# Robotic Monitoring of Gravitationally Lensed Quasars

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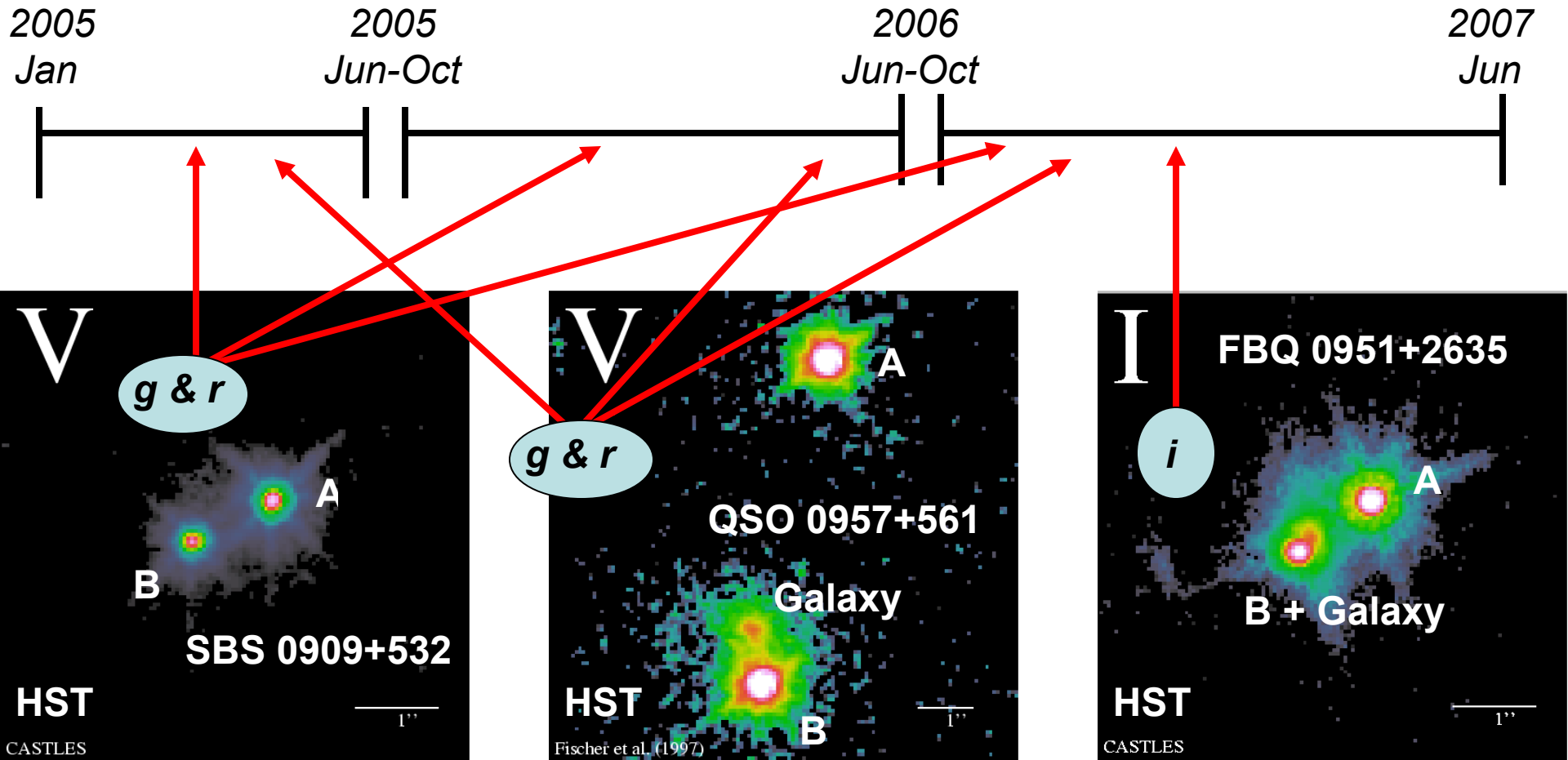
# THE PROGRAM

