Cosmology : Present and Future

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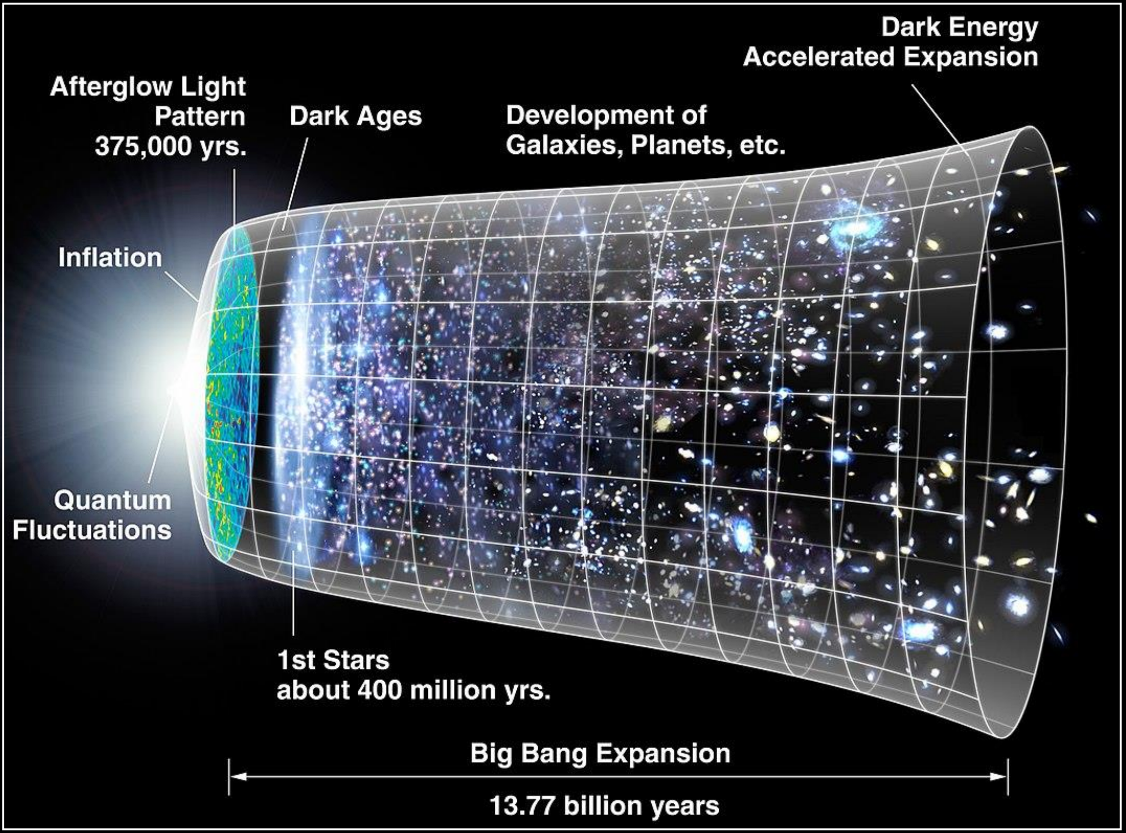
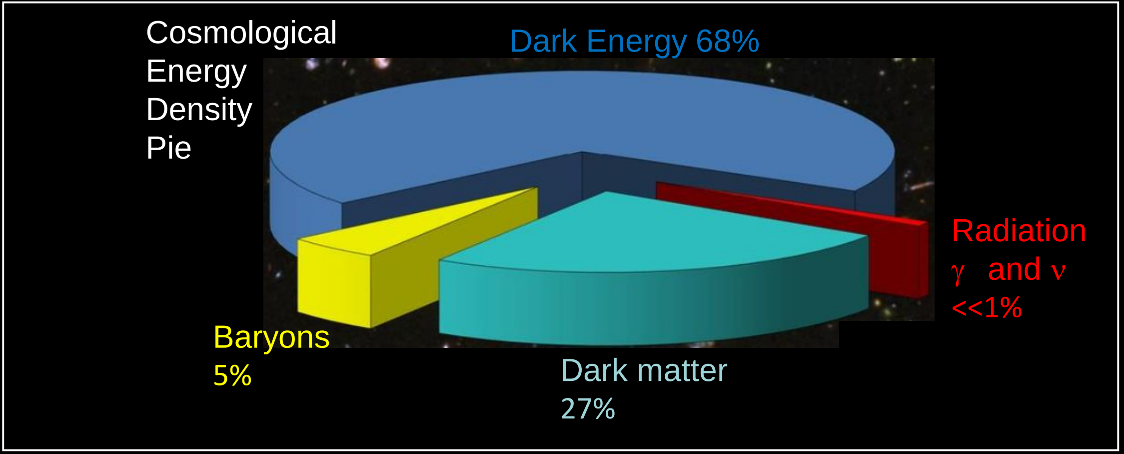
Current Cosmological «Model»

- Scenario:
  - The universe is **expanding and cooling** since the big-bang (a starting ponit with infinite densitiy, infinite temperature).
  - A sequence of **bound states** follows (baryogenesys, nucleosynthesis, atoms, molecules, gravitationally bound structures: stars, galaxies, clusters, superclusters).
- Model:
  - An empirical model, called ΛCDM, 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 homegenus 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 R^3)
- With these assumptions, the model fits measurements over several decades in length scale, and more than 13 Gyr of cosmic time.

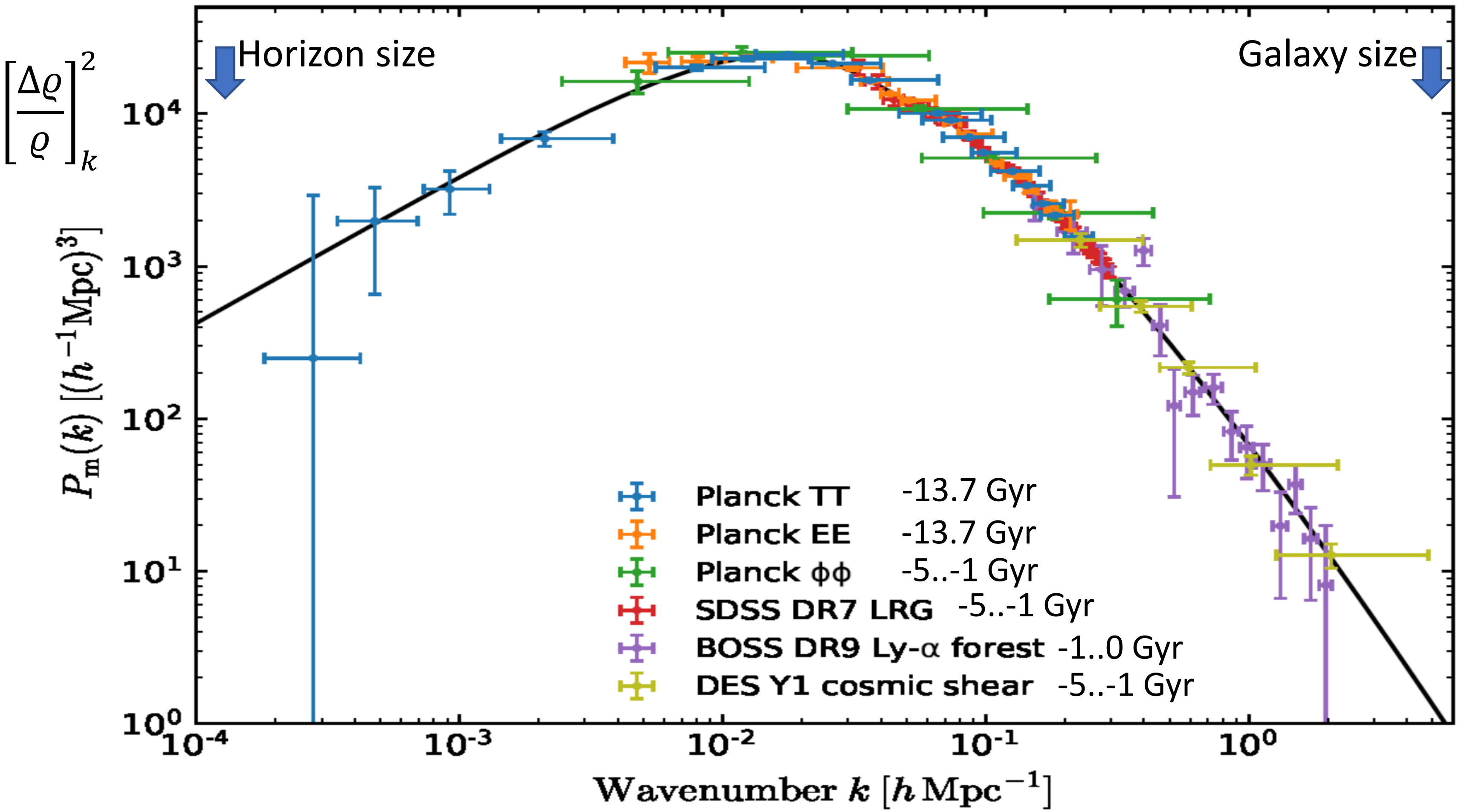
arXiv 1807.06205

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
  - θ_{MC} : acoustic angular scale = ratio of comoving sound horizon at recombination and angular diameter distance of recombination: r_s/D_A
  - τ : 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:

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038

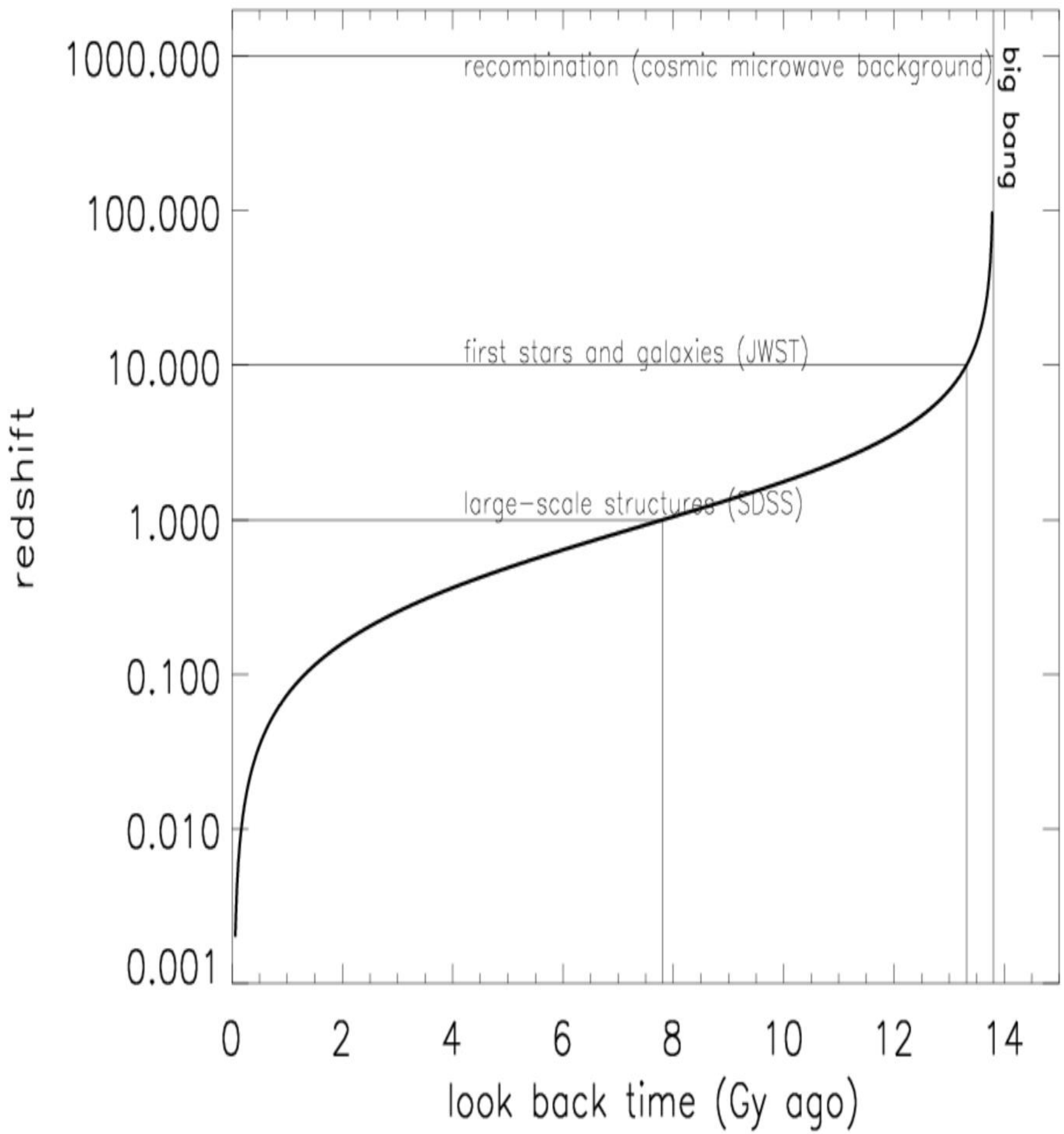
arXiv 1807.06205



- **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) ΛCDM model (black line), demonstrating its explanatory power.

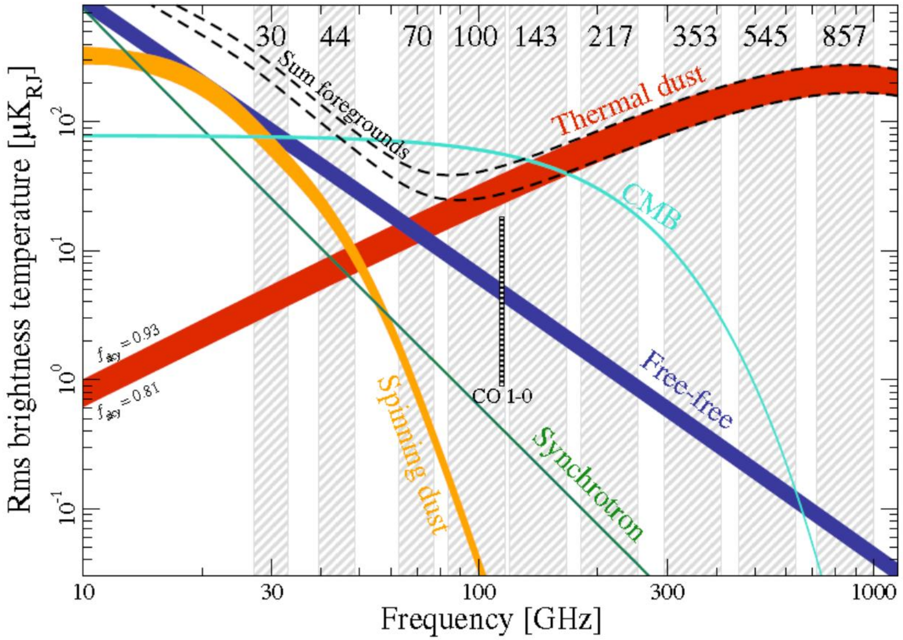
The observables of cosmology

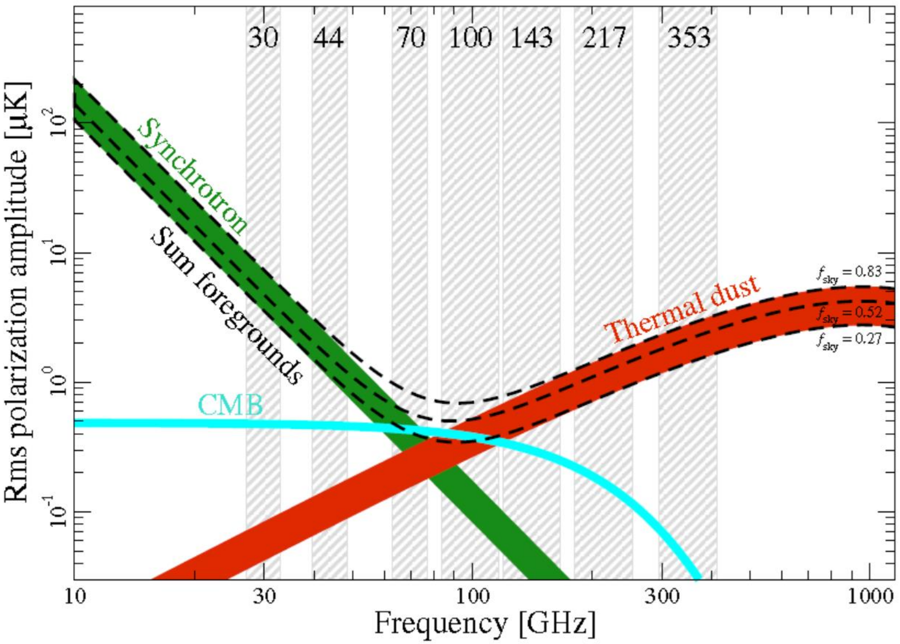
- Large-scale structure ($z=0…2$, $t-t_o=0…-8$ Gyr)
  - Redshift of galaxies -> redshift surveys (optical)
  - Lensing of galaxies -> shape surveys (optical)
- Cosmic Microwave Background ($z=1100$, $t-t_o=-13.7$ Gyr and earlier …)
  - Spectrum
  - Anisotropy
  - Lensing
  - Polarization



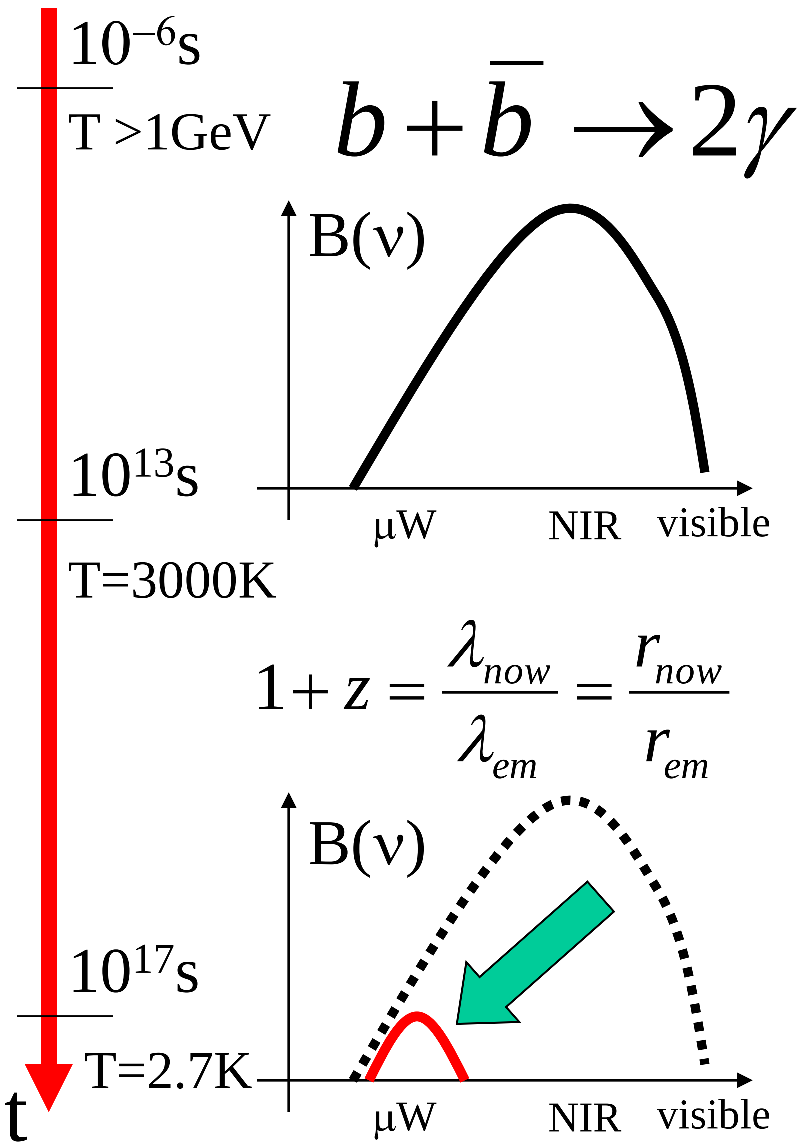
CMB data

- Long development of CMB anisotropy and polariazation 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

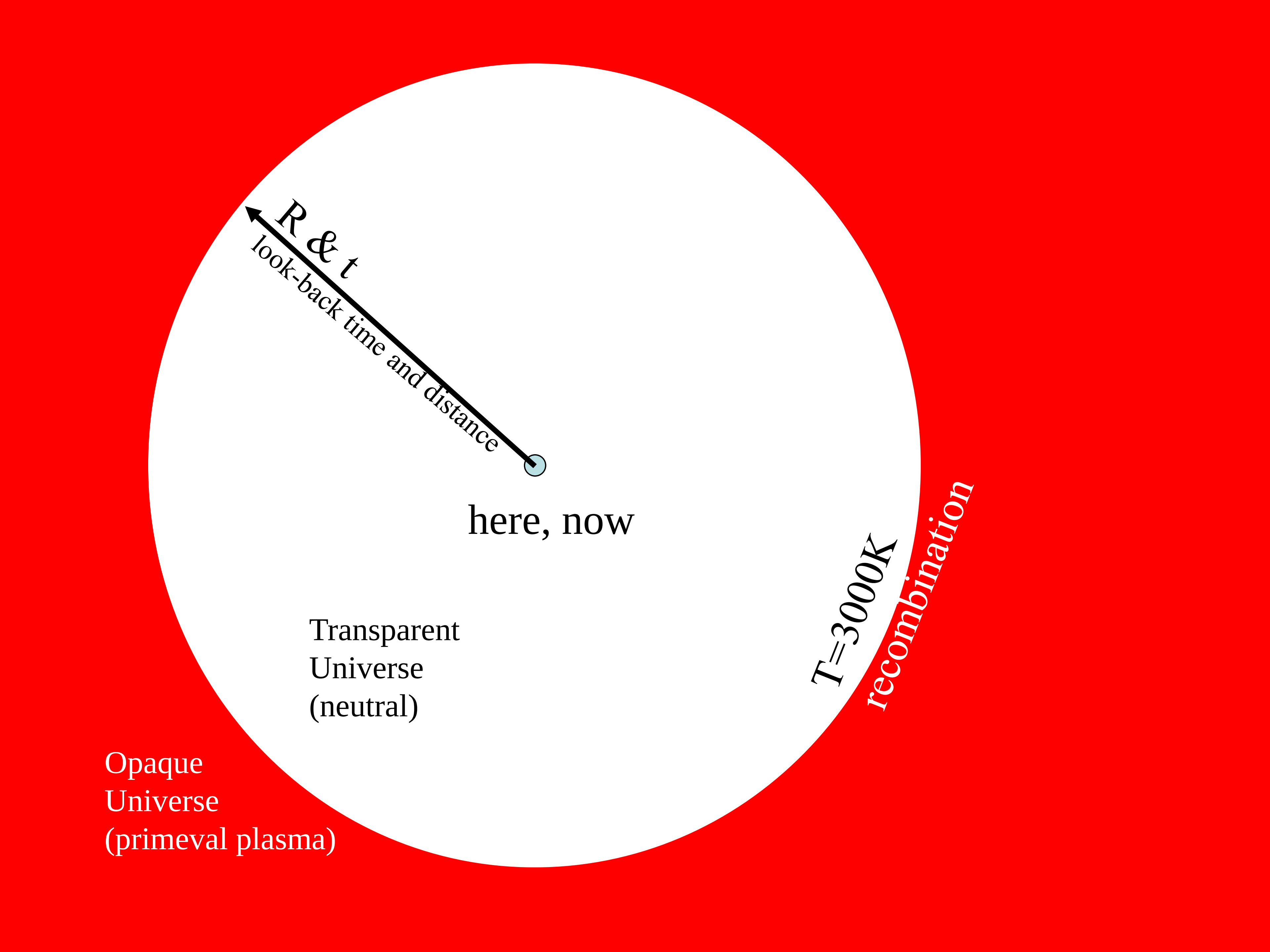


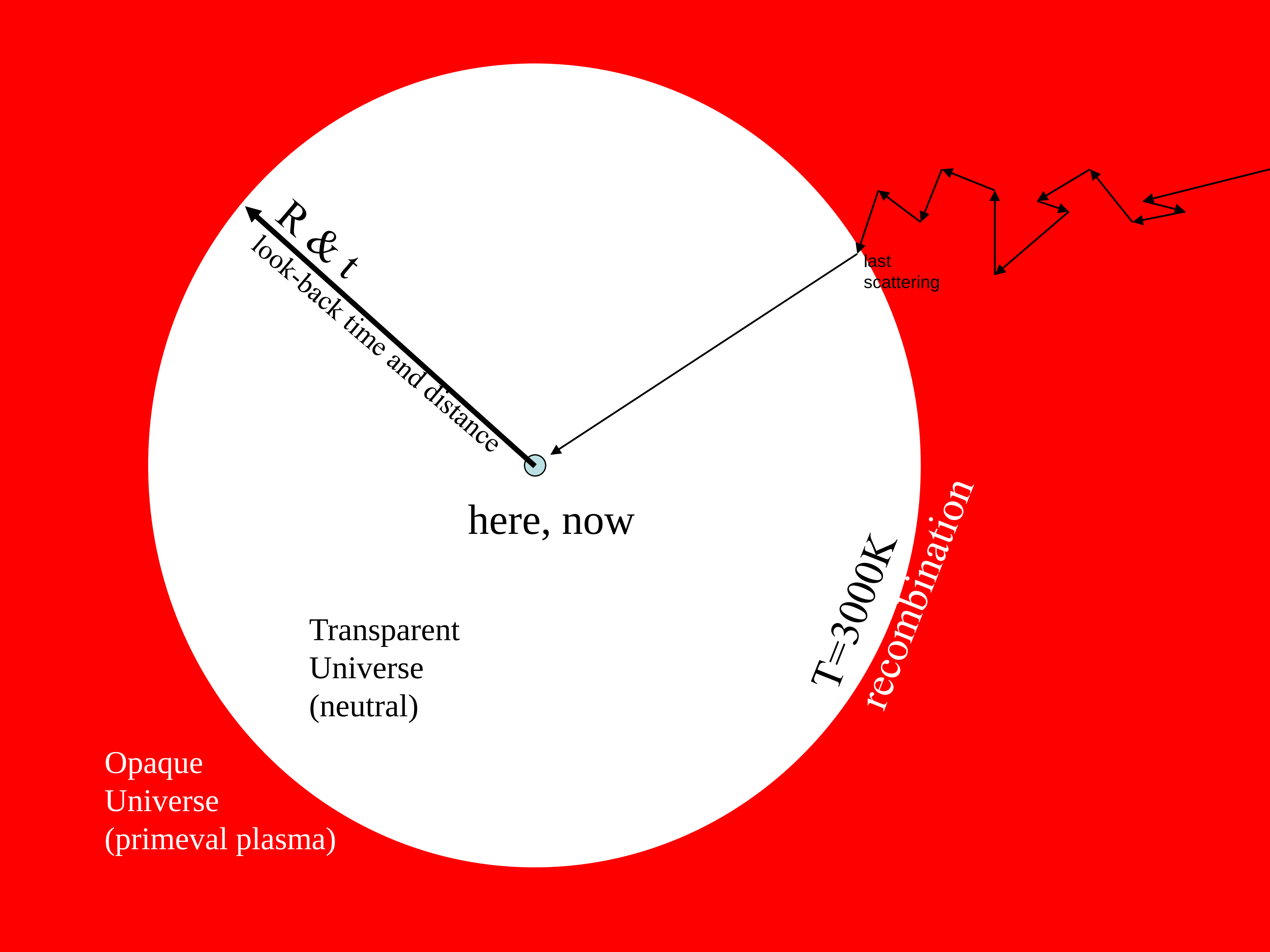
According to modern cosmology:

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 380000 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: 410γ/cm^3, ~1 meV**

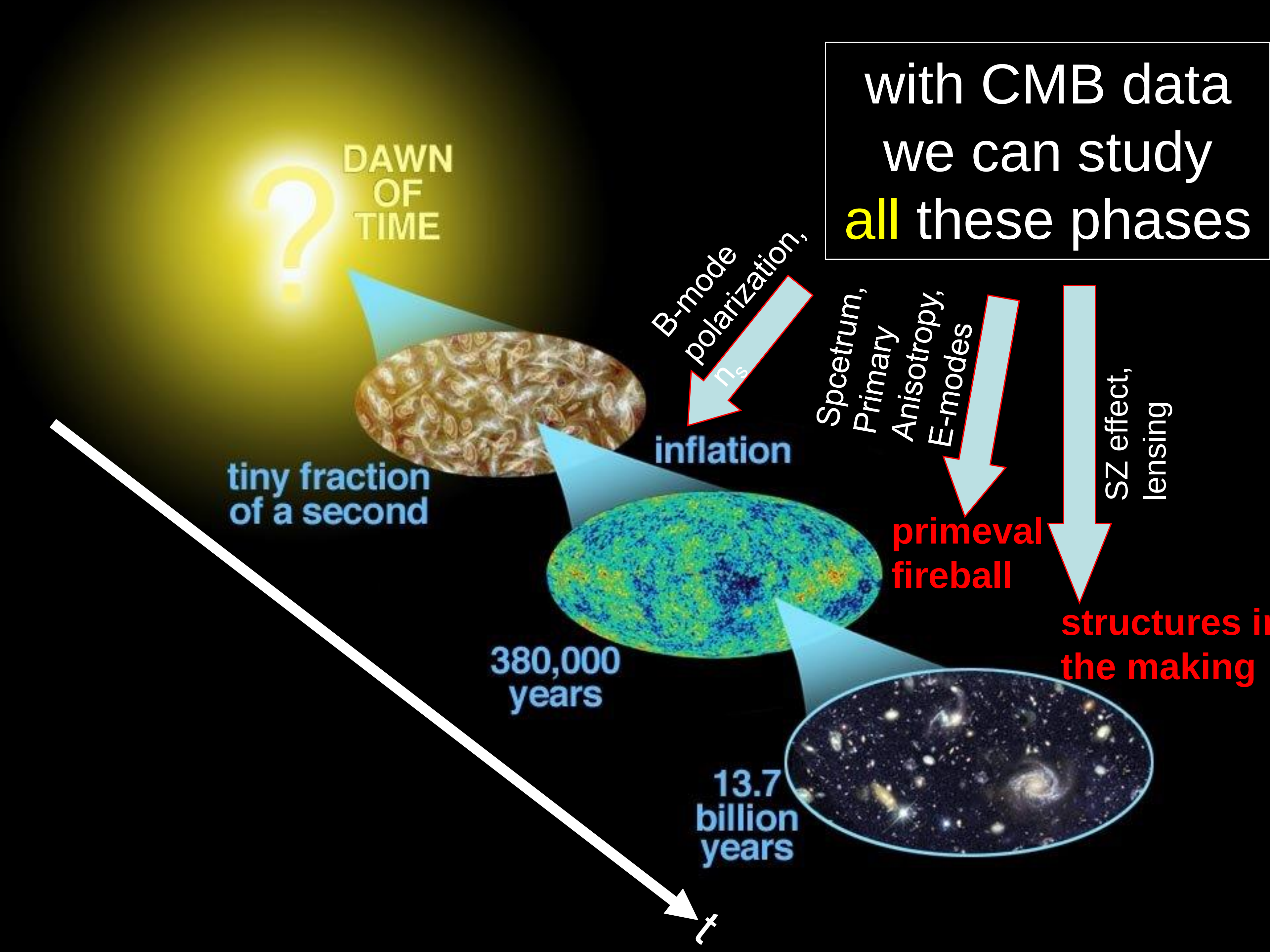
These photons carry
significant information
on the structure, evolution and
composition of our universe


R & t
look-back time and distance
here, now
T=3000K
recombination
Transparent
Universe
(neutral)
Opaque
Universe
(primeval plasma)


R & t
look-back time and distance
last scattering
here, now
T=3000K
recombination
Transparent Universe (neutral)
Opaque Universe (primeval plasma)

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,
n_s
Spcetrum,
Primary
Anisotropy,
E-modes
SZ effect,
lensing
inflation
tiny fraction
of a second
primeval
fireball
380,000
years
structures in
the making
13.7
billion
years
t

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:

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

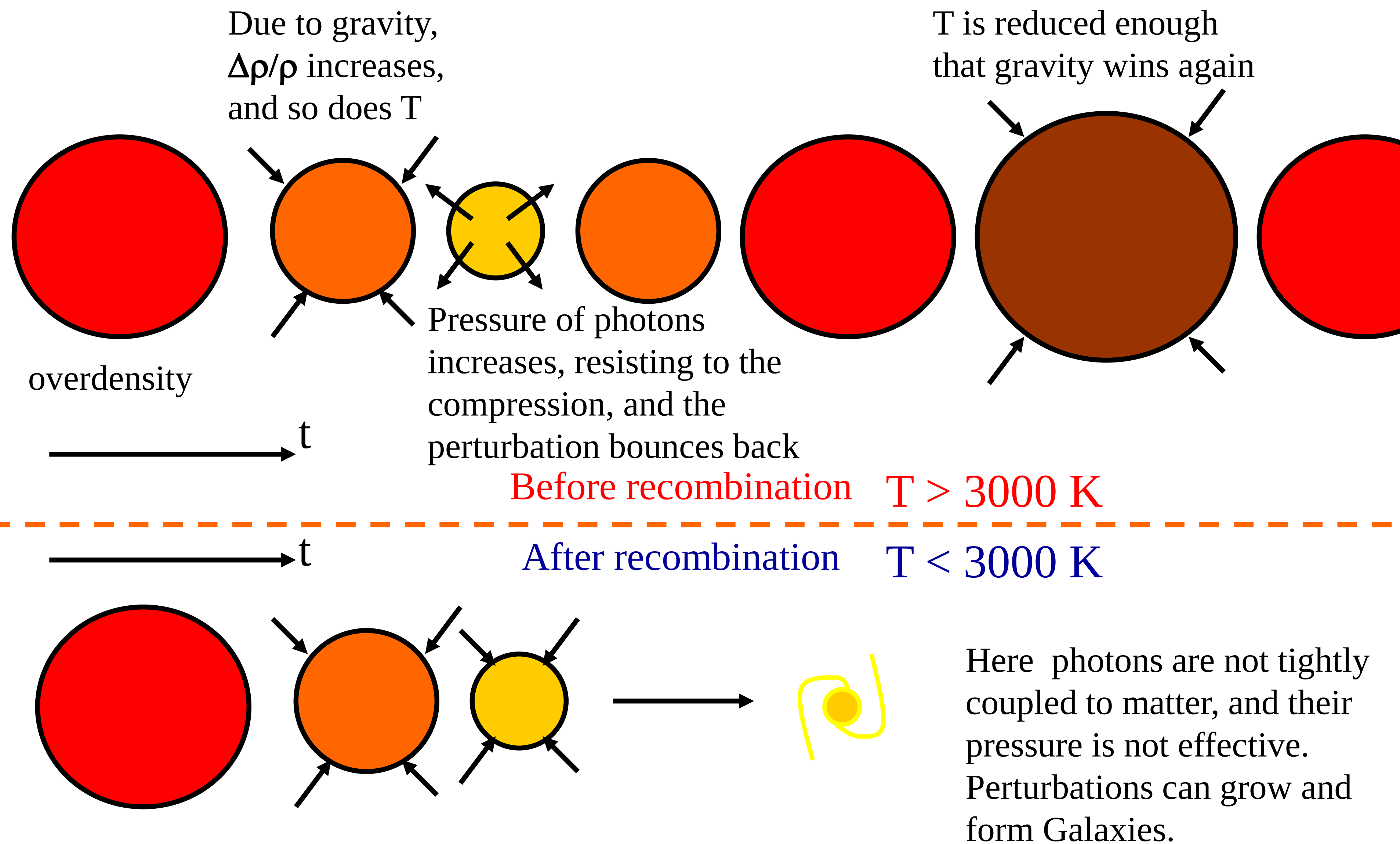
Sachs-Wolfe (gravitational redshift) | Photon density fluctuations | Doppler effect from velocity fields

- 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)

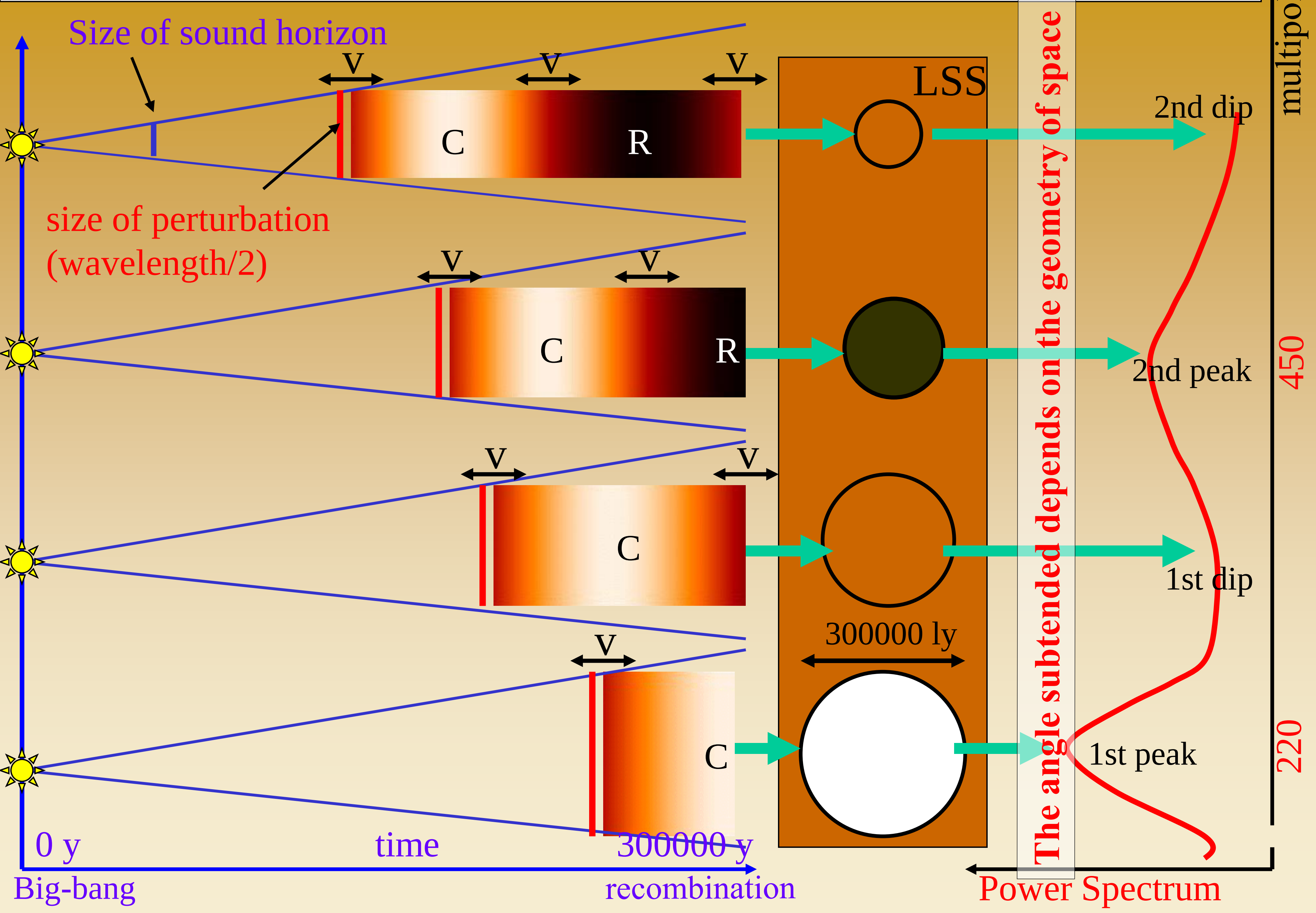
- The primeval plasma of photons and matter oscillates :
- self-gravity vs radiation pressure.
- We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
- Statistical theory: all information encoded in the angular power spectrum of the image.

Density perturbations ($\Delta\rho/\rho$) were **oscillating** in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).



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.



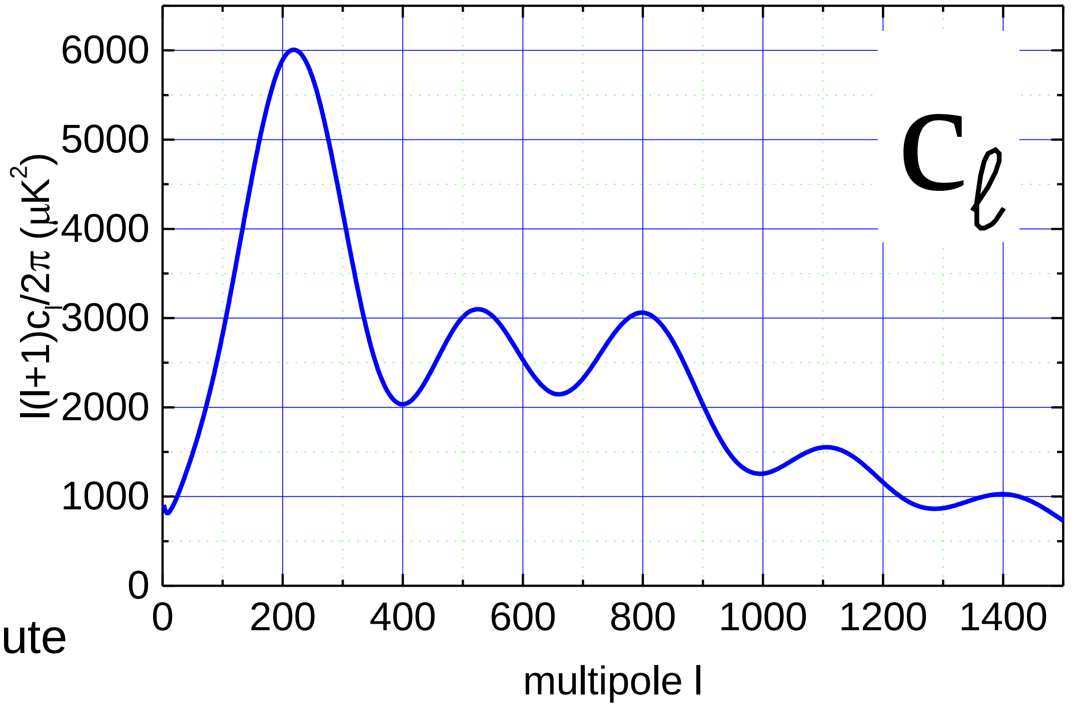
Expected power spectrum:

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

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

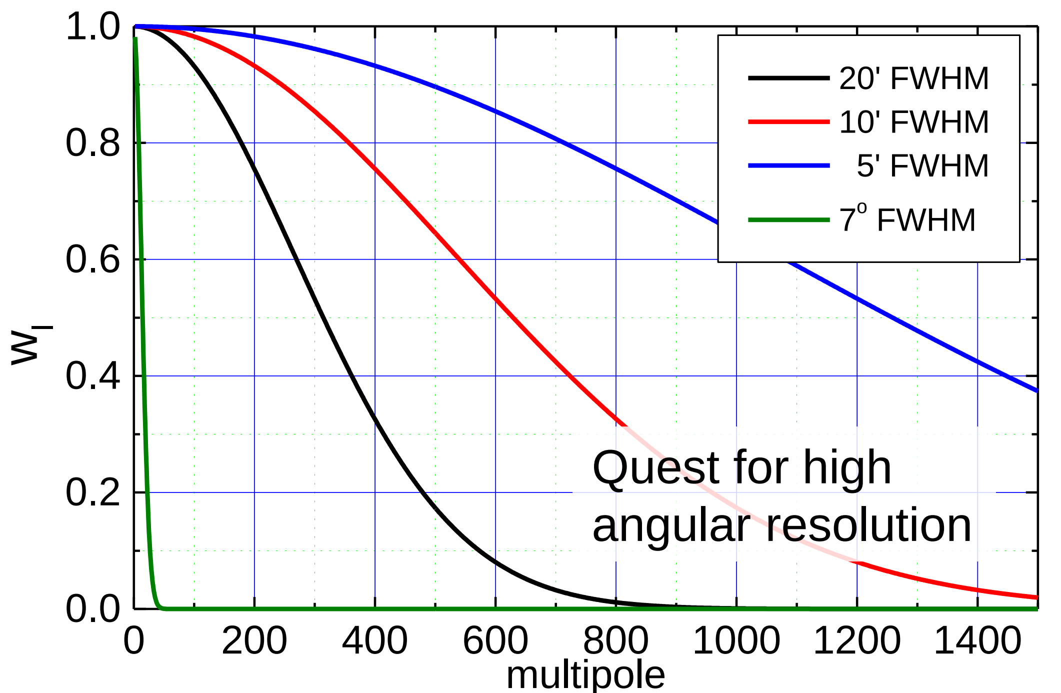
$$\langle \Delta T^2 \rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)c_\ell$$

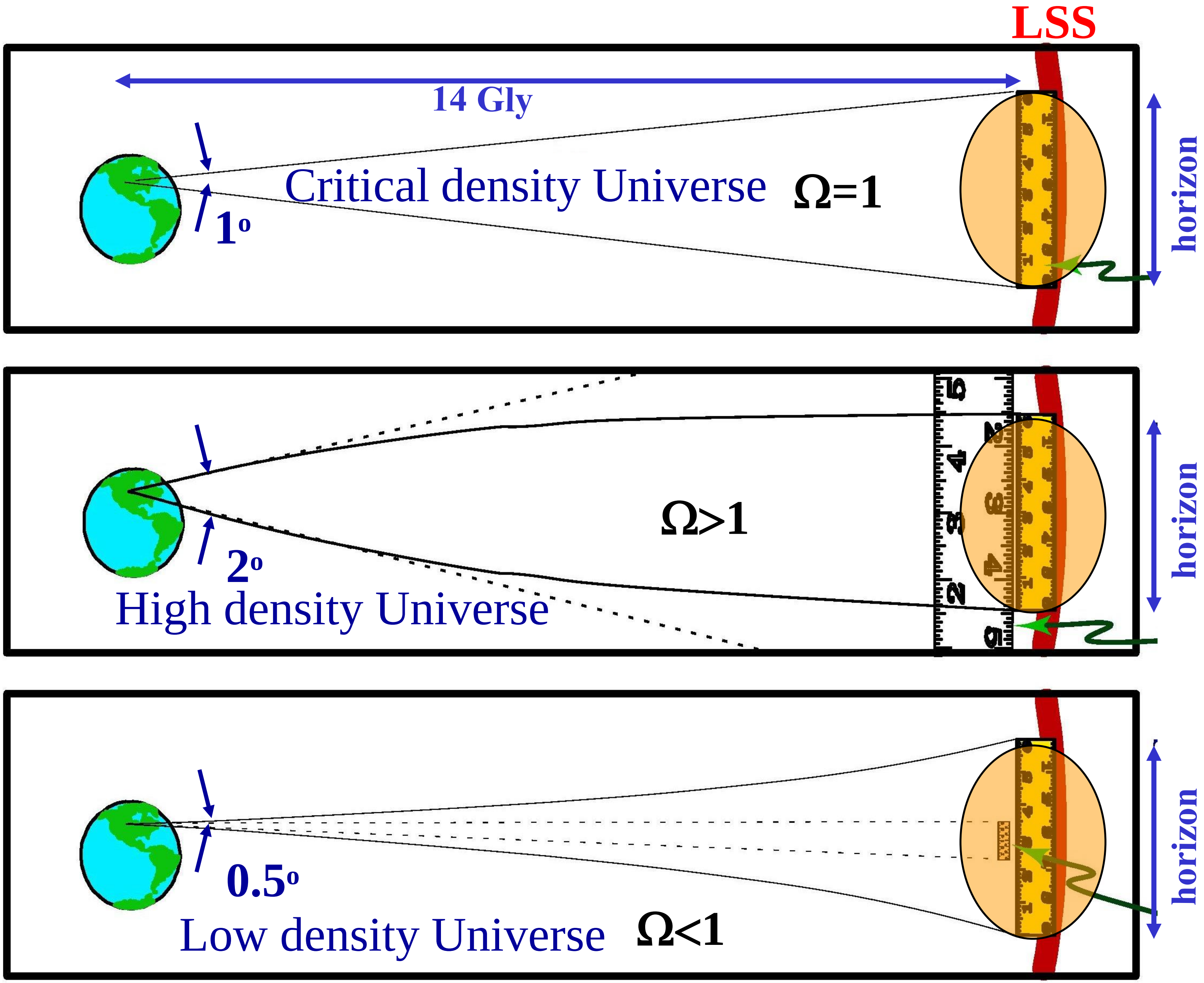
See e.g. http://camb.info to compute c_ℓ for a given cosmological model



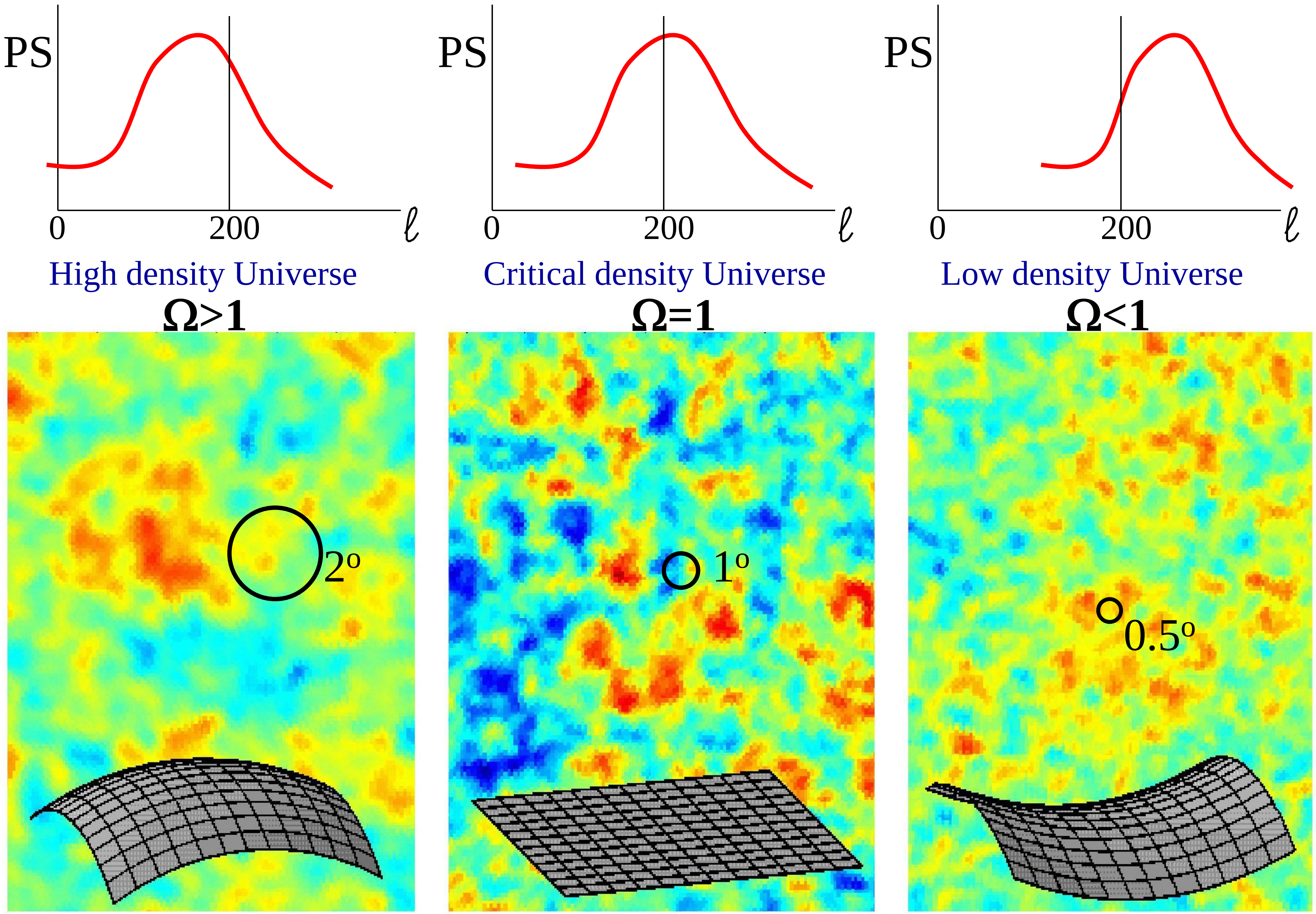
An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

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





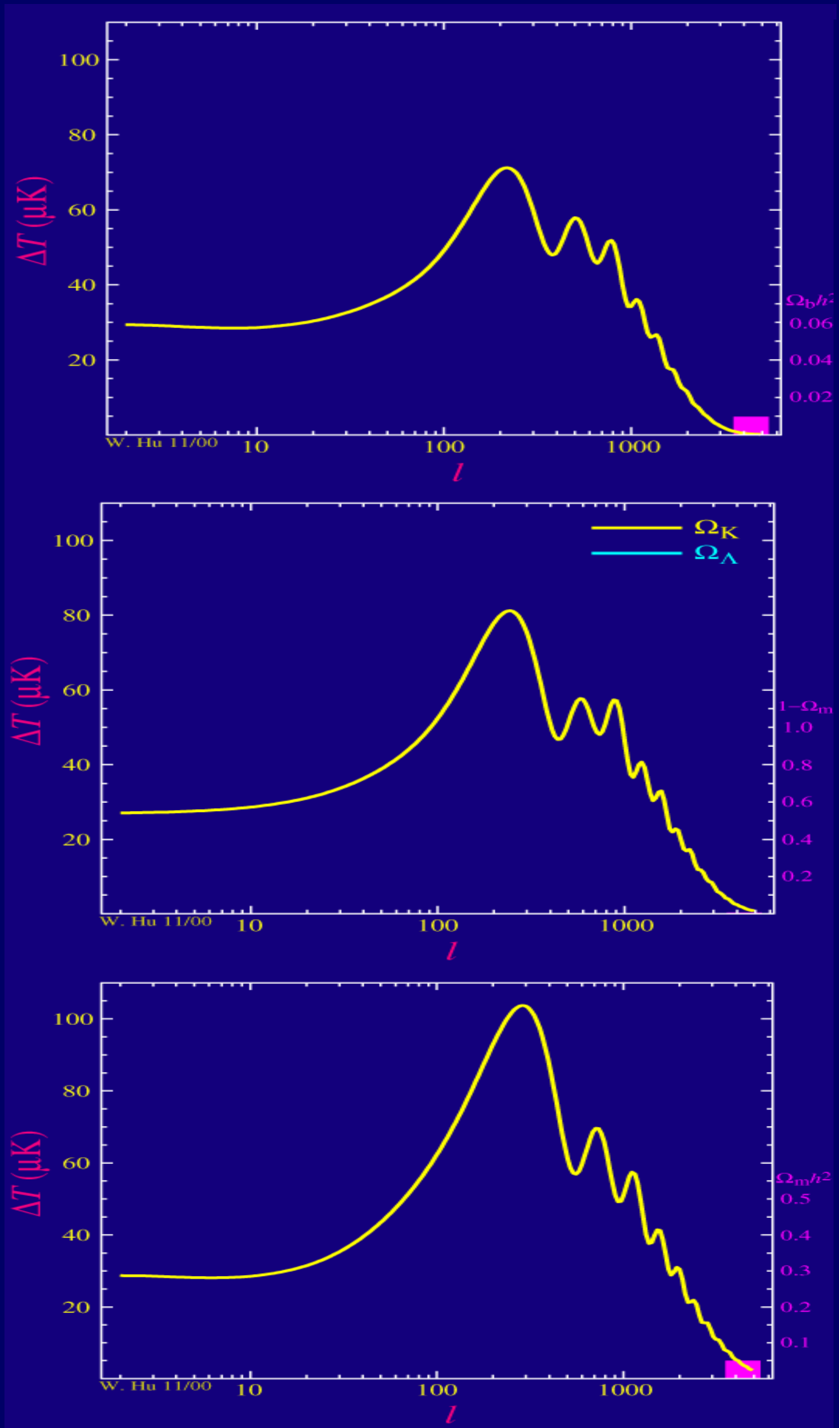
The image and PS are modified by the geometry of the universe



The mass-energy density of the Universe can be measured in this way.

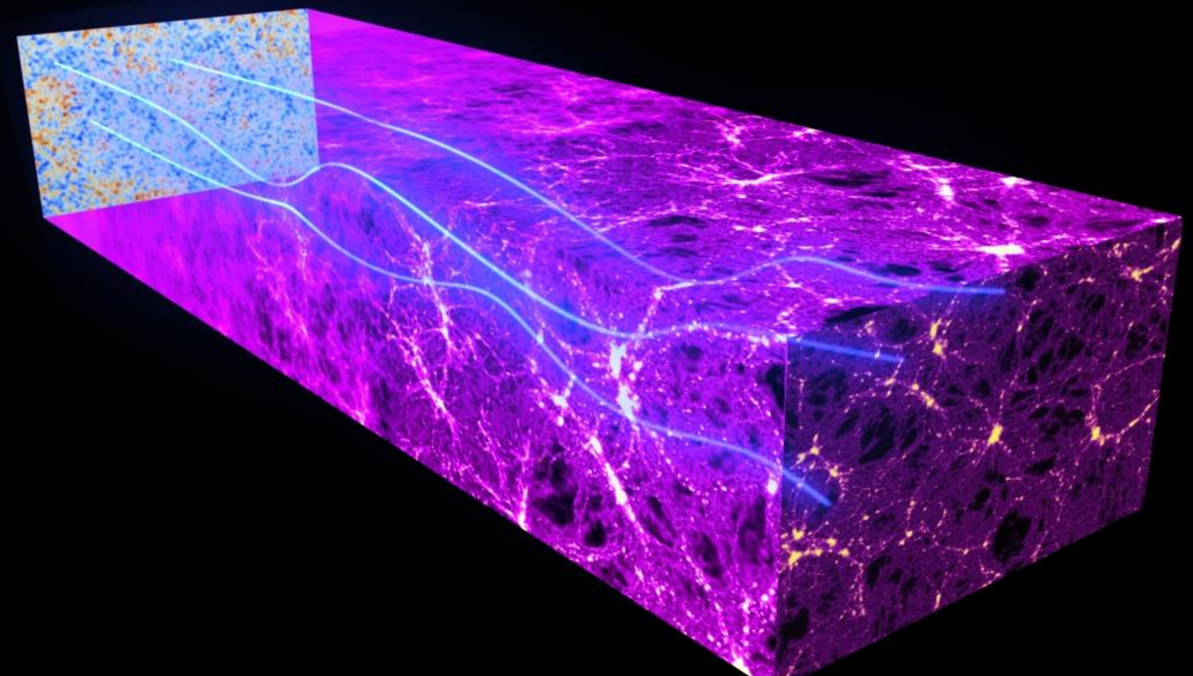
Composition

- 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.



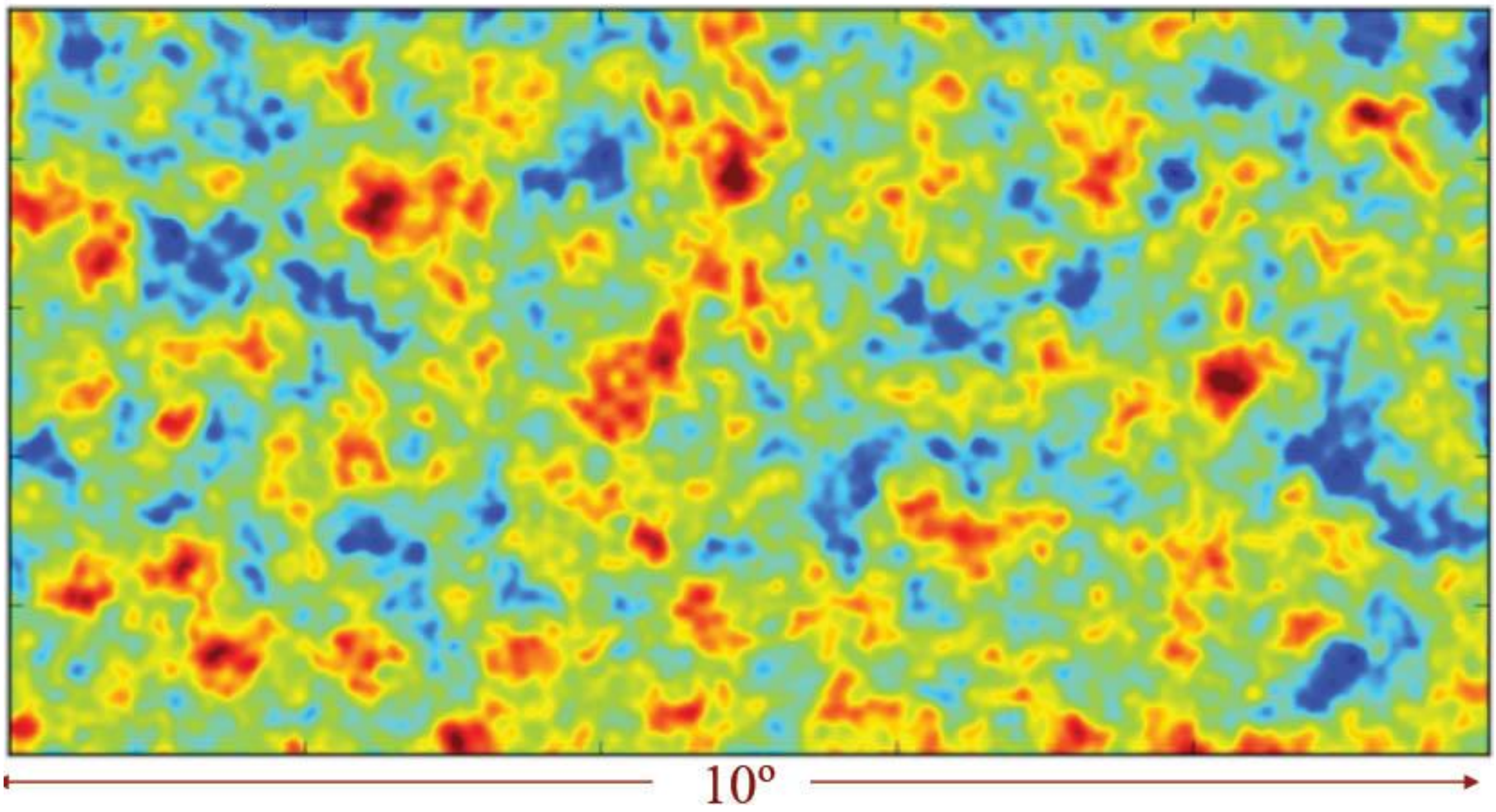
CMB anisotropy (lensing)

- 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.



