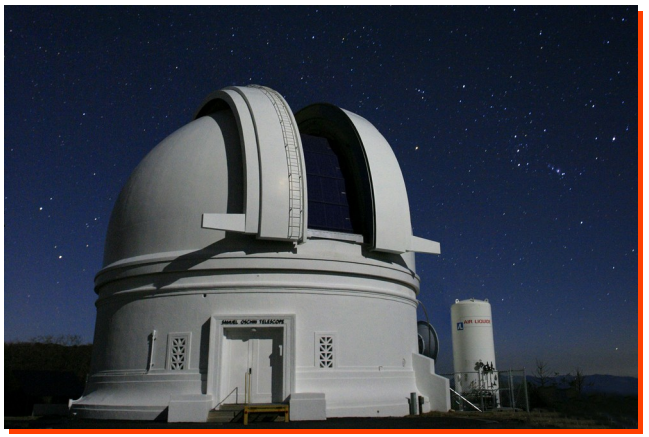



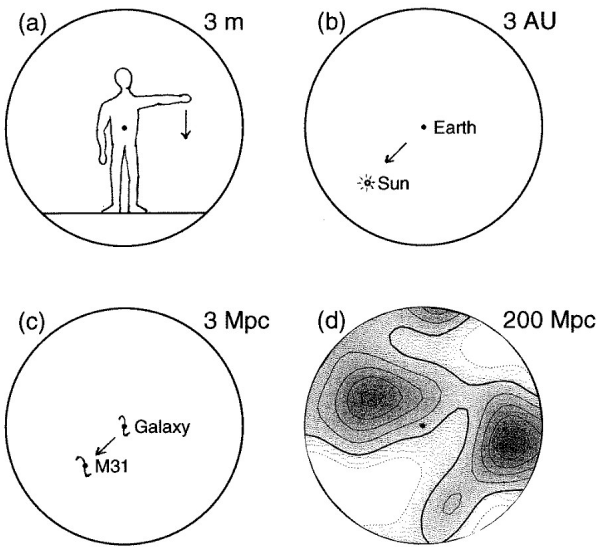

Supernova cosmology with the Zwicky Transient Facility

Leander Lacroix
LPNHE

Thesis advisor: Nicolas Regnault

Introduction to cosmology and the concept of dark energy

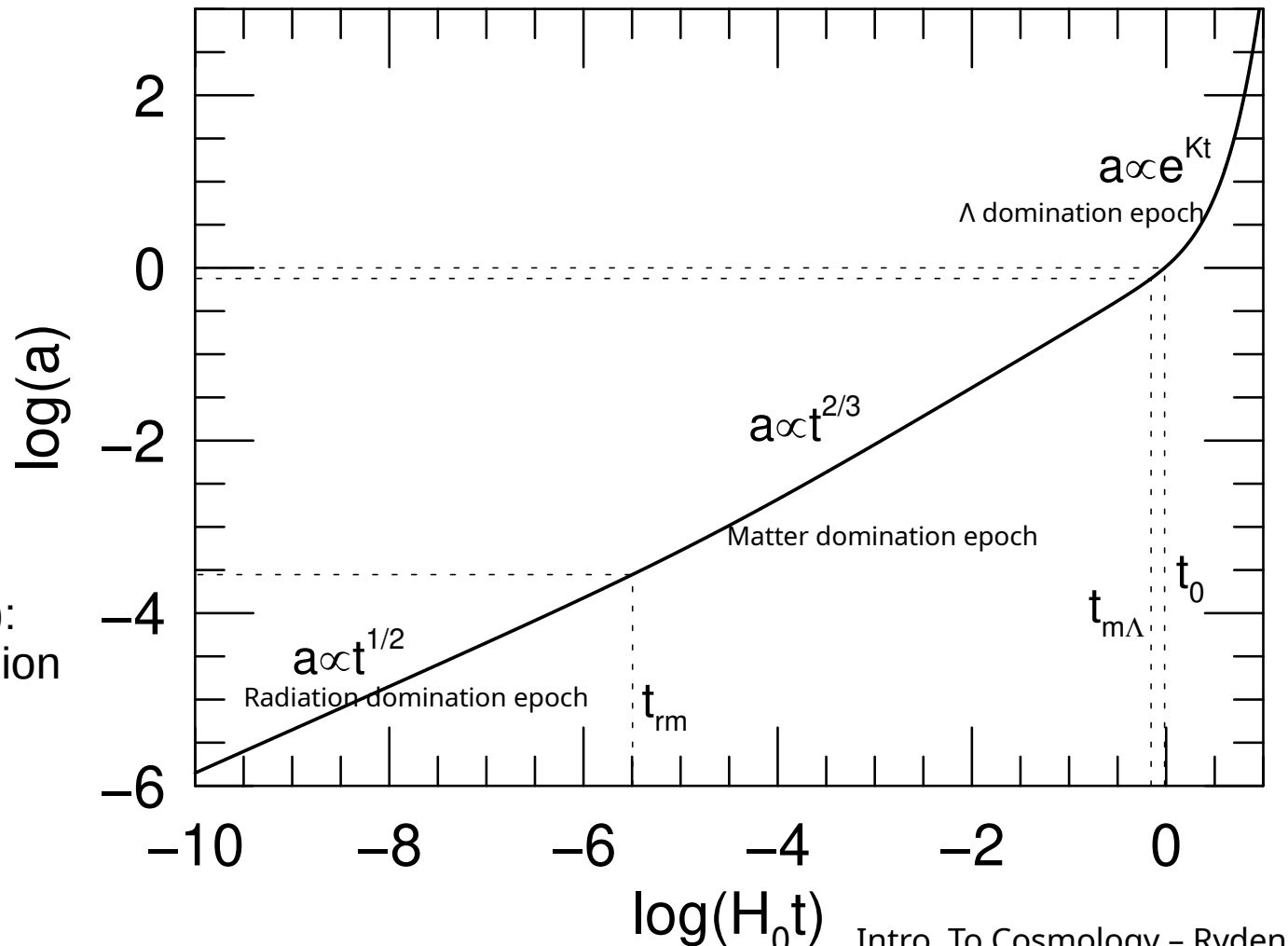
- Since end of 20th century, standard model of cosmology: Λ-CDM
- 6 parameters that describes our observations
- It supposes (at very large scale):
  - Isotropic
  - Homogeneity
- Is flat
- With components (today):
  - Radiation ~10^{-5}%
  - Matter ~30% (5% barionic matter, 25% dark matter)
  - Dark energy ~70%
- Expansion described by the Friedmann equation



Intro. to Cosmology (Ryden 2014)

Cosmic acceleration

Scale factor a(t): quantify expansion

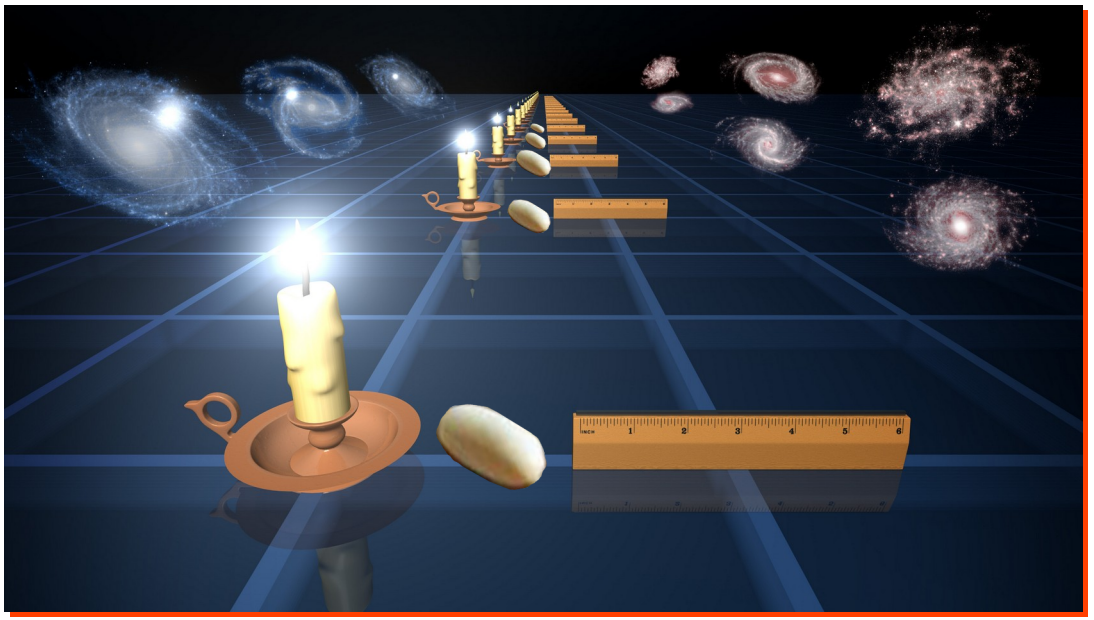


Cosmic acceleration

- What is the cause of cosmic acceleration?
  - Cosmological constant – Λ?
  - Homogeneous fluid of negative pressure???
  - Slowly evolving scalar field?
  - General Relativity does not hold at high redshift?
    - If it were the case, large scale structures growth would be different
- Theory untangling is done by precise measurements
  - Tests of the Λ-CDM model

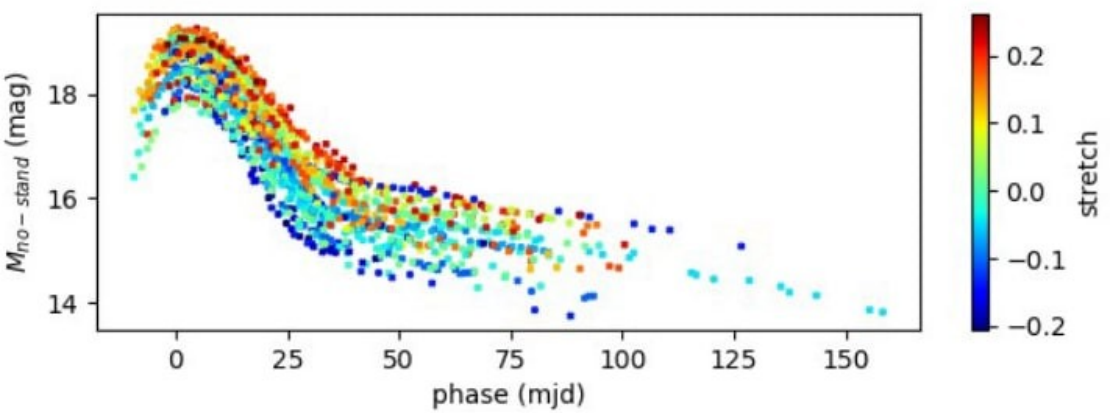
Probing the expansion history

- Equivalent as probing the Universe content
  - Fraction of components (baryonic matter, radiation, dark energy)
- Distance – redshift relation: 3 complementary probes
  - Type Ia supernovae luminosity
    - Standard candle
  - Angular size of BAO peak
    - Standard ruler
  - Binary black hole mergers
    - Standard siren

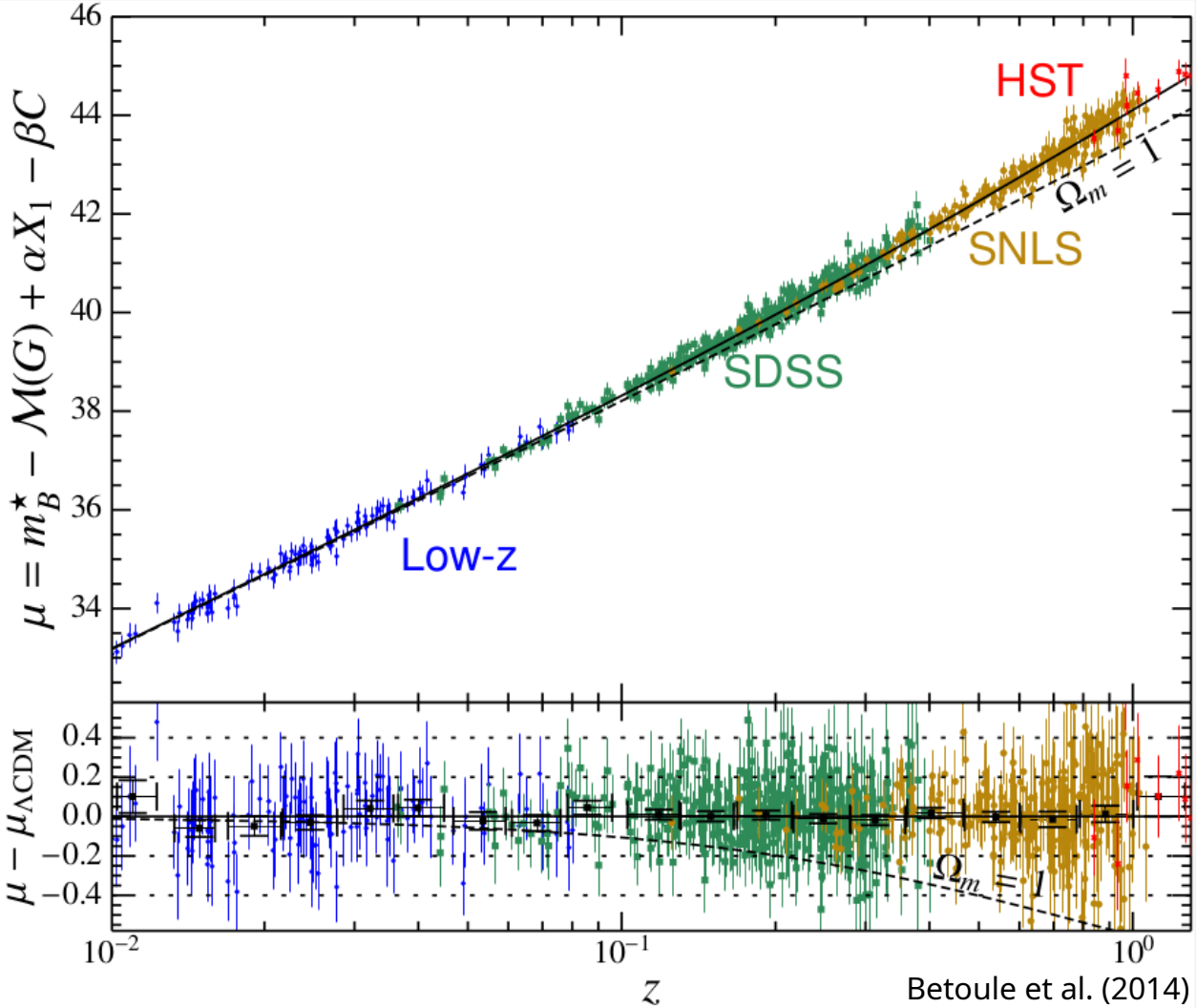


Using supernovae as standard candle

- SN Ia variability (intrinsic variability: ~40%)
  - Brighter-slower relation
  - Brighter-bluer relation (empirical)
- After standardization variability: ~15%
- Standardized distance modulus
- Empirical SN Ia models
  - SALT 2, SALT 3
  - NaCl

