Cosmology: Present and Future

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Current Cosmological «Model»

- **Scenario:**
  - The universe is **expanding and cooling** since the big-bang (a starting point with infinite density, infinite temperature).
  - A sequence of **bound states** follows (baryogenesis, nucleosynthesis, atoms, molecules, gravitationally bound structures: stars, galaxies, clusters, superclusters).

- **Model:**
  - An empirical model, called \( \Lambda \text{CDM} \), with only 6 free parameters, fits remarkably well a variety of cosmological measurements.
Current Cosmological «Model»

- **Assumptions of the model:**
  - Physics is the same everywhere in the universe and at all times
  - General Relativity is the correct description of Gravity
  - At large scales the universe is statistically homegenous and isotropic
  - The universe was much hotter and denser in the past and has been expanding since very early times
  - There are 5 basic constituents of the energy density of the universe:
    - Dark Energy (behaving like vacuum energy)
    - Dark matter (pressureless, stable and interacting with normal matter only gravitationally)
    - Regular atomic matter
    - CMB Photons
    - Neutrinos that are almost massless (for structure formation) and stream like non-interacting relativistic particles at the time of recombination
  - The curvature of space is very small
  - Density fluctuations were present everywhere at early times, and are Gaussian, adiabatic, and nearly scale-invariant as predicted by inflation
  - The topology of the Universe is trivial (i.e. like $\mathbb{R}^3$)
- **With these assumptions, the model fits measurements over several decades in length scale, and more than 13 Gyr of cosmic time.**

*arXiv 1807.06205*
Current Cosmological «Model»

- The 6 «golden» parameters (for CMB analysis):
  - \( \Omega_b h^2 \) energy density of normal matter, times normalized expansion rate squared
  - \( \Omega_c h^2 \) energy density of cold dark matter, times normalized expansion rate squared
  - \( \theta_{\text{MC}} \): acoustic angular scale = ratio of comoving sound horizon at recombination and angular diameter distance of recombination: \( r_s / D_A \)
  - \( \tau \): optical depth to recombination (Thomson)
  - \( A_s \) amplitude of the power spectrum of initial density perturbations
  - \( n_s \) spectral index of power spectrum of initial density perturbations

- Planck results:

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<th>Planck + BAO</th>
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arXiv 1807.06205
**Data:** Power spectrum of density fluctuations versus wavenumber

- Inferred from different cosmological observables: observations of the CMB, and of the large-scale distribution of matter in different forms (Luminous Red Galaxies, Hydrogen clouds, dark matter)
- They span >13 Gyr of cosmic time and three decades in length scales
- They are all **fit** by the minimal (6 parameters) $\Lambda$CDM model (black line), demonstrating its explanatory power.
The observables of cosmology

- Large-scale structure (z=0...2, t-t_o=0...-8 Gyr)
  - Redshift of galaxies -> redshift surveys (optical)
  - Lensing of galaxies -> shape surveys (optical)

- Cosmic Microwave Background (z=1100, t-t_o=-13.7 Gyr and earlier ...)
  - Spectrum
  - Anisotropy
  - Lensing
  - Polarization
CMB data

• Long development of CMB anisotropy and polarization experiments (COBE, BOOMERanG, WMAP, DASI ... )

• Current best set of data Planck, BICEP/KECK, SPT, ACT, Polarbear, ...

• Sensitivity of current polarization surveys such that Galactic foregrounds are the main issue, and must be monitored and removed to obtain clean cosmology data.
What is the CMB

According to modern cosmology:

An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 µs after the Big Bang ($10^9 \gamma$ for each baryon)

- **Thermalized** in the primeval fireball (in the first 380,000 years after the big bang) by repeated scattering against free electrons

- **Redshifted** to microwave frequencies and diluted in the subsequent 14 Gyrs of expansion of the Universe

- **Today**: $410 \gamma/cm^3$, $\sim 1$ meV
These photons carry significant information on the structure, evolution and composition of our universe
here, now

Transparent Universe (neutral)

Opaque Universe (primeval plasma)
here, now

R & t
look-back time and distance

Transparent Universe (neutral)

Opaque Universe (primeval plasma)

T=3000K
recombination

last scattering
The spectrum

• CMB photons are produced when matter and radiation are in tight thermal equilibrium (Thomson scattering in the primeval plasma)
• The spectrum of the CMB has to be a blackbody.
• The expansion of the universe preserves the shape of a blackbody spectrum, while its temperature decreases as the inverse of the scale factor.
• Measuring a blackbody spectrum of the CMB, we can prove the existence of a primeval fireball phase of the universe.
• To be consistent with the primordial abundance of light elements, a temperature of a few K is expected (Gamow)
with CMB data we can study all these phases

DAWN OF TIME

B-mode polarization, SZ effect, lensing

Spectrum, Primary, Anisotropy, E-modes

inflation

primeval fireball

structures in the making

380,000 years

13.7 billion years

tiny fraction of a second
CMB anisotropy (intrinsic)

• Different physical effects, all related to the small density fluctuations $\delta \rho / \rho$ present 380000 yrs after the big bang (recombination) produce CMB Temperature fluctuations:

\[
\frac{\delta T}{T} = \frac{1}{3} \frac{\delta \phi}{c^2} + \frac{1}{4} \frac{\delta \rho_\gamma}{\rho_\gamma} - \frac{\vec{v} \cdot \vec{n}}{c}
\]

- Sachs-Wolfe (gravitational redshift)
- Photon density fluctuations
- Doppler effect from velocity fields

• Scales larger than the horizon are basically frozen in the pre-recombination era. Flat power spectrum of $\delta T/T$ at large scales.

• Scales smaller than the horizon undergo acoustic oscillations during the primeval fireball. Acoustic peaks in the power spectrum of $\delta T/T$ at sub-degree scales.
CMB anisotropy (intrinsic)

• The primeval plasma of photons and matter oscillates:
• self-gravity vs radiation pressure.
• We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
• Statistical theory: all information encoded in the angular power spectrum of the image.
Density perturbations (\(\Delta \rho / \rho\)) were oscillating in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).

Due to gravity, \(\Delta \rho / \rho\) increases, and so does \(T\).

Pressure of photons increases, resisting to the compression, and the perturbation bounces back.

Before recombination \(T > 3000\) K

After recombination \(T < 3000\) K

Here photons are not tightly coupled to matter, and their pressure is not effective. Perturbations can grow and form Galaxies.

After recombination, density perturbation can grow and create the hierarchy of structures we see in the nearby Universe.
In the primeval plasma, photons/baryons density perturbations start to oscillate only when the sound horizon becomes larger than their linear size. Small wavelength perturbations oscillate faster than large ones.
An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. $\sigma$:

$$W_{\ell}^{LP} = e^{-\ell(\ell+1)\sigma^2}$$

Expected power spectrum:

$$\Delta T(\theta, \varphi) = \sum_{\ell,m} a_{\ell m} Y_{\ell}^m(\theta, \varphi)$$

$$c_{\ell} = \langle a_{\ell m}^2 \rangle$$

$$\langle \Delta T^2 \rangle = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) c_{\ell}$$

See e.g. http://camb.info to compute $c_{\ell}$ for a given cosmological model.
Critical density Universe $\Omega = 1$

High density Universe $\Omega > 1$

Low density Universe $\Omega < 1$

The image and PS are modified by the geometry of the universe.
The mass-energy density of the Universe can be measured in this way.
Composition

- The composition of the universe (baryons, dark matter, dark energy) affects the shape of the power spectrum.
- Accurate measurements of the power spectrum allow to constrain the energy densities of the different components of the universe.
CMB anisotropy (lensing)

- Photons travelling in the universe for 13.7 Gly interact with massive structures, and are deflected (gravitational lensing)
- The result is a modified image of CMB anisotropy, which can be analyzed to study the distribution of mass (mainly dark matter) all the way to recombination.
intrinsic CMB anisotropy

Typical deflection: 2.5′
lensed CMB anisotropy

Typical deflection: 2.5′
CMB polarization (E)

• CMB photons are last scattered at recombination.
• It’s a Thomson scattering, and any quadrupole anisotropy in the incoming photons produces a degree of linear polarization in the scattered photons.
• Density perturbation produce a small degree of linear polarization (E-modes)
\( e^- \) at last scattering
Converging flux
Same flux as seen in the electron rest frame

