COSMOS

Cosmic Orbital and Suborbital Microwave ObservationS

FIG. 3.—Cutaway drawing of the Xcal. The diameter of the Xcal is ∼20 cm. Light striking the cone suffers seven specular reflections before escaping from the cone.

Observing the Cosmic Microwave Background now and in the next decade

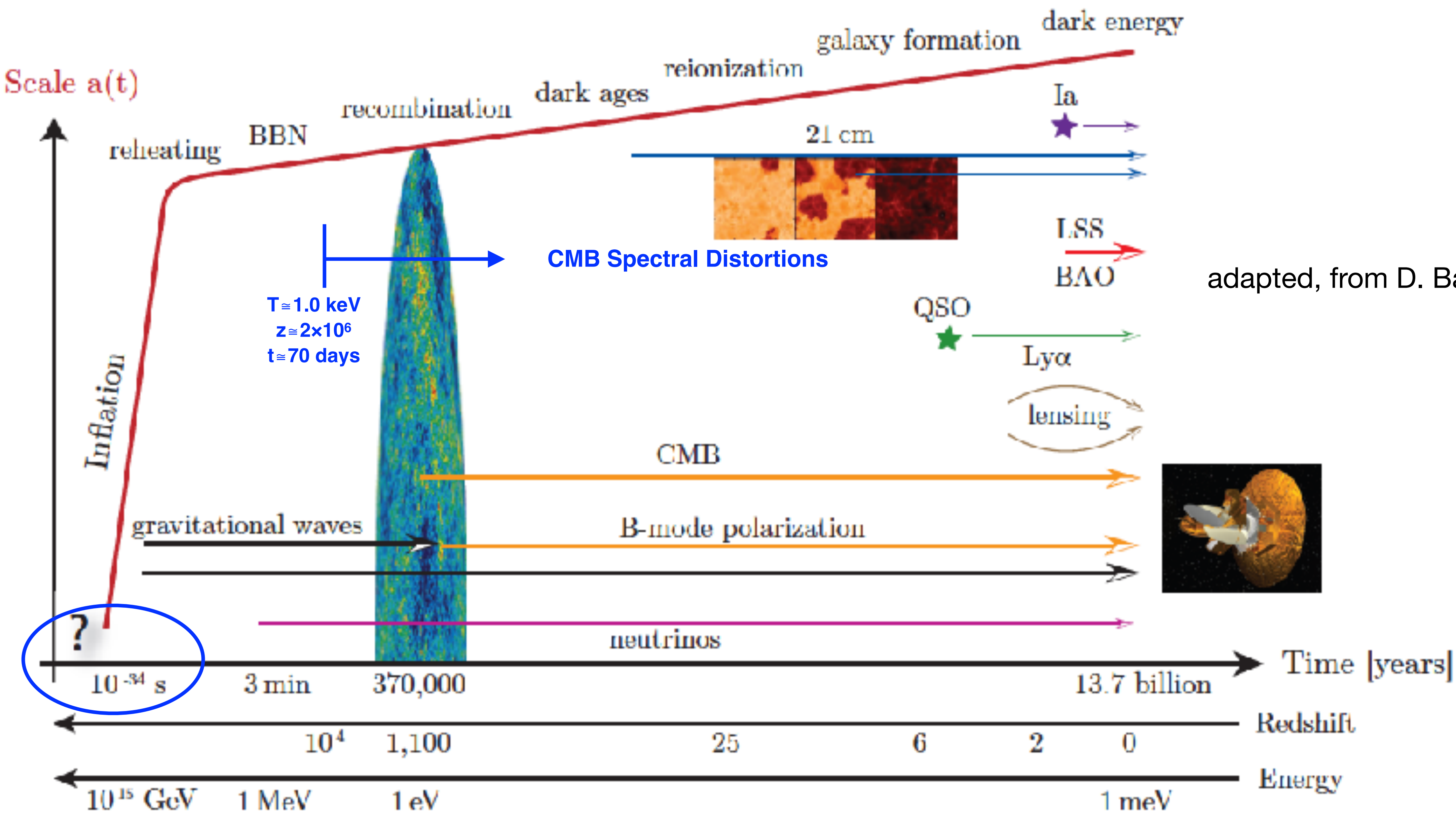
Andrea Tartari, Università di Pisa & INFN Sezione di Pisa

Congresso SIF - 13/09/2021

Outline

- CMB B-mode search status
- B-modes early detections and a technological revolution
- Forthcoming experiments and their science goals: a landscape
- Prospects for primordial B-mode search (discovery?)
- Finale: conclusions, the next decade and beyond

CMB B-modes

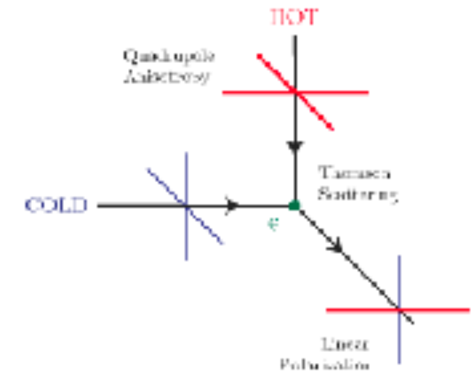


adapted, from D. Baumann

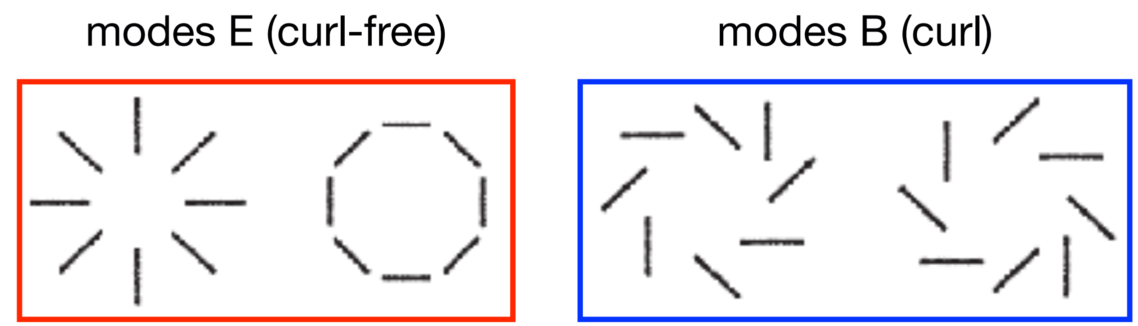
The CMB (its frequency spectrum, its polarised and unpolarised angular power spectra) is a goldmine to explore the physics of Inflation.

- During Inflation, primordial scalar (density) and tensor perturbations are generated due to quantum $\delta\phi$ around $\bar{\phi}$ => "inflated" to a cosmological scale.
- Their power spectra $P_S(k)$ and $P_T(k)$ encoded key predictions of Inflation
- They leave peculiar imprints on the CMB at the last (Thomson) scattering

