Euclid and LSPE:
INFN data analysis for cosmology

Francesco Piacentini
Sapienza University of Rome – Physics Department

on behalf the LSPE and Euclid INFN collaborations

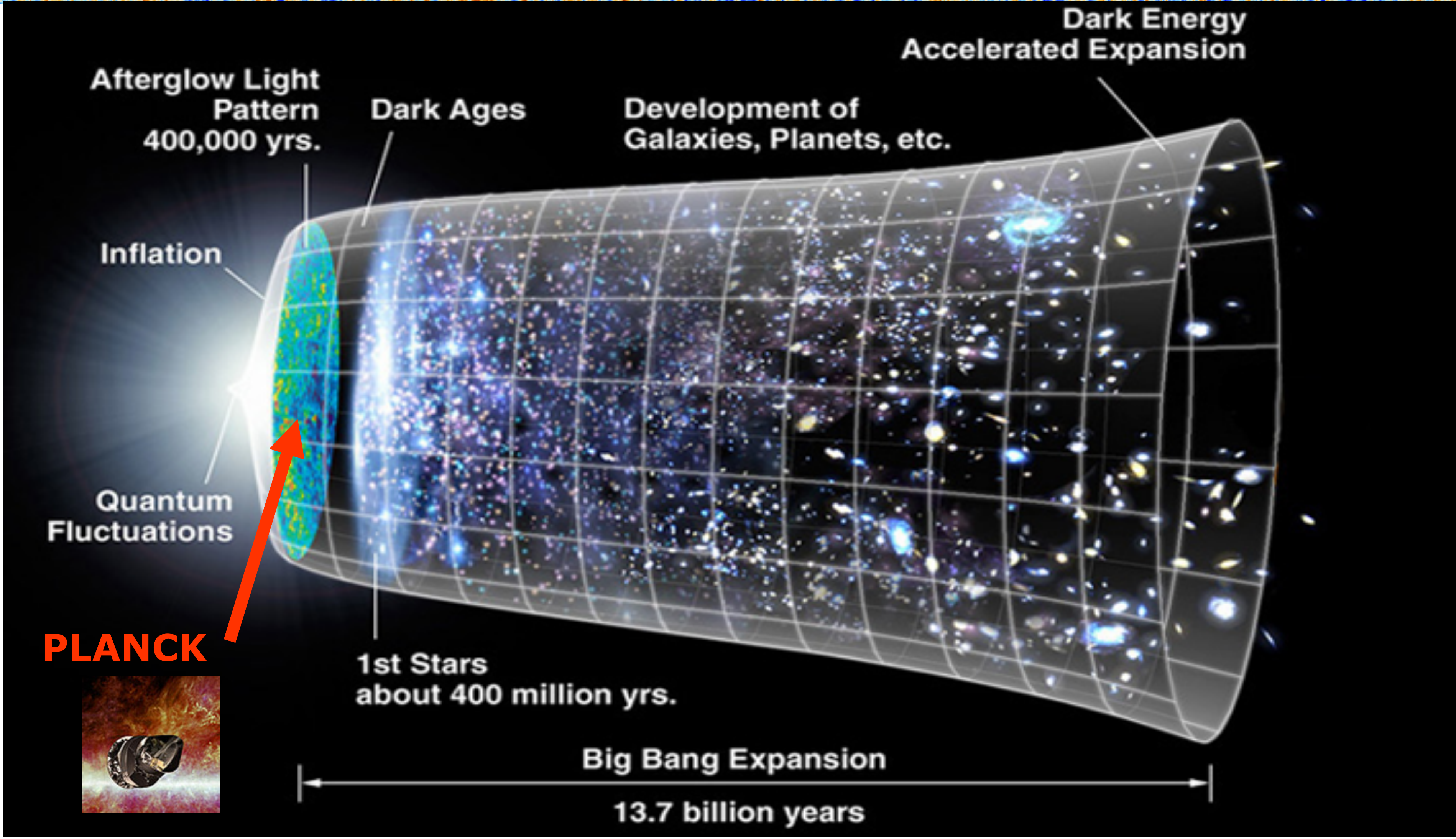
LSPE INFN: **Ferrara, Genova, Milano, Pisa, Roma1, Roma2**

