The PAU
(Physics of the Accelerating Universe)
Camera and Survey
at the William Herschel Telescope

Francisco Javier Castander (ICE, IEEC-CSIC)
on behalf of the Pau Survey collaboration

PAU motivation

Probing Cosmology

- Cosmology is probed mainly measuring the expansion rate of the universe H(z) and the growth rate of structure g(z)
- One way: survey to measure the distribution of matter P(k,z) with galaxies as tracers

PAU motivation

Main observational probes

- Weak lensing (geometry & growth)
- Clustering: BAO, RSD, P(k) (geometry & growth)
- Supernovae (geometry)
- Clusters of Galaxies (growth & geometry)

Survey requirements

- The precision to which the galaxy power spectrum can be measured depends on:
  - Sample variance: how many independent samples of the relevant scale (~100 Mpc/h for BAO) one probes ⇒ volume
  - Shot noise (Poisson): how many galaxies included in each sample ⇒ density

Feldman, Kaiser, Peacock, ApJ 426,23 (1994)

$$\frac{\Delta P(k)}{P(k)} \propto \frac{1}{\sqrt{V}}\left(1+\frac{1}{nP(k)}\right)$$

P(*k*): power spectrum

n: galaxy density

PAU motivation

Requirements for Cosmology Survey

- Sample large volumes
- Sample enough (many) objects
- Determine distance (how accurate?)

PAU motivation

PAU strategy

- Use photometry to obtain redshifts
- Many cosmological applications only require “rough” spectroscopic precision (~10 Mpc/h)
- Broad band imaging does not provide enough resolution
- Need sufficient spectral resolution to obtain accurate photometric redshifts => narrow band filters
- Previously: COMBO-17, ALHAMBRA, COSMOS, Subaru
- Simulations: MICE

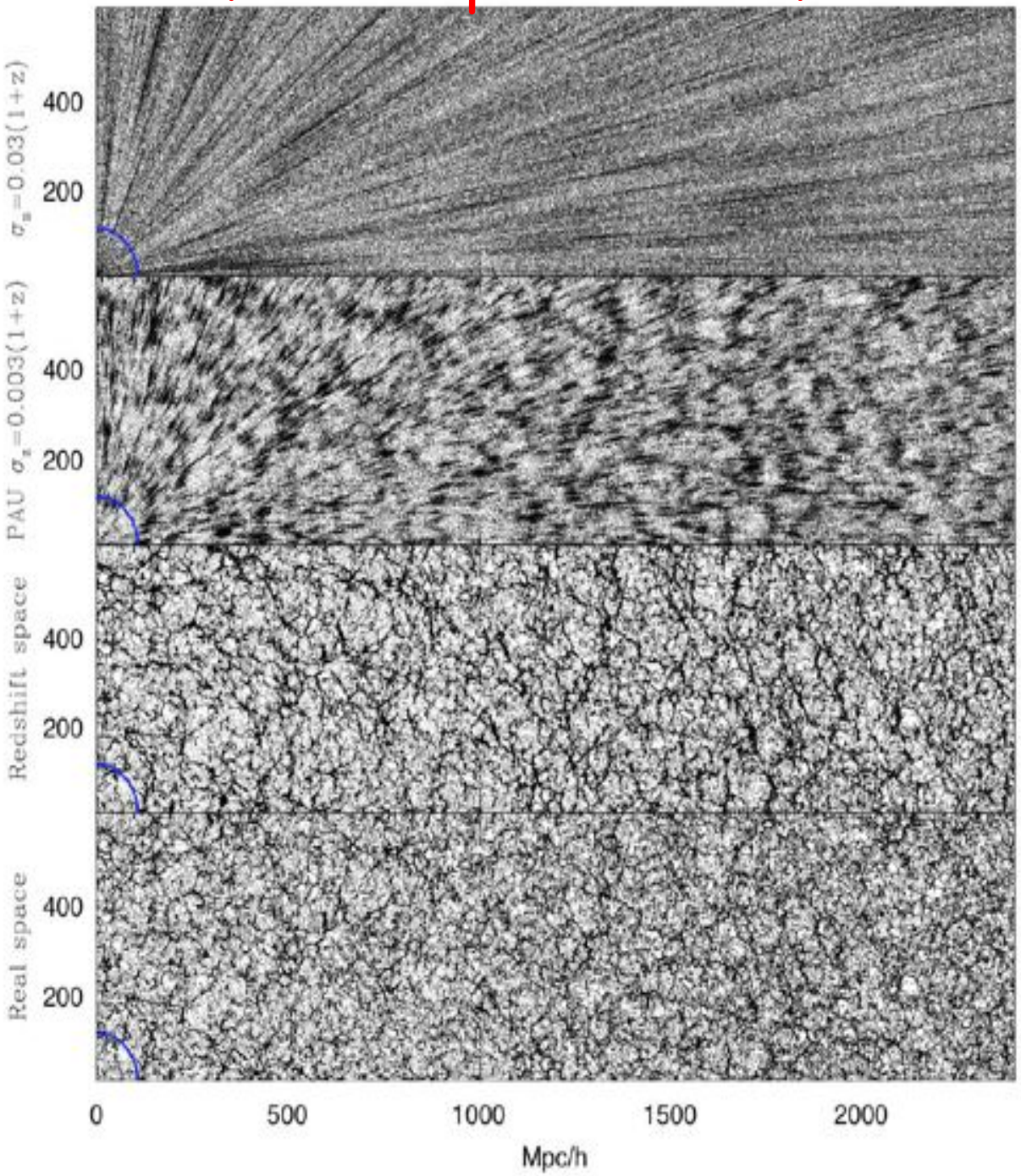
Visual illustration of the importance of z resolution

z-space, $\Delta z = 0.03$ *(1+z)* + peculiar velocities

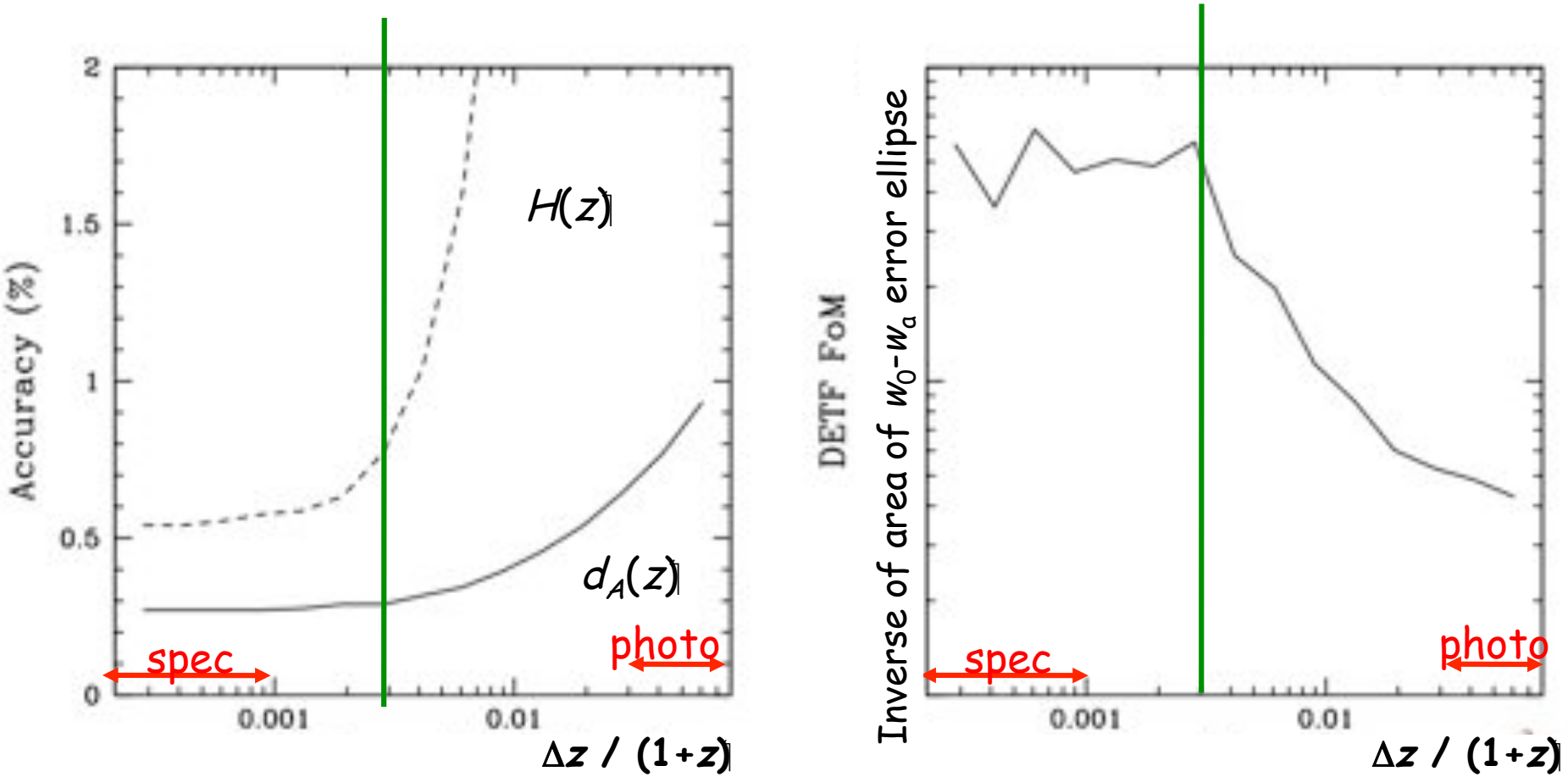
z-space, $\Delta z = 0.003$ *(1+z)* + peculiar velocities

