Laser guide stars for astronomy adaptive optics

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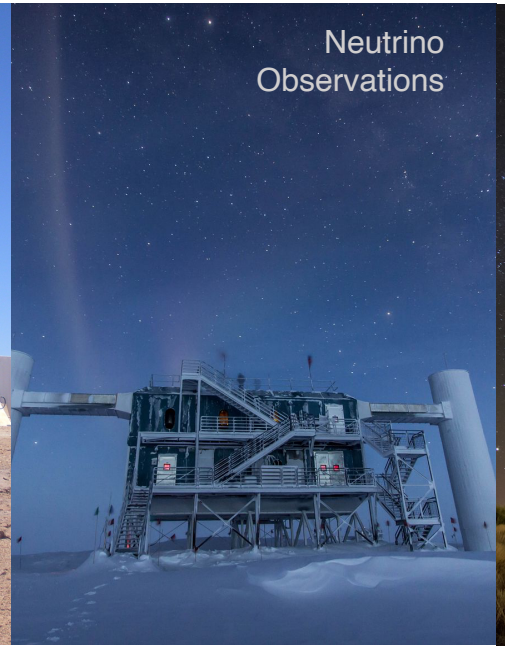
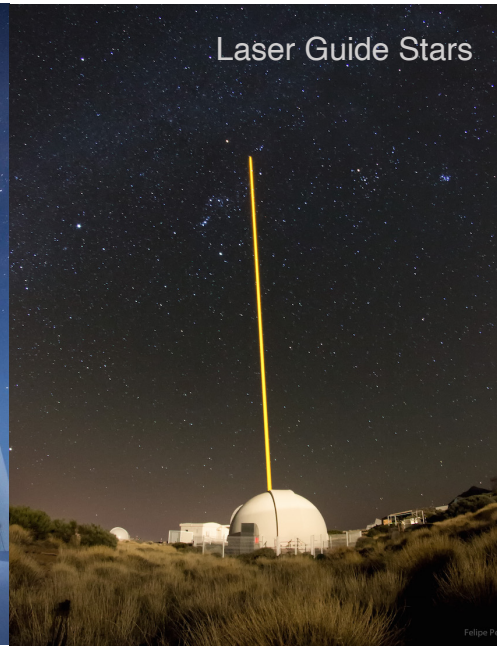
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

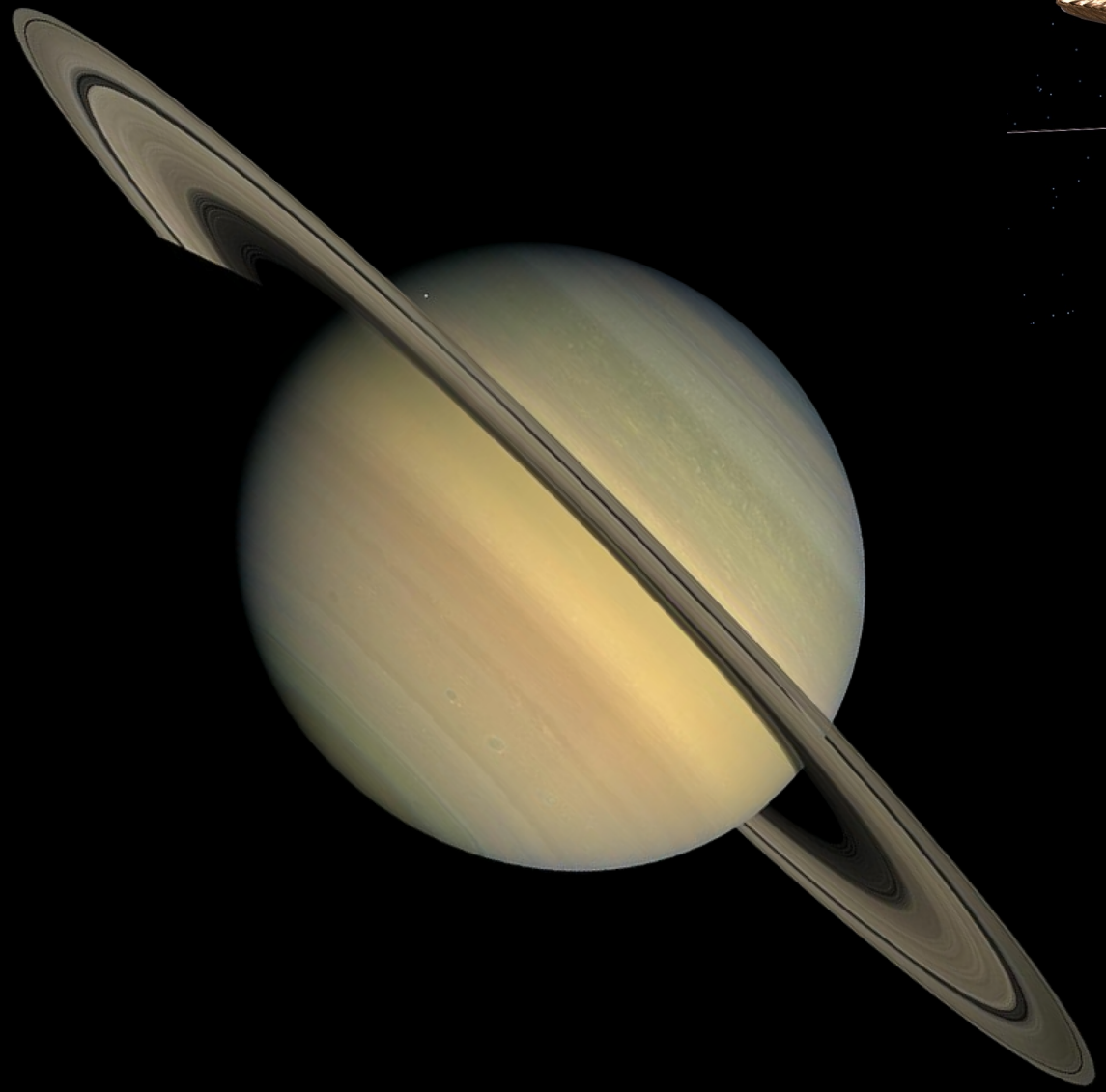
cnrs

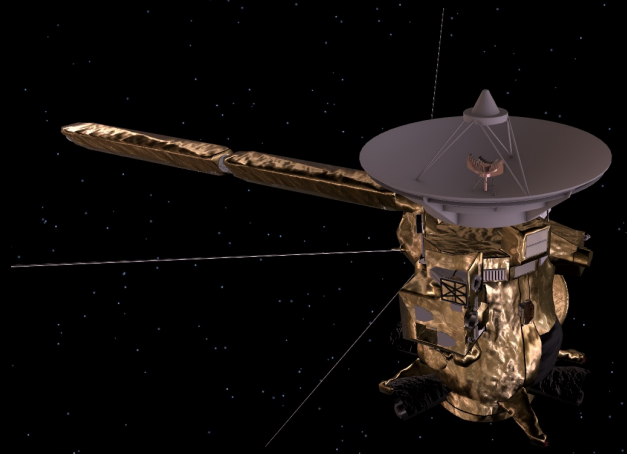
Marie Skłodowska-Curie Actions

- Marie Sklodowska-Curie Postdoctoral Fellow, LAM, Marseille
- PhD Physics, JGU-Mainz, Germany (2019)
- Telecommunications Engineering, UdeC, Chile (2011)





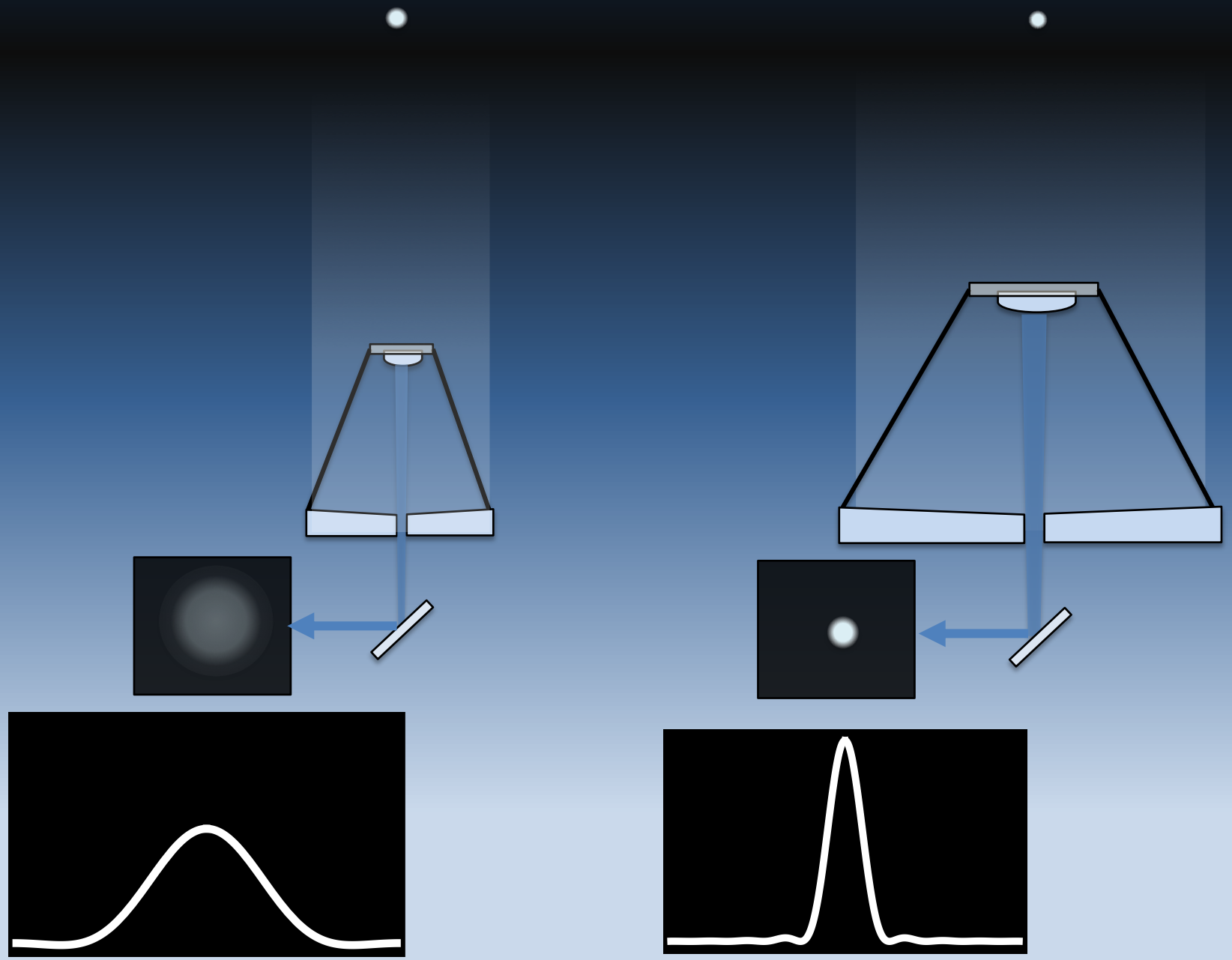




Cassini-Huygens

NASA/JPL/Space Science Institute

Amateur telescope (~200 mm diameter)



$$\theta \approx \frac{\lambda}{D}$$

Diffraction-limited resolution

λ : Wavelength

D : Diameter pupil

Wavefront

Atmospheric turbulence

$n(\boldsymbol{r})$

σ_φ

n_1 n_2 n_3

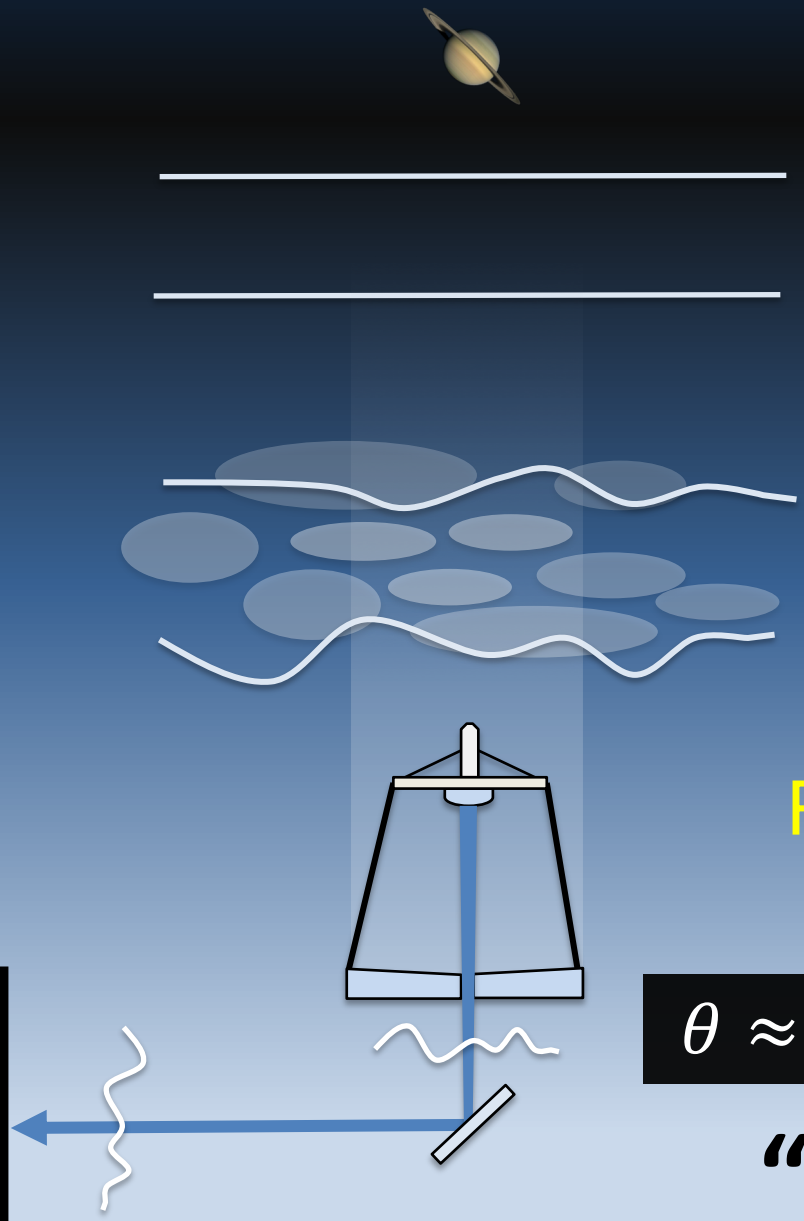
Fried's coherence length

r_0 ~ 5 - 30 cm

φ_{RMS}=1 rad

$\boldsymbol{r_0}$

D



Fried parameter

r_0 ~ 5 - 30 cm

$$\theta \approx \frac{\lambda}{D} \rightarrow \frac{\lambda}{r_0}$$

Resolution ground-based telescope

$$\theta \approx 25\ mas \rightarrow 1000\ mas\ (1'')$$

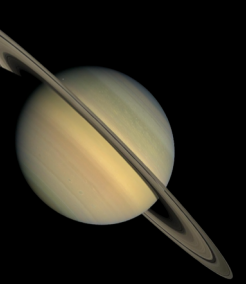
λ = 1000 nm
D = 8 m
r_0 = 0.2 m

“seeing limited”