Euclid INFN: **Bologna, Lecce, Milano, Padova**

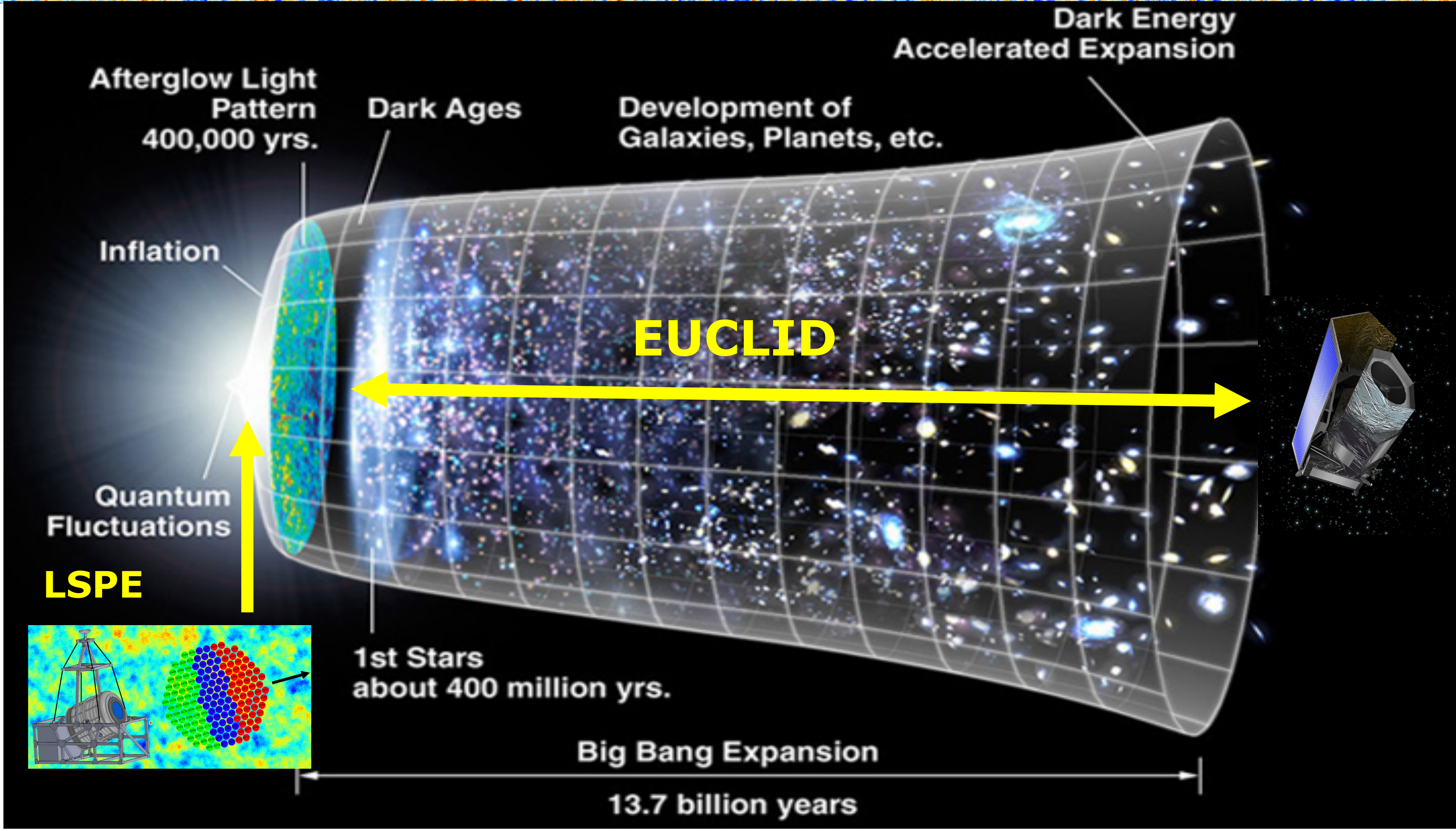
LSPE
Large Scale Polarization Explorer

Euclid consortium

Frontiers of observational cosmology



Frontiers of observational cosmology

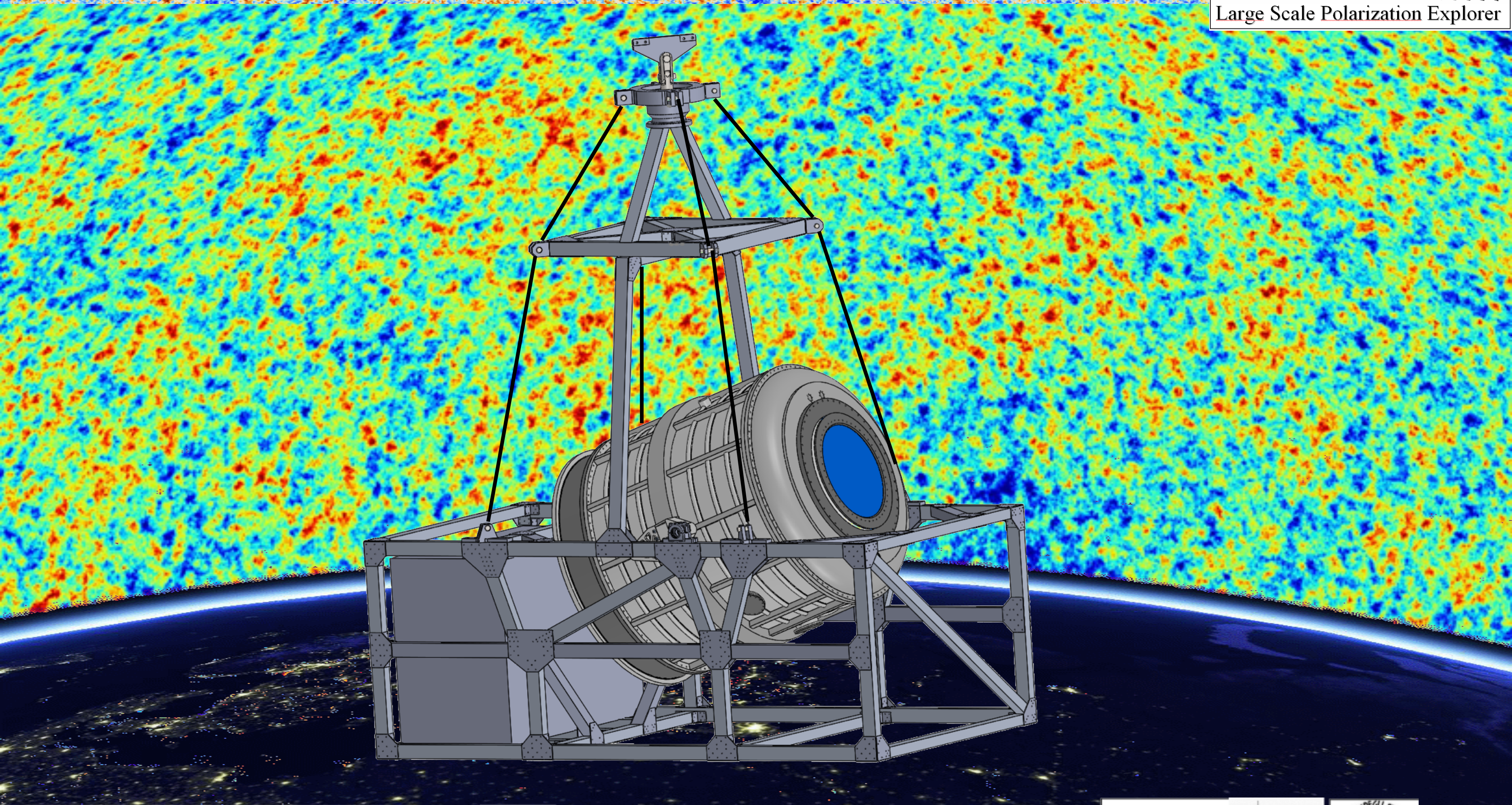


Frontiers of observational cosmology

- **INFLATION**
  - Primordial gravitational waves
    - Polarization pf the Cosmic Microwave Background radiation
      - **LSPE** balloon + ground telescope
- **DARK ENERGY**
  - Accelerated Universe
    - Distribution of Galaxies and Dark Matter at different redshift (to 10 Gy back in time)
      - **Euclid** Space telescope

INFLATION with LSPE

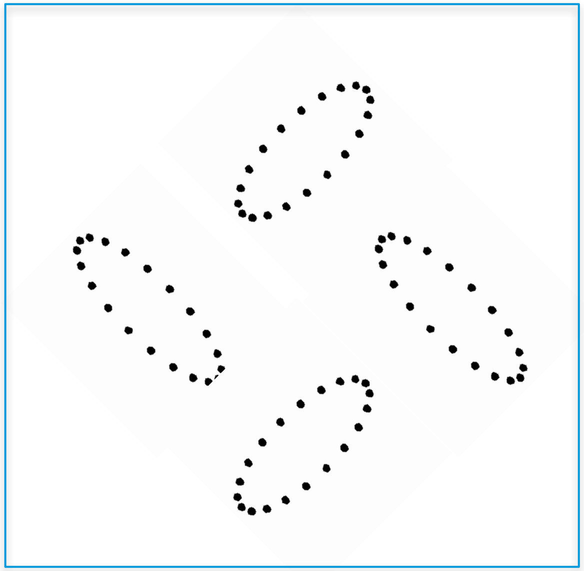
LSPE
Large Scale Polarization Explorer



SAPIENZA UNIVERSITÀ DI ROMA
UNIVERSITÀ DEGLI STUDI DI MILANO
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
IASF bo
IEIIT
IFAC
UNIVERSITY OF CAMBRIDGE
MANCHESTER 1824
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
UNIVERSITÀ DEGLI STUDI DI TRIESTE
INFN Istituto Nazionale di Fisica Nucleare

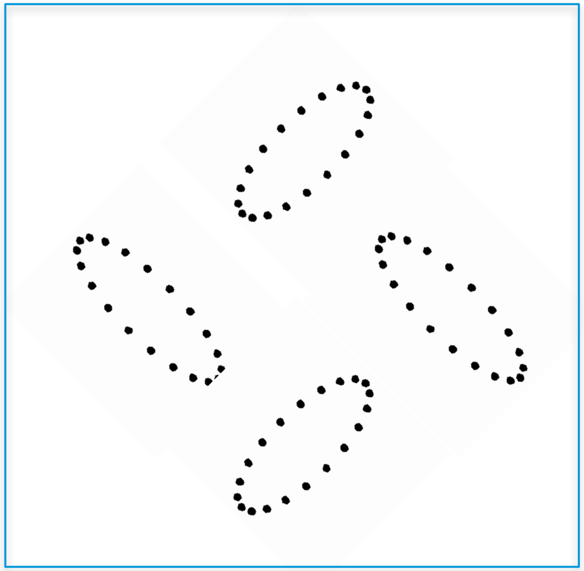
Frontiers of observational cosmology: CMB

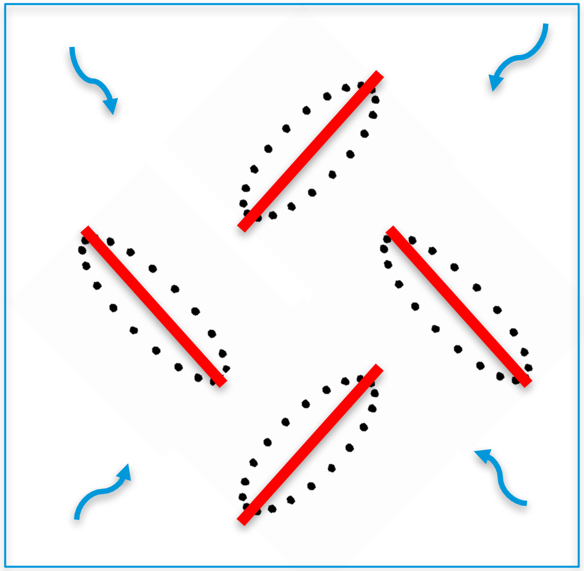
- Deep measure of polarization of the Cosmic Microwave Background radiation
  - Can investigate the **Inflation** on the very Early Universe
  - By detection of **primordial gravitational waves**
  - Through their imprint into the **CMB polarization**
  - GW + Plasma



Frontiers of observational cosmology: CMB

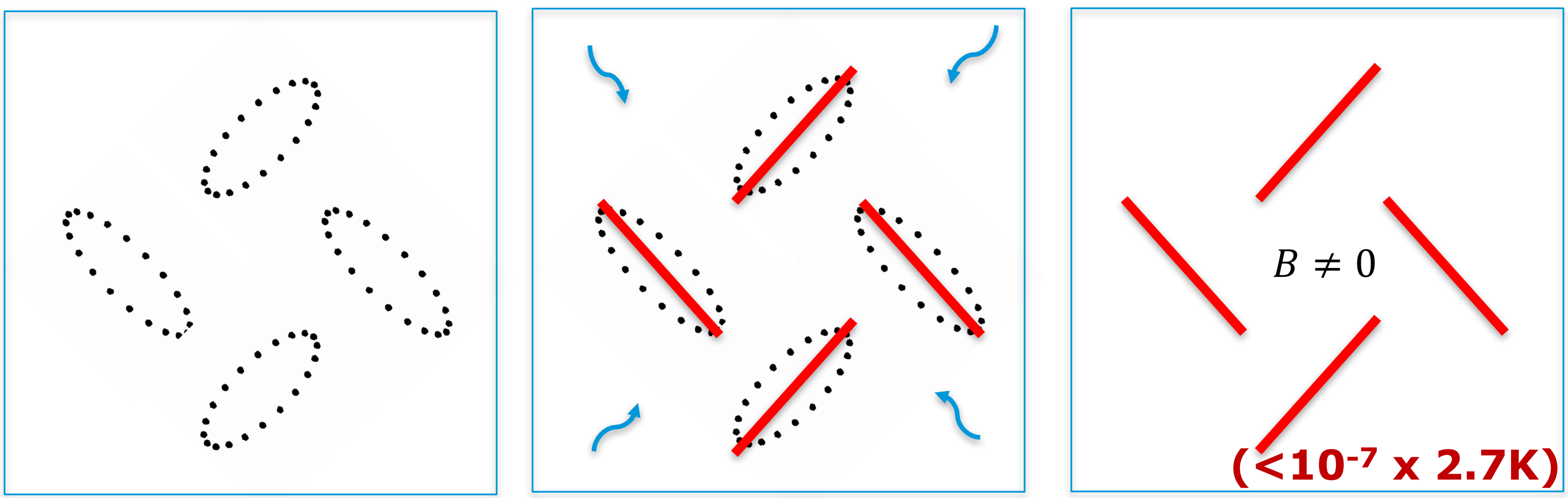
- Deep measure of polarization of the Cosmic Microwave Background radiation
  - Can investigate the **Inflation** on the very Early Universe
  - By detection of **primordial gravitational waves**
  - Through their imprint into the **CMB polarization**
  - GW + Plasma + photons + Thomson scattering





Frontiers of observational cosmology: CMB

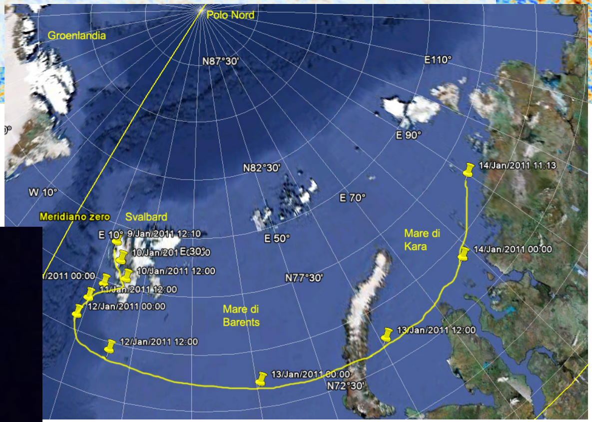
- Deep measure of polarization of the Cosmic Microwave Background radiation
  - Can investigate the **Inflation** on the very Early Universe
  - By detection of **primordial gravitational waves**
  - Through their imprint into the **CMB polarization**
  - GW + Plasma + photons + Thomson scattering => **B-modes**
  - CMB polarization as an antenna for primordial gravitational waves

