Calibration of wide-field imagers : lessons learned from SNLS

N. Regnault

(LPNHE, Paris)

Outline

- Context
- Uniformity of imager response (filters, ghosts ...)
- "Brighter-fatter effect"
- Flux metrology
  - Why does calibration matter so much ?
  - Fundamental flux standards
  - Building robust metrology chains
  - The "JLA" (SNLS+SDSS) effort
- Instrumental calibration : the SnDICE project

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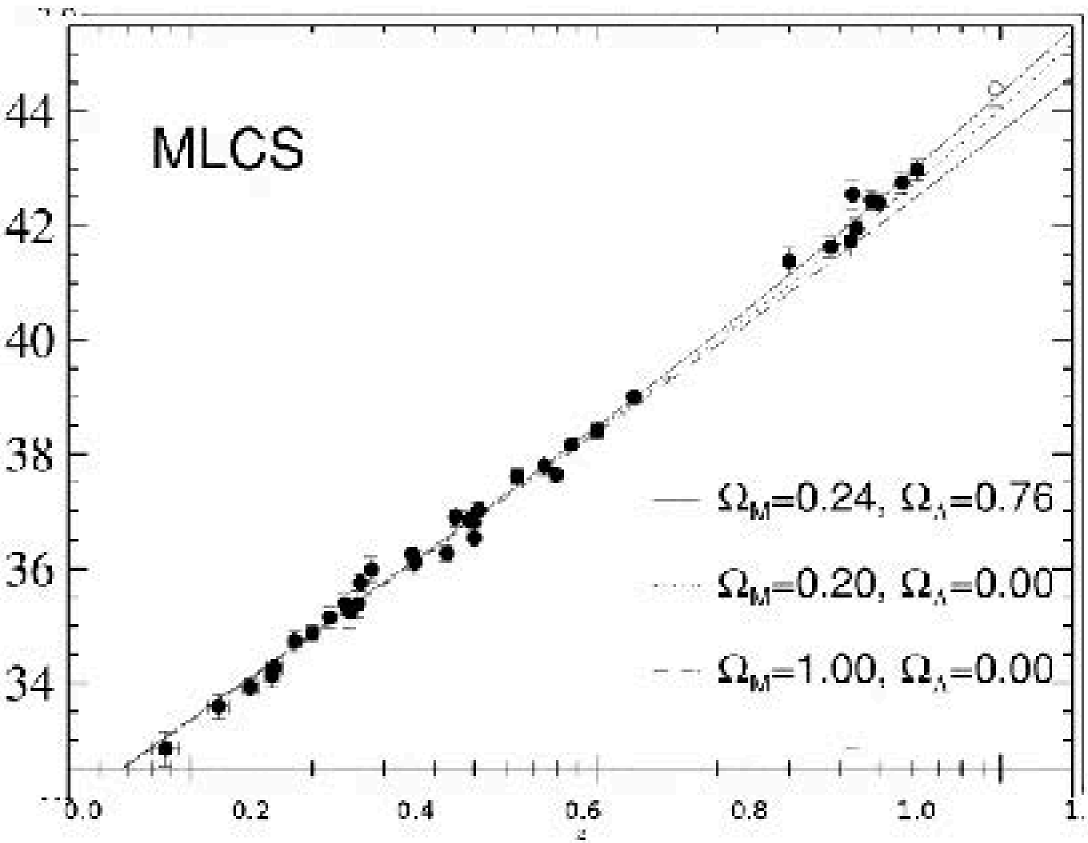
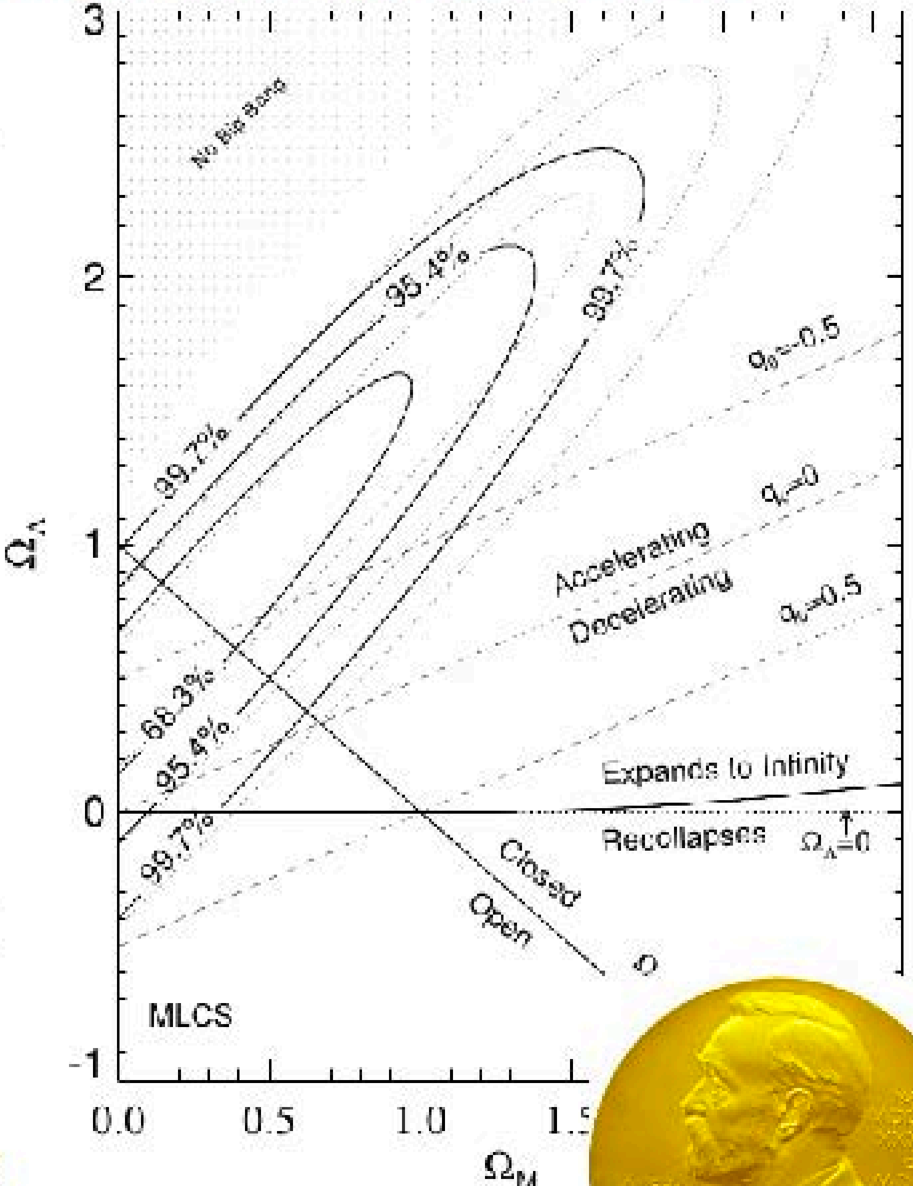
Mapping the expansion with SNe Ia



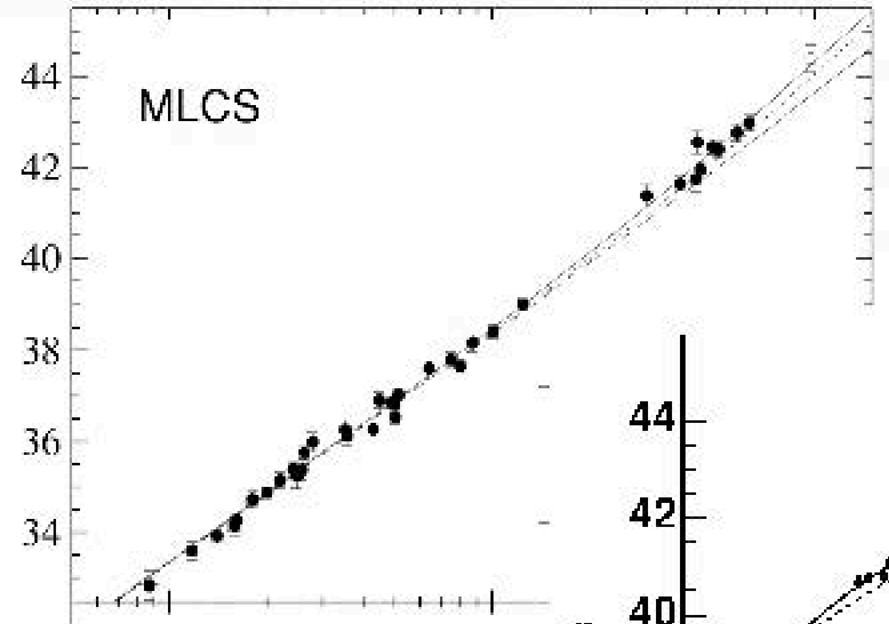


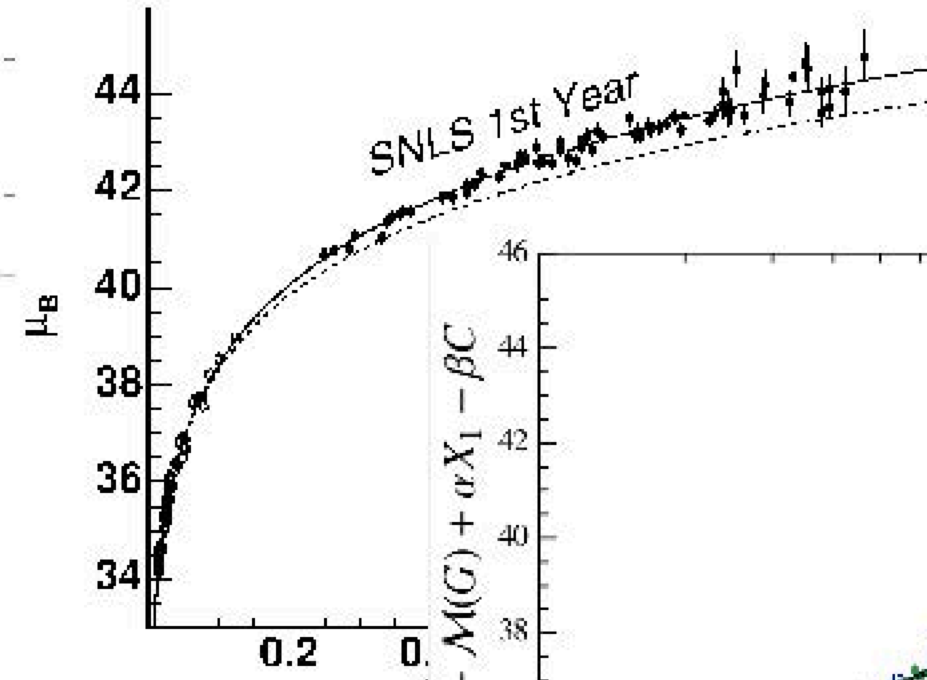
First (convincing) evidence for accelera

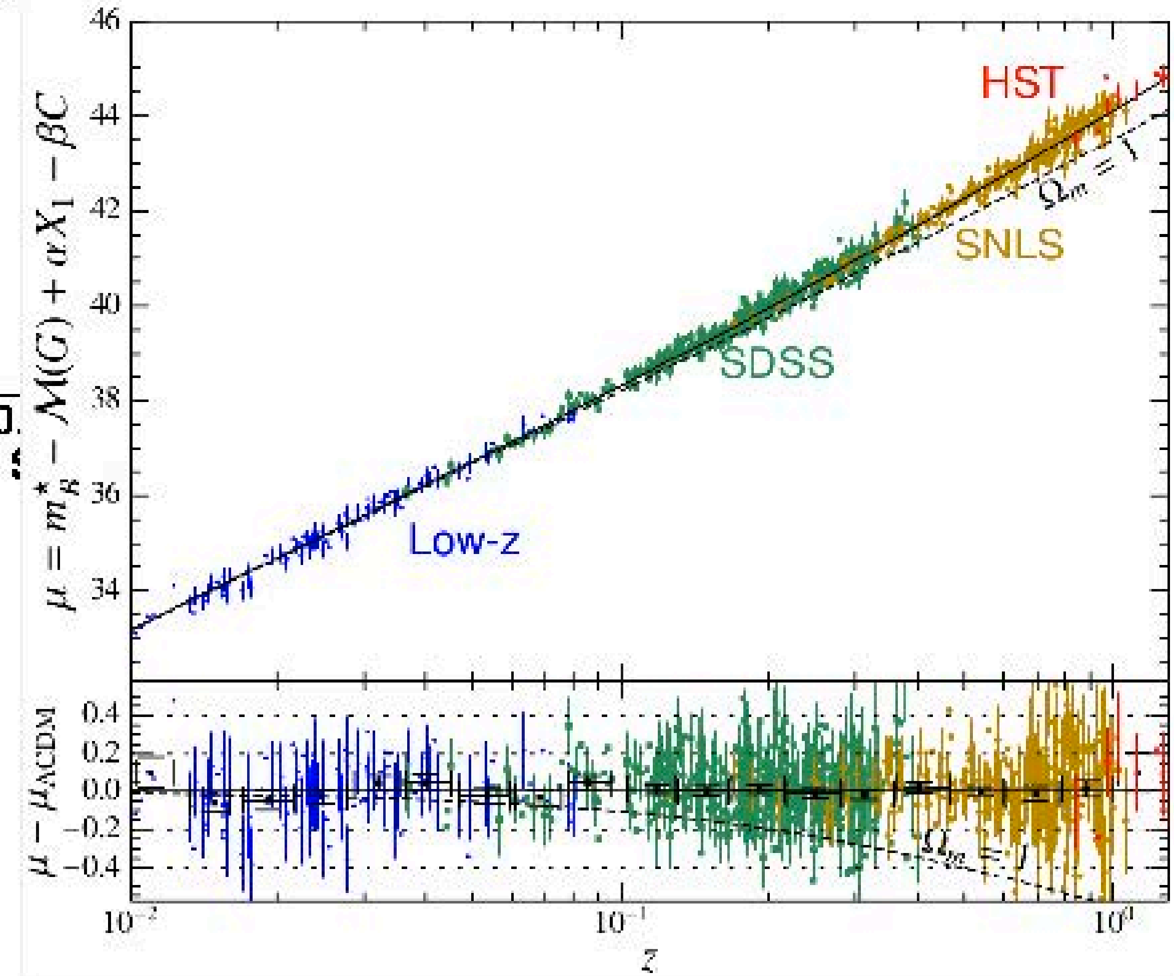
$\rightarrow \Lambda > 0$


MegaCam : 1 deg2
1500 hours on CFHT
1500 hours on 8-m telescopes
~ 500 SNeIa with spec-id

Supernova cosmology



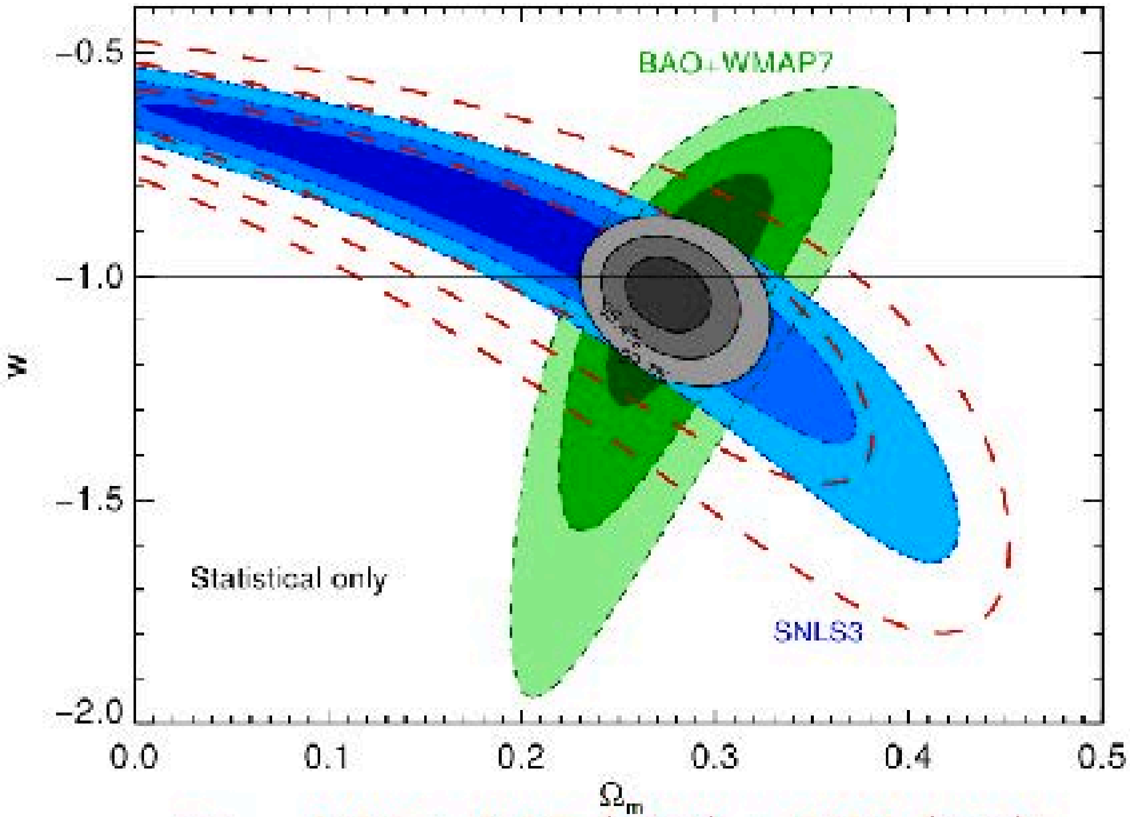




- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) Sne

(x 20 in statistics)

SYSTEMATICS



w = -1.06 ± 0.05 (stat) ± 0.06 (sys)

- SNLS3 analysis

  (Guy et al, '10, Conley et al, '11, Sullivan et al, '11)

