New calibration methods

N. Regnault

LPNHE

Outline

- Why calibration ?
- Calibration requirements
  - For a 4th generation survey (e.g. LSST)
  - For a third generation survey (e.g. Subaru)
- Primary flux references
  - CALSPEC & NIST
- Survey flux metrology chain
  - Survey uniformity, GAIA
- Characterization of the survey telescope
  - Bench & in-situ throughput measurements
- Conclusion

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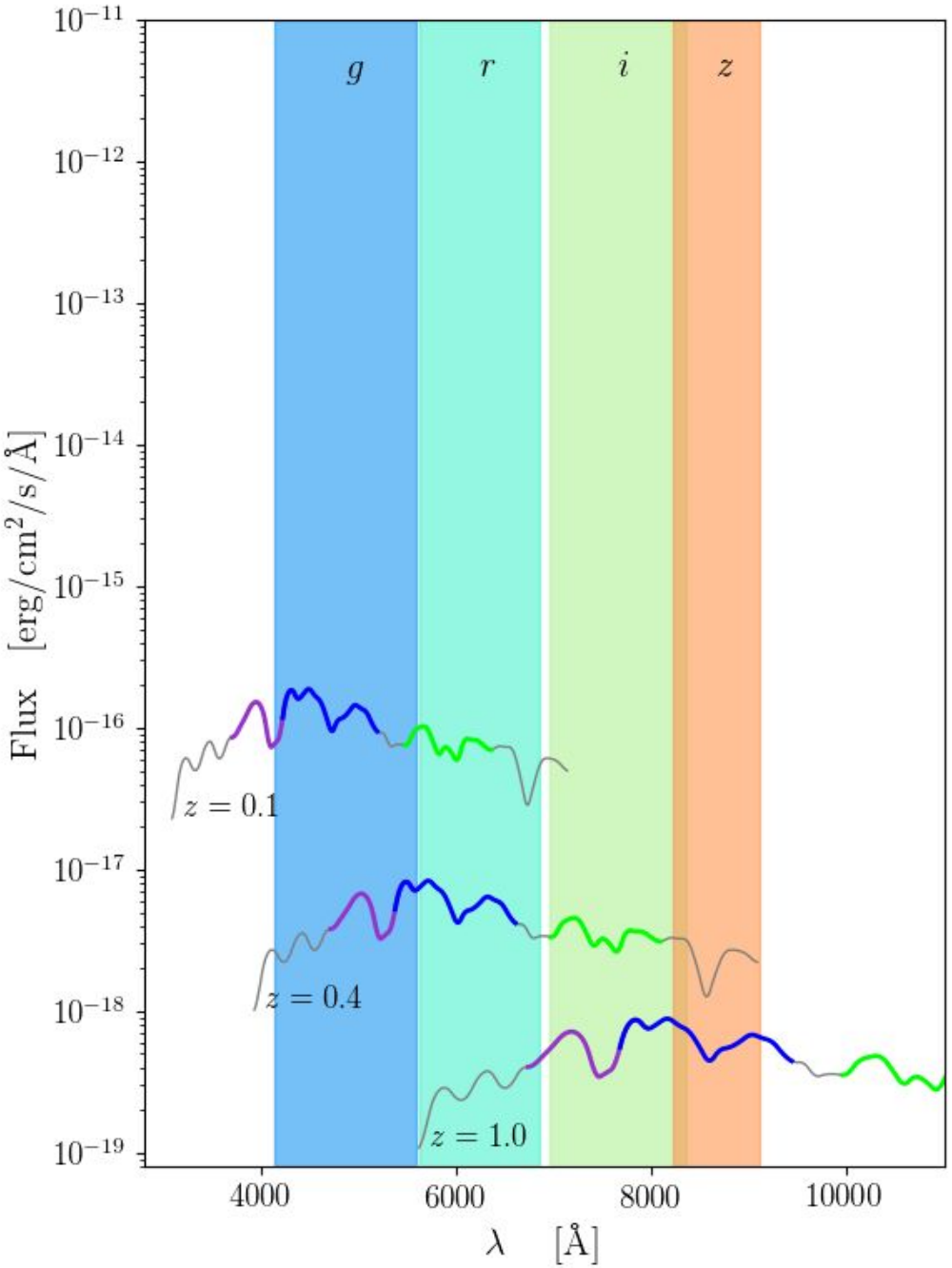
Why calibration ?

- Cosmological signal from comparison of
  - Nearby SNe (g,r)
  - Distant SNe (i,z)
- SNe measured at different locations of the sky
  - Far away from each other
  - Far away from primary flux references
  - In different observing conditions (IQ, atm. transparency)
- Indirect measurement
  - Need instrument model to interpret fluxes
  - Need SN model + instrument model to infer rest frame fluxes



Distances to low-z SNe rely on blue bands (g,r)

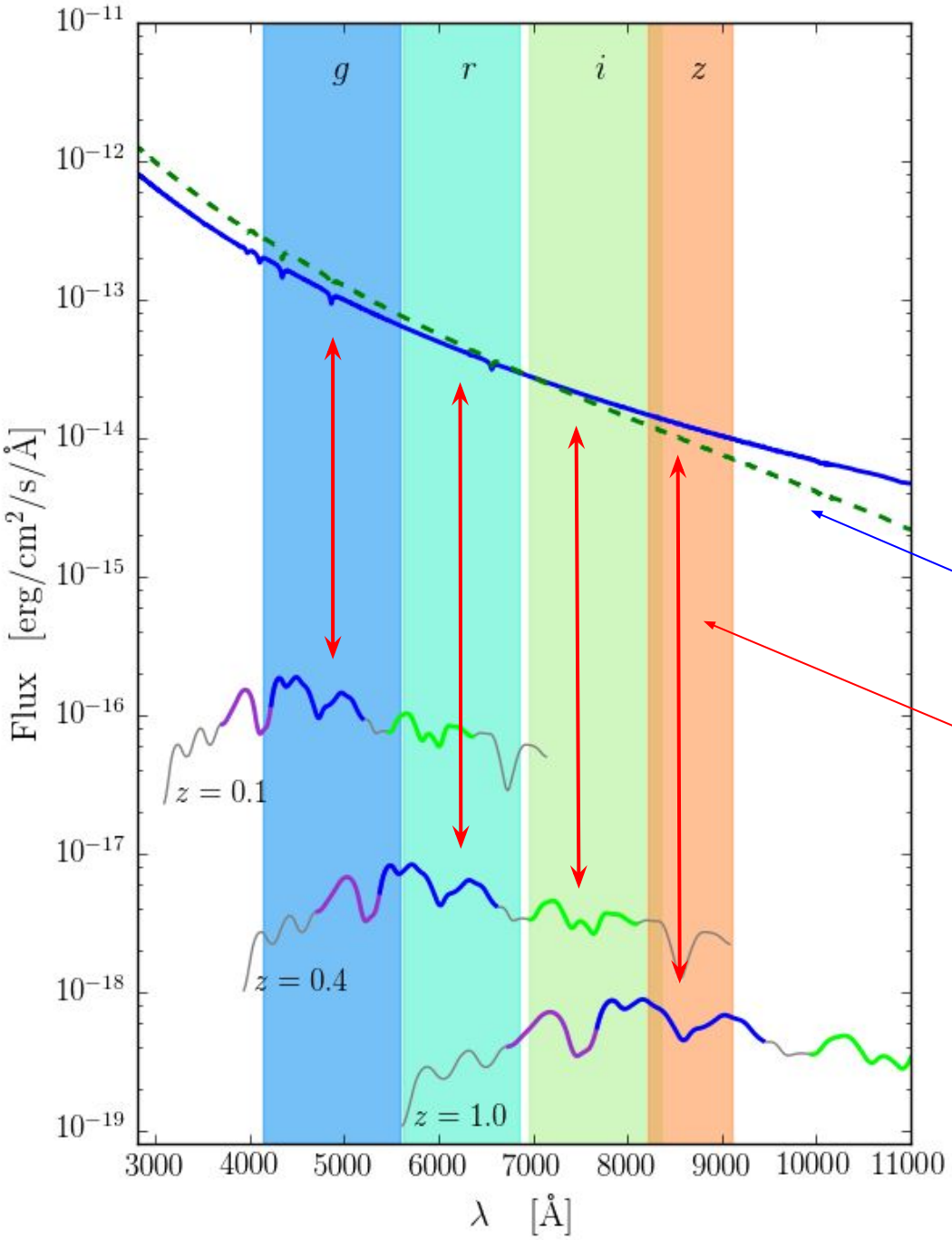
Distances to high-z SNe rely on red band (i,z)

Critical calibration ingredients:

- relative (band-to-band) flux calibration
- positions of filter cut-on/cut-off

Calibration errors affect

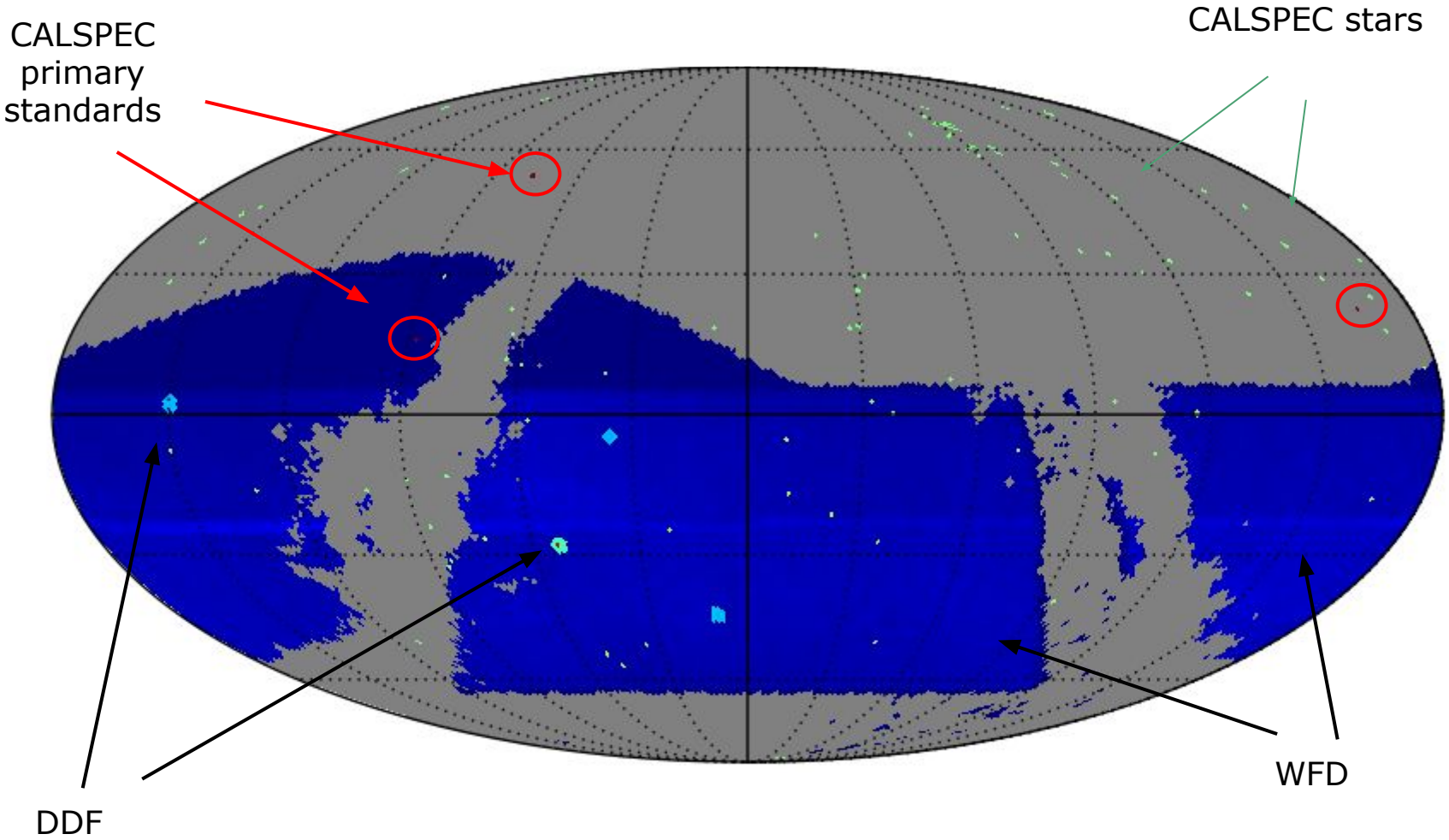
- SN magnitudes
- SN empirical model
- -> SN distances (x2)



- Relative flux calibration
  - Primary flux reference
  - Flux metrology chain

$$\varphi_{\mathrm{SN},b}[\gamma/\mathrm{s}] = \frac{\varphi_{\mathrm{SN},b}[\mathrm{ADU/s}]}{\varphi_{\mathrm{WD},b}[\mathrm{ADU/s}]} \times \varphi_{\mathrm{WD},b}[\gamma/\mathrm{s}]$$

Survey uniformity



Instrument model & SN model

SN fluxes interpreted as:

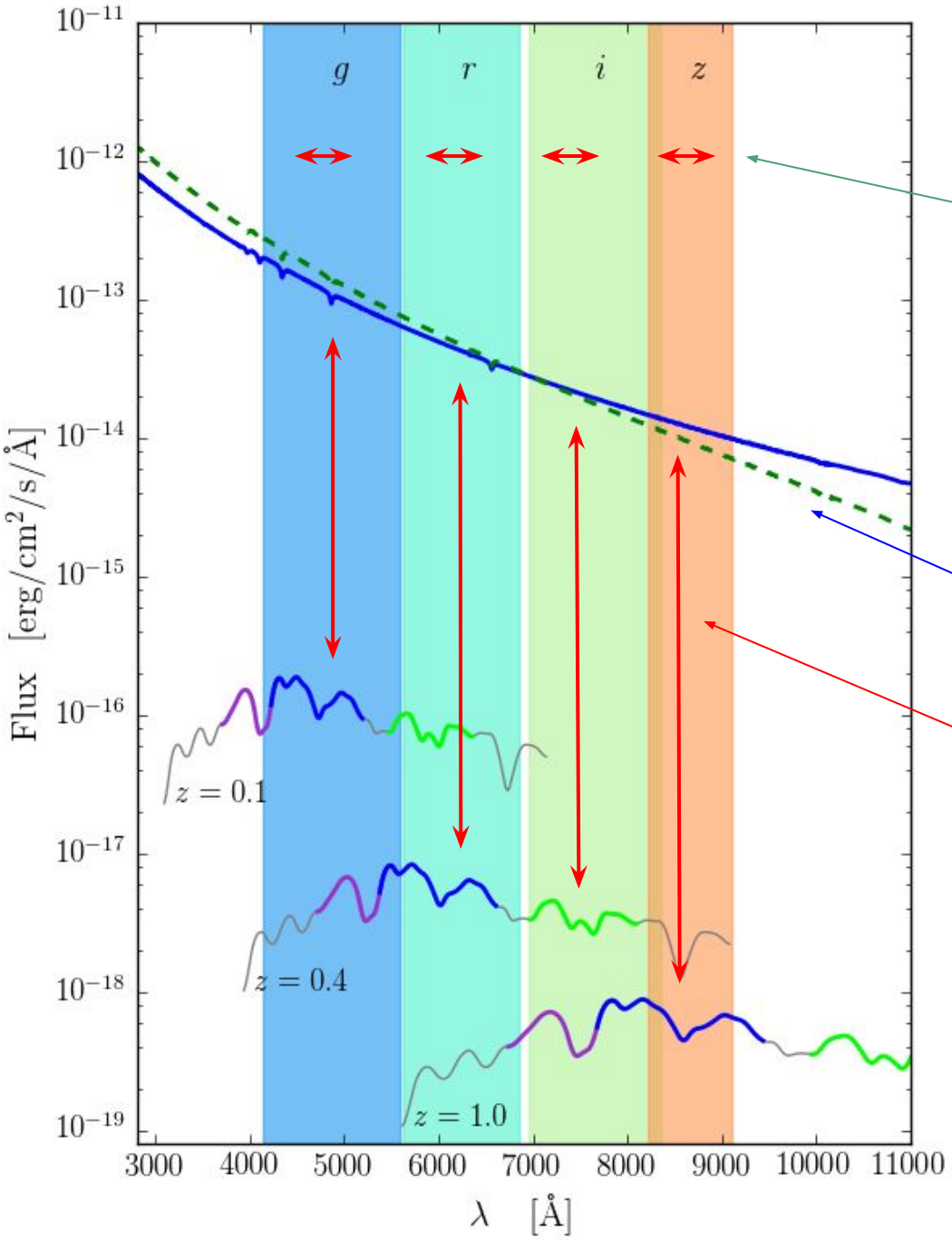
$$\phi \propto \int S\left(\frac{\lambda}{1+z}, p|\theta_{SN}\right) T(\lambda) \frac{\lambda}{hc} d\lambda$$

