The bright side of

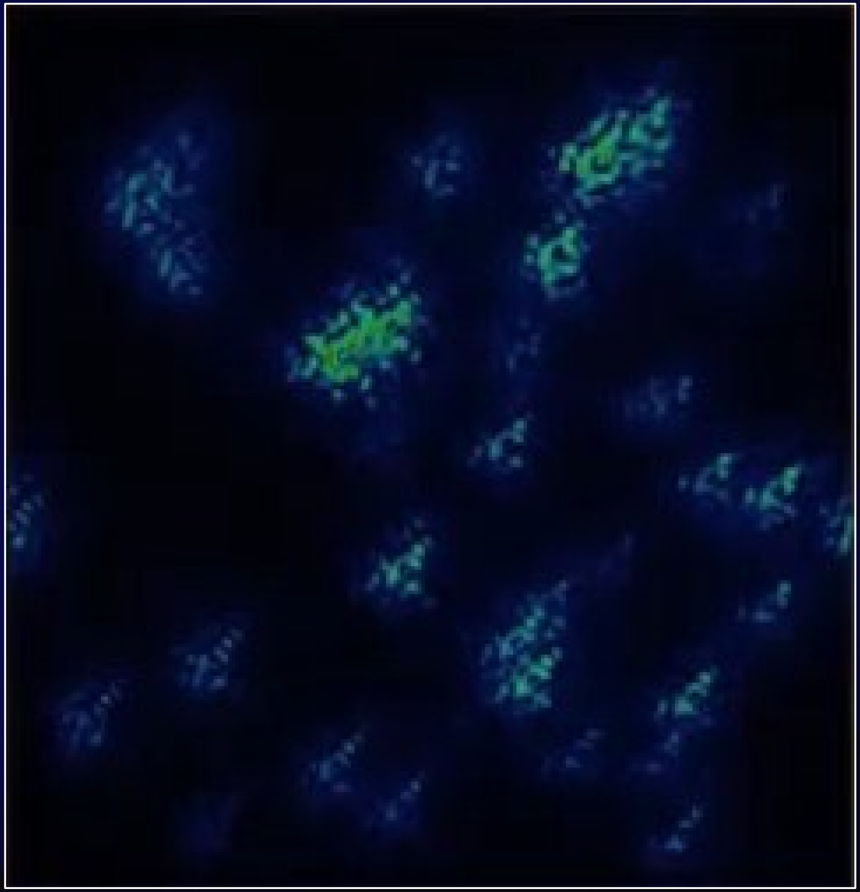
Multi-conjugate Adaptive Optics

E.Marchetti

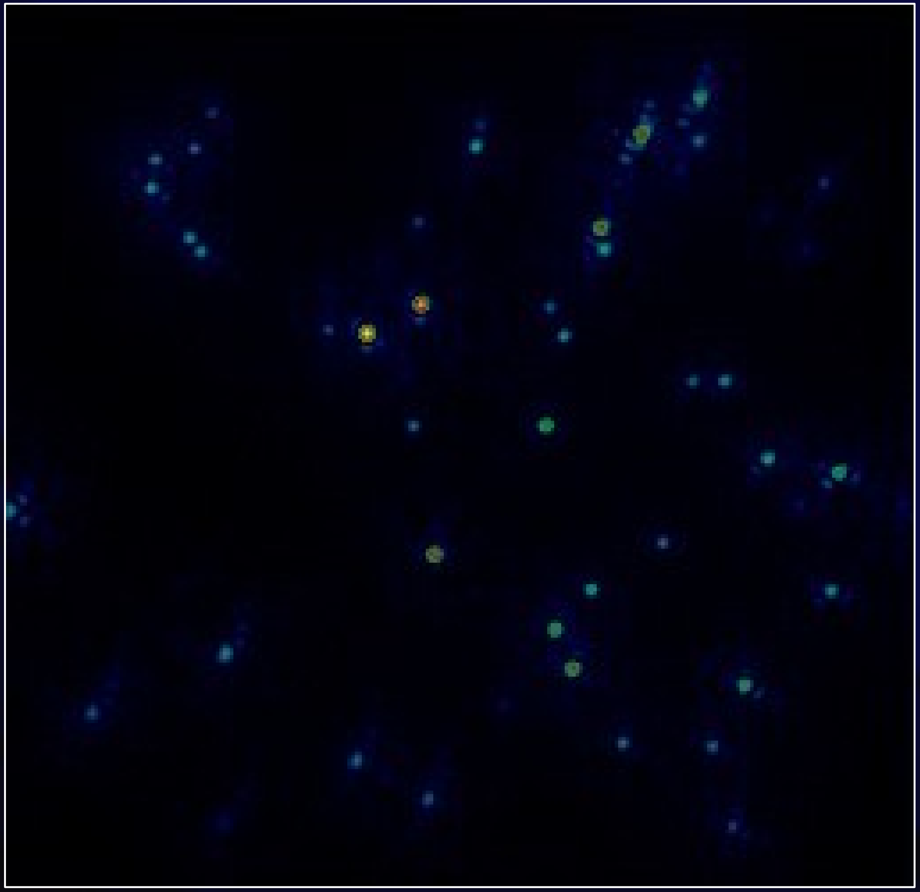
European Southern Observatory - Germany

What happens in classical AO

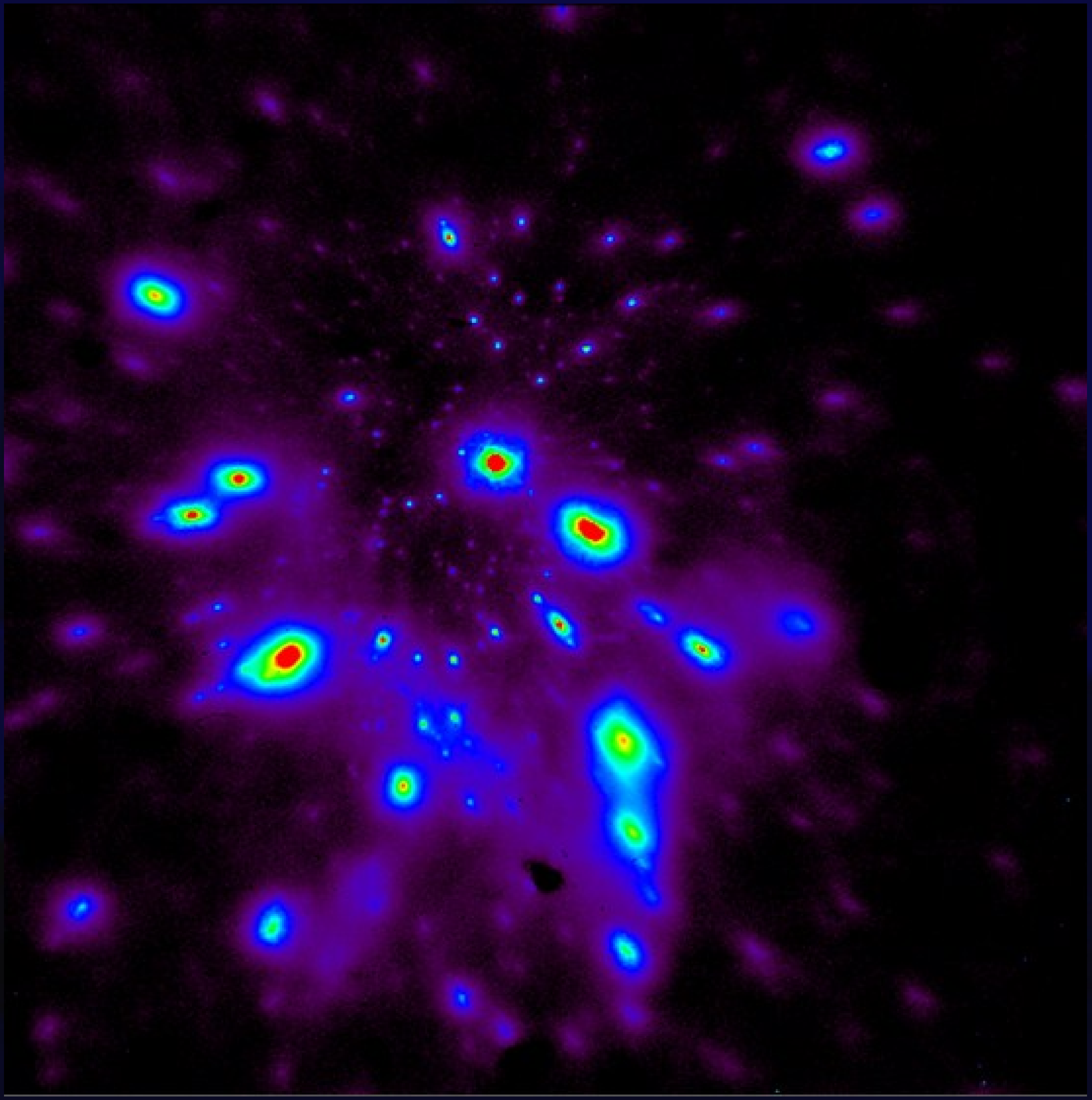
Open loop

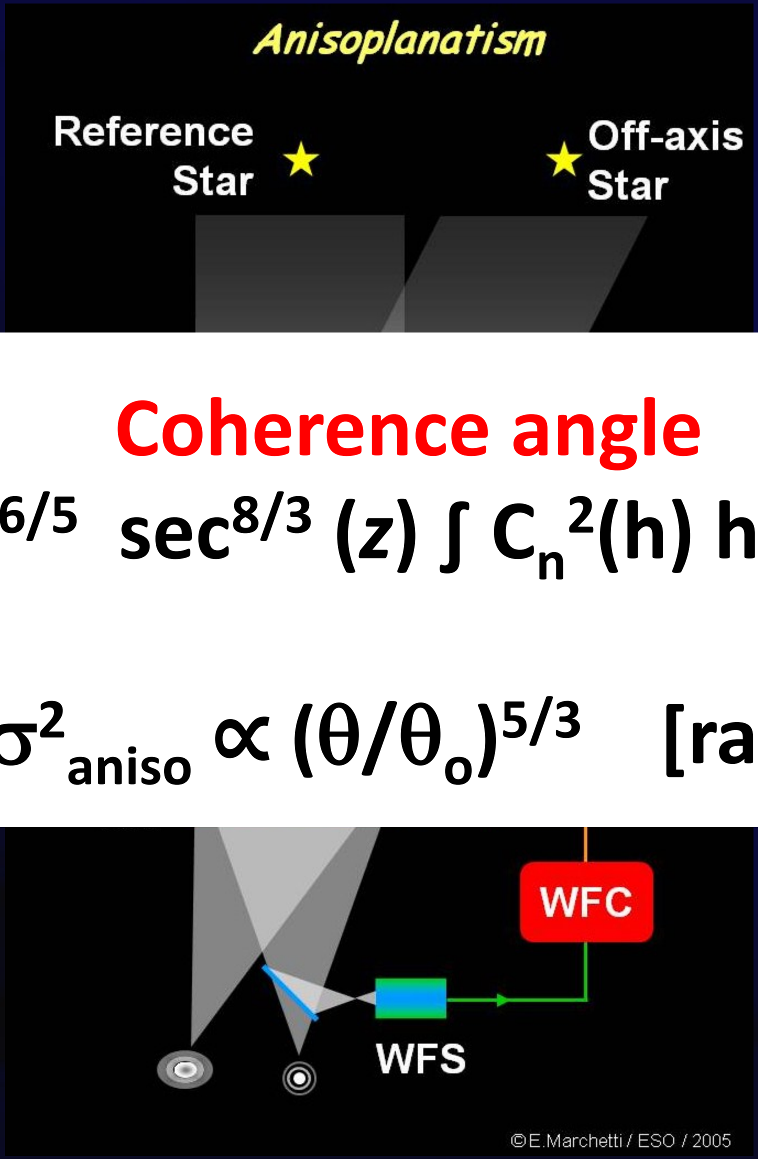


Close loop



Why MCAO?



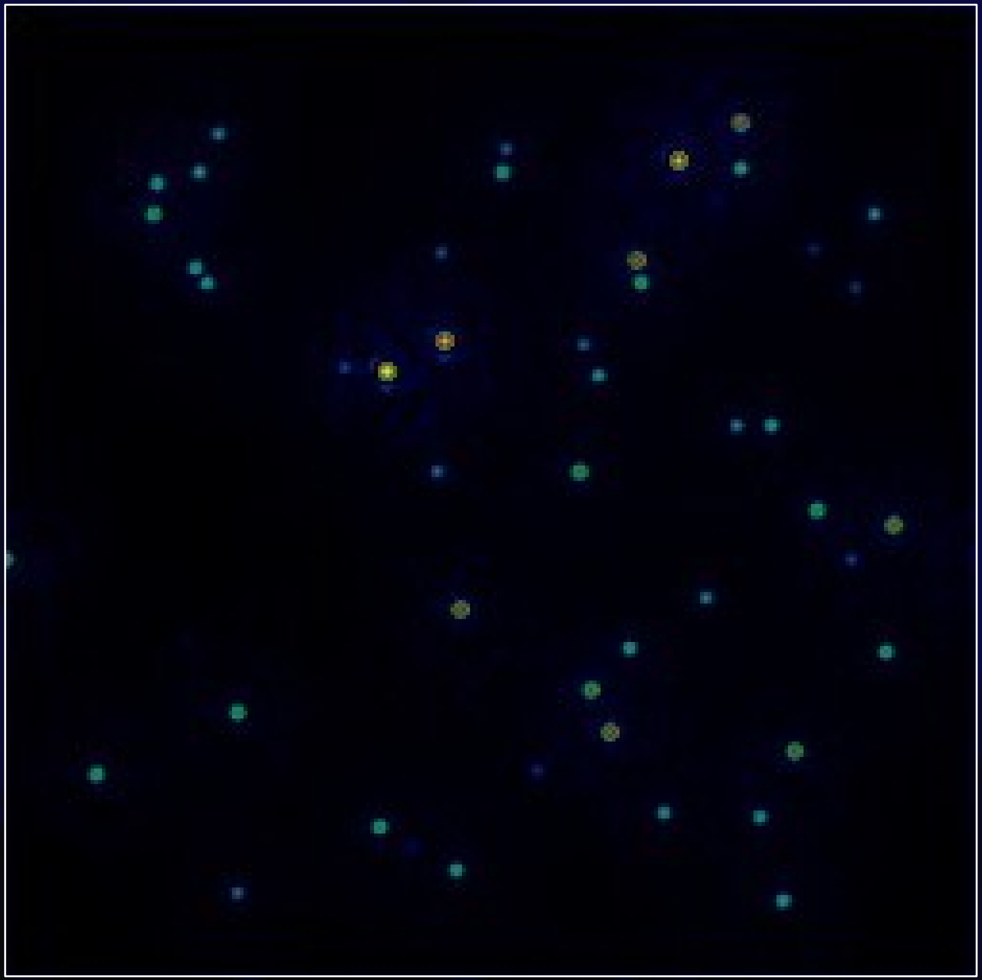


Coherence angle

$$\theta_o \propto \lambda^{6/5} \sec^{8/3}(z) \int C_n^{2}(h)\, h^{5/3} \quad [rad]$$

$$\sigma^2_{aniso} \propto (\theta/\theta_o)^{5/3} \quad [rad]$$

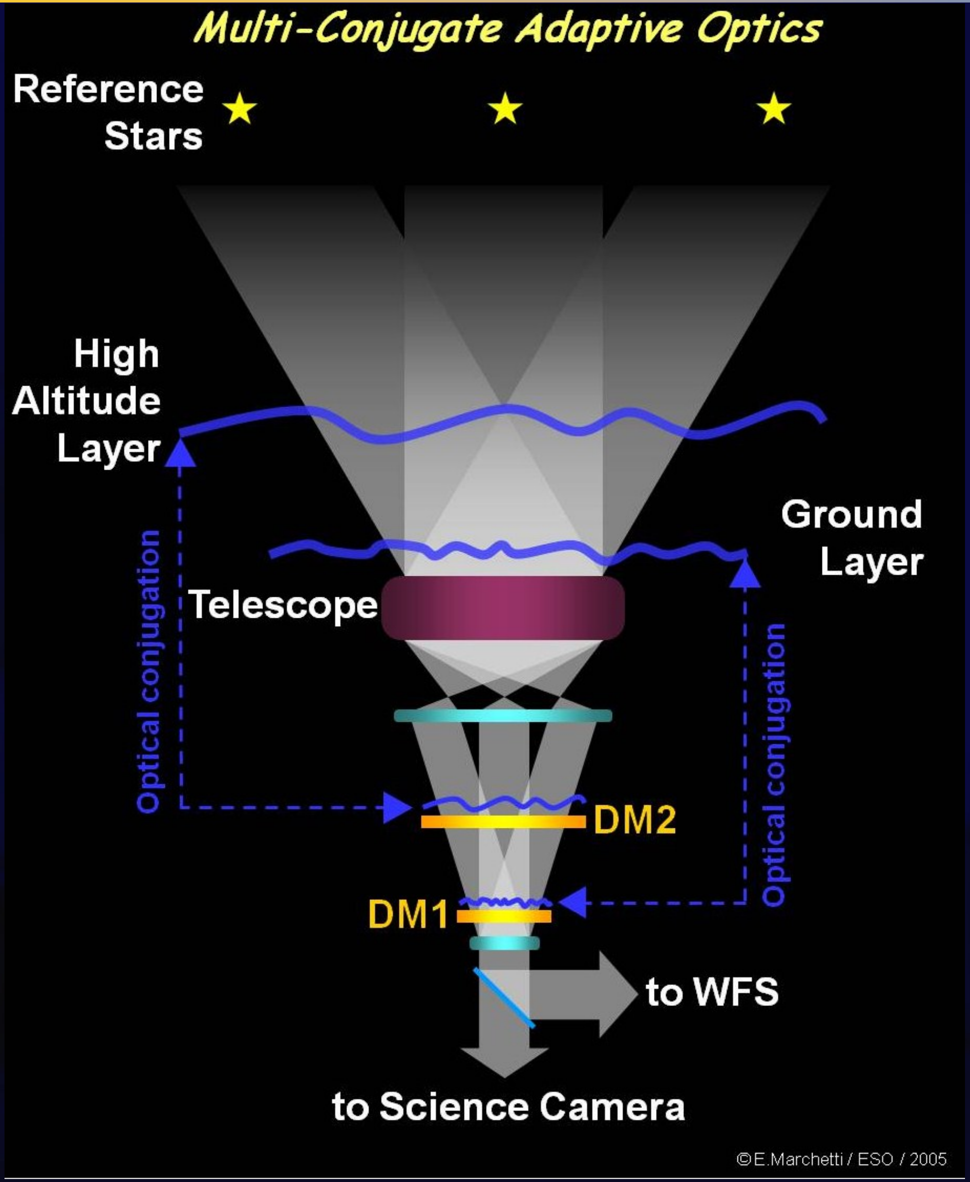
Dreaming at... MCAO



MCAO Timeline

- *1975 – R.H.Dicke introduces the concept of MCAO*
- 1988 – J.M.Beckers revamps the use of MCAO for astronomy

Multi Conjugate Adaptive Optics



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MCAO basic principles

Probing atmospheric turbulence volume in a large FoV by means of several guide stars (and WFSs)

↓

Reconstruct tomographically the wavefronts at defined altitudes (prior knowledge of vertical distribution of turbulence is an asset)

↓

Project the wavefronts onto altitudes where DMs are conjugated to

↓

Compensate for turbulence with the DMs

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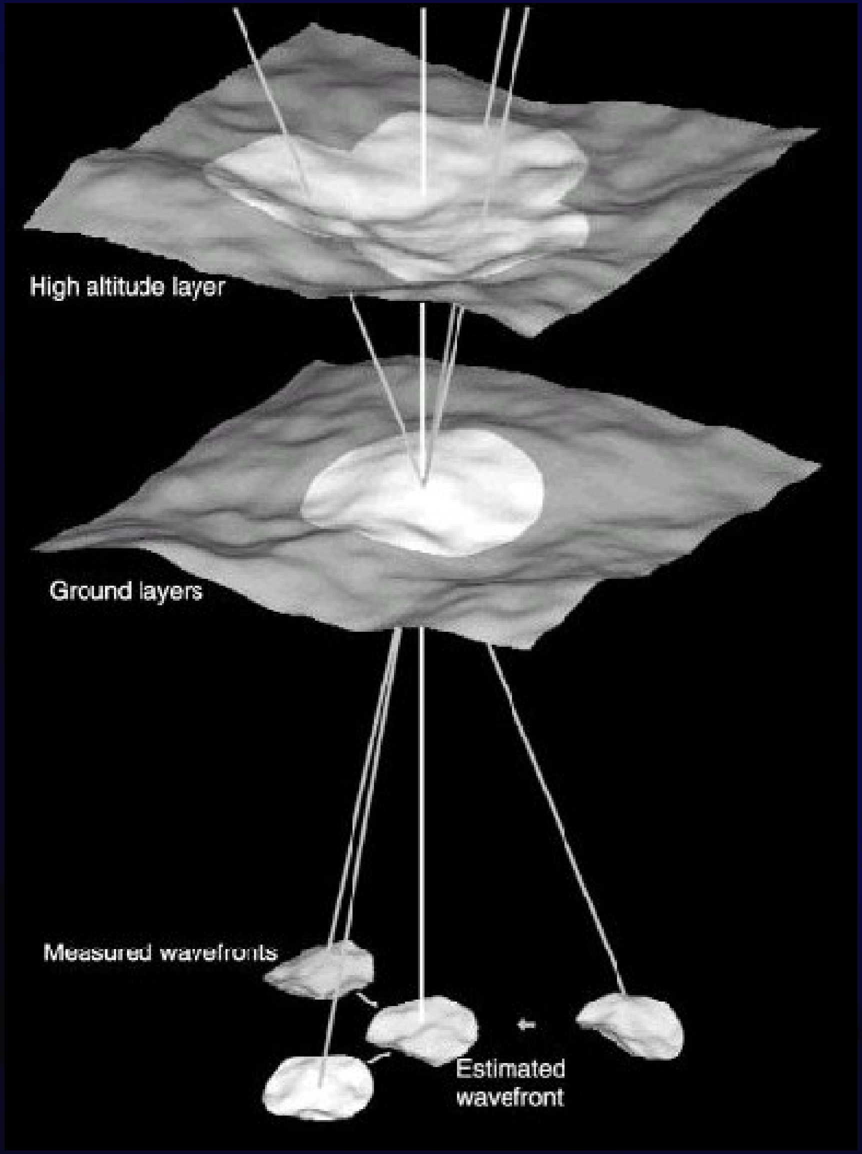
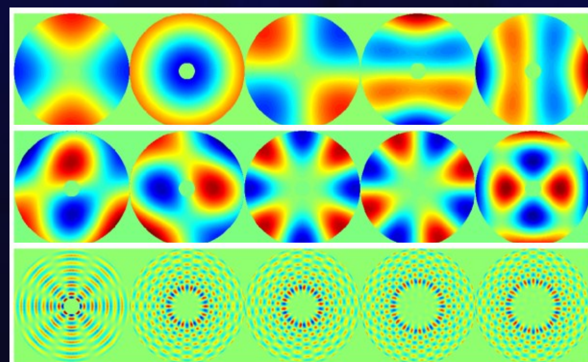
Slicing the atmosphere

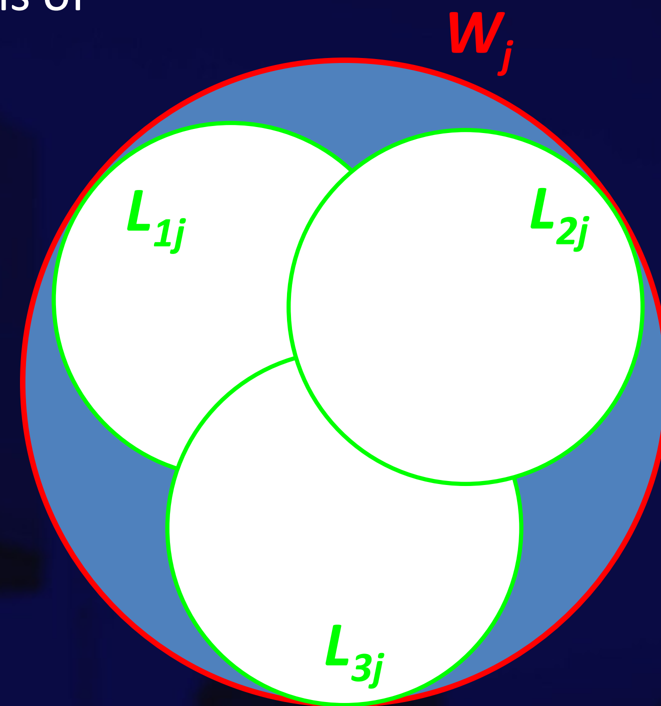


Modal Tomography

- The wavefront in the direction of the *i-th* guide star at the *j-th* layer is described as a linear combinations of ***P*** "modes"

$$L_{ij} = \begin{bmatrix} a_4 \\ a_5 \\ a_6 \\ \vdots \\ a_P \end{bmatrix}$$





- The total wavefront in the direction of *i-th* guide star is a linear combination of the ***N*** layers

$$L_i = \sum_{j=1}^{N} L_{ij}$$

- Project the wavefront of the metapupil ***W*** at *j-th* layer into the *i-th* direction

$$L_{ij} = A_{ij} W_j \qquad L_i = \sum_{j=1}^{N} L_{ij} = \sum_{j=1}^{N} A_{ij}\, W_j \qquad L = A\, W \qquad W = A^{+}\, L$$