- Systematic uncertainties

  ~ half of the error budget

  mostly photometric calibration

Priority : controlling the systematics

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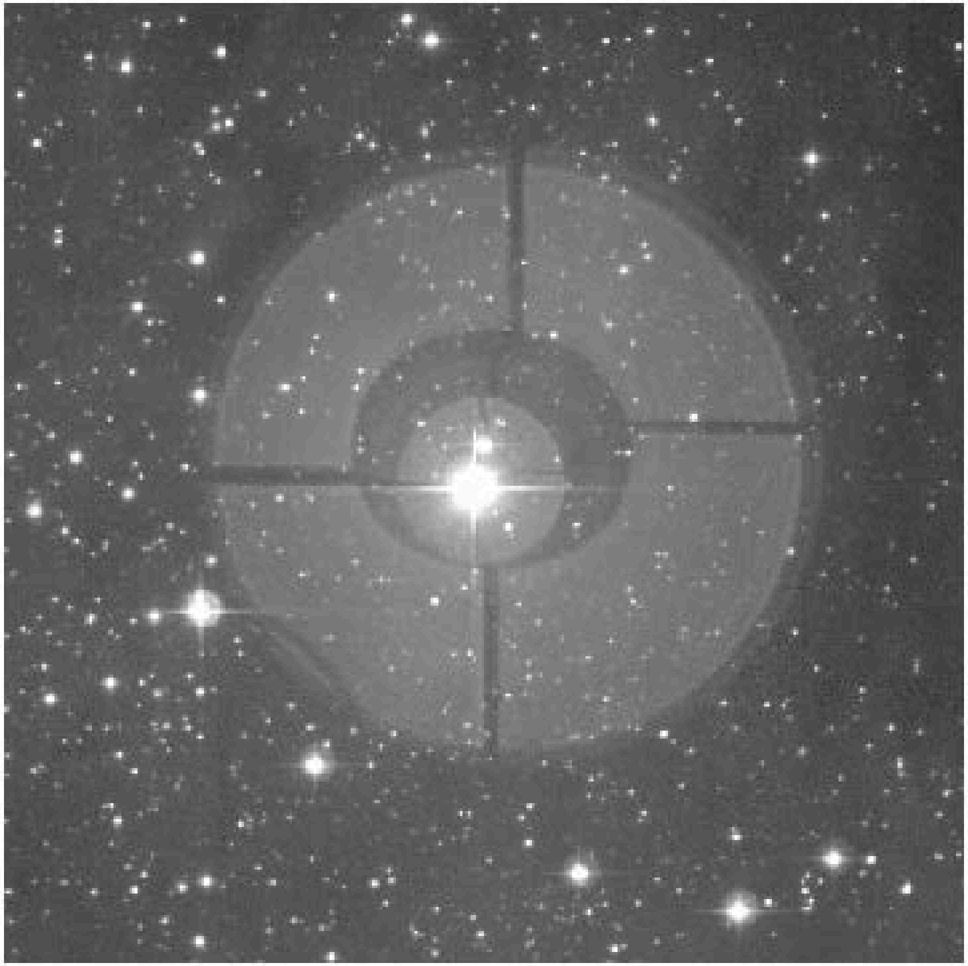
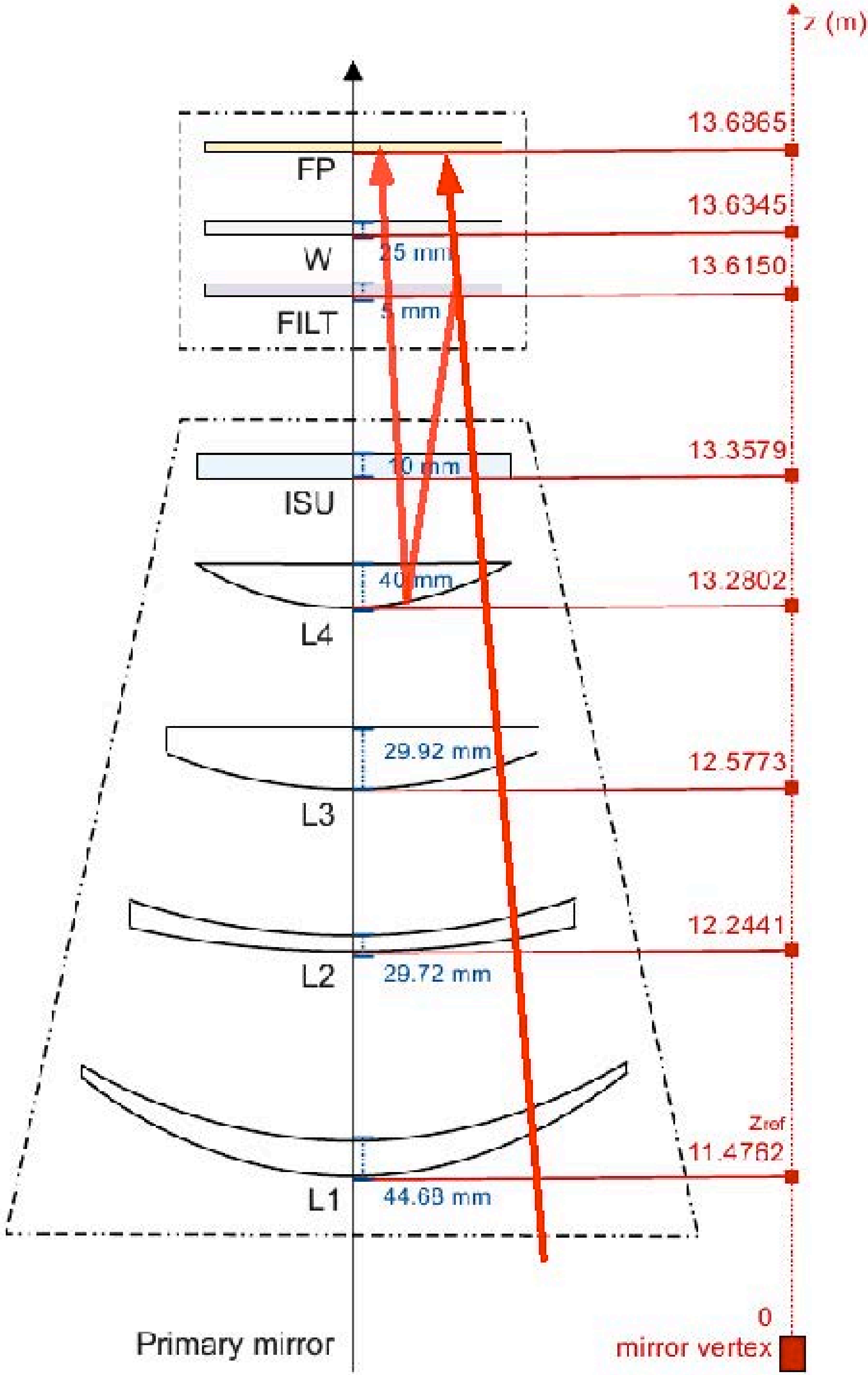
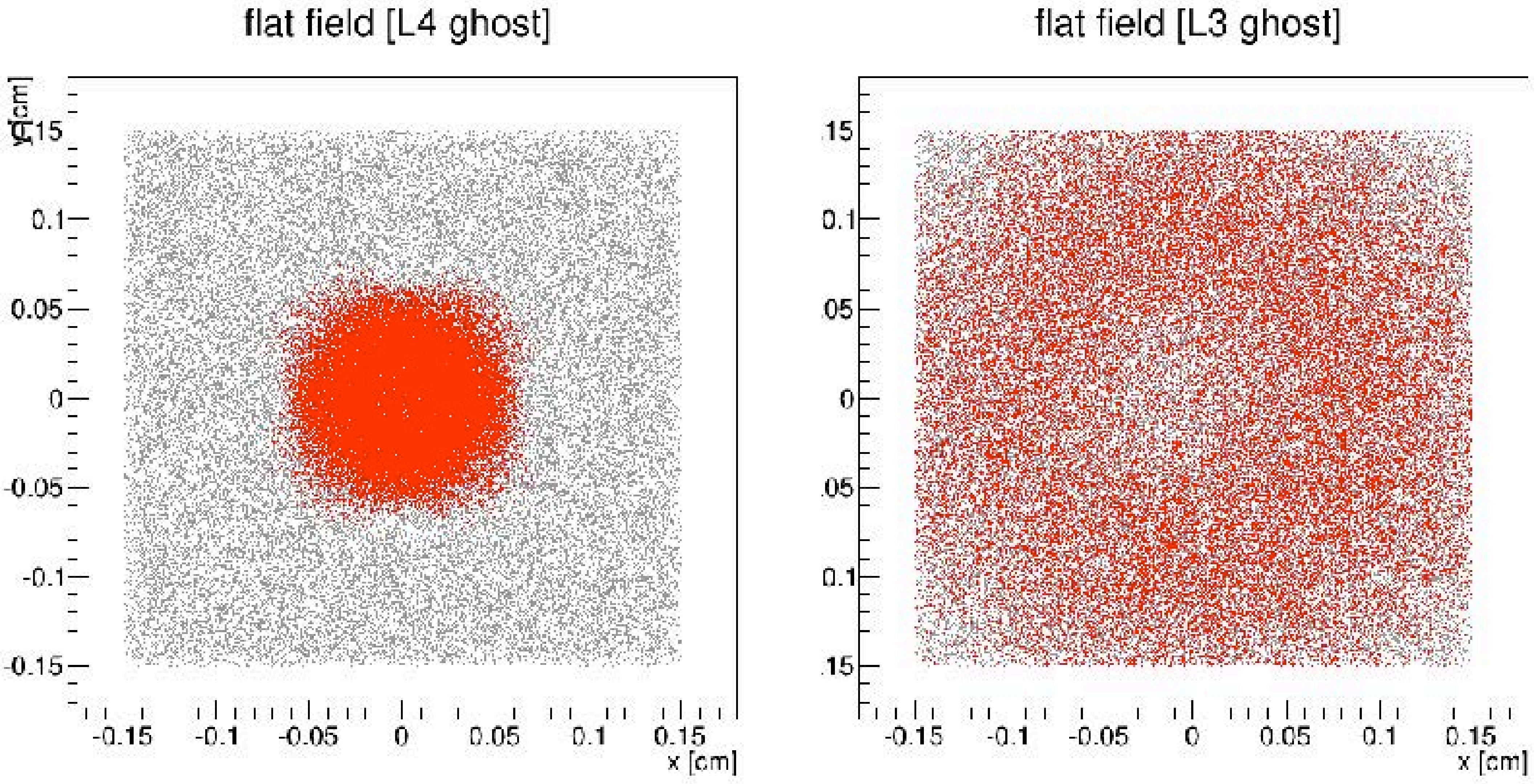
Instrument response



(Regnault et al, '09)
(Betoule et al, '13)

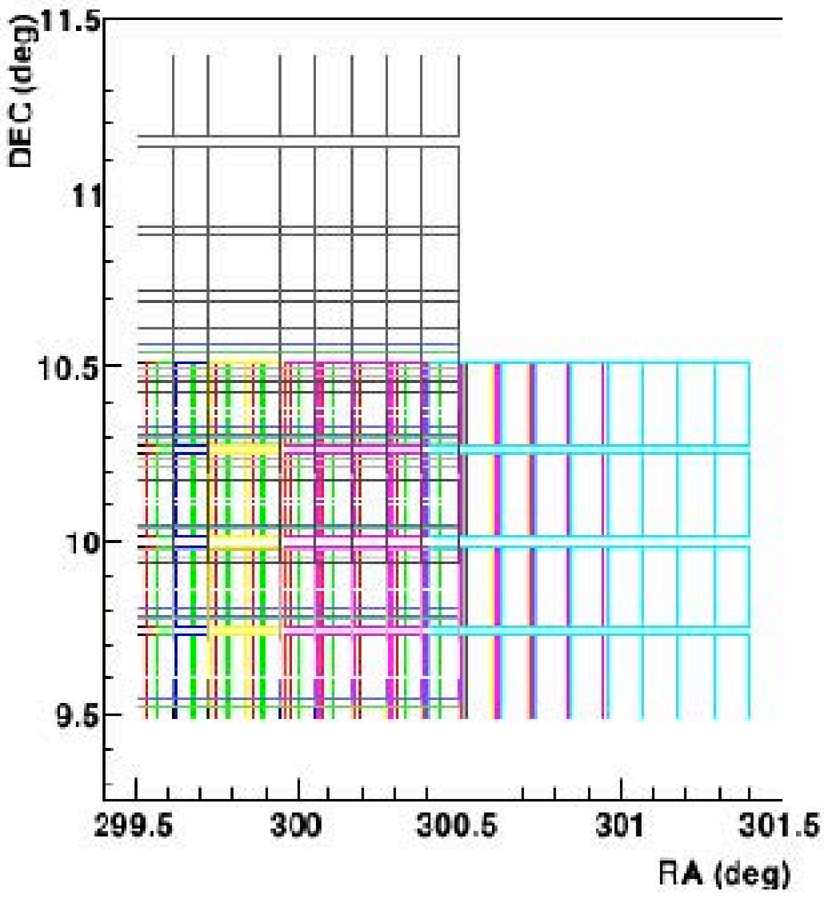
- Flat fields
  - Affected by plate scale variations (well measured)
  - contaminated by ghosts (reflections in the WFC)..
- Filter uniformity ?
  - e.g. MegaCam filters vary by ~ 5-nm from center to corner.


z (m)
13.6865
13.6345
13.6150
13.3579
13.2802
12.5773
12.2441
Zref
11.4762
0
mirror vertex
FP
W
25 mm
FILT
5 mm
10 mm
ISU
40 mm
L4
29.92 mm
L3
L2
29.72 mm
L1
44.68 mm
Primary mirror



flat field [L4 ghost]
flat field [L3 ghost]
y [cm]
x [cm]
x [cm]
-0.15
-0.1
-0.05
0
0.05
0.1
0.15

Mapping the instrument response



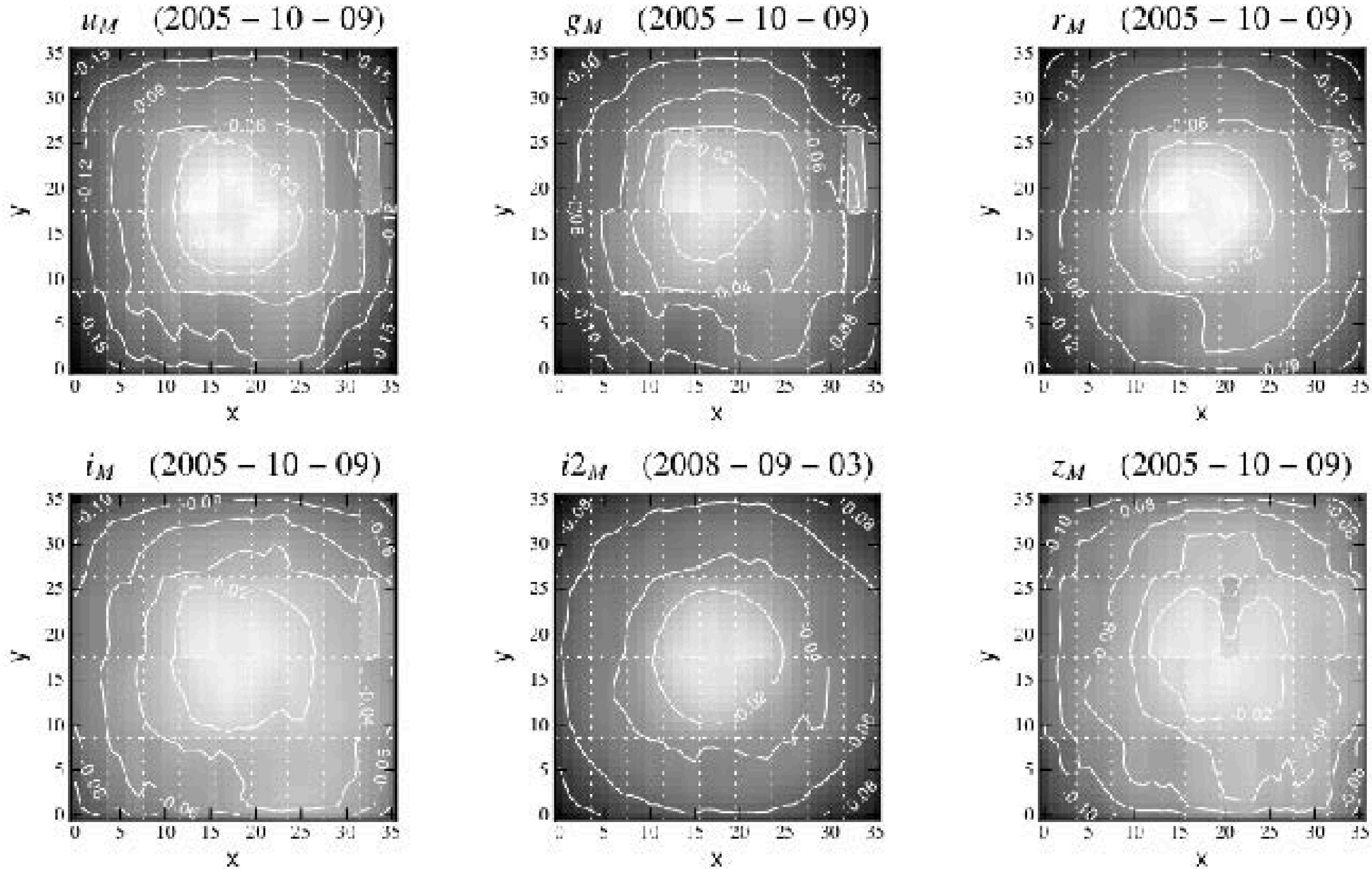
- Dithered observations of dense stellar fields
  - Logarithmically Increasing steps (1.5' $\longrightarrow$ 0.5 deg)
  - Observed every ~ 6 months
- Model

$$m(x) = m(x_0) + \delta zp(x) + \delta k(x) \times col$$

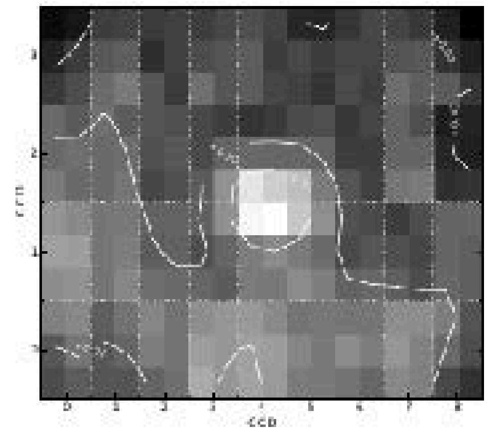
Star mags @ center (~ 100,000 pars)

Maps (~ 100 pars)

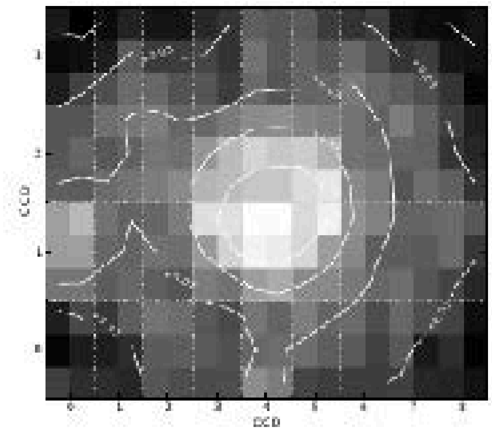
Plate scale + ghosts



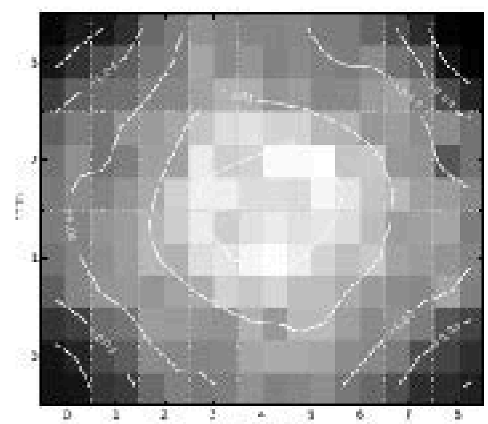
Filter variations (in WL)



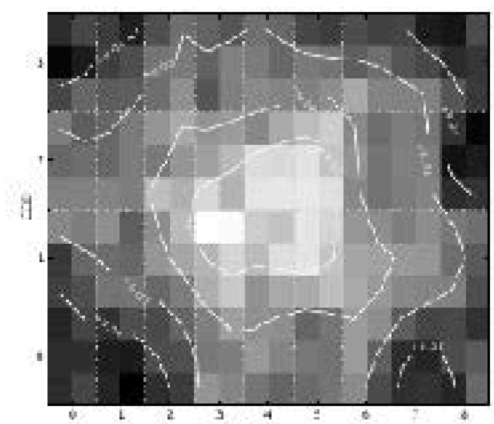
(a) $\delta \tilde{k}$[illegible]$(\mathbf{x})$



