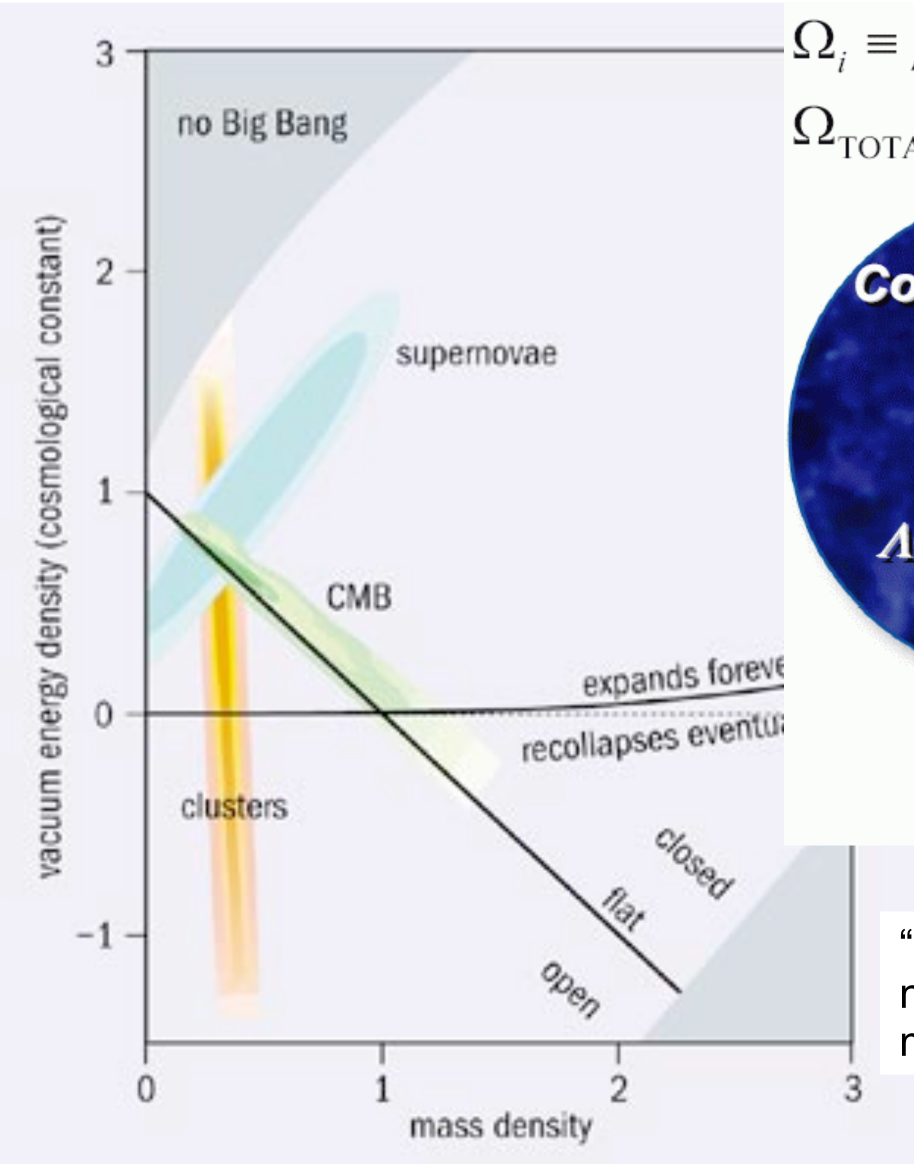
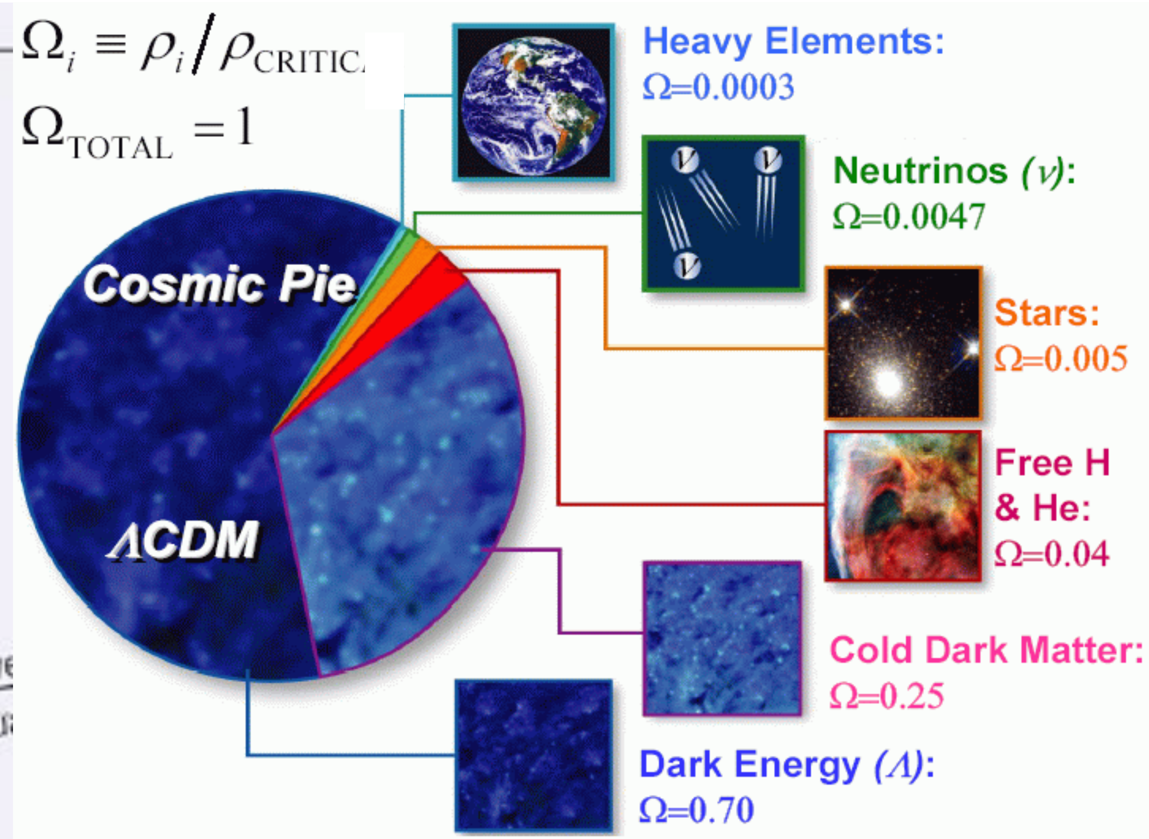
The PAU Survey at the WHT

Ramon Miquel
ICREA / IFAE Barcelona

Modern Cosmology Workshop, Benasque, August 21st 2012

The New Standard Model





"The last Copernican revolution. (...) Not only we are not at the center of the universe, we are not even made of the stuff most of the universe is made of."

B. Sadoulet

Dark Energy Studies

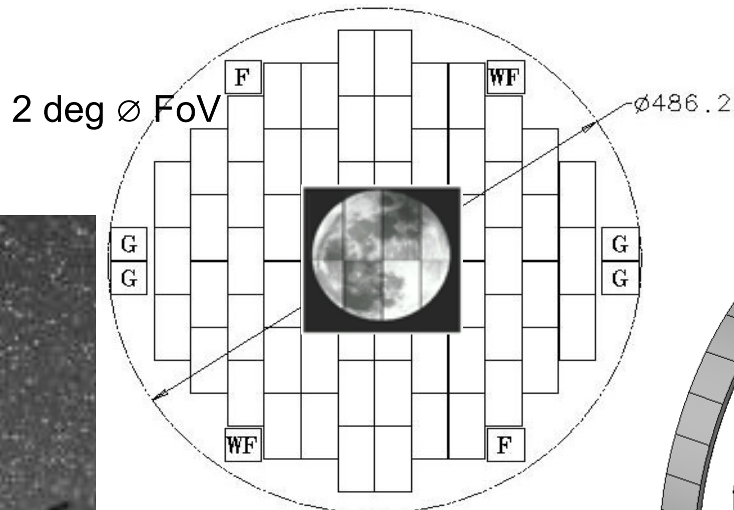
- What is causing the acceleration of the expansion of the universe?
  - Einstein's cosmological constant Λ?
  - Some new dynamical field ("quintessence," Higgs-like)?
  - Modifications to General Relativity?

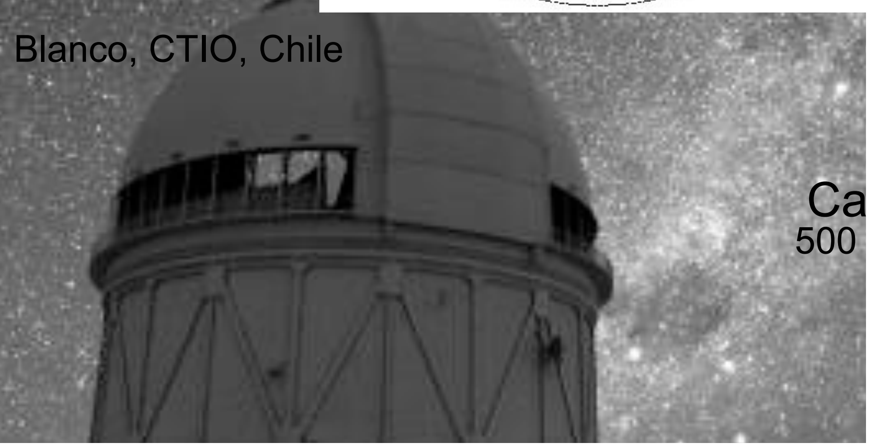
} "Dark Energy"

- Dark energy effects can be studied in two main cosmological observables:
  - The history of the expansion rate of the universe: supernovae, weak lensing, baryon acoustic oscillations, cluster counting, etc.
  - The history of the rate of the growth of structure (galaxies) in the universe: weak lensing, large-scale structure, cluster counting, etc.
- For all probes other than SNe, large galaxy surveys are needed:
  - Spectroscopic: 3D (redshift), medium depth, low density, selection effects
  - Photometric: "2.5D" (photo-z), deeper, higher density, no selection effects

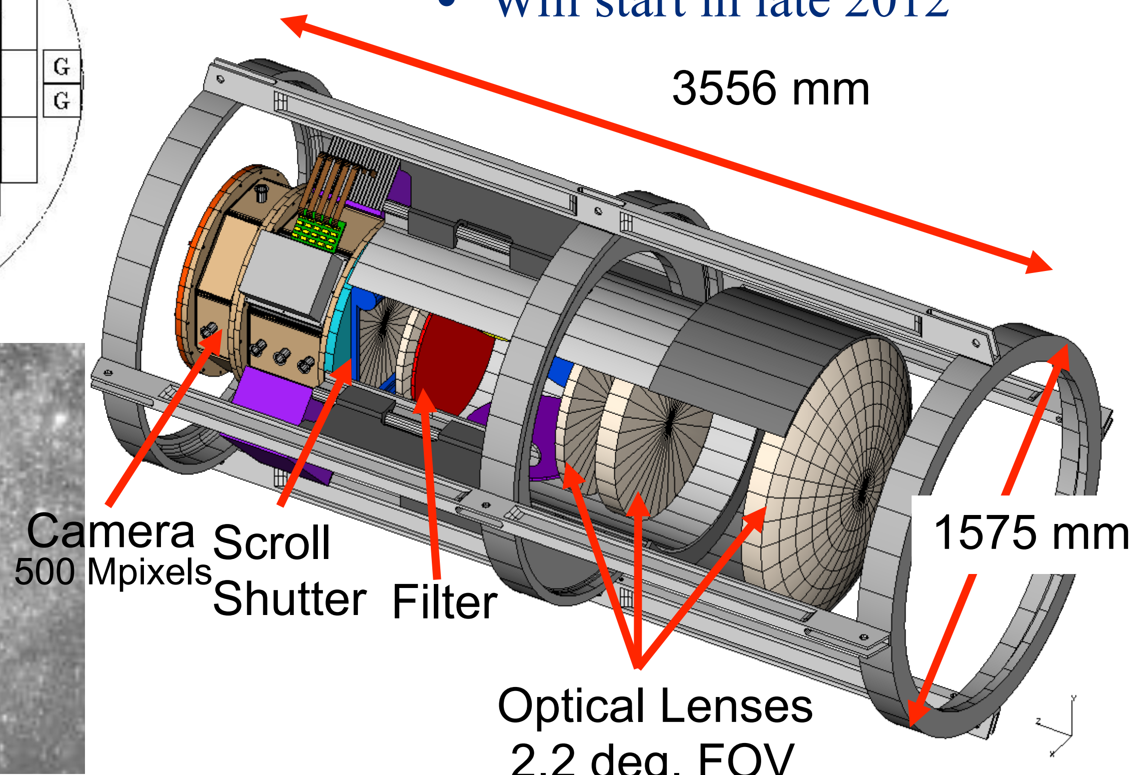
Dark Energy Survey (DES)

- 5000 deg^2 galaxy survey in 5 bands. 300M galaxies up to z < 1.4. Also ~4000 SNe.
- Involves groups in USA, Spain, UK, Brazil, Germany, Switzerland.





- 525 nights in 5 years
- Will start in late 2012

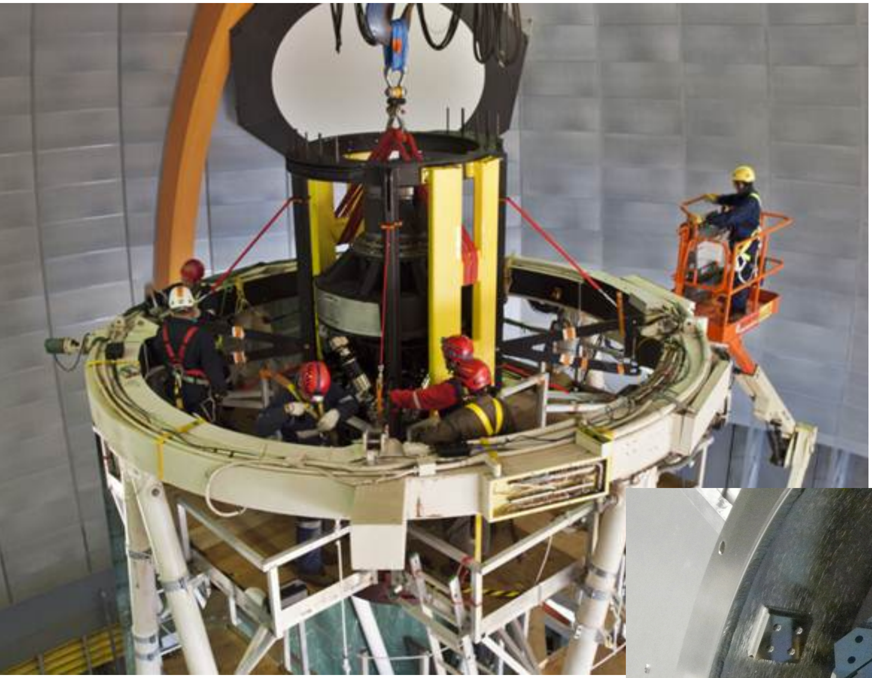


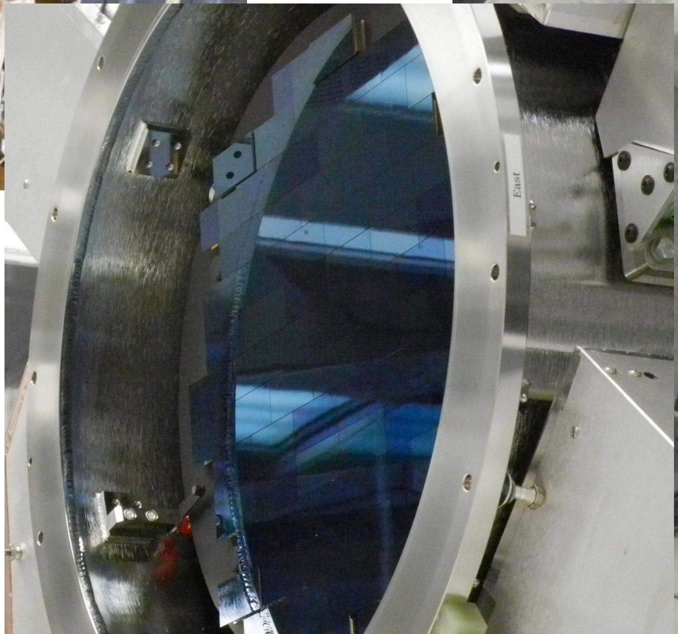
DES Camera Installation

DARK ENERGY SURVEY

July 2012

May 2012





- First light expected by September 2012
- Survey starts in December 2012

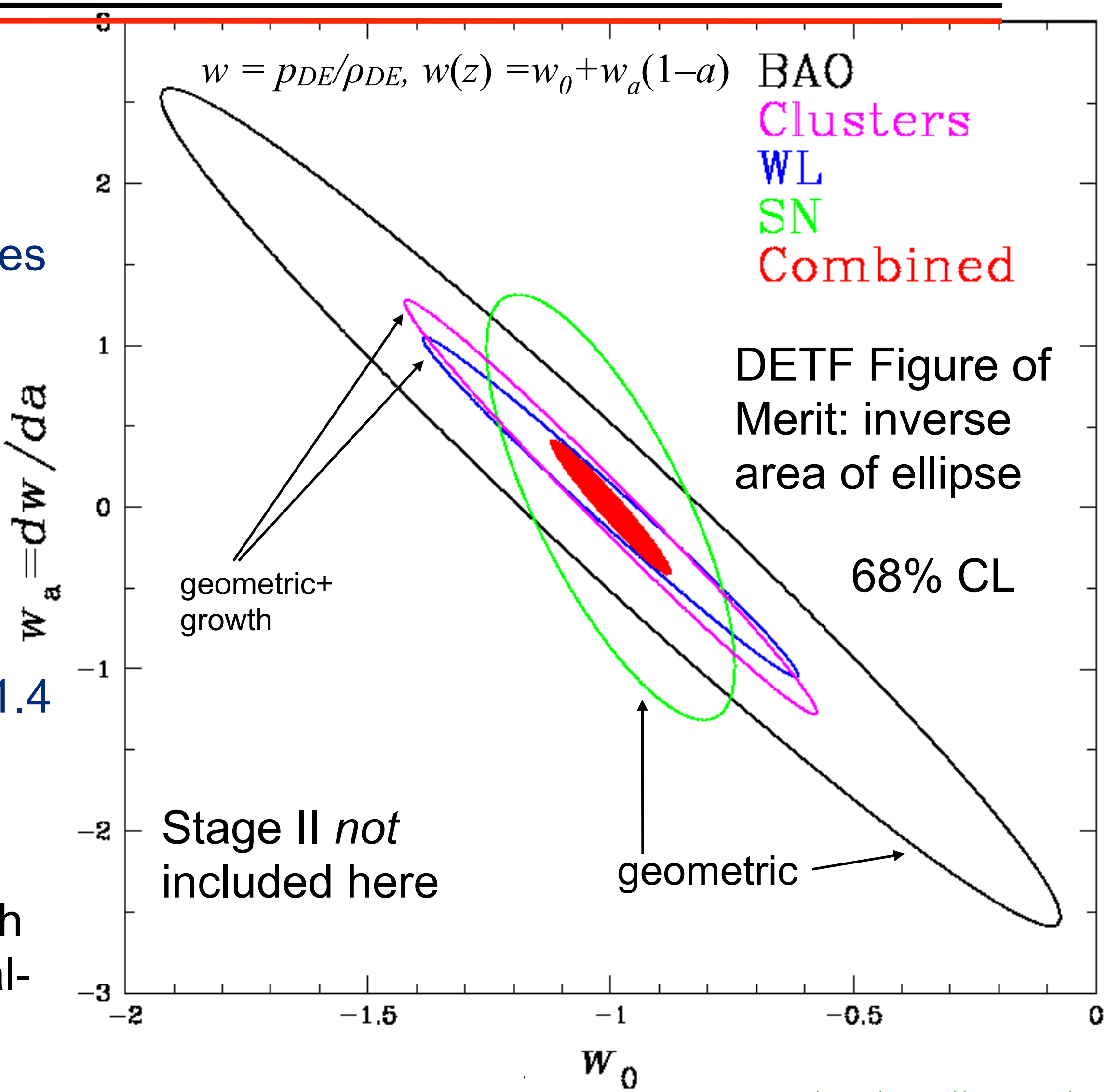
DES Science Reach

DARK ENERGY SURVEY

Four Probes of Dark Energy

- Galaxy cluster counting: N(M,z)
  - Measure redshifts and masses
  - ~10,000 clusters to z=1 with $M > 2\times10^{14}\ M_\odot$
- Weak lensing (shear)
  - ~300 million galaxies with shape measurements
- Galaxy distribution (incl. BAO)
  - ~300 million galaxies to z ~ 1.4
- Supernovae
  - ~4000 type-Ia SNe to z ~ 1

Probes are complementary in both systematic error and cosmological-parameter degeneracies



Huterer, Ma, Miquel, Weller, et al.