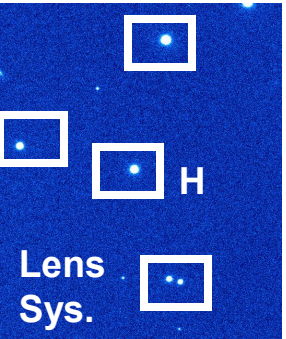
►The first phase of the nightly monitoring program with the 2 m Liverpool Robotic Telescope (LRT) began in 2005 January and finished in 2007 July. This Liverpool Quasar Lens Monitoring (LQLM) I project was carried out with the RATCam optical CCD camera on the LRT, using *gri* Sloan filters. The field of view and the pixel scale (binning 2 × 2) were ~ 4.6′ × 4.6′ and 0.278″, respectively.



# THE PIPELINES (→ QSO 0957+561)

► A LRT pre-processing pipeline is applied to all frames ( http://telescope.livjm.ac.uk/Info/TelInst/Inst/RATCam/index.php) before the data are passed to users. This performs three basic instrumental reductions: bias subtraction, trimming of the overscan regions, and flat fielding. We also correct bad pixels on the CCD (*Kerins et al. 2006*). Through a direct inspection of images and headers, we then pre-select frames (verifying some elemental conditions) to subsequent analysis.

► In a second step, our **CROWED-FIELD PHOTOMETRY PIPELINE** (**CPP**) does aperture photometry of bright field stars and quasar images. This IRAF procedure is used to estimate initial instrumental fluxes and source positions on each frame. The CCP also cuts the original frames in order to produce square subframes with 64 pixels side: lens system subframes and subframes of stars. An empirical PSF (based on the 2D profile of the H star) is used when modelling subframes through IMFITFITS (PSF fitting) software (*McLeod et al. 1998*). The CPP is written in Python, and incorporates the capabilities of IRAF, through the PyRAF interface, and IMFITFITS as well as additional numerical and graphical tools.




Star subframe (one star) → PSF

Lens system subframe (two quasar images and lensing elliptical galaxy) → PSF + PSF + [de Vaucouleurs profile ⊗ PSF]

► We also use a **TRANSFORMATION PIPELINE** (**TP**; in Python programming language) to get SDSS magnitudes from instrumental magnitudes that are corrected for systematic effects. Only frames with SNR ≥ 100 over QSO 0957+561A are taken into account (e.g., in the *g* band, this selection lead to 170 frames).

