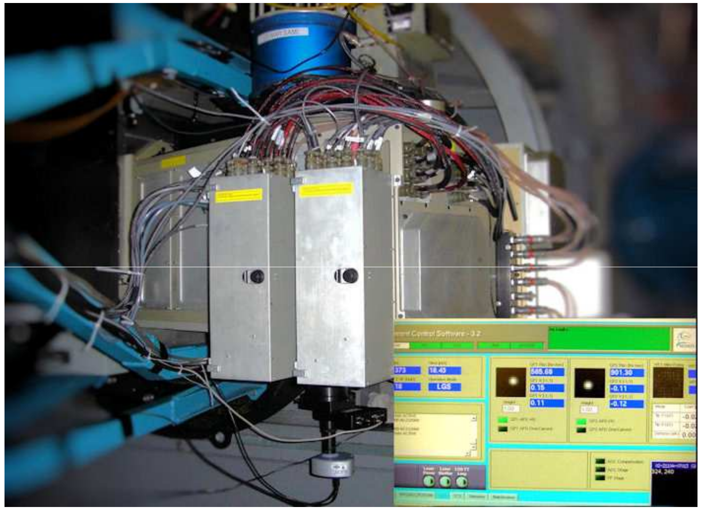
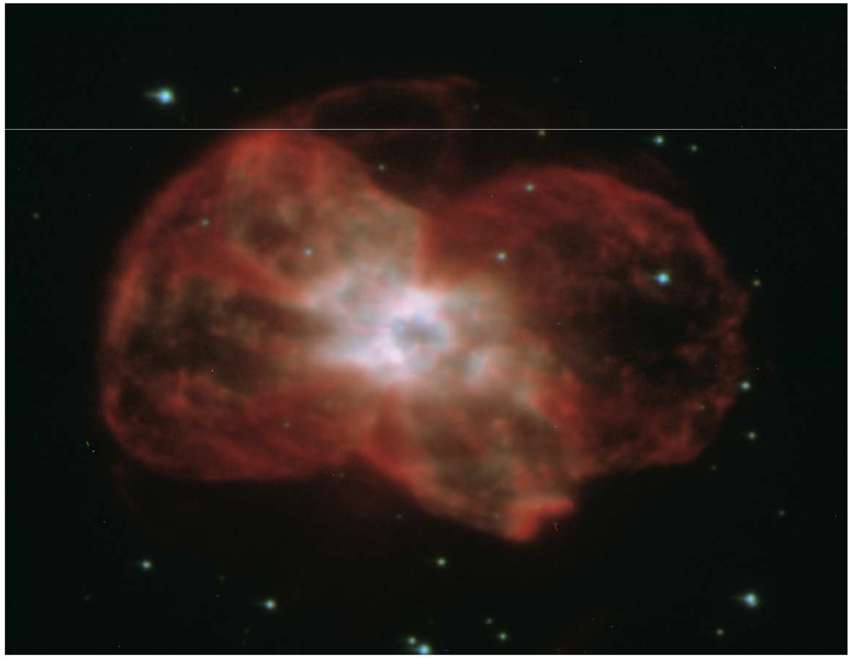
SOAR Adaptive Module (SAM):
the user's perspective





Andrei Tokovinin

Outline

- I: What is SAM?
- II: Capabilities: why use SAM?
- III: Science with SAM
- IV: Before, during, and after your observations
- V: Using SAM data for science
- VI: Broader perspective (competition, active optics, speckle)

Why SOAR needs AO?

- "Small" (4-m) telescope with a narrow field. Its niche was declared to be **high angular resolution**.
- "Classical" AO: **NO** (poor sky coverage, narrow field, IR only, competition with 8-m)
- Ground-Layer AO: **YES** (optical wavelengths, full sky coverage, moderate field).
- SAM was built as a GLAO instrument. First laser light: Apr 2011, commissioned: Nov 2013, science verification: Jan 2014. Cost: ~4.5M USD, time: 12 calendar years, manpower: ~20 man-years.

Ground-layer adaptive optics

Selectively compensate only low turbulent layers
to improve the “seeing” over a wide field (F. Rigaut, 2001)

SAM uses one UV Rayleigh laser to selectively
sense the ground layer. The compensation is partial.

SAM is a “sandwich” between telescope and instrument, it
does not produce science data by itself!

SAMI (built-in imager) and visitor instrument (SIFS?)

I: What is SAM?

- AO module on optical ISB relays image 1:1 with partial seeing correction
- SAMI: built-in CCD imager (4096x4112, 45mas pixel,

FoV 3 arcmin, 1 filter wheel)

- UV laser and its projection system
- Software, computers, documents

Google:
"SOAR Adaptive
Module"

www.ctio.noao.edu/new/Telescopes/SOAR/Instruments/SAM/

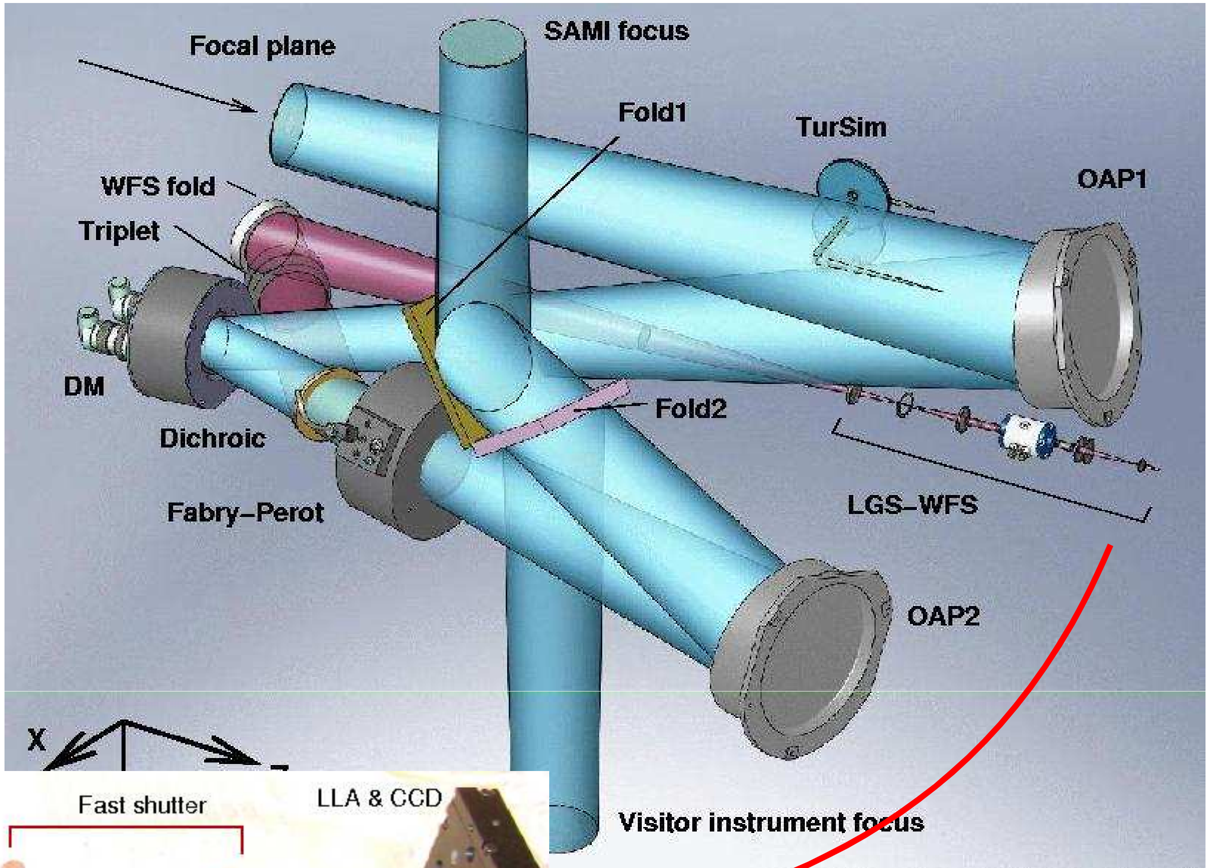
Documentation available

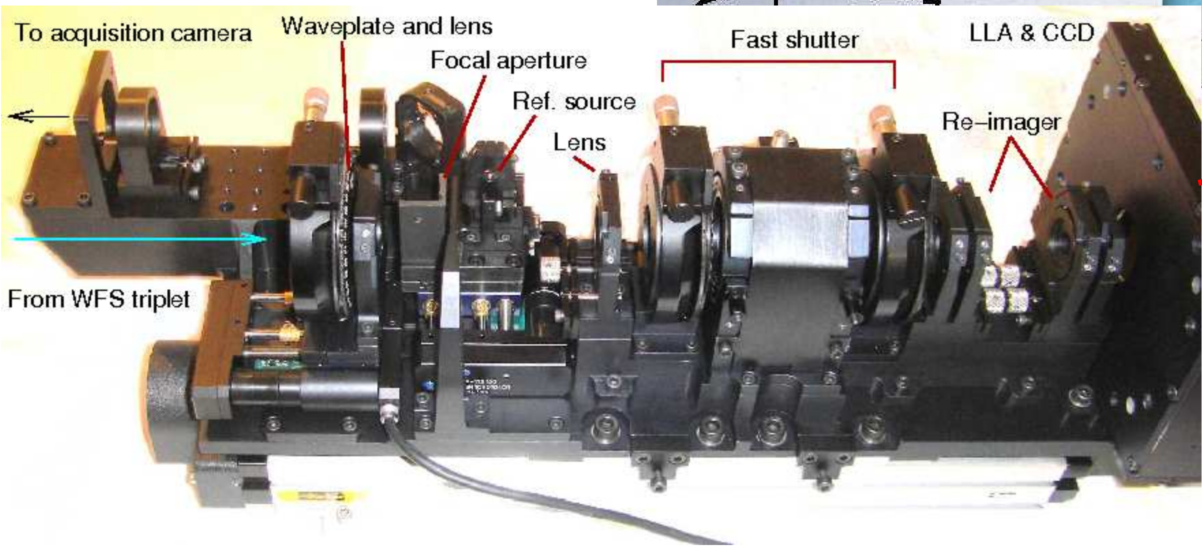
- User guide (short instruction)
- Manuals on SAMI and its software
- Several SAM manuals
- Commissioning report
- Science verification report
- SPIE papers on SAM

To-to:
Refereed paper
Complete description

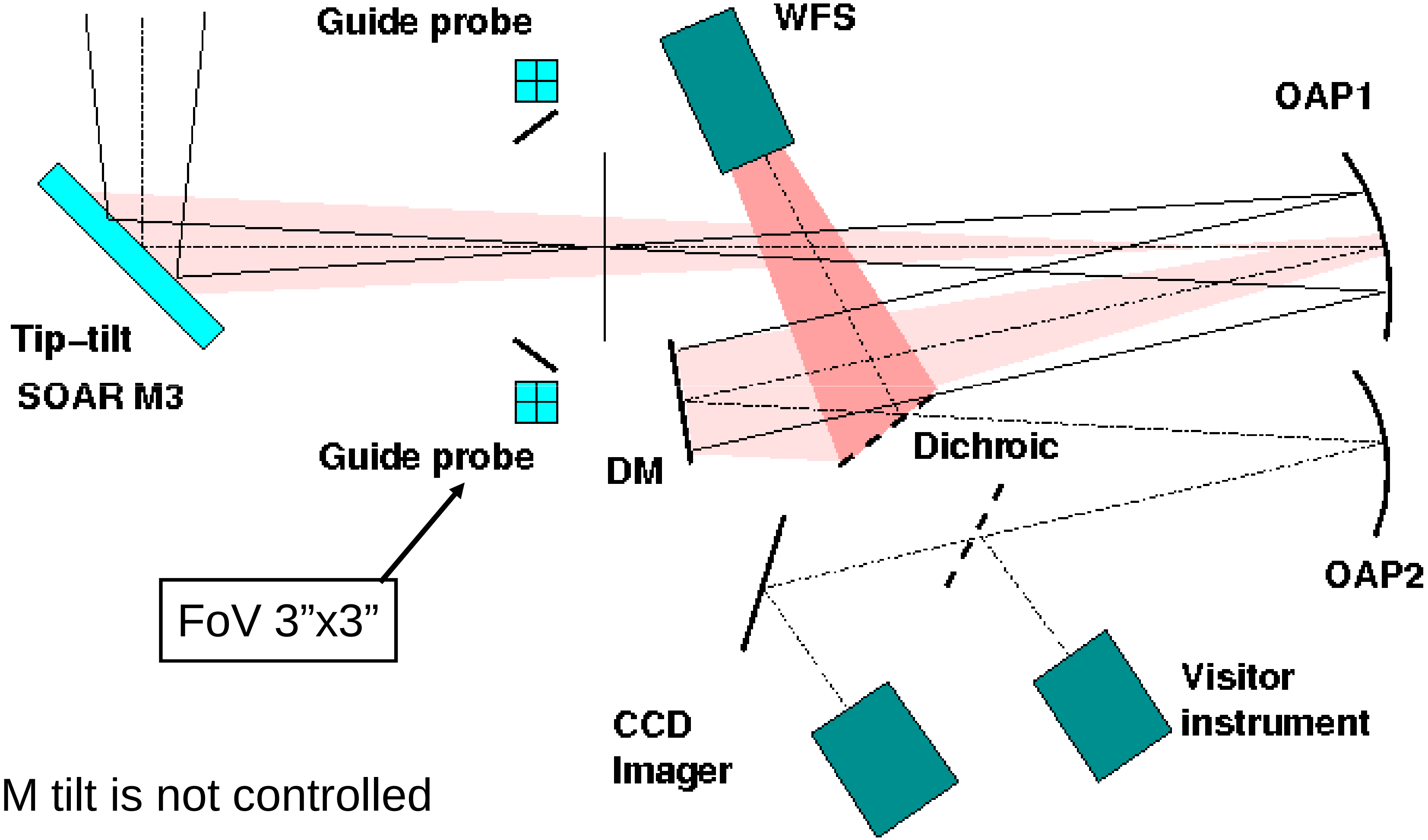
www.ctio.noao.edu/new/Telescopes/SOAR/Instruments/SAM/

