CMB observations: implications for inflation and early Universe

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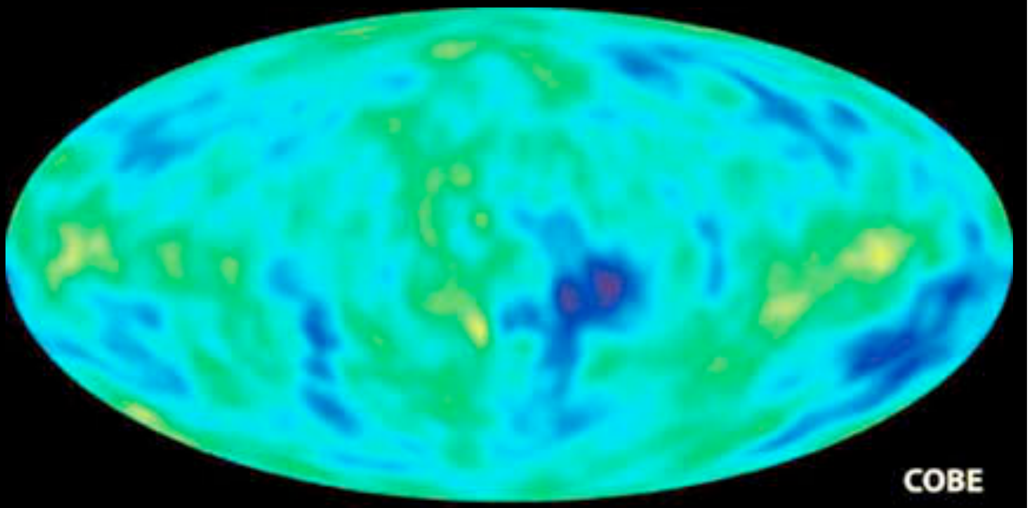
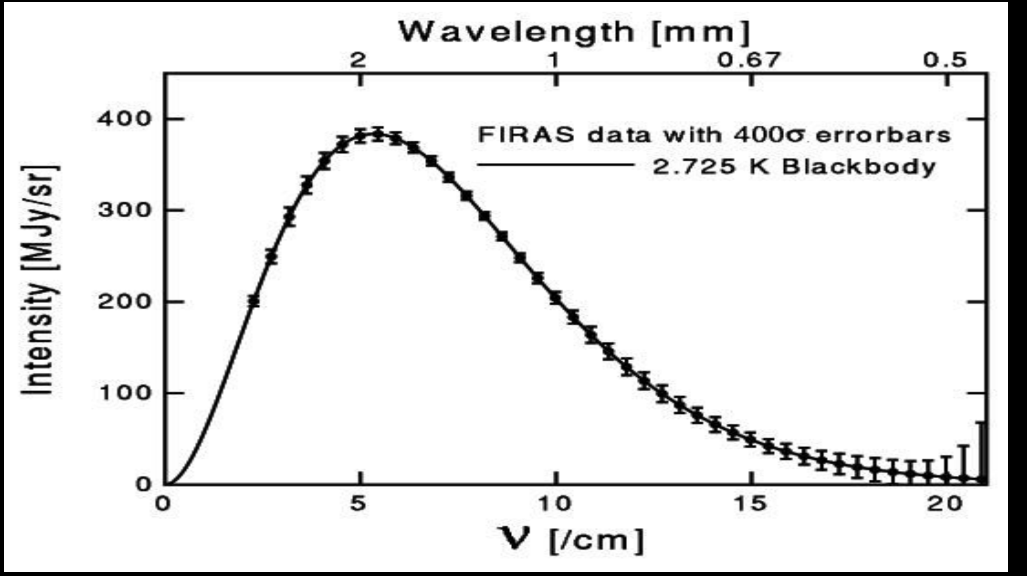
COSMIC MICROWAVE BACKGROUND

- In the last ~25 years CMB has represented the most powerful tool in cosmology
- First there was COBE: FIRAS (monopole spectrum) + DMR (anisotropies)





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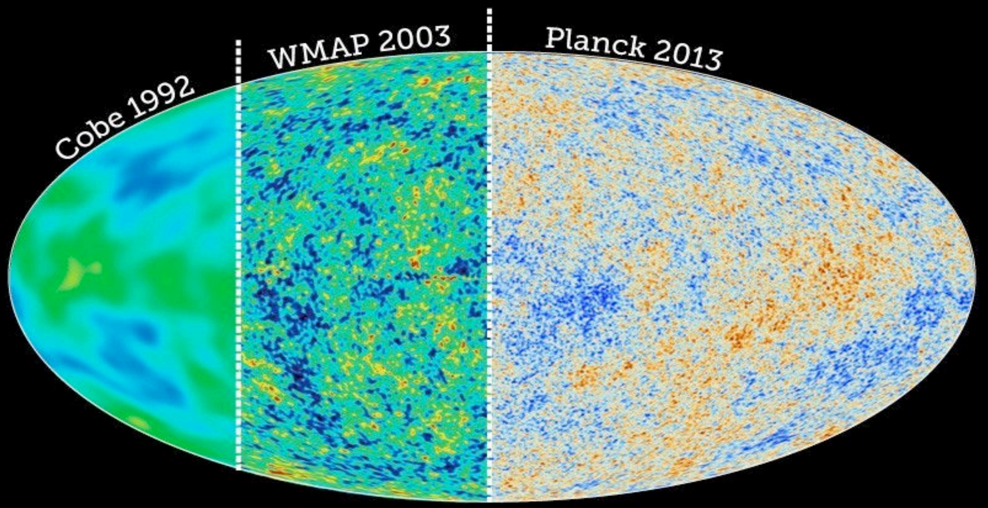

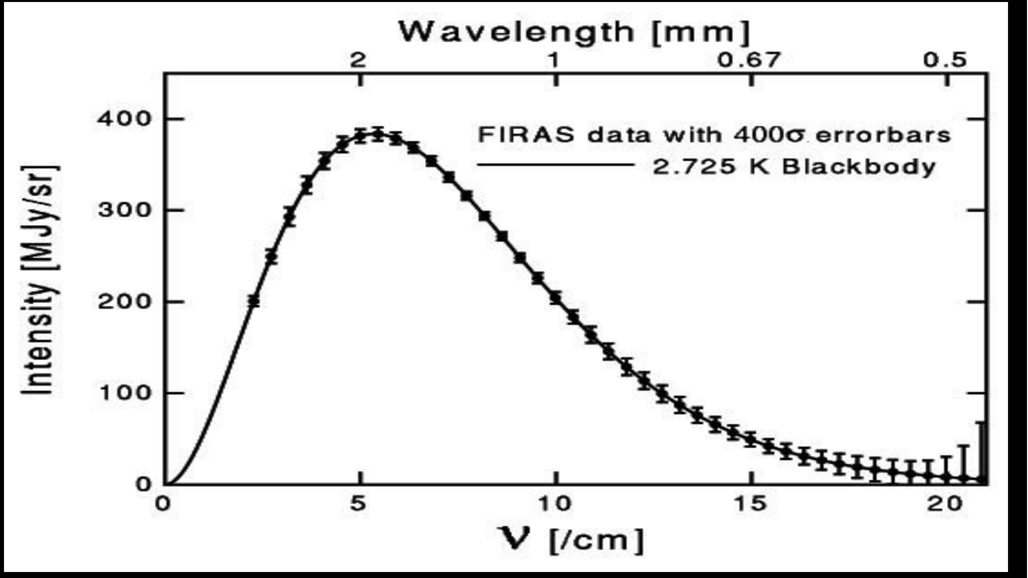

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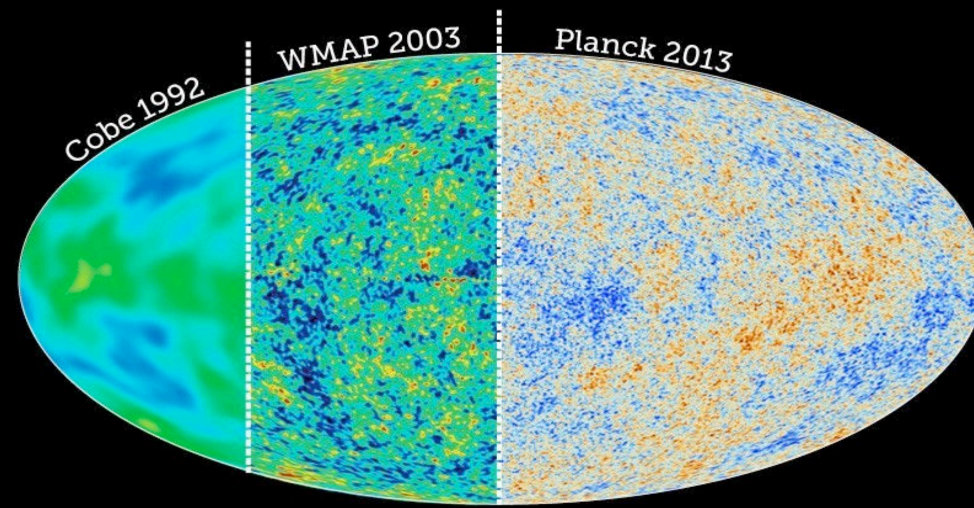
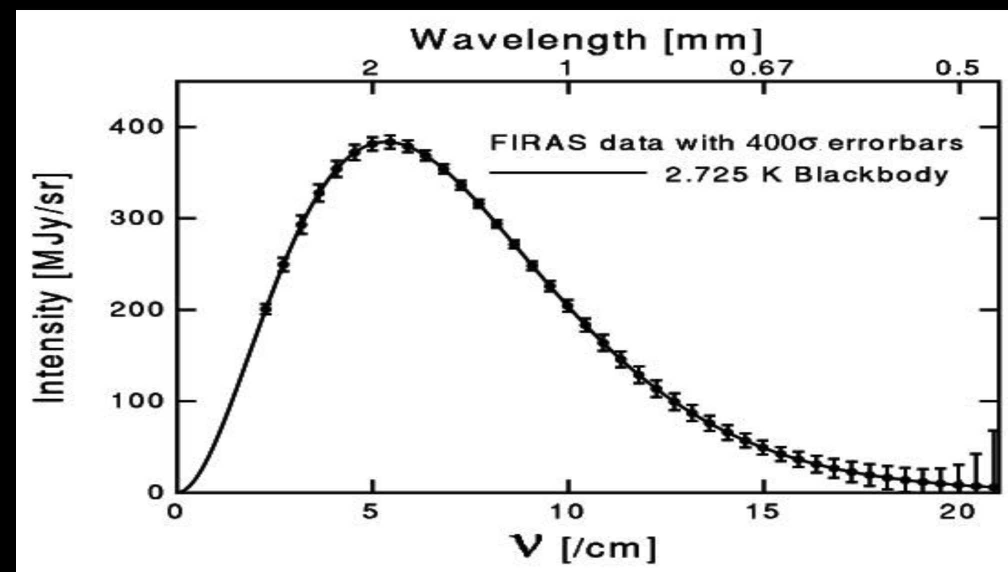
- Besides Planck and WMAP, incredible progress include measurements performed in Antarctica, Atacama, and stratosphere:
  - BOOMERanG
  - DASI
  - (AdV-)ACT(-pol)
  - SPIDER
  - South Pole Telescope (3G)
  - BICEP-KECK
  - Polar Bear/Simons Array
  - ARCADE
  - TRIS
  - CLASS
  - QUIJOTE

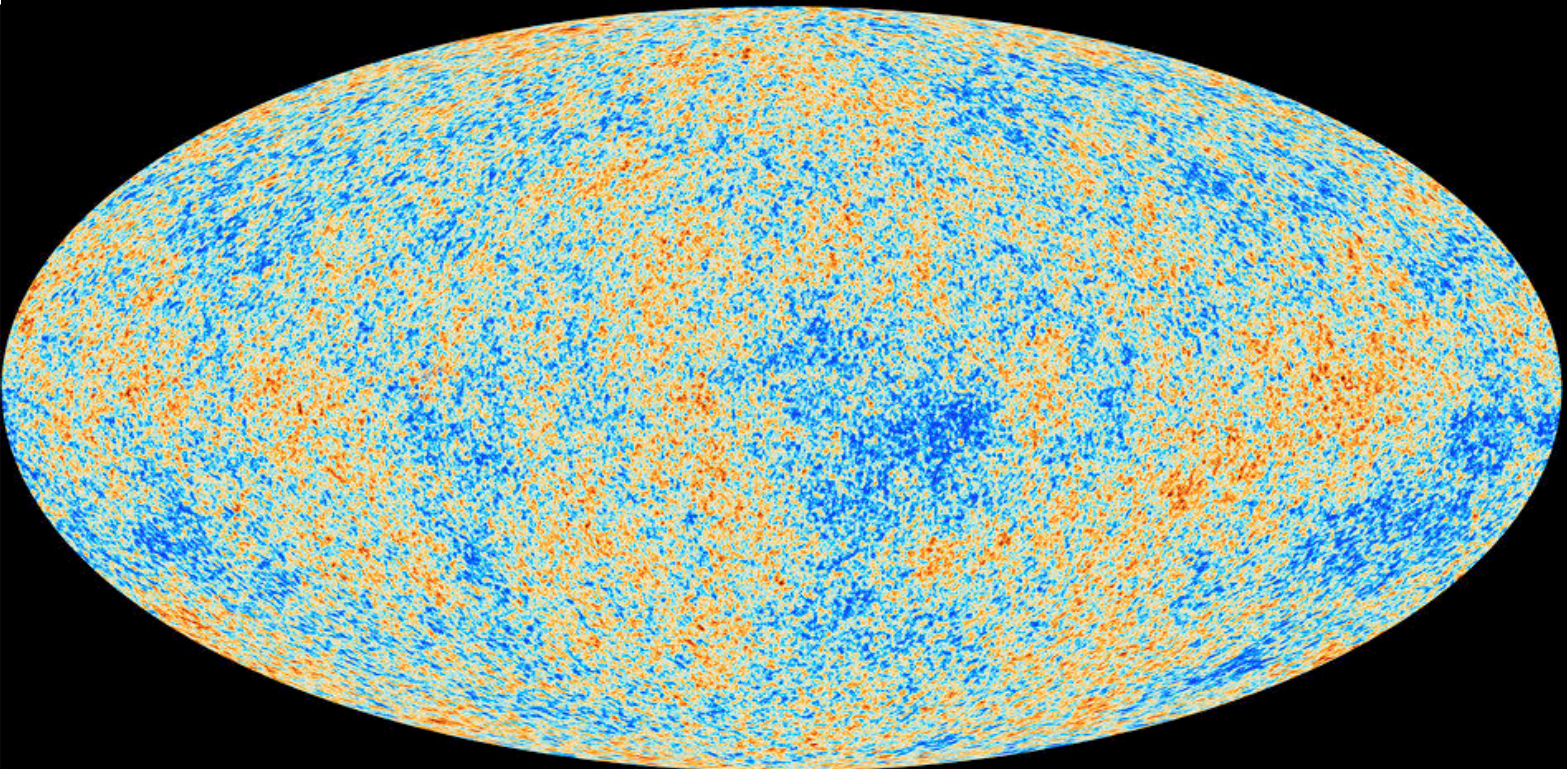




…although not much has happened in the frequency spectrum measurements field

LSS AS SEEN BY PLANCK

- Universe is opaque beyond z~1100



ESA/Planck Collaboration

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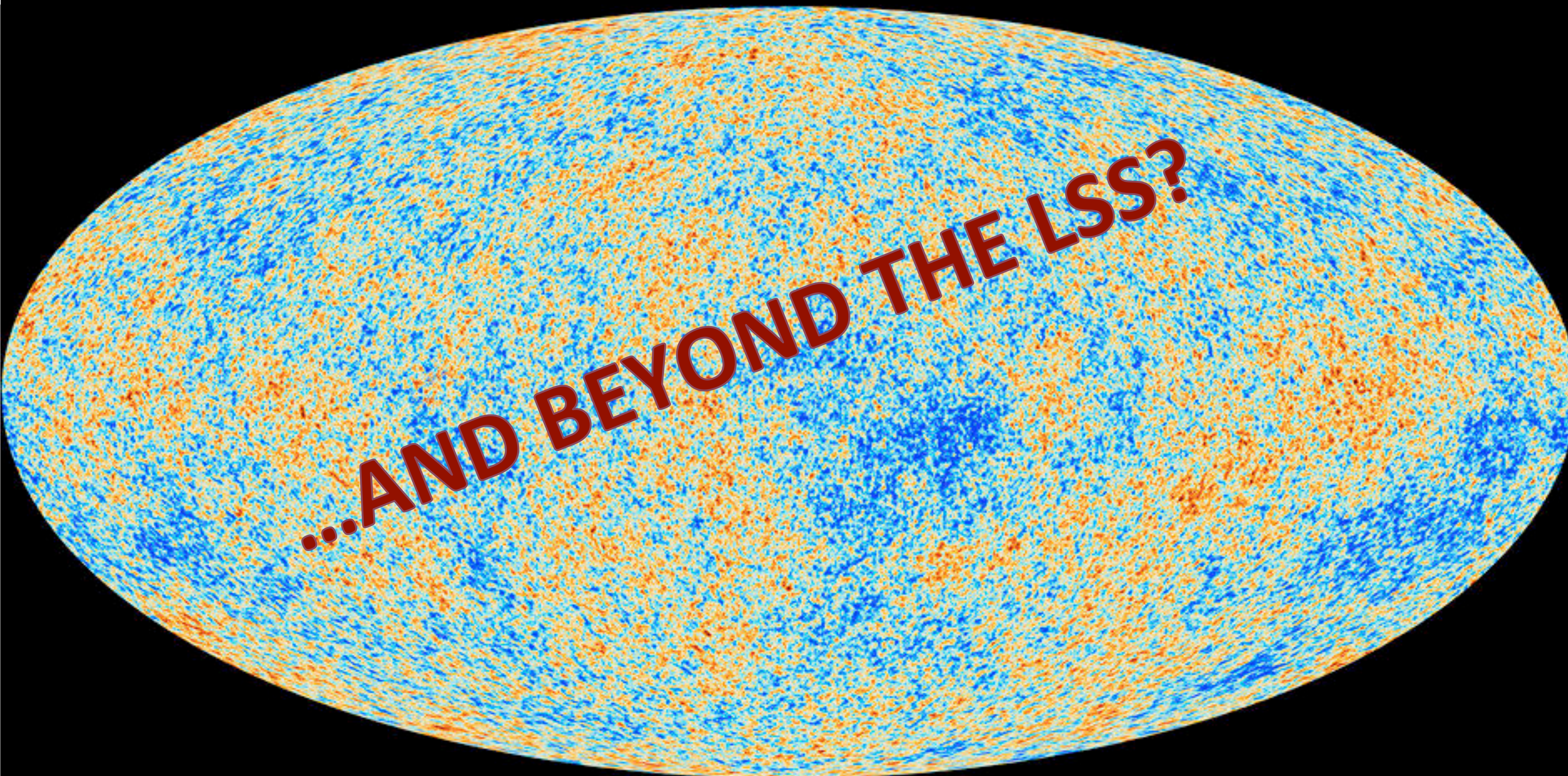

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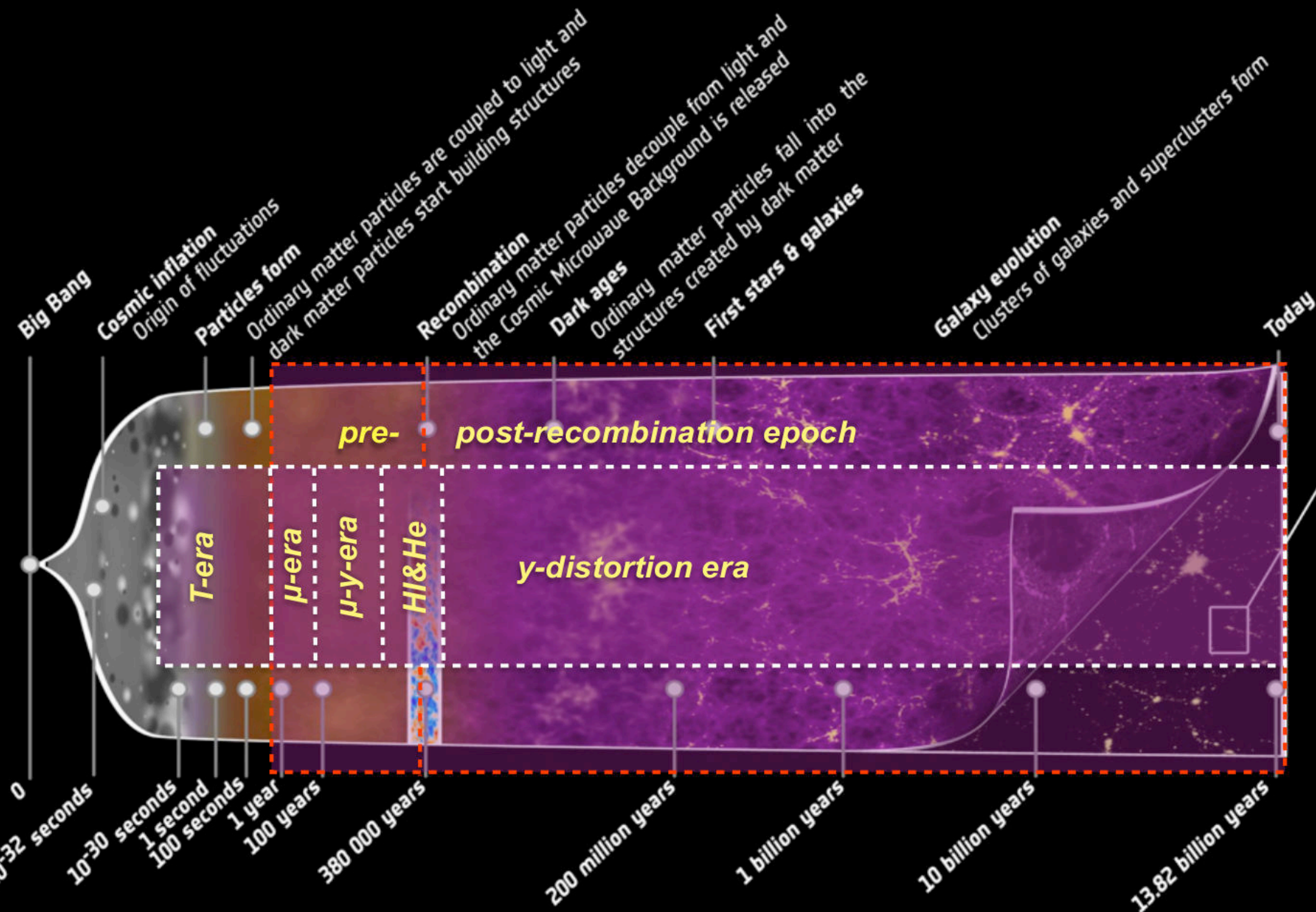

