Cosmology & experiments @ IN2P3

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LPSC Grenoble

Outline

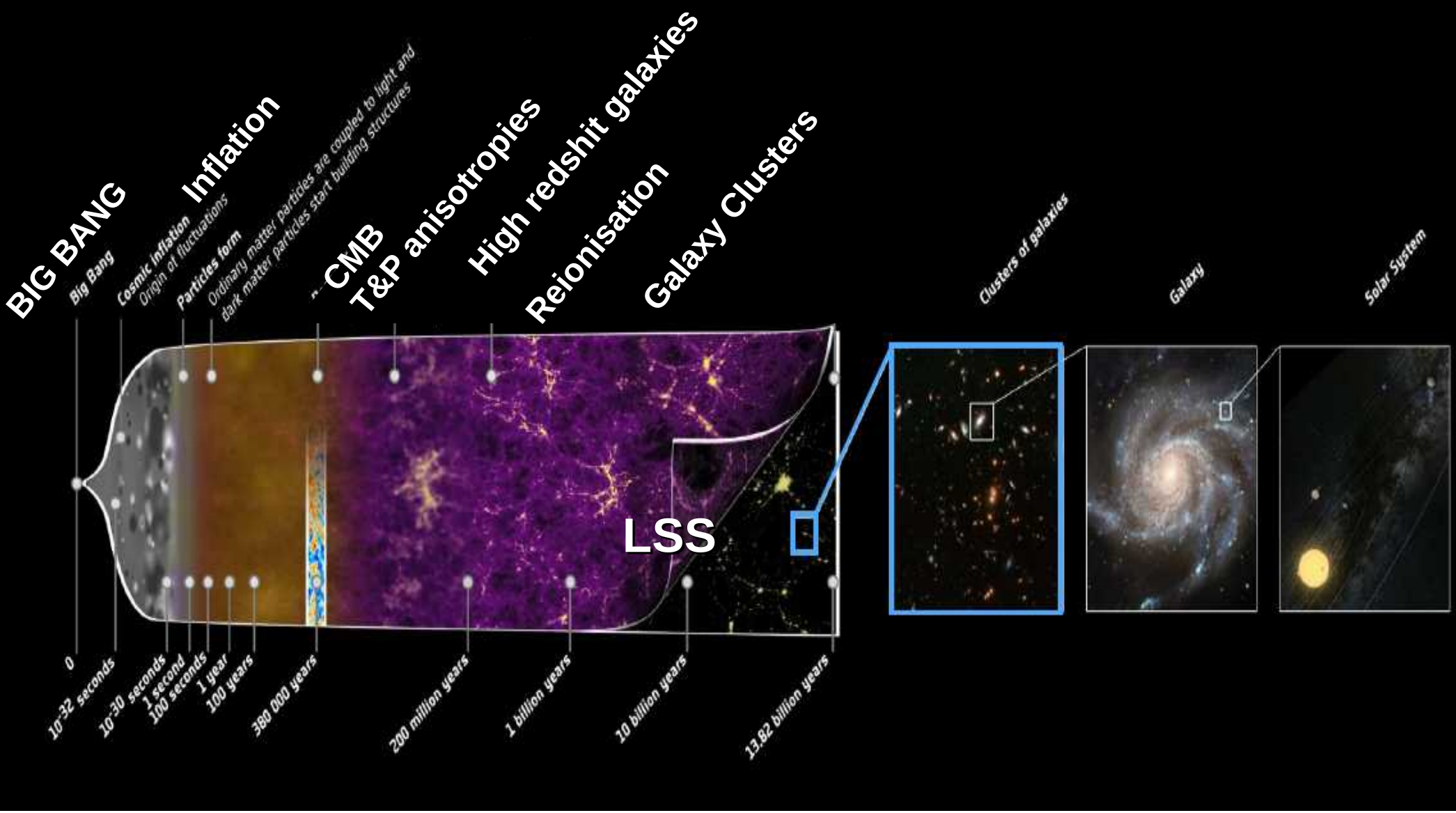
I. Cosmology in a nutshell

II. Large Scale Structure (LSS) experiments

III. Cosmic Microwave Background (CMB) experiments

IV. Challenges

Brief history of the Universe



Cosmological model and parameters

Inflation :

- exponential expansion lead by scalar field
- origin of comological perturbations

Big Bang theory:

- univers expands and cool down with time
- primordial nucleosynthesis and CMB

+

Λ-CDM model:

Describe the energy and matter content of the univers

Gravitational evolution of Large Scale Structure

Late Photons-matter interaction

Early universe:

n_s, n_t : scalar and tensor spectral indices

r : tensor-to-scalar ratio – primordial gravitational waves

A_s :amplitude of scalar perturbations

Geometry :

H_0 : Hubble constant

Energy densities and matter content:

$\Omega_X = \rho_X / \rho_c$ (X/critical density)

$\Omega_{m, CDM, b}$: total, cold dark matter, baryonic matter density

$\Omega_{\gamma, \nu}$: photon, neutrino density

Ω_Λ : dark energy density

Late universe:

σ_8: matter fluctuation amplitude at 8 Mpc/h-1 scales

z_r, τ_r : reionization redshift and opacity

Current (selected) results and challenges

CMB + SNIA + BAO

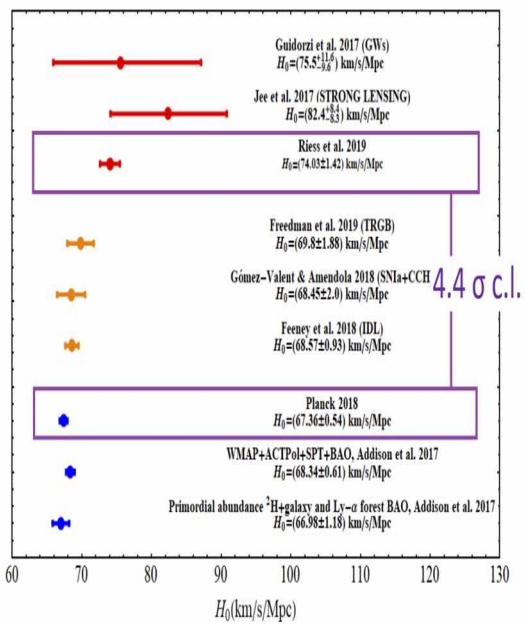
- Inflation seems to work very well but still need a definitive proof
  measuring primordial gravitational waves on CMB B-modes

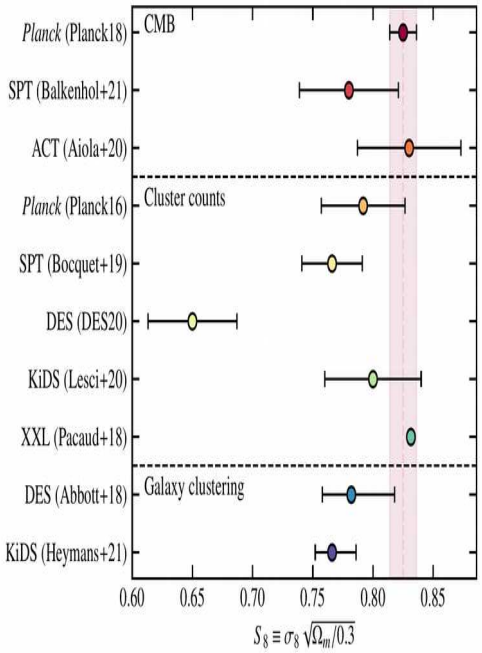
- Energy density of the Universe measured below % level
  - Energy density of the Universe dominated by dark energy
  - Most of the matter in the Universe (84%) is dark matter

What is the nature of these components ?

- Inconsistency between CMB and LSS results
  - expansion rate : H_0
  - structure formation : σ_8

Is this due to systematics or new physics ?





- Neutrino physics
  measuring neutrinos masses

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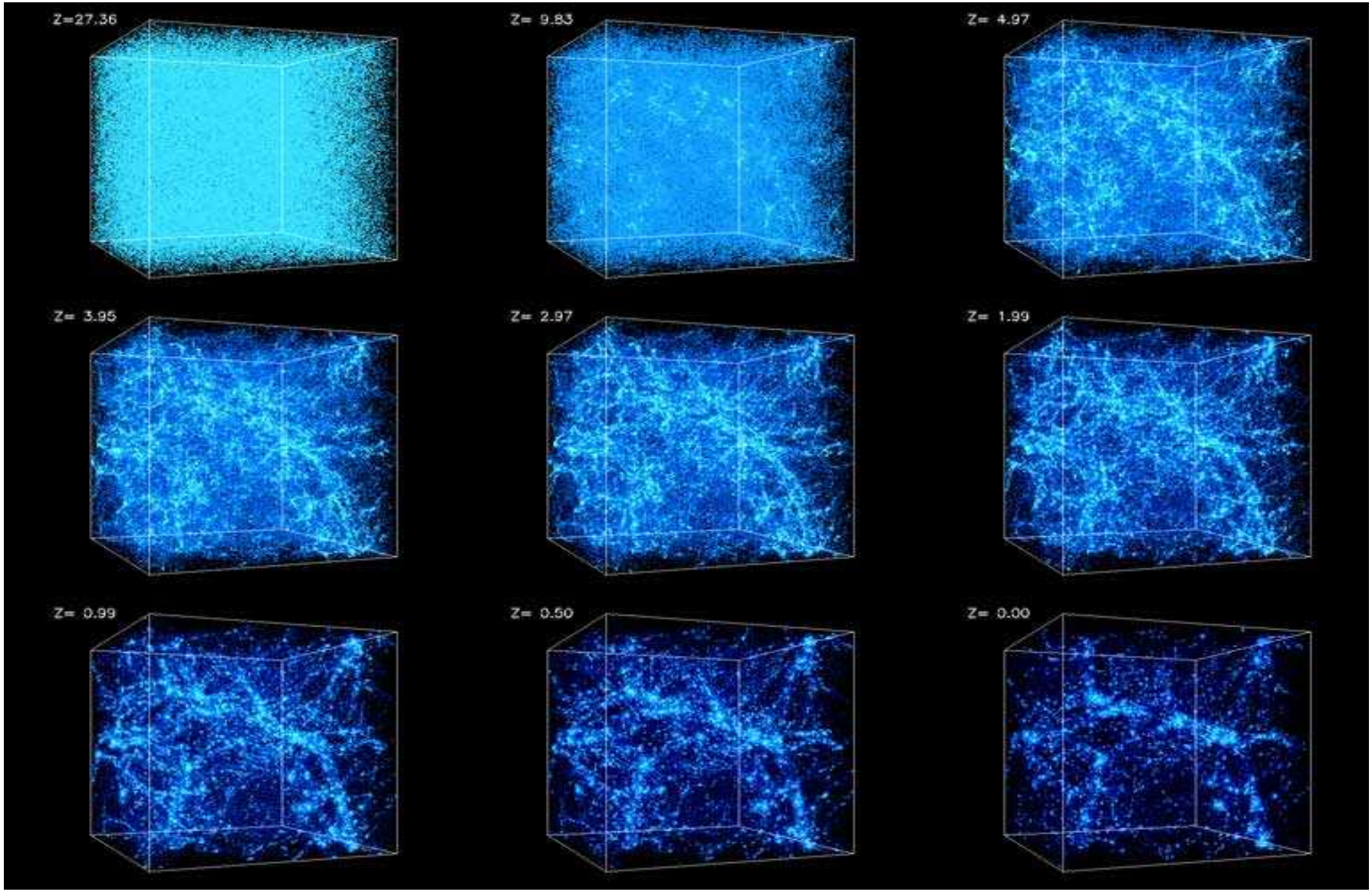
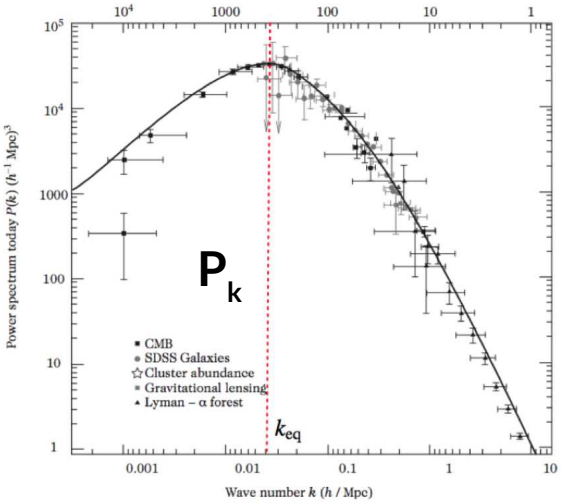
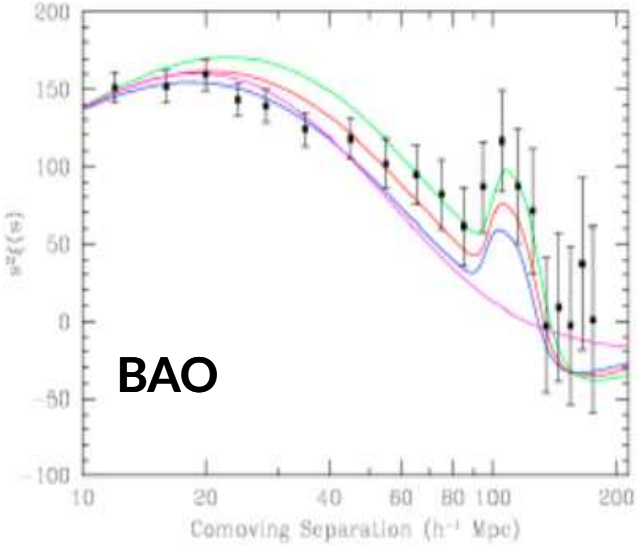
Large Scale Structure evolution



