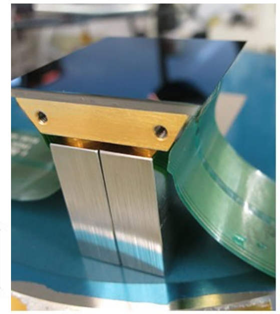
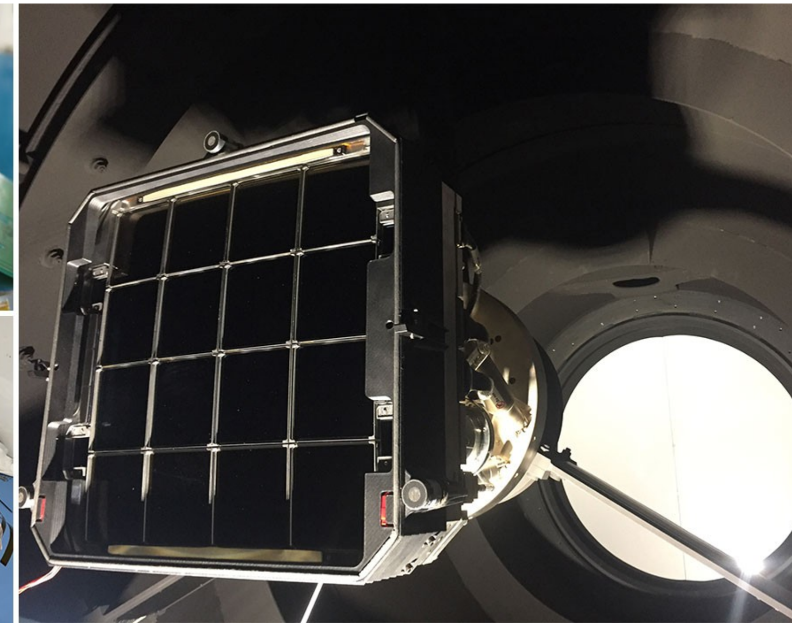
Precision supernova photometry with the Zwicky Transient Facility

Leander Lacroix for the ZTF participation group

The Samuel Oshin P48 telescope

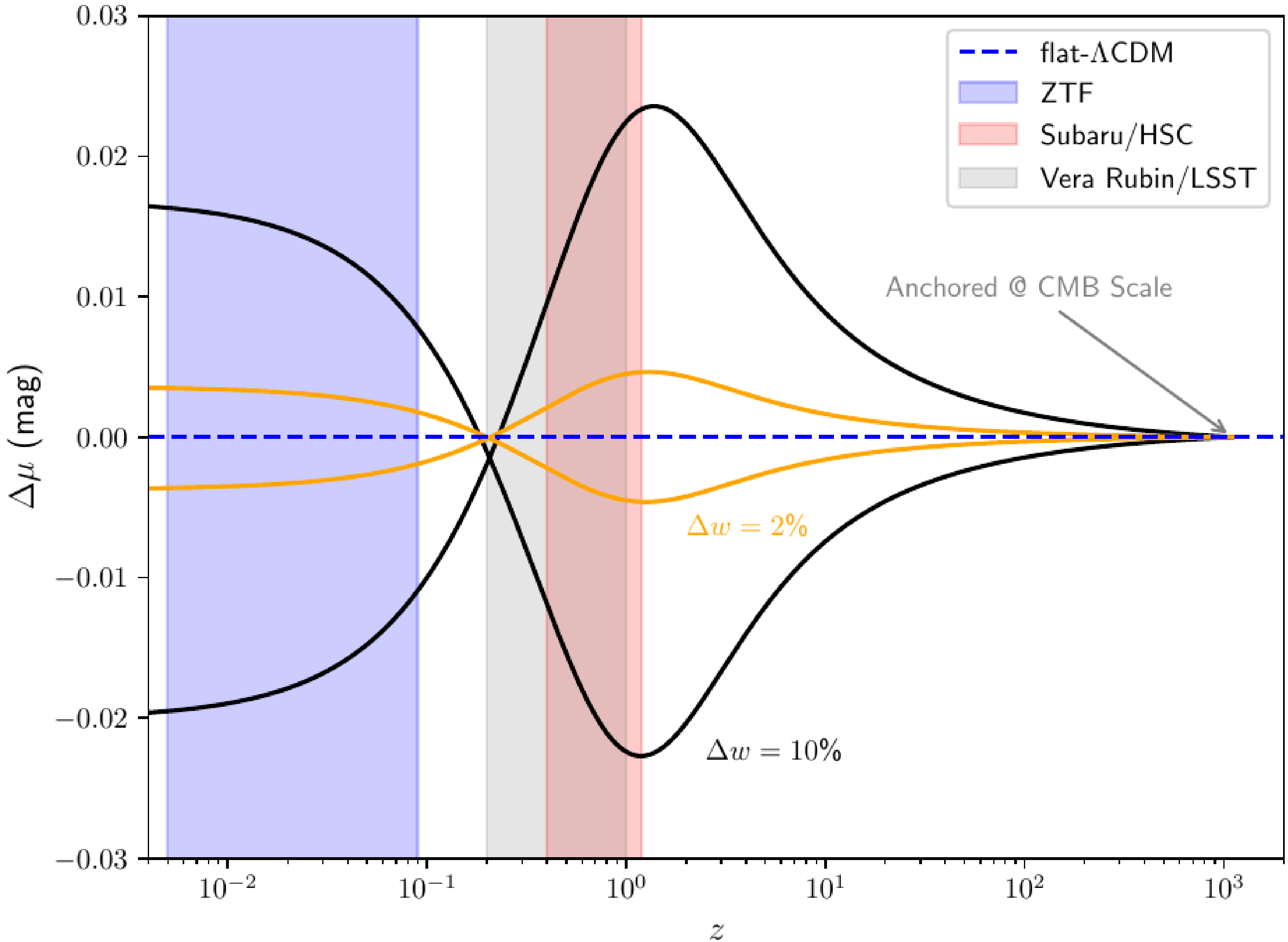
ZTF Camera Technical Specifications	
Telescope	Samuel Oschin (48-inch Schmidt)
Field of View	47 square degrees
Detectors	16 e2v 6k x 6k CCD231-C6
Pixel size	15 micron
Pixel scale	1.0"/pixel
Median Delivered Image Quality	2.0" FWHM
Exposure Time	30 sec
Readout Time	10 sec
Median Time Between Exposures	15 sec
Median Single Visit Depth (5σ, R band)	20.4 mag (all lunar phases)
Filters	ZTF g, ZTF r, ZTF i
Areal Survey Rate	3750 square degrees/hour