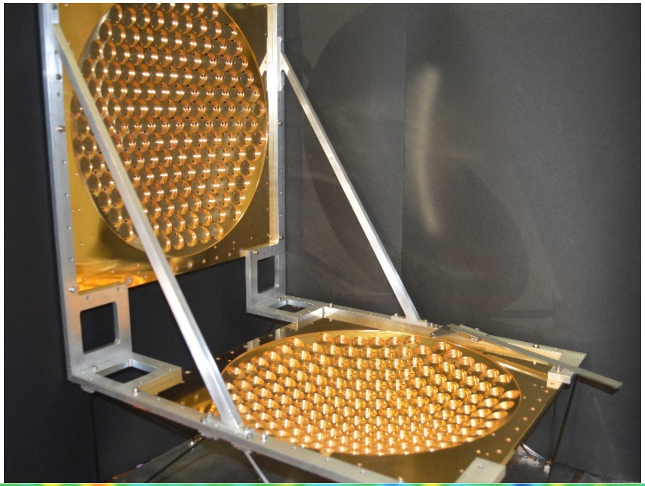


LSPE instrumentation / 1

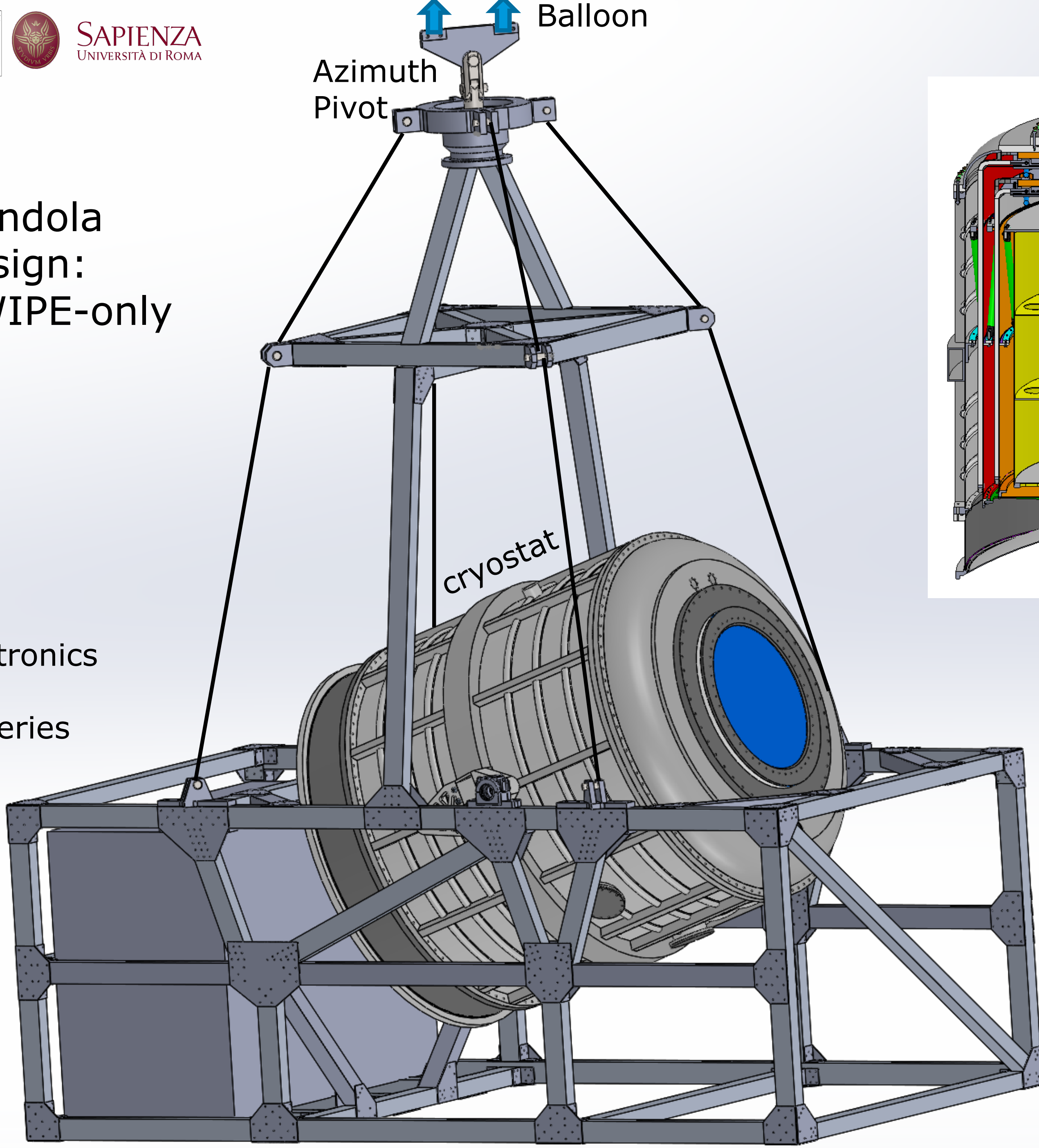
- LSPE SWIPE: Winter Arctic **stratospheric balloon**:
  - Svalbard, Dec 2018
  - Full dark for 15 days
  - Powered by batteries
  - Microwave: 150 - 220 - 240 GHz
  - 300 mK cryogenic system
  - Spinning telescope
  - 500 mm aperture
  - 1.5 deg angular resolution
  - Covering 30% of the sky

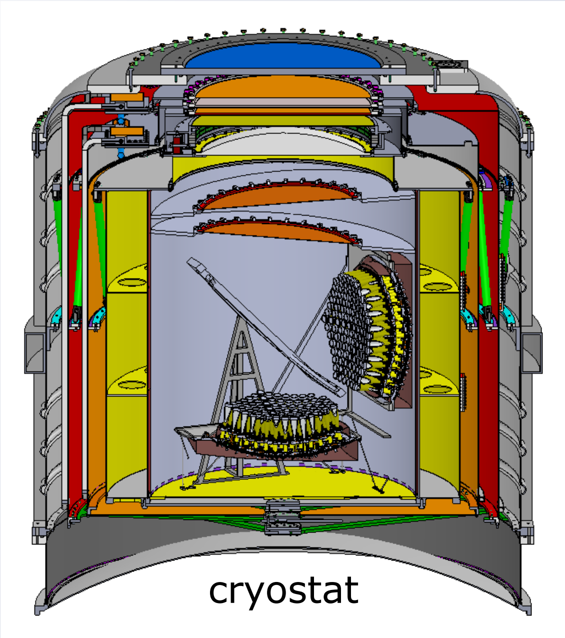
  - INFN contribution:
    - Multimode TES bolometers
    - readout for TES bolometers
    - Cryogenic facility





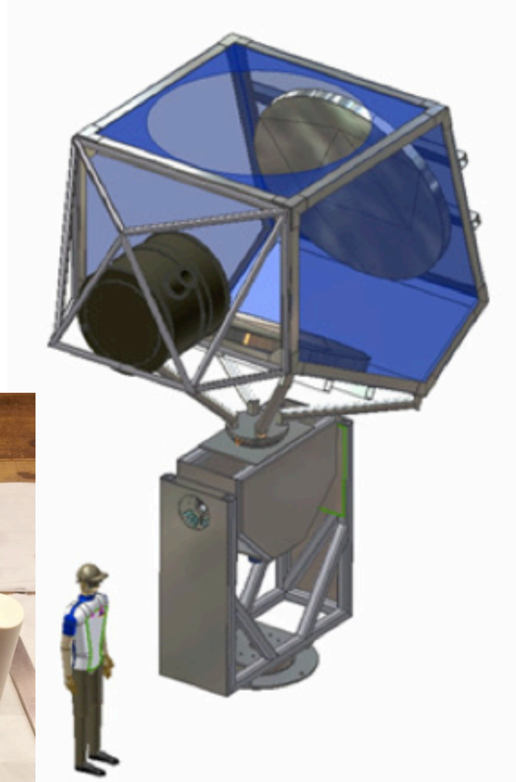
Gondola design: SWIPE-only

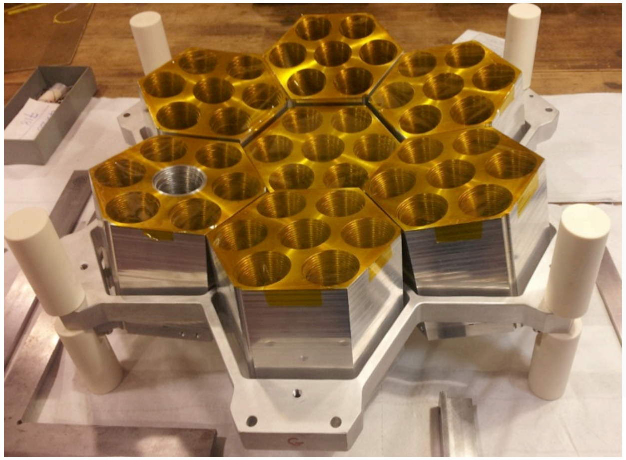




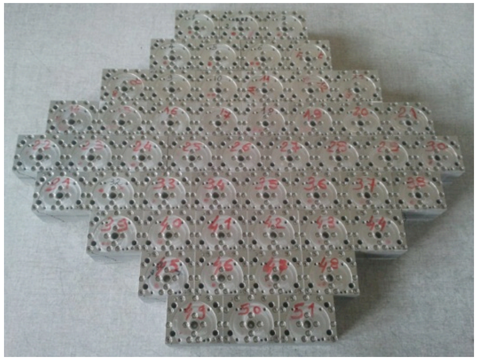
LSPE instrumentation / 2

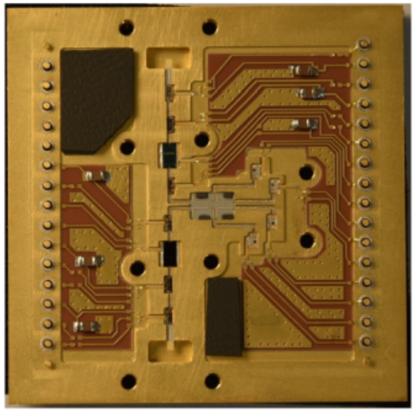
- LSPE STRIP: **Ground based**
  - Tenerife, Mar 2018
  - 2 years campaign
  - Microwave: 43 - 90 GHz
  - 20K cryogenic system
  - Spinning telescope
  - 1500 mm aperture
  - 0.3 deg angular resolution
  - Covering 30% of the sky (same as SWIPE)