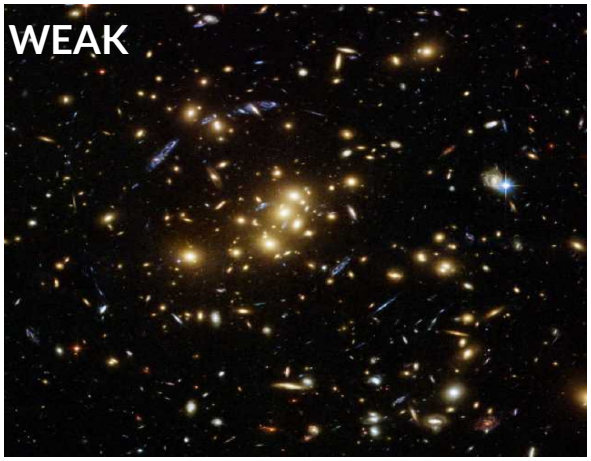
Large Scale Structure probes

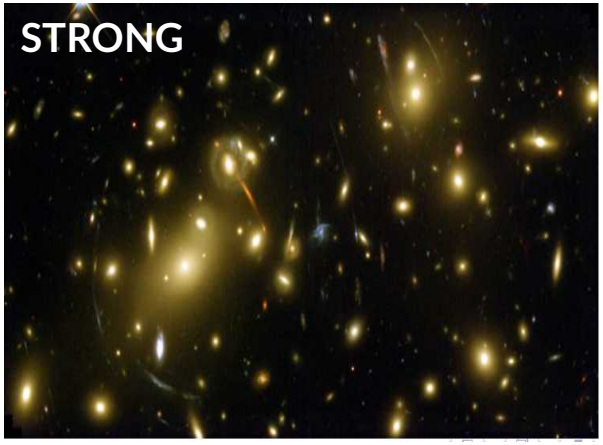
- Galaxy clustering



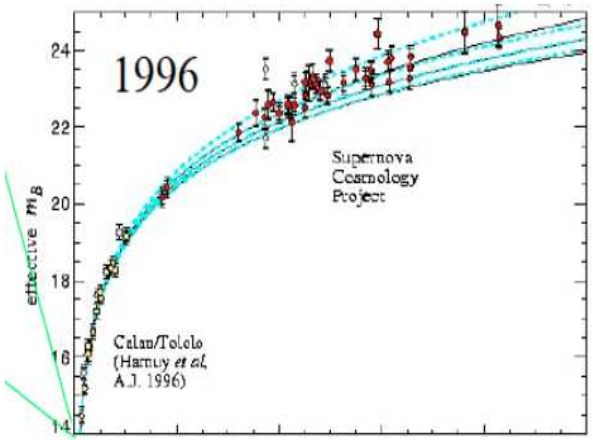


- Lensing : weak & strong

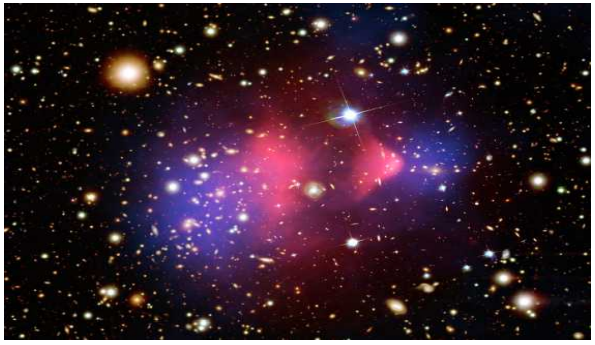




- Supernovae type I



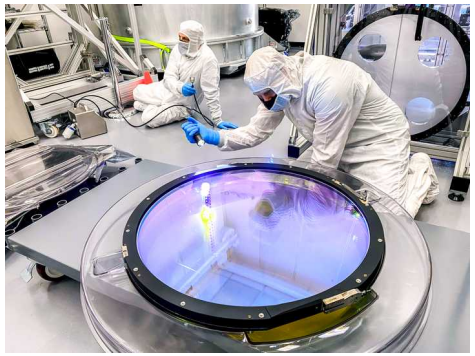
- Clusters of galaxies

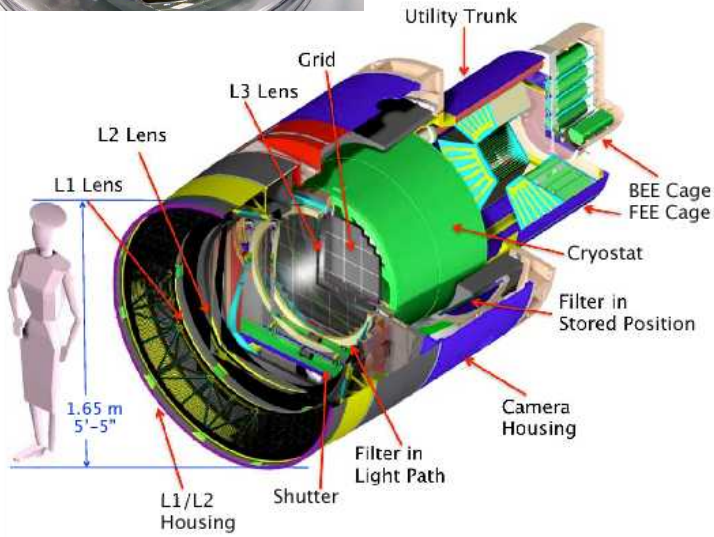


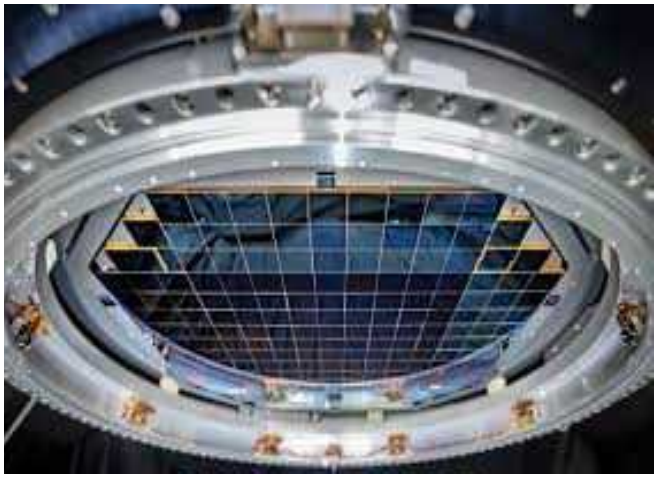
Vera Rubin observatory (LSST)

Installed at Cerro Pachón (2647 m) in Chile
First lights expected in 2022 ?

Must scan ~1/2 of the visible sky every 3/4 nights during 10 years in 6 frequency bands with high sensitivity







Key numbers

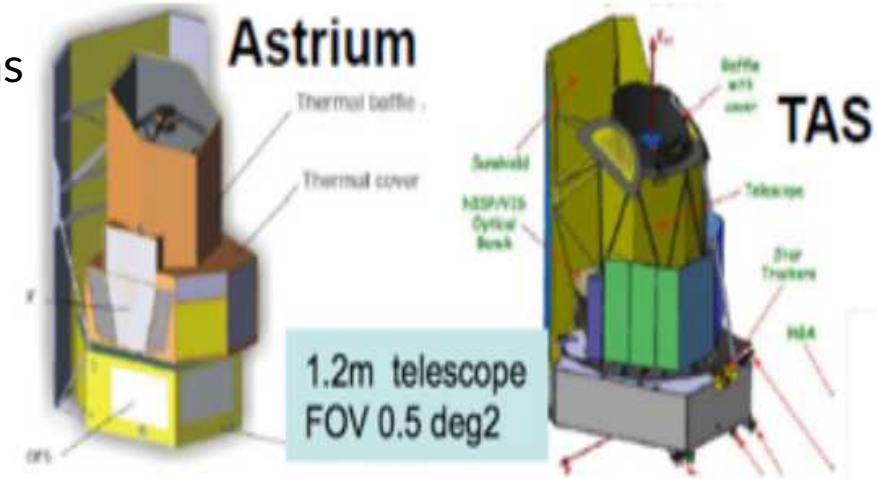
- 8,4 m telescope
- 189 4kx4k CCDs = 32 Gpixels
- 0.2 arcsec/ pixel

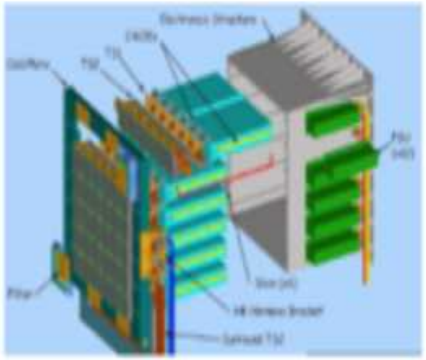
6 filter bands (u,g,r,i,z,y)
20 TB/night
20 Billions galaxies
17 Billions stars

Strong contribution from IN2P3

EUCLID satellite

- M class ESA space mission
- All-sky visible and IR observations in photometry and spectroscopy
- 2 surveys : shallow (15000 deg^2), deep (2 x 20 deg^2)
- Launch 2022
- 7 years operation





The Visible imager (VIS)
36 E2V CCD, 0,1"PSF
1 broad band R+I+Z (550-900nm)

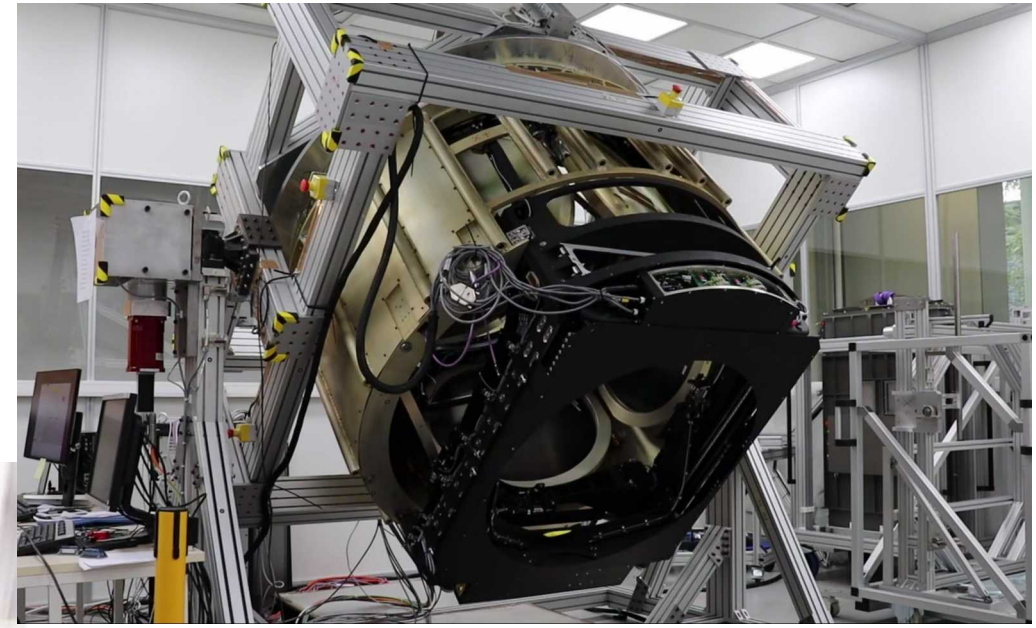
The Infrared spectro/photometer (NISP)
16 H2Rg infra red pixel detectors,0,3" PSF,
3 IR bands Y,J,H (920-2000 nm)
NIR slitless spectroscopy (1100 – 2000 nm) R ~ 350

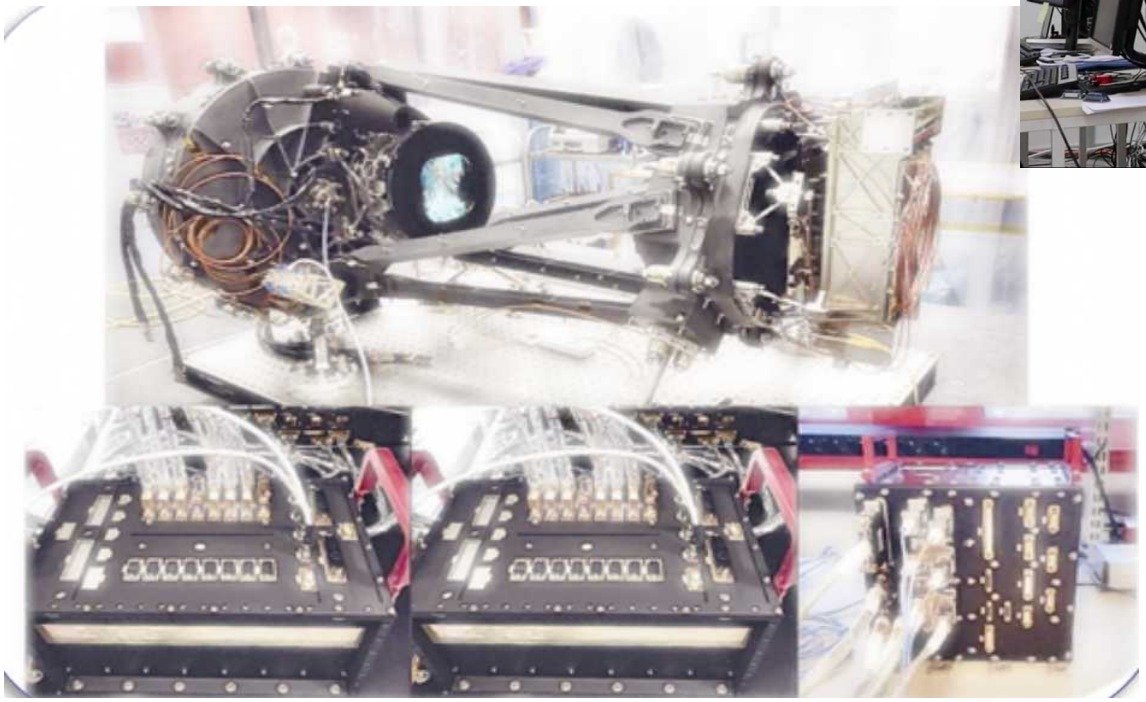
Strong contribution from IN2P3

Instrumentation à l'IN2P3

Filter wheel for LSST

Large high precission mechanical system





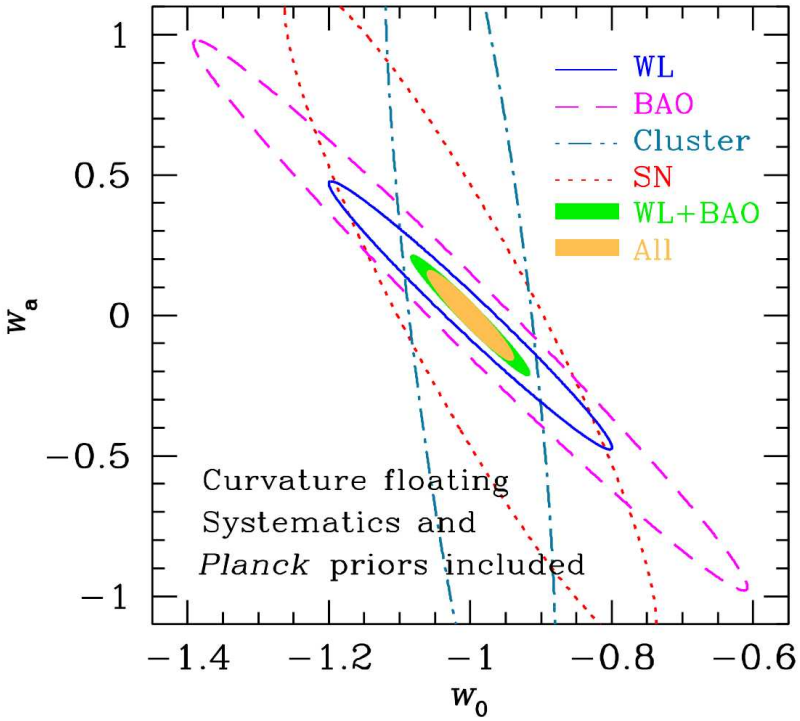
Assembly of EUCLID NISP instrument

Space hardware constraints

Science with LSST & EUCLID

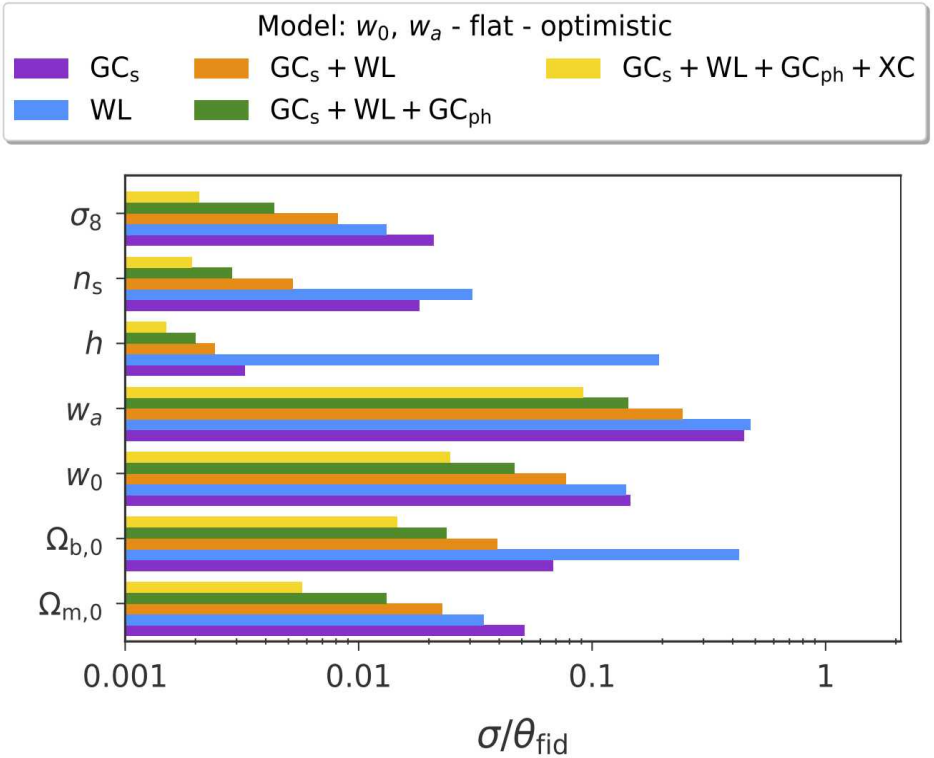
LSST

Transient science : SNIa, solar system objects
% level uncertainties.
High precision on dark energy nature



EUCLID

Exquisite lensing science with VIS
Very high redshift objects with NISP
% level uncertainties
High precision on dark energy nature