Optics of SAM





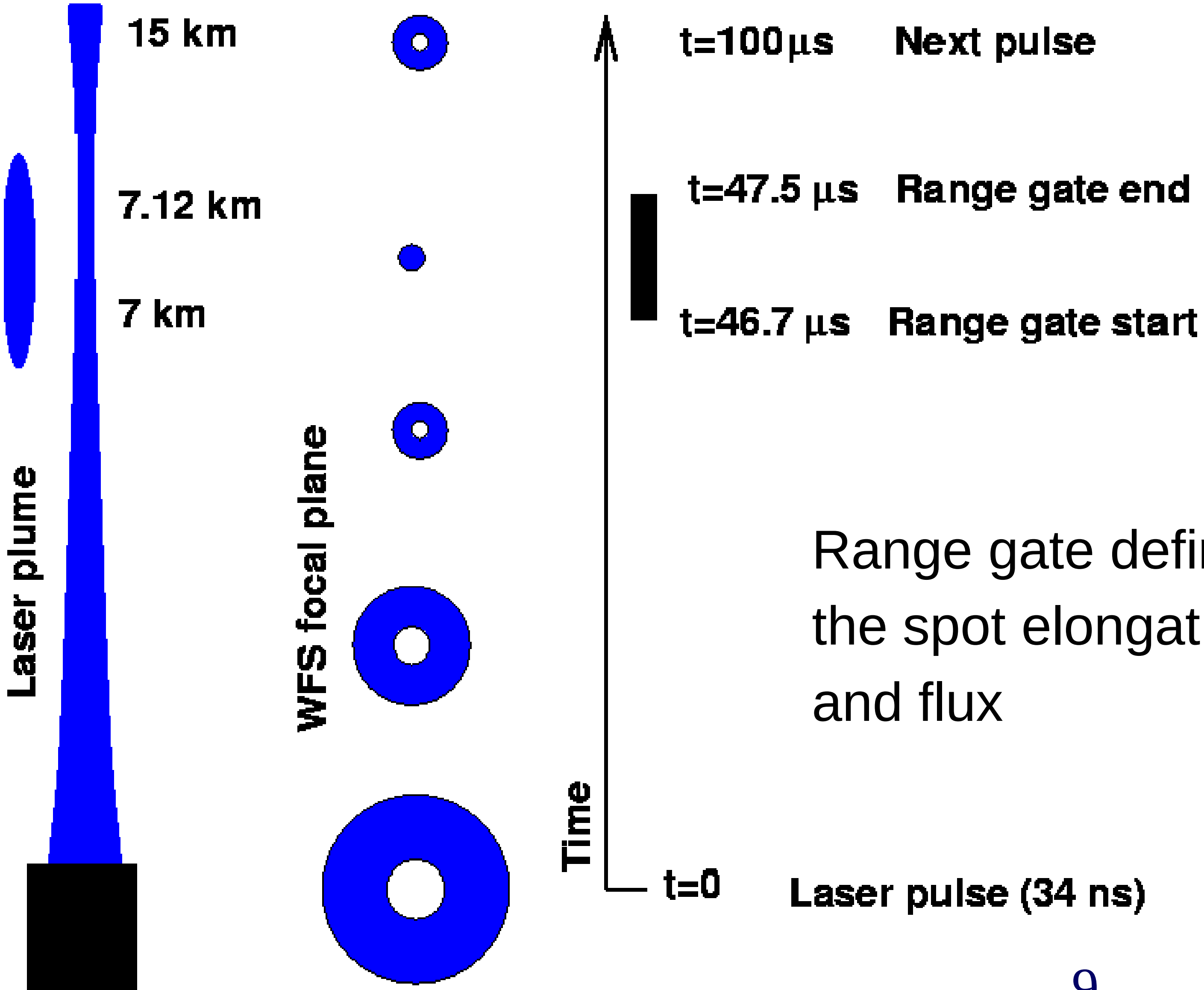
SAM at a glance



FoV 3”x3”

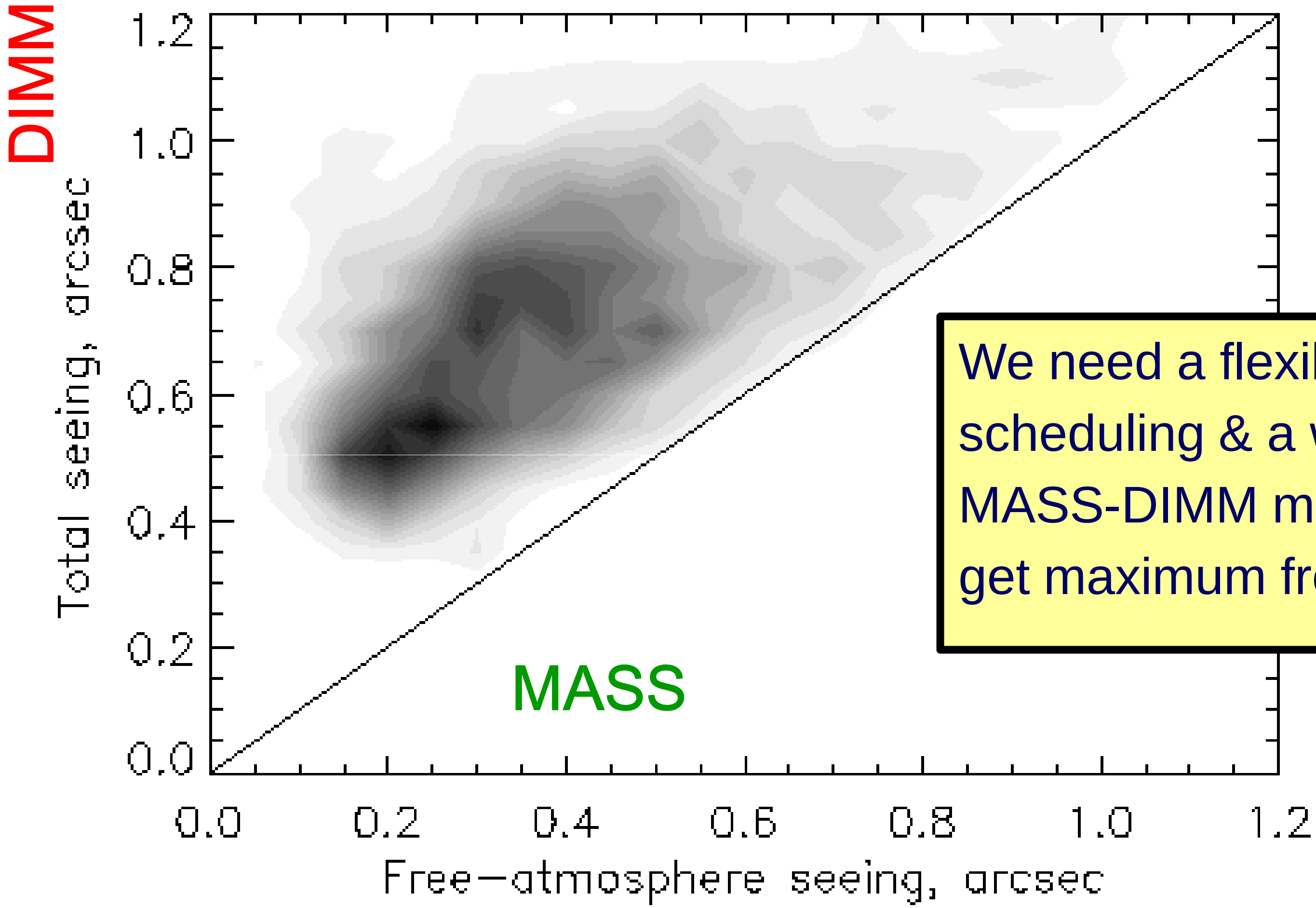
DM tilt is not controlled
and it works!

Rayleigh LGS (λ=355nm)



Range gate defines the spot elongation and flux

Seeing: total (DIMM) and free-atmosphere (MASS)



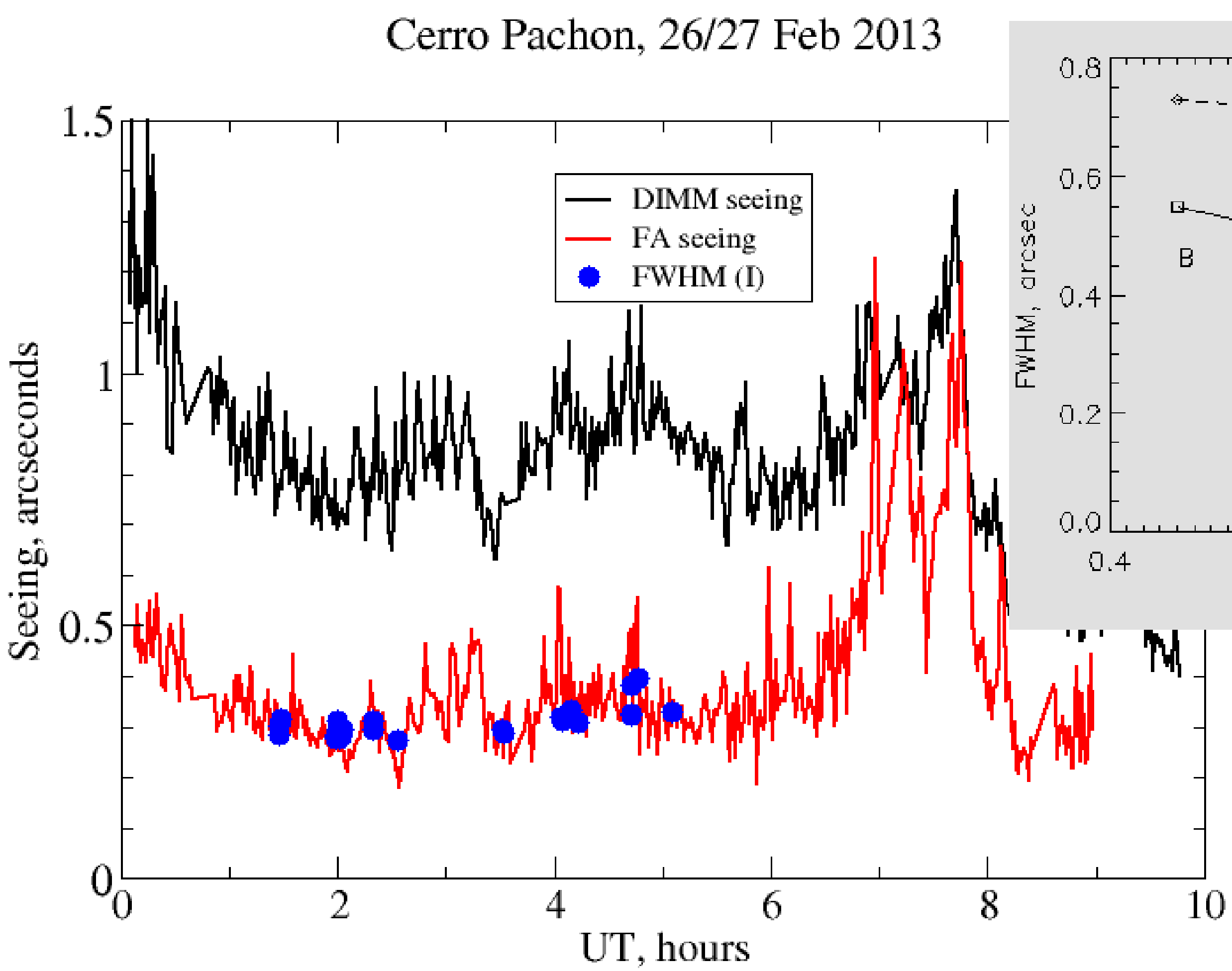
We need a flexible scheduling & a working MASS-DIMM monitor to get maximum from SAM!

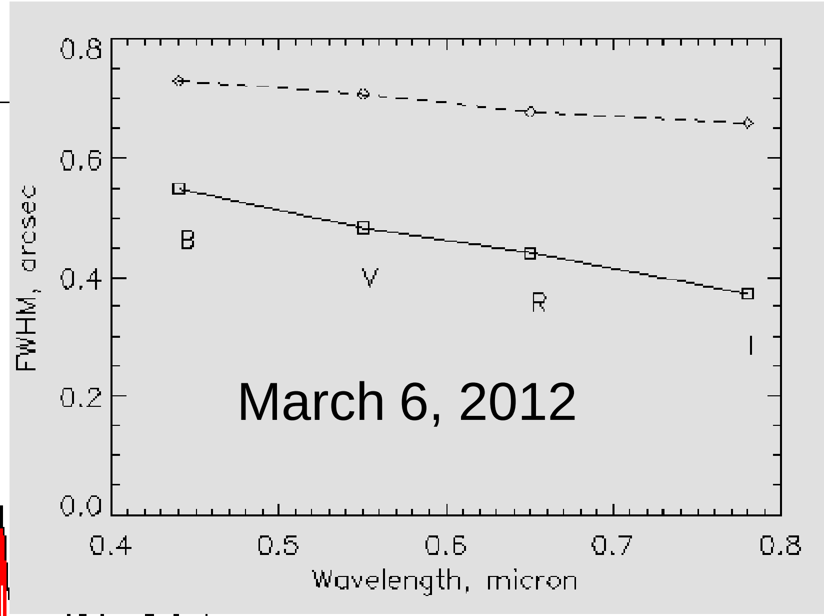
Calm nights with FA seeing <0.25” happen regularly

II: SAM capabilities

- Improve FWHM resolution (close to free-atmosphere seeing in the I and z bands)
- Guide stars to R=18 in 5' FoV (full sky cov.)
- Wavelength >400nm (no UV!)
- As efficient as SOI, but no gap between CCDs
- ADC is available
- Can work without laser, in open loop