DES Photo-z Precision

DARK ENERGY SURVEY

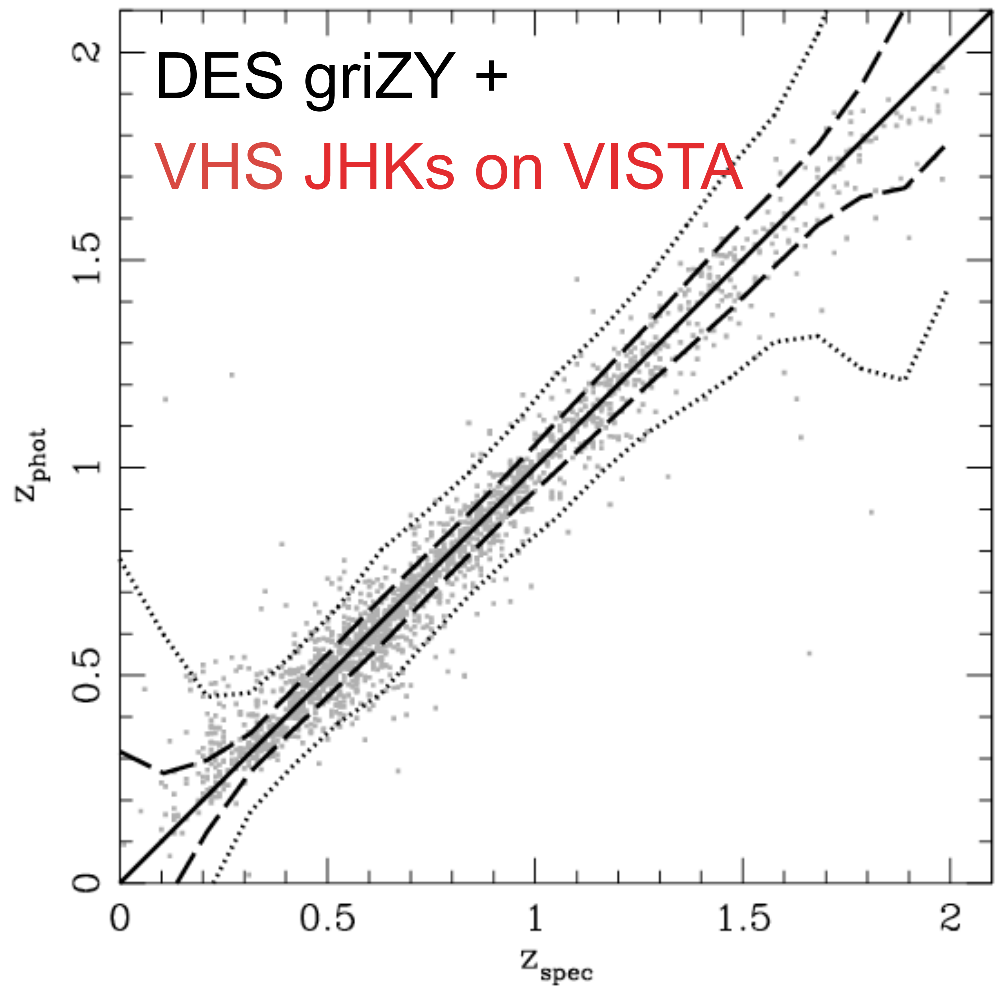
DES +VHS

10σ Limiting Magnitudes

g	24.6		
r	24.1	J	20.3
i	24.0	H	19.4
Z	23.8	Ks	18.3
Y	21.6		

+2% photometric calibration error added in quadrature

$\sigma(z) \sim 0.05\times(1+z)$



PAU = Physics of the Accelerating Universe

- ~45 particle physicists (theoreticians and experimentalists), astronomers, astrophysicists, cosmologists…
- Awarded in 2007 a Spanish Consolider-Ingenio 2010 project (€5M over 5 years). PI: Enrique Fernández (IFAE)
- Main goals:
  - Design, build and commission a large FoV CCD camera
  - Perform a galaxy survey with it
  - Understand dark energy from theory point of view
- Telescope not part of Consolider project

Main Deliverable

- Build a large FoV camera, equipped with a large number of narrow-band filters (~40). Use Consolider funds (€5M) for this purpose.

- Place the camera in a suitable telescope. At the time of the proposal:
    - Javalambre telescope (new project)
    - ING (Isaac Newton Group of Telescopes, UK+NL+ES) at La Palma
    - ESO telescopes in Chile

- In the summer of 2009 we started contacts with the WHT telescope (part of the ING). The ING board agreed to host PAU in June of 2010. MoU signed in February 2012.

- PAUCam will be a visiting instrument at the WHT, and will be available to the community when not used by PAU.

PAU@WHT

Among other things the MoU establishes that:

- PAUCam will be a visitor instrument **also available for public use**.
- We will station a support astronomer at La Palma integrated with the WHT personnel.
- We will also provide a public data-reduction pipeline.

PAU@WHT Personnel

Senior Scientists
Post-docs
PhD Students
Engineers
Technicians

CIEMAT

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

ICE/IEEC

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

IFAE

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

PIC

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

UAM

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

PAU@WHT Personnel

PI : E. Fernández (UAB/IFAE)
Co-Is: E. Sánchez (CIEMAT), E. Gaztañaga(IEEC/CSIC), R. Miquel (IFAE/ICREA), J. García-Bellido (IFT/UAM), M. Delfino (PIC)

PAU Camera PI: F. Castander
Project Manager: C. Padilla. **Systems Engineer**: L. Cardiel
DAQ: J. de Vicente. **Mechanics**: F. Grañena. **Control**: O. Ballester. **Optics and integration**: R. Casas, J. Jiménez

PAUDM & Science PI: E. Gaztañaga
Simulations: F. Castander. **Operations**: N. Tonello. **Data Reduction**: S. Serrano. **QA & Validation**: I. Sevilla

The Survey Team

D. Alonso[4], J. Asorey[2], O. Ballester[3], A. Bauer[2], C. Bonnett[2], A. Bueno[4], J. Campa[1], L. Cardiel[3], J. Carretero[2], R. Casas[2], F. Castander[2], J. Castilla[1], M. Crocce[2], M. Delfino[5], J.F. de Vicente[1], M. Eriksen[2], S. Farrens[2], E. Fernández[3], P. Fosalba[2], J. García-Bellido[4], E. Gaztañaga[2], F. Grañena[3], A. Izard[2], J. Jiménez[2], C. López[2], L. C. López[3], F. Madrid[2], M. Maiorino[3], P. Martí[3], G. Martínez[1], R. Miquel[3], C. Neissner[5], L. Ostman[3], A. Pacheco[5], C. Padilla[3], C. Pio[3], A. Pujol[2], J. Rubio[4], E. Sánchez[1], D. Sapone[4], S. Serrano[2], I. Sevilla[1], P. Tallada[5], N. Tonello[5].

1 Ciemat – Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

2 IEEC – Institut d'Estudis Espacials de Catalunya; CSIC; ICE – Instituto de Ciencias del Espacio; Institut de Ciències de l'Espai CSIC

3 IFAE – Institut de Física d'Altes Energies; UAB – Universitat Autònoma de Barcelona

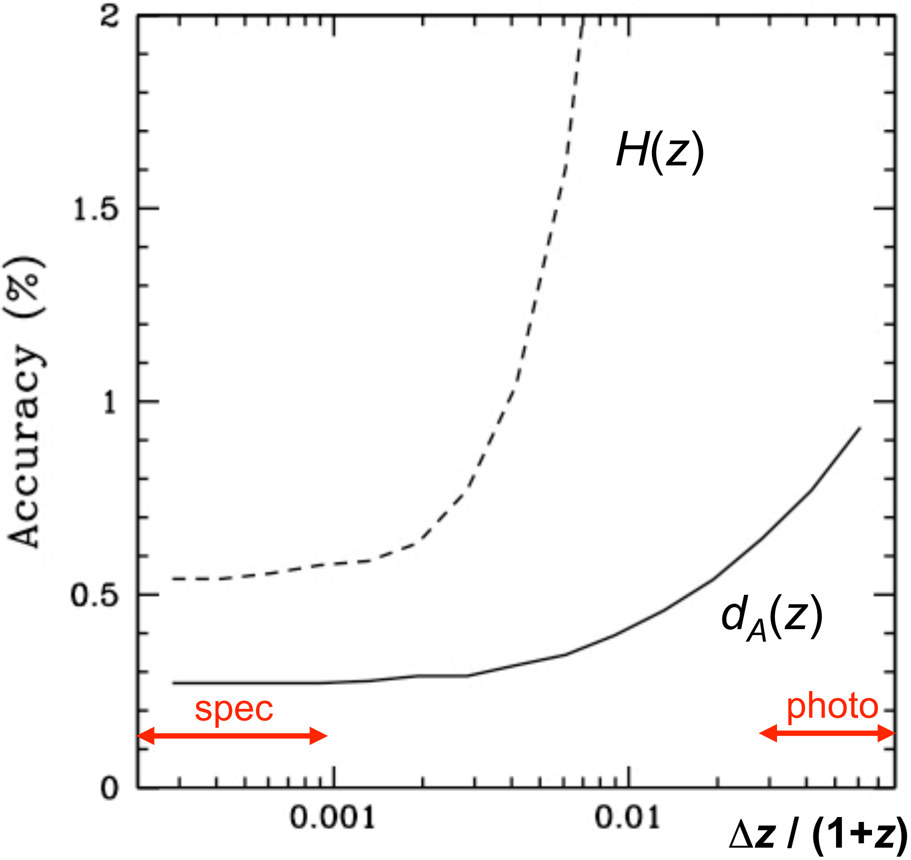
4 ift – Instituto de Física Teórica UAM/CSIC

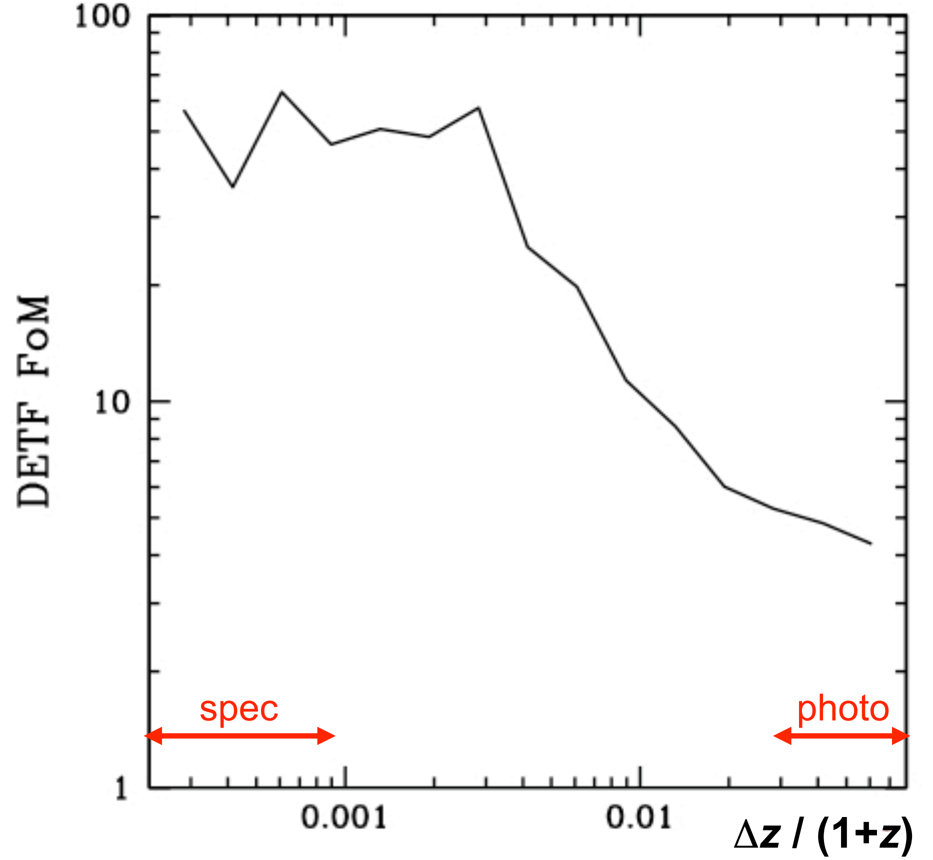
5 PIC – port d'informació científica

The PAU@WHT Project in a Nutshell

- New camera for WHT with 18 2k x 4k CCDs covering 1 deg ⌀ FoV.
- 42 100Å-wide filters covering 4300-8600 Å in 6 movable filter trays, which also include standard ugriZY filters.
- As a survey camera, PAUCam covers ~2 deg^2 per night in all filters.
- It can provide low-resolution (R ~ 50) spectra for >30000 galaxies, 5000 stars, 1000 quasars, 10 galaxy clusters, per night.
- Expected galaxy redshift resolution **$\sigma(z) \sim 0.003\times(1+z)$.**
- Main science goal is dark energy, with two main probes:
  - Redshift-space distortions
  - Weak-lensing magnification
- For both probes, PAU's large galaxy density (compared to spectroscopic surveys) and high redshift accuracy (compared to broadband photometric surveys) combine to provide a competitive determination of the dark energy parameters.
- First light expected in **early 2013.**

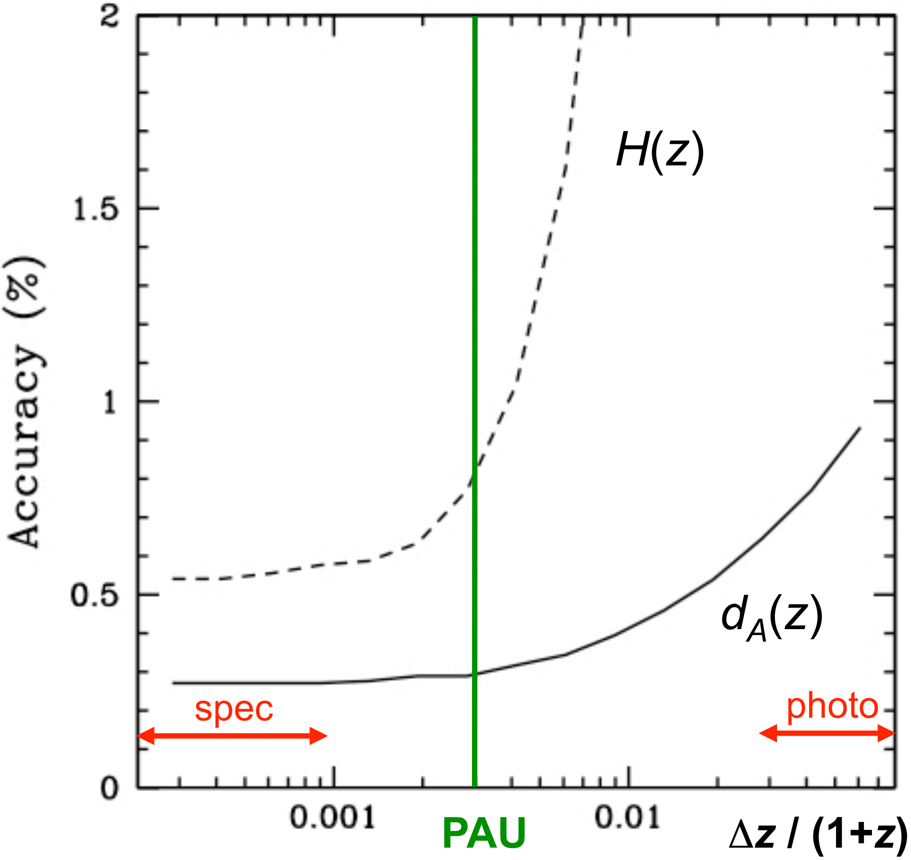
Requirements on Redshift Precision (BAO)

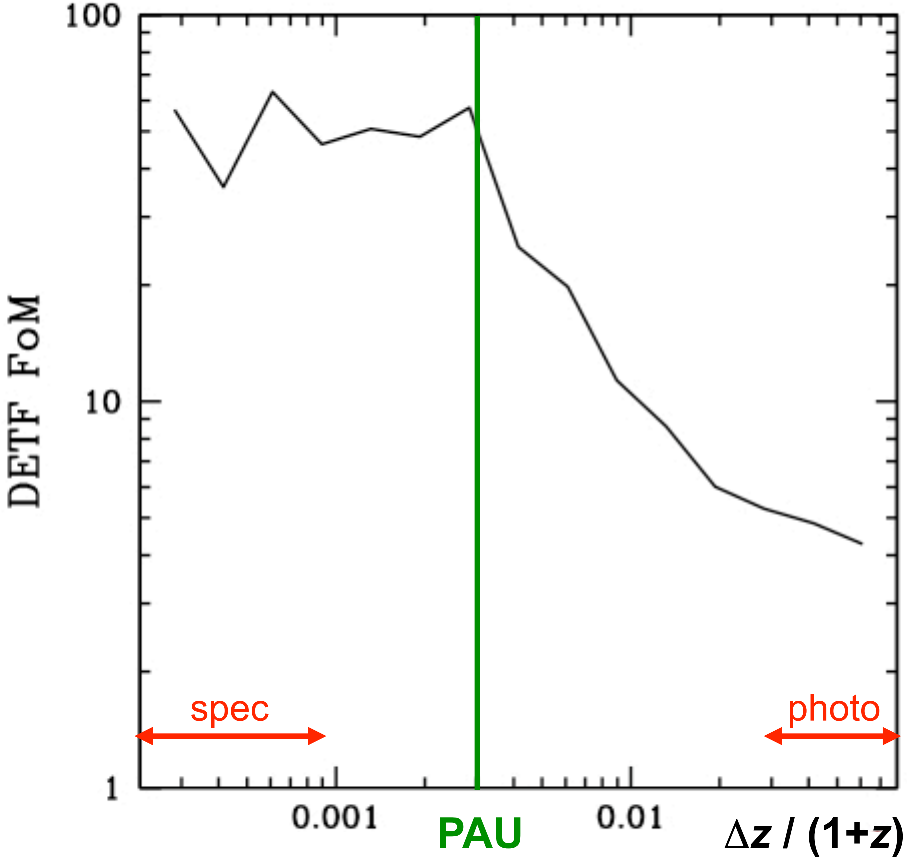




N. Padmanabhan

Requirements on Redshift Precision (BAO)





N. Padmanabhan

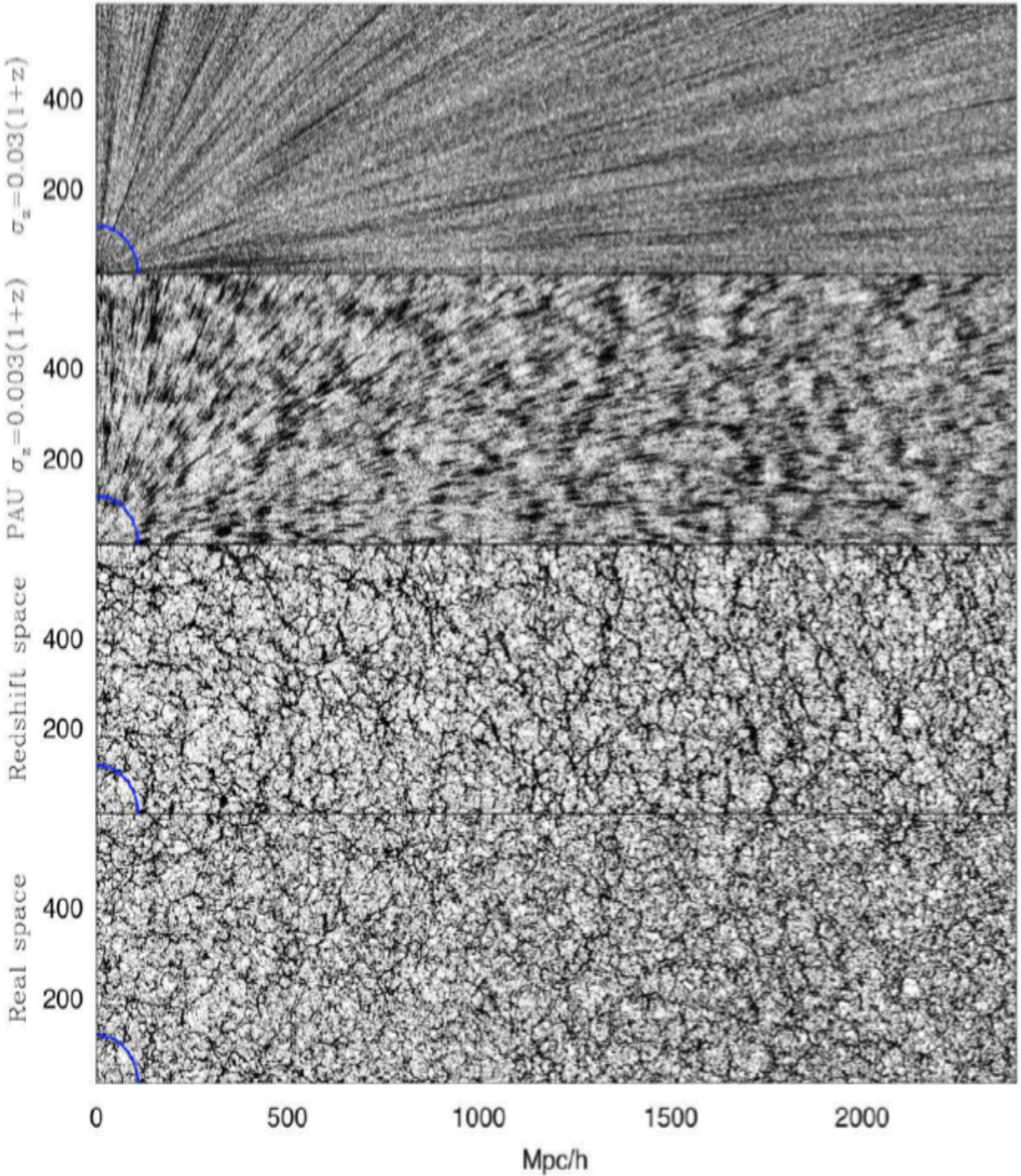
The Importance of Redshift Resolution

z-space, Δz = *0.03(1+z)*
+ peculiar velocities
(DES)