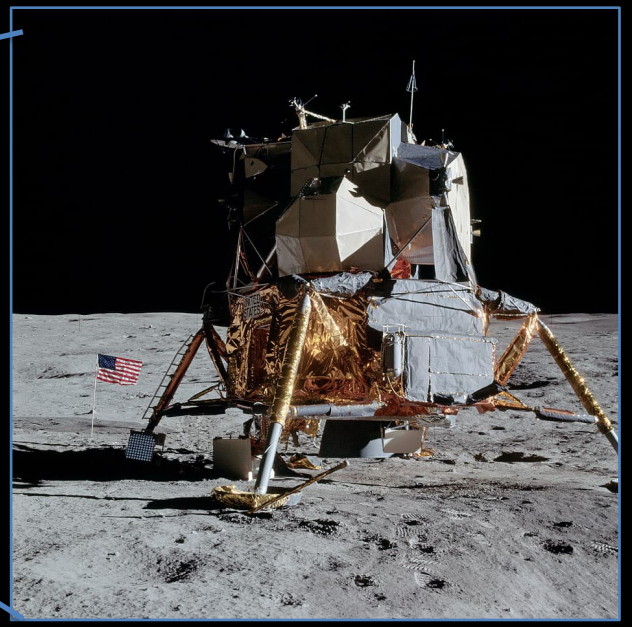
~ 0.5°

$x \frac{1}{100}$

~ 20 arcsec

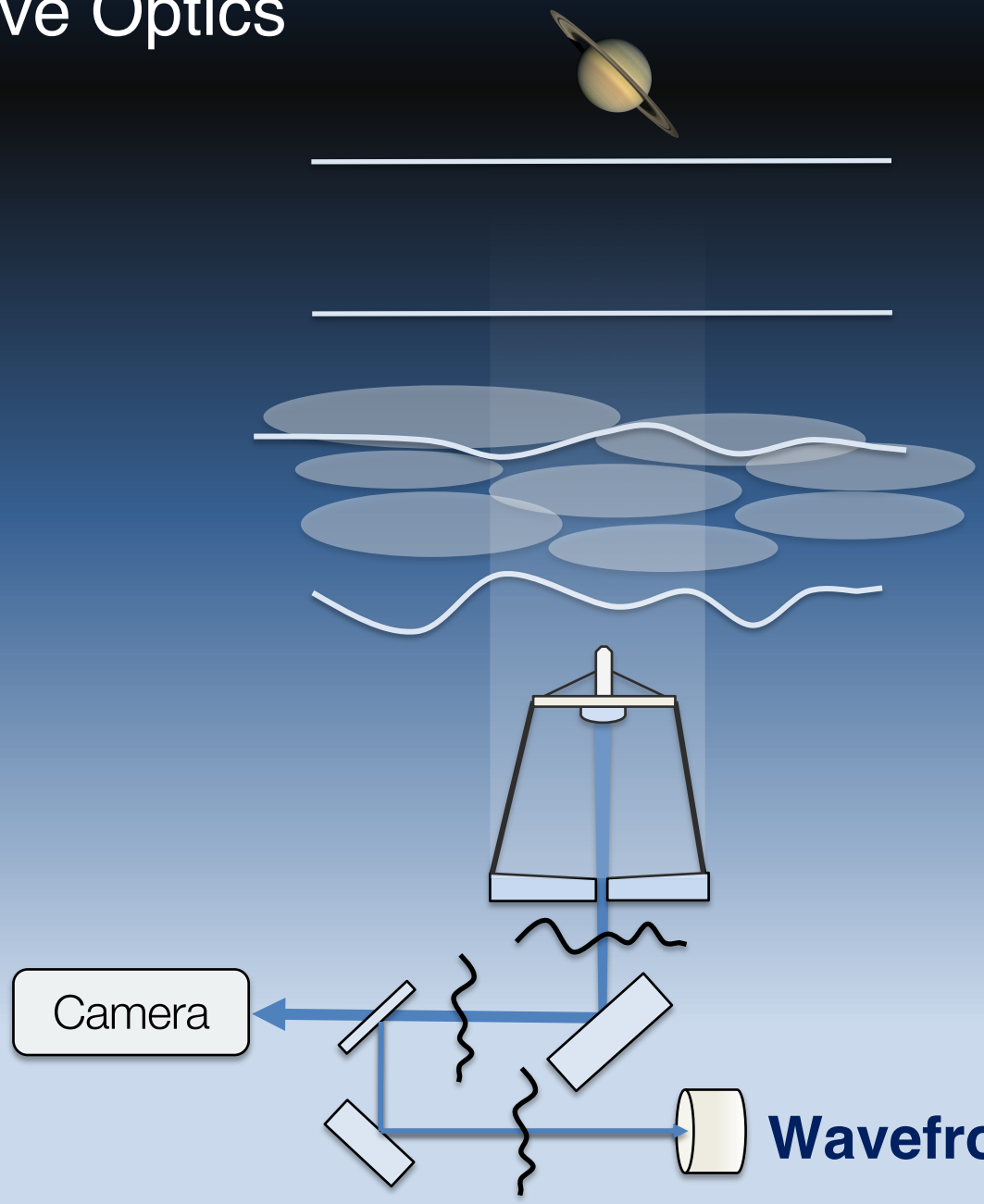


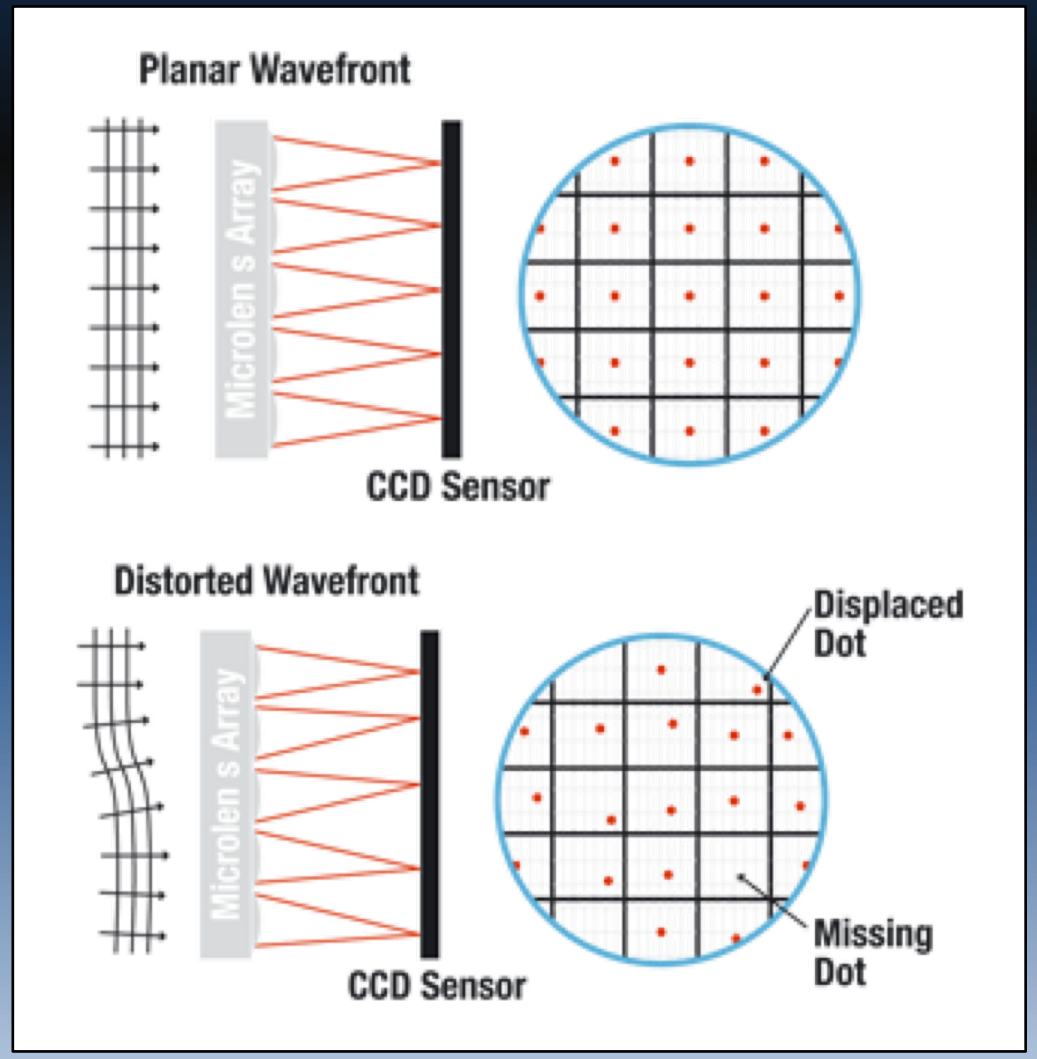
$x \frac{1}{10\,000}$



~ 2 mas

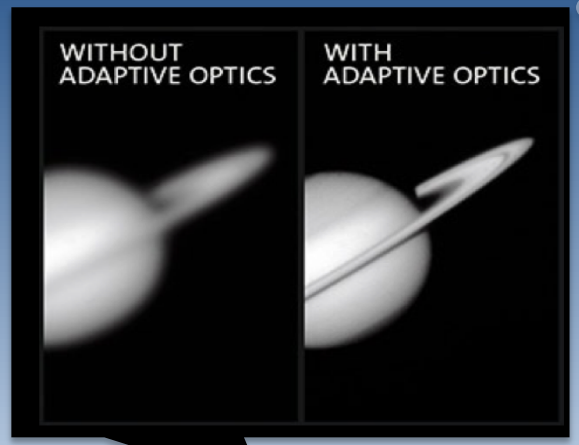
Adaptive Optics

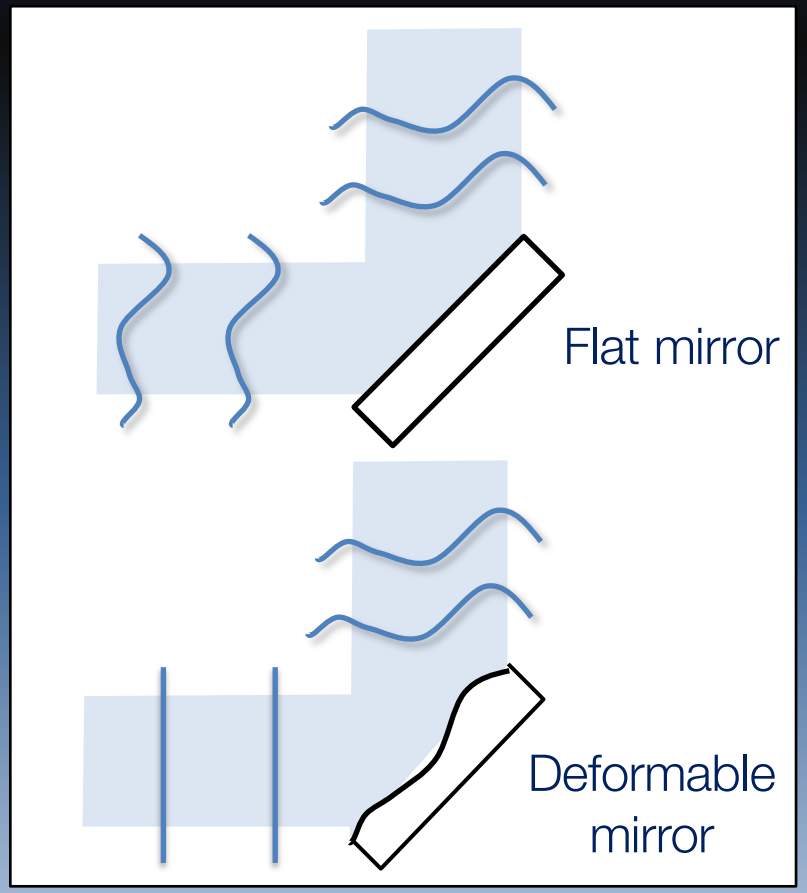


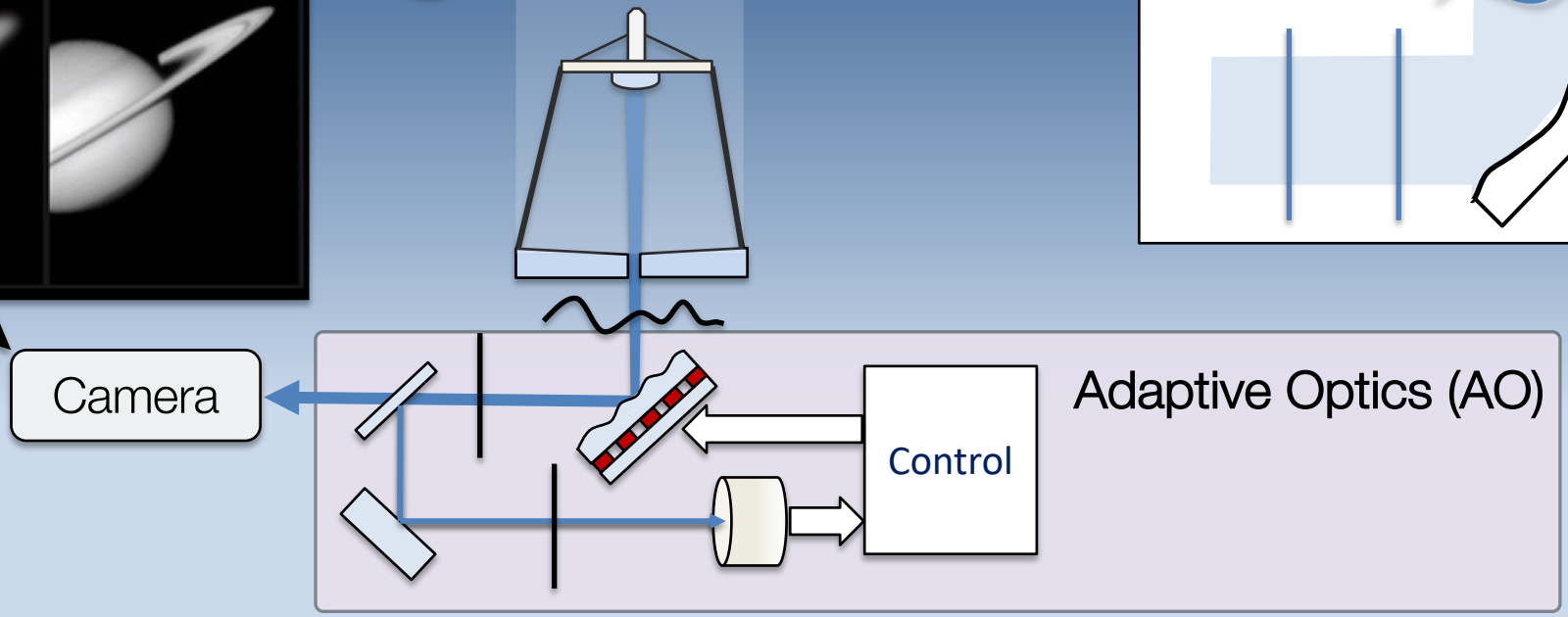


Shack-Hartmann wavefront sensor
(illustration from Thorlabs Inc.)

Adaptive Optics







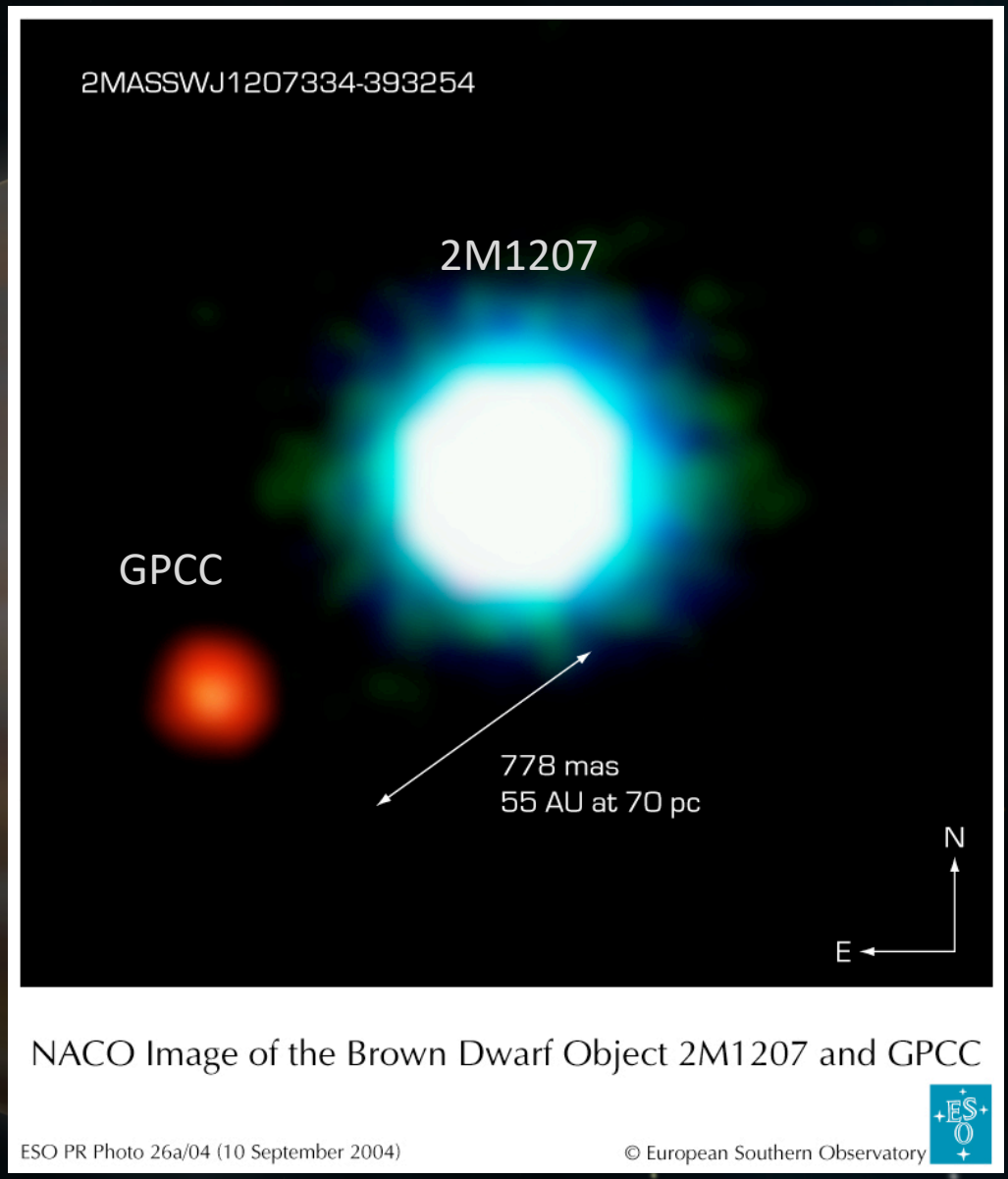
Test MUSE/GALACSI at Paranal Observatory

ESO/P. WEILBACHER (AIP)

The feeble image is more than 100 times fainter than that of 2M1207. "***If these images had been obtained without adaptive optics, that object would not have been seen,***" says *Gaël Chauvin*.

https://www.eso.org/public/news/eso0428/

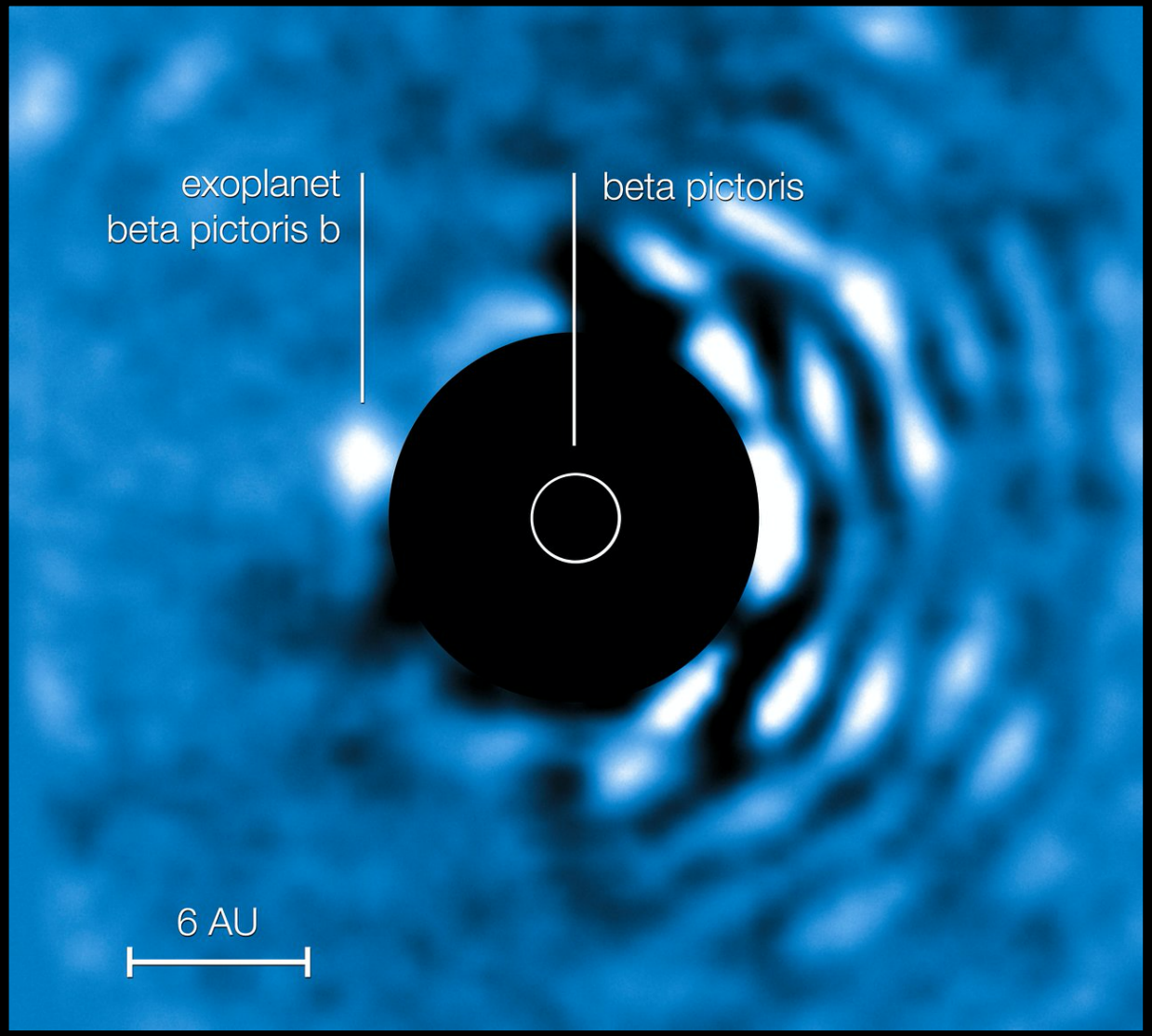
Resolution w/o AO: 500 mas
Resolution with AO: 100 mas



