Large-Scale Polarization Explorer

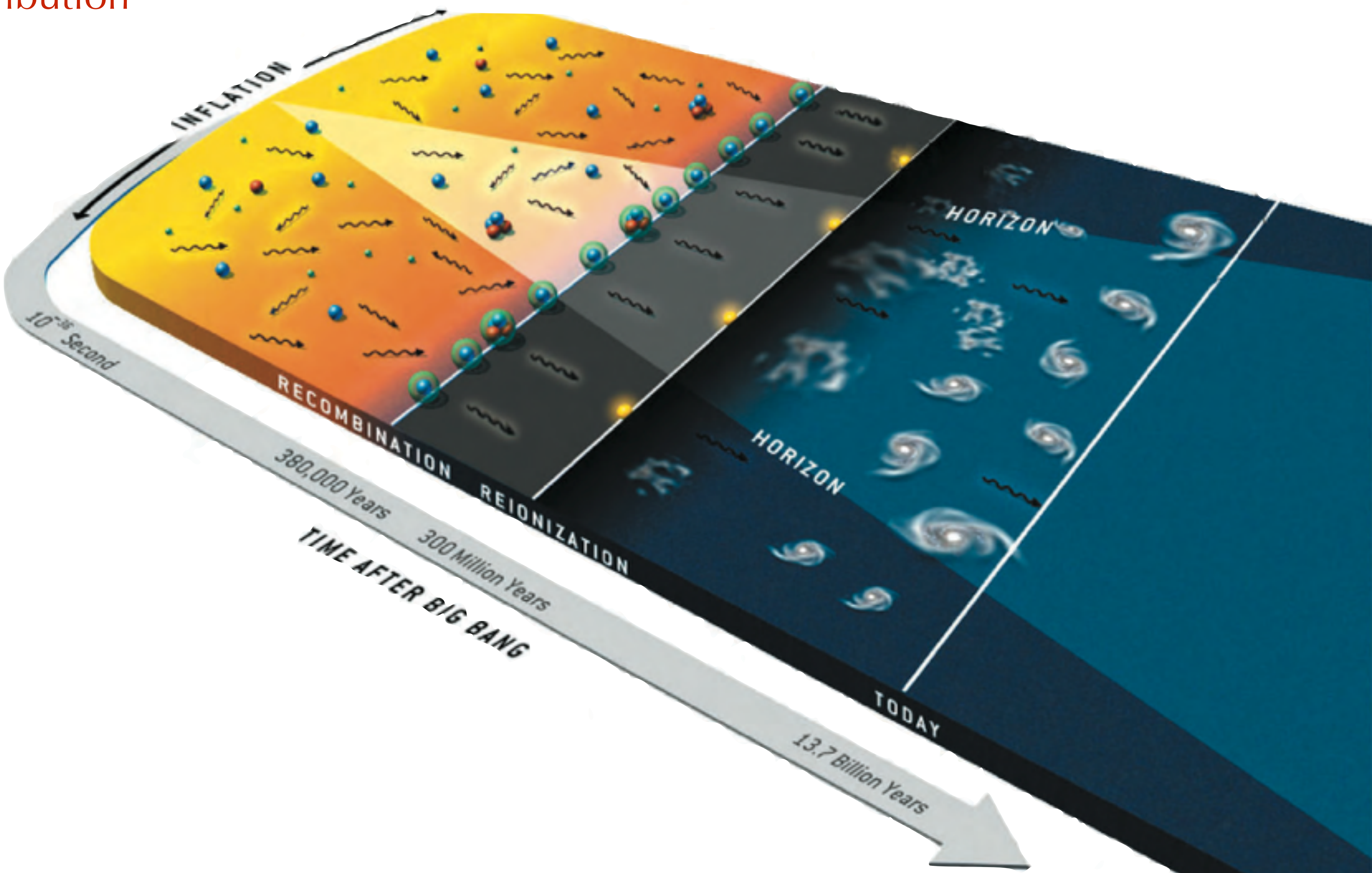
Una collaborazione ASI/INFN nello spirito di "What Next"

INFN Giovanni Signorelli

Presentazione Preventivi in Sezione di Pisa - 1.7.2014

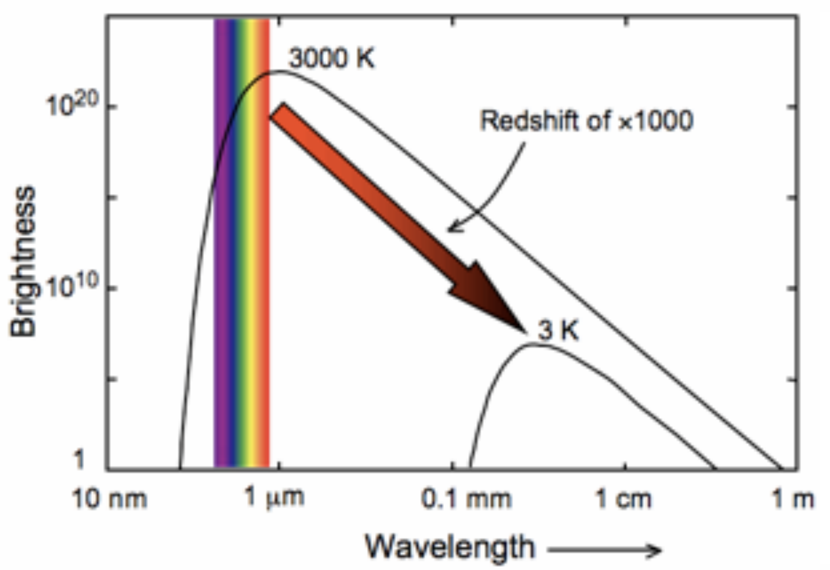
Summary

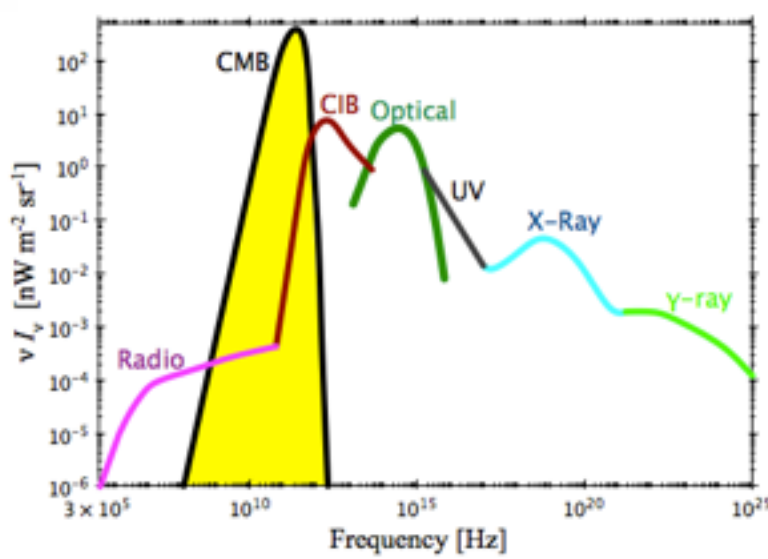
- CMB Science: detection of B-modes
- LSPE experiment
- Status of the project
- Our contribution

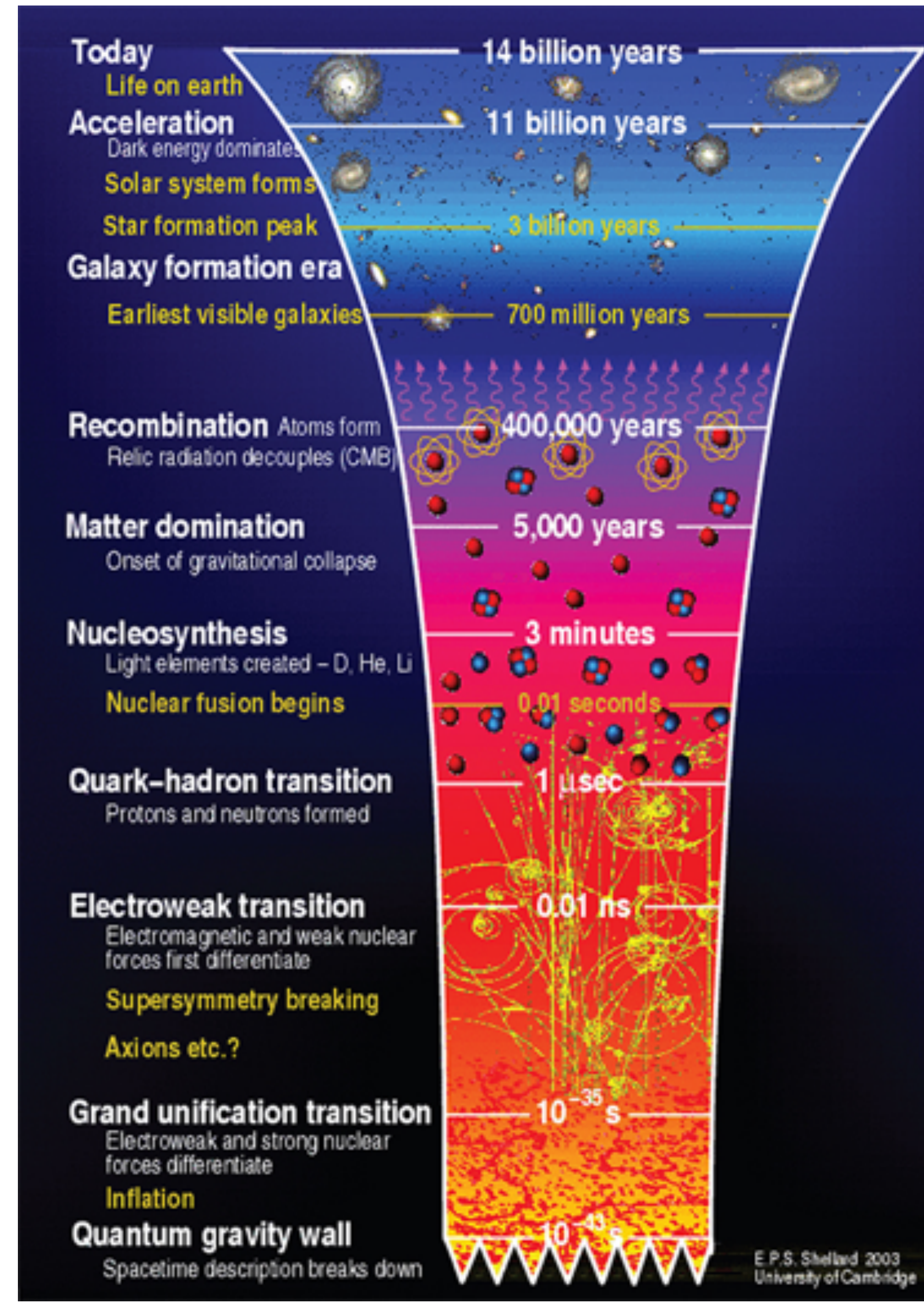


La fisica della CMB radiation

- According to modern cosmology CMB is an abundant background of photons filling the universe
  - generated in the very early universe
    - <4μs from the Big Bang
    - 10^9 γ/barion
  - thermalized by repeated scattering
    - against electrons → z = 1100 (last scattering)
    - black-body spectrum
  - redshifted to microwave frequency
    - T ~ 2.725 K, 1 meV
    - diluted to ~ 410 γ/cm^3







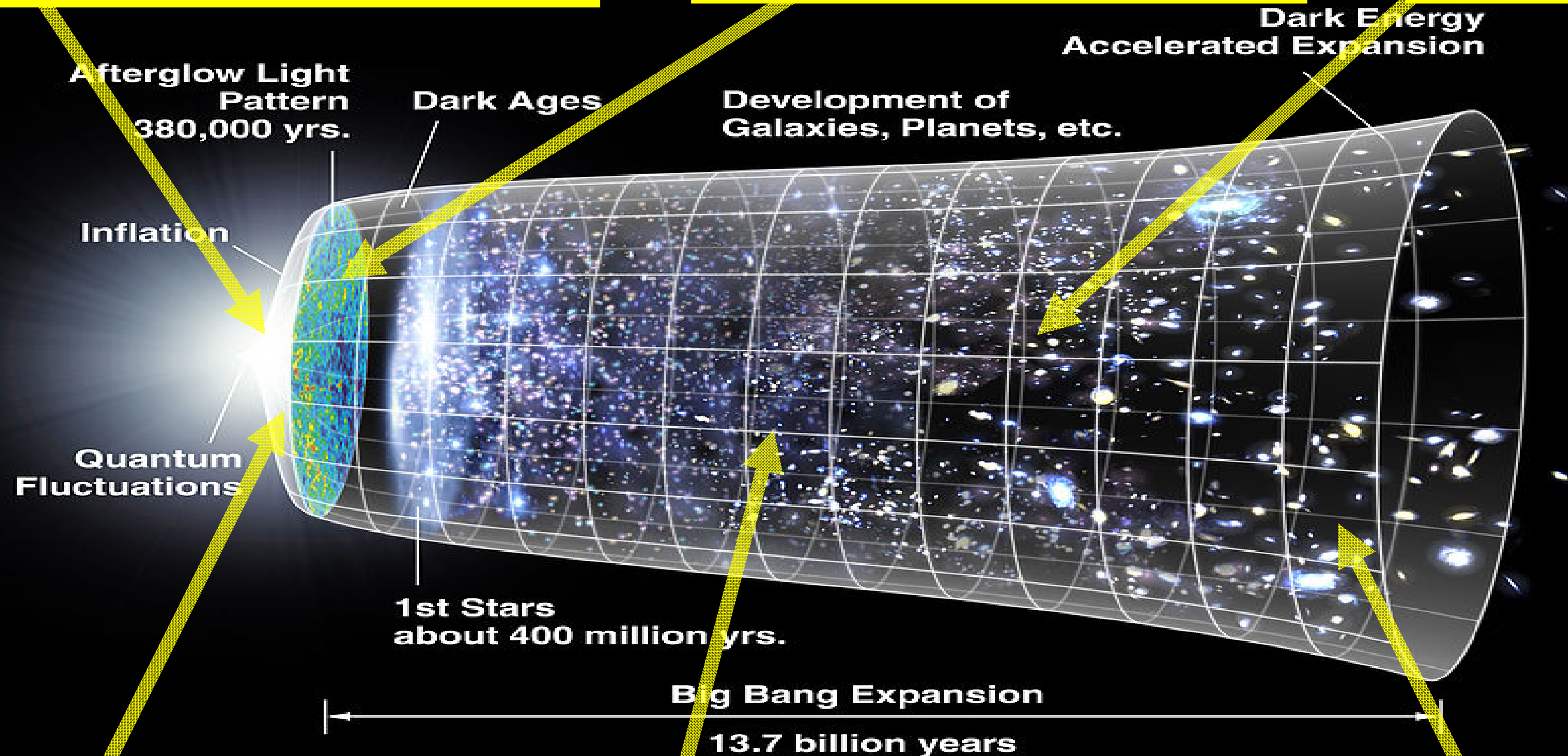
- Carry significant information on the Universe structure, evolution and composition

CMB measurements can probe all phases of the evolution of the Universe

measurement of CMB polarization, Gaussianity, Search for the gravitational waves produced during inflation. Also spectral distortions to probe inflation.

Physics of the primeval fireball (acoustic oscillations of the primeval plasma)

LSS (galaxy clusters) via Sunyaev-Zeldovich effect (SZ):



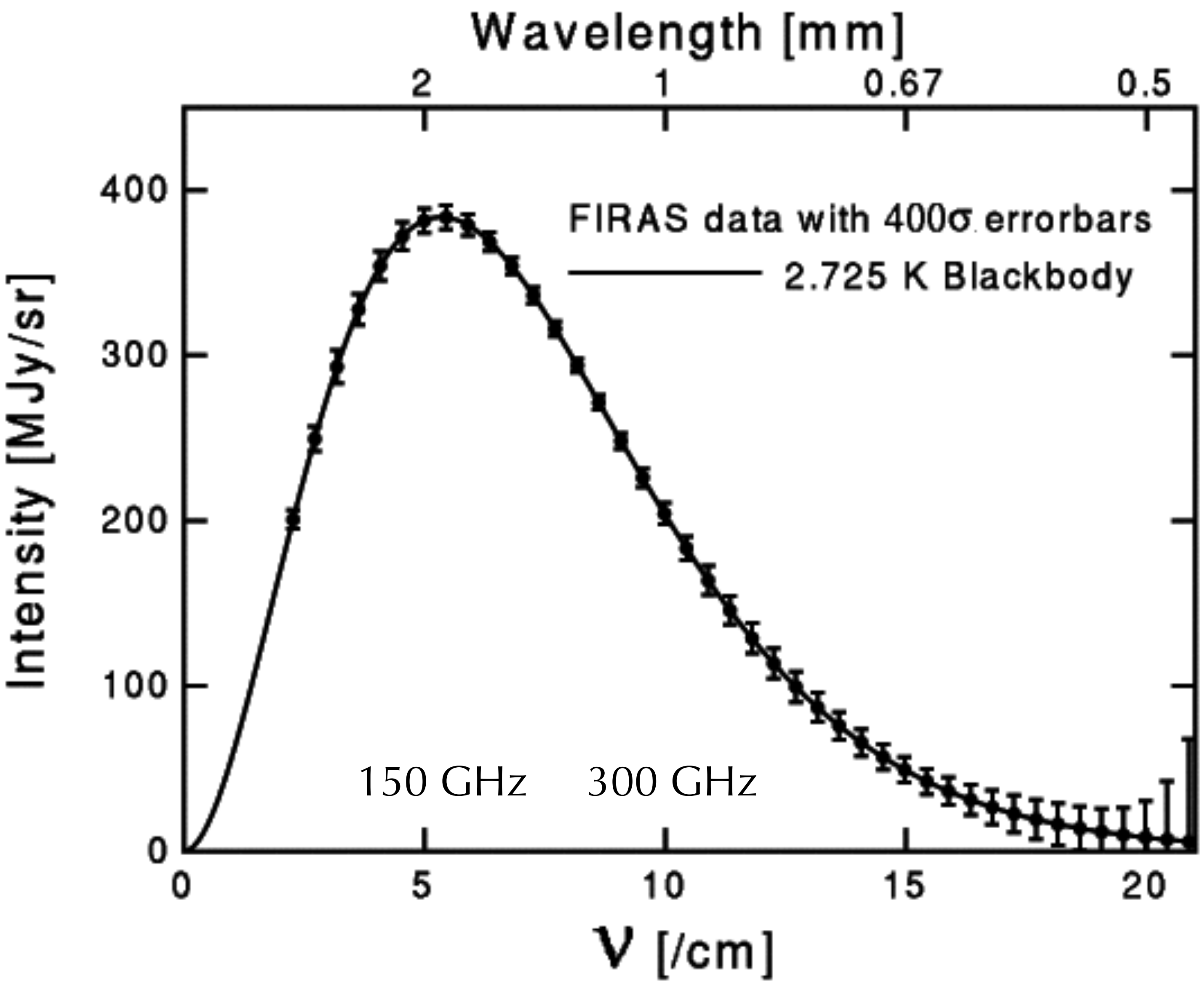
Probe epochs before recombination and new physics using CMB spectral distortion measurements

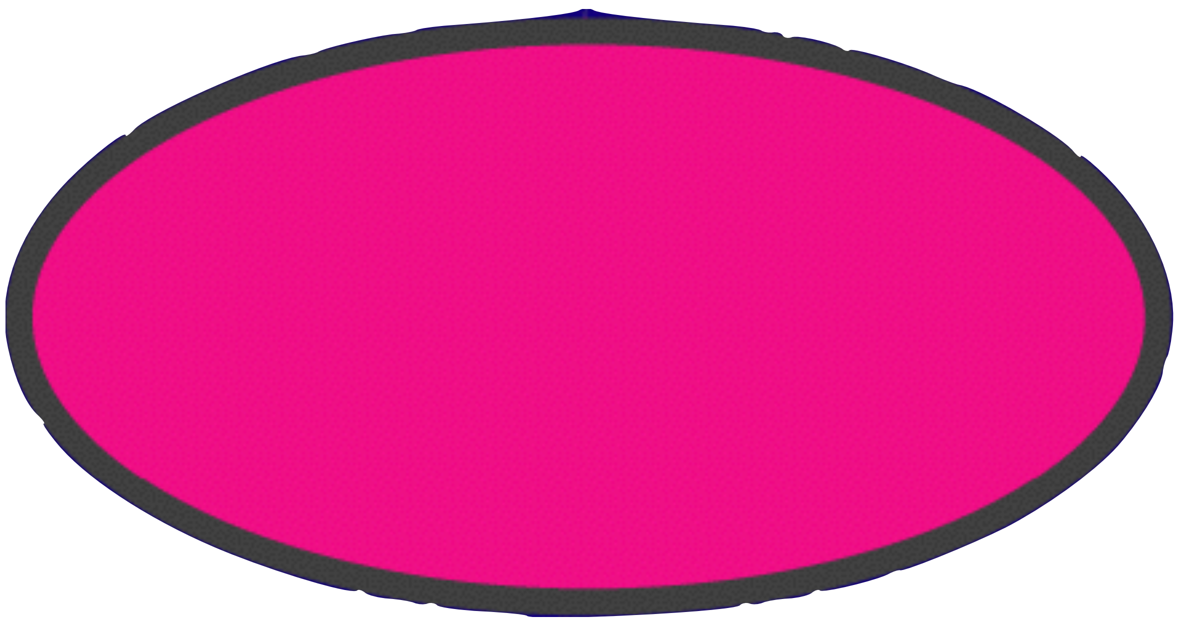
Map the gravitational potential all the way to z=1100 through CMB lensing

