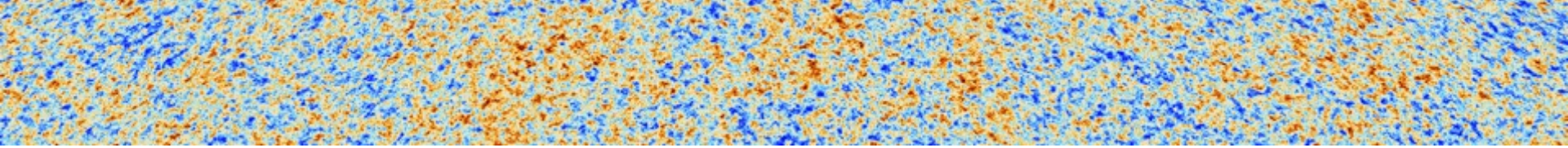


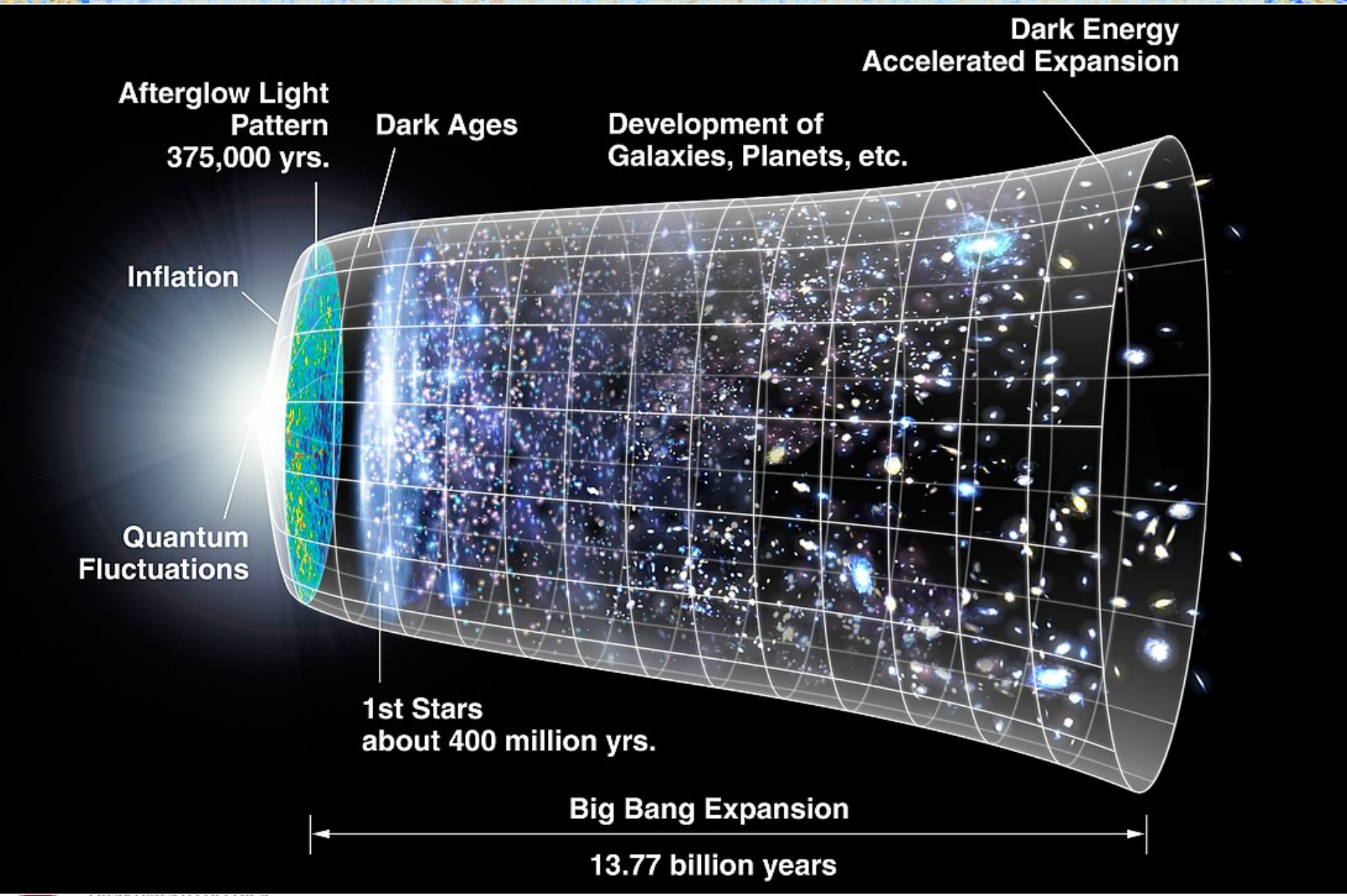
COSMOLOGY
focus on CMB measurements

Francesco Piacentini

INFN Roma1 Retreat, Assisi, June 17, 2019

DIPARTIMENTO DI FISICA
SAPIENZA
UNIVERSITÀ DI ROMA

Riassunto e contestualizzazione delle attività (senza essere dettagliati)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

