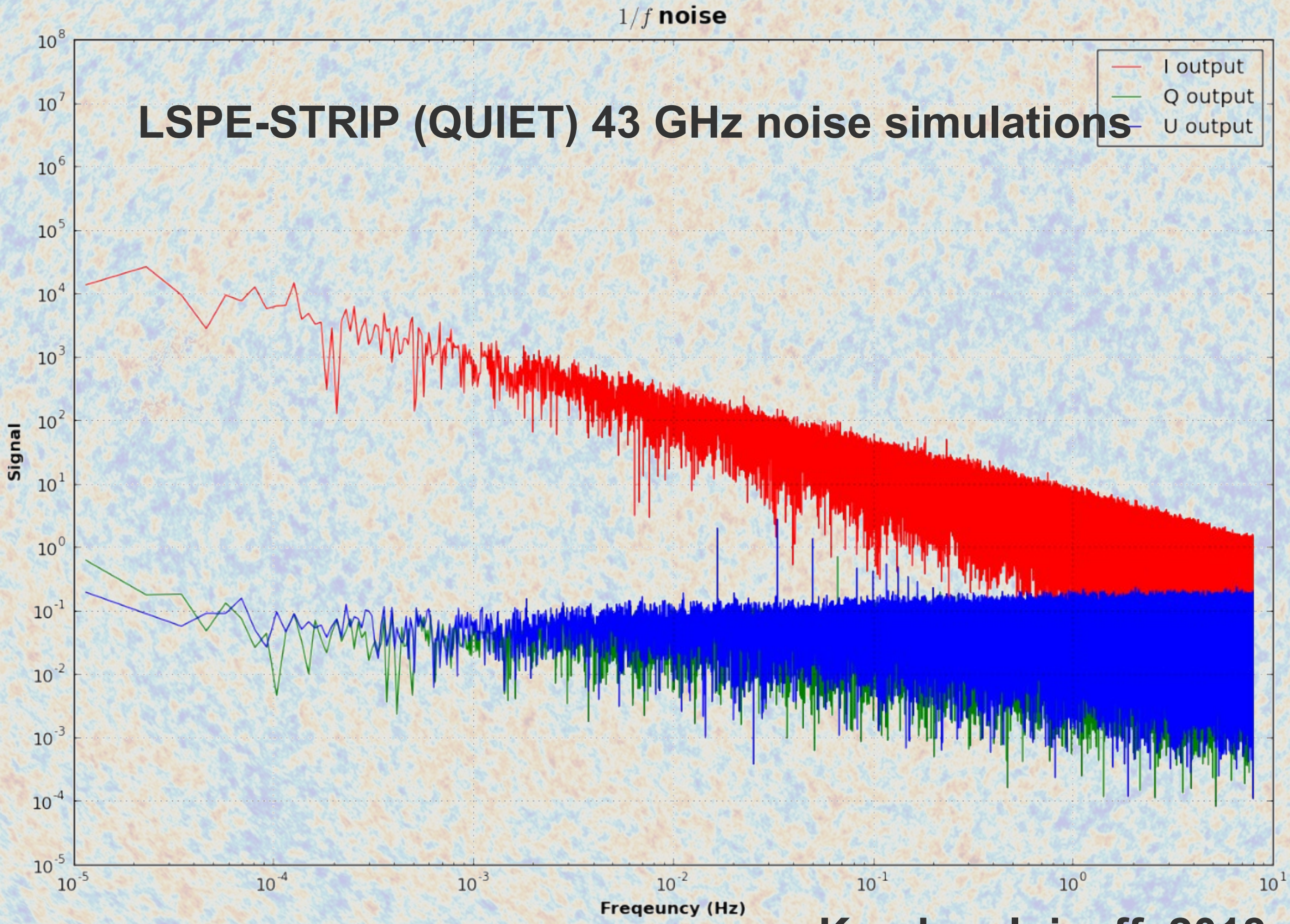


- One of the most critical effects
- Can arise because of various depending on the instrument (e.g. bandpass mismatches, OMT or polarizer non idealities)
- Needs be kept below 0.1%