©Caltech

Photometry goals for precision *w* cosmology



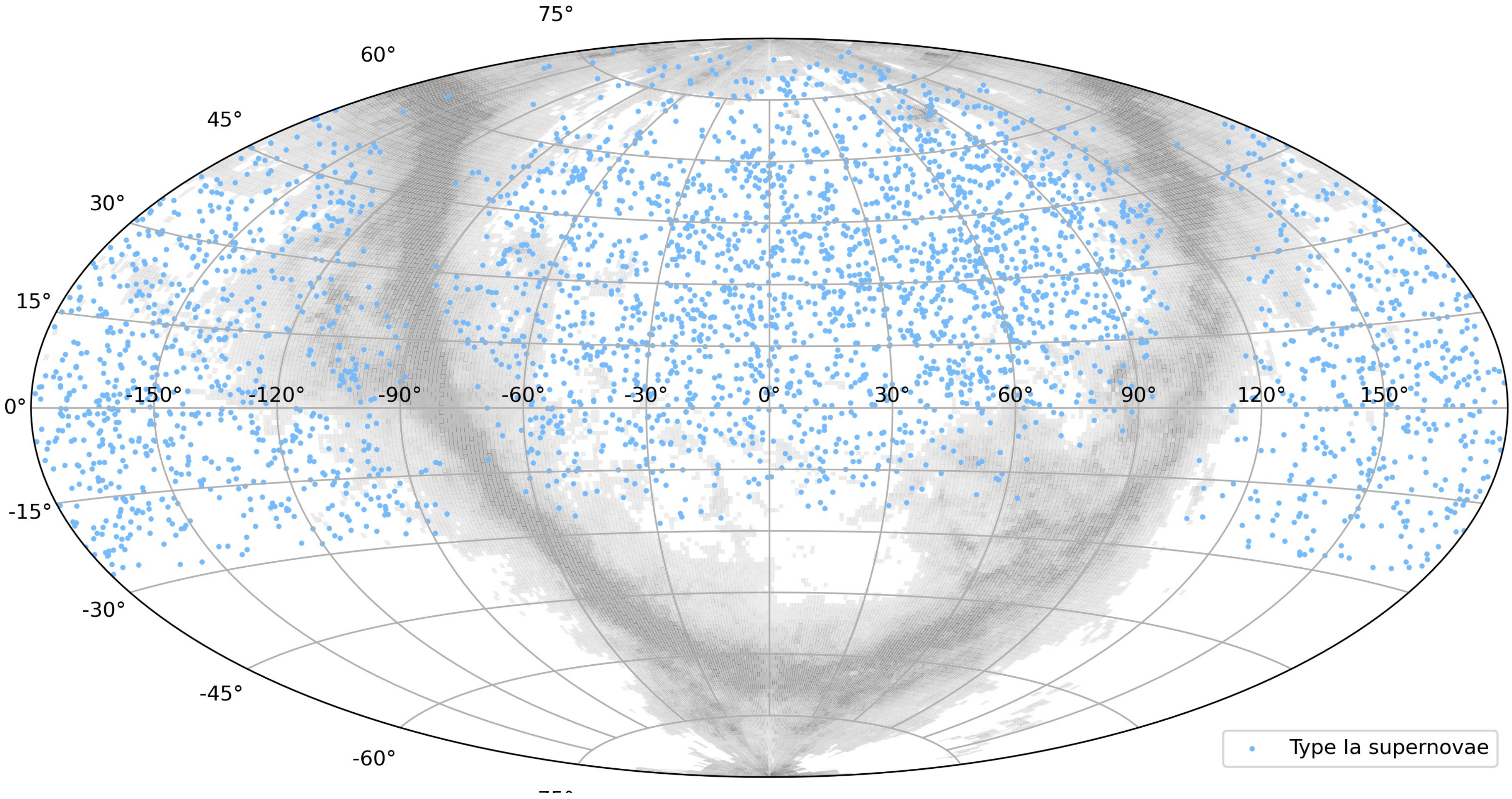
Credit: Dylan Kuhn @ LPNHE

Ingredients for SN flux metrology

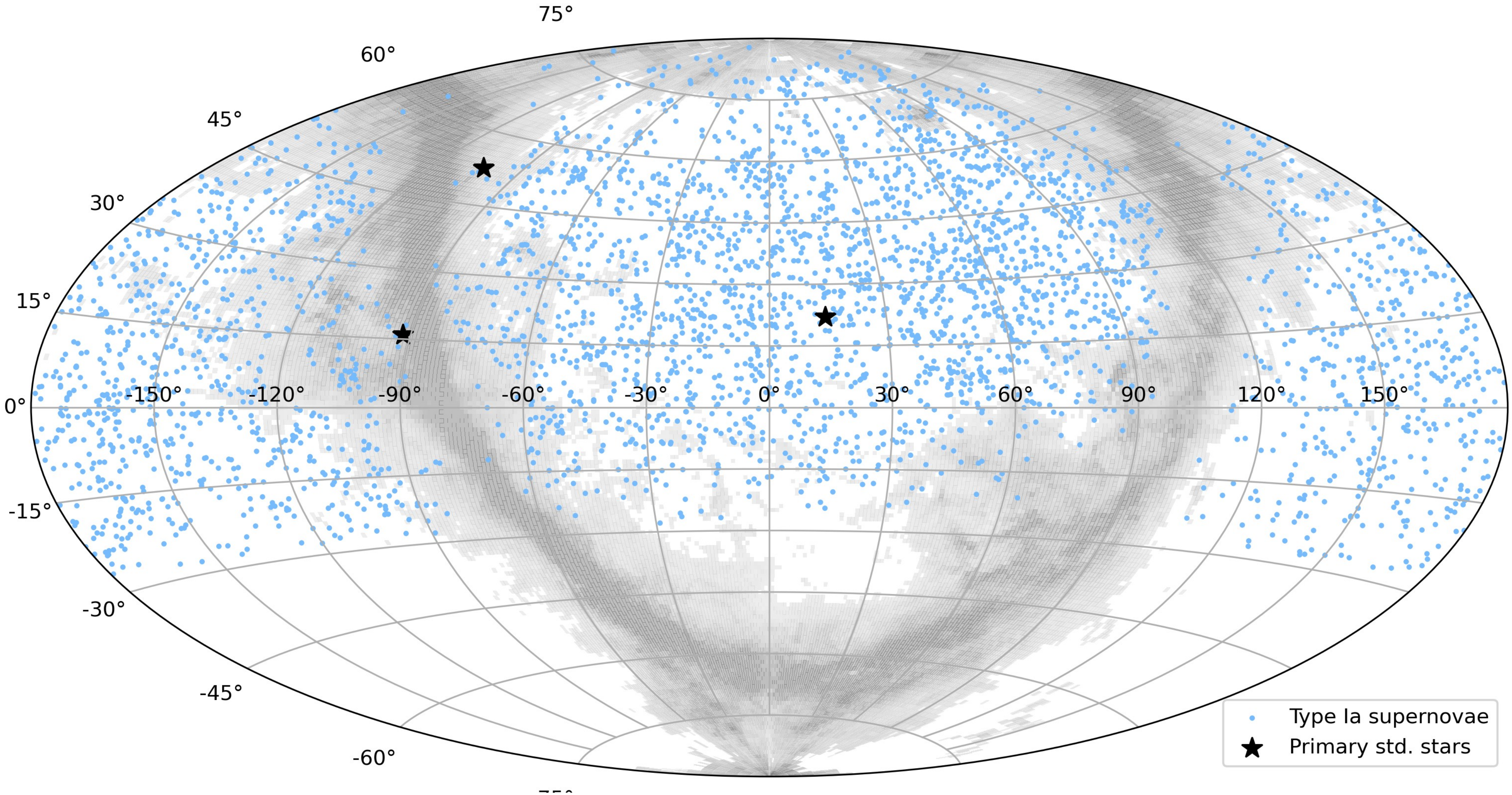
- Repeatability matters:
  - ZTF pipeline repeatability: 2%
  - Our goal: 0.1% (for $\Delta w = 1\%$ and ~10k Ia Sne)
  - Work on systematical error at the ‰ level
- Ingredients:
  - Survey calibration → **UberCal**
  - Instrument non uniformity caracterisation → **starflats**
  - Efficient SN lightcurve extraction → **scene modeling**
  - Instrument throughput model
  - Internal detrending pipeline