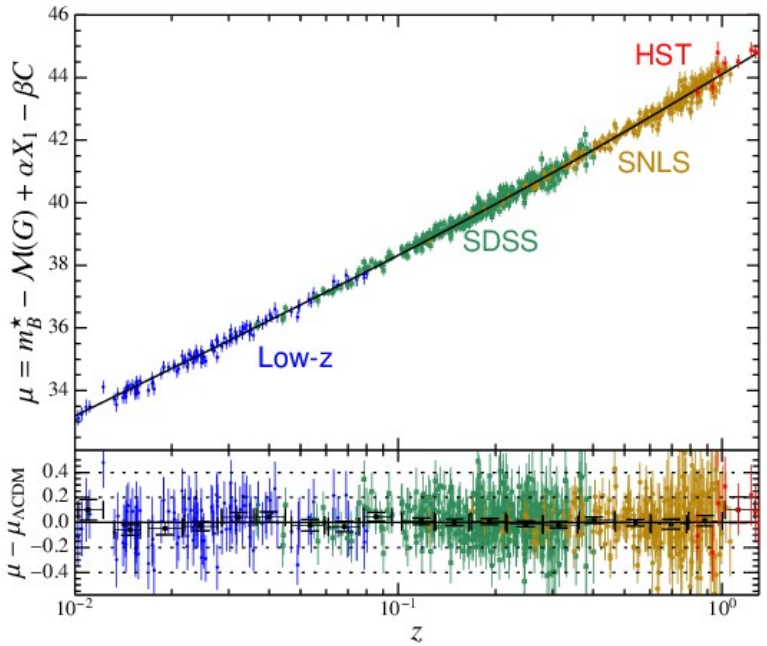


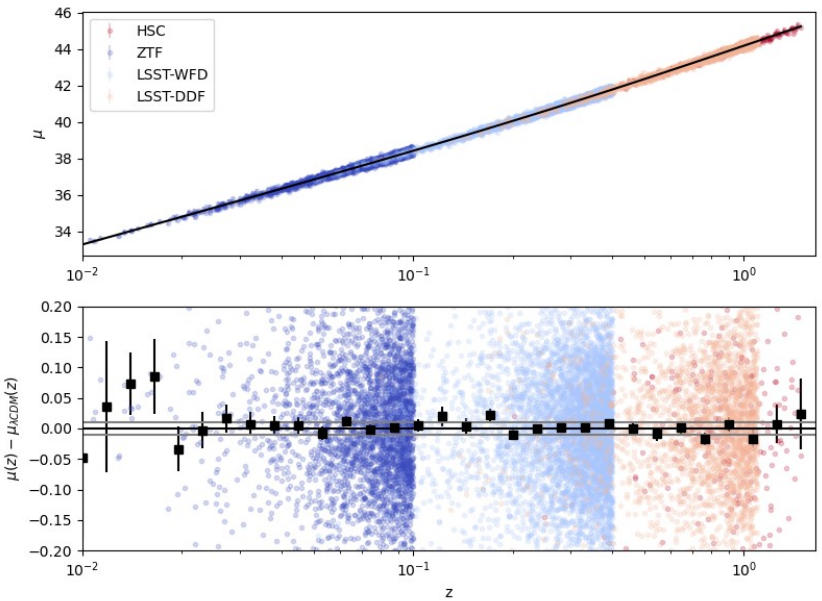
Mapping the expansion history with type Ia SNe



Betoule et al. (2014)

Next step



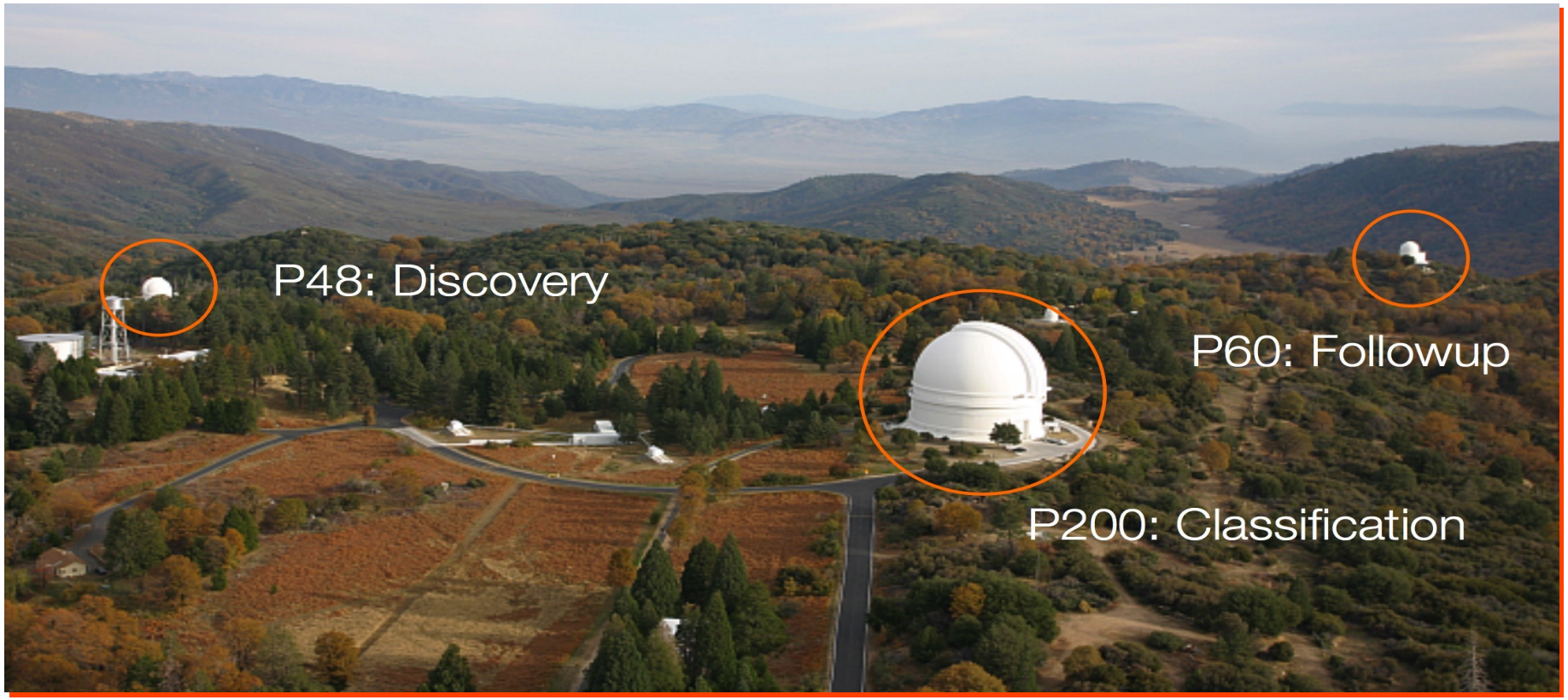


- 2014 : O(1000) SNe (JLA++)
- 2022 : O(5000) SNe
- 2025 : O(10000) SNe

The Zwicky Transient Facility (ZTF) survey

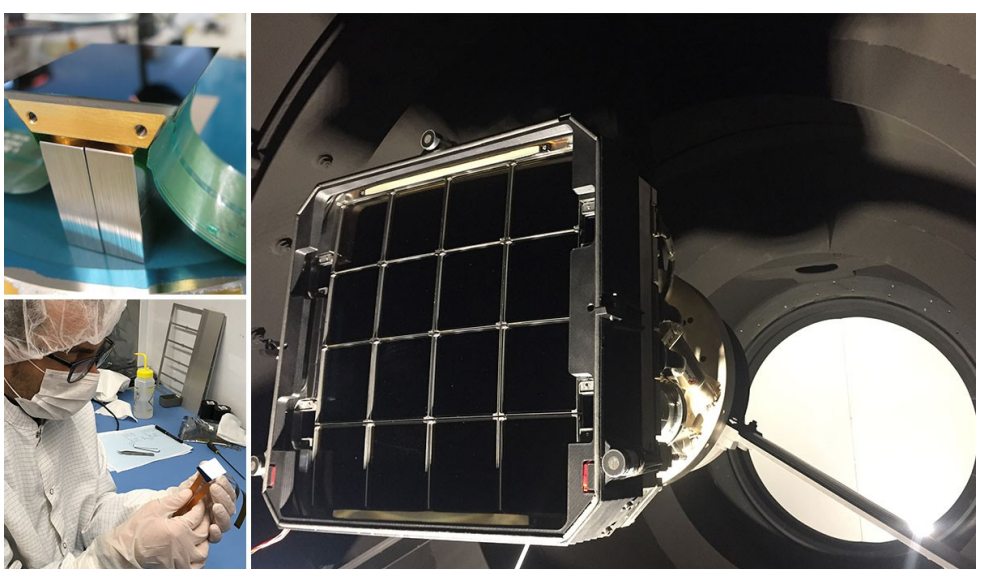
- Low redshift northern hemisphere survey, designed for rare transient events, solar system objects tracking
  - Large field of view (47 deg^2 per exposure, ~200 times the Moon)
  - High cadency (twice the extragalactic sky per night)
  - 3 filters: g r i
  - 2 dedicated spectrograph
  - Automated operation
- Camera mounted on the Samuel Oschin telescope ! (P48, ~1.2m)

Palomar Observatory

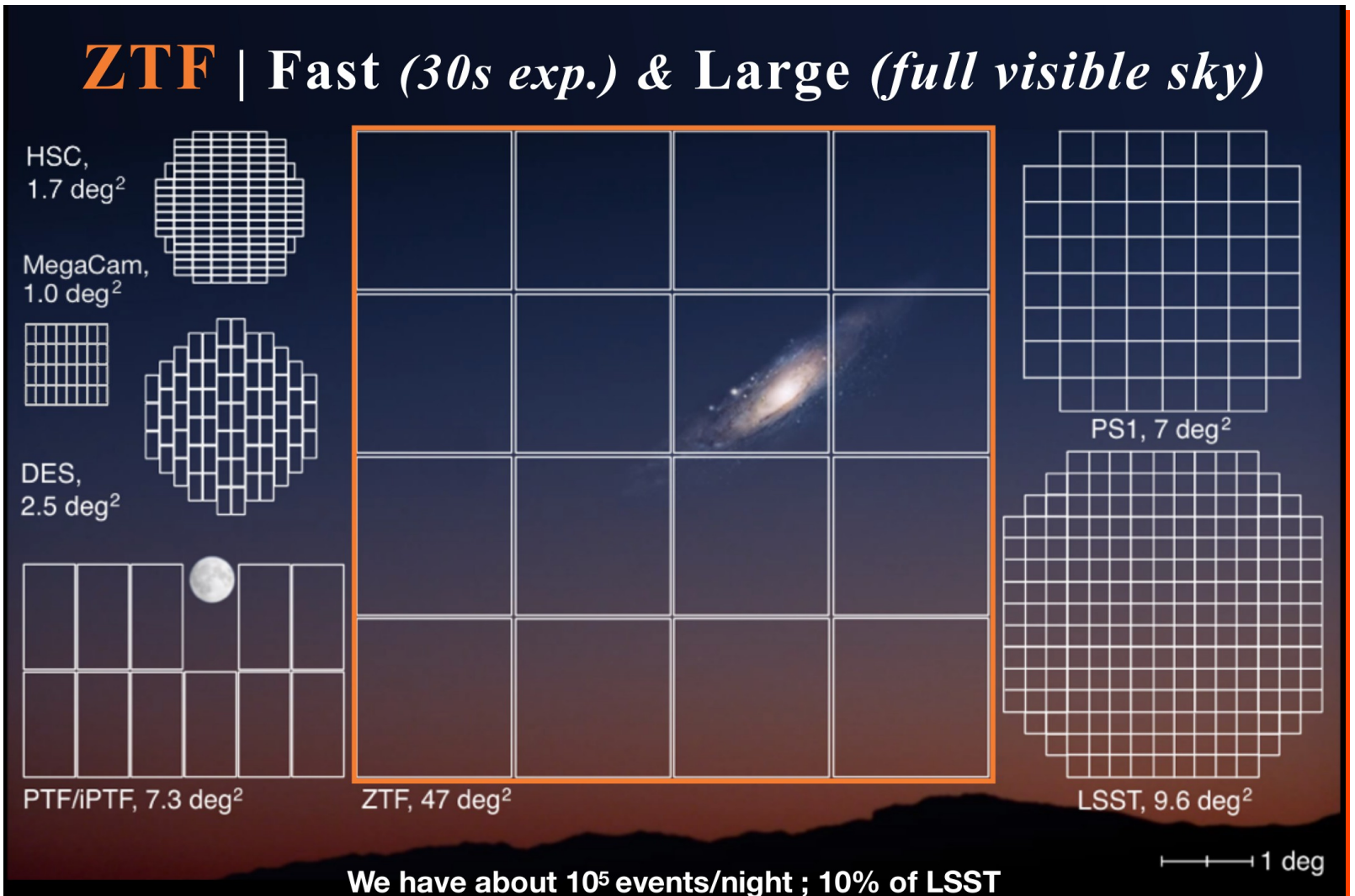


The ZTF camera

- 16 × 6144 × 6160 CCD array (606 Mpixels)
  - Subdivided into 64 quadrants (3072x3080)
  - 1 pixel ~ 1.”01
    - Close to the Nyquist pixel sampling limit!