NACO Image of the Brown Dwarf Object 2M1207 and GPCC

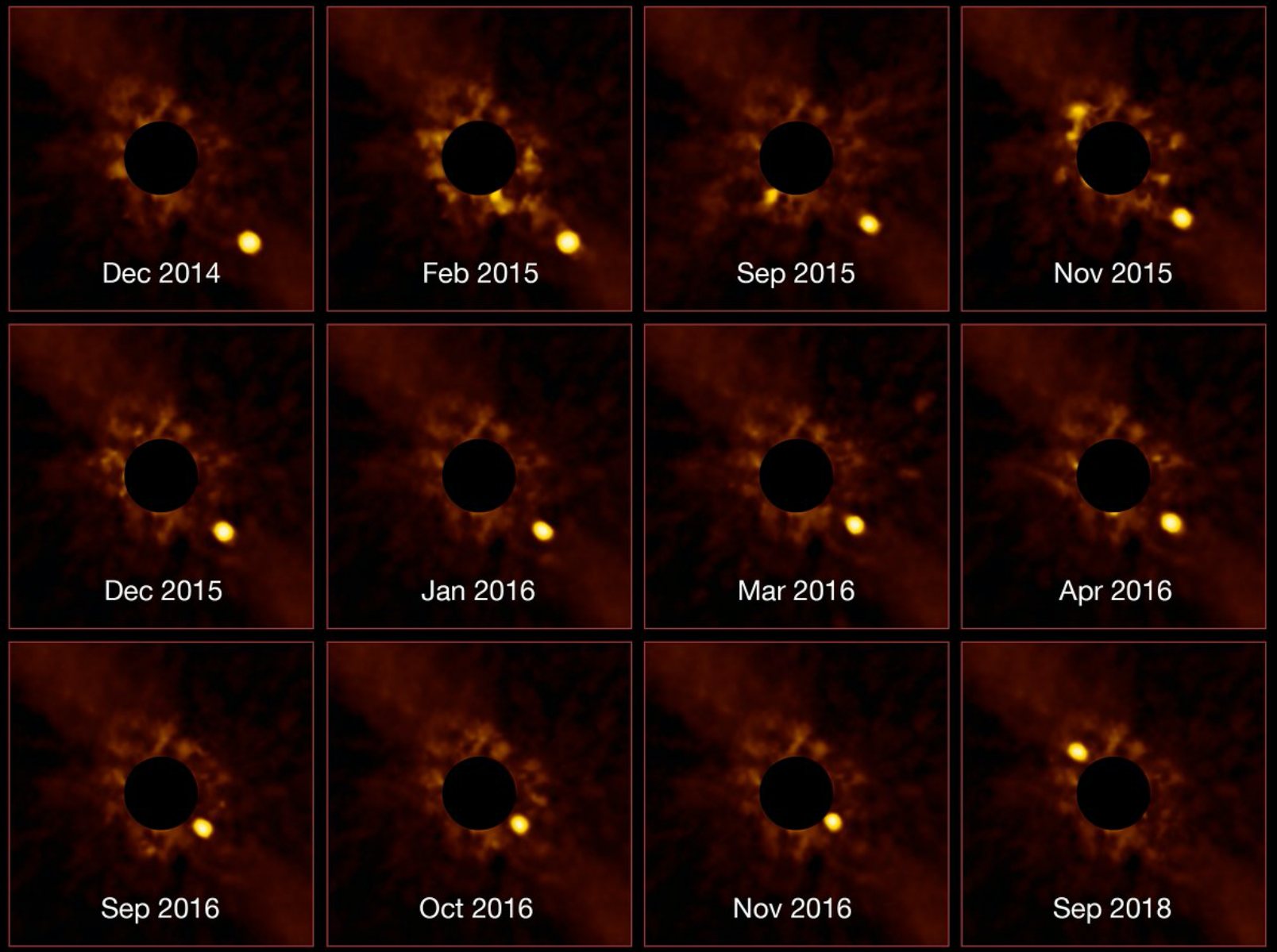
ESO PR Photo 26a/04 (10 September 2004)

G. Chauvin et al. , "A Giant Planet Candidate near a Young Brown Dwarf", A&A, 435, 2004



Beta Pictoris B
65 light years
400 mas separation

Lagrange, A.-M. et al, "A probable giant planet imaged in the β Pictoris disk". *A&A,* **493** (2), 2009



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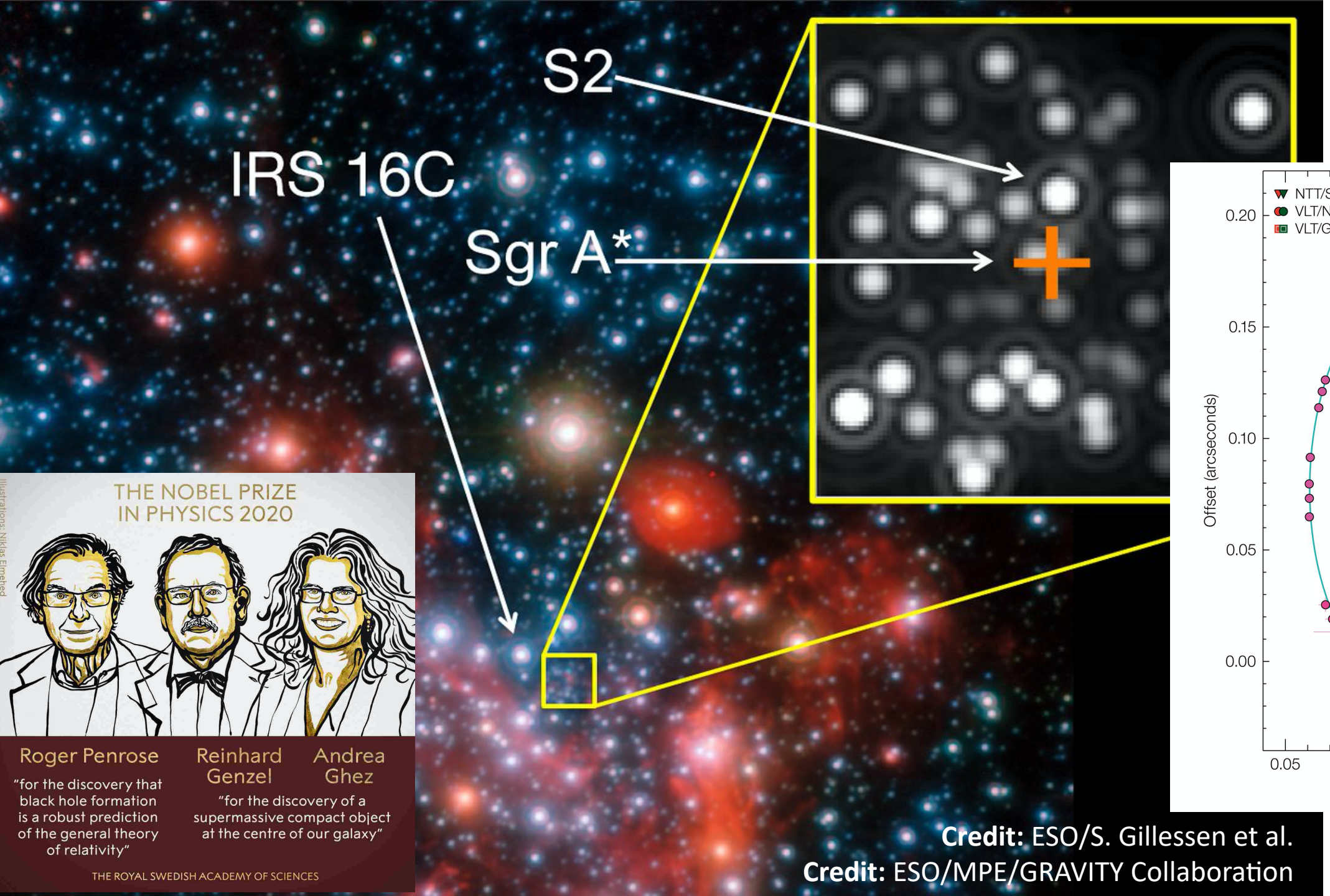
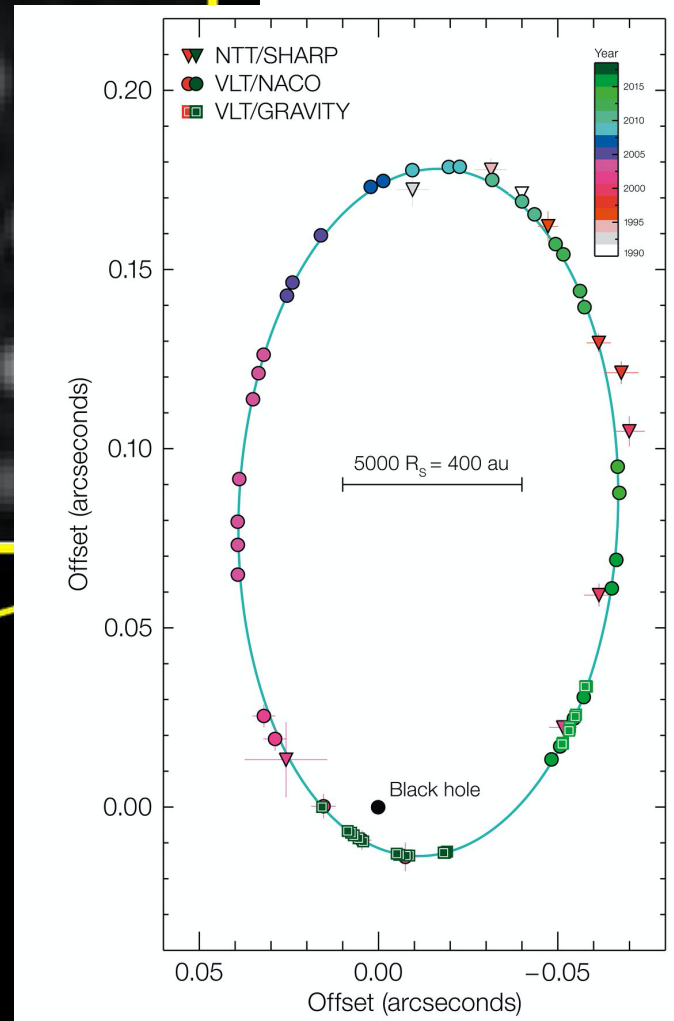
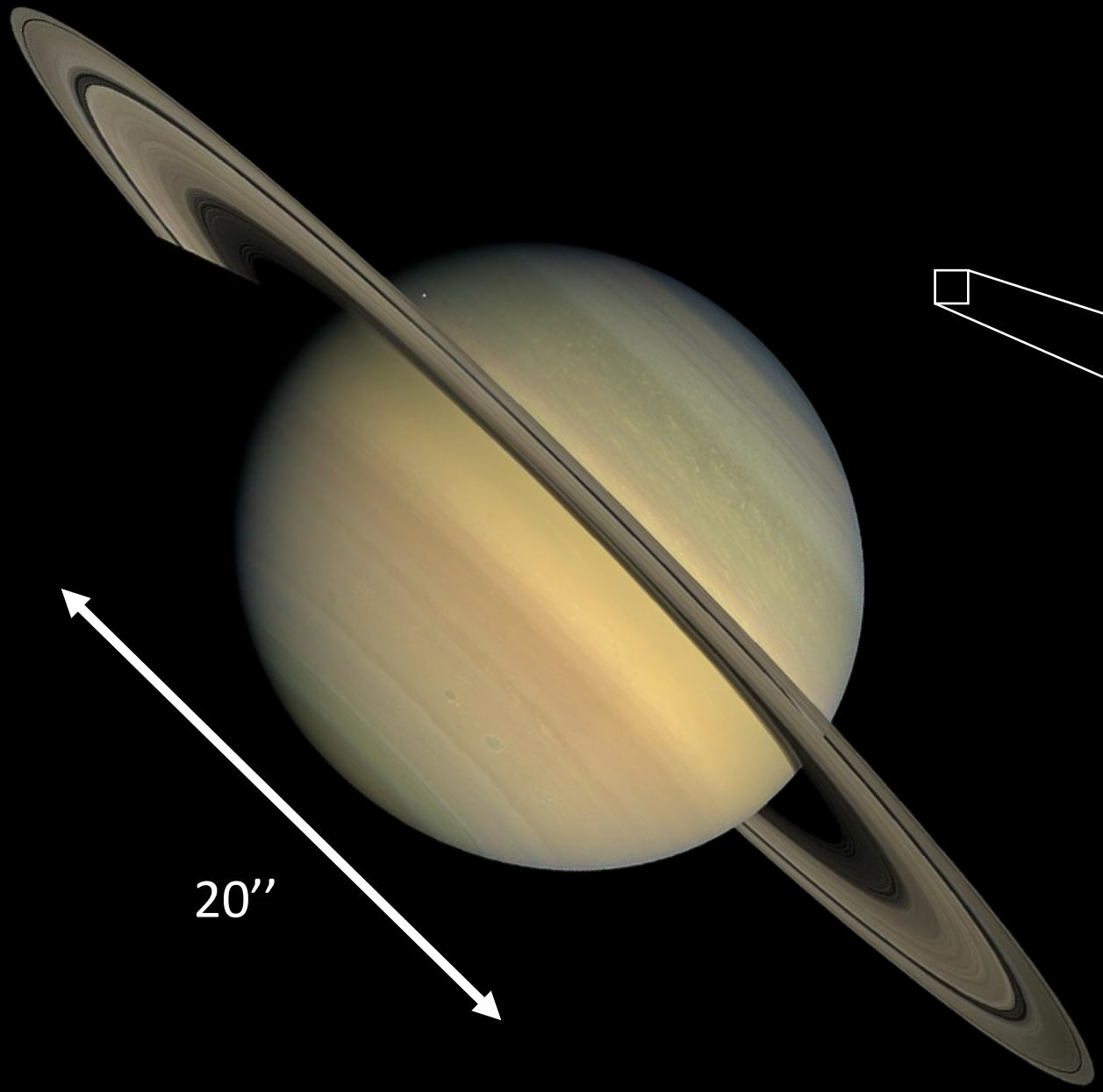
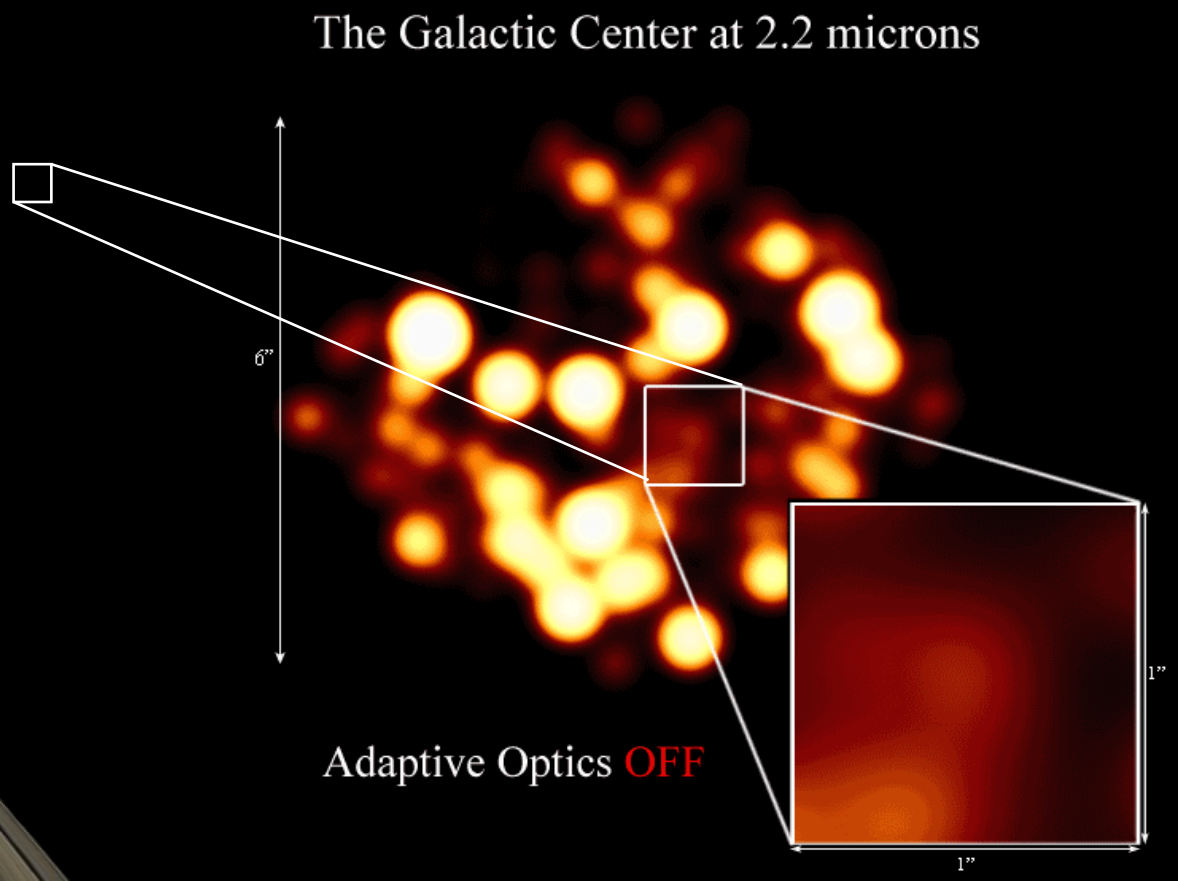


