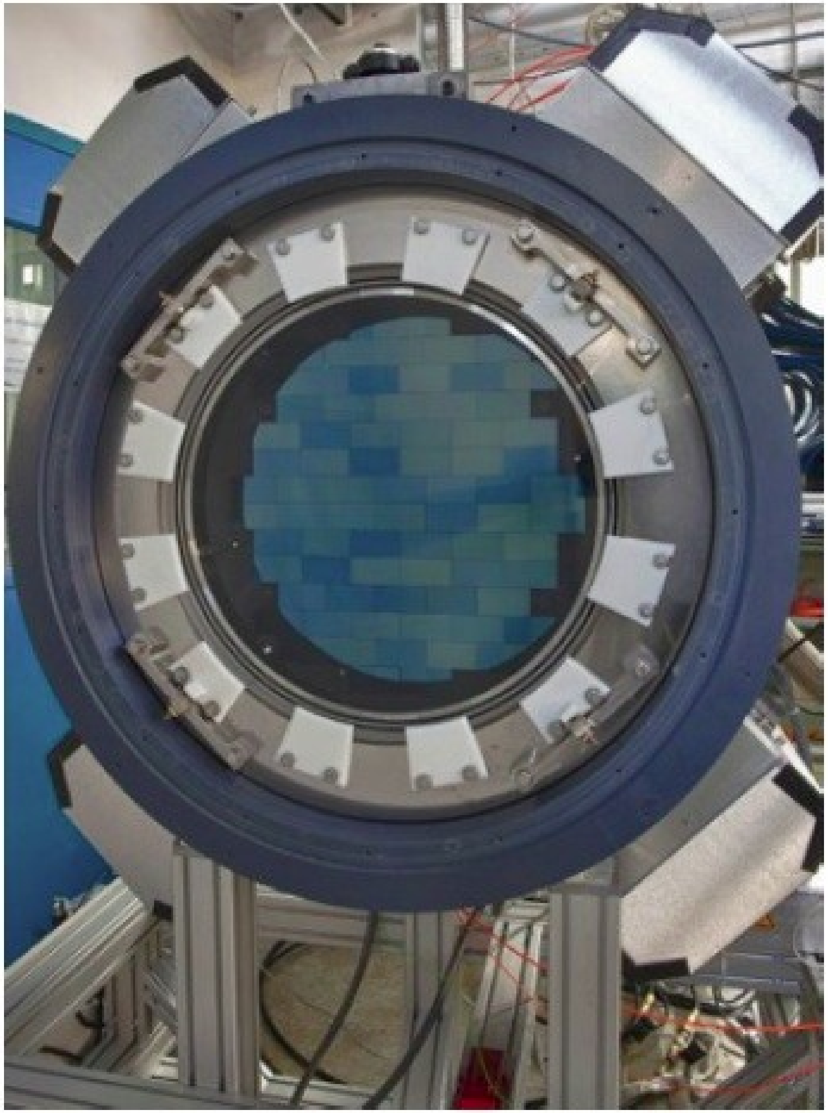
Photometric Calibration of Wide Field Imagers

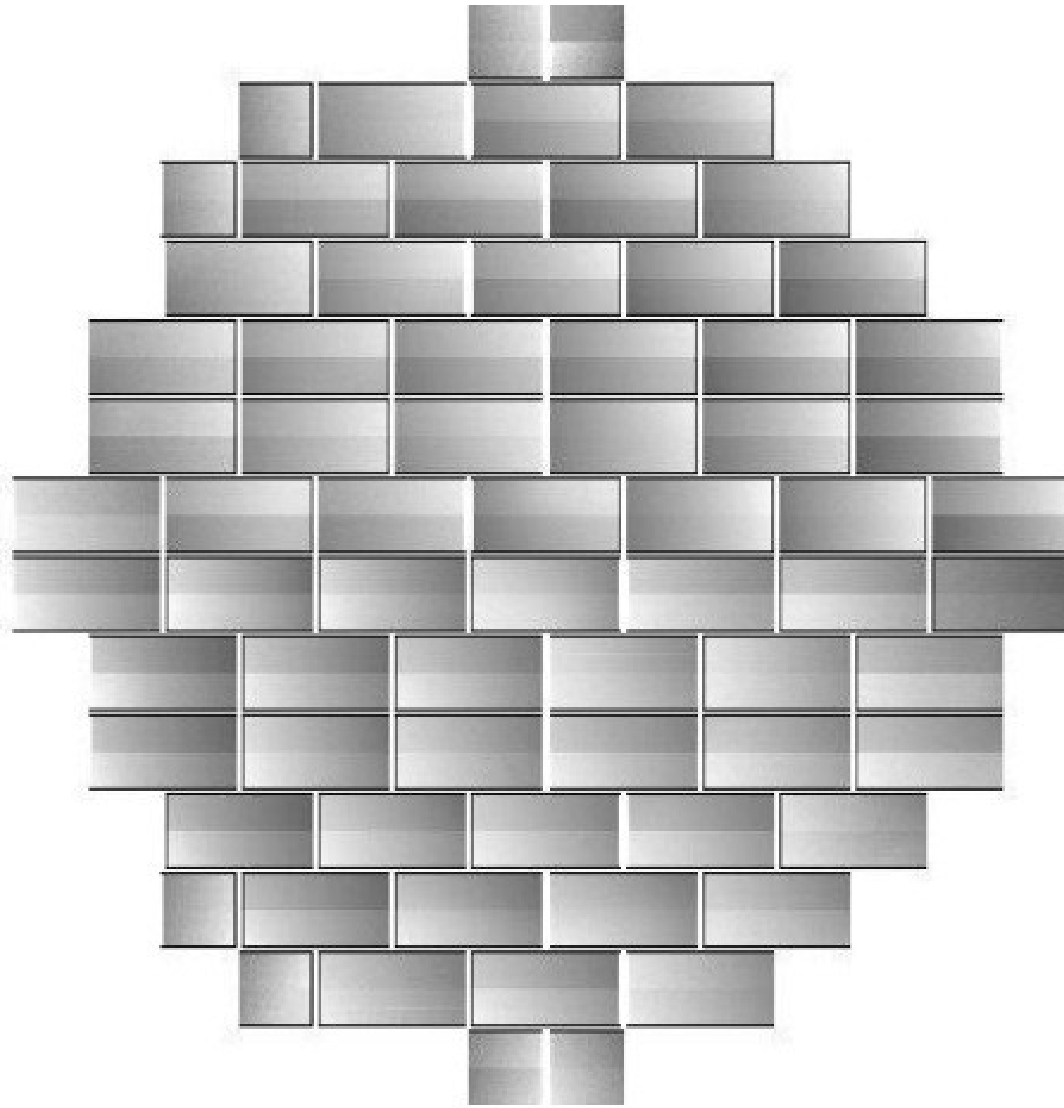
(On supernovae, stars & Light emitting diodes)

Nicolas Regnault
(LPNHE)

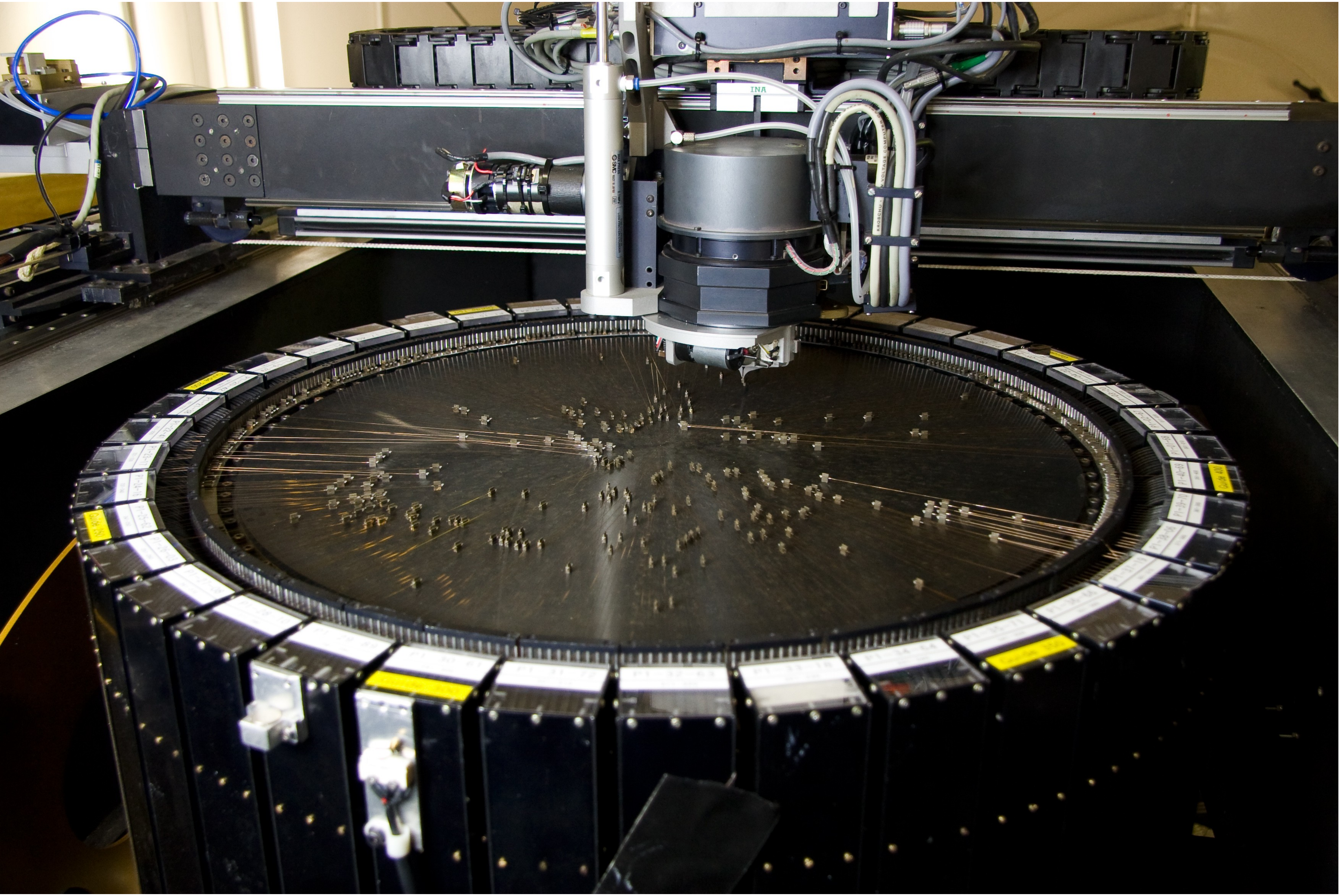
Outline

- Supernova Cosmology
- Why does calibration matter so much ?
- Stellar Calibration
- Instrumental calibration: the DICE project
- Conclusion

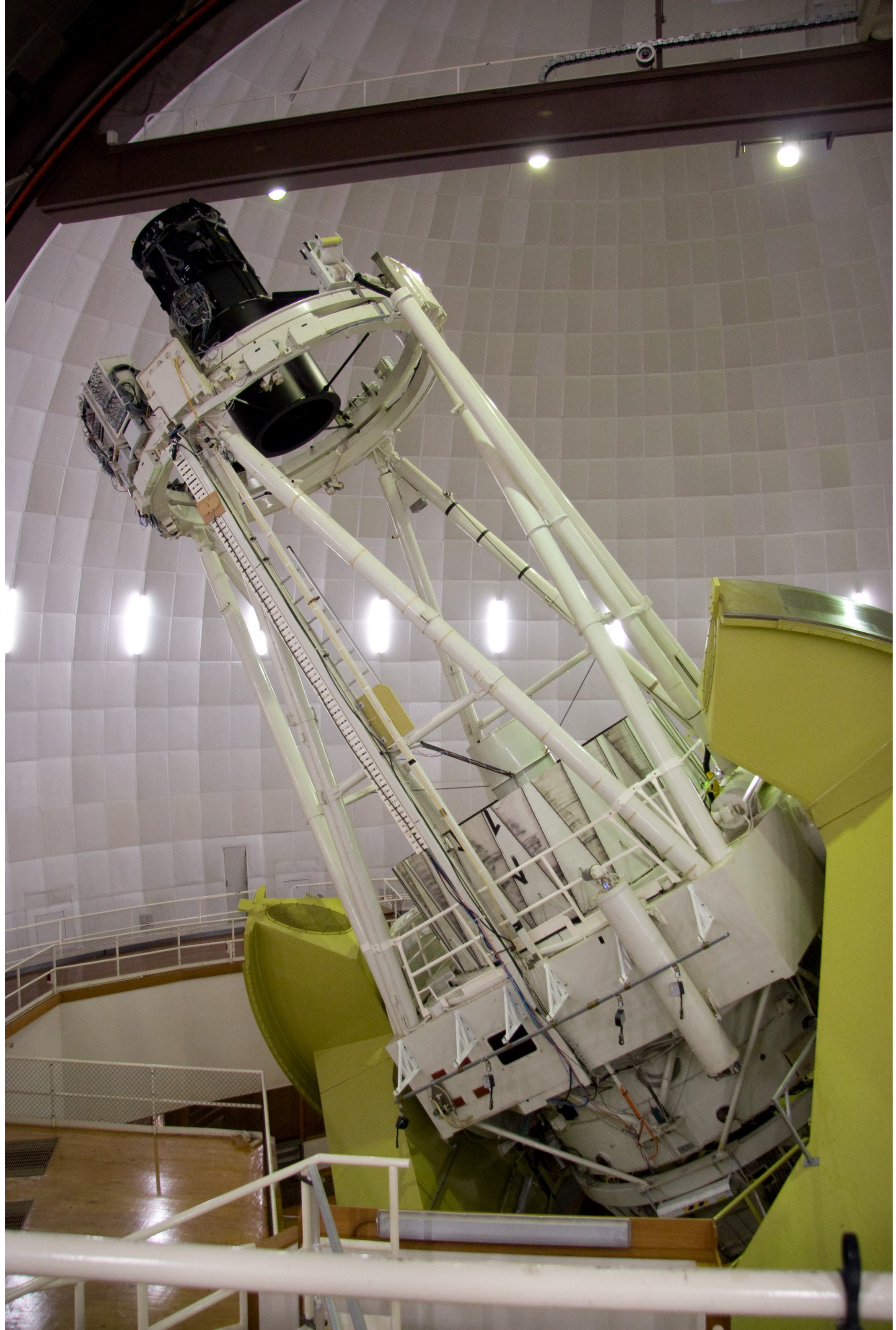




Dark Energy Camera (540 Mpixels)



AAOmega



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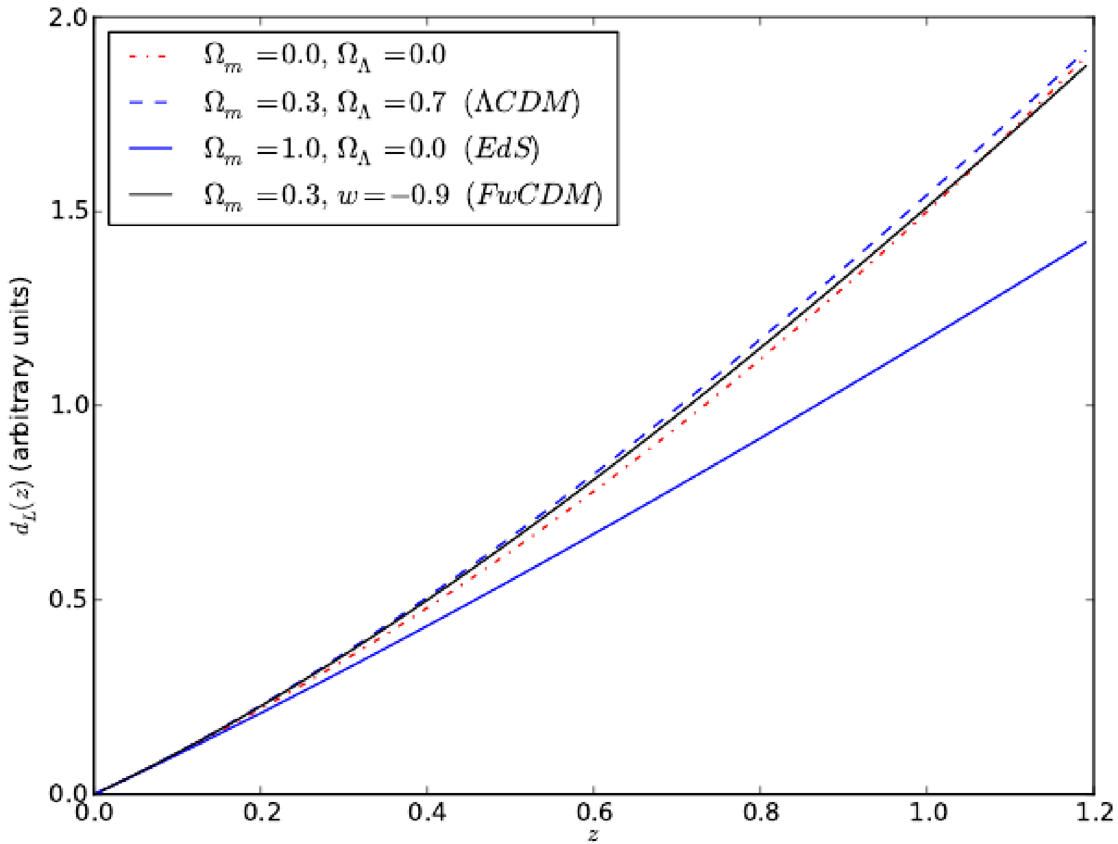
Standard Candles in Cosmology



→ 1 parameter well measured !

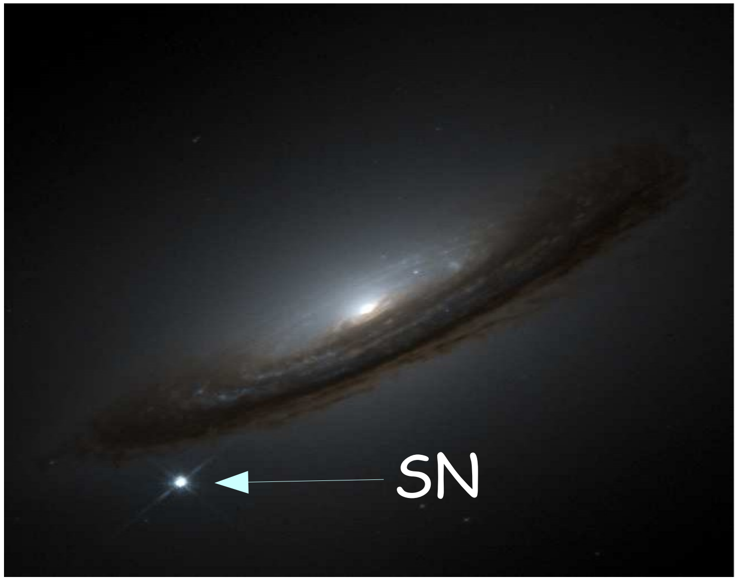
- Observables:
  - Redshift $z = \delta\lambda/\lambda$
  - Apparent flux
- Standard candles

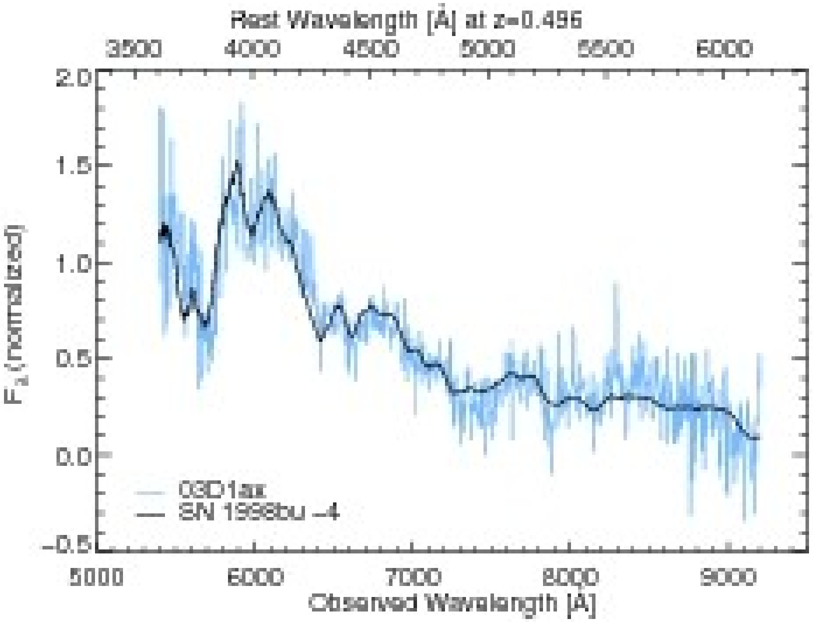
  $f = L / 4\pi\, d_L^2(z)$

- $d_L(z)$ → integrated history of the expansion

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_m(1+z)^2 + \Omega_k(1+z)^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Type Ia Supernovae





Thermonuclear explosions

- C/O White Dwarfs
- Rare events (~1 / Gal / 1000 yr)
- Transients (~ 1 month)
- Very bright (~10^{10} solar luminosities)
- $\sigma(L_{max})$ ~ 40%

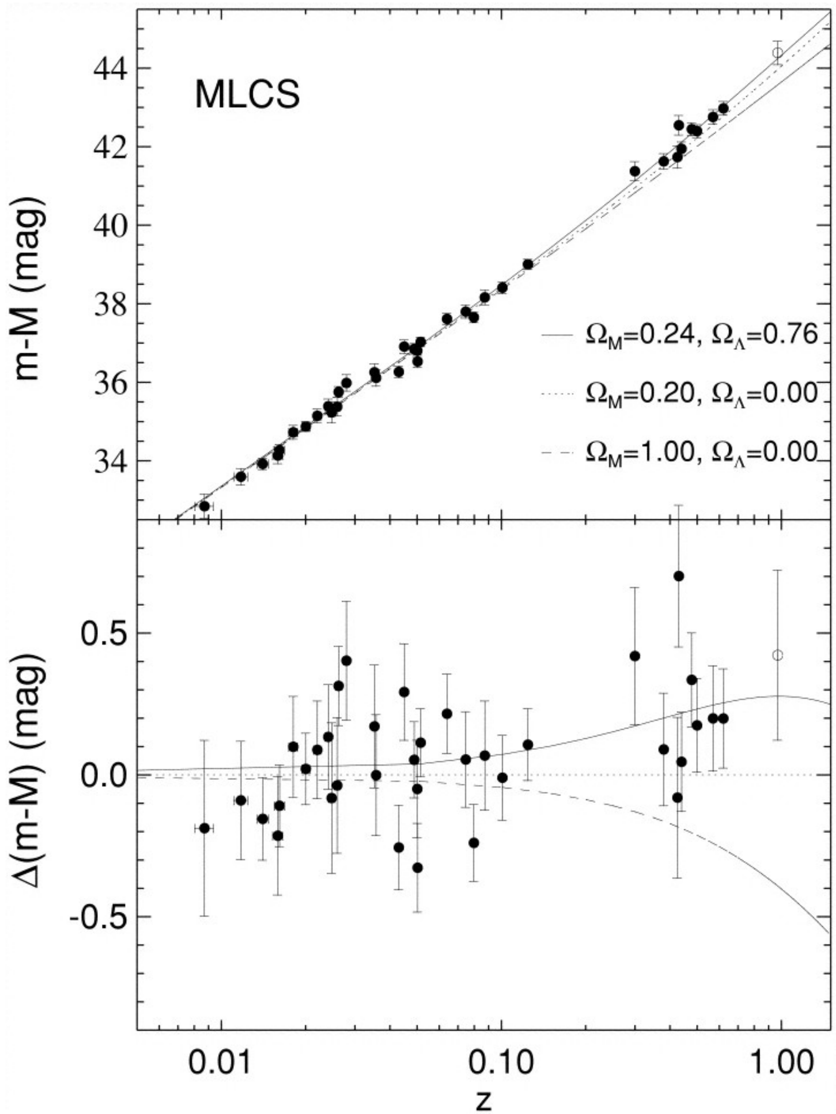
Standardizable → σ(Lmax) ~ 15%

Spectroscopy

→ Identification (broad features)

→ Chemical composition & velocities

Mapping the expansion of the Universe



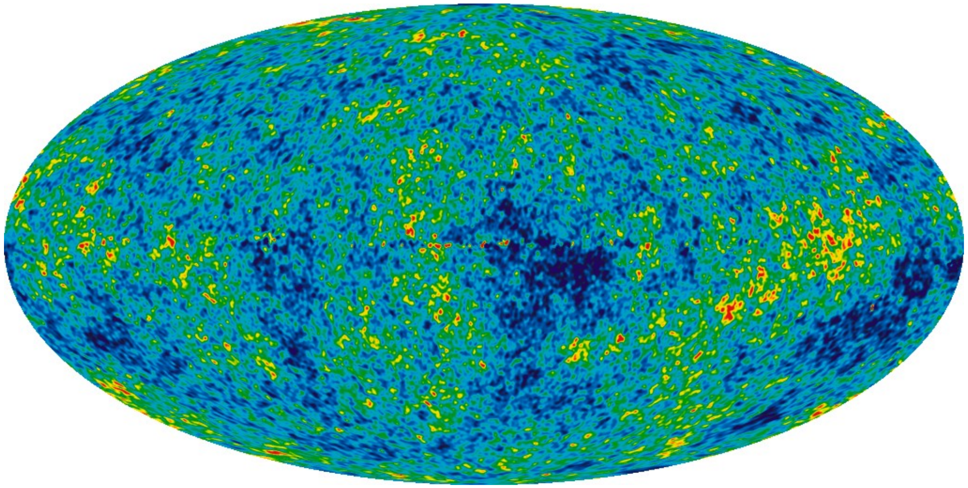
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

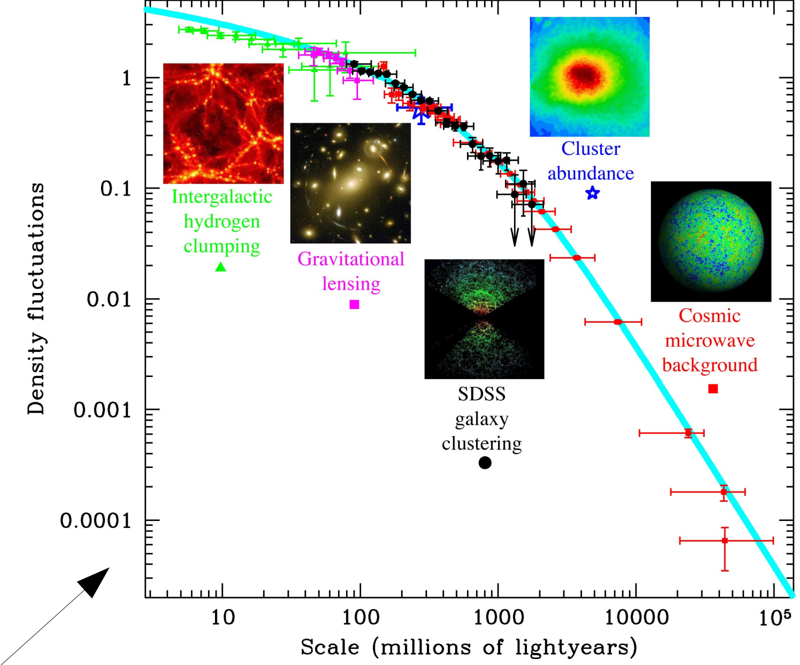
Cosmological constant ?
Vaccum energy density ?
Exotic source of energy ?
Signature of modified gravity ?
.... ???

$$p = w\,\rho$$

$w < -1/3$ for acceleration



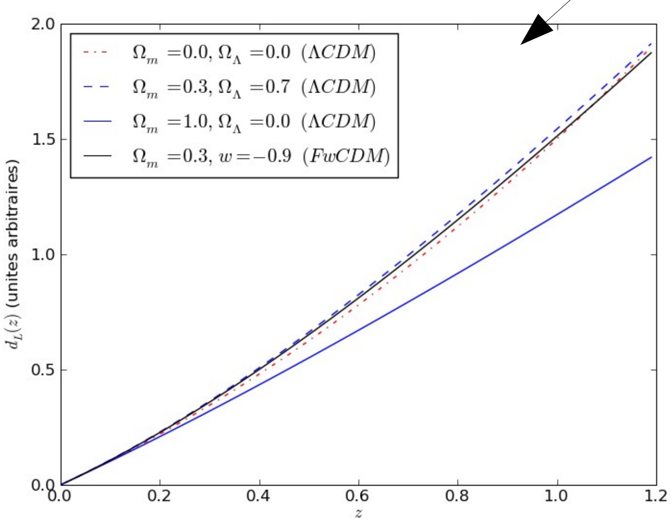
CMB anisotropies



Density fluctuations

ΛCDM

Geometric tests



Cosmological probes

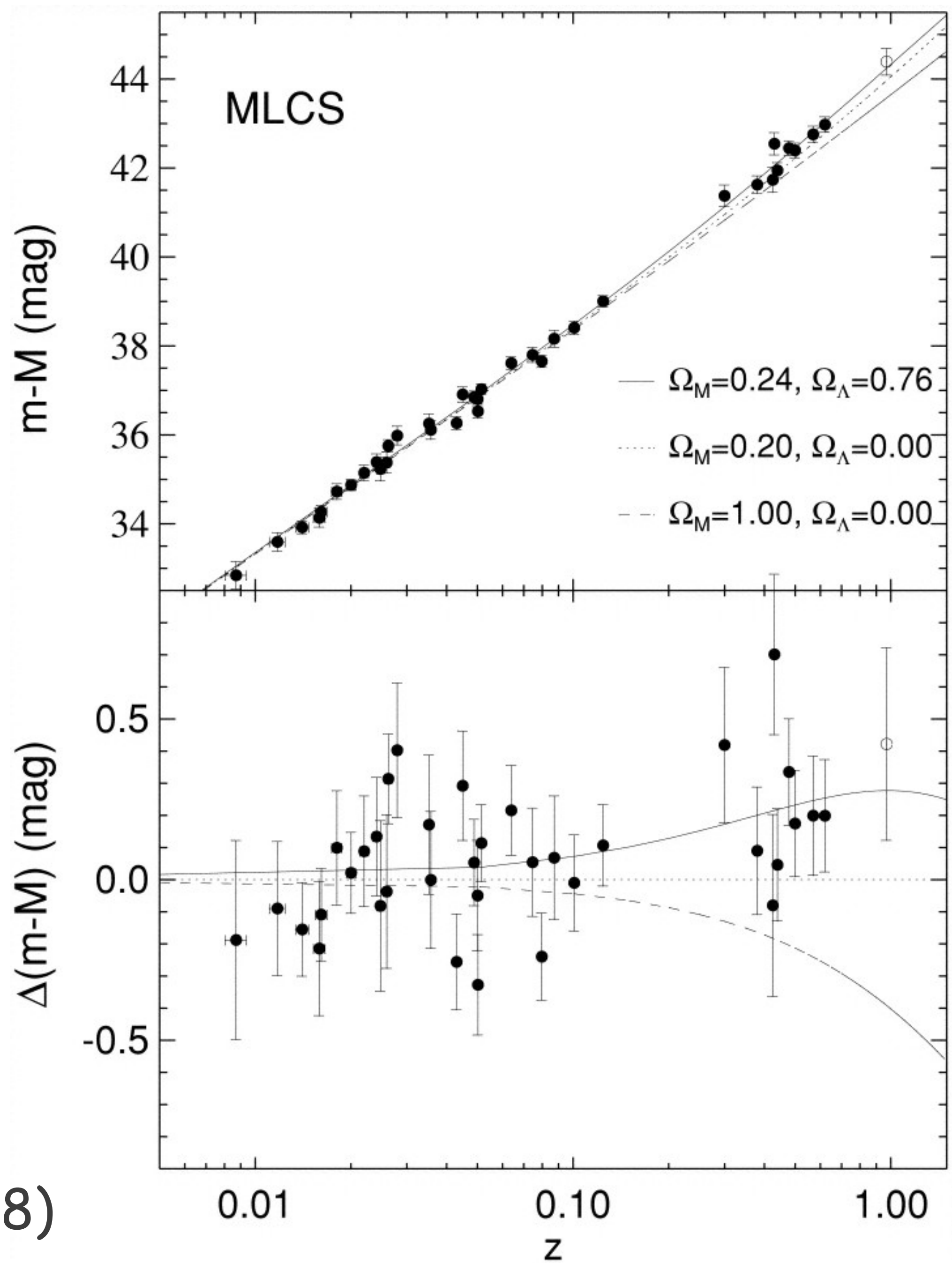
→ CMB

→ growth of structures

→ geometrical tests

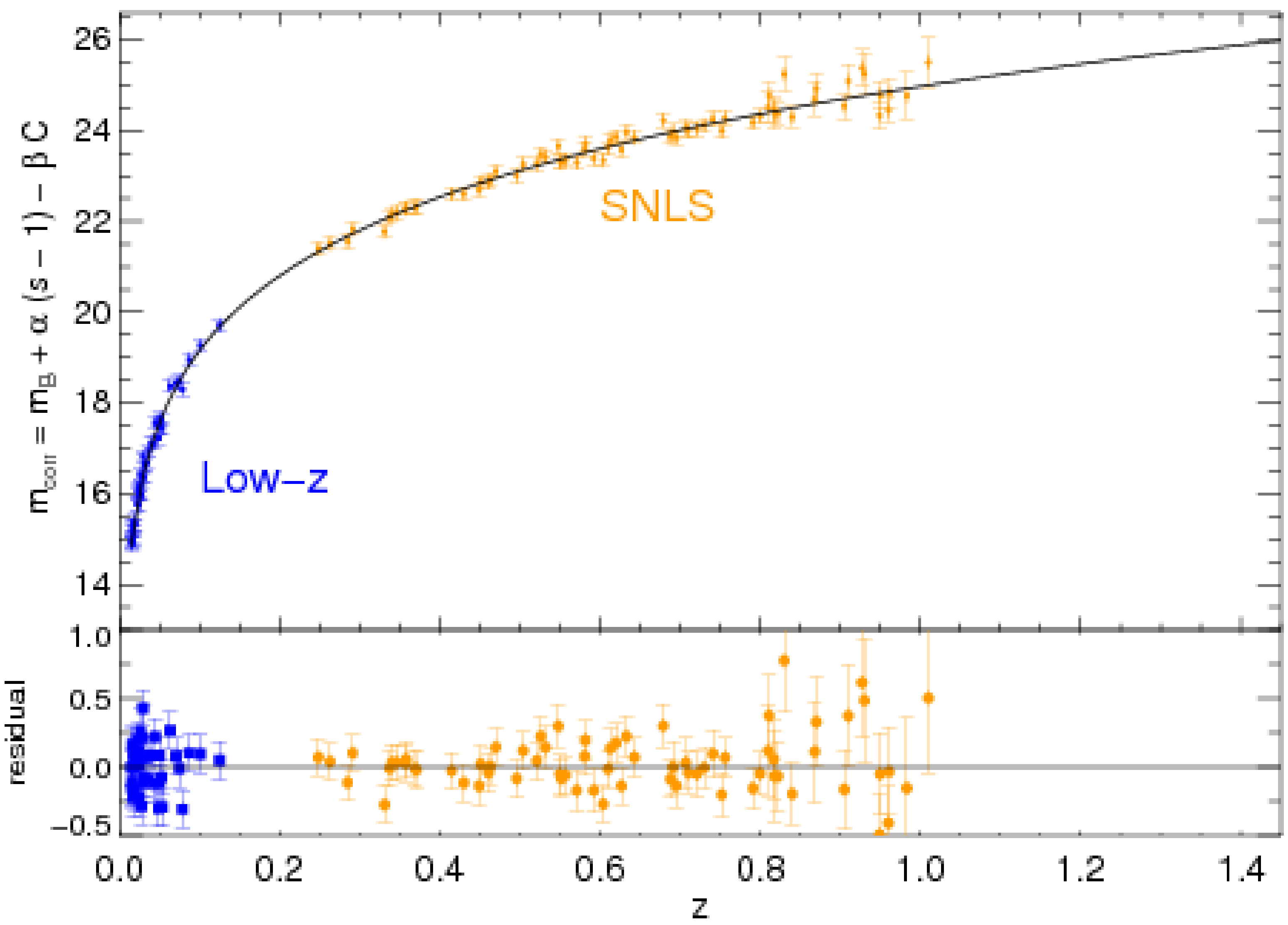
Degeneracies

1998...



