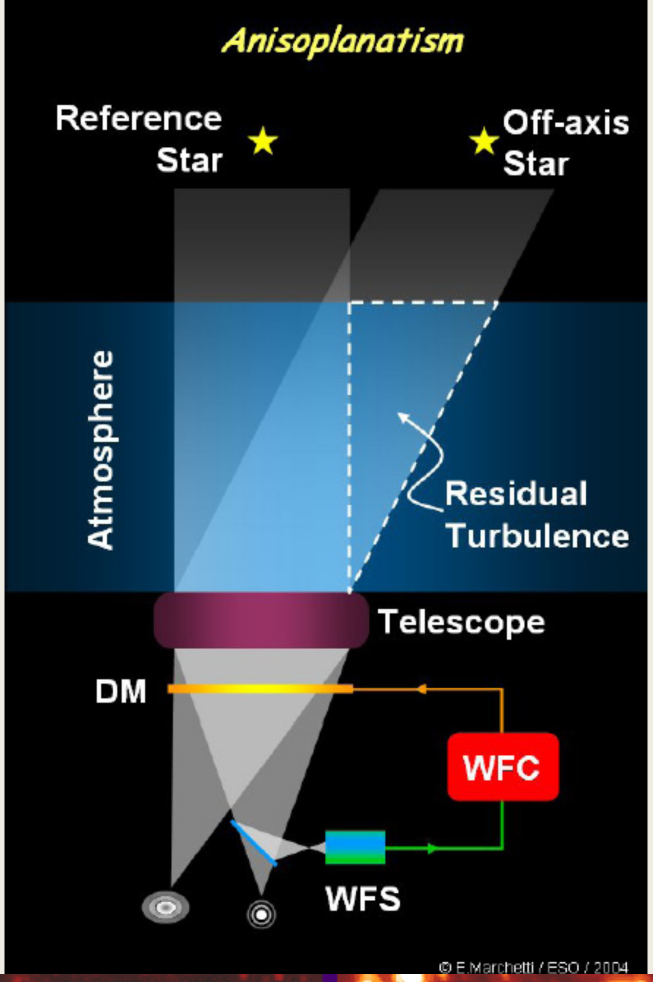
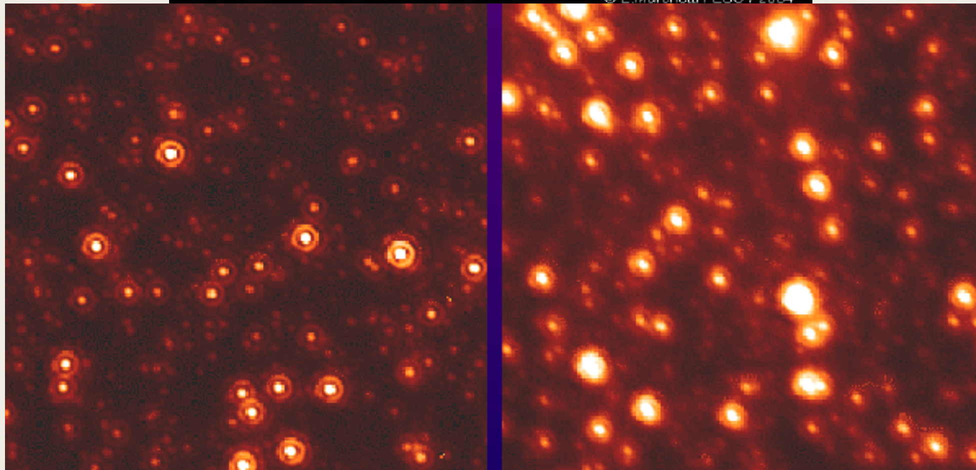
CALIBRATIONS FOR A MCAO IMAGING SYSTEM

P. Hibon
B. Neichel (LAM), V. Garrel (Gemini South), R. Carrasco (Gemini South)

Classical AO : limitations

- Anisoplanatism : WFS measure the phase perturbations integrated only along the direct line of sight, in directions different from the guide star.
  -> a degradation in the off-axis corrections to the wavefront.
- depends on a number of parameters : the vertical distribution of turbulence, the wavelength, order of the AO system (how many modes are corrected)...
- isoplanatic angle : angle from the guide star at which the Strehl ratio is reduced by 50%.
  varies with wavelength and airmass.

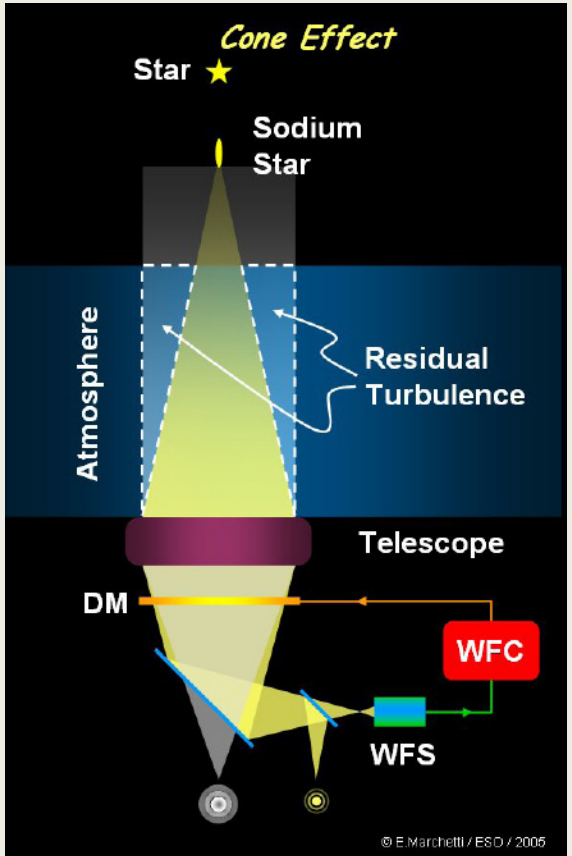




Classical AO : limitations

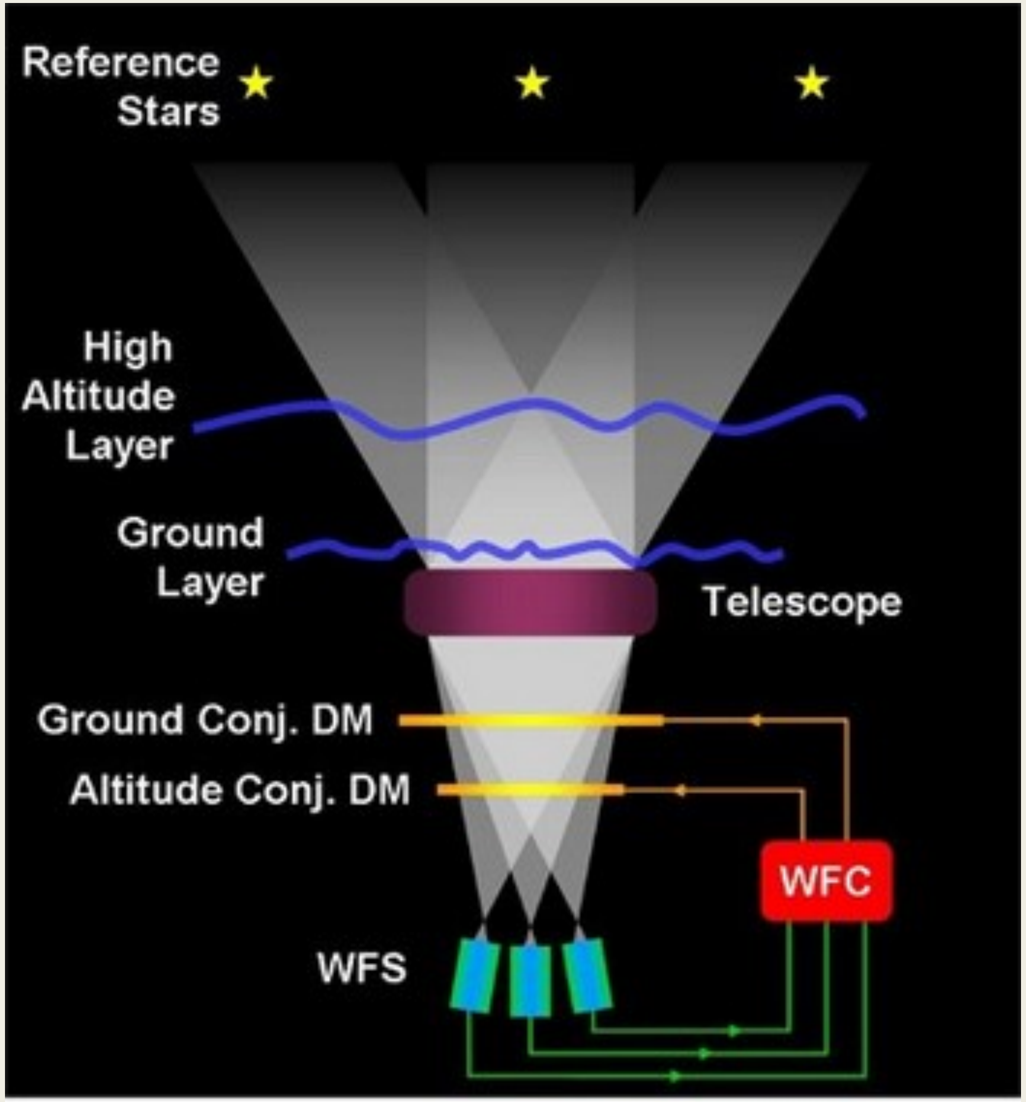
- ***Sky Coverage***
  AO compensation using natural guide stars can only be obtained in the vicinity of relatively bright stars (R~15 mags). This puts a severe restriction on sky coverage; in fact limiting the accessibility of the sky to only 5%.