- Spectrophotometric model (SALT2, SALT3, SNEMO…)
- Trained from real data
- **Carries calibration uncertainties !**

- Instrument transmission
- Shape measured (bench / in-situ)
- Throughput at a given time btained from star observations

Constraints on SN models:

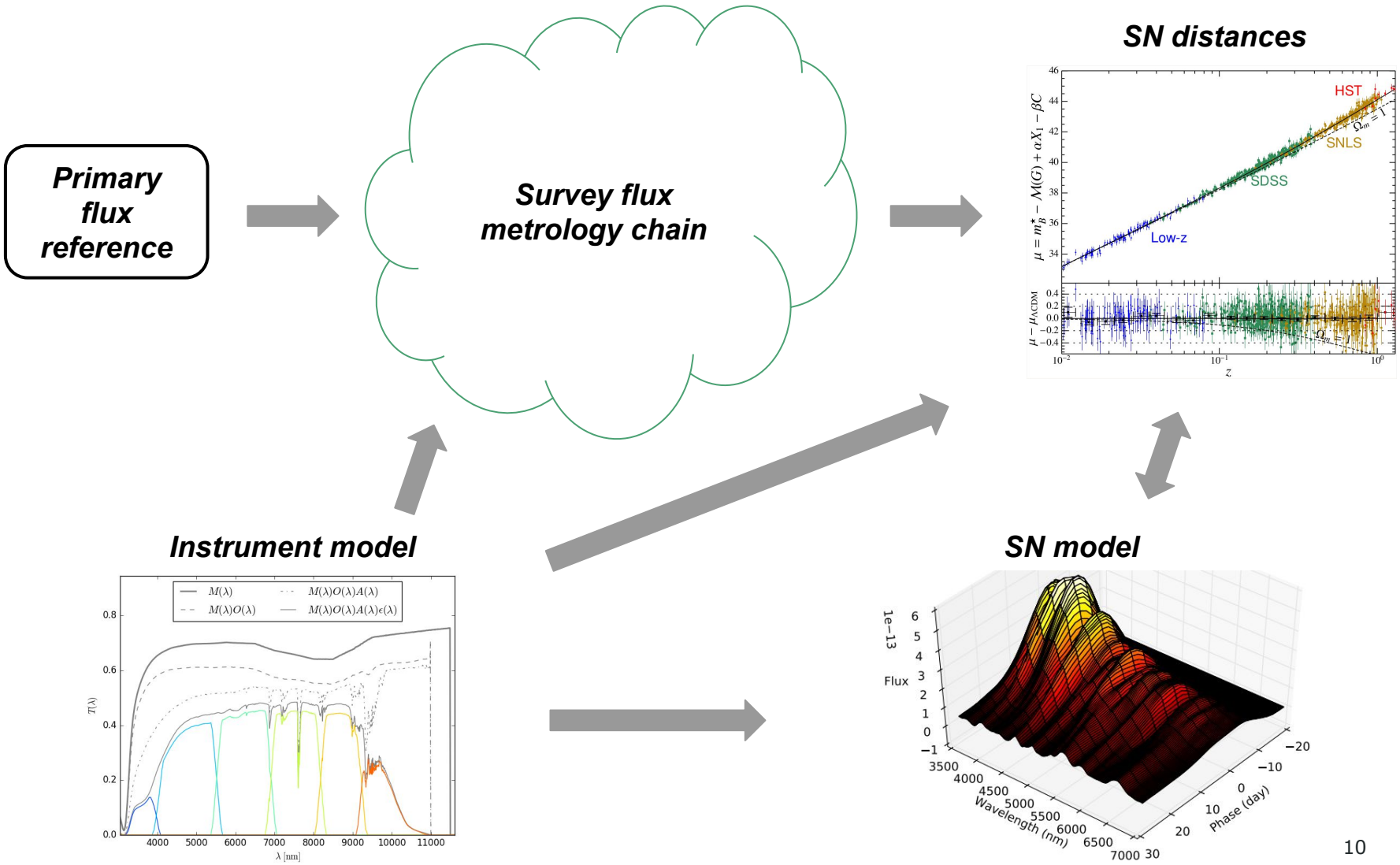
- Need a way to propagate calibration uncertainties
- Should be trained primarily on the cosmo sample (to benefit from its calibration)



- Filter metrology
  - On bench
  - In situ (e.g. with stable monochromatic light source)
- Relative flux calibration
  - Primary flux reference
  - Flux metrology chain

$$\varphi_{\mathrm{SN},b}[\gamma/\mathrm{s}] = \frac{\varphi_{\mathrm{SN},b}[\mathrm{ADU/s}]}{\varphi_{\mathrm{WD},b}[\mathrm{ADU/s}]} \times \varphi_{\mathrm{WD},b}[\gamma/\mathrm{s}]$$

Calibration ingredients



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(See also DESC SRD
(Mandelbaum, Scolnic, Hlozek)

Calibration requirements

- For a given dataset, what is the impact of calibration on the cosmological parameters (e.g. the DETF FoM)
- To answer this question, need to build a fast emulator of the SN analysis, including the training

Calibration parameters

$$m_b = 2.5\log_{10}(1+z) + \mu(z, \theta_{\rm cosmo}) + M_X + P\left(\frac{\bar{\lambda}_b + \delta\lambda_b}{1+z}\right) + cQ\left(\frac{\bar{\lambda}_b + \delta\lambda_b}{1+z}\right) + c\beta + zp_b + \delta zp_b$$

measurements

cosmological parameters

SN parameters

"SALT2" 1D surfaces

SN standardization

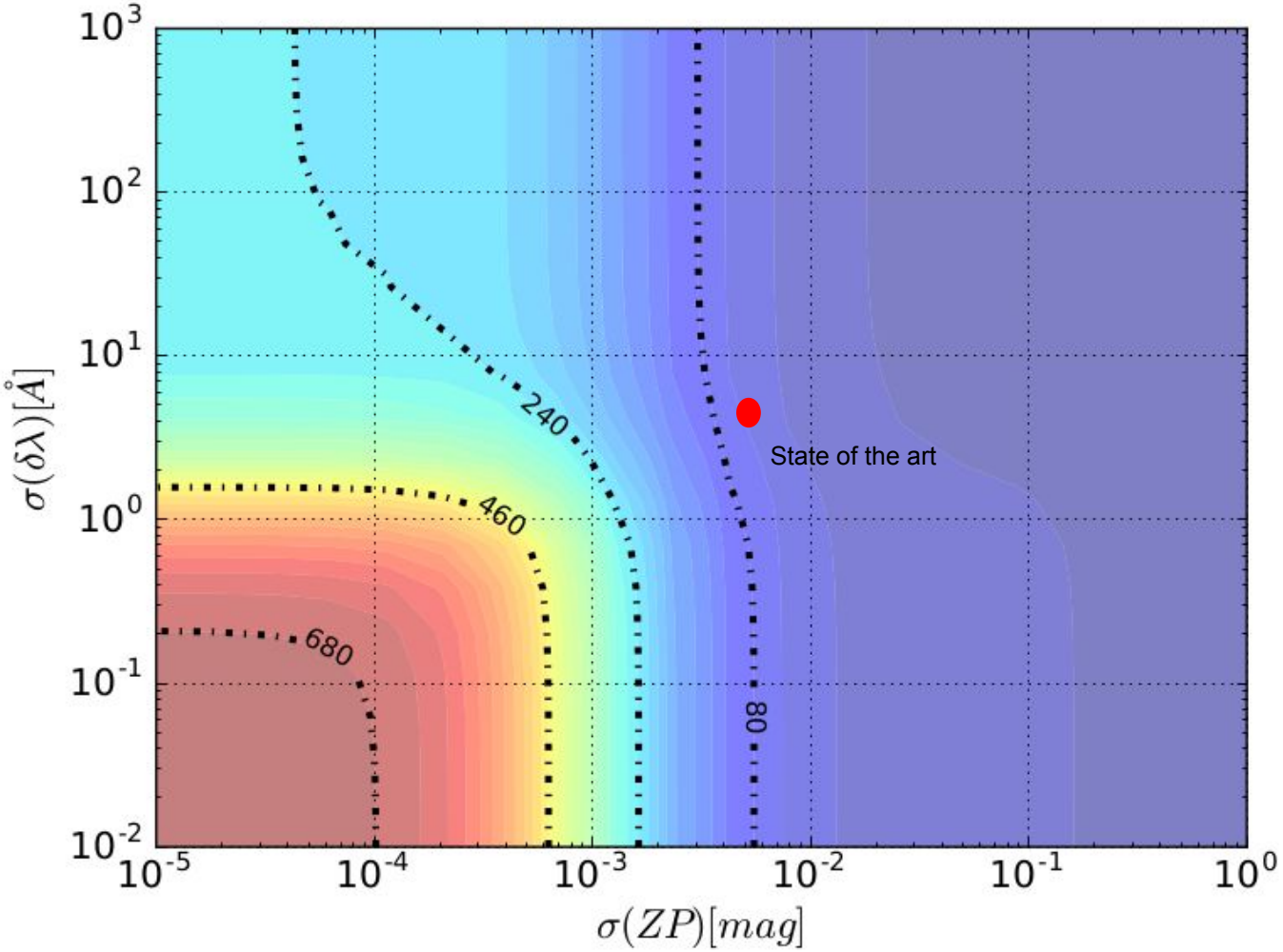
Work led by F. Hazenberg (LPNHE)

Calibration requirements

- Model
  - Compress light curves into amplitudes
  - Reduce SALT2 to 2 polynomials (mean “surface” + color law)
  - Keep color standardization (large penalty associated to beta)
  - Fisher analysis taking all all parameters taken into account simultaneously
  - Marginalize over nuisance parameters and yield a FoM
- ~ 20 minutes to simulate light curves,
- ~ 1 second to obtain the FoM from light curve amplitudes

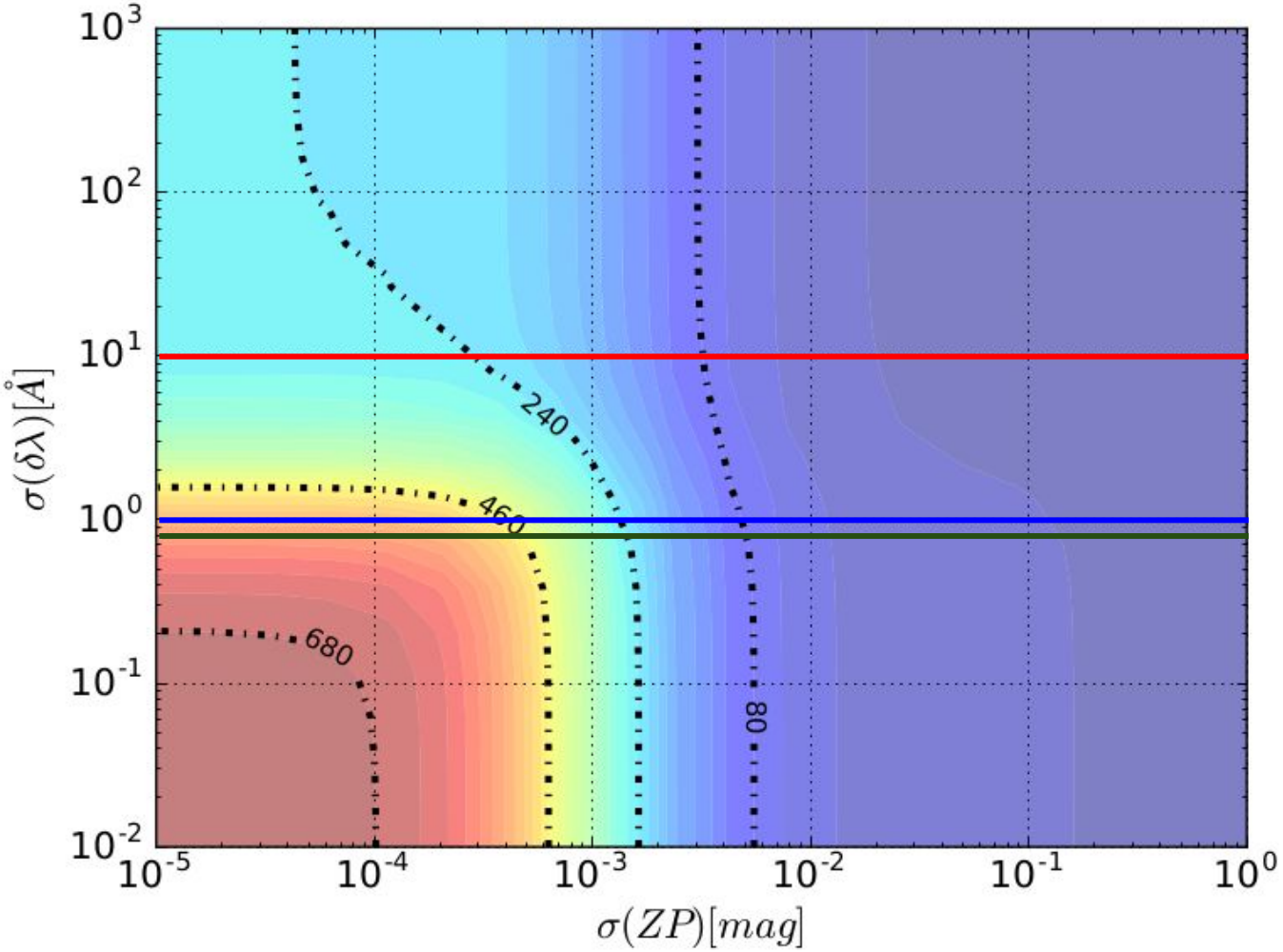
Work led by F. Hazenberg (LPNHE)