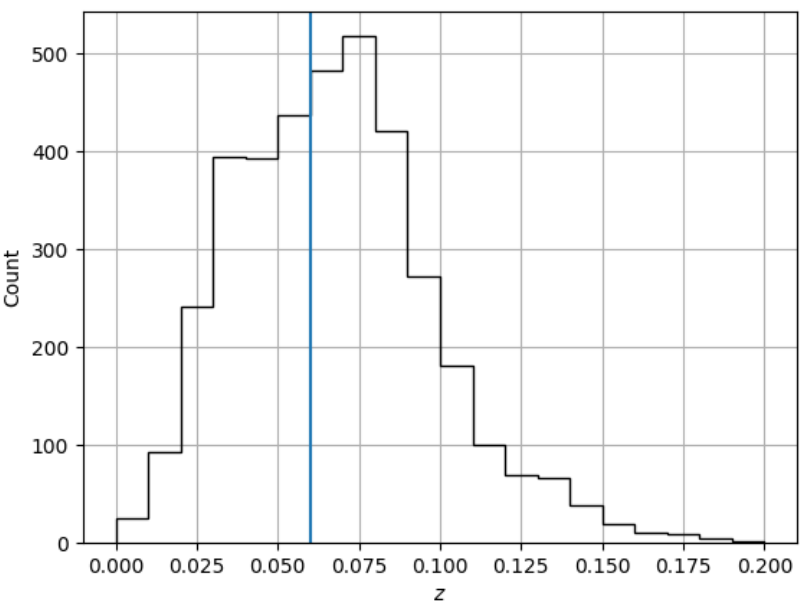


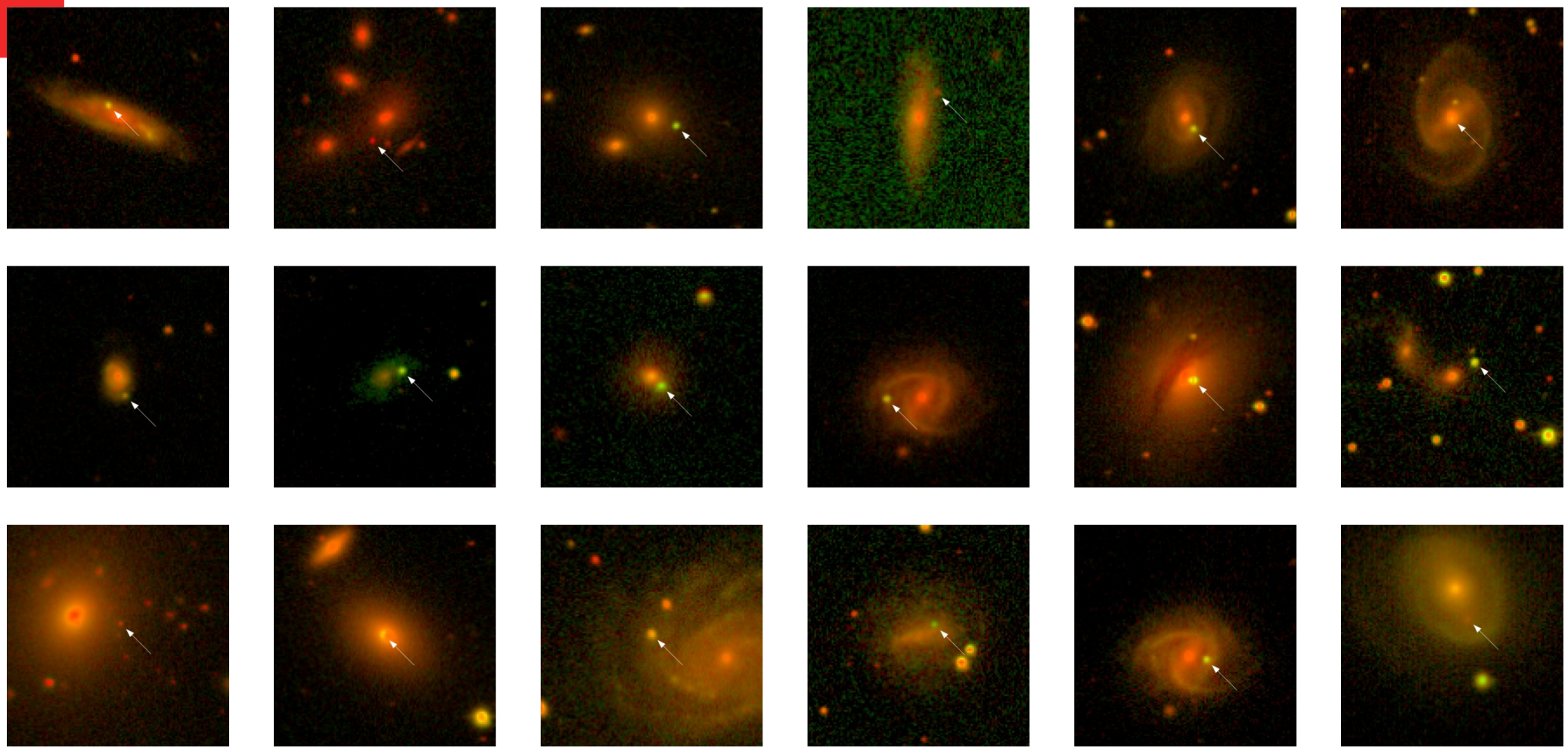
ZTF camera field of view

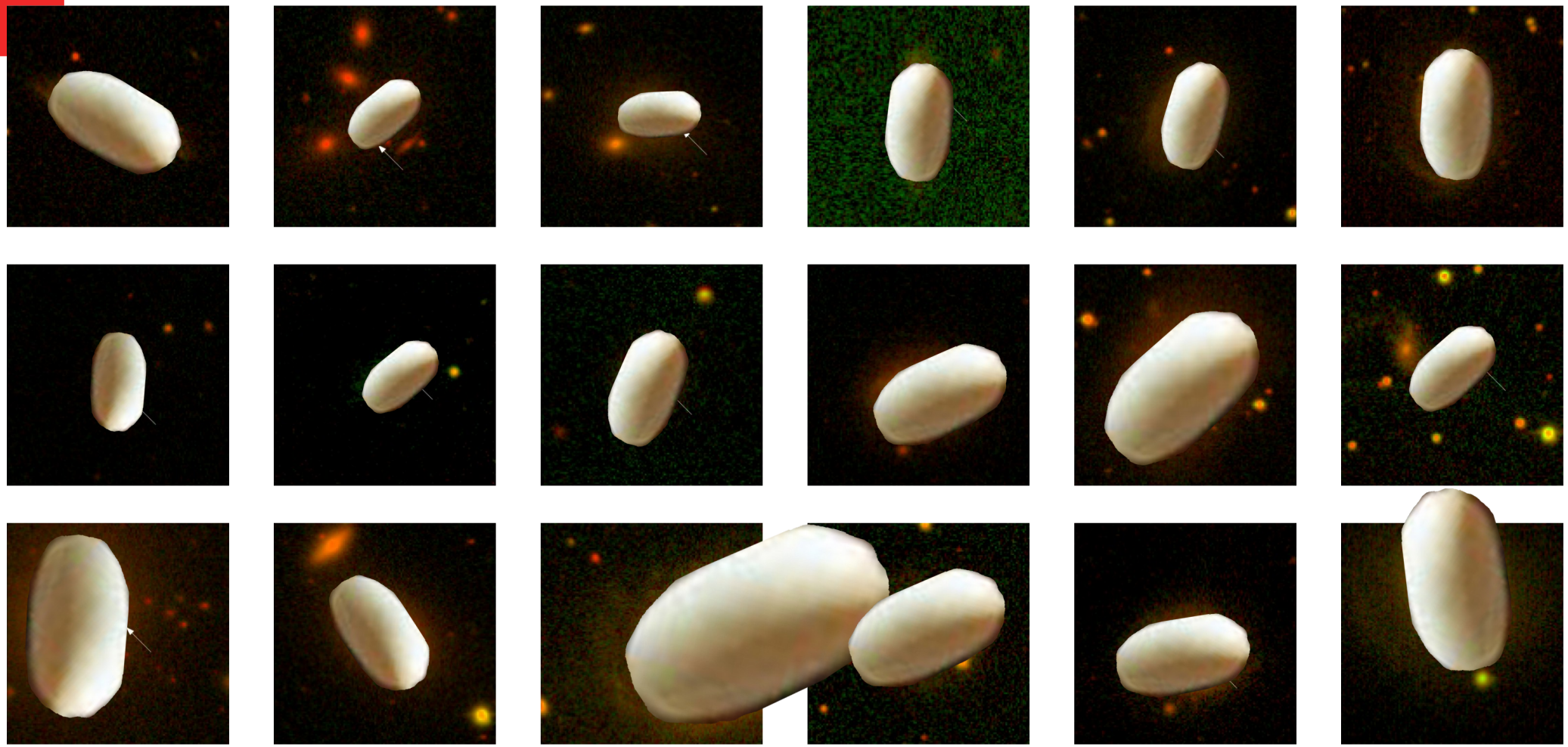


The ZTF SNe Ia dataset

- 40k SNe up to z = 0.15
- ~ 4k spectroscopically identified SN Ia, homogeneously distributed
  - Sample complete to z=0.06 (~1,7k)
  - 250 TB on disk!
  - At the end of the survey: 6k SNe








