IFAE

SI defense:
DE Cosmology
&
Tests of DES Charge Coupled Devices

Treball de recerca de 3er cicle del programa de Doctorat en Física

sota la direcció del Dr. Ramon Miquel i el Dr. Manel Martínez

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Universitat Autònoma de Barcelona

Outline

- DE introduction
- The Dark Energy Survey
- The SLAB
- DES CCDs
- Tests
- Conclusions

- DE -> Modern & unknown

DE ~ expansion

- Universe expanding
  - Observational evidence from supernovae for an accelerating universe and a cosmological constant (A.Riess et al., 1998)
  - Measurements of Ω and Λ from 42 high redshift supernovae. (S. Perlmutter *et al.*, 1999)

They found that the expansion rate of the Universe is increasing with time studying type-Ia supernovae. 10-15% larger than expexted

Something has to be taken into account…

- Einstein wanted a static universe.

  GR don't permit it (Matter attracts gravitionally)

  He added a term (*cosmological constant*) to arrange a static UNI

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \boxed{- \Lambda g_{\mu\nu}} = 8\pi G T_{\mu\nu}$$

  Hubble law -> expansion -> problem!

DE: we don't know what it is but it has to be there

- Cosmological principle: Universe is isotropic and homogeneous (on large scales)

- Metrics: equation which gives the distance between two points
  - SR -> Minkowsky metric

$$ds^2 = -c^2 dt^2 + dr^2 + r^2 d\Omega^2$$

  - GR -> Robertson-Walker metric

$$ds^2 = -c^2 dt^2 + a(t)\left[dr^2 + S_k(r)^2 d\Omega^2\right]$$

t: cosmic time

r: comoving coordinates

a: scale factor -> expansion or contraction

Dynamics: relations between curvature & content

i: matter, radiation

- *Friedmann equation*. Rel. among a(t), k, ε(t) & R_0

$$H(t)^2 = \frac{\dot{a}(t)^2}{a(t)^2} = \left(\sum_i \frac{8\pi G}{3c^2} \varepsilon_i(t) \right) - \frac{kc^2}{R_0^2 a(t)^2}$$

- *Fluid equation*. Rel. among a(t), ε(t) & P(t)

$$\sum_i \dot{\varepsilon}_i + 3\frac{\dot{a}}{a}(\varepsilon_i + P_i) = 0 \longrightarrow \varepsilon_i = \varepsilon_{i,0} a^{-3(1+w)}$$

- *Acceleration equation*. Rel. among a(t), ε(t) & P(t)

$$\frac{\ddot{a}}{a} = \sum_i -\frac{4\pi G}{3c^2}(\varepsilon_i + 3P_i)$$

- *Equation of state*. Rel. between ε(t) & P(t)

$$P_i = w_i \varepsilon_i \qquad \text{where } w_i < 1$$

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DARK ENERGY

$w_{DE} < -1/3$

Λ

$w_\Lambda = -1$

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$$\Omega_i = \frac{\varepsilon_i}{\varepsilon_C}$$

- *Fluid equation*. Rel. among a(t), ε(t) & P(t)

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_M}{a^3} + \frac{\Omega_R}{a^4} + \frac{\Omega_{DE}}{a^{3(1+w)}} + \frac{1-\Omega_o}{a^2}$$

$$\sum_i \dot{\varepsilon}_i + 3\frac{\dot{a}}{a}(\varepsilon_i + P_i) = 0 \longrightarrow \varepsilon_i = \varepsilon_{i,0} a^{-3(1+w)}$$

$$\Lambda = -\frac{8\pi G}{c^2}\varepsilon$$

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New component

- Λ ~ fluid
- Λ has a negative effective pressure.

$$P_\Lambda = -\varepsilon_\Lambda = -\frac{c^2}{8\pi G}\Lambda$$

As UNI expands, work is done on Λ fluid. -> E_Λ remains constant

$$W = -\int P dV \longrightarrow$$ ***Energy of the empty space (vacuum)***

- Classical physics
  - ("Nothing can come from nothing." King Lear)
- Quantum physics
  - Fluctuations satisfying $\Delta E \Delta t \geq h$

E associated to the virtual particles

$$\varepsilon_{VAC} \sim \frac{E_P}{l_P^3} \approx 3 \times 10^{133}\, eV \times m^{-3}$$

$$\sim 10^{124}\, \varepsilon_{critical}$$

Theory and observations don't match

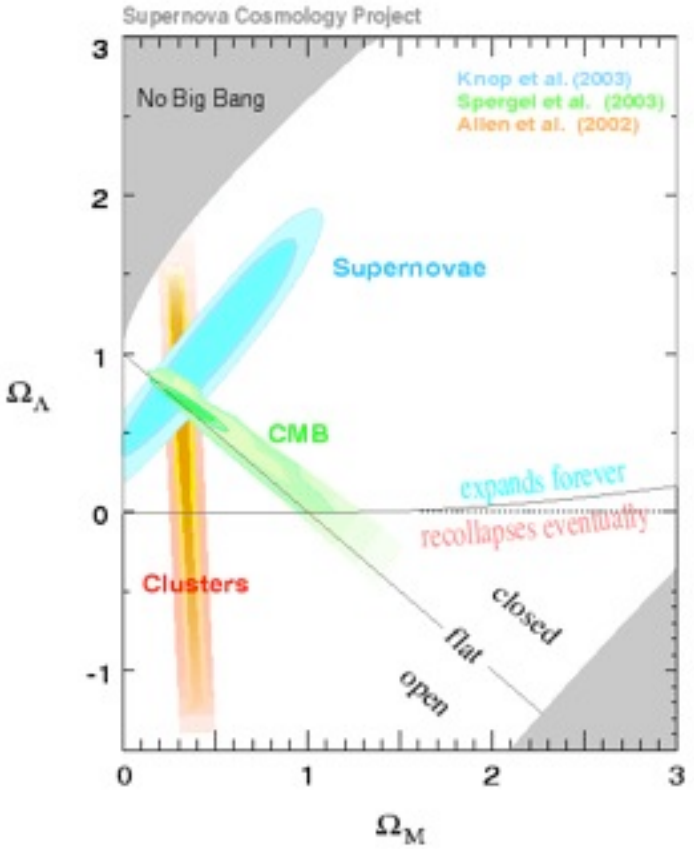
DE >> gravity

- Universe only with Λ (or Λ -dominated)

Friedmann equation $\dot{a}^2 = \frac{8\pi G \varepsilon_\Lambda}{3c^2} a^2 \longrightarrow a(t) = e^{H_0(t-t_0)}$

Universe exponentially expanding

Infinitely old, infinite horizon distance



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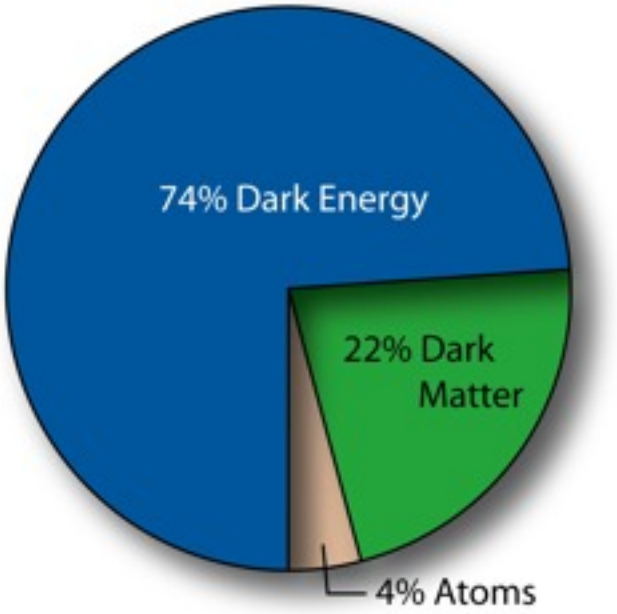
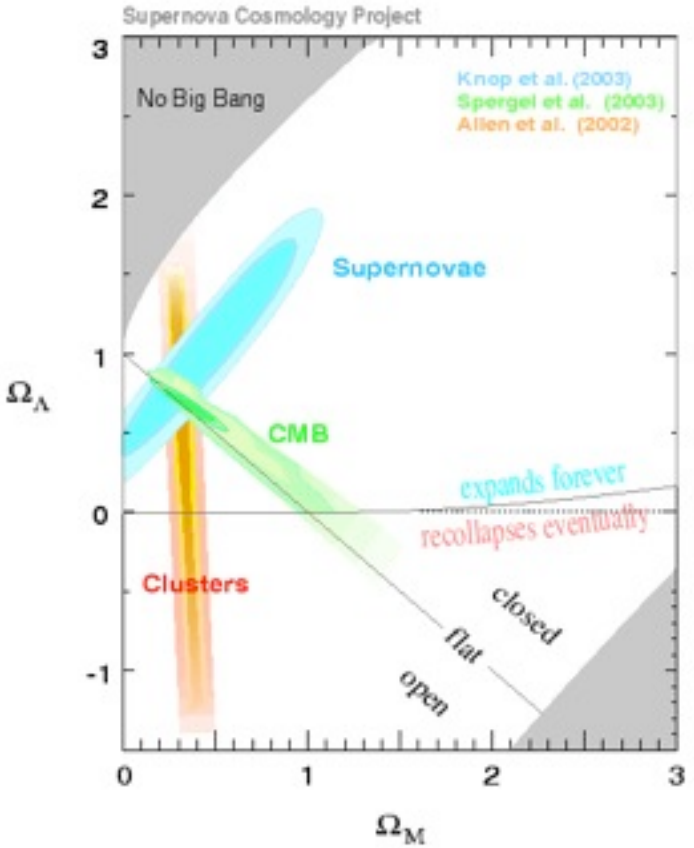


The best model is

$\Omega_M \approx 0.3$

$\Omega_\Lambda \approx 0.7$



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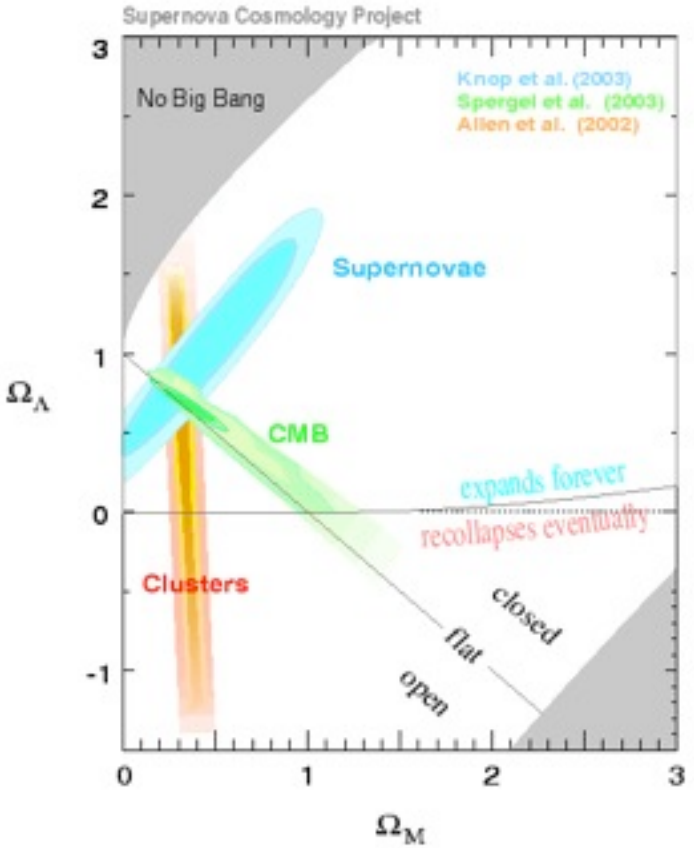

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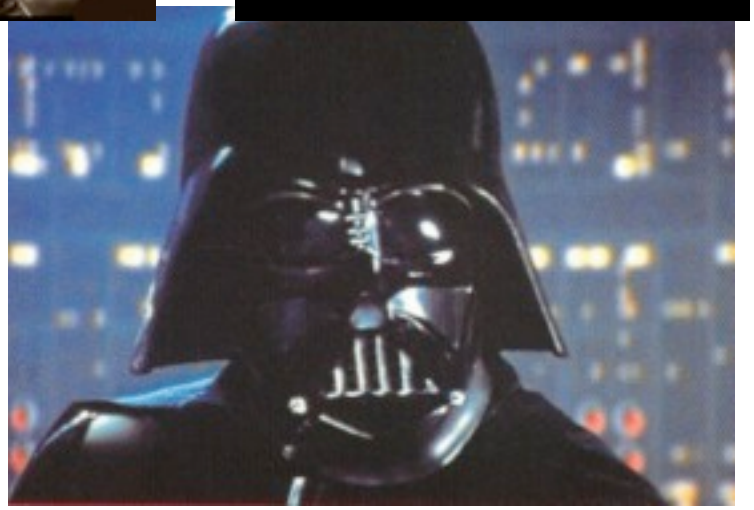

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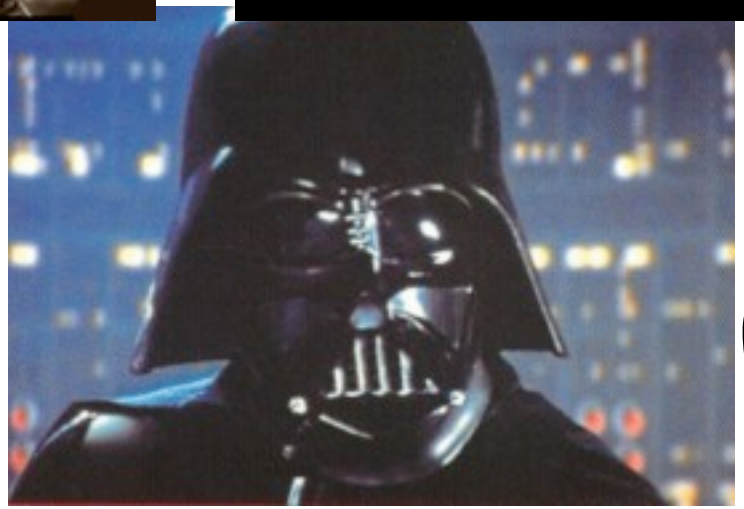

What can be?

- Transient phenomenon, which will disappear in the future
- Cosmological constant (ΛCDM model)
- Scalar field (quintessence). Λ is not constant, exhibits slow variation
- Modified gravity (Gauss-Bonet: extradimensions)

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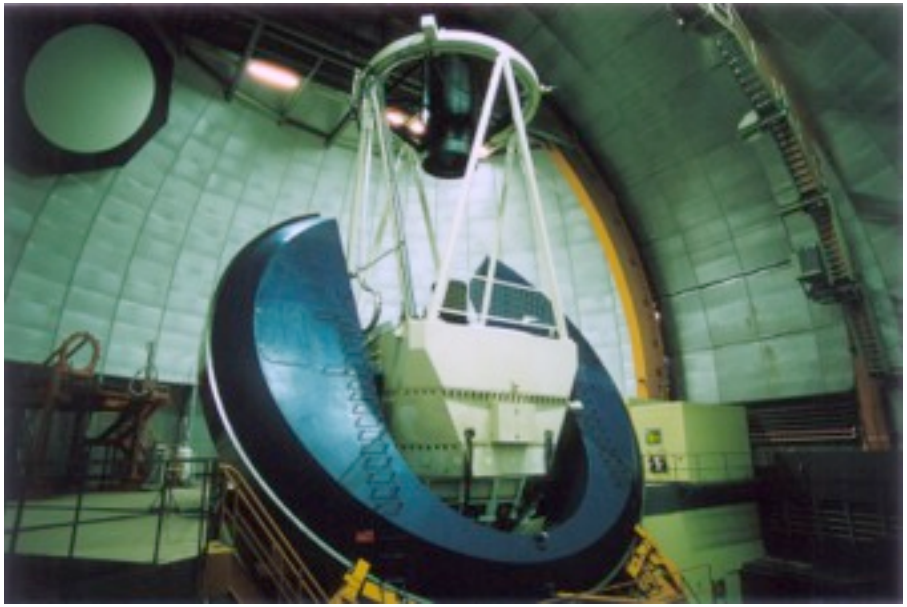
The Dark Energy Survey

· Optical & NIR survey

· Dark energy properties

$$P_{DE} = w\varepsilon_{DE}$$

· 4m Blanco telescope (CTIO-NOAO)



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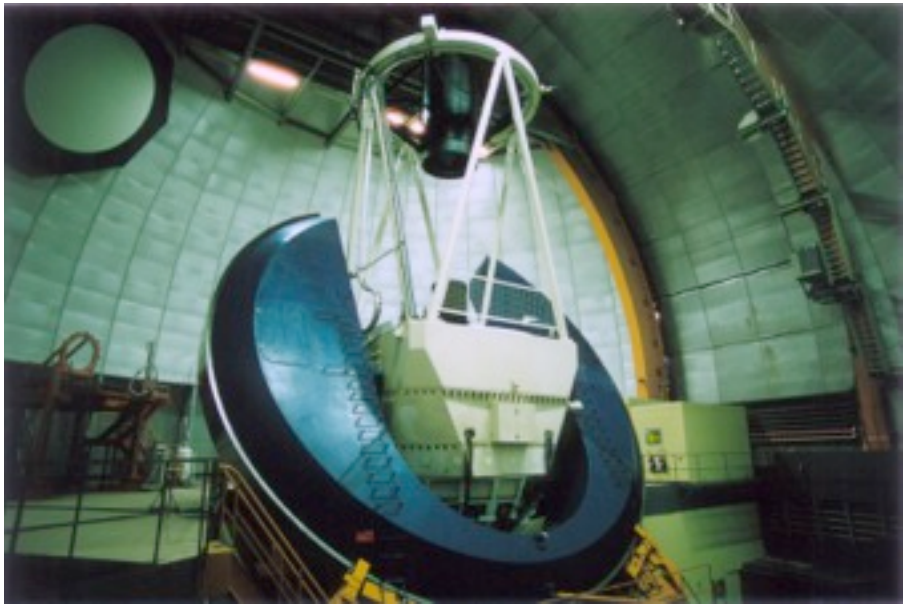

