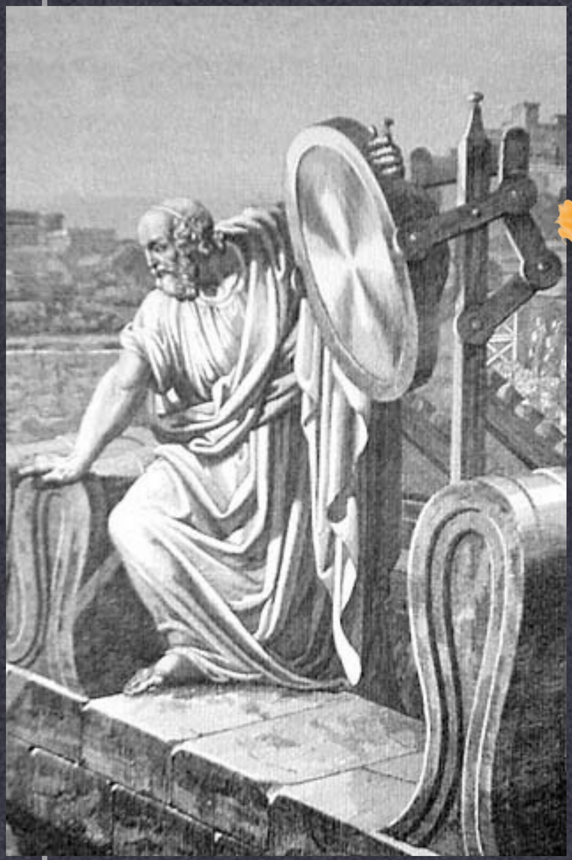
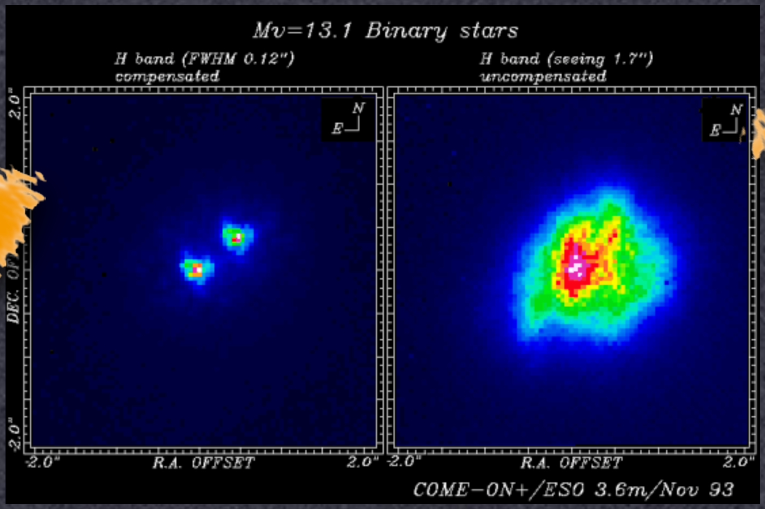
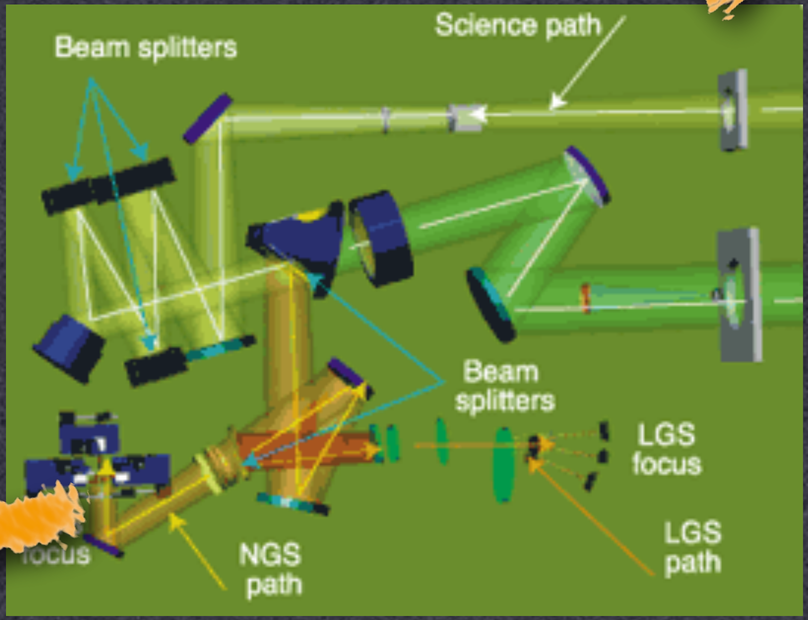




A Brief History of Adaptive Optics

François Rigaut
Australian National University



Talk Research and Sources

Australian National University

- **Hardy**'s book ("Adaptive optics for astronomical telescopes"): an extensive chapter on AO history, a first hand report
- **Roddier**'s book ("Adaptive optics for astronomy")
- **Beckers**' 1993 Annual Review of A&A paper.
- Various web resources, within others:
  - **CfAO** list of links
  - Google, Google image
  - **Fuka**'s history of AO page (2002)
- **Rousset**'s Come-ON & Come-ON+ presentation (2009)
- Discussions with **J.Beckers, N.Hubin, B.Ellerbroek, G.Rousset, R.Ragazzoni, C.Max, D.Gavel, T.Fusco, E.Diolaiti, A.Moore, R.Conan, E.Gendron, etc…**

What is AO?

- “A technique to compensate atmospheric turbulence using a wavefront sensor and phase corrector in a close loop arrangement.”

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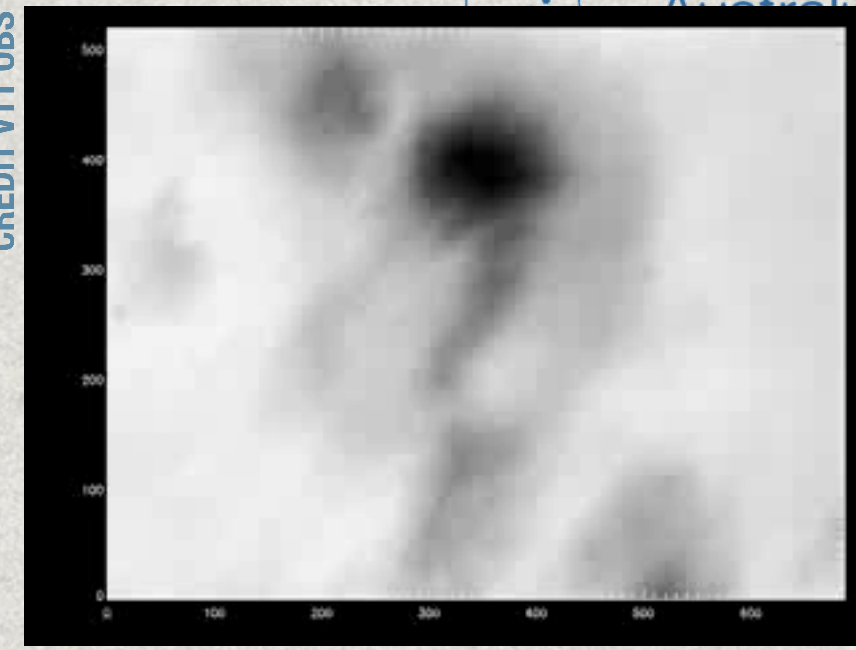

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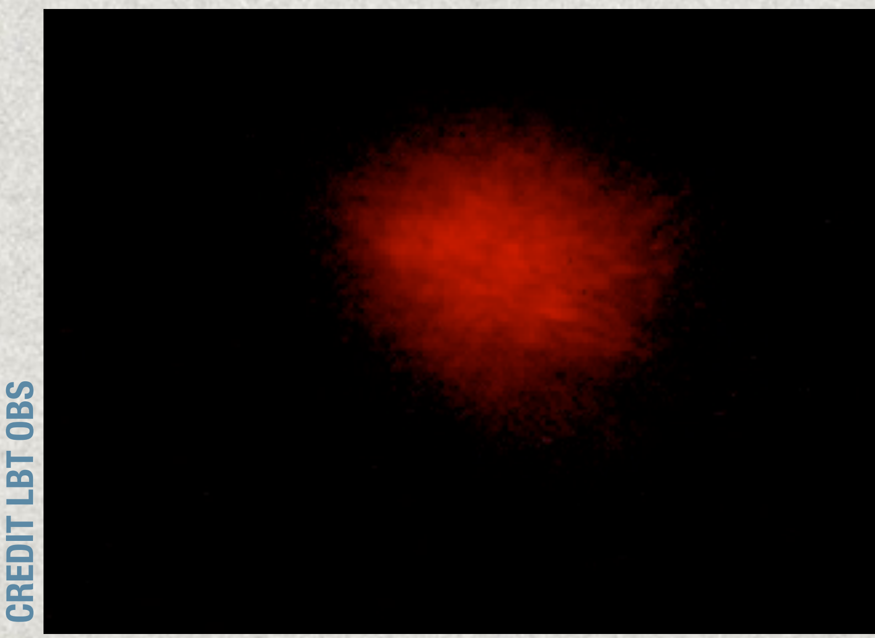

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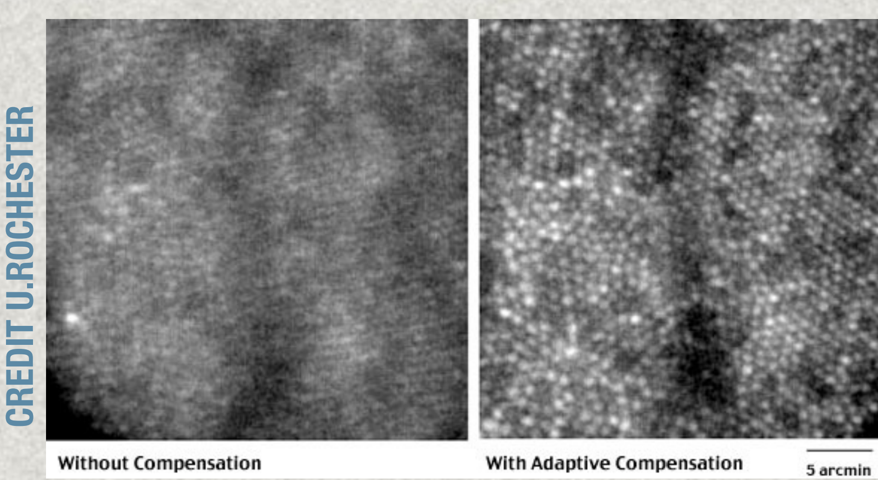

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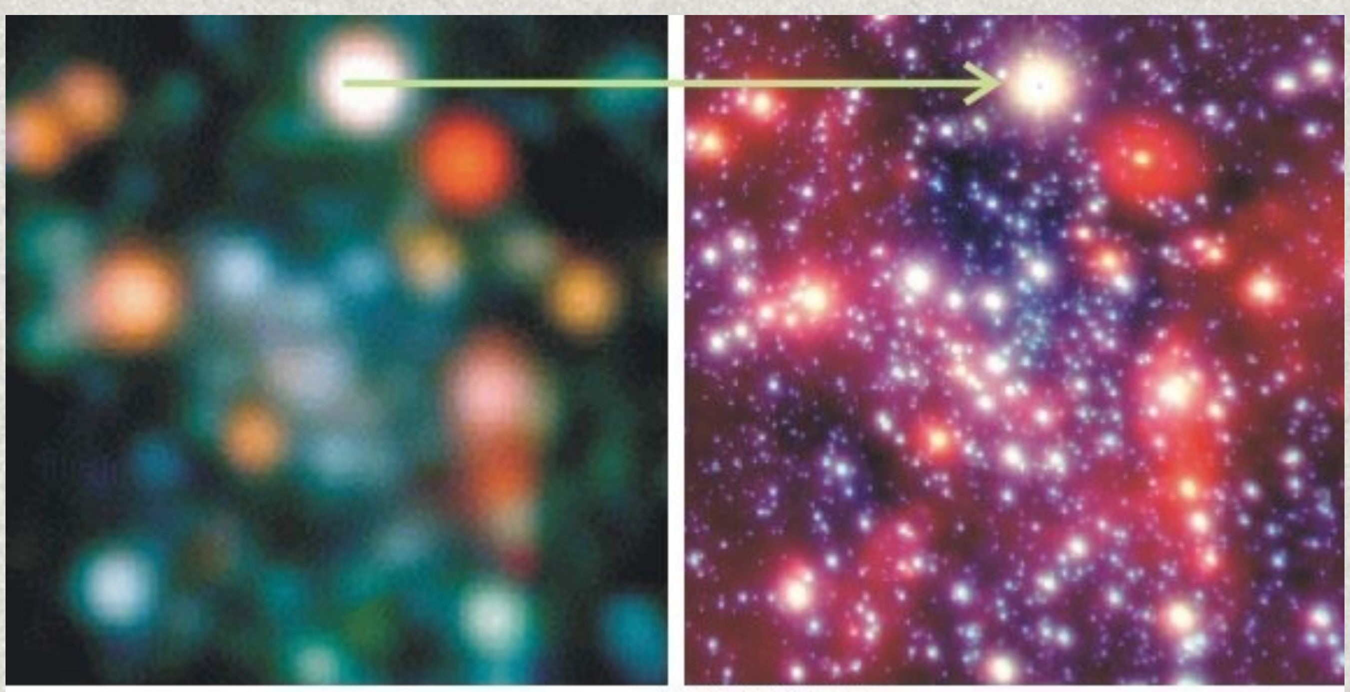

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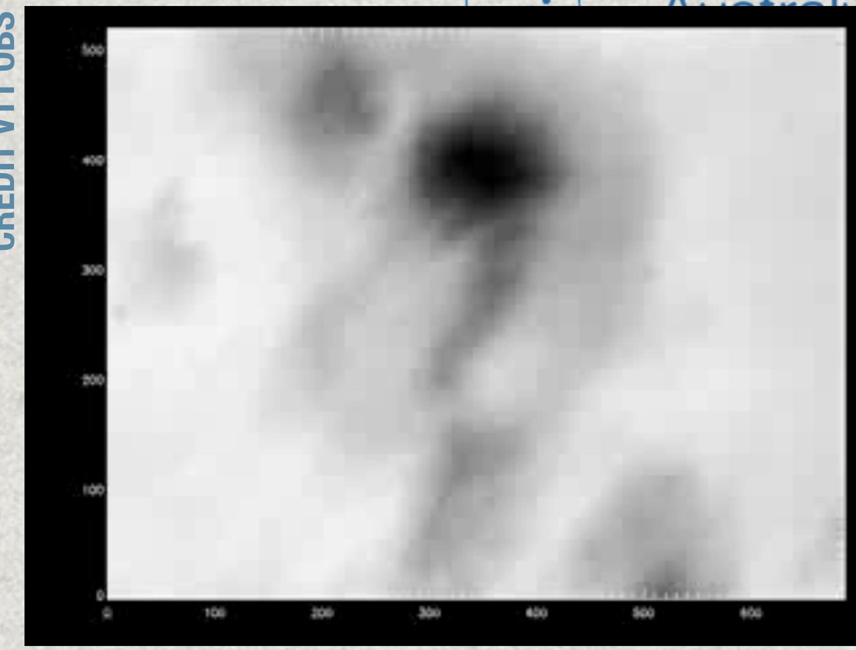

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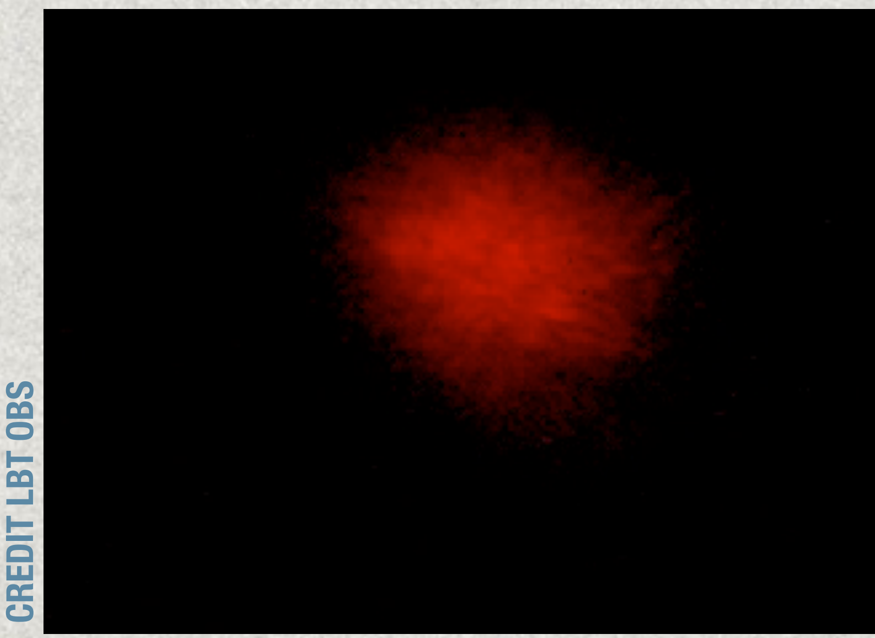

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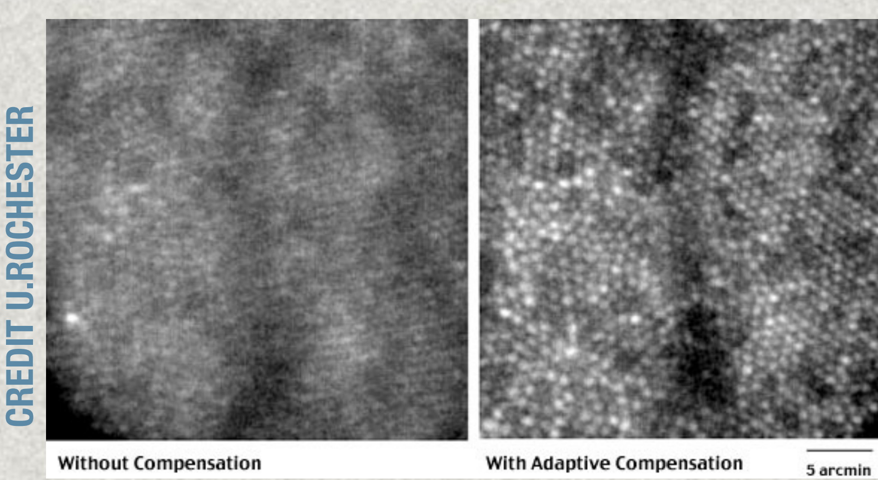

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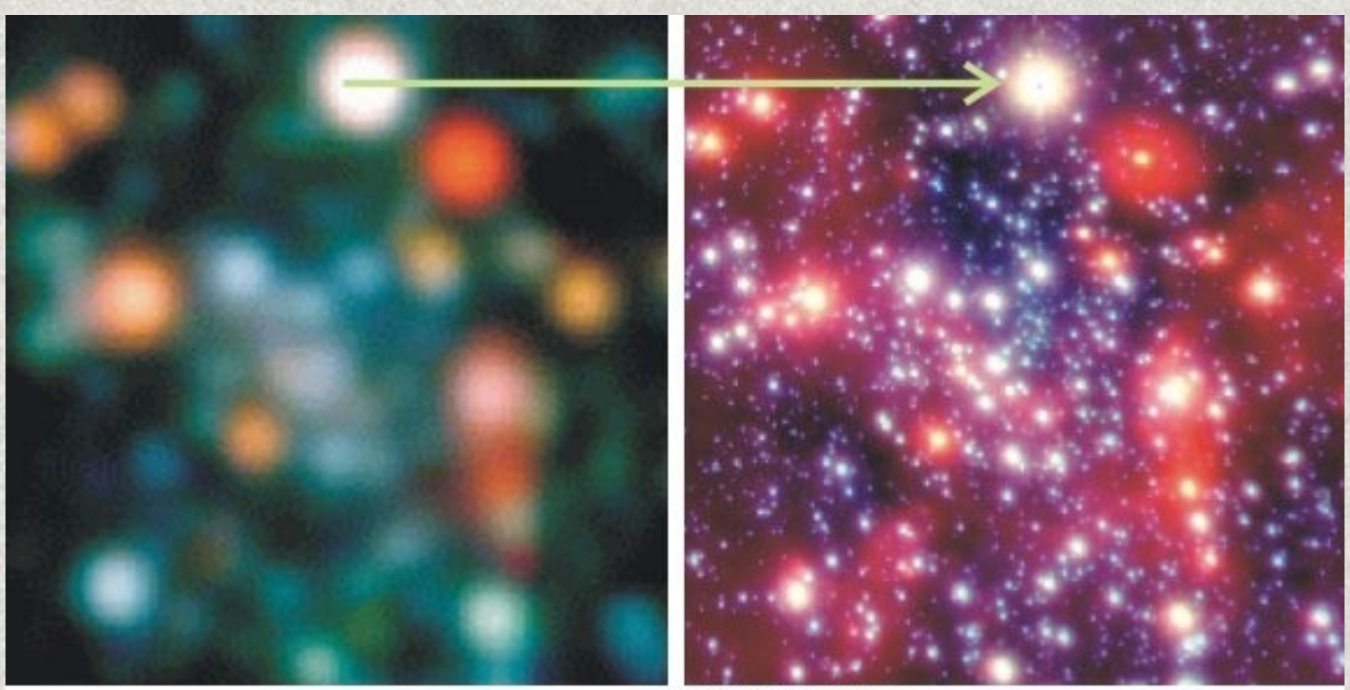

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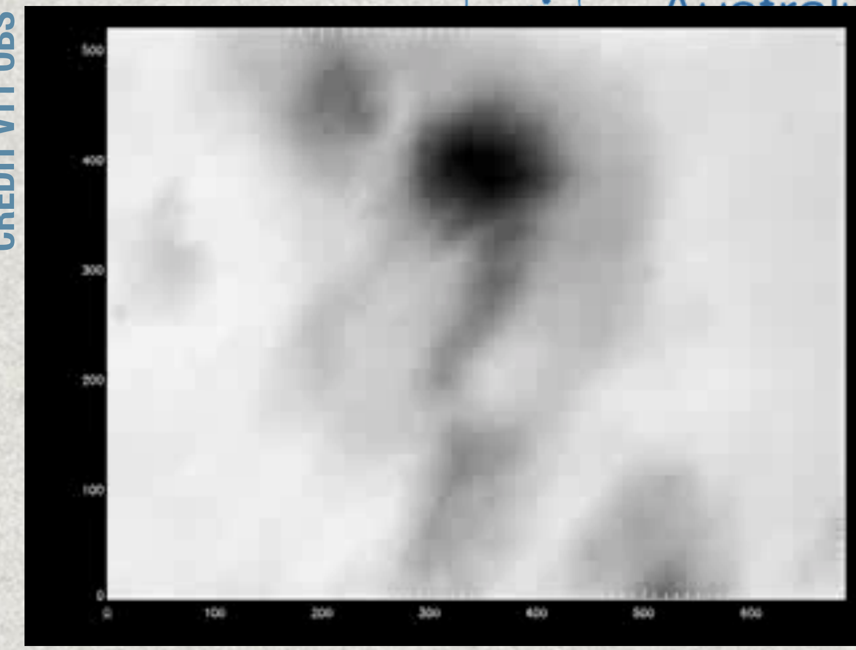

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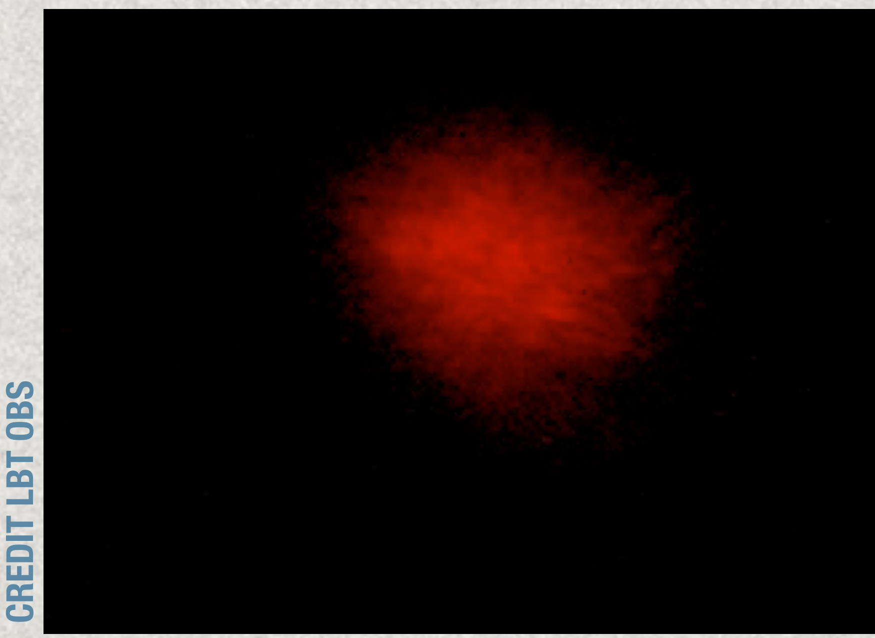

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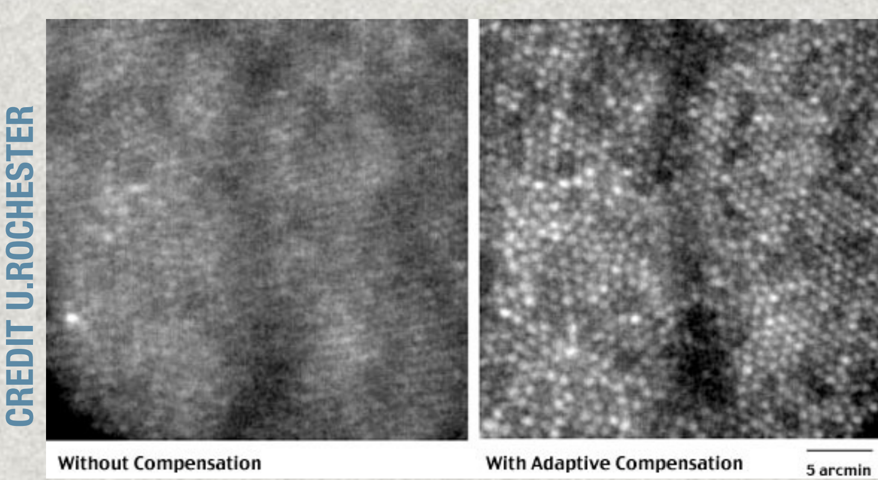

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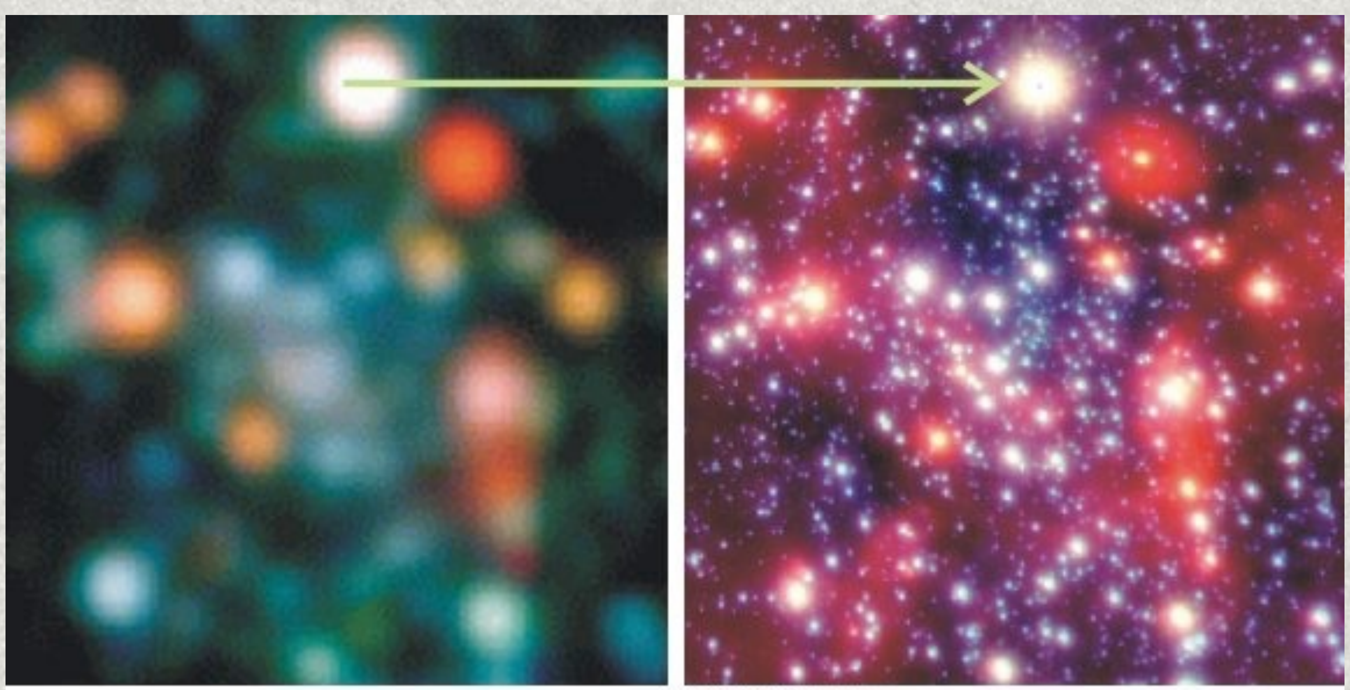

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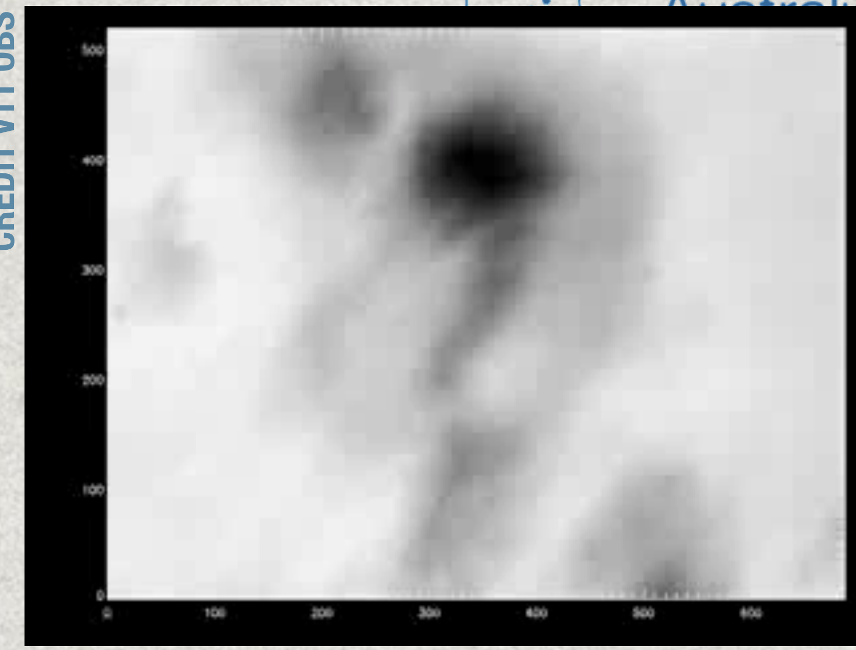

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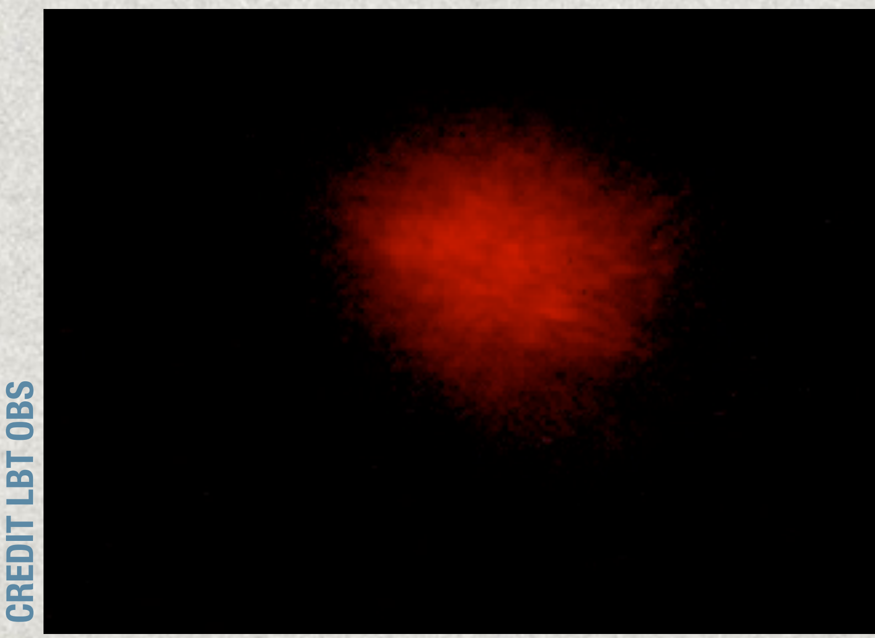

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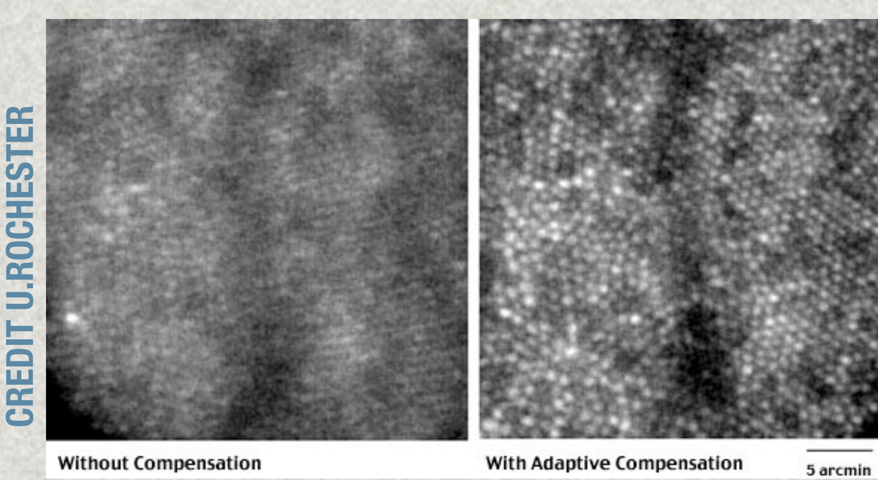

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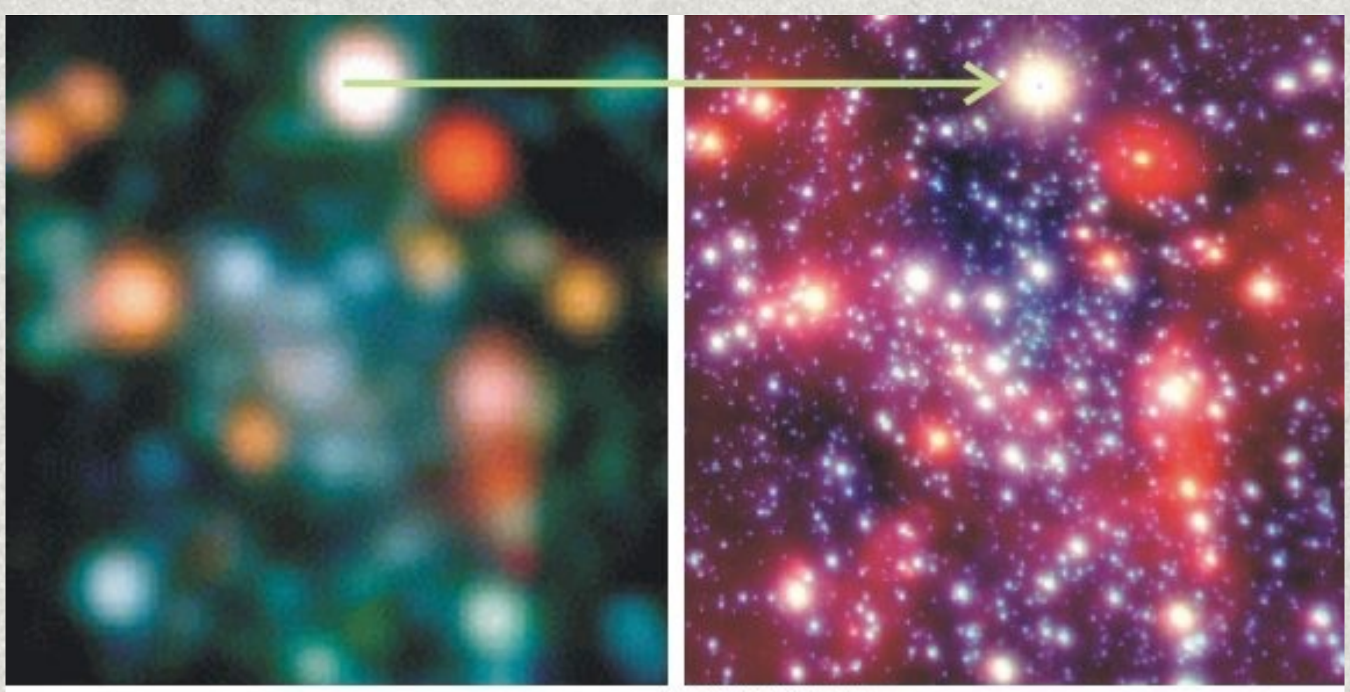

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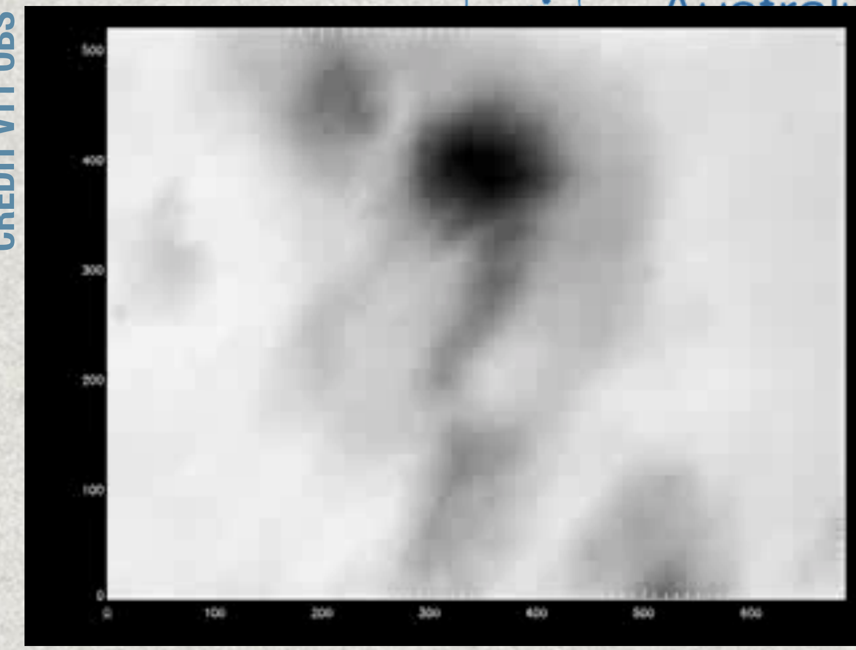

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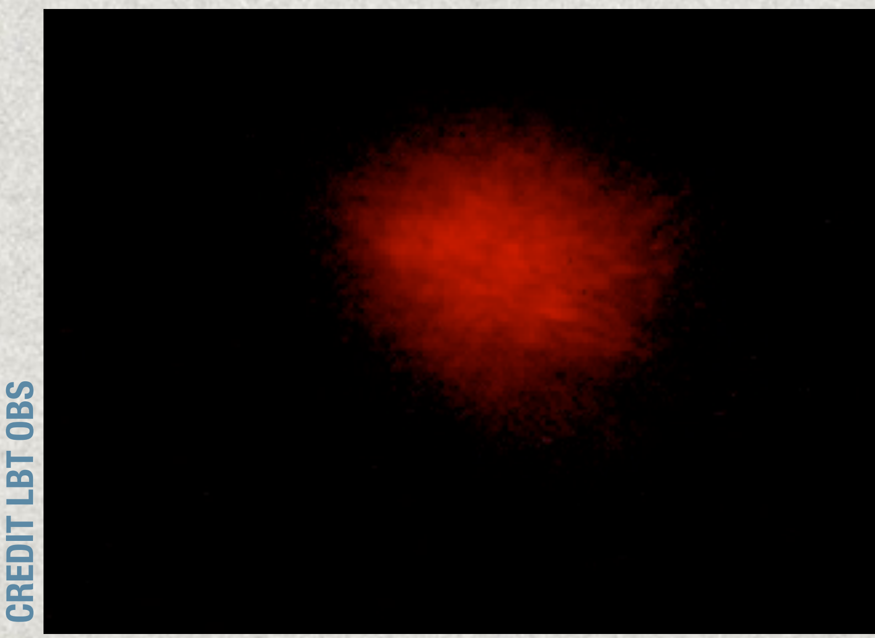

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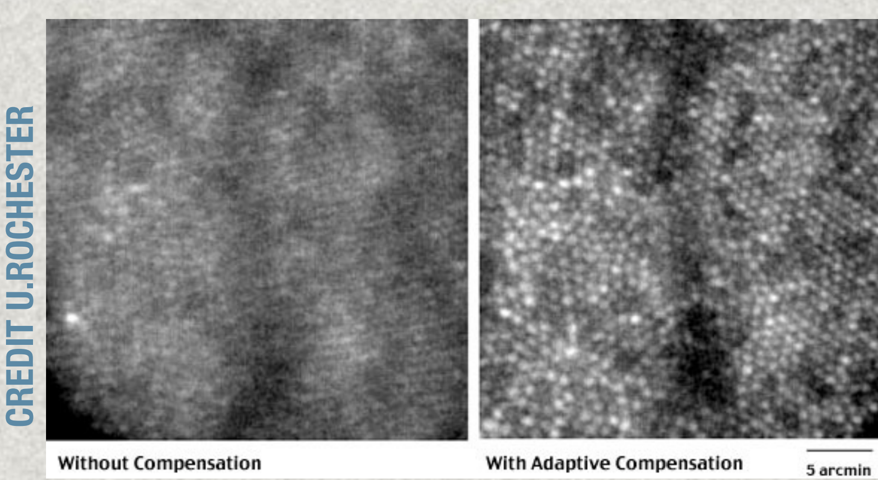

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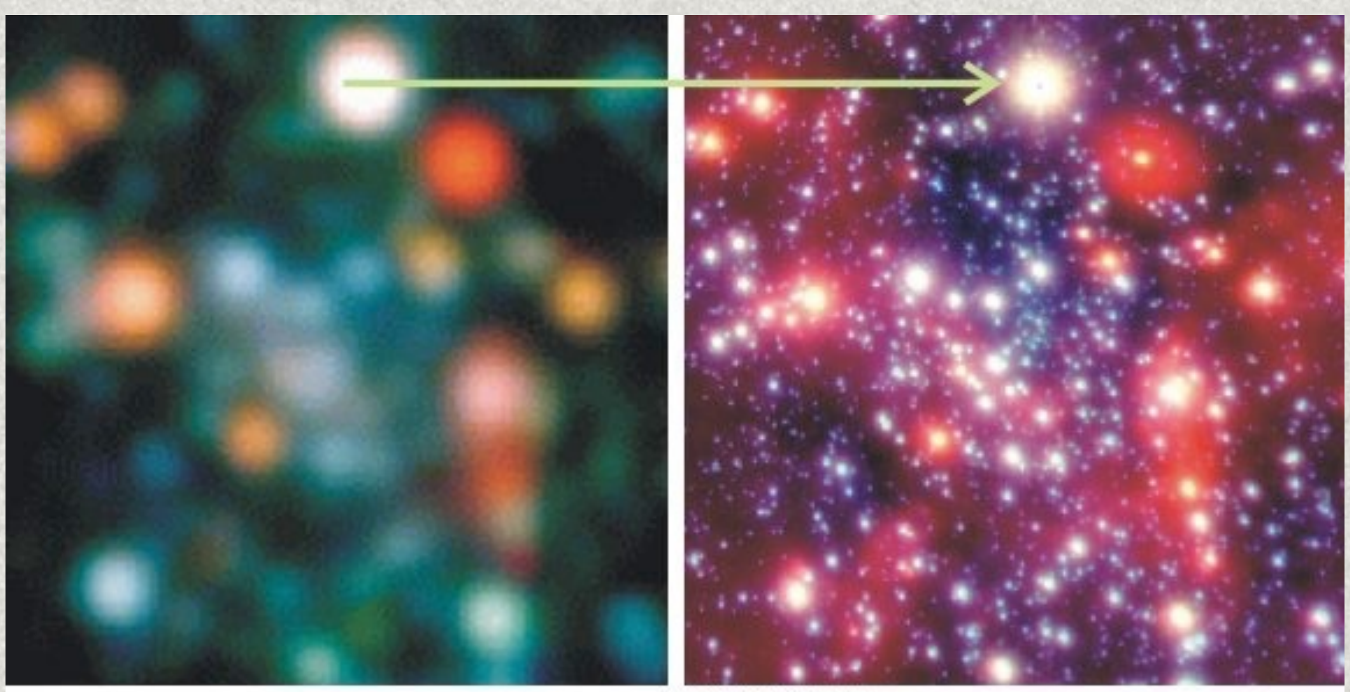
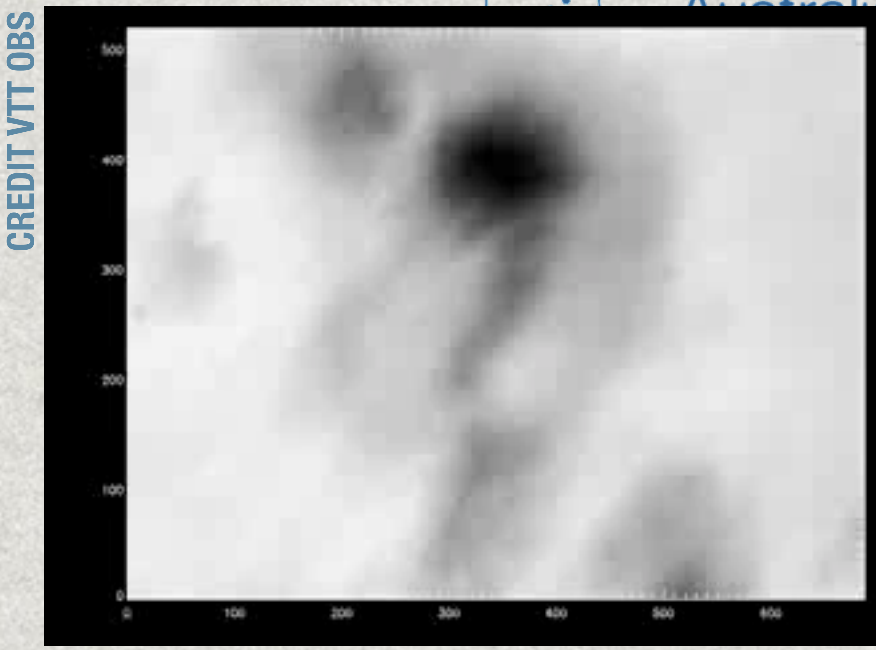


What is AO?

- “A technique that uses a combination of wavefront sensor(s) and corrector(s) to fully or partially compensate for quickly varying optical disturbances.”