6k SNe la !!!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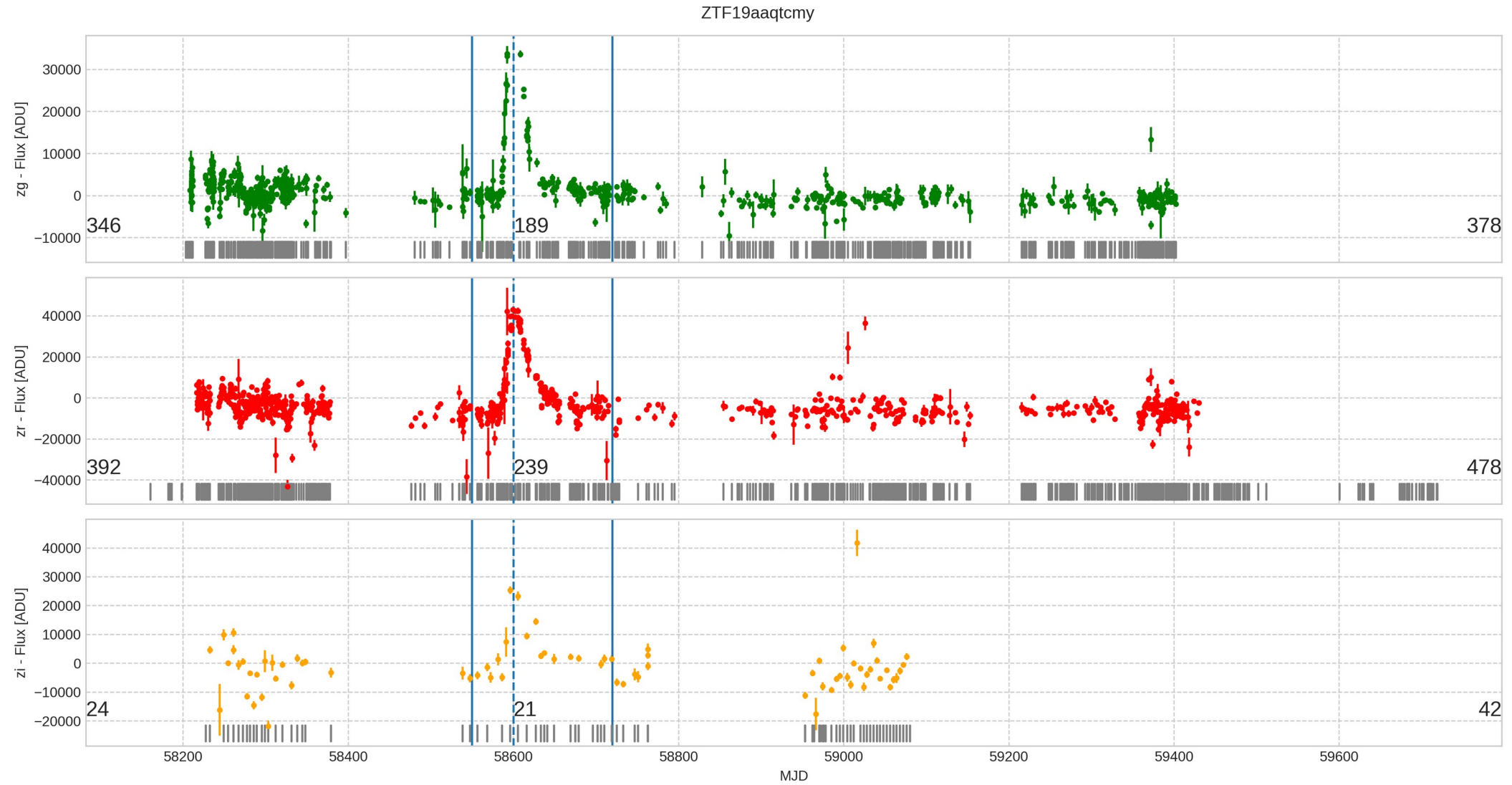
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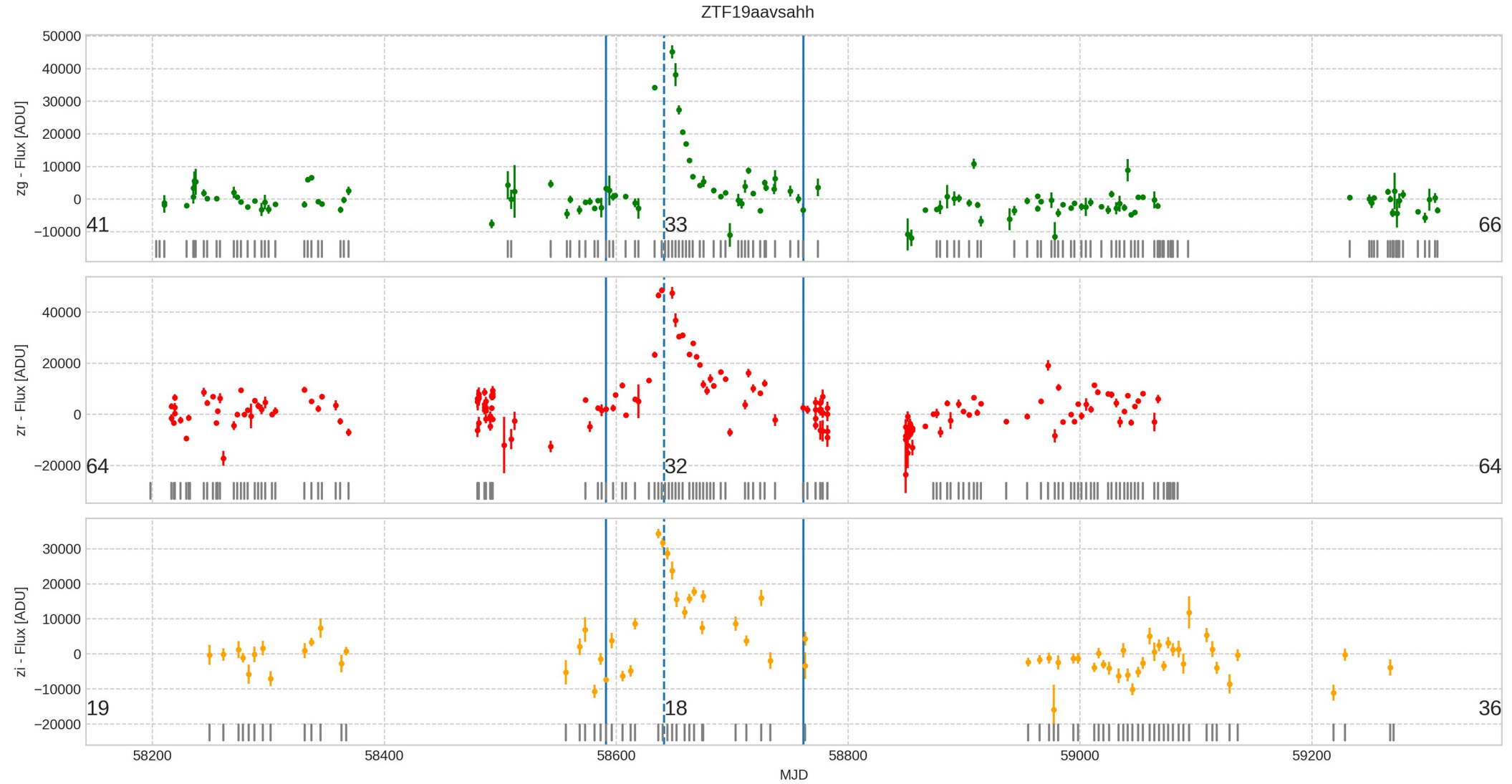
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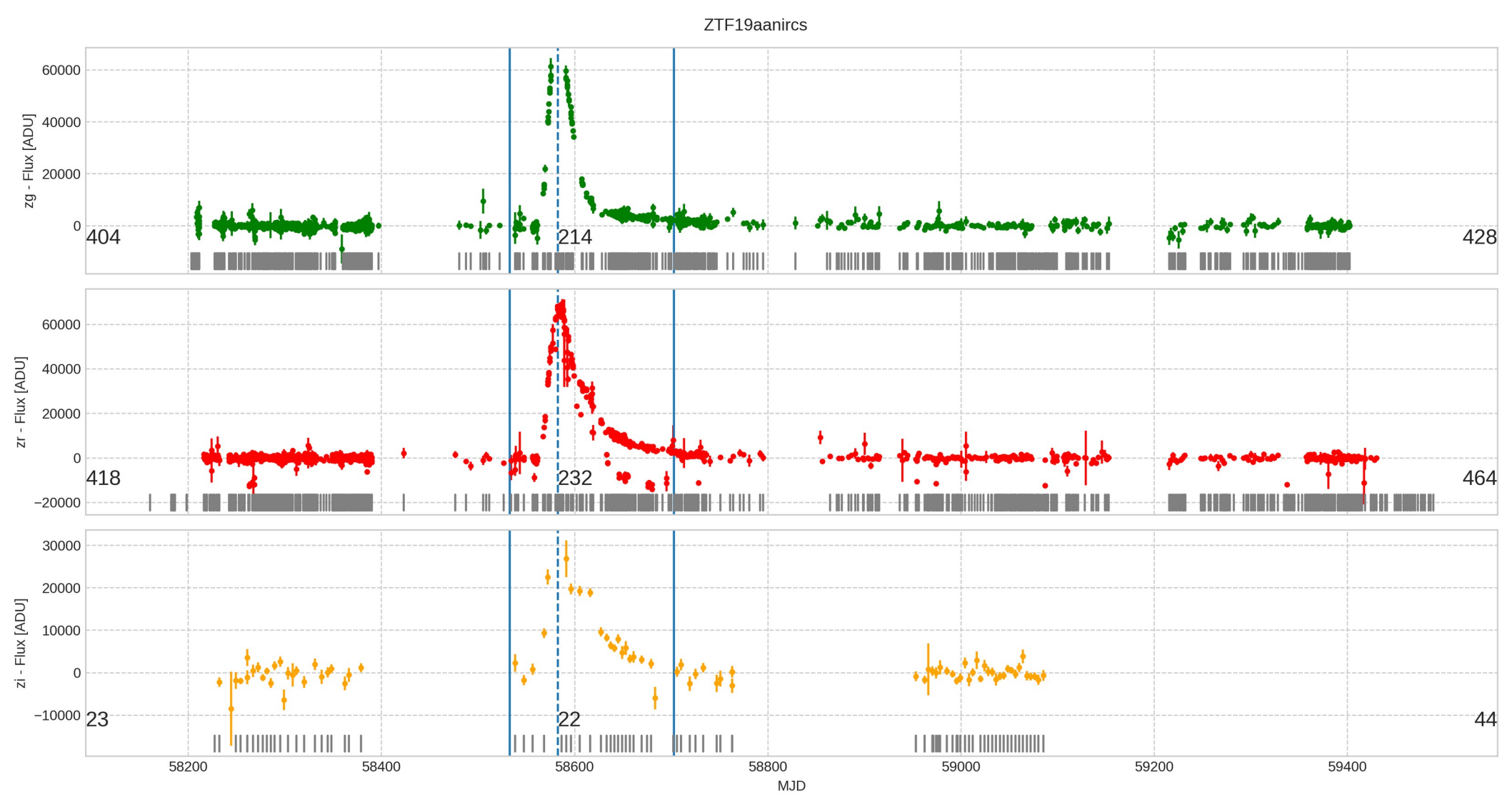
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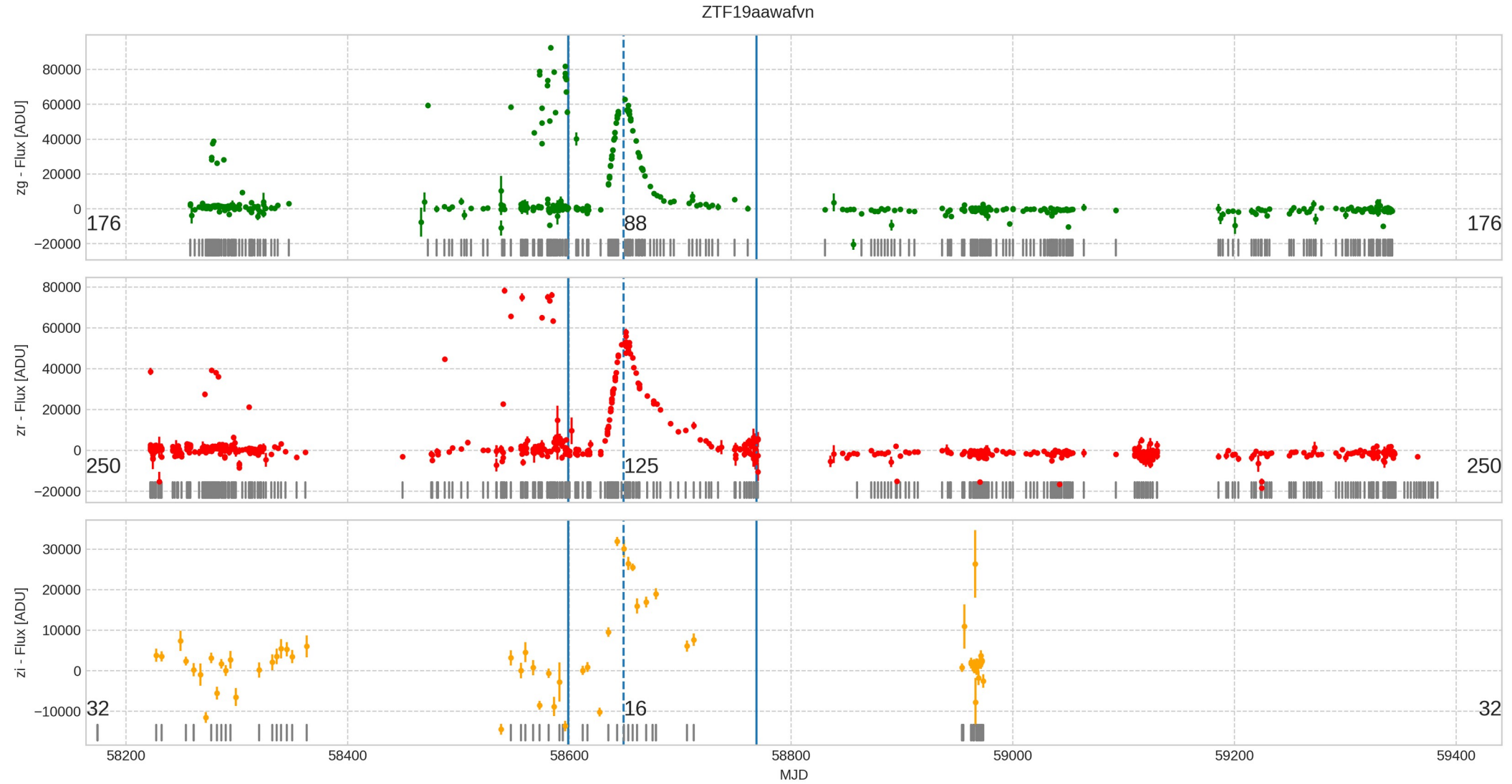
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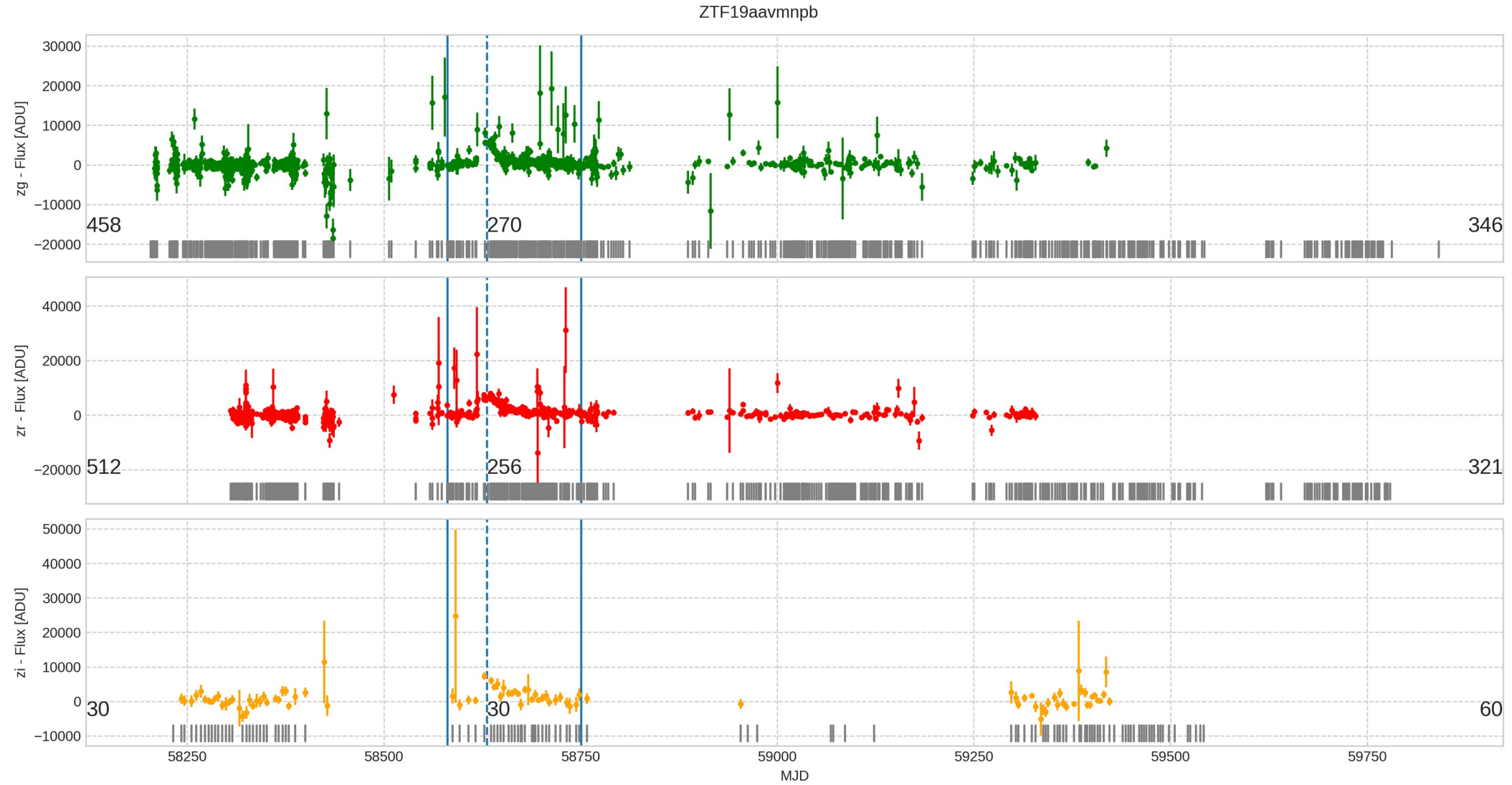
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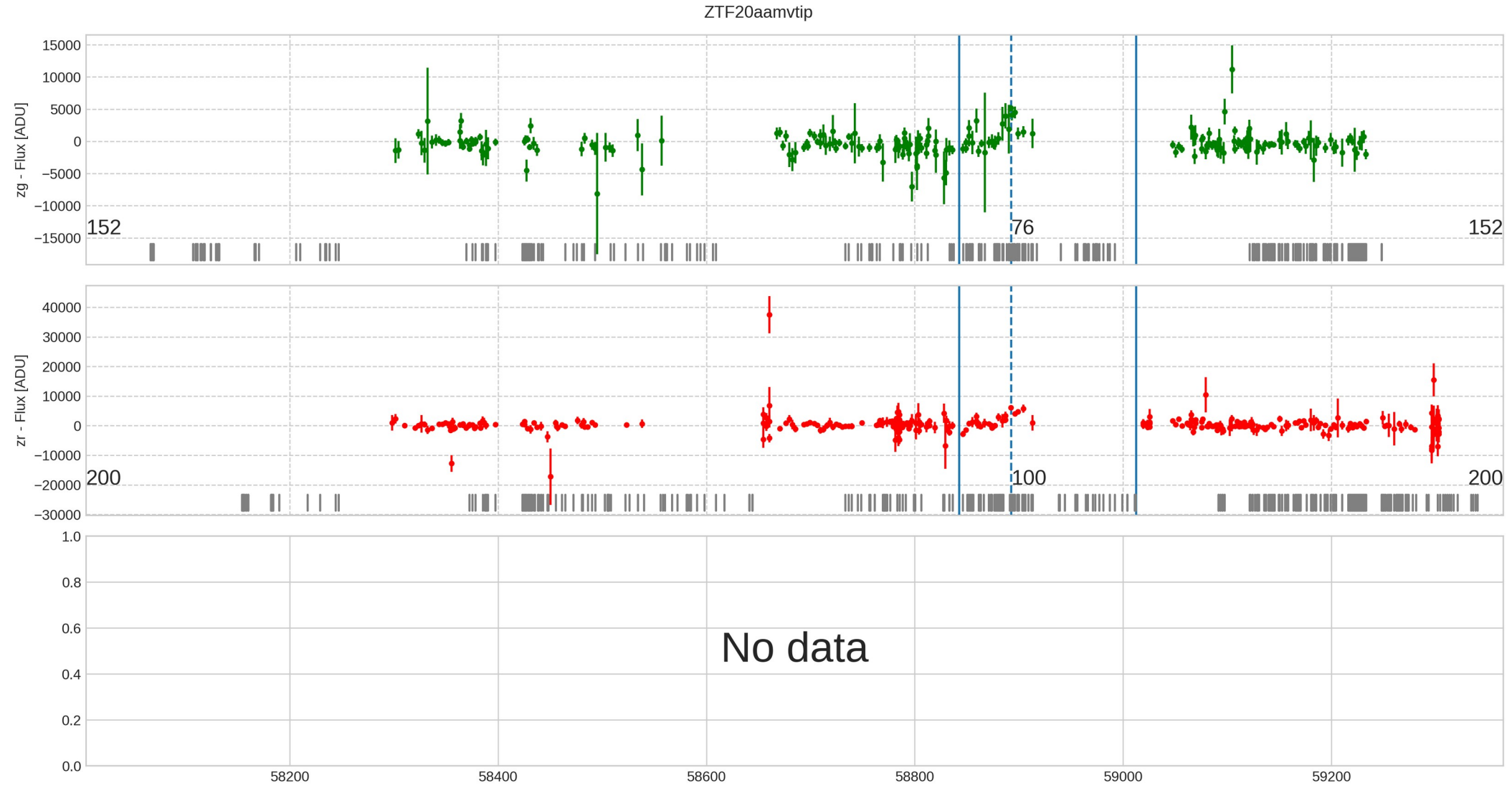
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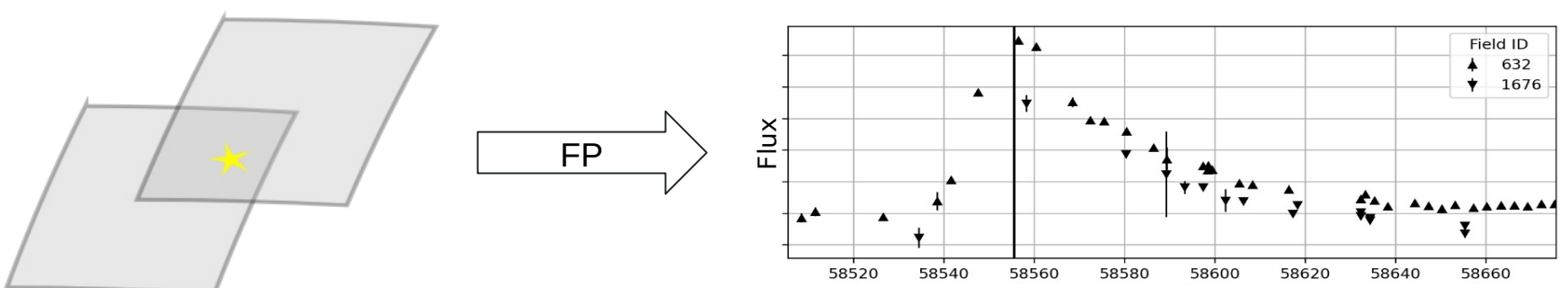
Calibration effort for precision cosmology