(b) δk[illegible]$(\mathbf{x})$

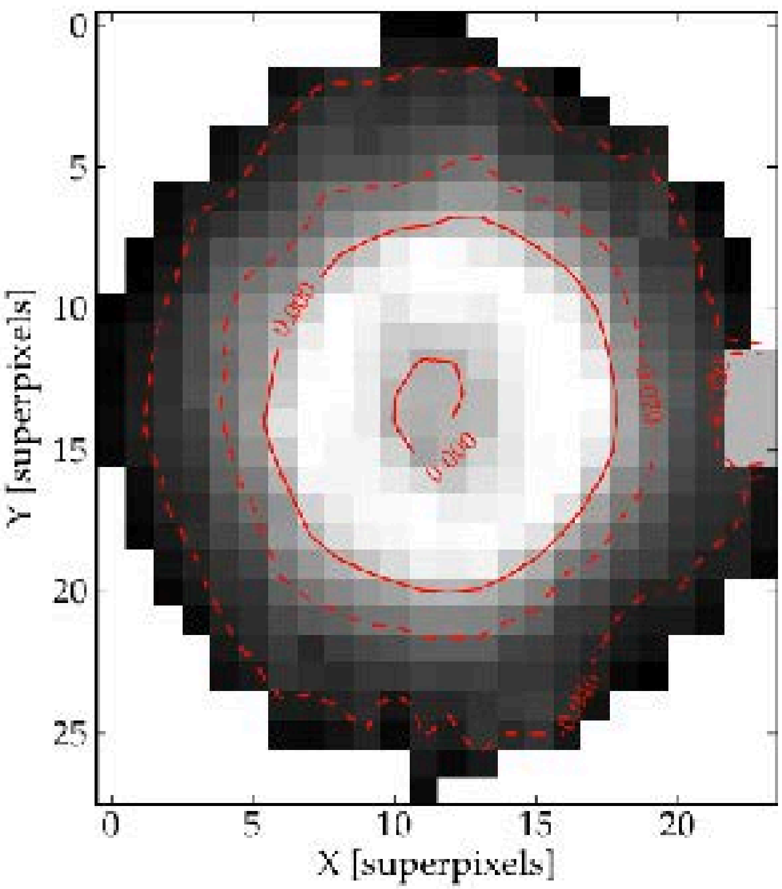


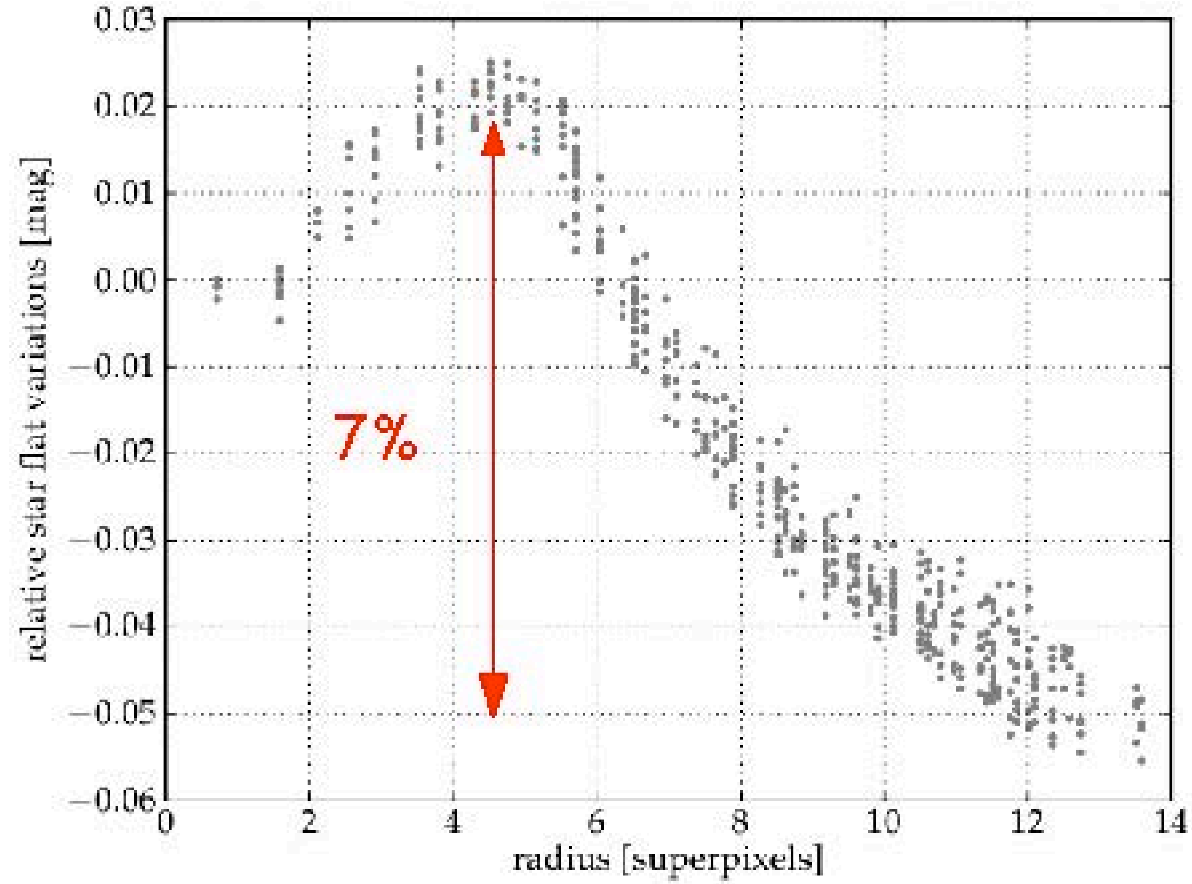
(c) δk[illegible]$(\mathbf{x})$

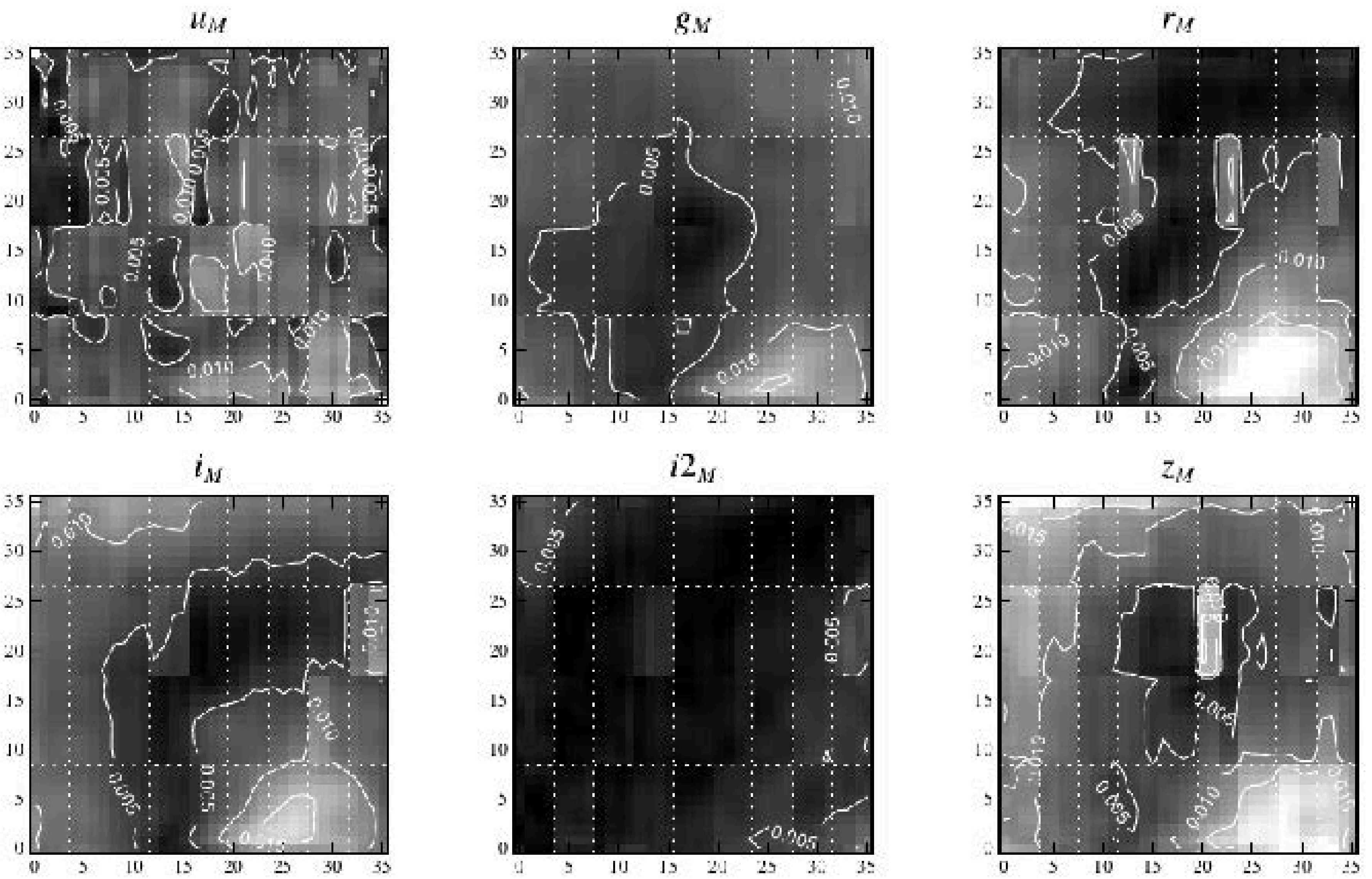


(d) δk[illegible]$(\mathbf{x})$

G-BAND


Y [superpixels]
X [superpixels]
0
5
10
15
20
25


relative star flat variations [mag]
radius [superpixels]
7%
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
0
2
4
6
8
10
12
14



u_M
g_M
r_M
i_M
$i2_M$
z_M

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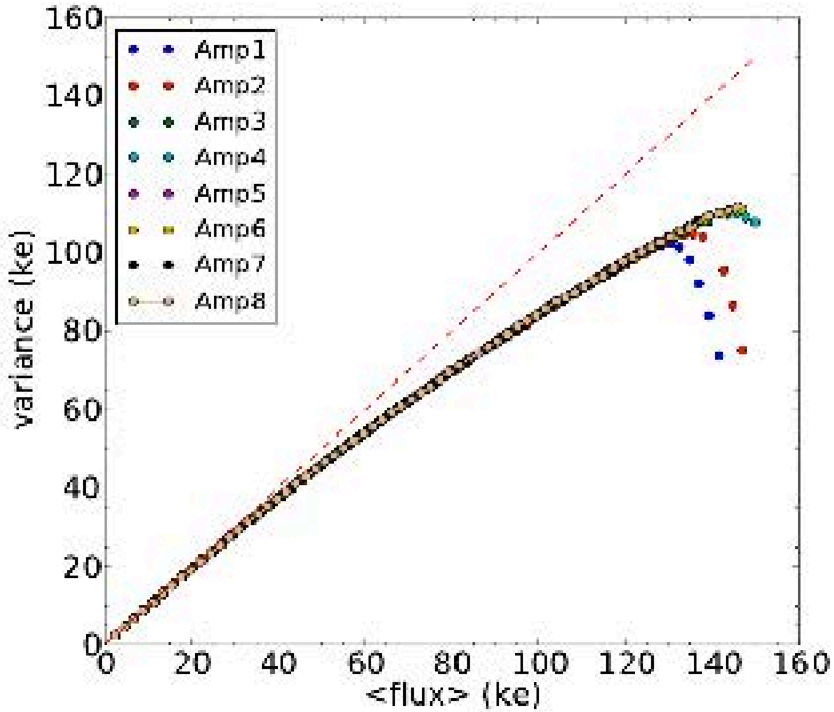
Facts

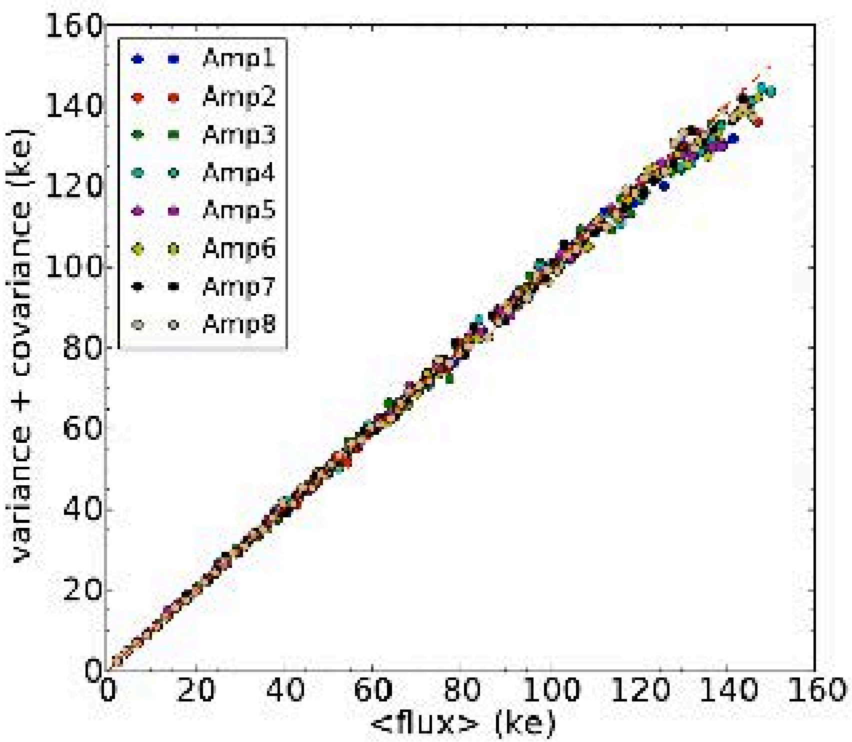
- There are statistical correlations in flat fields
  - decay rapidly with distance
  - Pixel-to-pixel covariances grow quadratically with flux

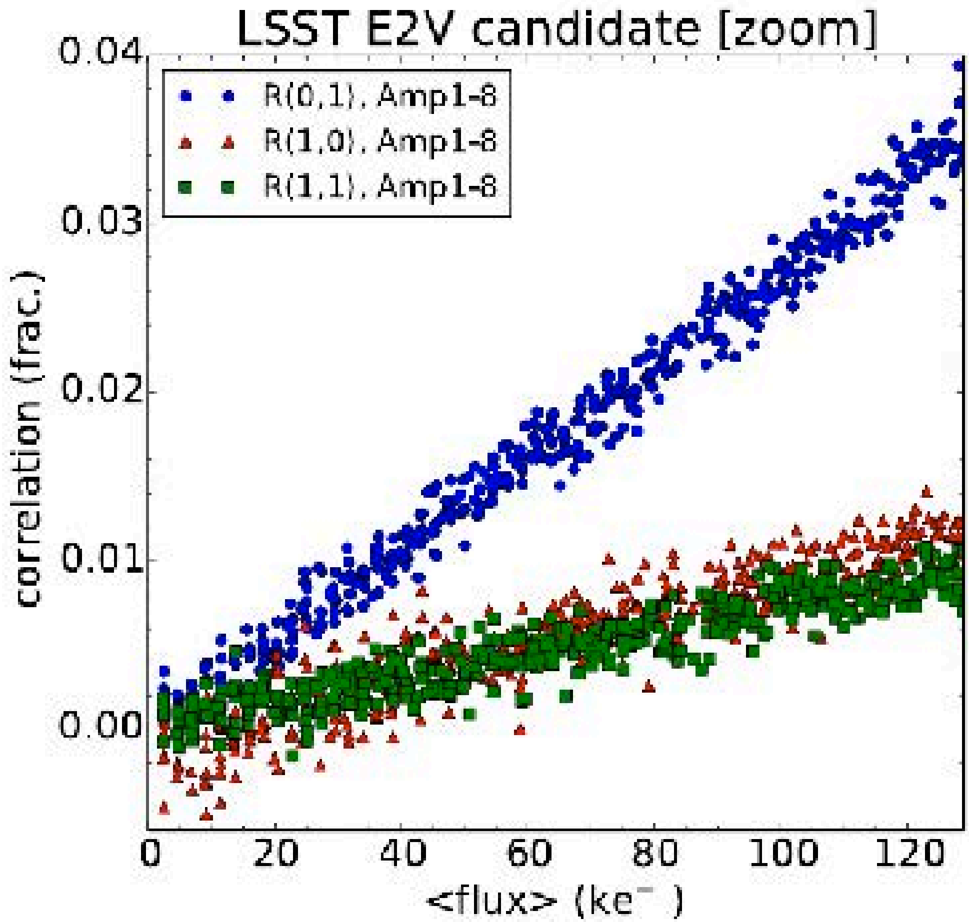
    $\longrightarrow$ Photon transfer curve not linear
- PSF seems to vary with flux
  - Brighter stars are fatter than fainter stars
  - Small impact on SN photometry
  - Potentially strong impact on galaxy shape measurements.

(Antilogus et al '14)
(Guyonnet et al, in prep)

PTC & PIXEL CORRELATIONS



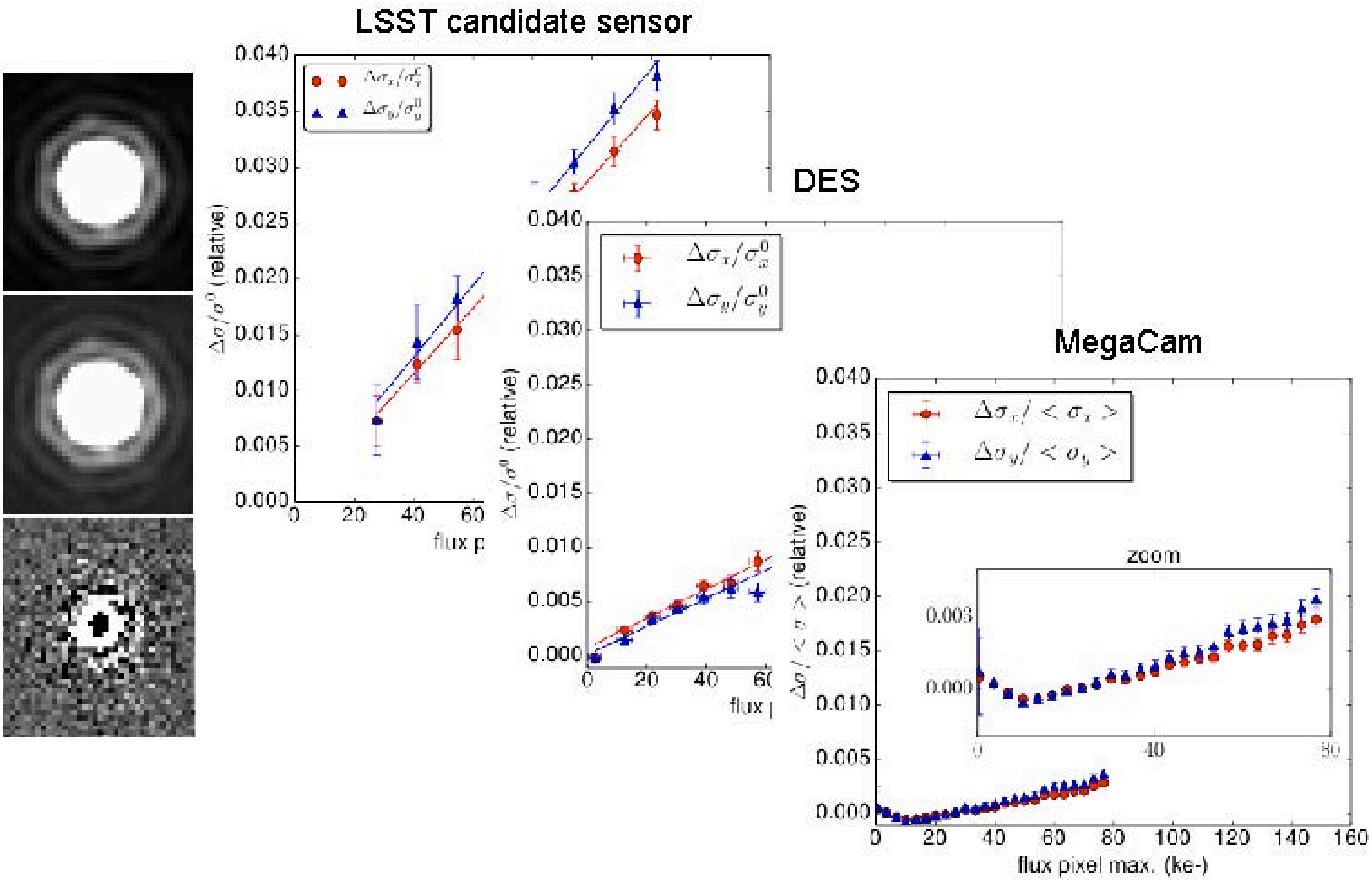




- Effect similar in all 8 amps
  $\longrightarrow$ intrinsic to the CCD !

(Guyonnet et al, in prep)

“Brighter fatter effect”



Are these effects related ?

- Charge accumulated in CCD pixels perturbs the drift electric field

  → subsequent electrons won't drift the same way.

  → pixel size "shrinks" as charge accumulates.

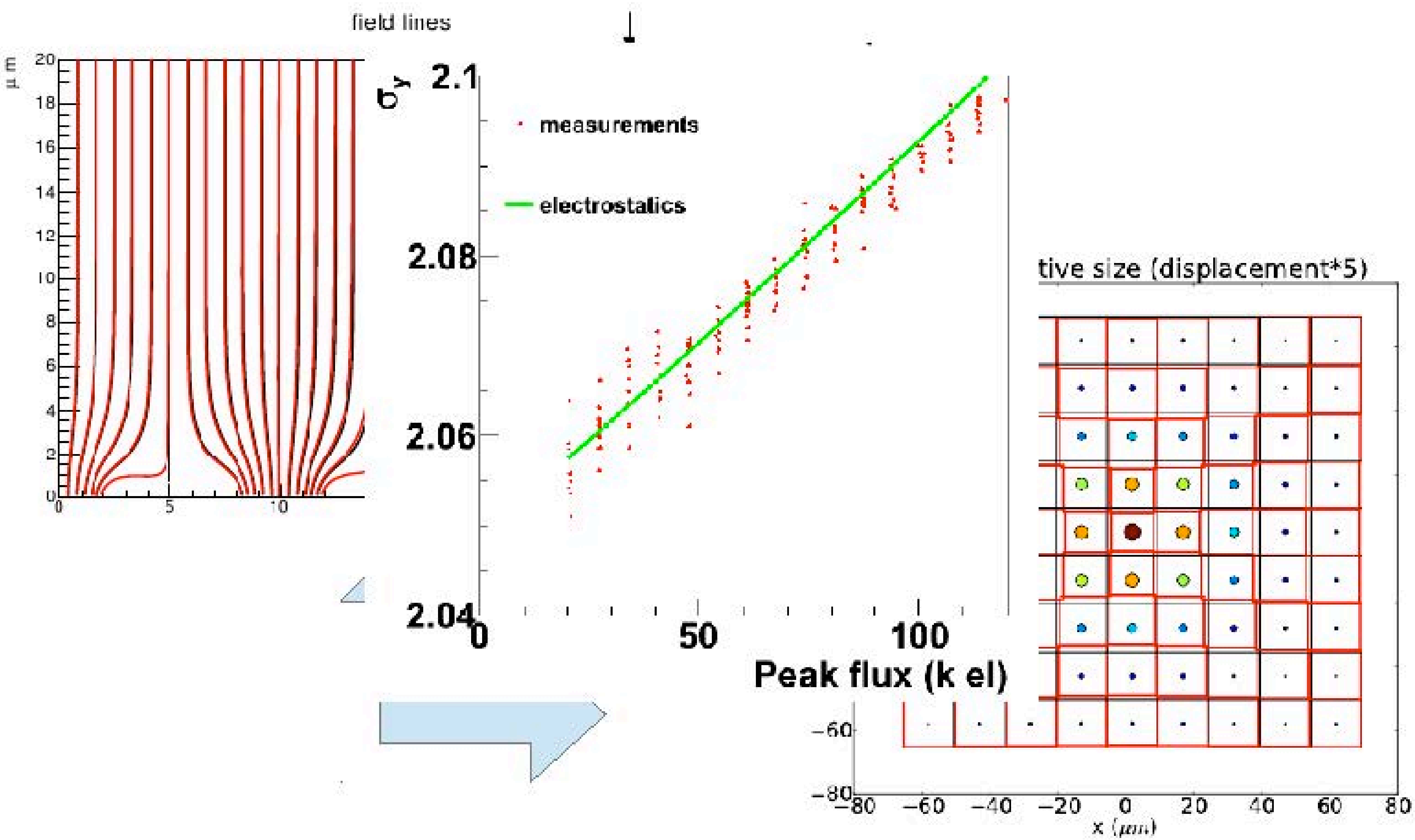
  → correlations between pixels

  → stars / spots seem to "widen" as flux increases

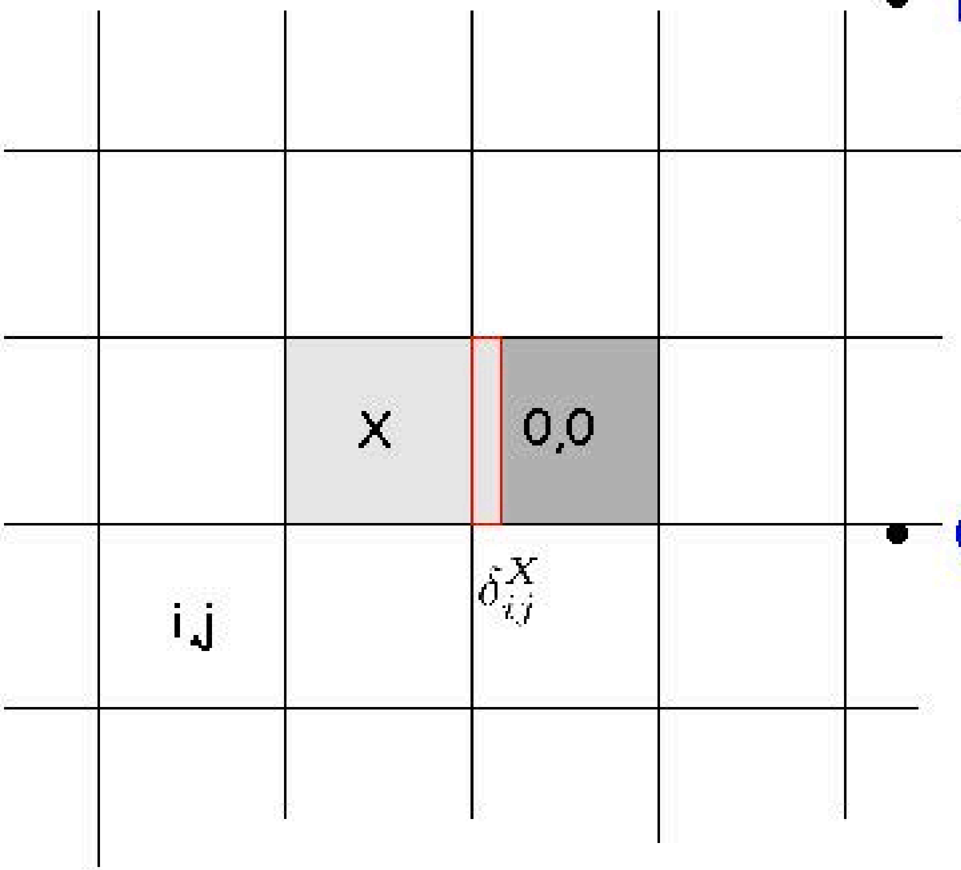
- Goals

  - Empirical model to reproduce this ?
  - Alter the average PSF models to account for the effect

