# Lucky Imaging
## Life in the visible after HST

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Southampton Seminar Series
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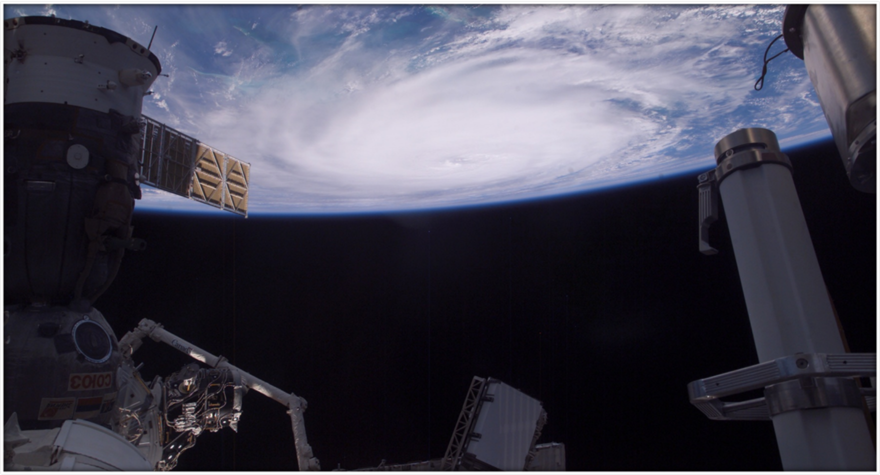
# Outline

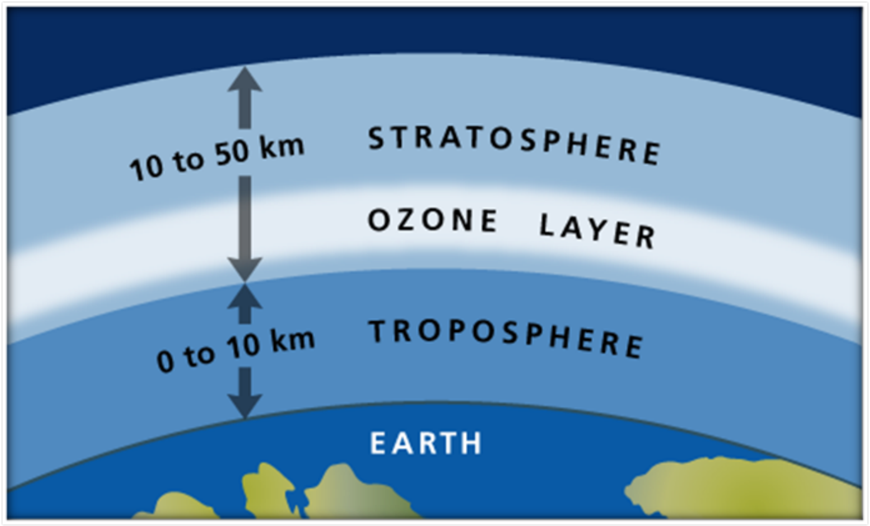
1. Atmospheric effects
2. High spatial resolution astronomy
3. Adaptive optics
4. Lucky imaging
5. Lucky imaging + AO

# Outline

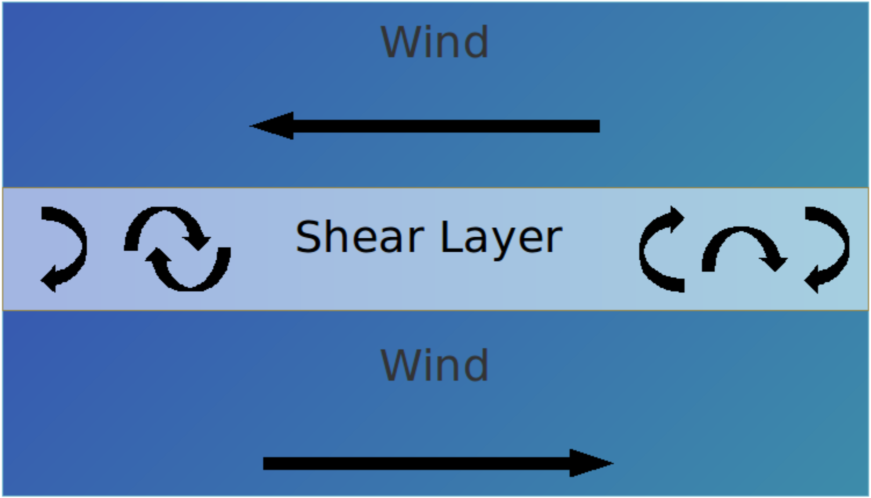
# Coping with weather



# Atmospheric structure

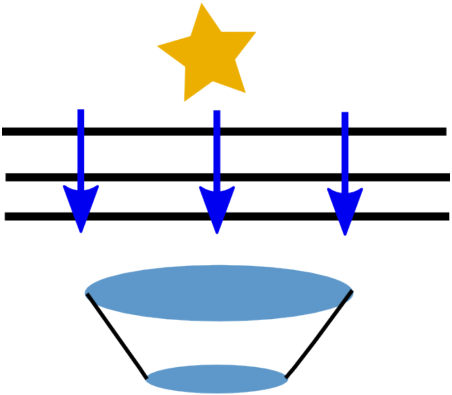


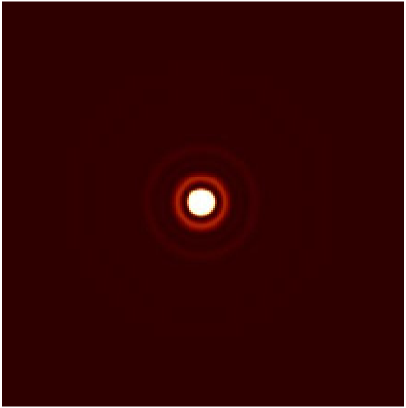
# Boundary layers



# Kelvin-Helmholtz instability –> turbulence

# Wavefront perturbations

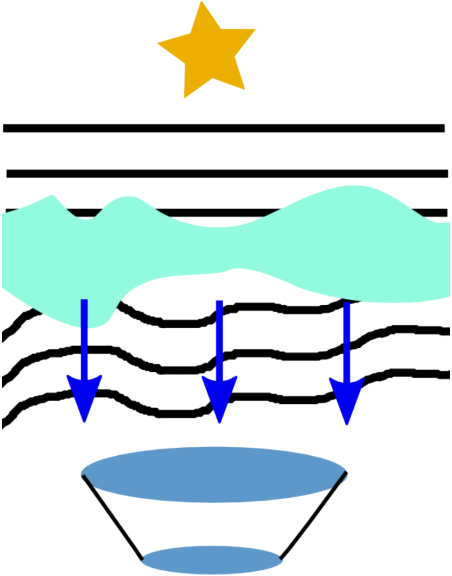


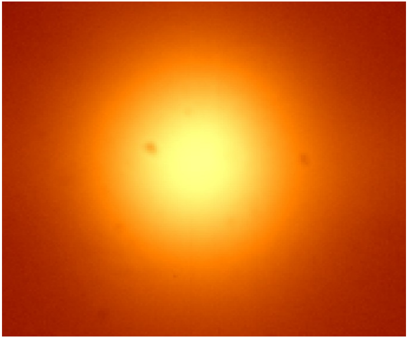


Planar wavefronts:

Resolution $\propto \frac{\lambda}{D}$

# Wavefront perturbations



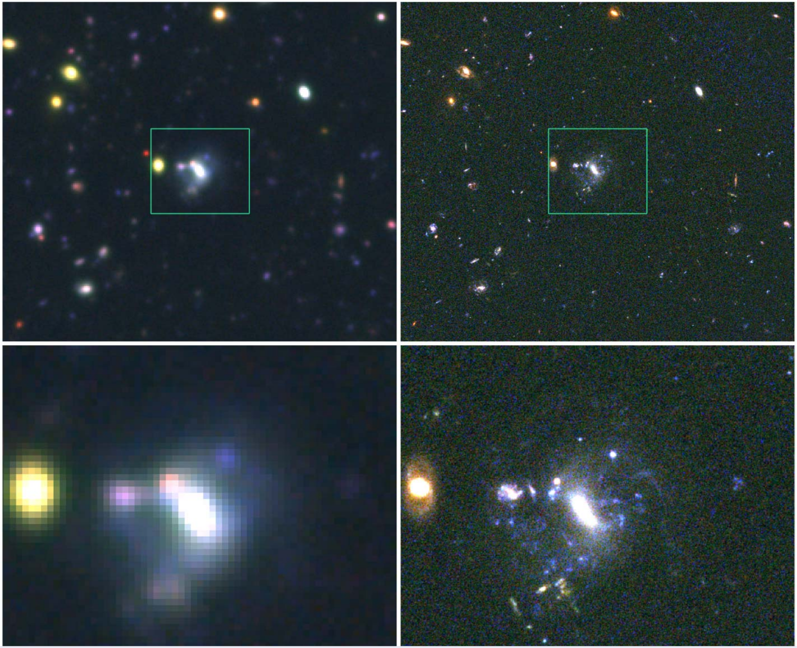


Perturbed wavefronts:

Resolution $\propto \dfrac{\lambda}{r_0}$

(long exposure on a large telescope)

Ground: Subaru (8m) Space: *HST* (2.4m)

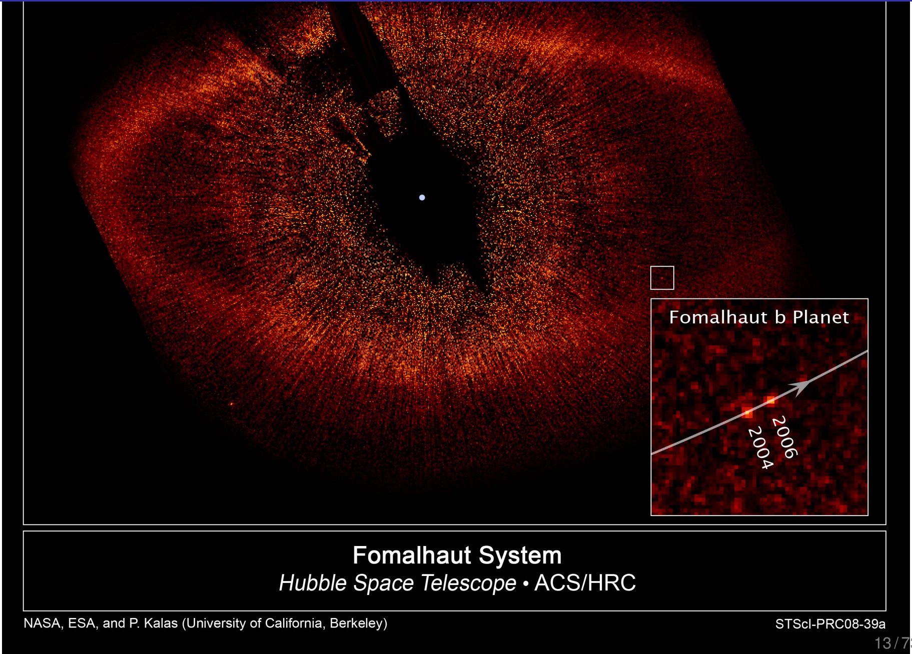


*GOODS North, Subaru @ 0.8" seeing* *Hubble UDF*

# Outline

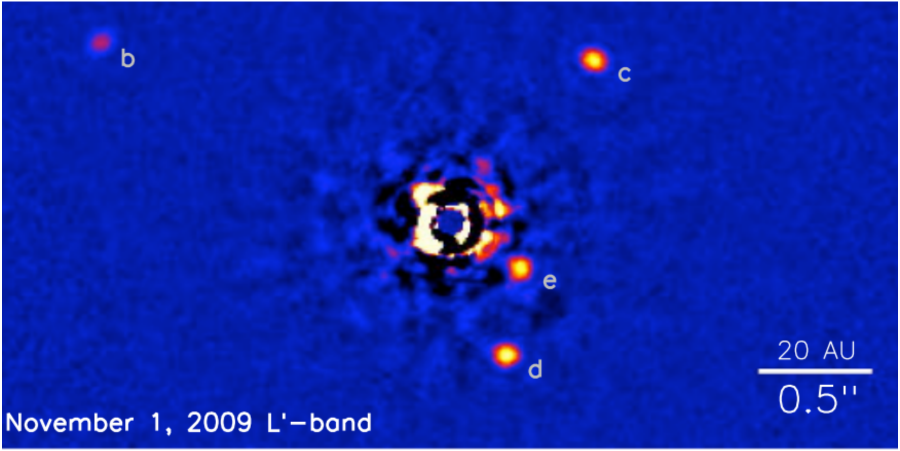
# Why bother?

