

Supernova cosmology with the Zwicky Transient Facility

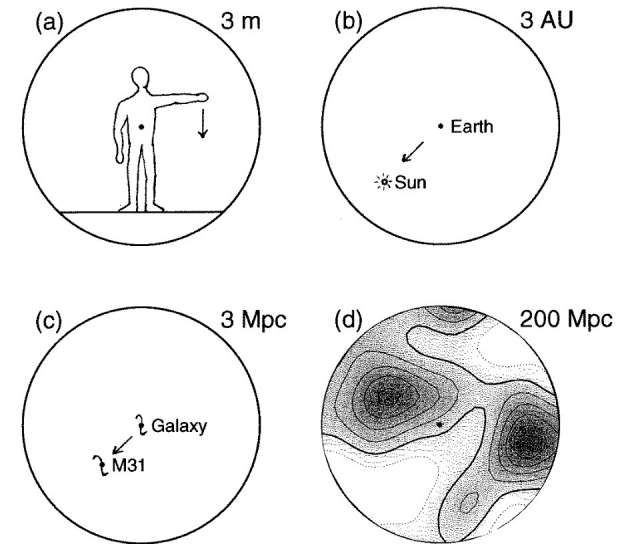
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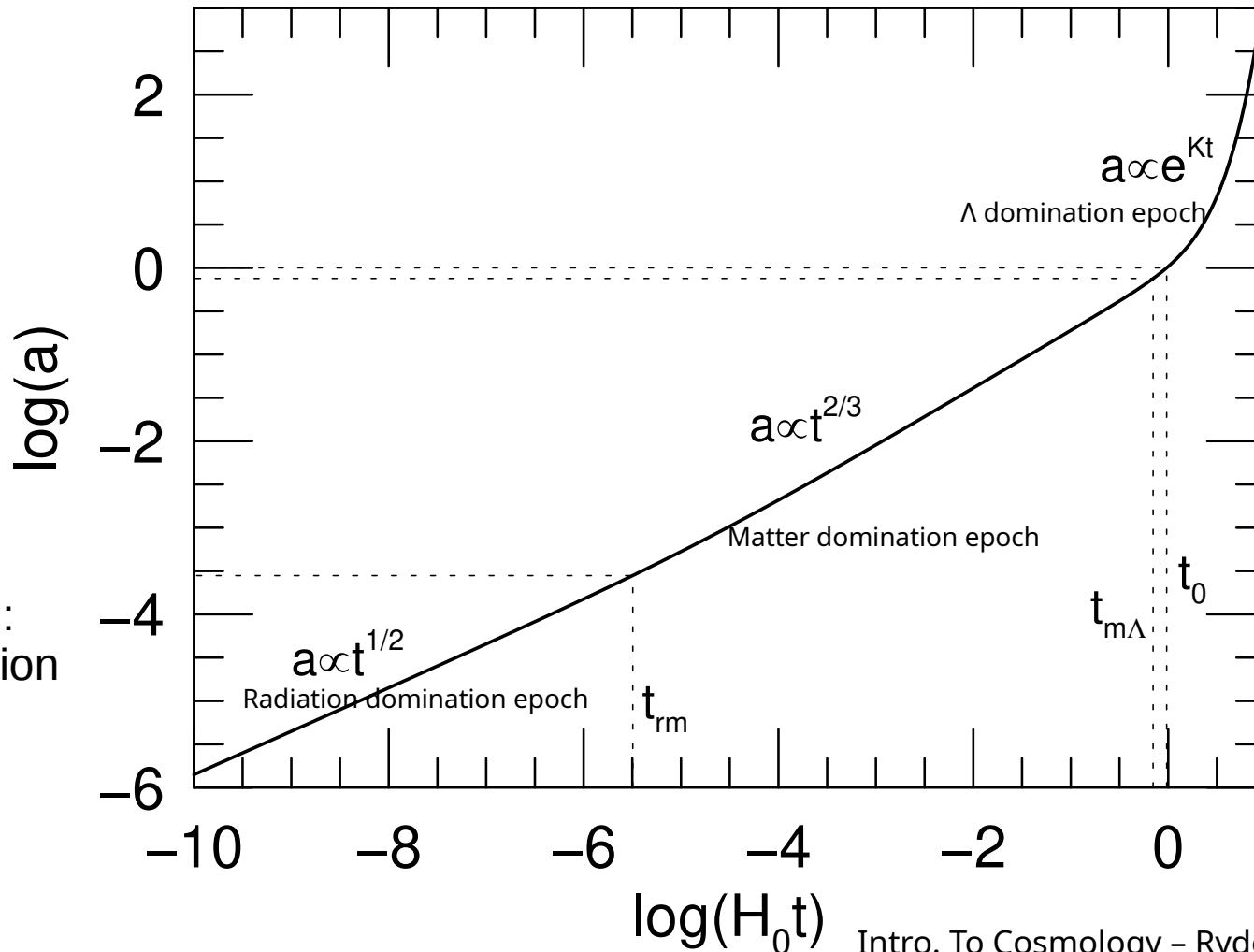
Introduction to cosmology and the concept of dark energy

- 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 $\sim 10^{-5}\%$
 - Matter $\sim 30\%$ (5% barionic matter, 25% dark matter)
 - Dark energy $\sim 70\%$
- Expansion described by the Friedmann equation



Intro. to Cosmology (Ryden 2014)