Dipole: our motion

CMB Observables

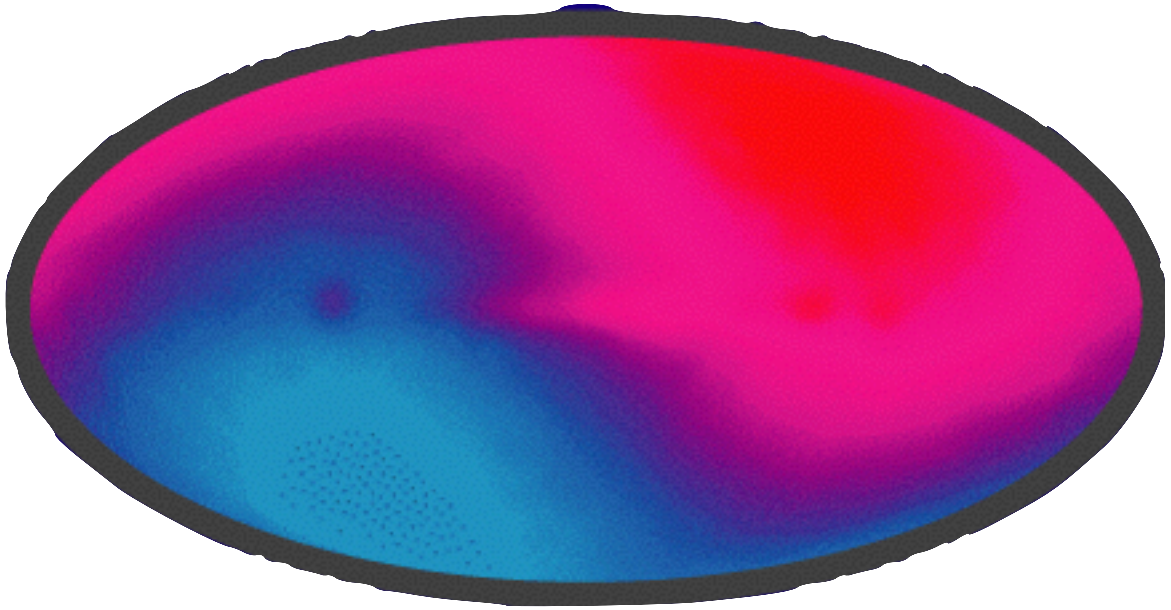
- Monopole term: 2.725 K blackbody O(1)
  - discovered in 1965
  - best measurement done by FIRAS instrument on COBE satellite (absolute temperature instrument)





CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK O(10^{-3})
  - Doppler shift caused by the Solar system motion relative to the nearly isotropic blackbody field
  - $v_{\text{solar system}}$ = (369.0 ± 0.9) km/s
  - determine the "absolute rest frame" of the Universe



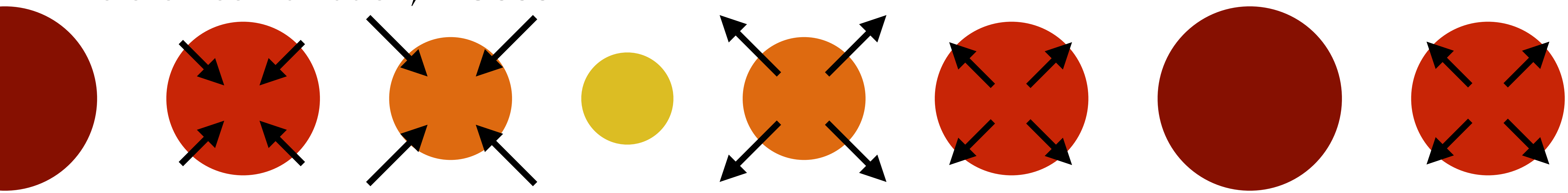
CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
- Anisotropy: 100 μK rms

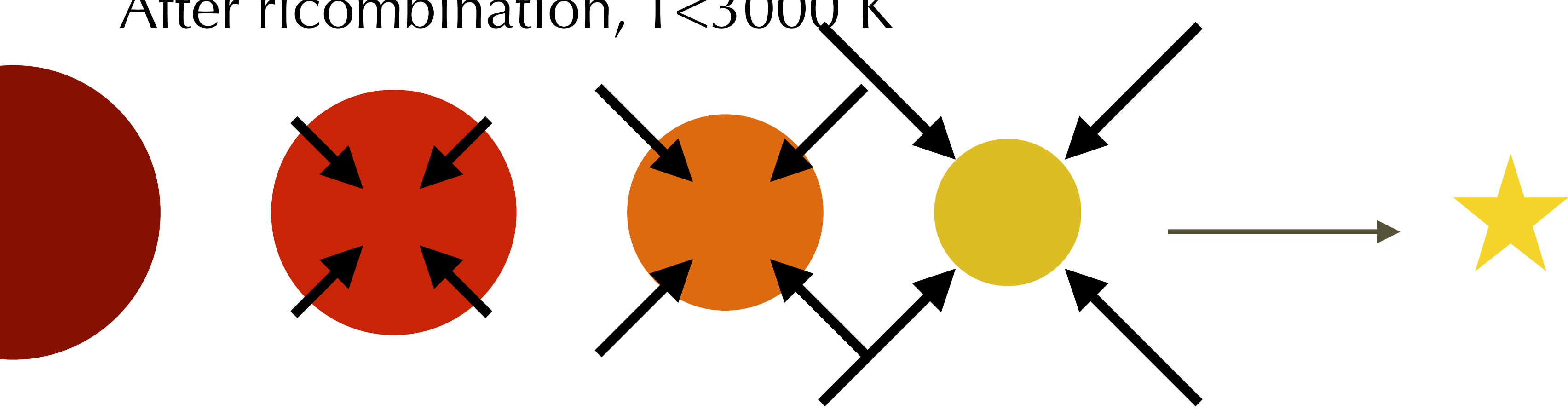
$O(10^{-5})$

  - precise power spectrum forecasts
  - very well measured COBE → WMAP → Planck
    - Density perturbation in the primeval photon-matter plasma oscillate
    - self gravity vs. radiation pressure
    - all information is encoded in the angular power spectrum of the image

Before ricombination, T>3000 K

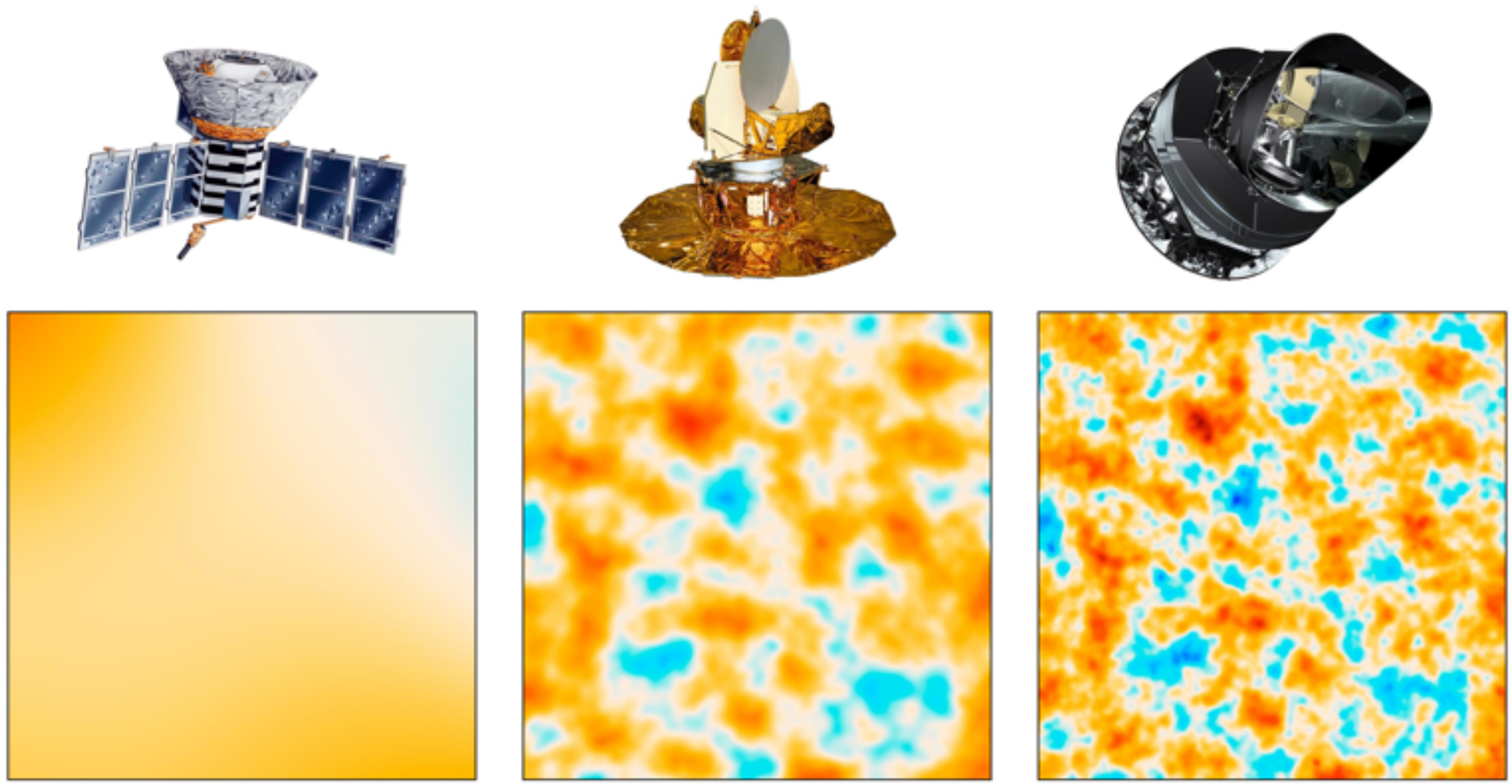


After ricombination, T<3000 K



CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
- Anisotropy: 100 μK rms — $O(10^{-5})$
  - precise power spectrum forecasts
  - very well measured COBE → WMAP → Planck



COBE | WMAP | Planck

CMB Observables

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O(10^{-5})

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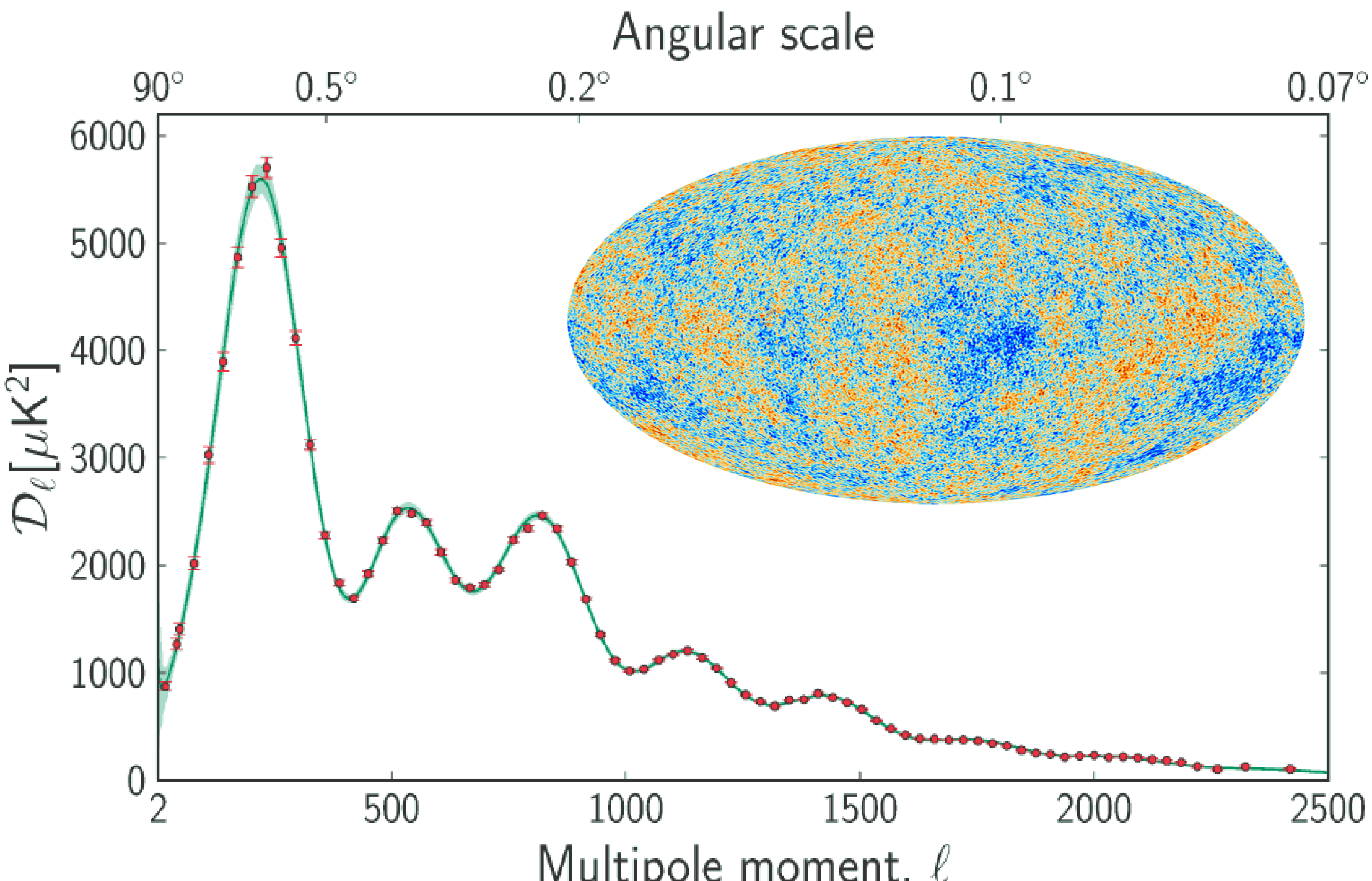
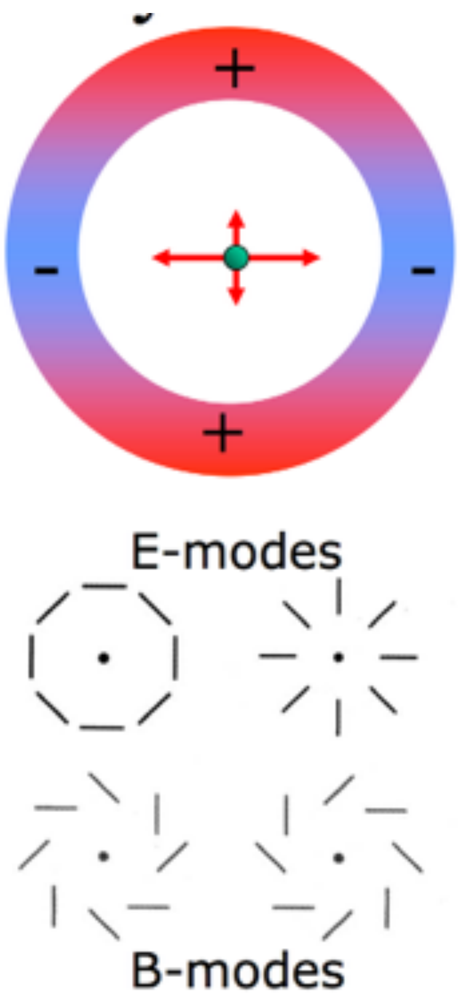
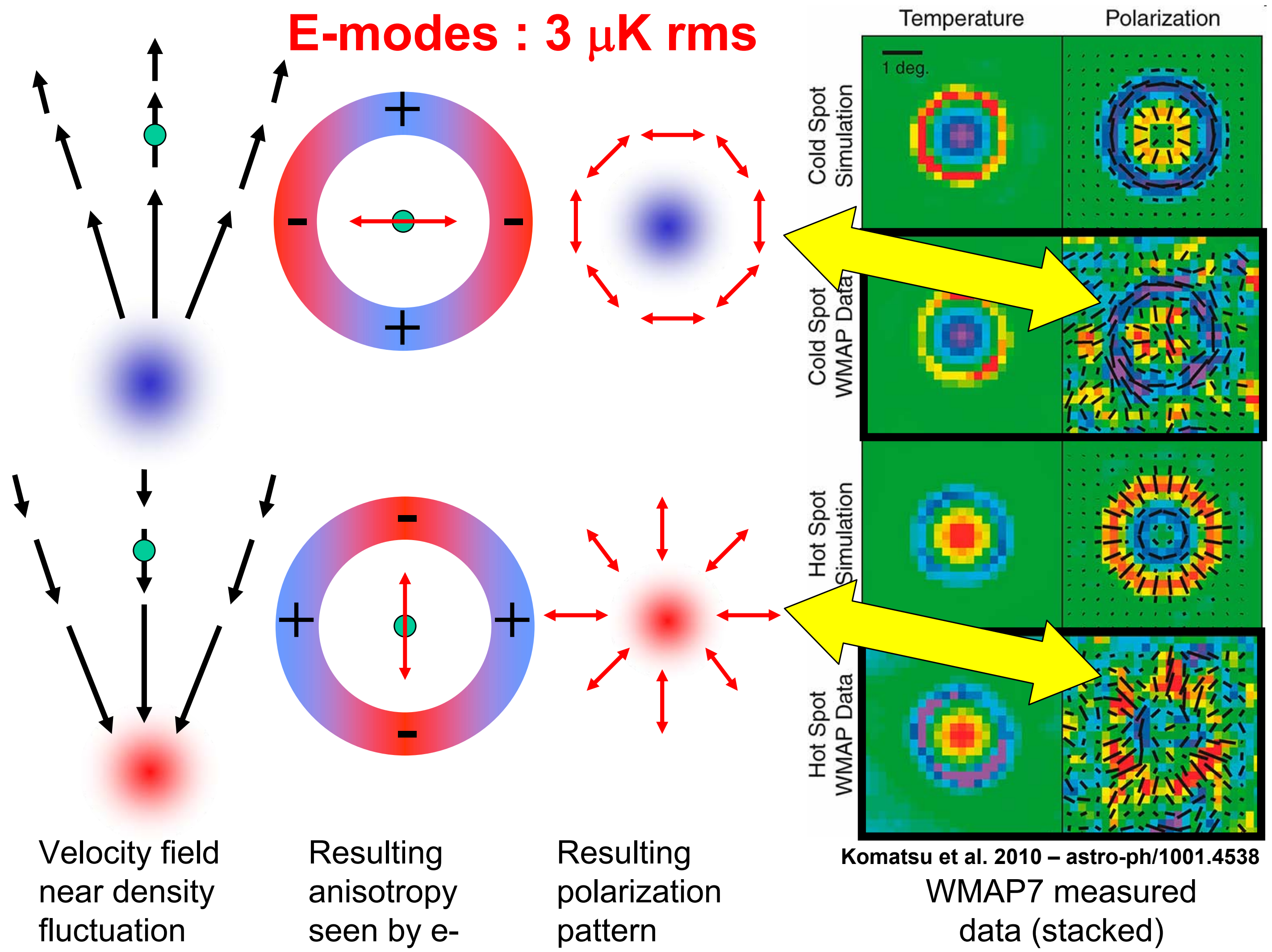


CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
- Anisotropy: 100 μK rms
- E-mode polarization: 3 μK rms — $O(10^{-7})$
  - Linear polarization is induced via Thomson scattering by the quadropole anisotropy at ricombination (z=1100)