- ***Cone Effect***
  LGS created at a finite distance.
  The return beam that WFS uses does not pass through the same volume as a beam coming from an astronomical object at infinity.
  This geometrical effect worsens as telescope diameter increases. An order of magnitude for the Strehl ratio loss is 50% at 1 micron for an 8-m telescope.



MCAO : Multi-Conjugate Adaptive Optics

- 3D Compensation for atmospheric turbulence in a 3-D fashion
- MCAO provides uniform image quality (diffraction-limited in the near-IR) over a much wider field than regular AO.
- Important for astrophysical problems requiring a relatively wide field of view or very accurate photometry.
- MCAO also removes the "cone effect" associated with the use of laser guide stars.
- The average sky coverage in H band is approximately 50% over the whole sky.

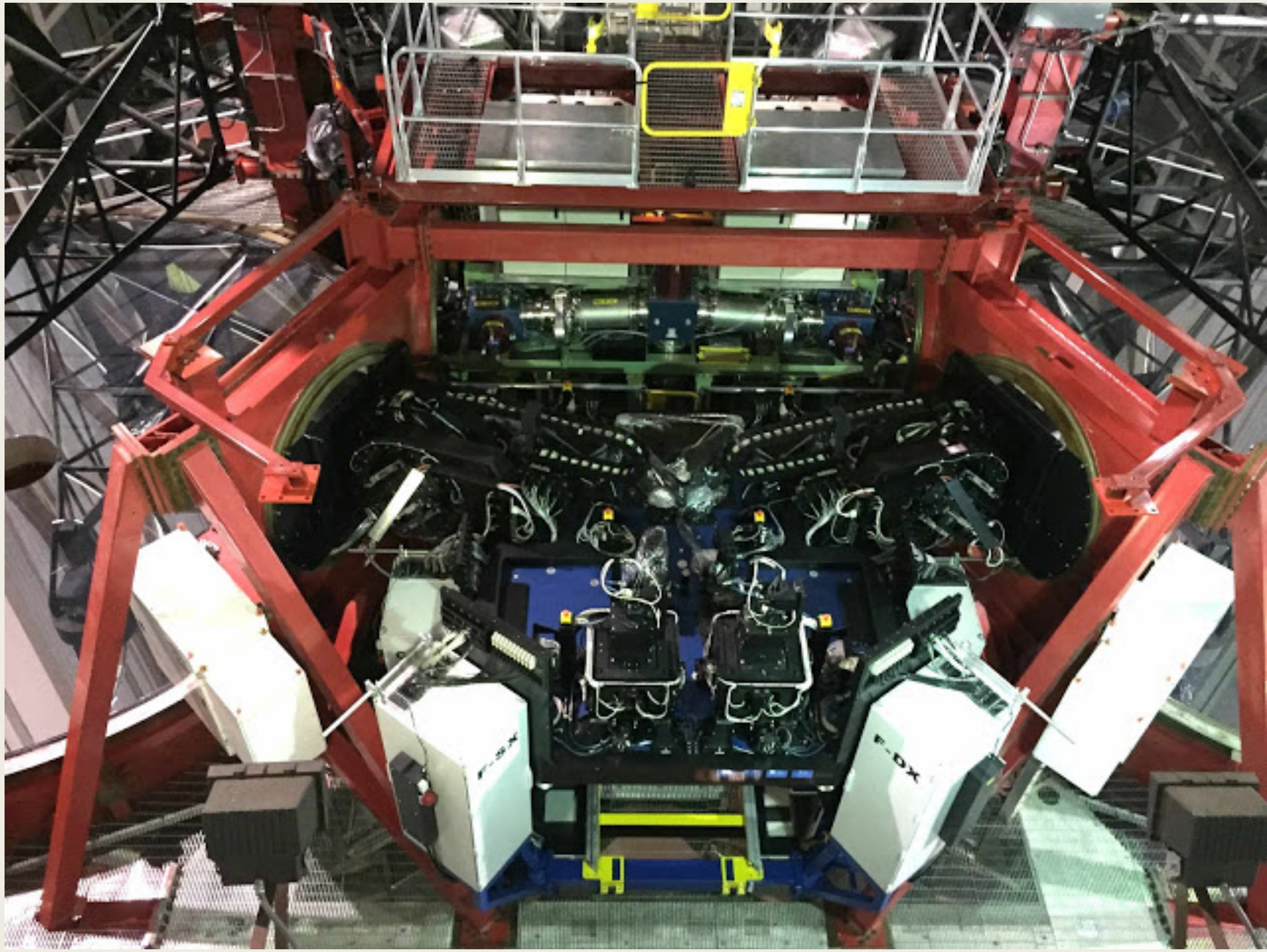


MAD : Multi-Adaptive Conjugated Optics Demonstrator

- MCAO prototype
- was installed at the UT3 Nasmyth focus for performing some validation runs and science demonstration runs.
- Perform WFAO correction in K-band over 2arcmin on sky using V< 14 NGS
- used for science for 33 nights including the 10 nights of GTO time
- At least 19 articles in refereed journals

LINC-NIRVANA

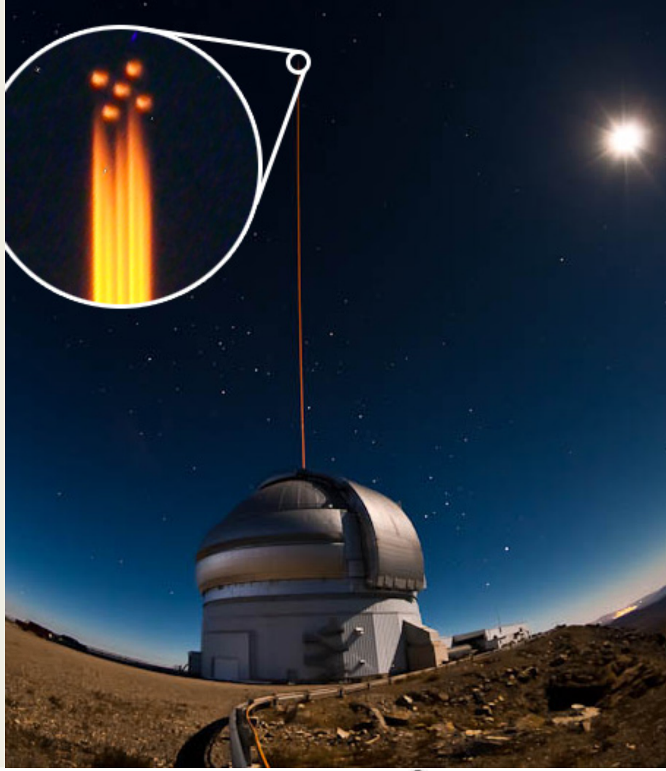
- NIR imaging instrument for the LBT offering both multi-conjugate adaptive optics (MCAO) and interferometric beam combination for ultra high spatial resolution.
- Installed on the telescope in Sept. 2016

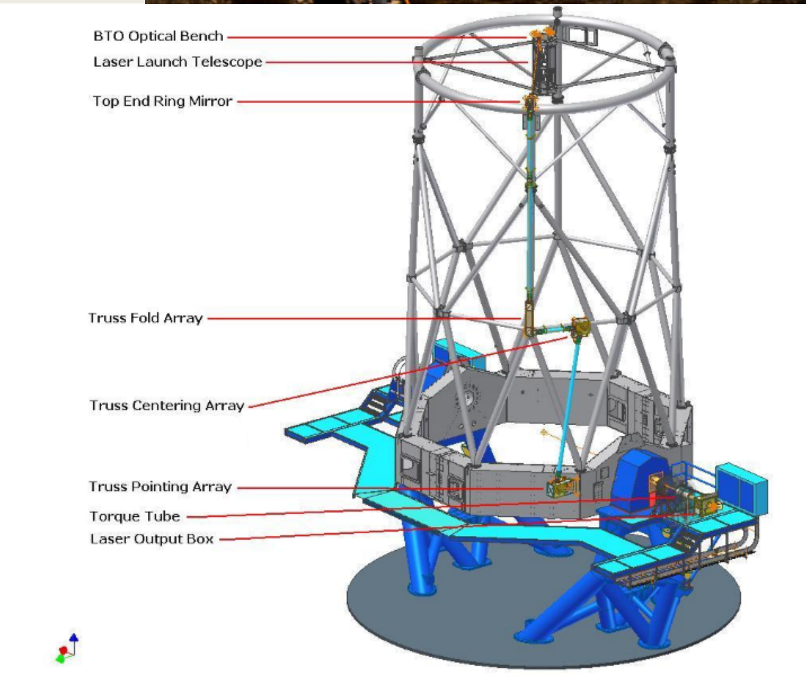


GeMS

Gemini **M**ulti-Conjugate Adaptive Optics **S**ystem

- GeMS consists of three main subsystems:
  - *LGSF : source of coherent light.*
  - *the Laser System,*
  - *Beam Transfer Optics (BTO),*
  - *Laser Launch Telescope (LLT),*
  - *Safety Systems.*
  - *Canopus.*
- The BTO : relays the laser beam(s) from the output of the Laser
  - *System to the input of the LLT.*
  - *multiple mirrors, lenses, and beam splitters, as well as various sensors and diagnostic equipment.*