Very strong synergy between the two instruments

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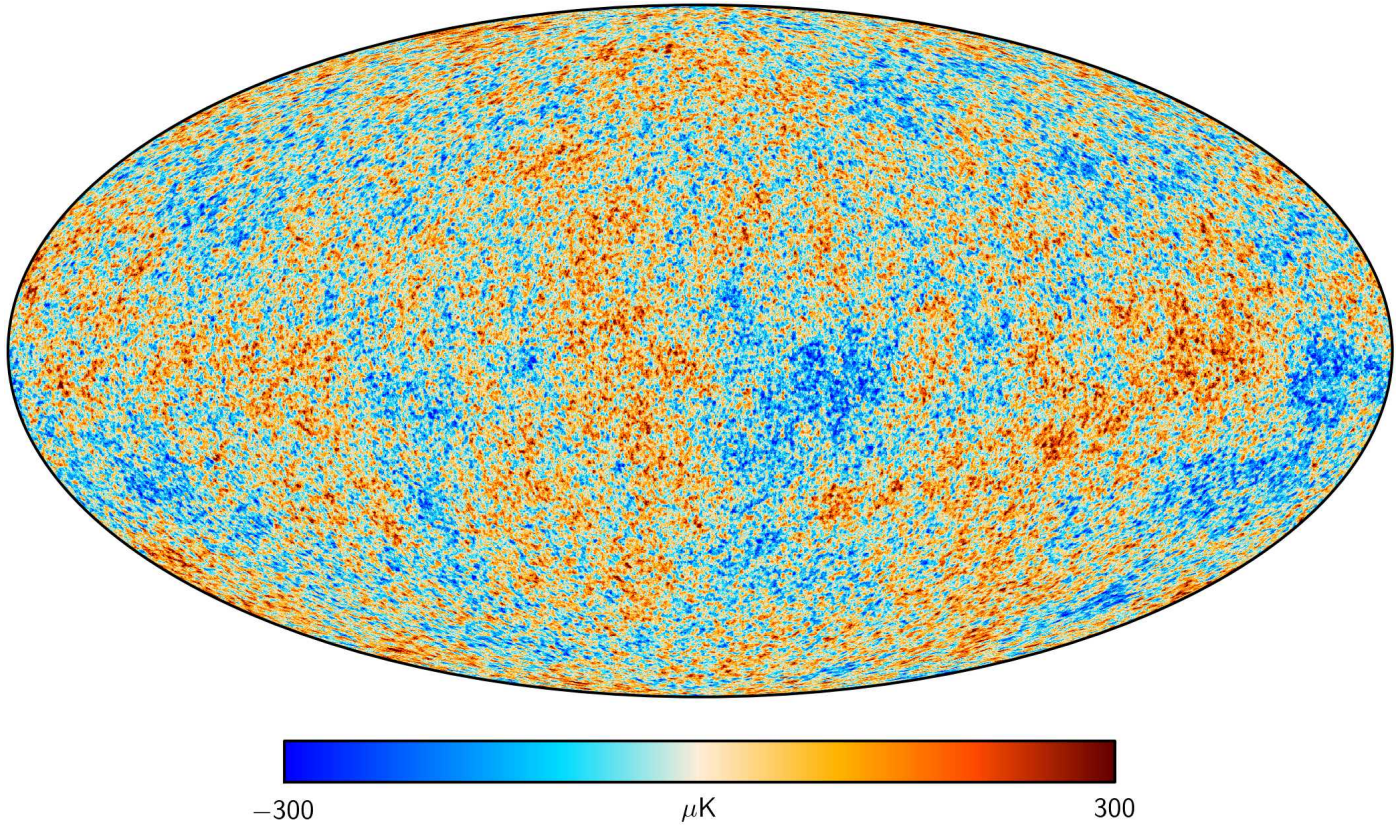
IV. Conclusion

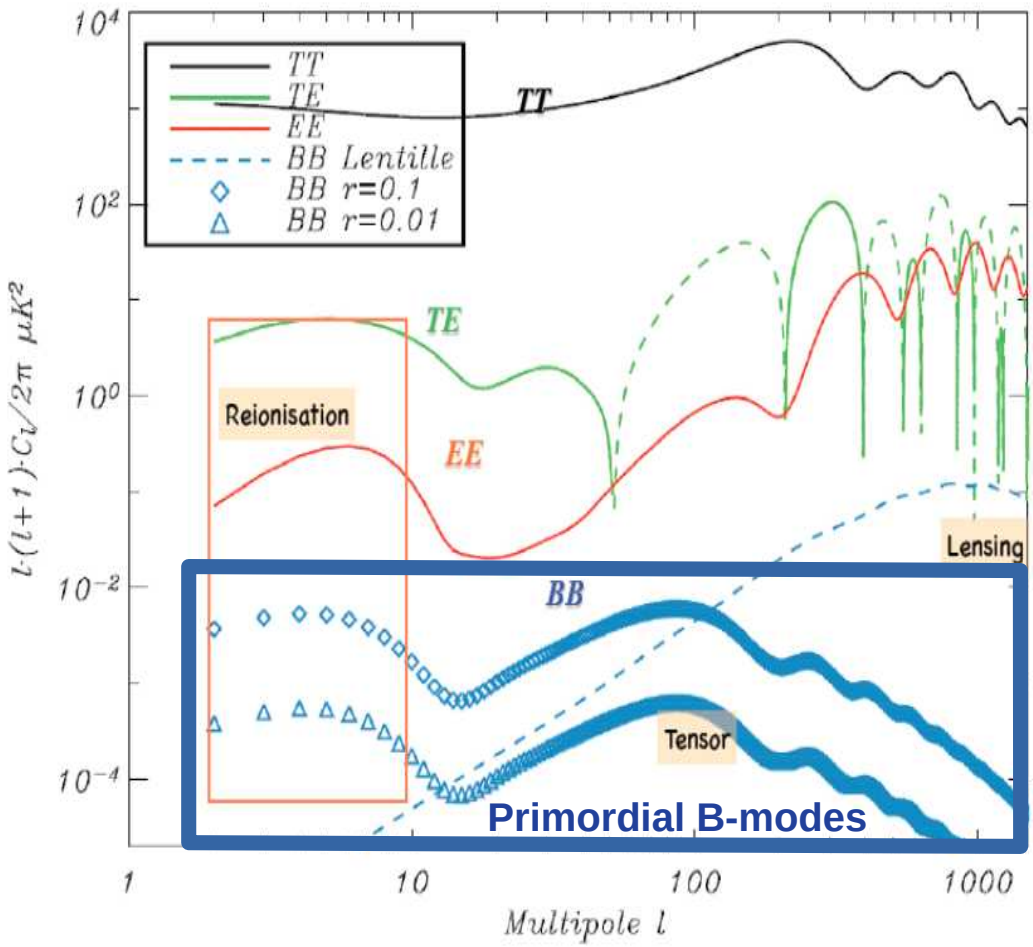
Cosmic Microwave Background

Formed at decoupling, cool down with Universe expansion, today BB emission at 2.726 K with temperature and polarisation anisotropies

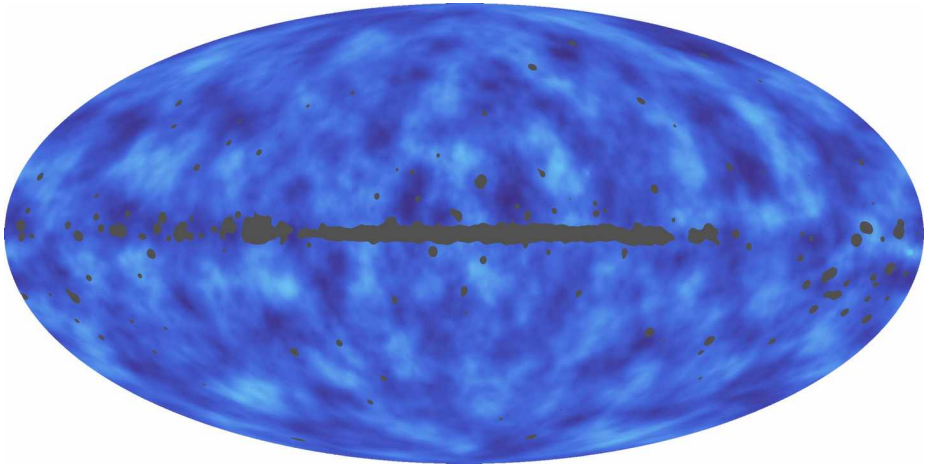


CMB probes

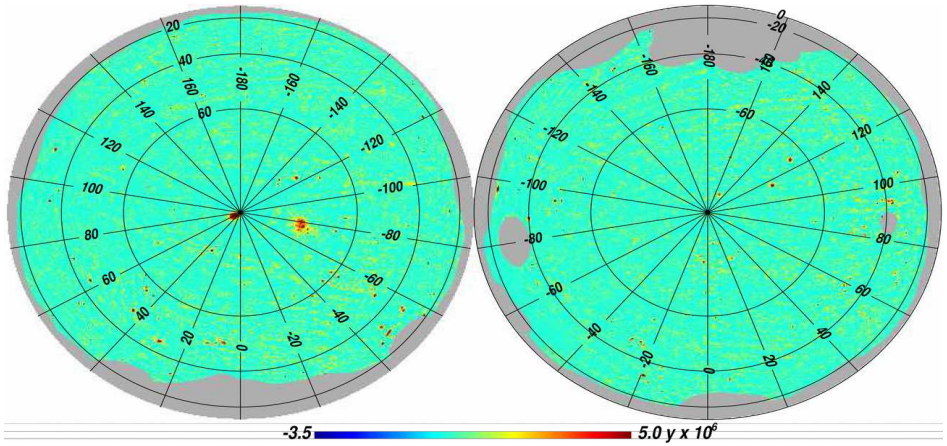
Temperature and polarisation power spectra of primary CMB anisotropies



Integrated lensing potential

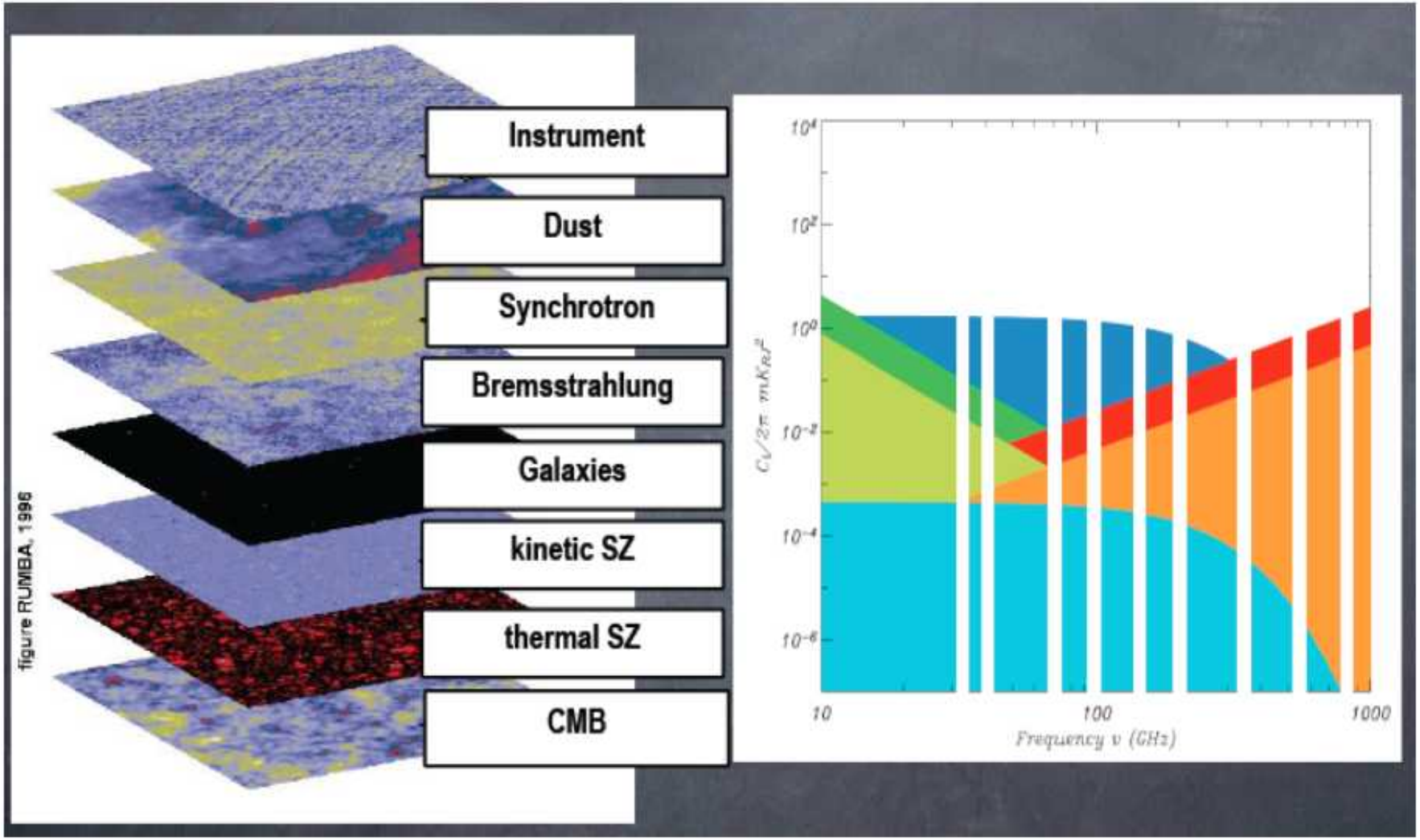


Clusters of galaxies via the Sunyaev-Zeldovich effect



Observing the CMB sky

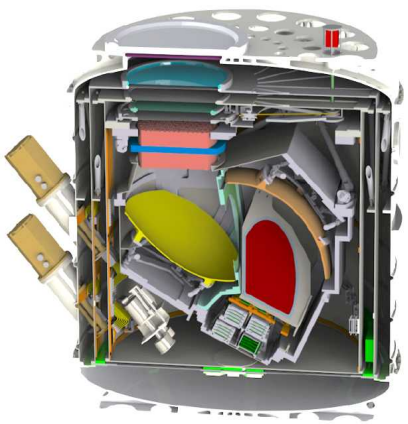
Foreground emission dominates the signal – use spectral behavior to remove it

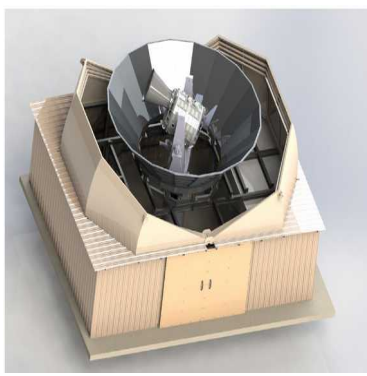


B-modes instruments : ground based

QUBIC

- Lead by APC group
-TD to be installed in 2021 at Alto Chorrillos in Argentina
- Bolometric interferometer
- 1 degree résolution
- Operates at 150 and 220 GHz
- 256-1024 bolometers @ 300 mK



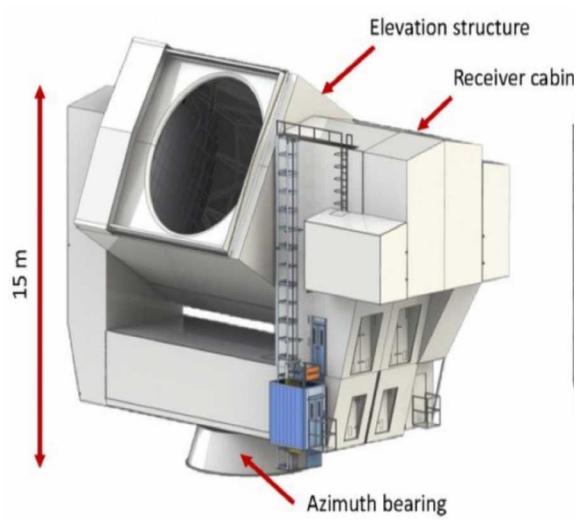


In final configuration and for 3 years of observations : $\sigma(r) = 0.021$

Simons Observatory

- 3 x 0.4 m (SAT) + 1x 6 m (LAT) telescope
- Being deployed in Cerro Toco, Chile at 5360 m
- Sky coverage : 10 % (SATs), 40 % (LATs)
- Polarized photometer
- 6 frequency bands from 27 to 280 GHz
- 30000 + 62000 multi-chroic bolometers @ 100 mK