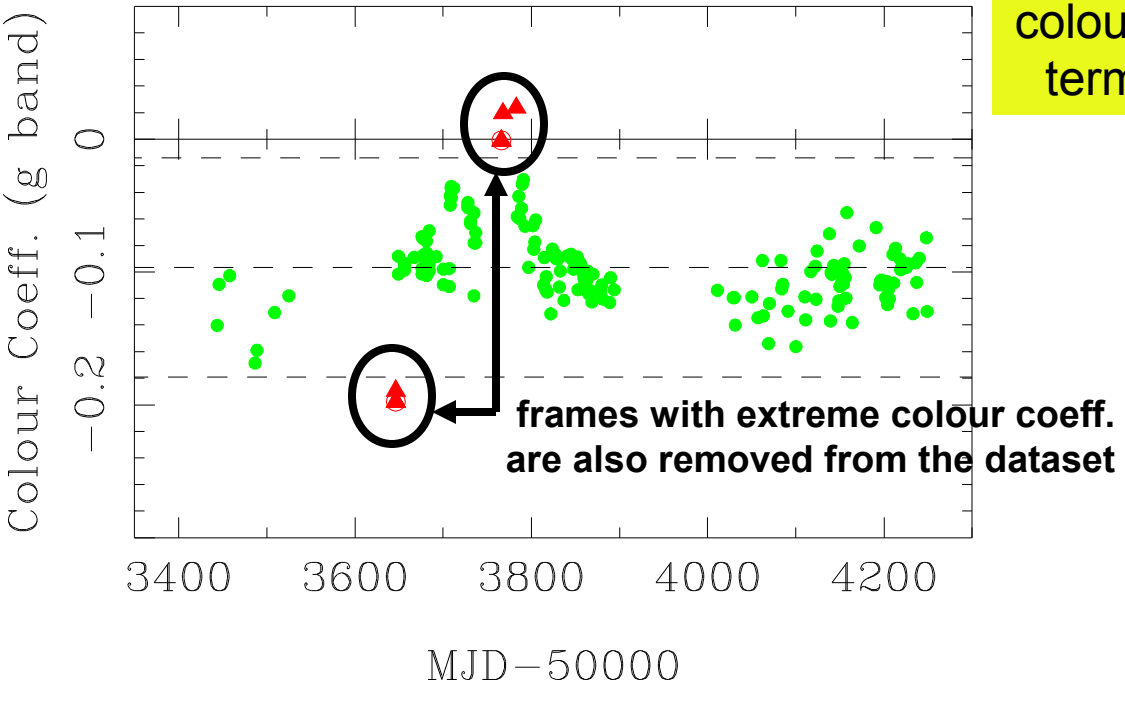
*g* Sloan band

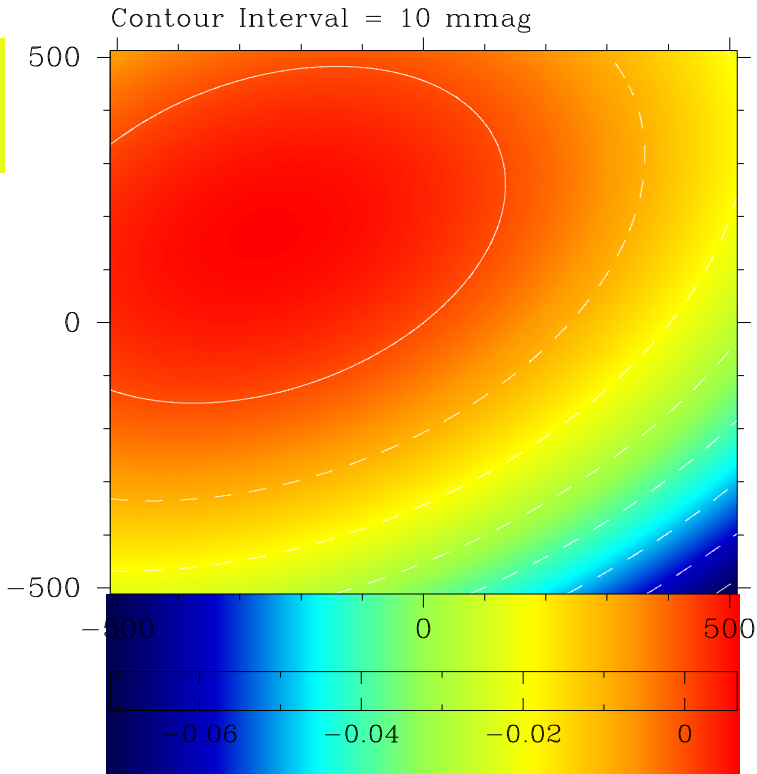
inhomogeneity term
(x,y) ≡ 2D position on the CCD

$$\text{STARS: } g_{inst}(t_j) - g_{SDSS} \rightarrow \alpha\,(t_j) + \beta\,(t_j)(g - r)_{SDSS} + \sum_{0 < n+m \leq 2} \gamma_{nm}\, x^n(t_j)\, y^m(t_j)$$