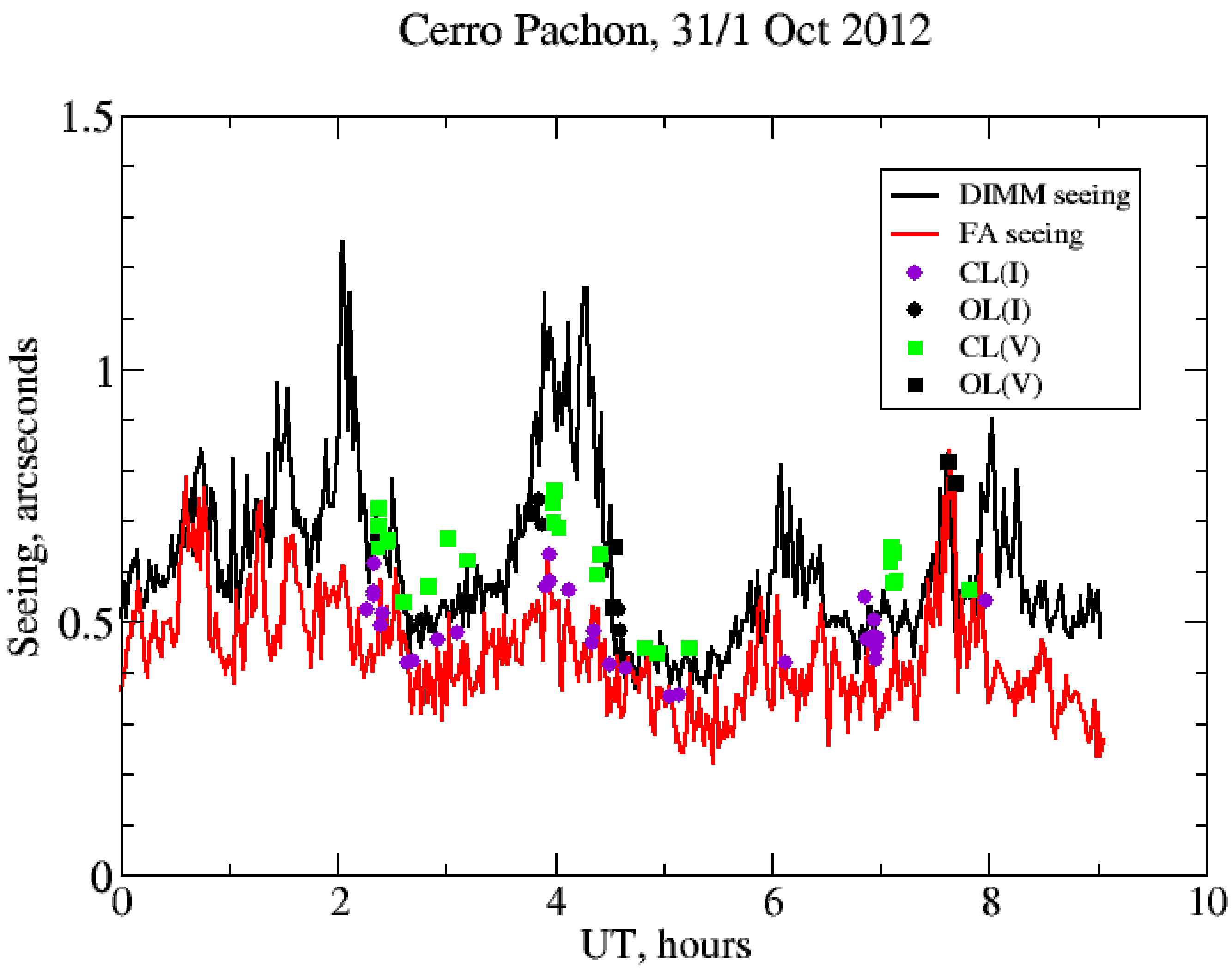
Performance: two good nights





Median FA seeing at Pachon 0.40”

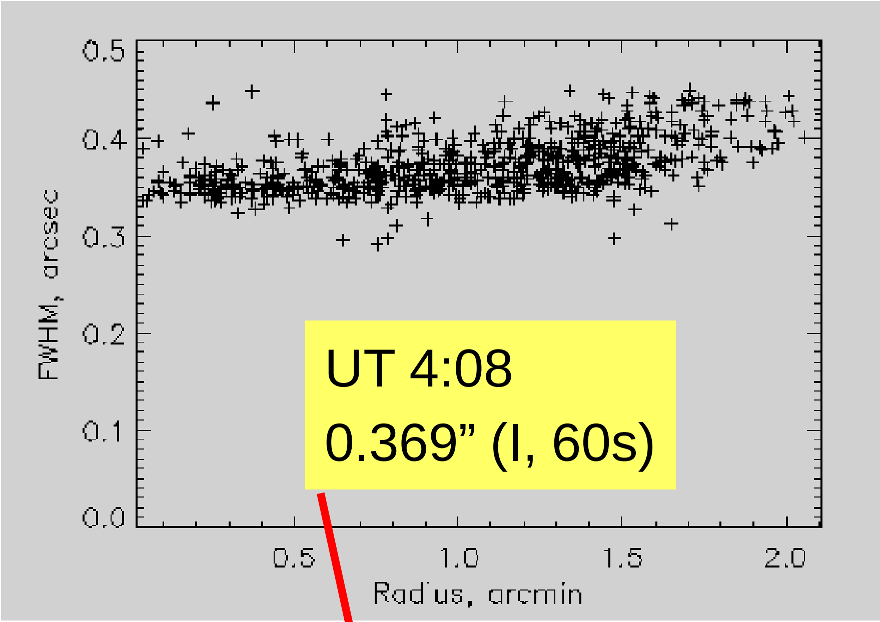
Performance: a poor night (with good seeing)

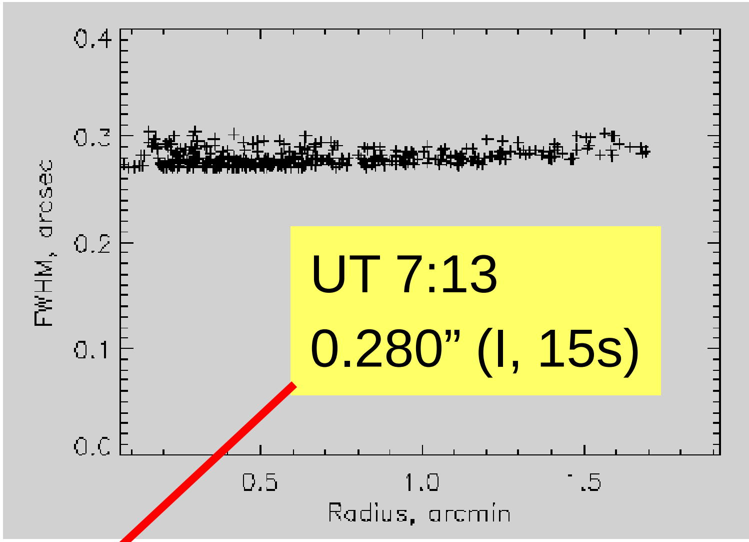


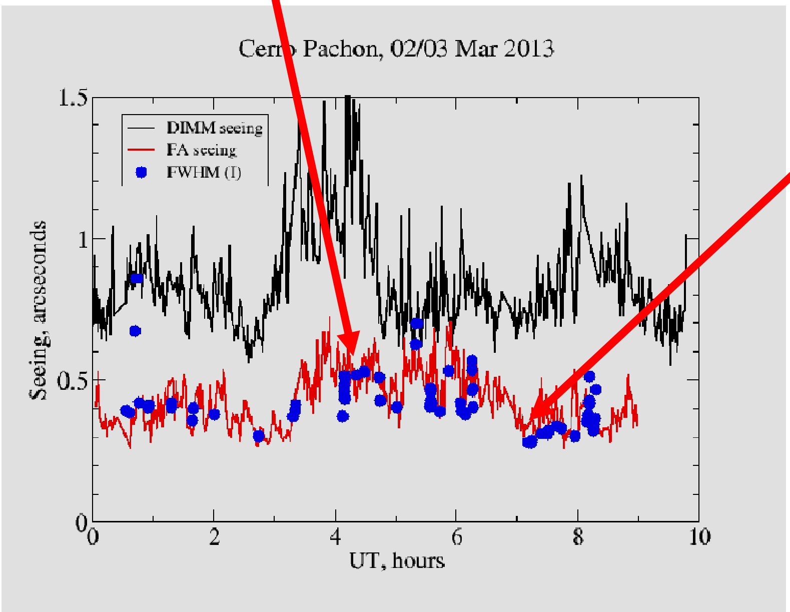
Small gain in FWHM

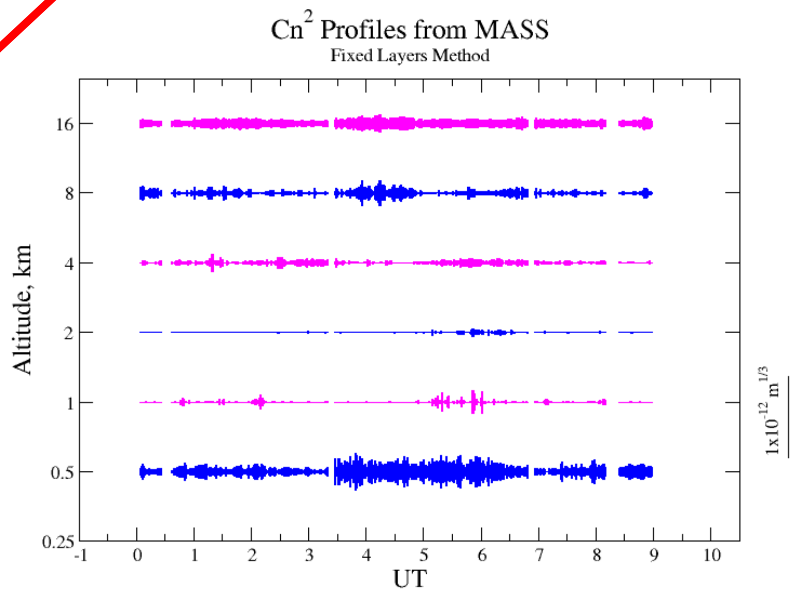
No direct correlation between SAM resolution and site seeing

Correction uniformity over the field









SAM performance metrics

- FWHM uniformity over the field (often <2%)
- PSF: Moffat profile with β~2
- Energy gain ½ of FWHM gain (e.g. 1.4 instead of 2)
- Ellipticiy small (typ. <0.05)

SAMI parameters: gain 2.1 el/ADU, RON 4 el, Readout time ~5s (with 2x2 binning), pixel scale 45mas, no bad columns

III: Science with SAM

- Stellar: clusters, crowded fields, binaries
- Nearby galaxies (star formation, globular-cluster systems, AGNs)
- Distant galaxies (clusters, weak and strong lensing)
- Follow-up of DECAM, LSST (e.g. Supernovae)
- Astrometry? To be studied

- NO: Low surface brightness
- NO: high dynamic range

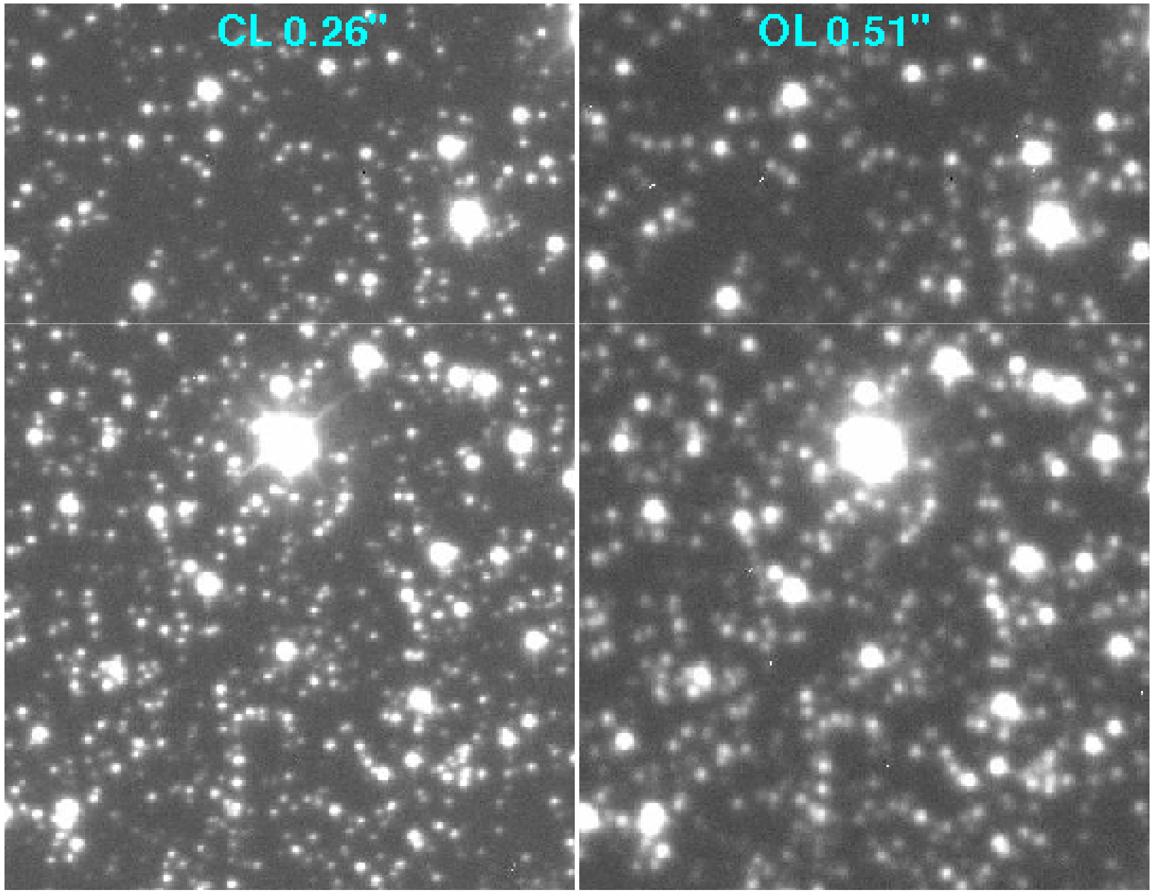
SAM science 1: stars

- Stellar populations in crowded fields

L.Fraga et al., AJ
ArXiv:1304.4880
globular cluster
NGC 6496

Competition with HST
Collaboration with GEMS

Non-uniform PSF is OK



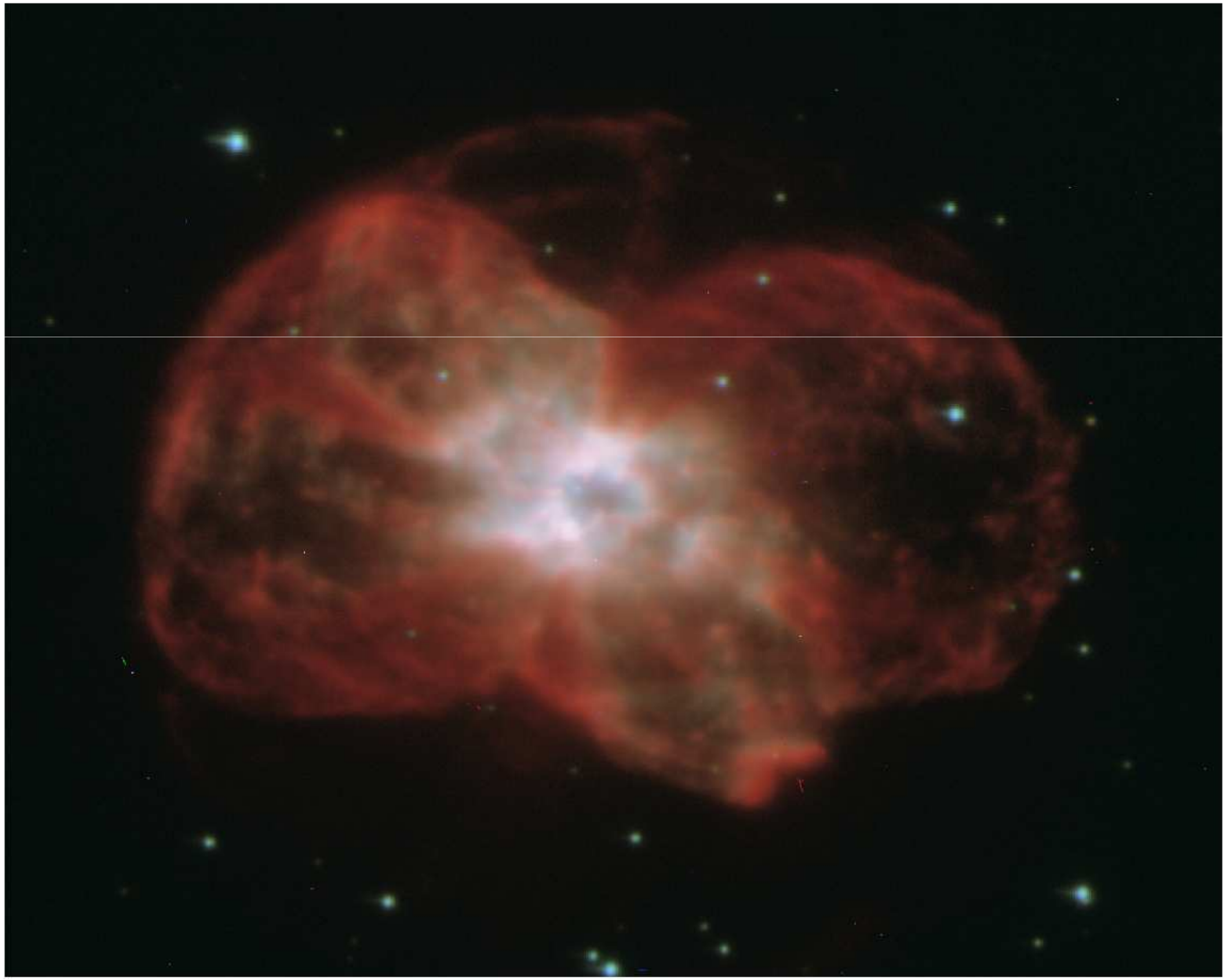
SAM science 2.