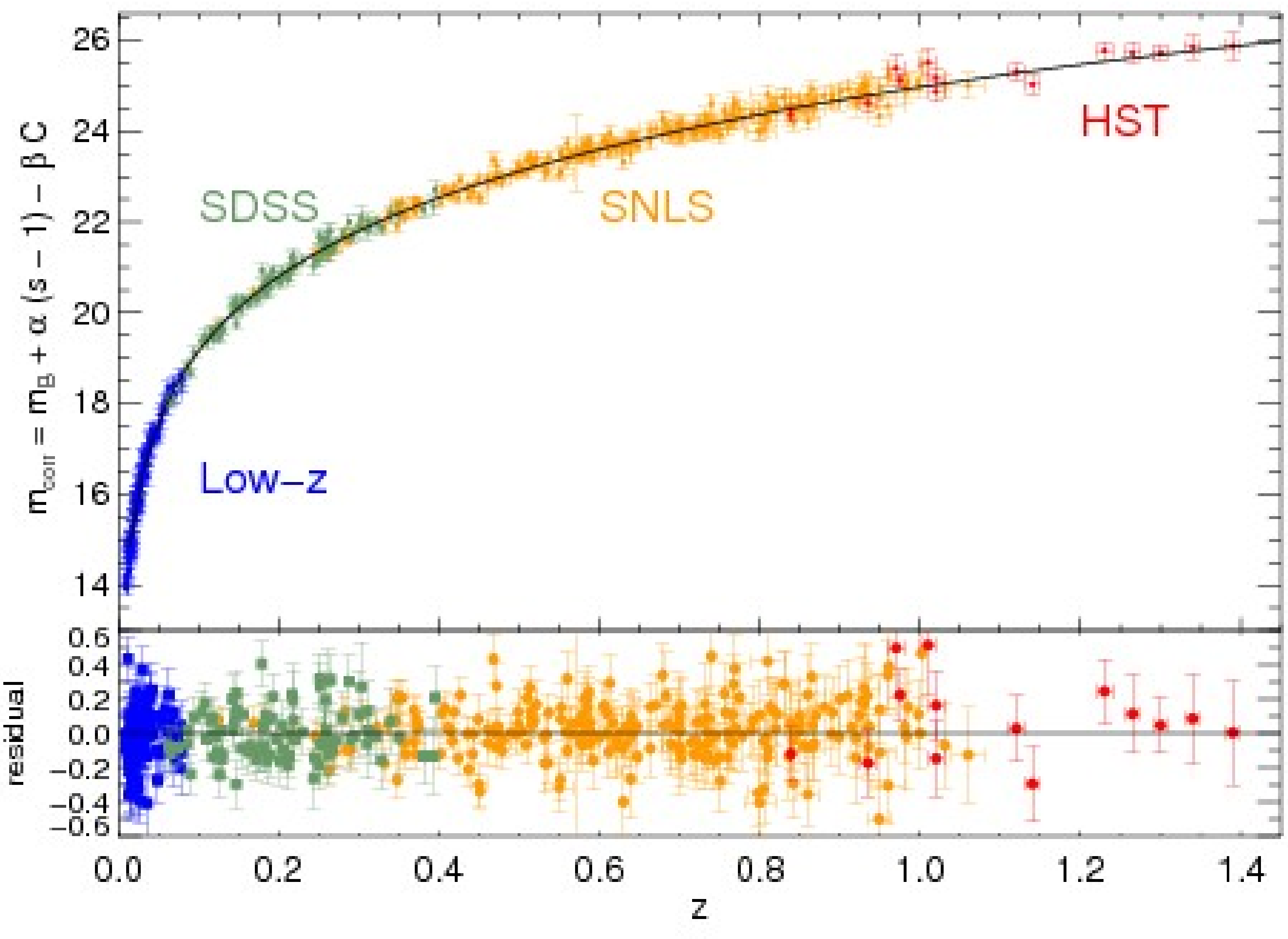
(Riess et al, 1998)

2006…

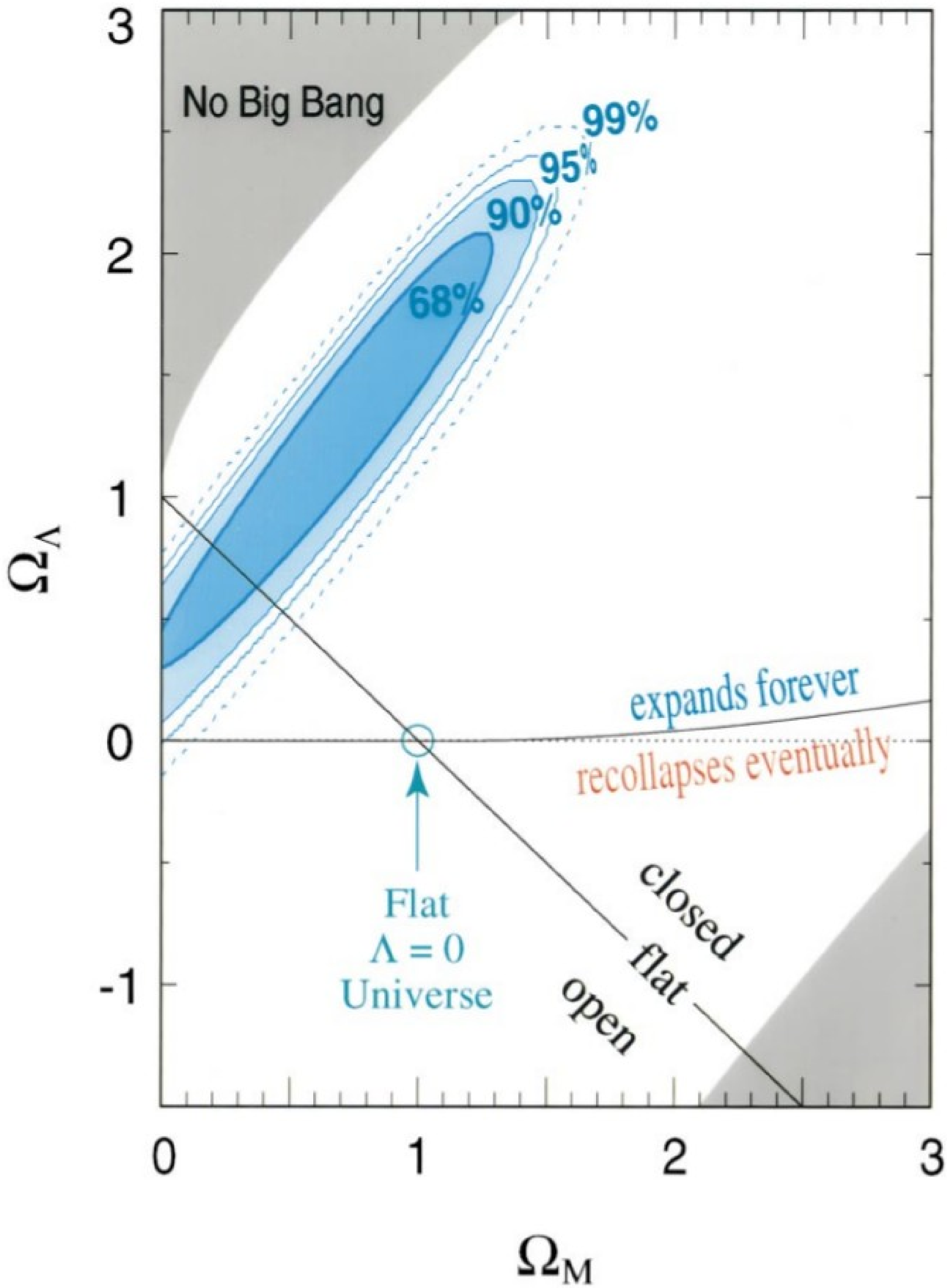


(Astier et al, 2006)

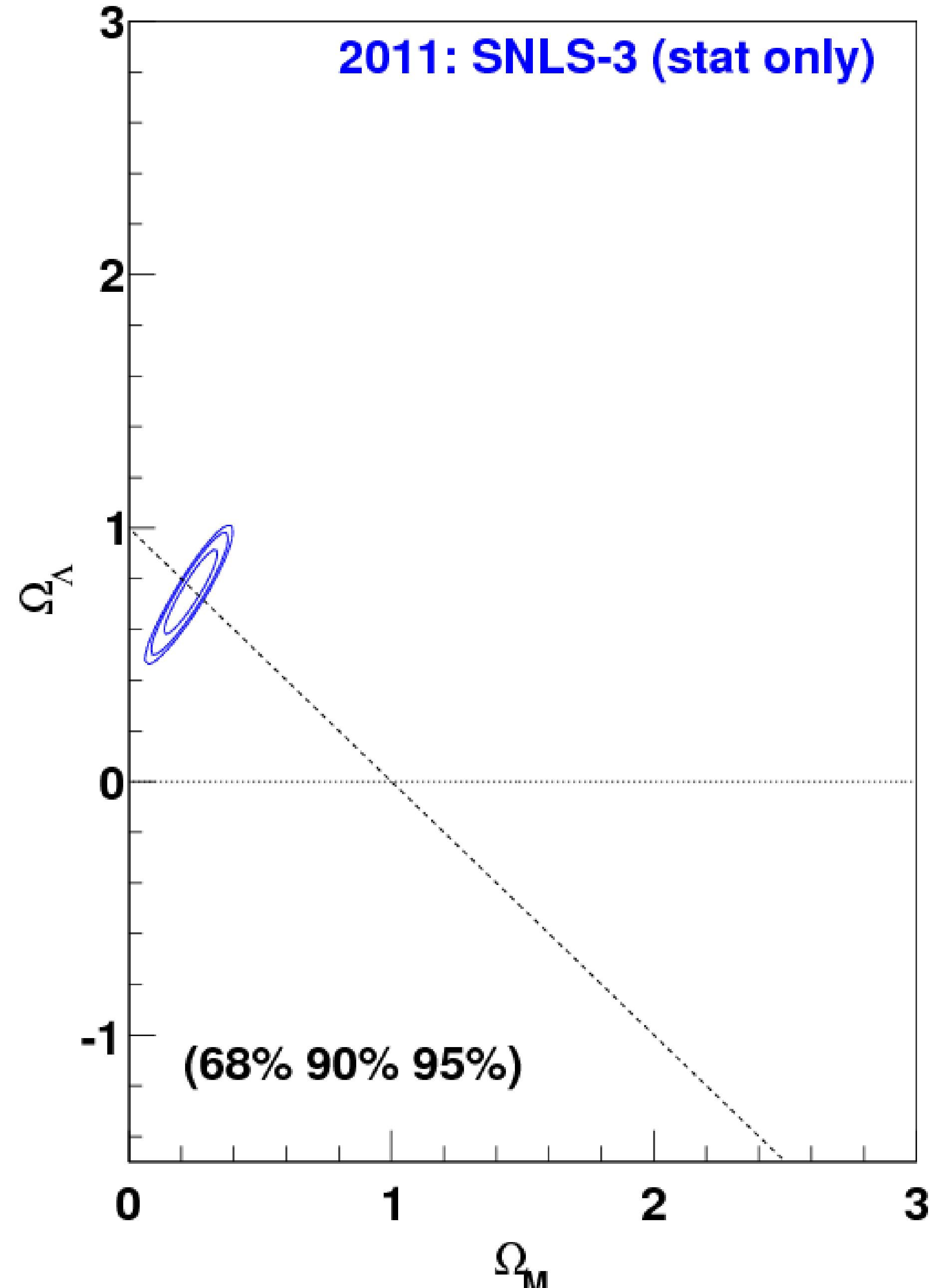
2011...



(Guy et al, 2010, Conley et al, 2010)



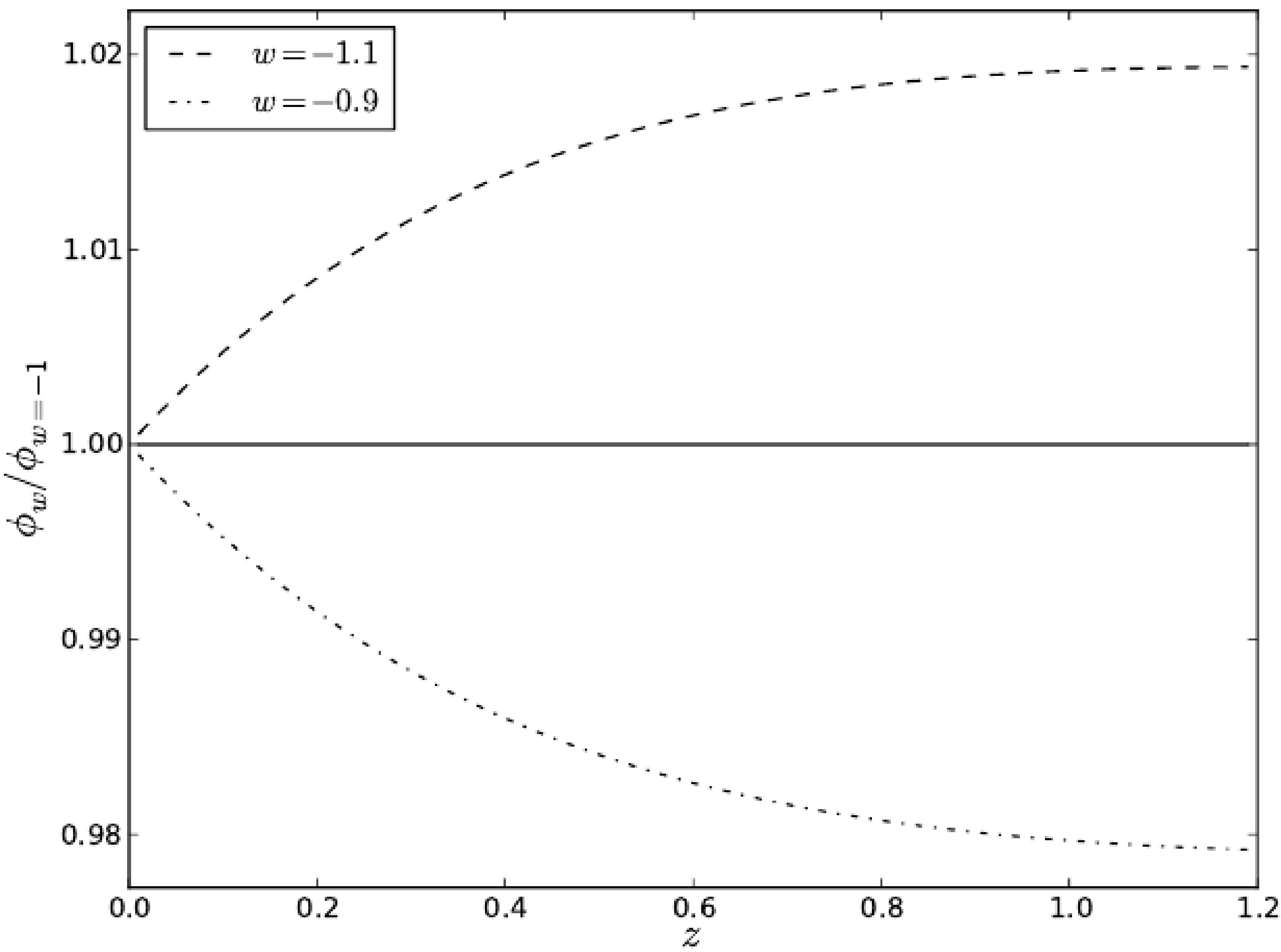
No Big Bang
99%
95%
90%
68%
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_Λ
Ω_M



2011: SNLS-3 (stat only)
(68% 90% 95%)
Ω_Λ
Ω_M

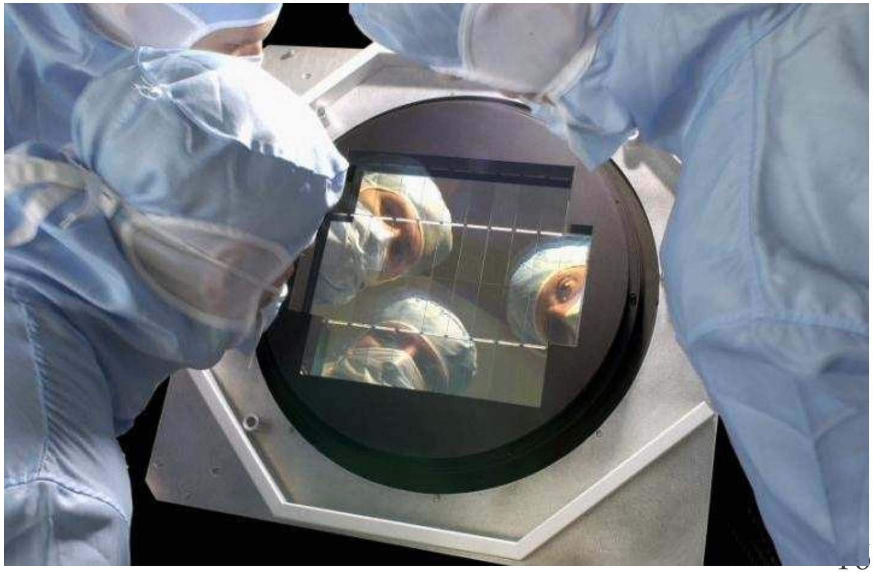
w = -1

An era of precision measurements...



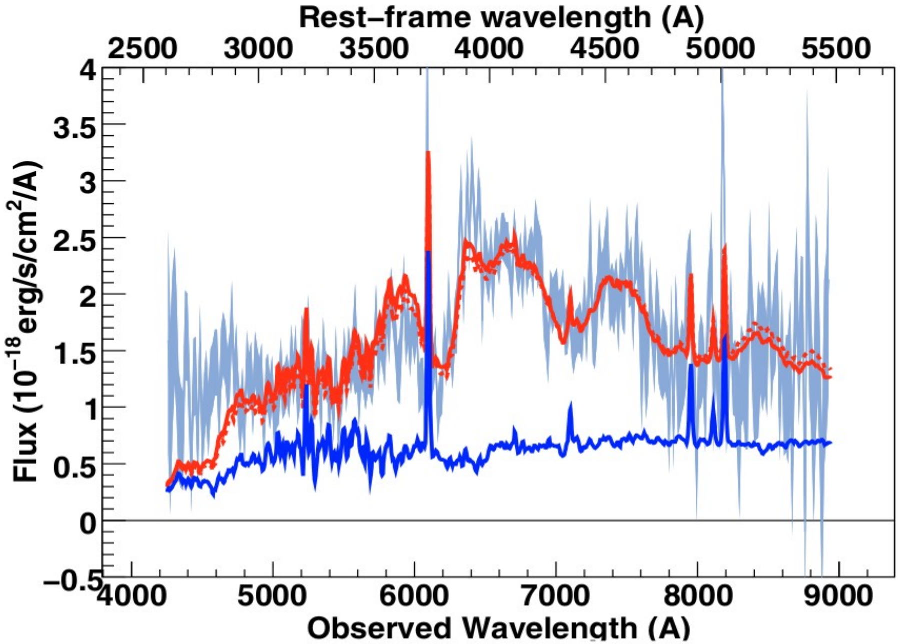
Supernova Legacy Survey

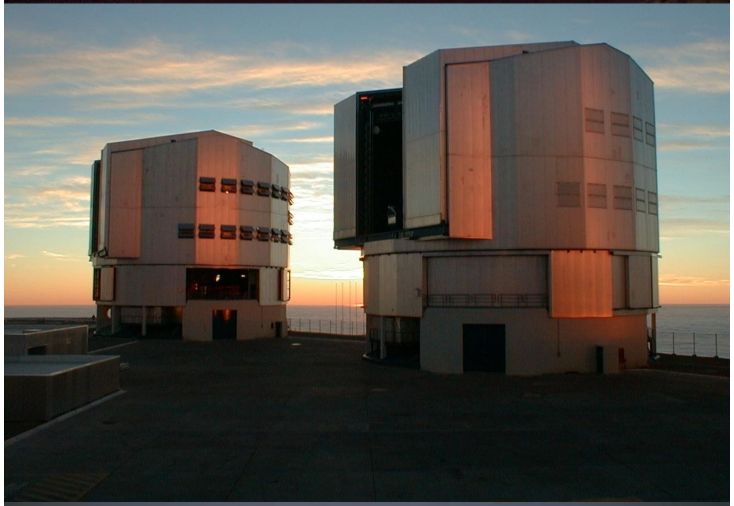
- 5 year survey @ CFHT (2003 - 2008)
  - Detection of Sne Ia @ $0.3 < z < 1$
  - Multiband follow-up (griz: 350 nm → 950 nm)
  - (rolling search)
- MegaCam
  - 1 deg2 - 0.18'' / pixel
  - 36 2k x 4.5k CCDs
- Mauna Kea
  - Median IQ ~ 0.7''



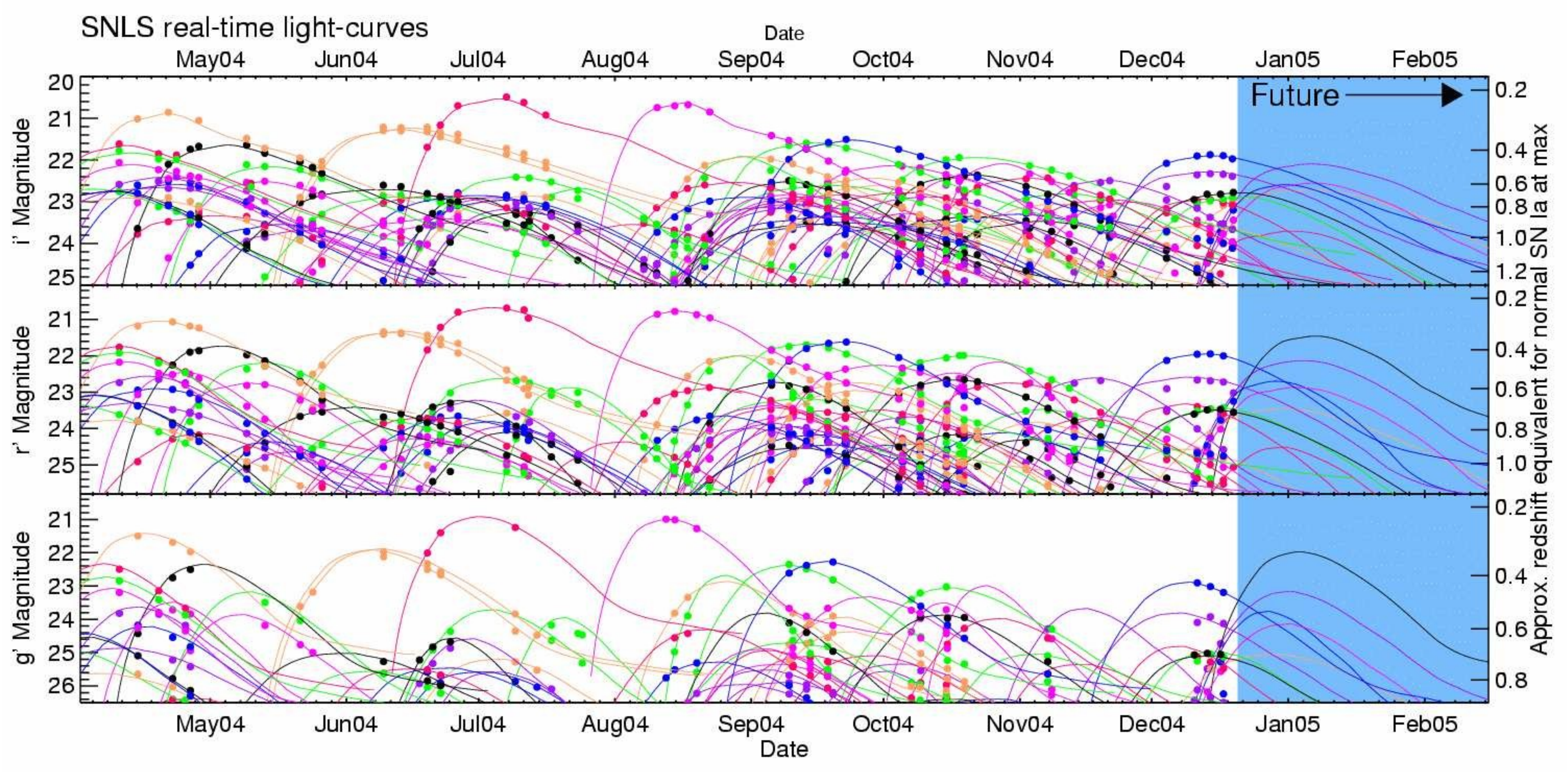
SNLS

- Spectroscopic Follow up
  - On 8-m class telescopes (Keck, VLT, Gemini)
  - Redshifts, classification & evolution studies

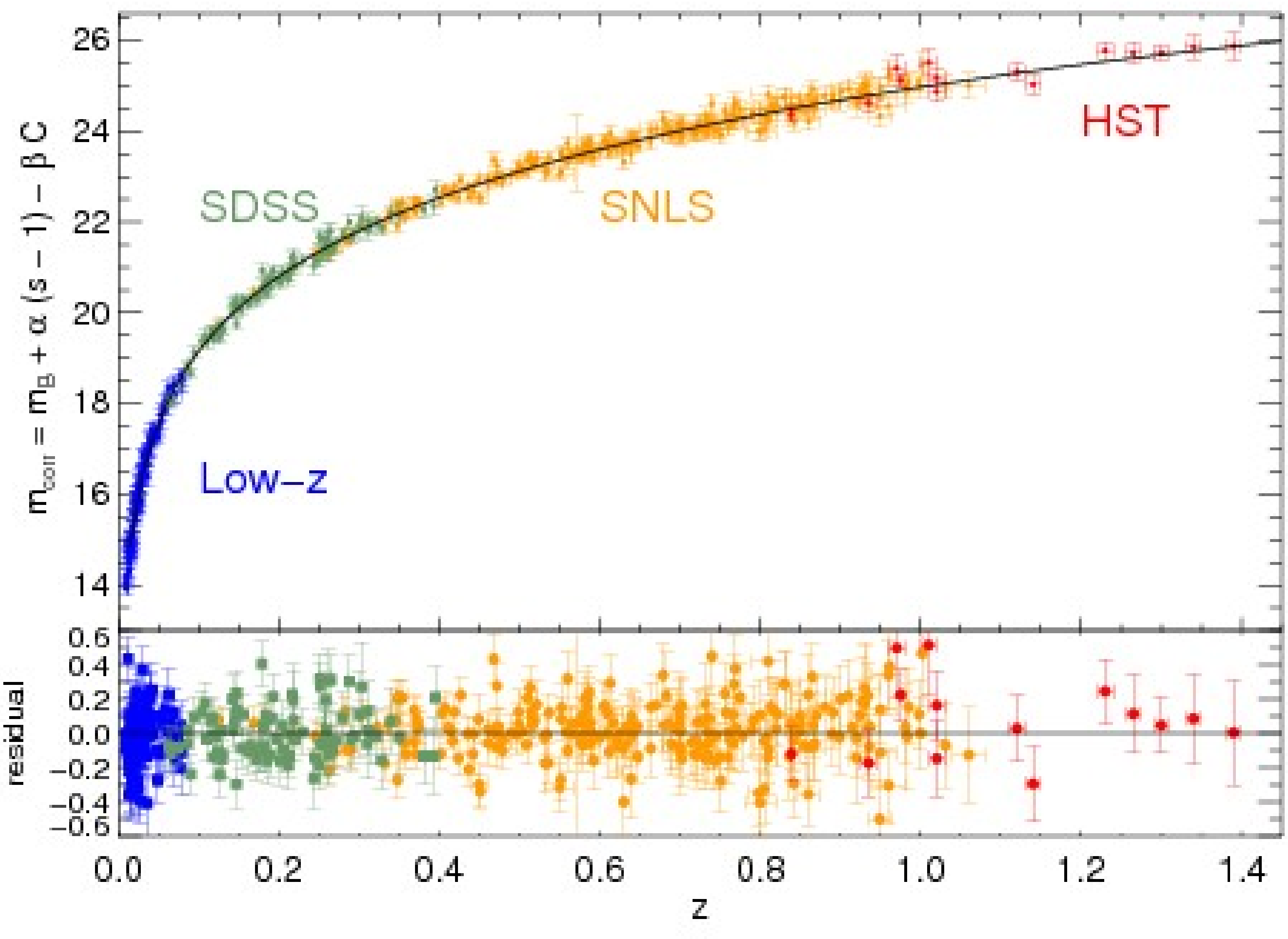




Rolling Search

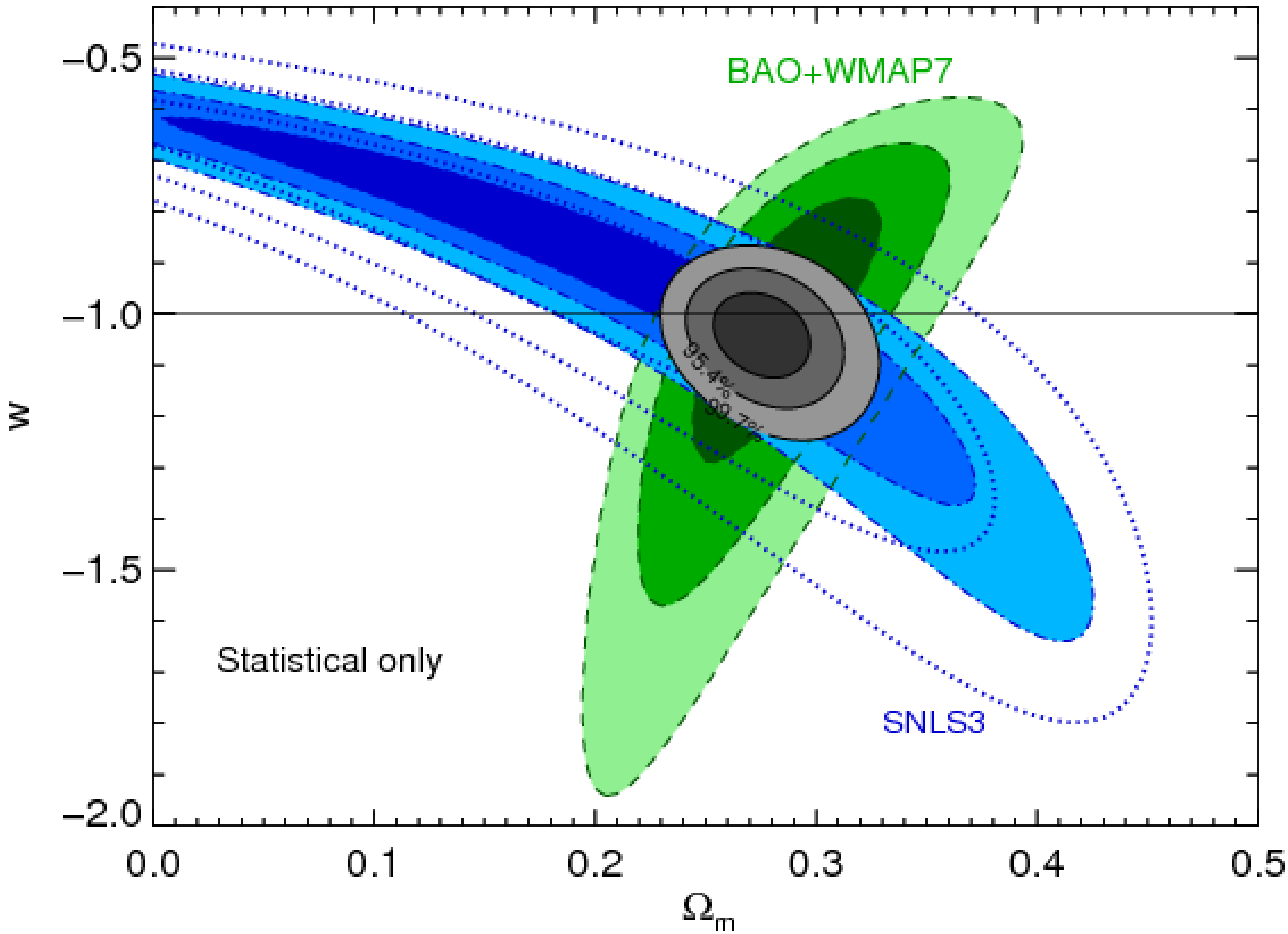


SNLS3



(Guy et al, 2010, Conley et al, 2010)

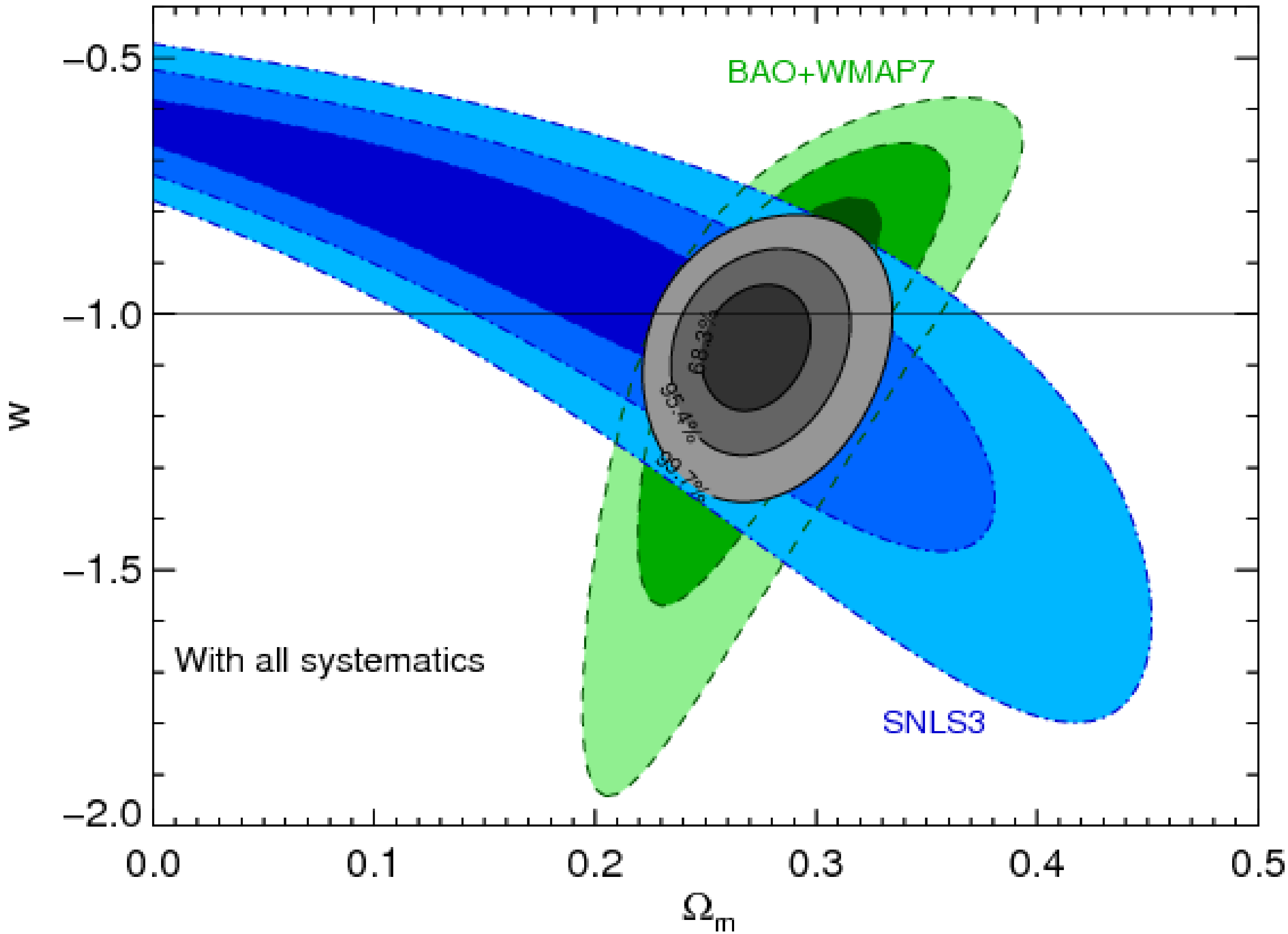
Constraints on w



w = -1.06 ± 0.05 (stat) ± 0.06 (sys)

(Sullivan et al, 2011)

Constraints on w



w = -1.06 ± 0.05 (stat) ± 0.06 (sys)

(Sullivan et al, 2011)

Systematics

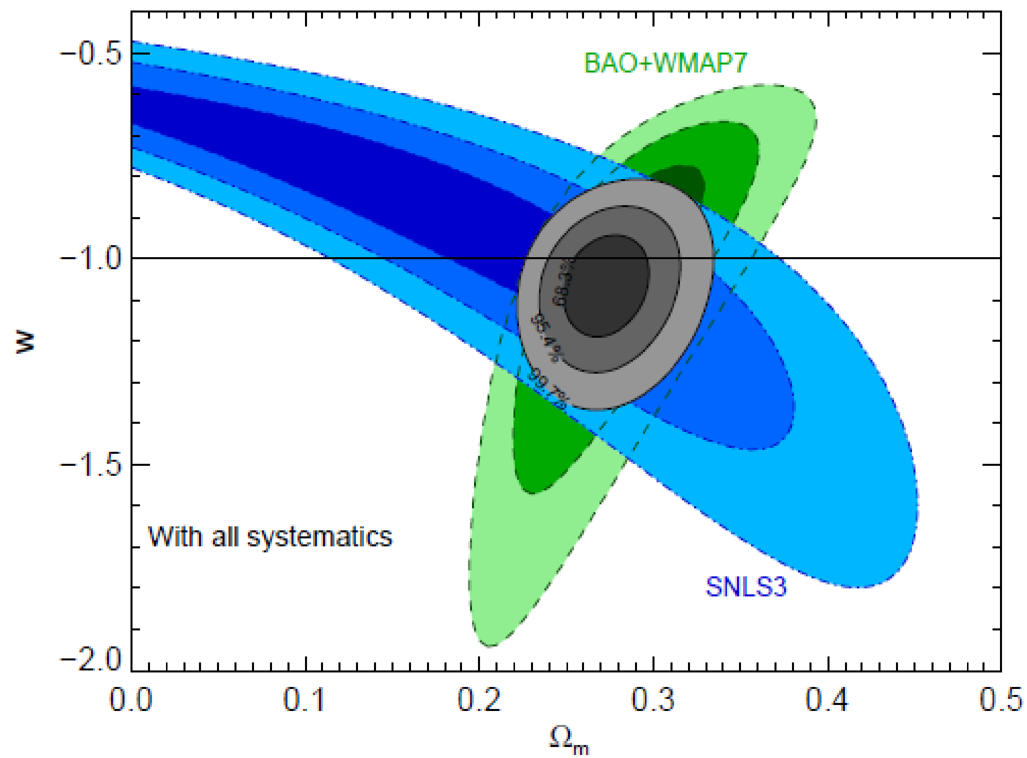
Table 7: Identified systematic uncertainties

Description	Ω_m	w	Rel. Area [a]	w for Ω_m=0.27
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85	$-1.08^{+0.10}_{-0.11}$
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79	-1.06 ± 0.10
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02	-1.027 ± 0.059
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03	-1.034 ± 0.059
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07	-1.037 ± 0.060
non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05	-1.032 ± 0.060
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02	-1.028 ± 0.059
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08	-1.034 ± 0.061

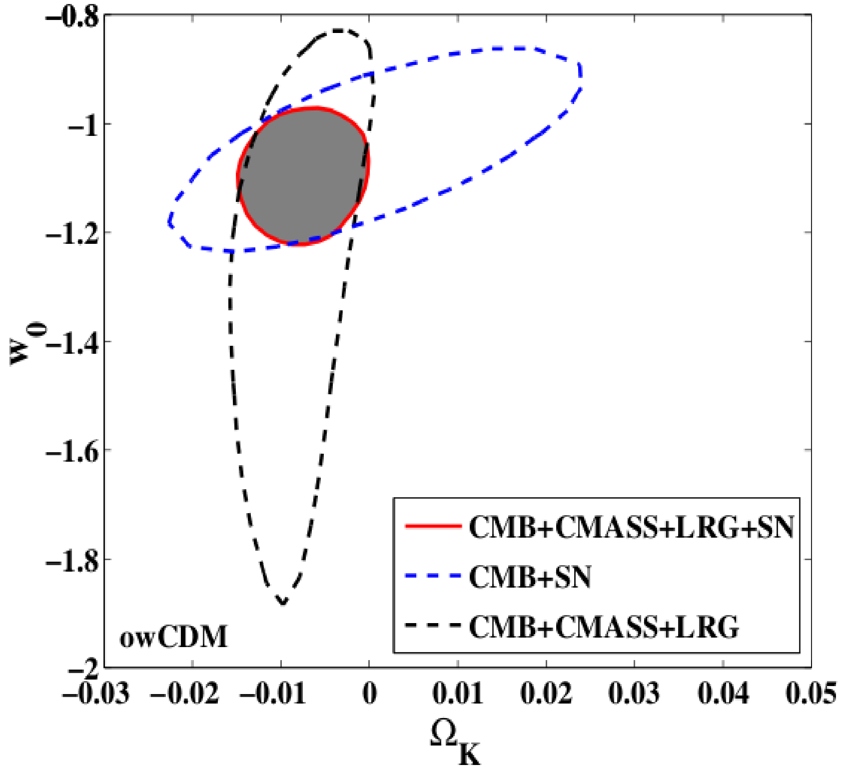
(Conley et al, 2011)

Constraints on w

- Constraints on w primarily from Sne Ia
- Won't be outperformed (WL, BAO) before ~ 2018 - 2020.