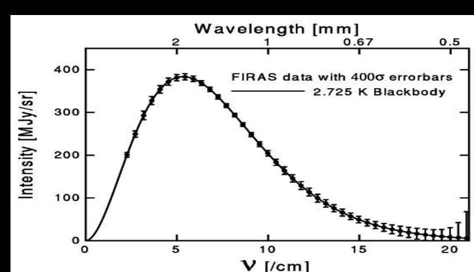

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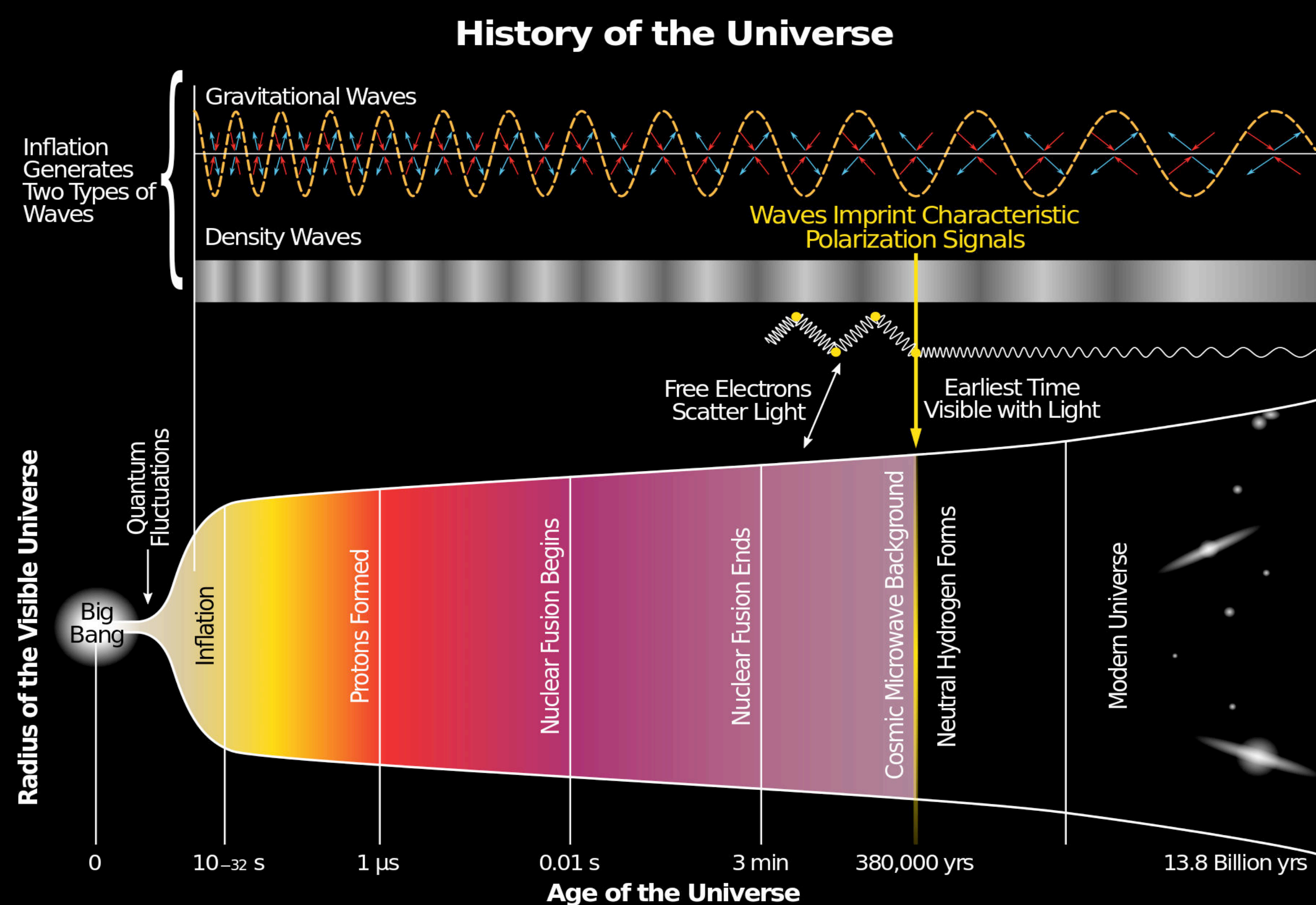
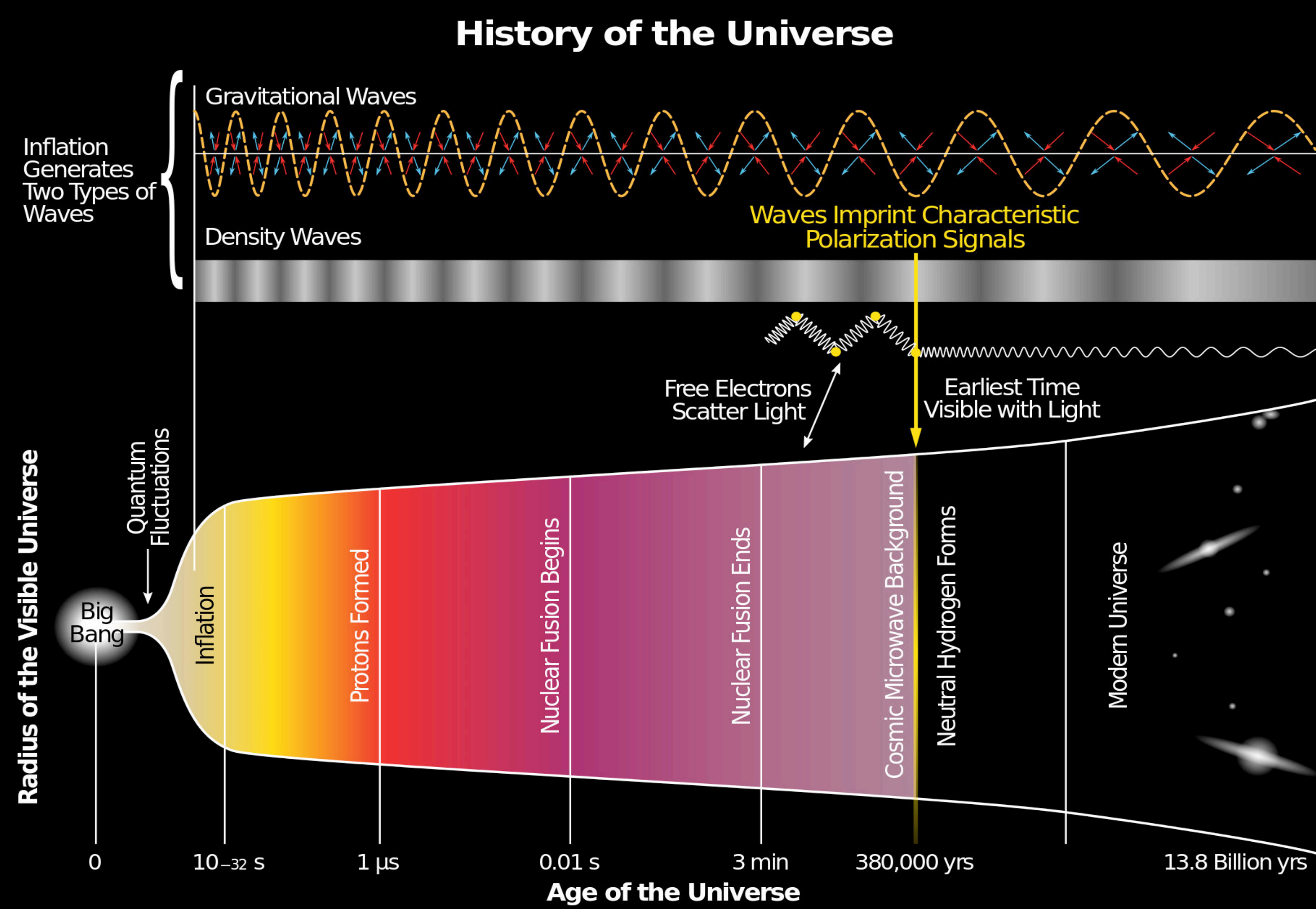
2. Using the CMB as a giant antenna to detect the imprint of the inflationary gravitational waves originated at 10^{-36}s. This needs finer and finer CMB (B-modes) polarization anisotropy study: huge observational effort going on



INFLATION



- Inflation is a period of exponential acceleration of the Universe at the very beginning of it (~10^{-36}s)
- It was invoked to explain flatness problem, super-horizon isotropy, absence of magnetic monopoles
- It provides a convincing theory and predicts a stochastic GW background (it is testable)

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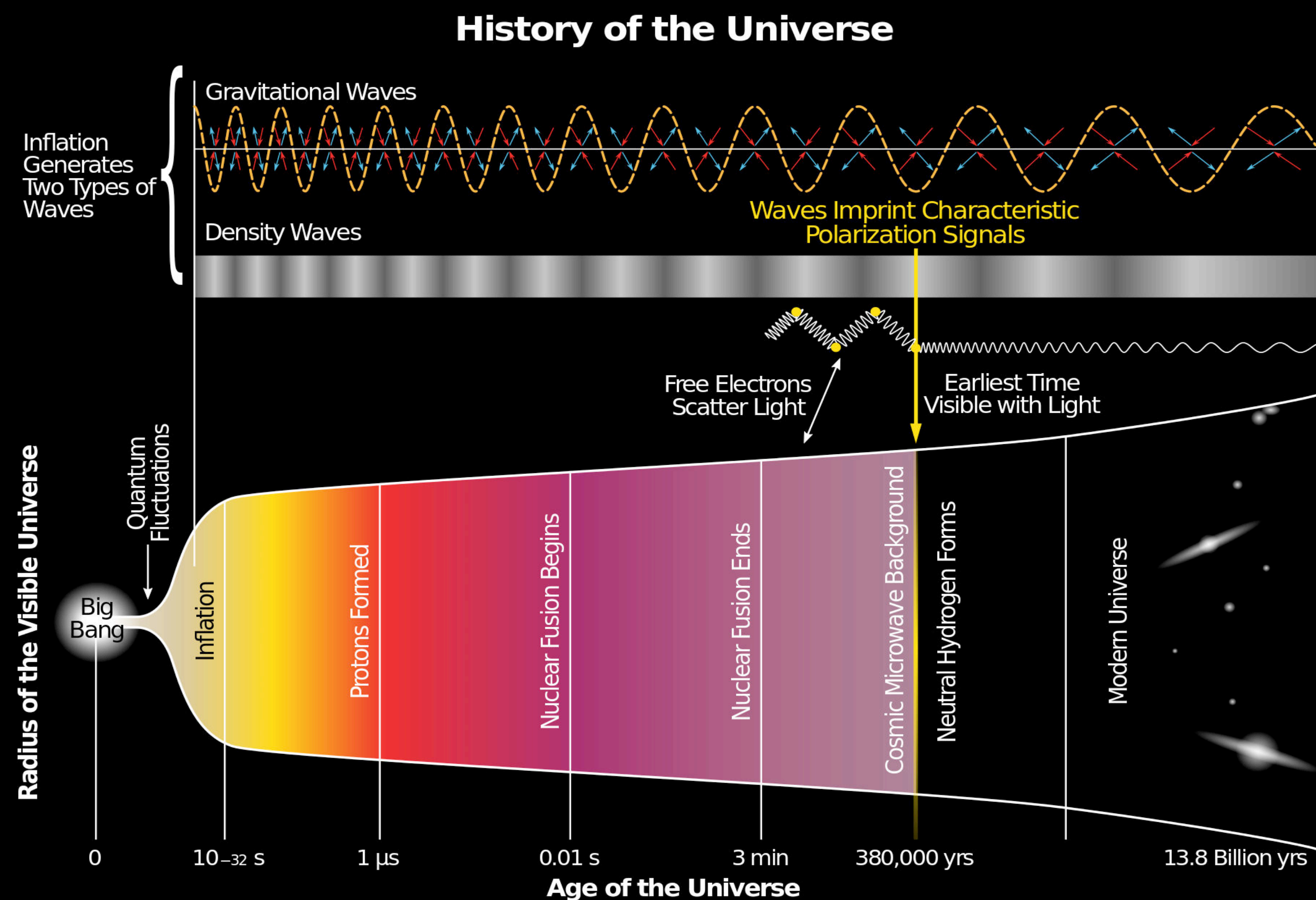

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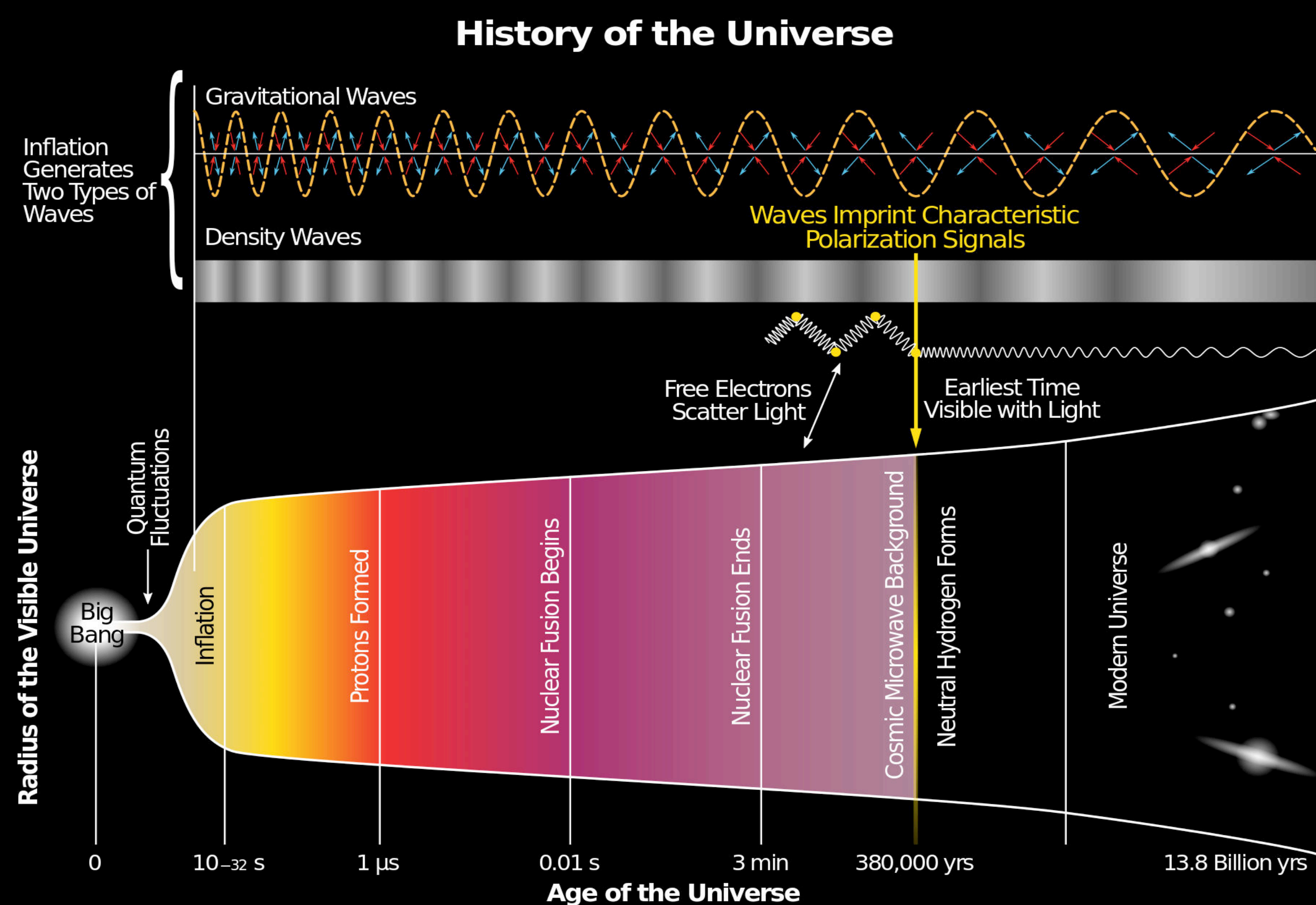

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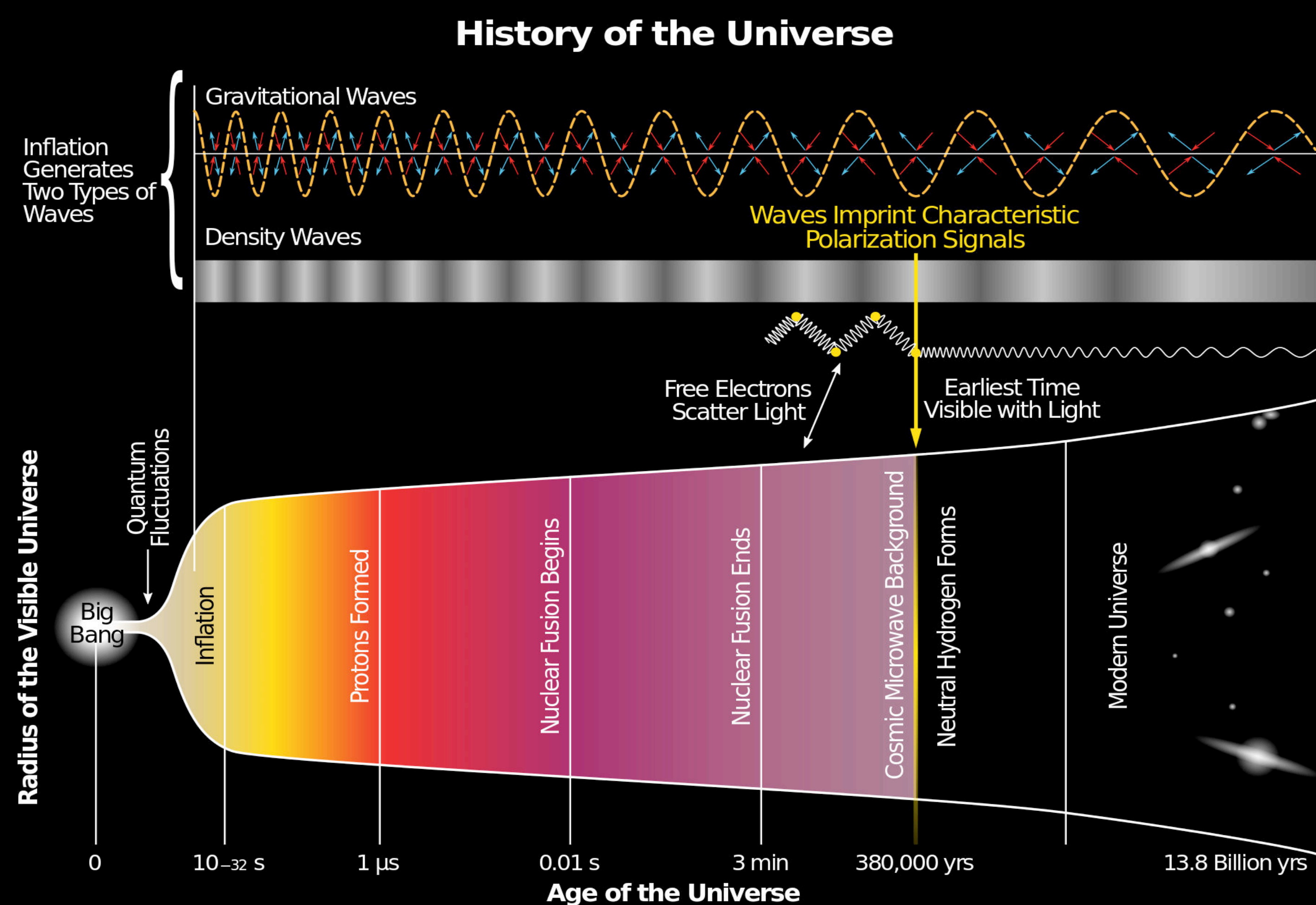

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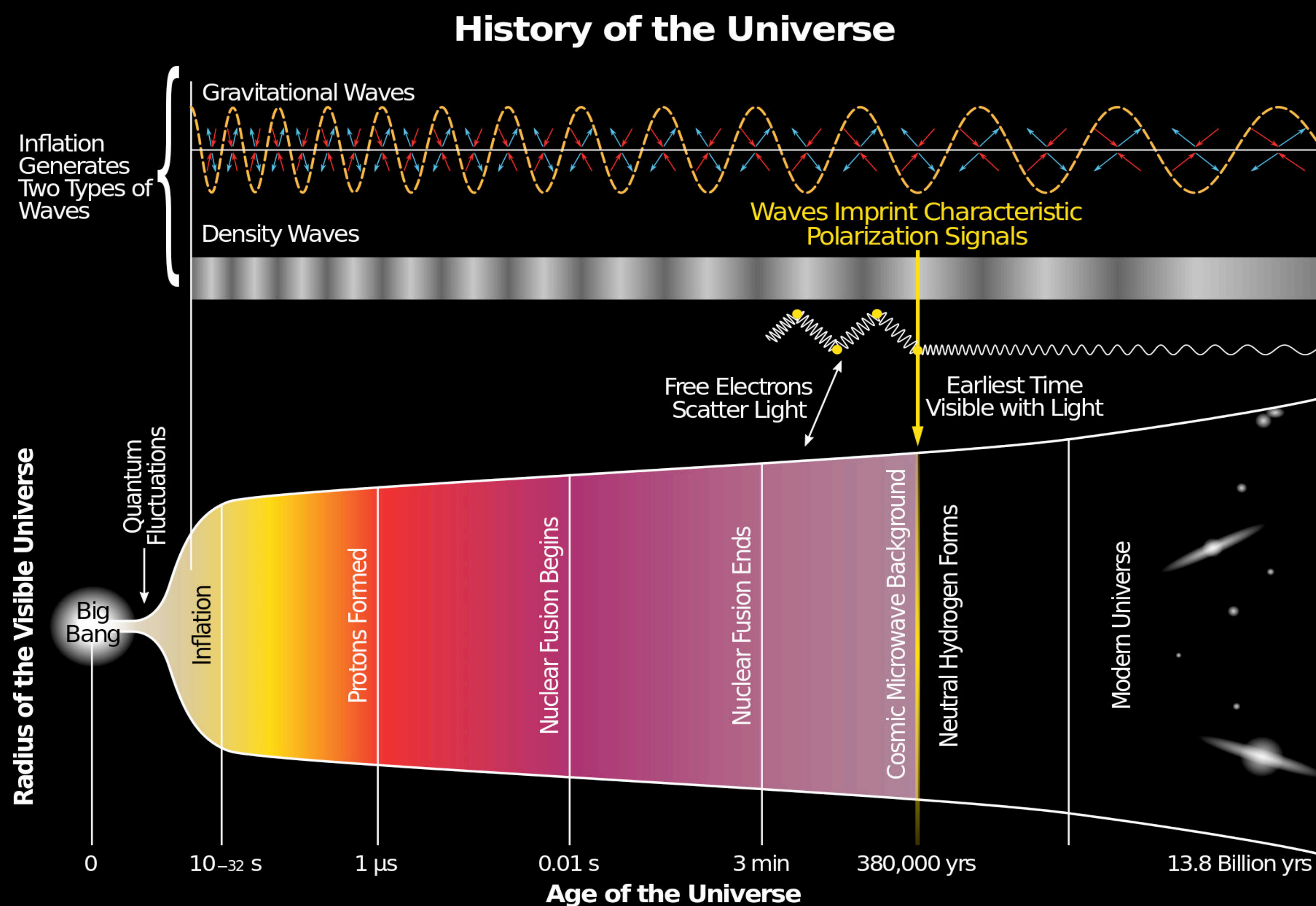