ΛCDM model – 6 parameters to fit all data

Fitted parameters

Derived parameters

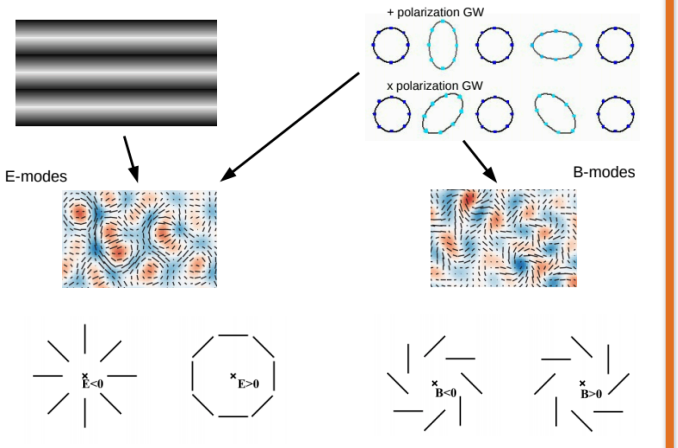
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020

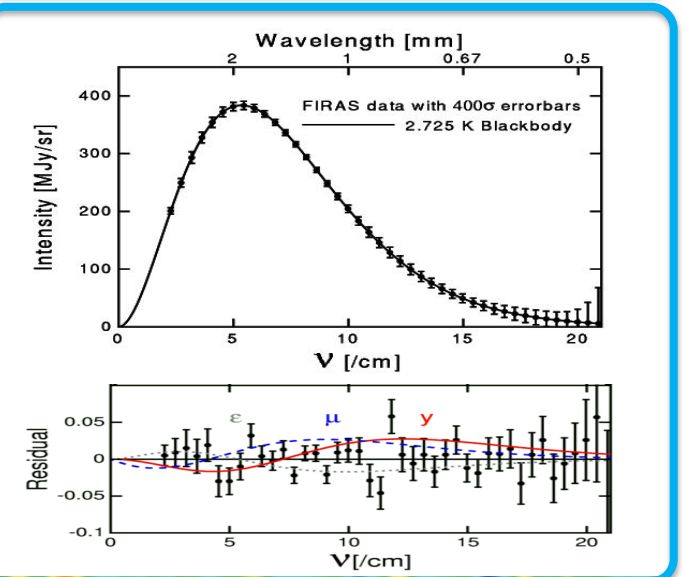
Planck **2018 results. VI. Cosmological parameters** Submitted

CMB - Current observational efforts

- **Measurement of polarization of the Cosmic Microwave Background radiation**
  - In particular the small fraction of polarization due to **primordial gravitational waves**
  - This allows to explore the **physical parameters of the inflation**
  - Probes physics at **extremely high energy**
  - Imprint in the CMB polarization **B-mode**
    - The CMB polarization acts as a GW antenna in the primordial Universe

- **Measurement of the spectral distortion on the frequency spectrum of the CMB**
  - Not much effort after **FIRAS 1994**
  - Probes the thermal history at different stages of the evolution
  - Energy evolution to track particles decoupling, annihilation…





CMB maps

Target signal 1

CMB anisotropy at small angular scales, to improve cosmological parameters determination