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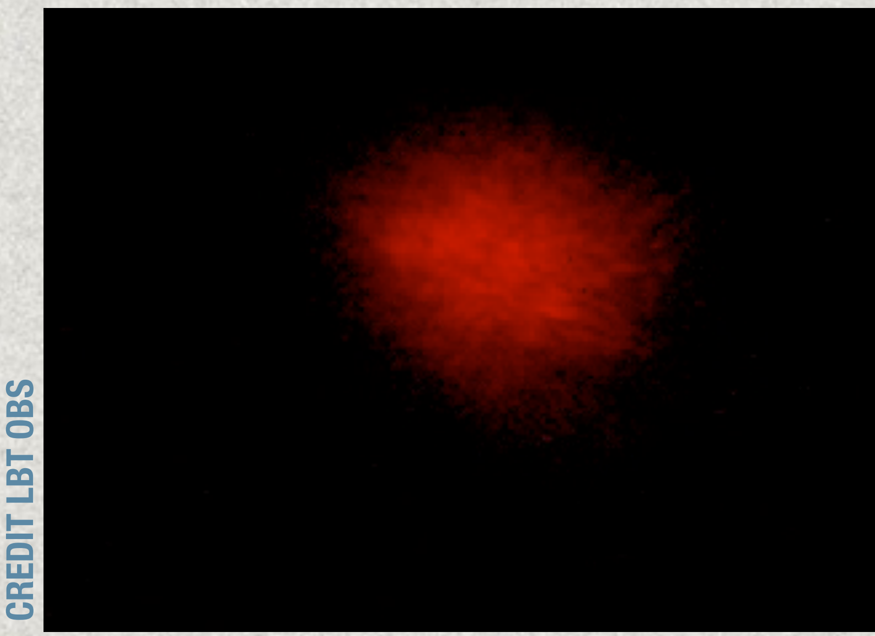

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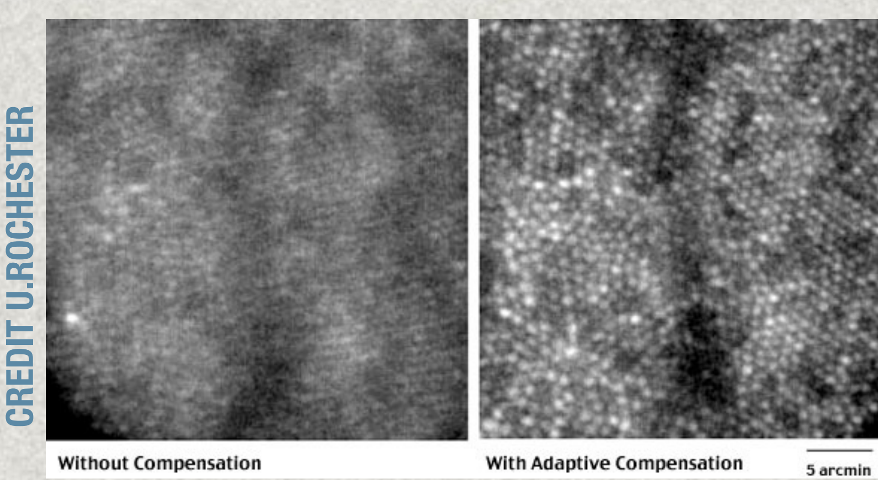

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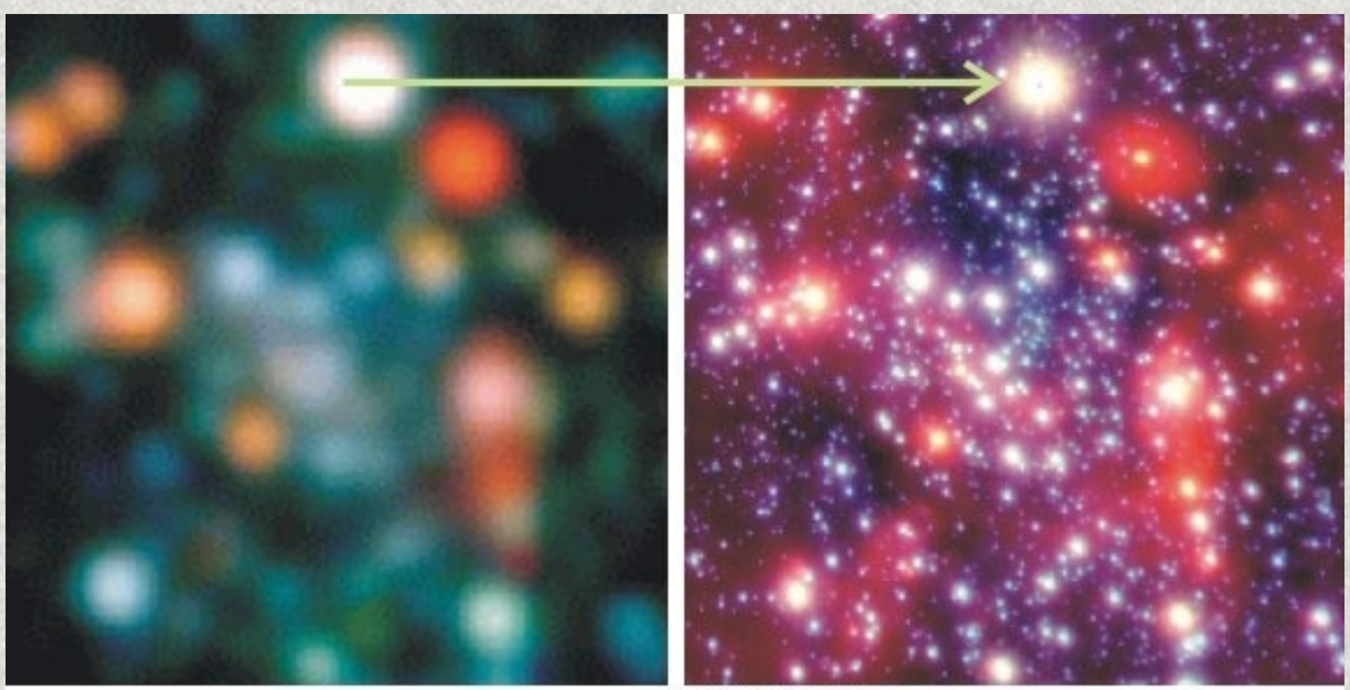

CREDIT ESO/VLT

What is AO?

- “A technique that uses a combination of wavefront sensor(s) and corrector(s) to fully or partially compensate for quickly varying optical disturbances.”
- Fields of application: Astronomy (night-time & Solar), medical (eye), space debris, defence (passive & active), telecom, industrial.
- Many "breeds" of AO: AO, LGS AO, GLAO, MCAO, ExAO, LTAO, MOAO, etc...

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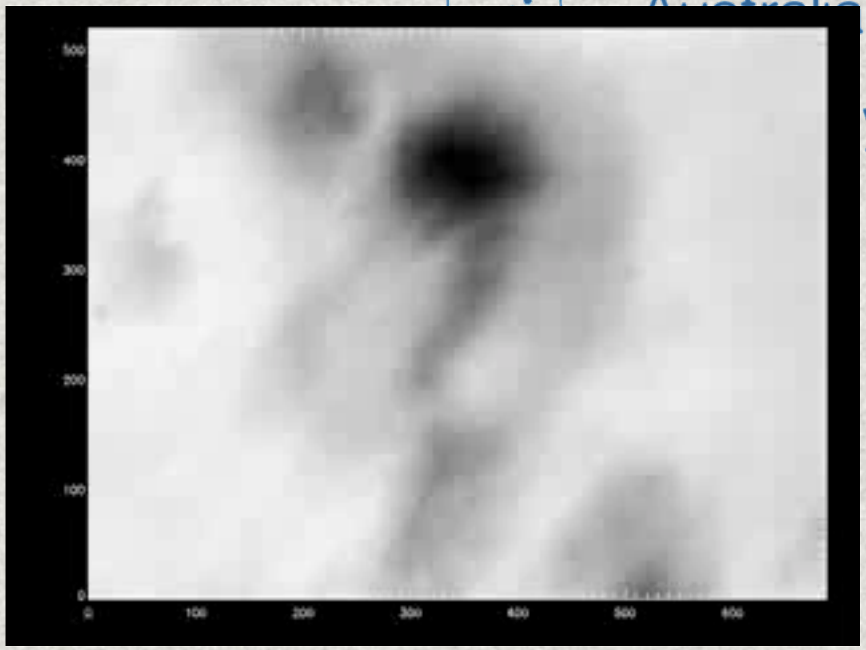

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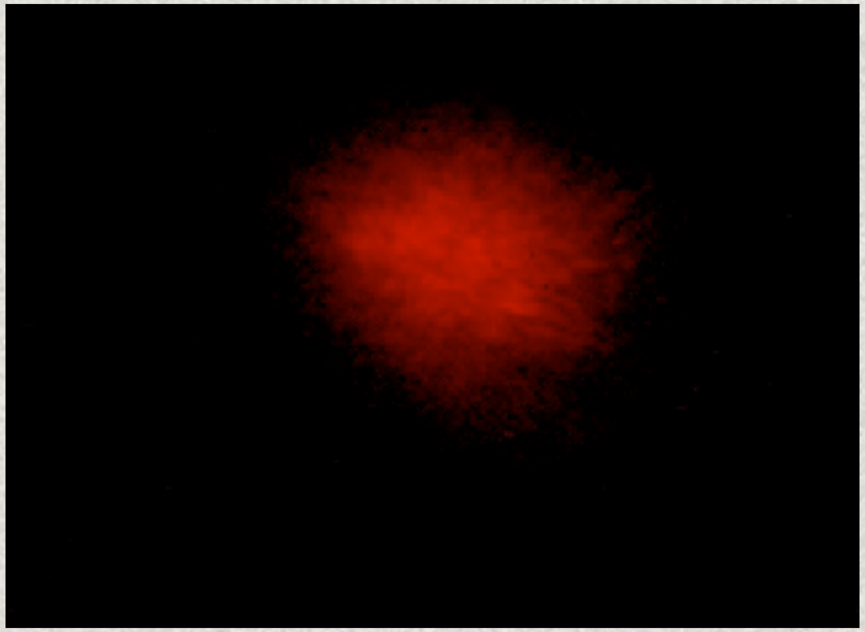

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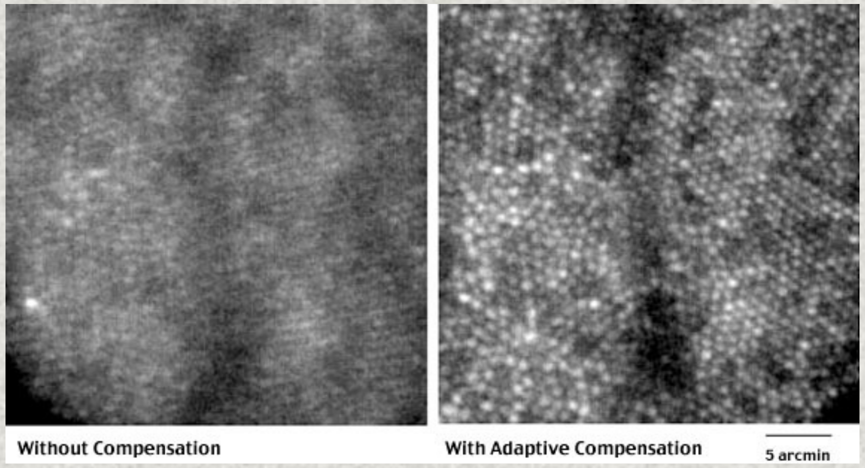

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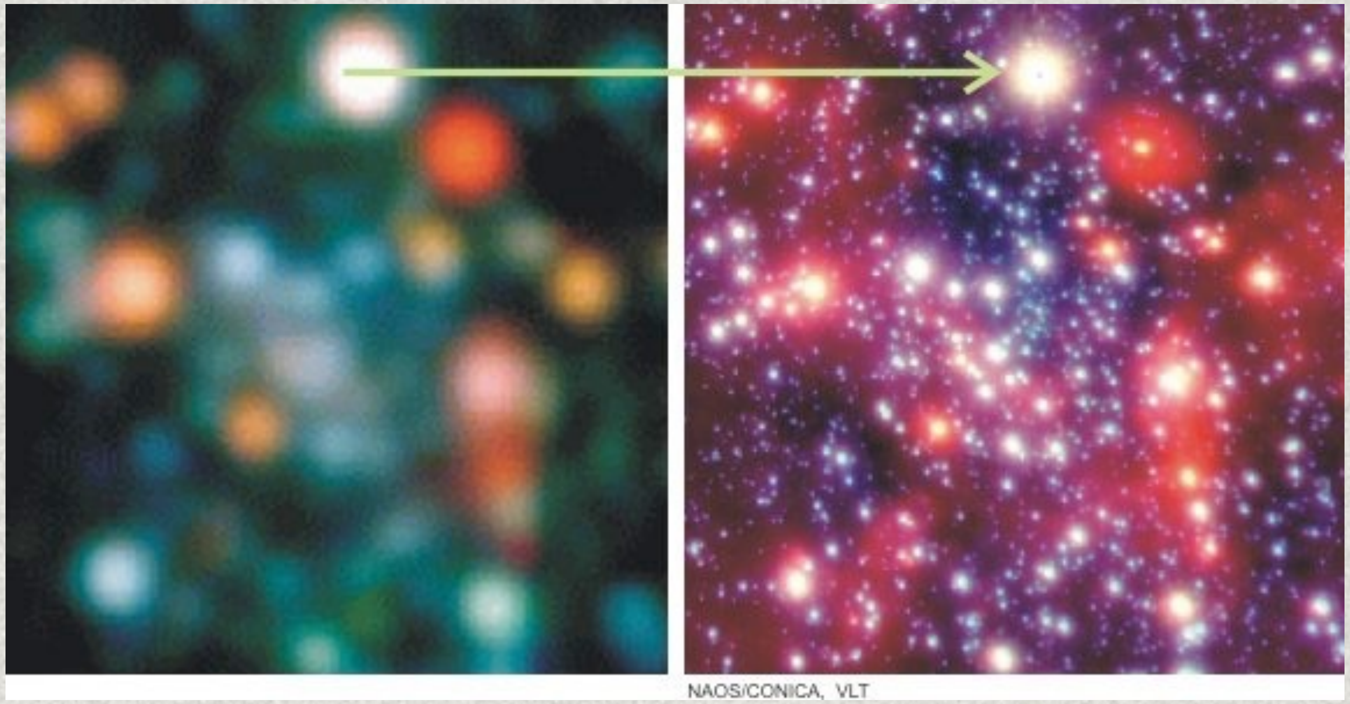

Not just Astronomy !

- **Astronomy**
- **Defence**: Satellites surveillance, SDI
- **Medical**: Ophthalmology, Oncology
- **Industry**: Cutting and welding
- **Space**: Space debris
- **Lasers** : Femtosecond lasers pulses using adaptive optics, Laser propagation (thermal blooming, air building to building propagation), Fiber coupling, precision focus of high energy laser (Fusion), high precision measurements using laser (LIGO and VIRGO)

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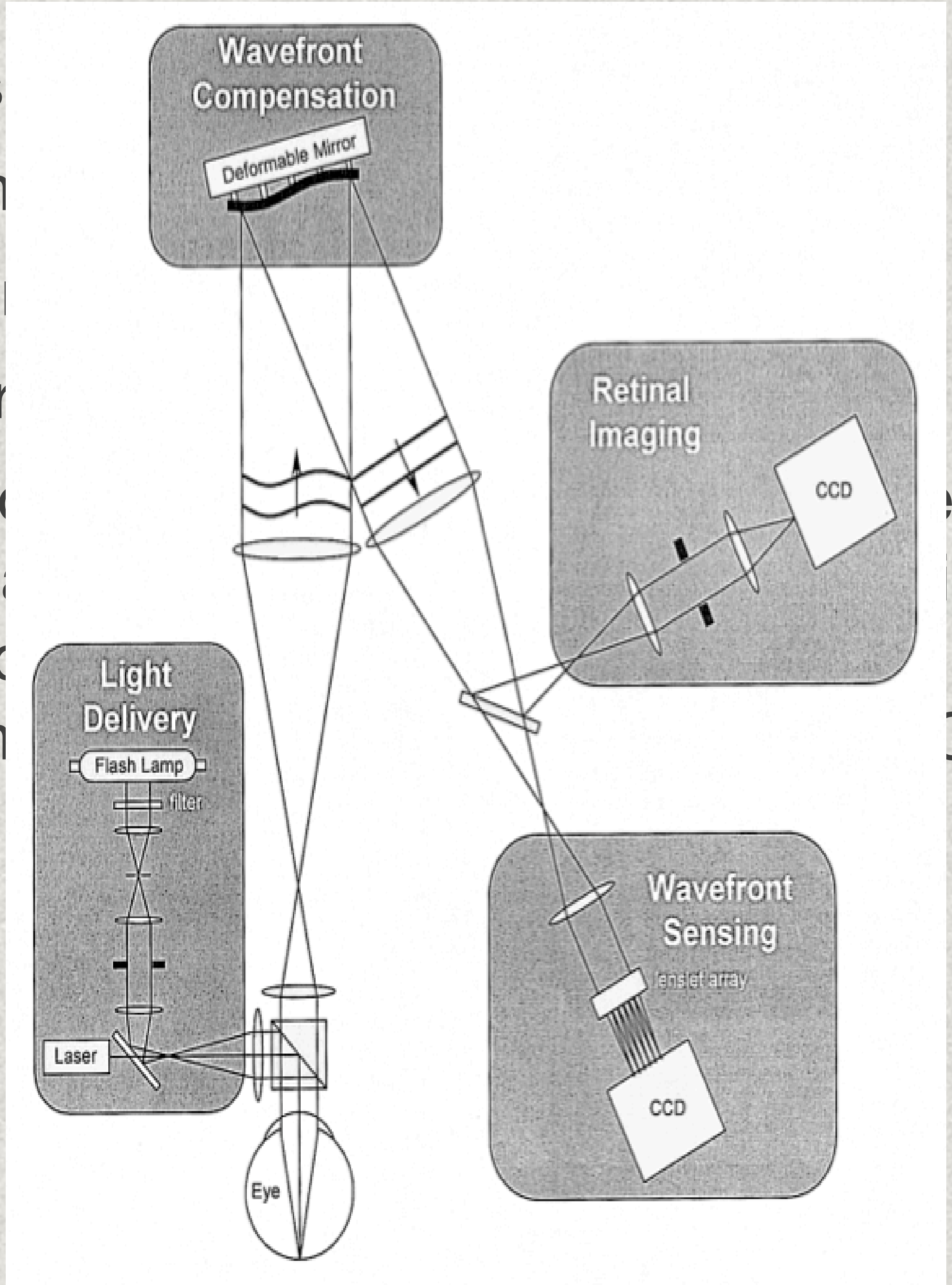

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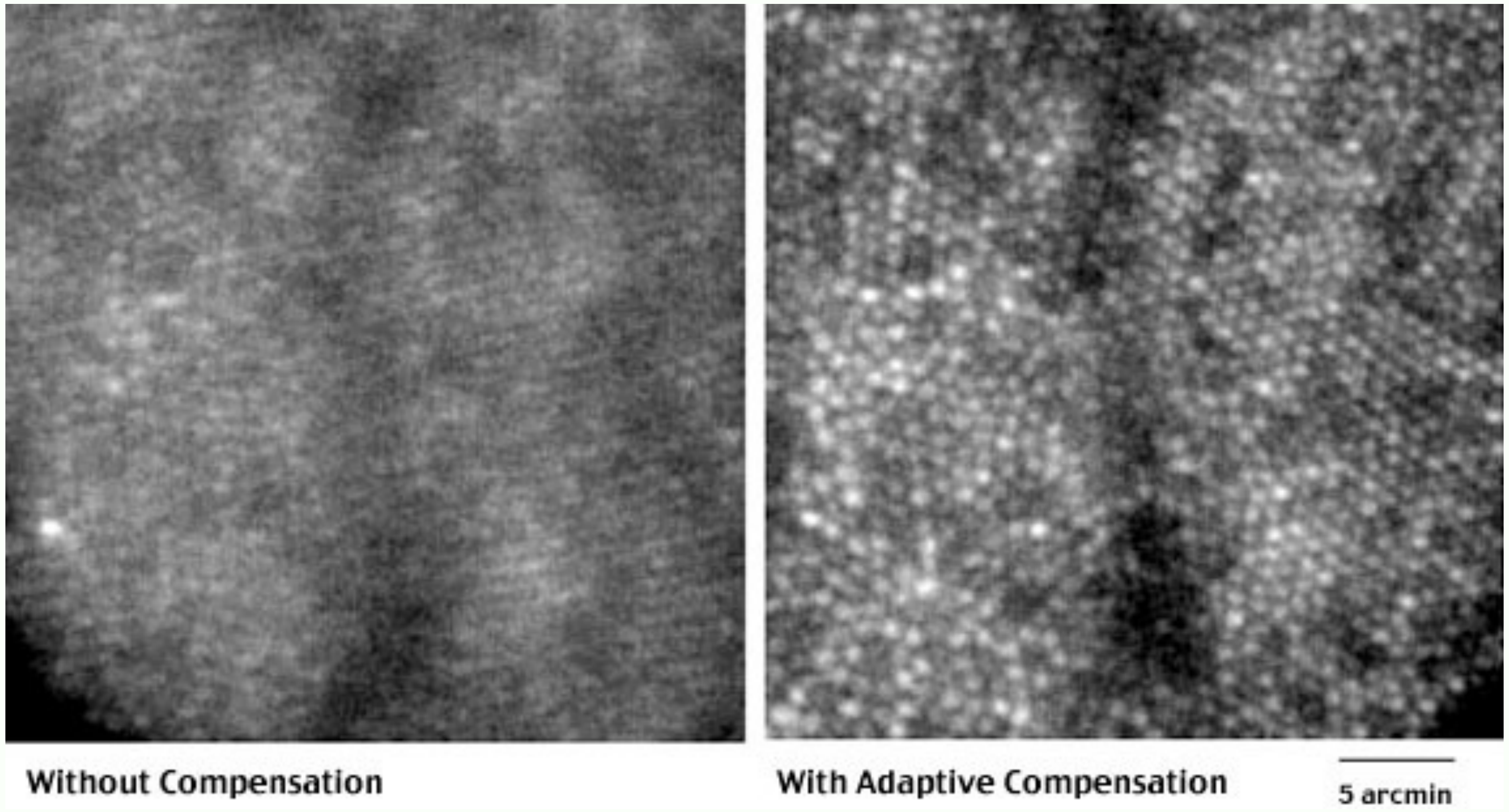
Austin Roorda, Rochester (CfAO)



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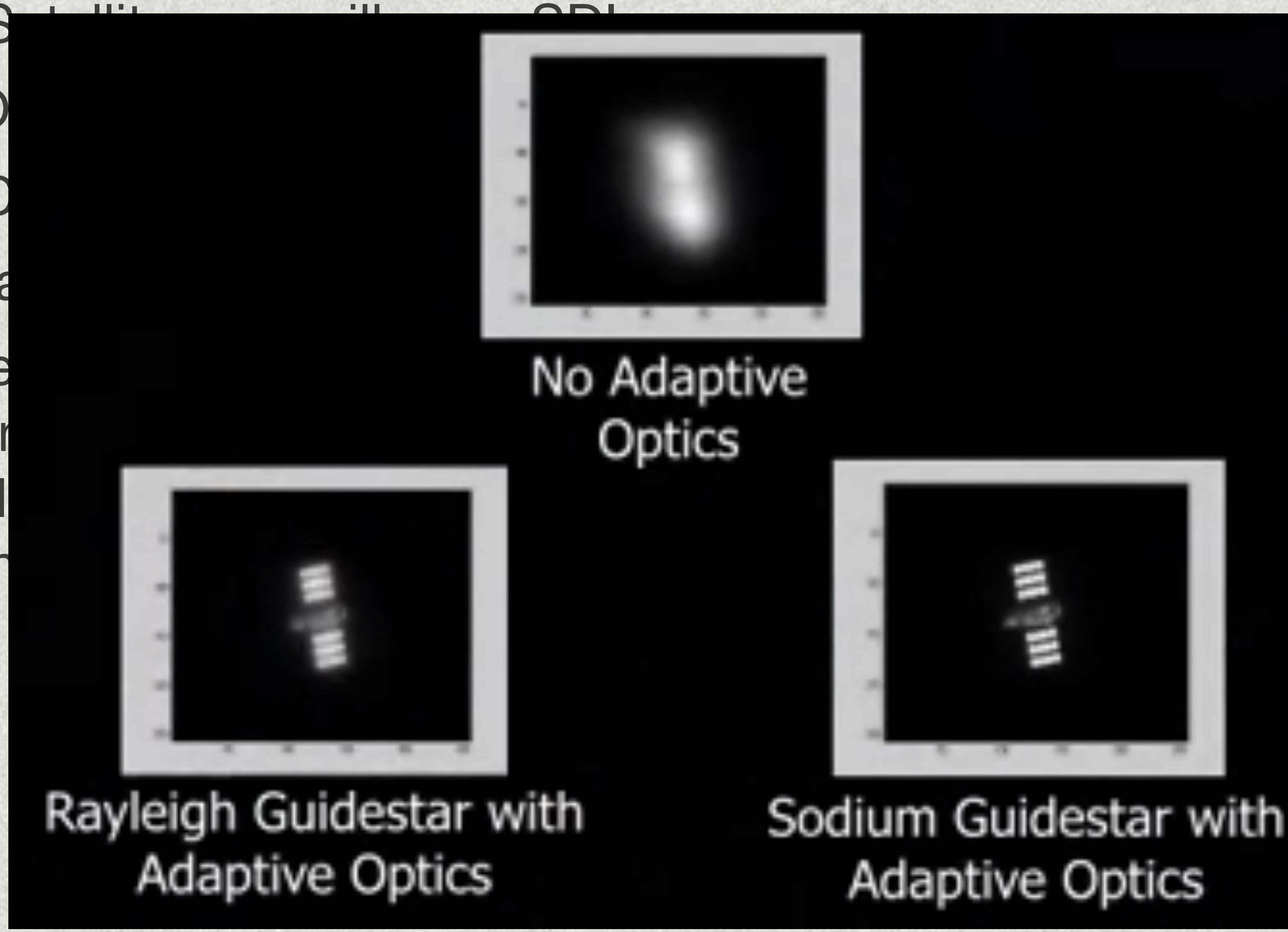
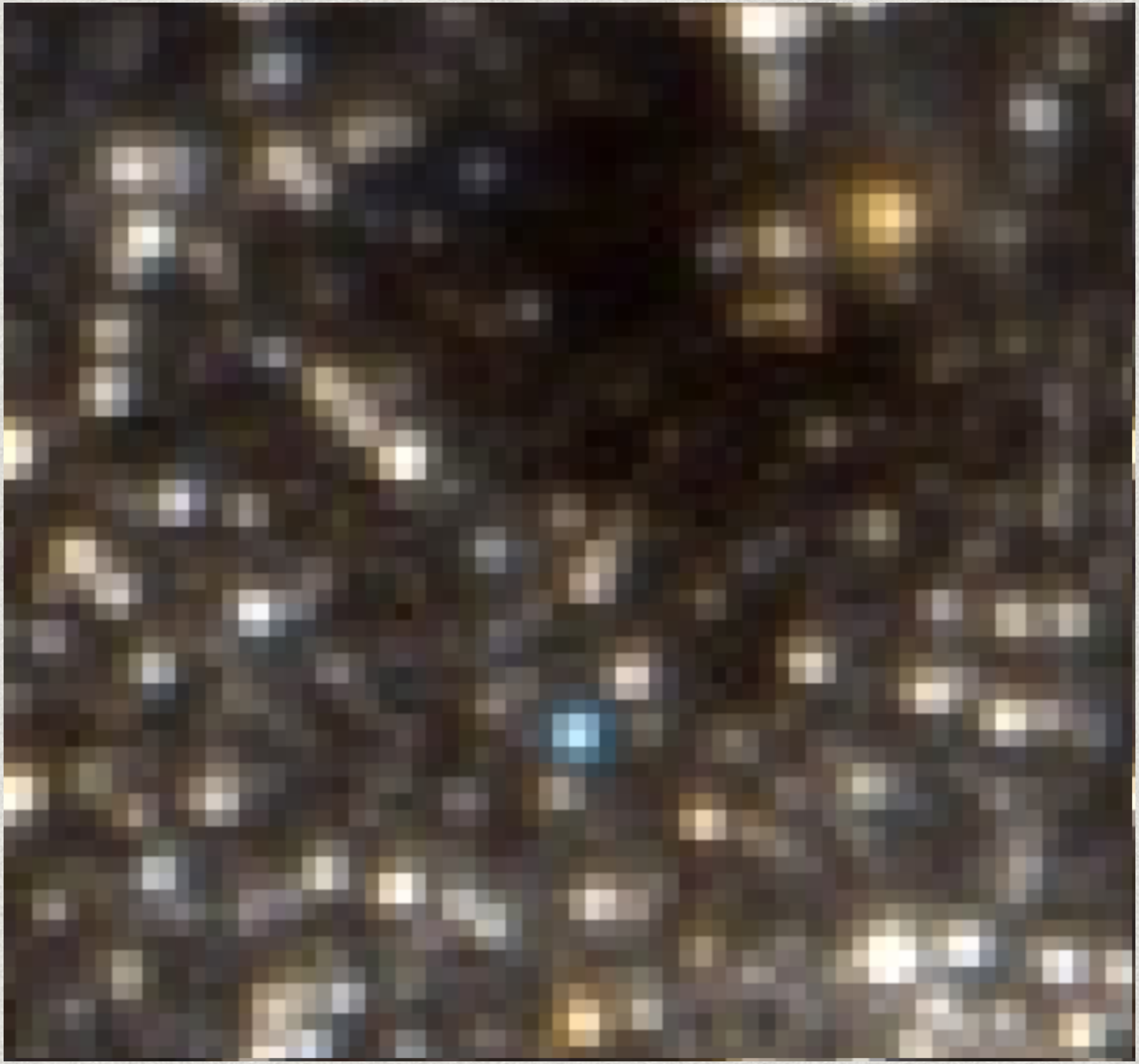


What is Adaptive Optics?

Galactic center

Australian National University

SEEING LIMITED
UH 2.2-M TELESCOPE
FWHM = 0.65”
PI W.BRANDNER


CREDIT W.BRANDNER (UOFH) & GEMINI OBSERVATORY

FIELD OF VIEW
30”X30”

WAVELENGTH
2.2MICRONS

Galactic center

Australian National University

AO COMPENSATED
GEMINI TELESCOPE
FWHM = 0.10”

FIELD OF VIEW
30”X30”

WAVELENGTH
2.2MICRONS

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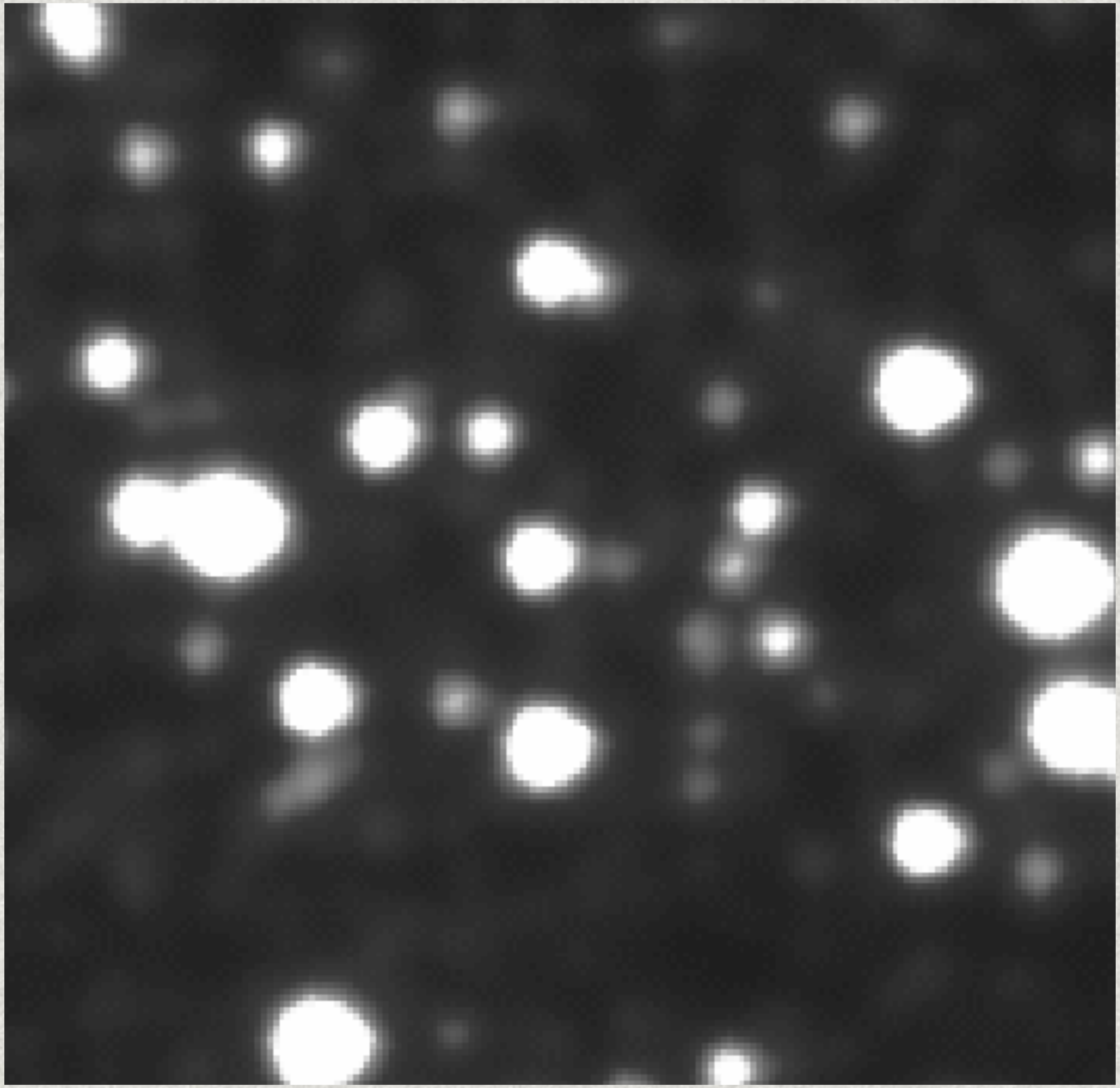
M13 Globular Cluster



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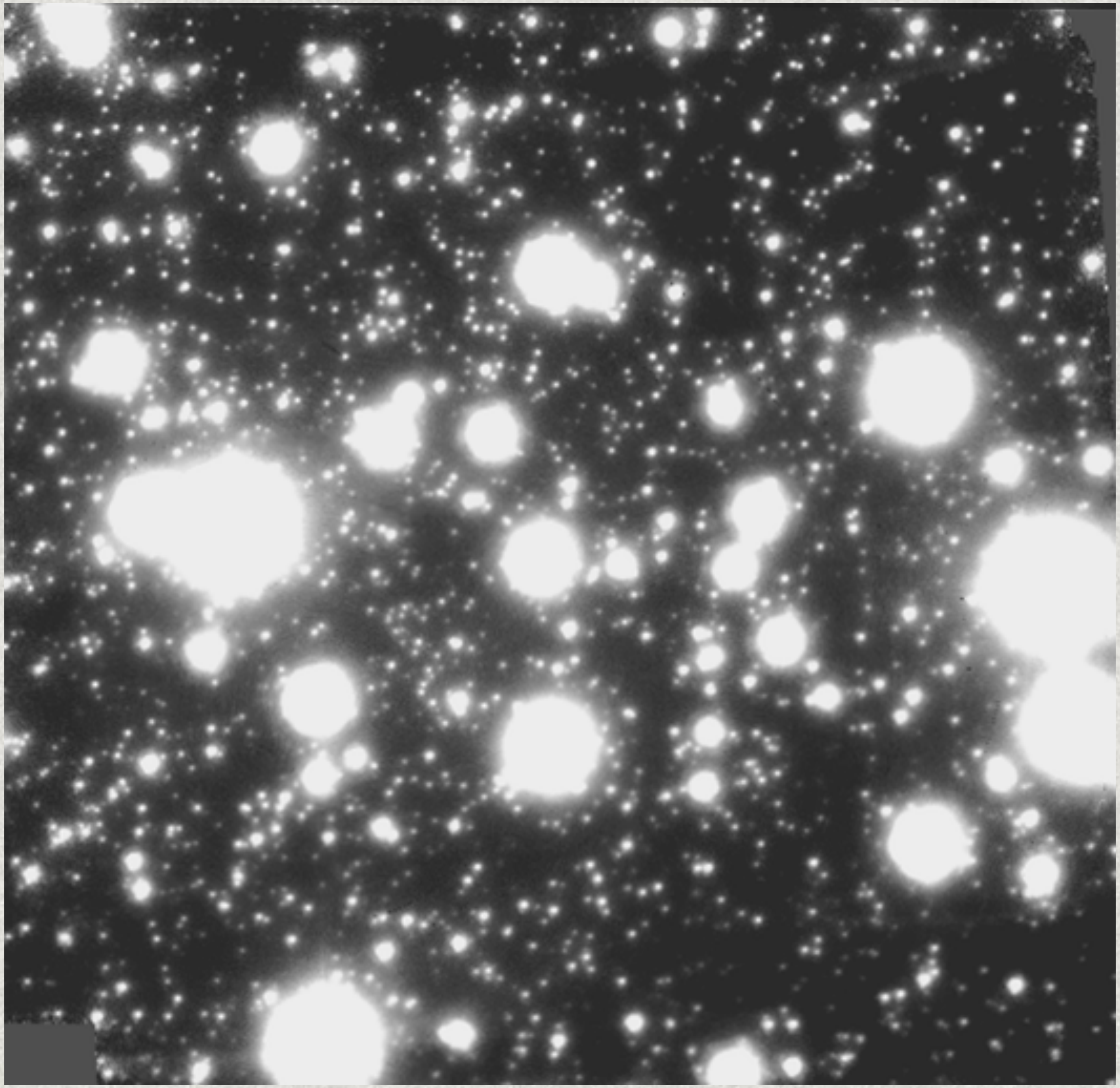

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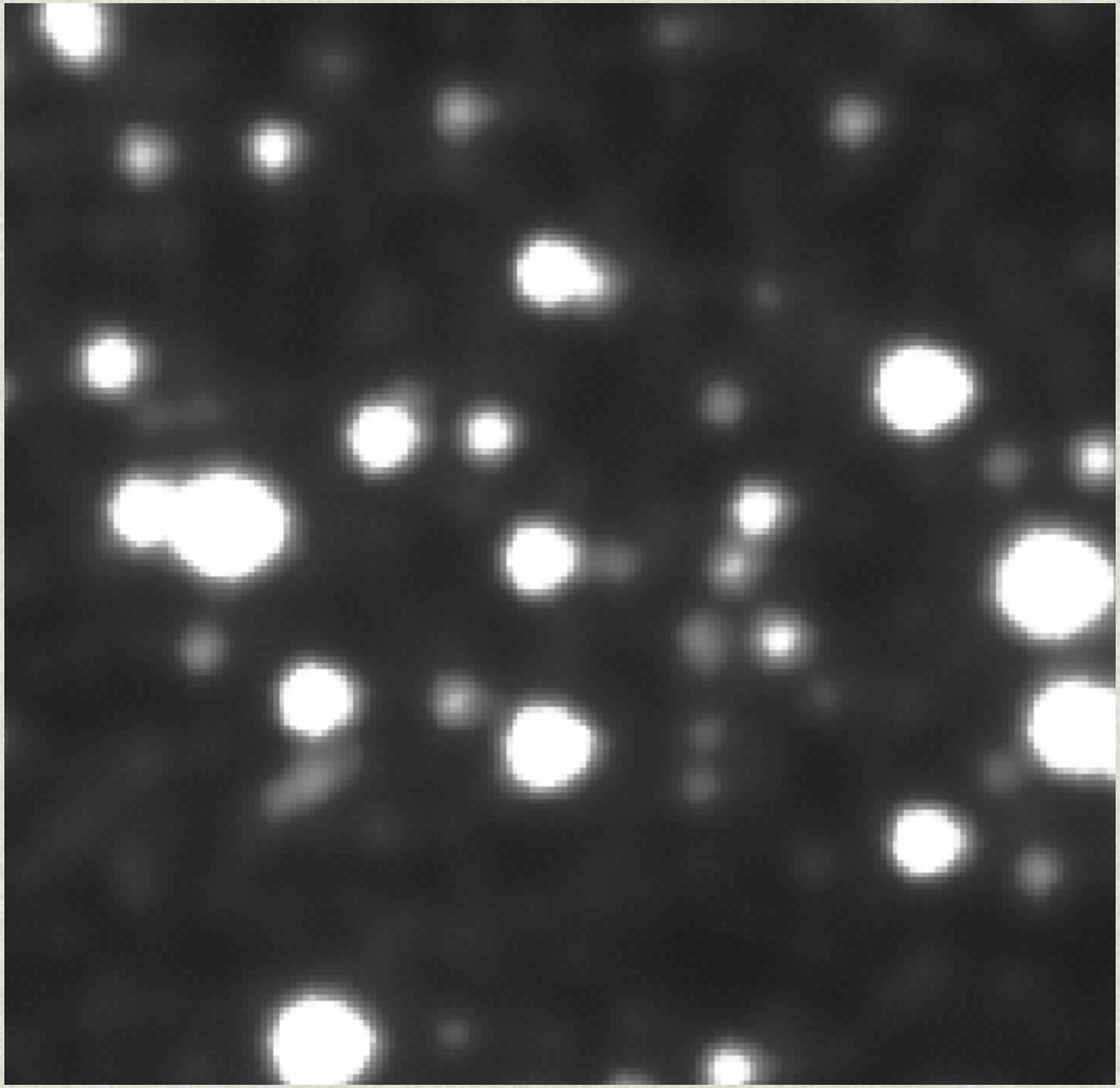


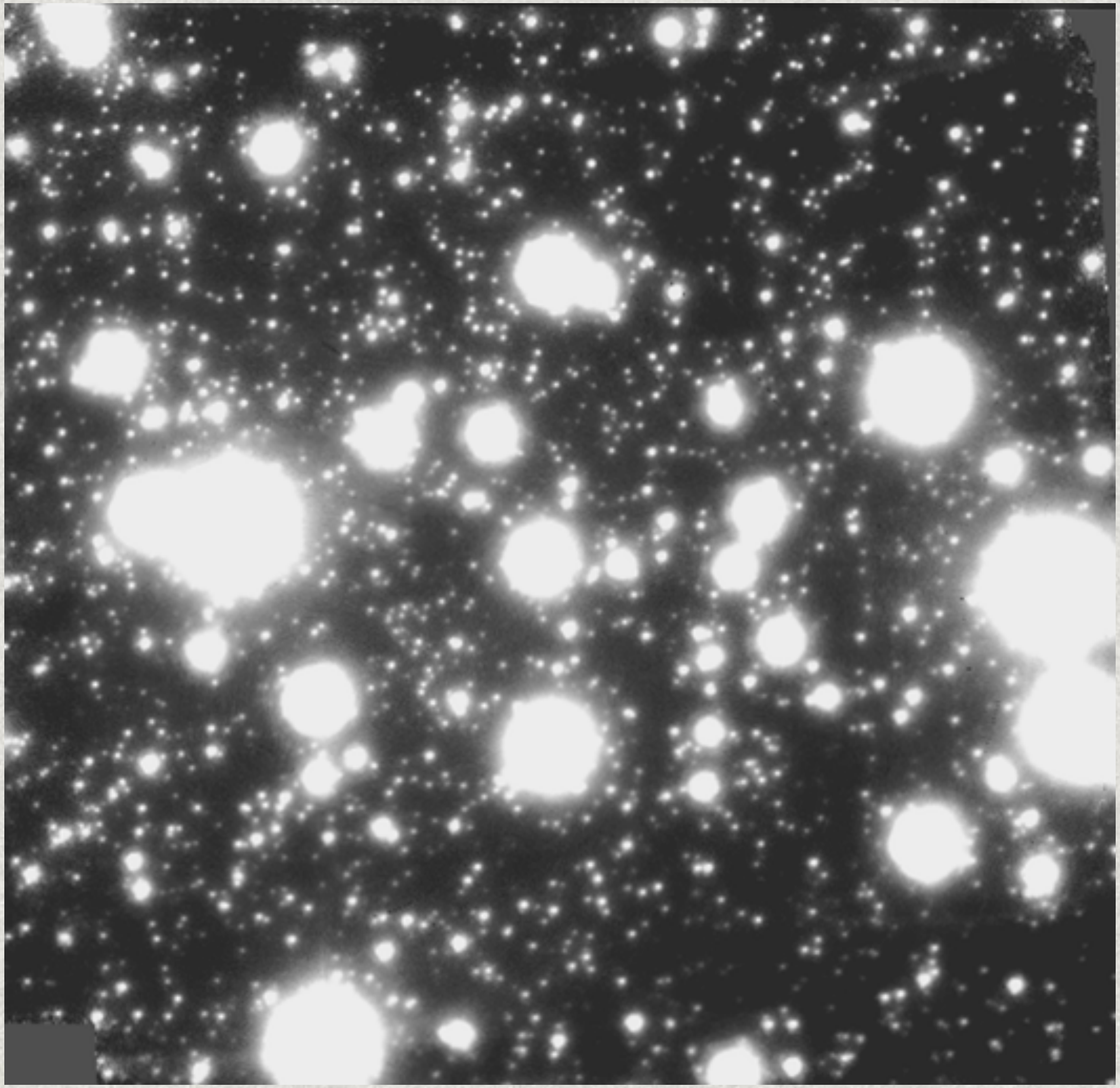
CREDIT GEMINI OBSERVATORY

IMAGE SIZE
WITHOUT AO: 0.6”
WITH AO: 0.08”

FIELD OF VIEW
20”X20”

M13 Globular Cluster

Australian National University



CREDIT GEMINI OBSERVATORY

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WITH AO: 0.08”

FIELD OF VIEW
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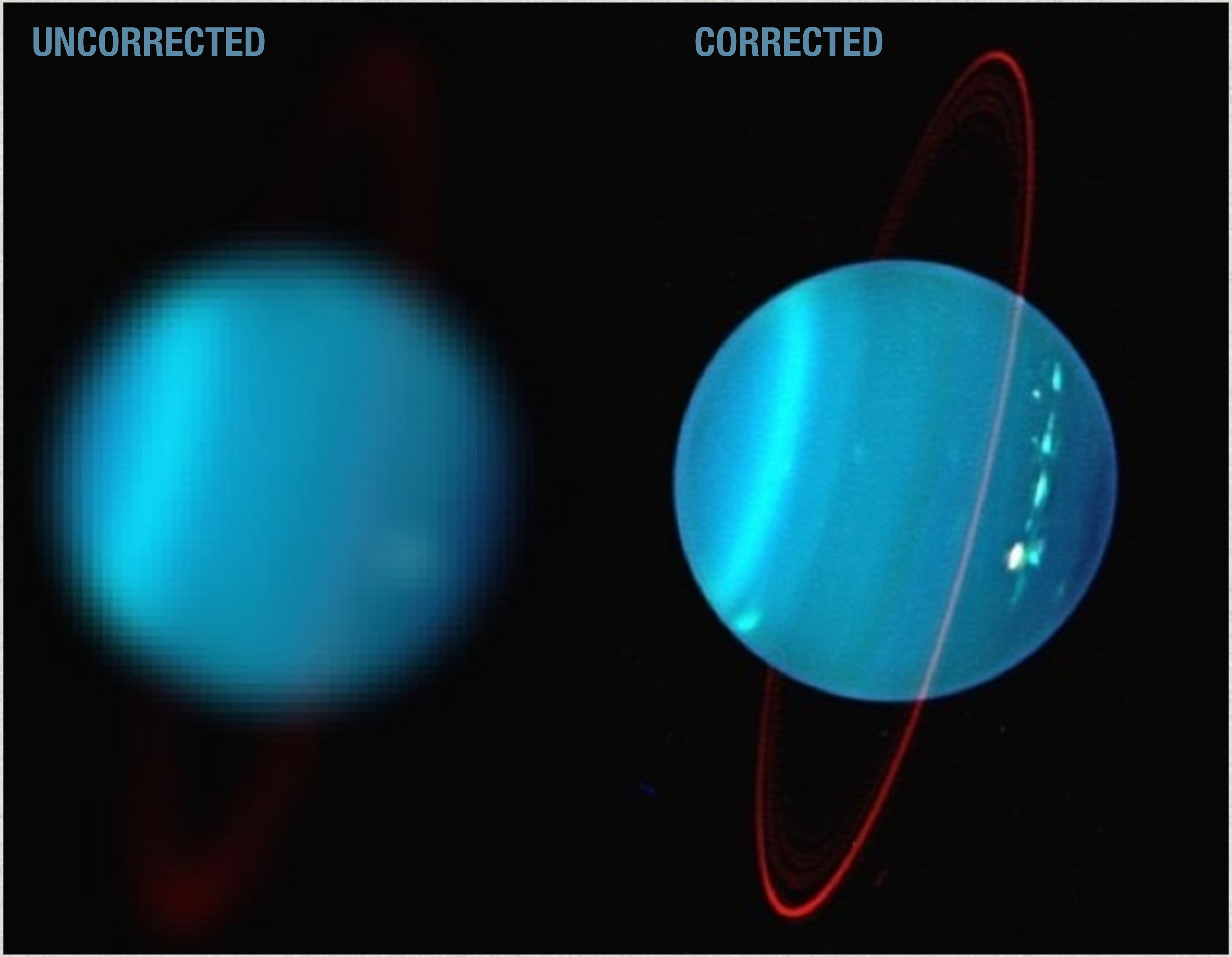
Uranus, with and w/o AO

Australian National University



URANUS

∅ 4”

KECK II

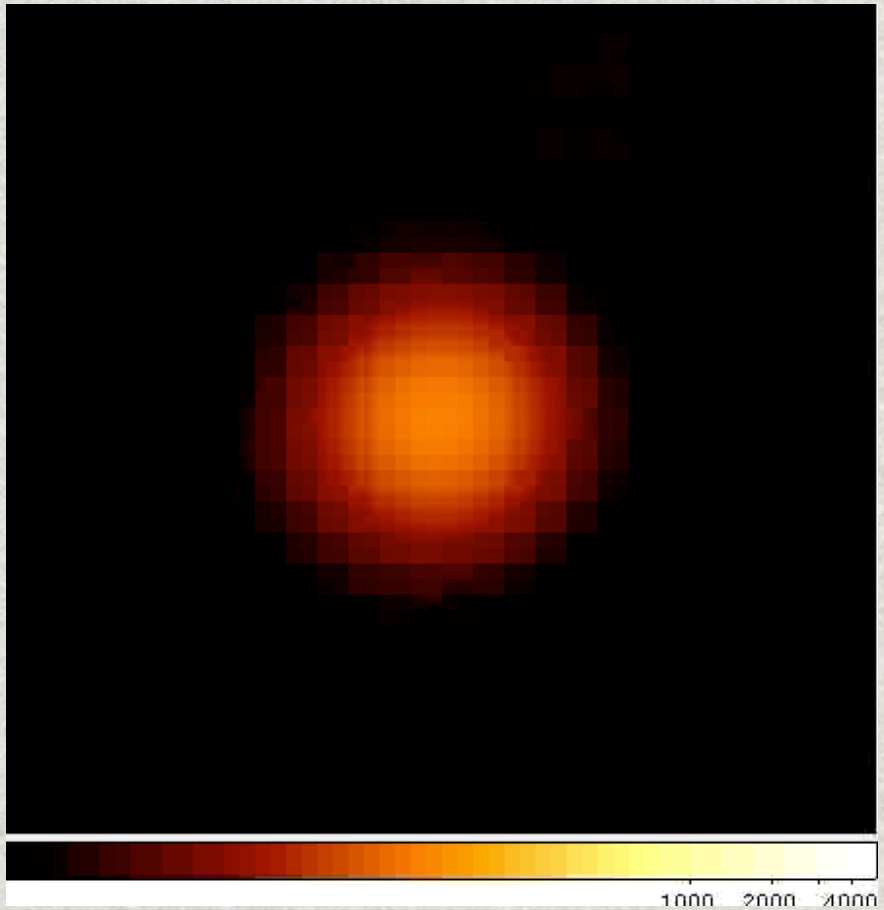
NEAR IR

CREDIT KECK OBSERVATORY

What does AO do?