Electrostatic simulation



Empirical model



- Drift field perturbed by pixel charges
  - Pixel "boundaries" move slightly
  - e- drift to adjacent pixels

$$\delta q_{00}^X = \sum_{ij} a_{ij}^X q_{ij} (q_{00} + q_X)$$

- One can show that (flat field)

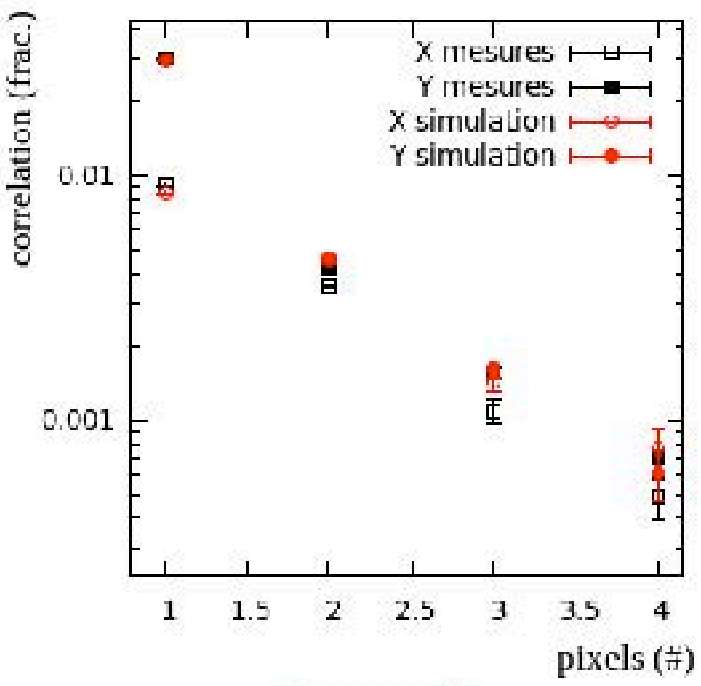
$$\mathrm{cov}(q'_{i,j}, q'_{00}) = 4V\mu \sum_X a_{ij}^X$$

Quadratic behavior in flux
(as observed)

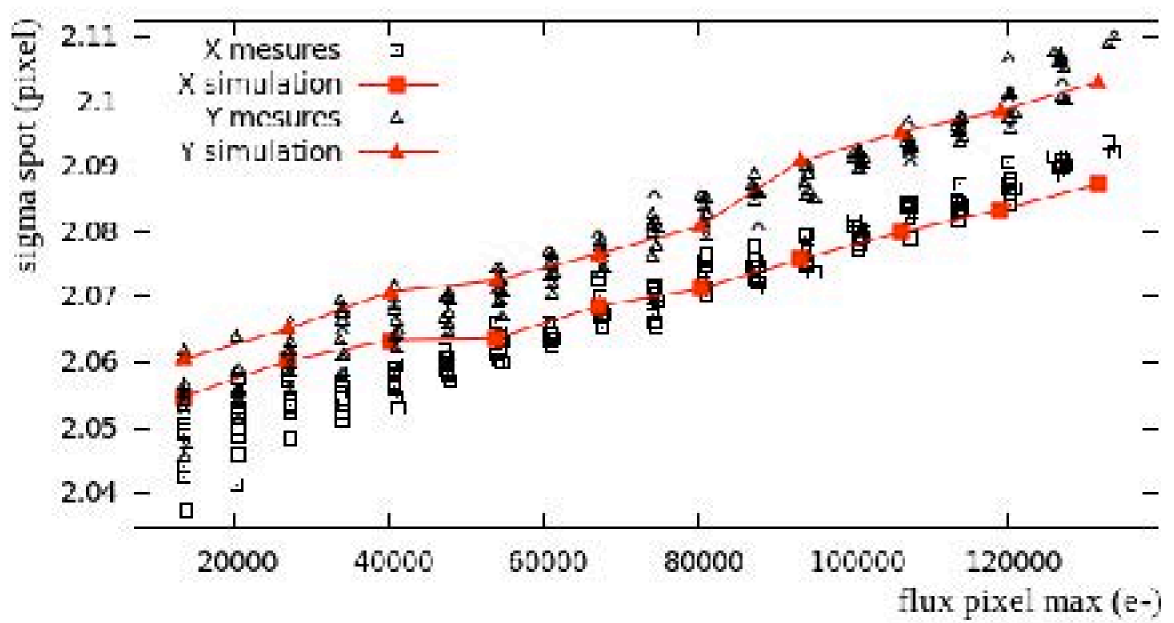
$$\delta_{ij}^X = a_{ij}^X \times q_{ij}$$

(Antilogus et al, '14)
Guyonnet et al, in prep)

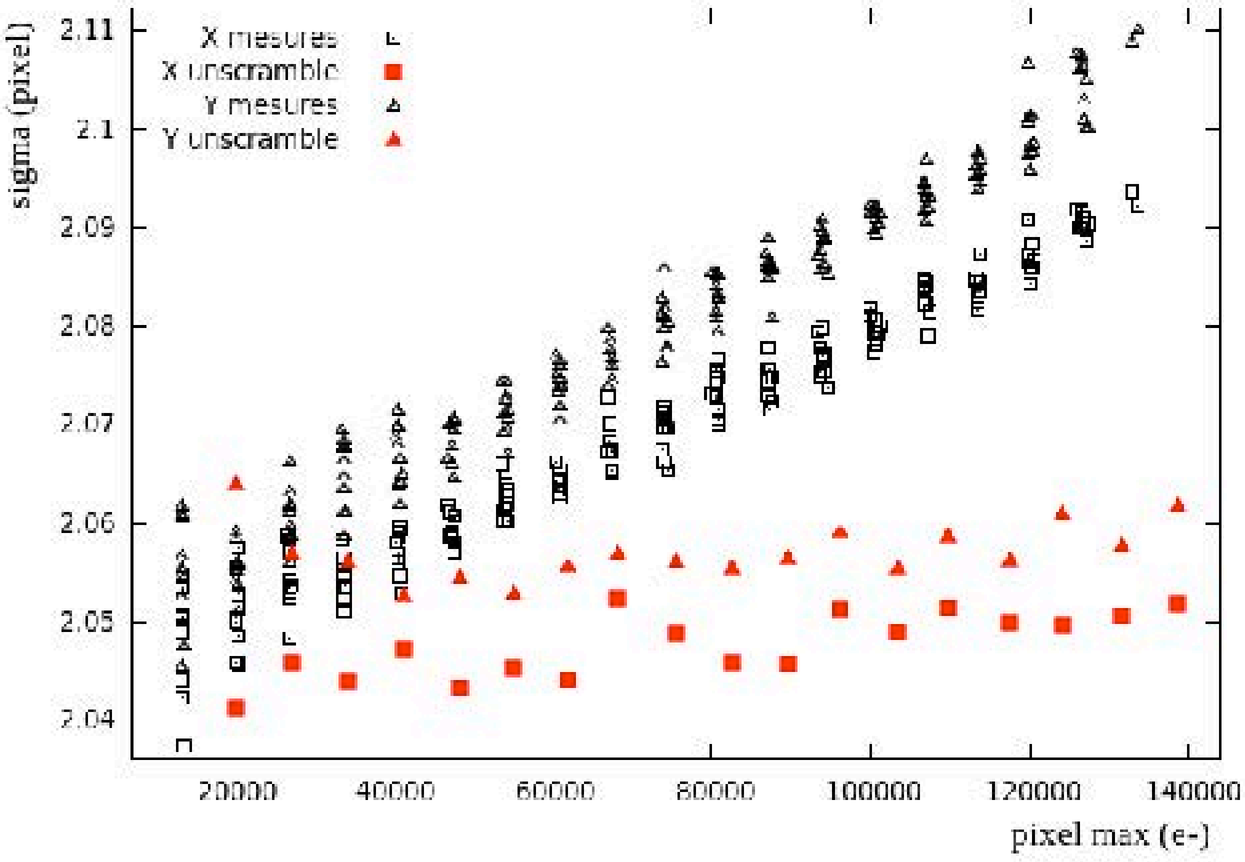
TESTING THE MODEL ON THE LSST SENSORS



1) Parametrize the a_ij (~ 3 coefficients)
2) Constrain parametrization on flatfields
3) Apply model to (stacked) low flux spots
→ does reproduce the BF relation!



Testing the model on the LSST sensors



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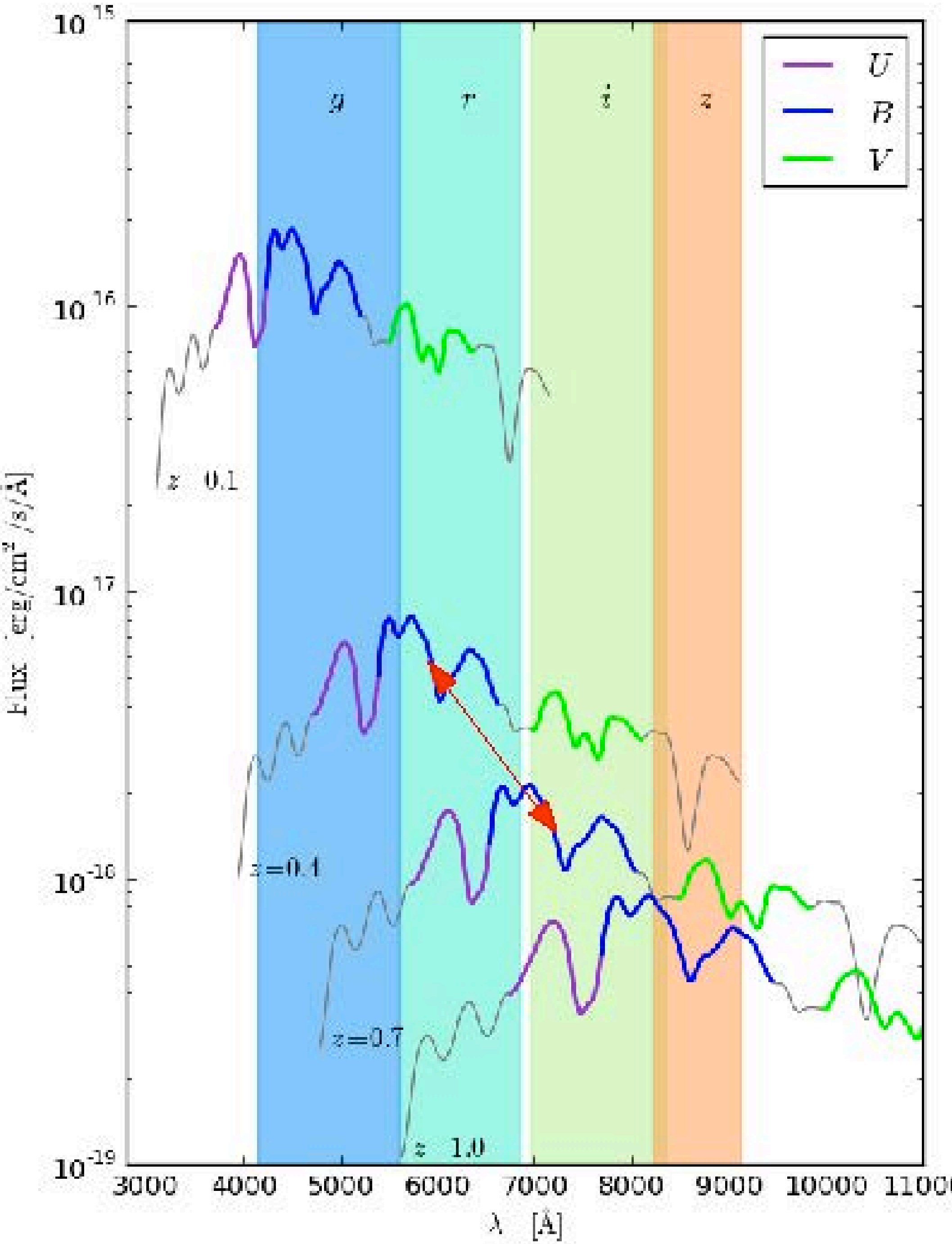
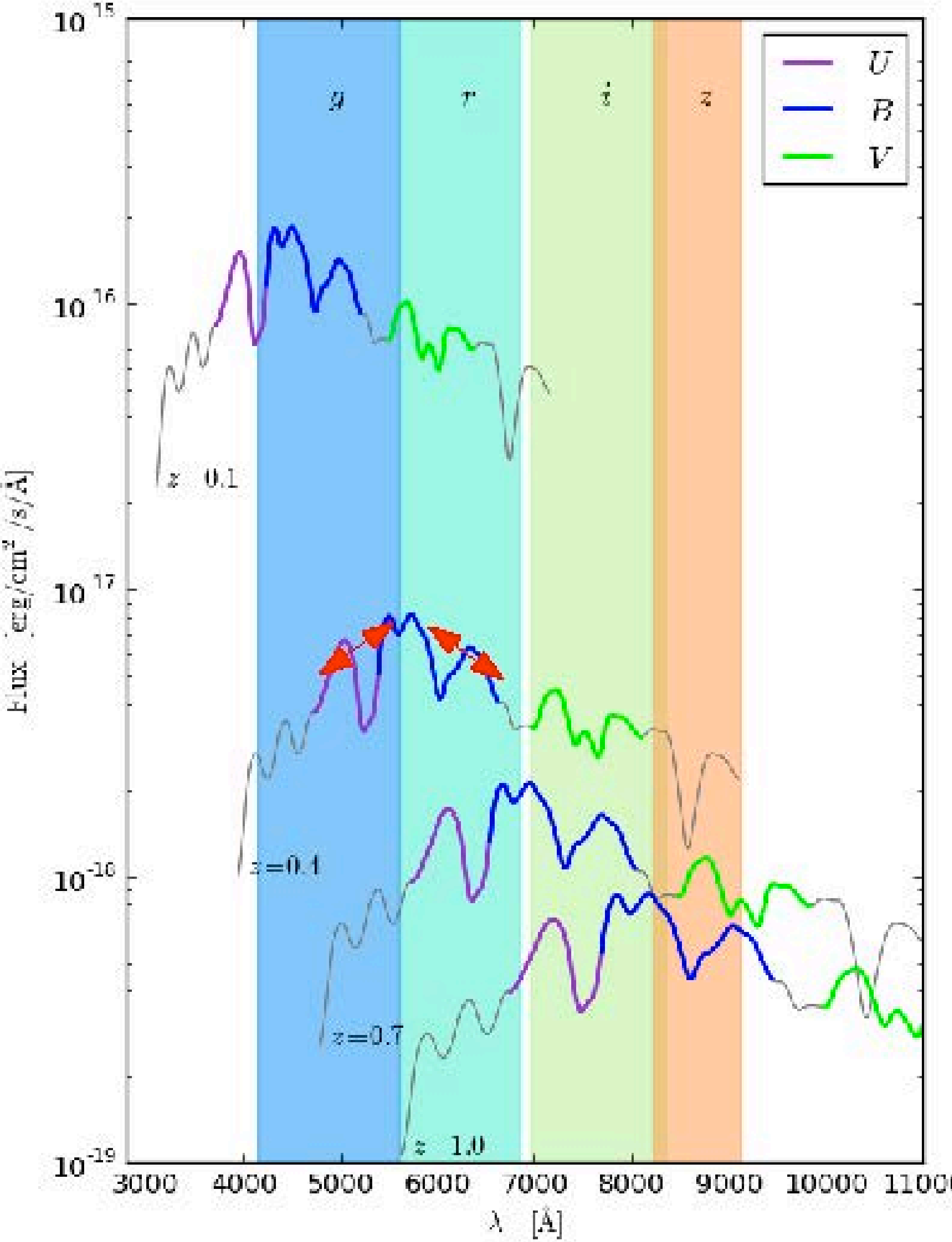
Why does calibration matter so much ?



- Ingredients
  - Flux ratios between (observer) bands

    → (relative) flux calibration

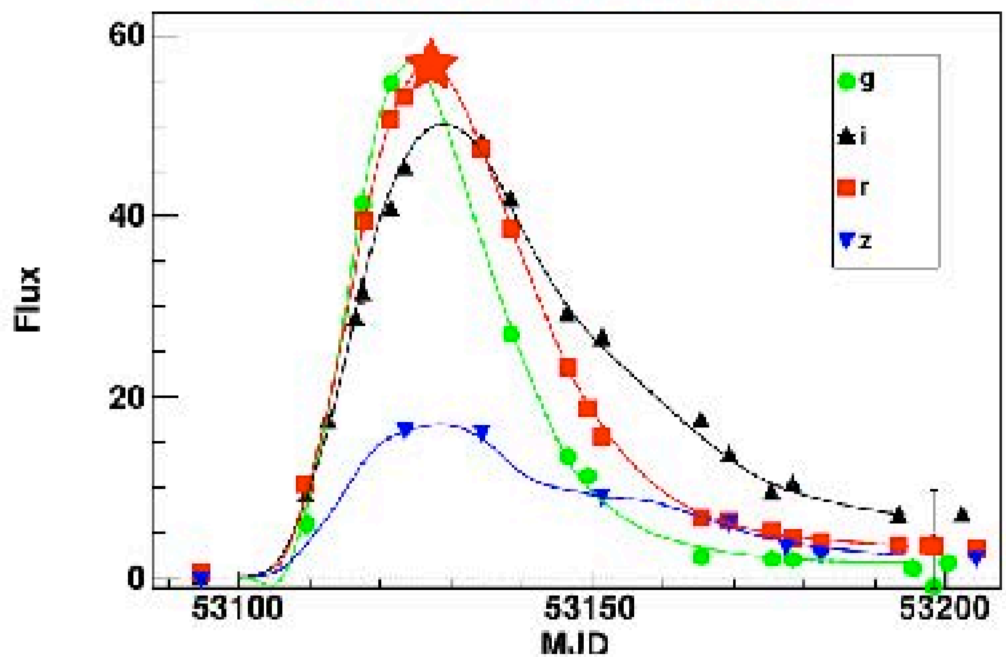
Why does calibration matter so much ?