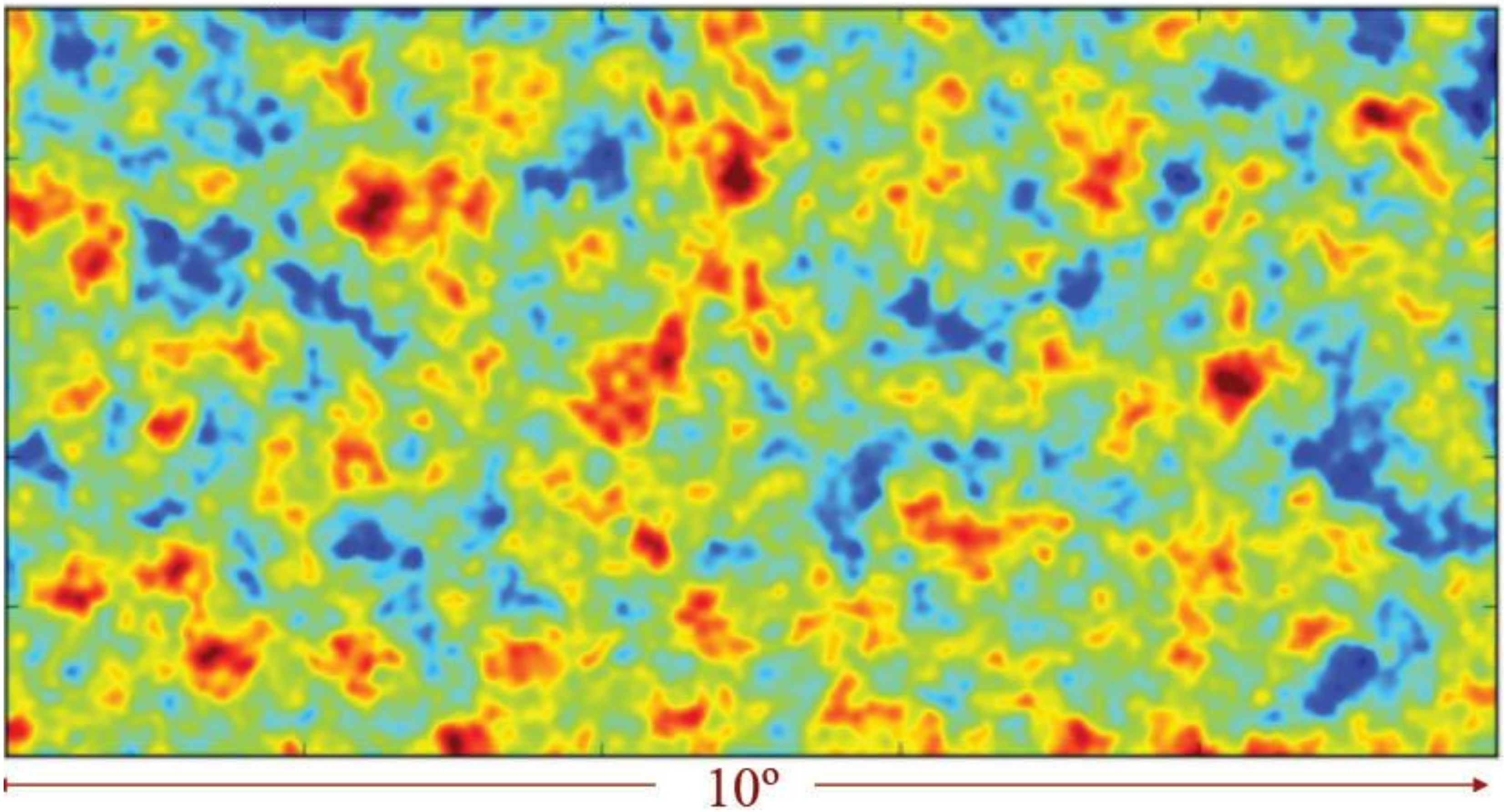
Typical deflection: 2.5’

intrinsic CMB anisotropy



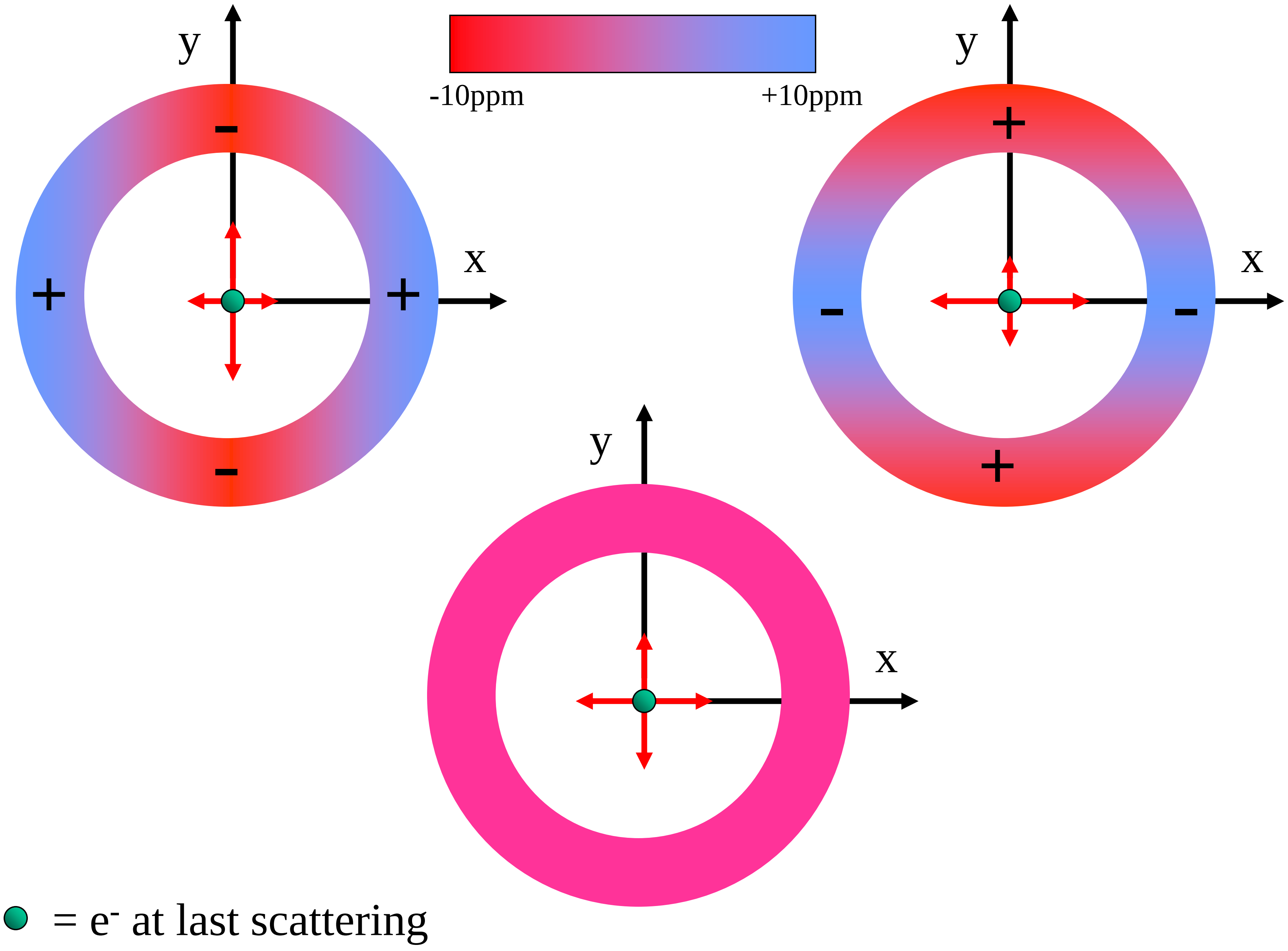
Typical deflection: 2.5’

lensed CMB anisotropy

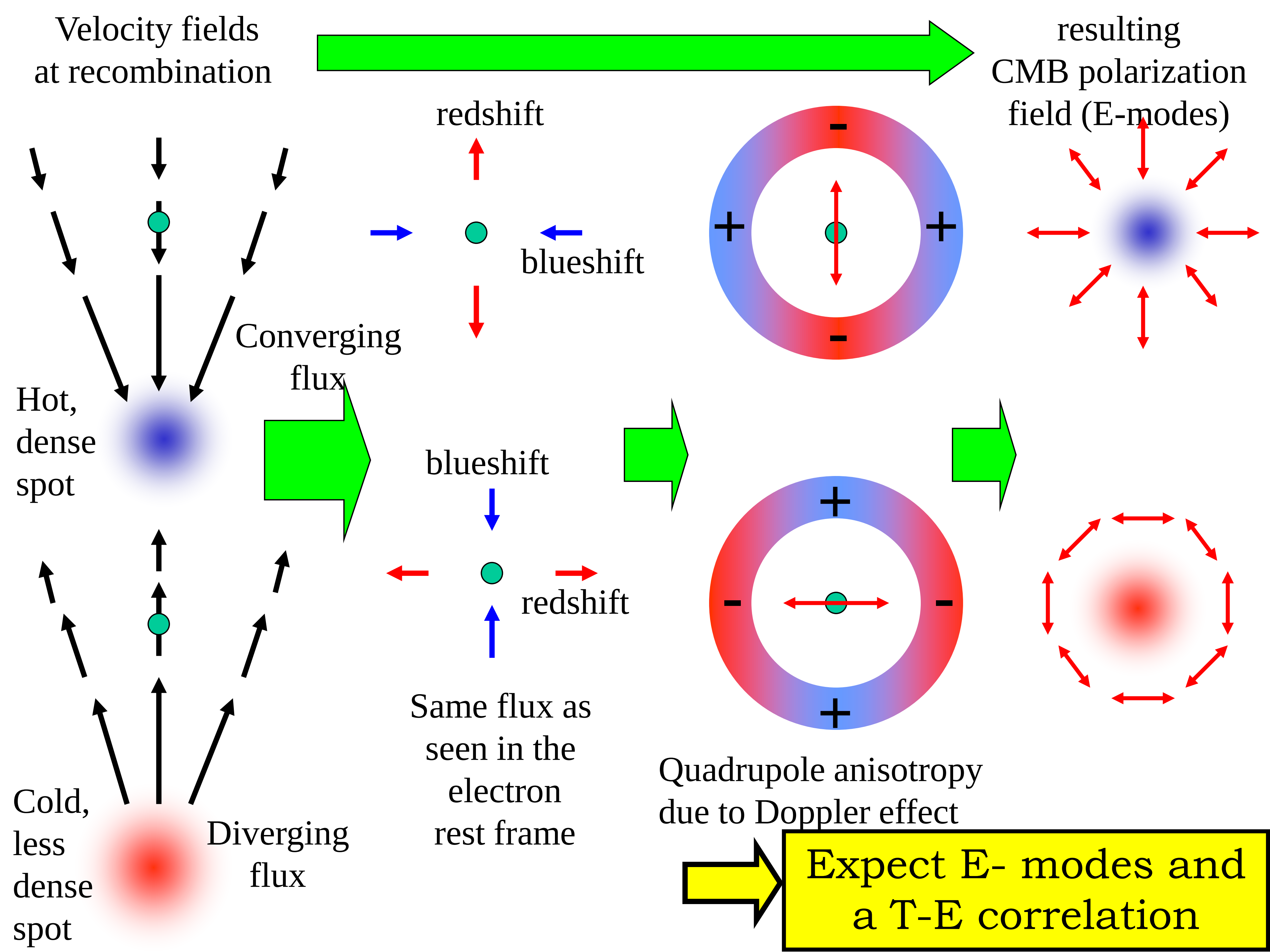


CMB polarization (E)

- 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)



y
x
-10ppm
+10ppm
= e- at last scattering


Velocity fields
at recombination
resulting
CMB polarization
field (E-modes)
redshift
blueshift
Converging
flux
Hot,
dense
spot
blueshift
redshift
Same flux as
seen in the
electron
rest frame
Cold,
less
dense
spot
Diverging
flux
Quadrupole anisotropy
due to Doppler effect
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>.

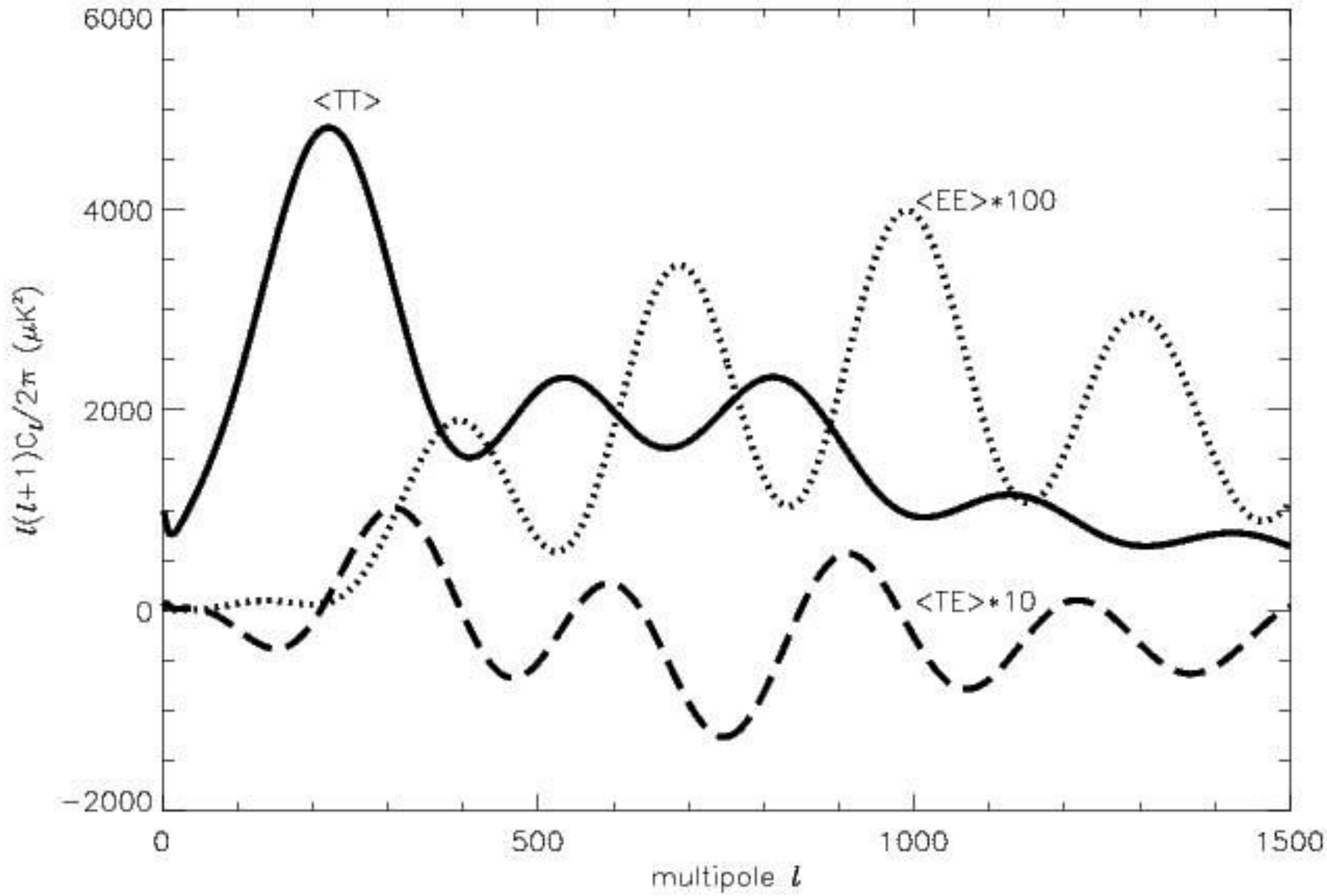


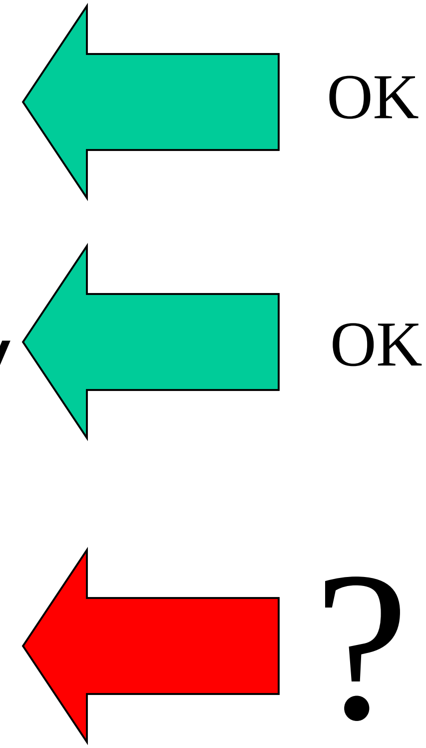
Figure 1.7: Estimated power spectra for the cosmological parameters: $\Omega_b = 0.05$, $\Omega_{cdm} = 0.3$, $\Omega_\Lambda = 0.65$, $\Omega_\nu = 0$, $H_0 = 65$ km/s/Mpc, $\tau = 0.17$. The temperature power spectrum, $\langle TT \rangle = C_\ell^T$, the E-modes power spectrum $\langle EE \rangle = C_\ell^E$ multiplied by a factor 100 to make it visible and the cross power spectrum between temperature and polarization, $\langle TE \rangle = C_\ell^{TE}$ multiplied by a factor 10. The spectra are computed using the publicly available code CMBFAST (http://www.cmbfast.org),

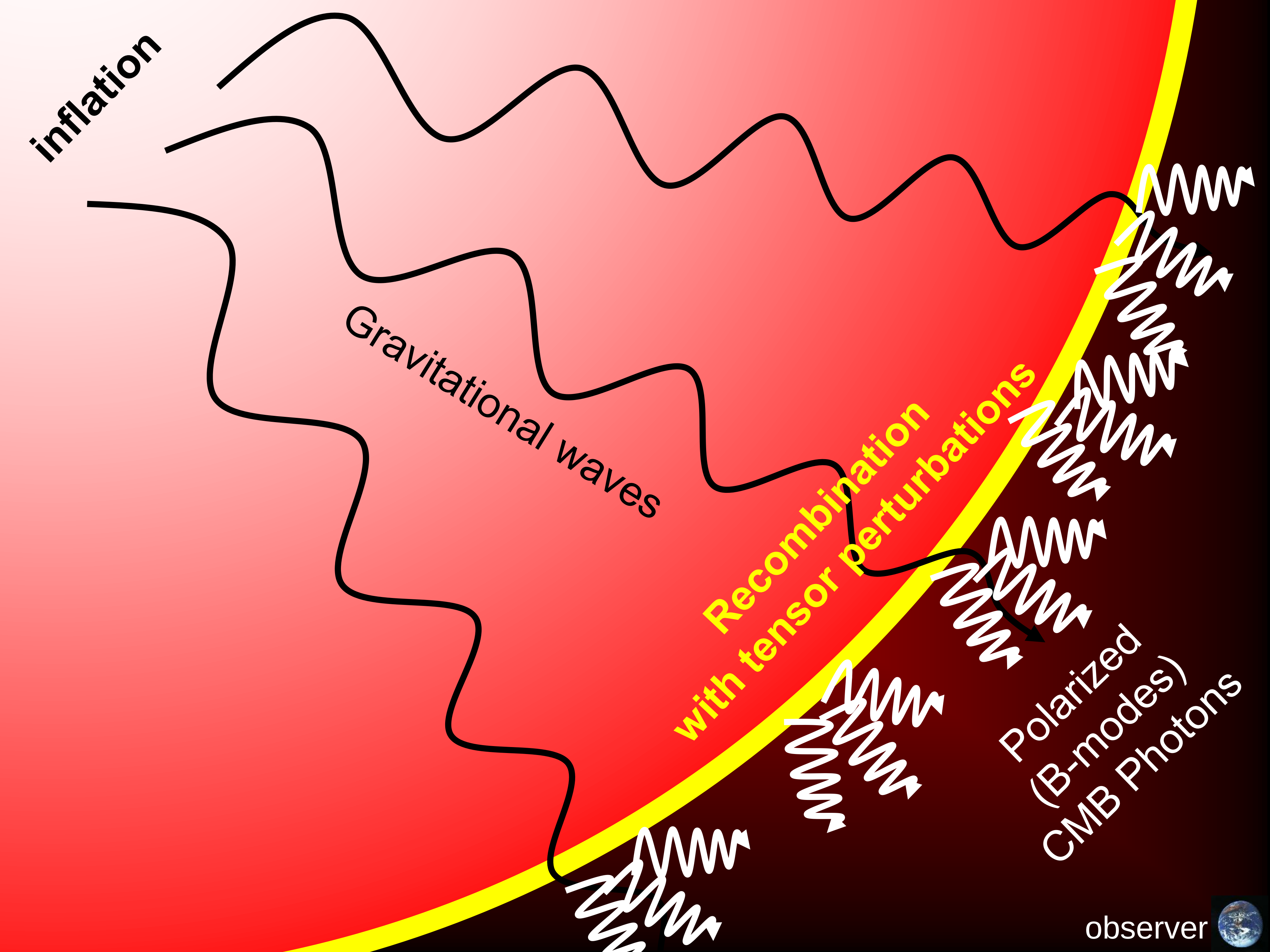
CMB polarization (B)

- 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…

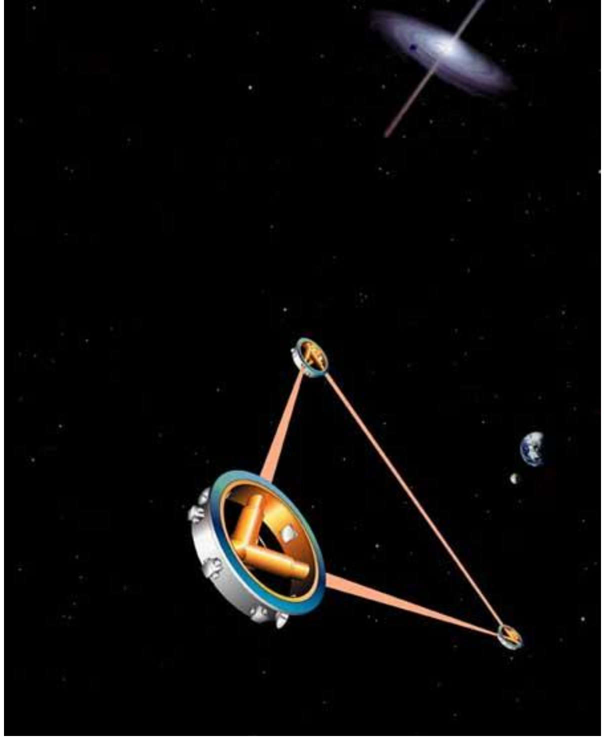
- It stretched geometry of space to nearly Euclidean
- It produced a nearly scale invariant spectrum of density fluctuations
- It produced a stochastic background of gravitational waves.

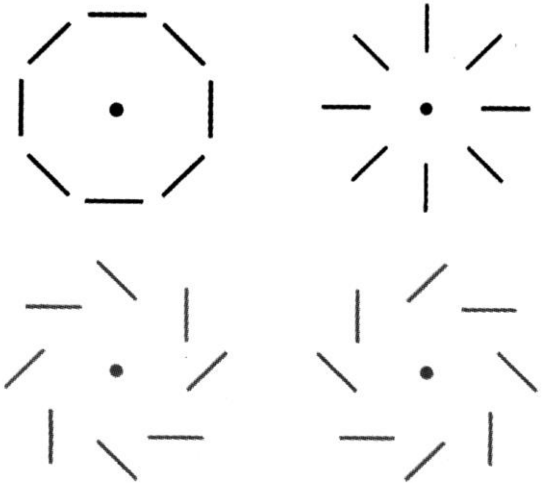



inflation
Gravitational waves
Recombination
with tensor perturbations
Polarized
(B-modes)
CMB Photons
observer

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.





B-modes from P.G.W.

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

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

Inflation potential

- and

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

- There are theoretical arguments to expect that the energy scale of inflation is close to the scale of GUT i.e. around 10^{16} GeV.
- The current upper limit on anisotropy at large scales gives T/S<0.5 (at 2σ)
- A competing effect is lensing of E-modes, which is important at large multipoles.

E-modes & B-modes

Spin-2 quantity — Spin-2 basis

$$(Q \pm iU)(\vec{n}) = \sum_{\ell,m} \left(a^{E}_{\ell m} \pm i a^{B}_{\ell m}\right) {}_{\pm 2}Y_{\ell m}(\vec{n})$$

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

E-modes produced by scalar and tensor perturbations

$$a^{E}_{\ell m} = \frac{1}{2}\int d\Omega W(\vec{n})\left[(Q+iU)(\vec{n})\,{}_{+2}Y_{\ell m}(\vec{n}) + (Q-iU)(\vec{n})\,{}_{-2}Y_{\ell m}(\vec{n})\right]$$

B-modes produced **only** by tensor perturbations

$$a^{B}_{\ell m} = \frac{1}{2i}\int d\Omega W(\vec{n})\left[(Q+iU)(\vec{n})\,{}_{+2}Y_{\ell m}(\vec{n}) - (Q-iU)(\vec{n})\,{}_{-2}Y_{\ell m}(\vec{n})\right]$$

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: …

Conceptual Importance of B-modes

1. Quantum fluctuation of the metric

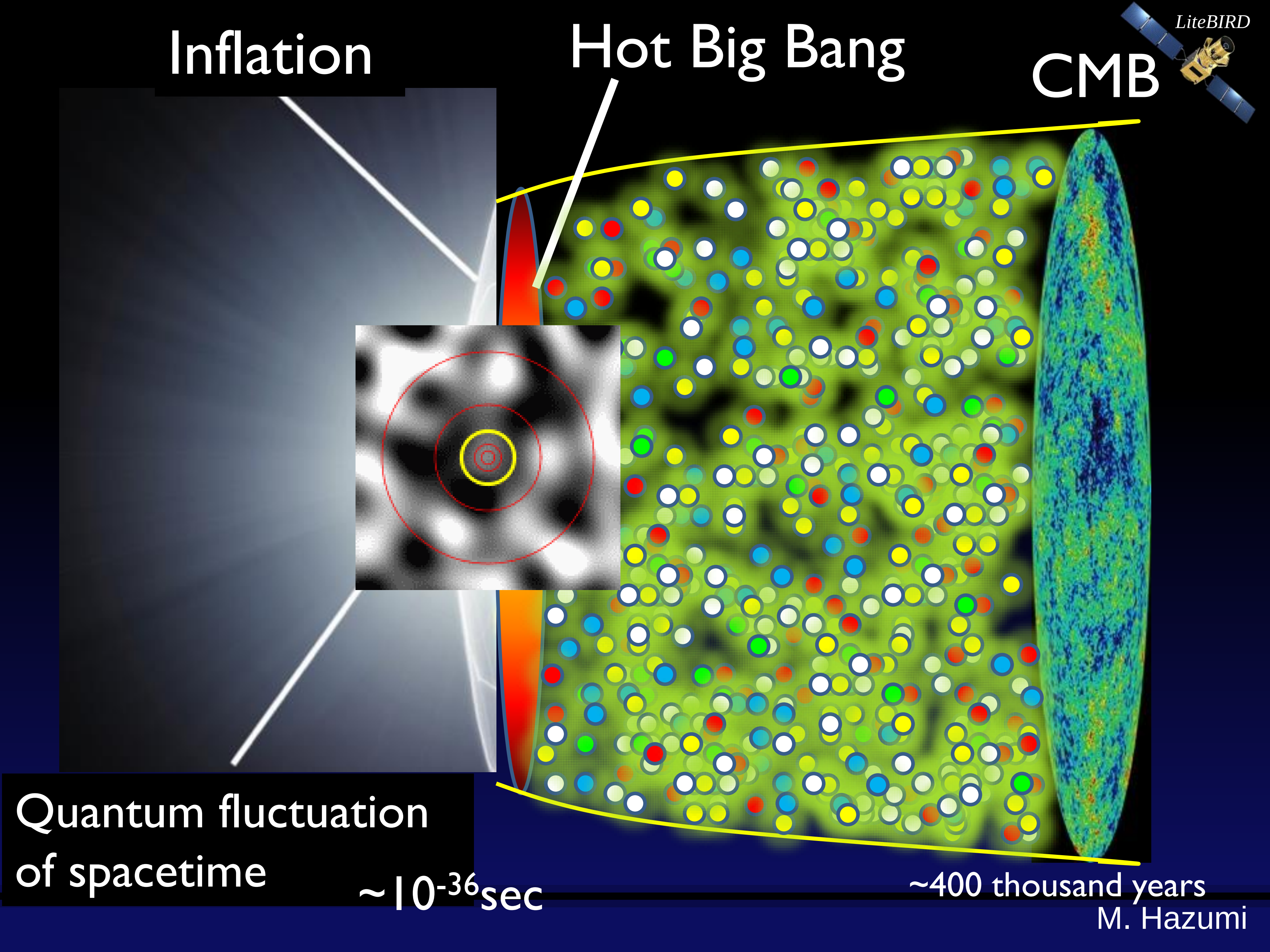
$$\langle \hat{h}^{\dagger}(\vec{k},\eta)\hat{h}(\vec{k}',\eta)\rangle = |v(\vec{k},\eta)|^2(2\pi)^3\delta^3(\vec{k}-\vec{k}').$$

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

2. Physics at GUT scale

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

M. Hazumi



Inflation
Hot Big Bang
LiteBIRD
CMB
Quantum fluctuation
of spacetime
~10-36sec
~400 thousand years
M. Hazumi

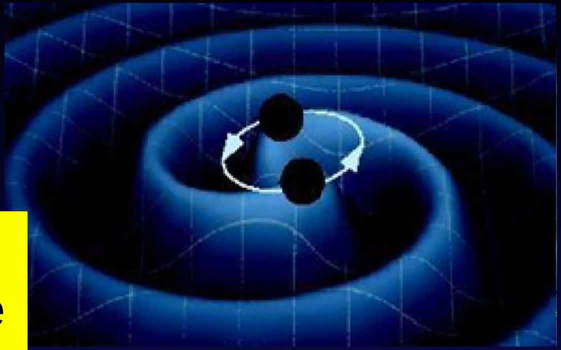
LiteBIRD

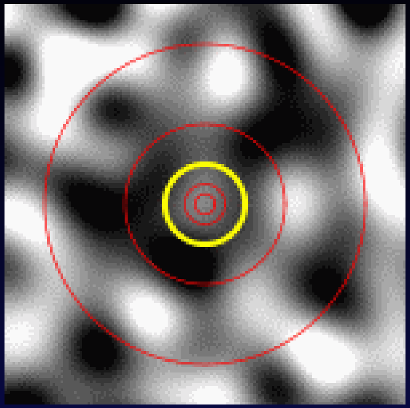
Big leap from LIGO/VIRGO to LiteBIRD

within Einstein's theory of general relativity

beyond Einstein

The 2017 Nobel Prize in Physics





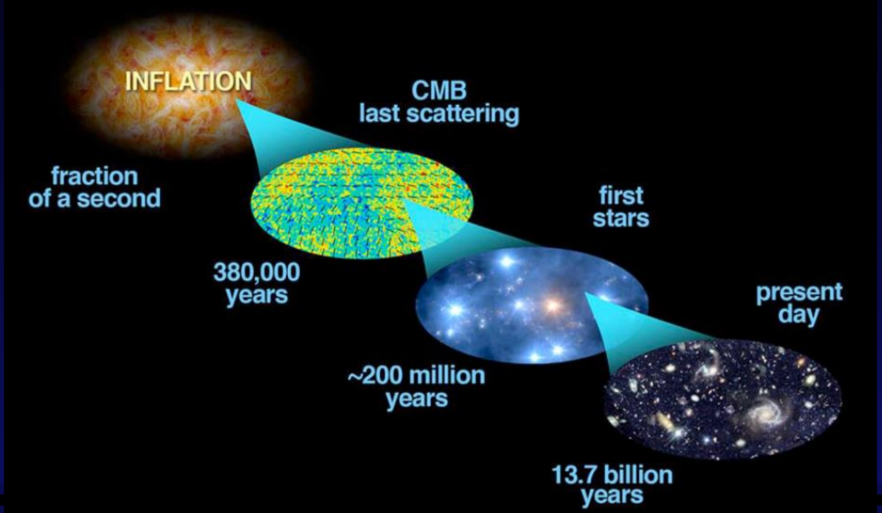
LIGO/VIRGO: gravitational waves with classical origin

LiteBIRD: gravitational waves with quantum origin

"Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time."

Final report of the task force on cosmic microwave background research
"Weiss committee report"
July 11, 2005, arXiv/0604101

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

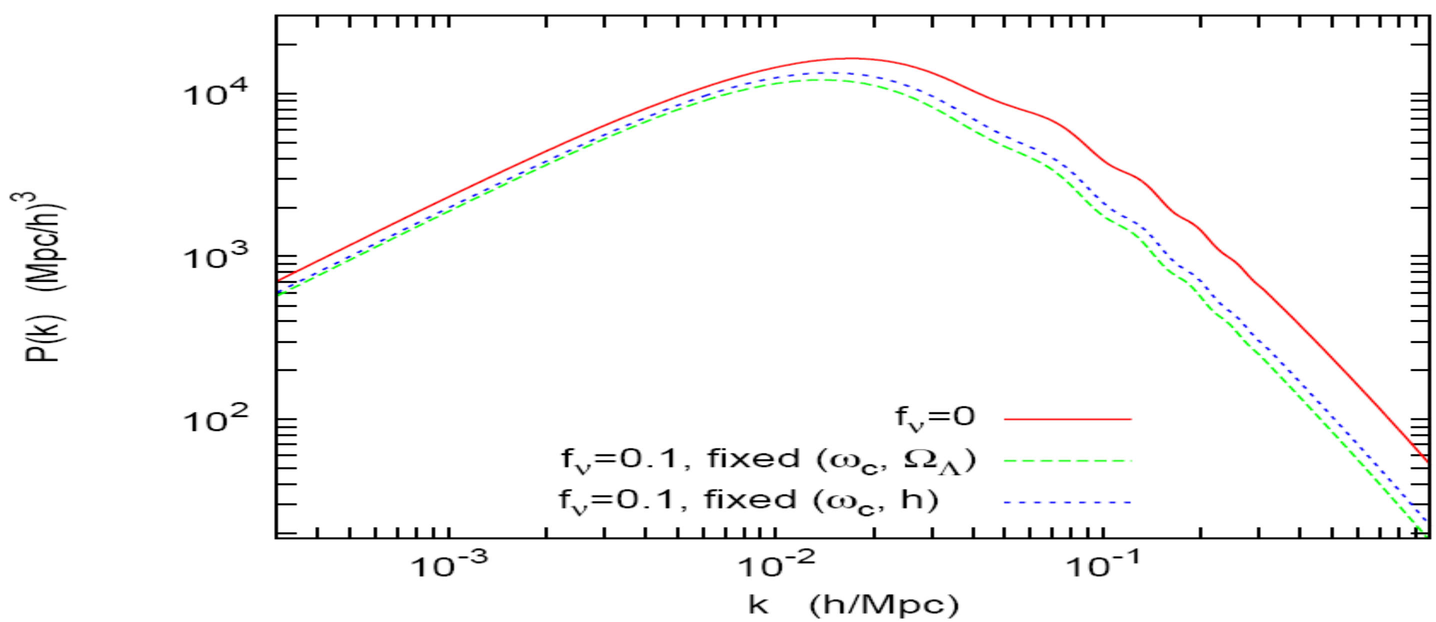
$$P_m(k,z) = \left\langle \left| \frac{\delta\rho}{\rho} \right|_{k,z}^2 \right\rangle = Ak^n \cdot T^2(k,z)$$

Wavenumber (Mpc^{-1})

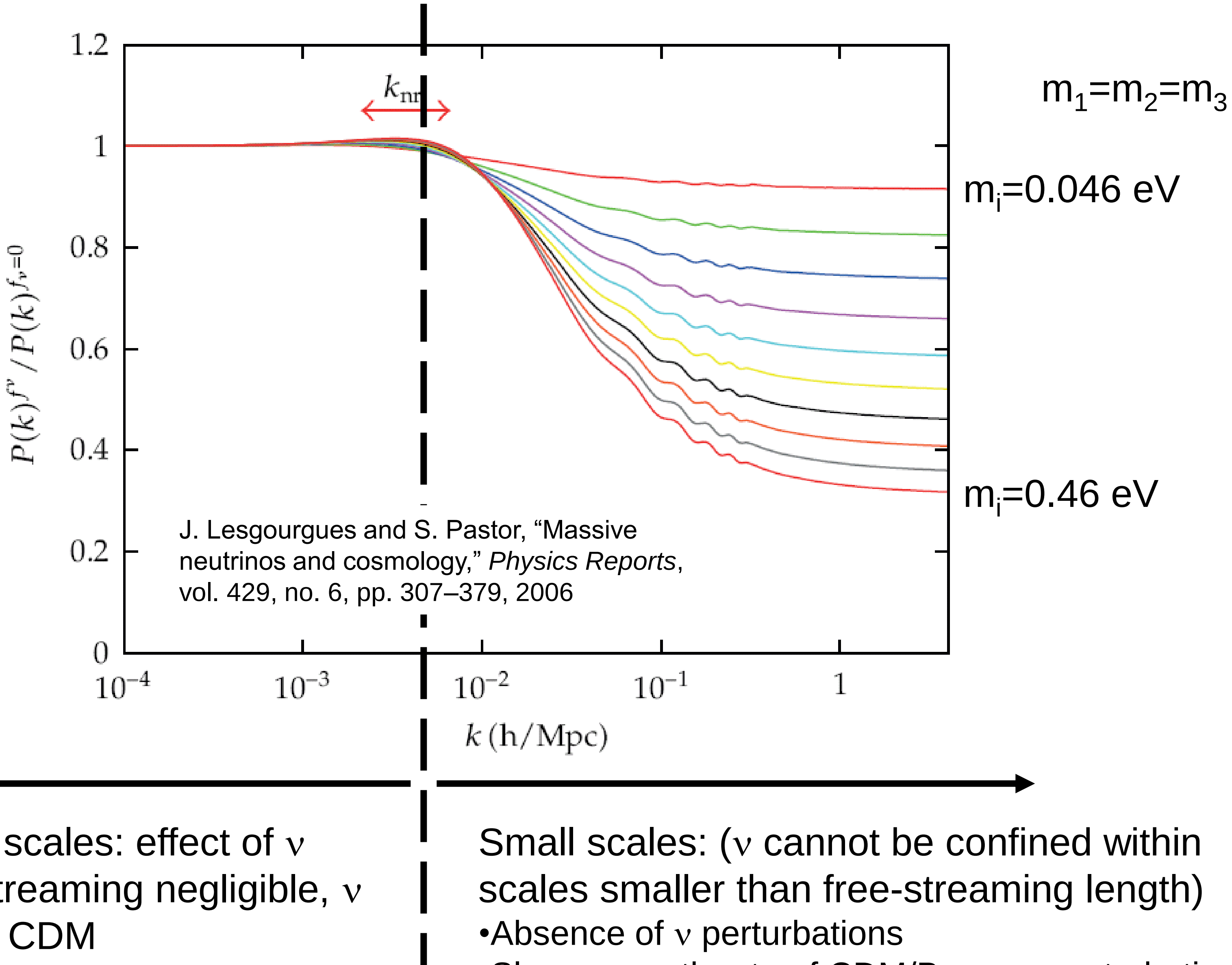
Redshift (epoch)

Primordial (inflation ?)

Transfer function describing the growth of density fluctuations



Effects on Matter power spectrum



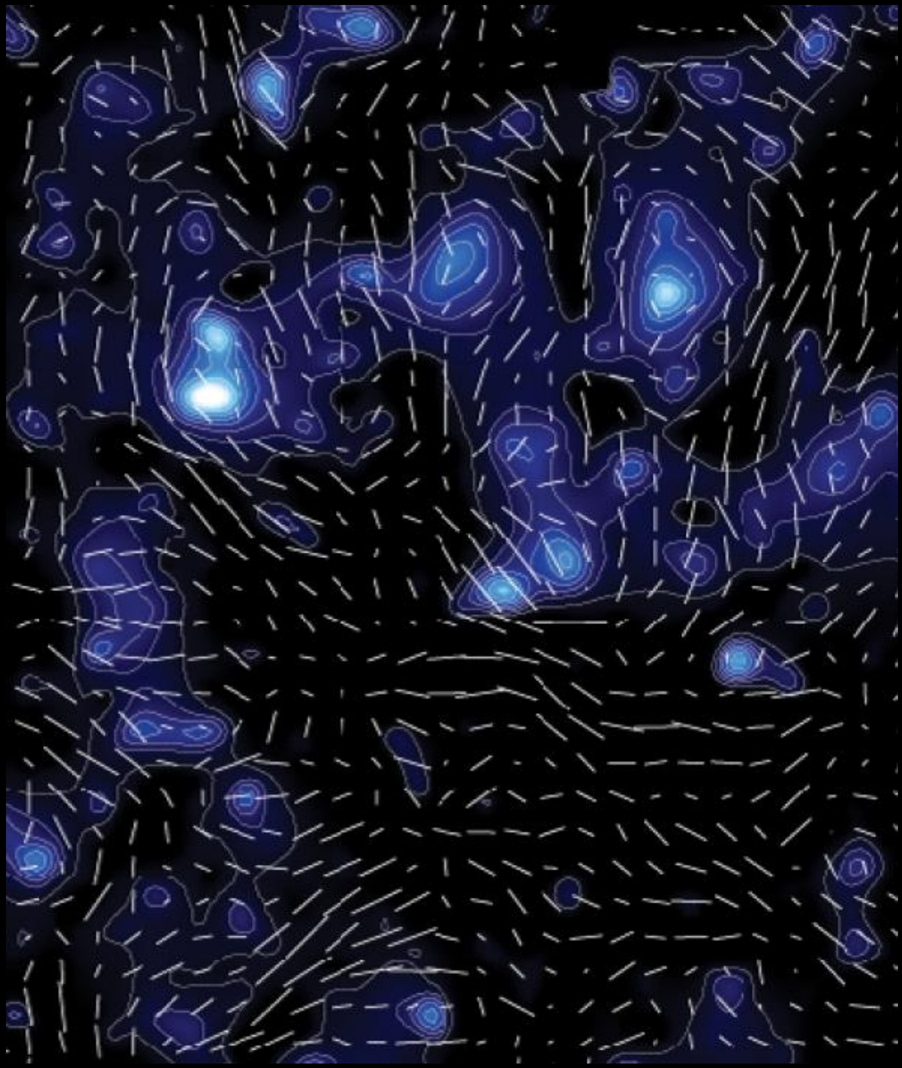
Large scales: effect of ν free-streaming negligible, ν act as CDM

Small scales: (ν cannot be confined within scales smaller than free-streaming length)

- Absence of ν perturbations
- Slower growth rate of CDM/Baryons perturbations

Galaxy lensing surveys

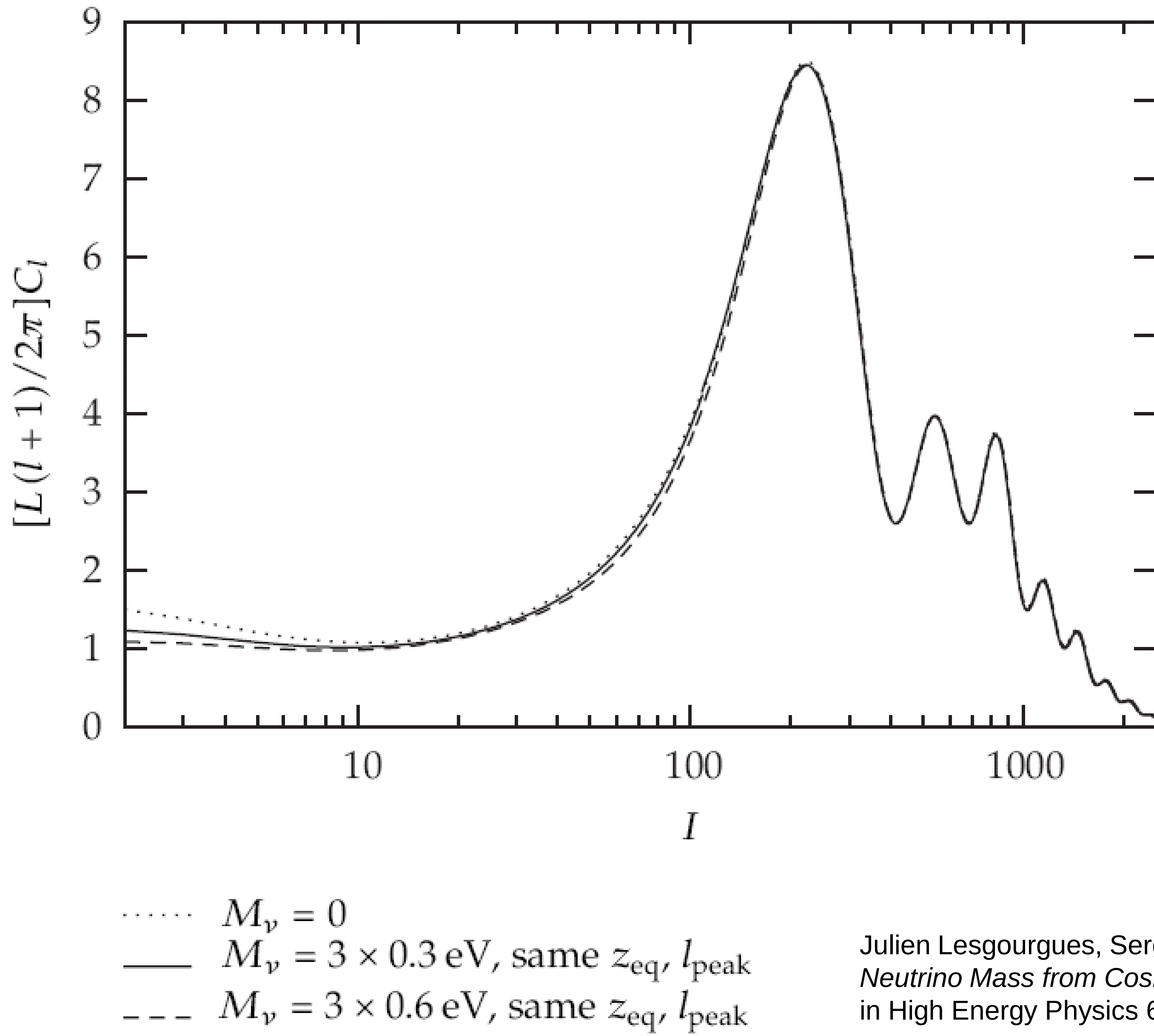
- Images of galaxies are distorted by weak gravitational lensing, due to the intervening total mass distribution between the sources and the observer
- Stretching the image in a direction and squeezing in the orthogonal direction (cosmic shear)
- Distortions coherent over size of density fluctuations, 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 .

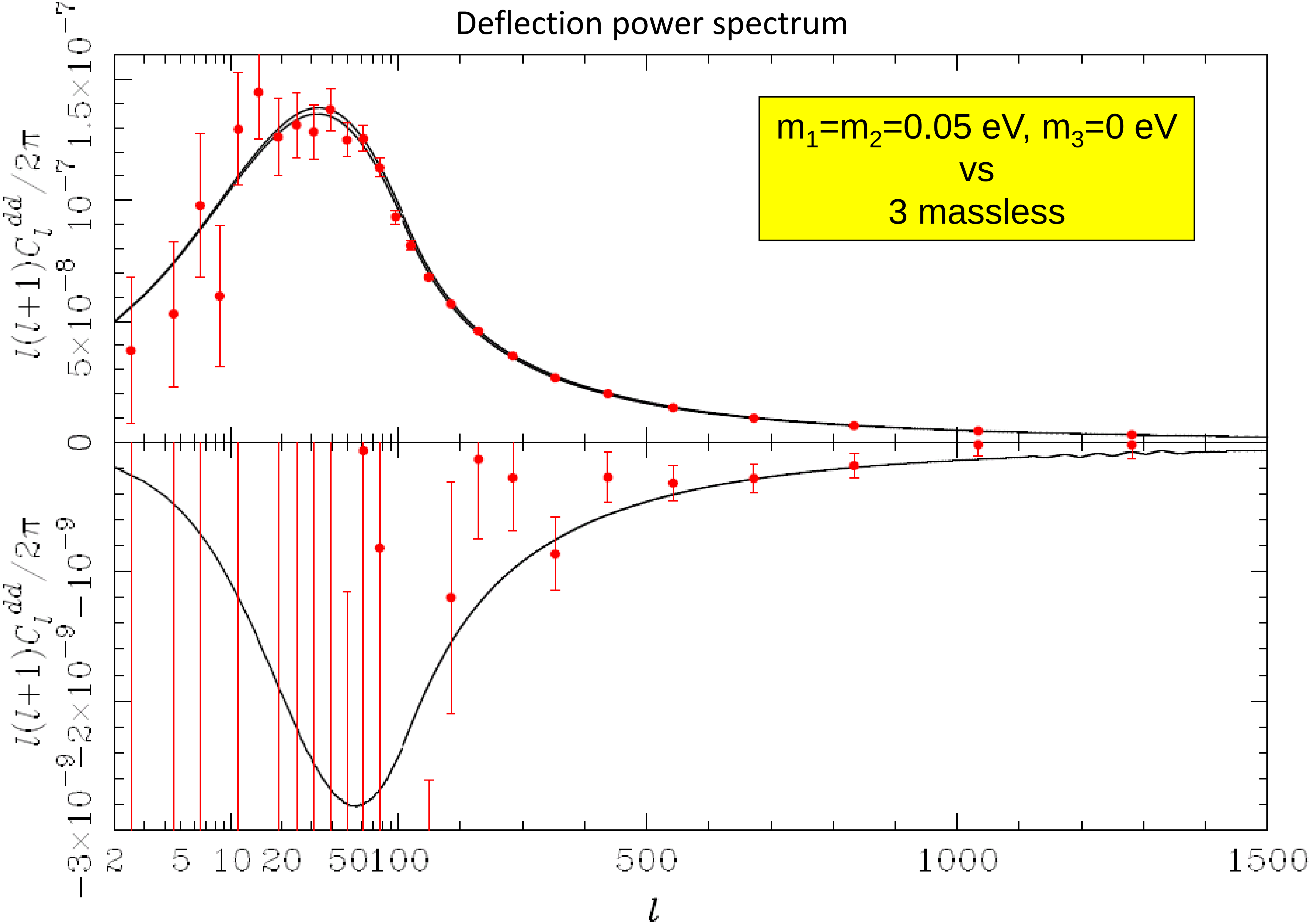
ν mass and the power spectrum of the CMB

- If M_n<1eV , 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 Ω_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 n mass. **More powerful probes, BUT SUFFER THE SAME "ASTROPHYSICS" PROBLEMS OF MATTER PS**



Julien Lesgourgues, Sergio Pastor : *Neutrino Mass from Cosmology* Advances in High Energy Physics 608515 (2012)

Deflection power spectrum



CMB constraints on neutrinos

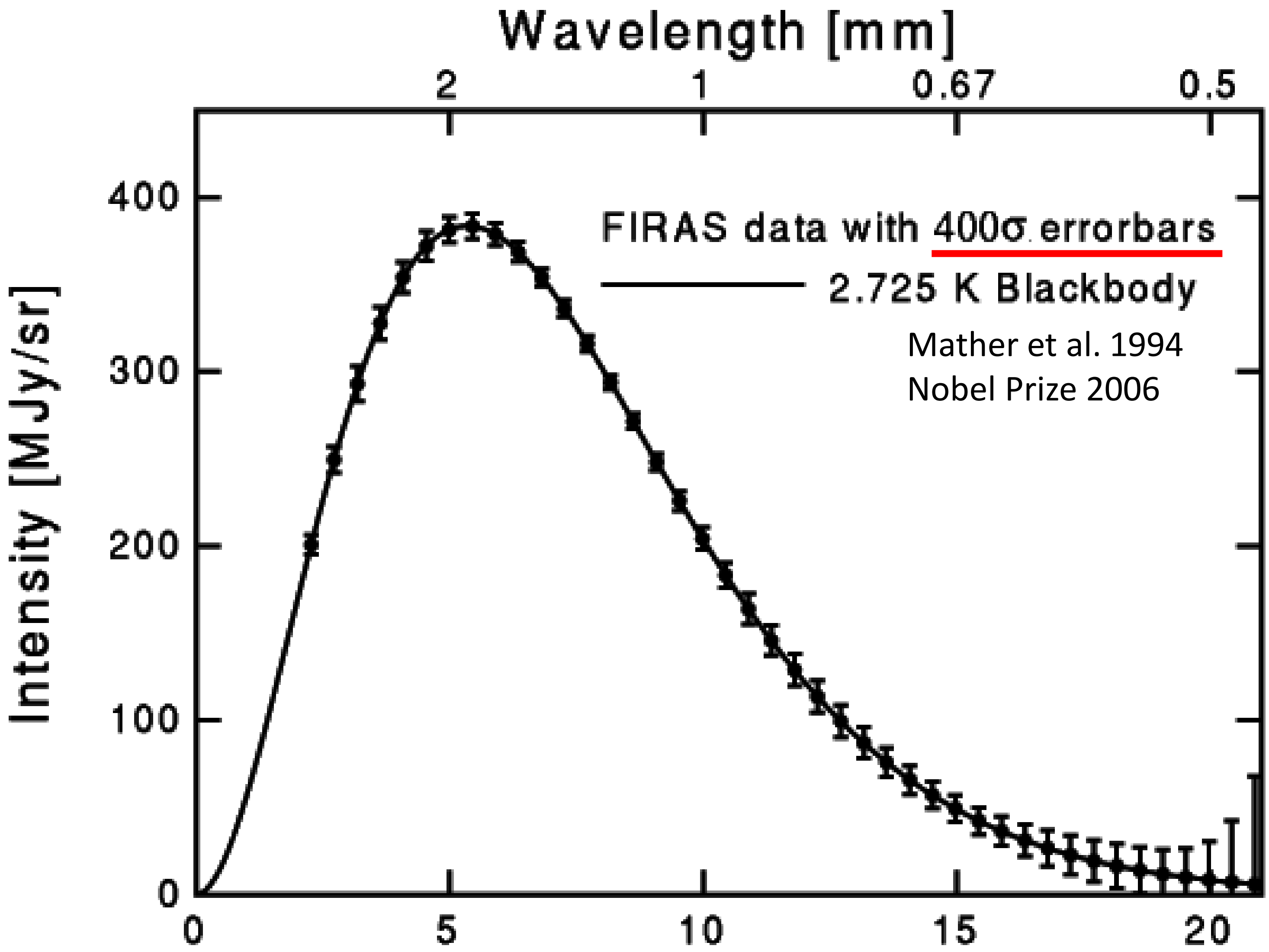
- Cosmological effects of neutrinos (see e.g. Lattanzi and Gerbino 2017):
  - For masses of the order of 0.1 eV νs are still relativistic at recombination and their effect on the anisotropy spectrum is small.
  - The main effect of massive νs is at later times, when they alter the expansion history, and the shape of the matter power spectrum. Increasing m_ν increases the expansion rate at z>1, and modifies the distance-redshift relation. However, this is contrained by the scale of the acoustic peaks (θ_{MC}), so aother parameters must change to leave the same θ_{MC} when Σm_ν increases, i.e. suppressing large-scale power. This results in a broad suppression of the matter power spectrum at fixed CMB amplitude.
  - Since νs 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 Σm_ν <0.12 eV (95% CL).

Most of this has been **measured** very successfully, and used to constrain cosmology.

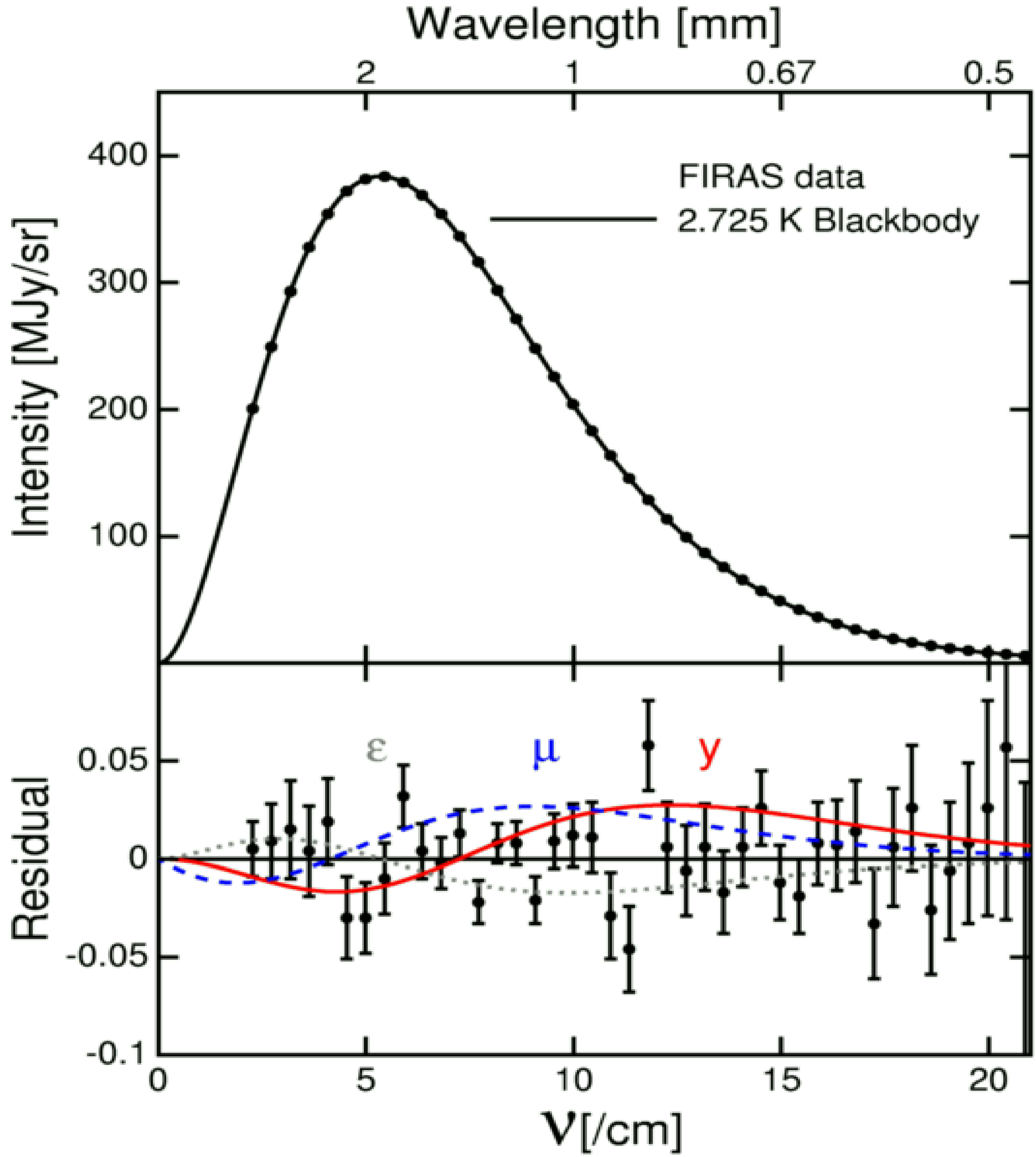
- Spectrum
- Intrinsic anisotropy (power spectrum)
- Lensing
- E-modes polarization
- SZ effect
- B-modes polarization

Spectrum

The spectrum: a proof of the primeval fireball



wavenumber σ (cm^{-1})



Depending on the physical process, the expected **spectral distortions** have a different shape (ε, μ, y)
See e.g.: **The evolution of CMB spectral distortions in the early Universe**
J. Chluba
R. A. Sunyaev
MNRAS (2012) 419 1294

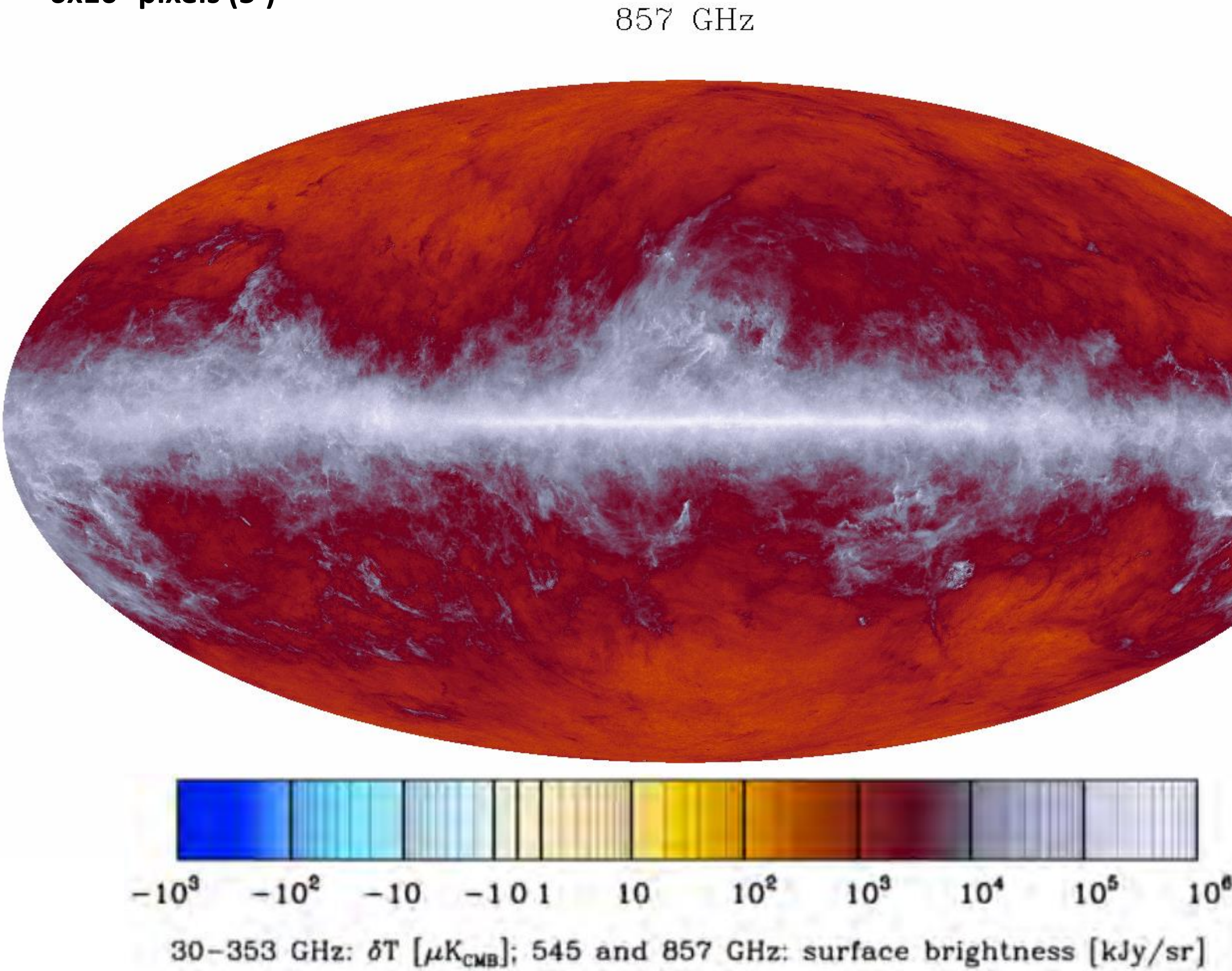
No distortions have been observed to-date (may be not ? See Bowman et al. Nature 2018).