Diverging flux

Quadrupole anisotropy due to Doppler effect

Resulting CMB polarization field (E-modes)

Velocity fields at recombination

Hot, dense spot

Cold, less dense spot

Expect E-modes and a T-E correlation
• E-modes are irrotational

• E modes are related to velocities, while T is related mainly to density

• We expect a power spectrum of the E-modes, \( <EE> \), with maxima and mimina in quadrature with the anisotropy power spectrum \( <TT> \).
Figure 1.7: Estimated power spectra for the cosmological parameters: $\Omega_b = 0.05$, $\Omega_{cdm} = 0.3$, $\Omega_\Lambda = 0.65$, $\Omega_\nu = 0$, $H_0 = 65$ km/s/Mpc, $\tau = 0.17$. The temperature power spectrum, $\langle TT \rangle = C^T_\ell$, the $E$-modes power spectrum $\langle EE \rangle = C^E_\ell$ multiplied by a factor 100 to make it visible and the cross power spectrum between temperature and polarization, $\langle TE \rangle = C^{TE}_\ell$ multiplied by a factor 10. The spectra are computed using the publicly available code CMBFAST (http://www.cmbfast.org),
CMB polarization (B)

- CMB photons are last scattered at recombination.
- It’s a Thomson scattering, and any quadrupole anisotropy in the incoming photons produces a degree of linear polarization in the scattered photons.
- Tensor perturbations (gravitational waves) produce a small degree of linear polarization with curl properties (B-modes)
- Also, lensing of E-modes does the same at smaller scales
If inflation really happened...

- It stretched geometry of space to nearly Euclidean.
- It produced a nearly scale invariant spectrum of density fluctuations.
- It produced a stochastic background of gravitational waves.

OK
OK
?
Quadrupole from P.G.W.

- If inflation really happened:
  - It stretched geometry of space to nearly Euclidean
  - It produced a nearly scale invariant spectrum of gaussian density fluctuations
  - It produced a stochastic background of gravitational waves: Primordial G.W. The background is so faint that even LISA will not be able to measure it.

- Tensor perturbations also produce quadrupole anisotropy. They generate irrotational (E-modes) and rotational (B-modes) components in the CMB polarization field.

- Since B-modes are not produced by scalar fluctuations, they represent a signature of inflation.
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:

\[
\left( \frac{T}{C} \right)^{1/4} \equiv \left( \frac{C_{GW}^2}{C_{Scalar}^2} \right)^{1/4} \approx \frac{V^{1/4}}{3.7 \times 10^{16} \text{ GeV}}
\]

\[
\sqrt{\frac{\ell(\ell+1)}{2\pi}} c_{\ell \text{ max}}^B \overset{\approx}{=} 0.1 \mu K \left[ \frac{V^{1/4}}{2 \times 10^{16} \text{ GeV}} \right]
\]

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 current upper limit on anisotropy at large scales gives \(T/S < 0.5\) (at 2\(\sigma\)).

A competing effect is lensing of E-modes, which is important at large multipoles.
E-modes & B-modes

Spin-2 quantity

\[(Q \pm iU)(\hat{n}) = \sum_{\ell,m} \left( a^E_{\ell m} \pm ia^B_{\ell m} \right) \pm 2 Y_{\ell m}(\hat{n}) \]

Spin-2 basis

- From the measurements of the Stokes Parameters \(Q\) and \(U\) of the linear polarization field we can recover both irrotational and rotational \(a_{\ell m}\) by means of modified Legendre transforms:

E-modes produced by scalar and tensor perturbations

\[a^E_{\ell m} = \frac{1}{2} \int d\Omega W(\hat{n}) \left[ (Q + iU)(\hat{n}) + (Q - iU)(\hat{n}) \right] Y_{\ell m}(\hat{n}) + (Q - iU)(\hat{n}) - 2 Y_{\ell m}(\hat{n}) \]

B-modes produced only by tensor perturbations

\[a^B_{\ell m} = \frac{1}{2i} \int d\Omega W(\hat{n}) \left[ (Q + iU)(\hat{n}) + (Q - iU)(\hat{n}) \right] Y_{\ell m}(\hat{n}) - (Q - iU)(\hat{n}) - 2 Y_{\ell m}(\hat{n}) \]
The signal is extremely weak

- Nobody really knows how to detect this.
  - Pathfinder experiments are needed
- Whatever smart, ambitious experiment 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 systematics.
- There is still a long way to go: ...
1. Quantum fluctuation of the metric

\[ \langle \hat{h}^\dagger (\vec{k}, \eta) \hat{h}(\vec{k}', \eta) \rangle = |v(\vec{k}, \eta)|^2 (2\pi)^3 \delta^3(\vec{k} - \vec{k}'). \]

e.g. Dodelson “Modern Cosmology” Eq.(6.52)

2. Physics at GUT scale

\[ V^{1/4} = 1.06 \times 10^{16} \times \left( \frac{r}{0.01} \right)^{1/4} \text{ [GeV]} \]
Quantum fluctuation of spacetime

\[ \sim 10^{-36} \text{sec} \]

~400 thousand years

M. Hazumi
Big leap from LIGO/VIRGO to LiteBIRD

within Einstein’s theory of general relativity

beyond Einstein

LIGO/VIRGO: gravitational waves with classical origin
LiteBIRD: gravitational waves with quantum origin

M. Hazumi
“Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time.”

Cosmic inflation predicts generation of primordial gravitational waves due to quantum fluctuation of spacetime.

M. Hazumi
LSS and neutrino masses

• This lensing effect is due to the distribution of mass (mainly dark) at large scales.
• The formation of large scale structures in the universe depends on the presence and mass of free-streaming neutrinos.
Matter power spectrum

\[ P_m(k, z) = \left\langle \left( \frac{\delta \rho}{\rho} \right)^2 \right\rangle_{k, z} = A k^n \cdot T^2(k, z) \]

- **Wavenumber** (Mpc\(^{-1}\))
- **Redshift** (epoch)
- **Primordial** (inflation ?)
- **Transfer function describing the growth of density fluctuations**

![Graph of matter power spectrum](chart.png)

- \( P(k) \) (Mpc/h\(^3\))
- \( k \) (h/Mpc)
- \( f_v = 0 \)
- \( f_v = 0.1 \), fixed (\( \omega_c \), \( \omega_\Lambda \))
- \( f_v = 0.1 \), fixed (\( \omega_c \), \( h \))
Effects on Matter power spectrum

Large scales: effect of $\nu$ free-streaming negligible, $\nu$ act as CDM

Small scales: ($\nu$ cannot be confined within scales smaller than free-streaming length)
- Absence of $\nu$ perturbations
- Slower growth rate of CDM/Baryons perturbations

Galaxy *lensing* surveys

- Images of galaxies are distorted by weak gravitational lensing, due to the intervening total mass distribution between the sources and the observer.
- Stretching the image in a direction and squeezing in the orthogonal direction (cosmic shear).
- Distortions coherent over size of density fluctuations, tend to align the major axis of galaxies over the same size.
- The lensing potential can be retrieved from the distortion map.
- Possible to recover the lensing potential in redshift bins.

Dark matter distribution (color) inferred from shear field measurements (lines, from Massey et al. 2007). Each line is estimated averaging the shapes of about 200 galaxies present in the pixel.
ν mass and the power spectrum of the CMB

• If $M_\nu < 1\text{eV}$, massive neutrinos become non-relativistic after H recombination.

• The shape of the power spectrum of the CMB is mostly determined by physics before recombination (acoustic oscillations), so the effect of massive neutrinos on the CMB PS is small.