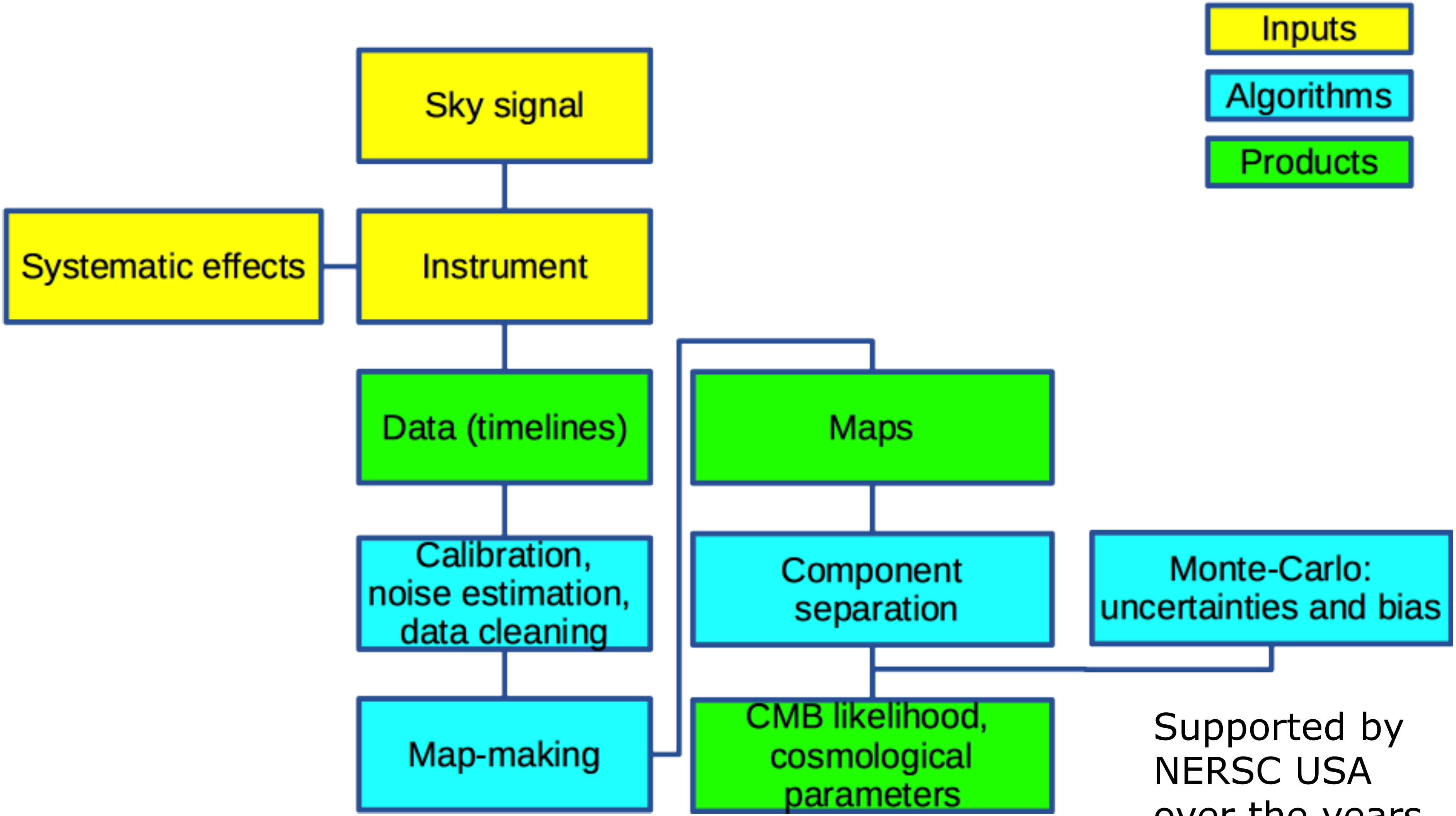


  - INFN contribution:
    - Telescope mount
    - Test instrumentation





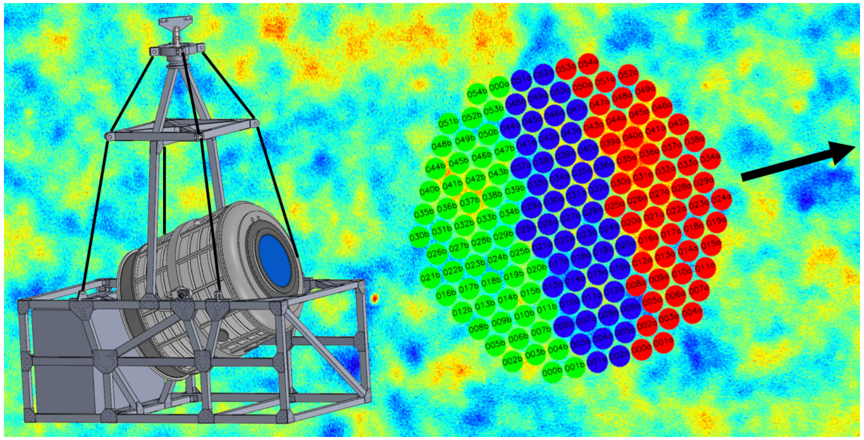
Typical CMB experiment data flow



Supported by NERSC USA over the years

Example: LSPE SWIPE Instrument simulator

- Simulation of:
  - 326 detectors
  - Each one sampled at 100 Hz for 15 days ($42 \cdot 10^9$ samples)
  - Each sample is the convolution of the sky with the angular response (on a 5 degrees radius)
  - Intensity and polarization signal
  - Noise and systematic effects
  - Time domain Filtering effects
  - Projection to sky maps



LSPE SWIPE Computational model and resources

- Units: core hr = 1 core used for 1 hour wall time
    - NERSC allocation 2016 **11 G core hr** in 2016 for new CMB experiments (10)

- Architecture
    - Open MPI architecture
    - Some OpenMP library
    - Large amount of data exchange

- Machine type
    - HPC cluster
    - ~200 cores minimum
    - Highest possible value of RAM/core: 16GB/core ideal
    - InfiniBand connection

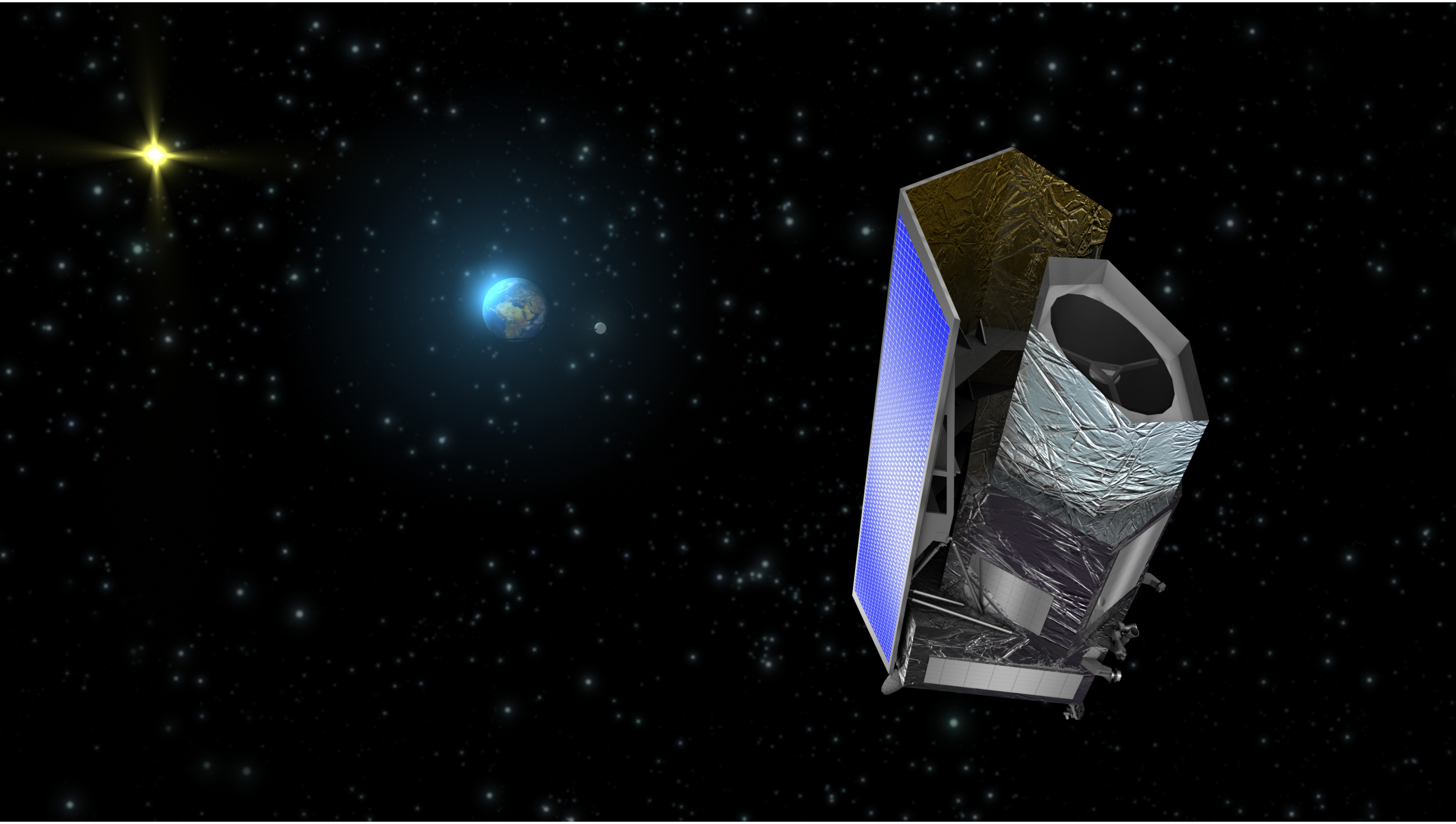
LSPE SWIPE Computational model and resources

- Heaviest tasks are:
  - Instrument simulator:
    - Parallel Fortran code
    - The more complex version requires **1.3 k core hr** for one simulation
    - 326 detectors (~100 per band); 16 GB RAM for each detector
    - **1000 simulations require 1.3 M core hr**
  - Mapmaking, with correlated noise
    - Parallel Fortran code
    - Can produce pixel-pixel inverse noise covariance matrix
    - 320 cores x 10 hr with 10 GB RAM per core, for one map
    - **300 maps require 1 M core hr**

LSPE Computational model and resources

- Heaviest tasks are:
  - CMB component separation
    - R&D to select adequate methods for LSPE
    - Not computationally demanding (~ 32 core node)
  - Power spectrum estimation (QML) – **Bolpol**
    - MPI/OpenMP
    - Flexible (32 to 1000+ cores)
  - Cosmological parameter estimation
    - Critical piece is likelihood code
      - pixel based (32-256 cores adequate)
      - power spectrum based: minimal computational burden at likelihood level, but heavily relies on simulations and QML