(Sullivan et al, 2011)



(Anderson et al, 2012)

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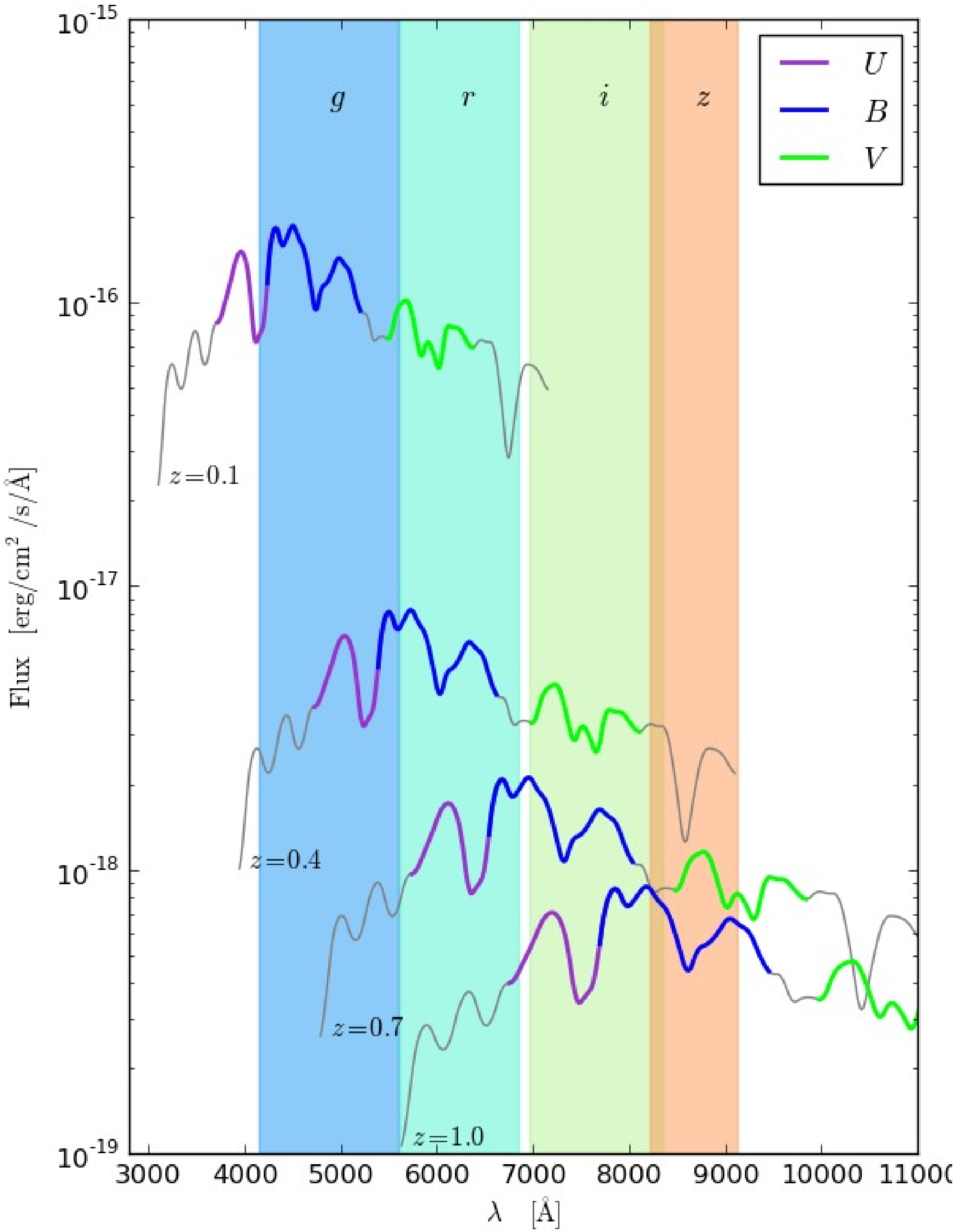
Why does calibration matter ?



- Spectrophotometric model

  -> interpolate between flux measurements (SALT2, SiFTO...)
- Flux intercalibration between

  blue and red bands.
- Distances from:
  - restframe (B,V) [z < 0.65]
  - restframe (U,B) [z > 0.65]

  → two regimes

  → strongly rely on SN model

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Ingredients

- Primary Flux Standard(s) [$S_{ref}(\lambda)$]
  - Vega ?
  - CALSPEC white dwarfs / solar analogs ?
- Metrology Chain [m_{ref}]
  - Primary standard observations → science observations
- Filter transmissions [$T(\lambda)$]

$$\phi = 10^{-0.4(m-m_{\rm ref})} \times \int S_{\rm ref}(\lambda)\ \ T(\lambda) d\lambda$$

Fundamental Flux standard(s)

CALSPEC

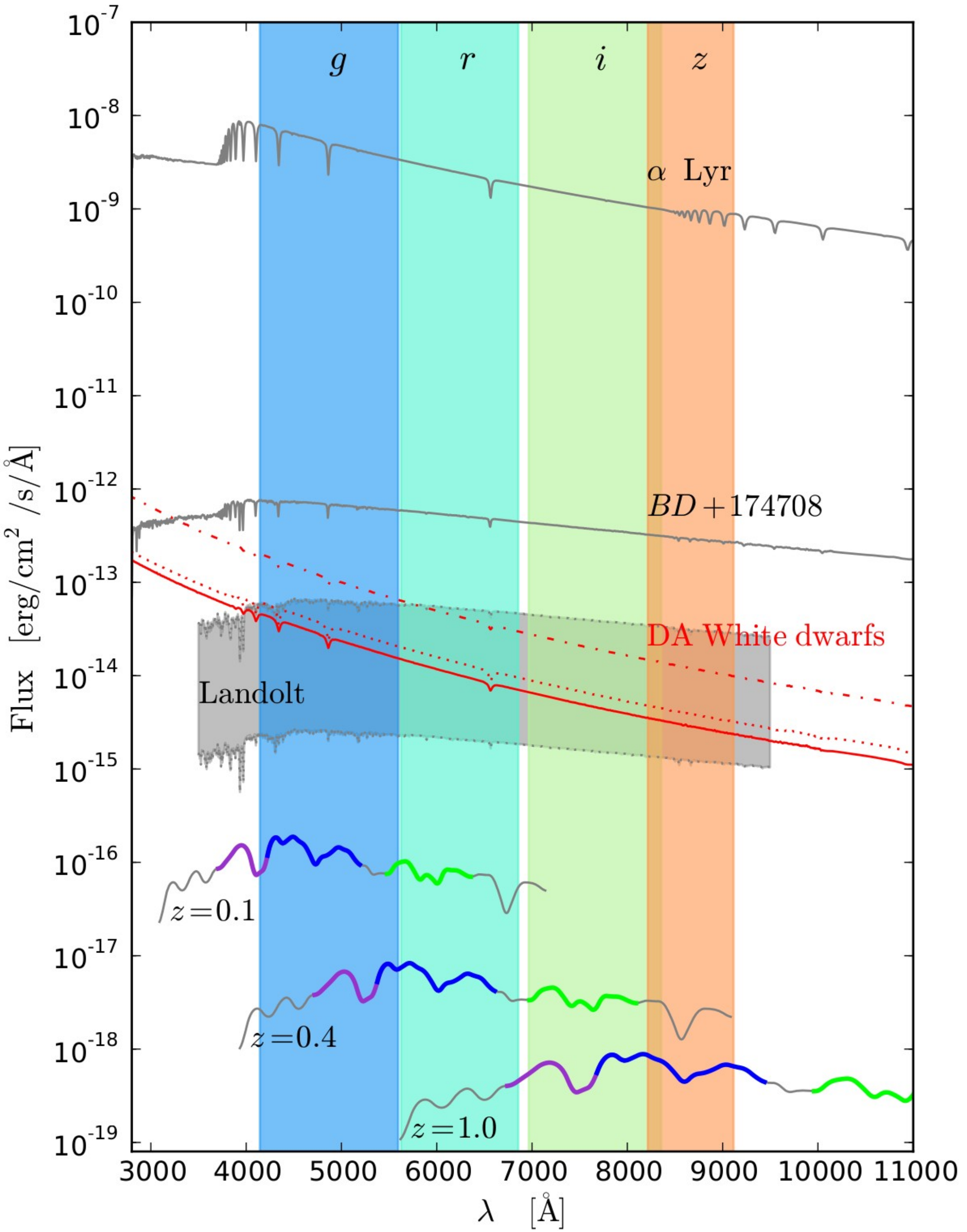
Models of 3 Hot DA white dwarfs

HST STIS / NICMOS flux calibration

~ 60 secondary flux standards

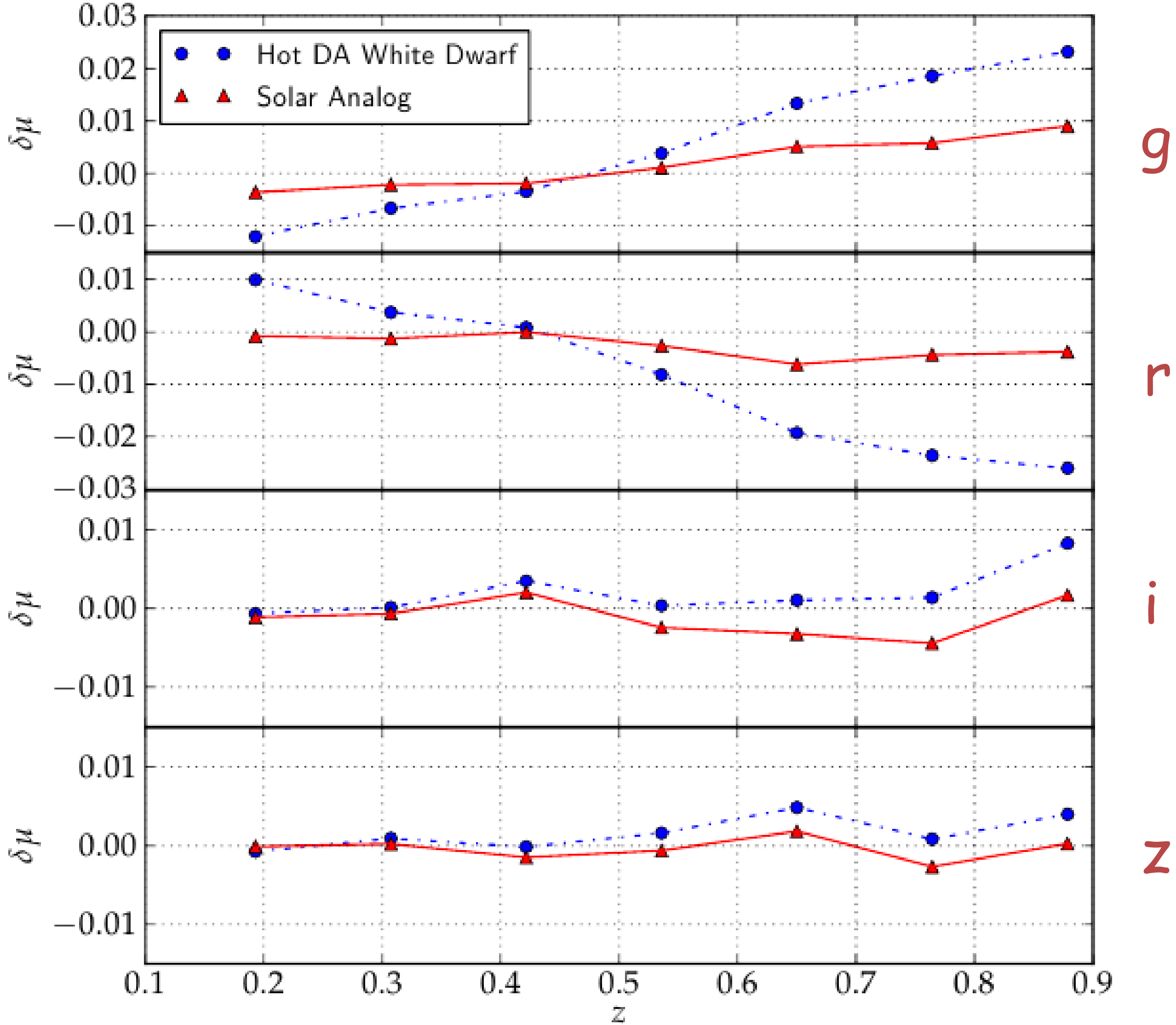
(BD +17 4708 + Fainter, redder solar analogs)

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



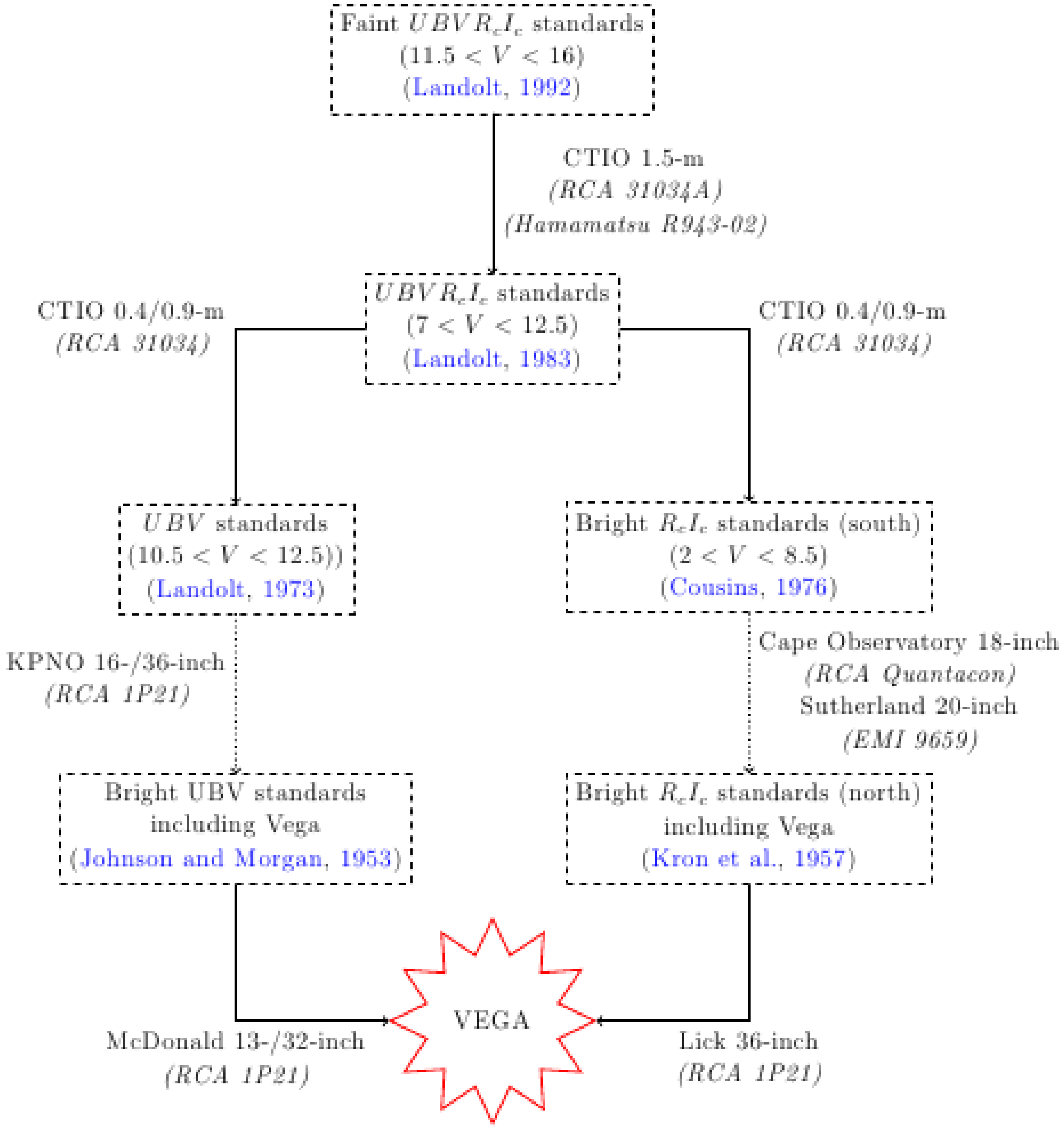
g
r
i
z
α Lyr
BD +174708
DA White dwarfs
Landolt
z = 0.1
z = 0.4
z = 1.0
Flux [erg/cm² /s/Å]
λ [Å]
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
10-16
10-17
10-18
10-19
3000
4000
5000
6000
7000
8000
9000
10000
11000

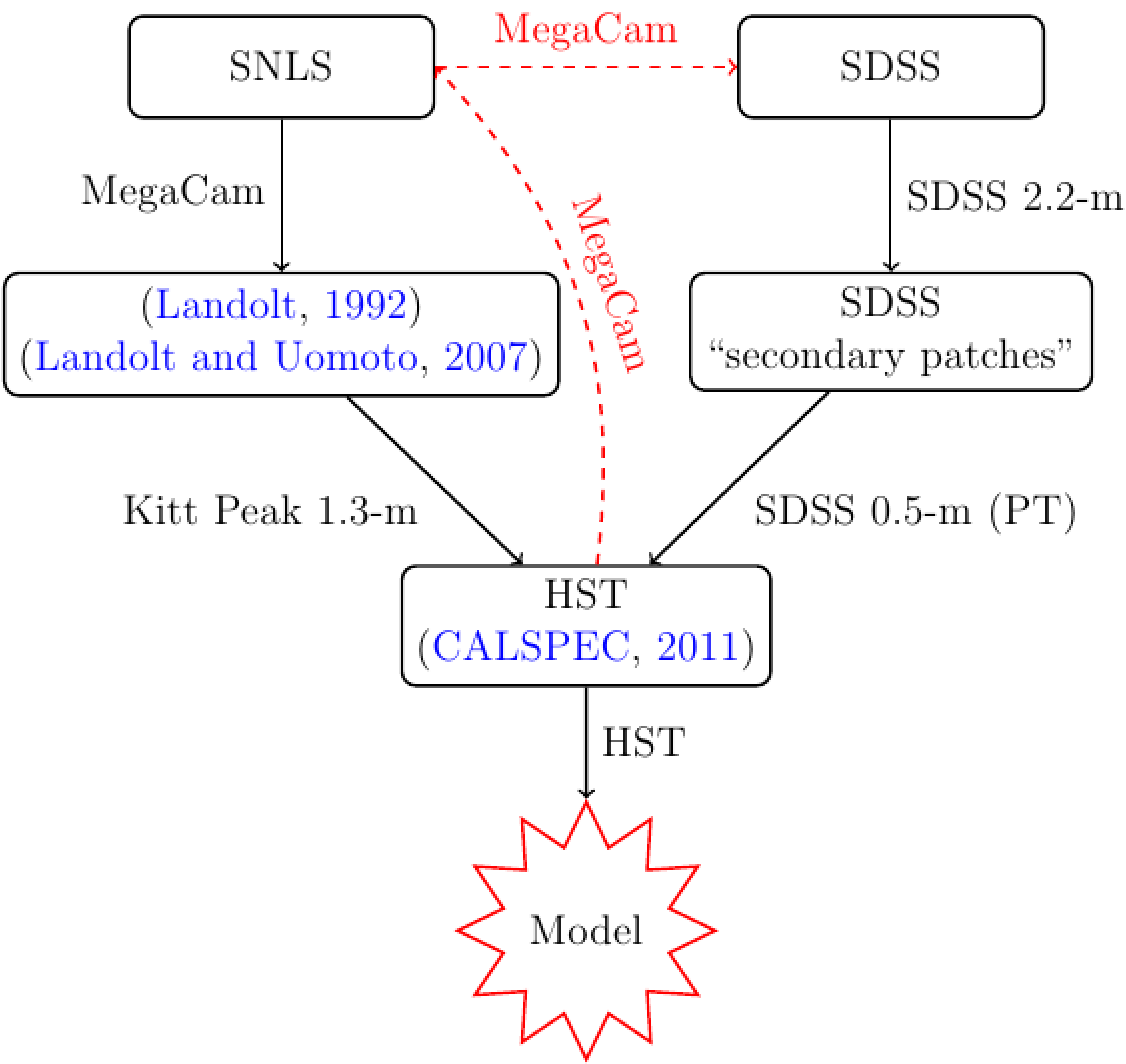
Red or blue standards ?



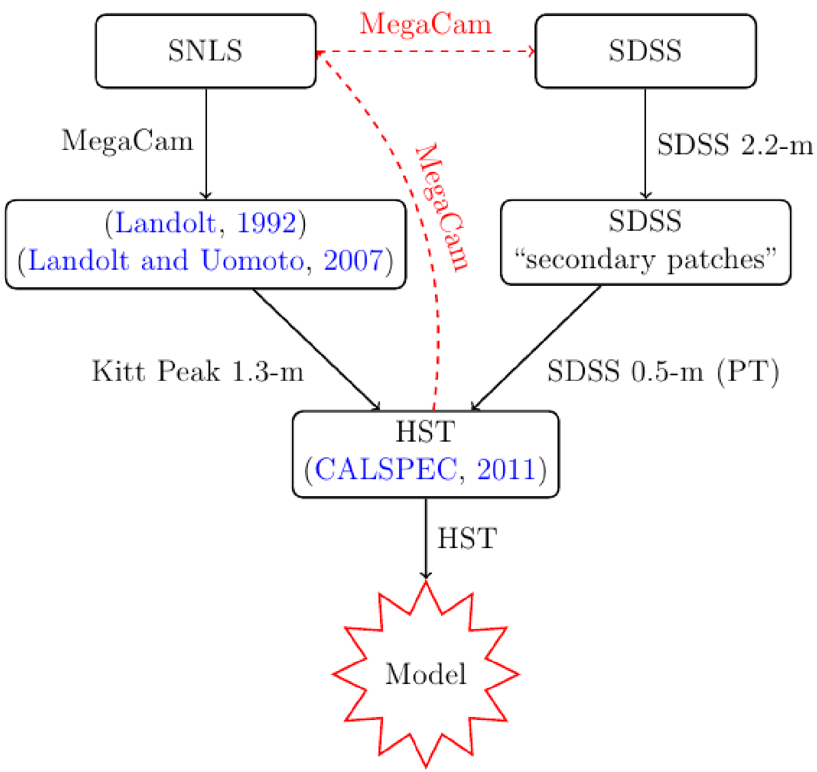
$\Delta\mu = \partial\mu/\partial\lambda \times \delta\lambda$ (from SNLS3)

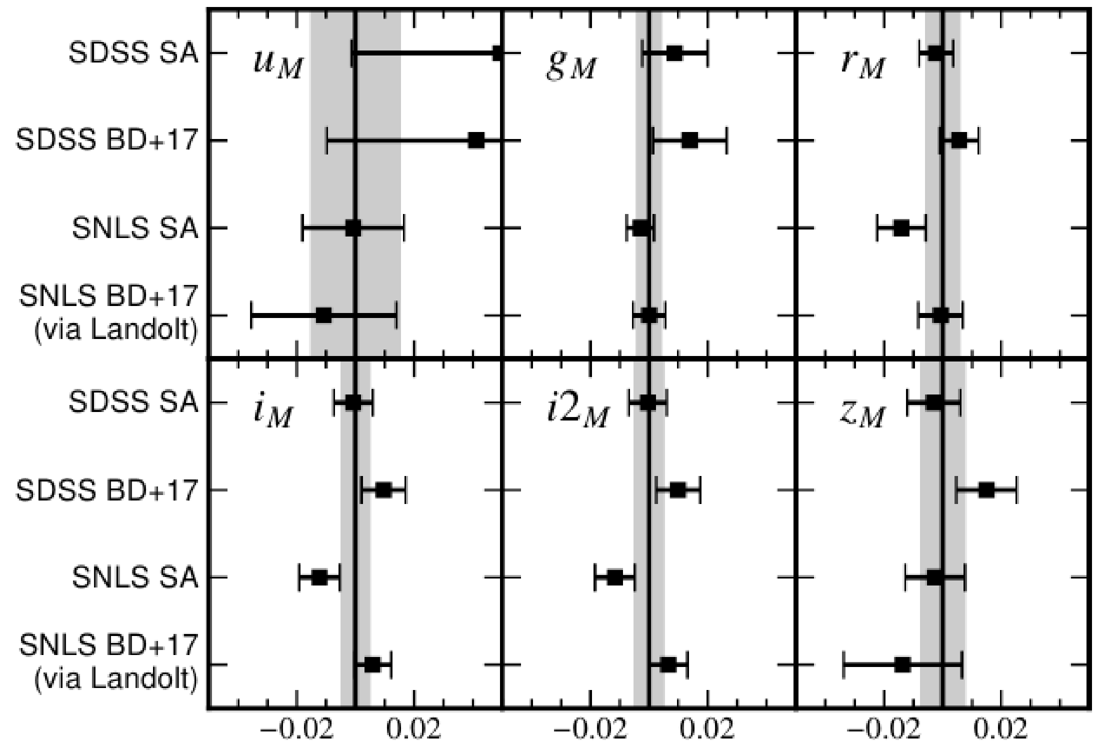
→ Better know your filters !


Faint $UBVR_cI_c$ standards
$(11.5 < V < 16)$
(Landolt, 1992)
CTIO 1.5-m
(RCA 31034A)
(Hamamatsu R943-02)
$UBVR_cI_c$ standards
$(7 < V < 12.5)$
(Landolt, 1983)
CTIO 0.4/0.9-m
(RCA 31034)
CTIO 0.4/0.9-m
(RCA 31034)
UBV standards
$(10.5 < V < 12.5)$)
(Landolt, 1973)
Bright R_cI_c standards (south)
$(2 < V < 8.5)$
(Cousins, 1976)
KPNO 16-/36-inch
(RCA 1P21)
Cape Observatory 18-inch
(RCA Quantacon)
Sutherland 20-inch
(EMI 9659)
Bright UBV standards
including Vega
(Johnson and Morgan, 1953)
Bright R_cI_c standards (north)
including Vega
(Kron et al., 1957)
VEGA
McDonald 13-/32-inch
(RCA 1P21)
Lick 36-inch
(RCA 1P21)


SNLS
MegaCam
SDSS
MegaCam
SDSS 2.2-m
MegaCam
(Landolt, 1992)
(Landolt and Uomoto, 2007)
SDSS
“secondary patches”
Kitt Peak 1.3-m
SDSS 0.5-m (PT)
HST
(CALSPEC, 2011)
HST
Model

Independent calibration paths



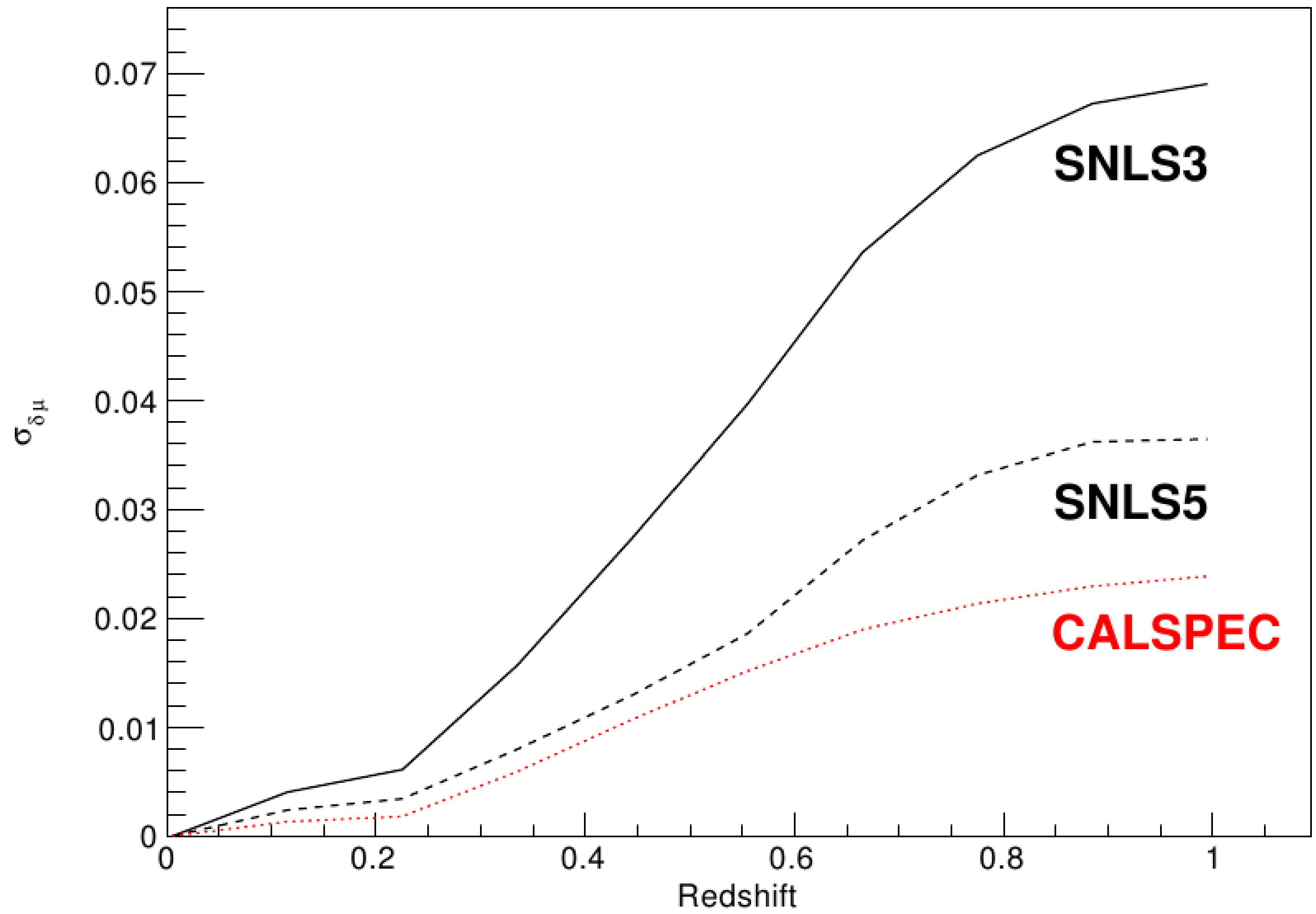


- Agree within the error bars

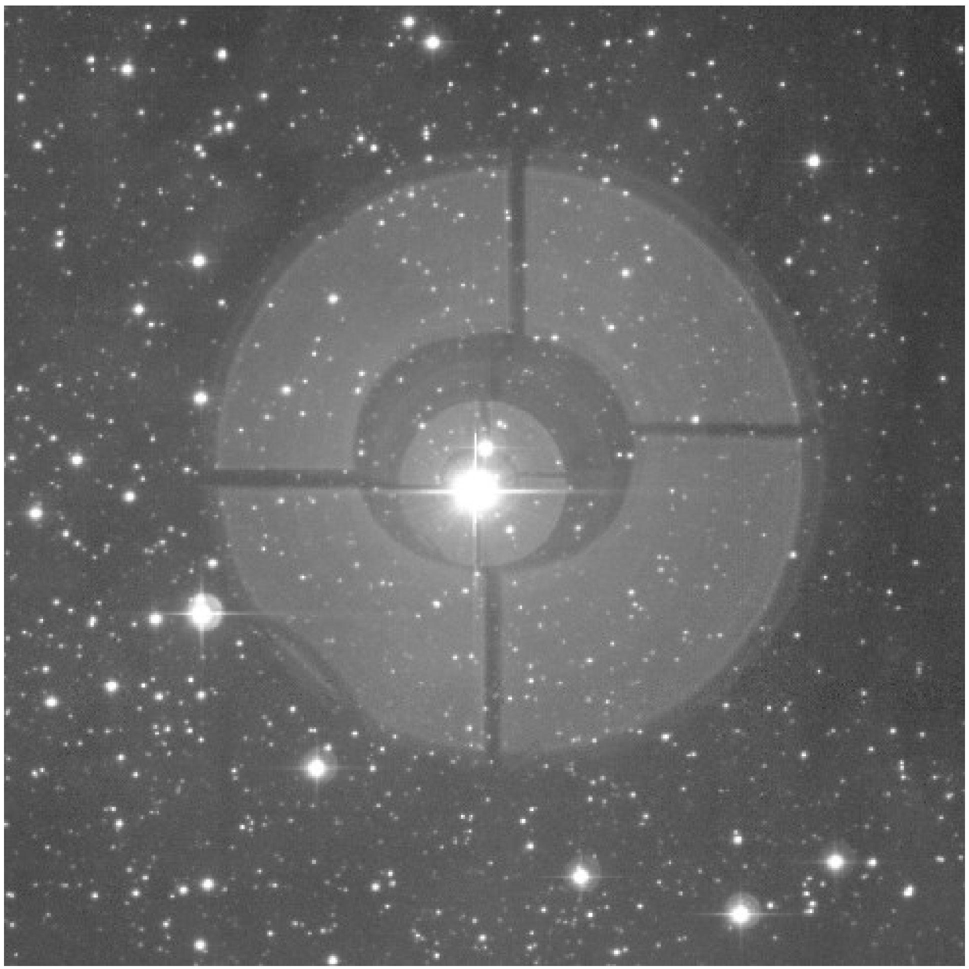
u	g	r	i	i2	z
0.0145	0.0035	0.0051	0.0042	0.0043	0.0069

(Betoule et al, 2012)

Impact on SNIa luminosity distances

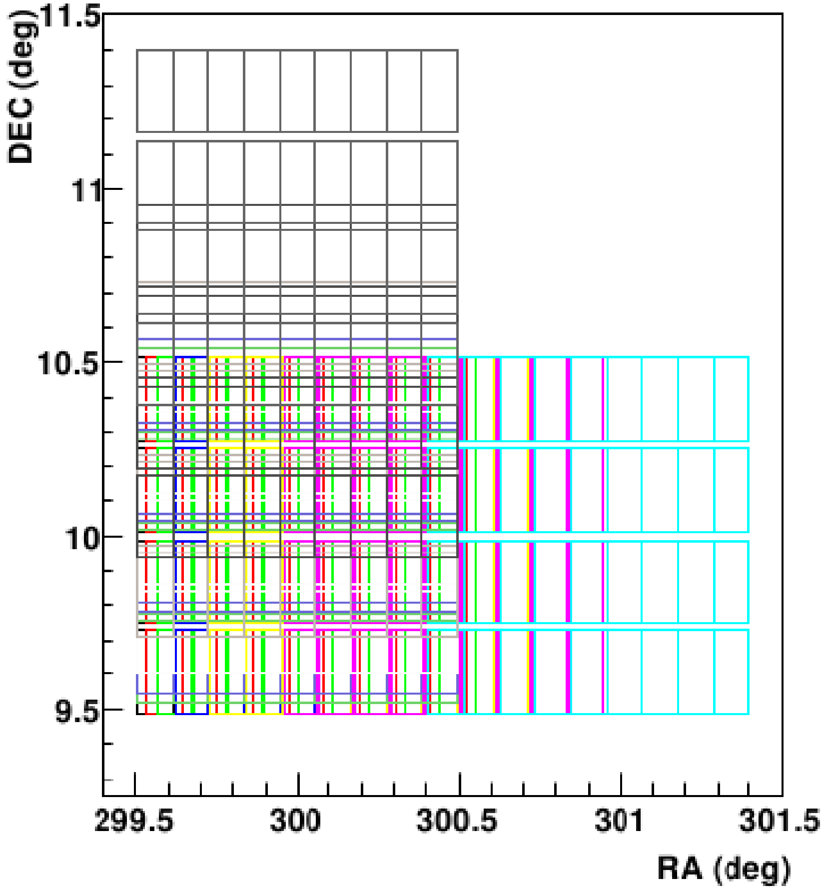


Mapping the instrument response



- Twilights
  - Affected by plate scale
  - contaminated by ghosts (reflections in the WFC)
- Filters are not uniform
  - Transmissions vary by up to ~ 5 nm (center to corner)

Mapping the instrument response



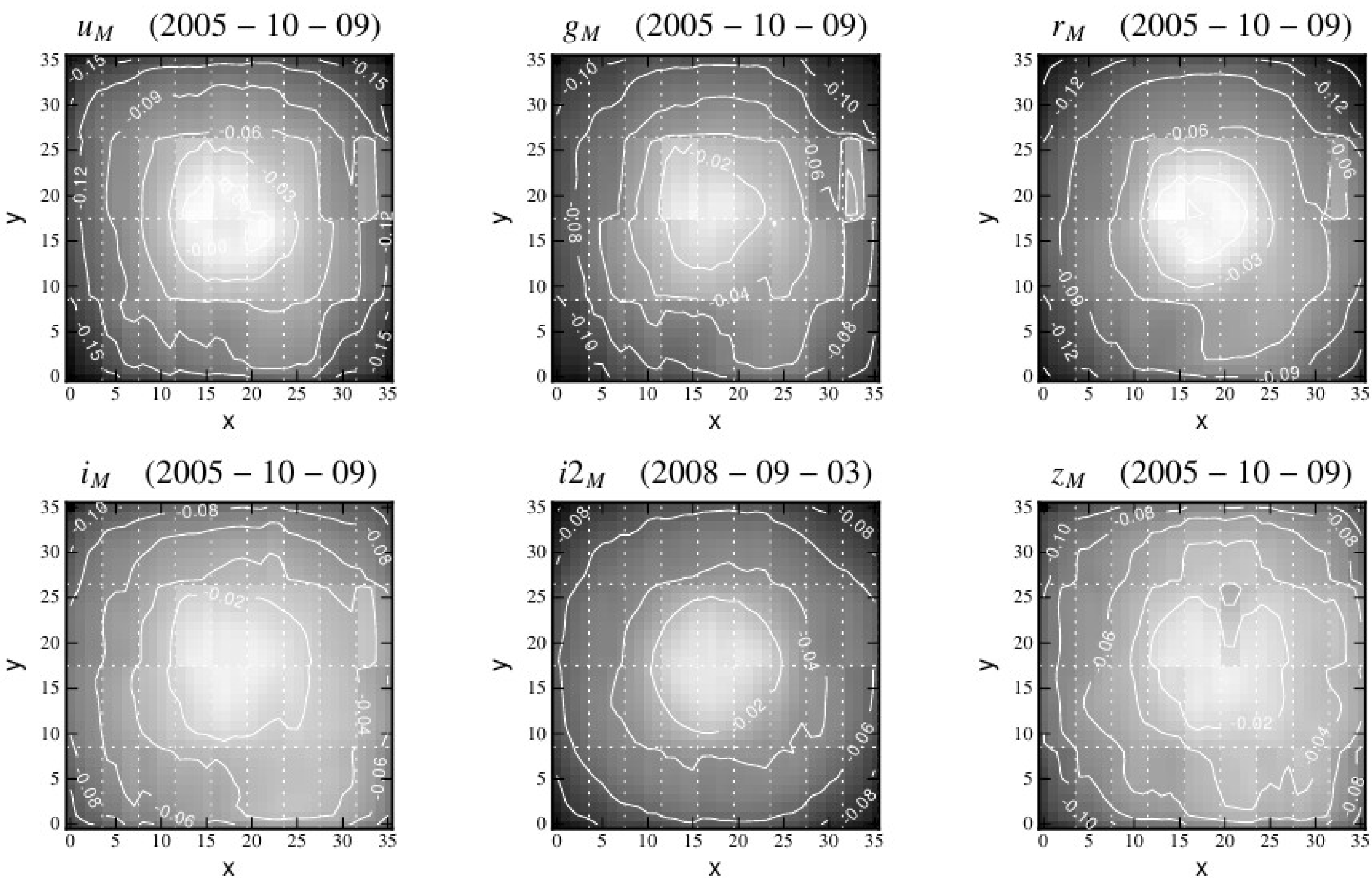
- Dithered observations of dense stellar fields
  - Logarithmically Increasing steps (1.5' → 0.5 deg)
  - Observed every ~ 6 months
- Model

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

Star mags @ center (~ 100,000 pars)