# Exoplanets


Fomalhaut b Planet
2004
2006
Fomalhaut System
*Hubble Space Telescope* • ACS/HRC
NASA, ESA, and P. Kalas (University of California, Berkeley)
STScI-PRC08-39a

# Exoplanets

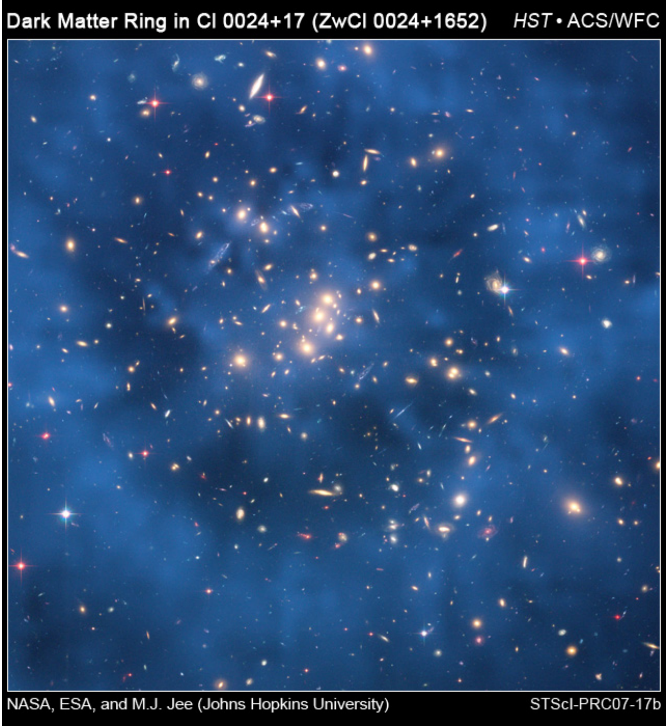
## Keck II - AO using angular differential imaging



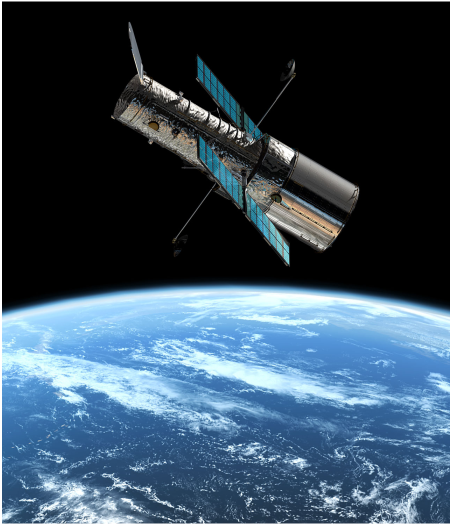

*HR8799 — Marois et al., 2010*

# Globular clusters

*HST mosaic of M53 (spot the blue stragglers!)*


Dark Matter Ring in Cl 0024+17 (ZwCl 0024+1652)
HST • ACS/WFC
NASA, ESA, and M.J. Jee (Johns Hopkins University)
STScI-PRC07-17b

# The cost of space astronomy



HST:
$\approx$ \$2 billion at launch (1990)
\$9.6 billion lifetime cost, including servicing missions

*Image: ESA*
*Source: NY Times: "Refurbishments Complete, Astronauts Let Go of Hubble"*

# Ground based astronomy

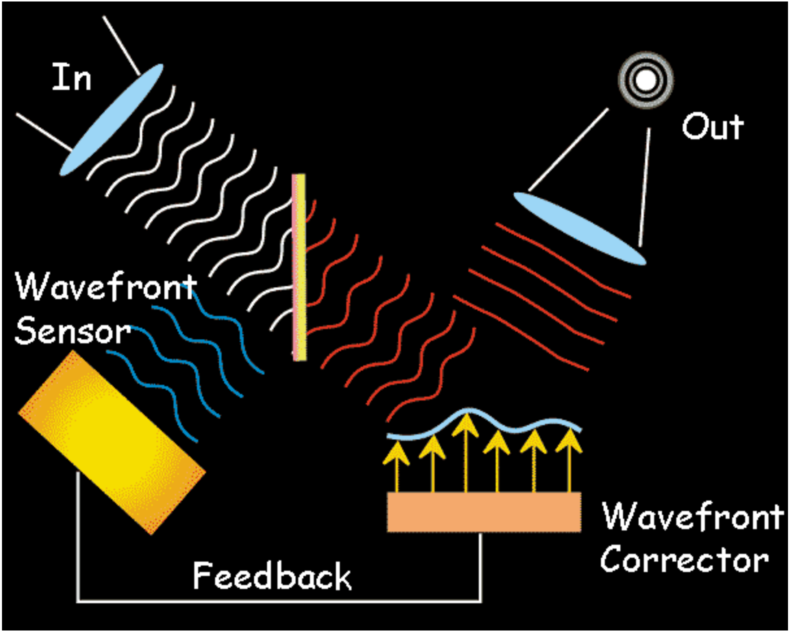
VLT:
$330 M€ to build
$16.9 M€ annual running costs

'Expensive' is relative

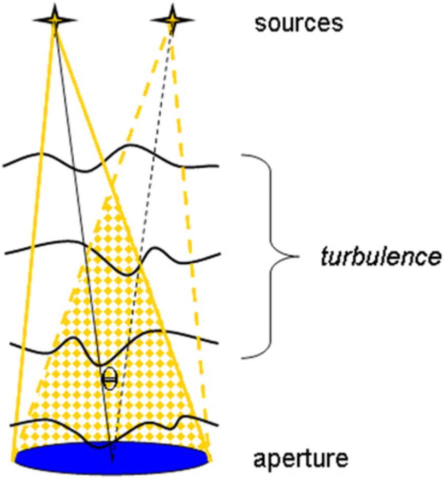
*Image: ESA*
*Source: www.eso.org*

# Outline

# AO: The basic idea



# Guide stars and sky coverage




*Isoplanatic patch* = area for which perturbations roughly the same

Require $r_{mag} \leq 10$ star within 5” – 40”, depending on observation wavelength and atmospheric conditions