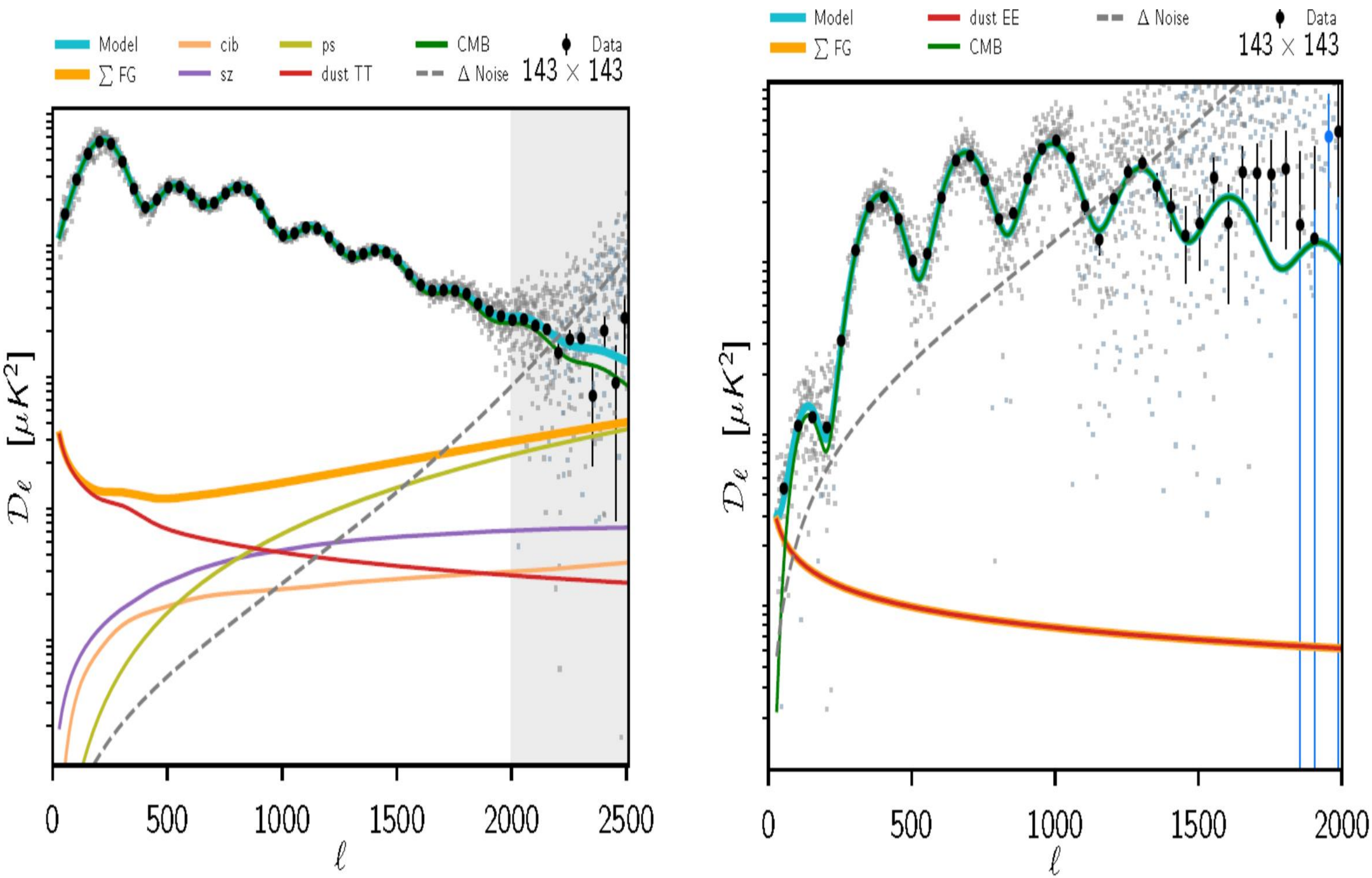
Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. 354 37

Anisotropy and Polarization

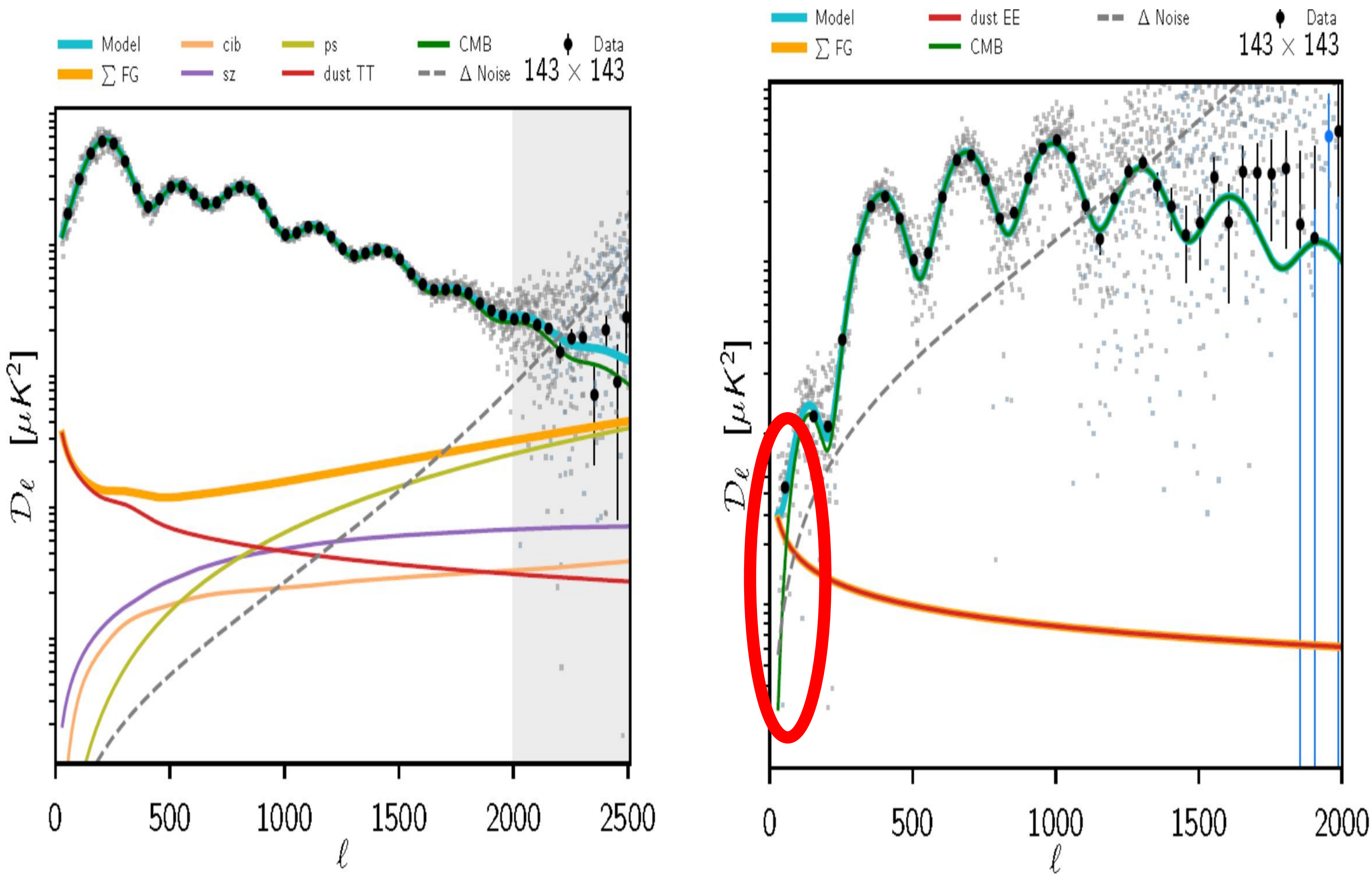
Planck Legacy Maps

$6x10^6$ pixels (5')





$$\mathcal{D}_\ell = \ell(\ell+1)\,C_\ell/(2\pi)$$ Power spectra at 143 GHz



$$\mathcal{D}_\ell = \ell(\ell + 1)\, C_\ell/(2\pi)$$

Power spectra at 143 GHz

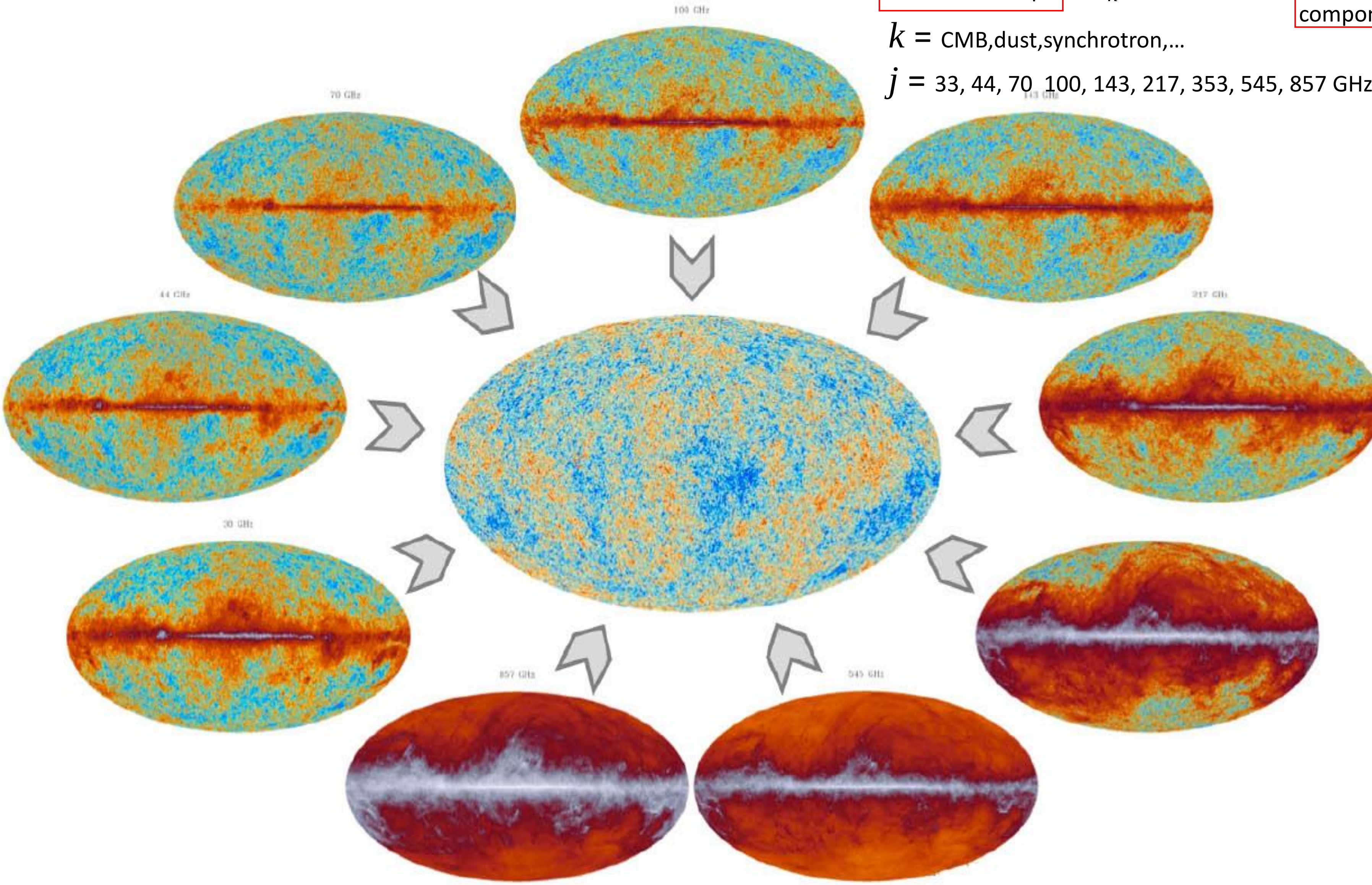
components separation

$$\Delta T(\nu_j,\ell,b) = \sum_k a_k(\nu_j,\ell,b)\, C_k(\ell,b)$$

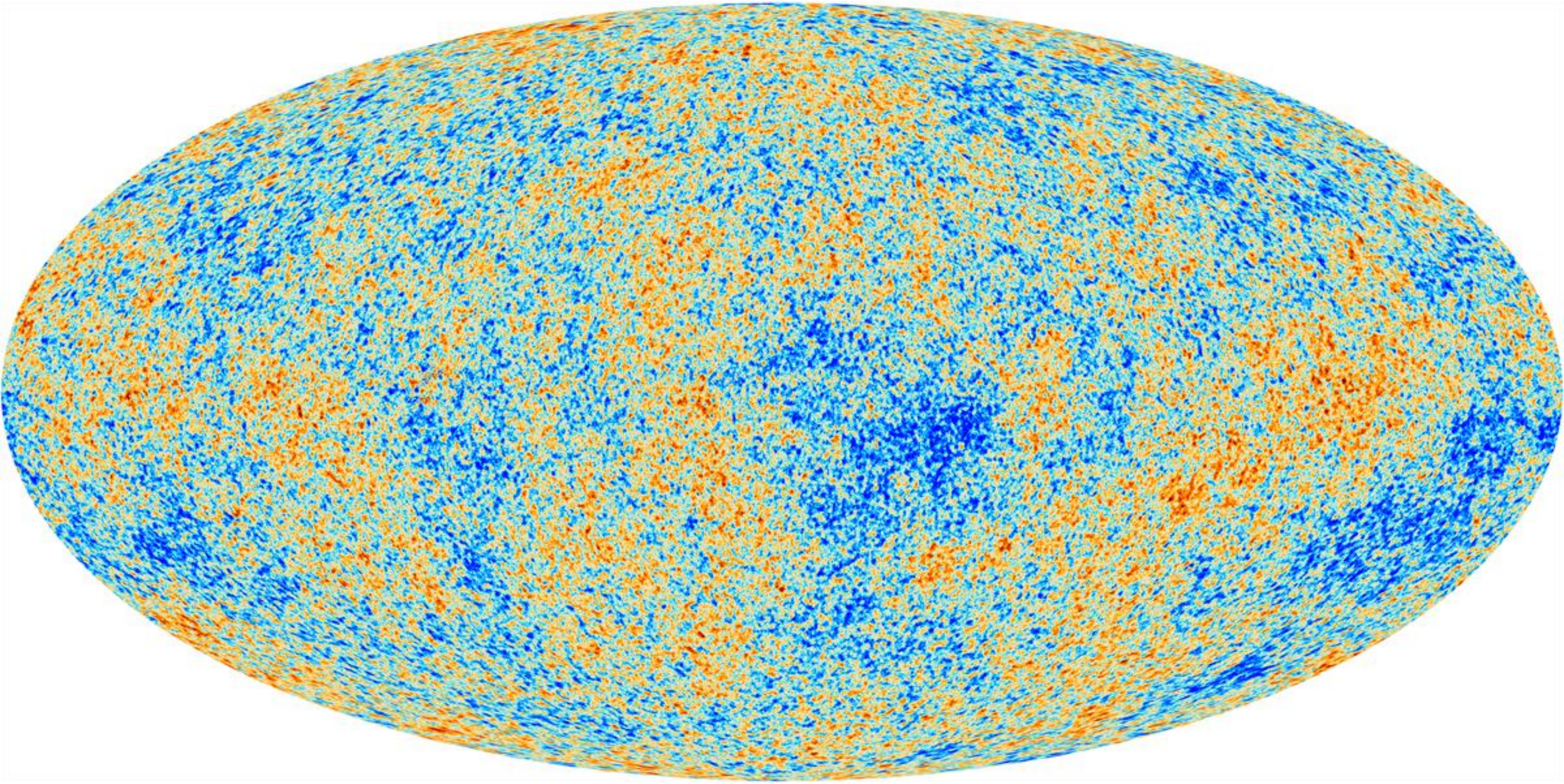
Measured maps — physical components

k = CMB,dust,synchrotron,…

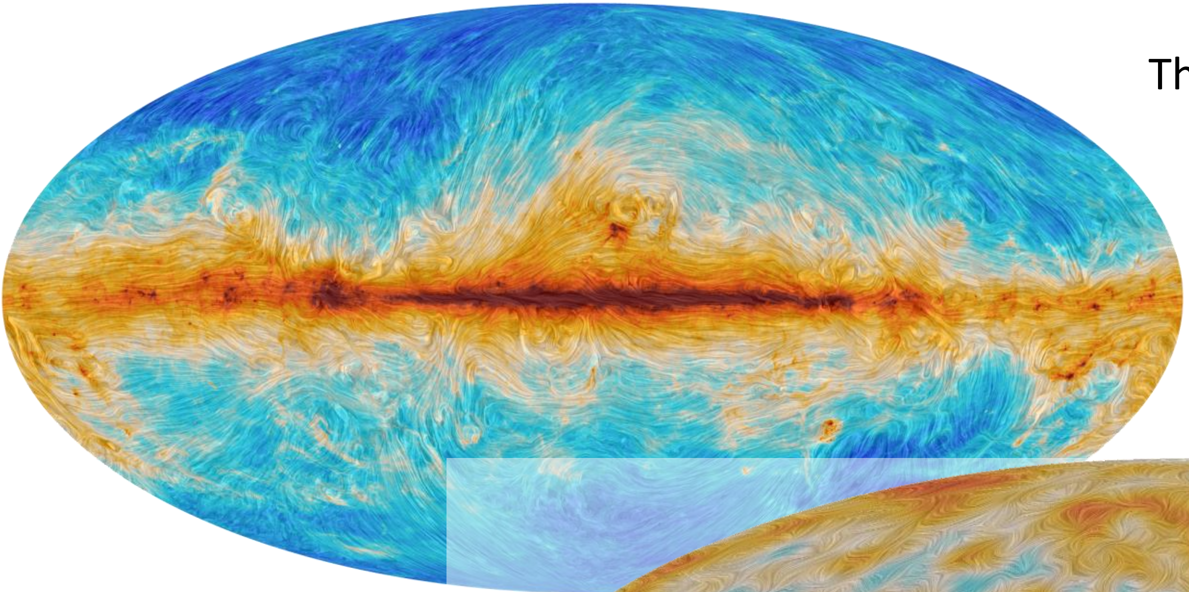
j = 33, 44, 70 100, 143, 217, 353, 545, 857 GHz

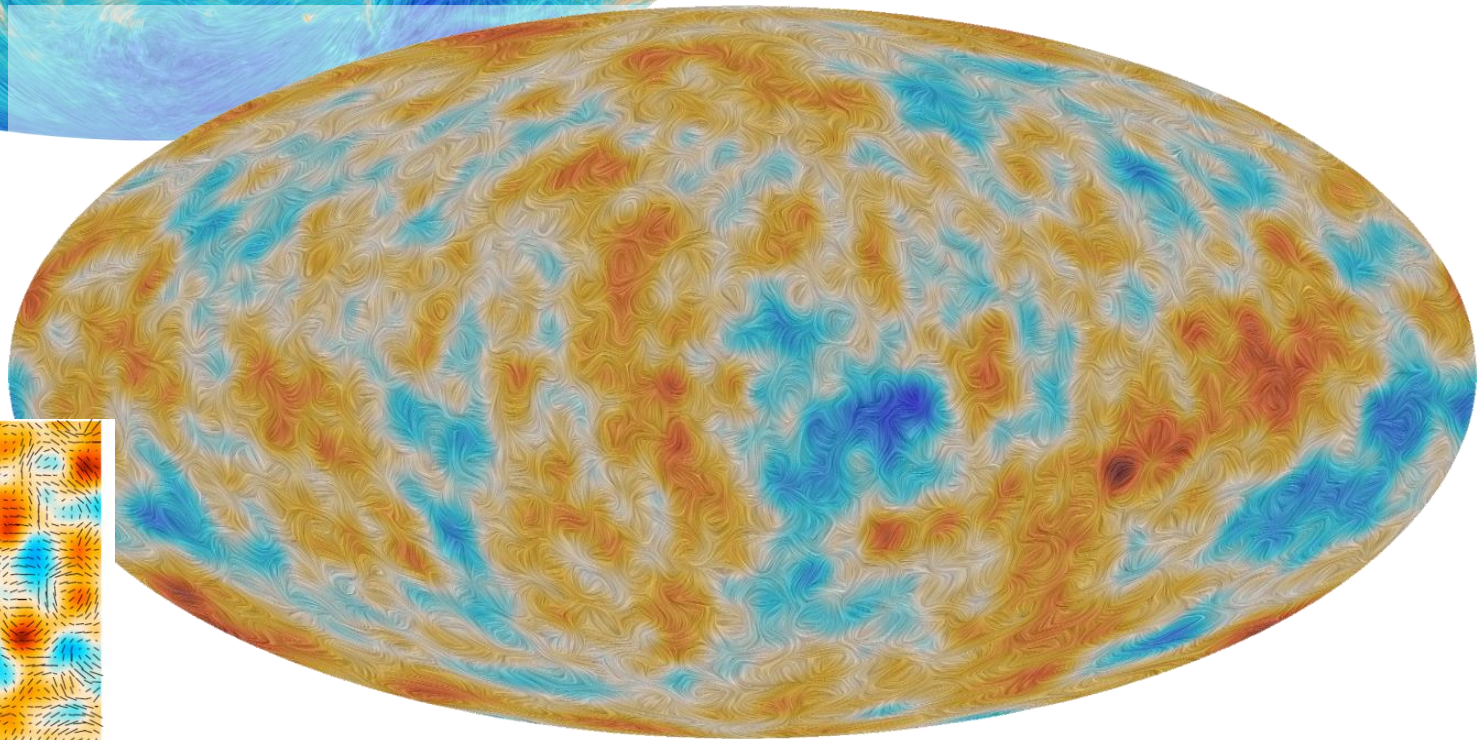


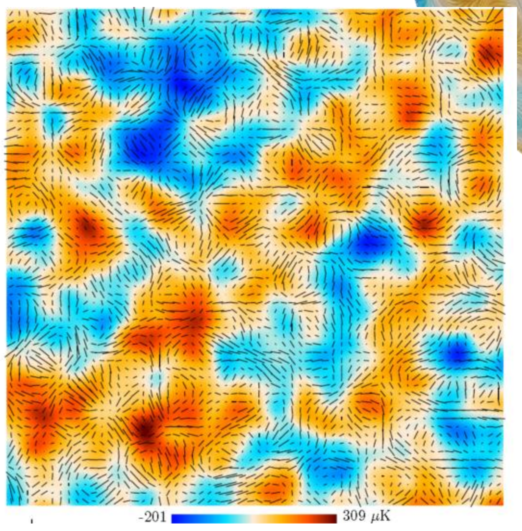
The CMB component: anisotropy

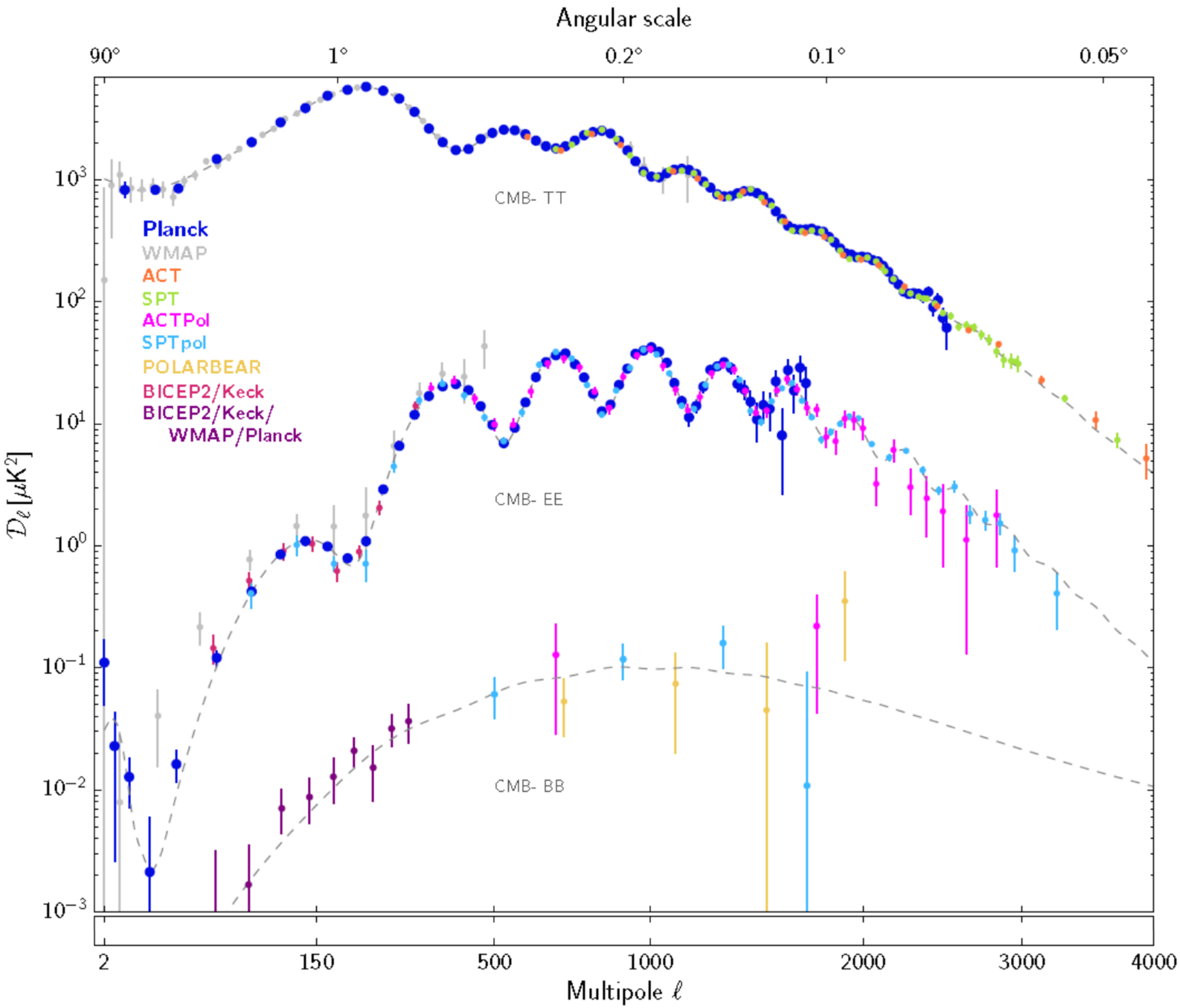


The CMB component: polarization

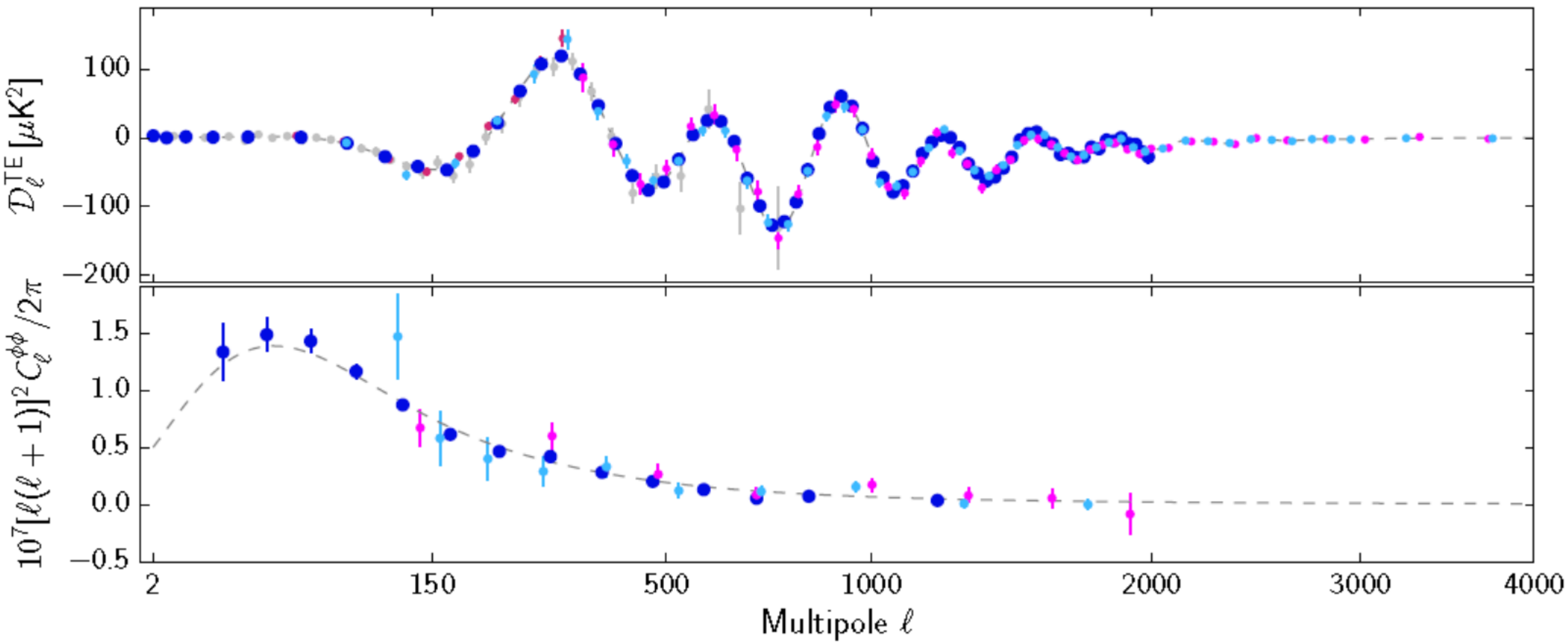




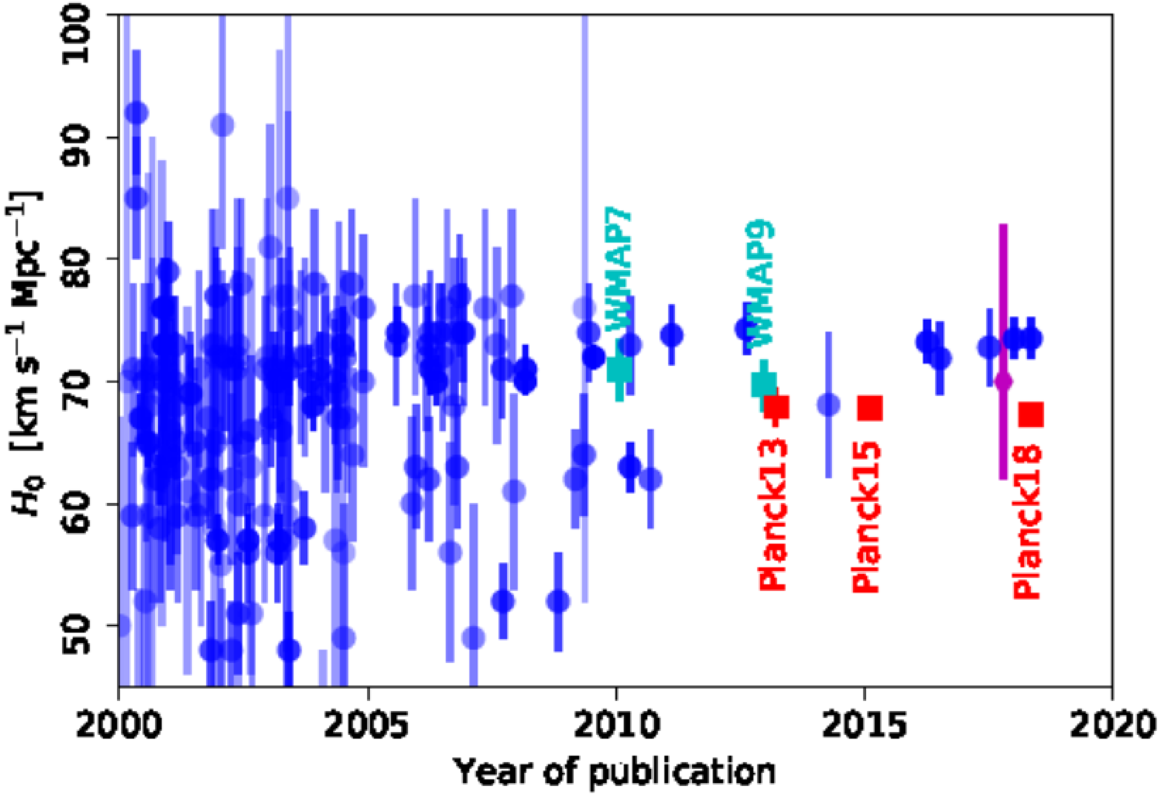




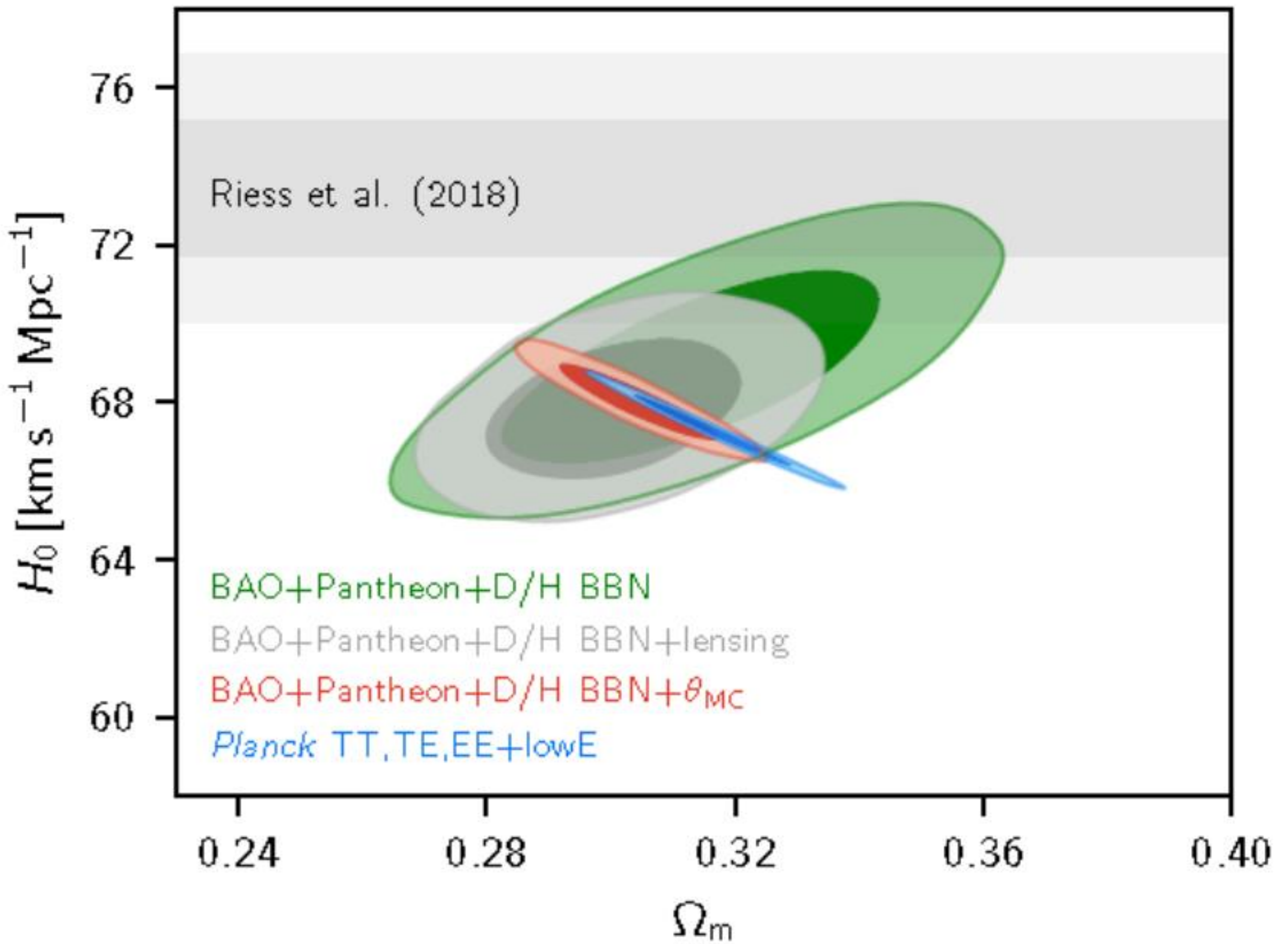
Angular scale
90°
1°
0.2°
0.1°
0.05°
CMB- TT
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/
WMAP/Planck
CMB- EE
CMB- BB
$\mathcal{D}_\ell\,[\mu K^2]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
2
150
500
1000
2000
3000
4000
Multipole ℓ



$\mathcal{D}_\ell^{\mathrm{TE}}\,[\mu\mathrm{K}^2]$
100
0
−100
−200
$10^7[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
1.5
1.0
0.5
0.0
−0.5
2
150
500
1000
2000
3000
4000
Multipole ℓ



H_0 [km s^{-1} Mpc^{-1}]
100
90
80
70
60
50
2000
2005
2010
2015
2020
Year of publication
WMAP7
WMAP9
Planck13
Planck15
Planck18



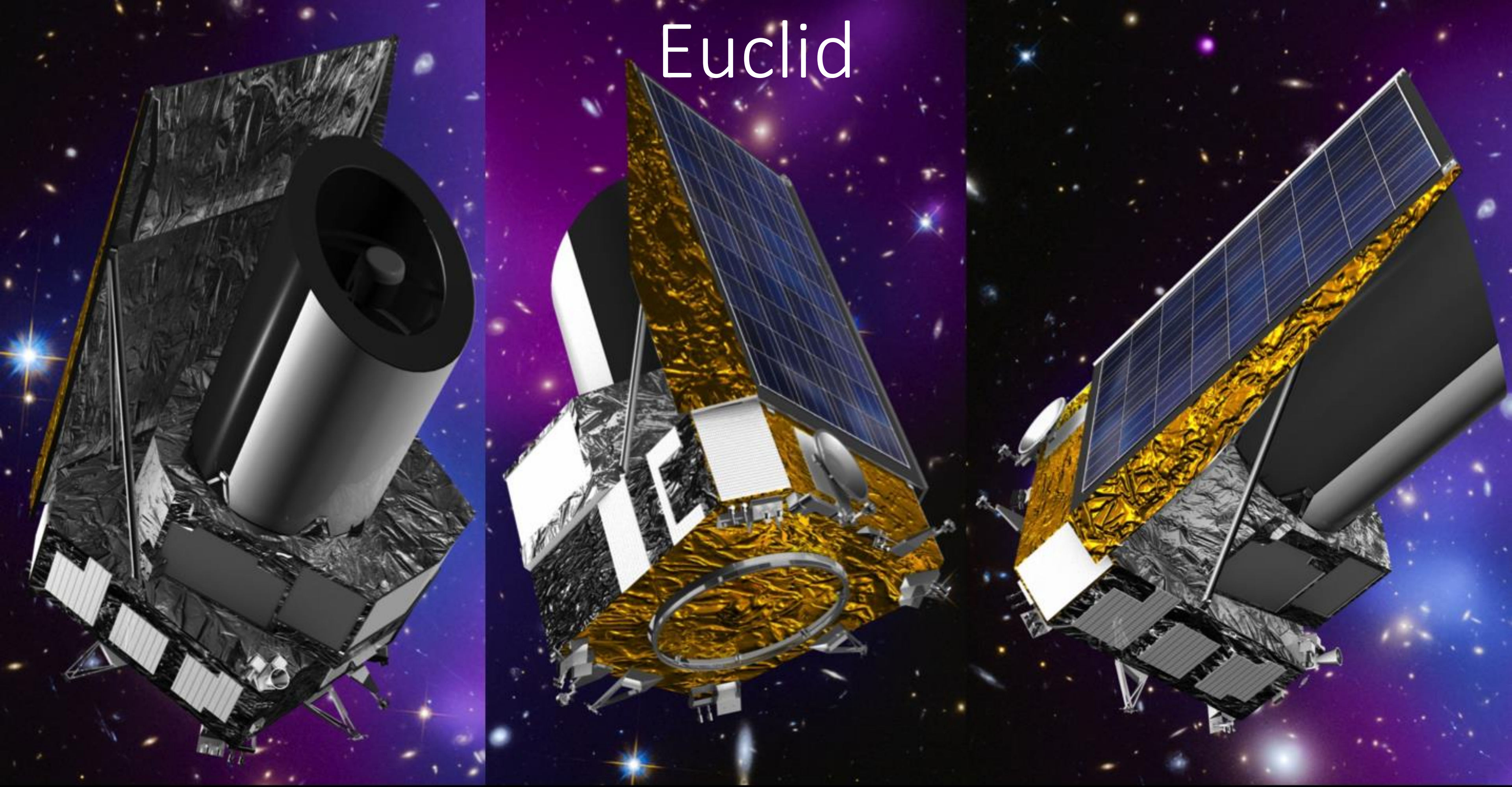
Riess et al. (2018)
H_0 [km s^{-1} Mpc^{-1}]
76
72
68
64
60
BAO+Pantheon+D/H BBN
BAO+Pantheon+D/H BBN+lensing
BAO+Pantheon+D/H BBN+θ_{MC}
Planck TT,TE,EE+lowE
0.24
0.28
0.32
0.36
0.40
Ω_m

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

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 …)

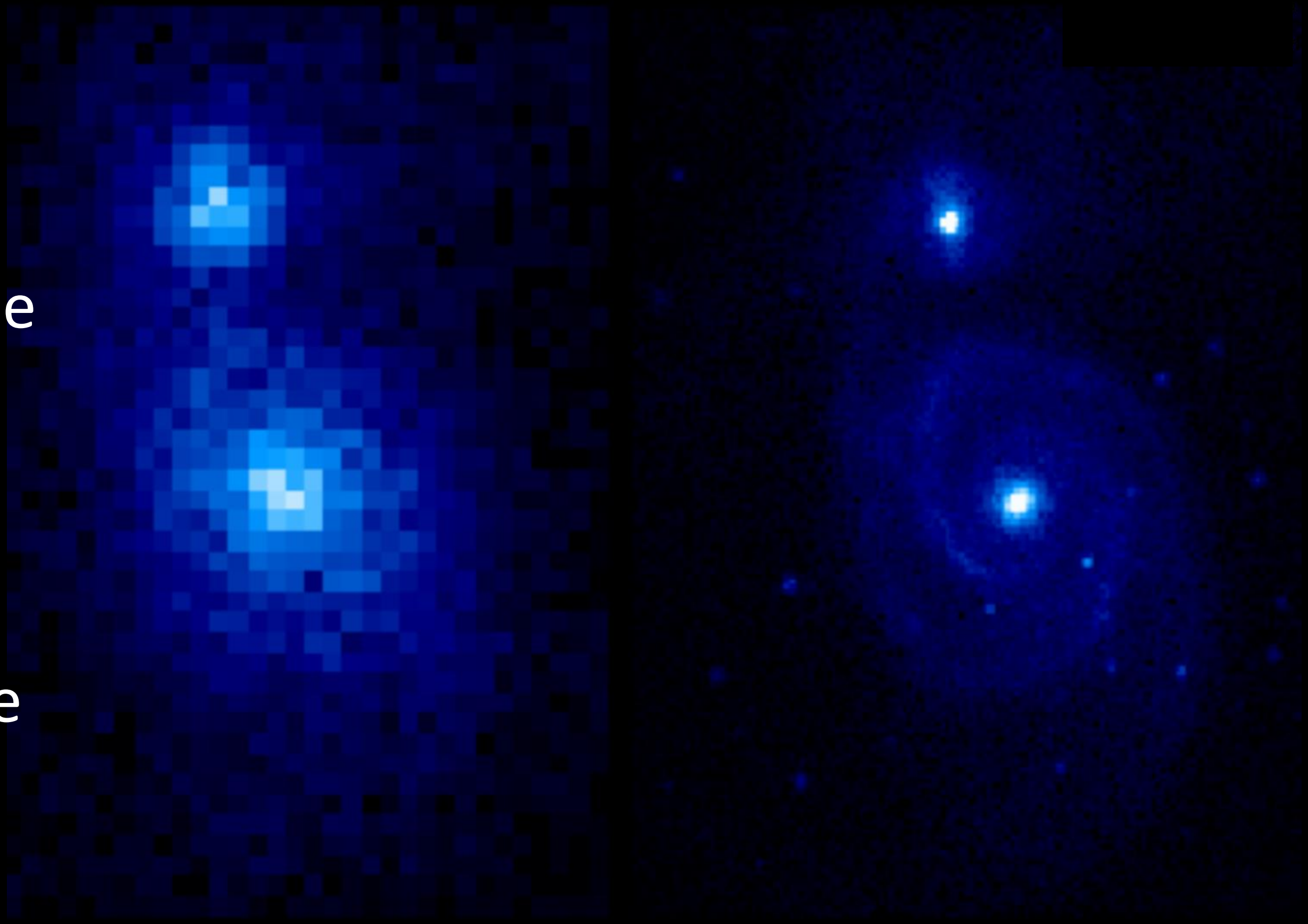
Euclid



- 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

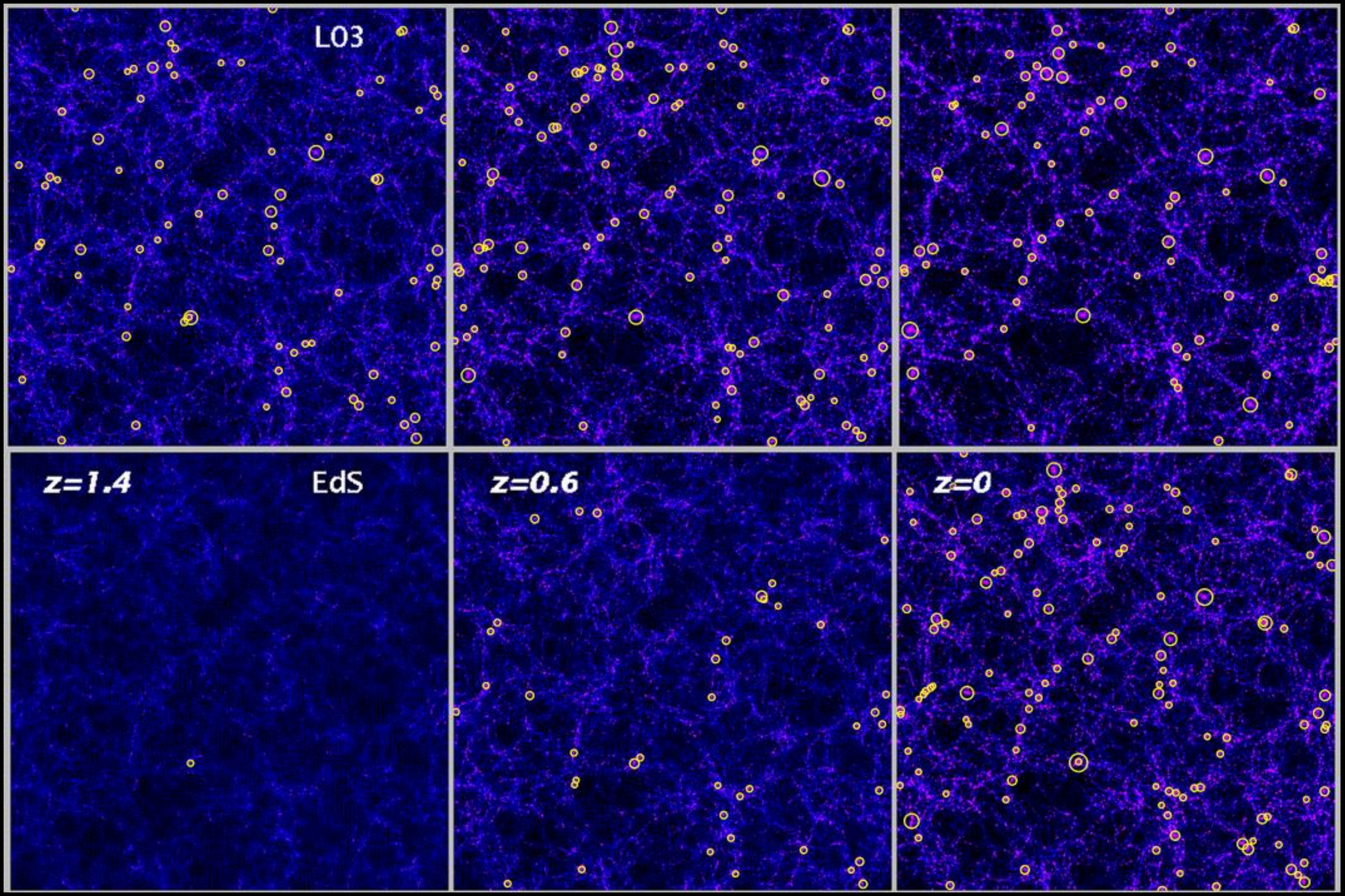
- For galaxies at z=1 EUCLID has the same resolution of the SDSS at z=0.05
- The EUCLID survey will be 3 magnitudes deeper than the SDSS



2.4m SDSS-like @ z=0.1   Euclid @ z=0.1

Borgani & Guzzo 2001
Andreon+ 2009

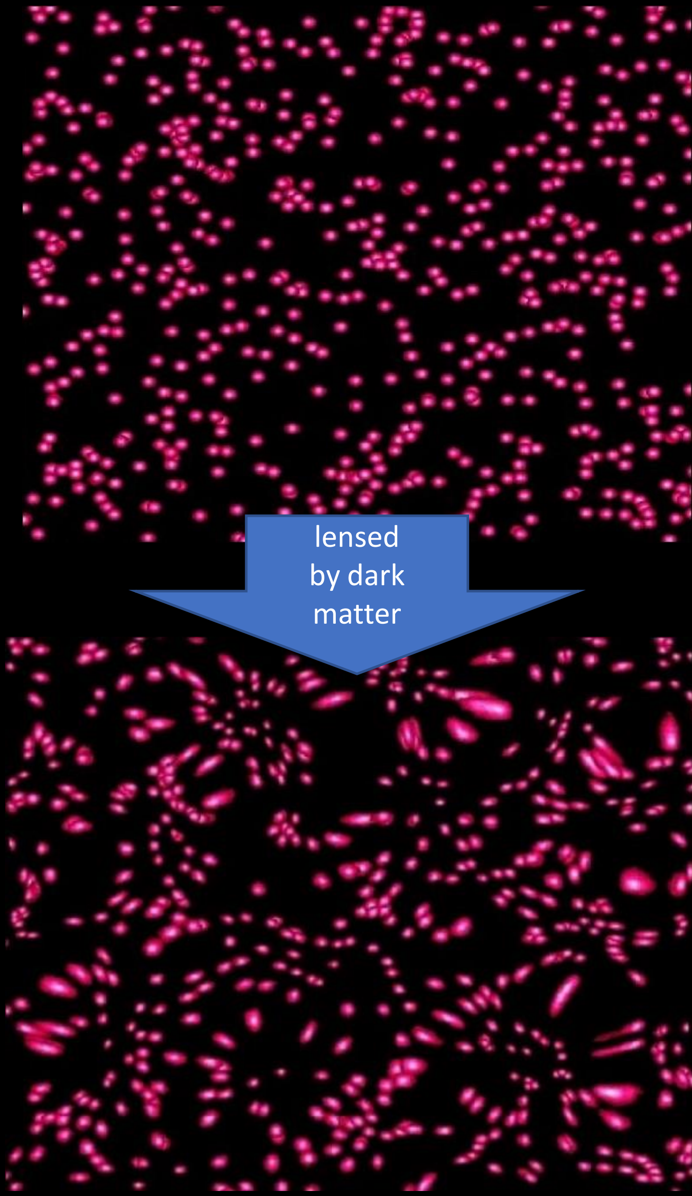
The evolution of cosmic structures depends dramatically on the presence of Dark Energy and on its nature.