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- Monopole term: 2.725 K blackbody
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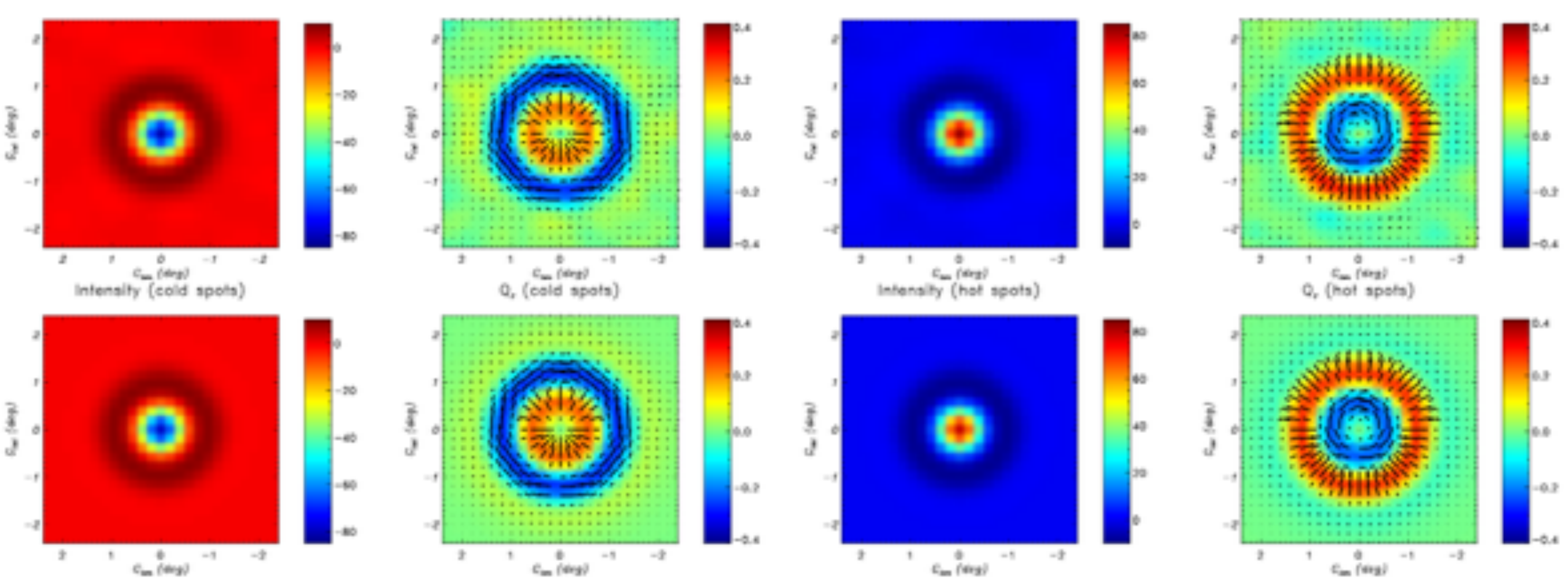
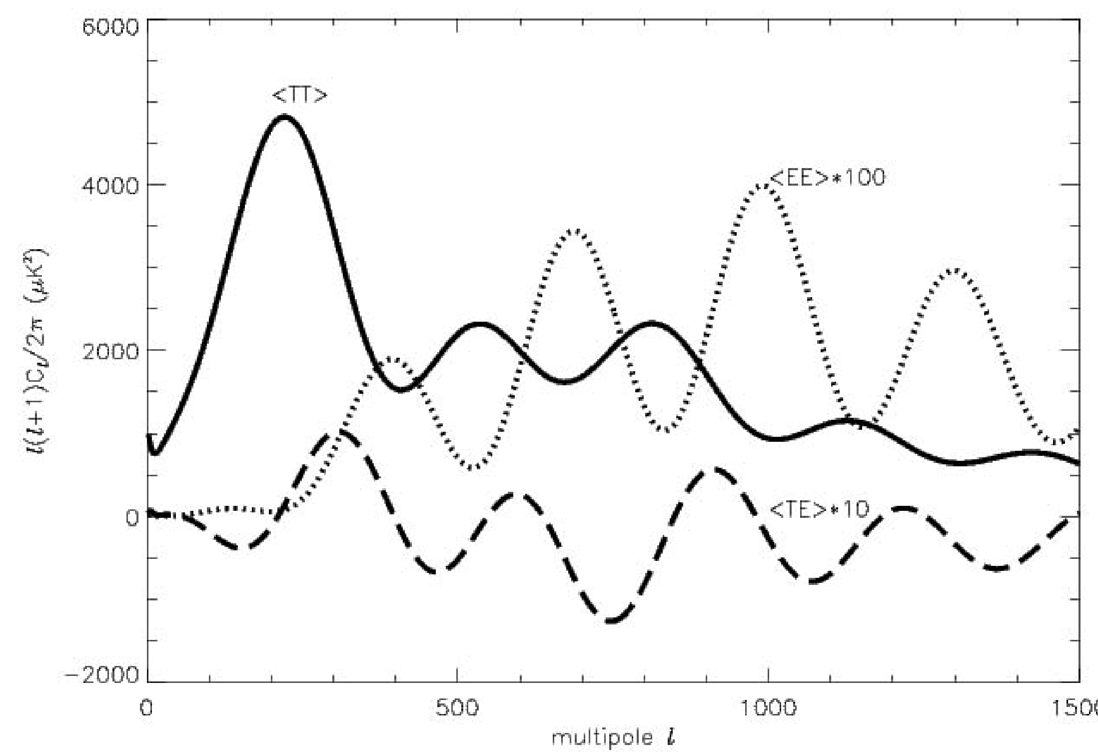
- Anisotropy: 100 μK rms
- E-mode polarization: 3 μK rms O(10^{-7})
  - Linear polarization is induced via Thomson scattering by the quadropole anisotropy at ricombination (z=1100)
  - Precise power spectrum forecast
  - π/2 with respect to the density fluctuations
  - well measured





CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
- Anisotropy: 100 μK rms
- E-mode polarization: 3 μK rms
- B-mode polarization: <500 nK rms
  - depends on lensing of E-modes
  - depends on the inflation process and the background of primordial gravitational waves

$O(10^{-8})$

CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
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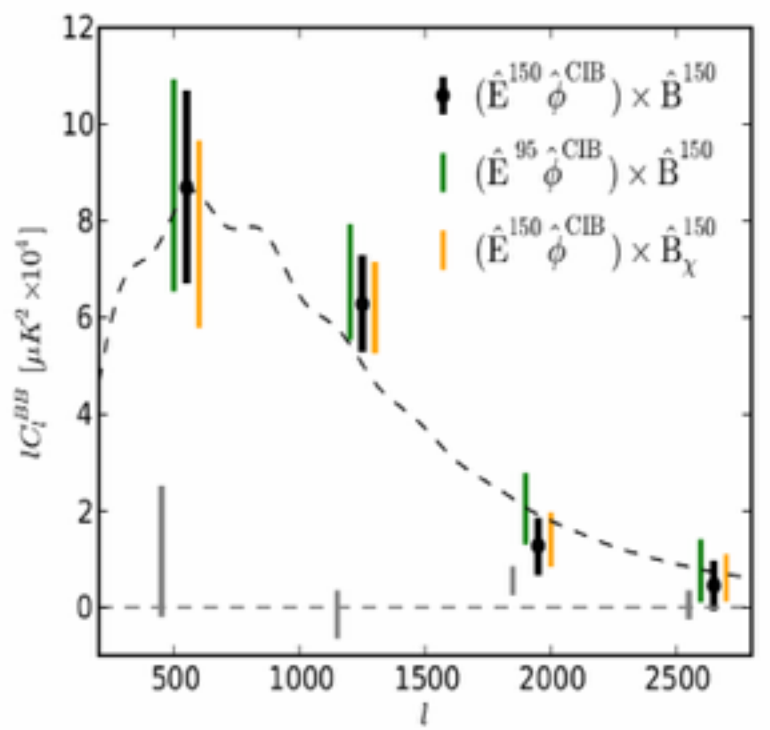
- E-mode polarization: 3 μK rms
- B-mode polarization: <500 nK rms O(10^{-8})
  - depends on lensing of E-modes
  - sensitive to the mass distribution, hence can shed light to dark matter and neutrino masses issues
  - lensed B-mode is maximum at multipoles around 1000 (ϑ~0.2 deg) while primordial B-modes are maximum at multipoles around 100 (ϑ~2 deg)



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O(10^{-8})

  - depends on the inflation process and the background of primordial gravitational waves

- An inflation phase at E=$10^{16} \div 10^{17}$ GeV ($10^{-33} \div 10^{-36}$ sec) is currently the most popular scenario to explain
  - the origin of our Universe
  - the geometry of our Universe
  - the origin of the structures of the Universe
  - the smoothness of the CMB at scales > horizon
- It is a predictive theory
  - Any curvature is flattened by the huge expansion
  - Adiabatic, gaussian density perturbation as origin of large structures
  - Power spectrum of scalar perturbation is approximately scale invariant
  - Tensor perturbations produce a background of primordial gravitational waves

CMB Observables

- Monopole term: 2.725 K blackbody
- Dipole term: 3.355 mK
- Aniso
- E-mo
- B-mo O(10^{-8})
  - d tional
    w

B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

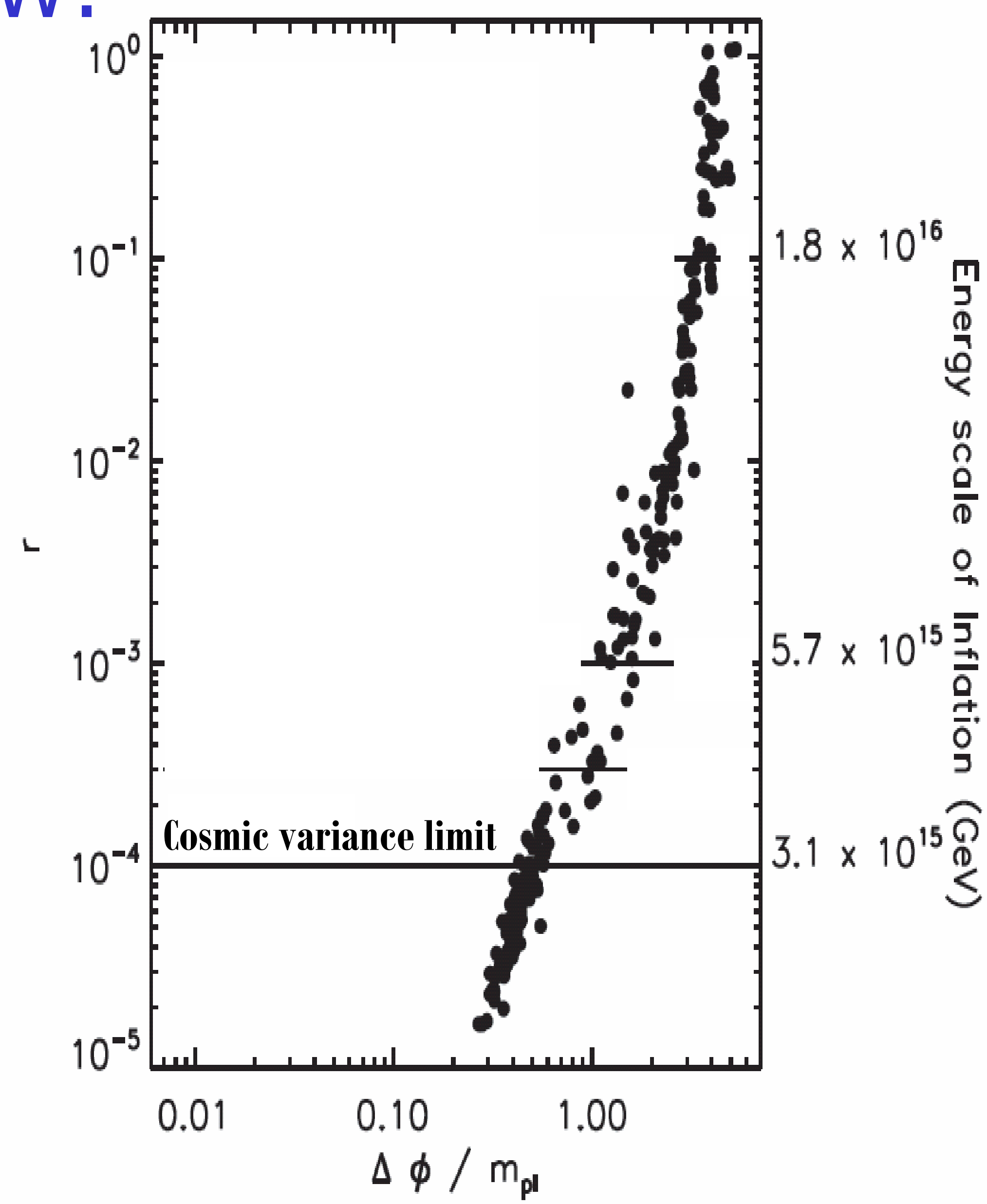
Inflation potential

$$r = \left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times10^{16}\,\mathrm{GeV}}$$

- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}c^B_{\ell\max}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The measurement of B-modes is a good way to investigate fundamental physics at extremely high energies and select among different models of inflation.



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- B-mode polarization: <500 nK rms $O(10^{-8})$

  - depends on the inflation process and the background of primordial gravitational waves
  - The signal is extremely weak
  - The detection of the B-modes
    - needs an extremely sensitive instrument
    - needs an extremely careful control of systematic effects
    - needs independent experiments with orthogonal systematic effects

  - for a robust detection of B-modes, independent measurements and precise measurements of polarized foregrounds are mandatory

CMB Observables

- Monopole term: 2.725 K blackbody
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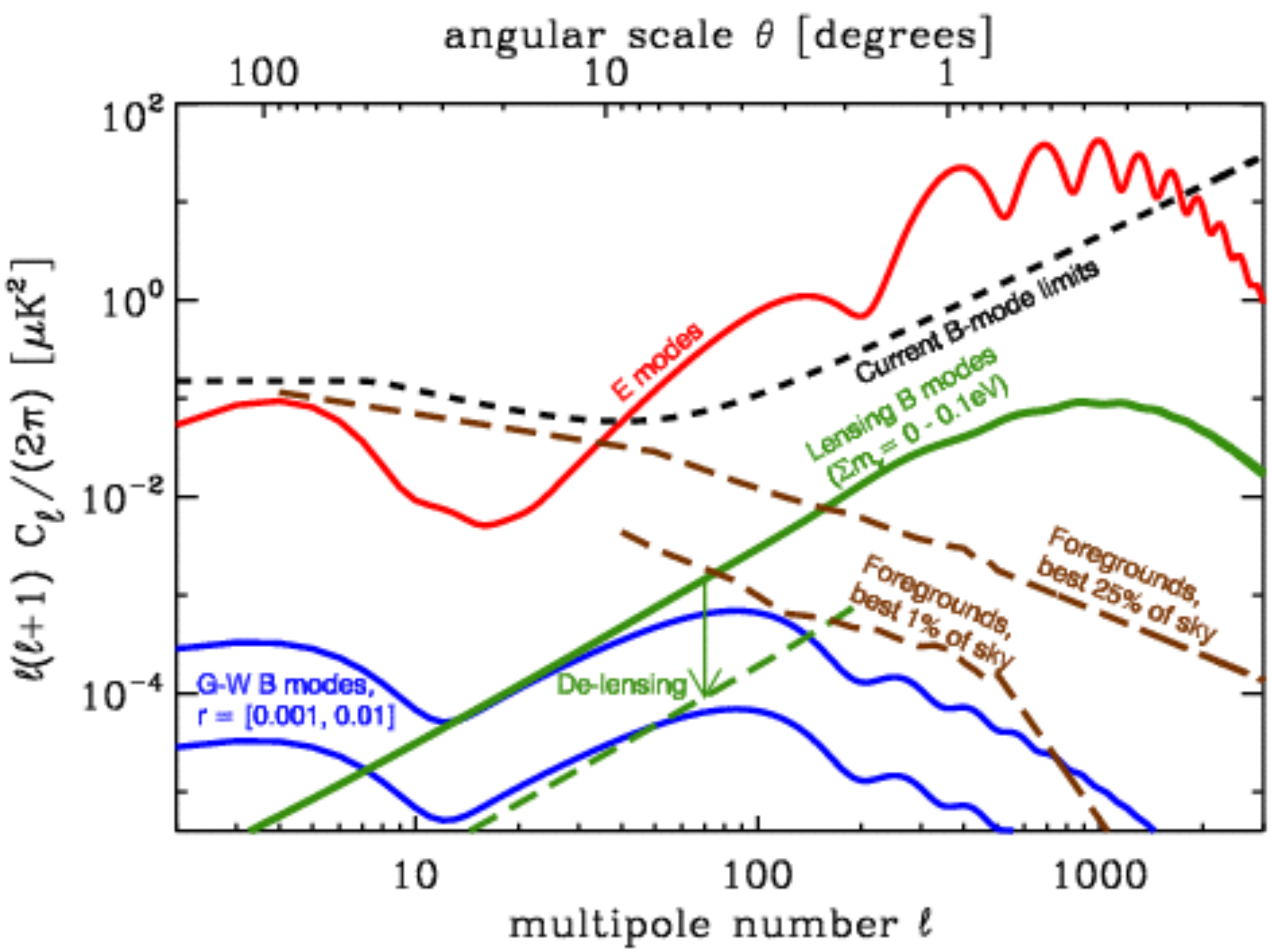
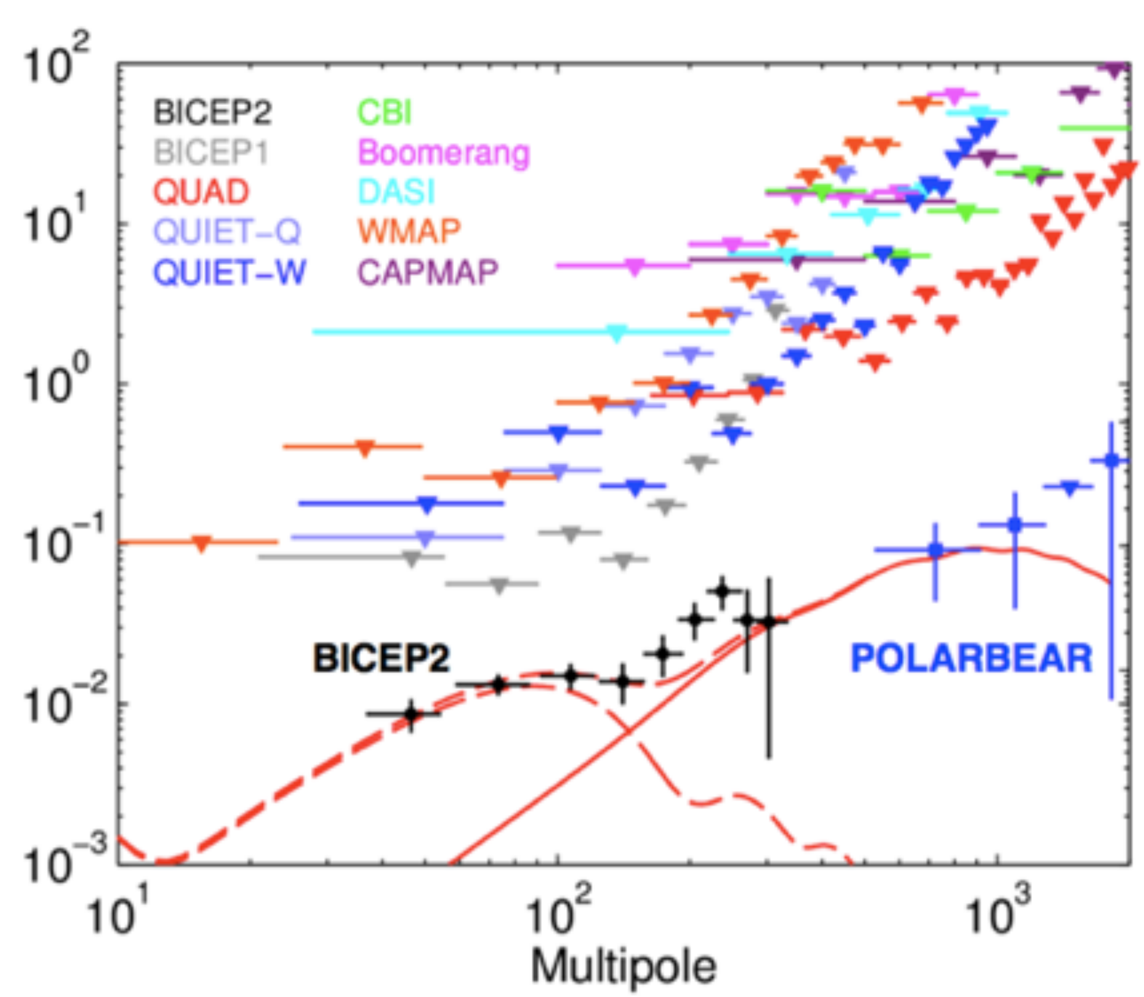
r = scalar/tensor