- Reduce image “size”=width=FWHM ➜ **See more details**
- Concentrate the light, against sky background and/or detector noise ➜ **See fainter objects**

CREDIT MAGAO TEAM



CREDIT MAGELLAN TELESCOPES / MAGAO TEAM

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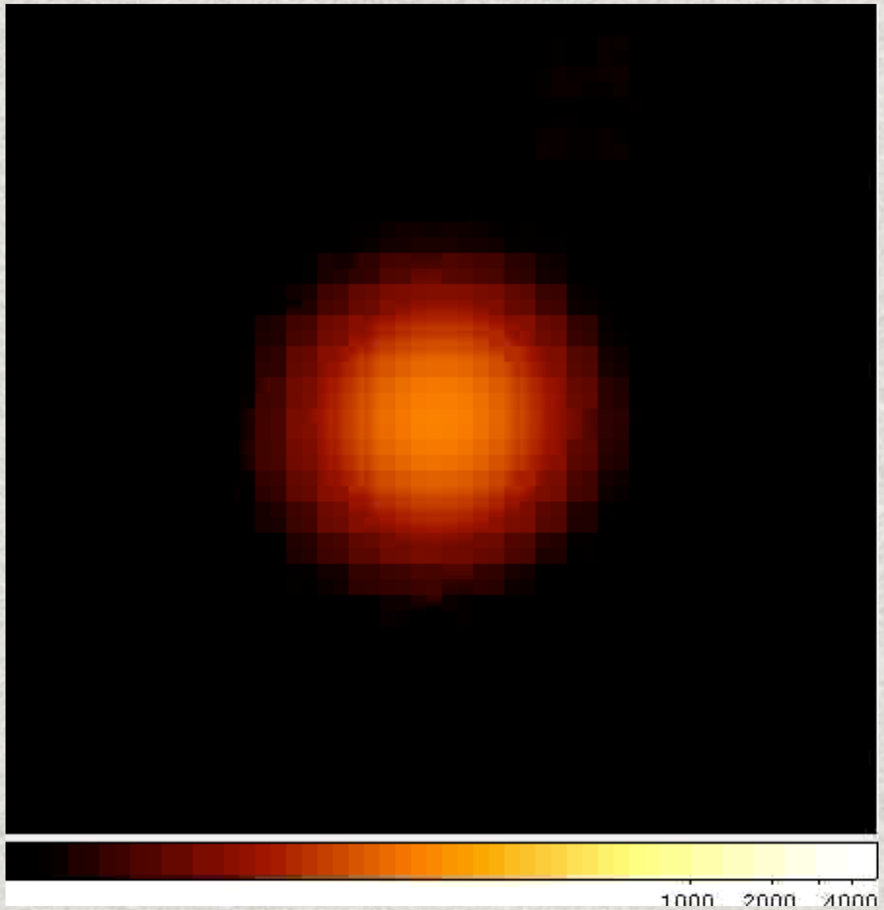

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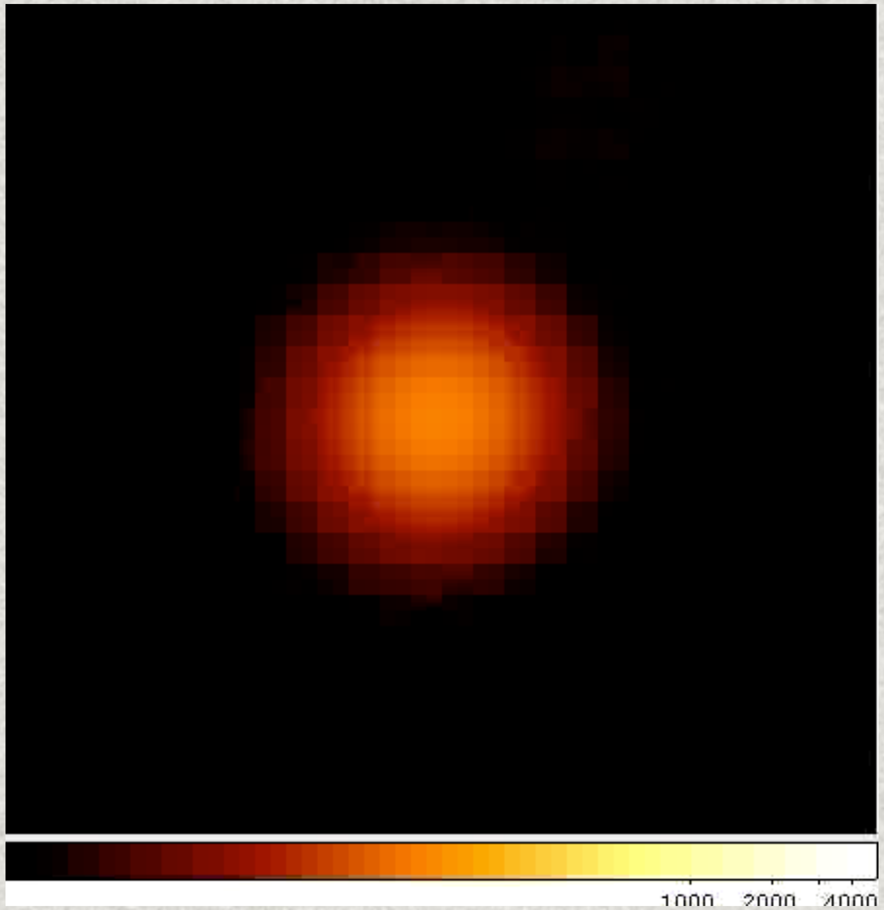


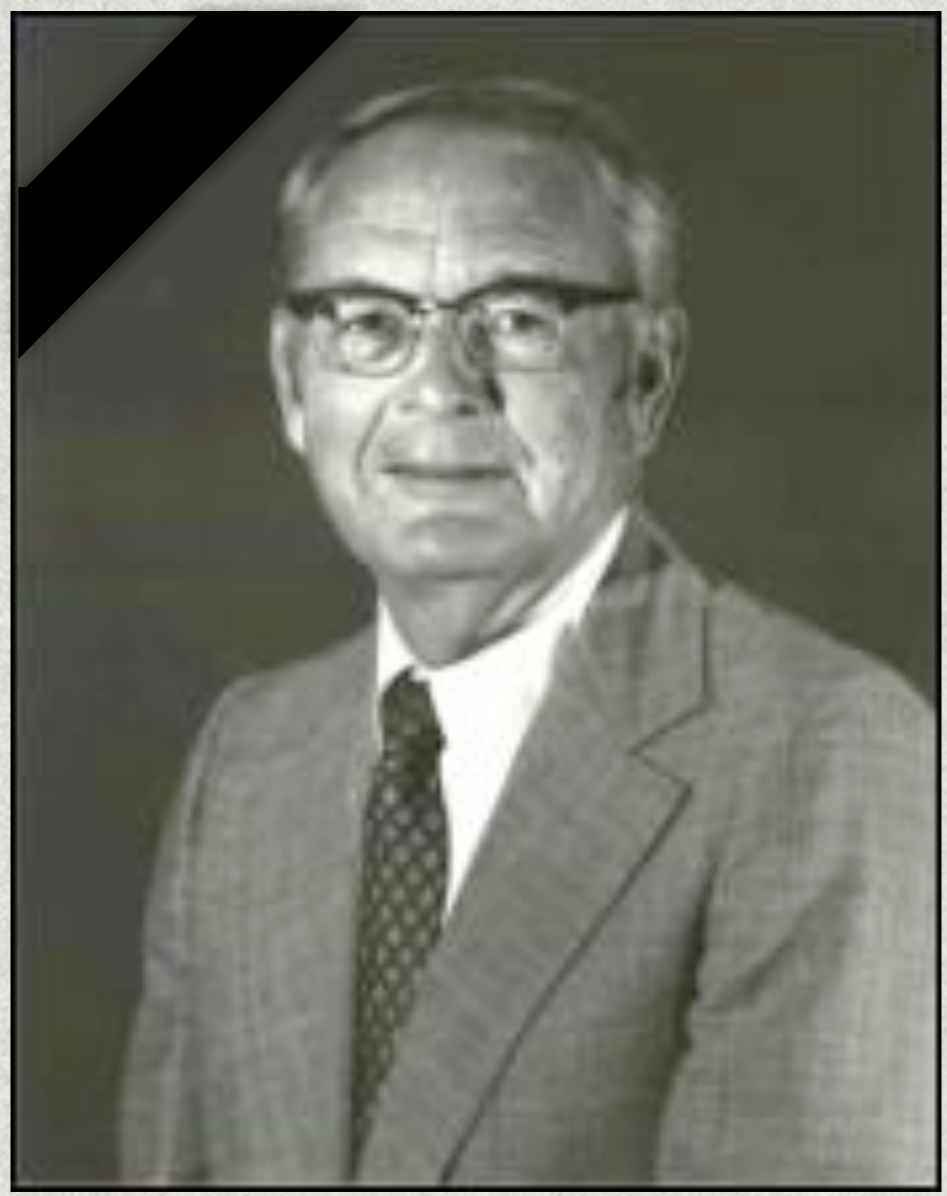
CREDIT MAGELLAN TELESCOPES / MAGAO TEAM

A brief history of Adaptive Optics

Horace Babcock (1912-2003)

Australian National University

- Generally viewed (rightly) as the inventor of adaptive optics
- Seminal paper: "*The Possibility of Compensating Astronomical Seeing*", PASP, October1953
- Worked at MIT, Caltech, then as Director and astronomer at Mt Wilson and Mt Palomar



The History of AO

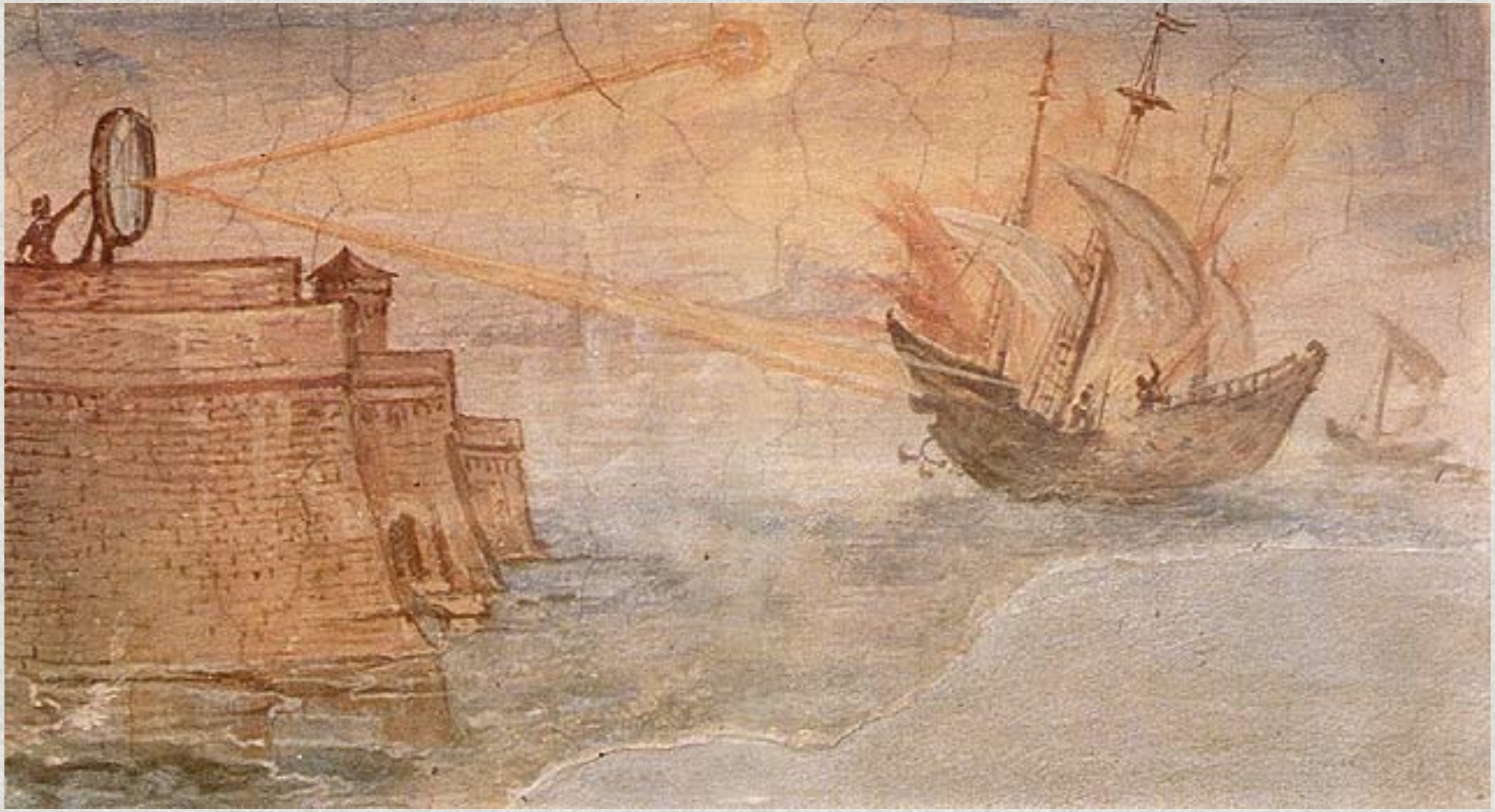
Australian National University

- 212 BC - 1953: Prehistory of Adaptive Optics
  - *Archimedes, Galileo, Newton, Foucault, Hartmann, paving the road*
- 1953 - 1973: From concept to reality
  - *Babcock, Linnik, Shack, Fried, ...*
- 1973 - 1989: The military years
  - *Hardy, Buffington, Greenwood and the DARPA efforts*
- 1989 - 1995: Astronomical AO comes to age
  - *Come-on, UH curvature, PUEO*
- 1996 - 2010: The big boom
  - Recognition of AO by astronomy and telescope communities
  - Eruption of instruments *and* new concepts
  - Opens the door to ELTs
- Astronomical AO becomes mainline with the ELTs

The Prehistory of AO (212BC - 1953)

Australian National University

- 212 BC: Archimedes allegedly uses (powered) mirrors to burn and drive away Roman ships. Once again, military applications drive science and technology.



- Cleomedes (1rst Century AD): Atmospheric refraction

The Prehistory of AO (212BC - 1953)

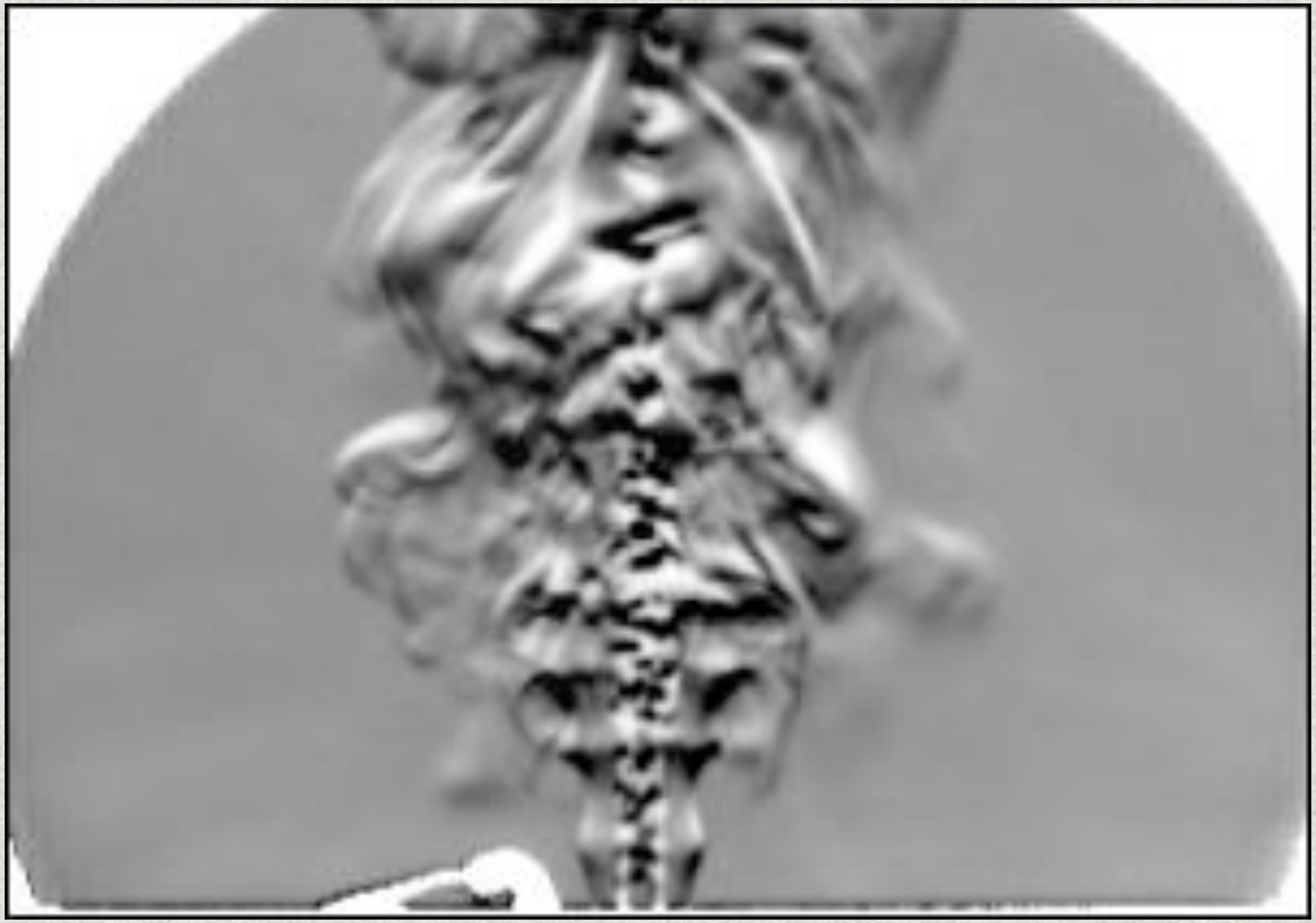
Australian National University

- 1704: Newton describe the effects of atmospheric turbulence in *Opticks*:

> *"If the Theory of making Telescope could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by [...] the twinkling of the fix'd Stars. [...] The only Remedy is a most serene and quiet Air, such as perhaps can be found on the tops of the highest Mountains above the grosser Coulds."*

The Prehistory of AO (212BC - 1953)

- 1859: Foucault's knife-edge test. A first order, qualitative Wavefront Sensor
  - long exposures: figure of telescope optics
  - short exposures: mirror figure + atmospheric turbulence



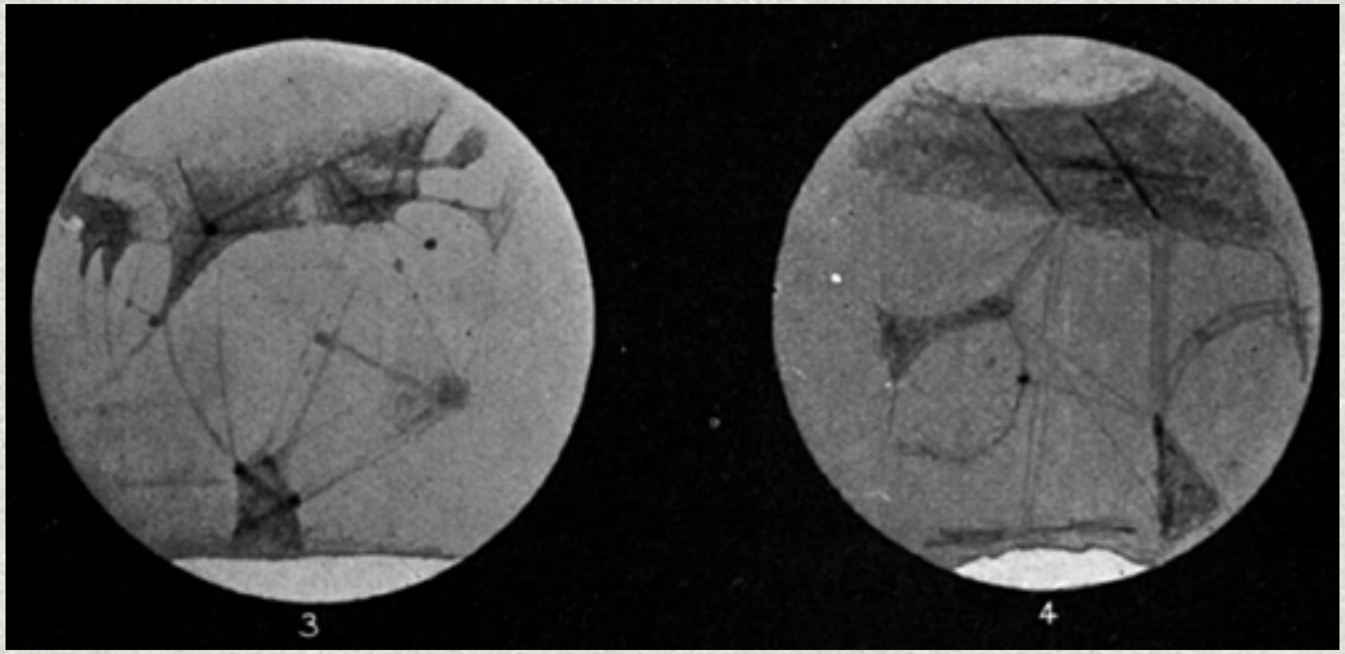
20th Century Players

- Karl Strehl
- Andrei Kolmogorov
- Fritz Zernike
- Roland Shack
- David Fried

- And many others: Roddier, Tatarski, Greenwood...

Precursors of AO

- **Drawings** made in the early days is a form of intelligent frame selection, but is more similar to lucky imaging, sans quantitative selection criteria
- **Tip-Tilt stabilisation** has all aspects of AO (speed, close loop) except high order (Babcock again or HRCam @ CFHT, etc)



Babcock's realizations

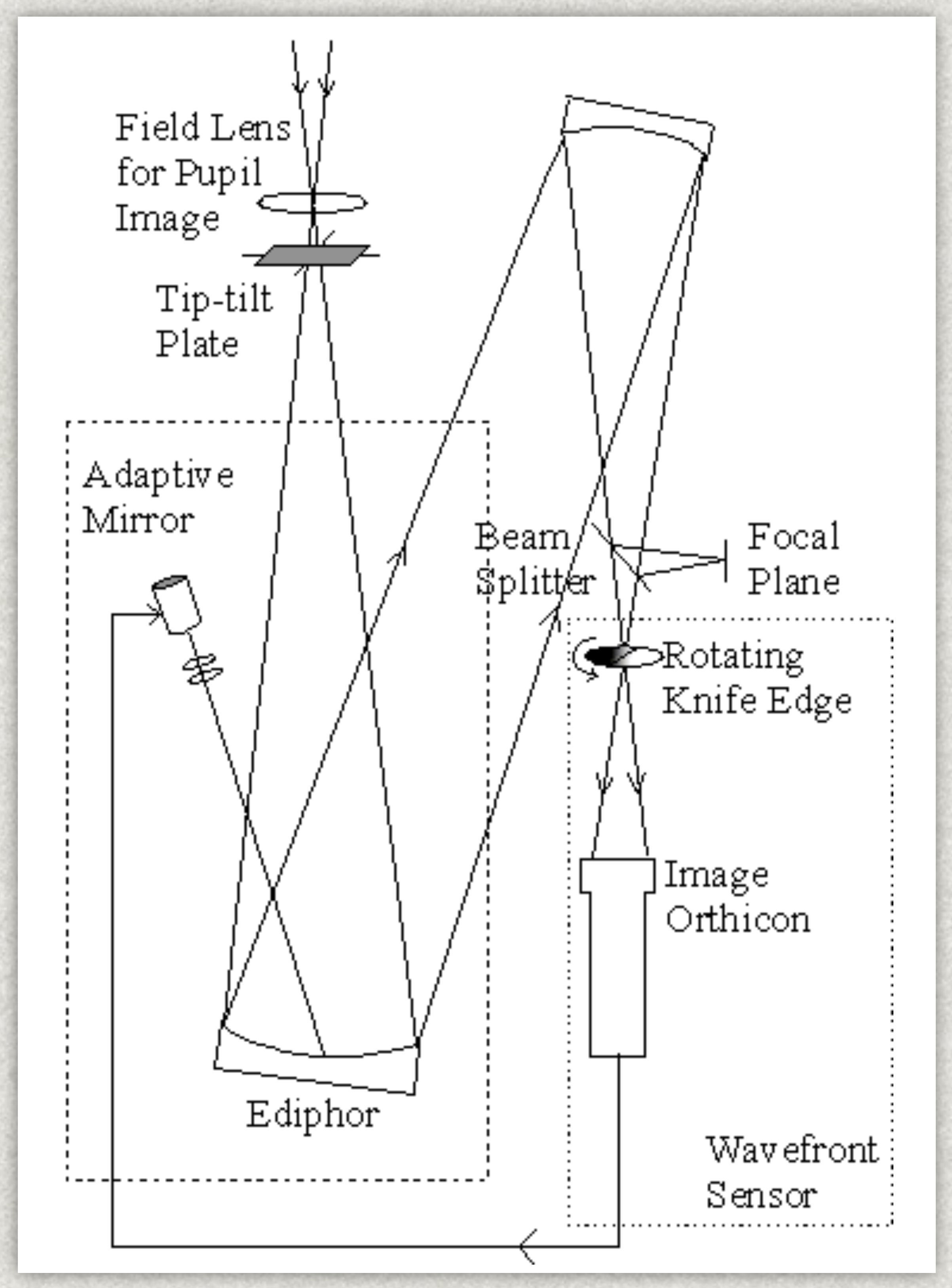
Australian National University

- Babcock role was not contained to proposing AO. A few of his realisations relative to image compensation:
  - 1947: Built the first 2D automatic guider using a rotating knife edge 1/3 Hz sampling.
  - 1953: AO seminal paper
  - 1953: Improved guider using a separate Tip-Tilt plate and rotating knife edge (60Hz sampling, 10Hz bandwidth)
  - 1958: Proposal of a new kind of DM (electrostatic membrane)

Babcock's original idea

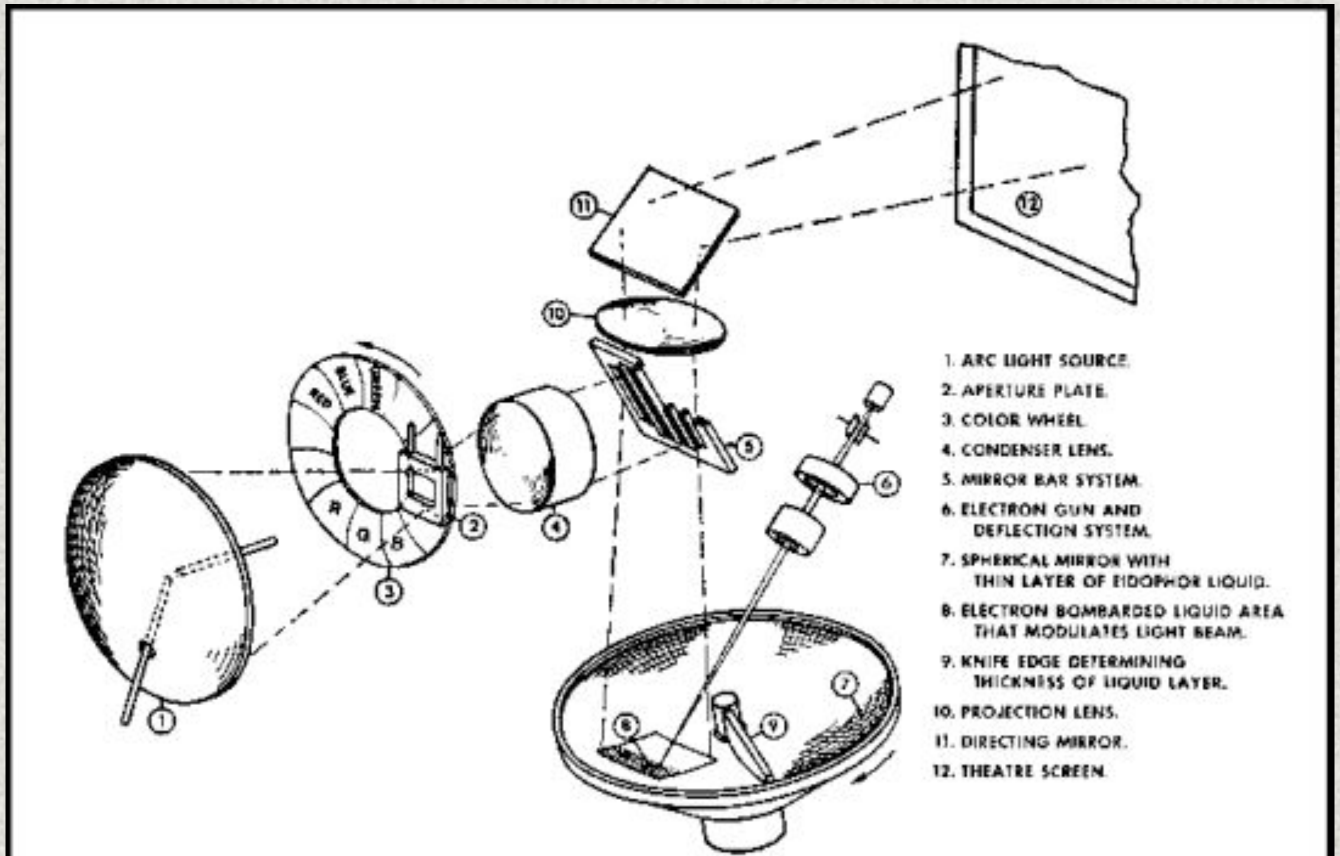
Australian National University

- The 1953 paper included a concrete implementation proposal. All is there:
  - Pupil re-imaging
  - Separate TT corrector
  - Wavefront sensor and corrector
  - Close loop arrangement



Babcock’s original idea

- Babcock’s DM: the **Eidophor**
- Babcock also understood the limitations we are still struggling with:
  - Need for a bright star
  - Correction only valid close to the guide object
  - ...and therefore limited sky coverage
- Babcock was presented the Hale Prize in 1992



Essential parts of the Eidophor projector.

V.P. Linnik (1957)

- Babcock's proposal (1953) was paralleled in a 1957 paper by V.P. Linnik (U.S.S.R.):
  - First proposal to use a segmented mirror
  - White light interferometer
  - Realisation of guide star limitations lead Linnik to the first proposal of an artificial guide star (in airplane 8-10km high)

The DARPA years

- 1972: At the heart of the cold war years, DARPA (Defense Advanced Research Projects Agency) looks for a mean of identifying/imaging USSR low earth orbit satellites.
  - Contract Itek (Hardy and coll.).
  - Problem more difficult than for Astro
    - fast moving target (require 10kHz sampling)
    - any seeing conditions, visible wavelength.
  - Many technologies to develop:
    - fast wave-front sensing (shearing interferometer)
    - Reconstructor (analog, array of resistor; local)
    - DM: Feinlieb et al ➜ MPM* 21 actuators
  - More theory: WFSs for white light, extended sources.

* MPM = Monolithic Piezoelectric Mirror

The DARPA years (cont'd)

Australian National University

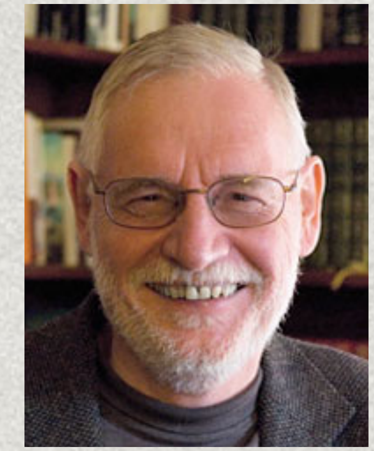
- December 1973 ! : First lab tests of the Real-Time Atmospheric Compensator (RTAC). First close loop ever. Very successful tests.
- Summer 1974: RTAC field tests. Horizontal propagation. Successful.
- In Parallel, "Multi-dithered" methods investigated by Buffington et al. Image sharpening method using hill climbing. Some success but difficult to scale to large apertures/large number of actuators.
- Next generation was designed on the principle of RTAC

The DARPA years (cont'd)

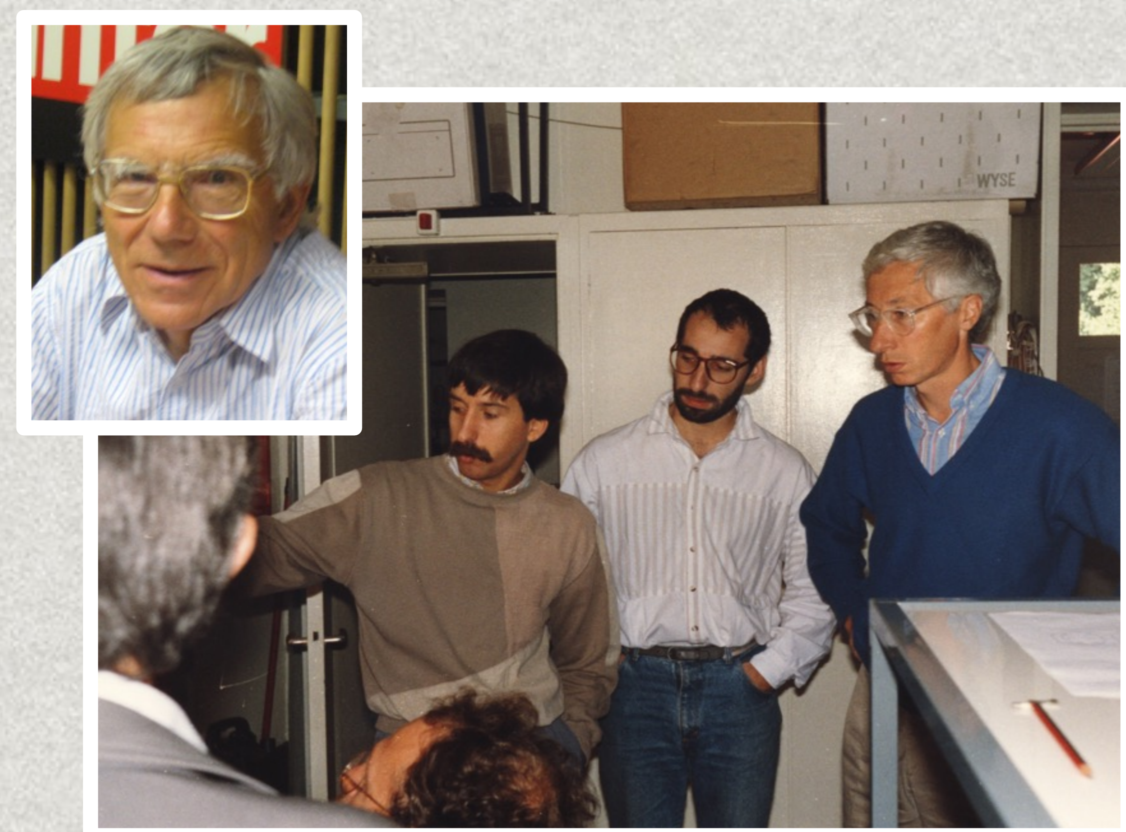
- 1974-1982: CIS (Compensated Imaging System).
  - first light in 1982
  - 168 actuators ! Separate TTM
  - Shearing interferometer w/ photomultiplier tubes
  - Bandwidth 1000Hz !
  - Cass. mounted on AMOS 1.6-m Maui telescope
  - Full fledge diagnostics report system
  - In use till 1994. Hardy refers to it as the grandfather of AO systems (A shameful grandfather that has made himself known only very late to its descendants)
- 1992: Special issue of J.O.S.A including many declassified results. "Reserved" to military programs.

Astronomical AO: early years

- First known project for night time astronomy @ NOAO in 1985-87. Beckers, Roddier & Kibblewhite. “*Too many primadonas**”. Project is stopped in ~1987



- In Europe, the VLT agreement is signed. Pierre Léna (CNRS), J.-C. Fontanella (ONERA) and Fritz Merkle (ESO): AO is required to take full advantage of ***8-m interferometric coupling***. Start of COME-ON (1987-1992).

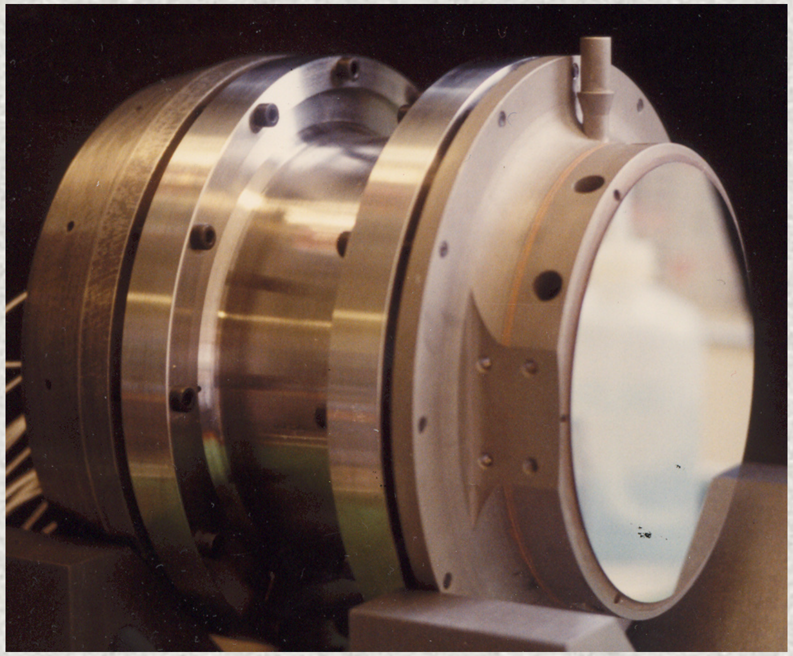


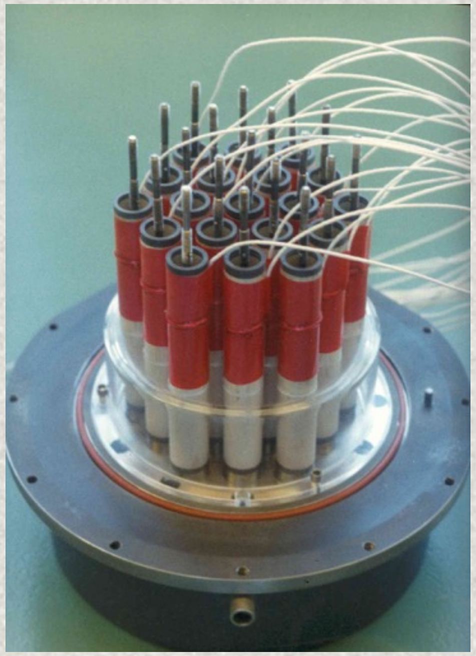
* Beckers 2008

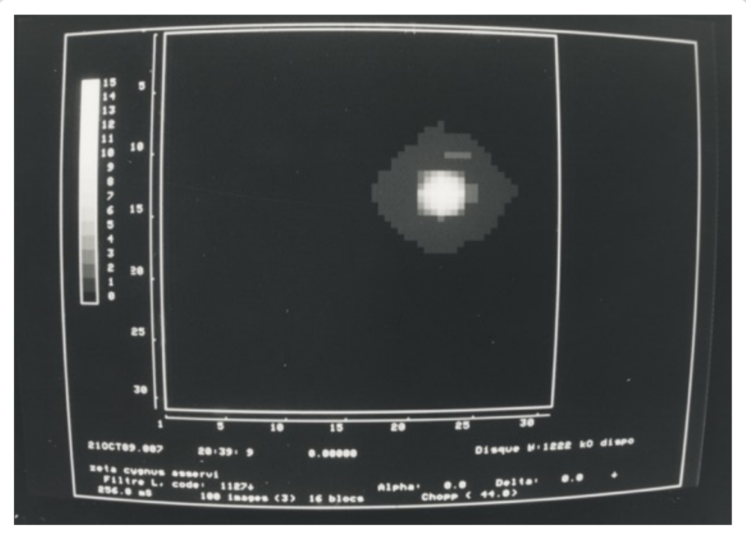
The COME-ON System

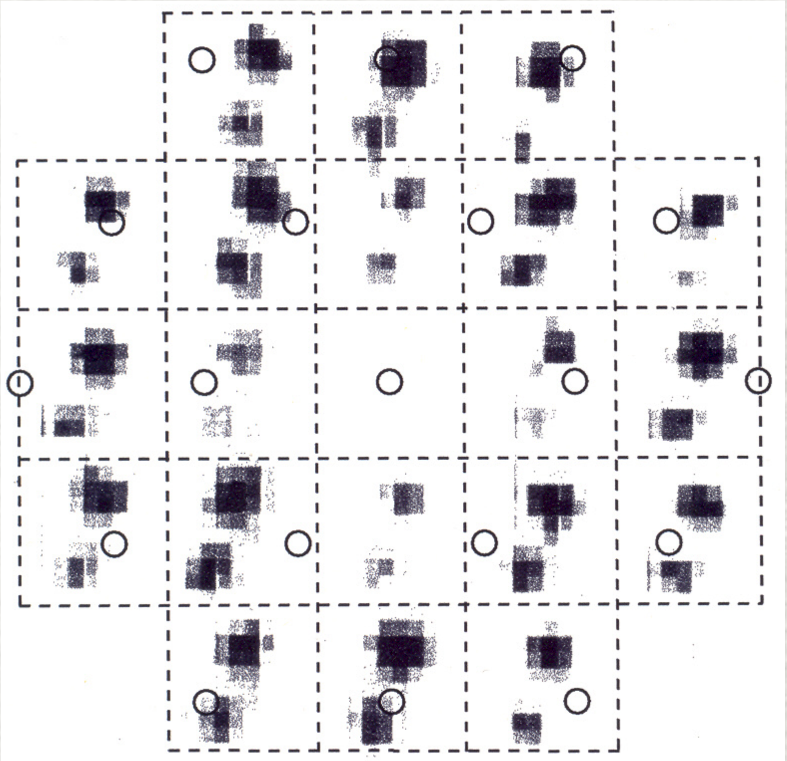
Australian National University

- COME-ON spins off partly from French's own "defence" efforts in AO. Deformable mirrors and expertise available from Laserdot & ONERA (LATEX, SILVA).
- Bench integrated in Meudon (Kern et al 1989)
- 19 actuators Piezostack mirror
- 20 subapertures Shack-Hartmann sensor, with image amplifier (QE≃7%)
- 32x32 IR Camera