Cosmic acceleration



Scale factor $a(t)$:
quantify expansion

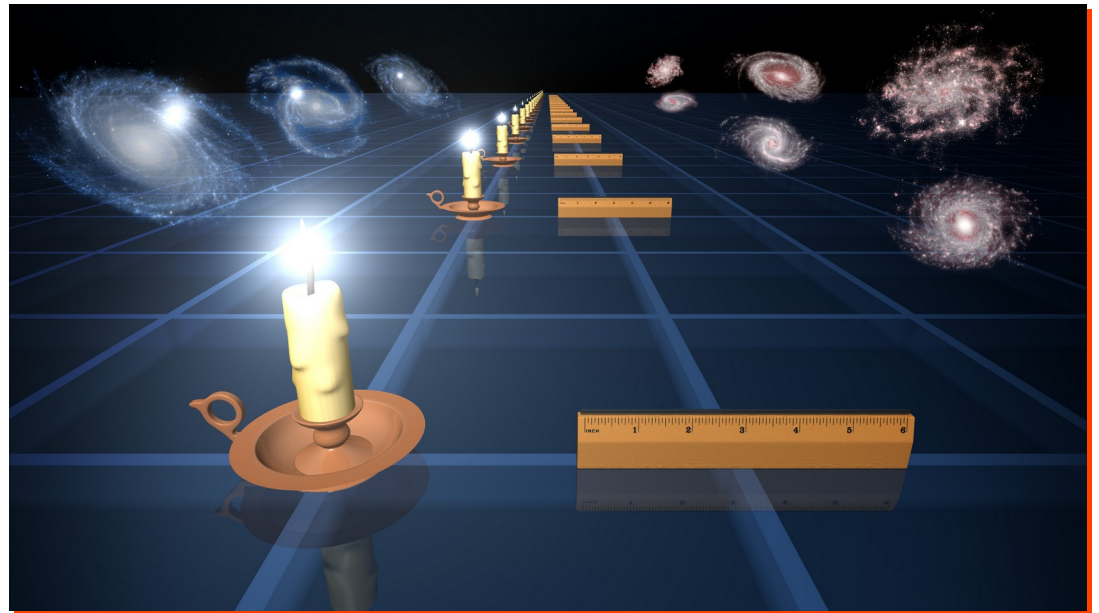


Cosmic acceleration

- 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

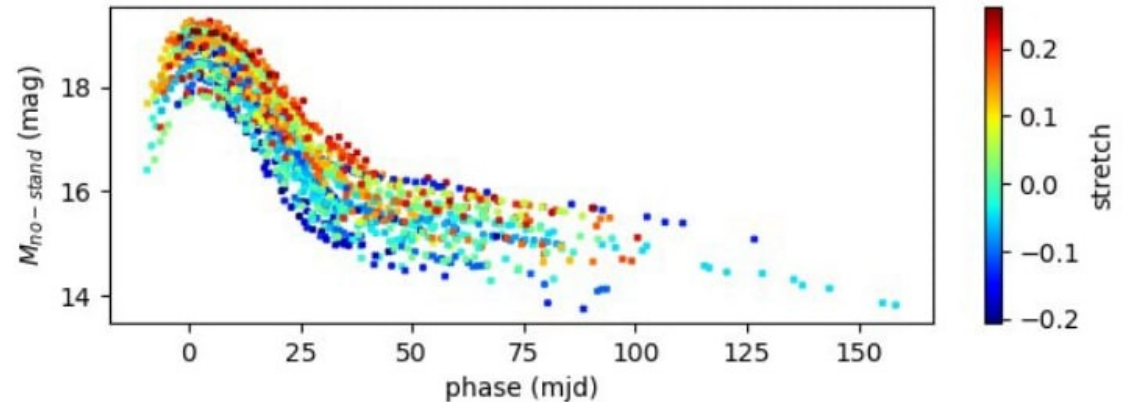
Probing the expansion history

- 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

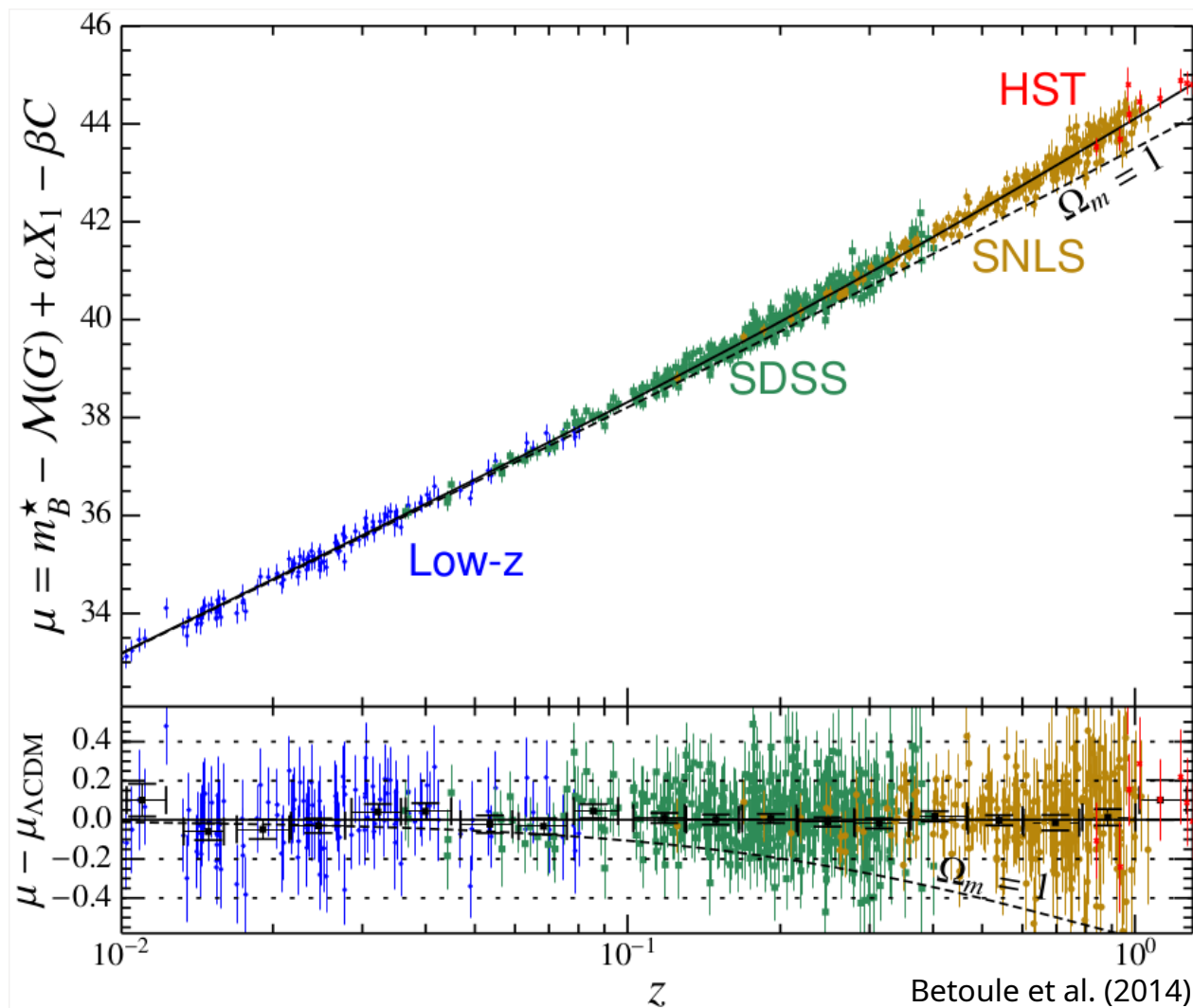


Using supernovae as standard candle

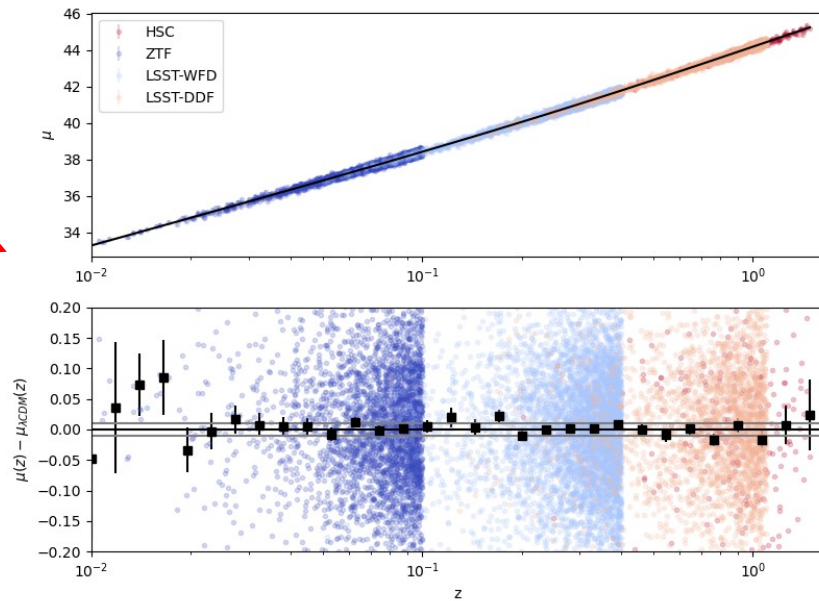
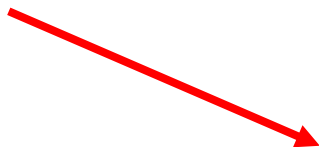
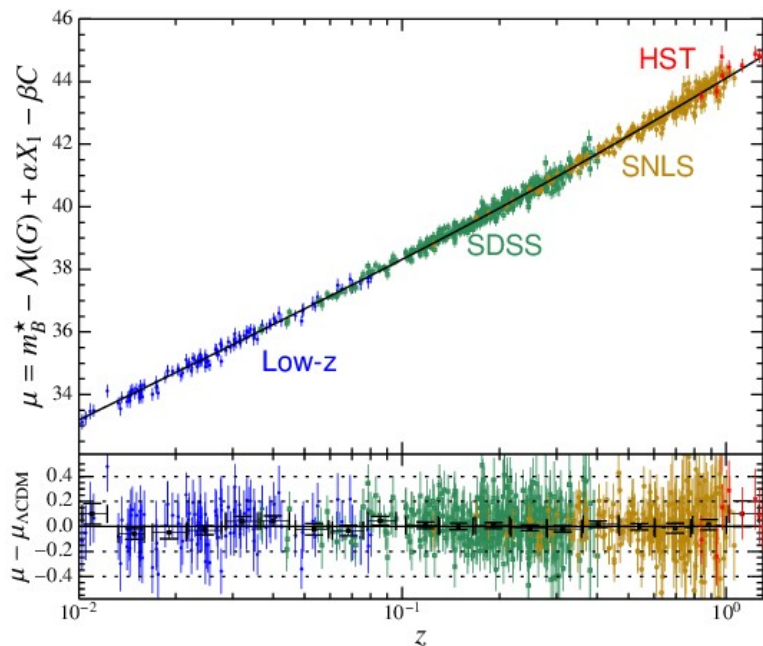
- SN Ia variability (intrinsic variability: ~40%)
 - Brighter-slower relation
 - Brighter-bluer relation (empirical)
- After standardization variability: ~15%
- Standardized distance modulus
- Empirical SN Ia models
 - SALT 2, SALT 3
 - NaCl



Mapping the expansion history with type Ia SNe



Next step



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

The Zwicky Transient Facility (ZTF) survey

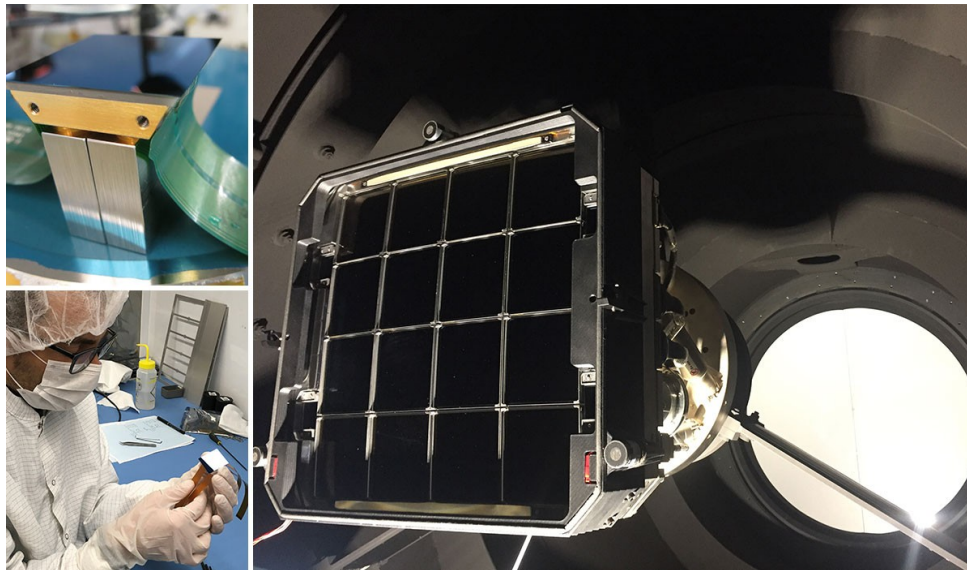
- Low redshift northern hemisphere survey, designed for rare transient events, solar system objects tracking
 - Large field of view (47 deg^2 per exposure, ~ 200 times the Moon)
 - High cadency (twice the extragalactic sky per night)
 - 3 filters: g r i