The Dark Energy Survey

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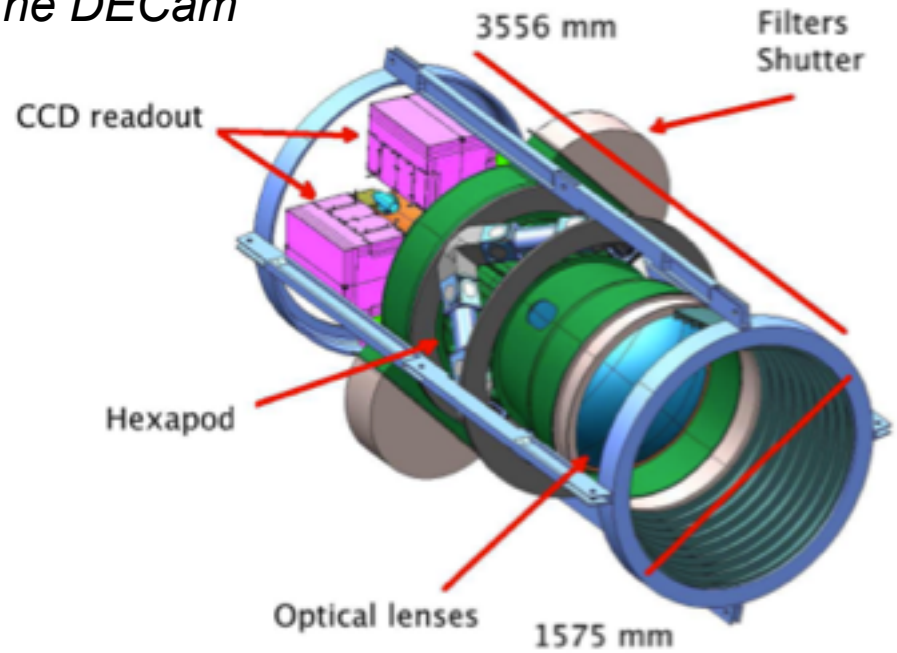
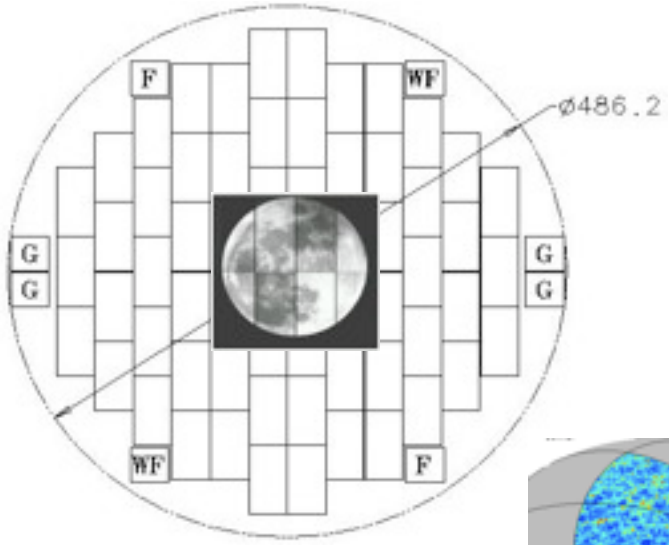
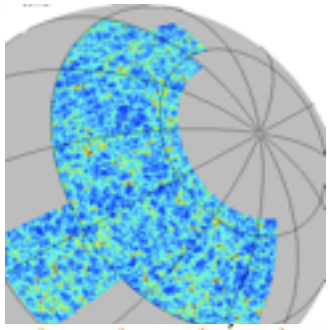
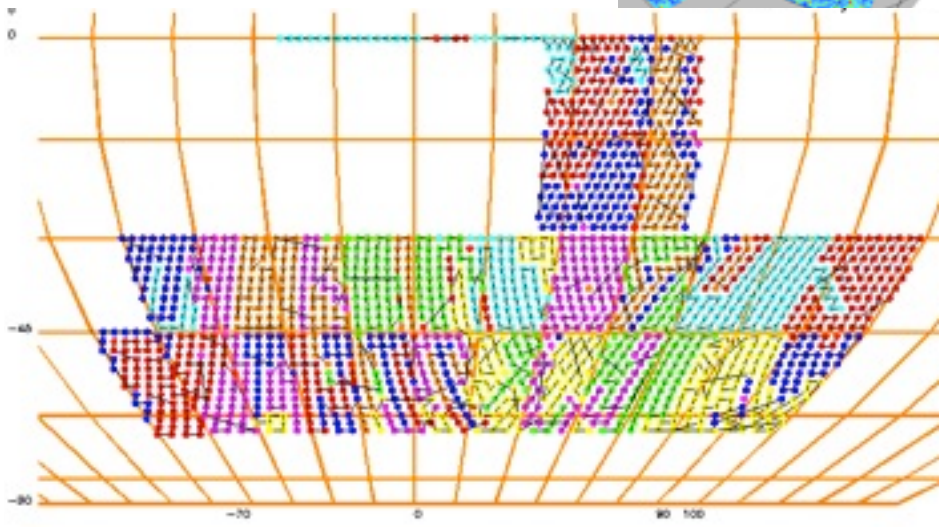






- CCD mosaic camera
- 3 sq deg field of view
- 62 LBNL CCDs (4k x 2k pixels)
- griZY filters
- 5000 sq deg

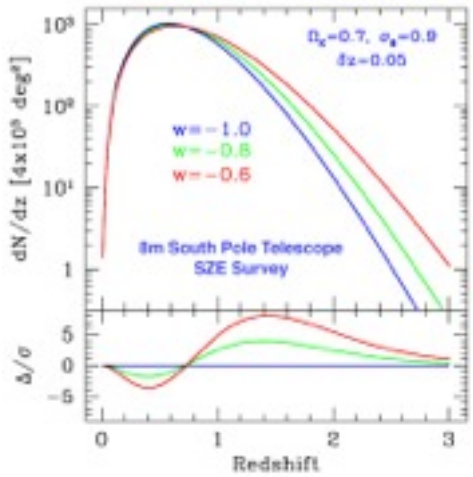
300 milion galaxies
15000 clusters
1200 SNIa



DES techniques

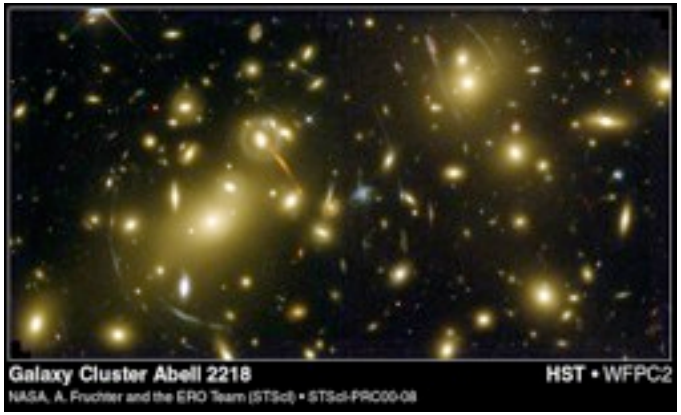
Galaxy clusters redshift distribution

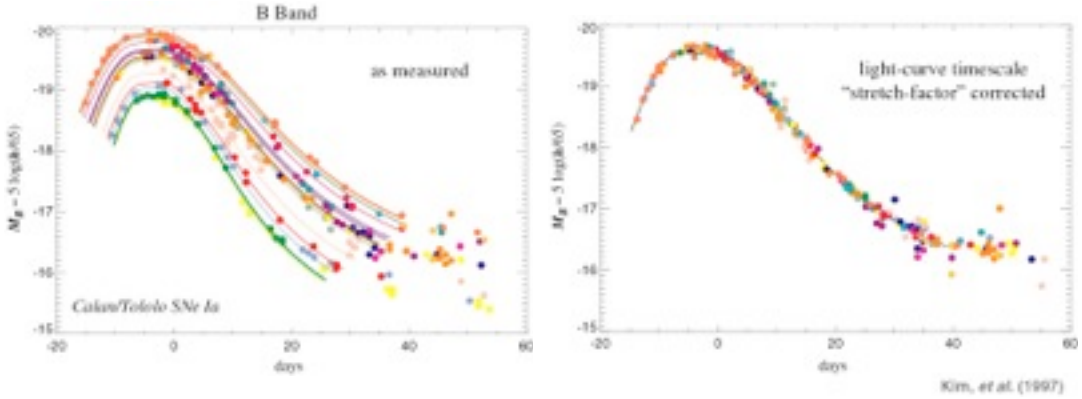
Galaxy cluster density mass function (SPT)



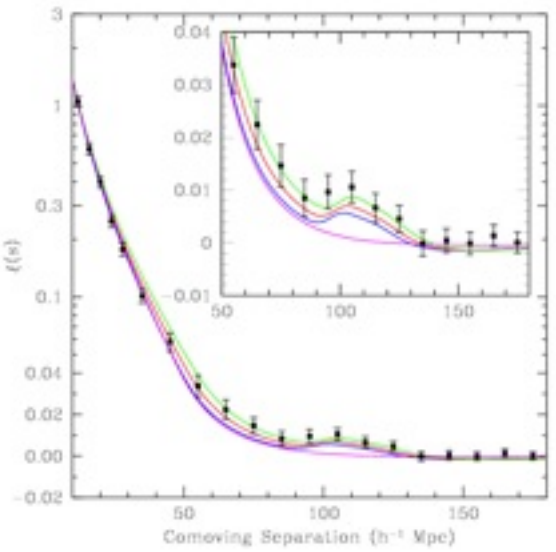
Weak lensing

Evolution of the distorsions pattern





SNeIa: Distance to standard candles



Correlation Vs redshift

Baryon acoustic oscillations

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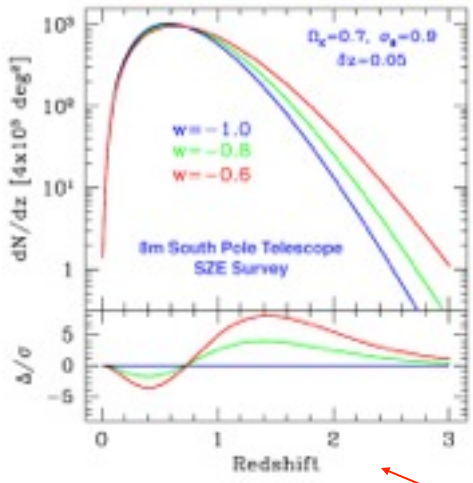

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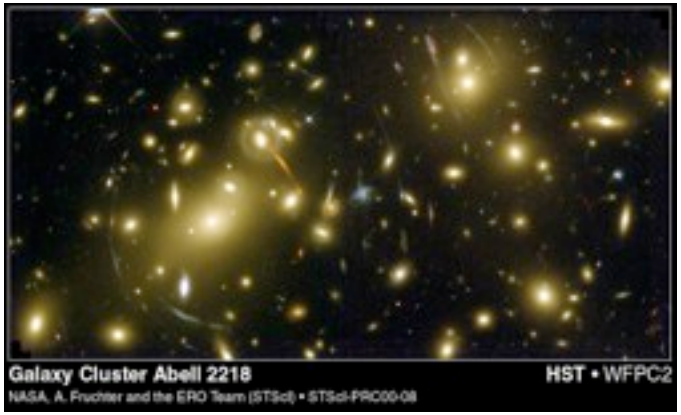
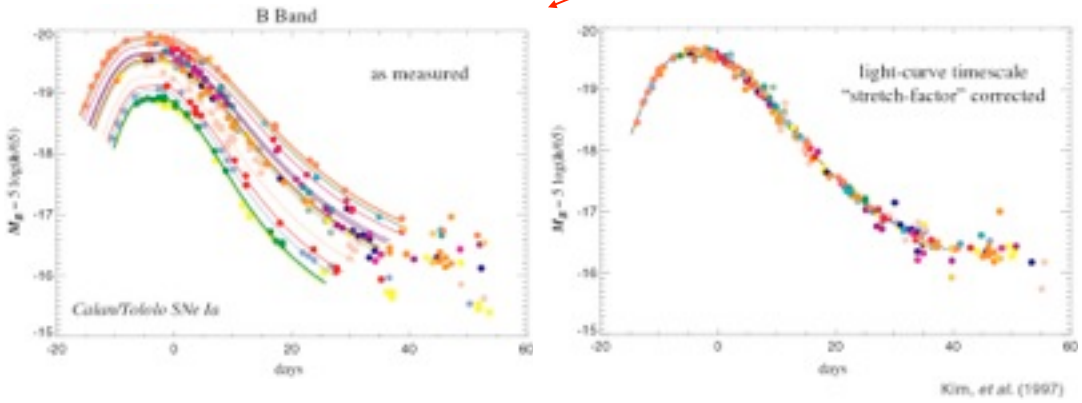


Growth of density perturbations

Geometry of the Universe



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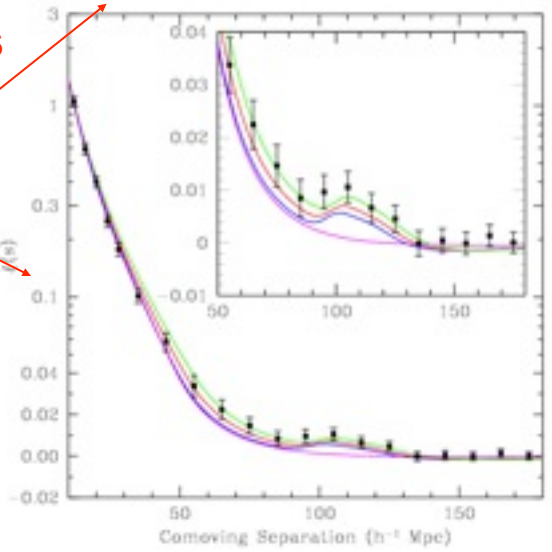

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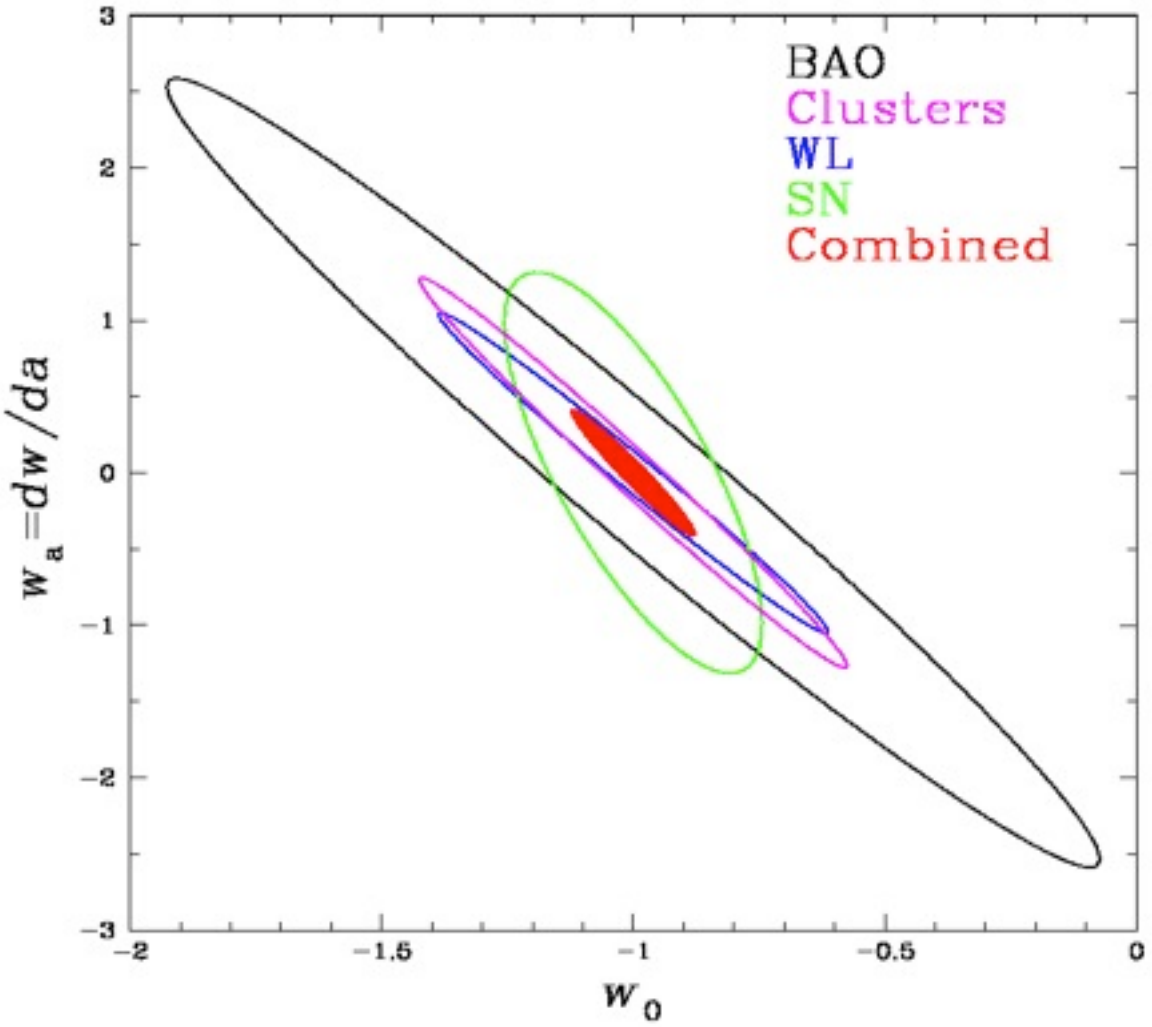
Baryon acoustic oscillations