Calibration requirements for LSST



20000 SNe from WFD + 15000 from DDF

Calibration requirements for LSST



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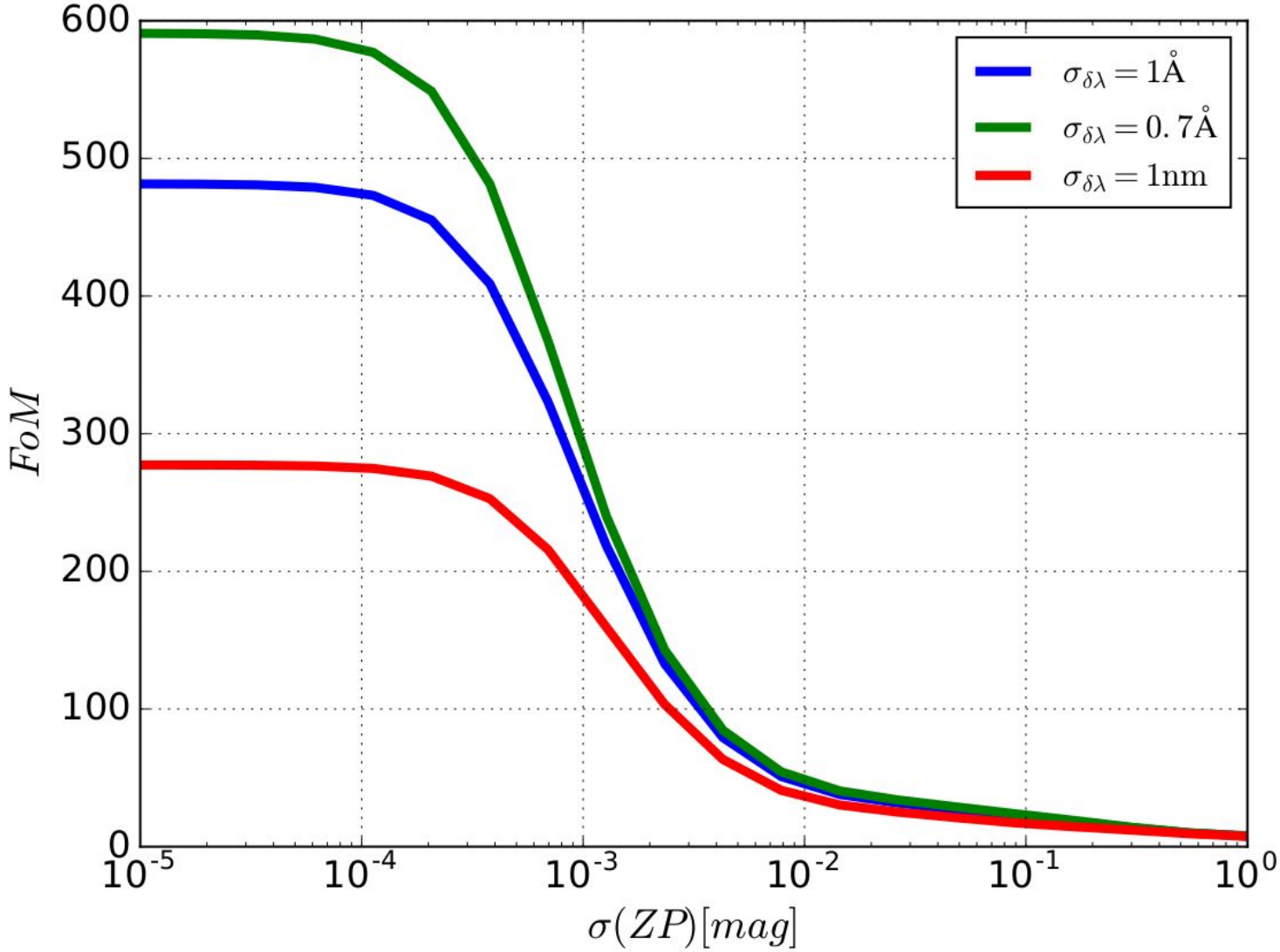

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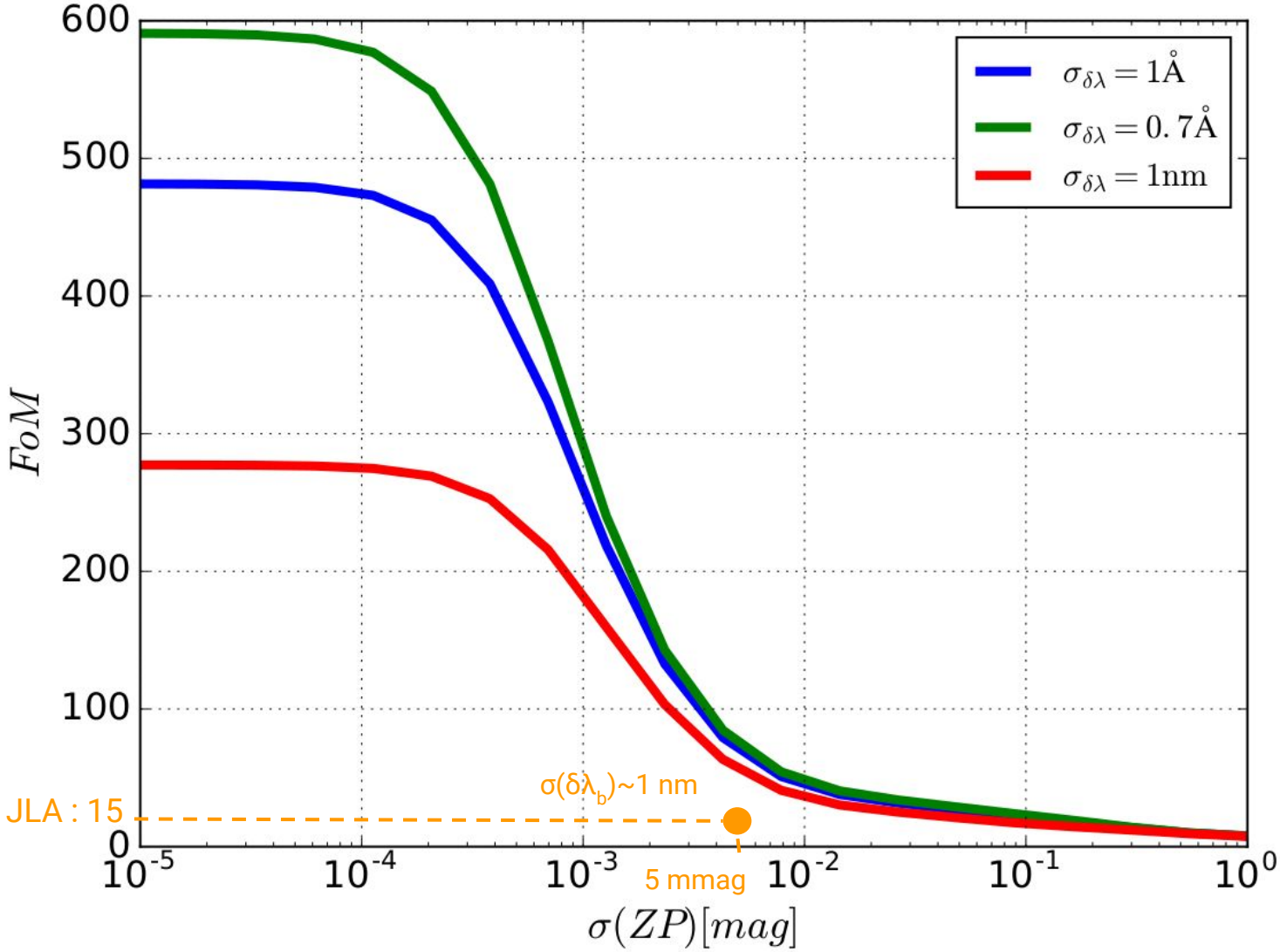
Calibration requirements for LSST



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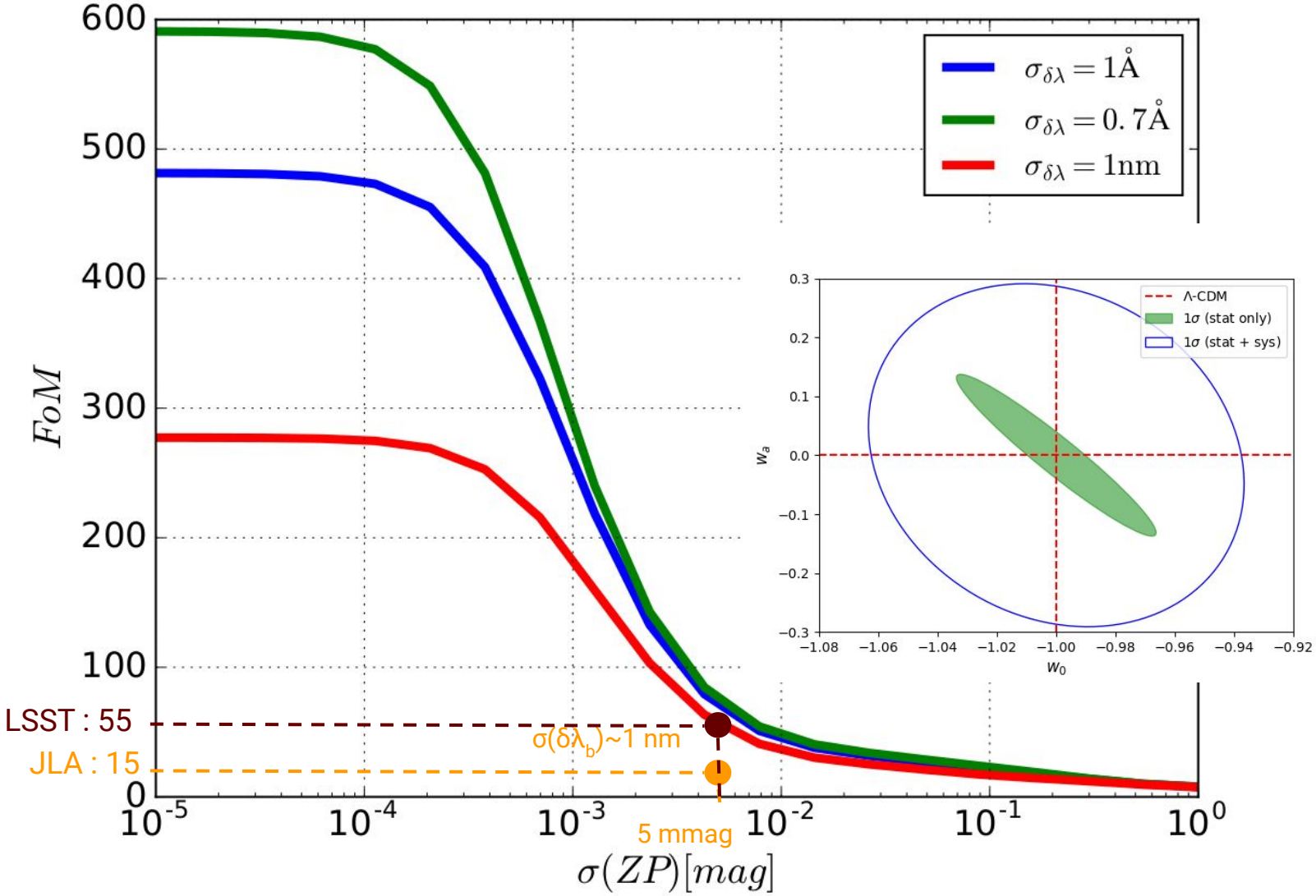

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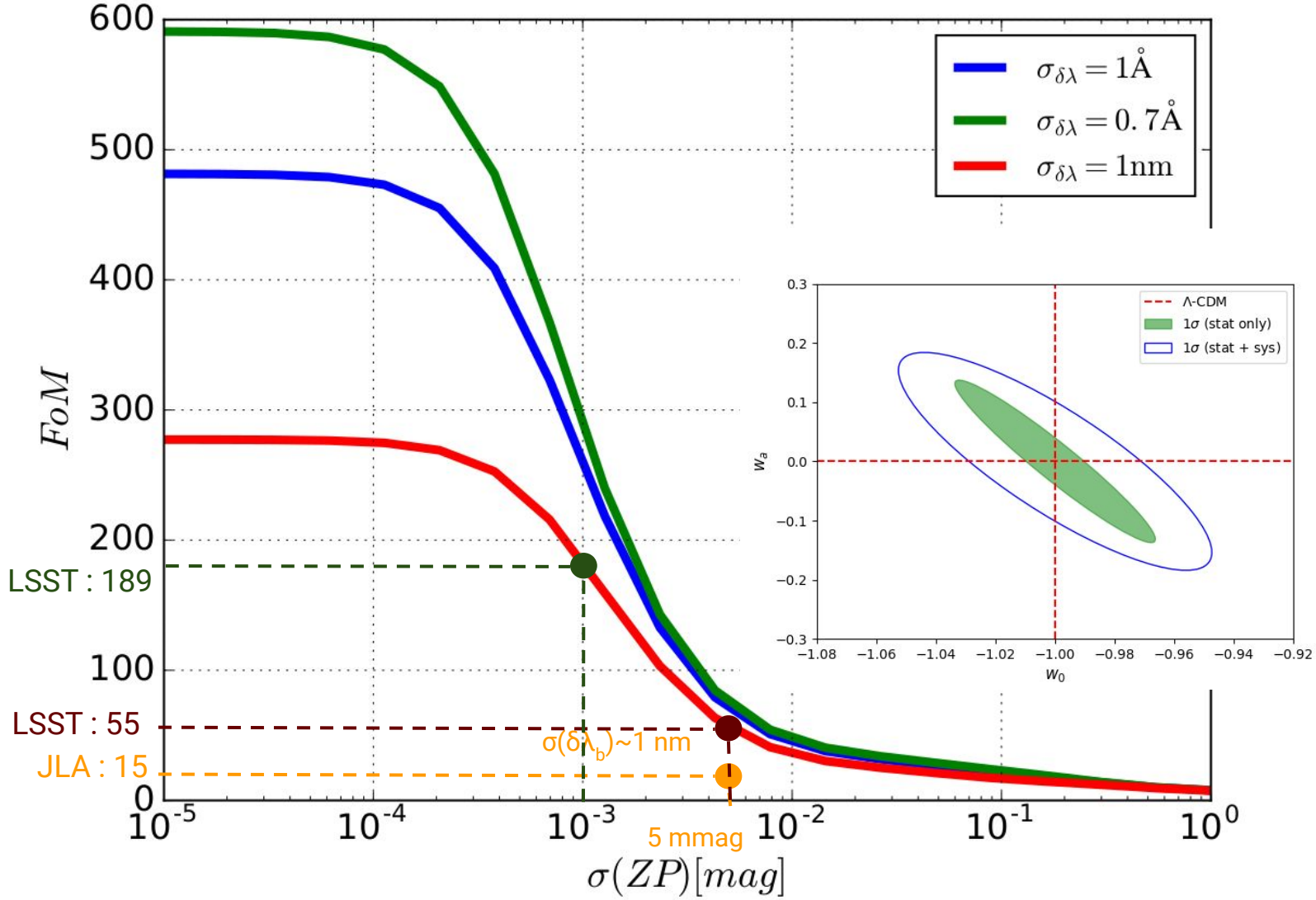
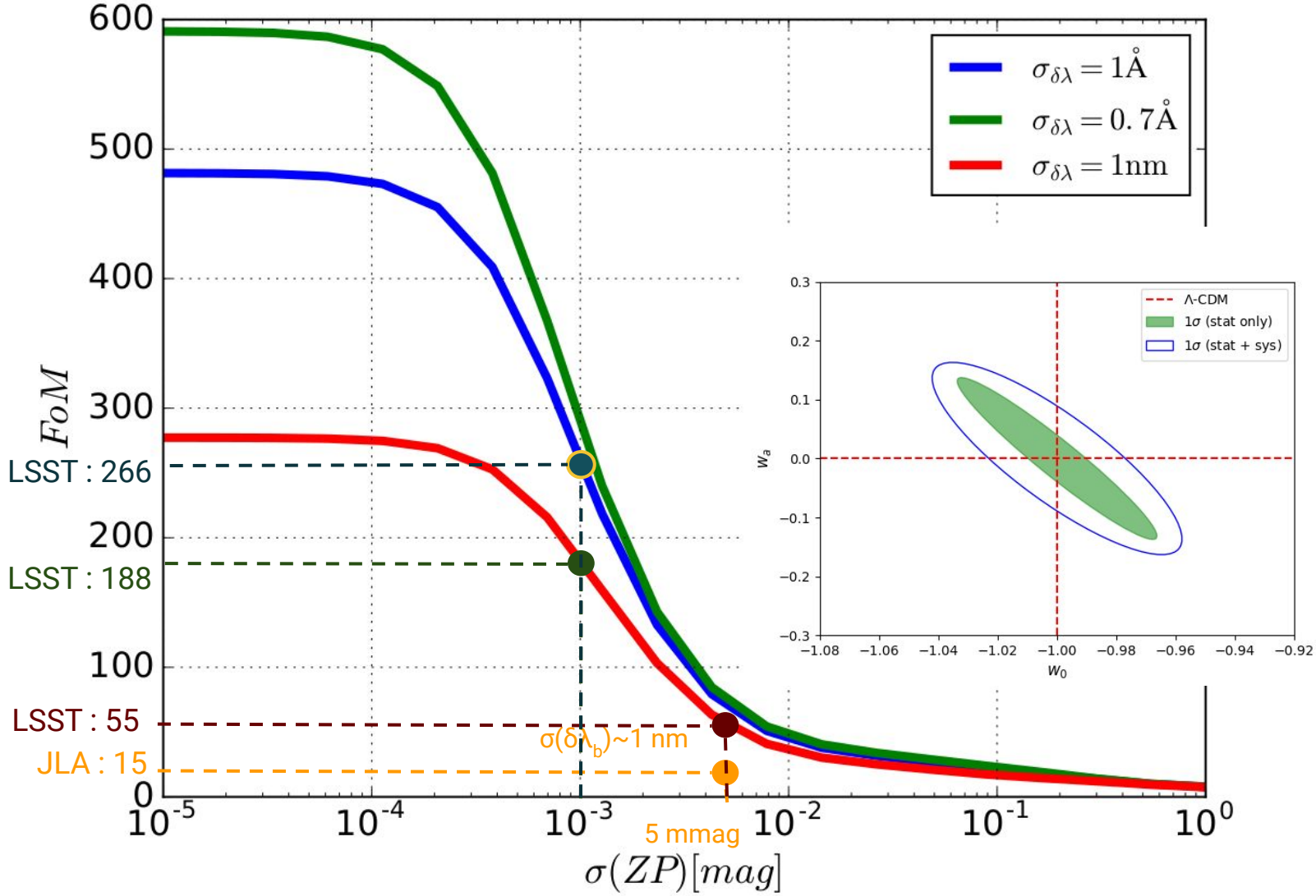