zero-point term

colour term

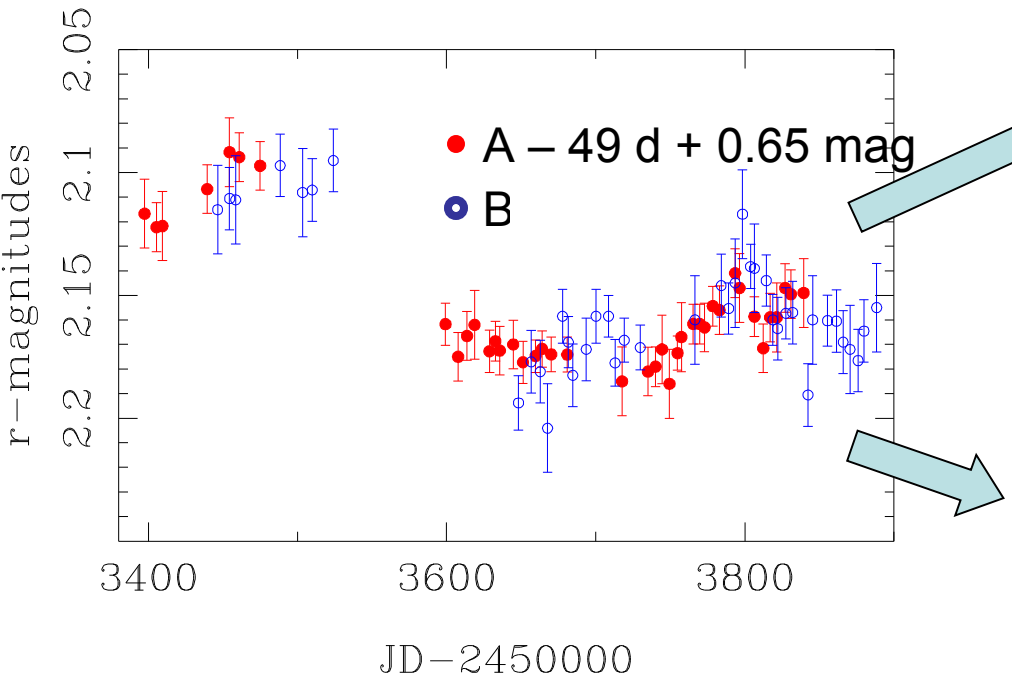


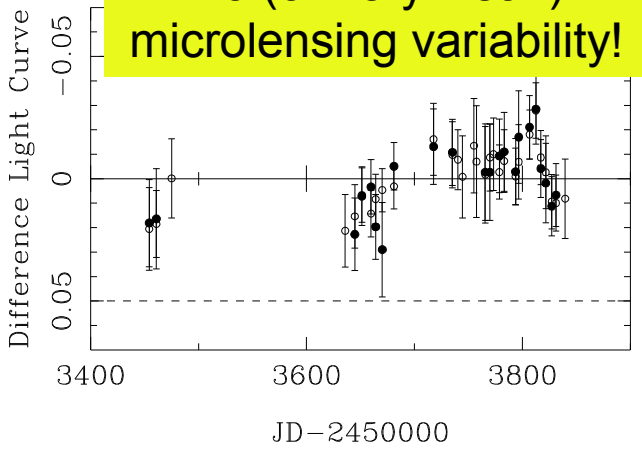
# SCIENTIFIC OUTPUT (→ SBS 0909+532 & QSO 0957+561)

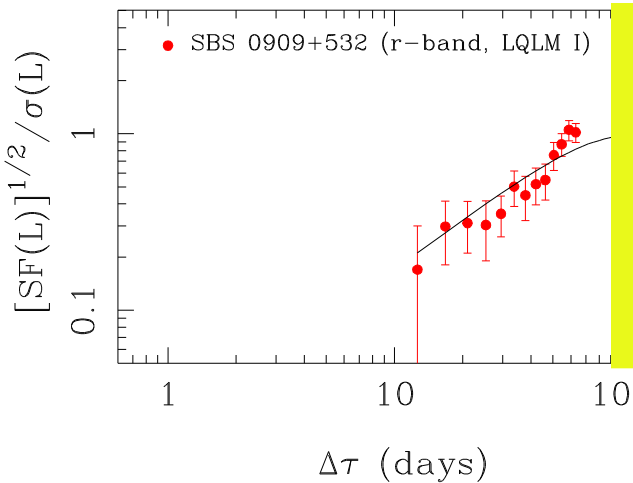
## SBS 0909+532

● In the *r* band, photometry to the 1% level is achieved for both quasar components (light curves with average errors of ~ 10-13 mmag)




No (or very weak) microlensing variability!