- ZTF is great to capture transient events in the close universe
  - Why not use it for SN Ia cosmology?
- Precision cosmology needs proper calibration
  - ZTF pipeline repeatability: 2%
  - Our goal: 0.2%
- French team joined phase II
  - Calibration of the instrument, survey and light curves to get a cosmology grade dataset
  - Science prospects
    - Hubble diagram
    - Dark energy equation of state constraints
    - $f\sigma_8$

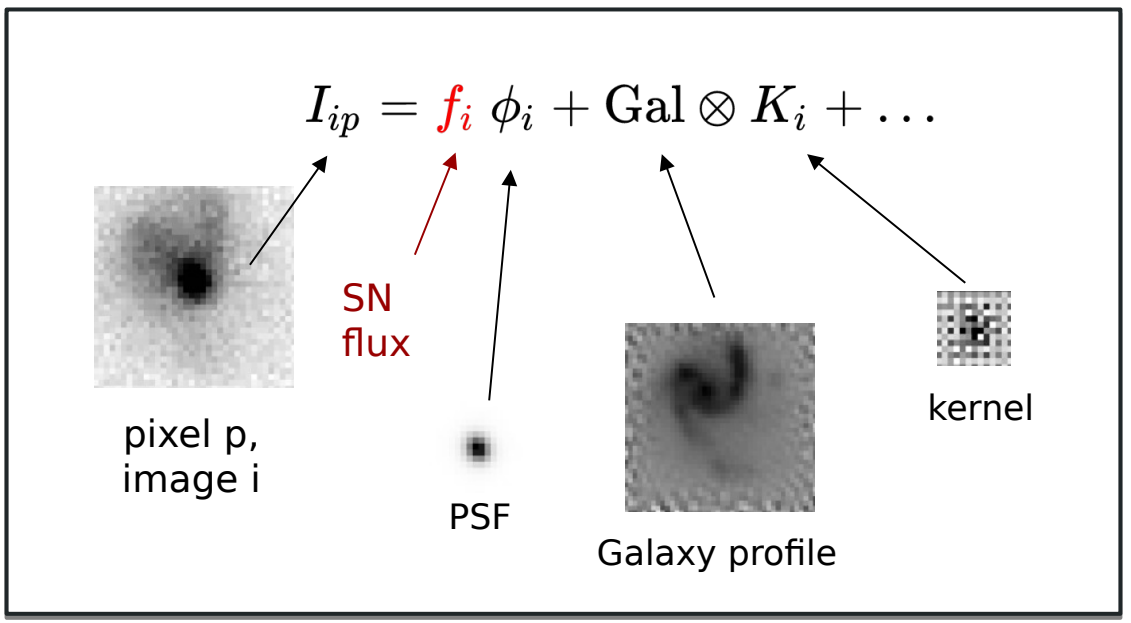
Light curve calibration

- ZTF already provides SNe lightcurves
  - Relies on forced photometry: flux estimation from difference images
- Weaknesses:
  - Flux calibration can not be applied to surrounding stars, i.e. no direct calibration propagation
  - Can not use PSF photometry
  - Lightcurve duplication if SN lives on different fields



Scene Modeling Photometry (SMP)

- Statistically optimal maximum likelihood flux estimator



Simultaneously fit:
- SN flux sequence
- SN position
- Empirical galaxy profile

Scene Modeling Photometry (SMP)

Define reference quadrant – computations will be relative to it

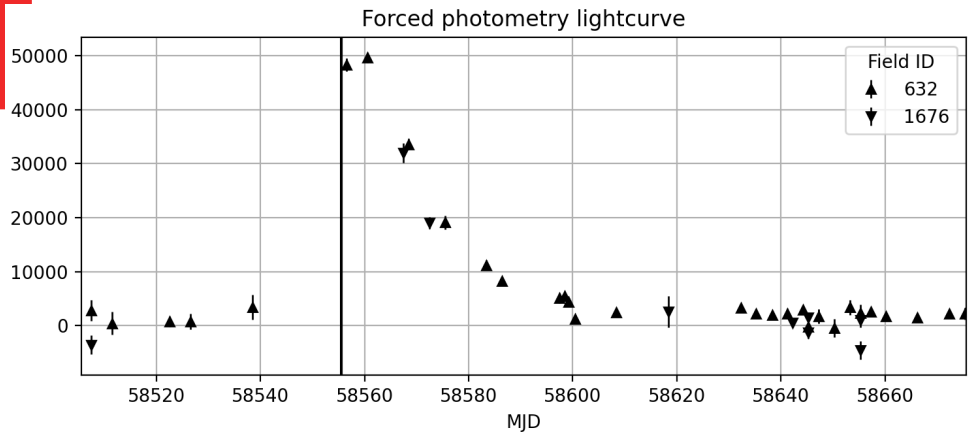
$$I_{i,p} = \alpha_i \phi_i (x_p - T_i(x_{\mathrm{SN}})) f_i + \alpha_i G_p(T_i^{-1}(x_p)) * K_i$$

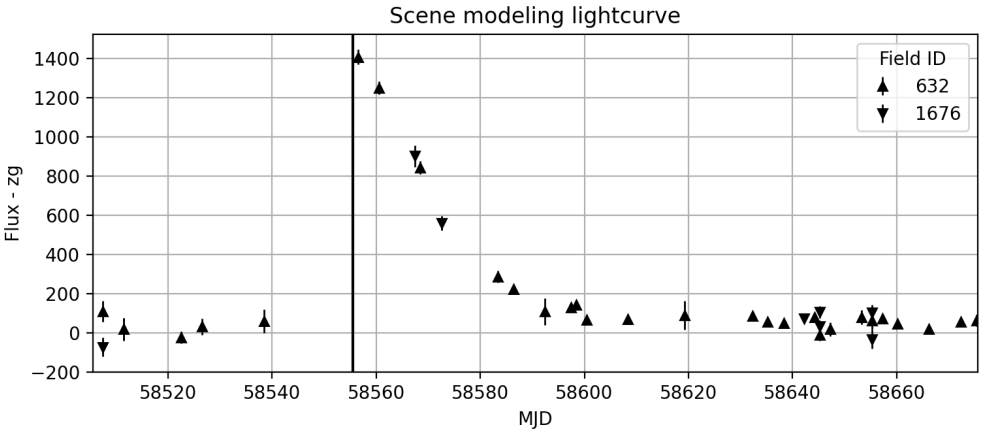
- Evaluated a priori
  - ϕ_i : intensity w.r.t. reference quadrant
  - α_i : PSF model
  - T_i : pixel mapping from reference quadrant
- Fitted by the model
  - x_{SN}: SN position
  - f_i : SN flux
  - G_p : Galaxy profile model
- Evaluated on the fly
  - K_i : reference to image #i convolution kernel

Pipeline implementation

- SMP implementation originally written for SNLS: “Poloka Toolkit”
  - Developed at LPNHE
- Handles the whole pipeline: from preprocessing to calibrated lightcurves
  - Works well and validated
- However:
  - Designed for deep field surveys
  - Extensively uses IO
  - Some operations are slow, in particular PSF modeling
  - Some other designs shortcomings
  - Relative astrometry and photometry still has to be handled

ZTF19aamaeve





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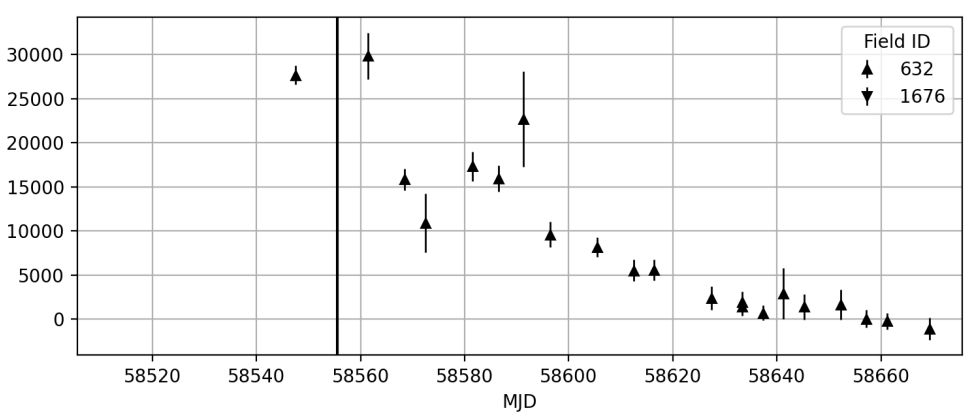

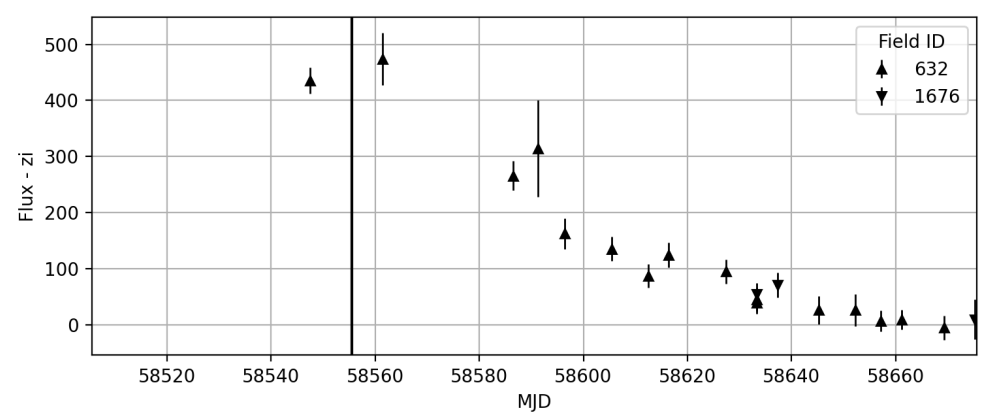

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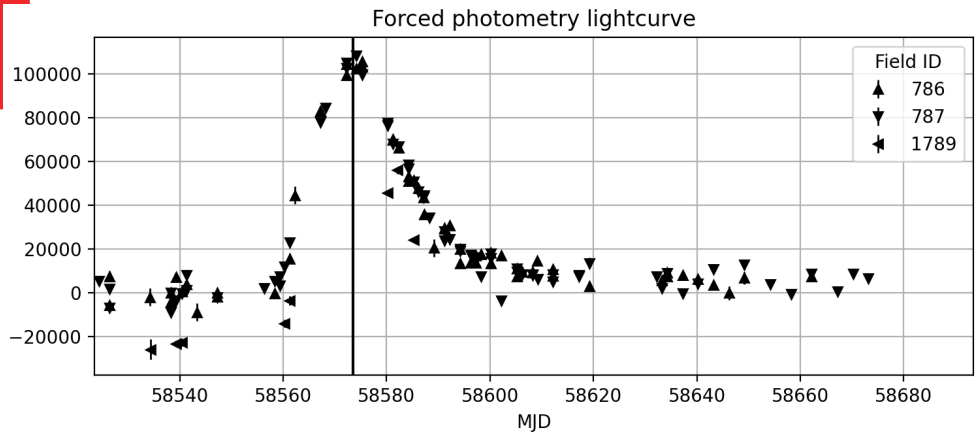