*See e.g. Racine, 2006*

# Laser guide stars

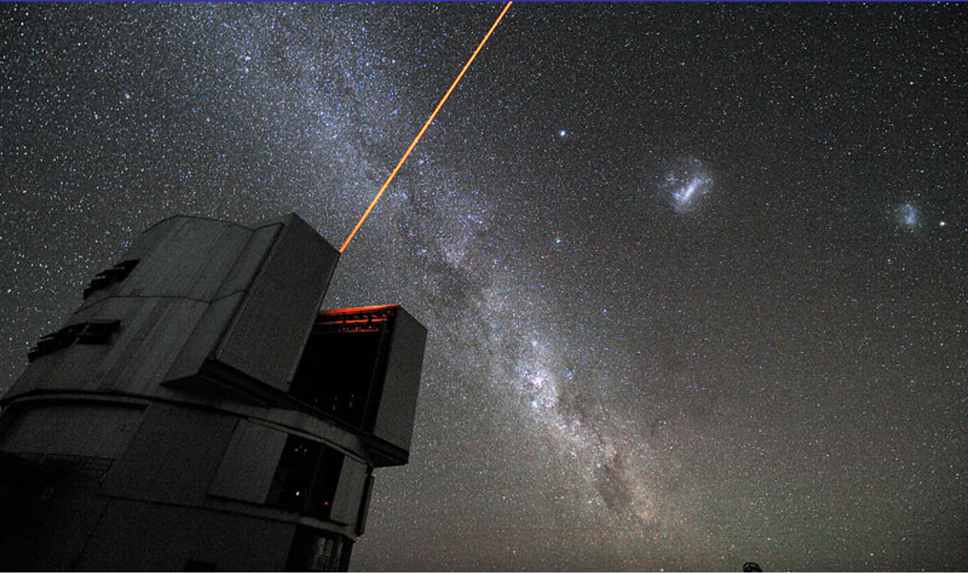


*Image: G. Hudepohl / ESO*

# Laser guide stars

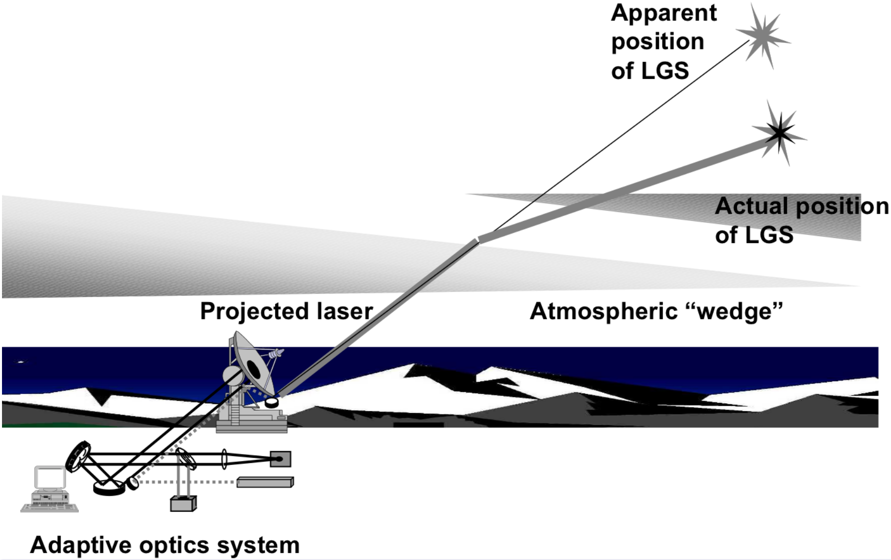



*Image: R. Tyson - An introduction to AO (2000)*

# Laser guide stars


Still require a tip-tilt NGS of $r_{mag} \leq 14$ within $\approx 40''$ of science target.

Good quality sky coverage $\approx 10\%$ at $30^\circ$ galactic latitude. (Strehl $\geq 0.3$, J band)

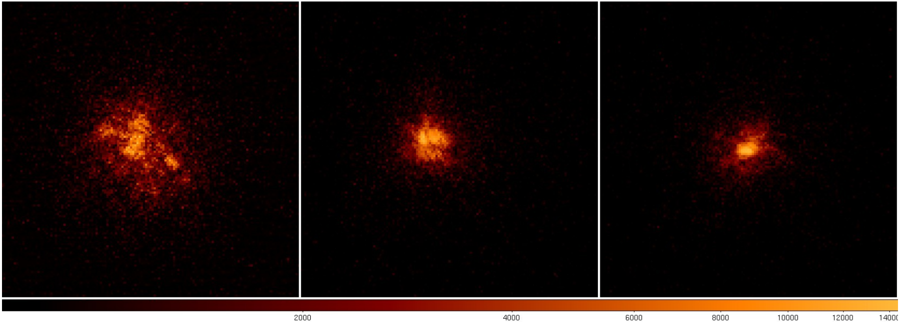
*Davies et al., 2008*
*Ellerbroek and Tyler, 1998*

# (Strehl?)

- The ratio of peak intensity compared to a perfect telescope (0 to 1)
- HST Strehl near 1, but suffers pixellation effects.
- AO Strehl usually varies from around 0.2 – 0.6
- Seeing "Strehl" depends on the telescope, but is typically $\approx 0.01$ on medium size telescopes in the visible.

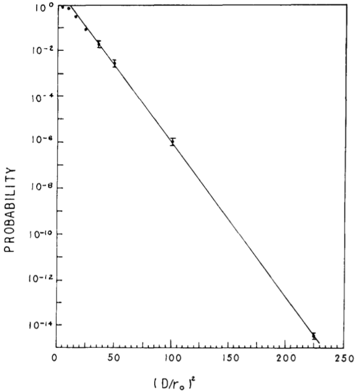
# Outline

# Seeing isn't stable




How often will we get a 'good' frame?

# Fried's probabilities




Probability of a lucky exposure (near diffraction limited):

$$P \approx 5.6 \exp\left[-0.1557(D/r_0)^2\right]$$

*Fried, 1978*

# Fried's probabilities

| $D/r_0$ | Probability |
|---|---|
| 2 | $0.986 \pm 0.006$ |
| 3 | $0.765 \pm 0.005$ |
| 4 | $0.334 \pm 0.014$ |
| 5 | $(9.38 \pm 0.33) \times 10^{-2}$ |
| 6 | $(1.915 \pm 0.084) \times 10^{-2}$ |
| 7 | $(2.87 \pm 0.57) \times 10^{-3}$ |
| 10 | $(1.07 \pm 0.48) \times 10^{-6}$ |
| 15 | $(3.40 \pm 0.59) \times 10^{-15}$ |

*Fried, 1978*

# How to take advantage of this?

- Cross-correlate speckle image with an Airy psf model
- Cross-correlation values provide a proxy for Strehl
- Cross-correlation positions give a good estimate of brightest speckle
- Select desired frames, then shift and add.