$$w(z) = w_0 + w_a(1-a) = w_0 + w_a \frac{z}{1+z} \qquad a = \frac{1}{1+z}$$



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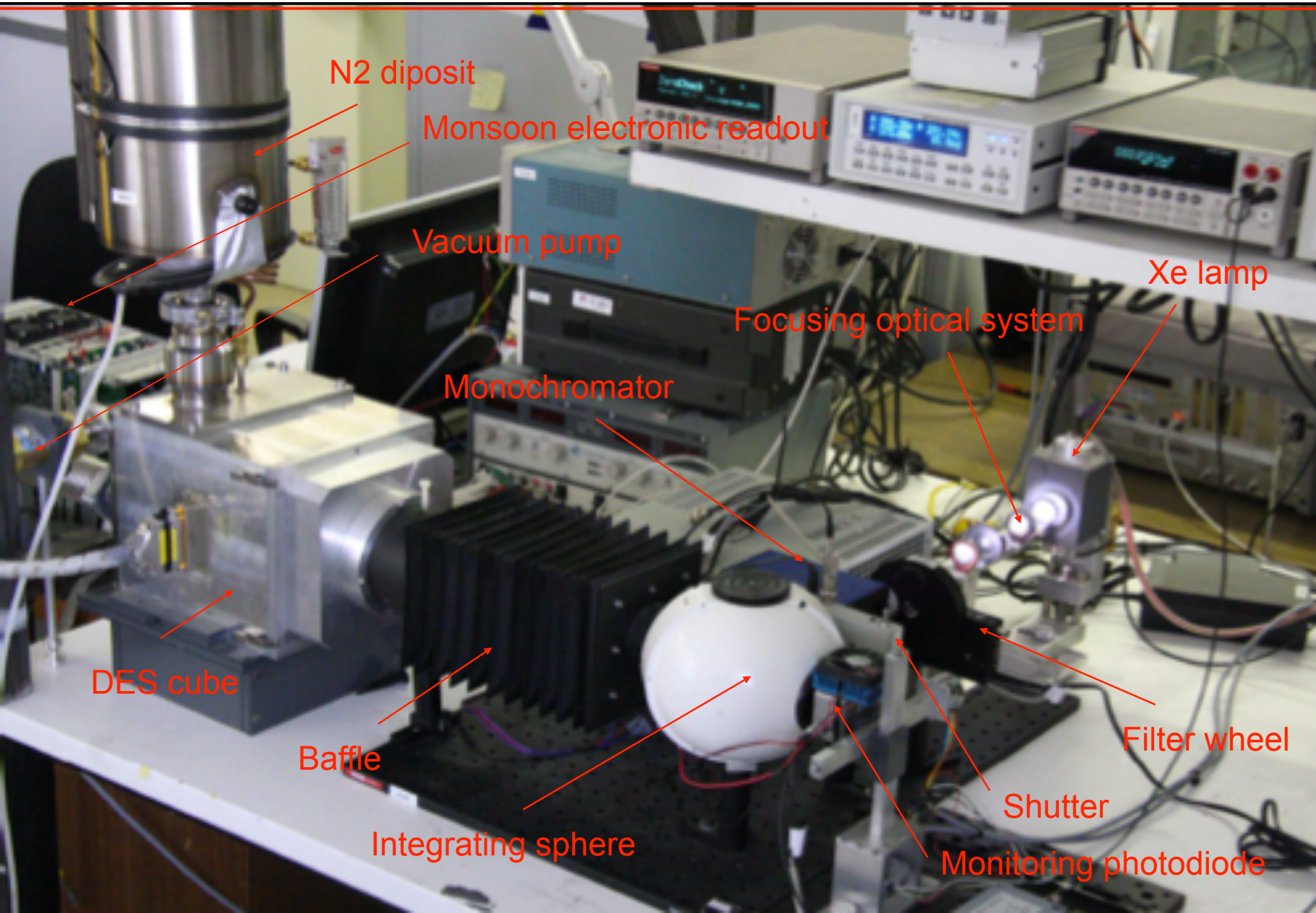
N2 diposit
Monsoon electronic readout
Vacuum pump
Xe lamp
Focusing optical system
Monochromator
DES cube
Baffle
Integrating sphere
Filter wheel
Shutter
Monitoring photodiode

Integrating sphere characterization

$$I(x, y) = I_0 \cos^4(\theta)$$

- We used a photodiode (light intensity to electrical intensity)
- Measurements of the uniformity at different distances from the sphere
- 6cm transversally. Steps of 0.5cm

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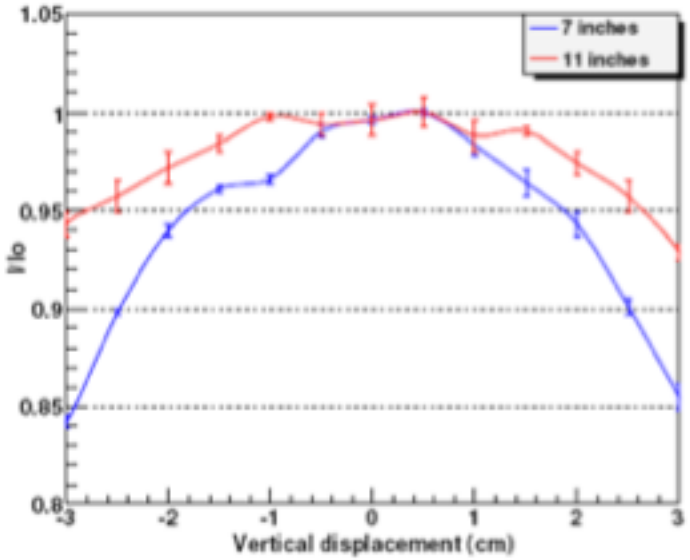

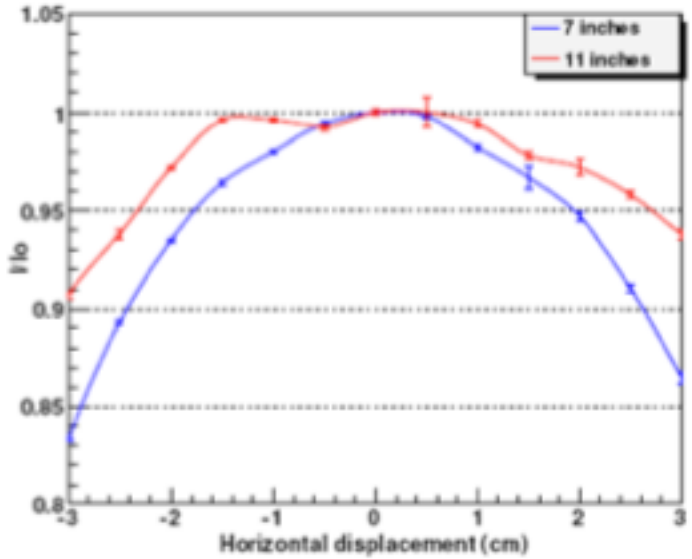

x (in)	d = -3 cm	-2 cm	-1 cm	0 cm	1 cm	2 cm	3 cm
7	0.84	0.94	0.98	1.00	0.98	0.94	0.86
11	0.93	0.97	0.99	1.00	0.98	0.97	0.94
14	0.96	0.97	0.99	1.00	0.99	0.97	0.96

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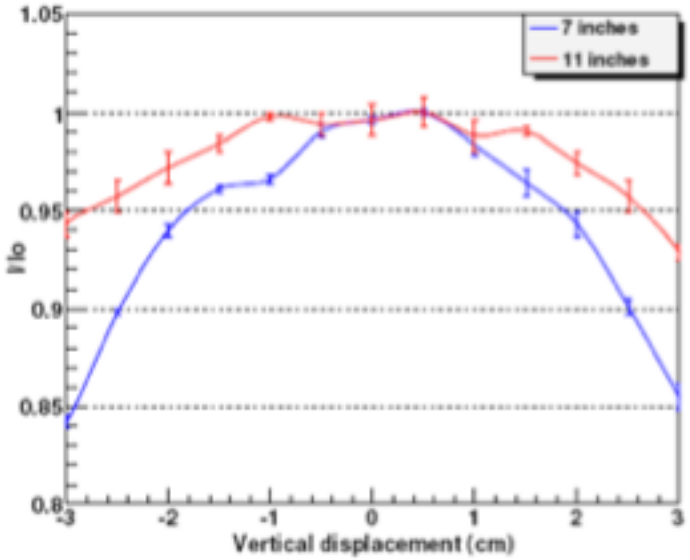

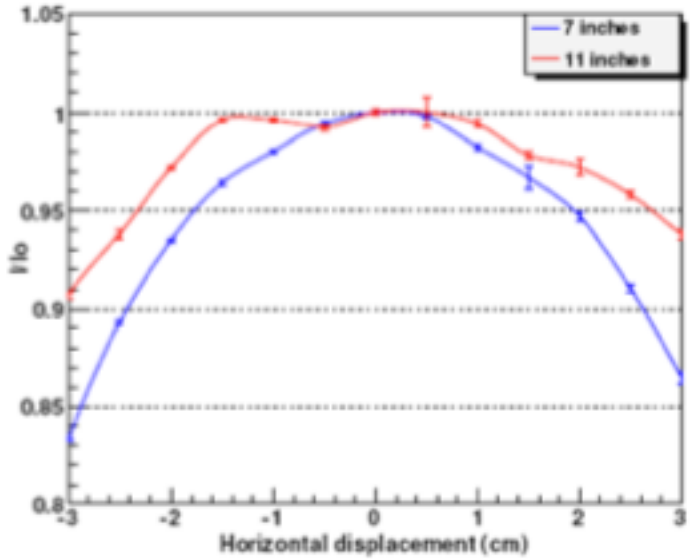

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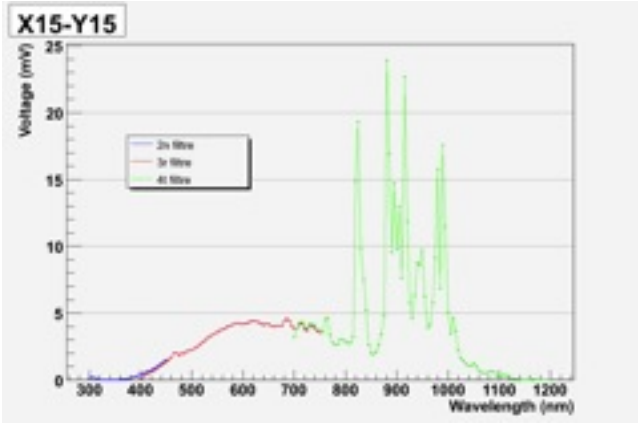
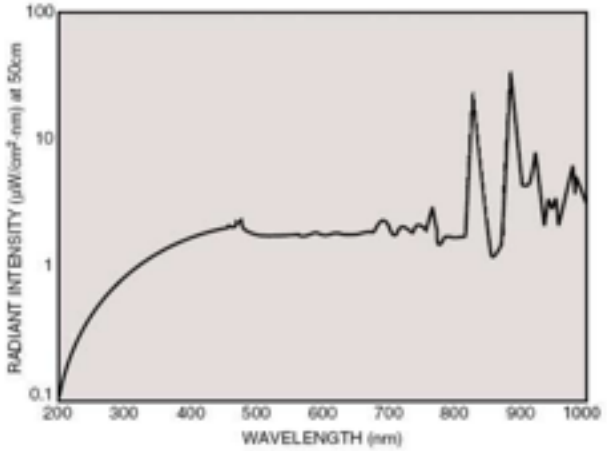
The farther the photodiode is from the sphere, the better uniformity provides

Uniformity maps

measured spectrum



manufacturer spectrum



6cm x 6cm surface

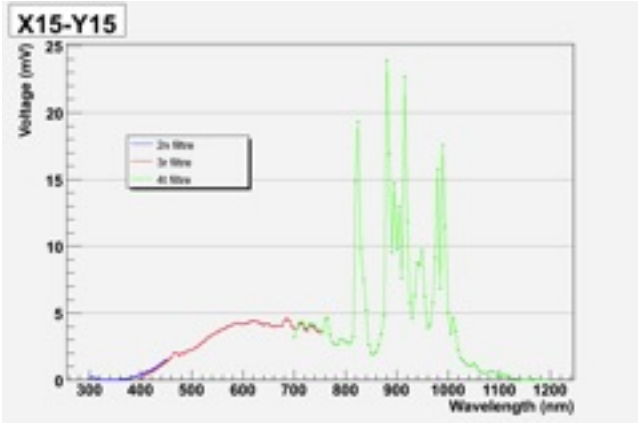
At 13 inches from sphere

From 300 to 1100nm

Every 5nm

Uniformity maps

measured spectrum



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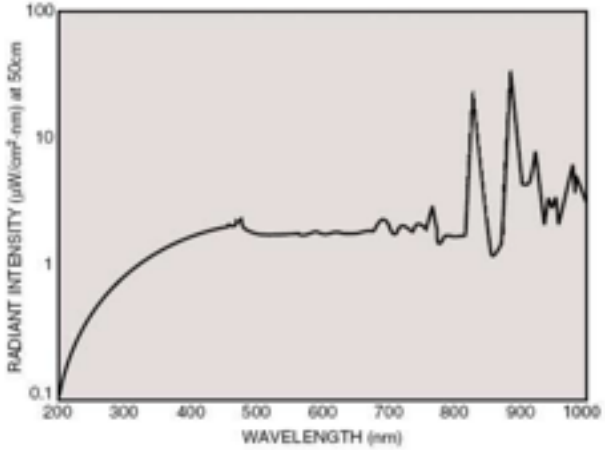

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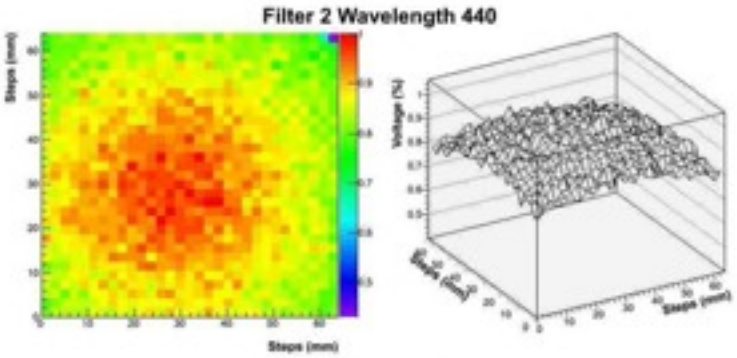

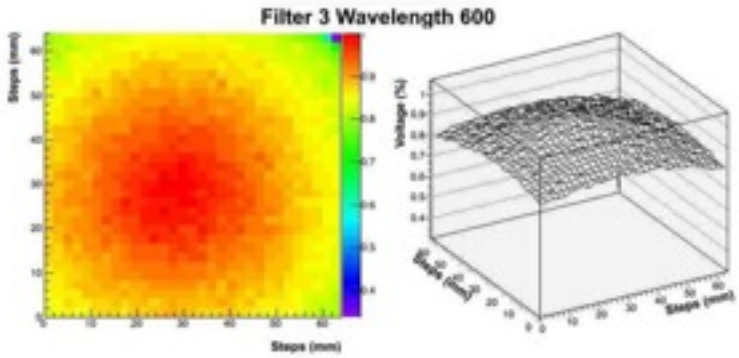

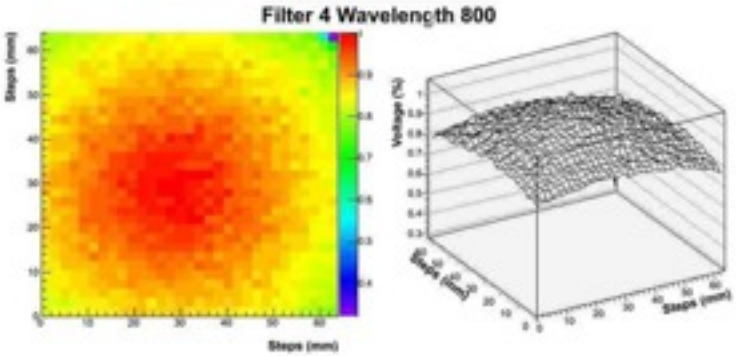

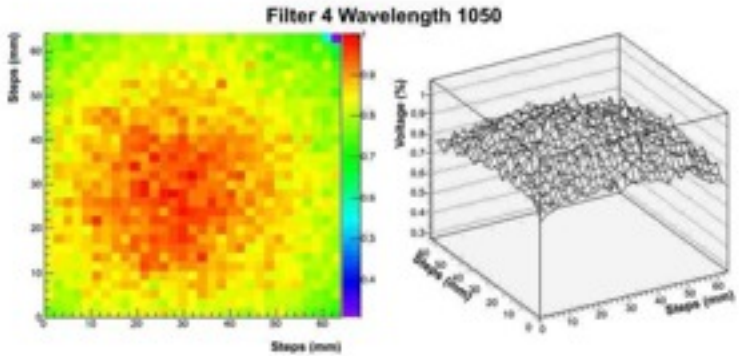

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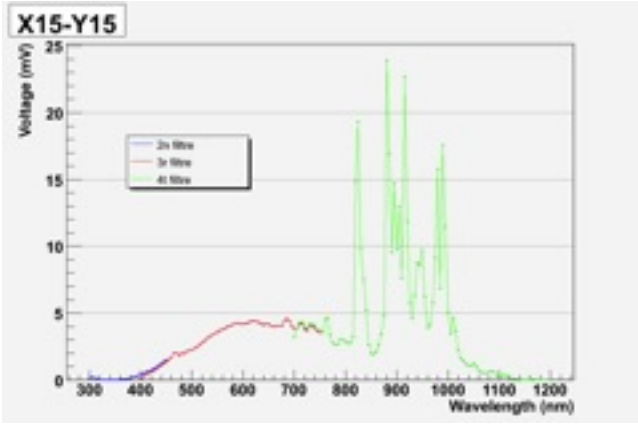