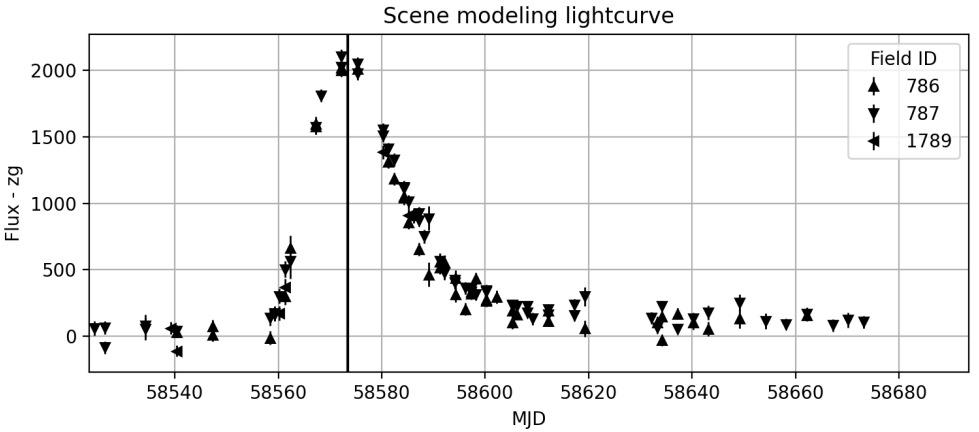

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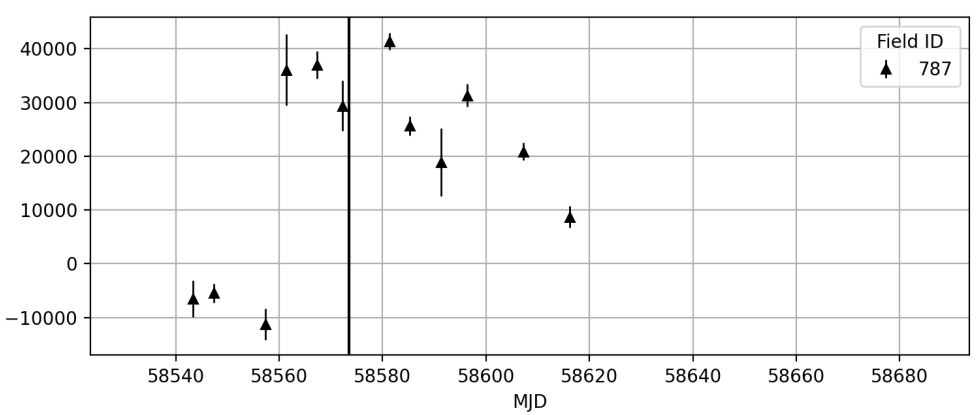

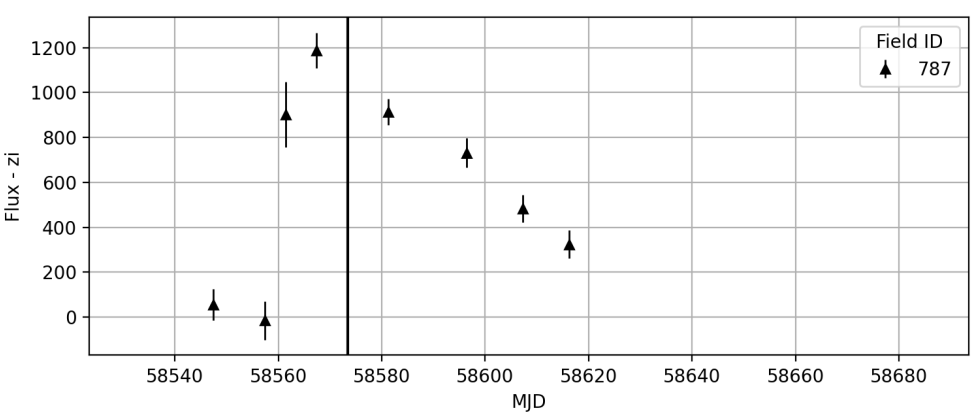

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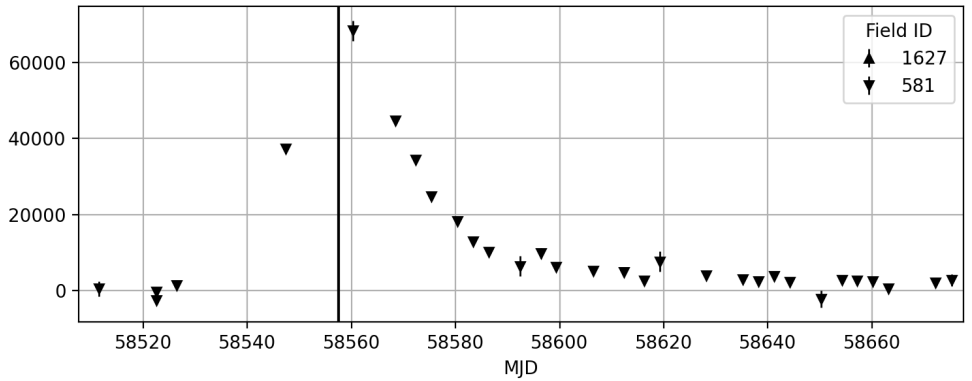
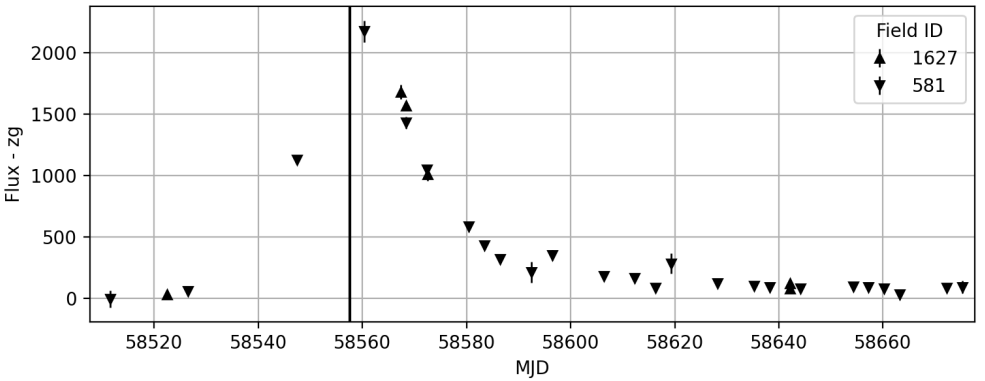
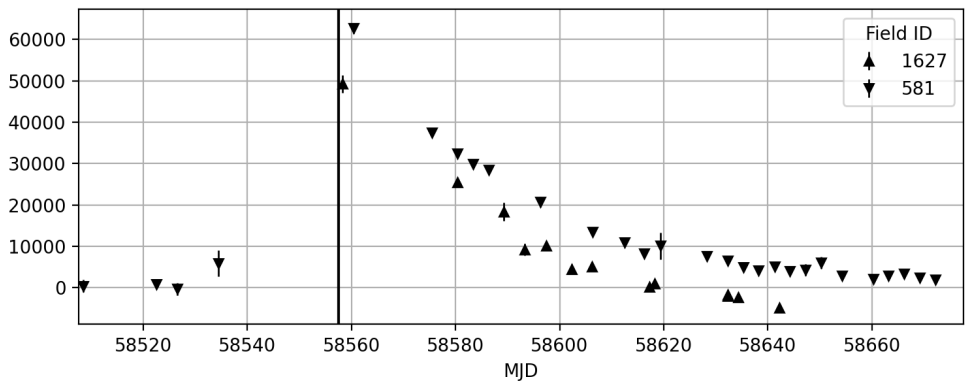
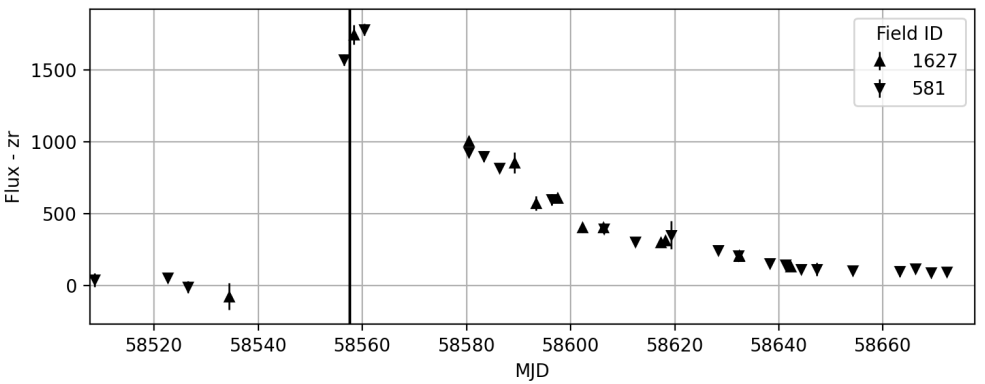
Forced photometry lightcurve

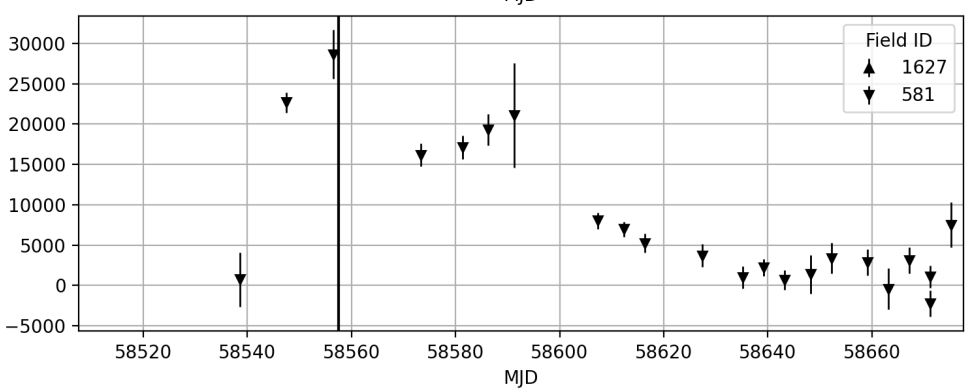


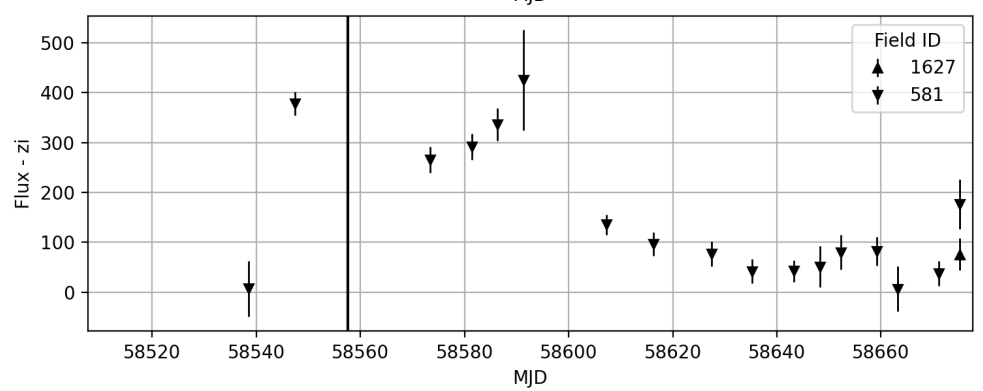
Scene modeling lightcurve











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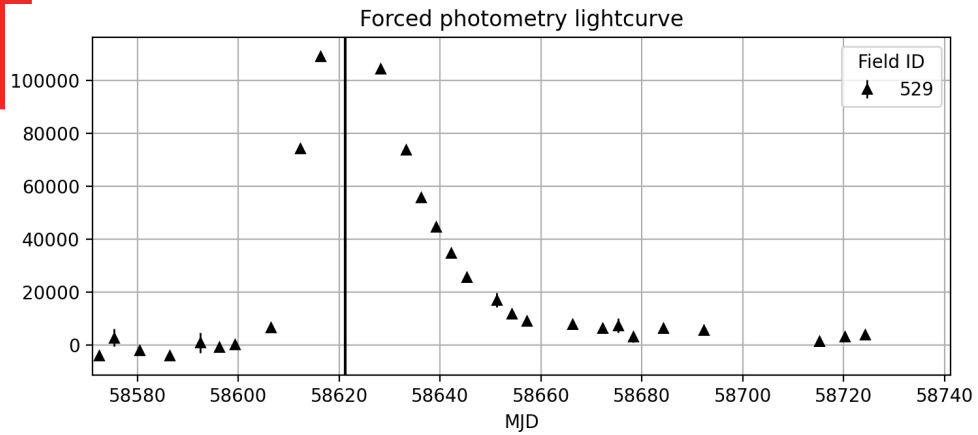