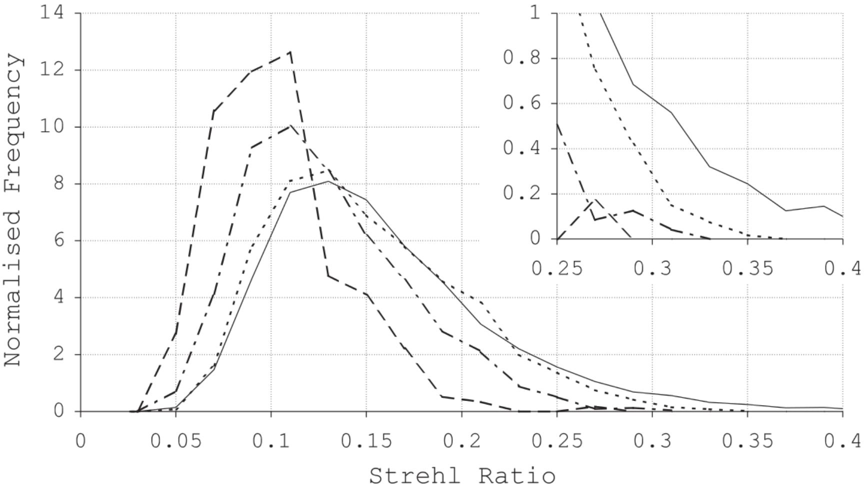
# Early tests

# Early tests

- 2.5m Nordic Optical Telescope
- 512 sq. pixel detector
- 185Hz frame rate
- 810nm observing wavelength
- Faint limit at 6th magnitude

# Early tests

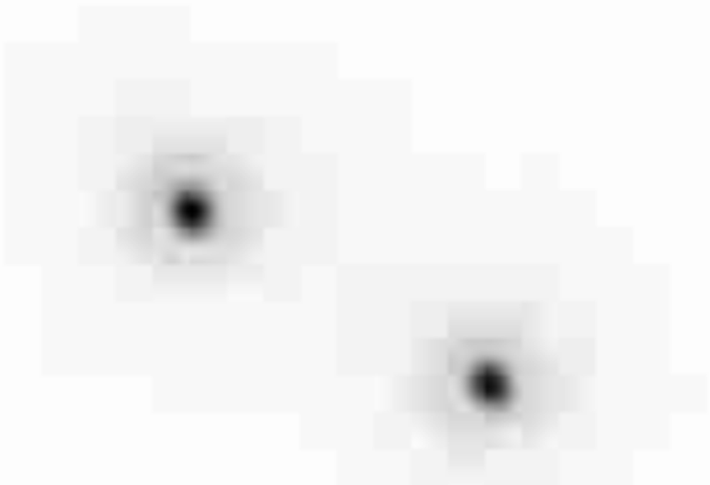
## Seeing width ≈ 0.4”




*Baldwin et al., 2001*

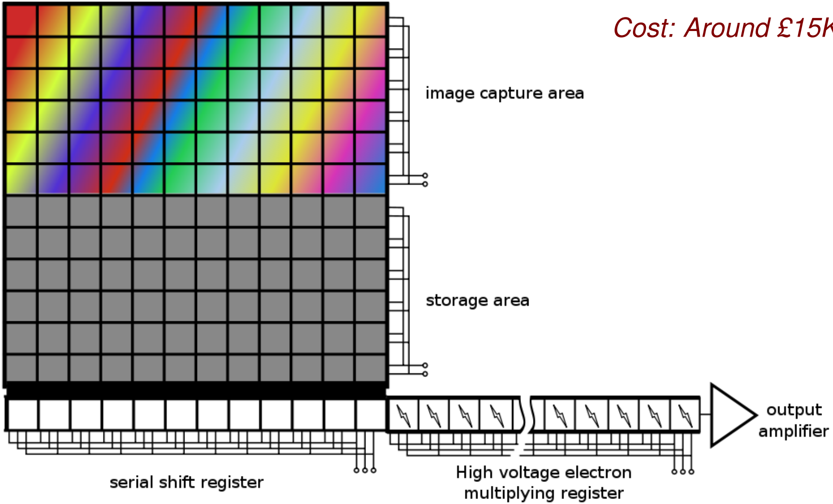
# Early tests

$\zeta$ Bootis, Seeing width $\approx$ 0.8”



*Baldwin et al., 2001*

# Fast imaging with EMCCD’s




*Cost: Around £15K*

# Fast imaging with EMCCD's

Conventional CCD:

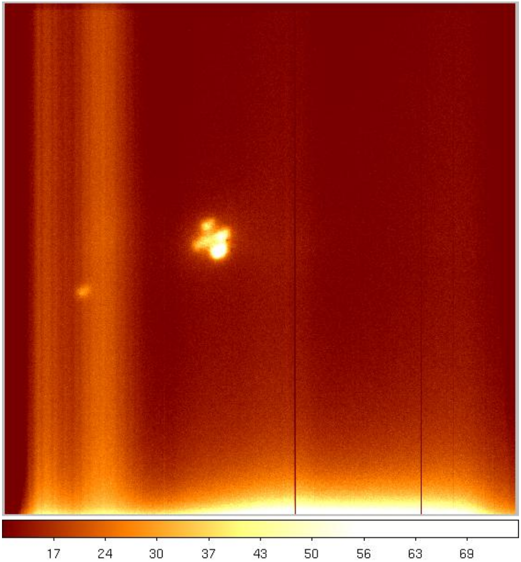
$$\mathrm{SNR} = \frac{M}{\sqrt{M + \sigma_N^2}}$$

EMCCD:

$$\mathrm{SNR} = \frac{M}{\sqrt{2M + (\sigma_N / g_A)^2}}$$

# Fast imaging with EMCCD's

Calibration:



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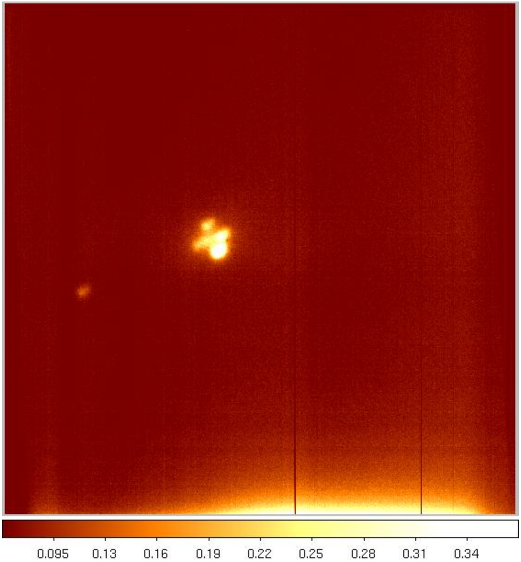