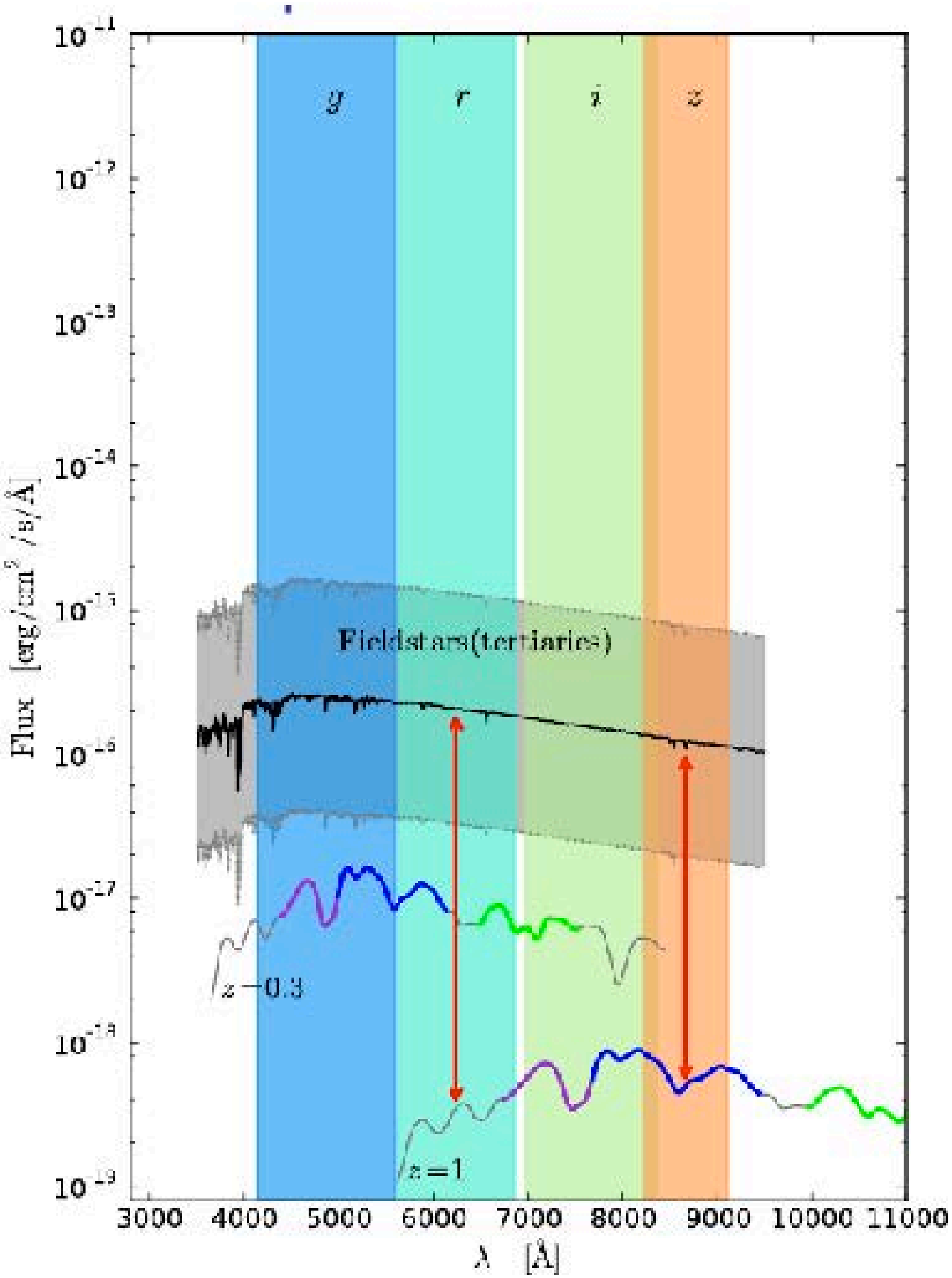
- Ingredients
  - Flux ratios between (observer) bands

    → (relative) flux calibration
  - Interpolate in time and wavelength

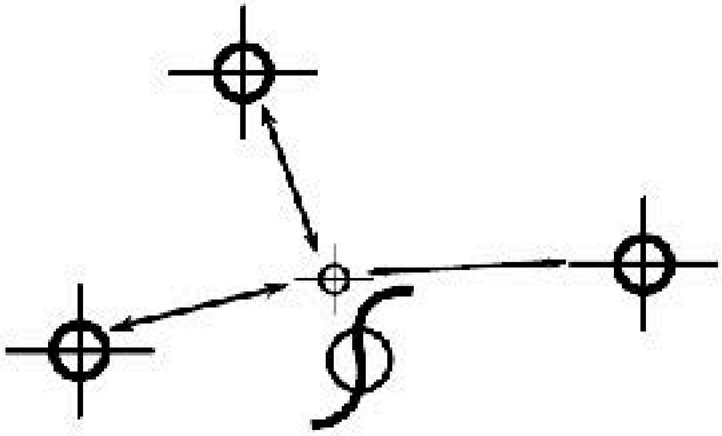
    → Light curve model



Calibration chain



- Instrument response
  - Measure flux ratios in a single image



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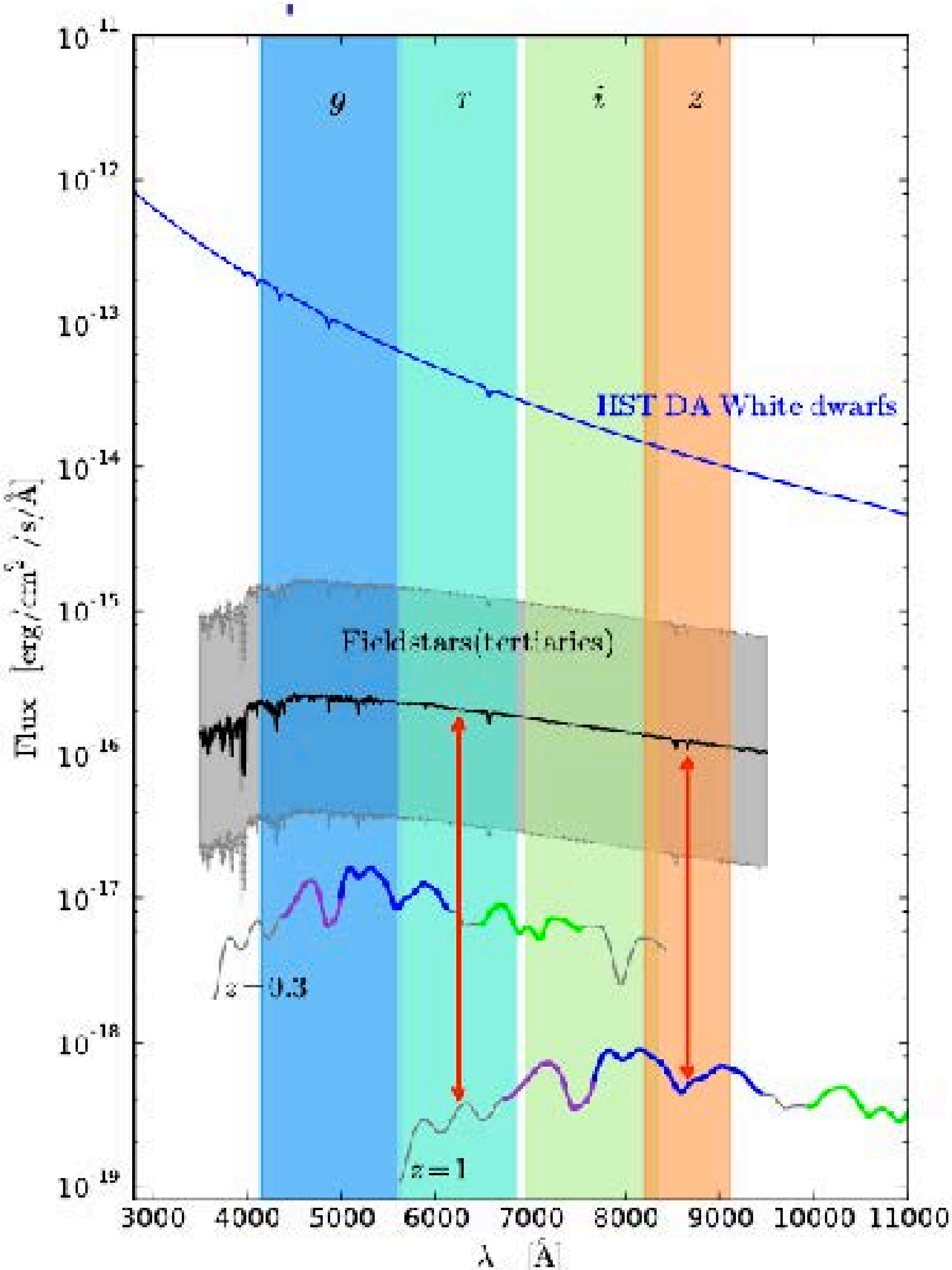

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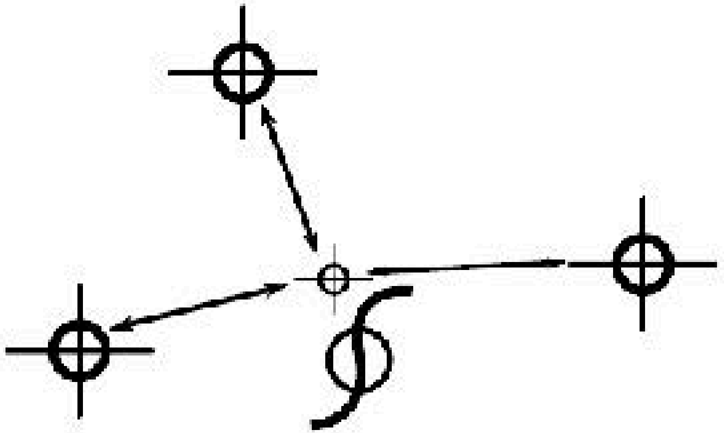
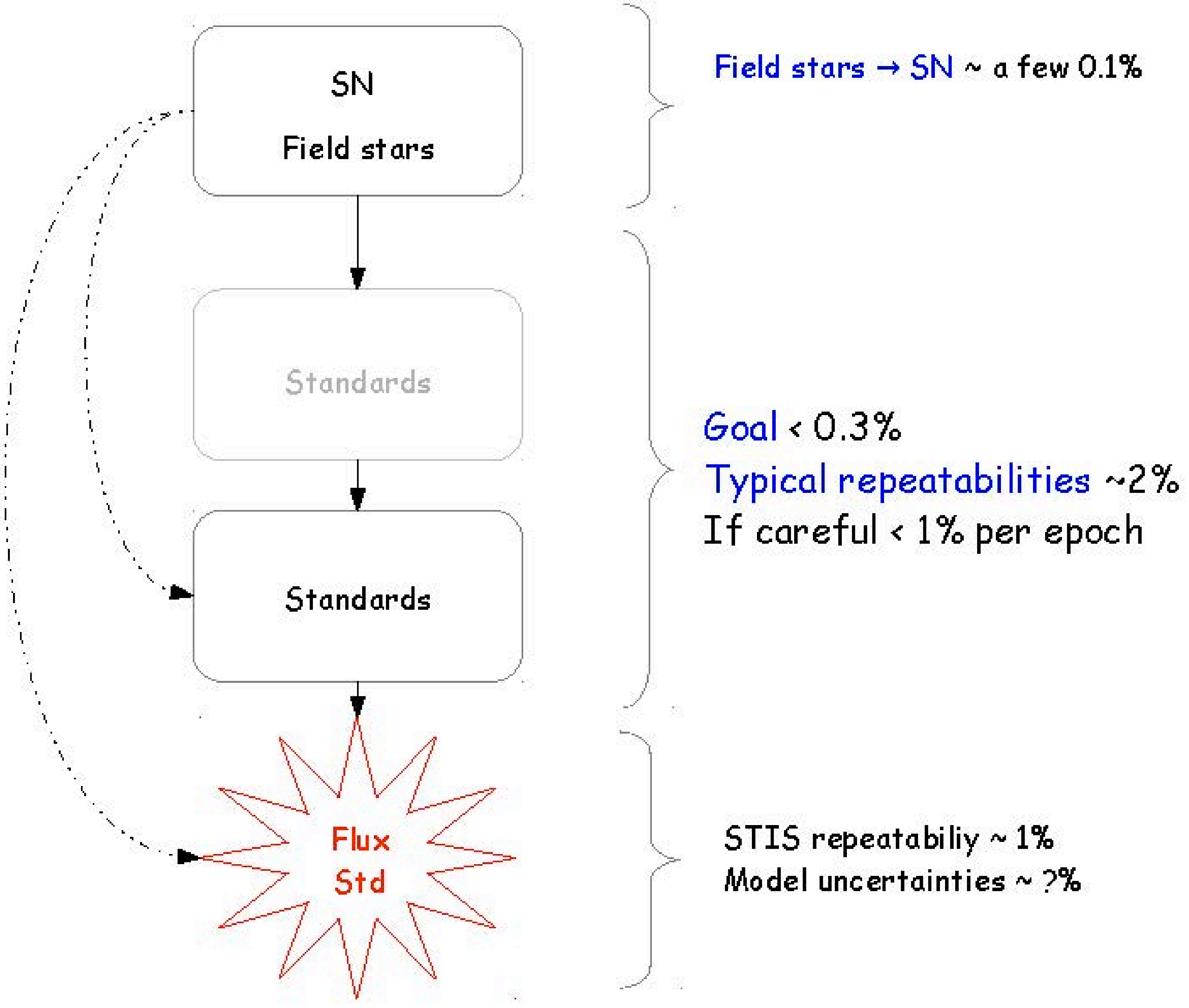


- Calibration transfer
  - HST standard as a primary calibration flux


SN
Field stars
Standards
Standards
Flux
Std
Field stars → SN ~ a few 0.1%
Goal < 0.3%
Typical repeatabilities ~2%
If careful < 1% per epoch
STIS repeatabiliy ~ 1%
Model uncertainties ~ ?%

Fundamental Flux standard(s)

CALSPEC

Models of 3+ Hot DA white dwarfs

HST STIS / NICMOS flux calibration

~ 60 secondary flux standards

(BD +17 4708 + Fainter, redder solar analogs)

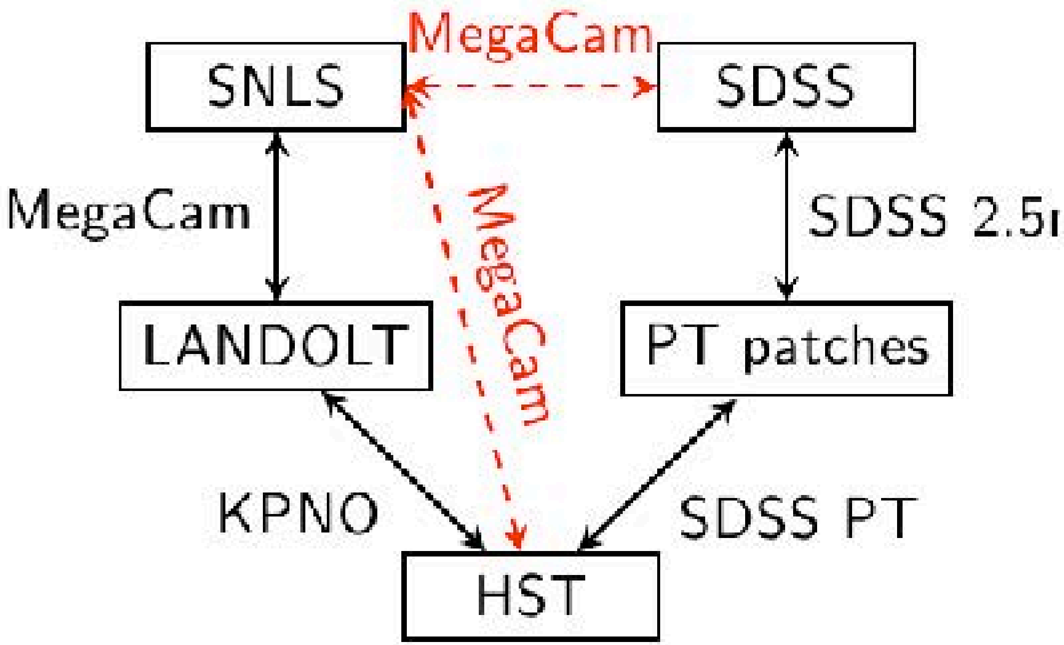
Updated every 2-3 years

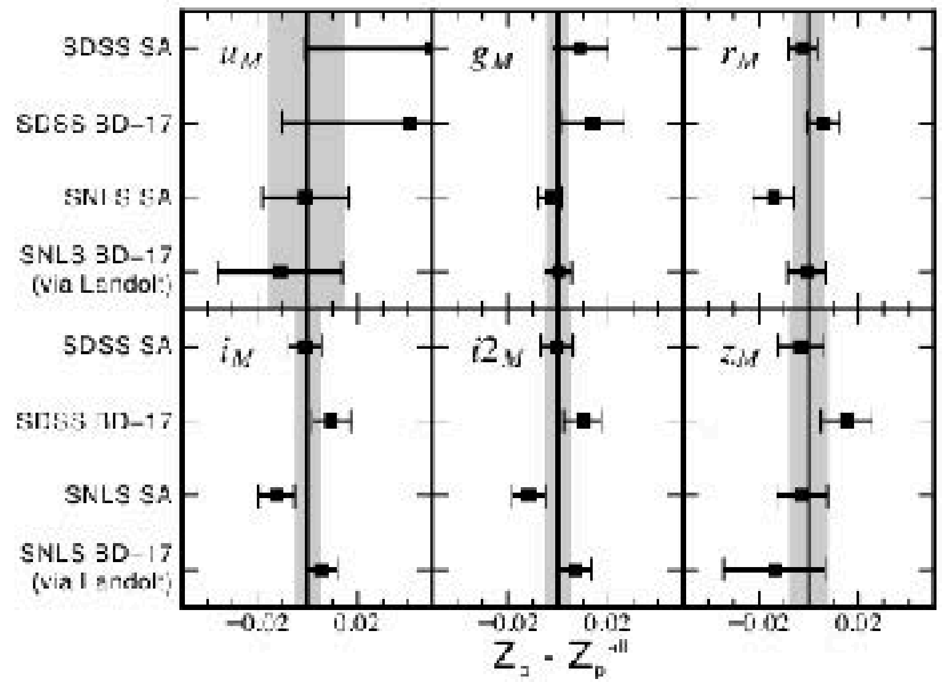
http://www.stsci.edu/hst/observatory/cdbs/calspec.html

SDSS/SNLS Joint Light Curves Analysis

- SNLS / SDSS JLA working group
  - Transverse WG to share data, code & expertise
  - Started in June 2010
  - Mainly focussed on systematics
- 4 papers
  - Calibration : Betoule & al, 2013
  - SNIa model systematics : Kessler et al, 2013, Mosher et al, 2014
  - Cosmology : Betoule et al, 2014

JLA : CALIBRATION





- Direct observations of SDSS & HST stars
- Several calibration paths
- 0.3% accuracy in gri

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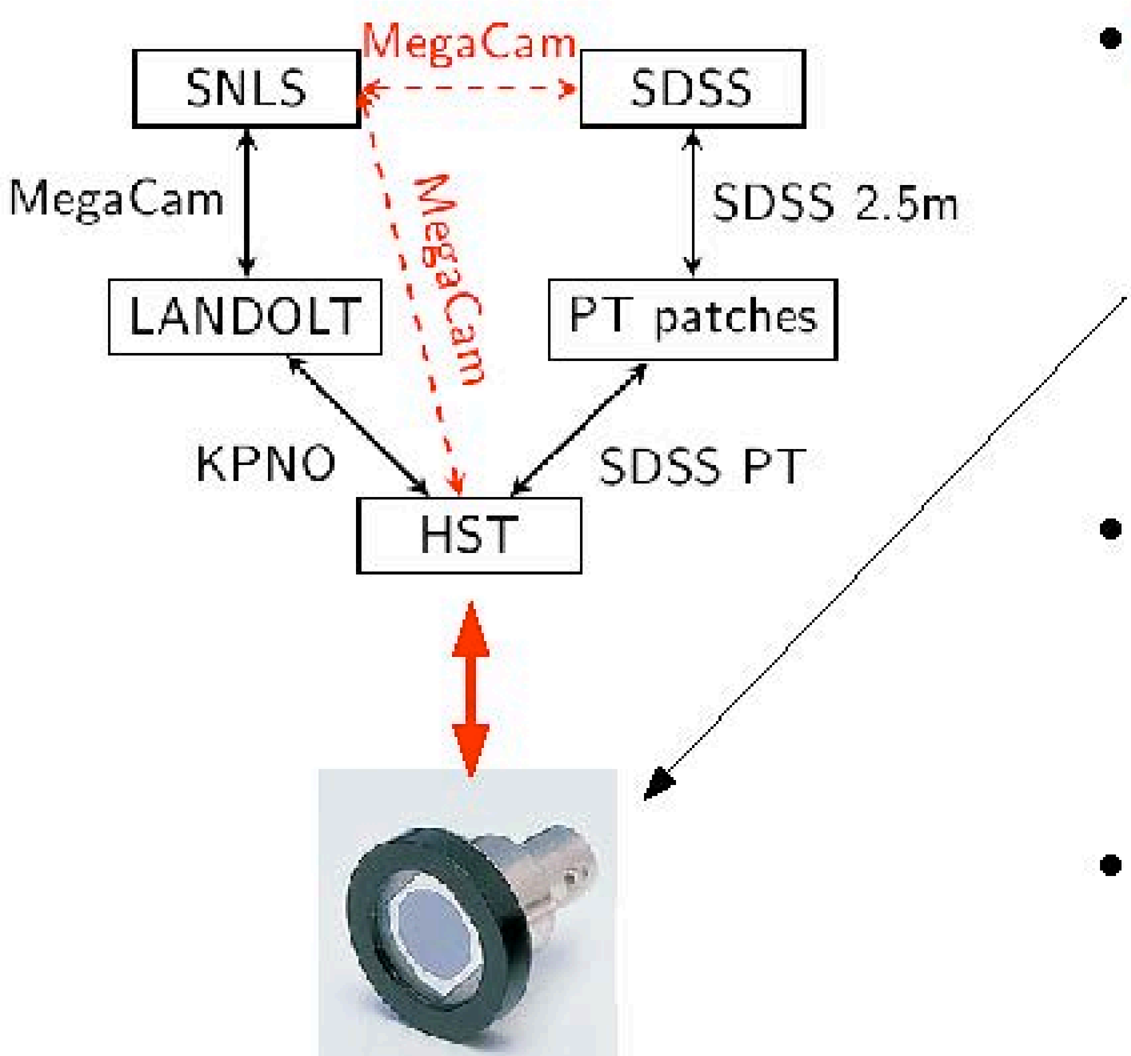
INSTRUMENTAL CALIBRATION