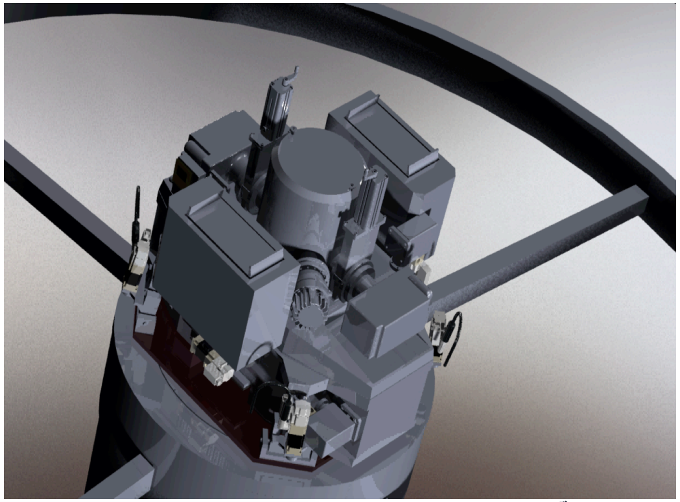
z-space, Δz = *0.003(1+z)*
+ peculiar velocities
(PAU)

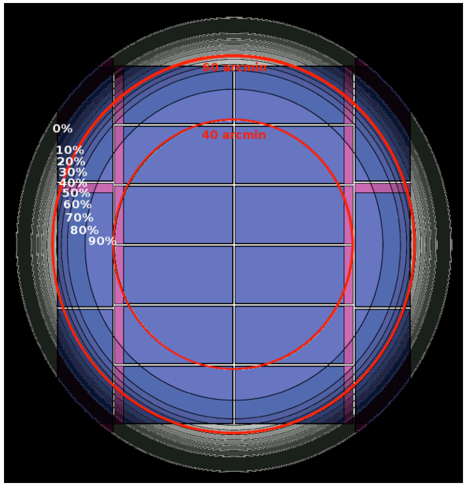
z-space, perfect resolution
+ peculiar velocities

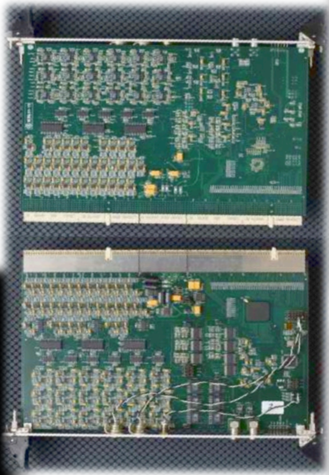
Real space

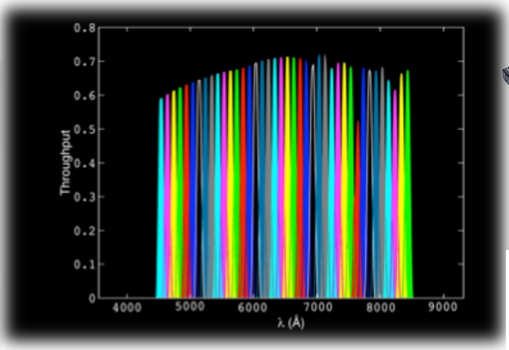


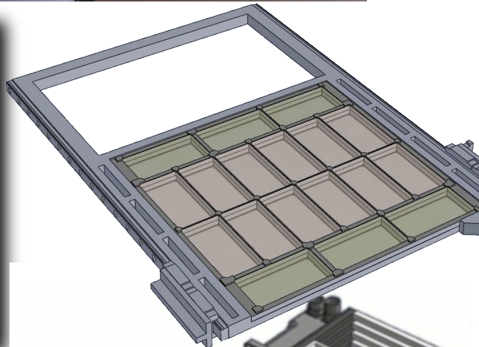
The PAU Camera at WHT in Pictures

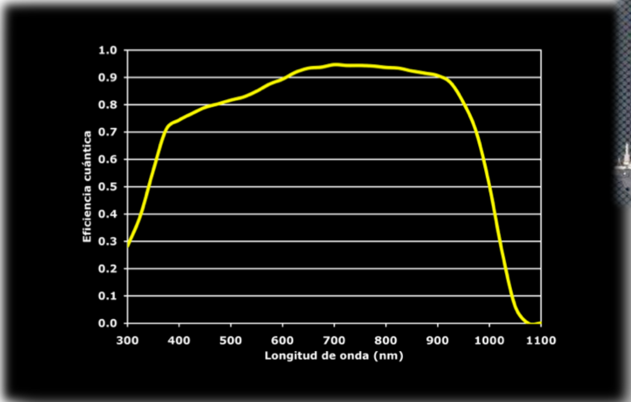


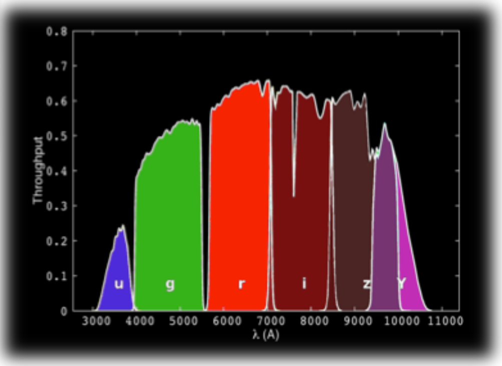


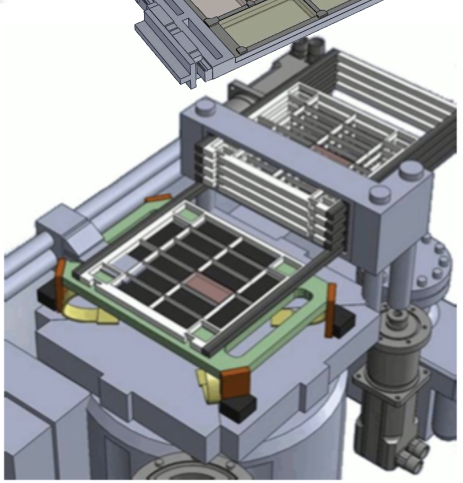






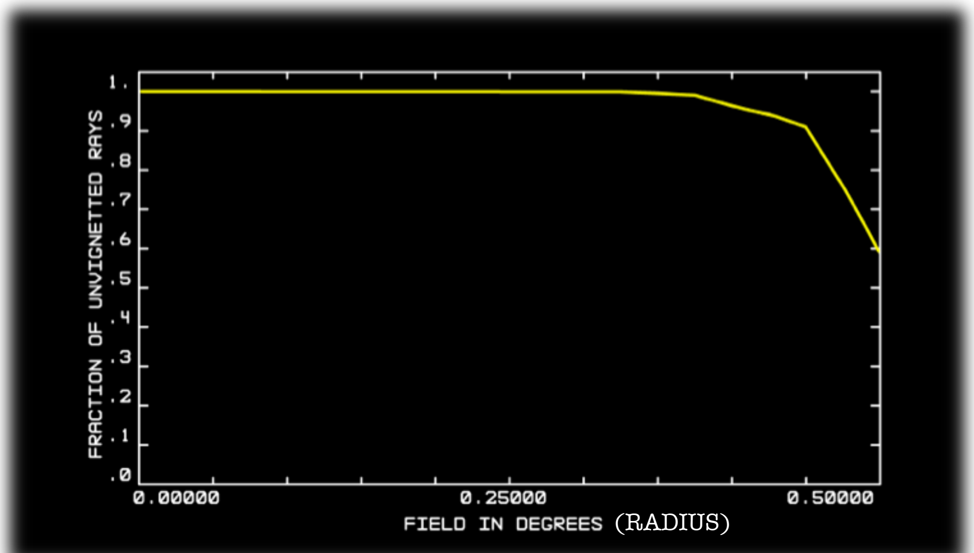


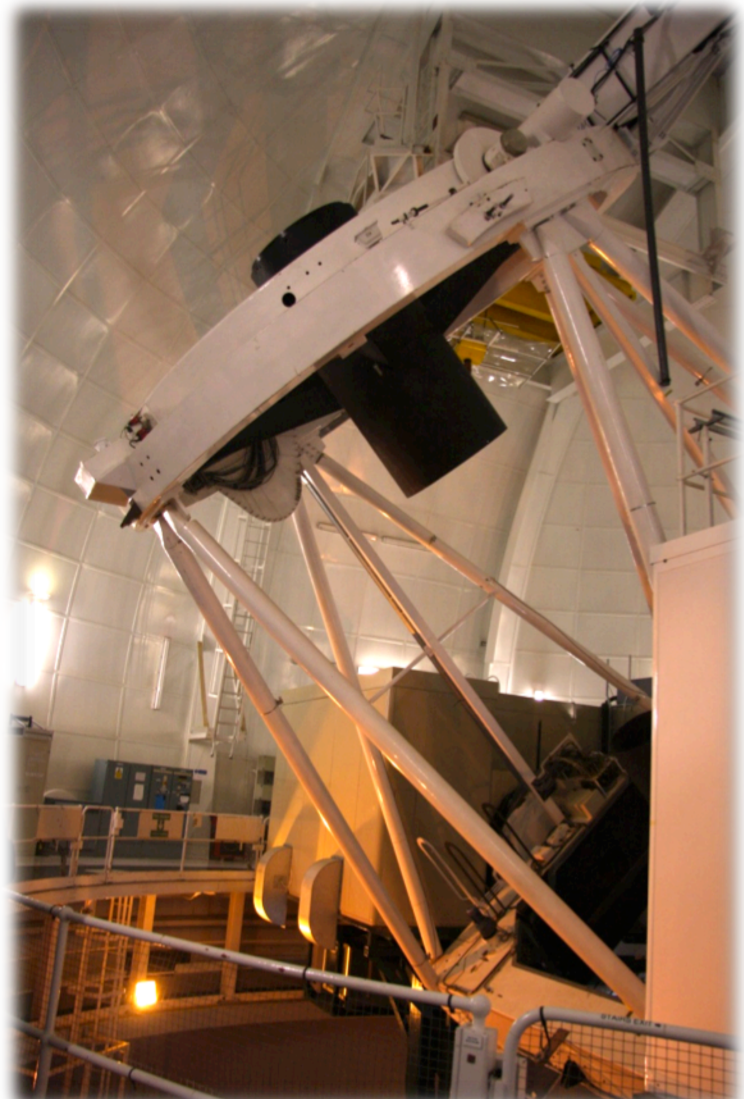




William Herschel Telescope (WHT)

- Located in the ORM, La Palma
- Used by UK, Netherlands & Spain
- Highly oversubscribed
- High scientific output so far
- Diameter: 4.2 m
- Prime focus: 11.73 m
- Focal ratio: f/2.8
- FoV: 1 deg ∅, 40' unvignetted
- Scale: 17.58''/mm ⇔ 0.26"/pixel

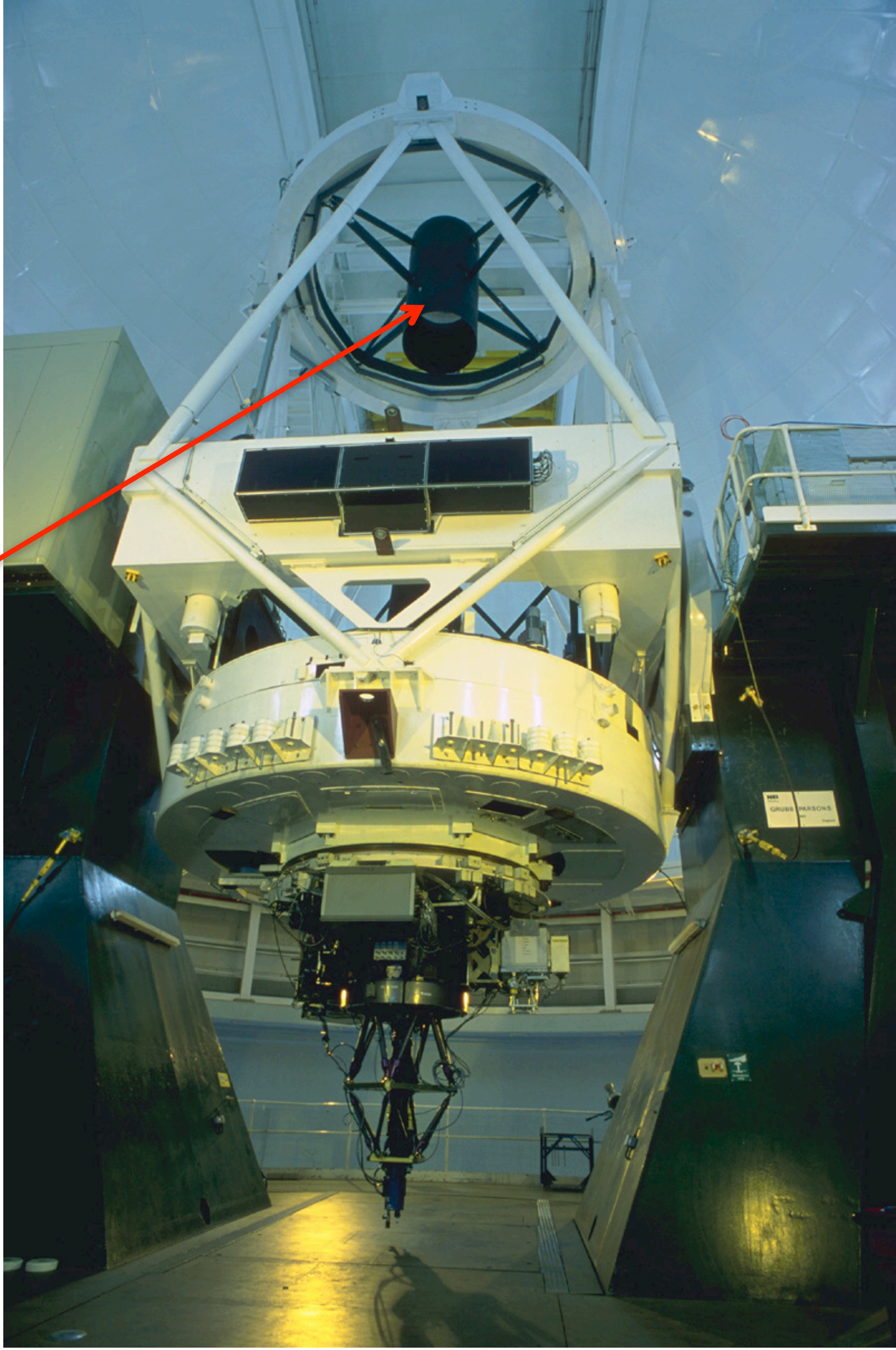




PAUCam

PAUCam will be mounted at the prime focus of the WHT:

Strong limitation in weight: max. 235 kg



PAUCam

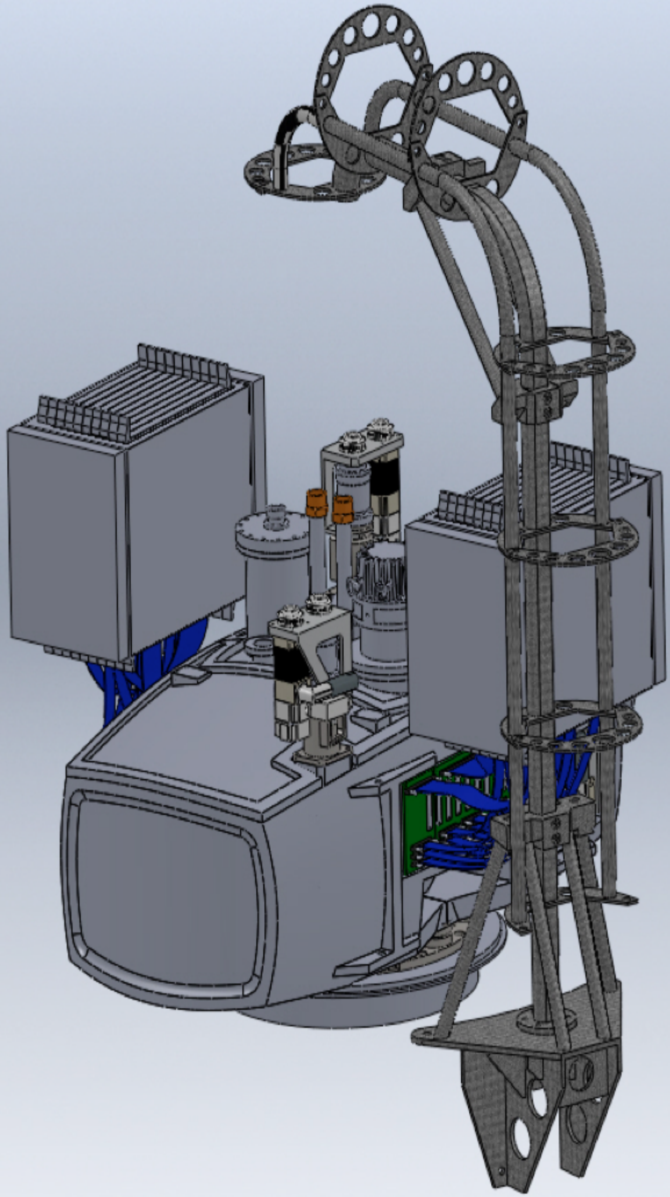
We appointed an External Review Panel for the design of the camera (193 pp. document), which convened in December 2010.