20000 SNe from WFD + 15000 from DDF

F. Hazenberg

Calibration requirements for LSST



20000 SNe from WFD + 15000 from DDF

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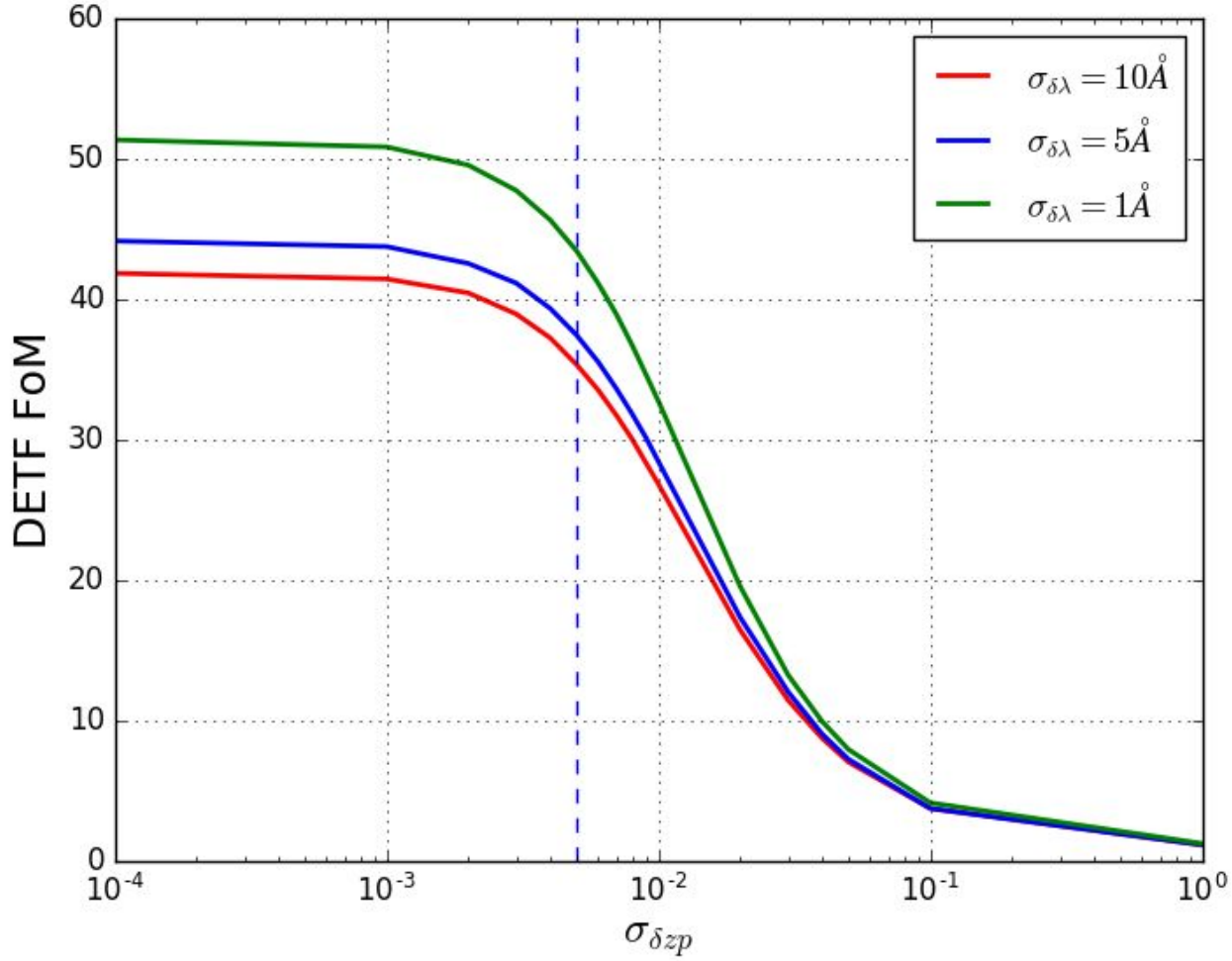
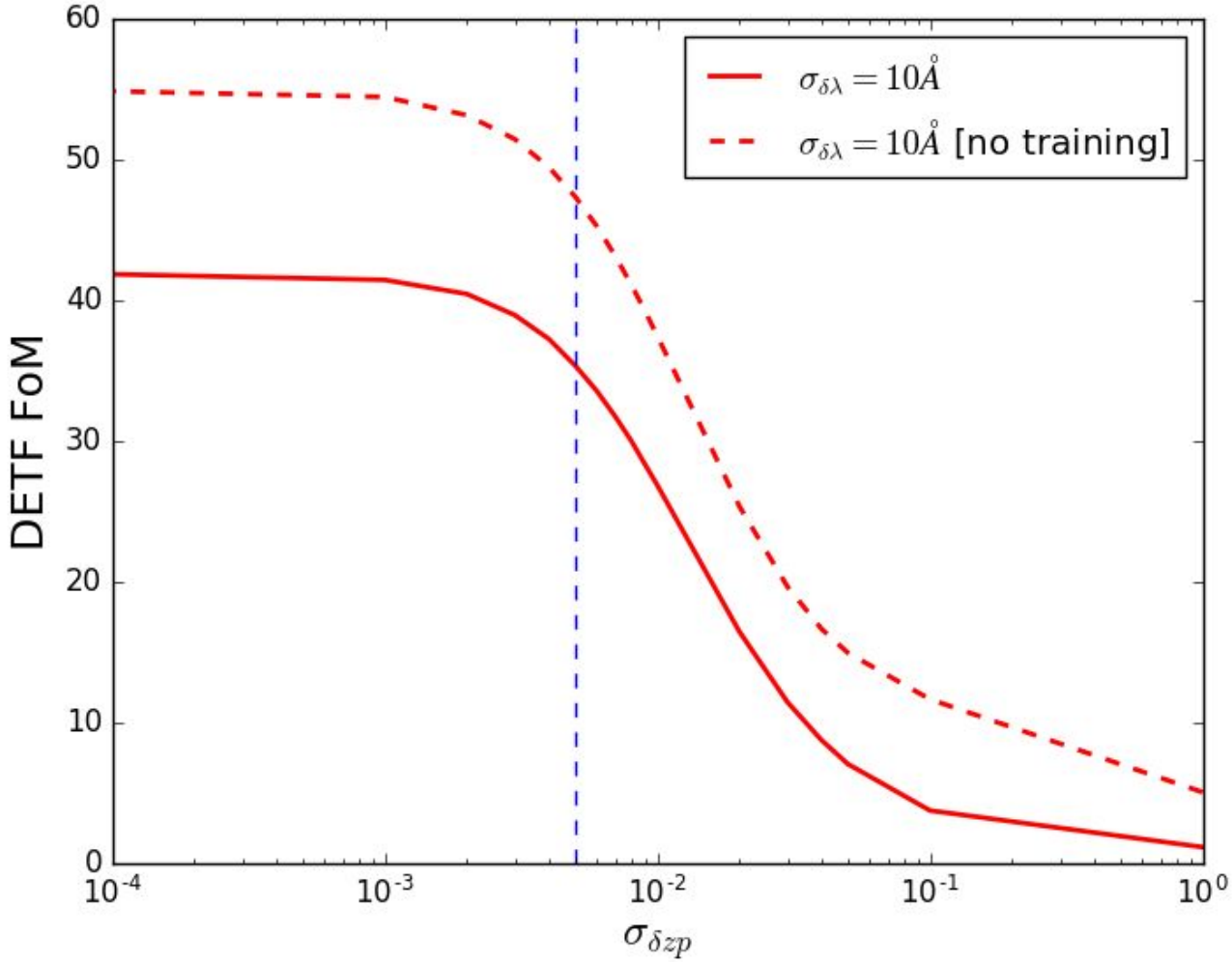
Calibration requirements in ~ 2020 ?



JLA + SSP(2 years) + 800 additional nearby SNe

Impact of training



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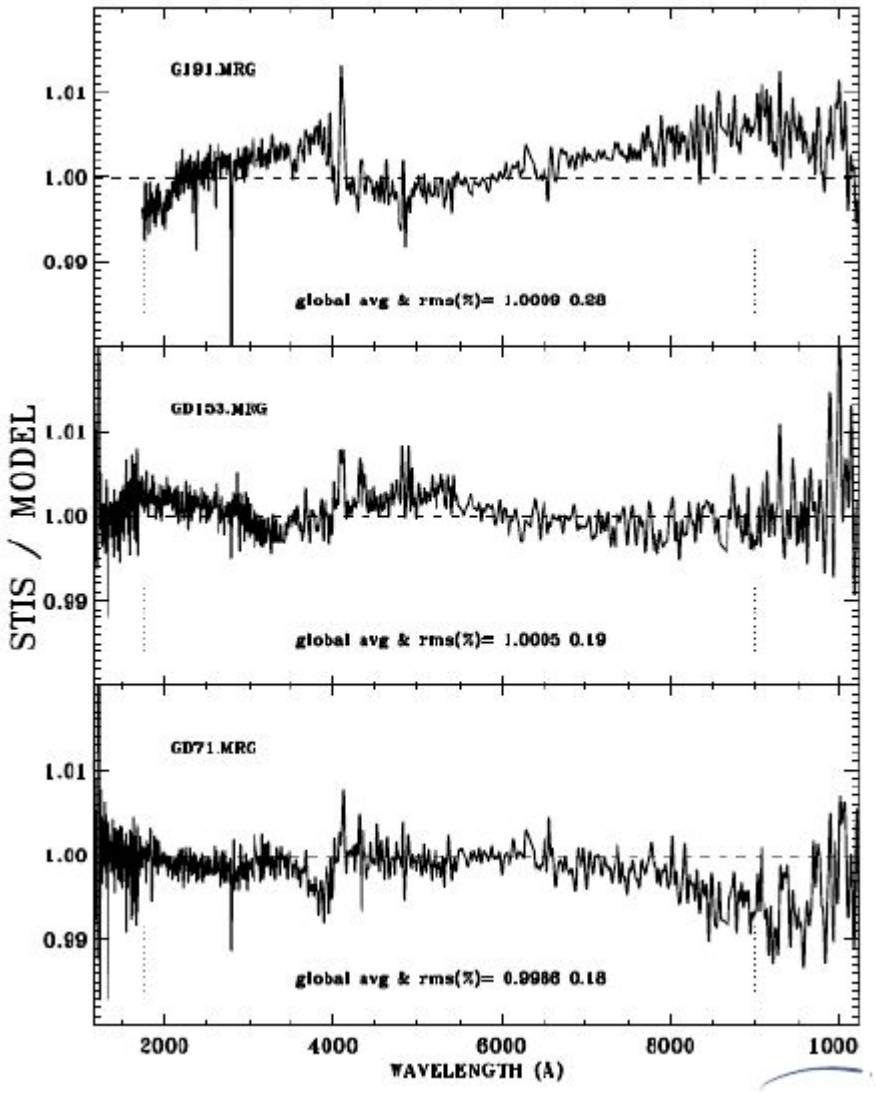
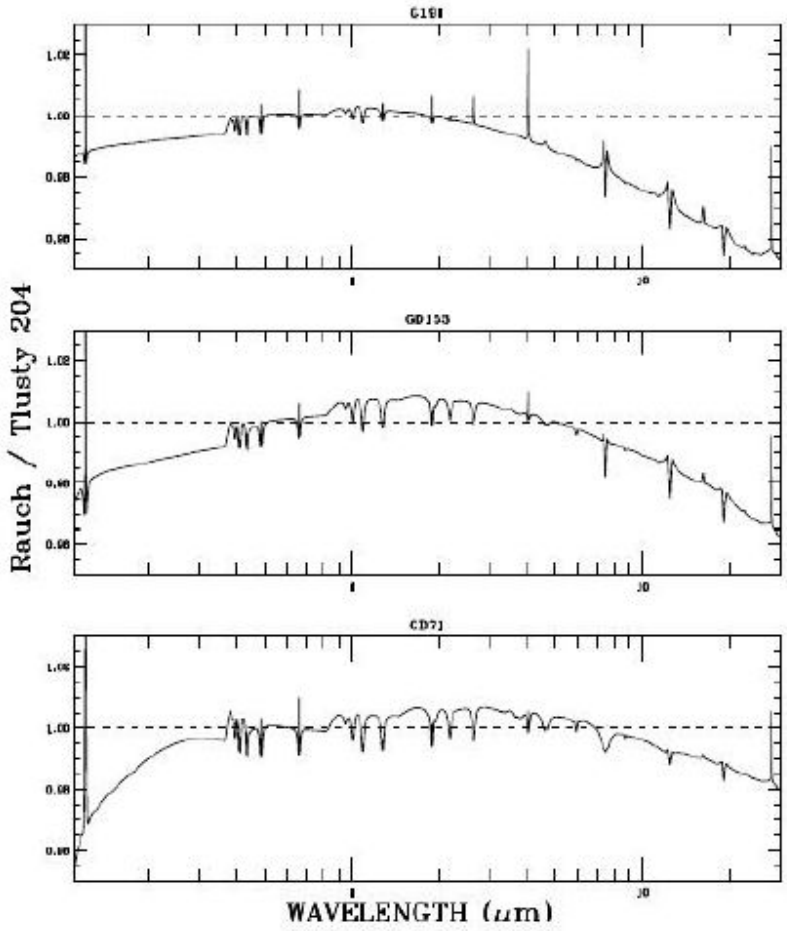
CALSPEC

- Primary flux references based on *DA white dwarf models*
- Bohlin, Gordon, Tremblay, 2014
  - 3 DA WD (G191B2B, GD153, GD71)
  - NLTE atmosphere models from (Rauch et al, 2013)
- The average defines the *HST*/STIS flux calibration
  - Residuals ~ 1% (visible)
- Extended to a larger network with *HST*/STIS



CALSPEC : model uncertainties ?