- Nebulae,

star formation

(proplyds etc)

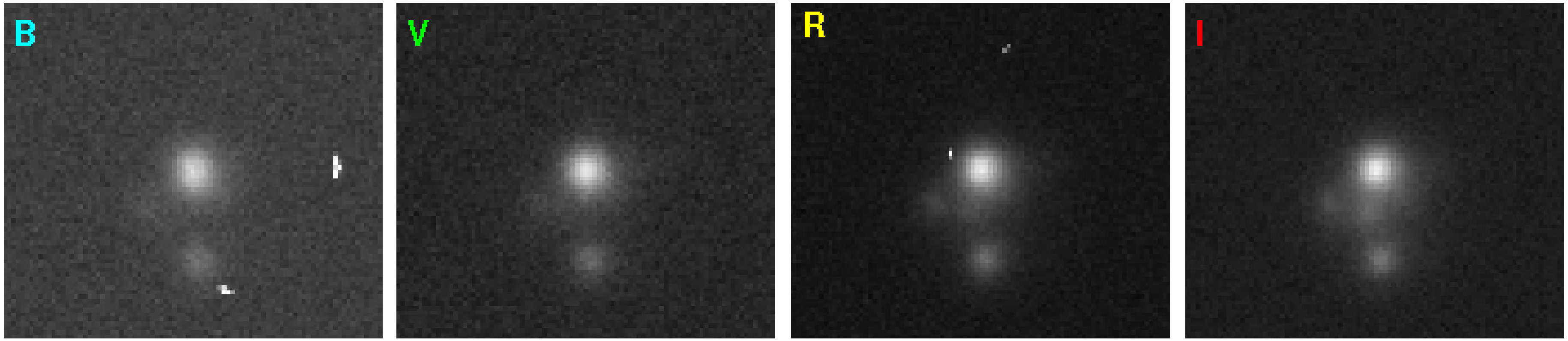
Best ground-based image of NGC 2440



Feb. 26, 2013
Exp. 60s
(Hα,V,B)→ (rgb)
FWHM 0.35”
Fragment
(nebula 72”)

SAM science 3.

- Small targets: galaxies, gravitational arcs, lensed quasars, solar-system bodies (Pluto, asteroids, comets), binary companions. Only on-axis FWHM matters!
- Future: imaging+spectroscopy (IFU and/or MOS)



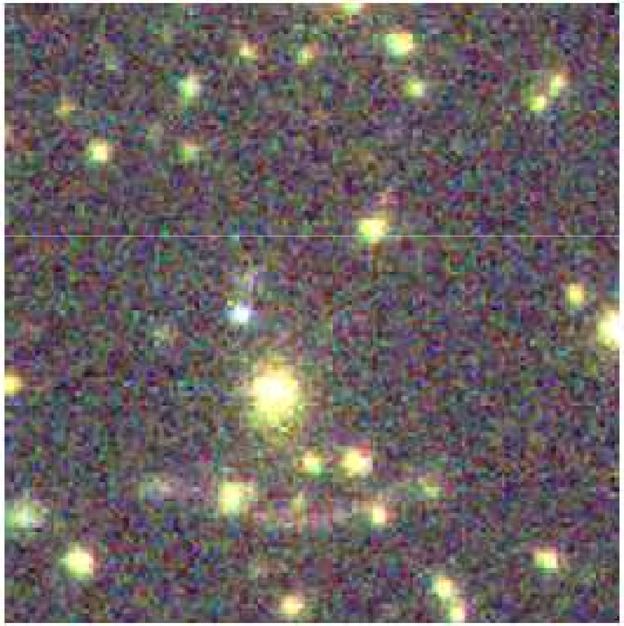
Lensed quasar SDSS_0924 (0.5” in *B*, 0.4” in *I*). Jan. 2013, 5-min. exp

SAM science verification program

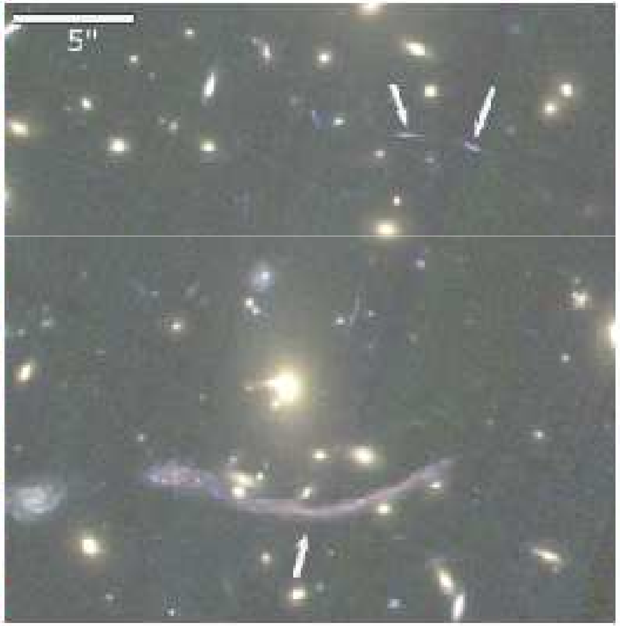
- 16 proposals for ~60h, mostly dark time
- 20h allocated (Apr. 17,18), lost to telesc. failure
- Galactic: clusters, planetary nebulae, pulsar shock, triple star
- Extragalactic: polar-ring galaxies, compact groups, gravitational lenses, “green beans”
- Solar system: Pluto, comets (non-siderial track?)

SAM looks at gravitational arc

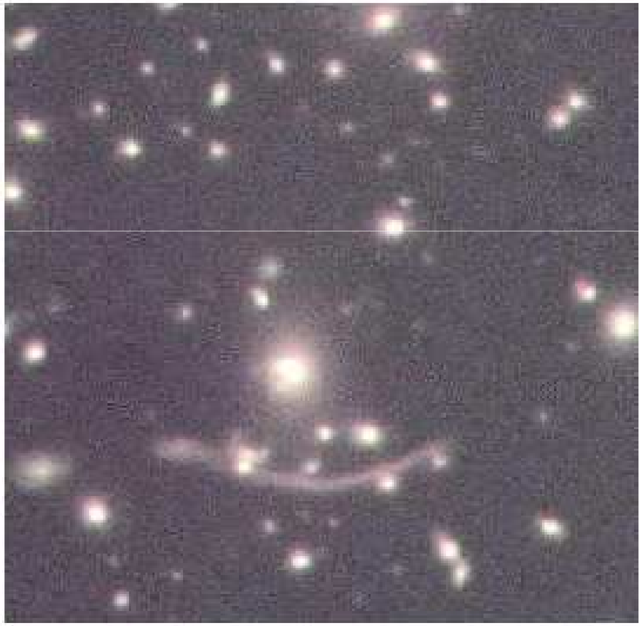
Abel 370



SDSS

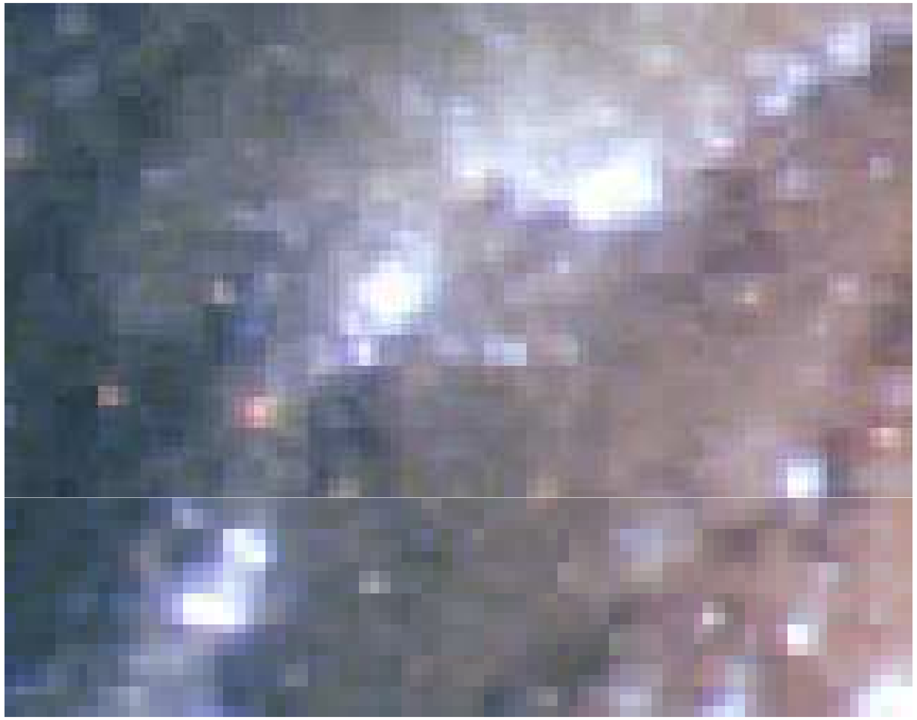


HST



SAM

Comparative imaging of NGC 1232



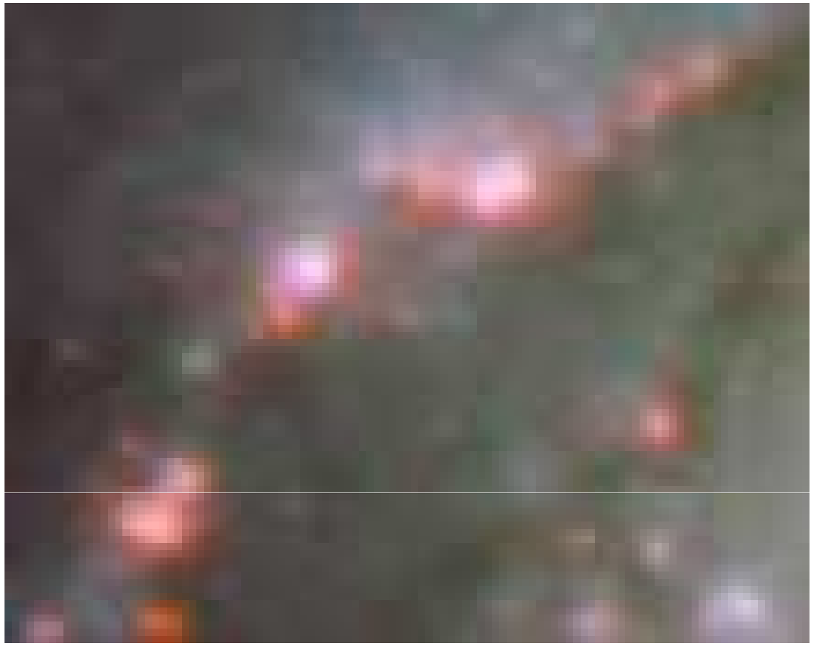
VLT (ESO PR 9845)

SAM

Image credit: ESO, LNA

NGC 1232: SAM vs. SOI

SAM



SOI

“Skidmark”

SAM project

by D. Murphy

(September 2013)

SAMI vs.