Dark Energy with Euclid



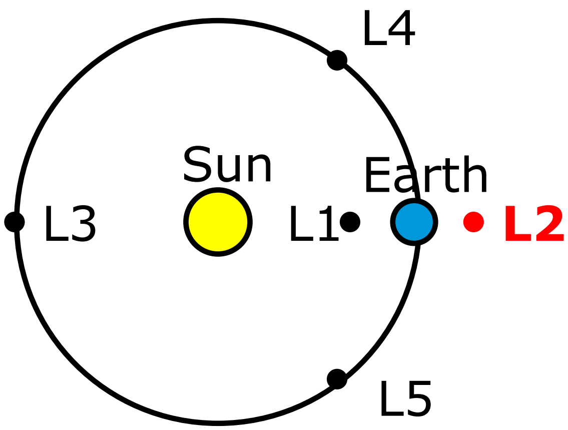
Euclid physics

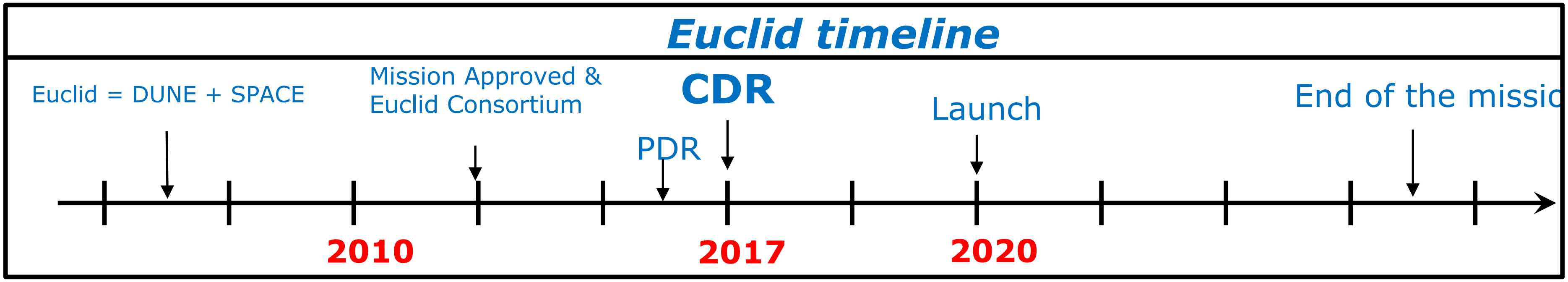
- *Why*: understand the physical **origin of the accelerated expansion** of the Universe
- *How*: **mapping matter** distribution at different redshifts (i.e. looking ~ 10 Gy back in time)
- Two fundamental questions:
  - Q1: Derive properties/nature of dark energy (DE)
  - Q2: Is the General Relativity still valid at cosmological scales? Modified Gravity?

→ As a "free by-product": information on Dark Matter, Neutrino masses and numbers

The Euclid mission

- Euclid is **medium class** mission of ESA **Cosmic Vision** program (2015 - 2025)
- **Launch: 2020** from ESA spaceport in Kourou (French Guyana) with Soyuz ST-2.1B rocket
- Orbit around the Lagrangian point **L2** of Sun-Earth system
- Nominal mission duration: **6 years**





Euclid Consortium

14 countries + NASA, ~ 1200 members

- Lead: Chair (Y. Mellier - IAP France) + EC Board
- France, Italy & UK are the major contributors
- 2 Italians in the EC Board (Cimatti & Scaramella)

Italian Participation

"Euclid-Italy" Team

- **~150 members**
- Financial support from **ASI**, partly from **MIUR** (PRIN)
- **ASI** support with SSDC)
- **Universities** : Bologna, Milano, Napoli, Padova, Roma1, Roma2, Roma3, SISSA (Trieste), SNS (Pisa), Trieste
- **INAF** : OABO, OABrera, OACT, OAA, OANA, OAPD, OARM, OATO, OATS, IASFBO, IASFMI, IAPS
- **INFN : Bologna, Lecce, Milano, Padova**

EUCLID payload

1.2m diameter telescope

2 instruments:

Visual Imager

VIS

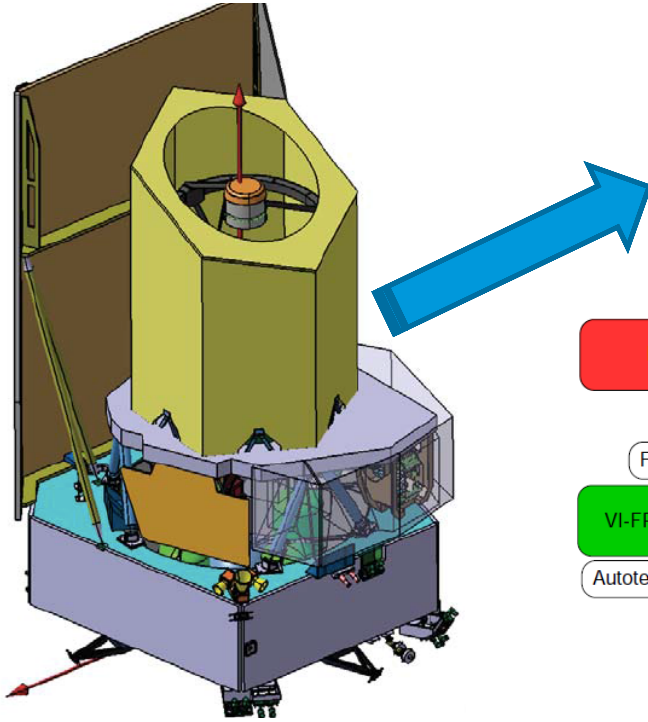
36 CCDs 4096 × 4132

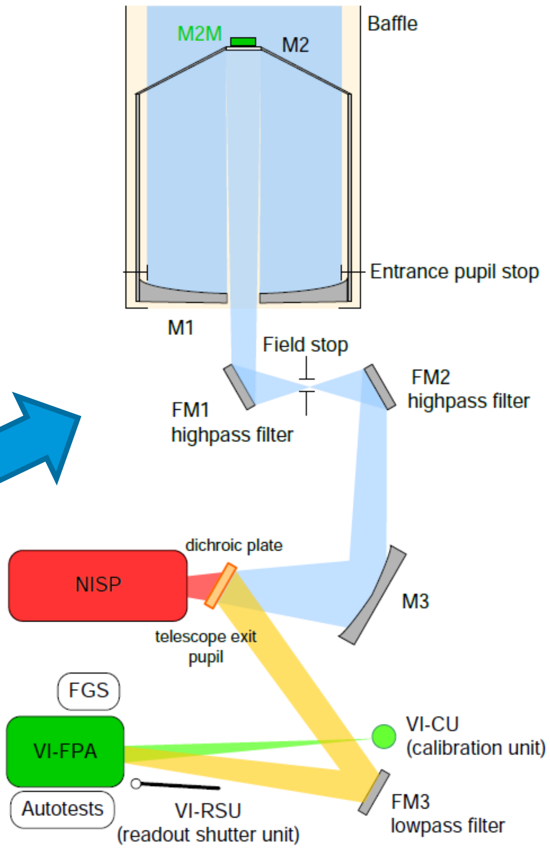
Near-Infrared Spectrometer and Photometer