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

Krachmalnicoff, 2013

Noise and stability



Krachmalnicoff, 2013

- 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

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	$<$ 8.8	$<$ 5.2	$<$ 9.5
	Galactic region	$<$ 17.0	$<$ 9.8	$<$ 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}]		$<$ 38.5	$<$ 13.7	$<$ 16.8
Sum of absolute and relative errors[g]	All sky	0.82 %	0.55 %	0.62 %

Challenge # 4

Meeting the calibration accuracy

Planck 2013, V

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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
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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

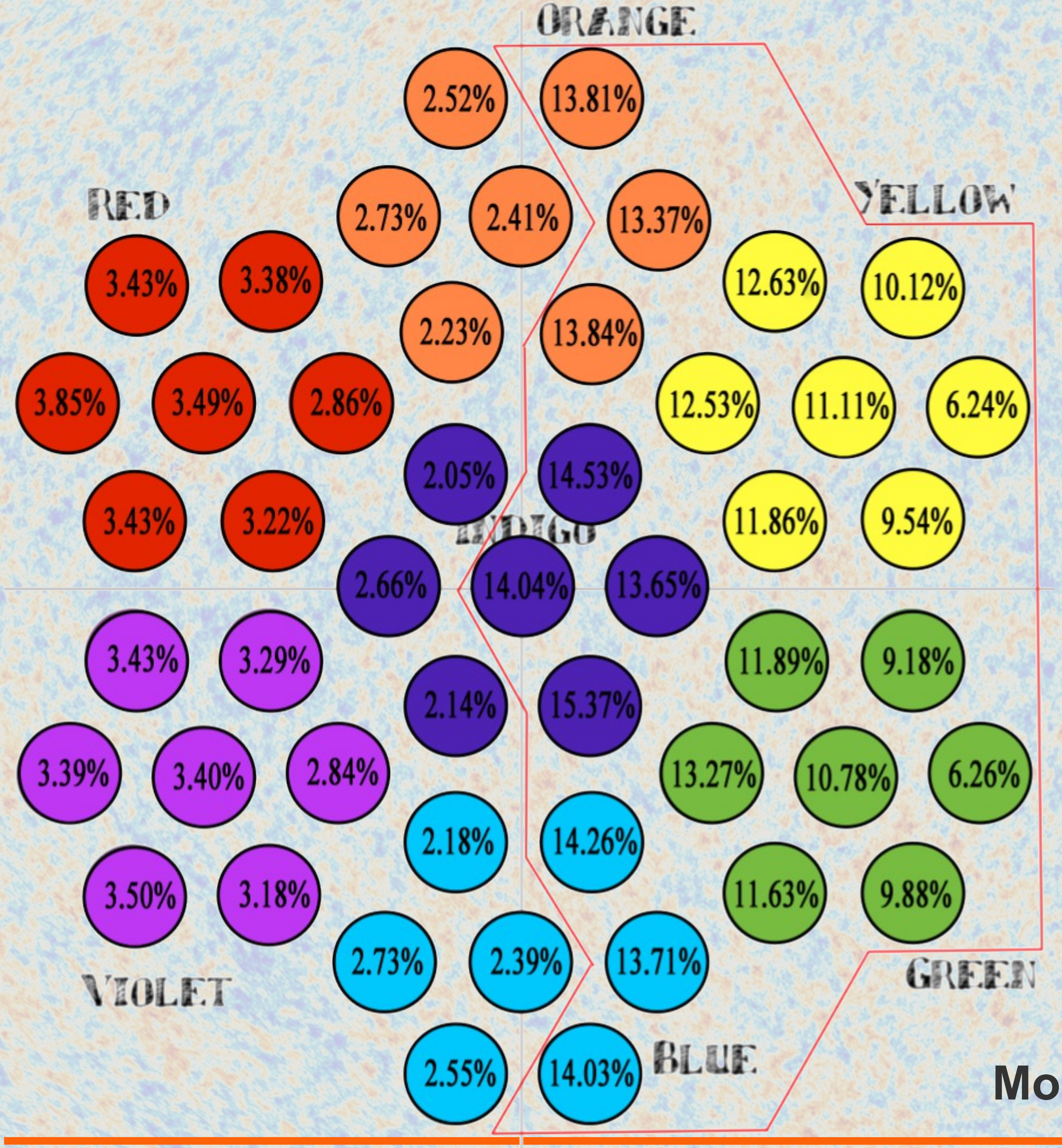
QUIET collaboration, ApJ, 2011

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%

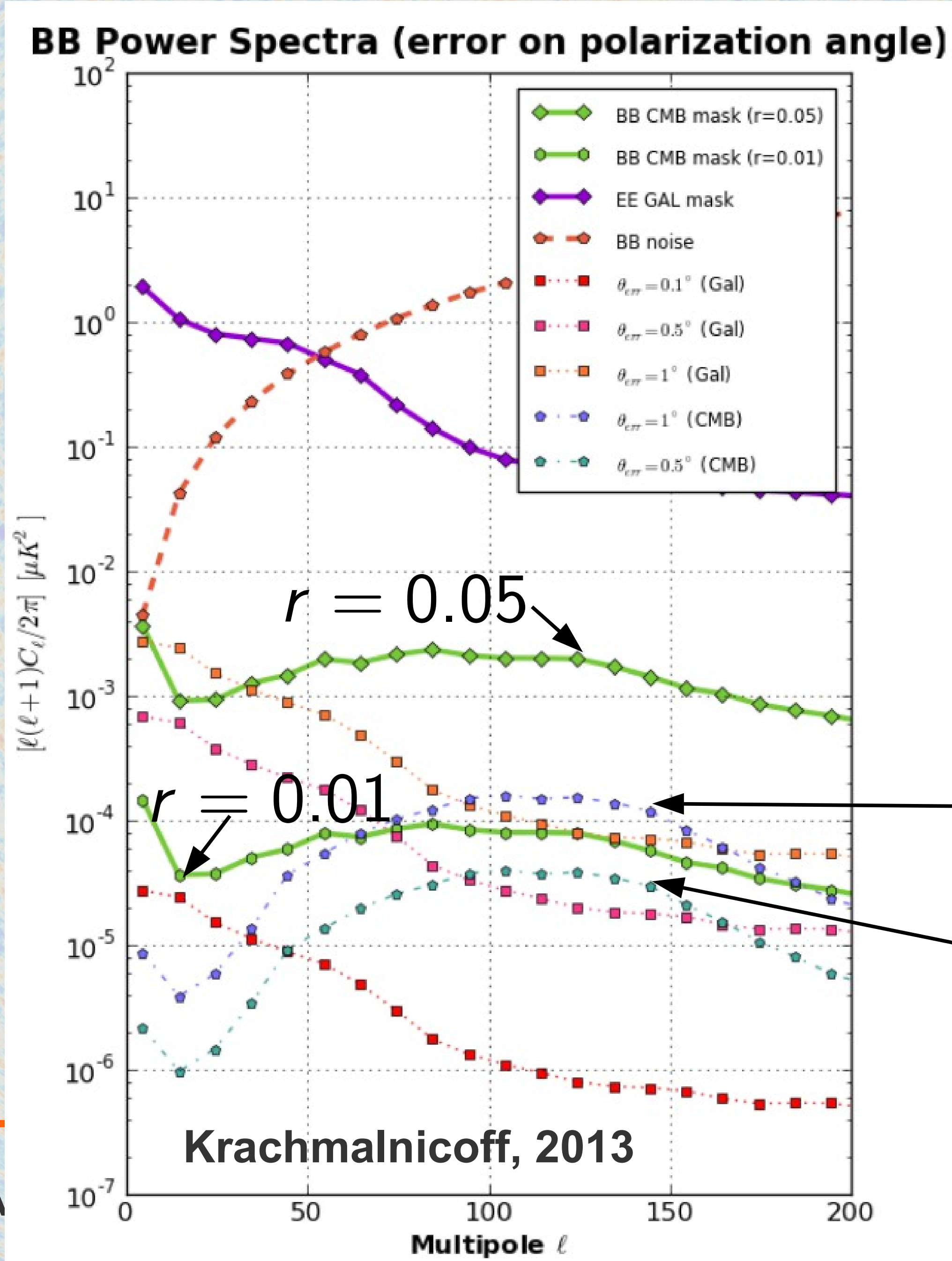
LSPE-STRIP preliminary calibration assessment