Target signal 2

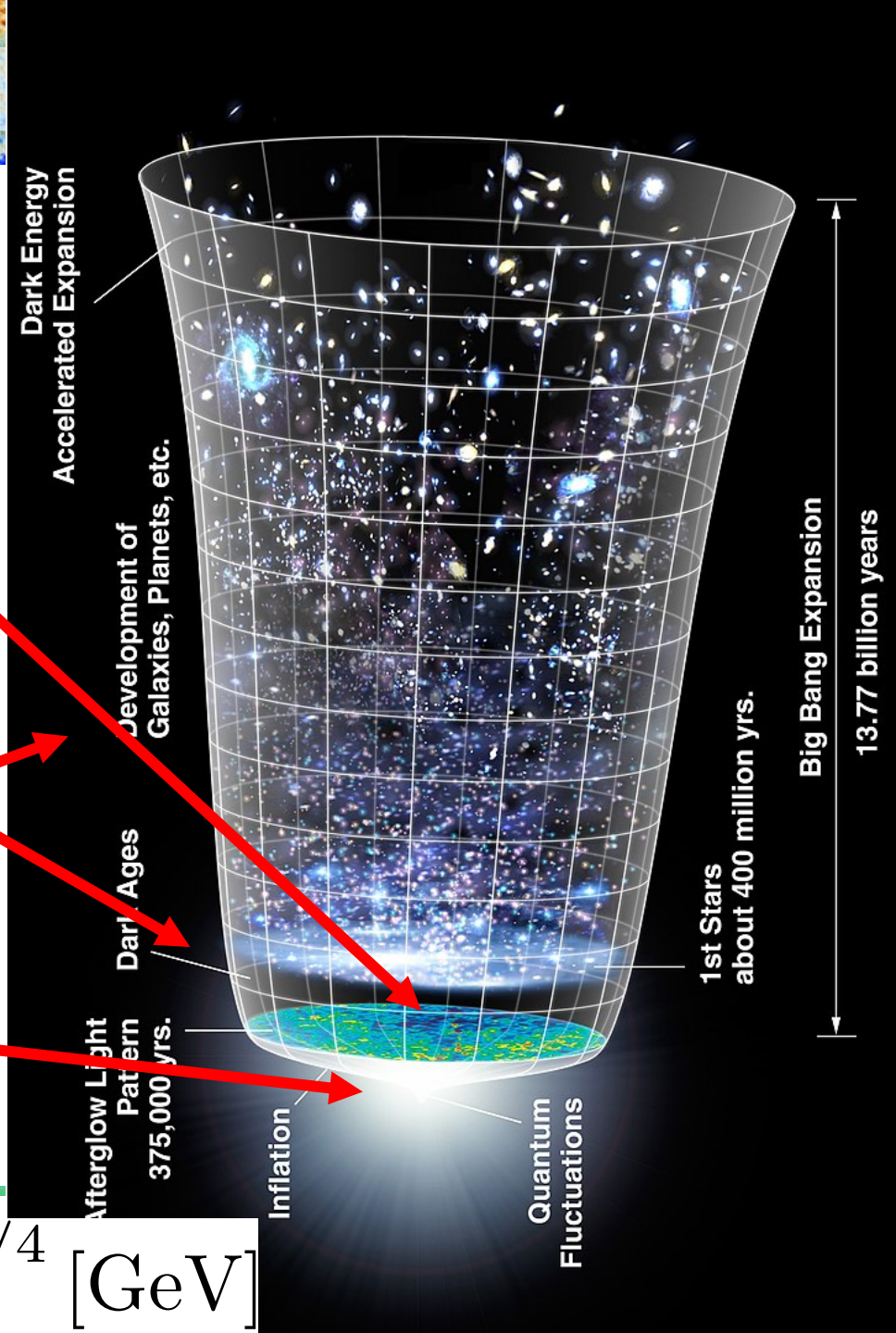
CMB E-mode polarization at large scales, probes the Universe re-ionization (first stars)

Target signal 3

Lensing effects due to distribution of large scale structures (dark matter)
Also measured by other probes
Signal well predicted

Target signal 4 (B-modes)

Inflationary gravitational waves
Not measured by other probes
Signal unknown – **parameter *r***
To probe physics at extremely high energy



$$V^{1/4} = 1.06 \cdot 10^{16} \left(\frac{r}{0.01}\right)^{1/4} [\mathrm{GeV}]$$

Primordial gravitational waves

2019 status - BICEP/Keck only (data 2015, paper 2018)