z-space, perfect z-resolution + peculiar velocities

Real space, perfect resolution

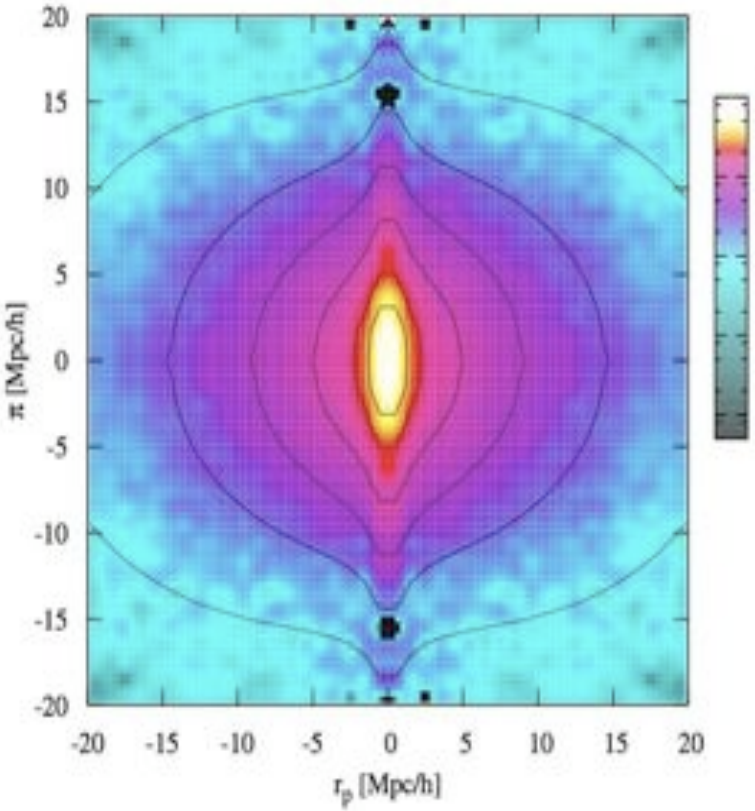


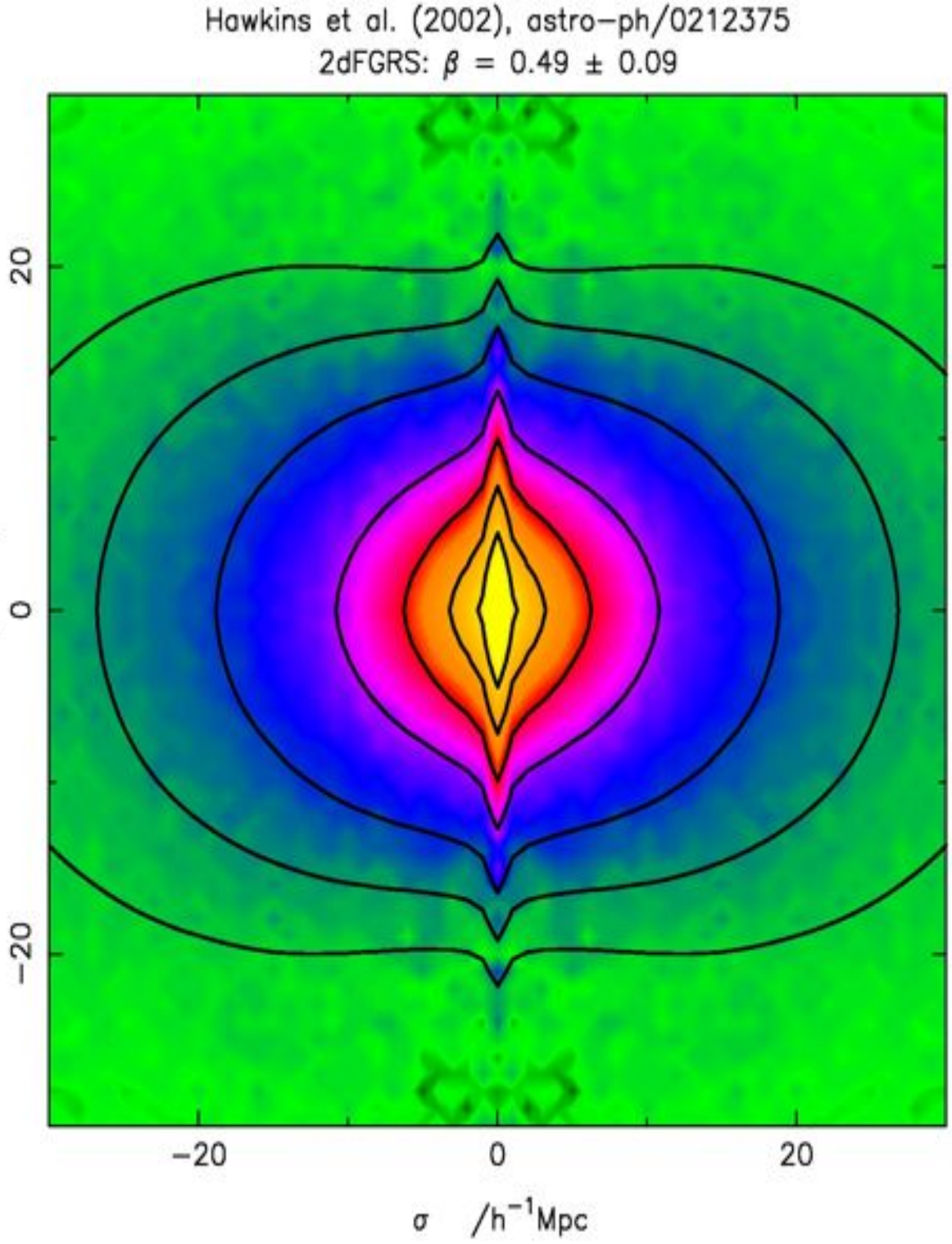
Requirements on Redshift Precision

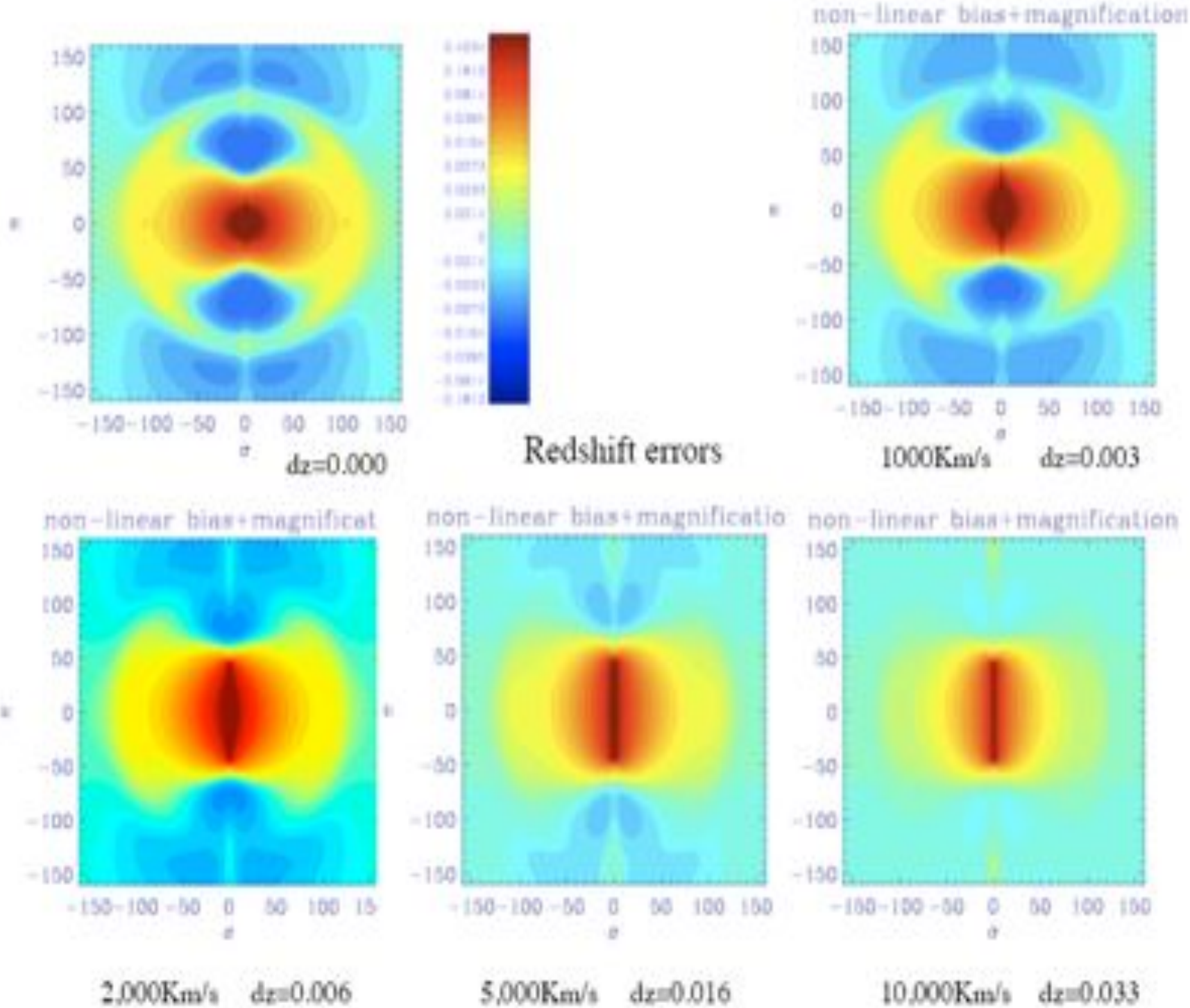


Padmanabhan

Redshift Space Distortions






non-linear bias+magnification
Redshift errors
dz=0.000
1000Km/s dz=0.003
2,000Km/s dz=0.006
5,000Km/s dz=0.016
10,000Km/s dz=0.033

PAU motivation

PAU survey

- The main goal of the PAU survey is to study cosmology/ dark energy characterizing the geometry and growth of structure of the universe
- Large volumes and moderate accurate photometric redshifts are needed for this purpose
- The idea is to build and operate a large field of view camera equipped with narrow band filters to achieve these goals

PAU beginnings

The PAU Project originated in the
Consolider Ingenio 2010 Program of (former) MICINN.

Project was approved in 2007 (ref. CSD2007-0060).

CIEMAT (Madrid), IAA (Granada), ICE-IEEC (Barcelona), IFAE-UAB (Barcelona), IFIC-UV (Valencia), IFT-UAM (Madrid), PIC (Barcelona).

Effective start beginning of 2008.

PAU at the WHT

- Fall 2009: approached the ING management about the possibility of installing PAUCam at the prime focus of WHT (4.2 m). Encouraged to pursue the idea.
- April 2010: submitted detailed proposal to ING board for wide-field camera, equipped with large number of narrow-band filters.
- June 2010: we got further encouragement from the ING board as a visiting instrument:

"The Board has approved the instrument visitor status for now, and is very keen on exploring additional means of access to the telescope that would give you the number of WHT nights needed for the proposed science."

PAU Team (almost 100% correlation with DES-Spain)

Color Code
Senior Scientists
Post-docs
Engineers
Doctoral Students
Technicians

CIEMAT

E. Sánchez, F. J. Rodríguez, I. Sevilla
J. Castilla, J. de Vicente
R. Ponce, F. J. Sánchez

ICE/IEEC

F. J. Castander, E.Gaztañaga, P. Fosalba, A. Bauer, C. Bonnet, M.Crocce, S. Farrens, S.Jouvel
R. Casas, J. Jiménez, F. Madrid, S. Serrano
J. Asorey, M. Eriksen, A. Izard, K. Hoffman, C.López, A. Pujol

IFAE

E. Fernández, R. Miquel, C. Padilla, A. Pacheco, (S. Heinis, starting in September)
O. Ballester, L. Cardiel, F. Grañena, C. Hernández, L. López, M. Maiorino, C. Pio
P. Martí, C. Sánchez
C. Arteche, J. Gaweda

PIC

M. Delfino,, V. Acín, J. Carretero, M. Caubet, J.Flix, C. Neissner, P. Tallada, N. Tonello, E. Planas

UAM

J. García-Bellido, D. Sapone, S. Nesseris
Alicia Bueno, David Alonso

PAU at the WHT: work for the last 2 years:

- **Interactions with WHT (technical/administrative).**
- **Preparation of the science of PAUS (PAU-Survey).**
- **Design and construction of PAUCam.**
- **Design and construction of the PAUCam data management system.**
- **Interactions with Consolider Program (political).**

PAU at the WHT (administrative)

Memorandum of Understanding
for collaboration services
between
The Isaac Newton Group of Telescopes
and
Institut de Física d'Altes Energies

Signed in Santa Cruz de La Palma, on 2 of February of 2012,

For the Isaac Newton Group of Telescopes:	For IFAE:
Marc Balcells Director ING	Matteo Cavalli-Sforza Director of IFAE

PAU at the WHT

Among other things the MOU establishes that:

- PAUCam will be a visitor instrument **also available for public use**. The camera will have 42 narrow-band filters and 6 wide-band filters (u.g.r.i.z.Y).
- We will station a “scientific postdoc” at La Palma integrated with the WHT personnel.
- We will also provide a public data-reduction pipeline.