R.Ragazzoni, E.Marchetti, F.Rigaut , A&A 342, L53 (1999)

Modal Tomography

- Important property of the projection matrix A: if the metapupil is a linear combination of modes up to radial order r, any circular portion inside it can be described with a linear combination of the same set of modes up to the same radial order
- Project the wavefront of the metapupil ***W*** at *j-th* layer into the any desired direction

$$W_{Tj} = T_j W_j \qquad\qquad W_T = T\,W$$

- Retrieving the wavefront along any desired direction from the wavefront observed in the direction of the guide stars

$$W_T = T\,A^{+}\,L$$

$$W_T = \boldsymbol{M}\,L$$

Tomographic matrix

R.Ragazzoni, E.Marchetti, F.Rigaut , A&A 342, L53 (1999)

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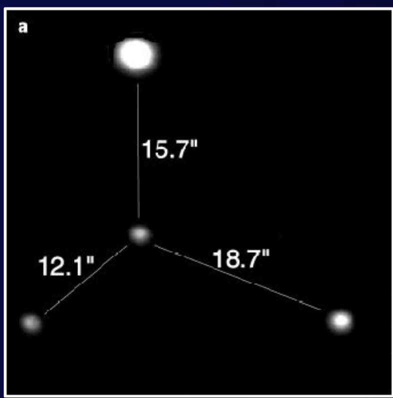
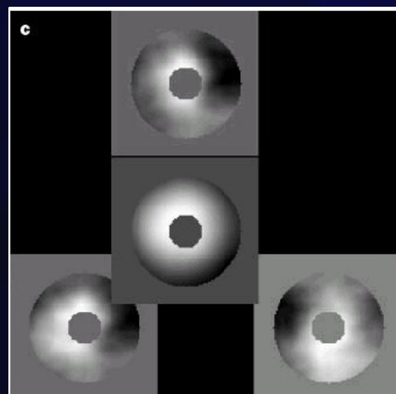
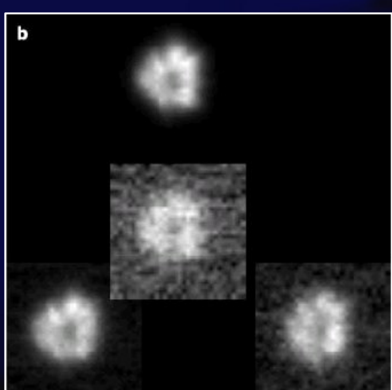
- 2000 – R.Ragazzoni, E.Marchetti & G.Valente provided on sky open loop demonstration of tomography

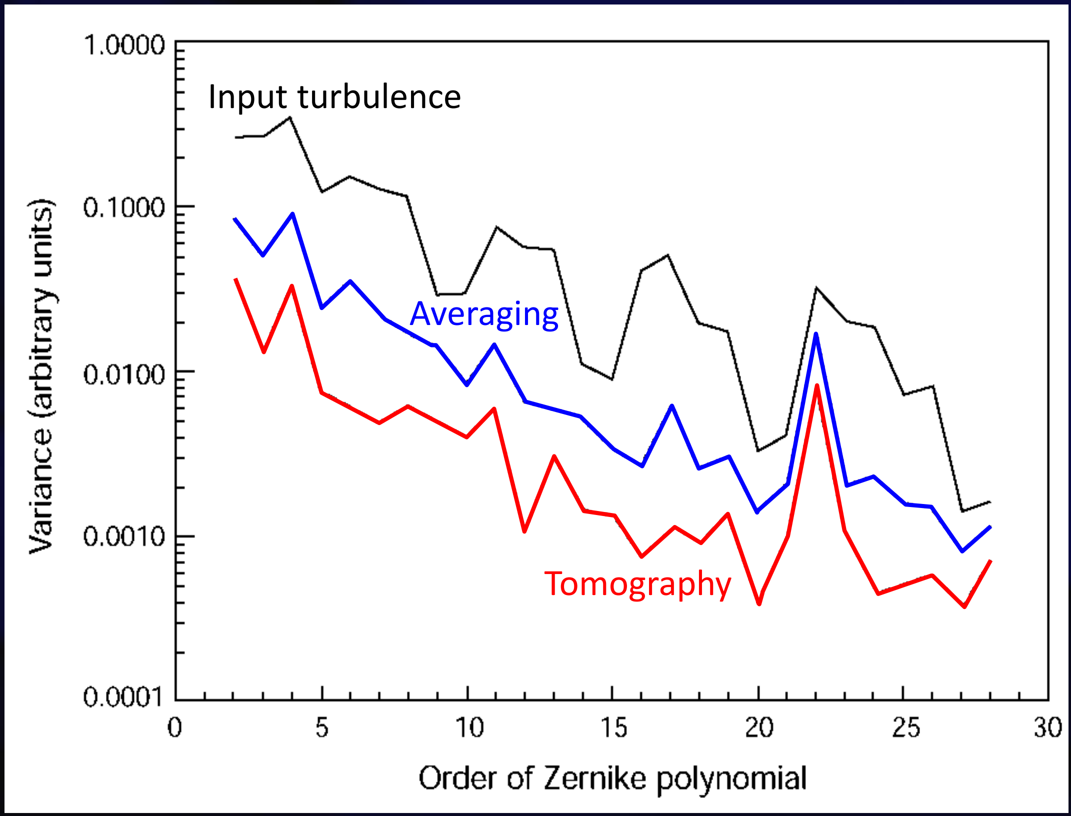
Open loop demonstration (2000)

- Open loop experiment run at Telescopio Nazionale Galileo (Canary Islands)
- Wavefront estimated from defocused images from nice star asterism
- Tomographic matrix obtained from open loop data stream







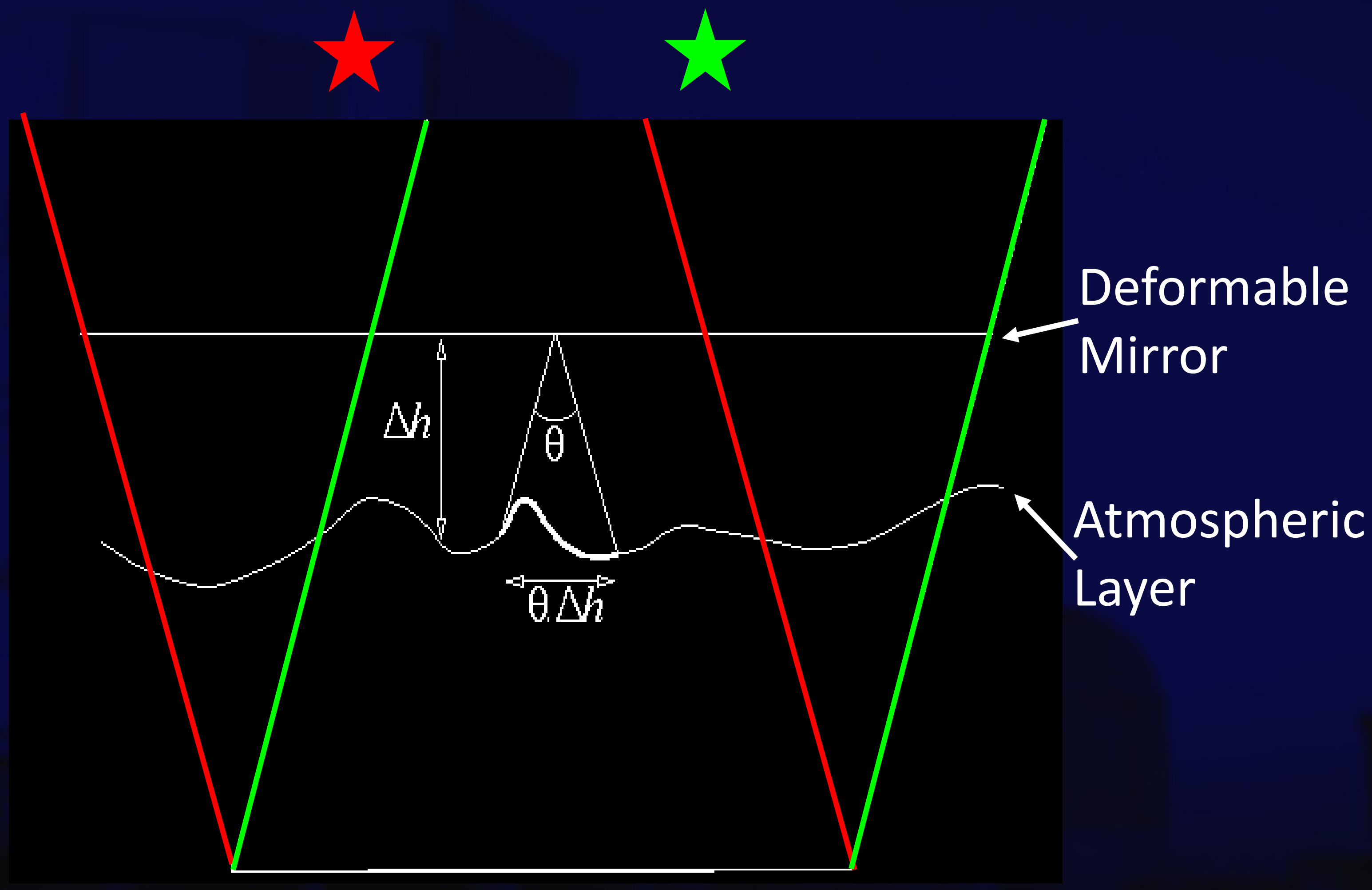


R.Ragazzoni, E.Marchetti, F.Valente, Nature 403, 54 (2000)

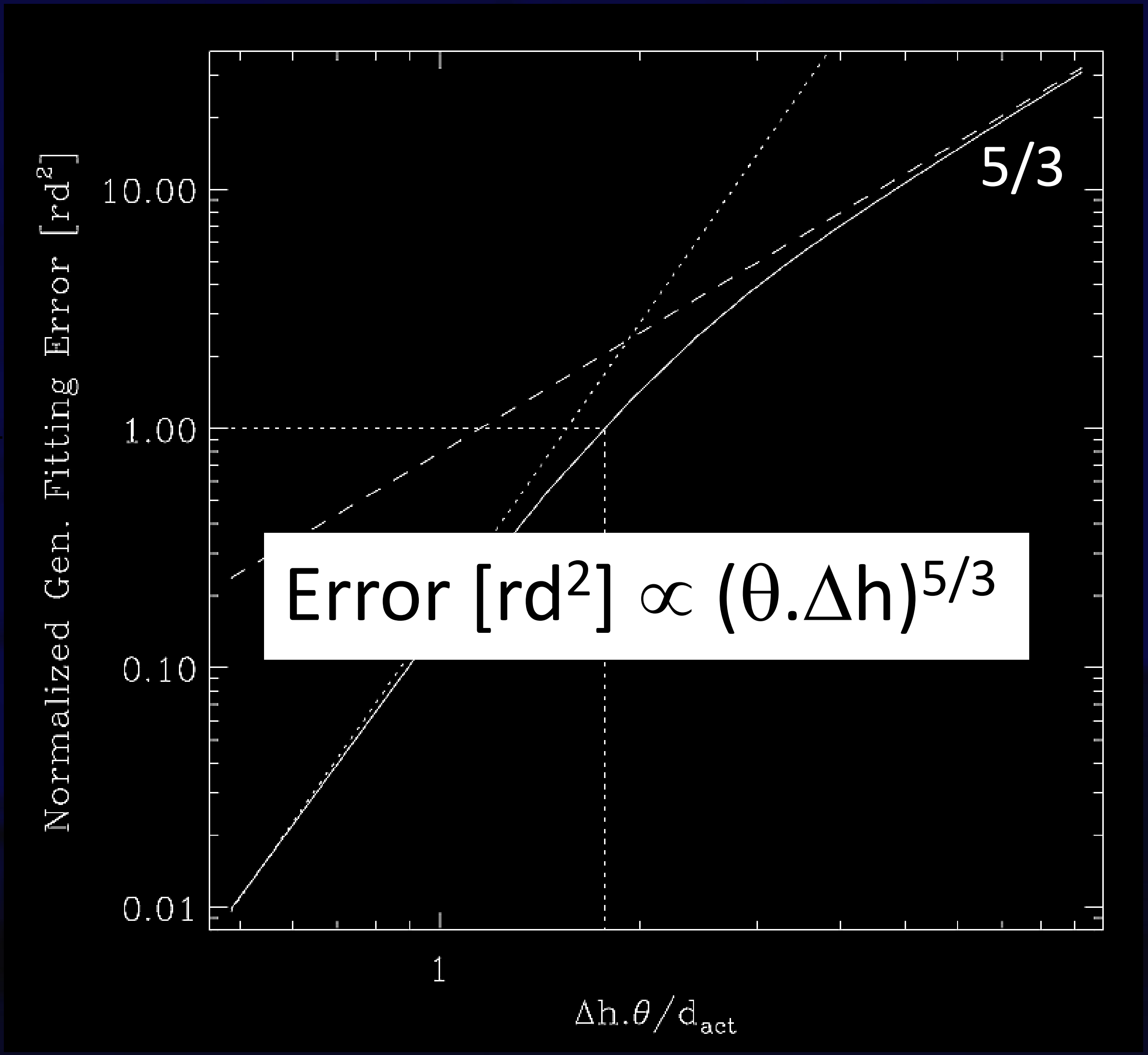
Designing an MCAO system: know your enemy

- Limitations, error sources and the related propagation helps in constraining the design parameters to the desired solution
  - Generalized fitting error
  - Generalized anisoplanatic error
  - Generalized aliasing
  - Tip-tilt problem with Laser Guide Stars
- Cycling Simulations → modelling → simulations …

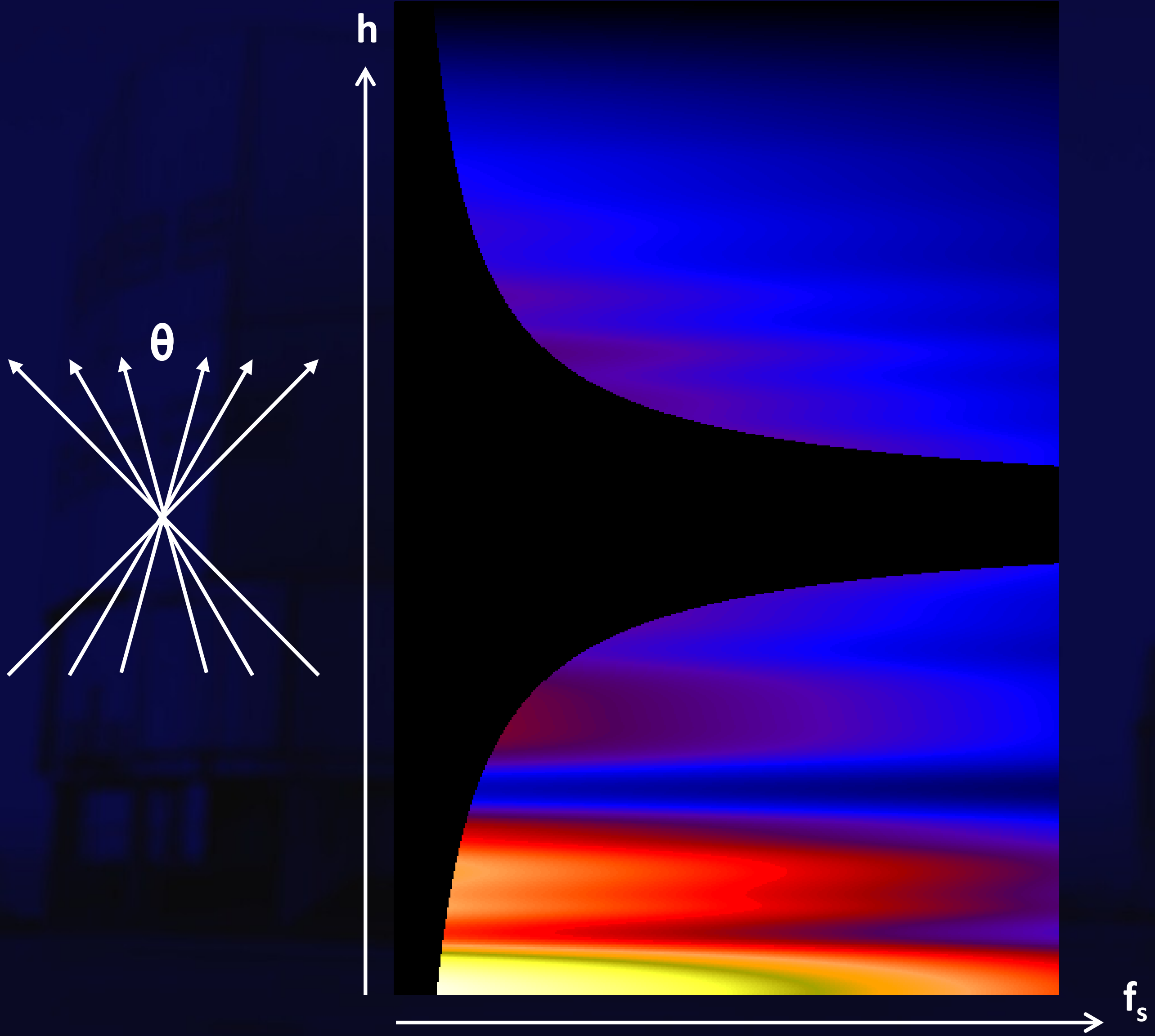
Generalized fitting error



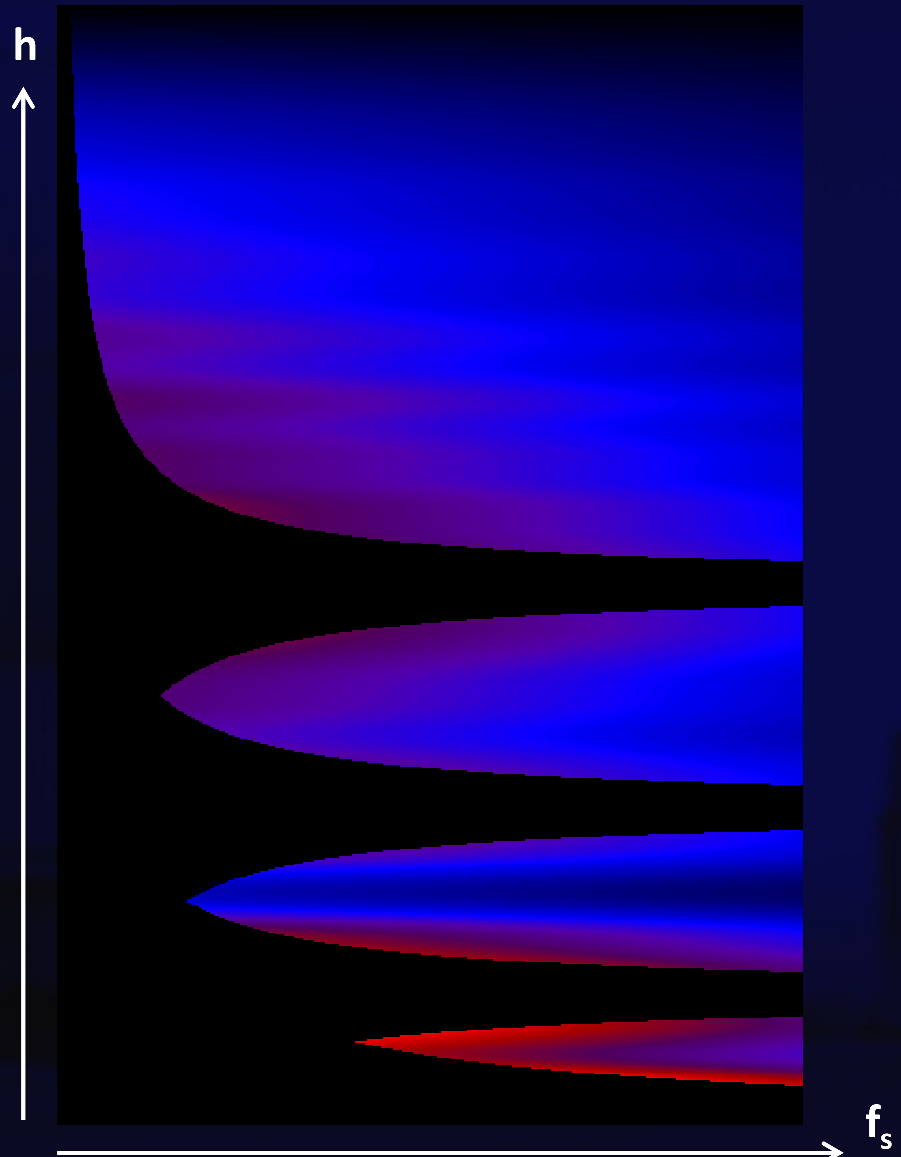
Generalized fitting error



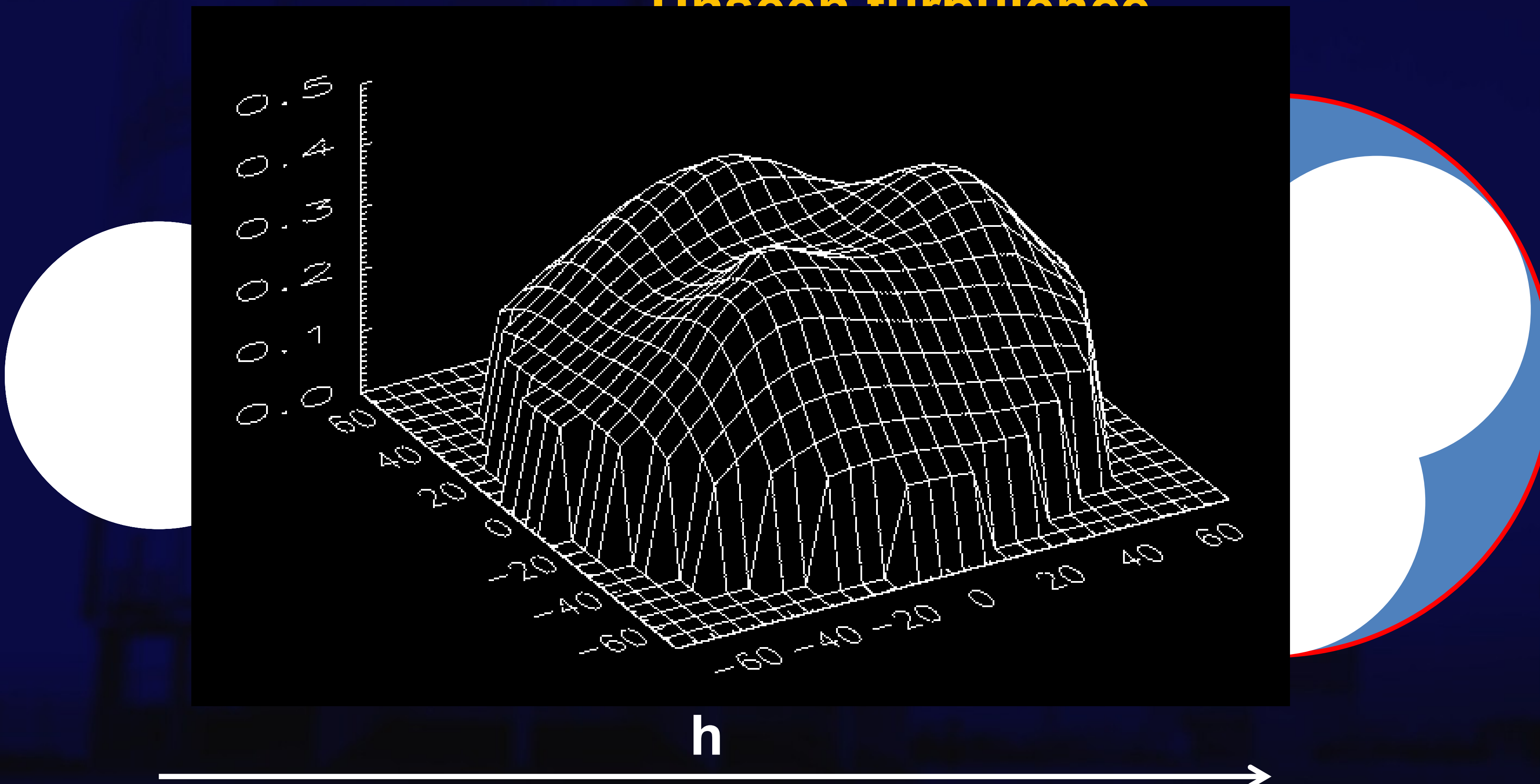
Generalized fitting error



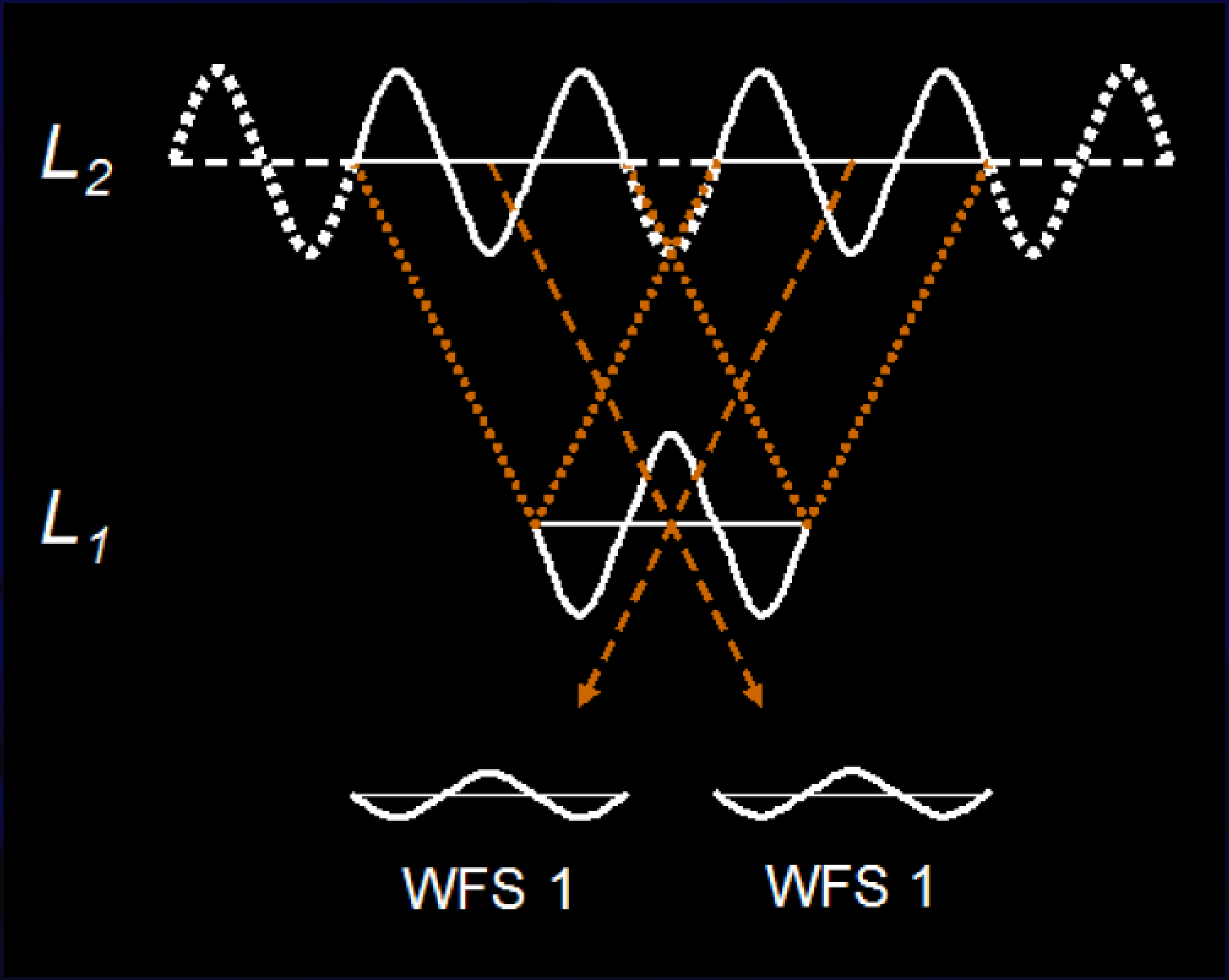
Optimizing DMs position



Generalized anisoplanatic error



Generalized aliasing error



Solving the generalized aliasing error

- Aliasing due to the unseen and/or badly seen modes propagate undesired noise in the MCAO control loop → The ***Interaction Matrix (IM)*** is badly conditioned