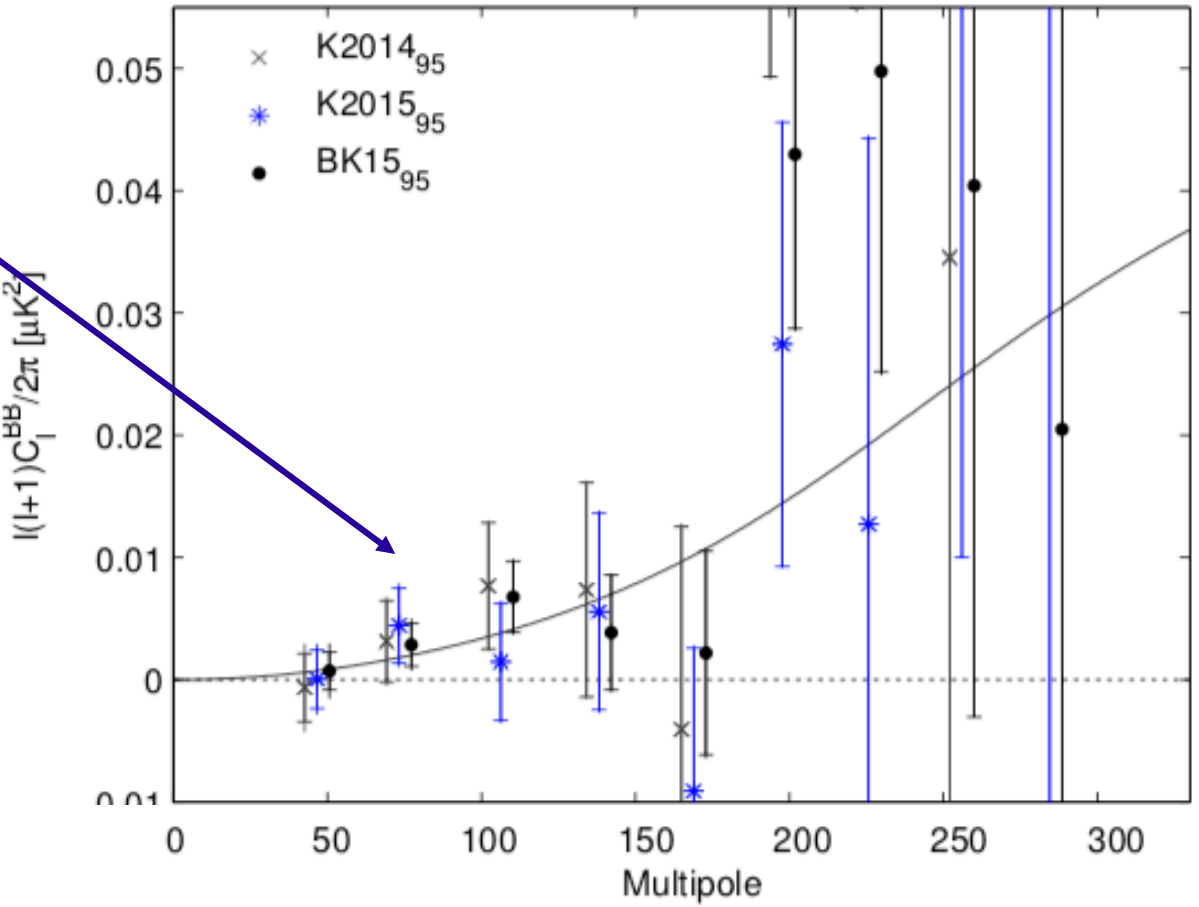
Target signal 4,
B-mode

Inflationary gravitational waves
Not measured by other probes
Signal unknown

Current limit
(direct detection, 95% confidence)

$$r_{0.05} < 0.07$$

https://arxiv.org/abs/1810.05216

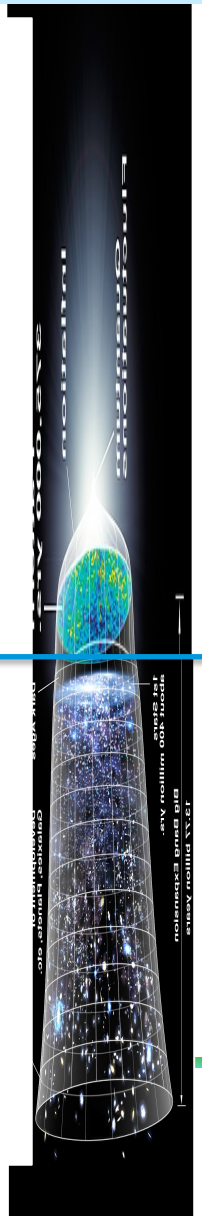


$$V^{1/4} = 1.06 \cdot 10^{16} \left(\frac{r}{0.01}\right)^{1/4} [\mathrm{GeV}]$$

CMB spectral distortions - physical mechanisms

Slide by Jens Chluba 2018

- *Cooling by adiabatically expanding ordinary matter* (JC, 2005; Chluba & Sunyaev 2011; Khatri, Sunyaev & Chluba, 2011)
- Heating by *decaying* or *annihilating* relic particles (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; Chluba, 2005; Chlyba & Sunyaev, 2011; Chluba, 2013; Chluba & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings* (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes* & *magnetic fields* (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Chluba & Sunyaev, 2011; Chluba et al. 2012; Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation* (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; Chluba & Sunyaev, 2006; Sunyaev & Chluba, 2009)