- 2 models, same physics
  - ~ 4 mmag 400 < λ < 1000 nm
- What about physics unaccounted for ?
  - Metal lines found in high-resolution spectra of G191B2B
  - Lyman / Balmer line problem
  - Convection / turbulence
  - …
- Need for alternate primary references with different systematics



(Bohlin, 2014)

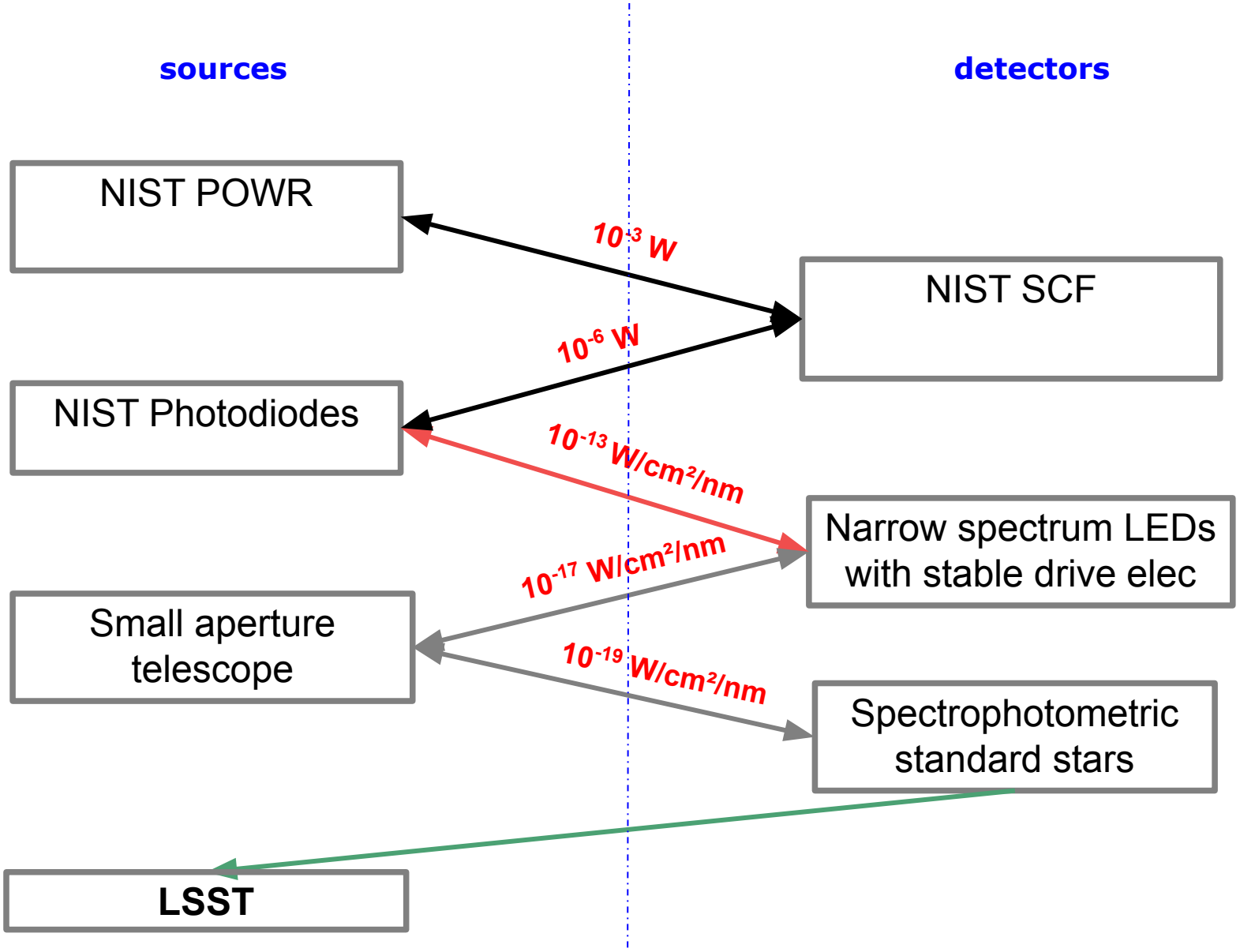
Comparing CALSPEC and NIST

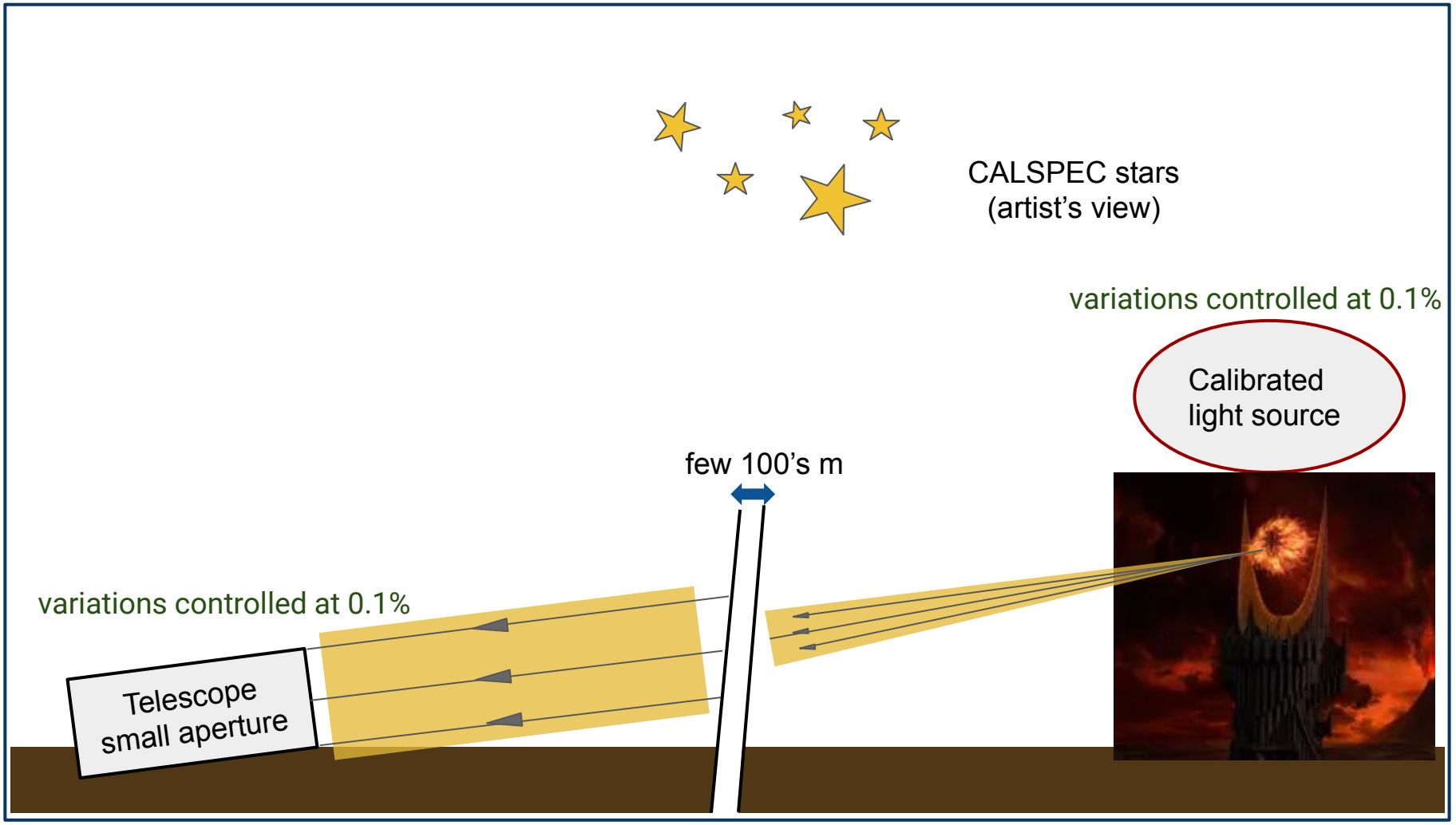
- Uncertainties on WD flux scale (~0.5%, Bohlin 2014)
- However,
  - It is easier, for large survey telescopes, to keep stars as flux references (real point sources, same calibration beam)
  - Producing a good calibration source for a large survey telescope (same beam as science beam) is very difficult
- Strategy
  - Keep using stars as calibration transfer tools
  - Keep CALSPEC as flux references (high quality spectrophotometric standards)
  - **Use a NIST-calibrated artificial source and a dedicated telescope to intercalibrate NIST and CALSPEC**

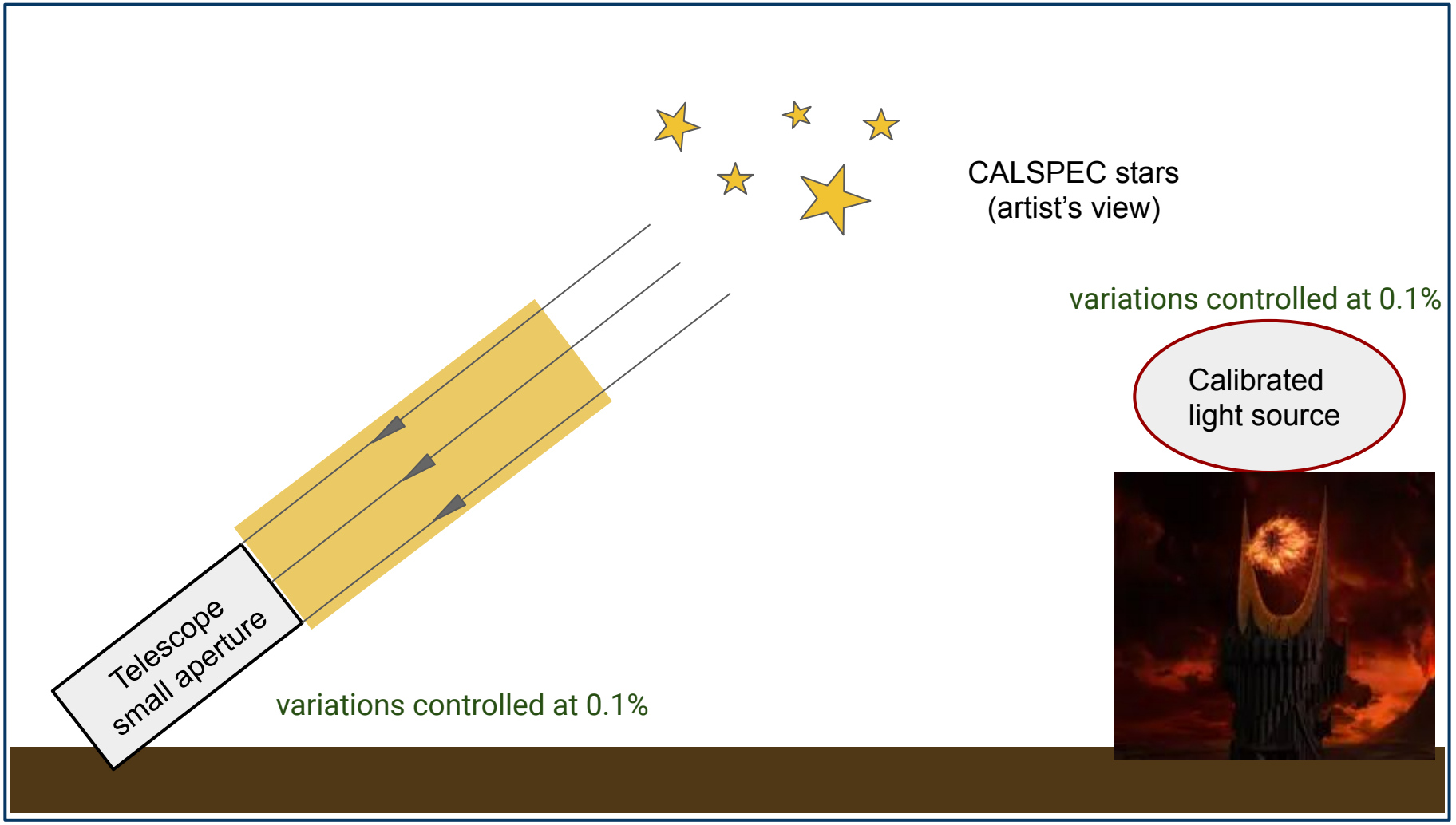
Projects

- First attempts by Stubbs & Tonry
  - e.g. Stubbs et al, 2010 (2010ApJS..191..376S) ~ 5% precision
- NIST stars
  - https://www.nist.gov/programs-projects/nist-stars
  - Use NIST calibrated spectrometer + additional hardware to monitor line of sight
  - Target bright standards (Vega)
- SCALA
  - See talk by G. Aldering (~ 1%)
  - Target all SNfactory calibration stars (include CALSPEC)
- starDICE
  - Use stable LED-based, NIST calibrated artificial source
  - dedicated, small focal length telescope
  - Target mainly CALSPEC stars

New metrology chain




CALSPEC stars
(artist's view)
variations controlled at 0.1%
Calibrated
light source
few 100's m
variations controlled at 0.1%
Telescope
small aperture

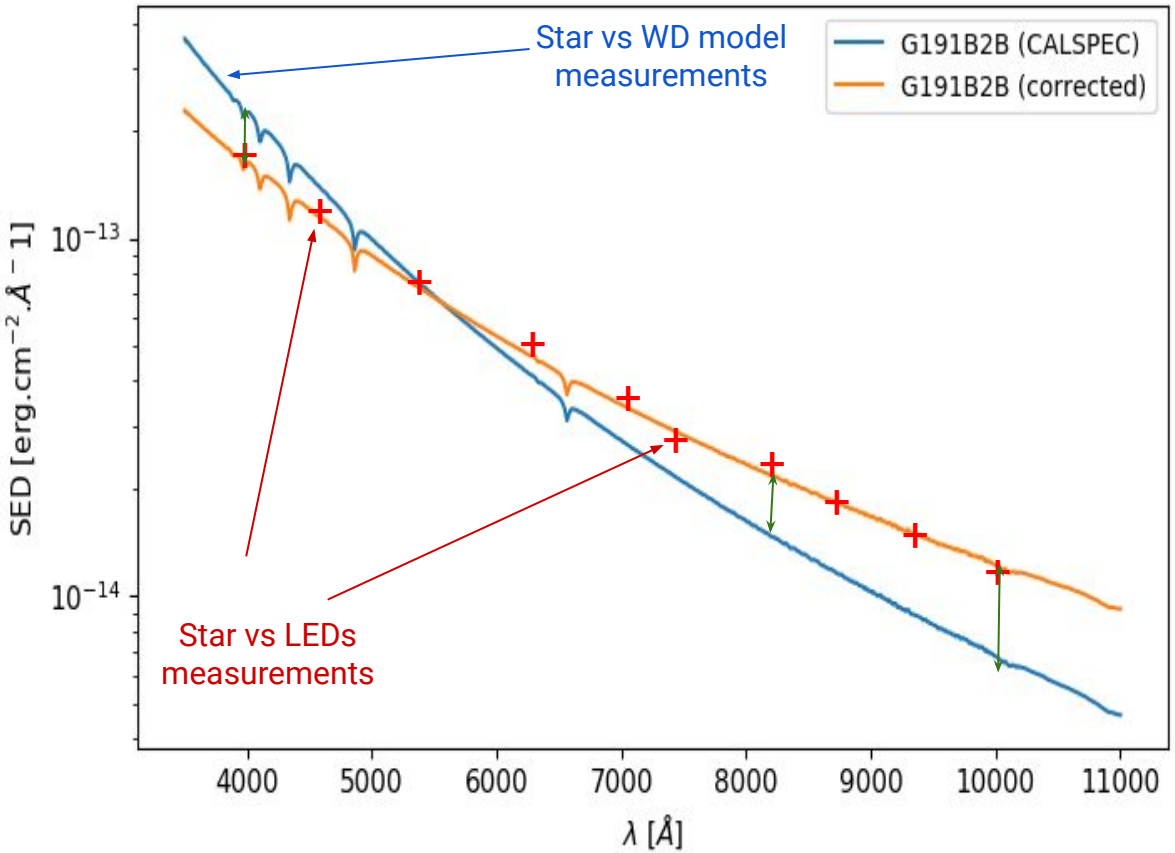

CALSPEC stars
(artist's view)
variations controlled at 0.1%
Calibrated
light source
Telescope
small aperture
variations controlled at 0.1%