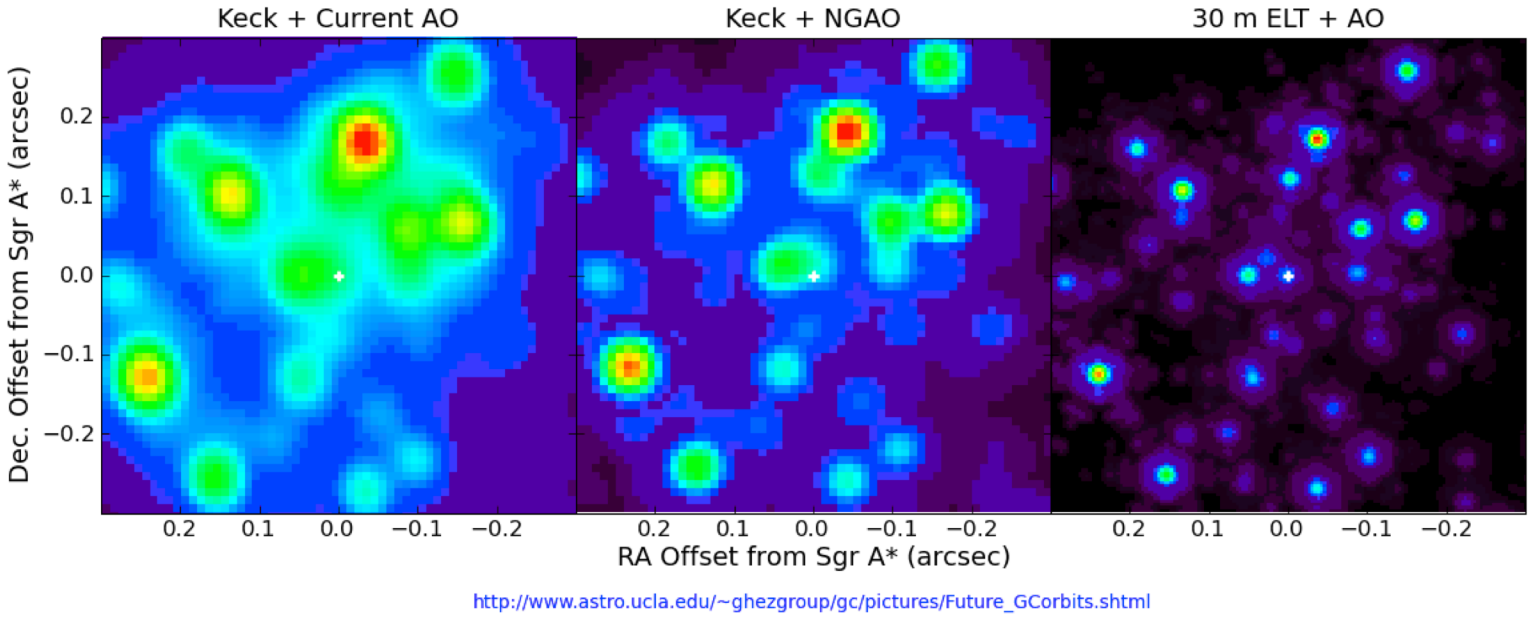


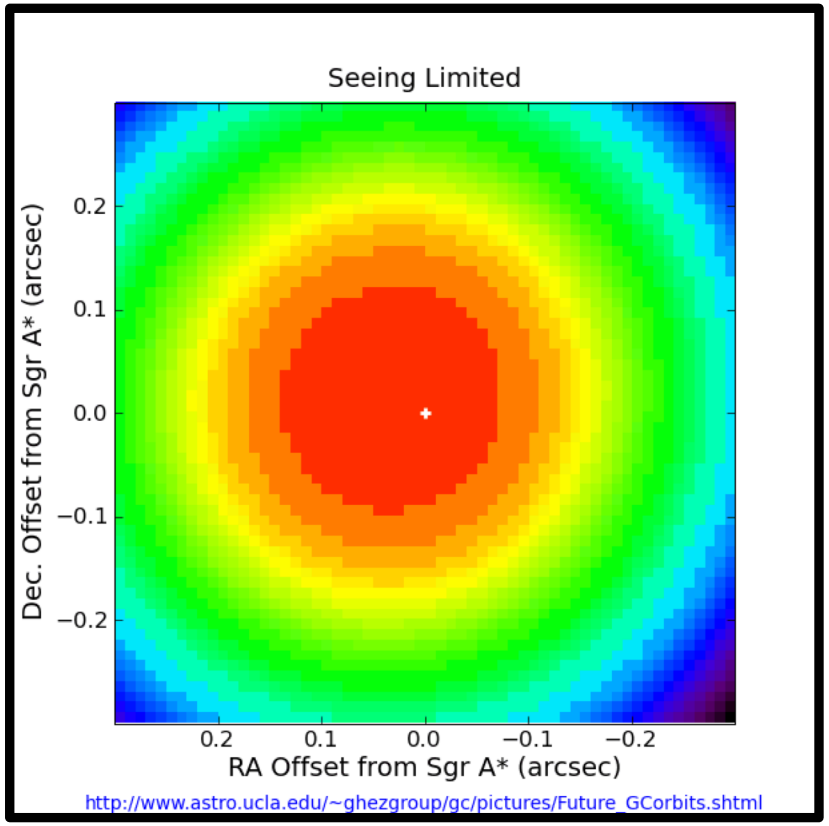
Credit: ESO/S. Gillessen et al.
Credit: ESO/MPE/GRAVITY Collaboration


20’’


The Galactic Center at 2.2 microns
6”
1”
1”
Adaptive Optics OFF

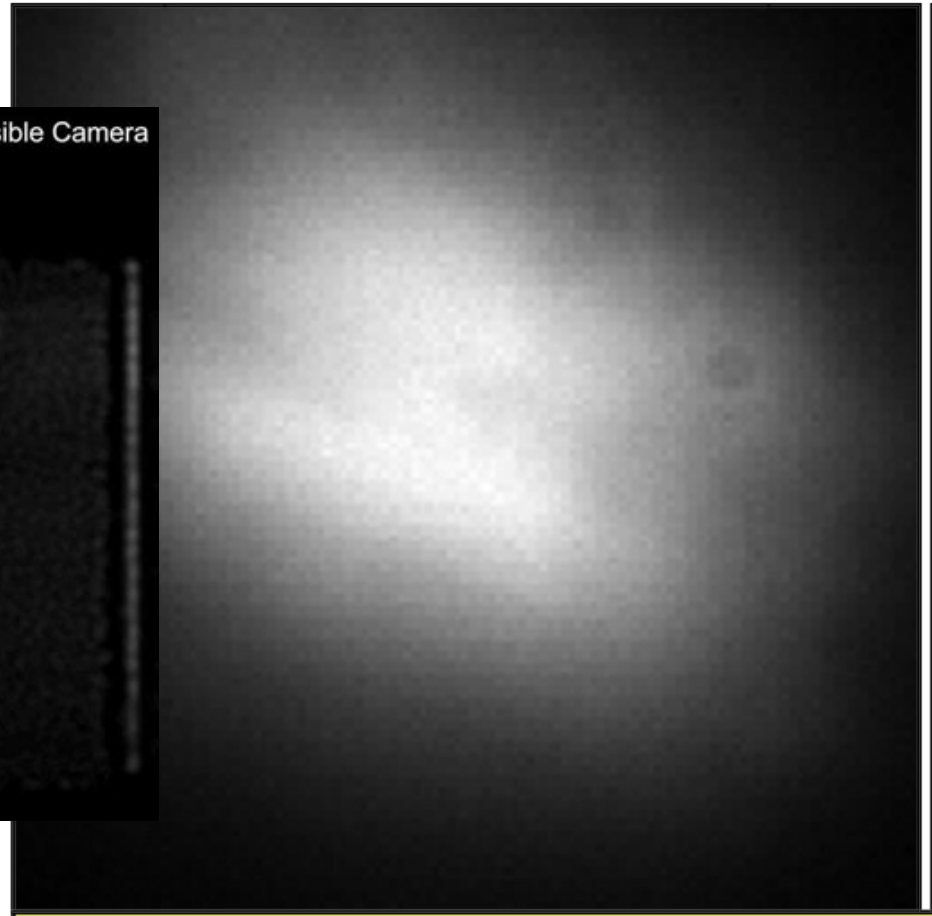
Andrea Ghez Group at UCLA
http://www.astro.ucla.edu/~ghezgroup/gc/animations.html

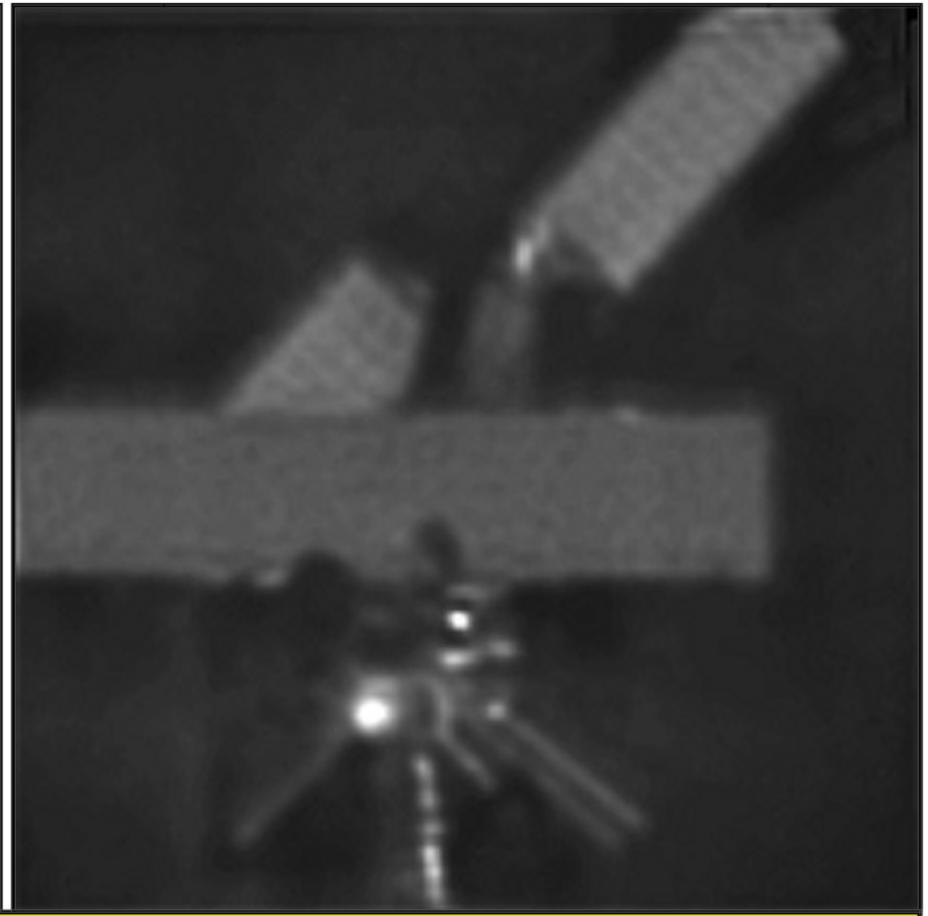




Airforce Maui Optical and Supercomputing Site

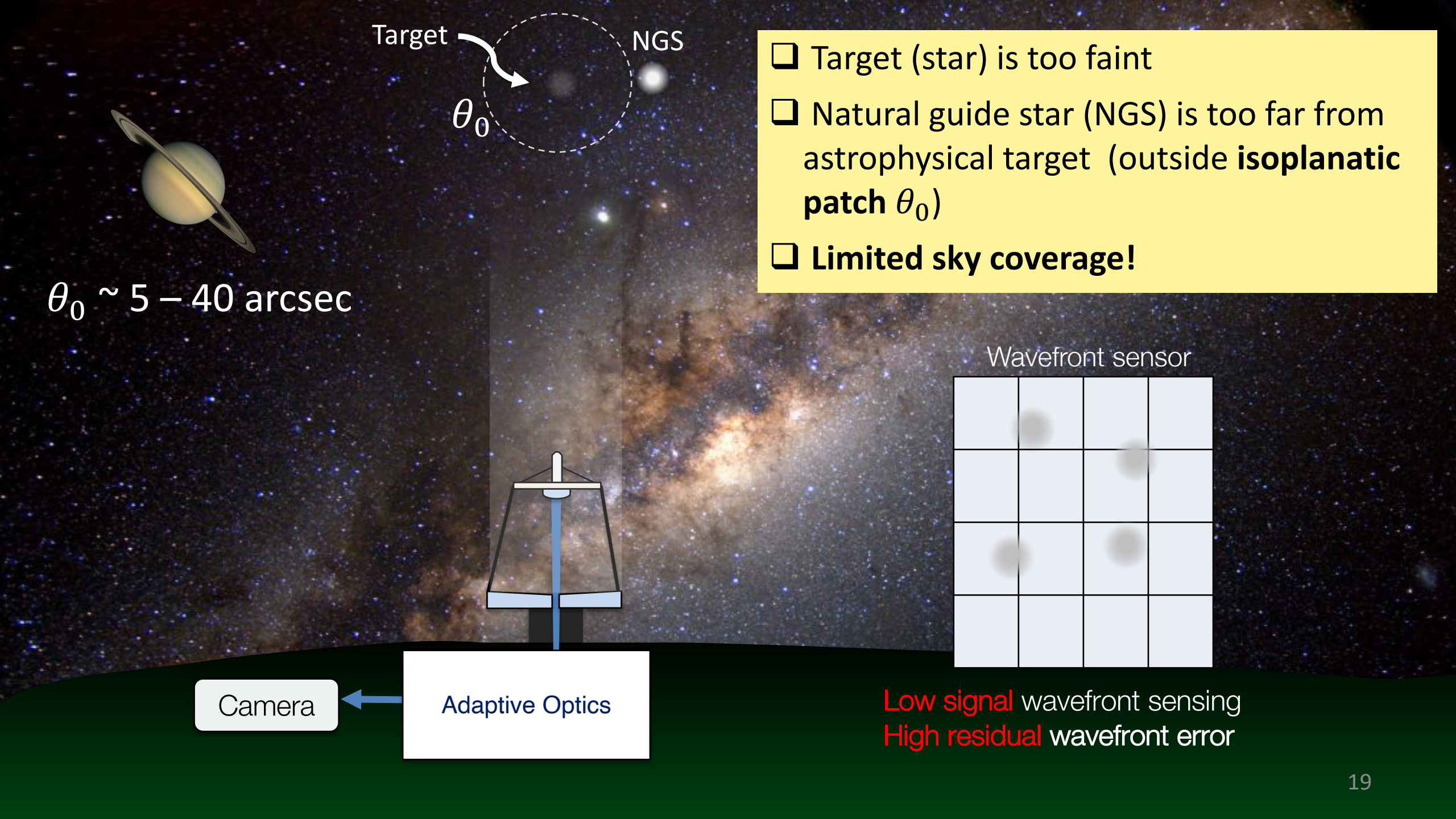
US Air Force Research Laboratory AFR





Uncompensated and Compensated Images of Satellite Seasat at 1000 Km Range

Taken by SOR 3.5 m Telescope with 941 Channel Adaptive Optics



- ❑ Target (star) is too faint
- ❑ Natural guide star (NGS) is too far from astrophysical target (outside **isoplanatic patch** θ_0)
- ❑ **Limited sky coverage!**