$O(10^{-8})$





CMB B-mode timeline

- Ground → Balloon → Space

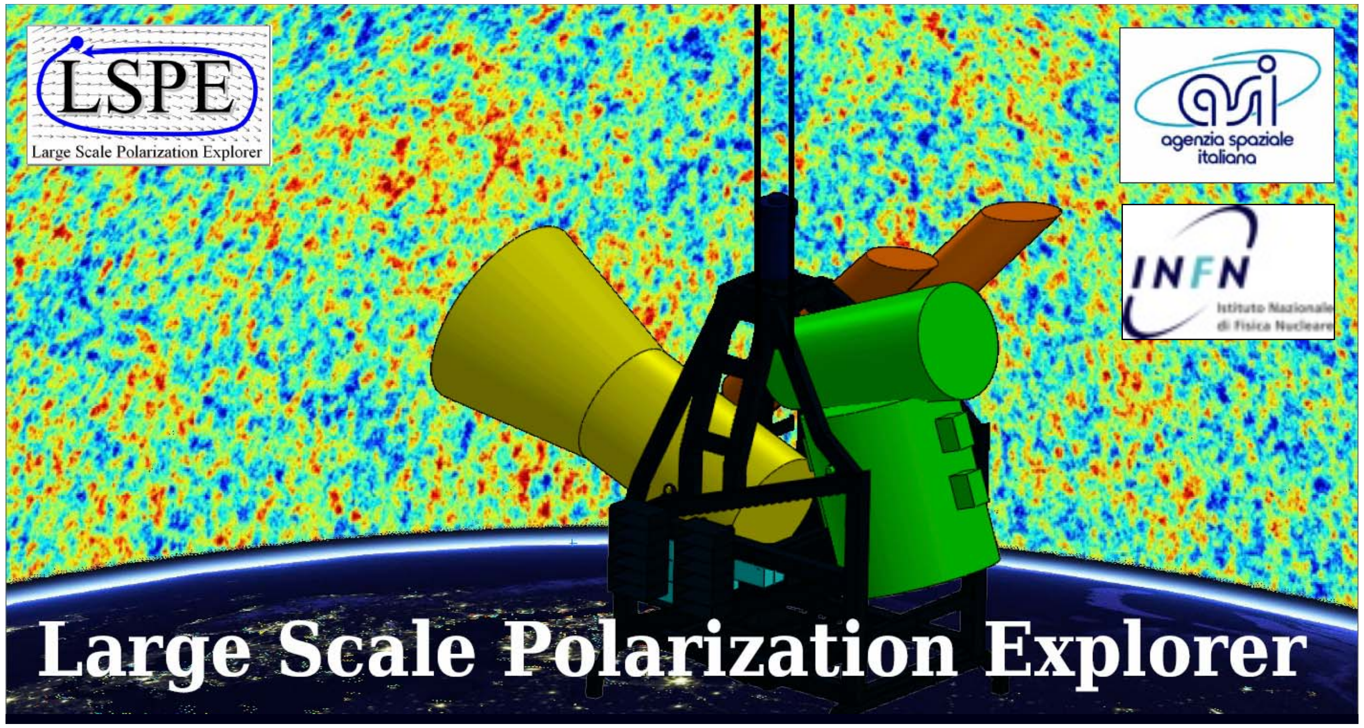
- 2009: $r < 0.7$ (BICEP) Chiang et al, 0906.1181

- 2013: Stage II experiments detect lensing B-modes
- 2014: $r \lesssim 0.1$ from Inflationary B-modes (BICEP 2) ?
- 2013-2016: Stage II experiments
  $\sigma(r) \sim 0.03$, $\sigma(N_{eff}) \sim 0.1$, $\sigma(\Sigma m_\nu) \sim 0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r) \sim 0.01$, $\sigma(N_{eff}) \sim 0.06$, $\sigma(\Sigma m_\nu) \sim 0.06$eV;

- 2020-2025: Stage IV experiment, **CMB-S4**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.020$, $\sigma(\Sigma m_\nu) = 16$ meV

The LSPE experiment

- The Large-Scale Polarization Explorer is a stratospheric balloon to validate some technical choices towards a space mission + physics results
- Balloon experiments can use the latest technology to be proved for space experiments
- All Italian technology
    - EBEX → SPIDER → LSPE
    - small → intermediate → large angular scale
- only a set of consistent detection obtained by completely independent instruments can be convincing



The LSPE collaboration

The LSPE collaboration: G. Amico[a], P. Battaglia[b], E. Battistelli[a], A. Baù[c], P. de Bernardis[a], M. Bersanelli[b], A. Boscaleri[d], F. Cavaliere[b], A. Coppolecchia[a], A. Cruciani[a], F. Cuttaia[e], A. D’ Addabbo[a], G. D'Alessandro[a], S. De Gregori[a], F. Del Torto[c], M. De Petris[a], L. Fiorineschi[f], C. Franceschet[b], E. Franceschi[f], M. Gervasi[c], D. Goldie[g], A. Gregorio[h,p], V. Haynes[i], N. Krachmalnicoff[c], L. Lamagna[a], B. Maffei[i], D. Maino[c], S. Masi[a], A. Mennella[c], Ng Ming Wah[i], G. Morgante[e], F. Nati[a], L. Pagano[a], A. Passerini[c], O. Peverini[l], F. Piacentini[a], L. Piccirillo[i], G. Pisano[i], S. Ricciardi[e], P. Rissone[f], G. Romeo[m], M. Salatino[a], M. Sandri[e], A.Schillaci[a], L. Stringhetti[n], A. Tartari[c], R. Tascone[l], L. Terenzi[e], M. Tomasi[n], E. Tommasi[o], F. Villa[e], G. Virone[l], S. Withington[g], A. Zacchei[p], M. Zannoni[c]

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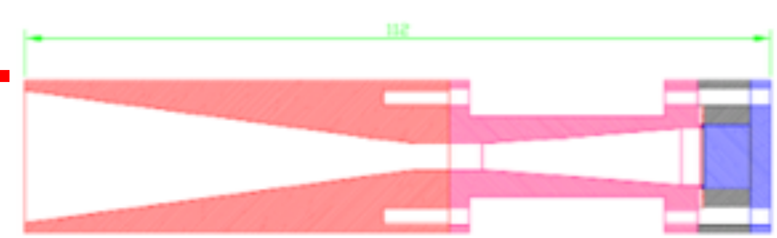
+ INFN Istituto Nazionale di Fisica Nucleare

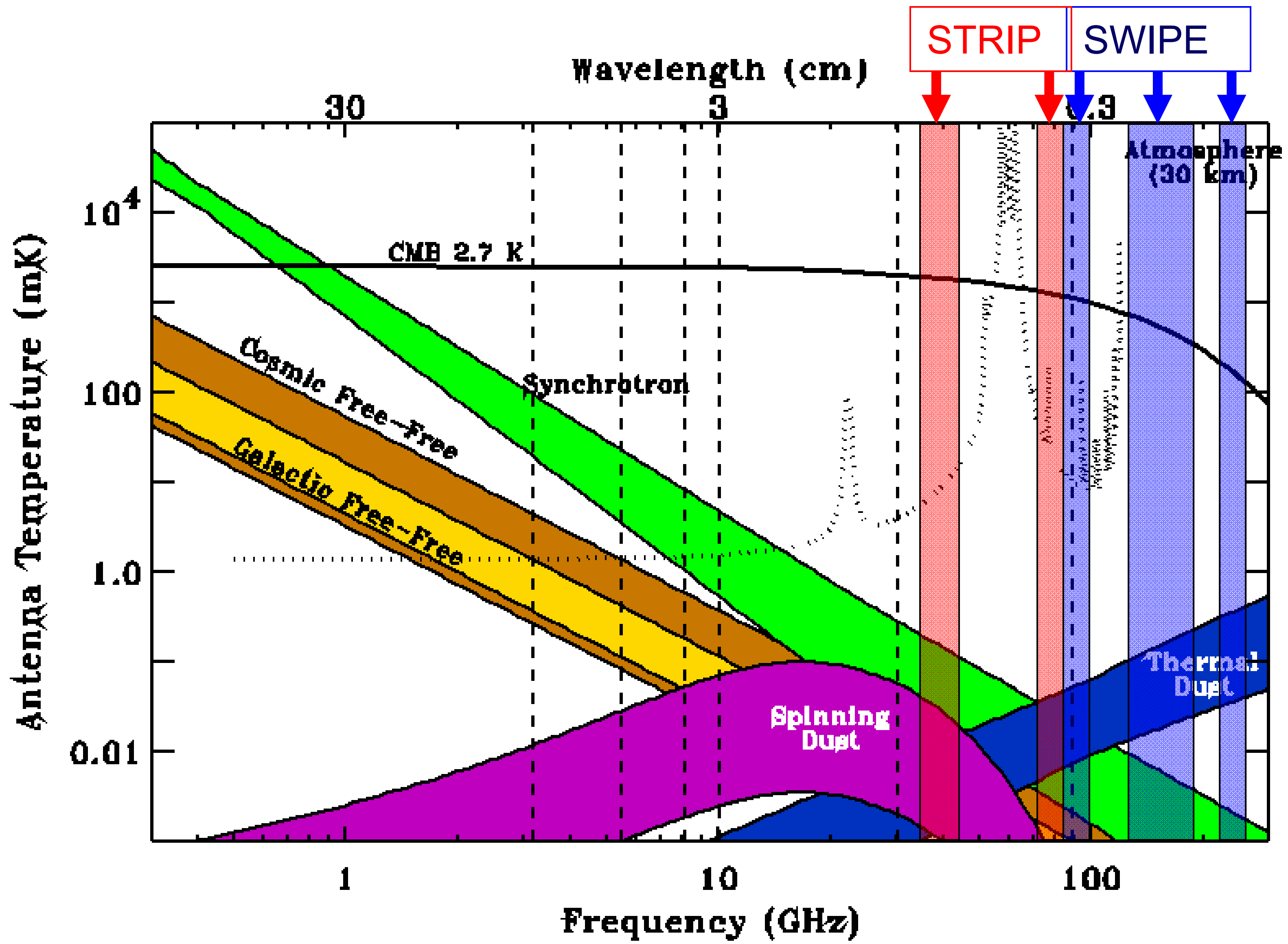
In a nutshell :

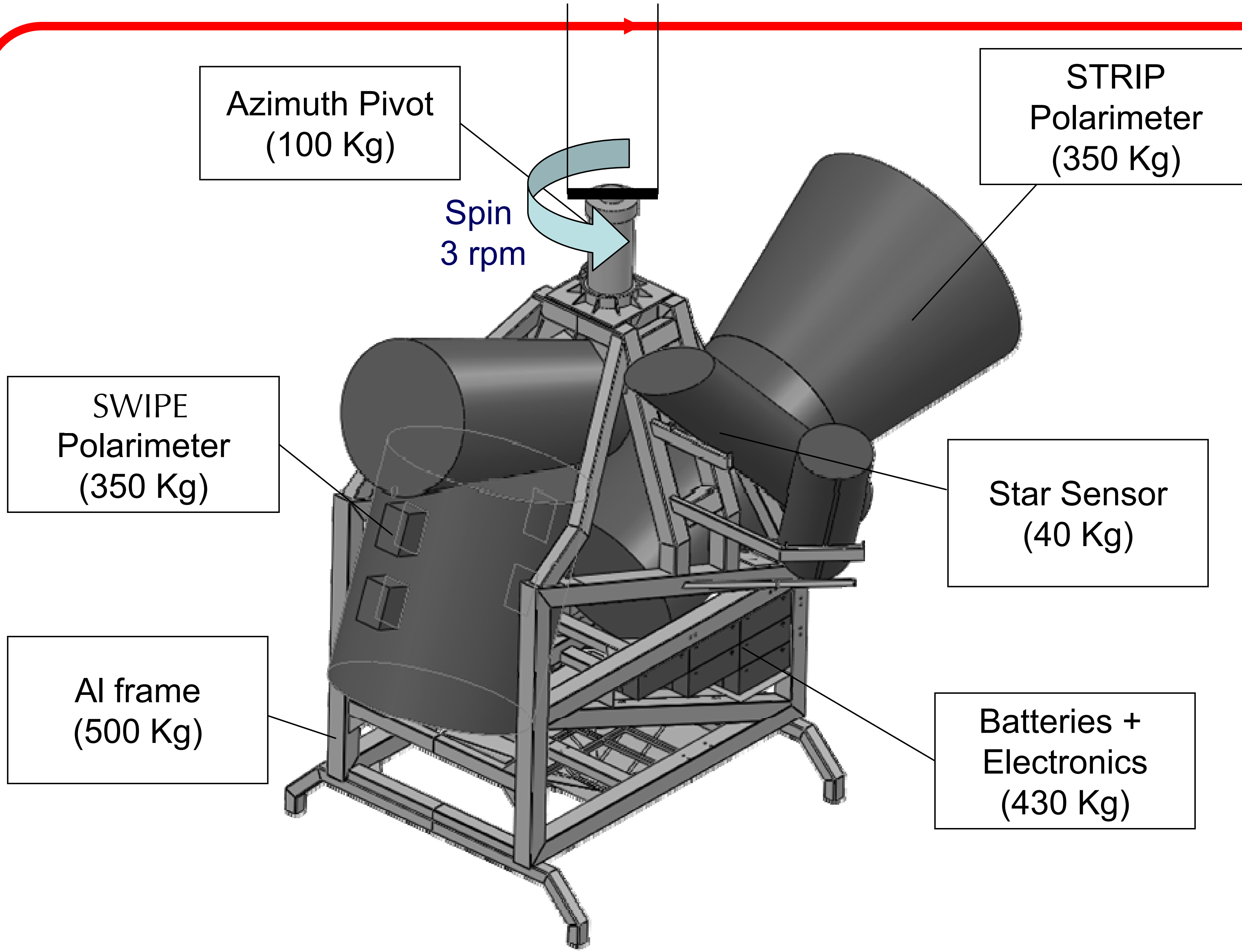
- The Large-Scale Polarization Explorer is
  - a spinning stratospheric balloon payload
  - flying long-duration, in the polar night
  - aiming at CMB polarization at large angular scales
  - using polarization modulators to achieve high stability
- Frequency coverage: 40 – 250 GHz (5 channels)
- Two instruments:
  SWIPE and **STRIP**
- Angular resolution: 1.5 – 2.3 deg FWHM
- Sky coverage: 20-25% of the sky per flight
- Combined sensitivity: 10 μK *arcmin* per flight

Instrument configuration

- Small signal at large angular scales requires :
  - **1.5° : Small telescope aperture sufficient (λ/D)**
  - **Wide frequency coverage (foregrounds) : two instruments**
  - **Large sky coverage (cosmic variance) : spinning payload – LDB night flight**
  - **Polarization modulator (to beat systematic effects) : HWP**
  - **Large mapping speed (to reach target survey senstivity) Two ways:**
    - **Traditional (EBEX, SPIDER …) : Large number of single-mode detectors**
    - **SWIPE-LSPE : Reasonable number of multi-moded detectors**



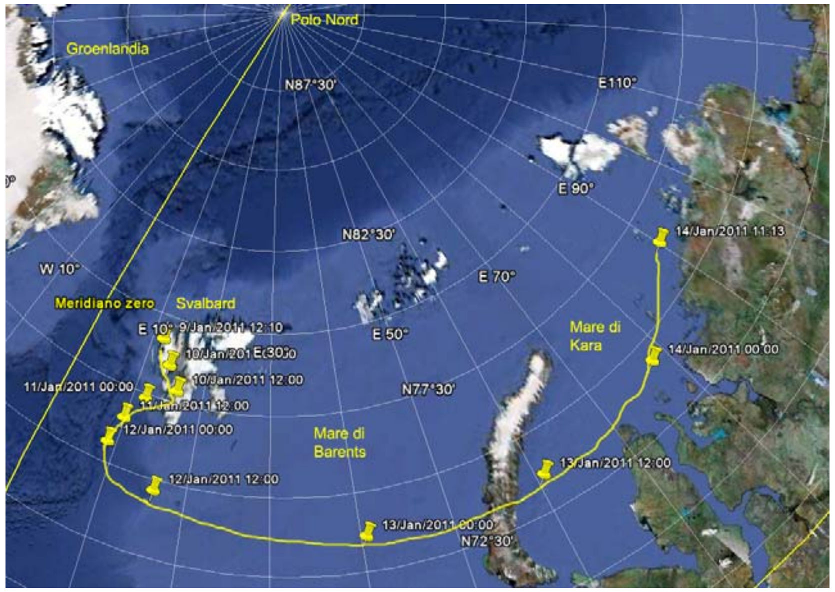

STRIP
SWIPE
Wavelength (cm)
30
3
0.3
Atmosphere (30 km)
10^4
100
1.0
0.01
CMB 2.7 K
Synchrotron
Cosmic Free-Free
Galactic Free-Free
Thermal Dust
Spinning Dust
Antenna Temperature (mK)
1
10
100
Frequency (GHz)

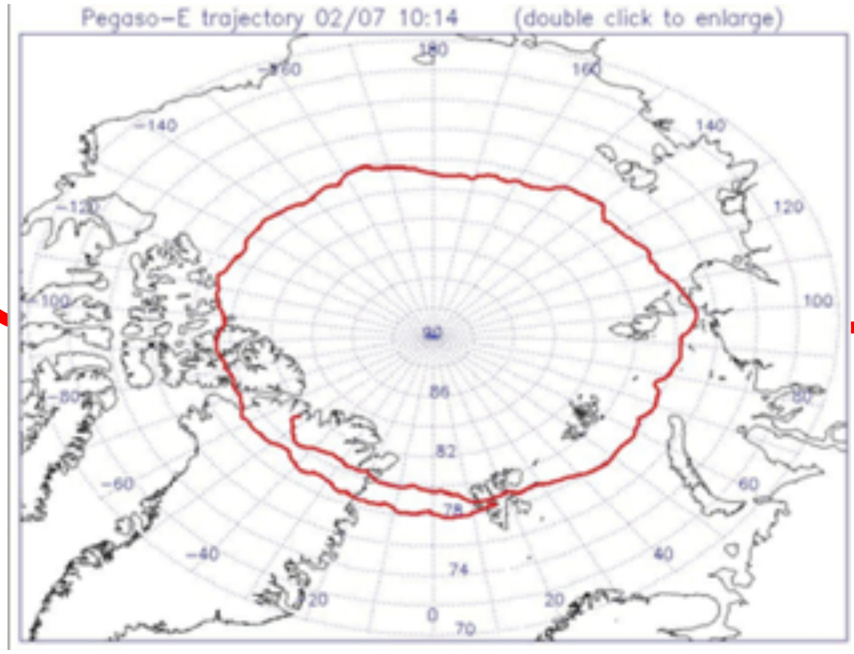


Sketch of the LSPE experiment. The height of the gondola for this configuration is about 4.5m.

The mission

- The experiment is flown (2015) as a stratospheric balloon payload during the polar night, in a long duration flight launched from Longyearbyen (Svalbard). See fig.3.
- In this way it can access most of the northern sky in a single flight,
  - without contamination from the sun in the sidelobes
  - within a cold and very stable environment
  - Accumulating more than 10 days of integration at float (38 km altitude).

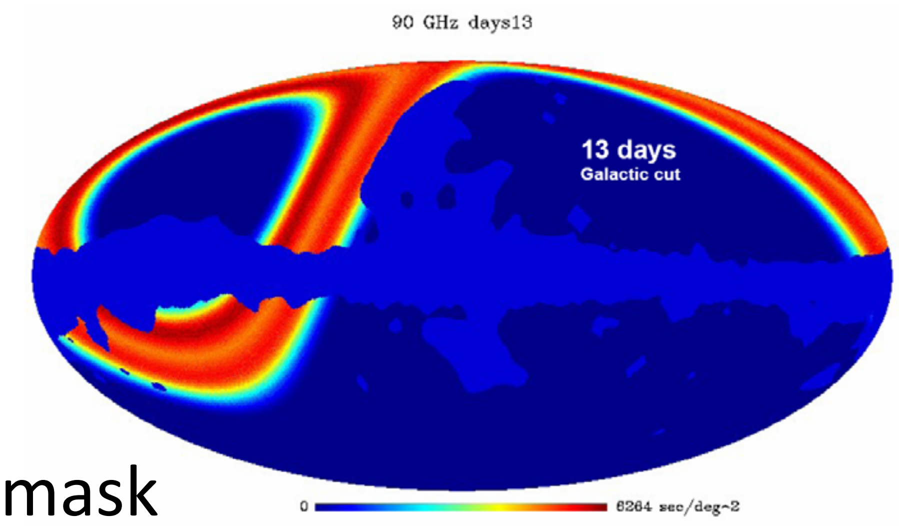


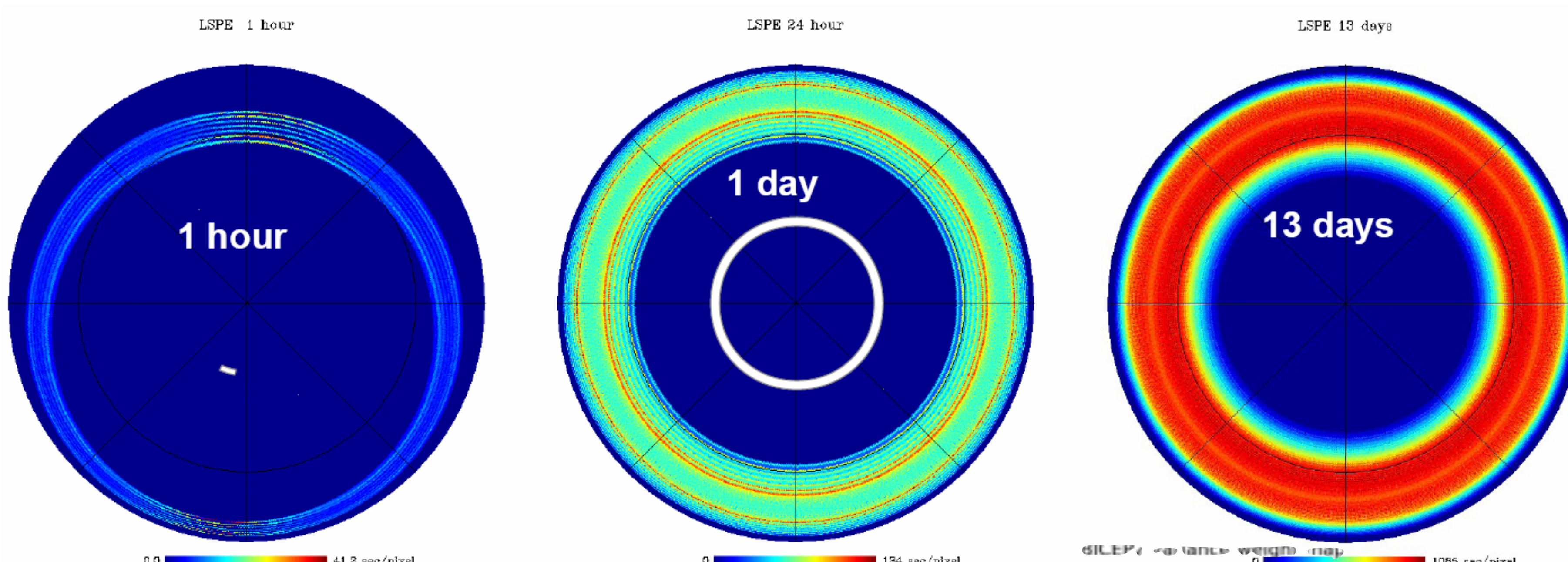


Specific technical problems for a winter polar flight:

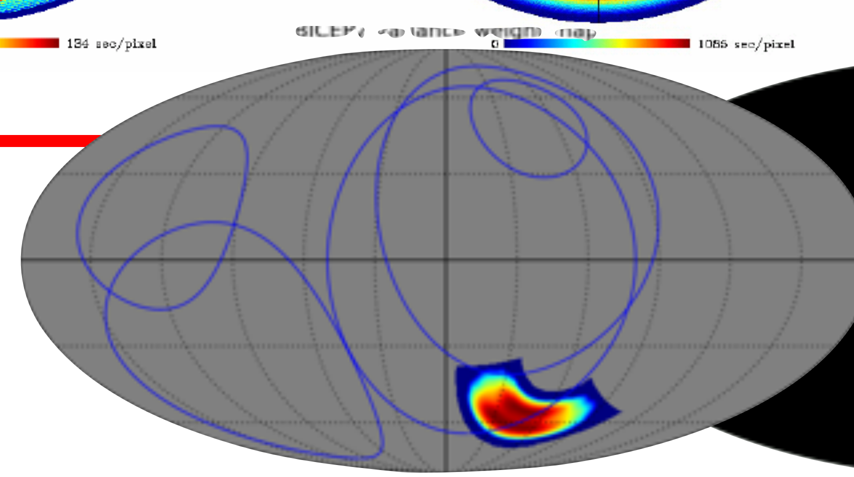
- Thermal management. The temperature of the stratosphere during the polar night is around -80^{o}C, and there is no solar radiation available to warm-up the payload.
  - Electronic systems must be thermally insulated from the environment to achieve self-heating conditions
  - Vacuum seals must be manufactured in indium or in special elastometers
  - Mechanical actuators play and lubrication must be specially designed for low temperature and low pressure
- Power supply for the experiment and the telemetry: 700 W for 15 days.
  - Electrical energy storage close to 1 GJ : lithium batteries
  - Located inside the same insulated box containing the powered electronics, to reach a temperature above 0^{o}C and maintain most of their nominal capacity.
- Data management: LSPE will produce a raw data rate of about 400kbps
  - Entirely stored on-board on solid state disks.
  - Selected data and essential housekeeping / flight info transmitted though the Iridium network
  - Line-of-sight telemetry at full rate available during the first day of the flight
  - Data-dumps when the system flies over selected locations hosting dedicated receiving stations.

- Spin rate : 3 rpm
- Latitude: +78° N
- Longitude : variable
- Elevation range : 30°-40°
- 23% of sky outside WMAP mask





BICEP2 coverage ~ SPIDER ⇒



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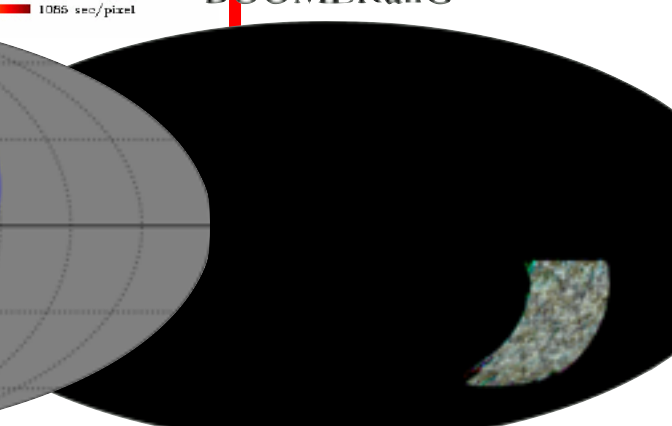
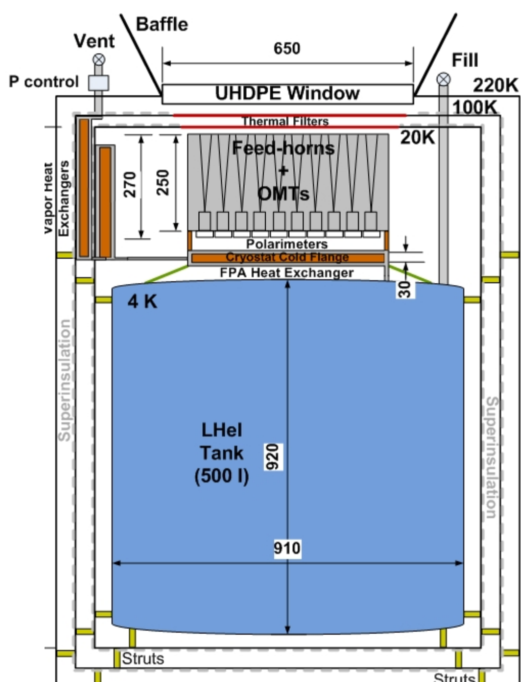


The STRIP Instrument

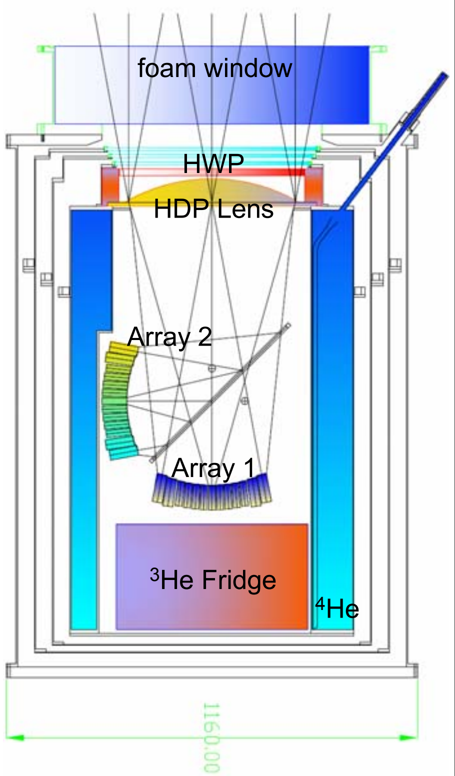
- An array of coherent polarimeters for accurate measurement of the low-frequency polarized emission, dominated by Galactic synchrotron.
- Its design is described in detail in a companion poster by Bersanelli et al.
- In the Table the performance of STRIP is compared to Planck-LFI.



	PLANCK LFI			STRIP	
Frequency (GHz)	30	44	70	**43**	**90**
Resolution (deg)	0.55	0.47	0.22	**1.0**	**0.5**
Sky coverage (%)	100	100	100	**18**	**18**
Obs Time (months)	30	30	30	**0.467**	**0.467**
Bandwidth (GHz)	4.5	4.1	12.0	**7.7**	**16.2**
N_horn	2	3	6	**49**	**7**
Tnoise (K)	11.3	17.0	33.2	**20**	**41**
Telesc. / window (K)		< 1		**7**	**8**
Tsky (antenna) (K)	2.068	1.804	1.382	**1.822**	**1.113**
1-s sensitivity ($\mu K \times s^{1/2}$)	147	173	153	**33**	**104**
Delta Q(U) per 1.5° pixel (micro-K)	3.27	3.95	3.77	**1.78**	**6.68**
	Improvement factor wrt Planck-LFI			**2.2**	**0.6**

The SWIPE Instrument

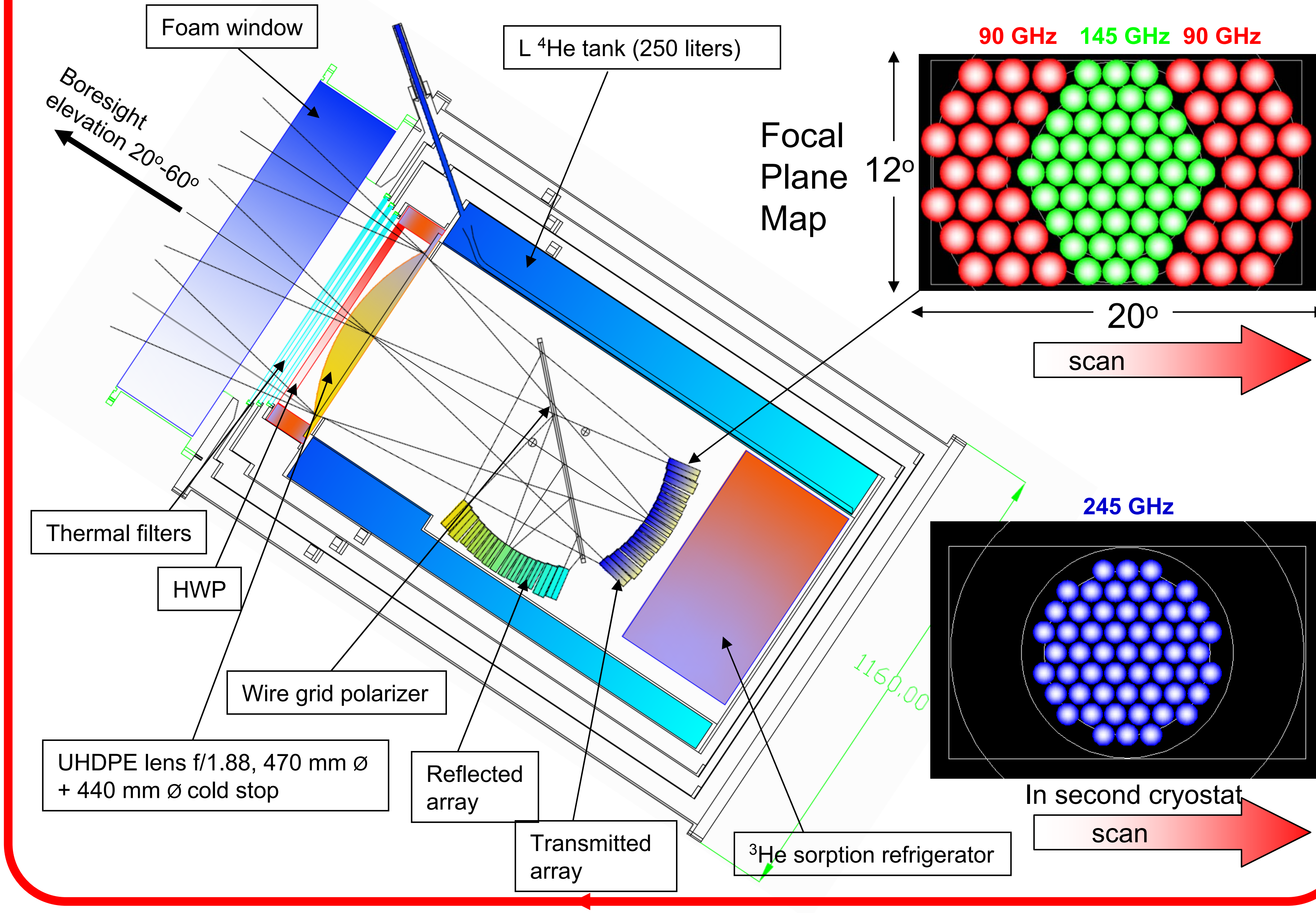
• An array of high-throughput bolometric polarimeters to measure accurately the linear polarization of the CMB and of the galactic dust foreground.
• Design described in detail in a companion poster by de Bernardis et al.
• In the Table the performance of SWIPE is compared to Planck-HFI.



	PLANCK – HFI						SWIPE		
Frequency (GHz)	100	143	217	353	545	857	95	145	245
FWHM Resolution (arcmin)	9	7	6	5	5	5	110	89	74
Sky coverage (%)	100	100	100	100	100	100	20	20	20
Obs Time (months)	30	30	30	30	30	30	0.467	0.467	0.467
Bandwidth (%)	33	33	33	33	33	33	25	25	25
N_det (polarized)	8	8	8	8	0	0	80	86	110
Channel NET (uK s^1/2)	25	31	45	140	//	//	1.9	1.8	1.9
Integration/beam (s)	33	20	15	10	-	-	660	415	225
Delta Q(U) (uK) on SWIPE beams	0.3	0.4	0.8	2.6	-	-	**0.10**	**0.13**	**0.17**
	Improvement factor wrt Planck-HFI						**2.7**	**3.2**	**4.9**

• Short Wavelength Instrument for the Polarization Explorer

Instrument Sketch



High mapping speed

- **Two ways:**
  - **Traditional (EBEX, SPIDER ...) : Large number of single-mode detectors**
  - **SWIPE-LSPE : Reasonable number of multi-moded detectors**

$$N_m \approx \frac{A\Omega}{\lambda^2} \qquad \begin{matrix} W \propto N_m \\ NET \propto \sqrt{N_m} \end{matrix} \Rightarrow S/N \propto \sqrt{N_m}$$

$$\theta \propto \sqrt{N_m}$$

- **Example: N_m = 25 modes. With respect to a single mode detector:**
  - **Increase by a factor 5 the SNR.**
  - **70 uK sqrt(s) -> 12 uK sqrt(s) per detector**
  - **Decrease by a factor 5 the angular resolution**
  - **15’ FWHM becomes 1.3° FWHM**

Light collectors and detectors

- Baseline detectors: spider-web bolometers with Transition Edge Sensors (TESs) thermistors:
  - extreme electro-thermal feedback, reasonable time constants, despite of the large absorber area necessary to couple to a multi-mode beam.
  - Rejection of primary cosmic rays present in the stratosphere and potentially very dangerous for CMB measurements.
- Baseline light collector: parabolic Winston horns
  - very high coupling efficiency in the main beam
  - high suppression of stray radiation, through the incoherent superposition of the propagated modes at large angles.
  - HFSS + custom-developed polarized far field calculation code: results in Fig. 5
  - Beam ellipticity is very small, a highly desirable feature for this instrument, and will be mitigated even more coupling the horn to the telescope and its Lyot-stop.
  - SWIPE will feature 80 horns at 95 GHz (each coupled to 23 modes), 86 horns at 145 GHz (35 modes), 110 horns at 245 GHz (64 modes). This setup will provide a performance comparable to that of competing instruments based on thousands of single-mode detectors.

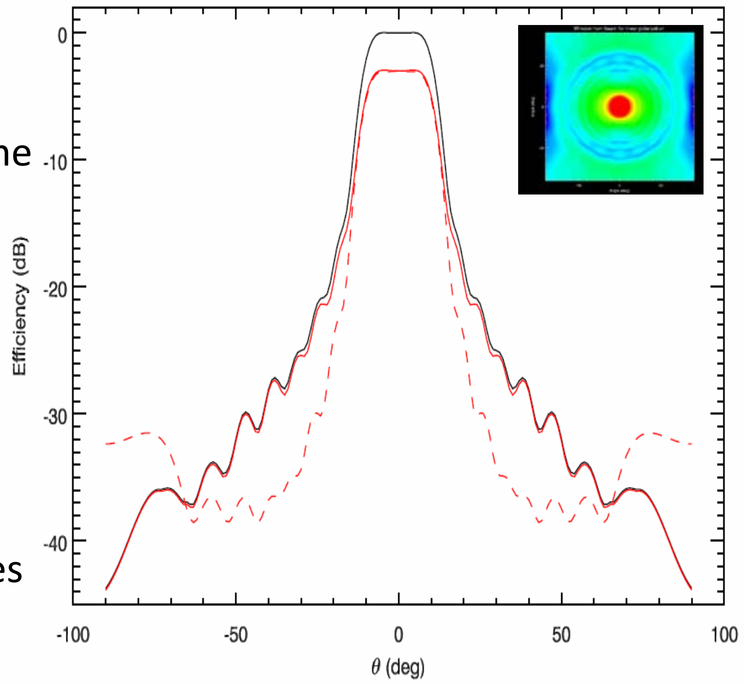
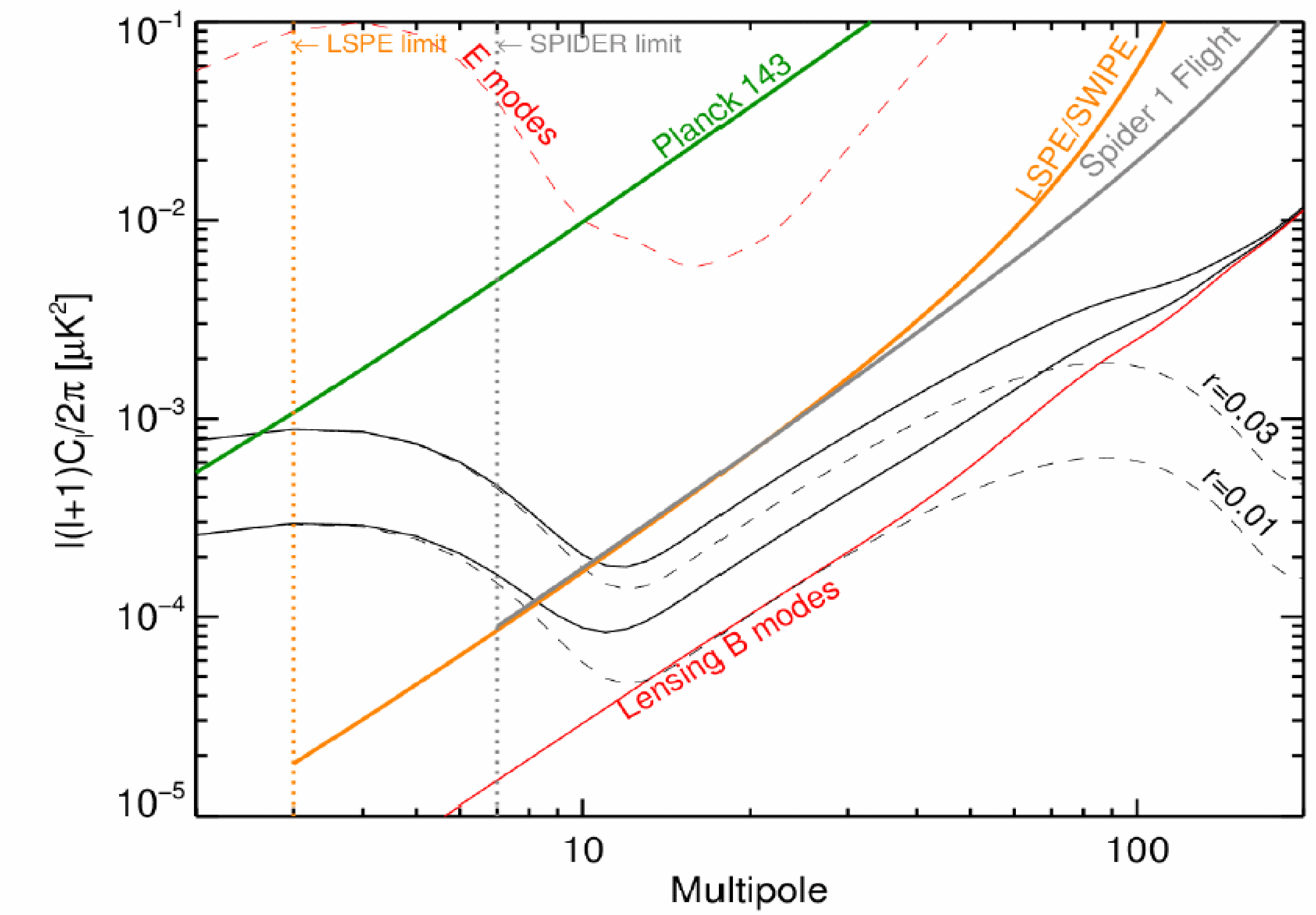
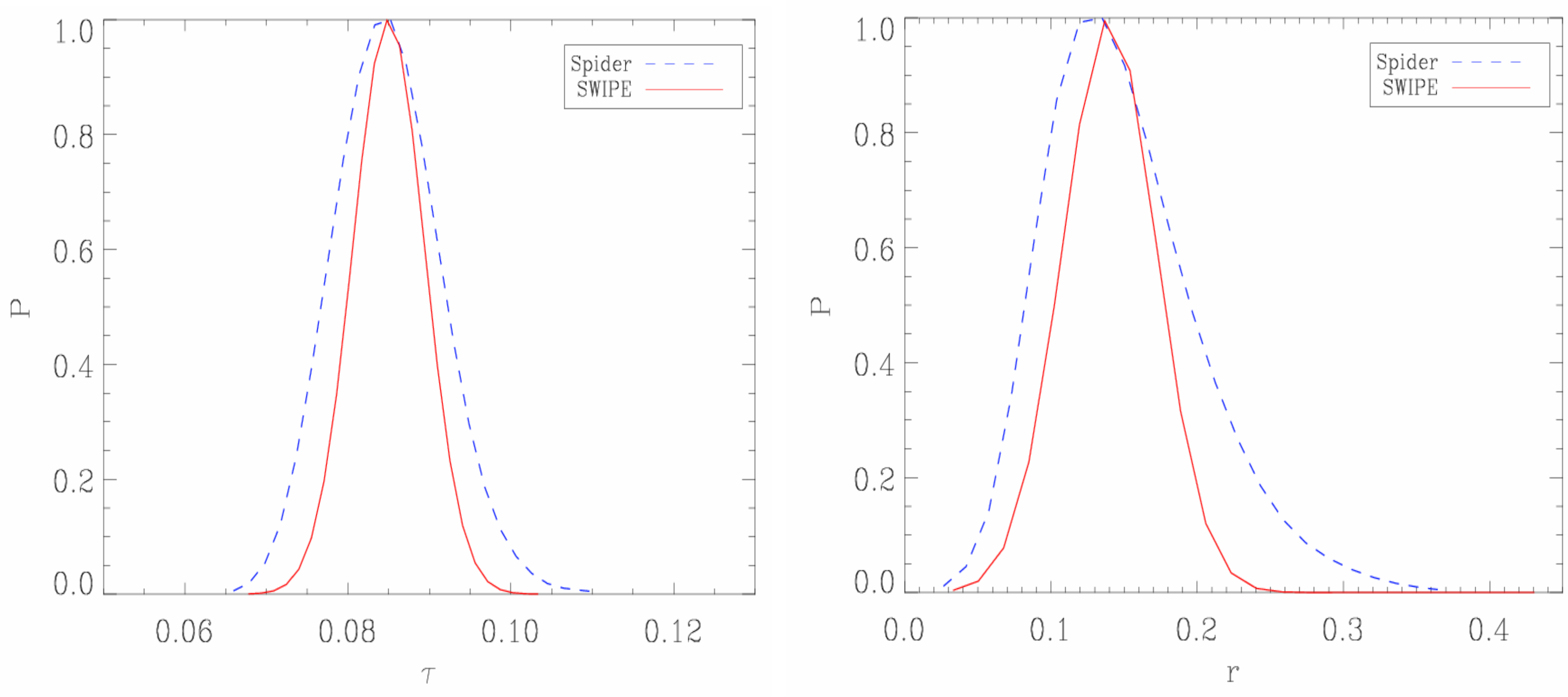


Figure 5. Far field calculation of the angular efficiency of a SWIPE Winston horn coupling 17 modes at 145GHz. The lower solid and dashed lines represent two orthogonal cross-sections for linearly polarized photons. For reference, the solid top line is the beam for unpolarized radiation. In the inset, 2D map of the same beam.