- 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

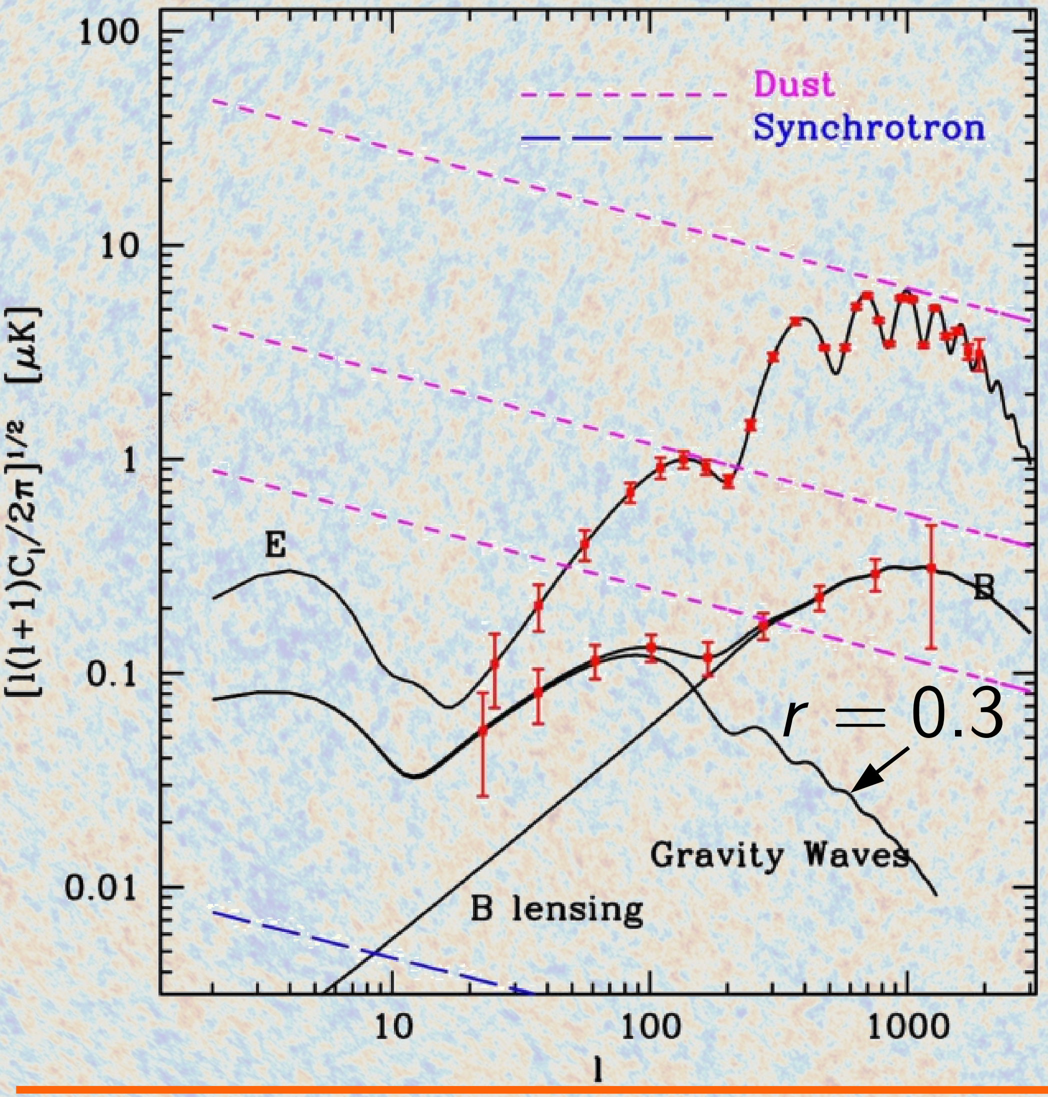
Challenge # 4