LED head
113.4m
Telescope

Source seen by the telescope

Telescope seen by the source

starDICE



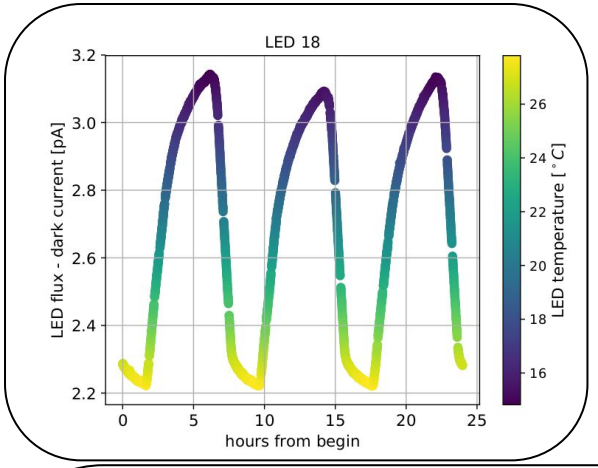
- Output of starDICE
  - a smooth recalibration function κ(λ)
  - Based on photometric measurements of LEDs & CALSPEC

starDICE

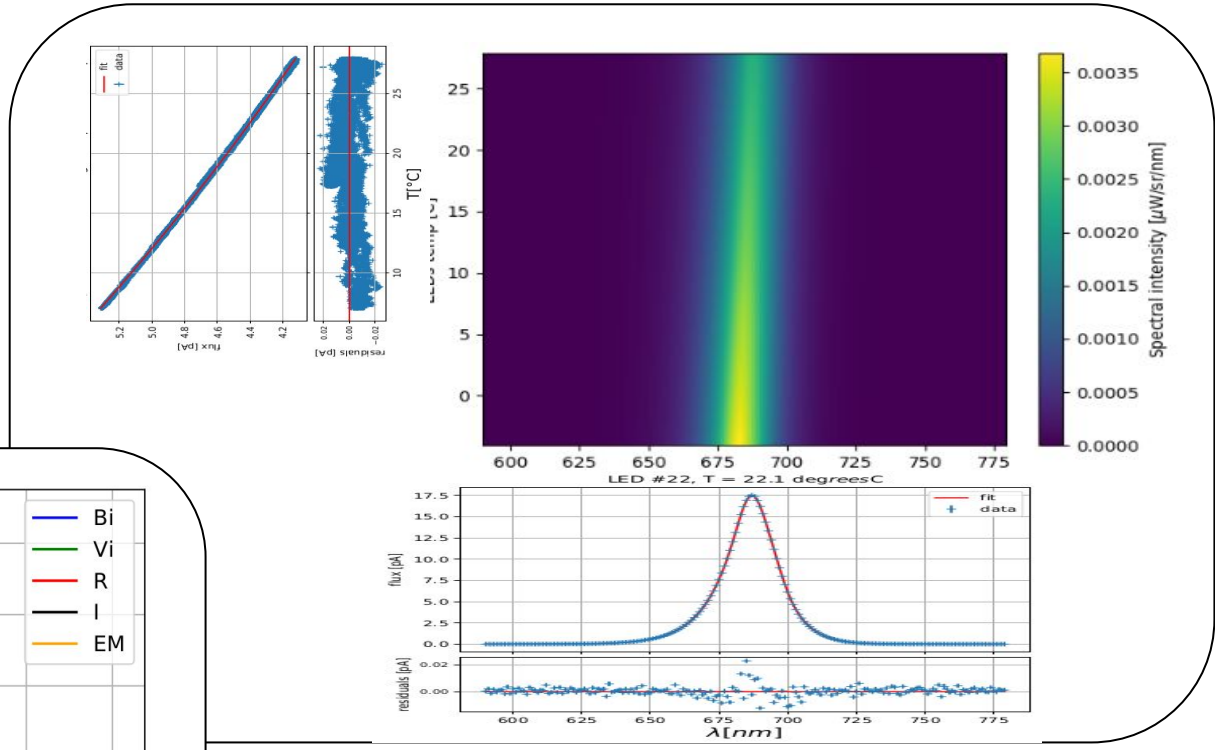
- Observations at Observatoire de Haute-Provence (south of France)
- Phase I completed
  - Bench measurements
    - Spectrophotometric characterization of the source
    - Assessment of source stability
    - Characterization of telescope & camera throughput
  - Measurements on site
    - ~ O(20) nights
    - O(4000) stellar observations (6 different CALSPEC stars)
    - O(3000) observations of LEDs
- Phase II starting
  - New telescope, new fainter source, monitoring hardware
  - O(100) nights

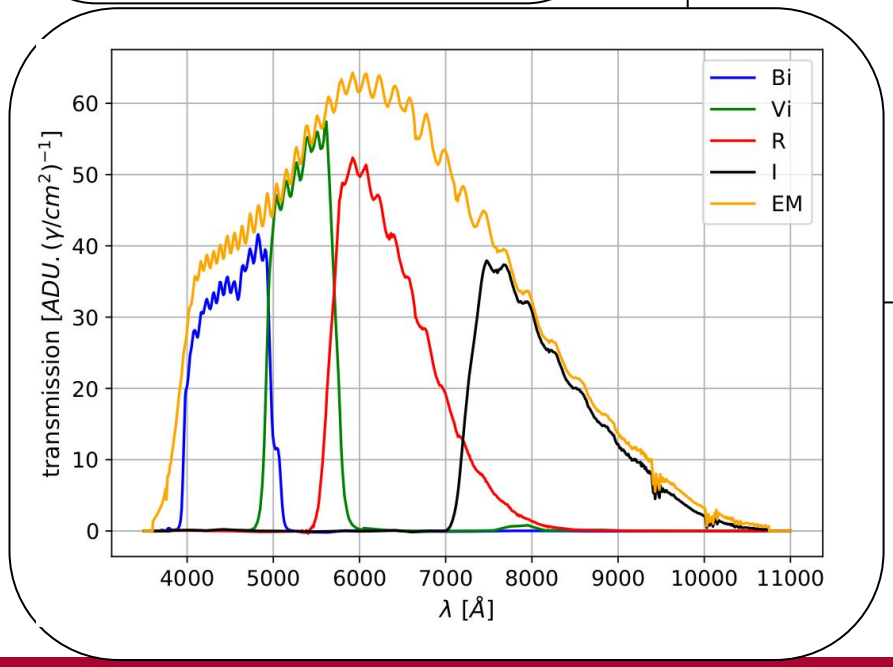
Bench measurements

LED flux vs. temperature



LED spectrophotometric characterization

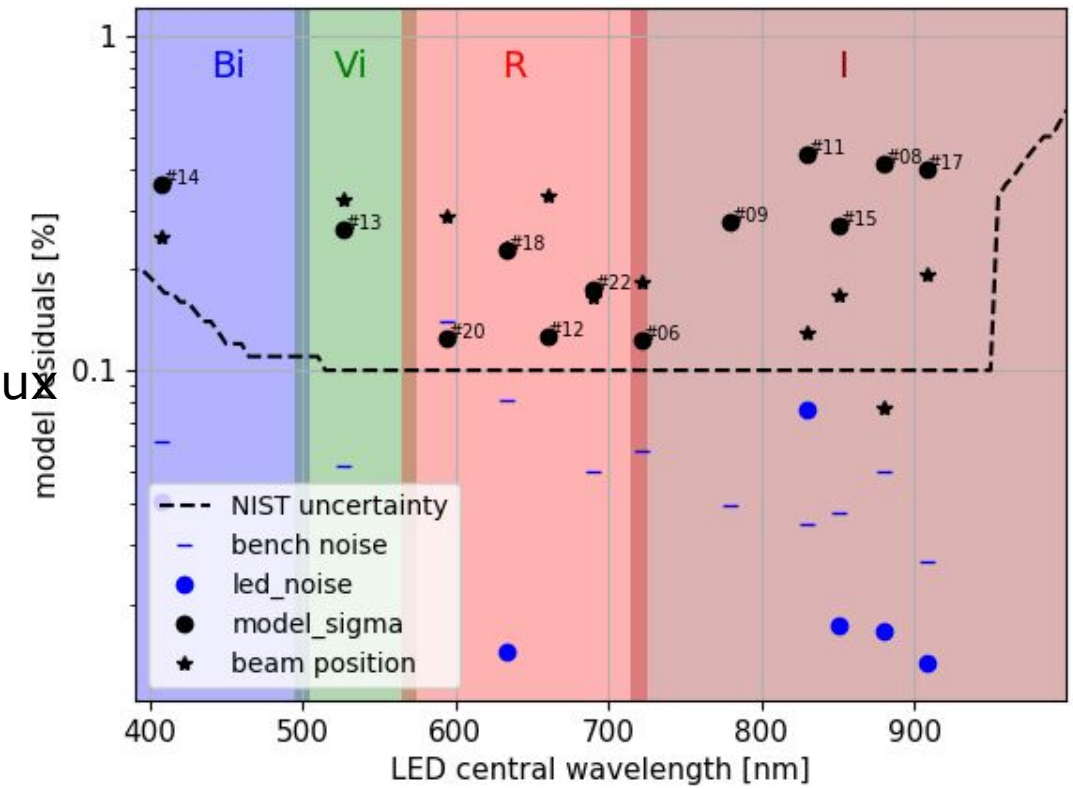




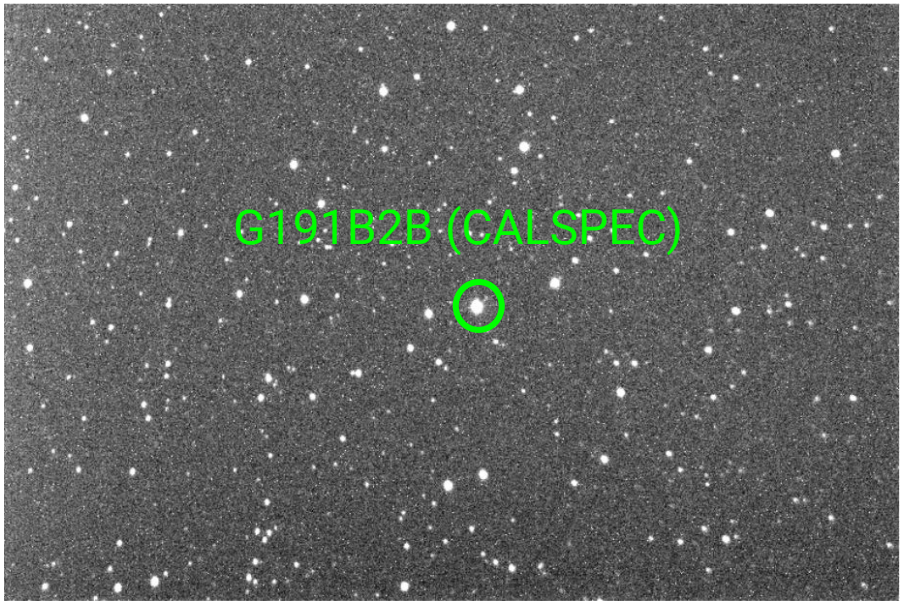
Telescope & detector throughput

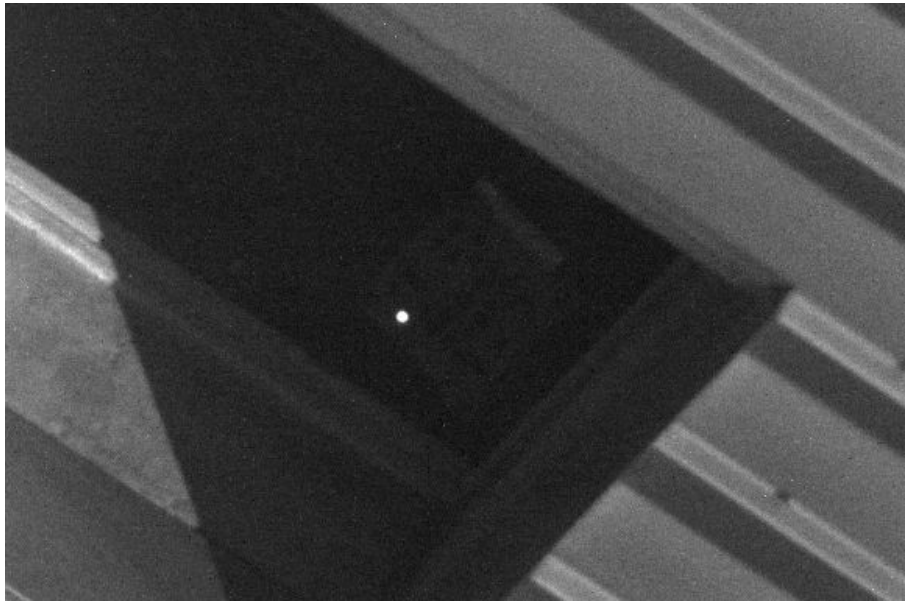
Accuracy of bench measurements

- 12 LEDs with S(λ,T)
- Bench noise and LED noise lower than 0.1%
- Model uncertainty < 0.5%
- Still ongoing
    - LED spectra at low flux