Constraining Cosmological Parameters



Constraining Cosmological Parameters



Left: Likelihood for the optical depth to reionization as estimated from Spider[3] (dashed line) and SWIPE (continuous line). **Right:** Same for the tensor to scalar ratio.
The two experiments have similar expected performance, but quite different measurement techniques.
The estimates have been obtained using the publicly available Markov Chain Monte Carlo package cosmomc as usual in this field. This is based on the direct evaluation of the likelihood in the pixel space, without any power spectrum estimation step, assuming the CMB sky to be gaussian distributed.

Conclusions and Acknowledgments

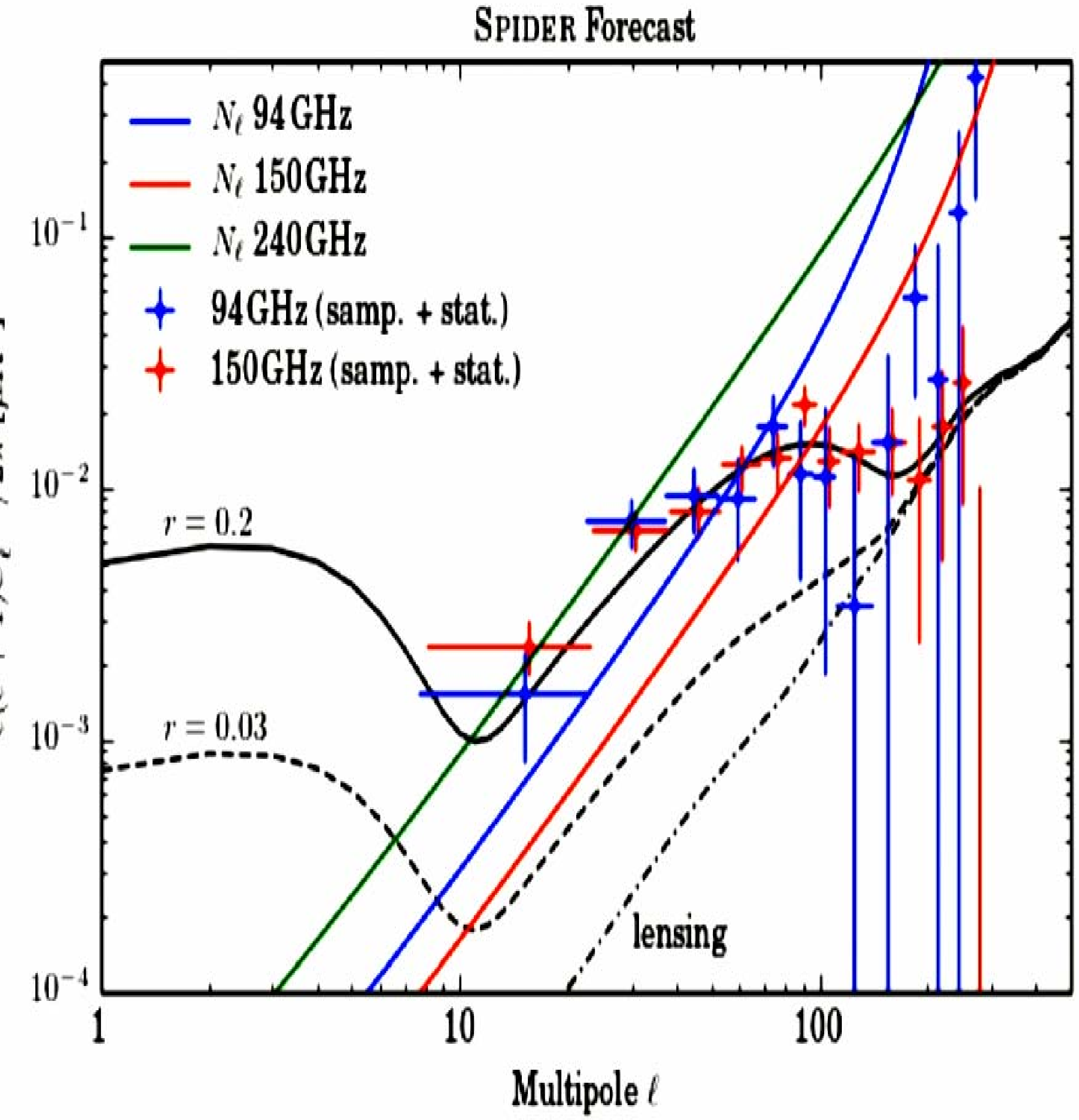
- LSPE is exploring large scales, where Planck detected “anomalies”
- Night time polar balloon flight
- Designed for polarization purity
- Deep measure of polarized foreground
- Two ~90 GHz channels with different technologies (HEMT, bolometers) for crosscheck of systematic effects
- Low frequency channel for control of synchrotron polarized foregrounds
- Technology development for next generation space mission
- The **r**=0.03 at 99.7 confidence level is achievable
- Upper limit at **r**=0.01
- Nominal timescale: launch on Winter 2014/15

LSPE
Large Scale Polarization Explorer

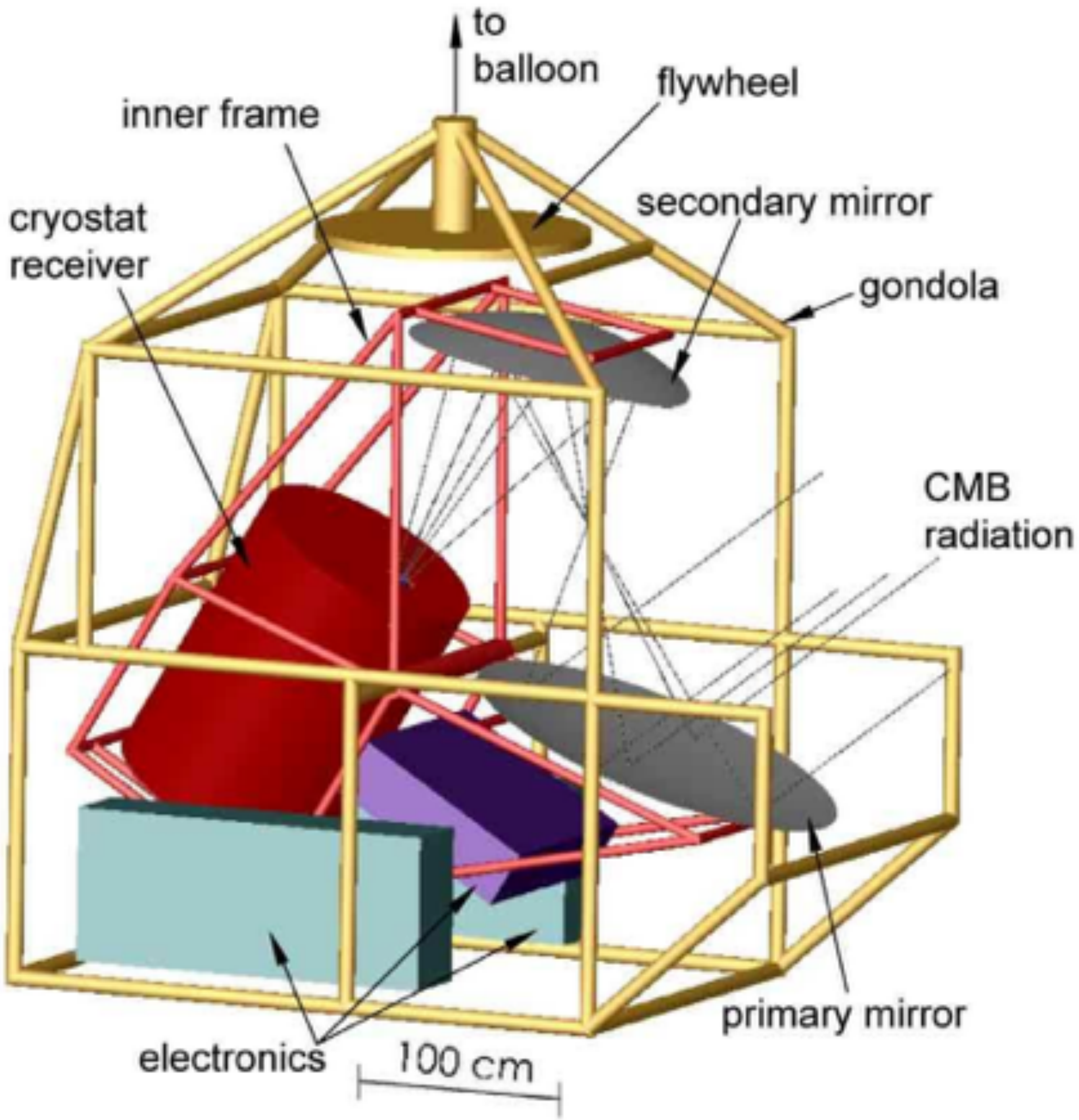
We gratefully acknowledge support from the Italian Space Agency through contract I-022-11-0 “LSPE”

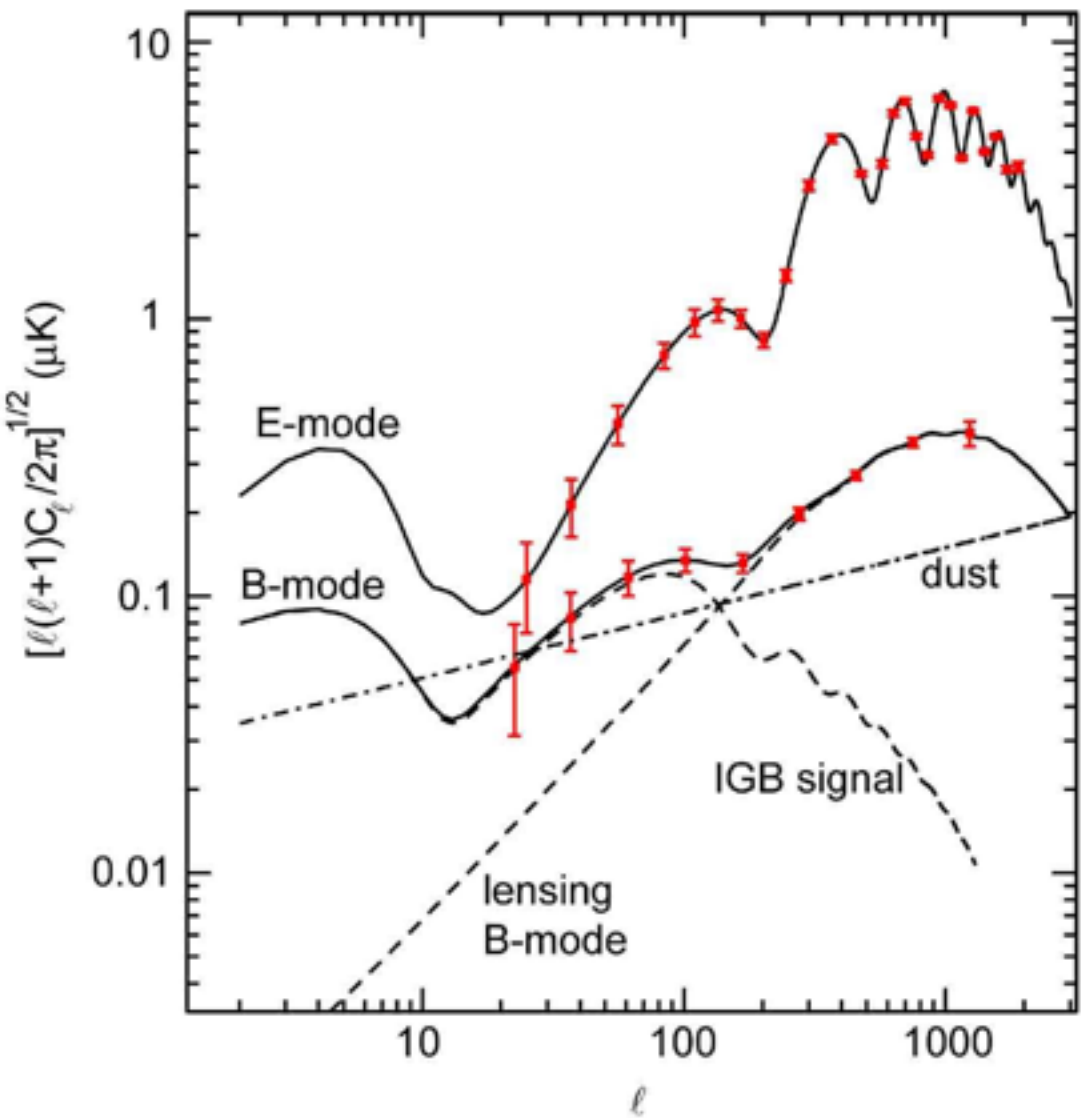
asi
agenzia spaziale italiana

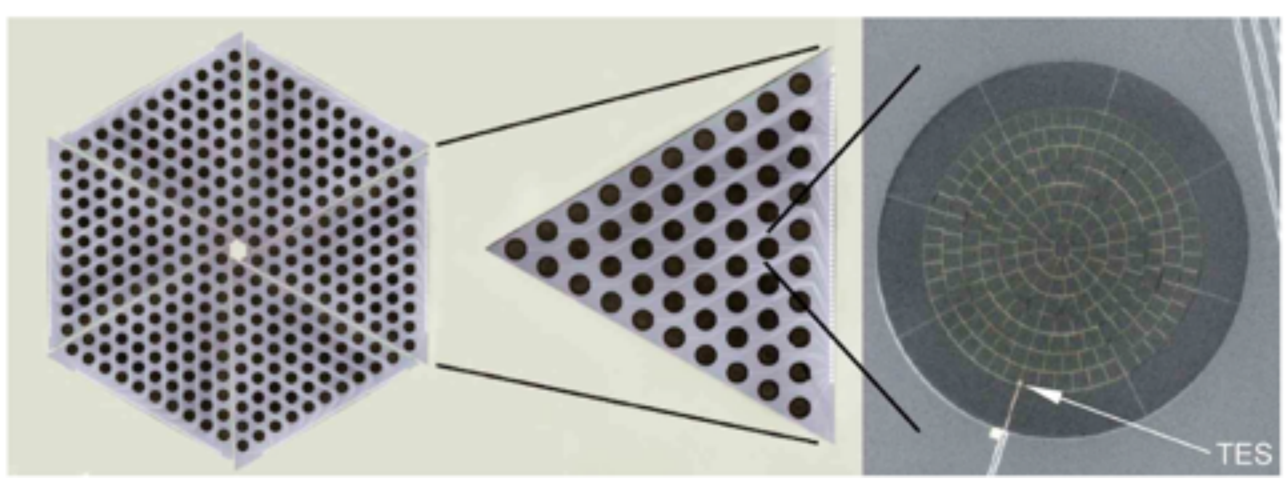
SPIDER


SPIDER Forecast
N_ℓ 94GHz
N_ℓ 150GHz
N_ℓ 240GHz
94GHz (samp. + stat.)
150GHz (samp. + stat.)
$r = 0.2$
$r = 0.03$
lensing
$\ell(\ell+1)C_\ell^{BB}/2\pi$ [μK^2]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
100
Multipole ℓ

EBEX


to
balloon
flywheel
inner frame
secondary mirror
cryostat
receiver
gondola
CMB
radiation
electronics
100 cm
primary mirror

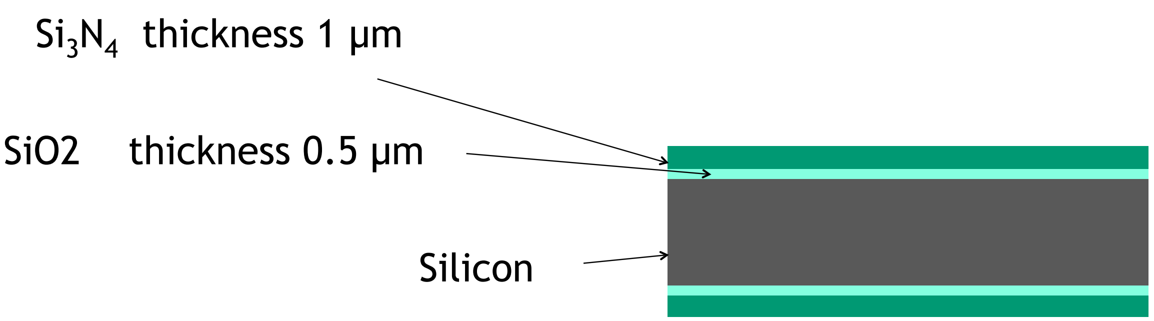

$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ (μK)
10
1
0.1
0.01
E-mode
B-mode
dust
IGB signal
lensing
B-mode
10
100
1000
ℓ


TES

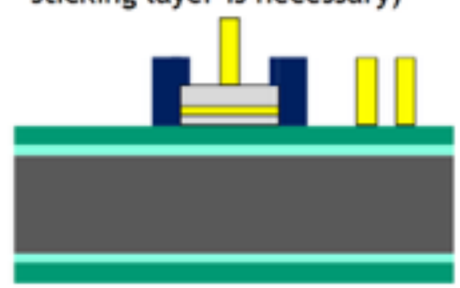
Instrument

- At INFN Genova the first "all Italian" spiderweb bolometer was realized (F. Gatti et al.)
- TiAu TES technology
- World's largest multimode detector
- Multimode detection demonstrated, noise measurements in progress

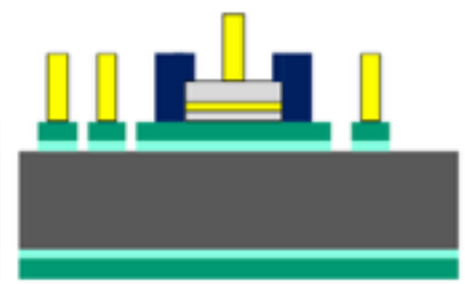
0 - starting from silicon wafer covered with SiO_2 and Si_3N_4



4 - Gold absorber deposition with lift-off process (a Ti sticking layer is necessary)