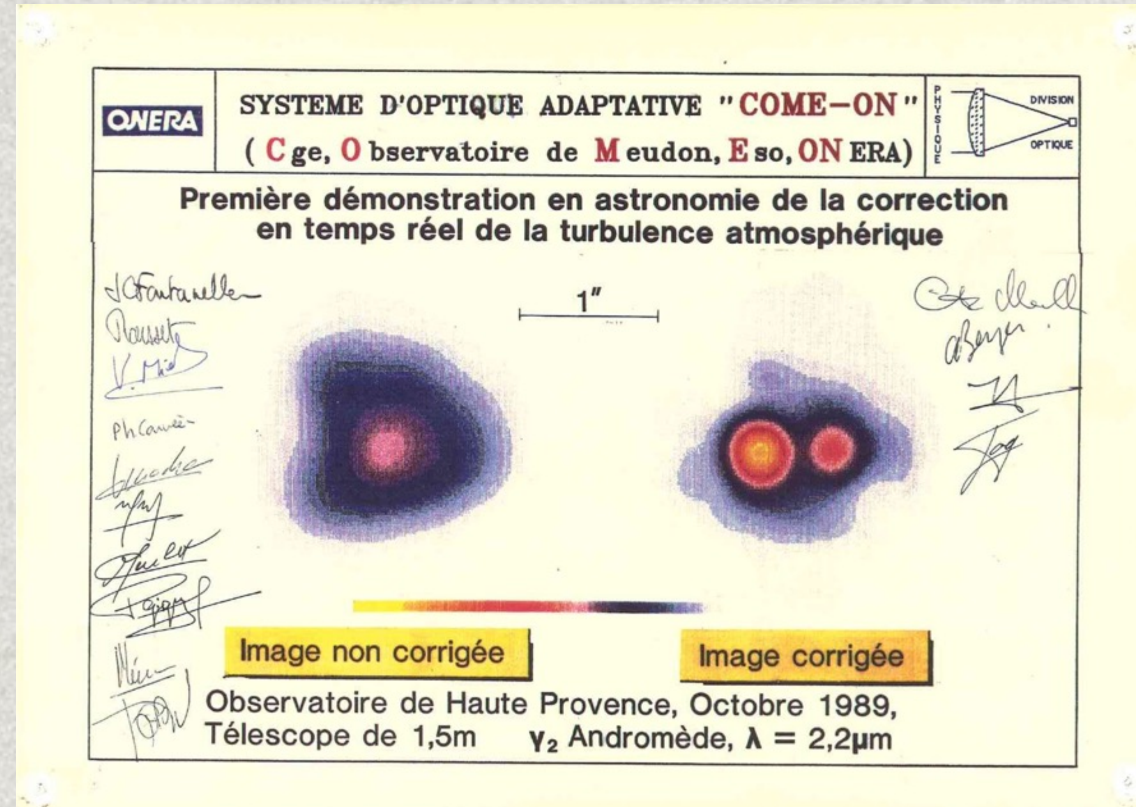


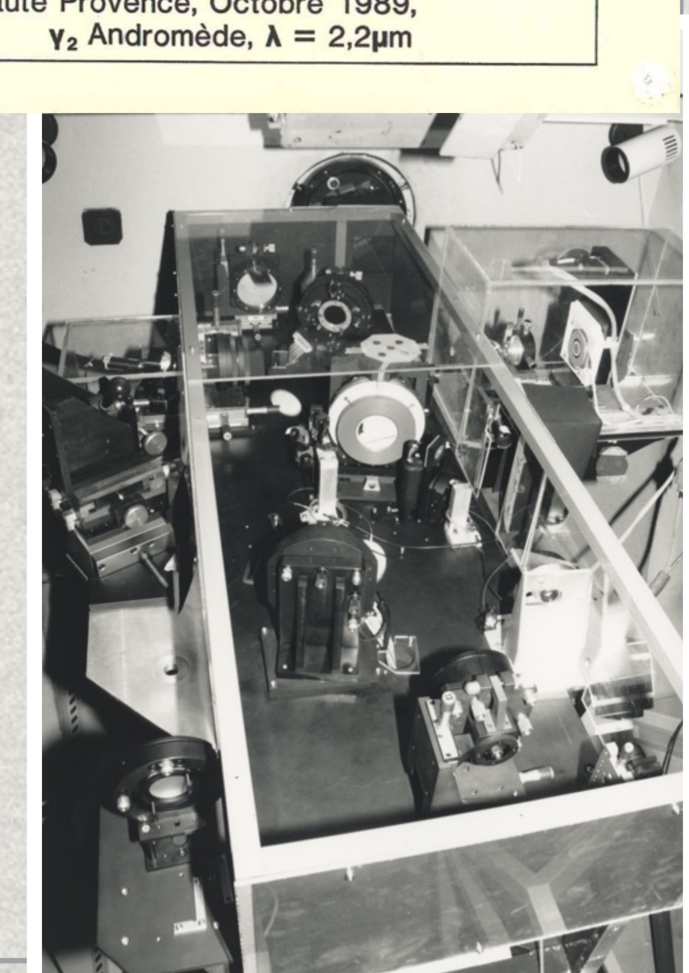


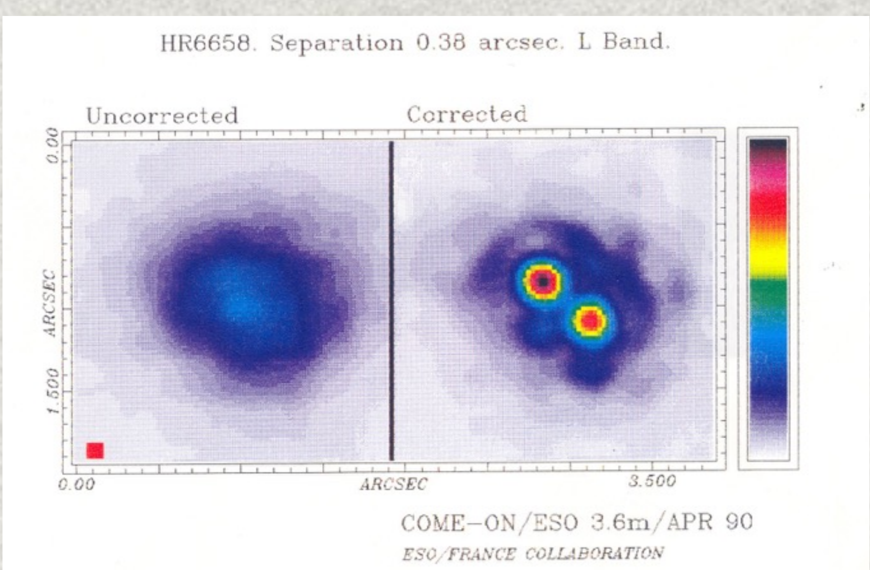
The COME-ON System

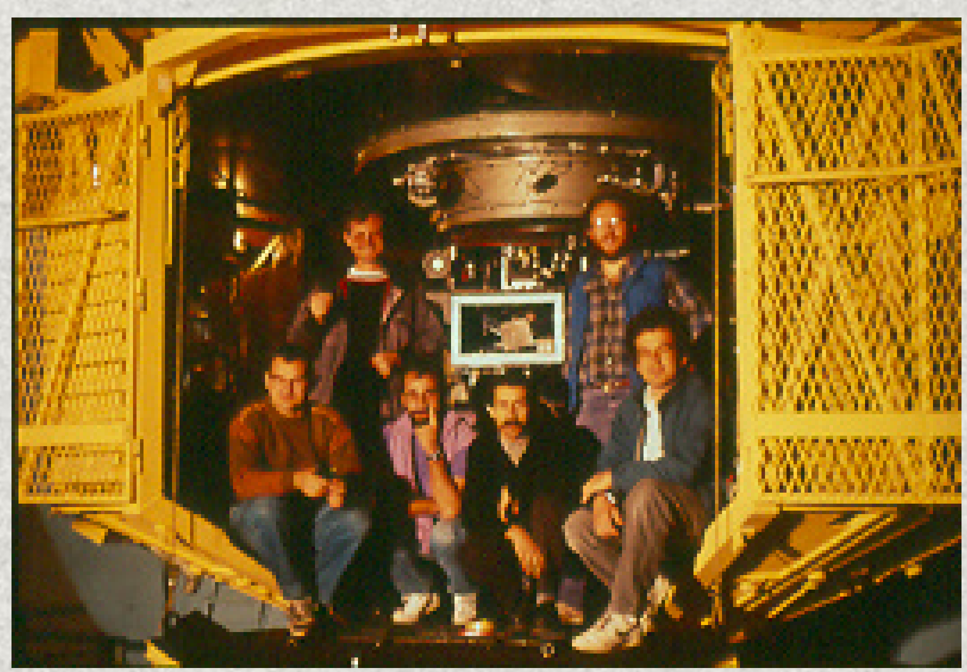
Australian National University

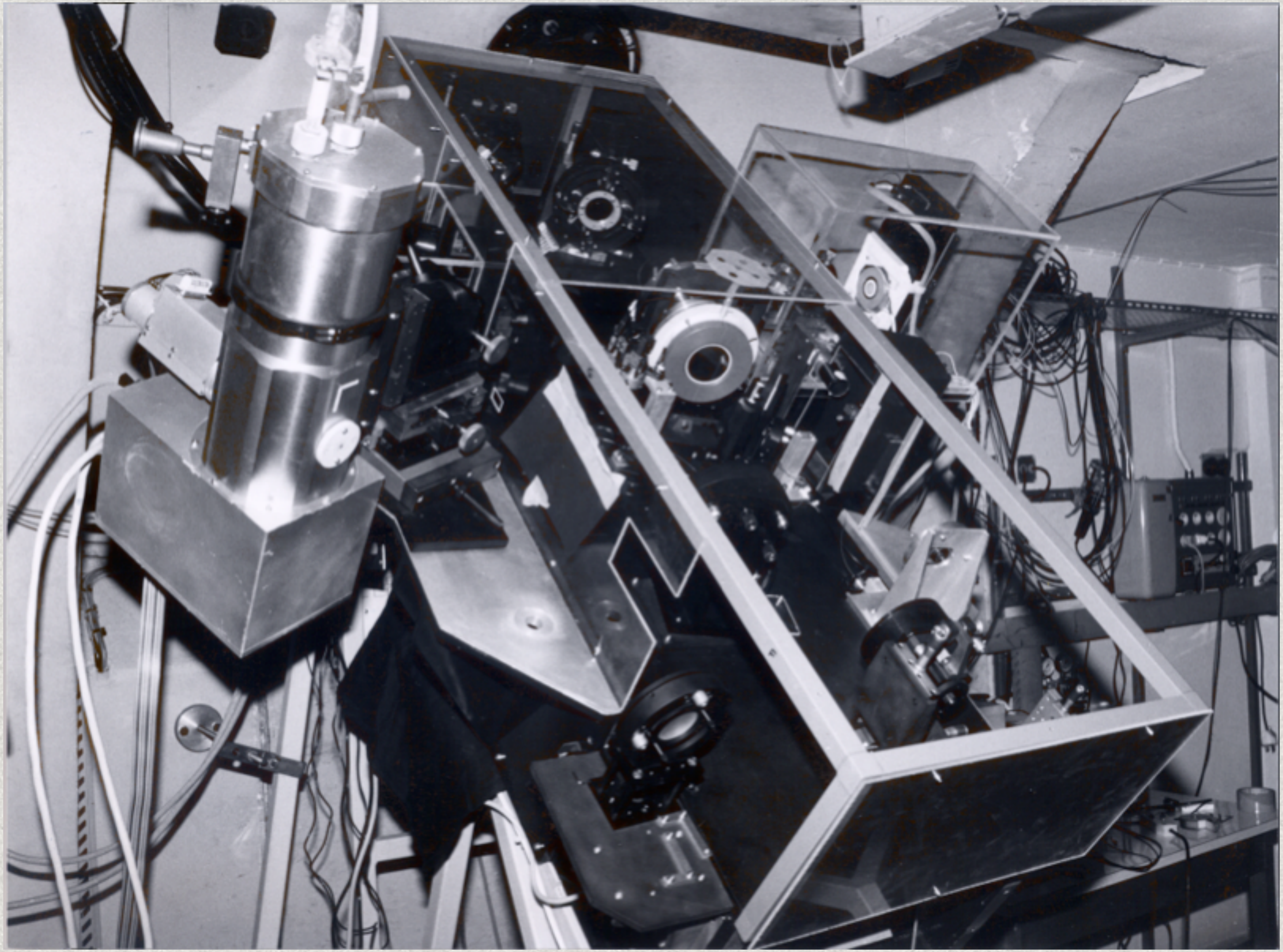
- First light in November 1989 at Observatoire de Haute Provence. Success: Diffraction limit achieved in the NIR in mediocre seeing conditions (Rousset et al 1990)
- Moved to the 3.6-m at ESO La Silla in 1990. Used successfully for several runs until 1992 (Rigaut et al 1992)

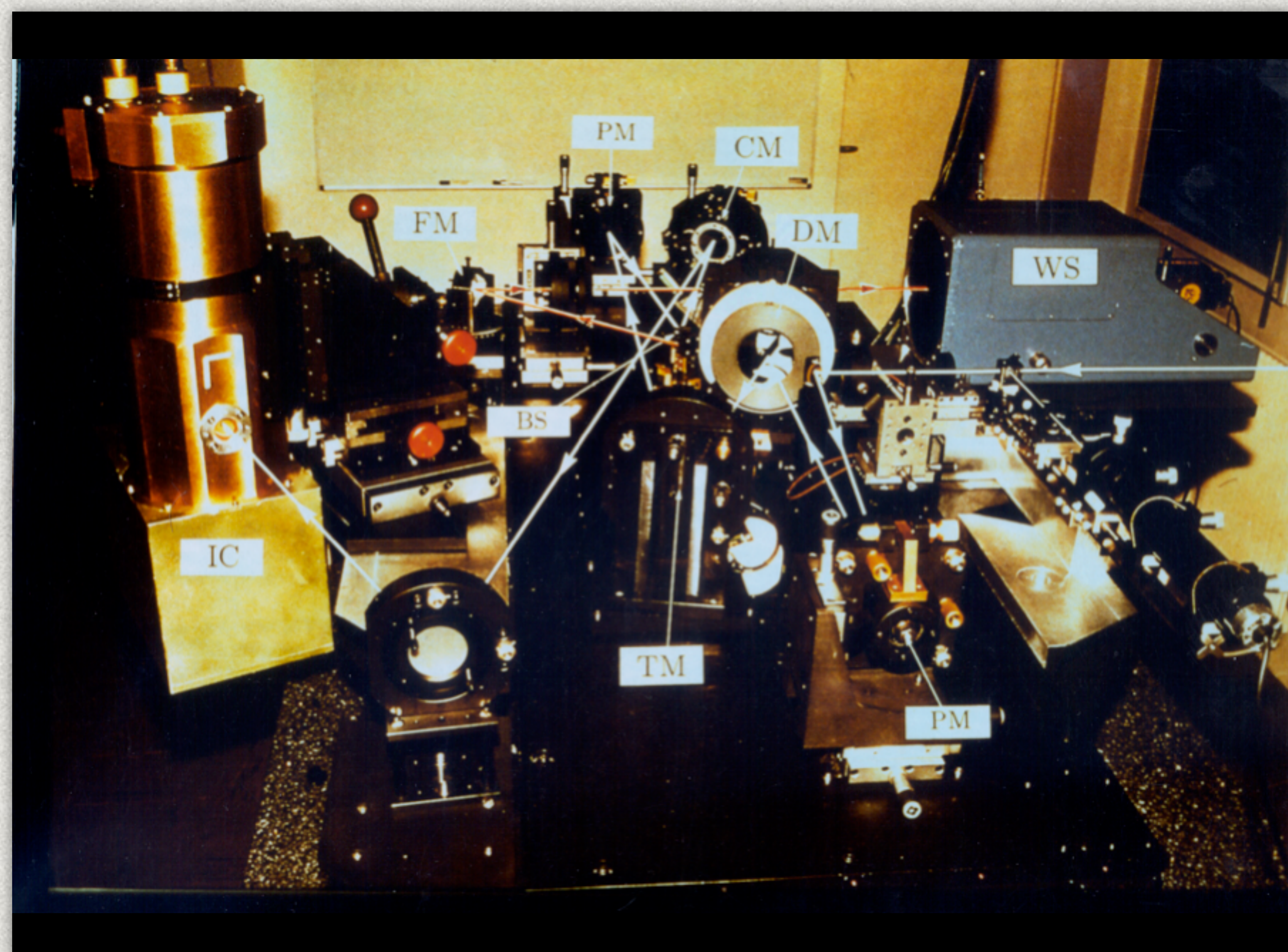








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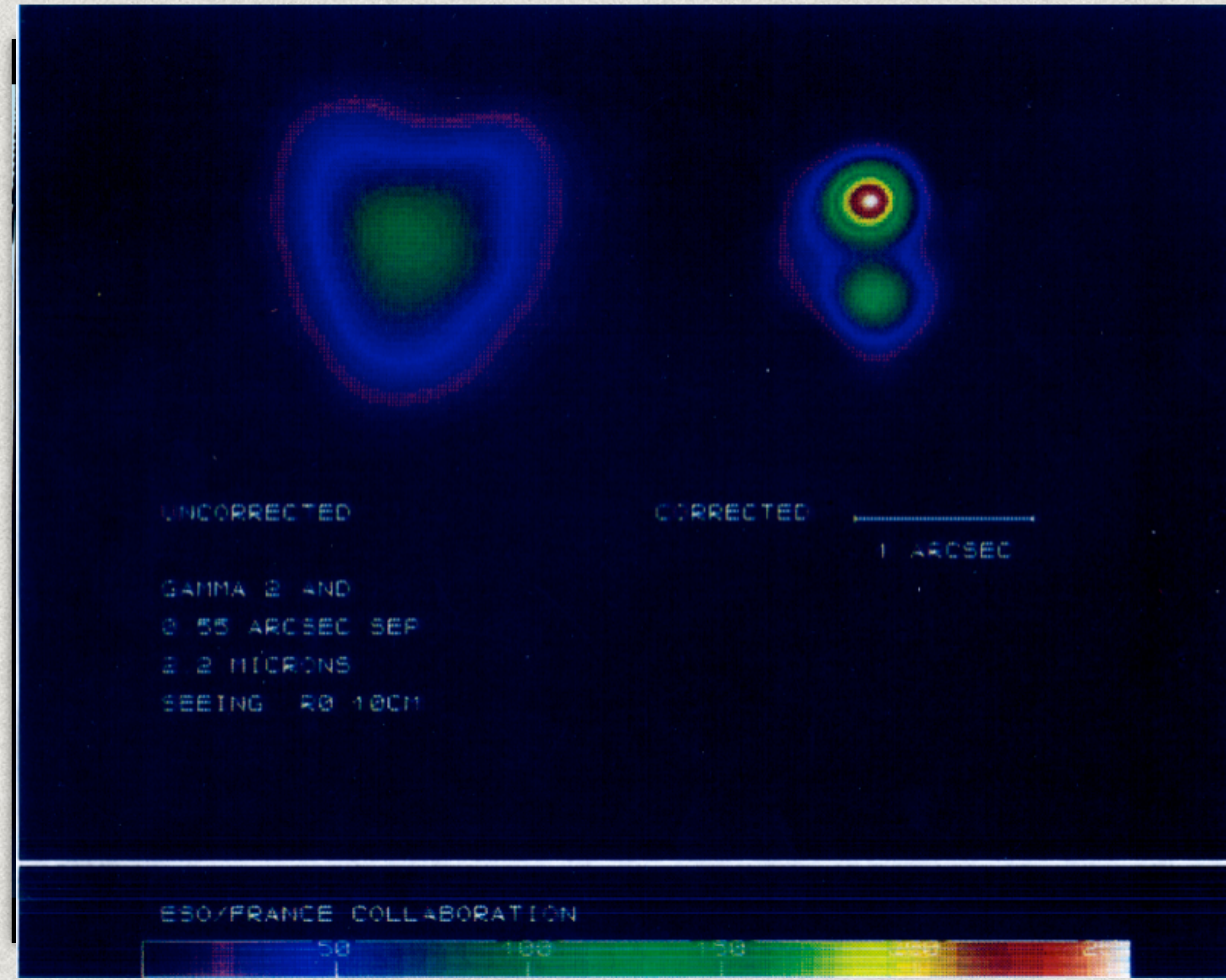
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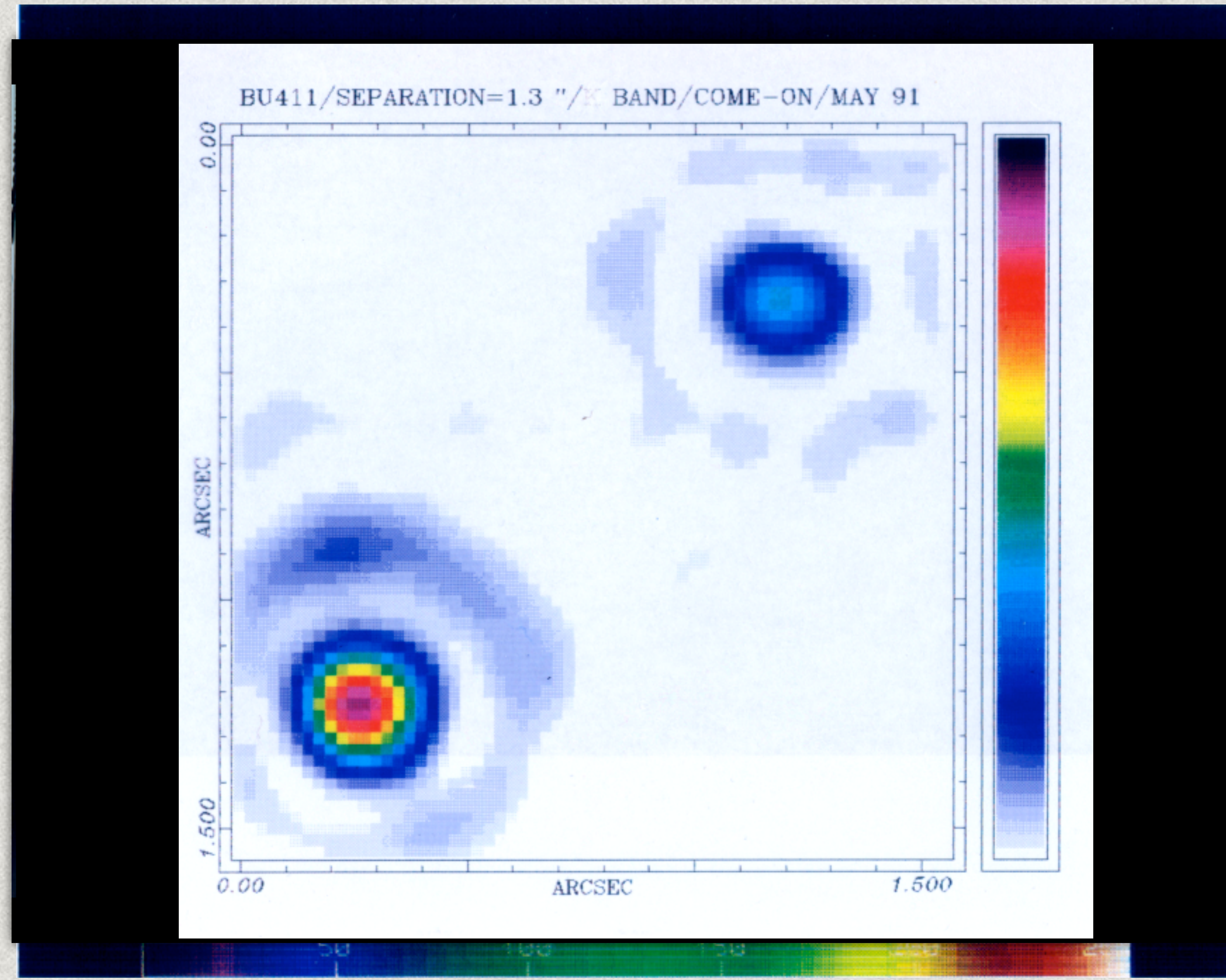
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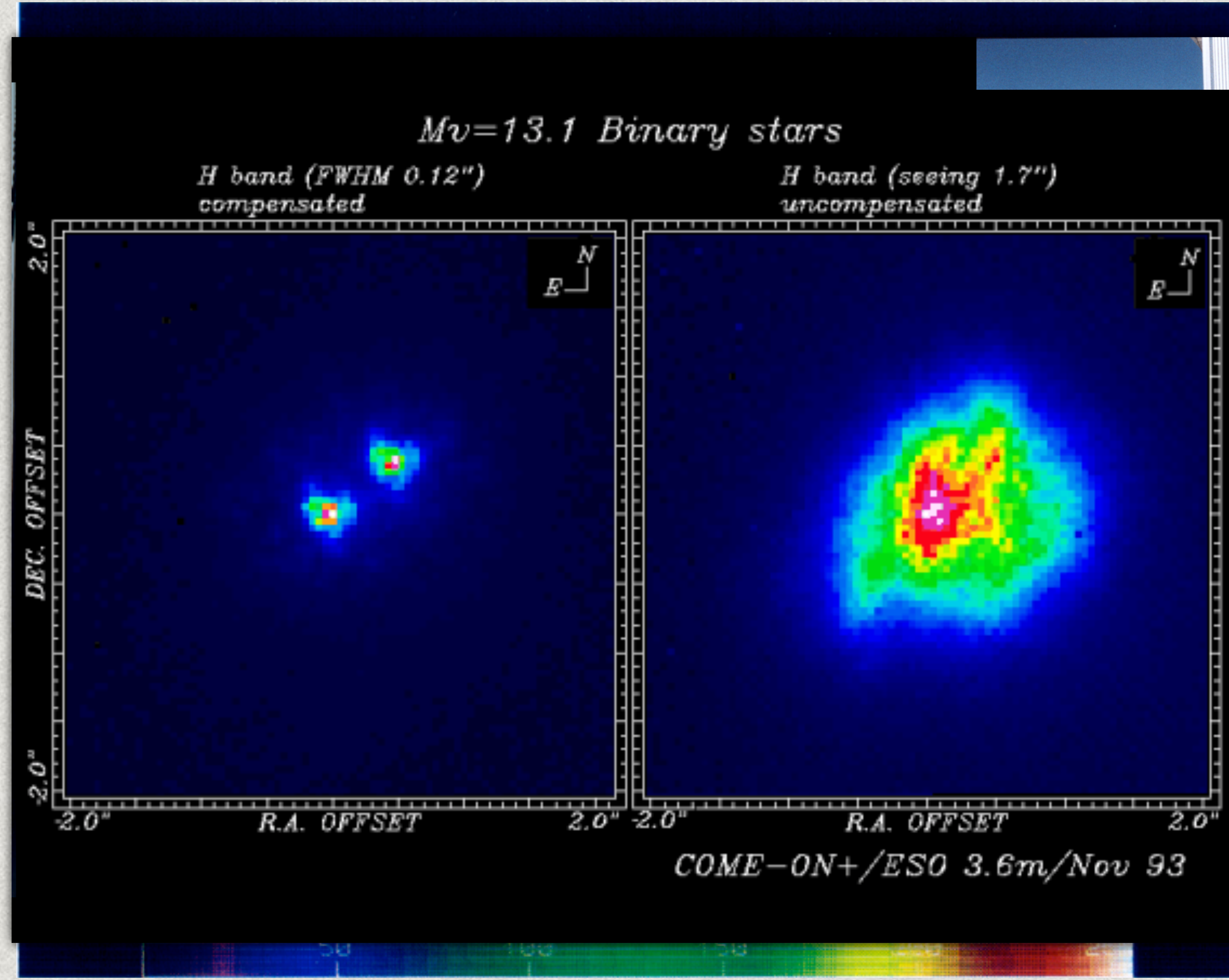
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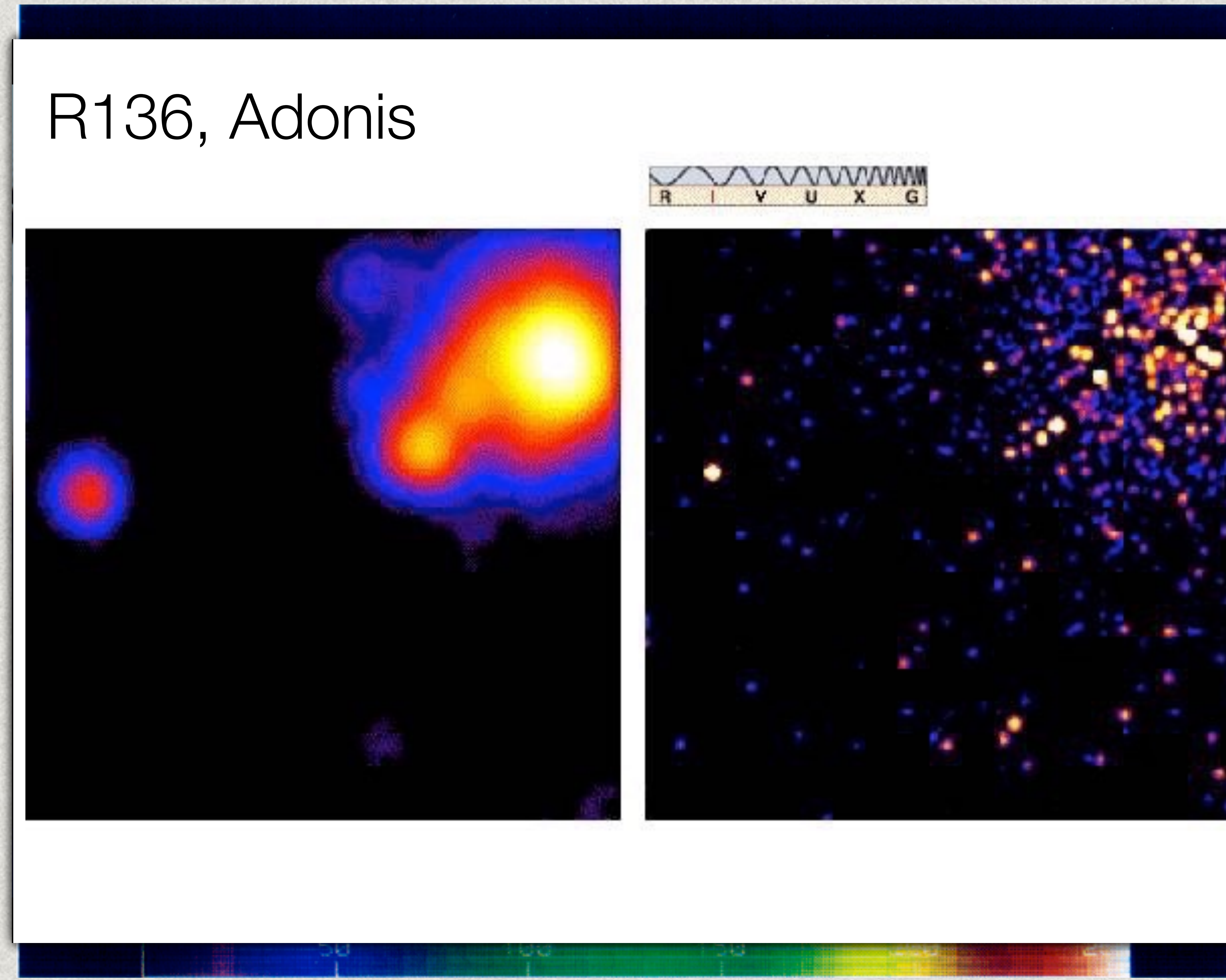
COME-ON+/ESO 3.6m/Nov 93

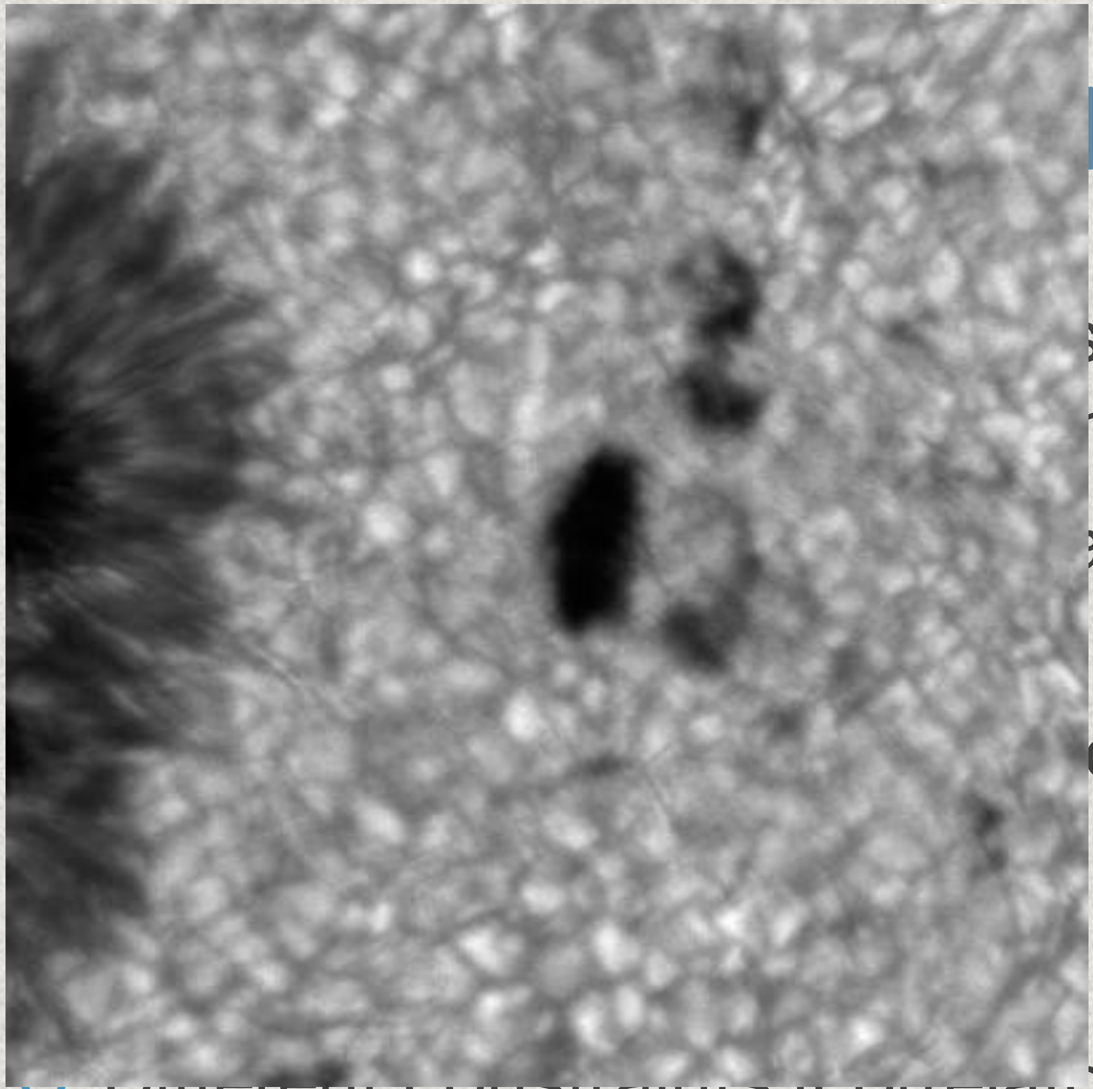
R136, Adonis



1kW per square meter...

Australian National University

- Meanwhile, solar astronomers were actively working: Lockheed/Itek put a system at Sac Peak in the mid-late 80's with FWHM gain of 3-4.
- Extensive program at Sac peak/Big Bear and 3 other facilities in the world.
  - Typically 70cm class telescopes
  - AO 24: 1998-2000
  - AO 76: 12/2002-now
- Different constraints (correlators)
- Limitation: Field of view ⇨ MCAO programs in the work



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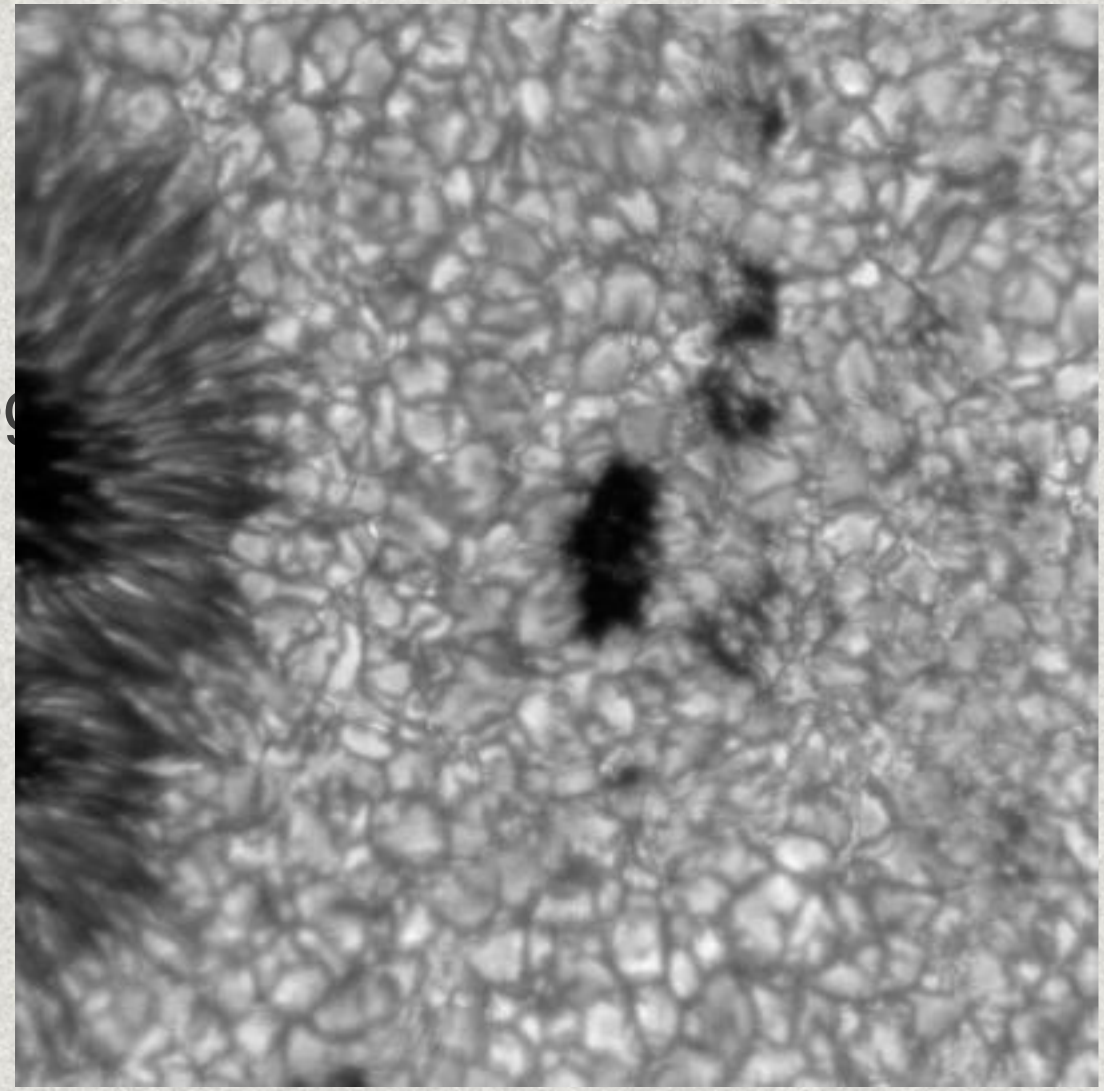

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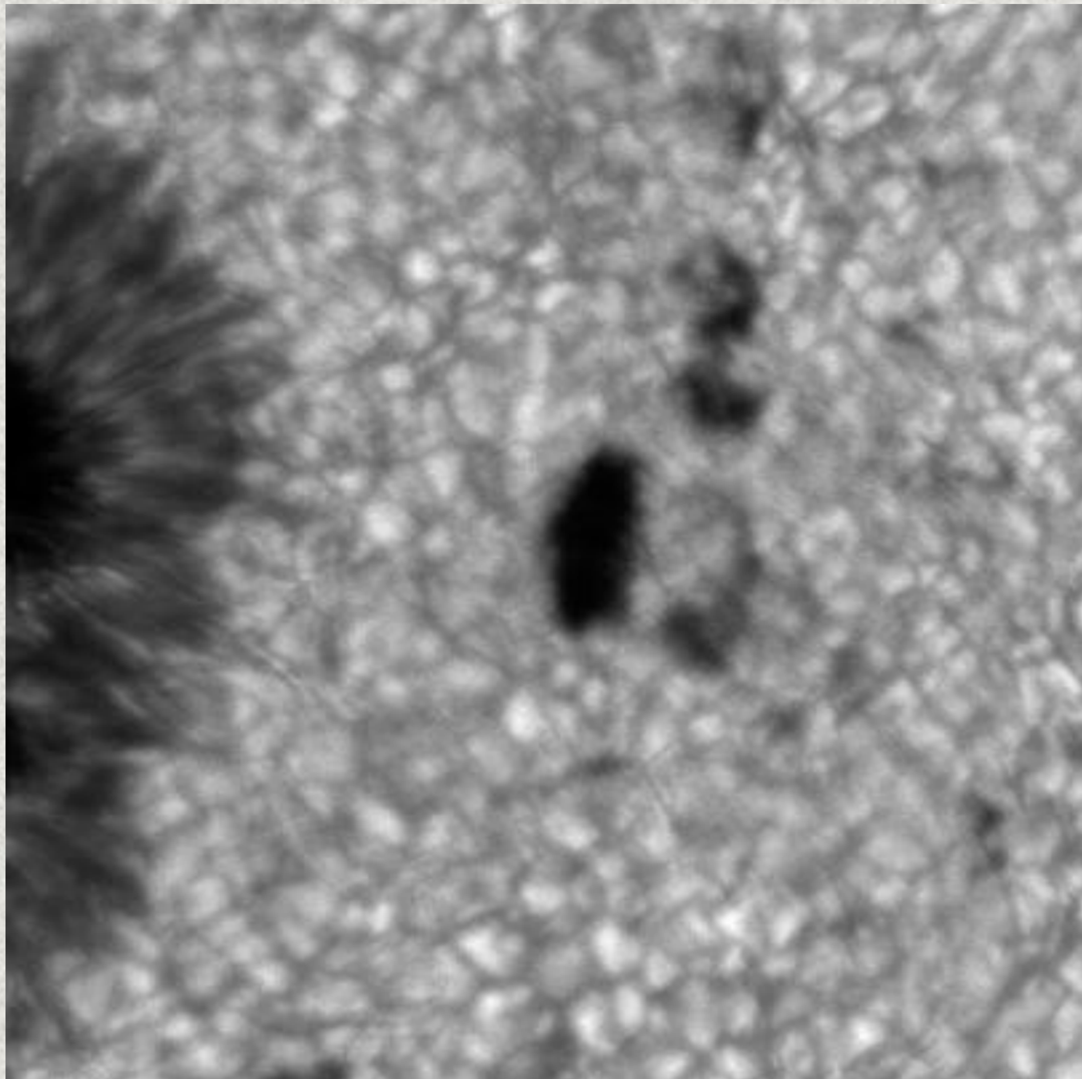

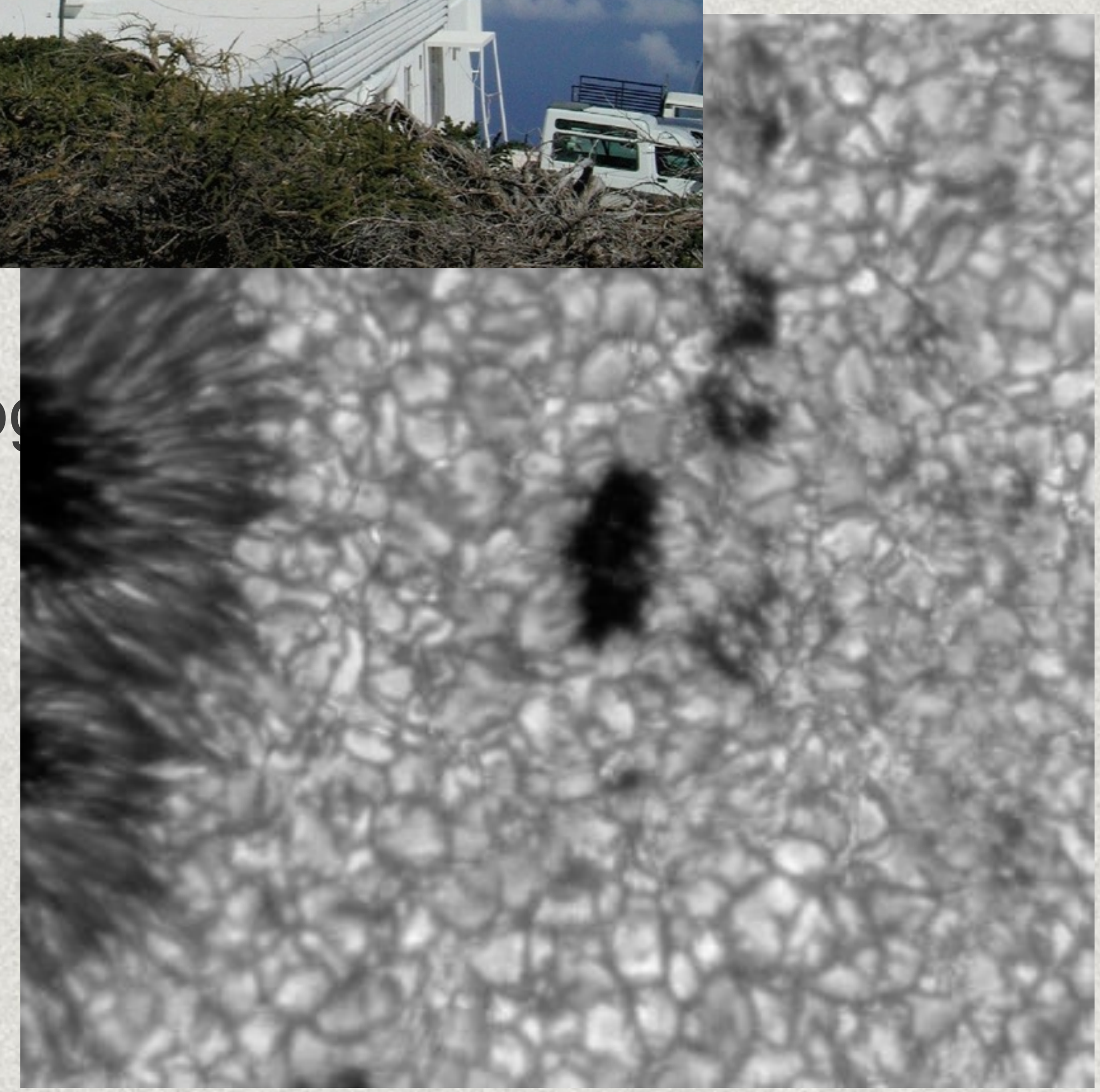

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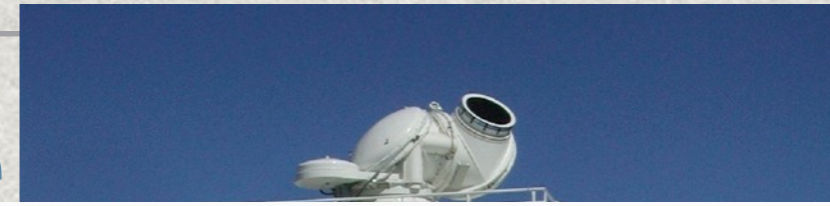
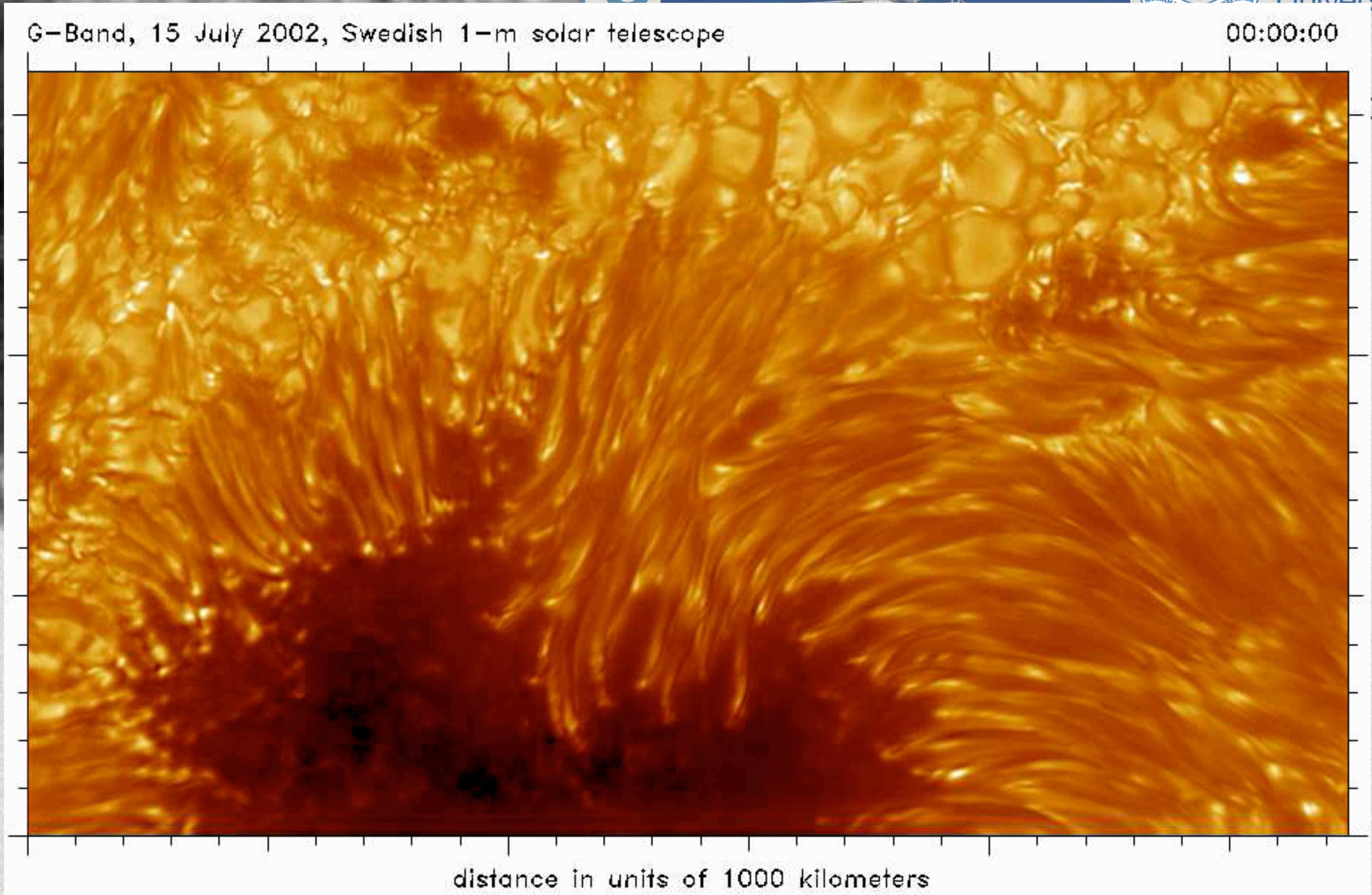


Australian National University



The Emergence of Curvature AO

Australian National University

- Shearing interferometer & Shack-Hartmann wavefront sensors: Shortcomings of optical 2D detectors prompted the curvature idea.
- Old technique, revived at NOAO by Roddier and Beckers (seminal paper Roddier 1988)
- Realisation at University of Hawaii. First light at the UH 2.2-m in 1992.
- Less expensive and more sensitive approach than Shack-Hartmann (limiting magnitude R ~ 17) prompted several facilities to build similar systems (CFHT/PUEO, OHP, ESO/MACAO, UKIRT)

PUEO: AO for non-believers

- Based on curvature concept
- Aimed at user friendly/efficient operation
- Adequate instrumentation (1k x 1k NIR camera, OASIS IFU)
- Proper characterisation, ease of operation and PSF calibration facilities make for increased astronomical exploitation: 64 papers published in the first 5 years of operation (1997-2002).