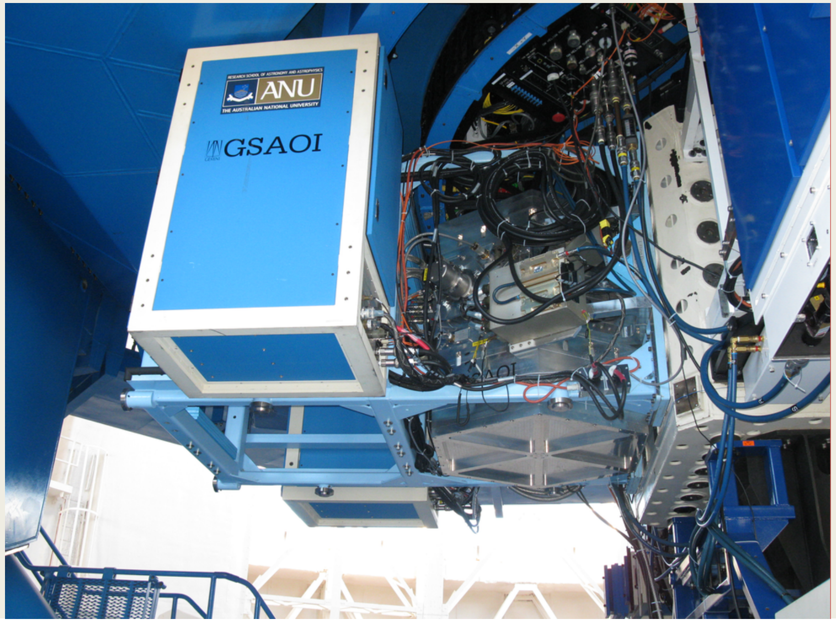


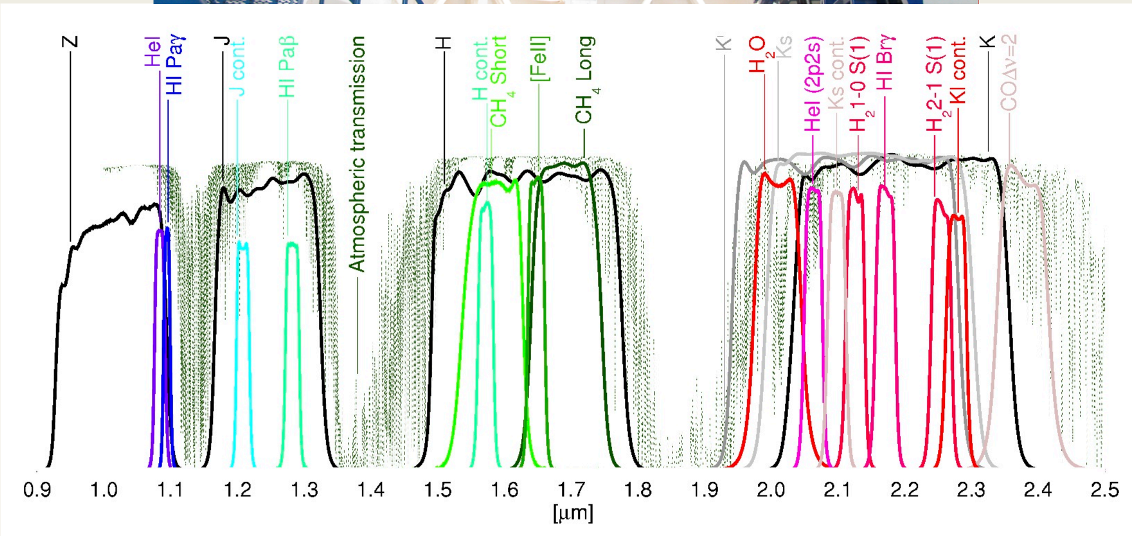
GeMS
Gemini **M**ulti-Conjugate Adaptive Optics **S**ystem

- Canopus is the Adaptive Optics bench of GeMS . It contains :
  - *Calibrations Sources*
  - *Deformable Mirrors,*
  - *TT Mirror*
  - *Science Beam Splitter Assembly*
  - *Science ADC*
  - *Output Focal*
  - *Laser notch filter*
  - *LGS WFS*
  - *NGS WFS*

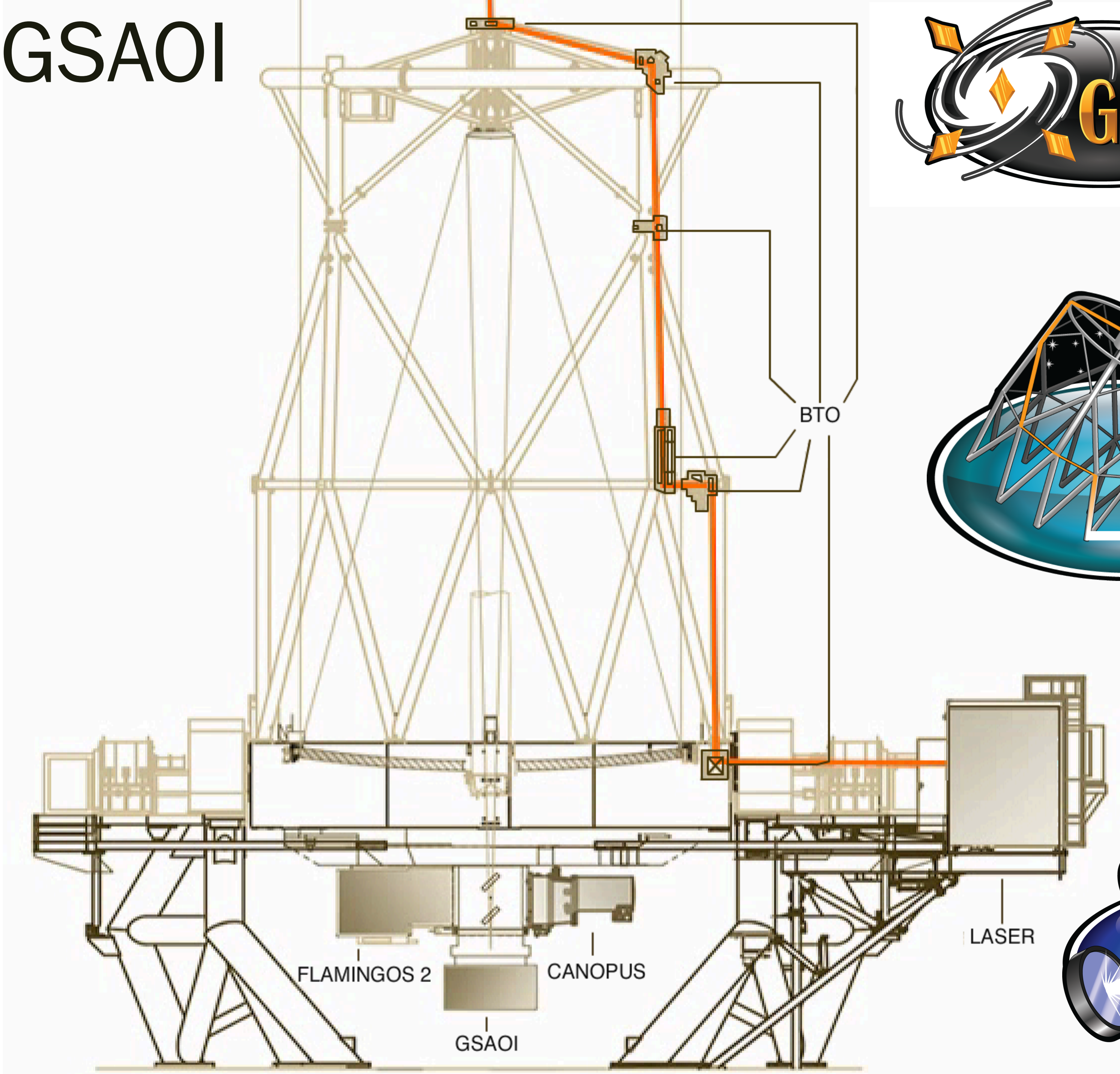
GSAOI
Gemini South Adaptive Optics Imager

- near-infrared adaptive optics camera used with GeMS
- 0.9 – 2.4 microns
- 85” x 85”
- 2 x 2 mosaic Rockwell HAWAII-2RG 2048 x 2048 arrays
  0.02”/pixel
- Z,J,H,K’,Ks,K + 21 NB filters.
- Mostly used for extragalactic studies and crowded fields.