- Large french team coordinated effort for calibration

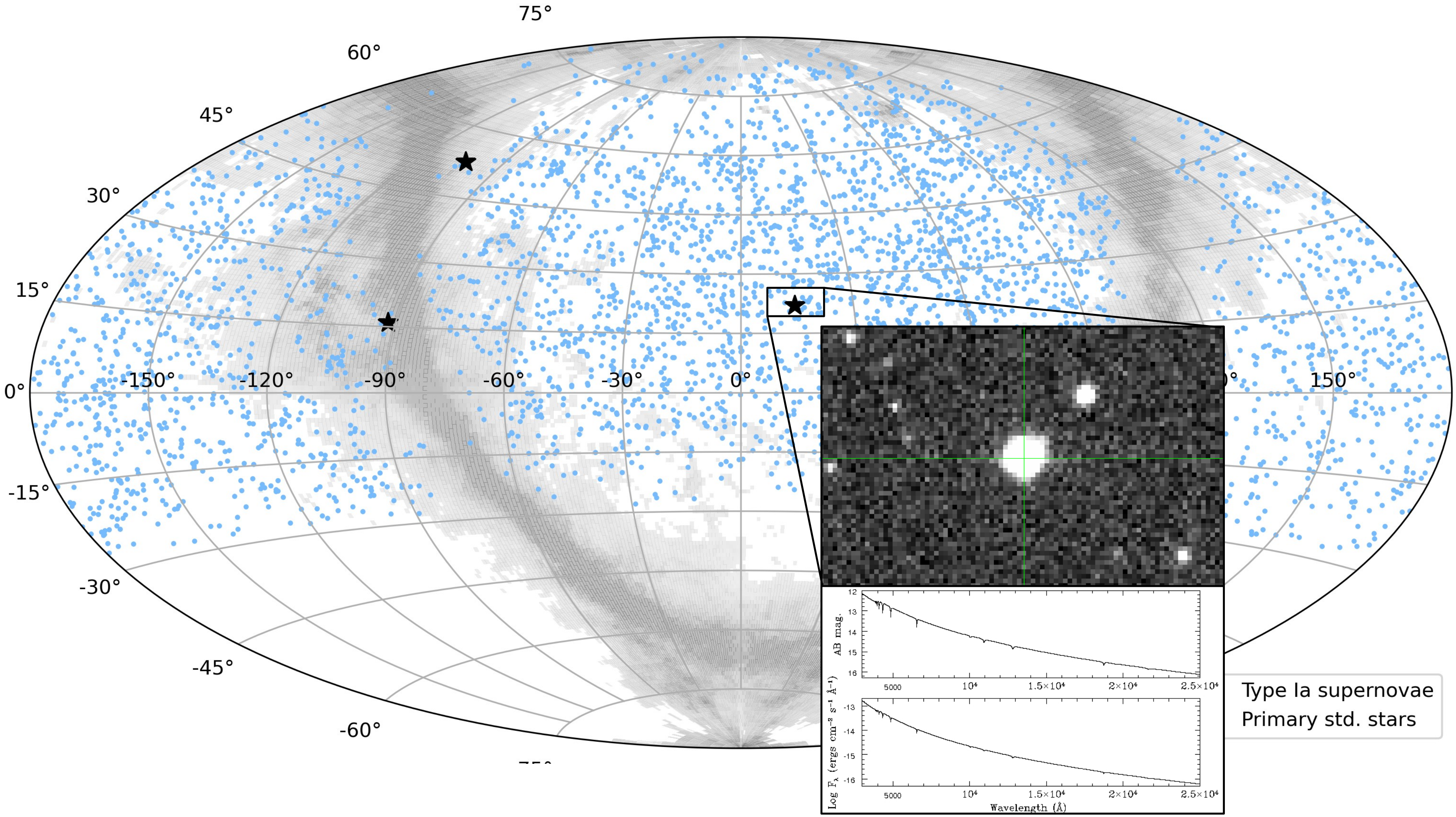
DR2 sample


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
Type Ia supernovae

DR2 sample & primary standard stars

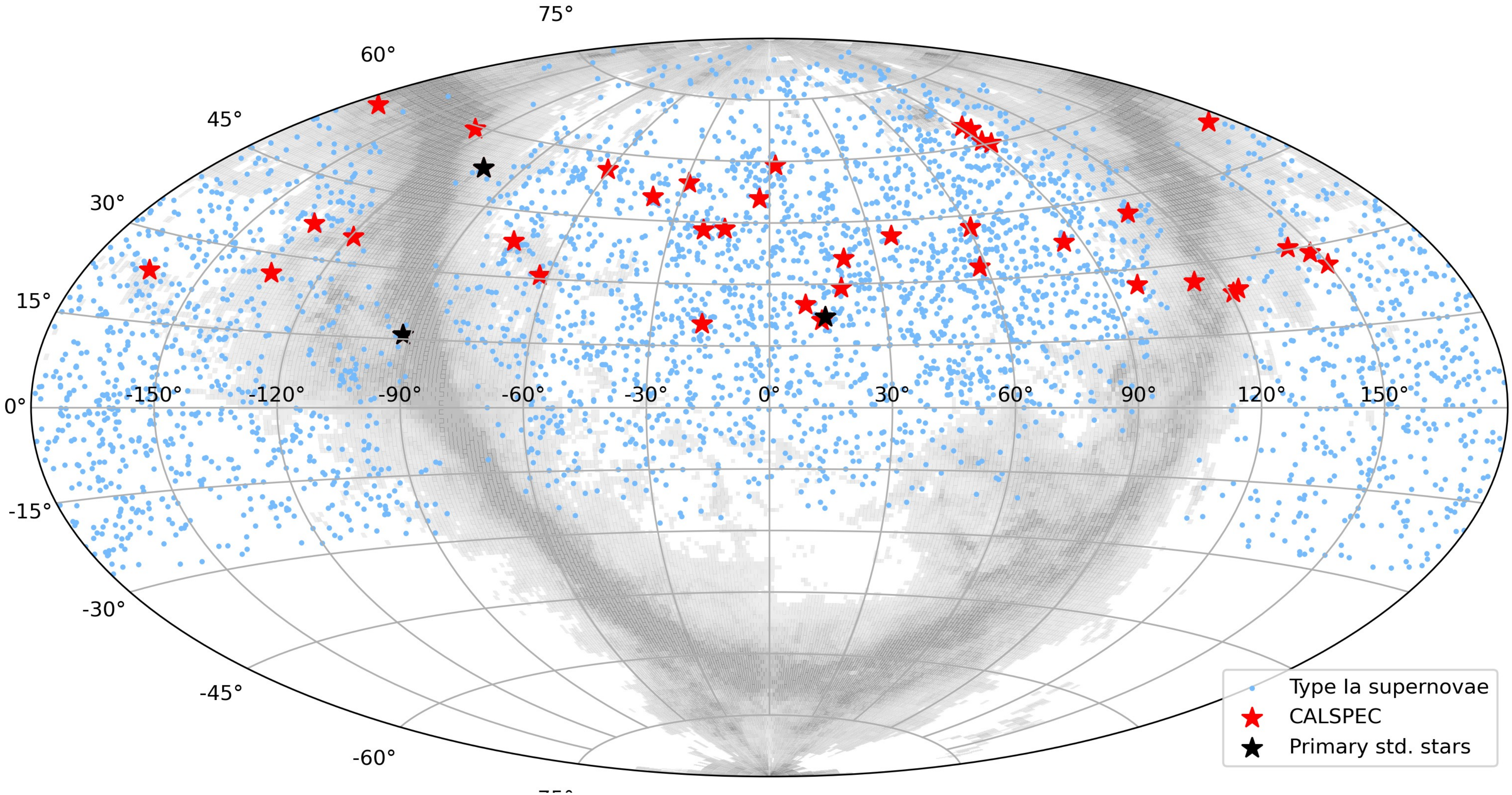


DR2 sample & primary standard stars



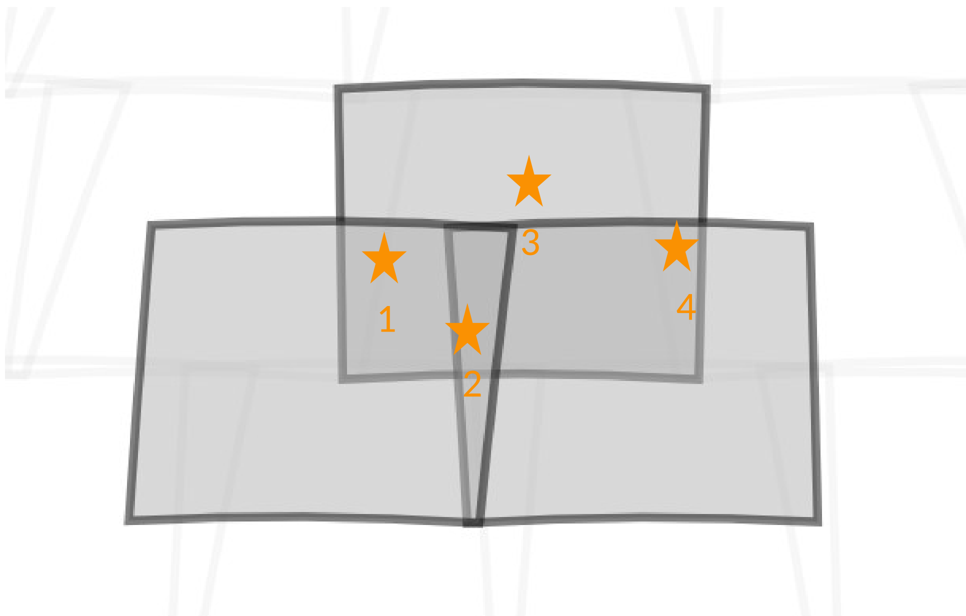
X-shooter ref. spectrum (Moehler et al. 2014a,b)

DR2 sample & primary std. & CALSPEC stars



Calibrating the field stars

The idea



$$m_1 + 0 = m_{11}^{obs}$$
$$m_2 + 0 = m_{21}^{obs}$$
$$m_3 + \Delta ZP_2 = m_{32}^{obs}$$
$$m_4 + \Delta ZP_2 = m_{42}^{obs}$$
$$m_1 + \Delta ZP_3 = m_{13}^{obs}$$
$$m_2 + \Delta ZP_3 = m_{23}^{obs}$$
$$m_3 + \Delta ZP_3 = m_{33}^{obs}$$
$$m_4 + \Delta ZP_3 = m_{43}^{obs}$$

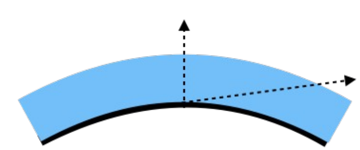
The fit (MLE)

$$m_{obs} - m_{ps_g} = \alpha(m_{ps_g} - m_{ps_r}) + ZP(t_{exposure}) + k(t_{night}) * \mathrm{airmass} + \delta ZP(u, v)$$

Color correction
vs PS1

Fast change from clouds
Slow change from mirror
aging?

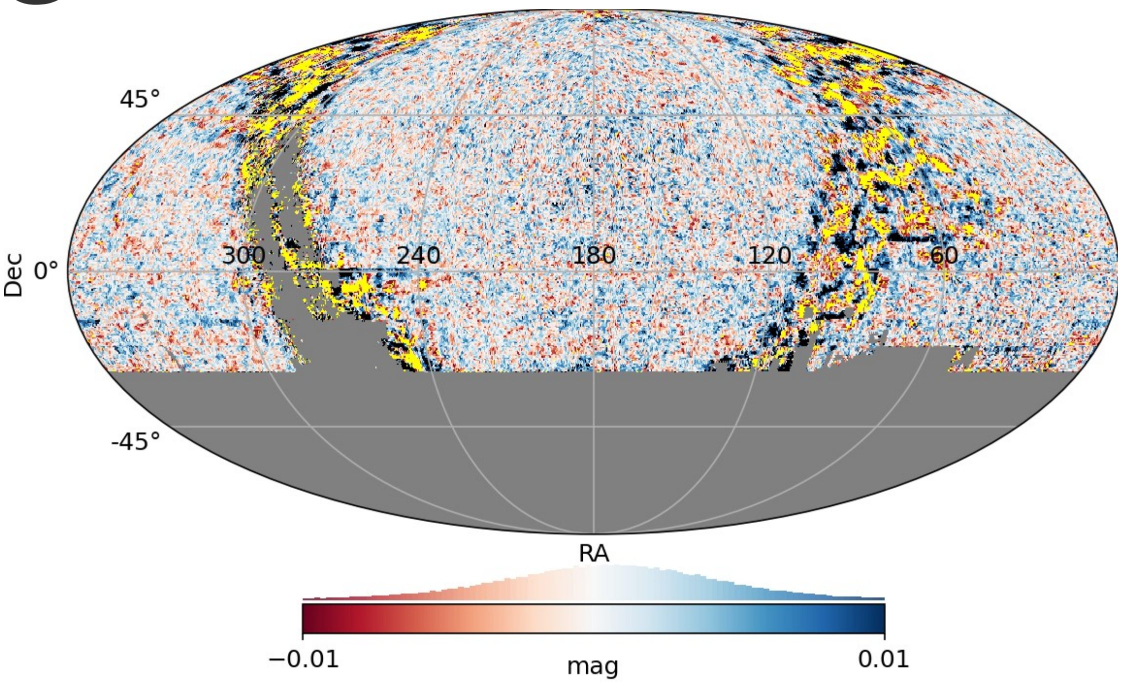
Low elevation
=
Observing through
high airmass