• However:
  – The presence of massive neutrinos modifies the evolution of the background universe. They count as radiation at matter/radiation equality, and as non-relativistic matter today. So their effect is either a change in the epoch of equality or a change in the $\Omega_m$ producing a change in the angular diameter distance of CMB. Both effect change the spectrum of the CMB. Small effects, and also degenerate with other parameter changes. To be used in combination with other observables. **BUT VERY STABLE!**
  – The fine structure of CMB anisotropy and polarization is affected by lensing, so is sensitive to the matter power spectrum, which in turn depends on $\Omega$ mass. **More powerful probes, BUT SUFFER THE SAME “ASTROPHYSICS” PROBLEMS OF MATTER PS**
\[ \frac{[L(l+1)/2\pi]}{C_l} \]

- \( M_\nu = 0 \)
- \( M_\nu = 3 \times 0.3 \text{ eV}, \text{ same } z_{eq}, l_{\text{peak}} \)
- \( M_\nu = 3 \times 0.6 \text{ eV}, \text{ same } z_{eq}, l_{\text{peak}} \)

Deflection power spectrum

$m_1 = m_2 = 0.05 \text{ eV}, m_3 = 0 \text{ eV}$

vs

3 massless
CMB constraints on neutrinos

• Cosmological effects of neutrinos (see e.g. Lattanzi and Gerbino 2017):
  • For masses of the order of 0.1 eV vs are still relativistic at recombination and their effect on the anisotropy spectrum is small.
  • The main effect of massive vs is at later times, when they alter the expansion history, and the shape of the matter power spectrum. Increasing $m_\nu$ increases the expansion rate at $z>1$, and modifies the distance-redshift relation. However, this is constrained by the scale of the acoustic peaks ($\theta_{MC}$), so another parameters must change to leave the same $\theta_{MC}$ when $\Sigma m_\nu$ increases, i.e. suppressing large-scale power. This results in a broad suppression of the matter power spectrum at fixed CMB amplitude.
  • Since vs free-stream, the matter power spectrum is suppressed at small scales. So, in addition to the effect on primary anisotropies, the late-times potentials are modified, and the spectrum of CMB lensing is also modified.
  • Planck data are now sensitive to
    • Changes in the distance to $z_{dec}$
    • Smoothing of the temperature and polarization power spectra
    • Shape of the lensing power spectrum
  • Resulting in a tight upper limit $\Sigma m_\nu < 0.12$ eV (95% CL).
Most of this has been measured very successfully, and used to constrain cosmology.

• Spectrum
• Intrinsic anisotropy (power spectrum)
• Lensing
• E-modes polarization
• SZ effect
• B-modes polarization
The spectrum: a proof of the primeval fireball

Wavelength [mm]

Intensity [MJy/sr]

wavenumber $\sigma$ (cm$^{-1}$)

FIRAS data with 400$\sigma$ errorbars

2.725 K Blackbody

Mather et al. 1994
Nobel Prize 2006
Depending on the physical process, the expected spectral distortions have a different shape \((\varepsilon, \mu, y)\). See e.g.: The evolution of CMB spectral distortions in the early Universe
J. Chluba
R. A. Sunyaev
MNRAS (2012) 419 1294

No distortions have been observed to-date (may be not? See Bowman et al. Nature 2018).

Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. 354 37
Anisotropy and Polarization
Planck Legacy Maps  
6x10^6 pixels (5')

857 GHz

30–353 GHz: $\delta T$ [\mu K_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]
$D_\ell = \ell(\ell + 1) \frac{C_\ell}{(2\pi)}$  

Power spectra at 143 GHz
\[ D_\ell = \ell(\ell + 1) C_\ell / (2\pi) \]  
Power spectra at 143 GHz
components separation

\[ \Delta T(v_j, \ell, b) = \sum_k a_k(v_j, \ell, b)C_k(\ell, b) \]

\( k = \text{CMB, dust, synchrotron, ...} \)

\( j = 33, 44, 70, 100, 143, 217, 353, 545, 857 \text{ GHz} \)

Measured maps
The CMB component: anisotropy
The CMB component: polarization
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<td>( H_0 )</td>
<td>67.36 ± 0.54</td>
<td>67.66 ± 0.42</td>
</tr>
<tr>
<td>( \Omega_\Lambda )</td>
<td>0.6847 ± 0.0073</td>
<td>0.6889 ± 0.0056</td>
</tr>
<tr>
<td>( \Omega_m )</td>
<td>0.3153 ± 0.0073</td>
<td>0.3111 ± 0.0056</td>
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<td>( \Omega_m h^2 )</td>
<td>0.1430 ± 0.0011</td>
<td>0.14240 ± 0.00087</td>
</tr>
<tr>
<td>( \Omega_m h^3 )</td>
<td>0.09633 ± 0.00030</td>
<td>0.09635 ± 0.00030</td>
</tr>
<tr>
<td>( \sigma_8 )</td>
<td>0.8111 ± 0.0060</td>
<td>0.8102 ± 0.0060</td>
</tr>
<tr>
<td>( \sigma_8 (\Omega_m / 0.3)^{0.5} )</td>
<td>0.832 ± 0.013</td>
<td>0.825 ± 0.011</td>
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<td>( z_{re} )</td>
<td>7.67 ± 0.73</td>
<td>7.82 ± 0.71</td>
</tr>
<tr>
<td>( \text{Age}[\text{Gyr}] )</td>
<td>13.797 ± 0.023</td>
<td>13.787 ± 0.020</td>
</tr>
<tr>
<td>( r_* [\text{Mpc}] )</td>
<td>144.43 ± 0.26</td>
<td>144.57 ± 0.22</td>
</tr>
<tr>
<td>( 100\theta_* )</td>
<td>1.04110 ± 0.00031</td>
<td>1.04119 ± 0.00029</td>
</tr>
<tr>
<td>( r_{	ext{drag}} [\text{Mpc}] )</td>
<td>147.09 ± 0.26</td>
<td>147.57 ± 0.22</td>
</tr>
<tr>
<td>( z_{eq} )</td>
<td>3402 ± 26</td>
<td>3387 ± 21</td>
</tr>
<tr>
<td>( k_{eq} [\text{Mpc}^{-1}] )</td>
<td>0.010384 ± 0.000081</td>
<td>0.010339 ± 0.000063</td>
</tr>
<tr>
<td>( \Omega_K )</td>
<td>-0.0096 ± 0.0061</td>
<td>0.0007 ± 0.0019</td>
</tr>
<tr>
<td>( \Sigma m_\nu \text{[eV]} )</td>
<td>&lt; 0.241</td>
<td>&lt; 0.120</td>
</tr>
<tr>
<td>( N_{\text{eff}} )</td>
<td>2.89_{-0.36}^{+0.36}</td>
<td>2.99_{-0.33}^{+0.34}</td>
</tr>
<tr>
<td>( r_{0.002} )</td>
<td>&lt; 0.101</td>
<td>&lt; 0.106</td>
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The future of research in cosmology

• Simply stated, improve the accuracy of current measurements of cosmological observables to understand the Universe and Fundamental Physics.

• Targets:
  • cosmological inflation and the very early universe
  • nature of dark matter
  • nature of dark energy and its equation of state
  • first stars and structure formation
  • neutrino masses ...
  • parity violations ...

• Methods:
  • Optical/NIR surveys of galaxies (Weak Gravitational Lensing, Baryonic Acoustic Oscillations, Redshift-space Distortions)
    • Ground-based: SDSS, DES, LSST ...
    • Space-borne: EUCLID (1.2m), CSS-OS (2m), JWST(6m), WFIRST (2m)
  • CMB polarization experiments
    • Ground-based experiments, e.g. Keck, QUBIC, SO, S4
    • Balloon-borne experiments, e.g. OLIMPO, LSPE, Bfore, IDS
    • Space-borne experiments, e.g. LiteBIRD
  • CMB spectrum - spectral distortions experiments
    • e.g. COSMO (ground and balloon)
  • Radio surveys (SKA, LOFAR)
    • HI surveys (medium and deep): 3D maps of galaxies to high redshift (up to z=6) and power spectra of density fluctuations per redshift bins
    • Signals from first stars (EDGES detection ...
EUCLID: ESA mission, launch 2022, 6 years of operations in L2
- 1.2m telescope, panoramic visible imager (VIS), near infrared 3-filter (Y, J and H) photometer (NISP-P), slitless spectrograph (NISP-S)
- Will map >15000 square degrees of the darkest sky, plus deep surveys
- 10 billion sources will be detected
- >1 billion galaxies will be used for ultrasensitive weak lensing and redshift surveys
Why from space

• For galaxies at $z=1$ EUCLID has the same resolution of the SDSS at $z=0.05$

• The EUCLID survey will be 3 magnitudes deeper than the SDSS
Borgani & Guzzo 2001
Andreon+ 2009

The evolution of cosmic structures depends dramatically on the presence of Dark Energy and on its nature.