 - 2 dedicated spectrograph
 - Automated operation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

Palomar Observatory



The ZTF camera

- $16 \times 6144 \times 6160$ CCD array (606 Mpixels)
 - Subdivided into 64 quadrants (3072×3080)
 - 1 pixel $\sim 1.''01$
 - Close to the Nyquist pixel sampling limit!



© Caltech

ZTF camera field of view

© Caltech

ZTF | Fast (*30s exp.*) & Large (*full visible sky*)

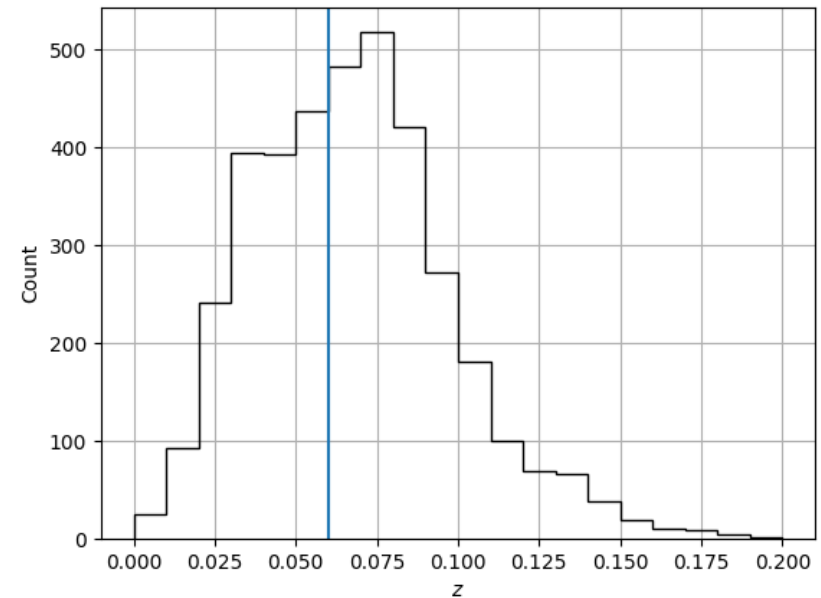


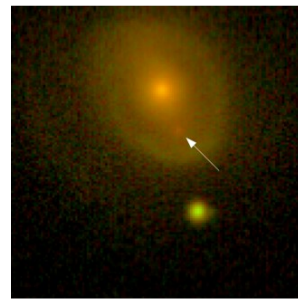
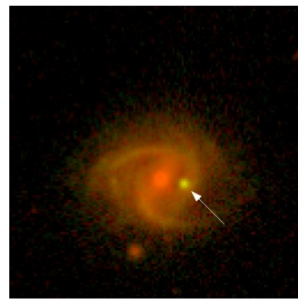
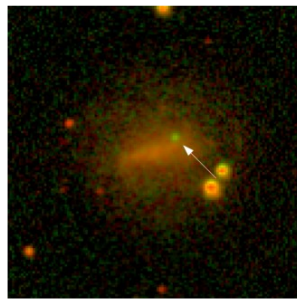
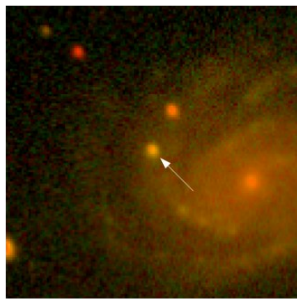
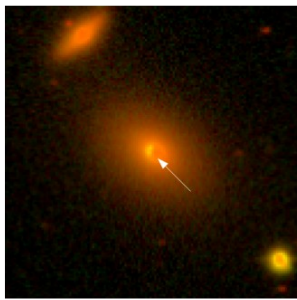
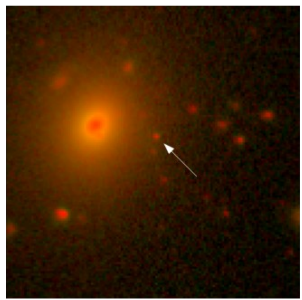
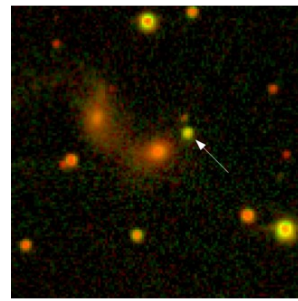
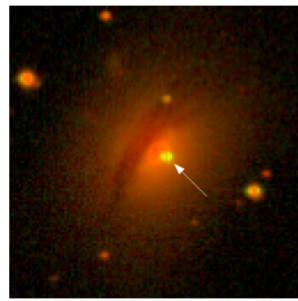
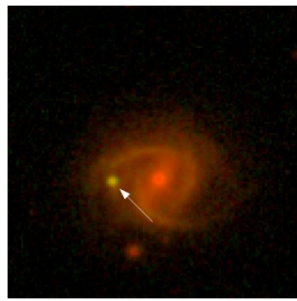
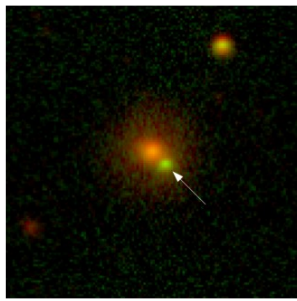
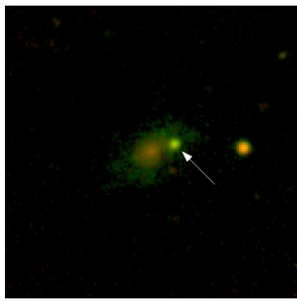
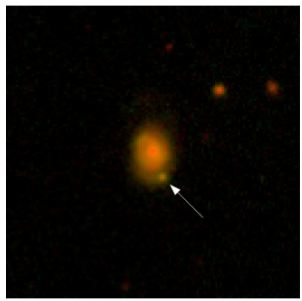
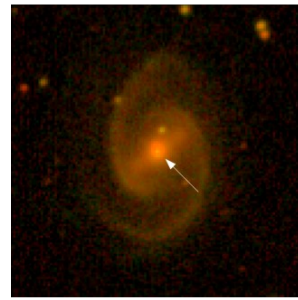
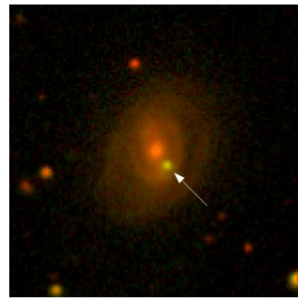
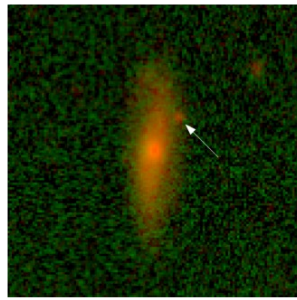
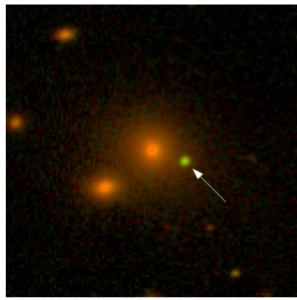
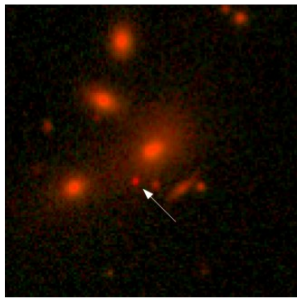
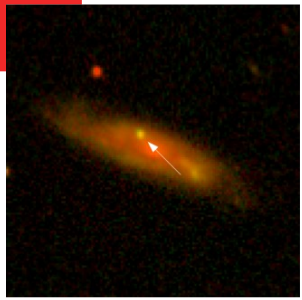
We have about 10^5 events/night ; 10% of LSST