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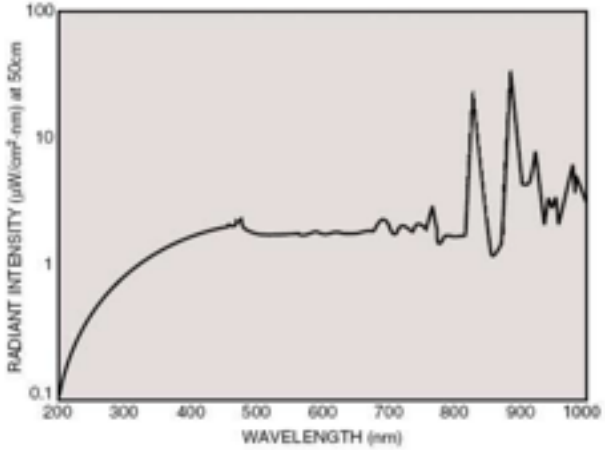

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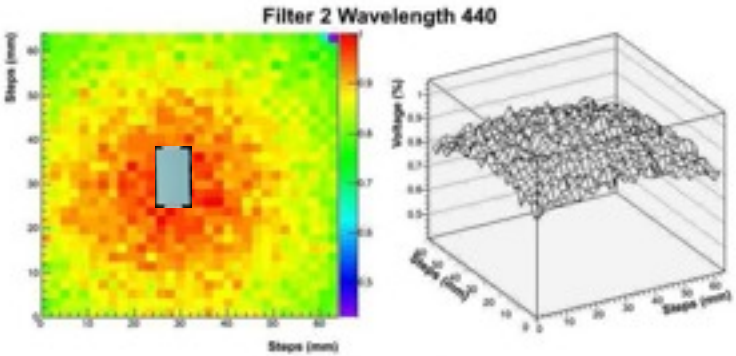
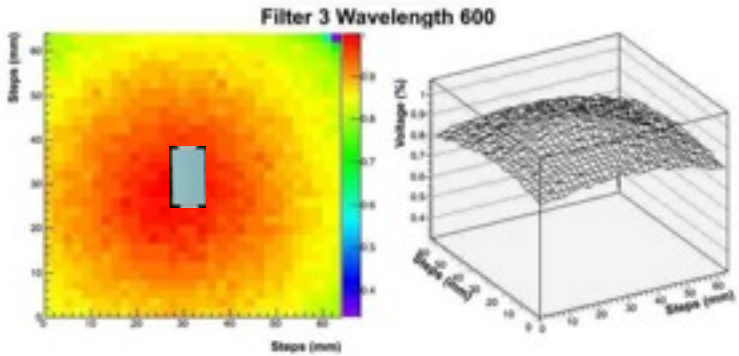
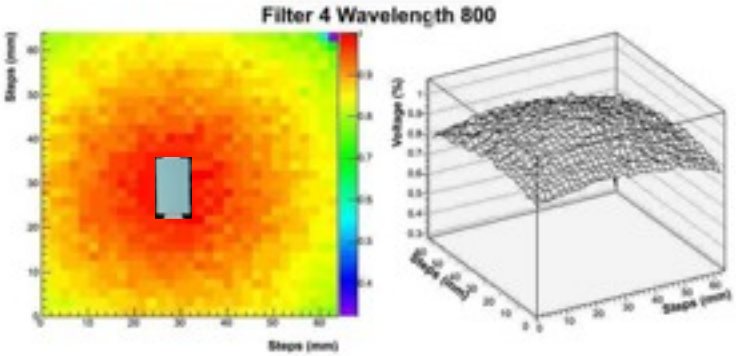
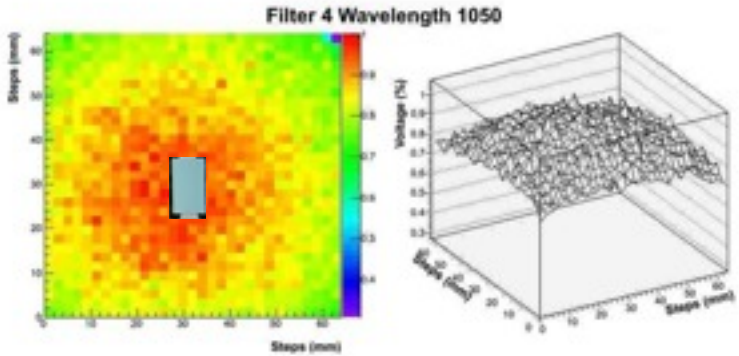








Characterization in absolute number of photons

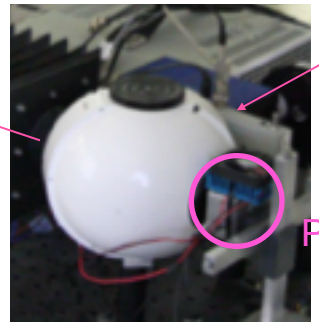
- Absolute calibration in number of photons
- Photodiode in the other output sphere port
- Loss between the light emitted and the light detected
- This relative measurement is necessary to measure the QE in the future

$$R(\upsilon) = \frac{I_P(\upsilon)}{I_{CCD}(\upsilon)}$$

$$QE = \frac{p_{\text{int}}}{p_0 R(\upsilon)}$$

Characterization in absolute number of photons

From the lamp



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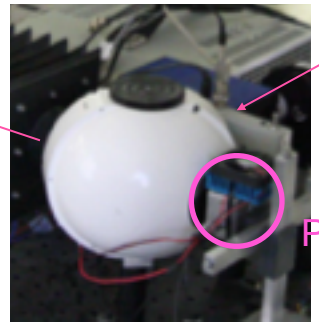

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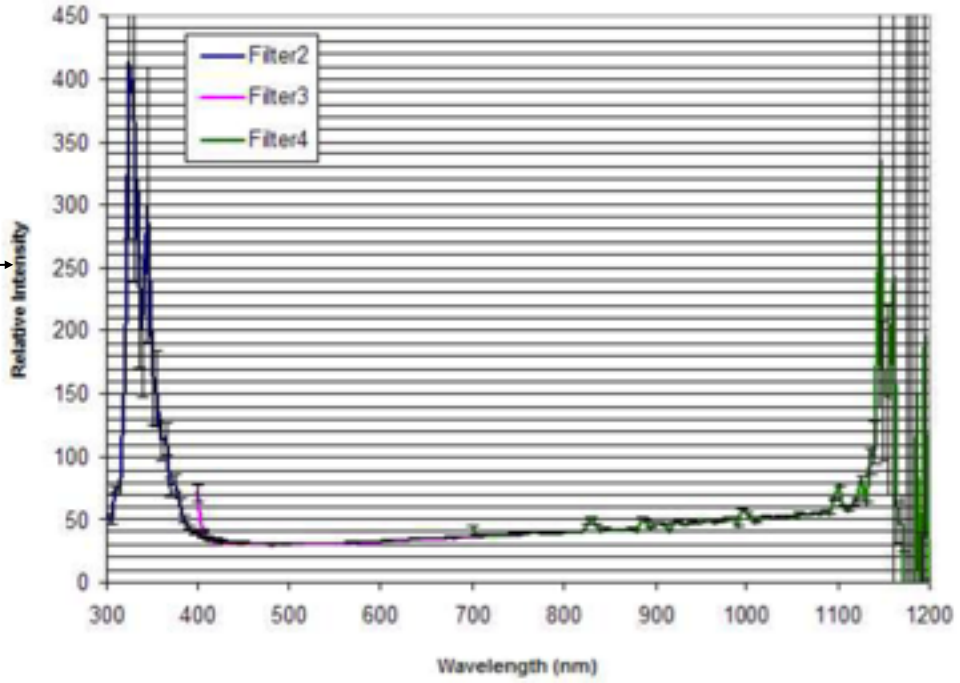


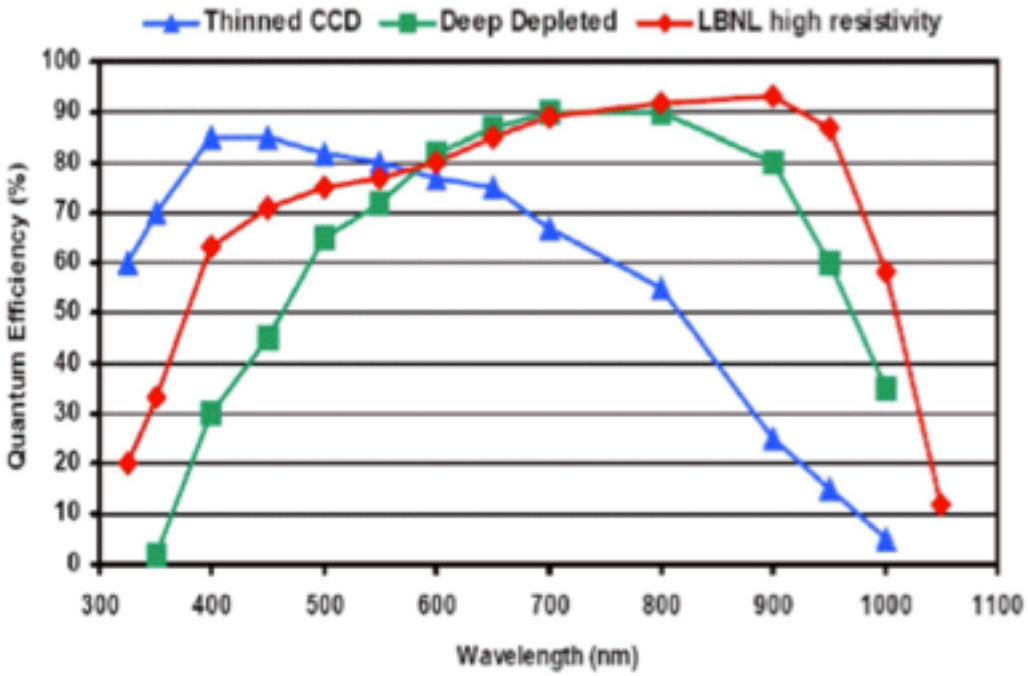
Coating (BaSO) does not integrate all the wavelengths in the same way

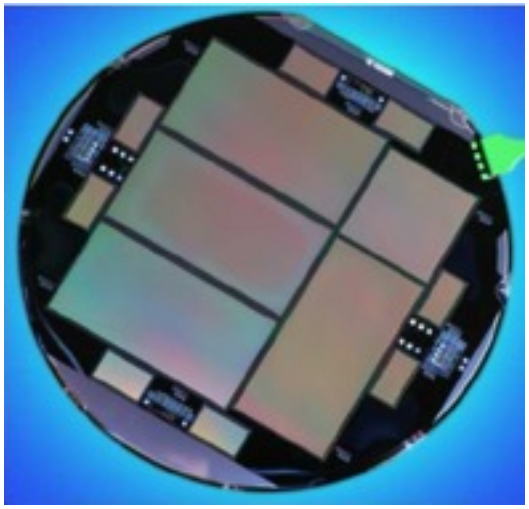
Outline

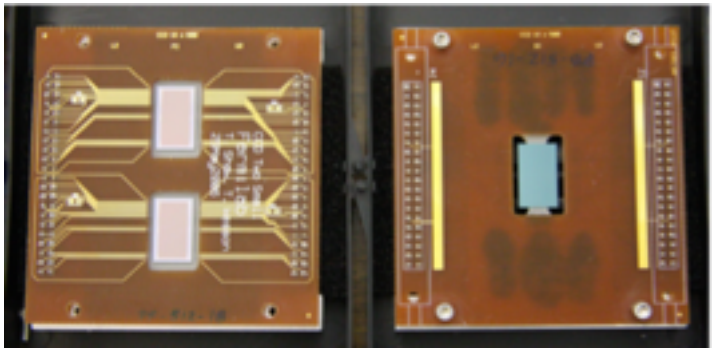
- DE introduction
- The Dark Energy Survey
- The SLAB
- DES CCDs
- Tests
- Conclusions

DES CCDs

LBNL Design
- Sizes: 2kx4k, 2kx2k, 0.5kx1k
- 250 μm thick
-15μm pixels (0.27”/pixel)
- readout 250 kpix/sec, readout time ~17sec
- QE> 50% at 1000 nm







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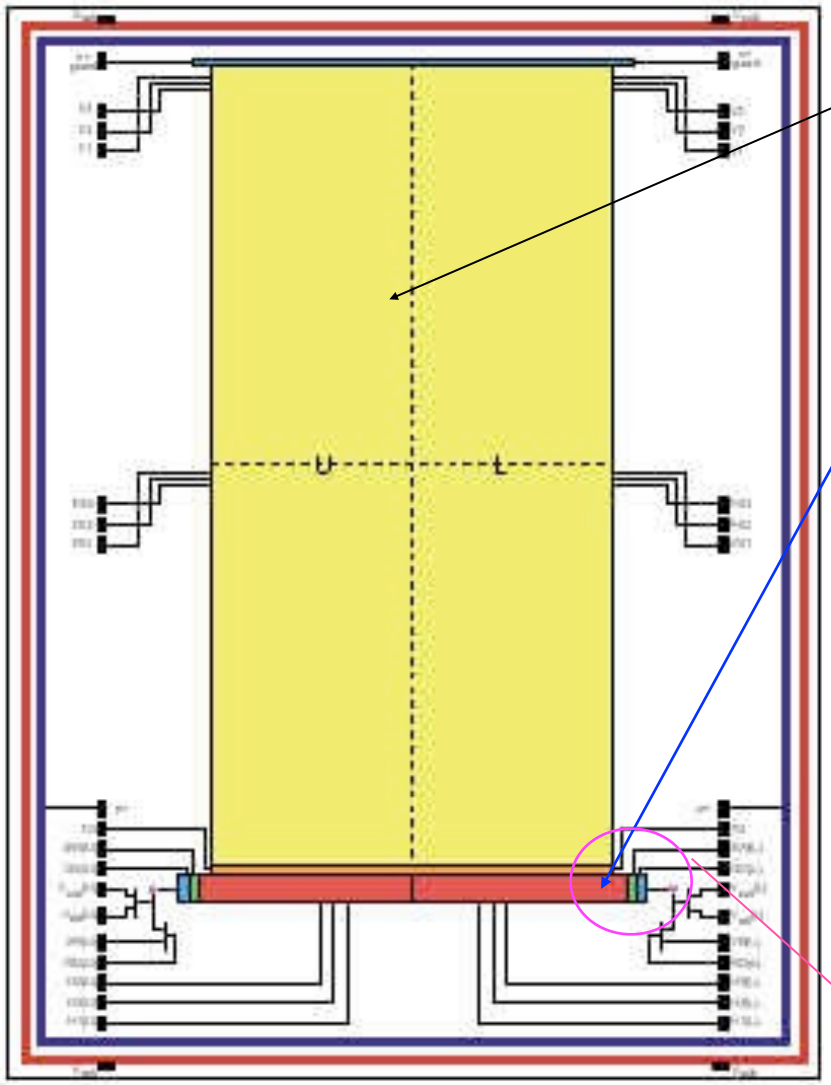
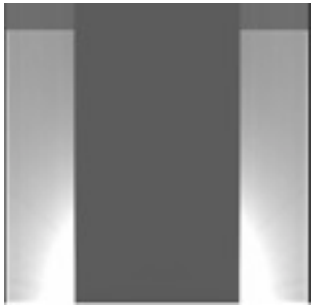


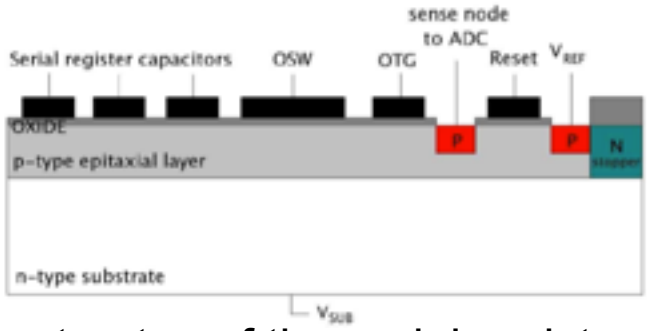
Vertical clocking moves charge towards serial register

Horizontal clocking moves charge along serial output register to video output amplifiers

2 channels (U,L) to read each half part of the CCD

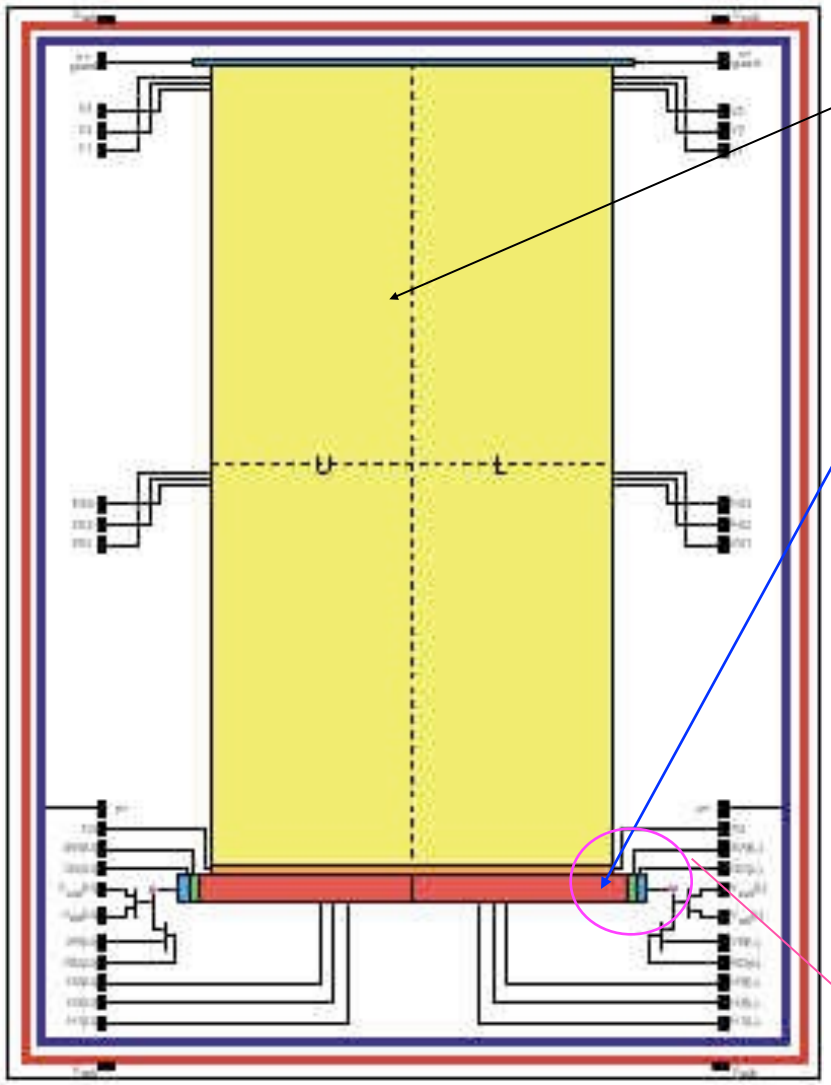
Over clocks are done to measure the dark current