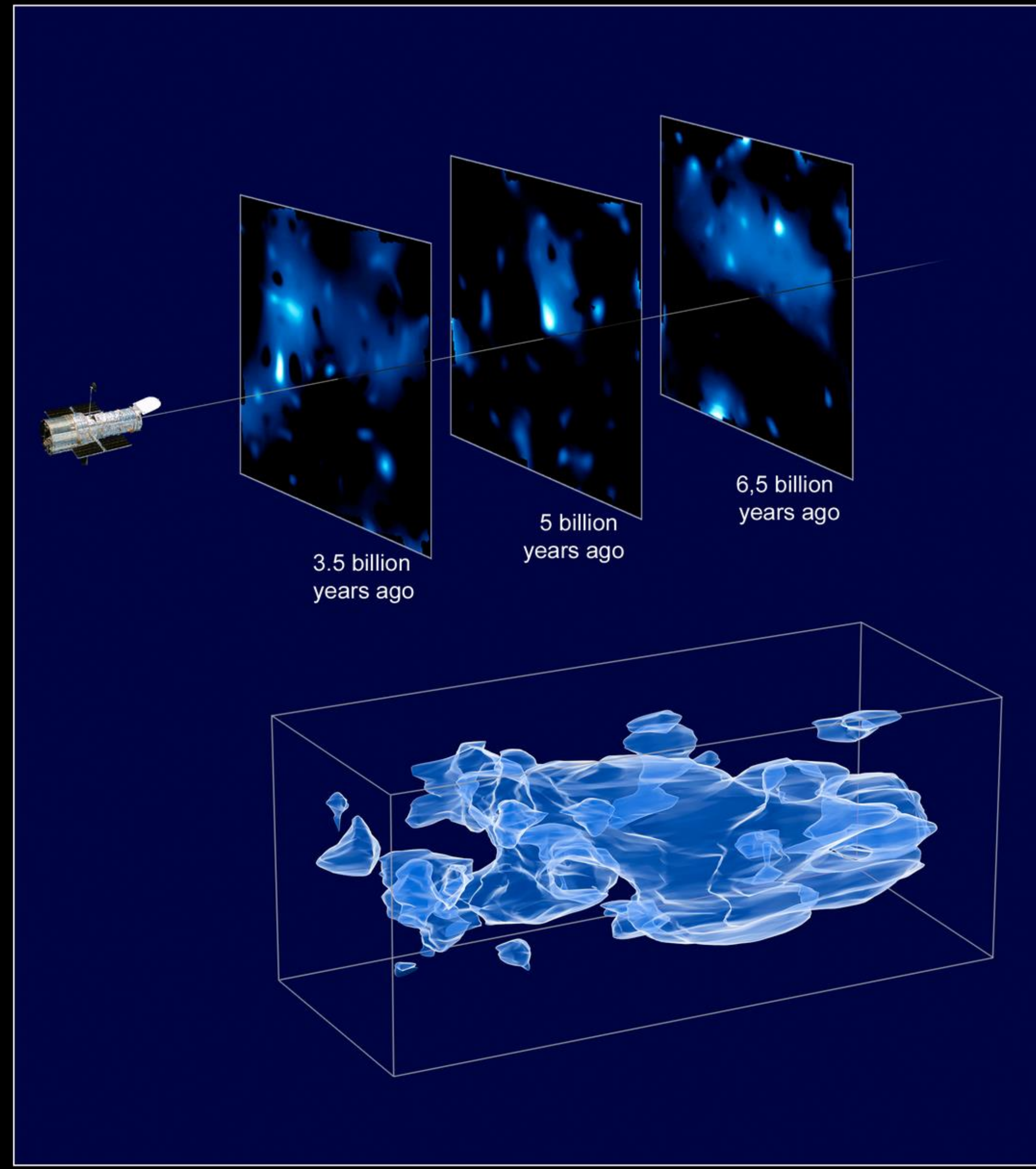


with DE

without DE

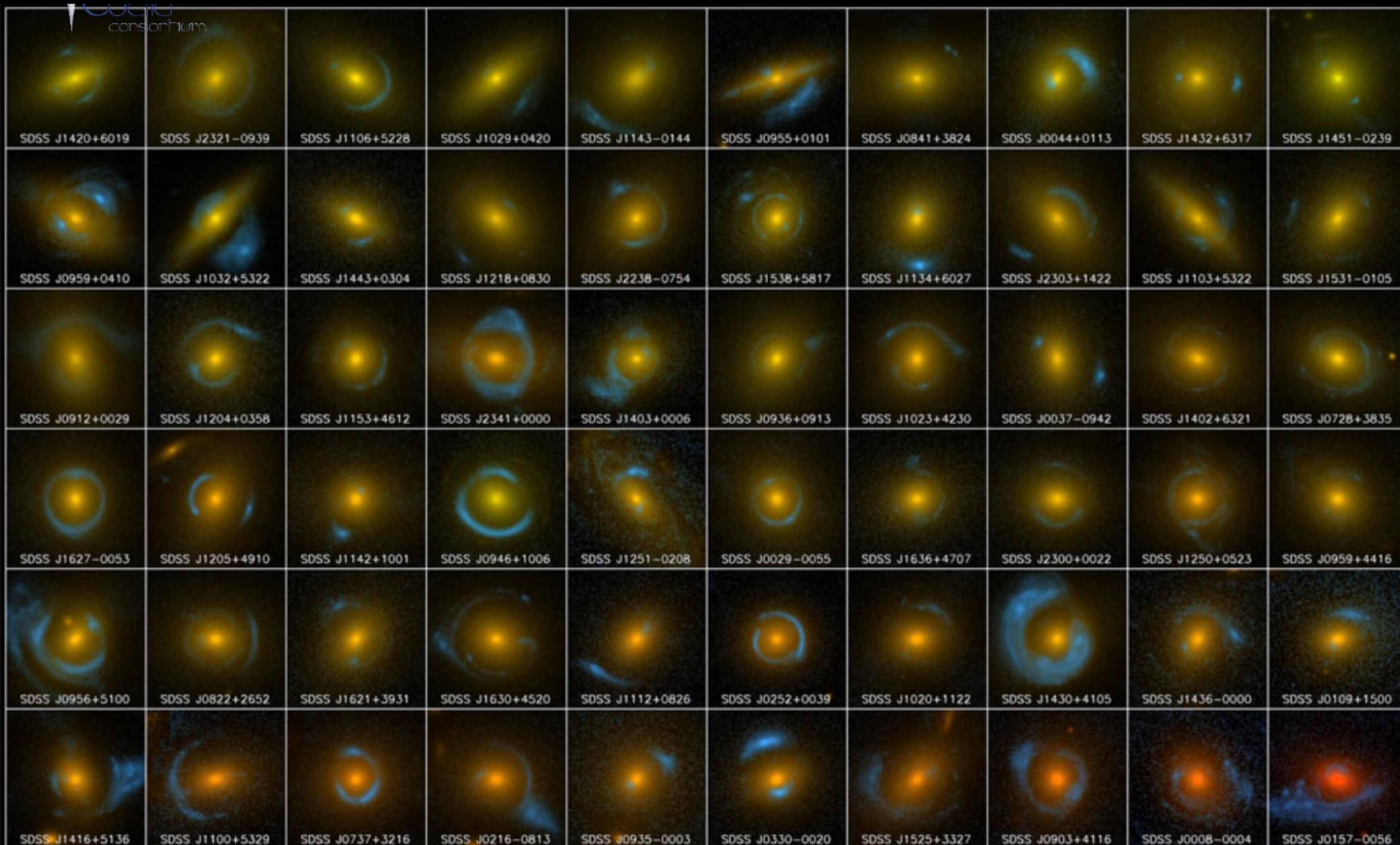
Euclid will study Galaxy Clustering (Baryonic Acoustic Oscillations and Redshift Space Distortion) with unprecedented accuracy, to measure the equation of state of DE





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

SLACS HST



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

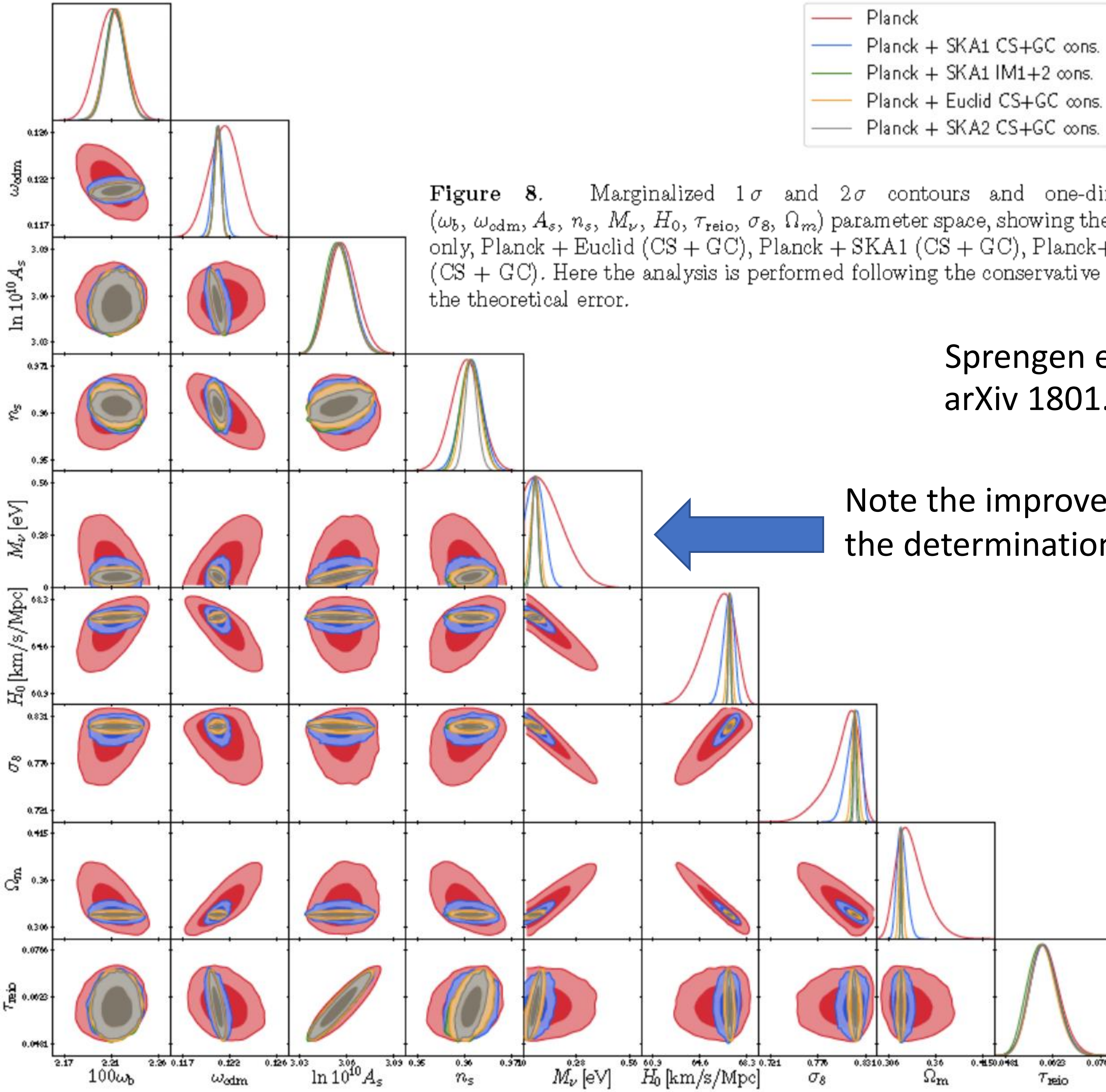


Figure 8. Marginalized 1σ and 2σ contours and one-dimensional posteriors in the (ω_b, ω_{cdm}, A_s, n_s, M_ν, H_0, τ_{reio}, σ_8, Ω_m) parameter space, showing the expected sensitivity of Planck-only, Planck + Euclid (CS + GC), Planck + SKA1 (CS + GC), Planck+SKA1-IM and Planck + SKA2 (CS + GC). Here the analysis is performed following the conservative approach for the description of the theoretical error.

Sprengen et al. JCAP 2019
arXiv 1801.08331

Note the improvement on the determination of m_ν

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 (τ) 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 f 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 definine the main axis of the polarimeter with high precision (<<0.1°) promises to improve the absolute reconstruction of the polarization directions.

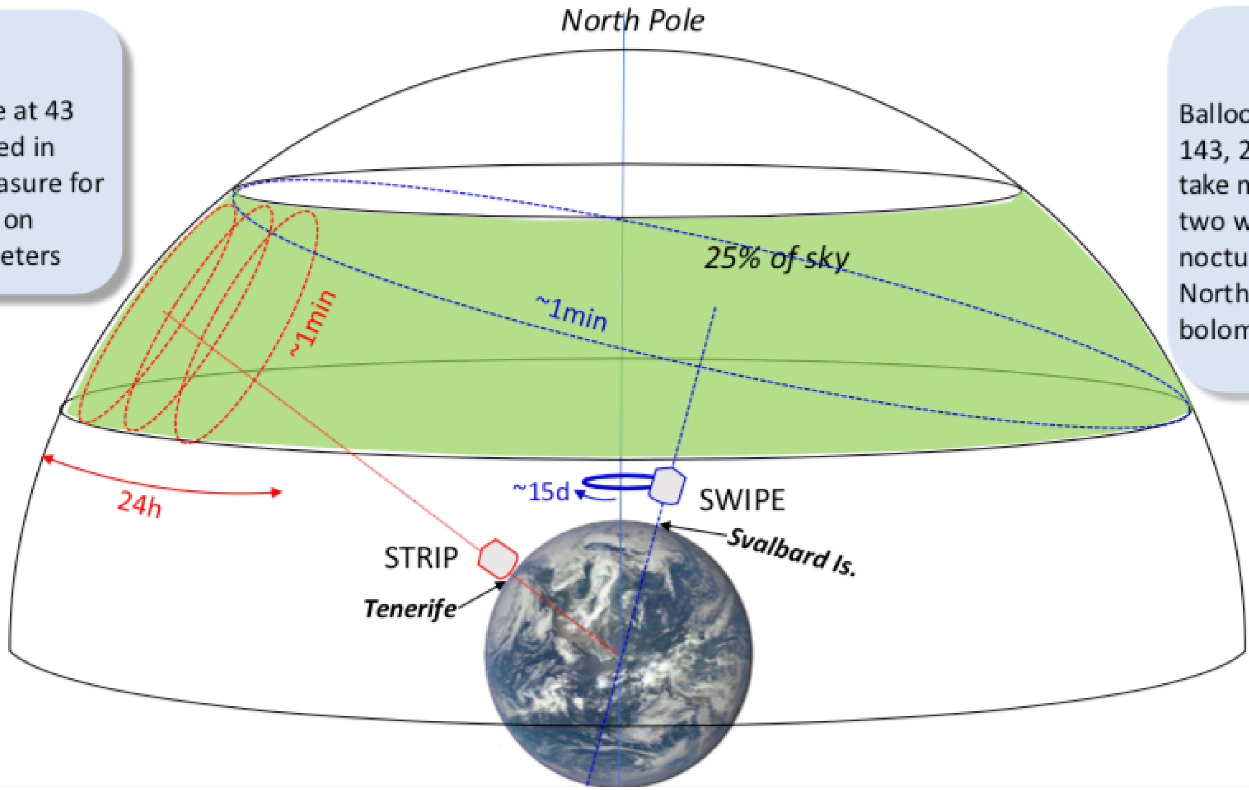
LSPE in a nutshell

- 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

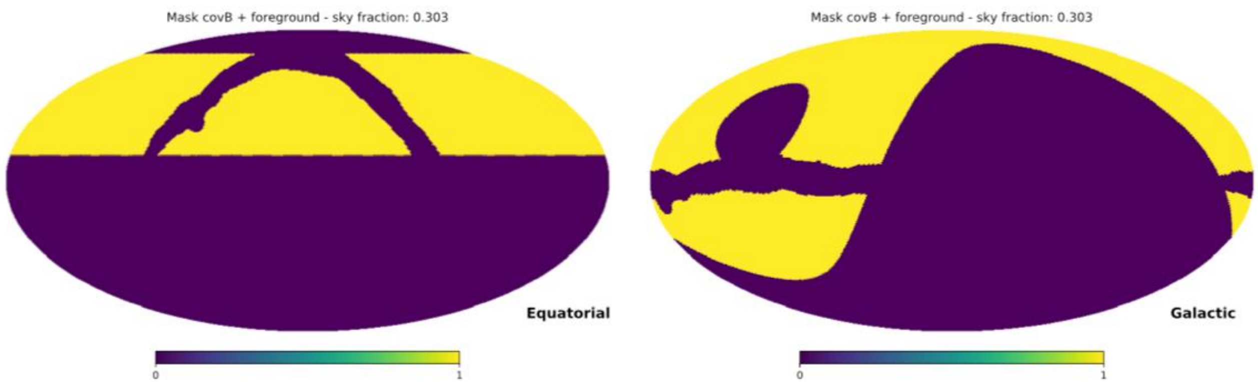
Ground telescope at 43 and 95 GHz located in Tenerife. Will measure for two years. Based on coherent polarimeters



SWIPE

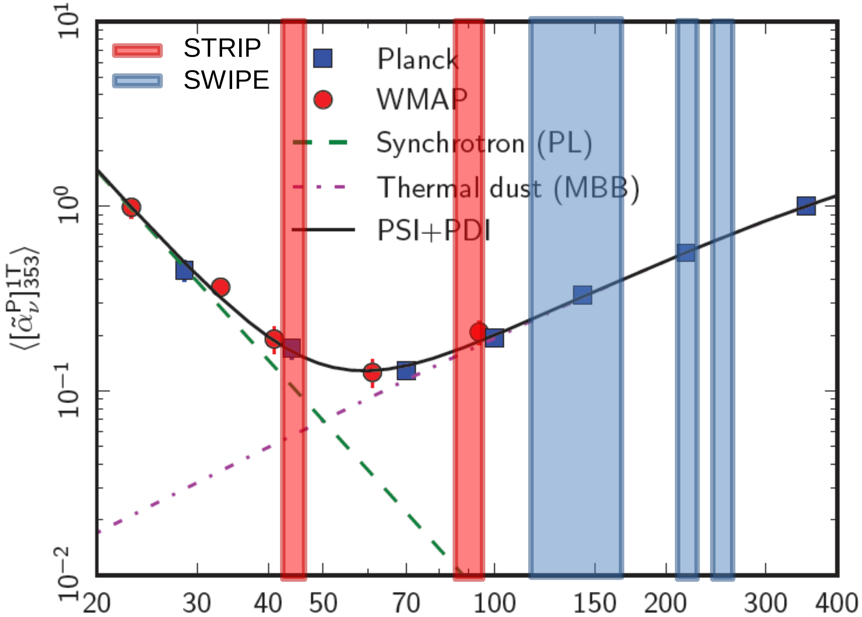
Balloon borne telescope at 143, 220 and 240 GHz. Will take measurements for two weeks during a LDB nocturnal flight around the North Pole. Based on TES bolometers

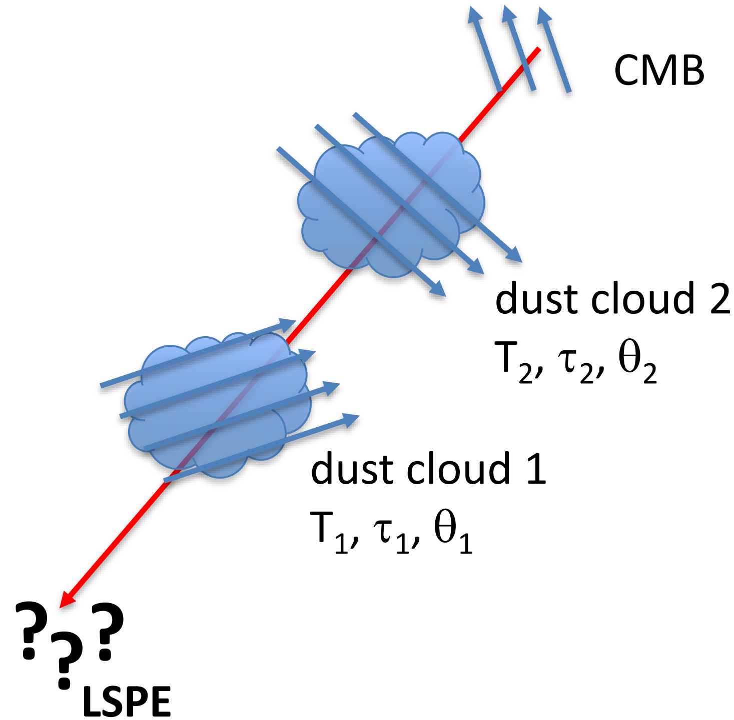
Credit A. Mennella



Credit L. Pagano, F. Piacentini

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

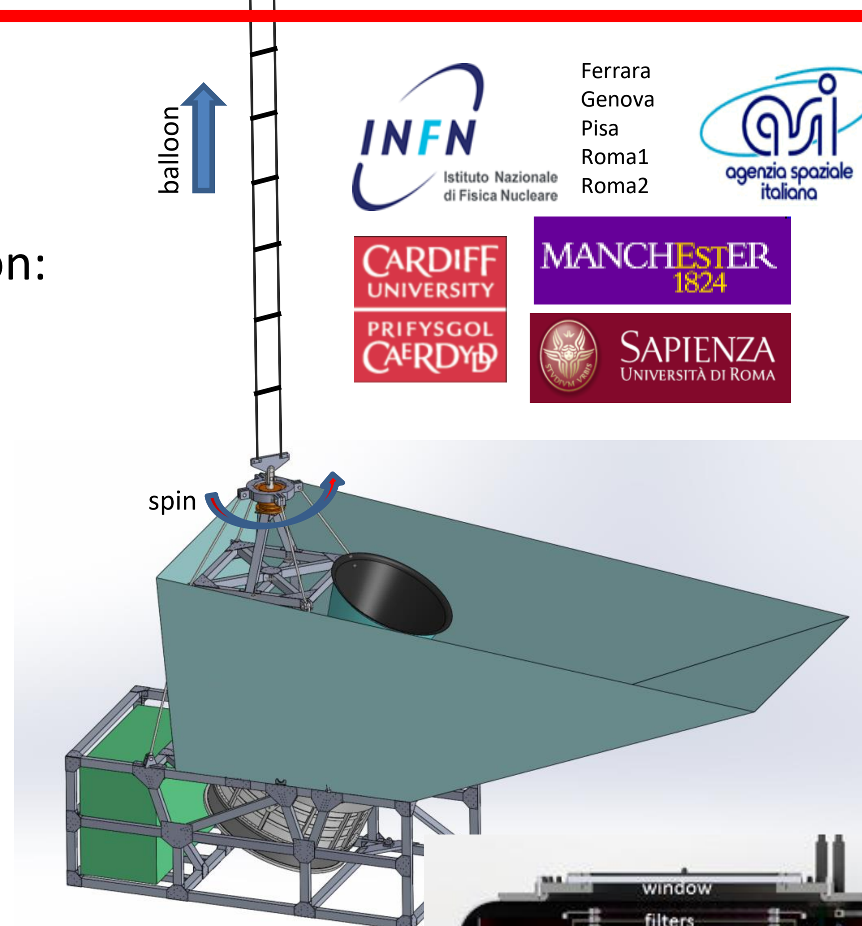
LSPE Large Scale Polarization Explorer

INFN Istituto Nazionale di Fisica Nucleare — Ferrara, Genova, Pisa, Roma1, Roma2

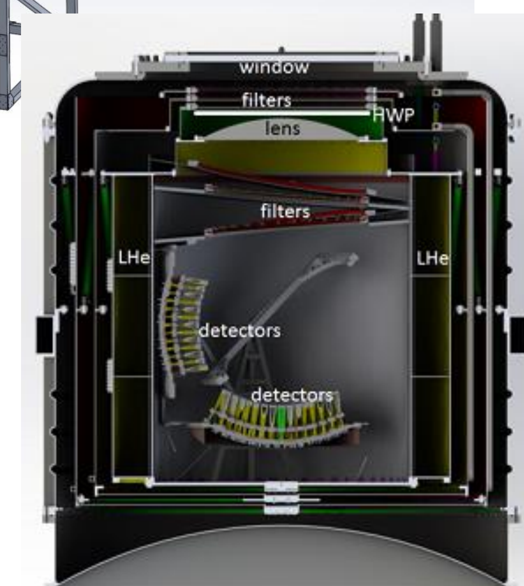
asi agenzia spaziale italiana

Cardiff University / Prifysgol Caerdydd — Manchester 1824 — Sapienza Università di Roma

- 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 L^4He 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.

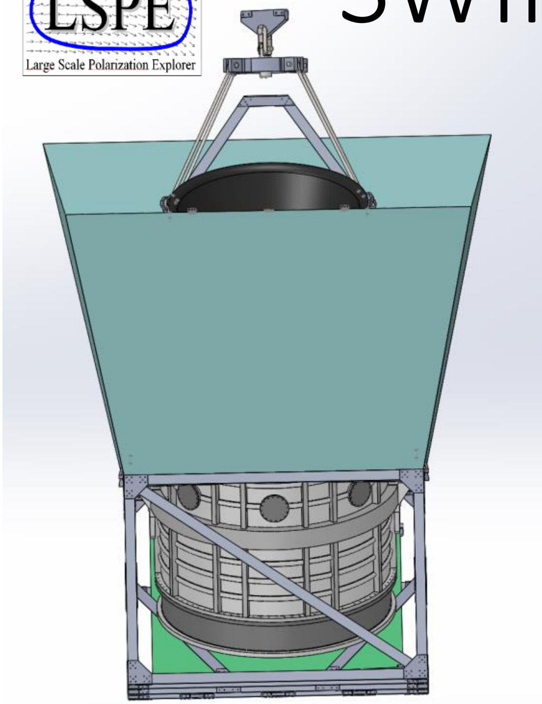


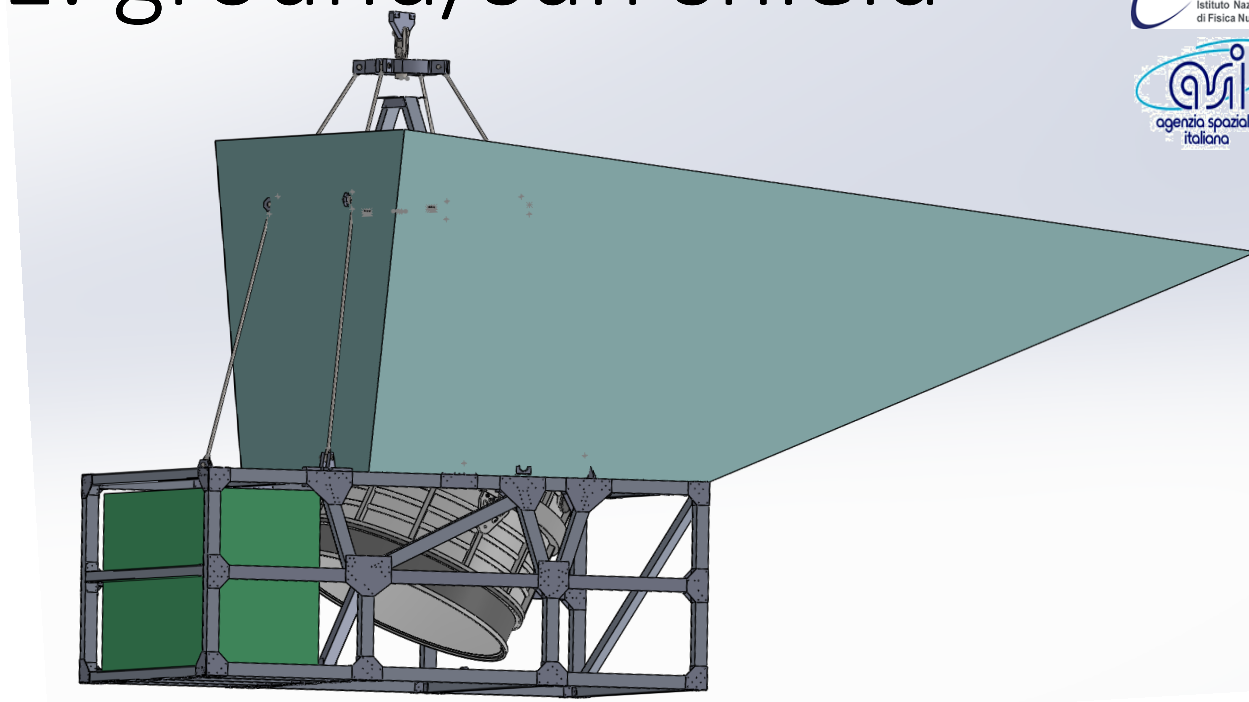
SWIPE gondola



SWIPE receiver

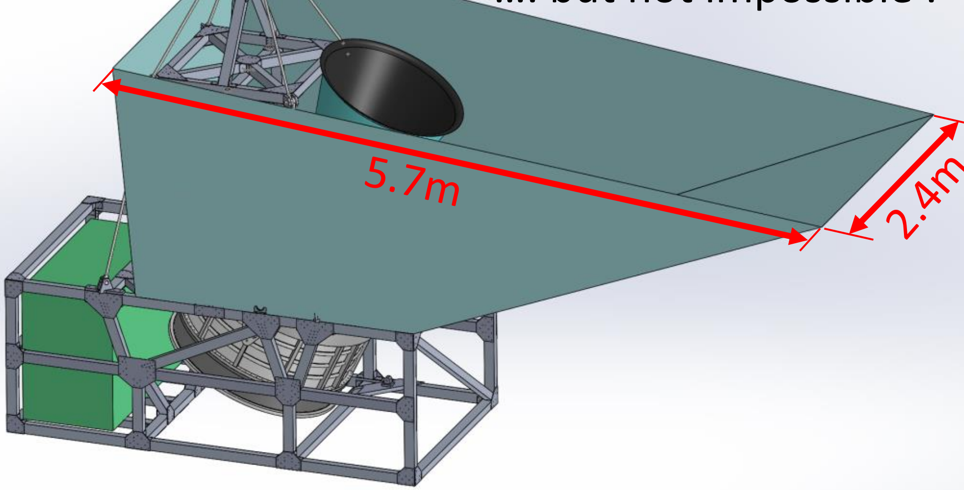
SWIPE: ground/sun shield

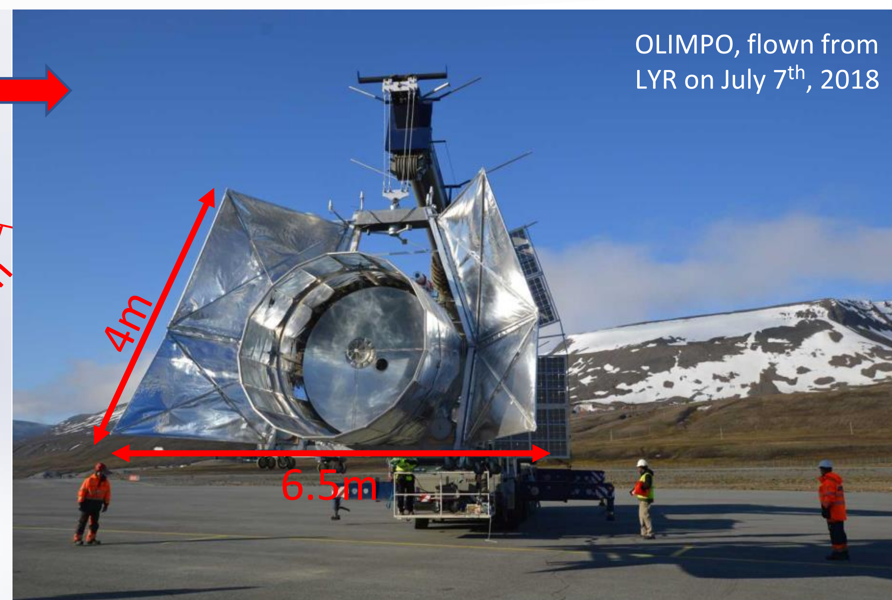




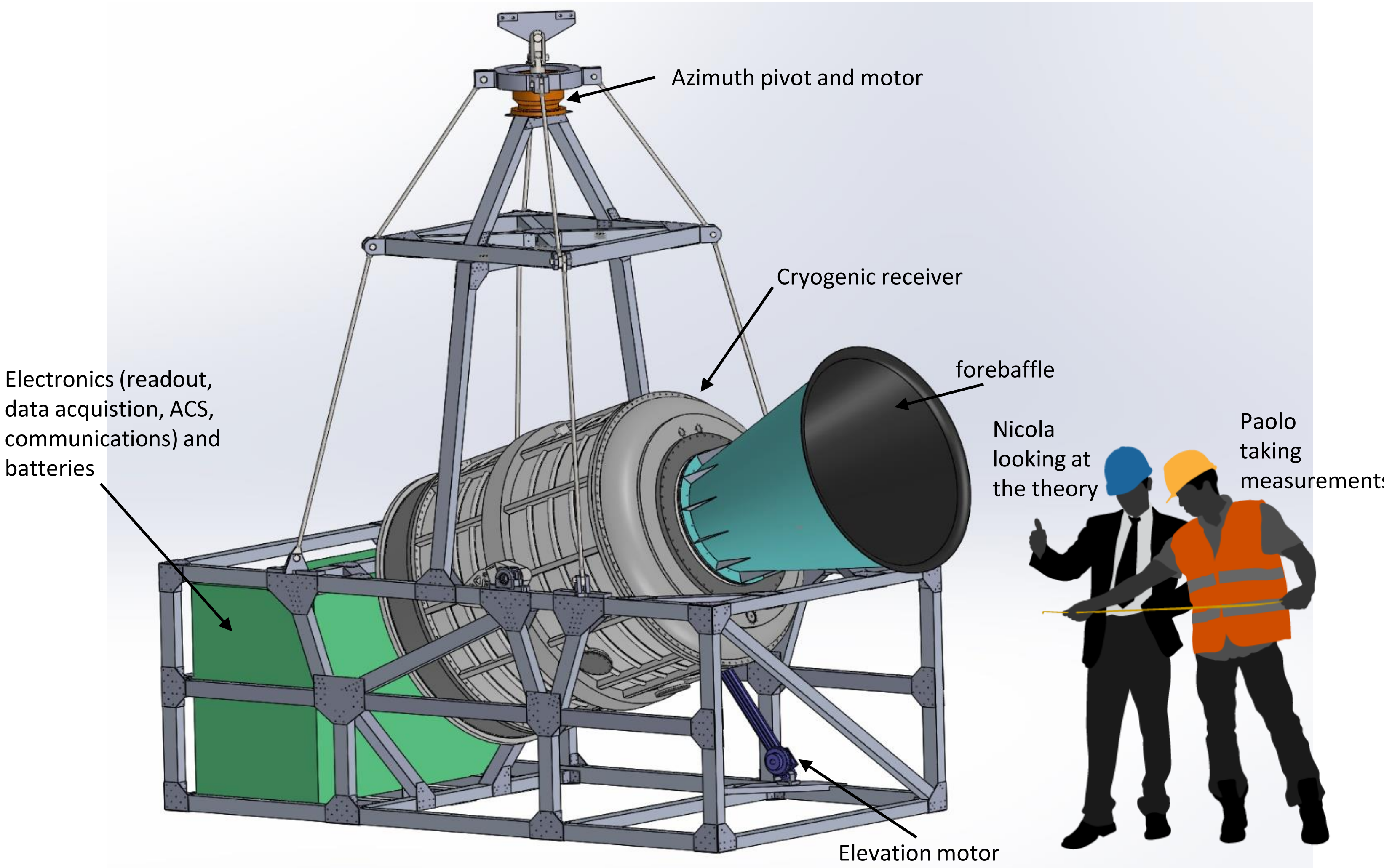
The ground shield is very large ..

.... but not impossible :





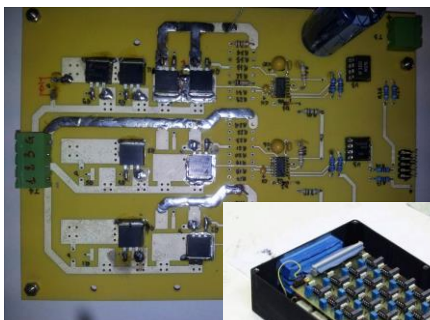
LSPE/SWIPE

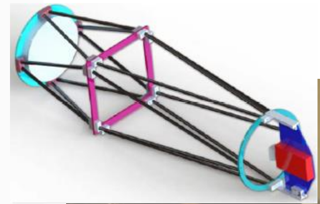


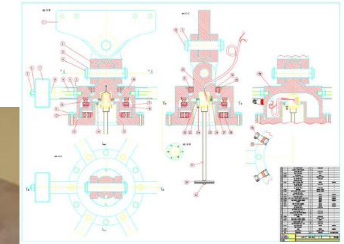
Rendering without ground/sun shields – a 1.6 tons payload

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))

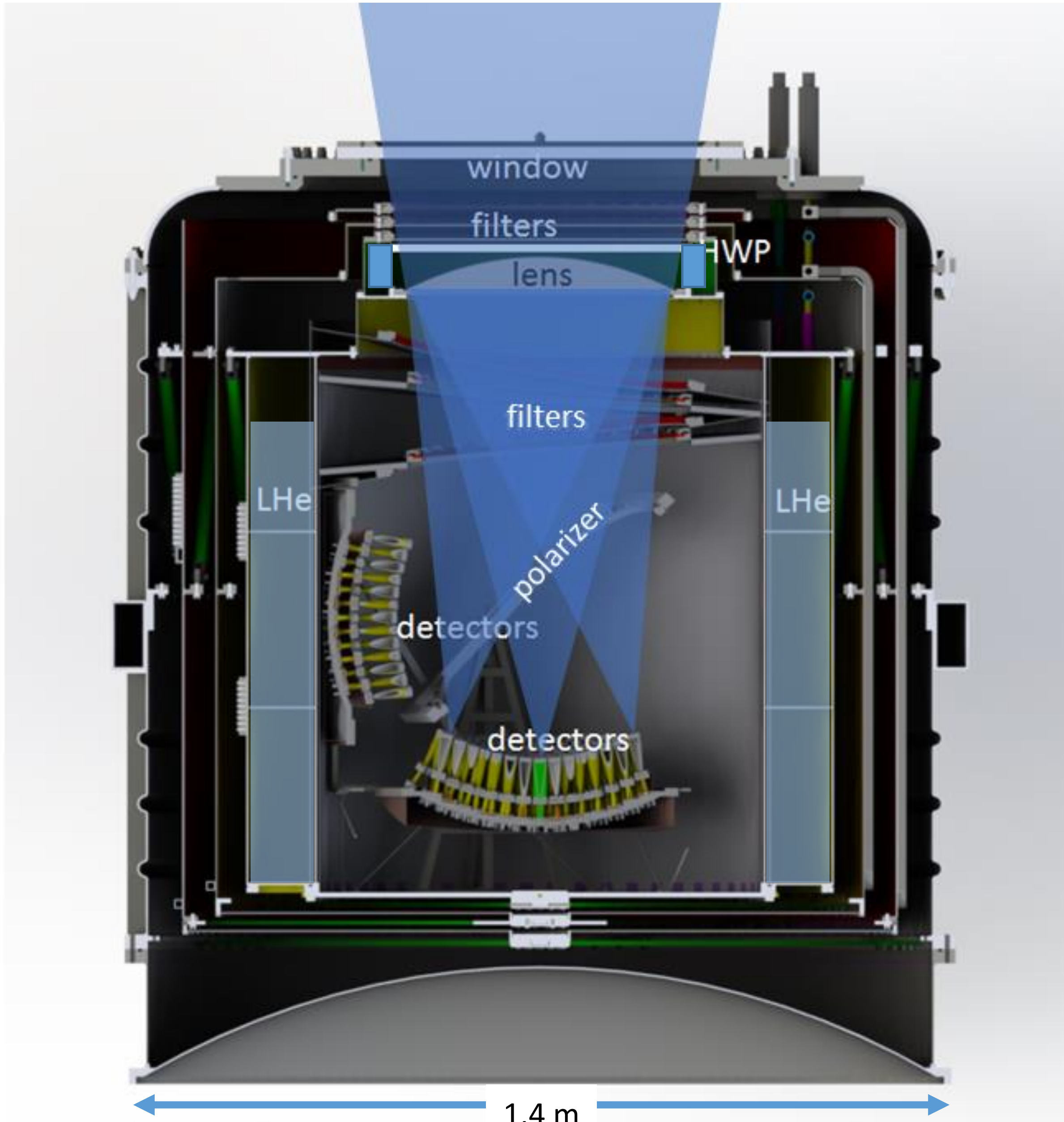






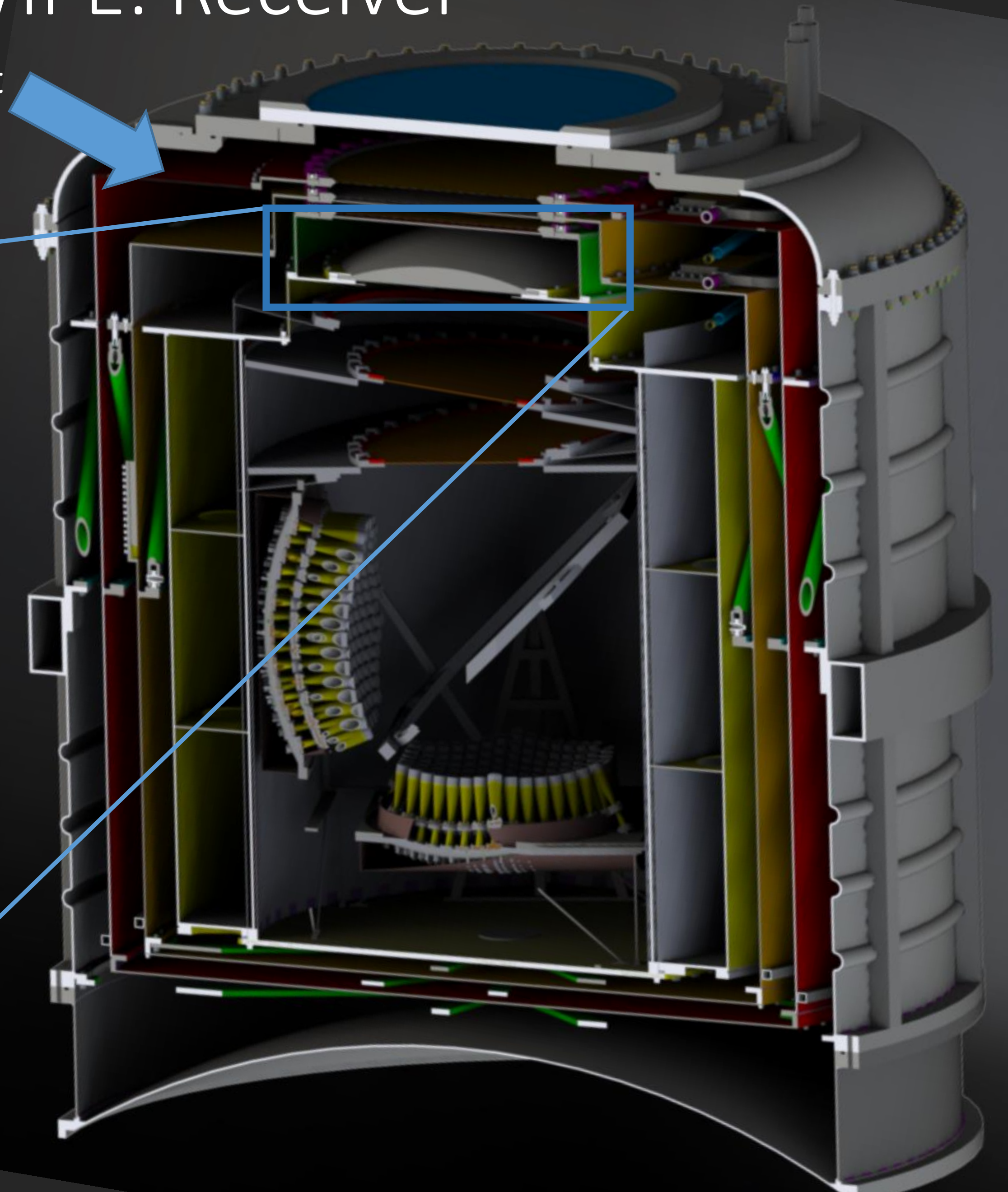
SWIPE - receiver

- 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**

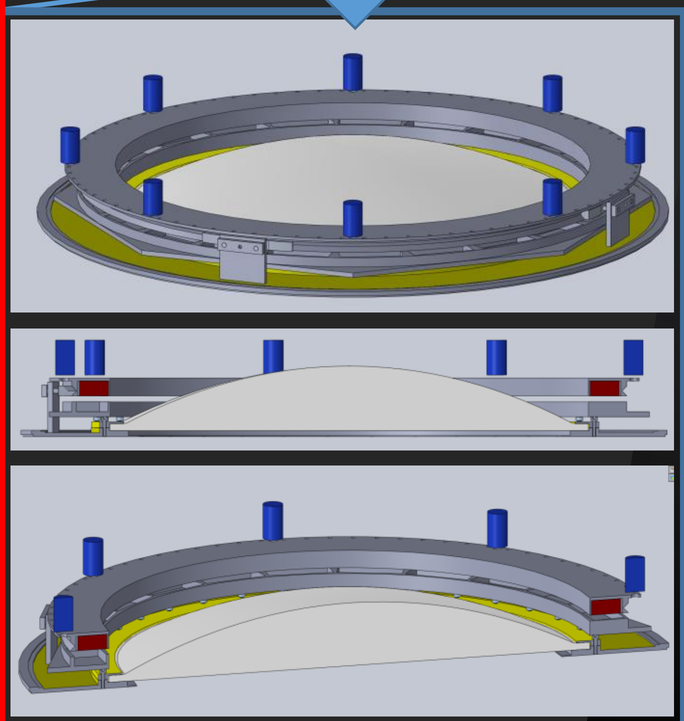


LSPE/SWIPE: Receiver

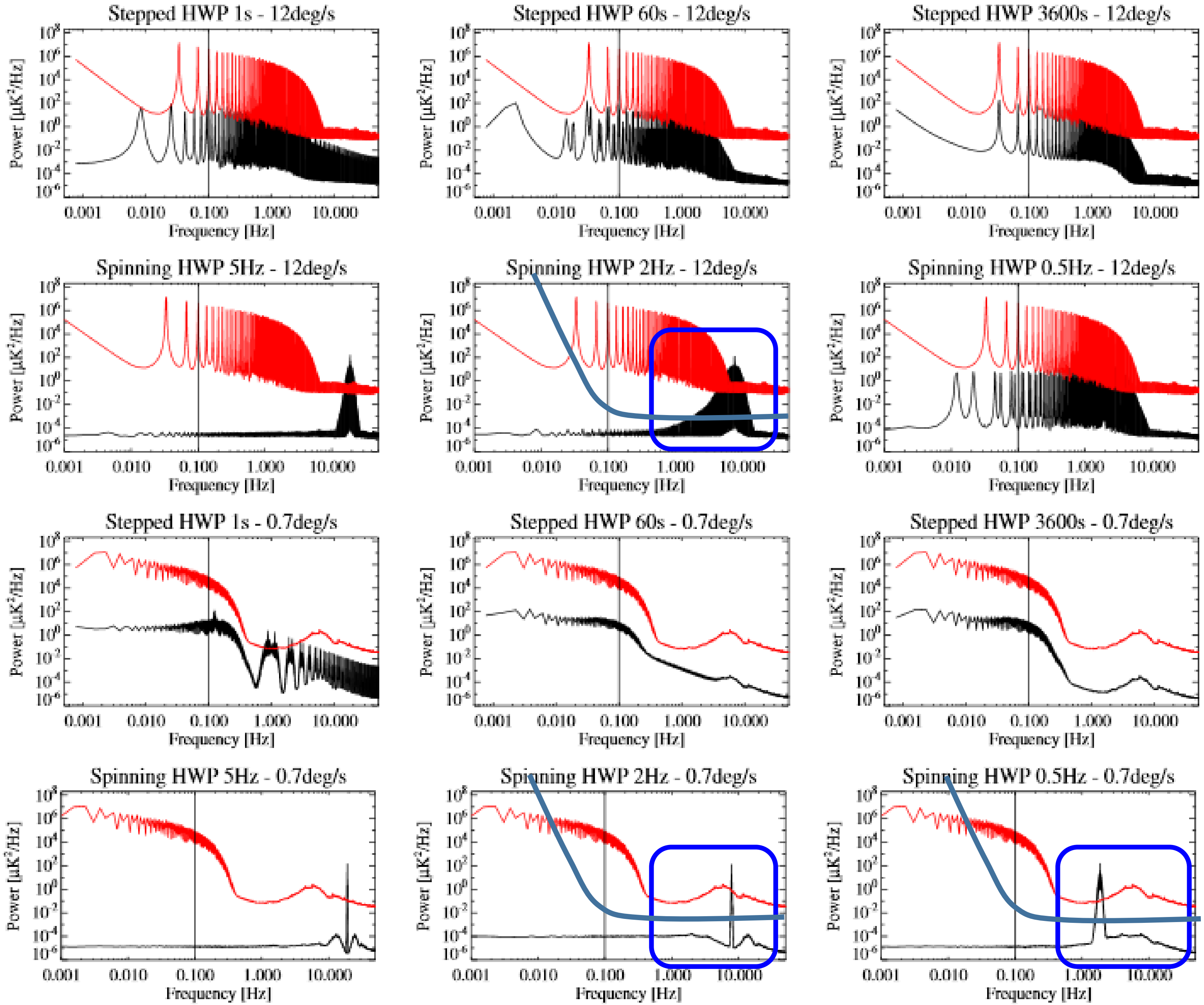
LSPE-SWIPE polarimeter and cryostat



LSPE-SWIPE polarization modulator



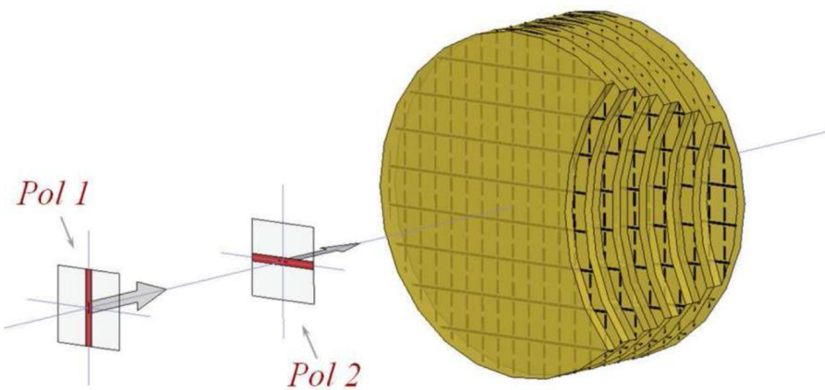
Fast (1-2 rps) levitating HWP rotator and HDPE lens



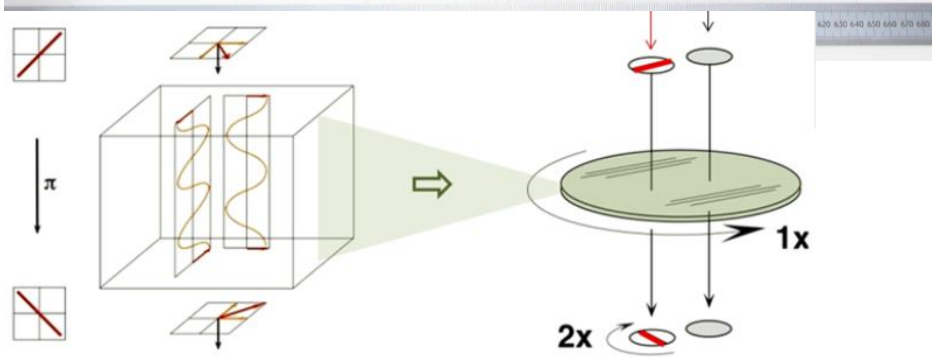
Buzzelli et al., A&A 609, A52 (2018)

SWIPE – HWP

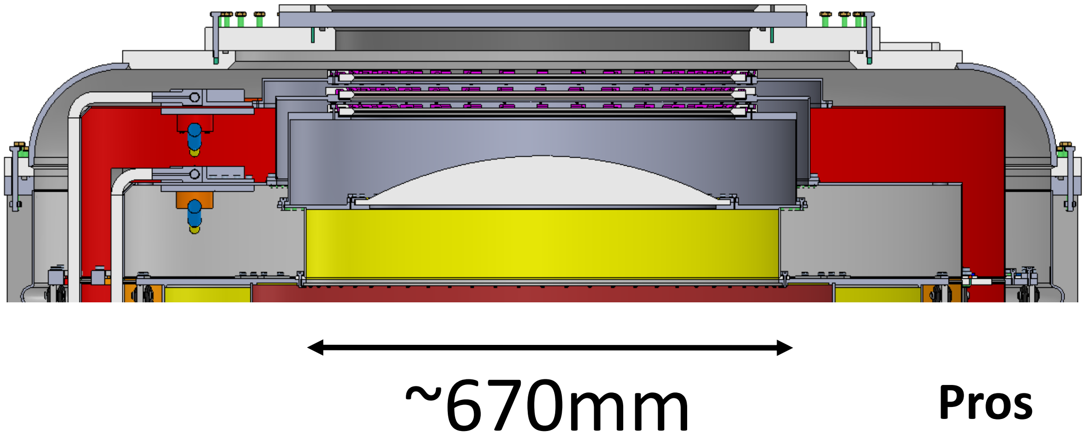
- Is a cold (2K), large (50 cm useful dia.), wide-band meta-materials HWP, placed immediately behind the window and thermal filters stack.
- HWP characteristics for the ordinary and extraordinary rays are well matched: $(T_o-T_e)/T_o < 0.001$, $X_{pol}<0.01$, over the 100-300 GHz band.
- Simulations show that continuous rotation has advantages in terms of 1/f noise mitigation and angles coverage.
- A custom superconductive rotator has been developed.



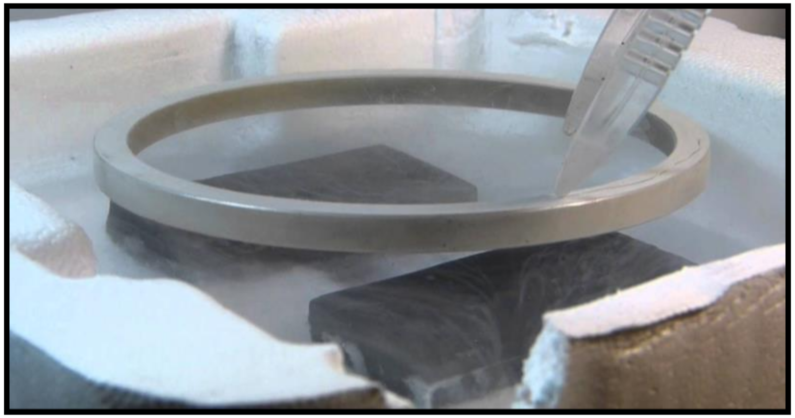
Pisano et al., Proc. SPIE, Vol. 9153, id. 915317 (2014)



SWIPE – HWP rotator



Permanent magnet ring



High Temperature Superconductors

Pros

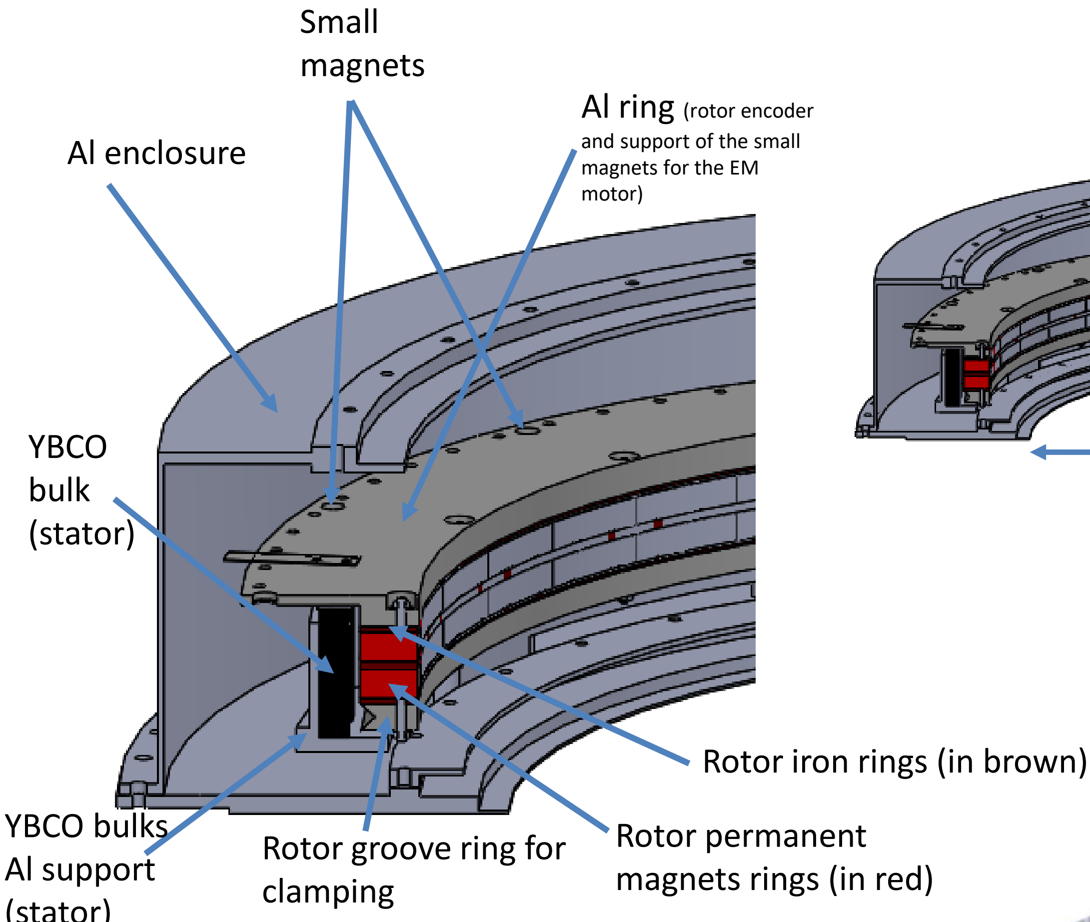
- NO stick-slip friction
- NO extra-effort to cool HTSs
- Passive stable levitation
- Low Coefficient of friction
- Continuous rotation (0-10Hz)

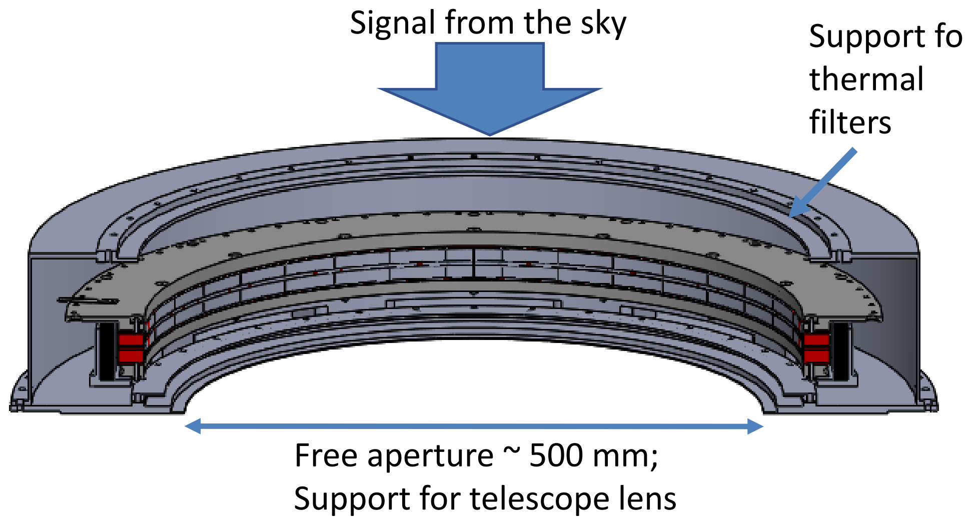
Cons

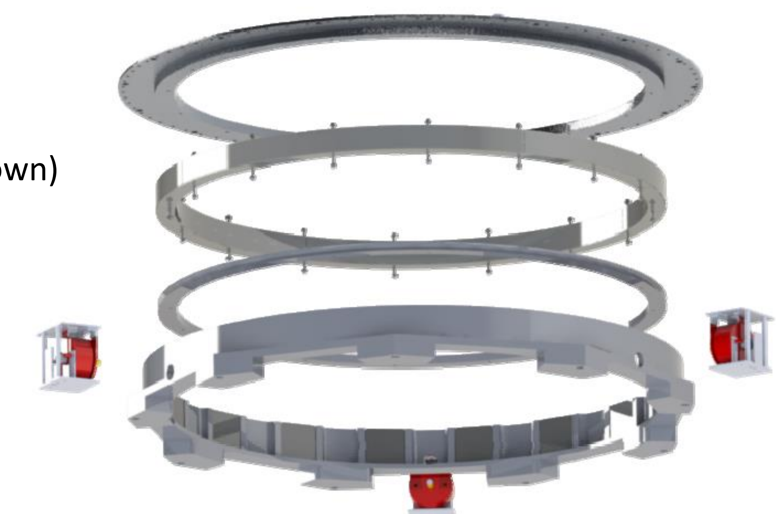
- Variable magnetic field
- Clamp mechanism at 4K

S. Hanany et al., IEEE Trans.Appl.Supercond. 13 (2003) 2128-2133
T. Matsumura et al., IEEE Trans.Appl.Supercond. 26 (2016)

SWIPE – HWP rotator - General layout





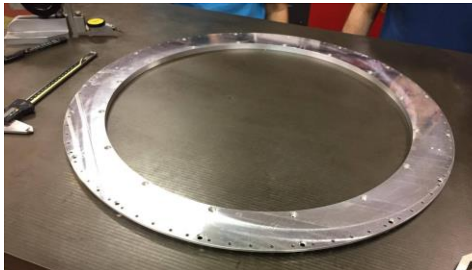


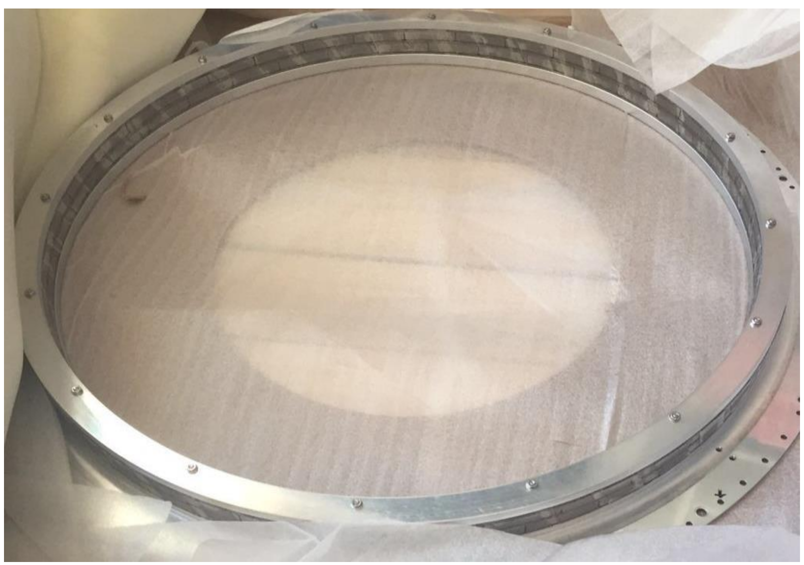
1T field strength in the gap. Total mass 9 kg.