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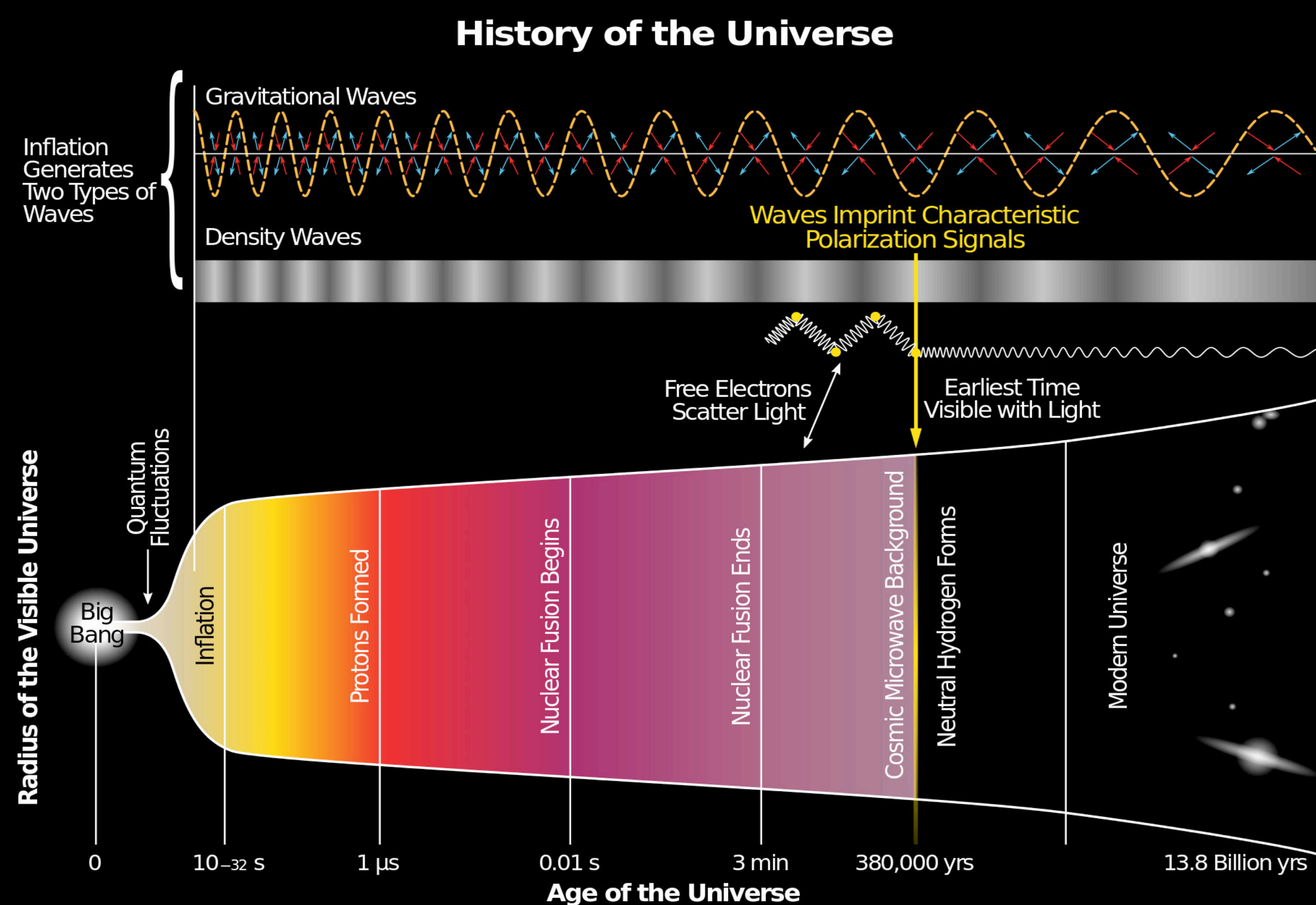
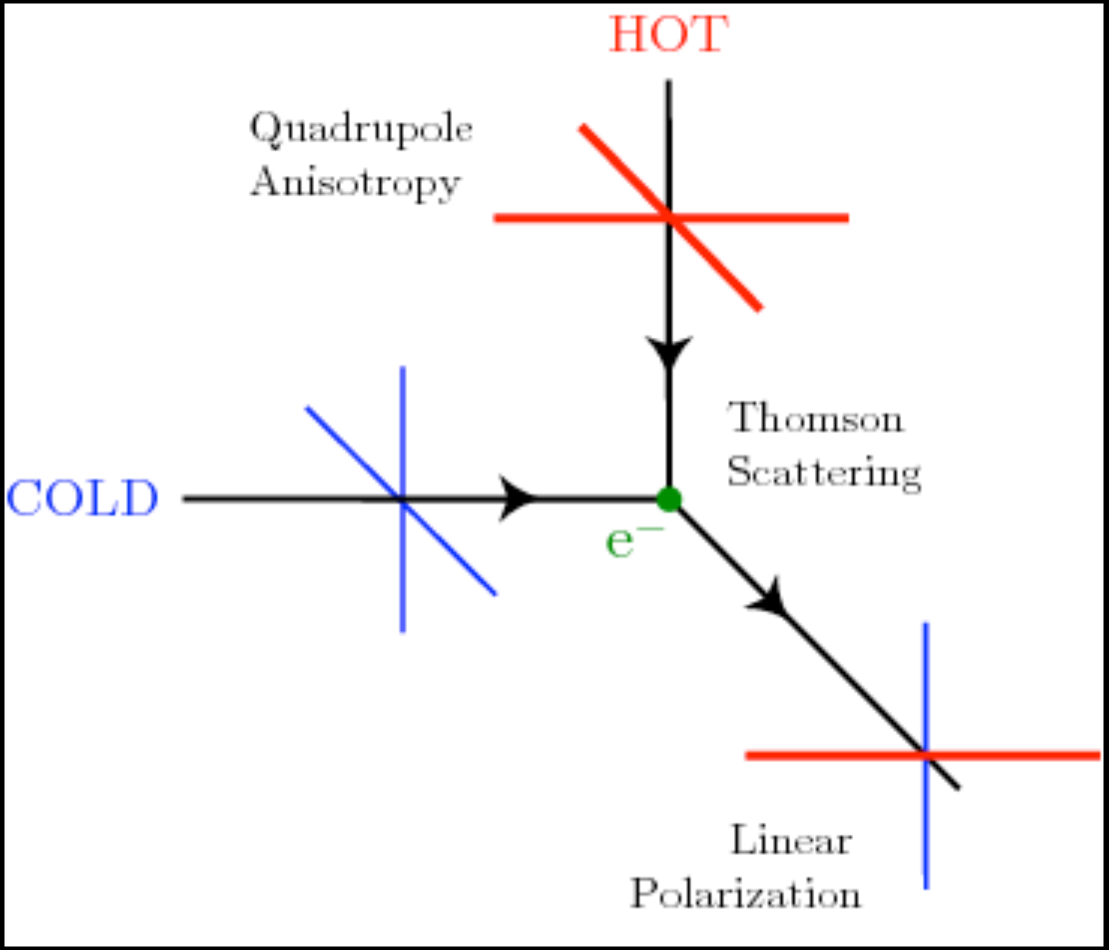
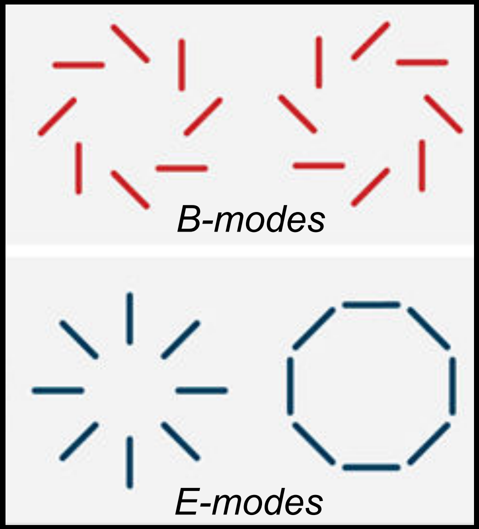


$$r \equiv \frac{Tensor(gravitational)\,pert.ampl.}{Scalar(density)\,pert.ampl.}; \qquad energy = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}} GeV; \qquad time = 10^{-36}\left(\frac{r}{0.01}\right)^{-\frac{1}{2}} s;$$

CMB polarization

- CMB polarization is an incredible source of cosmological information
- Thomson (last) scattering is fully polarized however, if the last scattering electrons "see" isotropic radiation around them, the net polarization is zero
- The presence of a local quadrupole gives rise to a net polarization





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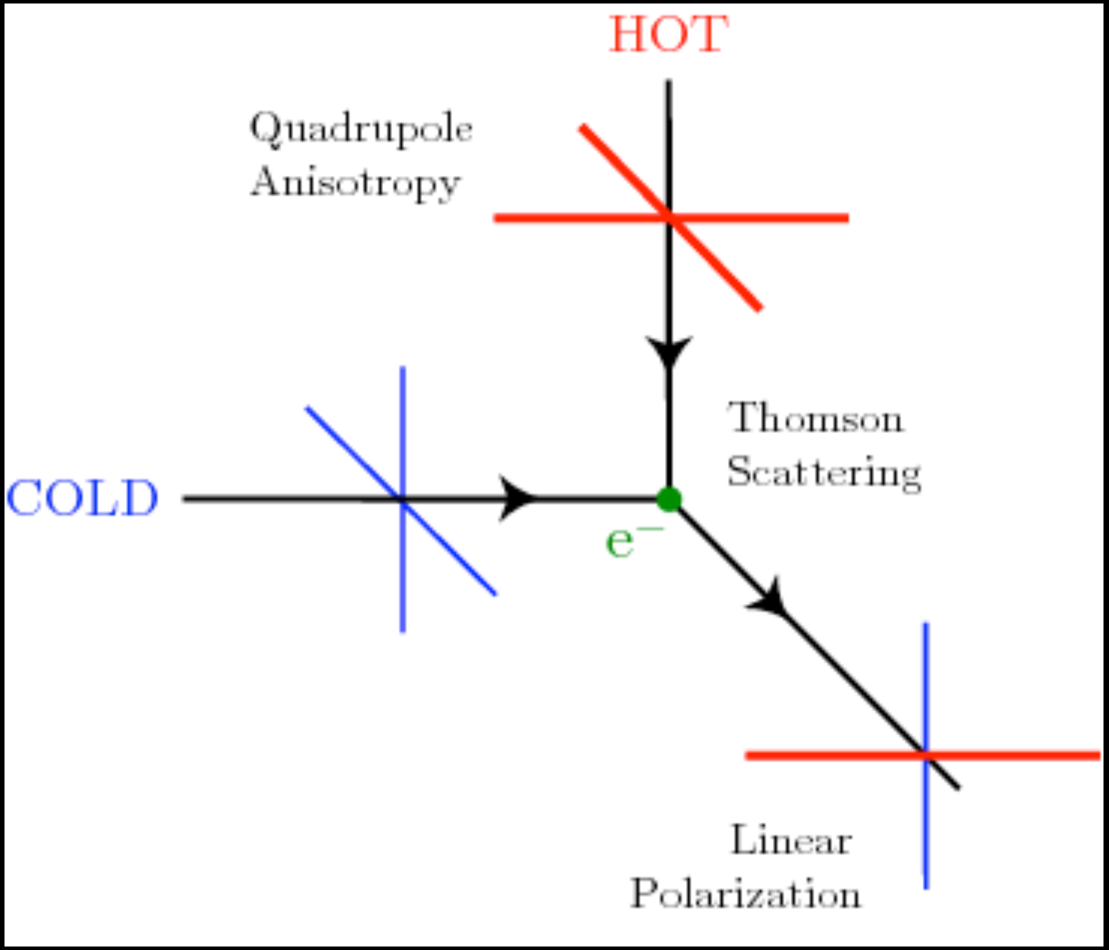

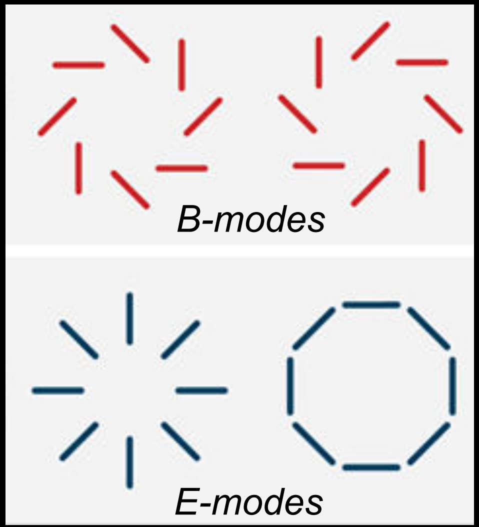

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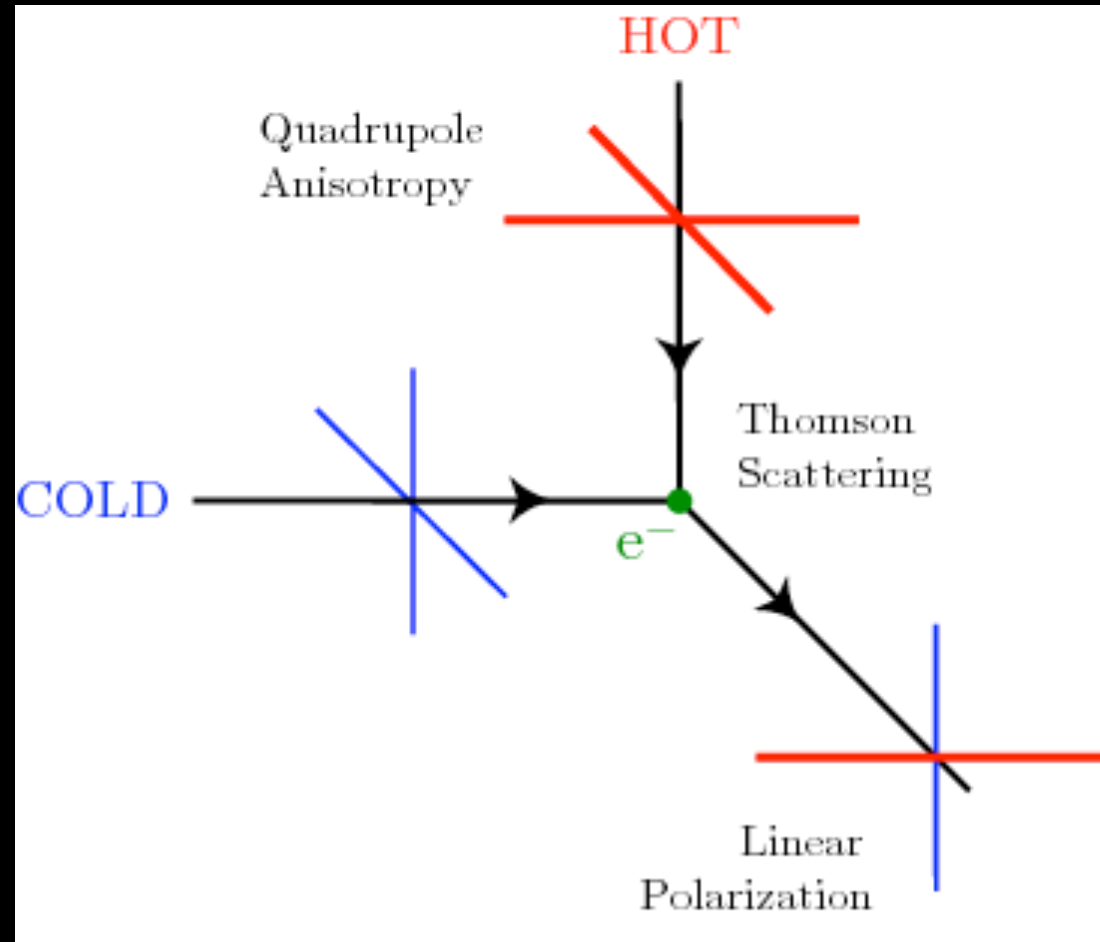
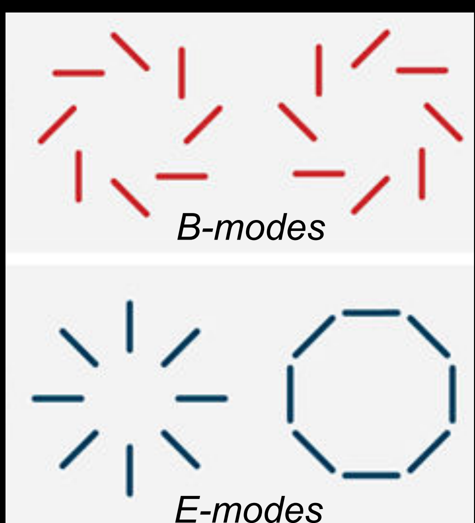
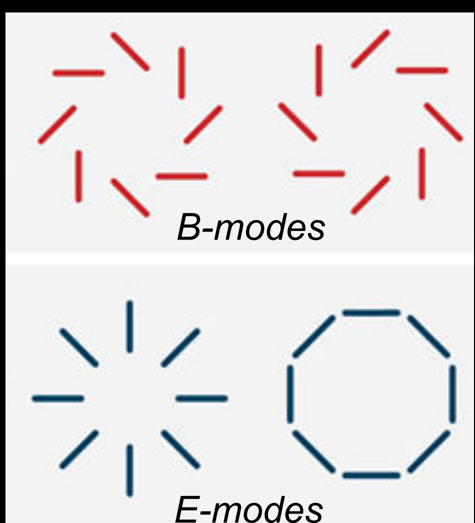


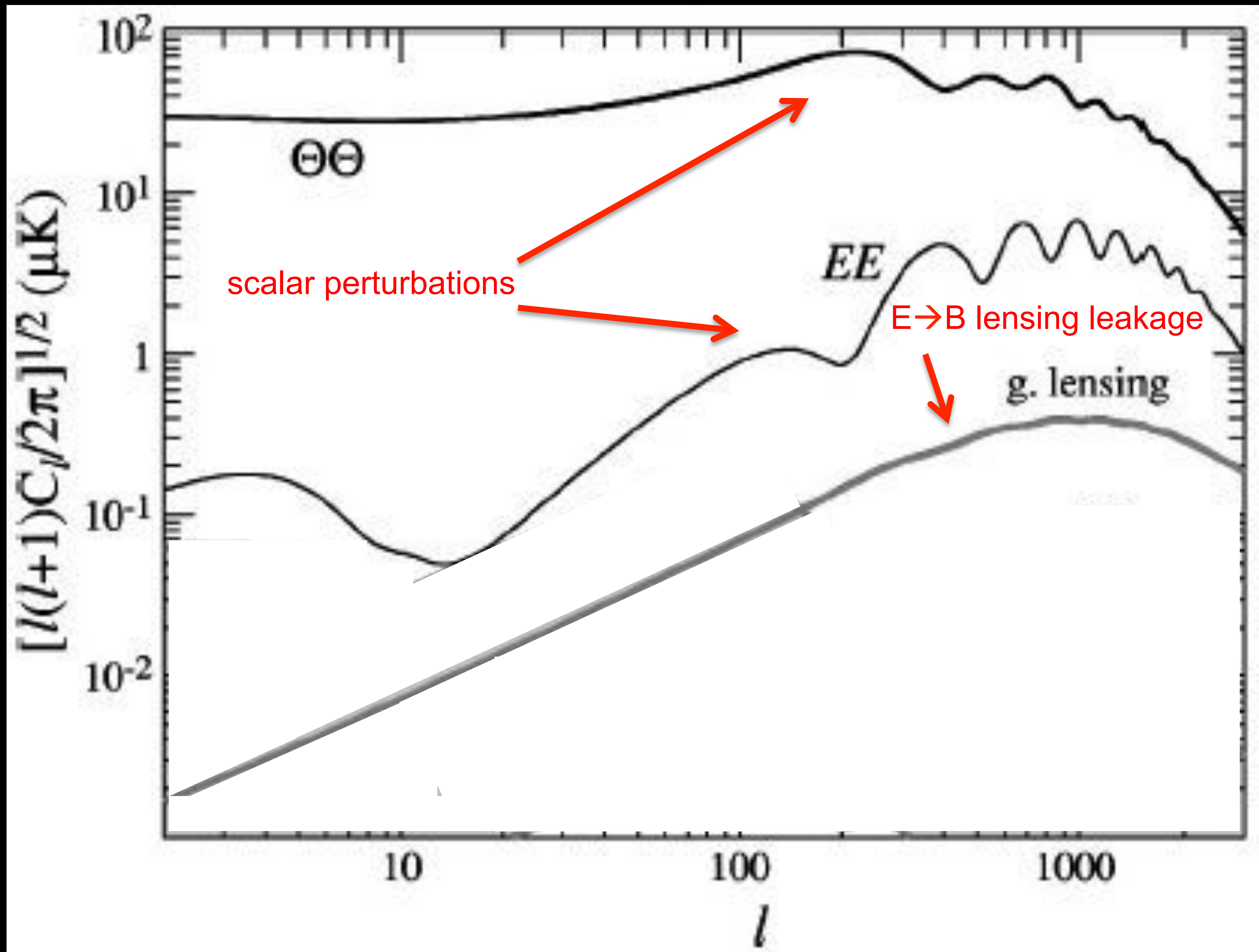


- Density perturbations do give a local quadrupole with a polarization pattern with a pair symmetry, curl free → E-modes
- GW perturbations give any kind of polarization pattern, also odd parity, curl components → B-modes

CMB polarization: E-modes and B-modes

- E-modes can be converted into a curl component whose pattern is characterized by an odd parity: B-modes
- This is due to large structures at small angular scales through gravitational lensing





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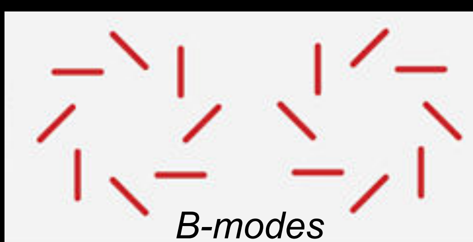
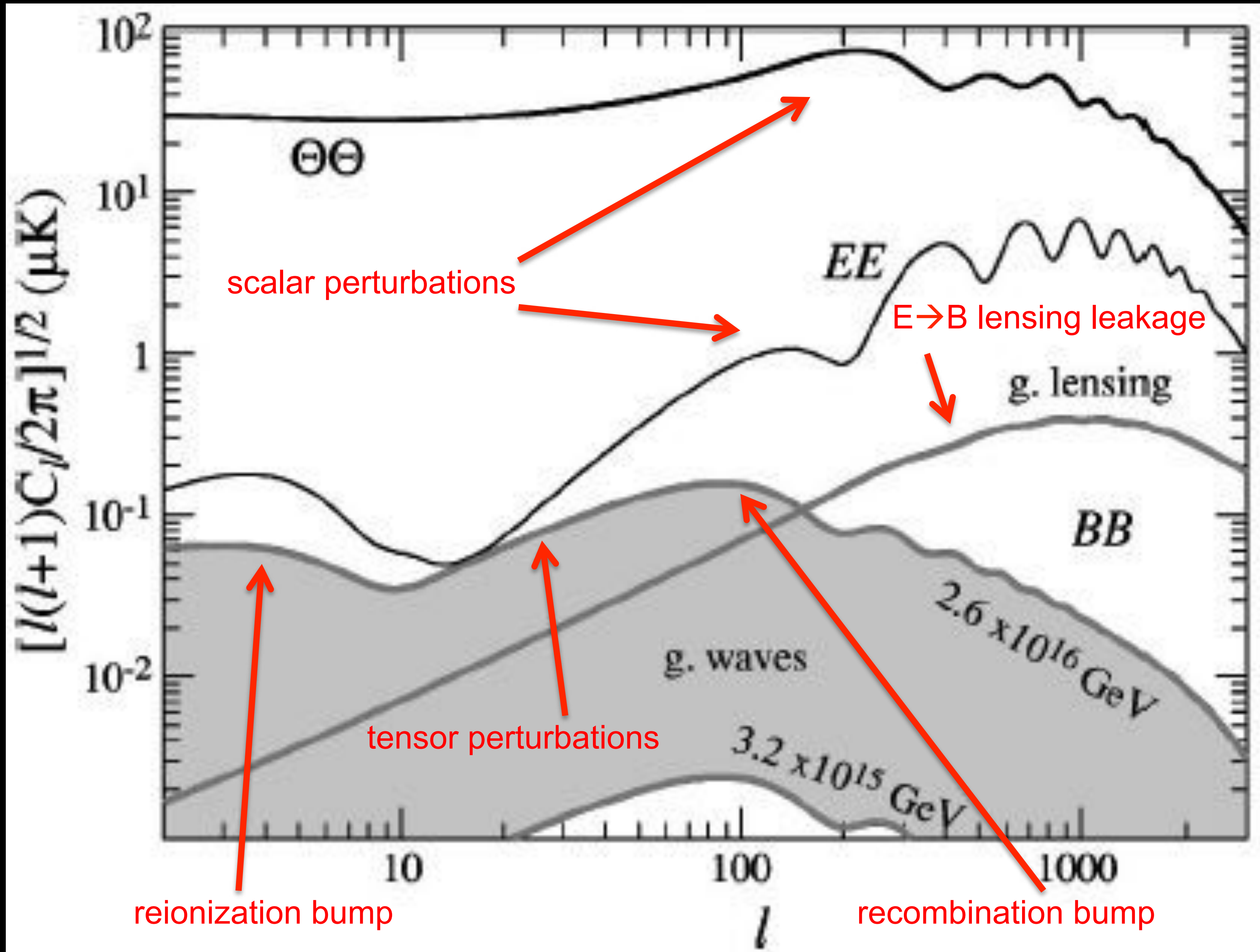
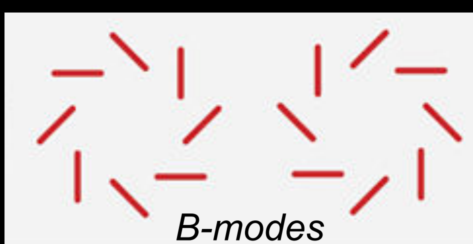