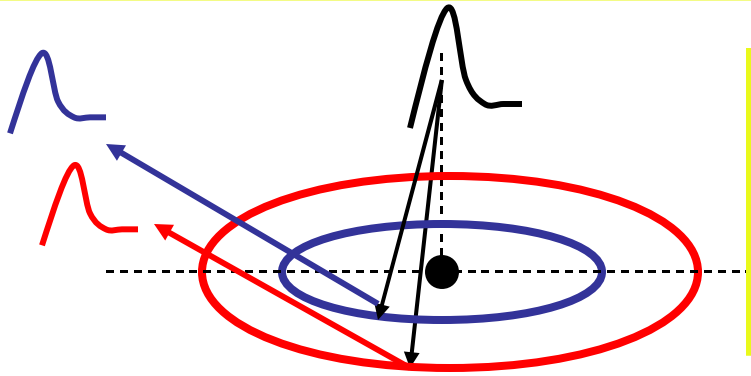




Symmetric triangular flares with τ ~ 100 d ($\chi^2$/dof ~ 1)

$\Delta t_{BA}$ = - 49 ± 6 d (1σ ; B is leading)

# QSO 0957+561

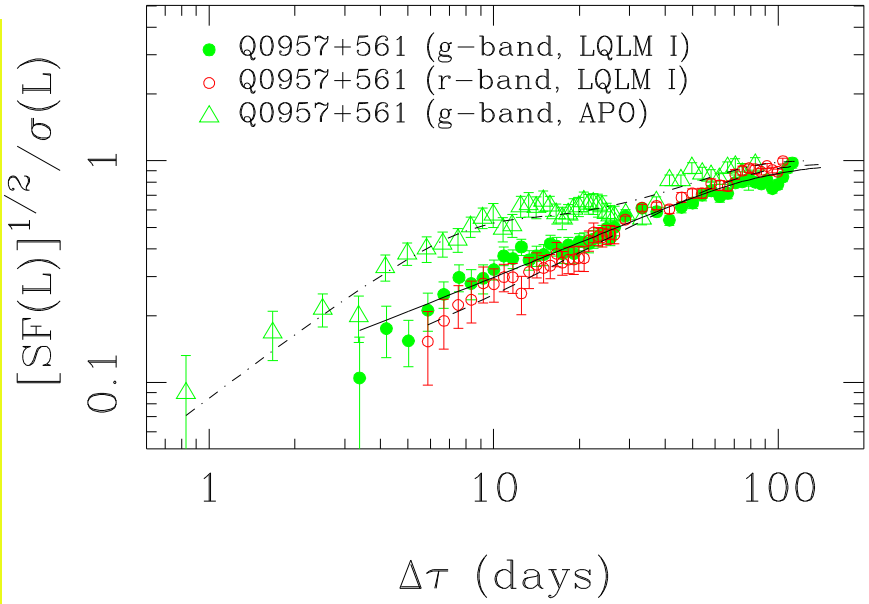
The final records in the *g* and *r* bands (1-2% photometric accuracy) do not contain microlensing events, and they are used to measure time delays between quasar components and optical bands



time lag between both fluctuations

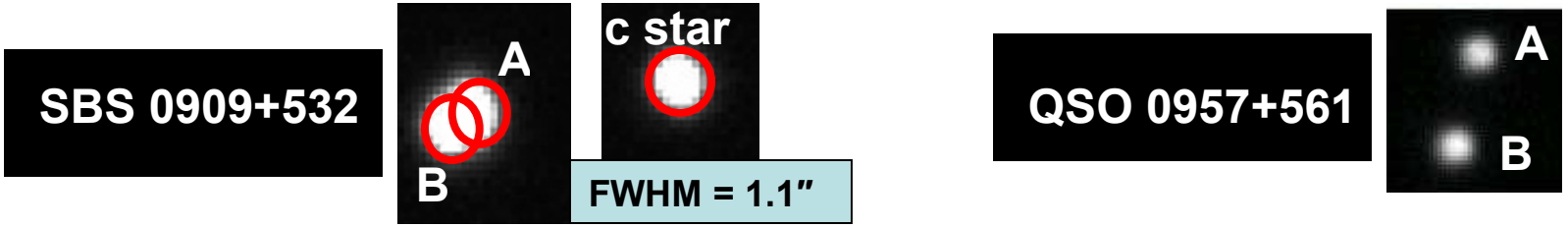
New and previous time delays indicate that most observed variations are very probably due to reverberation within the gas disc around the supermassive black hole