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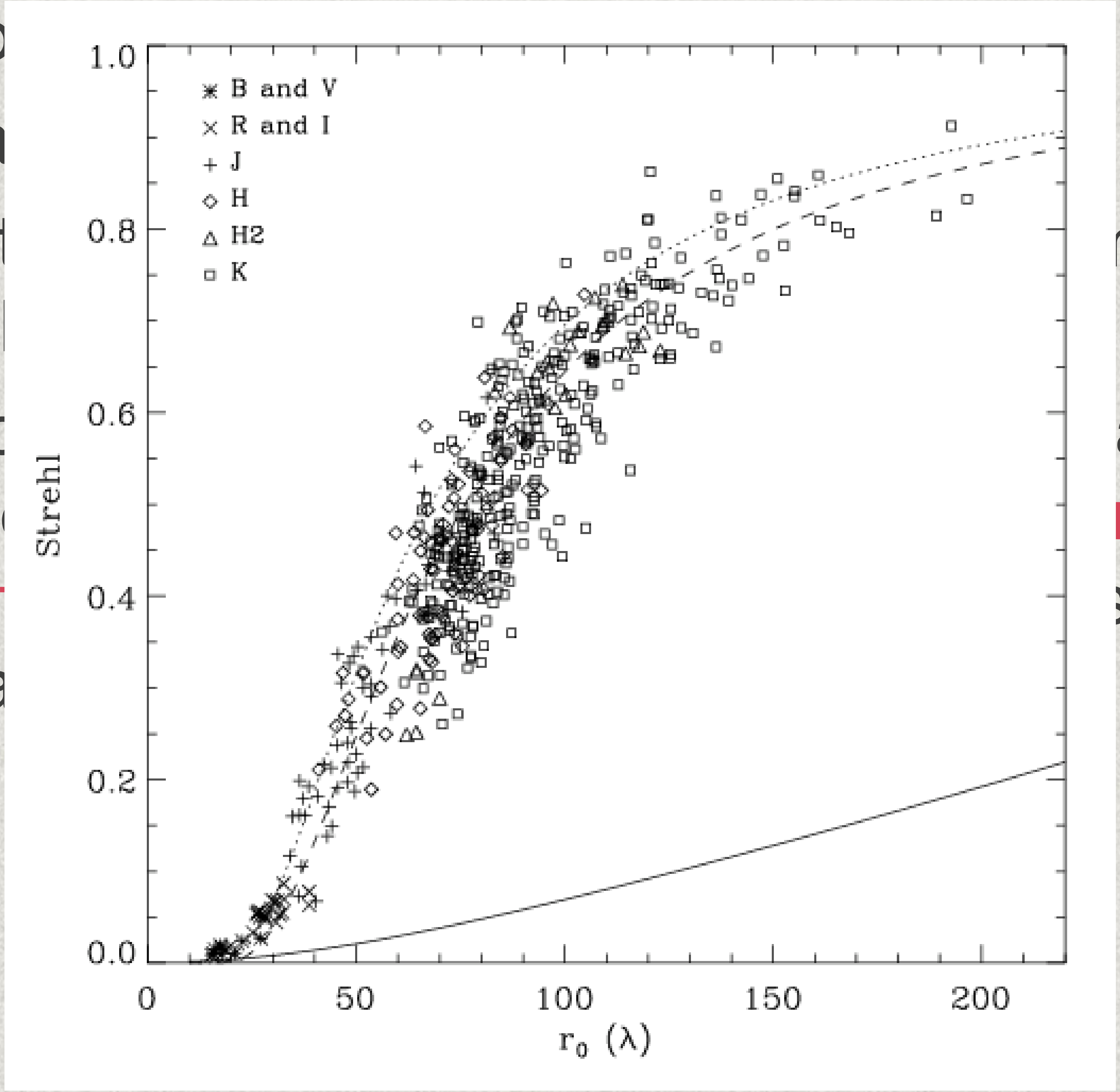

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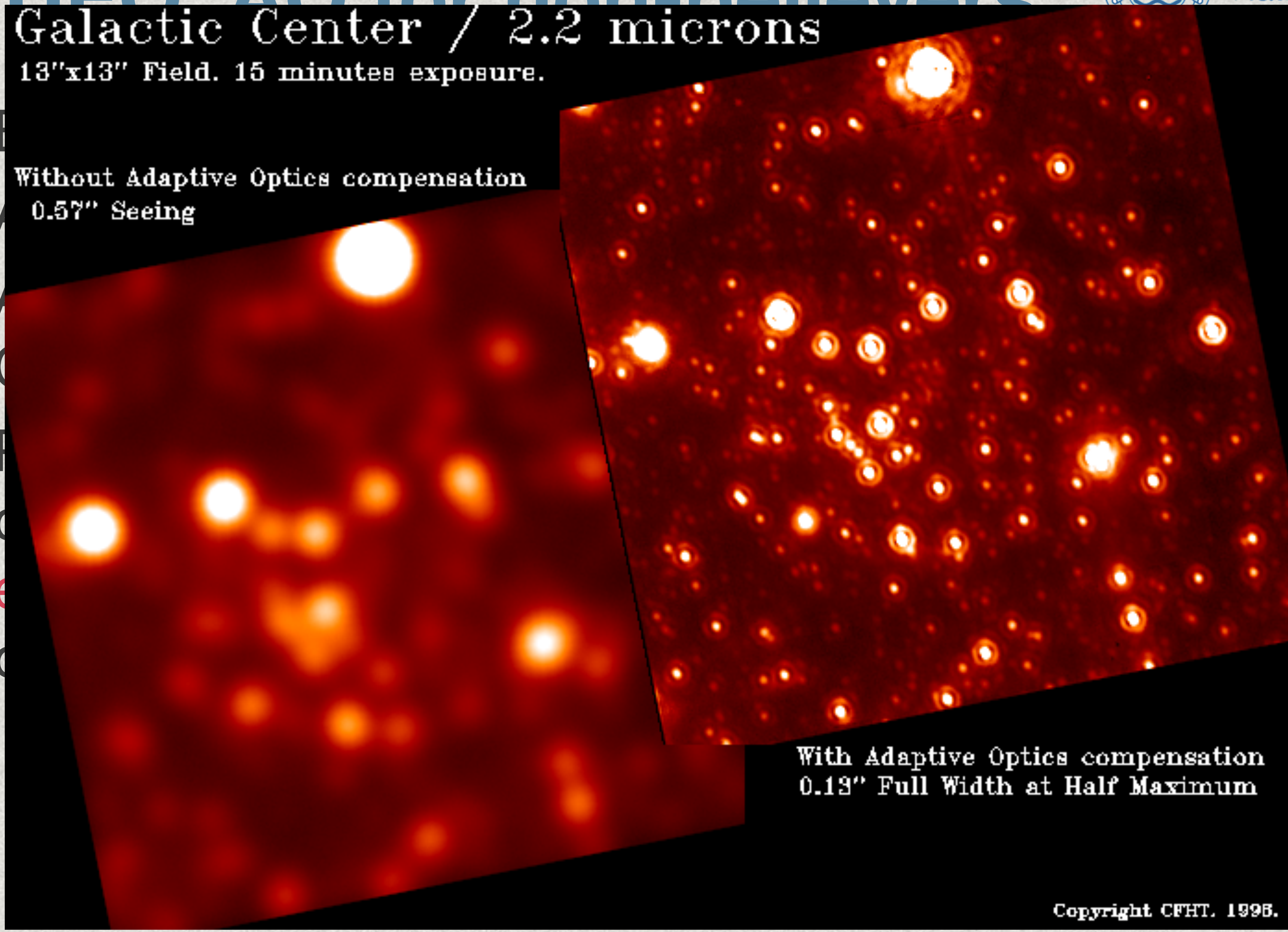

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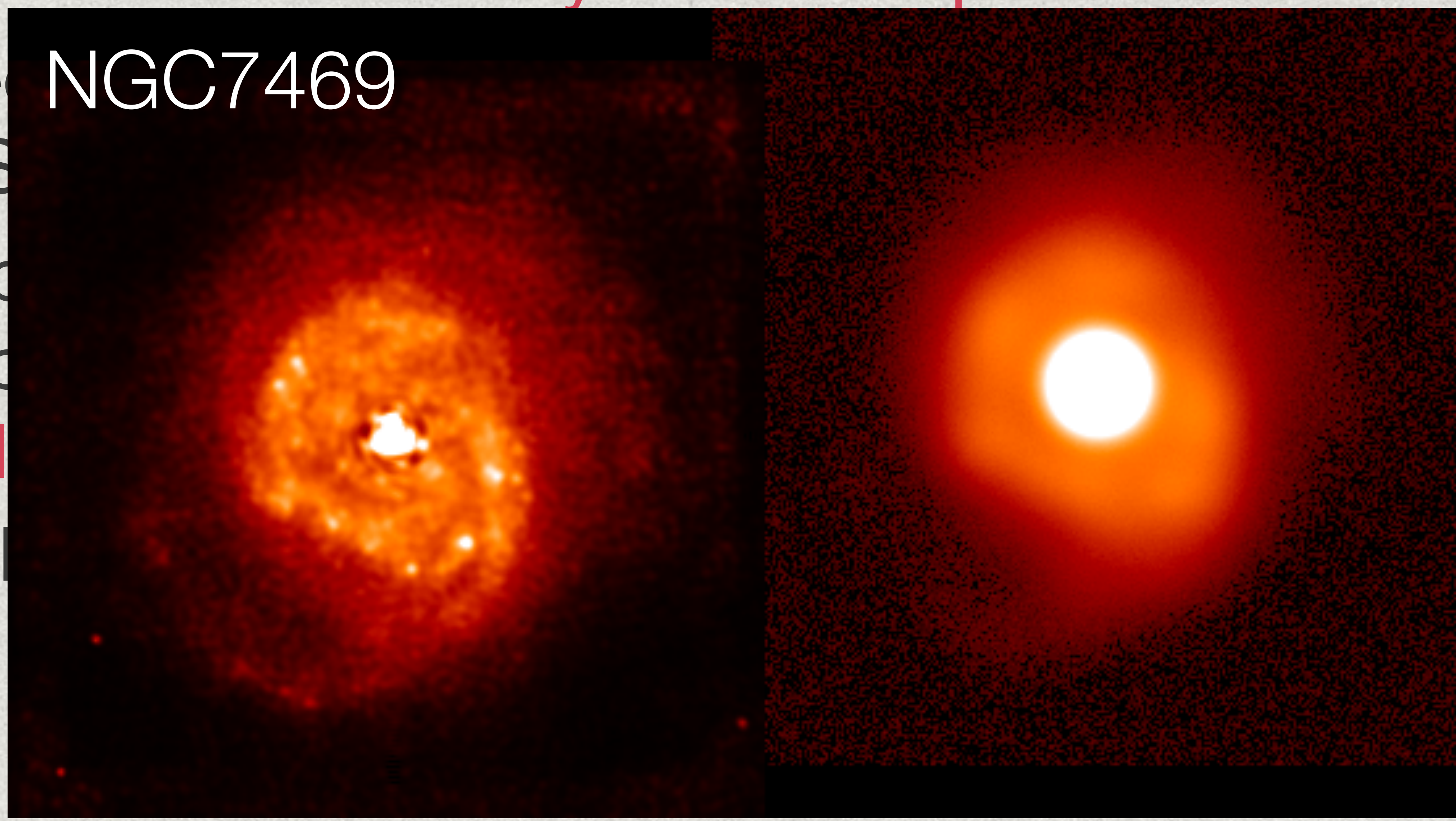


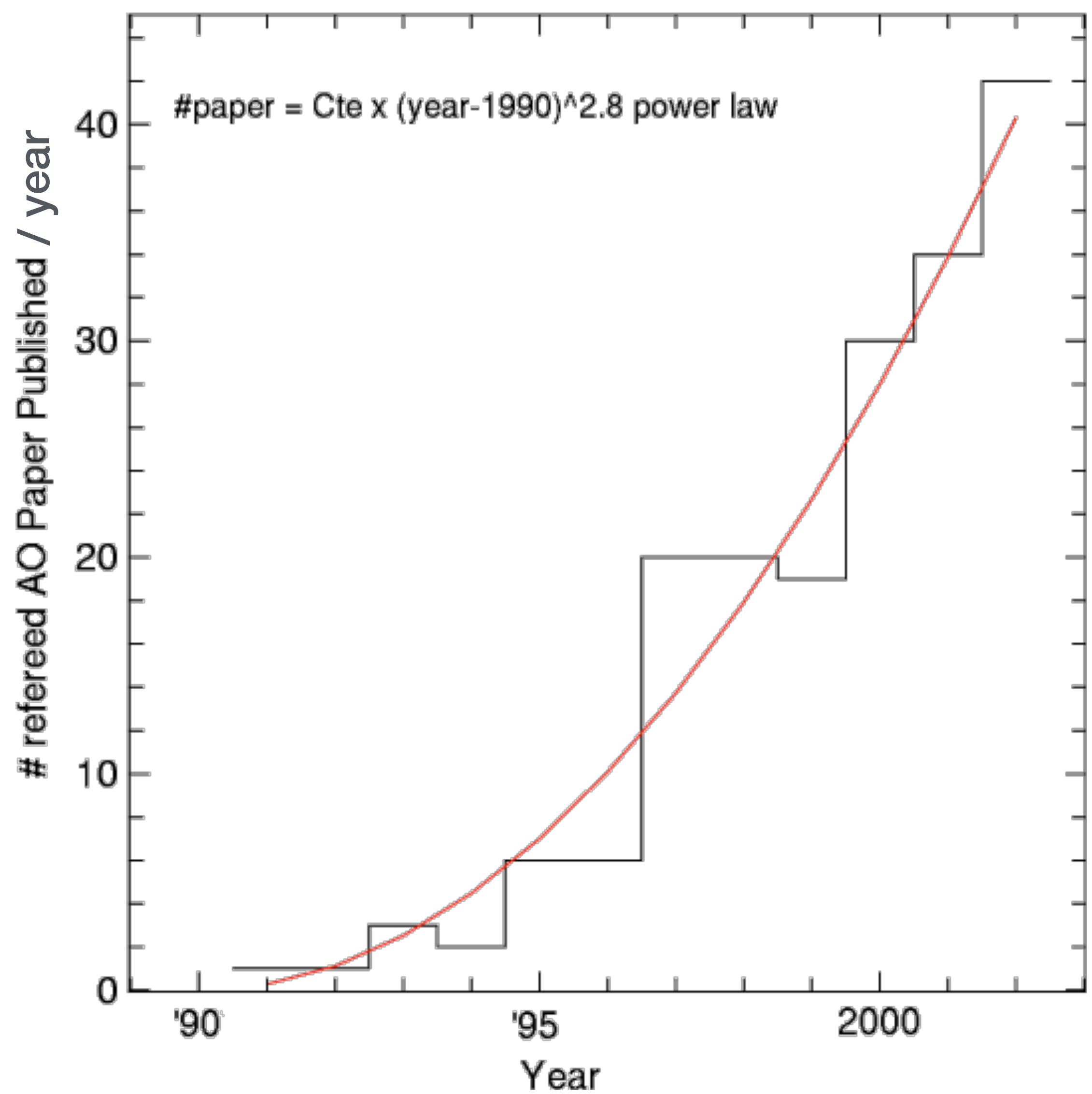
1996-2005: The booming years

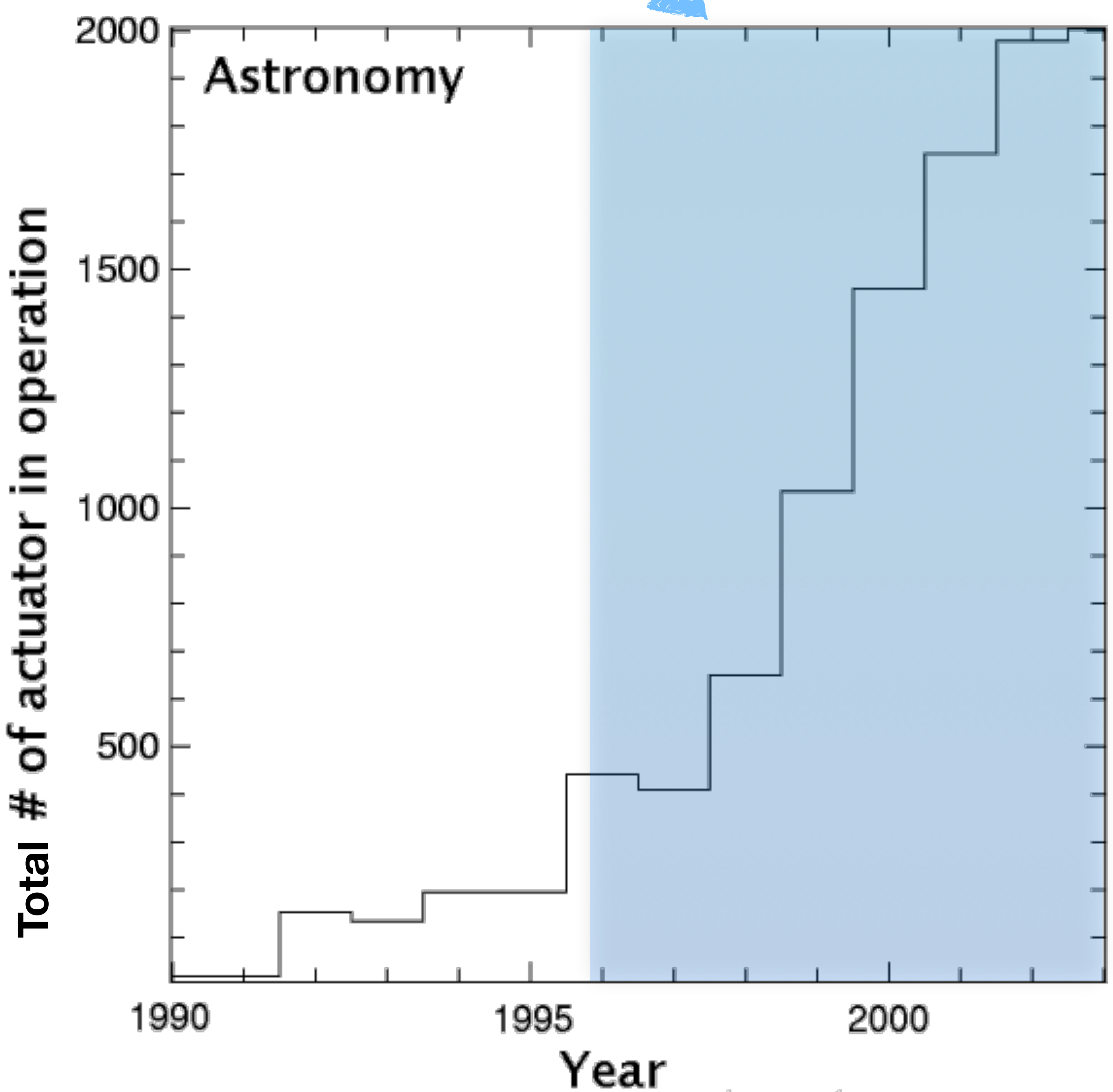
Australian National University

- Starting in 1996, things are starting to get out of hand:
  - Blooming of systems everywhere (CFHT, Mt Wilson, Hokupa'a, followed by 8-m systems in 1999-2000)
  - Prompted by the success of COME-ON (1990+5 years development time) and international competition.
  - Puts aside lack of science papers and data reduction issues.
  - Second wave after PUEO demonstrated automation is possible
  - From 2005, getting even mainline with ELTs

1996-2005: The booming years

Australian National University





1996-2005: The booming years

- Things are also booming on the theory of AO side:
  - 1995-1998: Work on LGS and LGS related issues (Tip-Tilt, e.g. Ragazzoni)
  - 1998-now: Score of new concepts:
    - Pyramid WFS (Ragazzoni, Esposito, *ADOPT@TNG*)
    - Multi-Conjugate AO (Ellerbroek, *GeMS@Gemini, MAD@ESO*)
    - Ground Layer AO (Rigaut, Tokovinin)
    - Multi-Object AO (Gendron, Gavel, Conan, e.g. *Falcon*)
  - Many papers published ! Active field of research.
- Growing recognition and interest by media

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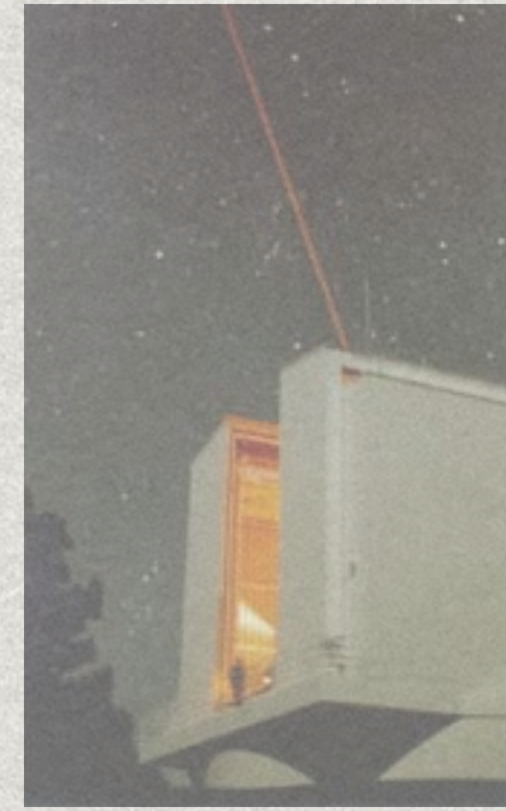
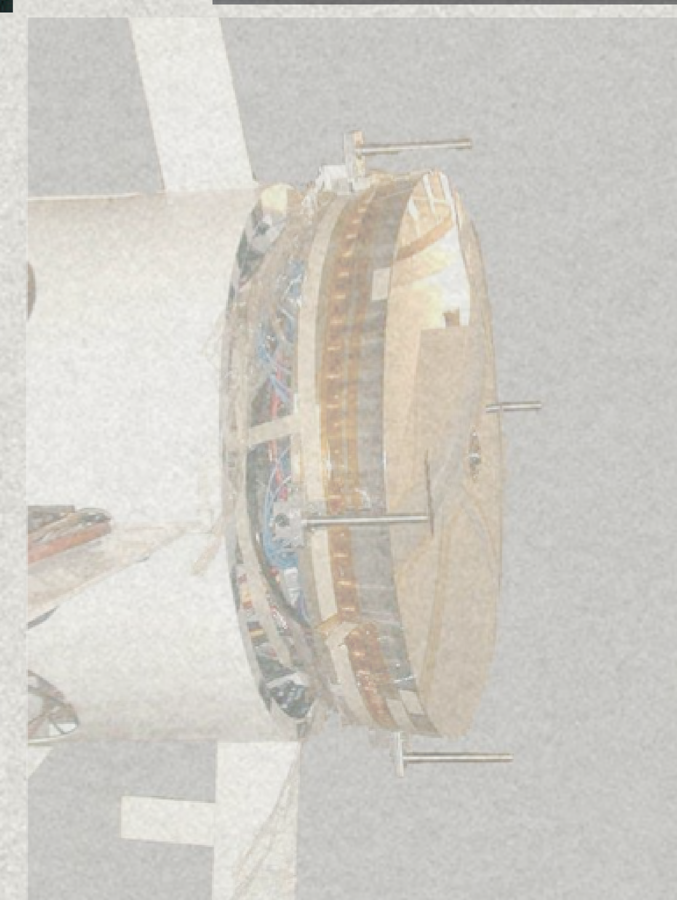
1996-2005: The booming years

- New technologies demonstrated:
- Laser Guide Stars:
  - Early efforts at the MMT, Calar Alto, Lick
  - Operational LGS systems at:
    - Keck (3 generations GSL),
    - ESO (2 generations GSL),
    - Gemini (1.5 generation GSL),
    - Subaru (1.5 generation GSL)
  - New, dependable lasers now available
- Deformable Secondaries
  - in 2005: MMT 6.5-m 336 actuators. Lowest emissivity system (dichroic = dewar entrance window). Up to 20% Strehl ratio, nice and round images
  - Since extremely well performing systems, with 93% H band Strehl at LBT (and visible AO @ Magellan)





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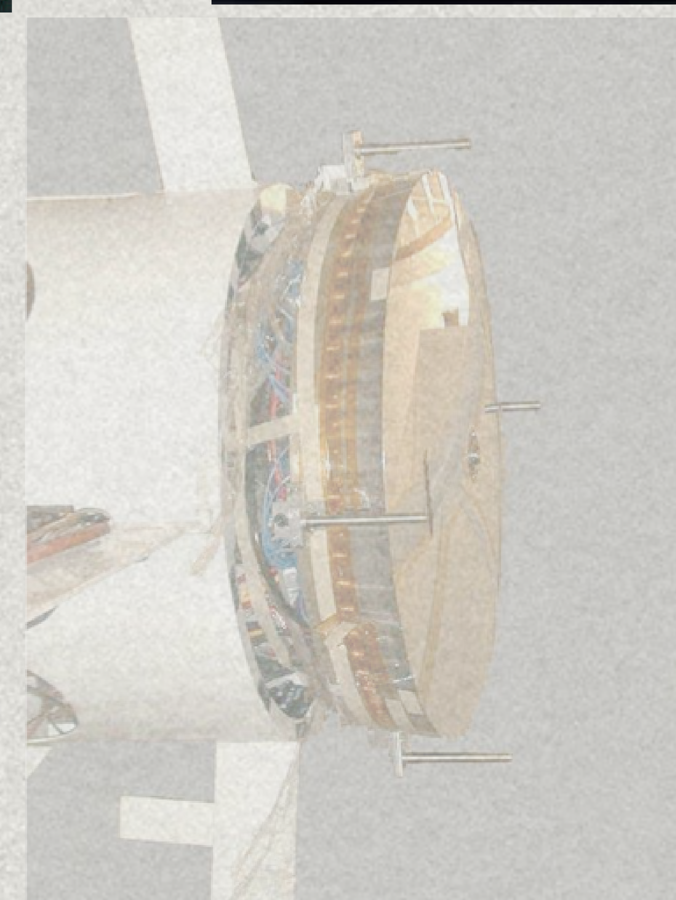

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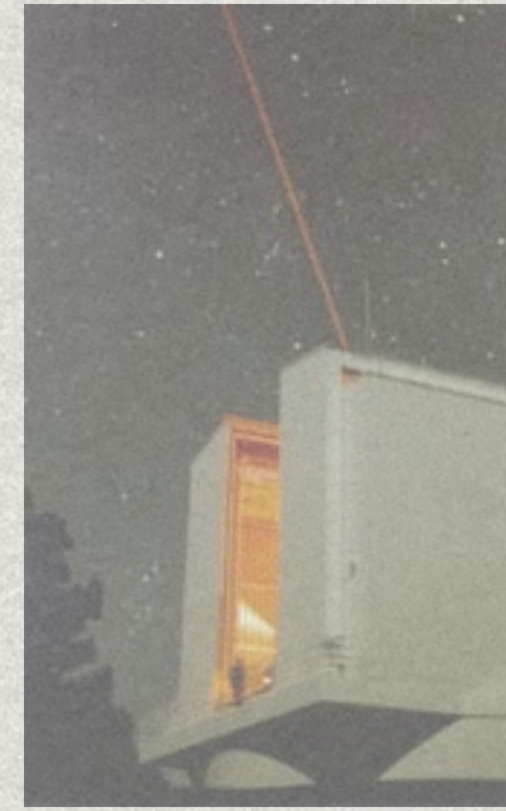

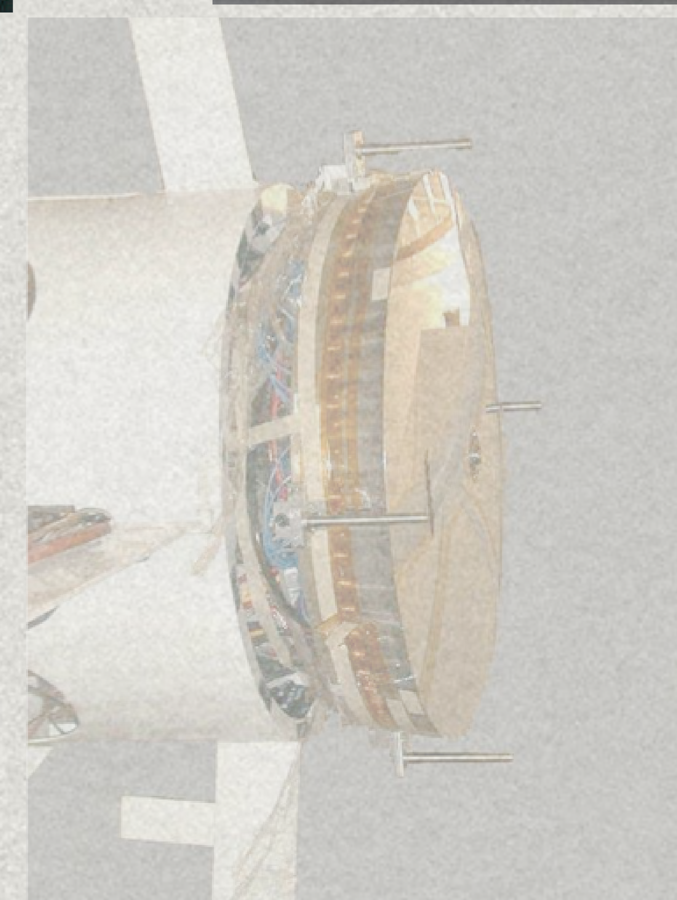

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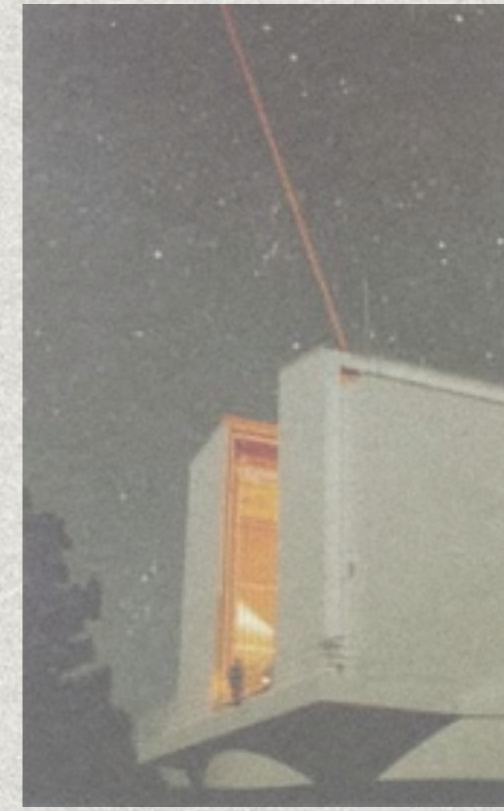

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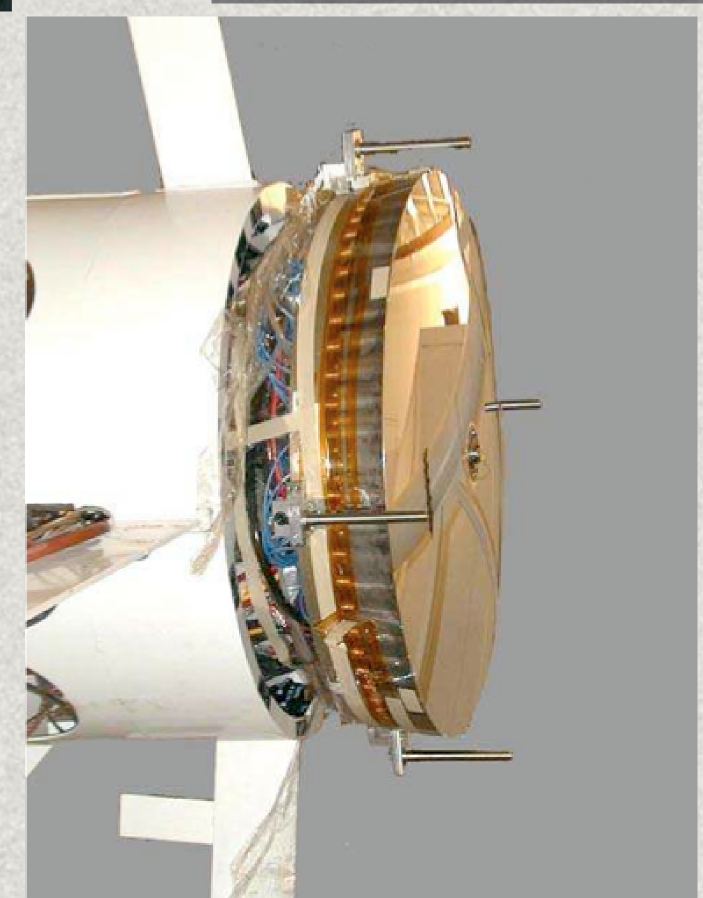

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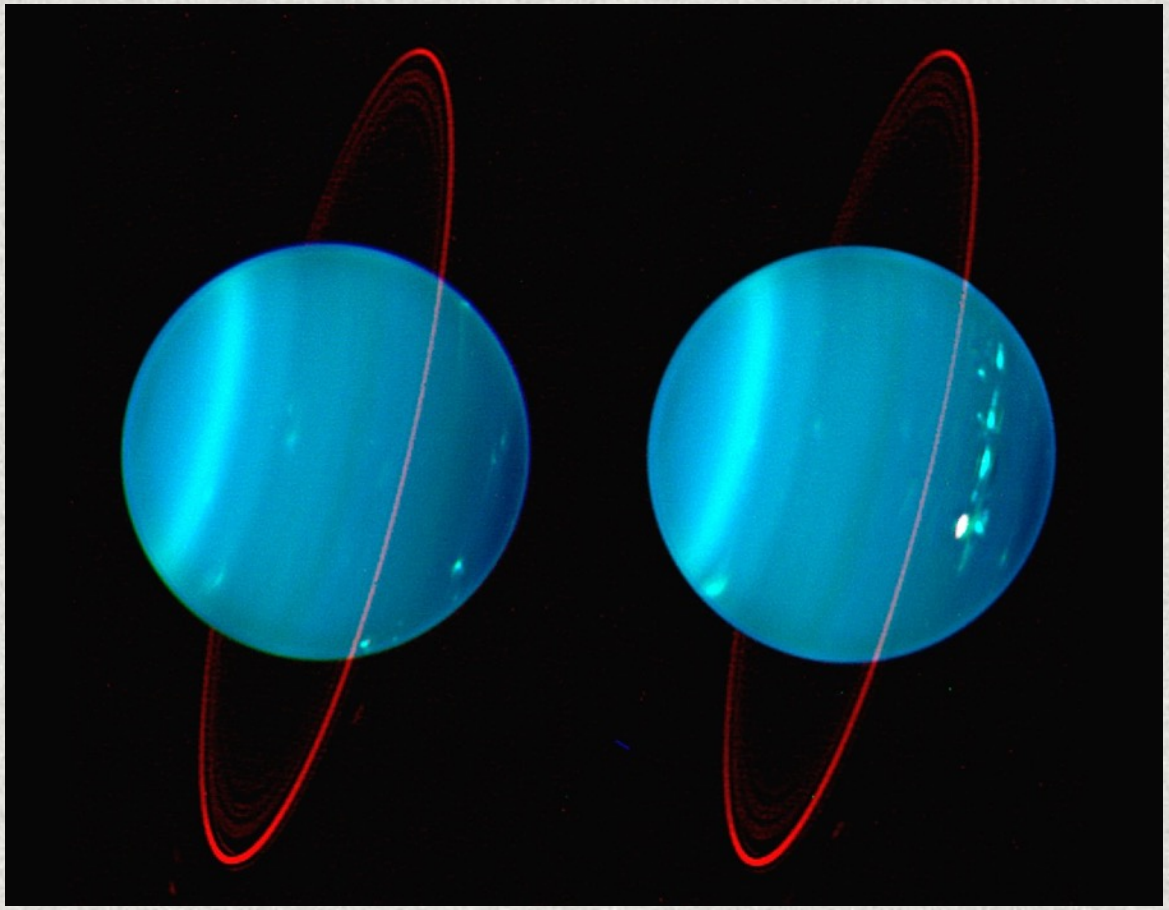
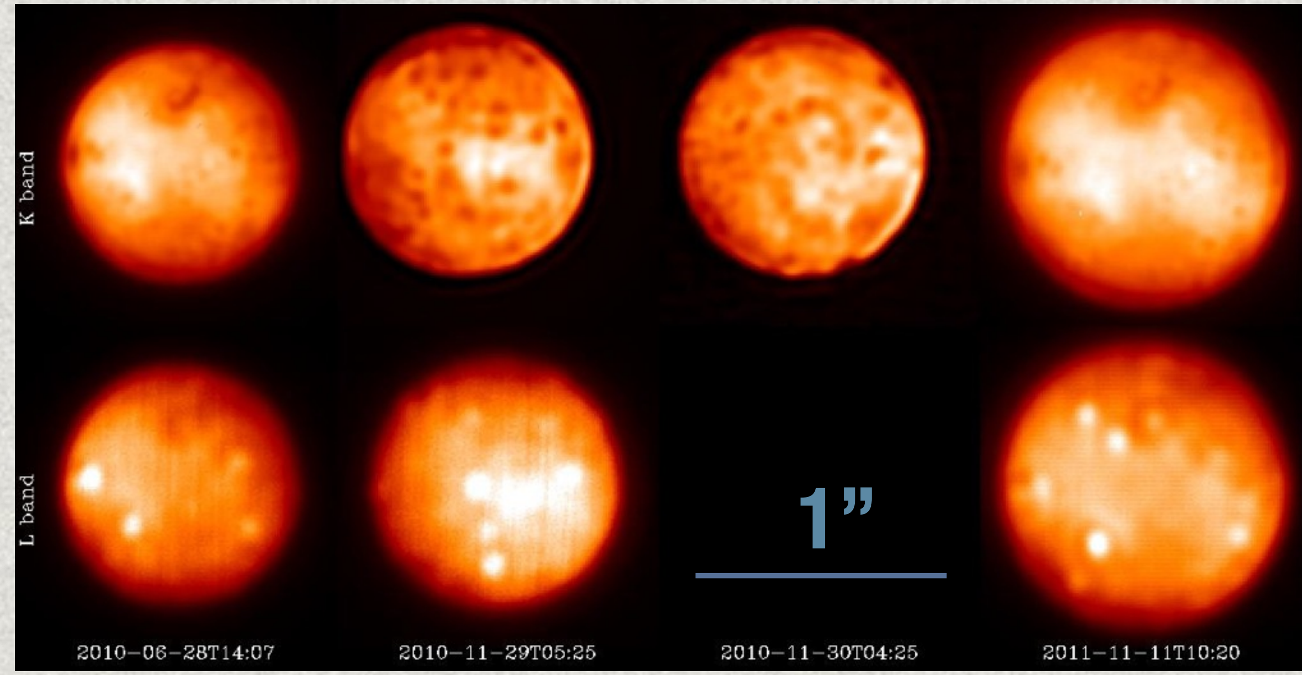
Science with AO

Solar System

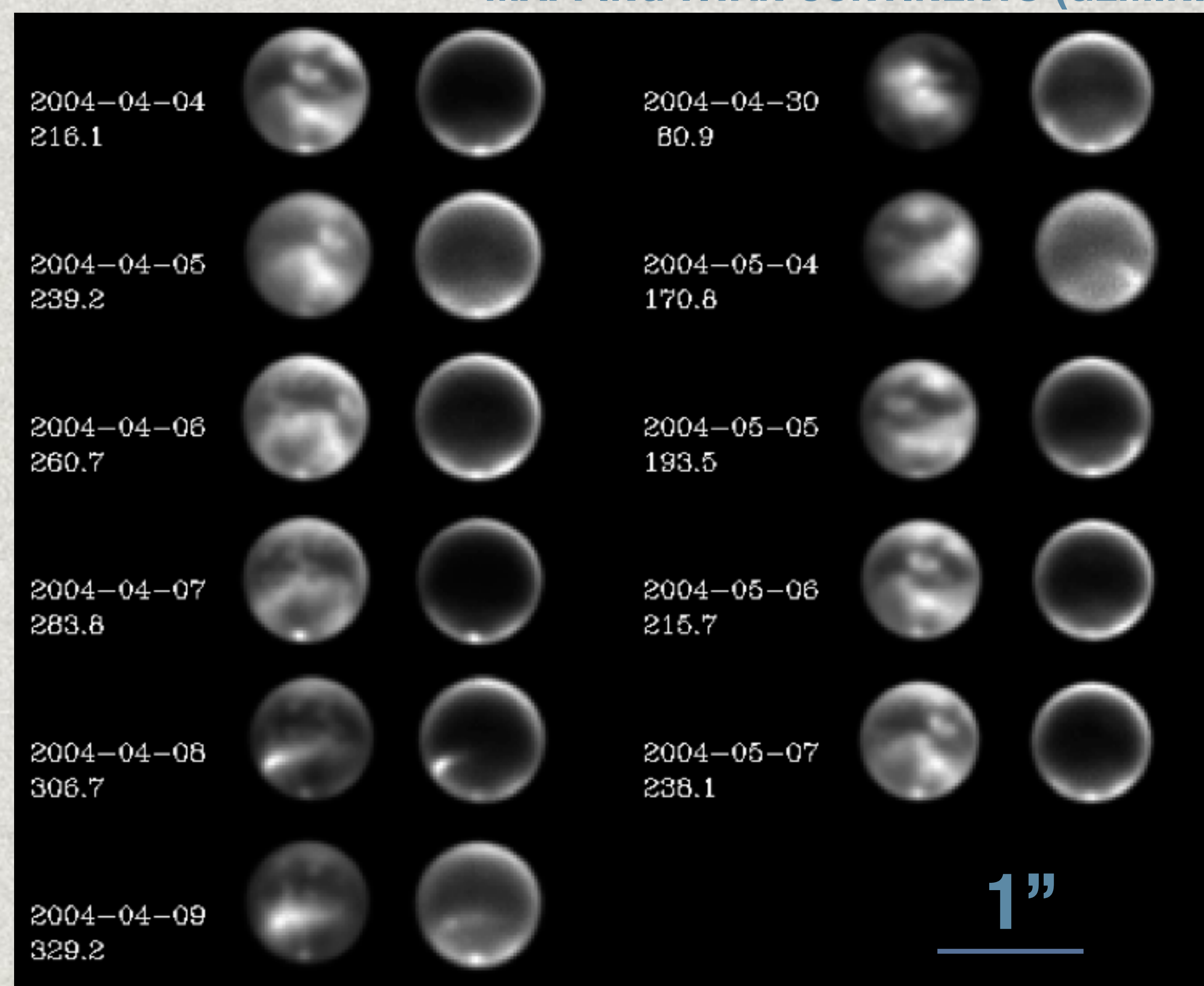


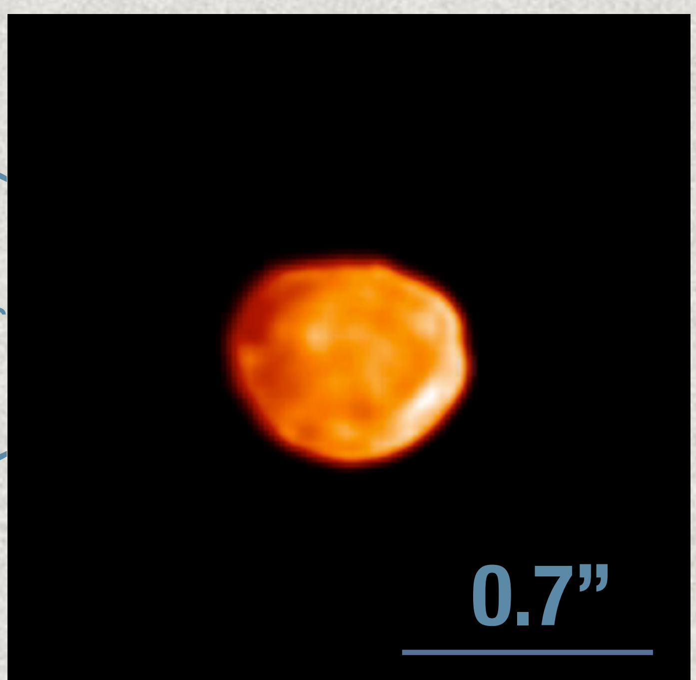
WEATHER (URANUS, KECK)



MONITORING VOLCANOES ON IO (KECK)

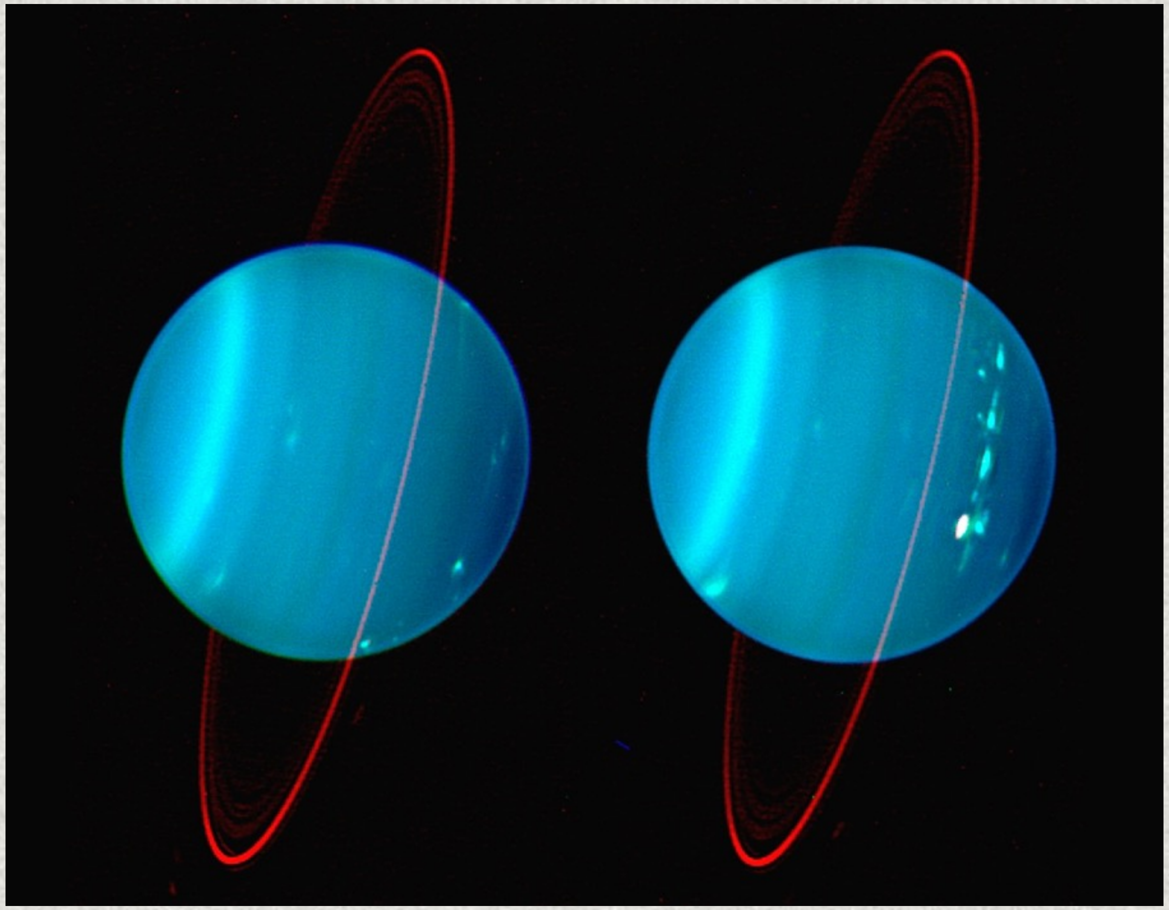
MAPPING TITAN CONTINENTS (GEMINI)





ASTEROID (VESTA, KECK)

Solar System



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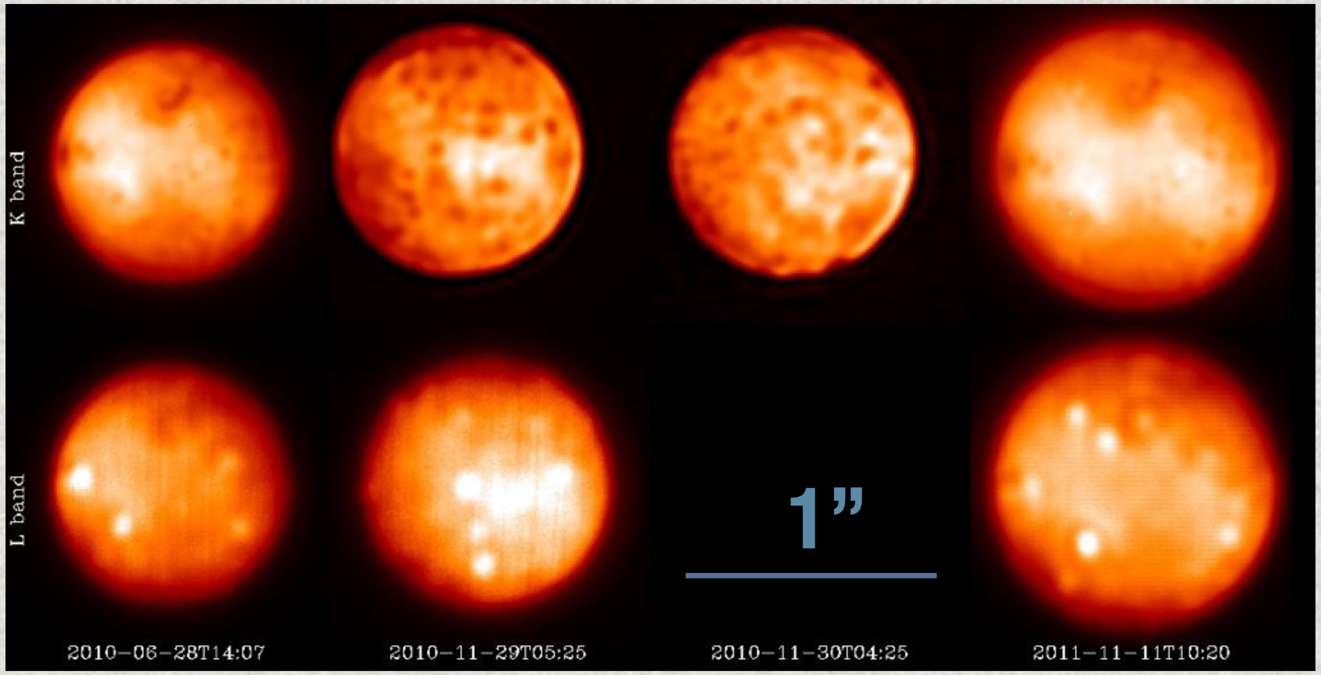