Low signal wavefront sensing
High residual wavefront error

Ionosphere

10 km

Mesosphere

90 km

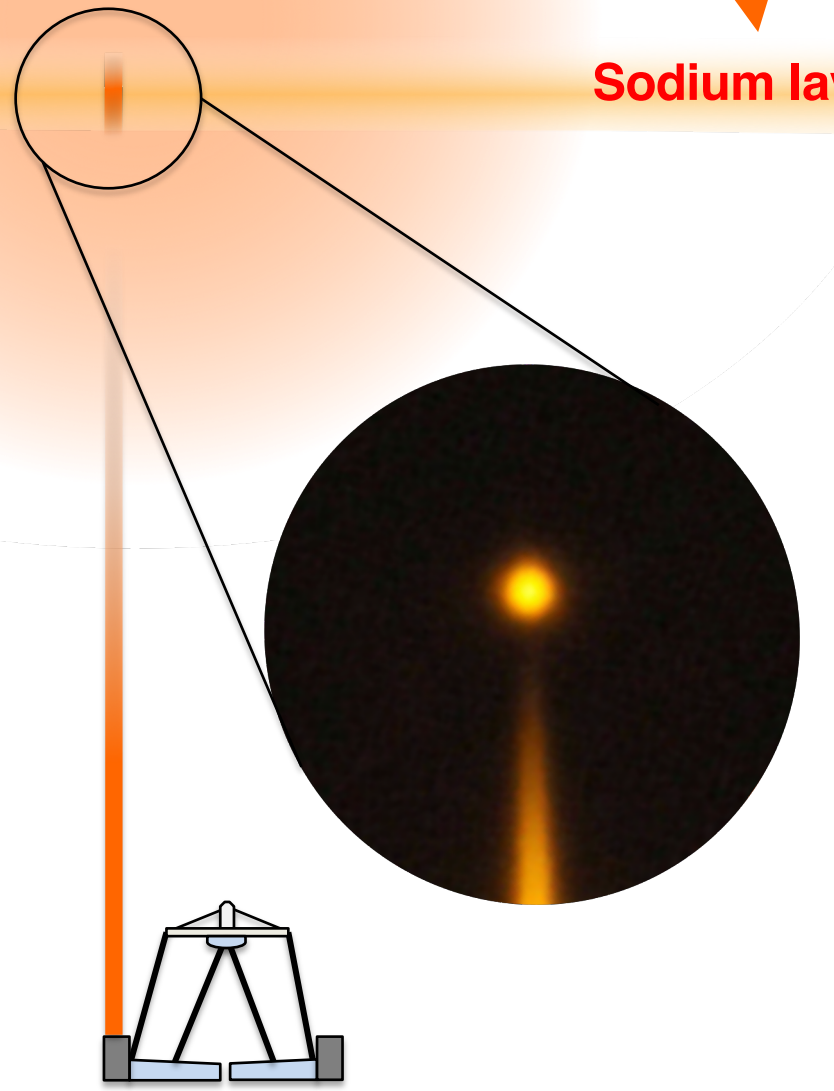
Stratosphere

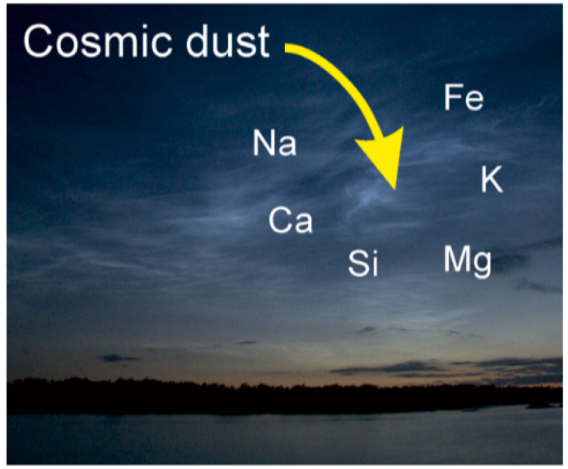
Laser guide star

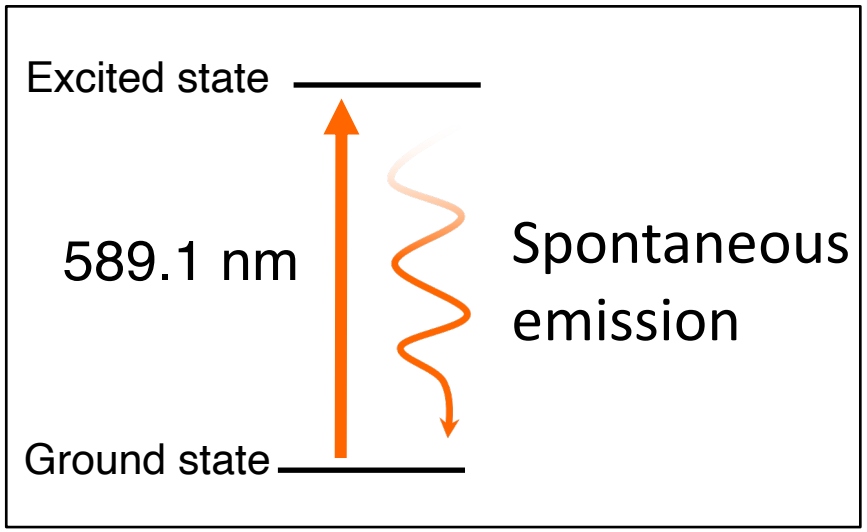
1 T/day

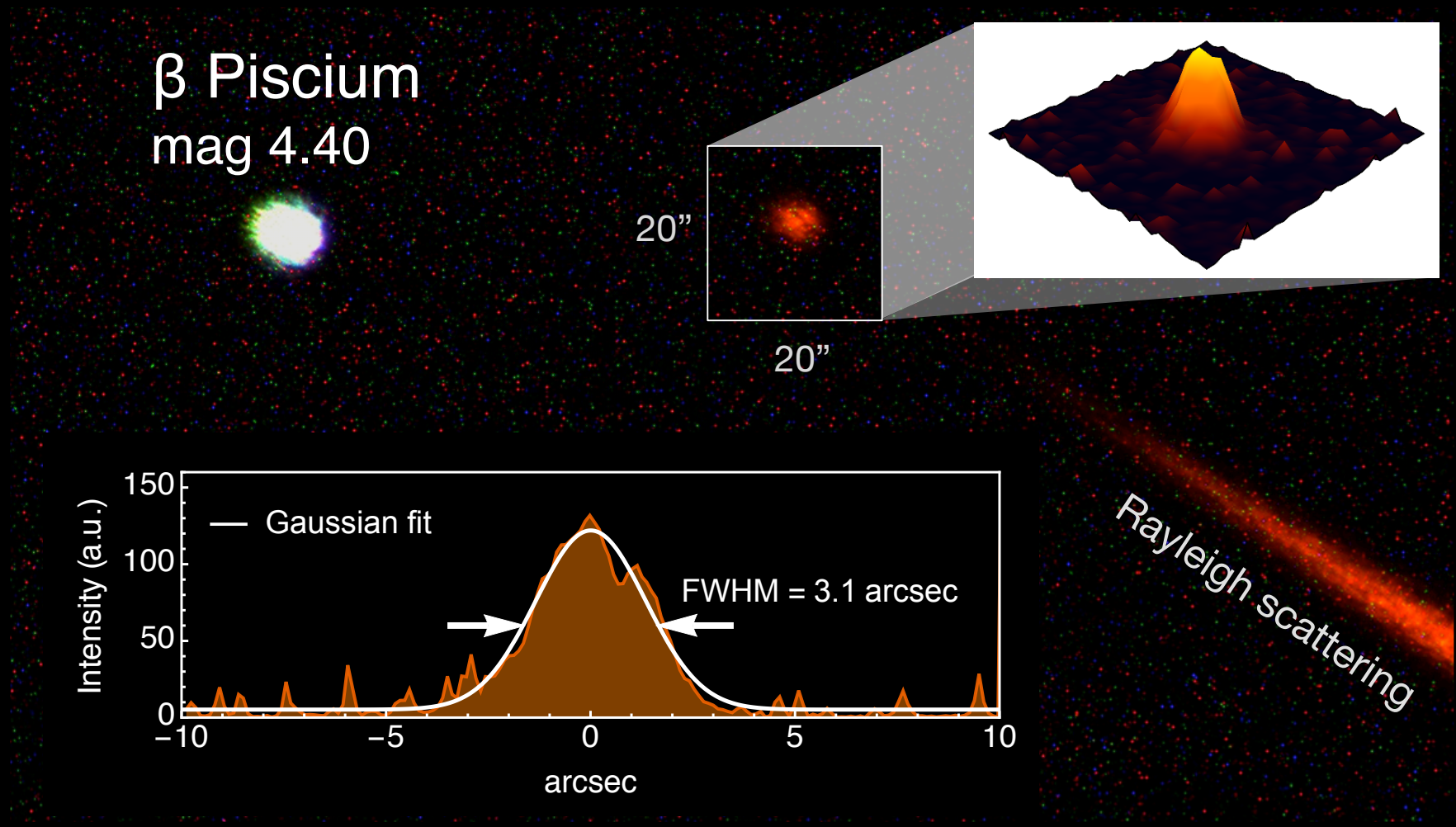
Sodium layer

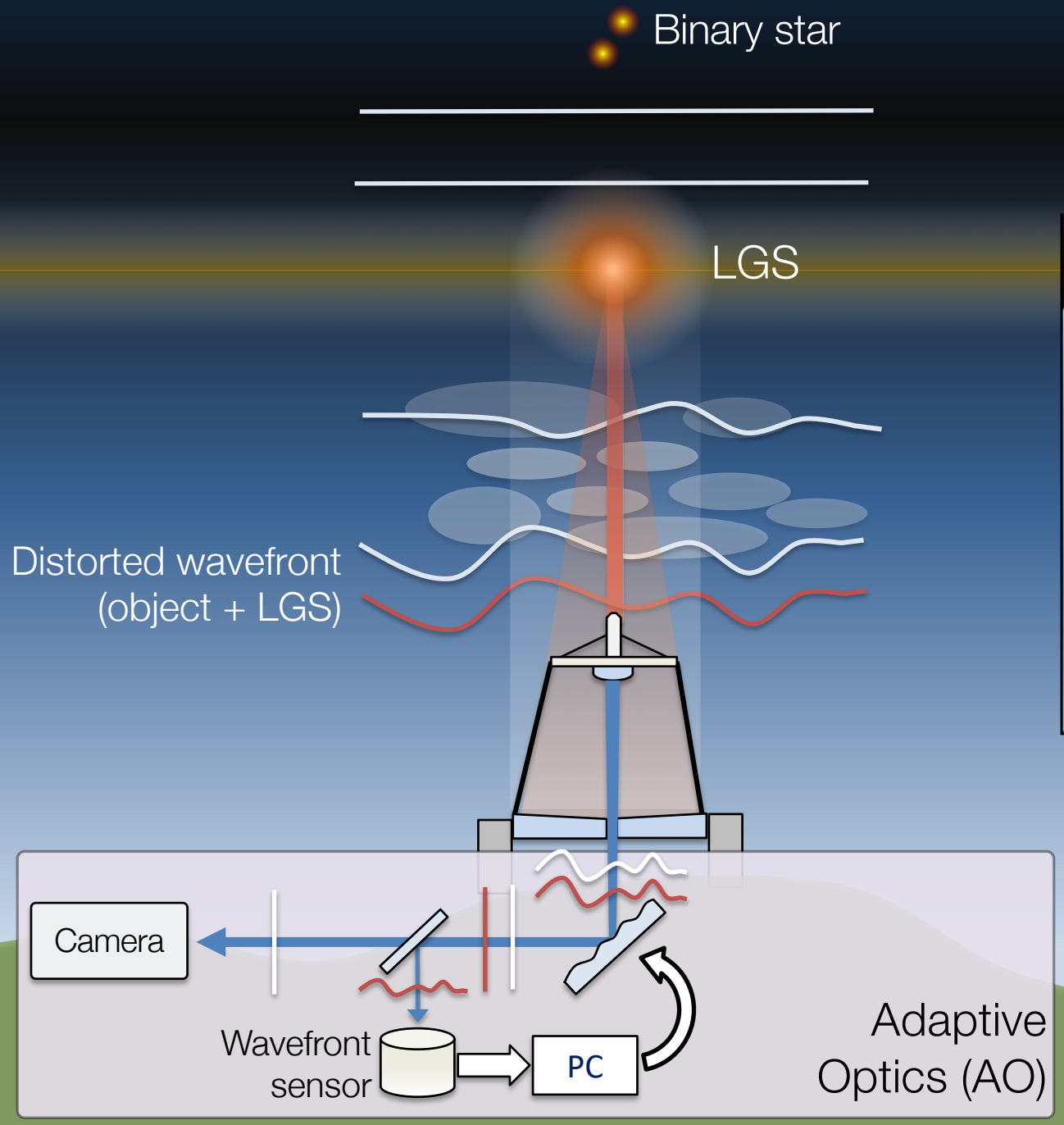
NaO^+ e^- e^- Na^+ O_2 Na N_2 NaOH NaO_2 $NaHCO_3$

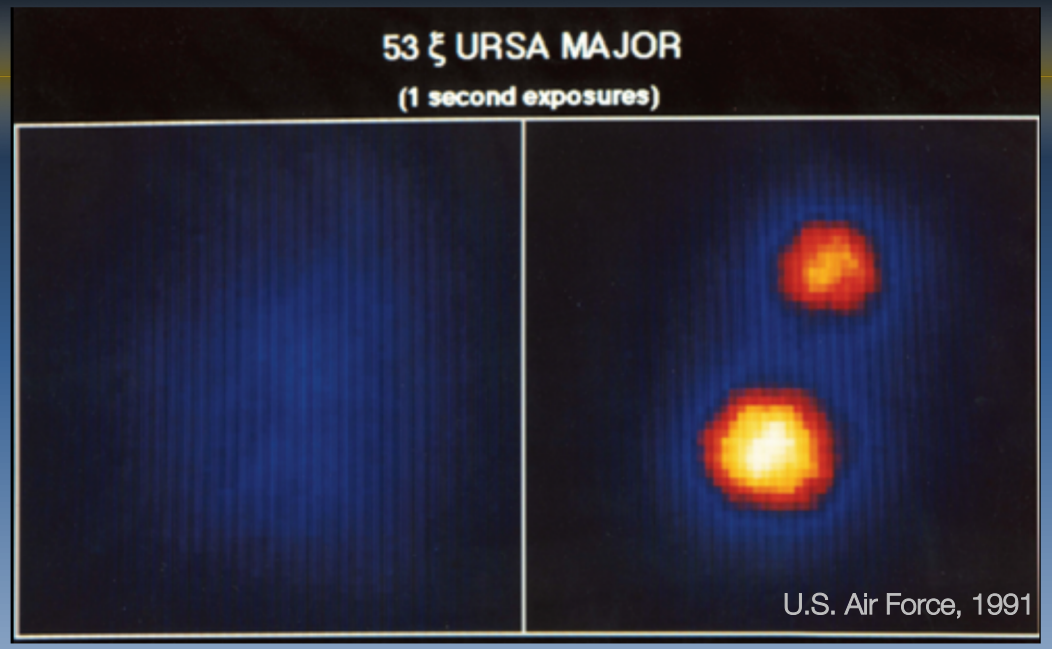







β Piscium
mag 4.40
20”
20”
150
100
50
0
Intensity (a.u.)
Gaussian fit
FWHM = 3.1 arcsec
−10
−5
0
5
10
arcsec
Rayleigh scattering

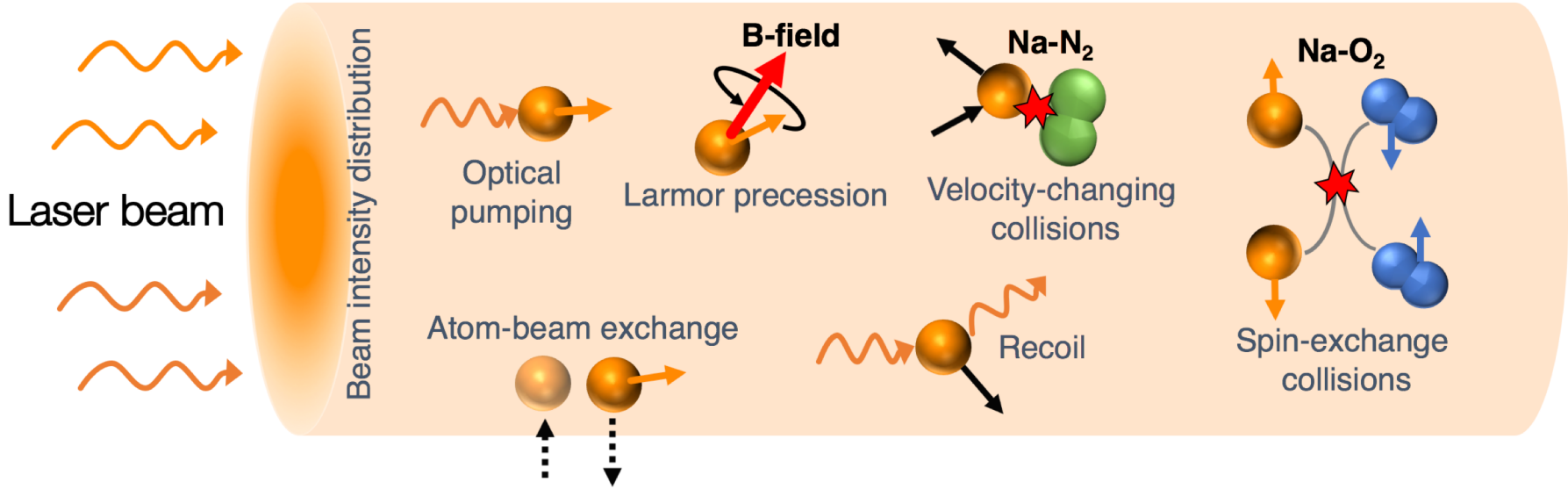




Uncompensated

Compensated
with LGS/AO

Sodium layer



Density matrix

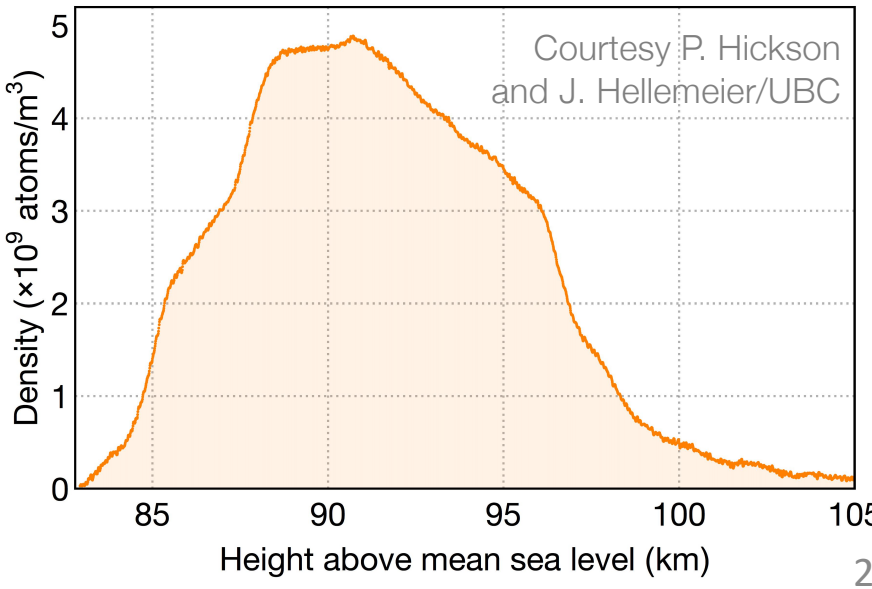
Relaxation matrix

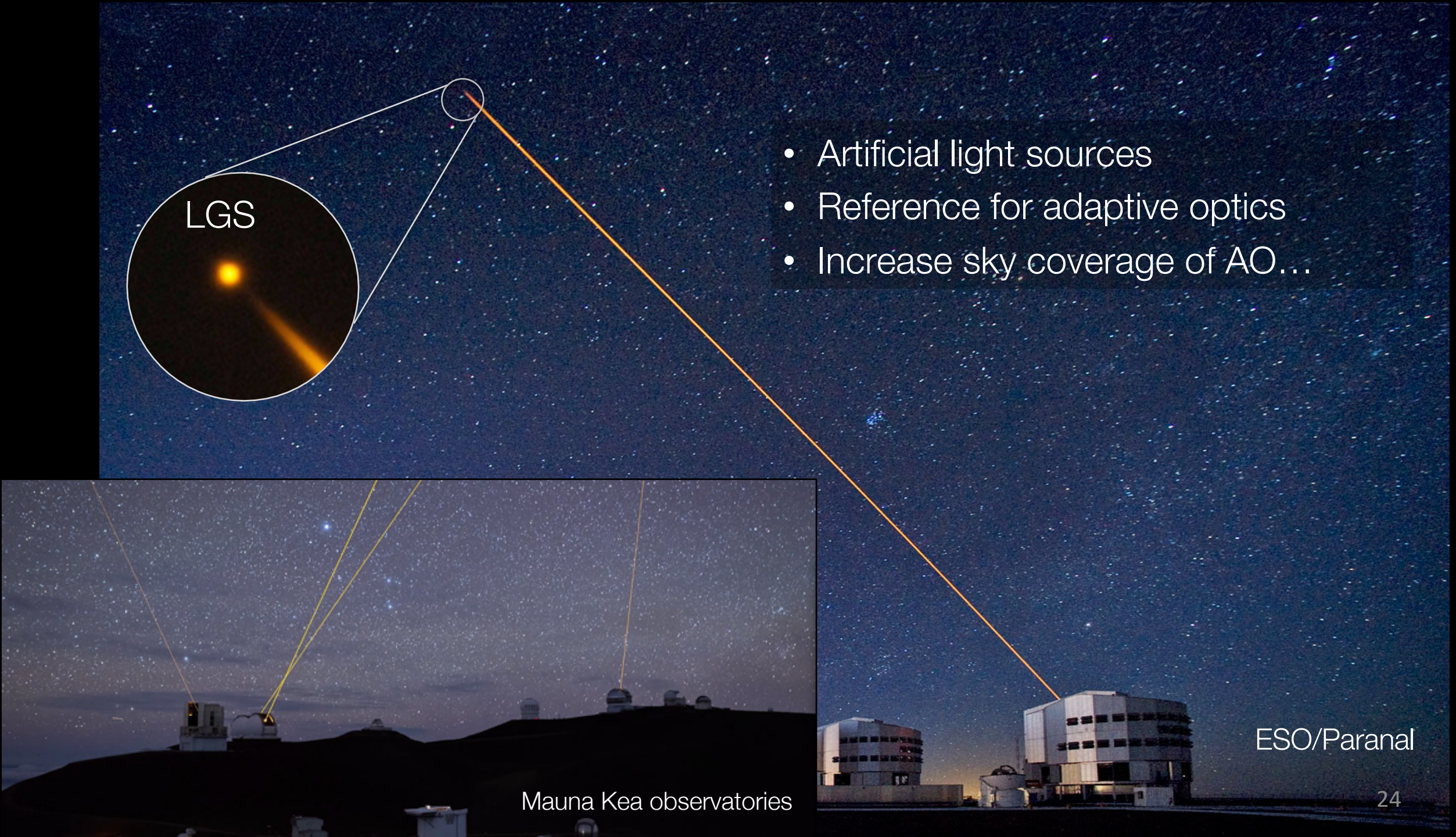
$$\frac{d}{dt}\rho = \frac{1}{i\hbar}[H,\rho] + \Lambda(\rho) + \beta$$