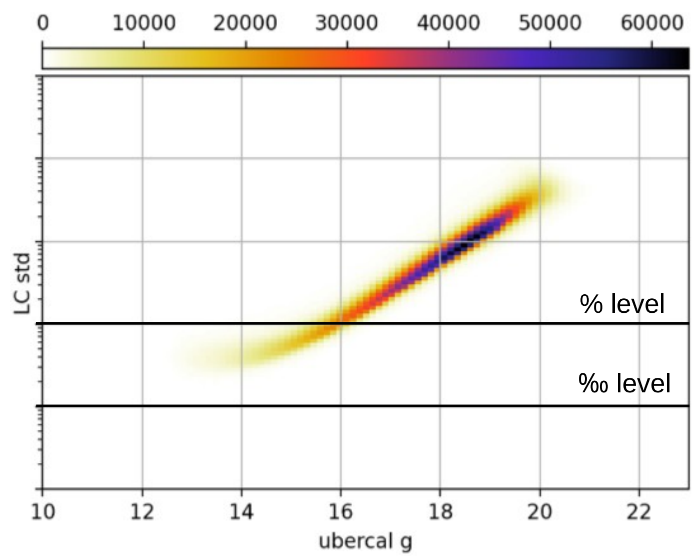


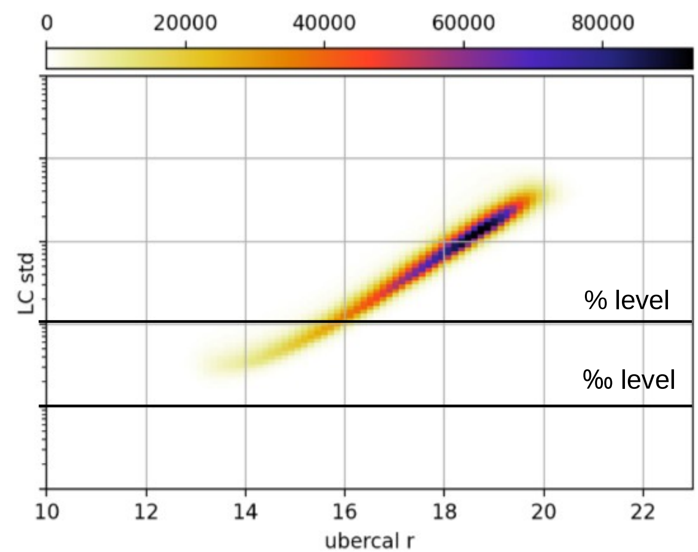
Gain variability
CCD width variation
Dust spots
Fringing
Laser annealing
...

Calibrating the field stars

- For now: anchored on PS1 as a large scale rigidifier
  - Needs slight modification of observing strategy (as for DES, SDSS...)
- Main product: uniform star catalog of the whole survey



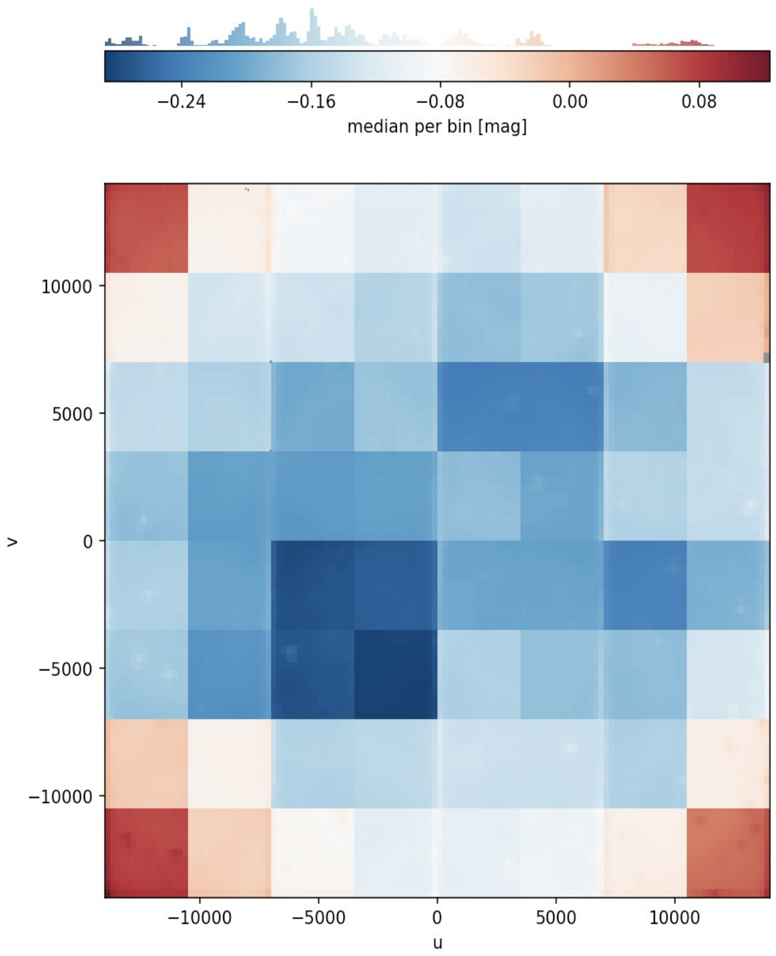


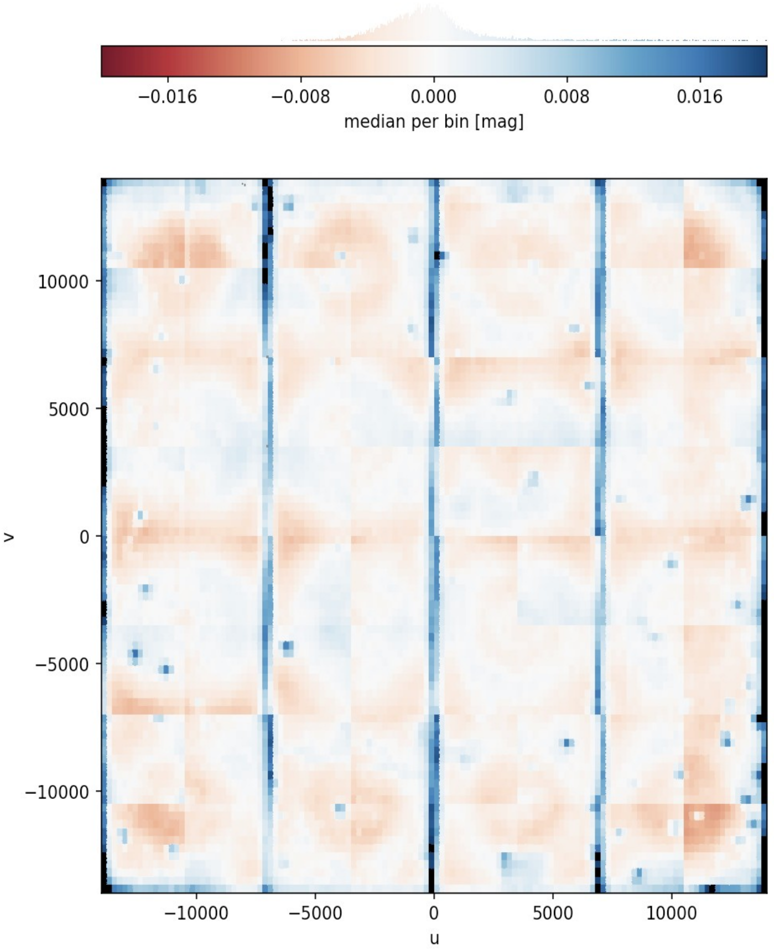


Conclusion:
- Good repetability for bright stars
- Anchored on PS1 as a large scale rigidifier