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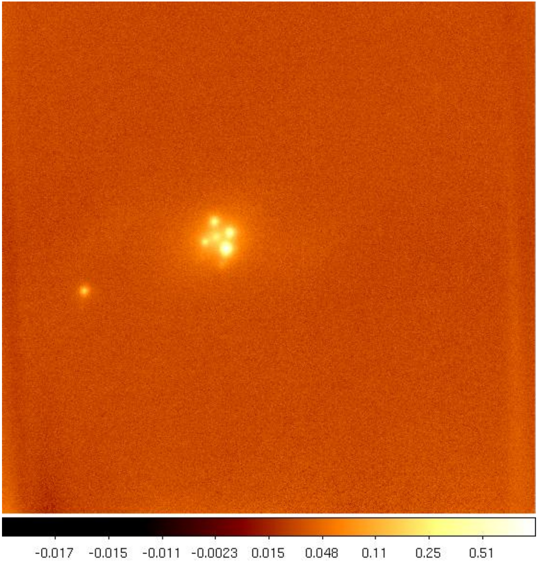
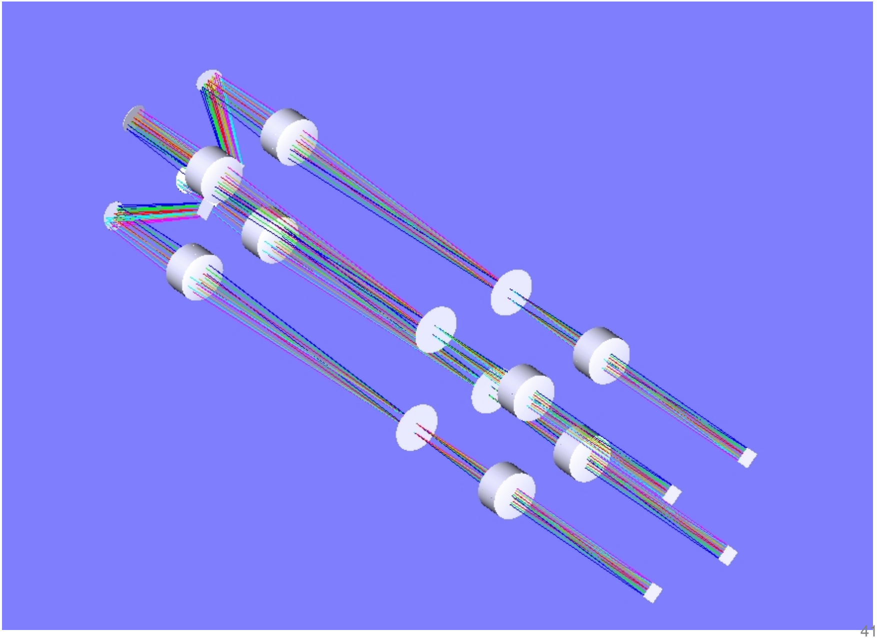


# Fast imaging with EMCCD's

- Limited pixel size, $1K^2$
- Can only get 30 sq. arcseconds Nyquist sampled on 2.5m telescope.
- Readout electronics are a bottleneck on the frame rate

# 2009 — LuckyCam goes wide field



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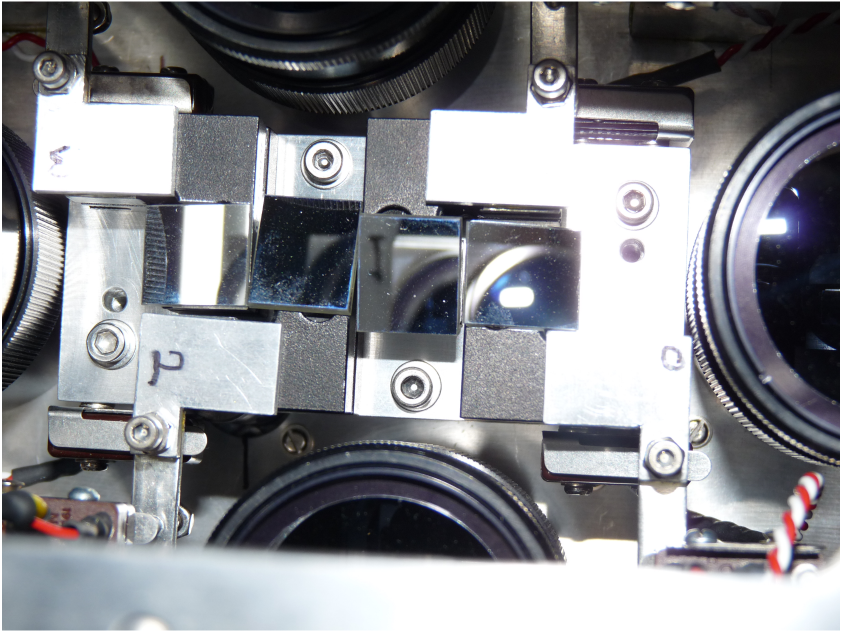

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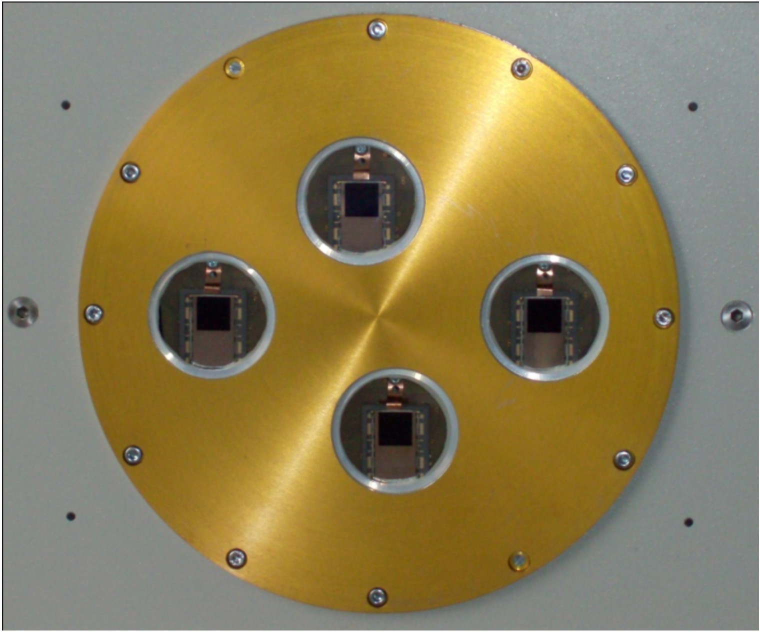