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

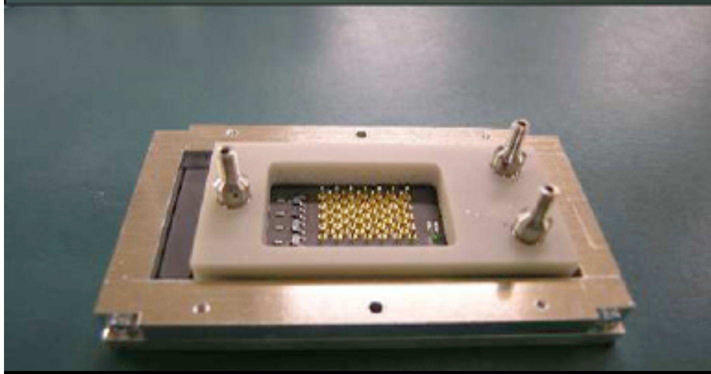


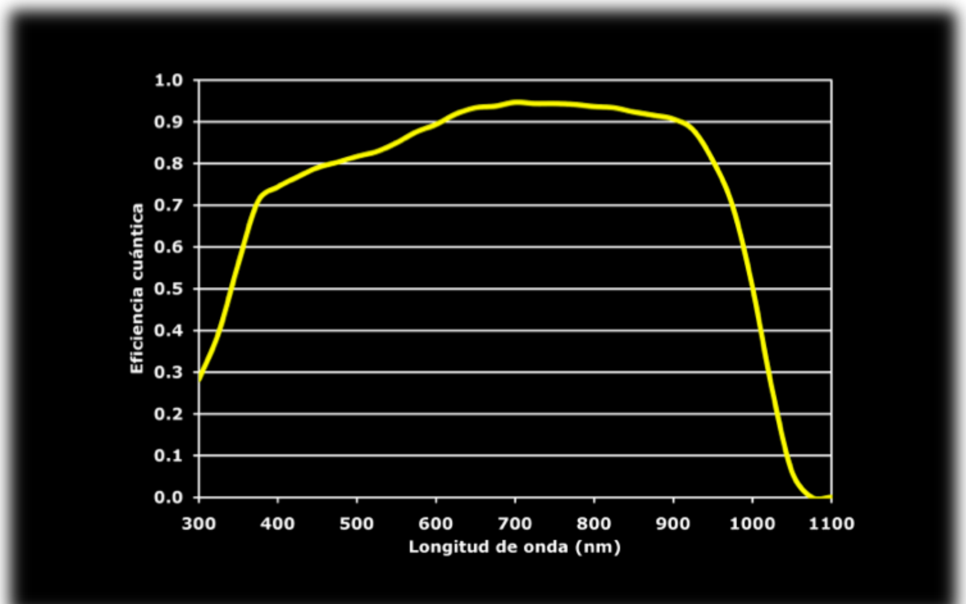
Body of camera made of carbon fiber, shaped to minimize wall thickness

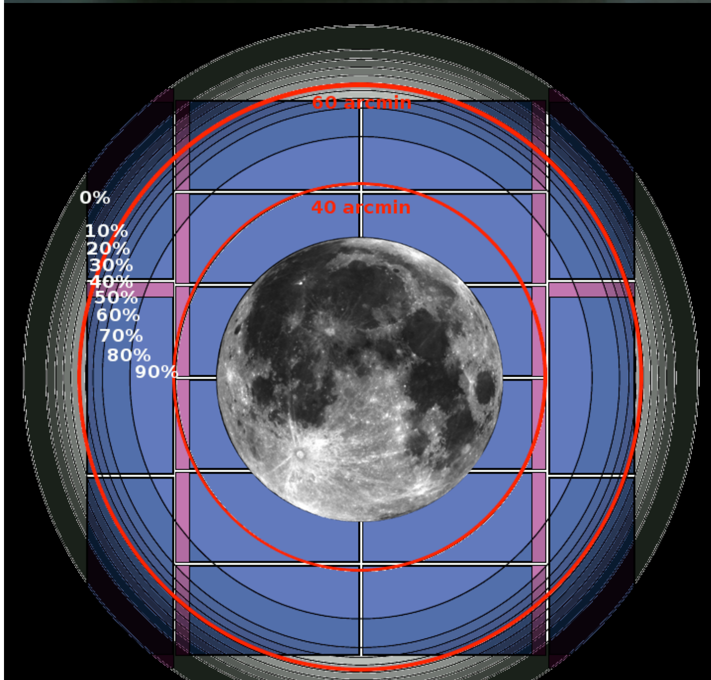
PAUCam Detectors

Hamamatsu new CCDs:

- 18 4k x 2k 15 µm pixels
- Excellent sensitivity across the entire wavelength range from 0.3 to over 1 µm.
- 20 delivered, being characterized at CIEMAT and IFAE

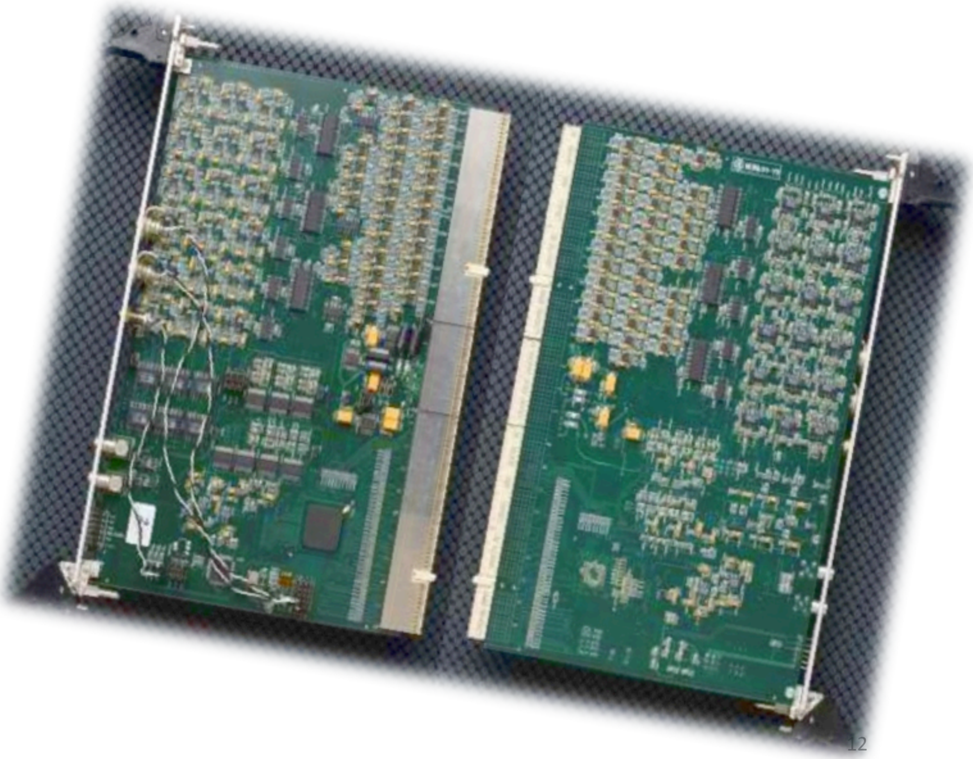




PAUCam Electronics

Monsoon architecture (NOAO)

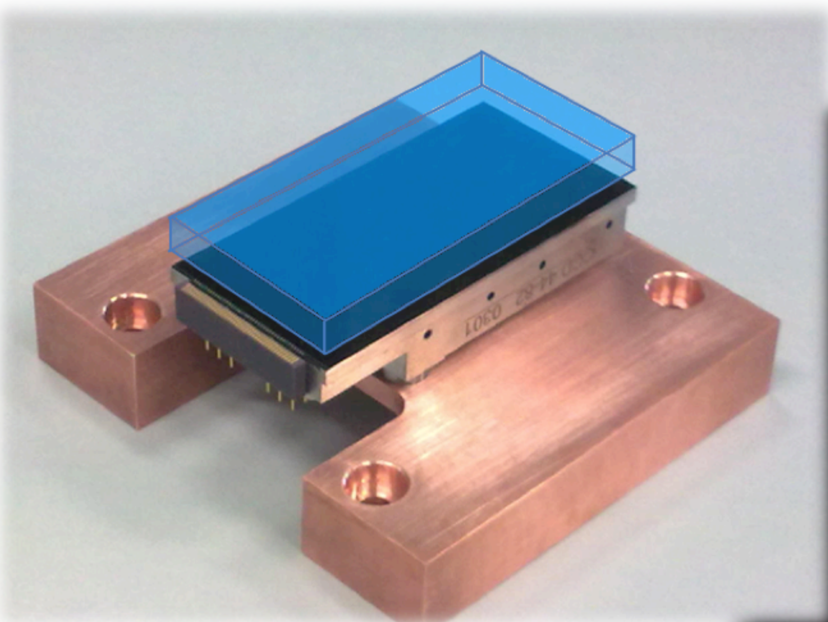
- Same as used for DES (CIEMAT and IFAE)
- 3 clock and bias board
- 7 acquisition boards
- 3 master control boards
- 18 pre-amp & routing boards

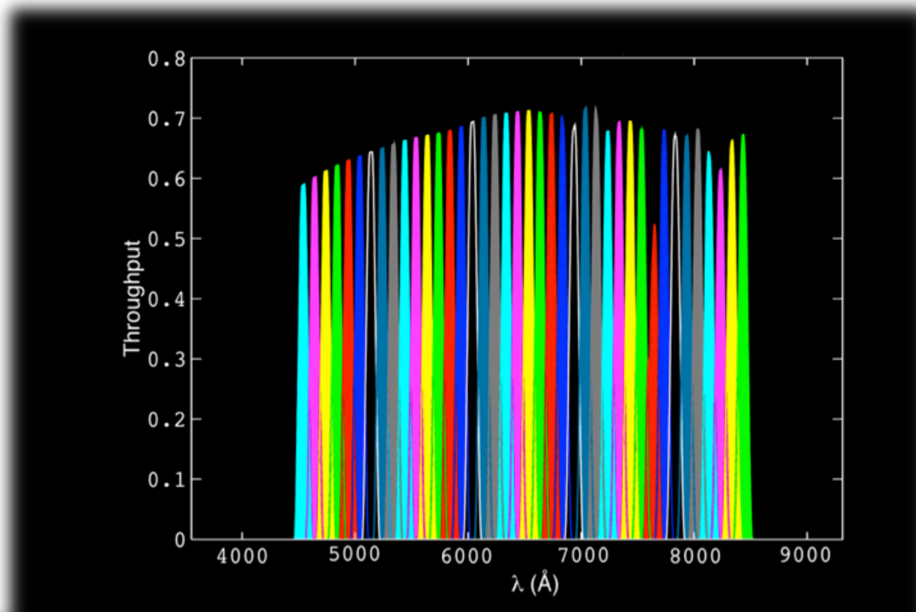


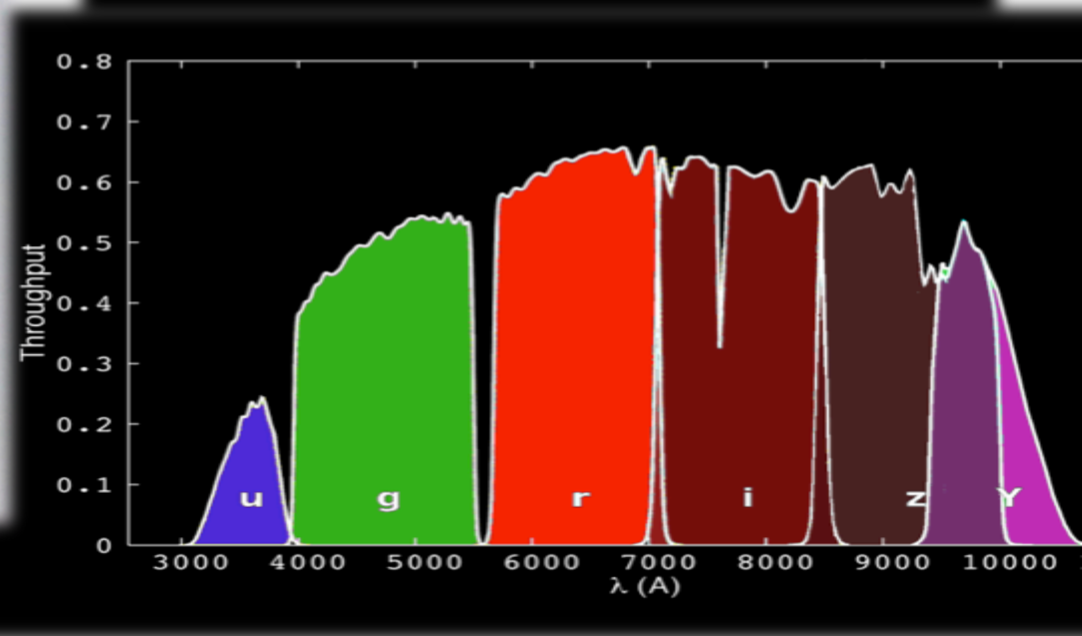
PAUCam Filter System

- 42 narrow-band filters
- FWHM = 100 Å
- Spectral range: λ=4300-8600 Å
- Rectangular transmission profile

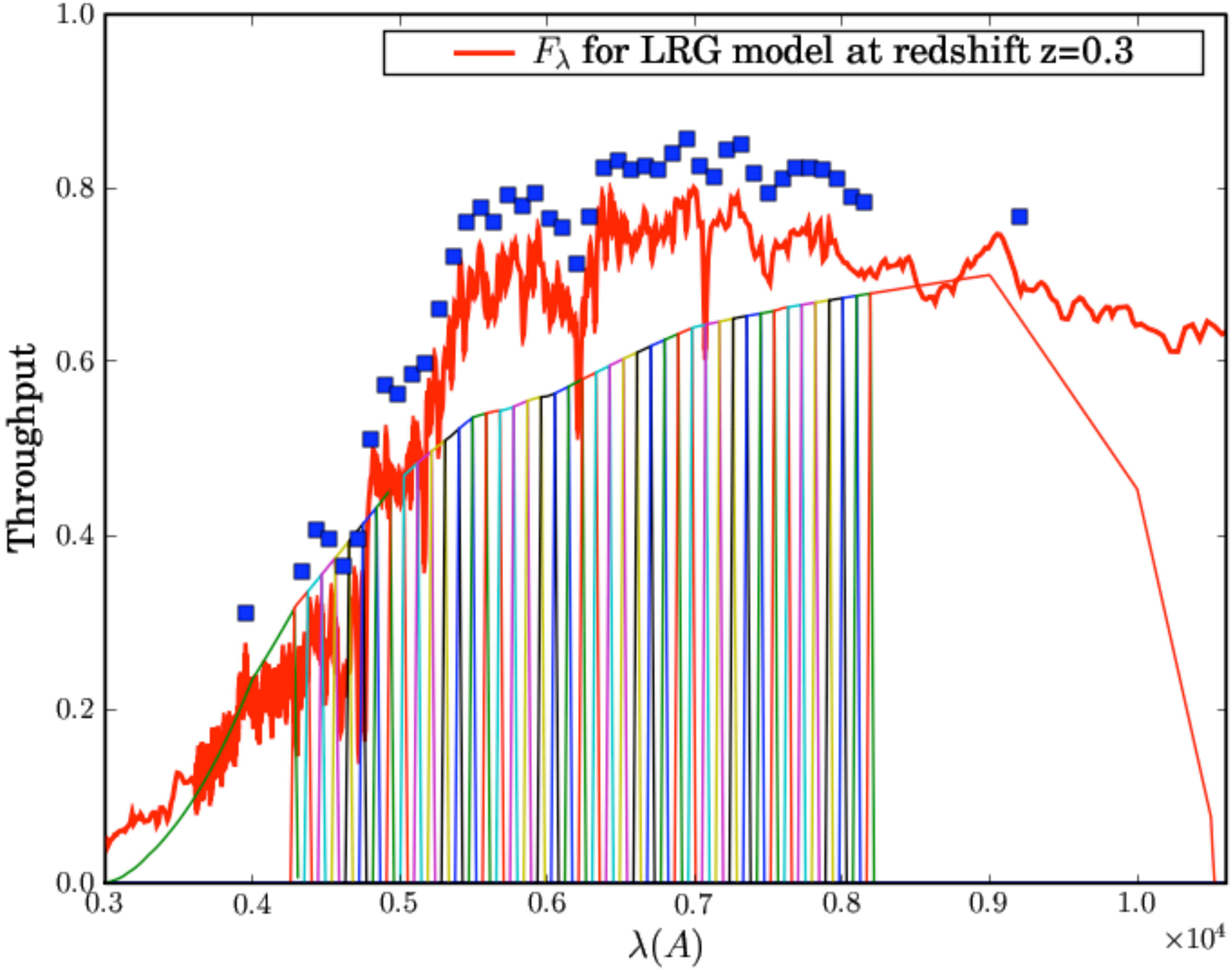
- 6 broad-band filters
- ugriZY (SDSS & DES)