CMB B-modes

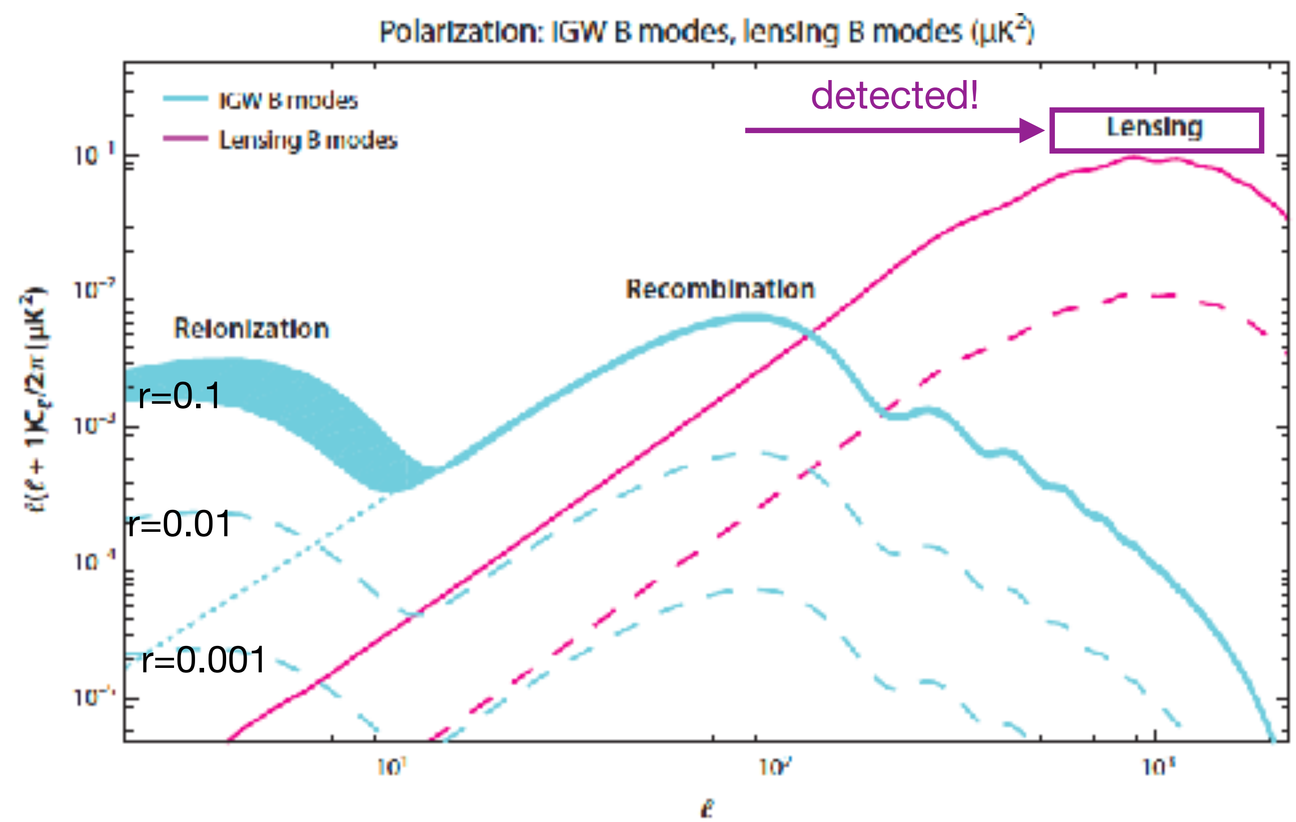


- Thomson scattering of anisotropic radiation field, Y_{20} and $Y_{2\pm2}$ => linear polarisation patterns
- Primordial scalar fluctuations ⇒ E-modes
- Primordial tensor fluctuations ⇒ modes B+modes E
- Under parity PT=T, PE=E, PB=-B. Cross-correlations <TB> and <EB> must vanish. Test of systematics, or new physics (difficult!)



$$r \equiv \frac{P_T}{P_S} \simeq 0.1 \left[\frac{V_{inf}}{(2 \times 10^{16} GeV)^4}\right]$$

Kamionkowski & Kovetz, The Quest for B Modes from Inflationary Gravitational Waves, Annu. Rev. Astron. Astrophys. 2016

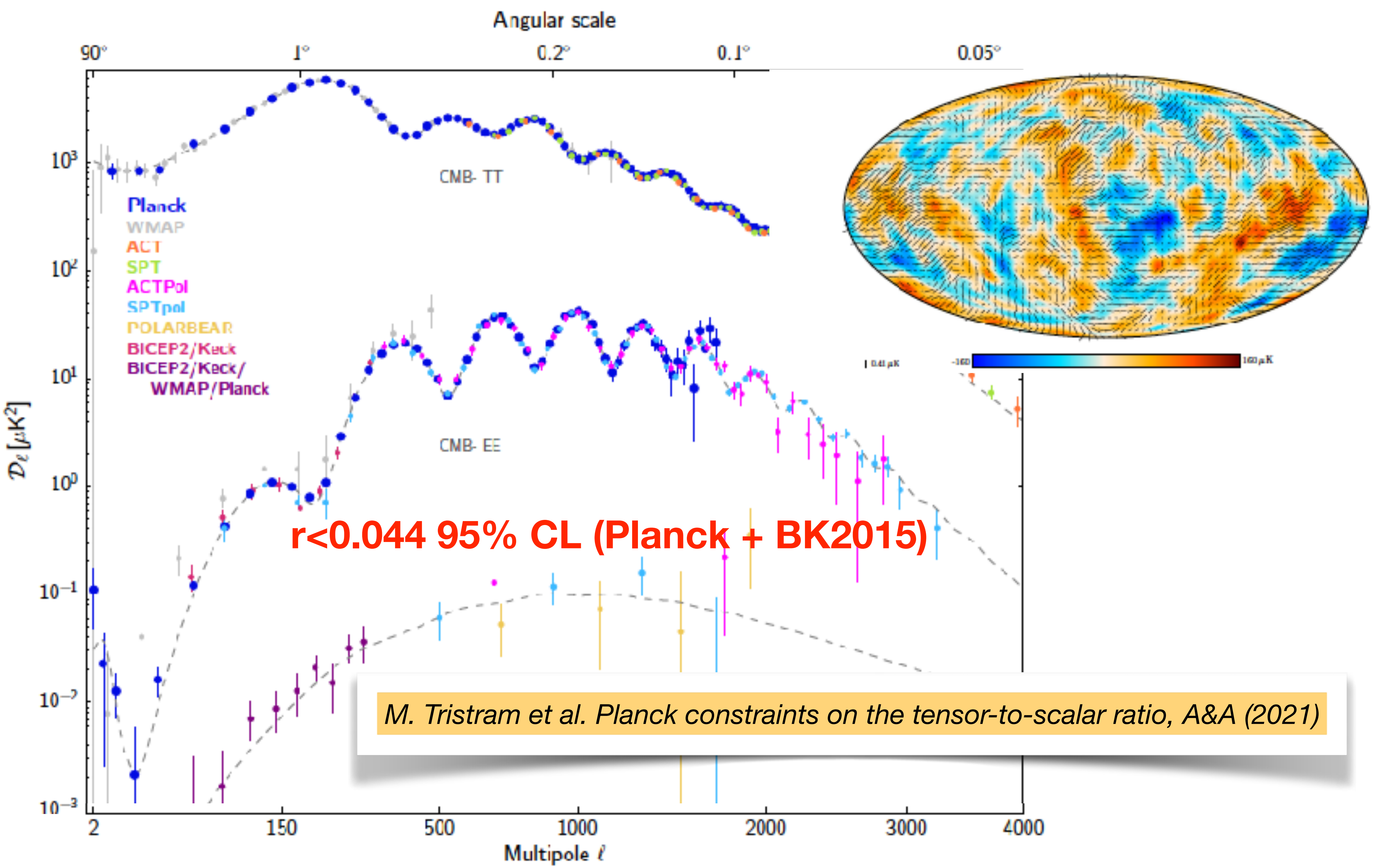


A parameter driving the design of future experiments

B-modes after Planck

Planck 2018 results. I. The Cosmological Legacy of Planck, A&A

6 orders of magnitude since COBE (1994)



r<0.044 95% CL (Planck + BK2015)

M. Tristram et al. Planck constraints on the tensor-to-scalar ratio, A&A (2021)

A new era (2014 +): B-mode measurements

PRL 112, 241101 (2014) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] G. C. Hilton,[11] V. V. Hristov,[2] K. D. Irwin,[12,13,11] K. S. Karkare,[5] J. P. Kaufman,[14] B. G. Keating,[14] S. A. Kernasovskiy,[12] J. M. Kovac,[5,*] C. L. Kuo,[12,13] E. M. Leitch,[15] M. Lueker,[2] P. Mason,[2] C. B. Netterfield,[4,16] H. T. Nguyen,[6] R. O'Brient,[6] R. W. Ogburn IV,[12,13] A. Orlando,[14] C. Pryke,[9,7,†] C. D. Reintsema,[11] S. Richter,[5] R. Schwarz,[9] C. D. Sheehy,[9,15] Z. K. Staniszewski,[2,6] R. V. Sudiwala,[1] G. P. Teply,[2] J. E. Tolan,[12] A. D. Turner,[6] A. G. Vieregg,[5,15] C. L. Wong,[5] and K. W. Yoon[12,13]

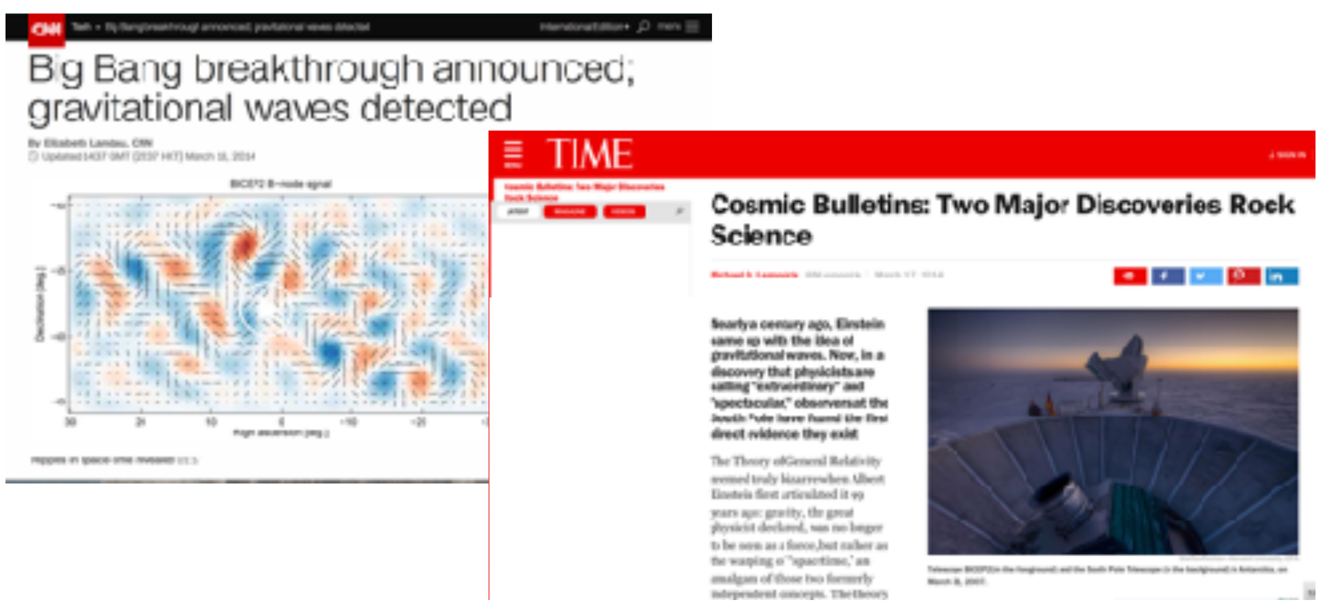
(BICEP2 Collaboration)