Last gates of the serial register

DES CCDs



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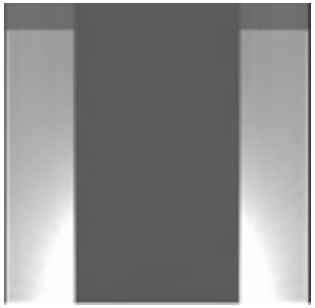

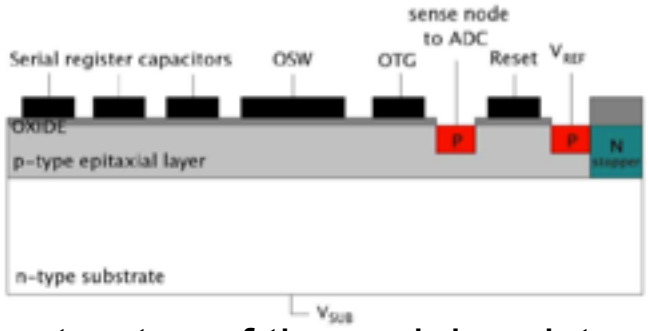

Last gates of the serial register

Bias voltages table provided by LBNL

Signal	*Typical voltage (V)*
Substrate bias (V_{SUB})	40
Reset drain (V_{REF})	-12
Output transfer gate (V_{OTG})	3.5
Vertical clocks (V_1, V_2, V_3)	5.5, -2.5, 5.5
Horizontal clocks (H_1, H_2, H_3)	8.5, -3.5, 8.5
Output Summing well (V_{OSW})	-4

Charge is accumulated and a reading is done

- Clear image: to empty the wells
- Exposed image: shutter open
- Non-exposed image: shutter closed
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CCD performance functions

Charge generation

ability to intercept an incoming photon through the photoelectric effect

Charge collection

ability to reproduce an image from the ellectrons collected

Charge transfer

ability to transfer collected charge from one potential well to another

Charge measurement

ability to detect and measure the charge collected in each pixel

Parameter	*Test*	*Task*
Dark count	PTC	Charge generation
Linearity	PTC	Charge measurement
Full-well capacity	PTC	Charge collection
Amplifier's gain	PTC	Charge measurement
Pedestal	PTC	Charge collection
Amplifier's gain	MUON	Charge measurement
Diffusion	MUON	Charge collection
Charge transfer efficiency	MUON	Charge transfer
Energy Vs ADU	MUON	Charge measurement
Amplifier's noise	NOISE	Charge measurement
Charge transfer efficiency	CTI	Charge transfer
Charge transfer efficiency	XRAY	Charge transfer
Energy Vs ADU	XRAY	Charge measurement

	LBNL CCD performance	DES requirements
Pixel array	2048 × 4096 pixels	2048 × 4096 pixels
Pixel size	15 μm × 15 μm	15 μm × 15 μm
<QE (400-700 nm)>	~70%	>60%
<QE (700-900 nm)>	~90%	>80%
<QE (900-1000 nm)>	~60%	>50% at 1000 nm
Full well capacity	170,000 e^-	>130,000 e^-
Dark current	2 e^-/hr/pixel at −150°C	<~25 e^-/hr/pixel
Persistence	Erase mechanism	Erase mechanism
Read noise	7 e^- @ 250 kpix/s	< 10 e^- @ 250 kpix/sec
Charge Transfer Inefficiency	$< 10^{-6}$	$<10^{-5}$
Charge diffusion	6 μm	< 7 μm (*)
Linearity	Better than 1%	1%

Tests

- Automatic Tcl/Tk script to take the images for the tests (*MecStart).*
- 826 FITS images stored in the DES computer

  - Images:
    - Otg 140 images
    - Votgscan 196 images
    - Ptc 320 images
    - Noise 10 images
    - Cti 160 images
  - Other tests:
    - Xray about 100
    - Muon about 100

- A Linux script distribute the FITS in folders for each test, and execute the analysis tools
- Useful regions of FITS images are converted to text files with the ADUs of the pixels
- The results are plotted using ROOT
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CCD Testing Report

Device ID	pb-512-19
Type	Back Illuminated
Size	1024x512
Thickness	250 μm
Operator	Lluis Galbany
Analysis	Lluis Galbany

Results Analysis:

	Right Amp. (RH)	**Left Amp. (LH)**
Gain (ADU/e)	1.223 ± 0.000	3.118 ± 0.000
Noise (ADU)	12.410 ± 0.023	11.267 ± 0.020
Full Well Capacity(e)	~ 180000	~ 180000
Nonlinearity $> 1\%$ (s)	12 ± 1	9 ± 1
Output Gate for Charge Inj. Vref=-12V (V)	2.6 ± 0.1	2.1 ± 0.1
Minimal H+ for CTI requirements (V)	5.5 ± 0.5	6.0 ± 0.5
Minimal H- for CTI requirements (V)	-10.0 ± 0.5	-10.0 ± 0.5
Minimal V+ for CTI requirements (V)	1.0 ± 0.5	1.0 ± 0.5
Minimal V- for CTI requirements (V)	-10.0 ± 0.5	-10.0 ± 0.5
CTI calculus from Fe^{55} source	$3.13\ 10^{-6}$	$4.01\ 10^{-7}$

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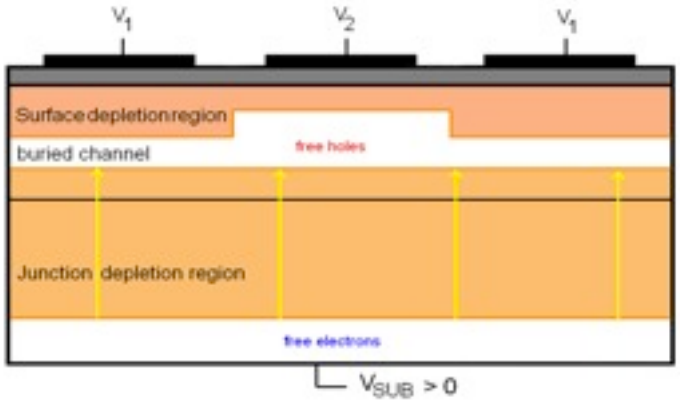
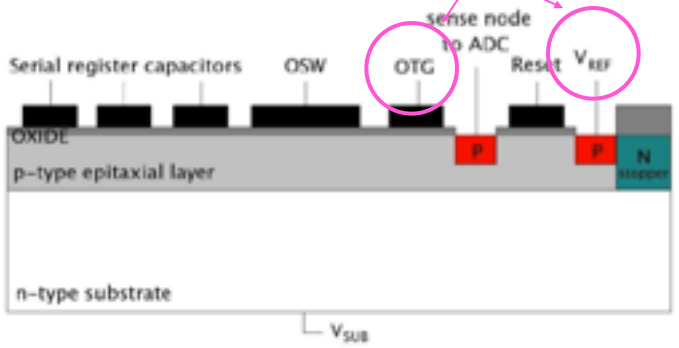
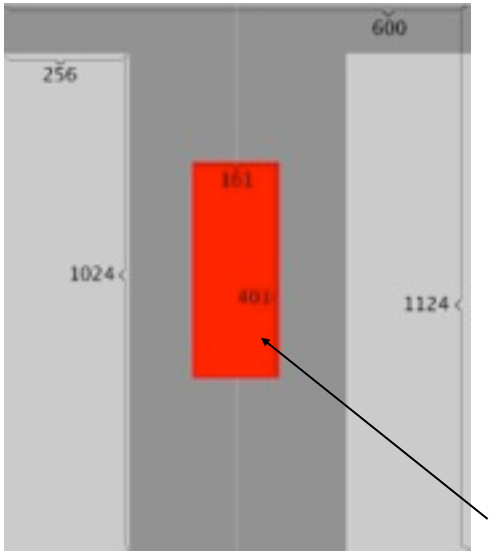
OTG & VOTGSCAN tests

A preliminary test to determine the operation region of the CCD



$$V_{EFF} = V_{REF} - V_{OTG-CI}$$



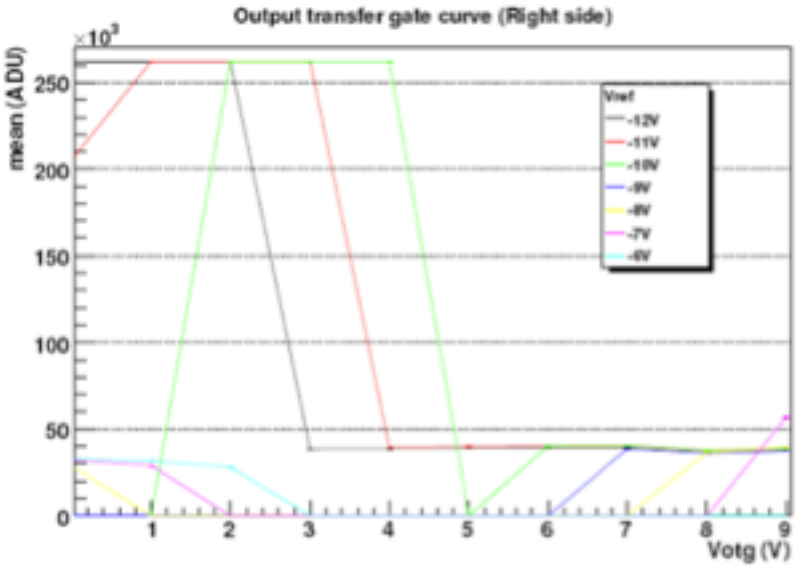


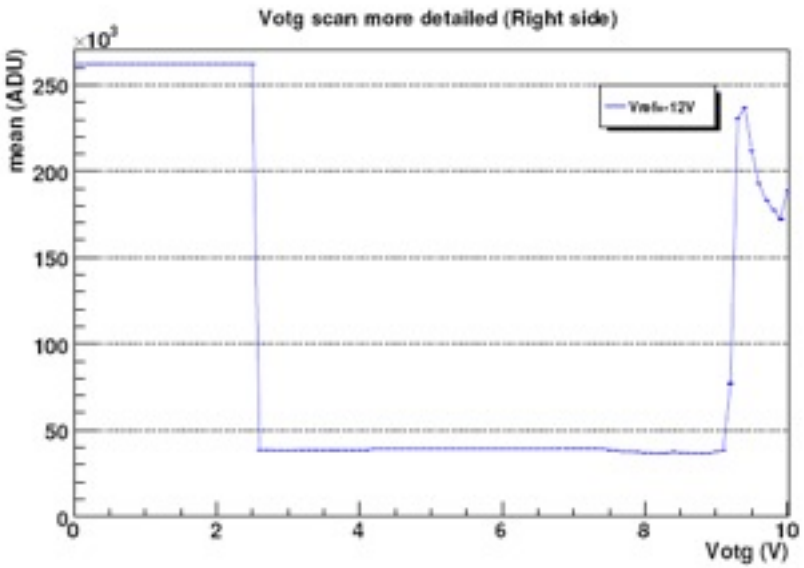
Images: 1 Clear + 20 sec exposed

for each pair (V_{OTG} from 0 to 9V, V_{REF} from -12 to -6V)

Mean signal as a function of V_{OTG} for each value of V_{REF}

OTG & VOTGSCAN tests

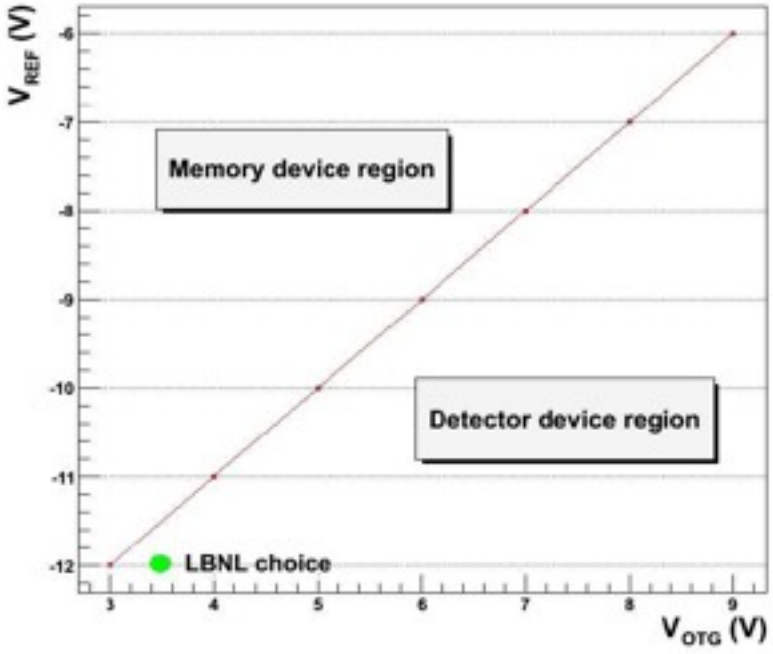




Plots generated.

From the values at which the charge injection occurs is plotted the output charge tranfer plot

A new votgscan test is done, fixing V_{REF} to -12V and scanning V_{OTG} each 0.1V



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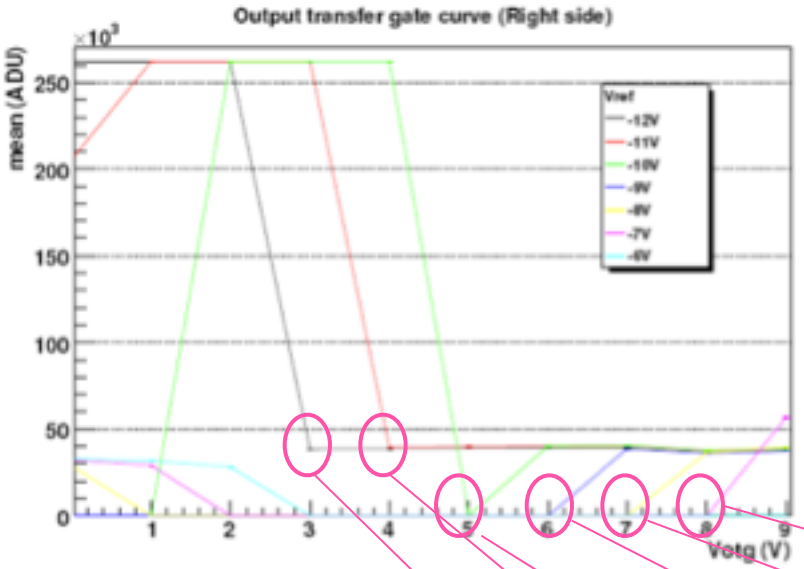

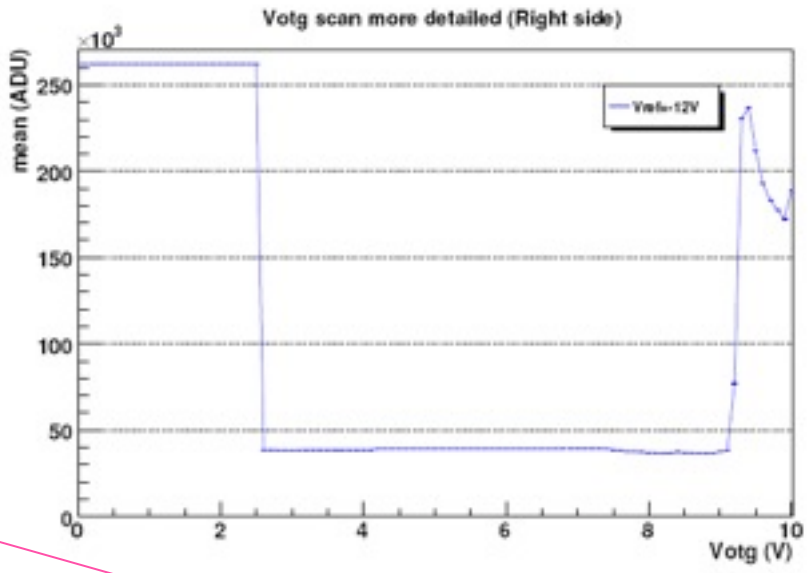

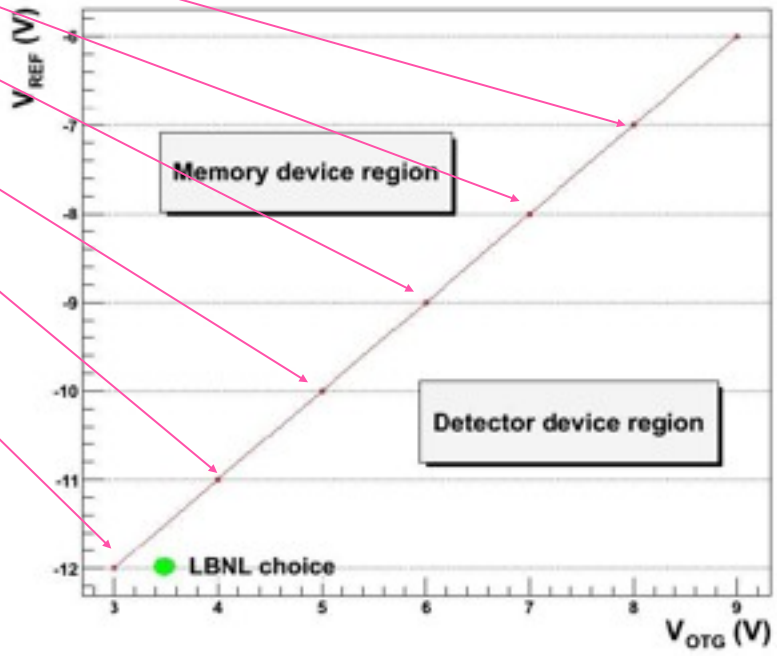

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PTC test

The photon transfer curve data is used to determine:

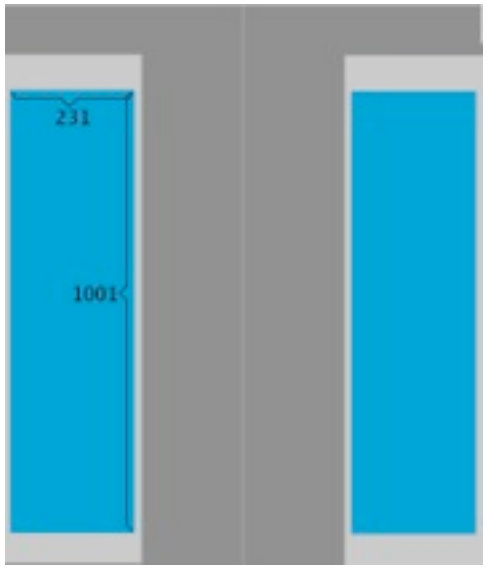
- the linearity
- the full well capacity
- the conversion gain (ADU vs electrons)
- pedestal

Incident photons emitted (n)
Quantum efficiency (eh/n)
Sense node sensitivity (V/eh)
Amplifiers gain (ADU/V)

Signal in a pixel $S(ADU) = PQ_E S_V A_V$

Gain: number of electrons needed to produce one ADU

$$K = \frac{1}{S_V A_V} \xrightarrow{\text{Poisson}} K = \frac{S}{\sigma_S^2}$$

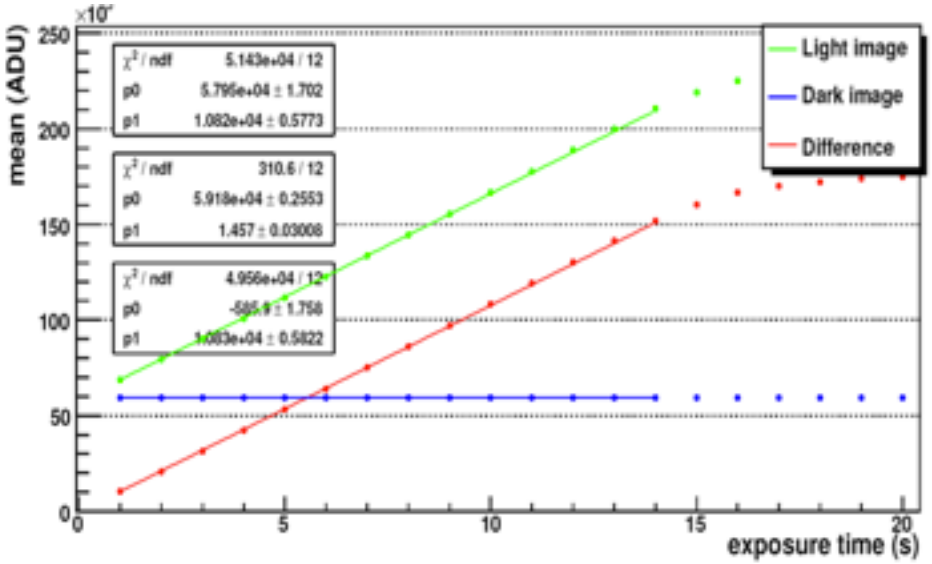


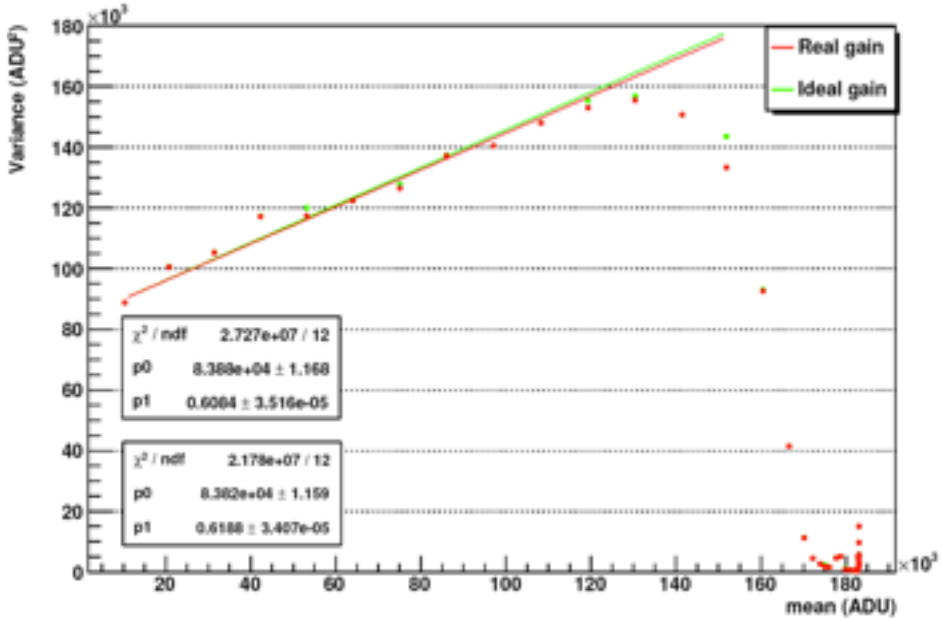
Images: 1 clear + 1 non-exposed + 1 clear + 1 exposed

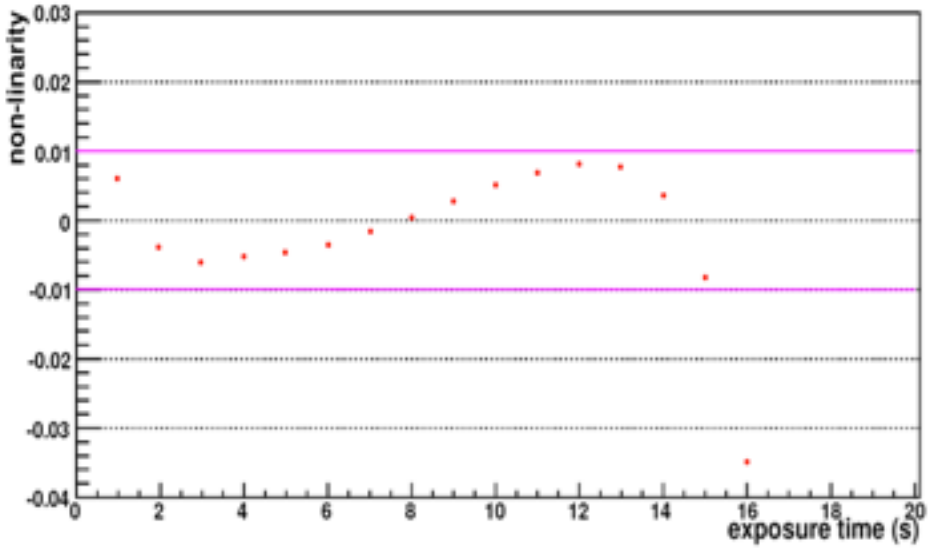
For each exposure time from 1 to 40 seconds

Mean signal as a function of exp. Time
Variance as a function of mean signal

PTC test



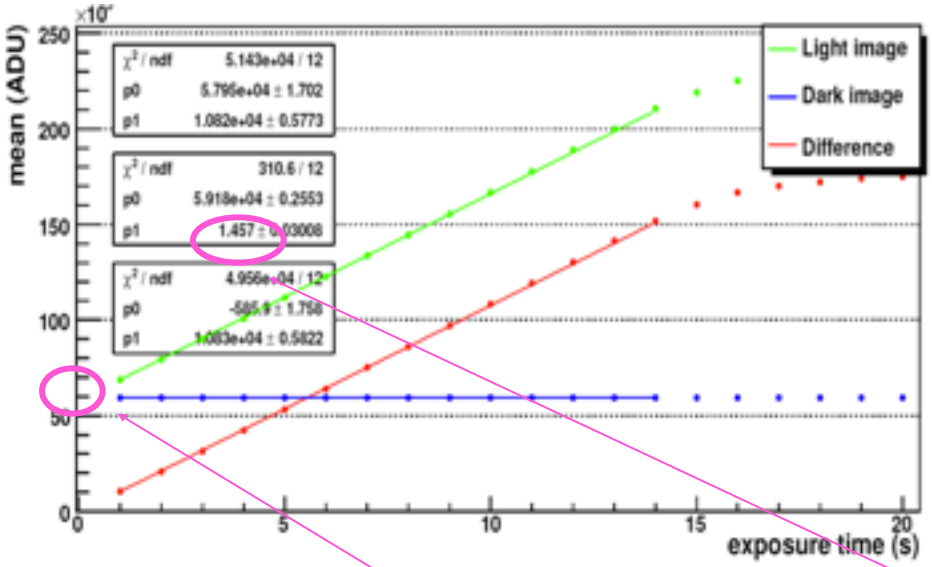


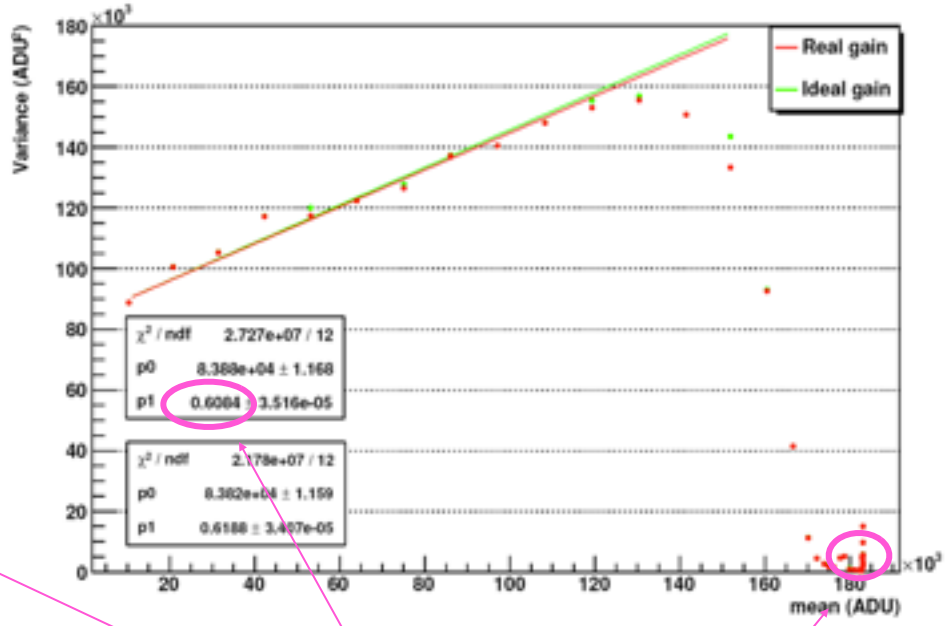


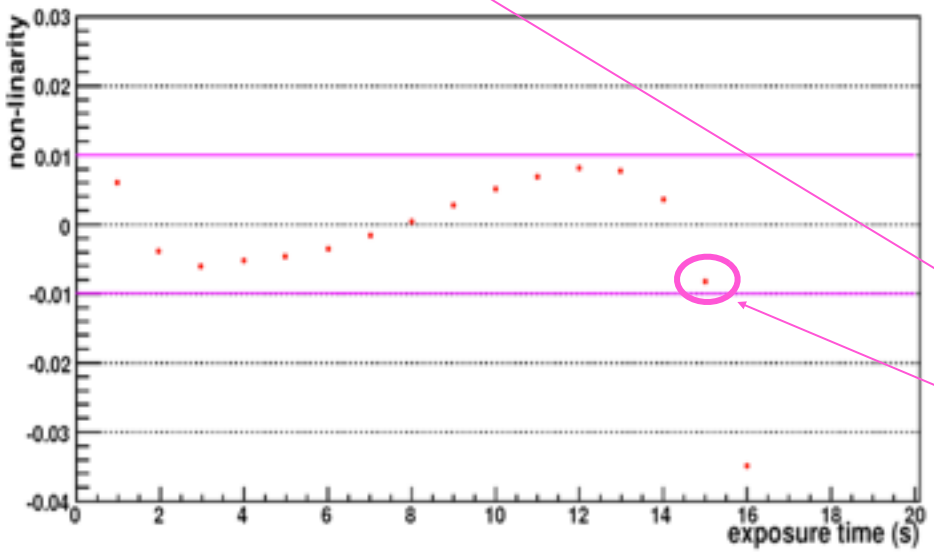
Plots generated:

- Gain measurement
- Pedestal, well capacity & dark current
- Linearity

PTC test







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MUON test

Relation between signal in one pixel and the energy loss by a muon

Minimum-ionizing particles (MIP)

In Si: 270eV/μm

3.65eV/electron ⟶ 74 electrons/μm

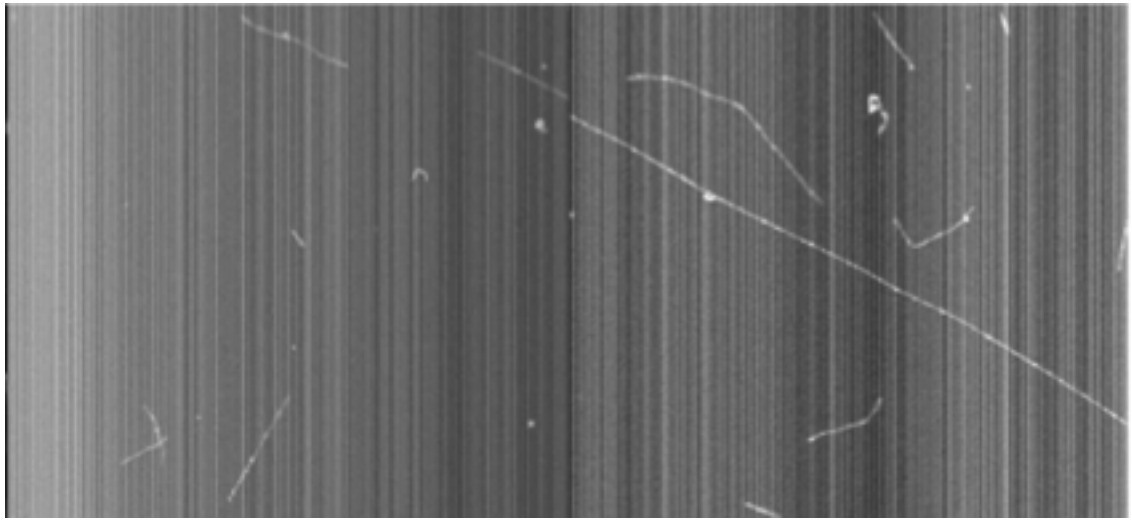
The <u>most probable charge deposition</u> in a 15μm of Si, is 1100 electrons

(Maximum of 21.21μm, 1555 electrons)

100 non-exposed images of 15 seconds, and hope to have good luck!