GeMS + GSAOI



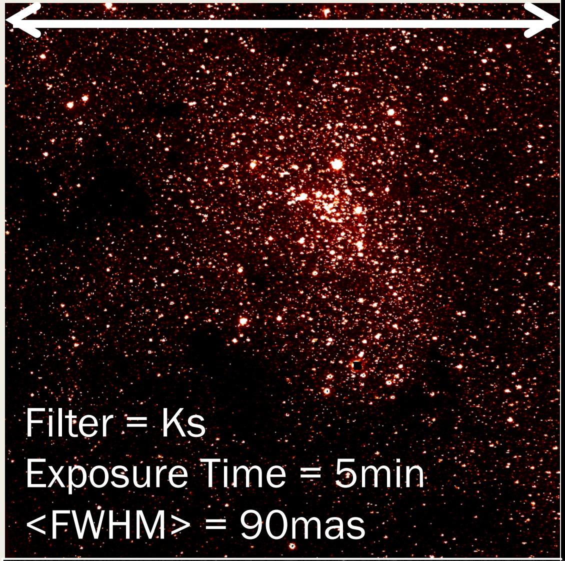
GeMS + GSAOI

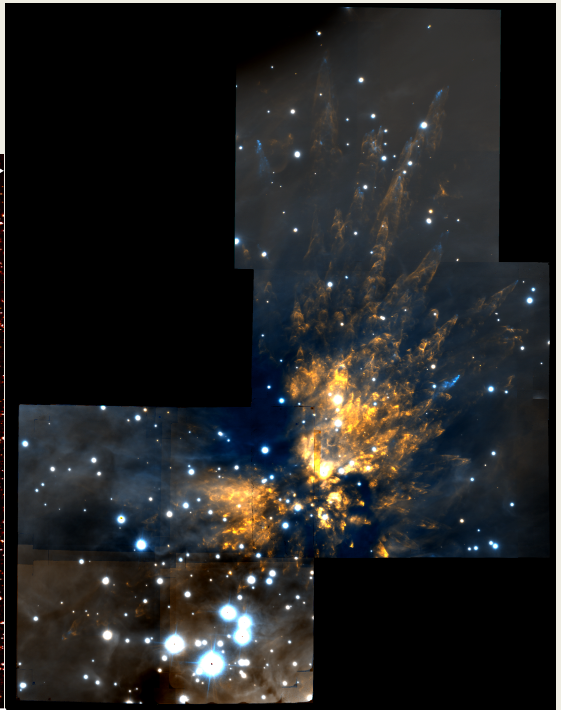
- very uniform over a 85”x85” FOV to a few % rms in the FOV, both in terms of Strehl ratios and more general PSF characteristics.
- Images are close to be diffraction-limited, in terms of FWHM, over the full field of view.
- Strehl ratio under median seeing conditions varies from 15% to 50% in the 1-2.5 micron range and 0-30 degrees zenith angle, with relative uniformity from 1 to 5%.
- 3 NGSs needed to get the best compensation from GeMS.
- Sky coverage of ~55% for all the portion of the sky reachable from Gemini South
- Under median seeing conditions : 1.5 to 1.7 magnitude sensitivity gain over the 1-2.5 micron range on point sources

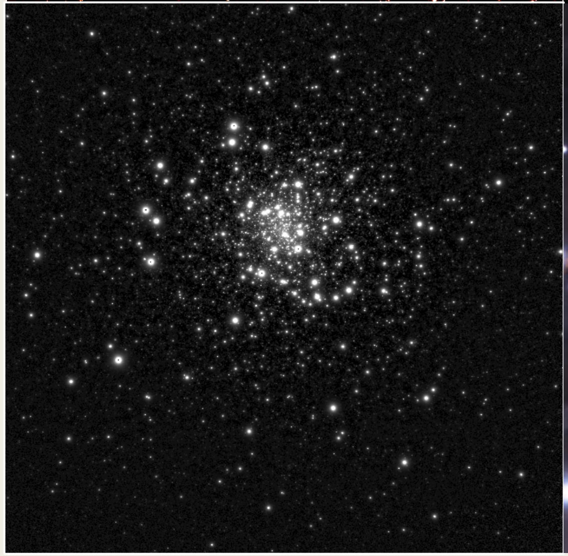
What kind of science with GeMS ?

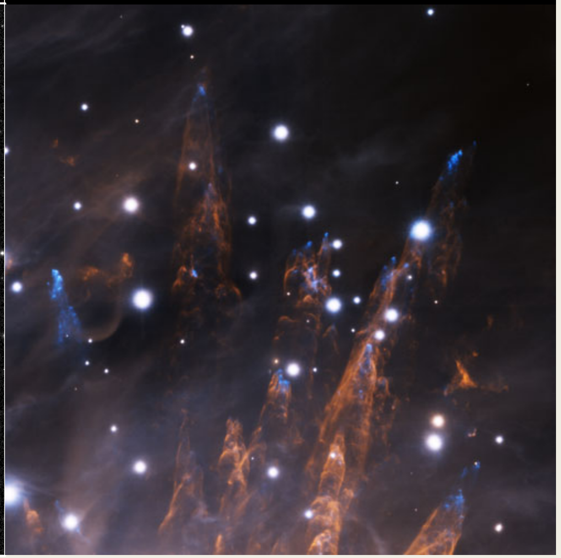
- Galactic Center
- Orion
- Globular Clusters
- Exoplanets
- **Why WFAO is good for astrometry ?**
  - *Large FoV => more reference stars*
  - *PSFs are uniform over the field*
  - *Active control of plate scales (specific to MCAO)*

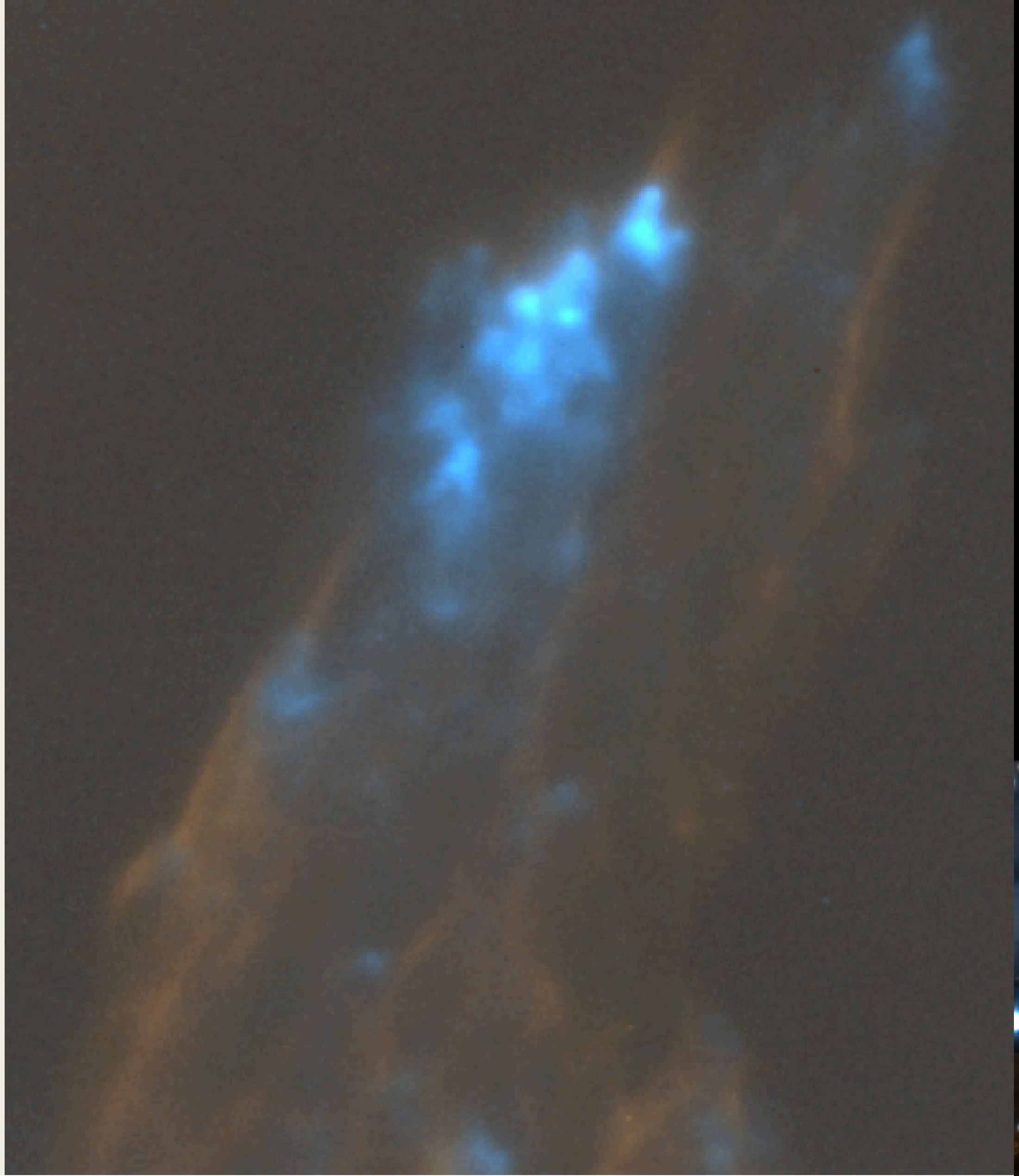
➡ Precise astrometry would require accurate calibration, and PSF knowledge