Camera non uniformities

- Map zero point variation on focal plane

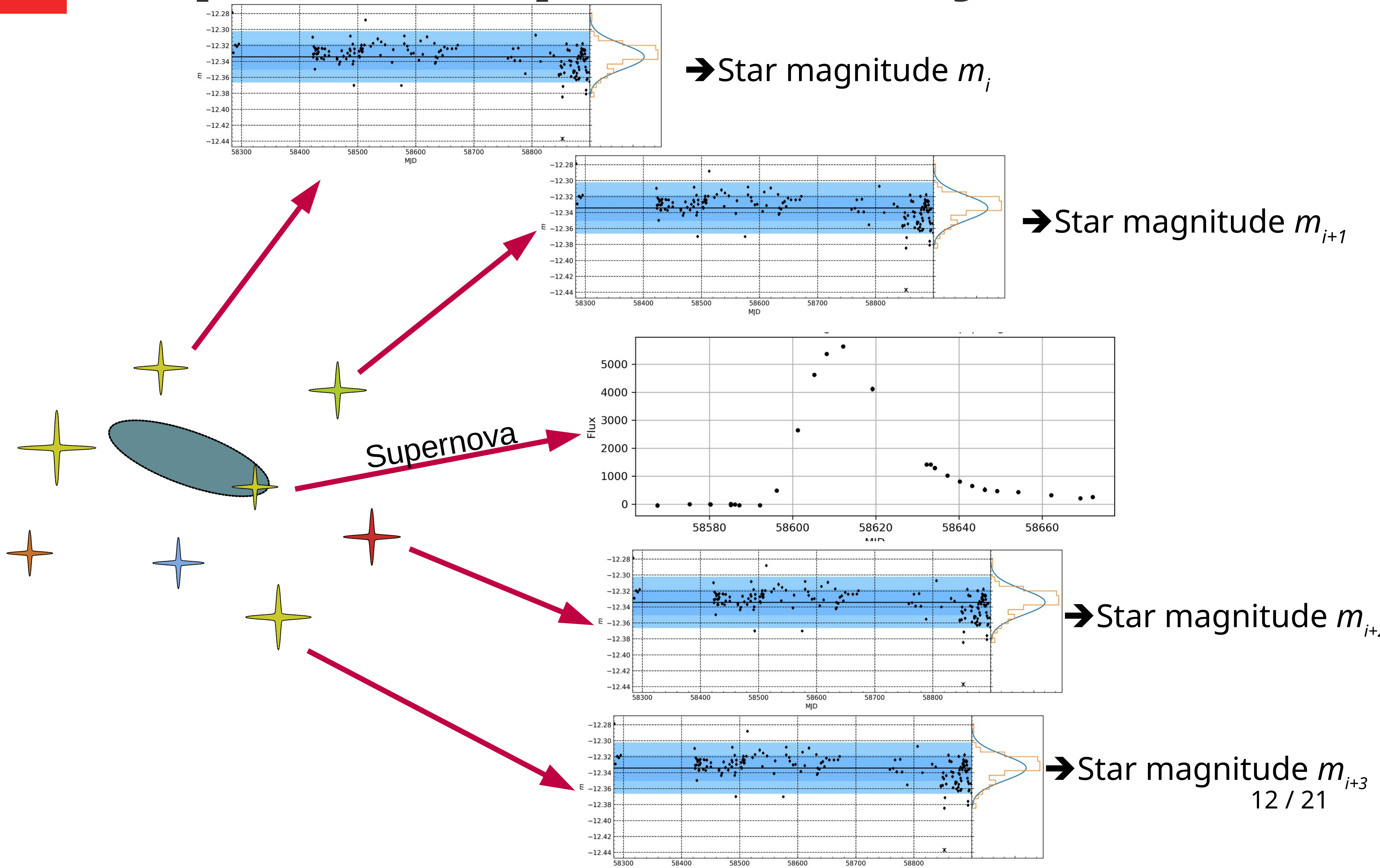




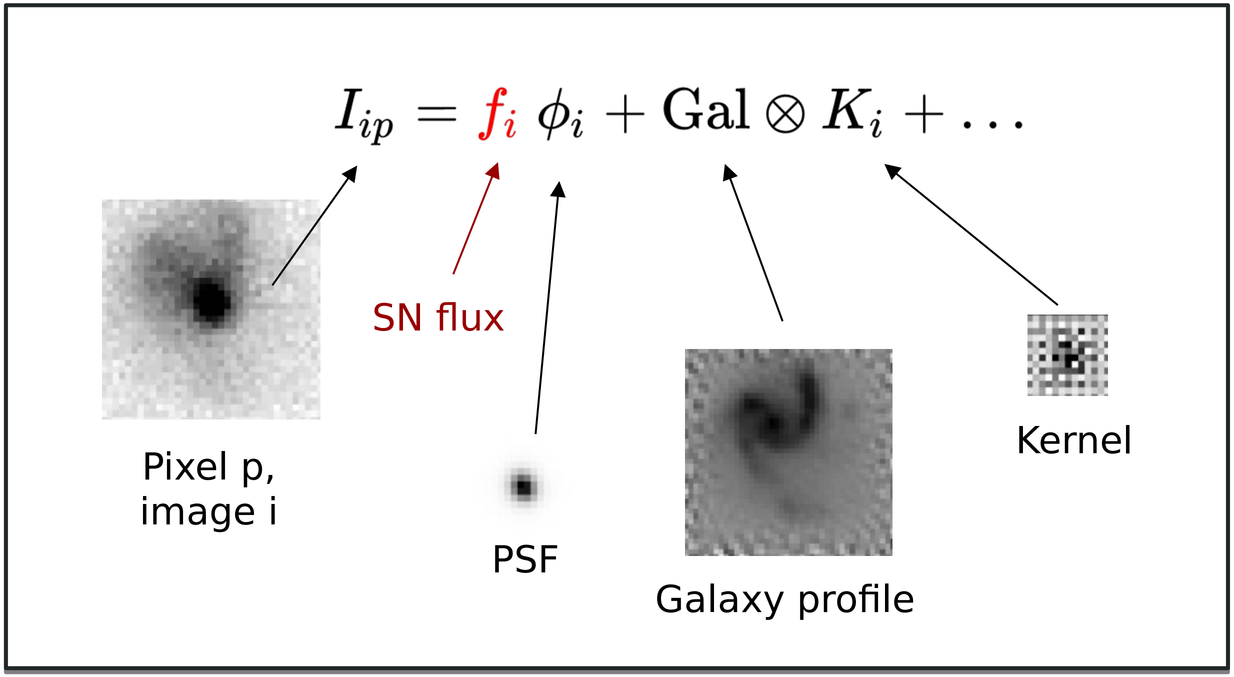
From UberCal fit

B. Racine et al

Supernova photometry



Scene Modeling Photometry (SMP)



- Statistically optimal maximum likelihood flux estimator
- Directly work at the pixel level
- Models the “scene” (SN flux and background galaxy)
- Same flux estimator for SN and field stars → auto cancellation of systematics

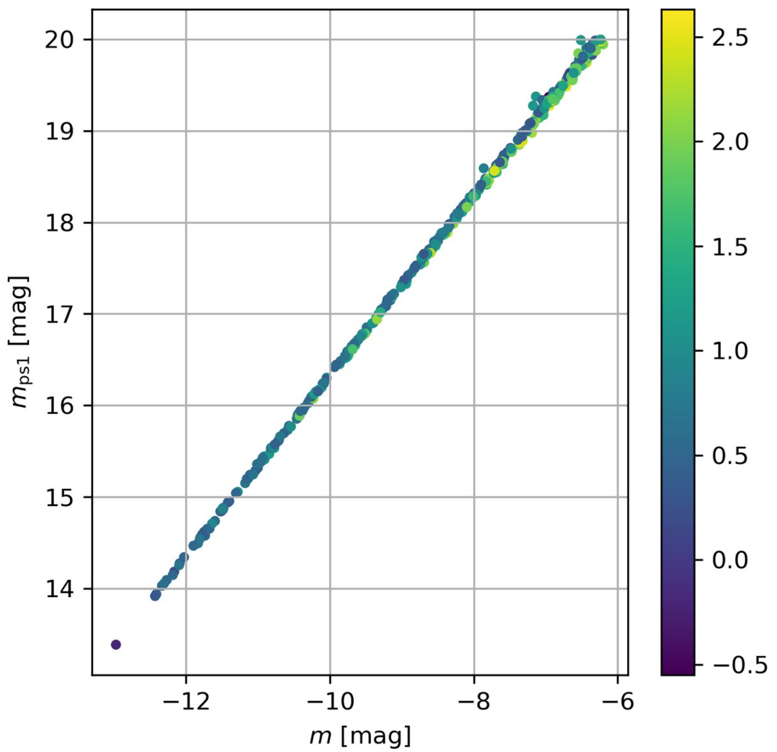
Simultaneously fits

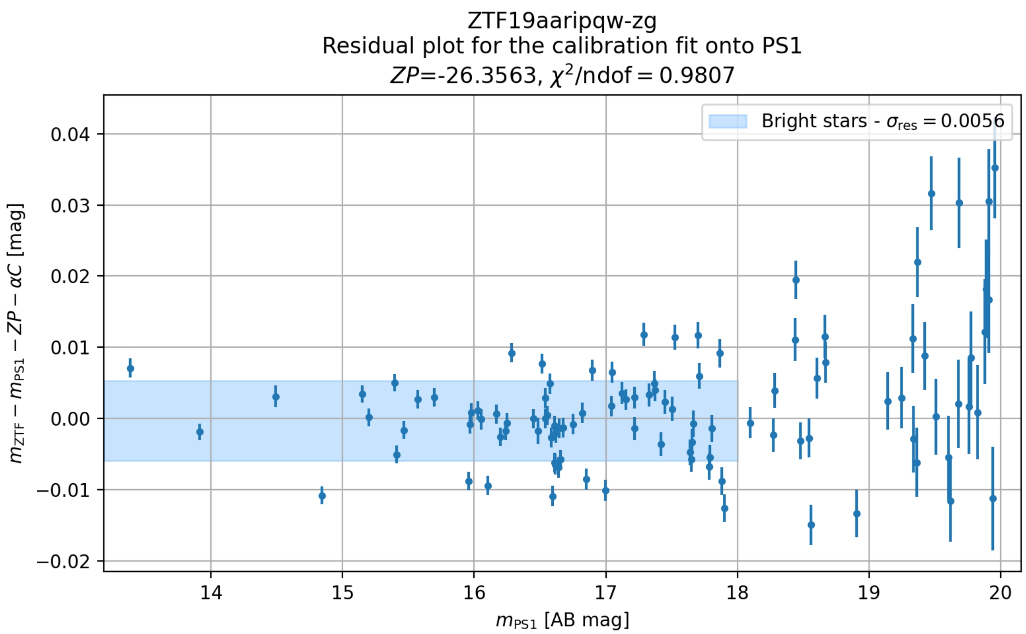
- SN position
- Galaxy profile
- Fluxes ← lightcurve!

Lightcurve calibration

- For each star lightcurve, fit constant magnitude model
  - High χ^2 → variable stars – removed
- Find Zero Point (ZP) → compare with calibrated catalog

Fitted star magnitude vs external catalog (ps1)