5 - RIE etching after positive photolithography

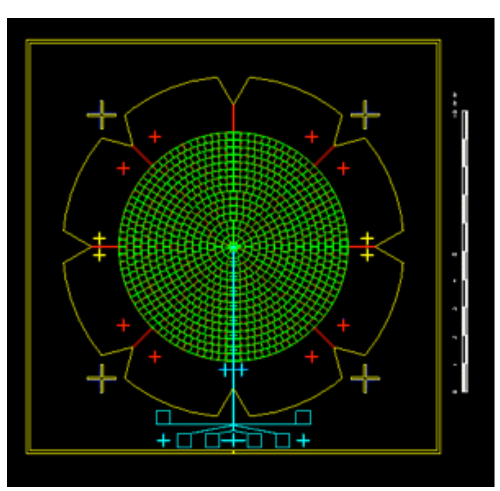


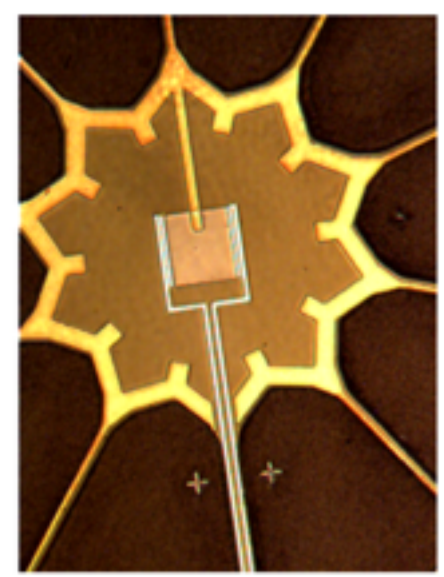
Lithographic masks assembled:

Chip dimension 15 x 15 mm

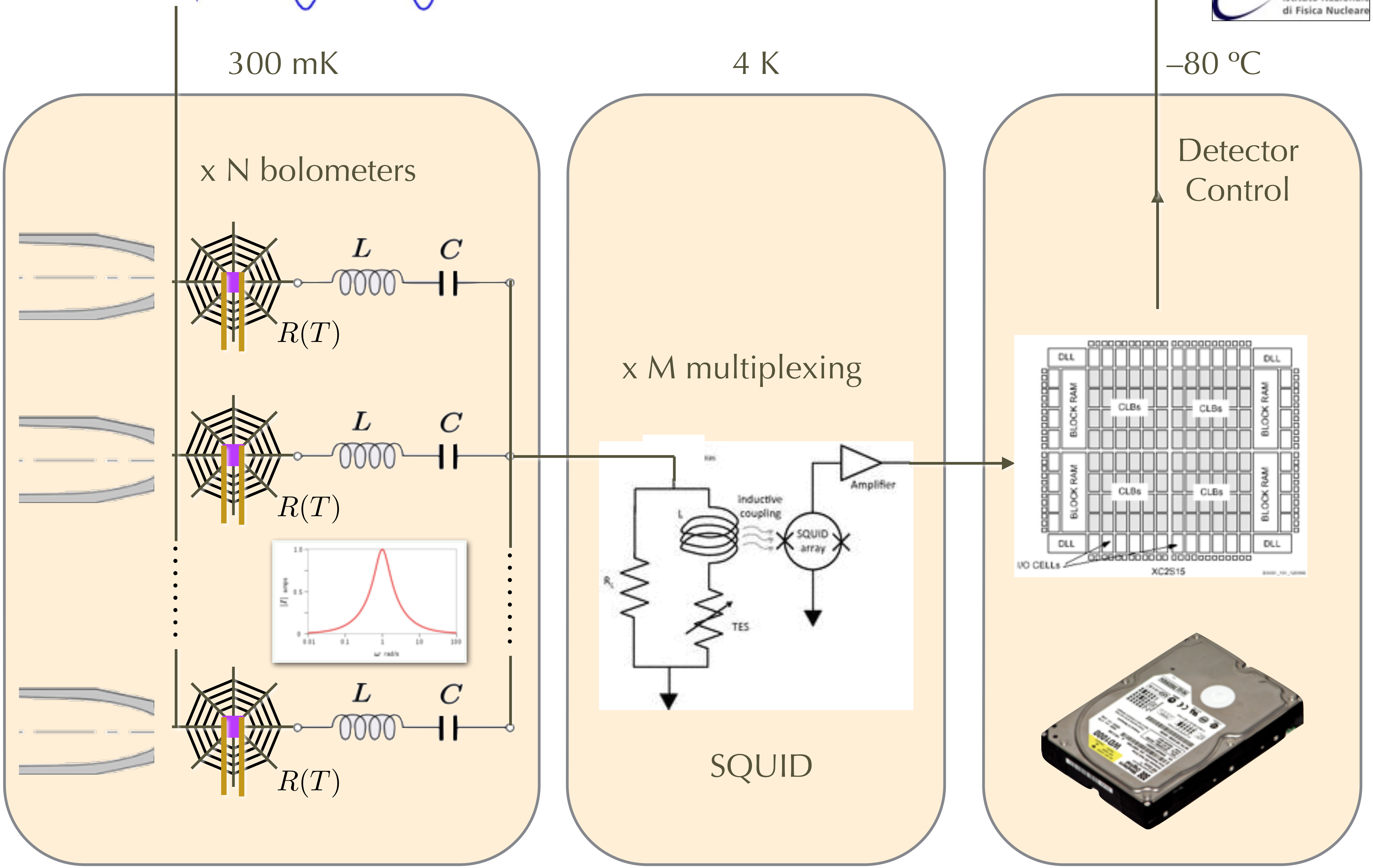
Absorber diameter 8 mm

Spiderweb mesh size 250 μm





Il "rivelatore"



Le Sezioni INFN Partecipanti

- Rivelatore complesso e che necessita di integrazione "fine"
  - ⇒ Divisione "fluida" ⇒ Singola responsabilità ma collaborazione su tutti gli items

- Roma I (P. de Bernardis, R.Naz.)
  - Accoppiamento ottico e test ottico sensori bolometrici
- Genova (F. Gatti)
  - Costruzione e test elettrico sensori bolometrici
- Pisa (G. Signorelli)
  - Costruzione e collaudo elettronica di lettura sensori bolometrici → data flow
  - Facility di test criogenica
  - Esperienza in sezione
    - Spazializzazione
    - Criogenia
- Roma Tor Vergata (E. Coccia)
  - Elettronica Criogenica, infrastruttura integrazione navicella

- Tutti: Simulazioni, analisi dei dati e loro sfruttamento scientifico

Strict time schedule

- R&D ambizioso
  - validazione della tecnologia multimodo con sensori Italiani e controllo/lettura sviluppato in Italia
  - Durata nominale 2015–2018
  - Volo su pallone previsto nell'inverno boreale 2015/2016
- Alta probabilità di avere dati di fisica a breve termine

Attività previste per il 2015

- Inizio dell'attività il prima possibile (2014)
- Progettazione e realizzazione dell'elettronica analogica/digitale di controllo, lettura dei ~100 bolometri
  - 3 mbar, –80 ºC. Progetto termico della meccanica
  - Progettazione-realizzazione dei risuonatori LC
  - Test dei rivelatori criogenici
- In stretta collaborazione con le sezioni di Roma e Genova

Anagrafica per il 2015

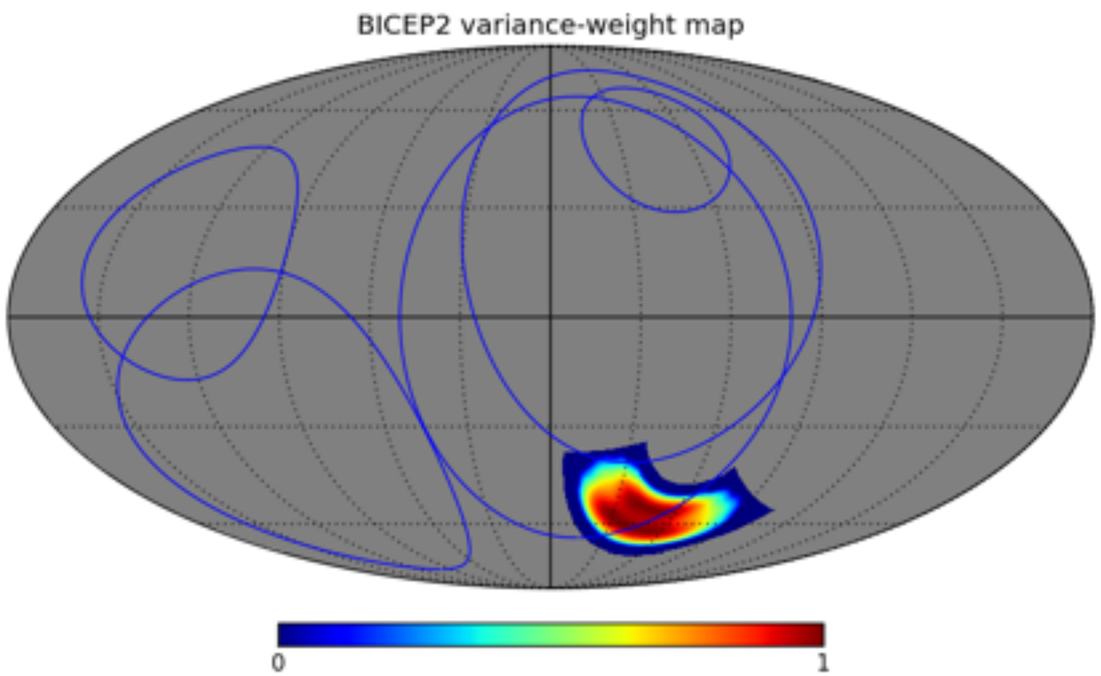
Giovanni Signorelli	Ric. INFN	R.Loc.	0.7
Alessandro Baldini	Dir. Ric.		0.3
Marco Grassi	Dir. Ric.		0.3
Donato Nicolò	Ric. Univ.		0.3
Fabrizio Cei	Ric. Univ.		0.3
Carlo Bemporad	P.O. (Ass. Sen.)		0
Marco Incagli	P. Ric. INFN		0.3
Franco Spinella	Tecnologo		0.25
TOTALE		FTE	2.45
+ interesse da parte	del gruppo teorico		

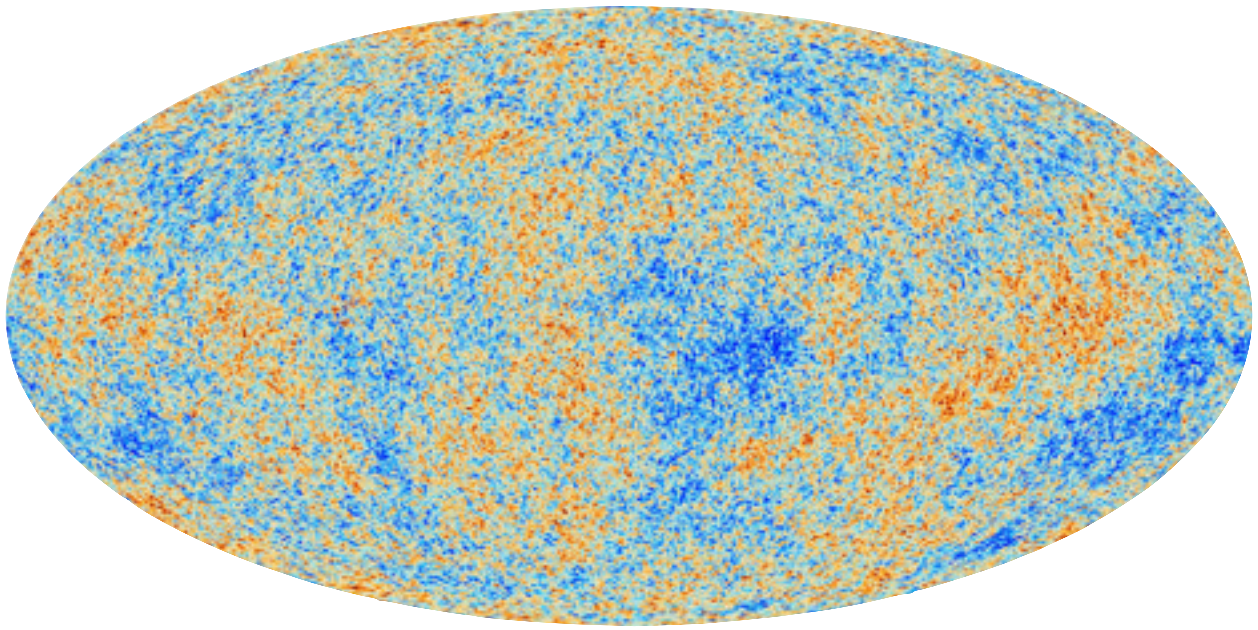
Conclusione

- Ingresso dell'INFN nella fisica della CMB
  - grossissima competizione internazionale
  - tecnologie di punta Italiane
- Competenze complementari a quelle della comunità esistente
- Possibilità di "fare fisica" in un breve lasso di tempo
- Per la sezione
  - Up-to-date nella spazializzazione
  - Estendere la criogenia in Sezione fino al K e sotto

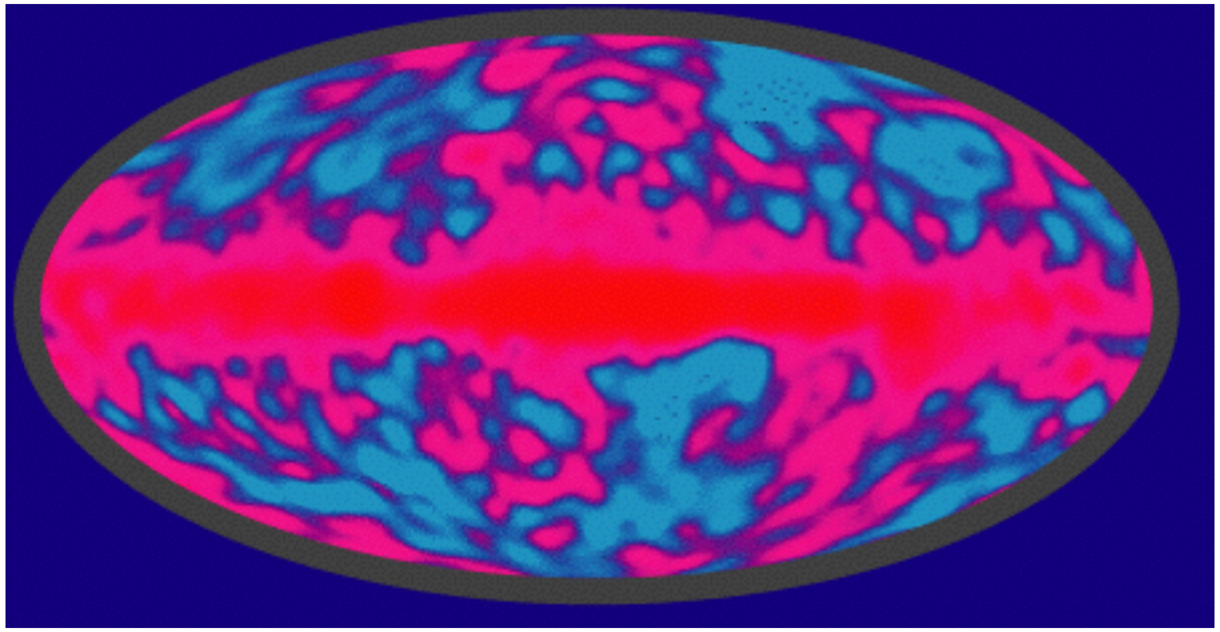
- Richieste per il 2015:
  - O(90÷100 k€)
    - 50k€ elettronica
    - 15k€ termalizzazione
    - 15÷25 k€ test criogenici
    - 10k€ missioni
  - Set-up laboratorio criogenico al mK

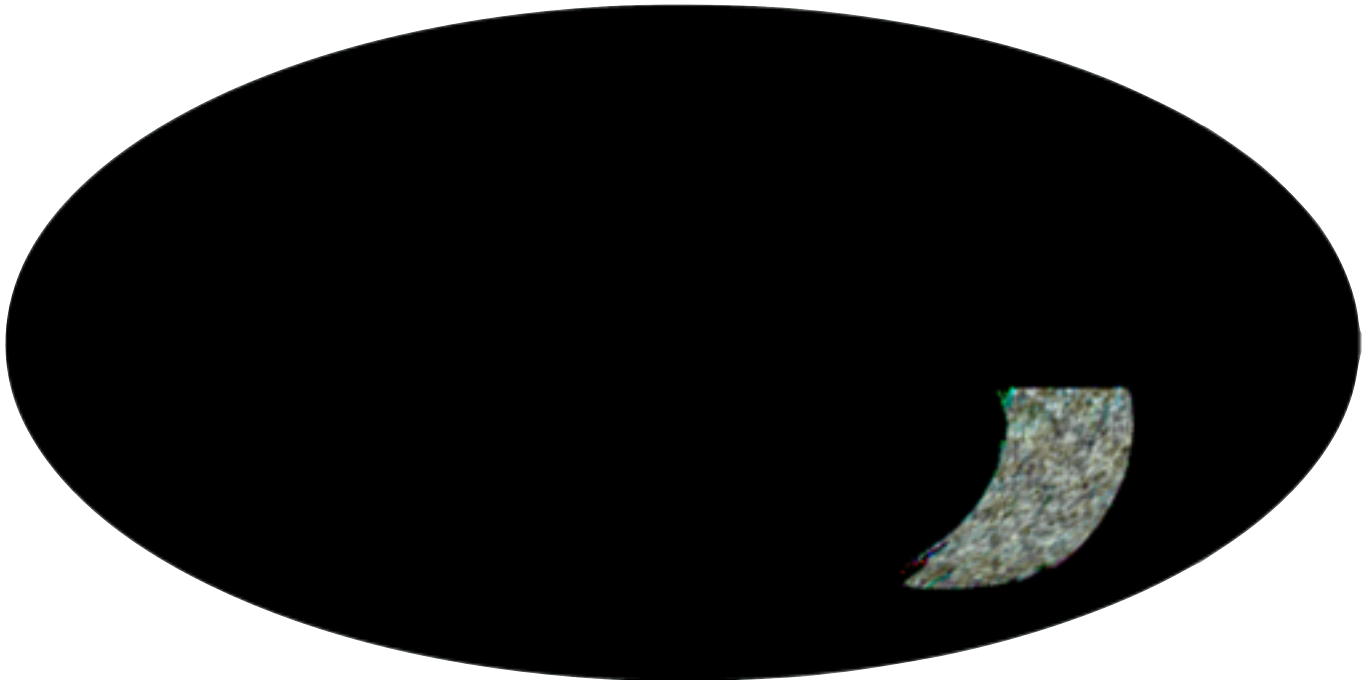
FINE





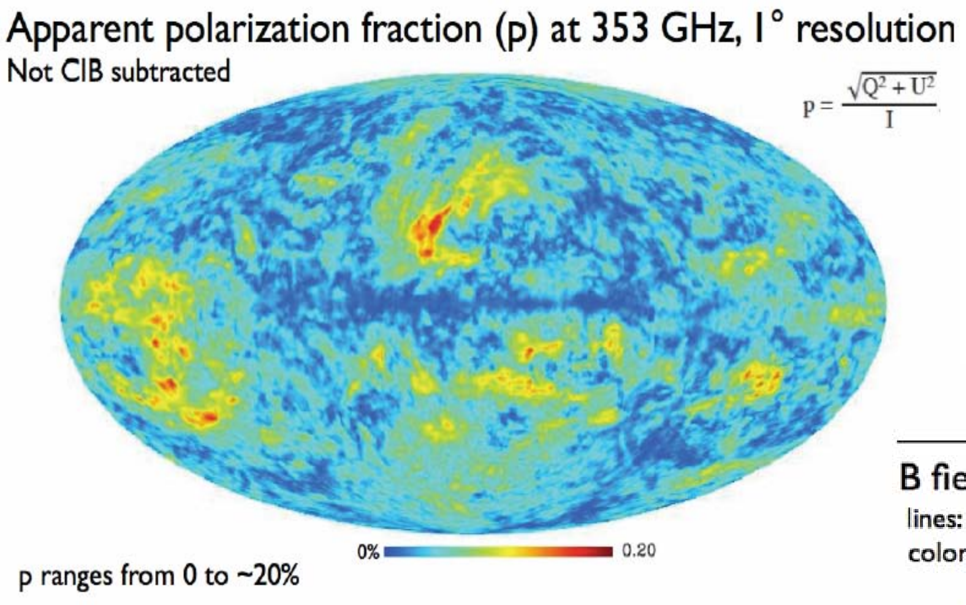
BOOMERanG

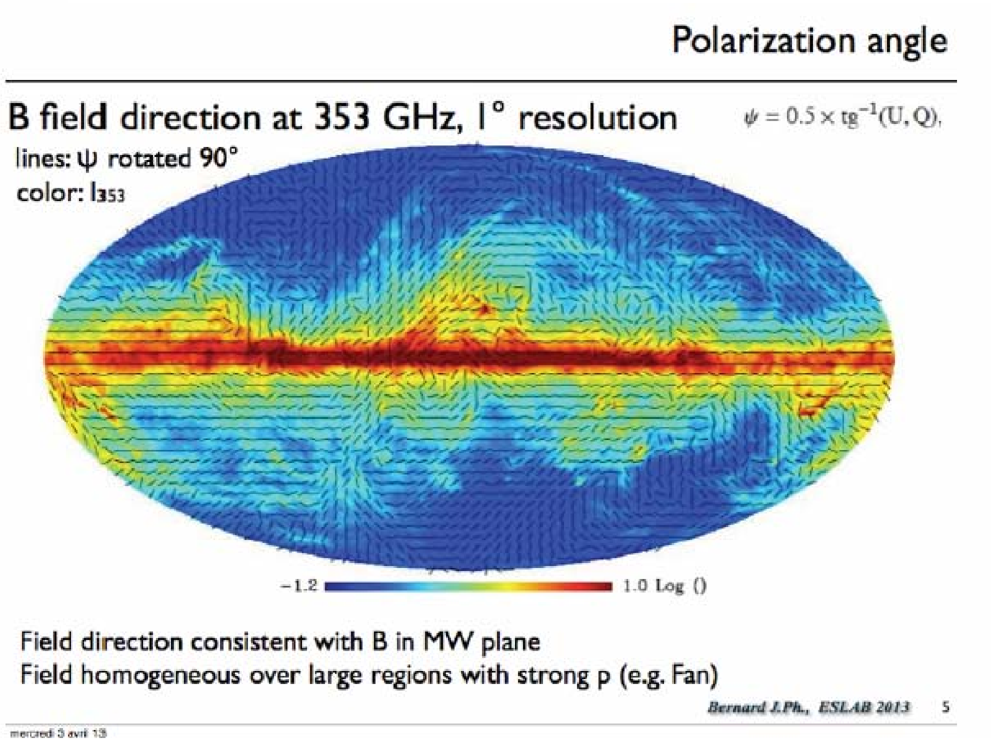




Interstellar dust polarization

- Only information available from Planck at the moment: two maps shown at a conference (ESLAB 2013, J.P.Bernard talk)