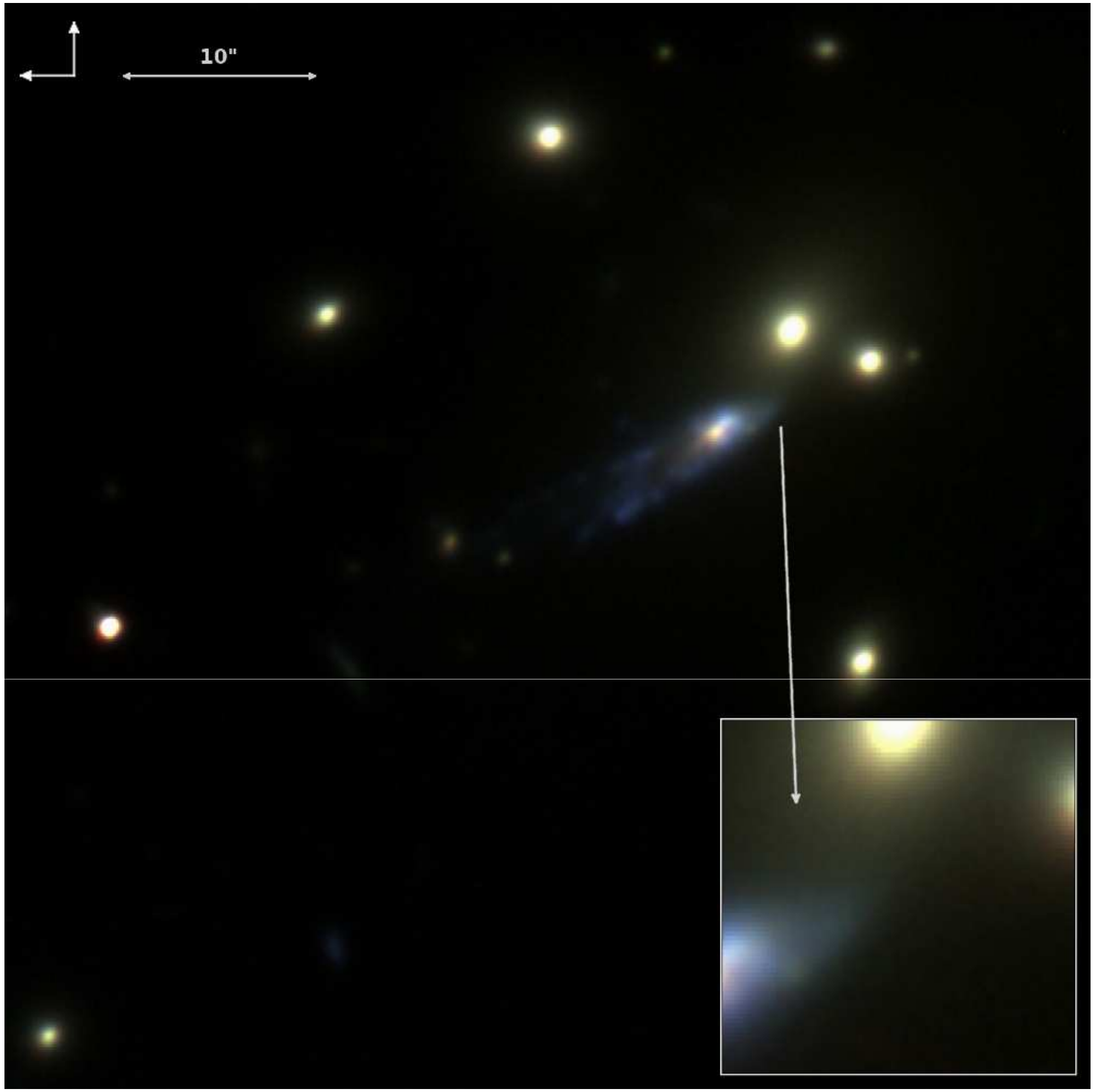
SOI:

Better guider

No gap

As efficient

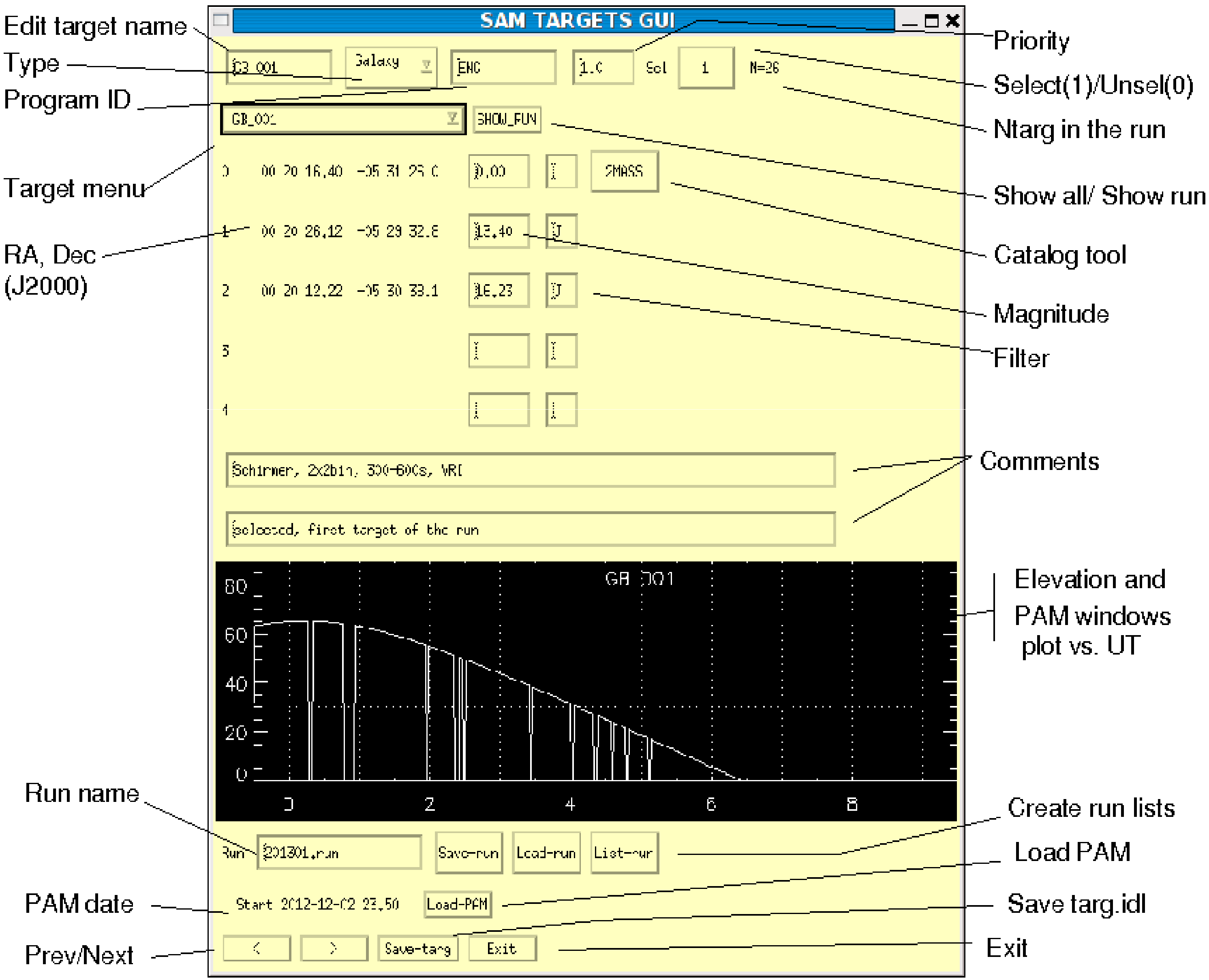
Cons: no UV, 3' FoV



IV: Before, during, & after observations

- Laser propagation is subject to the Laser Clearing House restrictions.
- Target list submitted to LCH 3 days in advance, in special format, by CTIO. No last-minute changes!!!
- LCH sends PAM files on the day of observation. SAM operator loads the file. Beware of blanket closures!

SAM Observing Tool



Before...

- Why use SAM? Plan your work!
- Send the instrument setup form (filters) to SOARops
- Send target list to CTIO ($\rightarrow$ LCH), plus standards
- Select position angle of SAM, guide stars
- Think of backup program for poor FA seeing

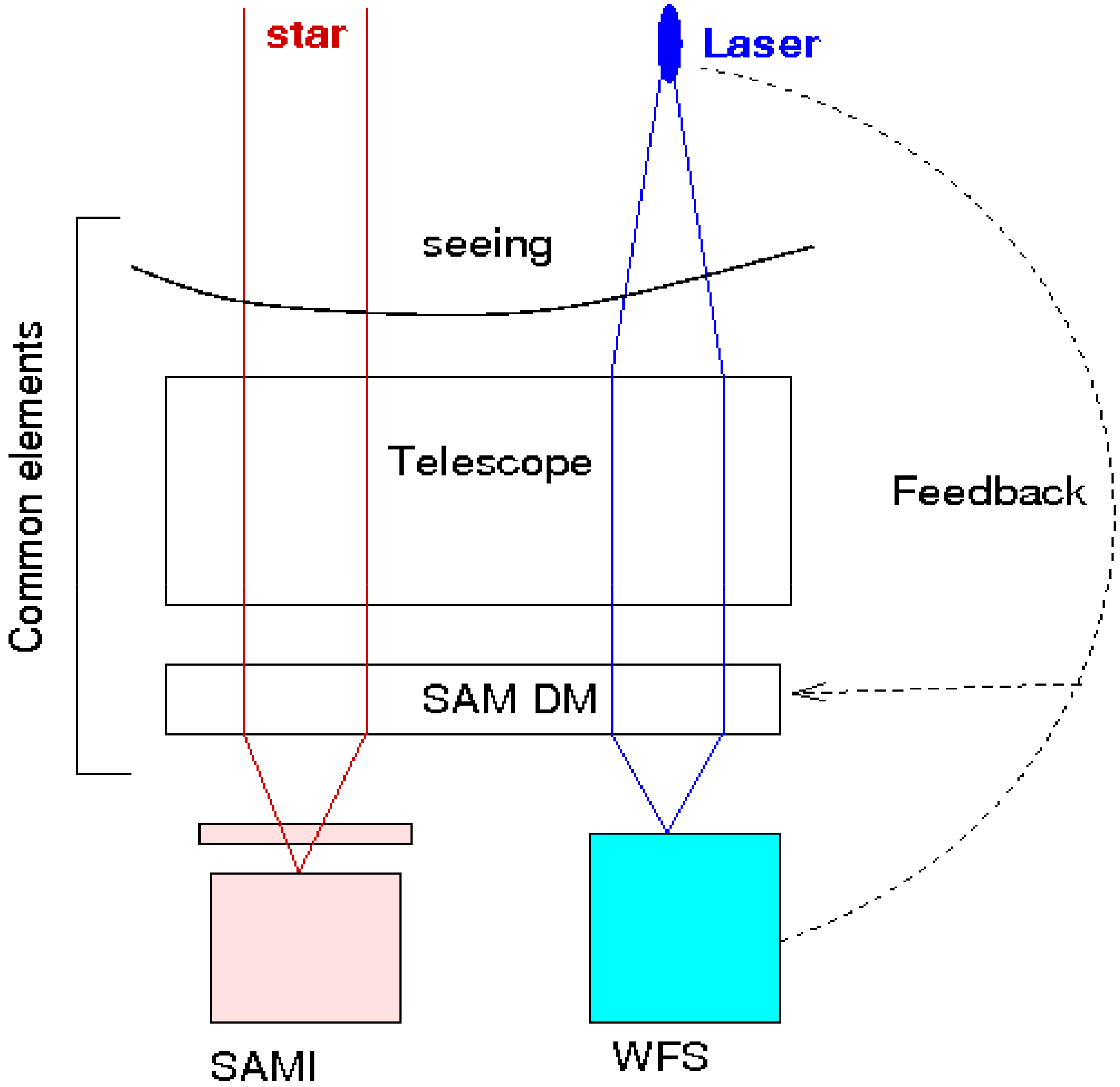
During observations

- SAM is prepared for the run by the instrument scientist (check, calibration of AO)
- Take sky flats (dome flats not good) and biases
- SAM is supported. Observer takes science data and interacts with SAM operator.
- Setup overhead <15min (can be 5-7min)
- Center your target before acquiring guide stars!
- Dithers: pros and cons. Small dithers OK.

Observing procedure with SAM

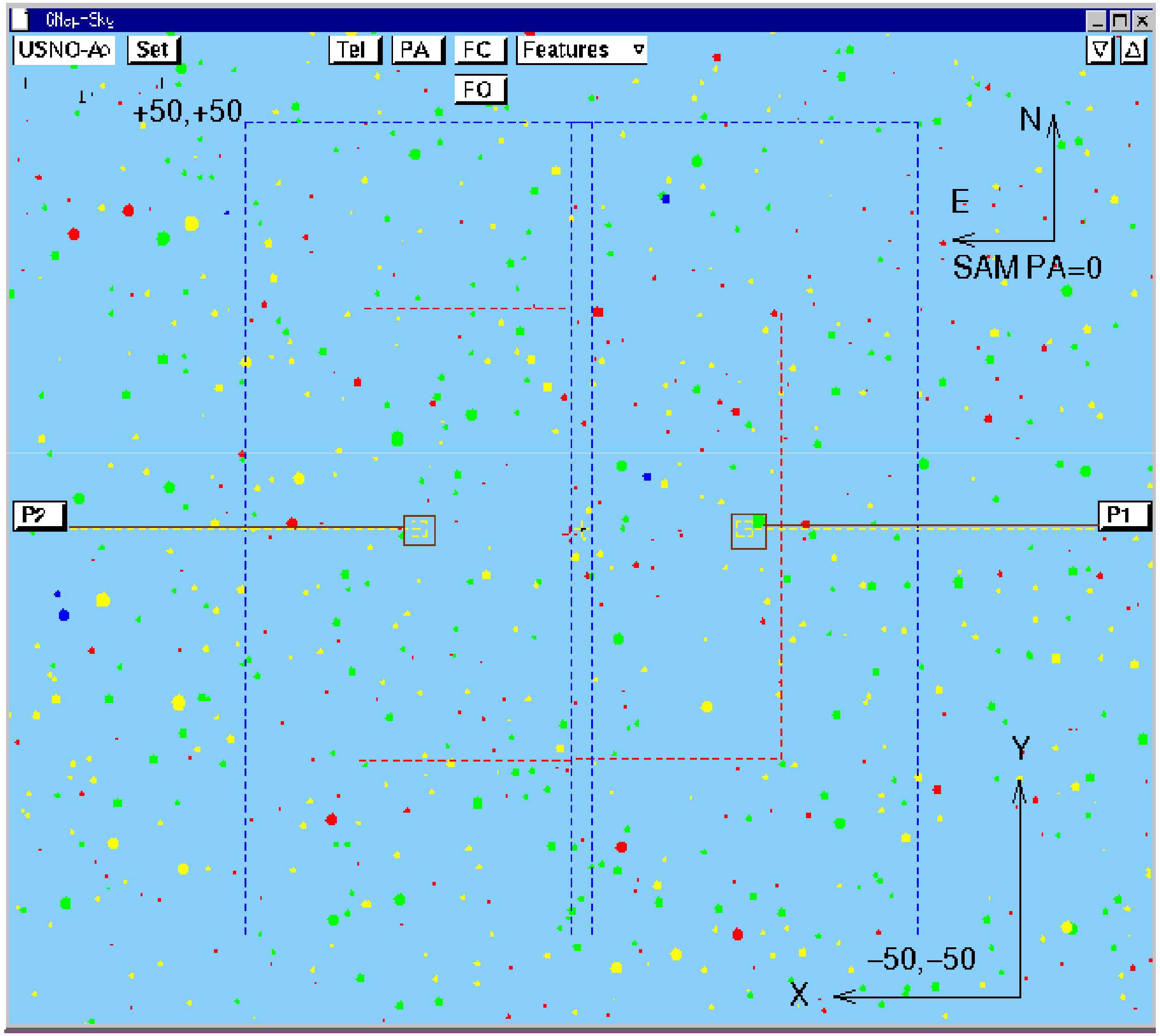
- Point the target, take pointing exposure, determine field offset (identify 1 star with known coordinates in the image)
- Acquire two guide stars (USNO, 2MASS, “wobble tool”)
- Acquire the LGS (<1min), close all loops
- Take science exposures. Large dither=new target
- Pause during LCH closures or other problems