NISP

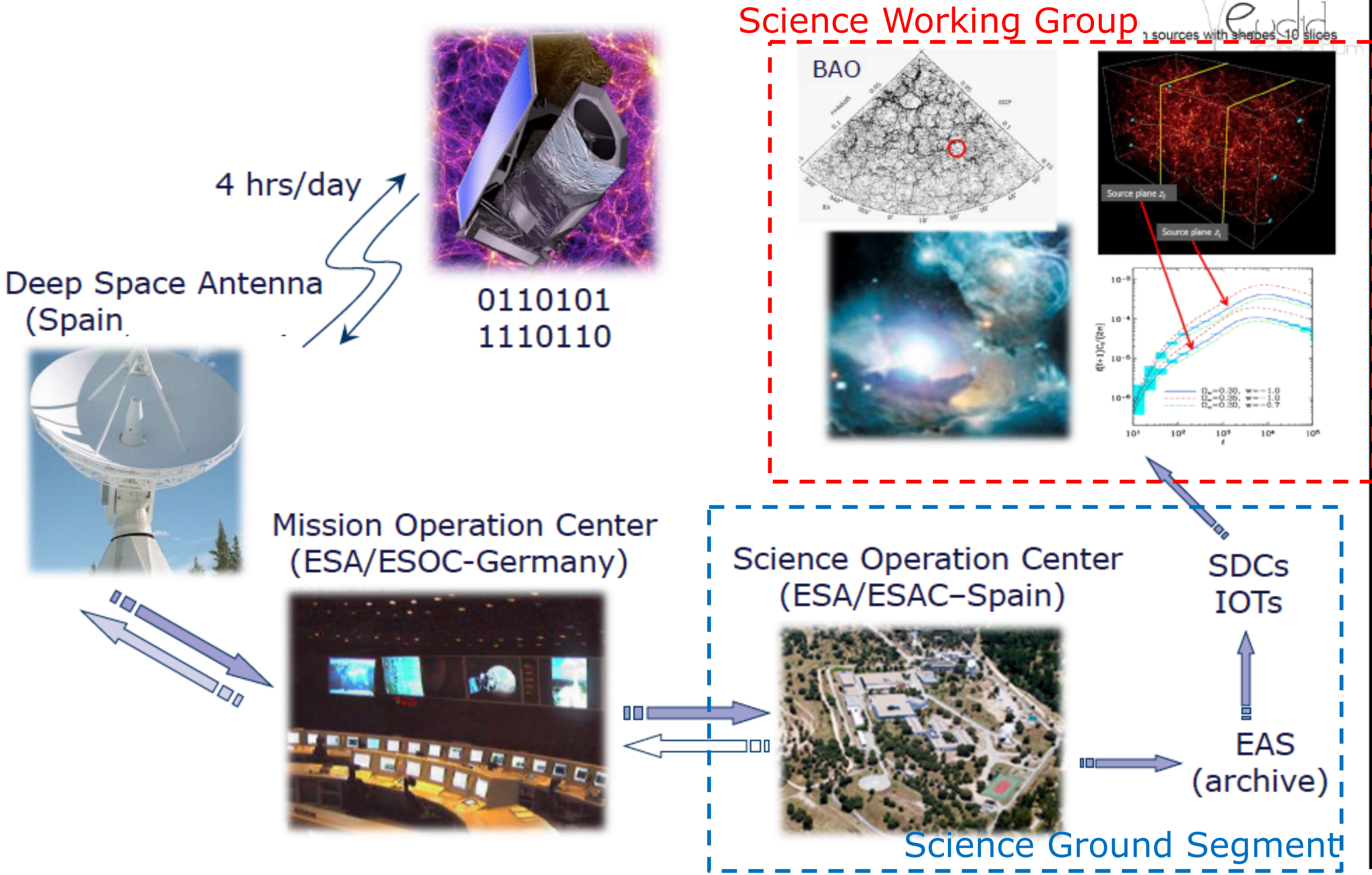
16 IR matrices 2048x2048

900-2000 nm





Euclid Data Flow

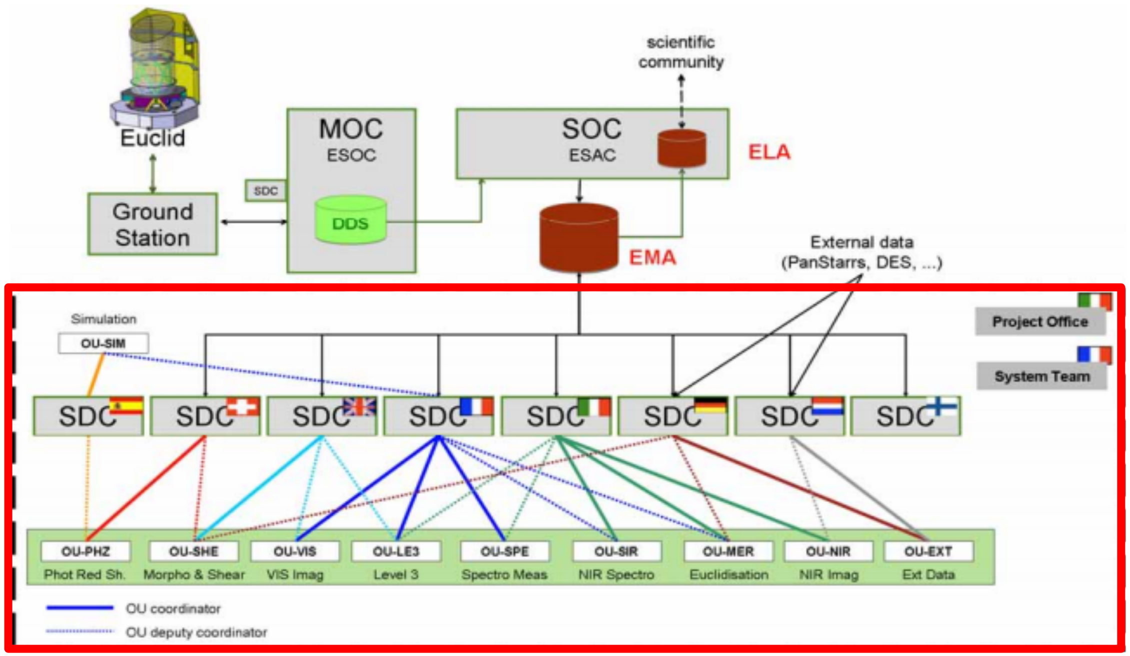


Euclid Science Ground Segment

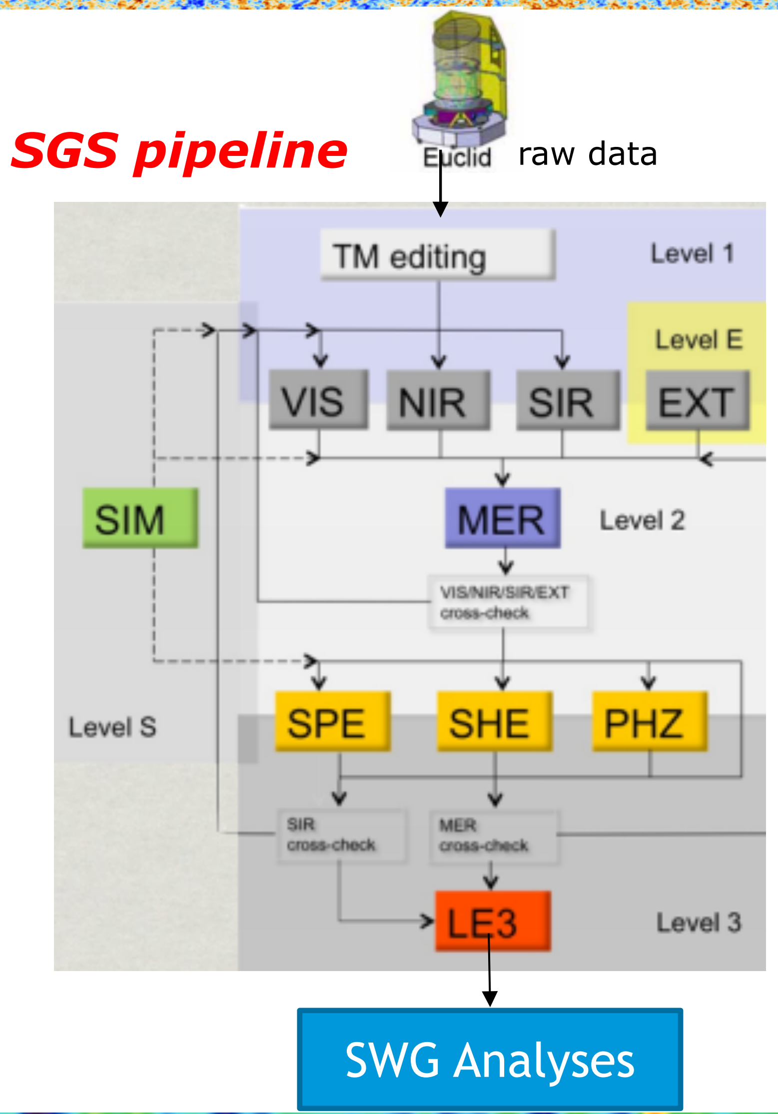
- Production of **science-ready data** from **raw data** are performed in national **Science Data Centers** managed by **Euclid consortium**

> ❑ **>2 billion** galaxies with shapes, photometry, photometric-z
> ❑ **>30 – 50 million** galaxies with spectra and spectroscopic-z
> ❑ External data (ground-based photometry and spectroscopy)

850 Gbits/day **26 PB/year**



Euclid data pipeline



Data are organized in different levels

- **Raw data** from satellite
- **Level 1**: edited telemetry
- **Level 2**: calibrated signal from instrument
- **Level 3**: physical observables (redshift, shear) reconstruction
- **Level Q**: quick release
- **Level E**: external data from ground-based experiment
- **Level S**: simulation

Science data centers resources are not available for scientific analyses

Science Working Groups tasks / Packages

Cosmology:

- Weak Lensing
- Galaxy Clustering
- Theory
- Clusters of galaxies
- CMB Cross-correlations
- Strong Lensing

Legacy:

- Primeval Galaxies
- Galaxy and AGN evol.
- Nearby Galaxies
- Milky Way
- Planets
- SNs & Transient

Cosmological Simulations

Science Working Group (SWG)

Work Packages

- WP1: Integrated Sachs-Wolfe (ISW)
- WP2: Rees-Sciama
- WP3: Lensing Extraction
- WP4: CMB lensing likelihood
- WP5: Cross-Correlation estimators
- WP6: SZ maps and Euclid Cluster Cross-Correlation
- WP7: Validation

Each WG task is divided in **Work Packages**.

Not supported by data centers
INFN contribution

INFN involvement in Euclid

- **Euclid** is a CSN2 research program *Bo, Le, Mi, Pd Divisions ~ 30 people*
- INFN groups current involvement
  - Assembly, Integration and Verification of the NISP Warm Electronics
  - Data analysis & simulation (before and after the launch)
- HPC computing systems required - Minimum size
  - **intermediate-size HPC/MPI with high-speed low-latency communication**
  - **1000 cores**
  - **RAM/core: 8GB**
  - **Storage: ~ 1 PB**
- To address physics topics as:
  - *medium-size cosmological simulations*: ***~3Mcore hr, 500 TB***
  - *N-body simulations with neutrino masses and dynamical dark energy*:
    ~3Mcore hr, 500 TB
  - *and several others*

LSPE / Euclid common effort

INFN data analysis activity for LSPE, Euclid, Planck: HPC needs

21 March 2016

Francesco Piacentini ("Sapienza" Università di Roma, INFN Roma 1)
Matteo Tenti (INFN - CNAF)
Paolo Natoli (Università di Ferrara, INFN Ferrara)

On behalf of the **LSPE** and **COSMO_WNEXT** collaborations

ABSTRACT

We draft the HPC needs for the analysis and simulation pipelines of LSPE, EUCLID and Planck within the INFN activity. The summary of the required resources is reported in Table 2.

1. LSPE-INFN

1.1. LSPE: very short introduction

LSPE (Large Scale Polarization Explorer) is a stratospheric balloon-borne tele measurement of the polarization of the cosmic microwave background radiation (C

The payload, in its baseline version, contains two instruments: STRIP, the lo P.I. Marco Bersanelli (Univ. Milano); and SWIPE, the high frequency instrument (Univ. Roma Sapienza, INFN-Roma1).

The instrumentation and balloon flight is mainly granted by the Italian Sp entered the project funding the detector and readout system of one of the two instr high frequency instrument). INFN also plans to grant data analysis for missi exploitation for LSPE-SWIPE, which is based on 326 multimoded bolometers means of a cryogenic refractive telescope, and feed-horns. Polarization is mod Wave Plate and a wire grid polarizer.

1.2. LSPE: data analysis activity

The LSPE data follow the path described in figure 1. In yellow we indic and from the instrument; in cyan the algorithms; in green the data products.

1.2.1. Instrument simulator

The instrument simulator produces synthetic instances of the observatio and taking into account instrument characteristics, performance, calibration, uncertainties and systema effects. The instrument simulator is an important tool in the pre-launch phase to define the instrument requirements in terms of sensitivity, coverage, mission planning, calibration quality, and control of systematic

2016 - Common document on computational requirements LSPE-SWIPE / CosmoWN

4. LSPE-COSMO_WNEXT requests

	LSPE	COSMO_WNEXT PLANCK + EUCLID	JOINT REQUESTS
N. of cores	$650^{\dagger}$	800	$800 \div 1450$
FLOPs	$9 \cdot 10^{19}$	$\sim 5 \cdot 10^{20}$	$\sim 10^{21}$
RAM/core (GB)	8	8	8
Disk space (TB)	350	400	750
Node interconnection	40 GB Infiniband		

† For LSPE, the number of cores depends on the RAM/core: total RAM required is $\simeq 5200$ GB.

Table 2: LSPE, COSMO_WNEXT and joint computing requests in terms of number of cores, RAM/core and disk space.