- Signatures due to first supernovae and their remnants (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Observations

1) Ground

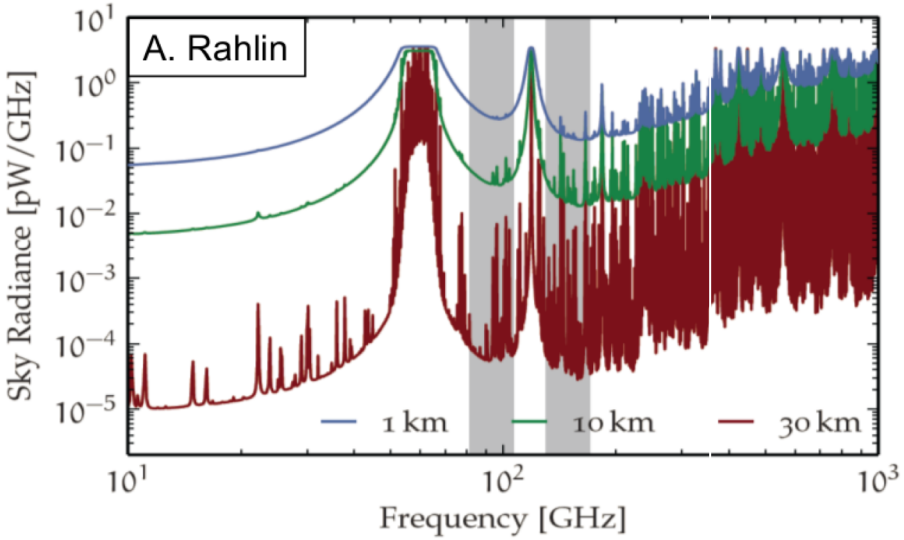
- Mid-Large telescopes (up to 10 meters)
- Atmosphere limits instruments to low spectral frequencies (up to 150 GHz)
- Long integration time (years), low noise
- Requires "extreme" locations, dry and high:
  - Antarctica, Atacama, …

2) Balloon

- Smaller telescope (up to ~3m)
- Can go to higher frequencies
- Short integration time (2 weeks)
- High risk

3) Satellite

- Can go to higher frequencies
- Long integration time (years)
- Small telescope (up to ~2m), or deployable
- Cost

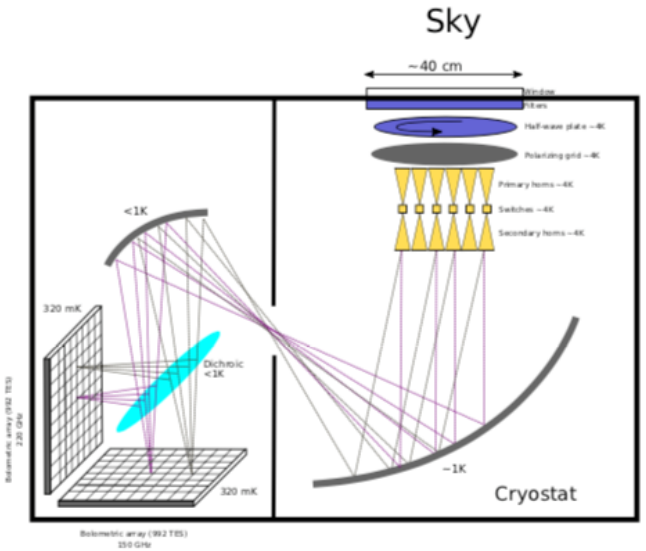


Riassunto delle competenze presenti

QUBIC - Q&U Bolometric Interferometer for Cosmology

- **GROUND**
- Alternative technology: **bolometric interferometry**
- Combines the **sensitivity** of the bolometers, with the **control of systematic** effects of an interferometer

- In calibration phase (demonstrator, 1/4 of the focal plane, fringes well detected)
- Will be installed in Argentinian Andes