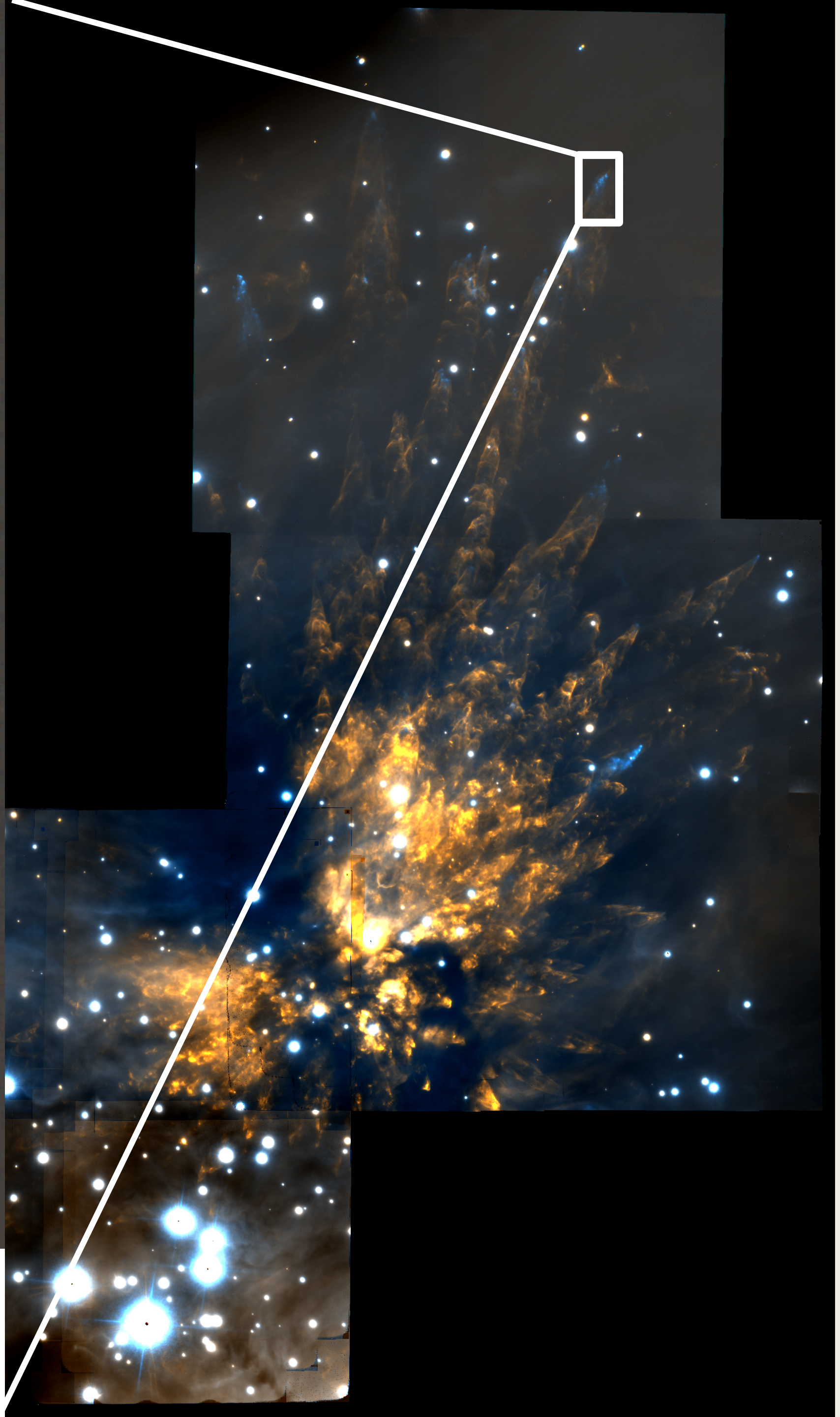












The Orion Fingers: Near-IR Adaptive Optics Imaging of an Explosive Protostellar Outflow

John Bally[1], Adam Ginsburg[2], Devin Silvia[3], and Allison Youngblood[1]

Calibrations for GeMS + GSAOI.

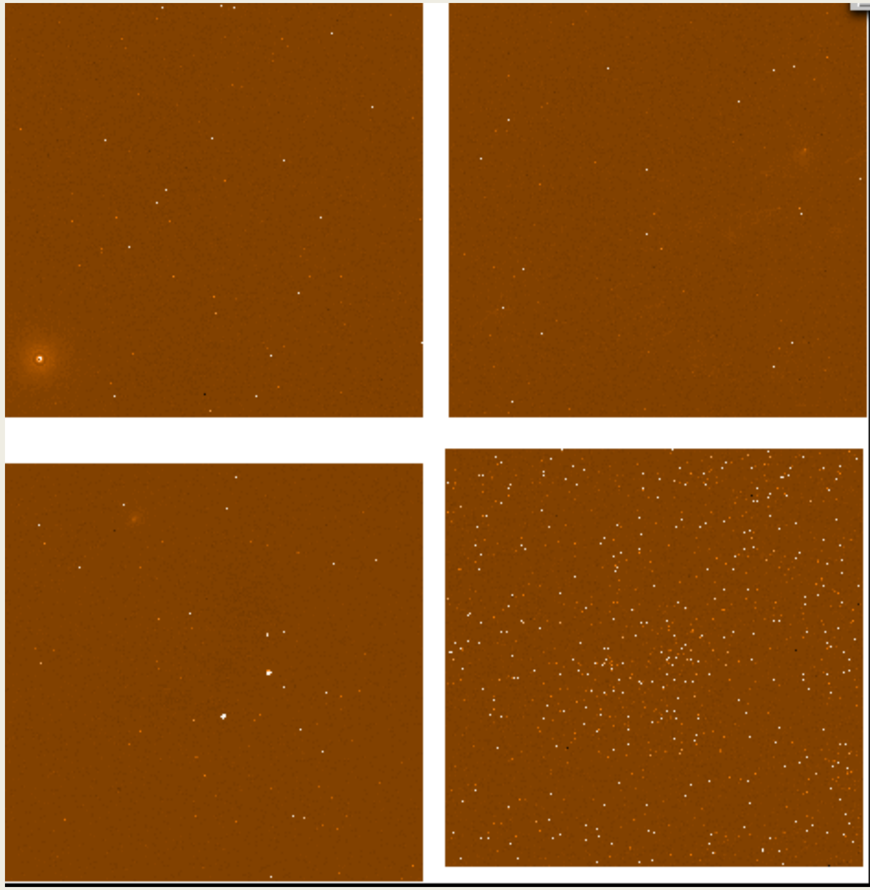
- NCPA
- Darks
- Flats
- BPM
- Flux standard stars

NCPA : non-common path aberrations

- one of the most important calibration and compensation.
- aberrations between science and WFS light paths.
  compensated by using WFS slope offsets.
- The difficulty : calibrating these aberrations
  -> a wave-front sensing device in the science path is needed.
  The aberrations measured in the science path are compensated by adding the inverse aberrations to the AO WFS.
- In GeMS, the problem is more complex:
  compensate for NCPA over the entire field of view simultaneously.
  aberrations are not constant over the field of view.
  -> have to be calibrated and compensated depending on the position in the field of view.
- More individual PSFs : better stability and improved SNR properties

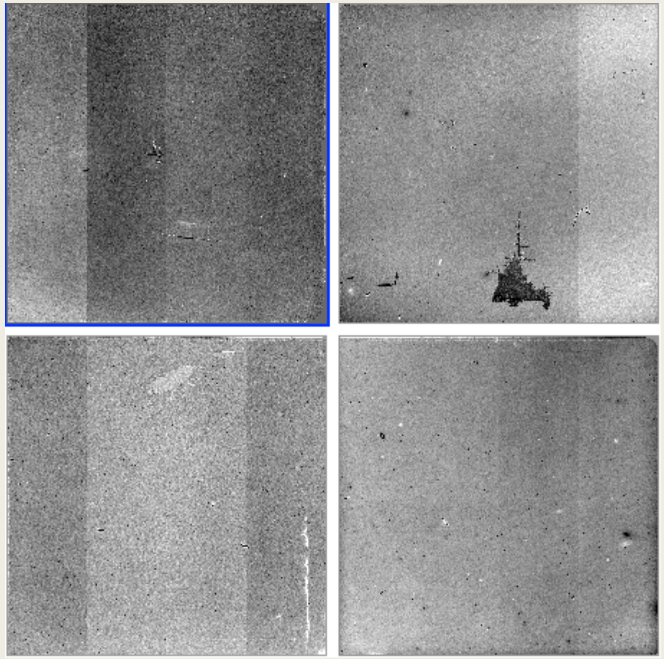
Dark

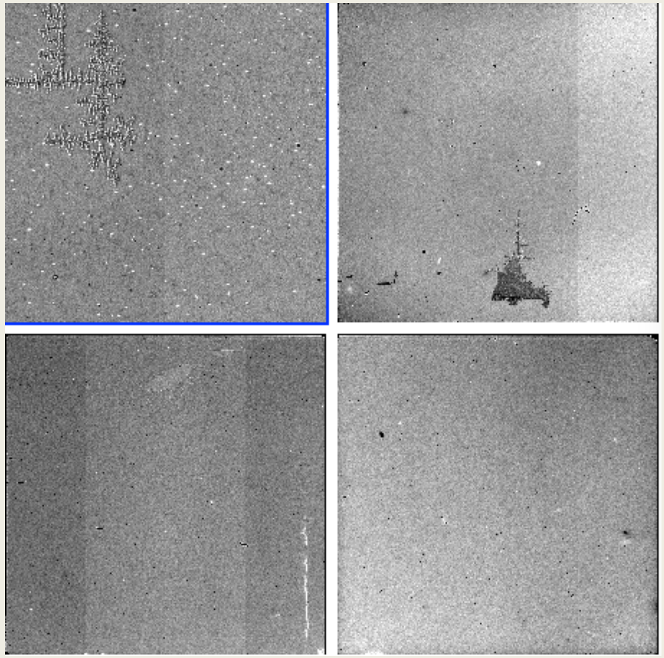
- The dark current for GSAOI is of the order of 0.01 e-/s/pixel, implying on a total dark charge of ~12e- for the longest integration time allowed (20min).
- Daily darks taken with the same exposure time as the science frames are NOT necessary,
  Both the dark current and the cross-shaped "warm" pixels are accounted for when subtracting the sky.
- Darks (or rather "flats-off") are not really required for Dome or Twilight Flats
- *Project* : create a library of dark frames with different exposure times, which can be downloaded from the Gemini Observatory Archive and used for data reduction if necessary.



Flats

- Dome flats : BB + NB used during the semester.
- A set of 15 flats with the dome lamps ON and OFF are observed per filter per laser run. OFF flats are taken for the H and K BB + NB filters.
- GCAL flats obtained by request in all filters.
- GCAL flats do not correspond to the same optical path as the science frames
- Twilight flats in the BB filters only (Z, J, H, K, Ks, Kp) are taken as often as possible.
- No plan to take twilights in the NB filters as part of routine baseline calibrations : no significant difference against the domeflats.