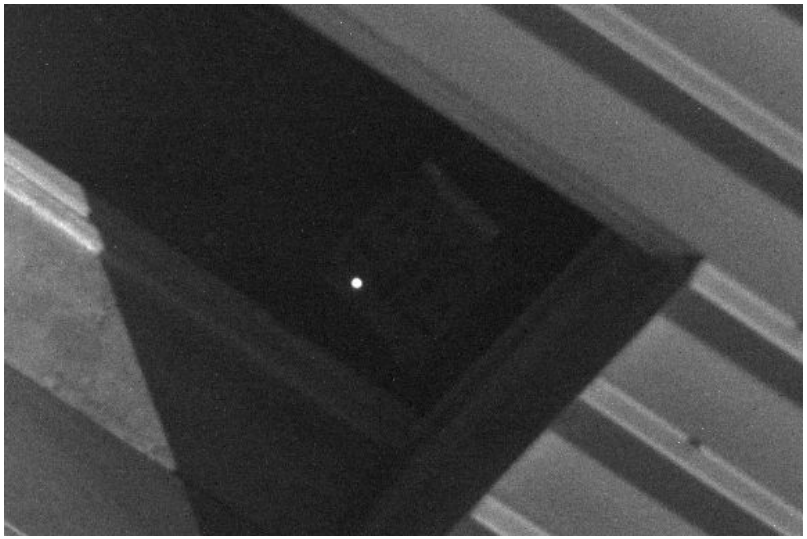


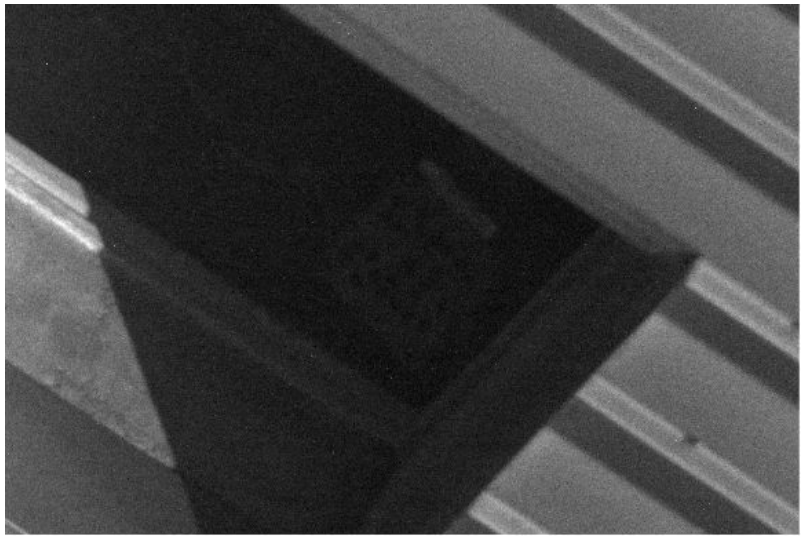
Data taking

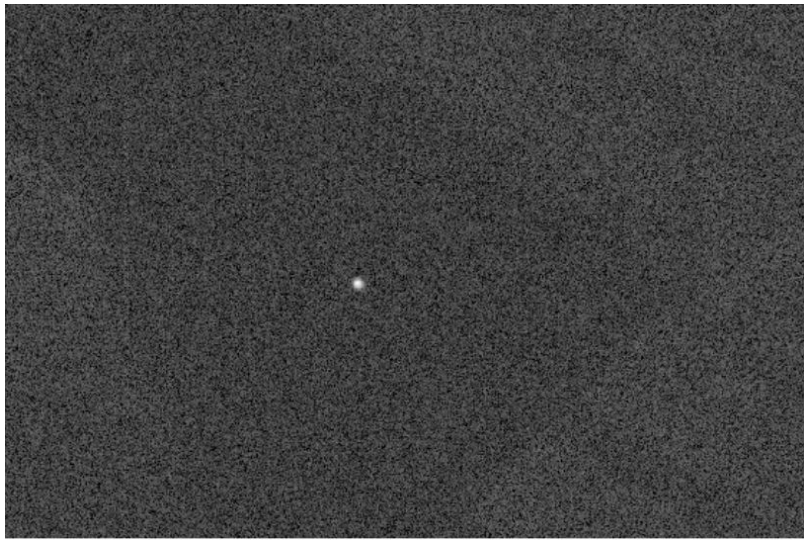


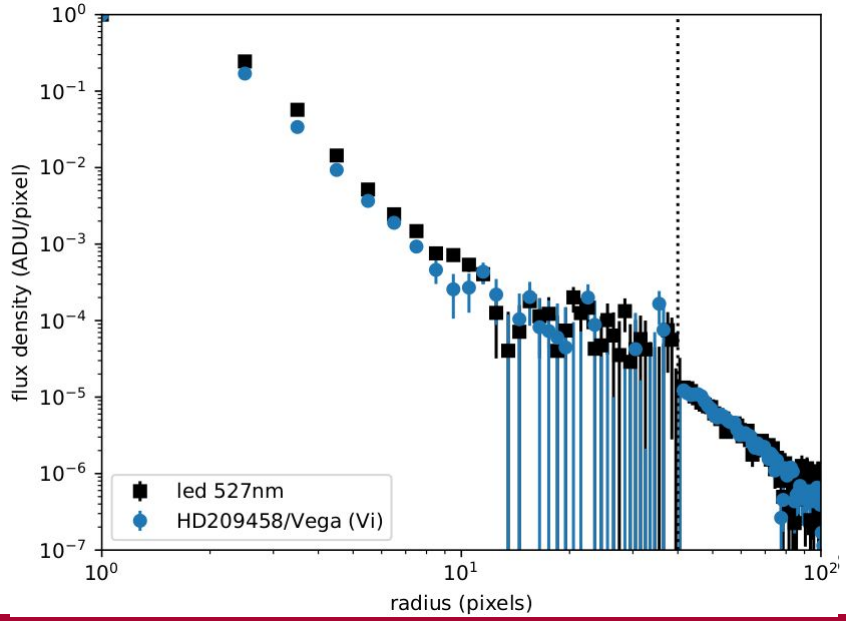


LED imaging









F. Hazenberg

Uncertainties

- Low current LED spectra (5.7%)
- Gray atmospheric variations (1.7%)
- Atmosphere models (1.5%)
- LED temperature dependent flux (0.4%)
- Flux solid angle (0.4%)

- New spectroscopic bench
- Cloud monitoring
- OHP monitoring + models
- New standardization technique (LED rev voltage monitoring)
- New LED maps + laser alignment

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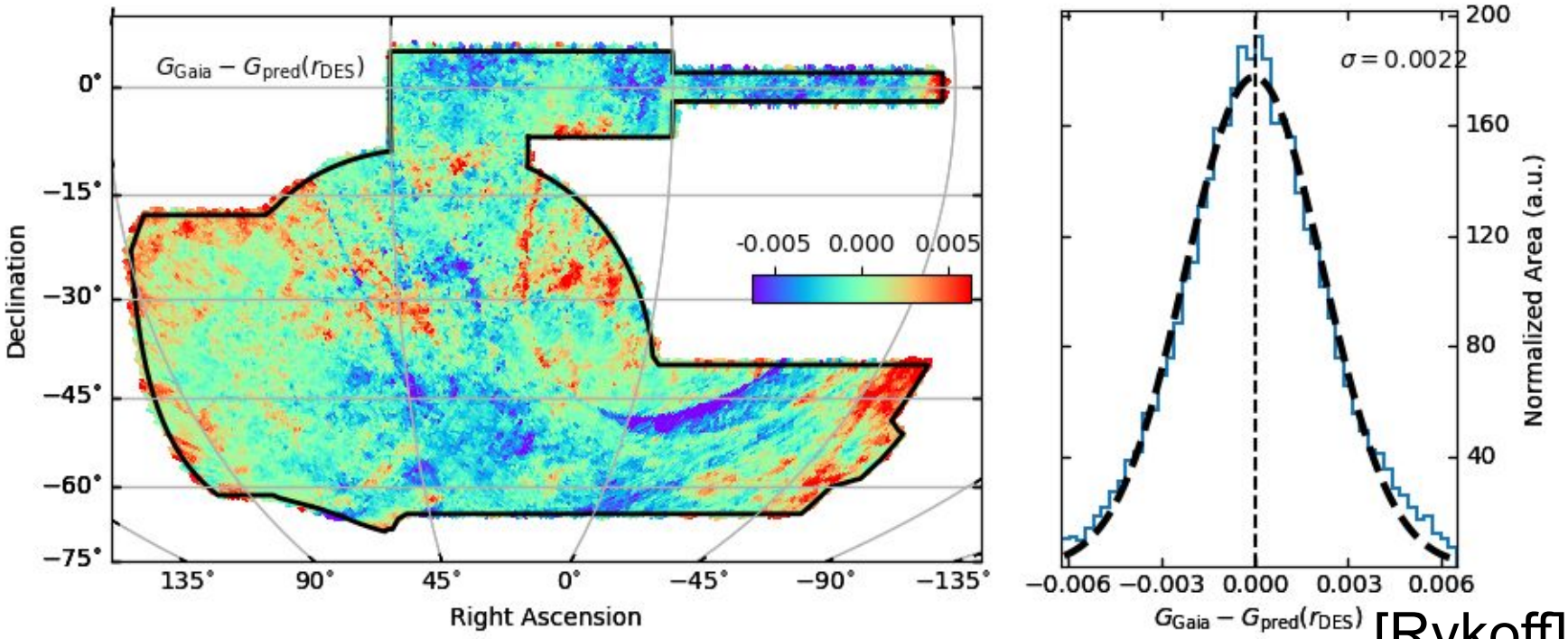
Uniformity: DES and Gaia DR2

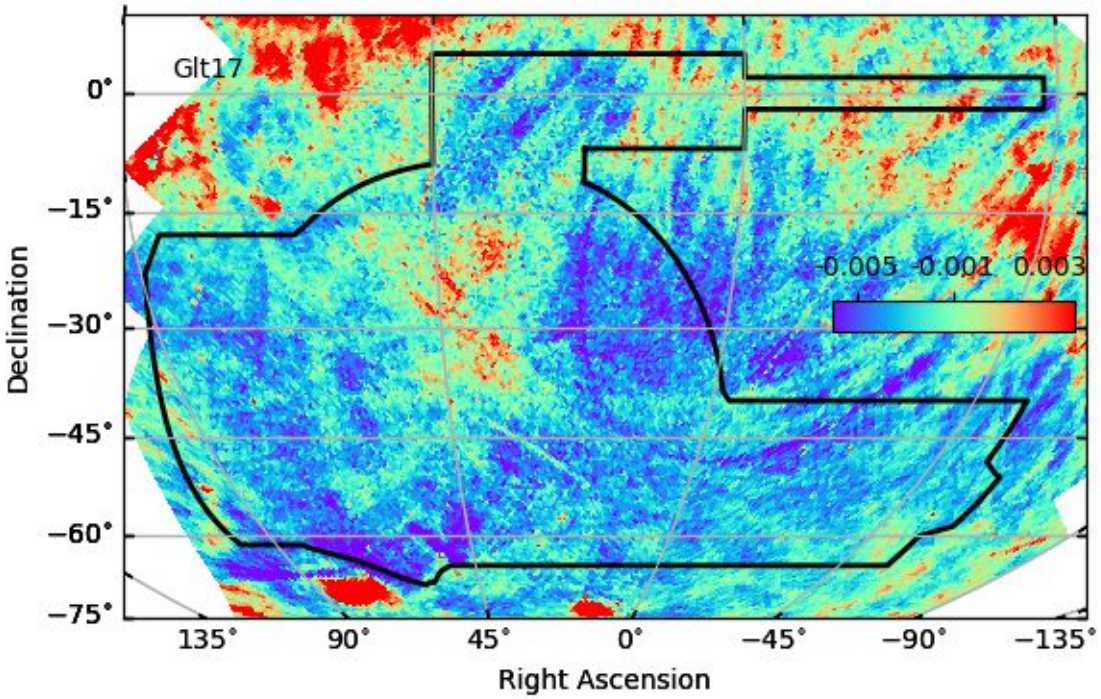
- Test uniformity of DES r-band with Gaia DR2 G-band
- 2.2 mmag uniformity at low Galactic latitude
  - MW Galaxy contamination because Gaia G-band is very broad, making comparison strongly dependent on SED

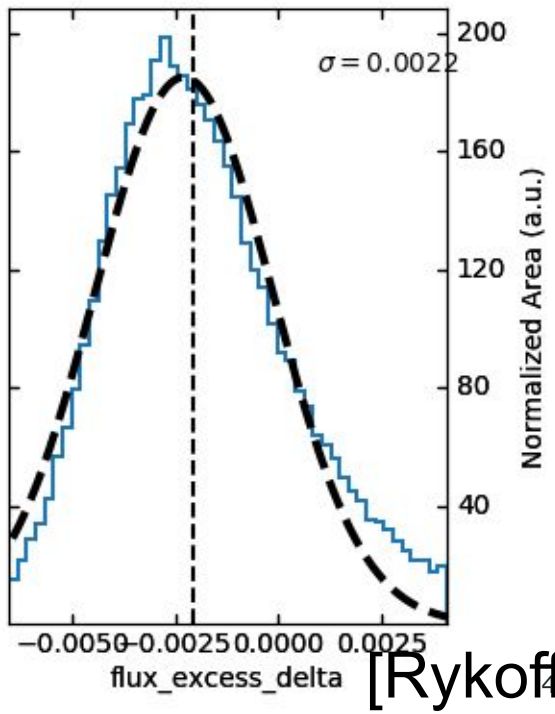


[Rykoff]

Uniformity: Gaia as a Reference

- Testing internal Gaia uniformity (Blue channel "BP"; red channel "RP"; broad "G" band)
- Map Gaia "flux excess" == (f_BP + f_RP) / f_G
- To be able to use Gaia for mmag precision will require more work
- Additional challenge of using spectrophotometry





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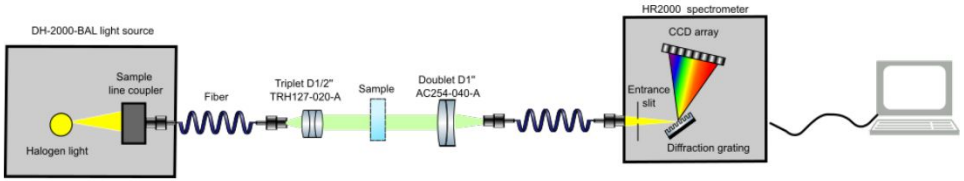
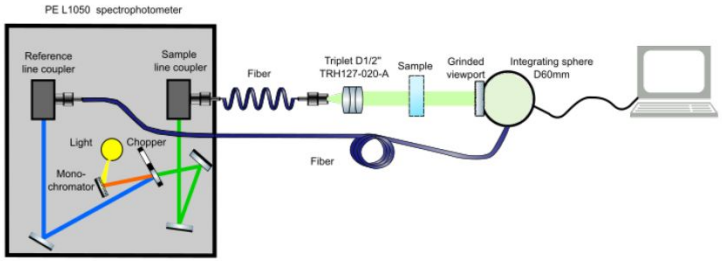
Re-characterization of the MegaCam filters

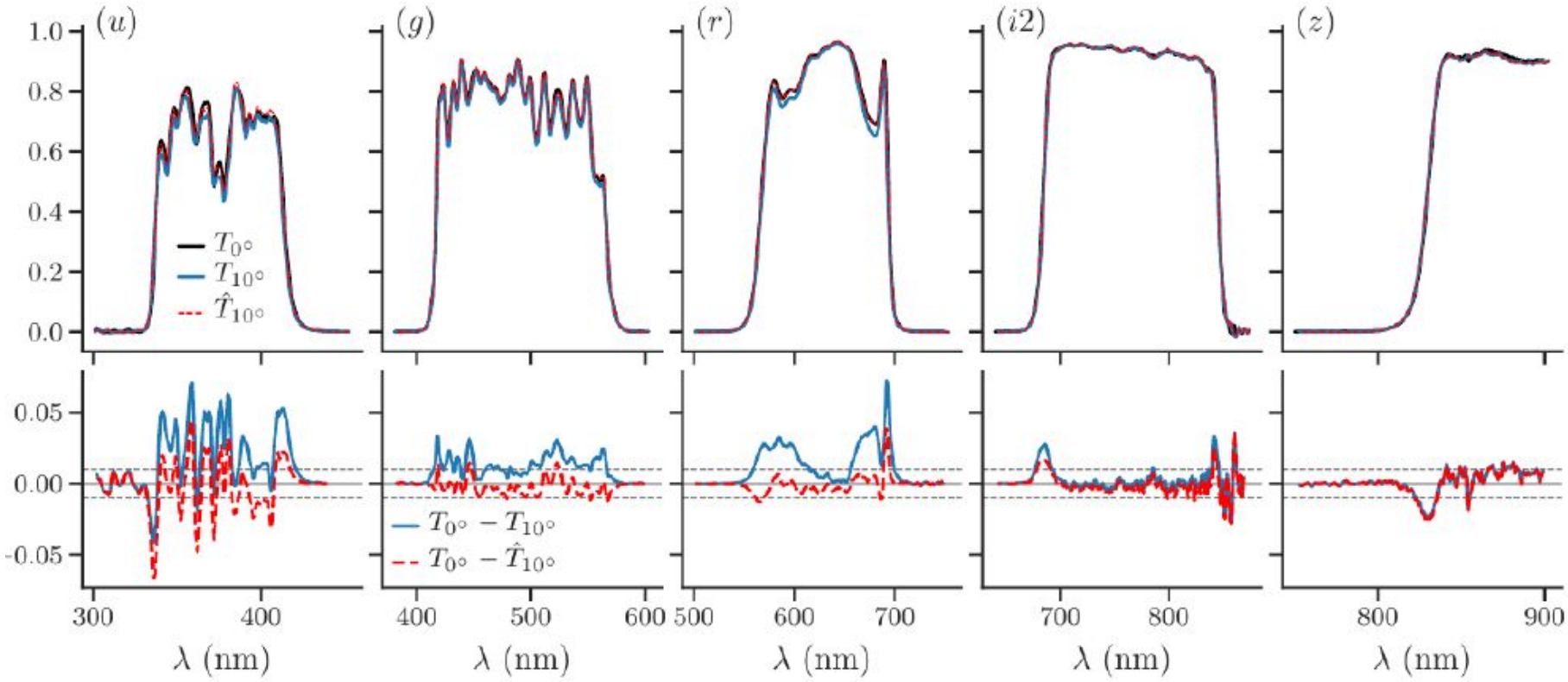
- MegaCam filters decommissioned in Feb 2016
- Sent to LMA (Lyon) in Dec 2016 for a complete re-characterization
- Two setups
  - Fast spectroscopic scan (1cm beam, normal incidence)
  - Slow spectrophotometric scan (variable incidence0