PAU at the WHT (administrative-technical)

We have appointed an External Review Panel, of the design of PAUCam (193 pg. document), which convened in Dec. of 2010.

Members: D. Baade, O. Boulade, M. Riva, O. Iwert, R. Sharples, F. Zerbi.
Also attended: M. Balcells (ING Director) and D. Cano (WHT chief engineer).

From the report:

> The Board wishes to compliment the PAUCam team for the great amount of work done in the definition and preliminary study of the instrument, as well as in the assembly of a complete and comprehensive document such as the one the Board examined.
>
> The Board wishes to underline the very well shaped and focussed Science Case for PAUCam presented in the document under scrutiny. The science objectives are indeed well defined and worthwhile. The Board is convinced that the Team has deep and active expertise at the engineering level for most of the areas related with this specific instrument design and construction.

PAUCam

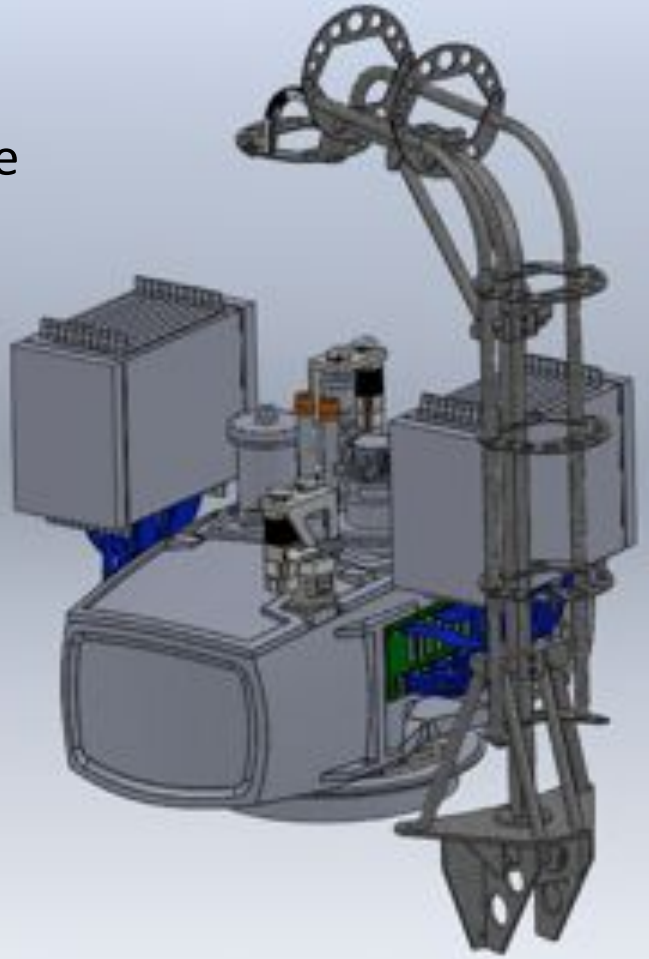
PAUCam will be mounted at the prime focus:

Strong limitation in the weight: **max. 235 kg**.

PAUCam

Many pieces are ready.

Mold being fabricated.
Takes 2-3 weeks to make enclosure.



Body of camera made of carbon fiber, shaped to minimize wall thickness

PAUCam focal plane

8 central CCDs with almost 100% illumination.

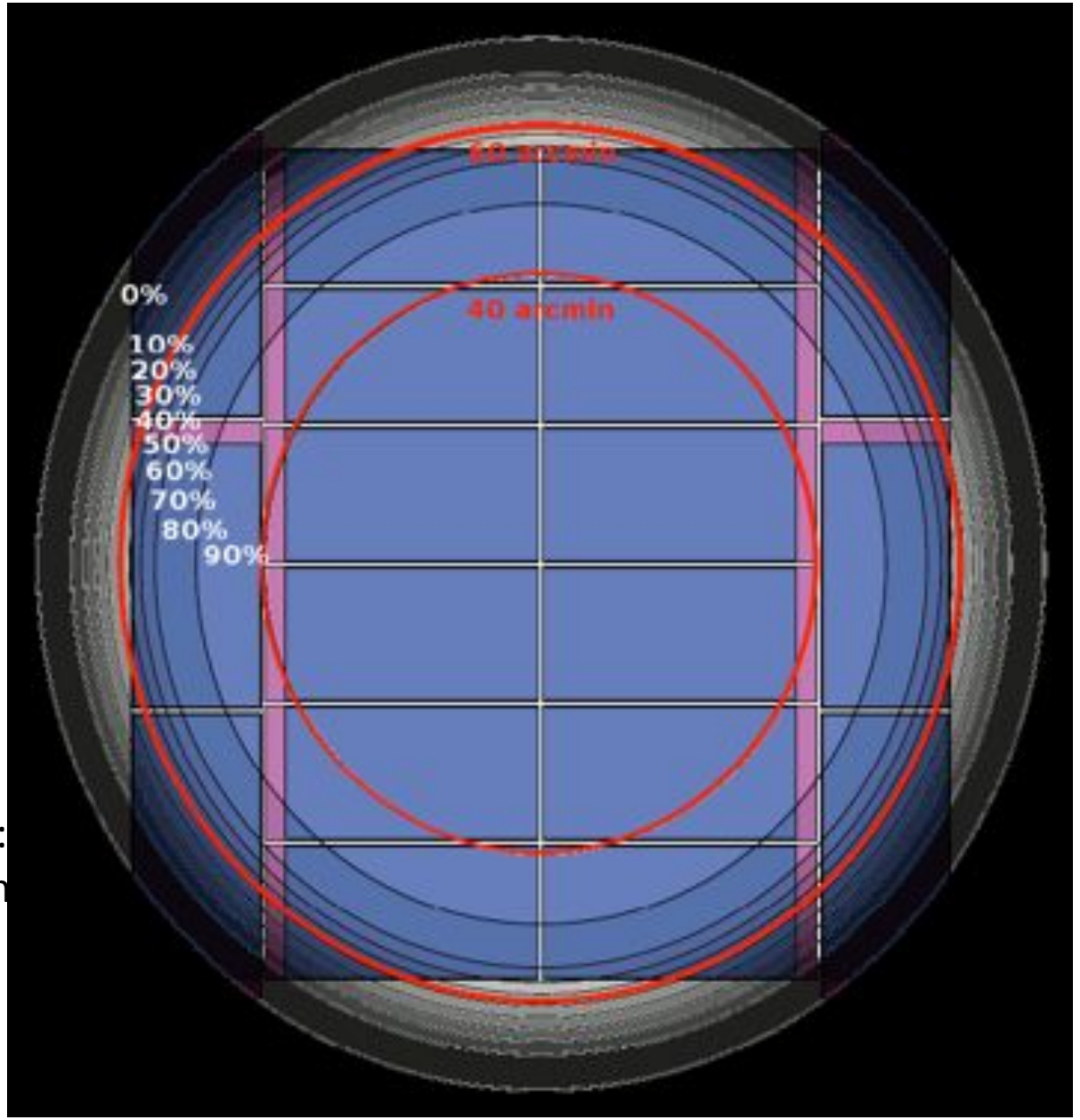
Rest of the CCDs:

- 2 for guiding
- 8 for additional photons

42 narrow band (10nm) filters covering the range ≈ 440-860 nm

6 wide band filters u.g.r.i.z.Y.

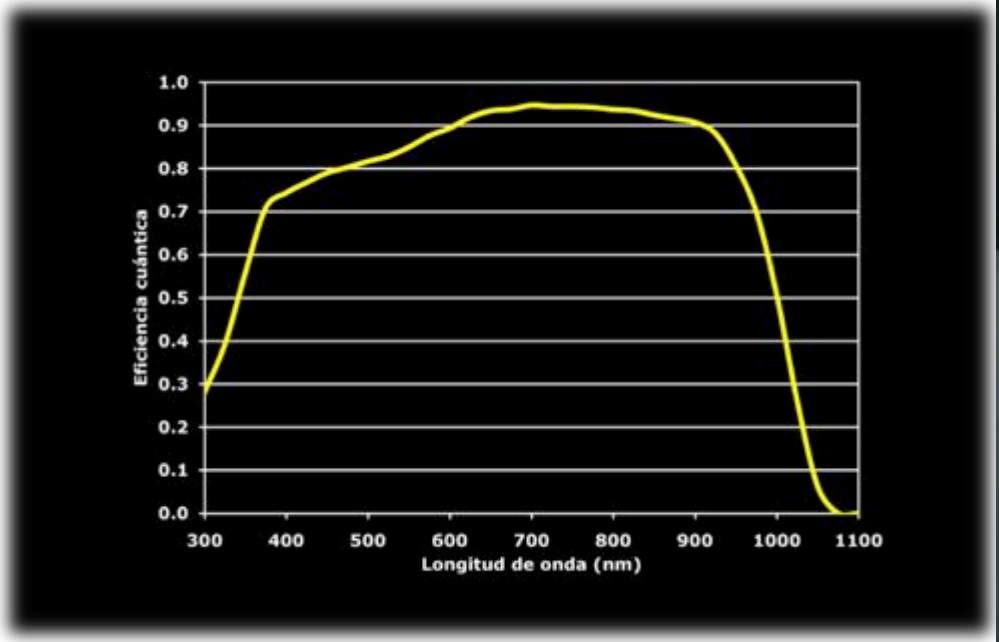
Optimization of filter arrangement:
7 narrow band and 1 broad band in central CCDs.