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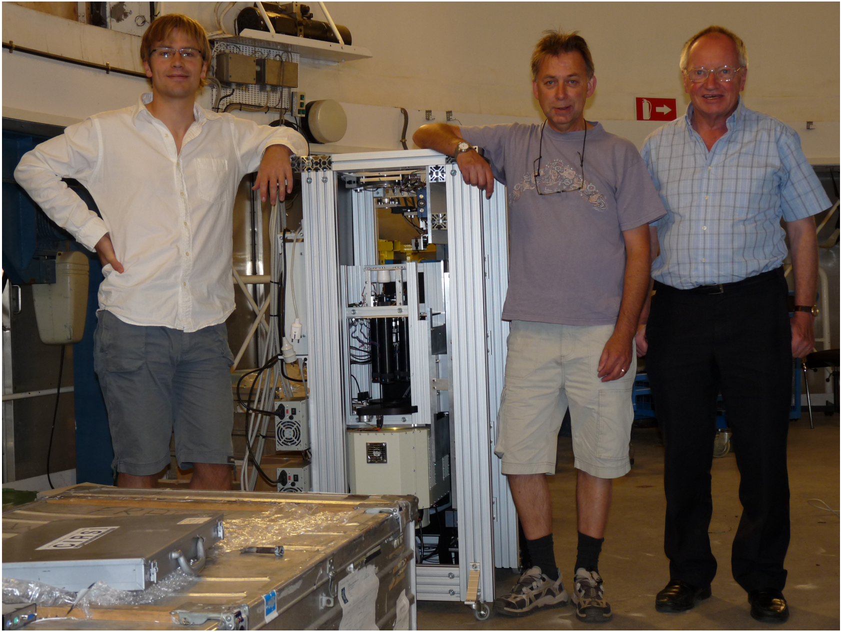

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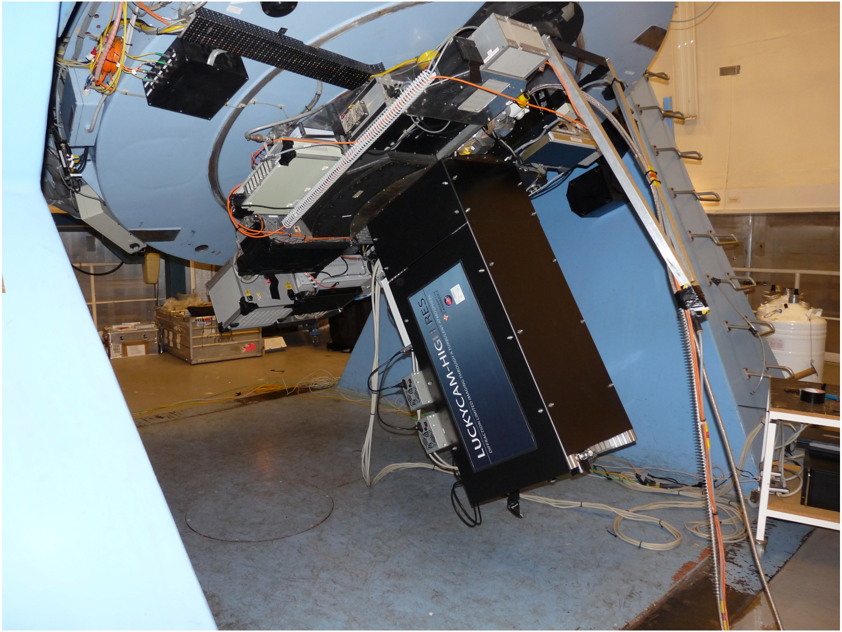
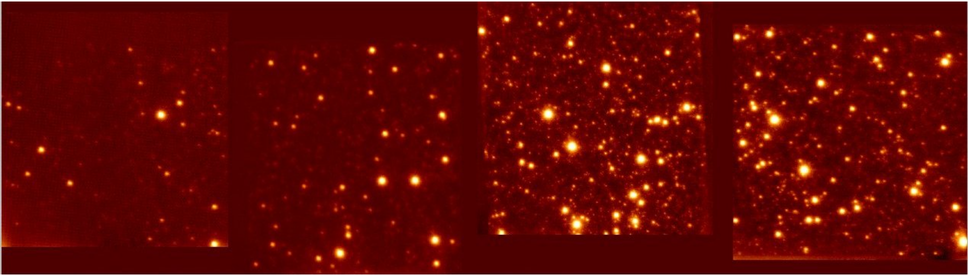


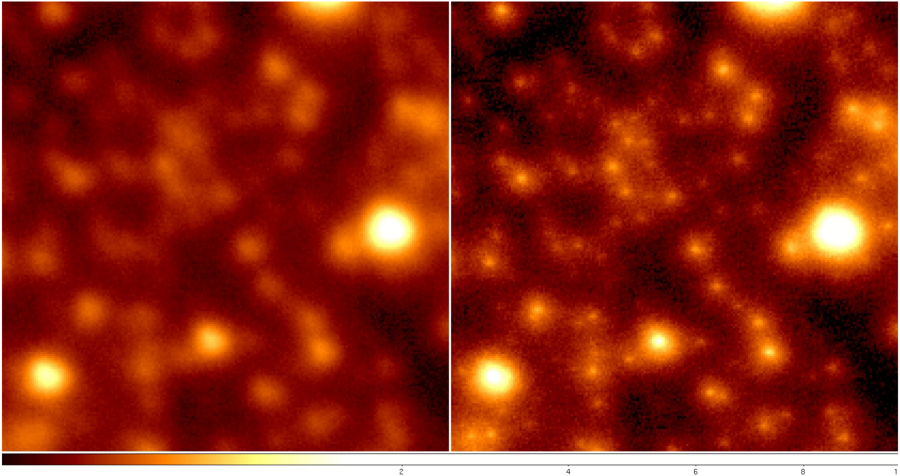
# Wide fields of view: M13

- 120 x 30 arcsecond FoV @ 33mas per pixel
- Challenging data storage and processing requirements
- Astrometric calibration is non-trivial