Total Hamiltonian

Repopulation matrix

Sodium layer profile



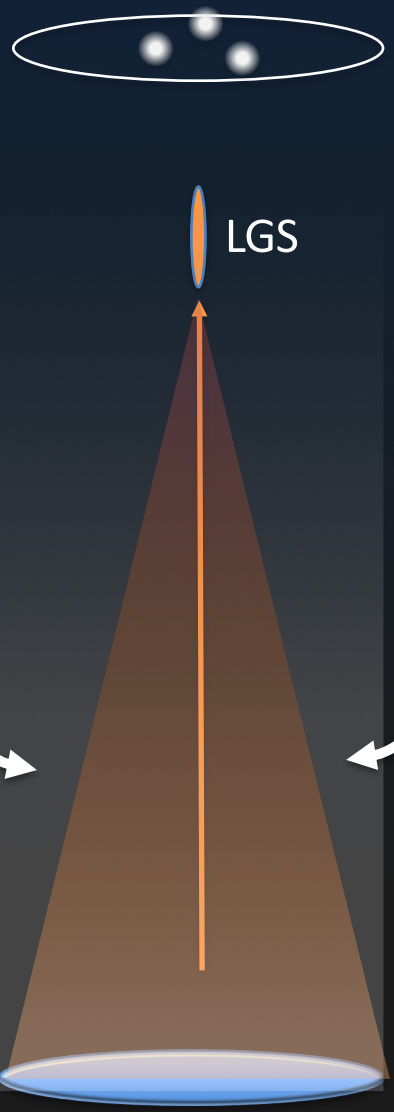


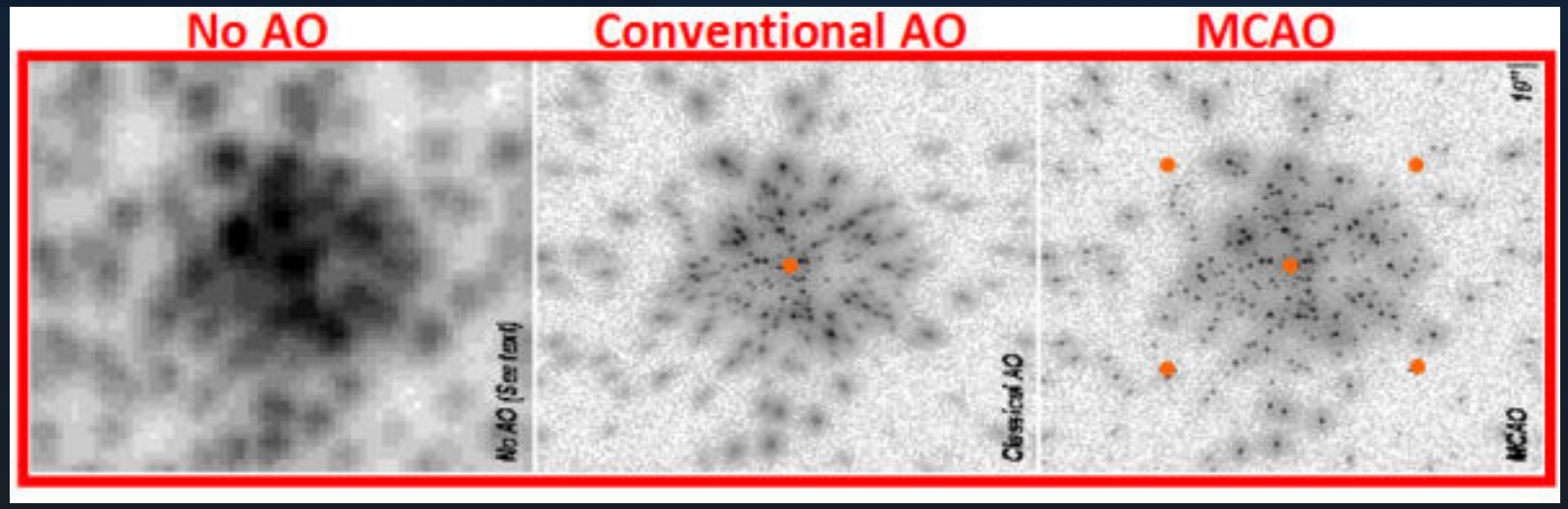
- Artificial light sources
- Reference for adaptive optics
- Increase sky coverage of AO…

Mauna Kea observatories

ESO/Paranal

❑ Cone effect

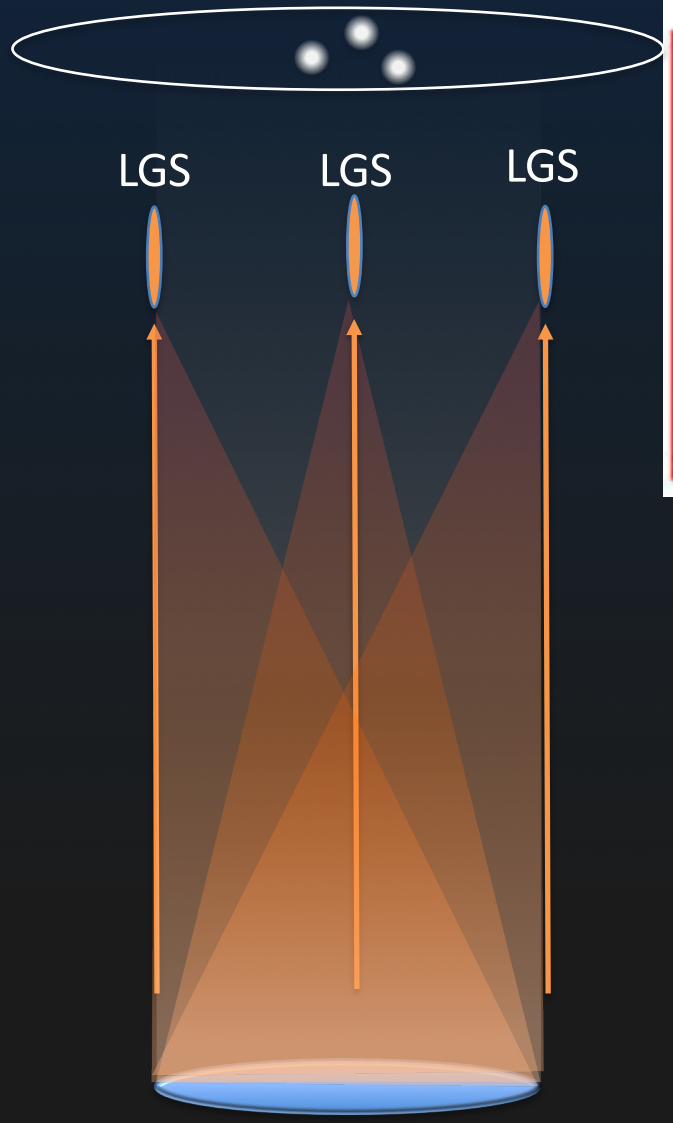


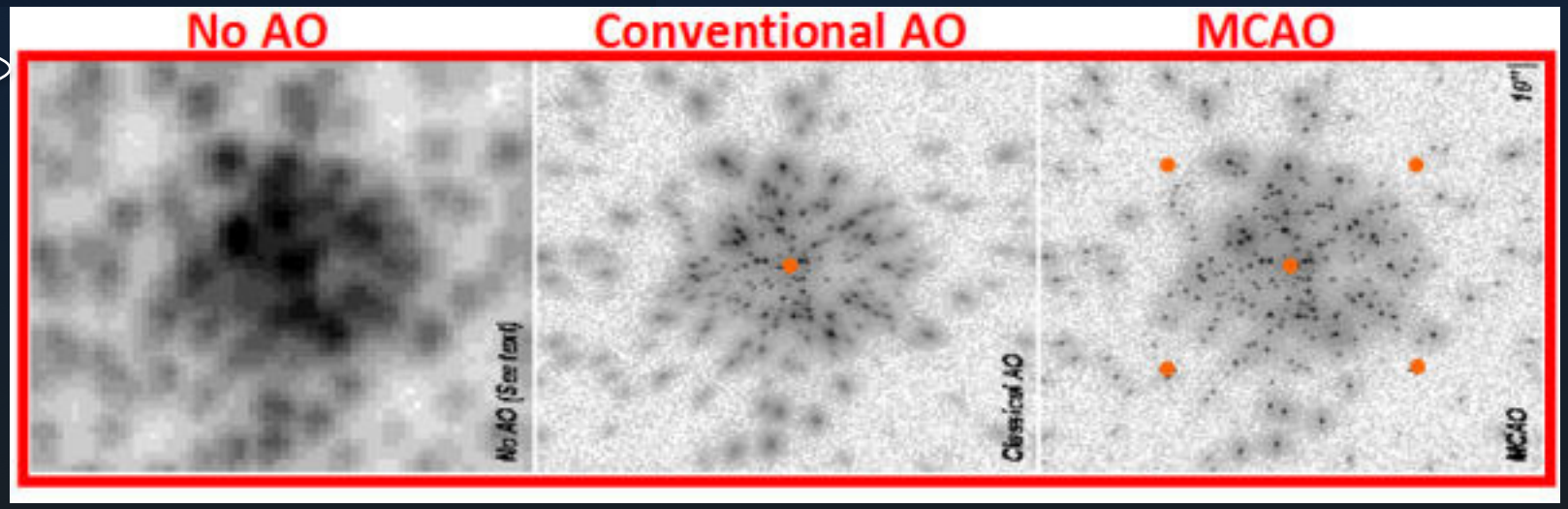


Gemini Observatories

- ❑ Incomplete correction (high residual error)
- ❑ Decreasing radial correction (limited field of view)

- Cone effect



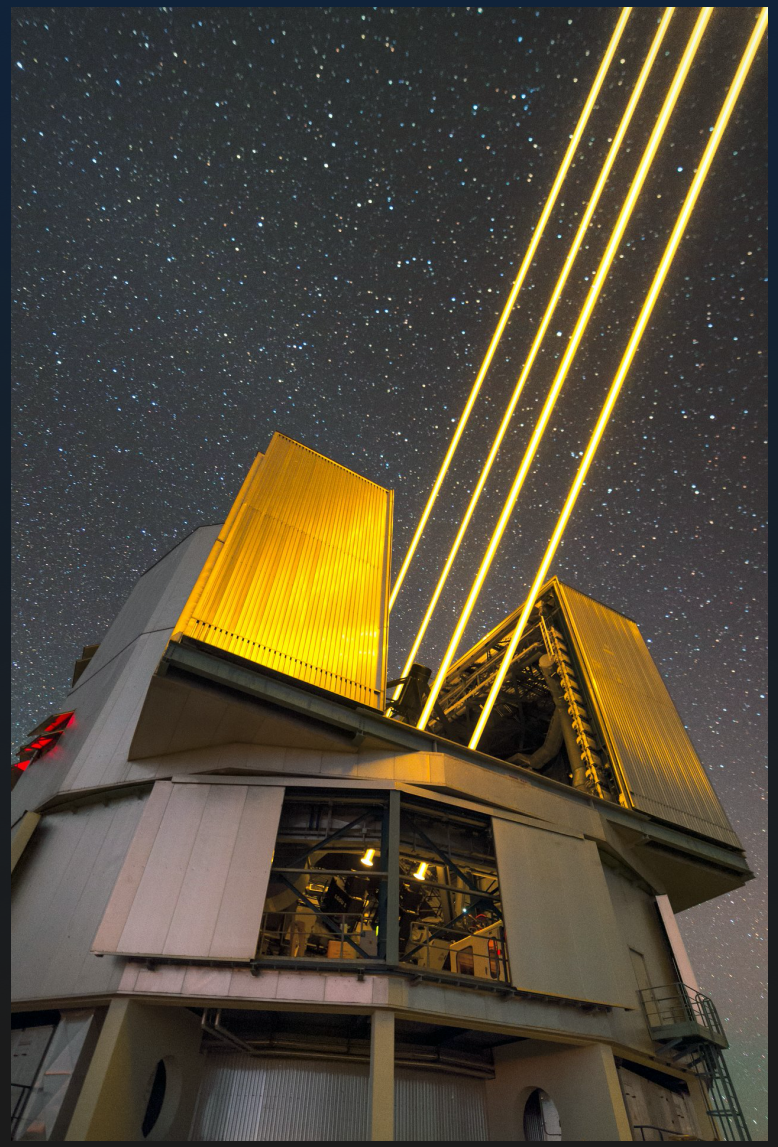


Gemini Observatories

Multi-Conjugate Adaptive Optics (MCAO)

- Reduce residual error (higher Strehl ratio)
- Increased number of guide stars (NGS and LGS) and WFS
- Increased field of view and sky coverage

Laser Guide Stars: MCAO

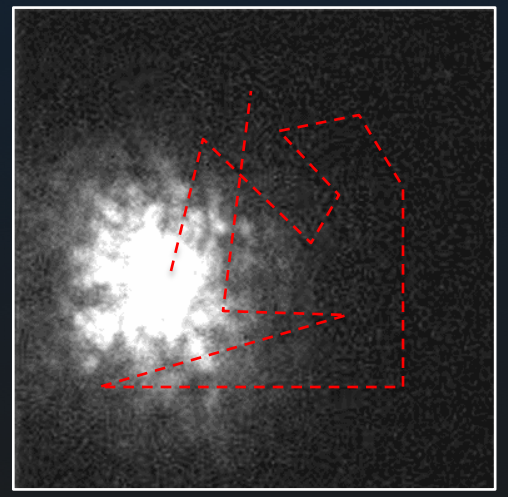


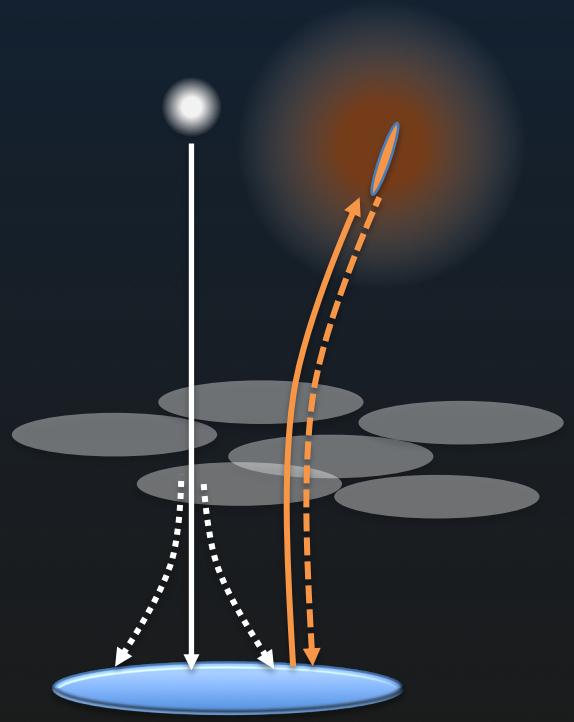
ESO/P. Horálek

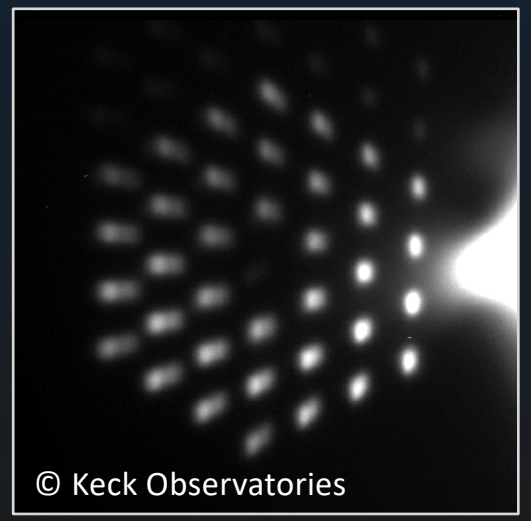
S. Guisard

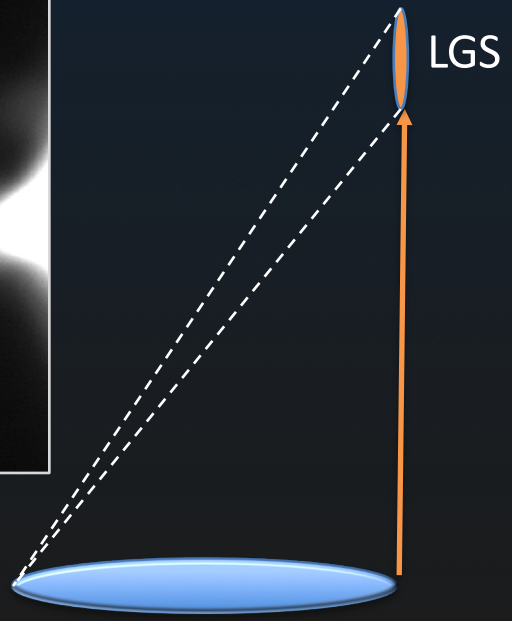
Laser Guide Stars: Limitations

- Double atmospheric path → LGS tip/tilt insensitive
- Sodium layer is ~10 km thick → LGS elongation