Conclusion

- LSPE and Euclid tackle the current frontiers in cosmology

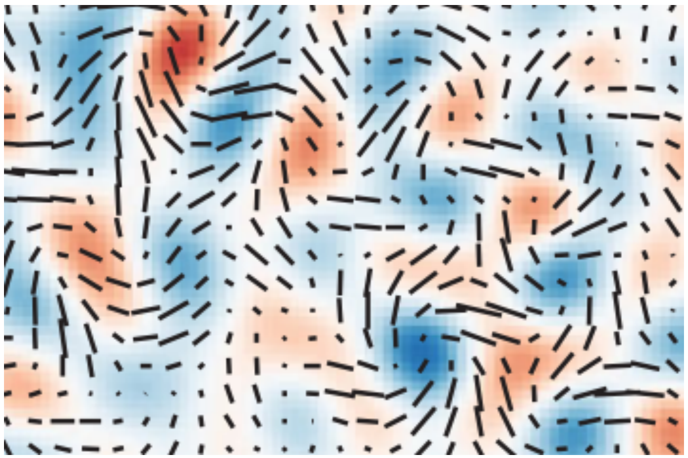
- The data analysis tasks are different, but:
  - Have a complementary scientific objective
  - Have an overlapping scientific community
  - Require similar computational architecture (HPC)

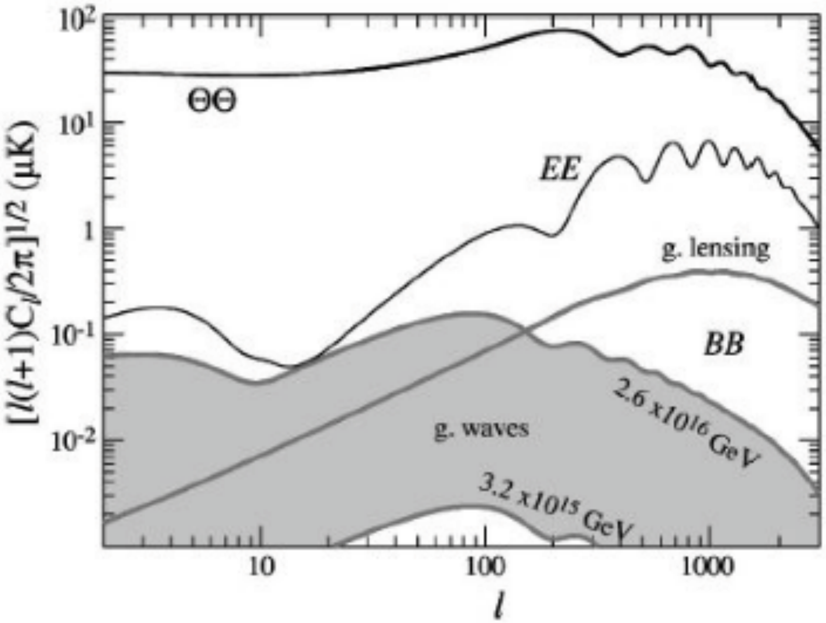
  - All that pushes for a common effort:
    - Set-up a common computational infrastructure
    - Sharing resources
    - Sharing expertise
    - Sharing manpower

Extra

Frontiers of observational cosmology: CMB

- The B-mode polarization signal is extracted thanks to its symmetry properties
- The distribution of amplitude of the the B-mode
  - Has a peculiar shape
  - Is proportional to the background of gravitational waves





CMB polarization B-modes (rms) < 0.2 μK (10^{-7} x 2.7K)

$$\left[\ell(\ell+1)C^{BB}_{\ell_{\rm peak}}\right]^{1/2} = 0.024(E_{\rm inf}/10^{16}{\rm GeV})^2\mu{\rm K}$$

CMB: Data analysis techniques

- Data analysis techniques for CMB have been developed over the years, pushed by more and more sophisticated instruments

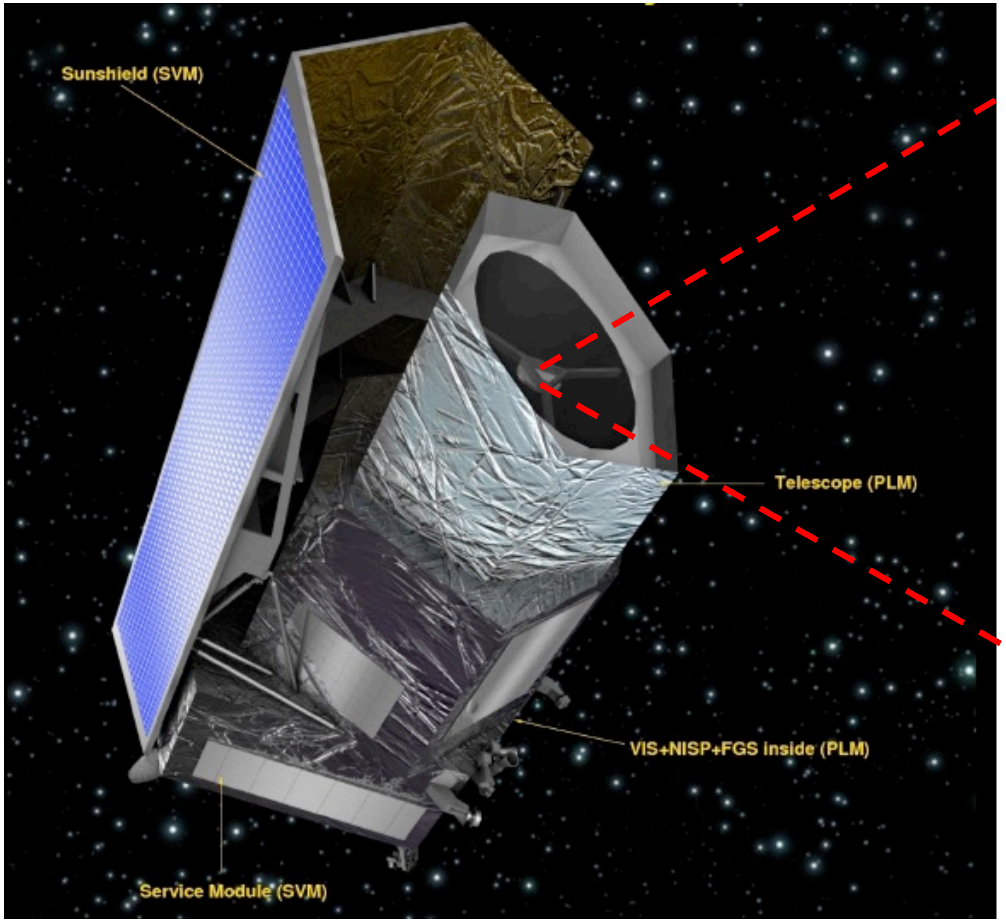
- NERSC have always supported this task effectively with its resources

- In short:
    - Timeline calibration
    - Time to map conversion (**map-making**)
    - Map decomposition (**component separation**)
    - Map to statistical angular distribution (**Power Spectrum Estimation**)
    - Cosmological parameters estimation (**likelihood**)
    - Statistical errors assessment by **instrument simulation** (Montecarlo)
    - Systematic errors assessment by **instrument simulation** (Montecarlo)

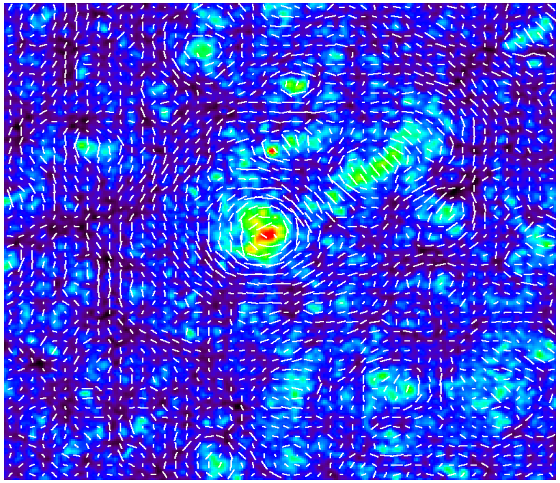
Extracting the signal

- The faint CMB polarization signal must be extracted from:
  - CMB radiation = 2.726 K
  - CMB dipole = 3.346 mK (10^{-3})
  - CMB anisotropy (rms) $\simeq$ 80 μK (10^{-5})
  - CMB polarization (rms) $\simeq$ 1 μK (10^{-6})
  - Instrument noise
  - Instrument systematic effects
  - CMB polarization B-modes (rms) < 0.2 μK (10^{-7})