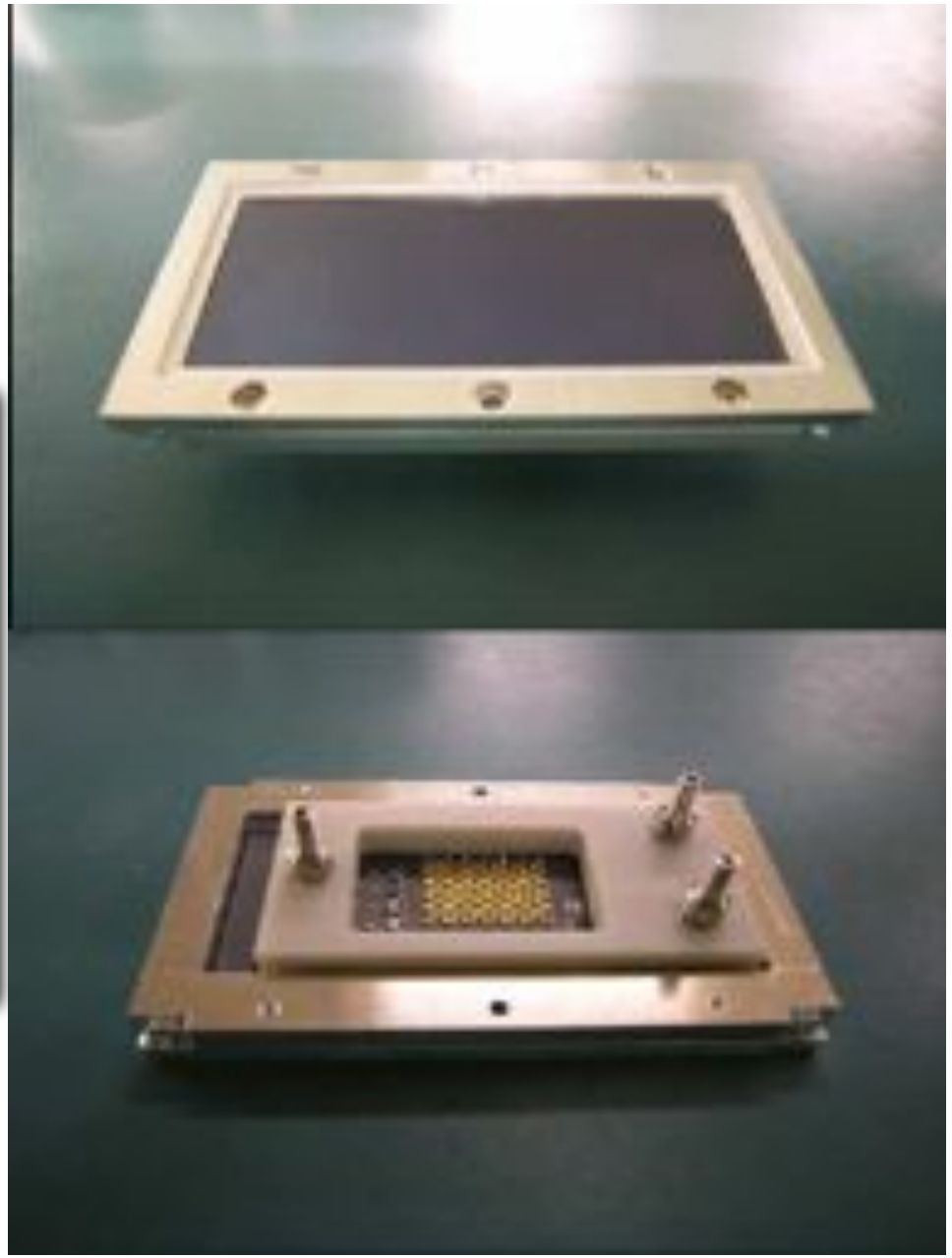


PAUS CCDs

Detectors

- **Hamamatsu photonics (2k X 4k) 15μm pixels**
- **Telescope f/2.8 ➔ 0.26" /pixel.**





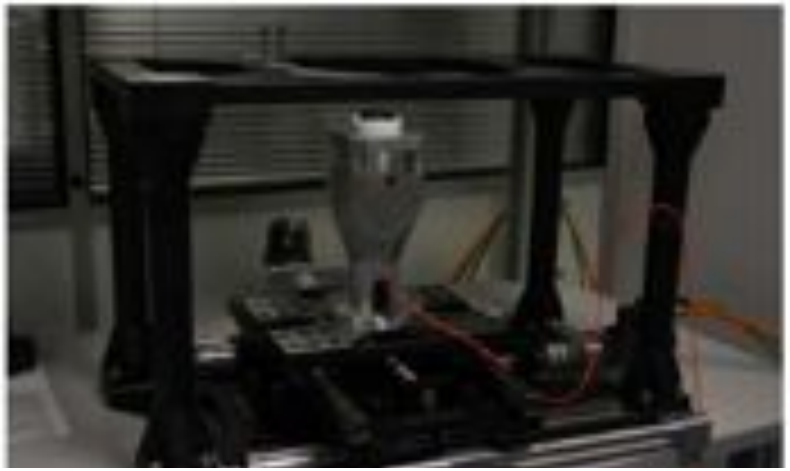
All CCD are already in our labs. being characterized.

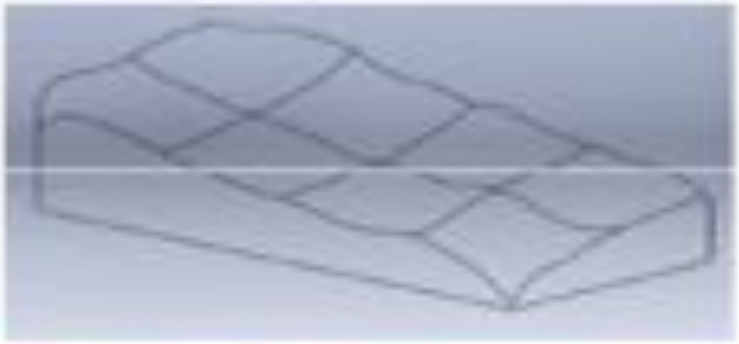
PAUS CCDs

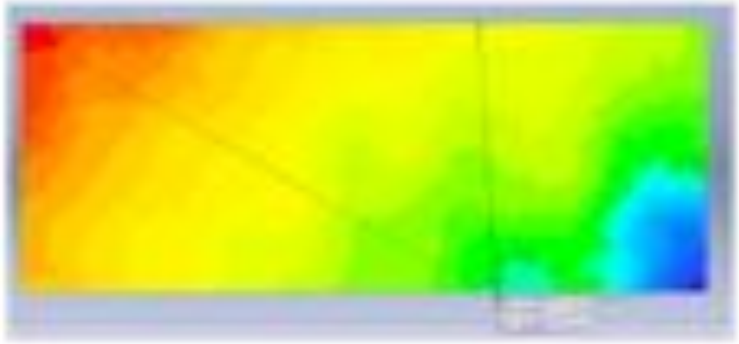
Two set ups to characterize CCDs are ready, including software, one at CIEMAT the other at IEEC-IFAE.