Euclid will study Galaxy Clustering (Baryonic Acoustic Oscillations and Redshift Space Distortion) with unprecedented accuracy, to measure the equation of state of DE
Euclid will study Weak Gravitational Lensing with unprecedented accuracy, to discover the nature of dark matter via its distribution and its effect on the growth of cosmic structures.
Euclid will also study Strong Gravitational Lensing with unprecedented accuracy, again producing invaluable info on dark matter.
Euclid will also study Strong Gravitational Lensing with unprecedented accuracy, again producing invaluable info on dark matter.

Euclid VIS Legacy: after 2 months (66 months planned)
Figure 8. Marginalized 1σ and 2σ contours and one-dimensional posteriors in the $(\omega_b, \omega_{cdm}, A_s, n_s, M_\nu, H_0, \tau_{reio}, \sigma_8, \Omega_m)$ parameter space, showing the expected sensitivity of Planck-only, Planck + Euclid (CS + GC), Planck + SKA1 (CS + GC), Planck + SKA1-IM and Planck + SKA2 (CS + GC). Here the analysis is performed following the conservative approach for the description of the theoretical error.

Note the improvement on the determination of $m_\nu$.

Sprengen et al. JCAP 2019
arXiv 1801.08331
B-modes in CMB polarization
B-modes forthcoming soon: QUBIC
hear J.C. Hamilton tomorrow

bolometric interferometer: novel technique, independent and necessary for a cross check of any detection
B-modes forthcoming soon: LSPE-SWIPE and LSPE-STRIP

Bolometric Imager
Stokes Polarimeter
Large number of measured CMB modes
Cryogenic spinning HWP modulator
LSPE in a nutshell

- The Large-Scale Polarization Explorer is an experiment to measure the polarization of the CMB at large angular scales.

- Science drivers:
  - The B-modes from inflation are mainly at large scales ($r$)
  - Polarization signatures from reionization ($\tau$) are mainly at large scales
  - Rotation of the polarization angles (related to new physics)
  - Sensitive polarized dust survey at frequencies close to the CMB ones
  - Sensitive polarized synchrotron survey at frequencies close to the CMB ones

- Instrumental approach:
  - The use of a large number of multimode detectors promises to improve the sensitivity wrt to Planck-HFI
  - The use of a polarization modulator (in SWIPE) promises to solve several systematic effects affecting the performance of Planck-HFI at large scales
  - The use of a single large polarizer, common for the entire focal plane, to define the main axis of the polarimeter with high precision (<<0.1°) promises to improve the absolute reconstruction of the polarization directions.
The Large-Scale Polarization Explorer is an experiment to measure the polarization of the CMB at large angular scales.

- Frequency coverage: 40 – 250 GHz (5 bands)
- 2 instruments: STRIP & SWIPE covering the same northern sky
- **STRIP** is a ground-based instrument working at 44 and 90 GHz (hear Marco Bersanelli in a while)
- **SWIPE** works at 140, 220, 240 GHz
  - collects 8800 radiation modes
  - uses *a spinning stratospheric balloon payload* to avoid atmospheric noise, flying *long-duration, in the polar night*
  - uses a *polarization modulator* to achieve high stability
  - Angular resolution: 1.3° FWHM
  - Sky coverage: 20-25% of the sky per flight / year
  - Combined sensitivity: 10 μK arcmin per flight

See astro-ph/1208.0298, 1208.0281, 1208.0164 and forthcoming updates
**LSPE – Experiment Strategy**

**STRIP**
Ground telescope at 43 and 95 GHz located in Tenerife. Will measure for two years. Based on coherent polarimeters.

**SWIPE**
Balloon borne telescope at 143, 220 and 240 GHz. Will take measurements for two weeks during a LDB nocturnal flight around the North Pole. Based on TES bolometers.

Credit: A. Mennella

Credit: L. Pagano, F. Piacentini

Mask convolved foreground - sky fraction: 0.303

Equatorial

Galactic
LSPE: Foregrounds cleaning strategy

- **44 GHz**: Monitor polarized synchrotron
- **90 GHz**: Atmospheric monitor
- **140 GHz**: Main CMB channel
- **220 + 240 GHz**: Monitor level, slope and possible rotation of polarized dust emission. To date - extrapolated from 350 GHz
SWIPE: general design

- SWIPE is a Stokes Polarimeter, based on:
  - a simple 50 cm aperture refractive telescope,
  - a cold HWP polarization modulator,
  - a beamsplitting polarizer, and
  - two large focal planes,
  - filled with multimode bolometers at 140, 220, 240 GHz.

- Everything is cooled by a large L⁴He cryostat and a ³He refrigerator, for operation of the bolometers at 0.3K

- The instrument is flown at 40 km altitude to mitigate the effects of earth’s atmosphere, and scans the sky spinning in azimuth.
SWIPE: ground/sun shield

The ground shield is very large .. .... but not impossible.

OLIMPO, flown from LYR on July 7th, 2018
LSPE/SWIPE

Rendering without ground/sun shields – a 1.6 tons payload
SWIPE: Simple ACS

- ACS based on the successfull pivot flown on BOOMERanG and OLIMPO.
- Azimuth spin of the entire payload up to 3 rpm (with 3A current for a 1600kg load).
- Attitude determination from the same gyros and star sensors flown on Archeops (Nati et al. A fast star sensor for spinning balloon payloads Review of Scientific Instruments, 74, 4169-4175, (2003))
SWIPE - receiver

- A Stokes (HWP + polarizer + power detector) polarimeter, panoramic
- Simple implementation
- Two large focal planes (8800 modes), at 0.3K, in a large cryostat, cooling also the lens (490mm diam. and a 460 mm diam. cold stop ) and the polarization modulator (HWP at about 10-15 K).
- FOV: 20° split by a 500mm diam., 45° tilted wire grid into 2 Focal Planes 300 mm diam (f/1.75)
- Most components being machined, some ready
LSPE/SWIPE: Receiver

- LSPE-SWIPE polarimeter and cryostat
- LSPE-SWIPE polarization modulator
- Fast (1-2 rps) levitating HWP rotator and HDPE lens
• Is a cold (2K), large (50 cm useful dia.), wide-band meta-materials HWP, placed immediately behind the window and thermal filters stack.

• HWP characteristics for the ordinary and extraordinary rays are well matched: \((T_o-T_e)/T_o < 0.001, \chi_{pol}<0.01\), over the 100-300 GHz band.

• Simulations show that continuous rotation has advantages in terms of 1/f noise mitigation and angles coverage.

• A custom superconductive rotator has been developed.

SWIPE – HWP rotator

~670mm

Pros

• NO stick-slip friction
• NO extra-effort to cool HTSs
• Passive stable levitation
• Low Coefficient of friction
• Continuous rotation (0-10Hz)

Cons

• Variable magnetic field
• Clamp mechanism at 4K

SWIPE – HWP rotator - General layout

1T field strength in the gap. Total mass 9 kg.
SWIPE – HWP rotator – parts procured

Stator with YBCO bulks

Groove ring for C/R

Rotor with permanent magnets

smaller diameter Prototype arXiv:1706.05963v3
SWIPE – HWP rotator – clamp/release

Stator

Rotor

Clamp / Release (1/3)

Frictionless actuator for operation @ 2K

Fabio Columbro, Paolo de Bernardis, and Silvia Masi

A clamp and release system for superconducting magnetic bearings

SWIPE: Cryogenic Testbed

Based on a pulse-tube cooler

A. Rocchi
Single lens 490mm in dia: plano-convex lens curved focal plane

Dimensions:
HDPE Lens (L1) diameter = 480 mm
Aperture Stop (AS) = 440 mm
Entrance Pupil = 450 mm
FOV = 20 deg
f/1.88
Curved Focal plane (CFP_T o CFP_R) diameter = 300 mm
Lens thickness = 65 mm
HDPE lens with AR by porous PTFE

Constraints:
Thermal filters max c.a. diameter = 500 mm
Wire Grid (WG @45 deg tilt) max c.a. diameter = 500 mm
HWP max c.a. diameter = 500 mm
Single lens 490mm in dia: plano-convex lens curved focal plane

Corrected focal plane vs bands
Single-Mode vs Multi-Mode design: how, when and why go Multi-Mode

- Diffraction- and photon-noise limited operation over quite a broad band demonstrated
- Solid modeling techniques
- Instrument design is complicated but huge experience accumulated by community over the last few years.
- Large numbers of detectors needed to break photon noise limit

- Reduce the number of individual sensitive elements each hitting the photon noise limit more easily
- Sensitivity per individual device scales like $N_{\text{modes}}^{1/2}$
- Comparatively larger detector units and coarser angular resolution.
- Viable and cost-effective when sensitivity is a stronger requirement than diffraction-limited operation (e.g. Planck 545 and 857 GHz)
- CMB spectral distortion and large scale B-mode searches can fully take advantage of m-m design (PIXIE, LSPE)

L. Lamagna
LSPE/SWIPE: multimode optics

- Whole system multimode
- Full EM simulation described in: Legg, Lamagna, Coppi, de Bernardis, Giuliani, Gualtieri, Marchetti, Masi, Pisano, Maffei, Development of the multi-mode horn-lens configuration for the LSPE-SWIPE B-mode experiment Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 991414 doi:10.1117/12.2232400
- Resulting beam approximately top-hat. 1.5° FWHM.
- Good polarization properties.