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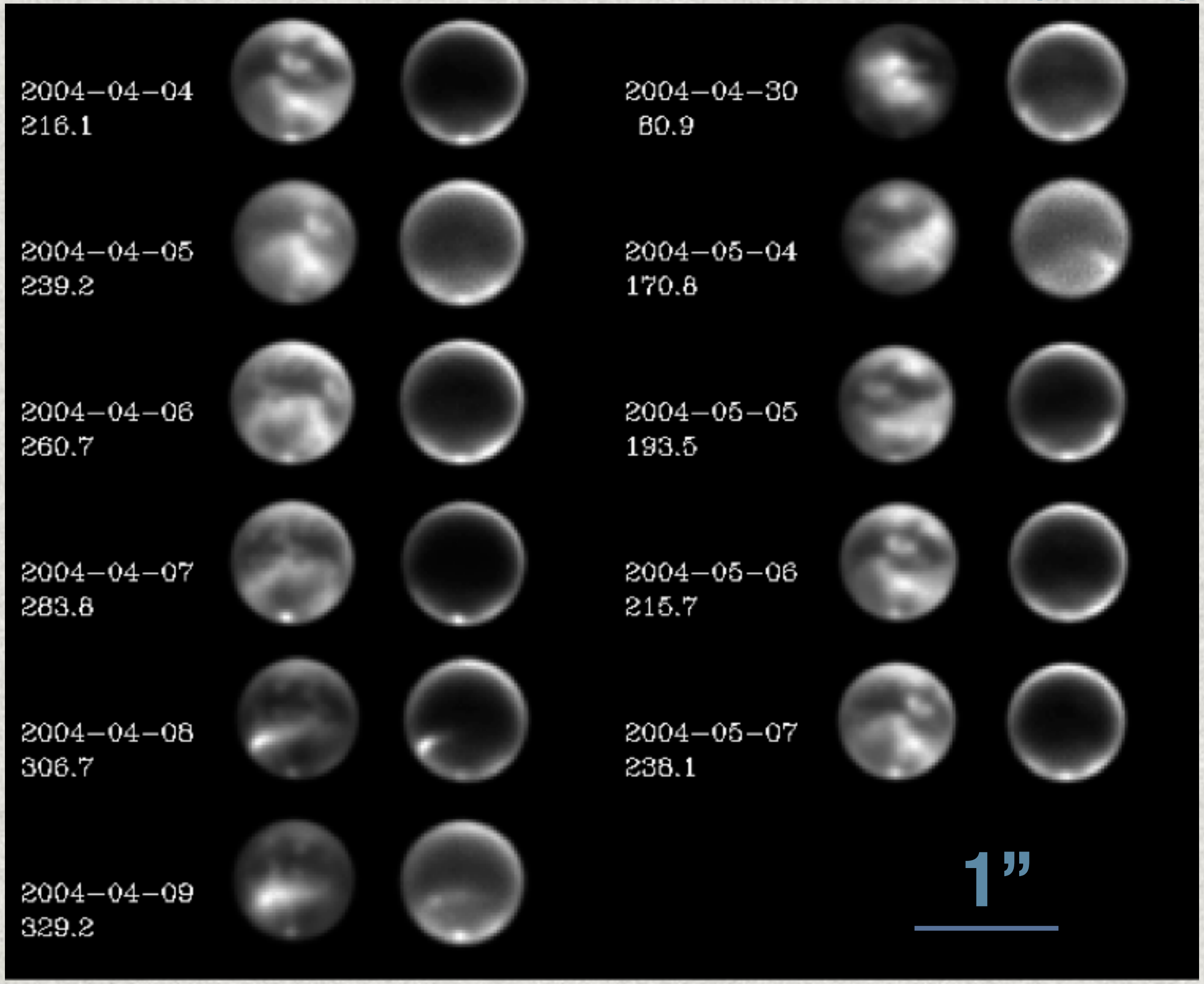

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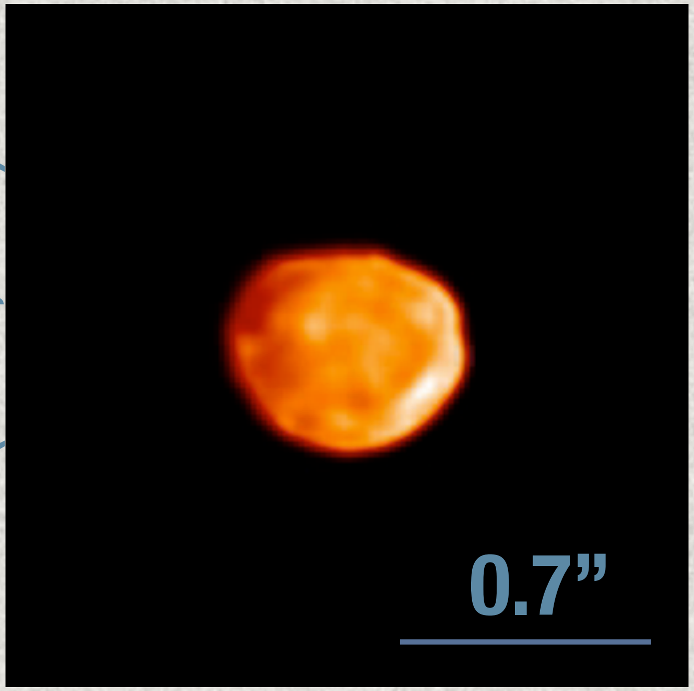

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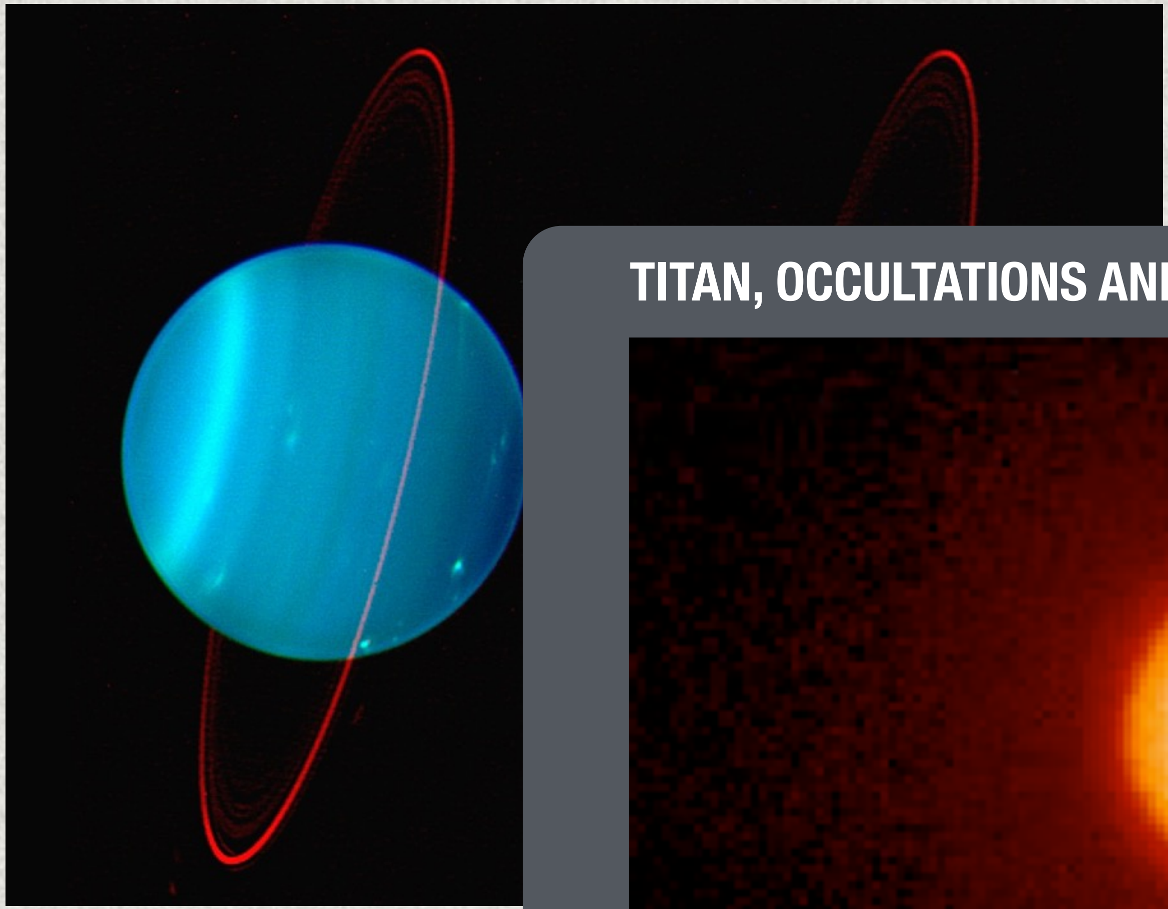
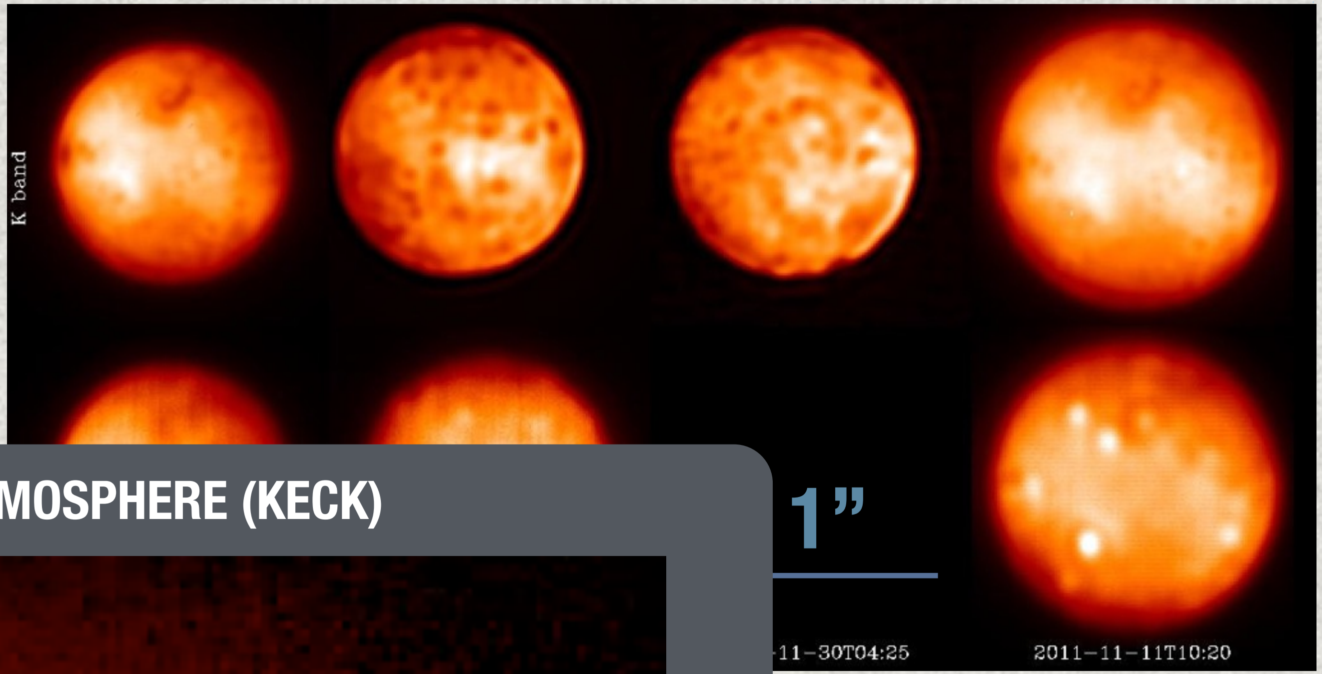
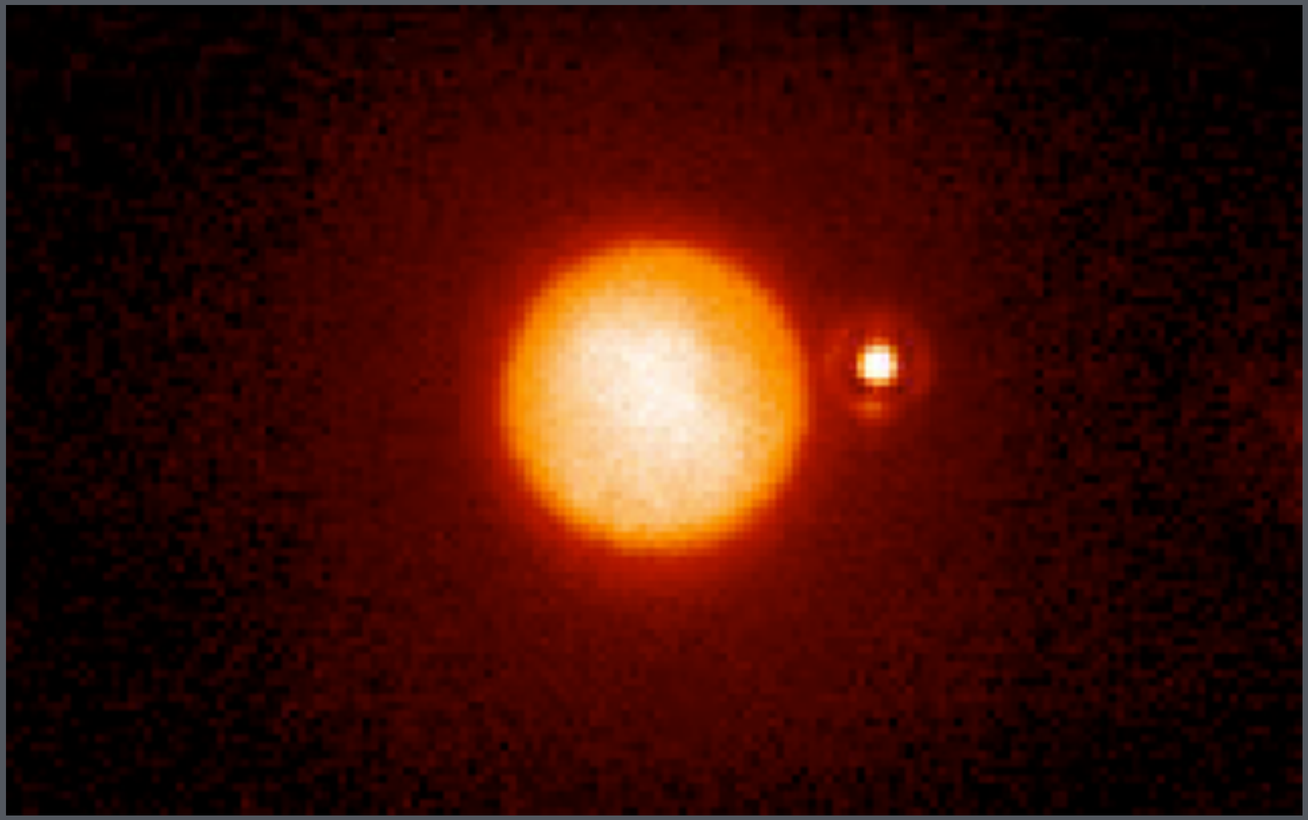


WEATHER (URANUS, KEC

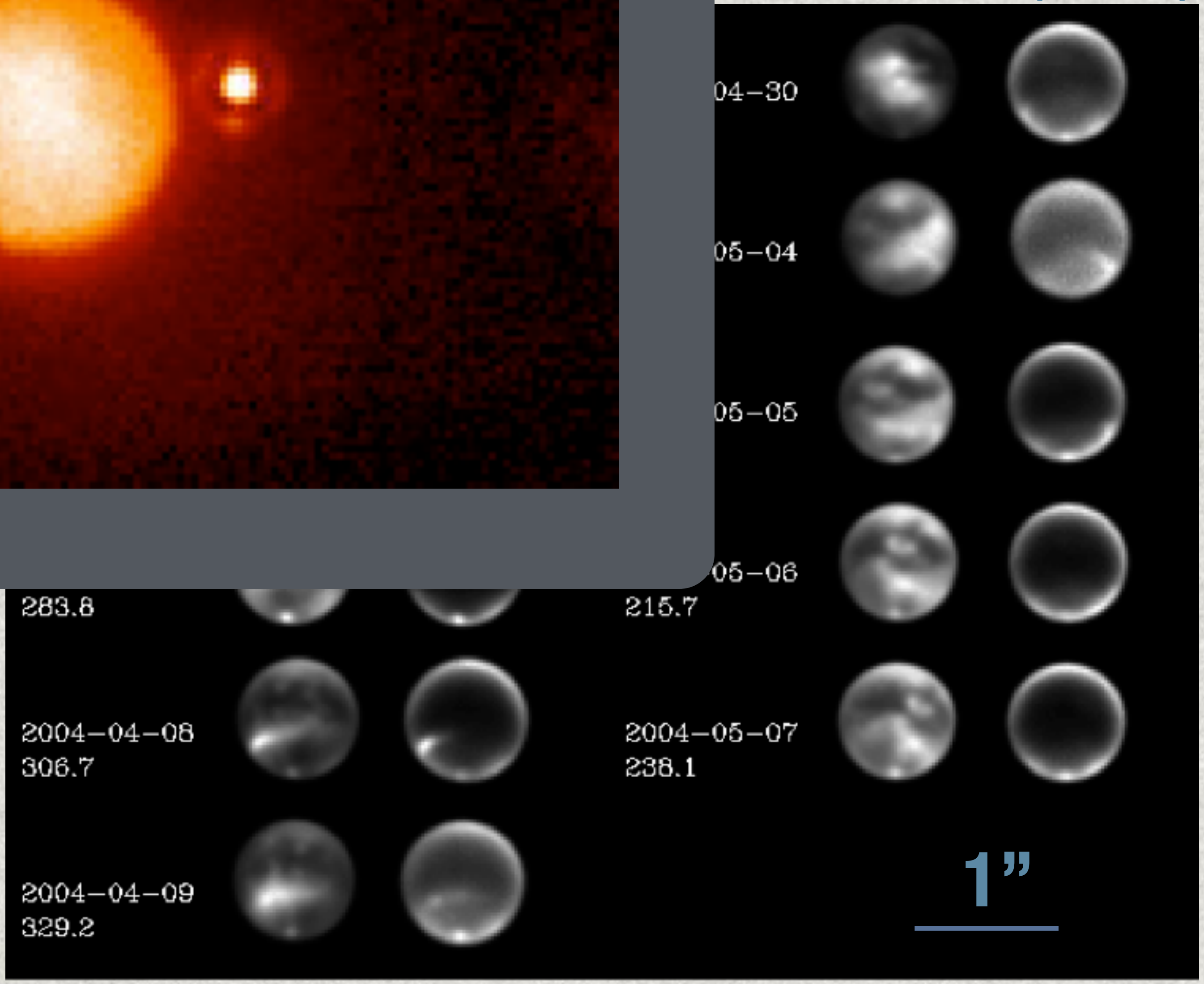


CK)

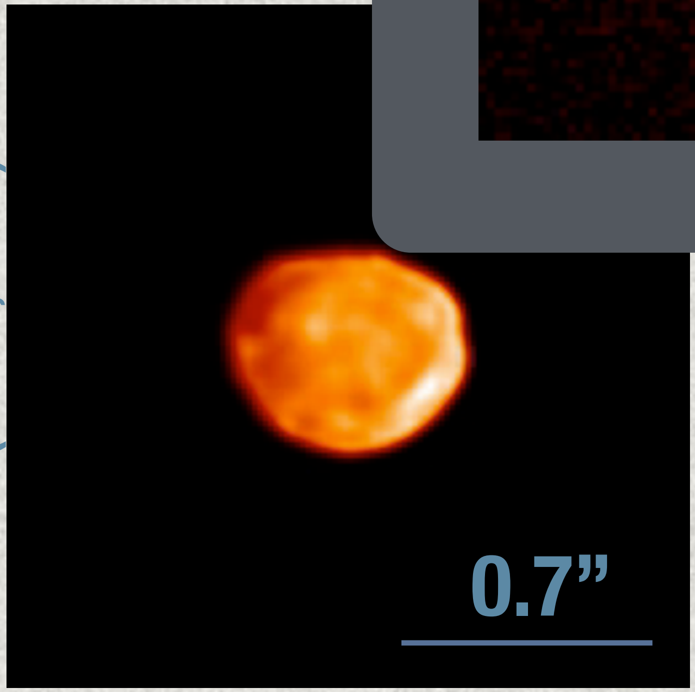
TITAN, OCCULTATIONS AND ATMOSPHERE (KECK)

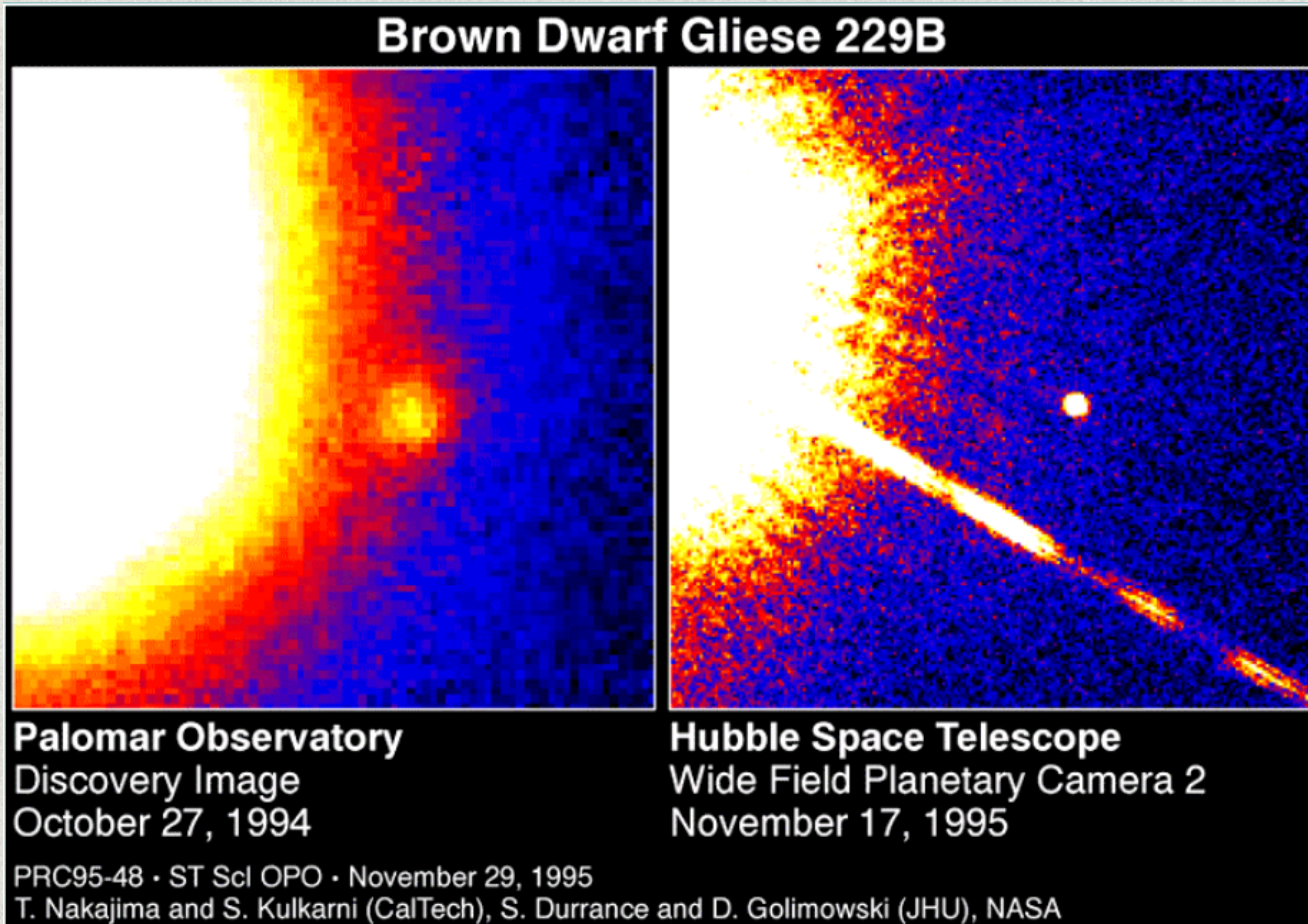


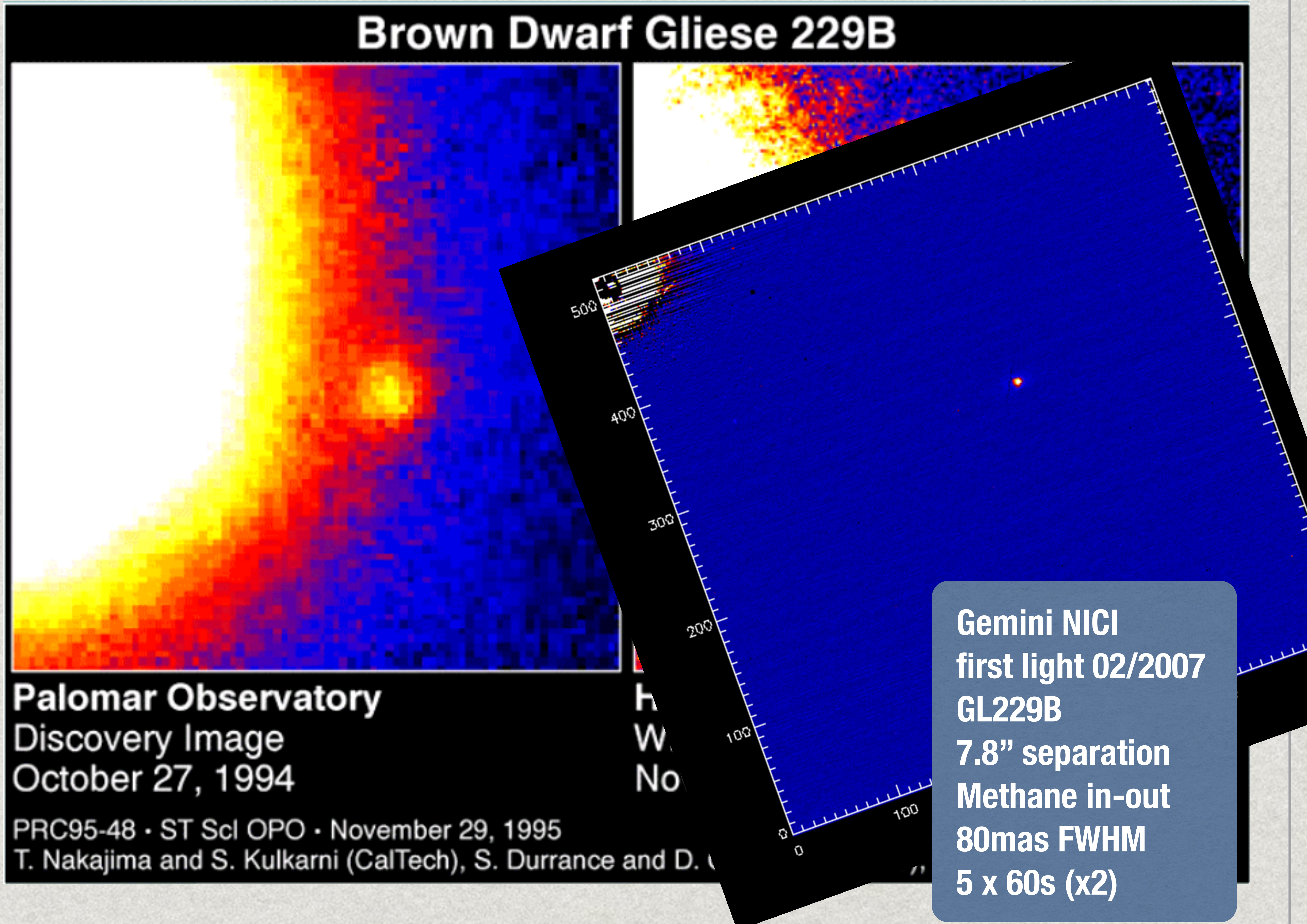
AN CONTINENTS (GEMINI)



ASTEROID (VESTA, KECK)



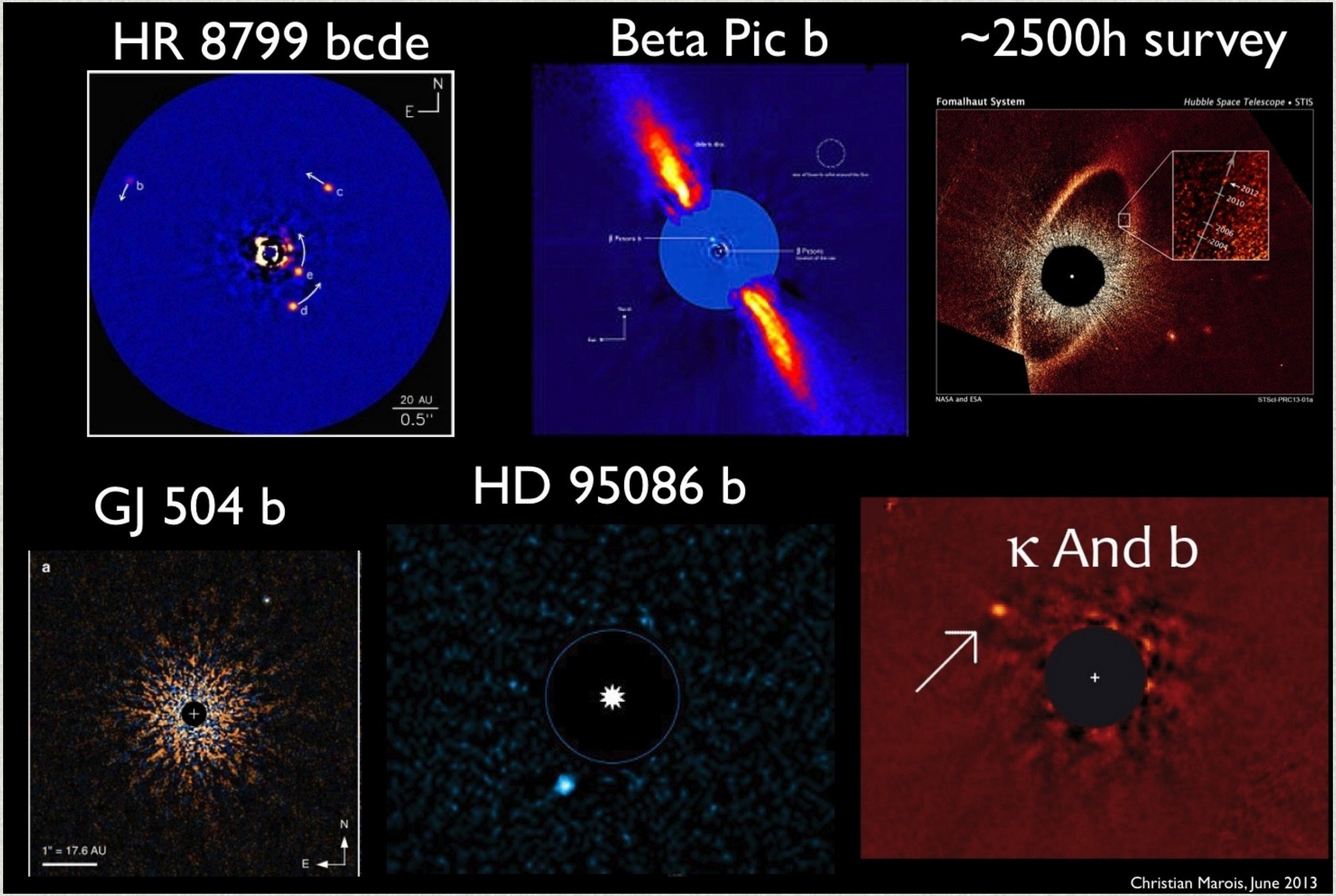

Brown Dwarf Gliese 229B
Palomar Observatory
Discovery Image
October 27, 1994
Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995
PRC95-48 • ST ScI OPO • November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA



Gemini NICI
first light 02/2007
GL229B
7.8” separation
Methane in-out
80mas FWHM
5 x 60s (x2)

Exoplanets (GPI & Sphere)

Australian National University



"FIVE KNOWN PLANETARY SYSTEMS IMAGED WITH CURRENT ADAPTIVE OPTICS SYSTEMS. FOMALHAUT SHOWN ON THE TOP-RIGHT IS THE ONLY SYSTEM DETECTED WITH THE HST. CREDIT: CHRISTIAN MAROIS."

The Galactic centre

Australian National University

CREDIT ESO

The Galactic centre

CREDIT ESO

The Galactic centre

CREDIT ESO

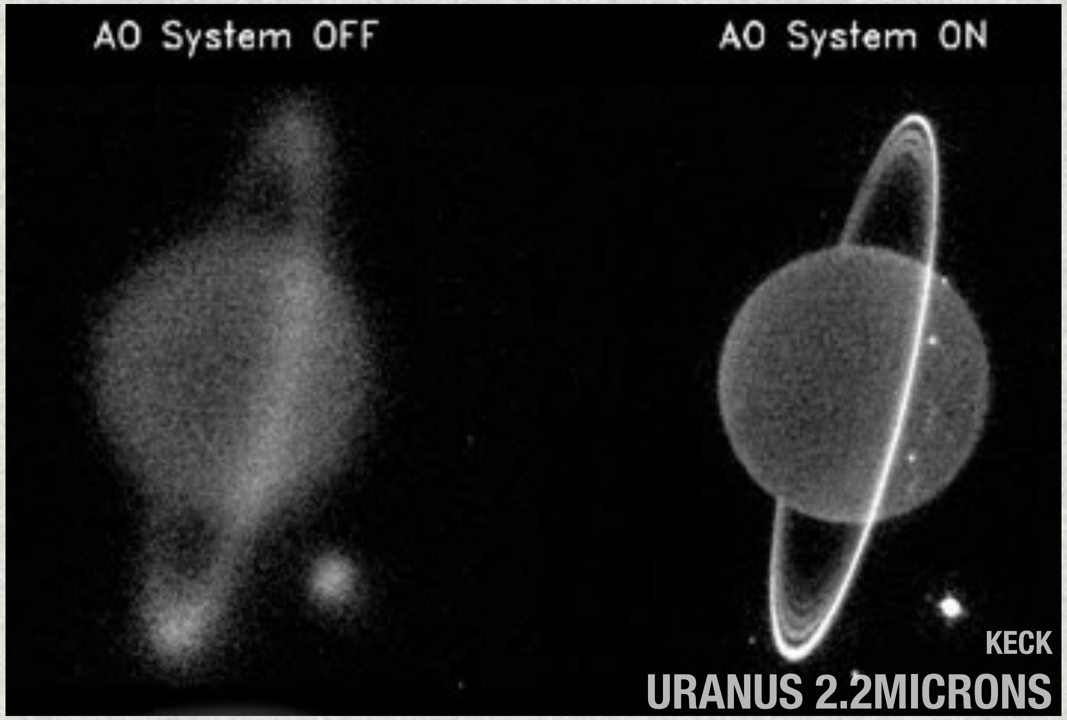
The Galactic centre

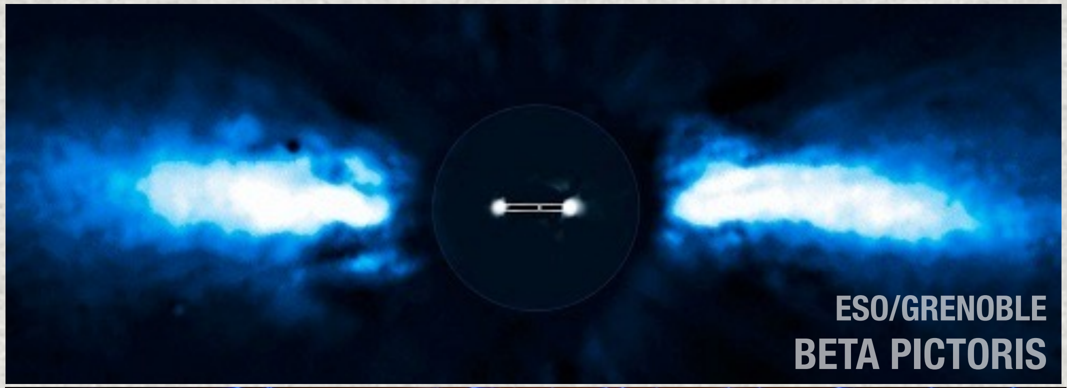
Australian National University

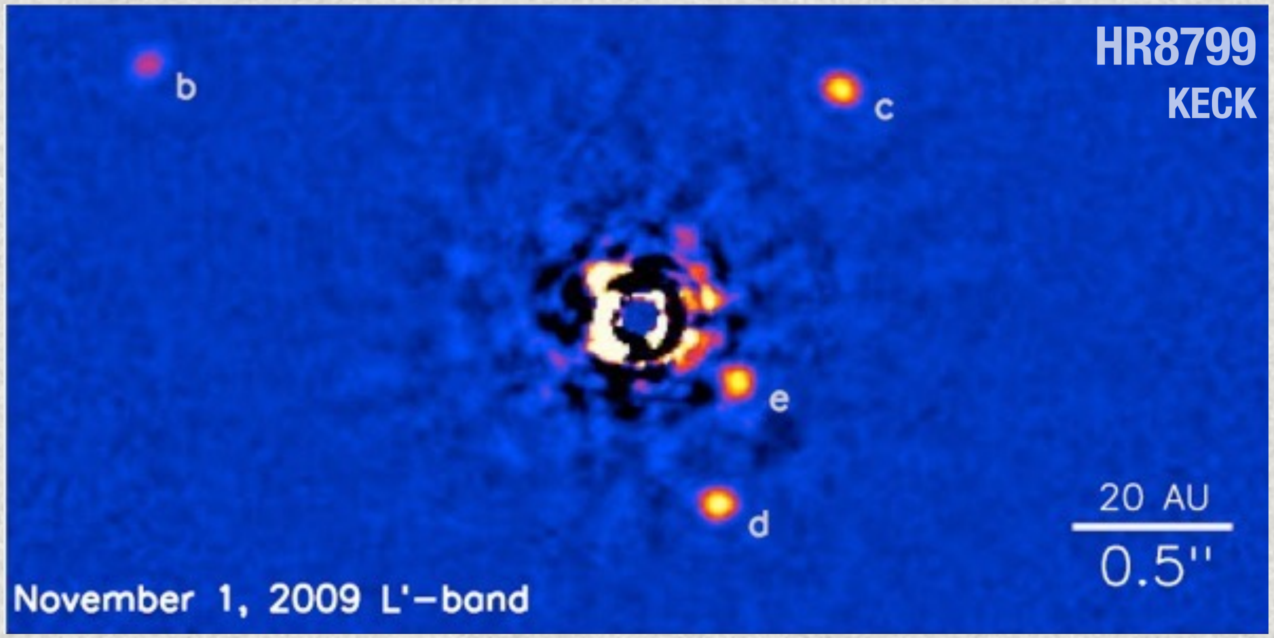
CREDIT ESO

Astronomy with Adaptive Optics

- Discovery of **black hole** at center of Milky Way
- Direct imaging of **first extra solar planetary system**
- Beta Pictoris and other **debris disks**
- **Multiple asteroid** systems
- Resolved stellar population in external galaxies
- Dynamic and chemical evolution of galaxies...