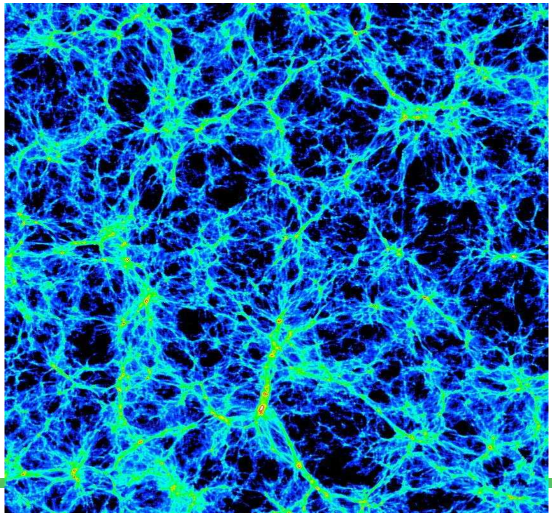
EUCLID double approach

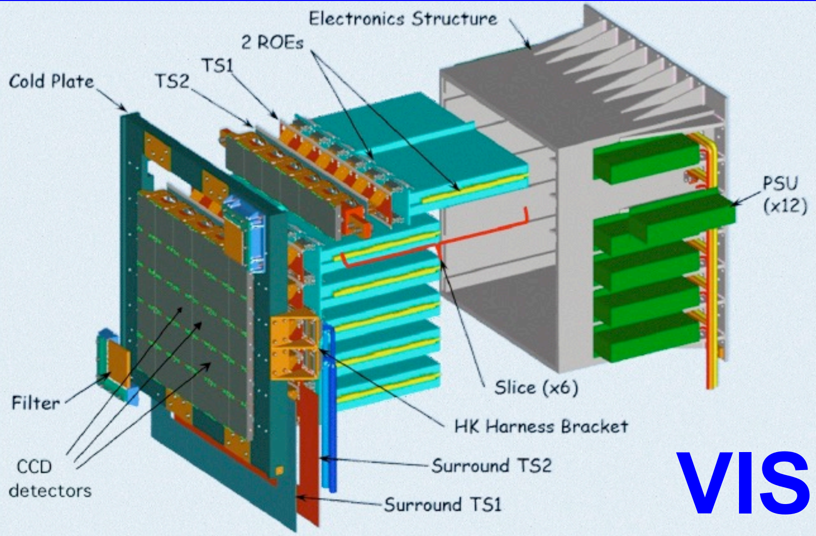


Weak gravitational lensing



Large scale structure

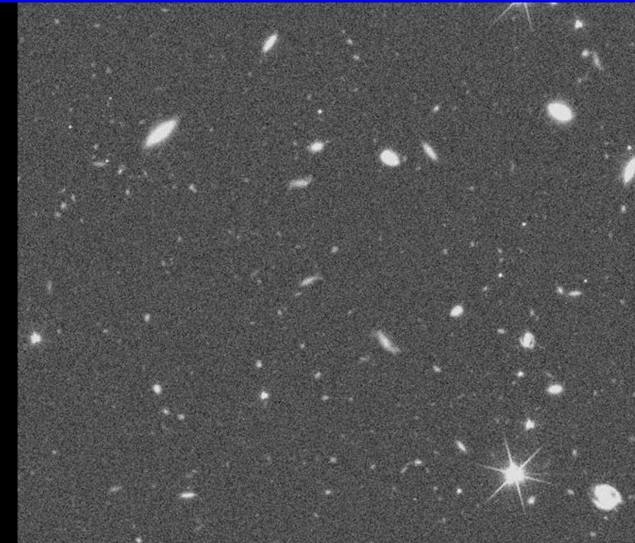




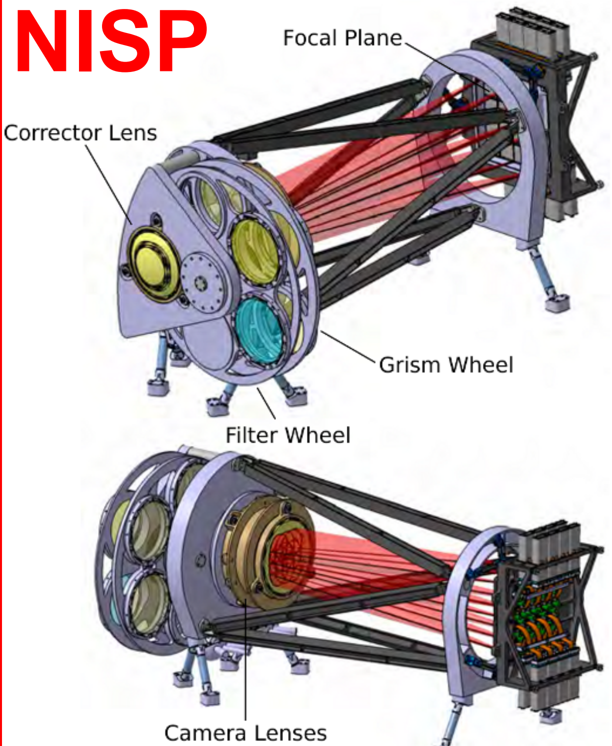
VIS

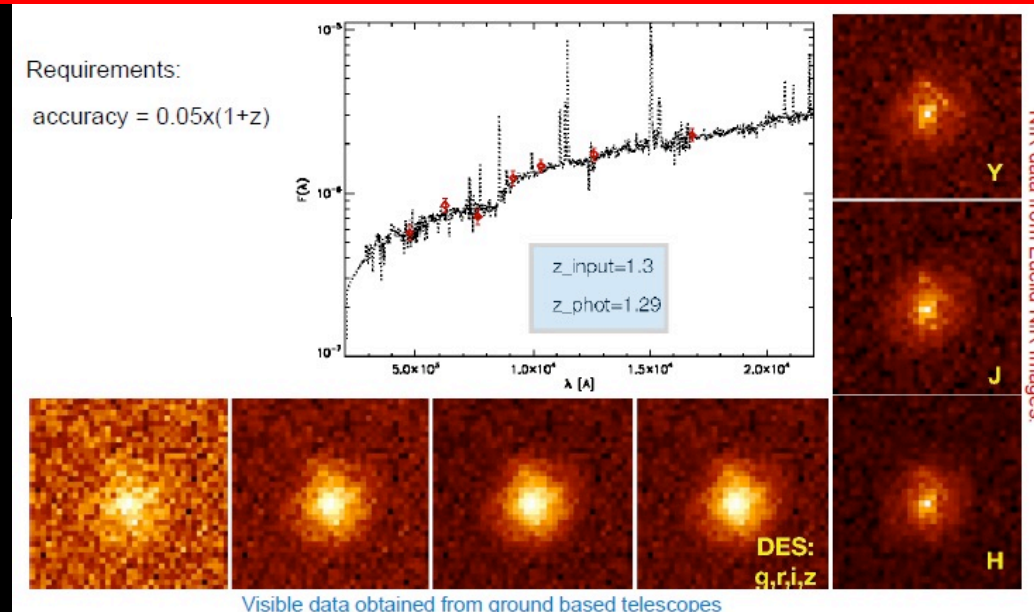
36 CCDs (4k x 4k each)
FoV = 0.55 deg^2
Imaging with 0.1" pixels
RIZ filter (0.55-0.92 μm)
Limiting mag = 24.5 (AB)

$N_{gal} \sim 2 \times 10^9$



NISP

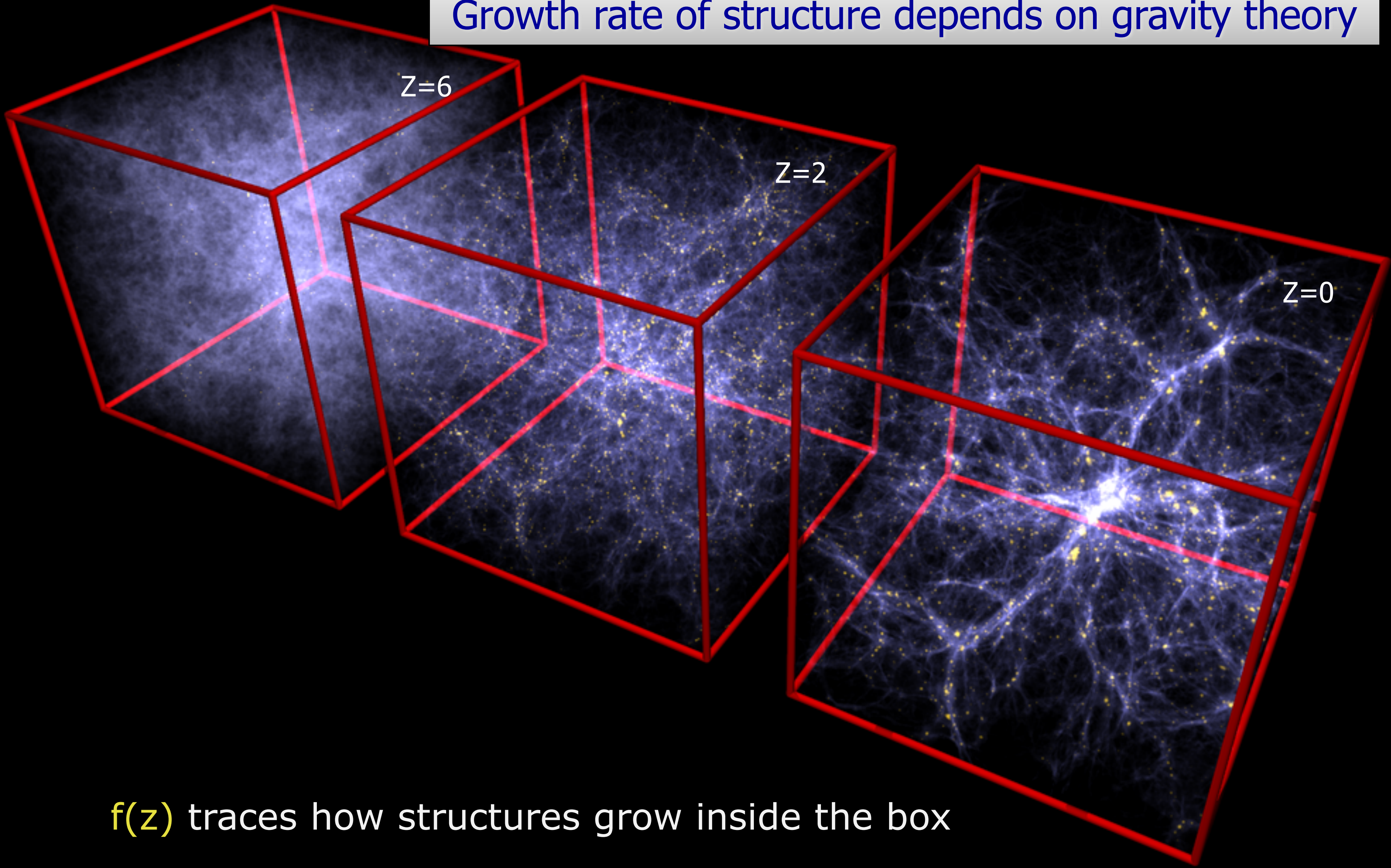




16 Hawaii-2RG HgCdTe Teledyne detectors (2k x 2k each)
Imaging with 0.3" pixel. FoV = 0.55 deg^2
Filters: Y (0.92-1.15 μm), J (1.15-1.37 μm), H (1.37-2.00 μm)
Limiting magnitude = 24.0 (AB)

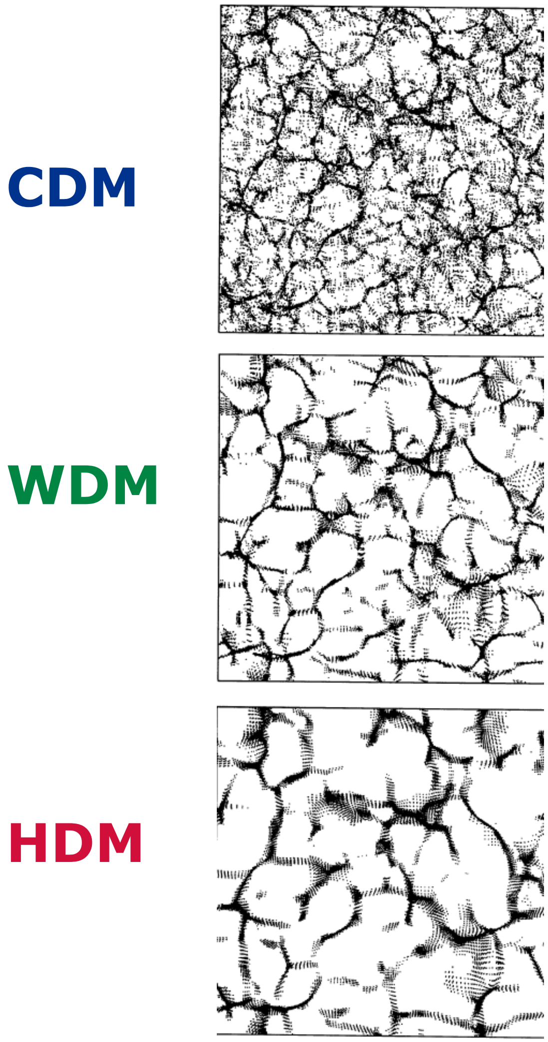
Check of gravity theory

Growth rate of structure depends on gravity theory



f(z) traces how structures grow inside the box

Dark matter and Neutrinos constrains



- Light DM particles suppress the collapse of structures on small scales (free streaming)
- Galaxy clustering can constrain the mass of light DM particles
- E.g.: standard neutrino (mass, hierarchy, number of species, BB relic background), WDM candidates with m~keV (sterile neutrino, gravitino)
- Neutrino experiments → Δm^2
- Cosmological measurements → Σm_ν
- current: $\Sigma m_\nu < 0.15$ eV if $w = -1$
  $\Sigma m_\nu < 0.49$ eV if $w \neq -1$

INFLATION with LSPE