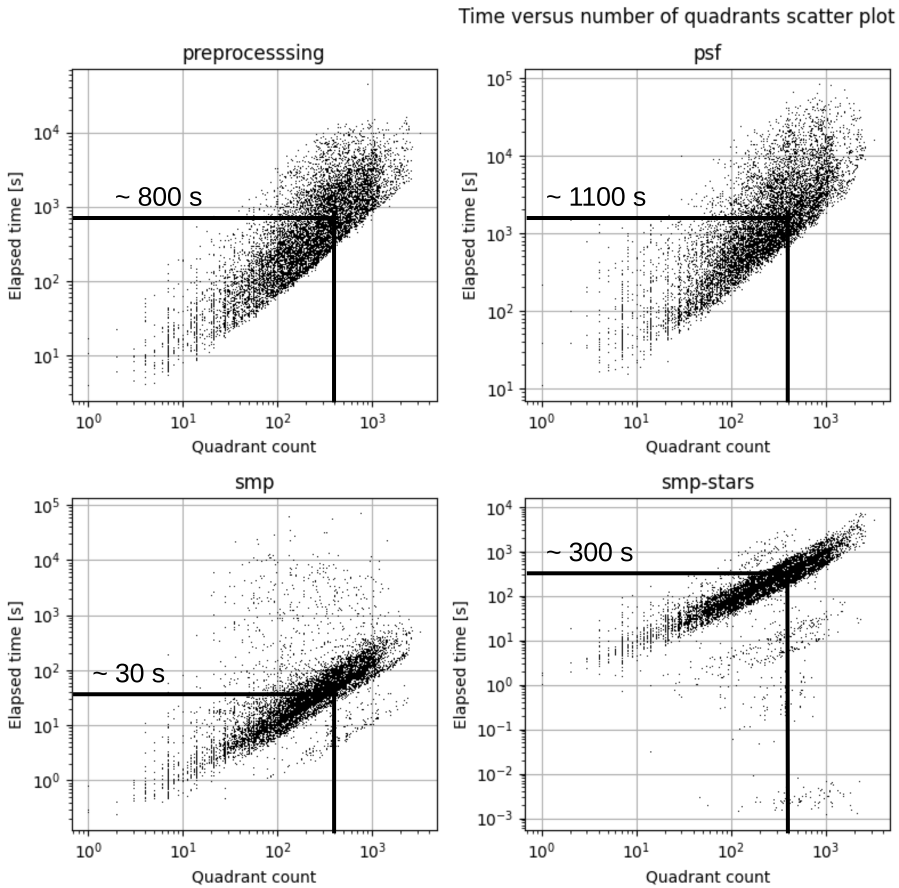




- Here: 0.5% dispersion for field stars
  - With ~50 stars → ‰ level

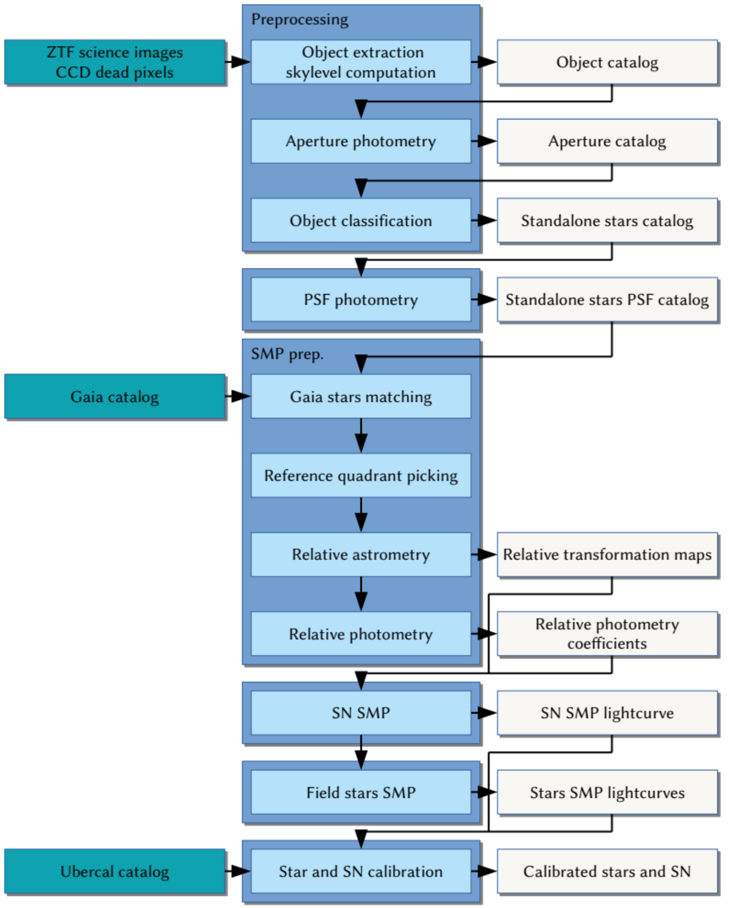
Scene modeling pipeline

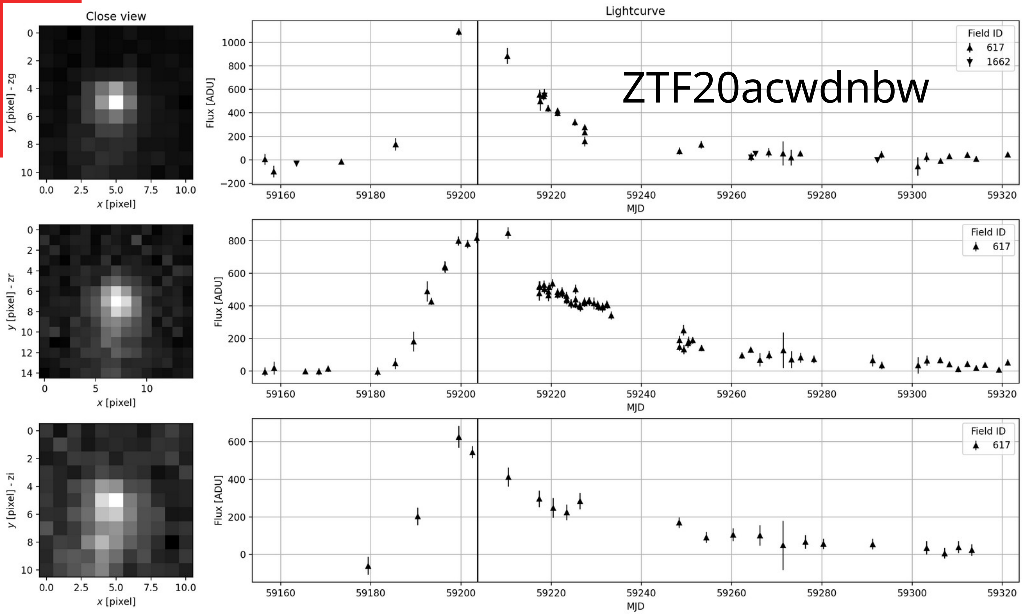
- 180 TB dataset - 3.6M quadrants
  - ~ 3600 SNe → ~10k lightcurves
  - ~ 1 week processing for whole DR2

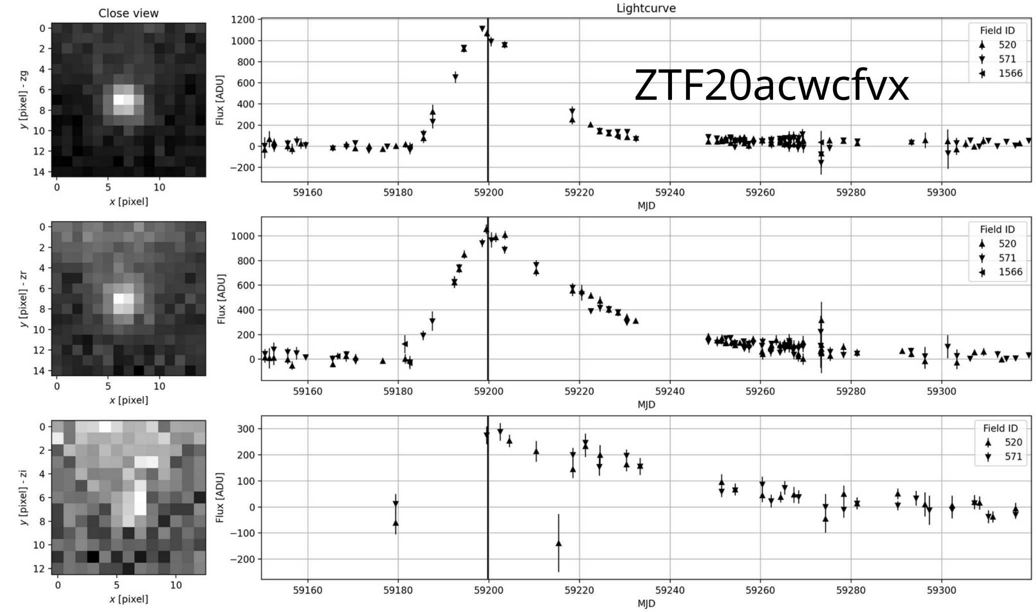


- Scales linearly
- Compute time dominated by PSF modeling

Typical SN: 300 exposures




ZTF20acwdnbw
Close view
Lightcurve
Field ID
617
1662
Flux [ADU]
MJD
x [pixel]
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi


ZTF20acwcfvx
Close view
Lightcurve
Field ID
520
571
1566
Flux [ADU]
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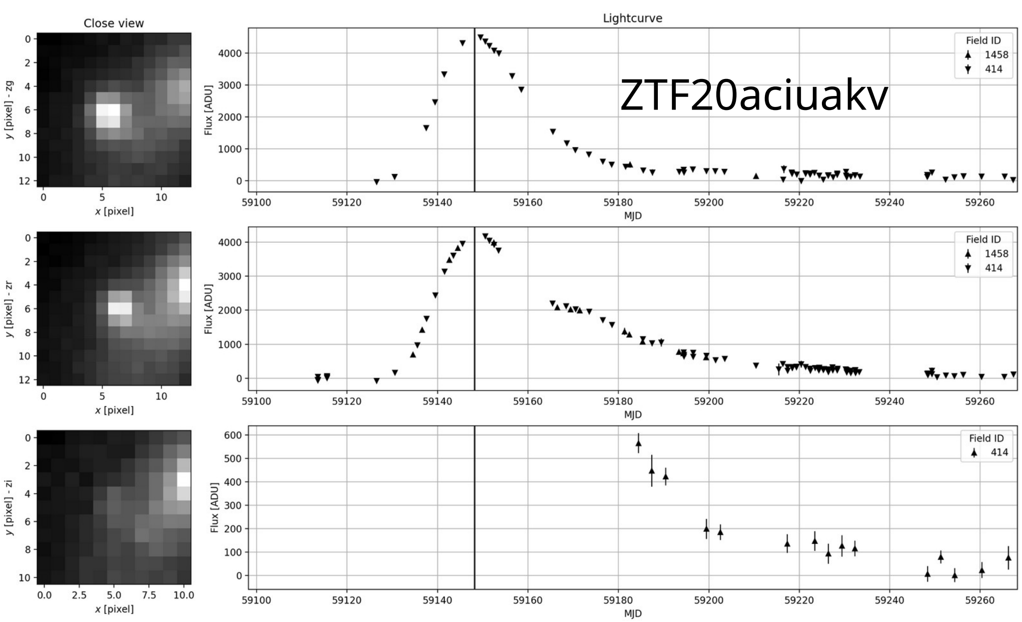
y [pixel] - zr
y [pixel] - zi