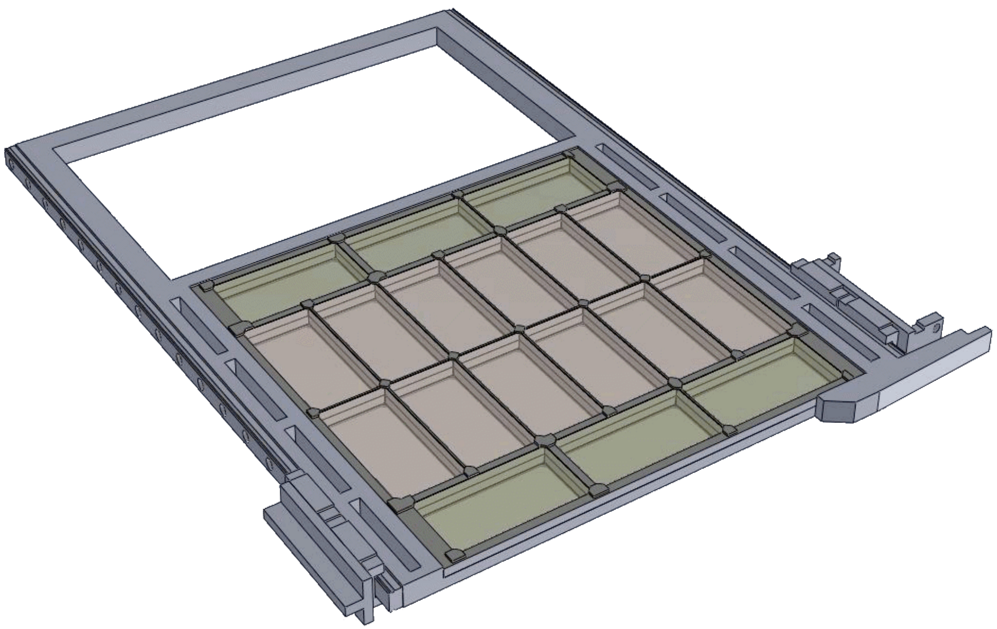


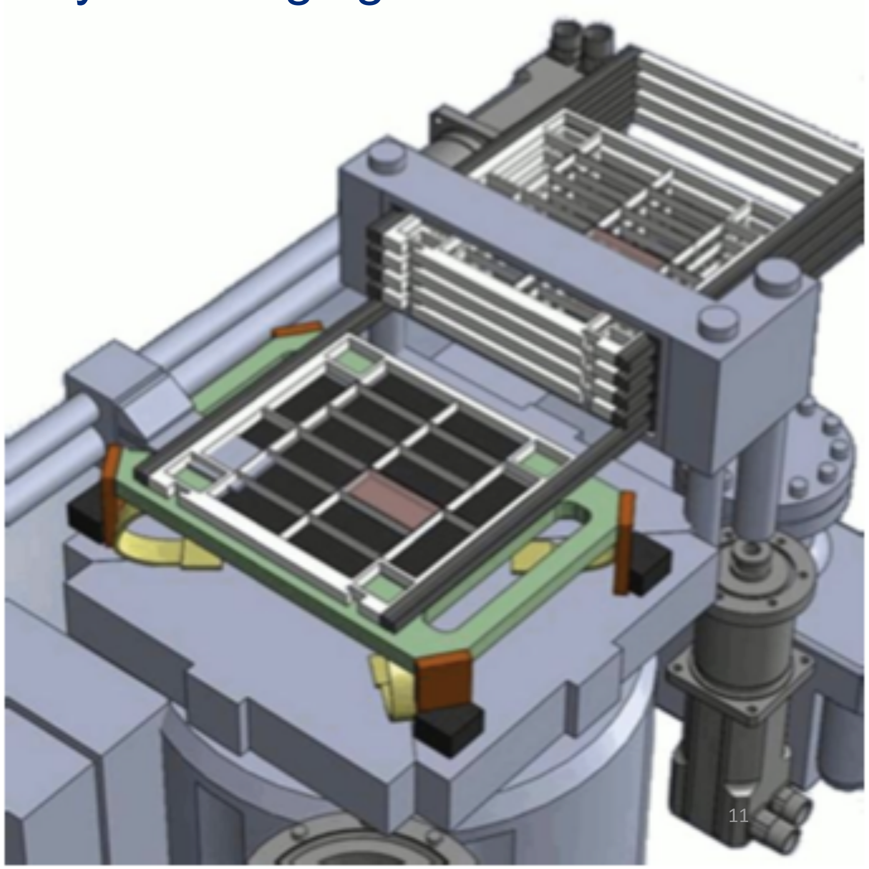
PAUCam Filter System



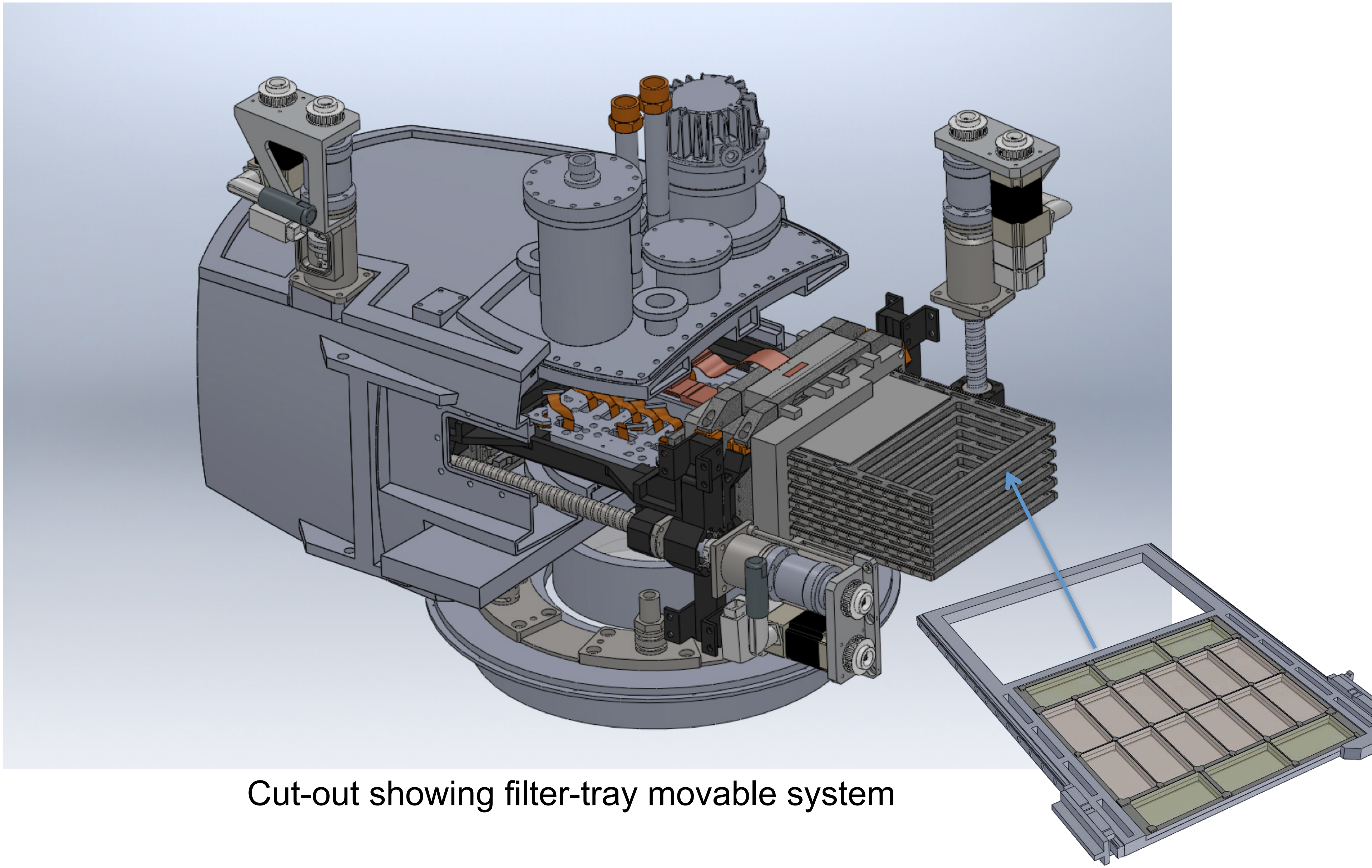
PAUCam Filter Trays

- Efficiency: filters need to be very close to sensors to avoid vignetting
- More filters than CCDs ➜ movable trays
- Jukebox-like system
- Movements in vacuum are technologically challenging





PAUCam Filter Trays



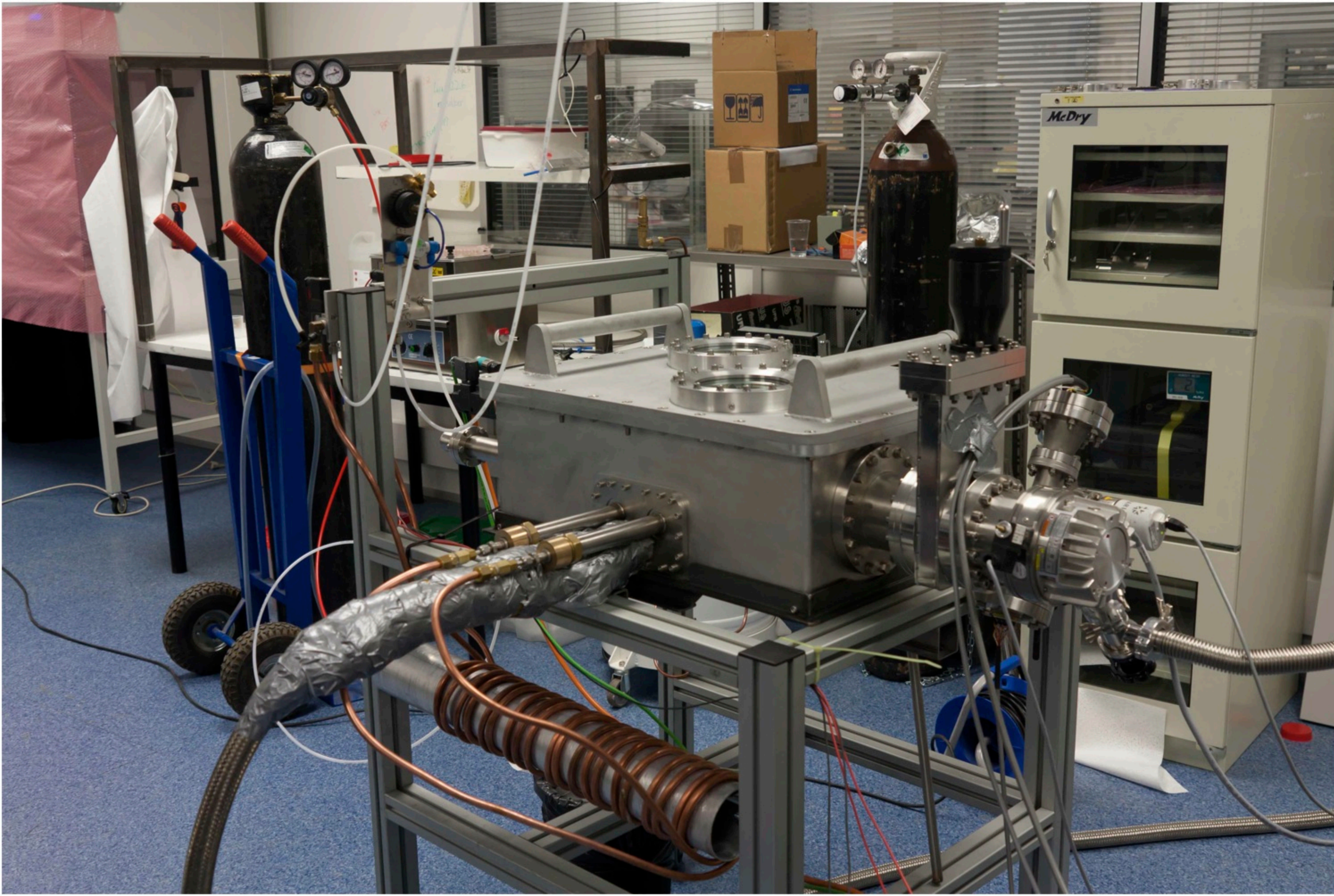
Cut-out showing filter-tray movable system

Status of PAUCam

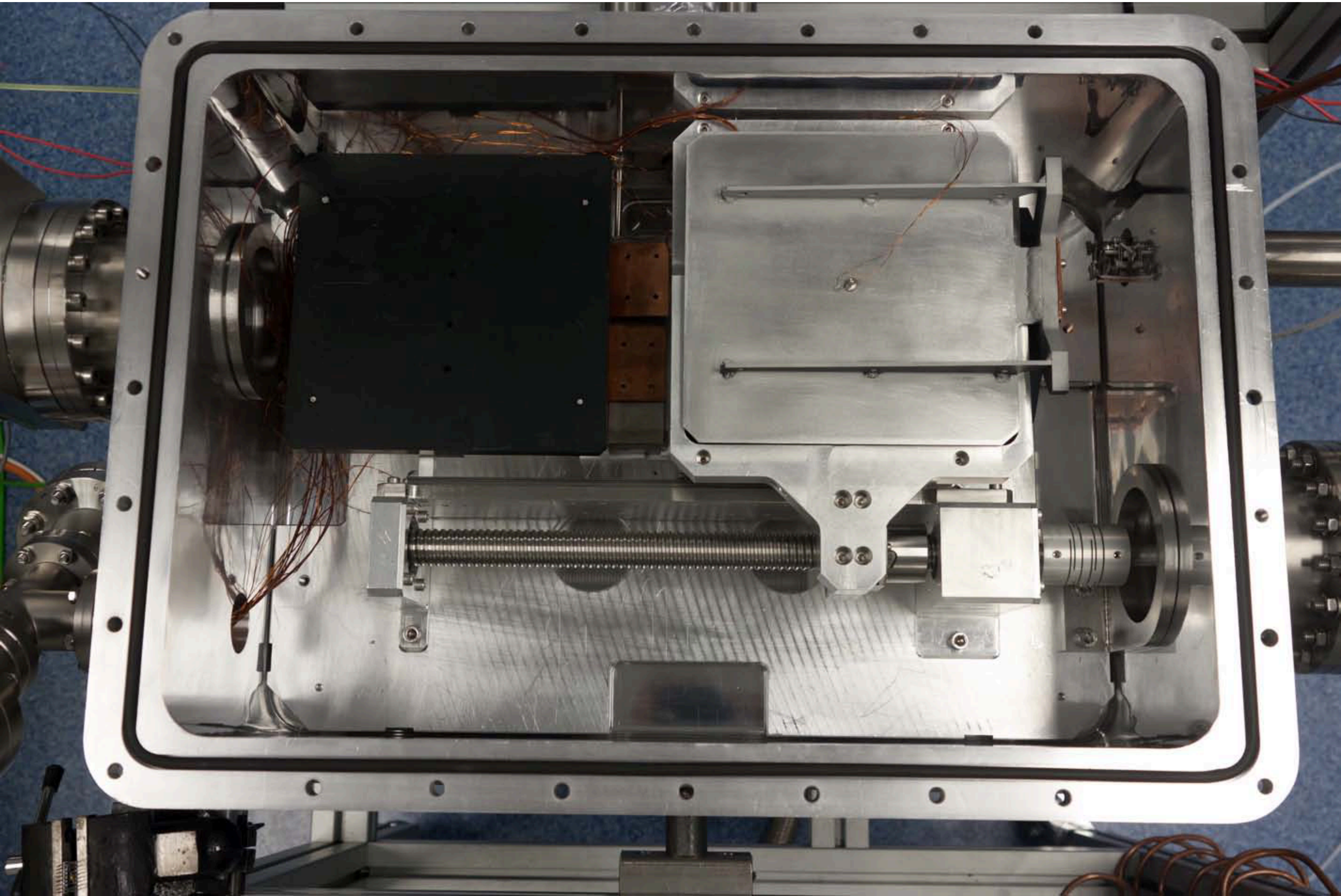
Construction of the PAU camera is well under way:

- Mechanical, vacuum and cryogenic challenges solved. Camera body just built. Vacuum tests about to start.
- CCDs in hand, being characterized. Filters being ordered.
- Control system hardware in hand, software being written.

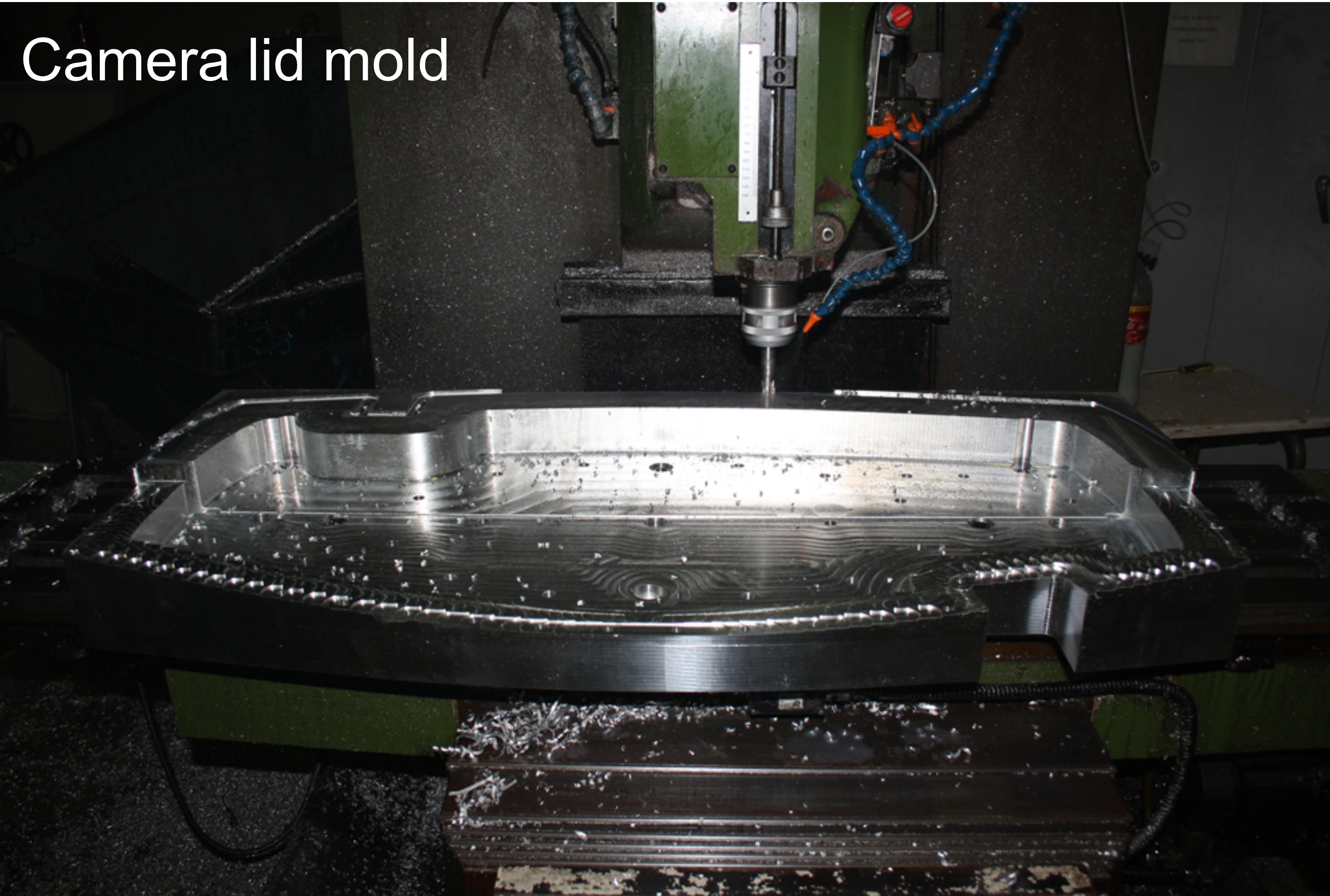
First protoype (summer 2011)



First protoype (summer 2011)



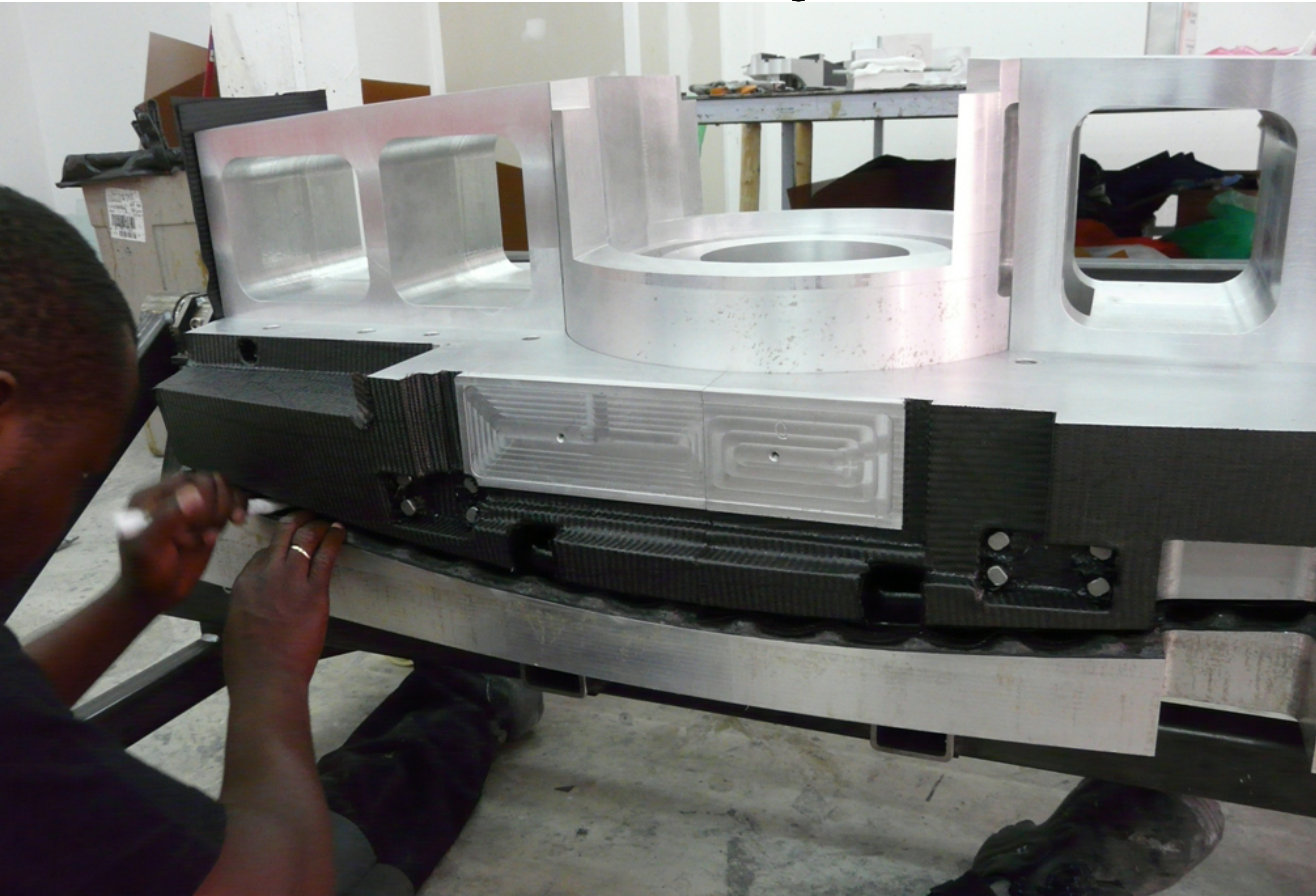
In-house fabrication of camera mold in Al



Mold pieces

Complete mold

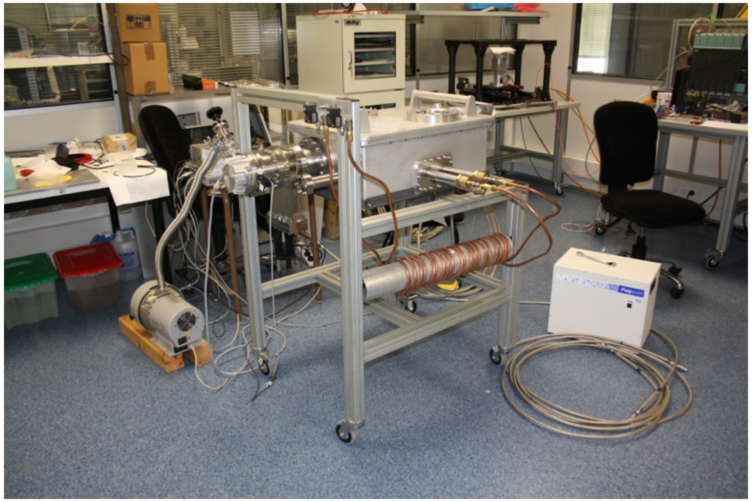
Mold covering



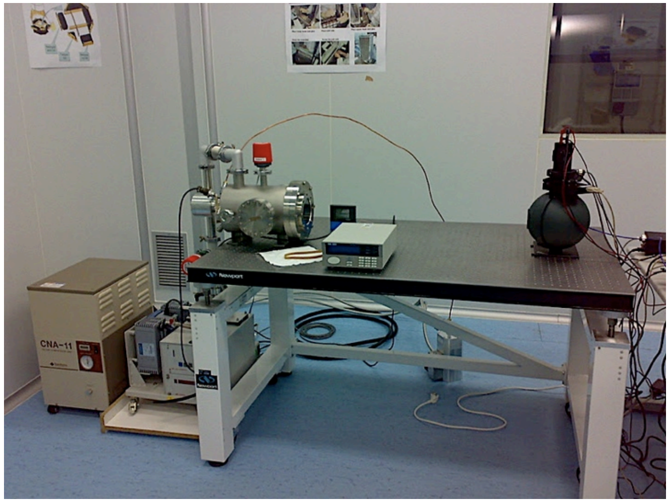
Camera body in carbon fiber

PAU Camera Construction

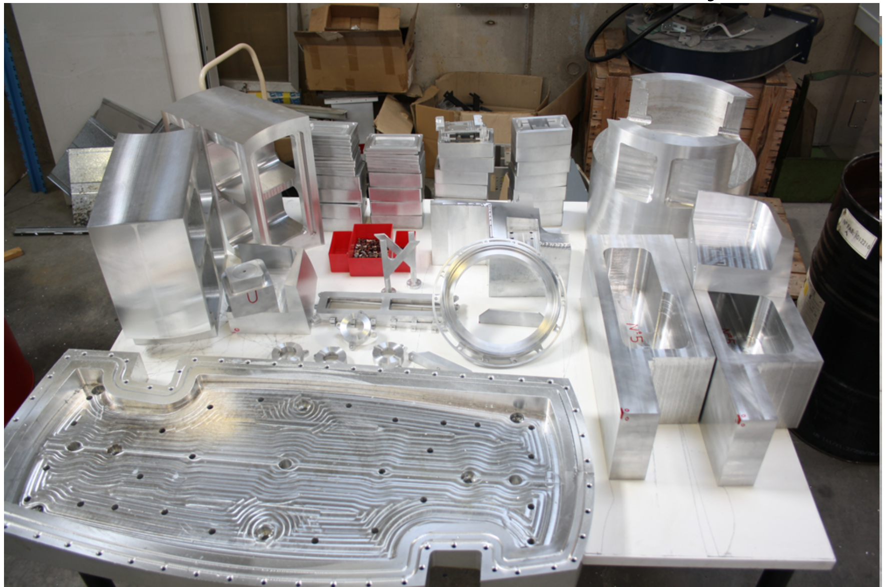
Cryogenics and vacuum tests on prototype