Hamamatsu S2281

- Stellar flux standards

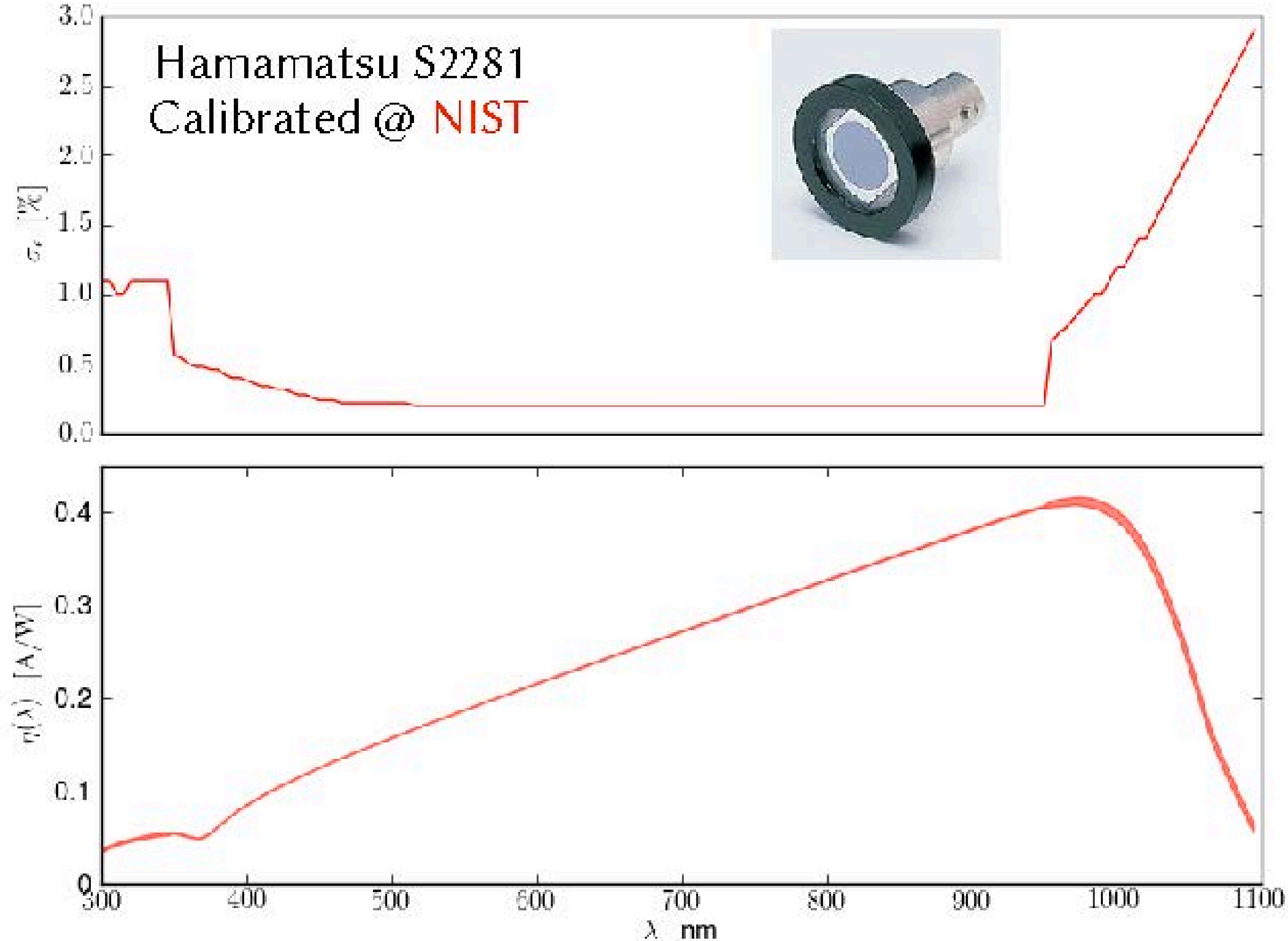
  vs

  Laboratory standards

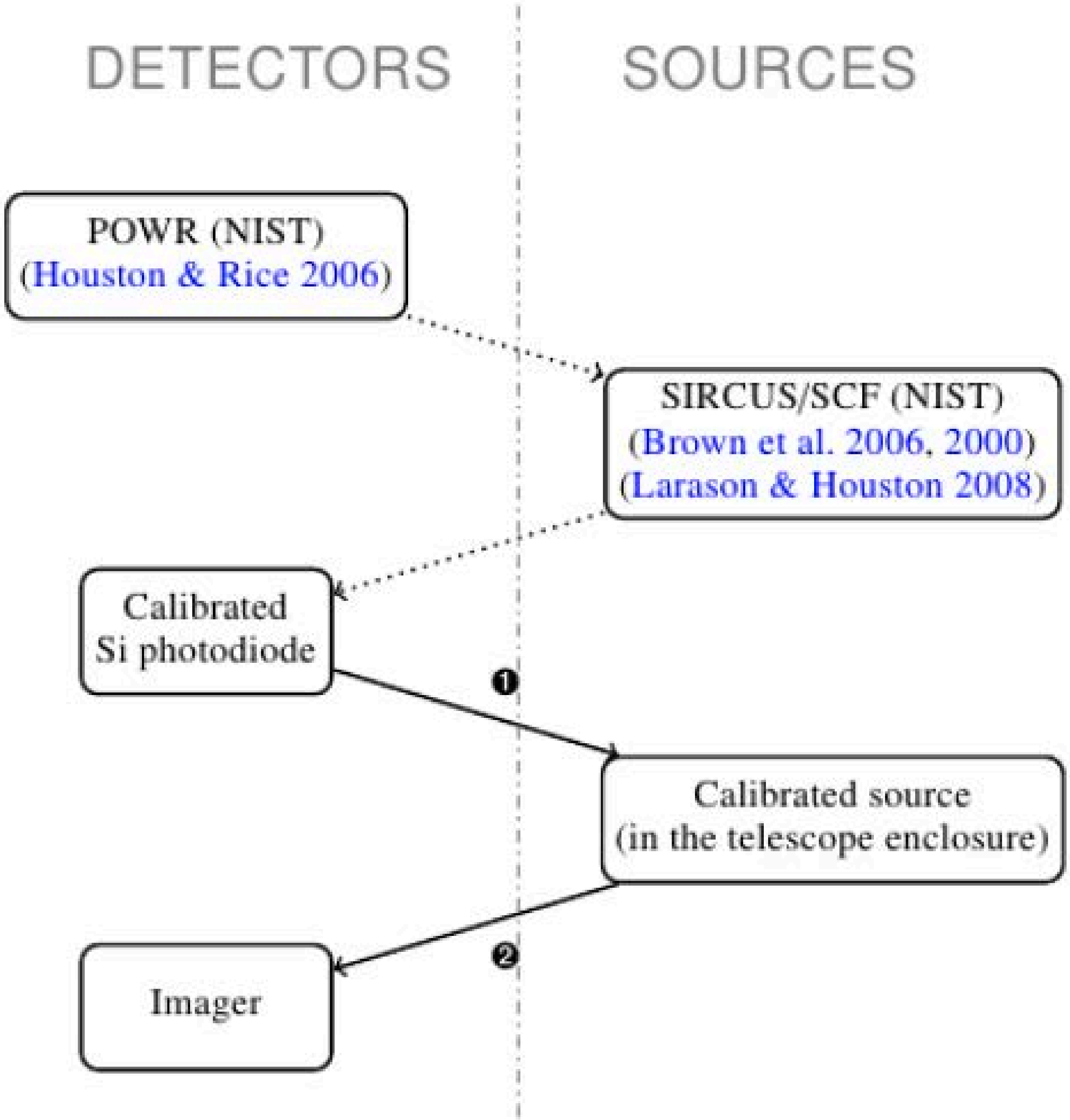
- Precision monitoring of large focal planes

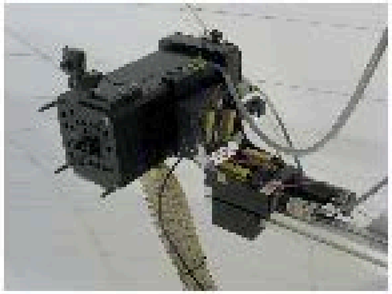
- 0.1% calibration accuracy

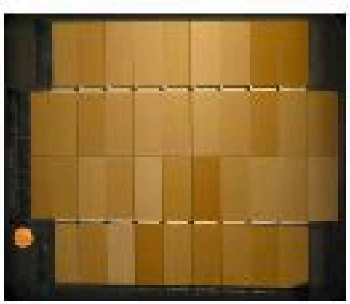
Switching to a Lab Standard



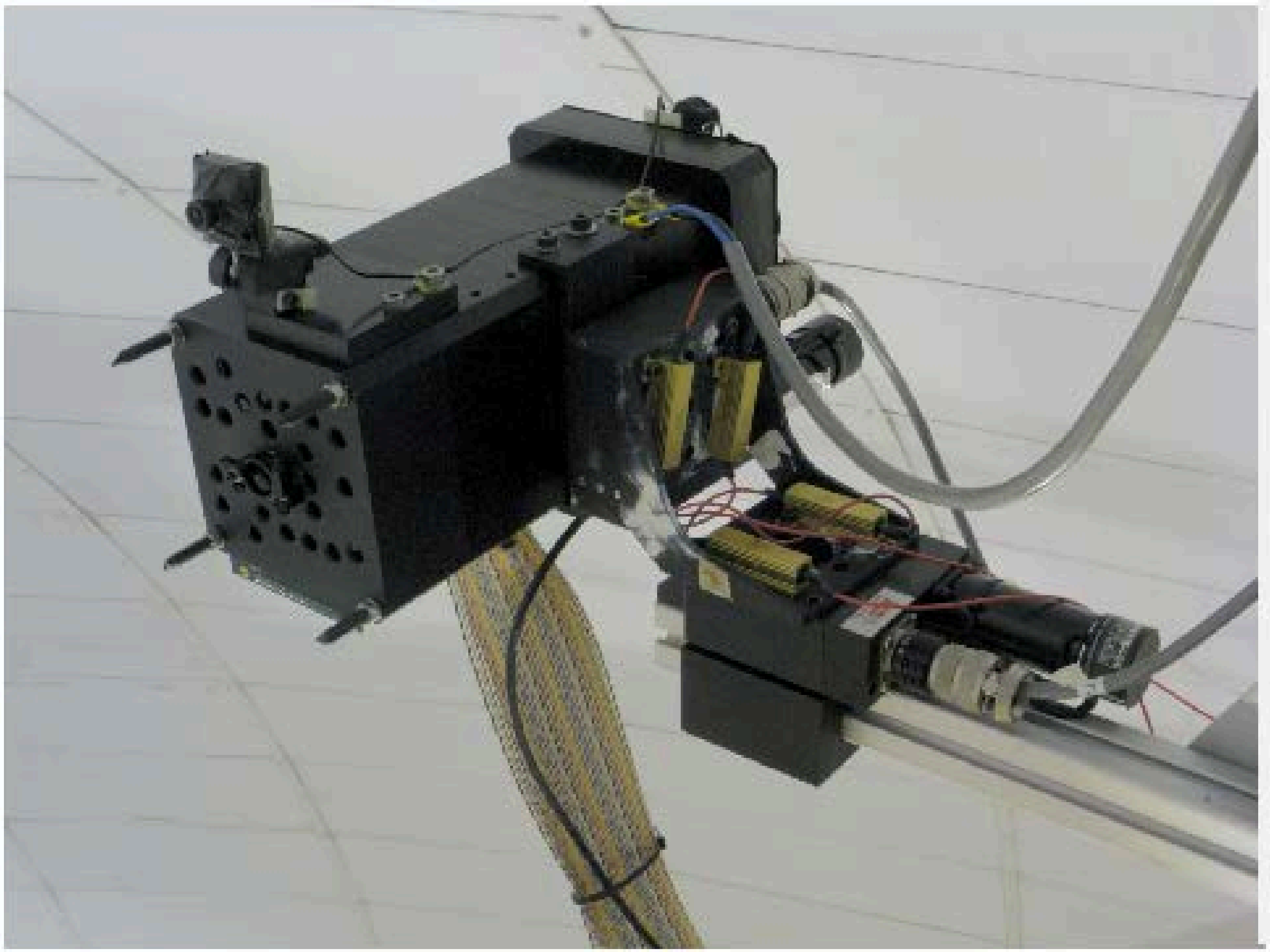
A NEW METROLOGY CHAIN

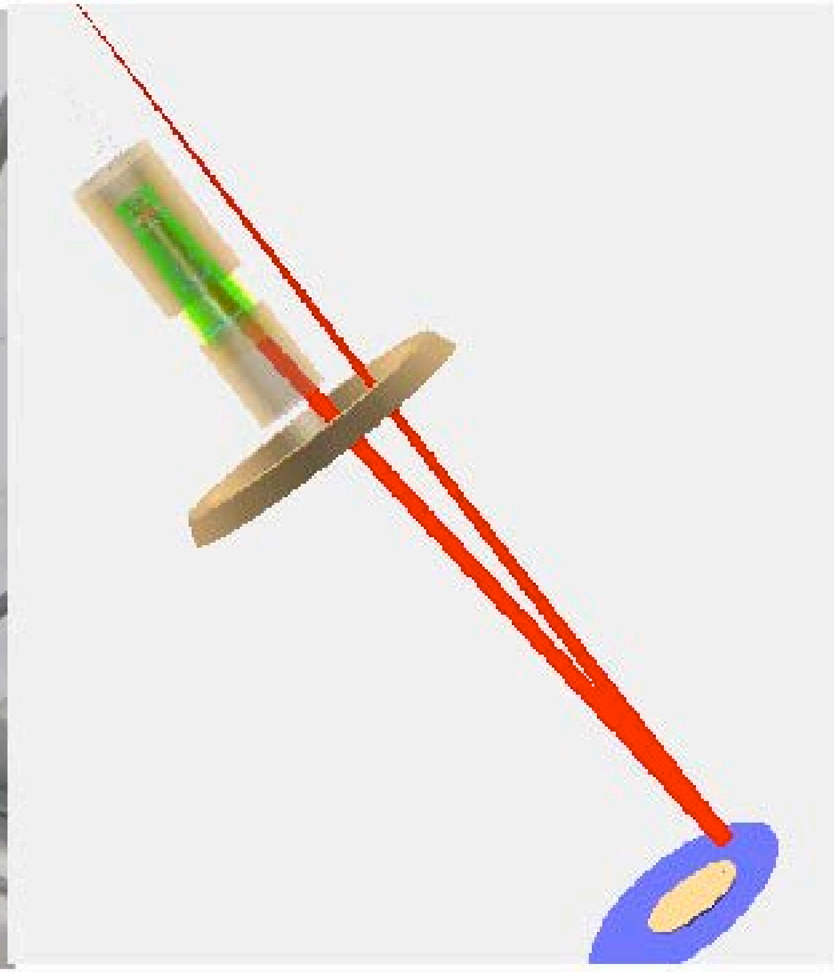




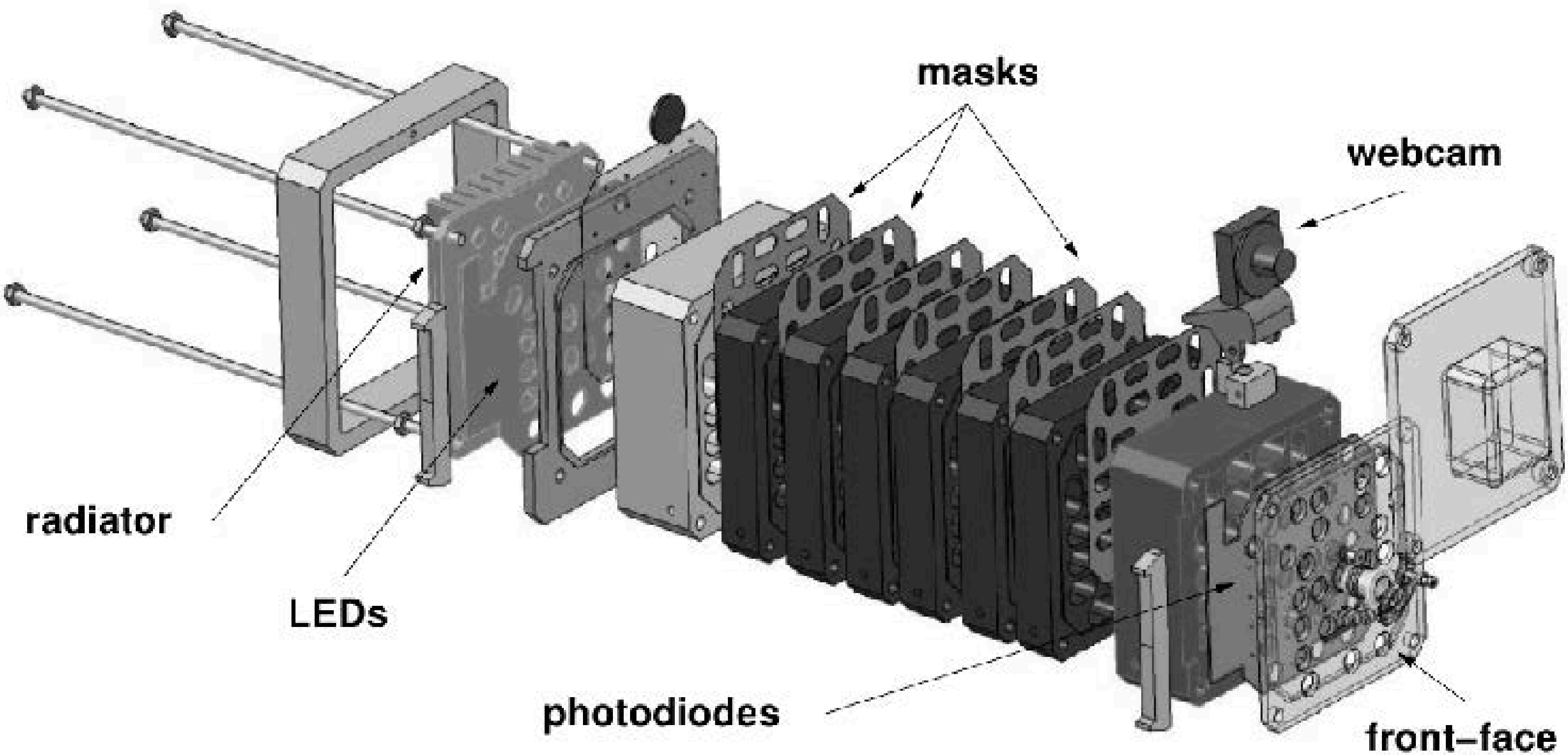


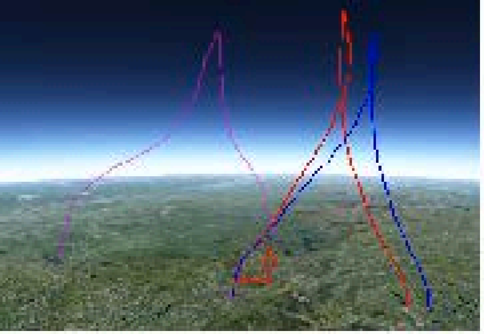
Instrumental calibration



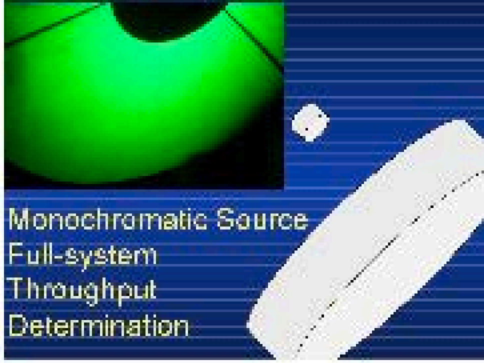


The SnDICE illumination system

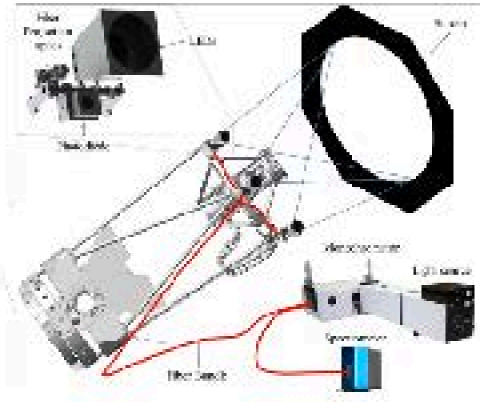


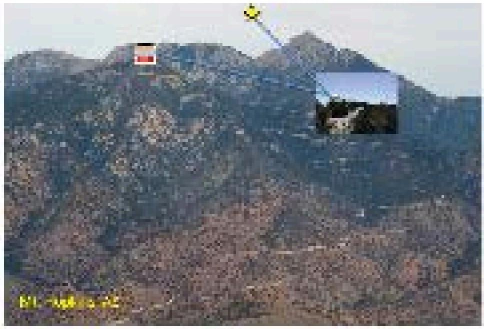


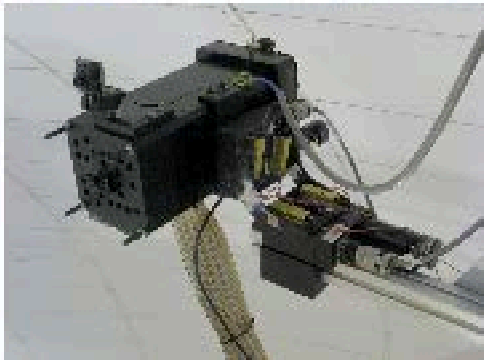
Calibration Projects



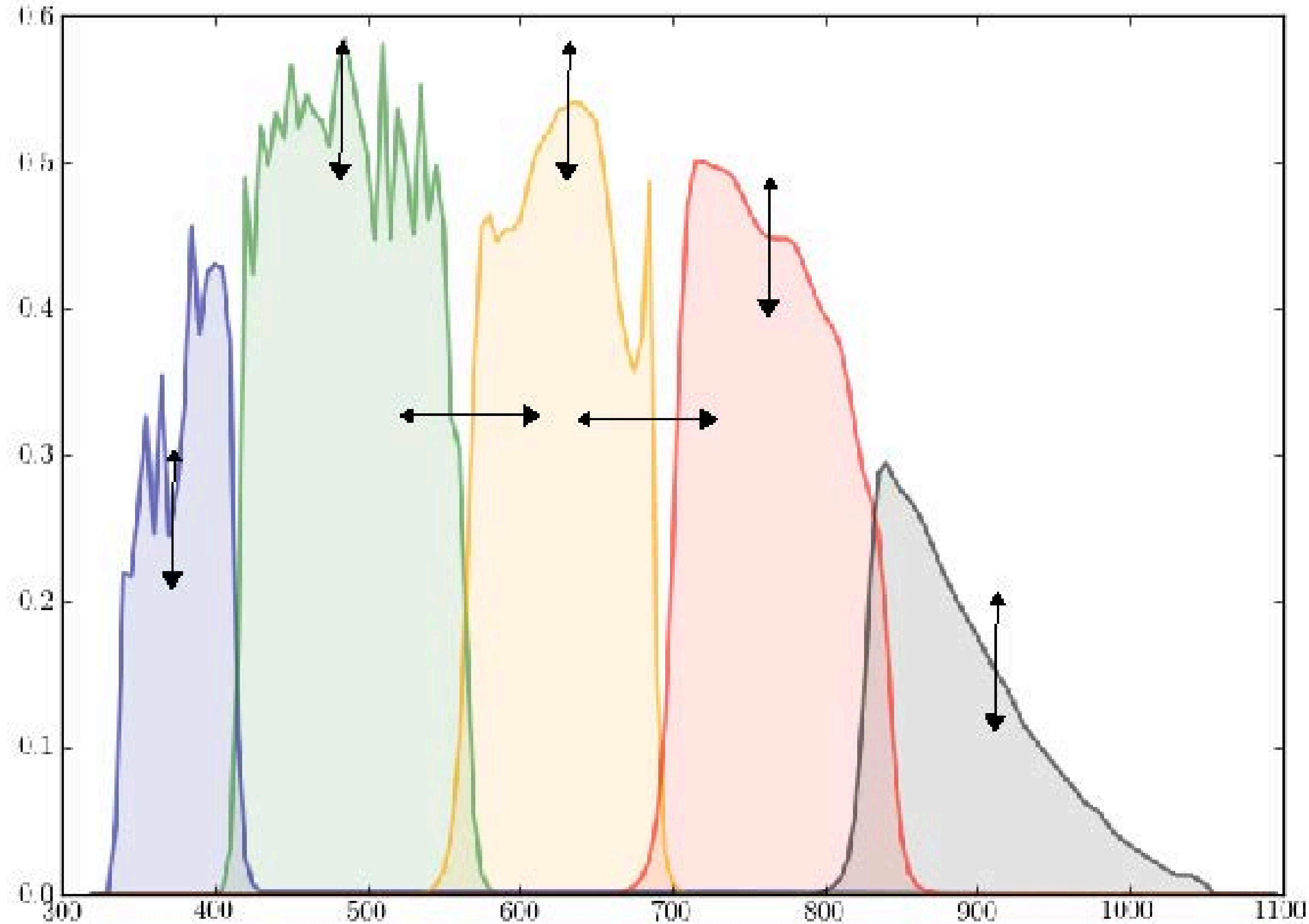
- Harvard (Stubbs et al)
  - ESSENCE
  - PanSTARRS
- Texas A&M (DePoy et al)
  - DES (Dark Energy Survey)
- NIST (Cramer et al)
  - Artificial star → recalibration of Vega
- ACCESS (Kaiser et al)
  - Small rocket-borne telescope (IR spectrophotometry)
- LPNHE
  - SnDICE (MegaCam)
  - SkyDICE (SkyMapper)