SWIPE – HWP rotator – parts procured

Stator with YBCO bulks

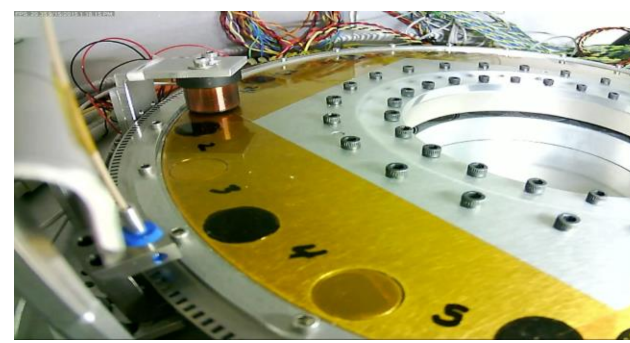
Groove ring for C/R





Rotor with permanent magnets

smaller diameter Prototype arXiv:1706.05963v3



Large Scale Polarization Explorer

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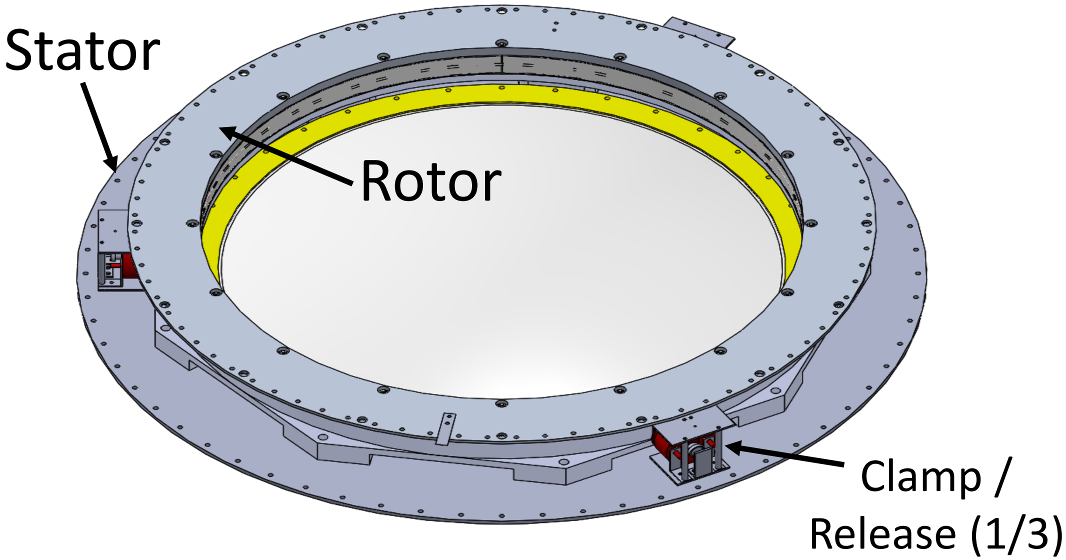
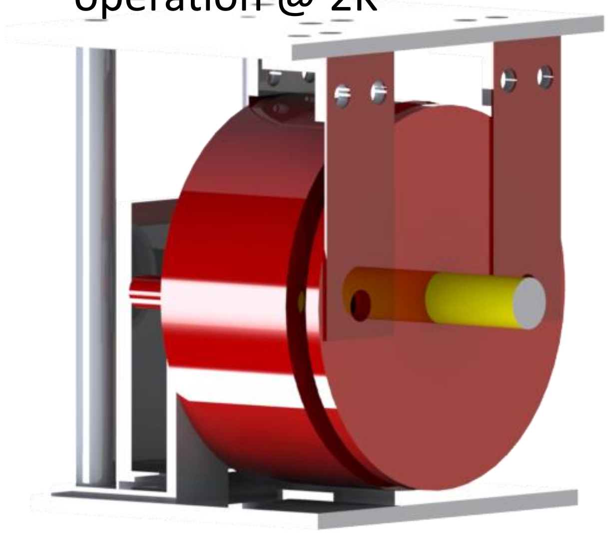
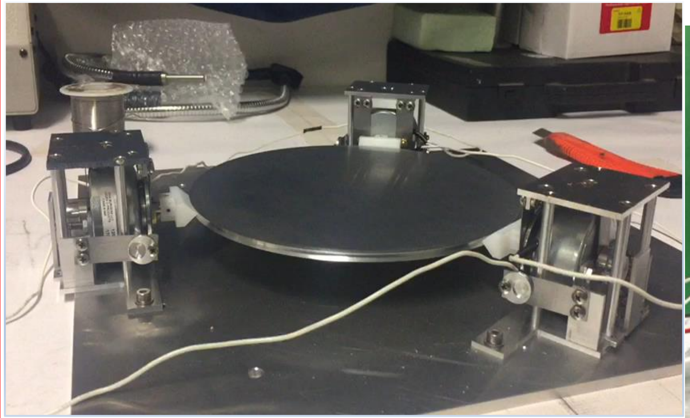
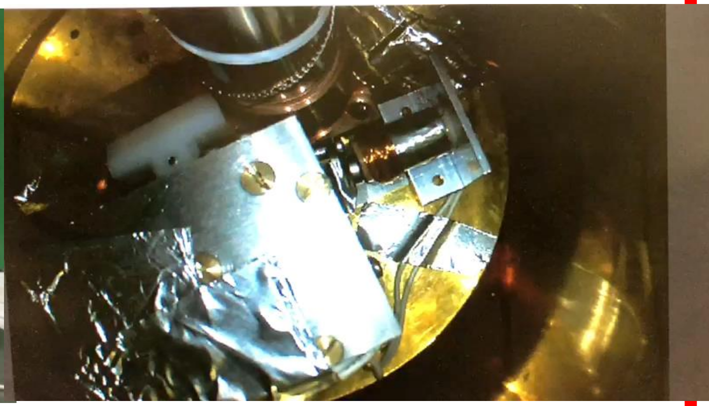
SWIPE – HWP rotator – clamp/release



Frictionless actuator for operation @ 2K







Fabio Columbro, Paolo de Bernardis, and Silvia Masi
A clamp and release system for superconducting magnetic bearings
Review of Scientific Instruments 89, 125004 (2018)

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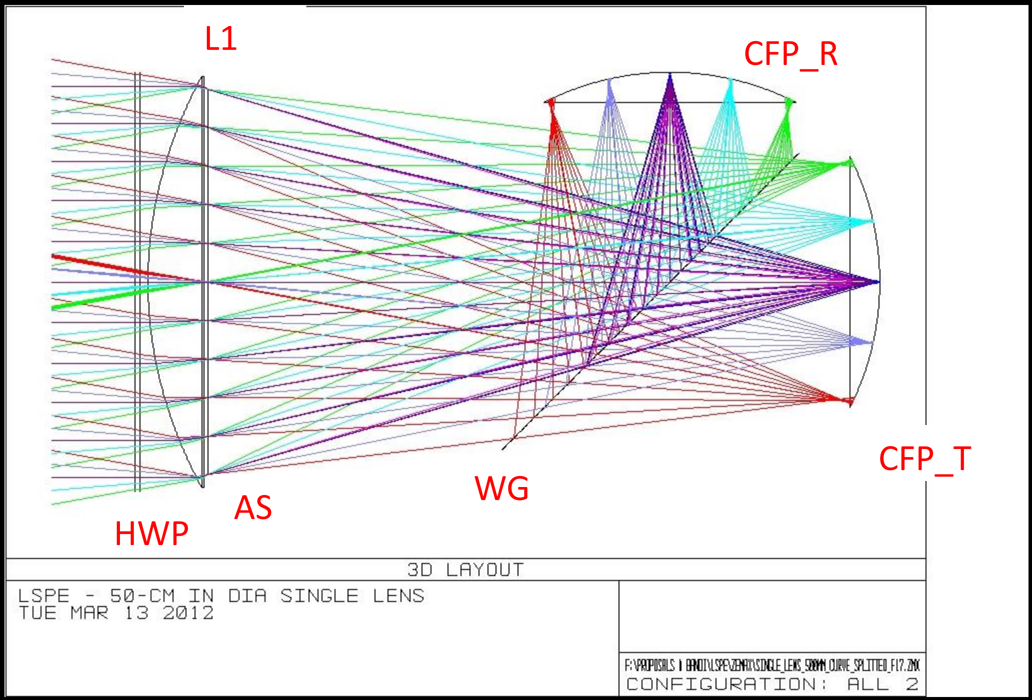
SWIPE: Cryogenic Testbed

Based on a pulse-tube cooler

A. Rocchi

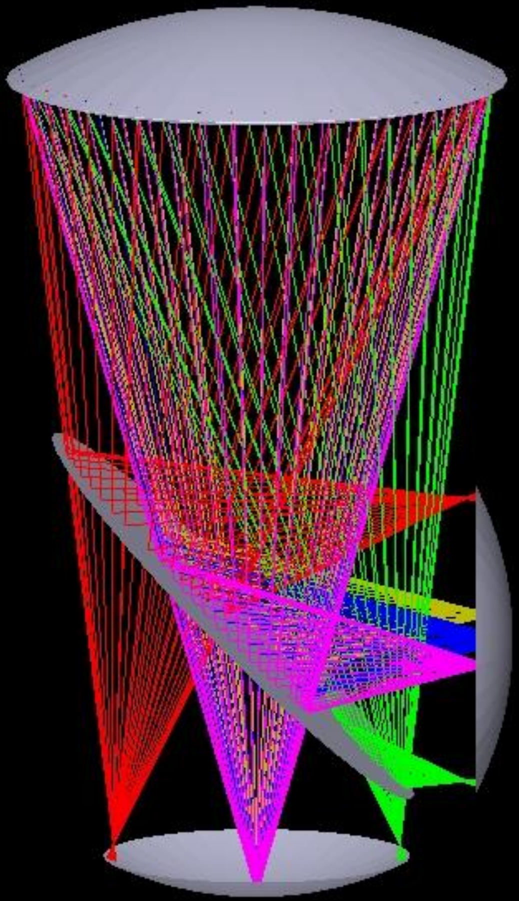
Single lens 490mm in dia: plano-convex lens curved focal plane



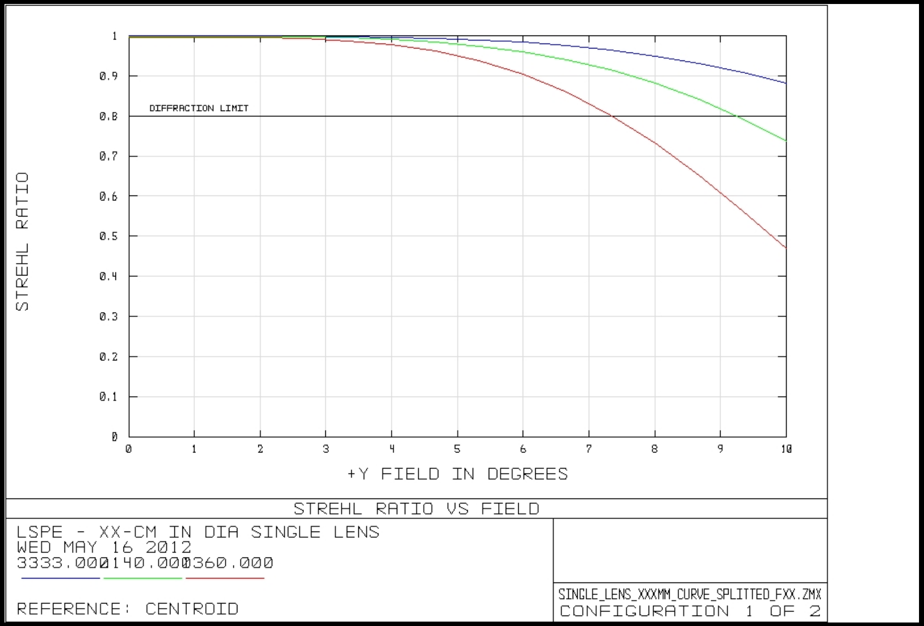
Dimensions:
HDPE Lens (L1) diameter = 480 mm
Aperture Stop (AS) = 440 mm
Entrance Pupil = 450 mm
FOV = 20 deg
f/1.88
Curved Focal plane (CFP_T o CFP_R) diameter = 300 mm
Lens thickness = 65 mm
HDPE lens with AR by porous PTFE

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

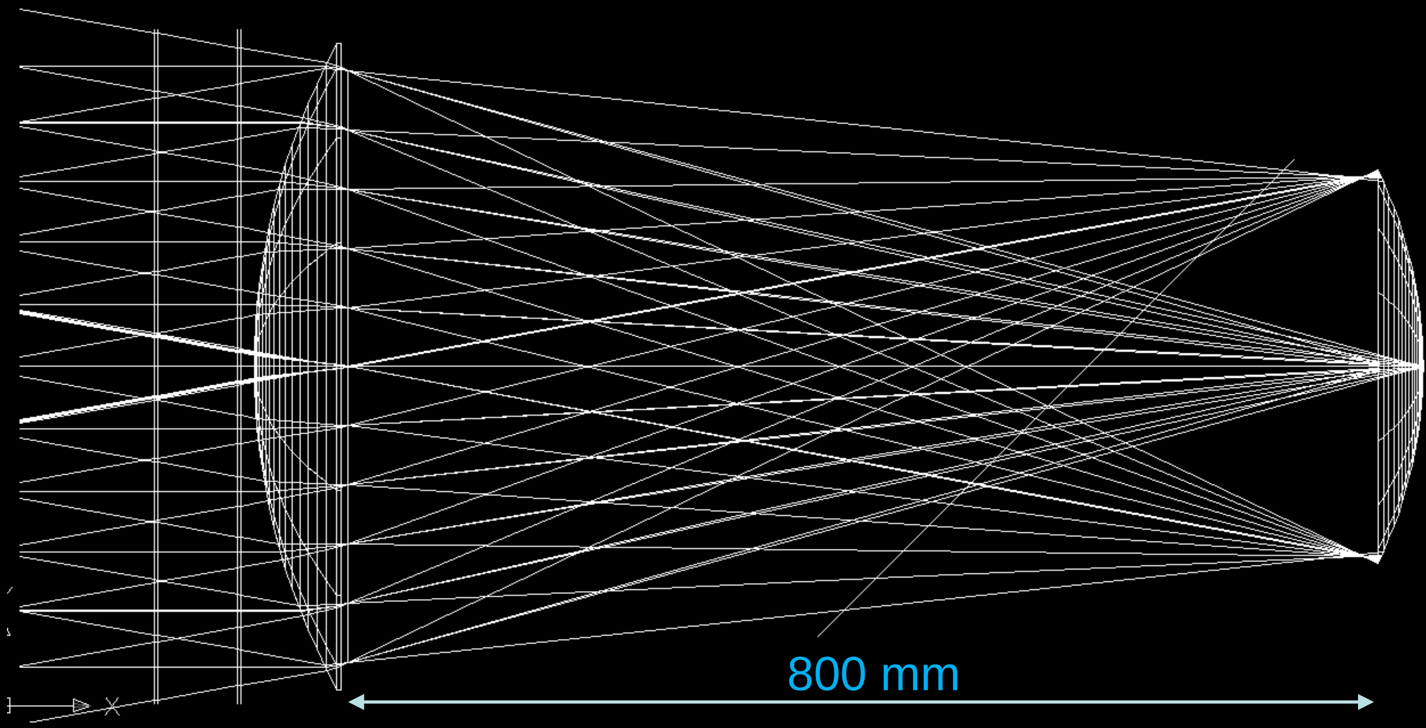
Single lens 490mm in dia: plano-convex lens curved focal plane

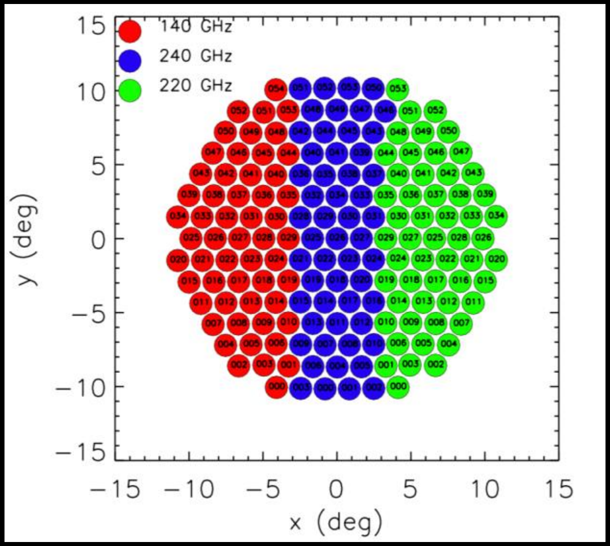


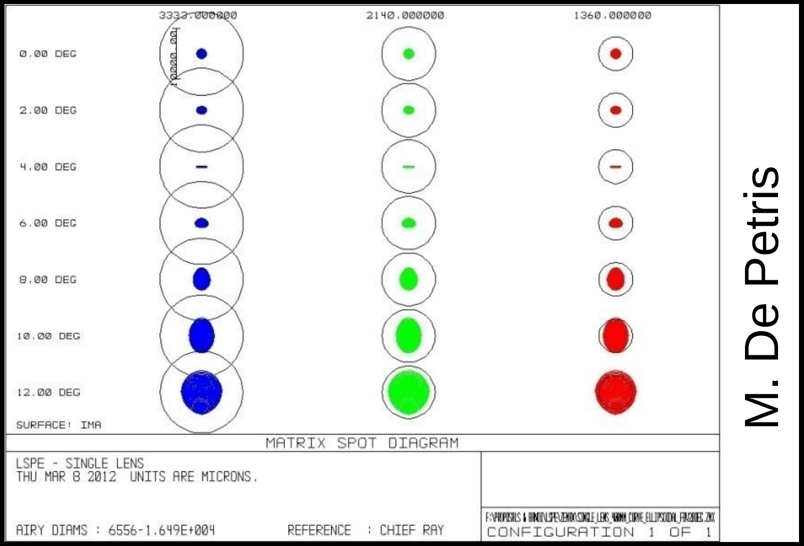
Corrected focal plane *vs* bands



SWIPE: Simple Optical Design





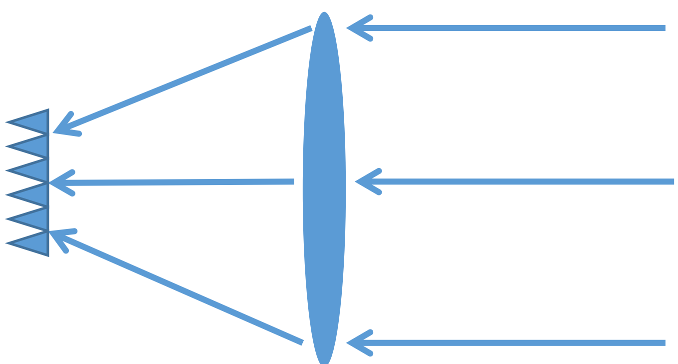


M. De Petris

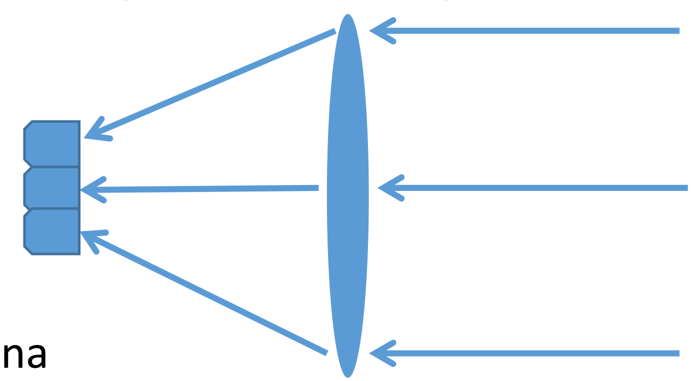
Single-Mode vs Multi-Mode design: how, when and why go Multi-Mode

- Diffraction- and photon-noise limited operation over quite a broad band demonstrated
- Solid modeling techniques
- Reliable methods for assessing real-life performance.
- 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 $N_{modes}^{1/2}$
- 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)



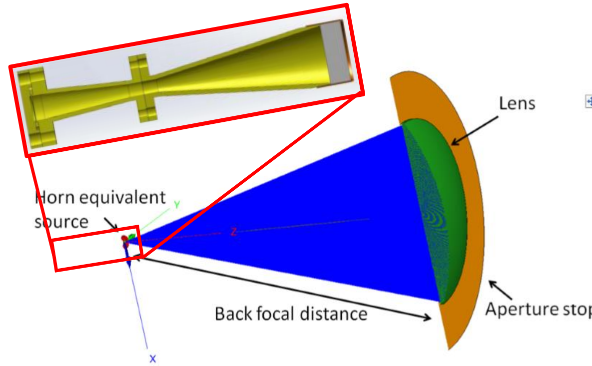
L. Lamagna



LSPE/SWIPE: multimode optics

- Whole system multi-mode
- 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.

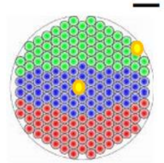
L. Lamagna. M. De Petris

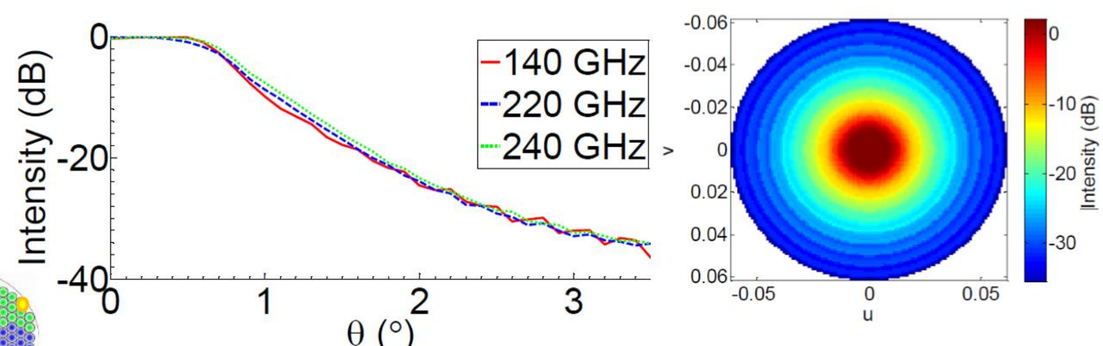


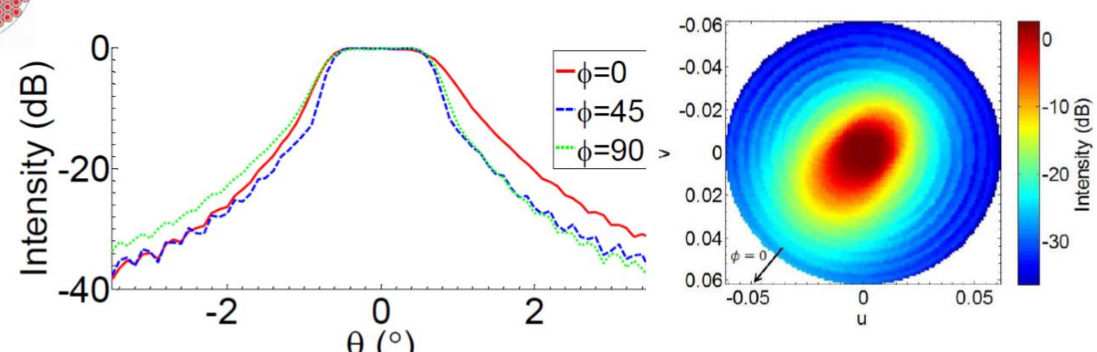
Diameter (mm)	428
Centre thickness (mm)	60
Focal length (mm)	805
Refractive index	1.57
Conic constant	-0.54
Cold stop diameter (mm)	420

Coupling analysis – small angle beams

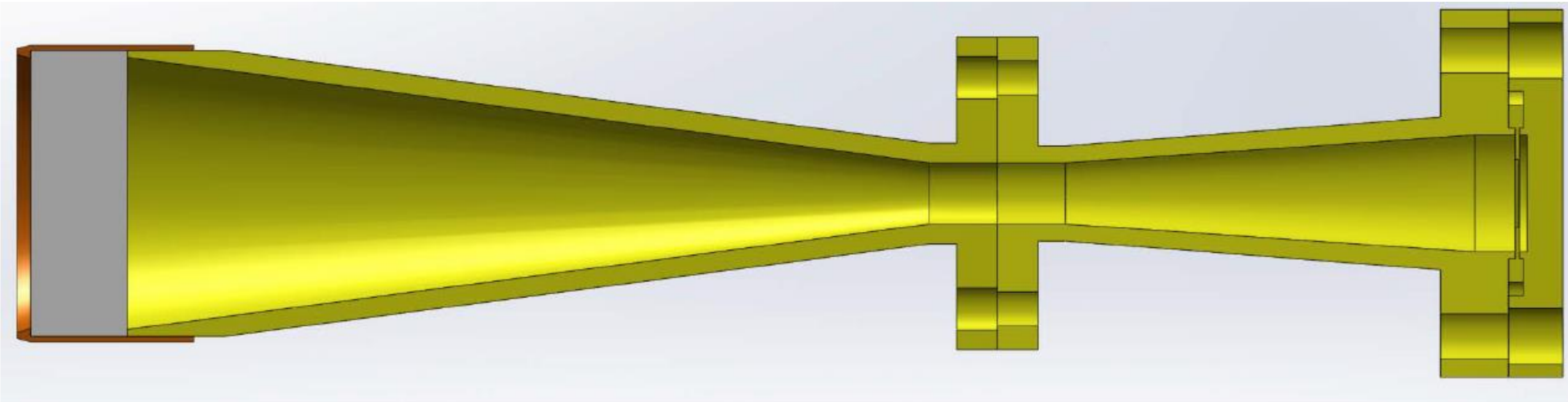
L. Lamagna, S. Legg







The SWIPE pixel assembly



Nominal freq (GHz)	Bandwidth	Min freq (GHz)	Max freq (GHz)
140	30%	119	161
220	5%	214.5	225.5
240	5%	234	246

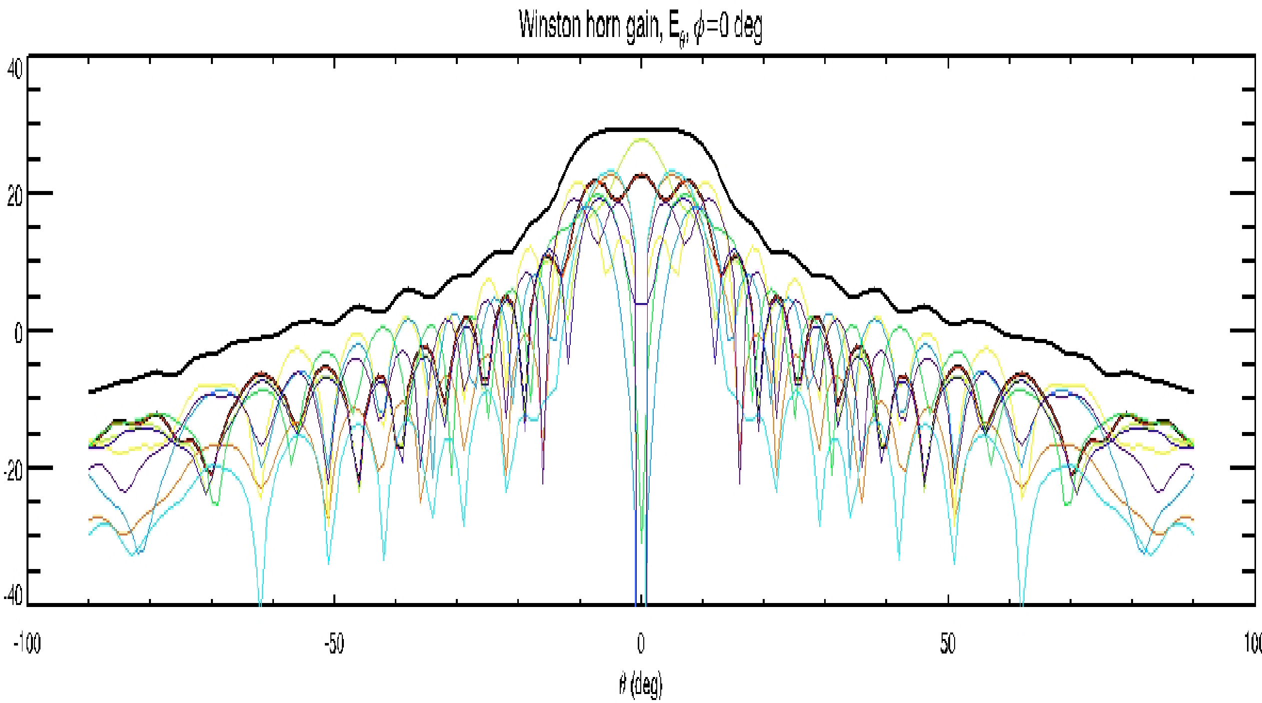
Table 1 – main features of the SWIPE bandpasses (source: C. Tucker, Cardiff Univ.)

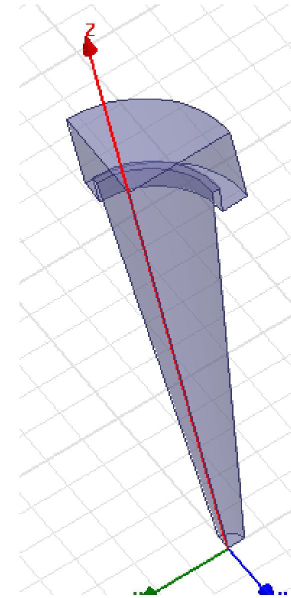
Channel	ν_{min}(GHz)	$N_{modes}(\nu_{min})$	ν_{max}(GHz)	$N_{modes}(\nu_{max})$	ν_{eff}(GHz)	$N_{modes}(\nu_{eff})$
140	119	10	161	17	140	12
220	214	28	226	31	220	30
240	234	32	246	35	240	34

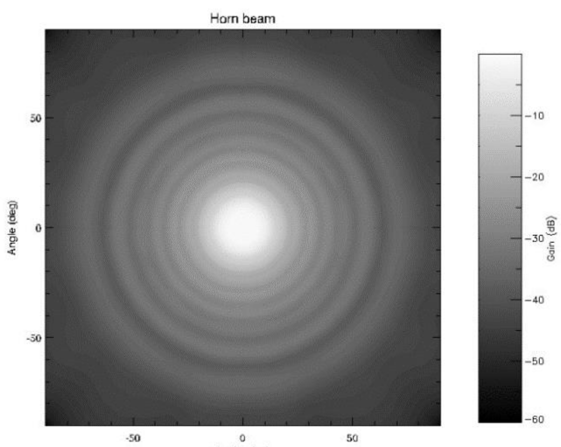
Table 2 – number of coupled modes N_{modes} at the center and at the edges of each SWIPE band. The total optical throughput at frequency ν is $N_{modes}c^2/\nu^2$.

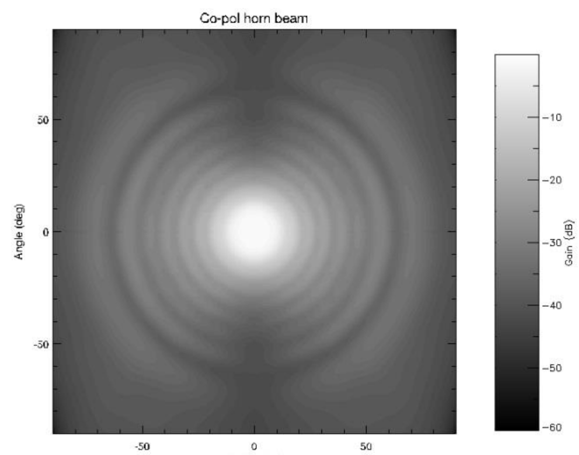
L. Lamagna

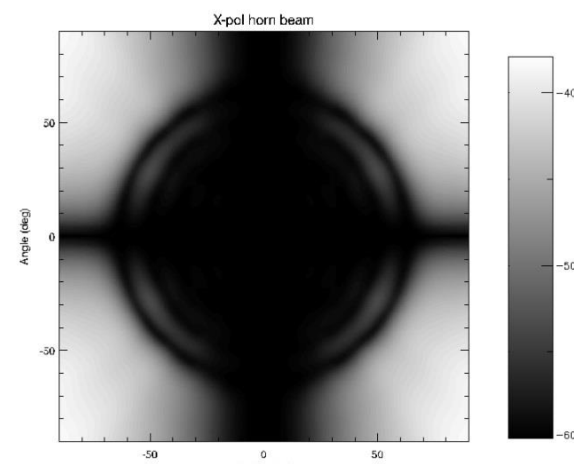
SWIPE: Horn beam





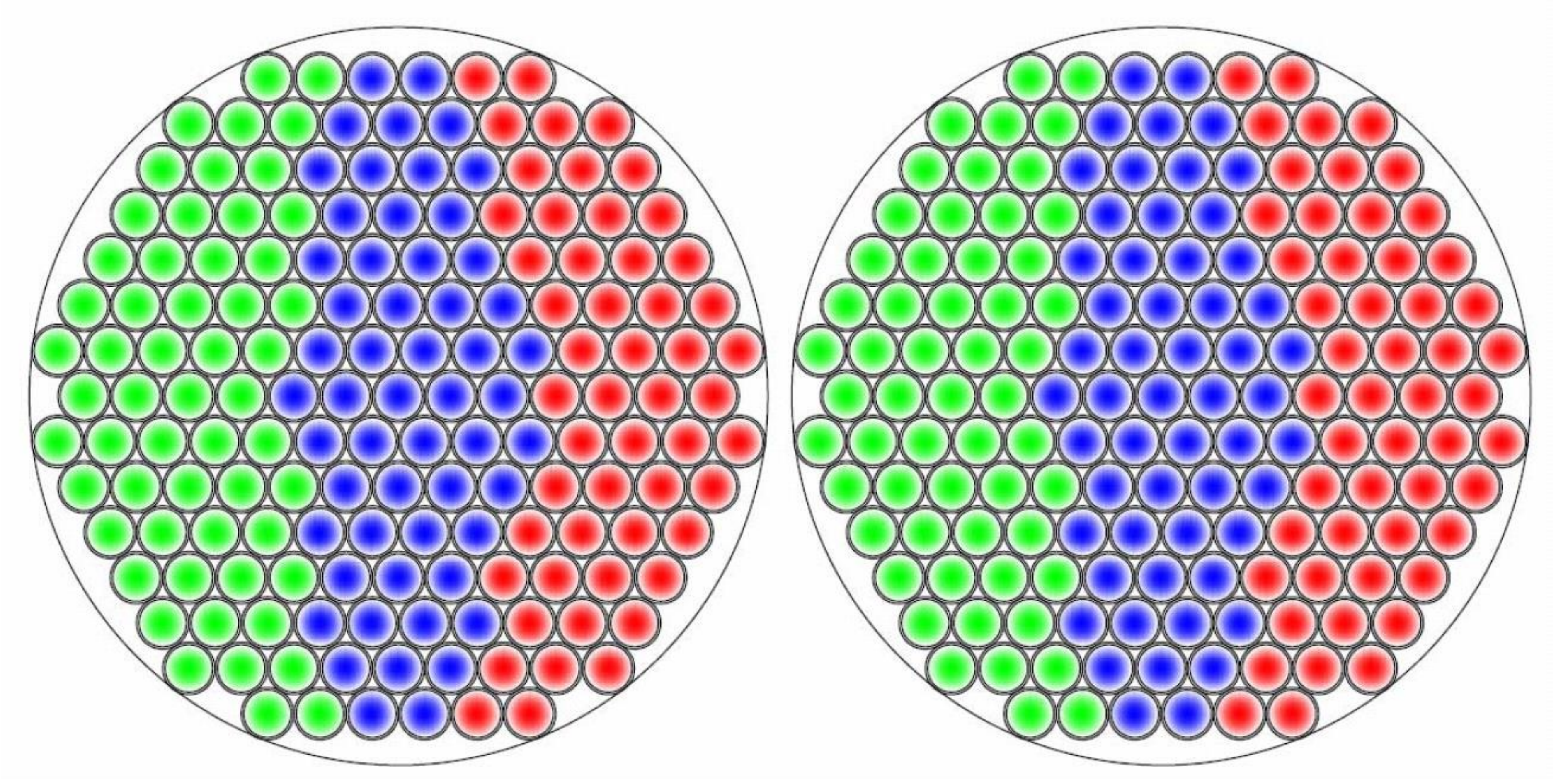






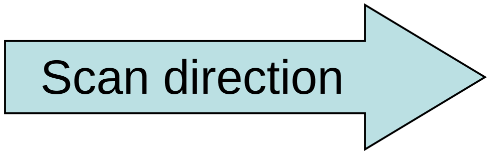
Lamagna et al., Proc. 36° ESA Antenna Workshop, manuscript 110138 (2015)

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



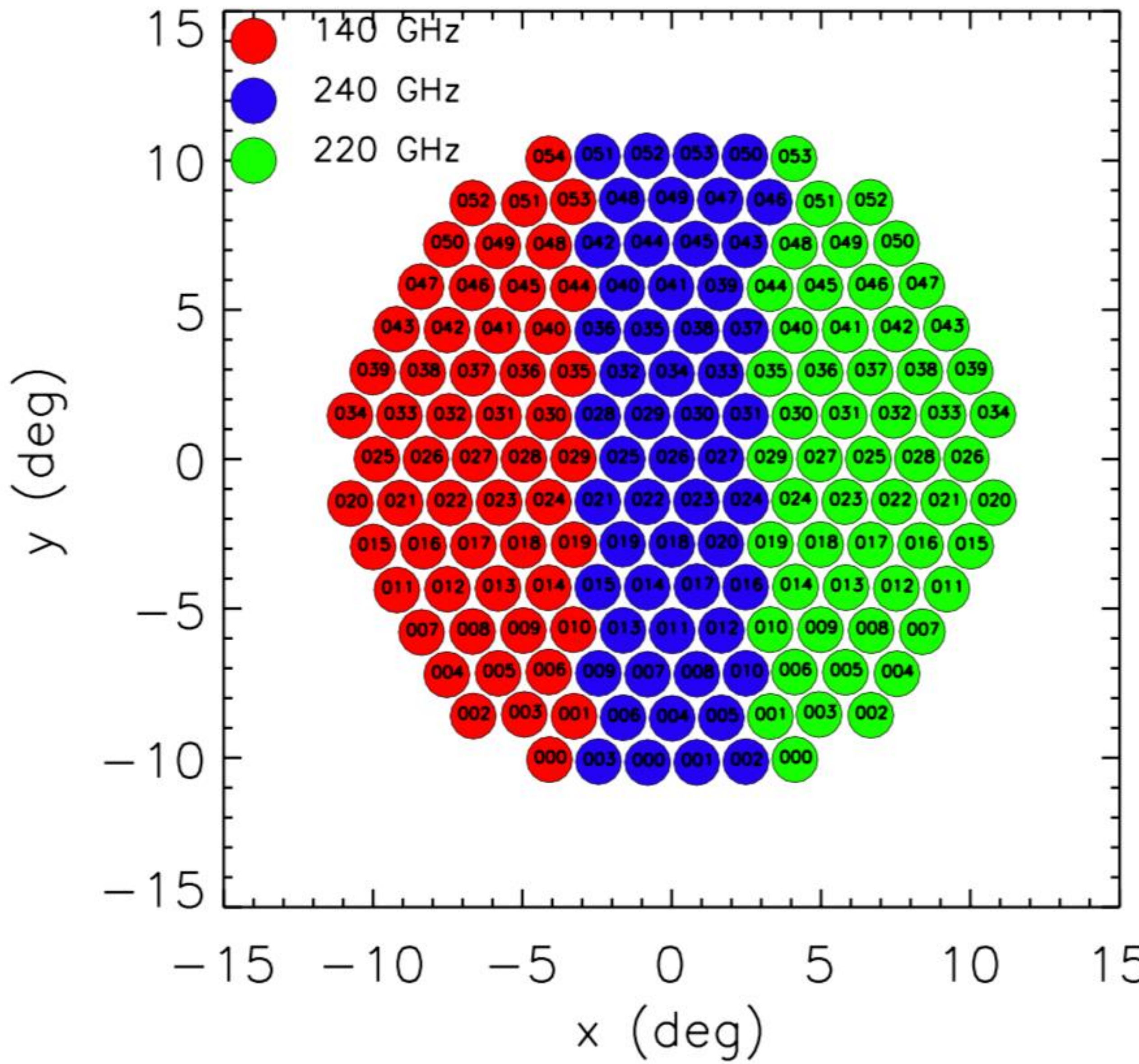
Reflected focal plane

transmitted focal plane



SWIPE: Focal Planes real estate

- 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 totalizes 4400 radiation modes for each focal plane (transmitted and reflected).



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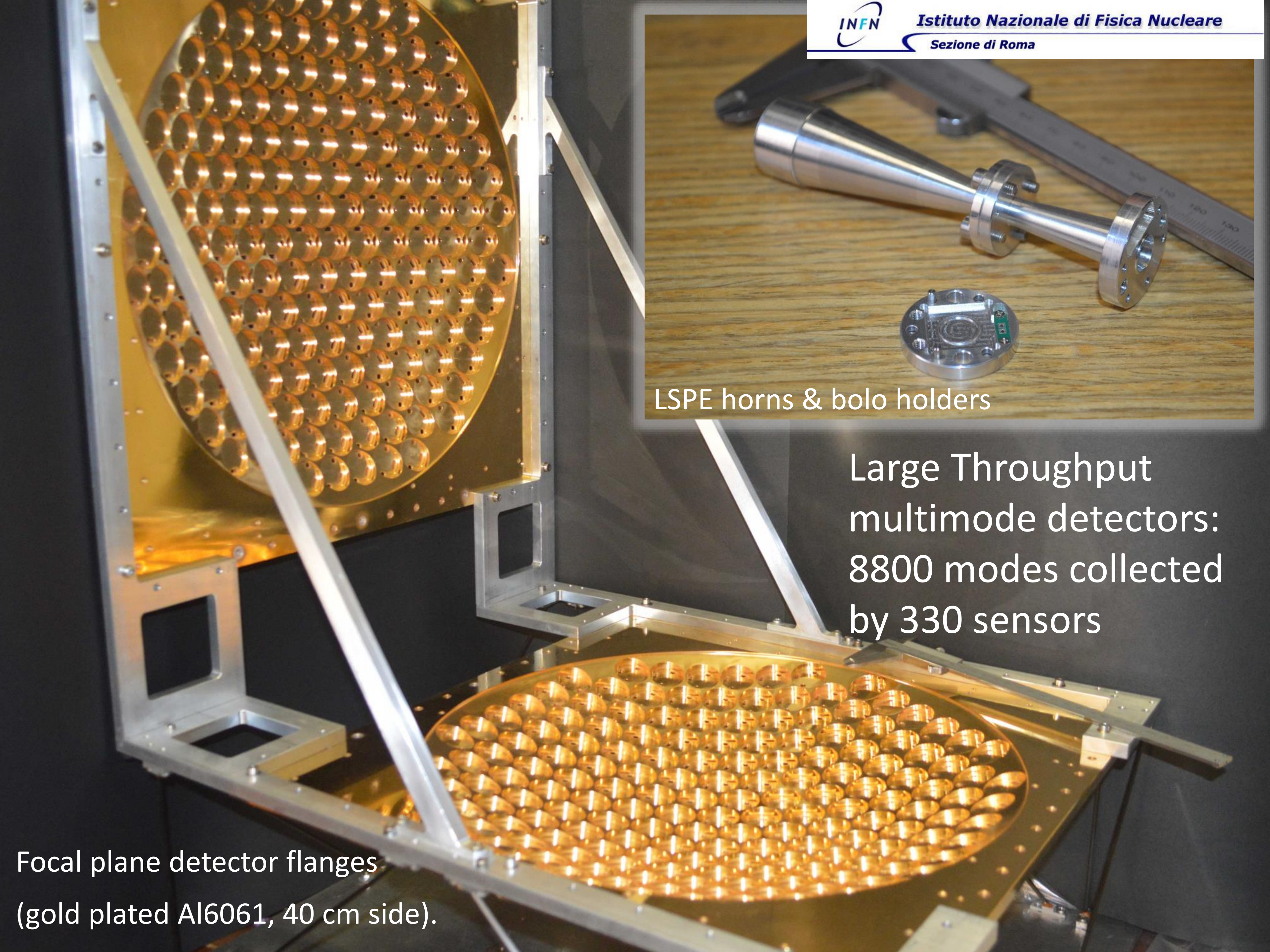
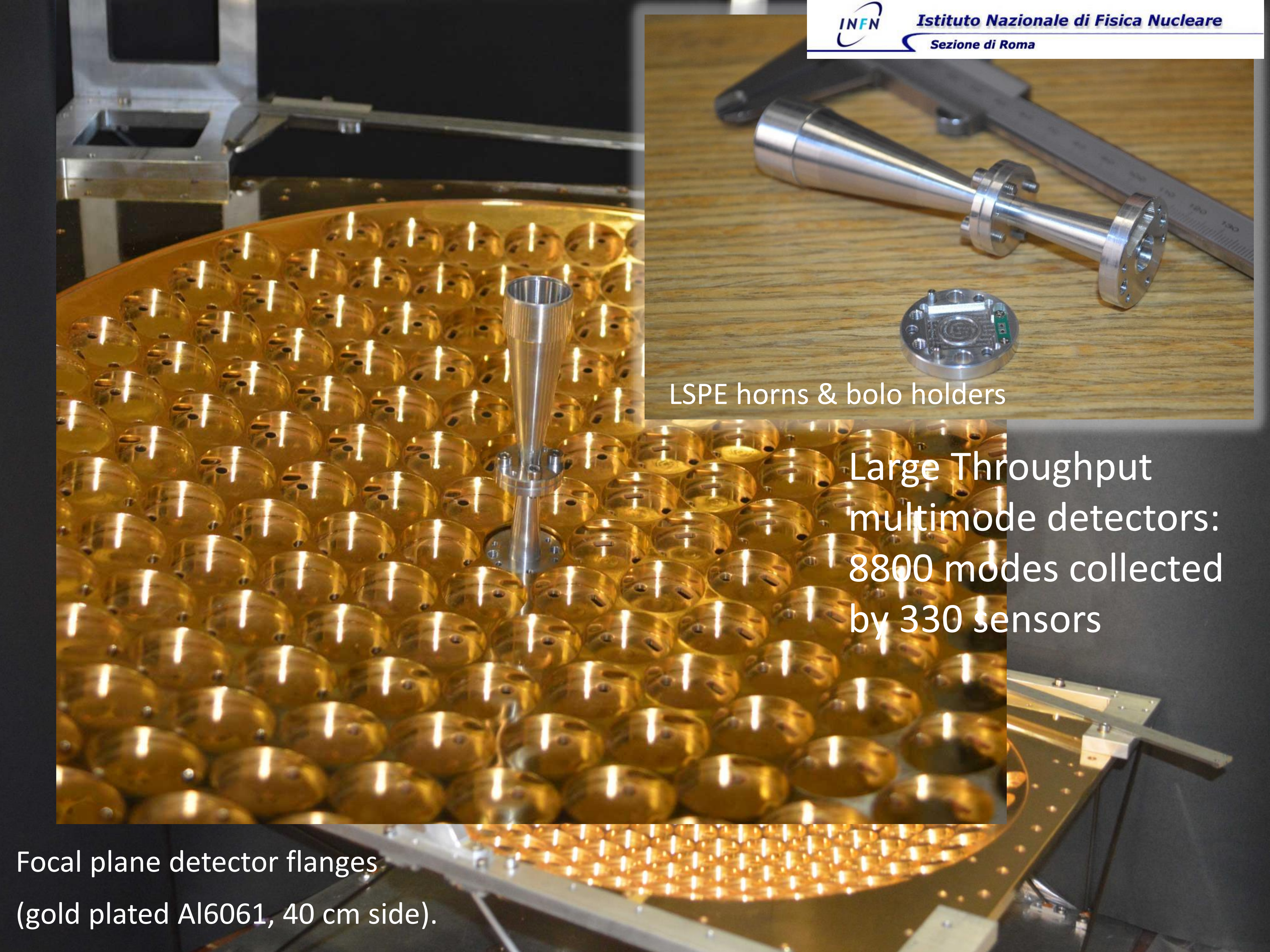
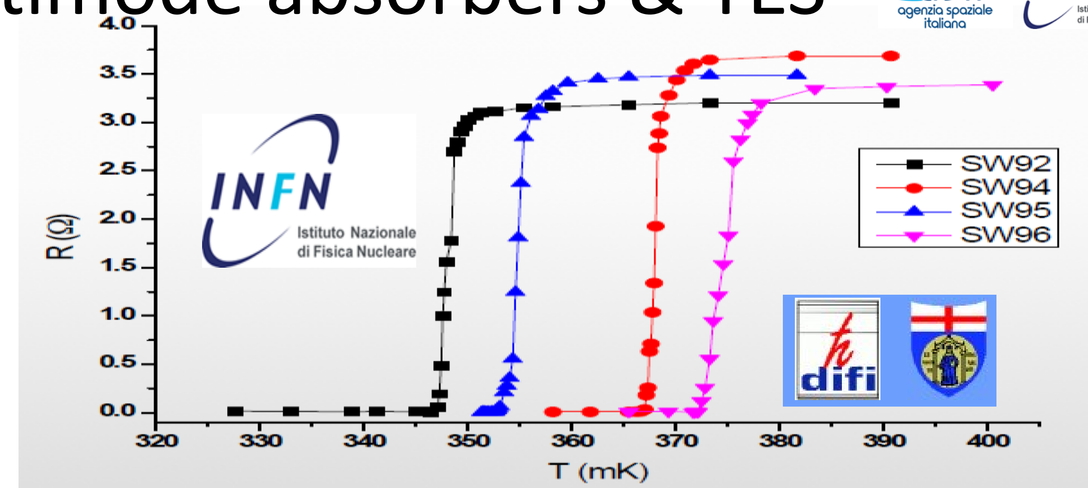
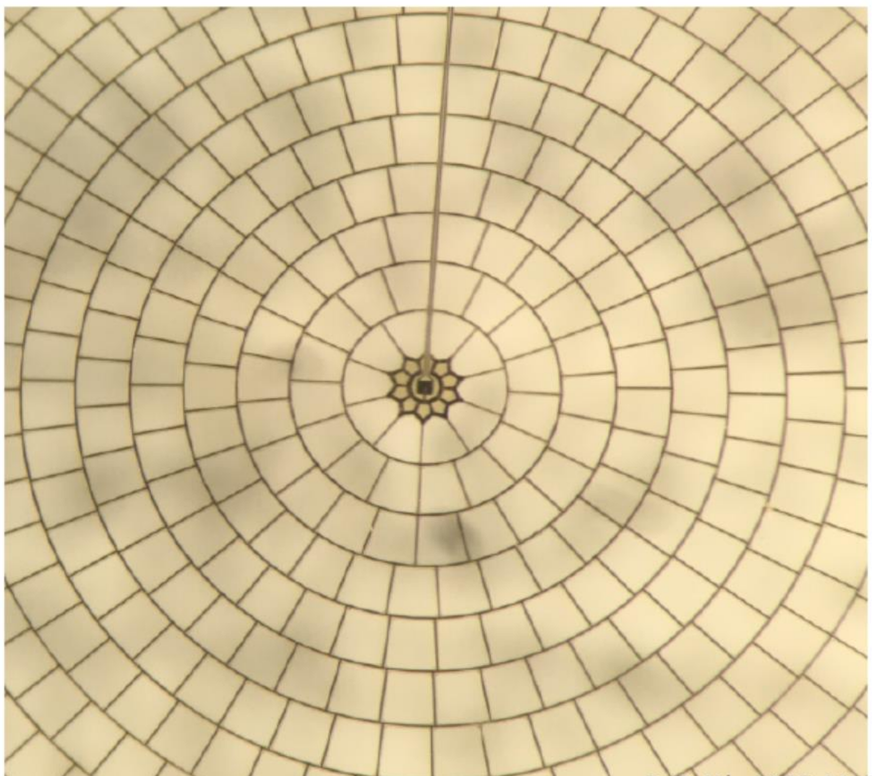


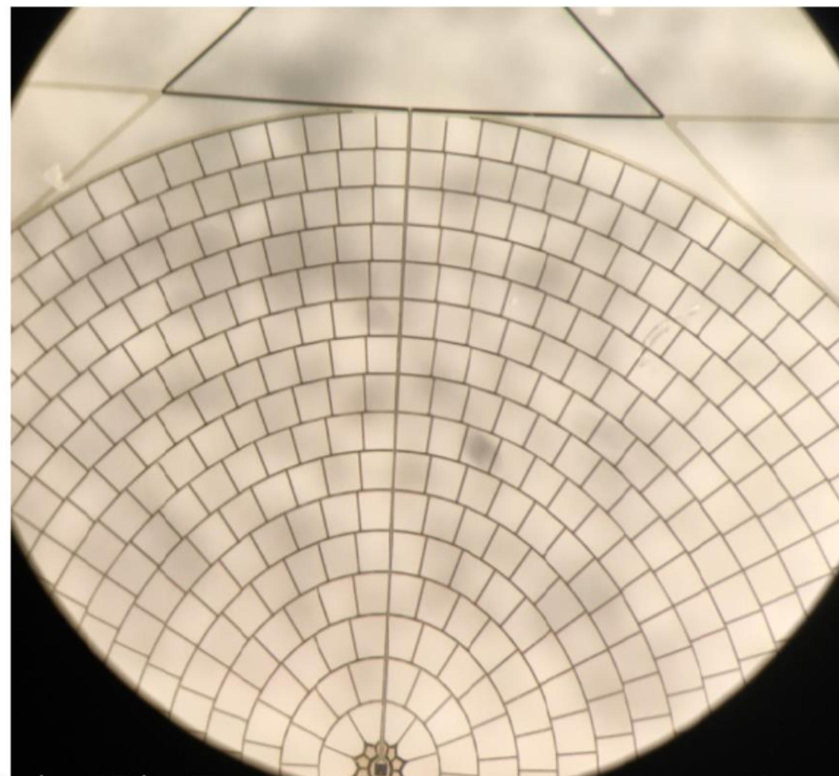

INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Roma
LSPE horns & bolo holders
Large Throughput
multimode detectors:
8800 modes collected
by 330 sensors
Focal plane detector flanges
(gold plated Al6061, 40 cm side).

SWIPE - multimode absorbers & TES

- The absorbers are large Si_3N_4 spider-webs (8 mm diameter, multimode)
- Sensors are Ti-Au TES
- Photon noise limited
- τ = 10 ms

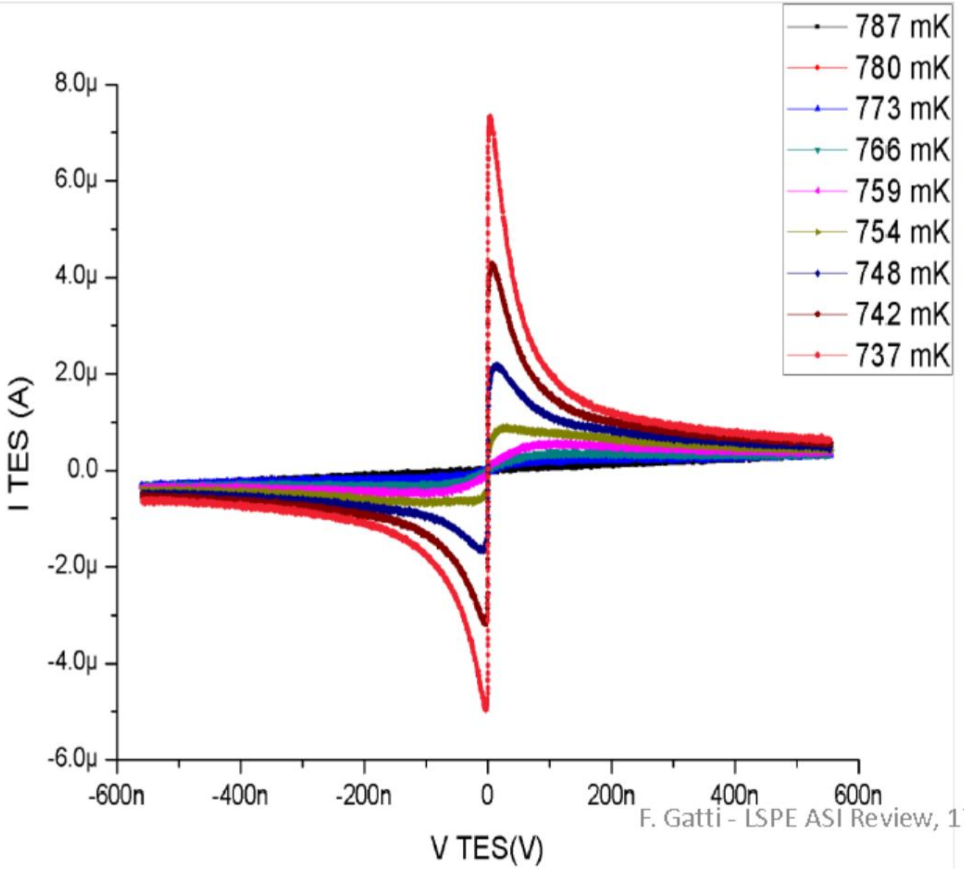




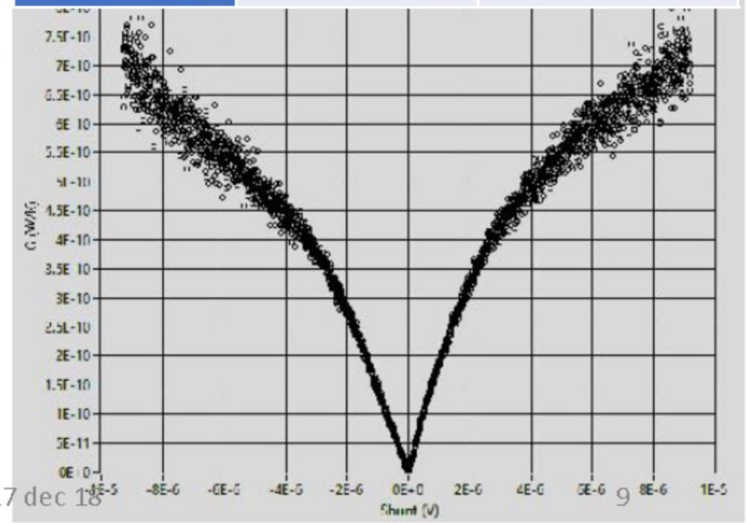


SWIPE - multimode absorbers & TES

- IV curves acquired with SQUID VTT J3, with M=36 μA/ϕ
- Voltage bias generated onto a shunt resistor of 7.34 mΩ
- The analysis allows to calculate the effective thermal conductance G and the NEP, including the electro-thermal feedback



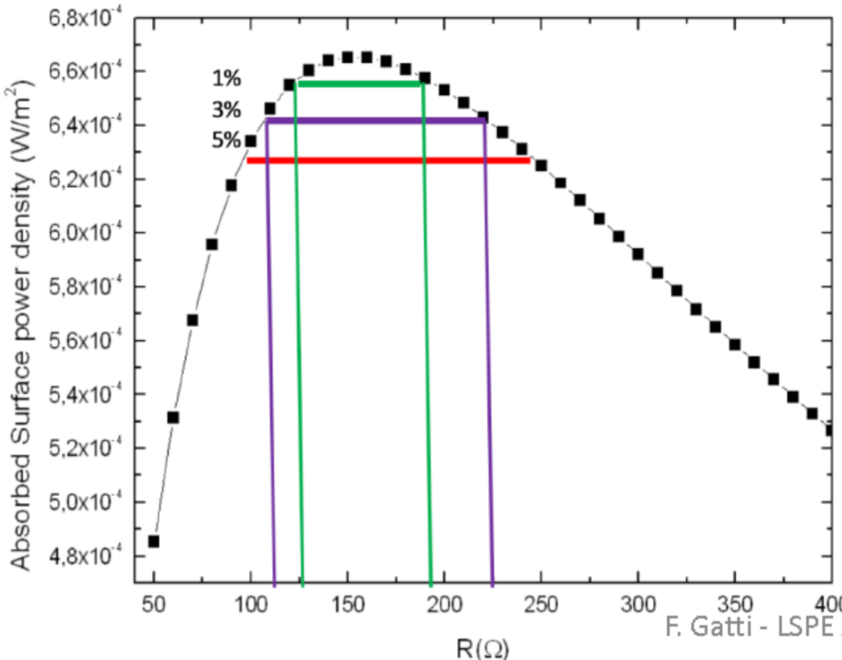
Vbias (uV)	G (10^{-11} W/K)	NEP 10^{-17} W/Hz$^{0.5}$
0.5	5	2.6
1.0	10	3.8
1.5	20	5.3
2.0	28	6.3



F. Gatti

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



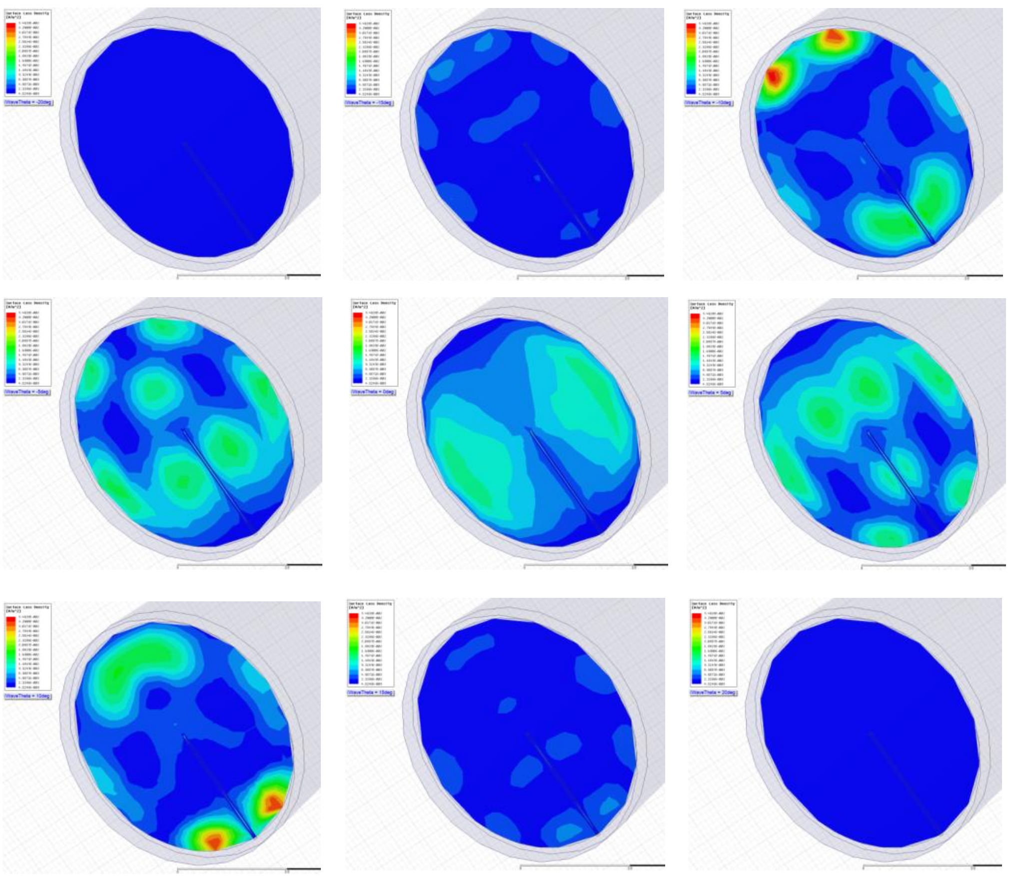
Parameters for Gold	Expct/meas. factor	Effect on heat capacity
RRR	1.5	1.5
3% Match. Fact.	1.8	1.8
G factor	2	-
Expctd Tau fact.	5	

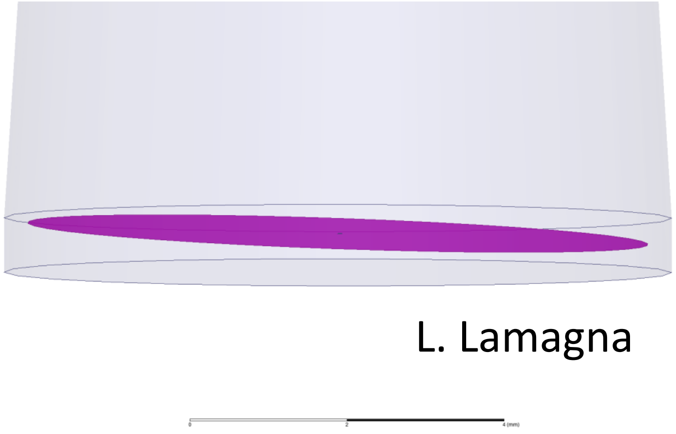
Parameter for Bi over Gold	Expctd/meas . factor	Effect on heat capacity
Resistivity Ratio	50(expec.) - 70(meas.)	3,4(expec.)- 2,4(meas.)
Specific heat ratio	1/170	
G fact.	2	
Expectd. Tau fact	5(meas.)- 7(expec.)	