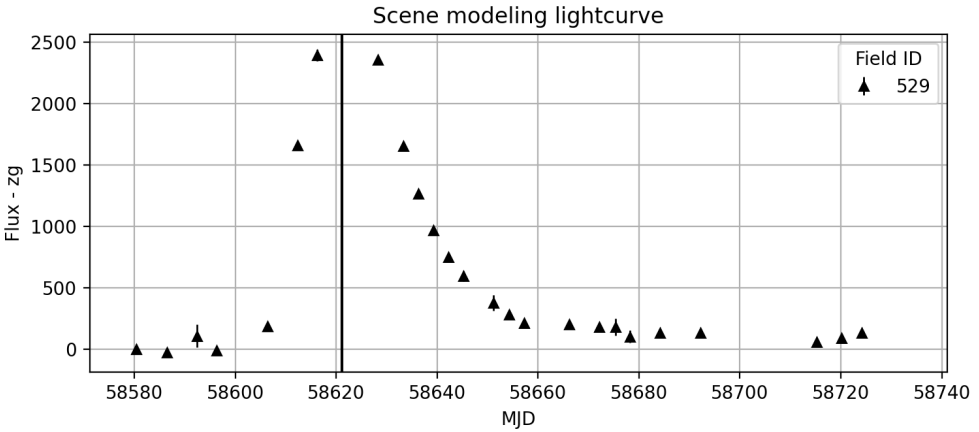

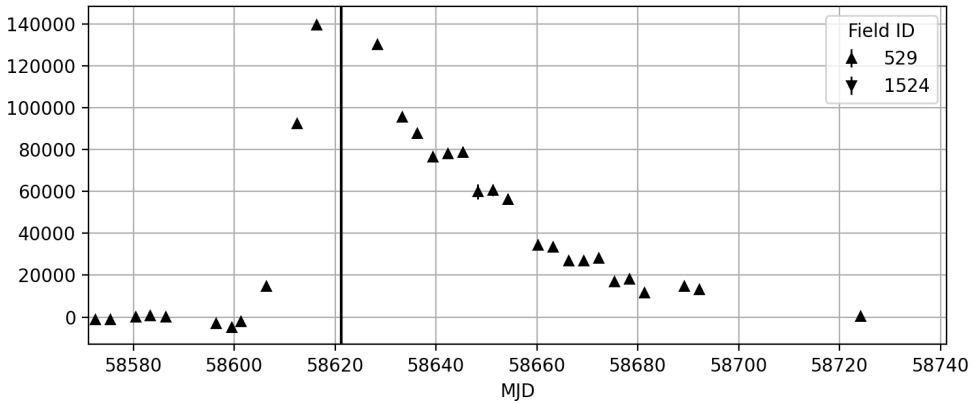

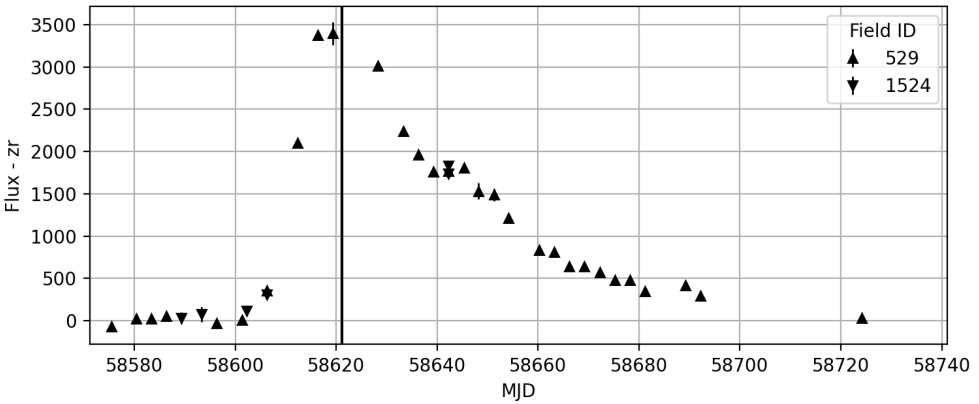

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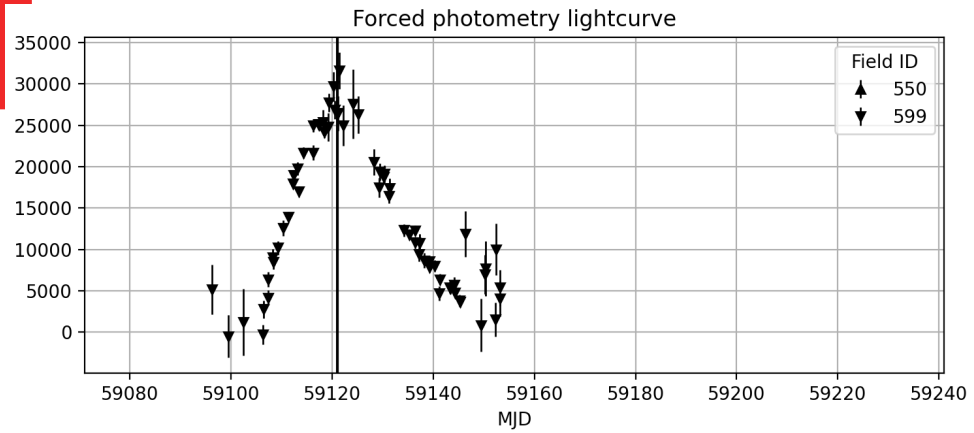
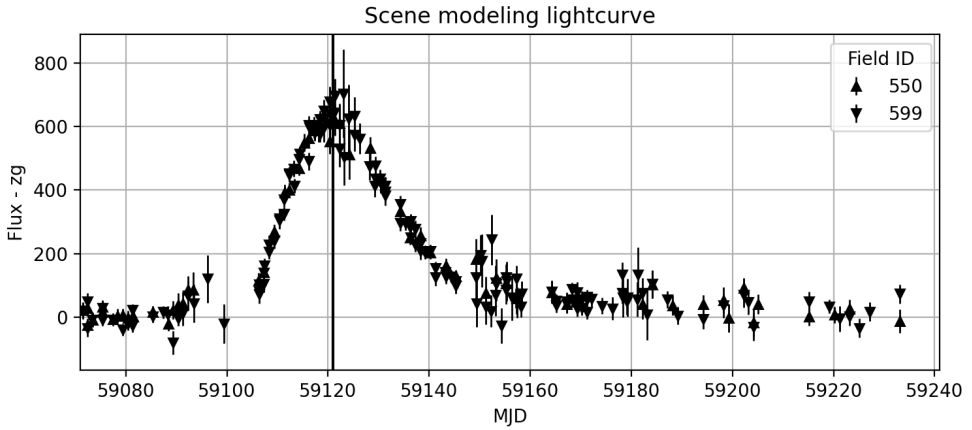
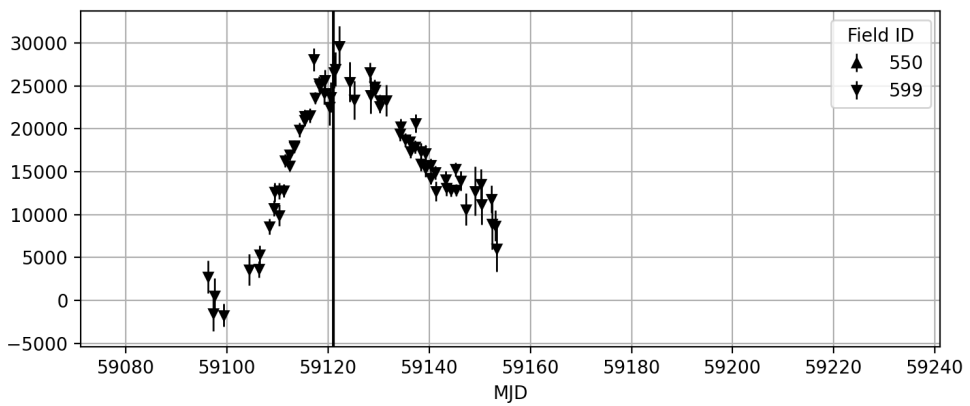
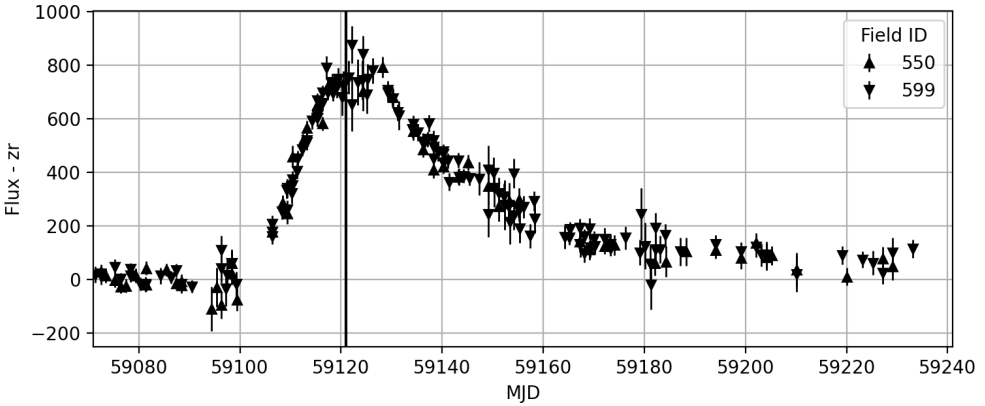