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

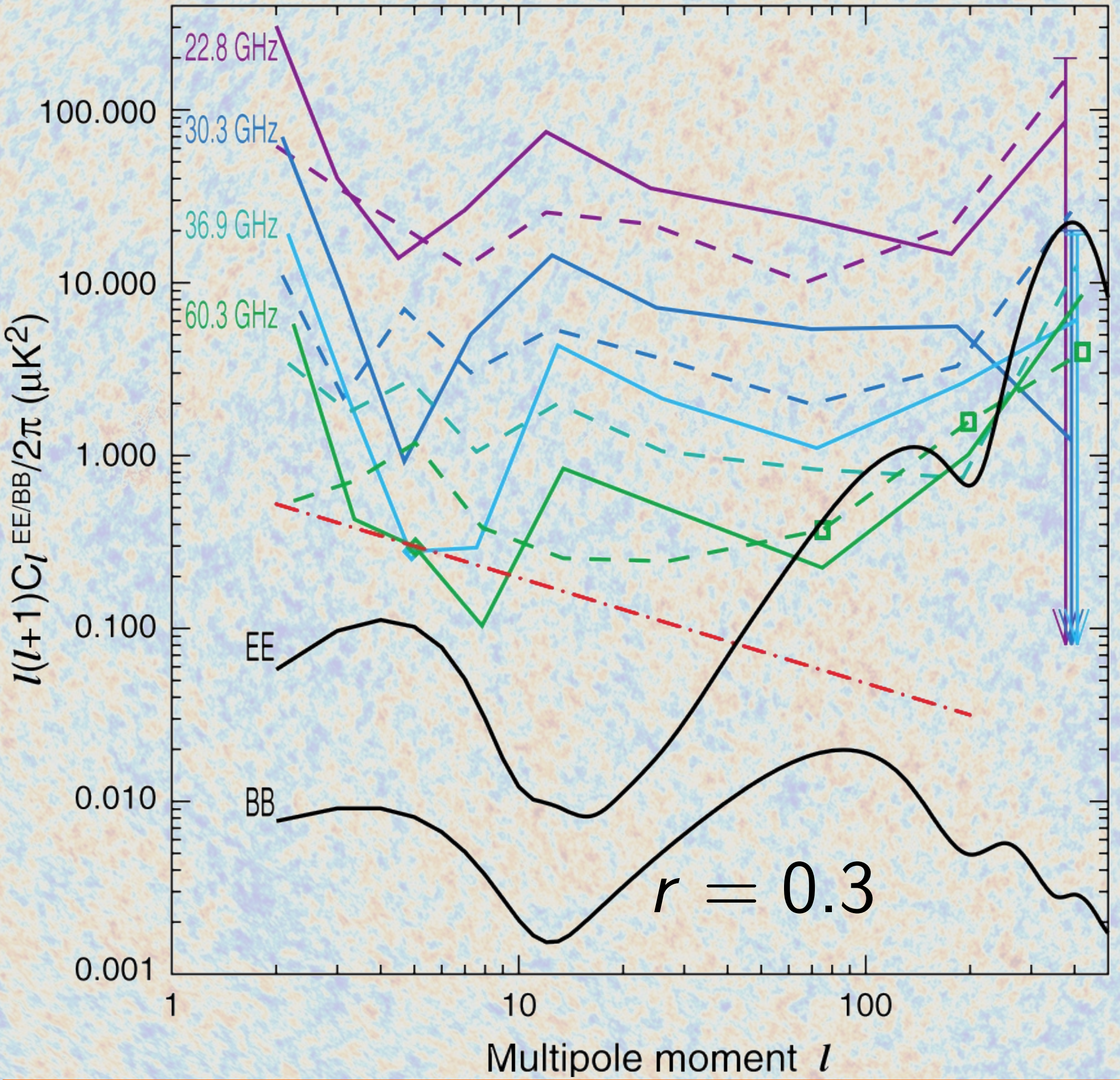
EBEX, Reichborn et al 2011