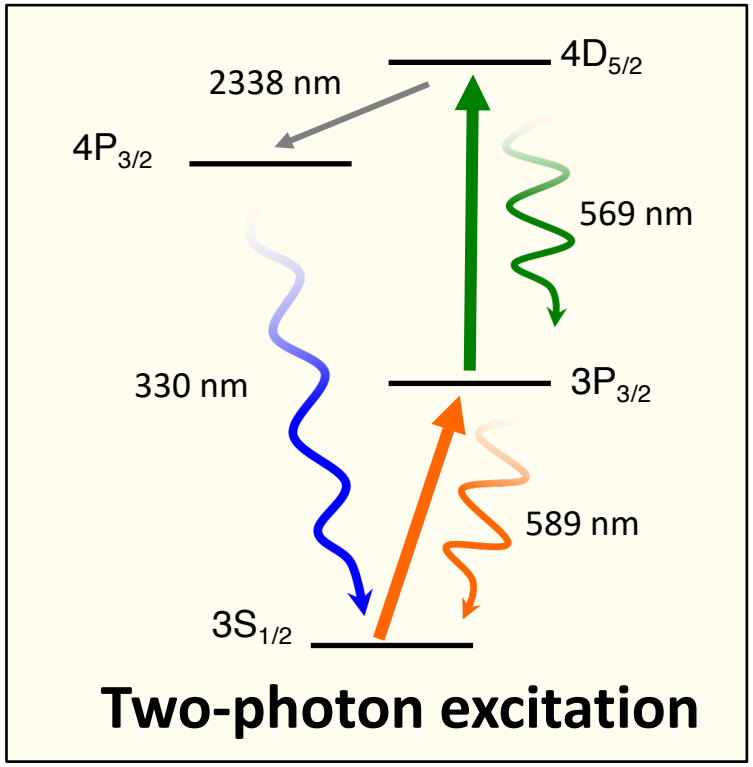


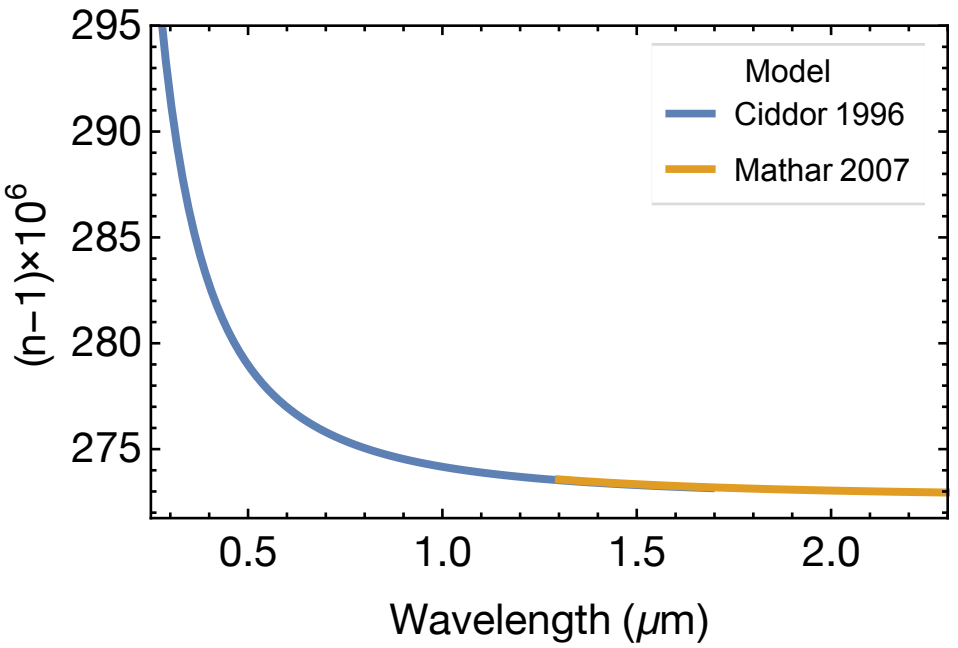


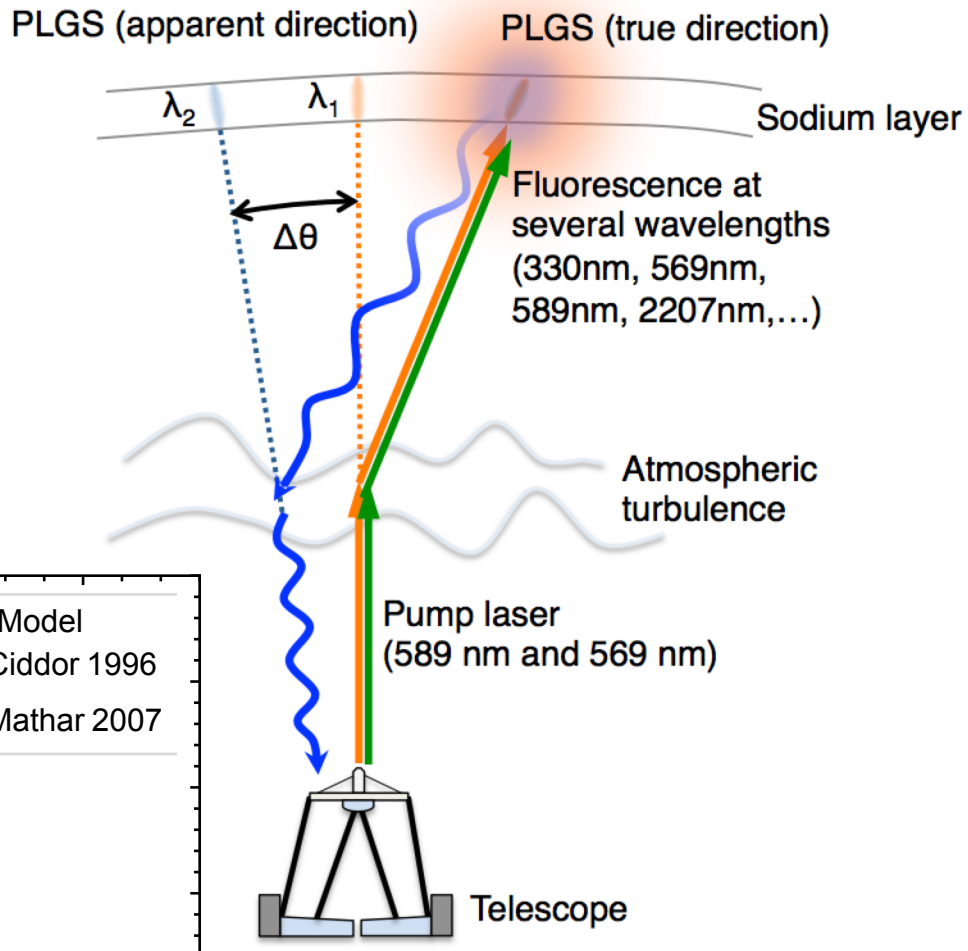


Polychromatic laser guide stars

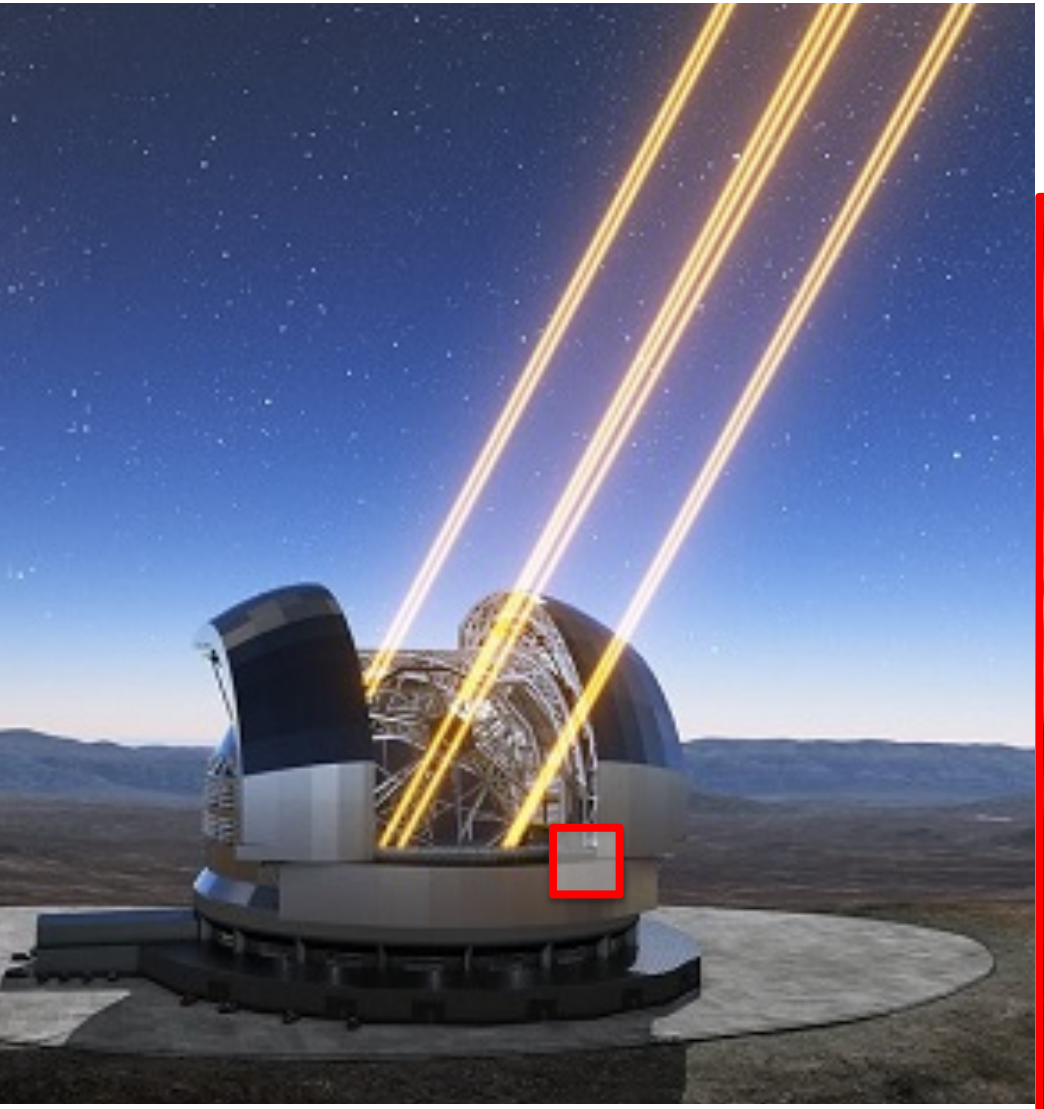
- Polychromatic laser guide star (PLGS) concept (R. Foy, A&A, 1995)
- Make use of 330 nm decay + 589 nm (spontaneous emission)
- Measurement of differential tilt to retrieve true tilt
- Great theoretical and experimental development during the 2000's



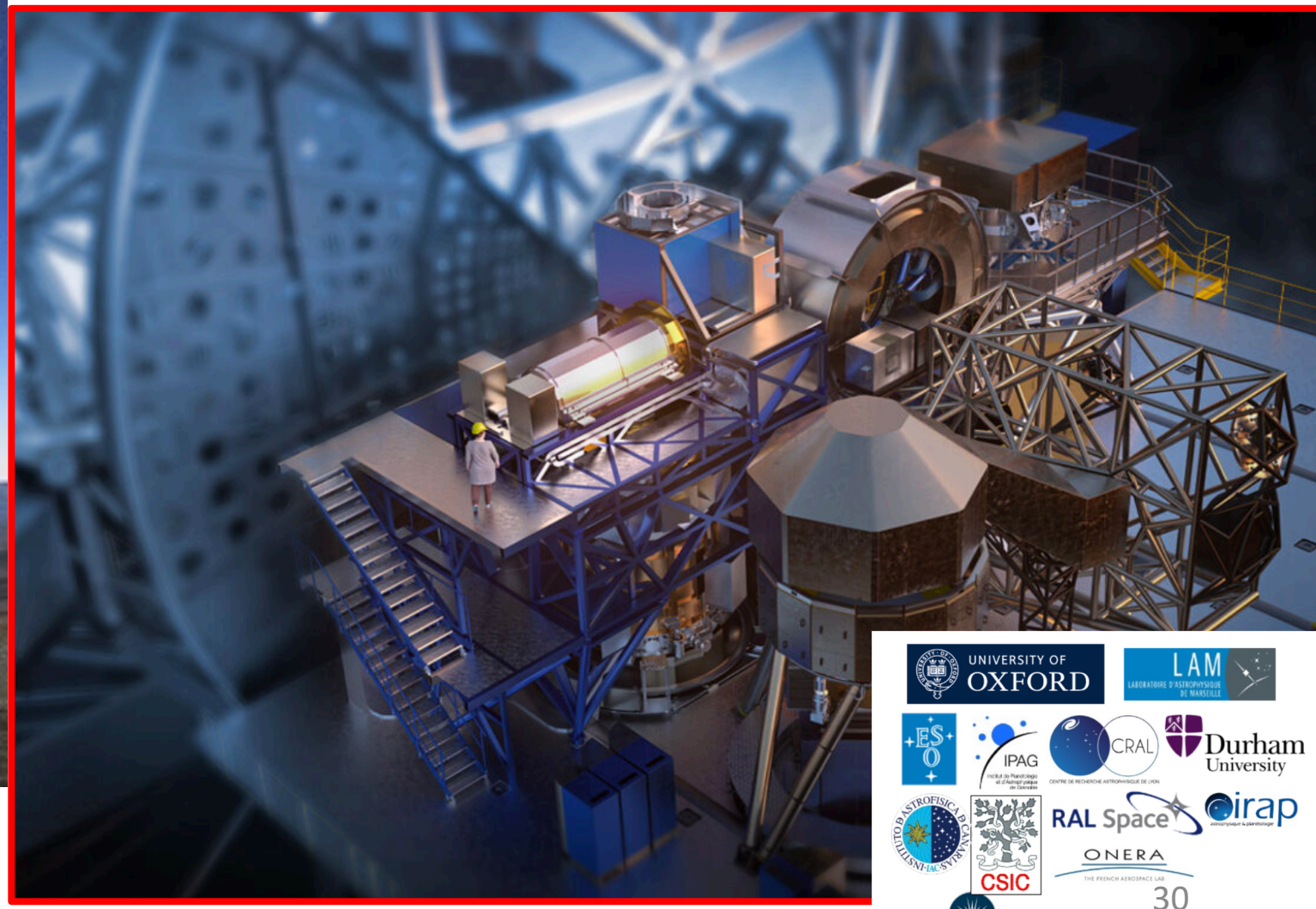




The European Extremely Large Telescope - ELT

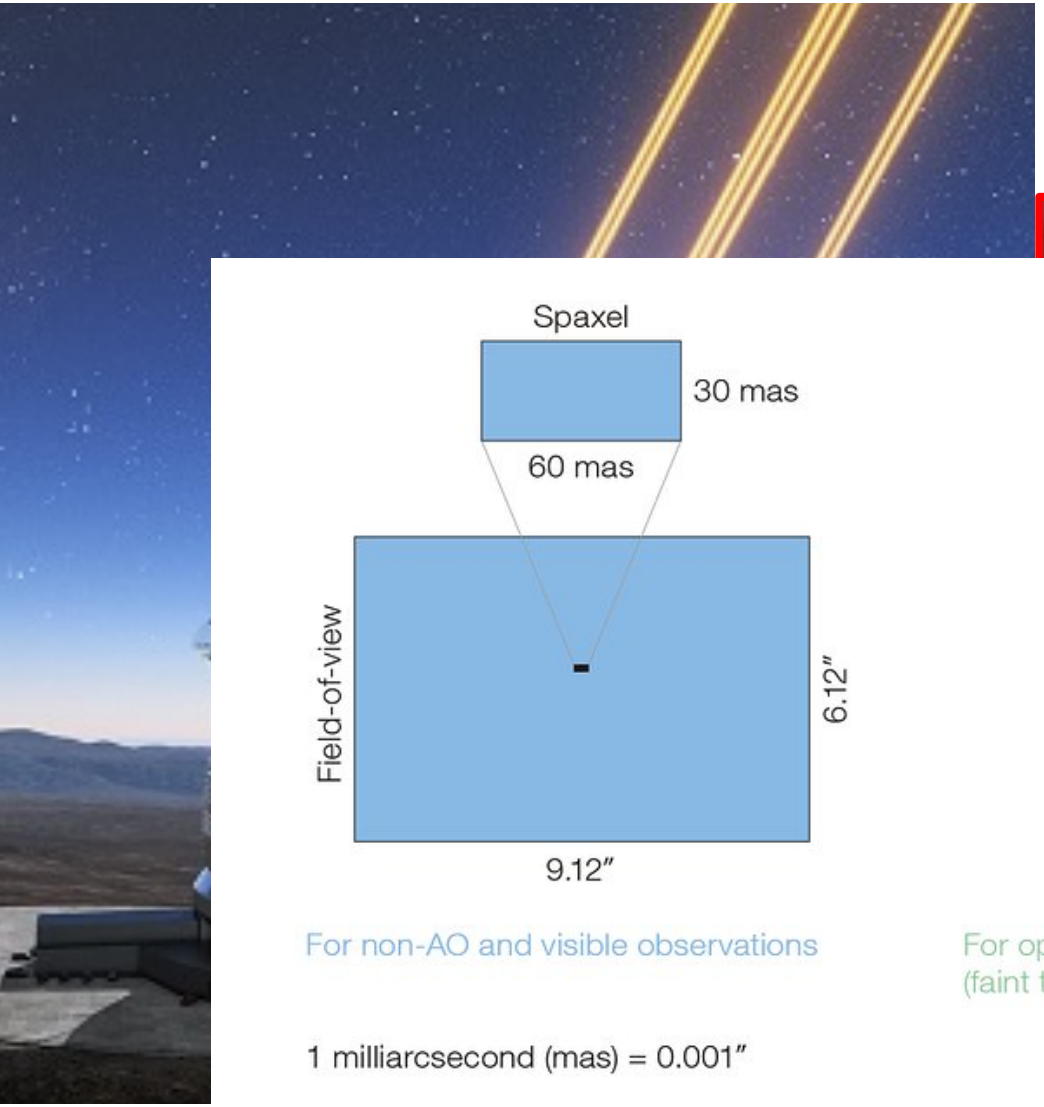


HARMONI: High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph



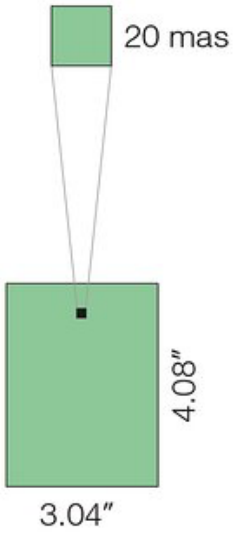
Science & Technology Facilities Council
UK Astronomy Technology Centre

The European Extremely Large Telescope – ELT



HARMONI: High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph

For non-AO and visible observations

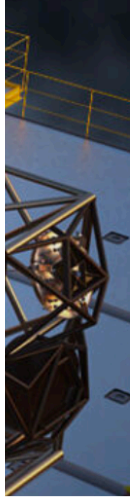


For optimal sensitivity (faint targets)

Best combination for sensitivity and spatial resolution

Highest spatial resolution (diffraction limited)