- B-modes can uniquely be produced by gravitational waves at
  - Medium scales
  - Large scales



CMB polarization: E-modes and B-modes

- Current status for CMB polarization measurements: AMAZING!
- B+K/Planck/ PolarBear: r<0.07
- Still a long way to go
- For r~0.01 de-lensing is important



- Some models predict r≥0.002 (Starobinsky)
- If so ~10^{16}GeV (GUT)

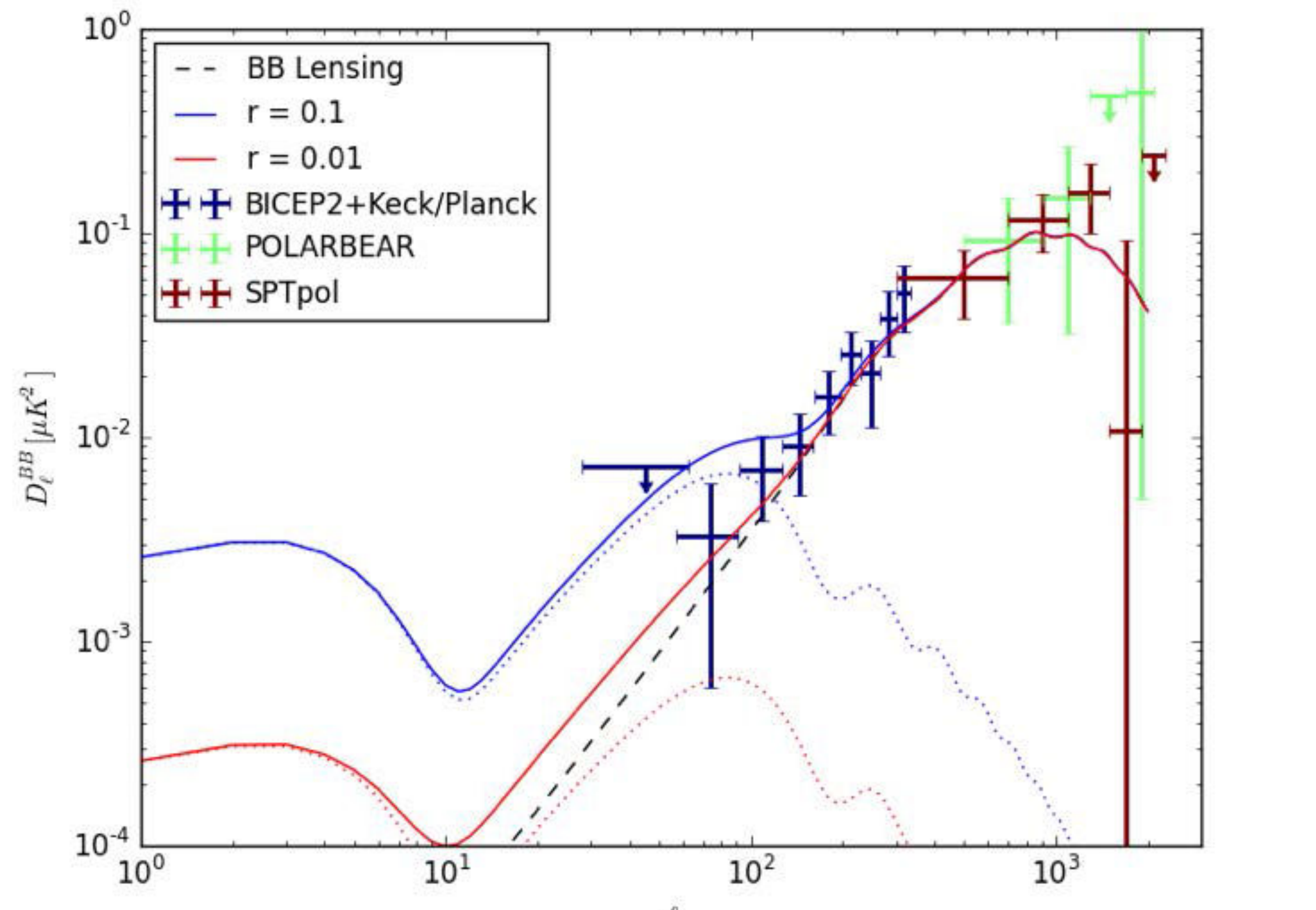


Fig. by NASA-LAMBDA

B-modes experiments

How to measure B-modes

- Complementarity:

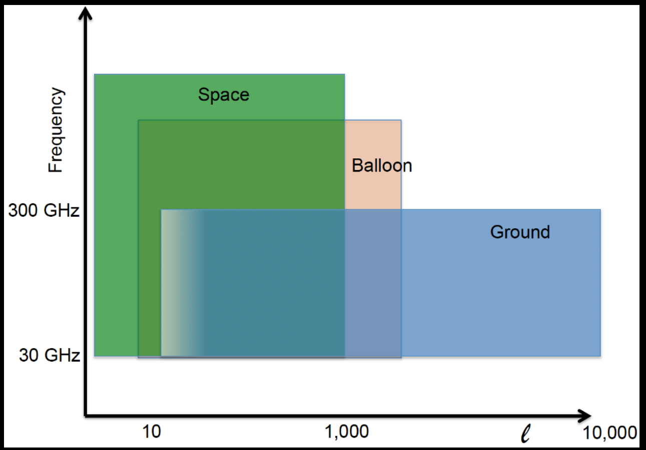
foreground

vs

sky coverage

vs

angular resolution



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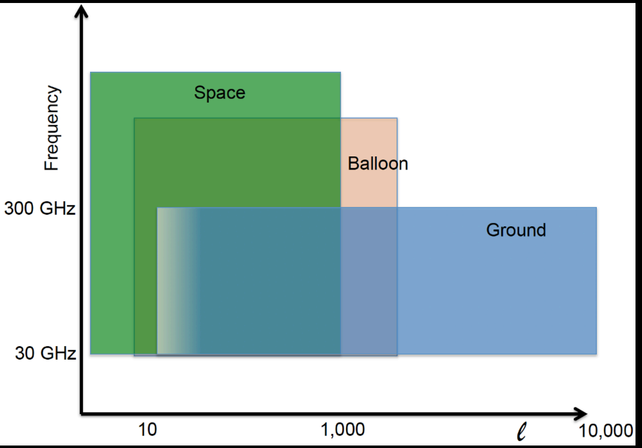
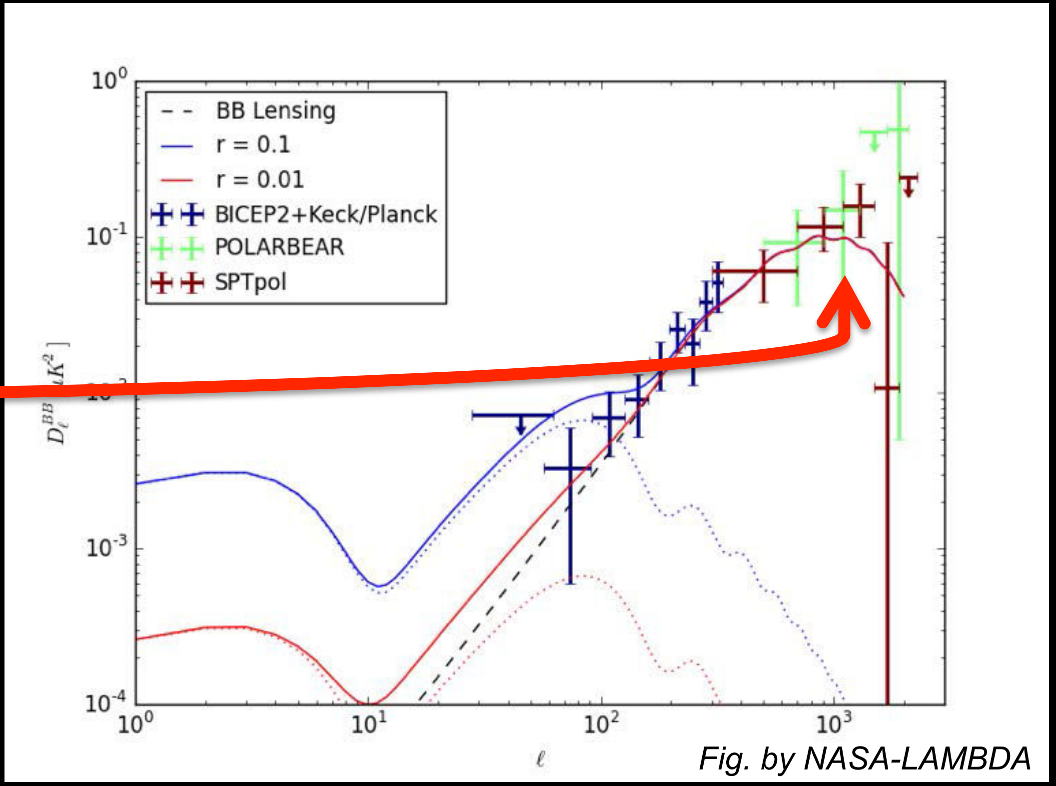


- B-modes power spectrum:

  (de-)lensing



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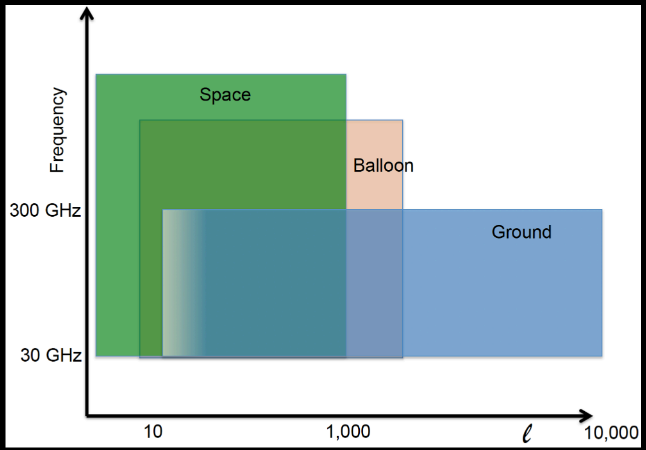

- B-modes power spectrum:

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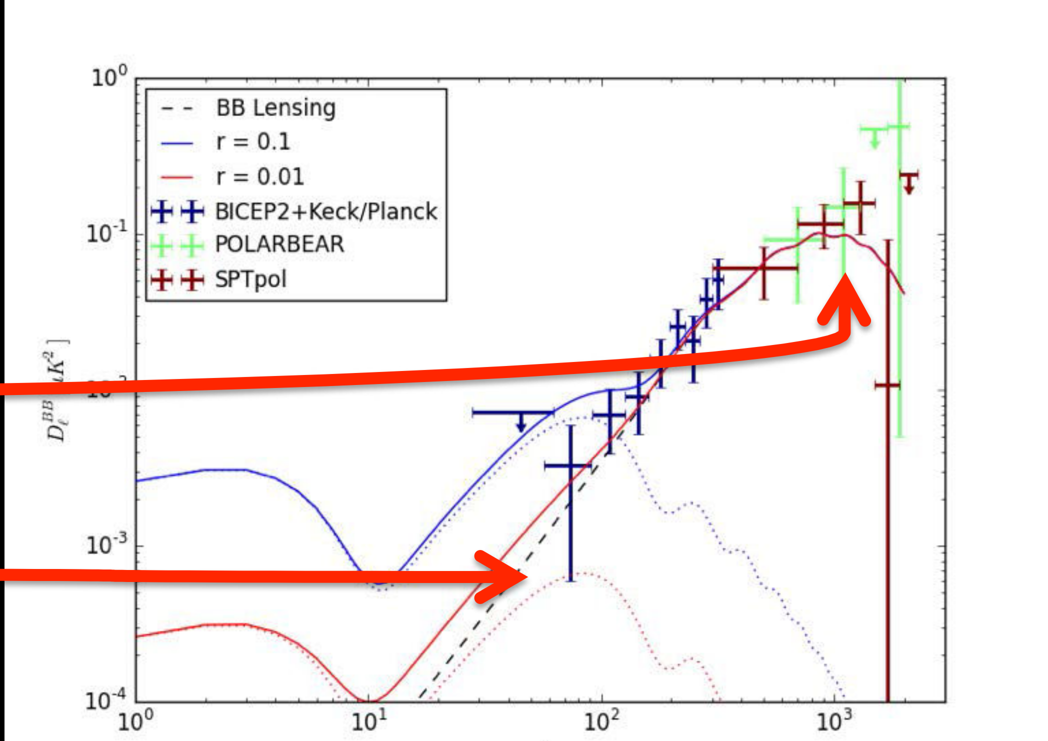
recombination bump



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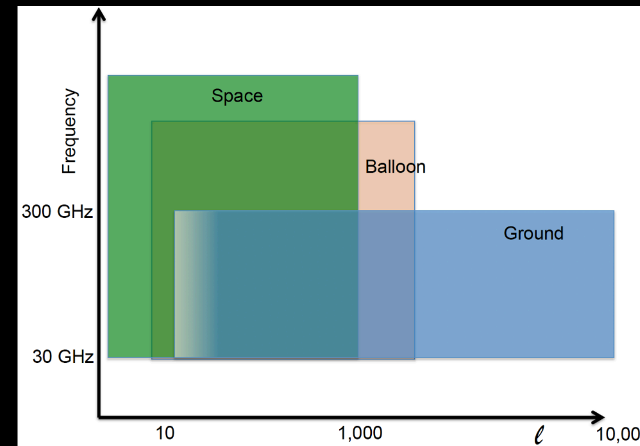


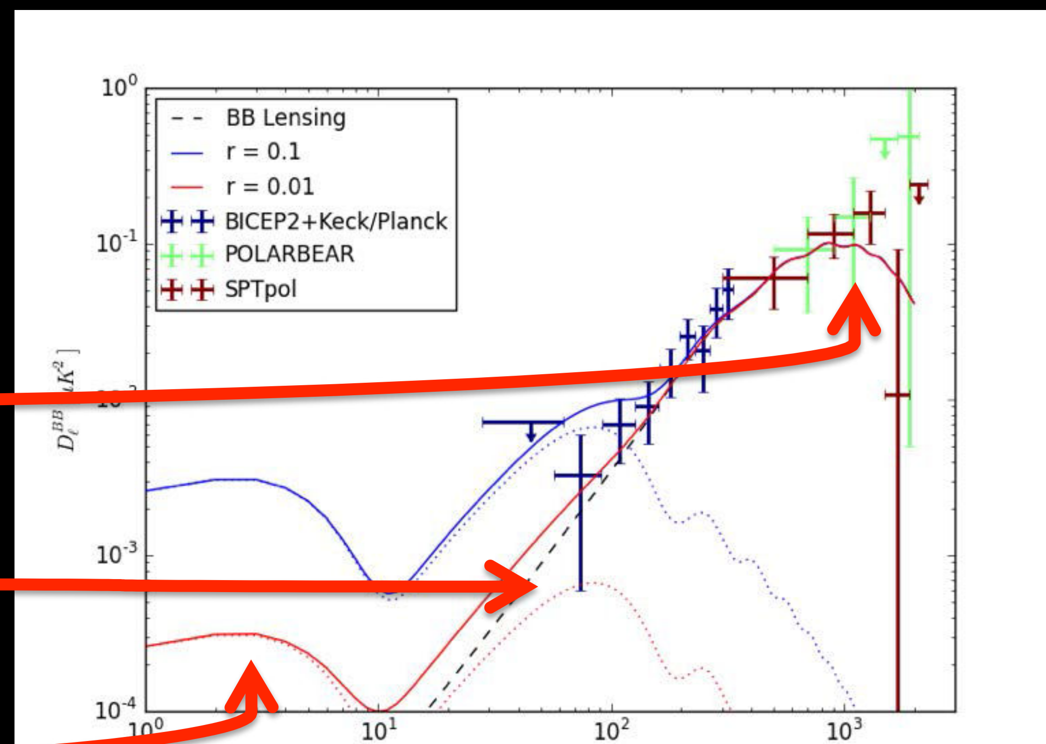
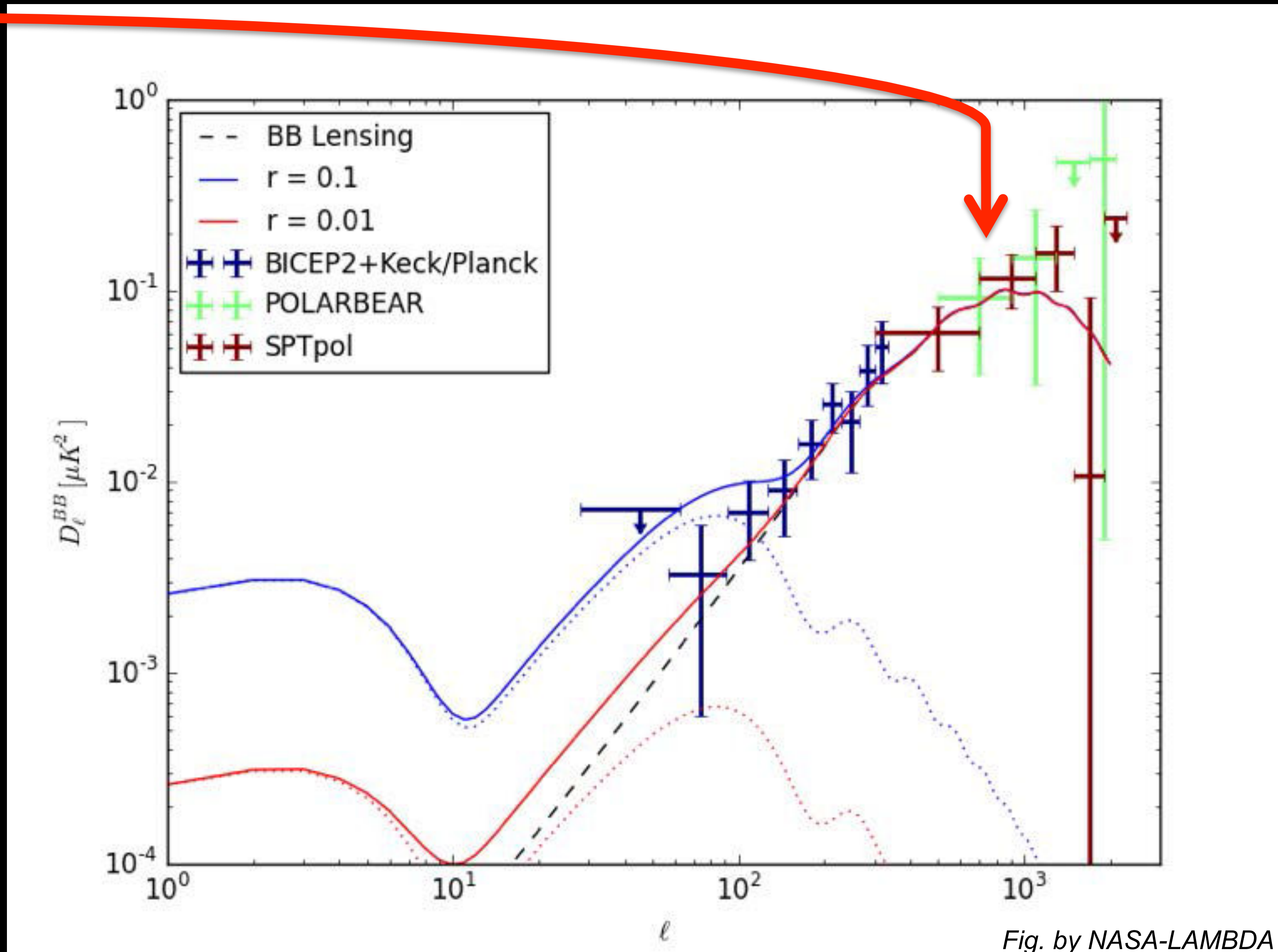


Fig. by NASA-LAMBDA

How to measure B-modes

(de-) lensing



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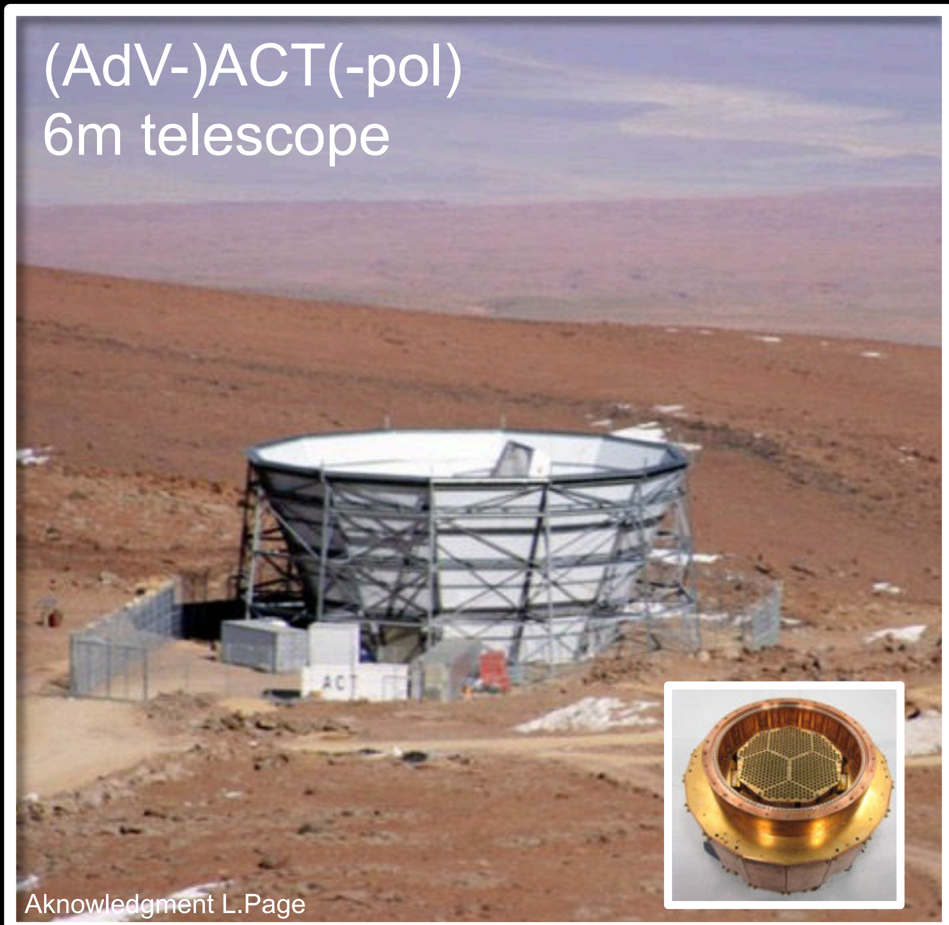
Large aperture experiments: ground