LAT

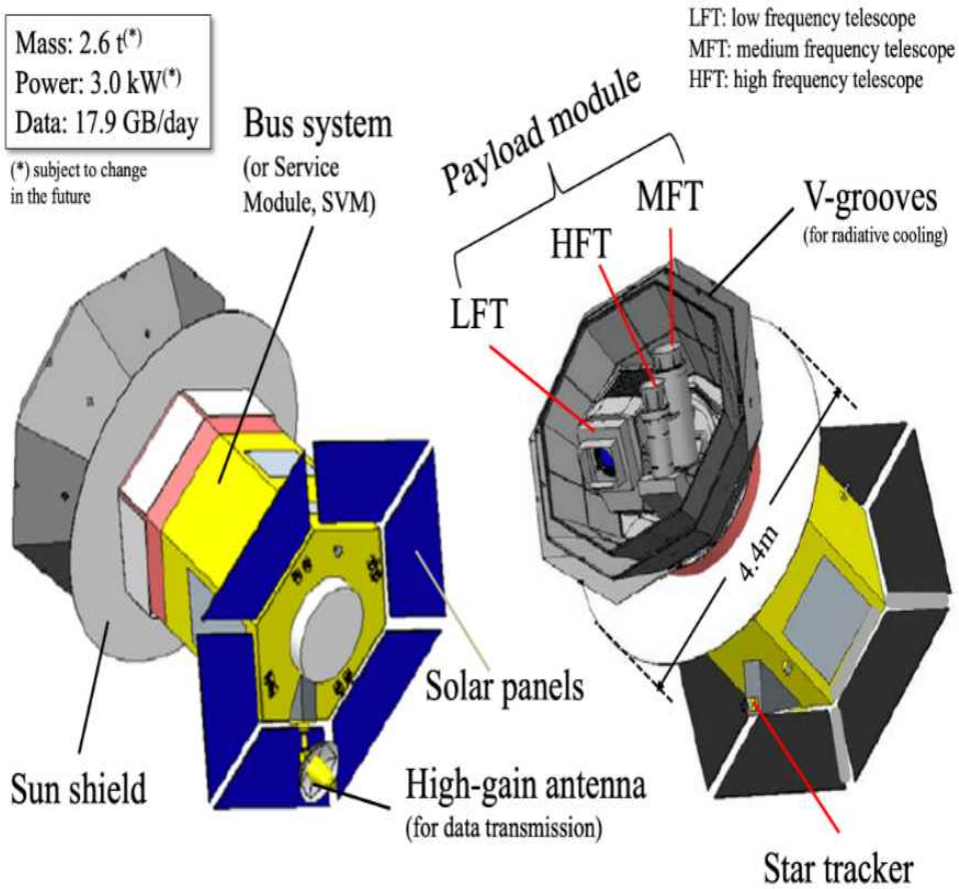


SAT

Final goal of $\sigma(r) = 0.002$ + 20000 clusters in SZ + gravitational lensing

B-modes instruments : LiteBIRD satellite

- L-class JAXA + ESA + NASA space mission
- To be launched in lates 2020s (Phase A)
- 3 years of observation from L2
- Full sky-coverage
- 3 instruments :
    - LFT : 40-140 GHz (10 bands)
    - MFT: 84-224 GHz (5 bands)
    - HFT: 166-448 GHz (5 bands)
- 1080 +2074 + 1354 bolometers @ 100 mK
- 0.5 degrees resolution @ 100 GHz
- Detailed measurement of foreground emission with low and high frequency



Expect to reach sensitivity on B-modes of σ(r) = 0.003 and good control of foregrounds

High resolution instruments

Detailed study of clusters, the Cosmic Infrared Background (CIB) and intensity mapping (developped at Grenoble)

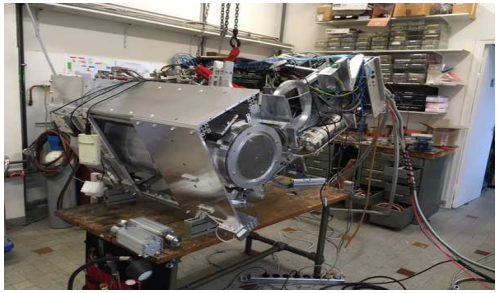
NIKA2

- Dual band mm camera
- Installed at the 30 m telescope (Grenade)
- Operated at 150 and 260 GHz @ 180 mK
- 17.7 (150) and 11 (260) arcsec resolution
- 616 + 2 x 1140 Kinetic Inductance Detectors (KID)

CONCERTO

- Low resolution spectrometer (1.5 GHz bin)
- Installed in 2021 at the 12 m APEX telescope (Chili)
- Operates from 120 to 350 GHz @ 180 mK
- 20 to 40 arcsec arcsec resolution
- 5000 KIDs

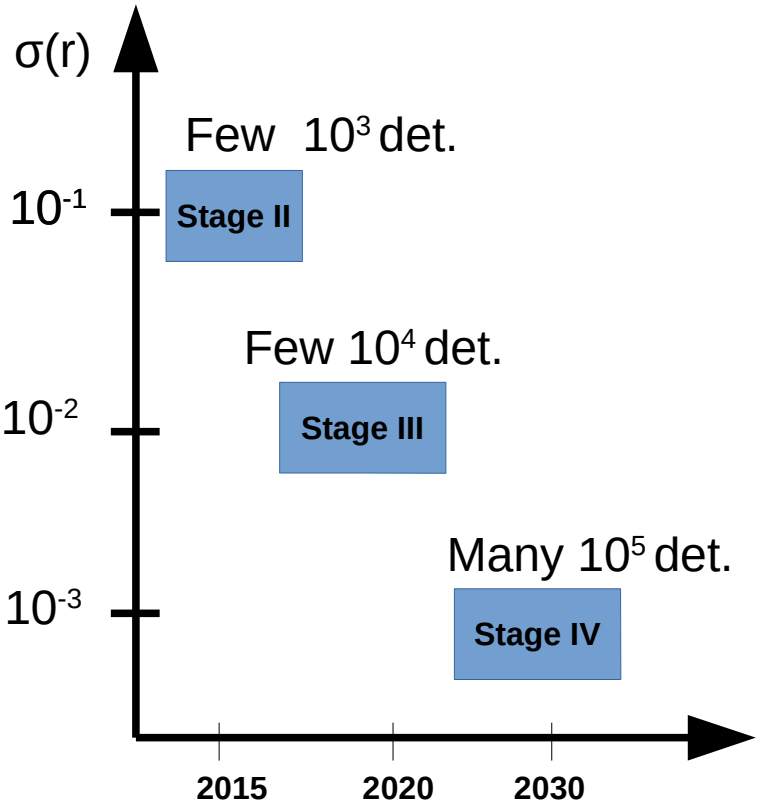
Able to resolve clusters of galaxies and measure their mass for cosmology



CII Intensity mapping for CIB
Cluster velocity distribution

Instrumental Challenges in CMB

Expected ground-based experiment deployement by US groups



How to be **competitive/complementary** with respect to the US ?

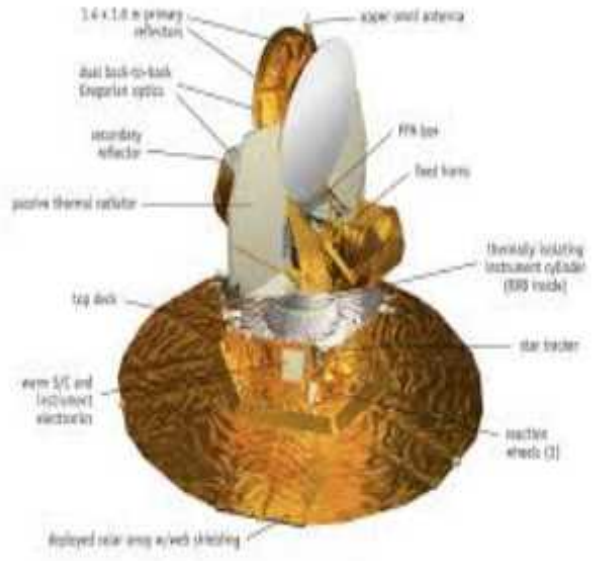
- Joint American groups taking advantage of instrumental expertise : cryogenics, electronics, mechanics, others
- Push forward developments on detectors and readout : e.g. KID detector chains, cold readout for TES bolometers
- Concentrate on other CMB physics : high resolution, clusters, lensing, etc
- Do B-modes from space with less sensitivity by better foreground contamination control: e.g. LiteBIRD

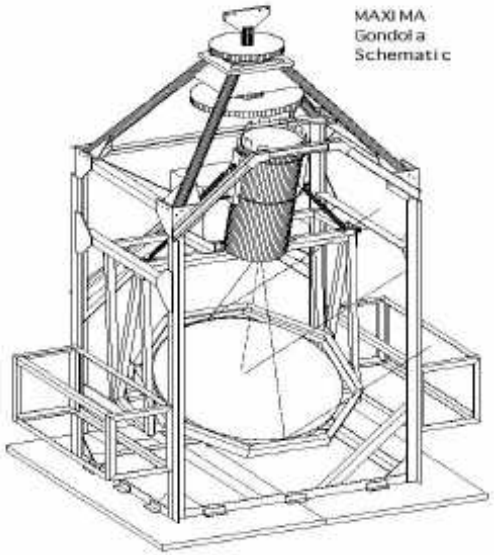
Instrumental expertise and developments will be crucial for exploring these options

Conclusions

- Cosmology has become a large and diverse experimental research area
- Multi-probe approaches are the present and the future for cosmology !!
- IN2P3 is strongly involved in the world leading cosmological experiments
- Long observation periods and large data sets will require strong man power commitments
- IN2P3 could lead synergies between LSST and EUCLID to make the most of them
- Next generation of CMB experiments will require hundreds of thousands of detectors and readouts – alternative detector chains at IN2P3 are promising
- Many exciting results expected in the next decade – stay tune !!

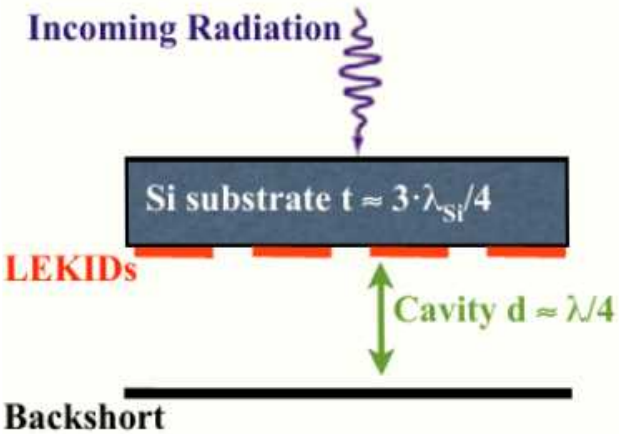
CMB experiments





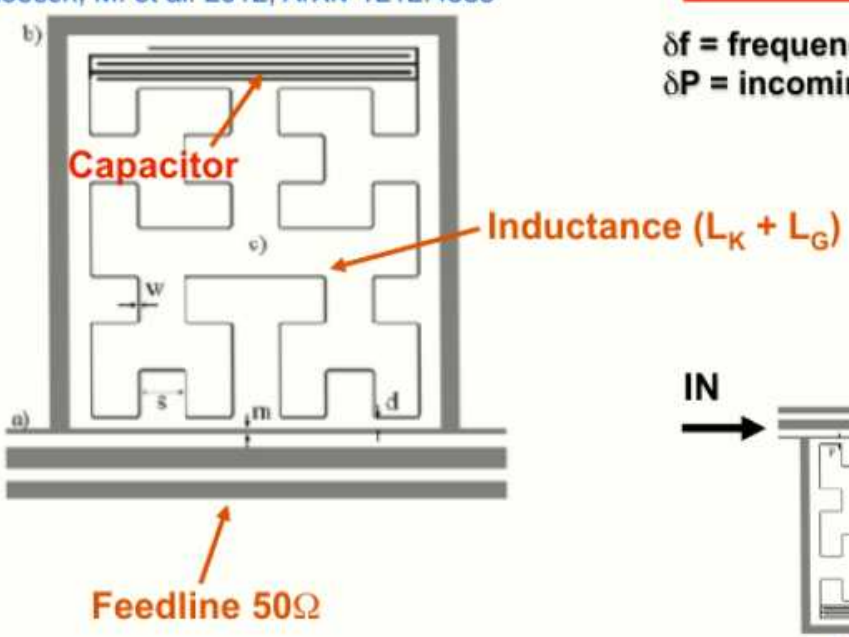
	Radio	mm
Telescopes	dish and horns	dish and horns
Detectors	HEMT + square law detectors	bolometer and/or KIDs
Cooling	18-50 K	100-300 mK
Observing mode	Ground, satellite	ground, balloon, satellite

Kinetic Inductance Detectors (KID)



Dual Polarisation (3rd-order Hilbert pattern)

Roesch, M. et al. 2012, ArXiv 1212.4585



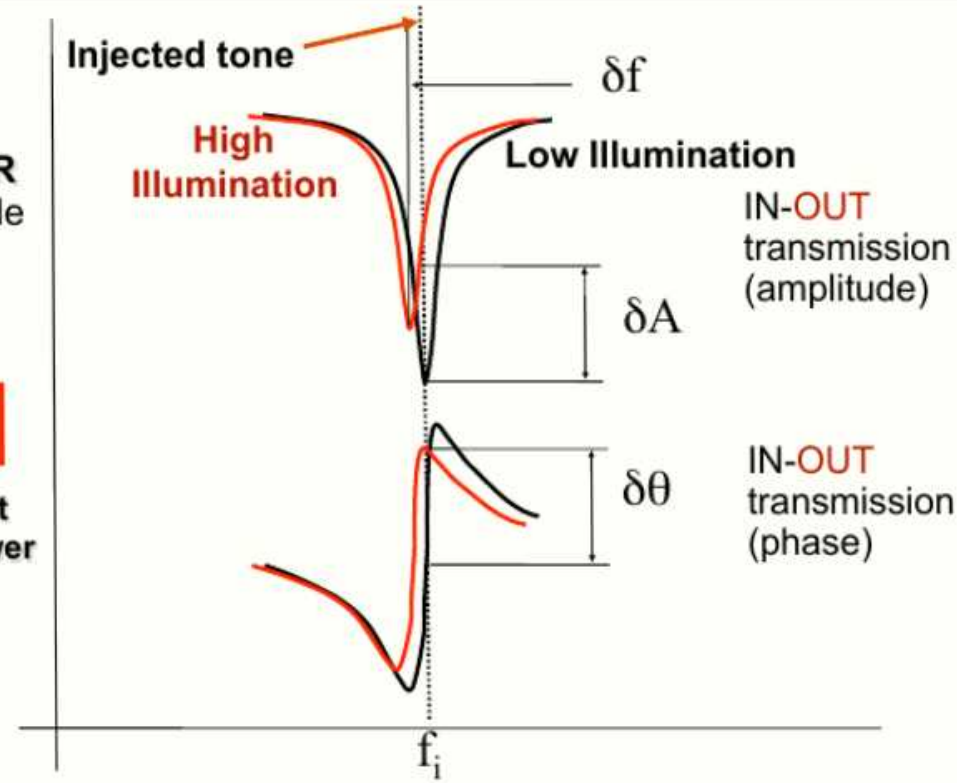
The incoming photons break Cooper pairs (supercurrent carriers) in a superconducting LC resonator → measurable signals