We also obtain the structure functions of the quasar luminosity at $\lambda_{rest} \sim 2100$ Å (*g*) and 2600 Å (*r*). We do not find clear evidence of a chromatic mechanism of variability: 100-d time-symmetric and 170-d time-asymmetric flares are produced at both restframe wavelengths. This supports the reverberation scenario. There is also evidence of an intermittent production of high-energy asymmetric fluctuations

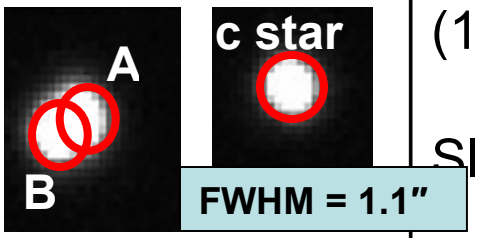
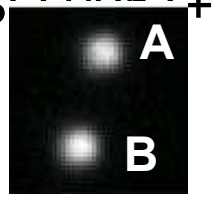
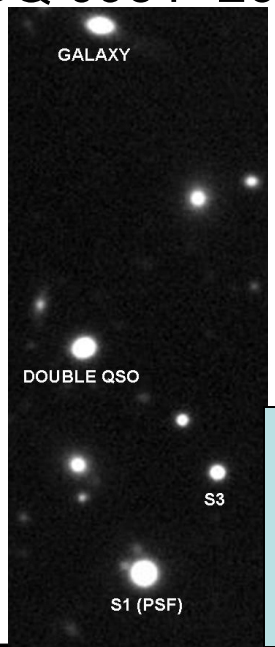


# ARCHIVING THE DATA

► All LQLM I frames of SBS 0909+532 and QSO 0957+561 are available at the **LIVERPOOL QUASAR LENS MONITORING** archive (http ://dc.zah.uni-heidelberg.de/liverpool/res/rawframes/q/form) on the German Astrophysical Virtual Observatory (GAVO). This archive is part of a larger optical database of gravitationally lensed quasars. The whole collection of frames consists of exposures from telescopes in the North Hemisphere (APO 3.5m in USA, LRT 2.0m in Spain, and AZT-22 1.5m in Uzbekistan).




► The GLENDAMA project has a website (http ://grupos.unican.es/glendama/index.htm) incorporating information on the current status of the LQLM program. In particular, the **SECOND DATA-TOOLS RELEASE** ( http://grupos.unican.es/glendama/LQLMI_DR.htm) includes a link to the lens image archive (at GAVO), as well as public access to the photometric pipelines and their outputs (quality of images, instrumental fluxes, transformation coefficients, calibrated and corrected magnitudes, etc). The data-tools release also contains final light curves and references.

| Name | Frames | *r* | *g* | *i* |
|---|---|---|---|---|
| SBS 0909+532   | 237 *g*-Sloan (100-200 s)<br>214 *r*-Sloan (120 s) | **2005 Jan-2006 Jun:**<br>**►Total number of frames = 153**<br>**►Total science time = ~ 18 ks = 5 h**<br>**► Success rate = 60%** | **• Only 60 high-quality frames (25% of the total). These verify FWHM ≤ 2″ and SNR (c star) ≥ 100** | |
| QSO 0957+561   | 286 *g*-Sloan (100-200 s)<br>264 *r*-Sloan (120 s) | **• Total science time of ~ 22.6 h during the 2.5-year program. Using constraints FWHM < 3″ and SNR (A) ≥ 100:**<br>**170 *g*-band frames (~ 60%)**<br>**167 *r*-band frames (~ 60%)** | | |
| FBQ 0951+2635   | 5 × 100 s (dither cross)<br>259 *i*-Sloan<br>↓<br>52 combined frames (nights) | **Stacked frame:**<br>**Total exposure time = 4.4 h**<br>**FWHM = 1.17″**<br>**SNR (S3 star) = 413** | | **• Only 22 combined frames (nights) verify FWHM < 1.5″ and SNR (S3 star) > 50** |