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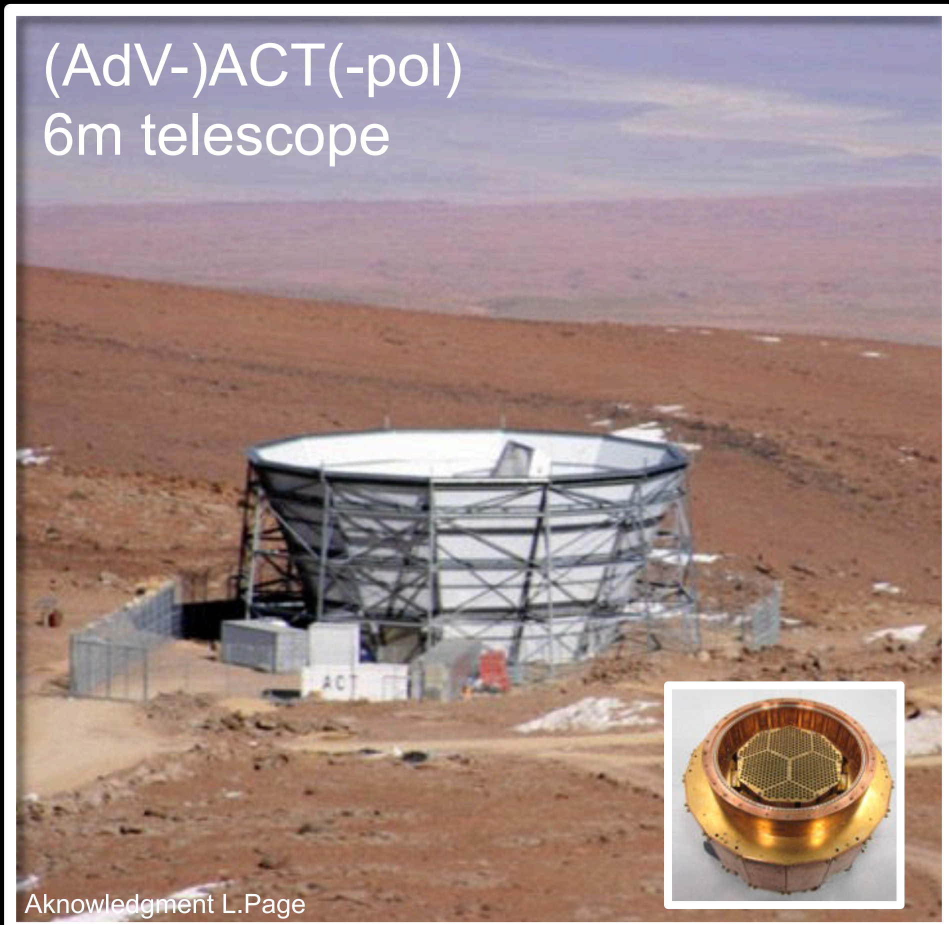

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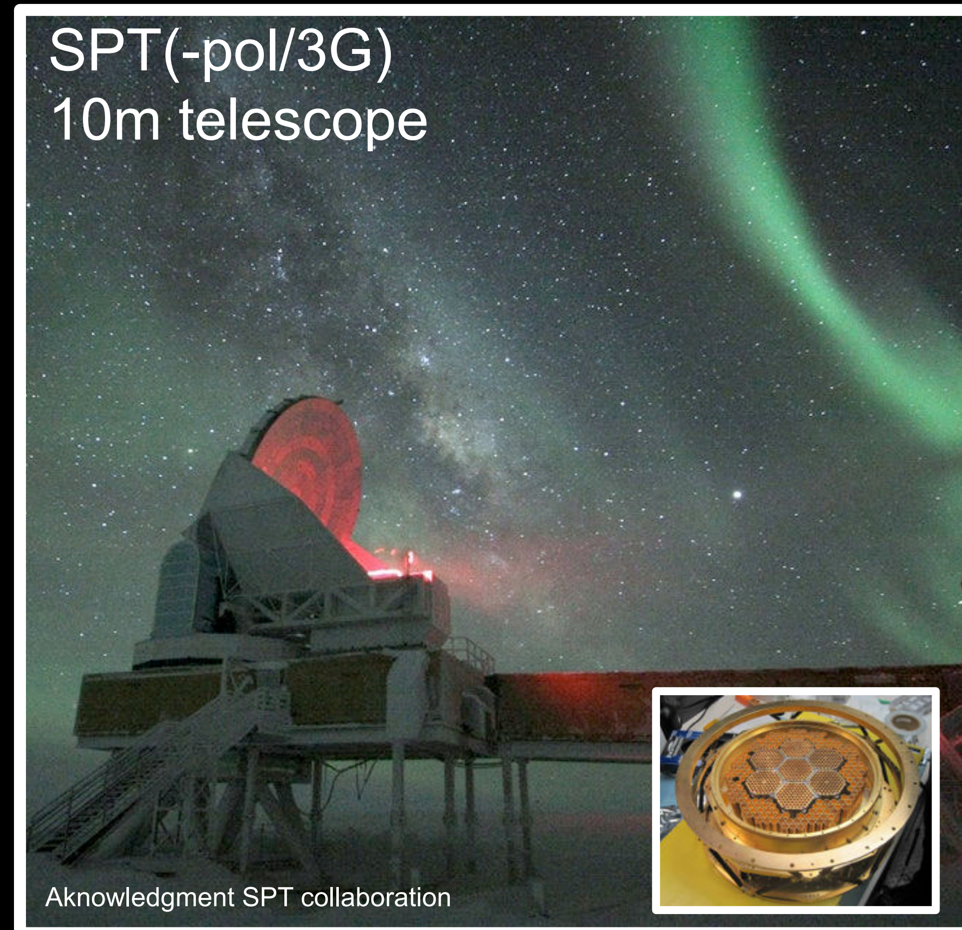
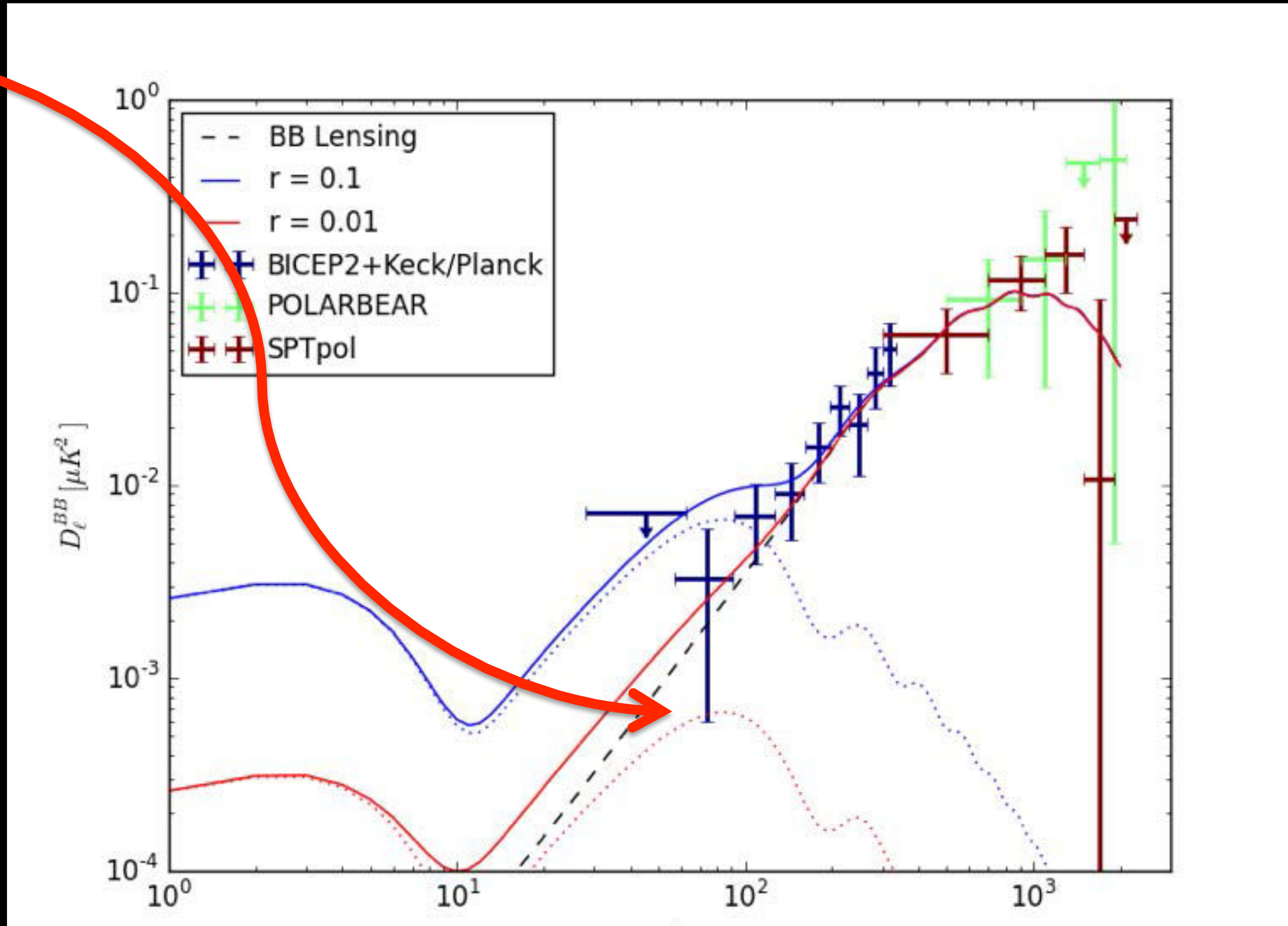


- J. Carlstrom (Chicago) et al.
- Deep, high (best!) angular res survey!
- Trial-band multichroic FDM'ed TES (90/150/220 GHz) with Sinuous Focal Plane
- SPT-3G : 16260 pixels → r<0.01

How to measure B-modes

recombination bump



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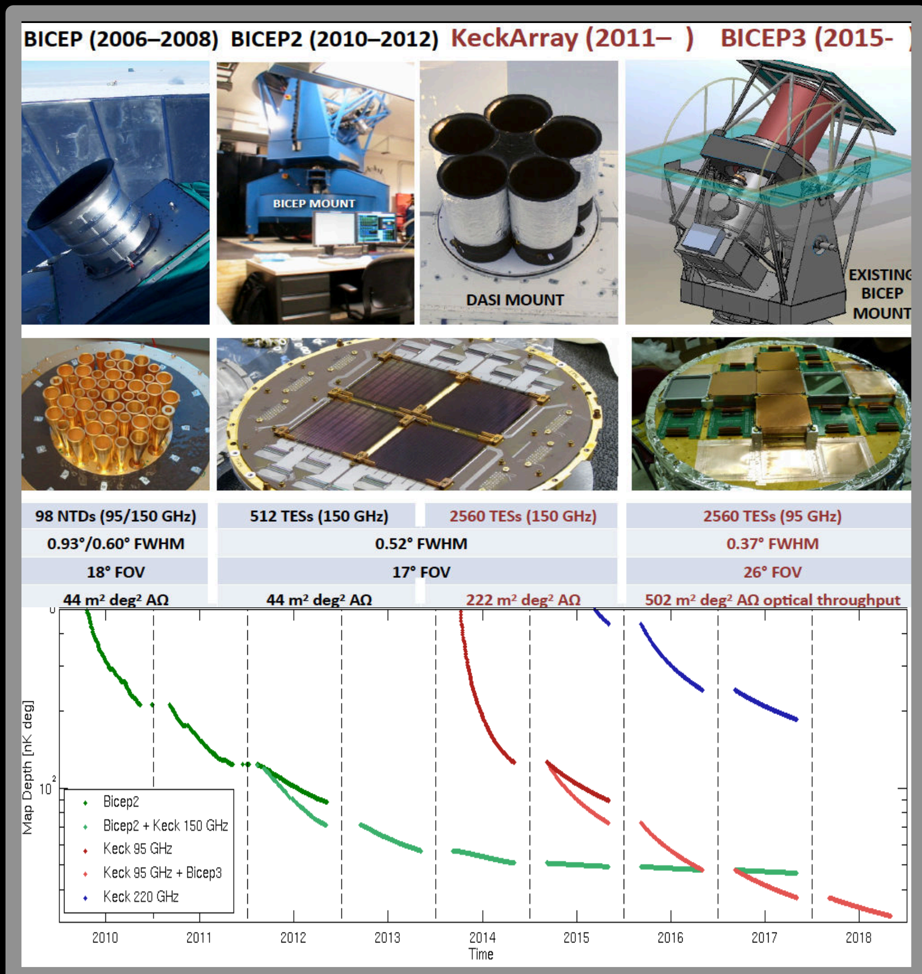
Medium aperture experiments: ground

Aknowledgment BICEP/Keck collaboration



- Kovach (Harvard) et al.; Kuo (Stanford) et al.
- Bock (Caltech) et al.; Pryke (Minnesota) at al.
- Super deep survey: so far the most sensitive
- Primordial B-modes optimized
- Simple optics; great detectors: slot antennas, microstrip filters, load dissipation, TES, TDM

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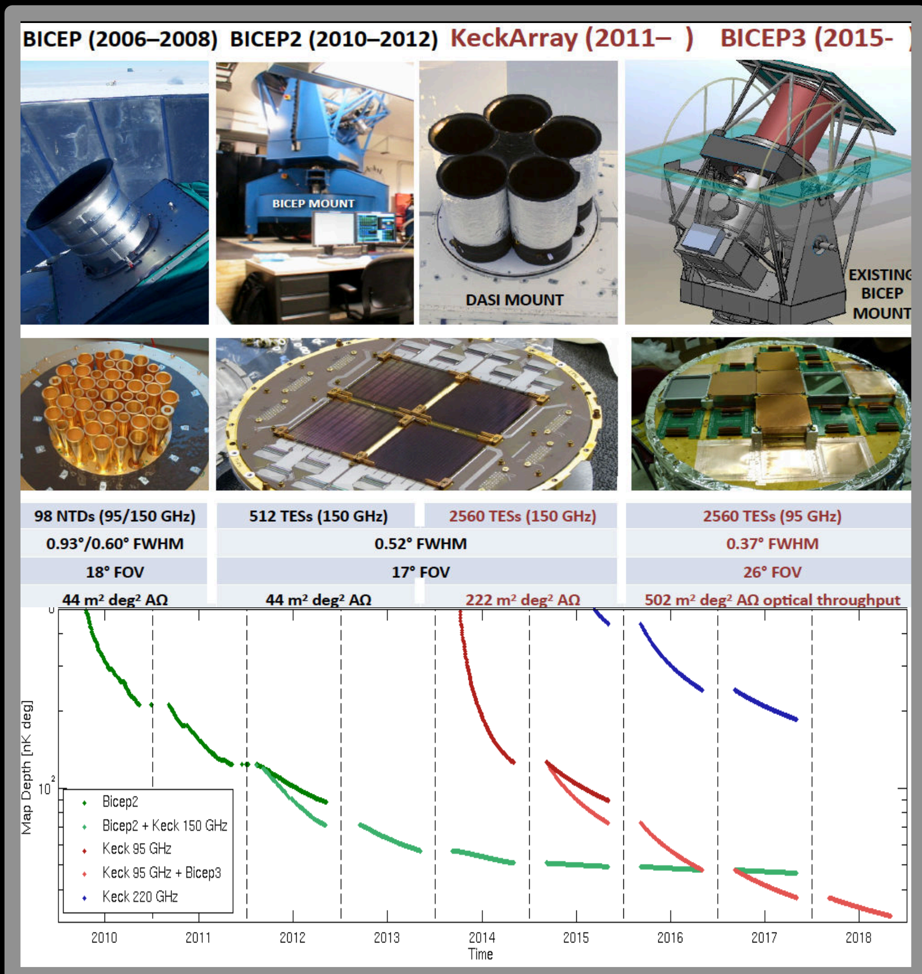

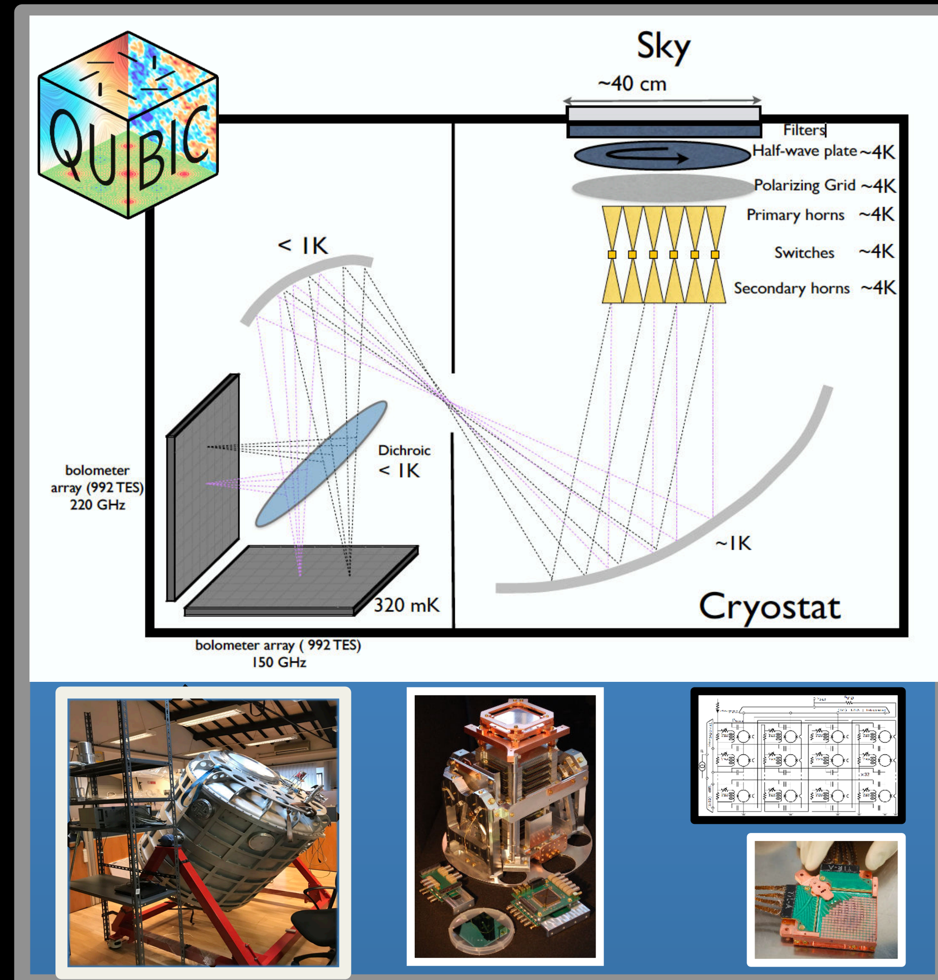

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- J-C Hamilton (APC) et al. (mainly French-Italian)
- The only European ground based effort (from end 2018)
- Primordial (recombination bump) B-modes: r<0.01
- Bolometric Interferometry: the systematic control of interferometers the sensitivity of bolos (2000 TES TDM)
- Next 6 module at 90-220GHz

QUBIC experiment

QUBIC

a Q&U Bolometric Interferometer for Cosmology

APC Paris, France
C2N Orsay, France
CSNSM Orsay, France
IAS Orsay, France
IRAP Toulouse, France
LAL Orsay, France
Universita di Milano-Bicocca, Italy
Universita degli studi di Milano, Italy
Universita La Sapienza, Roma, Italy
Maynooth University, Ireland
Cardiff University, UK
University of Manchester, UK
Brown University, USA
Richmond University, USA
University of Wisconsin, USA
Centro Atómico Constituyentes, Argentina
GEMA, Argentina
Comisión Nacional de Energía Atómica, Argentina
Facultad de Cs Astronómicas y Geofísicas, Argentina
Centro Atómico Bariloche and Instituto Balseiro, Argentina
Instituto de Tecnologías en Detección y Astropartículas, Argentina
Instituto Argentino de Radioastronomía, Argentina

QUBIC experiment

- **400 Elements Bolometric Interferometer**
  - Synthesized imaging on focal planes
  - 23.5 arcmin FWHM

→ Synthesized imager scanning the sky good beam control

- **TES Focal planes**
  - 2048 TES with NEP ~ 4×10^{-17} $W.Hz^{-1/2}$
  - 128:1 SQUIDs+ASIC Mux Readout

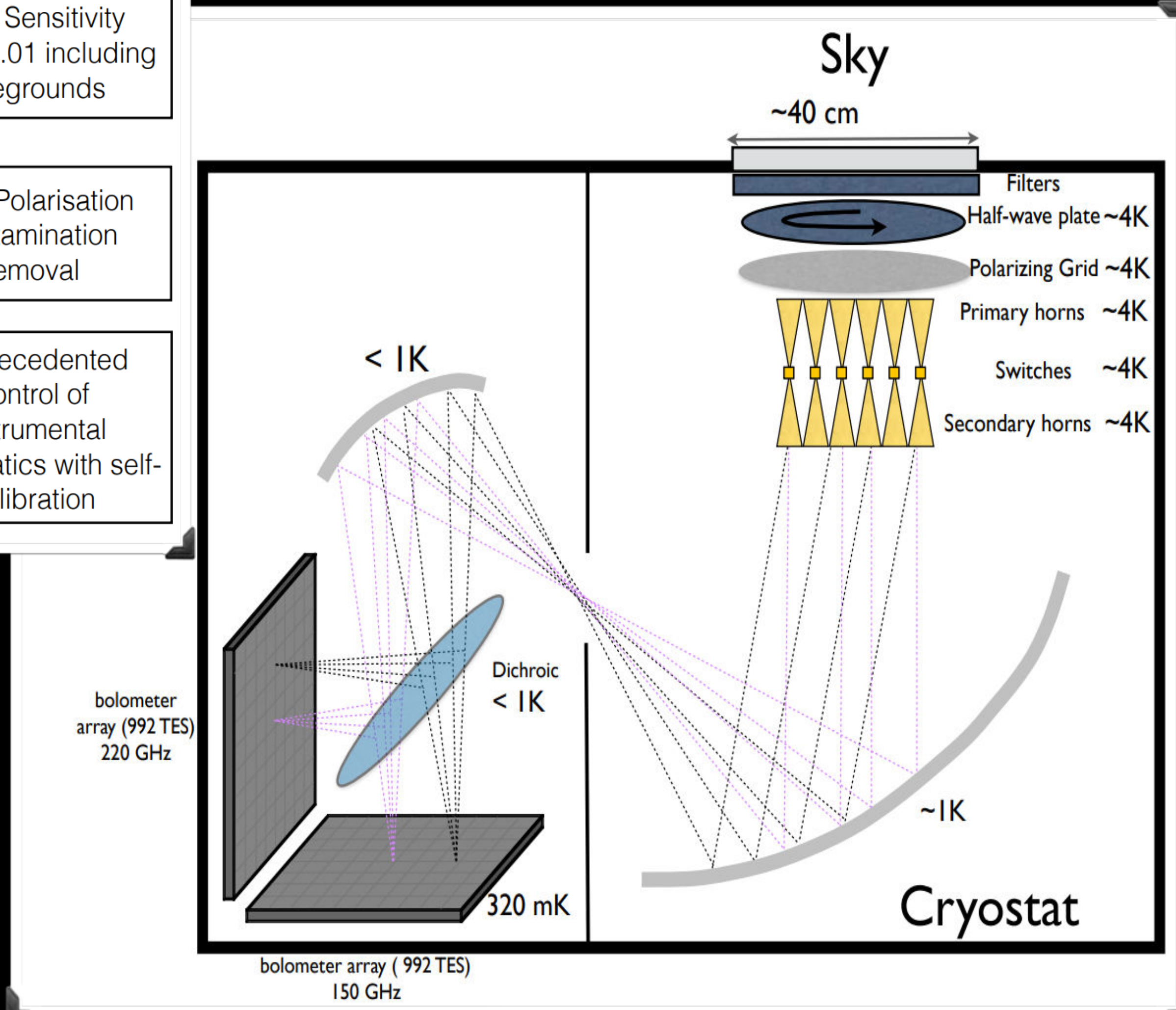
→ High Sensitivity σ(r) = 0.01 including foregrounds