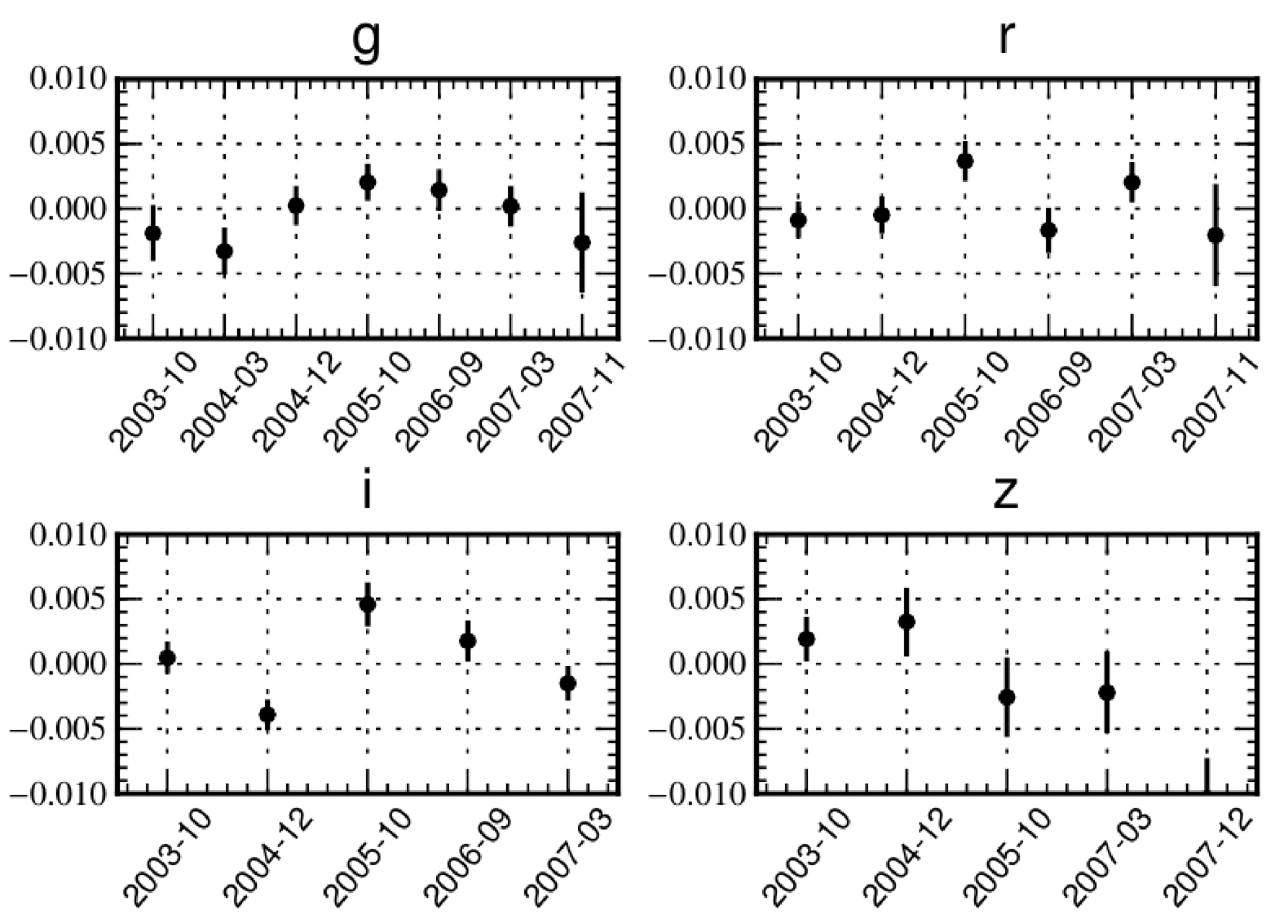
Maps (~ 100 pars)

Mapping the instrument response



(Betoule et al, 2012)

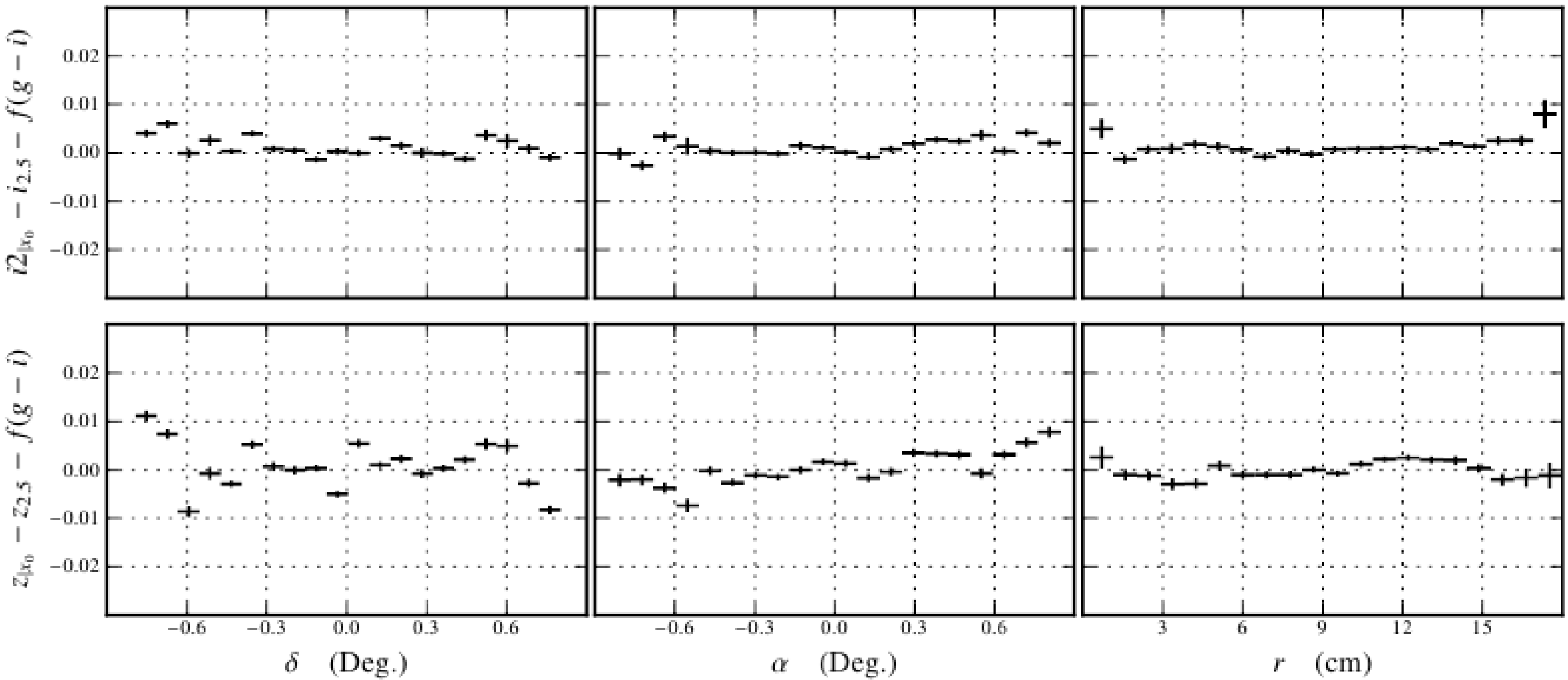
Impact of Flat-fielding errors



- Calibration residuals as a function of the photometric flat
- All epochs agree with a dispersion < 0.3% in all bands

(Betoule et al, 2012)

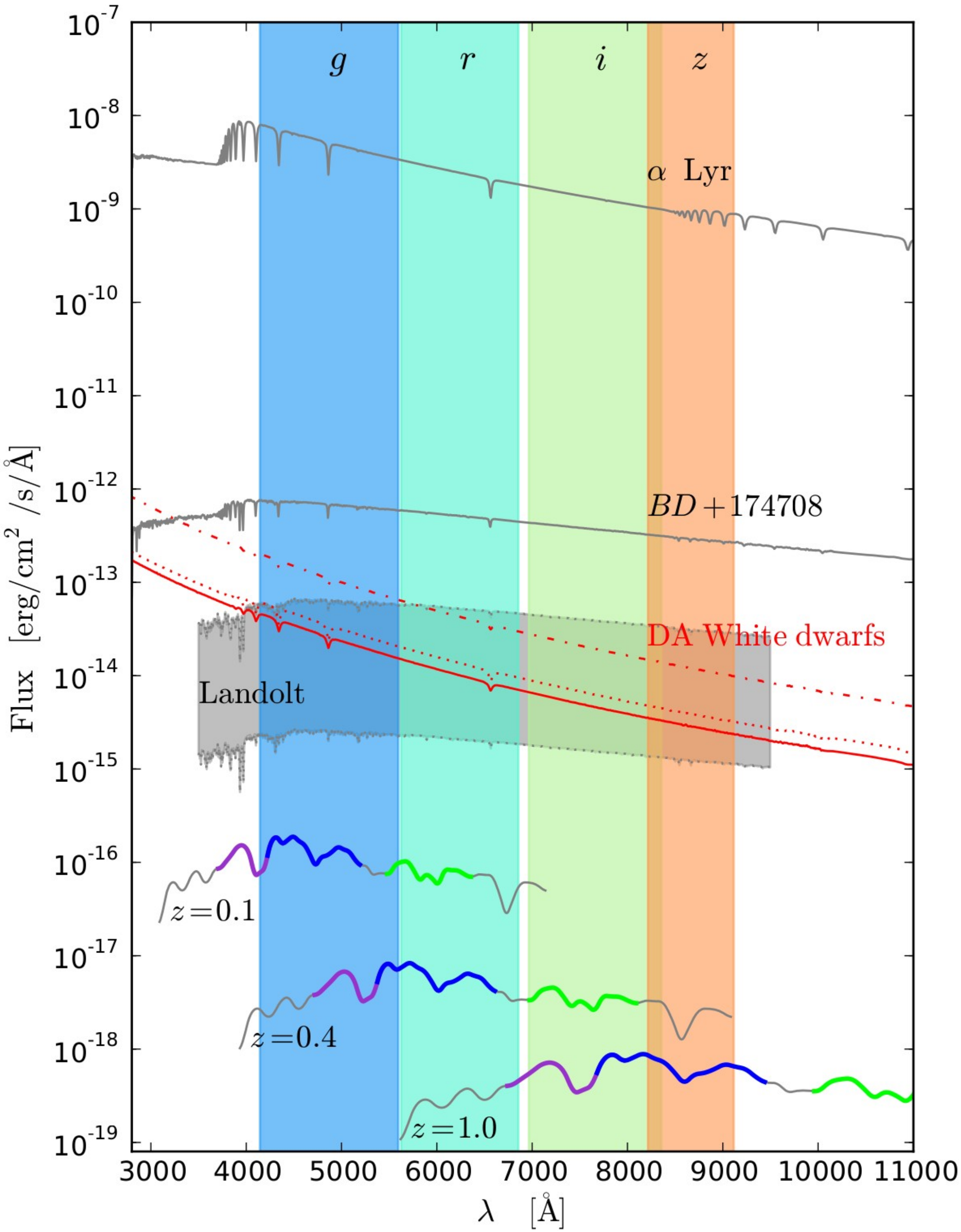
SNLS / SDSS Uniformity



- Detection of a (small) flat-fielding problem in the S82 catalog
- Recalibration of the SDSS S82 magnitudes
- Confirmation that MegaCam flat fielding is good at ~ 0.5%

Lessons learned

- Flat fielding at the percent level is difficult
  - Diverts time from the science observations
  - Grids sequences sensitive to seeing/zp variations
- Passband Models
  - Ongoing work to remeasure MegaCam passbands
- Pick the right fundamental standard !
  - With colors comparable to SN colors
- CALSPEC uncertainties hard to estimate
  - Modeling challenge ?
  - May decrease with more STIS observations...
  -



g
r
i
z
α Lyr
BD +174708
DA White dwarfs
Landolt
z = 0.1
z = 0.4
z = 1.0
Flux [erg/cm² /s/Å]
λ [Å]
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
3000 4000 5000 6000 7000 8000 9000 10000 11000

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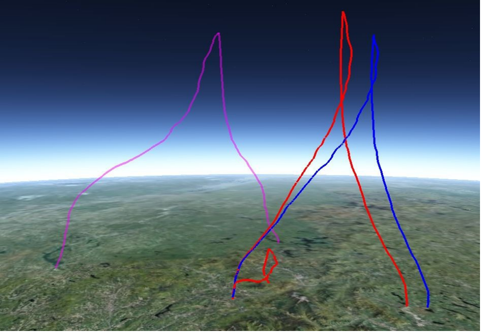
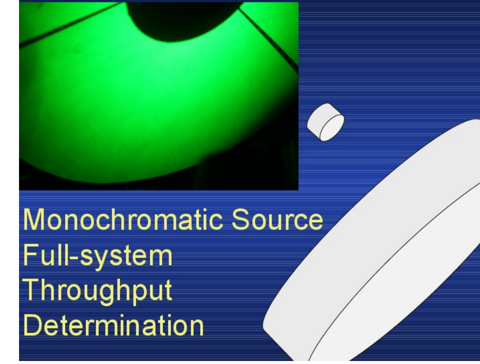
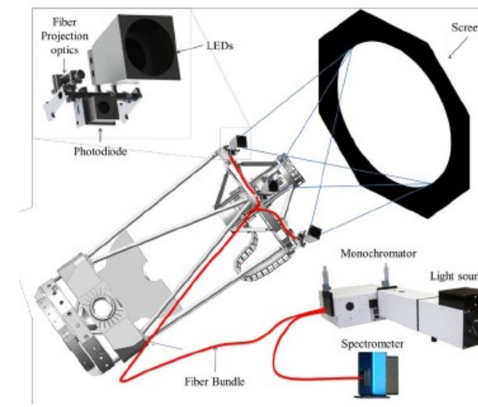


Calibration Projects

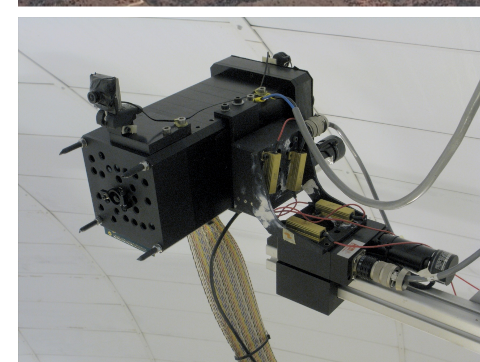


- Harvard (Stubbs et al)
  - ESSENCE
  - PanSTARRS

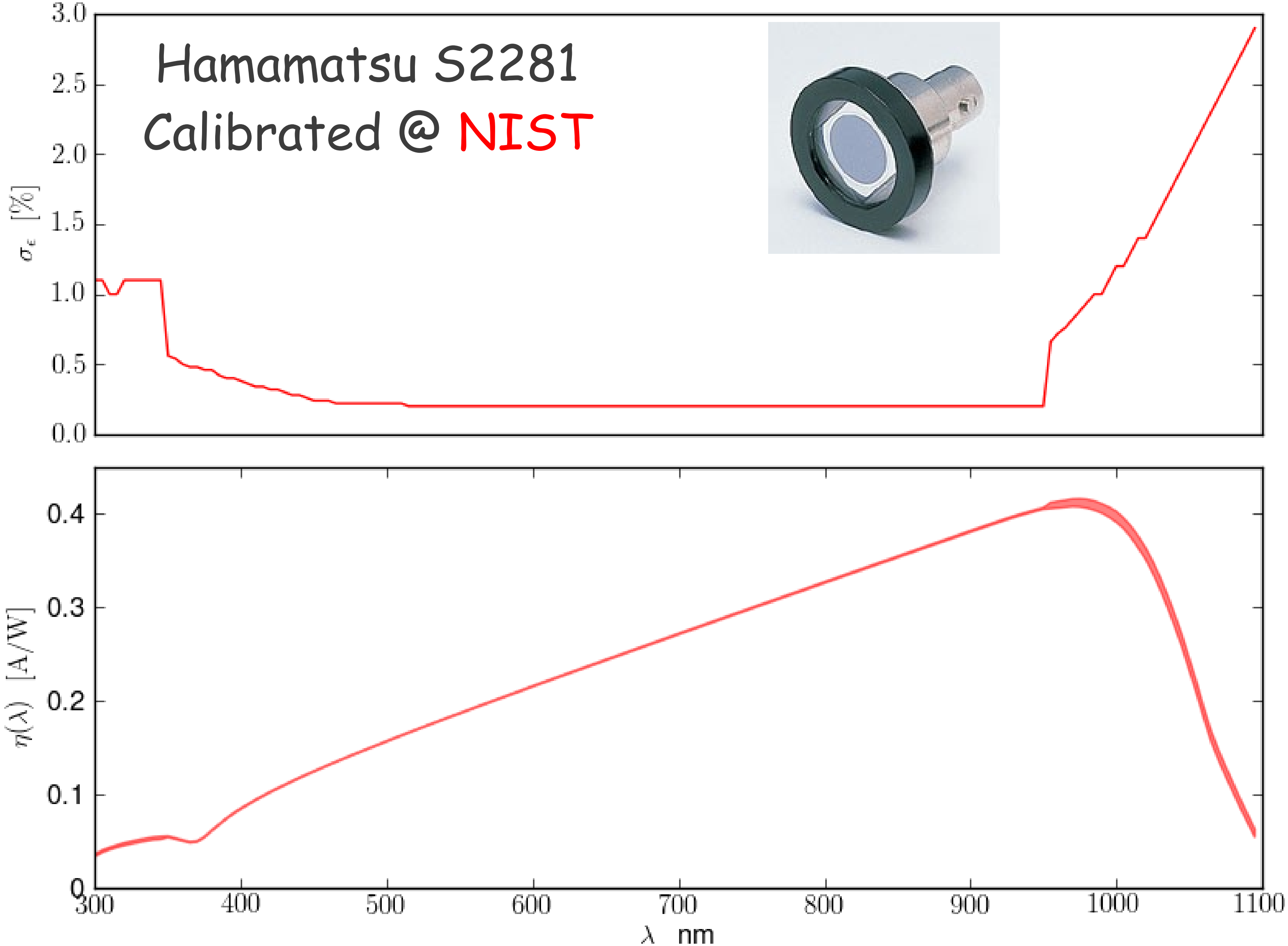


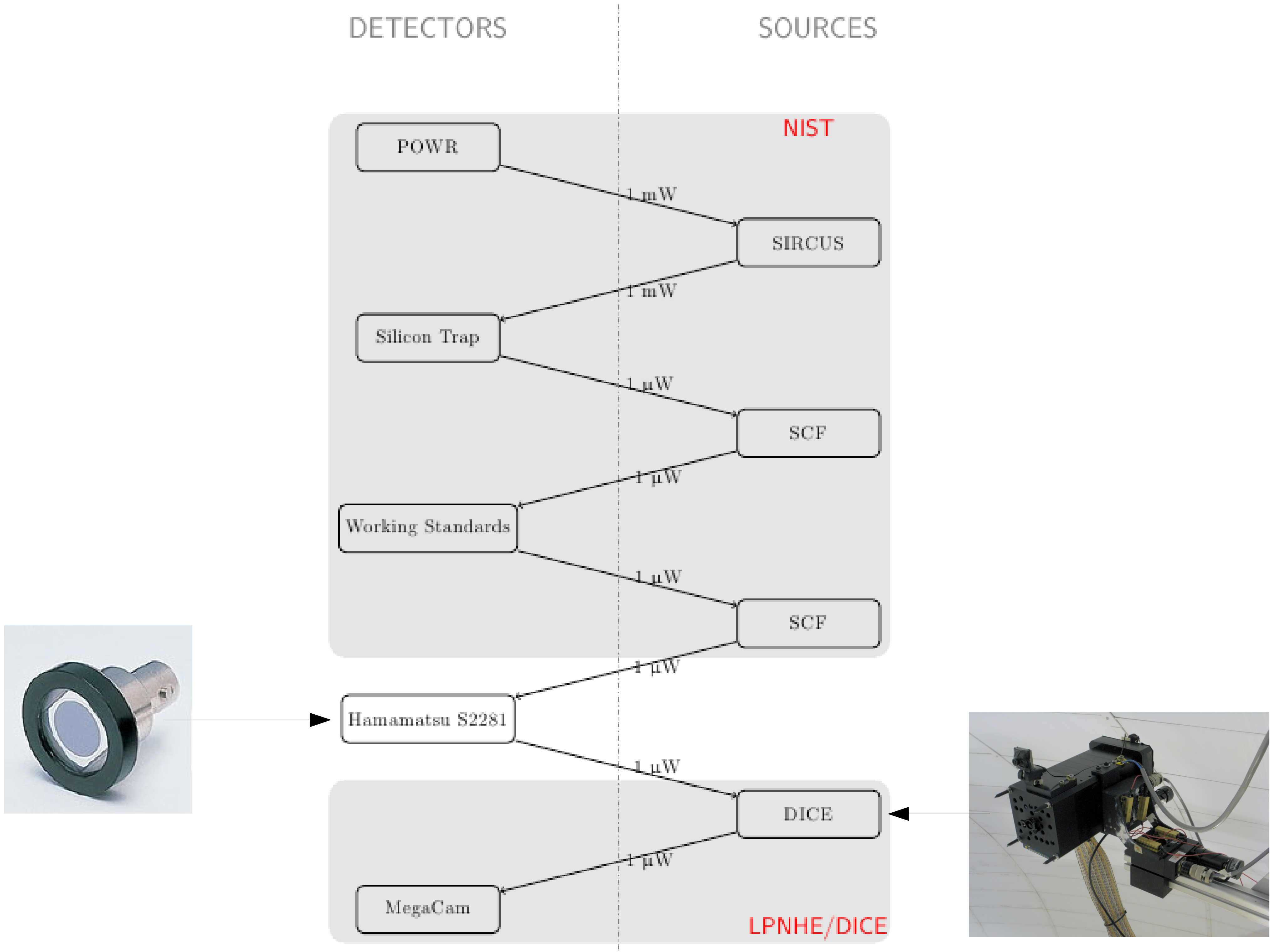
- Texas A&M (DePoy et al)
  - DES (Dark Energy Survey)
- NIST (Cramer et al)
  - Artificial star → recalibration of Vega

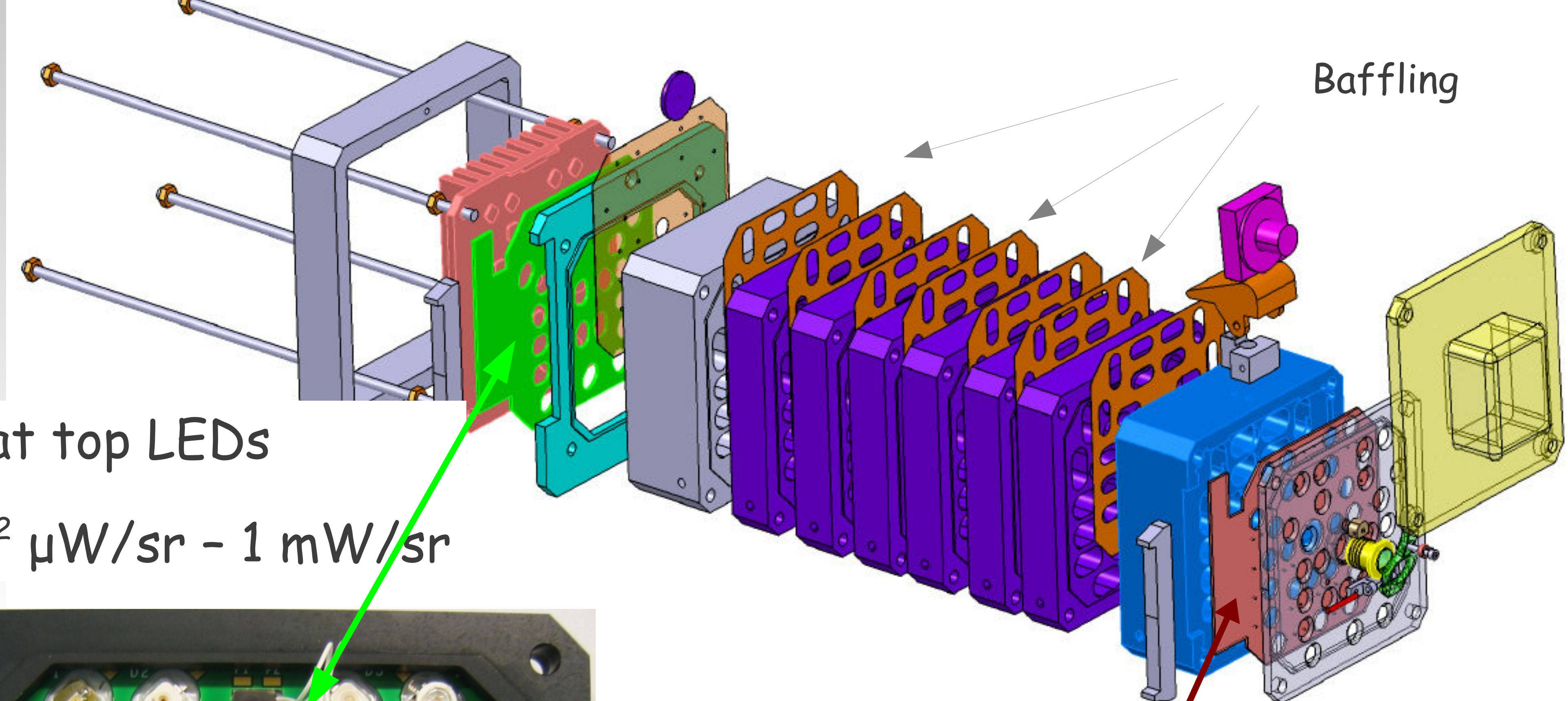
- LPNHE
  - SnDICE (MegaCam)
  - SkyDICE (SkyMapper)



What about using a Lab standard ?

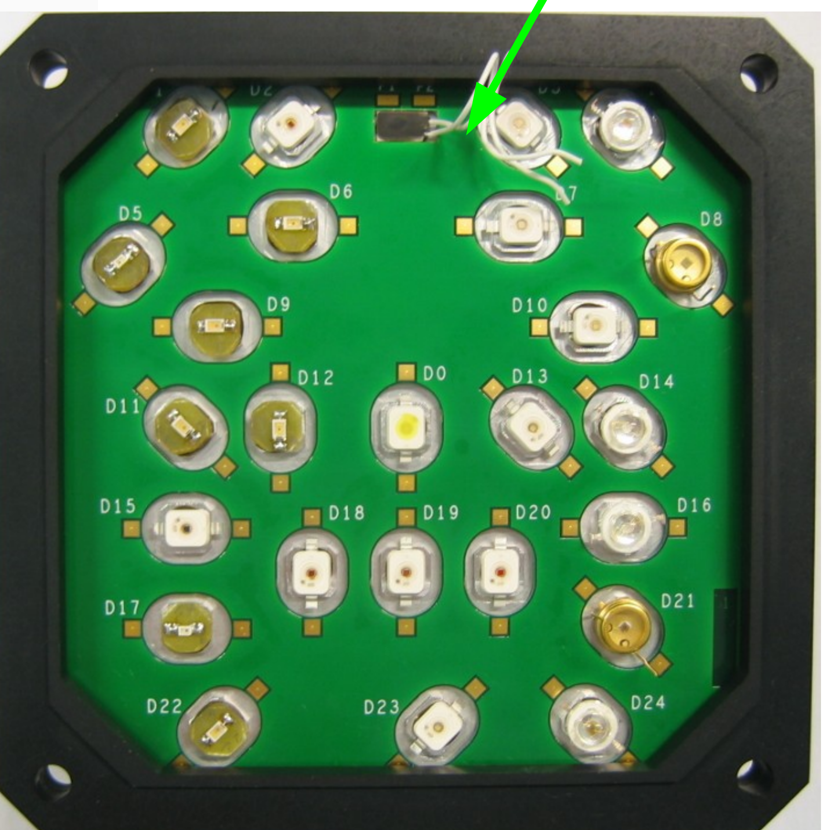


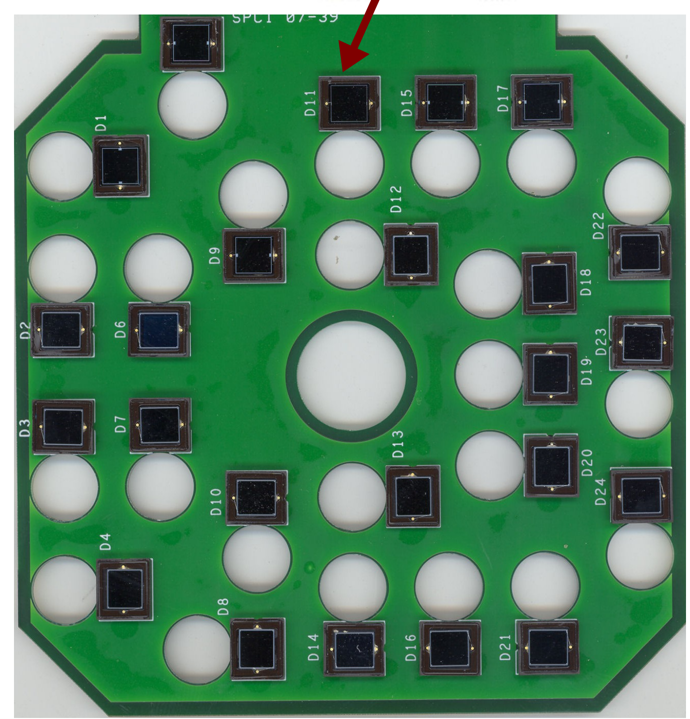

DETECTORS
SOURCES
NIST
POWR
1 mW
SIRCUS
1 mW
Silicon Trap
1 µW
SCF
1 µW
Working Standards
1 µW
SCF
1 µW
Hamamatsu S2281
1 µW
DICE
1 µW
MegaCam
LPNHE/DICE



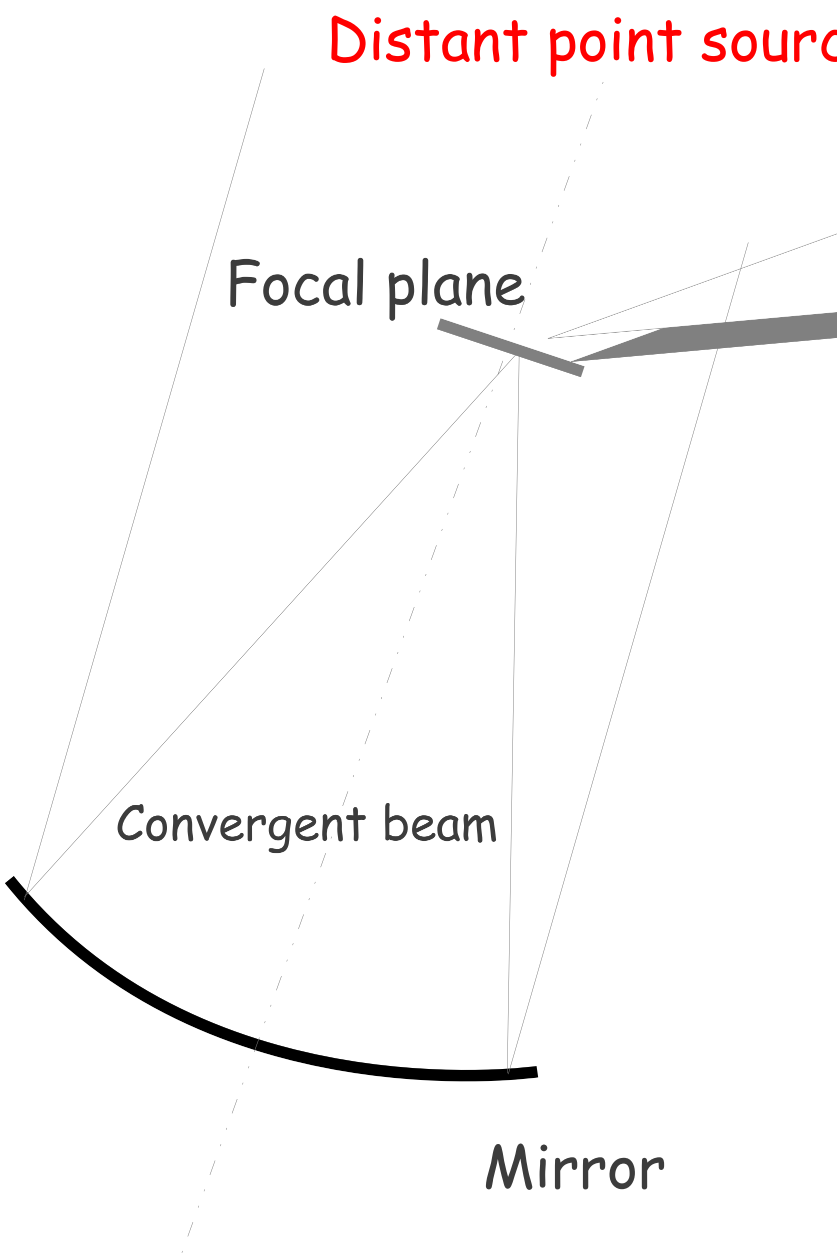
Flat top LEDs

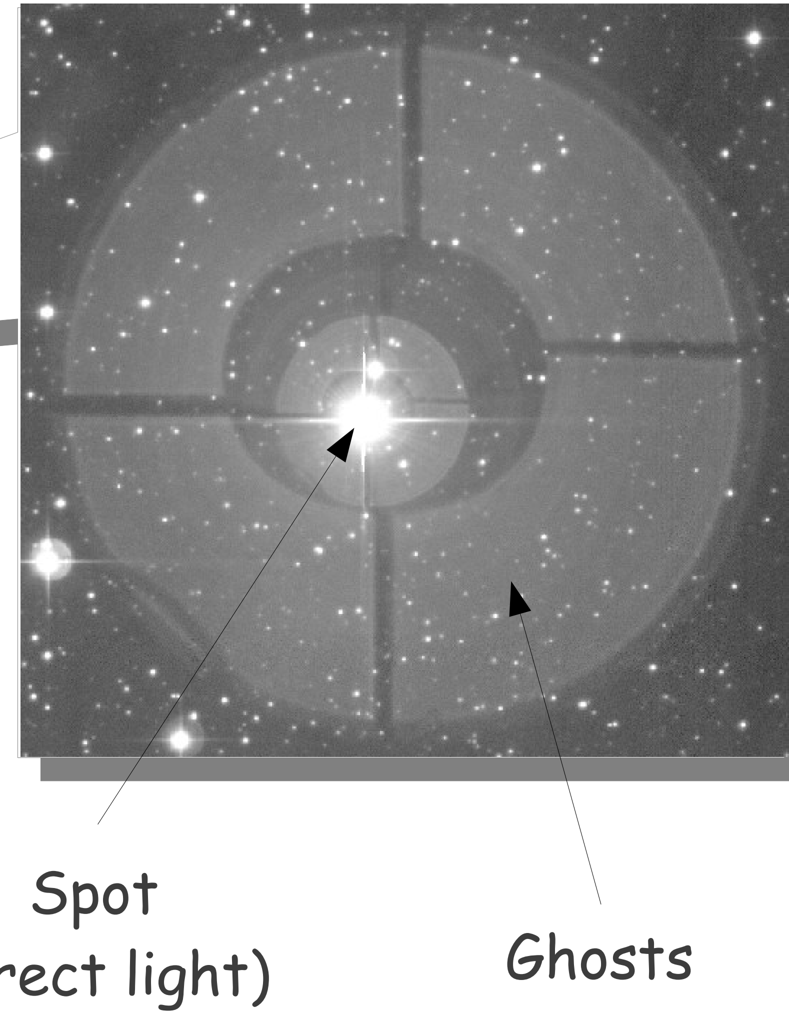
10^2 μW/sr – 1 mW/sr





Optical setup

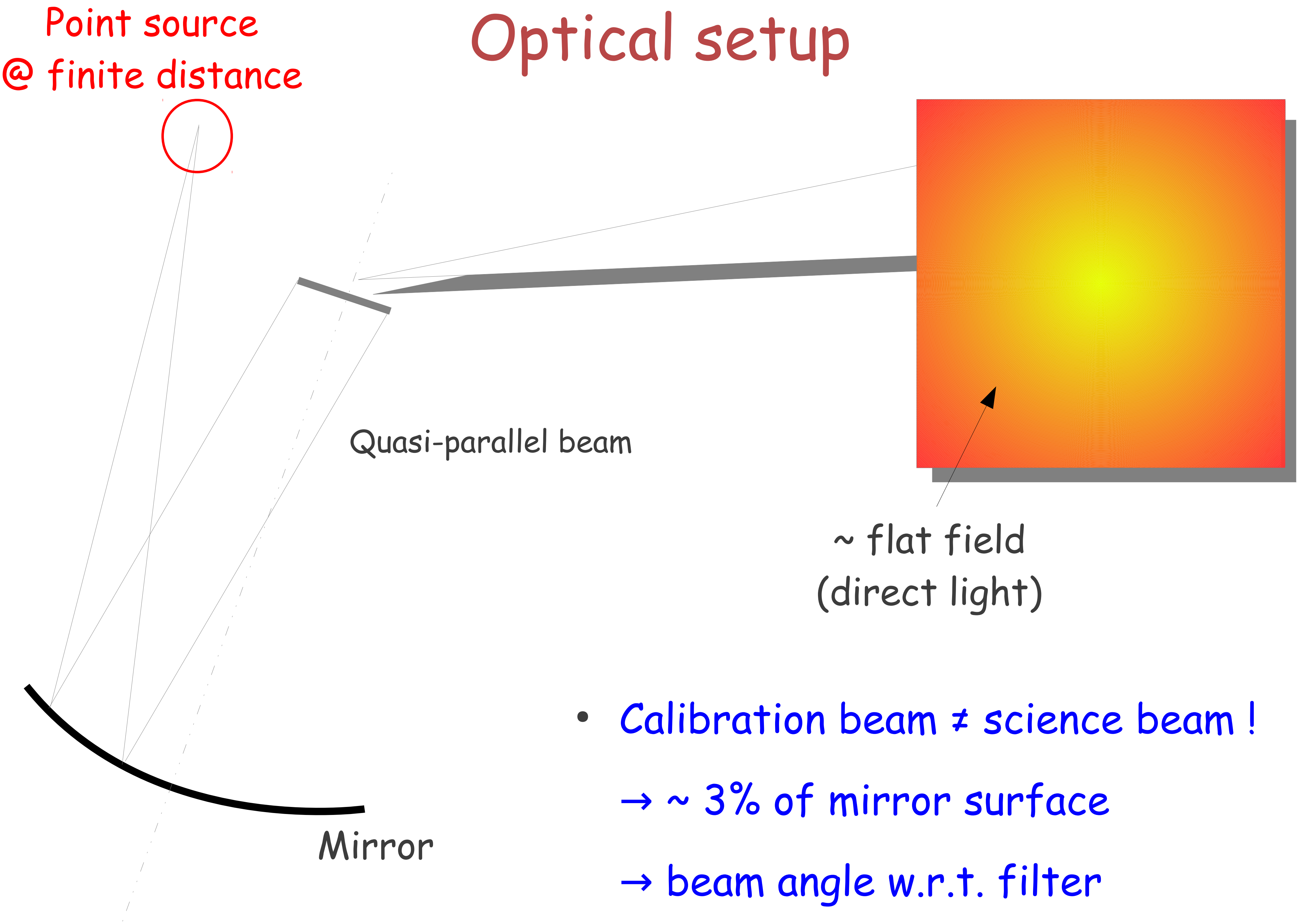




Ideally, one wants the calibration beam to be identical to the science beam

→ distant point source !