CCD testing station at CIEMAT

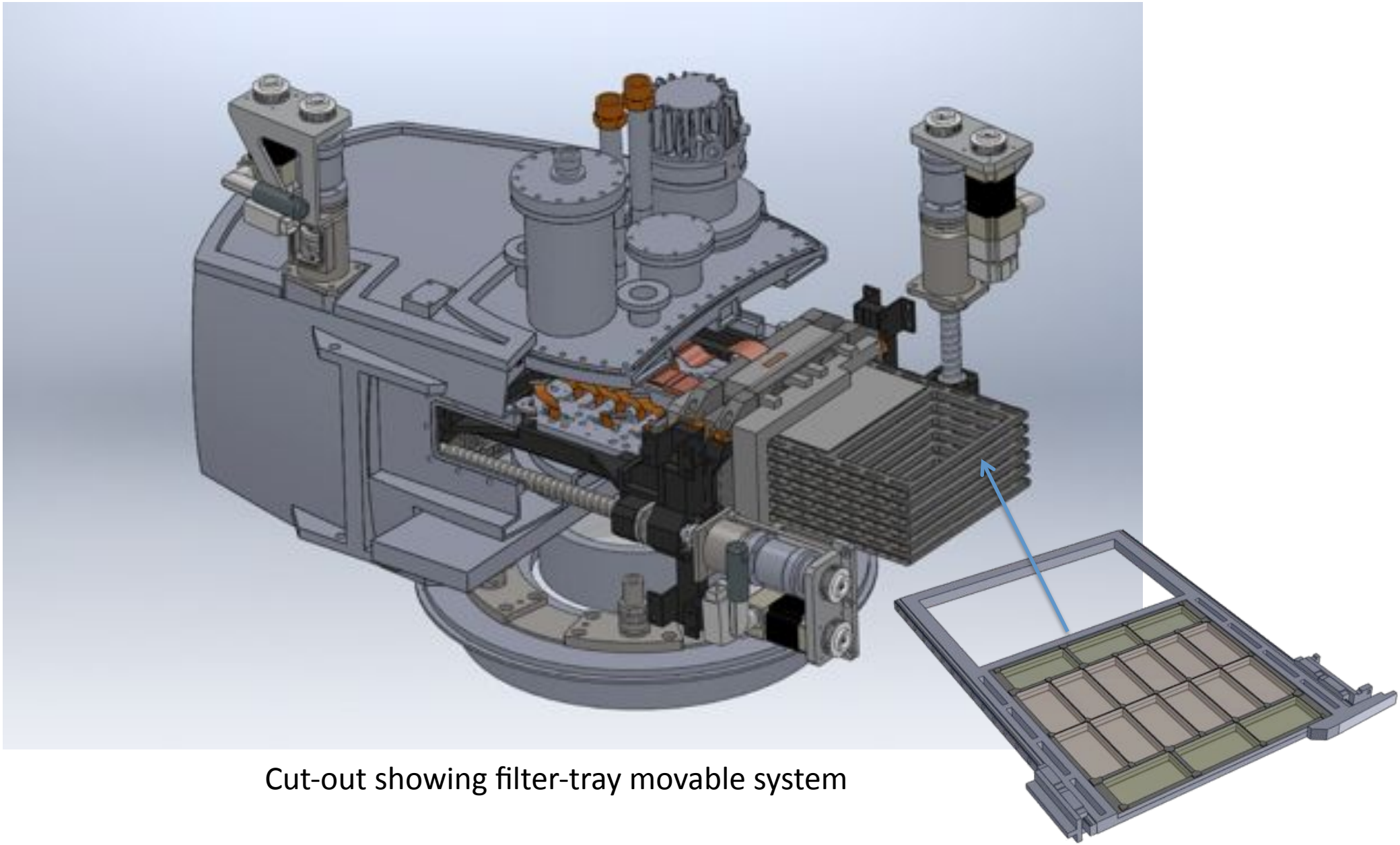
- PAU: XY Metrology table







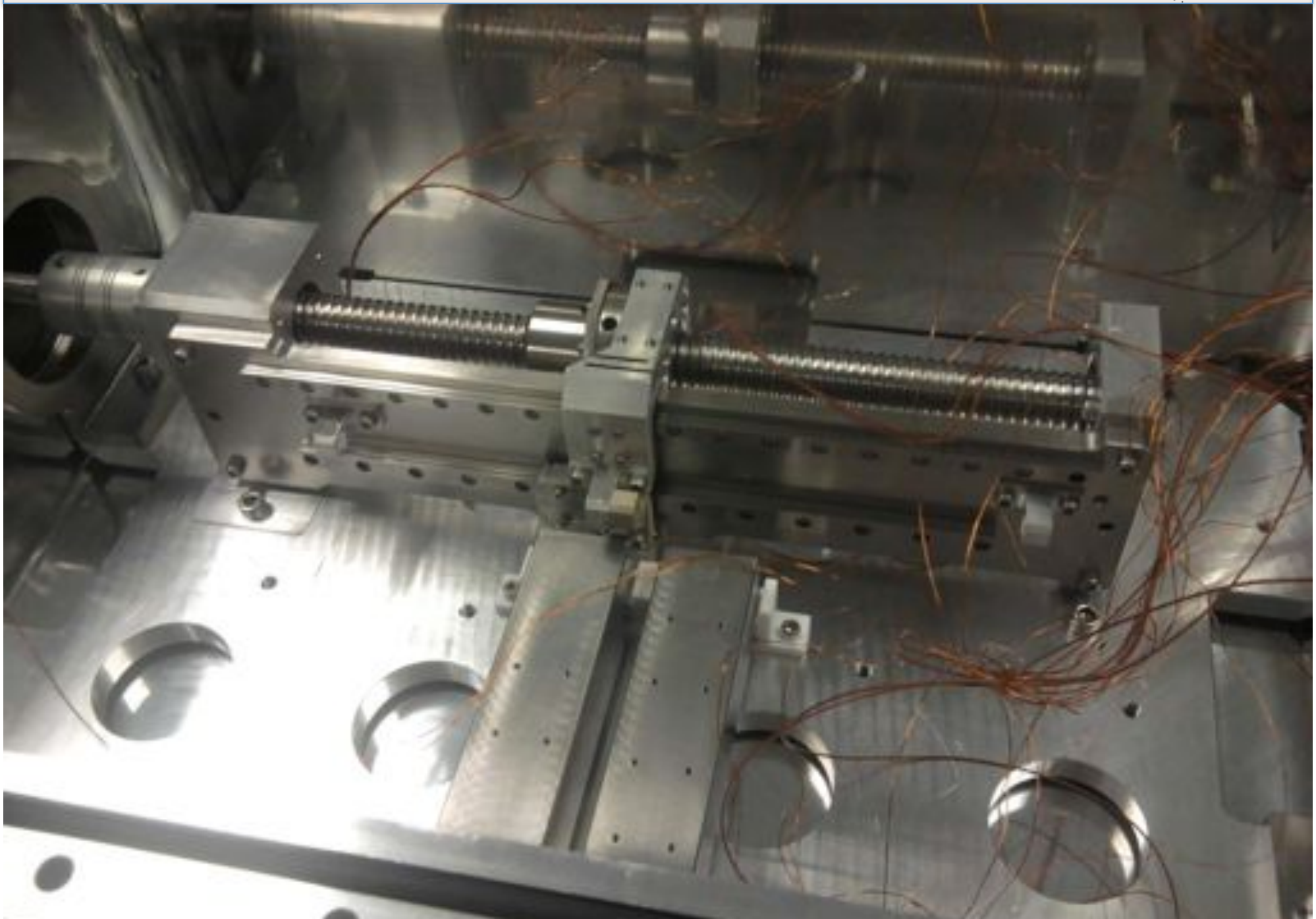
PAUCam



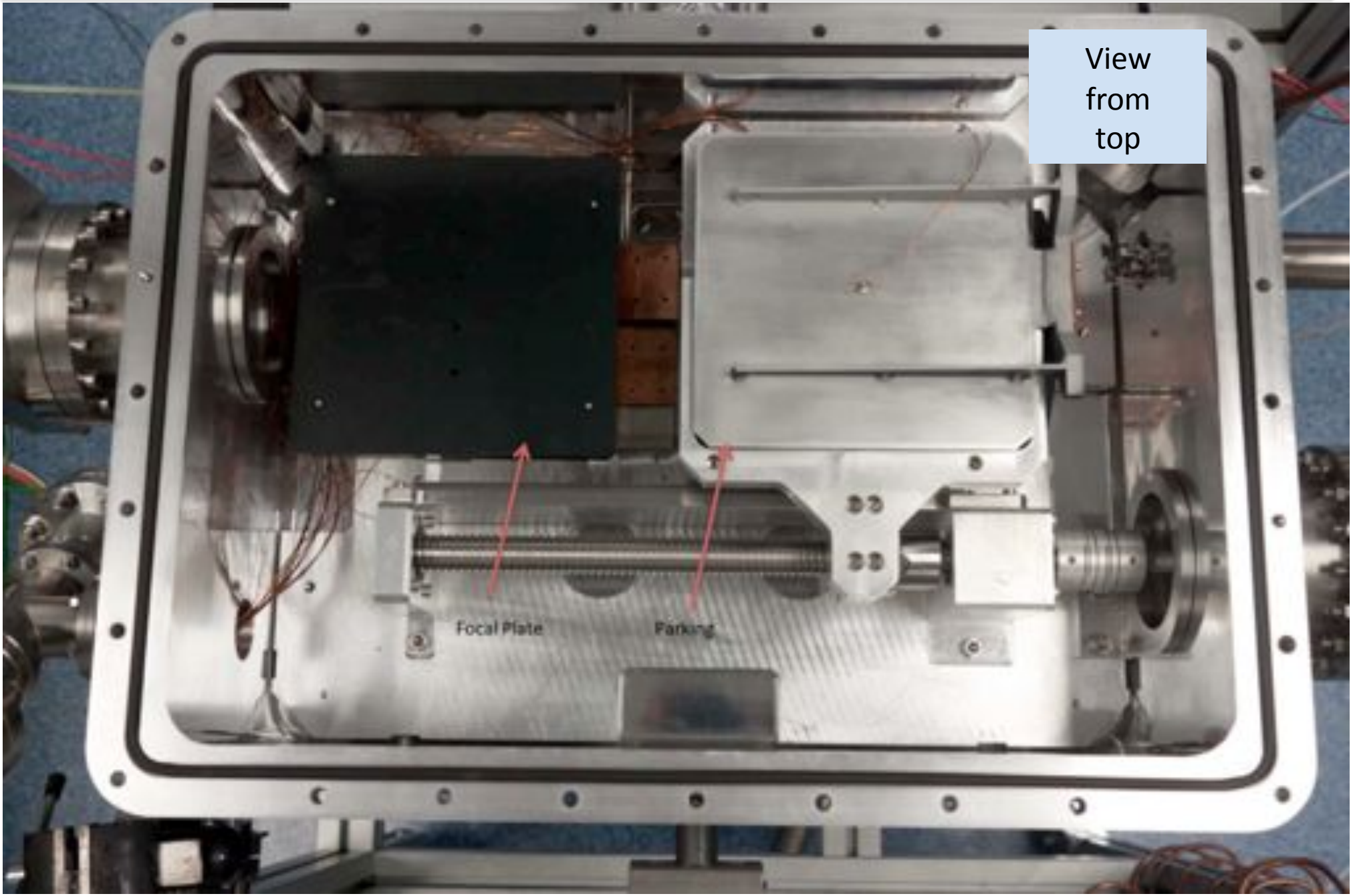
Cut-out showing filter-tray movable system

PAUCam (set up as of summer 2011)

PAUCam



PAUCam



PAUCam main work

- Electronics: CCDs in hand. Electronics will follow Monsoon standard.
  The group has delivered the entire electronics of DECam.

DES Clock & Bias Board

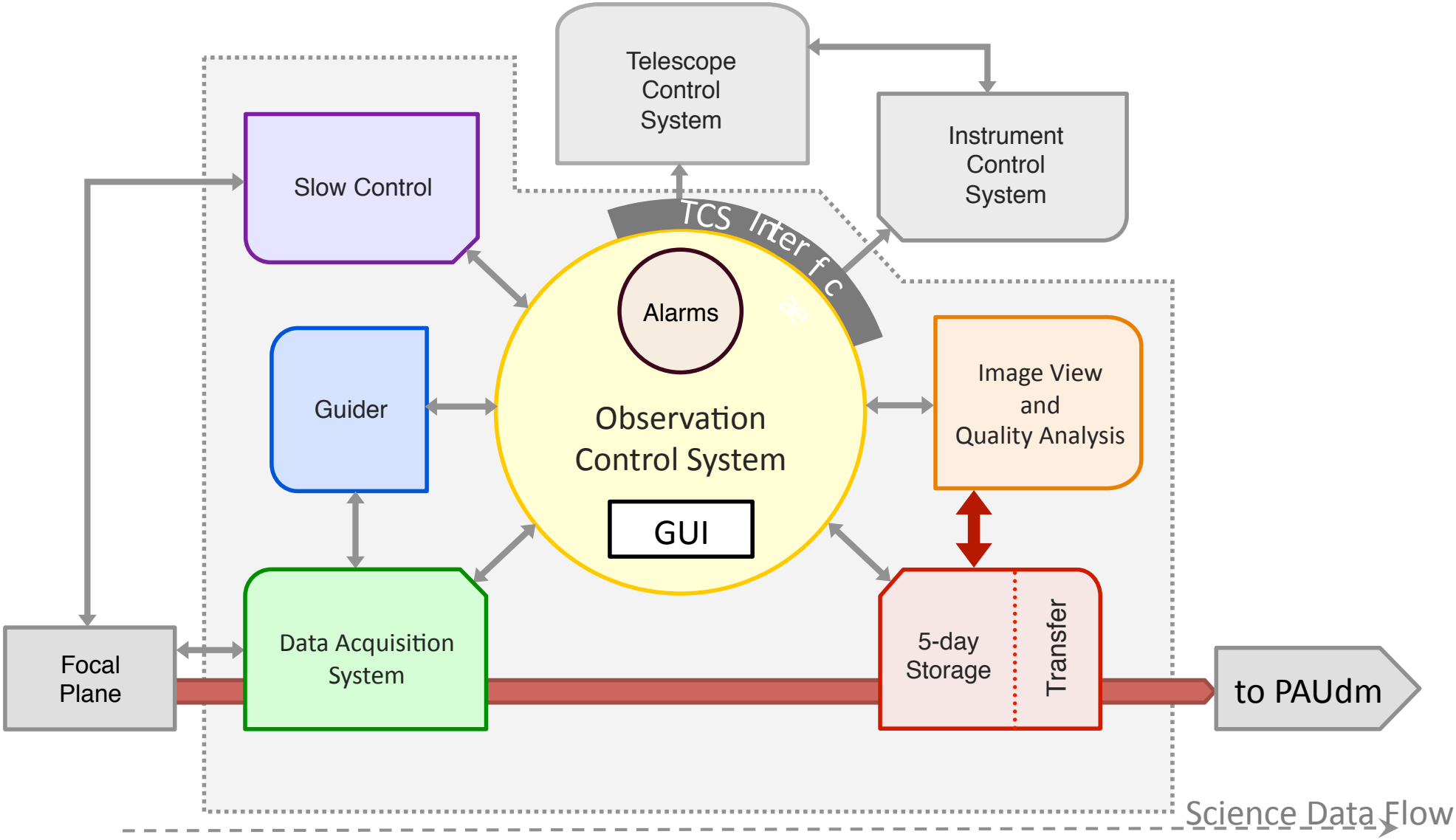
← DES Master Control Board

PAUCam

Many other elements of the camera are ready or being fabricated. Examples:

- Optics (entrance window): study done by FRACTAL. Ordered.
- Shutter: design ready, contract will go out soon.
- Cryotigers: one received, preliminary tests vey good.
- Assembly done in house. Clean room (an important infrastructure) is ready.

PAU Camera Control System



One computer already installed at the WHT. Tests of interface are already taking place.