PRL 113, 021301 (2014) PHYSICAL REVIEW LETTERS week ending 11 JULY 2014

Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment

P. A. R. Ade,[1] Y. Akiba,[2] A. E. Anthony,[3] K. Arnold,[4] M. Atlas,[4] D. Barron,[4] D. Boettger,[4] J. Borrill,[5,6] S. Chapman,[7] Y. Chinone,[8,9] M. Dobbs,[10] T. Elleflot,[4] J. Errard,[5,6] G. Fabbian,[11,12] C. Feng,[4,*] D. Flanigan,[9,13] A. Gilbert,[10] W. Grainger,[14] N. W. Halverson,[3,15,16] M. Hasegawa,[8,2] K. Hattori,[8] M. Hazumi,[8,2,17] W. L. Holzapfel,[9] Y. Hori,[8] J. Howard,[9,18] P. Hyland,[19] Y. Inoue,[2] G. C. Jaehnig,[3,16] A. Jaffe,[20] B. Keating,[4] Z. Kermish,[21] R. Keskitalo,[5] T. Kisner,[5,6] M. Le Jeune,[11] A. T. Lee,[9,22] E. Linder,[6,22] E. M. Leitch,[23,24] M. Lungu,[9] F. Matsuda,[4] T. Matsumura,[8] X. Meng,[9] N. J. Miller,[25] H. Morii,[8] S. Moyerman,[4] M. J. Myers,[9] M. Navaroli,[4] H. Nishino,[17] H. Paar,[4] J. Peloton,[11] E. Quealy,[9,26] G. Rebeiz,[27] C. L. Reichardt,[9] P. L. Richards,[9] C. Ross,[7] I. Schanning,[4] D. E. Schenck,[3,15] B. Sherwin,[9,28] A. Shimizu,[2] C. Shimmin,[9] M. Shimon,[4,29] P. Siritanasak,[4] G. Smecher,[30] H. Spieler,[22] N. Stebor,[4] B. Steinbach,[9] R. Stompor,[11] A. Suzuki,[9] S. Takakura,[31,8] T. Tomaru,[8] B. Wilson,[4] A. Yadav,[4] and O. Zahn[22]

(POLARBEAR Collaboration)



ASTRONOMY

Next Steps for Cosmology

Recent observations from Planck and BICEP2 reveal key signatures of the Big Bang—what are the next questions for CMB cosmology in space?

Joseph Silk[1,2] and Jens Chluba[2]

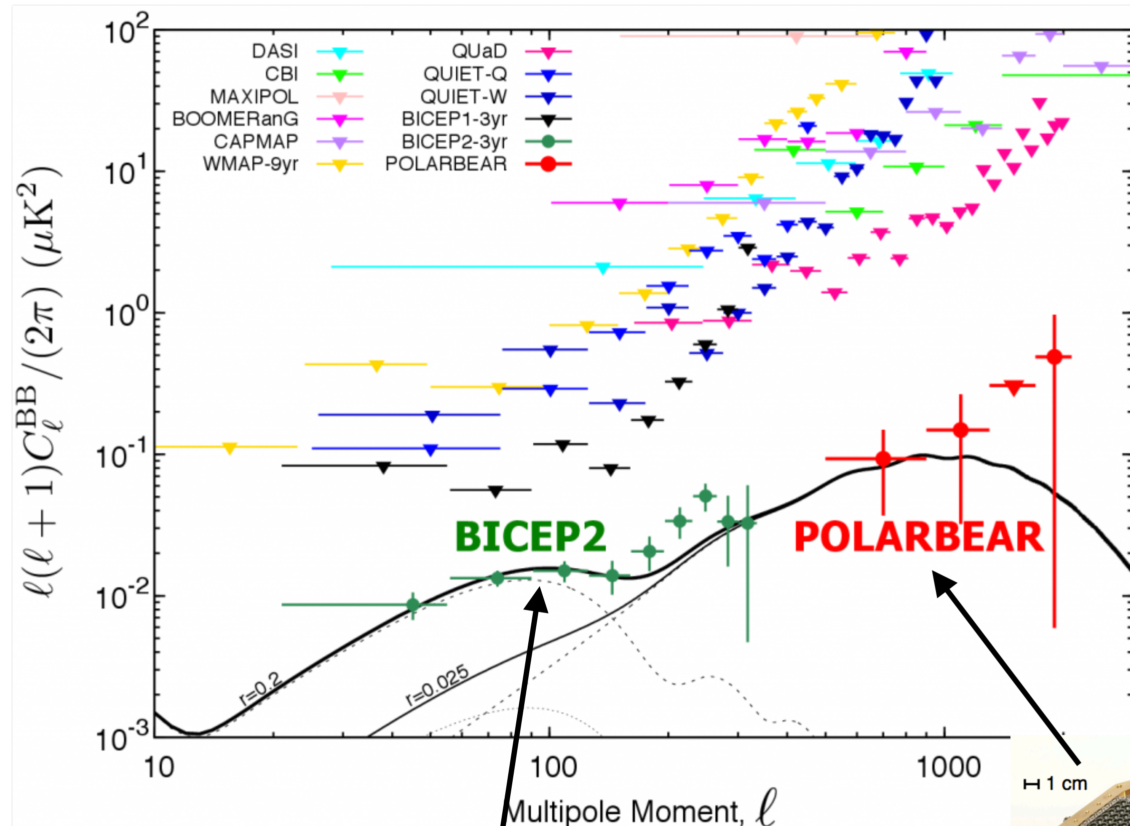
Experiments on the ground, balloons, and satellites have revolutionized our knowledge of the Big Bang by measuring the fossil glow from the first instants of the universe, the cosmic microwave background (CMB) radiation. Infinitesimal fluctuations in the photon temperature have been found, revealing the seeds of all large-scale 10^{-30} s after the Big Bang, when the seed density fluctuations are thought to have been created. It is believed that inflation also explains the size of the observable universe and the near Euclidean geometry of space.

Inflation has a remarkable implication. When it occurred, there was an immense explosion of space accompanied by the cre-

tic Polarization) collaboration announced (6) a first detection of tensor mode polarization at degree angular scales. That measurement transformed CMB science overnight. Previously, the precise level of tensor modes was uncertain, but now a definite target has been identified, and larger than even the optimists had expected.

A new era (2014 +): B-mode measurements

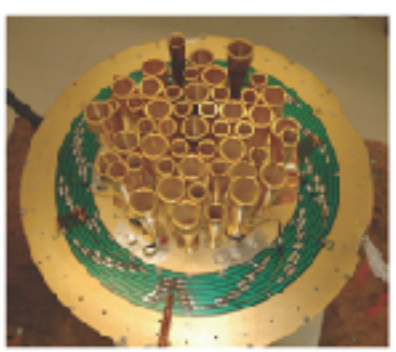
- The faintest polarised microwave signal become accessible thanks to the deployment of <u>superconducting bolometer arrays</u>. Transition Edge Sensors (TES).
- From individually diced and mounted devices, to monolithic arrays.
- O(10^3) detectors at telescope focal planes in the so-called "Stage-2" (S2). S3 ongoing, S4 strongly supported in the US.