Optical setup

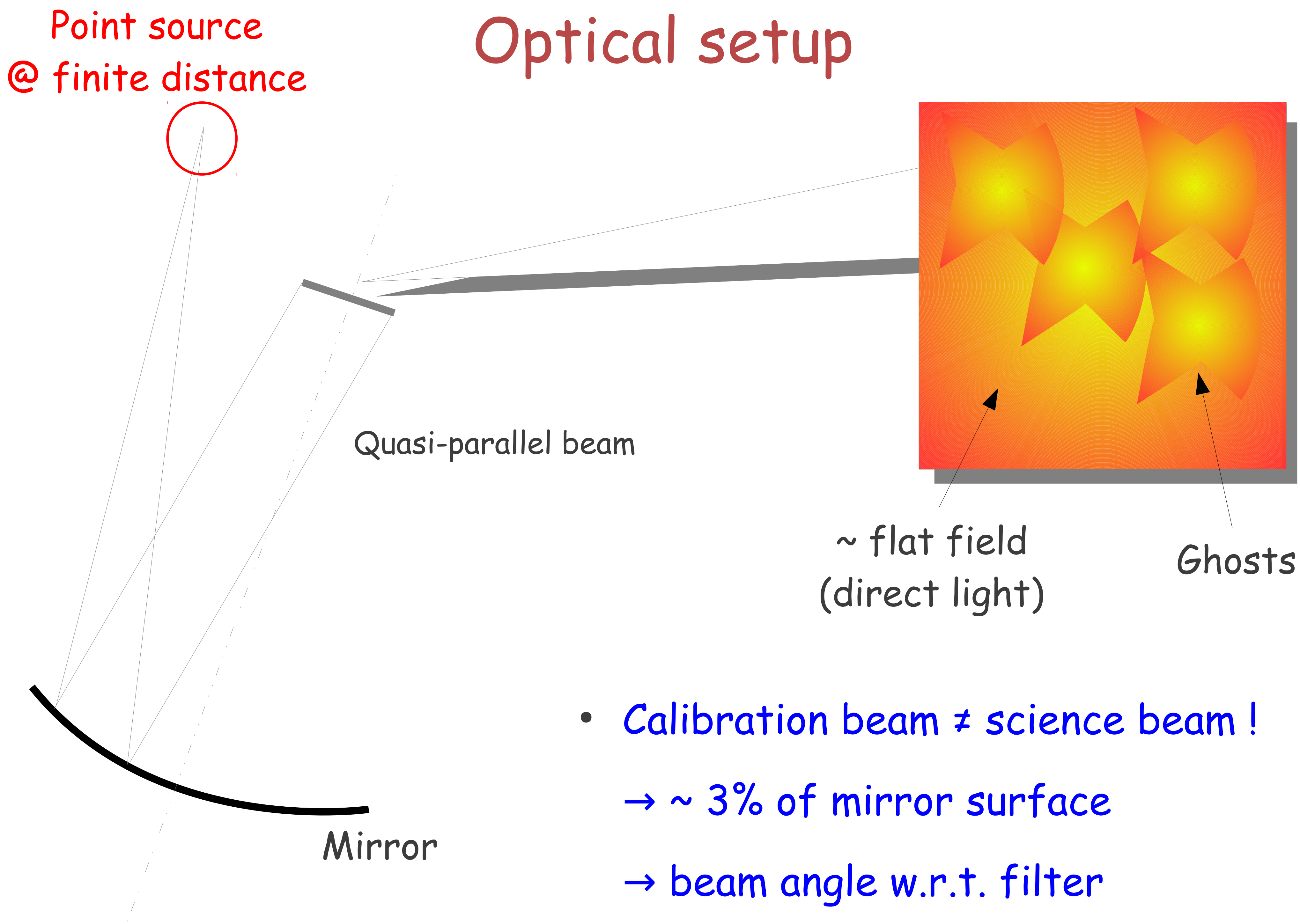


- Calibration beam ≠ science beam !

→ ~ 3% of mirror surface

→ beam angle w.r.t. filter

Optical setup



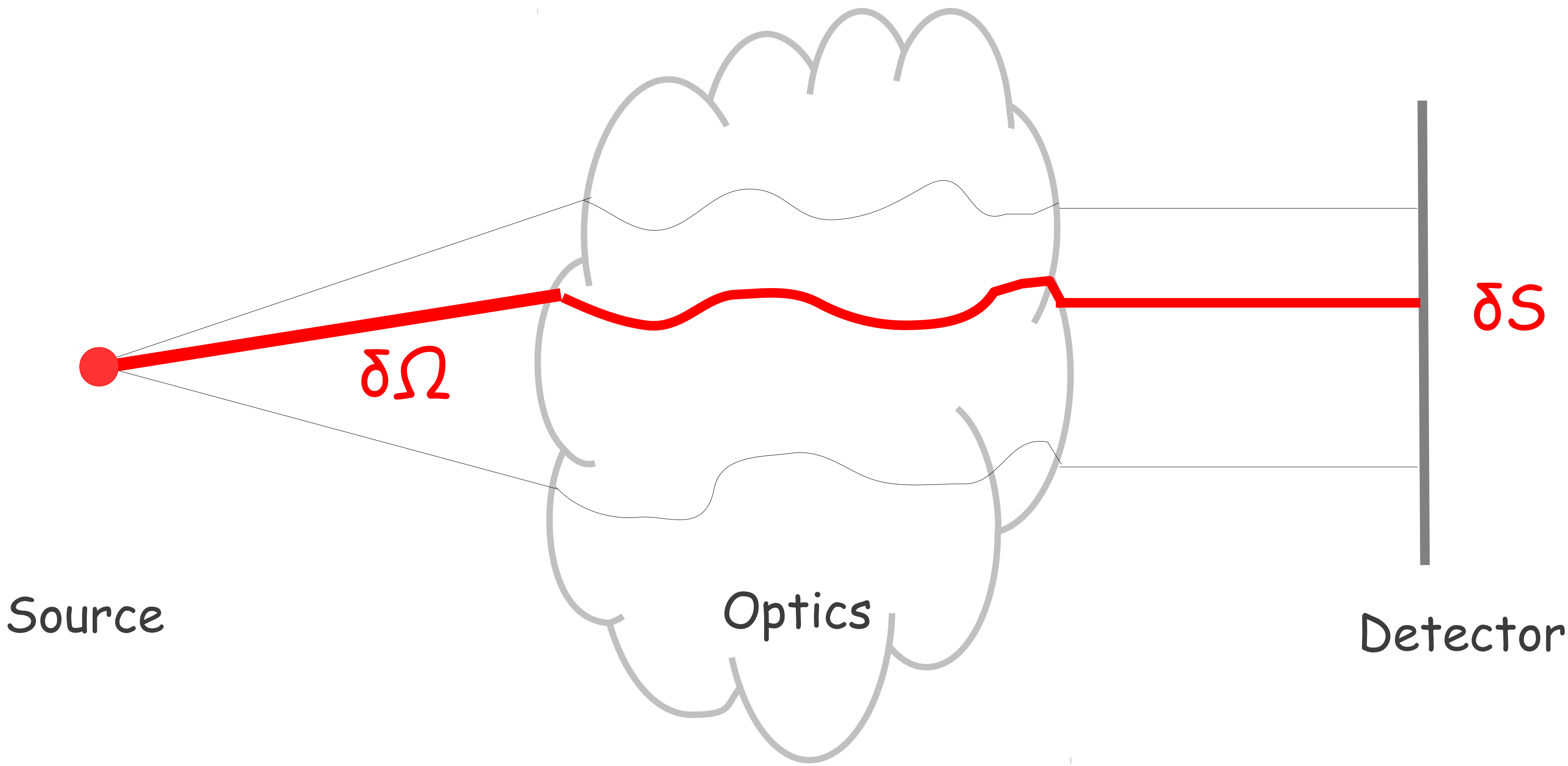
- Calibration beam ≠ science beam !

→ ~ 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

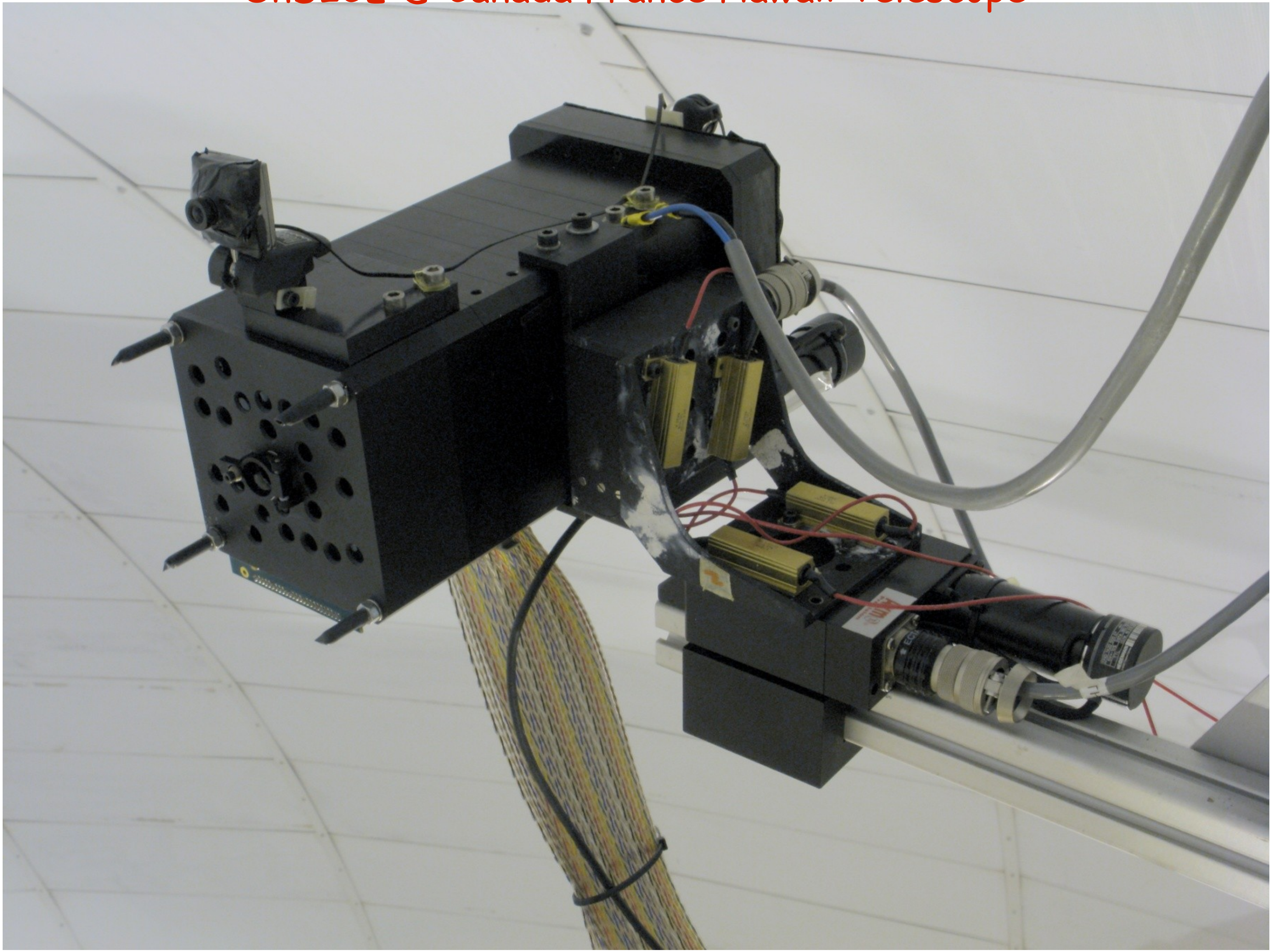
- Keep the design as simple as possible
  - → Direct illumination, no intermediate surfaces
  - → Just baffling, to shape the calibration beam
- Narrow spectrum LEDs
  - → Compact, stable calibration beams
  - →  Emission properties vary with temperature
- Calibrated on a spectrophotometric test bench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

DICE*

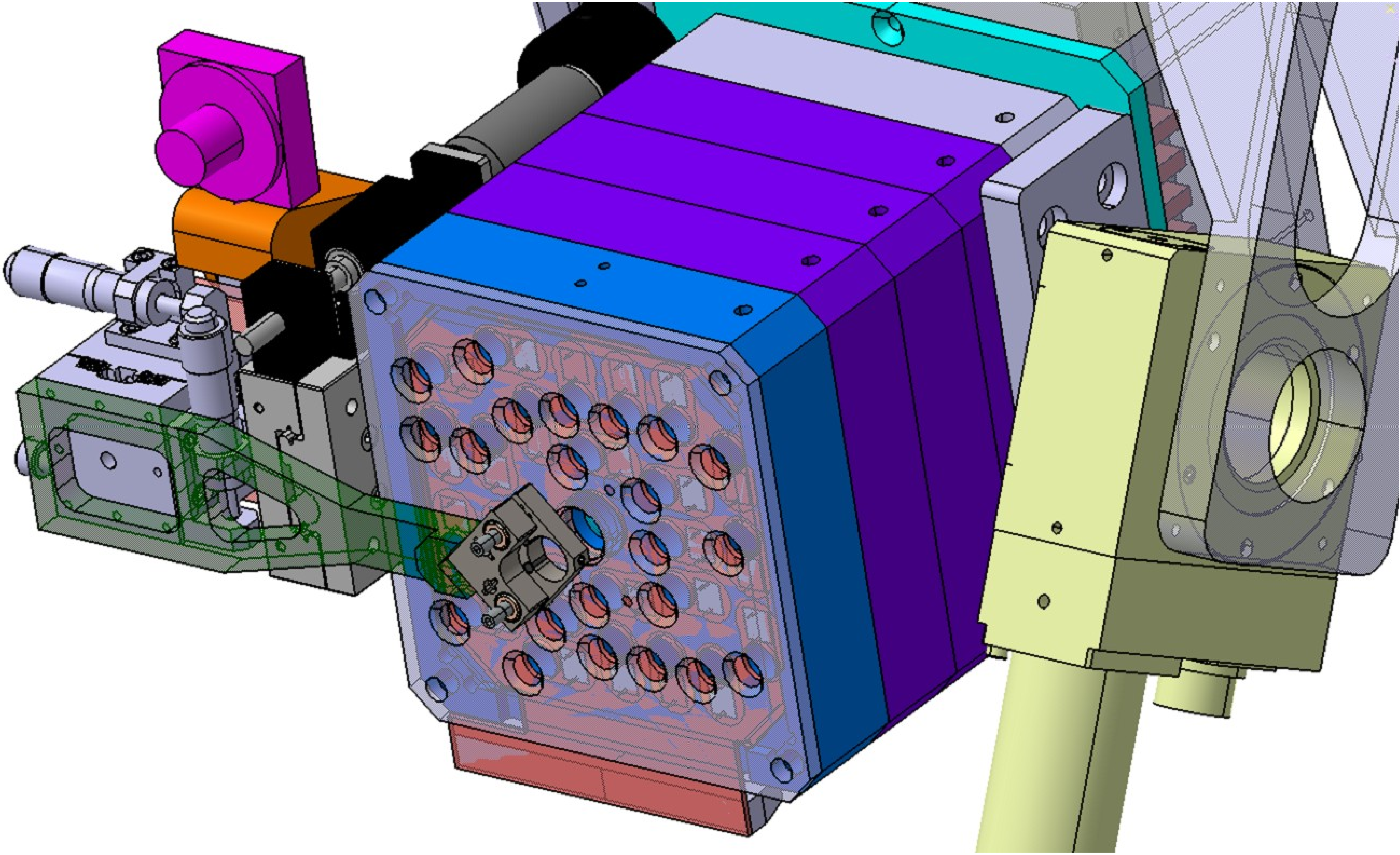
- Illumination system
  - Placed in the telescope enclosure
  - Point source @ finite distance
- Narrow spectrum LEDs
  - → Compact, stable calibration beams
  - → Direct illumination, no intermediate surfaces
- Spectrophotometric test bench
  - → spectra (erg/nm/s) & beam maps (erg/sr/s)
- Redundancies (photodiodes + monitoring)

(*) Direct Illumination Calibration Experiment

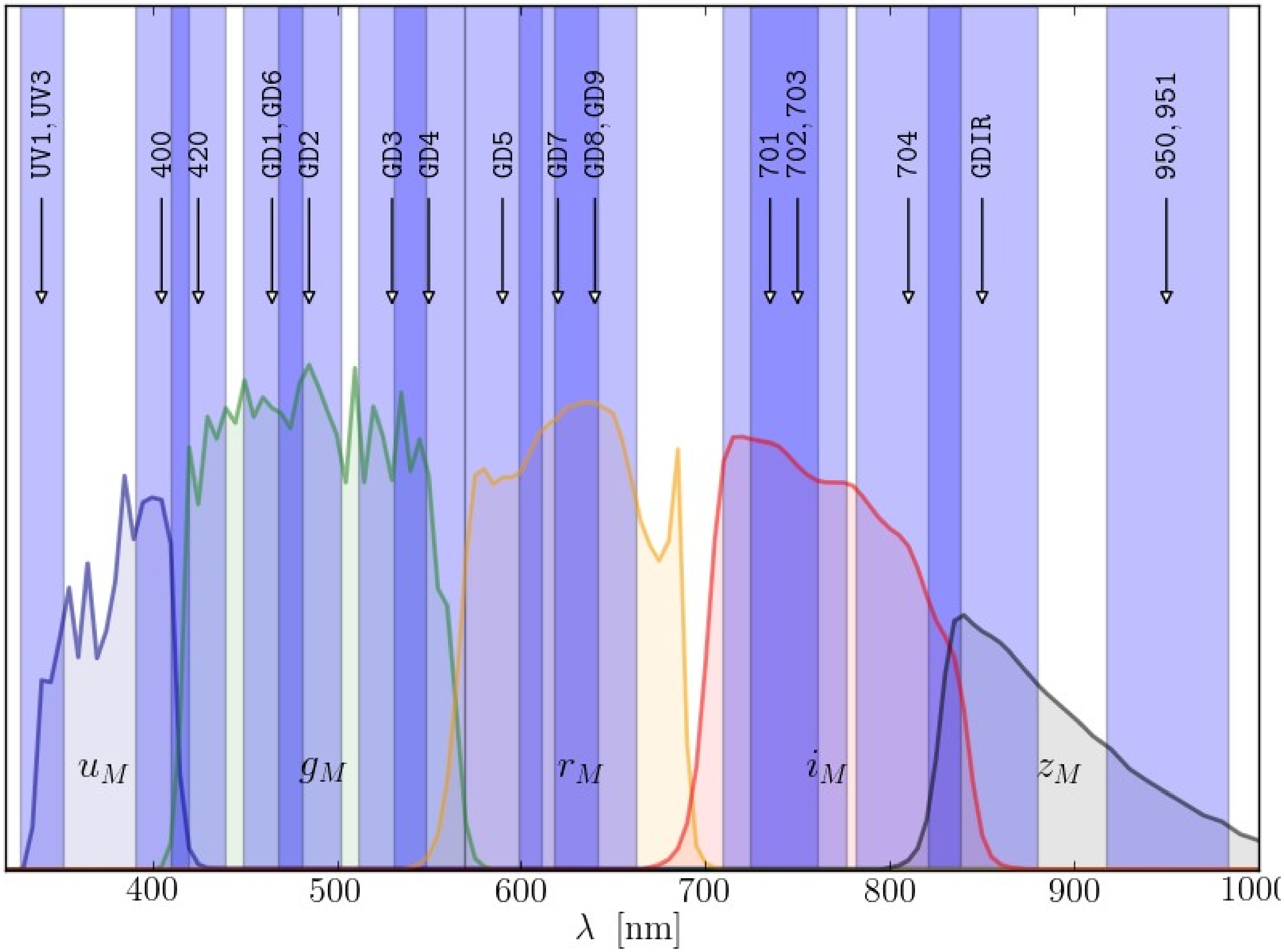
SnDICE @ Canada France Hawaii Telescope



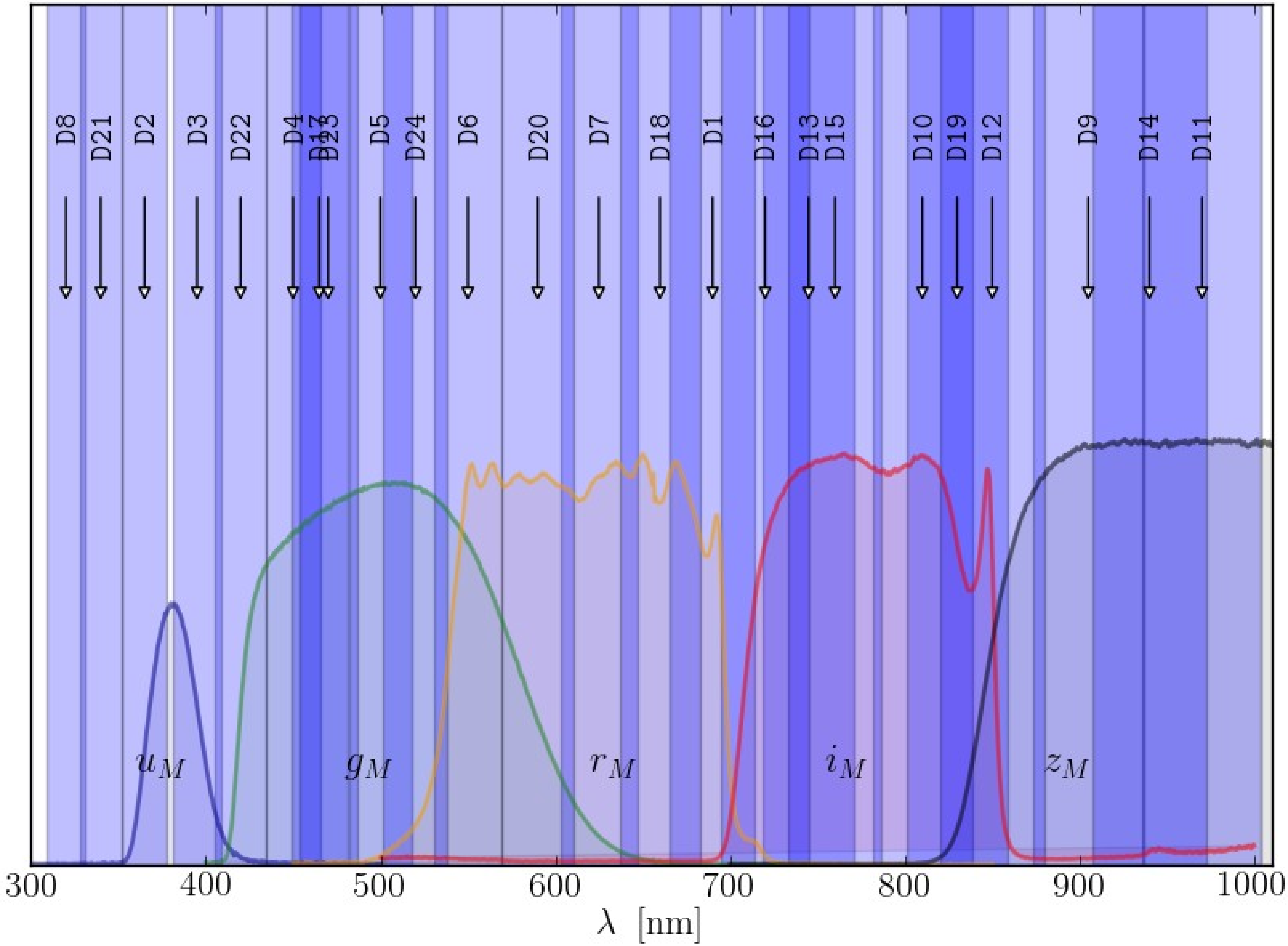
SkyDICE @ SkyMapper (Siding Springs Observatory, NSW, Australia)



SnDICE Wavelength coverage



SkyDICE Wavelength Coverage



Test bench studies

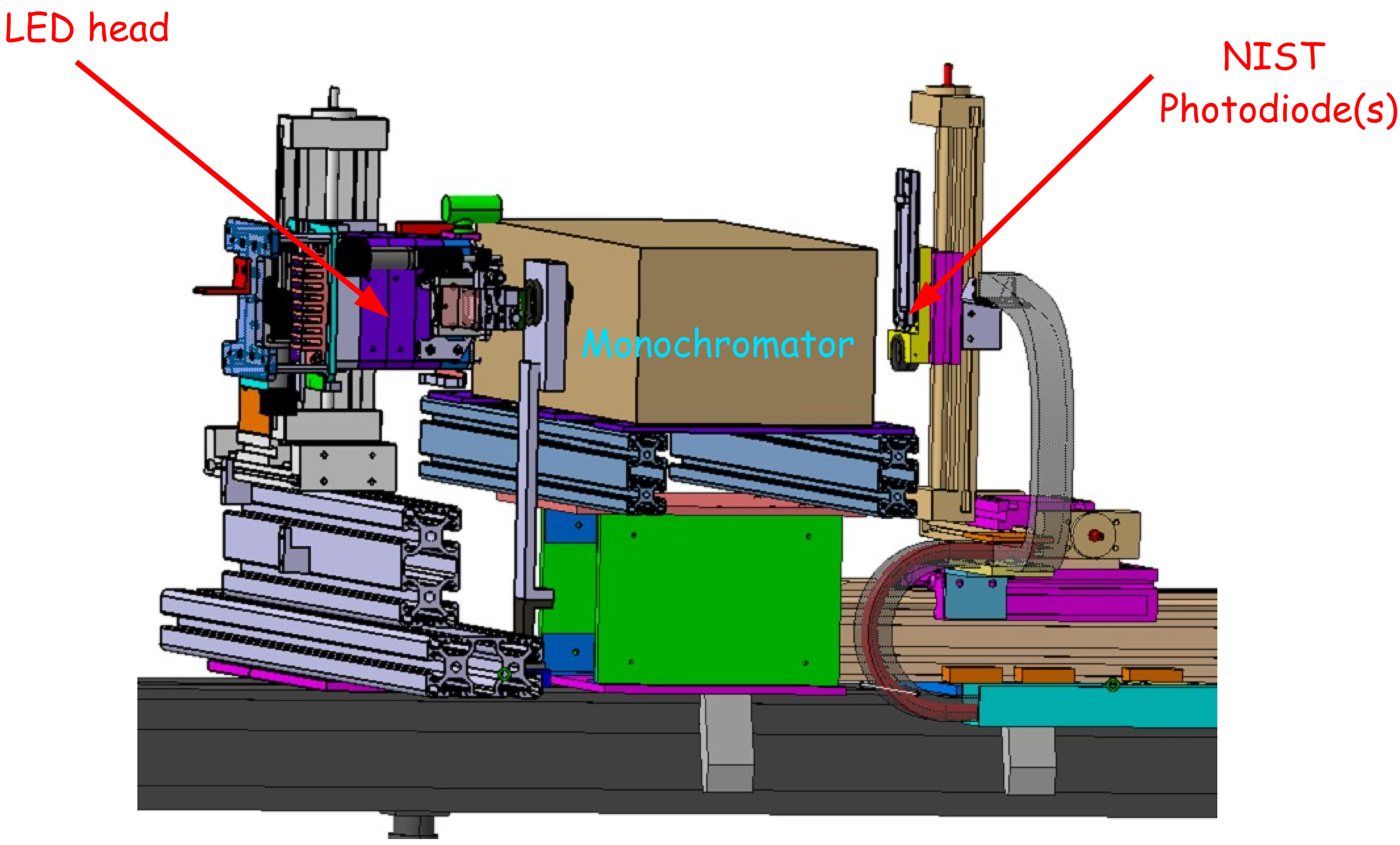
- Spectrophotometric test bench @ LPNHE
- Dark enclosure, 0 °C < T < 25 °C
  - not exactly thermalized, but
  - good temperature monitoring w/ thermistances
- Goals
  - Transfer NIST calibration → light source

    → Spectroscopic calibration of all LEDs

    → Photometric calibration of all LEDs

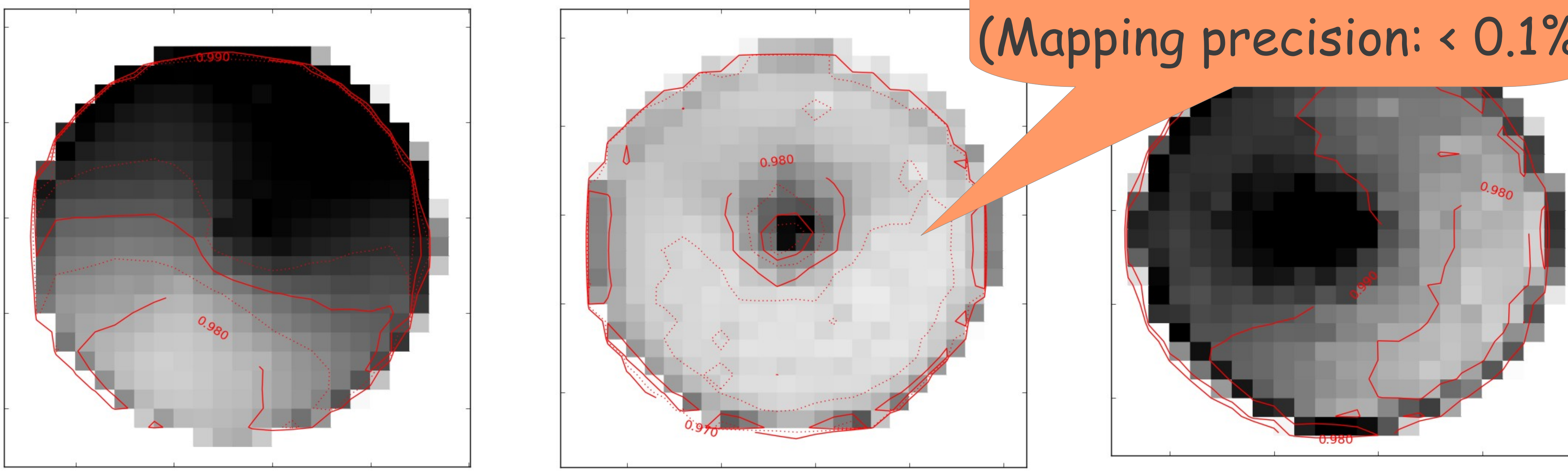
(cf. A. Guyonnet's thesis)

Spectrophotometric test bench



Photometric Calibration

Uniformity: ~ 1%
(Mapping precision: < 0.1%)



- Beam mapped with a calibrated photodiode

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

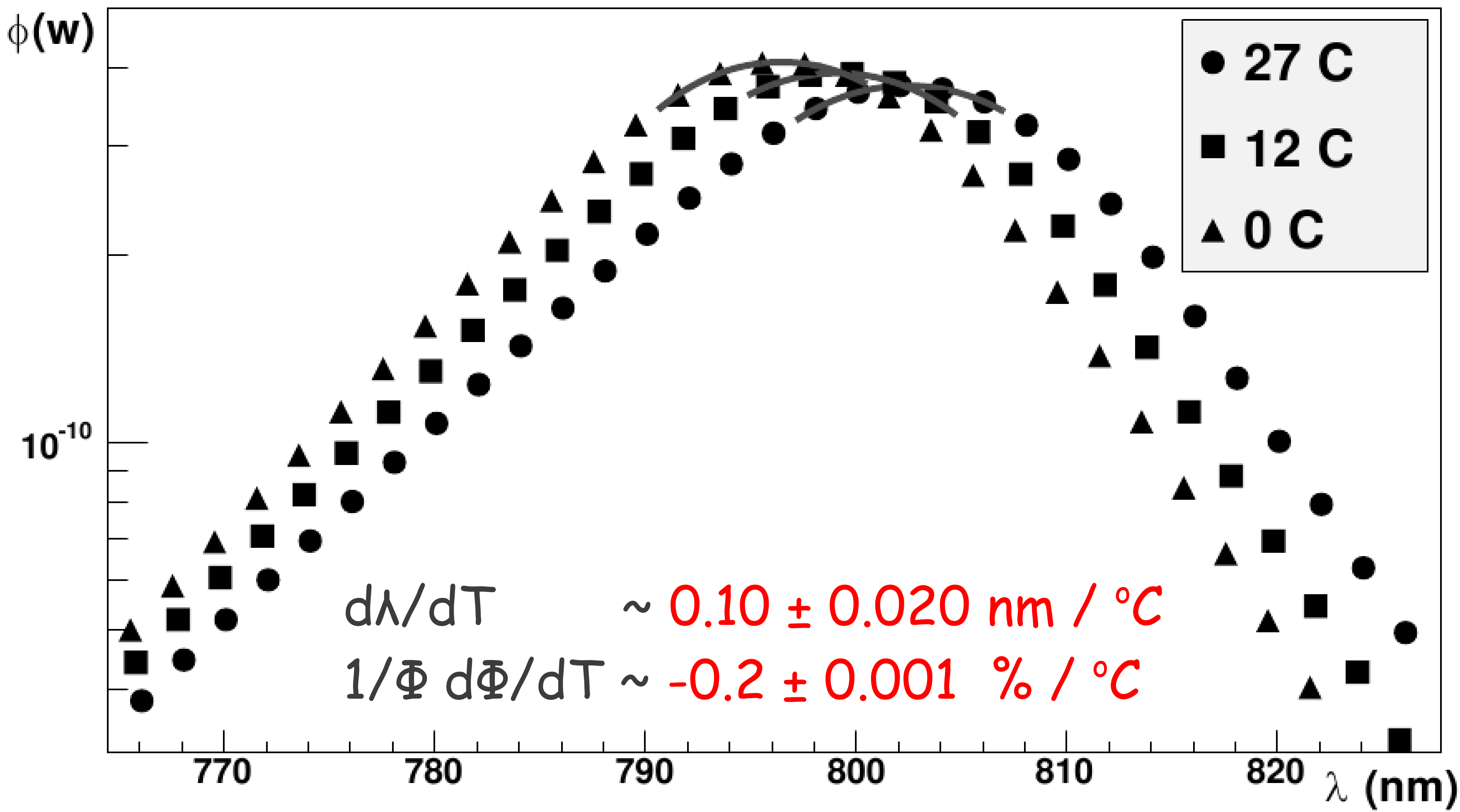
Photodiode current

Mean efficiency

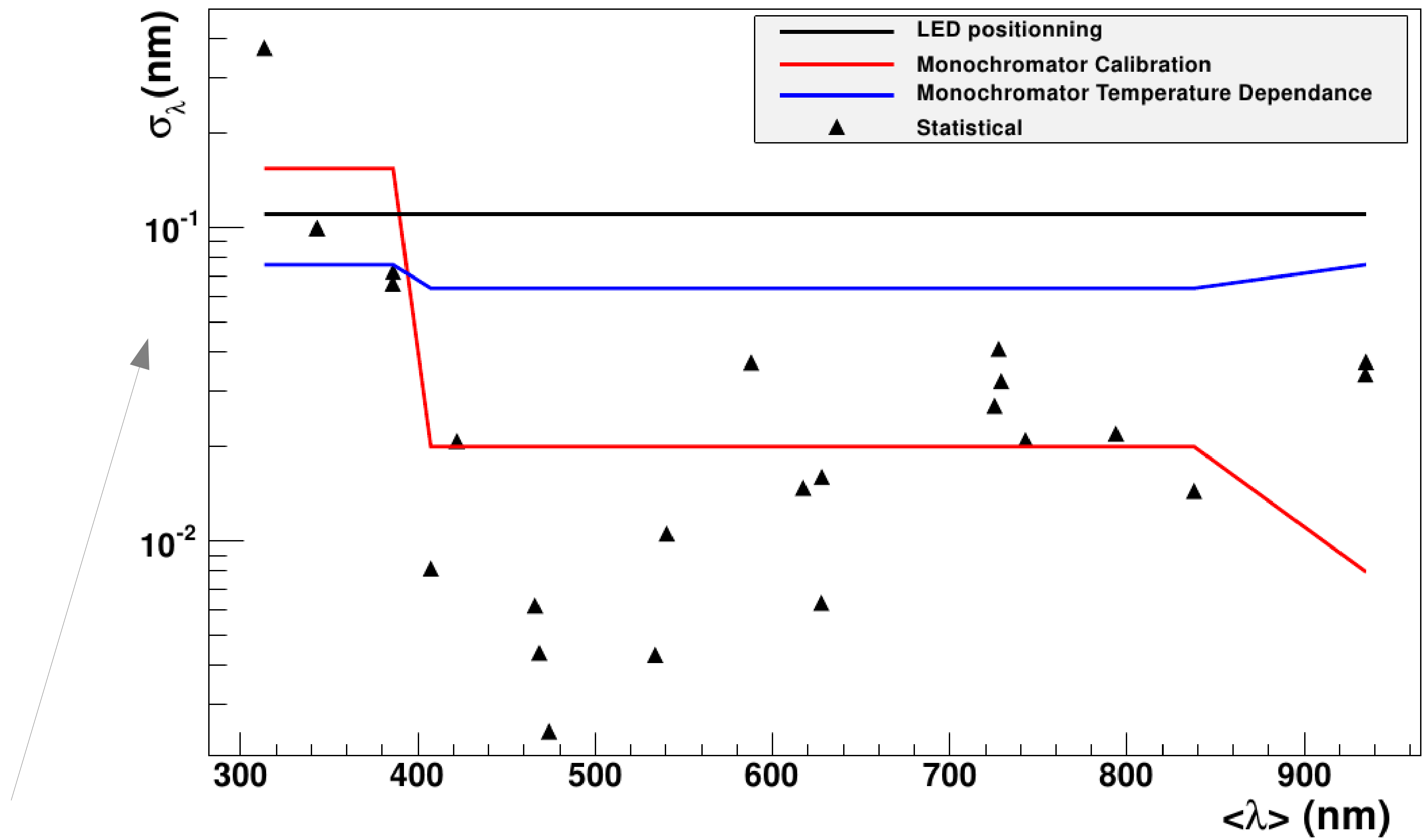
Beam Map (W / sr)