L. Lamagna. M. De Petris
The SWIPE pixel assembly

![Diagram of the SWIPE pixel assembly](image)

<table>
<thead>
<tr>
<th>Channel</th>
<th>$v_{\text{min}}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\text{min}})$</th>
<th>$v_{\text{max}}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\text{max}})$</th>
<th>$v_{\text{eff}}$ (GHz)</th>
<th>$N_{\text{modes}}(v_{\text{eff}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>119</td>
<td>10</td>
<td>161</td>
<td>17</td>
<td>140</td>
<td>12</td>
</tr>
<tr>
<td>220</td>
<td>214</td>
<td>28</td>
<td>226</td>
<td>31</td>
<td>220</td>
<td>30</td>
</tr>
<tr>
<td>240</td>
<td>234</td>
<td>32</td>
<td>246</td>
<td>35</td>
<td>240</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 1 – main features of the SWIPE bandpasses (source: C. Tucker, Cardiff Univ.)

Table 2 – number of coupled modes $N_{\text{modes}}$ at the center and at the edges of each SWIPE band. The total optical throughput at frequency $v$ is $N_{\text{modes}}C^2/v^2$.
SWIPE focal planes: 33% 140 GHz, 33% 220 GHz, 33% 240 GHz.
Total 330 detectors, with $A\Omega = 10\lambda^2, 21\lambda^2, 23\lambda^2$ @140, 220, 240.
The distribution of colors in the pixels has been optimized with a simplified scheme for foregrounds (dust) removal.

A roughly equal number of pixels in the three bands provides sufficient precision to extrapolate the dust signal from high frequency down to 150 GHz.

This configuration totals 4400 radiation modes for each focal plane (transmitted and reflected).
Focal plane detector flanges (gold plated Al6061, 40 cm side).

Large Throughput multimode detectors: 8800 modes collected by 330 sensors.

LSPE horns & bolo holders
Large Throughput multimode detectors: 8800 modes collected by 330 sensors

Focal plane detector flanges (gold plated Al6061, 40 cm side).
SWIPE - multimode absorbers & TES

- The absorbers are large $\text{Si}_3\text{N}_4$ spider-webs (8 mm diameter, multimode)
- Sensors are Ti-Au TES
- Photon noise limited
- $\tau = 10 \text{ ms}$
SWIPE - multimode absorbers & TES

- IV curves acquired with SQUID VTT J3, with $M=36 \, \mu A/\phi$
- Voltage bias generated onto a shunt resistor of $7.34 \, m\Omega$
- The analysis allows to calculate the effective thermal conductance $G$ and the NEP, including the electro-thermal feedback
**SWIPE - multimode absorbers & TES**

- Very large spider-web absorbers: long time constant, even with large electrothermal feedback
- Minimize heat capacity by using Bi metalization of the spider-web
- Optimization of resistance per square versus heat capacity
- Expected around 10-20 ms

<table>
<thead>
<tr>
<th>Parameters for Gold</th>
<th>Expt/meas. factor</th>
<th>Effect on heat capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRR</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>3% Match. Fact.</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>G factor</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Expctd Tau fact.</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter for Bi over Gold</th>
<th>Expt/meas. factor</th>
<th>Effect on heat capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity Ratio</td>
<td>50(expec.) - 70(meas.)</td>
<td>3.4(expec.) - 2.4(meas.)</td>
</tr>
<tr>
<td>Specific heat ratio</td>
<td>1/170</td>
<td></td>
</tr>
<tr>
<td>G fact.</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Expctd. Tau fact</td>
<td>5(meas.) - 7(expec.)</td>
<td></td>
</tr>
</tbody>
</table>

F. Gatti
Absorber properties

- EM simulations of absorber illumination, mode by mode, for several off-axis angles

- Despite of the different shapes, the integral is regular.
- Uniformity of absorption is very important to obtain a regular beam pattern.
- Internal conductivity of the absorber mesh also very important.
- RA measurements are warranted to be significant only in cold operating conditions
SWIPE - TES readout (mux)

Wiring and connections from 300 mK to 250 K

G. Signorelli
SWIPE - TES readout (mux)

- 14 Si chips, 2 Nb 15 μH inductors each, 5 open-circuited
- 28 SMD capacitors, ranging from 220 pF to 100 nF
- SMD resistors with $R = 1 \, \Omega$, $R_{\text{shunt}} = 100 \, \text{mΩ}$
- Readout with SQUID in FLL
- Tested @ 4 K

Test of a readout channel
SWIPE - TES readout (mux)

- Altera Cyclone V SoC
  - FPGA with 110'000 logic elements
  - 925 MHz dual-core micro-controller
- Mezzanine plug-ins for DAC and ADCs
  - 2 LTC1668 DACs (low noise, low power consumption)
  - 1 LTM9001-GA ADCs (16-bit, 25 MSPS)
- Gbit interface for data communication
- CAN & I2C interfaces to control low noise amps

FDM board tested and working
First comb generation algorithm

G. Signorelli
**LSPE/SWIPE: cryogenic system**

**LSPE-SWIPE**
- Aluminum cryostat
- Large cold volume (1m$^3$)
- 2 vapor cooled shields
- Fiberglass support system
- 250L of superfluid $^4$He @ 1.6K
- > 15 days hold time
- $^3$He refrigerator 0.28K

(Coppi et al. 2016SPIE.9912E..65C)
## LSPE/SWIPE: cryogenic system

Expected performance versus gas exchange efficiency (30 s.i. shields)

<table>
<thead>
<tr>
<th>$T_{\text{ext}}$ (K)</th>
<th>Efficiency</th>
<th>$T_{\text{shield1}}$ (K)</th>
<th>$T_{\text{shield2}}$ (Kelvin)</th>
<th>Hold time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>0.7</td>
<td>90</td>
<td>251</td>
<td>30</td>
</tr>
<tr>
<td>290</td>
<td>0.8</td>
<td>90</td>
<td>247</td>
<td>30</td>
</tr>
<tr>
<td>290</td>
<td>0.9</td>
<td>90</td>
<td>244</td>
<td>30</td>
</tr>
<tr>
<td>220</td>
<td>0.7</td>
<td>75</td>
<td>183</td>
<td>41</td>
</tr>
<tr>
<td>220</td>
<td>0.8</td>
<td>71</td>
<td>180</td>
<td>45</td>
</tr>
<tr>
<td>220</td>
<td>0.9</td>
<td>67</td>
<td>178</td>
<td>50</td>
</tr>
</tbody>
</table>
Cryostat development
parts being machined
Cryostat development
parts being welded

S. Masi, 3/12/2018
• If $r \ll 0.01$ LSPE-SWIPE provides a 95% CL U.L. $r < 0.03$
• If $r > 0.01$ LSPE-SWIPE provides a significant detection of $r$
• The measurement of the optical depth to recombination is improved significantly wrt Planck:

L. Pagano, F. Piacentini
Mission Requirements:

SWIPE limits (68% CL) to the tensor to scalar ratio versus integration time:

- Long integration time (8 days minimum, 15 days goal)
- Night flight (to cover all azimuths with a telescope spinning in azimuth)
Flight managed by ASI, scheduled for end of 2020
Longyearbyen - Svalbard
SWIPE: solar illumination issues

- With a careful choice of the launch date and launch site the length of the illuminated portions of the flight can be minimized (see forecast document *Analysis of Winter Polar stratospheric balloon trajectories, 23/10/2018*).