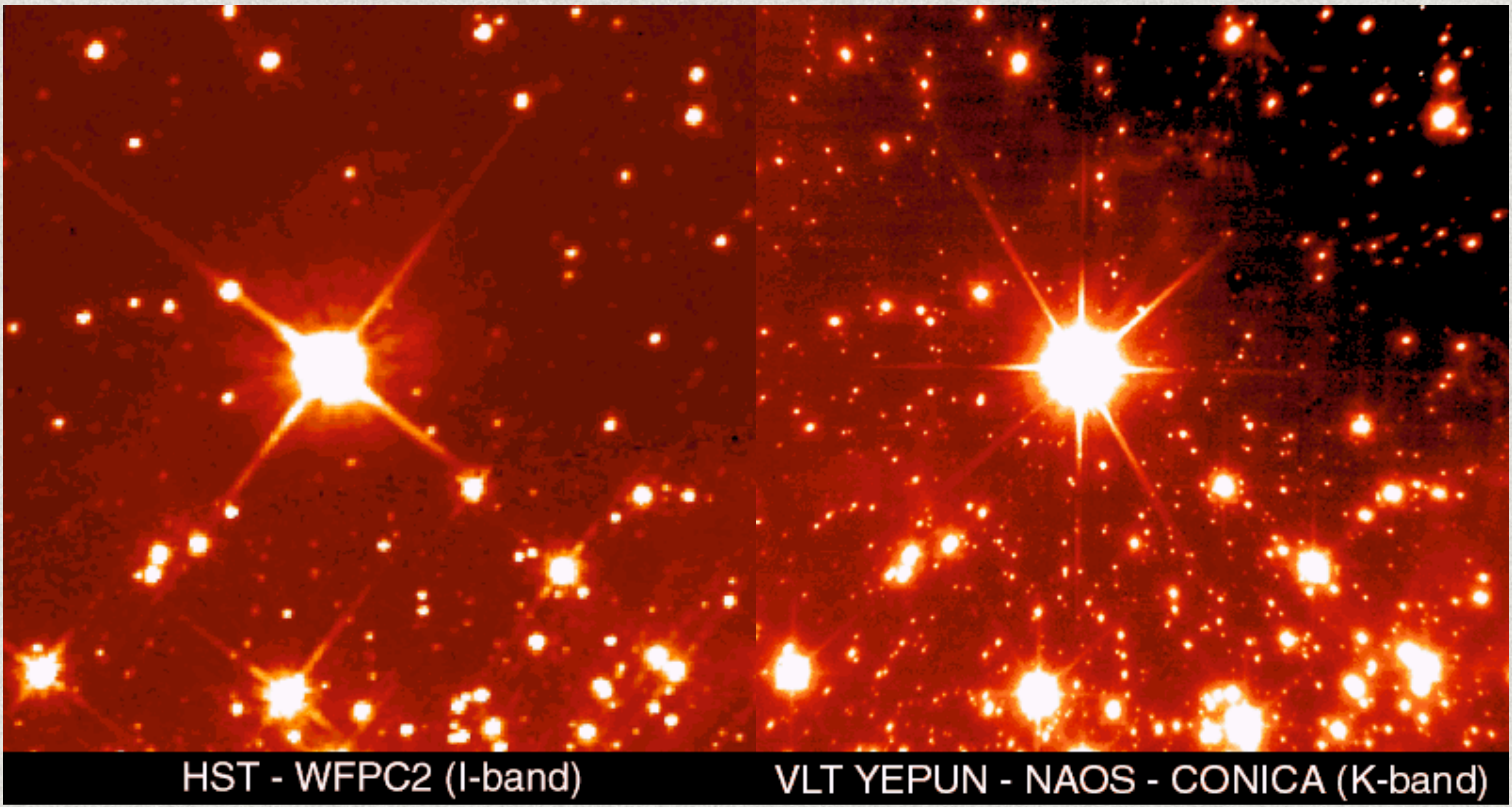




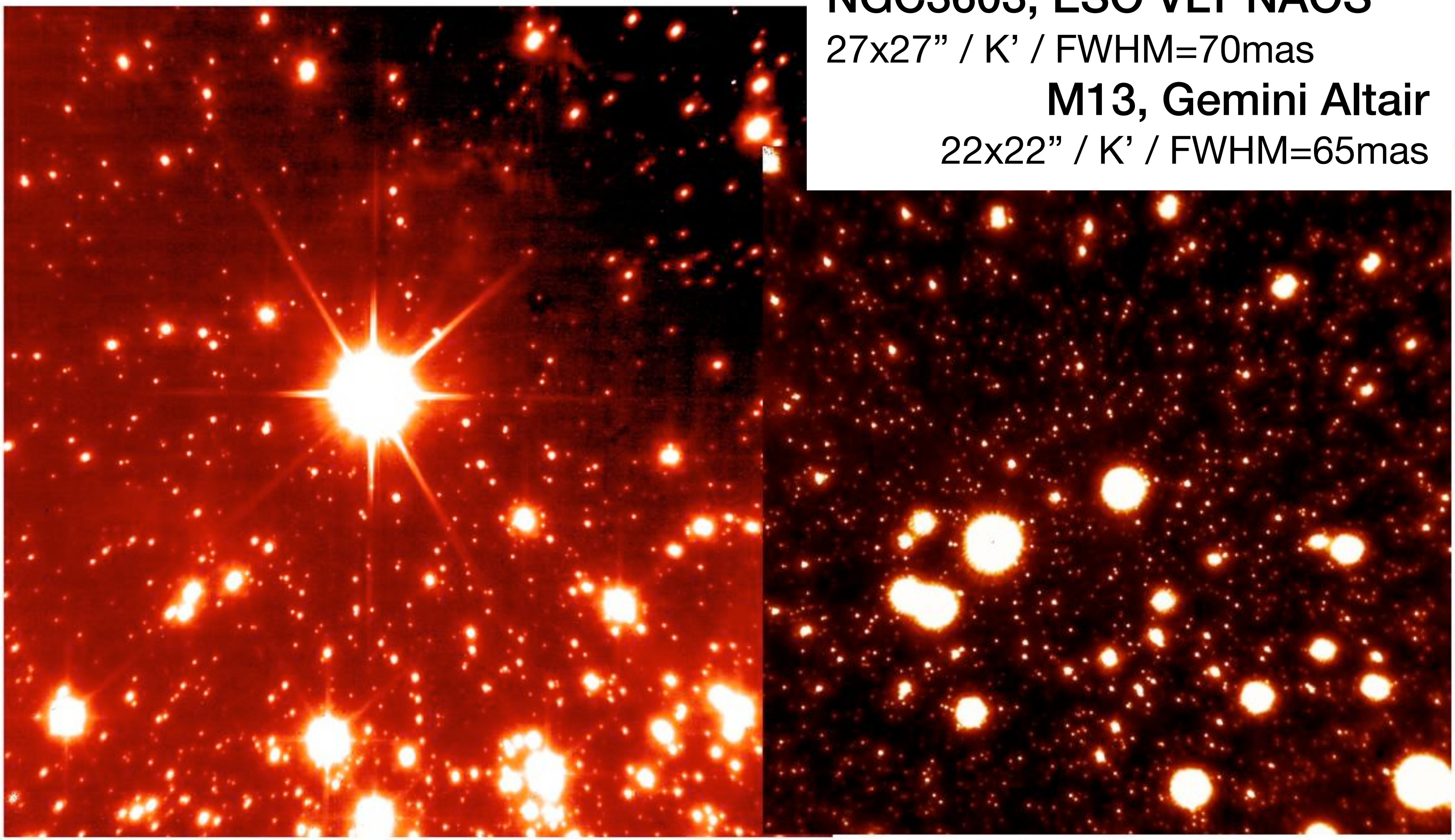


AO vs space facilities

Ground based AO vs HST



Ground based AO vs HST



NGC3603, ESO VLT NAOS

27x27" / K' / FWHM=70mas

M13, Gemini Altair

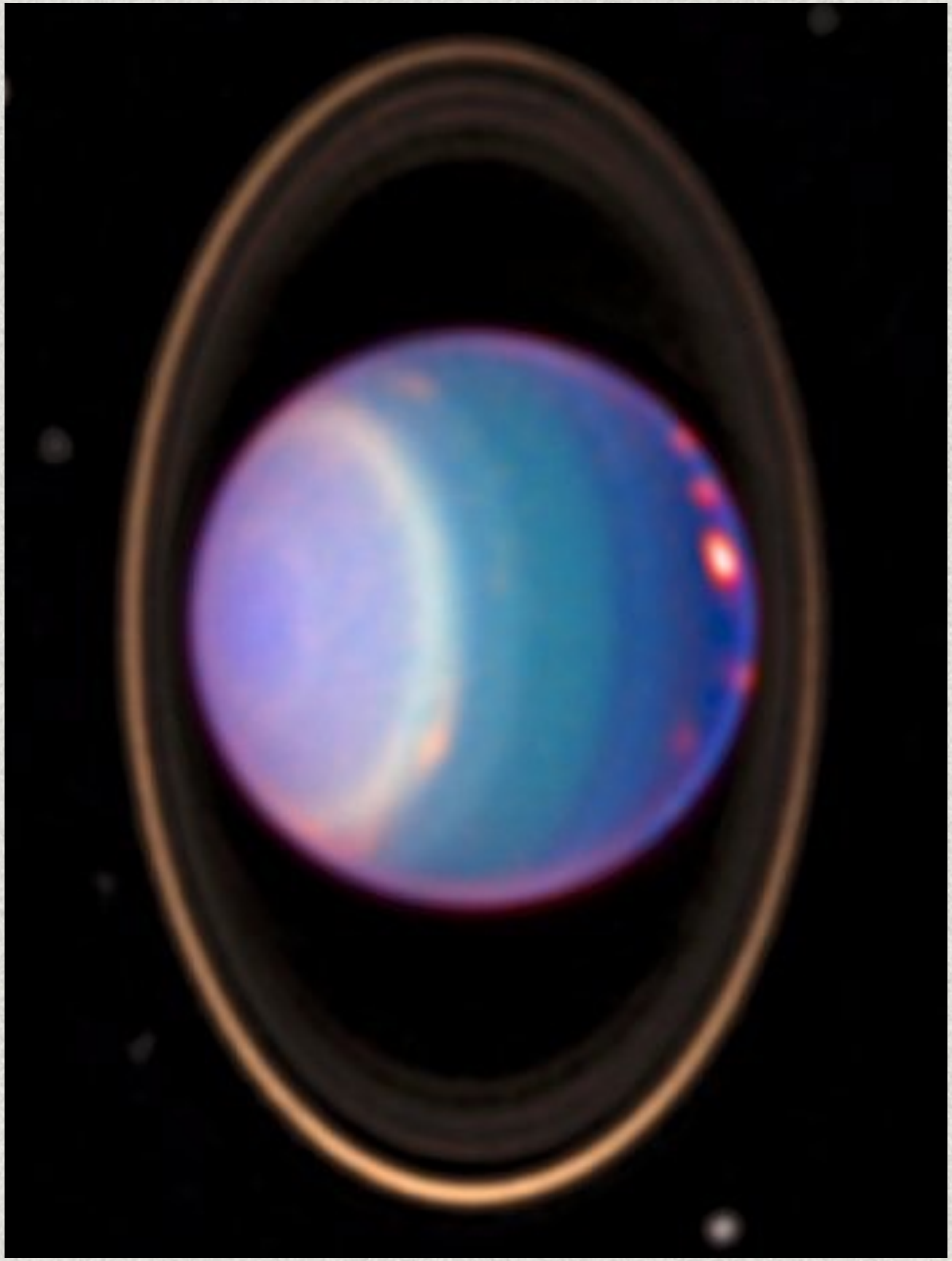
22x22" / K' / FWHM=65mas

AO vs HST

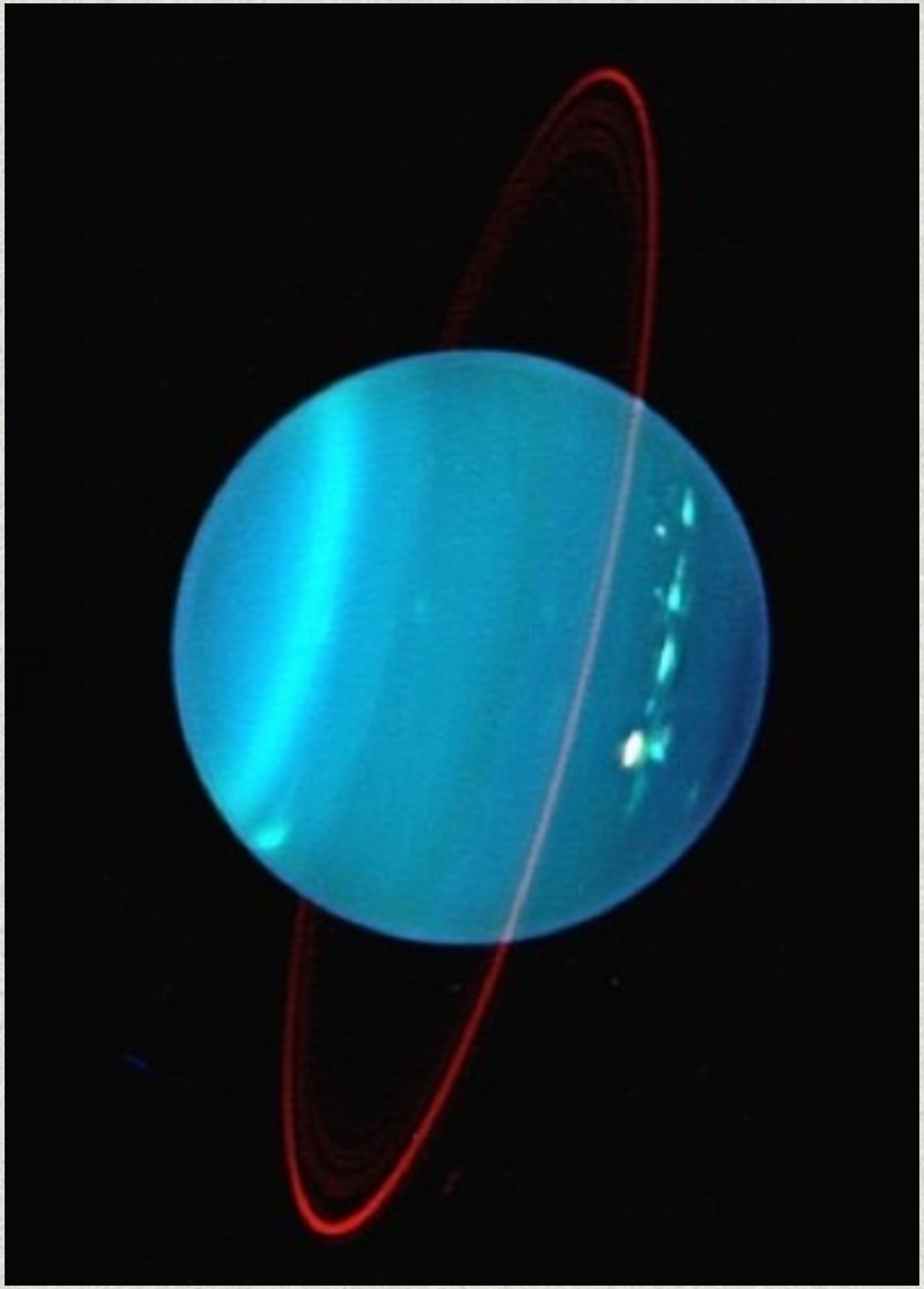
Australian National University

SAME WAVELENGTH, DIFFERENT EPOCHS

HUBBLE SPACE TELESCOPE, NICMOS



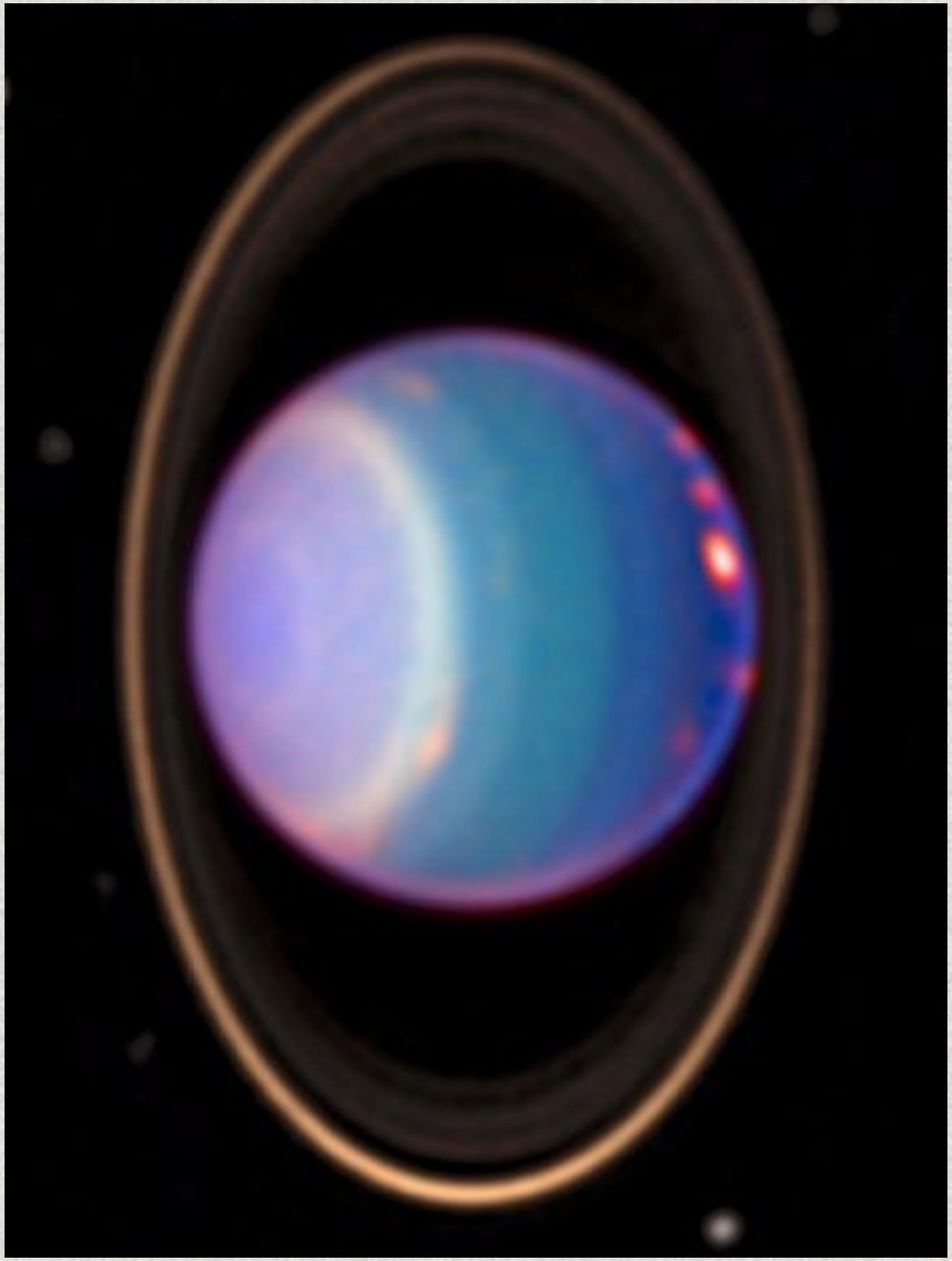
KECK WITH AO NEAR INFRA-RED (NIR)



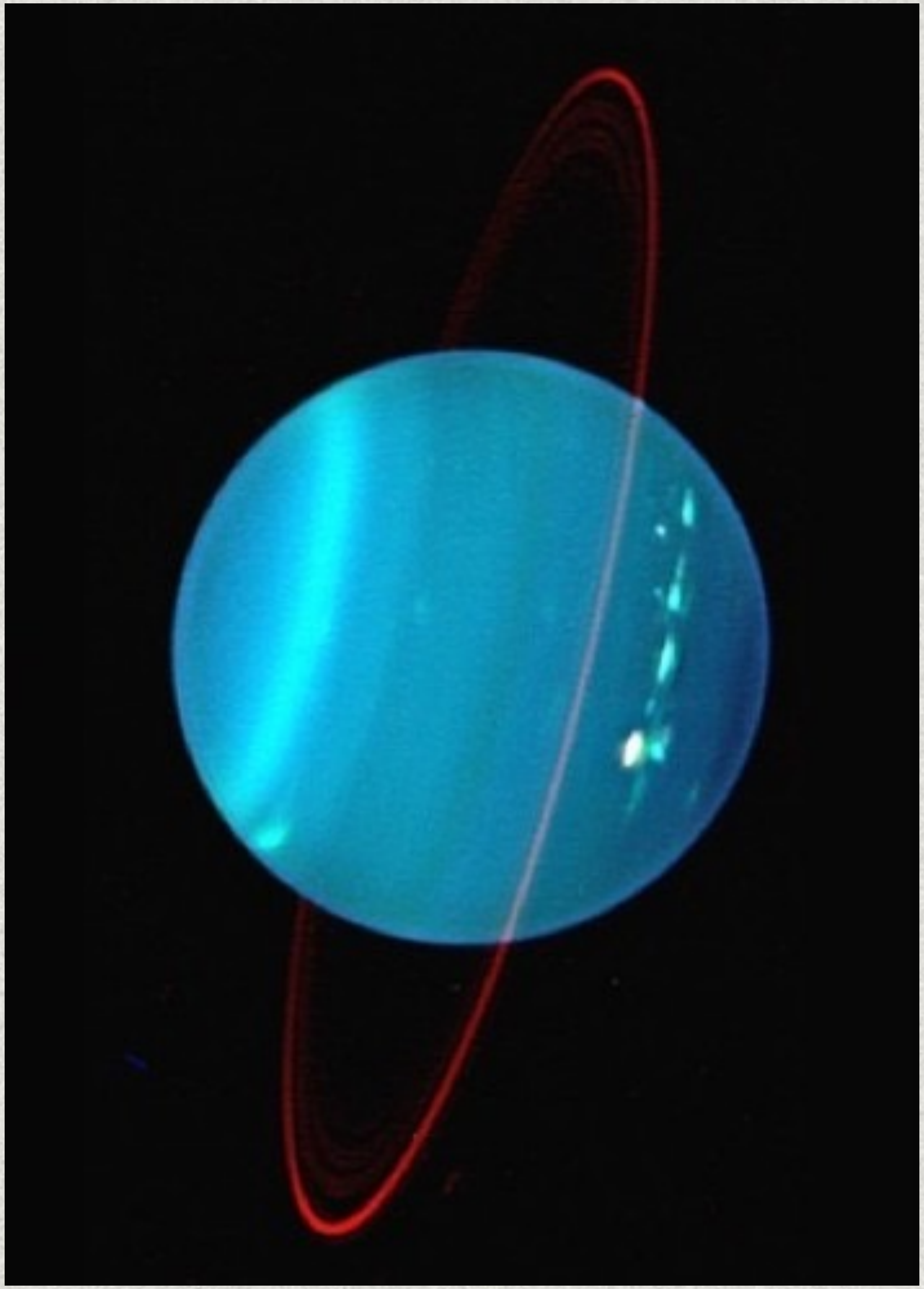
AO vs HST. YES, BUT…

SAME WAVELENGTH, DIFFERENT EPOCHS

HUBBLE SPACE TELESCOPE, NICMOS



KECK WITH AO NEAR INFRA-RED (NIR)



AO *can not* replace space facilities

Australian National University

AO pros

- AO is much cheaper. Millions vs Billions, e.g.:
  - Gemini ($90M/telescope) + Altair AO ($10M)
  - vs HST programme ($4.5B)
- Currently provide better or similar angular resolution than HST (0.05")

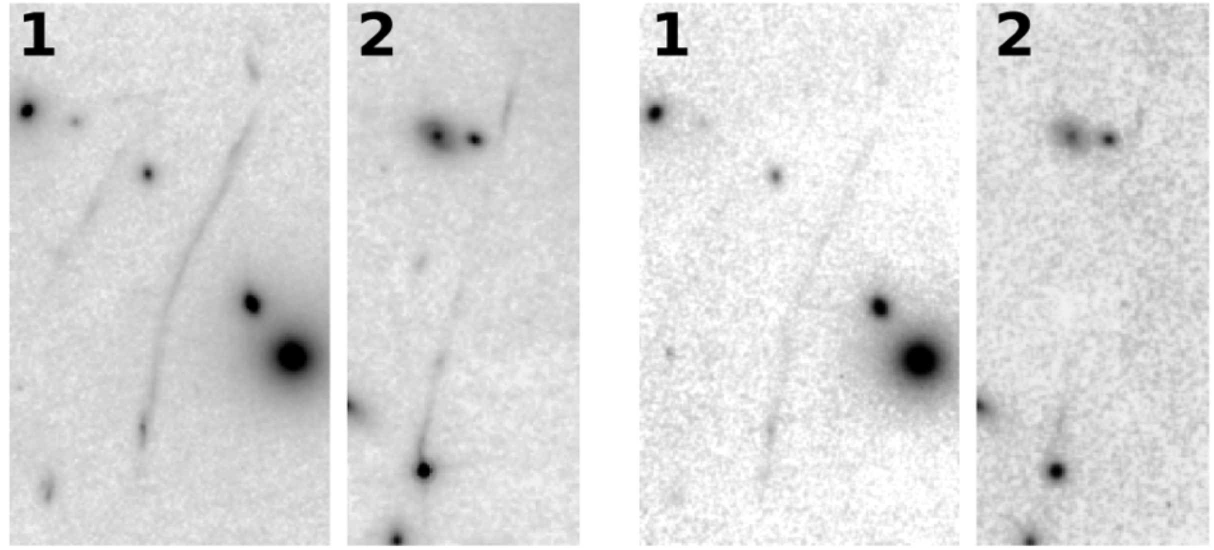
AO cons

- AO restricted to moderate field of view (⩽ 1arcmin) vs many arcmin for HST
- Atmosphere is opaque at some wavelengths (UV, NIR, etc)
- Sky background from atmosphere OH emission is 1000-10000x brighter than in space

AO is not a drop-in replacement for space facilities, but, coupled with large telescopes, can do better for some applications (narrow field, spectroscopy)

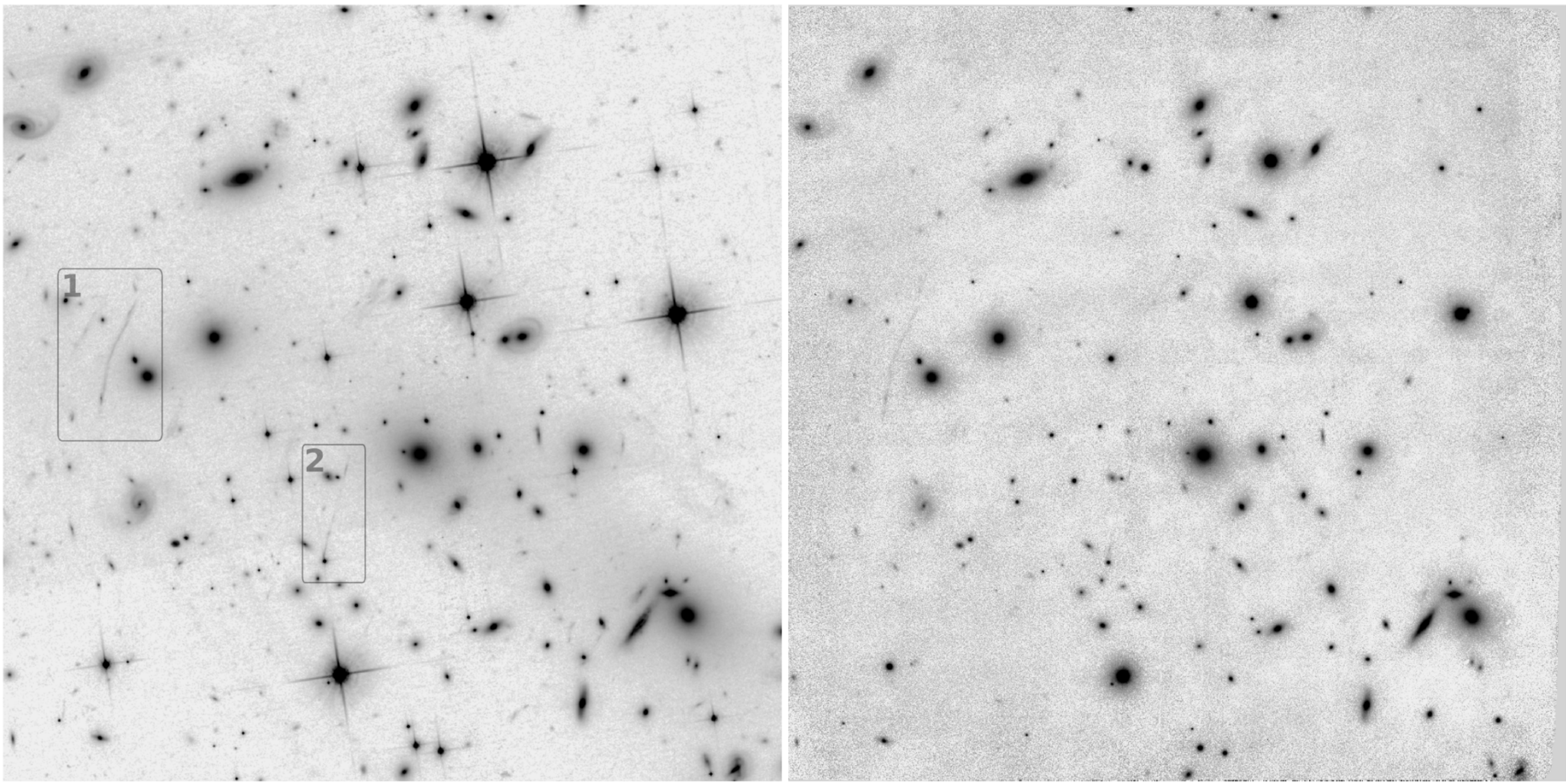
Bullet cluster
Gravitational arcs

HST ACS
F850LP
10124 sec



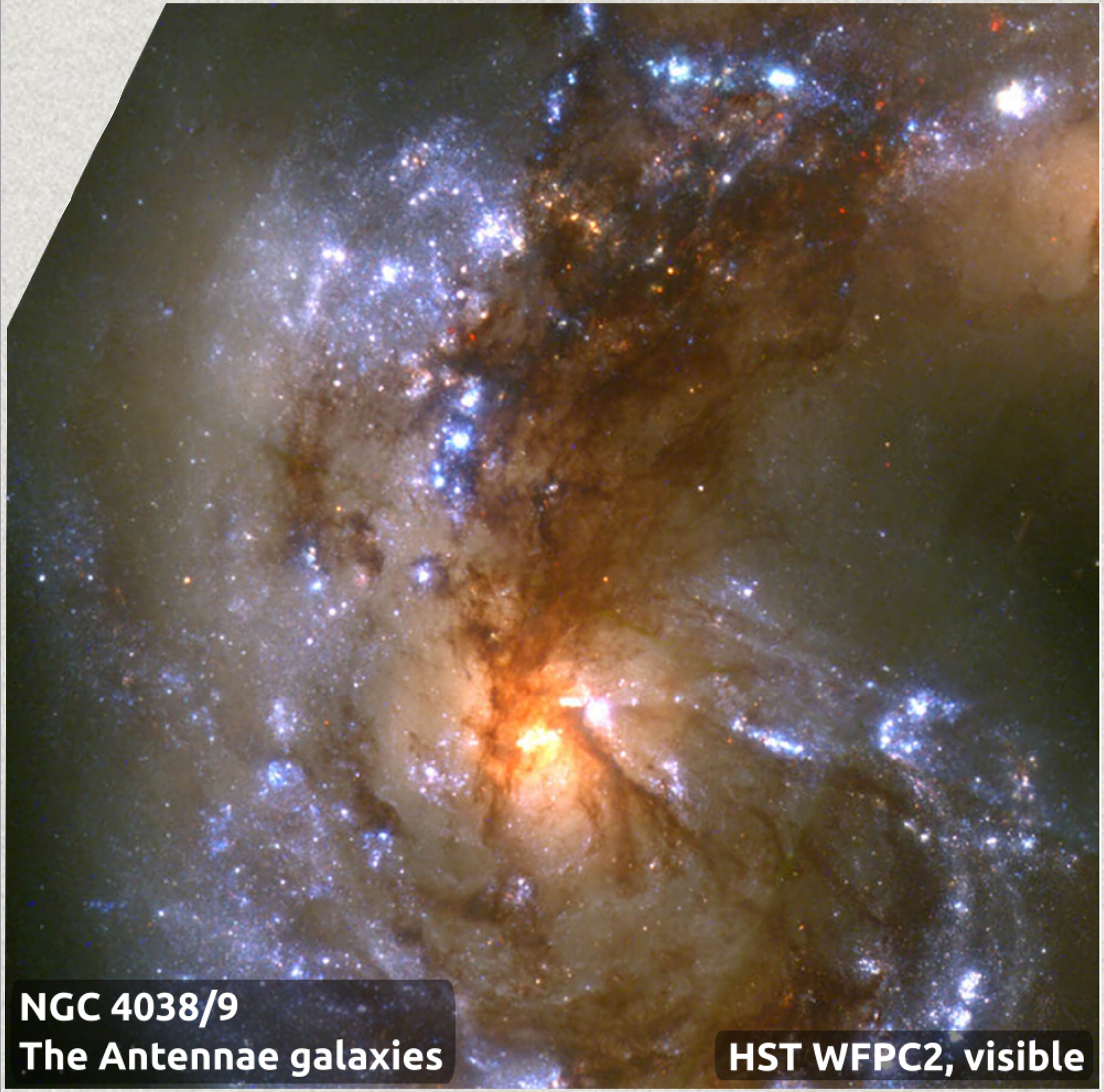
SKY BACKGROUND LIMITED!

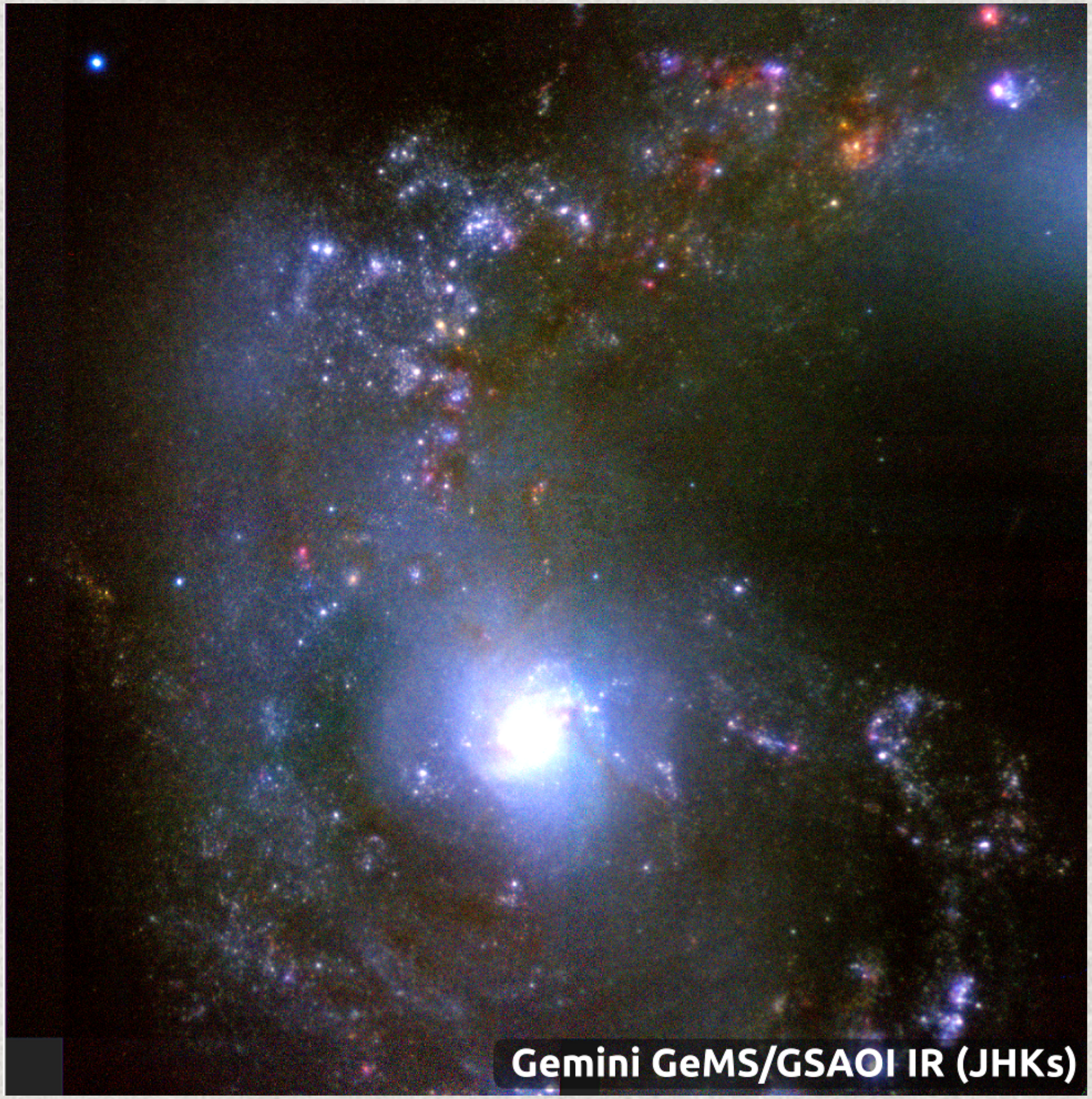
GeMS GSAOI
Kprime
1890 sec



AO/space complementarity

Australian National University





SAME ANGULAR RESOLUTION, DIFFERENT WAVELENGTHS, DIFFERENT VIEWS

M16, Pillar details

HST V band

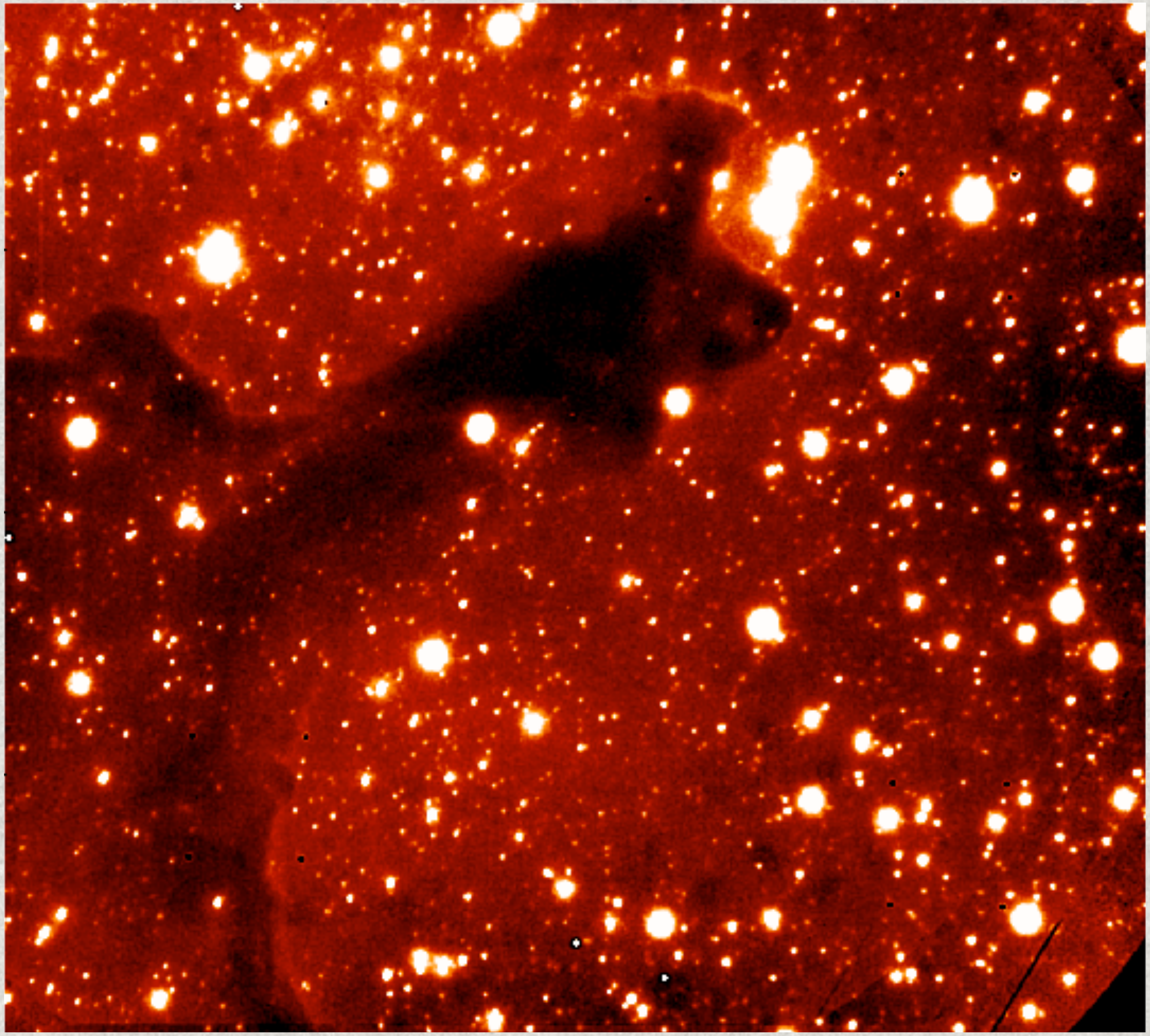
M16, Pillar details

- HST:
  - V Band
  - WFPC2

HST V band

M16, Pillar details

- HST:
  - V Band
  - WFPC2
- Gemini Altair LGS:
  - 4x120s
  - K' band
  - FoV 43"x40"
  - FWHM <100mas
  - Meets or exceeds HST V resolution



ALTAIR-LGS K'

M16, Pillar details

- HST:
  - V Band
  - WFPC2
- Gemini Altair LGS:
  - 4x120s
  - K' band
  - FoV 43”x40”
  - FWHM <100mas
  - Meets or exceeds HST V resolution

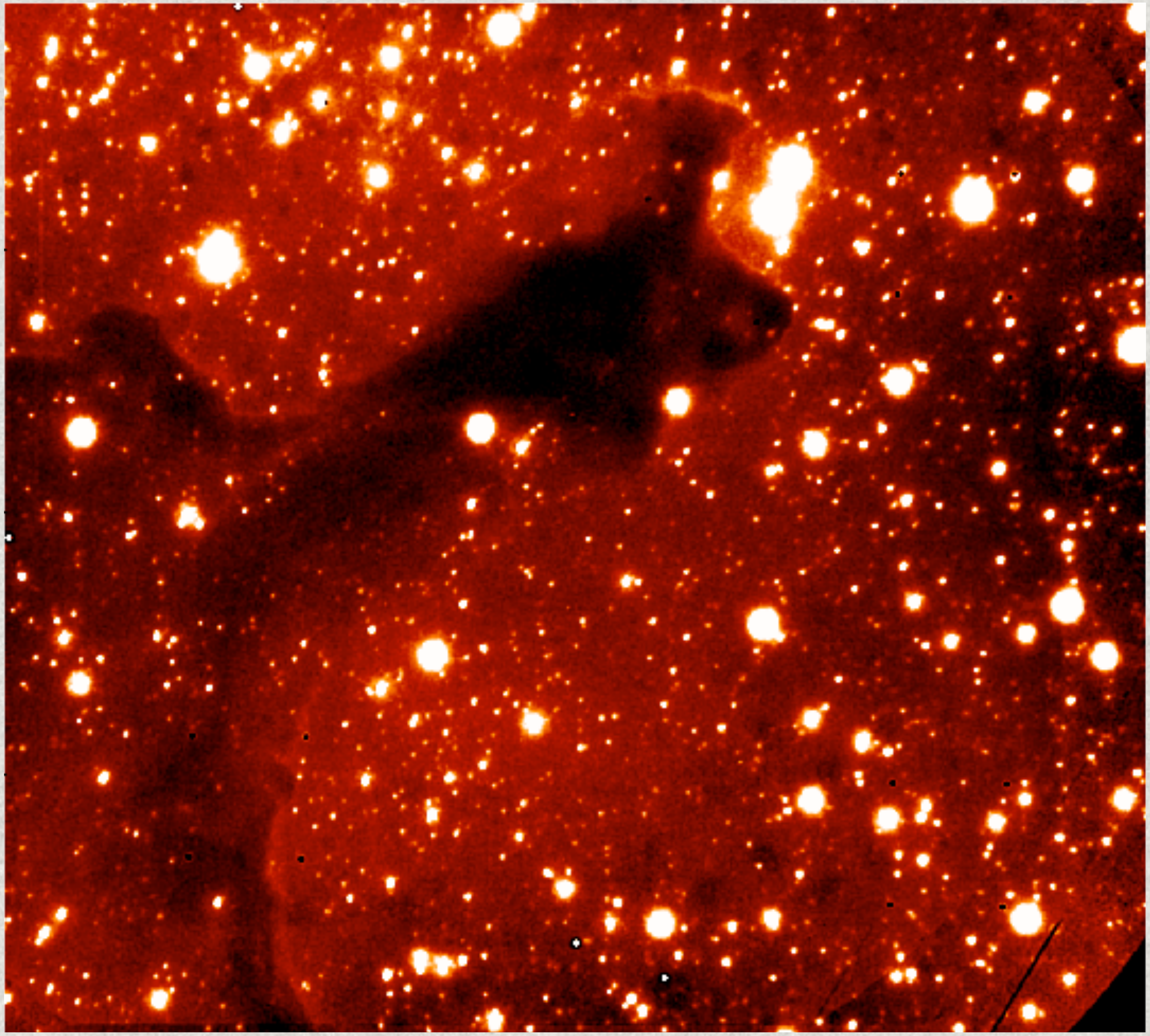
HST V band

ALTAIR-LGS K’

M16, Pillar details

- HST:
  - V Band
  - WFPC2
- Gemini Altair LGS:
  - 4x120s
  - K' band
  - FoV 43”x40”
  - FWHM <100mas
  - Meets or exceeds HST V resolution

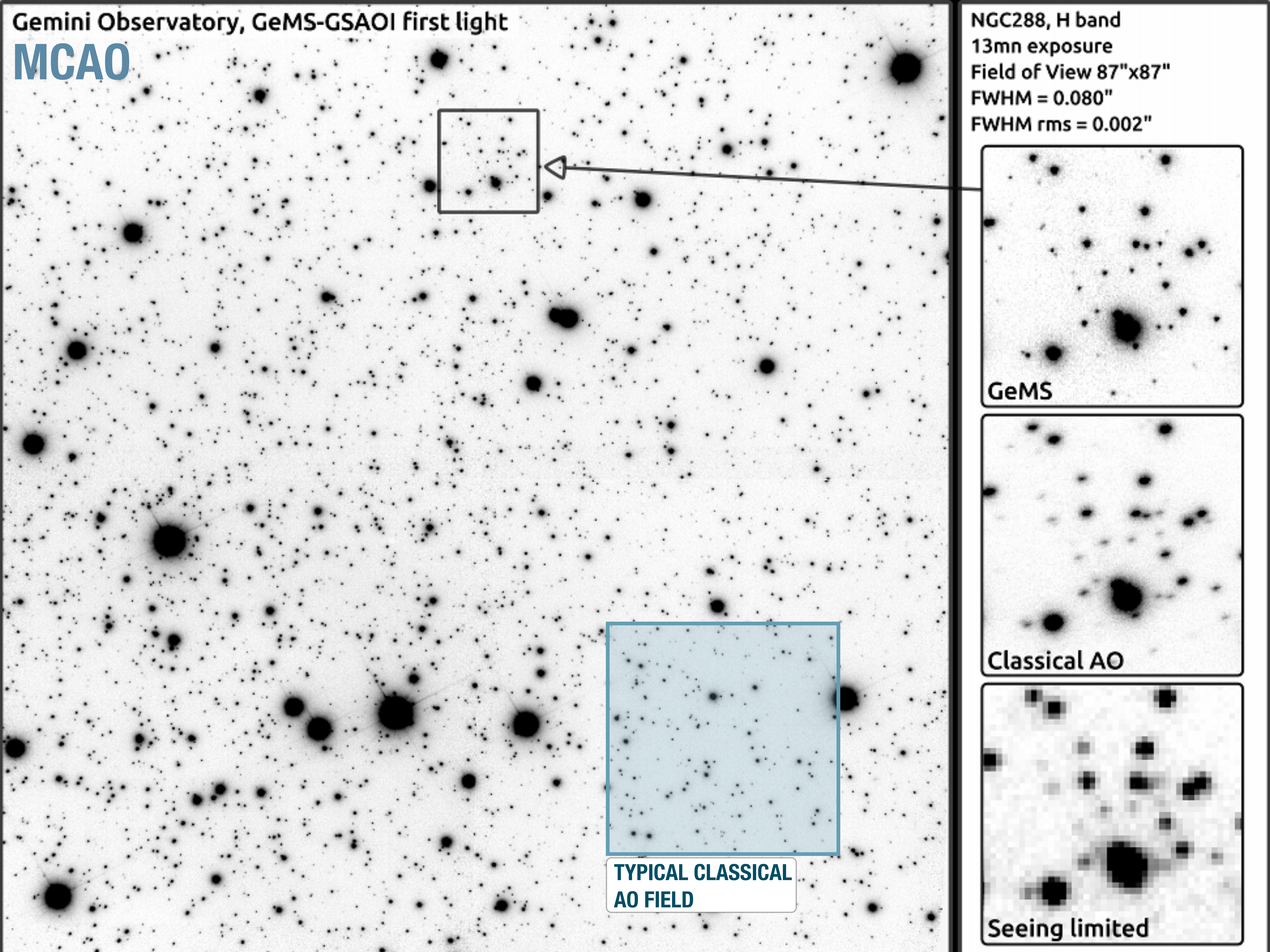
Similar resolution, different wavelengths: complementary



ALTAIR-LGS K’

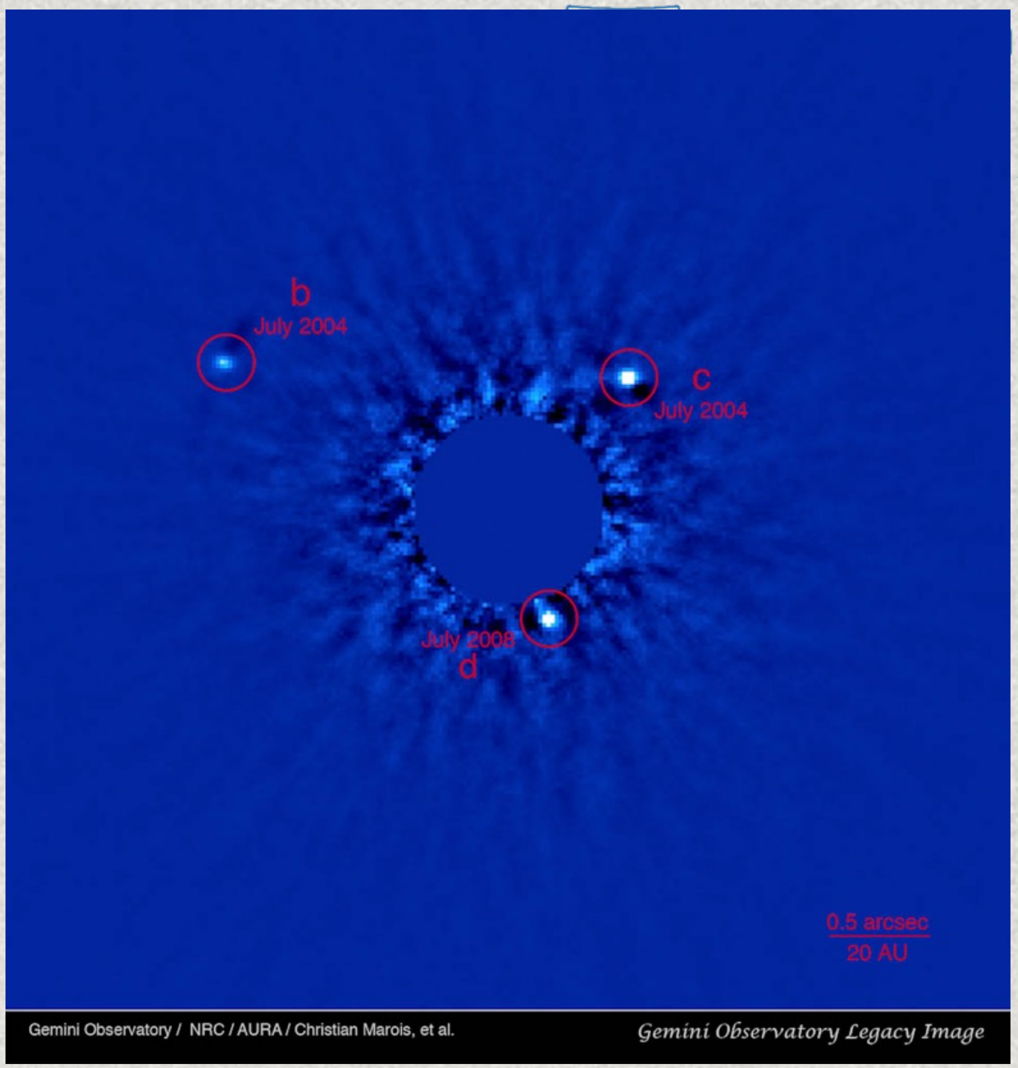
Australian National University

Where is AO going?

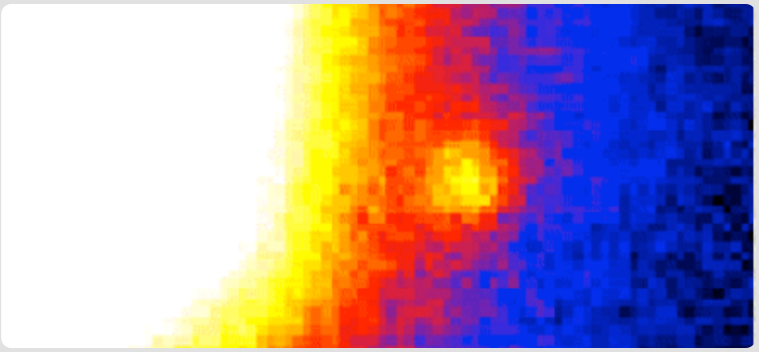

Gemini Observatory, GeMS-GSAOI first light
MCAO
NGC288, H band
13mn exposure
Field of View 87"x87"
FWHM = 0.080"
FWHM rms = 0.002"
GeMS
Classical AO
Seeing limited
TYPICAL CLASSICAL
AO FIELD

Extreme AO

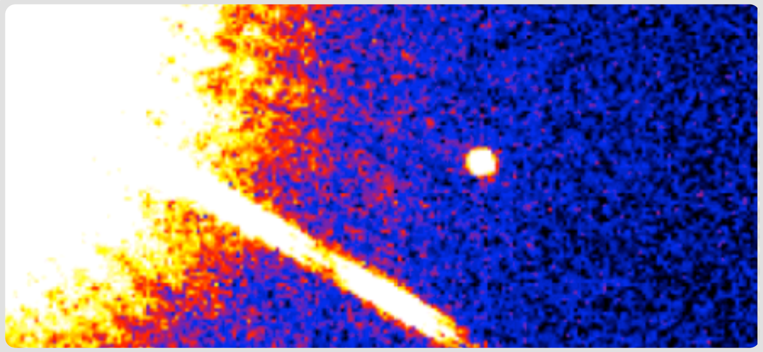
GEMINI
HR8799
3 GIANT JOVIANS
AO + ADI



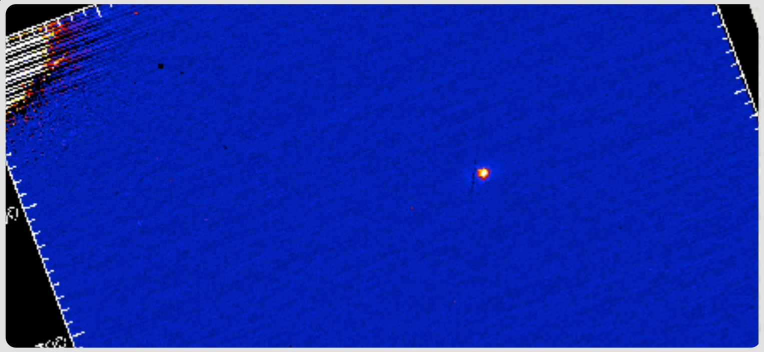
BROWN DWARF GLEISE 229B



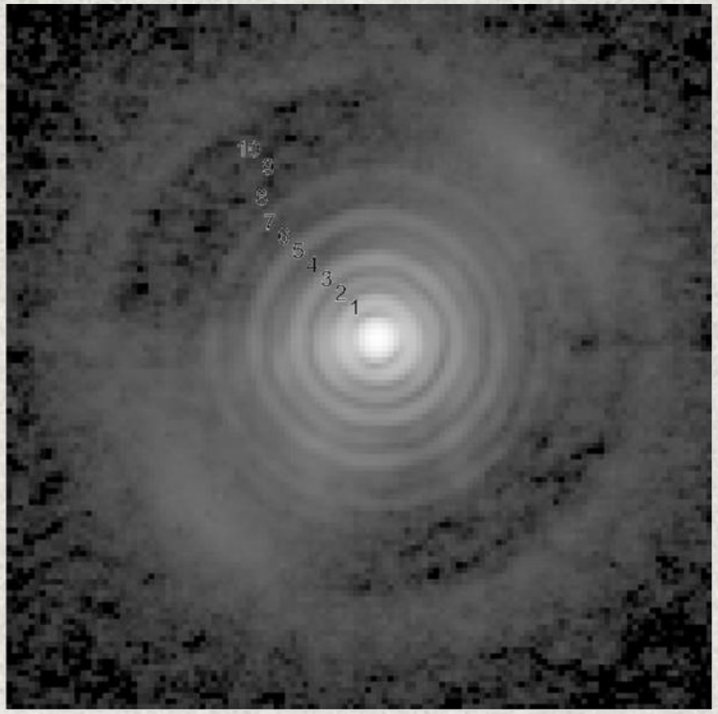
PALOMAR
DISCOVERY IMAGE
1994



HST
WFPC2
1995



GEMINI
NICI AO
2007



LBT, H BAND
STREHL=85%
PYRAMID WFS

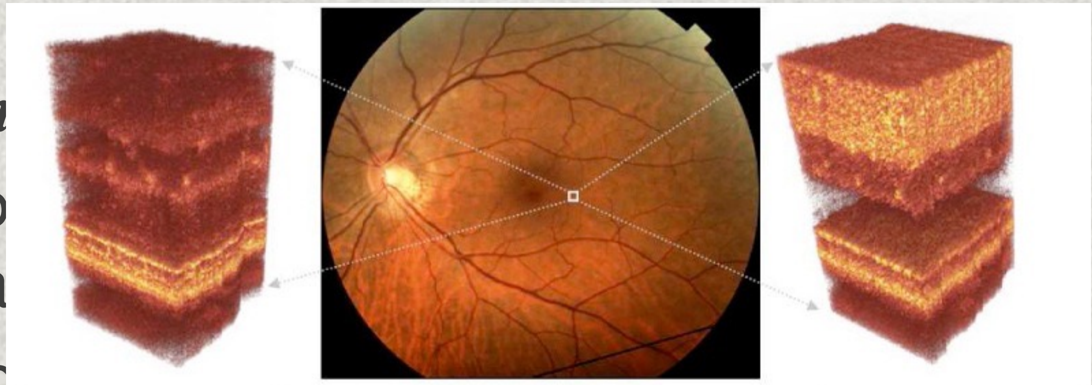
Cheap AO?