Focusing with SAM



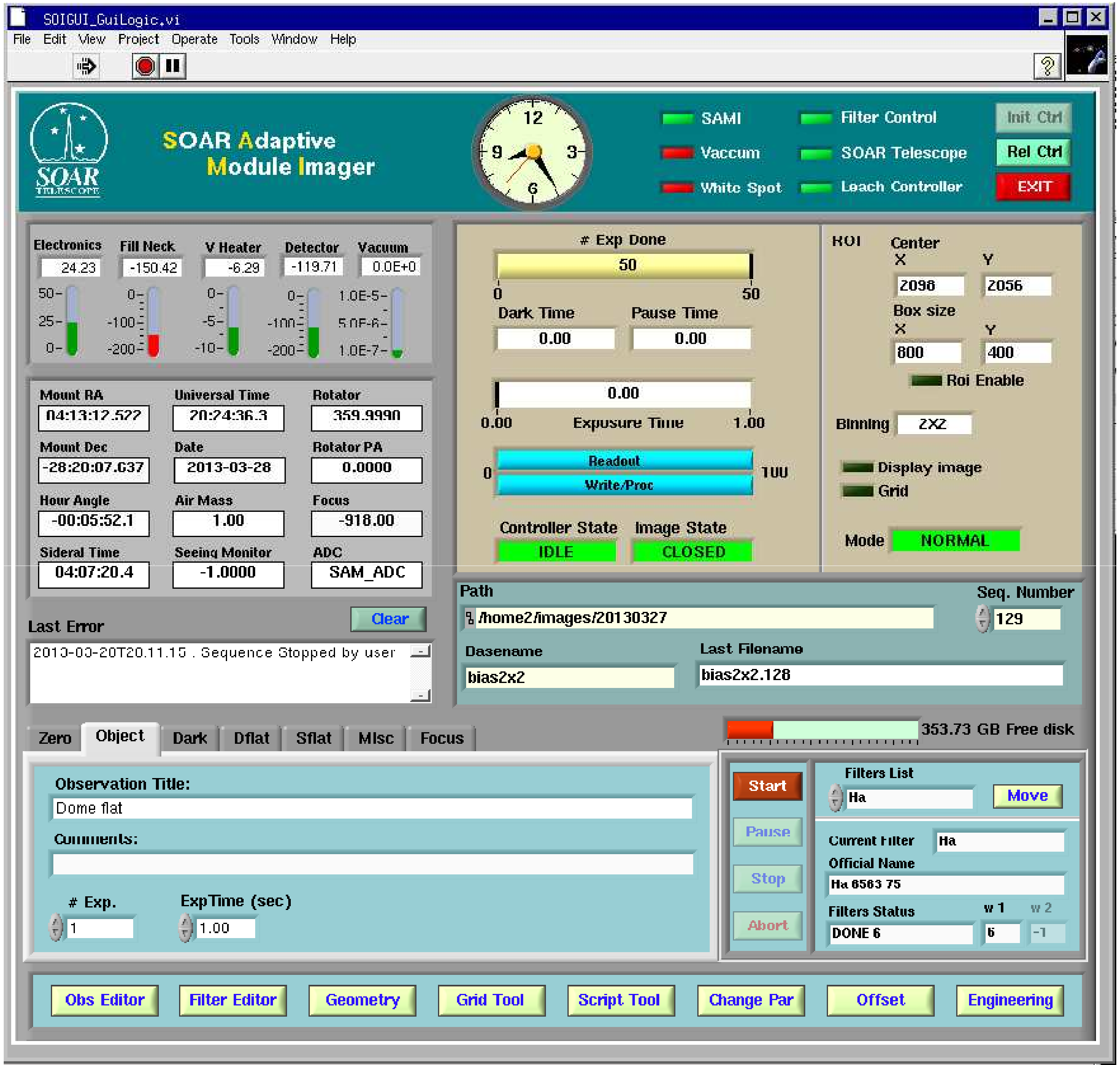
- Check/tune
- focus once per night

Acquisition of guide stars



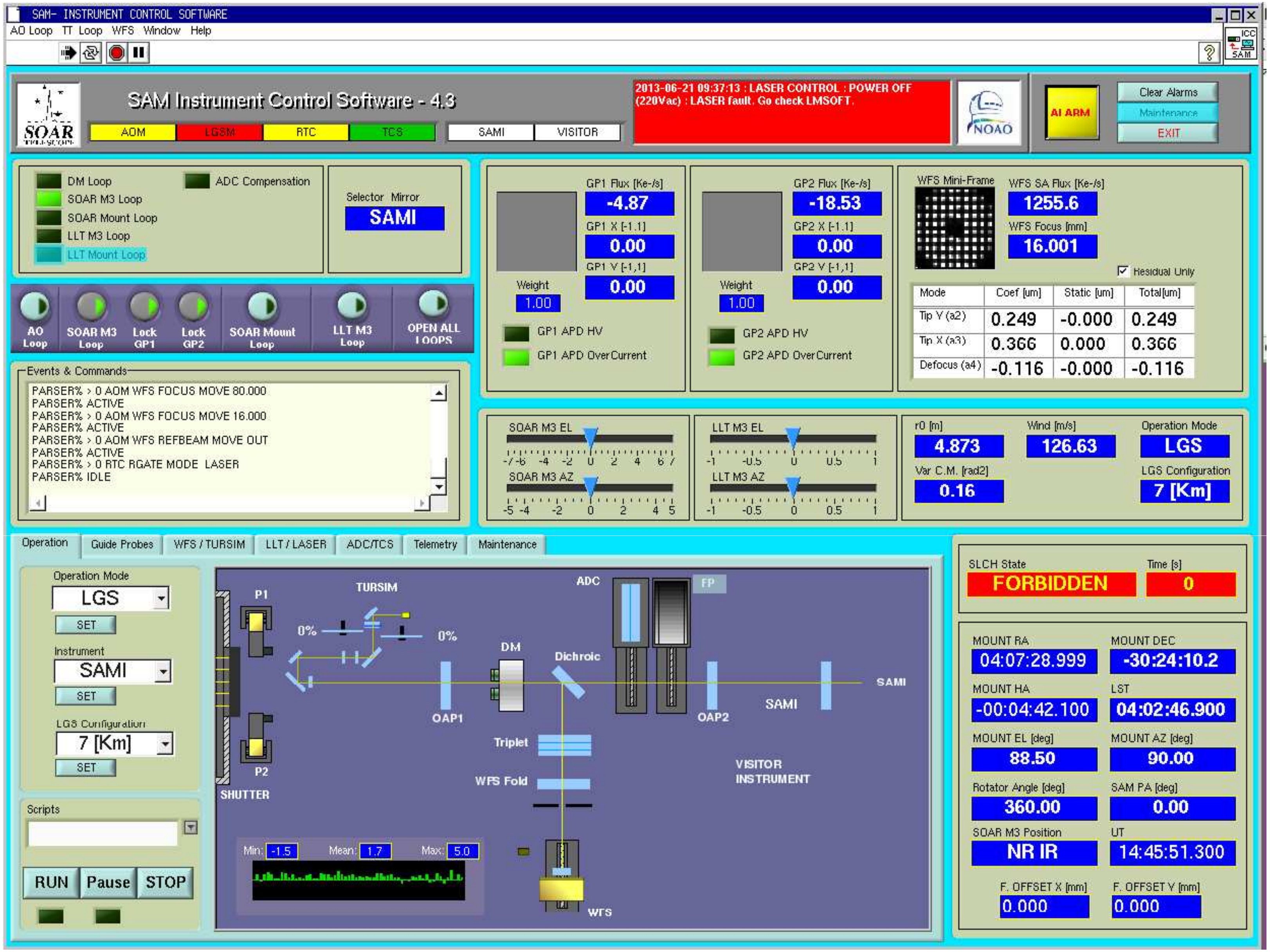
Identify star in the pointing image!

SAMI GUI



ds9+IRAF to display images & evaluate

ICS GUI


SAM- INSTRUMENT CONTROL SOFTWARE
AO Loop TT Loop WFS Window Help
SAM Instrument Control Software - 4.3
AOM LGSM RTC TCS SAMI VISITOR
2013-06-21 09:37:13 : LASER CONTROL : POWER OFF (220Vac) : LASER fault. Go check LMSOFT.
NOAO
ALARM
Clear Alarms
Maintenance
EXIT
DM Loop
SOAR M3 Loop
SOAR Mount Loop
LLT M3 Loop
LLT Mount Loop
ADC Compensation
Selector Mirror
SAMI
AO Loop
SOAR M3 Loop
Lock GP1
Lock GP2
SOAR Mount Loop
LLT M3 Loop
OPEN ALL LOOPS
GP1 Flux [Ke-/s] -4.87
GP1 X [-1,1] 0.00
GP1 Y [-1,1] 0.00
Weight 1.00
GP1 APD HV
GP1 APD OverCurrent
GP2 Flux [Ke-/s] -18.53
GP2 X [-1,1] 0.00
GP2 Y [-1,1] 0.00
Weight 1.00
GP2 APD HV
GP2 APD OverCurrent
WFS Mini-Frame
WFS SA Flux [Ke-/s] 1255.6
WFS Focus [mm] 16.001
Residual Only
Mode | Coef [um] | Static [um] | Total [um]
Tip Y (a2) | 0.249 | -0.000 | 0.249
Tip X (a3) | 0.366 | 0.000 | 0.366
Defocus (a4) | -0.116 | -0.000 | -0.116
Events & Commands
PARSER% > 0 AOM WFS FOCUS MOVE 80.000
PARSER% ACTIVE
PARSER% > 0 AOM WFS FOCUS MOVE 16.000
PARSER% ACTIVE
PARSER% > 0 AOM WFS REFBEAM MOVE OUT
PARSER% ACTIVE
PARSER% > 0 RTC RGATE MODE LASER
PARSER% IDLE
SOAR M3 EL
SOAR M3 AZ
LLT M3 EL
LLT M3 AZ
r0 [m] 4.873
Wind [m/s] 126.63
Operation Mode LGS
Var C.M. [rad2] 0.16
LGS Configuration 7 [Km]
Operation
Guide Probes
WFS / TURSIM
LLT / LASER
ADC/TCS
Telemetry
Maintenance
Operation Mode
LGS
SET
Instrument
SAMI
SET
LGS Configuration
7 [Km]
SET
Scripts
RUN Pause STOP
P1
TURSIM
ADC
FP
0%
0%
DM
Dichroic
SAMI
OAP1
OAP2
SAMI
Triplet
VISITOR INSTRUMENT
WFS Fold
P2
SHUTTER
Min: -1.5
Mean: 1.7
Max: 5.0
WFS
SLCH State FORBIDDEN
Time [s] 0
MOUNT RA 04:07:28.999
MOUNT DEC -30:24:10.2
MOUNT HA -00:04:42.100
LST 04:02:46.900
MOUNT EL [deg] 88.50
MOUNT AZ [deg] 90.00
Rotator Angle [deg] 360.00
SAM PA [deg] 0.00
SOAR M3 Position NR IR
UT 14:45:51.300
F. OFFSET X [mm] 0.000
F. OFFSET Y [mm] 0.000

Scripting with SAM

- SAM has scripting (example: dithers). Hide the complexity of AO operation behind scripts.
- SAMI has scripting. Can control SAM, but this has not been tested, problems likely.
- LUA scripting language is very uncomfortable. Poor diagnostic and weird behavior.

SAM ADC: pros and cons

- ADS is available in SAM
- Deviates image by ~2”: complicates guide-star acquisition
- Extra light loss and reflections (in parallel beam)
- Used extensively for speckle, not with SAMI, so far

What can go wrong?

- Poor free-atmosphere seeing (50% chance): no gain!
- Cirrus clouds or blanket closure: no laser!
- SAM technical failure. Sometimes open-loop possible.
- Telescope failure
- Clouds, wind, snow,...

After observations

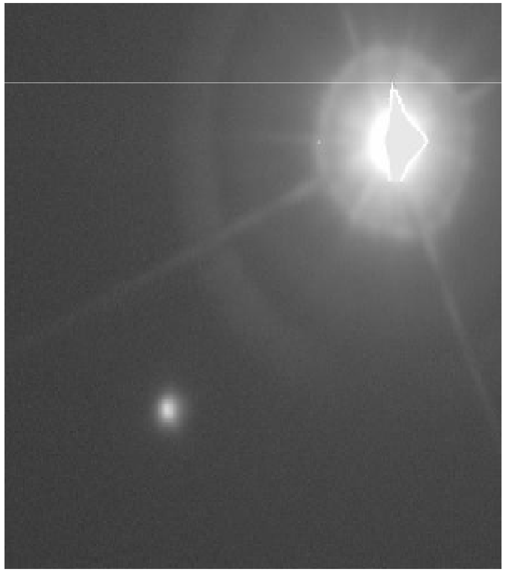
- Data are processed at CTIO (bias subtraction and flat field, join 4 extensions in a single frame)
- Get your data (no standard procedure yet, use FTP). NOAO archive?
- Extract what is needed (e.g. photometry)
- Publish! Publish! Publish!