F. Gatti

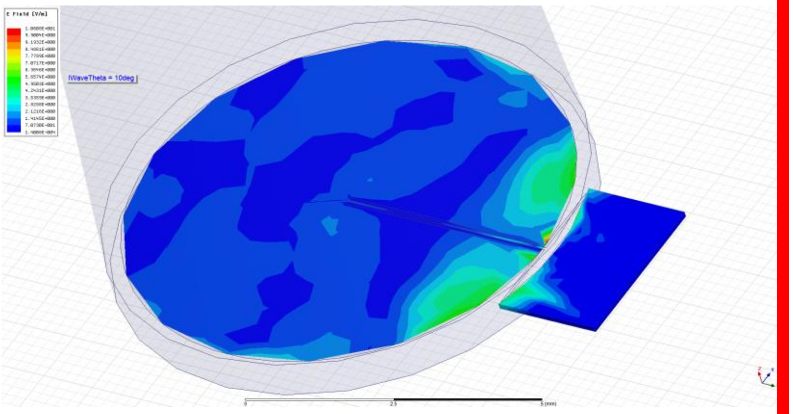
Absorber properties

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



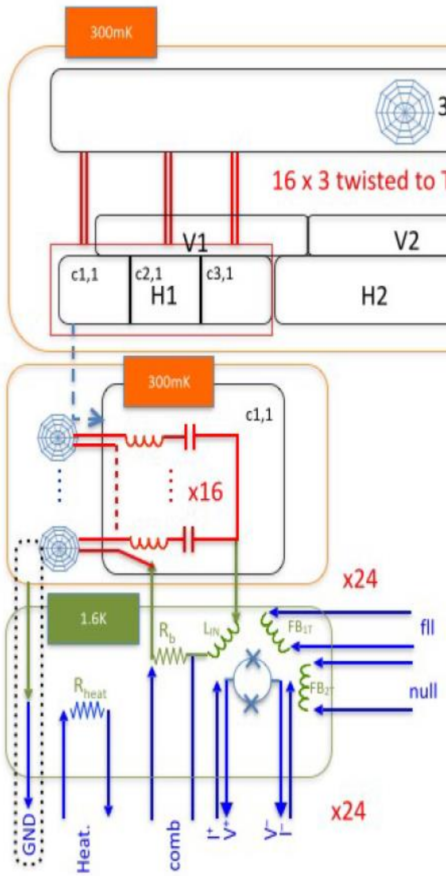


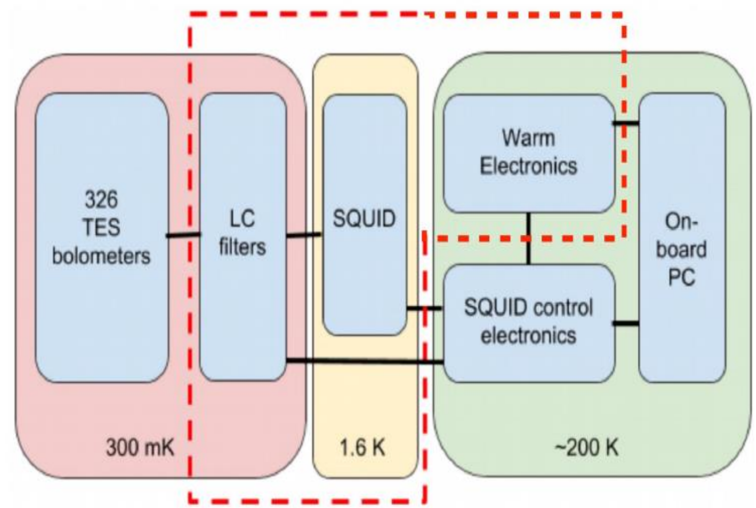
L. Lamagna



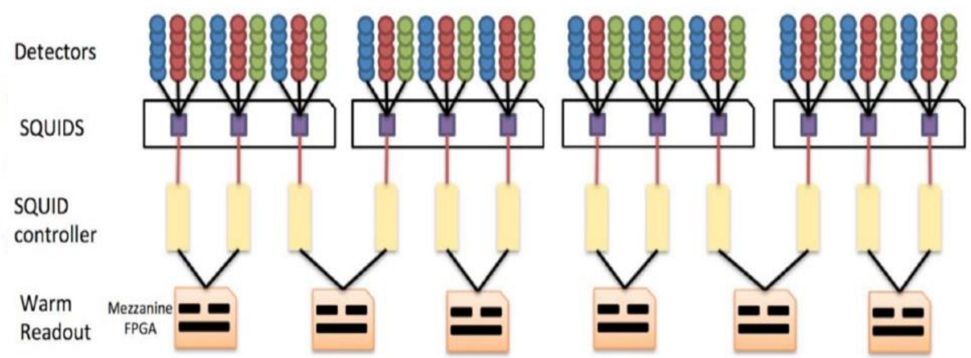
- **Despite of the different shapes, the integral is regular.**
- **Uniformity of absorption is very important to obtain a regular beam pattern.**
- **Internal conductivity of the absorber mesh also very important.**
- **RA measurements are warranted to be significant only in cold operating conditions**

SWIPE - TES readout (mux)





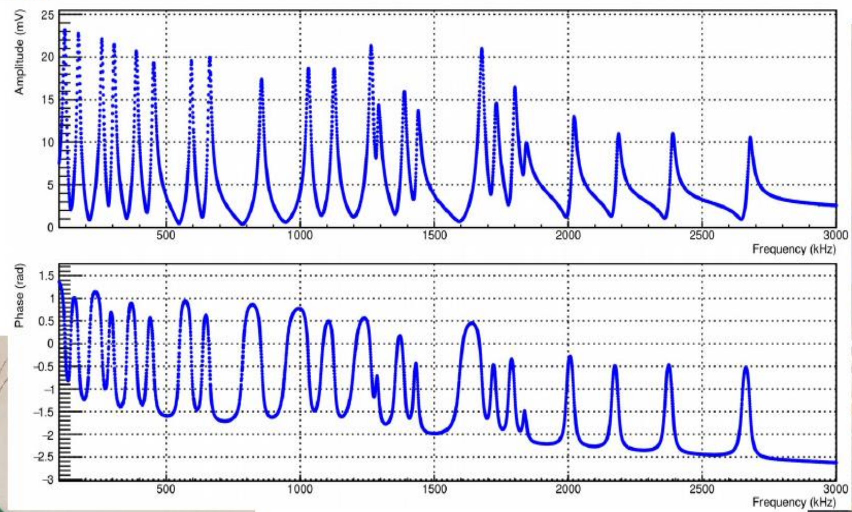
Wiring and connections from 300 mK to 250 K

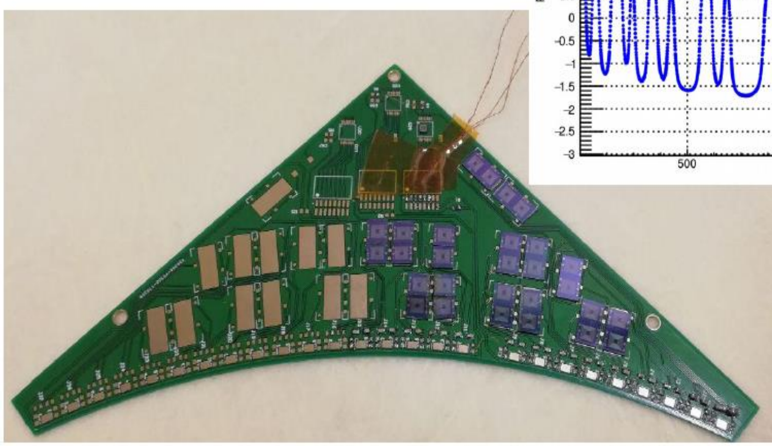


G. Signorelli

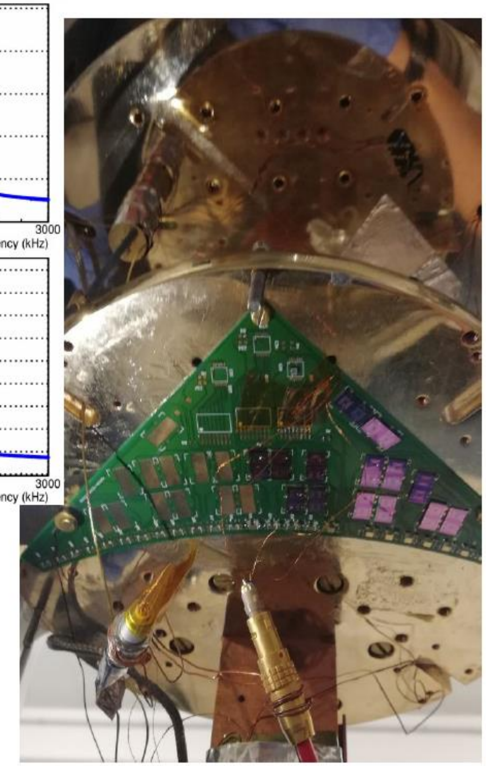
SWIPE - TES readout (mux)

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





Test of a readout channel

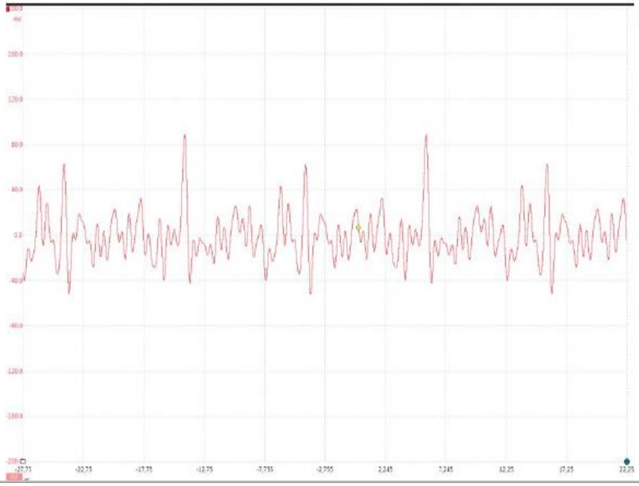


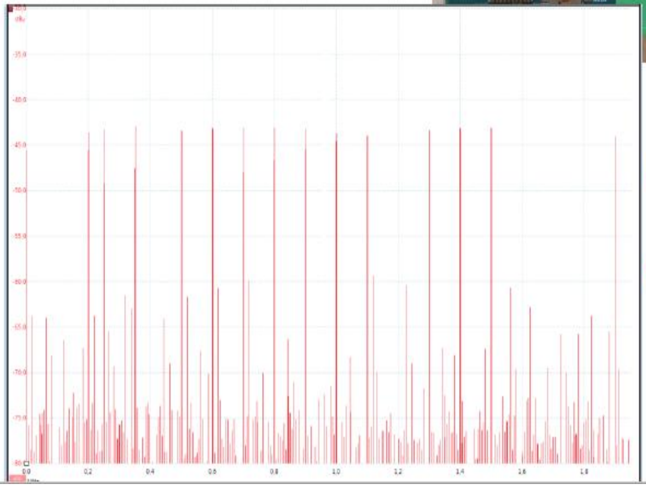
G. Signorelli

INFN PISA Istituto Nazionale di Fisica Nucleare Sezione di Pisa

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

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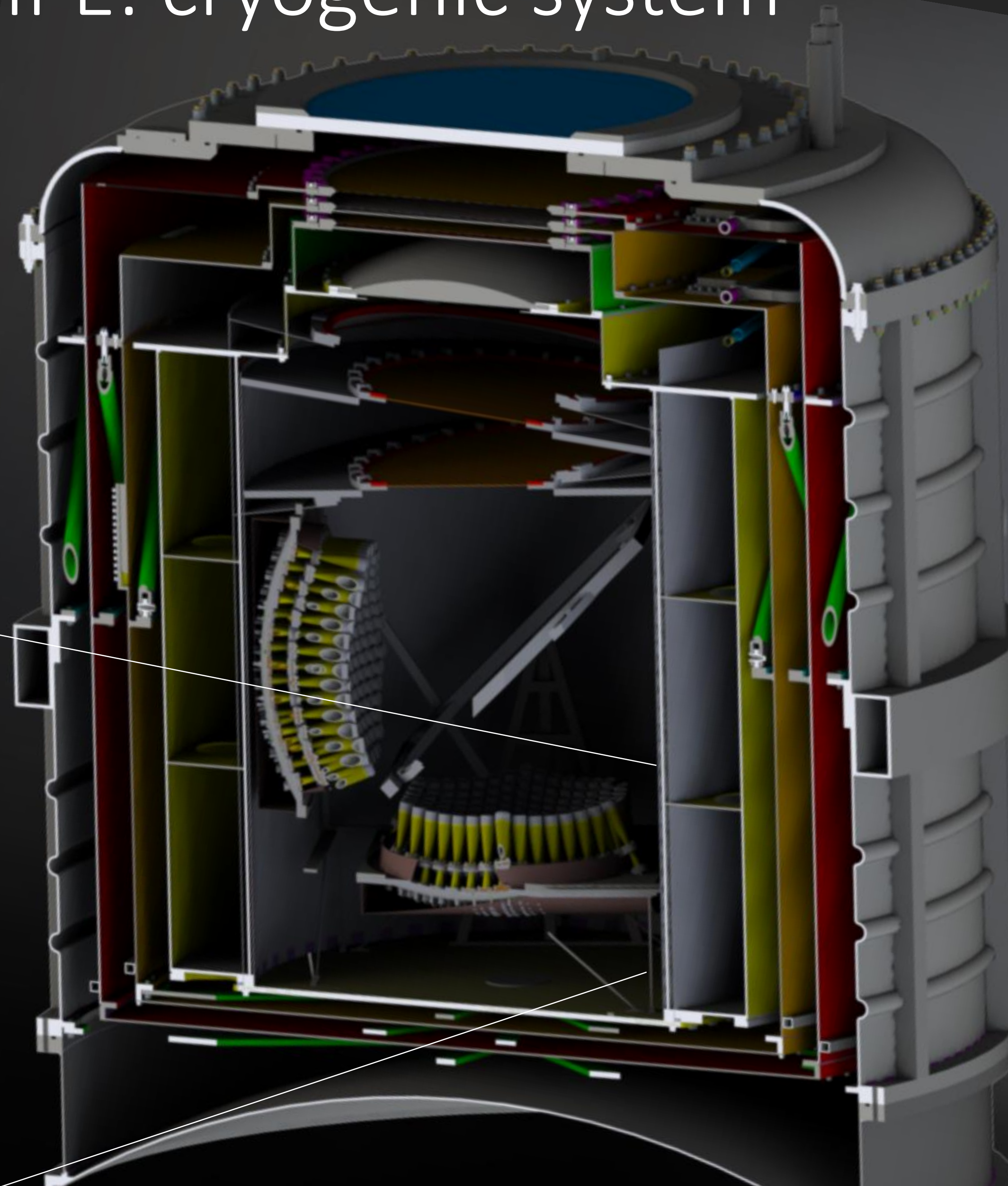
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

LSPE/SWIPE: cryogenic system

LSPE-SWIPE

- Aluminum cryostat
- Large cold volume ($1m^3$)
- 2 vapor cooled shields
- Fiberglass support system
- 250L of superfluid ^4He @ 1.6K
- > 15 days hold time
- ^3He refrigerator 0.28K
  (Coppi et al. 2016SPIE.9912E..65C)



LSPE/SWIPE: cryogenic system

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

T_{ext}(K)	Efficiency	$T_{shield1}$ (K)	$T_{shield2}$ (Kelvin)	Hold time (days)
290	0.7	90	251	30
290	0.8	90	247	30
290	0.9	90	244	30
220	0.7	75	183	41
220	0.8	71	180	45
220	0.9	67	178	50

LSPE Large Scale Polarization Explorer

Cryostat development

parts being machined

INFN Istituto Nazionale di Fisica Nucleare

agenzia spaziale italiana

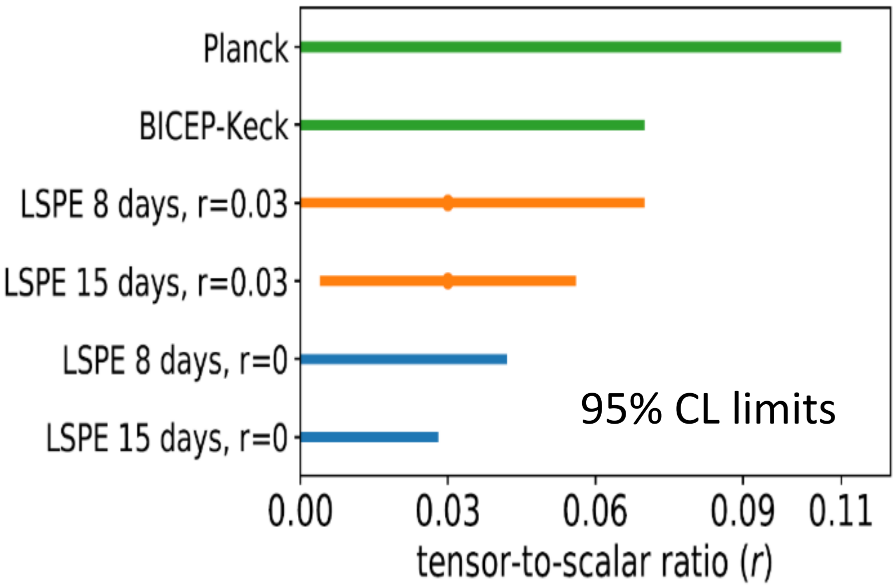
S. Masi, 3/12/2018

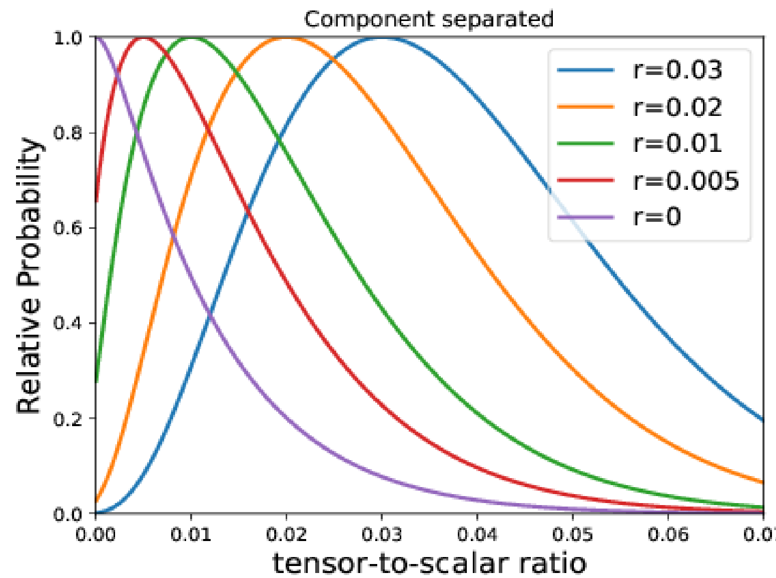
Cryostat development

parts being welded

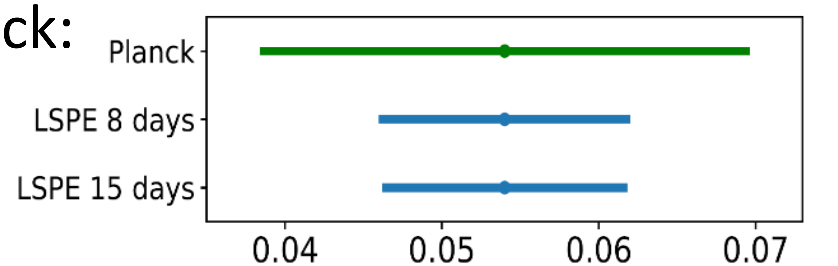
S. Masi, 3/12/2018

Expected performance of SWIPE-LSPE , from realistic simulations, in a single flight





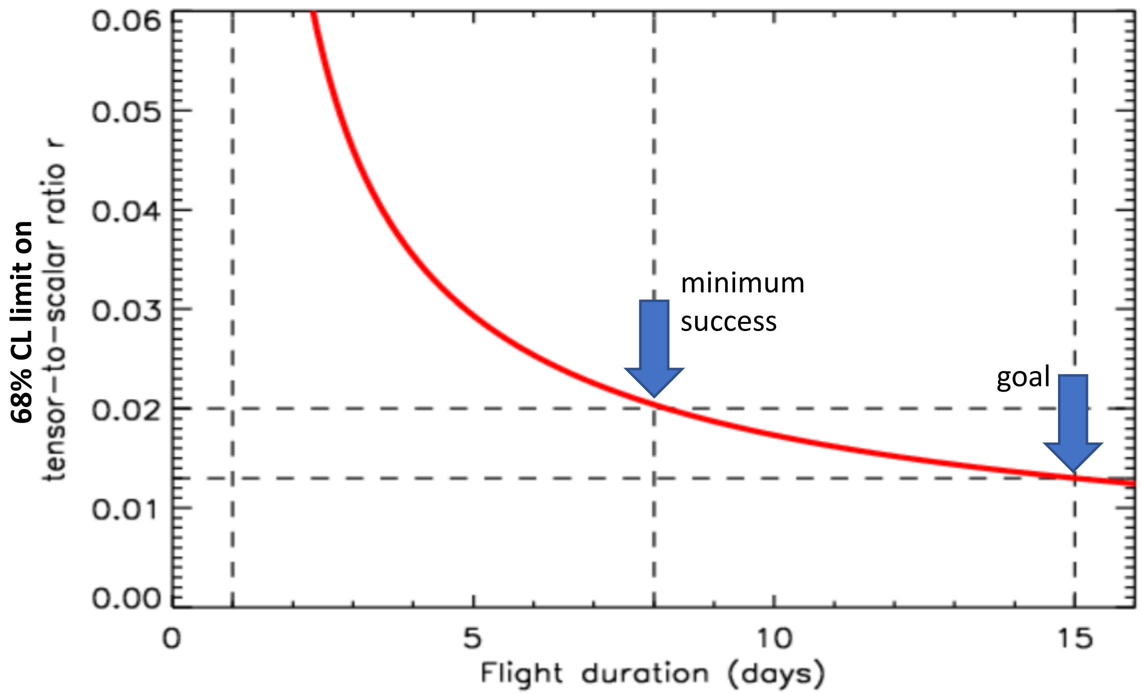
- If $r << 0.01$ LSPE-SWIPE provides a 95% CL U.L. $r < 0.03$
- If $r > 0.01$ LSPE-SWIPE provides a significant detection of r
- The measurement of the optical depth to recombination is improved significantly wrt Planck:



L. Pagano, F. Piacentini

Mission Requirements:

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



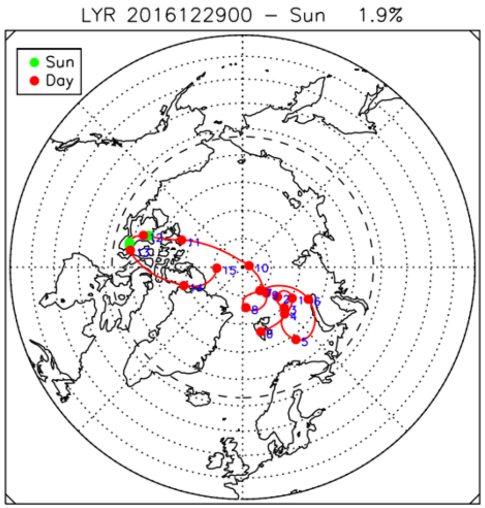
- Long integration time (8 days minimum, 15 days goal)
- Night flight (to cover all azimuths with a telescope spinning in azimuth)

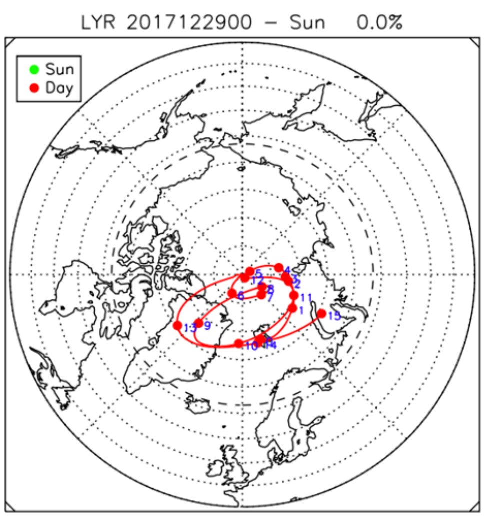
SWIPE : night flight

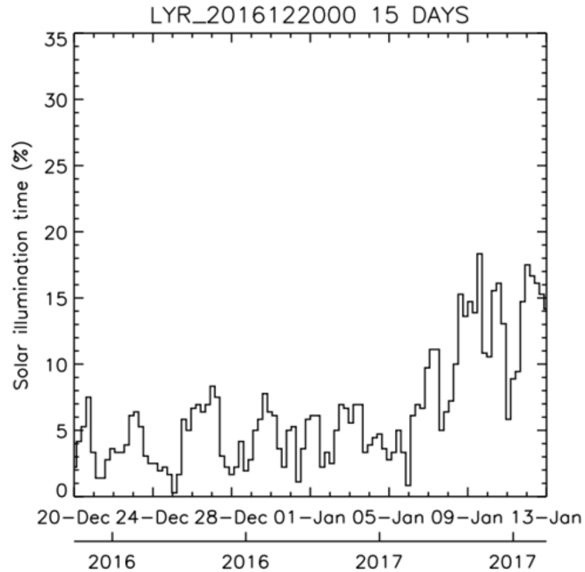
Flight managed by ASI, scheduled for end of 2020
Longyearbyen - Svalbard

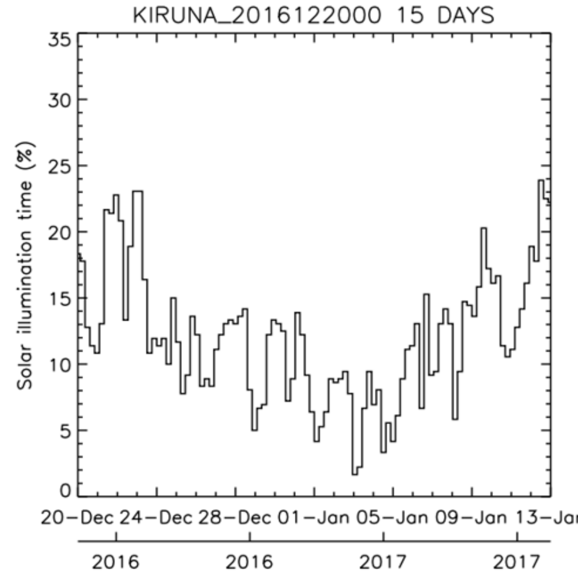
SWIPE: solar illumination issues

- 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.

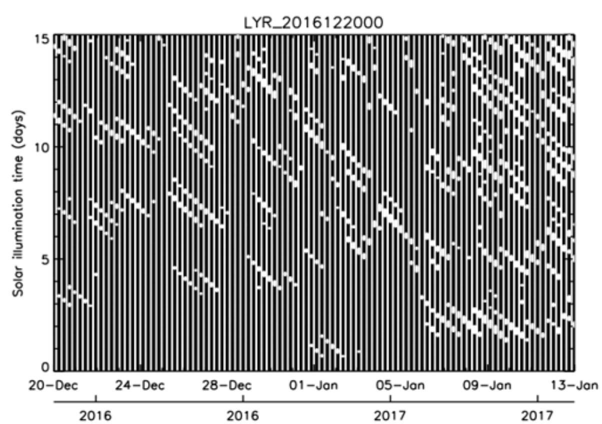


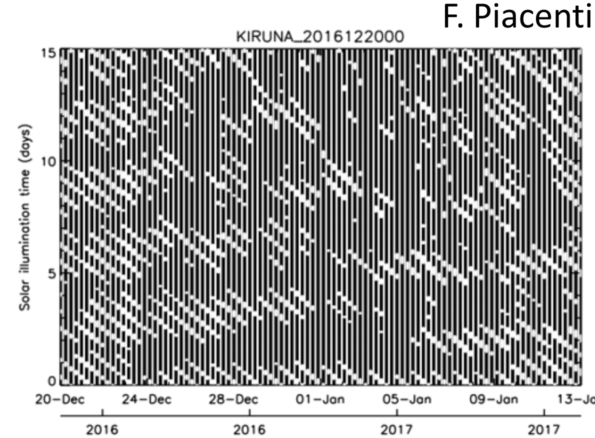






F. Piacentini





B-modes future:
LiteBIRD

Bolometric Imager
Stokes Polarimeter
in deep space !

Slides from Masashi Hazumi (PI)

LiteBIRD Summary

Probing the Universe before the hot Big Bang

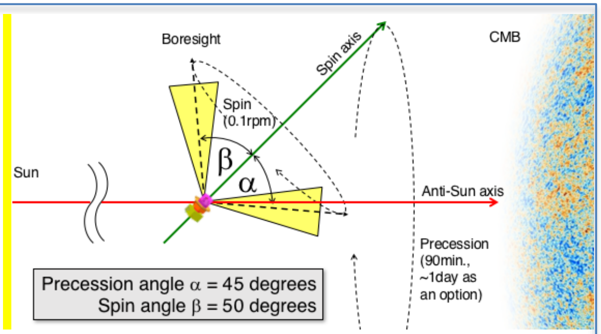
Scientific objectives

Mission for Fundamental Physics, recently selected by JAXA

- 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: **$\delta r < 0.001$** (δr: 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

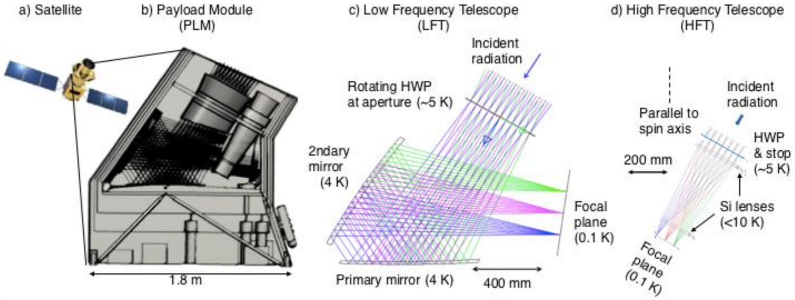
Observations

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



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.

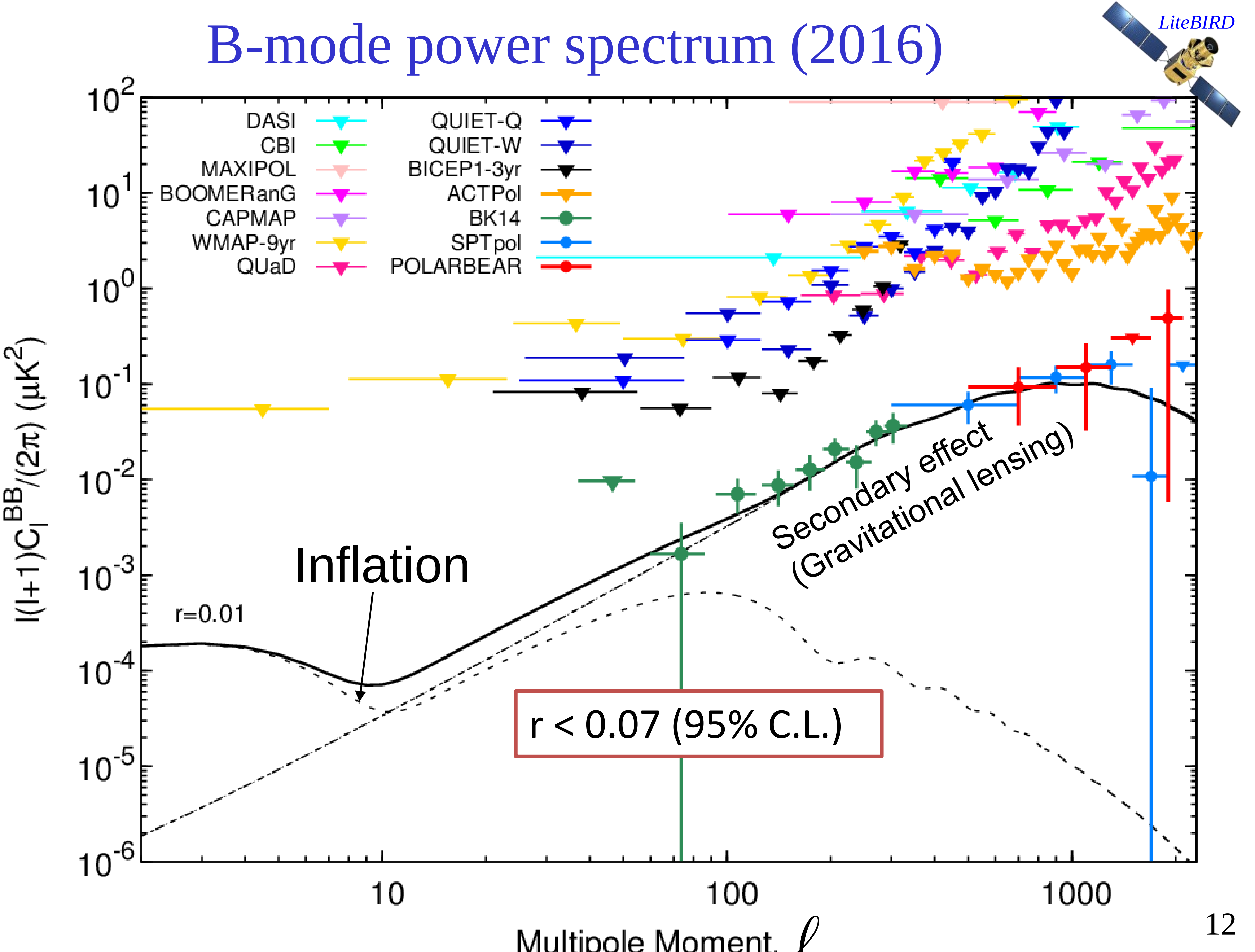
International collaboration

- 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

Project status/plan

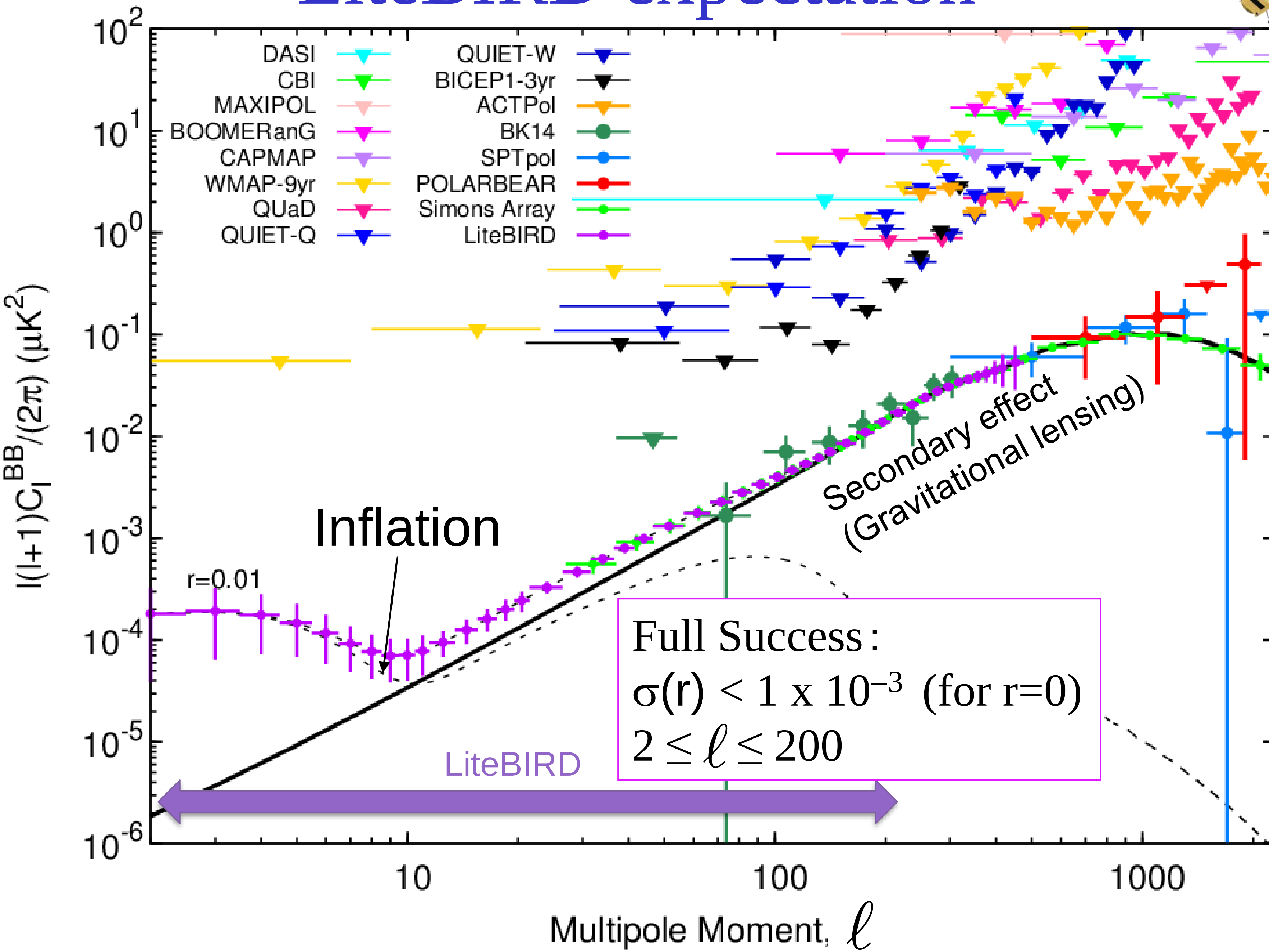
- Phase A1 (Sep. 2016 – Aug. 2018)
- Final selection in JFY 2018
- Launch in >2027 w/ JAXA H3

B-mode power spectrum (2016)



LiteBIRD expectation

LiteBIRD
Yuji Chinone



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

LiteBIRD

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. σ(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 >5sigma 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 σ(r) with external observations

Topic	Example Method	Example Data
Delensing	Large CMB telescope array	CMB-S4 data Namikawa and Nagata, JCAP 1409 (2014) 009
	Cosmic infrared background	Herschel data Sherwin and Schmittfull, Phys. Rev. D 92, 043005 (2015)
	Radio continuum survey	SKA data Namikawa, Yamauchi, Sherwin, Nagata, Phys. Rev. D 93, 043527 (2016)
Foreground removal	Lower frequency survey	C-BASS upgrade

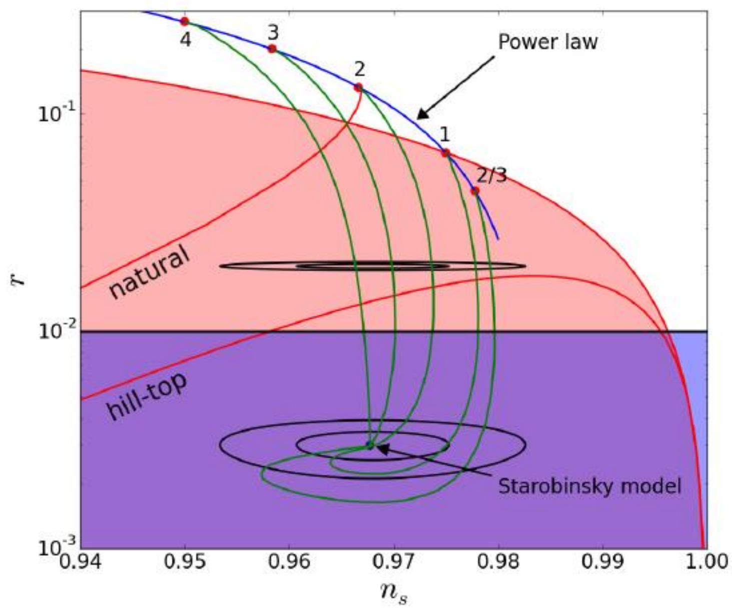
- Delensing improvement to σ(r) can be factor ~2 or more.
  - **e.g. ~6sigma observation in case of Starobinsky model**
  - Need to make sure systematic uncertainties are under control.

In case of discovery, what can happen ?

LiteBIRD

1. Find a correct inflation model in the (r, n_s) plane
2. Find no inflation model in the 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

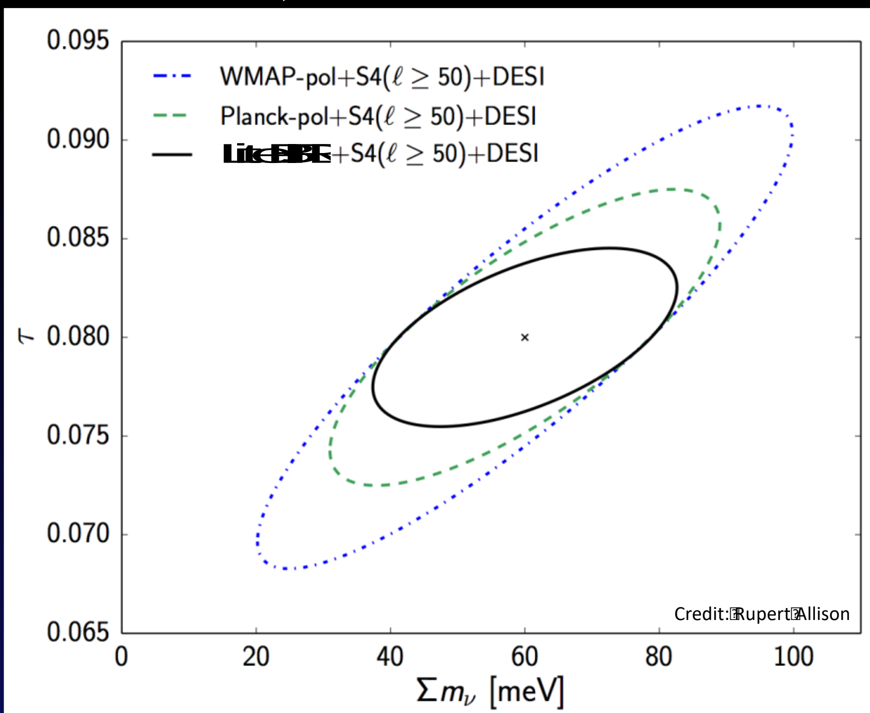
Any of the cases above is extremely exciting !

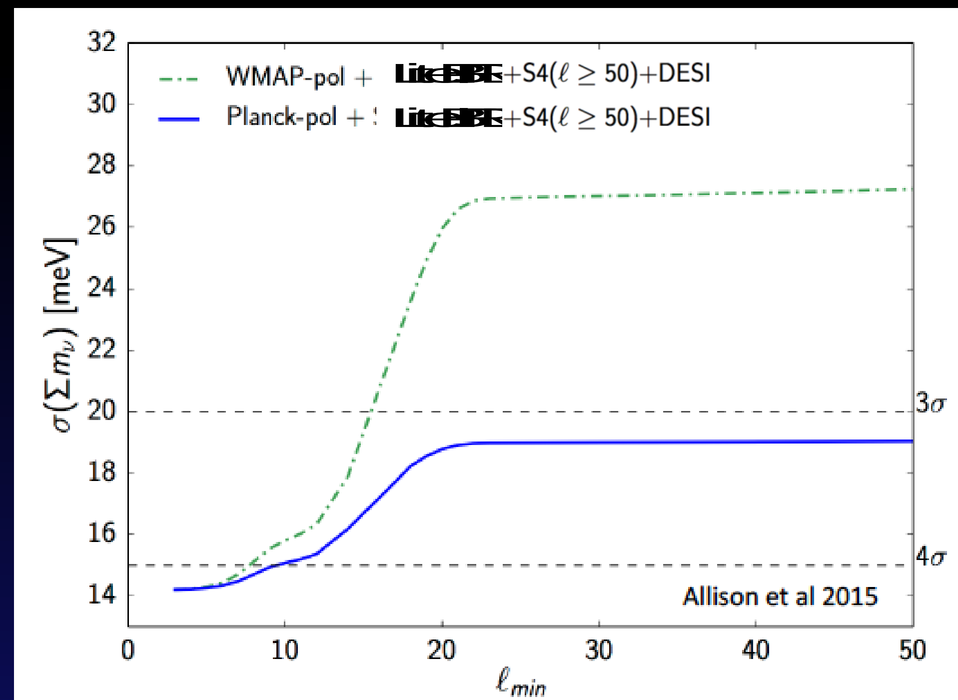


2) τ(optical depth) and neutrino mass

LiteBIRD

- Better E-mode measurement for < 20 improves τ
- Better τ improves Σm_ν
- Σm_ν > 58meV from oscillation measurements





Low ℓ measurements contribute to Σm_ν !

LiteBIRD

3)/4) Origin of gravitational waves

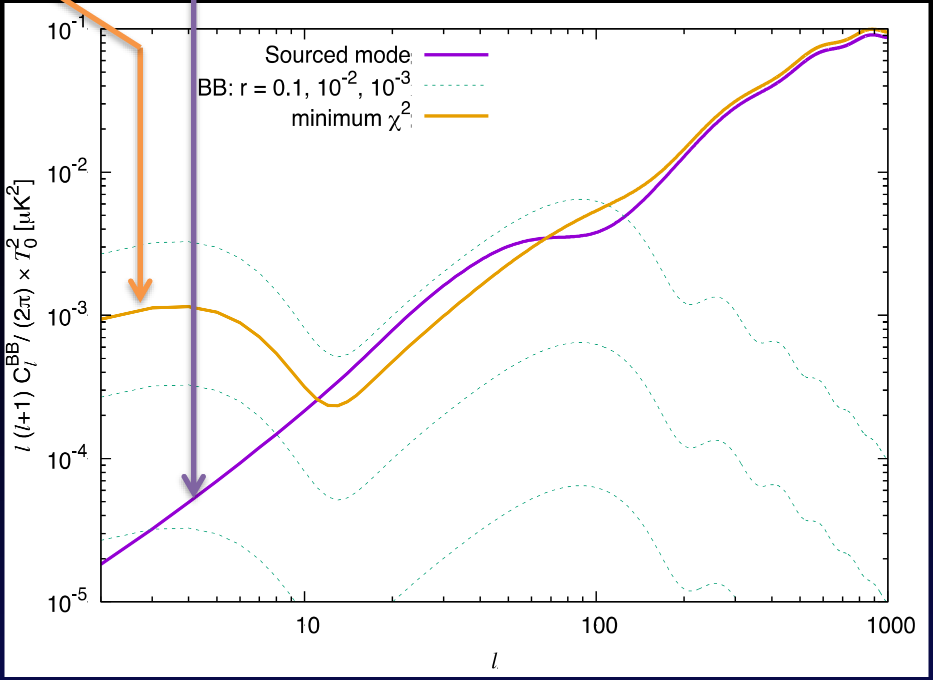
M. Shiraishi, C. Hikage, T. Namikawa, R. Namba, MH, Phys. Rev. D 94, 043506 (2016)

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 >3σ

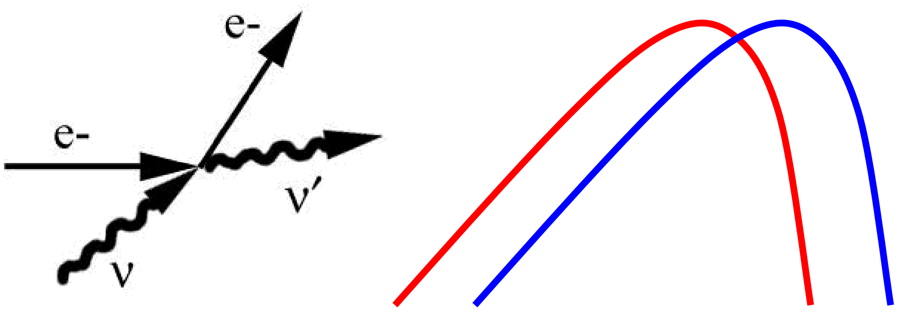


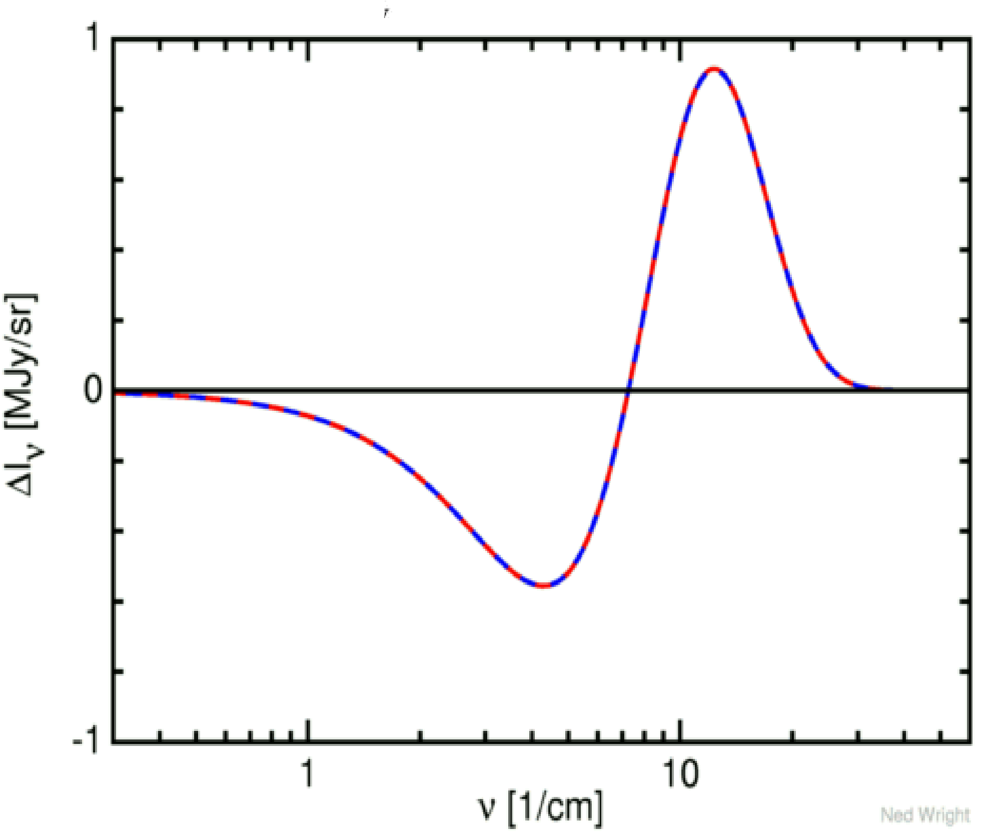
"Pseudoscalar model" from Namba, Peloso, Shiraishi, Sorbo, Unal, arXiv1509.07521 as an "evil example model"; indistinguishable w/ BB for ell > 10 alone.

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.**





A&A 538, A86 (2012)
DOI: 10.1051/0004-6361/201118062
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Astronomy & Astrophysics

Low-resolution spectroscopy of the Sunyaev-Zel'dovich effect and estimates of cluster parameters

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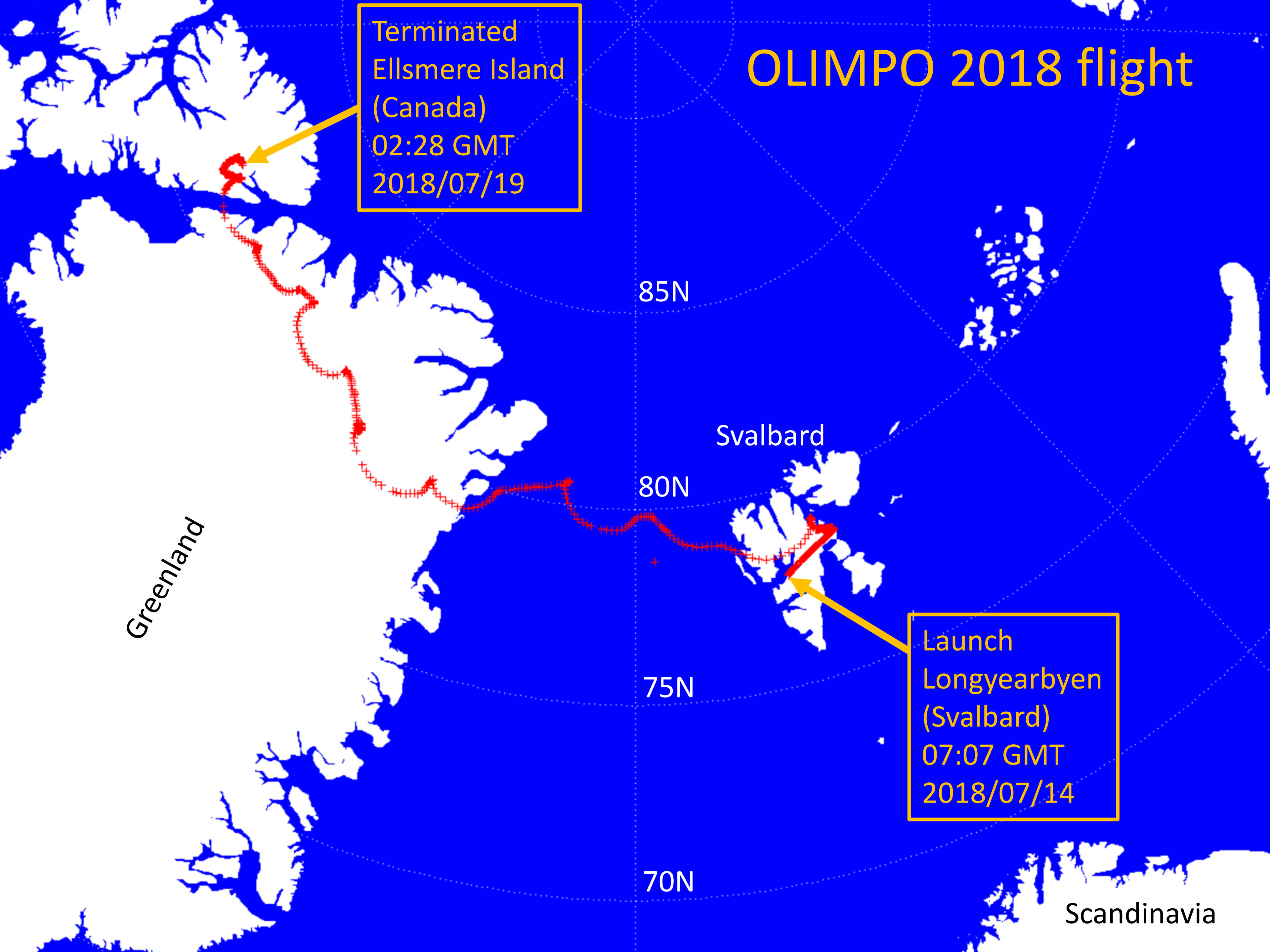
ABSTRACT

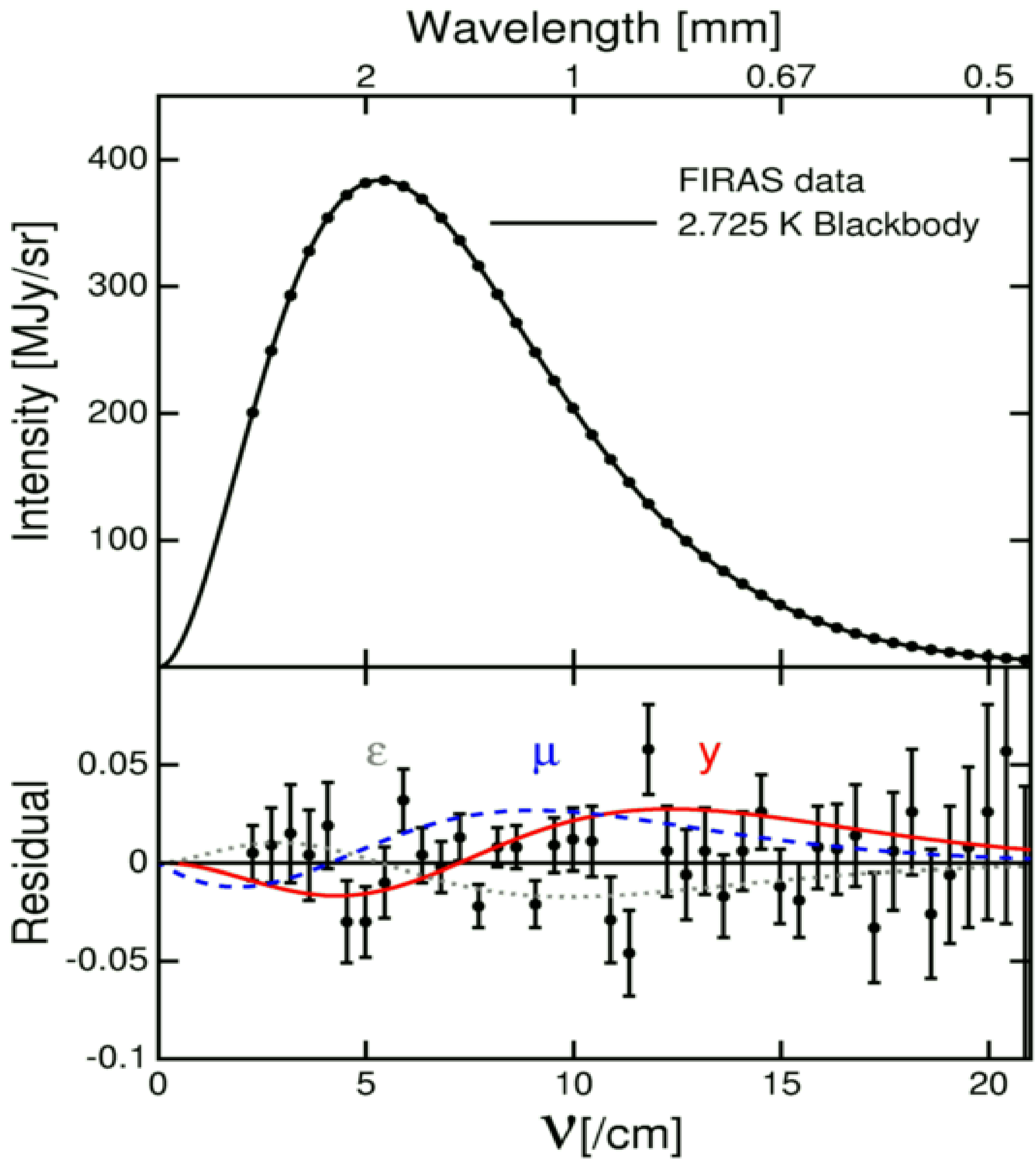
Context. The Sunyaev-Zel'dovich (SZ) effect is a powerful tool for studying clusters of galaxies and cosmology. Large mm-wave telescopes are now routinely detecting and mapping the SZ effect in a number of clusters, measure their comptonisation parameter and use them as probes of the large-scale structure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

OLIMPO

- 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


OLIMPO 2018 flight
Terminated
Ellsmere Island
(Canada)
02:28 GMT
2018/07/19
85N
80N
75N
70N
Svalbard
Greenland
Launch
Longyearbyen
(Svalbard)
07:07 GMT
2018/07/14
Scandinavia



Depending on the physical process, the expected spectral distortions have a different shape (ε, μ, 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).