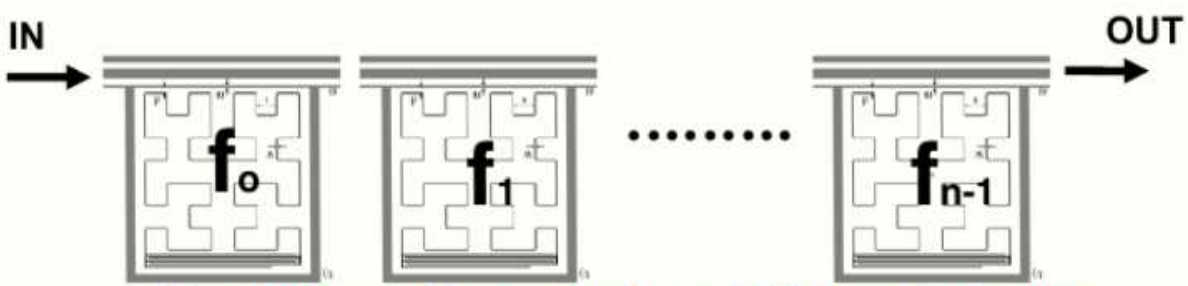
Dark, $T << T_c$

Light: **increase in R**
Change in amplitude (ΔA) and phase

$$\delta f \propto \delta L_K \propto \delta P$$

δf = frequency shift
δP = incoming power



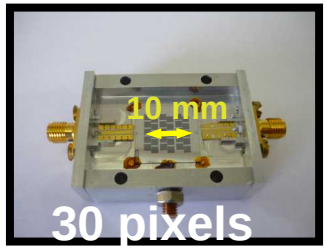


Brief Grenoble KID+readout history

2000
KID Concept
(Caltech-JPL)

NIKA0

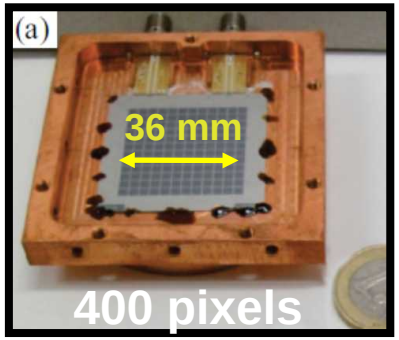
2009



NIKA1

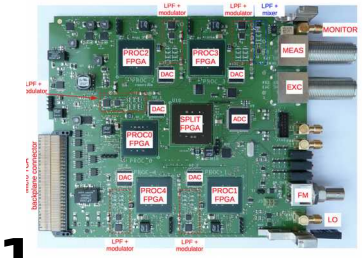
x 2

2010-2013



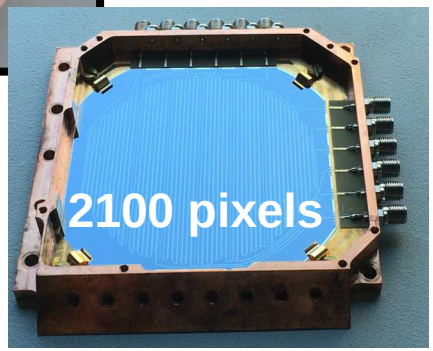
NIKA2

x 20



2014-2017

CONCERTO



2008

We "join" the KID community

2009

30 pixels → NIKA0 (first ever KID camera)

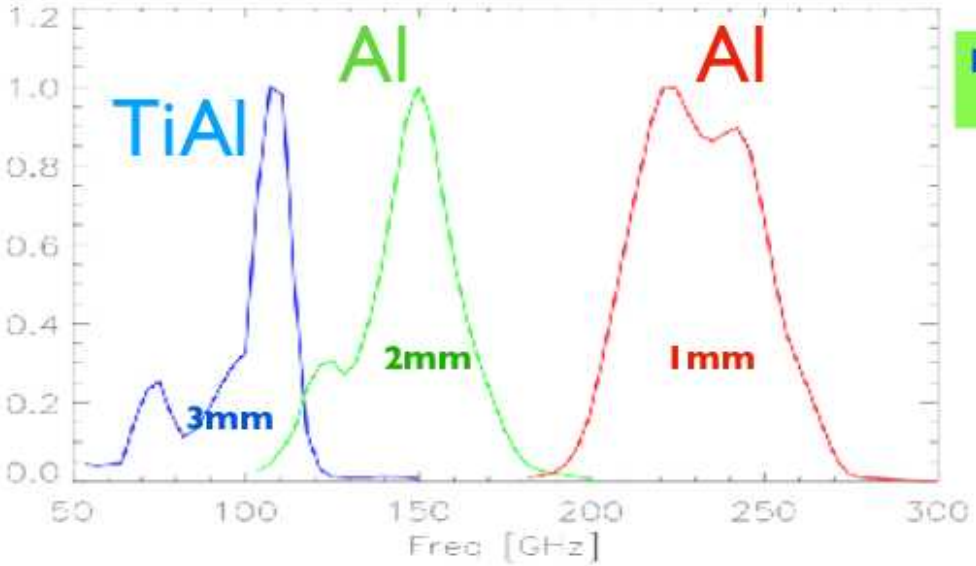
2014 - 2017

- Background-limited **(NEP < 10^{-17} W/Hz$^{0.5}$)**
- Readout line 2.5 m long !! Litho !!
- Al high-quality, uniform thickness film (≈10nm)

2019

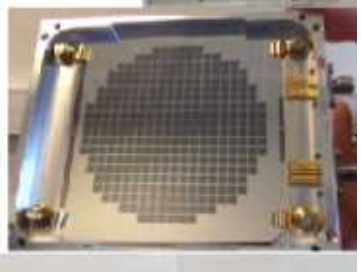
- 2100 pixel arrays

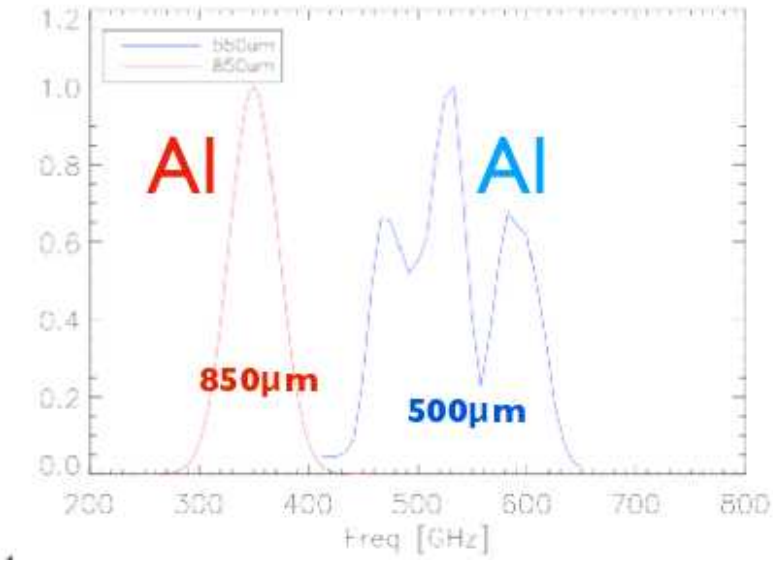
KID spectral response



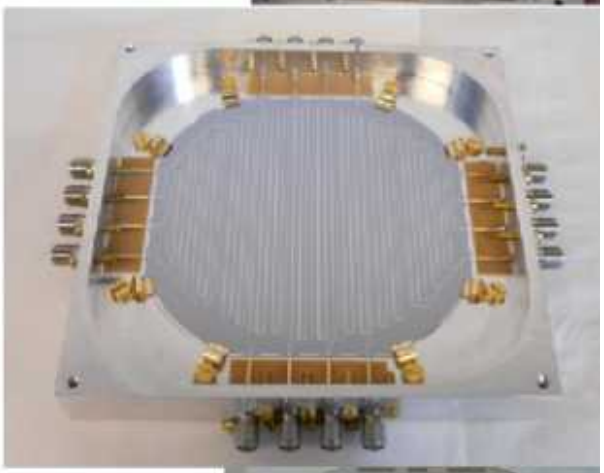
LEKID Demonstrators for space (132pix)
3mm - 2mm - 1mm - 850µm - 500µm

LEKID Array for KISS Interferometer (300pix) TiAl@3mm



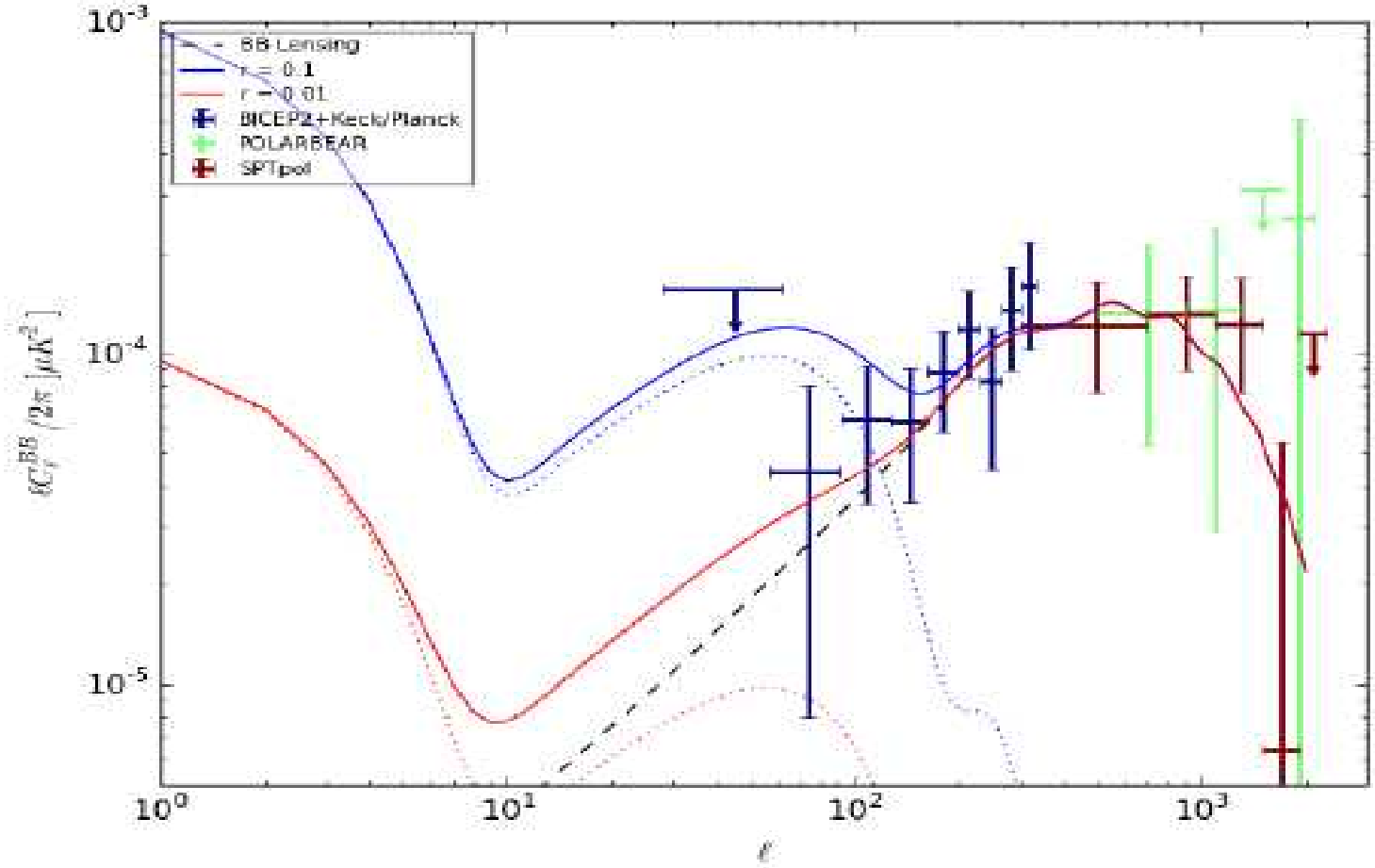


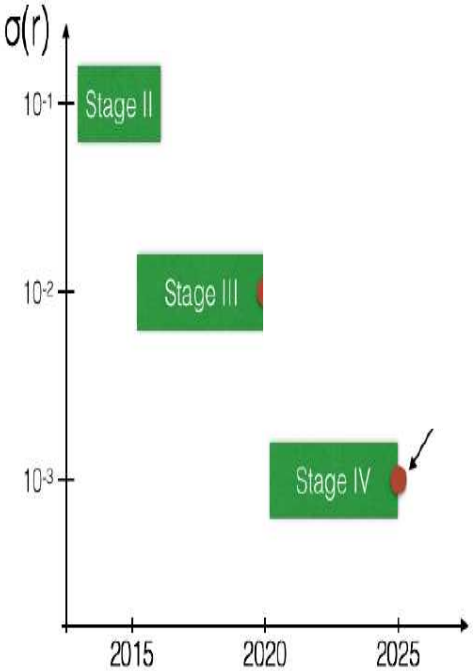
LEKID Array for NIKA2 (2000pix) Al@3mm



LEKID Array for Ballon (500 pix) Al@500µm

CMB intensity and polarisation power spectra : the quest for B-modes





Current results are limited by foreground contamination, r<0.07 @ 95 % C.L. [BICEP, KECK & Planck]

« Some » current (planned) CMB experiments

Project	Country	Location	Status	Frequencies (GHz)	ℓ range value	Ref.	$\sigma(r)$ goal no fg.	with fg.
QUBIC	France	Argentina		150,220	30-200		0.006	0.01
Bicep3/Keck	U.S.A.	Antartica	Running	95, 150, 220[1]	50-250	[22]	$2.5\ 10^{-3}$	0.013
CLASS	U.S.A.	Atacama	≥ 2016	38, 93, 148, 217	2-100	[29]	$1.4\ 10^{-3}$	0.003
SPT3G	U.S.A.	Antartica	2017	95, 148, 223	50-3000	[23]	$1.7\ 10^{-3}$	0.005
AdvACT	U.S.A.	Atacama	Starting	90, 150, 230	60-3000	[24]	$1.3\ 10^{-3}$	0.004
Simons Array	U.S.A.	Atacama	≥ 2017	90, 150, 220	30-3000	[25]	$1.6\ 10^{-3}$	0.005
LSPE	Italy	Artic	2017	43, 90, 140, 220, 245	3-150	[30]	0.03*	
EBEX10K	U.S.A.	Antartica	≥ 2017	150, 220, 280, 350	20-2000	[28]	$2.7\ 10^{-3}$	0.007
SPIDER	U.S.A.	Antartica	Running	90, 150	20-500	[26]	$3.1\ 10^{-3}$	0.012
PIPER	U.S.A.	Multiple	≥ 2016	200, 270, 350, 600	2-300	[27]	$3.8\ 10^{-3}$	0.008

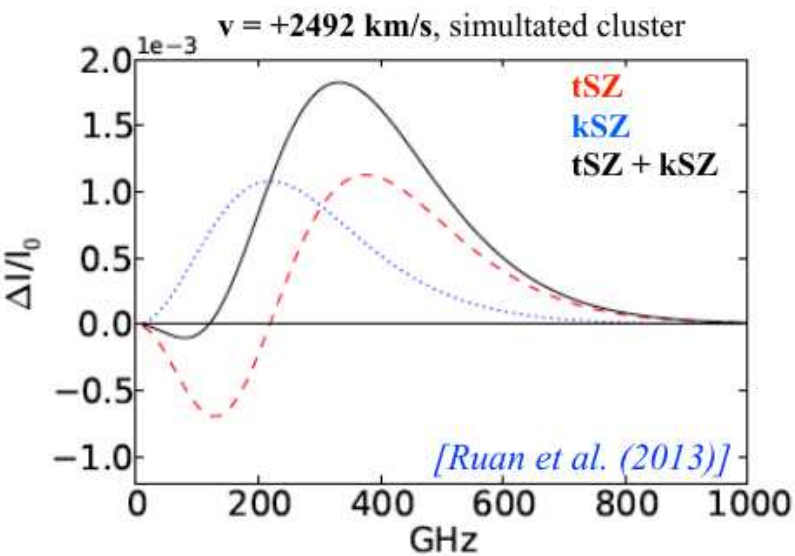
+ proposed satellites : LITEBIRD (2028), PRISTINE (?), CORE (2035?)
+ ground S4 (2030 ?)