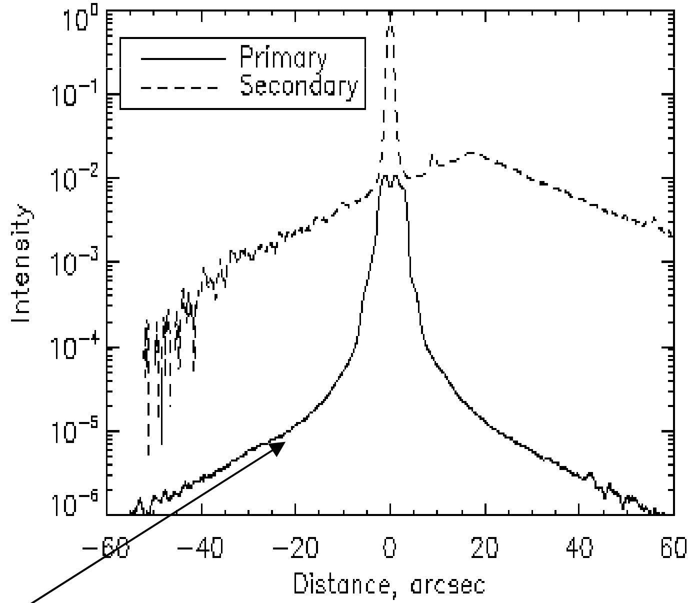
V. Science use of SAM data

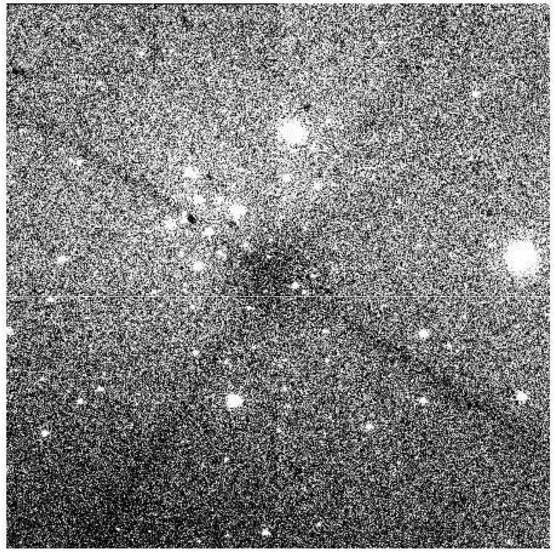
- Artifacts
- Photometric calibration
- Distortion
- Astrometry
- Binary stars

Artifacts in SAM+SAMI

- “Blue leak” (strong in B-filter, weak in SDSS g')
- Scattered light: as in SOI (filters!)
- Parasite light in g' (switch off camera)



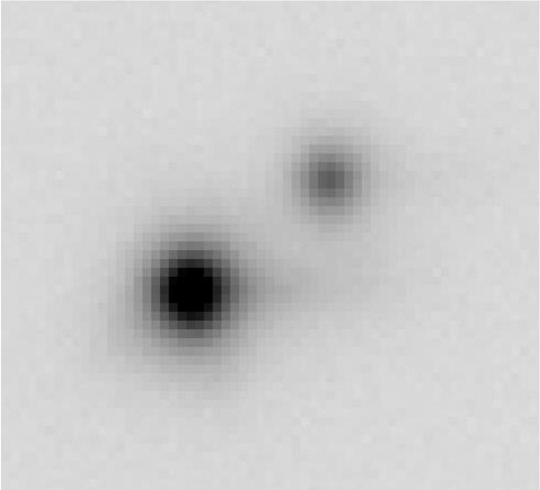




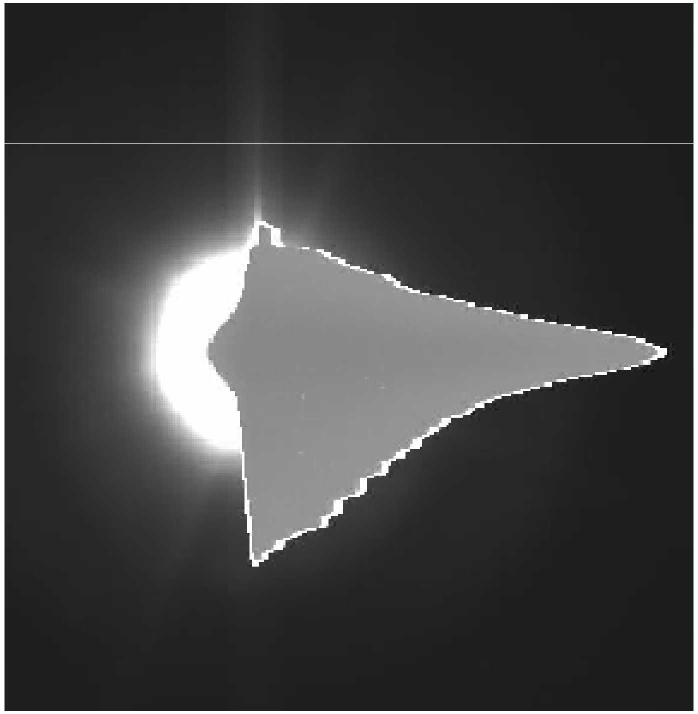
B-filter, 3 min

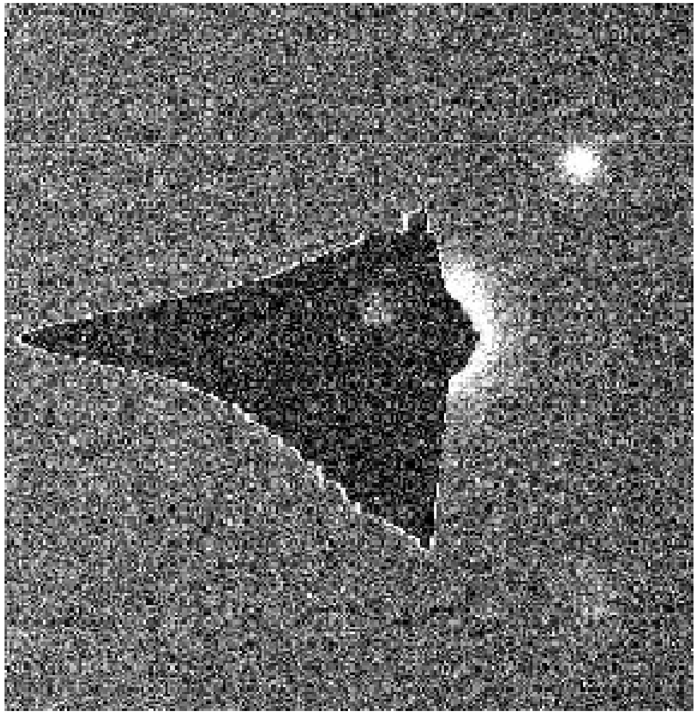
10^{-5} at 20”

Artifacts 2.



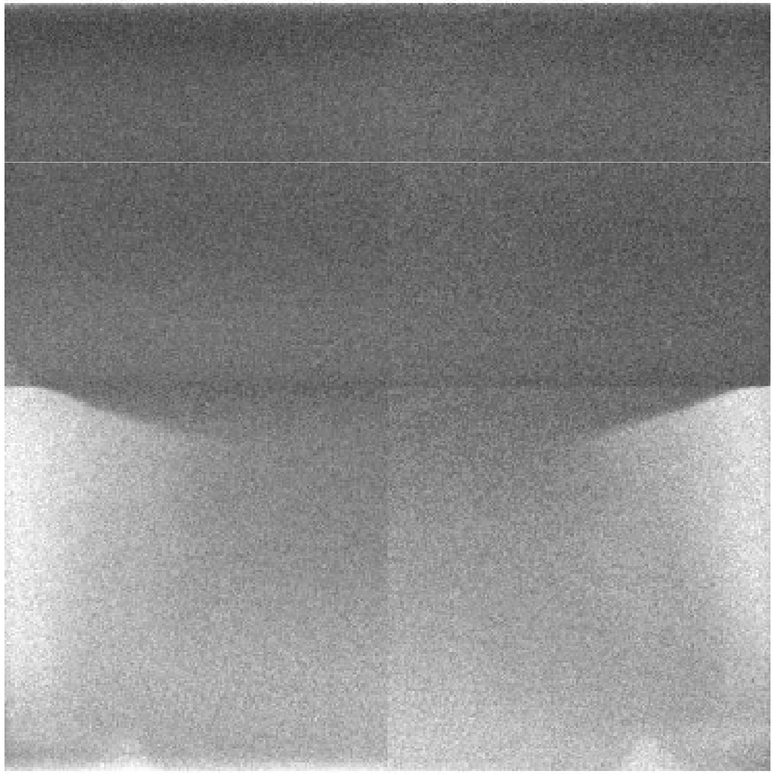
- “Tails” of the PSF (SAM DM)
- Strong saturation: “ghosts” and after-glow

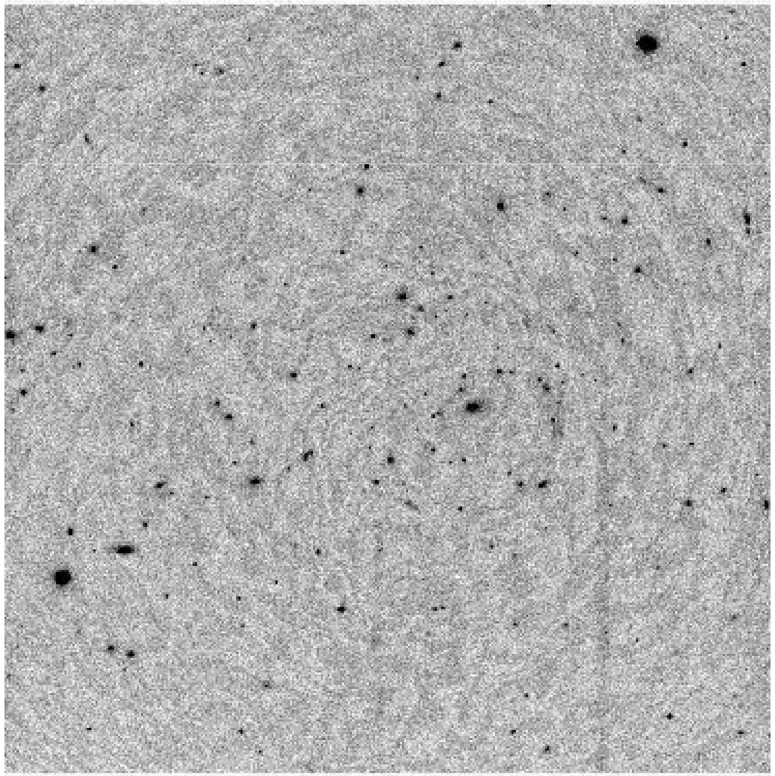




Artifacts 3 (SIFS dewar)

- Mysterious “Arcs” and fringing in z'
- Overscan changes vertically



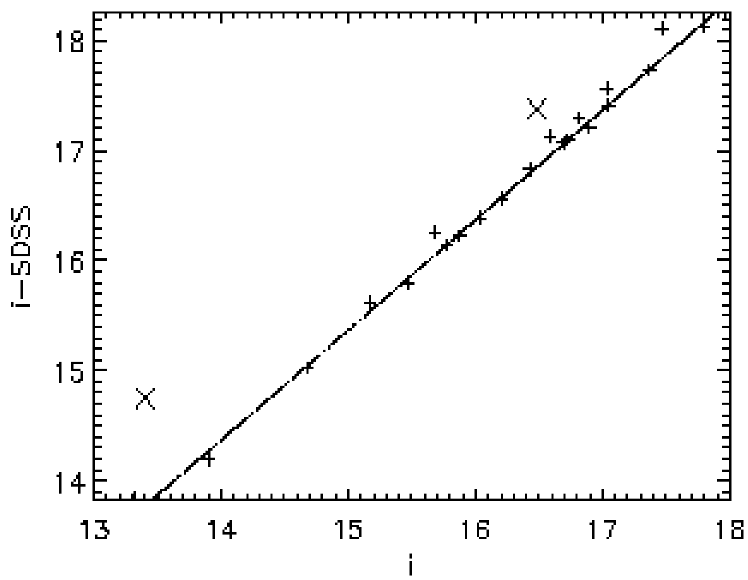


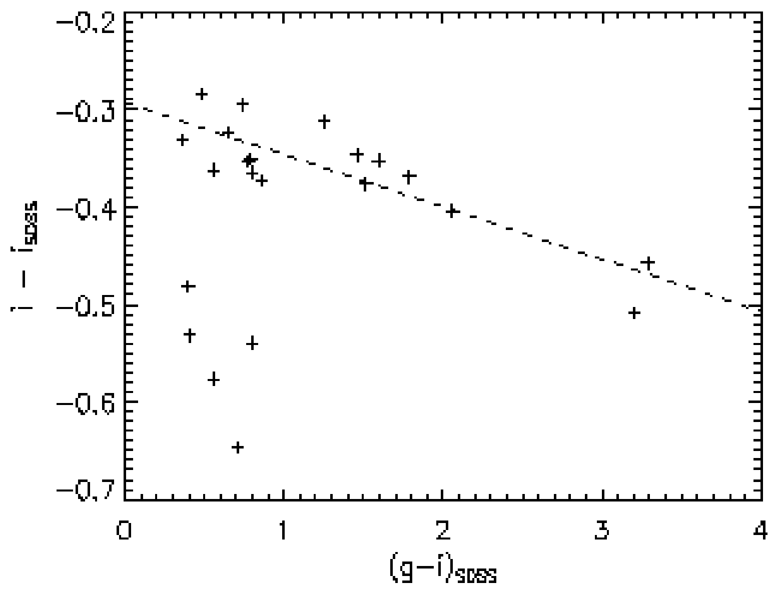
Photometric calibration of SAMI

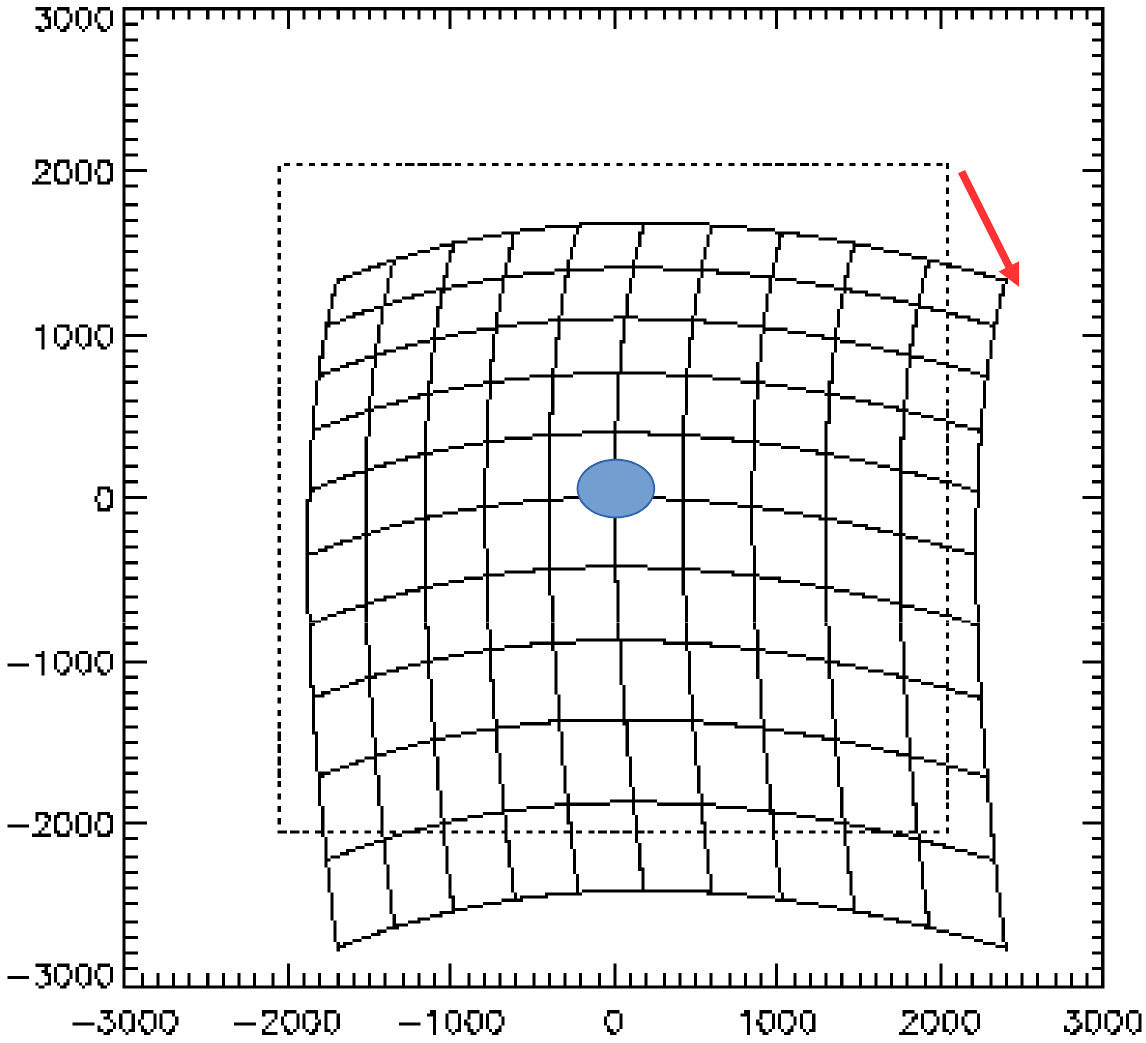
Filter	mag0
g'	25.6
r'	25.0
i'	25.3
z'	24.8