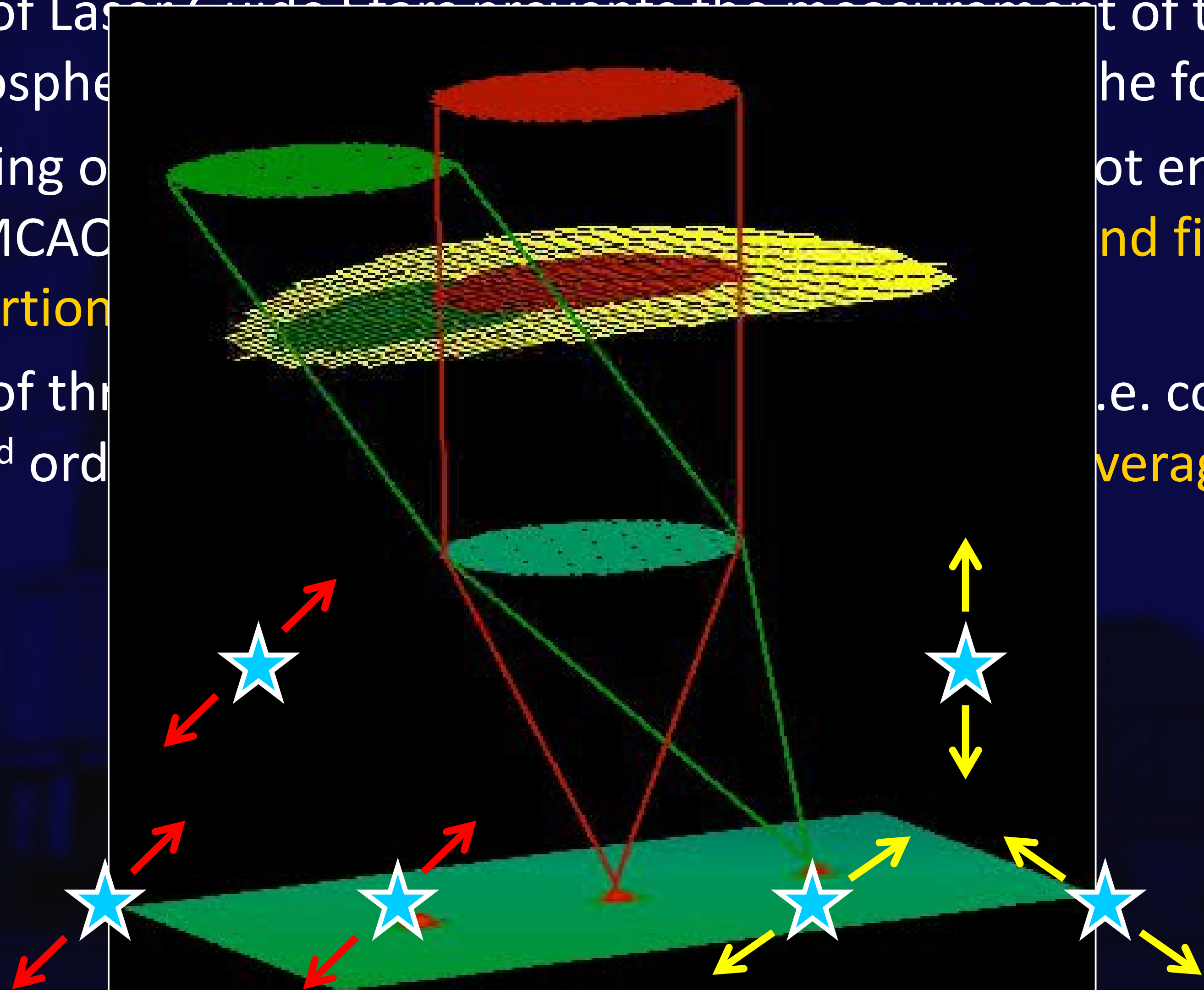
$$\varphi = R \cdot s \qquad R = IM^{-1}$$

- ***Reconstructor R*** can be computed truncating the unseen/badly seen modes (Truncated LSE), sub-optimal solution
- Adding *"knowledge"* works better: regularization of ***R*** (MAP) provides optimal solution to bad conditioning

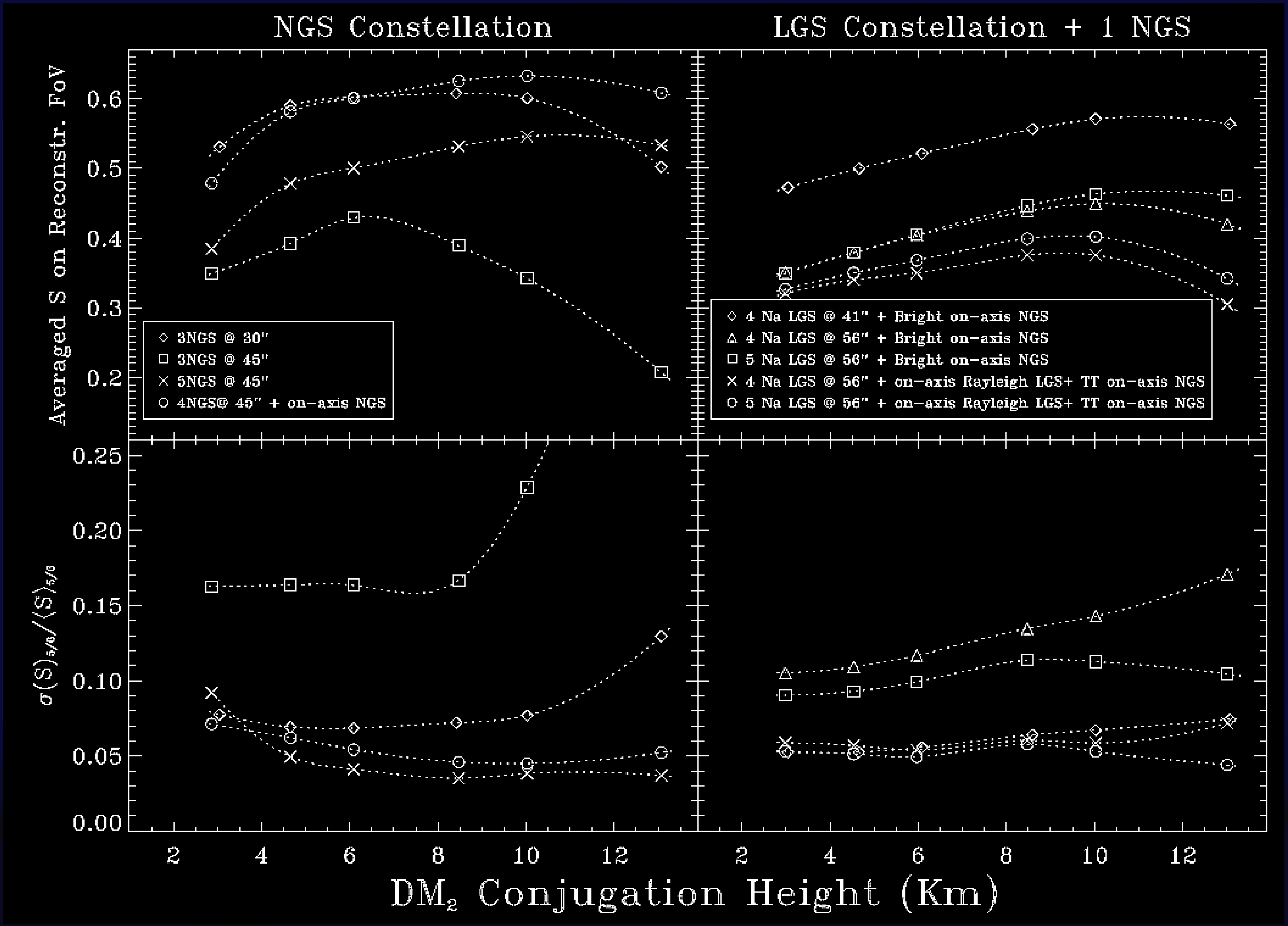
$$R = C_\varphi IM^T [IM\, C_\varphi IM^T + C_w]^{-1}$$

Tip-tilt problem with Laser Guide Stars

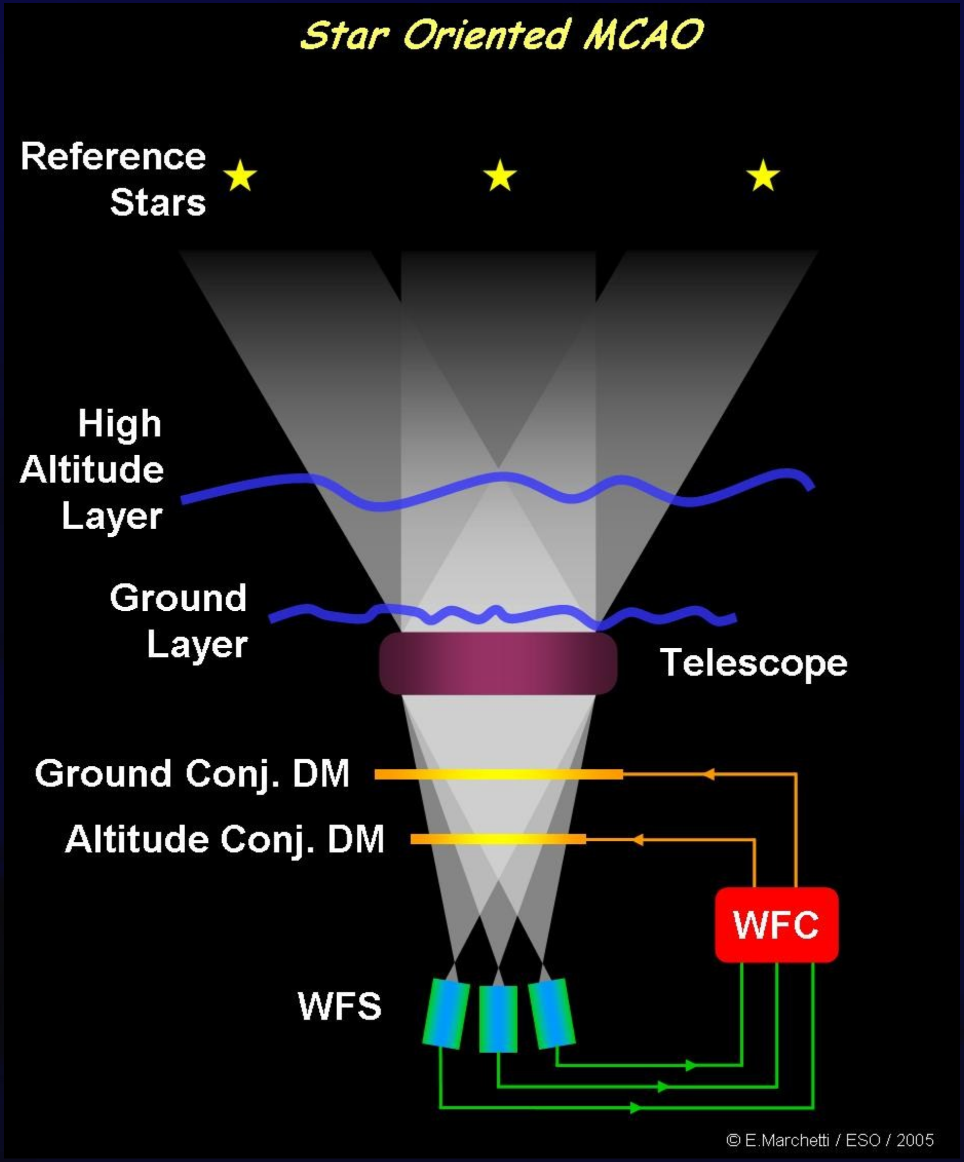
- Use of Las … t of the atmosphe … he focus
- Sensing o … ot enough for MCAO … nd field distortion
- Use of thr … .e. control of 2nd ord … verage



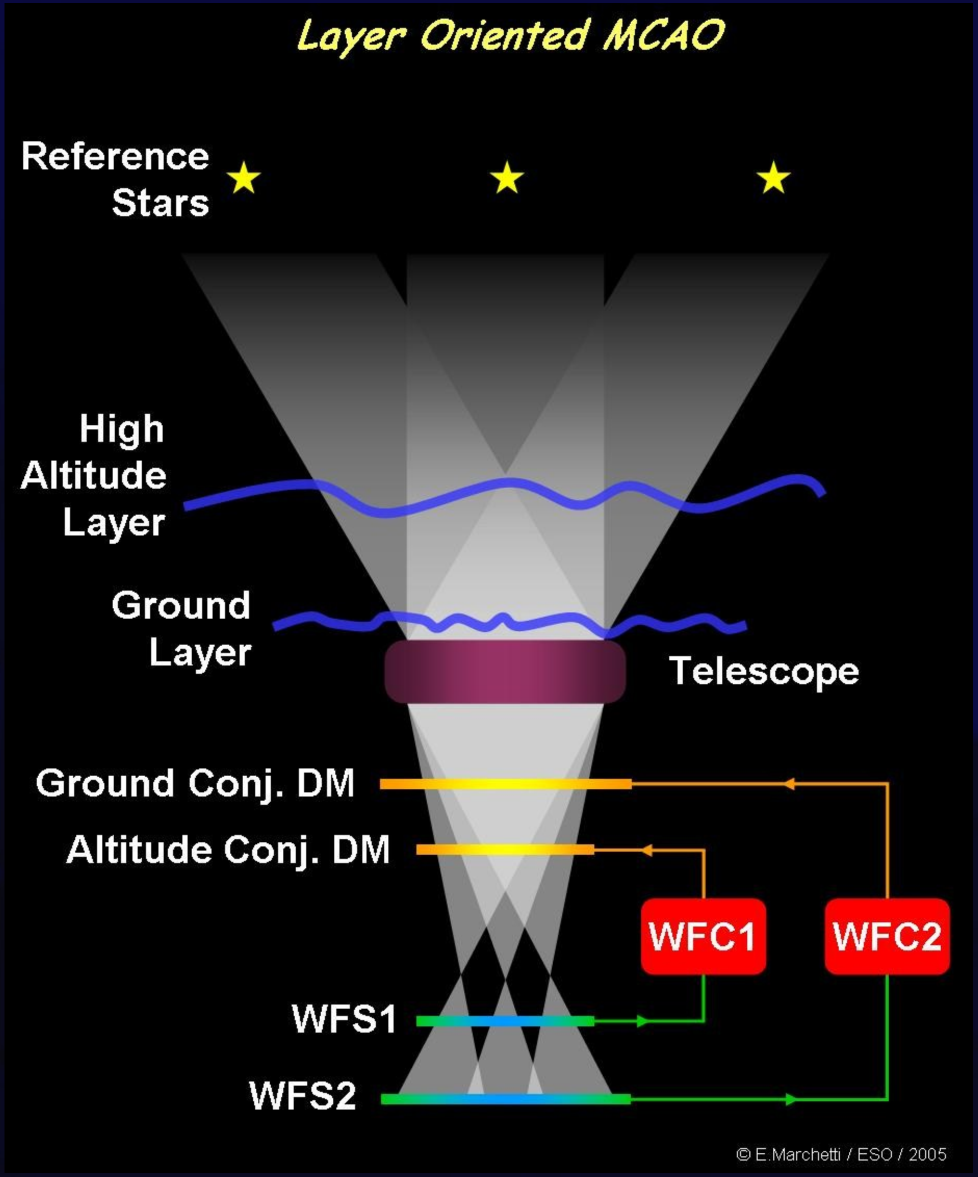
Multi-parametric space simulations



Star Oriented MCAO



Layer Oriented MCAO



Layer Oriented MCAO

- Optimal use of photons
  - $N_{ph} \propto$ Area(sub-ap) x T_{int}
    - Area(sub-ap) $\propto r_0^2$
    - $T_{int} \propto r_0$
    - $N_{ph} \propto r_0^3$
    - r_0(layer) > $r_{0,tot}$ (always!)
- Calibration independent from guide star location

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- 1999 – R.Ragazzoni, E.Marchetti & F.Rigaut proposed the modal tomography as efficient solution
- 2000 – R.Ragazzoni, E.Marchetti & G.Valente provided on sky open loop demonstration of tomography
- 1st January 2002 – MAD project launched

MCAO Demonstrator (MAD) in an nutshell

Probing atmospheric turbulence in 2 arcmin FoV

↓

Several (2…8) guide stars for wavefront sensing

↓

Correcting locally the turbulence: two DM at 0 and 8.5 km

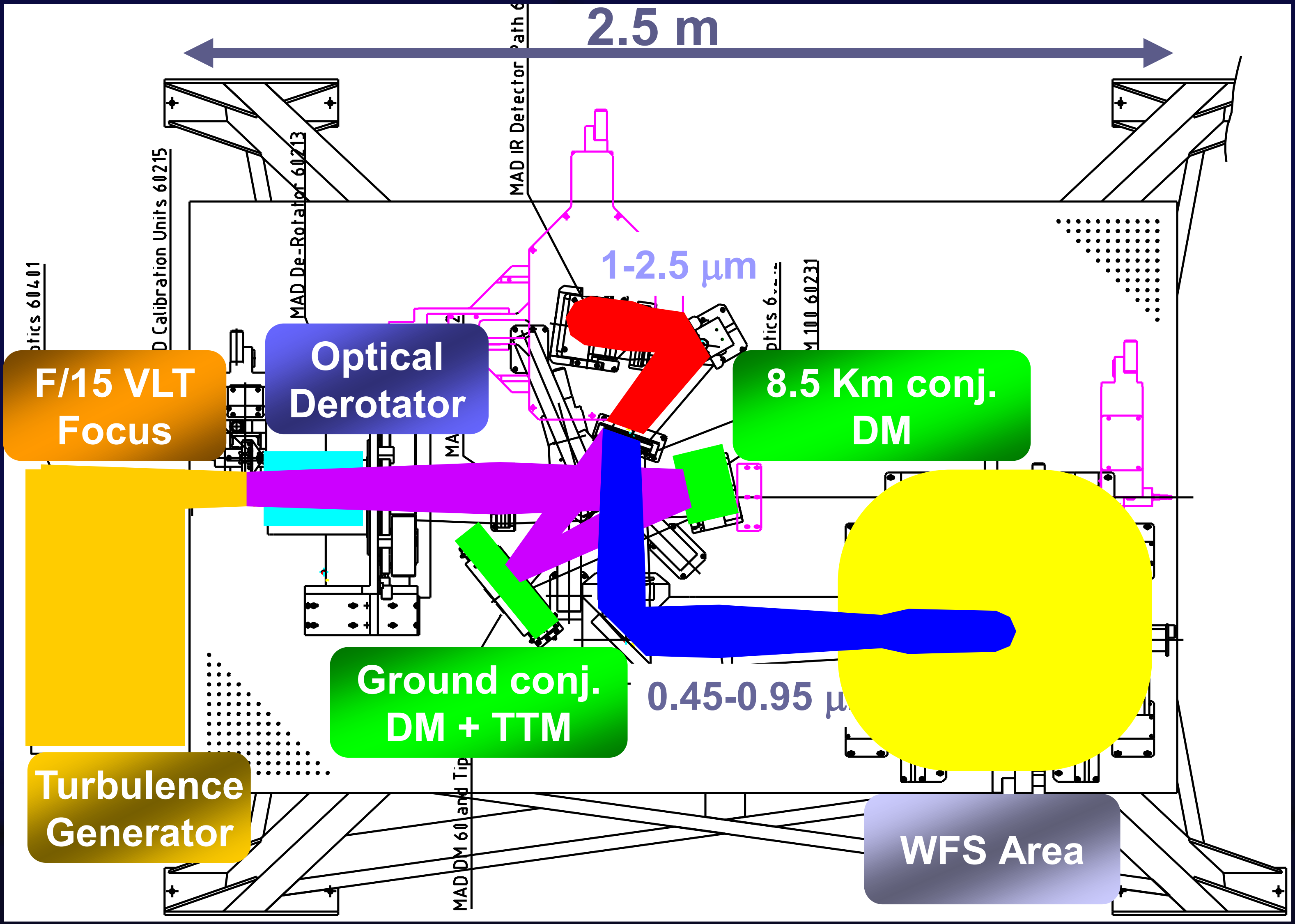
↓

Near Infrared imaging camera (1-2.5 μm)