- We do not plan to carry out science measurements during these periods, but the instrument should be prepared to survive short solar illumination periods.

F. Piacentini
B-modes future: LiteBIRD

Bolometric Imager
Stokes Polarimeter
in deep space!

Slides from Masashi Hazumi (PI)
LiteBIRD Summary

**Scientific objectives**

- A definitive search for the CMB B-mode polarization from cosmic inflation
  - Either making a discovery or ruling out well-motivated large-field models
  - The discovery will be the first compelling evidence for gravitational waves from quantum origin
  - Full success: $\delta r < 0.001$ ($\delta r$: the total uncertainty on the tensor-to-scalar ratio, which is a fundamental cosmology parameter related to the power of primordial gravitational waves)
- Giving insight into the quantum nature of gravity and other new physics

**Observations**

- 3-year surveys in L2 at deg. scales (~30’ @ 150 GHz)
- 15 bands b/w 34 GHz and 448 GHz

**International collaboration**

- Japan: LFT, HWP, precoolers, spacecraft, launch, operation
- US: Focal-plane units for LFT and HFT, cryogenic readout
- Canada: warm readout (DfMUX)
- Europe: HFT, Sub-K cooler
- All: Data analysis and scientific exploitation

**System overview**

- Two telescopes (LFT and HFT)
  - Polarization modulator on each telescope
  - Powerful foreground removal w/ 15 bands
  - Cooling chain to provide 0.1K base temp.

**Project status/plan**

- Final selection in JFY 2018
- Launch in >2027 w/ JAXA H3

**Mission for Fundamental Physics, recently selected by JAXA**

- Probing the Universe before the hot Big Bang
B-mode power spectrum (2016)

$r < 0.07$ (95% C.L.)

Inflation
LiteBIRD expectation

\[ I(l+1)C_l^{BB}/(2\pi) \text{ (}\mu\text{K}^2) \]

- DASI
- CBI
- MAXIPOL
- BOOMERanG
- CAPMAP
- WMAP-9yr
- QUaD
- QUIET-Q
- QUIET-W
- BICEP1-3yr
- ACTPol
- BK14
- SPTpol
- POLARBEAR
- Simons Array
- LiteBIRD

**Inflation**

\( r = 0.01 \)

**Full Success**: \( \sigma(r) < 1 \times 10^{-3} \) (for \( r=0 \))

\( 2 \leq \ell \leq 200 \)

**Secondary effect**

(Gravitational lensing)
Cosmology parameter $r$

- B-mode from primordial gravitational waves proportional to $r$ (=“tensor-to-scalar ratio”).
- $r$ is proportional to the energy potential of the inflaton, a new hypothetical particle responsible for inflation.
- The expected energy potential is around the scale of Grand Unification of three fundamental forces.
- Measurement of B-mode is thus one of the most important topics in cosmology and particle physics.
- Current experimental limit ($r < 0.07$ at 95% C.L.) is weak. An order-of-magnitude improvement required.
Full success of LiteBIRD

- $\sigma(r) < 1 \times 10^{-3}$ (for $r=0$)
- All sky survey (for $2 \leq \ell \leq 200$)*

Remarks

1. $\sigma(r)$ is the total uncertainty on the $r$ measurement that includes the following uncertainties**
   - statistical uncertainties
   - instrumental systematic uncertainties
   - uncertainties due to residual foregrounds and bias
   - uncertainties due to lensing B-mode
   - cosmic variance (for $r > 0$)
   - observer bias

2. The above should be achieved without delensing.

* More precise (i.e. long) definition ensures $>5$sigma $r$ detection from each bump for $r > 0.01$.

** We also use an expression $\delta r = \sigma(r=0)$, which has no cosmic variance.
Extra success

Improve $\sigma(r)$ with external observations

<table>
<thead>
<tr>
<th>Topic</th>
<th>Example Method</th>
<th>Example Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delensing</td>
<td>Large CMB telescope array</td>
<td>CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009</td>
</tr>
<tr>
<td></td>
<td>Cosmic infrared background</td>
<td>Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)</td>
</tr>
<tr>
<td>Foreground removal</td>
<td>Lower frequency survey</td>
<td>C-BASS upgrade</td>
</tr>
</tbody>
</table>

- Delensing improvement to $\sigma(r)$ can be factor $\sim 2$ or more.
- e.g. $\sim 6\sigma$ observation in case of Starobinsky model
- Need to make sure systematic uncertainties are under control.
In case of discovery, what can happen?

1. Find a correct inflation model in the \((r, n_s)\) plane
2. Find no inflation model in the \((r, n_s)\) plane
3. Establish large field variation \((\Delta \phi > m_P)\) and significantly constrain theories of quantum gravity such as superstring theories

Any of the cases above is extremely exciting!
2) $\tau$ (optical depth) and neutrino mass

- Better E-mode measurement for $\tau < 20$ improves $\tau$
- Better $\tau$ improves $\Sigma m_\nu$
- $\Sigma m_\nu > 58\text{meV}$ from oscillation measurements

Low $\ell$ measurements contribute to $\Sigma m_\nu$!
3)/4) Origin of gravitational waves


Vacuum fluctuation vs. Source fields

Observation of $l < 10$ is required to distinguish between two.

At LiteBIRD, this can be done easily.

Moreover, B-mode bi-spectrum ("BBB") is also used to detect source-field-originating non-Gaussianity at $> 3\sigma$

"Pseudoscalar model" from Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521 as an "evil example model"; indistinguishable w/ BB for $ell > 10$ alone.
Spectral distortions: OLIMPO, COSMO and COSMO-balloon
Sunyaev-Zeldovich effect

- CMB photons are inverse-compton scattered by the hot plasma in clusters of galaxies.
- Being a scattering effect, does not depend on the distance of the cluster from us.
- The spectrum is shifted towards higher energies – very characteristic spectral feature.
- Clusters can be observed against the bright background of the CMB, since they first emerge in the universe.
Low-resolution spectroscopy of the Sunyaev-Zel’dovich effect and estimates of cluster parameters

P. de Bernardis\(^{1,2}\), S. Colafrancesco\(^{3,4}\), G. D’Alessandro\(^{1}\), L. Lamagna\(^{1,2}\), P. Marchegiani\(^{3}\), S. Masi\(^{1,2}\), and A. Schillaci\(^{1,2}\)

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3 INAF – Osservatorio Astronomico di Roma, Monte Porzio Catone, Italy
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Received 9 September 2011 / Accepted 8 November 2011

ABSTRACT

Context. The Sunyaev-Zel’dovich (SZ) effect is a powerful tool for studying clusters of galaxies and cosmology. Large mm-wave telescopes are now routinely detecting and mapping the SZ effect in a number of clusters, measure their comptonisation parameter and use them as probes of the large-scale structure and evolution of the universe.

Aims. We show that estimates of the physical parameters of clusters (optical depth, plasma temperature, peculiar velocity, non-thermal components etc.) obtained from ground-based multi-band SZ photometry can be significantly biased, owing to the reduced frequency coverage, to the degeneracy between the parameters and to the presence of a number of independent components larger than the number of frequencies measured. We demonstrate that low-resolution spectroscopic measurements of the SZ effect that also cover frequencies >270 GHz are effective in removing the degeneracy.

Methods. We used accurate simulations of observations with lines-of-sight through clusters of galaxies with different experimental configurations (4-band photometers, 6-band photometer, multi-range differential spectrometer, full coverage spectrometers) and dif-
• The OLIMPO experiment is a first attempt at spectroscopic measurements of CMB anisotropy.