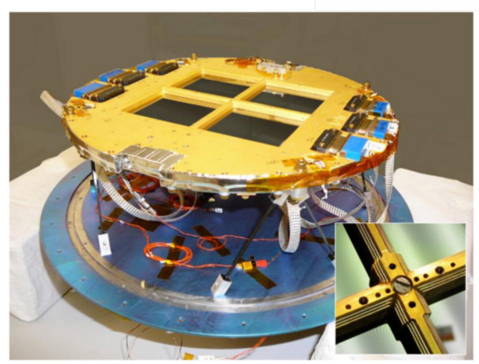


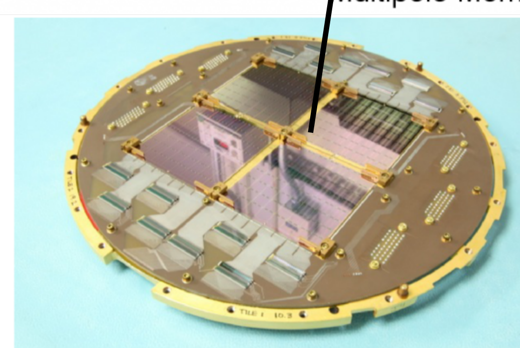
POLARBEAR

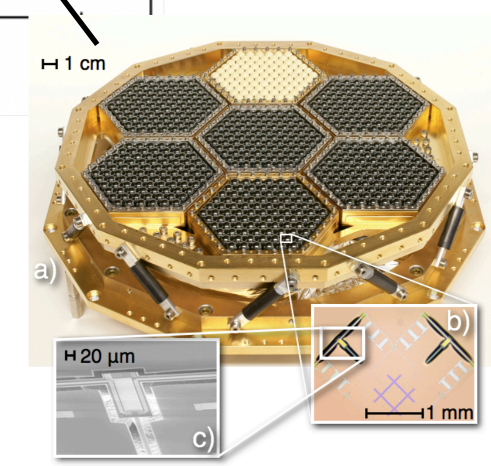
BICEP1

BICEP2









Major ideas in detection techniques => Major discoveries

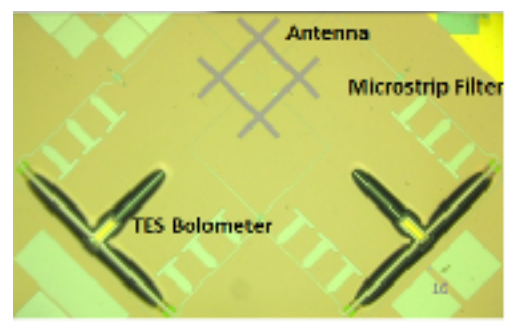
A new era (2014 +): B-mode measurements

- Remarkable achievements (milestones) which paved the way:

A. Transition Edge Sensors operated in a stable and high sensitivity mode: the Electrothermal Feedback
B. Successful design of complex superconducting microwave networks featuring a number of analog signal conditioning stages:
1. antenna beam-forming
2. phase control
3. polarisation separation
4. sum/difference trees
5. bandpass filtering
6. direct detection (TES)

C. Use of TES coupled to metallic mesh absorbers (à la Planck)

POLARBEAR1



K. Irwin, An application of electrothermal feedback for high resolution cryogenic particle detection, APL (1995)

Le Duc, et al., Fabrication of antenna-coupled transition edge sensors for polarimeter applications, NIMA (2006)

Gildemeister, Lee & Richards, A fully lithographed voltage-biased superconducting spiderweb bolometer, APL (1999)

A.

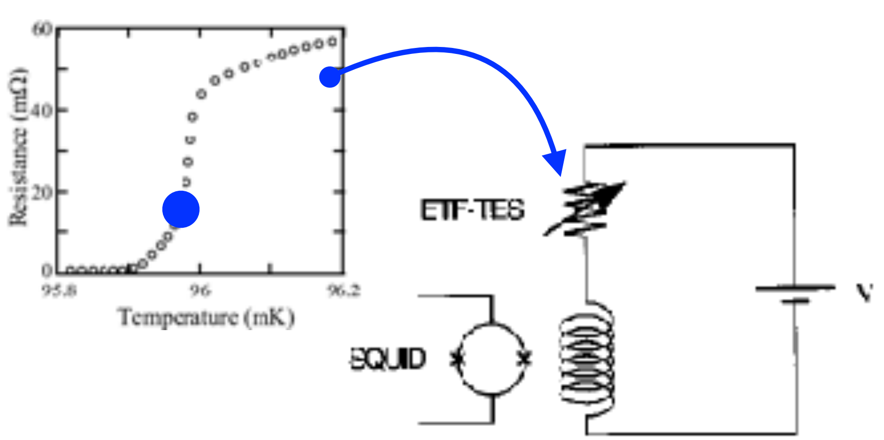
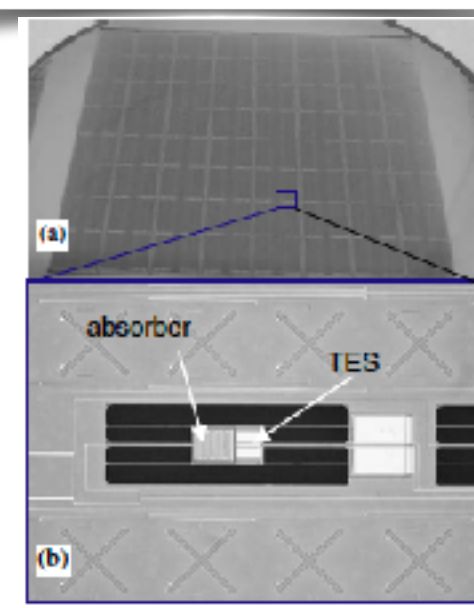


FIG. 1. Instrumentation of the ETF TES.

B.



C.

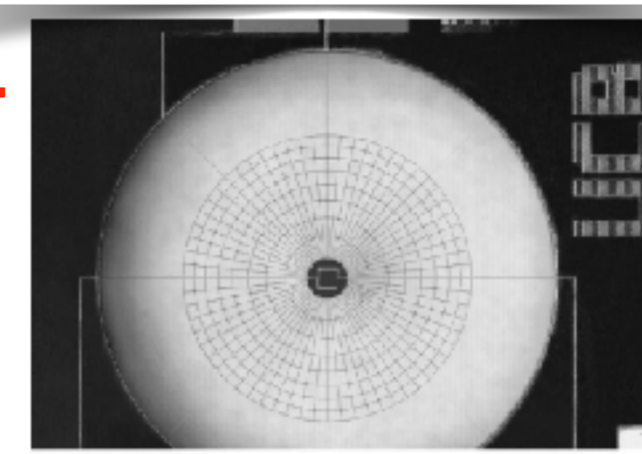


FIG. 1. Photograph of the fully lithographed bolometer on a Si_3N_4 membrane. The circular mesh is metallized to absorb radiation and is supported by eight radial legs. The voltage biased trilayer thermistor is located on a continuous region of membrane in the center and is electrically connected with superconducting leads.

More detectors for deeper maps in several bands

- Observe the sky in many bands to measure the foregrounds (many bands, more detectors…)
- Once each detector at the photon noise limit, need to increase the number of detectors to increase the mapping speed

$$MS = \eta \left(\frac{dP_{bb}}{dT} \right) \frac{N_{det}}{NEP^2}$$

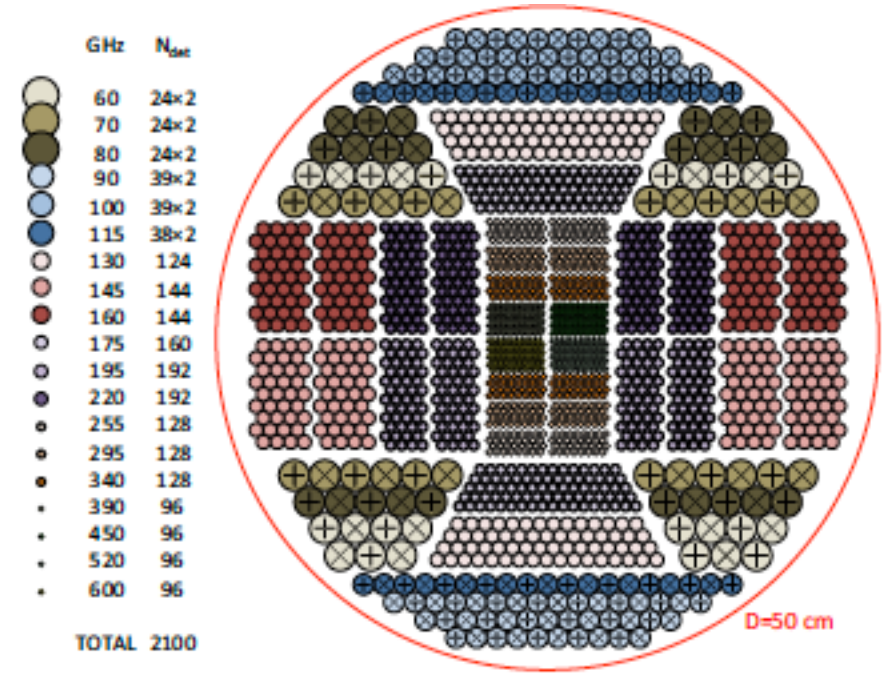


Figure 8. Arrangement of 2100 single-band, single-polarization detectors, in the focal plane of the *CORE* telescope. The scan direction is horizontal.