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

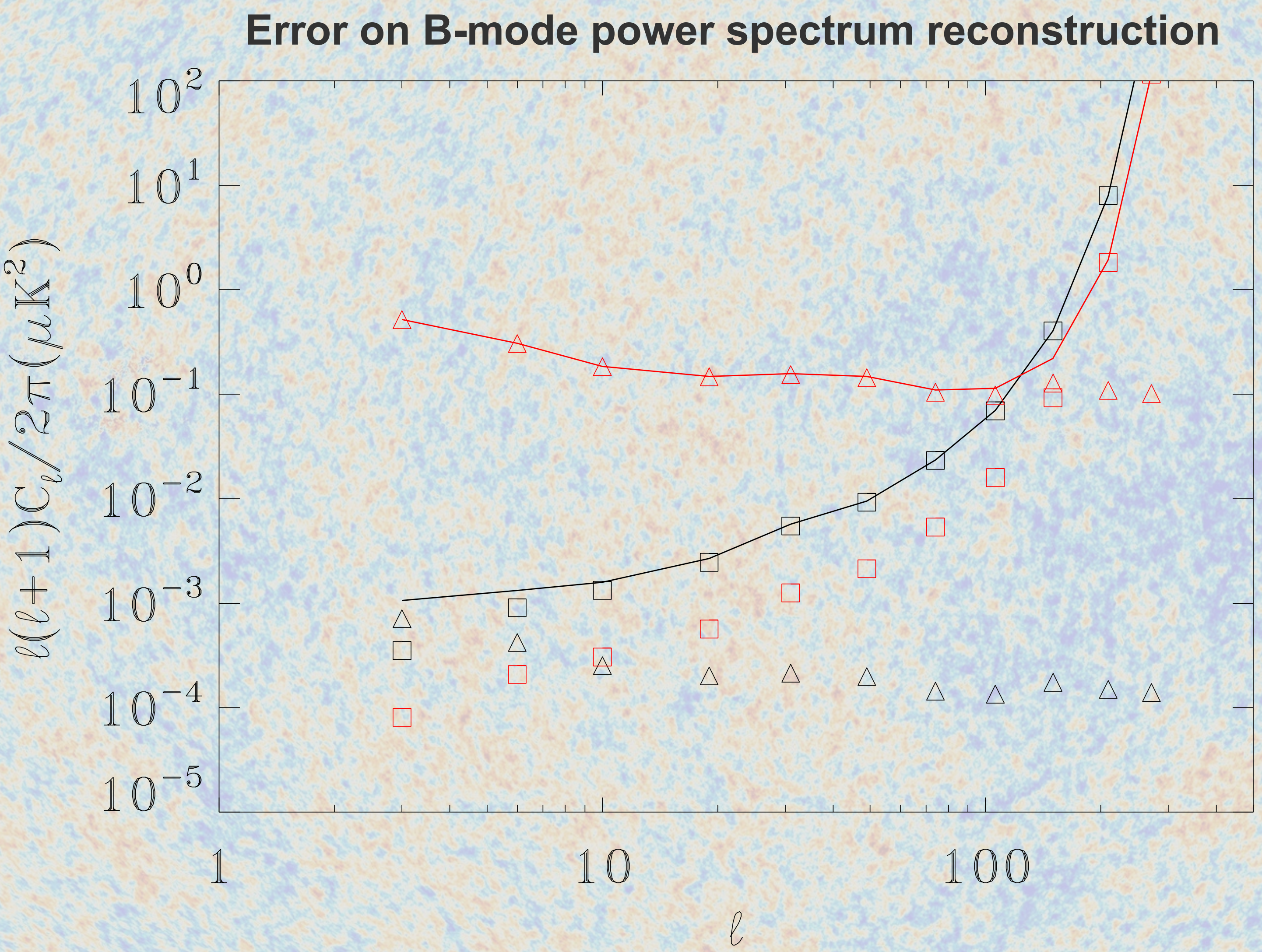
Challenge # 5
Meeting the foregrounds control