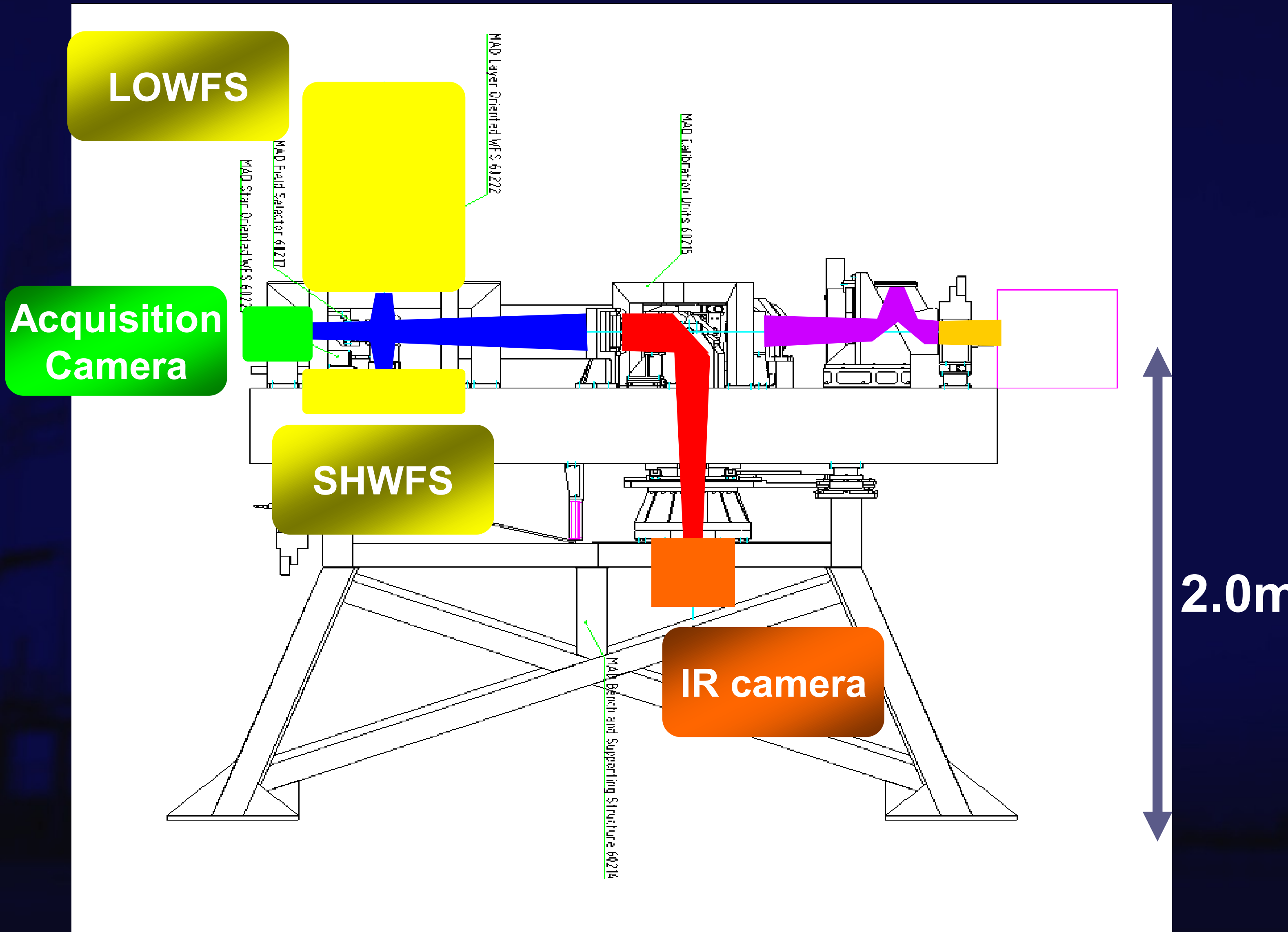
↓

Installed at the ESO's Very Large Telescope

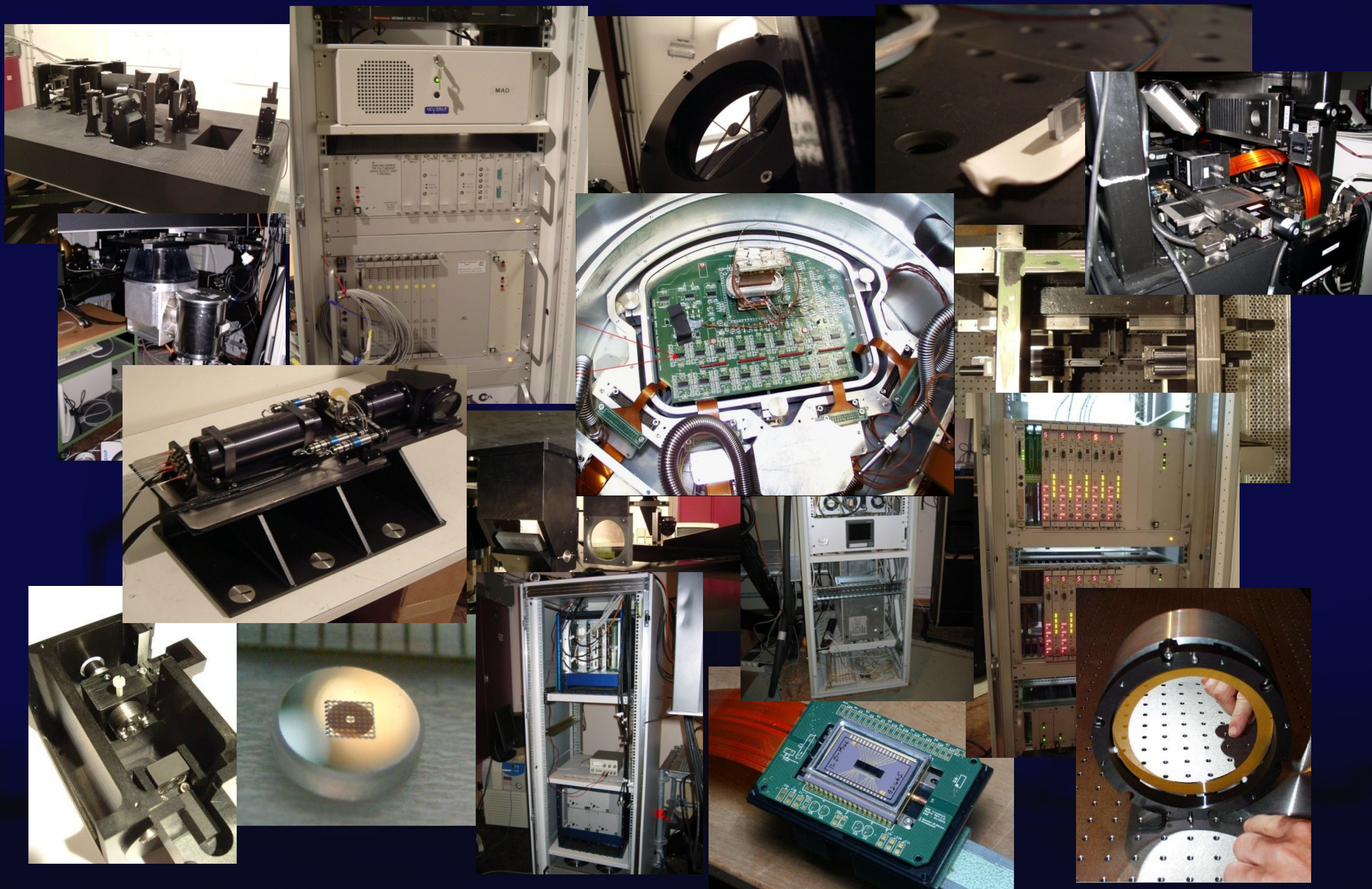
MCAO Demonstrator (MAD) in an nutshell



MCAO Demonstrator (MAD) in an nutshell



Designing & building MAD



Testing MAD in the laboratory

MCAO timeline

- 1988 – J.M.Beckers introduces the concept of MCAO
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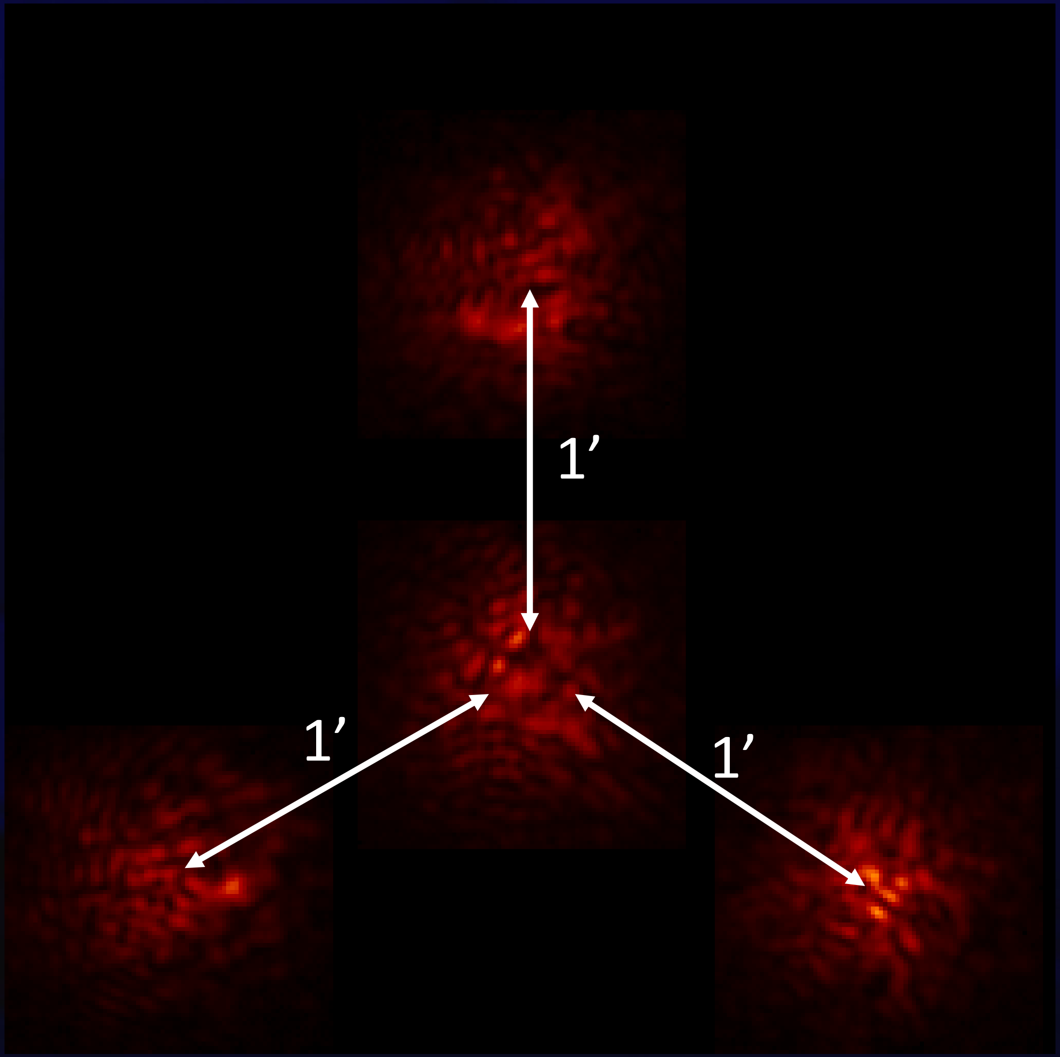
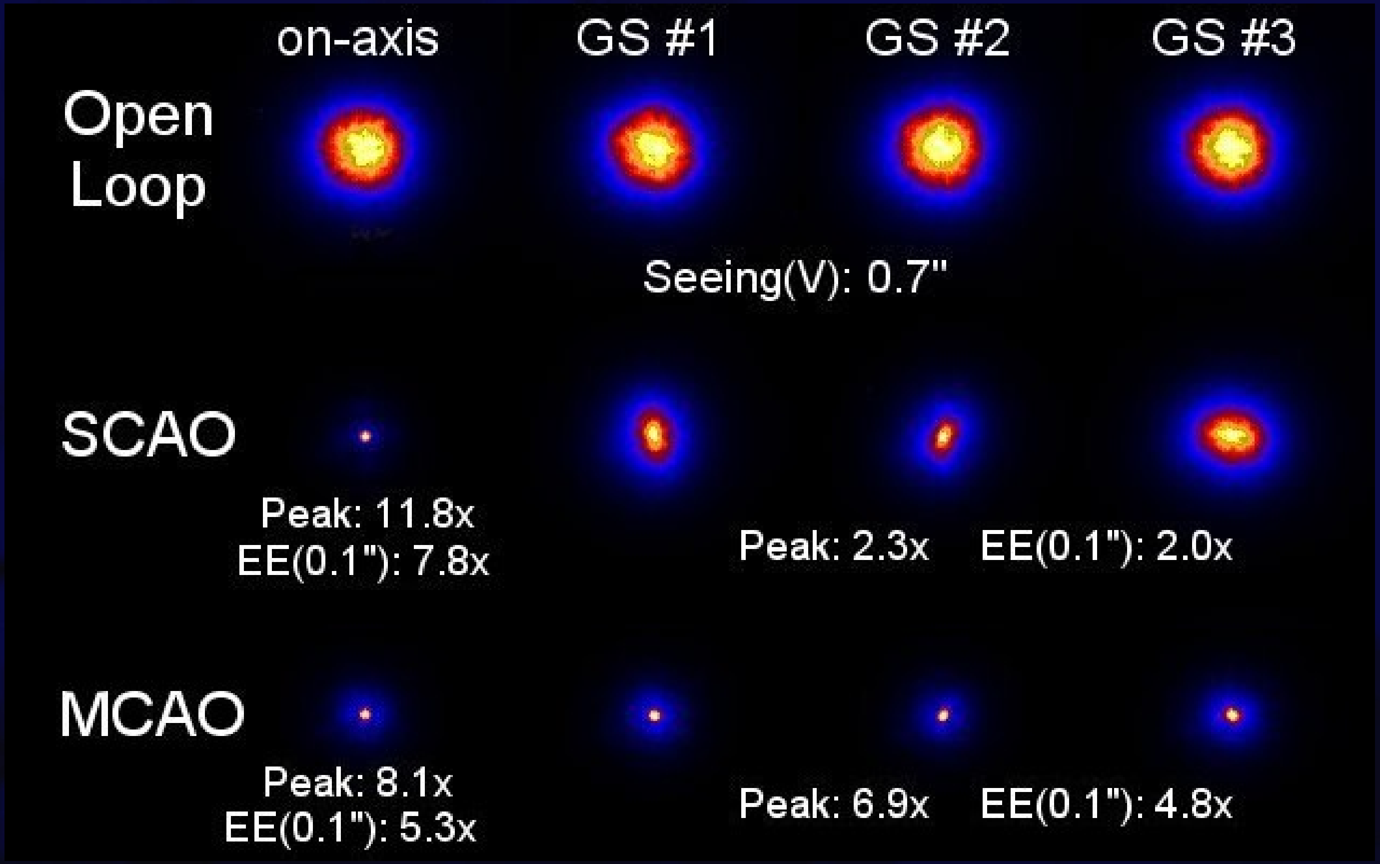
- 2000 – R.Ragazzoni, E.Marchetti & G.Valente provided on sky open loop demonstration of tomography
- 1st January 2002 – MAD project launched
- Early 2005 – MCAO closed loop at the German Solar Vacuum Tower Telescope (VTT)
- 25th October 2005 – MCAO closed loop with MAD in laboratory

MCAO close loop in the laboratory



MCAO close loop in the laboratory



From Munich to Paranal

MAD installation at Paranal

MAD @ Paranal

MCAO timeline

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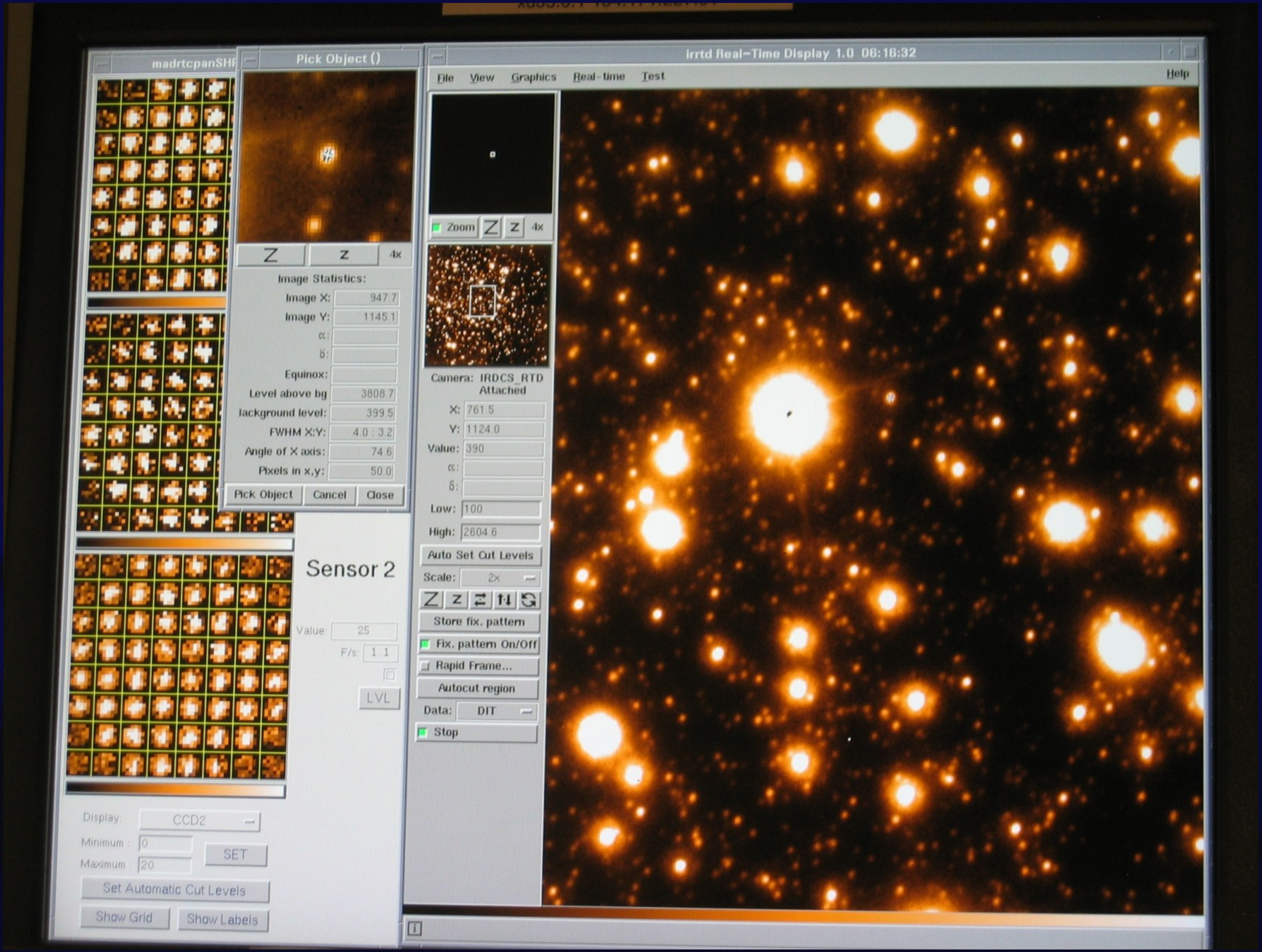
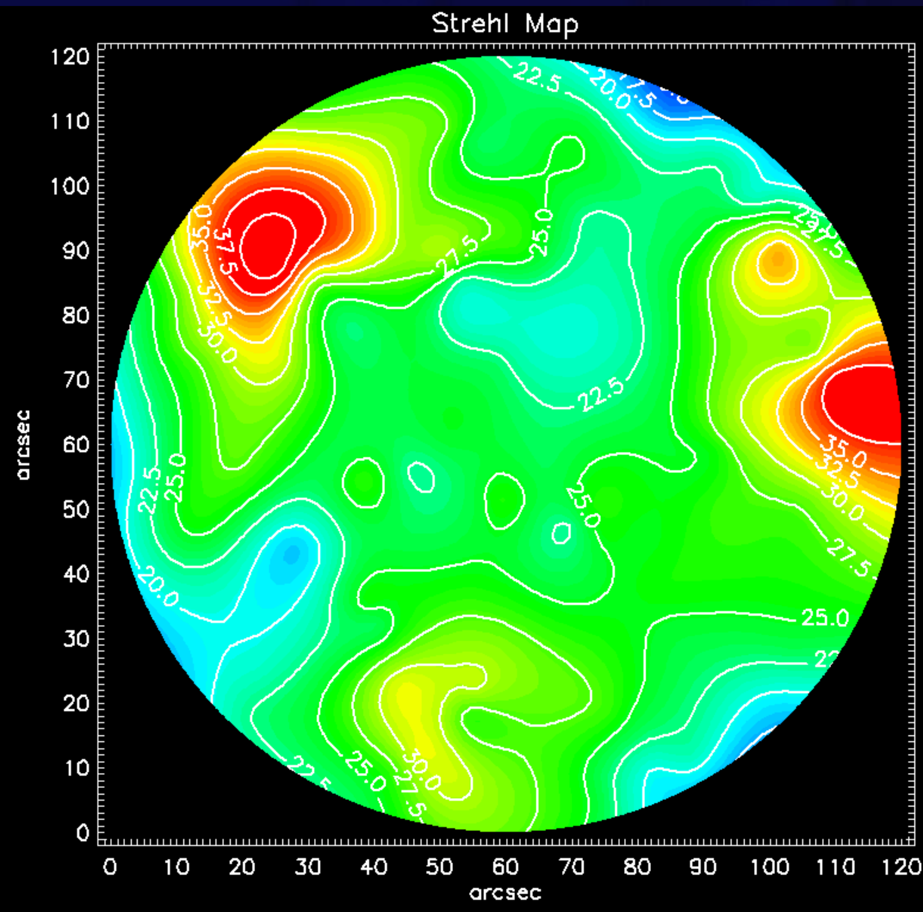
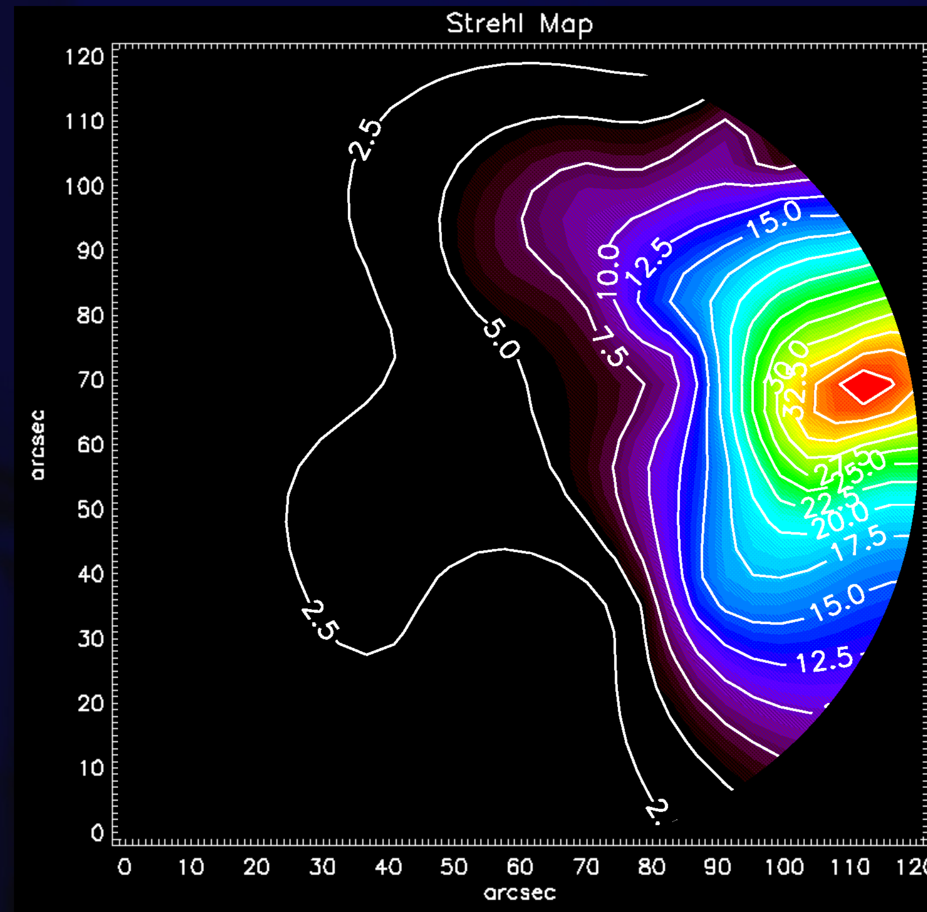
- 2000 – R.Ragazzoni, E.Marchetti & G.Valente provided on sky open loop demonstration of tomography
- 1st January 2002 – MAD project launched
- Early 2005(?) – MCAO closed loop at the German Solar Vacuum Tower Telescope (VTT)
- 25th October 2005 – MCAO closed loop with MAD in laboratory
- 25th March 2007 – MCAO closed loop with MAD on sky

Closing the loop



MCAO & Classical AO





> 20 referred papers

A&A 483, L5–L8 (2008)
DOI: 10.1051/0004-6361:200809631

Astronomy & Astrophysics

Letter to the Editor

Resolving stellar populations outside the Local Group: MAD observations of UKS 2323-326★

M. Gullieuszik[1], L. Greggio[1], E. V. Held[1], A. Moretti[1], C. Arcidiacono[1], P. Bagnara[1], A. Baruffolo[1], E. Diolaiti[2], R. Falomo[1], J. Farinato[1], M. Lombini[2], R. Ragazzoni[1], R. Brast[3], R. Donaldson[3], J. Kolb[3], E. Marchetti[3], and S. Tordo[3]

A&A 535, A63 (2011)
DOI: 10.1051/0004-6361/201016094

Astronomy & Astrophysics

MAD about the Large Magellanic Cloud★

Preparing for the era of Extremely Large Telescopes

G. Fiorentino[1,2], E. Tolstoy[1], E. Diolaiti[2], E. Valenti[3], M. Cignoni[2], and A. D. Mackey[4]

A&A 515, A26 (2010)
DOI: 10.1051/0004-6361/200913688

Astronomy & Astrophysics

A MAD view of Trumpler 14★,★★

H. Sana[1,2], Y. Momany[1,3], M. Gieles[1], G. Carraro[1], Y. Beletsky[1], V. D. Ivanov[1], G. De Silva[4], and G. James[4]