P. de Bernardis et al., Exploring cosmic origins with CORE: The instrument, JCAP (2018)

Definitions

- Noise Equivalent Power (NEP): power to produce an output S/N=1 in 1 Hz bandwidth (units W/√Hz)

Variance of blackbody photon occupation number $\Rightarrow \sigma_n^2 = n(1+n)$

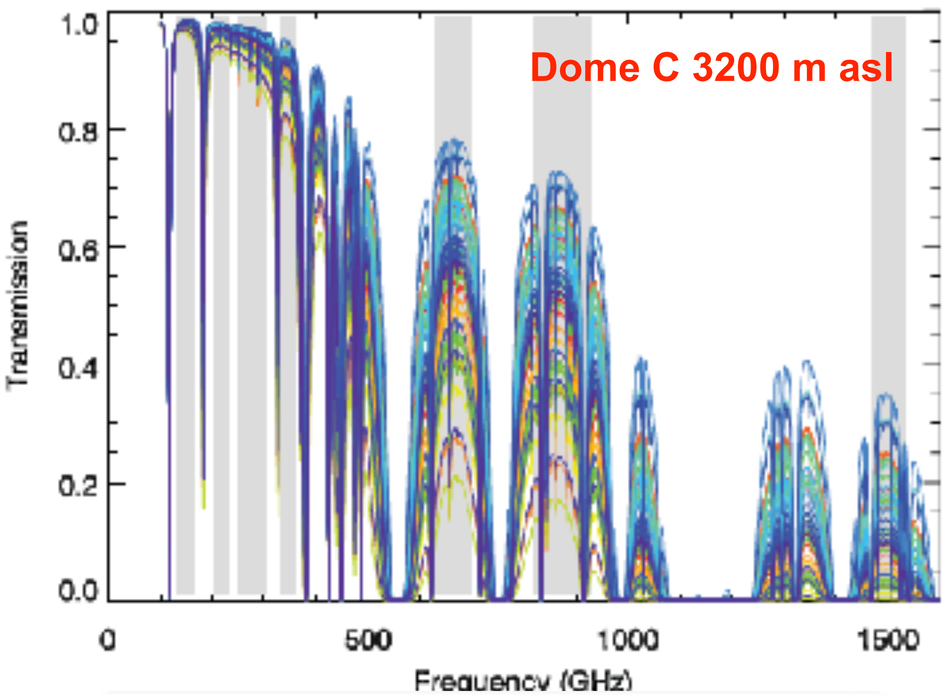
Photon noise (the ideal limit of a photometer) $\Rightarrow NEP_{ph} = \sqrt{2h\bar{\nu}P_{opt} + \xi P_{opt}^2 / \Delta\nu}$

In Background Limited Photometry (BLIP) $\Rightarrow NEP_{det} < NEP_{ph}$

J.M.Lamarre, AO 25, 1986

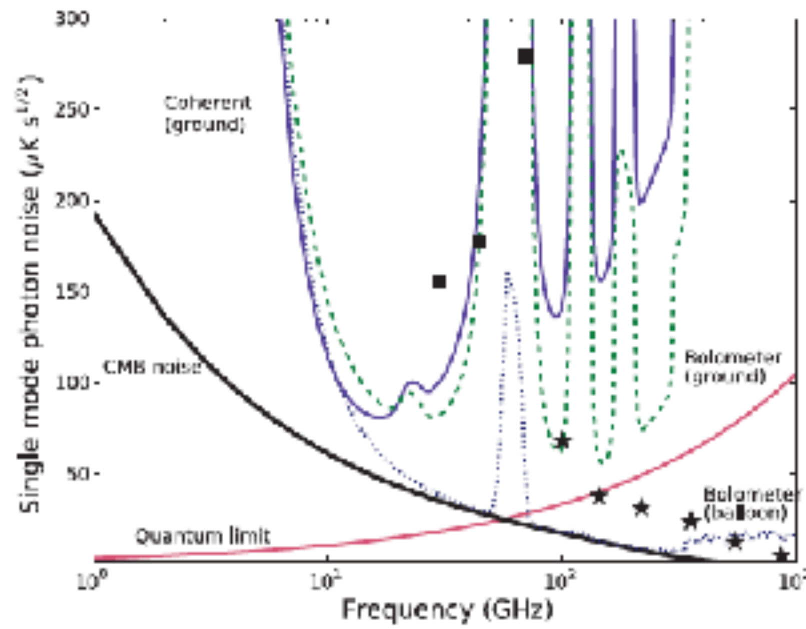
Ground vs Space

Transparency



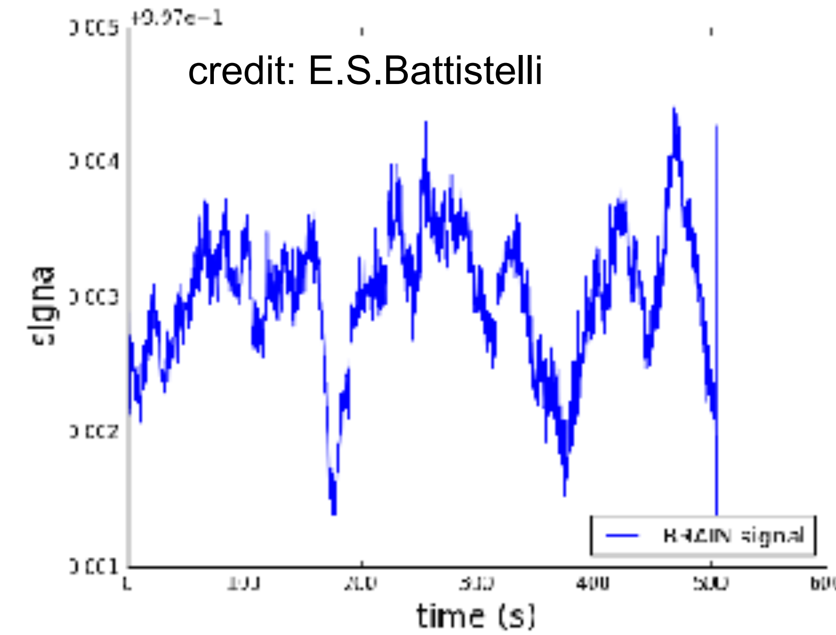
S. De Gregori et al. MNRAS 2012

Emissivity (white noise)



Hanany, Niemack & Page 2012

Instability (1/f)



1/f time series $\Rightarrow C_\ell \propto 1/\ell$

Tegmark PRD 56, 1997

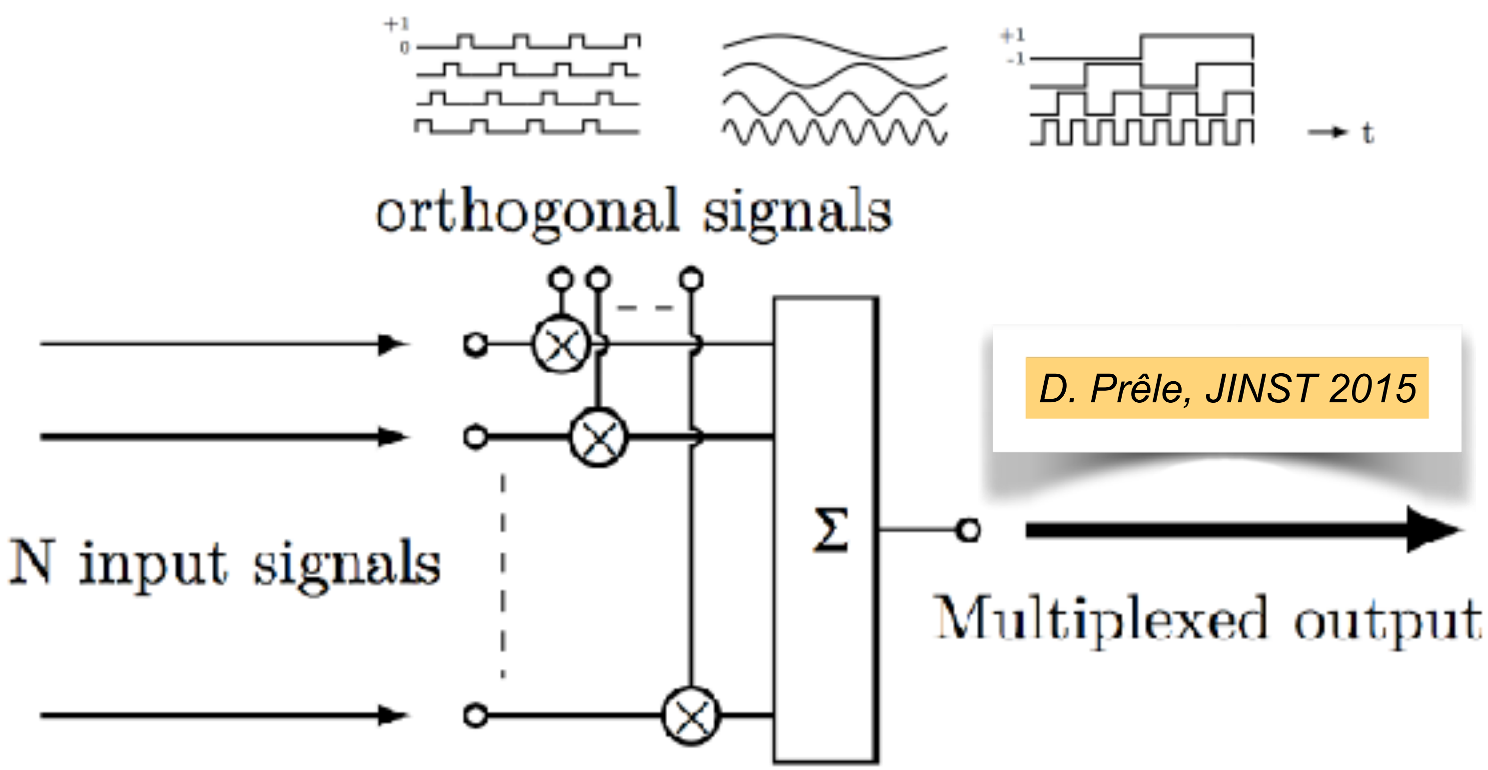
$$\frac{t_{int,gr}}{t_{int,sp}} \simeq \left(\frac{NEP_{ph,gr}}{NEP_{ph,sp}}\right)^2 \sim 50 - 100$$

➡About a factor 100 in detector number count for experiments targeting the same map size/depth from ground and from space (balloon also very efficient). Site dependent.