• A large balloon-borne telescope with a 4-bands photometric array and a plug-in room temperature spectrometer

• see http://planck.roma1.infn.it/olimpo for a collaborators list and full details on the mission

• Main scientific targets:
  – SZ effect in clusters → unbiased estimates of cluster parameters
  – Spectrum of CMB anisotropy → anisotropic spectral distortions
OLIMPO launched! 07:09 GMT, 14/Jul/2018, Longyearbyen (Svalbard)

- 5 days flight
- Great performance of Kinetic Inductance Detector Arrays, Telescope and Spectrometer.
- First Validation of KIDs in space conditions
Launch Longyearbyen (Svalbard) 07:07 GMT 2018/07/14

Terminated Ellsmere Island (Canada) 02:28 GMT 2018/07/19

OLIMPO 2018 flight

Greenland

Svalbard

85N

80N

85N

75N

70N

Scandinavia
Depending on the physical process, the expected spectral distortions have a different shape \((\varepsilon, \mu, y)\).

See e.g.: The evolution of CMB spectral distortions in the early Universe

J. Chluba
R. A. Sunyaev
MNRAS (2012) 419 1294

No distortions have been observed to-date (may be not? See Bowman et al. Nature 2018).

Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. 354 37
The observable is small, compared to ... everything.

• Great scientific importance of measuring spectral distortions in the CMB – Cosmology and Fundamental Physics.

• Distortion signals are guaranteed to exist, but are very small compared to
  • detector noise,
  • instrument emission,
  • atmospheric emission and fluctuations,
  • foregrounds,
  • the CMB itself.

• Intelligent measurement methods required. Experimentalists way behind theorists. Final measurement certainly to be carried out from space.

• Here focus on a pathfinder experiment, ground-based, which does not target at the smallest distortions, but tries to exploit at best existing, relatively cheap opportunities.
Absolute measurement approach

- The Martin-Pupplett Fourier Transform Spectrometer used in FIRAS and PIXIE has two input ports.
- The instrument is intrinsically differential, measuring the spectrum of the difference in brightness at the two input ports. Normally one port looks at the sly, the other onbe at an internal reference blackbody.

Sky measurement

\[ I_{SKY}(x) = C \int_{0}^{\infty} [S_{SKY}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1 + \cos[4\pi\sigma x]\}d\sigma \]

Calibration measurement

\[ I_{CAL}(x) = C \int_{0}^{\infty} [S_{CAL}(\sigma) - S_{REF}(\sigma)]rt(\sigma)\{1 + \cos[4\pi\sigma x]\}d\sigma \]
Satellite measurements can sample the CMB spectrum over the entire range 0-600 GHz. PIXIE!!! (https://asd.gsfc.nasa.gov/pixie/).

Ground based measurements are surely limited to frequencies in the atmospheric transmission windows.

If a ground-based measurement can be attempted from the ground, the site should be the high Antarctic Plateau (e.g. Dome-C or South Pole).

COSMO (COSmological Monopole Observer) targets this observable from Dome-C.
Why Dome-C: optical depth of the atmosphere (credits: AM code)

0 mm PWV, (1000 mbar, mostly N₂, O₂ and O₃, much more stable than H₂O)

+ <T>=200K in the winter
Why Dome-C: optical depth of the atmosphere (credits: AM code)

+ $\langle T \rangle = 200$K in the winter

Low-resolution version, in the range of interest here (AI LEKID detectors)
Consider the 2 mm and 1 mm atmospheric windows, which are very transparent (low emission) and where Aluminum KIDs work efficiently. Simulate measurements, mask lines, and attempt spectral template fitting for $y$, since it has a characteristic shape:

$$\text{meas} = \text{atmo} + \text{CMB} + \text{ISD} + \text{distor}(y=10^{-6}) - B_{\text{ref}}(300\text{K}, \varepsilon=0.02) + \text{noise (BLIP)}$$
a NAIVE SIMULATION of the measurement performance is encouraging:

\[
\text{meas}(\nu) = \text{atmo}(\nu) + \text{CMB}(\nu) + \text{ISD}(\nu) + \text{distor}(y=10^{-6}, \nu) - B_{\text{ref}}(300K, \nu, \varepsilon=0.02) + \text{noise (BLIP)}
\]

\[
\text{meas}(\nu) = \text{atmo}(\nu) + \text{CMB}(\nu) + \text{ISD}(\nu) + \text{distor}(y=10^{-6}, \nu) - B_{\text{ref}}(1.65K, \nu) + \text{noise (BLIP)}
\]

Spectral template fitting procedure to detect spectral distortion:

\[
\text{fit}(\nu) = A \ast \text{atmo}(\nu) + B \ast \text{CMB}(\nu) + C \ast B_{\text{ref}}(1.65K, \nu) + D \ast \text{ISD}(\nu) + E \ast \text{distor}(y=10^{-6}, \nu)
\]

**HP:** No 1/f (fast scan, see below)

Perfect knowledge of the spectral shape of atmospheric brightness (atmo(\nu))

\[y \text{ parameter} = 1.00e-06\]

NEP = 1.50e-16 W/sqrt(Hz)

integration time for each spectrum = 3600 s

photon noise per resolution bin (1 spectrum) = 1.52e-17 W/cm2/sr/cm-1

number of spectra simulated = 10001

corresponding to 416 days of observation

fractional atmospheric fluctuations = **1.00e-04** rms, correlated among spectral bins

(e.g. PWV fluctuation, see below)

# of used spectral bins = 40

A = atmos/model = 1.0000007 +/- 1.0019570e-006

B = cmb/model = 1.0000023 +/- 1.1284262e-006

C = refe/model = -0.99999581 +/- 2.1003349e-006

D = dust/model = 1.0000142 +/- 8.5398778e-006

E = DSZ/model = **1.21** +/- **0.11**

offset = -2.8e-017 +/- 1.4e-017

The amplitude of the y distortion is retrieved to 10% accuracy. However:

1. Assumed fractional fluctuations correlated, and very small. Is this reasonable?
2. Perfect knowledge of the spectrum of the atmosphere is impossible. Any deviation from reality in the model will be interpreted as a spectral distortion. Can we find a way to actually measure the atmospheric contribution?
Atmospheric fluctuations in the windows are strongly correlated among spectral bins (3 spectra: 90, 100, 110μm PWV @ 240K from AM).
1a) Atmospheric fluctuations in the windows are strongly correlated among spectral bins (3 spectra: 230, 235, 240 K & 90, 100, 110 μm PWV from AM).
Atmospheric noise (spectral density of atmospheric brightness fluctuations) @Dome-C @150 GHz as measured with the BRAIN pathfinder experiment
Masi et al. (2005) EAS Pub. Ser. 14 87
Battistelli et al. (2012) MNRAS 423 1293

1b) Atmospheric fluctuations are slow. If the measurement is fast, the effect of atmospheric fluctuations is strongly reduced.
COSMO: coping with the atmosphere

• We have to measure and subtract atmospheric emission, and we have to do it very quick.

• Recipe to mitigate the problem:

1. Work from a high altitude, cold and dry site (Dome-C, Antarctica) to minimize the problem
2. Measure the specific spectral brightness of atmospheric emission while measuring the brightness of the sky, modulating the optical depth
3. Use fast, sensitive detectors, and fast modulators.
**COSMO** sky/atmosphere scan strategy

Oversized (1.6m diameter), spinning flat mirror, 10° wedge (red/blue)

To scan circles (D=5°-20°) in the sky modulating atmospheric emission.

Center elevation ranges between 30° and 80° depending on cryostat tilt.