ZTF20aciuakv
Close view
Lightcurve
Field ID
1458
414
Flux [ADU]
MJD
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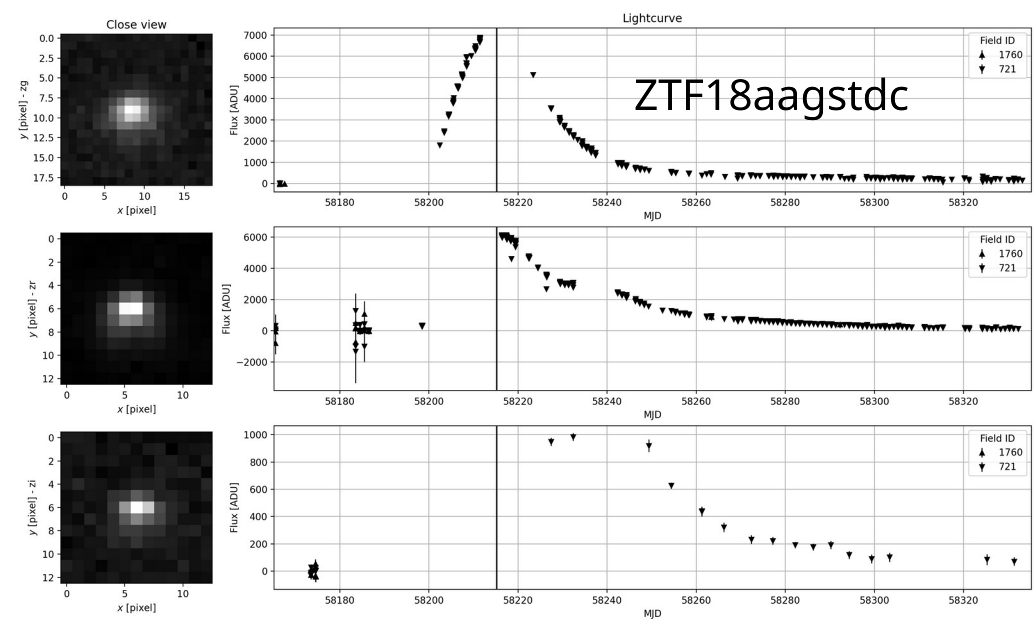
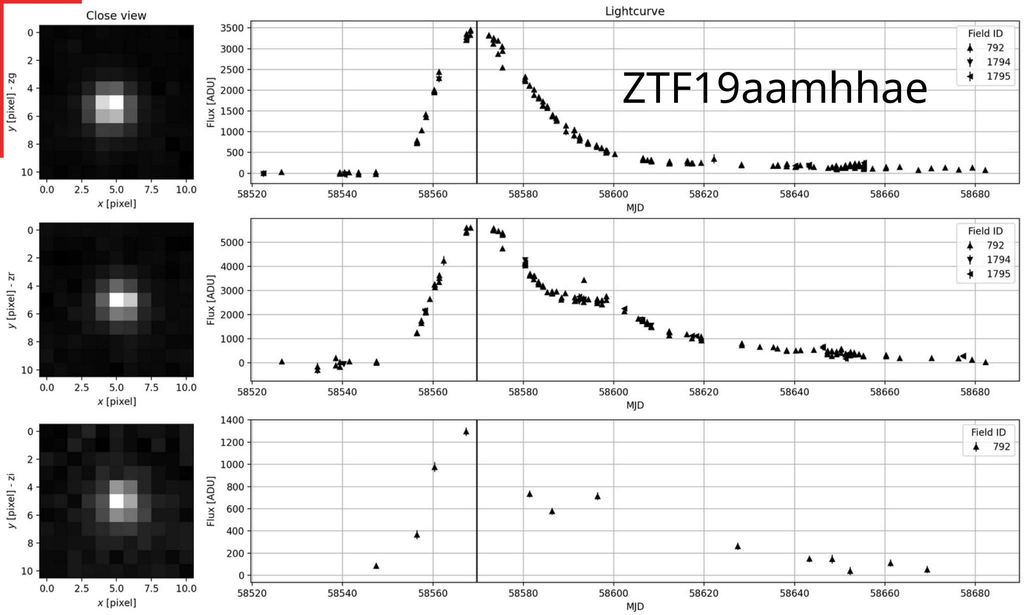
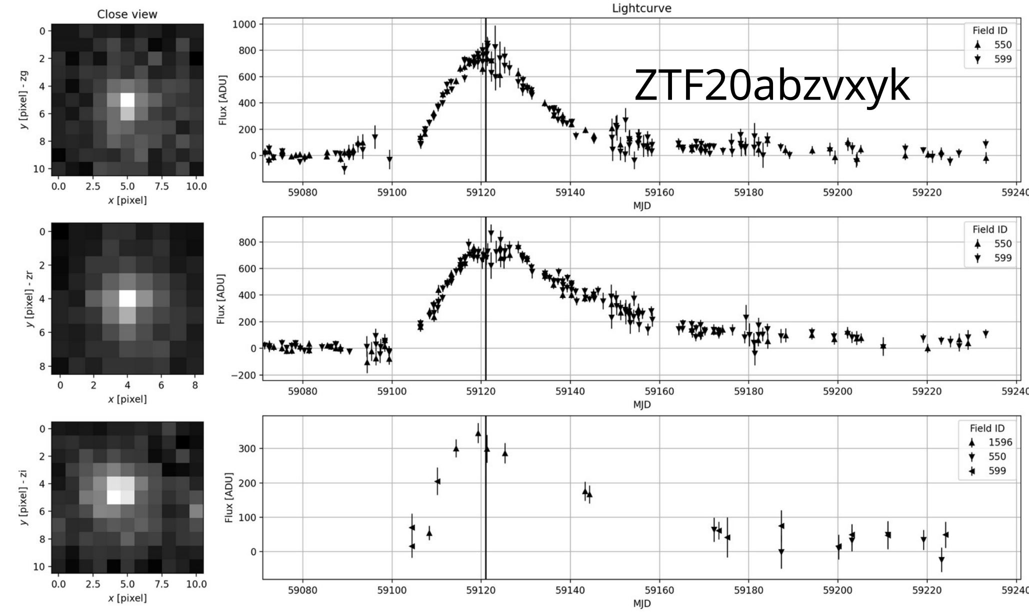
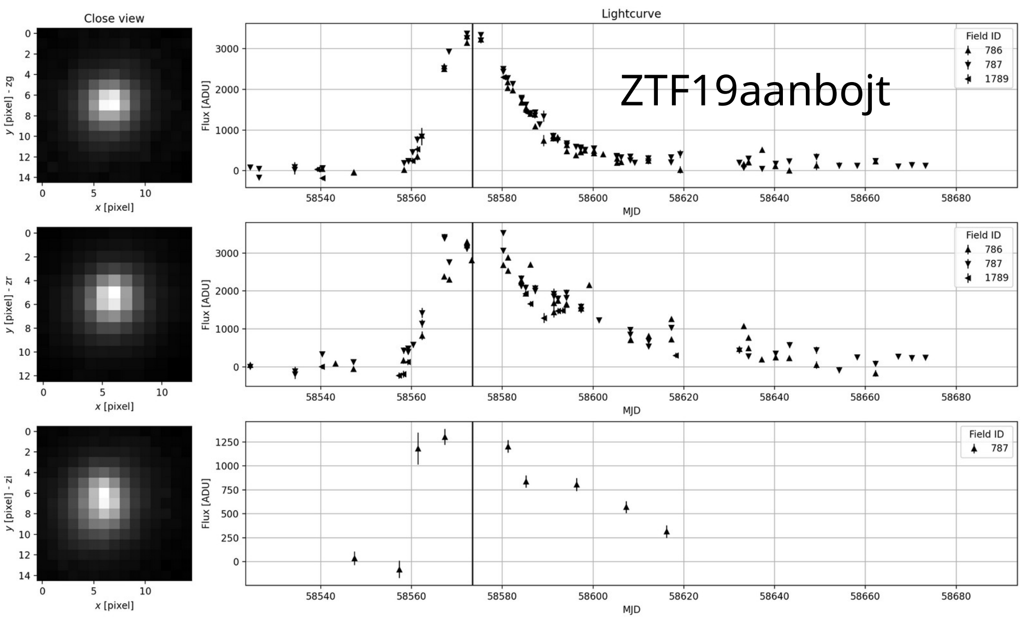
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi


ZTF18aagstdc
Close view
Lightcurve
Field ID
1760
721
Flux [ADU]
MJD
x [pixel]
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi


Close view
Lightcurve
ZTF19aamhhae
Field ID
792
1794
1795
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi
x [pixel]
Flux [ADU]
MJD


Close view
Lightcurve
ZTF20abzvxyk
Field ID
550
599
1596
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi
x [pixel]
Flux [ADU]
MJD