PAUCam

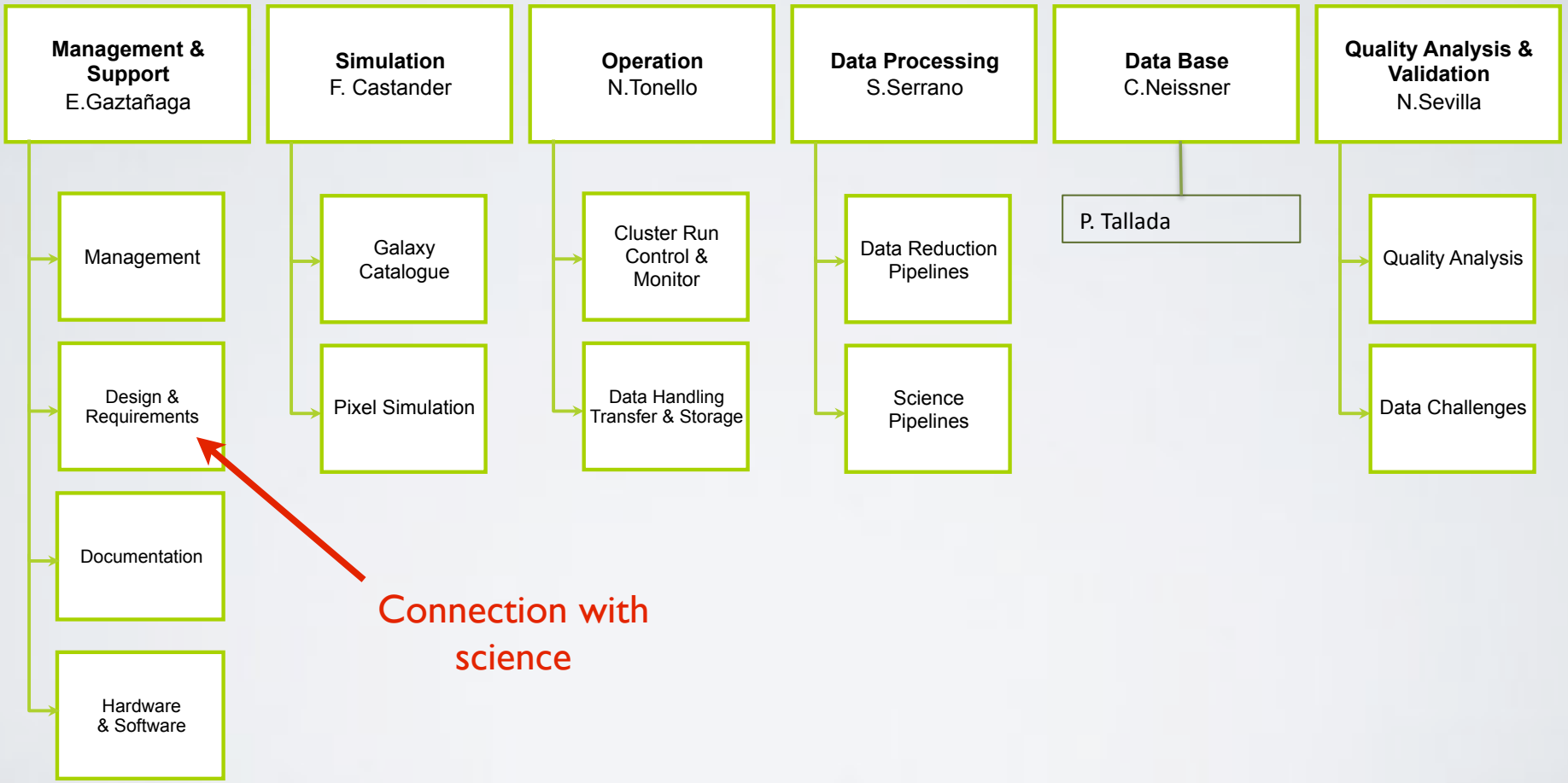
The aim is to have a working instrument ready by the end of the year.

Final verification, installation, calibrations... Much works remains to be done

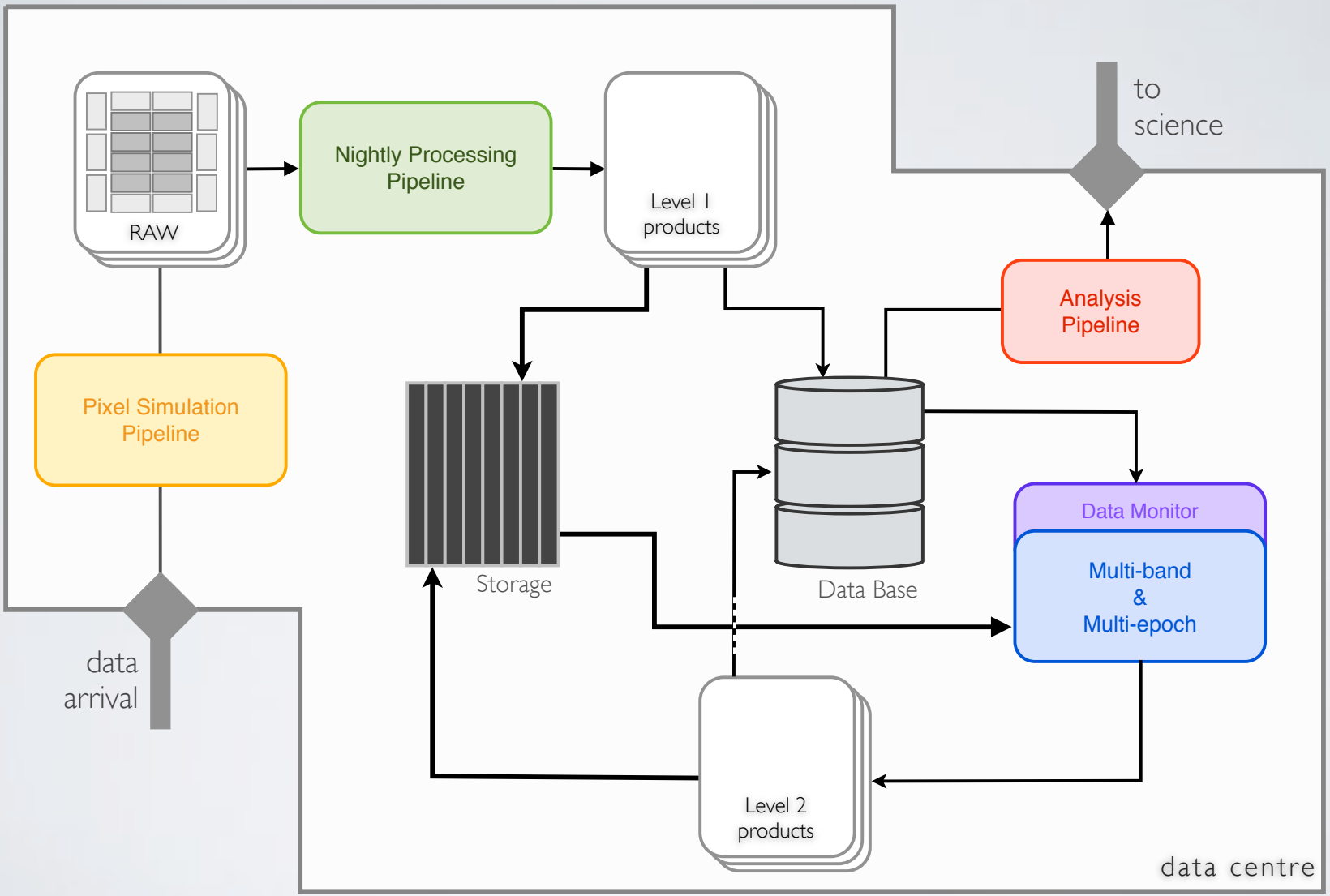
Collaborators are welcome

PAUS Data Management

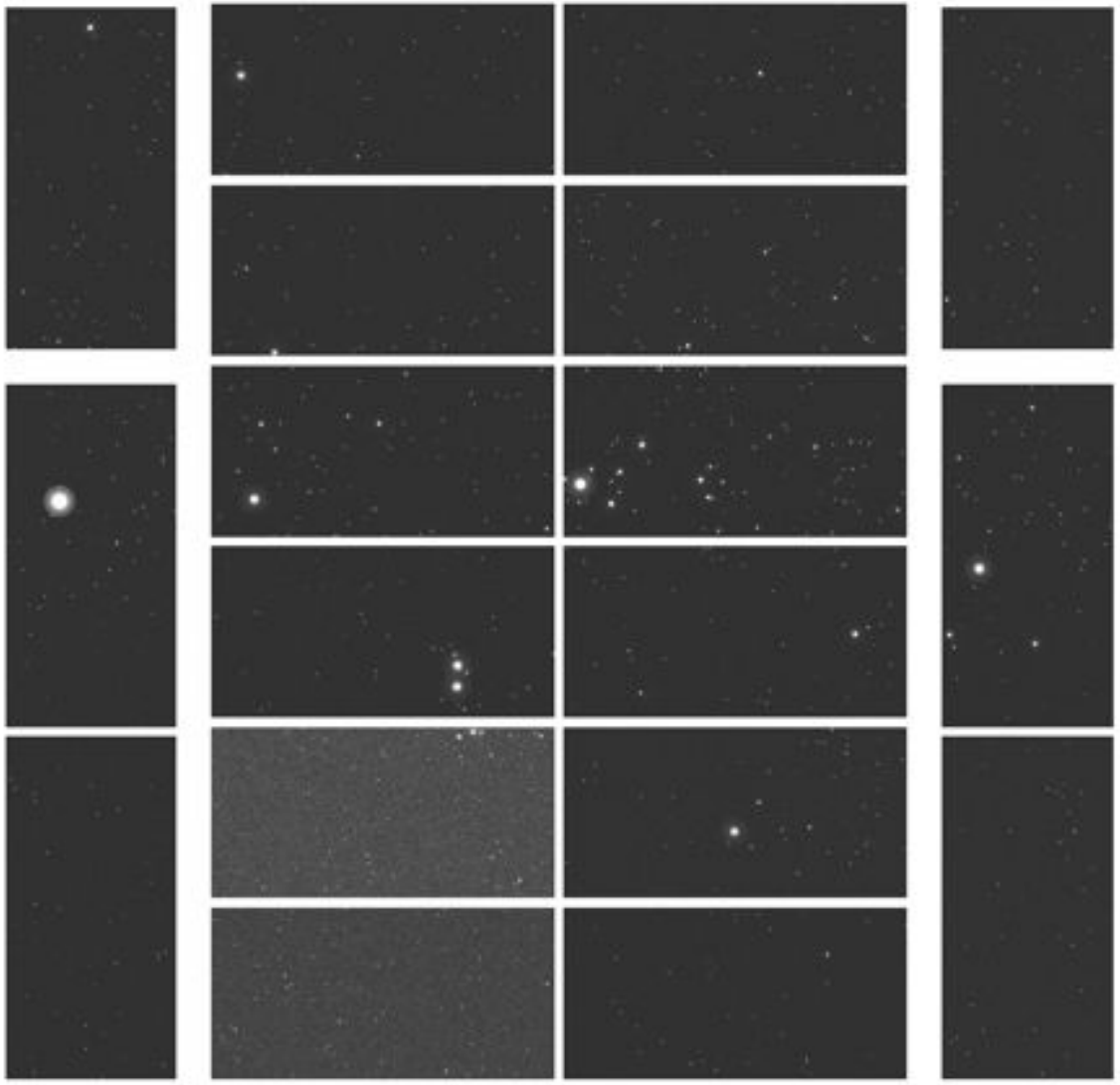
PAUdm Working Packages



Data processing pipeline



Data simulations



PAU Camera

Main characteristics

- Large field of view
- Narrow + Broad band filters
- Good spectral sensitivity
- Segmented filter trays

PAU Survey

Main characteristics

- The PAU Survey collaboration is in the process of building a new large field of view camera to be installed at the WHT prime focus reaching an etendue ~7 with its current corrector and conduct a large area survey
- The survey will obtain photometric redshift accuracy of dz/(1+z) <= 0.0035 for a large fraction of the observed galaxies