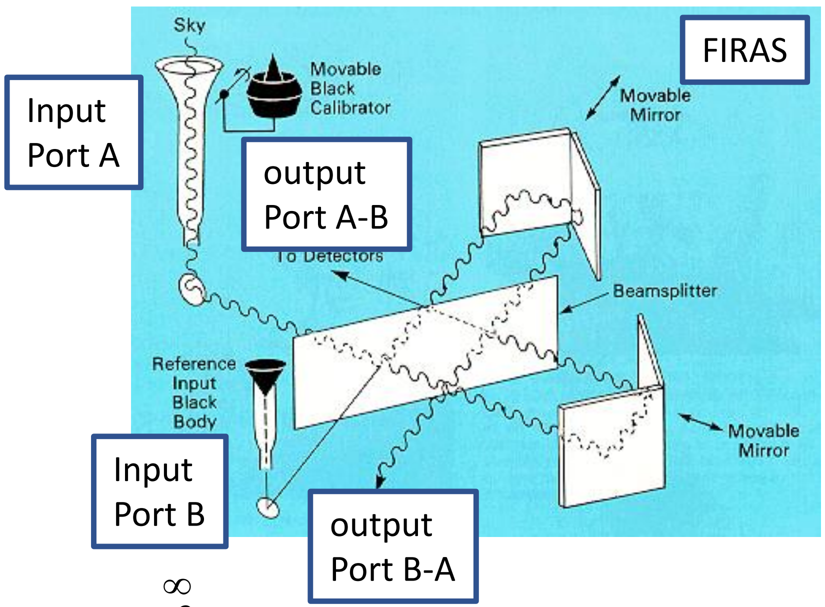
Current upper limits are at a level of 0.01% of the peak brightness of the CMB (COBE – FIRAS), Mather et al. (1990) Ap.J.L. 354 37

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 un 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

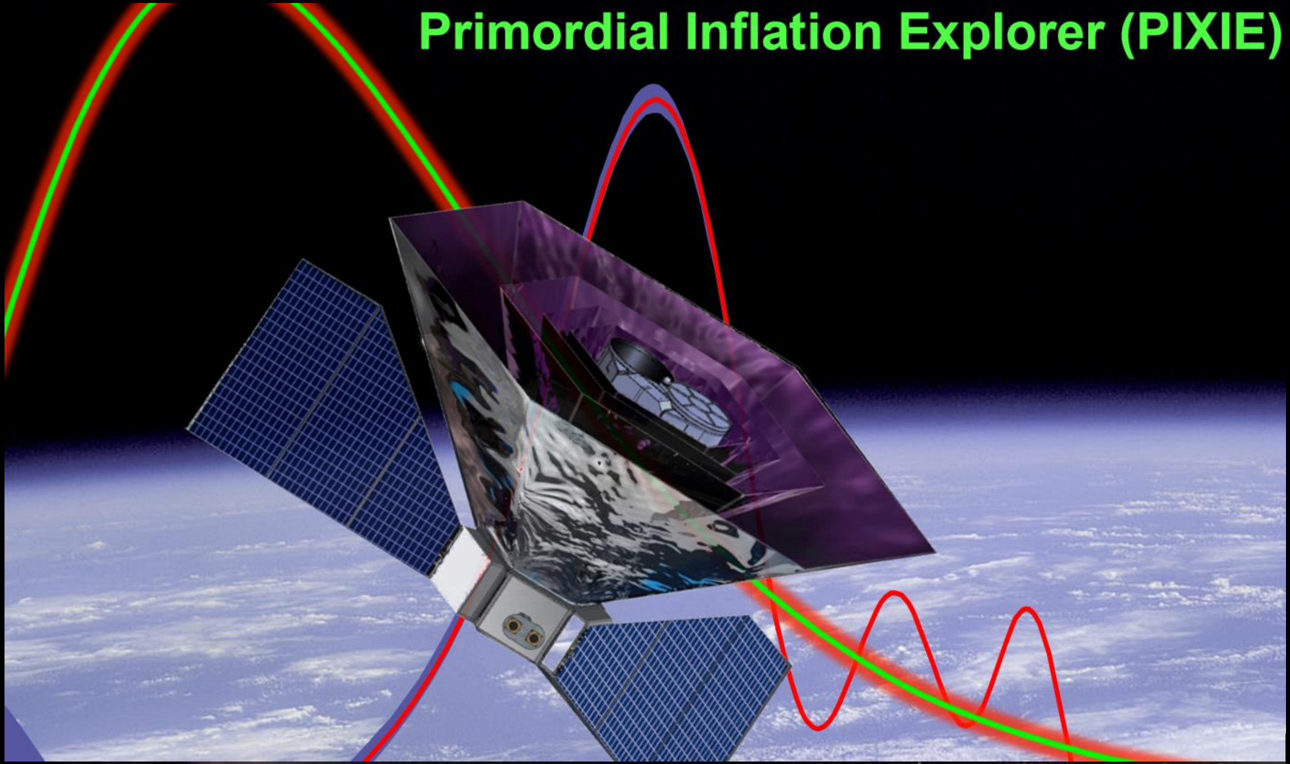


Sky measurement

$$I_{SKY}(x) = C\int_0^\infty [S_{SKY}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1 + \cos[4\pi\sigma x]\} d\sigma$$

Calibration measurement

$$I_{CAL}(x) = C\int_0^\infty [S_{CAL}(\sigma) - S_{REF}(\sigma)] rt(\sigma)\{1 + \cos[4\pi\sigma x]\} d\sigma$$



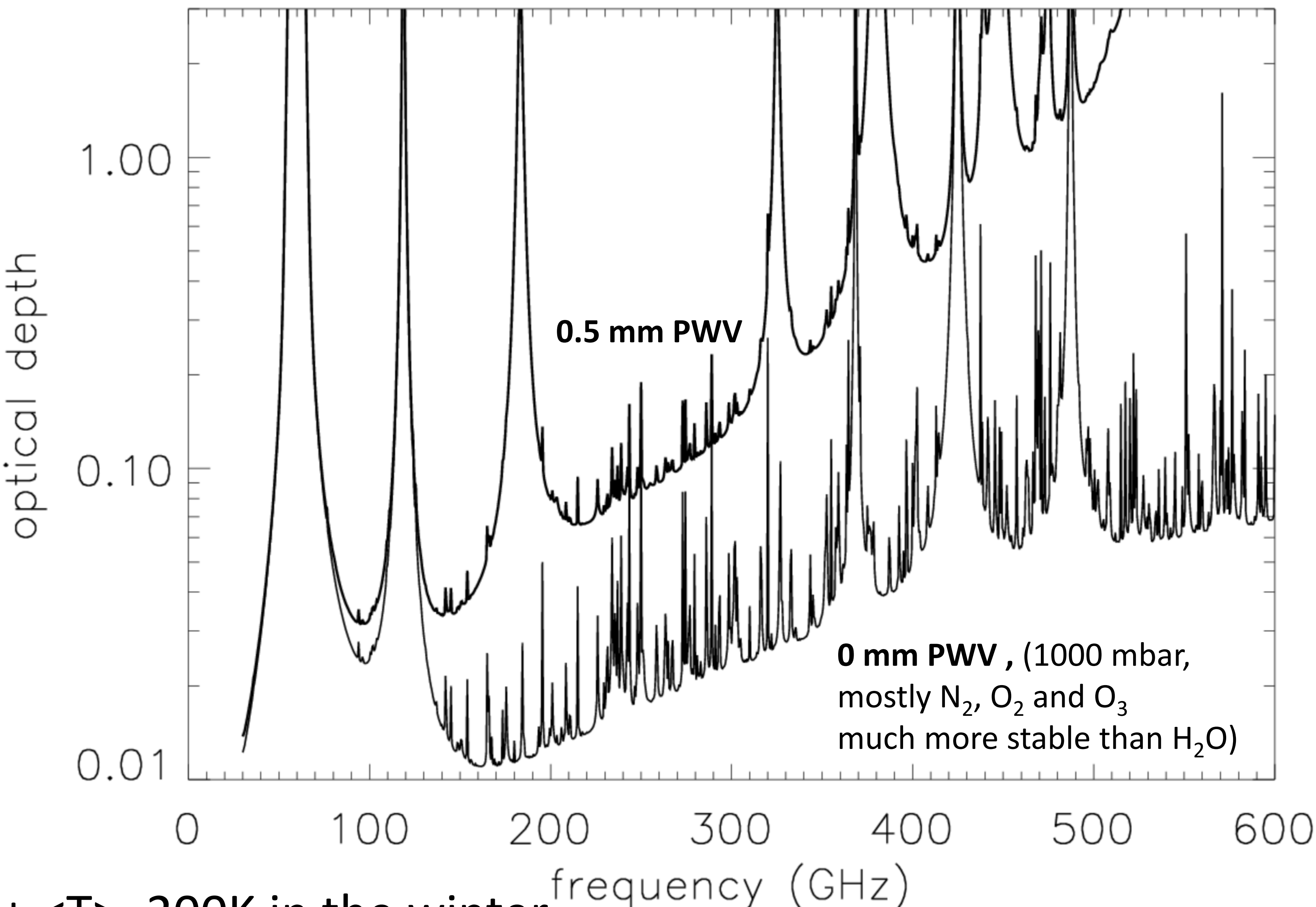
Satellite measurements can sample the CMB spectrum over the entire range 0-600 GHz.
PIXIE !!!
(*https://asd.gsfc.nasa.gov/pixie/*).

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 Soith Pole).

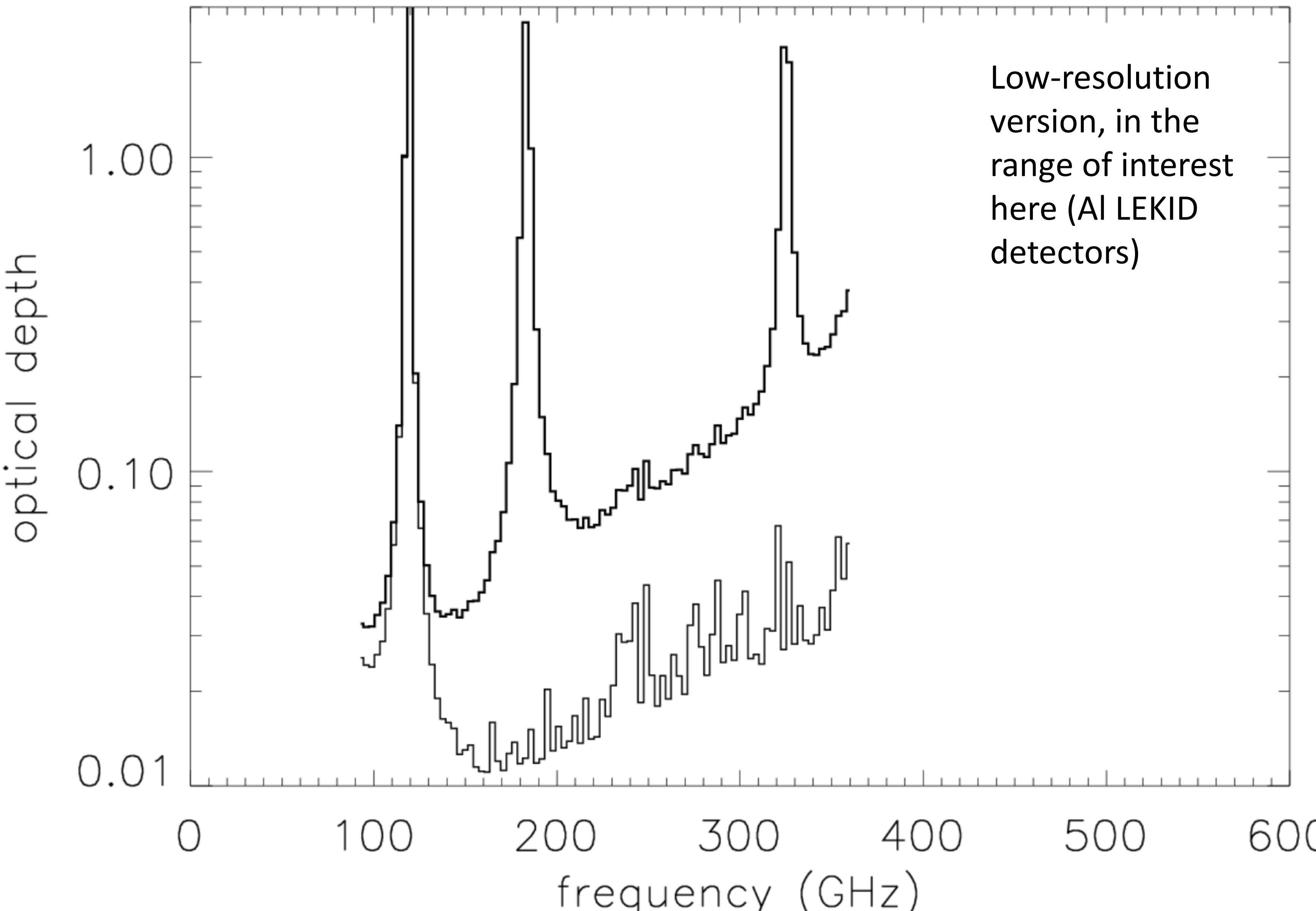
COSMO (COSmological Monopole Observer) targets this observable from Dome-C

Why Dome-C : optical depth of the atmosphere (credits : AM code)



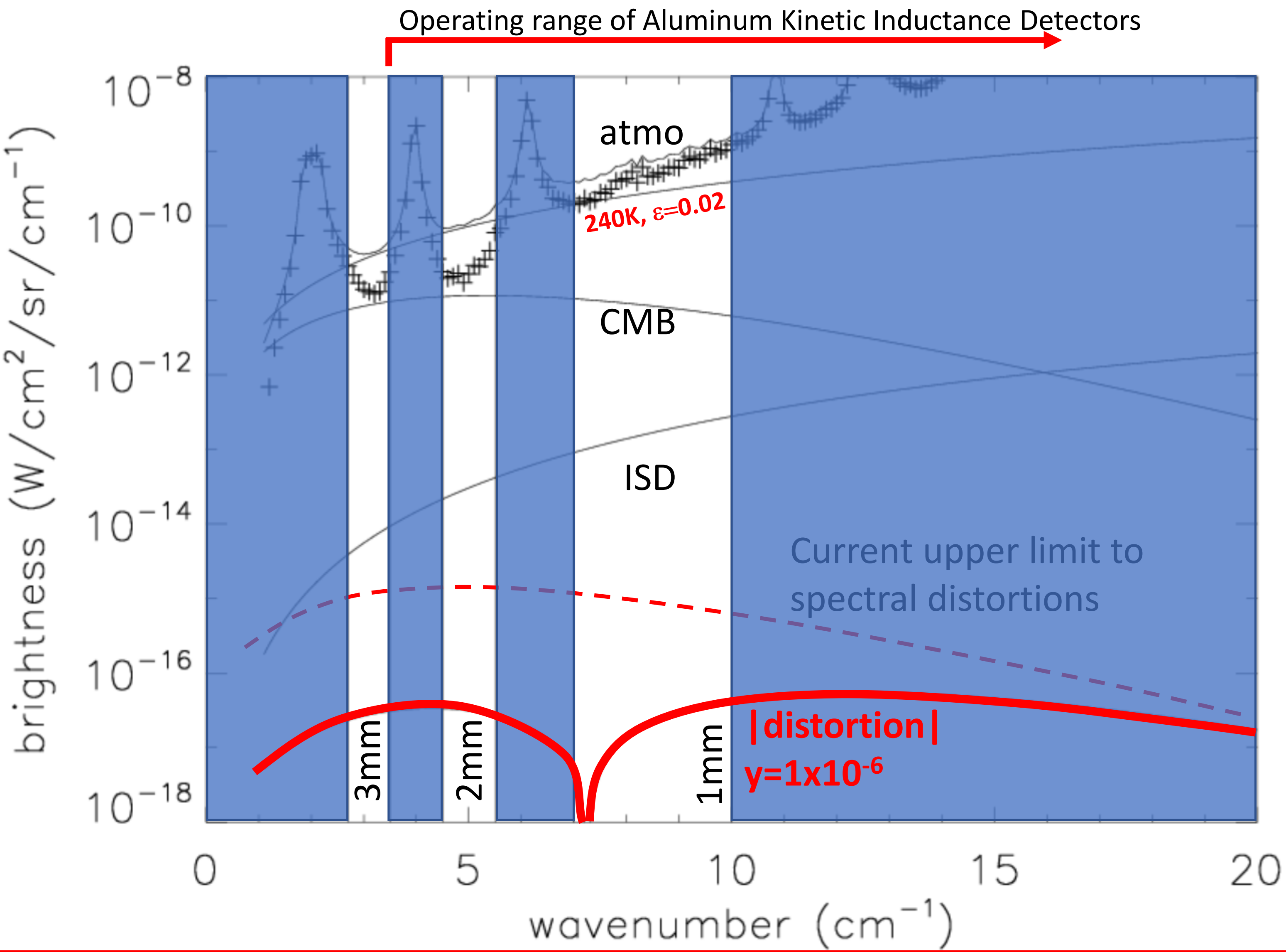
+ <T>=200K in the winter

Why Dome-C : optical depth of the atmosphere (credits : AM code)



Low-resolution version, in the range of interest here (Al LEKID detectors)

+ <T>=200K in the winter



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:

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

a NAIVE SIMULATION of the measurement performance is encouraging :

meas(ν) = atmo(ν) + CMB(ν) + ISD(ν) + distor($y=10^{-6}$,ν) - B_{ref} (300K, ν, ε=0.02) + noise (BLIP)
meas(ν) = atmo(ν) + CMB(ν) + ISD(ν) + distor($y=10^{-6}$,ν) - B_{ref} (1.65K,ν) + noise (BLIP)

Spectral template fitting procedure to detect spectral distortion:

fit(ν) = A*atmo(ν) + B*CMB(ν) + C*B_{ref} (1.65K,ν) + D*ISD(ν) + E*distor($y=10^{-6}$,ν)

HP: No 1/f (fast scan, see below)
Perfect knowledge of the spectral shape of atmospheric brightness (atmo(ν))

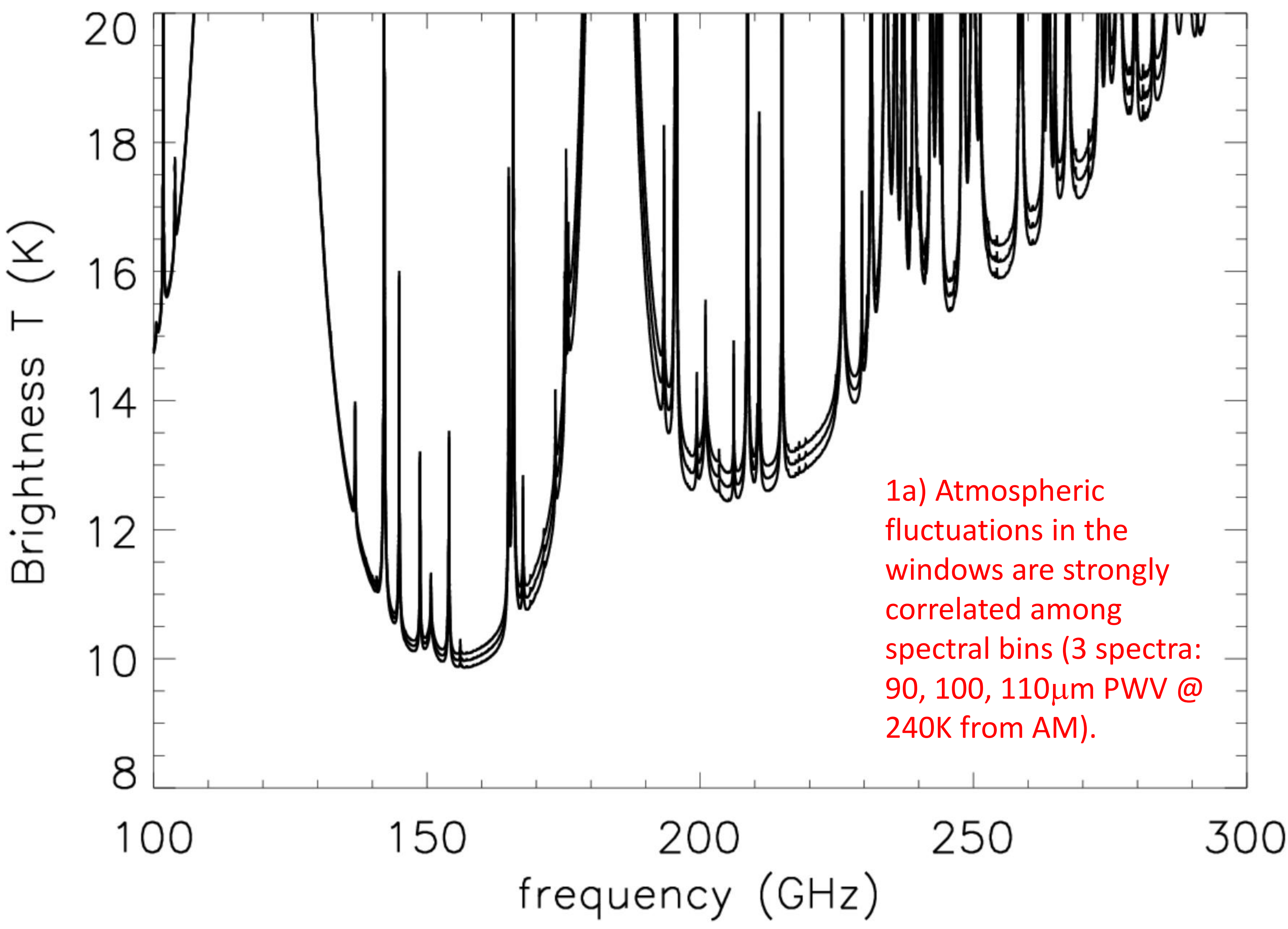
y parameter = 1.00e-06

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)

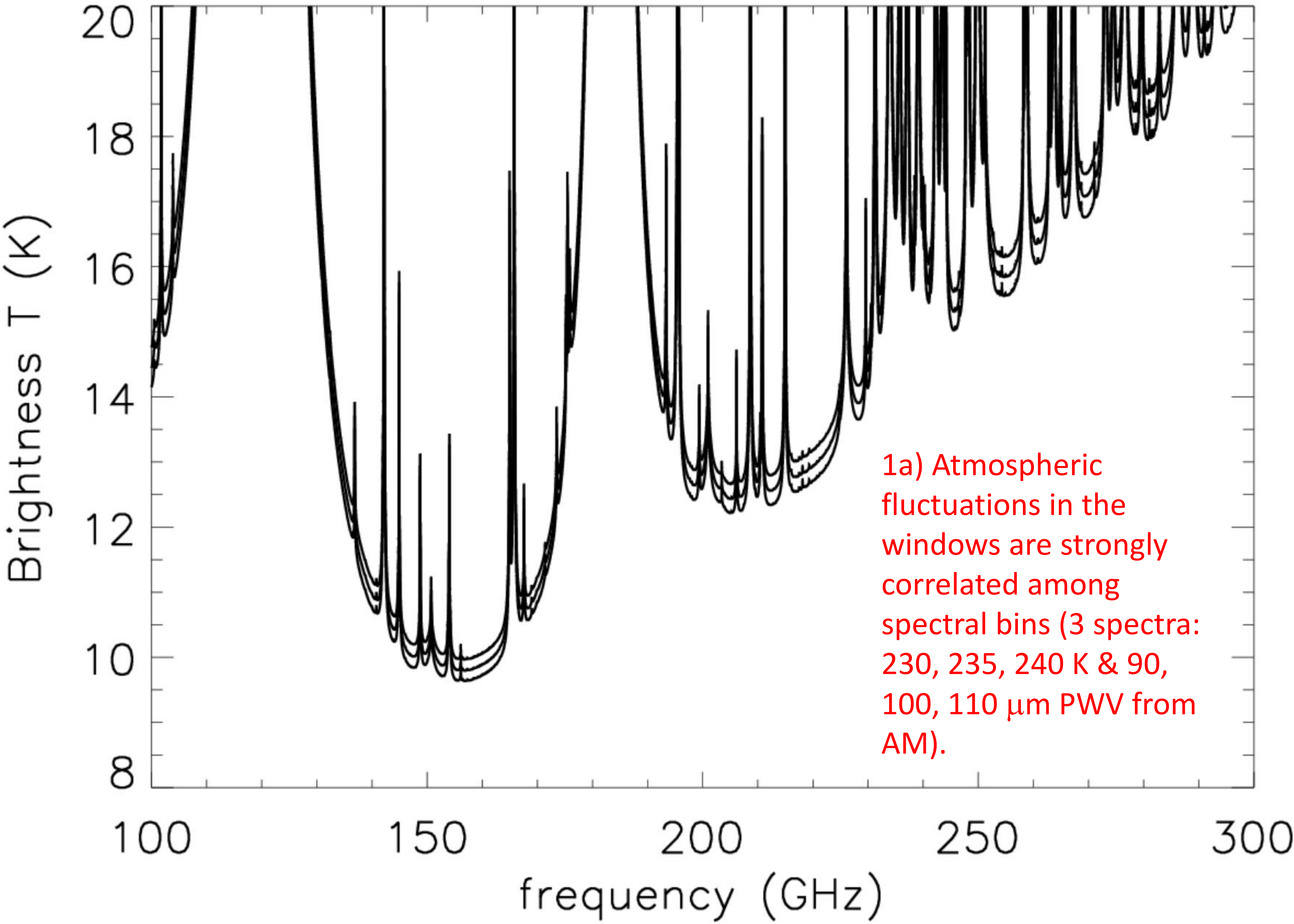
# of used spectral bins 40
A= atmos/model = 1.0000007 +/- 1.0019570e-006
B= cmb/model = 1.0000023 +/- 1.1284262e-006
C= refe/model = -0.99999581 +/- 2.1003349e-006
D= dust/model = 1.0000142 +/- 8.5398778e-006
E= DSZ/model = **1.21** +/- **0.11**
offset = -2.8e-017 +/- 1.4e-017

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

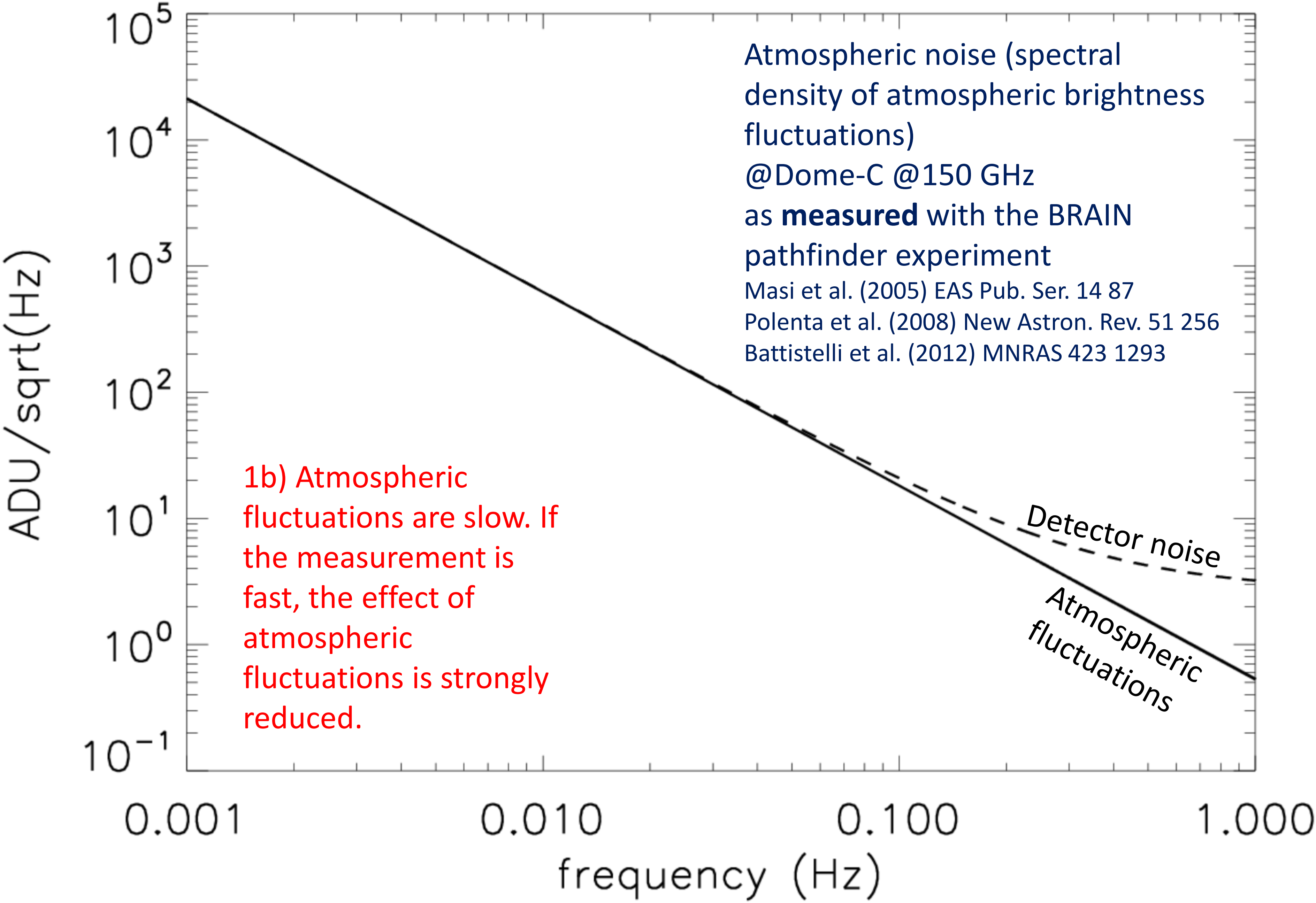
1. Assumed fractional fluctuations correlated, and very small. Is this reasonable ?
2. Perfect knowledge of the spectrum of the atmosphere is impossible. Any deviation from reality in the model will be interpreted as a spectral distortion. Can we find a way to actually *measure* the atmospheric contribution ?



Brightness T (K)
20
18
16
14
12
10
8
100
150
200
250
300
frequency (GHz)
1a) 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).
Brightness T (K)
frequency (GHz)
20
18
16
14
12
10
8
100
150
200
250
300



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
Polenta et al. (2008) New Astron. Rev. 51 256
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.
Detector noise
Atmospheric fluctuations
ADU/sqrt(Hz)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.001
0.010
0.100
1.000
frequency (Hz)

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

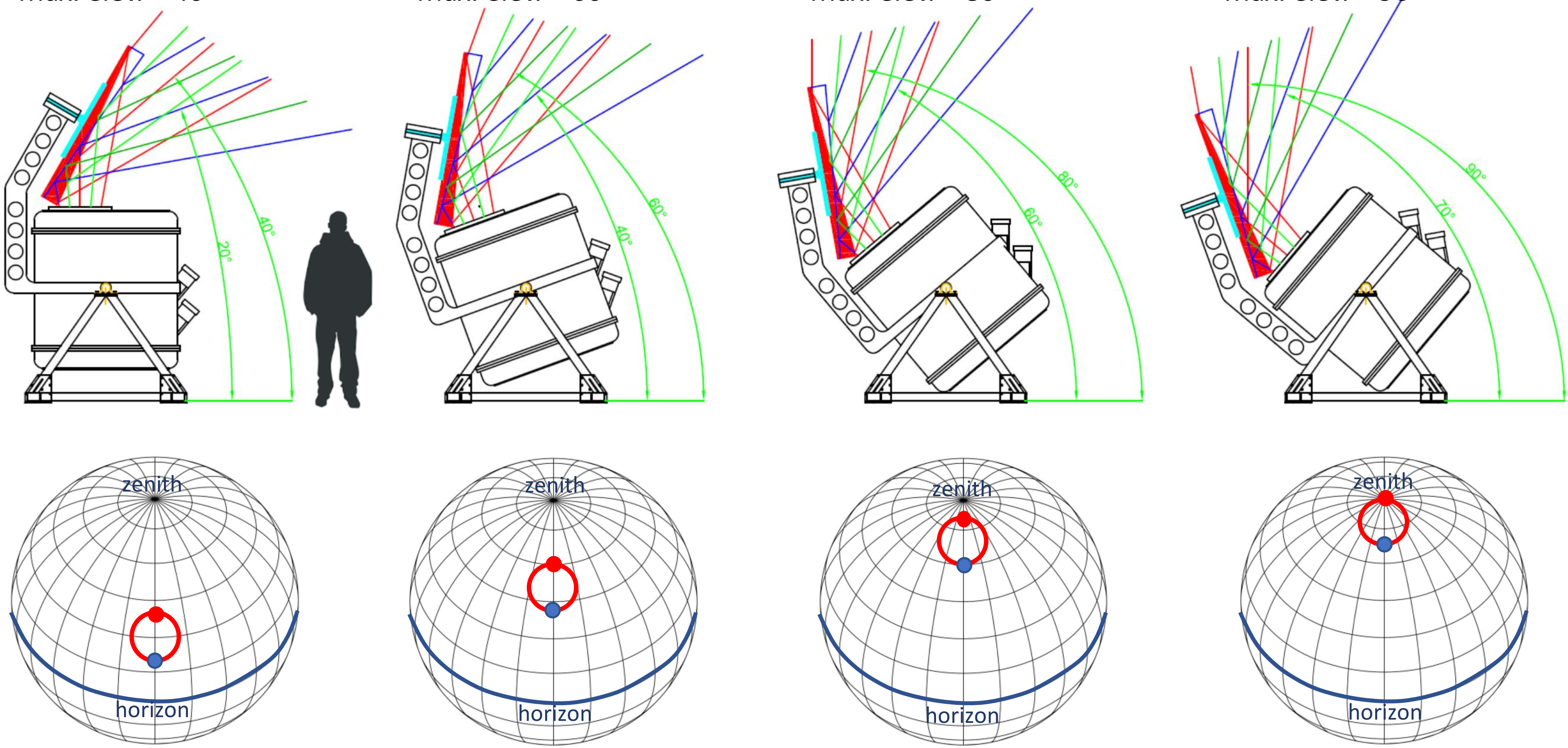
Oversized (1.6m diameter), spinning flat mirror, 10° wedge (red/blue)
To scan circles (D=5°-20°) in the sky modulating atmospheric emission.
Center elevation ranges between 30° and 80° depending on cryostat tilt.

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°



COSMO measurement timing

Exploits the availability of fast detectors (Kinetic Inductance Detectors - KIDs) and the know how of racing cars to beat atmospheric noise

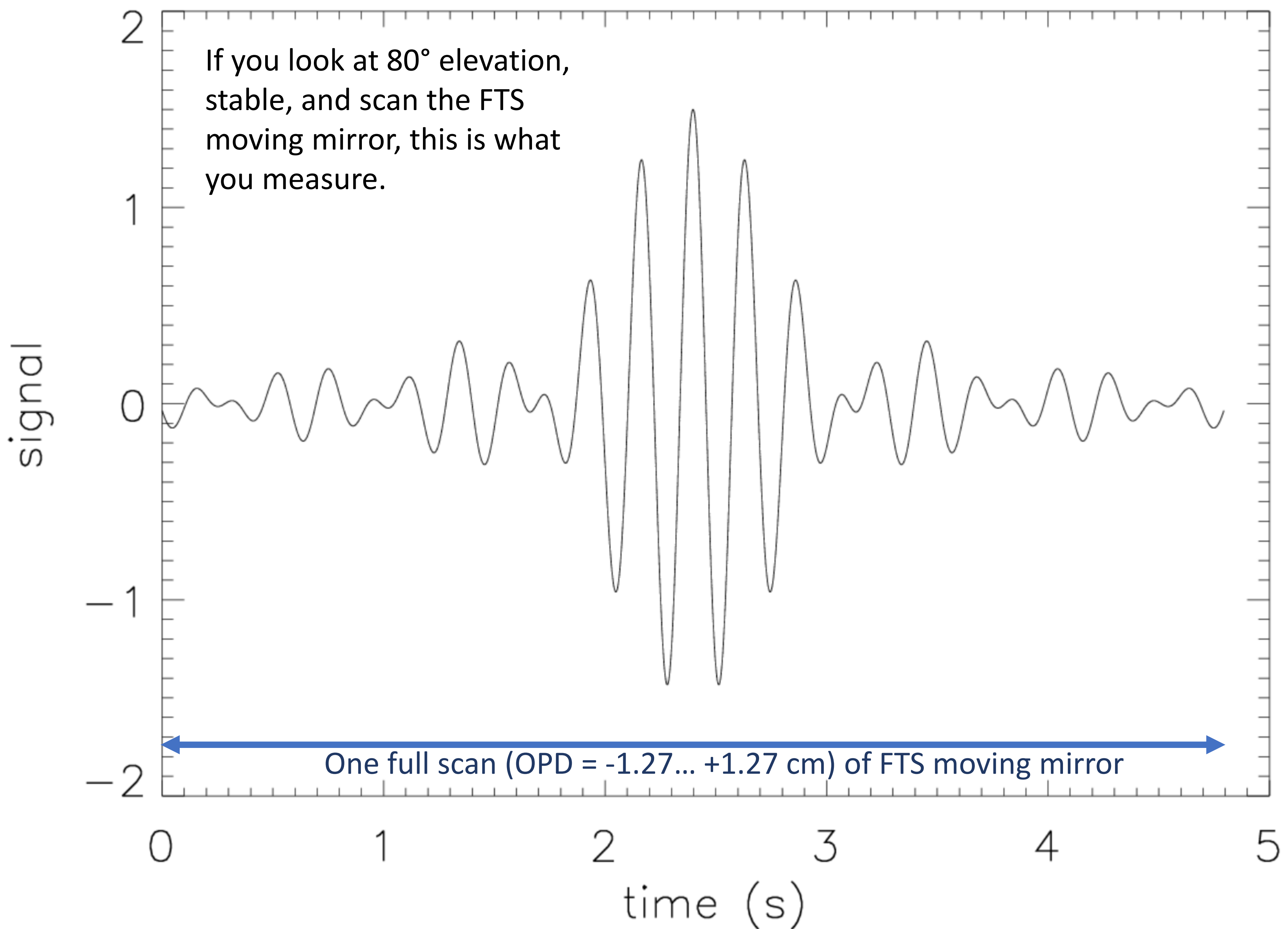
detector performance		
detector time constant	**5.00E-05**	**s**
5 time constants	2.50E-04	s
NET	100	uK/sqrt(Hz)
noise per sample	6.3	mK

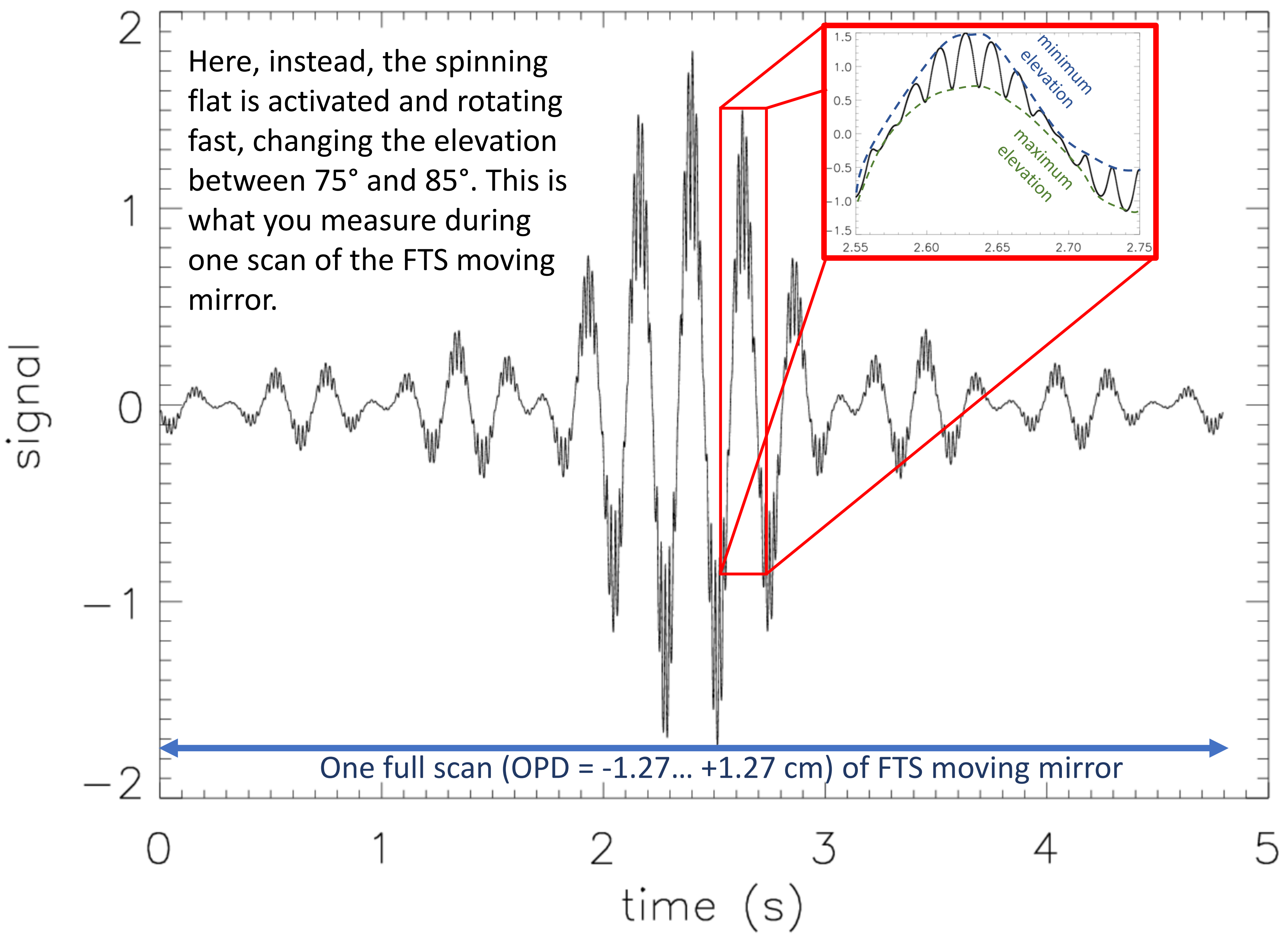
interferogram scan fast		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	0.064	s
interferograms per second	15.6	
mirror scan mechanism period	0.13	s
sky scan slow		
circle radius	5	deg
circle length	31.4	deg
beam size	0.5	deg
number of samples per circle (3 per beam)	188	
time per beam	0.192	s
time for 2 sky dips (downwards + upwards)	36.19	s
wedge mirror rotation rate	1.66	rpm
sky stability required for	18.10	s

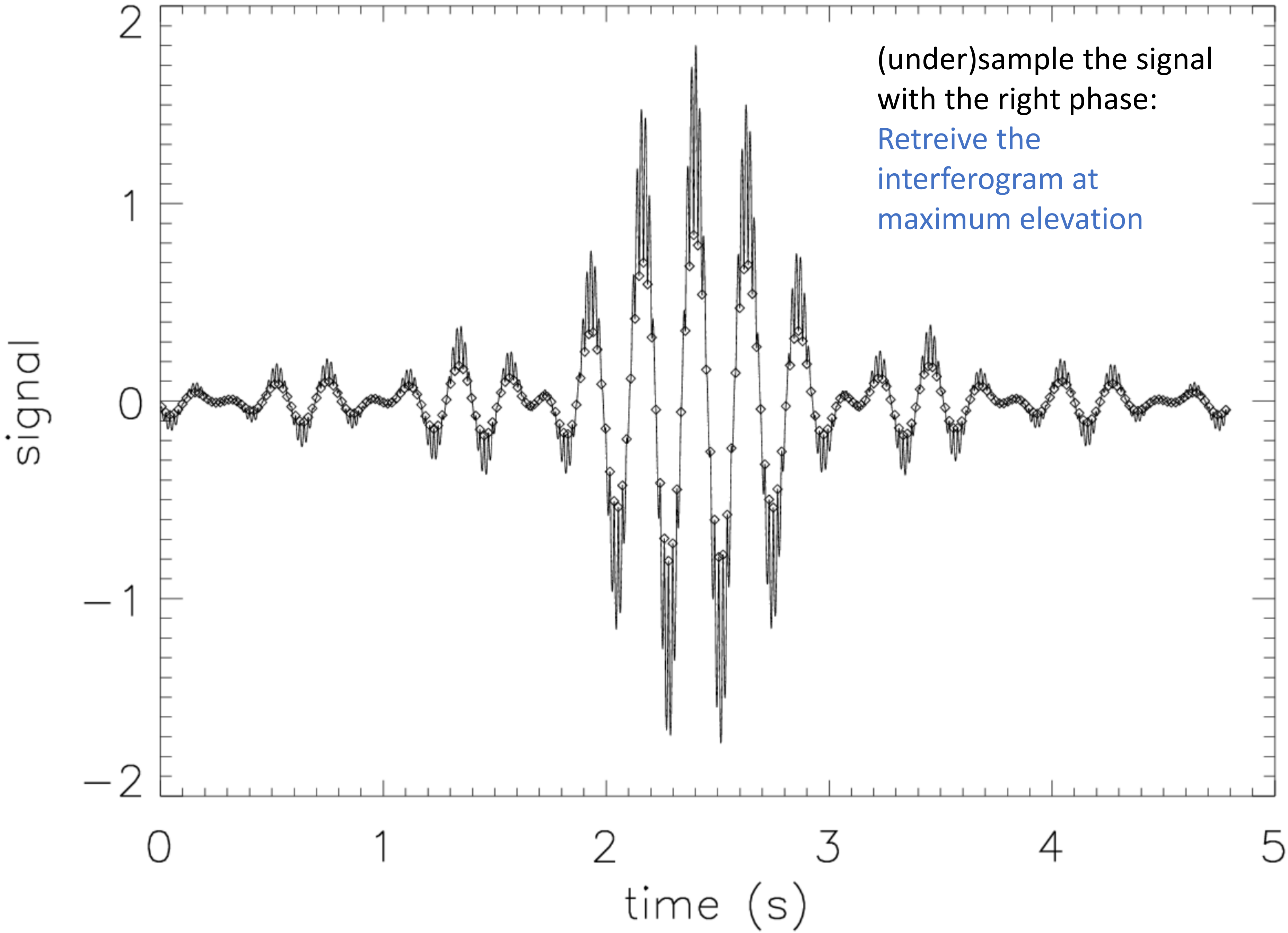
sky scan fast		
circle radius	5	deg
circle length	31.4	deg
beam size	1	deg
number of samples per circle (3 per beam)	94	
time per beam	2.50E-04	s
time for 2 sky dips (downwards + upwards)	2.36E-02	s
wedge mirror rotation rate	2546	rpm
interferogram scan slow		
maximum wavenumber (Nyquist)	20	cm-1
sampling step	0.0125	cm
resolution	6	GHz
resolution	0.200	cm-1
number of frequency samples	100	
number of samples in double-sided interferogram	256	
time to complete an interferogram	6.032	s
interferograms per second	0.2	
mirror scan mechanism period	12.06	s
sky stability required for	**6.03**	**s**

- This configuration requires a fast cryogenic mirror scanning mechanism
- High dissipation in the cryo system

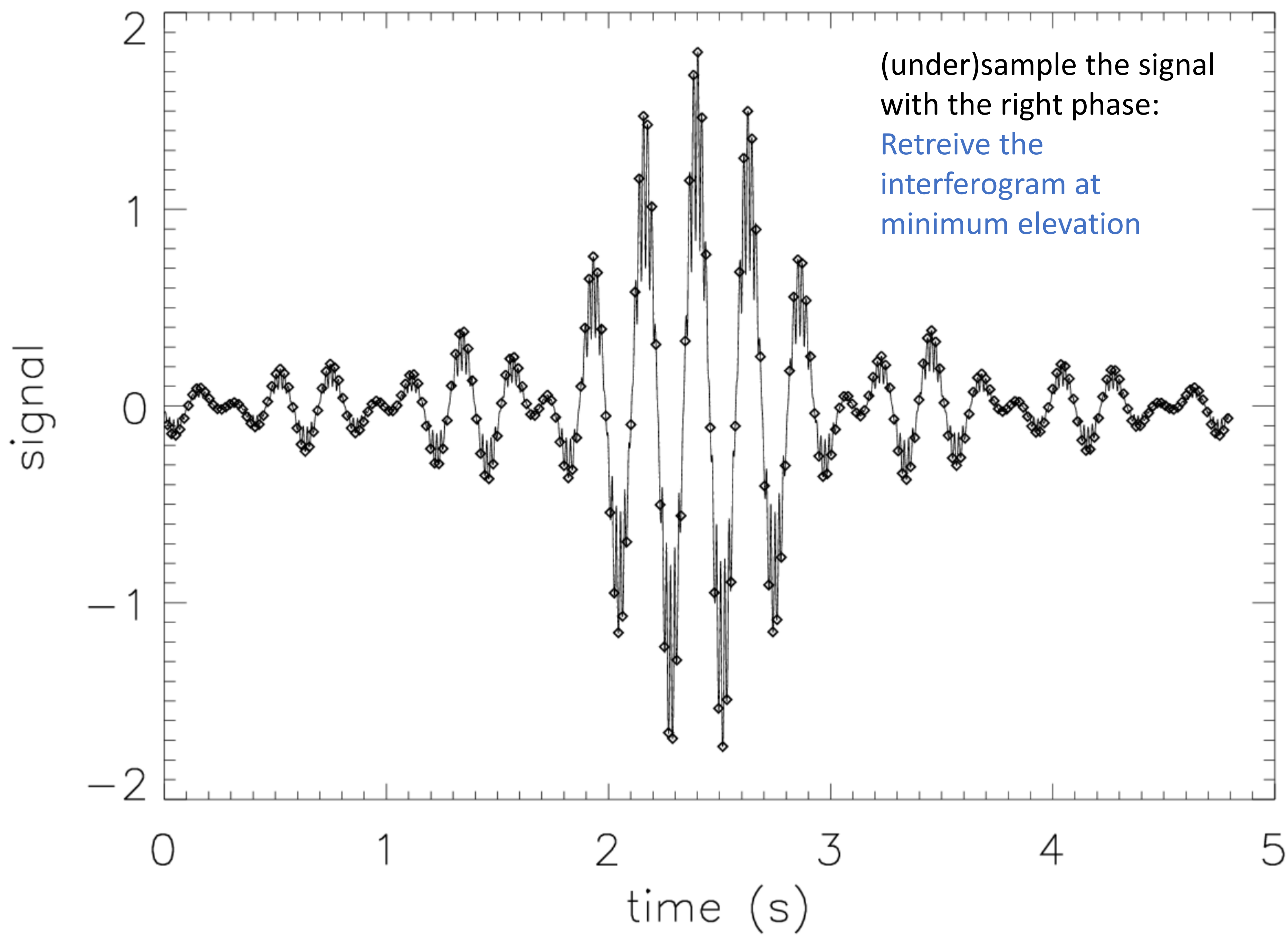
- This configuration requires a fast room-temperature mirror rotation device
- Not impossible.


If you look at 80° elevation, stable, and scan the FTS moving mirror, this is what you measure.
One full scan (OPD = -1.27… +1.27 cm) of FTS moving mirror
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5

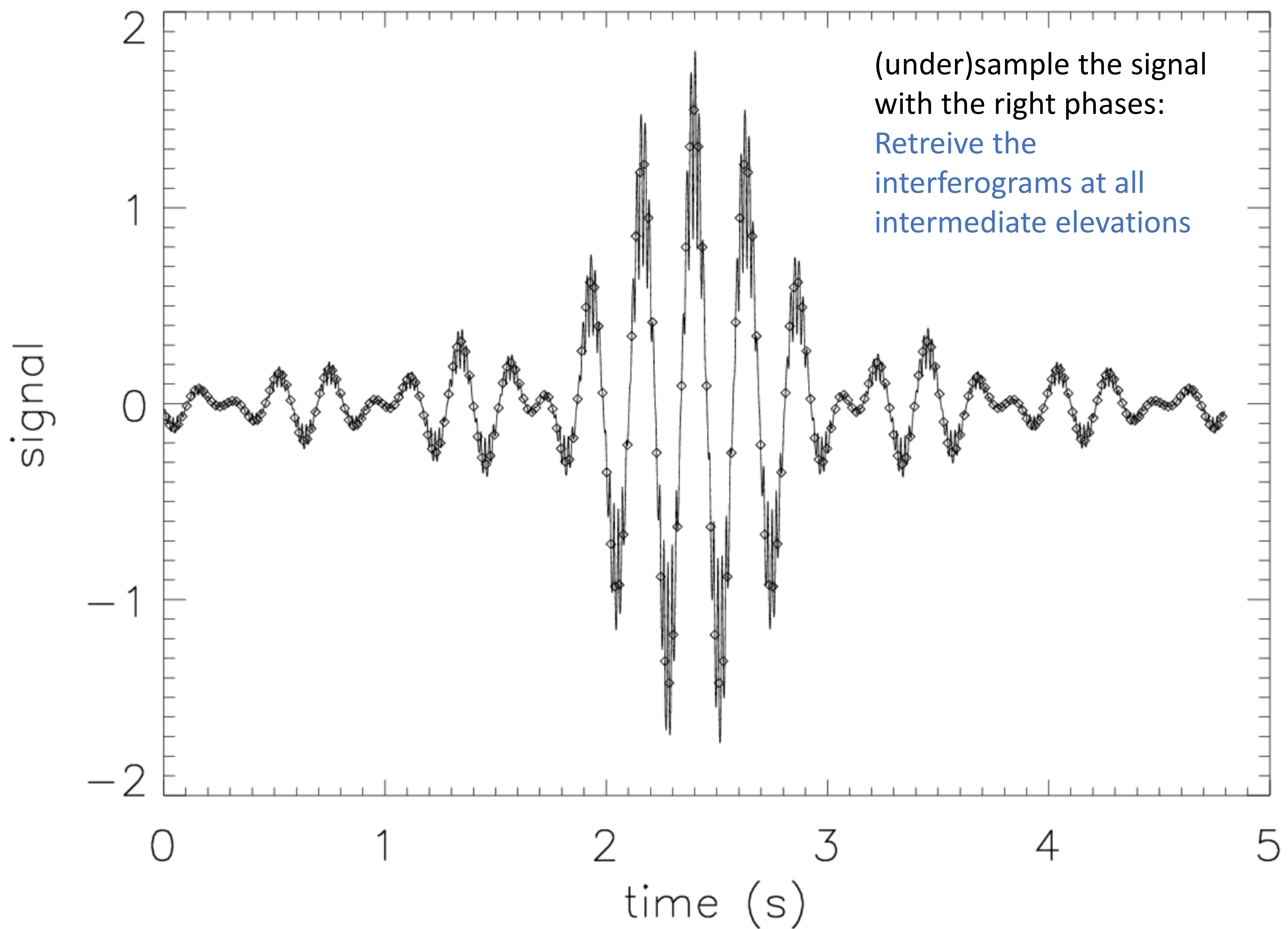

Here, instead, the spinning flat is activated and rotating fast, changing the elevation between 75° and 85°. This is what you measure during one scan of the FTS moving mirror.
minimum elevation
maximum elevation
One full scan (OPD = -1.27... +1.27 cm) of FTS moving mirror
signal
time (s)



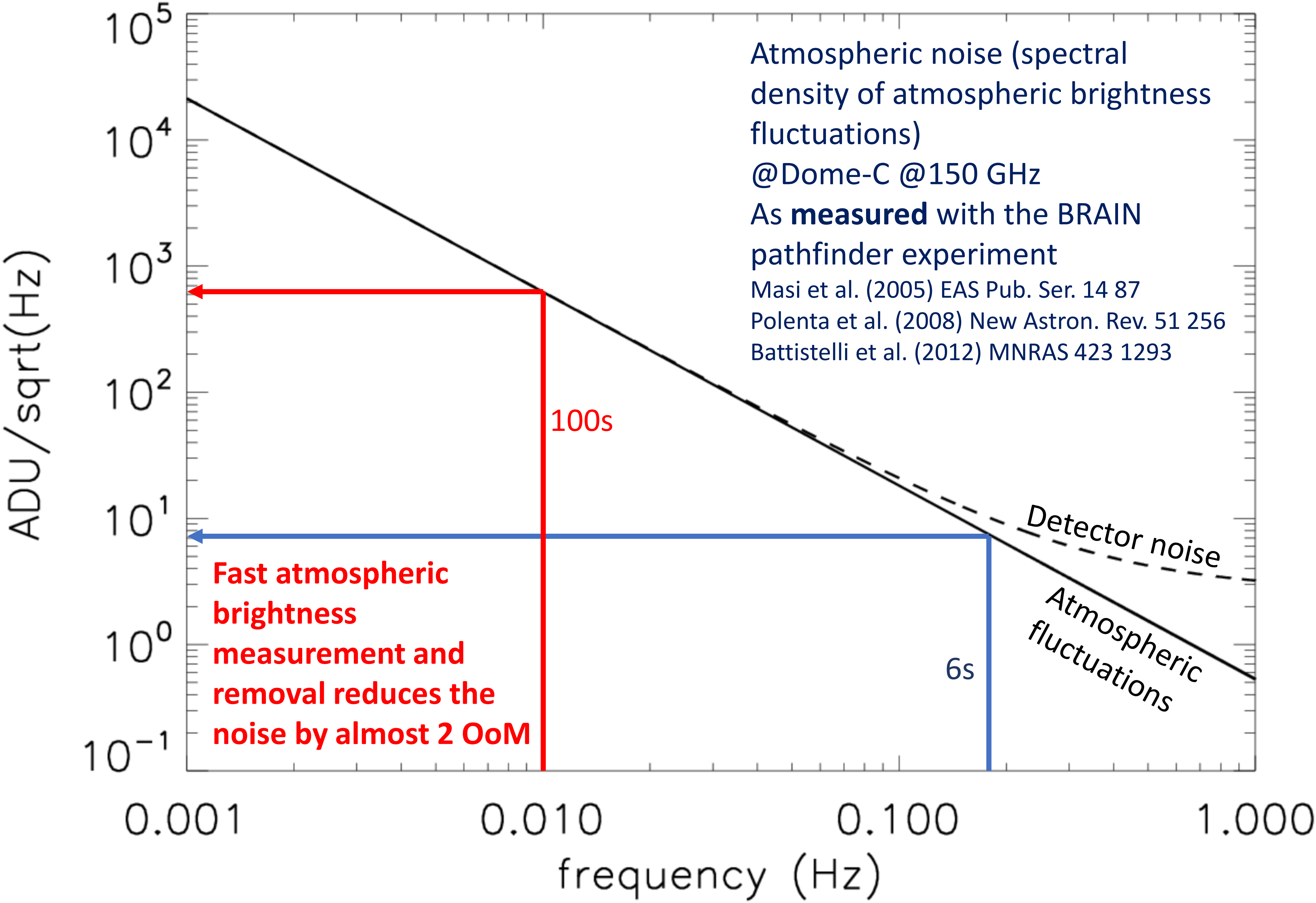
(under)sample the signal
with the right phase:
Retreive the
interferogram at
maximum elevation
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5



(under)sample the signal
with the right phase:
Retreive the
interferogram at
minimum elevation
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5



(under)sample the signal
with the right phases:
Retreive the
interferograms at all
intermediate elevations
signal
time (s)
2
1
0
−1
−2
0
1
2
3
4
5



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
Polenta et al. (2008) New Astron. Rev. 51 256
Battistelli et al. (2012) MNRAS 423 1293
100s
6s
Detector noise
Atmospheric fluctuations
Fast atmospheric brightness measurement and removal reduces the noise by almost 2 OoM
ADU/sqrt(Hz)
frequency (Hz)
0.001
0.010
0.100
1.000

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

$$B(\nu, e) = B(T_{atm}, \nu)\left(1 - e^{-\tau(\nu,e)}\right) + B_{sky} e^{-\tau(\nu,e)} - B(T_{ref}, \nu).$$

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

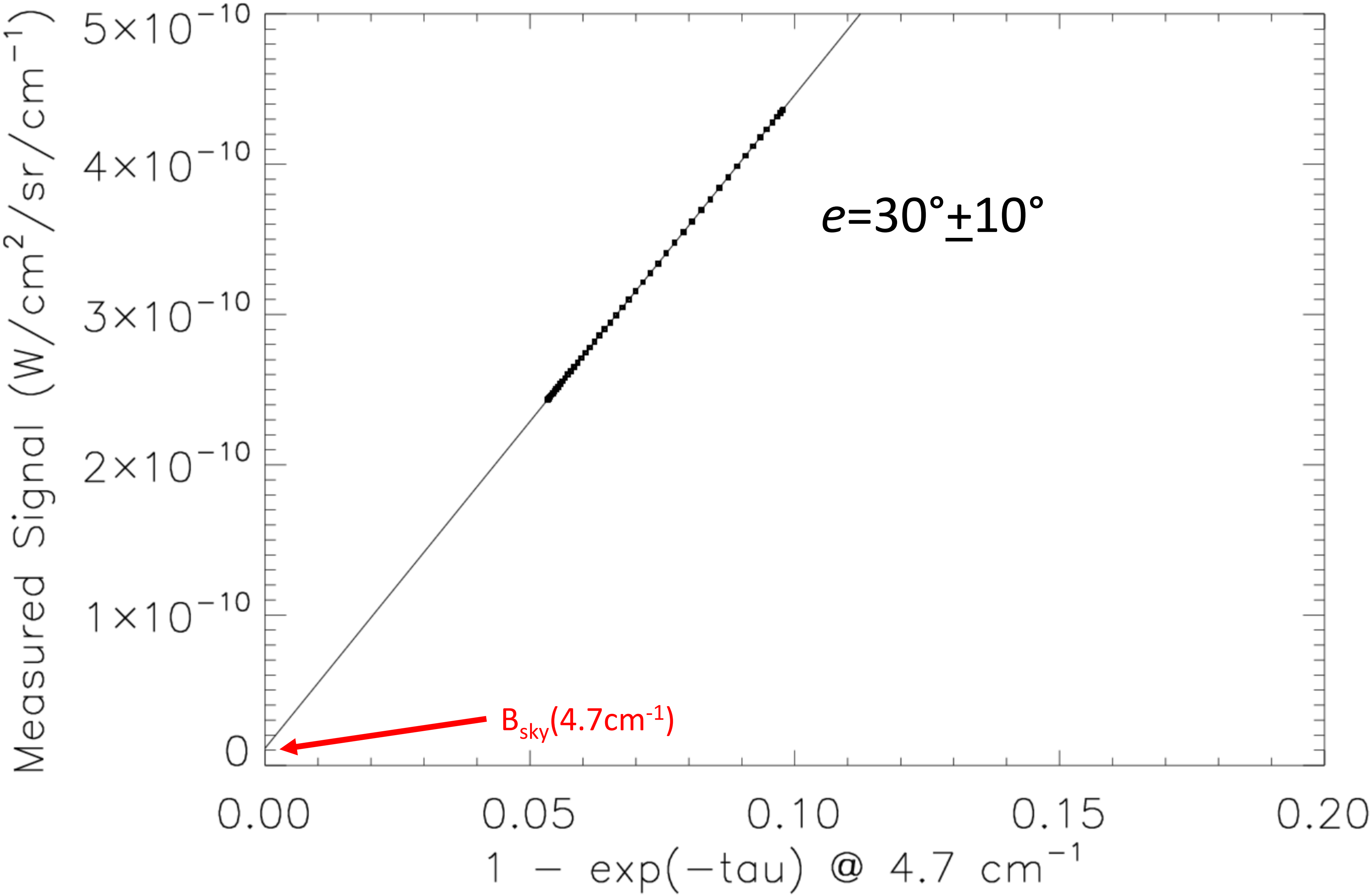
$$x = 1 - \exp(-\tau_z(\nu)/\cos(e))$$

$$B_{sky}(\nu) - B(T_{ref}, \nu) = a(\nu)$$

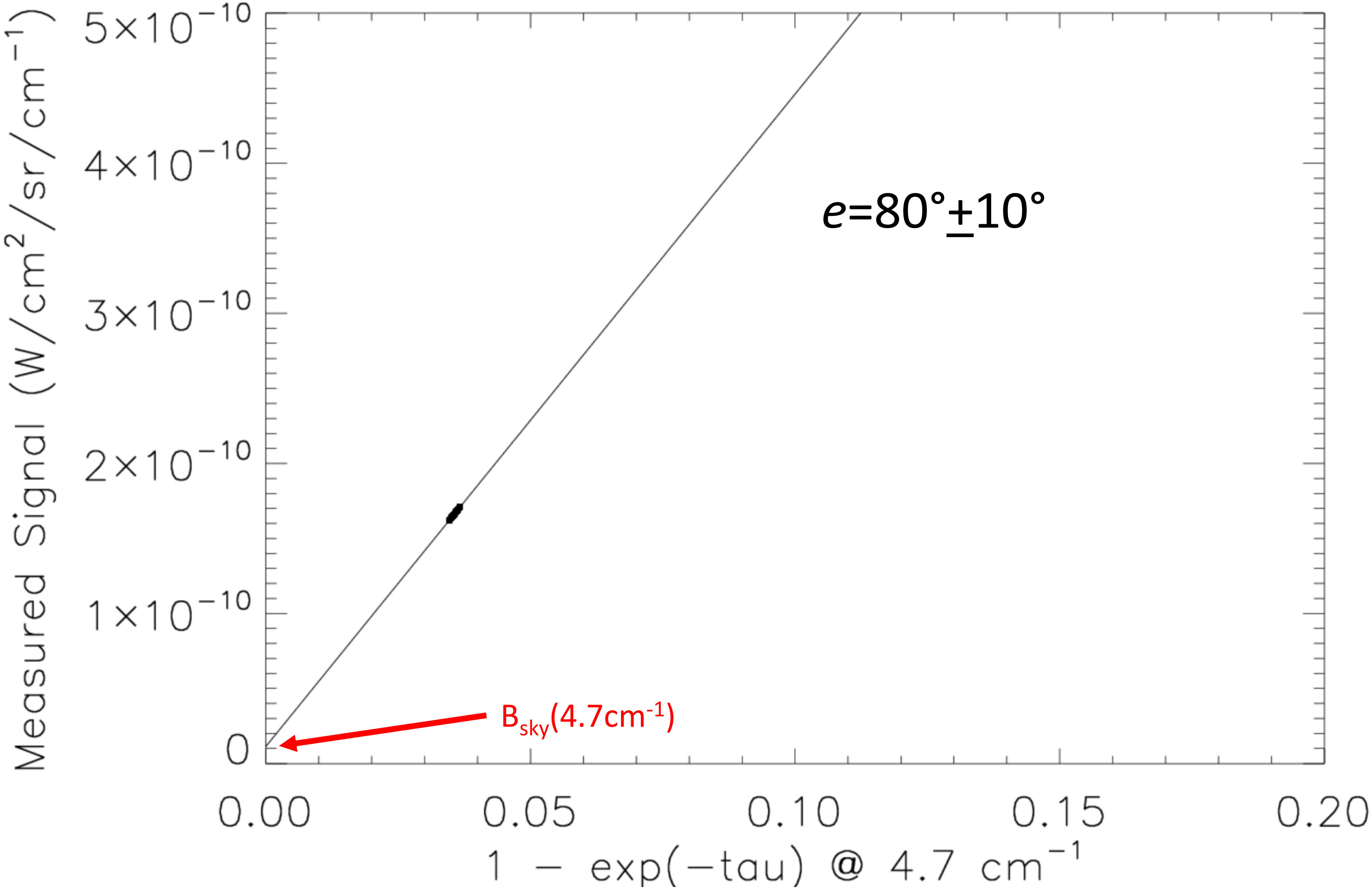
$$B(T_{atm}, \nu) = b(\nu) + a(\nu)$$

- 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.