➡Large angular scales accessible

TES Multiplexed Readout

➡ Progress on massive detector deployment has been accompanied by a <u>spectacular development of efficient and low-noise multiplexed (SQUID-based) readout electronics</u>.
➡ High-rate multiplexing in Time and Frequency domain [e.g. QUBIC TDM is 128:1]
➡ Possibility to reach 1000:1 with microwave Multiplexing (μMUX) - demonstrated
➡ <u>TES FDM actively developed at INFN-PI</u> for SWIPE/LSPE and future applications
➡ Low power dissipation per pixel required (e.g., 10 mW or less) & cryogenic operation

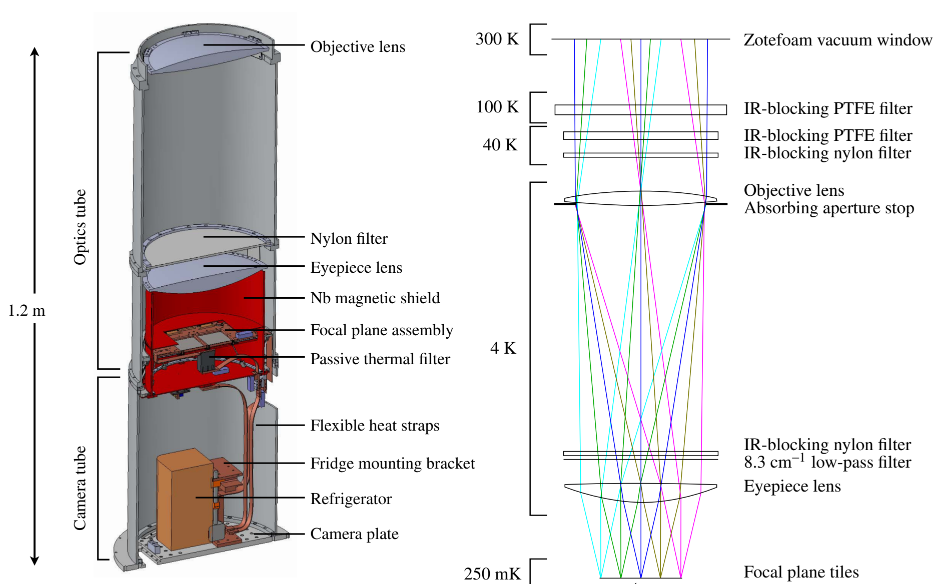


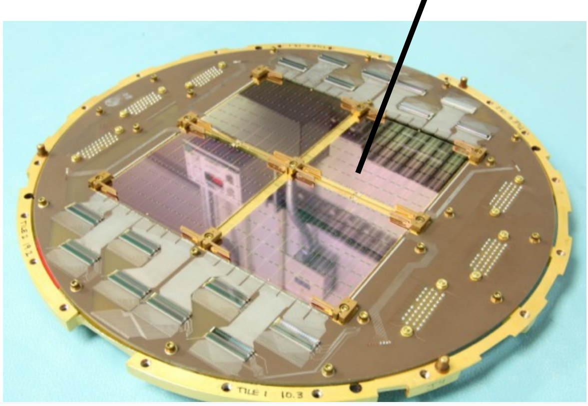
D. Prêle, JINST 2015

- A high throughput channel carrying N signals
- A set of orthogonal signals (sinusoids, Walsh codes, etc.)
- A summing node (in a cryogenic environment, <u>as cold as possible</u>)

TES-based architectures

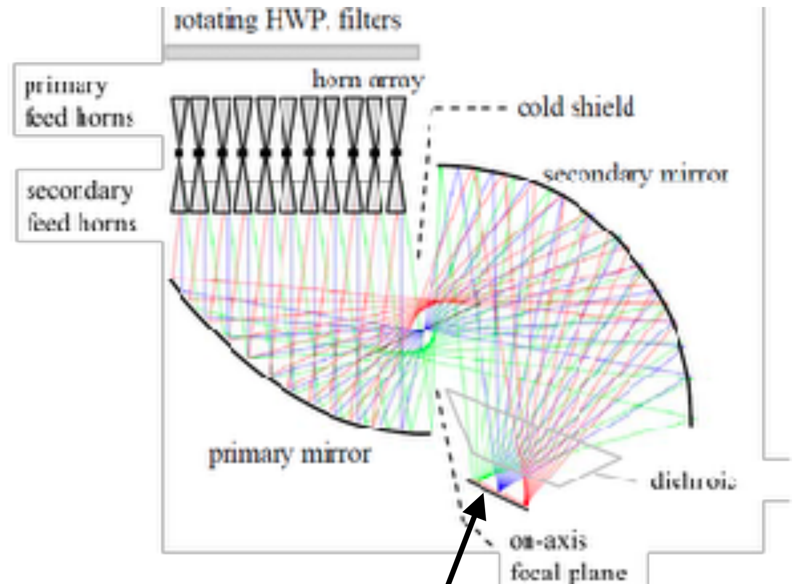
- **B-mode Imagers** with antenna-coupled TES arrays:
  - can be multichroic (up to 4 bands)
  - telescope illumination with phased arrays, lenslets, horns
  - BICEP3/SPIDER/Keck + CLASS + AdvACT+POLARBEAR2+SPT3G [N_{det} from 10^3 to 10^4]

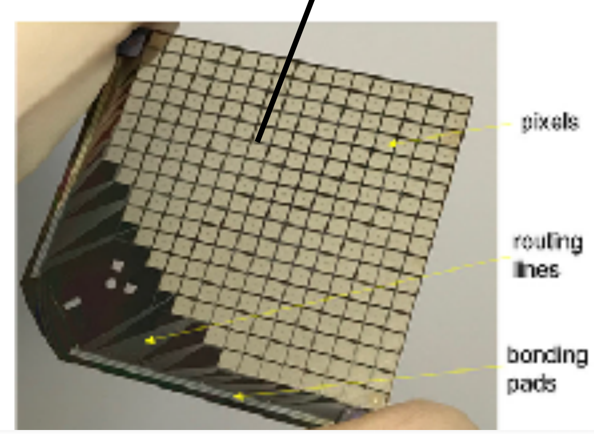




BICEP2 Collaboration, ApJ 2015

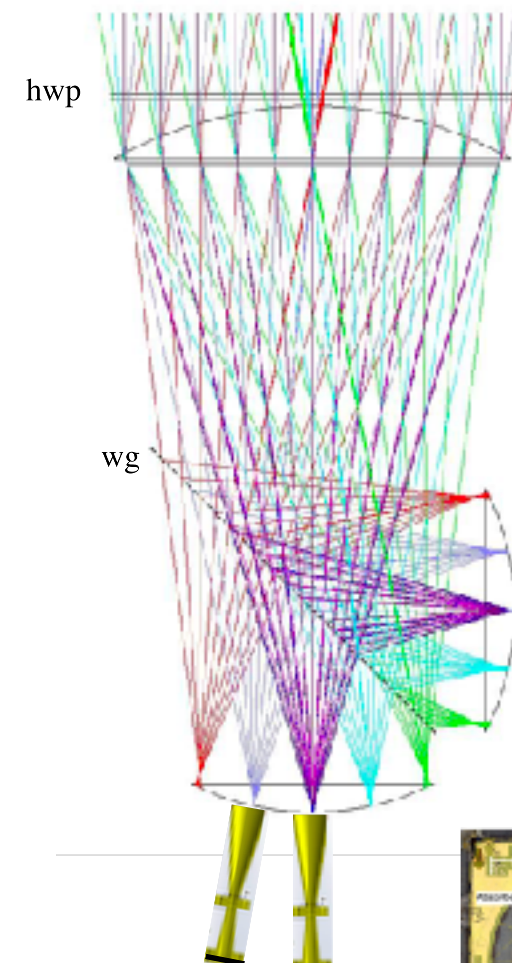
- **Interferometers**:
  - QUBIC (Fizeau)
  - Free-space coupling with metal mesh (IJCLab NbSi TES)
  - N_{det} 2×10^3
  - <u>Strong italian participation</u>