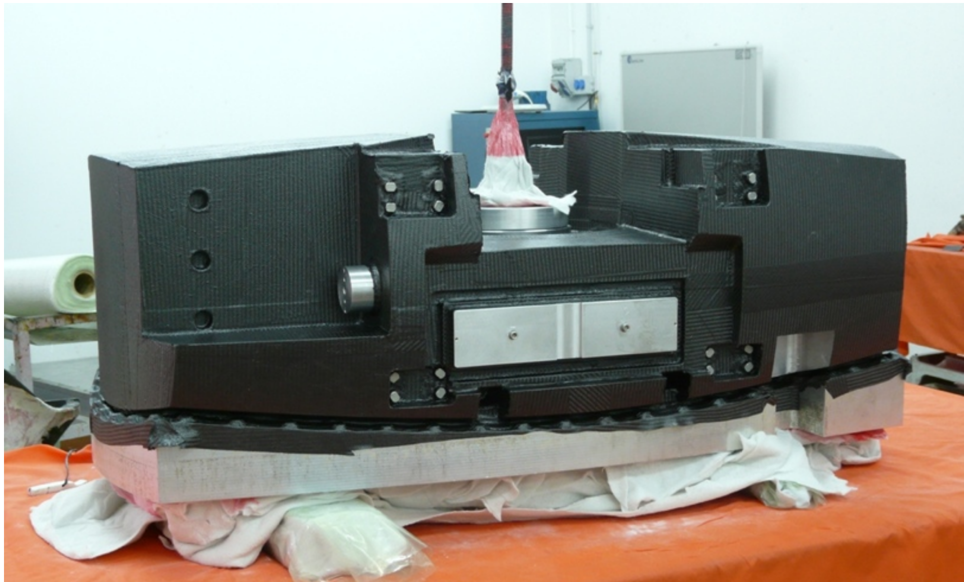
CCD test station



Aluminum mold of camera body



Camera body in carbon fiber

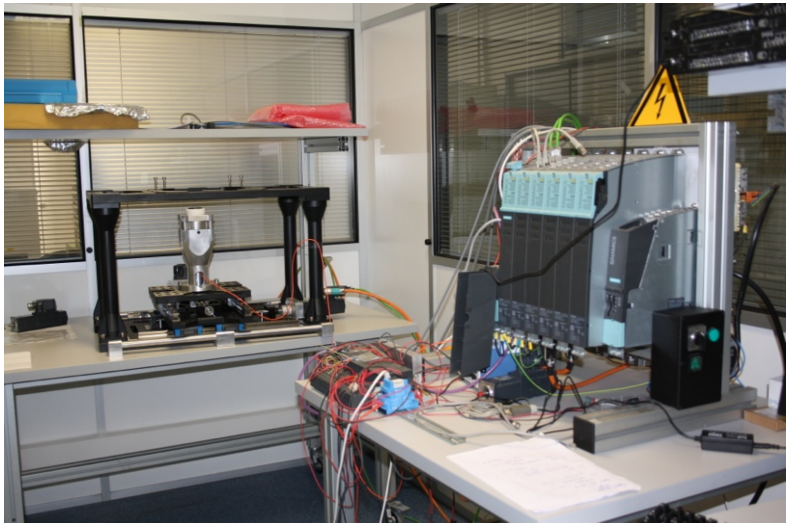


PAU Camera Construction

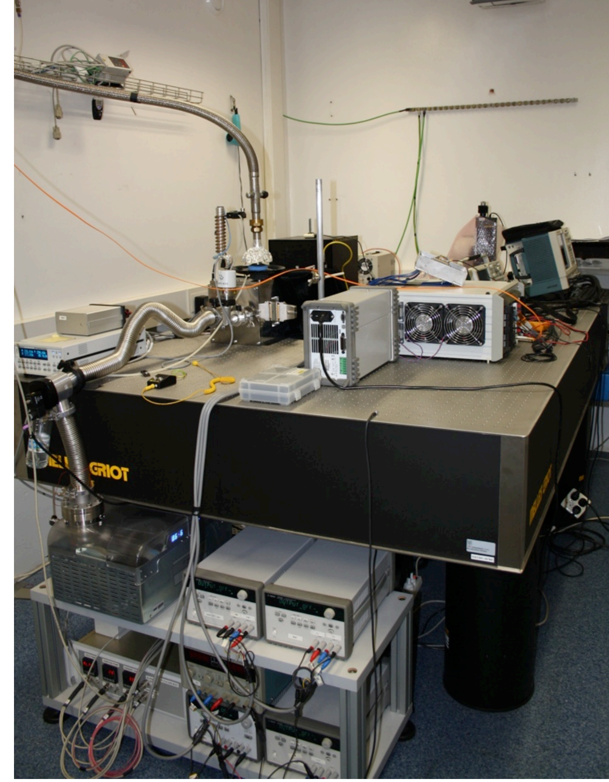
Many other elements of the camera are either ready or being fabricated. Examples:

- Optics (entrance window): study done by FRACTAL. Ordered.
- Shutter: design ready, contract will go out soon.
- Cryotigers: one received, first tests show excellent behavior.
- Assembly done in house. New clean room (a crucial infrastructure) is ready.

Lab Infrastructure for DES/PAU



3D metrology bench

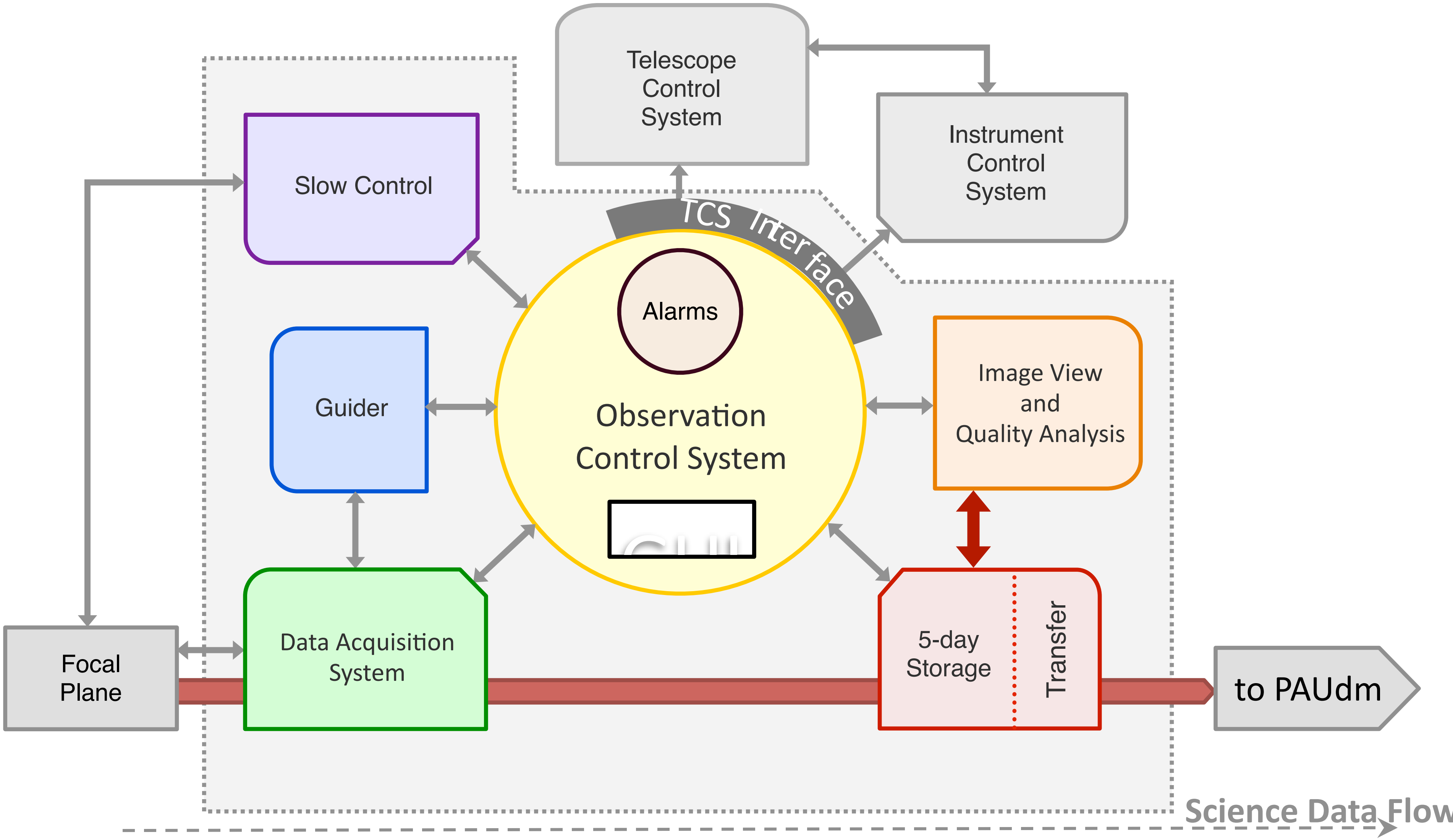


CCD test station

Clean room class 10K, 1K, 100

Fully computerized machining tool (lathe)

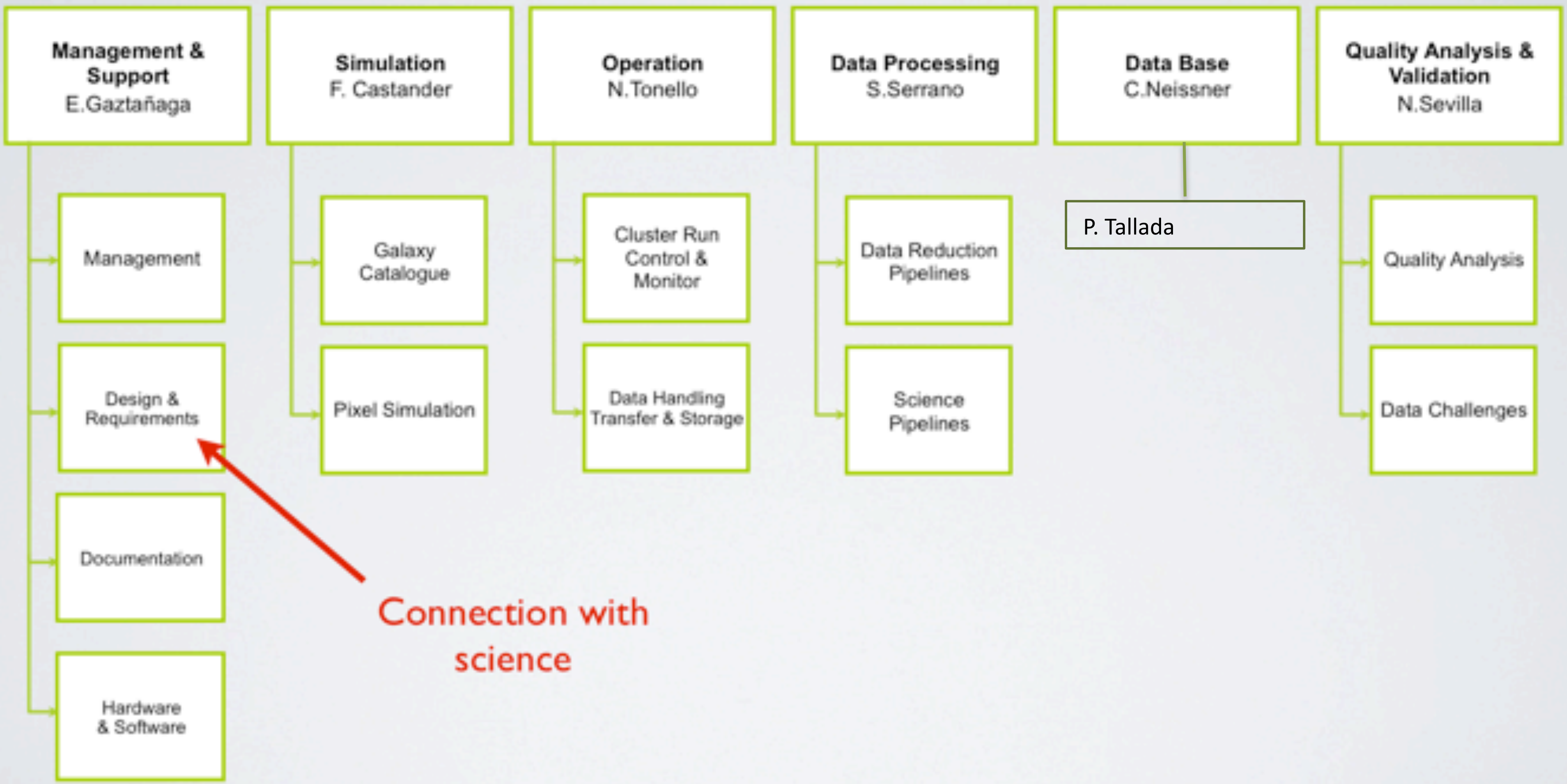
PAUCam Control System



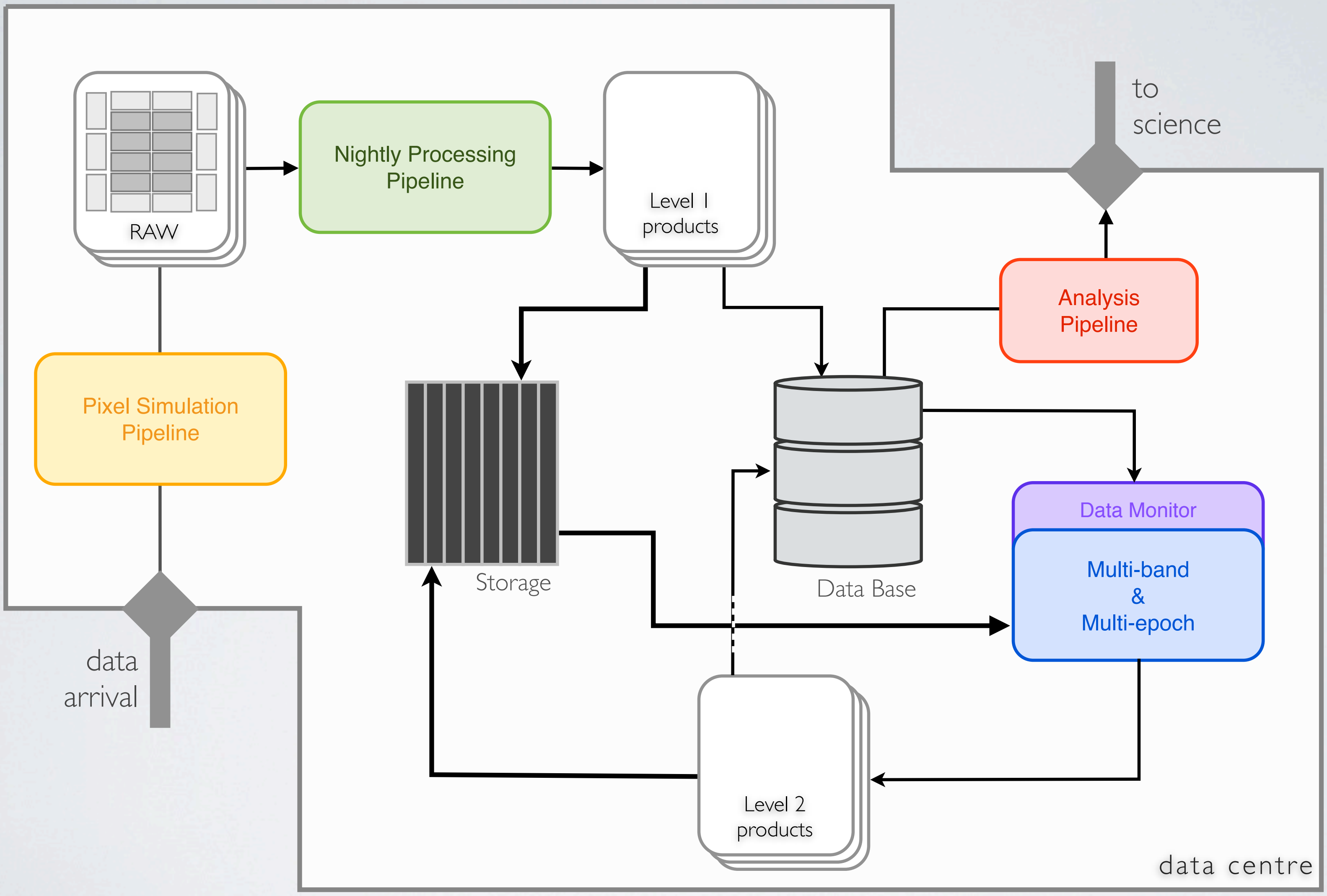
One computer already installed at the WHT. Tests of interface are already taking place.