(+ master dark)

We have to subtract from the signal, the signal in a pixel that was not crossed



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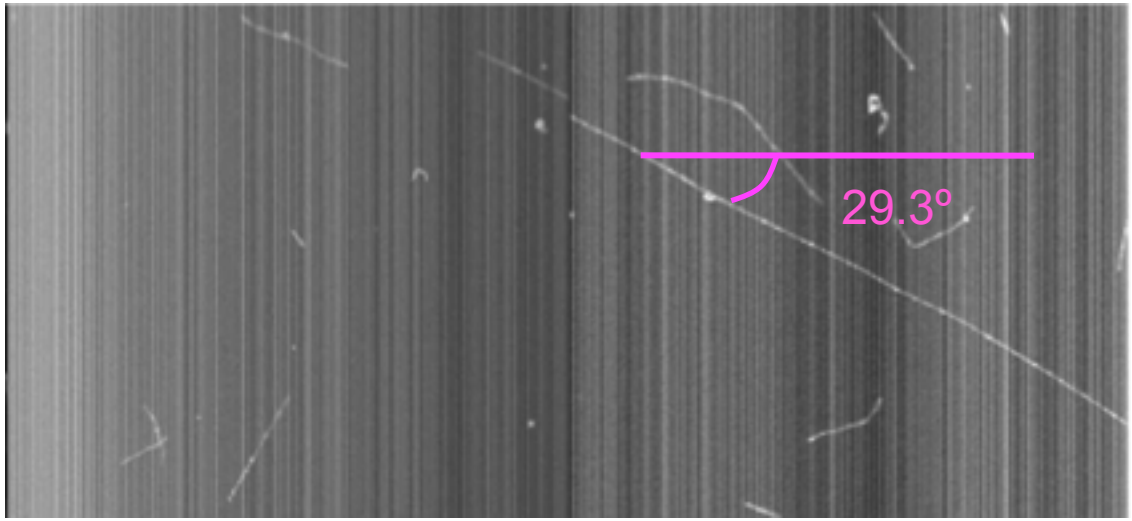


17.2μm ⟶ 1260 electrons

1408 ADU

K=0.85 electron/ADU

NOISE test

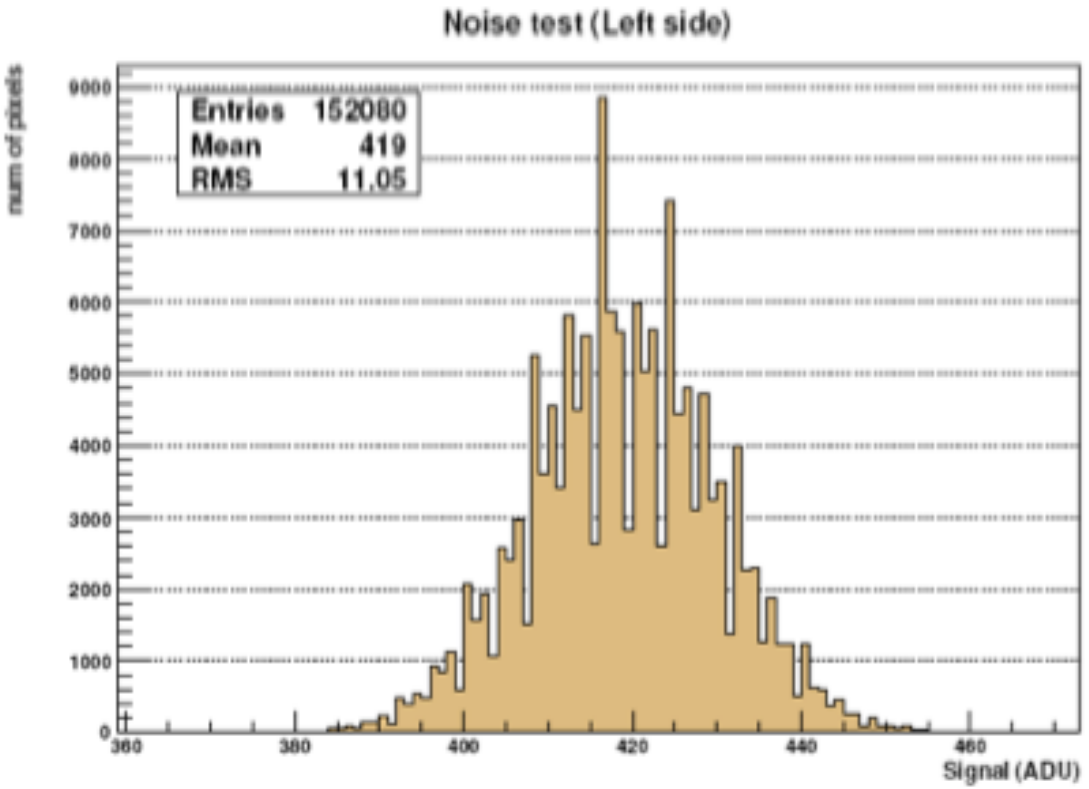
Measure of the noise generated by whole chain: read-out, thermal and shot noise

RMS of the signal distribution of the overscan region

Images: 10 consecutive readings

Average of the noise value

for the 10 images



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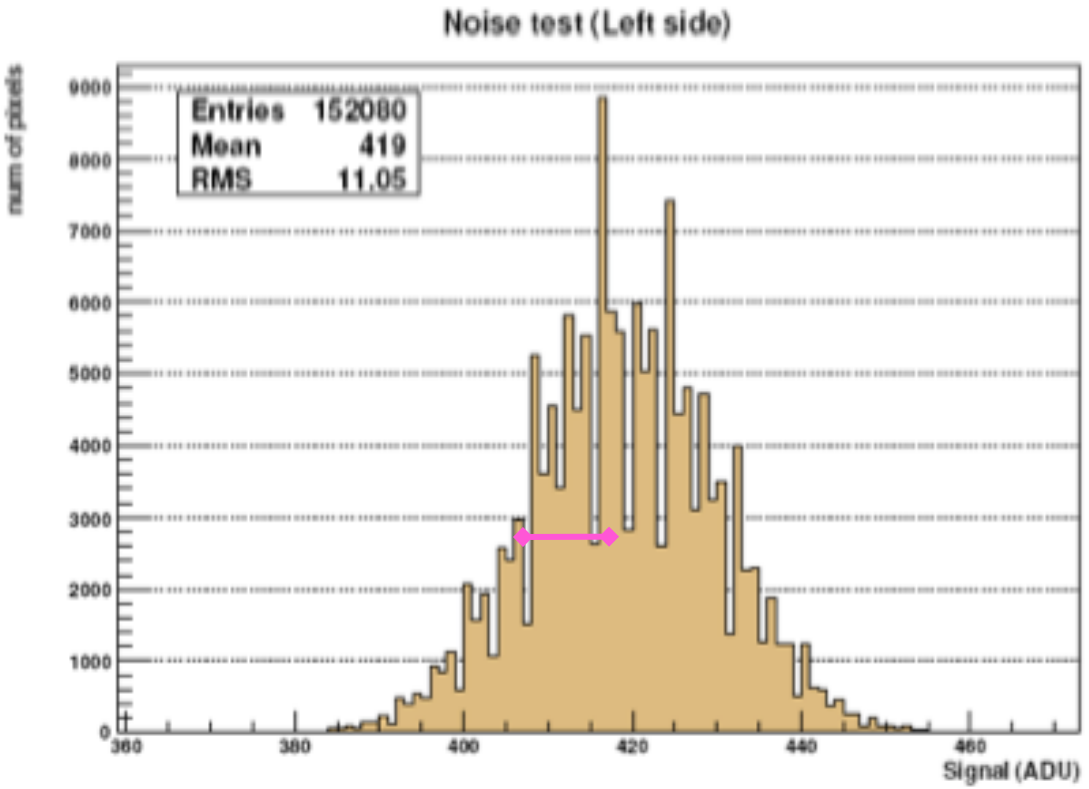


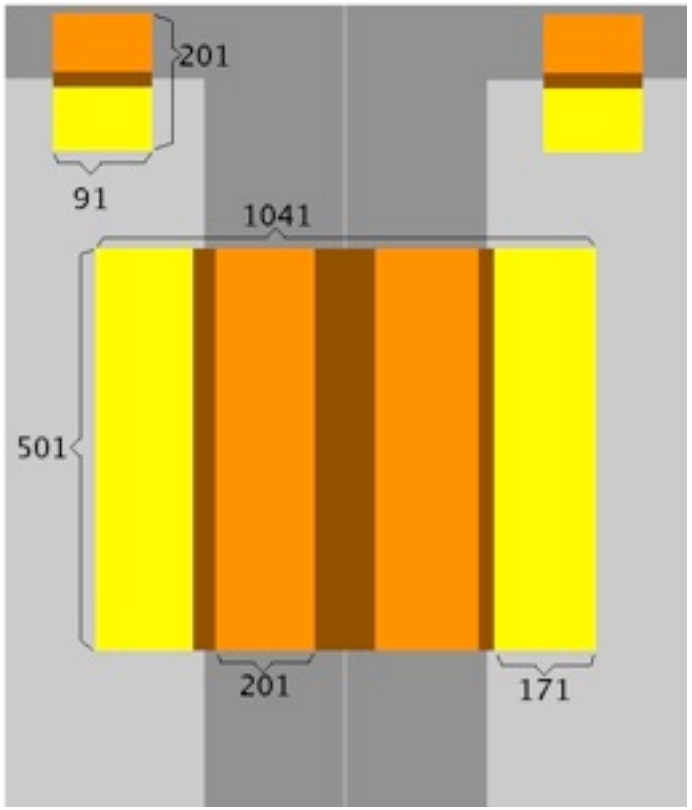
CTI test

Proper collection and transfer of charge in the potential wells: **C**harge **T**ransfer **I**nefficiency

4 subtests, one for each value related with the transfer process (H+/H-/V+/V-)

$$S_i = \frac{\mu_{col,i} - \mu_{pedestal}}{\mu_{mean} - \mu_{pedestal}}$$

$$CTI = \frac{S_{i,last.col}}{256}$$



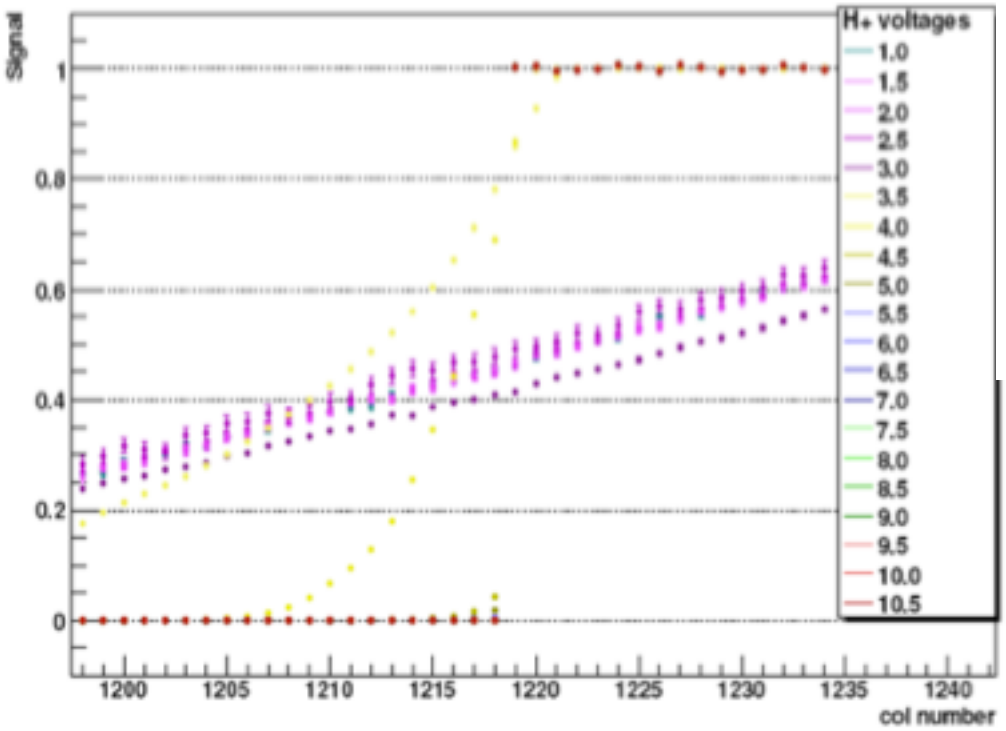
Images: 1 clear + 10 sec exposure
For each subtest, increasing 0.5V the appropiate voltage

Mean signal by columns in the transition to overscan region

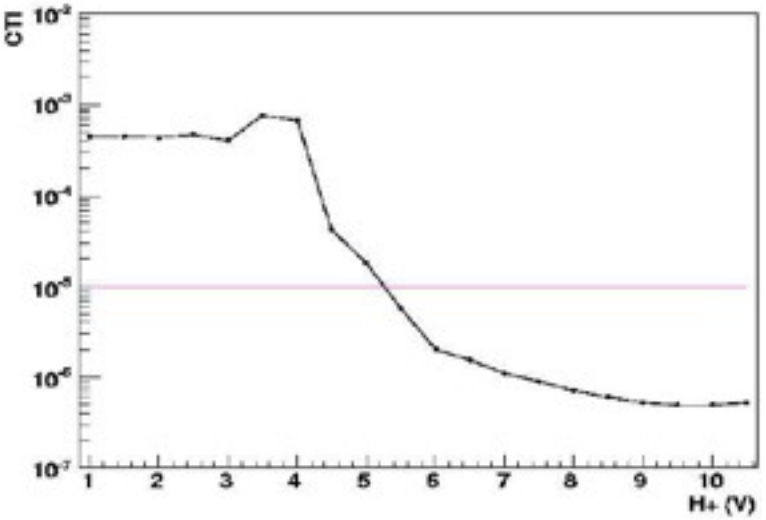
CTI and noise is measured in each image

CTI test

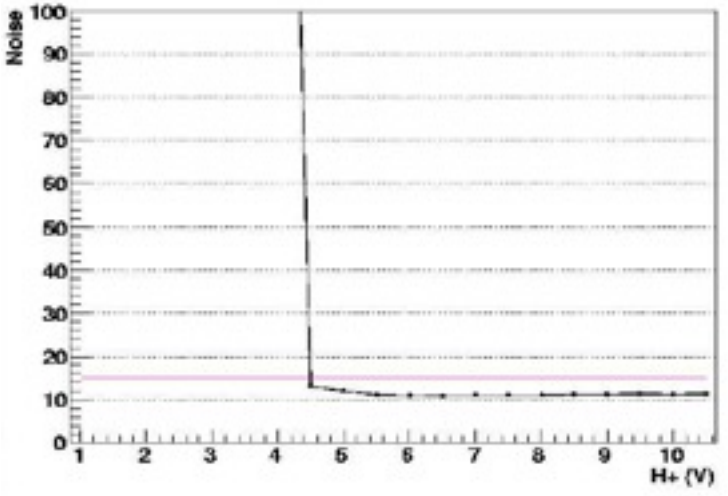
H+ example



Increasing the voltage of H+, the CTI improves



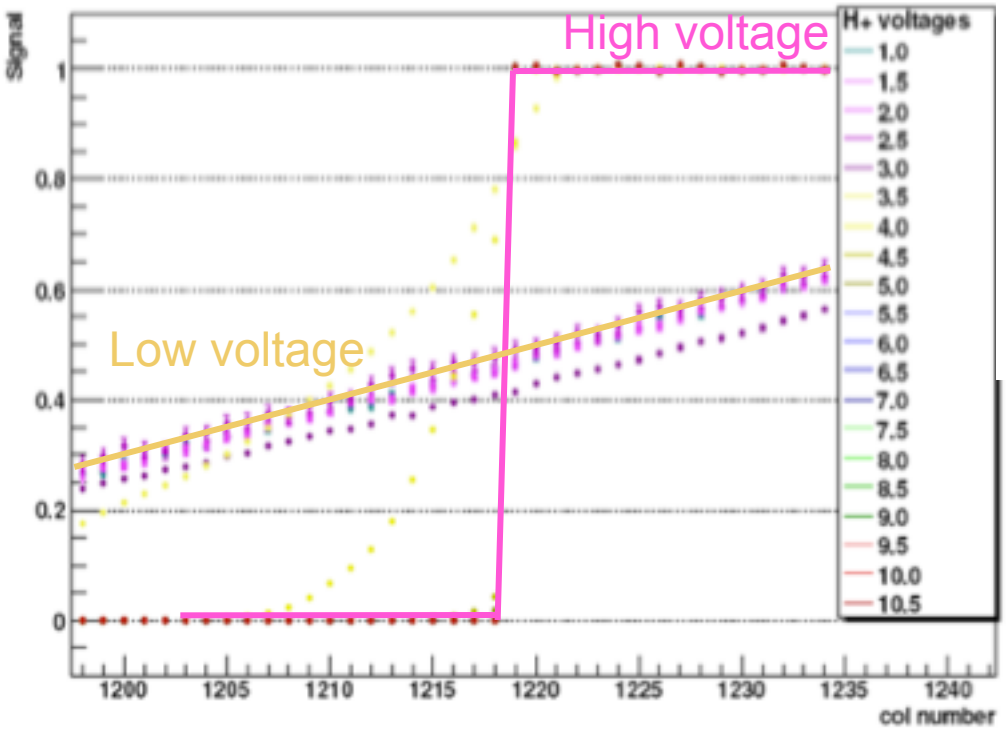
At some value the requirement is achieved



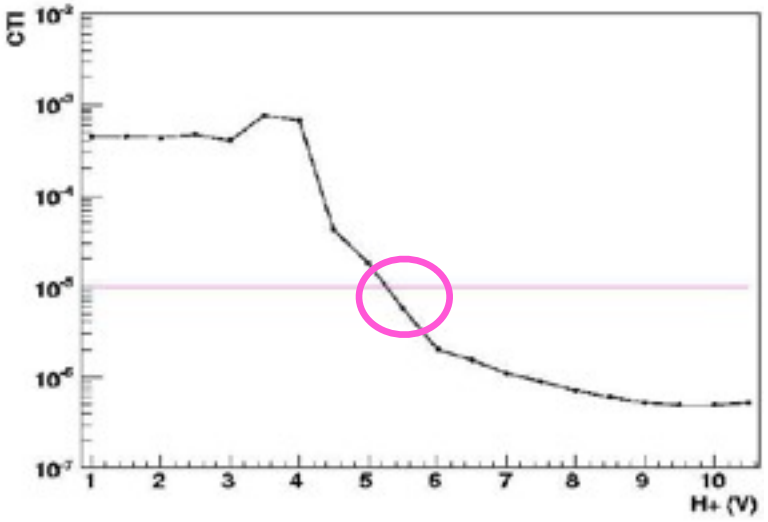
For low voltages the noise is too high

CTI test

H+ example



Increasing the voltage of H+, the CTI improves



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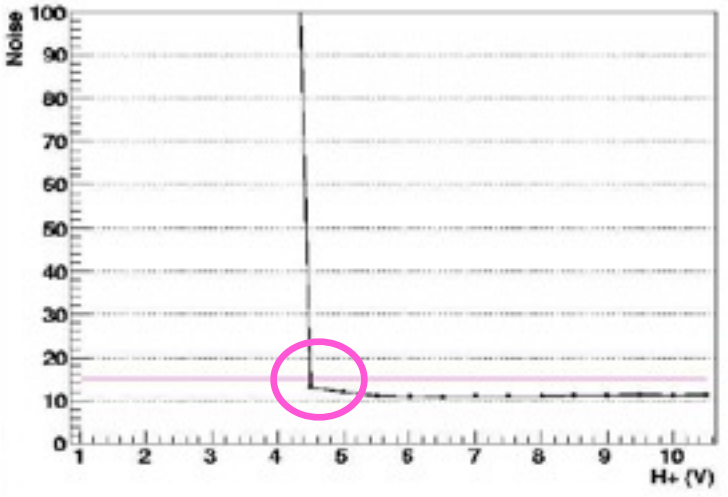