- **Frequency capabilities**
  - Two focal planes 150 & 220 GHz
  - Spectro-Imaging capabilities thanks to frequency dependance of the synthesized beam

→ Dust Polarisation contamination removal

- **Switches on each horn**
  - Ability to reconstruct baselines individually
  - Self-Calibration like an interferometer

→ Unprecedented control of instrumental systematics with self-calibration



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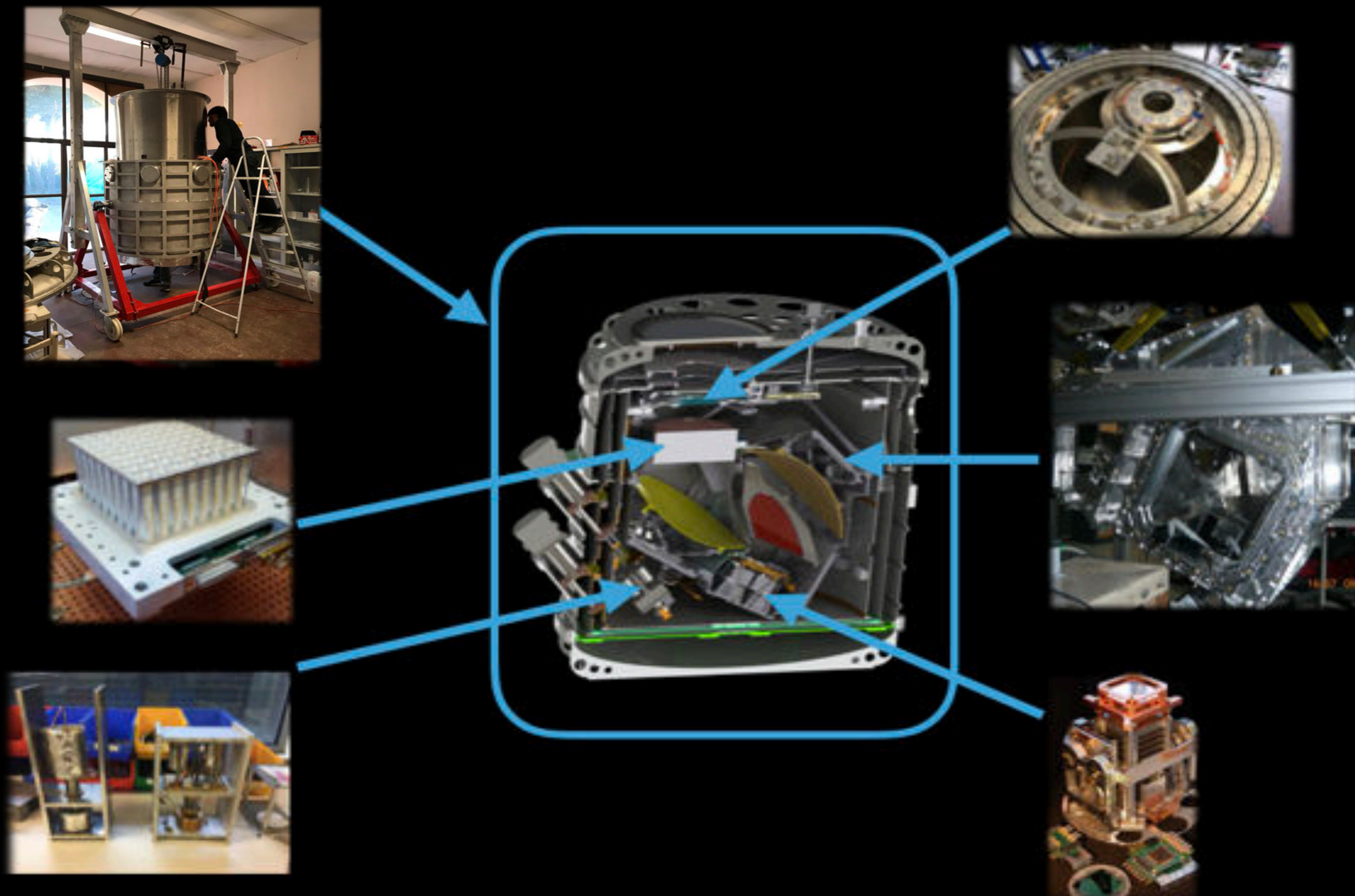


How to measure B-modes

reionization bump

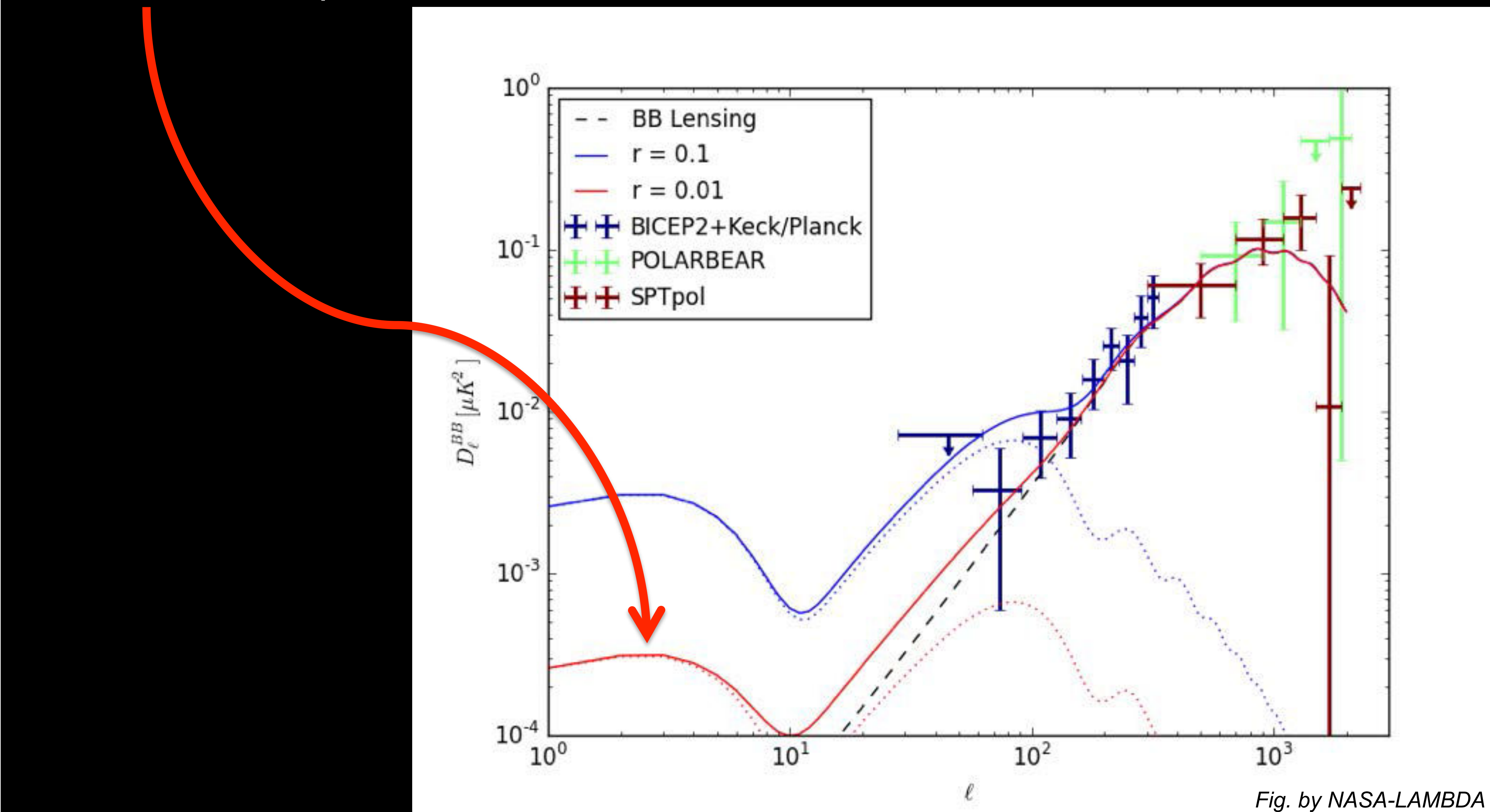
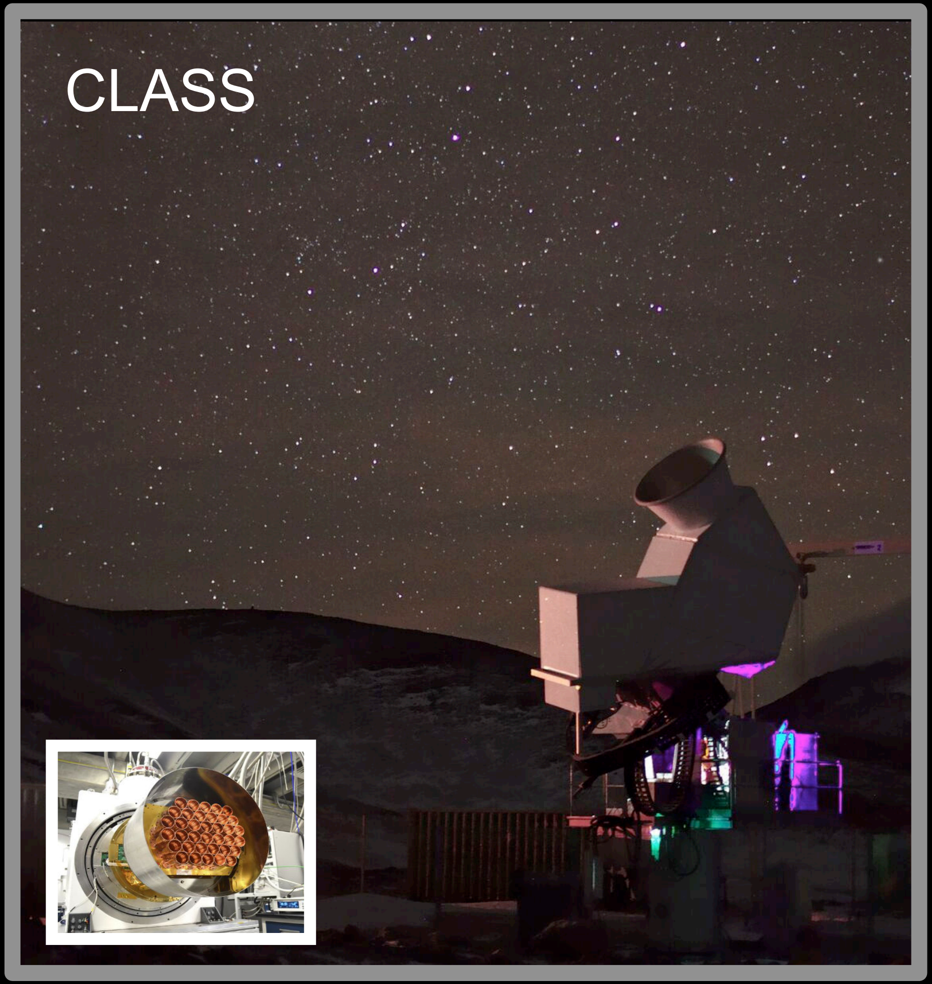


Fig. by NASA-LAMBDA

Small aperture experiments



Aknowledgment T.Marriage

- C. Bennet (John Hopkins) et al.
- Uses its particular position on the earth (Atacama) for a large (70%) sky coverage (2<l<150): unique!
- Frequency coverage 40GHz<v<220GH
- TDM’ed TES at 150mK
- First light occurred on 2016

Small aperture experiments

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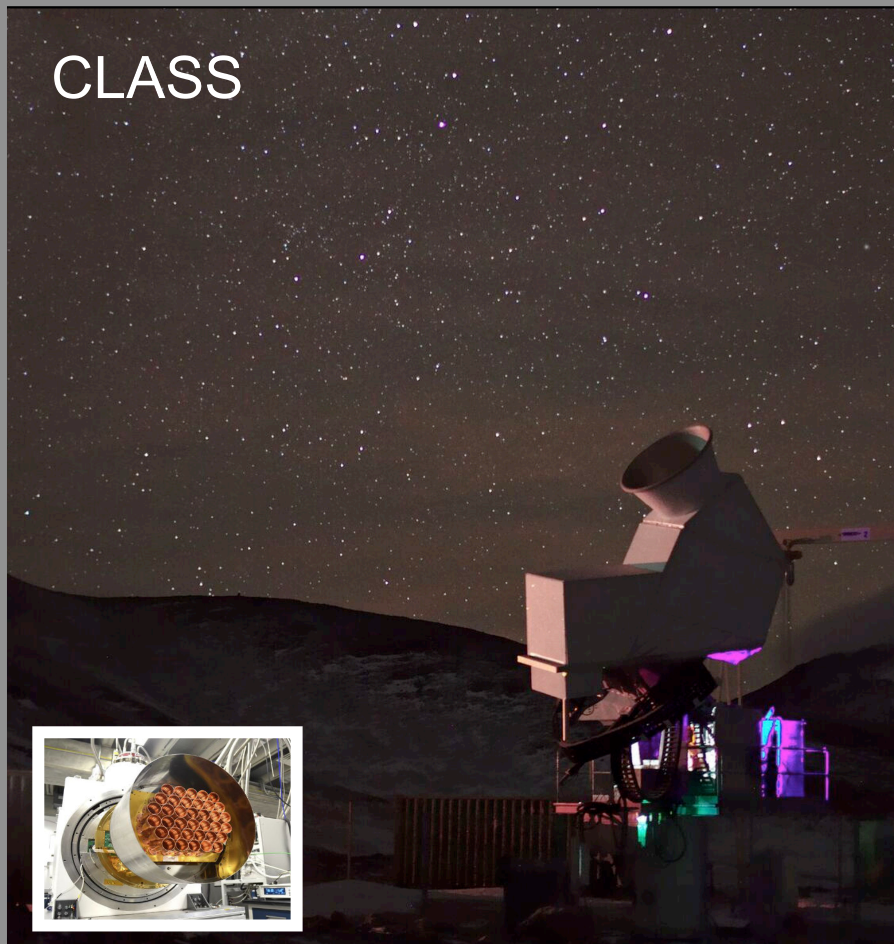

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- TDM'ed TES at 150mK
- First light occurred on 2016

- P. de Bernardis (Rome-Sapienza) et al.
- Frequency coverage 150-250GHz → r<0.02
- Multimoded TES bolometers
- Polar night LDB flight: can spin!
- Large angular scales (>25% sky): reionization bump
- First flight planned on 2019

LARGE SCALE POLARIZATION EXPLORER

asi agenzia spaziale italiana

SAPIENZA UNIVERSITÀ DI ROMA

LSPE

Large Scale Polarization Explorer

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC

MANCHESTER 1824

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IASF bo

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SISSA

INFN Istituto Nazionale di Fisica Nucleare

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UNIVERSITY OF CAMBRIDGE

UNIVERSITÀ DEGLI STUDI DI TRIESTE

UNIVERSITAS STUDIORUM FLORENTINA

UNIVERSITY OF OXFORD

UNIVERSITÀ DI PISA

INGV

IFAC

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

NASA JPL

UNIVERSITÀ DEGLI STUDI DI FERRARA - EX LABORE FRUCTUS -

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

LSPE: Large Scales Polarization Explorer

Acknowledgment to the LSPE collaboration

- Double instrument from ground and stratosphere:

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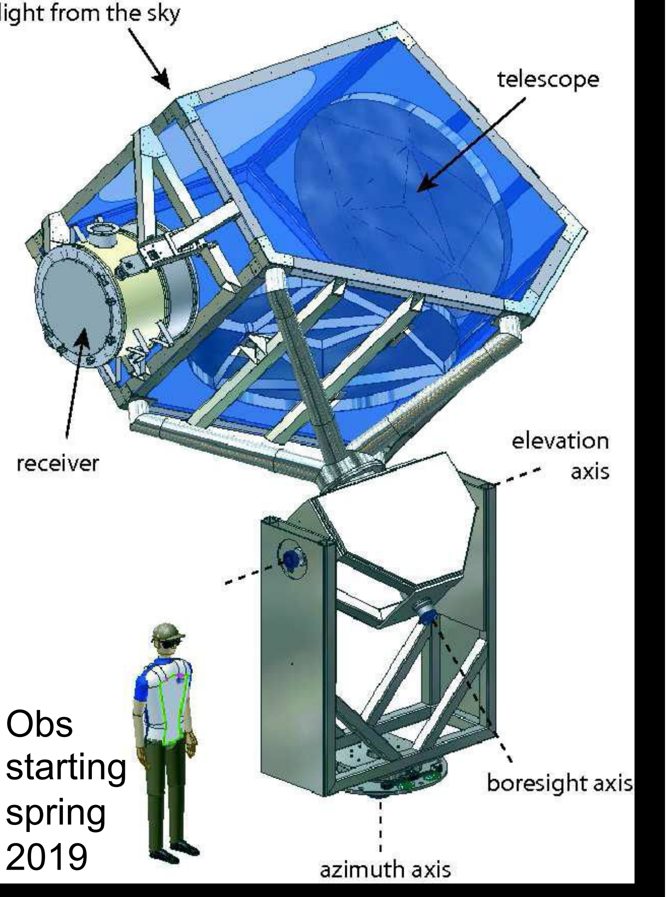
  - STRIP: coherent receiver from Teide observatory in Tenerife (PI: M. Bersanelli)



Obs starting spring 2019

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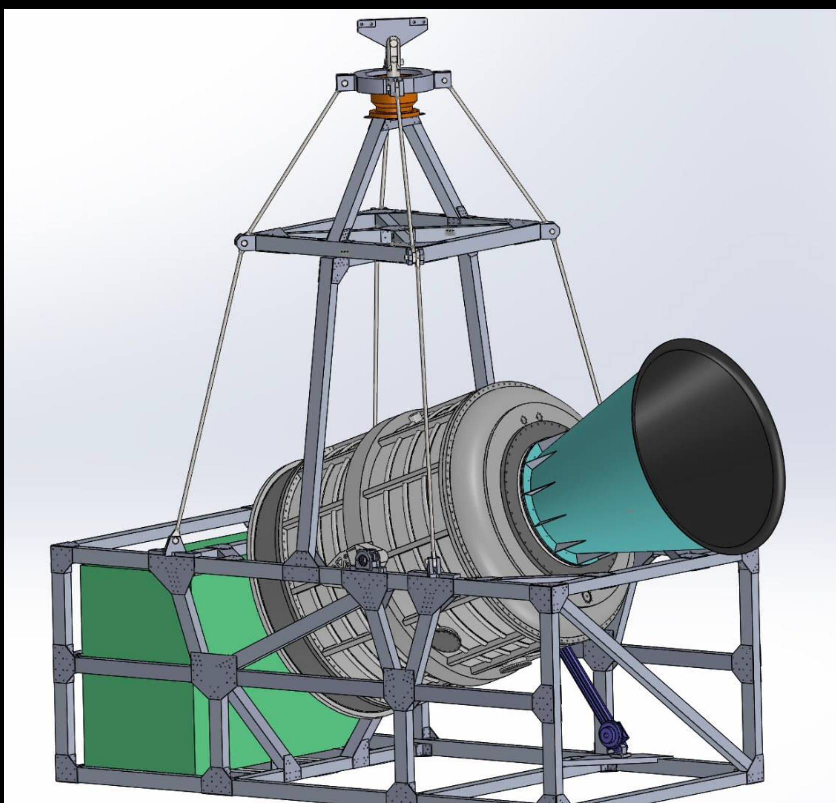
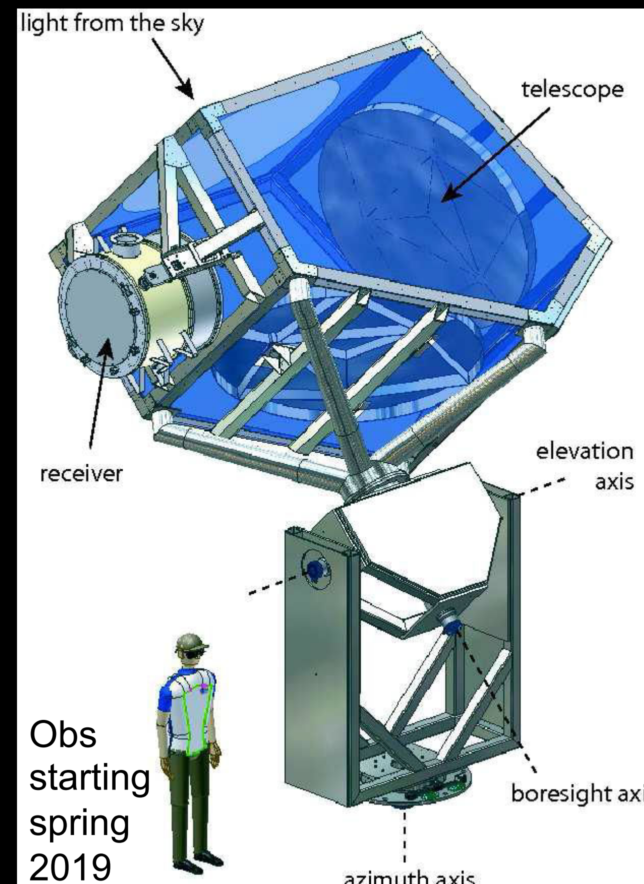