Data Management System

PAUdm Working Packages

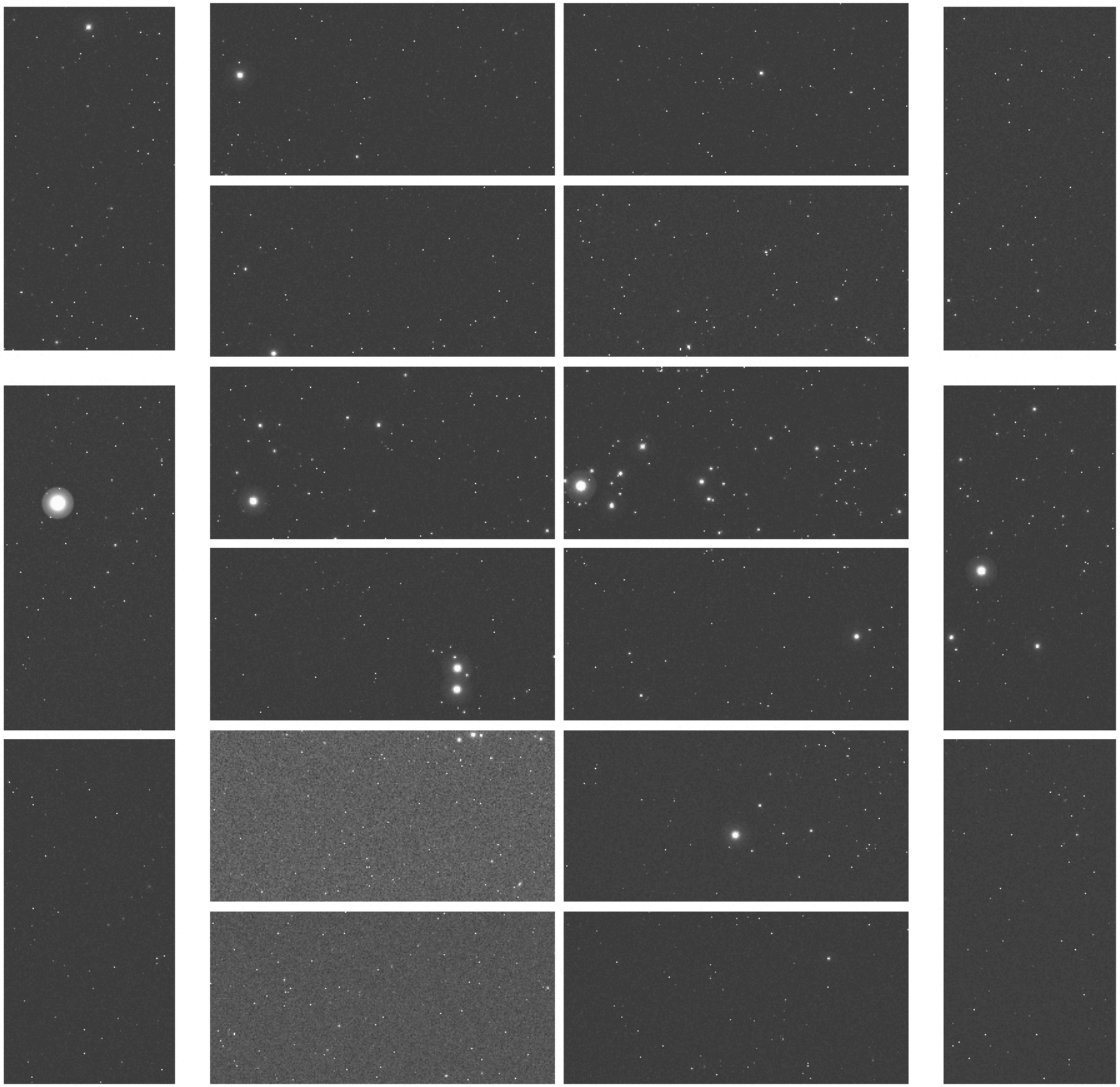


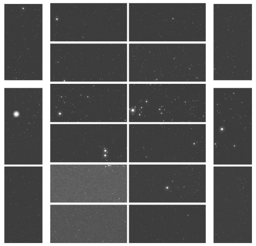
Pipelines



RAW
Nightly Processing Pipeline
Level 1 products
to science
Analysis Pipeline
Pixel Simulation Pipeline
Storage
Data Base
Data Monitor
Multi-band & Multi-epoch
data arrival
Level 2 products
data centre

PAUCam Simulations

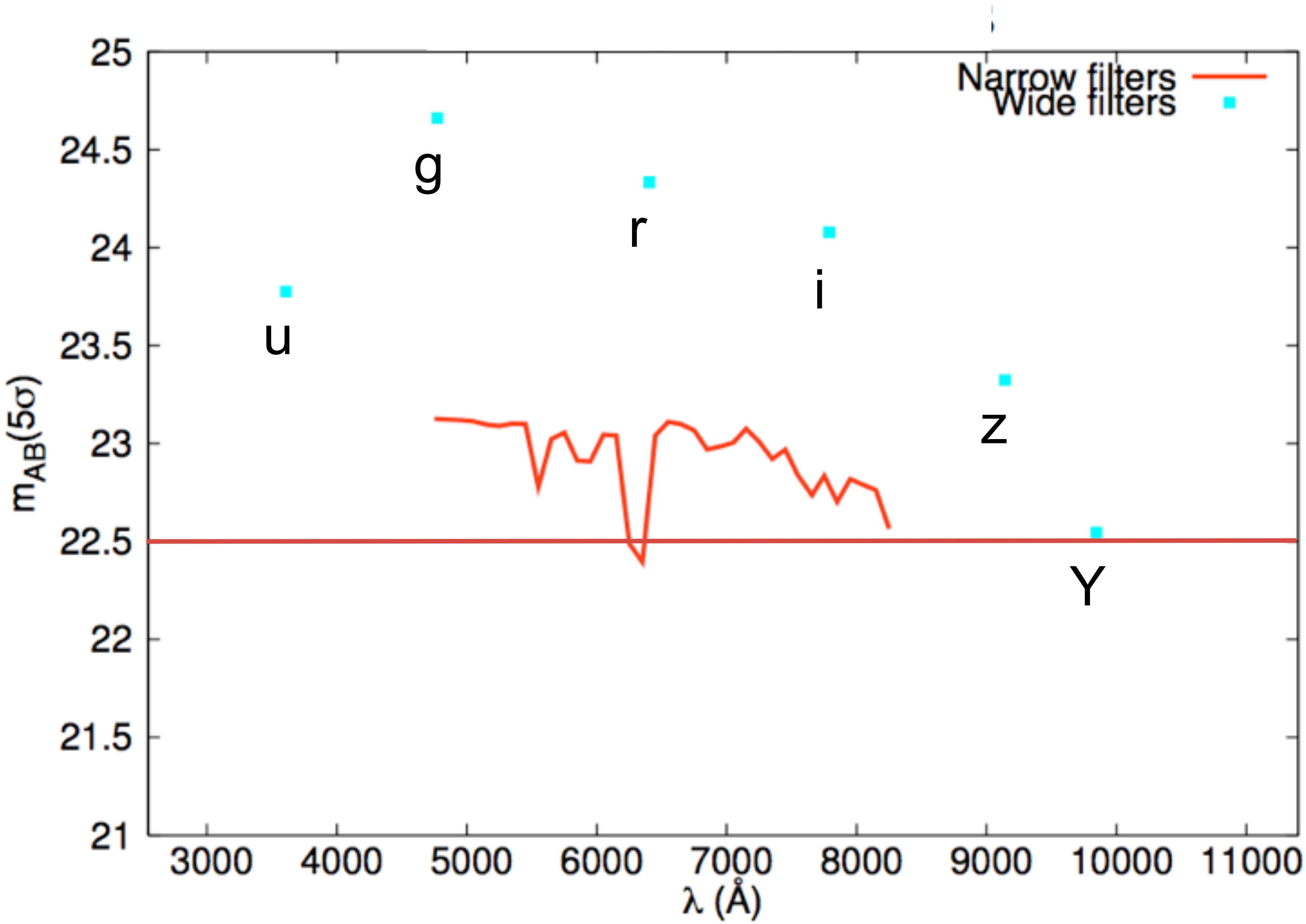




PAU Survey Strategy

- Use 8 central CCDs to define the survey footprint, use the other CCDs to increase S/N.
- Each central CCDs covers the whole survey area twice.
- 6 filters trays with 8 central filters (7 NB + 1 BB).
- Broad bands reach ~1.4 magnitudes deeper than narrow bands.
- Detect objects in the broad bands, and then get flux in the narrow bands.
- Push to low signal to noise.
- Surveying capability: sample 2 deg^2 / night to $i_{AB} < 22.7$ mag in all NBs and $i_{AB} < 24.1$ in all BBs ➜ >30000 galaxies / night
- Exposure times depend on tray: ~100 s for bluest, ~250 s for reddest.
- No selection effects.

Limiting Magnitudes (5σ)



2 exposures of ~100 s. Total time: 2 x 4174 s

PAU Science

- Survey strategy produces two samples:
  - "Spectroscopic" sample: excellent photo-z's with NB filters to $i_{AB} < 22.7$
  - "Photometric" sample: medium photo-z's with BB filters to $i_{AB} < 24.1$
- Science case depends on amount of time available
- Current science case, assuming 100 nights (200 deg^2):
  - Use bright sample for redshift-space distortions (typical of spectroscopic surveys)
  - Use faint sample for weak lensing magnification and/or shear (typical of imaging surveys)
  - Exploit the gains of cross-correlating both samples on the same area

Gaztañaga et al. 2012, MNRAS 422 2904 (astro-ph/1109.4852)

PAU Survey Samples

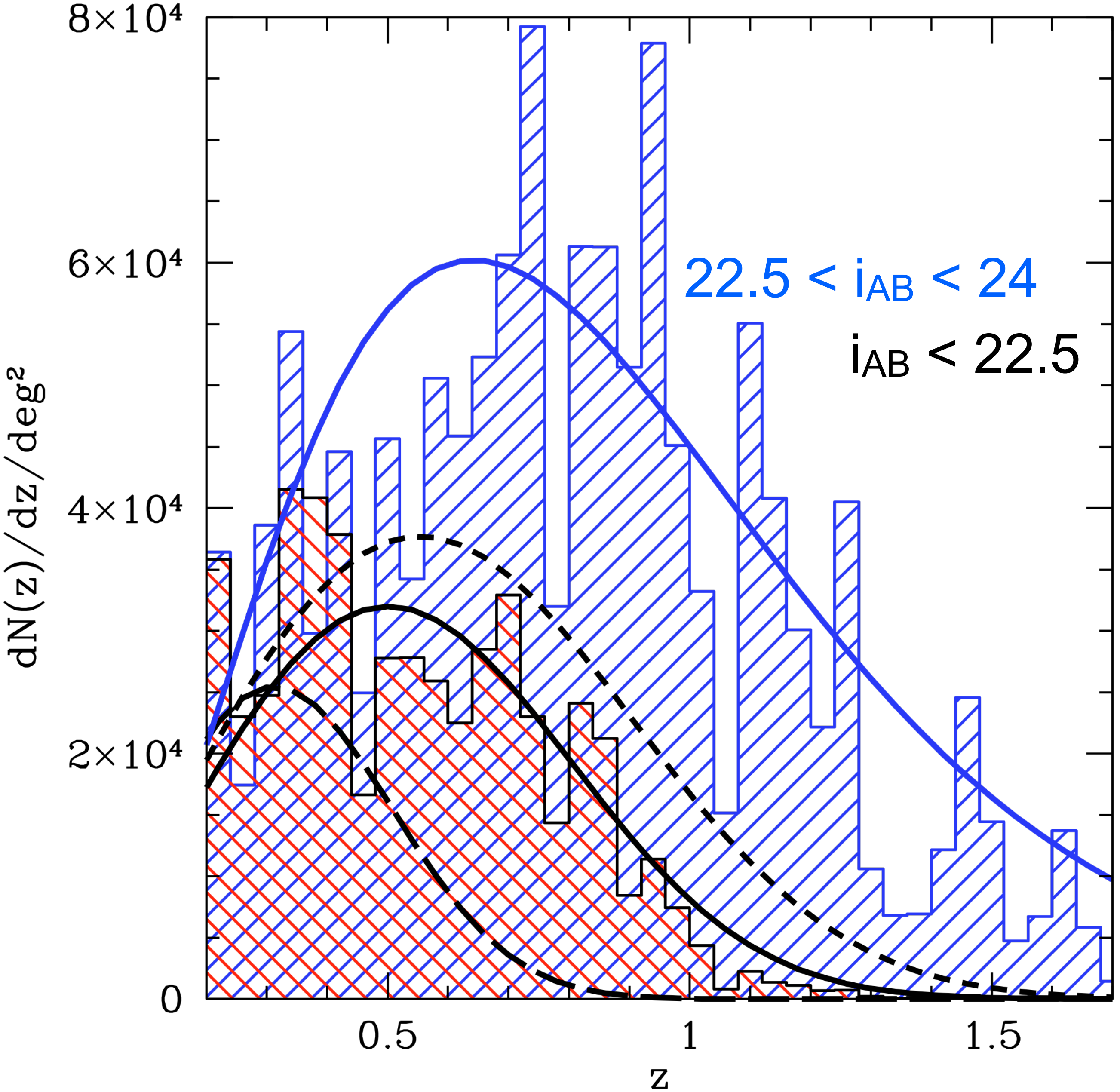
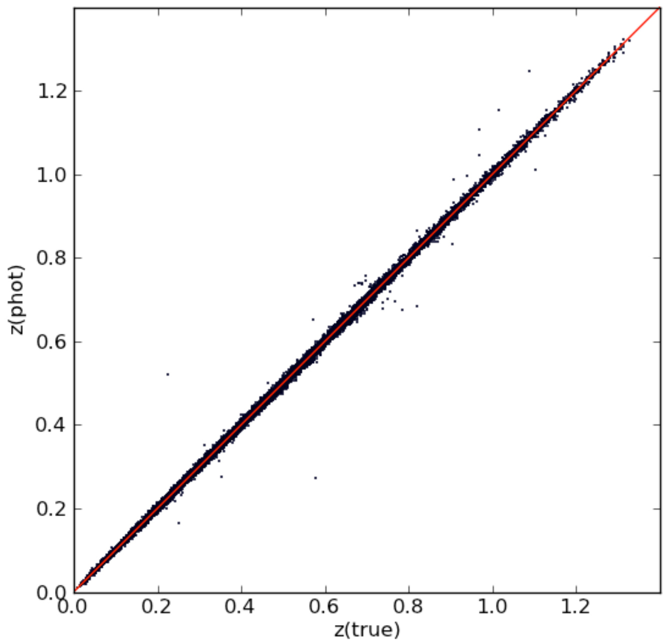
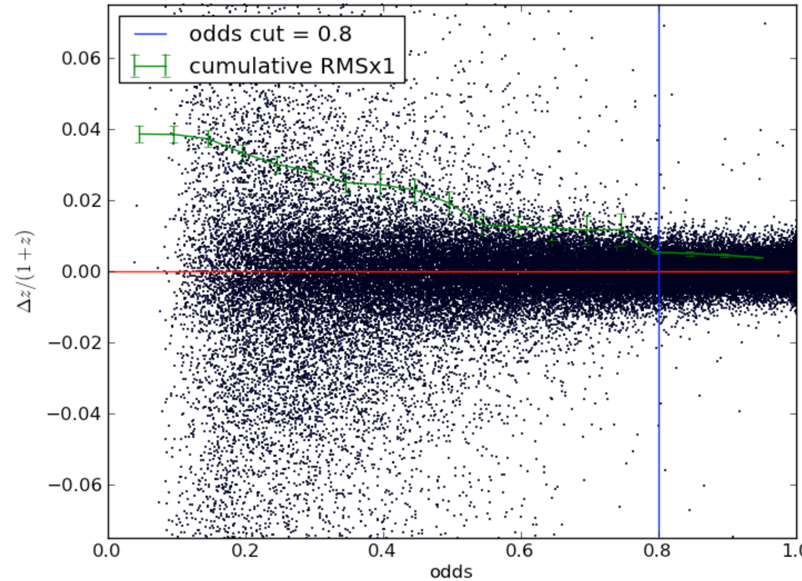
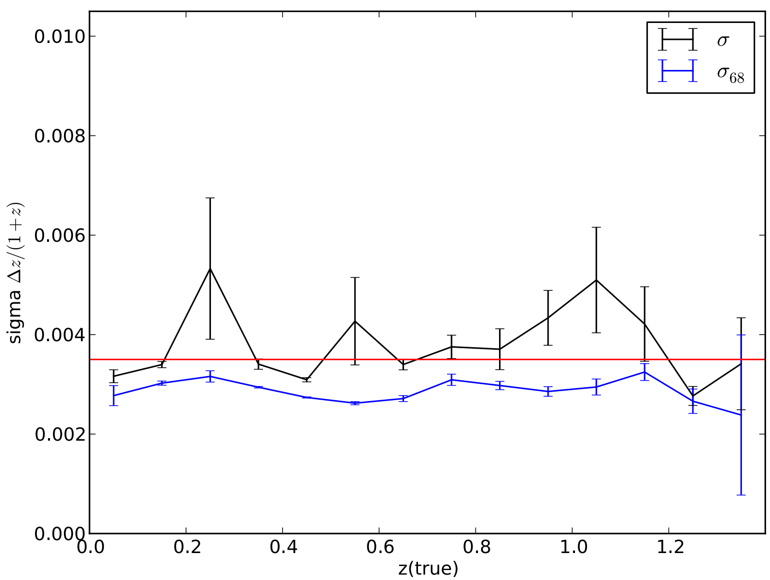


Photo-z Performance (Bright sample: i_{AB} < 22.5)







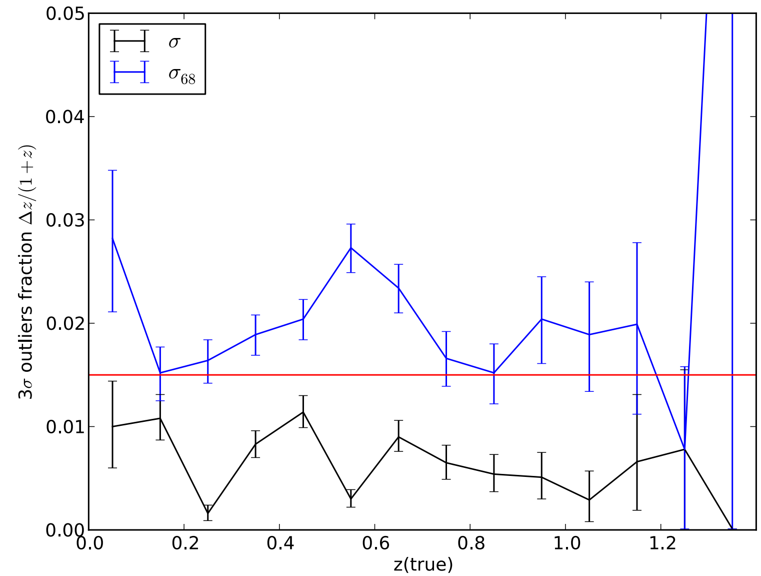
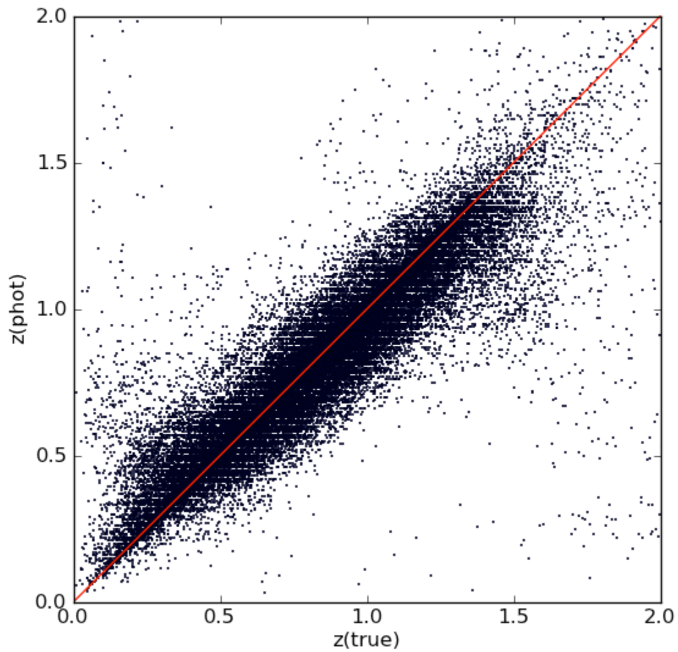
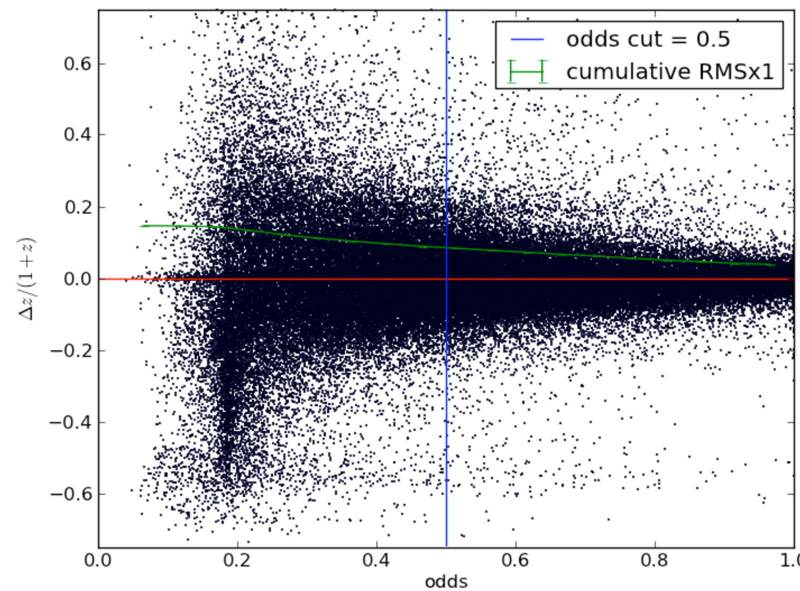
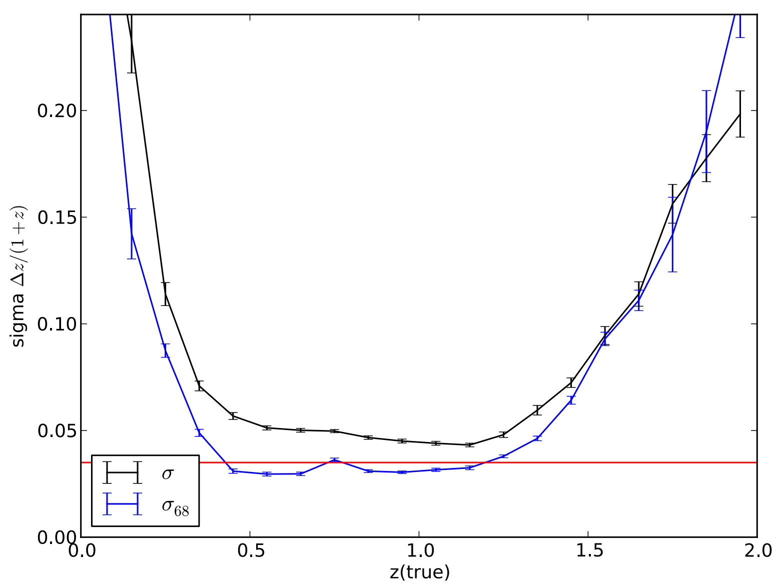
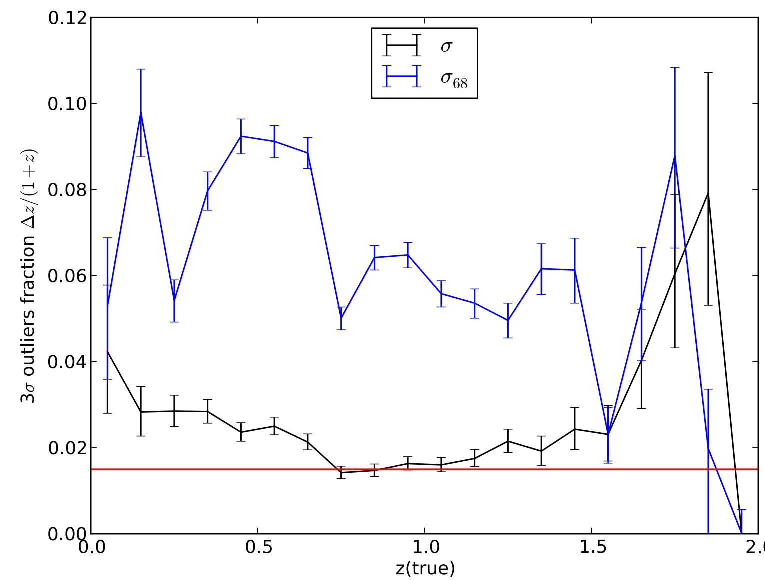