1 milliarcsecond (mas) = 0.001″



Durham University

CSIC ONERA

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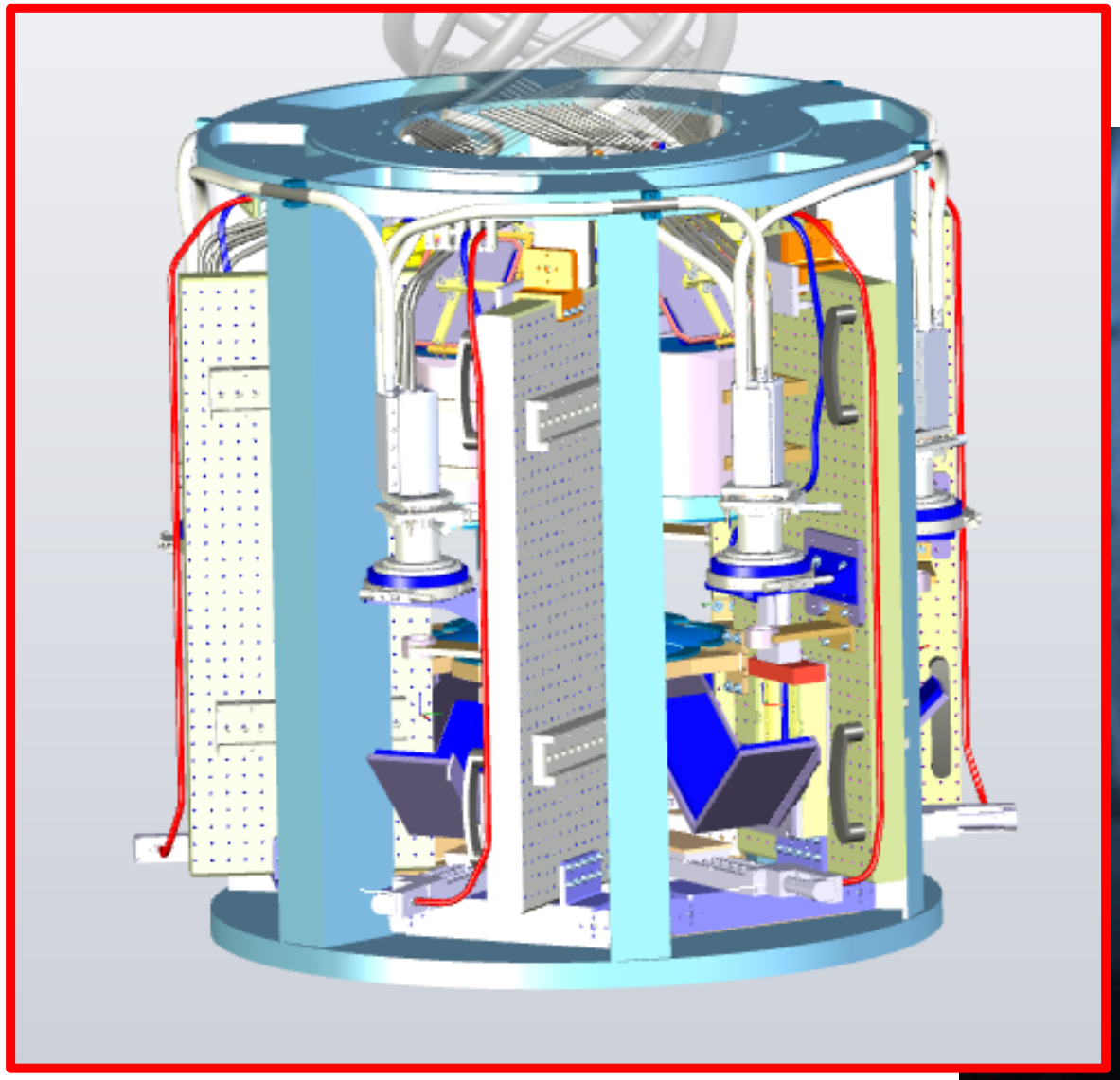
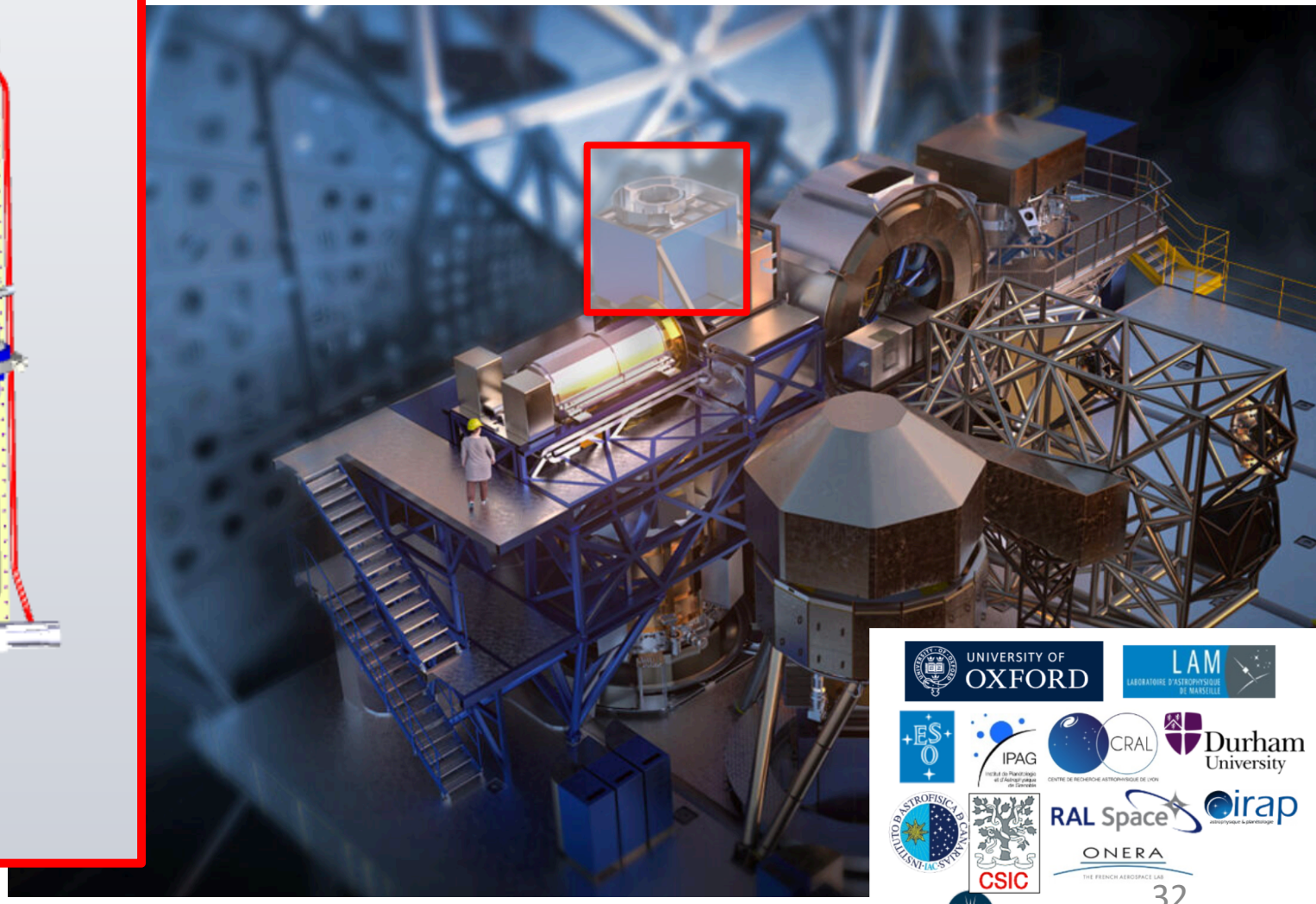
UK Astronomy Technology Centre

Laser Guide Star System



HARMONI: High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph



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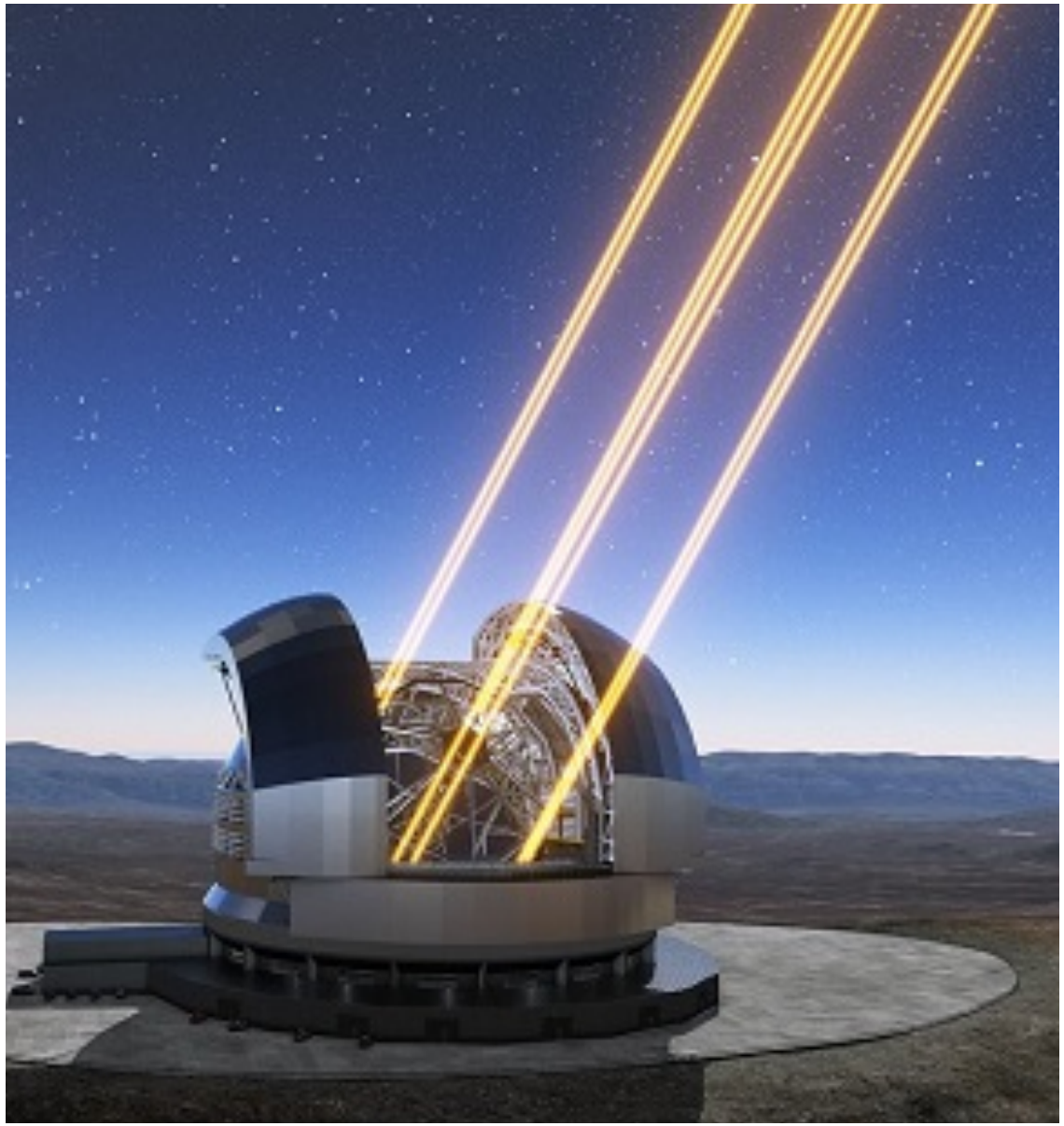
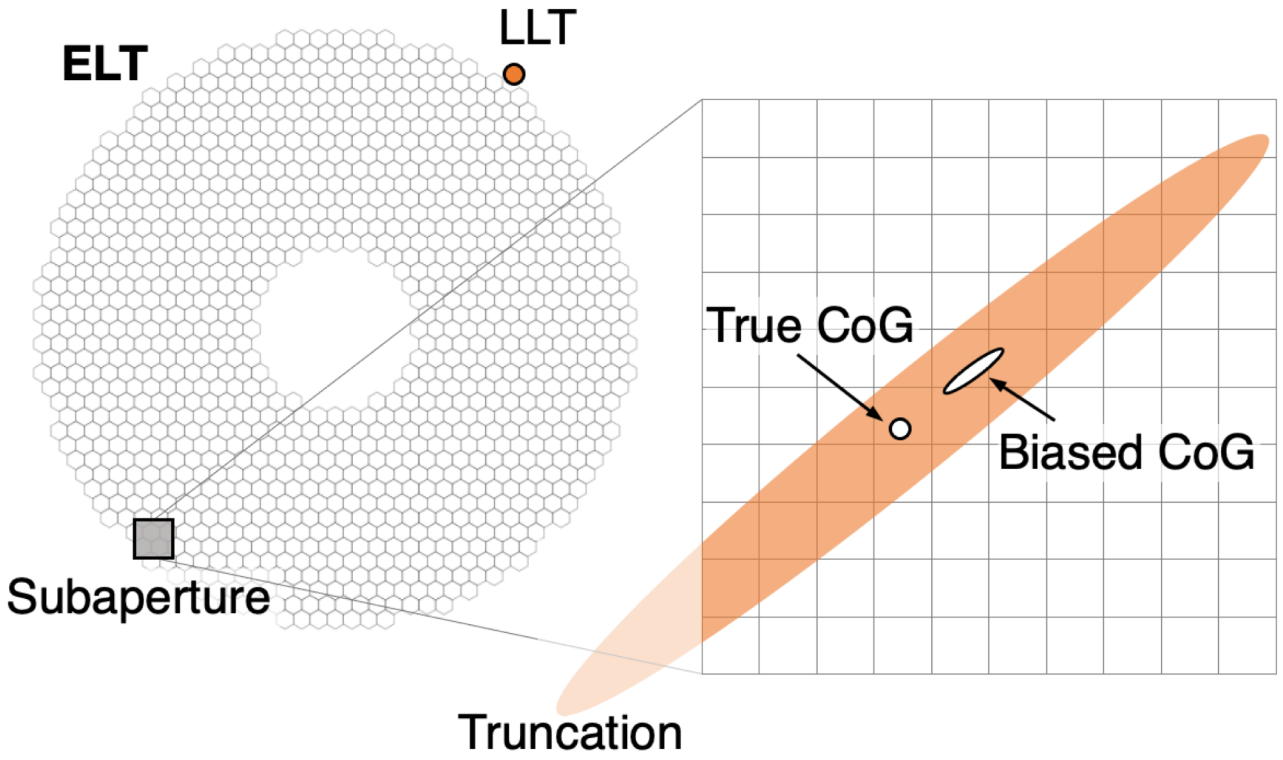
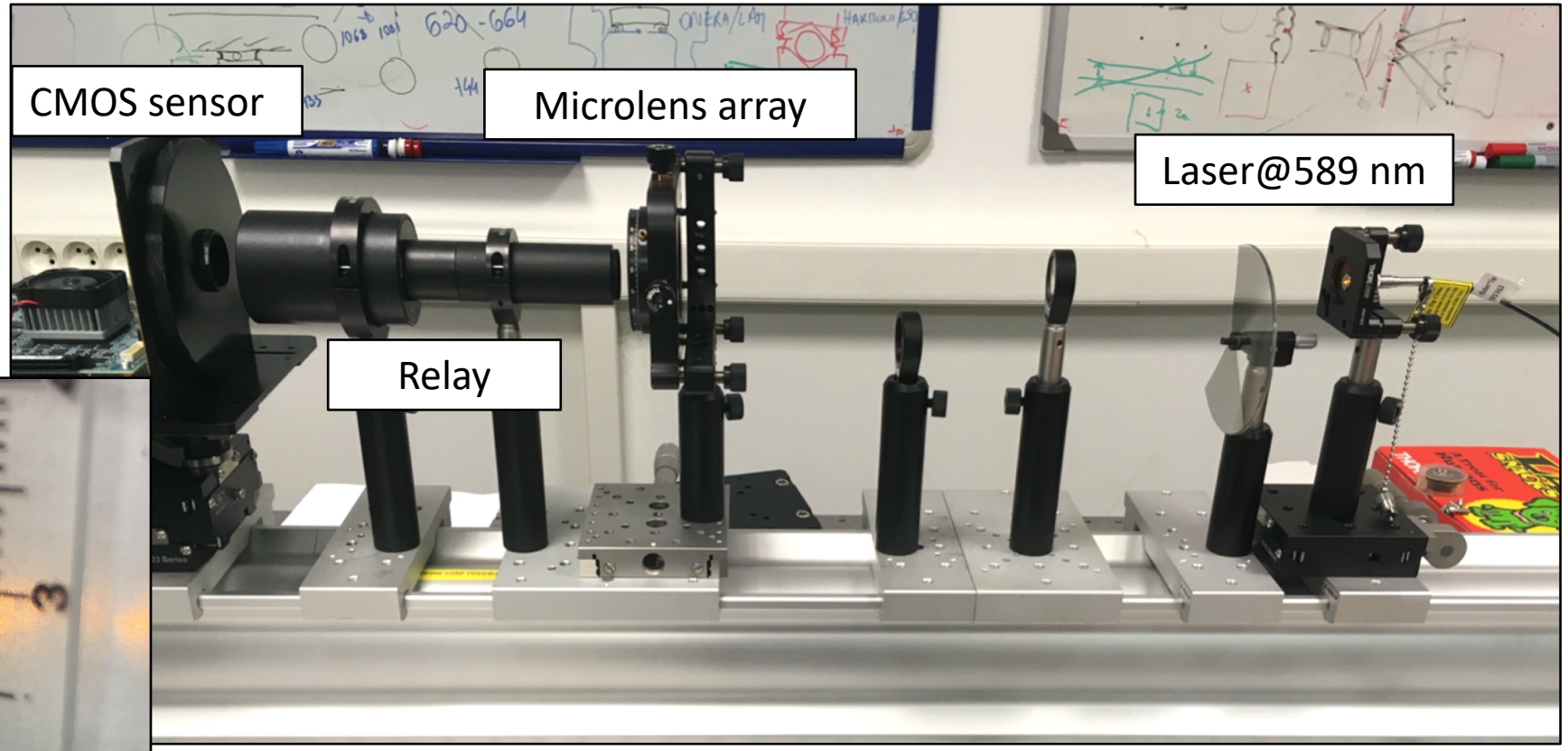
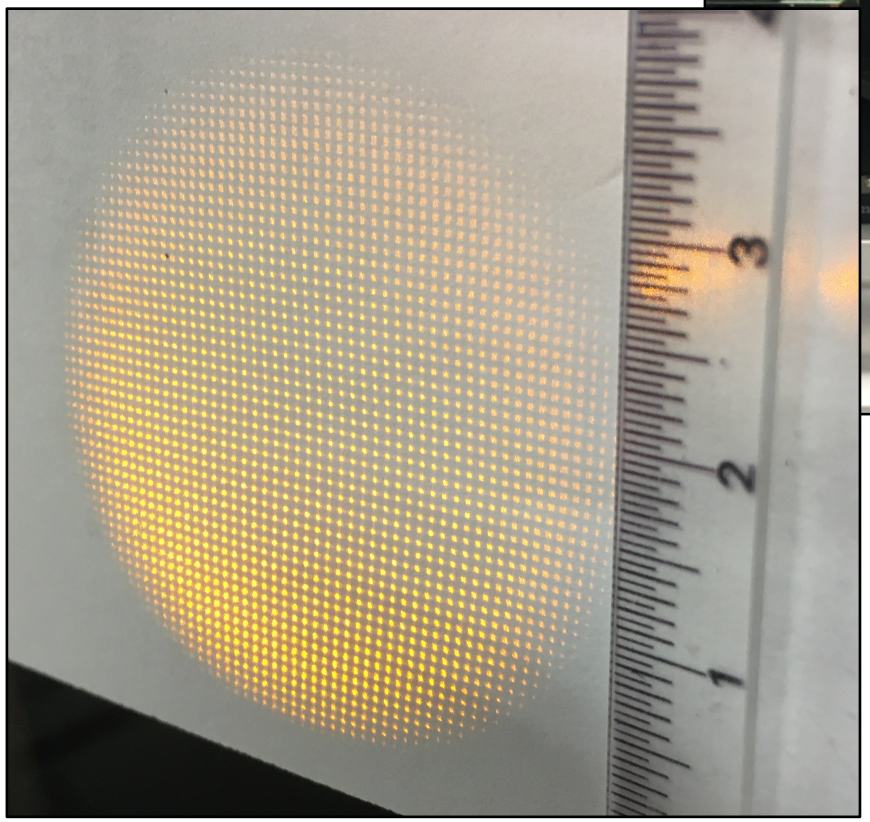


Strong LGS elongation



Laser Guide Star WFS Prototype





- 80x80 Shack-Hartmann WFS
- **Large CMOS sensor** (9μm, 1600x1000 pixels)
- Very low read out noise (< 3 e^-/pixel)
- Up to 500 Hz frame rate

8 m telescope resolution

38 m telescope resolution

VLT AO + SINFONI

HARMONI 20 mas LTAO

HARMONI 10 mas LTAO

HARMONI 4 mas LTAO

Summary

- Atmospheric **turbulence limits the spatial resolution** of ground-based telescopes
- Adaptive Optics enable astrophysical observations near **diffraction limit**
- Laser Guide Stars allows wavefront sensing in the absence of nearby natural guide stars
- Combination of several **LGS + NGS increase performance** of Adaptive Optics
- Future extremely large telescopes **require adaptive optics** instruments
- Deriving tip/tilt from LGS remains a fundamental limitation to overcome

Laser guide stars for astronomy adaptive optics

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