Bad Pixel Mask

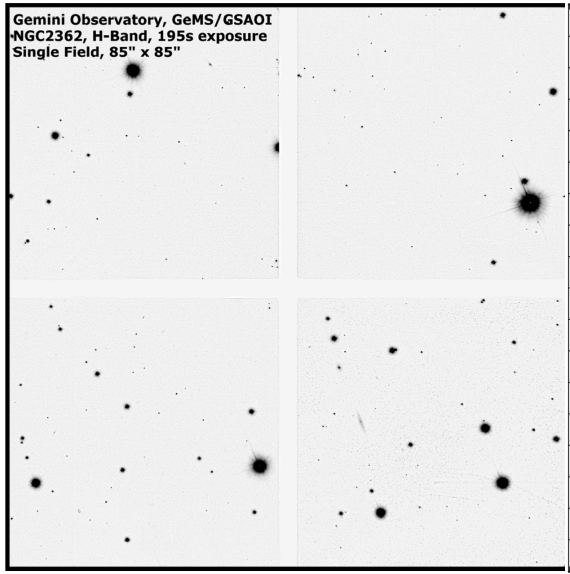
- GSAOI detectors : less than optimal cosmetic quality : presence of "dead" pixels, light-emitting pixels, "killed" spots + a significant number of hot pixels.
- Number of hot pixels detected dependent on the exposure time of the dark frames used.
- The standard BPM included in the Gemini GSAOI IRAF package is defined using 150sec darks.
- Users can require to take one set of 10-15 frames (darks + flats) per semester using darks with exposure times/filter tailored to their program in order to construct a BPM. Flats can be either GCAL or domeflats.

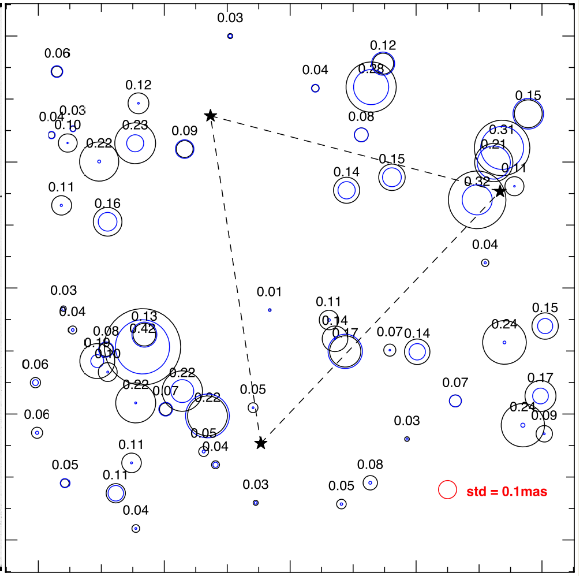
Flux standard stars

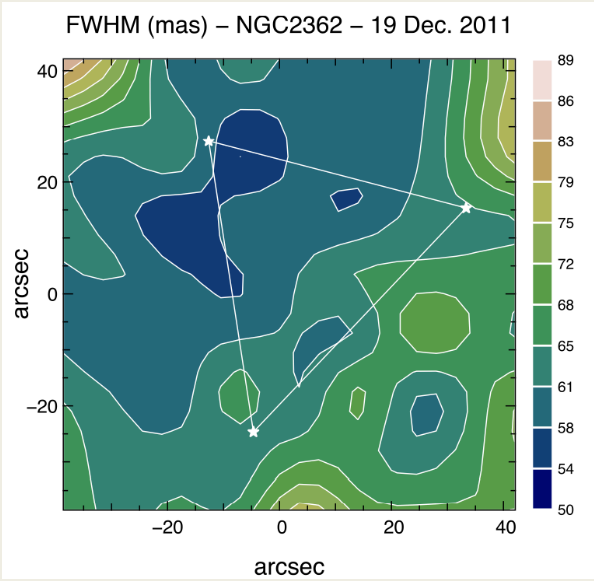
- From Persson et al. (1998).
- Only obtained in BB filters : J, H, K, Ks, Kp
- goal : to obtain at least 2-3 standards at different airmasses each observing night.
- Photometric accuracy limited to 5-10% due to
  - *uncertainties in the atmospheric extinction over Cerro Pachon,*
  - *flat-fielding and sky subtraction,*
  - *the precision in the gain determination for each of the arrays.*
- NO AO correction - natural seeing only.

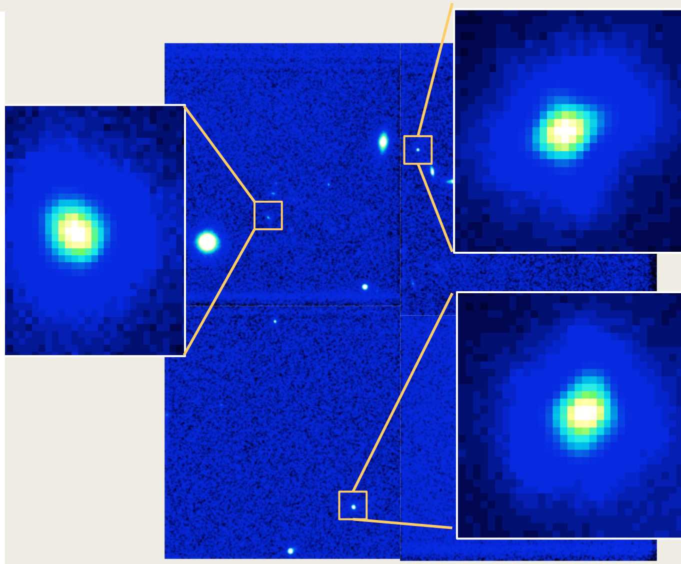
Challenge 1 :
PSF variations across the field and over time

- PSF dependent on the position in the field AND on the geometry of the guide star constellation (plus higher order terms such as laser power and return, relative brightness of the guide stars, etc).
- Little or no scientific gain in attempting to derive a PSF from a separate star field.

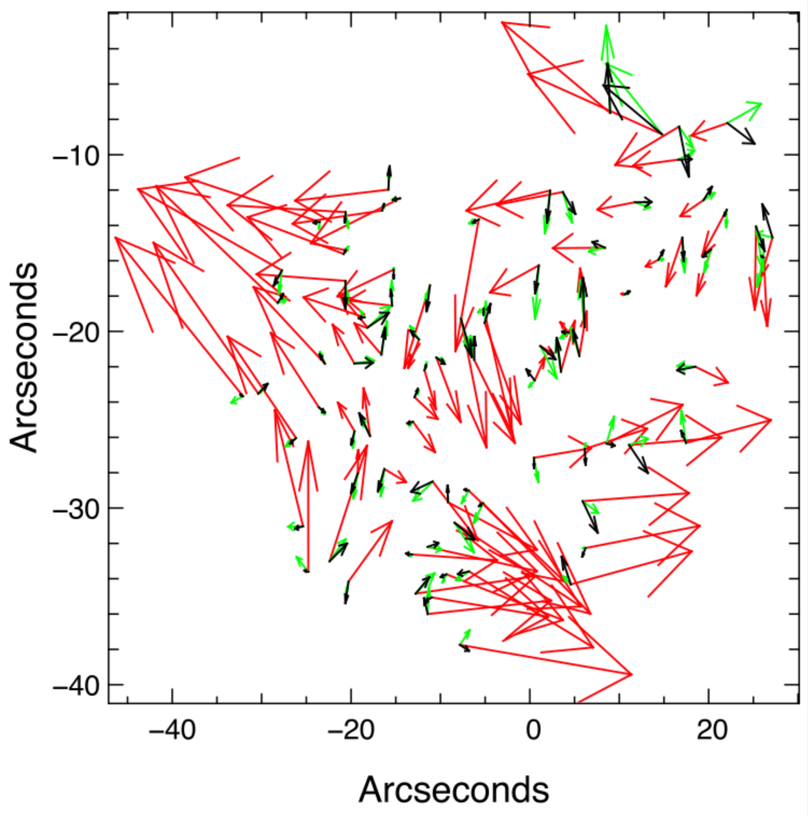


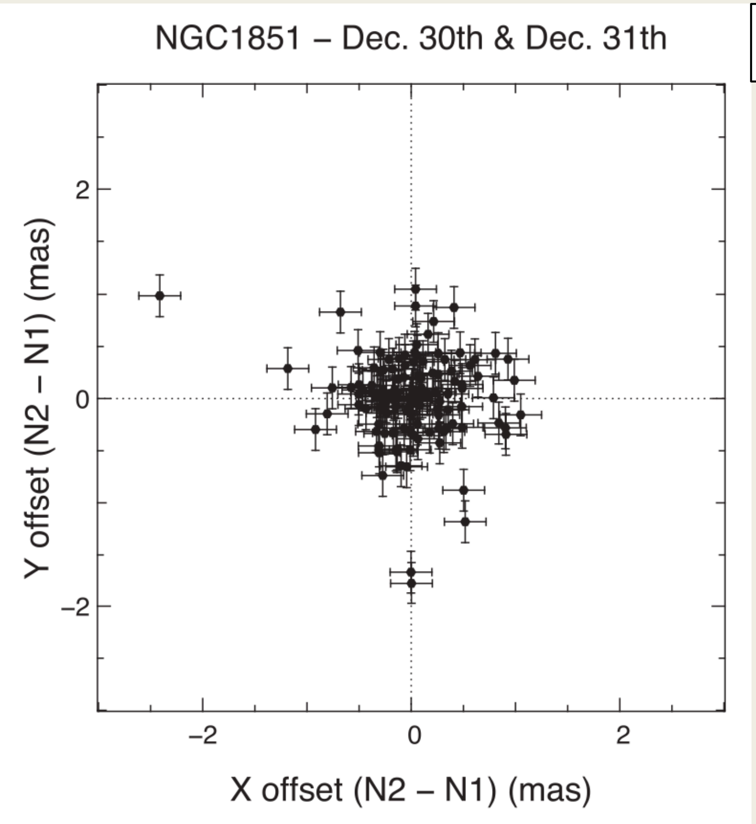






Challenge 2 :
Time variable distortion over Multi-Epoch obs.