Solid angle element

Spectroscopic calibration

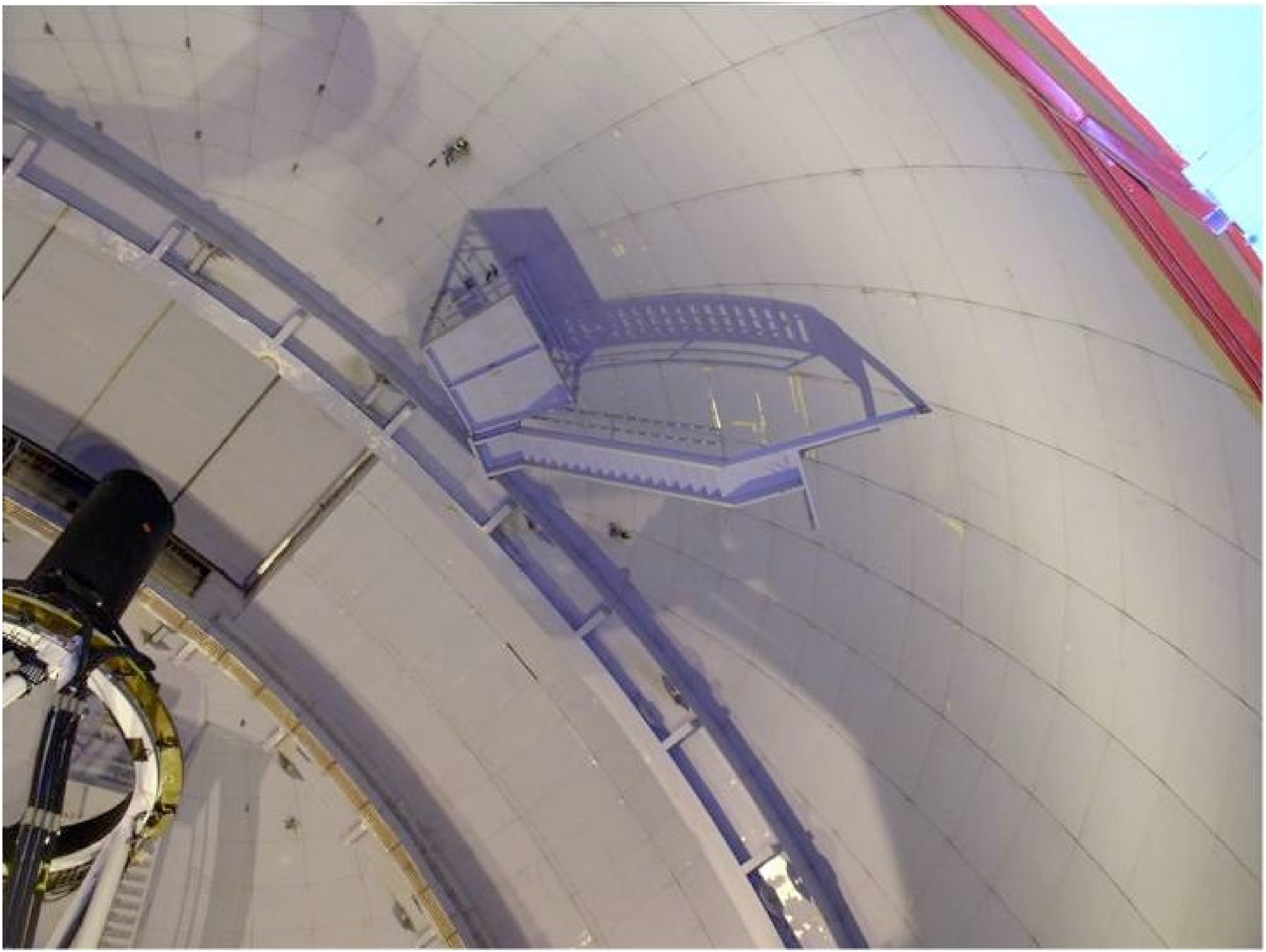


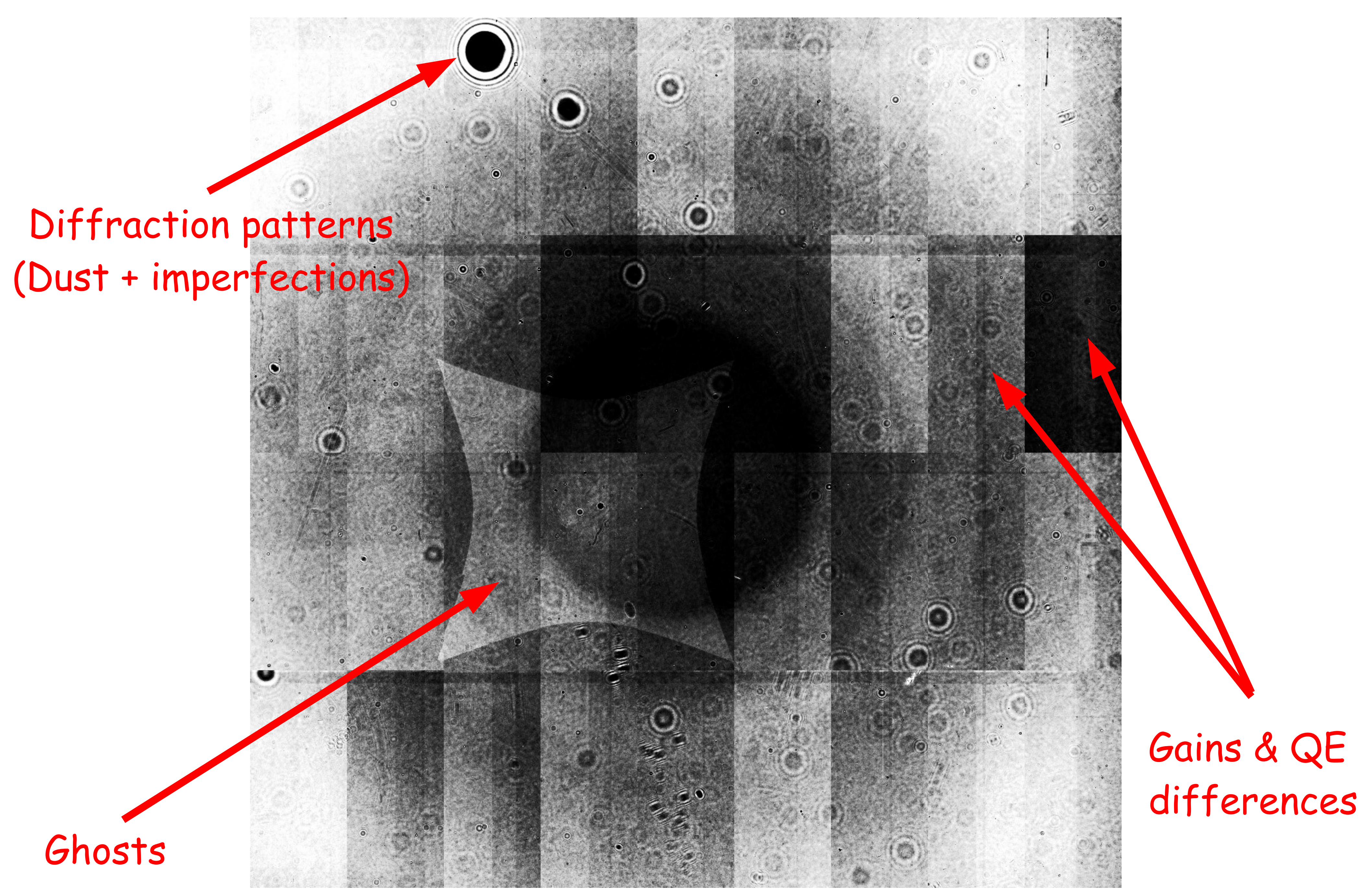
WL Calibration Accuracy

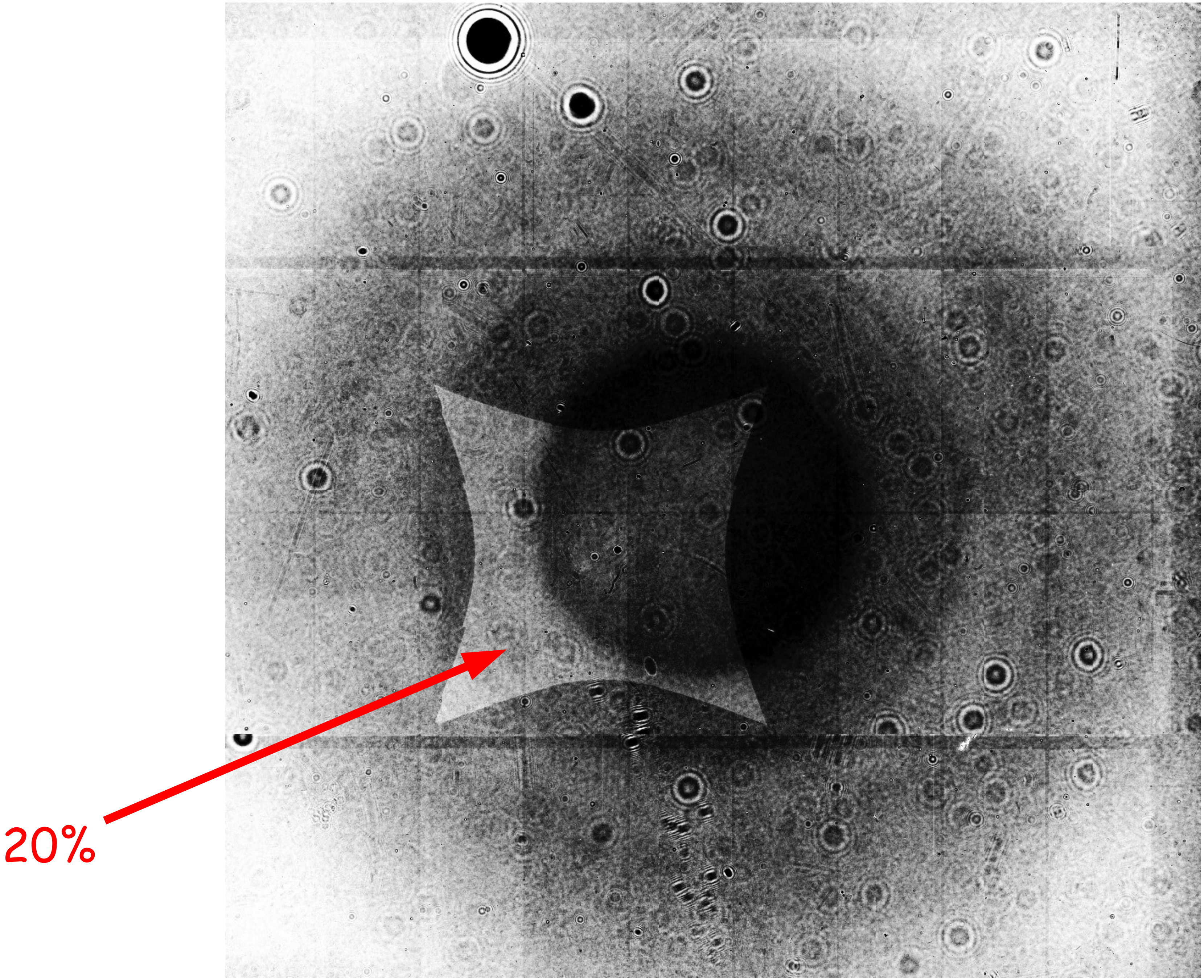


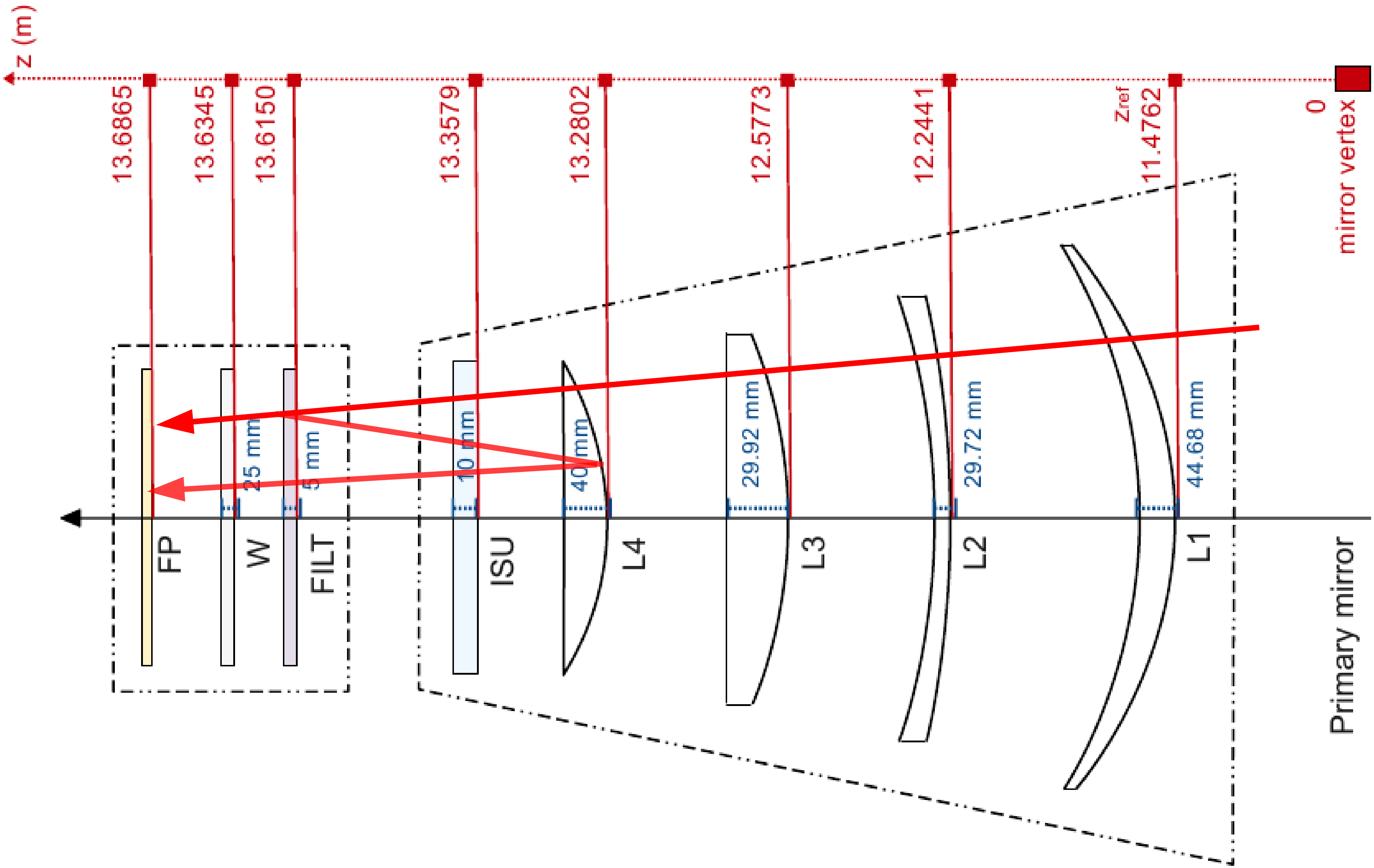
- σ <λ> ~ 0.1 nm, fully correlated (almost)
- Dominated by the calibration of the monochromator


CANADA-FRANCE-HAWAII TELESCOPE
www.cfht.hawaii.edu
AOB



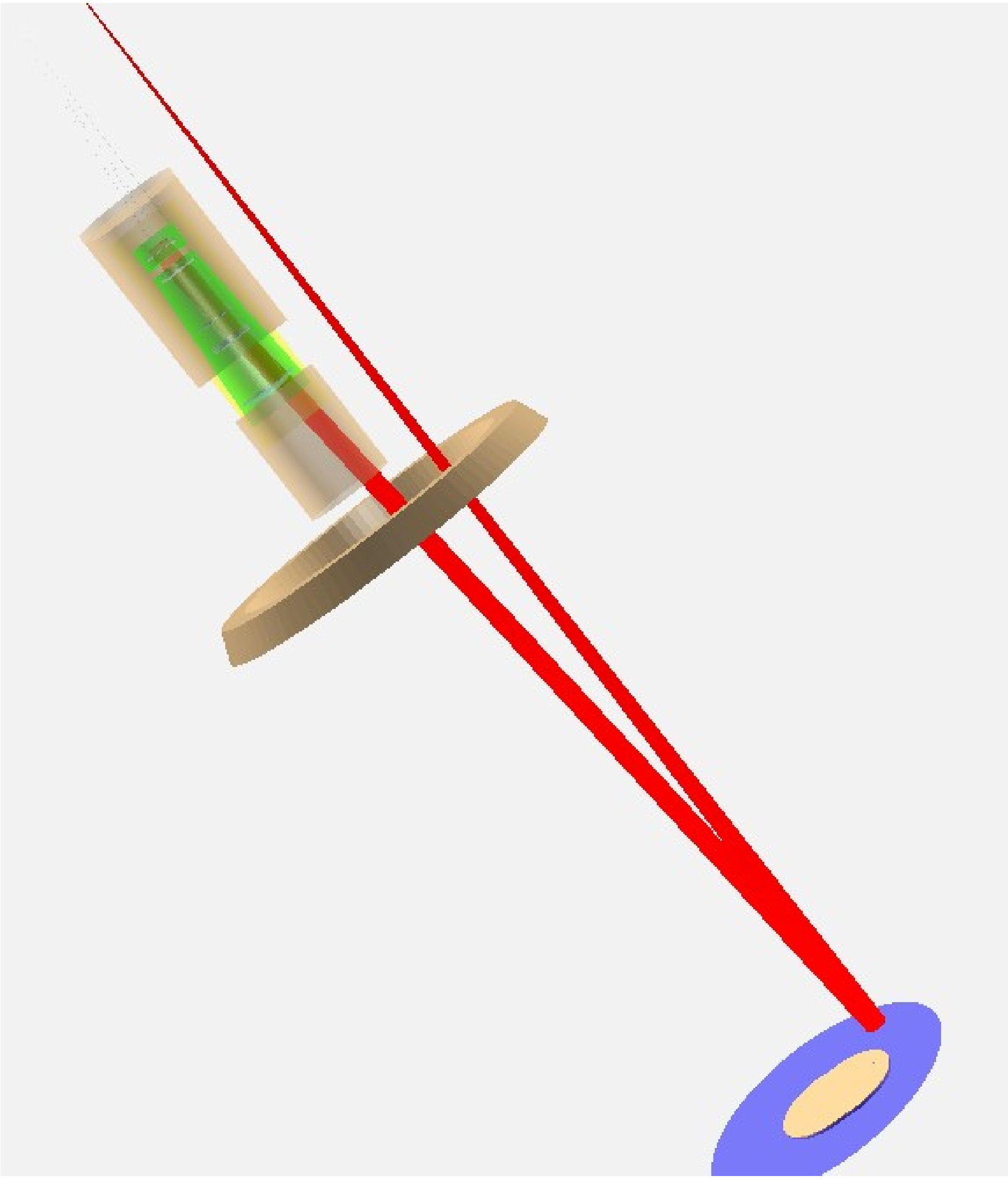

Diffraction patterns
(Dust + imperfections)
Ghosts
Gains & QE
differences

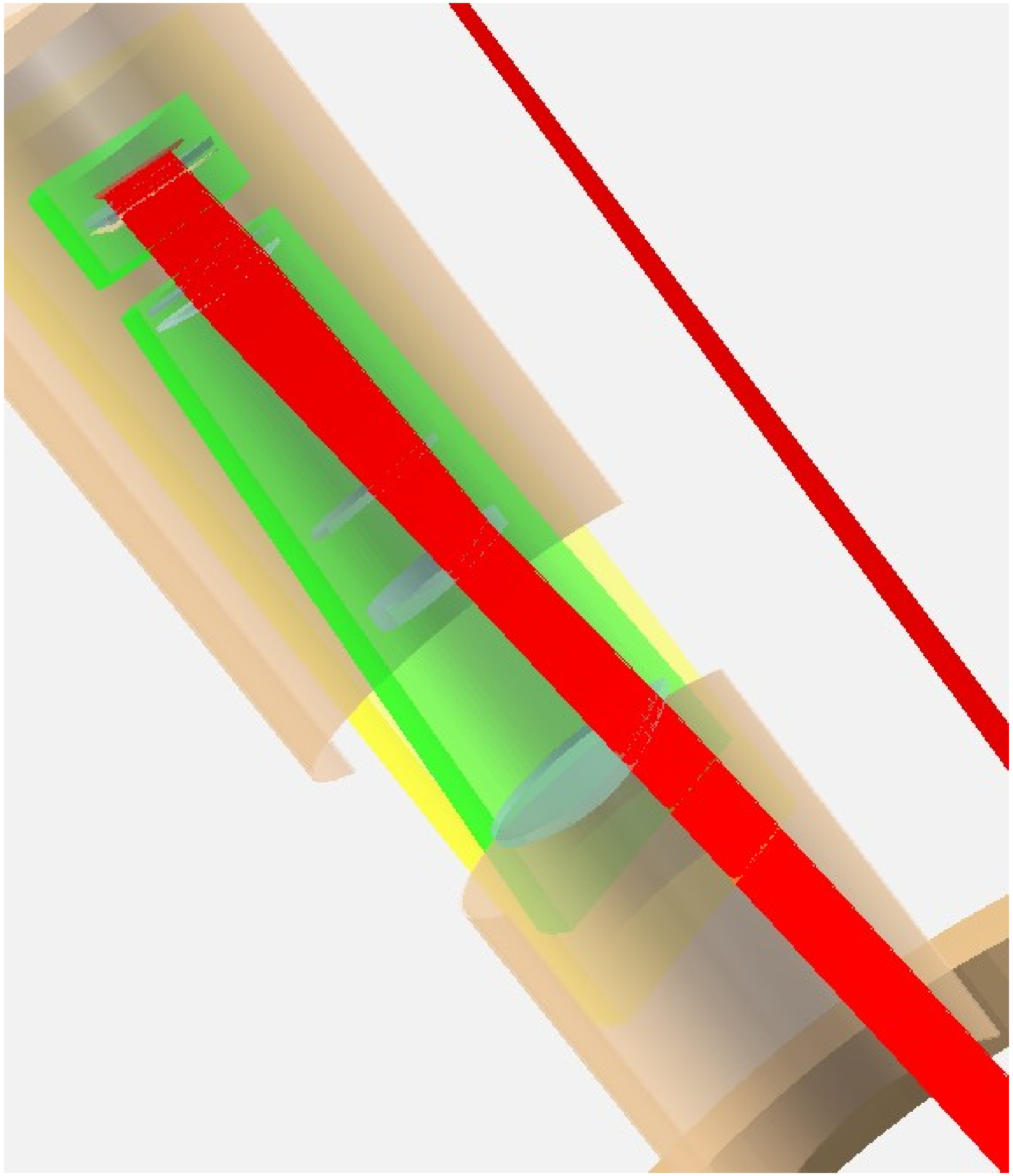

20%

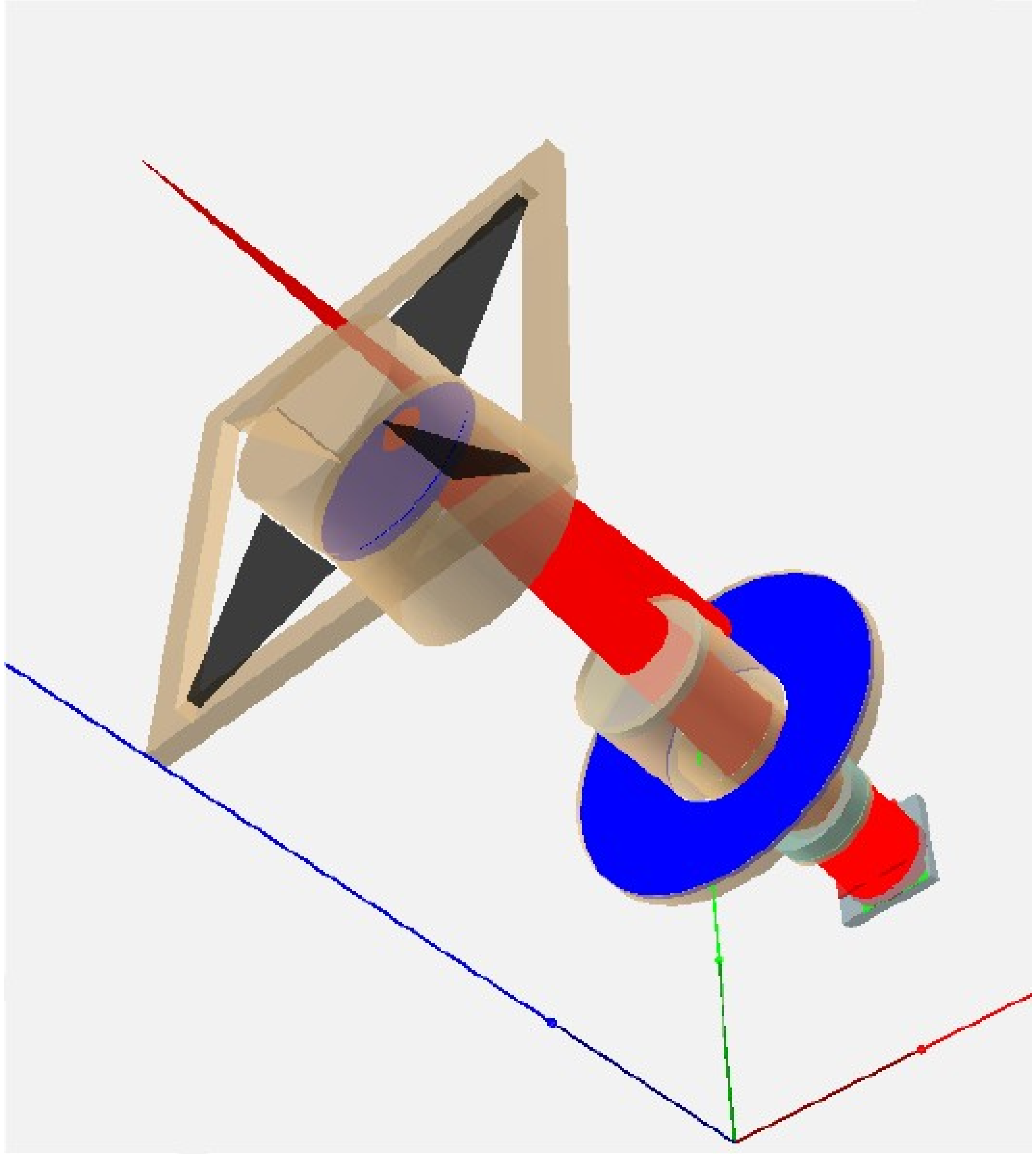

z (m)
13.6865
13.6345
13.6150
13.3579
13.2802
12.5773
12.2441
Zref
11.4762
0
mirror vertex
25 mm
5 mm
10 mm
40 mm
29.92 mm
29.72 mm
44.68 mm
FP
W
FILT
ISU
L4
L3
L2
L1
Primary mirror

(F. Villa's PhD)

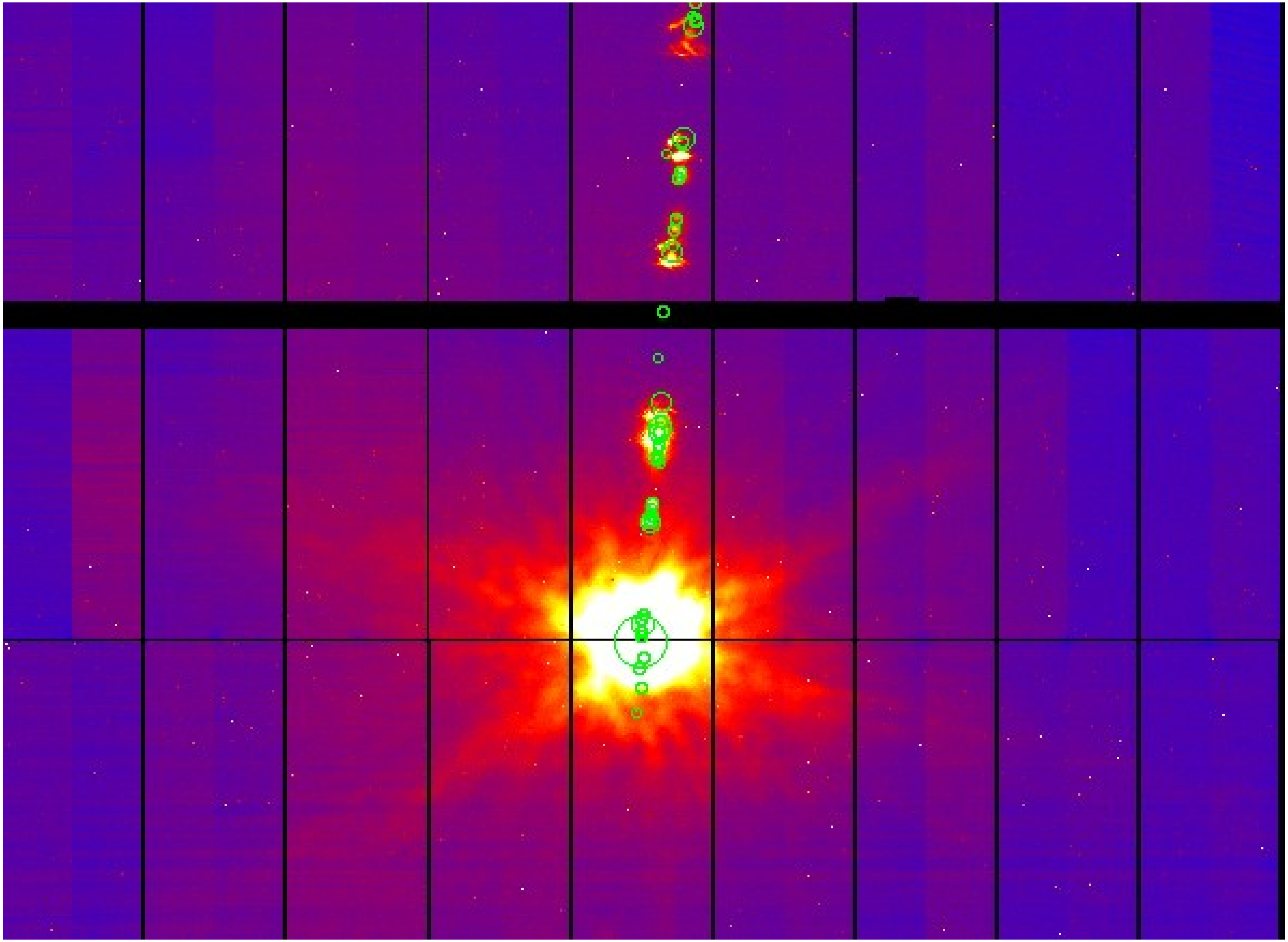
SNDice + MegaPrime model



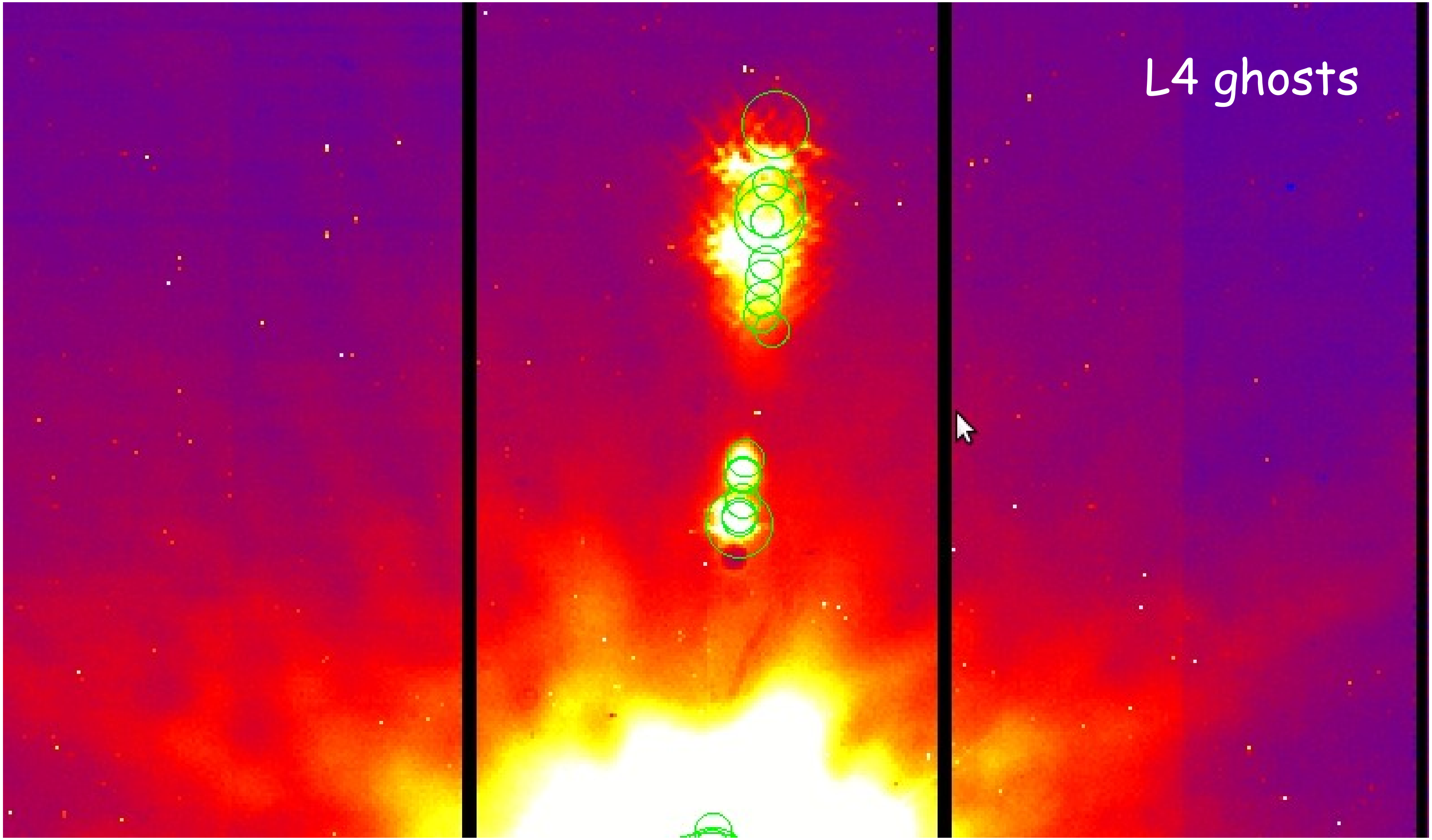




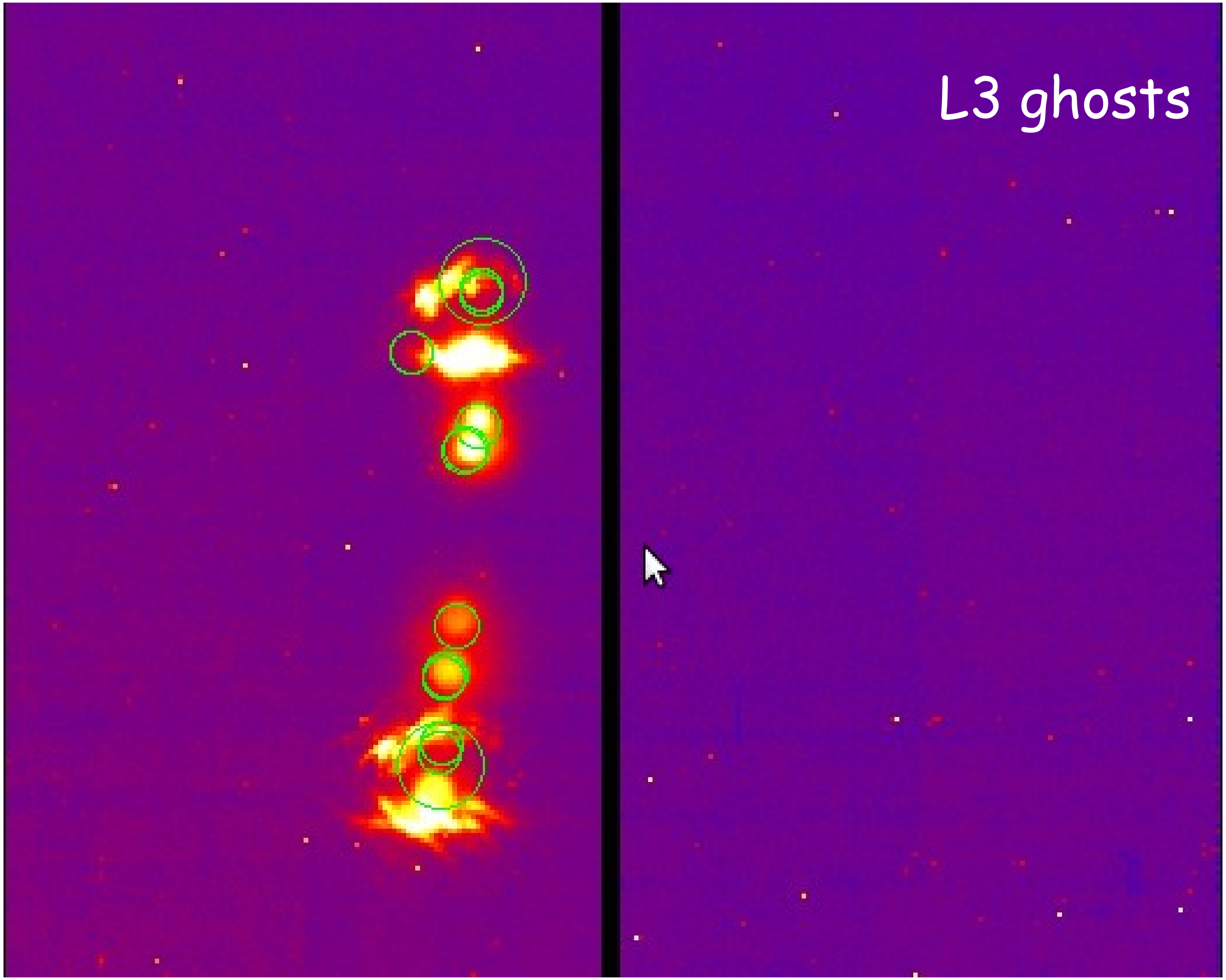
Model validation (alignment exposures)

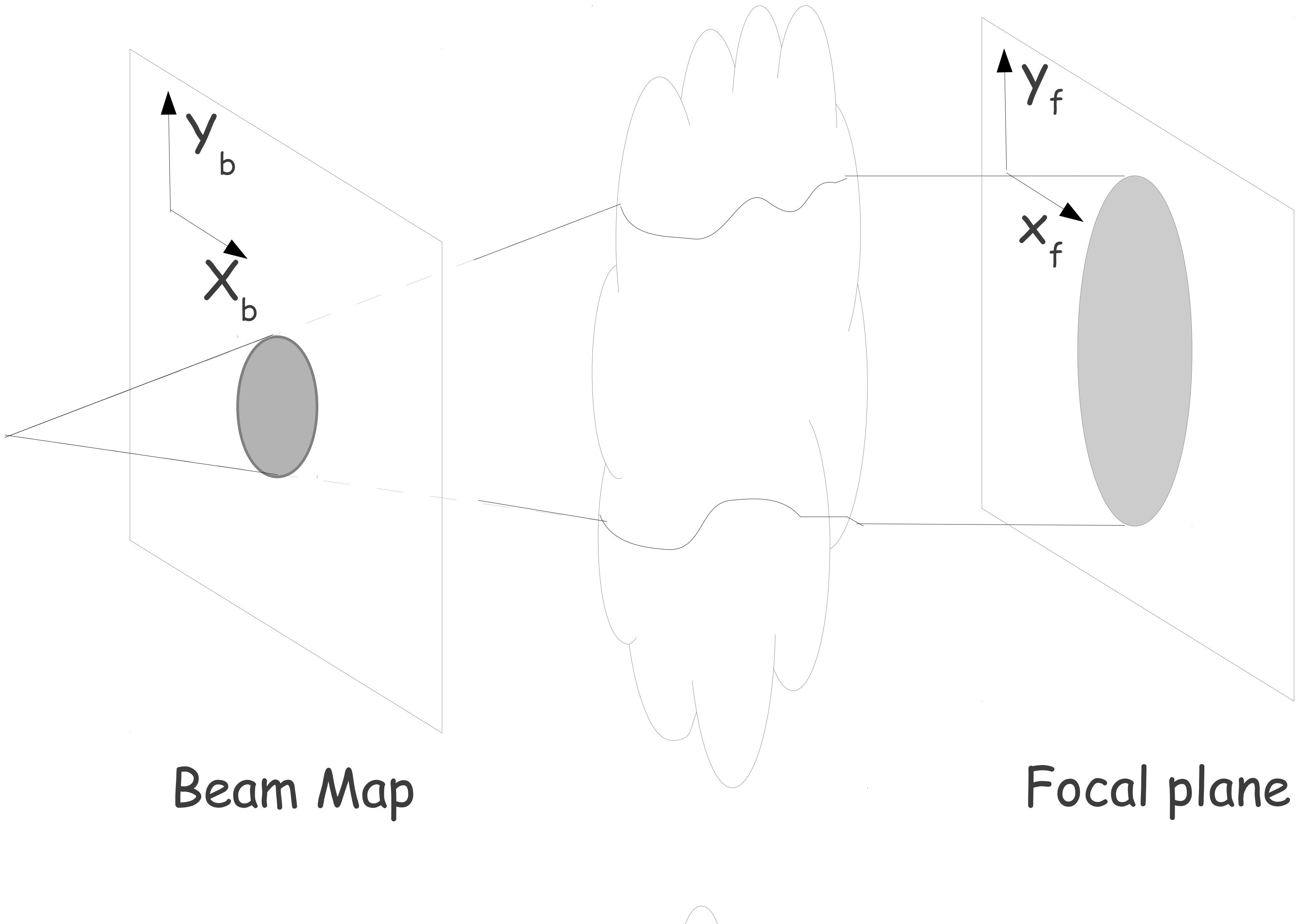


Model validation (alignment exposures)