1 deg

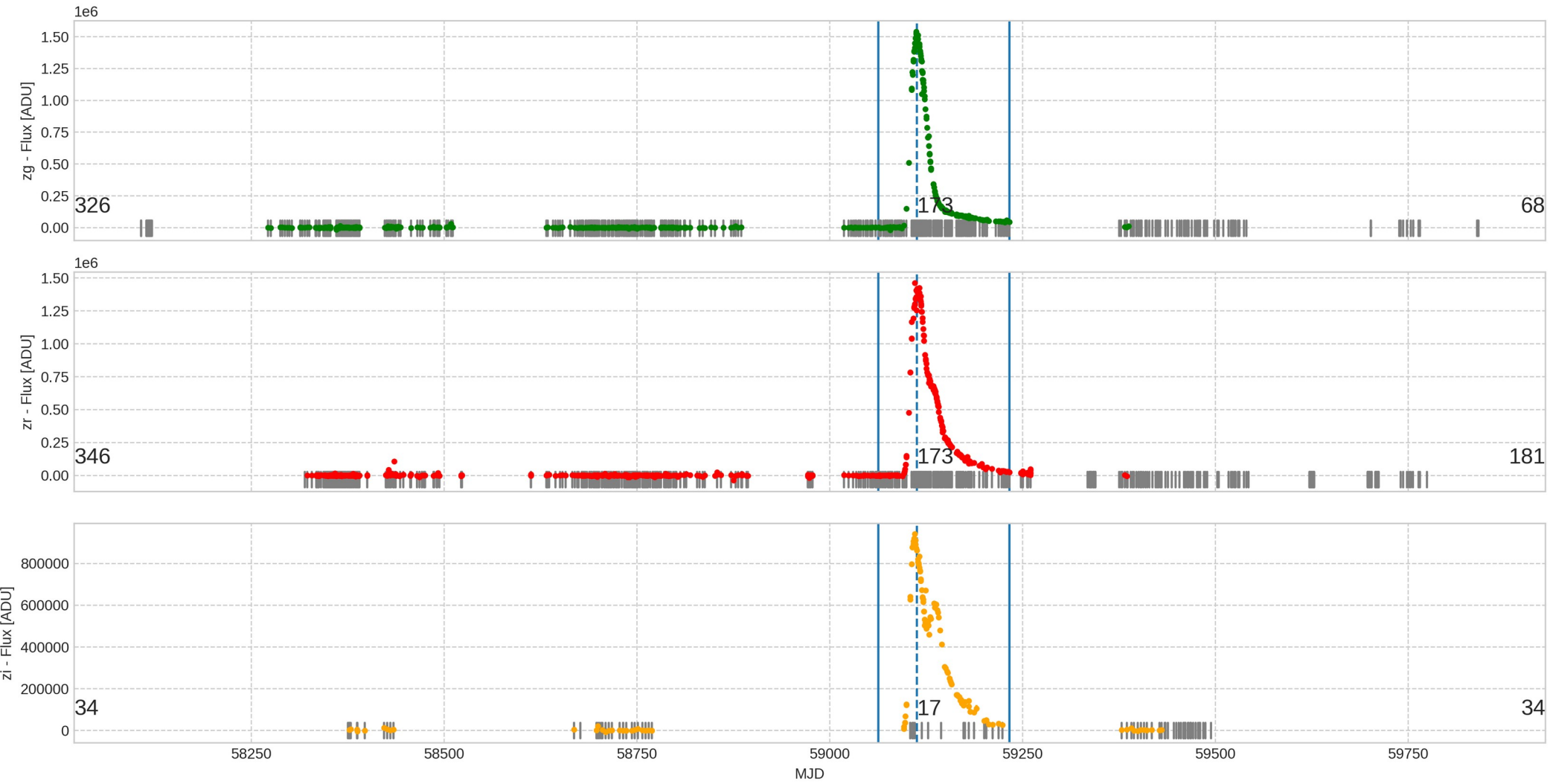
The ZTF SNe Ia dataset

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

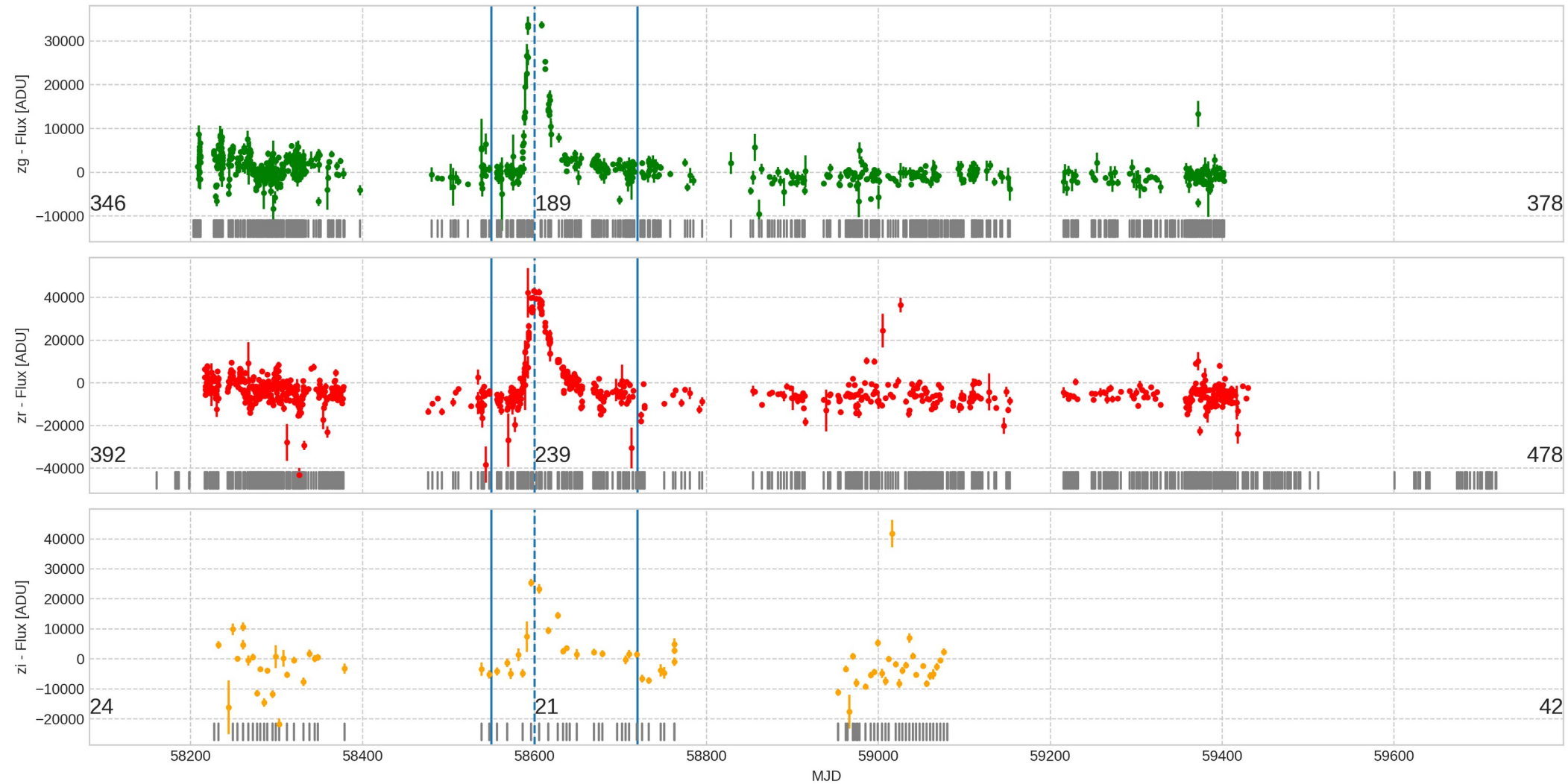




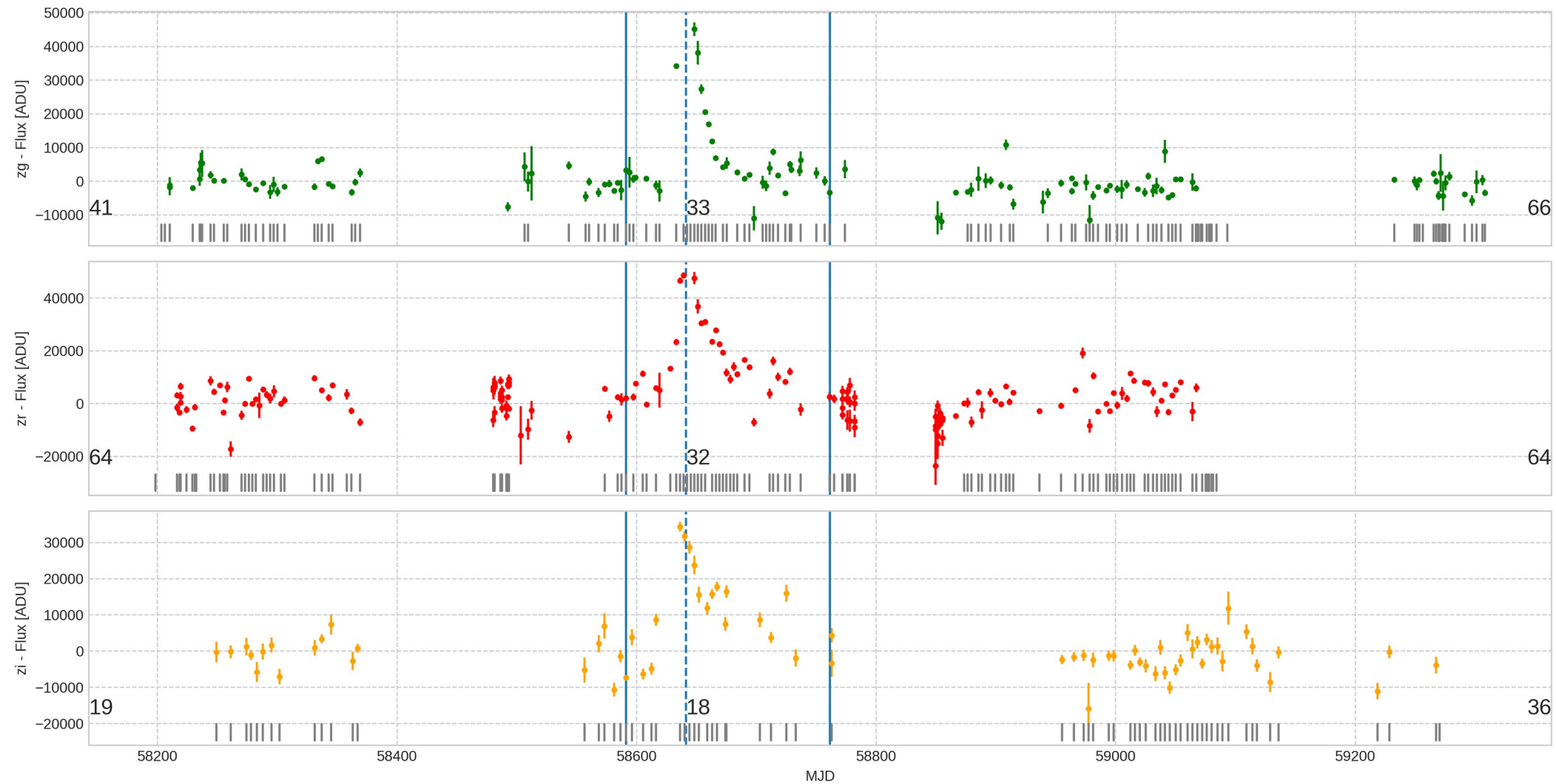
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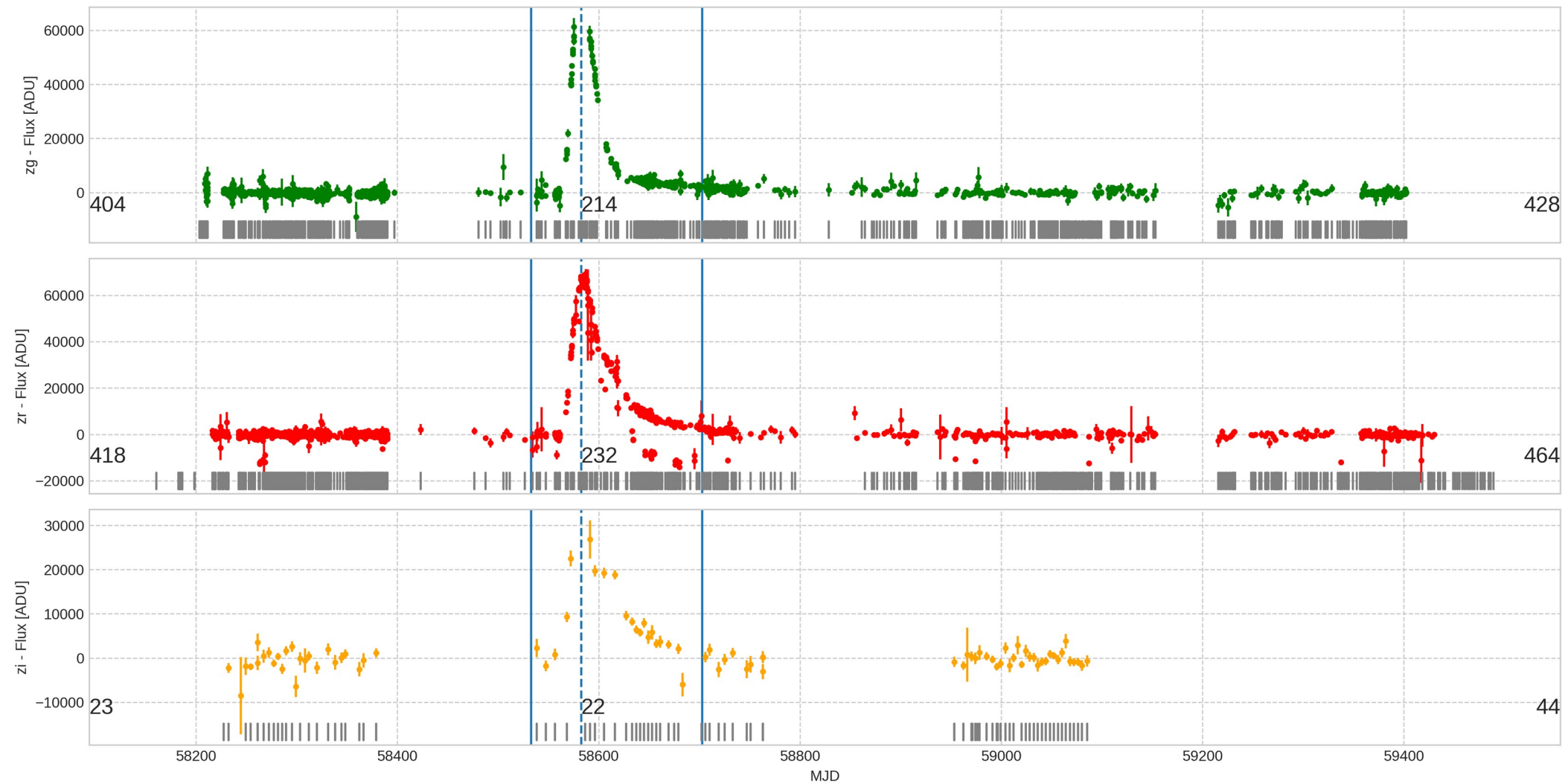


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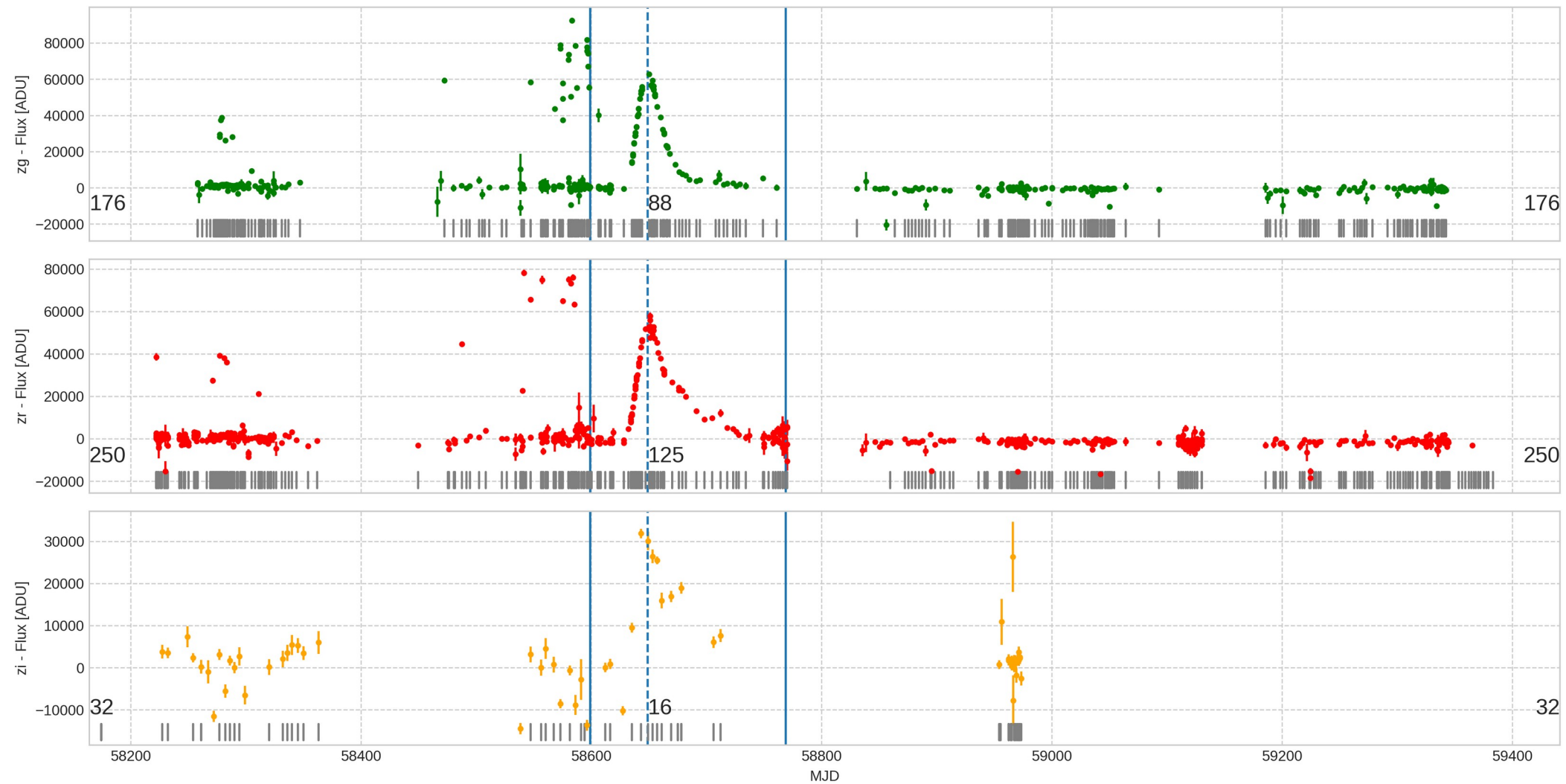