For low voltages the noise is too high

XRAY test

An alternative method to measure both the gain and the CTI

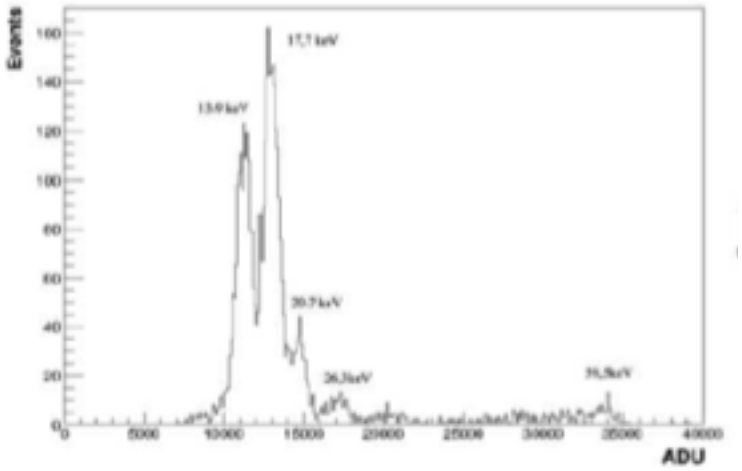
A source placed 2 cm in front of the CCD

GAIN

^{241}Am source used

Signal distribution

10 images of 10 second exposure

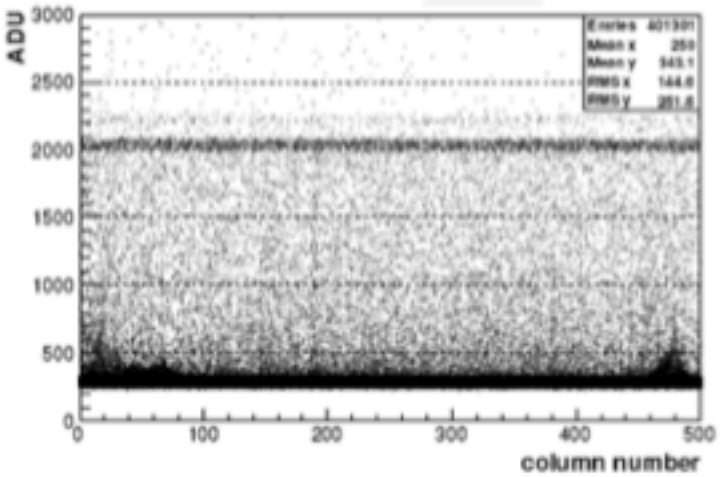


CTI

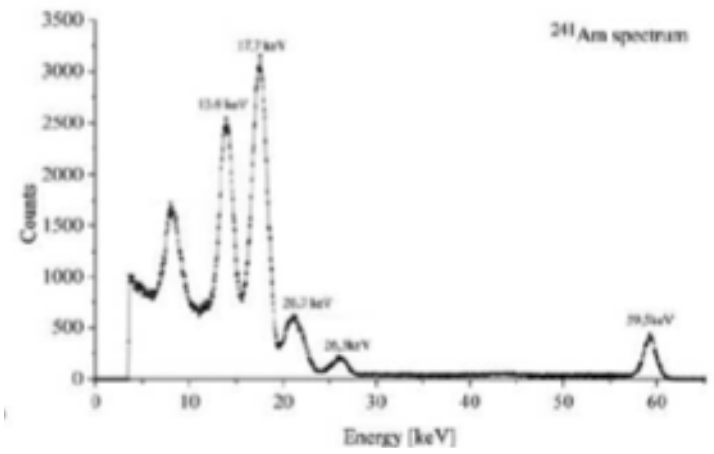
^{55}Fe source used

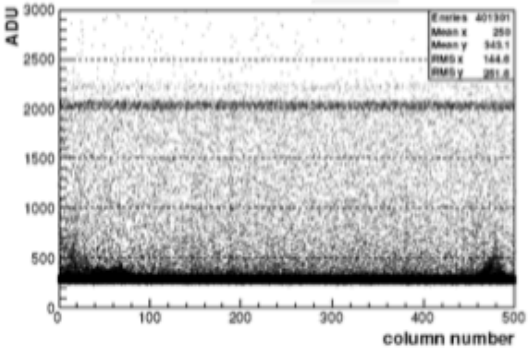
Histogram by columns

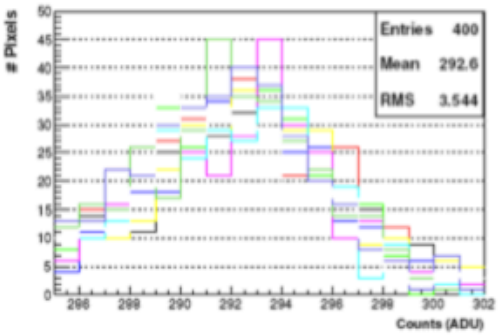
10 images of 10 seconds exposure



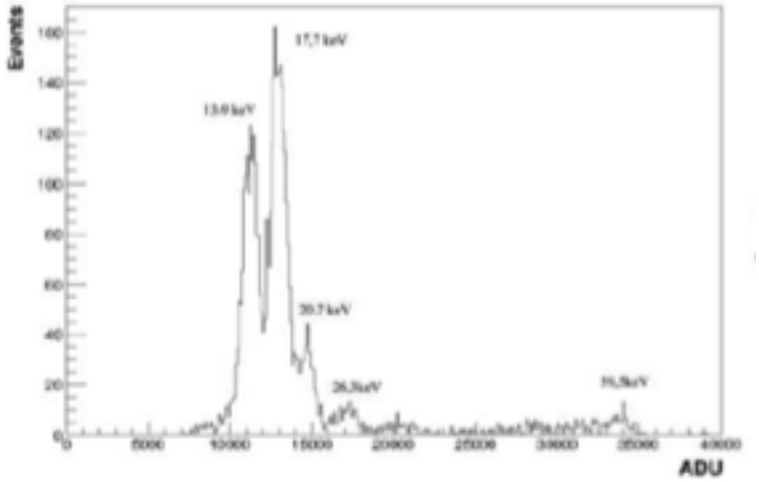
XRAY test

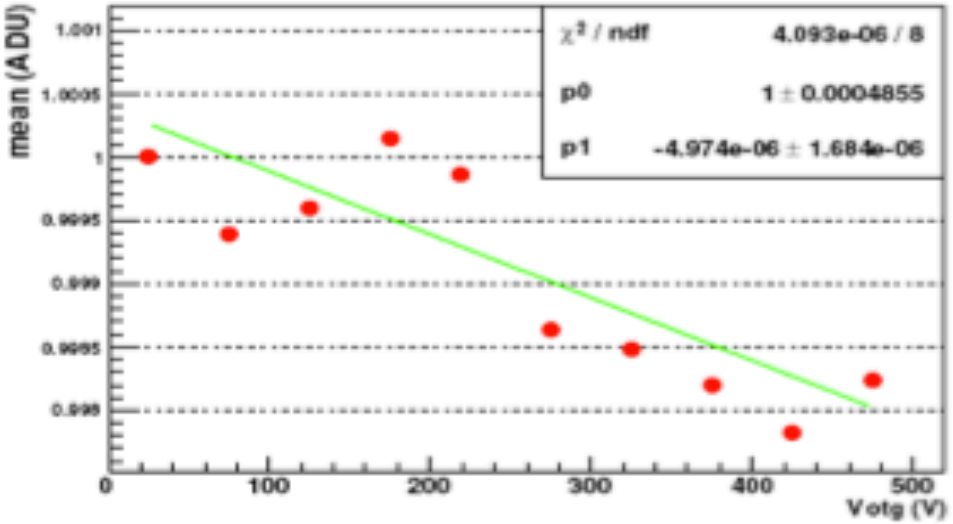






We plot the signal distibution for each 50 columns (in colors)





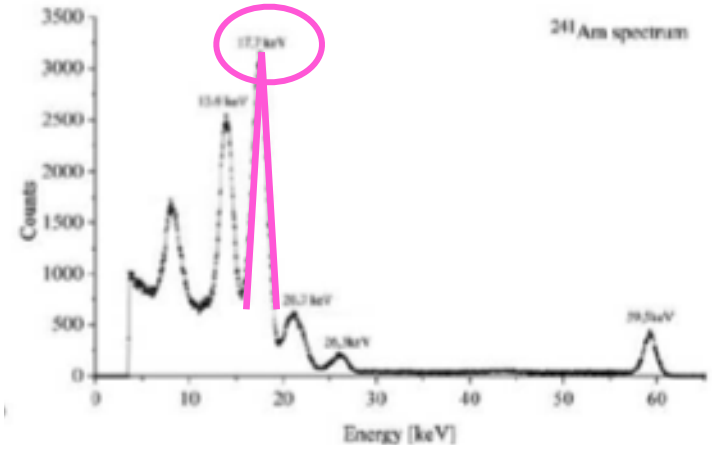
We can compare the number of ADUs of the peaks, with the energy of the peaks in the spectrum of the source (subtracting pedestal)

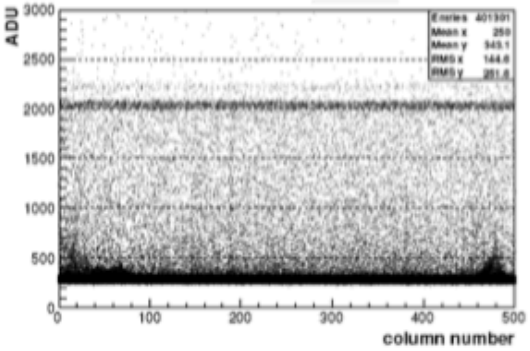
We take the mean value of the Kα of each distribution

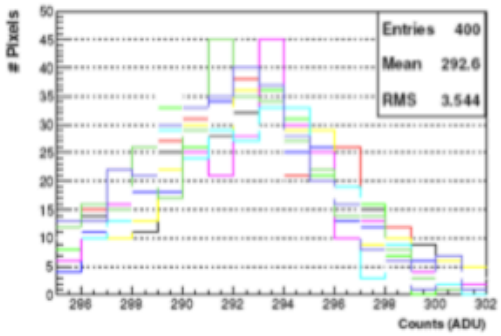
And normalize all to the first one

The slope is the CTI

XRAY test







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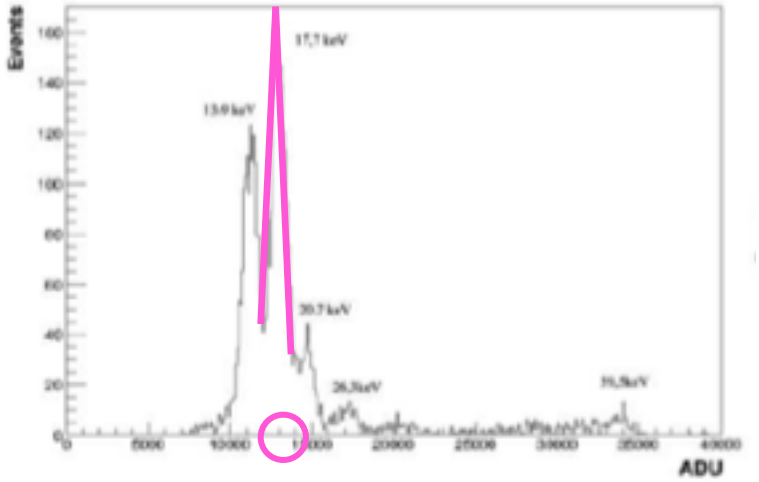

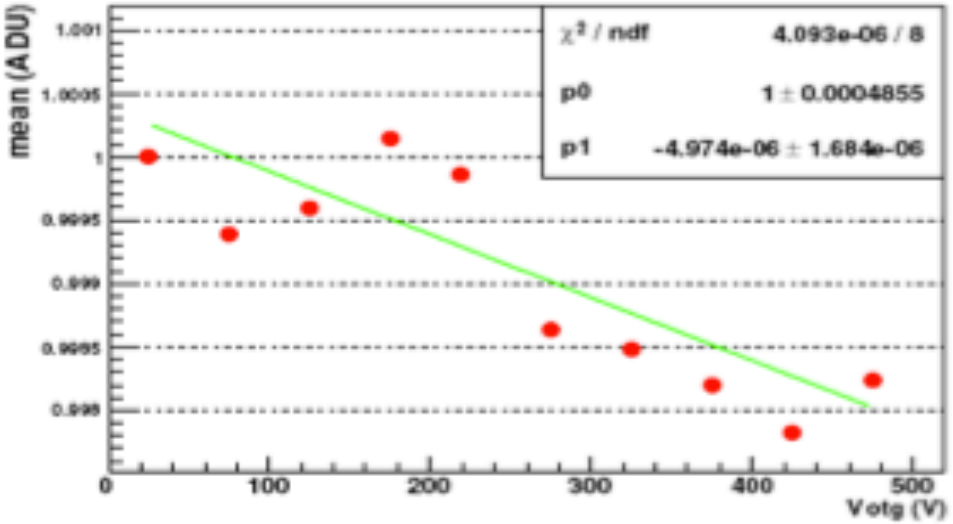

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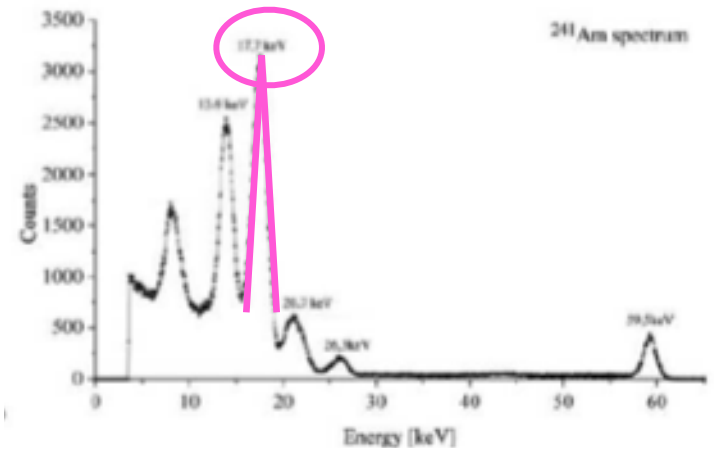
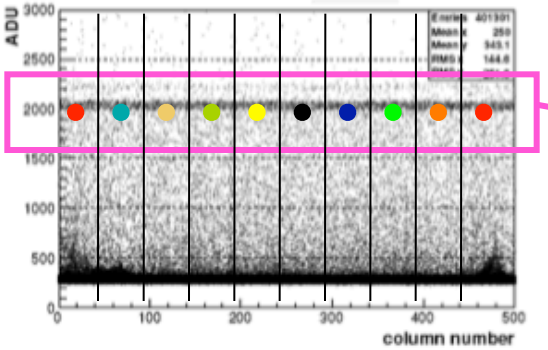
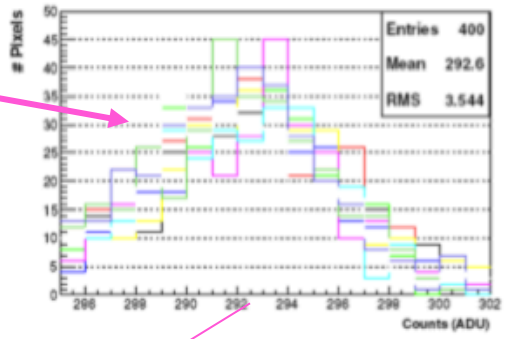
XRAY test







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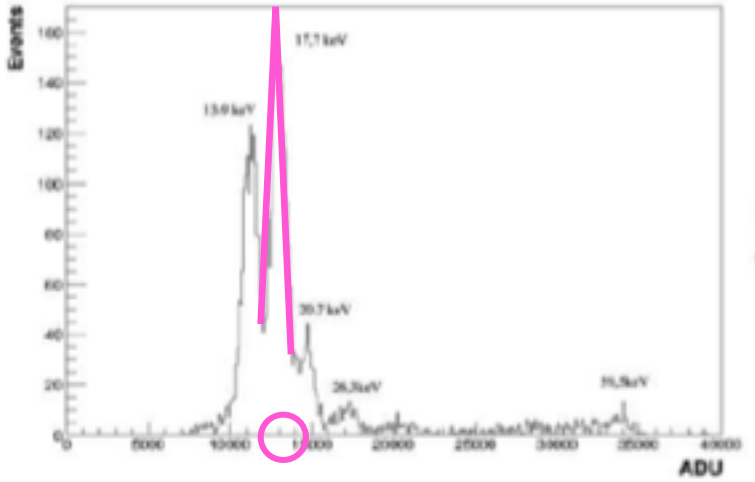

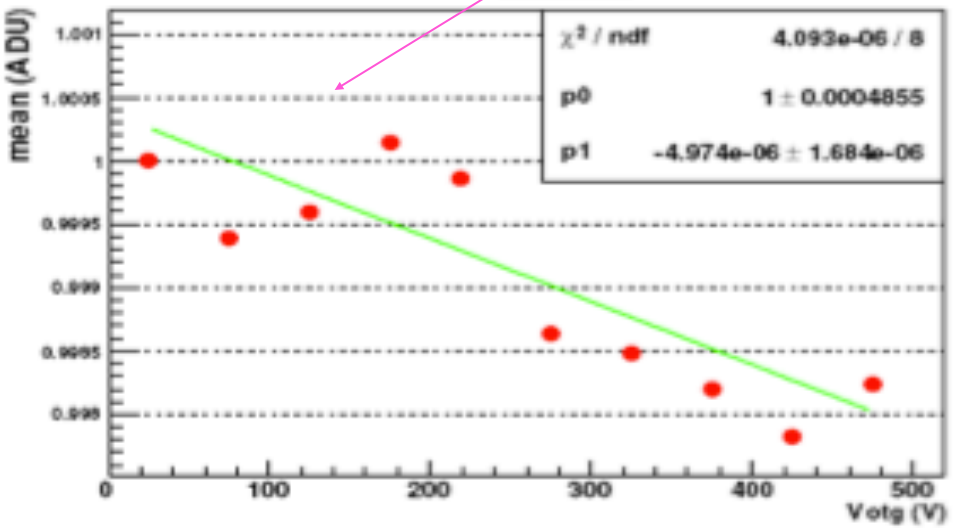

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Outline

- DE introduction
- The Dark Energy Survey
- The SLAB
- DES CCDs
- Tests
- Conclusions

Conclusions

- We have developed a test station in IFAE lab to perform tests to the DES CCDs
- We have an automated way to take the set of images for the tests
- We have learned how a CCD test station works, and now we are able to be a CCD test station for DES and other projects