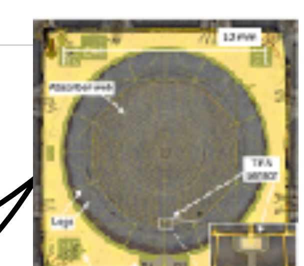




QUBIC Technical Design Report, 2017 (+ Series of papers under review + Marnieros et al. JLTP 2020)

- **Stokes polarimeters**:
  - SWIPE/LSPE, balloon
  - waveguide coupling with metal mesh (INFN-GE Ti TES) - Large throughput - Individually diced
  - N_{det} 326
  - <u>Italian lead (ASI, INFN)</u>

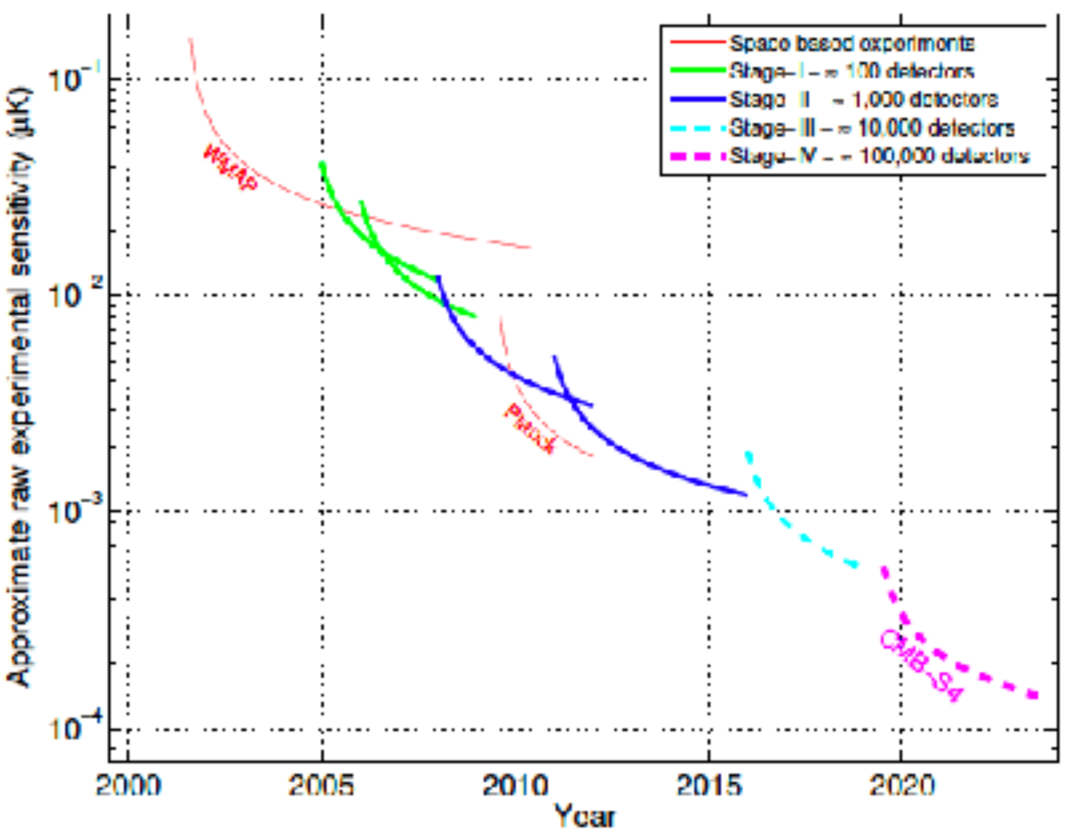


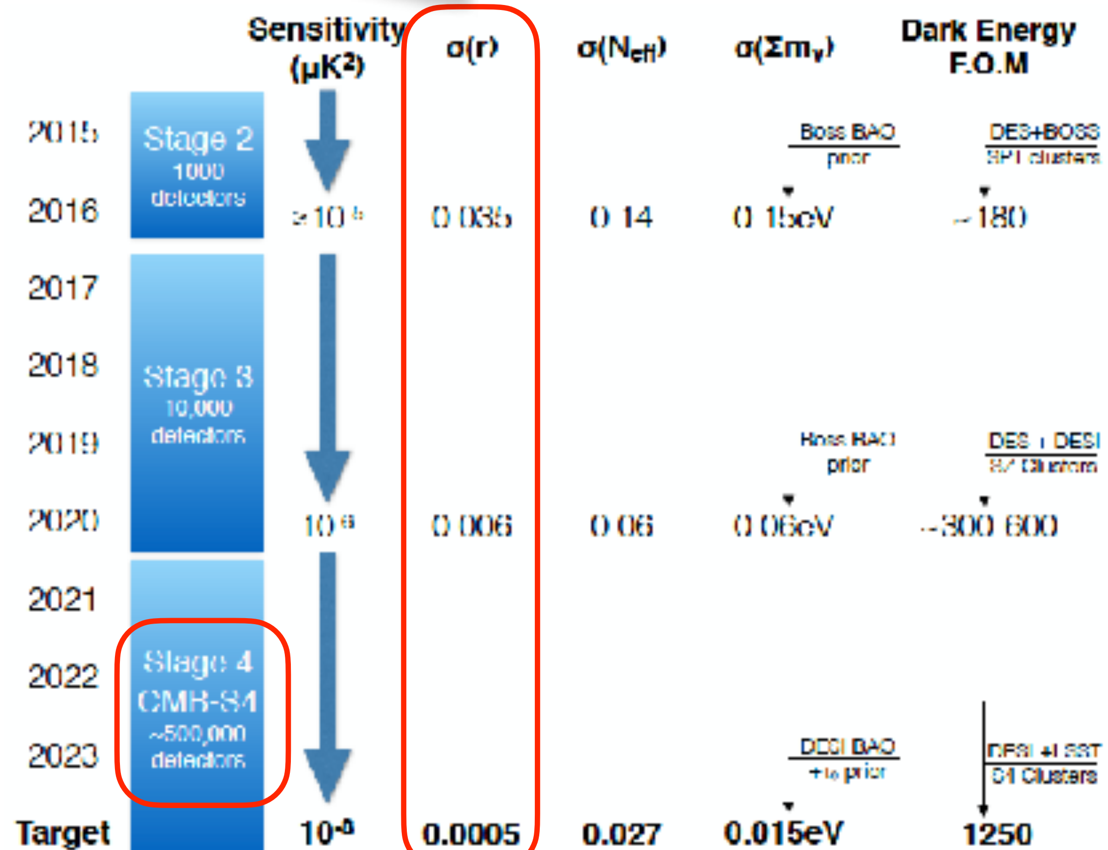


F.Columbro et al., JLTP 2020
F.Piacentini et al., JCAP 2021

Number of detectors *vs* $\sigma(r)$: *ground*

CMB-S4 collaboration, CMB-S4 Science Book First Edition, 2016





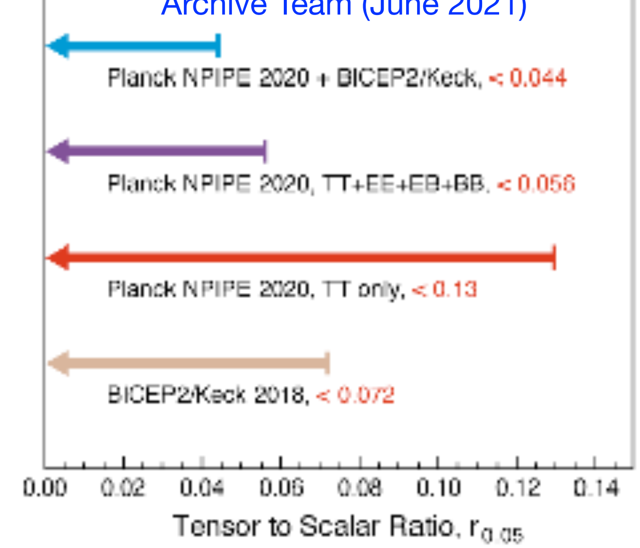
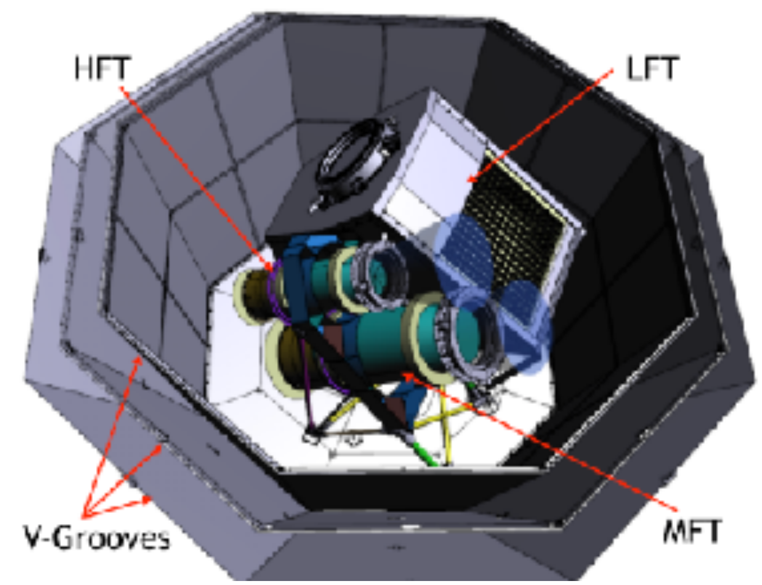