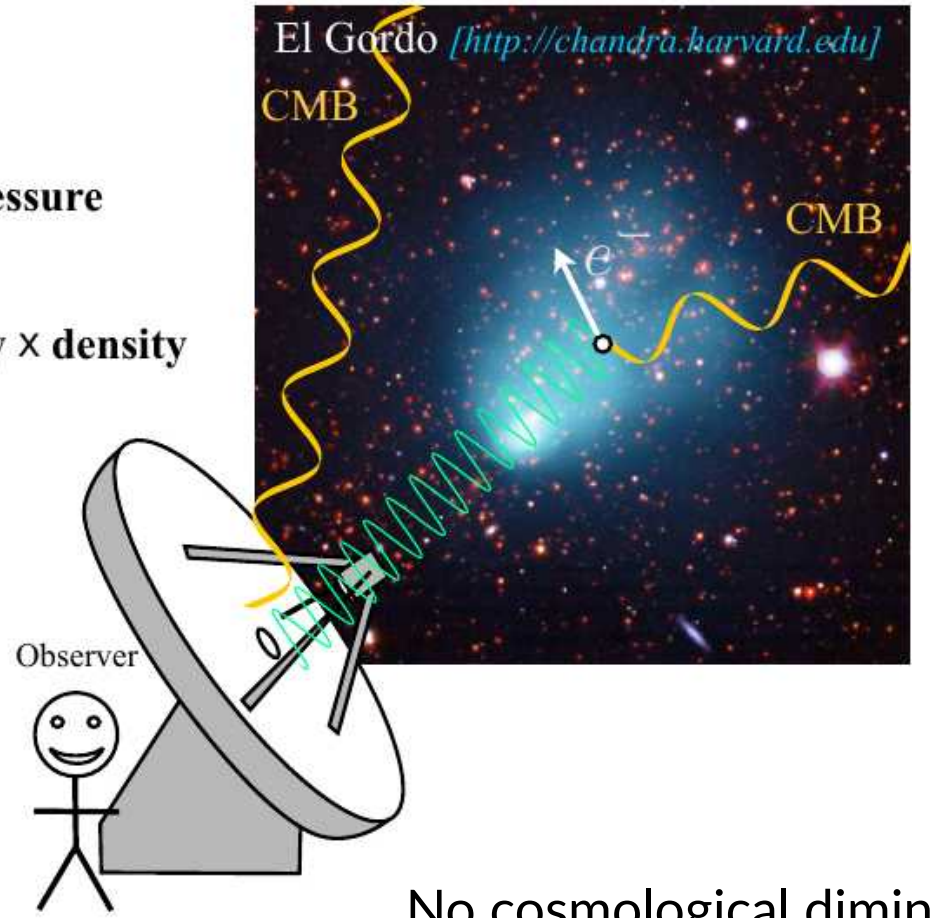
Sunyaev-Zeldovich effect

- **tSZ** = CMB spectral distortion from interaction with clusters' hot electrons
- **kSZ** = CMB Doppler shift from bulk motion of electrons (typically ~ tSZ/10)

$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\rm tSZ} + g_\nu \; y_{\rm kSZ}$$

$$\begin{cases} y_{\rm tSZ} = \dfrac{\sigma_{\rm T}}{m_e c^2} \displaystyle\int P_e d\ell & \Rightarrow \text{ Pressure} \\ y_{\rm kSZ} = \sigma_{\rm T} \displaystyle\int \dfrac{-v_z}{c} n_e d\ell & \Rightarrow \text{ Velocity × density} \end{cases}$$





No cosmological diming

➡ **SZ = probe for intracluster gas**

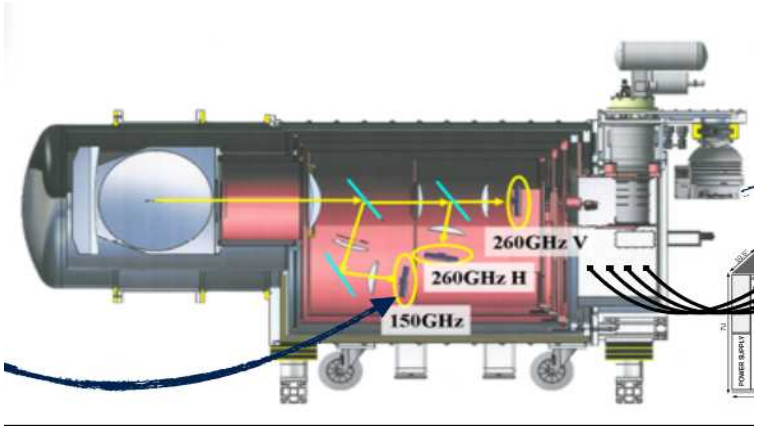
NIKA2

Dual band mm KID camera operating and 150 and 260 GHz

IRAM 30-m telescope at Pico Veleta (Spain)

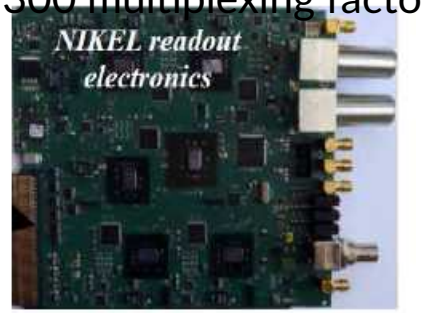
Specific optical system to obtain the largest FOV

Dilution cryostat: 180 mK nominal temperature



Arrays of 1140 (616) KIDs: 8 (4) independent feedlines with up to 200 KID each

300 multiplexing factor



20 boxes (one per feedline) arranged in 3 crates (one per array)

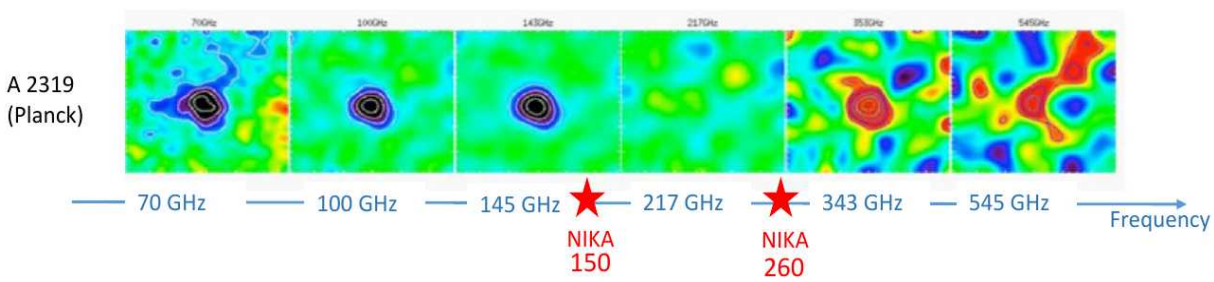
NIKA2

- September 2015 : installation at IRAM
- October 2015 : First lights
- September 2016 : complete instrumental setup
- April 2017 : commissioning succesfully finished ; performance better than expected
- Open to for public observations for at least one decade from now

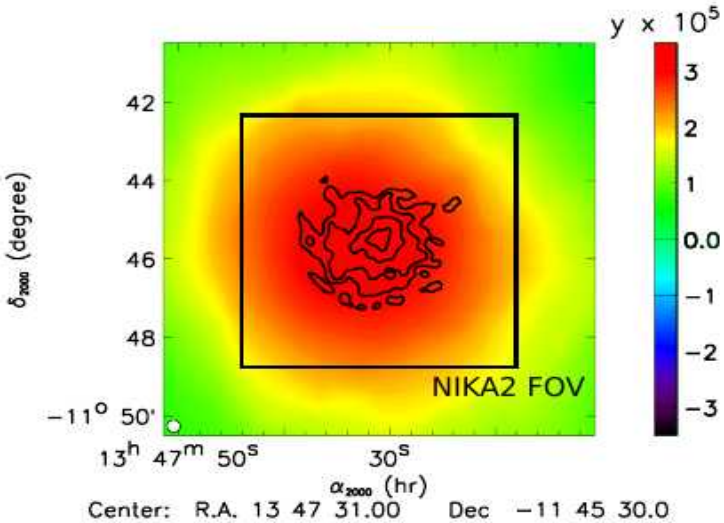
Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	9 mJy/s$^{1/2}$	33 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

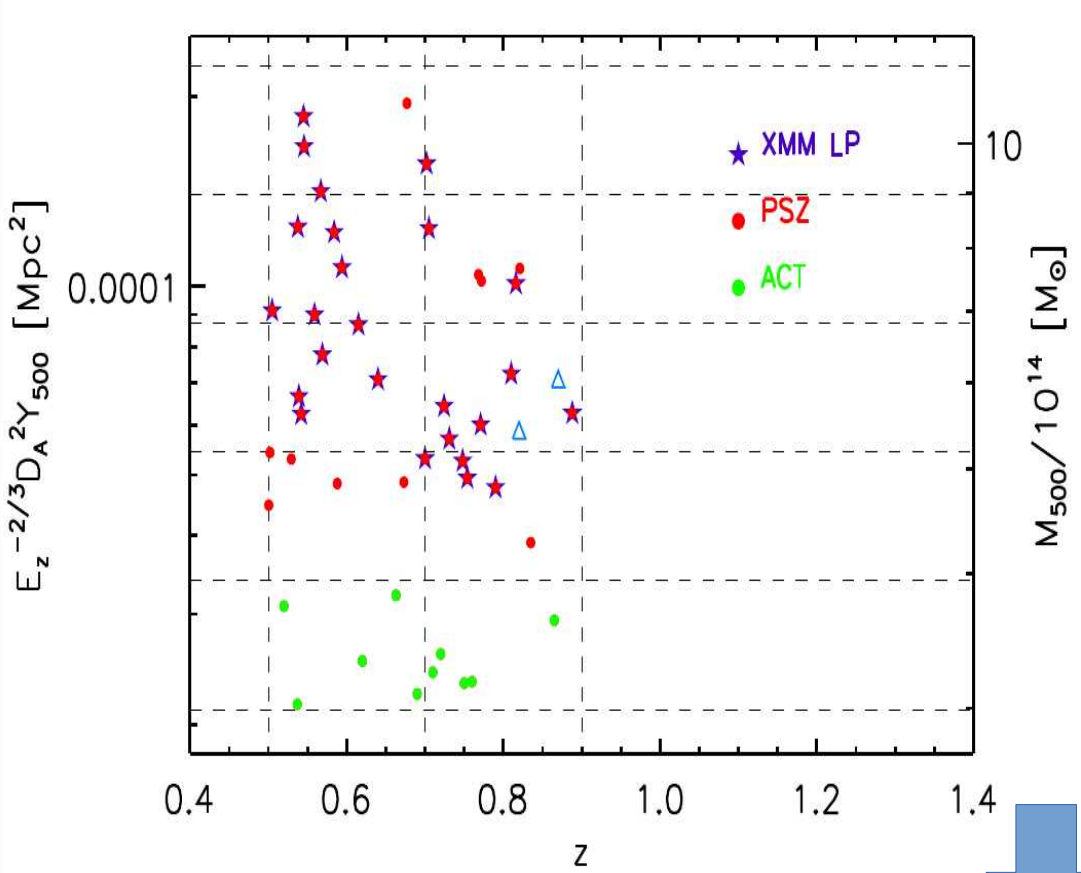
[NIKA collaboration, A&A, 2017,arXv:]

NIKA2 is well adapted for SZ observations of intermediate and high redshift



- Two frequency bands, negative & zero tSZ signal
- Large FOV : size of PLANCK beam
- High resolution : 17 times better than Planck





One of the 5 NIKA2 LP (1300h in total)

- **300 hours** of tSZ observation
- **50 high redshift clusters 0.5 < z < 1.0**
- tSZ selected clusters from Planck and ACT catalogues

Ancillary data

- X-ray follow-up with XMM
- Optical data using GranTeCan
- MUSIC hydrodynamic simulations

Main goals

- In-depth study of ICM
- Thermodynamic properties: pressure, density, temperature and entropy profiles
- Mass – tSZ flux relationship

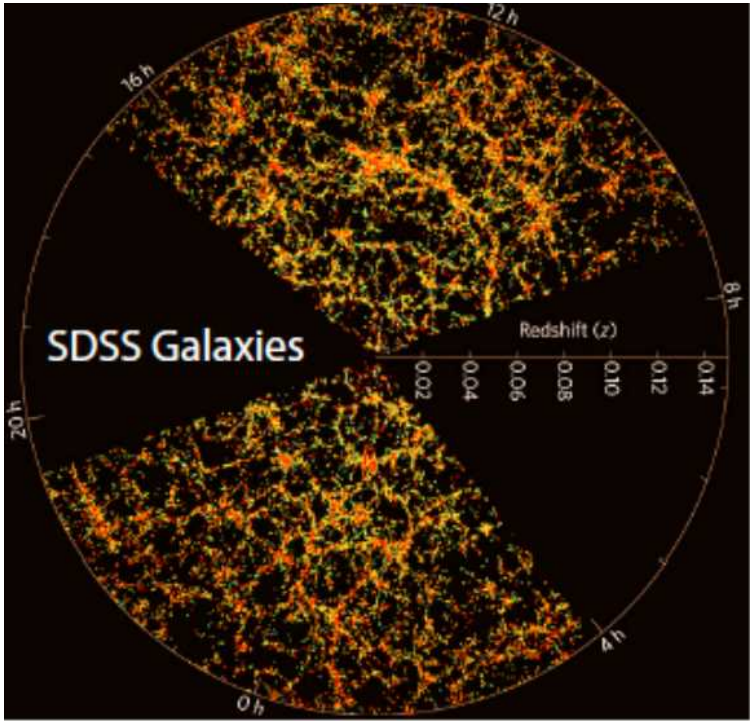
Redshift evolution of:

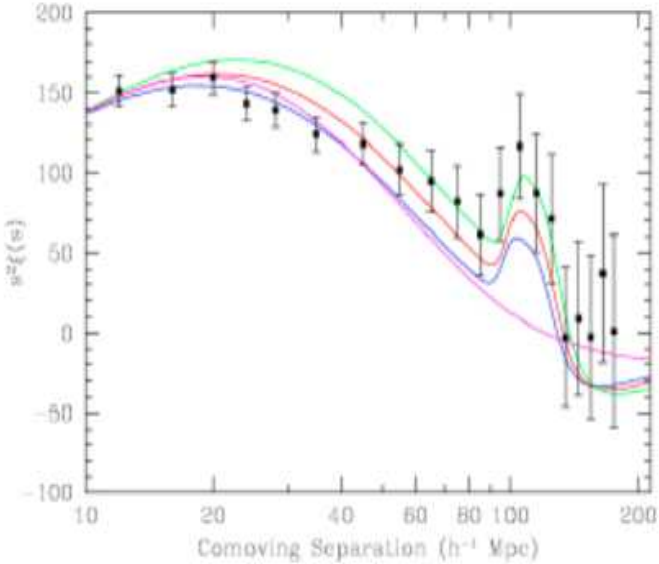
- Thermodynamic quantities profiles
- Scaling laws and hydrostatic bias

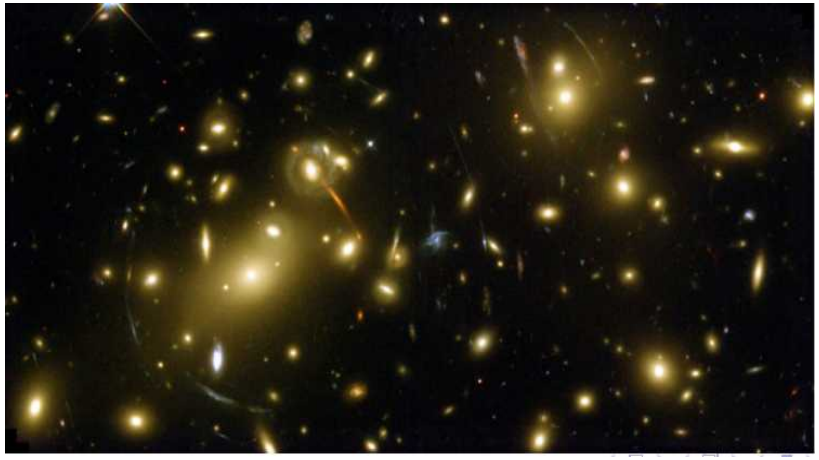
Variation of cluster properties with:

- Dynamical state (mergers)
- Morphology (ellipticity)