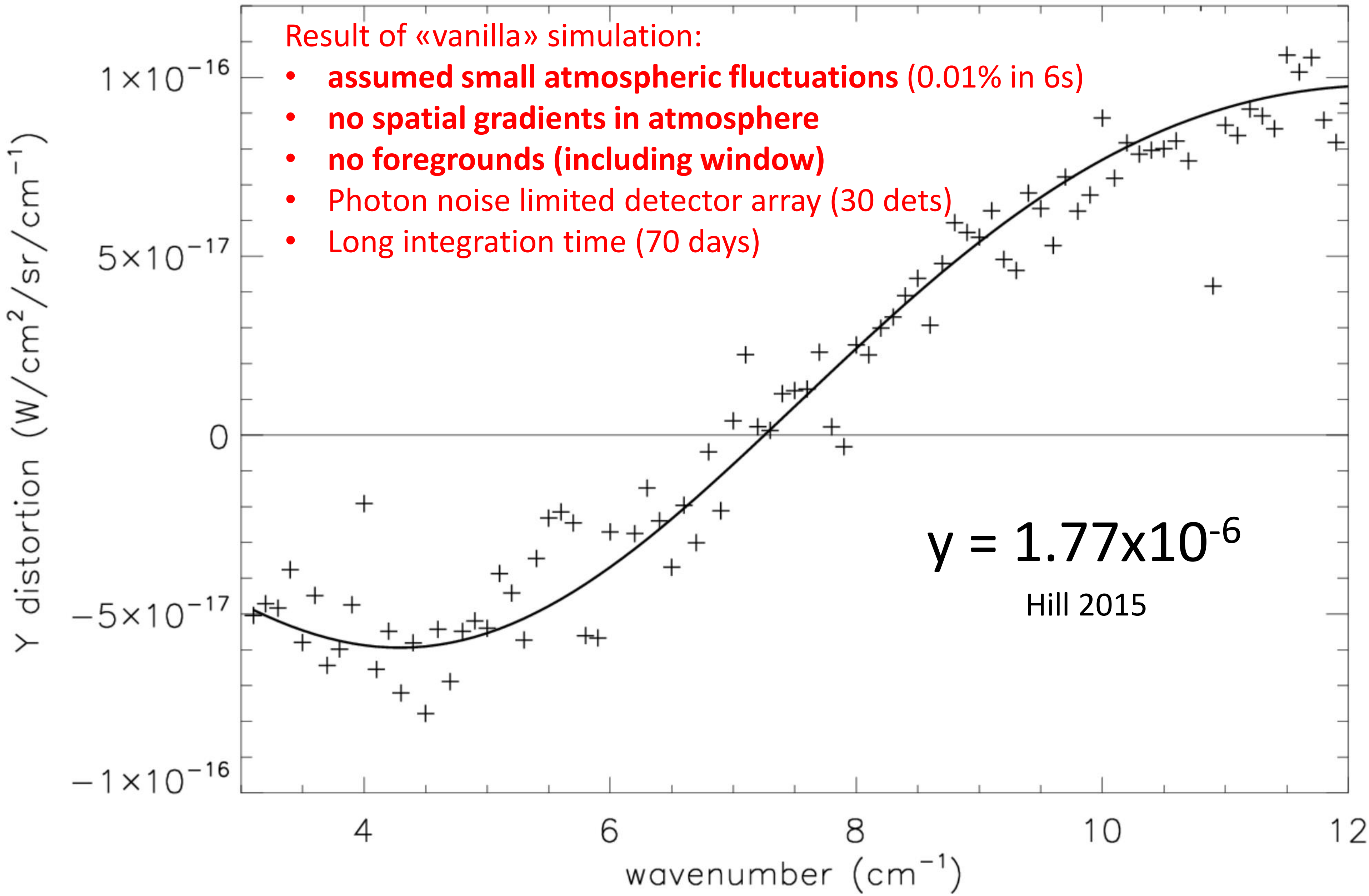
COSMO sky / atmosphere scan simulations



COSMO sky / atmosphere scan simulations



COSMO sky / atmosphere scan simulations

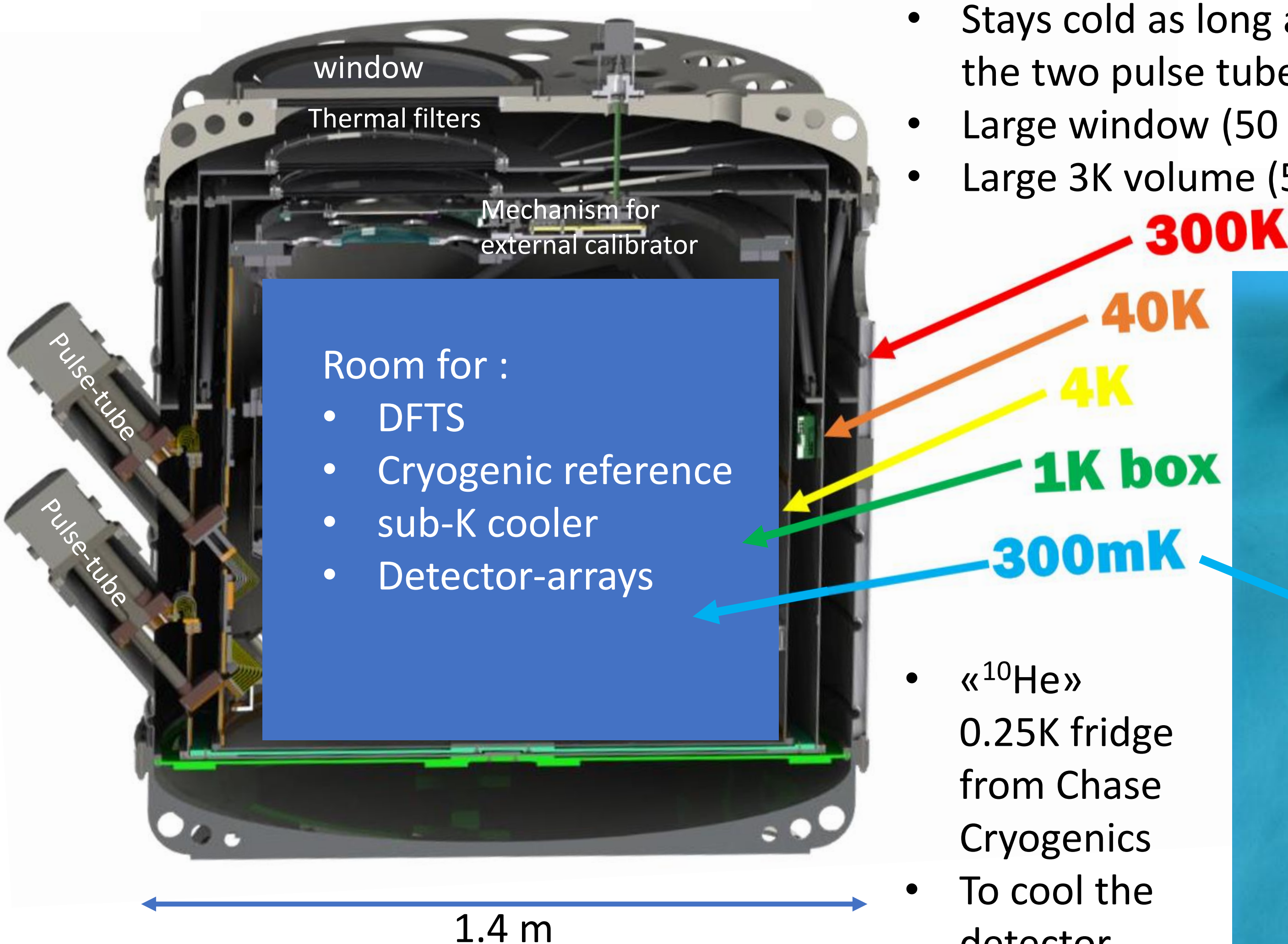


COSMO implementation

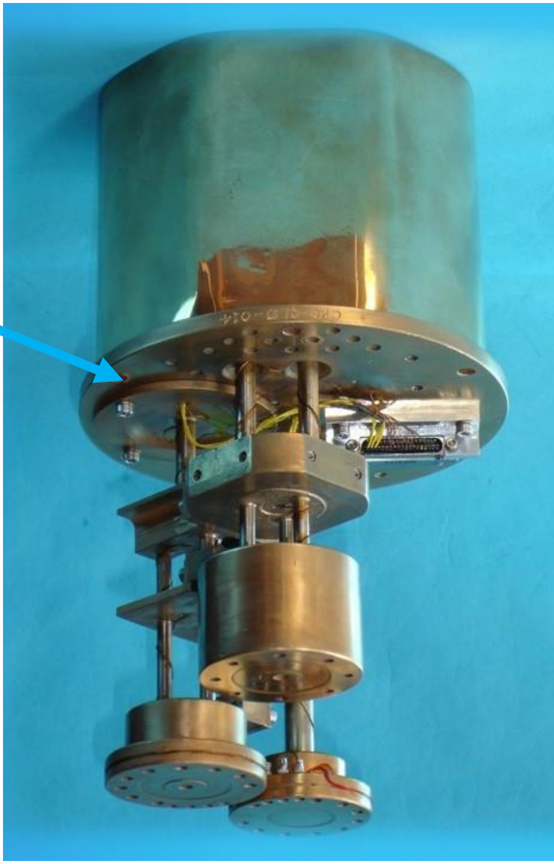
- As of today, still moving from *concept* into *instrument design*
- However:
  - PNRA proposal funded to provide cryogeinc system, optics, and logistic support for the Concordia base (PI Silvia Masi, partner institutions UniMI (Mennella), UniMIB (Zannoni))
  - PNRA proposal funded to support development 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)



- «^{10}He» 0.25K fridge from Chase Cryogenics
- To cool the detector arrays



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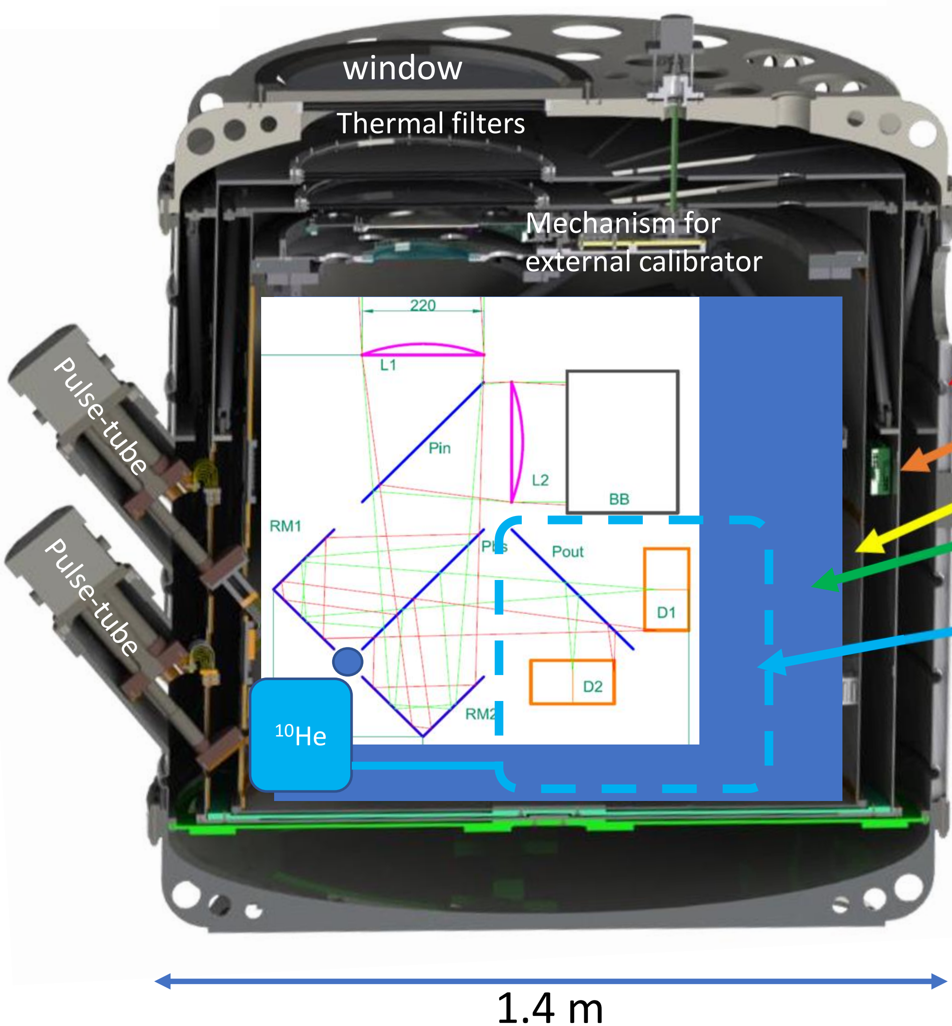

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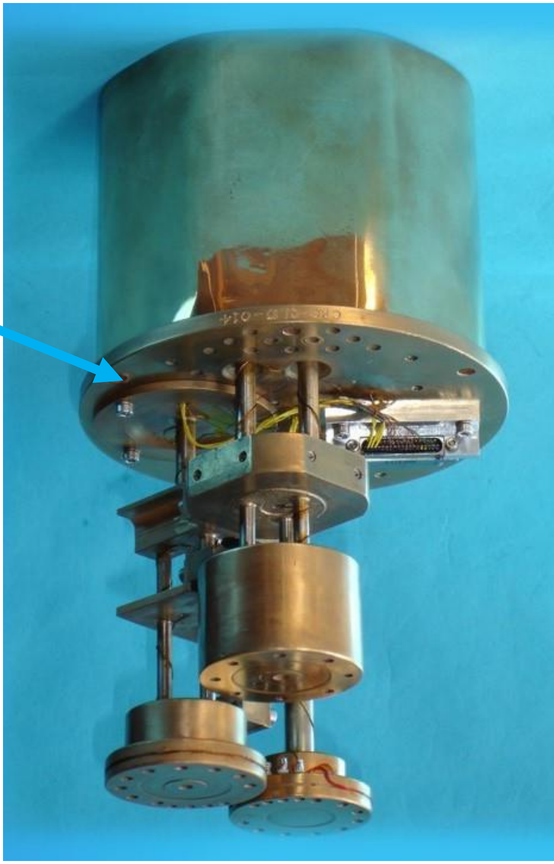
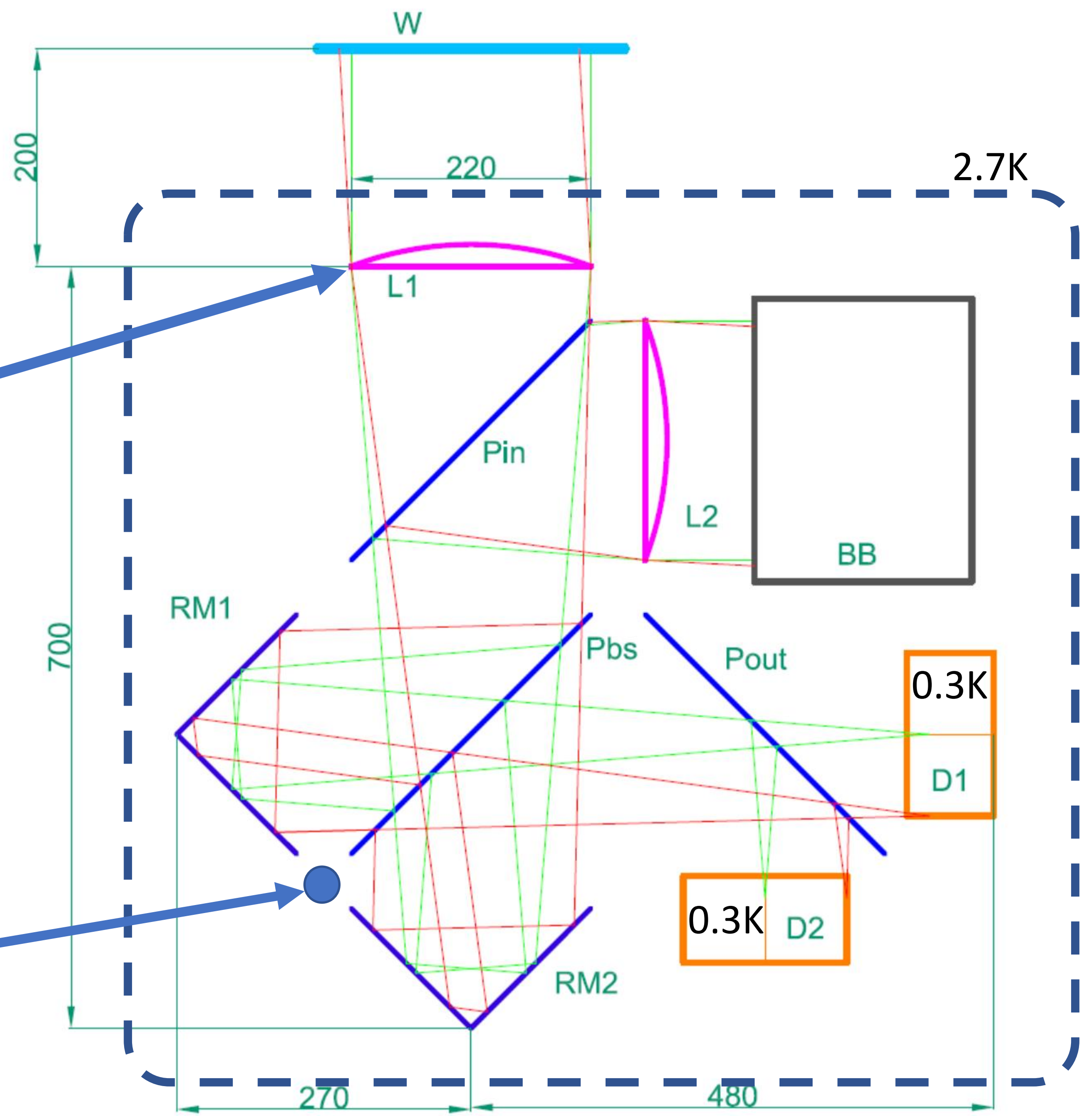


COSMO instrument basic design

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

Pivot for double pendulum design



COSMO continuous cryogenics

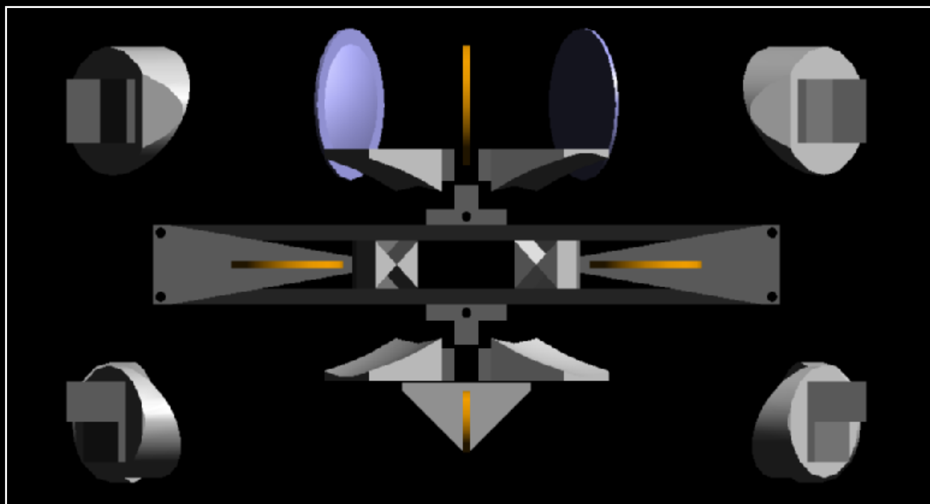
COSMO continuous cryogenics

WP3200: Cryogenic operation of a double pendulum

Sapienza Università di Roma

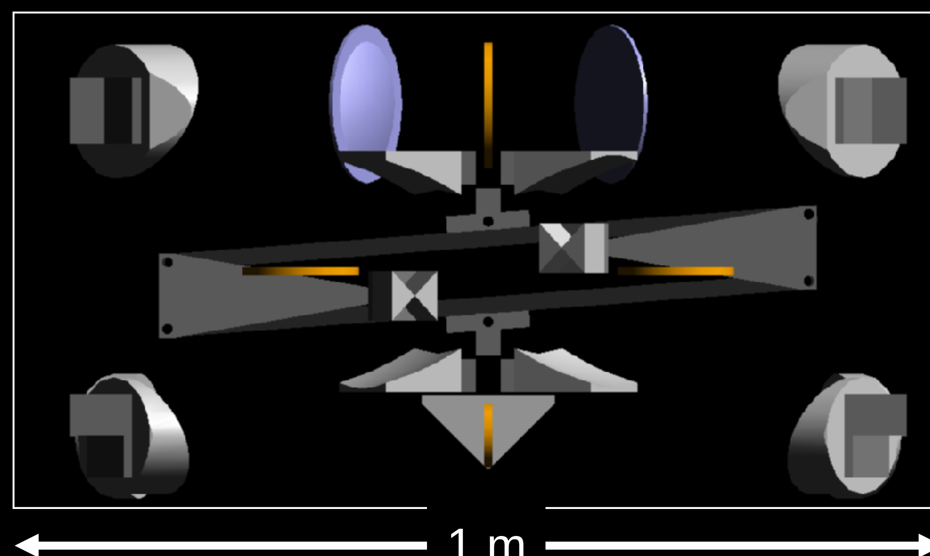
agenzia spaziale italiana

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

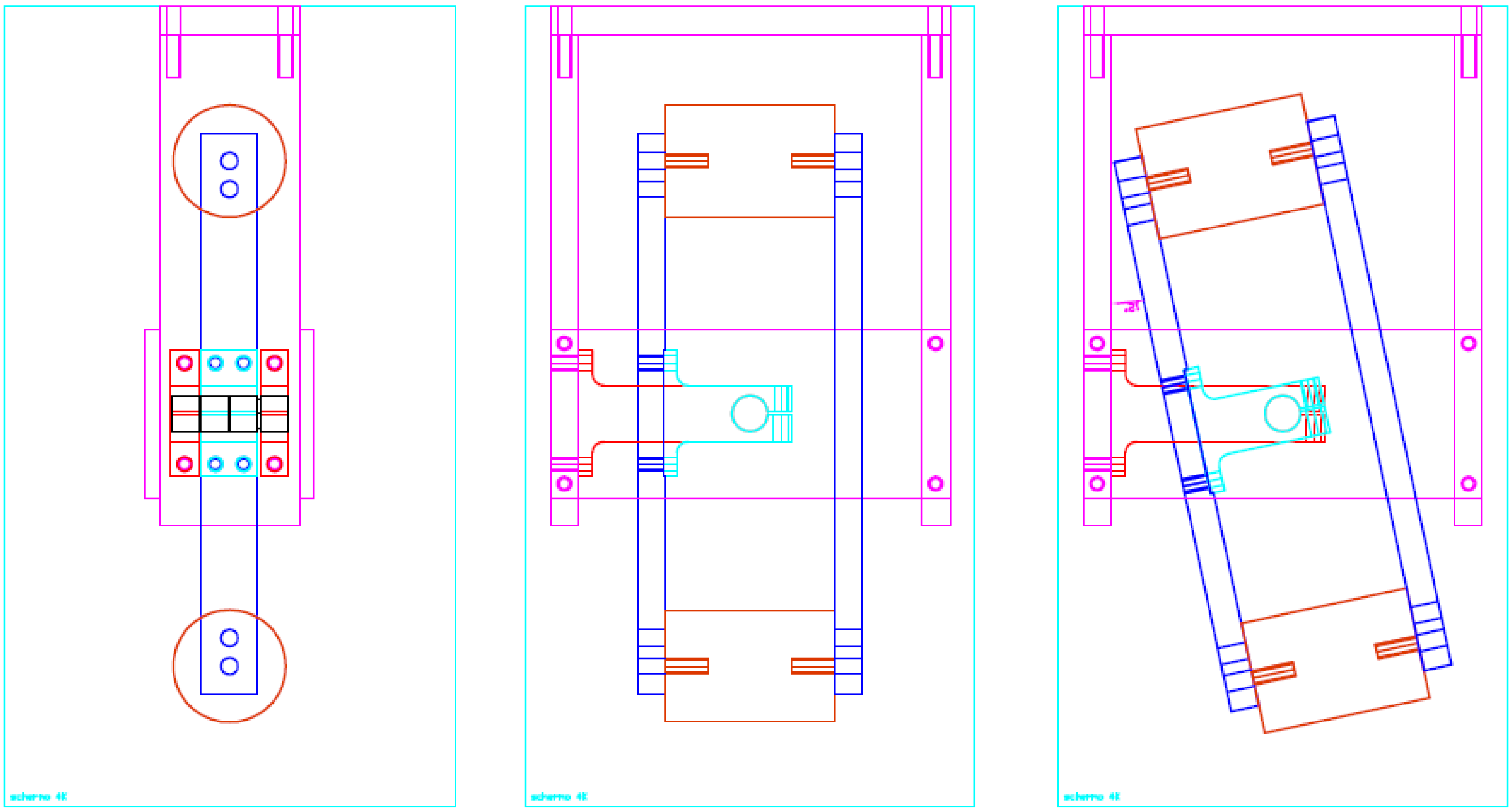
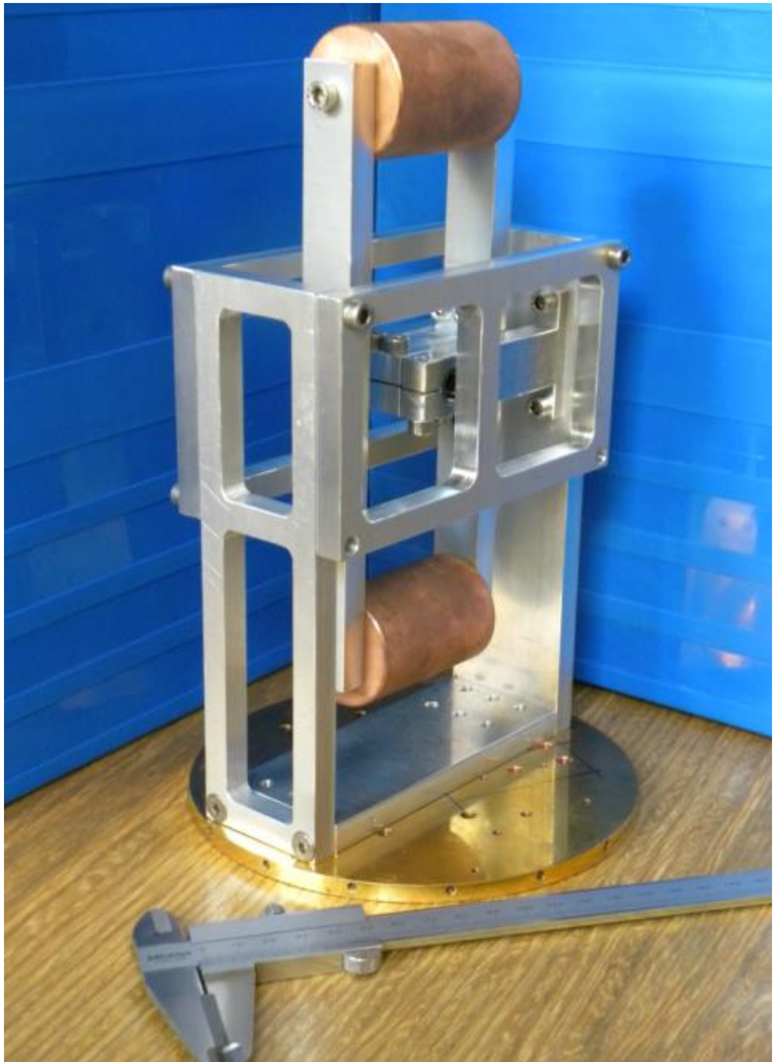


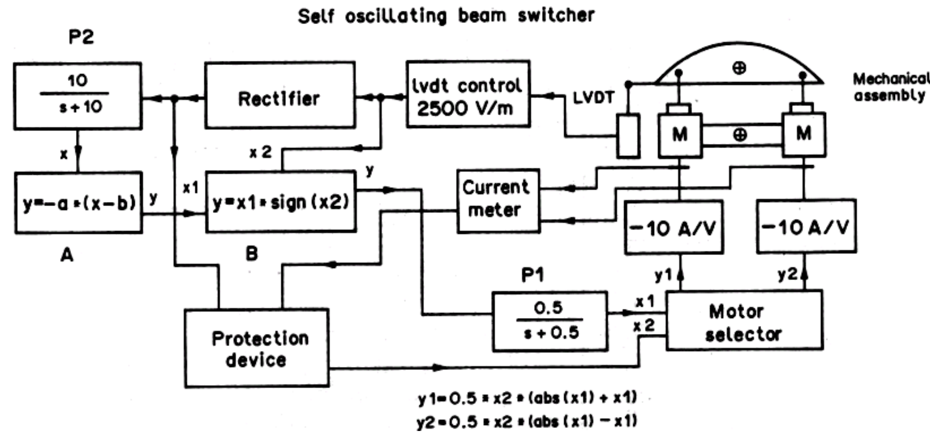
Figura 14: *disegno meccanico del dimostratore alloggiato all' interno dello stadio freddo del criostato (in colore ciano nel disegno, ha un diametro di 160 mm e una altezza di 285 mm). Il disegno è in scala. I due cilindri in rame sono rappresentativi, per massa e inerzia, degli specchi a tetto.*

WP3200: Cryogenic operation of a double pendulum

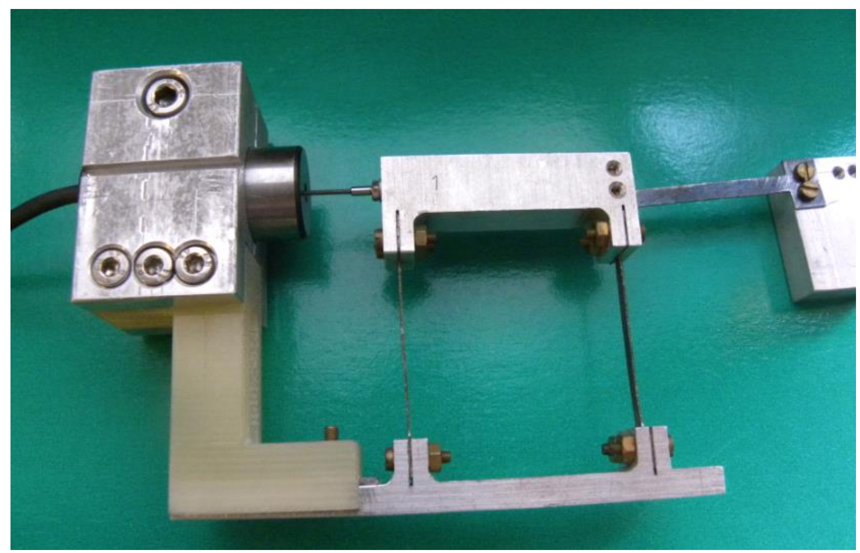
From the *Millimetron* study



Il dimostratore



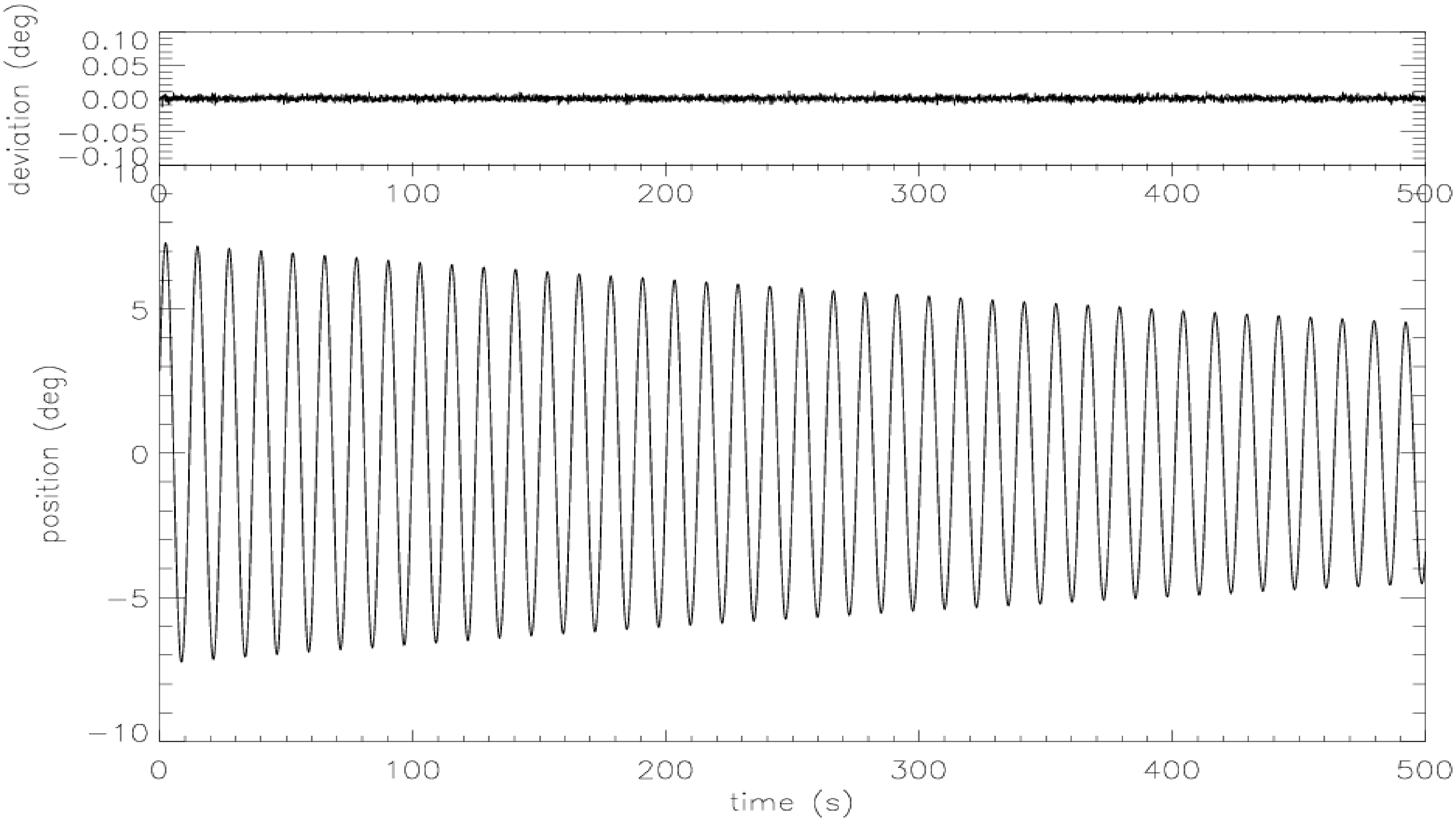
Schema a blocchi elettronica di controllo



LVDT con dispositivo elastico di linearizzazione del moto

WP3200: Cryogenic operation of a double pendulum

From the *Millimetron* study



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

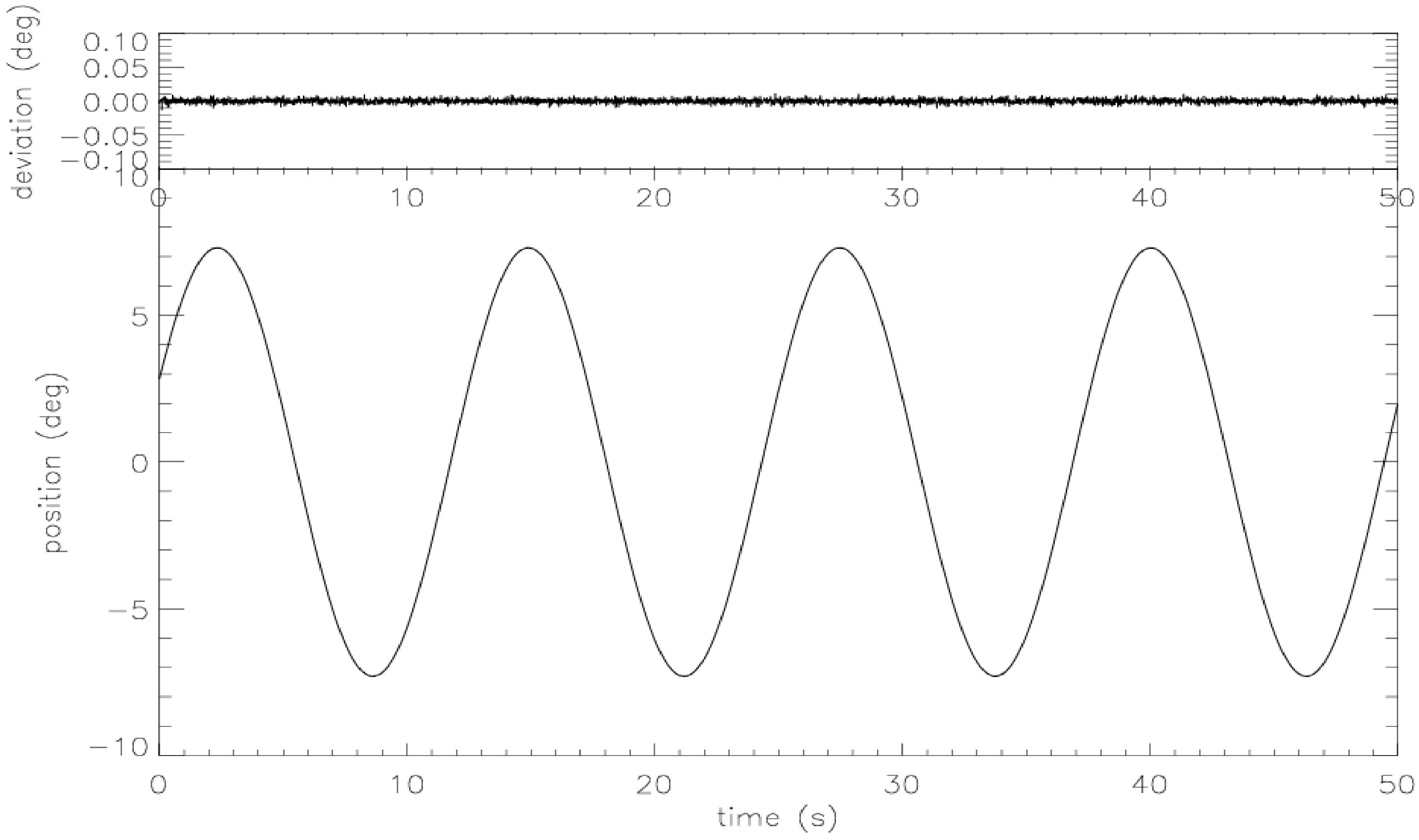
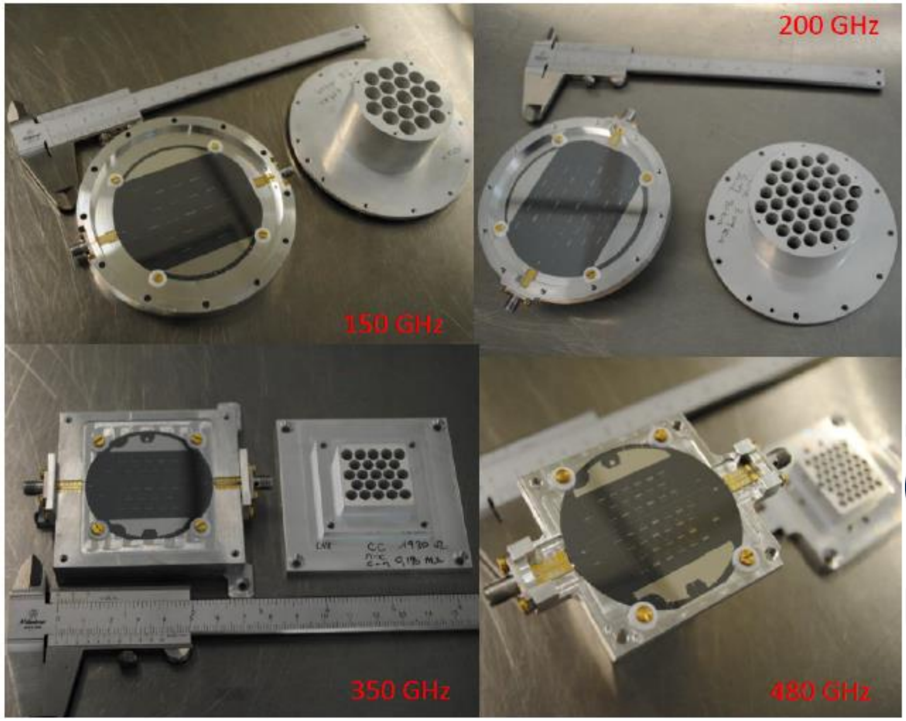


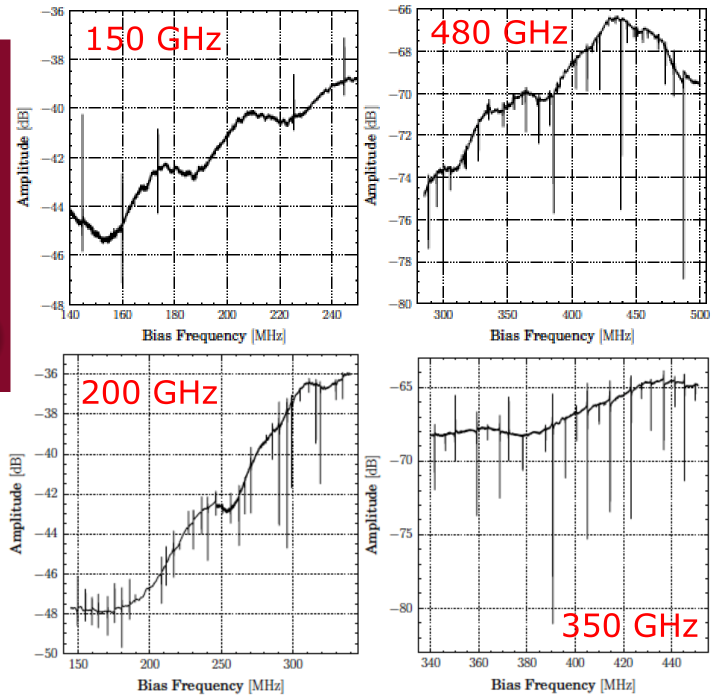
Figura 18: *tipica misura di oscillazione controllata del dimostratore, ottenuta dall' uscita demodulata dell' LVDT. Nel pannello in alto, differenza tra oscillazione misurata e oscillazione sinusoidale, consistente con il rumore di lettura.*

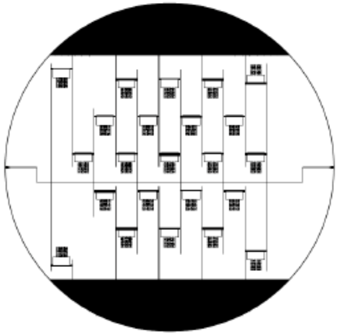
Kinetic Inductance Detectors

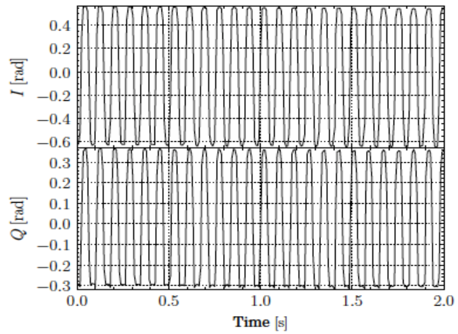


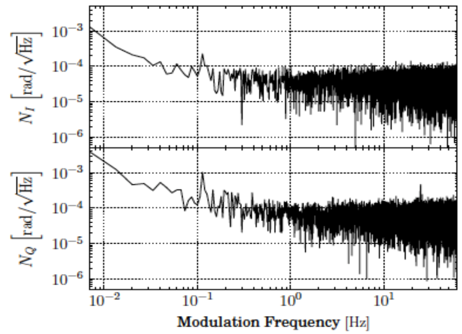
CNR IFN Istituto di Fotonica e Nanotecnologie

SAPIENZA UNIVERSITÀ DI ROMA









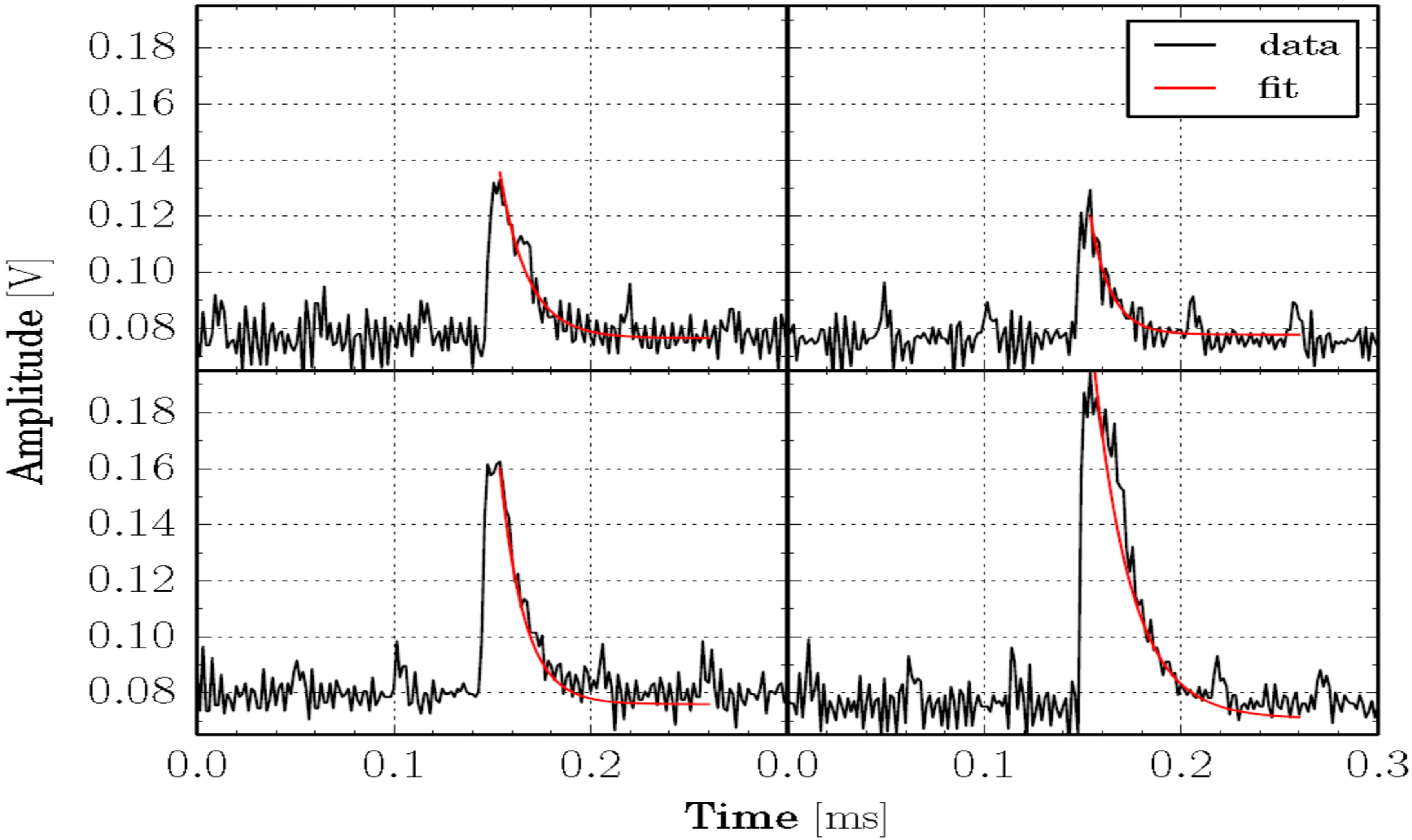
Channel	NET_{RJ} $[mK/\sqrt{Hz}]$
150 GHz	0.180
200 GHz	0.145
350 GHz	0.288
480 GHz	0.433

typical NET

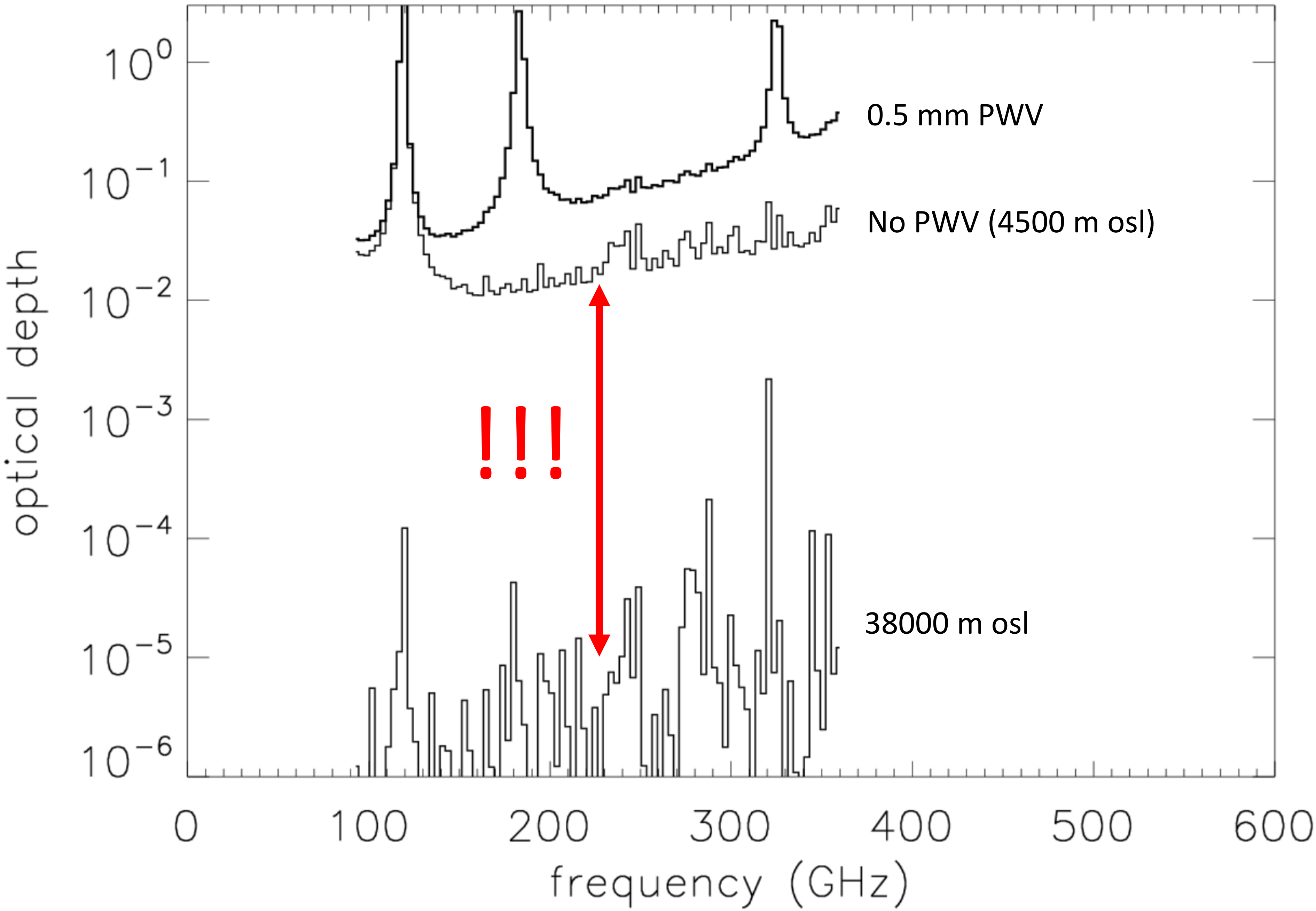
agenzia spaziale italiana

From Silvia Masi - OLIMPO

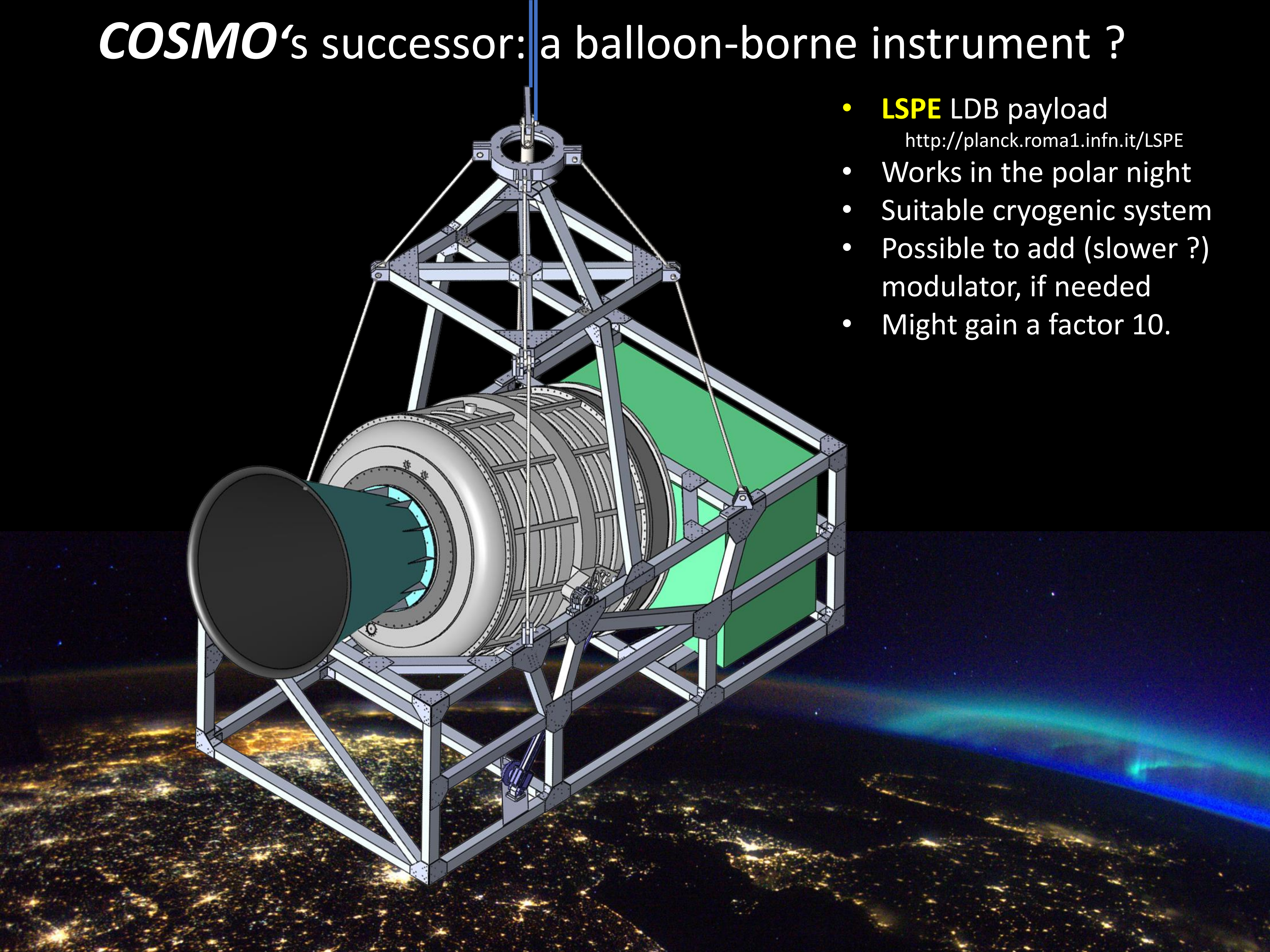
Cosmic rays events in OLIMPO KIDs



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