PAU Survey

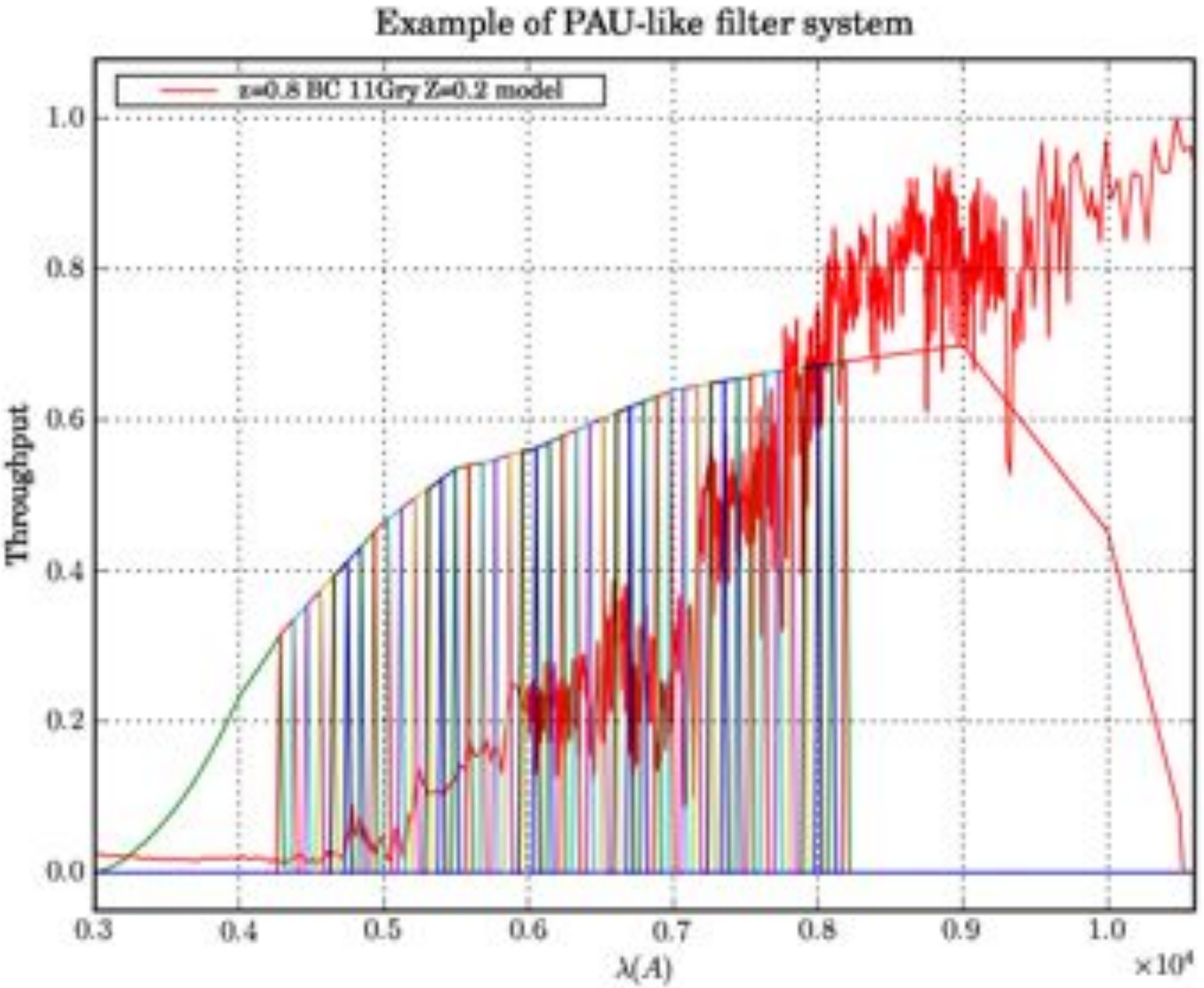
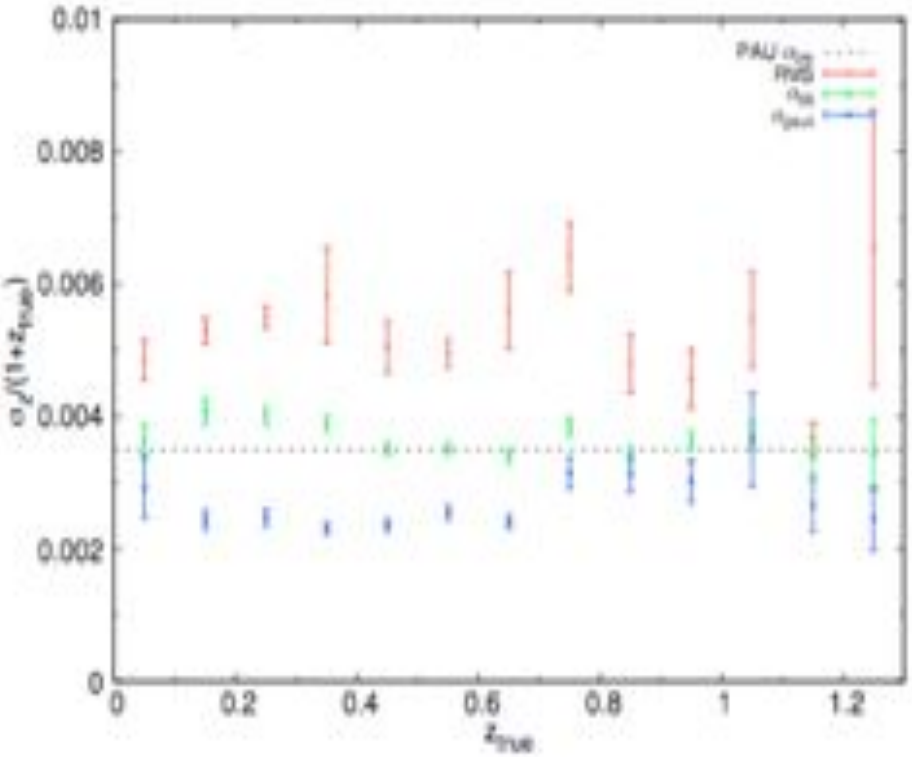
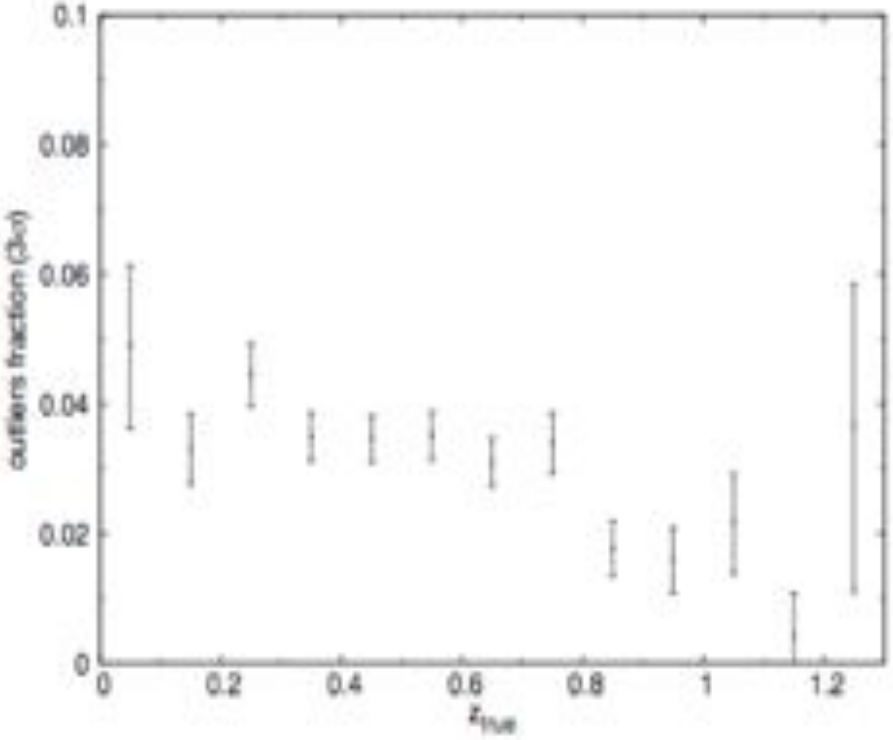

Example of PAU-like filter system
z=0.8 BC 11Gry Z=0.2 model
Throughput
1.0
0.8
0.6
0.4
0.2
0.0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
λ(A)
×10⁴

Photo-z performance





PAUS capabilities

2 deg^2 per night in all filters (42 narrow-band + 6 ugrizY):

It will deliver (per night) “low-resolution spectra” (R≈50) for:

- 30,000 galaxies
- 5,000 stars
- 1,000 quasars
- 10 clusters

PAUS (PAU-Survey) Scientific Goals

We expect to obtain ≈ 100 nights during the 4-year period 2013-2016.

Scientific goals for PAU/WHT will focus on measuring:

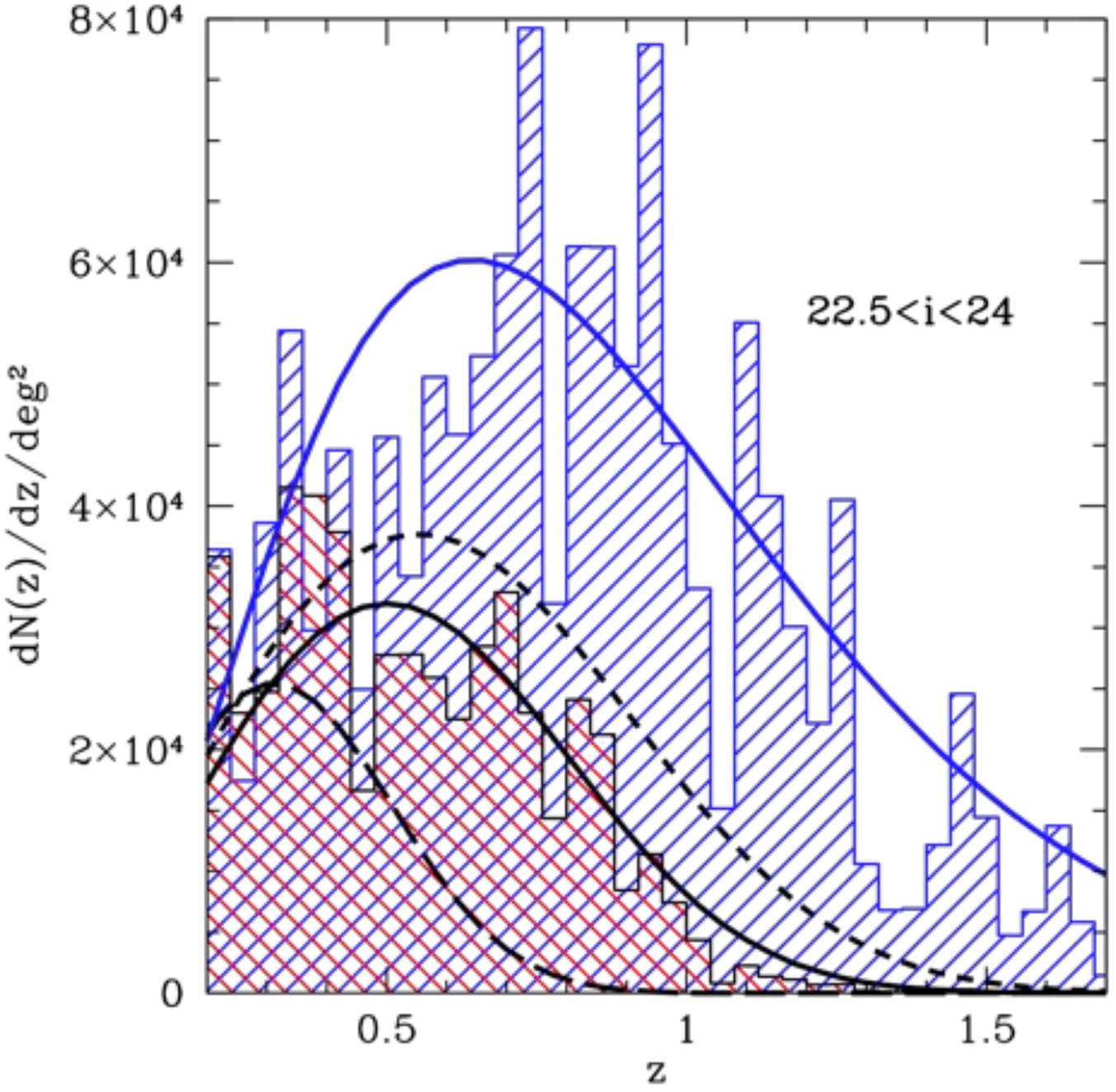
- **Red-shift Space Distortions.**
- **Weak Lensing Magnification.**

To exploit these, we will measure (over the same area):

- Bright galaxy sample ($i_{AB} < 22.5$) with high redshift resolution of $\sigma_z = 0.0035\ (1+z)$.
- Faint sample $22.5 < i_{AB} < 24$ with $\sigma_z = 0.05\ (1+z)$.