First flight winter 2019



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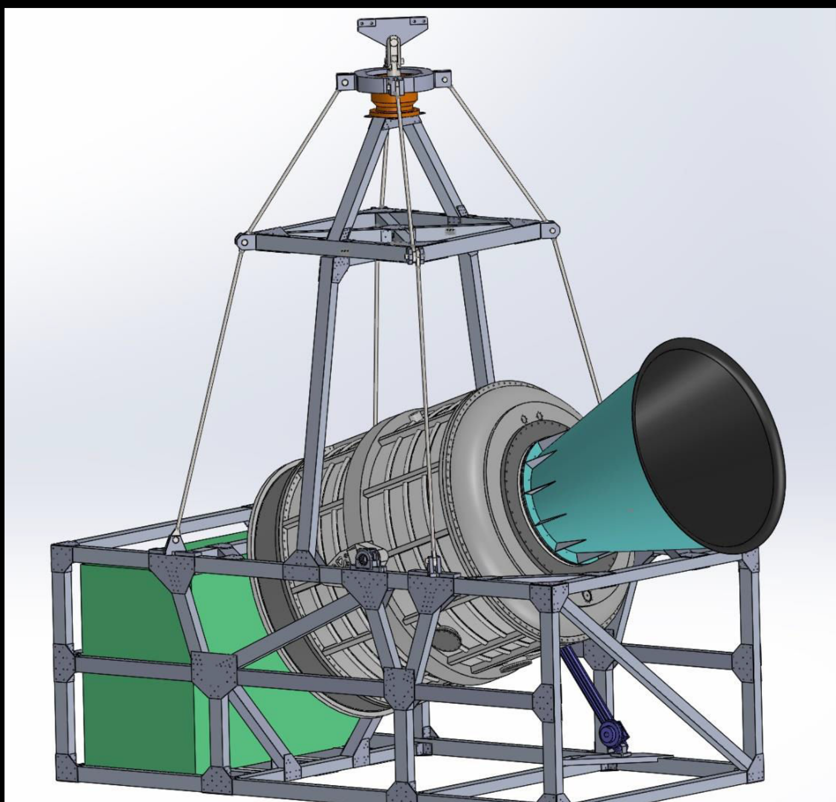
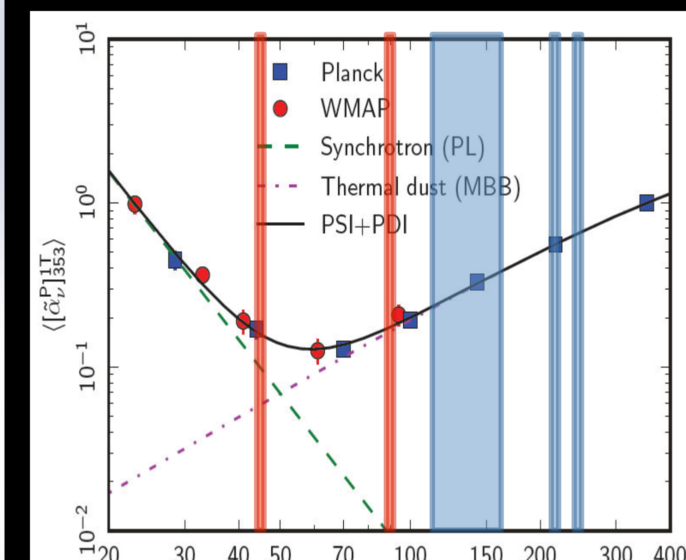
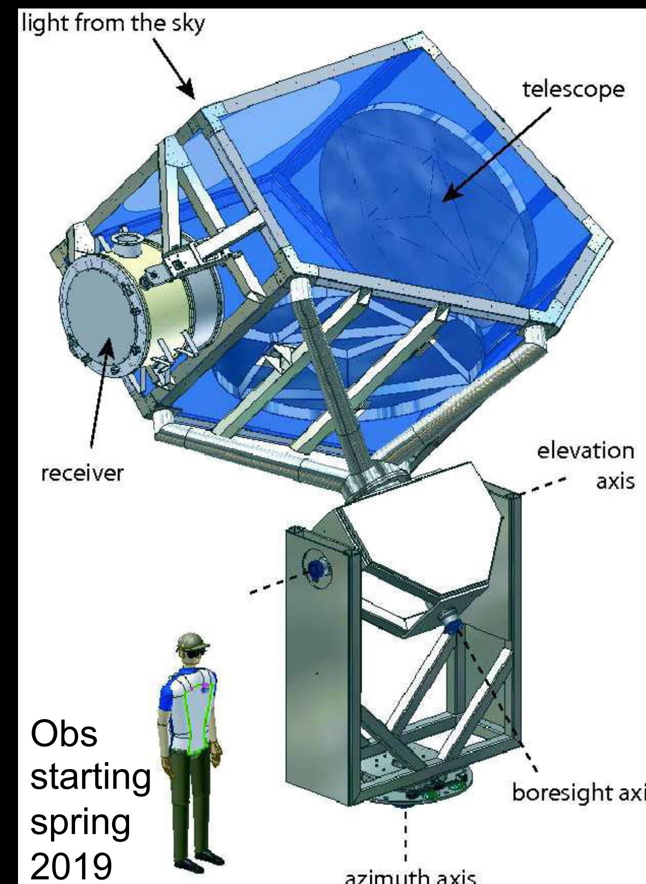


First flight winter 2019

- Frequency coverage to disentangle CMB from low and high frequency foregrounds: 40-250GHz



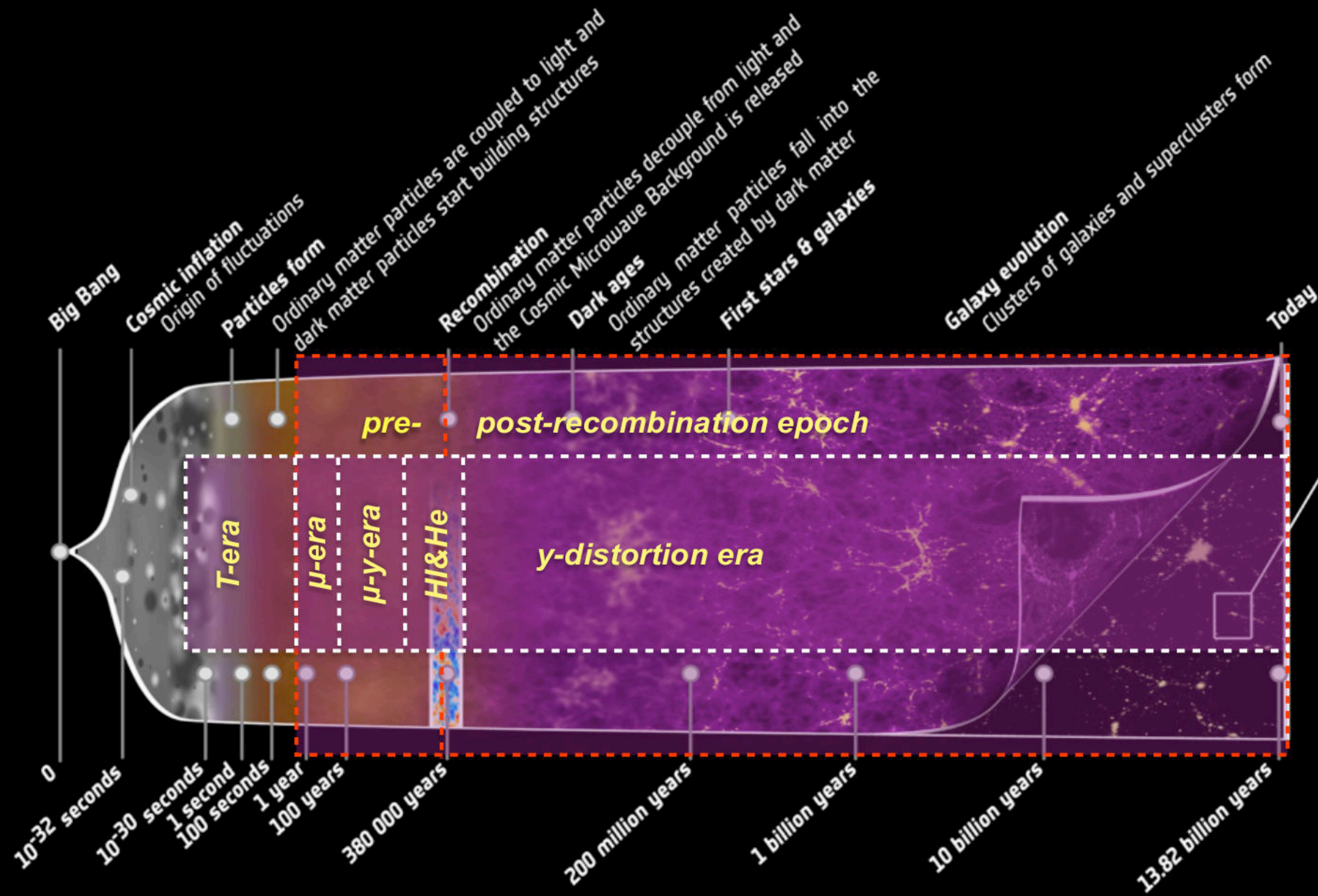


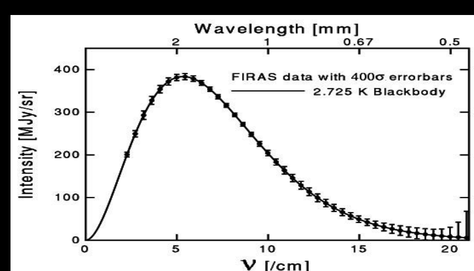
Obs starting spring 2019

GOING BEYOND THE LSS

- We have two ways to go beyond the LSS:

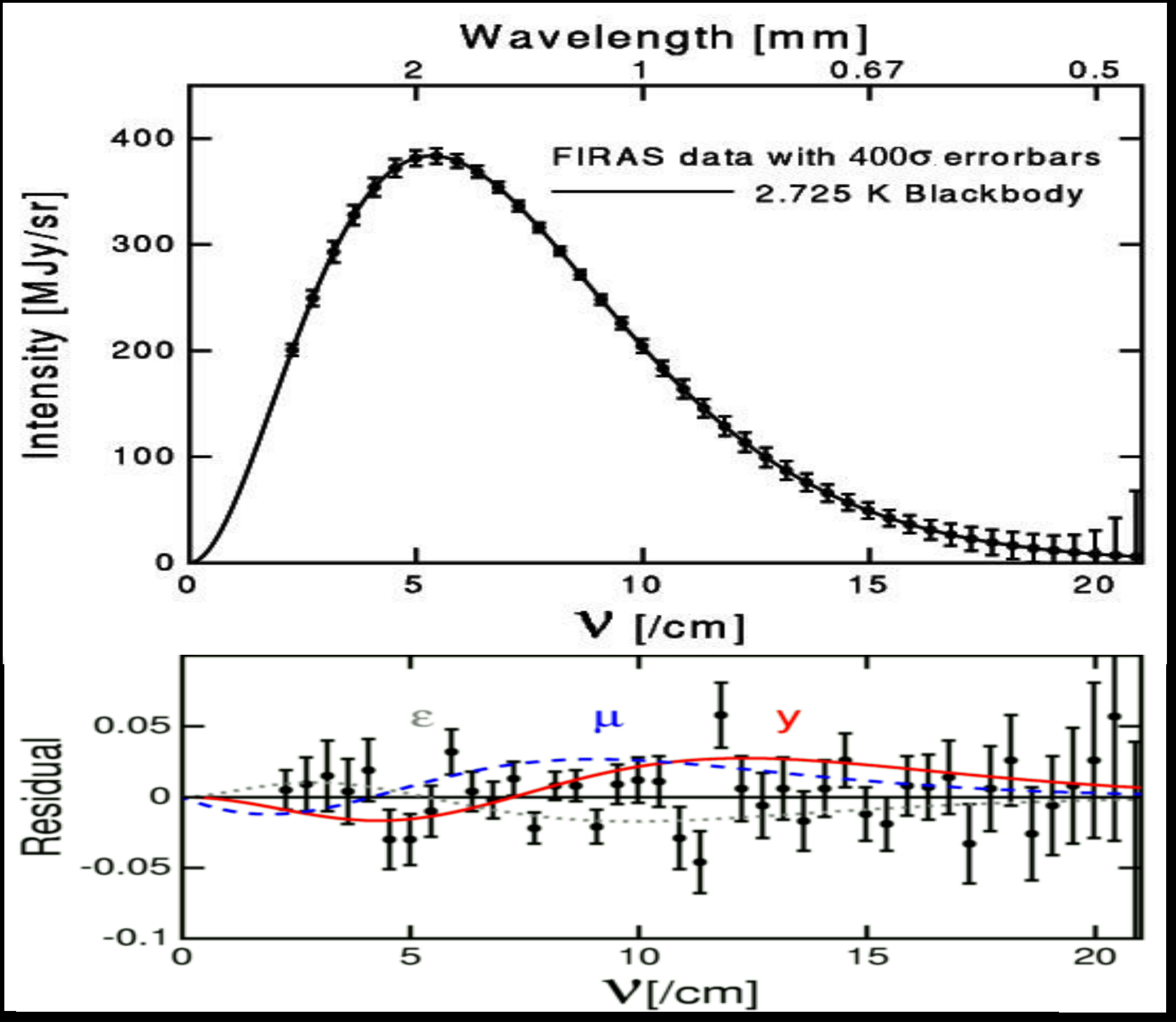
1. Measuring distortions of the CMB (monopole) frequency spectrum: distortions are expected in the Standard Model and can unveil exotic and non-Standard Scenarios as well as the history of the energy releases (including different scenarios of inflation)





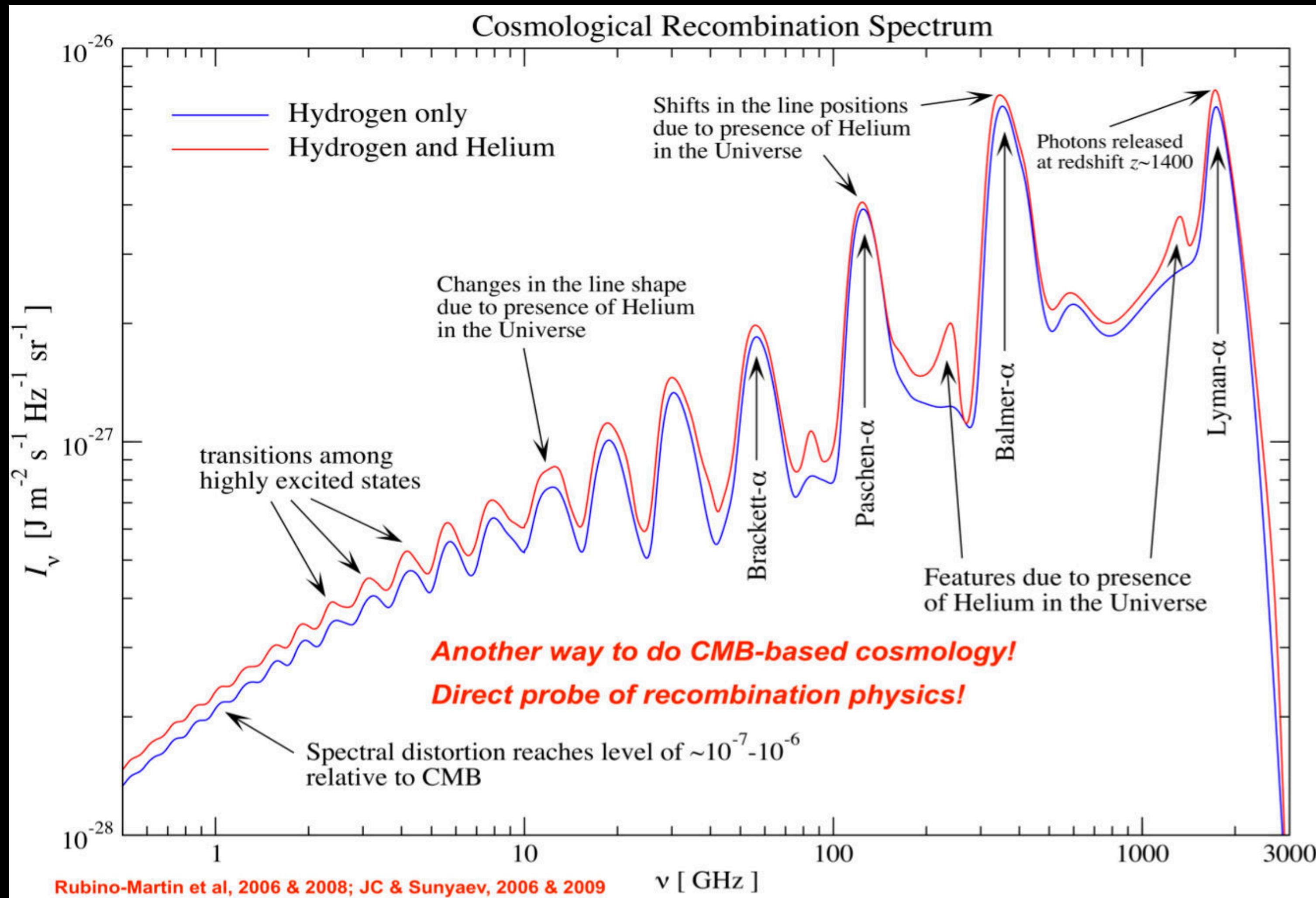
CMB: AN (ALMOST) PERFECT BLACK BODY

- Two conditions are needed for a body to be black:
  - To be opaque: a=ε=1
  - To be isothermal: no energy release or perfect thermalization



SPECTRAL DISTORTION: RECOMBINATION

- Two conditions are needed for a body to be black:
    - To be opaque: a=ε=1
    - To be isothermal: no energy release or perfect thermalization
- Imagine that…in the primordial plasma electrons and nuclei recombine to form Hydrogen and Helium
- This happens at $z<10^4$ ~1bayon for 10^9 photons
- This would teach us if recombination occurs the way we think it does. It opens a way to directly measure pre-stellar He abundance



Aknowledgment J. Chluba

SPECTRAL DISTORTION: DISSIPATION

- Two conditions are needed for a body to be black:
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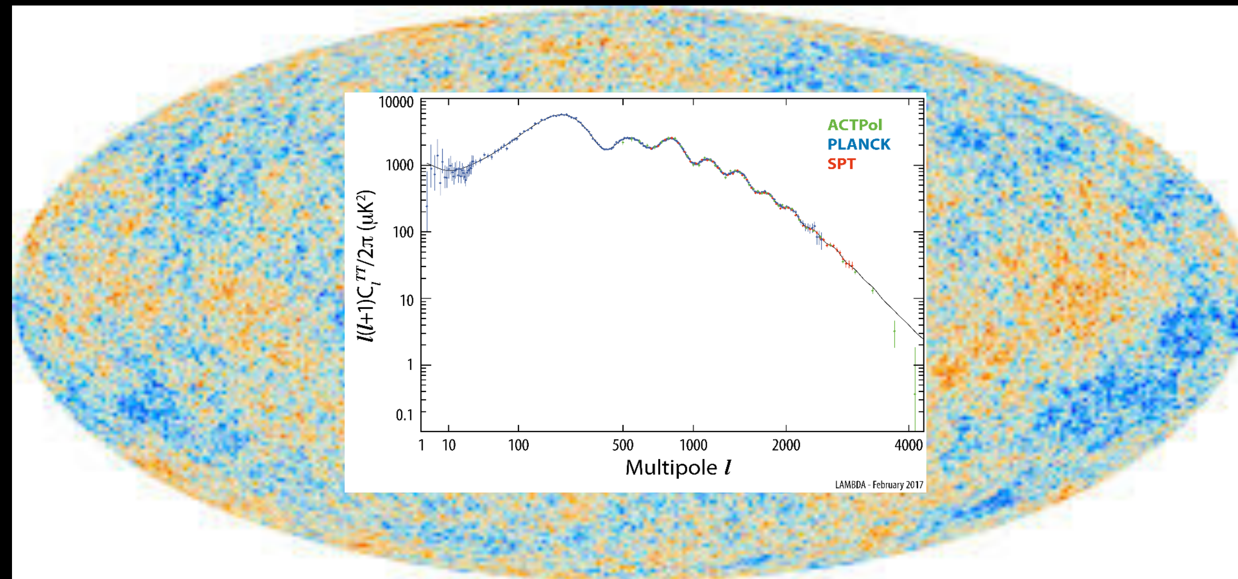
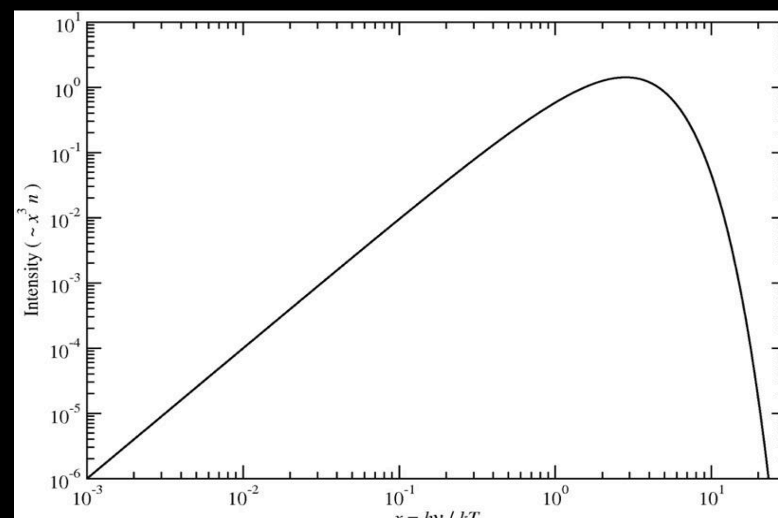
- Imagine that…in the CMB angular power spectrum the small scales get dissipated (Silk dumping).
- Sound waves dissipation inject energy and…multiple black bodies don’t average out into a black body while into a distorted emission
- If primordial anisotropies are non-gaussian, they create anisotropic spectral distortions





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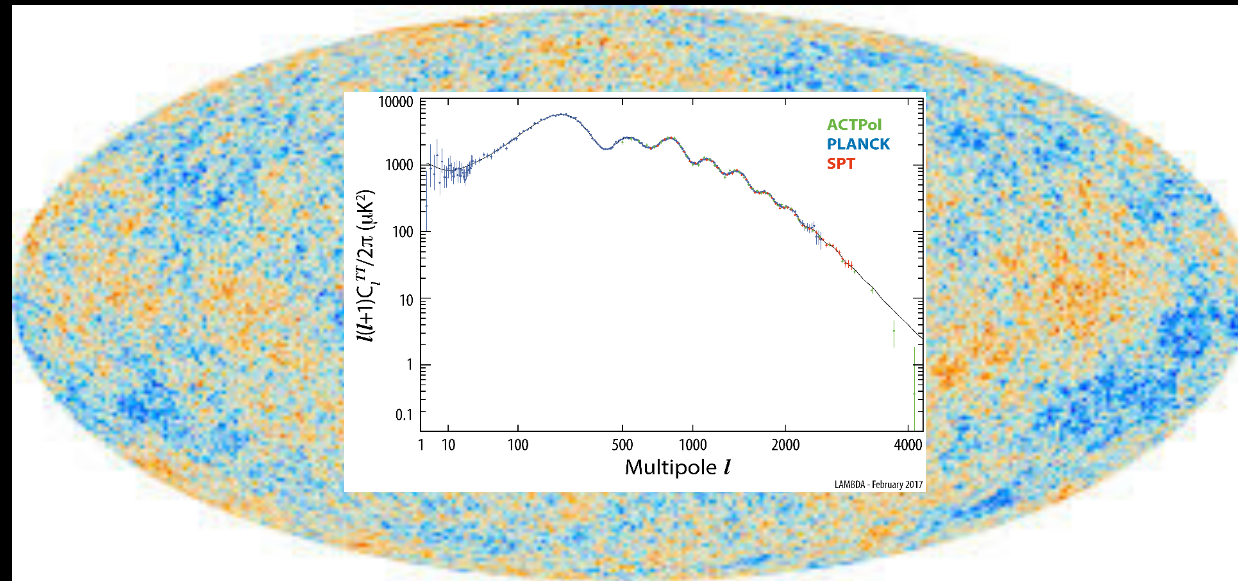