Part II :
LSS OBSERVATIONS

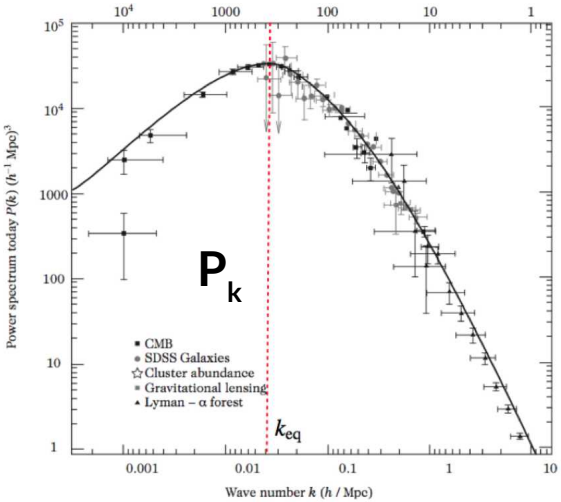


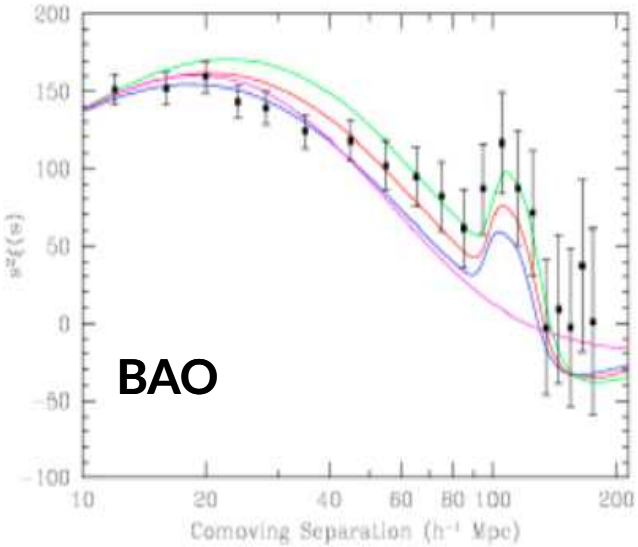




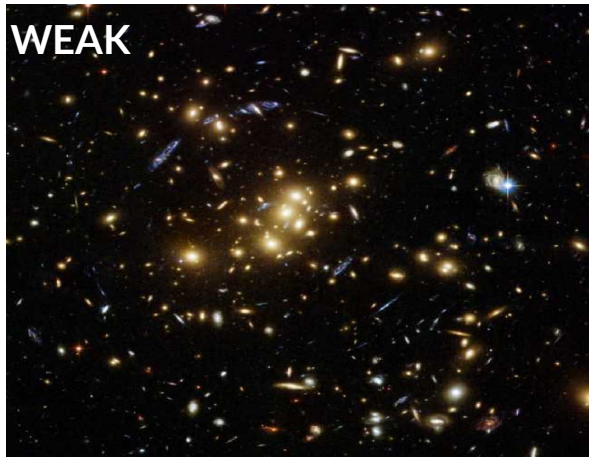
LSS observables

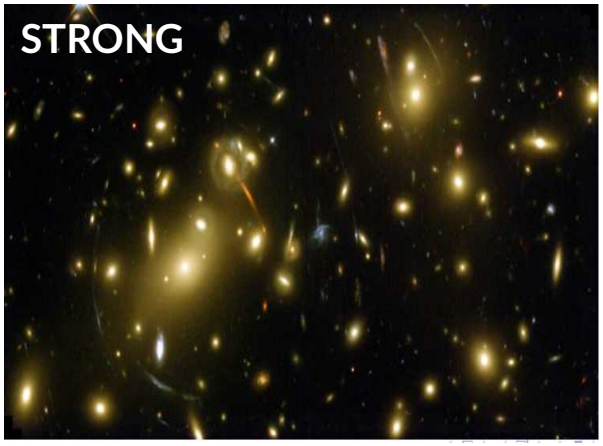
- Galaxy clustering



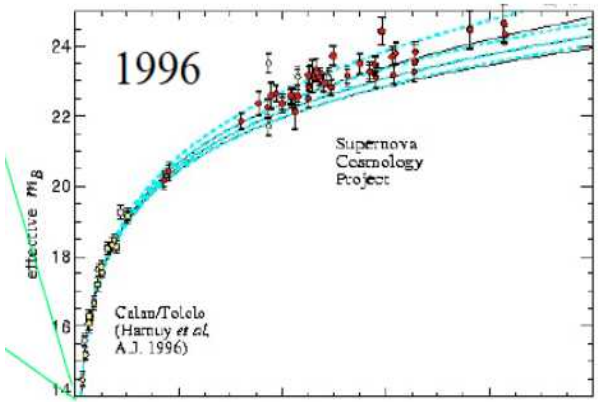


- Lensing : weak & strong

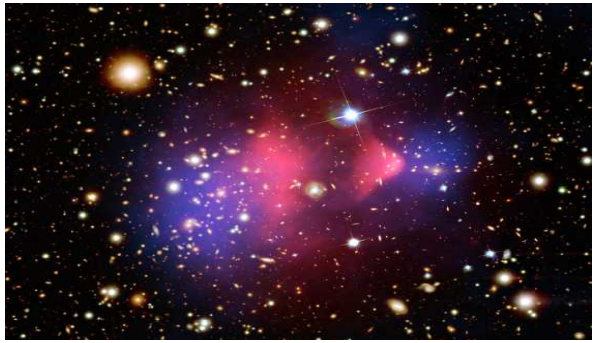


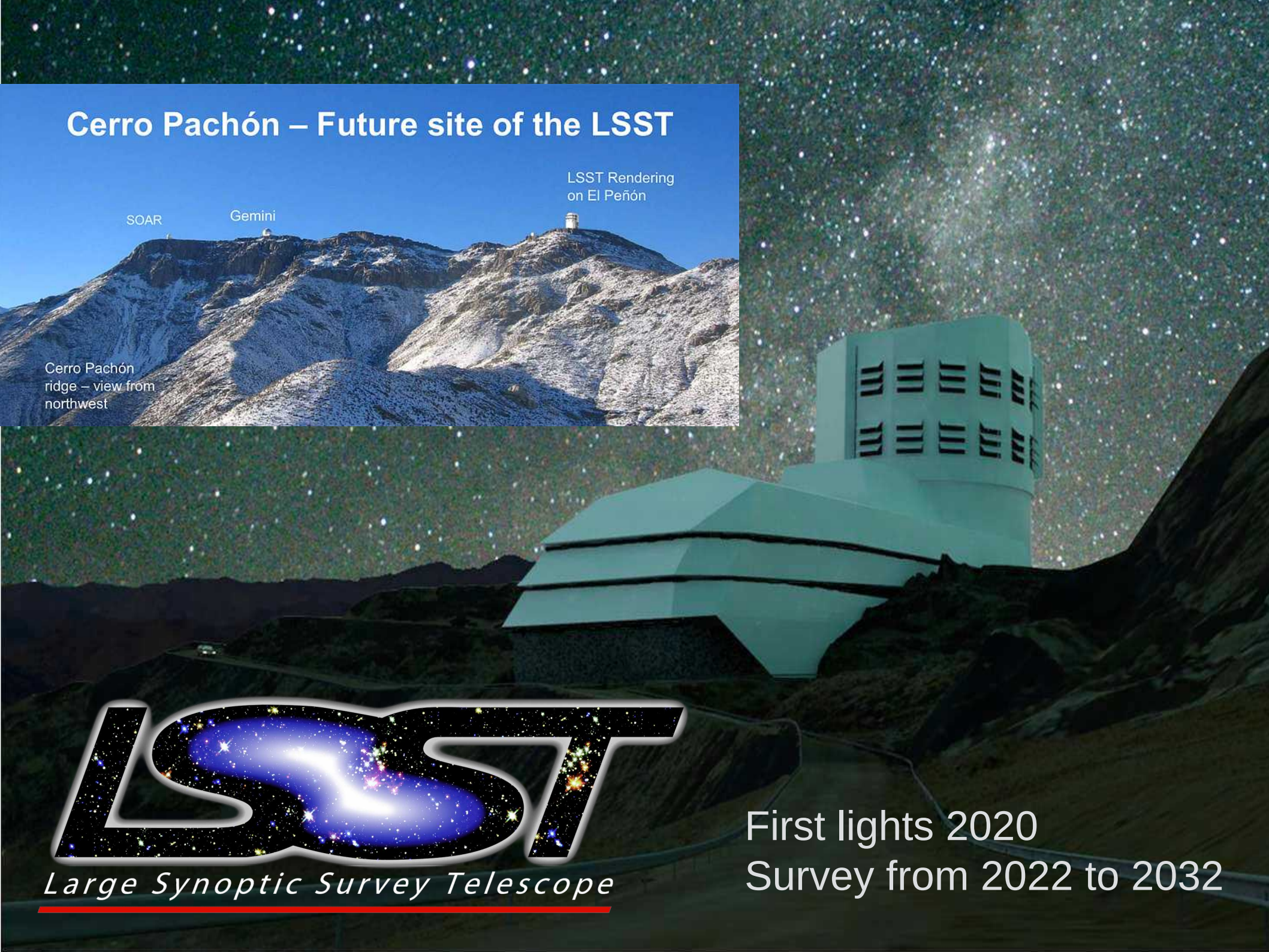


- Supernovae type I



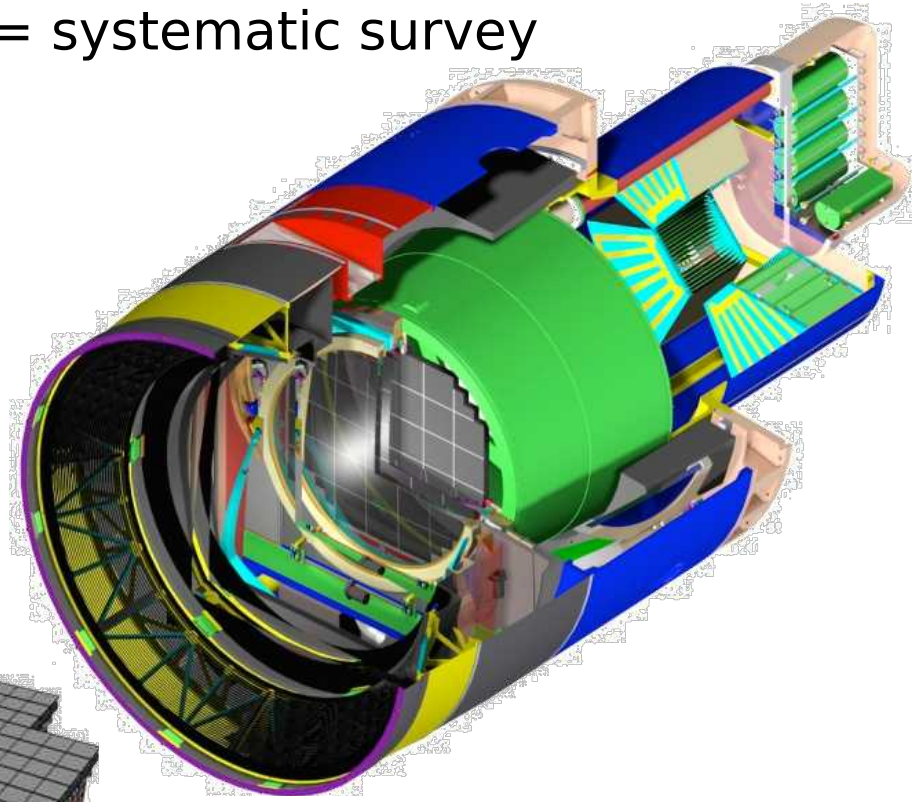
- Clusters of galaxies

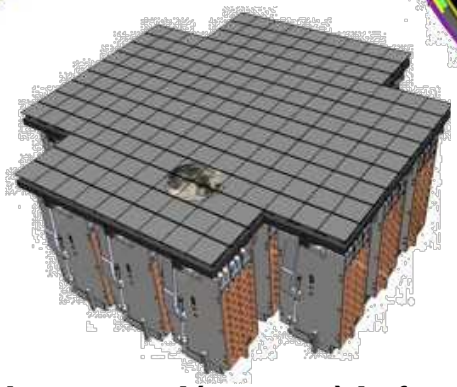



Cerro Pachón – Future site of the LSST
LSST Rendering on El Peñón
SOAR
Gemini
Cerro Pachón ridge – view from northwest
LSST
Large Synoptic Survey Telescope
First lights 2020
Survey from 2022 to 2032

LSST must scan ~1/2 of the visible sky every 3/4 nights during 10 years in 6 frequency bands with high sensitivity

Large = big
Synoptic = view all
Survey = systematic survey

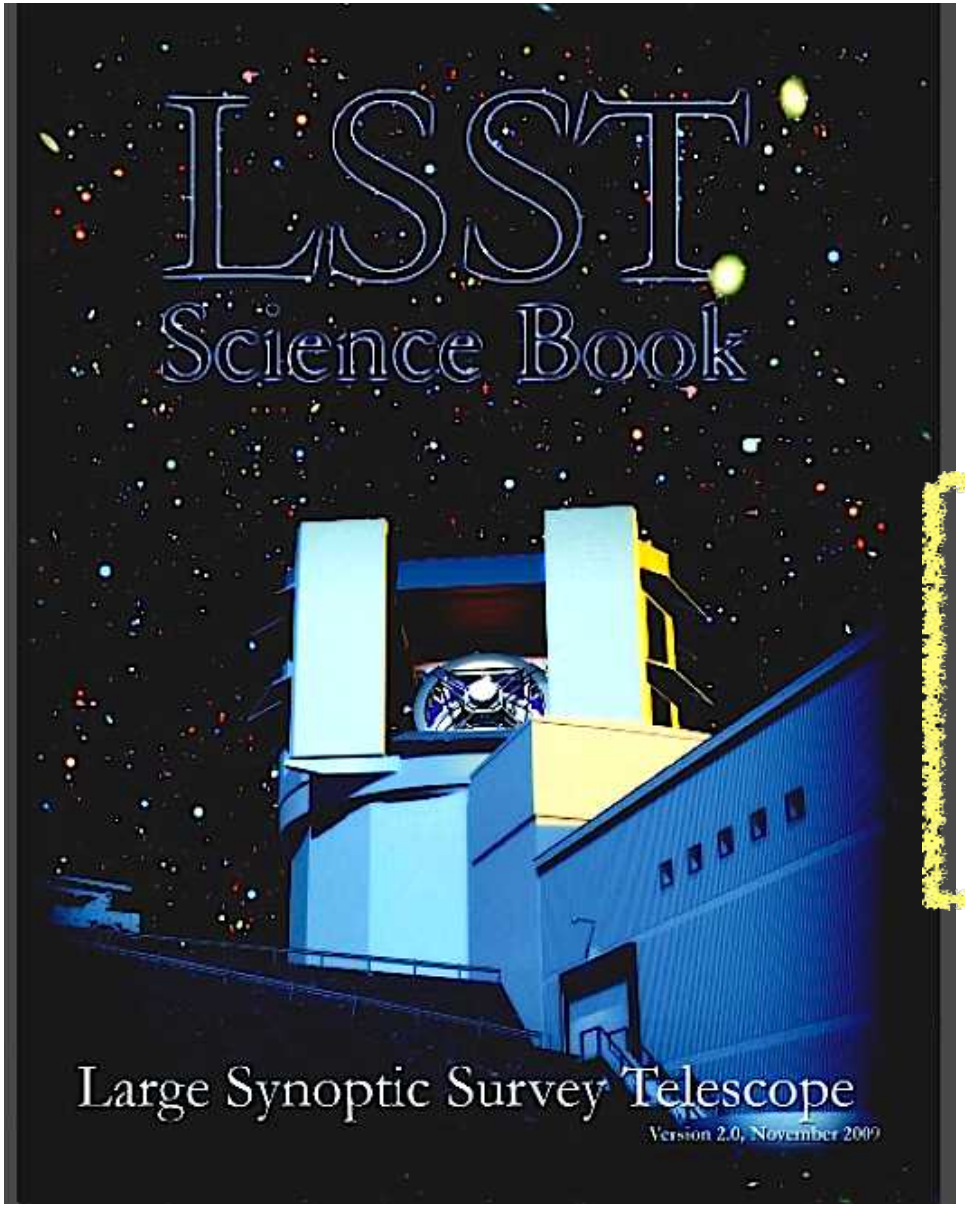




8.4 m diameter telescope to be able to detect faint objects

Large FOV camera with 6 filters from nearby IR to nearby UV, 3 millards of pixels