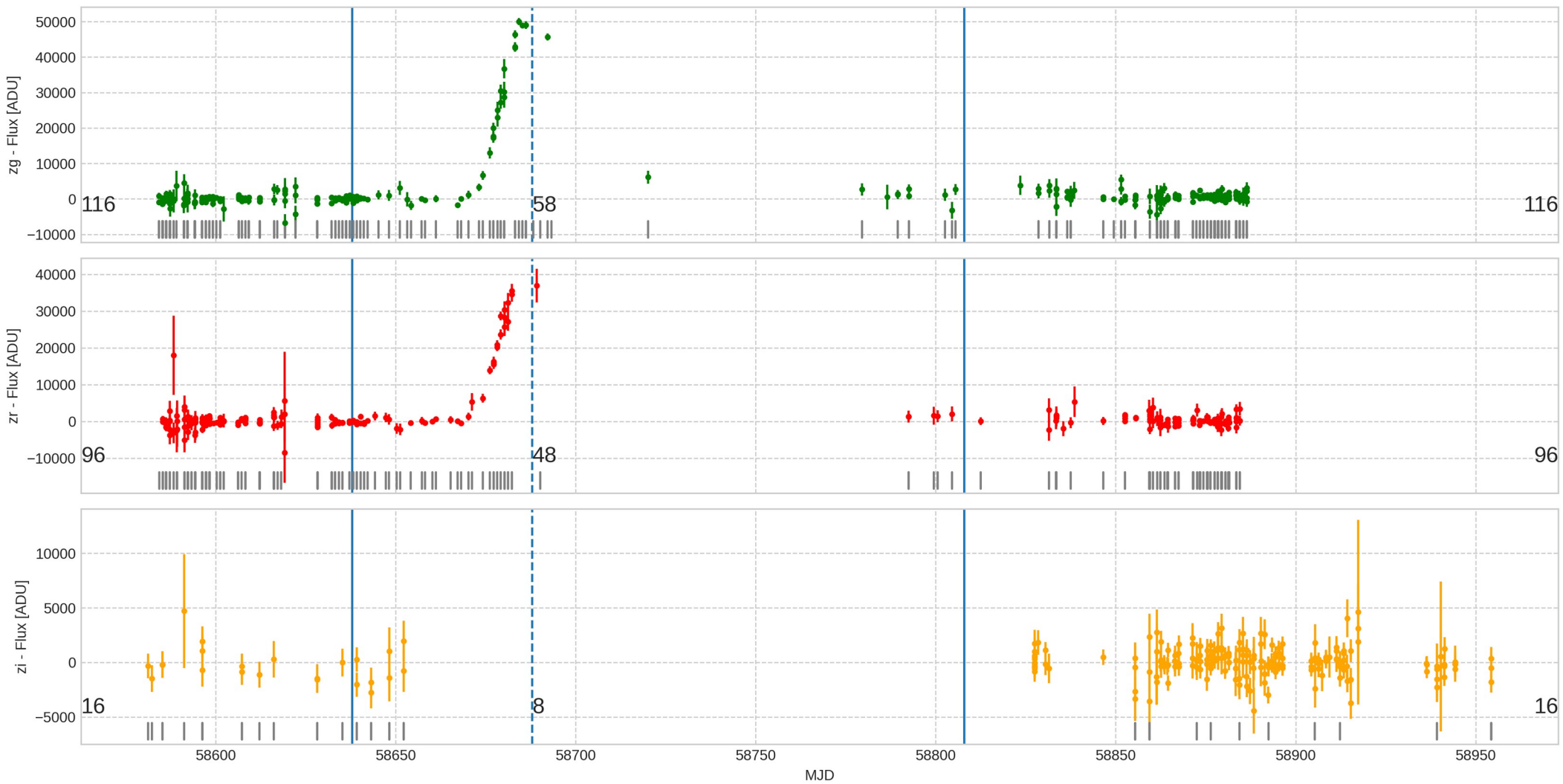
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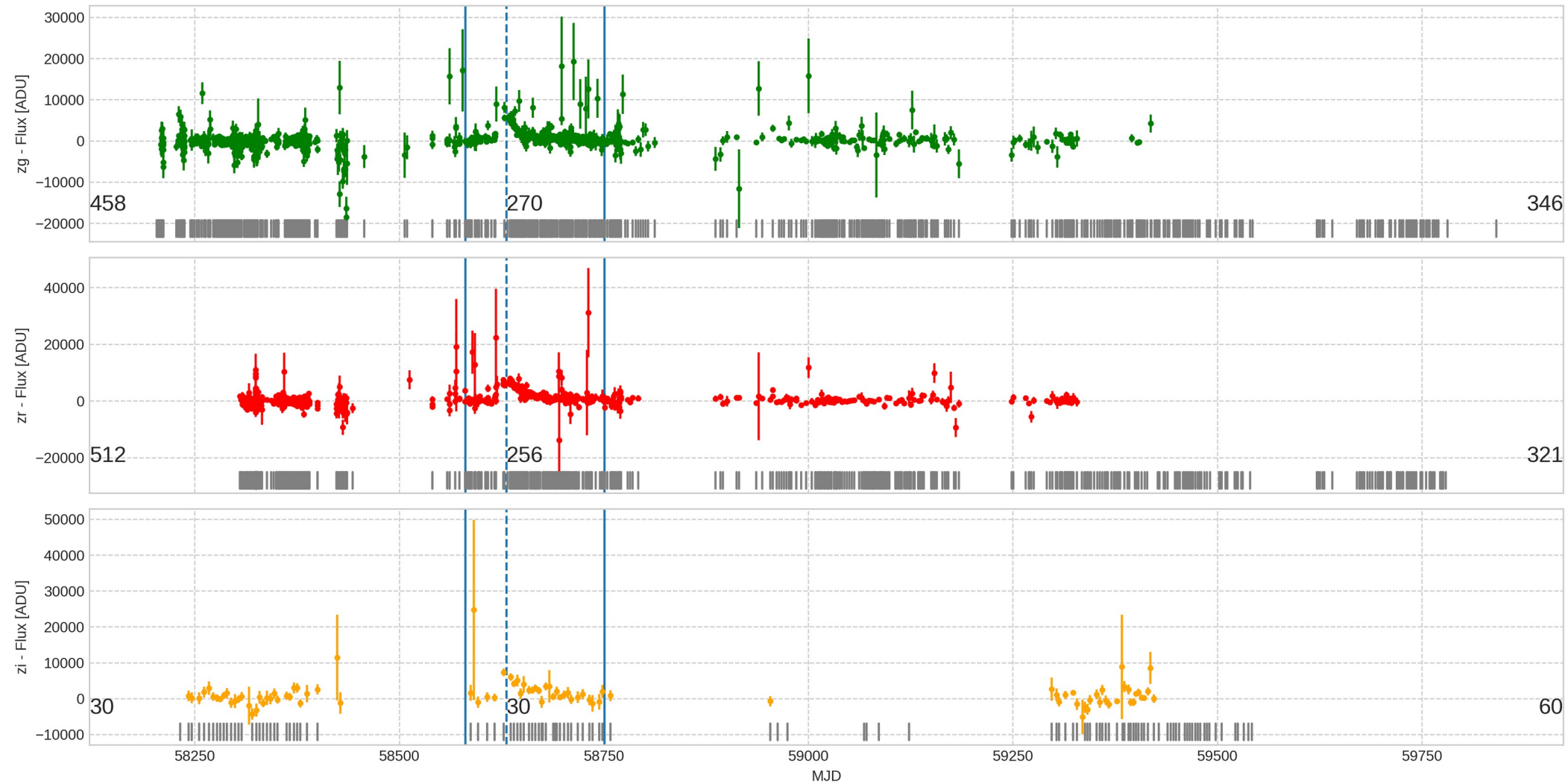


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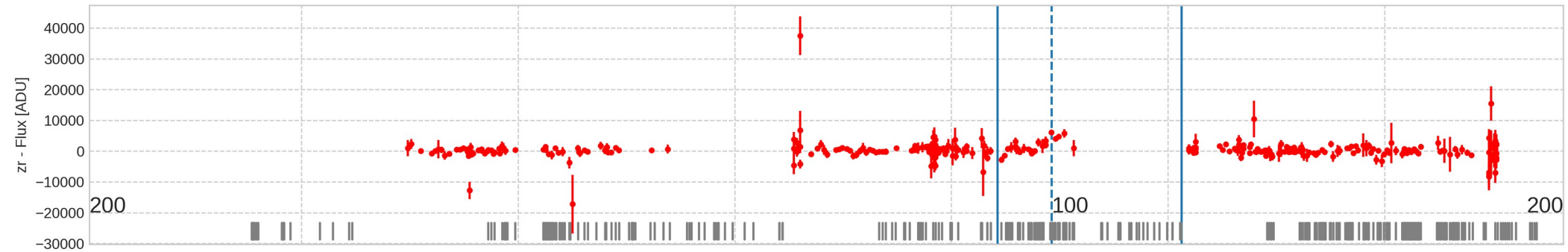
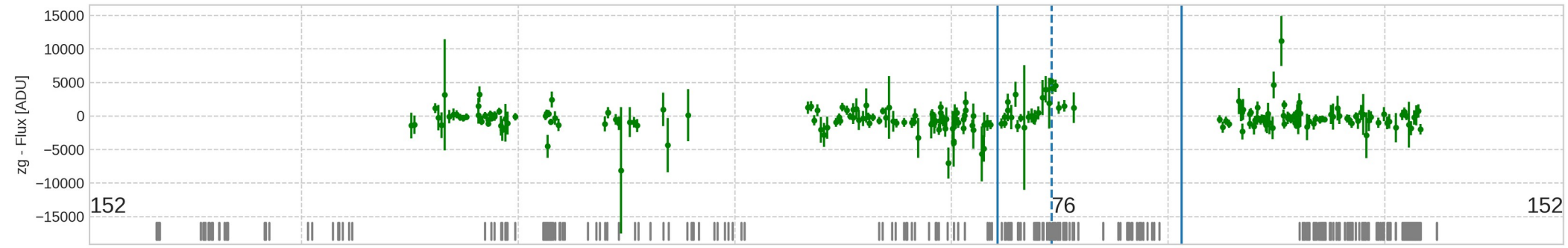




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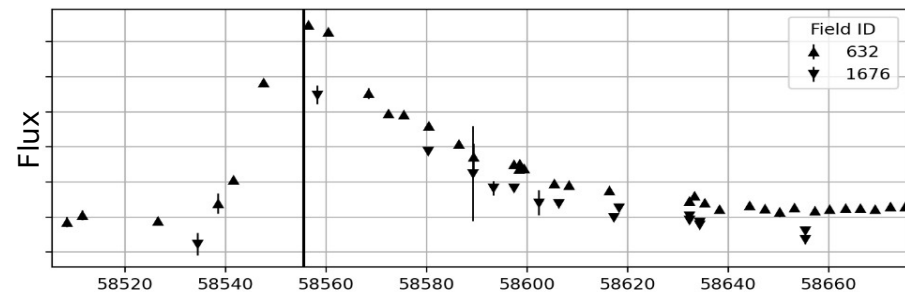
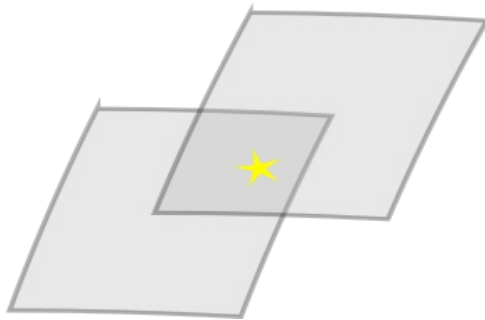


Calibration effort for precision cosmology

- 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
 - $f\sigma_8$

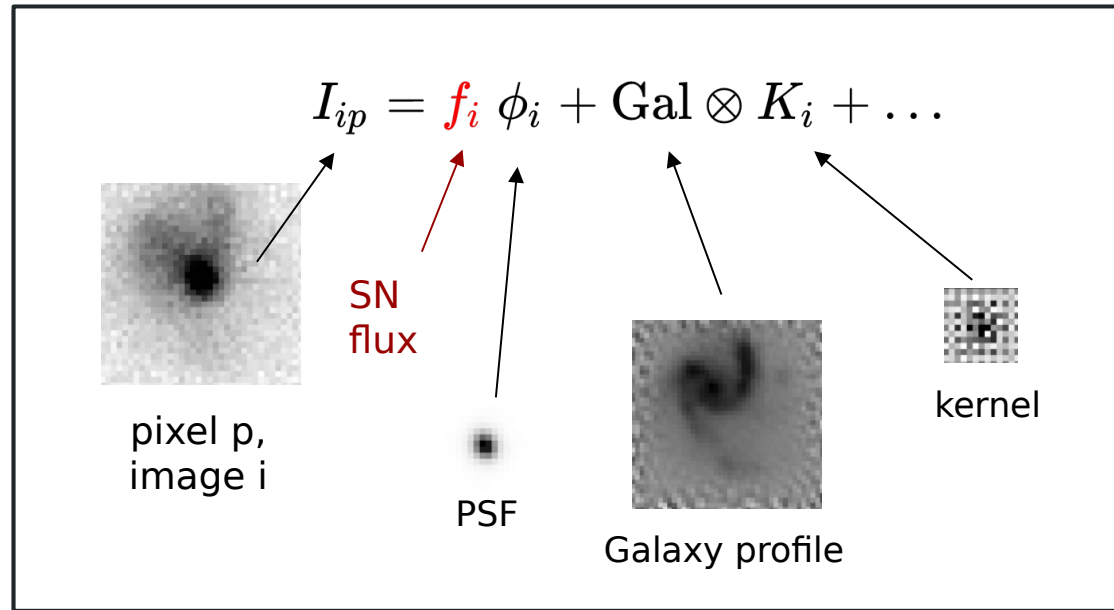
Light curve calibration

- 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
 - 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

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

➤ **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**

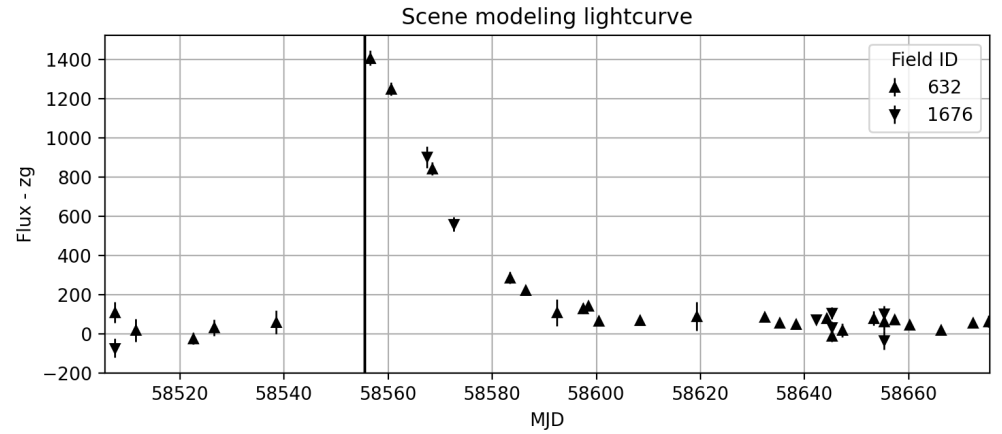
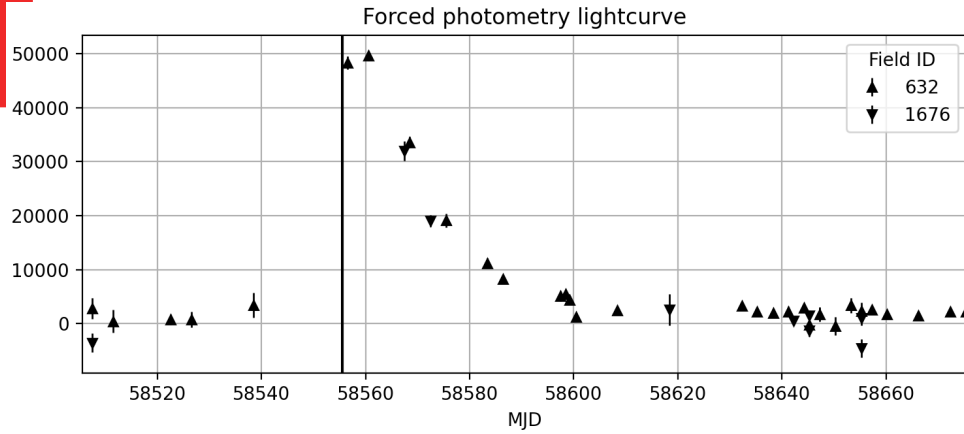
- K_i : reference to image #i convolution kernel