$$\Delta r_{0.05} = 0.01$$

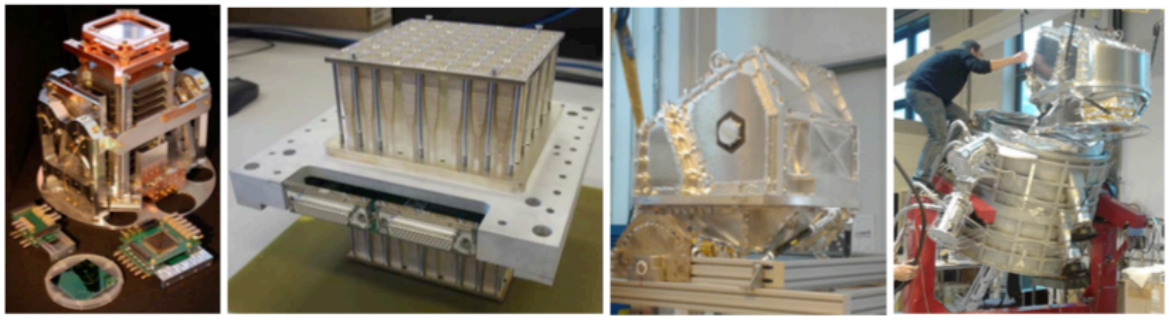
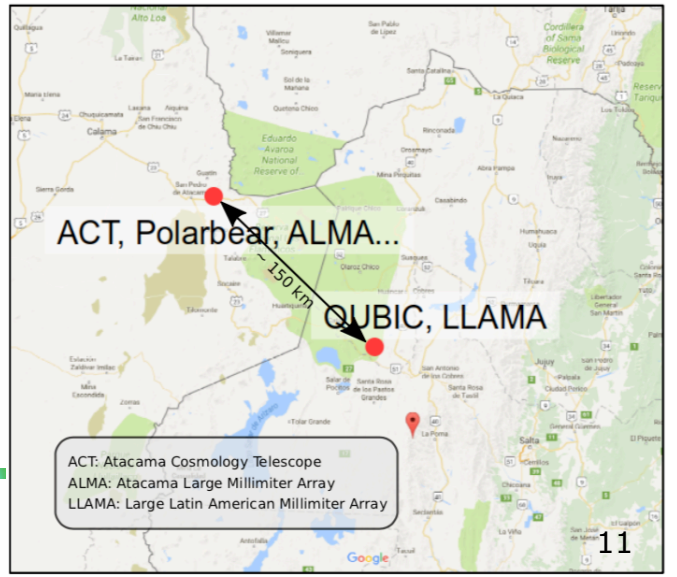
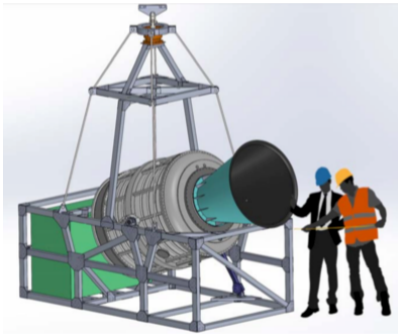


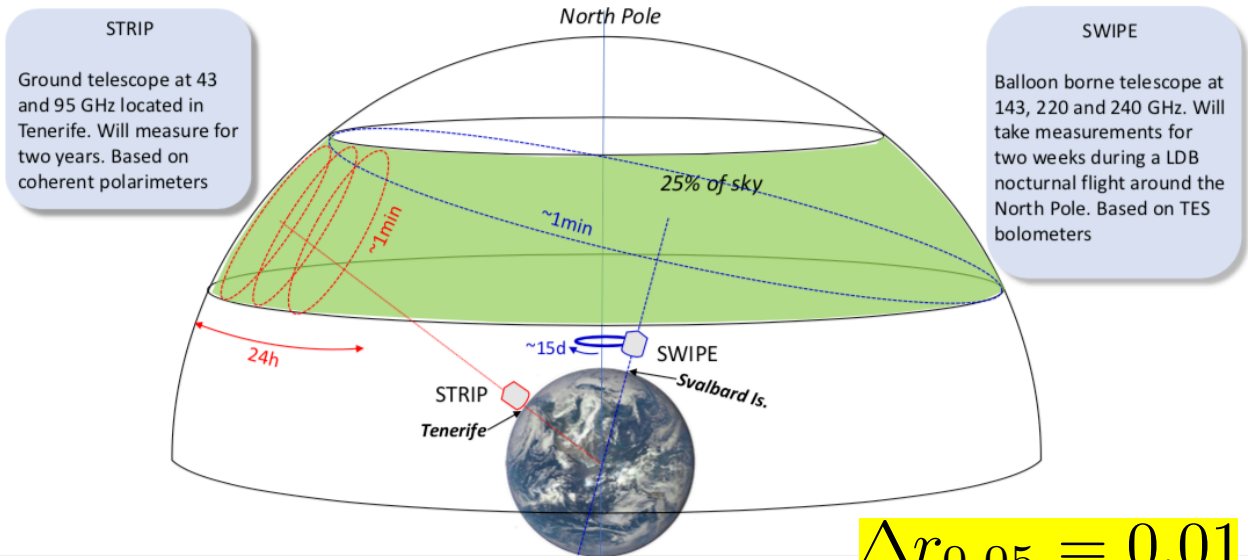
Figure 7. Status of the current QUBIC development. (**a**) The cryogenic section of the QUBIC detection chain; (**b**) the TD array of 64 + 64 back-to-back horns interfaced with their switches; (**c**) the integrated 1 K box; (**d**) integration of the 1 K box in the cryostat shell.