The Astrophysical Journal, 737:31 (9pp), 2011 August 10 doi:10.1088/0004-637X/737/1/31

A FOSSIL BULGE GLOBULAR CLUSTER REVEALED BY VERY LARGE TELESCOPE MULTI-CONJUGATE ADAPTIVE OPTICS*

Sergio Ortolani[1], Beatriz Barbuy[2], Yazan Momany[3,4], Ivo Saviane[3], Eduardo Bica[5], Lucie Jilkova[3,6], Gustavo M. Salerno[5], and Bruno Jungwiert[7,8]

The Astrophysical Journal Letters, 708:L74–L79, 2010 January 10 doi:10.1088/2041-8205/708/2/L74

ON A NEW NEAR-INFRARED METHOD TO ESTIMATE THE ABSOLUTE AGES OF STAR CLUSTERS: NGC 3201 AS A FIRST TEST CASE*

G. Bono[1,2], P. B. Stetson[3], D. A. VandenBerg[4], A. Calamida[5], M. Dall'Ora[6], G. Iannicola[2], P. Amico[5], A. Di Cecco[1], E. Marchetti[5], M. Monelli[7], N. Sanna[1], A. R. Walker[8], M. Zoccali[9], R. Buonanno[1,10], F. Caputo[2], C. E. Corsi[2], S. Degl'Innocenti[11,12], S. D'Odorico[5], I. Ferraro[2], R. Gilmozzi[5], J. Melnick[5], M. Nonino[13], S. Ortolani[14], A. M. Piersimoni[15], P. G. Prada Moroni[11,12], L. Pulone[2], M. Romaniello[5], and J. Storm[16]

Mon. Not. R. Astron. Soc. 418, 949–959 (2011) doi:10.1111/j.1365-2966.2011.19561.x

A benchmark for multiconjugated adaptive optics: VLT–MAD observations of the young massive cluster Trumpler 14★

B. Rochau,[1]† W. Brandner,[1] A. Stolte,[2] T. Henning,[1] N. Da Rio,[1,3] M. Gennaro,[1] F. Hormuth,[1] E. Marchetti[4] and P. Amico[4]

Mon. Not. R. Astron. Soc. 408, 731–751 (2010) doi:10.1111/j.1365-2966.2010.17167.x

The R136 star cluster hosts several stars whose individual masses greatly exceed the accepted 150 $M_\odot$ stellar mass limit

Paul A. Crowther,[1★] Olivier Schnurr,[1,2] Raphael Hirschi,[3,4] Norhasliza Yusof,[5] Richard J. Parker,[1] Simon P. Goodwin[1] and Hasan Abu Kassim[5]

Nature **462**, 483-486 (26 November 2009) | doi:10.1038/nature08581; Received 20 August 2009; Accepted 8 October 2009

The cluster Terzan 5 as a remnant of a primordial building block of the Galactic bulge

F. R. Ferraro[1], E. Dalessandro[1], A. Mucciarelli[1], G. Beccari[2], R. M. Rich[3], L. Origlia[4], B. Lanzoni[1], R. T. Rood[5], E. Valenti[6,7], M. Bellazzini[4], S. M. Ransom[8] & G. Cocozza[4]

Mon. Not. R. Astron. Soc. 391, 1650–1658 (2008) doi:10.1111/j.1365-2966.2008.14019.x

Multi-Conjugate Adaptive Optics VLT imaging of the distant old open cluster FSR 1415

Y. Momany,[1,2★] S. Ortolani,[3] C. Bonatto,[4] E. Bica[4] and B. Barbuy[5]

A&A 493, 539–546 (2009)
DOI: 10.1051/0004-6361:200810718

Astronomy & Astrophysics

Mon. Not. R. Astron. Soc. 405, 421–435 (2010) doi:10.1111/j.1365-2966.2010.16447.x

VLT-MAD observations of the core of 30 Doradus

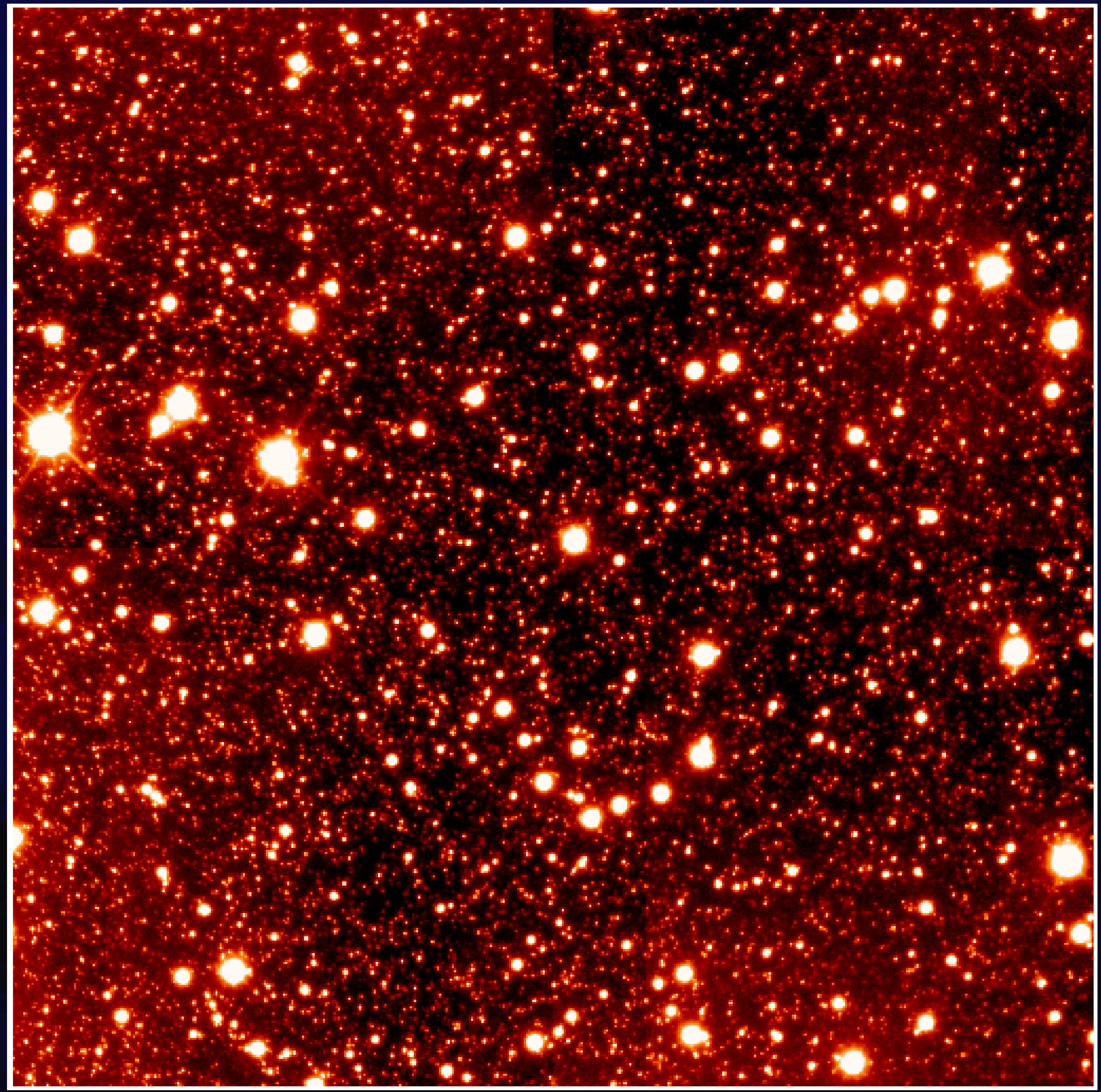
M. A. Campbell,[1★] C. J. Evans,[2,1] A. D. Mackey,[1] M. Gieles,[3] J. Alves,[4] J. Ascenso,[5] N. Bastian[6] and A. J. Longmore[2]

MCAO near-IR photometry of the globular cluster NGC 6388: MAD observations in crowded fields★

A. Moretti[1], G. Piotto[2], C. Arcidiacono[1], A. P. Milone[2], R. Ragazzoni[1], R. Falomo[1], J. Farinato[1], L. R. Bedin[3], J. Anderson[3], A. Sarajedini[4], A. Baruffolo[1], E. Diolaiti[5], M. Lombini[5], R. Brast[6], R. Donaldson[6], J. Kolb[6], E. Marchetti[6], and S. Tordo[6]

Omega Centauri

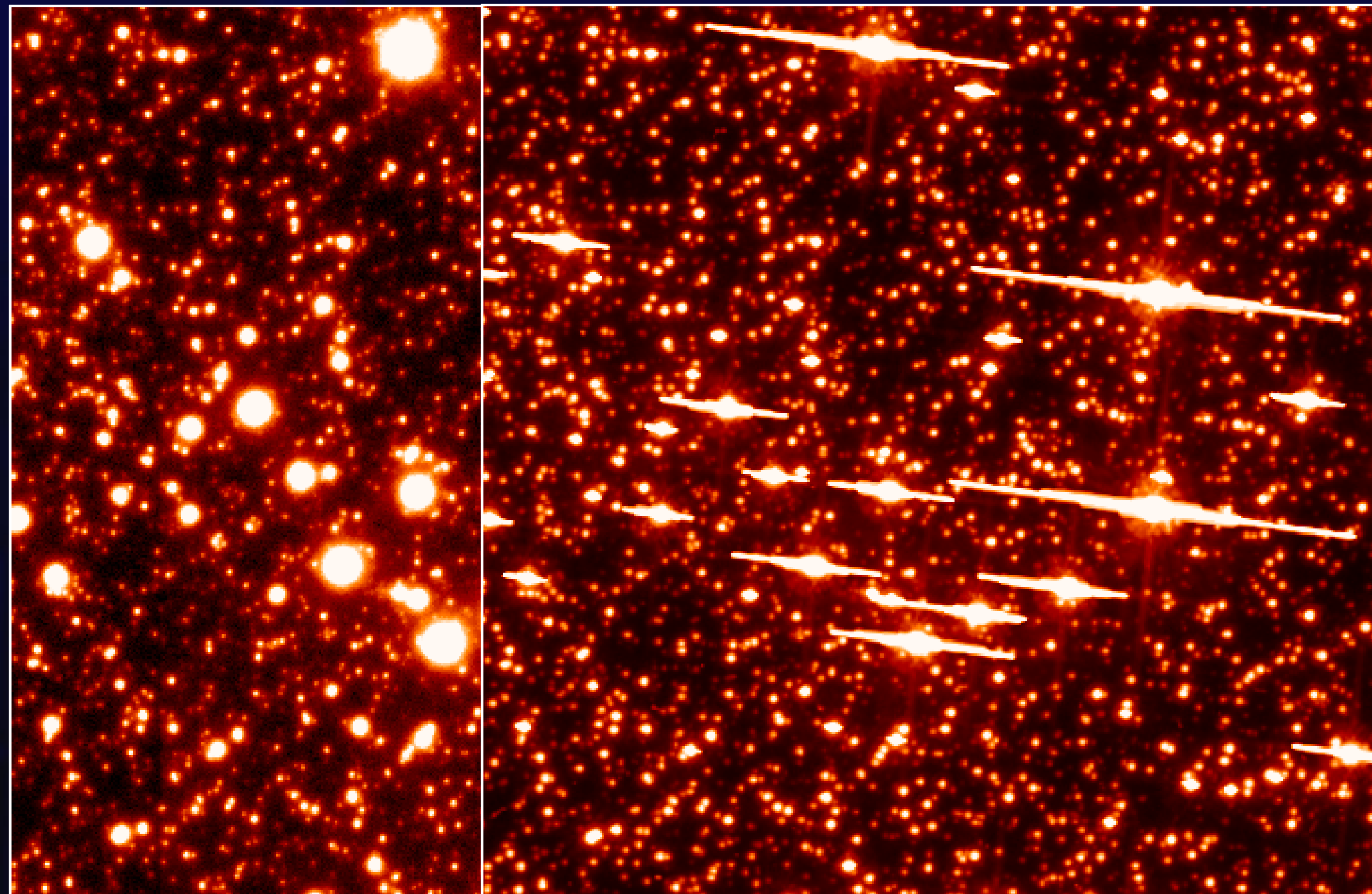
T_{exp}[Ks]: 600s
FWHM: 100mas
K~20.5
DIMM: 0.69”



1 arcmin

Omega Centauri

Guide stars @ 60” 20” x 20”



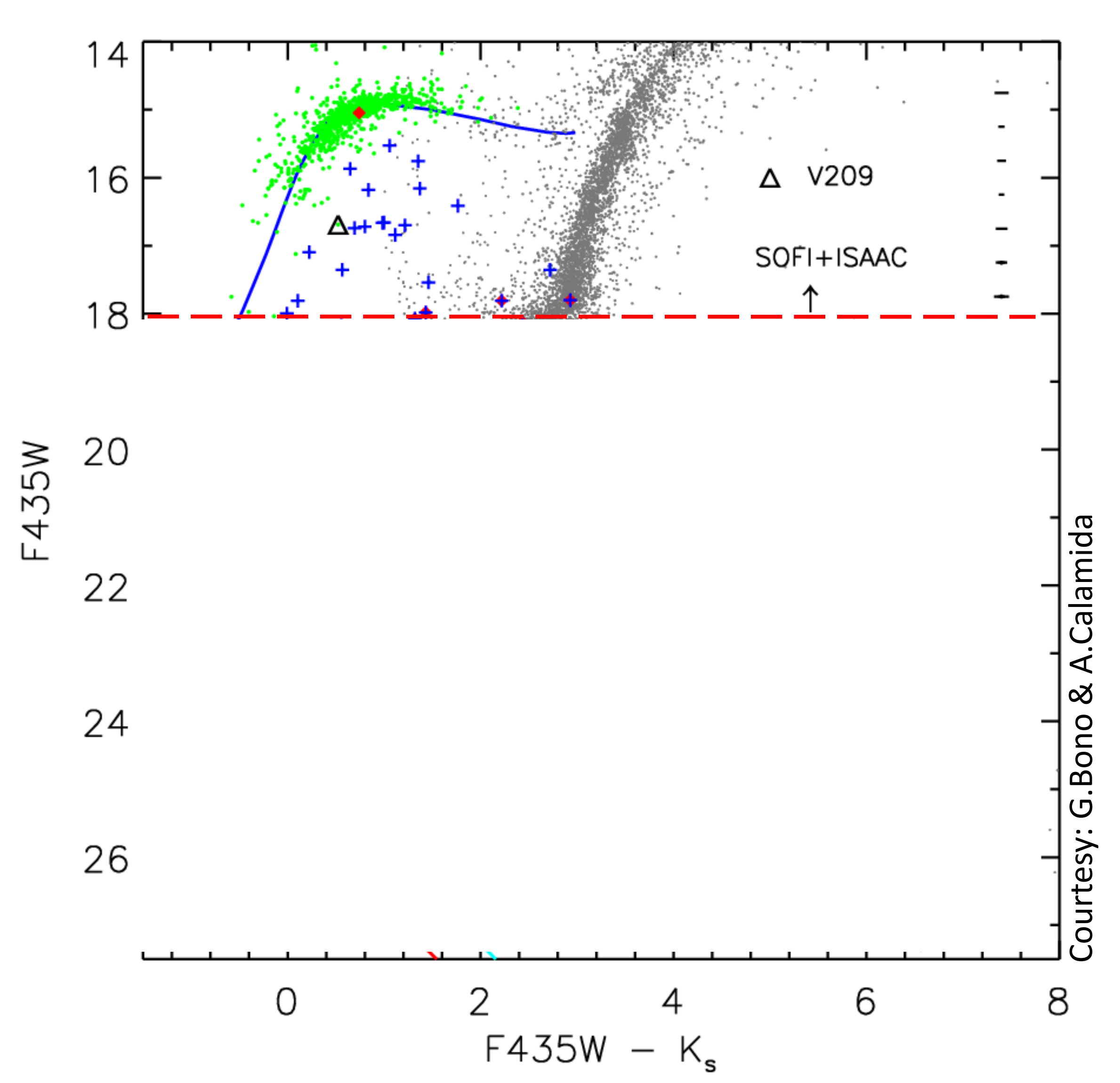
MAD [Ks] (0.028”/px) [illegible] [F435W] (0.050”/px)

FWHM: 100mas – T_{exp}: [illegible] 100mas – T_{exp}: 340s

Omega Centauri

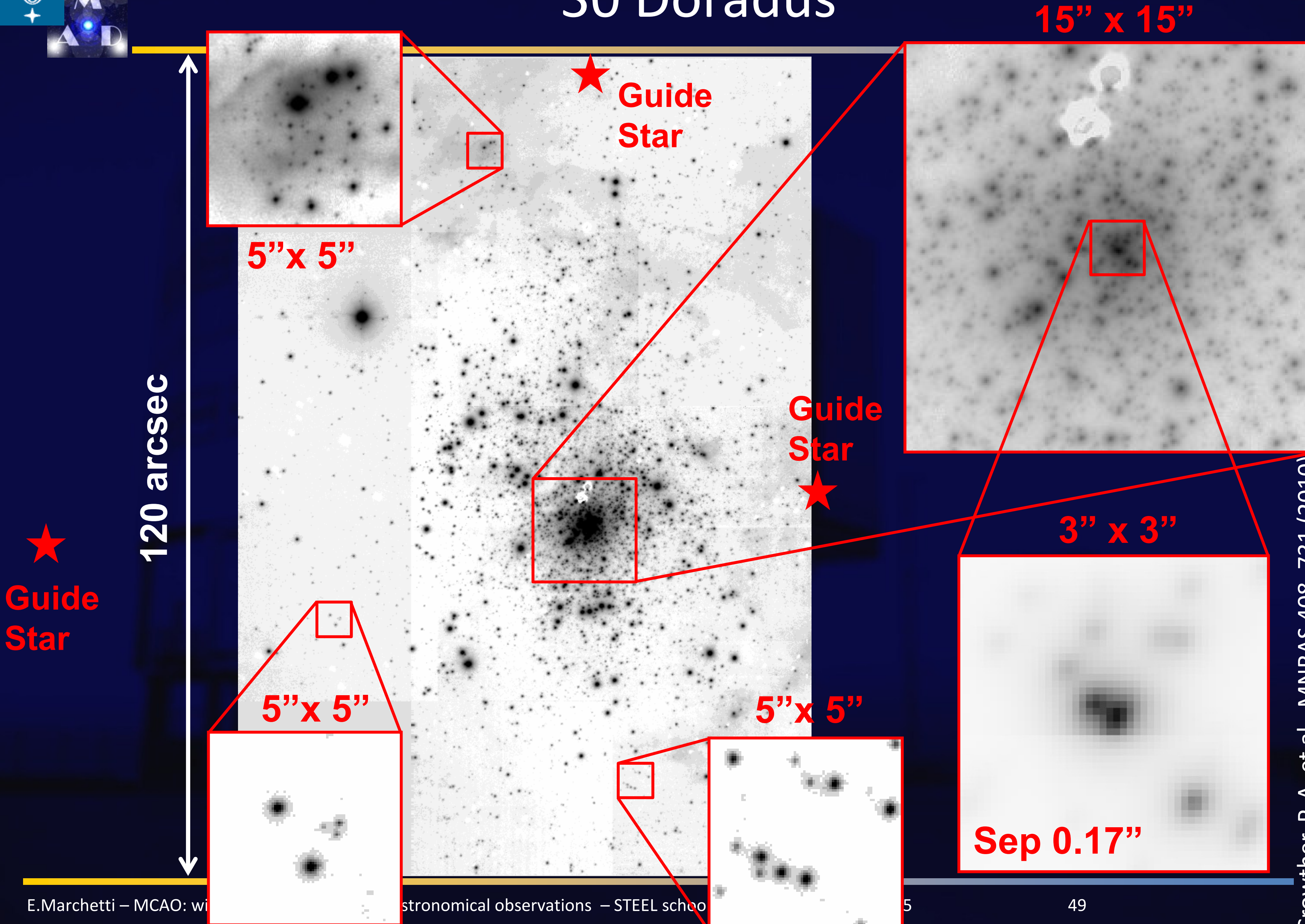
MAD completeness
w.r.t. HST/ACS
Ks: 90%

~10 WD detected in Ks
(first detection ever in GC)



Courtesy: G.Bono & A.Calamida

30 Doradus

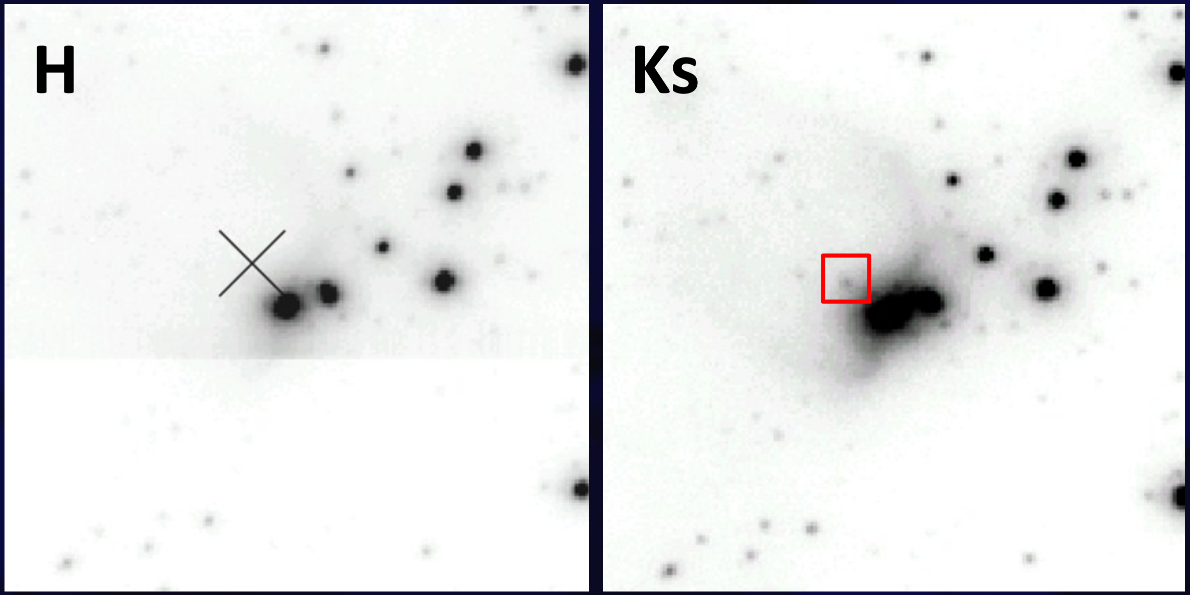


Crowther, P. A. et al., MNRAS 408, 731 (2010)

30 Doradus

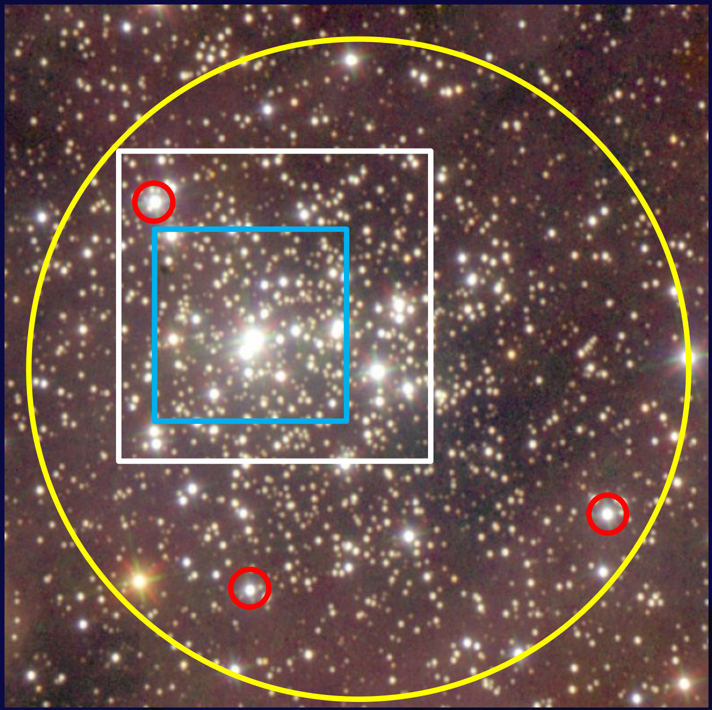
- Search for counterparts of Young Stellar Object (Spitzer)