Image credit: NASA / LAMBDA Archive Team (June 2021)

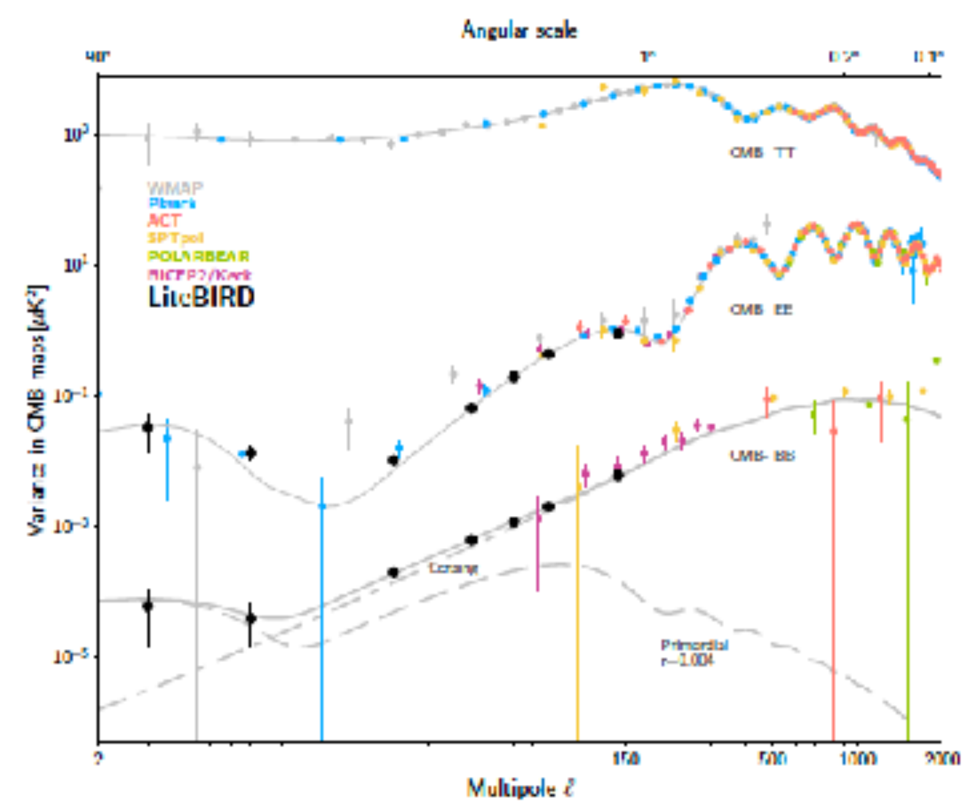
- Raw sensitivity is one figure of merit, scales with N_{det}. Not the full story about primordial B-modes.
- S2 to S4 ground based. Atmosphere. Reionization peak very difficult.
- Balloon and space open other opportunities for the large angular scales (>1°). Much smaller N_{det}, but lower NEP.
- N_{det}~250000 for small aperture instruments (r), 6 yrs

Space: the LiteBIRD mission

M. Hazumi et al., LiteBIRD satellite: JAXA's new strategic L-class mission for all-sky surveys of cosmic microwave background polarization, Proc. of SPIE Vol. 11443 114432F (2020)



- The only space mission in the Landscape
- Operation from L2, like WMAP and Planck
- Target B-mode Recombination and Reionization peaks, with a global $\delta r<0.001$ (δ is a complete error budget, including sys)
- Telescopes: 1 reflector + 2 refractors
- Frequency bands: 15, from 34 to 448 GHz
- Antenna-coupled TES technology
- Overall detector number ~4500
- Target launch date 2029 + 3 years of operation
- Strong italian involvement through ASI and INFN (+ Labs and University infrastructures)



Conclusions (for the next decade)

- Deeper and deeper polarised maps, in many bands, will allow to test one of the most compelling predictions of Inflation: the generation of primordial gravitational waves. The region around r=0.01 will be explored in great detail.
- This fascinating science contributed to boost the technology of superconducting detector (TES) arrays.
- TES arrays allowed the first detection of the lensing B-mode signal
- This technology is at the core of next decade experiments

Conclusions (beyond the next decade)

Back to the monopole (25 year after COBE-FIRAS)

Why is the CMB so closely thermal?

THE COSMIC MICROWAVE BACKGROUND SPECTRUM FROM THE FULL *COBE*[1] FIRAS DATA SET

D. J. FIXSEN,[2] E. S. CHENG,[3] J. M. GALES,[2] J. C. MATHER,[3] R. A. SHAFER,[3] AND E. L. WRIGHT[4]

Received 1996 January 19; accepted 1996 July 11

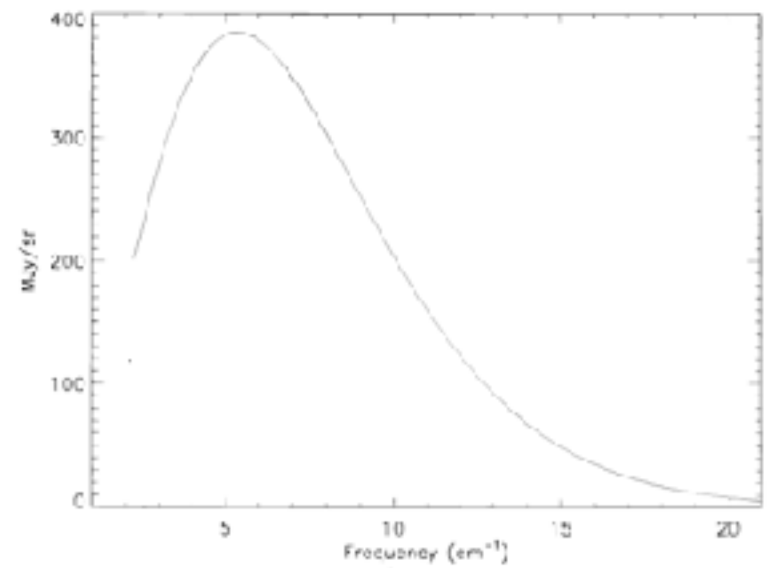


FIG. 4.—Uniform spectrum and fit to Planck blackbody (*T*). Uncertainties are a small fraction of the line thickness.

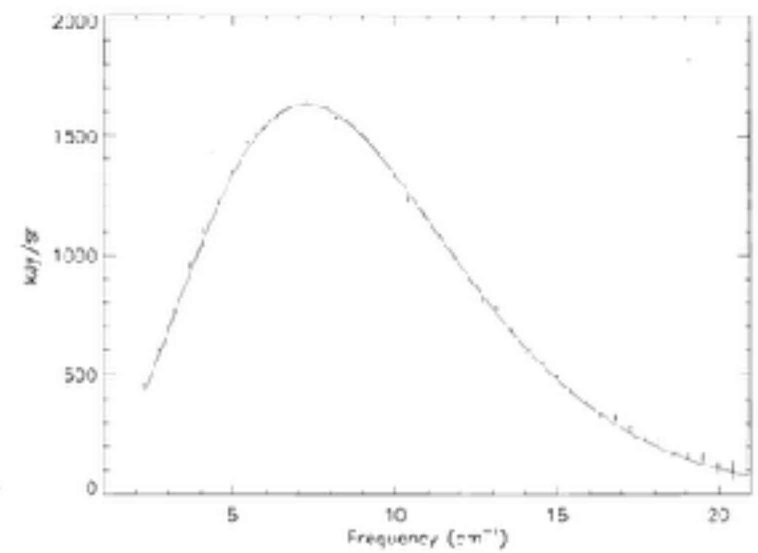


FIG. 5.—Dipole spectrum and fit to *dB/dT*. The vertical lines indicate plus and minus 1 σ uncertainties. The peak of uniform CMBR is approximately 400 MJy sr^{-1}.

esa

Voyage 2050 sets sail: ESA chooses future science mission themes

New physical probes of the early Universe

How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics that could be addressed by missions exploiting new physical probes, such as detecting gravitational waves with high precision or in a new spectral window, or by high-precision spectroscopy of the cosmic microwave background – the relic radiation left over from the Big Bang. This theme follows the breakthrough science from Planckand the expected scientific return from LISA, and would leverage advances made in instrumentation to open a huge discovery space. Additional study and interaction with the scientific community will be needed to converge on a mission addressing this theme.

Some hints here

Snowmass2021 - Letter of Interest

CMB Spectral Distortions: A new window to fundamental physics

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics & cosmology

Answer to Voyage 2050

Experimental Astronomy
https://doi.org/10.1007/s10686-021-09721-z

ORIGINAL ARTICLE

Microwave spectro-polarimetry of matter and radiation across space and time

Jacques Delabrouille, et al. *[full author details at the end of the article]*

Received: 29 July 2020 / Accepted: 2 March 2021 / Published online: 03 July 2021