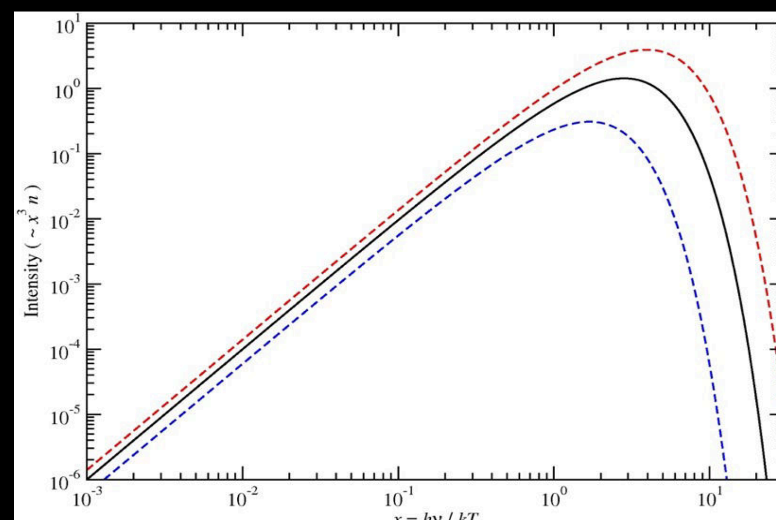

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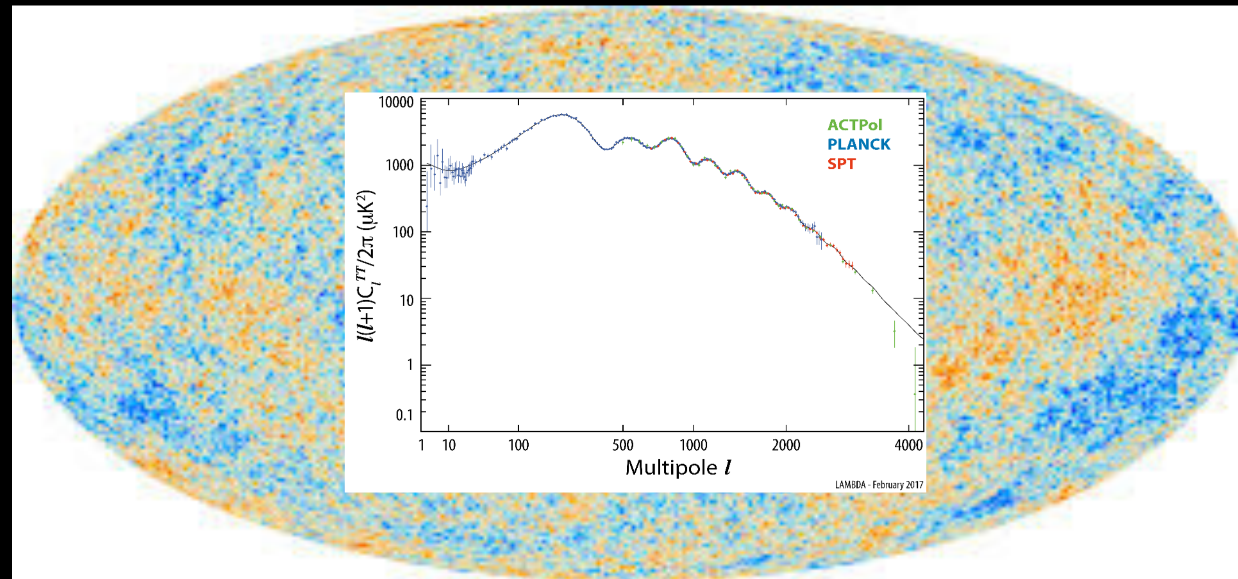
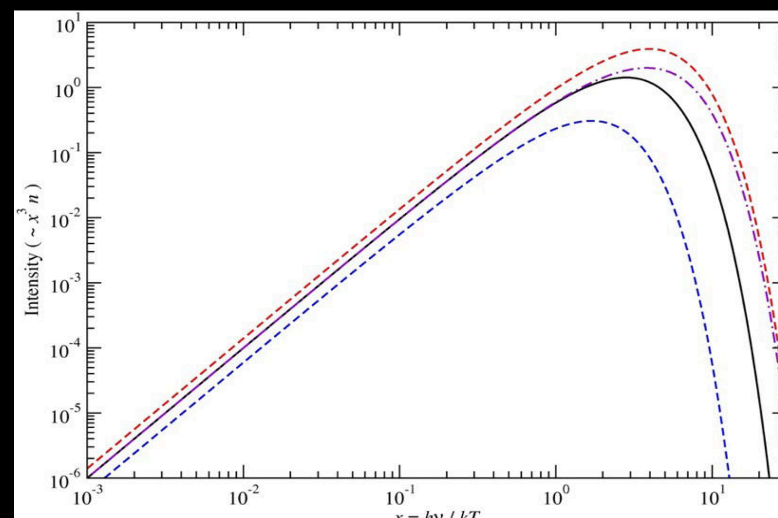
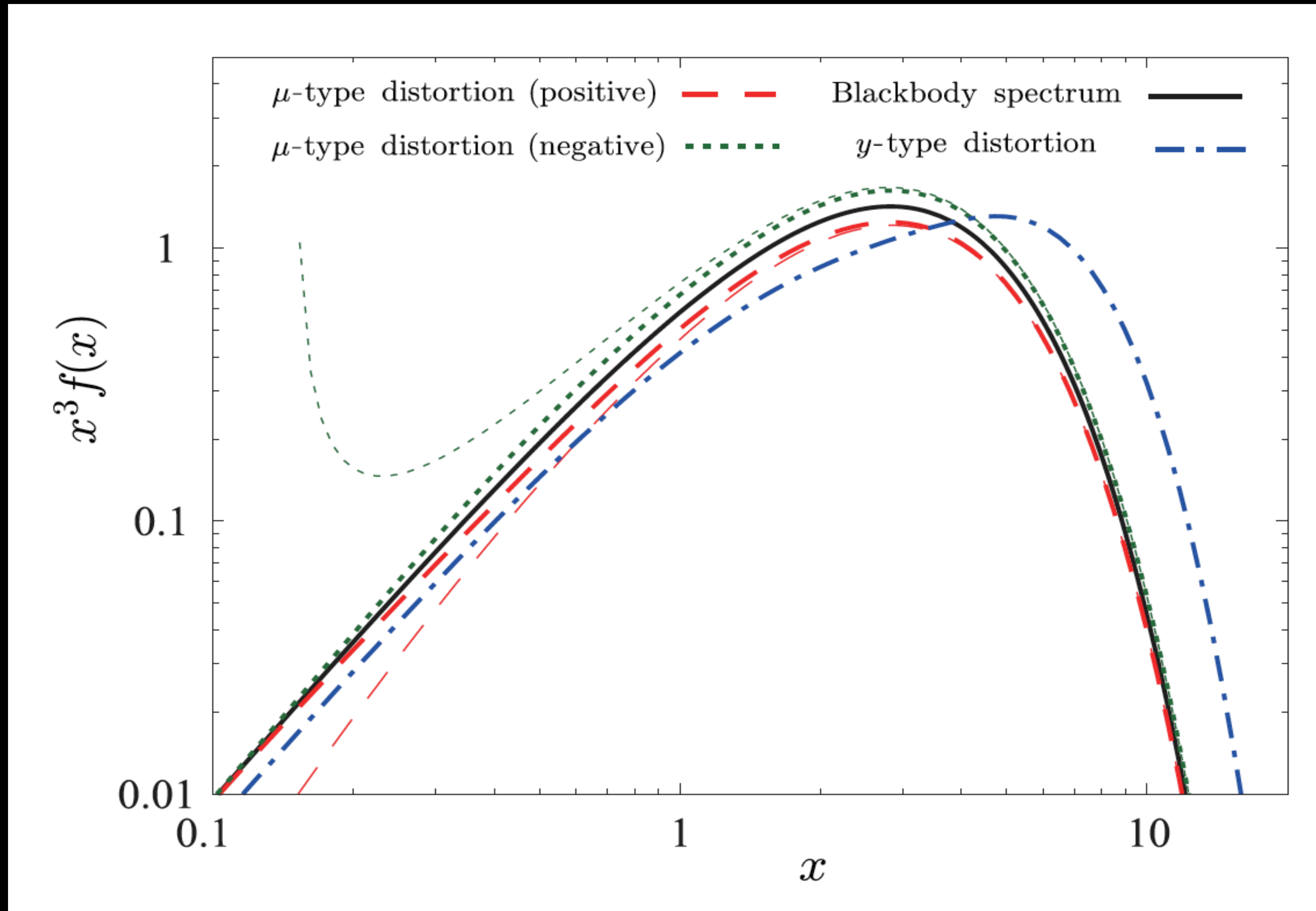




SPECTRAL DISTORTION: ENERGY RELEASE

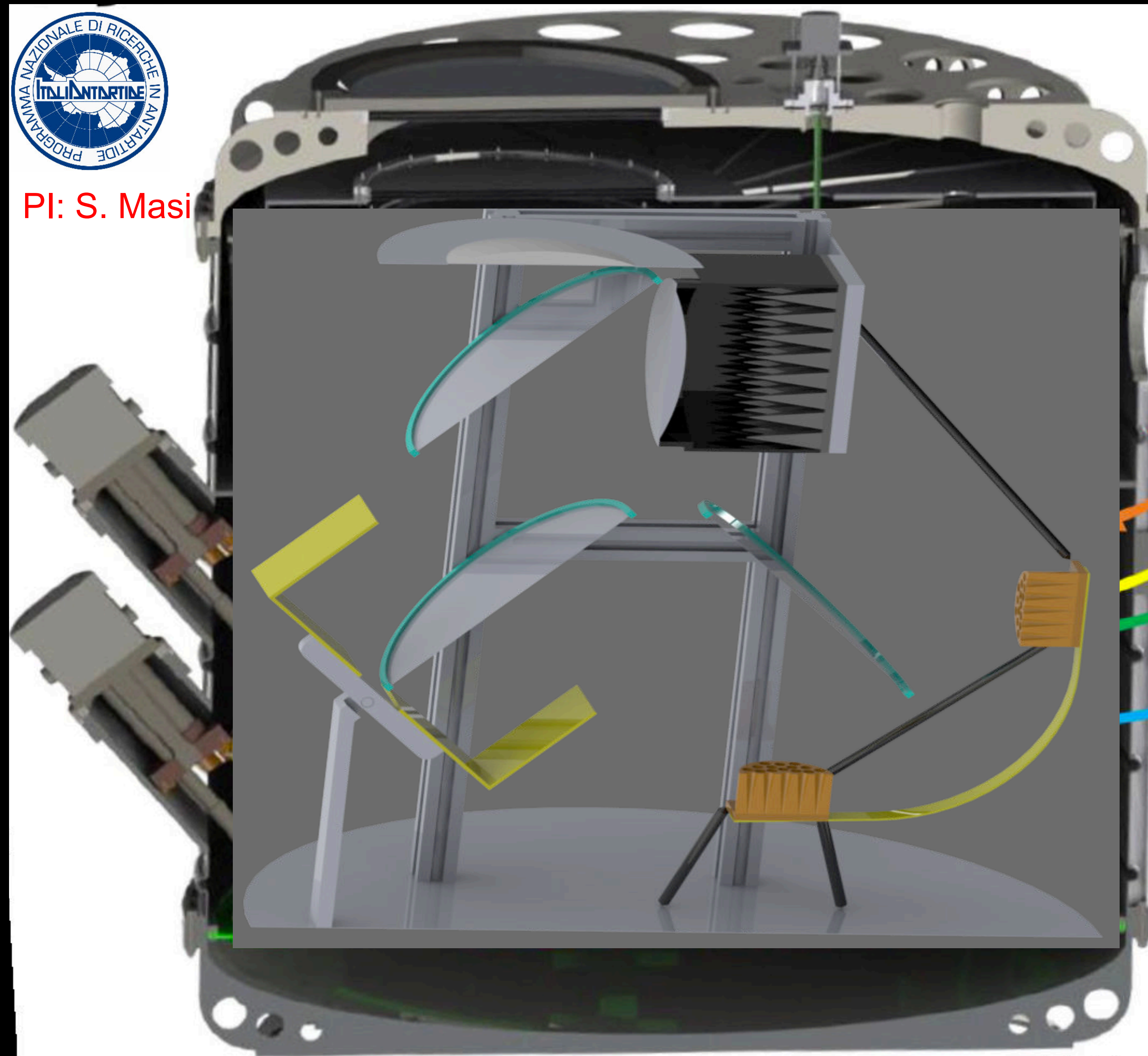
- Two conditions are needed for a body to be black:
  - To be opaque: a=ε=1
  - To be isothermal: no energy release or perfect thermalization
- Imagine that…there is energy release in the primordial plasma
- These include standard and non-standard scenarios:
  - Cooling by ordinary matter
  - Primordial magnetic fields
  - Decaying (DM?) or annihilating relic particles
  - Topological defects
  - Primordial black holes evaporation
  - …



Tashiro, PTEP 2014 , 06B107

COSMO: COSmological Monopole Observer

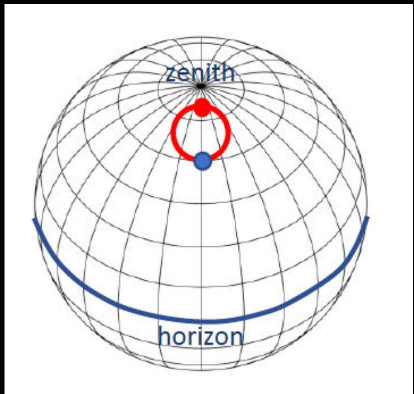
- Cryogenic differential Fourier Transform Spectrometer
- Cryogenic black body reference calibrator (and a second warm one)
- Sensitive detectors: Kinetic Inductance Detectors (KIDs)…ideal for large detectors arrays thanks to their multiplexability. The Sapienza group is investing in such development (*Paiella et al. JLTP, 184, 2016*)
- Control of the atmosphere: either on a satellite (see PIXIE/PRISM) or the best place on earth, ANTARCTICA, with dedicated simulations and a smart scanning strategy

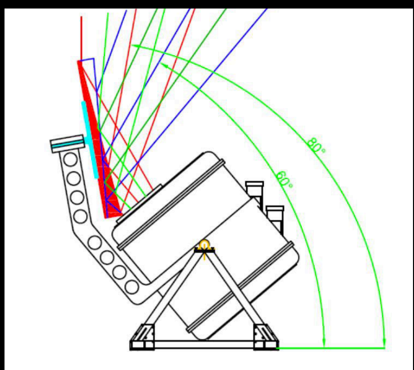


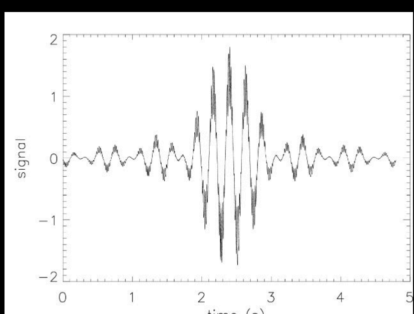
PI: S. Masi

Aknowledgment G. D'Alessandro

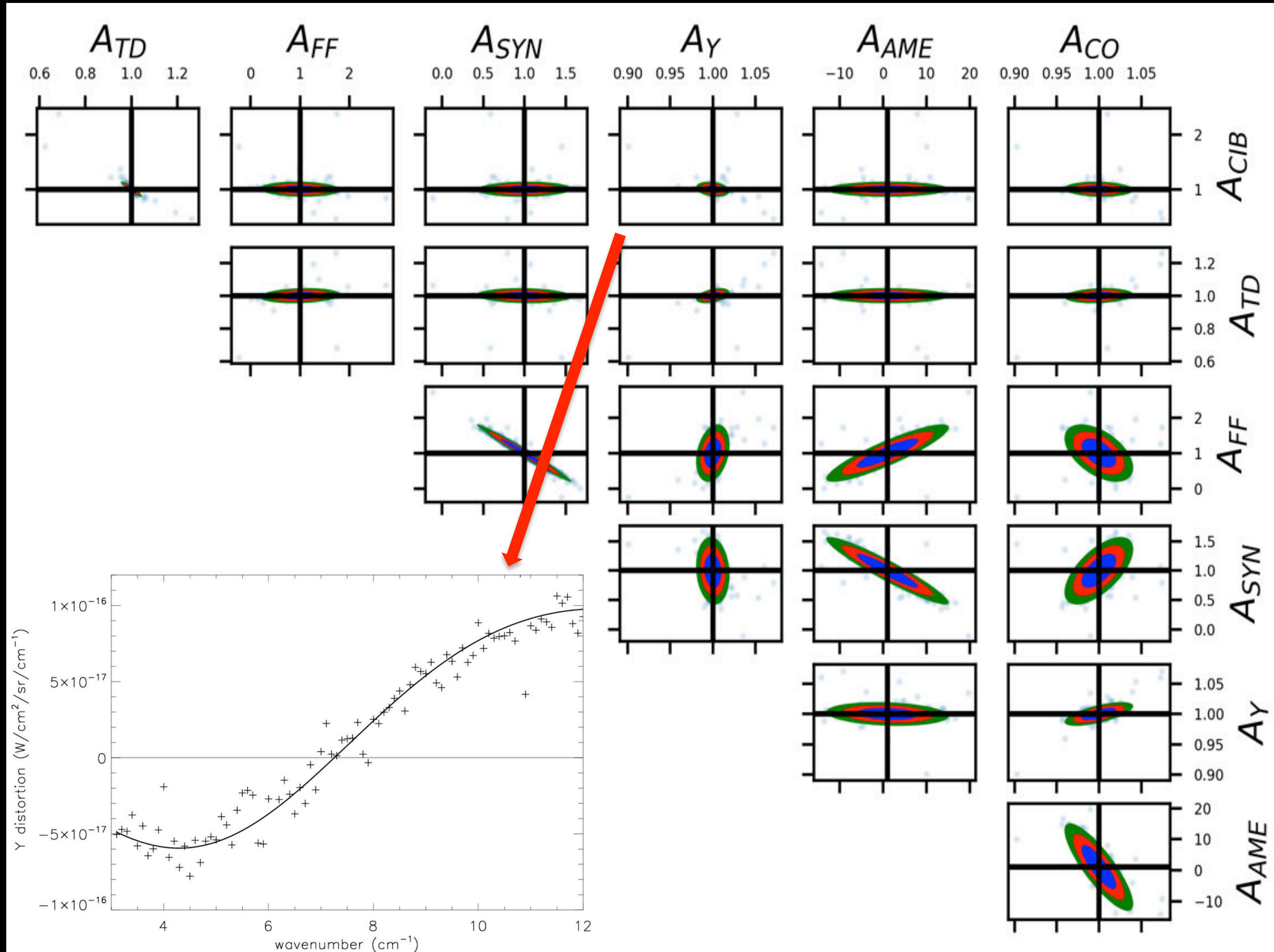
COSMO





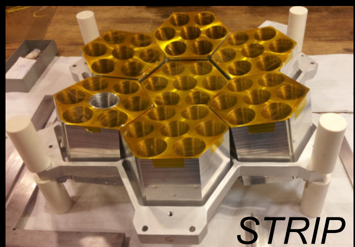


Aknowledgment P. de Bernardis

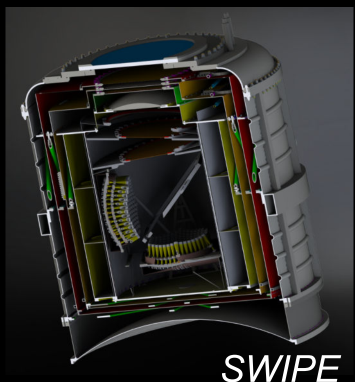


Aknowledgment S. Di Tano

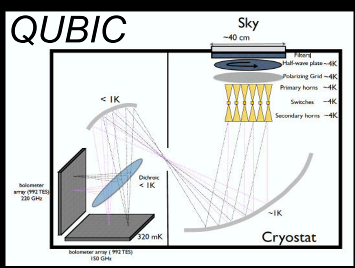
Conclusions



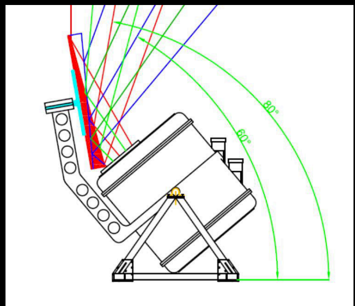
- LSPE-STRIP: 44-90GHz recently approved for ground observations from Tenerife. Essential for foreground separation



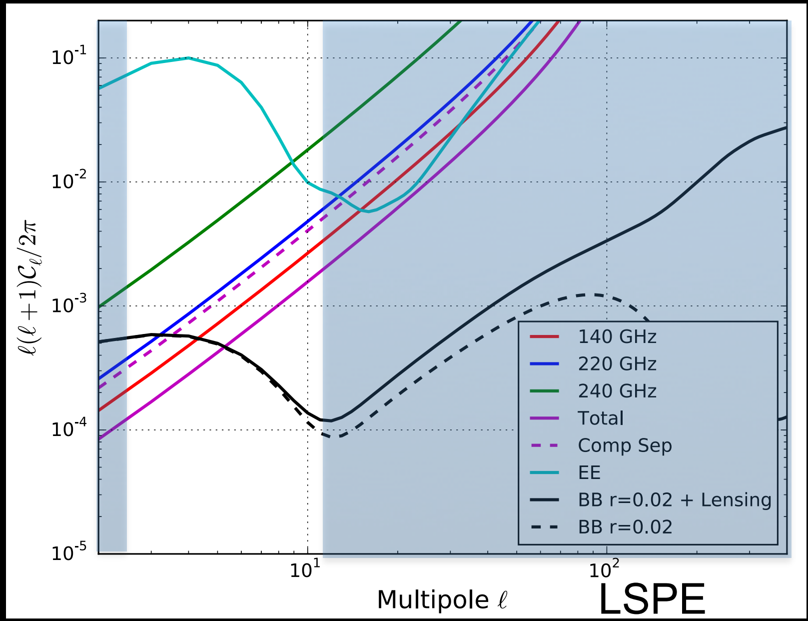
- LSPE-SWIPE: winter flight from Svalbard islands on 2019. It aims to measure the reionization bump through polar night LDB.
  NB: LSPE is the only experiment planned to measure northern sky!



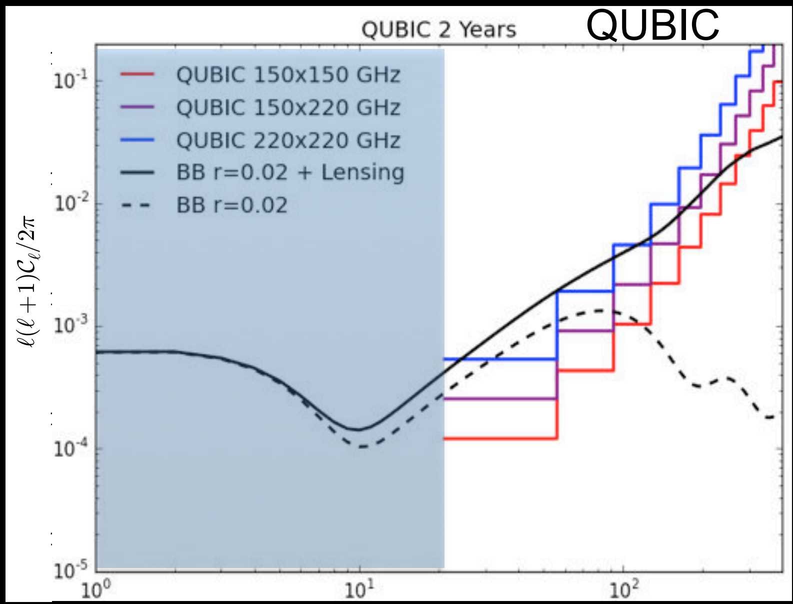
- QUBIC 1st module: from Argentina with a Bolometric interferometry. High systematic control/orthogonal wrt imagers



- COSMO: an attempt to go beyond the LSS through a CMB spectral distorsion experiment from Antarctica.



LSPE
vs
QUBIC



Aknowledgment L.Pagano and J.C. Hamilton

Thank you!

E.S. Battistelli
"Sapienza" University of Rome