YSO 053839.2 -690552.2



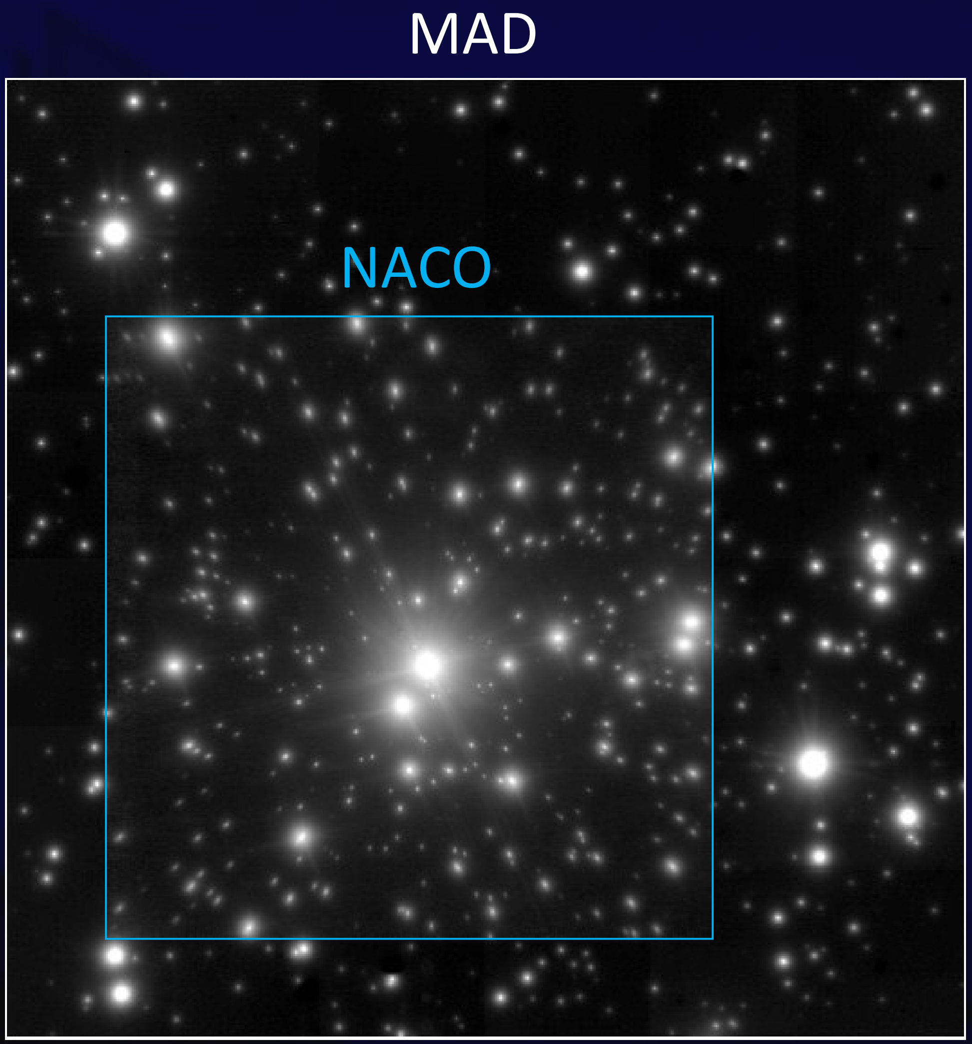
Campbell, M. A. et al., MNRAS 405, 421 (2010)

Trumpler 14



MAD [H] 0.028”/px
T_{epx}: 1680s
DIMM: 1.40”

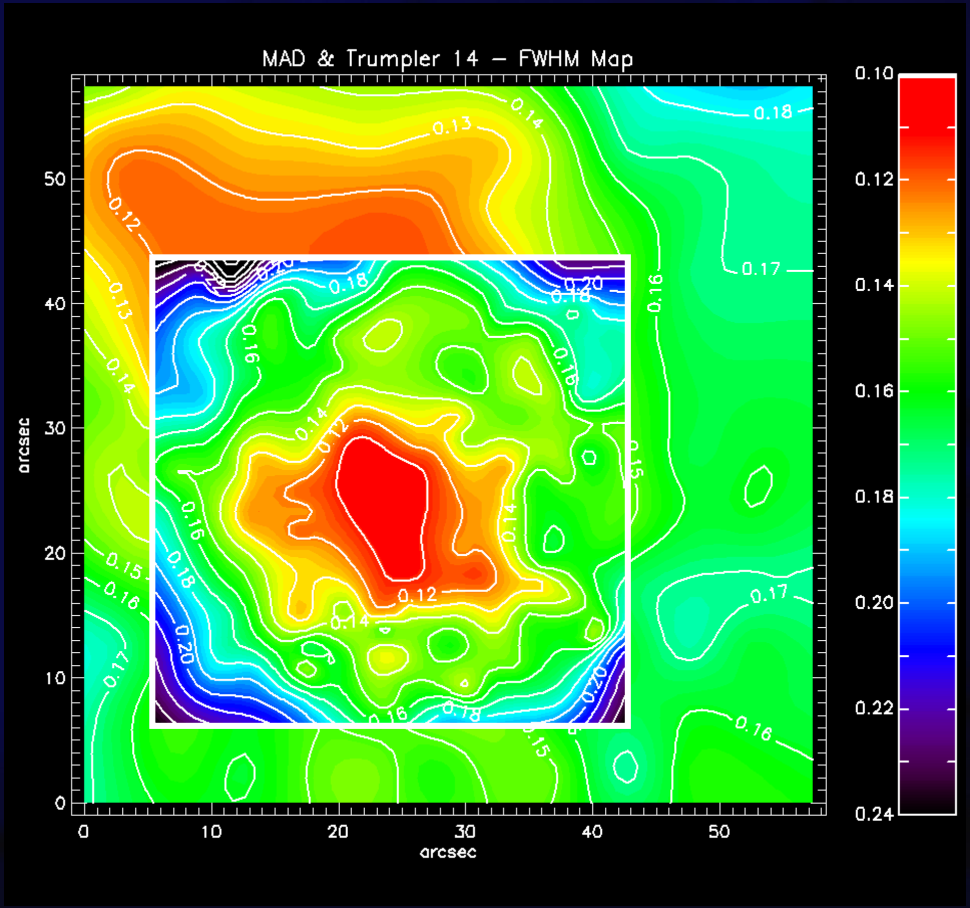
NACO [H] 0.054”/px
T_{exp}: 690s
DIMM: 0.85”

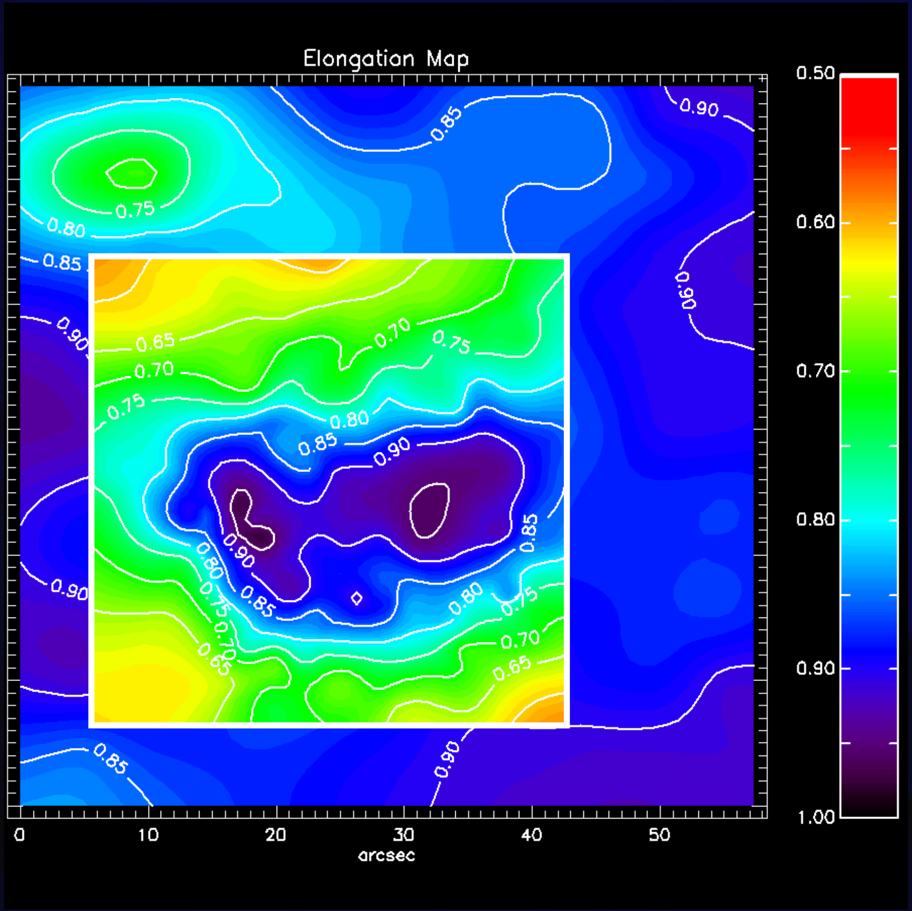


60” x 60”

Sana, H., A&A 515, A26 (2010)
Rochau, B. et al, MNRAS 418, 949 (2011)

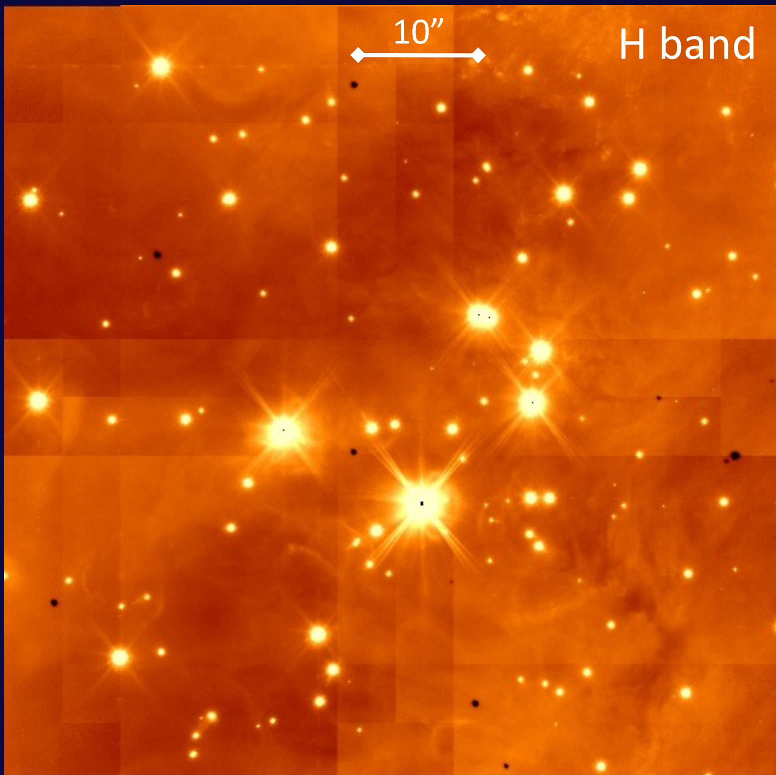
Trumpler 14

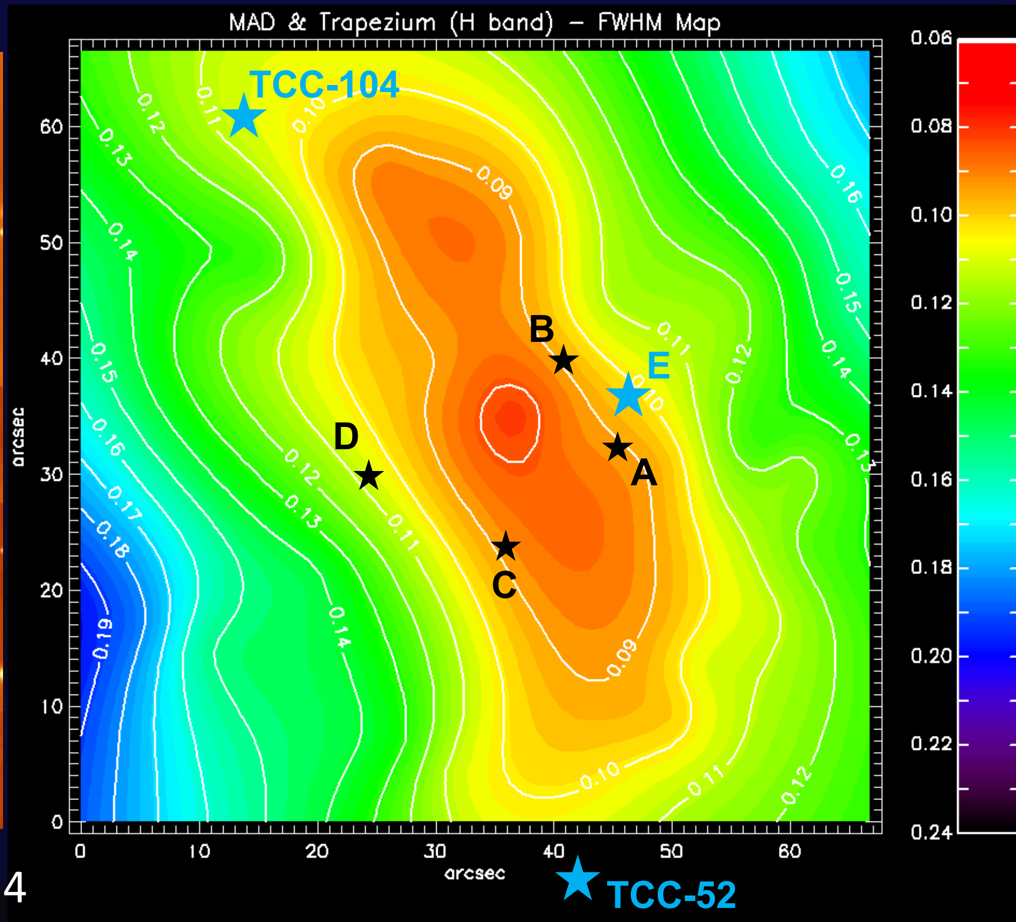

MAD & Trumpler 14 – FWHM Map
arcsec
arcsec


Elongation Map
arcsec

Orion's Trapezium

Courtesy: H.Bouy & M.Petr-Gotzens



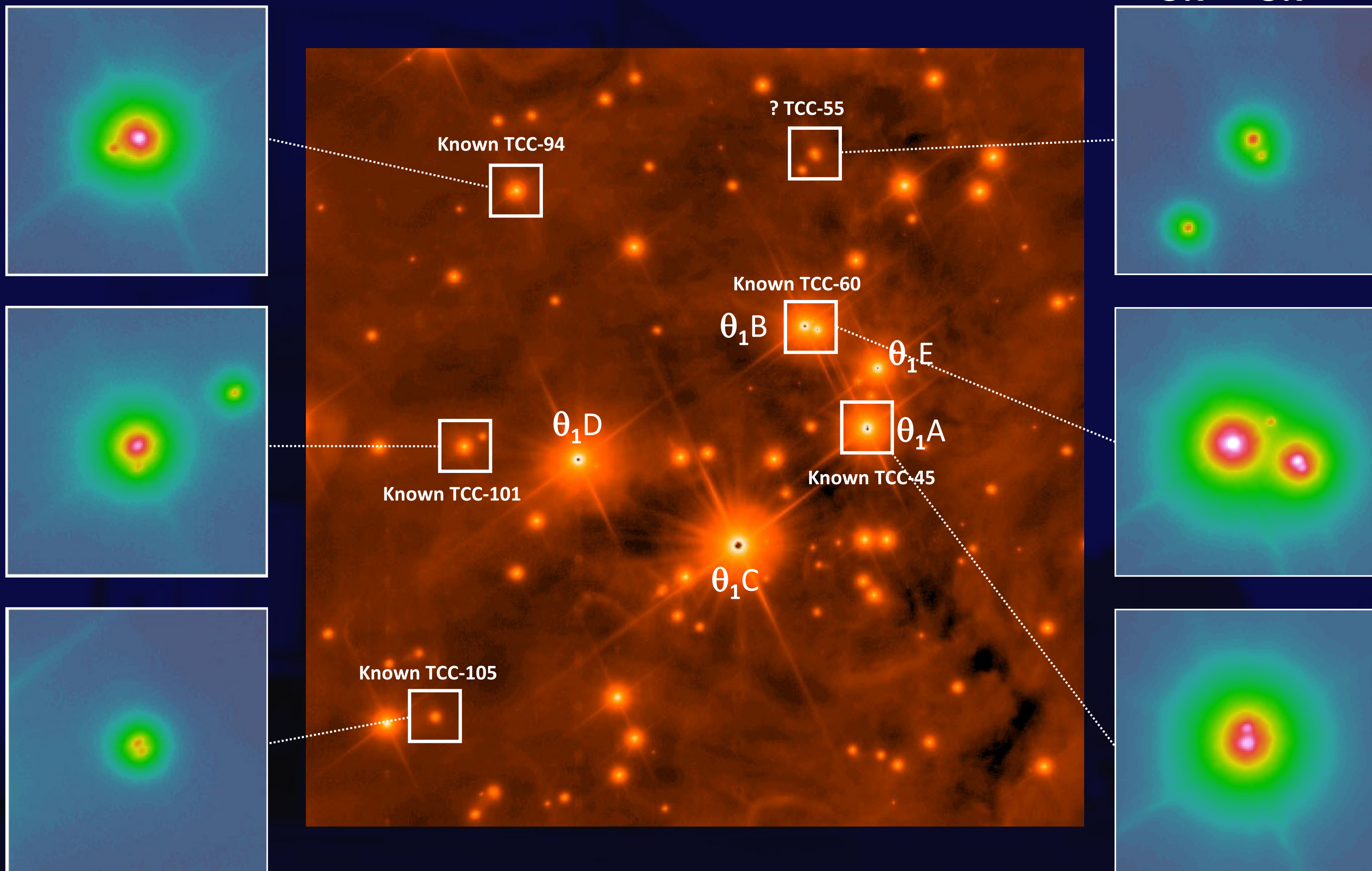


[Ks] T_{exp}: 720s, lim. magnitude (10s) 19.4
FWHM at center: 60mas, DIMM: 0.5"

[H] T_{exp}: 2400s, lim. Magnitude (10s): 20.5
FWHM at center: 75mas, DIMM: 0.5"

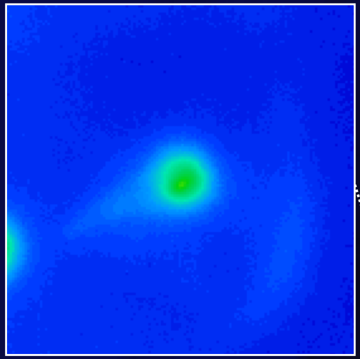
Trapezium Binaries

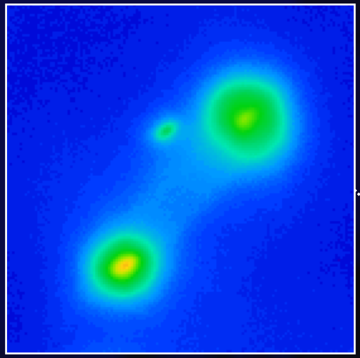
3.7"×3.7"

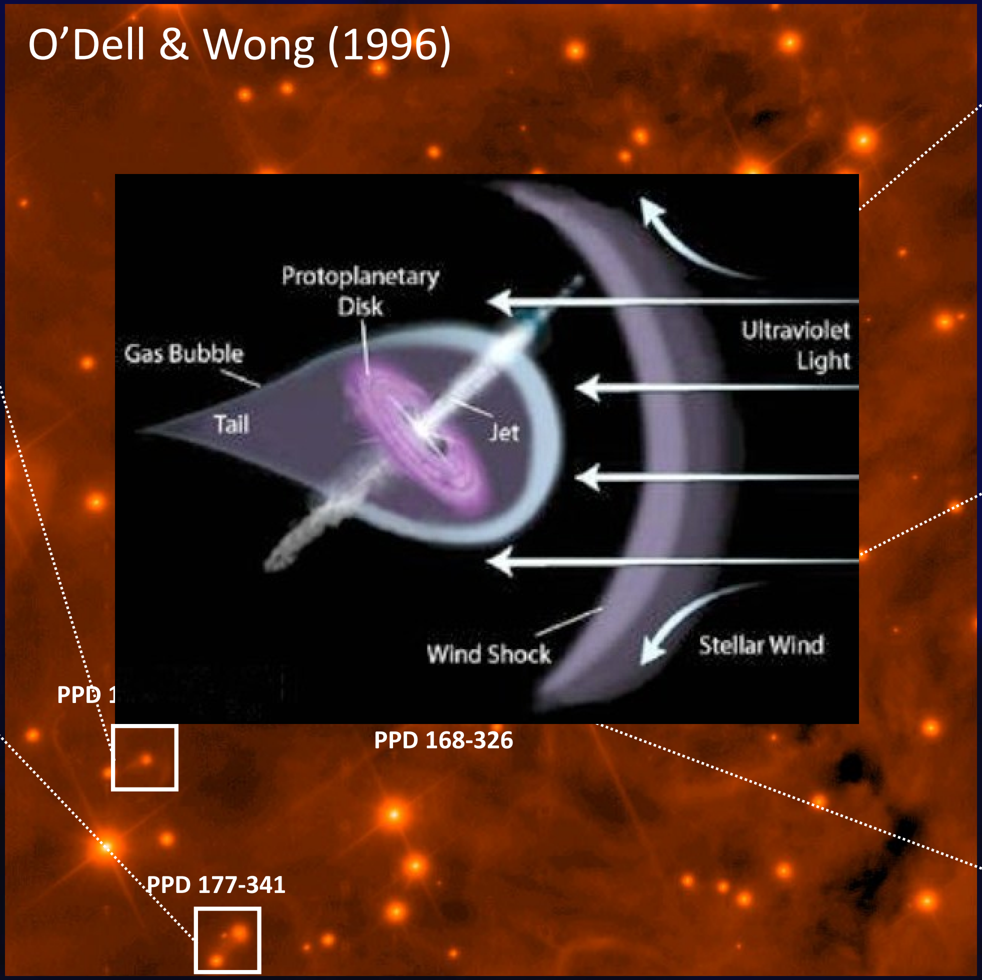


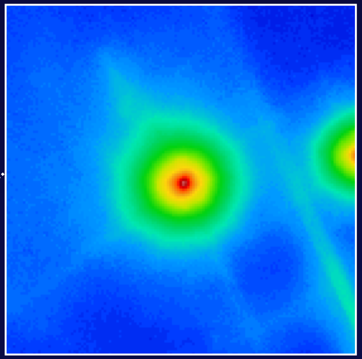
Trapezium Protoplanetary Disks

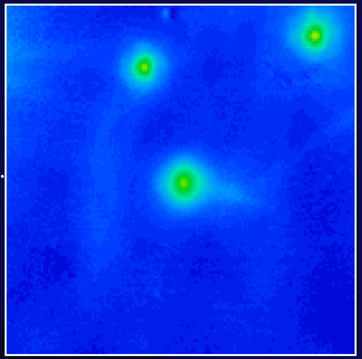
3.7”×3.7”