RMS ~ 0.2 mas

- New Calibration with a pinhole masks : to take before and after the science observations.
  to quantify high orders semi-static, low order to be checked on sky with targets
- Help determining the distortion variations.

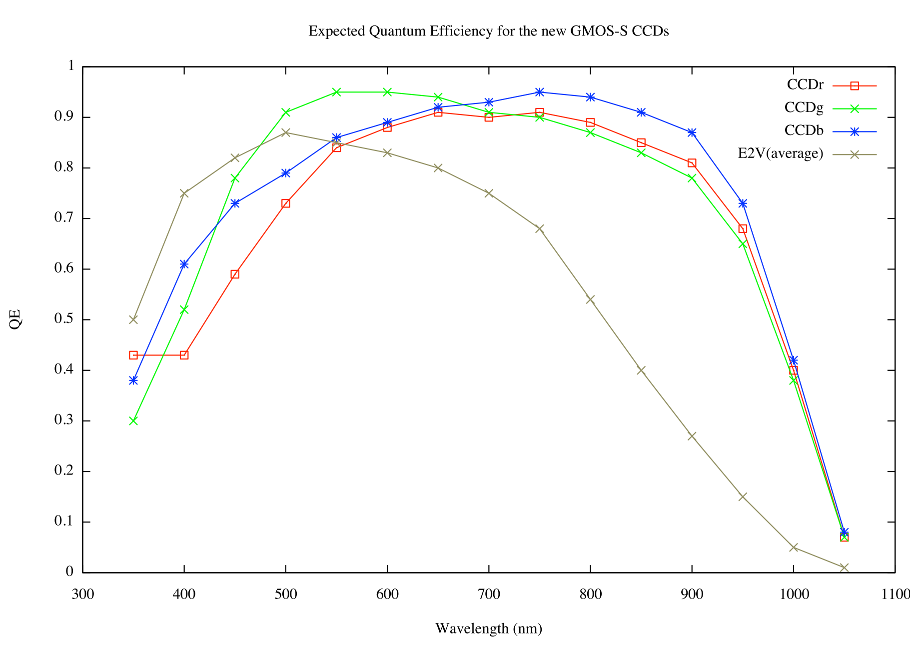
MCAO in the Visible : GeMS + GMOS

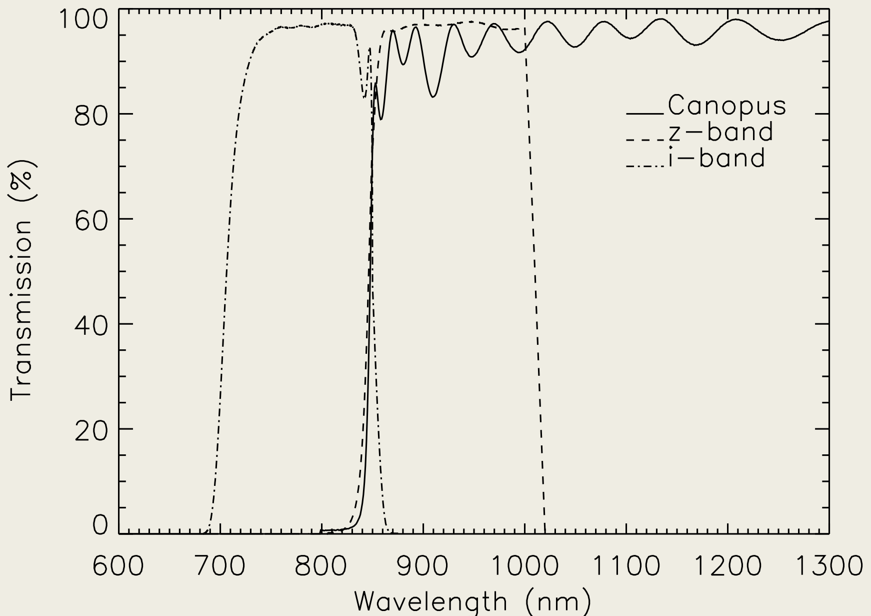
GMOS : Gemini Multi Object Spectrograph.
Most used instrument at Gemini South.

CCD : 3 2048x4068 e2V. Now replaced by Hamamatsu : better throughput in the red bands.

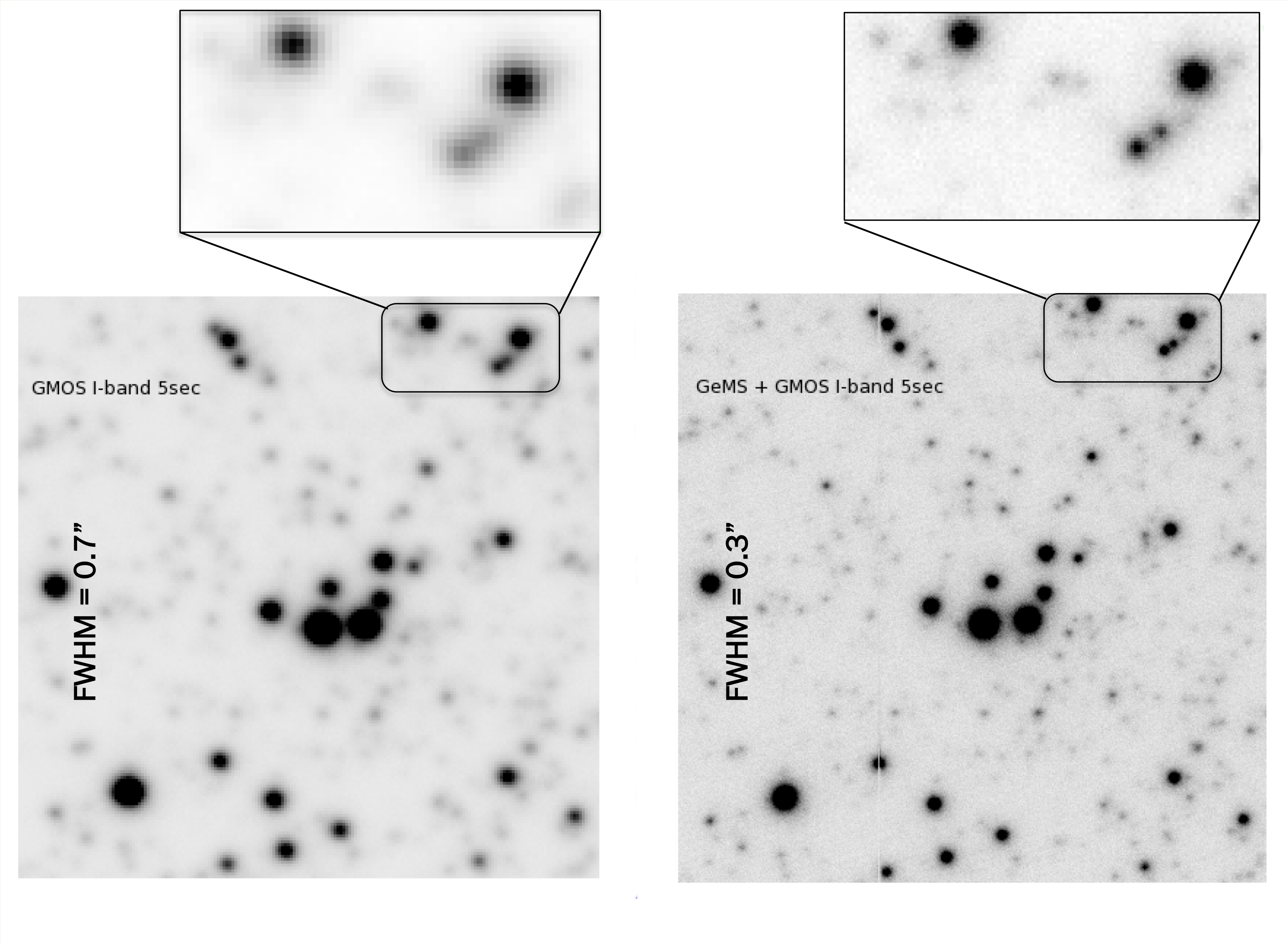
System	Field of View	Pixel Scale	Available Broad Filters
GMOS	5.5’ x 5.5’	73 mas	u, g, r, i, CaT, z
GeMS+GMOS	2.5’ x 2.5’	35.9 mas	i, CaT, z

14 targets observed between March and May 2012 : mostly globular clusters.