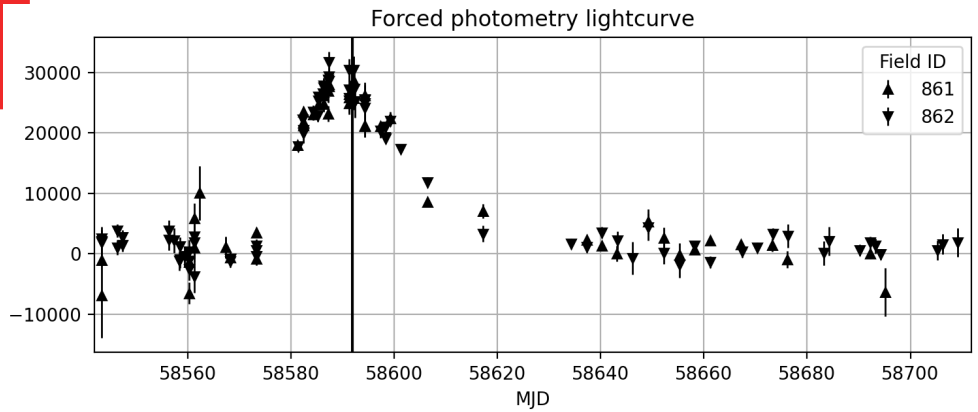


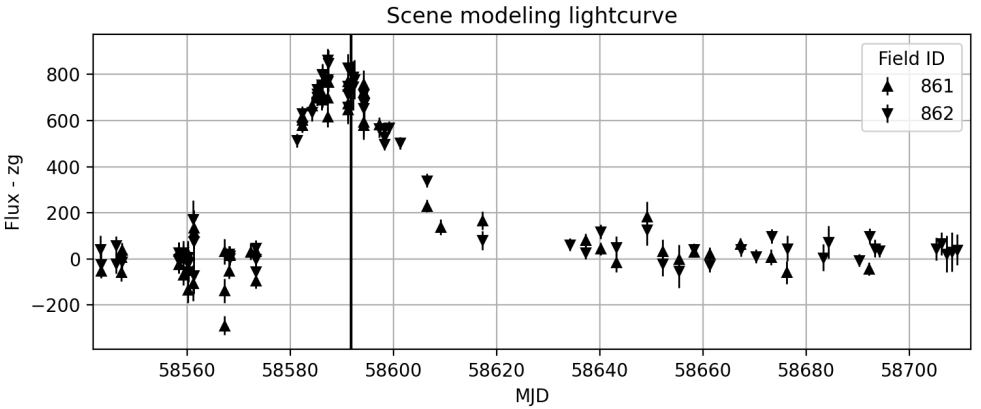


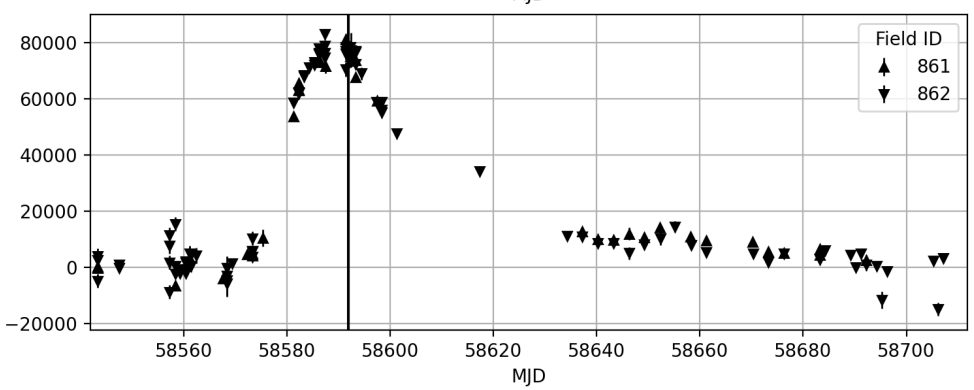


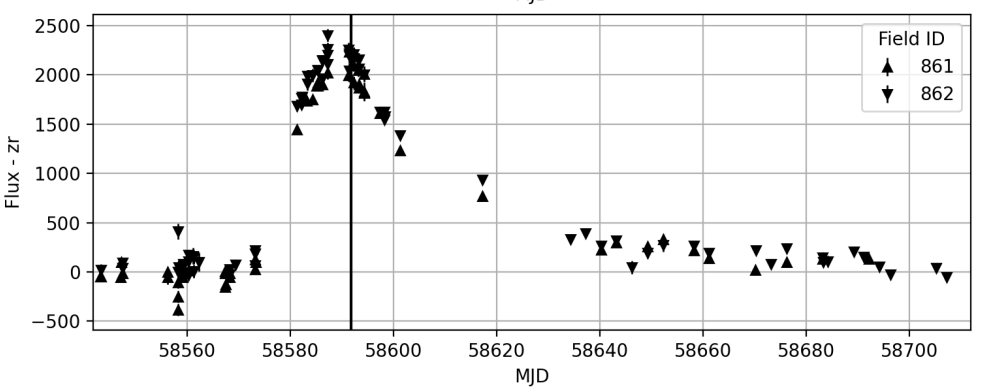
No data

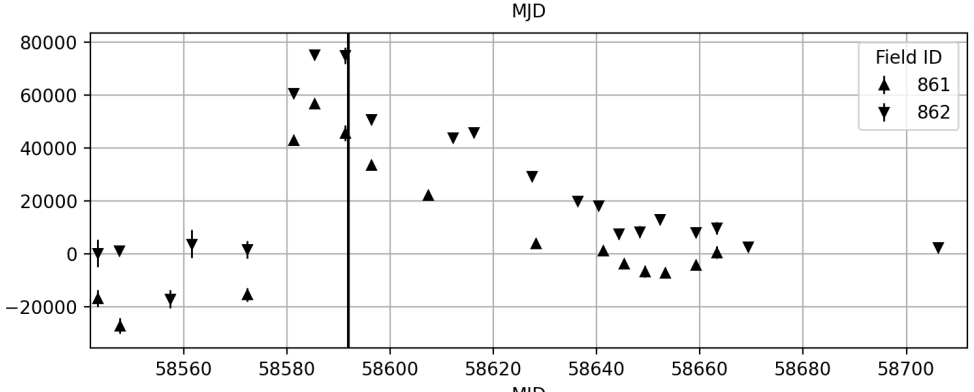
ZTF19aapeime

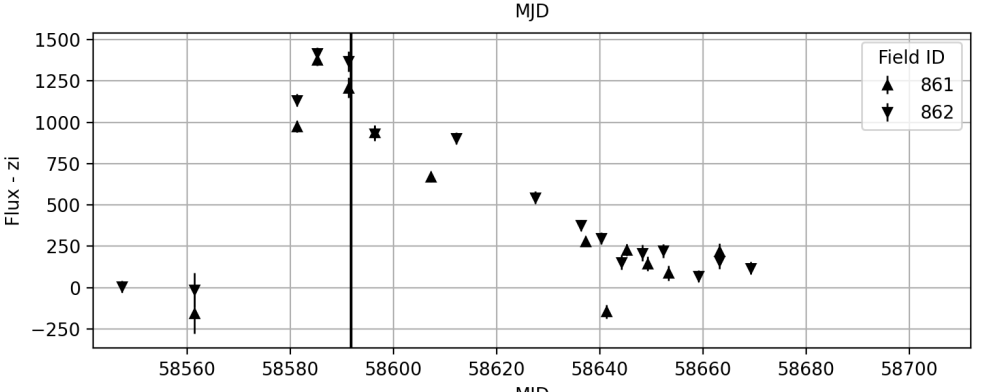










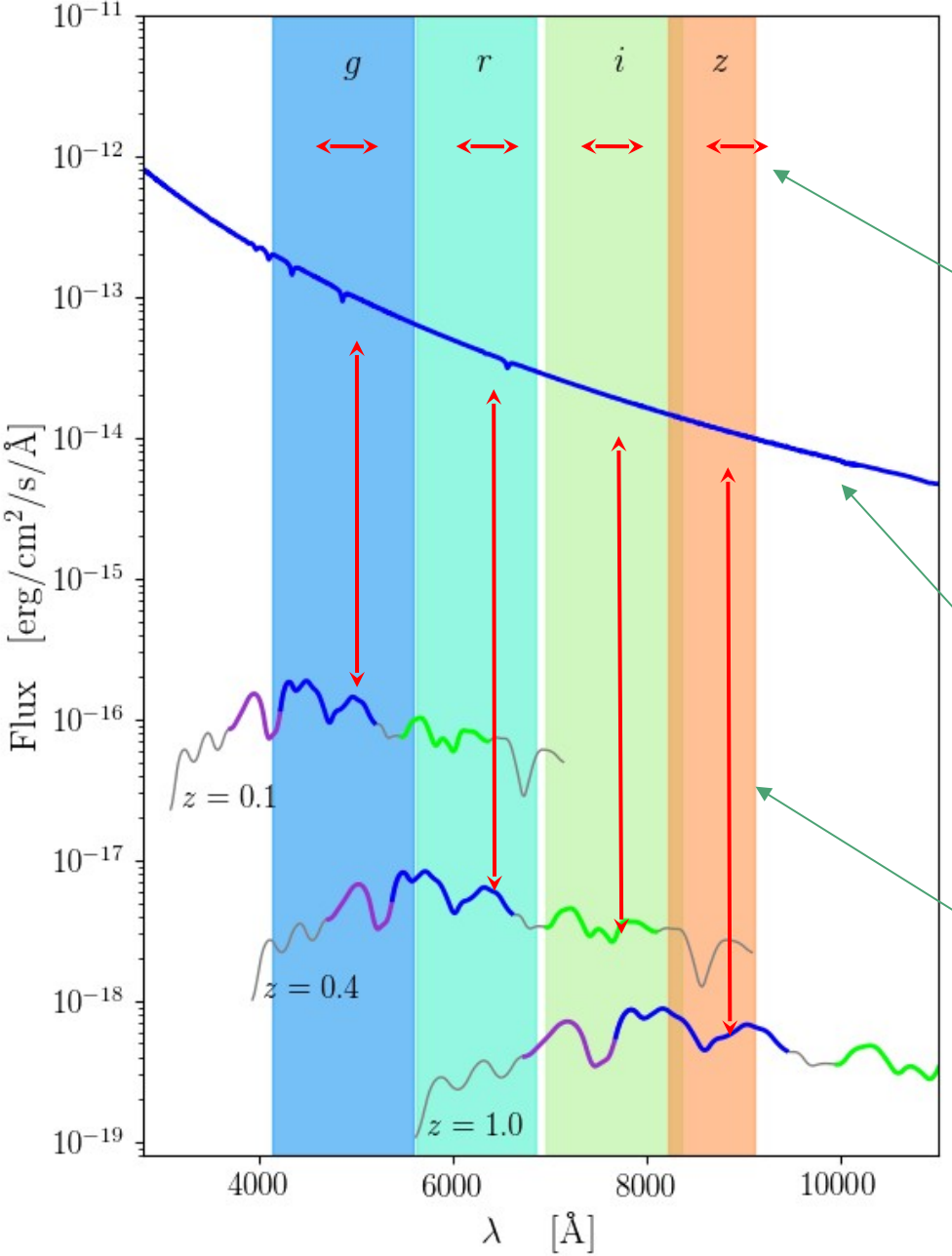


Future work

- Finish fine tuning the current pipeline implementation
  - Run it on the whole dataset
  - DR paper
- Understand some problems in pixel acquisition (induces bias in flux measurements)
- Implement a fast version of the pipeline (without “Poloka”)
- Cosmology!
  - Dark energy equation of state constraints, using HSC data

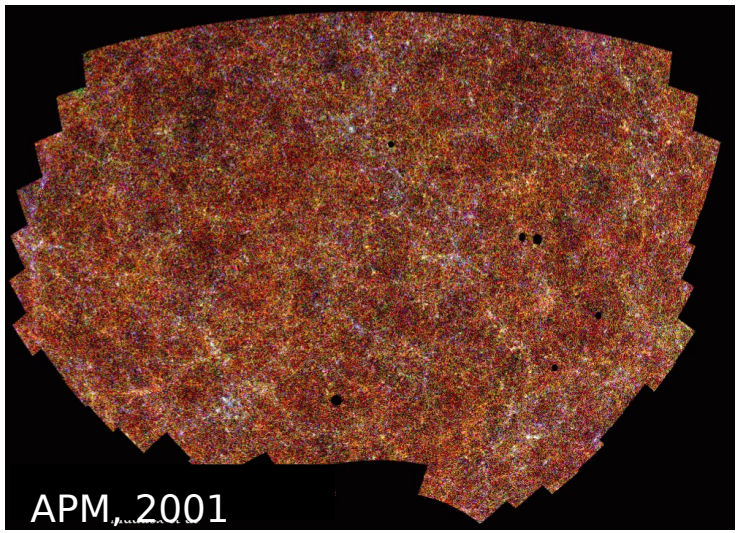
Thank you for your attention!

Backup

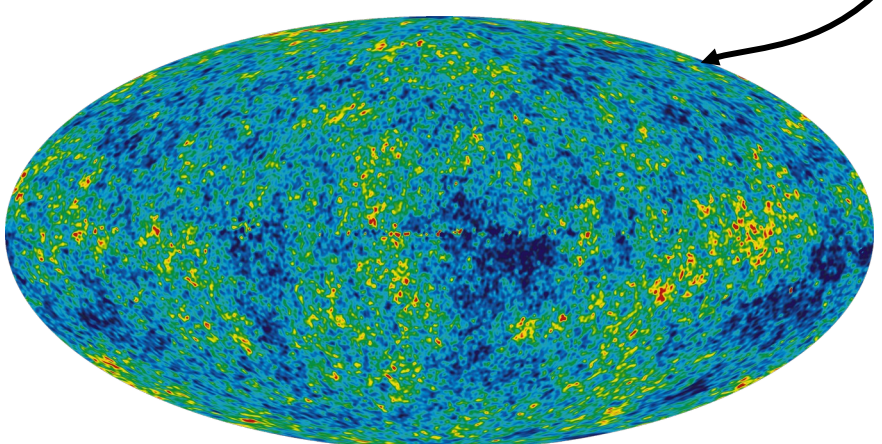


- Metrologie des filtres
  - calibration en λ
- Calibration relative en flux des bandes passantes
  - Donnée par une référence de flux
  - Étoile (bien modélisée)
  - Étalon de laboratoire
- Chaîne métrologie des flux
  - Du standard primaire aux images de science

Le modèle cosmologique

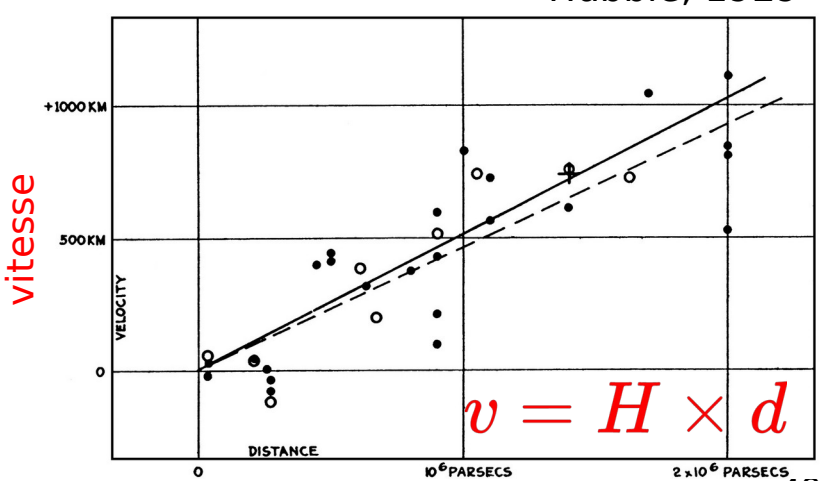


- Notre Univers est :
  - homogène (à peu près),
  - isotrope (très),
  - … et en expansion !



(Planck)

Hubble, 1929

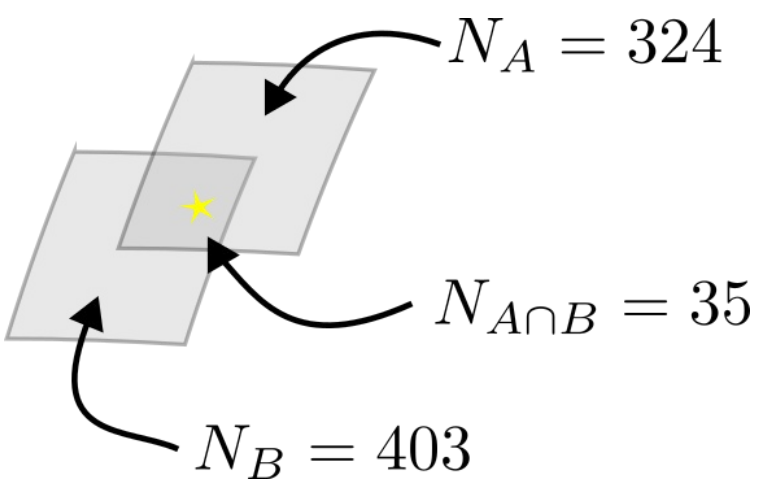


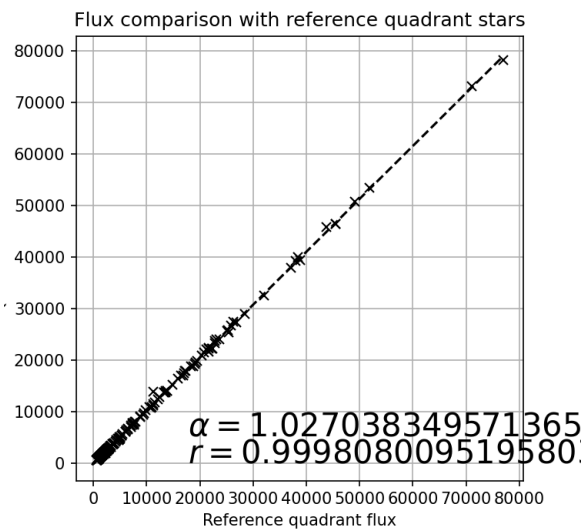
vitesse

distance

Relative photometry

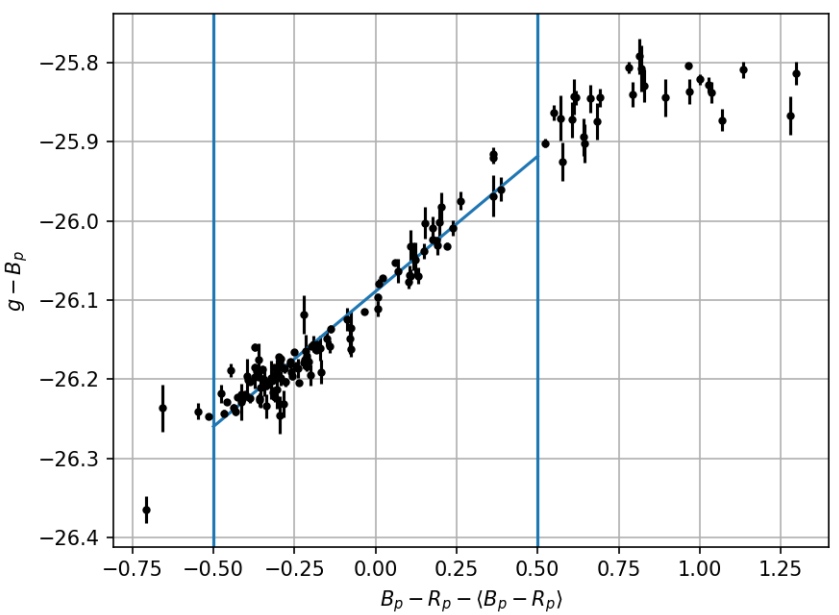
- SMP needs a way to map intensity from reference to other quadrants
  - Other formulation: fitting of relative ZP to reference
- First model: star fluxes linear fit on common stars
- Problem: when fields are different, not a lot of common stars





Relative photometry using Gaia

- Anchor stars using Gaia
- Fit: $m^{s,i} - m^{s,i}_{\mathrm{Gaia}} = k^i(Bp^s - Rp^s) + ZP^i$
- However: noise due to color transformations
  - But now Gaia DR3 gives us spectra!



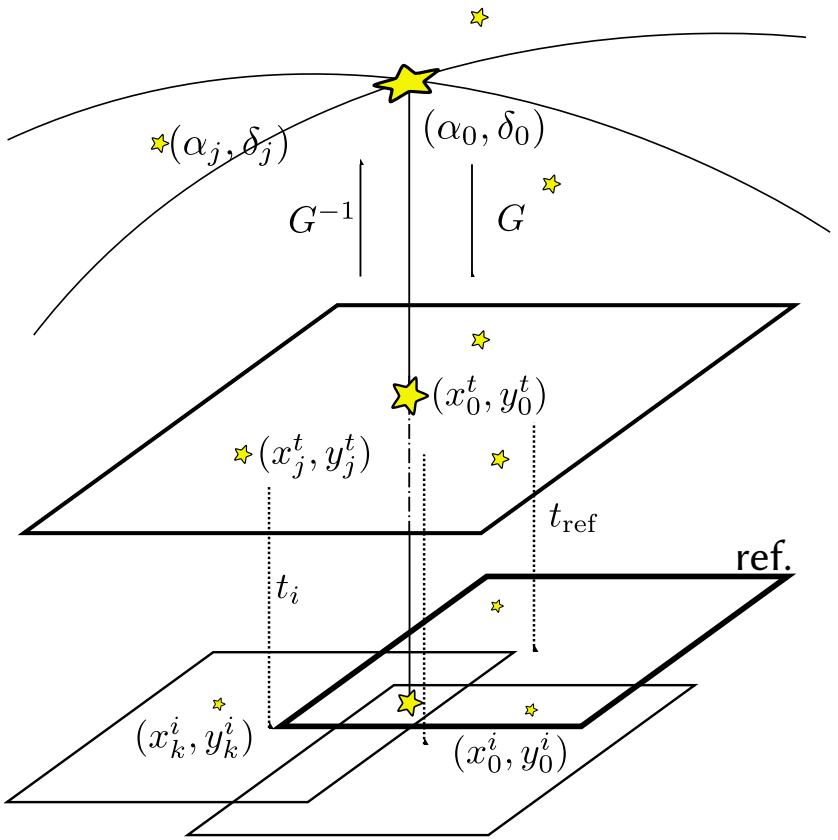
Relative astrometry

- SMP needs a way to map from the reference quadrant to others, using polynomials T_i
- First version: fit polynomials on common stars between reference and quadrants
- Same problem as for photometry!
  - Different fields results in low common stars count and undermined polynomials
  - Proper motion also needs to be determined

Relative astrometry using Gaia

- Same as for photometry: anchor stars with Gaia
  - We also don’t need to fit for proper motion anymore
- Introduce intermediate tangent plane (TP) centered on the SN

Idea: intermediate tangent plane



$$T_i = t_i \circ t_{\mathrm{ref}}^{-1}$$