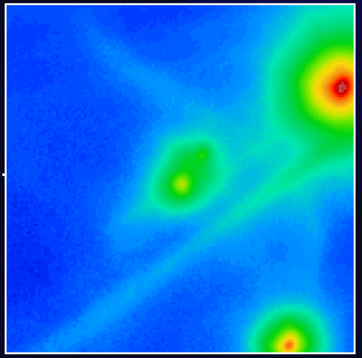




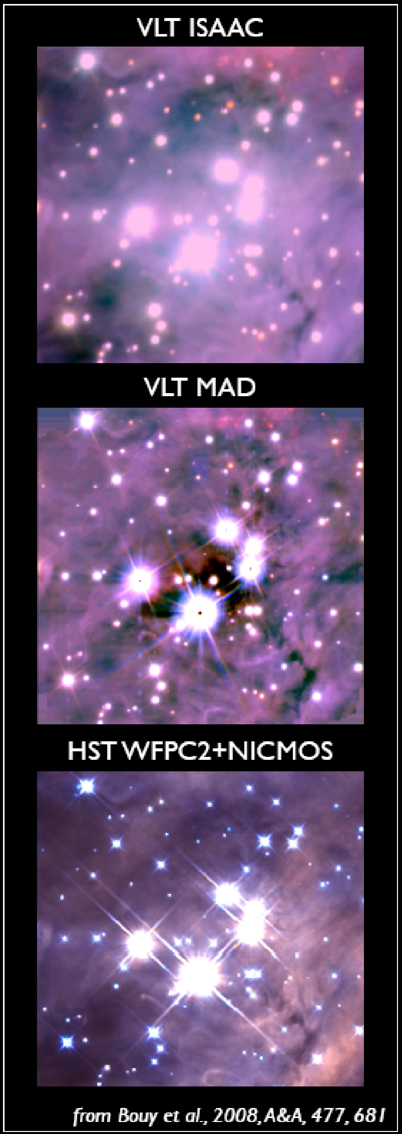


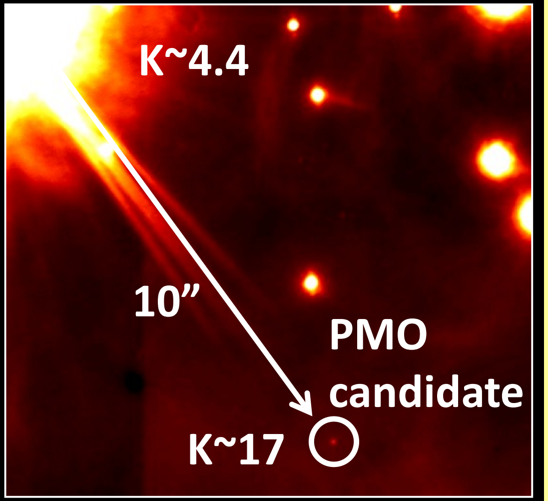


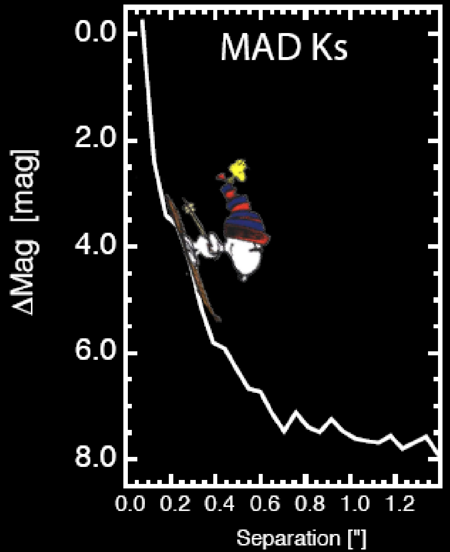


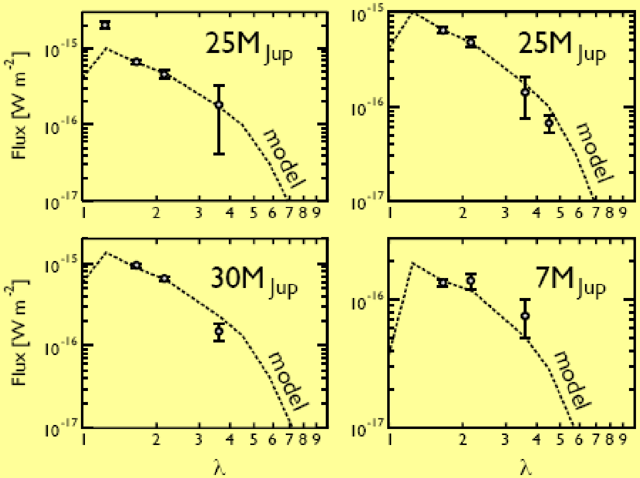


Trapezium Planetary Mass Objects

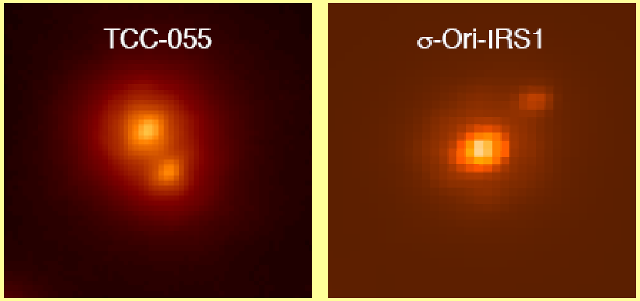








New Multiple Systems discovered with MAD

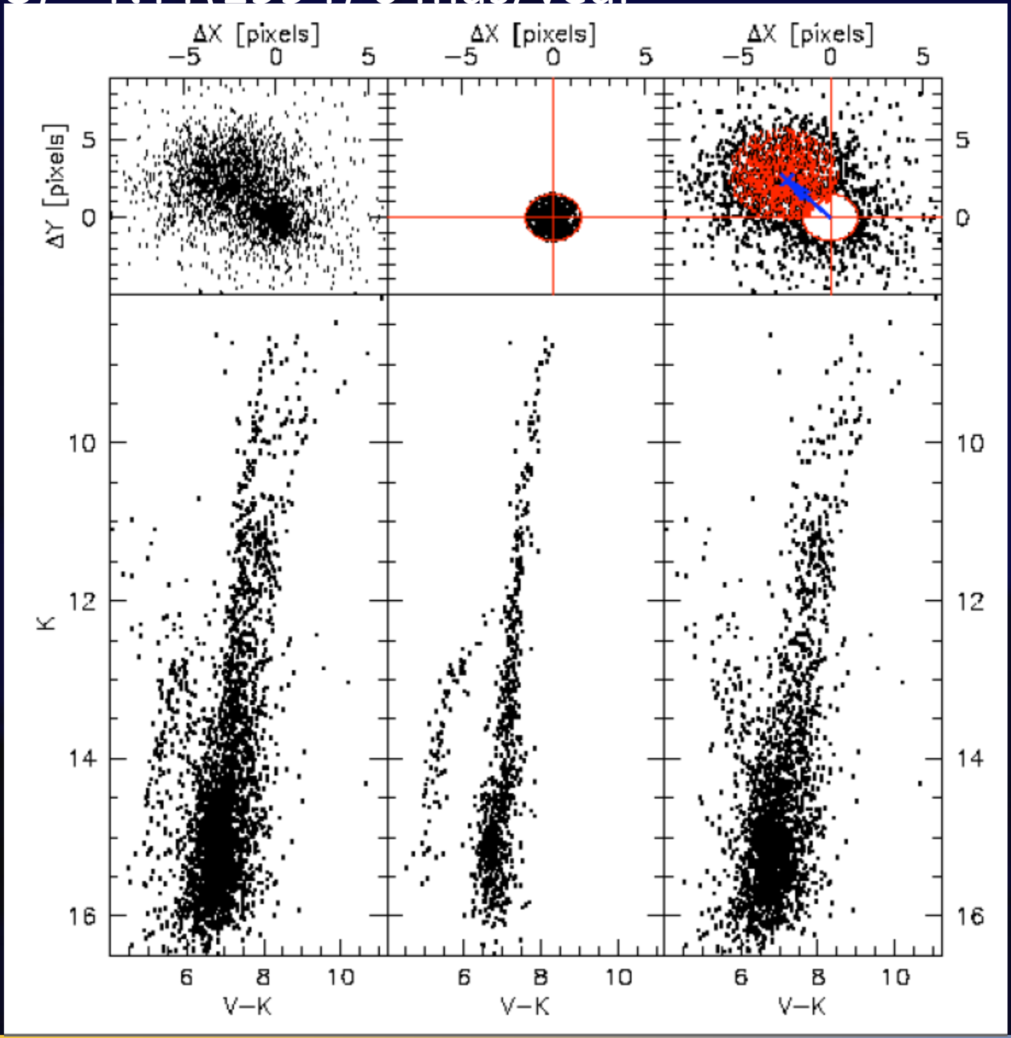


from Bouy et al., 2008, submitted to A&A and Bouy et al., 2008, A&A, 477, 681

Bouy, H. et al., A&A 477, 681 (2008)

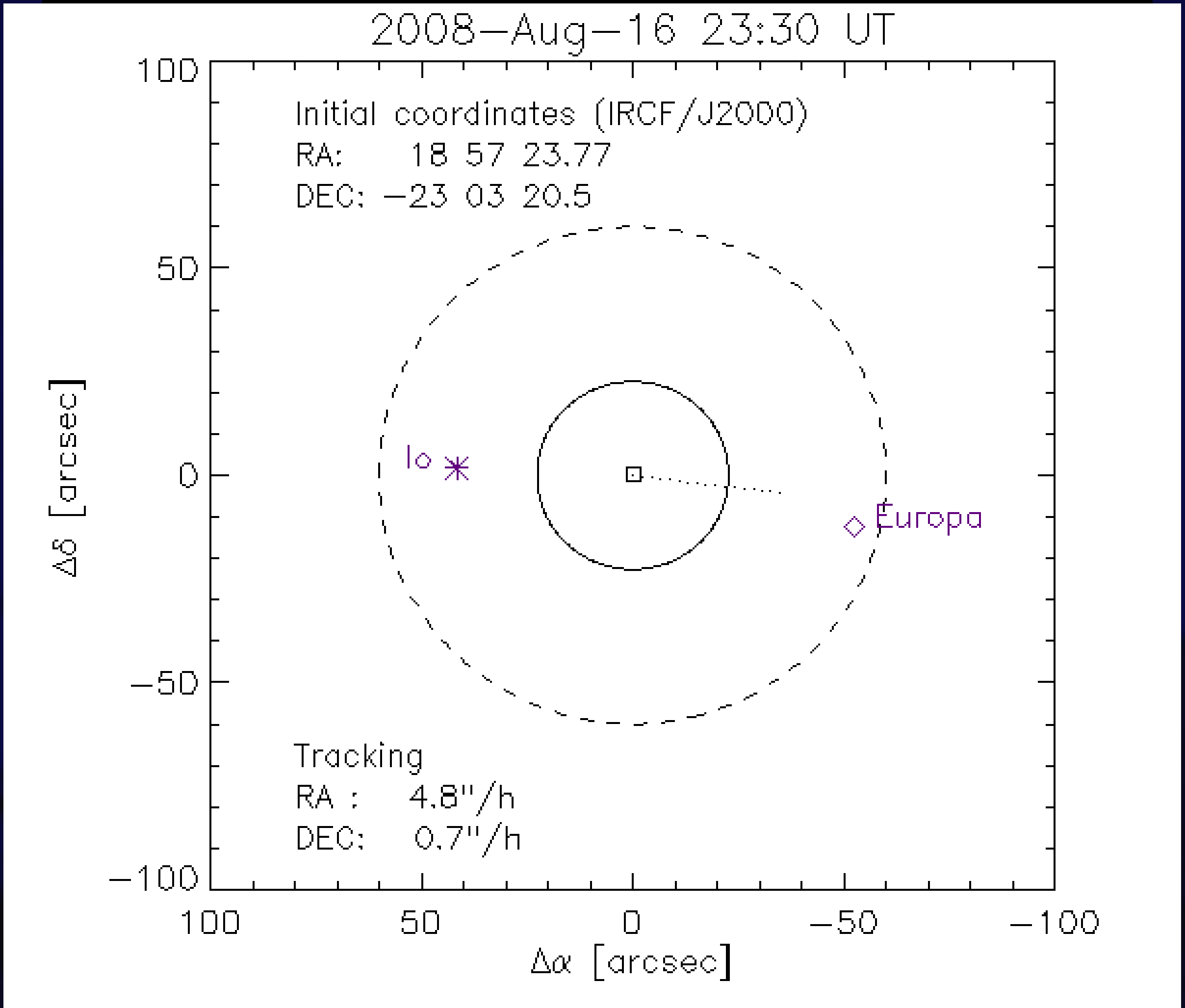
Astrometry with MAD

- Bulge globular cluster: HP1
- MAD(2008) – NTT(1994) 6 mas/year



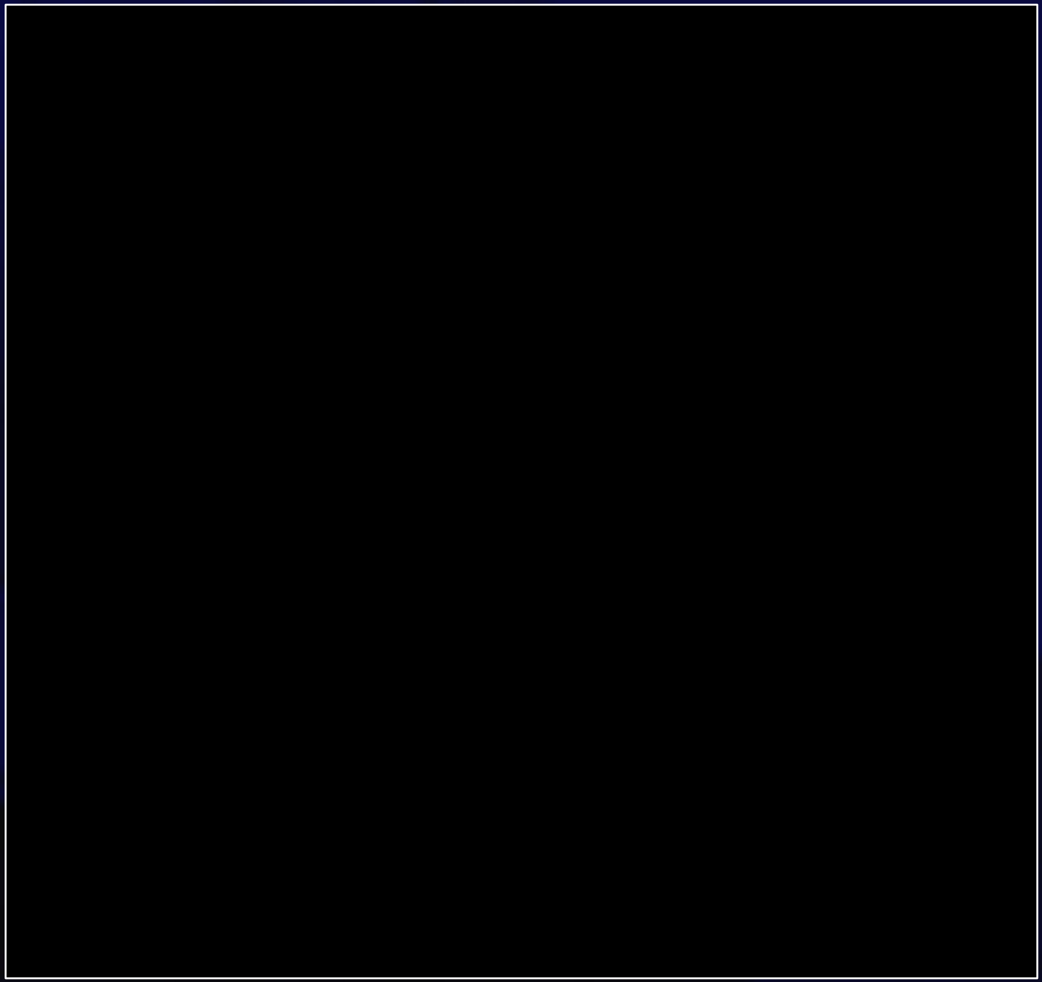
Ortolani, S. et al, ApJ 737, 31 (2011)

Jupiter



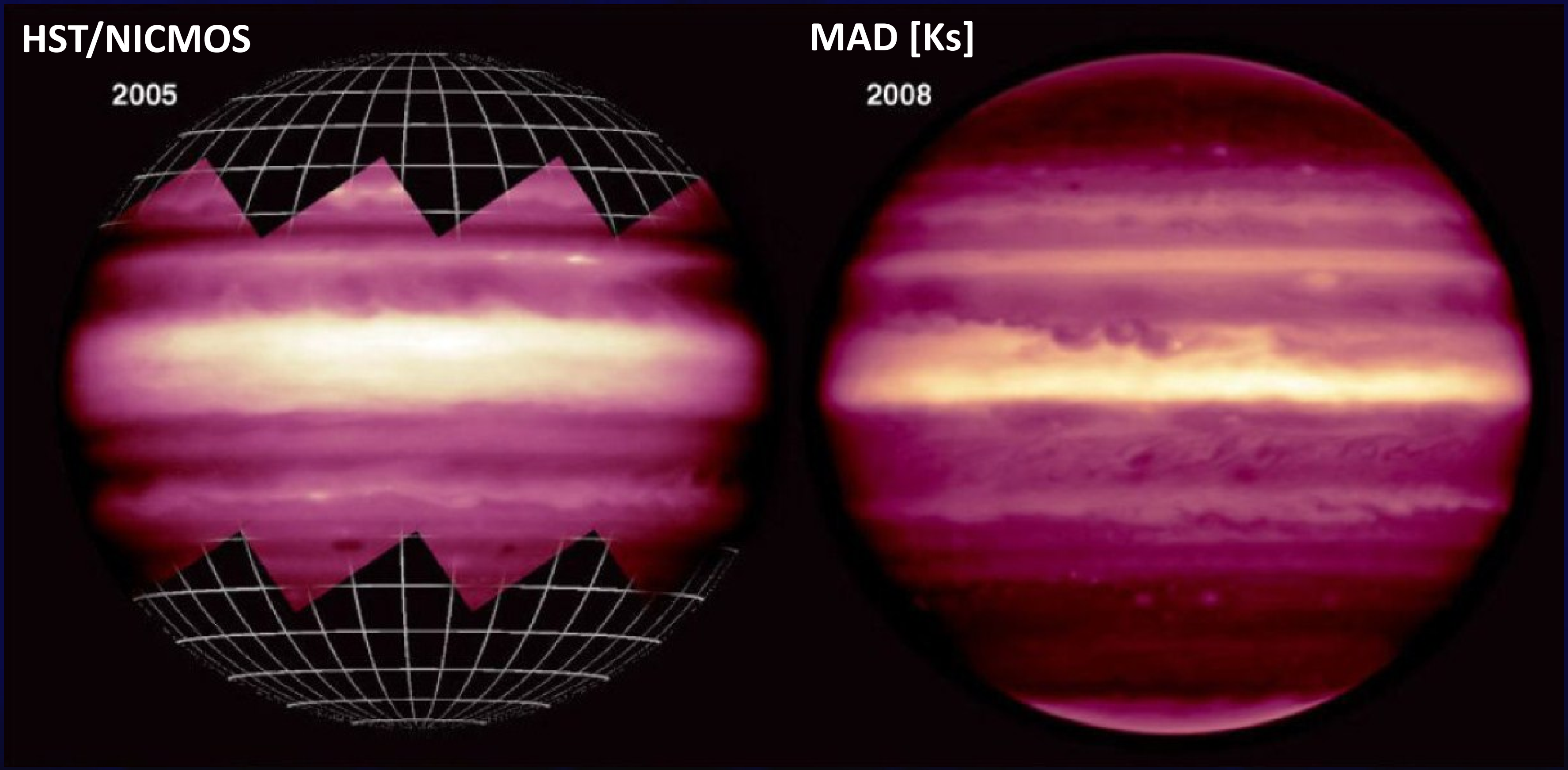
FWHM [Ks]: 90mas DIMM: 0.7" – 1.0"

Jupiter



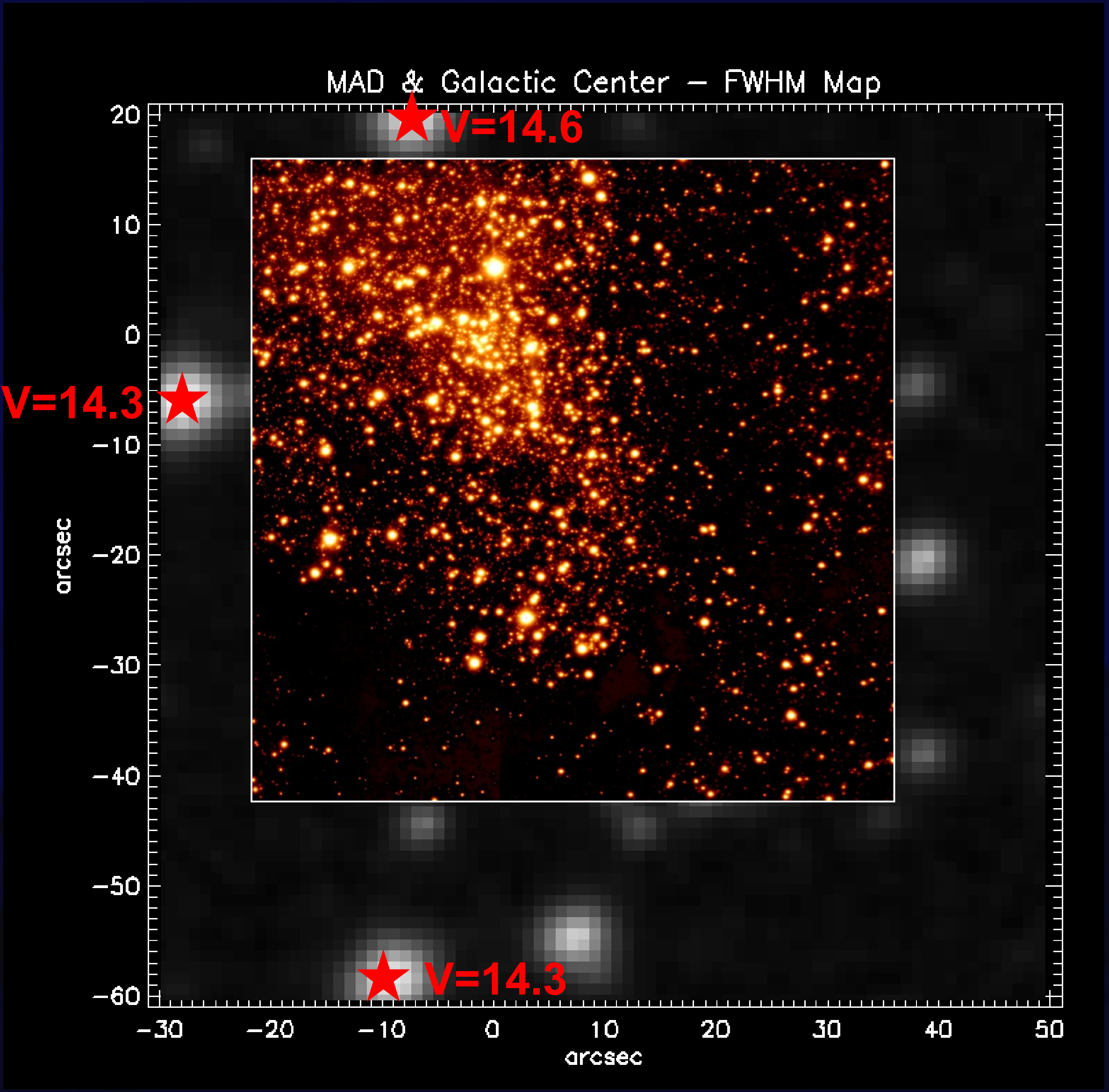
Jupiter

- Change in the equatorial haze due to planet-wide upheaval



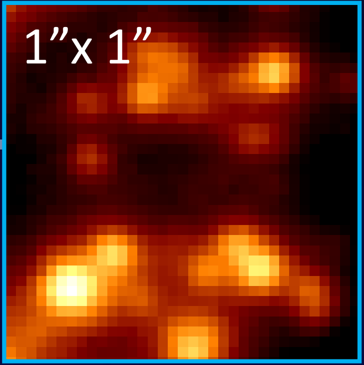
M.Wong et al., DPS 2008

Galactic Center

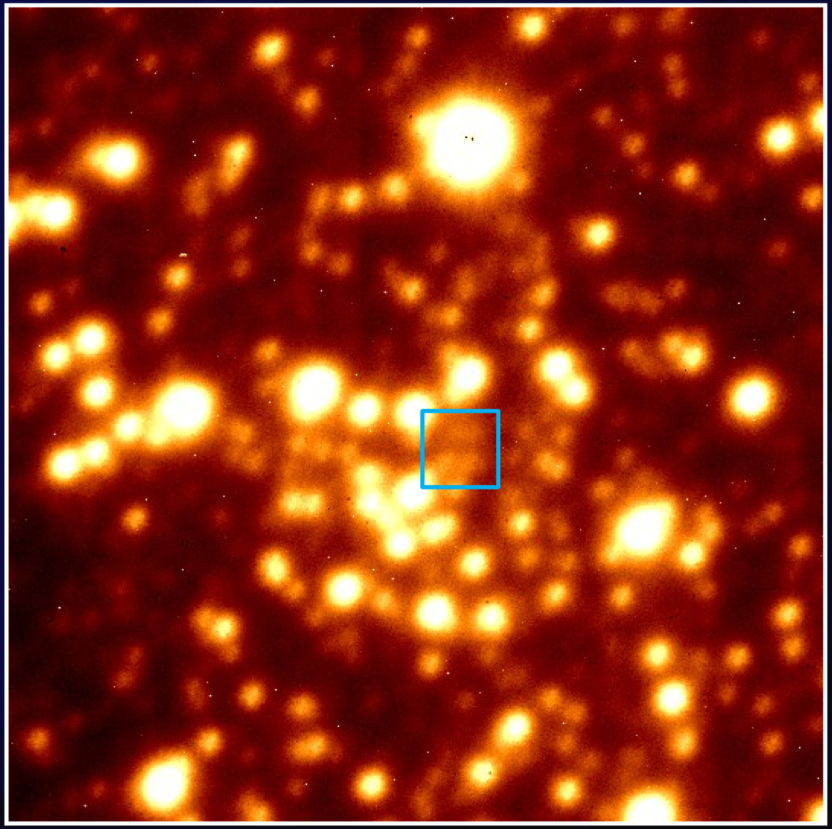


T_{exp}[Ks]: 50s
DIMM: 0.6"

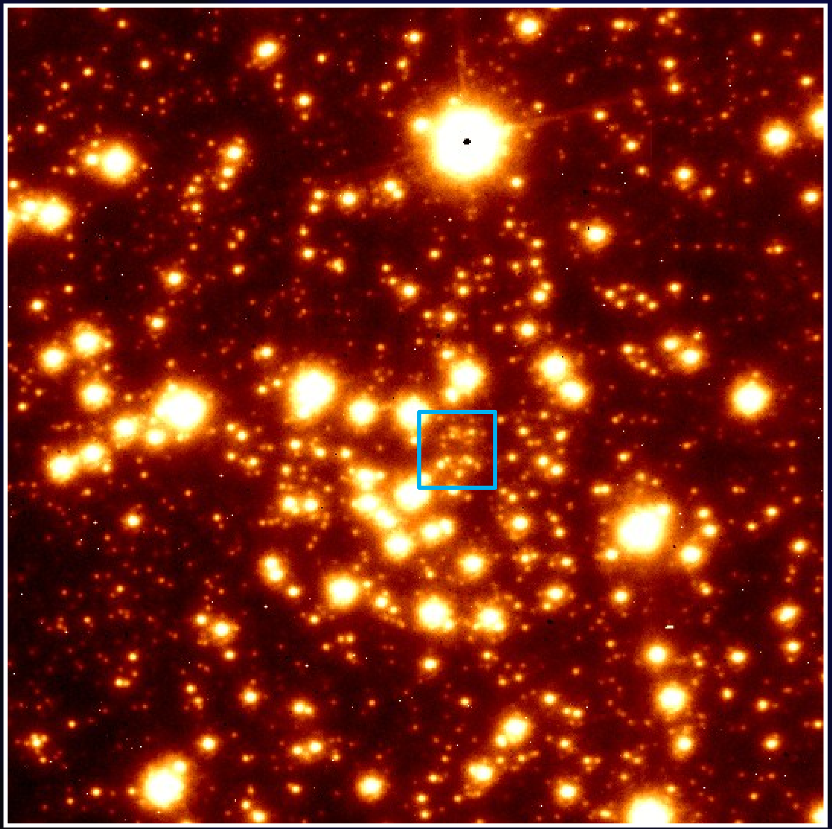
Galactic Center



T_{exp}[Ks]: 10s,   FoV: 15” x 15”,   DIMM: 0.6”