$$\text{Flux [ADU/s]} = 10^{-0.4(\text{mag} - \text{mag0})}$$

BVRI calibration: Fraga et al. 2013, AJ







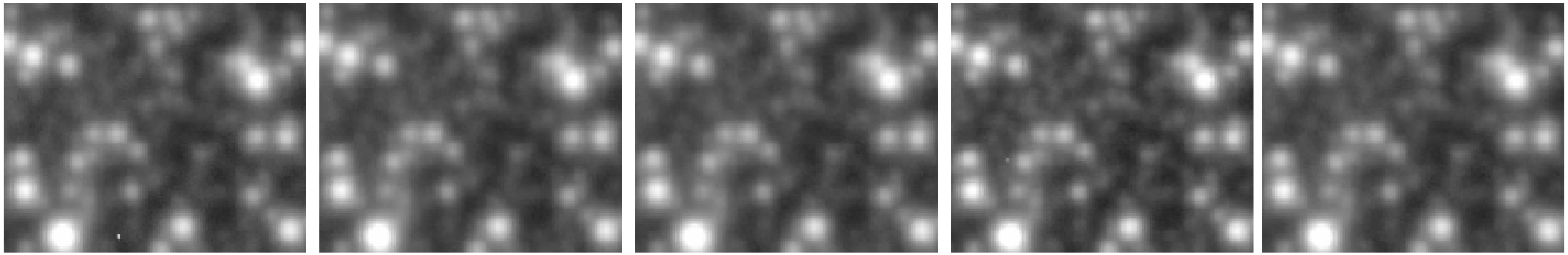
Distortion

SAM's optical relay introduces quadratic distortion up to 40 pixels or 1.8” (amplified 20x in the picture)

Photometric error 2%

Dealing with the distortion

- Do nothing --> coordinate error ~1”
- Correct measured X,Y (work with the text file)
- Use RA-TNX, DEC-TBX non-linear WCS (not FITS standard)
- “Un-warp” the image (samiwarp.pro, dcombine.pro)



M5 with 2” dithers

Astrometry with SAM

- Step 1: samiqastrometry.py to get correct WCS origin and orientation (does not change the pixel scale!) RMS ~0.7” before distortion correction, down to 0.15” after. SOAR rotator has variable offsets in angle!
- Step 2: fit to the reference catalog using quadratic and higher terms. So far, only 2MASS...

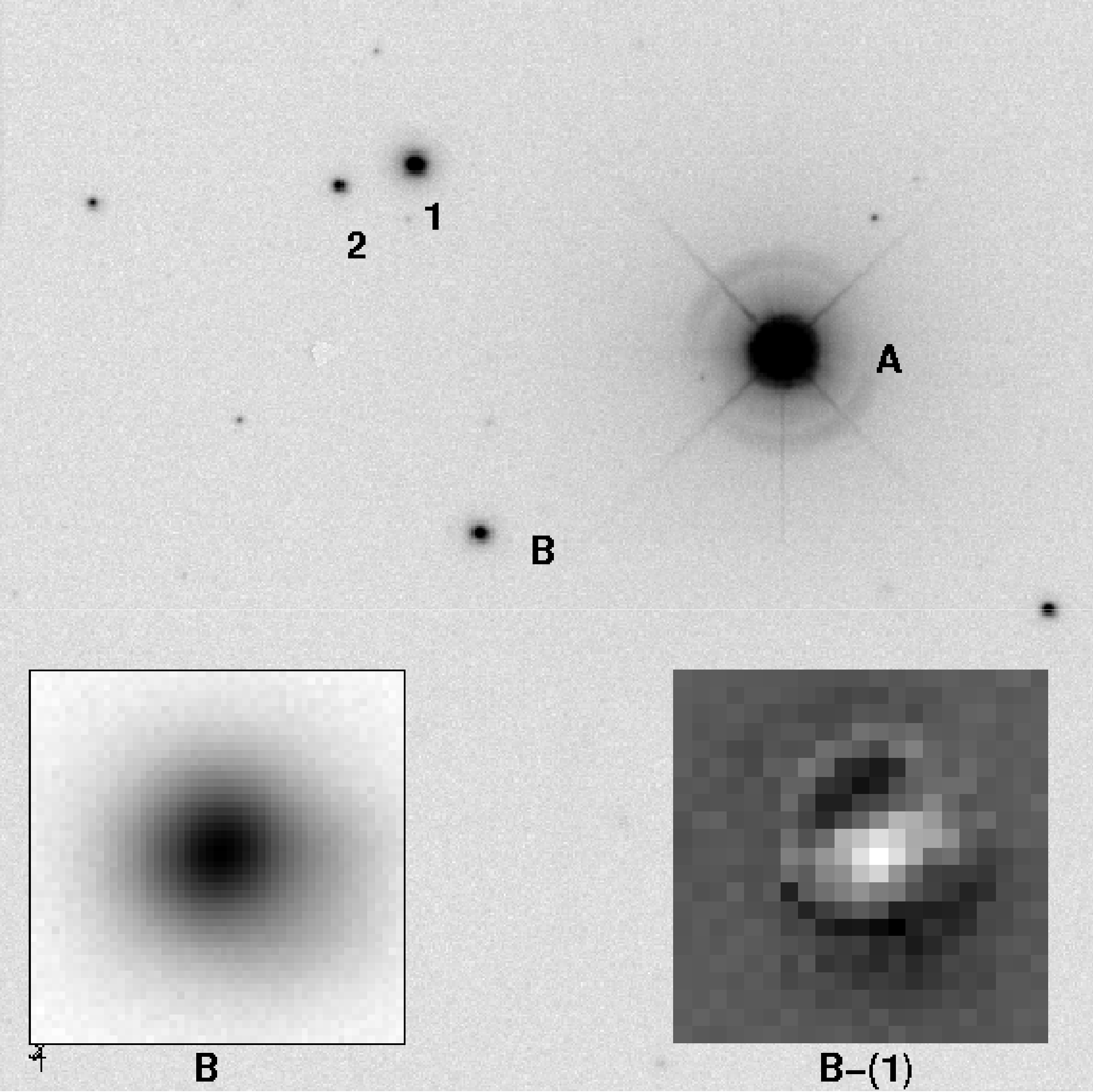
Astrometry with SAM: future

- Best seeing-limited astrometry: 0.3mas (VLT), 1-3 mas (many wide-field imagers). These are relative errors.
- Best AO astrometry: 0.15 mas (Keck, Galactic Center)
- SAM: use HST-observed cluster. TBD accuracy.

Need a tool with variable PSF
(Starfinder, DAOPHOT, custom)

Example: binary stars

- March 4, 2014: images of faint distant companions to nearby solar-type stars: are the companions binary?
- Mediocre conditions, resolution ~0.5” only
- 21 targets, 7 min. median overhead
- Paper accepted by AJ, ArXiv:1406.6045

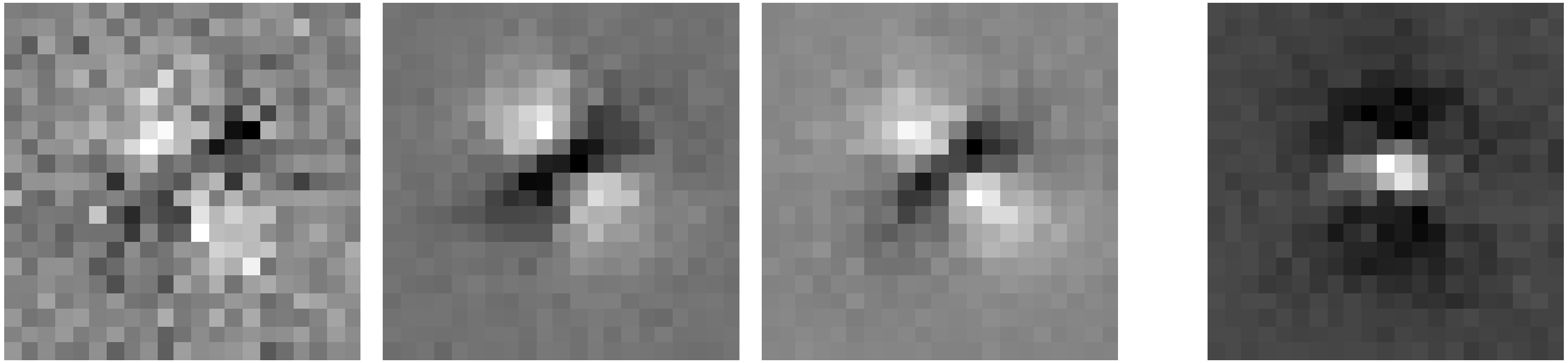


Data sample

HIP 50895
i' band,
binary 42",
V=8.12+16.3
FWHM 0.7"

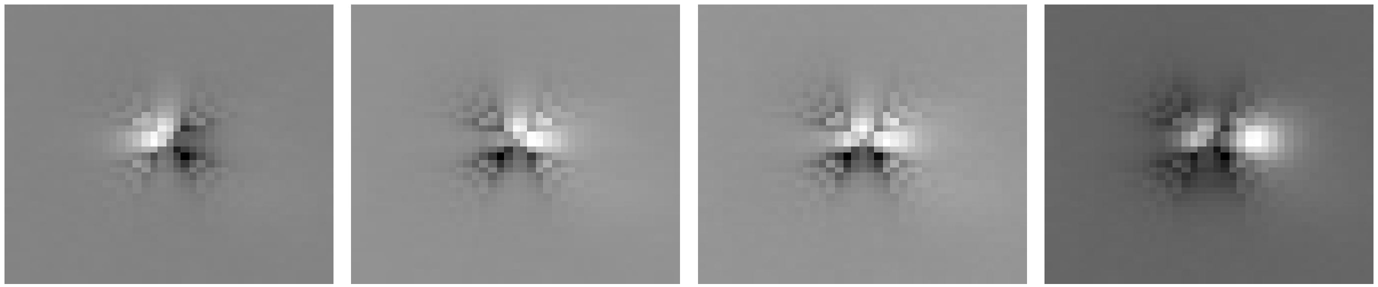
PSF match to ~5%

Result: one binary discovered



g i z z (two ref. stars)

HIP 53172B, 0.2”, equal components



PSF 0.18", dm=0 0.27" dm=1 0.54" dm=1

To SAM or not to SAM?

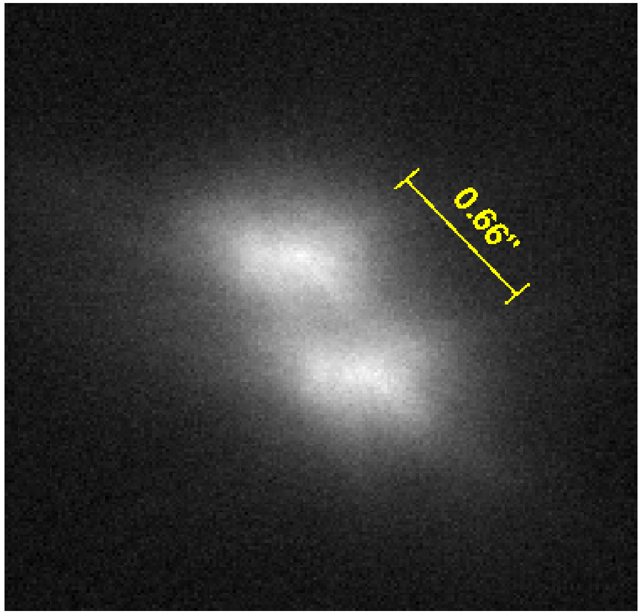
- Use SAM if you do not need blue wavelengths and wide field (it does not make things worse!) Open-loop?
- Not to SAM: low surface brightness or high-contrast objects, U/B filters.
- SAM for crowded fields and when resolution is critical

Everything has its cost...

- Resolution depends on wavelength, poor in the blue
- Dependence on FA seeing: need a backup program and flexible scheduling
- PSF has strong wings (Moffat function with beta ~ 2)
- Laser targets submitted to LCH 3 days in advance
- Complexity: SAM operation is simple, but the system is complex and requires maintenance and discipline
- Future failures...

Active optics, please!

- SAM often “sees” little ground-layer turbulence
- Still useful to correct focus and astigmatism
- Need real-time active optics for ALL SOAR instruments!
- Use regular guiders to adjust between exposures?
- Optimize dome environment



No AO correction,
only tip-tilt

SAM's competitors

- HST: most high-res. optical imaging and best science!
- GEMS: IR complement, rather than competitor
- Mag-AO: NGS system, PI instrument only.
- MUSE @ VLT: real competitor: GLAO, visible, 8-m!
- ARGOS @ LBT (IR only)

SAM with its UV laser and 3' FoV is unique and can bring SOAR ½ way to space!

Future II: AO spectroscopy

- Default plan (SAM+SIFS) is not happening
- SAM+BTFI: two monsters, not practical. Space for F-P!
- IFU for SAM+Goodman? (~350 fibers, 0.3” spaxel, 6”x6” FoV, efficiency ~70%)
- SAMOS (multi-slit)?

Diffraction-limited science @ SOAR

- Original SAM science case included NGS mode, dropped for simplicity. But it worked during commissioning!
- HRCam → speckle interferometry
- Resolution ~25mas (better than 8-m with AO!)
- SOAR offers unique high-resolution optical "window"

End