➔ PAUCam will use 42 narrow-band (10nm) filters covering ≈ 440-860 nm.

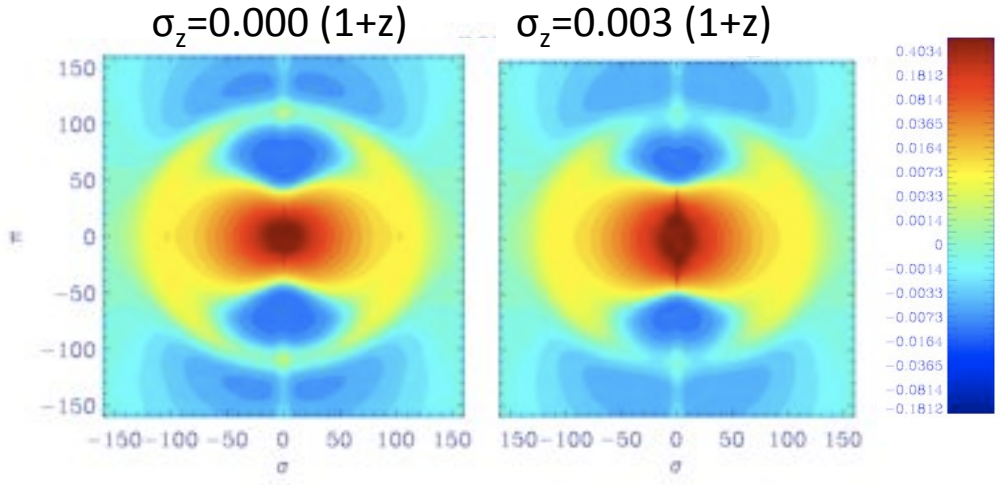
PAU Survey samples



PAUS Scientific Goals

- **Redshift Space Distortions.**
  - The Hubble relation between redshift and distance in the radial direction is modified by the peculiar velocity of galaxies.
  - Large structures give rise to bulk motions which affect the σ-π maps. Galaxies behind over-dense regions will appear nearer, while galaxies in front of dense regions will appear farther ➔ squashing of matter distribution in radial direction at large scales.

PAU photo-z resolution particularly well-suited for this measurement over bright sample.



Mpc/h

PAUS Scientific Goals

- **Weak-lensing magnification**
  - Lensing changes area of background image and magnifies/ demagnifies object fluxes ➔ density fluctuations correlated with density fluctuations in the foreground lenses.
  - Very precise photo-z's in foreground lenses allow to perform cross-correlations between well-defined narrow redshift bins.
  - The combination of RSD and MAG in the same data set is very powerful in breaking degeneracies between cosmological parameters ➔ a unique advantage of PAU.

PAUS Scientific Goals

- **Understanding Intrinsic alignments**
  - Intrinsic alignments one of the major lensing systematics that can affect future surveys (e.g., Euclid).
  - Knowledge of redshifts in weak lensing surveys can help understand the effect (e.g., CFHTLS + PAUS)

PAU at the WHT

Quantitative study accepted for publication (arXiv:1109.4852, MNRAS in press):

Cross-Correlation of spectroscopic and photometric galaxy surveys: cosmology from lensing and redshift distortions

Enrique Gaztañaga[1], Martin Eriksen[1], Martin Crocce[1], Francisco J. Castander[1], Pablo Fosalba[1], Pol Marti[2], Ramon Miquel[2,3], Anna Cabré[4]

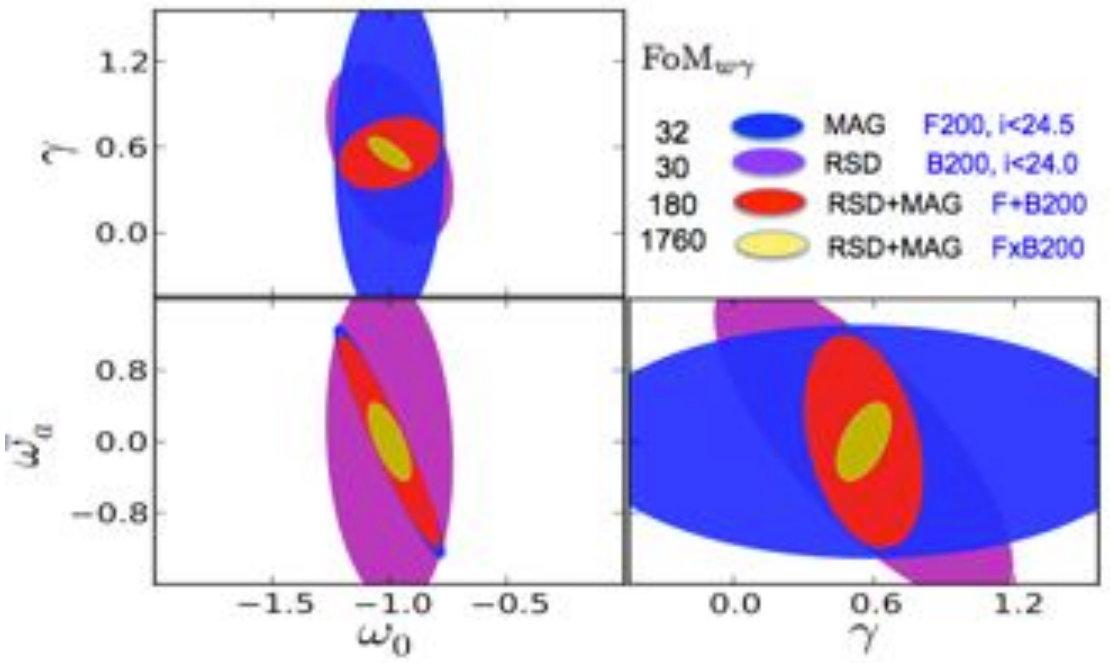
[1] *Institut de Ciències de l'Espai (IEEC-CSIC), E-08193 Bellaterra (Barcelona), Spain*
[2] *Institut de Física dAltes Energies (IFAE), E-08193 Bellaterra (Barcelona), Spain*
[3] *Institució Catalana de Recerca i Estudis Avançats (ICREA), E-08010 Barcelona, Spain*
[4] *University of Pennsylvania, Philadelphia, USA*

Effects are sensitive to both the equation of state parameter w and structure growth.

Figure of Merit for w_0, w_a and growth factor γ:

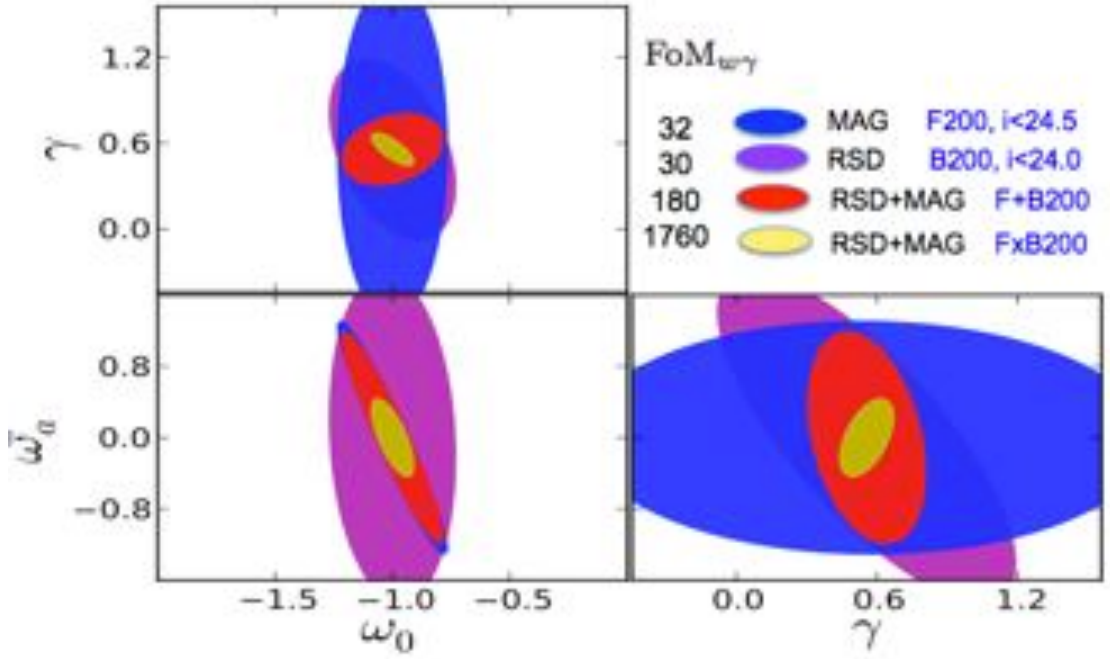
Combination of

1. 3D galaxy clustering (degenerate with galaxy biasing)
2. weak lensing measurements (shear in CFHTLS and magnification) which is unbiased but 2D
3. Redshift space distortions (which also measures galaxy bias and growth)



PAUS at WHT

- **Gains from combination of clustering with lensing** (Gaztanaga et al arXiv:1109.4852, MNRAS in press)
  - Improvement: use of thin redshift bins and measurement of bias affecting RSD and WL in different ways
  - Gain when both probes done in same area
  - $FoM_{w\gamma}$ with scaling: $FoM_{w\gamma} \simeq 2080\ A^{0.89}\ \eta^{0.2}\ 1.26^{m_i - 22.5}\ e^{-\sigma_z^2 - \Delta_\tau A^{0.05}}$
  - Comparison of using shear-shear, shear-galaxy and galaxy-galaxy cross and auto-correlations
  - Systematics may change performance
  - Survey planning
  - Possible further gains with higher orders



PAU Survey additional science

Although the survey is designed and optimized for DE, many other science topics could be addressed

- Galaxy evolution
- High redshift galaxies
- Interstellar dust
- Quasars and Lyα systems
- Clusters
- Weak gravitational lensing
- Strong gravitational lensing
- Galactic astronomy
- Stellar populations
- Halo stars
- Local group galaxies
- Serendipitous discoveries

Thank you