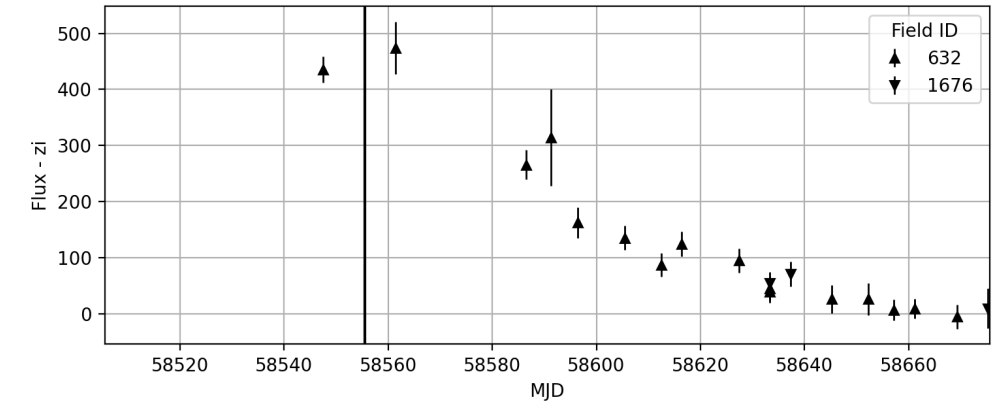
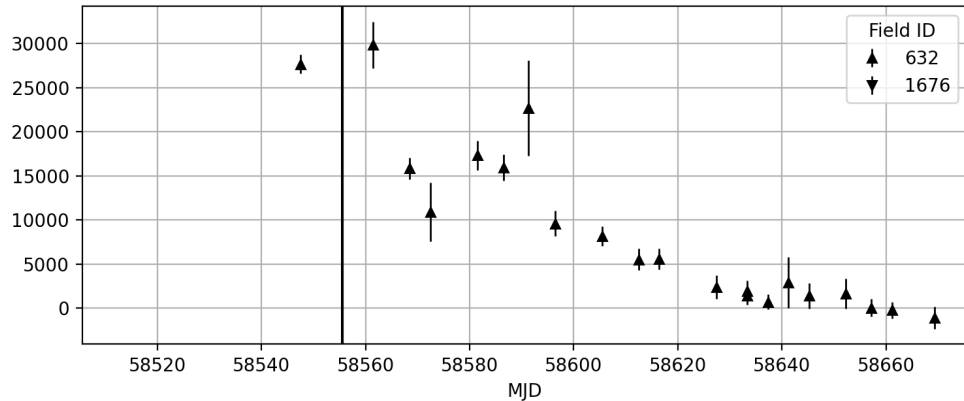
Pipeline implementation

- 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

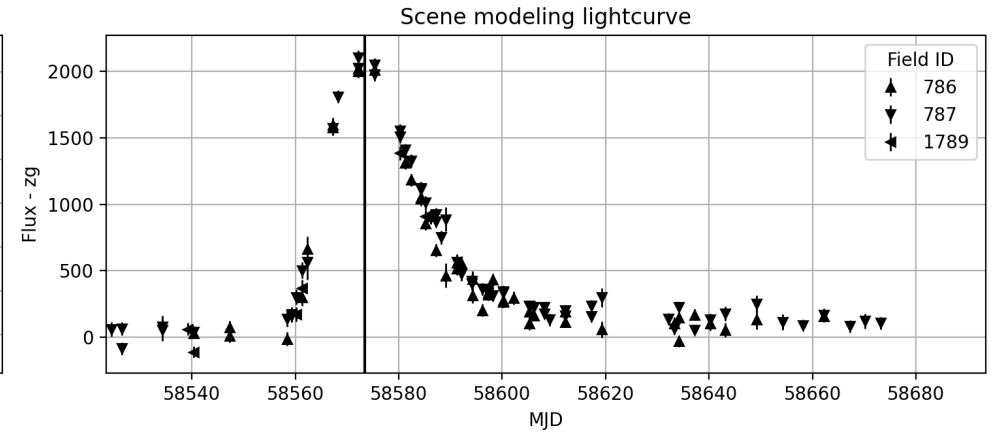
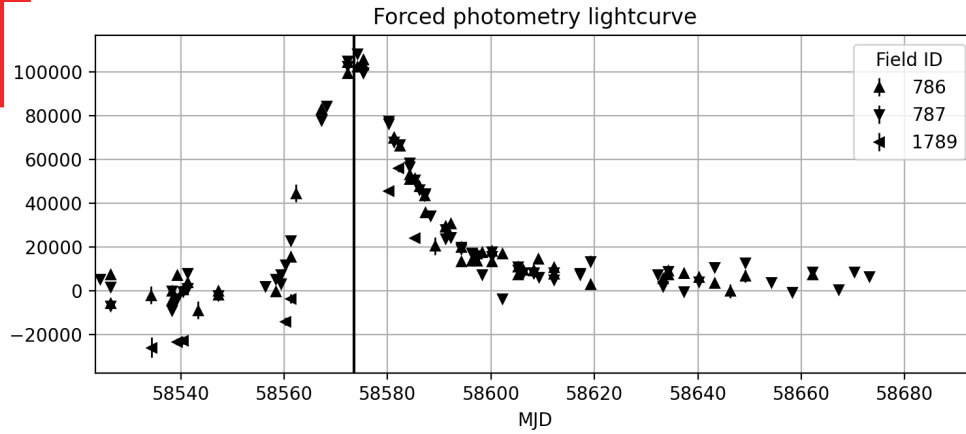
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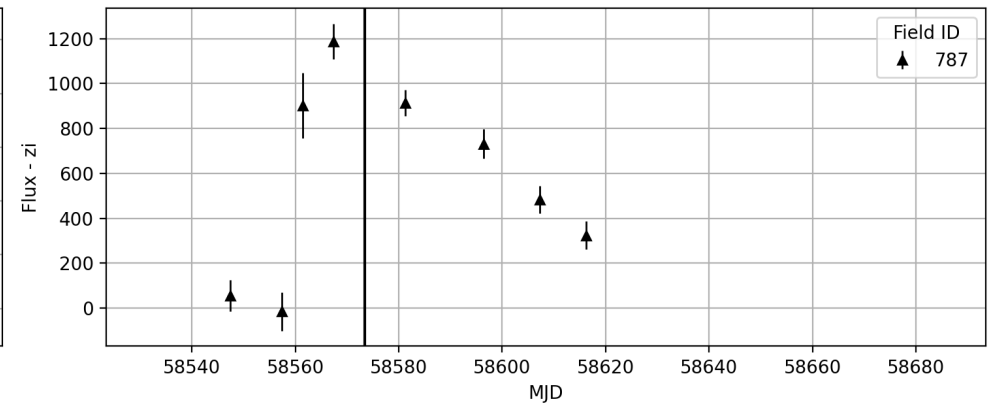
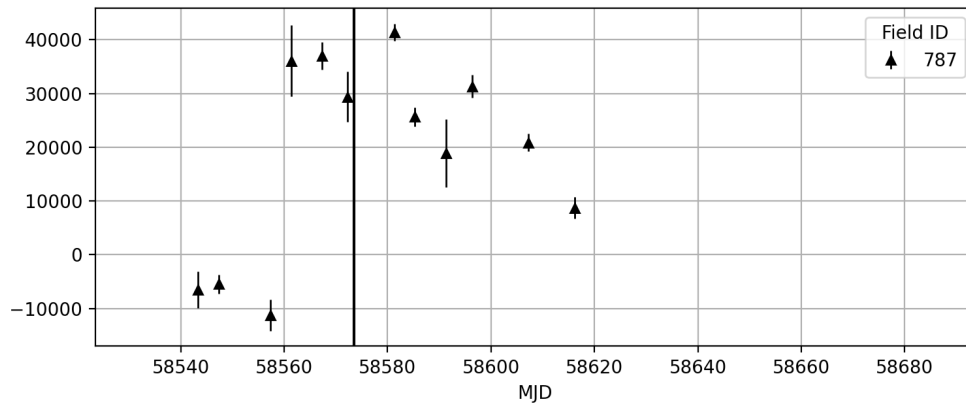
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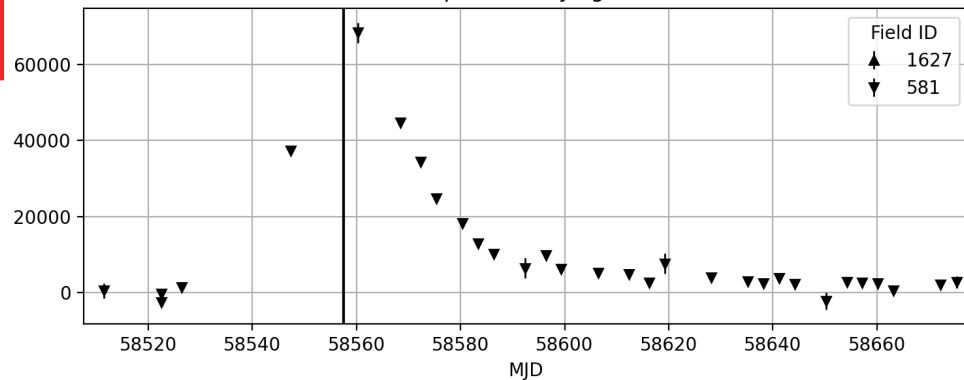