Photo-z Performance (Faint sample: 22.5 < i_{AB} < 24)



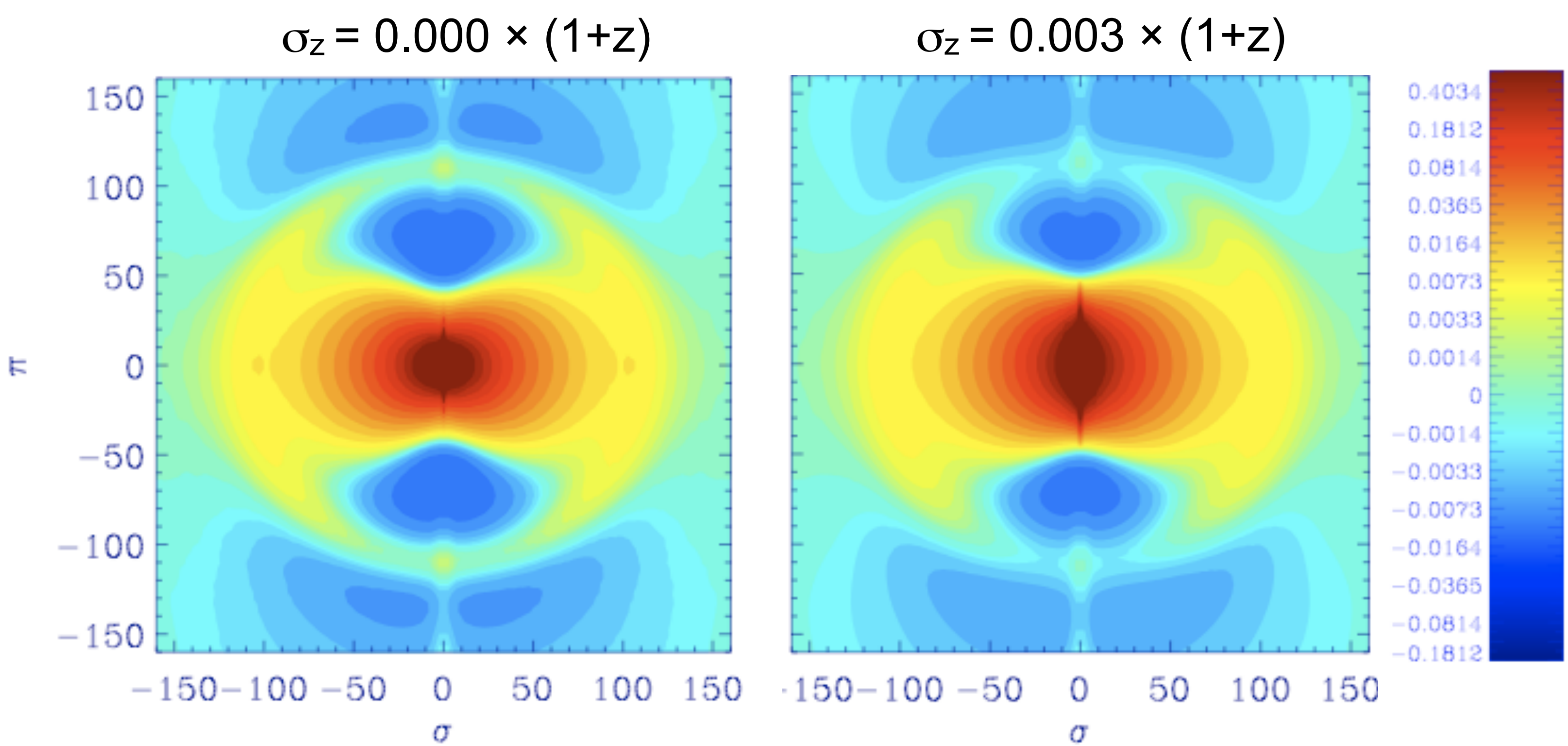


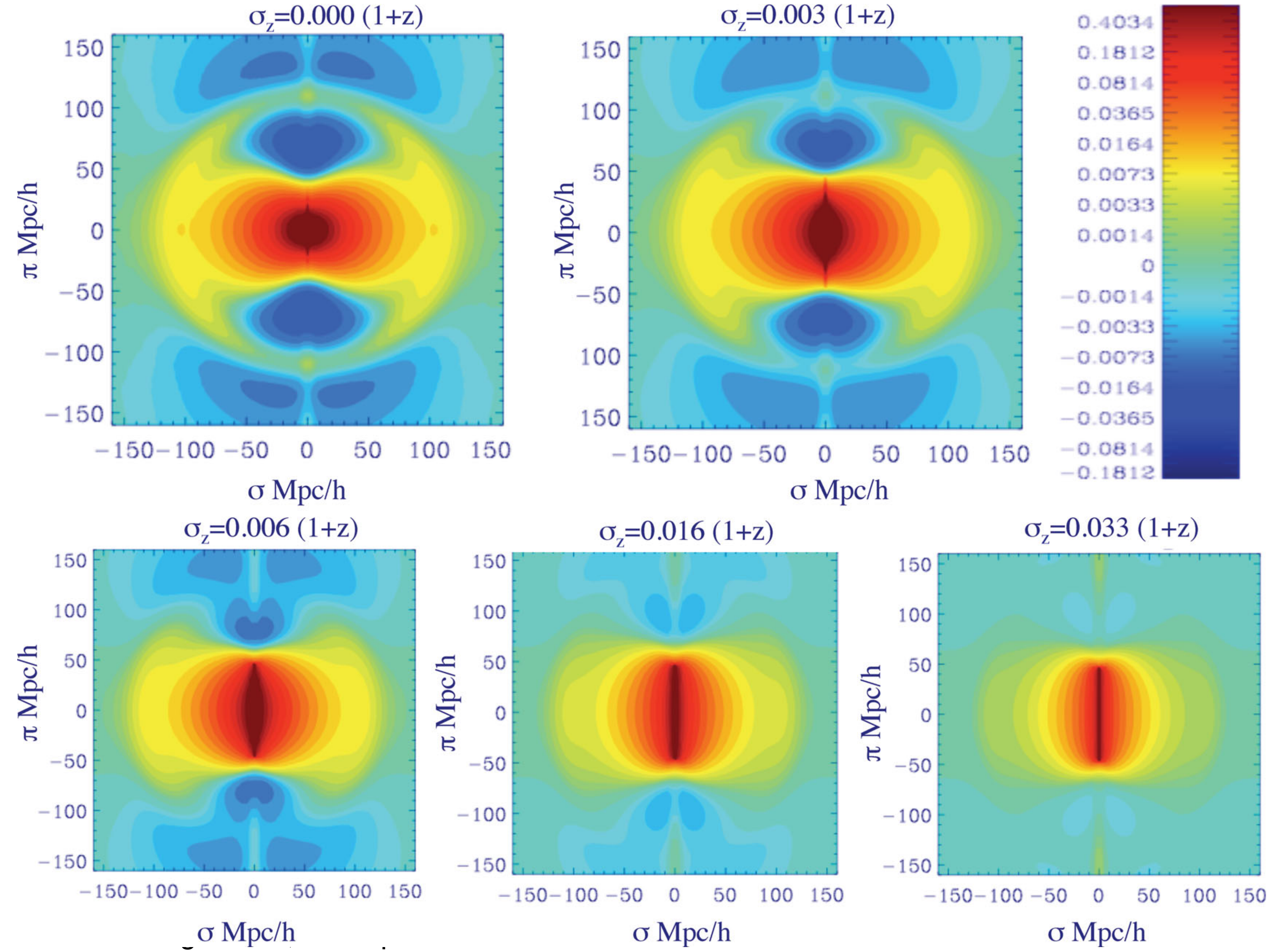




PAU's Primary Science Drivers (I)

- Redshift-space distortions (RSD):
  - Peculiar velocities of galaxies trace the matter density fields.
  - Anisotropies in the galaxy 2-point correlation function measure the growth of structure at a given redshift: probe of dark energy.
  - Relevant scales are ~10 Mpc/h, well matched to PAU's z precision.



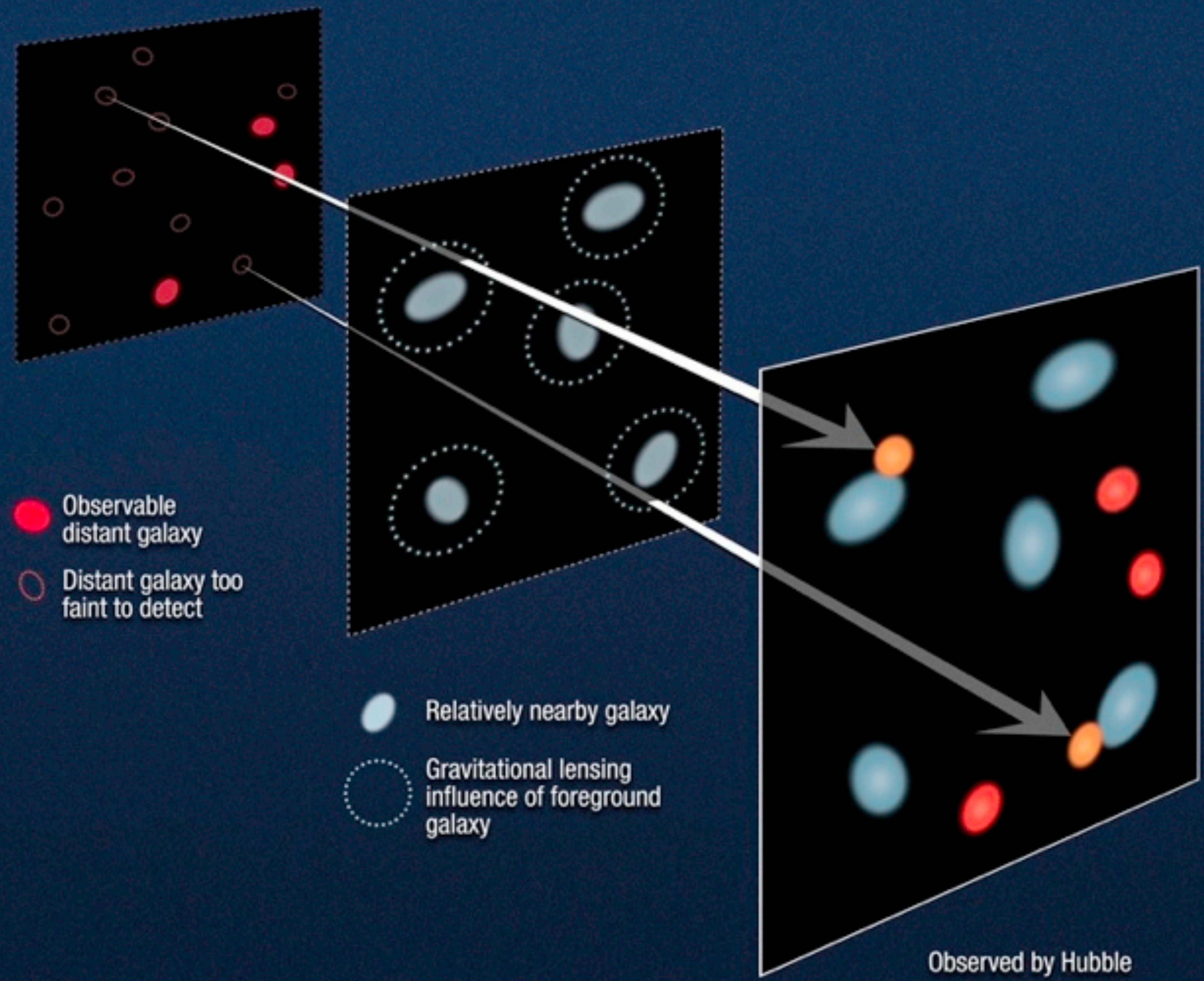


σz=0.000 (1+z)
σz=0.003 (1+z)
σz=0.006 (1+z)
σz=0.016 (1+z)
σz=0.033 (1+z)
π Mpc/h
σ Mpc/h
150
100
50
0
−50
−100
−150
0.4034
0.1812
0.0814
0.0365
0.0164
0.0073
0.0033
0.0014
0
−0.0014
−0.0033
−0.0073
−0.0164
−0.0365
−0.0814
−0.1812

PAU's Primary Science Drivers (II)

- Lensing magnification (MAG):
  - Gravitational lensing affects the measured galaxy number density.
  - Main observable is the cross-correlation between galaxies in different redshift bins as a function of angular separation.
  - Very precise photo-z's allow PAUCam to perform **cross-correlations between well-defined narrow redshift bins.**

- Combination of RSD and MAG includes:
  - 3D galaxy clustering, which is degenerate with galaxy bias.
  - Weak lensing magnification, which is unbiased.
  - Redshift-space distortions, which also measure bias, and growth.
  - Probes dark energy through both growth of structure and geometry.



Credit: NASA, ESA, Z. Levay and A. Field (STScI)

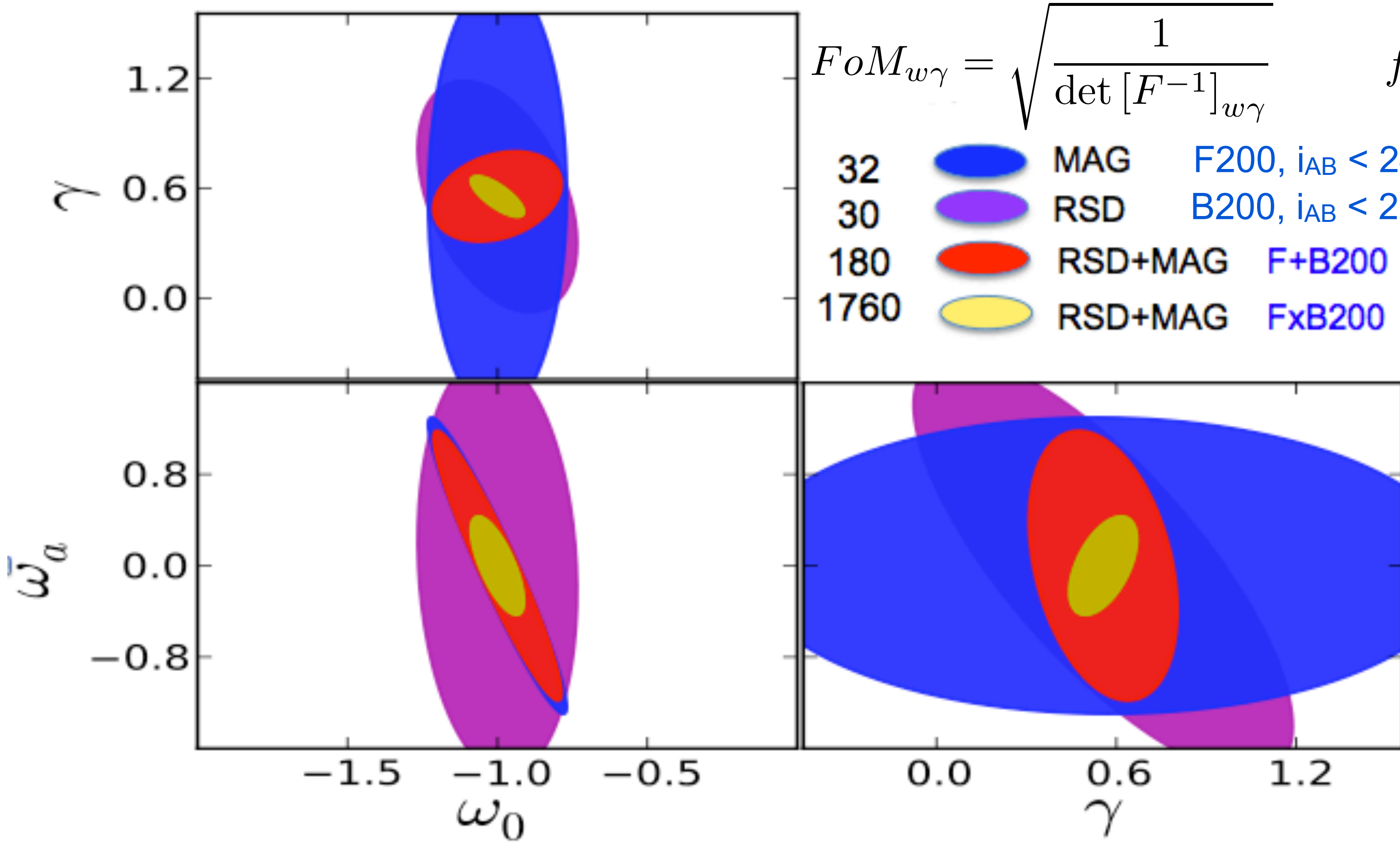
PAU Survey Science Reach

- 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.**

- **Figures of merit** with free Ω_m, Ω_{DE}, h, σ_8, Ω_b, w_0, w_a, γ, n_s, 4 bias parameters.

$$FoM_{w\gamma} = \sqrt{\frac{1}{\det\left[F^{-1}\right]_{w\gamma}}}$$

$$f = \frac{d\log D}{d\log a} = \Omega_m^{\gamma}(z)$$



(including Planck and stage-II SNe priors)

E. Gaztañaga, M. Eriksen, M. Crocce, F. Castander, P. Fosalba, P. Martí, R. Miquel, A. Cabré, MNRAS 422 (2012) 2904

Other Science

- Baryon Acoustic Oscillations
- Large Scale Structure
- Galaxy clusters
- Galaxy evolution
- Quasars and the Lyα forest
- Multiply imaged gravitational lenses
- High redshift galaxies
- Low surface brightness galaxies
- Intergalactic dust
- Halo stars
- Local group stars
- Brown dwarfs and cool stars
- Exoplanets
- ....

Summary

- Construction of PAUCam is well under way.
  - Mechanical, vacuum and cryogenic challenges solved. Camera body in carbon fiber just received, being tested.
  - CCDs in hand, being characterized. Filters being ordered this month.
  - Control system hardware in hand, software being written.
- Data management system designed, being written.
- An MoU with ING was signed earlier this year.
  - MoU contemplates ample time allocation for the survey (for a price...).
- Compelling science case based on complementarity of spectroscopic and imaging characteristics.
- Everything is on schedule to have first light in **early 2013**. The survey will start soon thereafter. **The PAU camera at WHT will be the most powerful imaging instrument at El Roque.**