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

Simple exercise
LSPE-STRIP



S. Ricciardi, 2012

Challenge # 5
Meeting the foregrounds control

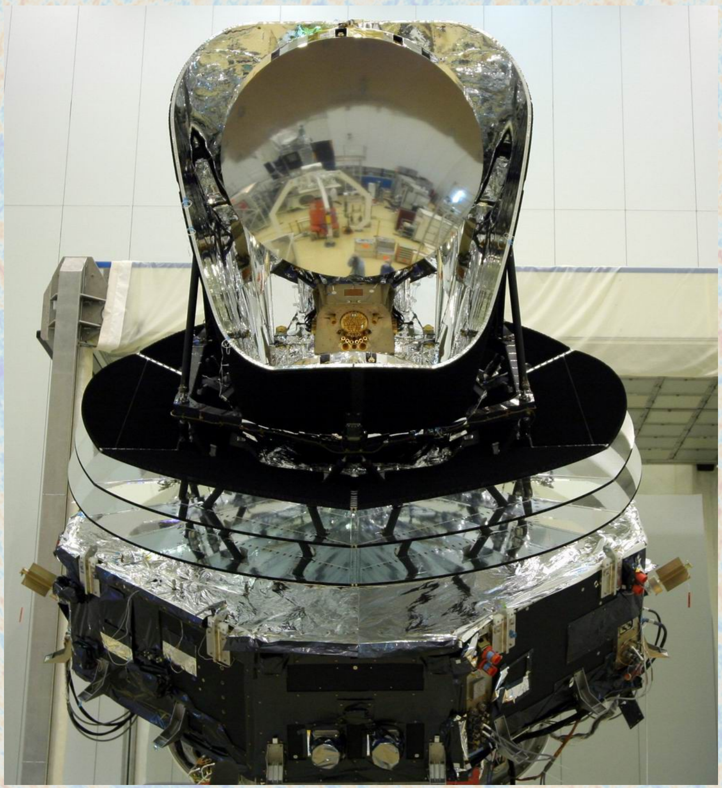
- **Extremely tough challenge.**
- At large angular scales the polarized CMB is foreground-dominated
- Wide frequency measurements with high sensitivity are necessary to control synchrotron and dust
- Combination of data from different instruments can be an important mitigation factor

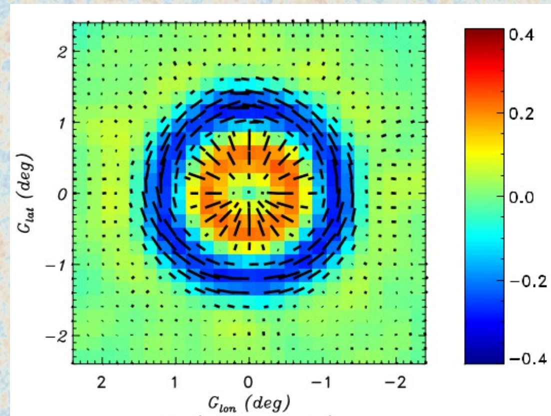
Conclusions

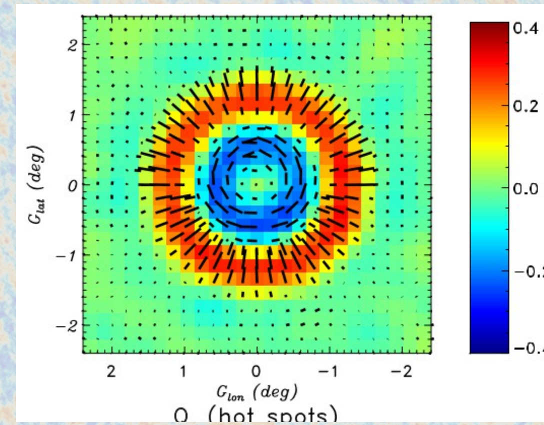
- **Precision polarization measurements are extremely hard**
- Several advances in detector technology available thanks to latest ground and balloon efforts
- Systematic effects and foregrounds are key for large scales measurements
- It is possible that a tensor B-mode detection will come in the next years, but certainly it is not at hand
- Space could be again key