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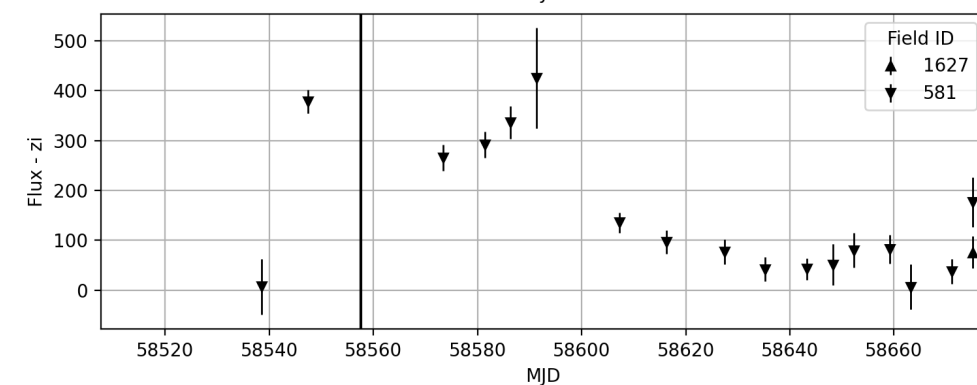
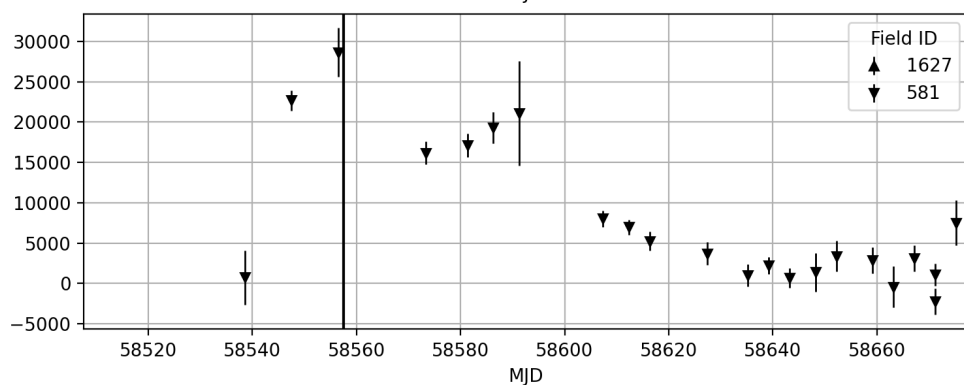
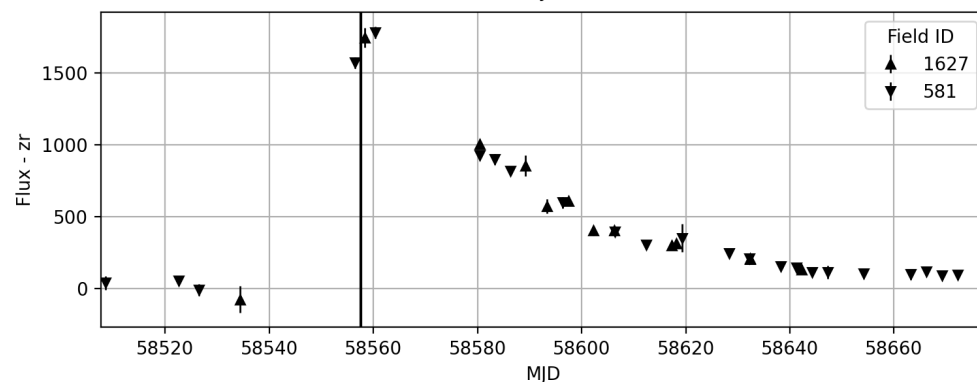
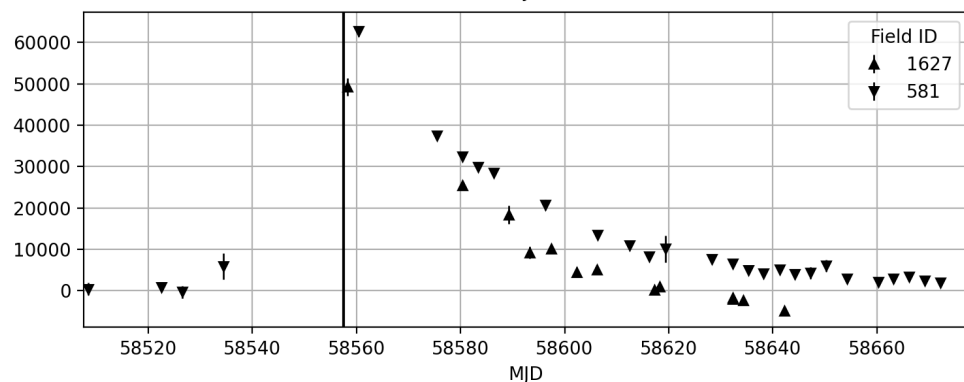
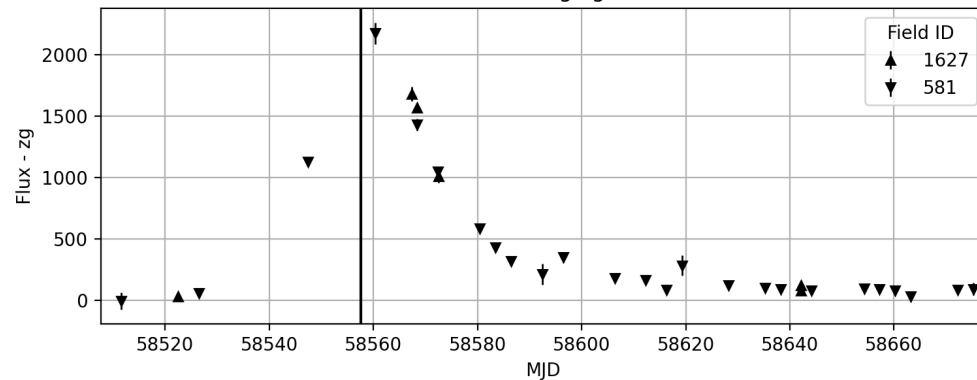


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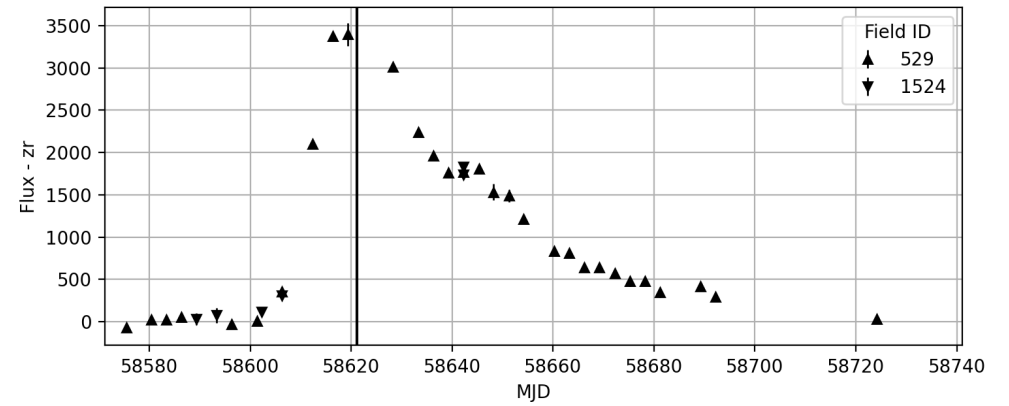
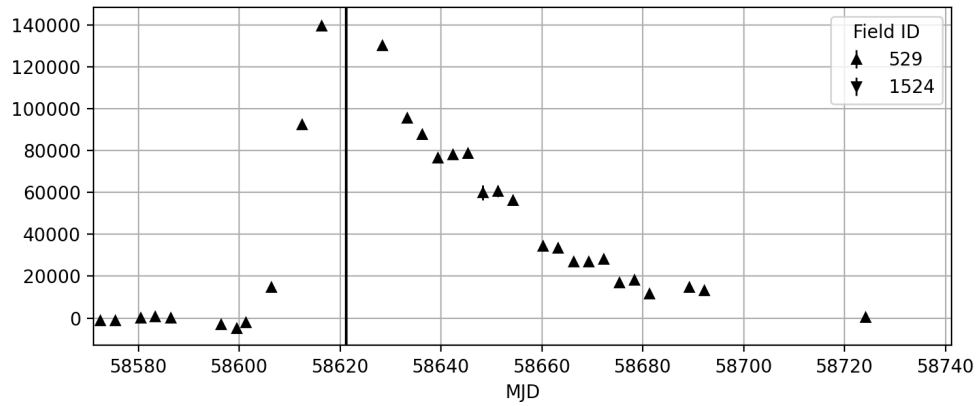
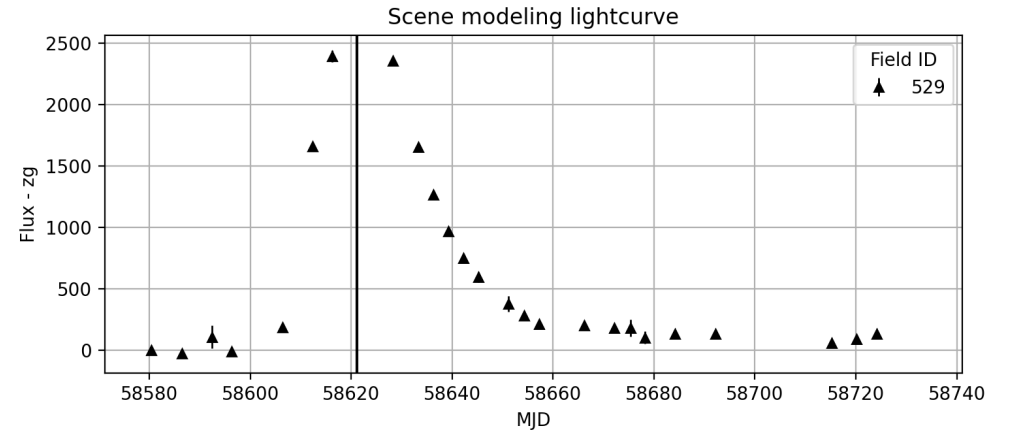
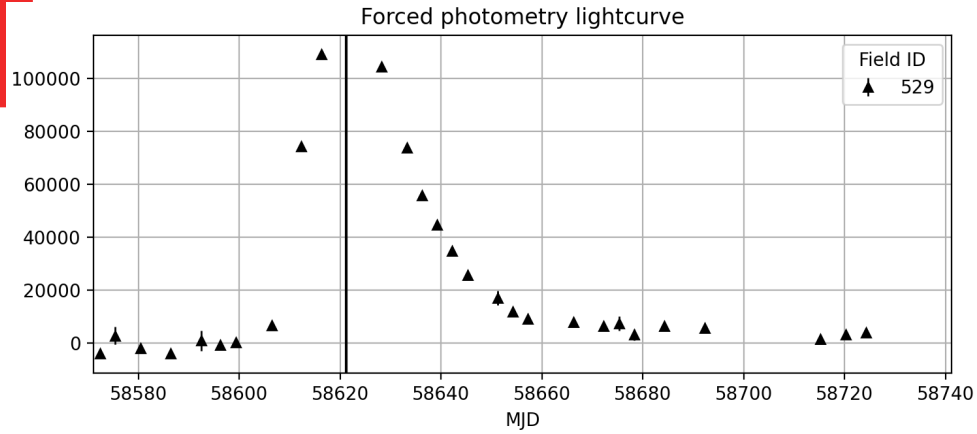
Forced photometry lightcurve



Scene modeling lightcurve

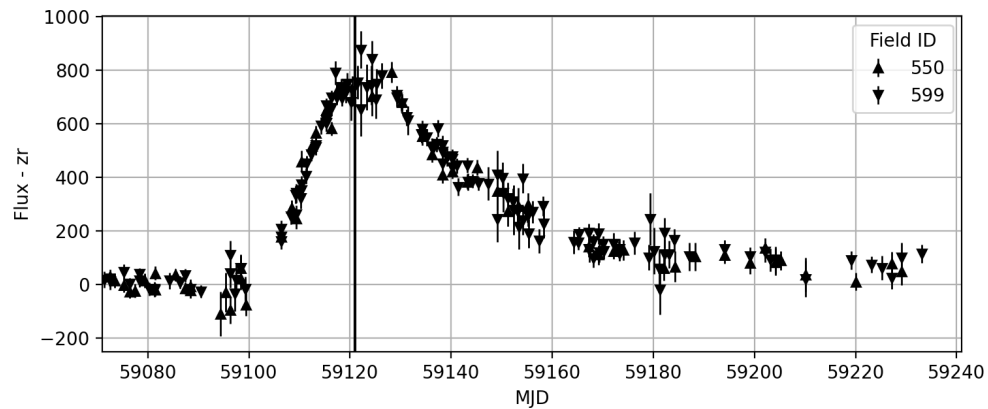
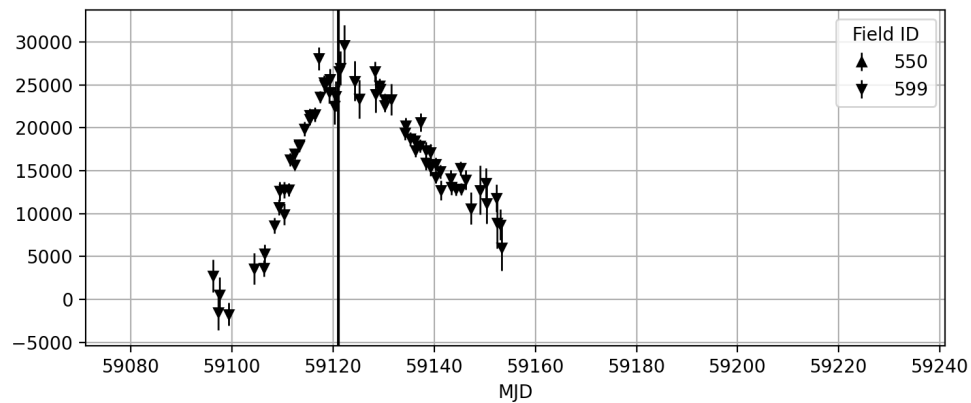
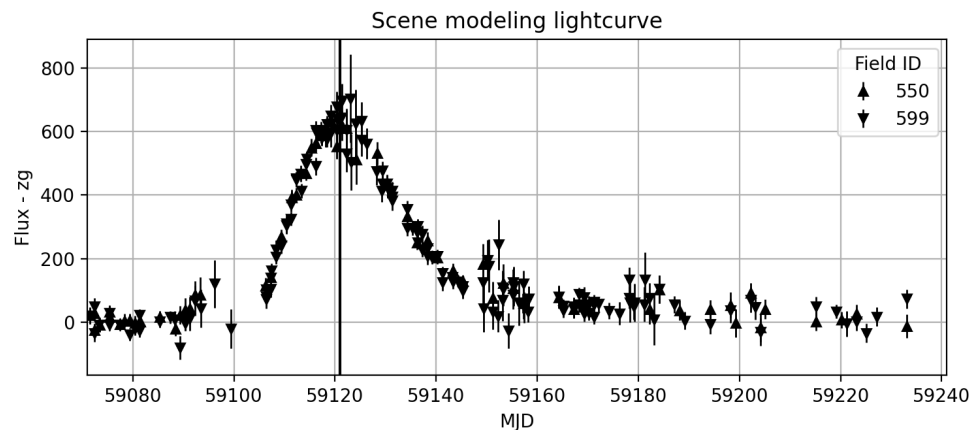
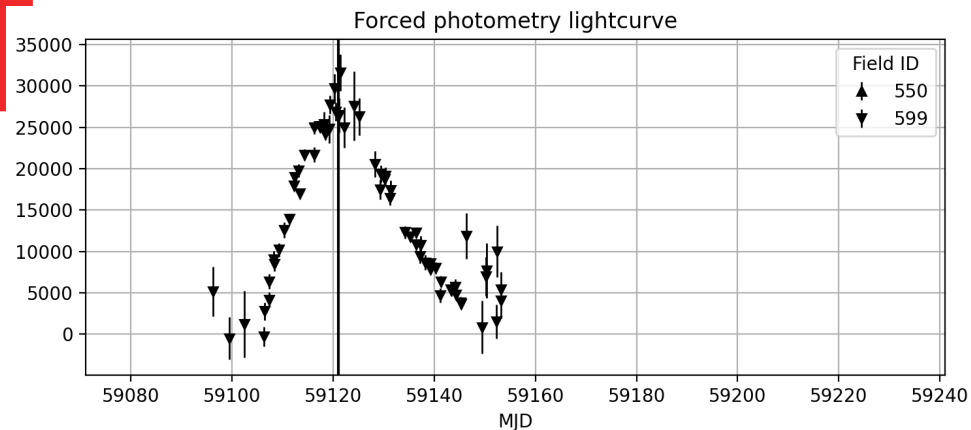