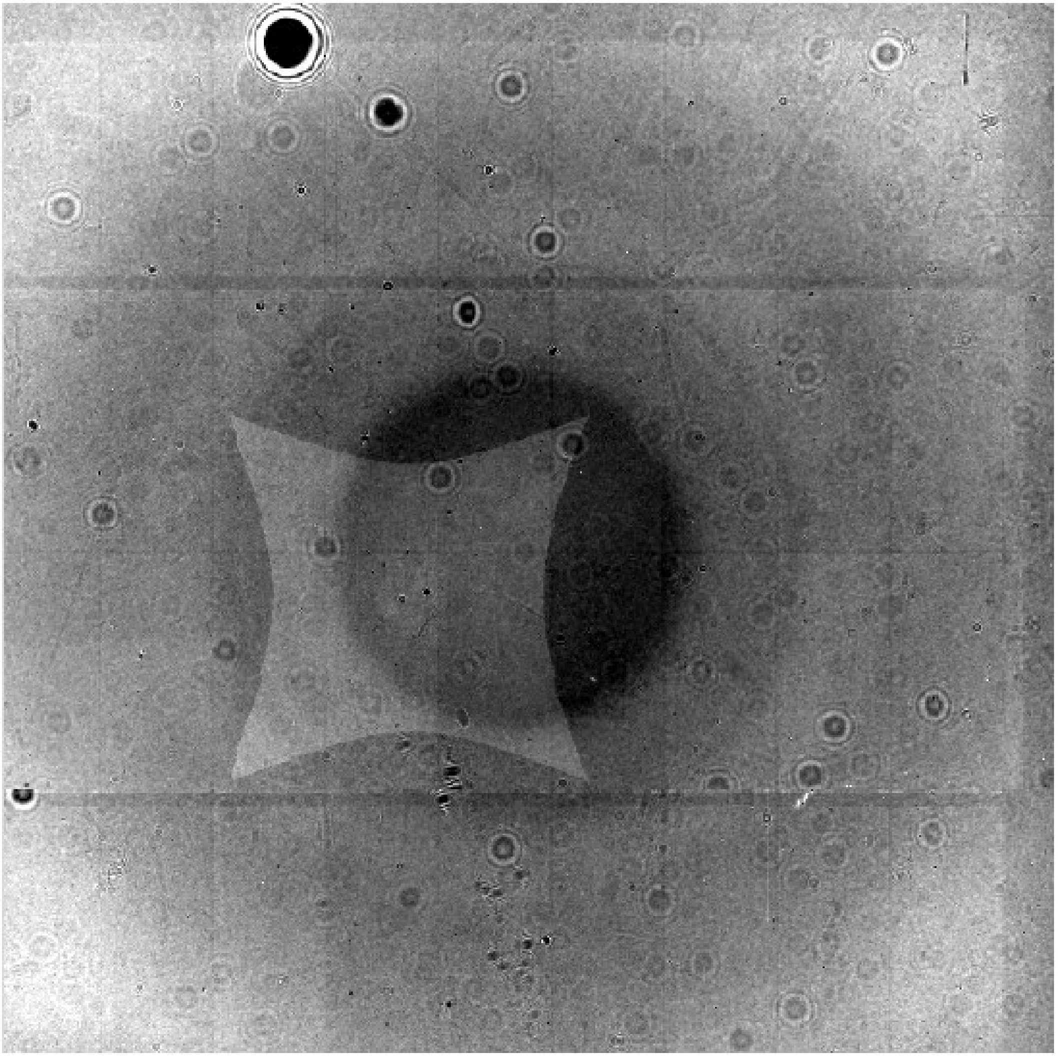
Model validation (alignment exposures)

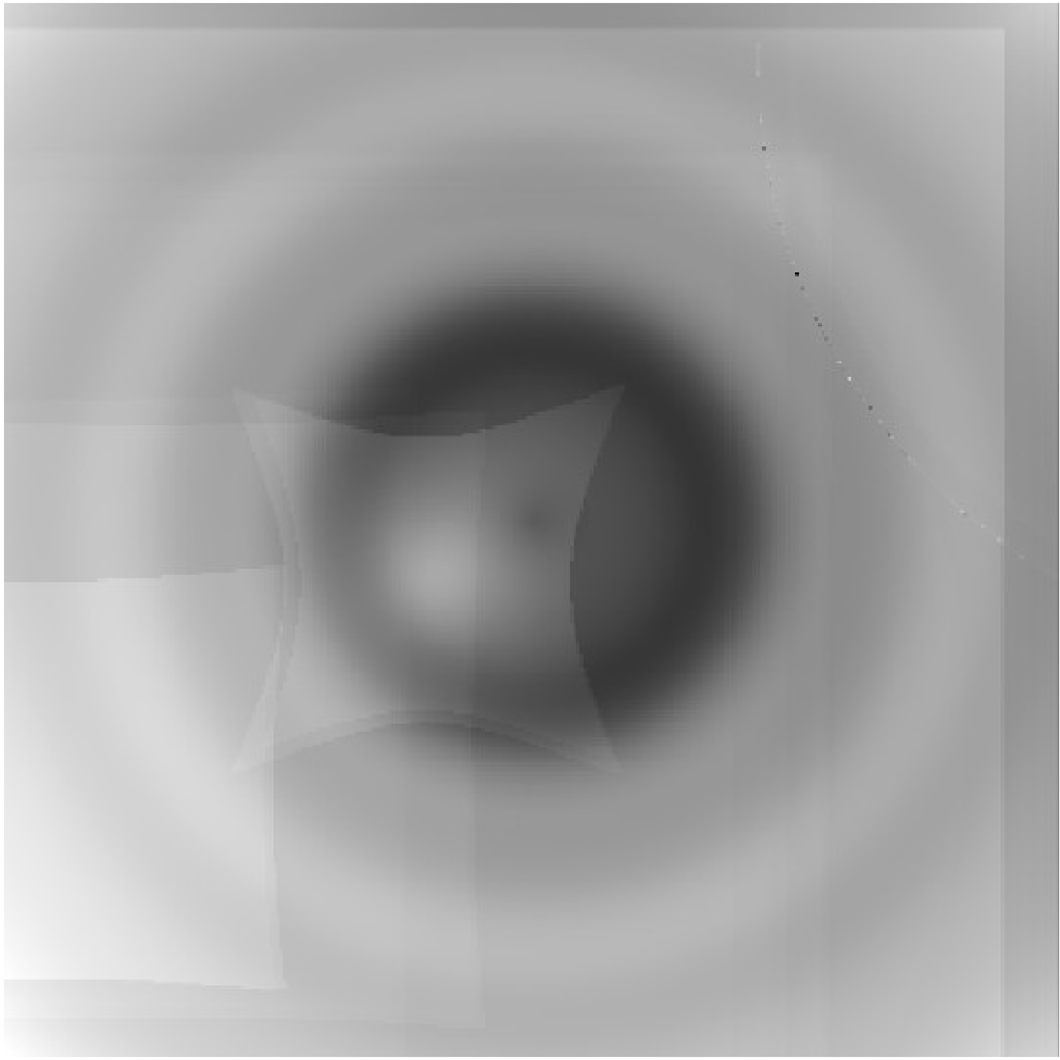




y_b
X_b
y_f
x_f
Beam Map
Focal plane

Ghost models





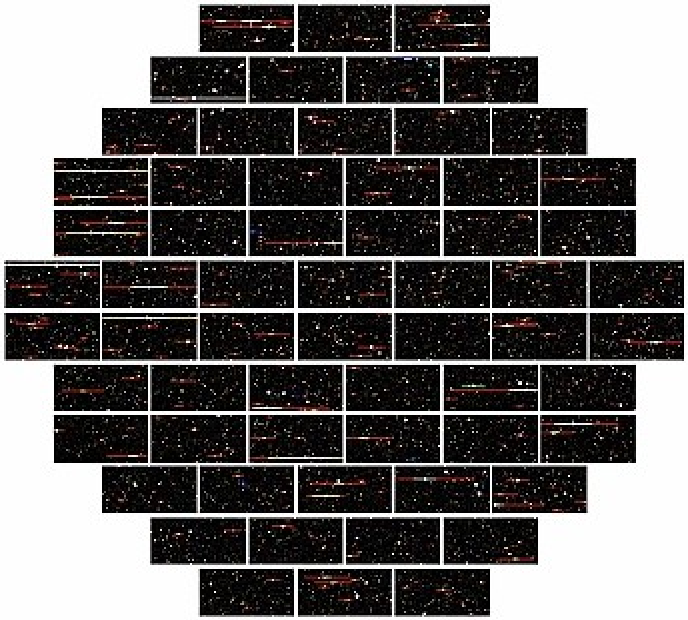
Ongoing work ...

The future

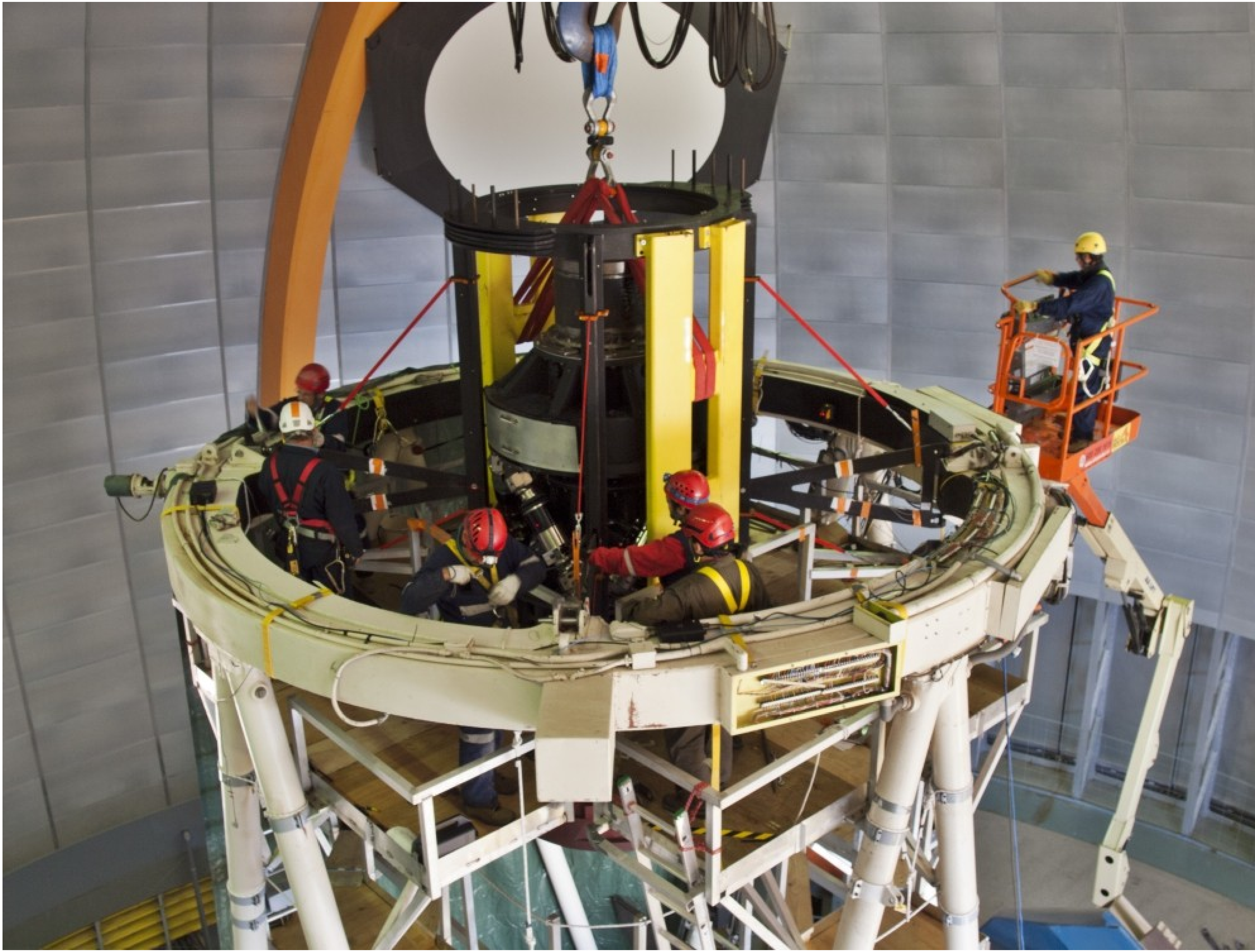
- Observational Cosmology is a new field !
  - The key technology (wide field imagers) is mature
  - Community has spent ~ 10 years building an expertise
  - Emerging probes !
    - → lensing magnification
    - → weak lensing
    - → BAO ...

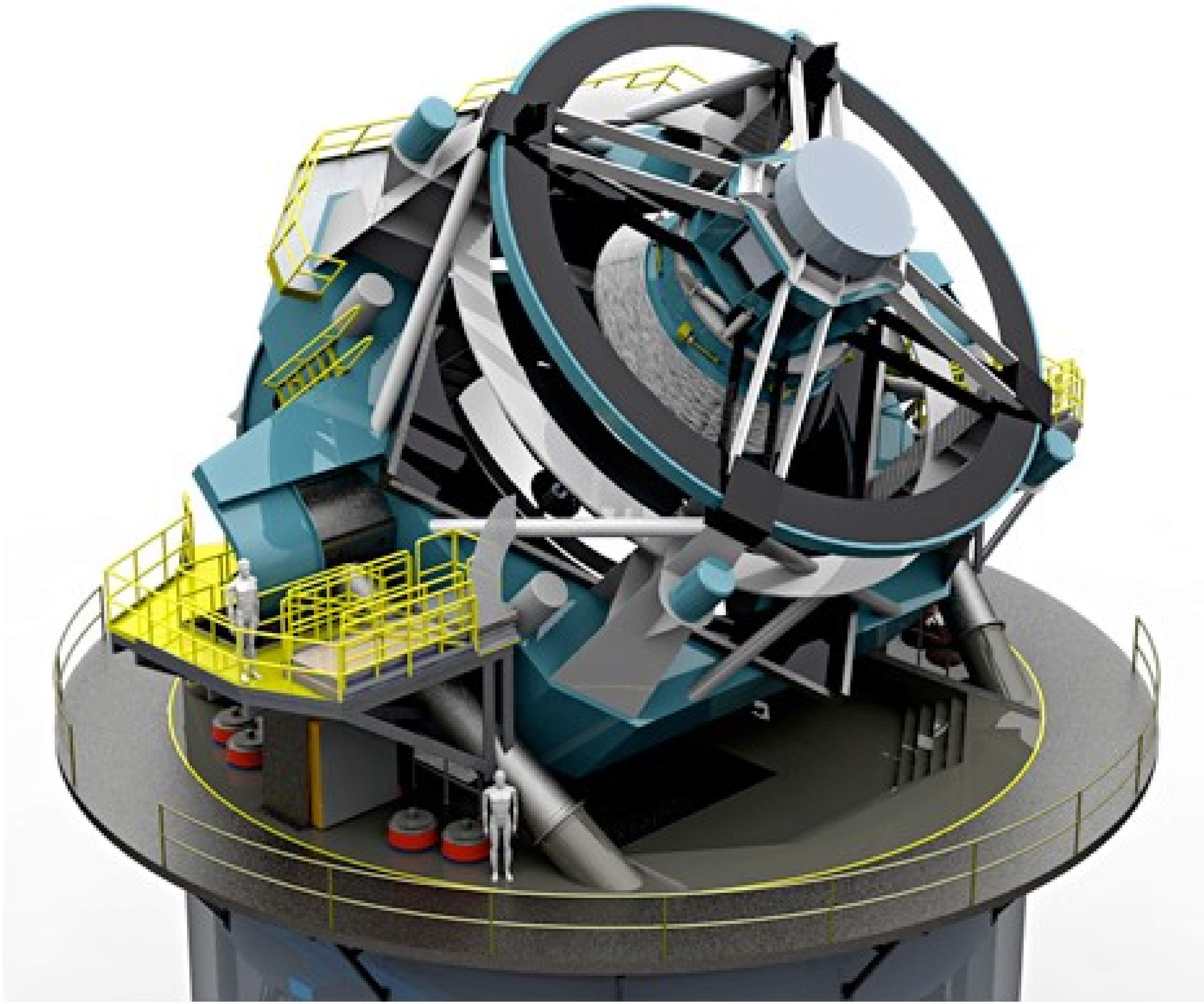
Dark Energy Survey

- Blanco 4-m telescope (CTIO, Chile)
- DECam (Fermilab)
  - 570 Mpixels, 74 red sensitive CCDs, ~ 3 deg^2
- 570 nights (5 years)
- Main survey
  - 5000 deg^2 (BAO + Lensing)
- SNe Ia (6 - 30 deg^2)
  - → 4000 SNe Ia @ z<1

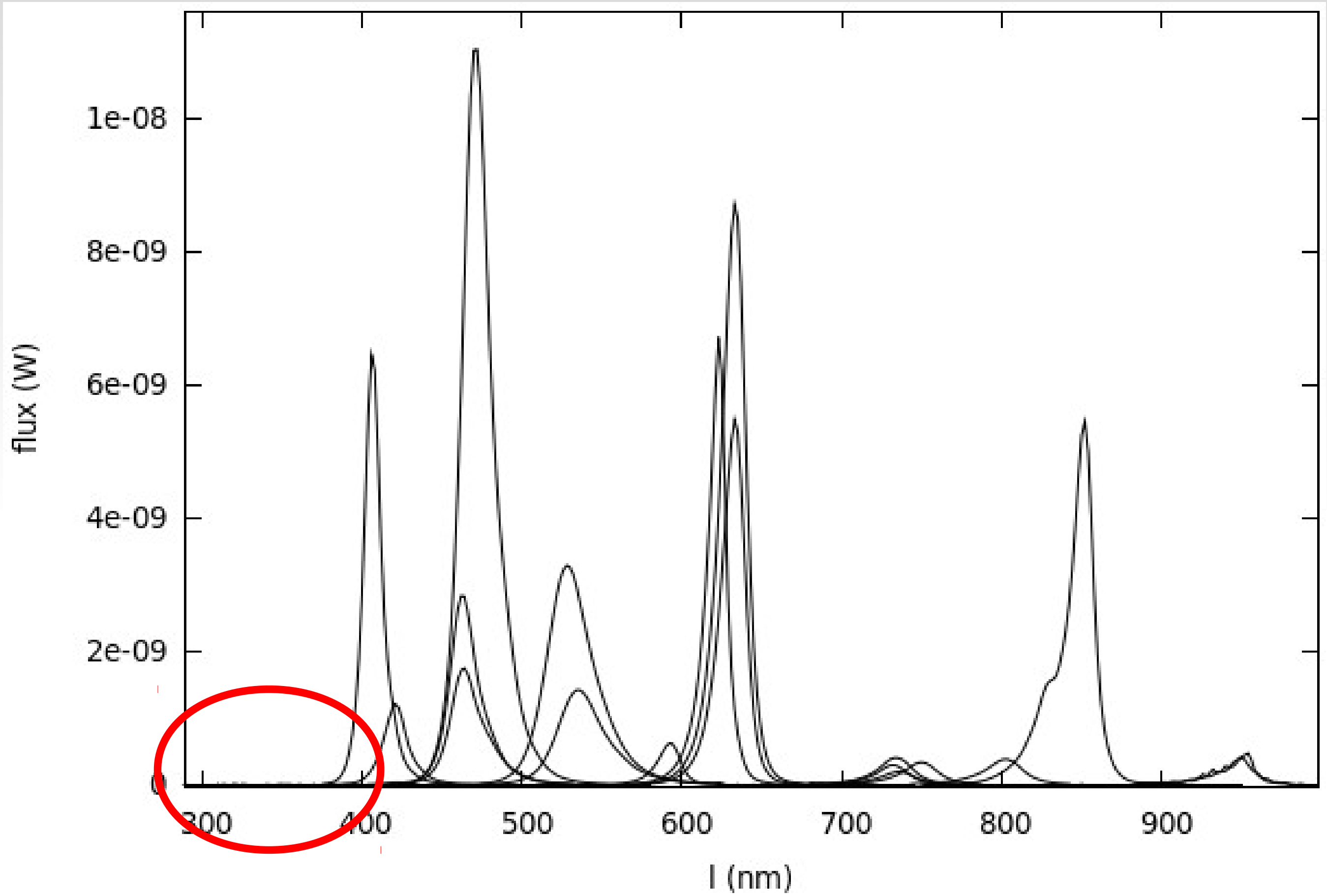


https://www.darkenergysurvey.org/

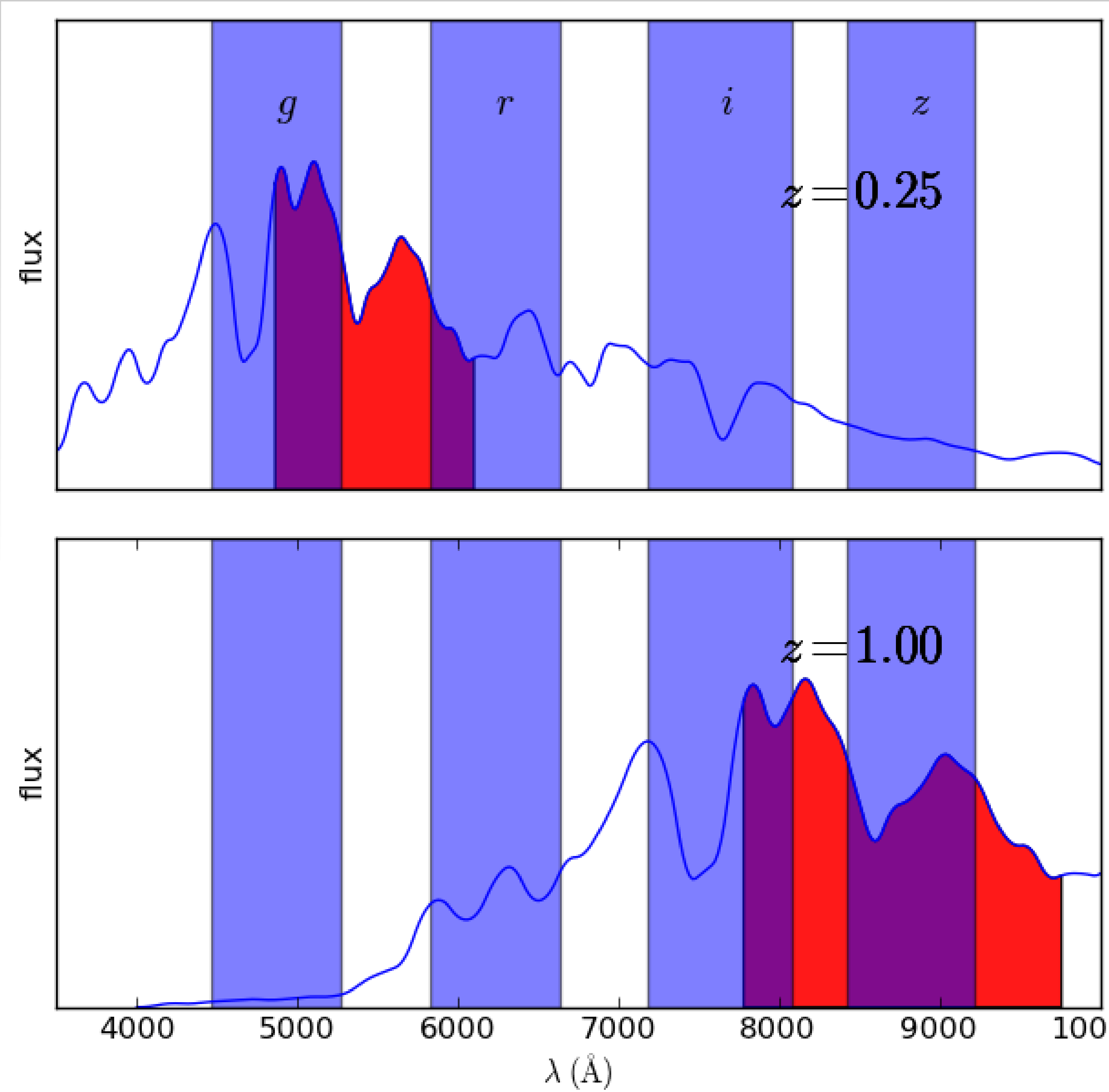




LED spectra



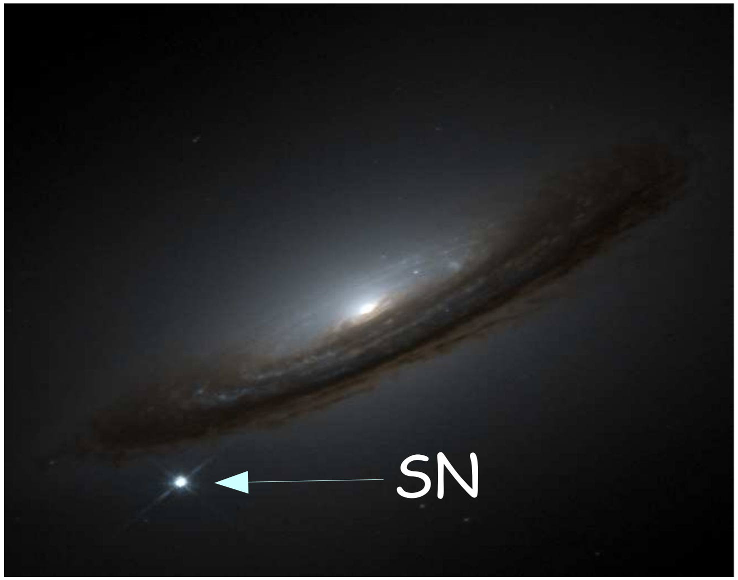
- δλ/λ ~ 8% (a few dozen nanometers)
- Smooth, slighly asymetric (towards the red)
- Shape evolve with temperature.


g
r
i
z
z = 0.25
flux
z = 1.00
flux
4000
5000
6000
7000
8000
9000
1000
λ (Å)

Instrument model (2)

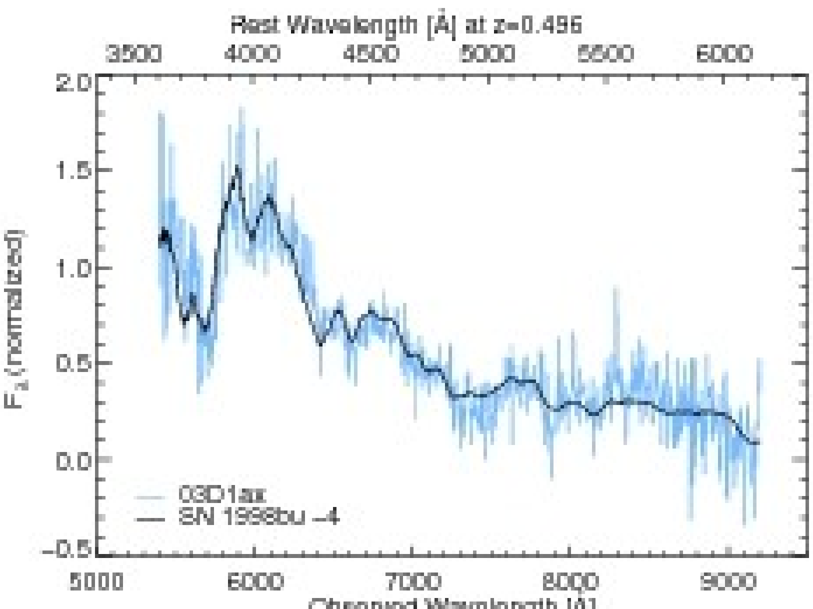
- What we need to know
  - The reponse of the optics (angles → meters)
  - A focal plane model (meters → pixel positions)
  - A fonction that gives the position & orientation of SNDice wrt the telescope (difficult!)
- We do not need to know (a priori)
  - The reflectivities / transmissions of the optical elements.
- Assumptions:
  - We can neglect the chromaticity of the optics (over the extension of one LED spectrum)

Supernovae de type Ia



- Explosions thermonucléaires (WD)
  - Événements rares (~1 / Gal / 1000 yr)
  - Lumineux (~10^{10} luminosités solaires)
  - Brefs (~ 1 month)
  - $\sigma(L_{max})$ ~ 40%

  Standardisables → σ(Lmax) ~ 15%

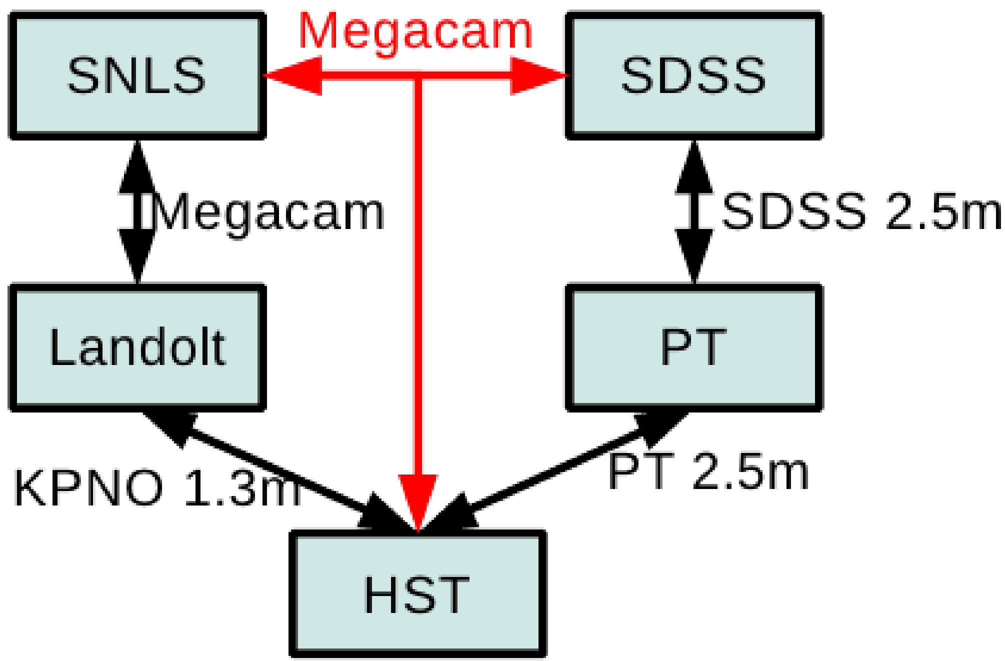


Spectroscopie

- Identification (raies larges)
- Composition chimique + vitesses

Stellar calibration

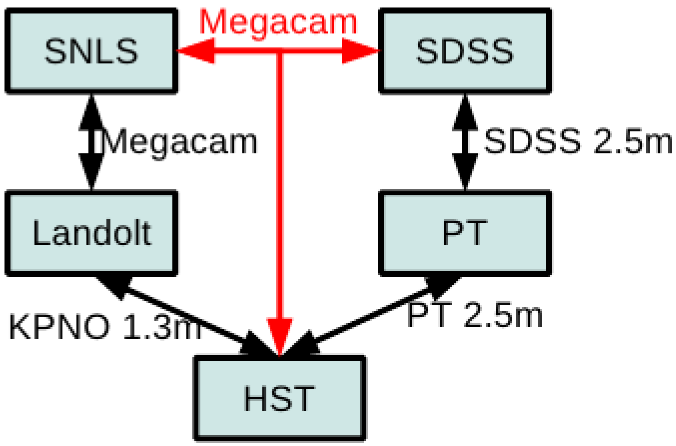
Survey field stars



Secondary standards

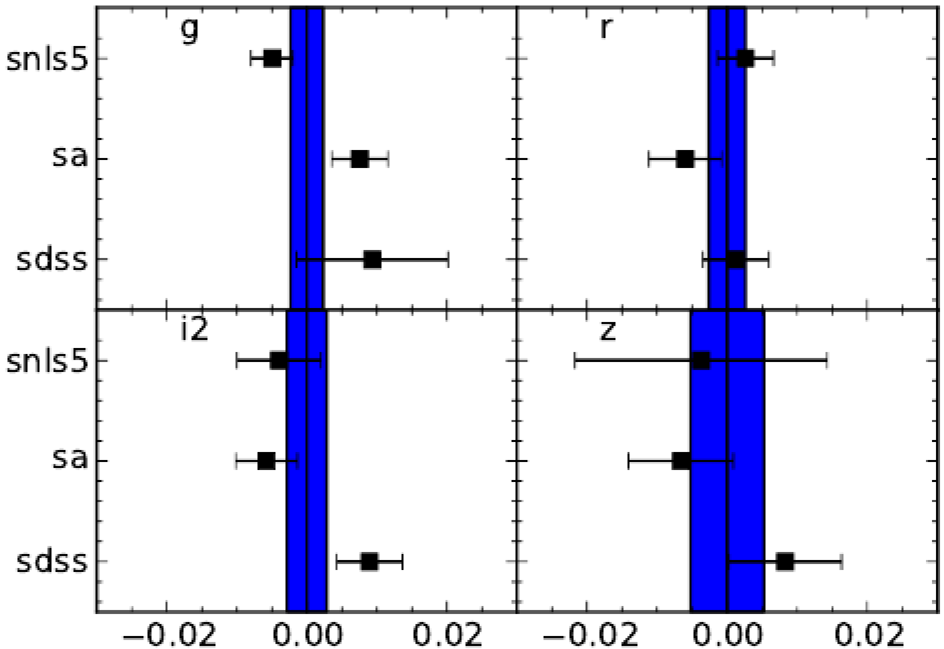
Fundamental calibrators
(HST white dwarf scale)
(CALSPEC)

Checking calibration



Closing the loop

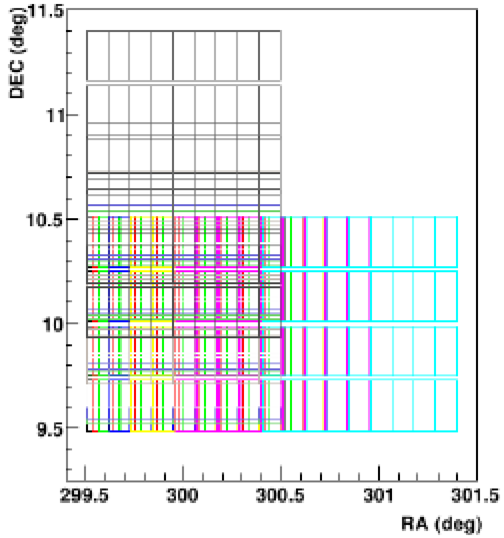
- 3 independant path
- Do agree within announced error bars



band	combined uncertainties
g	0.002
r	0.003
i2	0.003
z	0.006

LPNHE PARIS

Mapping the response: the grid observations



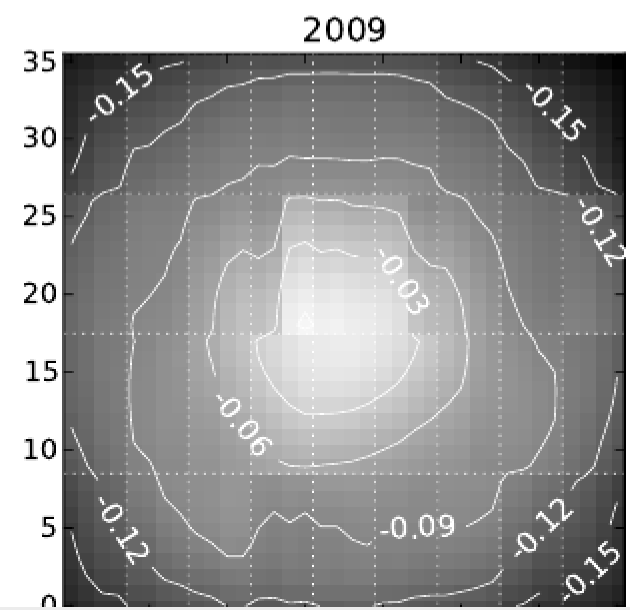
Dithered observations of dense stellar fields

- 13 exposures
- Logarithmically increasing steps from 1.5' to 1/2 deg
- 4-10 independent grid datasets /band
- $\rightarrow$ measure a correction δzp to the twilight flat-field

Observation model

$m_{\mathrm{ADU}}(x, star) =$
$m(x_0, star) + \delta zp(x) + \delta k(x)(g - i)$

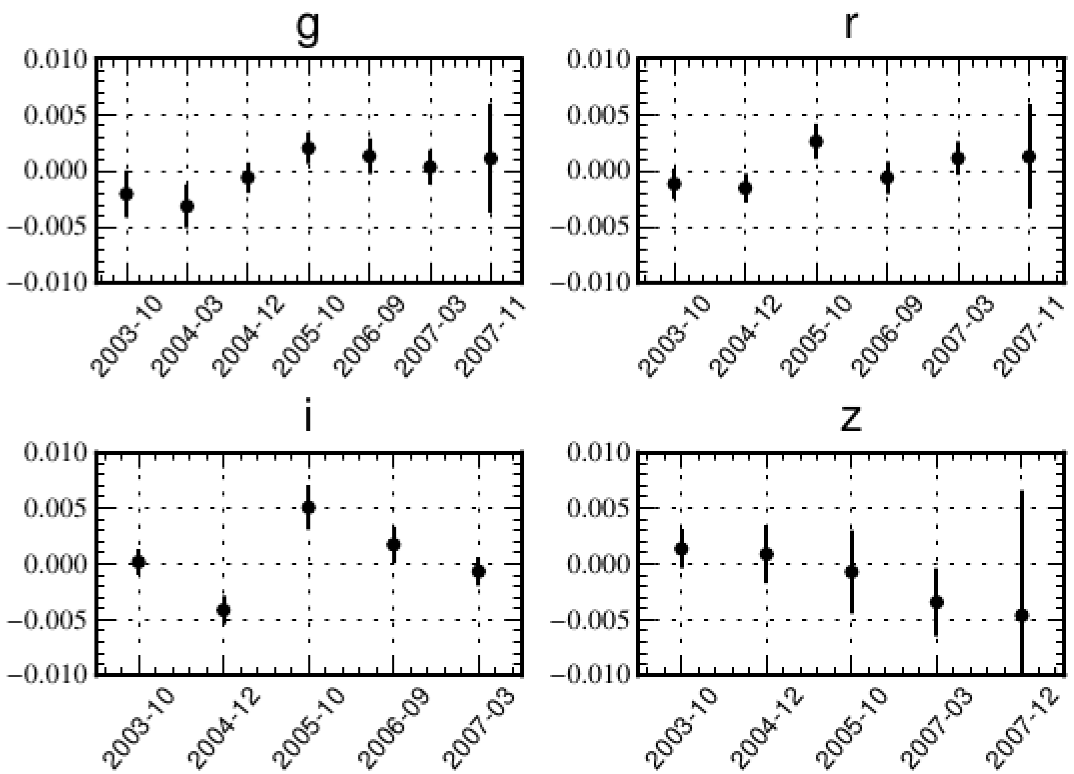
- $m(x_0) \sim 100000$ nuisance parameters
- $\delta zp \sim 100$ parameters