LSST scientific program



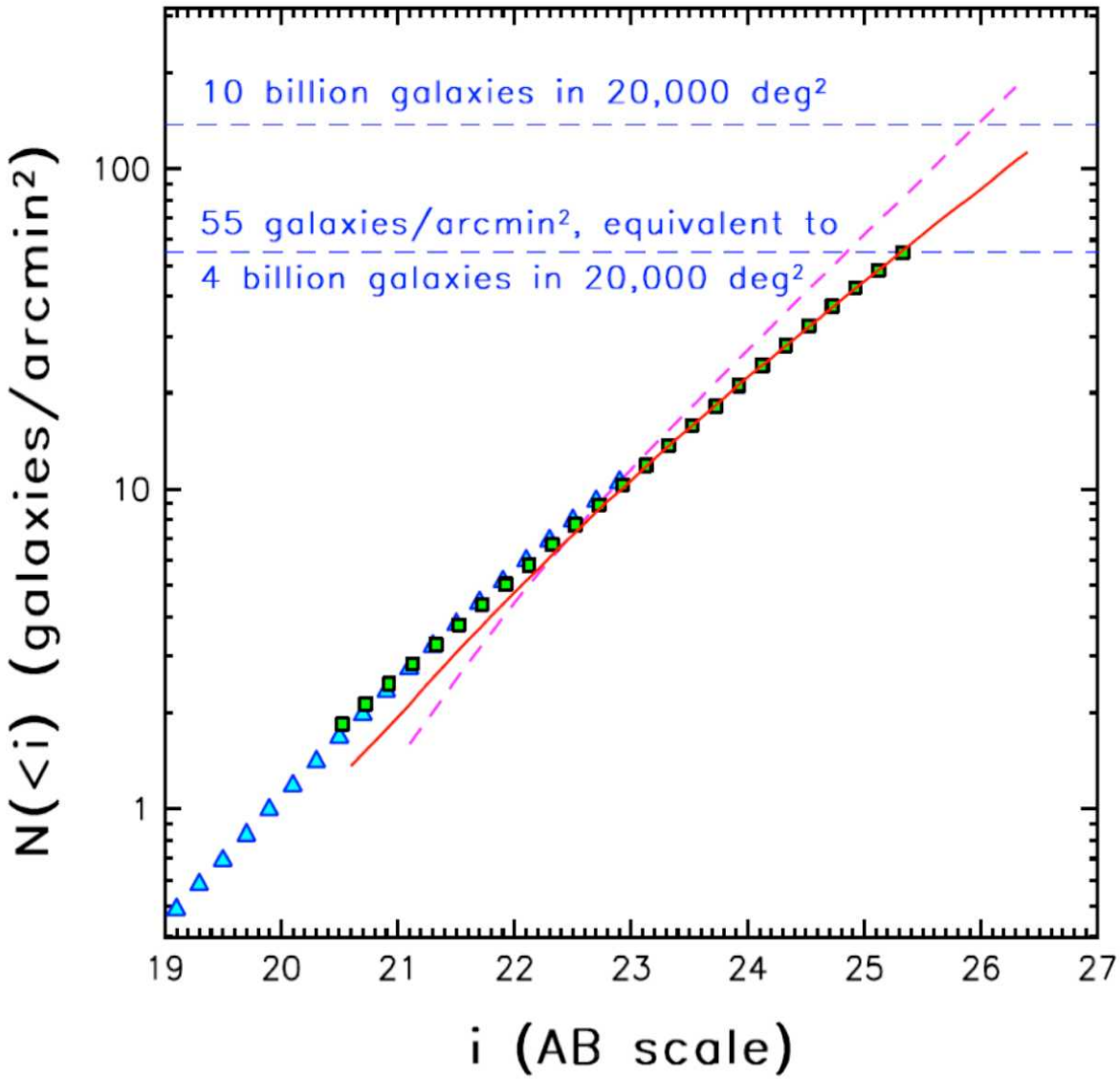
- ➔Solar system objects
- ➔Stellar populations
- ➔Our galaxy and the local environment
- ➔Variable sky objects
- ➔galaxies
- ➔Actifs galaxies
- ➔supernovae
- ➔Strong lensing
- ➔Weak lensing
- ➔Galaxy clustering
- ➔Clusters of galaxies

cosmologie

IN2P3 labs are fully involved in cosmological studies

www.lsst.org/lsst/scibook

Mesure the position/redshift of milliards of galaxies



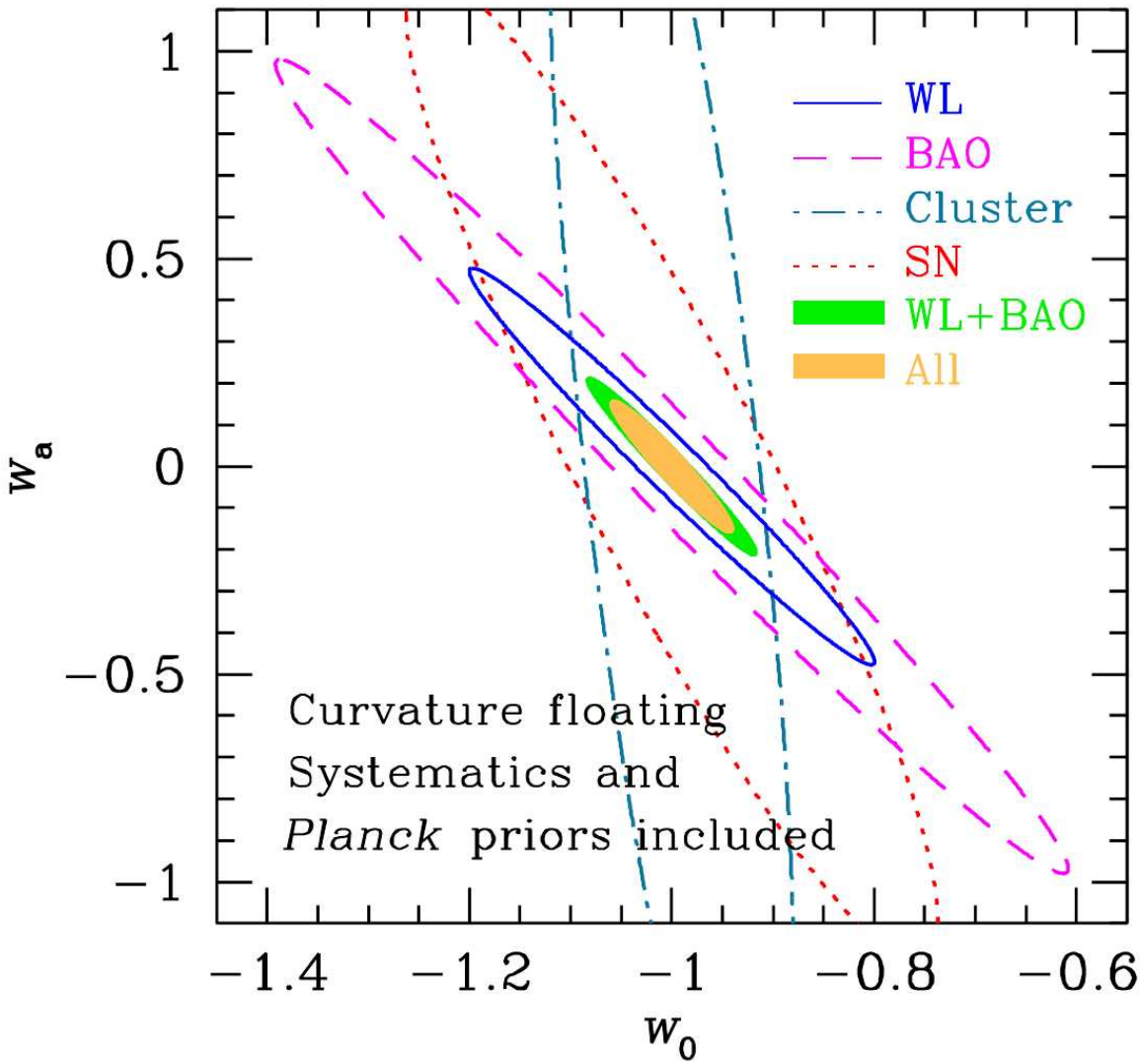
To use galaxies for cosmology we need to measure their redshift

Accurate photometry in 6 bands = very low resolution spectroscopy

Need to estimate redshift for 3-4 milliards for galaxies up to z=2-3

Although photometric redshift uncertainties smear out the distribution, the large statistic allows us to use galaxies for cosmology

Precision/accurate cosmology
Multi-Probe analysis



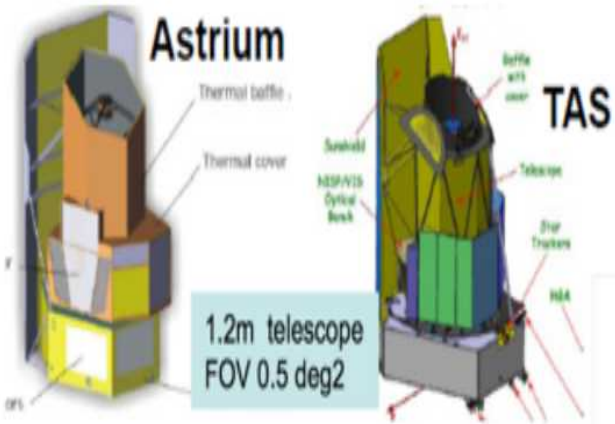
Example :

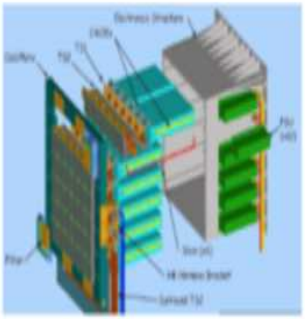
Measuring the nature of dark energy

$$p = w\,\rho$$
$$w(a) = w_0 + w_a\,(1-a)$$

EUCLID

The EUCLID instrument





The Visible imager (VIS)
36 E2V CCD, 0,1"PSF
1 broad band R+I+Z (550-900nm)

The Infrared spectro/photometer (NISP)
16 H2Rg infra red pixel detectors,0,3" PSF,
3 IR bands Y,J,H (920-2000 nm)
NIR slitless spectroscopy (1100 – 2000 nm) R ~ 350

- M class ESA space mission
- All-sky visible and IR observations in photometry and spectroscopy
- Exposure depth 24 magnitudes
- 2 surveys : shallow (15000 deg^2), deep (2 x 20 deg^2)
- Consists of 2 channels, and 3 instruments :
  - VIS, optical imager for lensing reconstruction (550-900 nm)
  - NISP, IR photometer (900 – 2000 nm) and spectrometer (1100- 2000 nm)
- Launch 2020-2021
- 7 years operation
- International collaboration, IN2P3 fully involved

EUCLID cosmological probes

Weak lensing (WL)

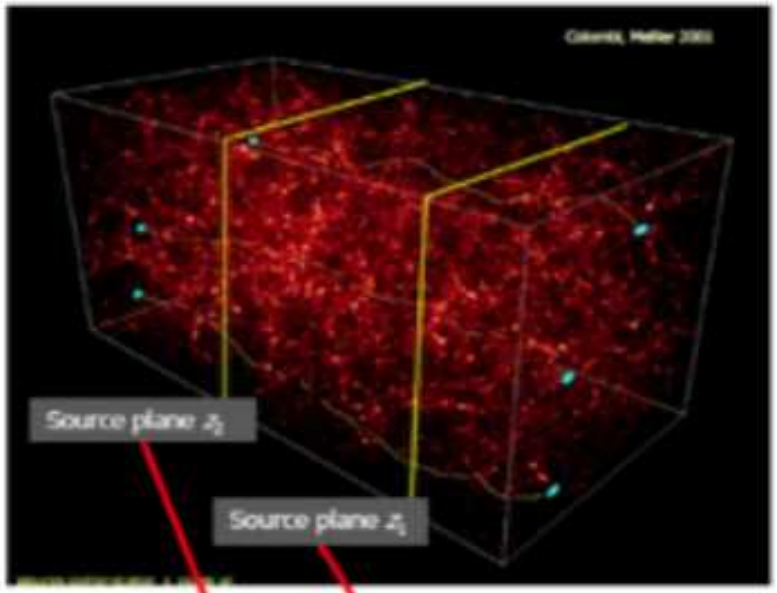
- distribution of matter, expansion history, growth rate, tomography
- 3-D cosmic shear measurements 0 < z< 2
- shape and photo-z from optical and NIR data
- 1.5 billion galaxies

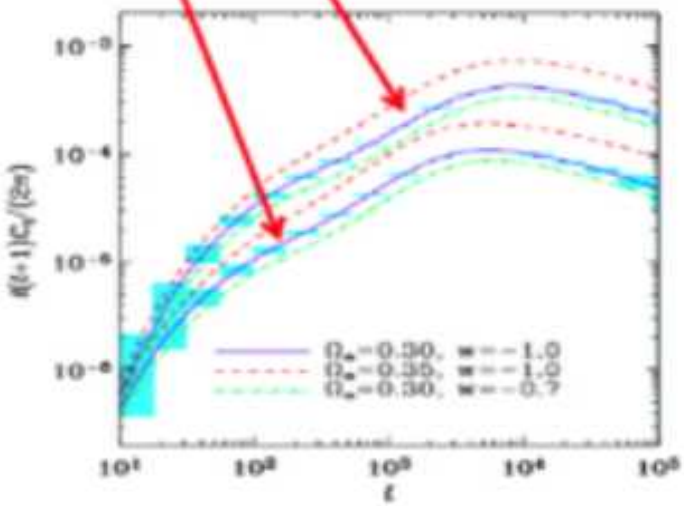
Galaxy clustering (GC)

- distribution of matter, expansion history, growth rate, tomography
- 3-D position measurements 0.7 < z< 2
- 3D distribution of galaxies from spectroscopy redshift
- measure position of 50 millions galaxies

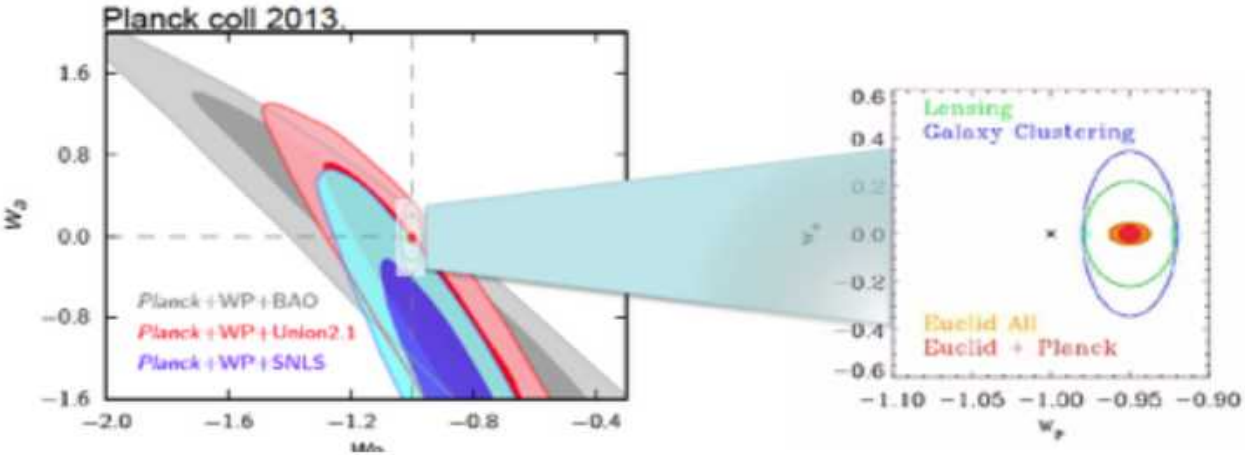
Clusters of galaxies

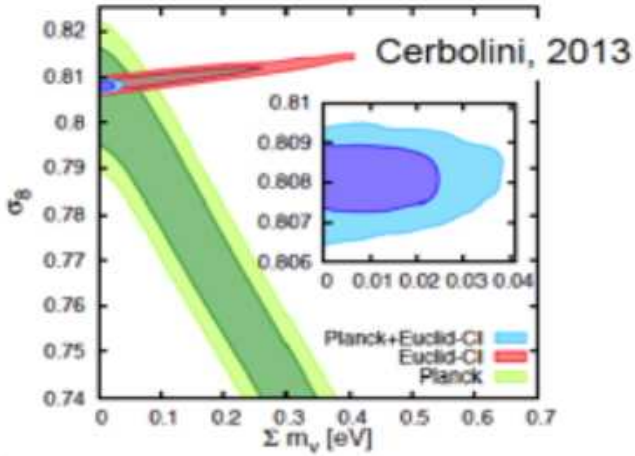
- measure cluster number counts as a function mass and redshift, power spectrum statistics,
- detection of about **60000** clusters





EUCLID expected performance





	Dark energy			neutrinos	Initial conditions	Modified gravity
Parameter	w_p	w_a	FOM	mν (eV)	F_{NL}	γ
Euclid alone	0,013	0,048	1540	0,027	5,5	0,009
Euclid +Planck	0.007	0.035	4020	0.019	2.0	0.007
Current	0.1	1.5	~10	0.58	100	0.2
Improve factor	>10	>50	>400	30	50	30

The Euclid mission

Observing the sky