Close view
Lightcurve
ZTF19aanbojt
Field ID
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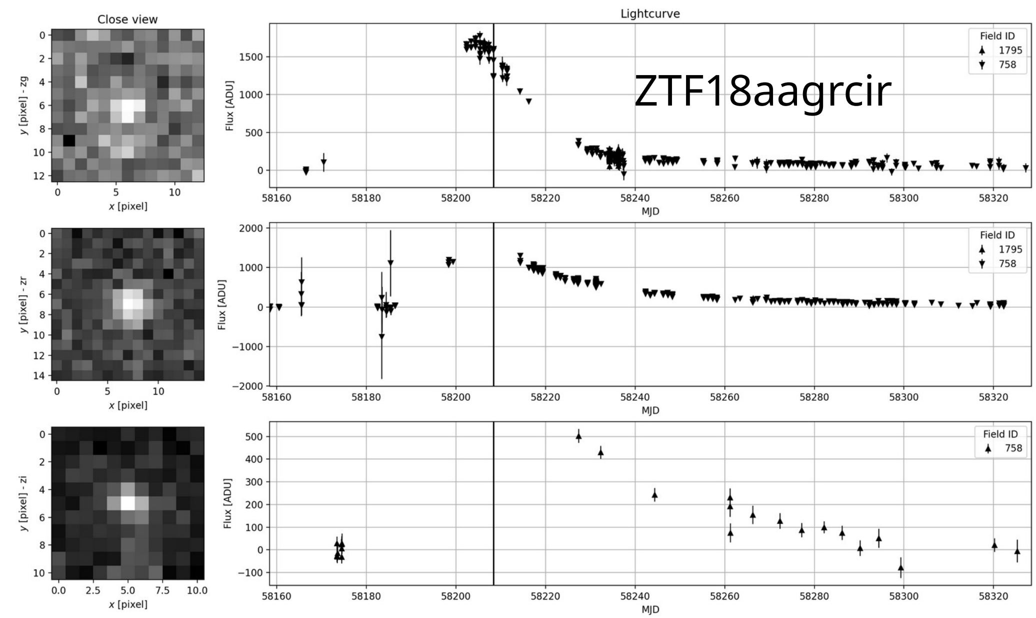
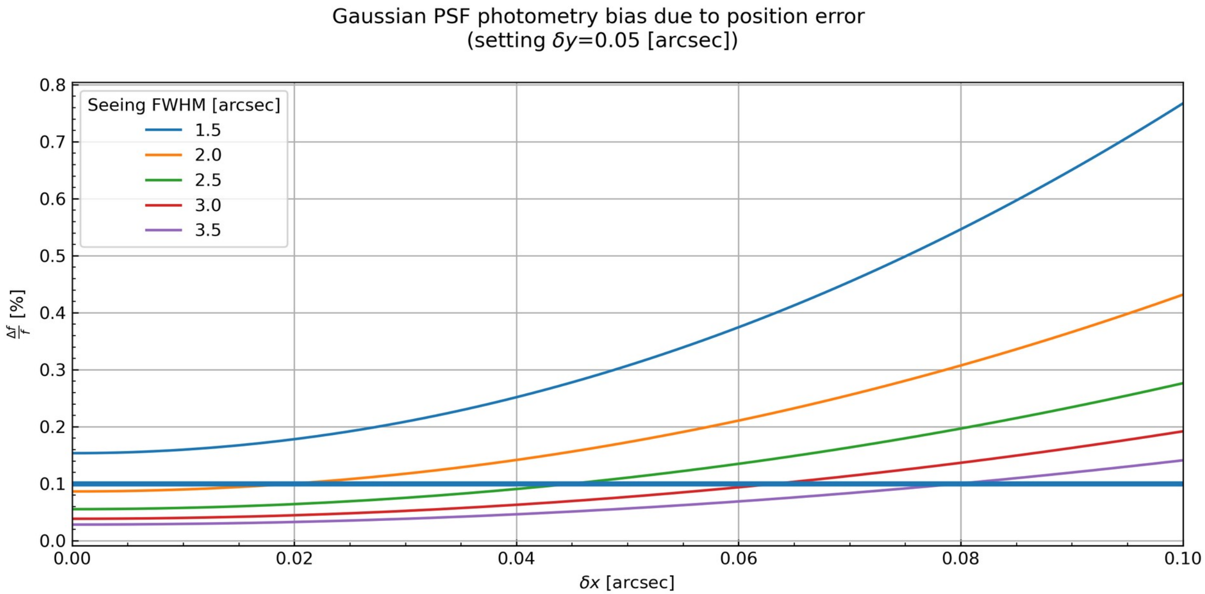
787
1789
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi
x [pixel]
Flux [ADU]
MJD


Close view
Lightcurve
ZTF18aagrcir
Field ID
1795
758
y [pixel] - zg
y [pixel] - zr
y [pixel] - zi
x [pixel]
Flux [ADU]
MJD

Scene modeling requirements

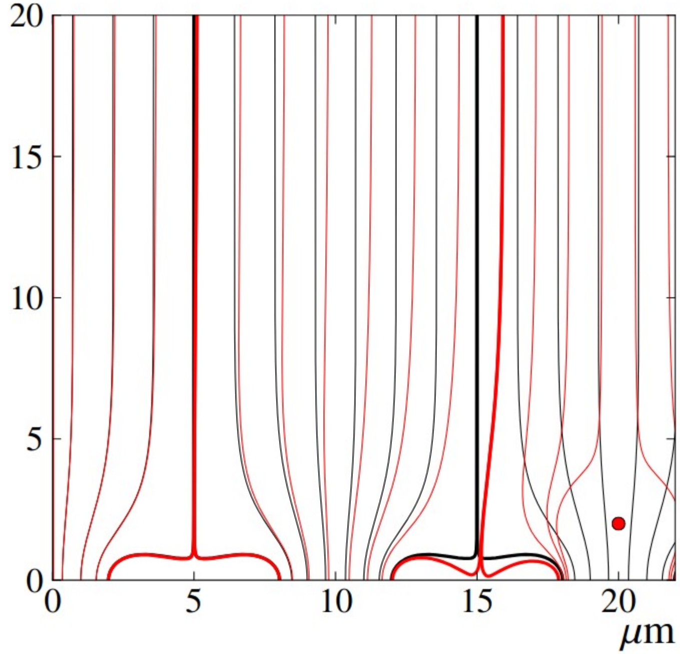
- Are we done? Not yet!
  - Still dominated by systematics
- Indeed: SMP has strict requirements
  - Robust and precise relative astrometry maps
  - PSF linearity → independent of flux



$$\frac{\Delta f}{f} = \frac{1}{4}\frac{\delta x^2 + \delta y^2}{\sigma_{\mathrm{IQ}}^2}$$

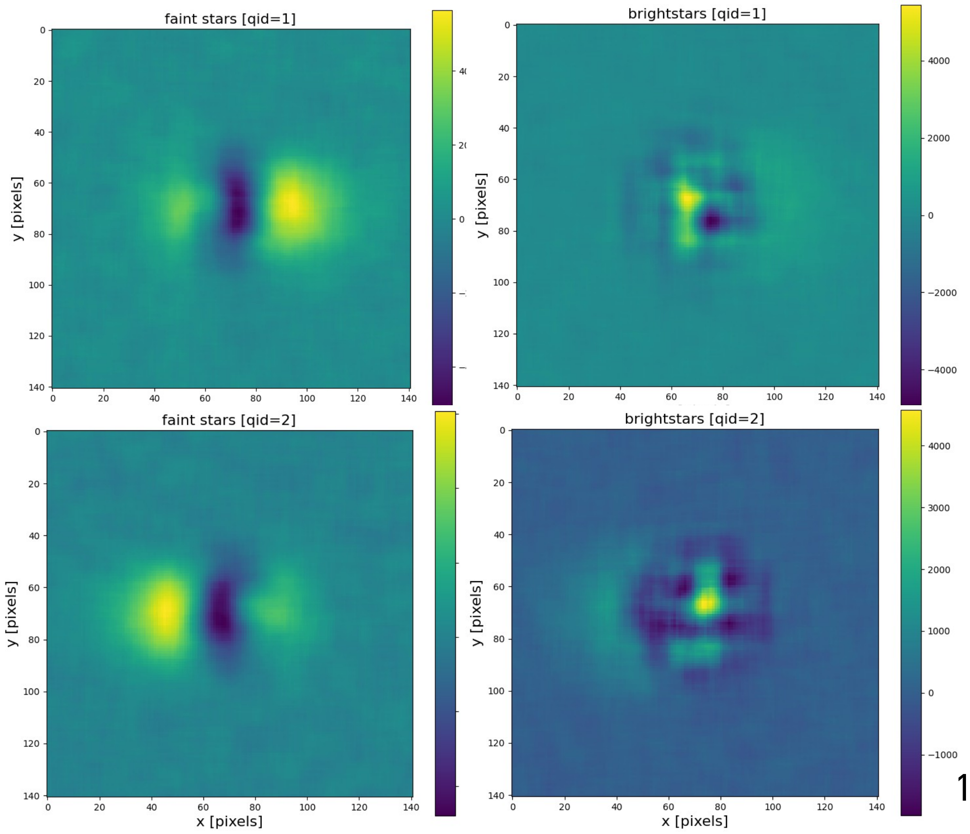
Sensor effects affecting PSF linearity

- Brighter-fatter
  - High flux
  - Expected
  - 1-2% effect (p-to-p)



(Guyonnet et al, 15, Astier ‘19, Astier & Regnault, ‘23)

- “Pocket effect”
  - Low flux – low background
  - Unexpected
  - 5-10% effect (p-to-p)



Toward DR 2.5

- Current state
  - Fast pipeline able to process full dataset
  - ‰ statistical precision
- However
  - Challenging instrumental effects need to be fully corrected (from raw pixels) → control of systematics at the ‰ level

These corrections implies full data processing

Conclusion

- Full pipeline: from raw pixels to calibrated lightcurves
- Scales well, suitable for spectroscopic ZTF III → ~10k SNe
  - Also enables photometric sample processing, i.e. ~40k SNe
- 10k low z Ia SNe → will be unmatched for years
- Prepares the LSST era

Thank you