Results

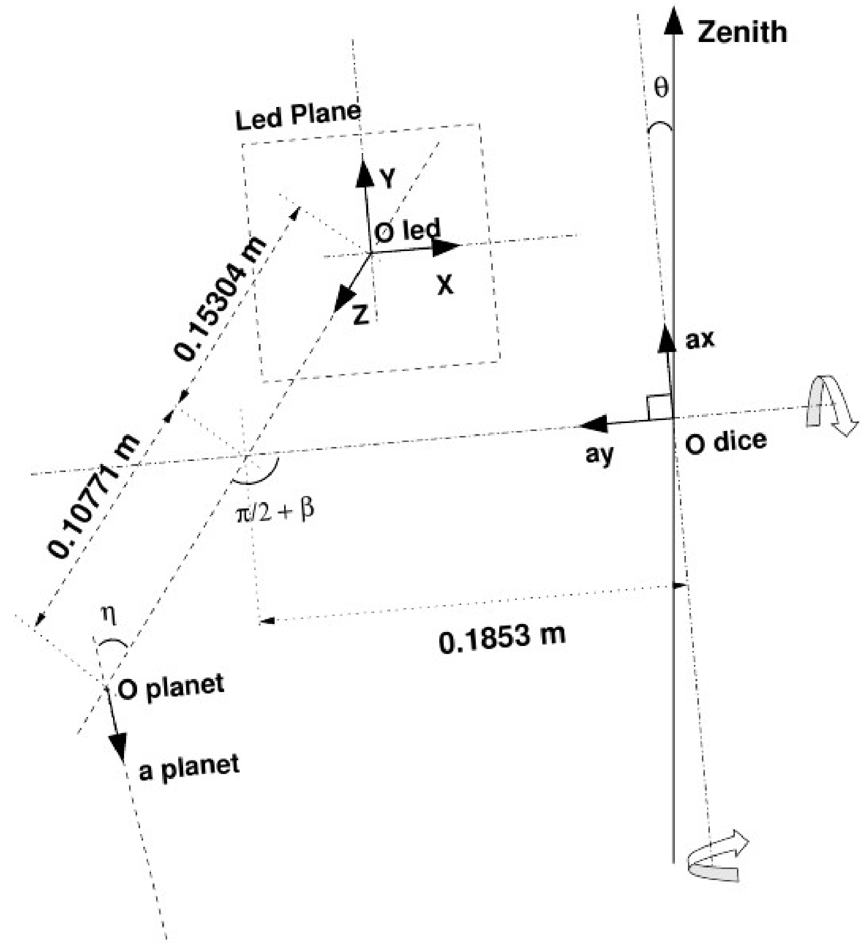
Evaluating the impact of flat-fielding errors on the calibration

- Independent observations → errors average out
- After selection ∼ 6 useable independent photometric corrections per band
- All epochs agree with *rms* $< .3\%$ in all bands

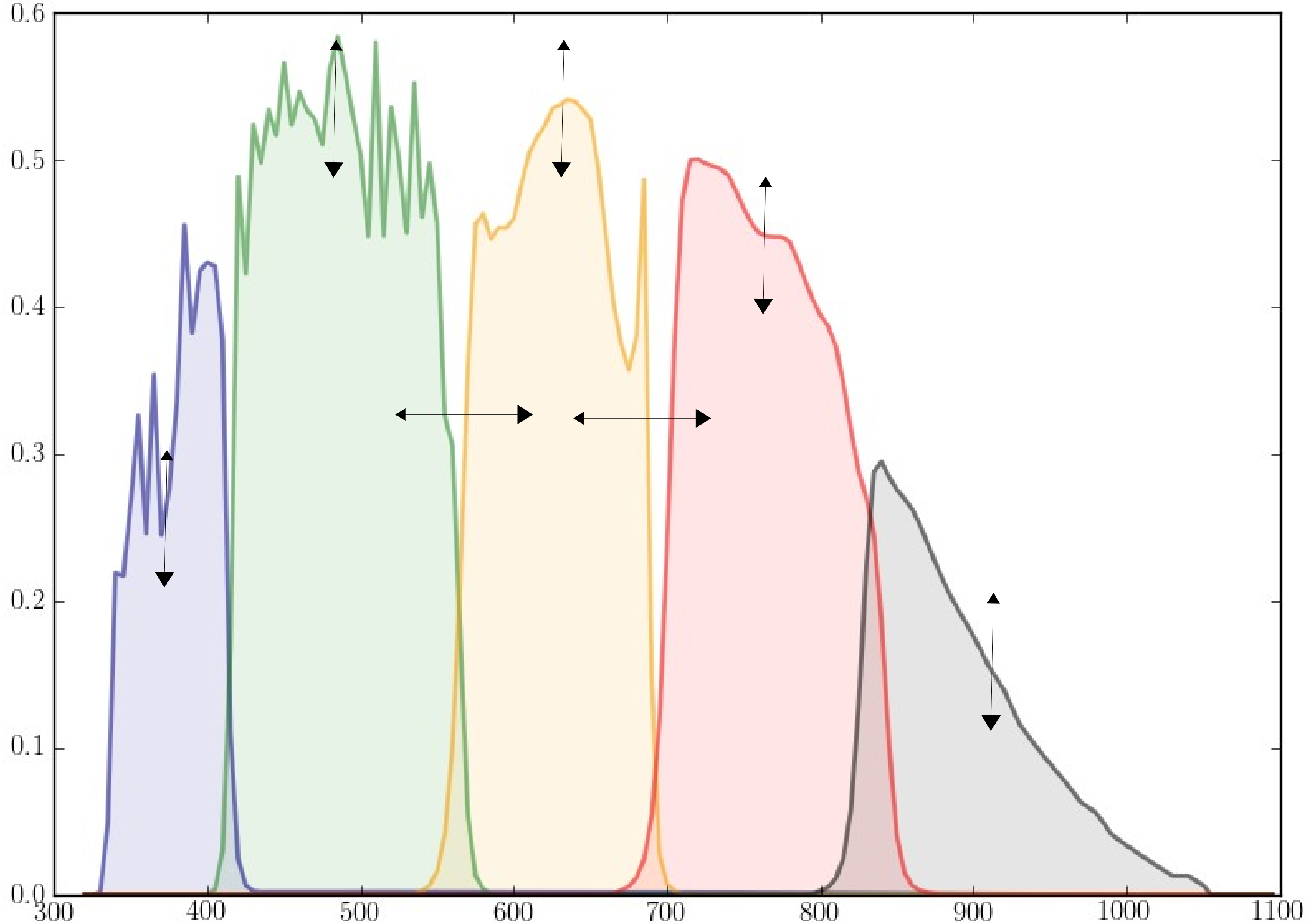


MegaCam - SNDice Geometry

- We do not know with precision (1) where the dome is (2) where SNDice is (3) the tilts and misalignments of the SNDice mount
- We use special alignment exposures. SNDice also generates a quasi-parallel beam → spot + ghosts.
- I spare you the details.

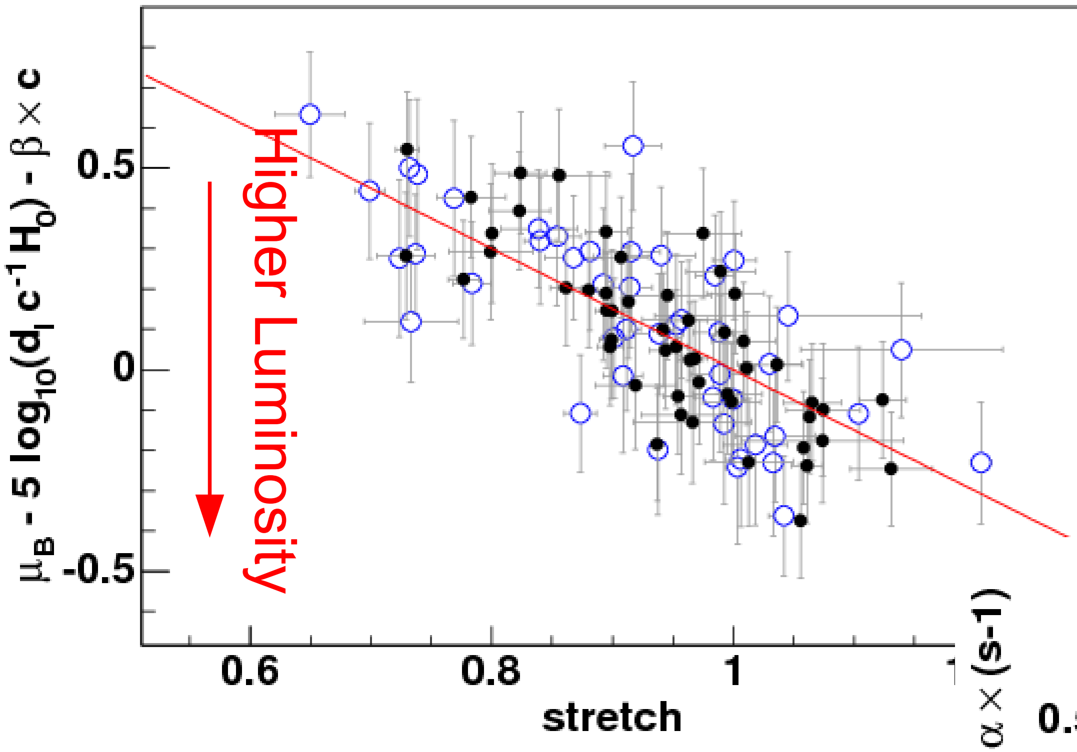


Calibration ?

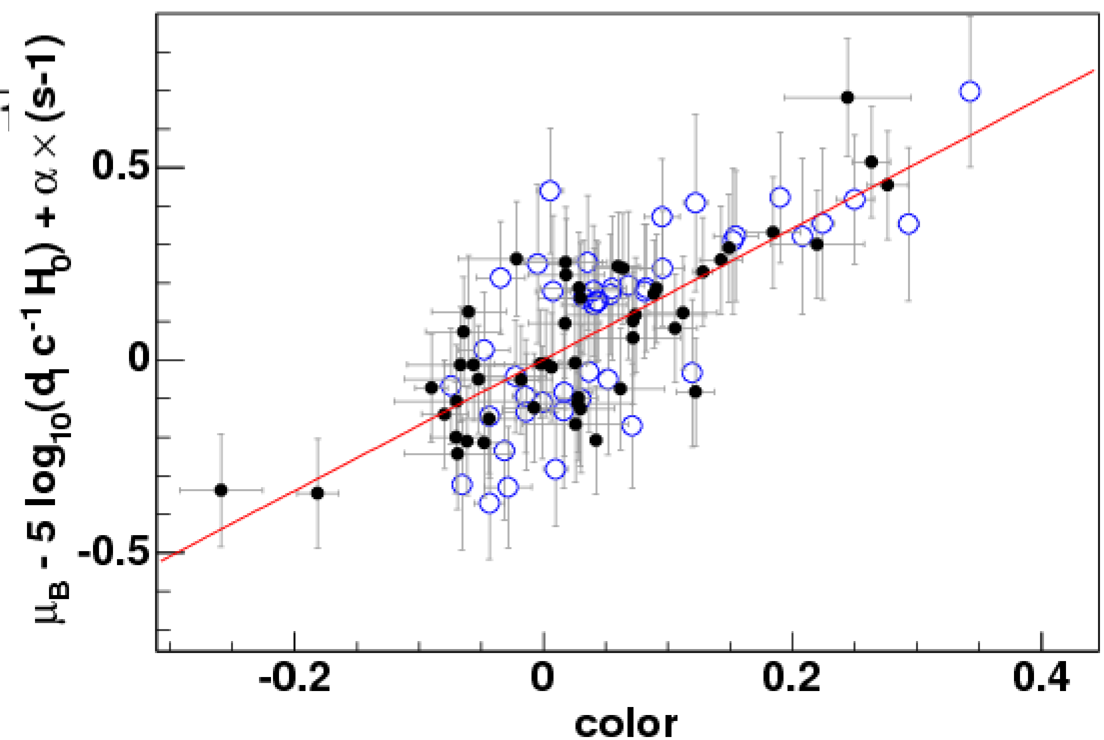


SN Ia "standardization"

"Brighter - slower"



"Brighter-bluer"



Also, spectroscopic features
see e.g. Bailey et al, (2009)

Cosmology with SNe Ia

- Standardizeable Candles

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

Resframe apparent magnitude @ maximum (m_B)

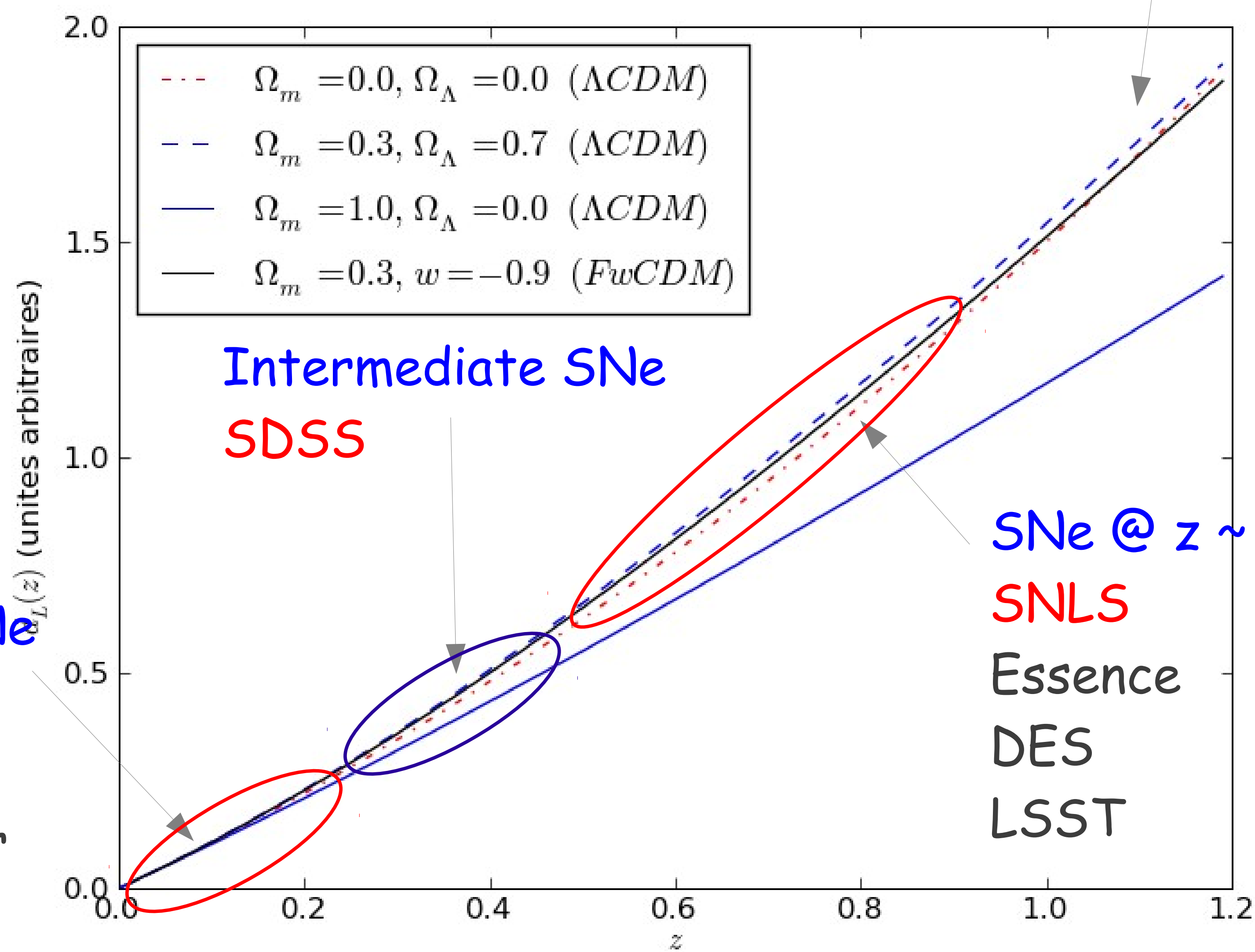
Absolute magnitude @ maximum (M_B)

Light curve shape correction ($\alpha(s-1)$)

Color correction. Accounts for (βc)
- extinction by dust
- intrinsic color variations

Hubble Diagrams

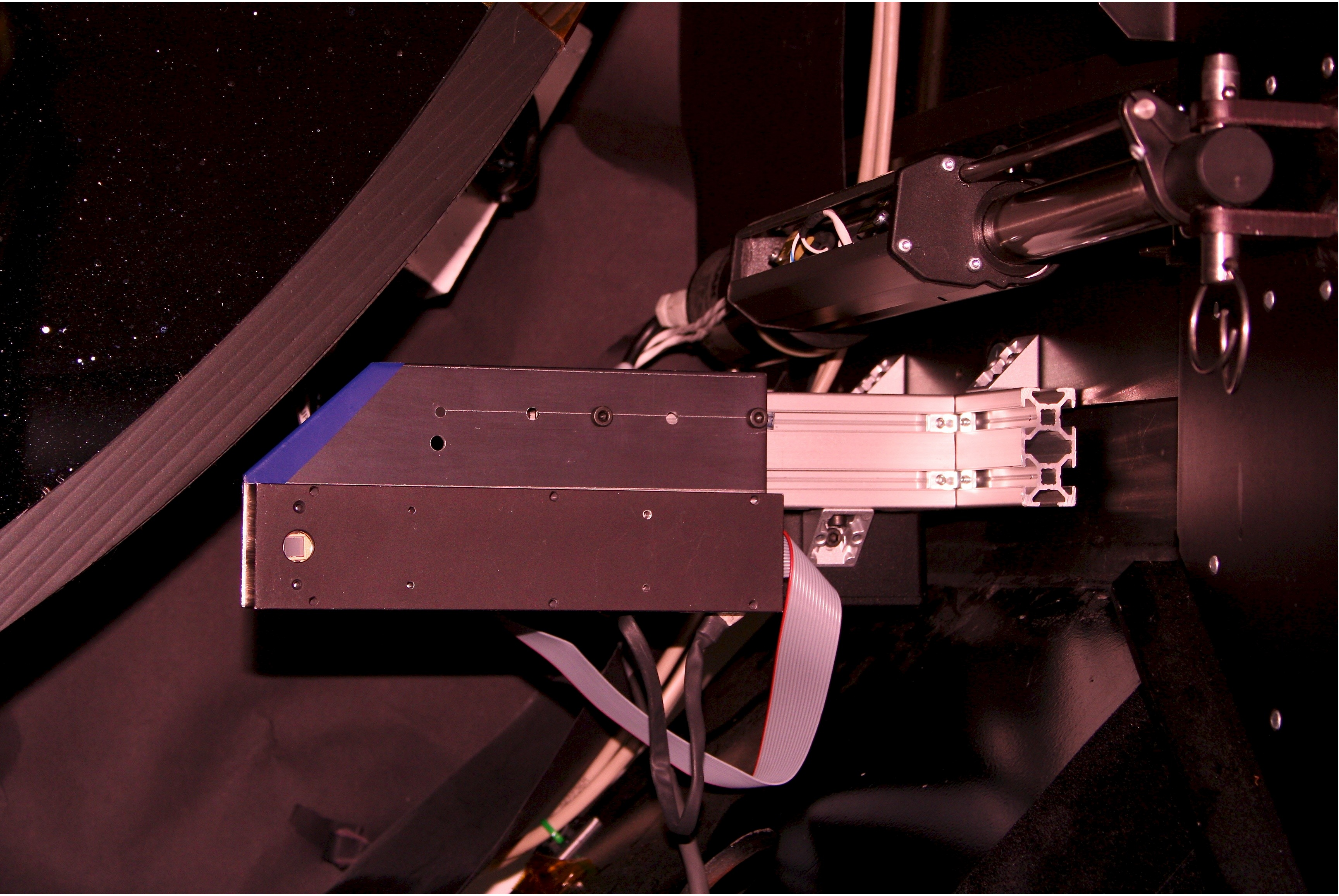
SNe @ z>1
HST
SNAP/JDEM
Euclid...



Intermediate SNe
SDSS

SNe @ z ~ 0.8
SNLS
Essence
DES
LSST

Nearby SNe
SNfactory
Cfa, KAIT,
SkyMapper
...



MegaCam - SNDice geometry

$$\chi^2(\theta) = \sum_i \sum_p w_{ip} \, \|\vec{x}_i - \vec{x}^{(p)}(s_i;\theta)\|^2$$

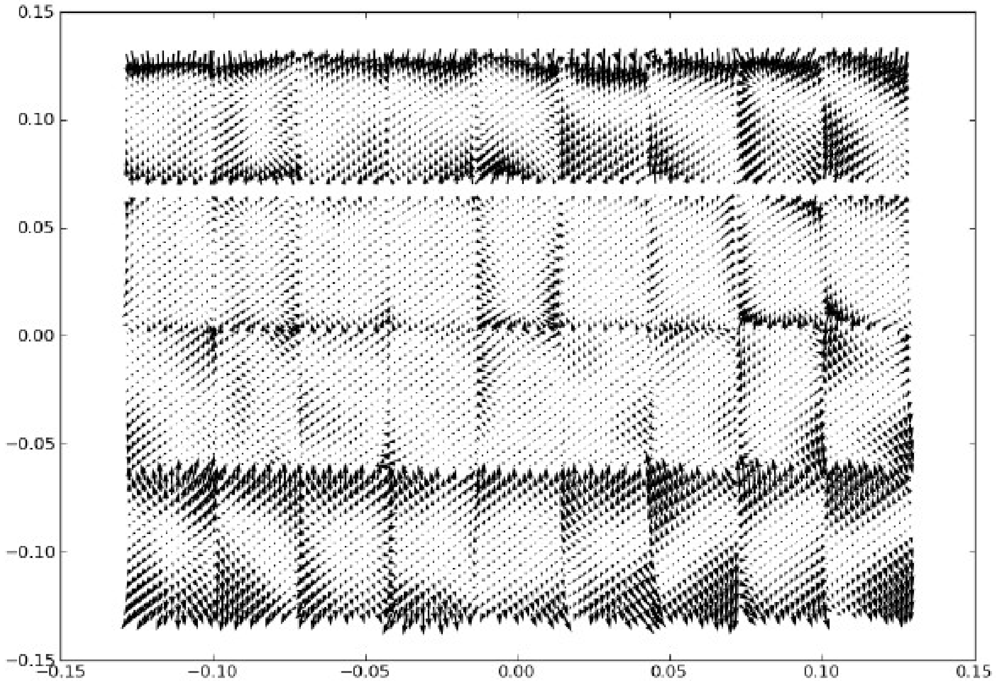
Θ : (1) Megacam/SNDice Geometry
(2) lenses

Model predictions

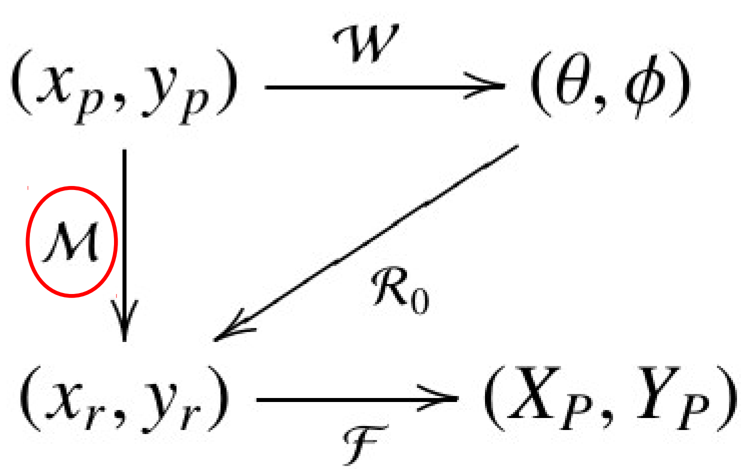
Sum on
(1) images (i)
(2) ghosts (p)

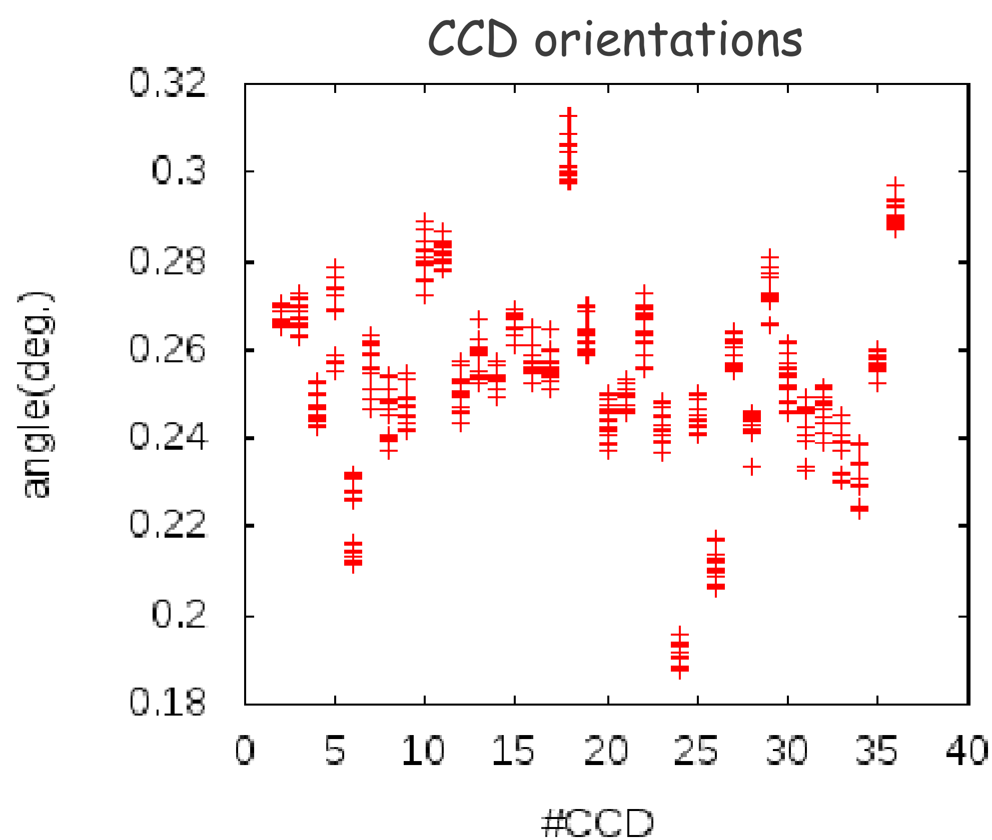
Ghost position measurements

Focal plane model

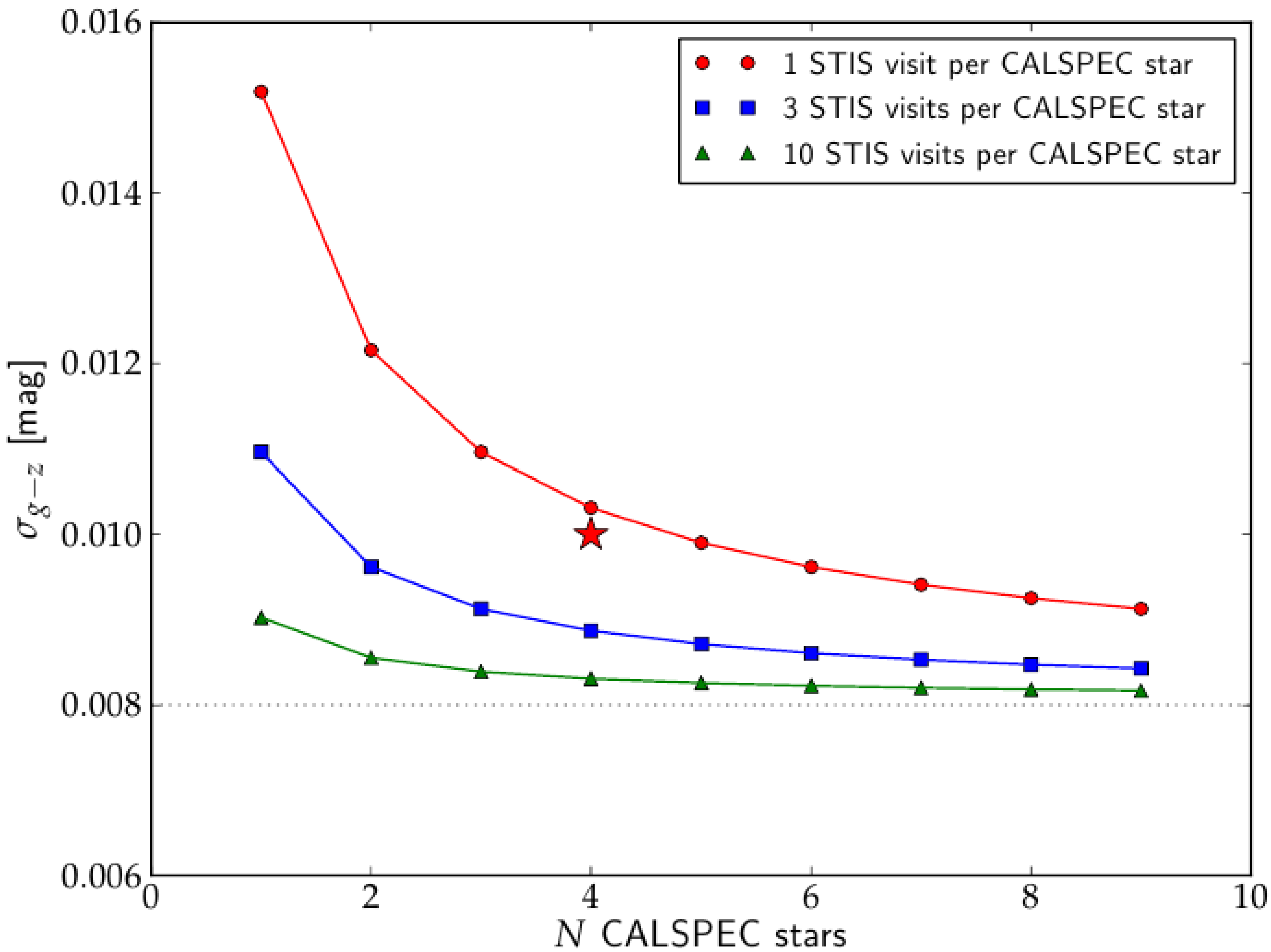


Use the information contained in the WCS transformations !





CALSPEC uncertainties ?



Stellar Calibration

- Relies on observations of stellar calibrators
  - Secondary standards (Landolt)
  - Primary standards (CALSPEC, Bohlin et al)
- Very precise, BUT
  - Controlling the imager uniformity is tough (dithered observations of dense stellar fields every ~ 6 months / 1 yr)
  - Passband maps $F(\lambda;x,y)$ not monitored in situ
  - How accurate is the SED of the primary standard ???

(see e.g. Betoule et al, 2012, Regnault et al, 09, Ivezic et al, 07)

Instrument model

$$I(\vec{x}_f) = T(\overline{\lambda}; \vec{x}_f) \times \mathcal{B}(\vec{X}_b) \left| \frac{\partial \vec{X}_b}{\partial \vec{x}_f} \right|$$

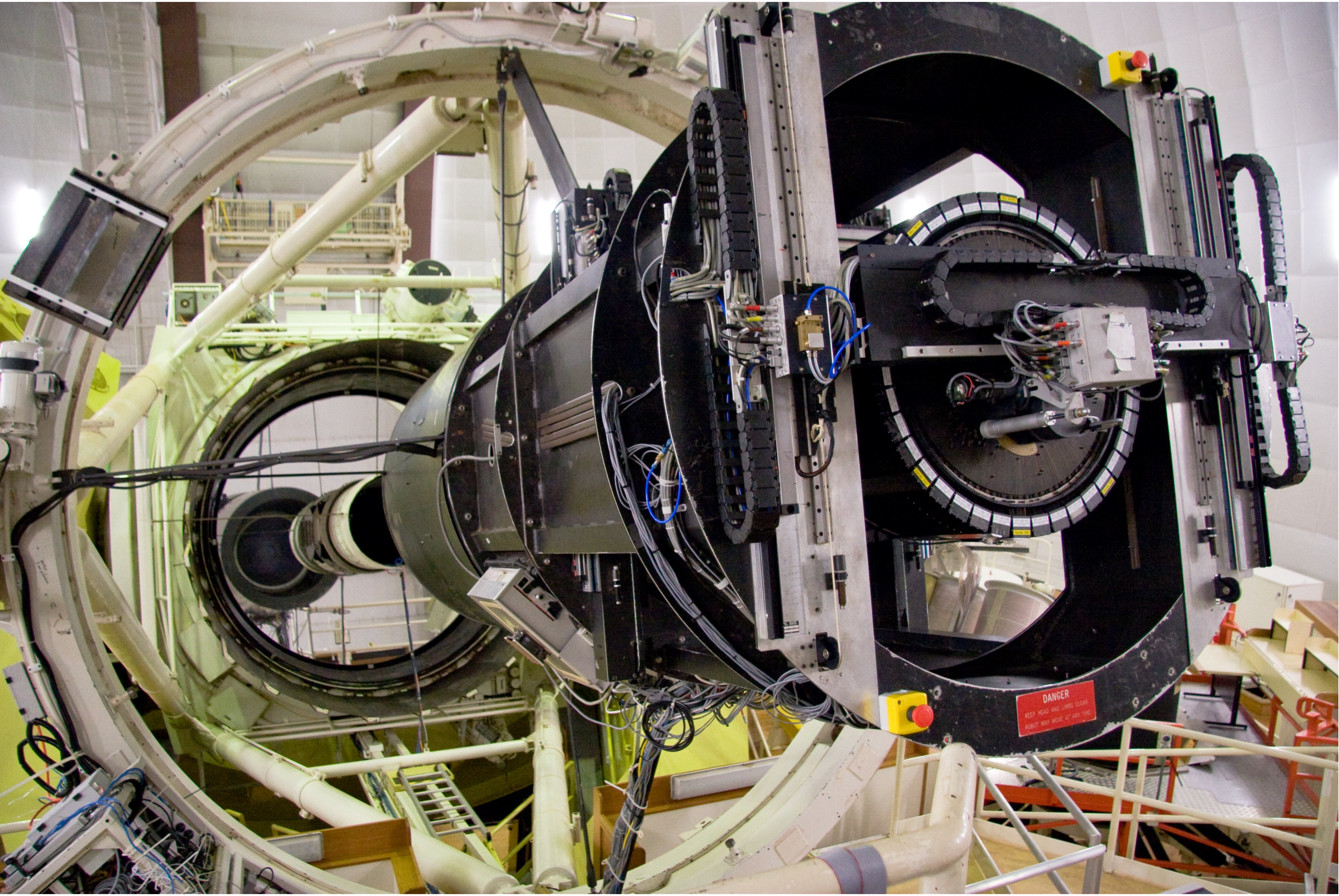
Focal plane irradiance

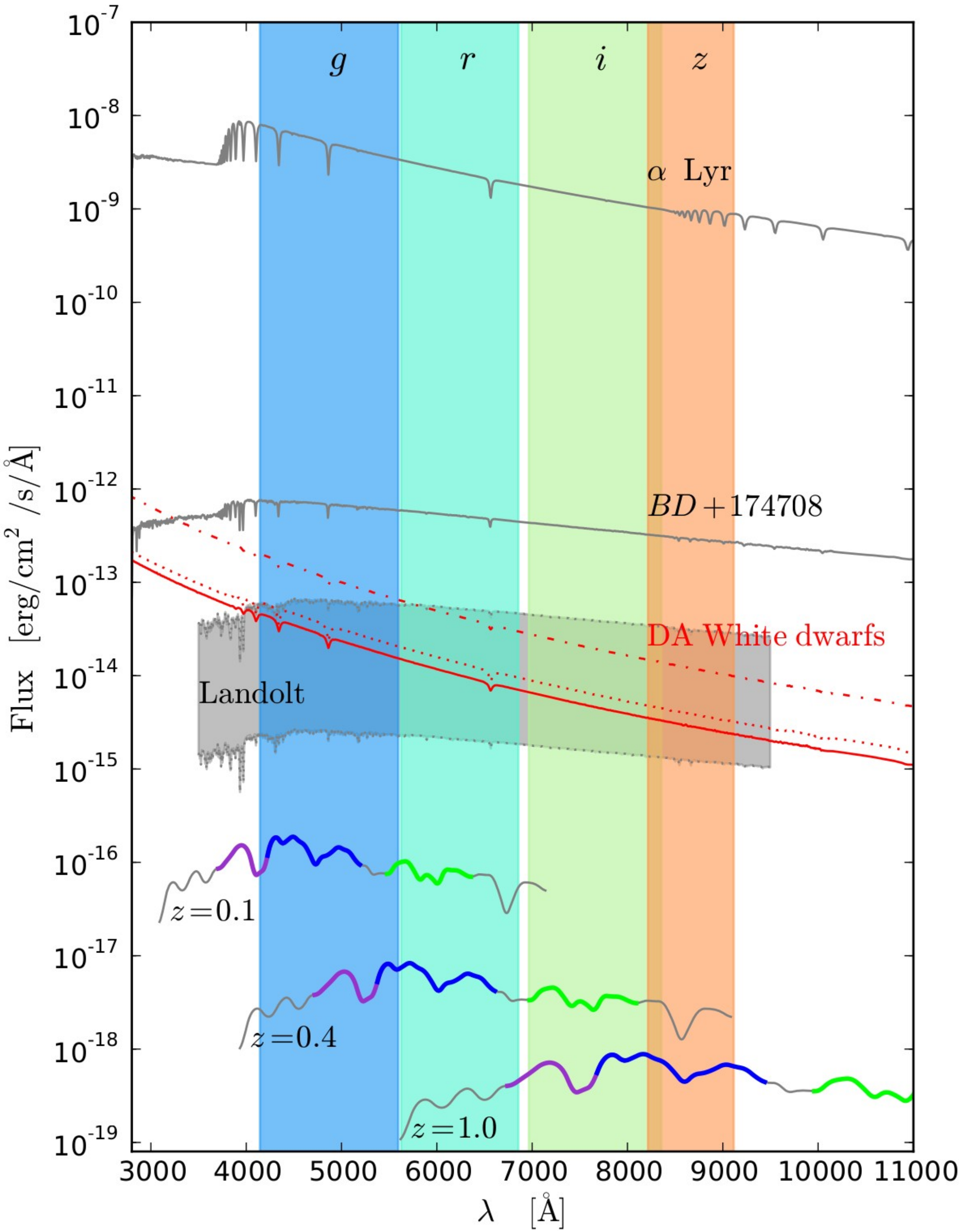
Beam map

Optics

- With ghosts:

$$I(\vec{x}_f) = \sum_p T_p(\overline{\lambda}; \vec{x}_f) \times \mathcal{B}(\vec{X}_b^{(p)}) \left| \frac{\partial \vec{X}_b^{(p)}}{\partial \vec{x}_f} \right|$$


DANGER
KEEP HEAD AND LIMBS CLEAR
ROBOT MAY MOVE AT ANY TIME



g
r
i
z
α Lyr
BD +174708
DA White dwarfs
Landolt
z = 0.1
z = 0.4
z = 1.0
Flux [erg/cm^2 /s/Å]
λ [Å]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
3000 4000 5000 6000 7000 8000 9000 10000 11000