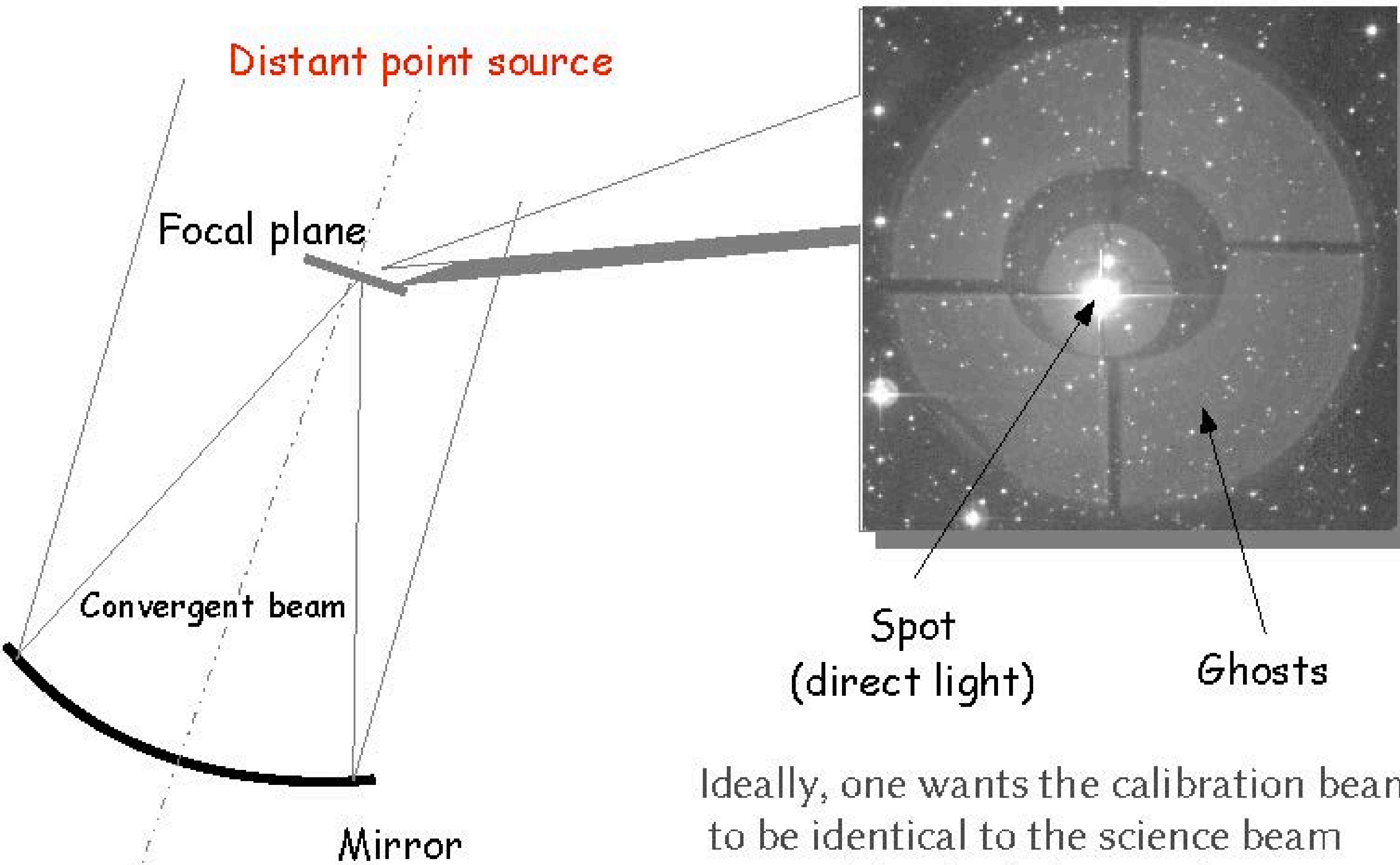




Calibration ?



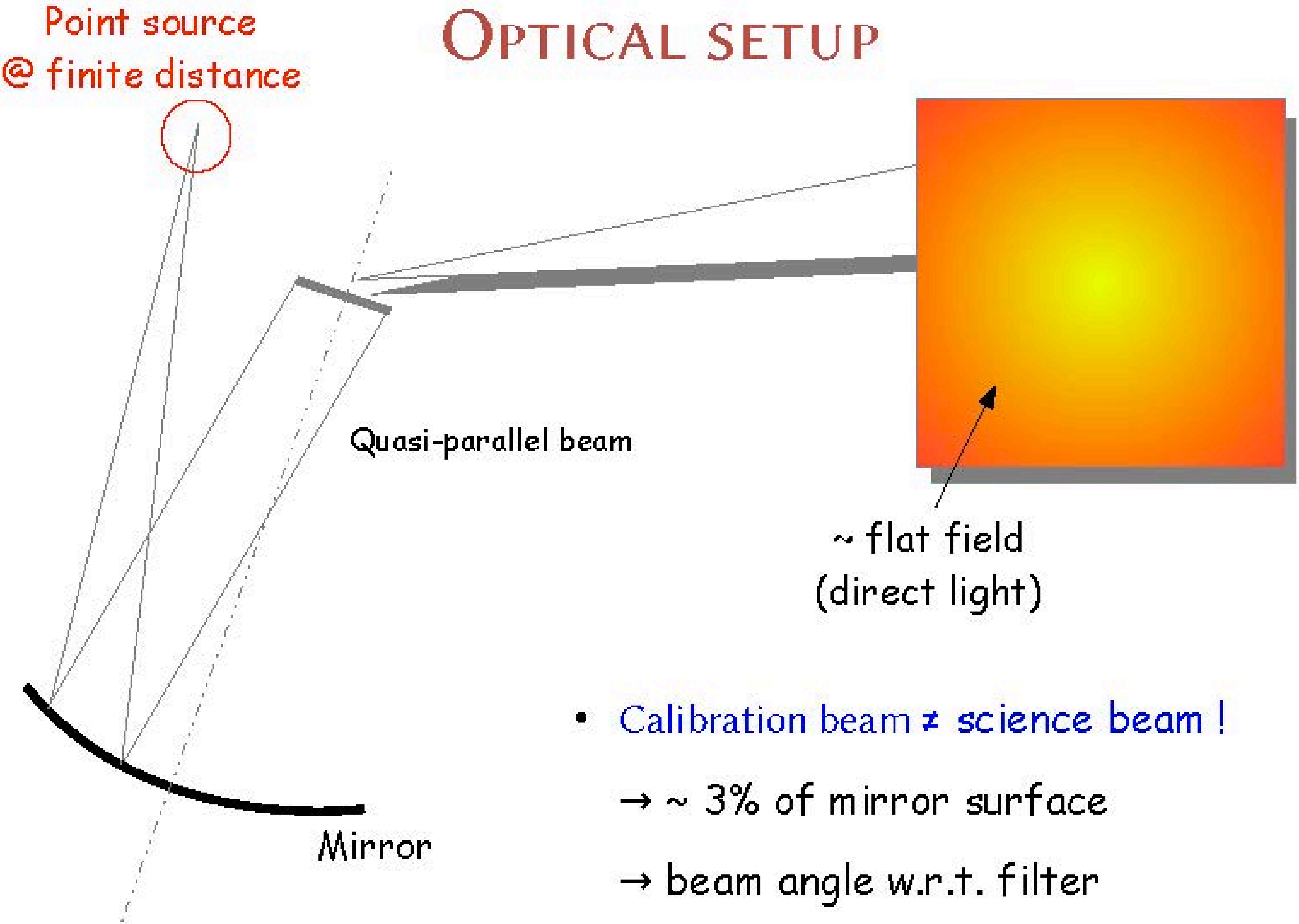
Optical setup



Ideally, one wants the calibration beam to be identical to the science beam

→ distant point source !

OPTICAL SETUP

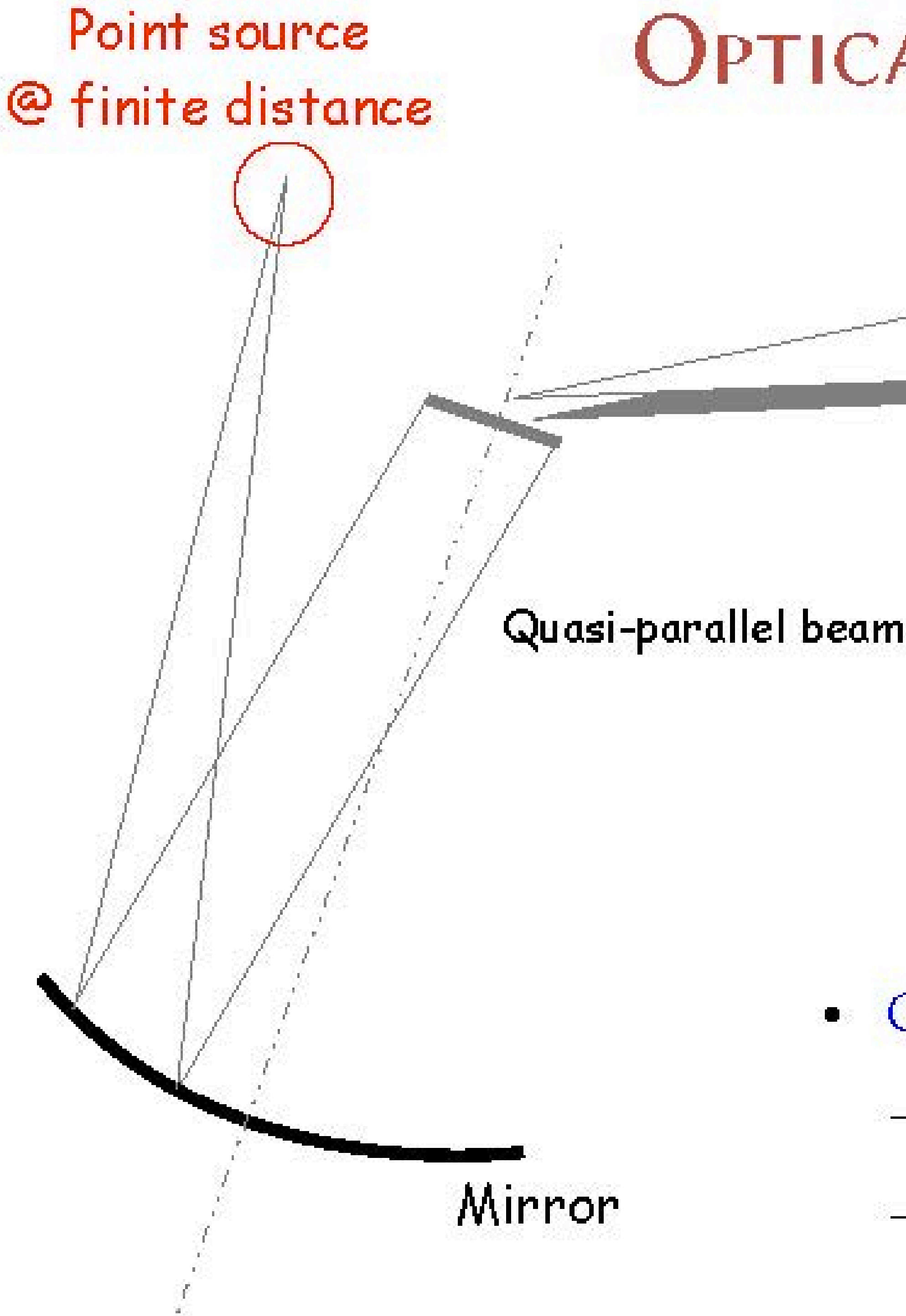


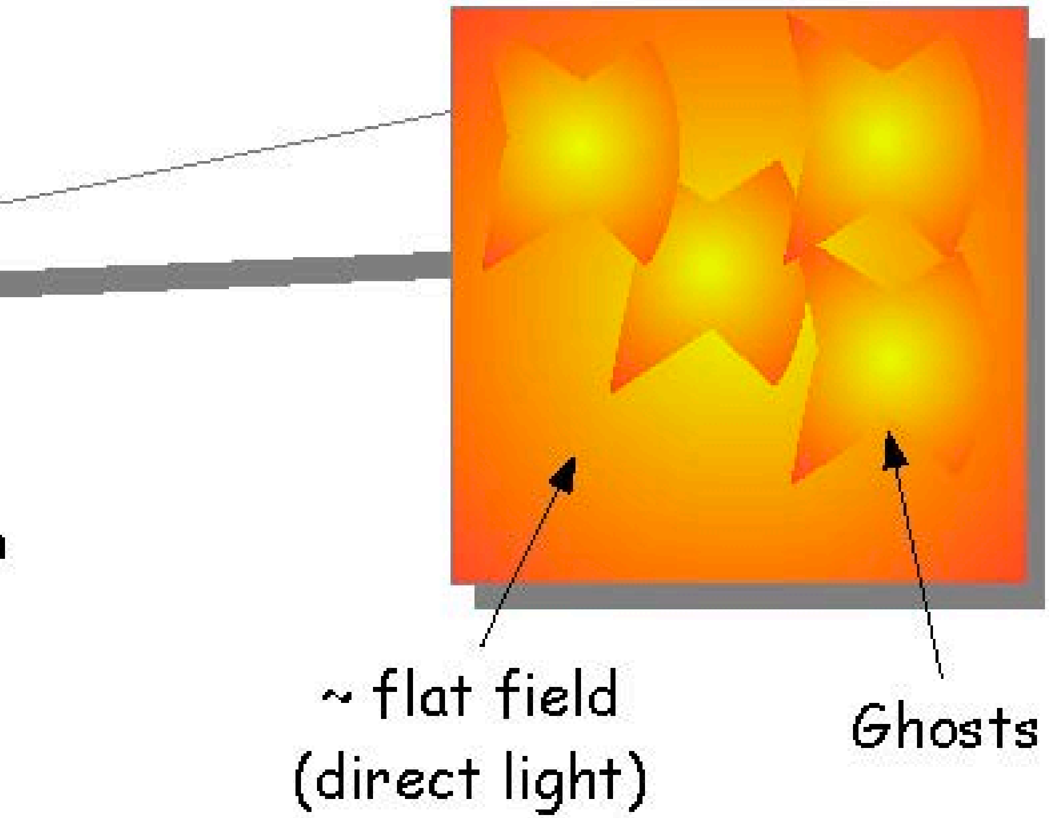
- Calibration beam ≠ science beam !

→ ~ 3% of mirror surface

→ beam angle w.r.t. filter

Optical setup





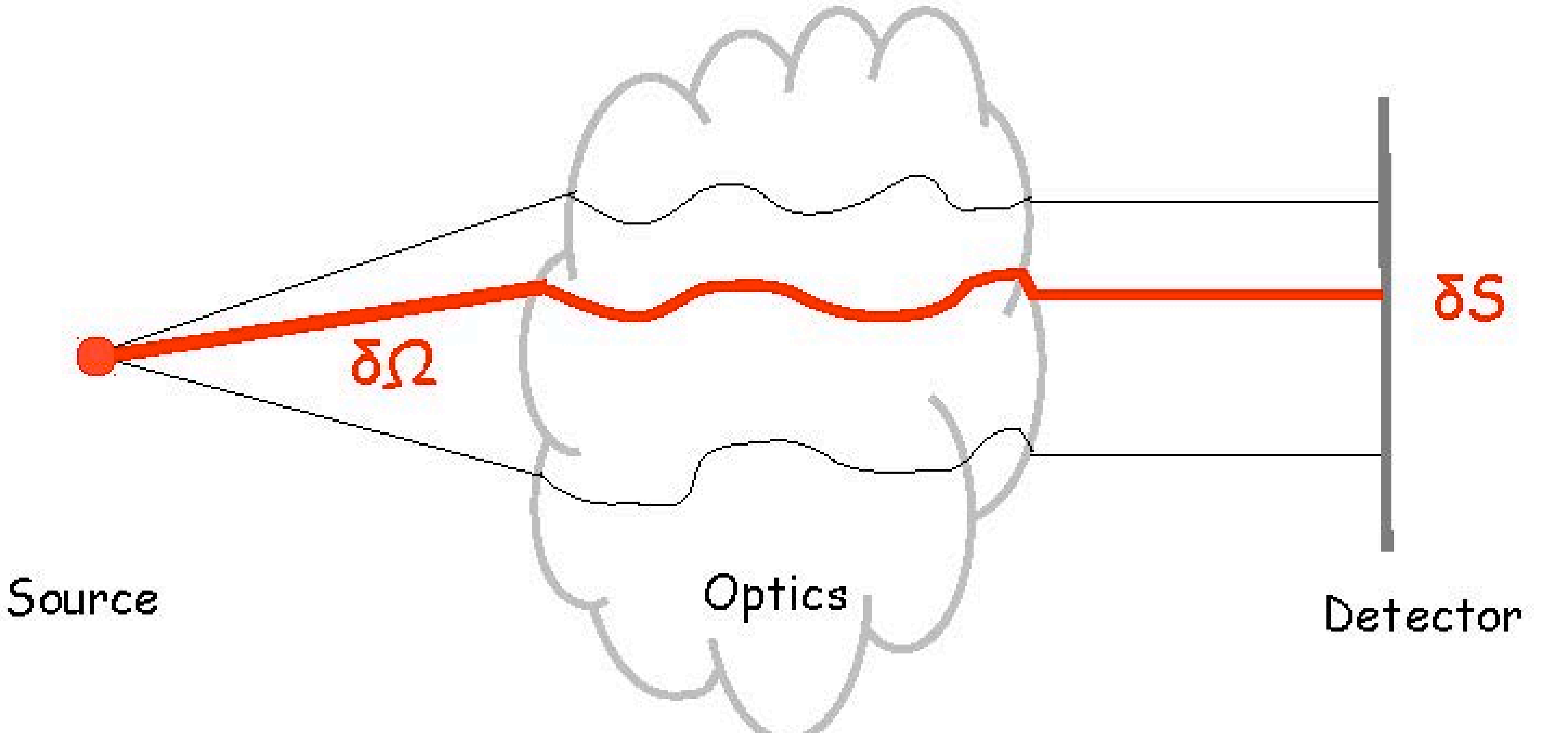
- Calibration beam ≠ science beam !