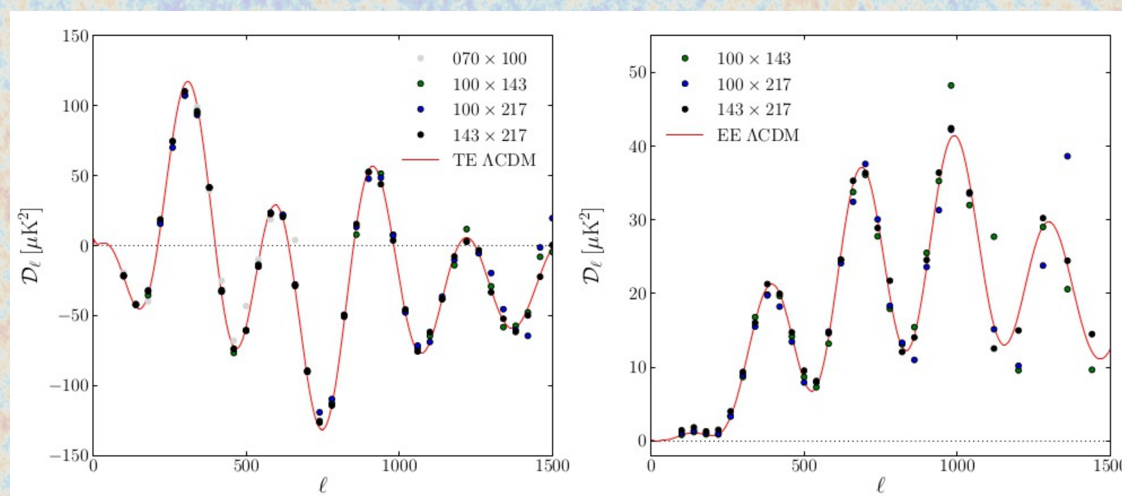
The future from space

Planck 2014 – polarization results



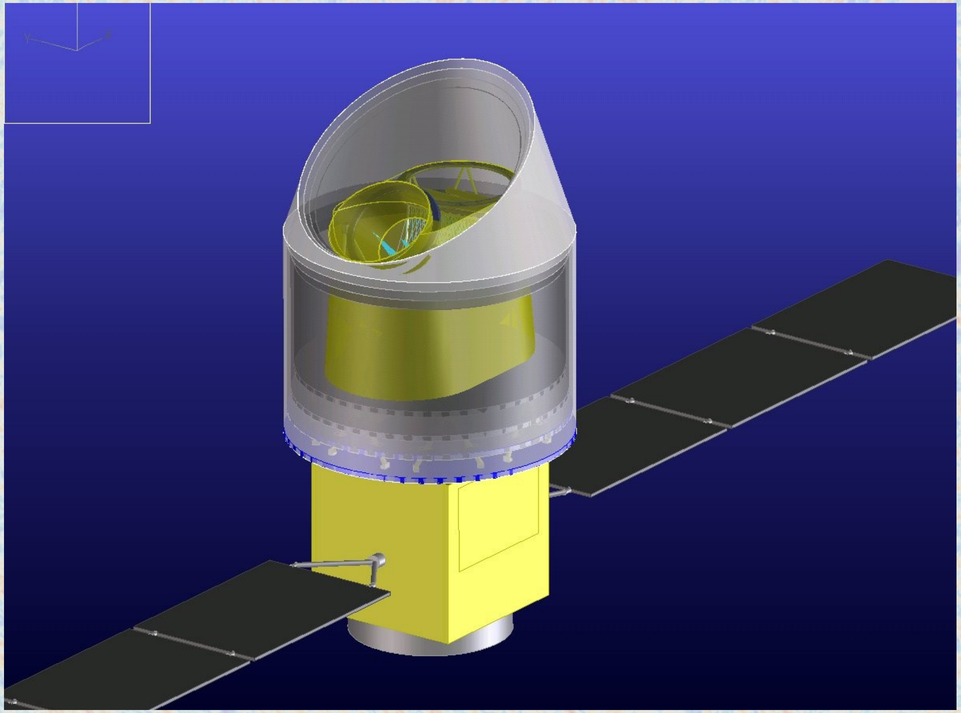






The future from space

LITEBIRD, Japanese (under assessment)
Launch planned 2020



European (under assessment)
Launch planned 2034