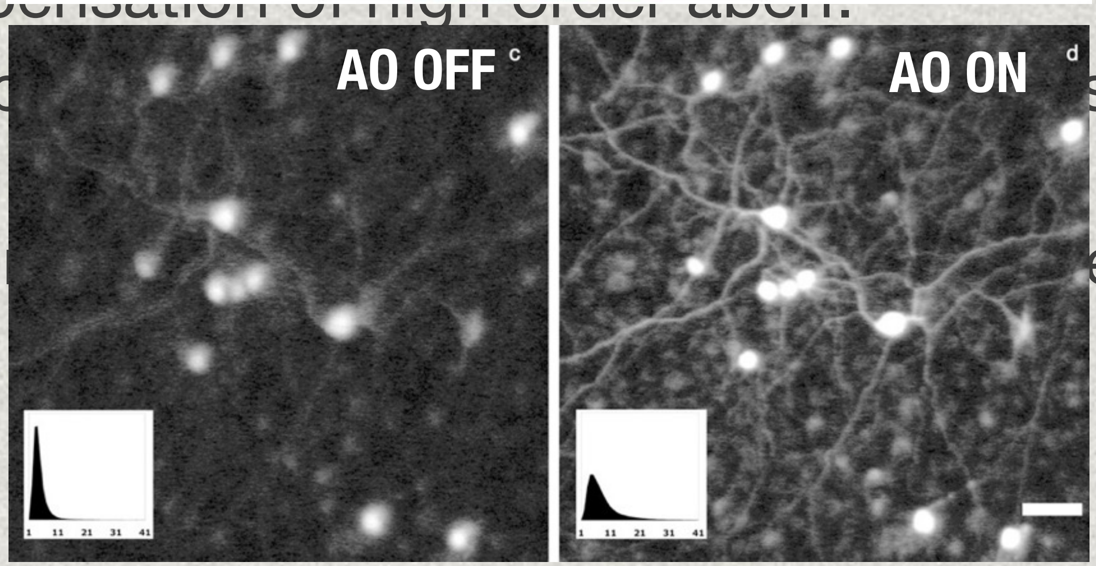
- **Price of AO components going down**
  - Deformable Mirrors now ~€400/actuators, reliable
  - Detectors still expensive, but price going down and perf going up
- For amateur astronomy? **NO**
  - Amateur telescopes almost always in bad sites.
    AO depends on $\mathbf{r_0^5}$! r_0^2 (fitting) x r_0 (servolag) x r_0^2 (anisoplanatism)
  - Amateur telescope budget << Professional telescope budget
  - Amateur essentially interested in wide field of view (many arcmin)
- For mid size professional telescopes? **YES**
  - Located in better site than amateur telescopes
  - Often looking for improvement of their local dome/seeing
- For laboratory purposes? **YES**
  - Some cheap components appearing (e.g. Thorlab US$4k DM)
  - Small to medium order systems controllable with cheap computing units

Medical adaptive optics

VISION SCIENCE

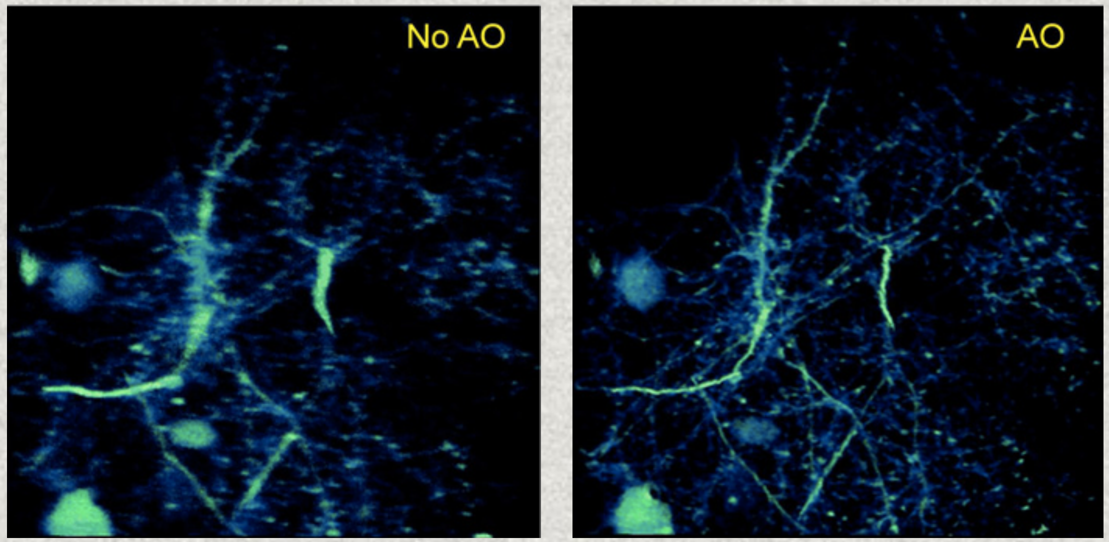
- Correct ocular aberrations real time and *in*
- Evaluation of eye diseases linked to photo
  retinopathy, macular degeneration and gla
- Measurements for refractive surgery compensation of high order aberr.
- Combined with confocal scanning laser op sel
  & retinal pigments
- Combined with Optical Coherence Tomog es
  of retinal structures (3x3x3µm)
- New instruments using MCAO
  for 5 degrees field of view





IMAGES OF RETINAL GANGLION CELLS, GRAY ET AL, 2008

DEEP TISSUE IMAGING



E.BETZIG

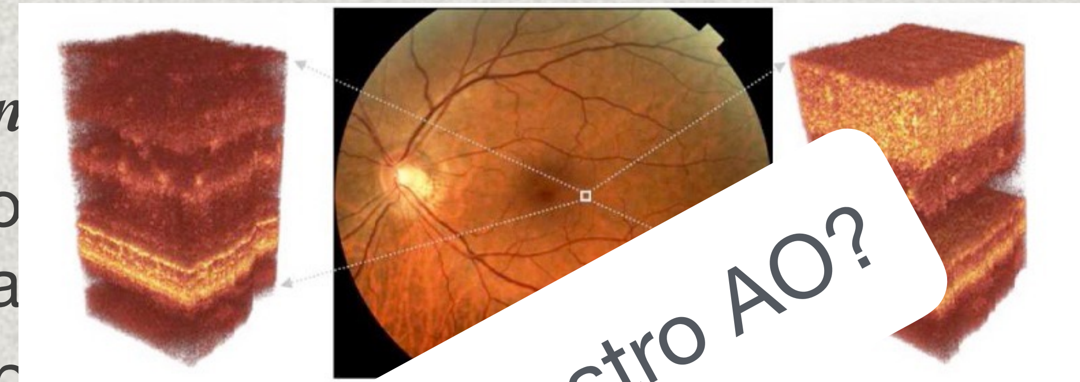
IMAGES OF INDIVIDUAL NEURONES W/ AO 2 PHOTONS MICROSCOPES

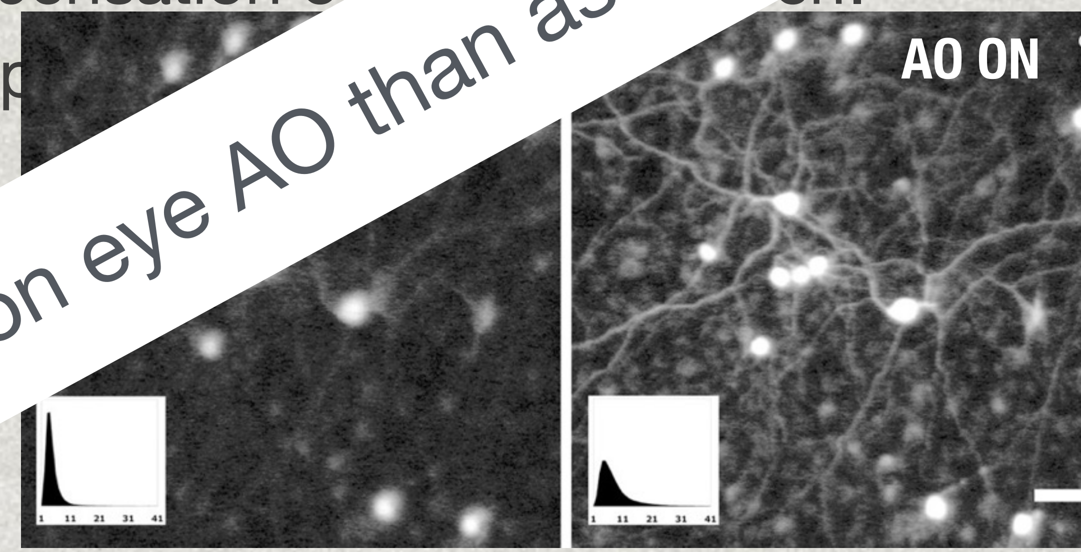
Medical adaptive optics

VISION SCIENCE

- Correct ocular aberrations real time and *in*
- Evaluation of eye diseases linked to photo retinopathy, macular degeneration and gla
- Measurements for refractive surgery comp
- Combined with confocal scanning laser op sel & retinal pigments
- Combined with Optical Coherence To es of retinal structures (3x3x3μm)
- New instruments using MC for 5 degrees field of v

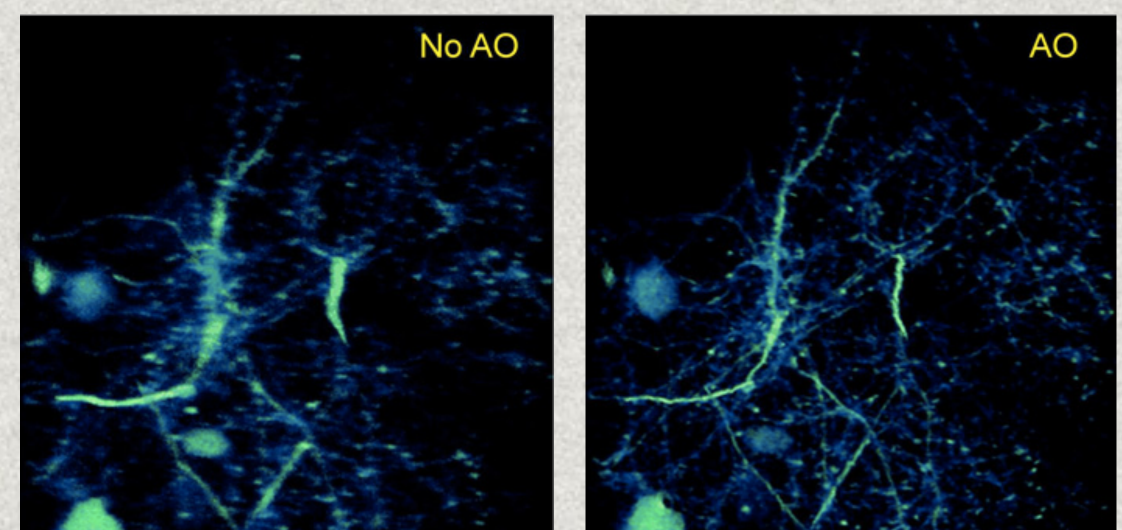
More papers published on eye AO than astro AO?





IMAGES OF RETINAL GANGLION CELLS, GRAY ET AL, 2008

DEEP TISSUE IMAGING

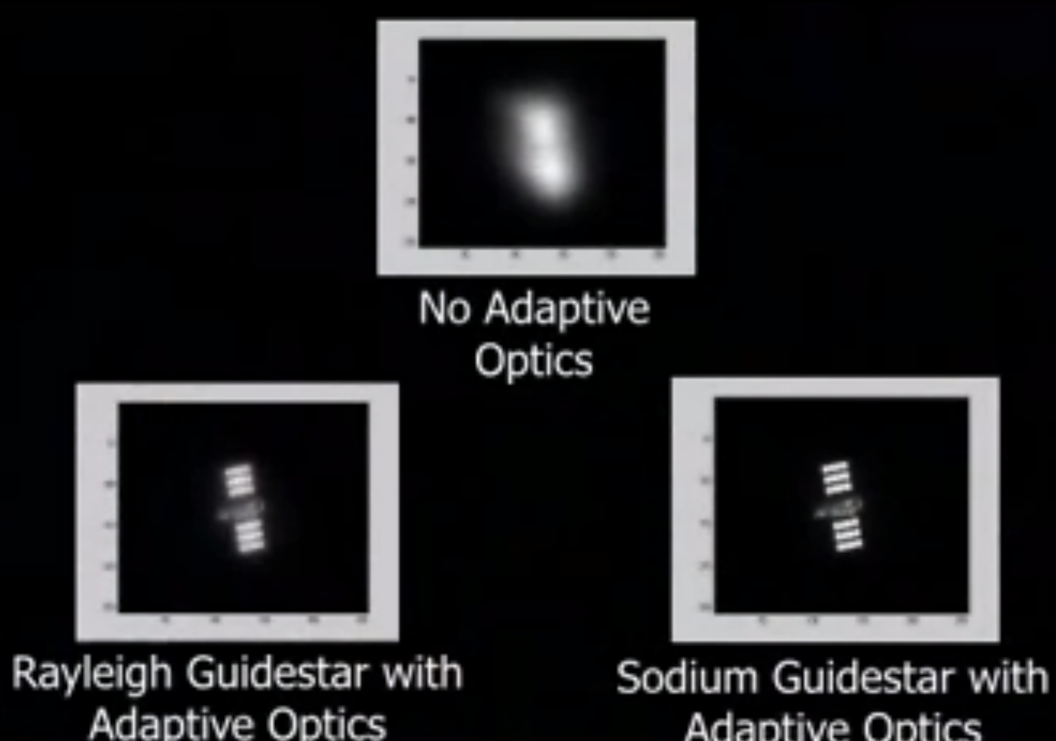


E.BETZIG

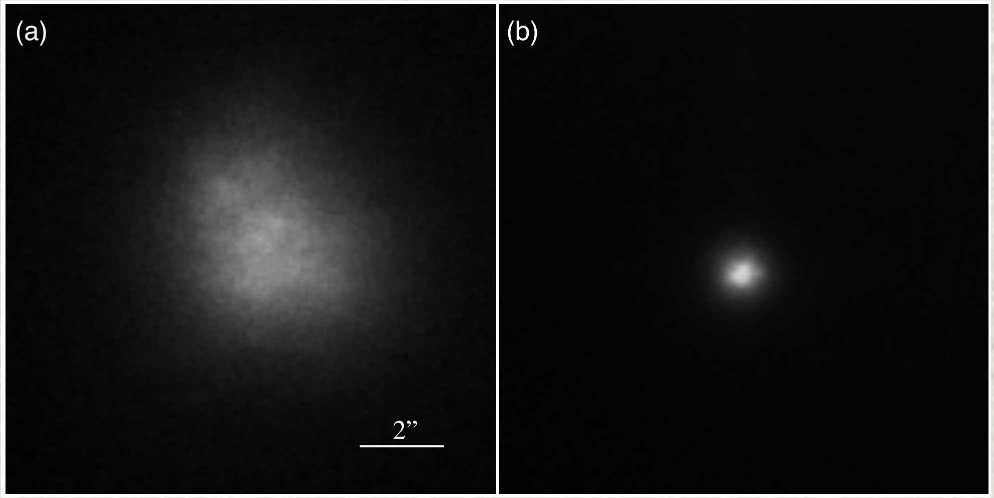
IMAGES OF INDIVIDUAL NEURONES W/ AO 2 PHOTONS MICROSCOPES

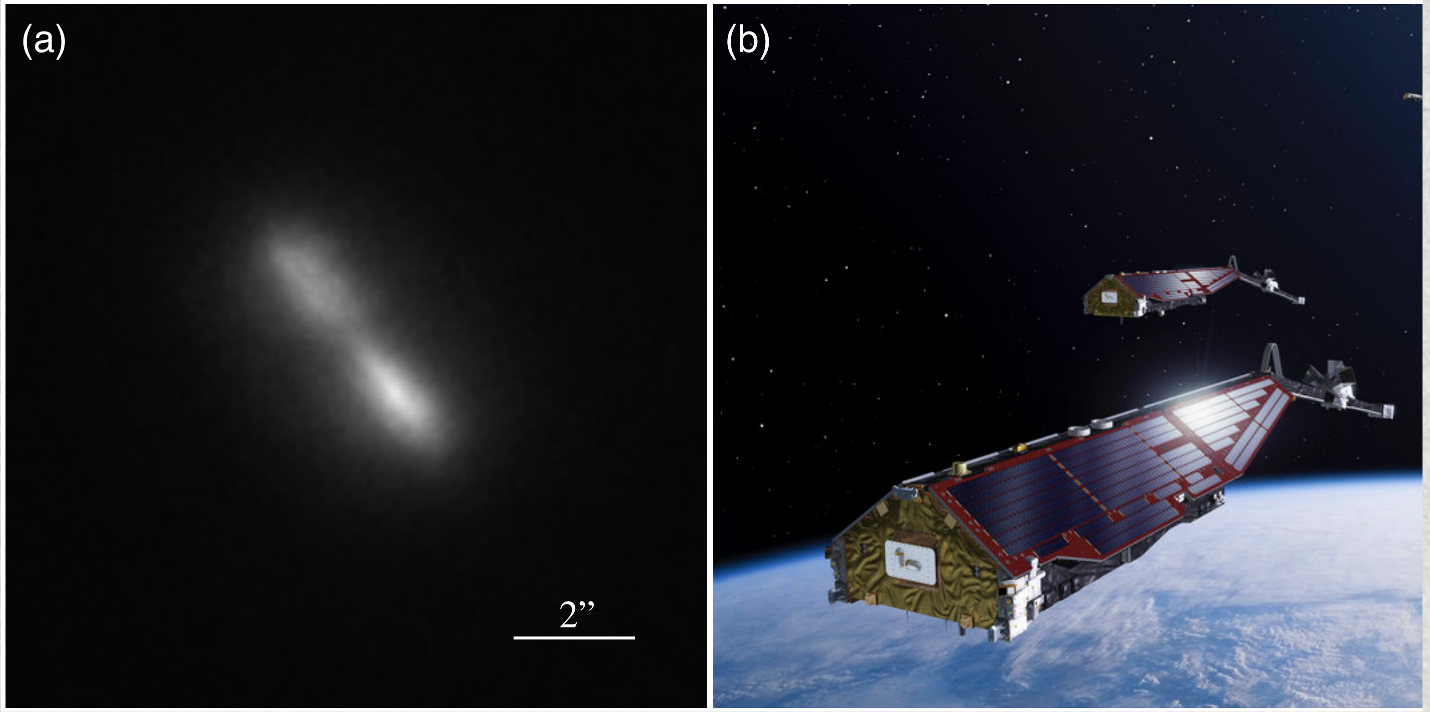
AO applications to space science

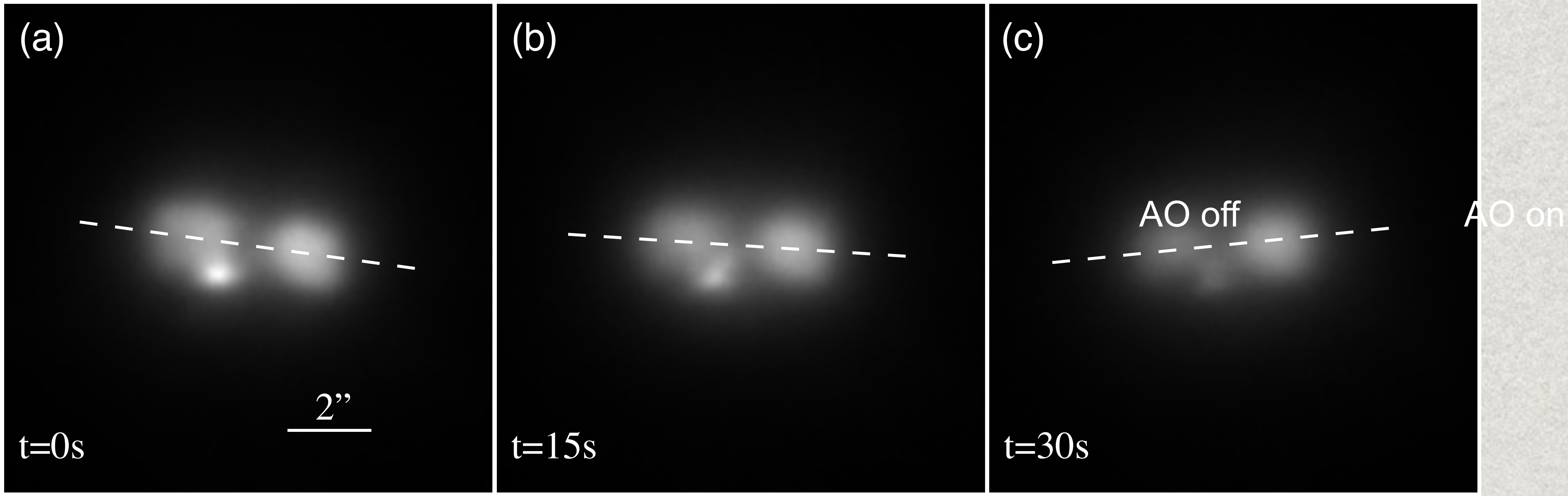
- Ground-space problems
  - Propagation through turbulence
- Problems related to quickly varying optical aberrations
- Satellite imaging (passive)
- Space debris tracking (passive)
- Space debris nudging (active)
- Space debris de-orbiting (active)
- Australia CRC for Space Environment Management (2014-2019)

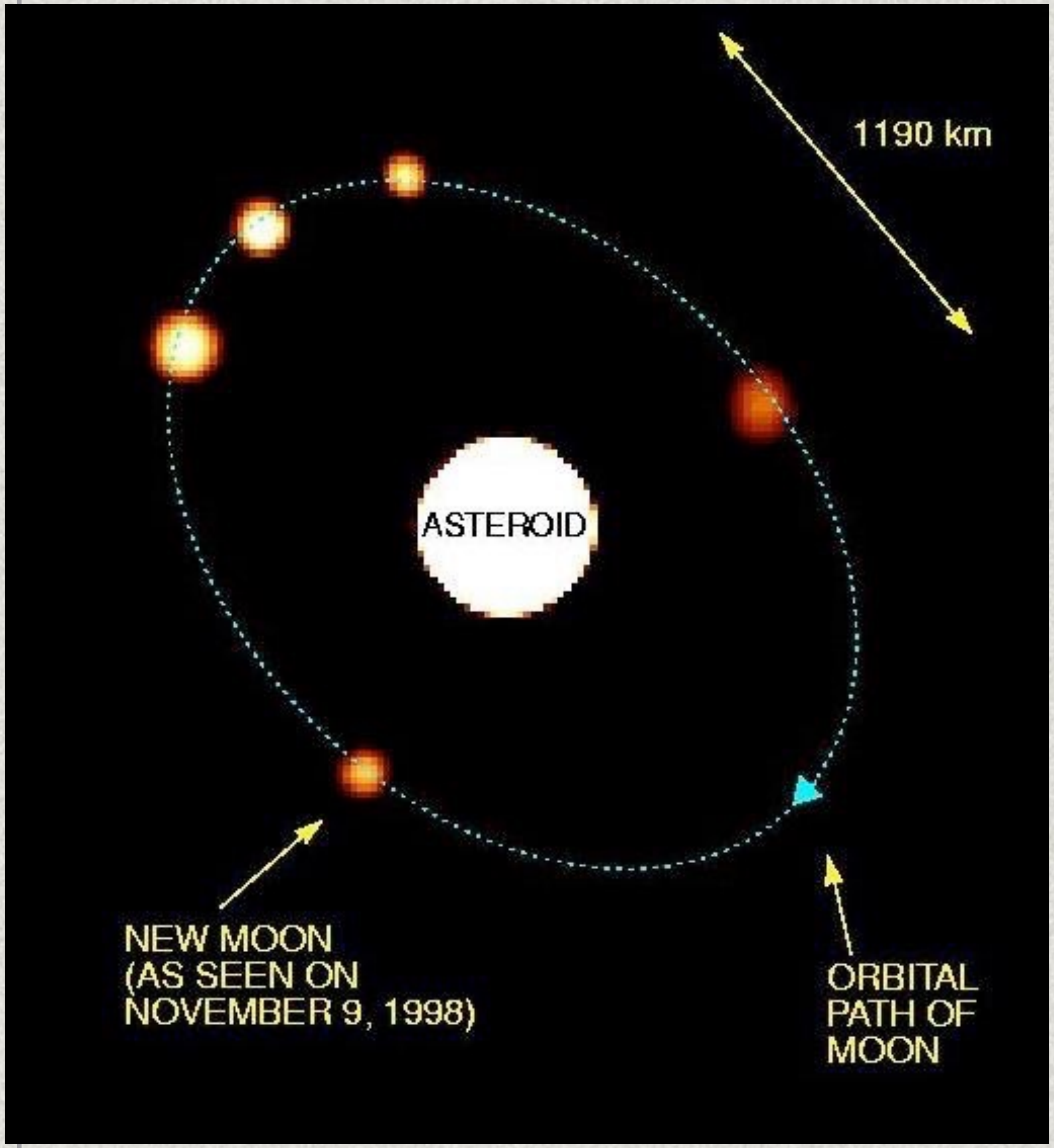


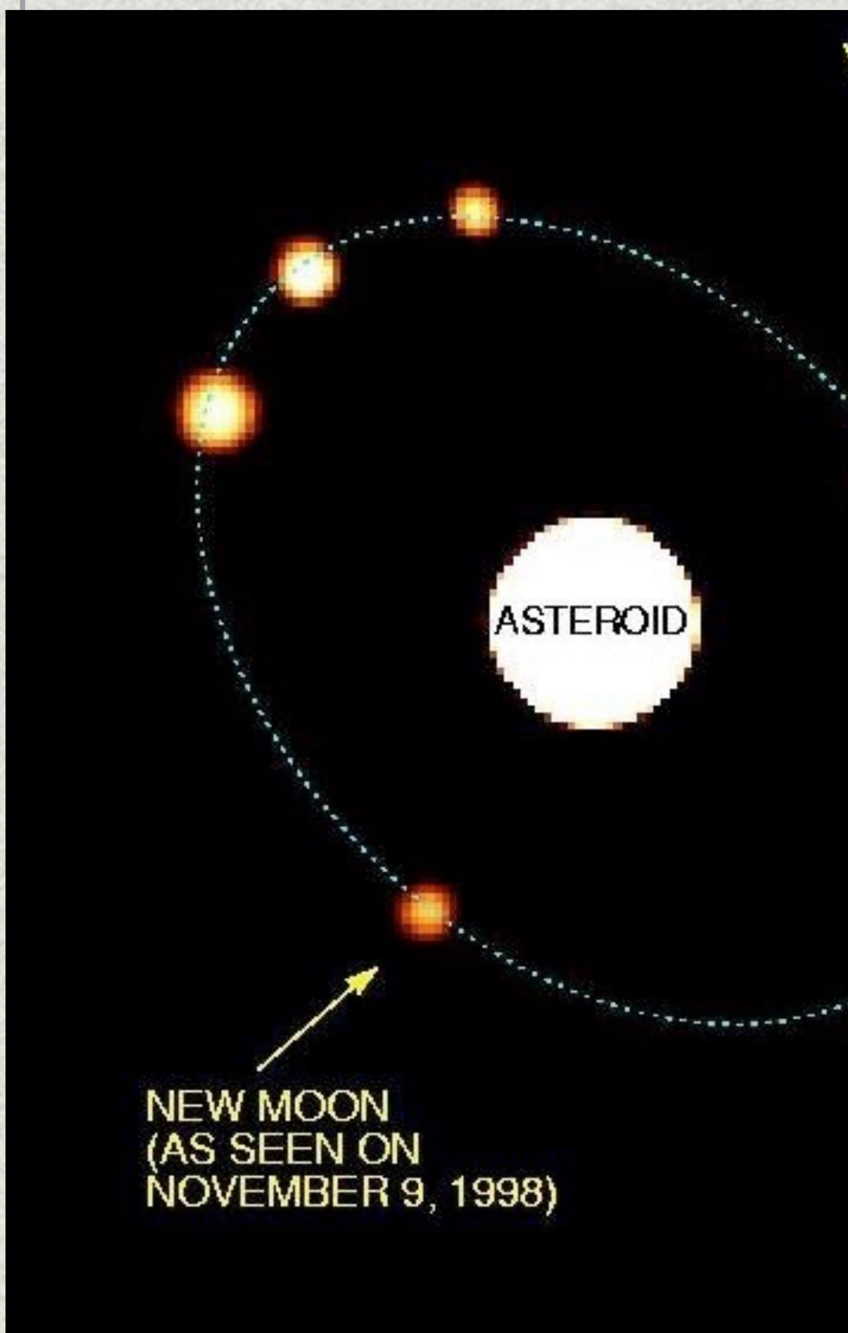
Satellite imaging @ Stromlo

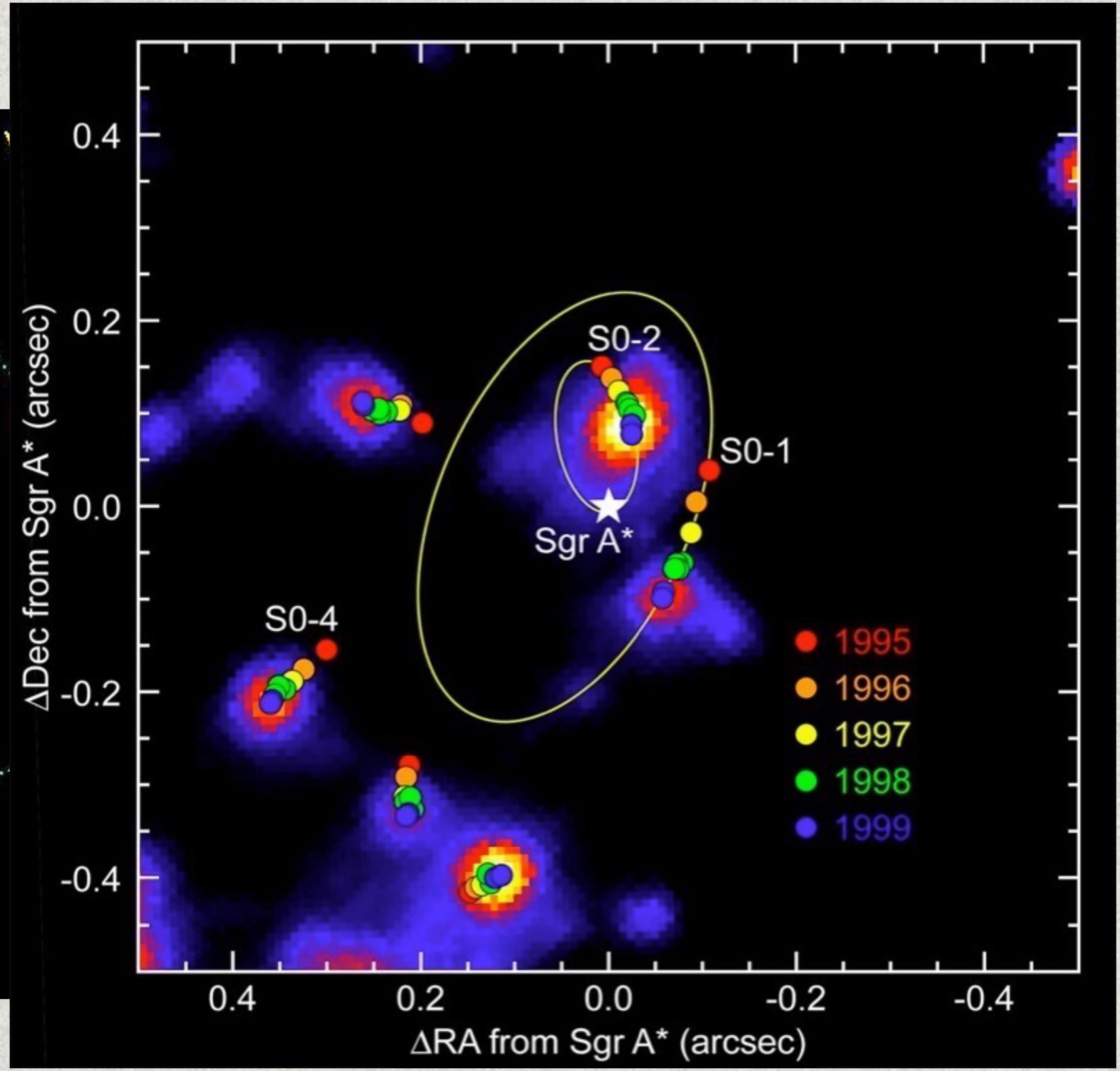


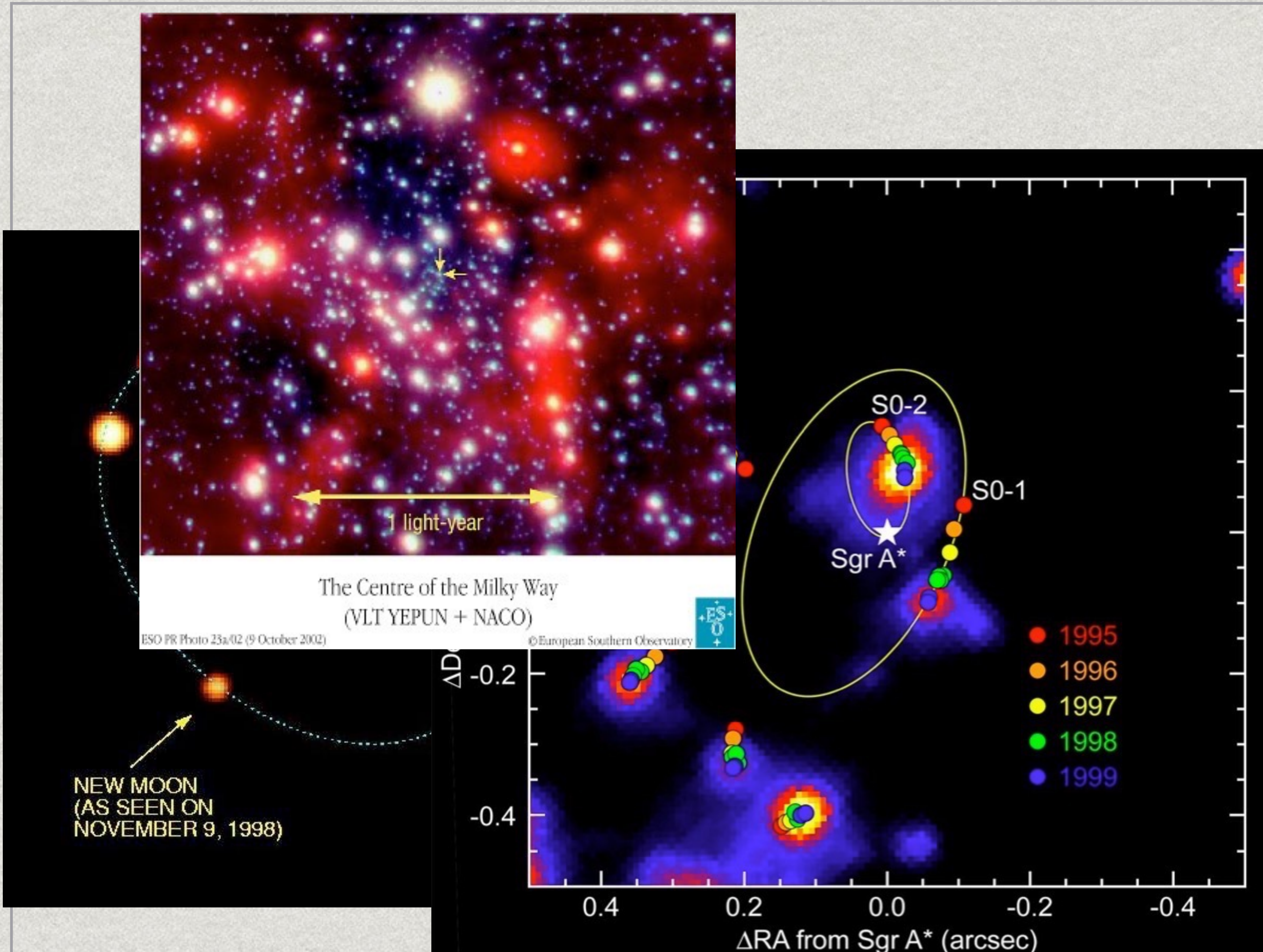


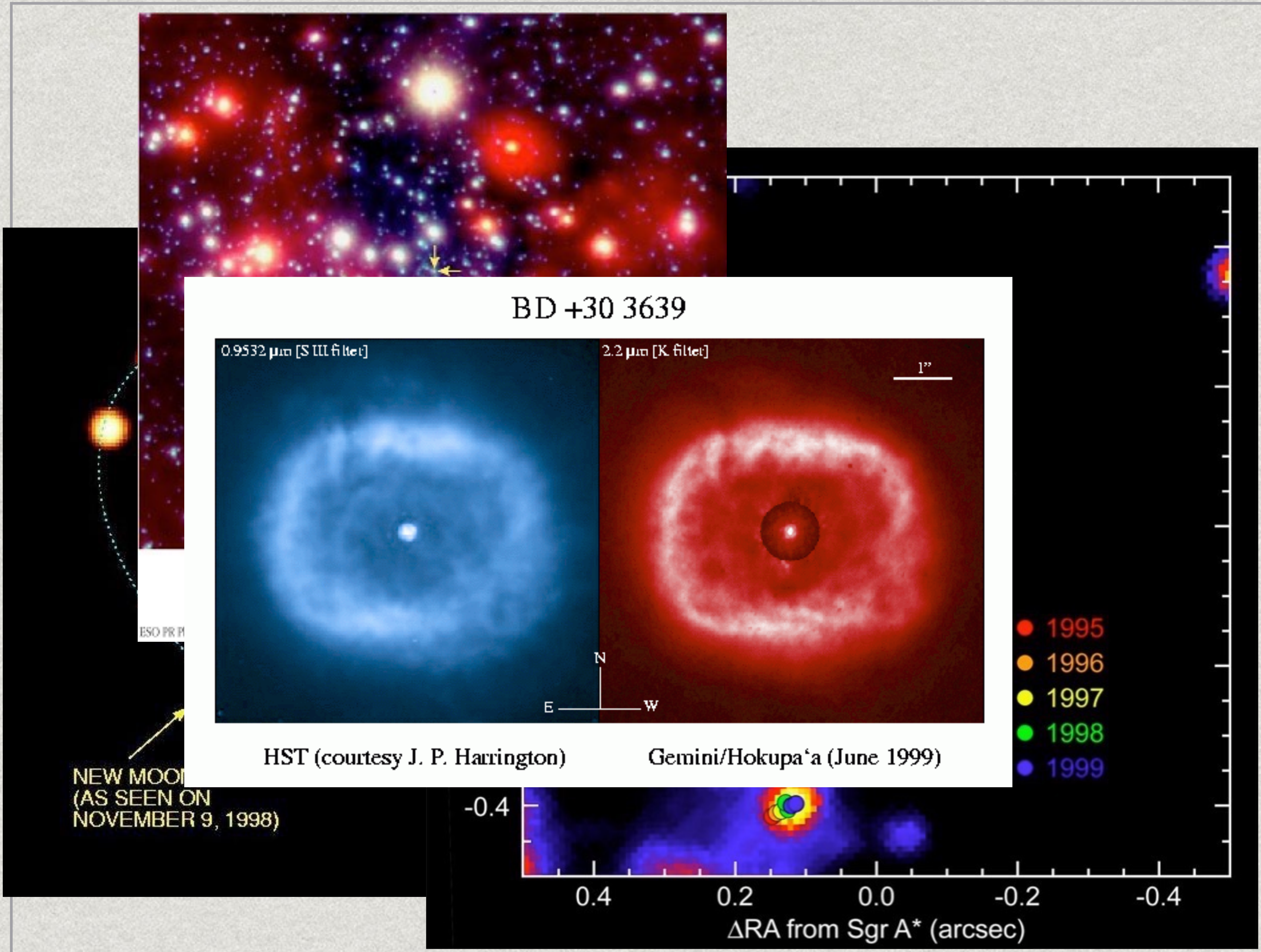


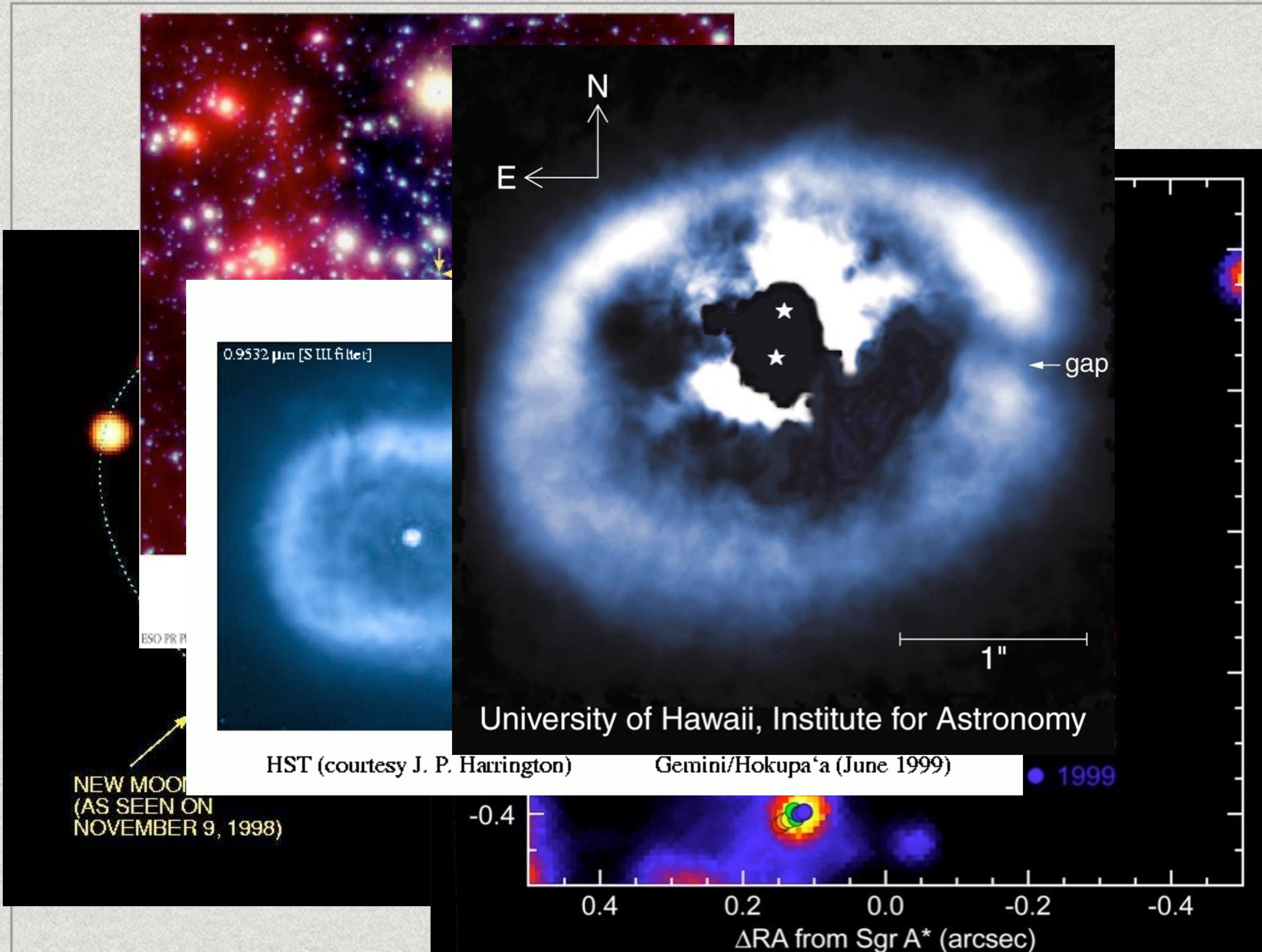

1190 km
ASTEROID
NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)
ORBITAL
PATH OF
MOON


ASTEROID
NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)

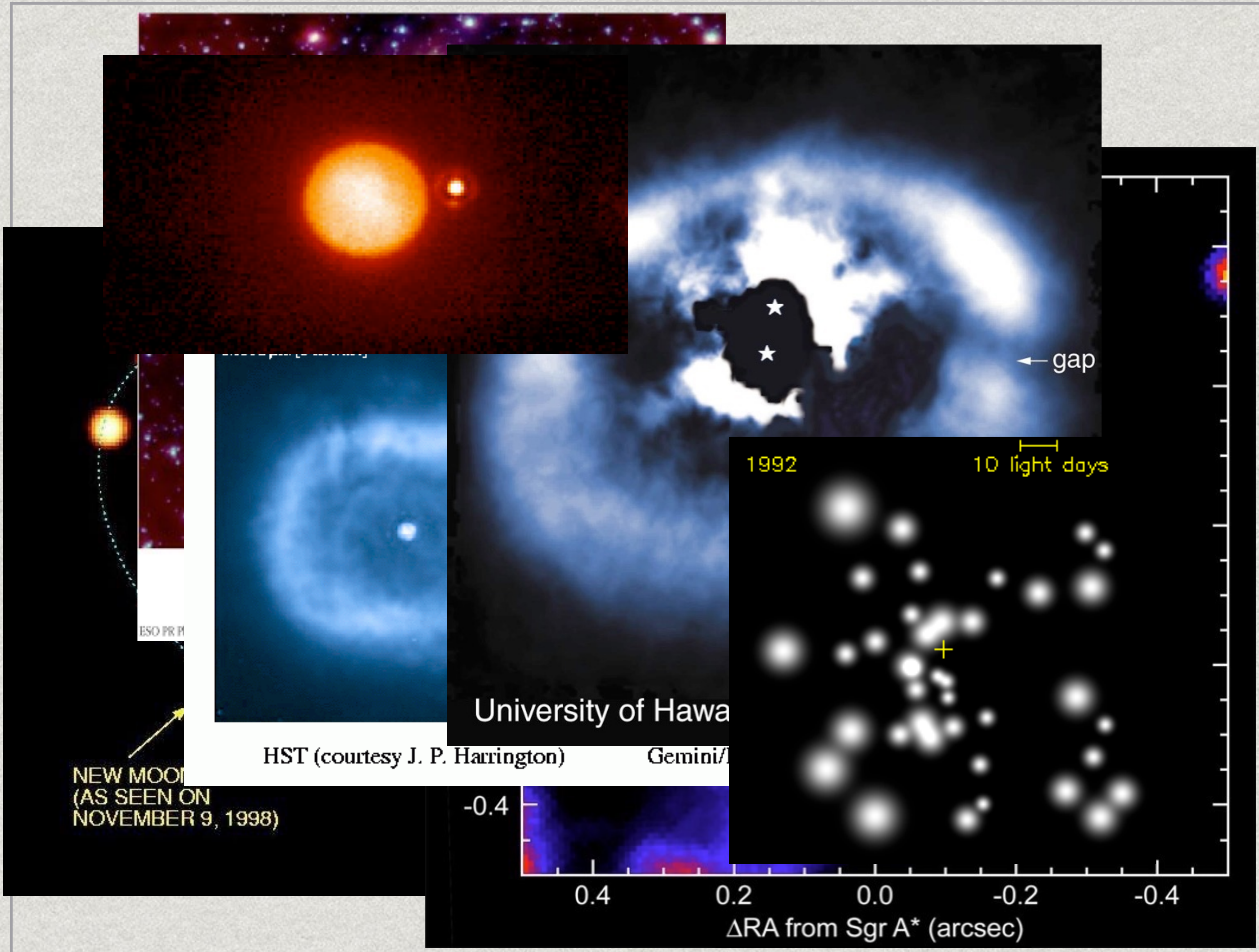

S0-2
S0-1
Sgr A*
S0-4
1995
1996
1997
1998
1999
0.4
0.2
0.0
-0.2
-0.4
ΔDec from Sgr A* (arcsec)
ΔRA from Sgr A* (arcsec)


1 light-year
The Centre of the Milky Way
(VLT YEPUN + NACO)
ESO PR Photo 23a/02 (9 October 2002)
©European Southern Observatory
NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)
S0-2
S0-1
Sgr A*
1995
1996
1997
1998
1999
-0.2
-0.4
0.4
0.2
0.0
-0.2
-0.4
ΔRA from Sgr A* (arcsec)


BD +30 3639
0.9532 μm [S III filter]
2.2 μm [K filter]
1"
N
E
W
HST (courtesy J. P. Harrington)
Gemini/Hokupa'a (June 1999)
NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)
1995
1996
1997
1998
1999
-0.4
0.4
0.2
0.0
-0.2
-0.4
ΔRA from Sgr A* (arcsec)



NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)
ESO PR P
0.9532 µm [S III filter]
HST (courtesy J. P. Harrington)
N
E
gap
1"
University of Hawaii, Institute for Astronomy
Gemini/Hokupa'a (June 1999)
1999
-0.4
0.4
0.2
0.0
-0.2
-0.4
ΔRA from Sgr A* (arcsec)



gap
1992
10 light days
University of Hawa
HST (courtesy J. P. Harrington)
Gemini/
NEW MOON
(AS SEEN ON
NOVEMBER 9, 1998)
-0.4
0.4
0.2
0.0
-0.2
-0.4
ΔRA from Sgr A* (arcsec)