LSPE - Large Scale Polarization Explorer

- **BALLOON + GROUND**
- CMB polarization at large scales
- Winter Polar Balloon (Roma1 ++)
- ground telescope in Tenerife (Milano ++)
- INFN largely involved; leading role in Roma1

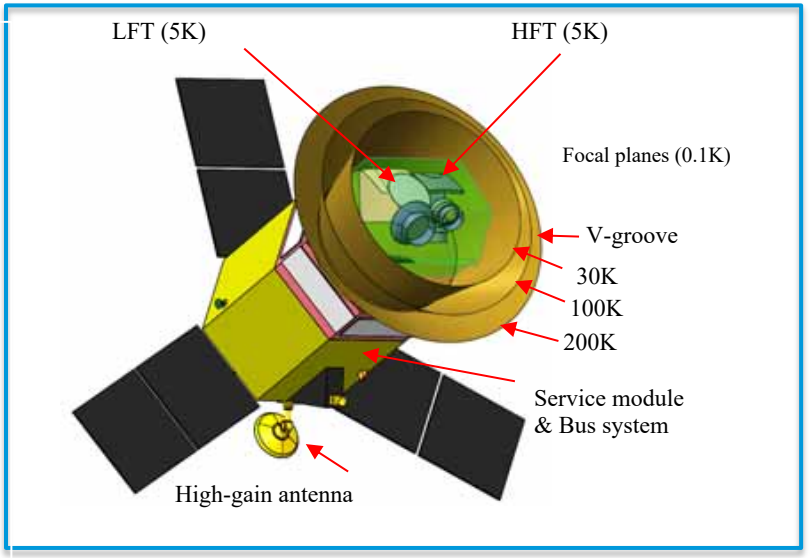


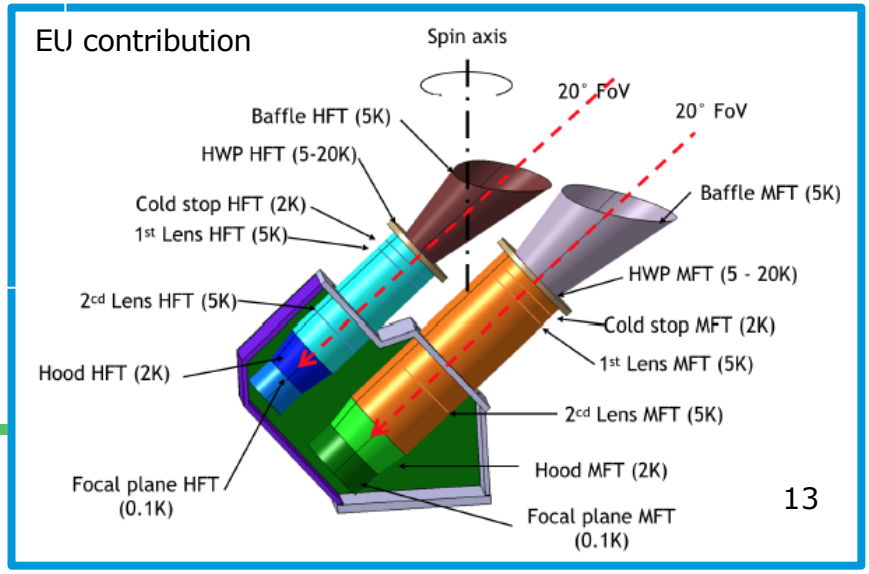


$$\Delta r_{0.05} = 0.01$$

LiteBIRD – a new space telescope for CMB

- **SPACE** - Led by JAXA (Japan space agency)
- Approved by JAXA in May 2019 – launch in "mid 2020s"
- 3 telescopes: Low Frequency, Mid Frequency, High Frequency
- Collaboration with NASA (detectors)
- Collaboration with ESA + European national agencies (ASI, CNES, …)
- Japan: Low frequency instrument: 34 – 161 GHz
- European contribution
  - Mid frequency instrument: 89-270 GHz
  - High frequency instrument: 238-448 GHz
  - INFN is involved in the electronics
- Sapienza has a leading role in Italy and Europe (providing hardware, European coordination, management)
- INFN-PI is proposing to provide hardware contribution
- INFN-Roma1 HW development: cryogenic, levitating HWP rotator, likely to be funded by ASI.
- Other activities: contribution to simulations and data analysis likely to be funded by INFN, to be organized.