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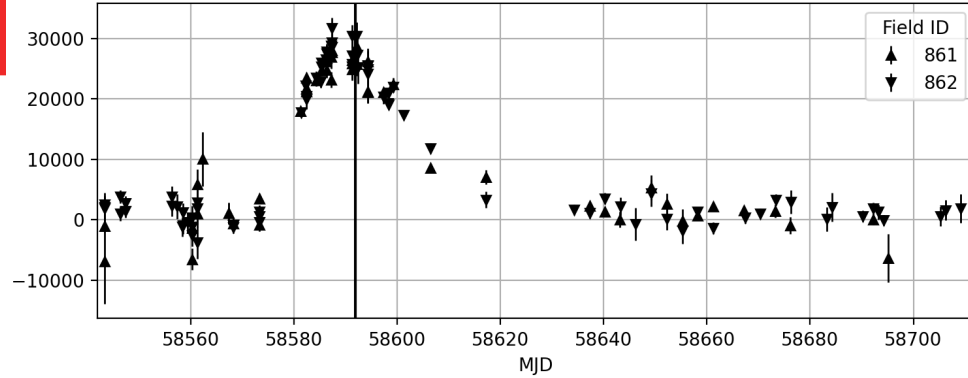
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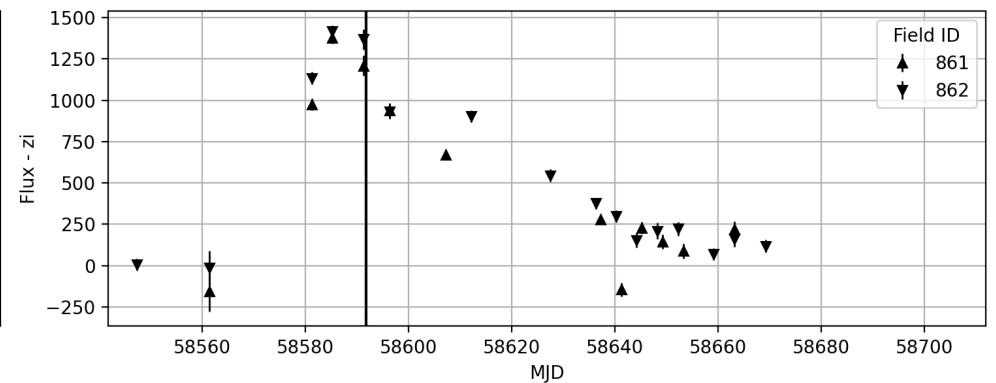
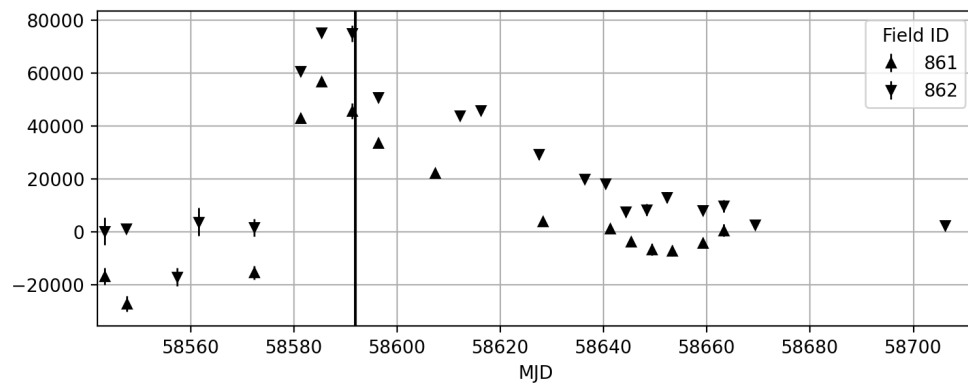
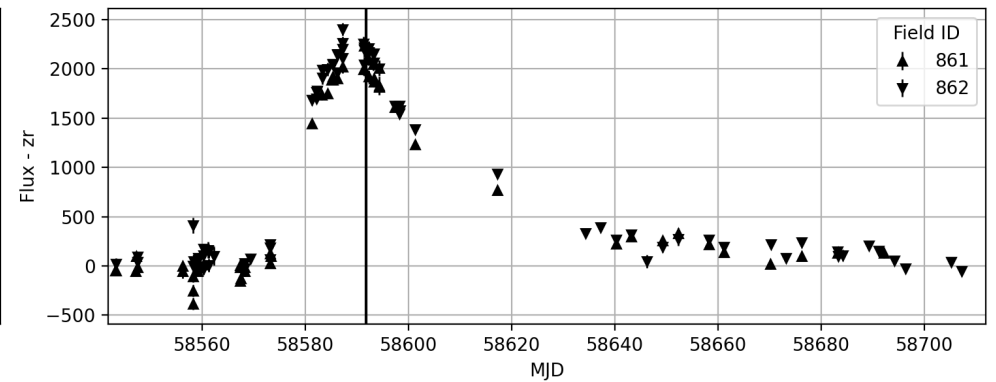
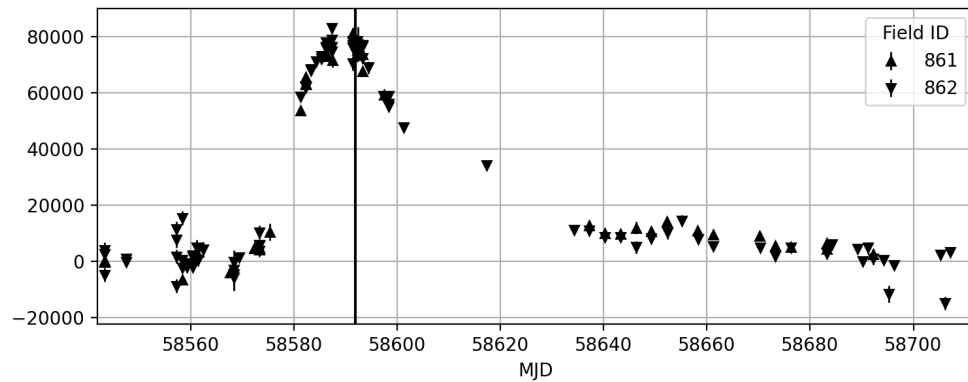
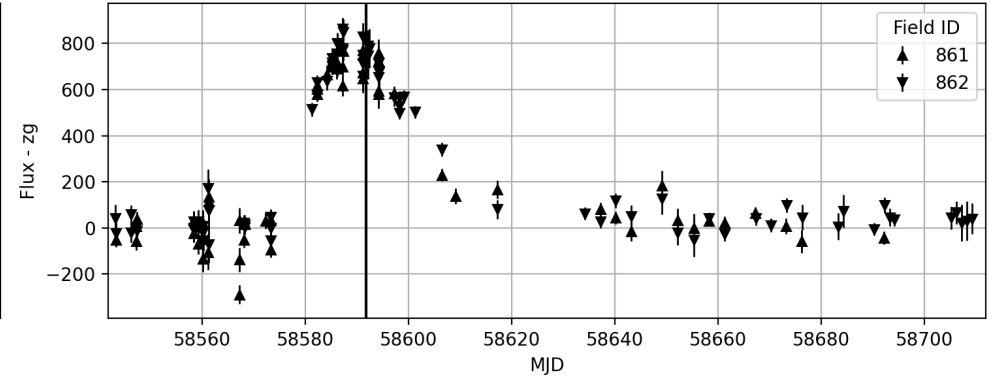
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Forced photometry lightcurve



Scene modeling lightcurve





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



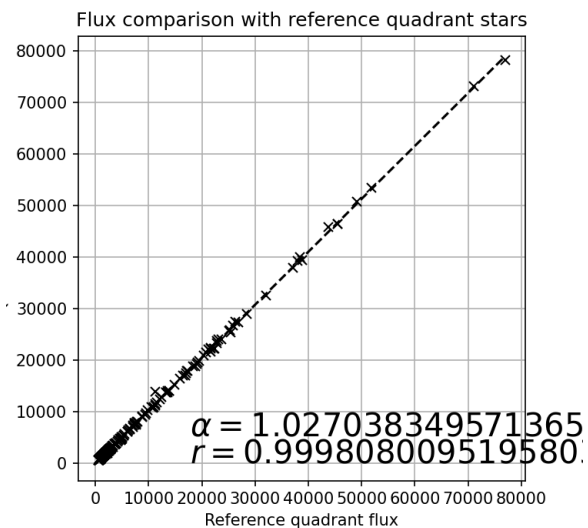
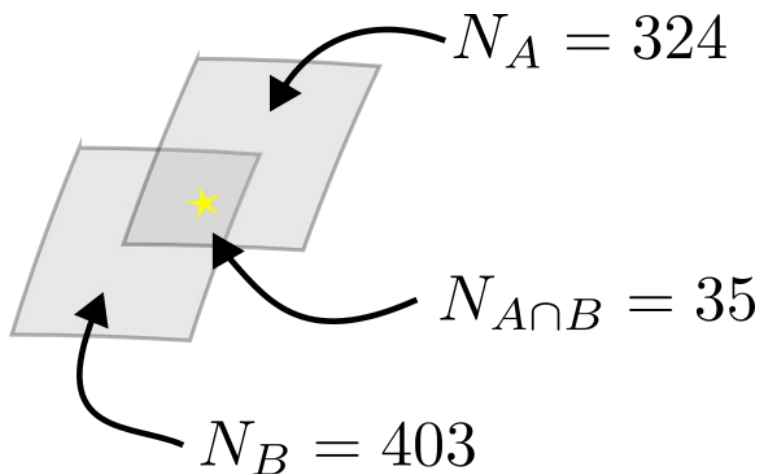
Thank you for your attention!



Backup

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 at the lightcurve scale

- Fit:

- $$m_{ij} = M_i + ZP_j$$

- With:

- m_{ij} : star flux measurement for star j in quadrant i

- M_i : fitted i star flux

- ZP_j : fitted j quadrant ZP (with $ZP_{\text{ref}}=0$)

- => Simple linear fit giving relative ZP from reference

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