- Measurements described in (sassolas et al, 2018, 2018SPIE10706E..4ES)
- Filters sent back to CFHT in June 2018

Filter measurements



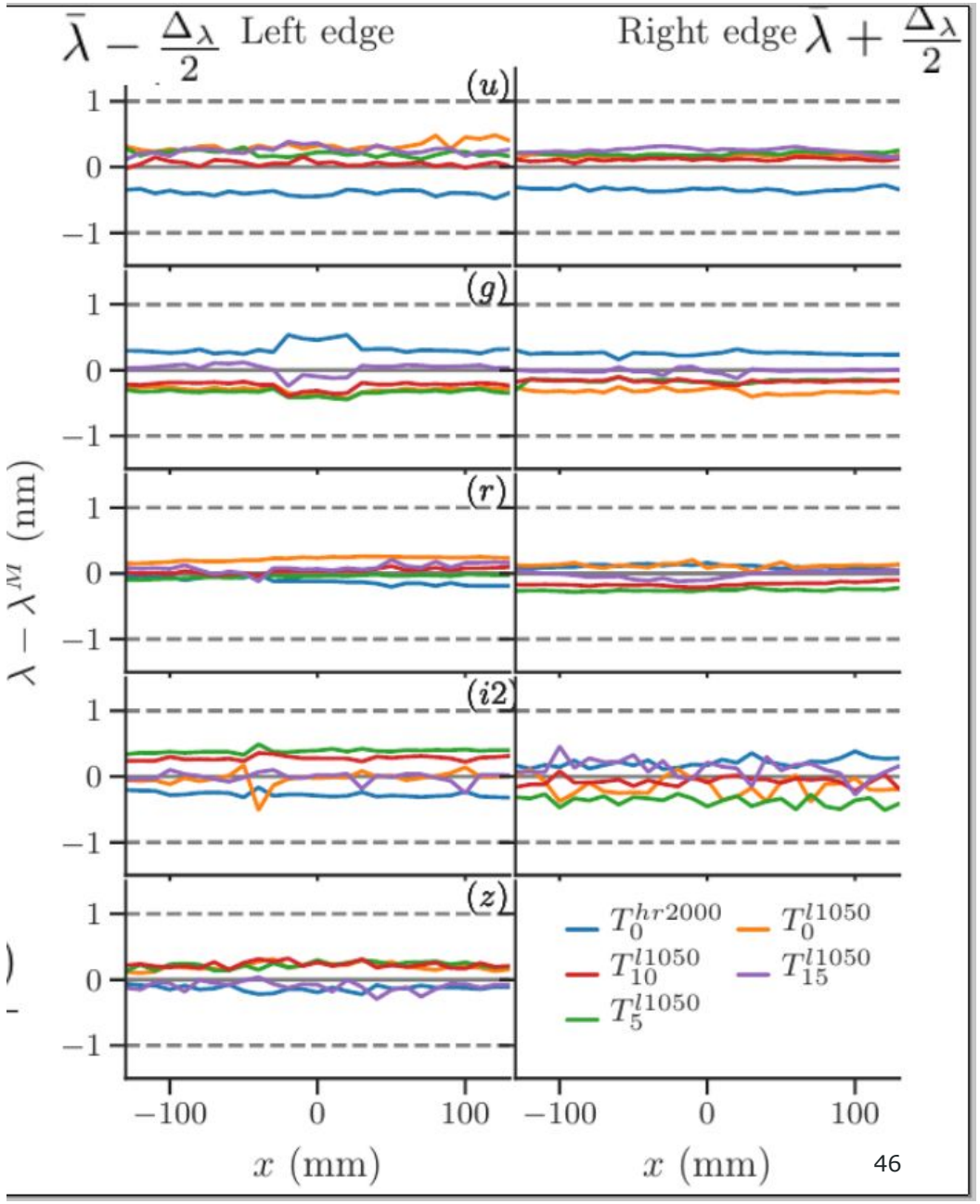
- Model fitted simultaneously on data from both setups
- Stray light within the bench taken into account (normal incidence)

(Betoule et al, in prep)

Consistency

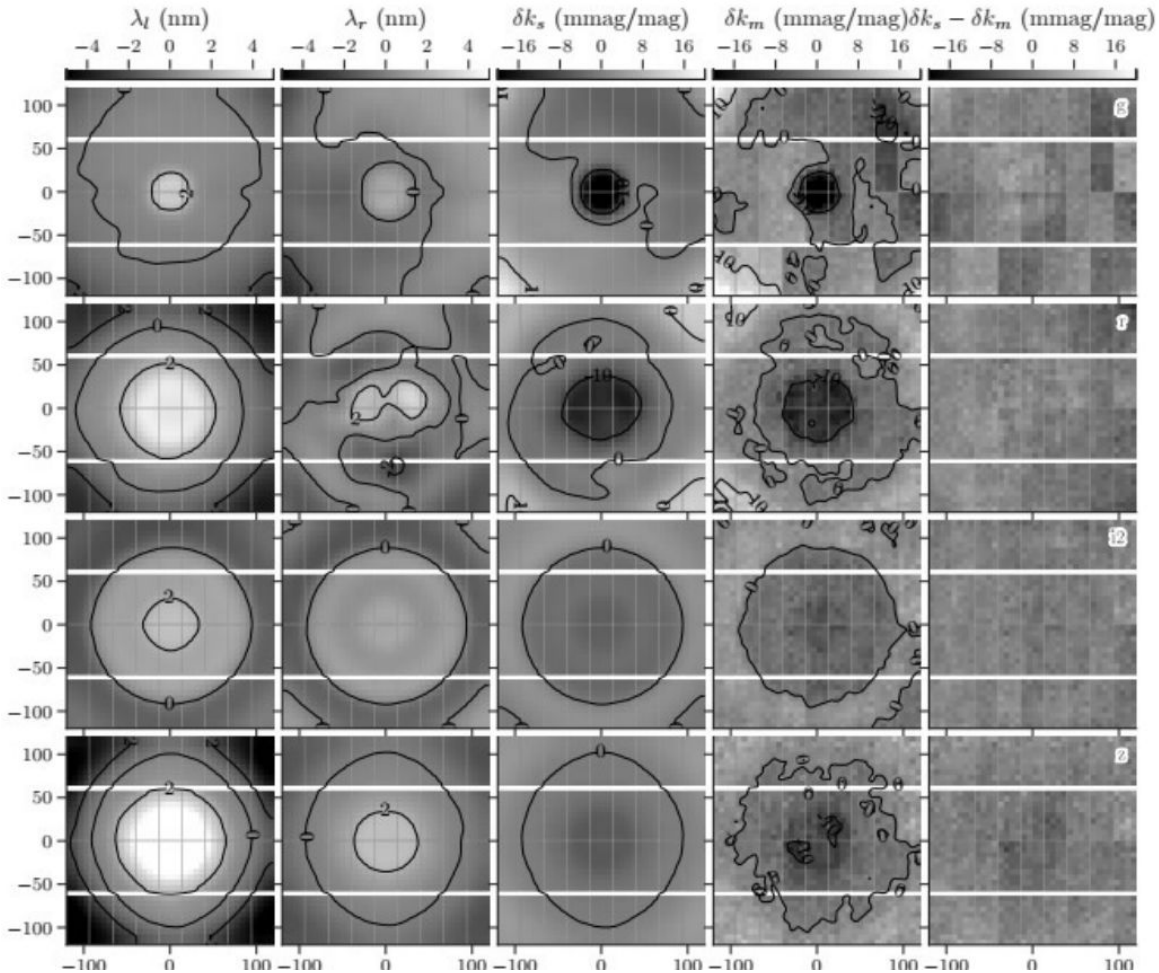
- Filter model fitted simultaneously on both sets of measurements

- The model describes measurements with a precision better than 0.5-nm



(Betoule et al, in prep)

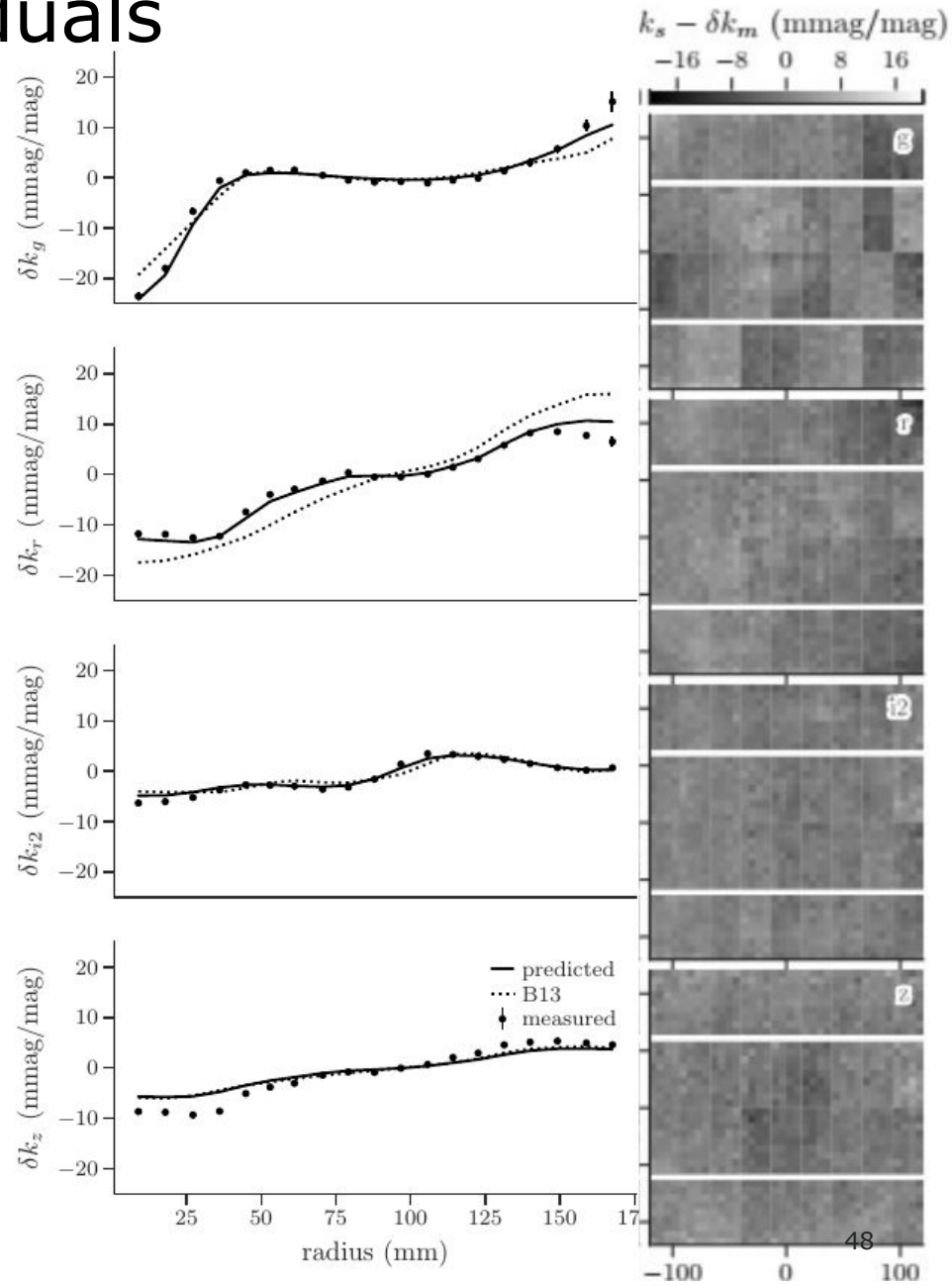
Filter uniformity maps



(Betoule et al, in prep)

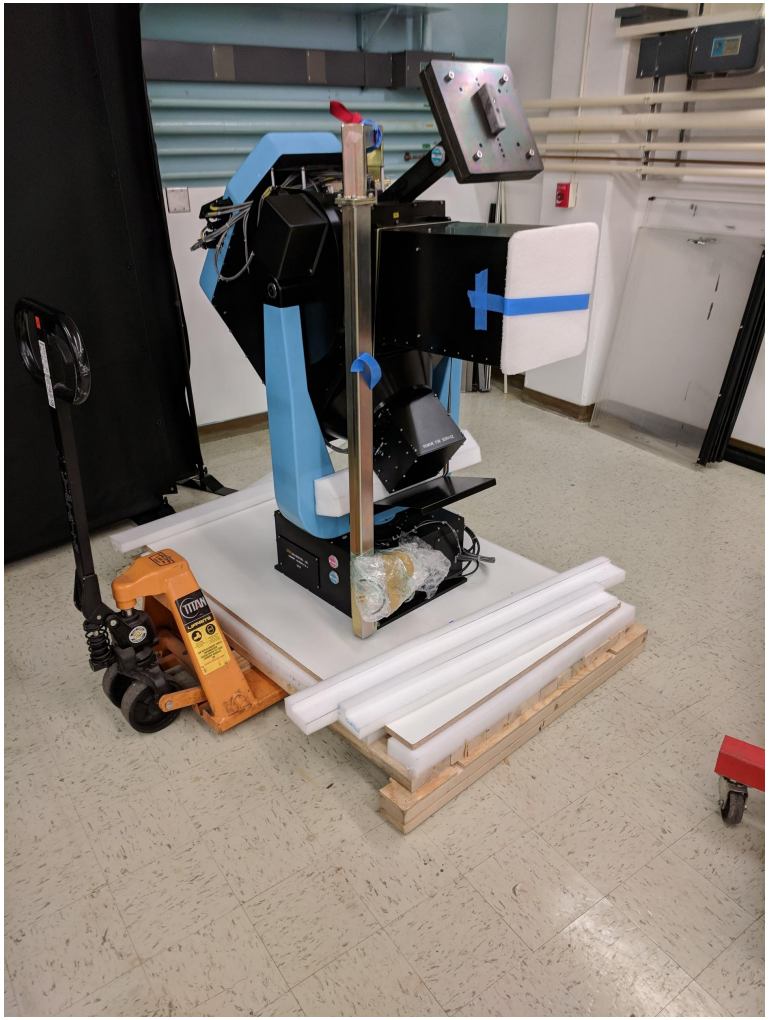
Radially averaged residuals

- Comparing relative color terms
  - Synthetic (B13, LMA)
  - Measured
- Re-measurement solves spatial issues observed in B13
- Agreement better than 4mmag/mag everywhere



In-situ measurements of filters

- LSST plans to use a Collimated Beam Projector (CoBP)
- No bench re-measurements of filters planned (so far)
- Tests of CBP precursors (aka "Harvard CBP) have been done on PanSTARRS and at CTIO
- CBP currently used to characterize and monitor starDICE telescopes
  - In the lab
  - In situ (at OHP)
- Will allow to assess accuracy and to gain experience



Conclusion

- Calibration requirements for 4th generation surveys will be very hard to meet
- Challenging goal
  - Relative flux calibration @ 0.1%
  - Characterization of filter wavelength positions @ 1A
  - Flux metrology chain controlled at better than 0.1%
- State of the art
  - Relative flux calibration :
    - ~0.5% (CALSPEC)
    - ~ 1% (NIST-CALSPEC)
  - Filter metrology : ~ 5A
  - Flux metrology chain < 0.5% (FGCM)
- ***Lots of instrumental work ahead***
  - *(starDICE, SCALA, filter metrology)*