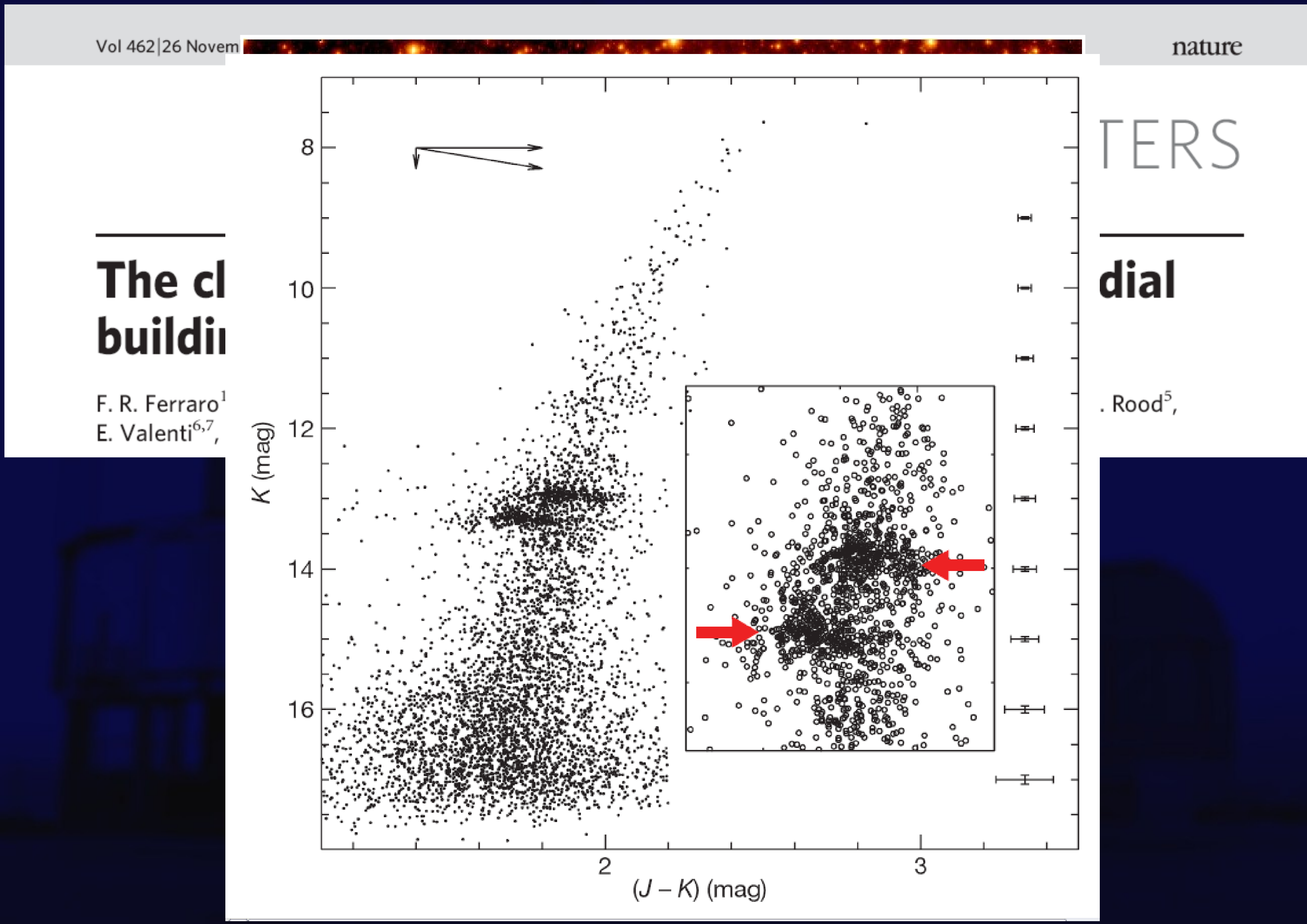


Open Loop



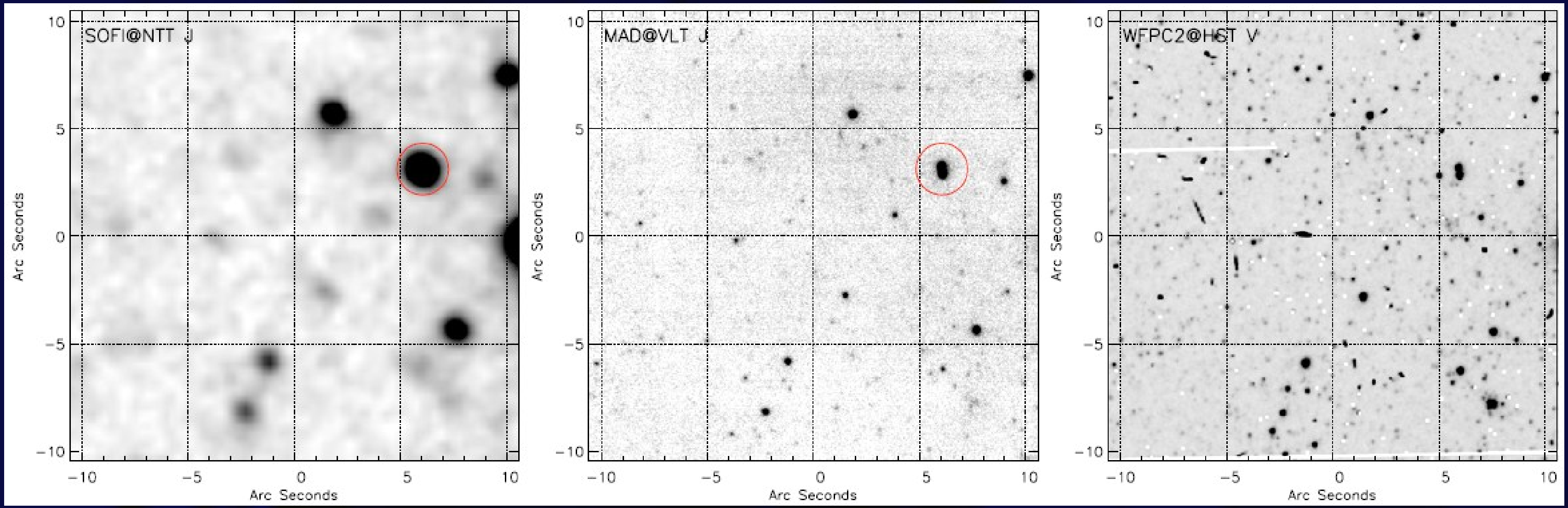
Closed Loop

MAD on Nature



Honorable mention

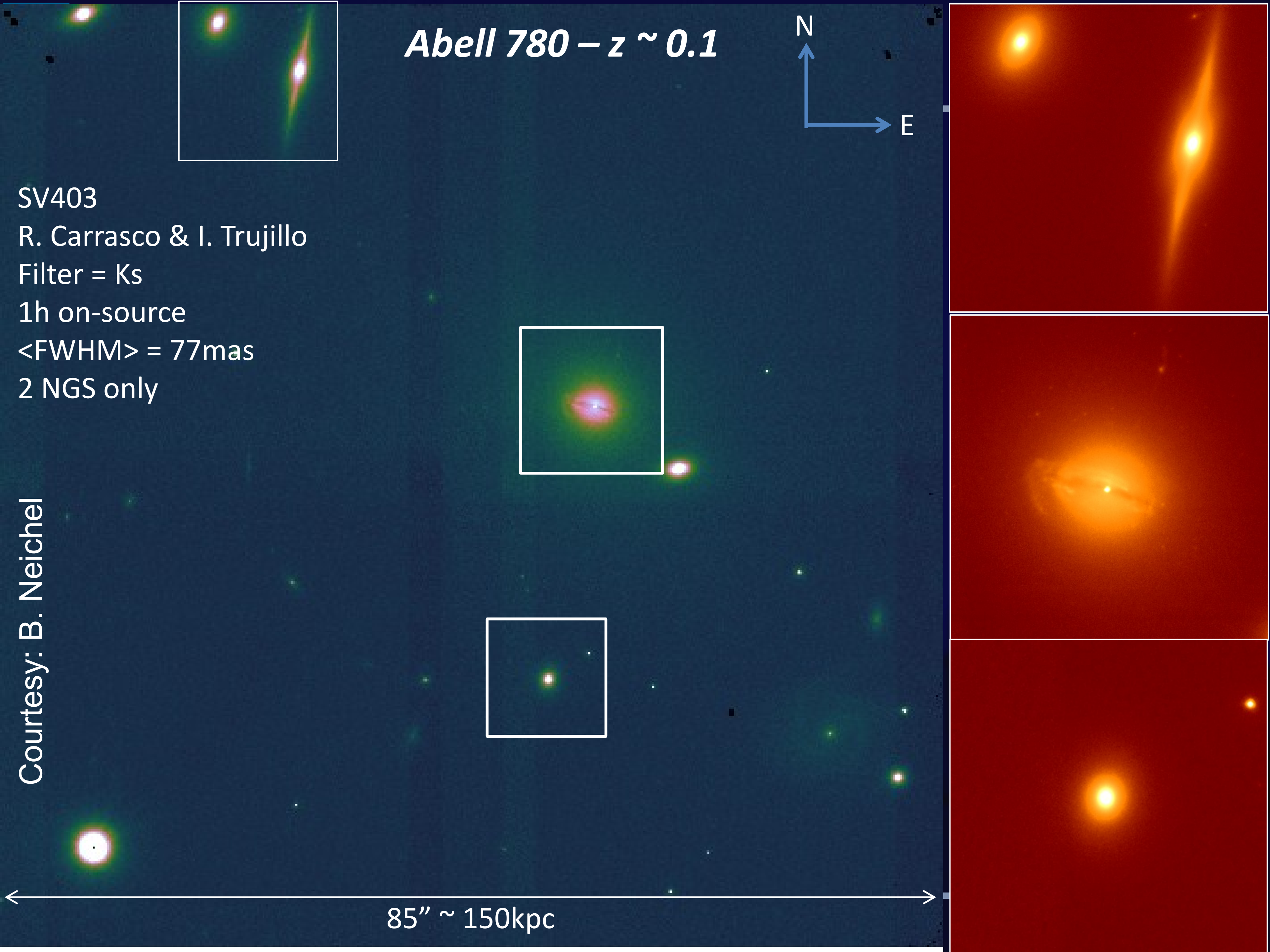
- First Pyramid WFS working at 8m telescope, first scientific paper with Pyramid LO-WFS
- Observations of dwarf irregular galaxy UKS 2323-326

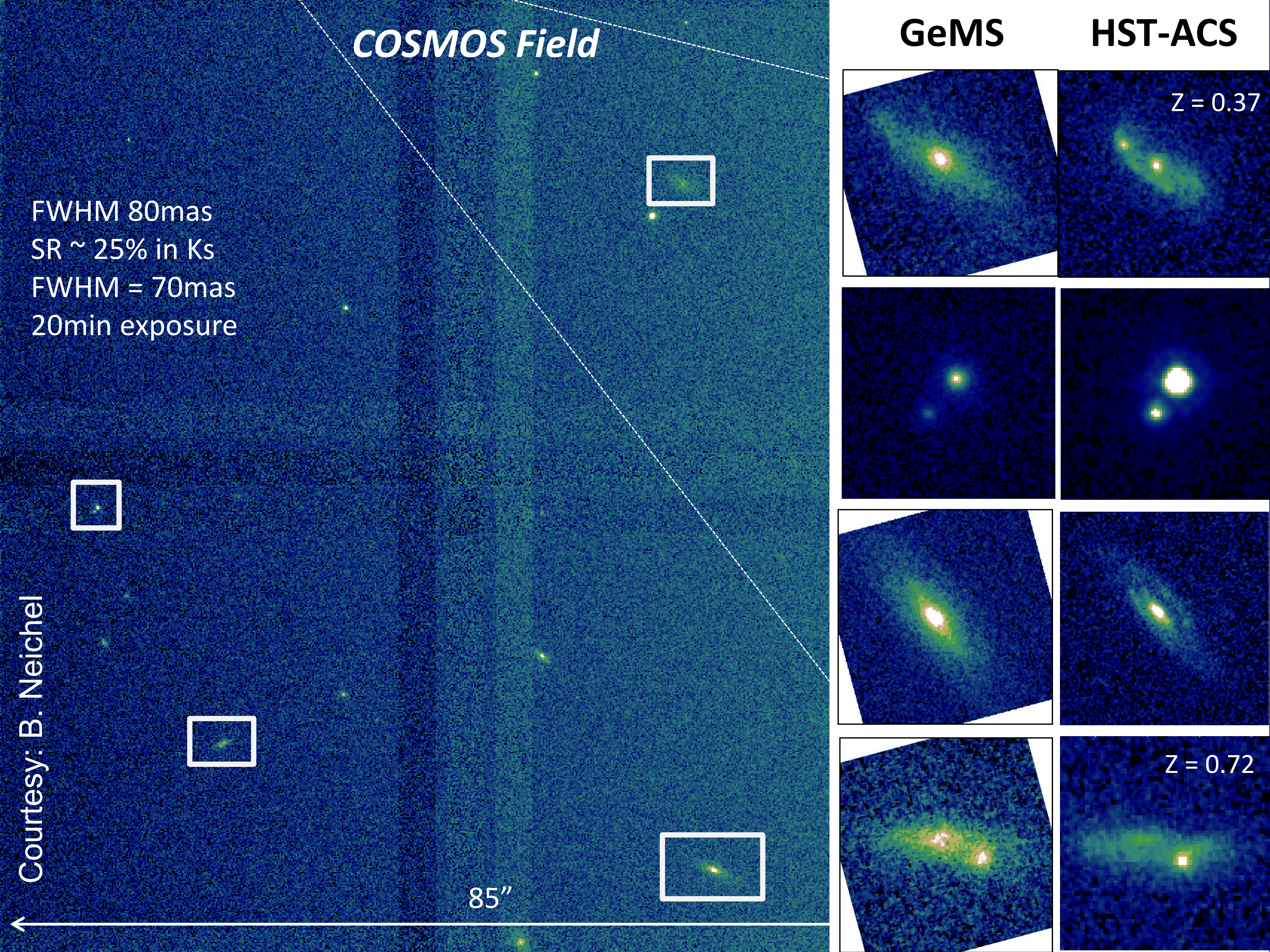


Gullieuszik et al., A&A 2008

GEMINI MCAO

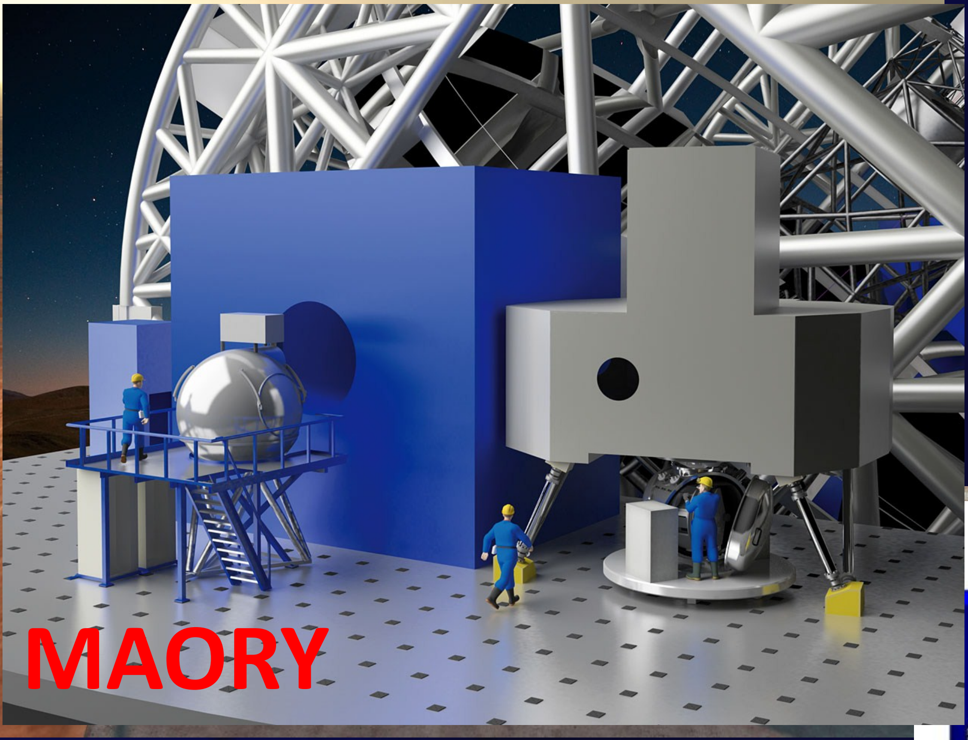

Credit: Gemini Observatory / AURA
Gemini Observatory Legacy Image

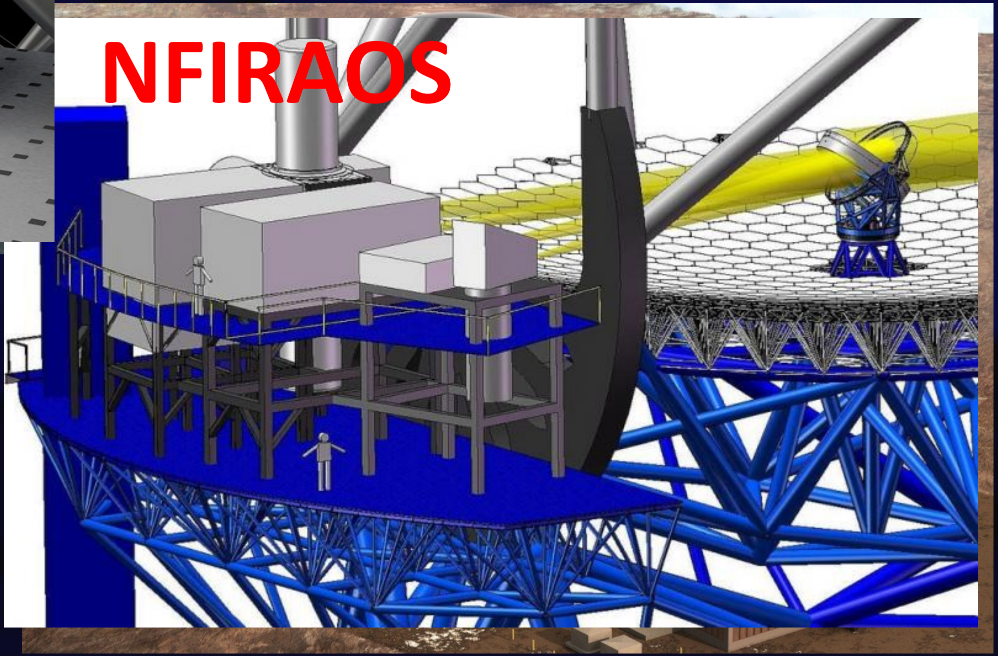

Abell 780 – z ~ 0.1
N
E
SV403
R. Carrasco & I. Trujillo
Filter = Ks
1h on-source
<FWHM> = 77mas
2 NGS only
Courtesy: B. Neichel
85" ~ 150kpc



COSMOS Field
GeMS
HST-ACS
FWHM 80mas
SR ~ 25% in Ks
FWHM = 70mas
20min exposure
Z = 0.37
Z = 0.72
85”
Courtesy: B. Neichel

What's next...

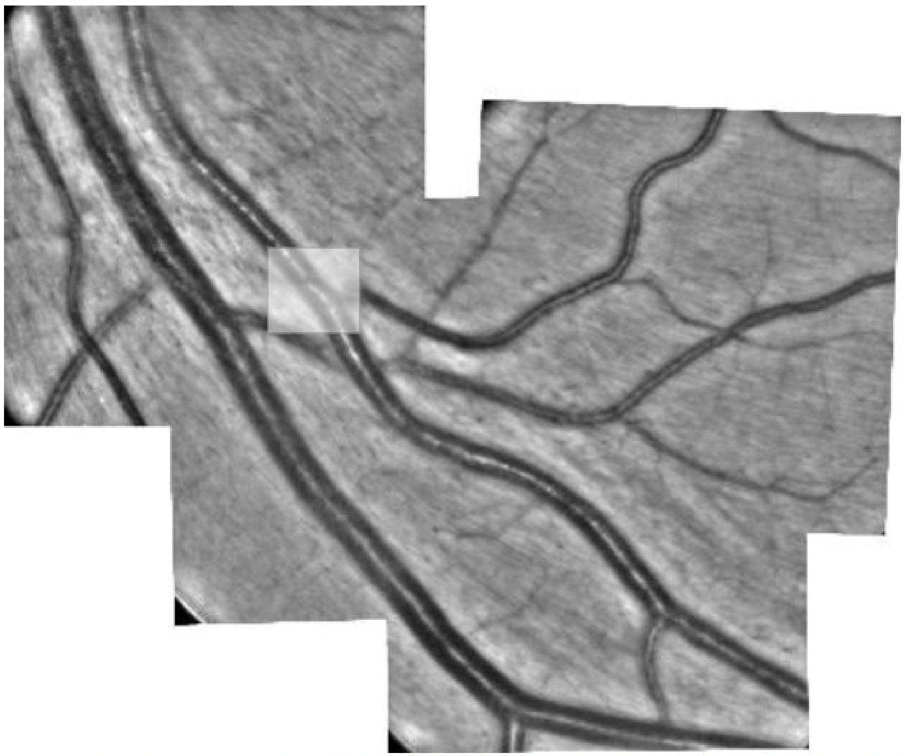




MCAO from another World

Source: University of Göteborg, Department of Ophthalmology – www.oft.gu.se/ao

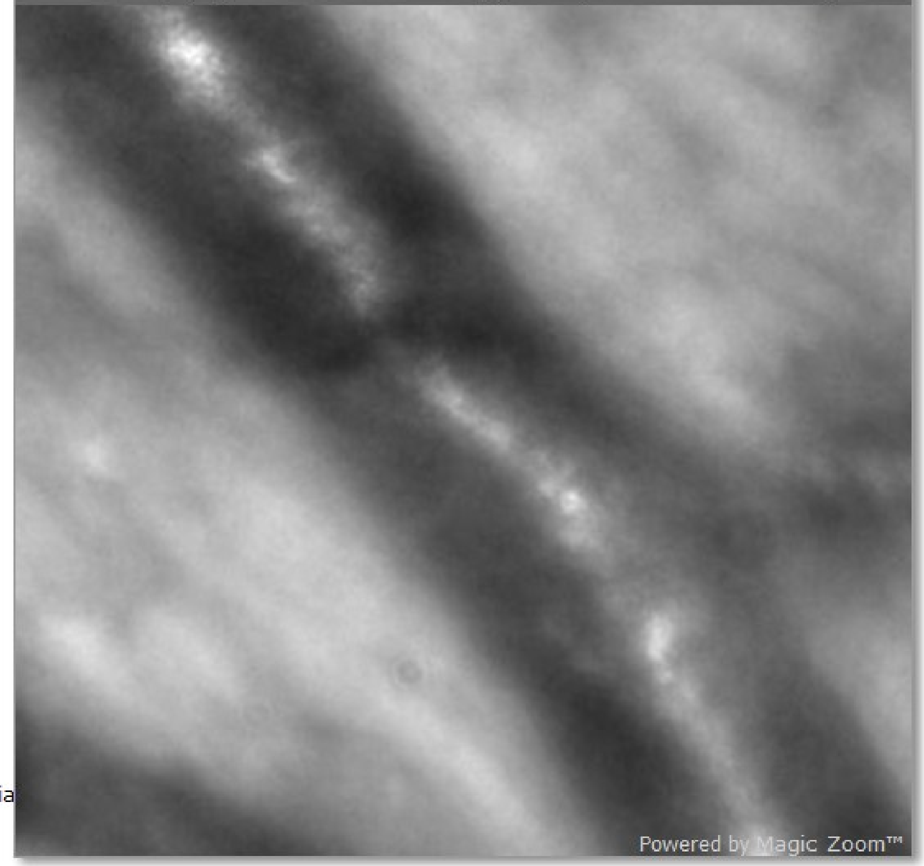
...



14 x 12 deg photomontage of four images showing major blood vessels and superficial nerve fiber layer (blind spot situated just above to the left of this image)

...

Close-up (approx. 1.4 x 1.1 deg) of superficial retinal layer.



Thaung, J. et al, Opt.Expr. 17, 4454 (2009) & Popovic, Z. et al., Invest. Ophthalmol. Vis. Sci., 52, 2649 (2011)

Thank you for listening!