  → ~ 3% of mirror surface

  → beam angle w.r.t. filter

Optical setup

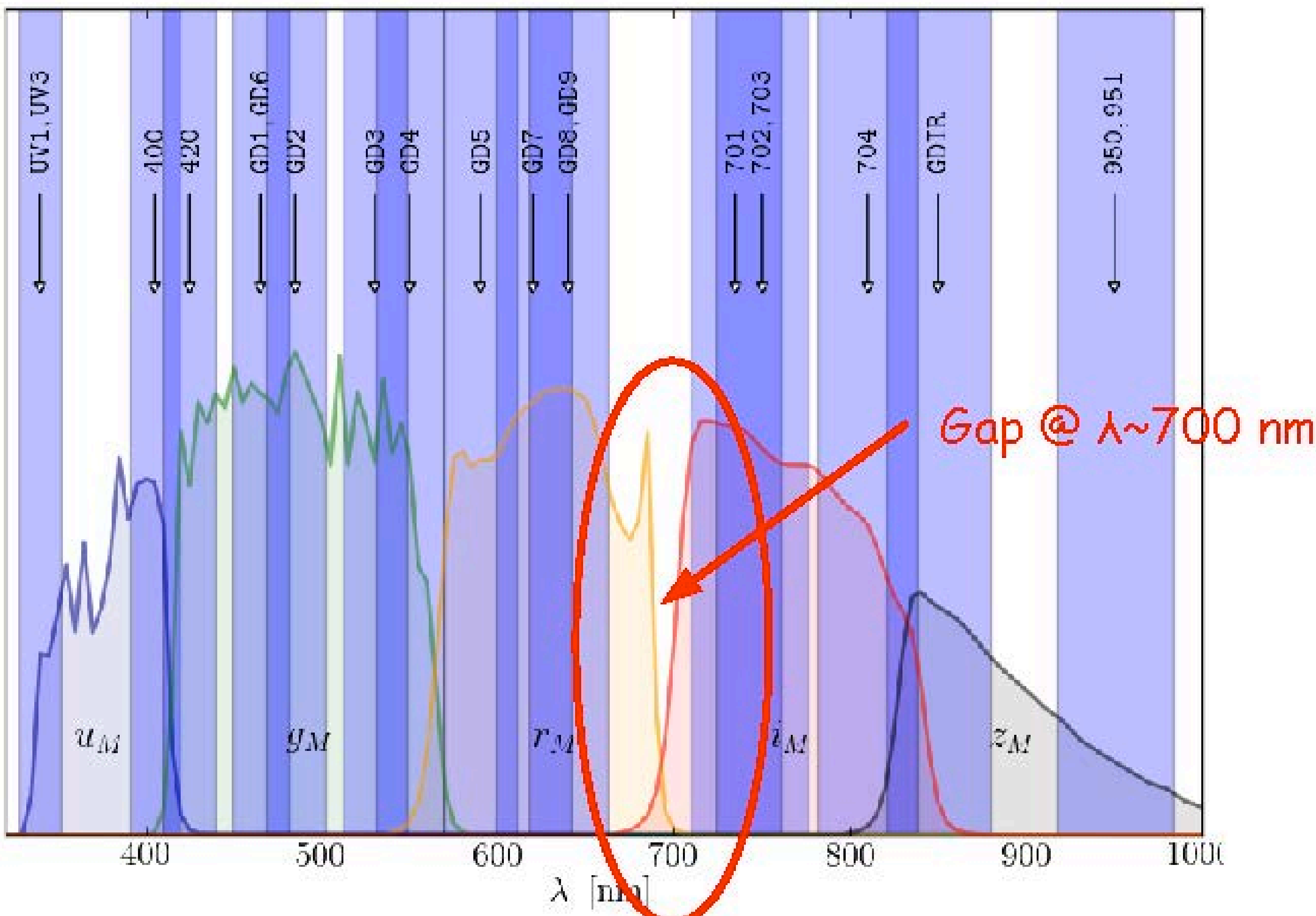
- One-to-one relationship between elementary beam solid angles and elementary focal plane surface elements.



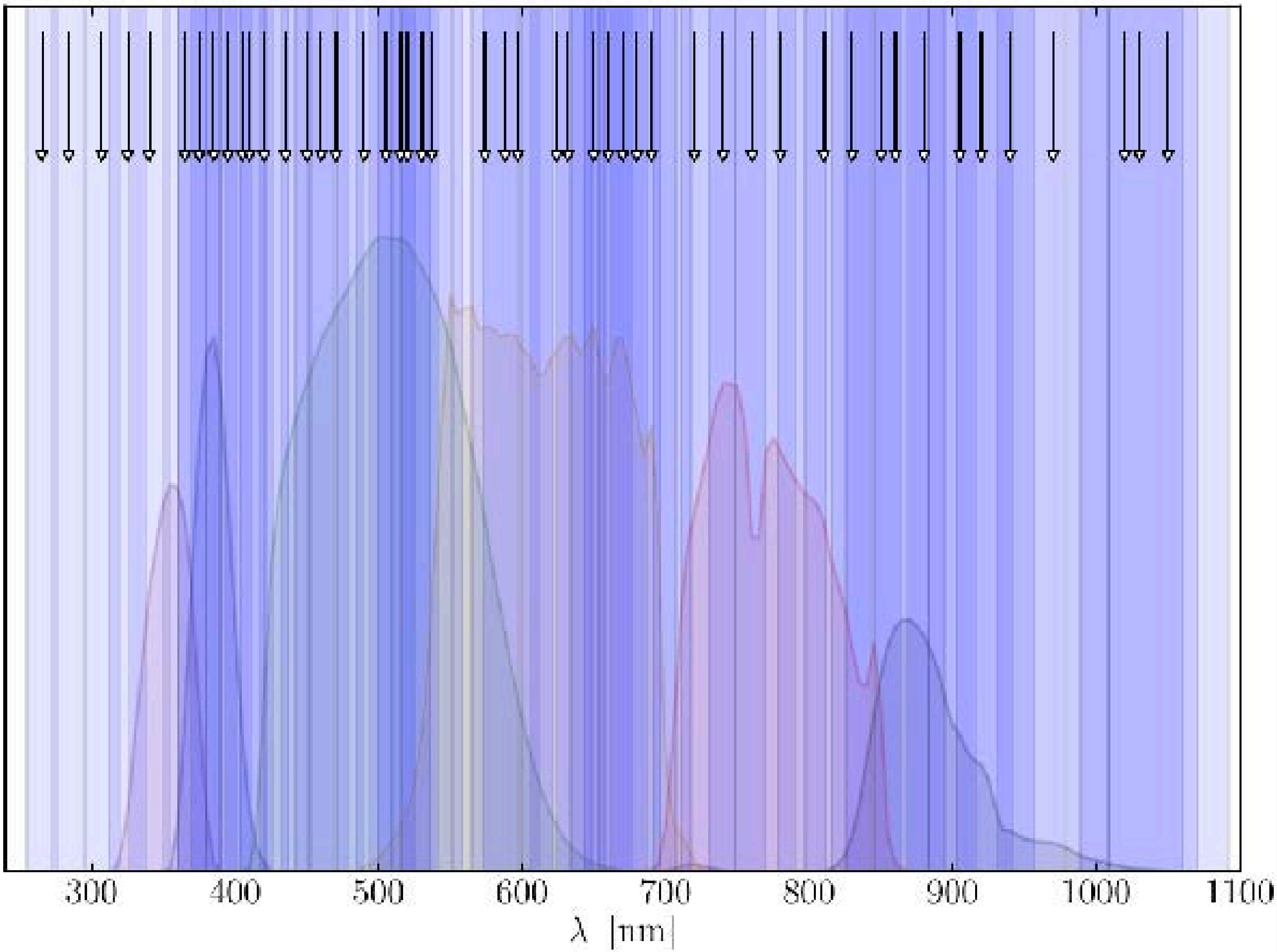
Illumination system

- Keep the design as simple as possible
  - → Direct illumination, no intermediate surfaces
  - → Just baffling, to shape the calibration beam
- Narrow spectrum LEDs
  - → Compact, stable calibration beams
  - → Emission properties vary with temperature
- Calibrated on a spectrophotometric test bench
  - → spectra (erg/nm/s) & beam maps (erg/sr/s)
- Redundancies (control photodiodes + monitoring)

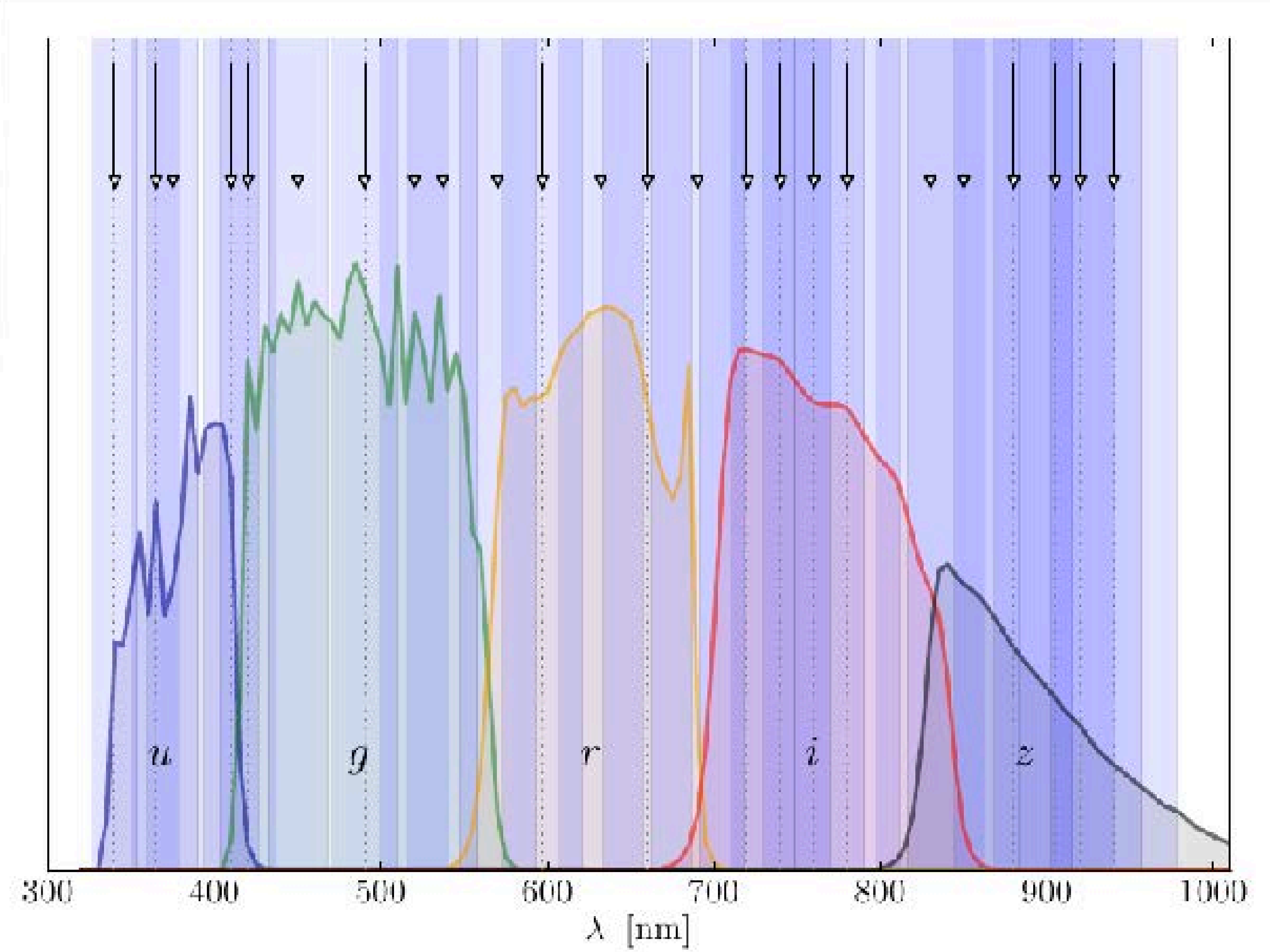
SnDICE Wavelength coverage



Todays' LED coverage



SnDICE2 LED coverage



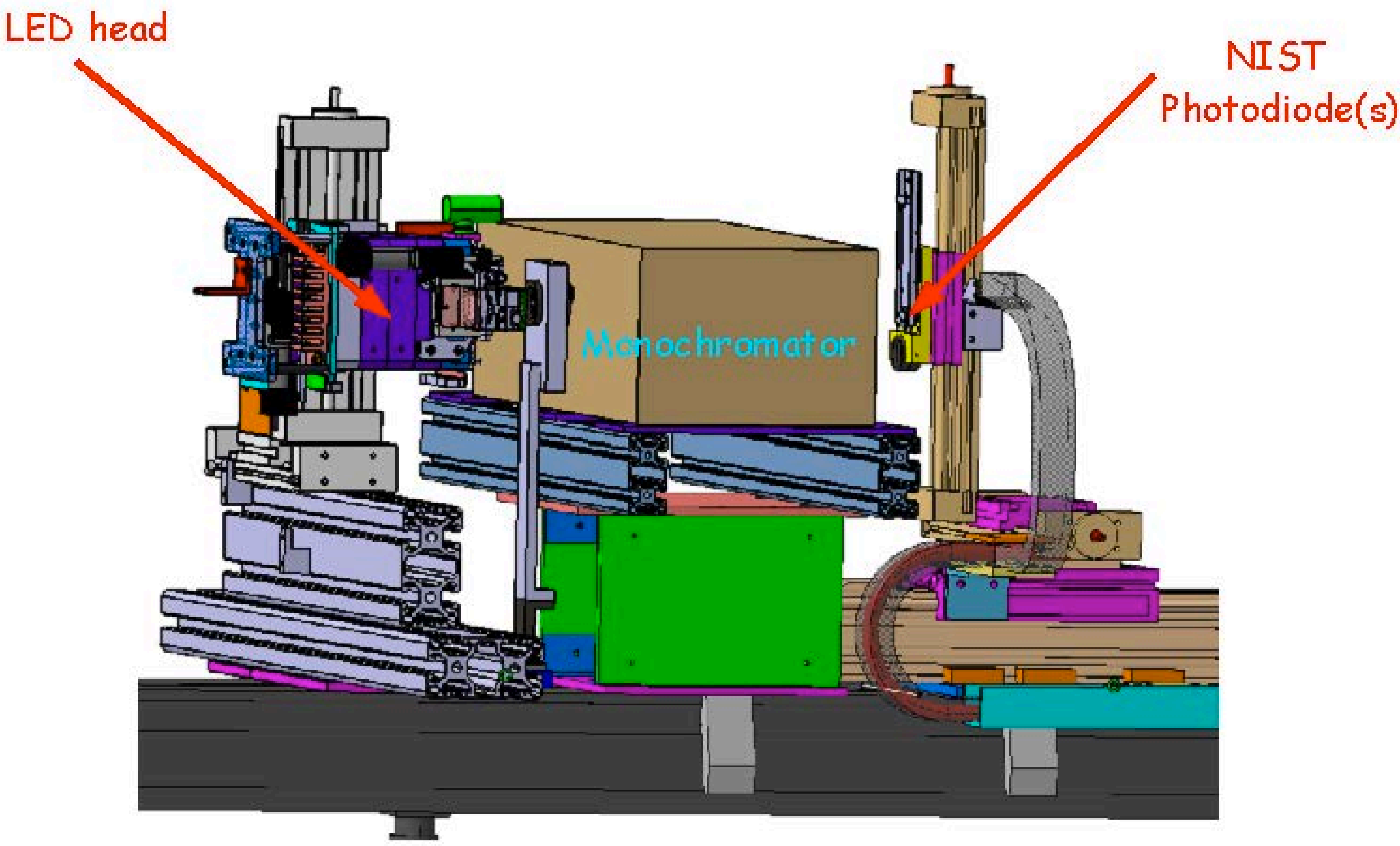
Test bench studies

- Spectrophotometric test bench @ LPNHE
- Dark enclosure, $0\,^{\circ}C < T < 25\,^{\circ}C$
  - not exactly thermalized, but
  - good temperature monitoring w/ thermistances
- Goals
  - Transfer NIST calibration → light source

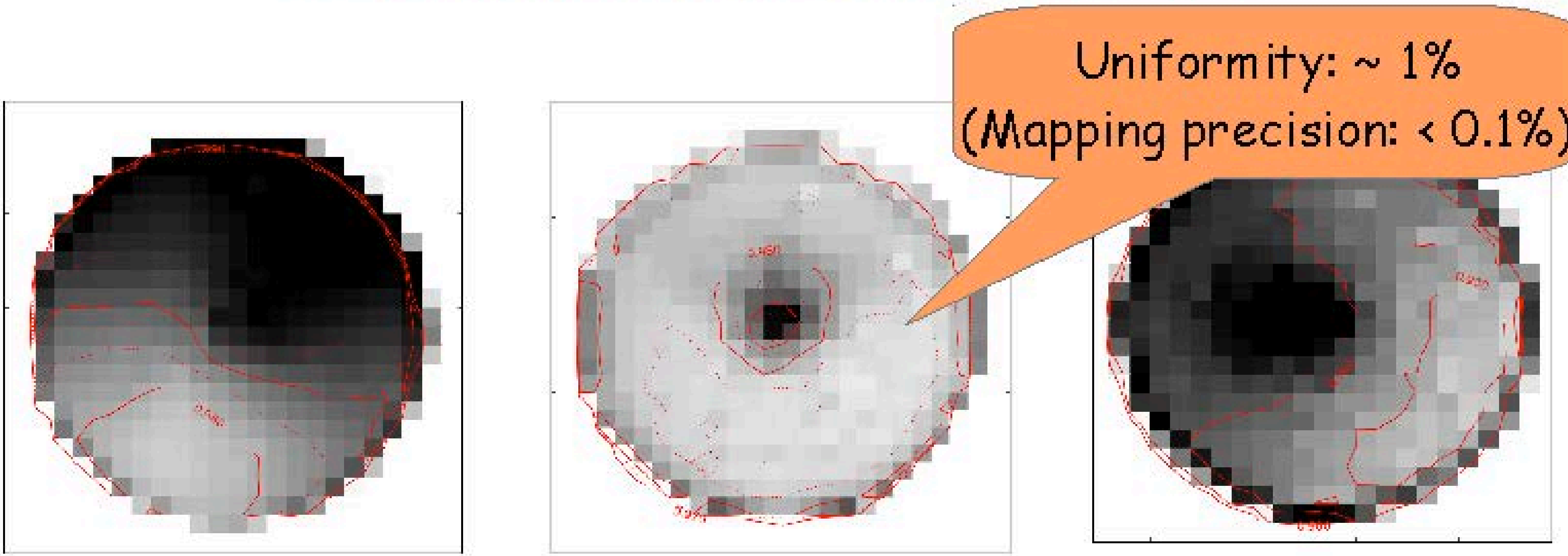
    → Spectroscopic calibration of all LEDs

    → Photometric calibration of all LEDs

Spectrophotometric test bench



Photometric Calibration



- Beam mapped with a calibrated photodiode

$$i_{PD} = \langle \eta \rangle \times \int_{PD} \mathcal{B}(\boldsymbol{r}) \frac{\boldsymbol{r}\, d\boldsymbol{S}}{r^3}$$

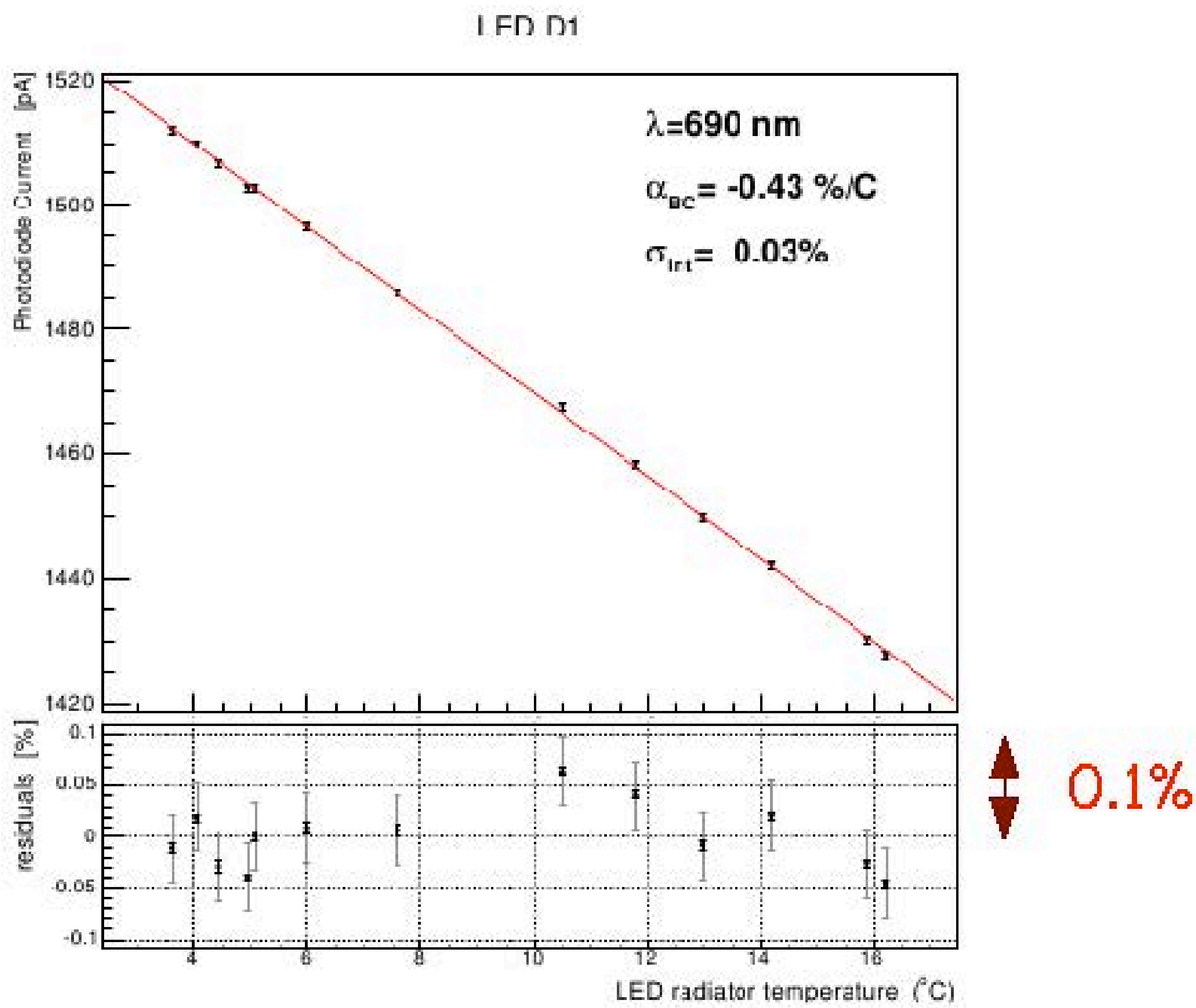
Photodiode current

Mean efficiency

Beam Map (W / sr)

Solid angle element

The "Cooler-brighter effect"



About 0.5% / °C for all LEDs