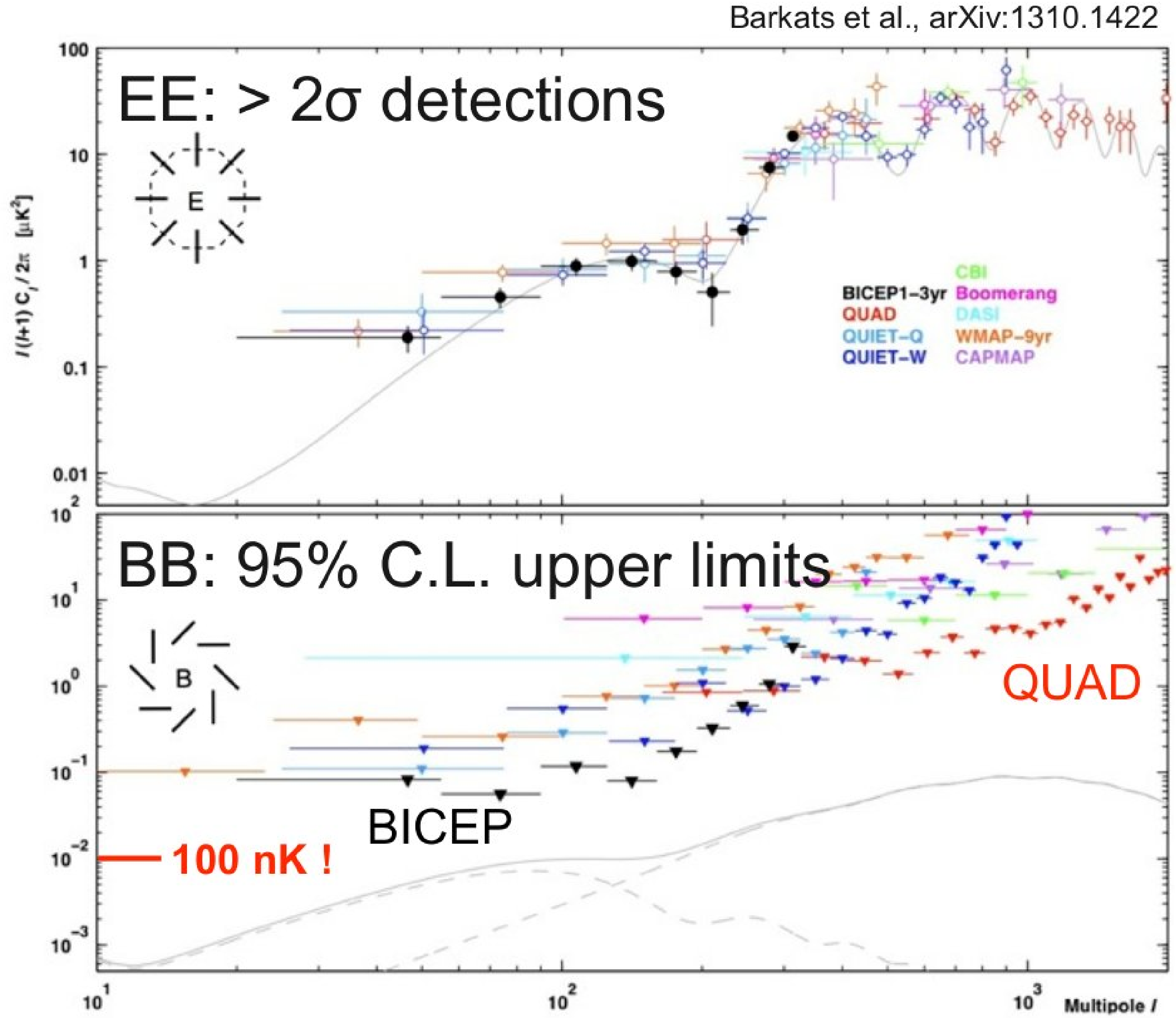


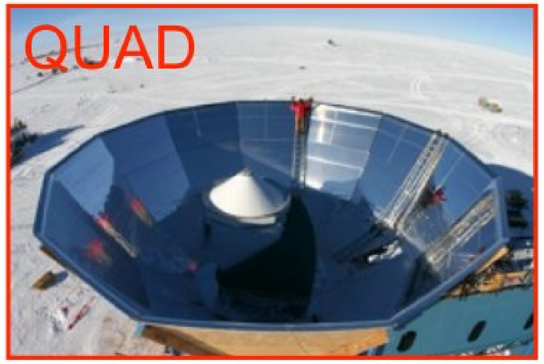


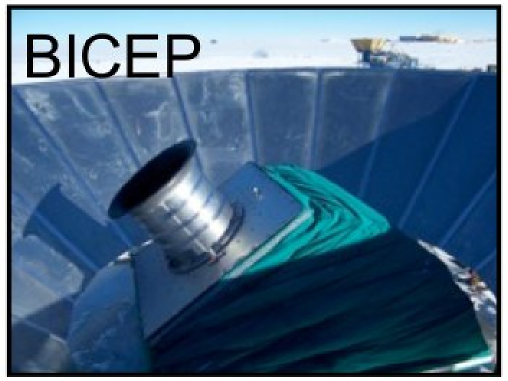
CMB Observables

- **Specific Brightness** : a 2.725K blackbody, well measured
- **Anisotropy** : 100 μK *rms*, precise power spectrum forecasts, very well measured
- **E-mode polarization** : 3 μK *rms*, precise power spectrum forecasts, well measured
- **B-mode polarization** : < 500 nK *rms*, depends on lensing of E-modes (detected) **and on the inflation process and the background of primordial gravitational waves** (one detection claimed)
- **Note:** For a robust detection of B-modes, independent measurements and precise measurements of polarized foregrounds are mandatory.

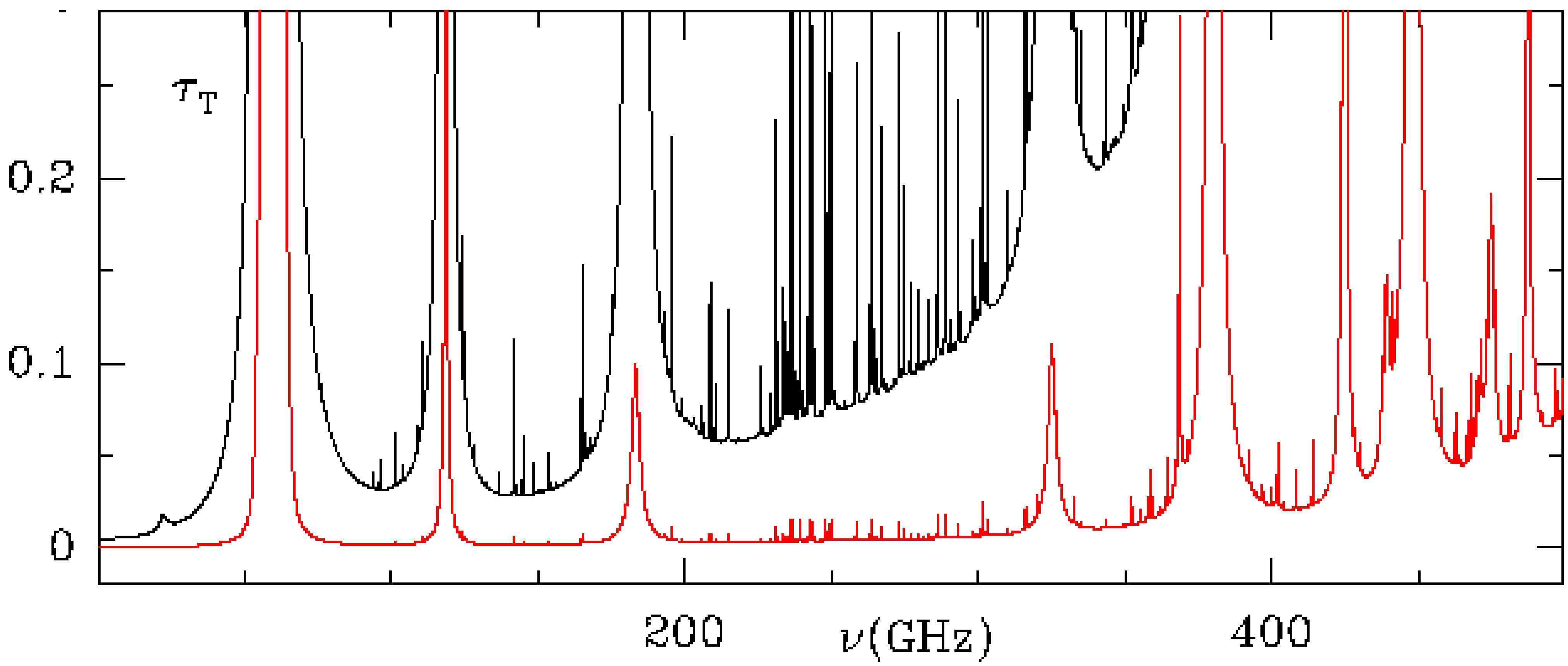
Status of B-mode experiments







Atmospheric optical depth vs. ν (GHz)



Red=South pole, black=stratospheric balloon

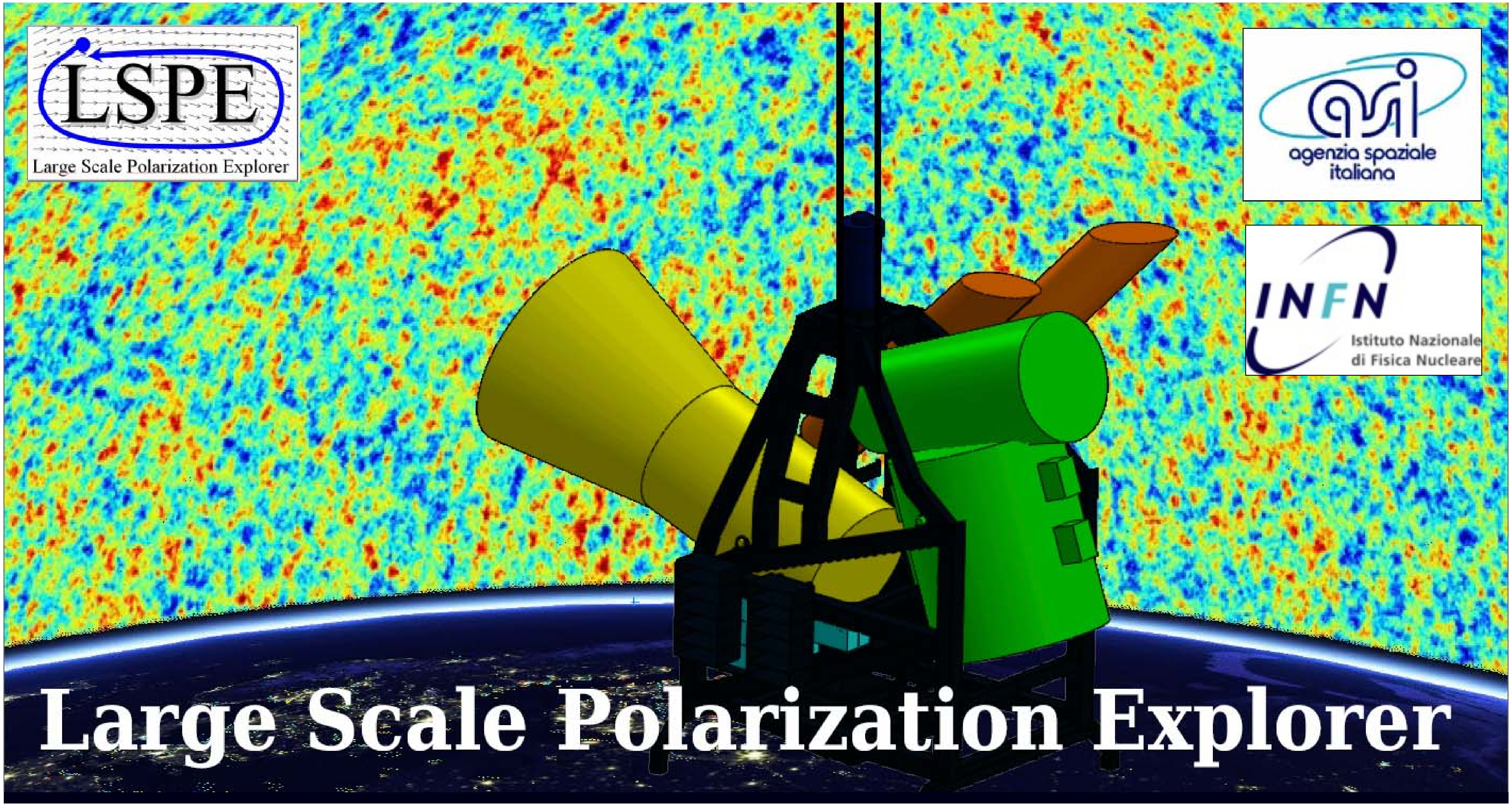
Richieste di finanziamento 2015

Capitolo	Voce	Subtotale	Totale
Costruzione Apparati			
Materiale Inventariabile			
Consumo			
Missioni Italia			
Missioni Estero			

Lensing of E-modes

- E-modes have been measured already with good accuracy, and will be measured with exquisite accuracy by Planck and other experiments.
- They depend on the distribution of mass (mainly dark matter) so their study can shed light on the nature of dark matter (including massive neutrinos).
- While the primordial B-mode is maximum at multipoles around 100 ($\theta=2°$), the lensed B-mode is maximum at multipoles around 1000 ($\theta=0.2°$), requiring high angular resolution polarization experiments

The LSPE experiment



B-modes from P.G.W.

- The amplitude of this effect is very small, but depends on the Energy scale of inflation. In fact the amplitude of tensor modes normalized to the scalar ones is:

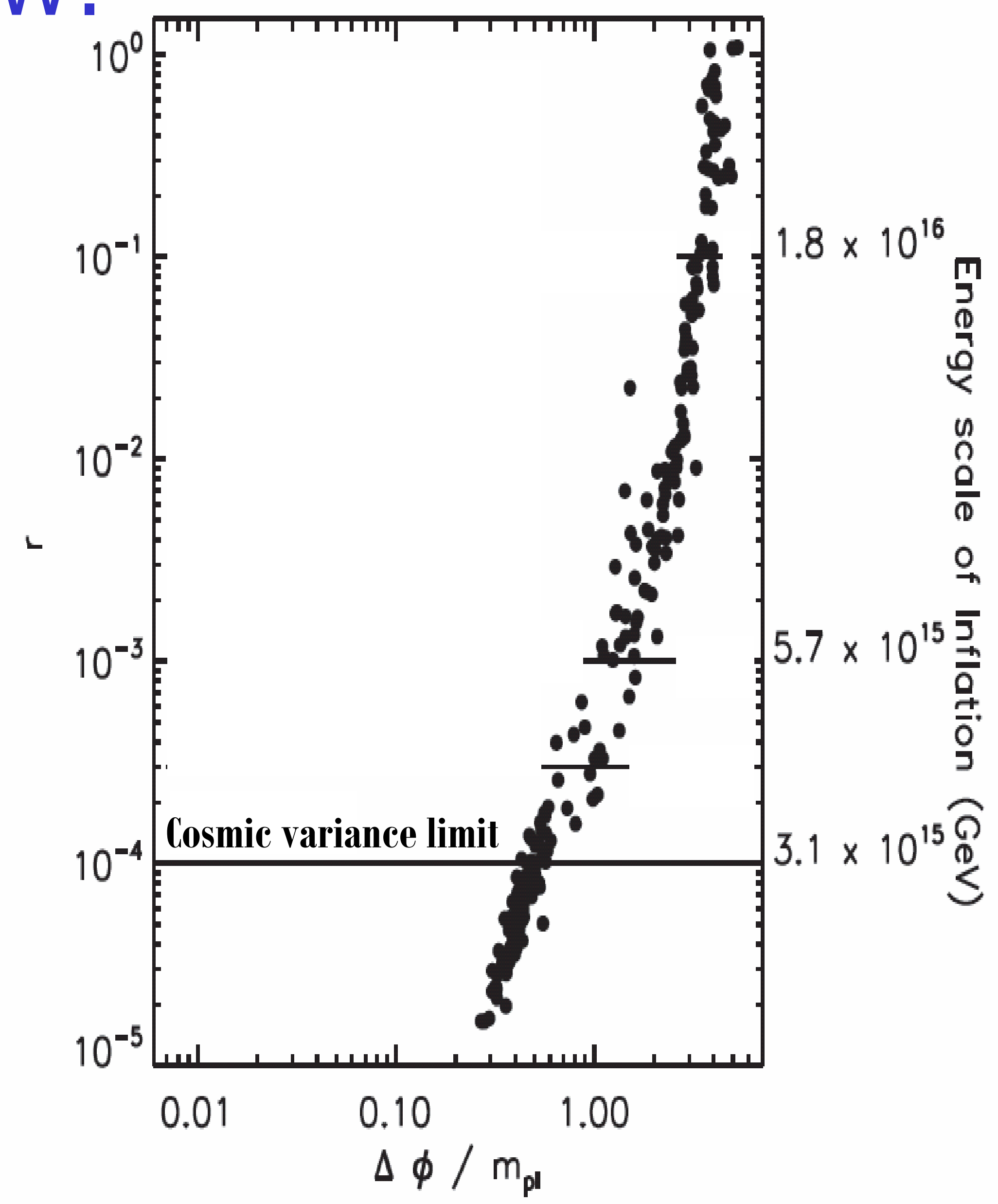
Inflation potential

$$r = \left(\frac{T}{S}\right)^{1/4} \equiv \left(\frac{C_2^{GW}}{C_2^{Scalar}}\right)^{1/4} \cong \frac{V^{1/4}}{3.7\times 10^{16}\,\mathrm{GeV}}$$

- and

$$\sqrt{\frac{\ell(\ell+1)}{2\pi} c^B_{\ell\max}} \cong 0.1\mu K\left[\frac{V^{1/4}}{2\times 10^{16}\,\mathrm{GeV}}\right]$$

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The measurement of B-modes is a good way to investigate fundamental physics at extremely high energies and select among different models of inflation.



The signal is extremely weak

- The current upper limit on anisotropy at large scales gives $r<0.11$ (at 2σ) – there is also a detection claim around $r=0.2$ (see later).
- These are sub-μK signals !
- A competing effect is lensing of E-modes, which is important at large multipoles.
- Whatever smart, ambitious instrument we design to detect the B-modes:
  - It needs to be extremely sensitive
  - It needs an extremely careful control of systematic effects
  - It needs careful control of foregrounds
  - It will need independent experiments with orthogonal systematic effects.
- A lot has been done, but there is still a long way to go: …

However …

- Extraordinary discoveries require extraordinary evidence
- **Is the BICEP2 B-modes signal really in the sky ?** My personal opinion is YES, despite of the tiny level, there is more than enough evidence for this in the papers. A systematics paper will be published soon, to fully convince.
- **Is the BICEP2 B-modes signal really primordial ?** My personal opinion is that these is NOT enough evidence for this in the papers.

CMB Polarization – Why ?

- Linear Polarization of CMB photons is induced via Thomson scattering by quadrupole anisotropy at recombination (z=1100, t =1.2x10^{13}s).

- In turn, quadrupole anisotropy is induced by
  - Density perturbations (*scalar* relics of inflation) producing a curl-free polarization vectors field (**E-modes**)
  - Gravitational waves (*tensor* relics of inflation) producing both curl-free and curl polarization fields (**B-modes**)

- No other sources for a curl polarization field of the CMB at large angular scales:
- **B-modes are a clear signature of inflation**.