MCAO in the Visible : Photometric Performance



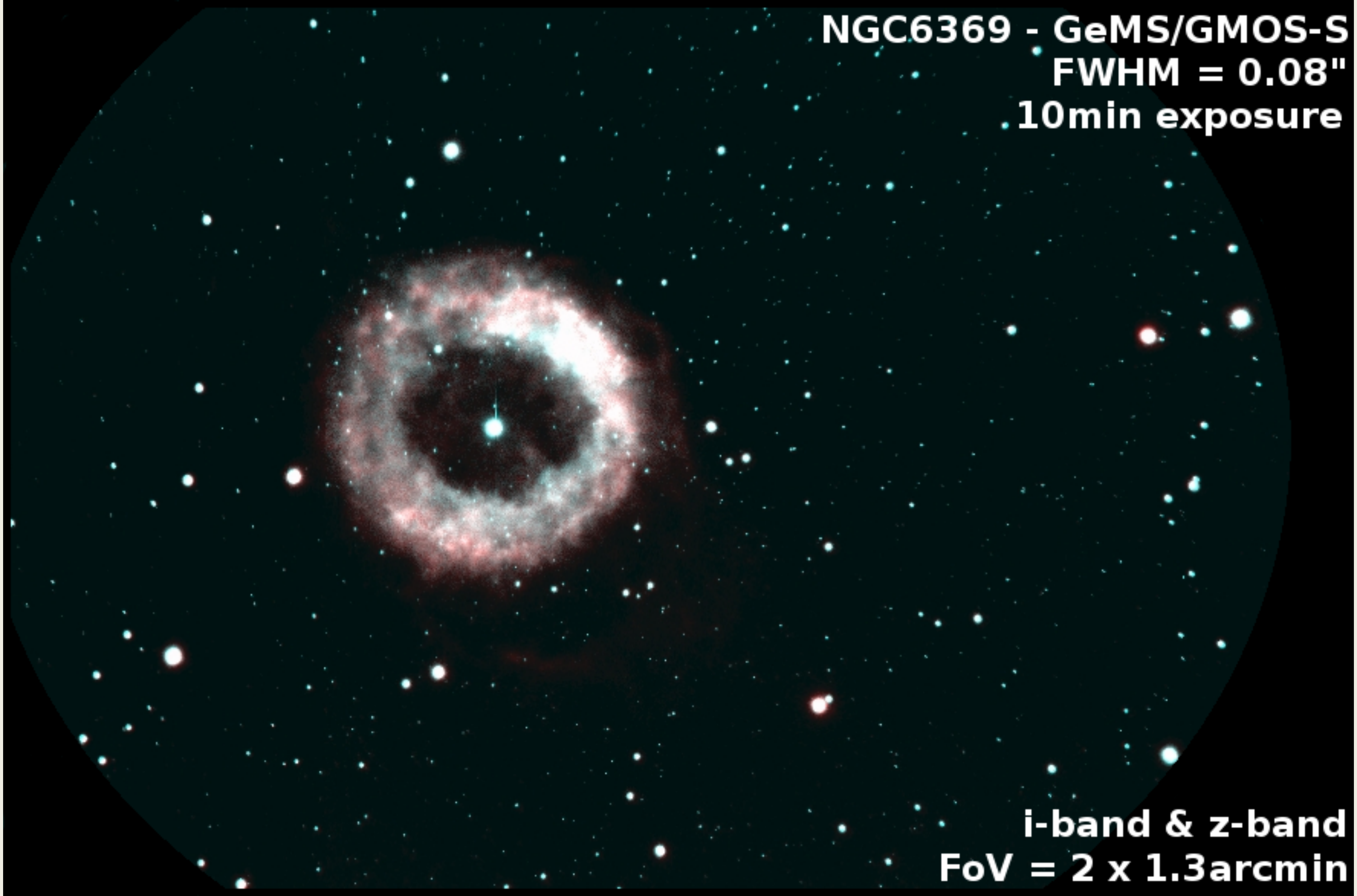
MCAO in the Visible : Other Performance

- Throughput : lower than GMOS simply due to the added number of mirrors in the MCAO system
- Sensitivity : improvement factor 1.2 in i-band
  1.5 in z-band.
- Flux : lost of a factor of 2.9 in i-band
  gain of a factor 1.5 in z-band.
- I-band most affected due to wavelength cutoff of the Beam Splitter used in the AO bench.
- Astrometric performance scales as expected with the photon noise :
  no systematic error are detected

Targets	NGC 2849	NGC 3201	NGC 3244	NGC 4590	NGC 5286	NGC 6496
Absolute Astrometric Error (mas)	2.47	4.73	2.8	3.2	4.4	5.4
Nber of undithered images	12	12	17	31	11	6

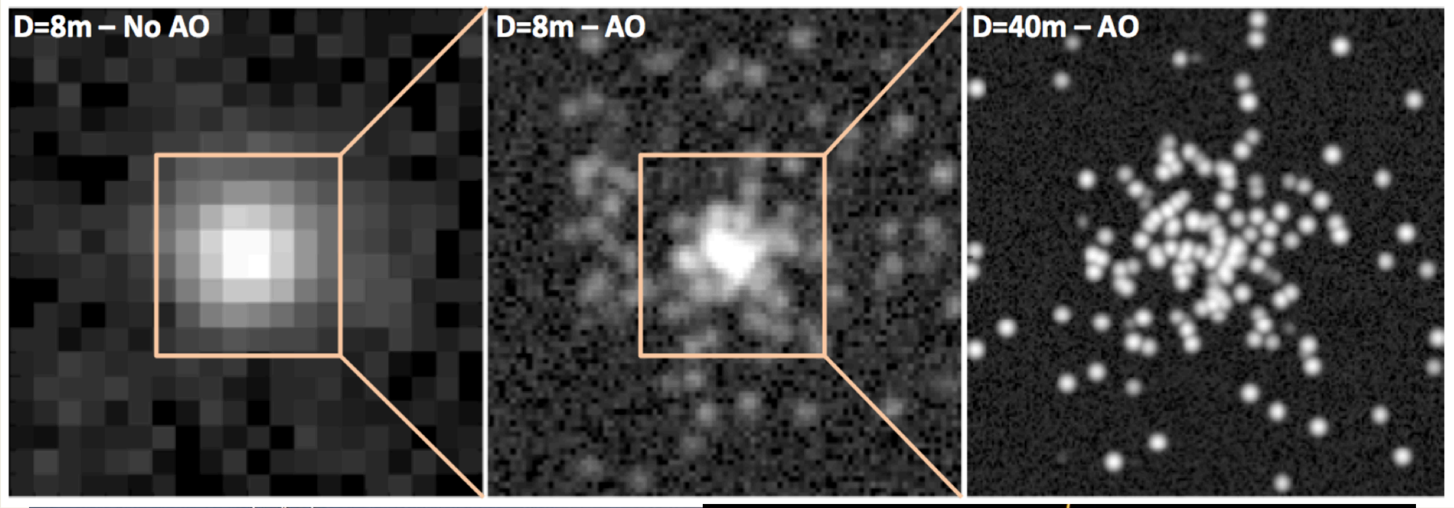
MCAO in the Visible : GeMS + GMOS

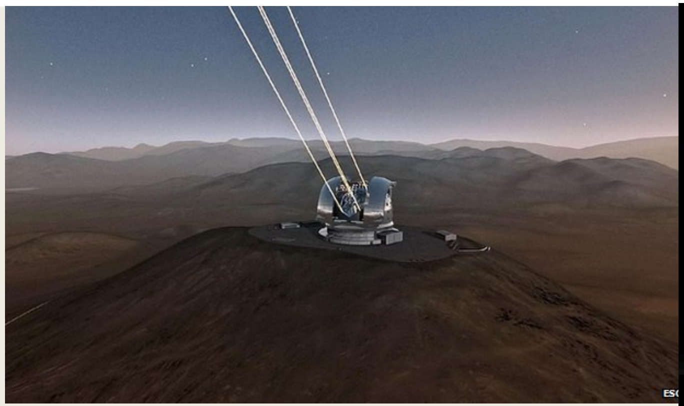
- A good WCS calibration will depend on two main points :
  - *the availability of appropriate reference catalogues*
  - *the AO corrections.*
- PSF uniformity over a large field + the ability to actively control the plate scale
  -> reduce the largest astrometric errors
  Need systemic residual distortions well under control
  -> the system should be carefully calibrated in WCS and the systematic errors should be kept low.
- Priority : explore the AO performance and test functionality of different MCAO subsystems rather than to carefully calibrate the astrometric performance.
- The targets : central part of globular clusters, i.e. very crowded fields,
  -> a perfect benchmark to check the PSF uniformity over the GeMS FoV.
- Challenge : Lack of precise unconfused references stars to derive an accurate WCS most of the catalogue can only offer a precision of about 1 arcsec (Lasker et al. 1990) : ~ 27 times larger than the plate scale of GeMS+GMOS (0.0359"/ pixel).


NGC6369 - GeMS/GMOS-S
FWHM = 0.08"
10min exposure
i-band & z-band
FoV = 2 x 1.3arcmin

Conclusion

- Plenty of science cases would benefit from precise astrometry
- Science “niche” for WFAO and ELTs
- Precise astrometry would require accurate calibration, and PSF





Expected performance ~50 μas !!
(but will certainly require perfect PSF and distortion control…)

GeMS Performance

Natural Seeing @550nm	FWHM (J)	FWHM (H)	FWHM (K)
<0.45"	0.08"	0.07"	0.06"
0.45" - 0.80"	0.13"	0.10"	0.09"
0.80" - 1.00"	0.15"	0.13"	0.12"

Natural Seeing @550nm	Strehl ratio (J)	Strehl ratio (H)	Strehl ratio (K)
<0.45"	10%	15%	30%
0.45" - 0.80"	5%	10%	15%
0.80" - 1.00"	2%	5%	10%

Special Calibrations needed for GeMS+GSAOI

- For each run :
- Targets with elevations higher than 45 degrees
- Bright sources from the science field to test and characterize the Canopus WFS and define the GSAOI Hot Spot position
- Astrometric fields to derive the GSAOI IAA, WCS

HOT SPOT

- = Instrument Origin
- First thing to check at the start of the night

GSAOI IAA

- The Hot Spot is the location that is defined as the position of the star when the wavefront sensor is "on-axis". This has to coincide with the telescope pointing axis so that when a star is acquired, it will be aligned with the wavefront sensor.
- done after the Hot Spot (Instrument origin) adjustment and before the WCS calibration

WCS

- Relative accuracy is currently ~0.3arcsec on average over the field. Absolute accuracy is around 5arcsec (limited by the precision in the telescope pointing).
- Usually : HST reference.

Outline

- MCAO Principle
- MCAO Systems
- GSAOI
- What kind of science?
- Baseline Calibrations
- Specific Calibrations