- **Cryostat tilt = 0°**
  - PT tilt = 40°
  - Min. elev. = 20°
  - Max. elev. = 40°

- **Cryostat tilt = 20°**
  - PT tilt = 20°
  - Min. elev. = 40°
  - Max. elev. = 60°

- **Cryostat tilt = 40°**
  - PT tilt = 0°
  - Min. elev. = 60°
  - Max. elev. = 80°

- **Cryostat tilt = 50°**
  - PT tilt = -10°
  - Min. elev. = 70°
  - Max. elev. = 90°
Exploits the availability of fast detectors (Kinetic Inductance Detectors - KIDs) and the know how of racing cars to beat atmospheric noise

<table>
<thead>
<tr>
<th>interferogram scan fast</th>
<th>detector performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum wavenumber (Nyquist)</td>
<td>500E-05s</td>
</tr>
<tr>
<td>sampling step</td>
<td>50.0125 cm</td>
</tr>
<tr>
<td>resolution</td>
<td>6 GHz</td>
</tr>
<tr>
<td>resolution</td>
<td>0.200 cm-1</td>
</tr>
<tr>
<td>number of frequency samples</td>
<td>100</td>
</tr>
<tr>
<td>number of samples in double-sided interferogram</td>
<td>256</td>
</tr>
<tr>
<td>time to complete an interferogram</td>
<td>0.064 s</td>
</tr>
<tr>
<td>interferograms per second</td>
<td>15.6</td>
</tr>
<tr>
<td>mirror scan mechanism period</td>
<td>0.13 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sky scan fast</th>
<th>interferogram scan slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>circle radius</td>
<td>5 deg</td>
</tr>
<tr>
<td>circle length</td>
<td>31.4 deg</td>
</tr>
<tr>
<td>beam size</td>
<td>1 deg</td>
</tr>
<tr>
<td>number of samples per circle (3 per beam)</td>
<td>94</td>
</tr>
<tr>
<td>time per beam</td>
<td>2.50E-04s</td>
</tr>
<tr>
<td>time for 2 sky dips (downwards + upwards)</td>
<td>2.36E-02s</td>
</tr>
<tr>
<td>wedge mirror rotation rate</td>
<td>2546 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sky scan slow</th>
<th>interferogram scan slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>circle radius</td>
<td>5 deg</td>
</tr>
<tr>
<td>circle length</td>
<td>31.4 deg</td>
</tr>
<tr>
<td>beam size</td>
<td>0.5 deg</td>
</tr>
<tr>
<td>number of samples per circle (3 per beam)</td>
<td>188</td>
</tr>
<tr>
<td>time per beam</td>
<td>0.192 s</td>
</tr>
<tr>
<td>time for 2 sky dips (downwards + upwards)</td>
<td>36.19 s</td>
</tr>
<tr>
<td>wedge mirror rotation rate</td>
<td>1.66 rpm</td>
</tr>
</tbody>
</table>

| time to complete an interferogram | 6.032 s |
| number of frequency samples | 100 |
| number of samples per circle (3 per beam) | 256 |
| time for 2 sky dips (downwards + upwards) | 2.36E-02s |
| wedge mirror rotation rate | 2546 rpm |

| sky stability required for | 18.10s |
| sky stability required for | 6.03s |

- This configuration requires a fast cryogenic mirror scanning mechanism
- High dissipation in the cryo system
- This configuration requires a fast room-temperature mirror rotation device
- Not impossible.
If you look at 80° elevation, stable, and scan the FTS moving mirror, this is what you measure.
Here, instead, the spinning flat is activated and rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.
(under)sample the signal with the right phase:
Retreive the interferogram at maximum elevation
(under)sample the signal with the right phase:
Retreive the interferogram at minimum elevation.
(under)sample the signal with the right phases:
Retreive the interferograms at all intermediate elevations
Atmospheric noise (spectral density of atmospheric brightness fluctuations) @Dome-C @150 GHz

As measured with the BRAIN pathfinder experiment
Masi et al. (2005) EAS Pub. Ser. 14 87
Battistelli et al. (2012) MNRAS 423 1293

Fast atmospheric brightness measurement and removal reduces the noise by almost 2 OoM
Another naive simulation

- Retreive all the interferograms at all different elevations, and Fourier transform them to obtain the measurements of the specific spectral brightness at all elevations. This is a very fast *sky-dip* measurement.
- The atmospheric contribution depends on the optical depth and on the temperature profile.
- For a naive single isothermal layer, the measured brightness at elevation $e$ is

\[
B(v, e) = B(T_{atm}, v)(1 - e^{-\tau(v, e)}) + B_{sky}e^{-\tau(v, e)} - B(T_{ref}, v).
\]

- which can be rewritten \( B(v, e) = a(v)x(v, e) + b(v) \)
- where

\[
x = 1 - \exp(-\tau_z(v)/\cos(e))
\]

\[
B_{sky}(v) = B(T_{ref}, v) = a(v)
\]

\[
B(T_{atm}, v) = b(v) + a(v)
\]

- So, for each frequency, a simple linear fit will provide the measurement of the sky brightness, with atmospheric emission removed.
- Since the length of the data record used for this procedure is very short (few seconds) slowly fluctuating atmospheric emission is continuously removed.
- The SNR of this determination will be low, but many measurements can be stacked to gain SNR for the monopole of sky emission.
COSMO sky / atmosphere scan simulations

\[ e = 30^\circ \pm 10^\circ \]
$e = 80^\circ \pm 10^\circ$

$B_{\text{sky}}(4.7\text{cm}^{-1})$
Result of «vanilla» simulation:
- assumed small atmospheric fluctuations (0.01% in 6s)
- no spatial gradients in atmosphere
- no foregrounds (including window)
- Photon noise limited detector array (30 dets)
- Long integration time (70 days)

\[ y = 1.77 \times 10^{-6} \]

Hill 2015
**COSMO** implementation

- As of today, still moving from *concept* into *instrument design*
- However:
  - PNRA proposal funded to provide cryogenic system, optics, and logistic support for the Concordia base (PI Silvia Masi, partner institutions UniMI (Mennella), UniMIB (Zannoni))
  - PNRA proposal funded to support development of KID detector arrays and coupling optics (PI Elia Battistelli, partner institutions CNR-IFN (Castellano), UniMI, UniMIB)
  - PRIN proposal being finalized to support development of optical design and construction of the cryogenic interferometer (PI P. de Bernardis, partners CNR-IFN (Cibella), UniMI, UniMIB)
  - Additional partner Cardiff University
- International interest expressed from other international institutions ... the experiment is gaining momentum.
**COSMO** continuous cryogenics

- Main cryostat based on pulse-tube coolers (3K, 0.9W each) + sub-K cooler (0.25K)
- Stays cold as long as there is power for the two pulse tubes
- Large window (50 cm dia)
- Large 3K volume (500 l)

Room for:
- DFTS
- Cryogenic reference
- sub-K cooler
- Detector-arrays

- «$^{10}\text{He}$» 0.25K fridge from Chase Cryogenics
- To cool the detector arrays
- Main cryostat based on pulse-tube coolers (3K, 0.9W each) + sub-K cooler (0.25K)
- Stays cold as long as there is power for the two pulse tubes
- Large window (50 cm dia)
- Large 3K volume (500 l)
- \(^{10}\text{He}\) 0.25K fridge from Chase Cryogenics
- To cool the detector arrays
COSMO instrument basic design

- 200 mm aperture
- 1.4m focal length
- 15 mm aperture dets
- 0.9° FWHM

Pivot for double pendulum design
COSMO continuous cryogenics
COSMO  continuous cryogenics
WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

Non abbiamo un criostato così grande!

Serve un dimostratore più piccolo, con la stessa inerzia e le stesse costanti elastiche.
WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

**Figura 14:** disegno meccanico del dimostratore alloggiato all’interno dello stadio freddo del criostato (in colore ciano nel disegno, ha un diametro di 160 mm e una altezza di 285 mm). Il disegno è in scala. I due cilindri in rame sono rappresentativi, per massa e inerzia, degli specchi a tetto.
WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

Il dimostratore

LVDT con dispositivo elastico di linearizzazione del moto
WP3200: Cryogenic operation of a double pendulum

Oscillazione libera del simulatore. Il tempo di decadimento (t_{1/2} = 17.3 min) permette di stimare la potenza necessaria a mantenere l’ oscillazione. Che risulta inferiore a 6 µW.
WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study

**Figura 18:** tipica misura di oscillazione controllata del dimostratore, ottenuta dall’ uscita demodulata dell’ LVDT. Nel pannello in alto, differenza tra oscillazione misurata e oscillazione sinusoidale, consistente con il rumore di lettura.
Kinetic Inductance Detectors

From Silvia Masi - OLIMPO
Cosmic rays events in OLIMPO KIDs
COSMO’s successor: a balloon-borne (ULDB) instrument?
COSMO’s successor: a balloon-borne instrument?

- **LSPE LDB payload**
  http://planck.roma1.infn.it/LSPE
- Works in the polar night
- Suitable cryogenic system
- Possible to add (slower?) modulator, if needed
- Might gain a factor 10.
The future of research in cosmology....

• Is bright!
• Lots of activity in optical, microwave, radio experiments, from the ground and from space
• A very important complement (and sometimes a driver) for fundamental physics research