LiteBIRD Full Success (simplified version)

- $\delta r < 1 \times 10^{-3}$ (for r=0)
- $2 \leq \ell \leq 200$

QUBIC / LSPE - Roma 1

Total of 7 people (5.4 FTE) with permanent position

All from university (teaching)

Ricercatori						
	Nome	Età	Contratto	Qualifica	Aff.	%
1	Battistelli Elia Stefano		Associato	Ricercatore	CSN II	50
2	Columbro Fabio		Associato	Dottorando	CSN II	50
3	Coppolecchia Alessandro		Associato	Assegnista	CSN II	50
4	D'Alessandro Giuseppe		Associato	Assegnista	CSN II	50
5	De Bernardis Paolo		Associato	Prof. Ordinario	CSN II	40
6	De Petris Marco		Associato	Ricercatore	CSN II	80
7	Lamagna Luca		Associato	Ricercatore	CSN II	30
8	Luzzi Gemma		Associato	Assegnista	CSN II	50
9	Masi Silvia		Associato	Prof. Associato	CSN II	60
10	Paiella Alessandro		Associato	Assegnista	CSN II	40
11	Piacentini Francesco		Associato	Prof. Associato	CSN II	40
				Numero Totale Ricercatori	11	FTE: 5.4

Ricercatori						
	Nome	Età	Contratto	Qualifica	Aff.	%
1	Battistelli Elia Stefano		Associato	Ricercatore	CSN II	50
2	Columbro Fabio		Associato	Dottorando	CSN II	50
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4	D'Alessandro Giuseppe		Associato	Assegnista	CSN II	50
5	De Bernardis Paolo		Associato	Prof. Ordinario	CSN II	60
6	Lamagna Luca		Associato	Ricercatore	CSN II	70
7	Luzzi Gemma		Associato	Assegnista	CSN II	50
8	Masi Silvia		Associato	Prof. Associato	CSN II	40
9	Melchiorri Alessandro		Associato	Prof. Associato	CSN IV	20
10	Paiella Alessandro		Associato	Assegnista	CSN II	60
11	Pascale Enzo		Associato	Prof. Associato	CSN II	50
12	Piacentini Francesco		Associato	Prof. Associato	CSN II	60
				Numero Totale Ricercatori	12	FTE: 6.1

Skills and expertise

- CMB Instrument design, assembly, calibration and operation (G31 group)
- Cryogenics (Masi)
- Electronics (de Bernardis)
- Optics / Quasi-optics / GHz-THz interferometry: simulation, design, testing (Lamagna)
- Small clean room for focal plane assembly (Coppolecchia)
- KIDs detectors simulation, design, optimization (Paiella)
- KIDs detectors testing, operation (OLIMPO experience - Masi et al. 2019, in press)
- Readout electronics (Battistelli)
- Data analysis (Piacentini)
- Scientific exploitation (Melchiorri)

Riassunto dei bisogni in risorse e competenze

NEEDS

- Resources:
  - Manpower
  - Stable personnel
  - Technicians:
    - Mechanics
    - Electronics
  - Tecnologo:
    - Clean room
    - Cryogenics
    - Operations of instruments
  - New activity on LiteBIRD space telescope

- Expertise:
  - Expert of FPGA firmware development
  - CAD technician
  - Electronics technician

ROMA1 Contribution

1) Ground

- **QUBIC** (with INFN)
- COSMO: CMB frequency spectrum from Antarctica

2) Balloon

- OLIMPO: flown in 2018
- **LSPE**: CMB polarization at large scales
  - Planned in 2020
  - INFN largely involved
- COSMO on Balloon

3) Satellite

- Planck mission (2009 – 2013) and analysis (2009 – 2019)
- **LiteBIRD**: CMB polarization at large scales
  - Approved by JAXA in May 2019
  - Relevant contribution from Europe (ESA, ASI, CNES, …)
  - Sapienza has a leading role in Italy and Europe (providing hardware, European coordination, management)
  - INFN-PI is proposing to provide hardware contribution
  - Roma1 HW development: cryogenic, levitating HWP rotator
    likely to be funded by ASI.
  - Other activities: contribution to instrument design, data analysis
    funded by INFN?
    to be organized.