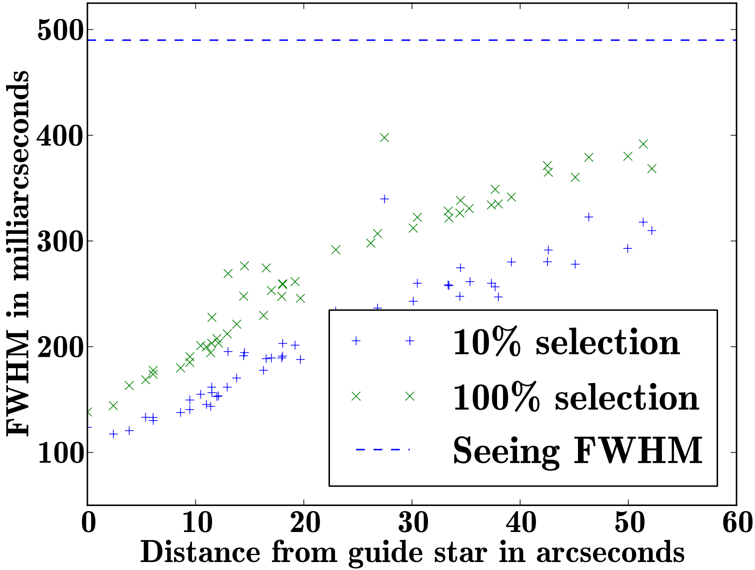
# Wide fields of view: M13

Zoom — 6.7 arcseconds across this FoV



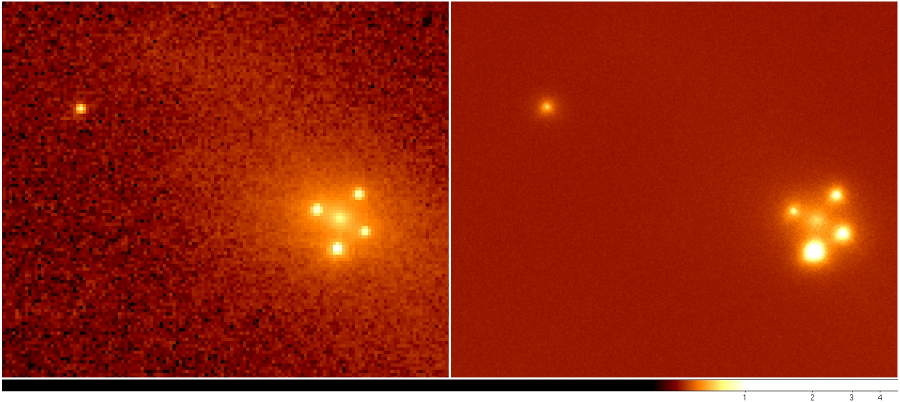

Conventional imaging     50% frame selection

# Wide fields of view: M13



# Guiding on a faint reference: the Einstein cross

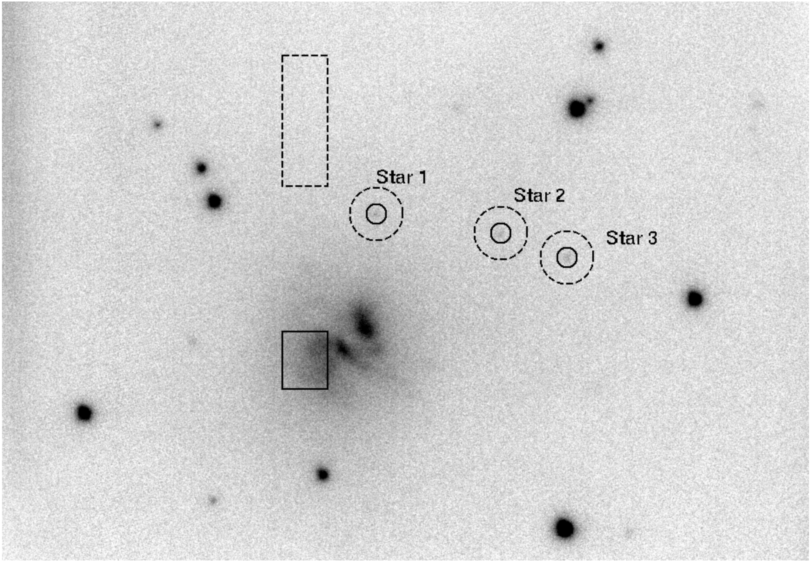
Guiding on a 17th mag. star — FWHM≈ 0.1”



# Science at the faint limit: thresholding

- Read out noise still 0.1 electrons.
- Faint limit around 23rd magnitude on a 2.5m telescope (good seeing)
- Thresholding eliminates read noise
- But for now we are limited by CIC

# Science at the faint limit: thresholding



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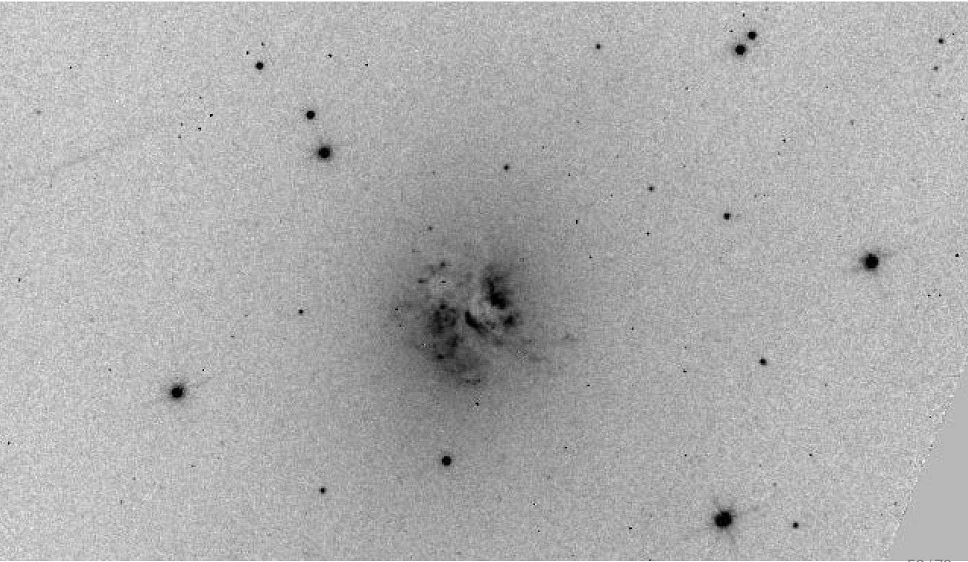
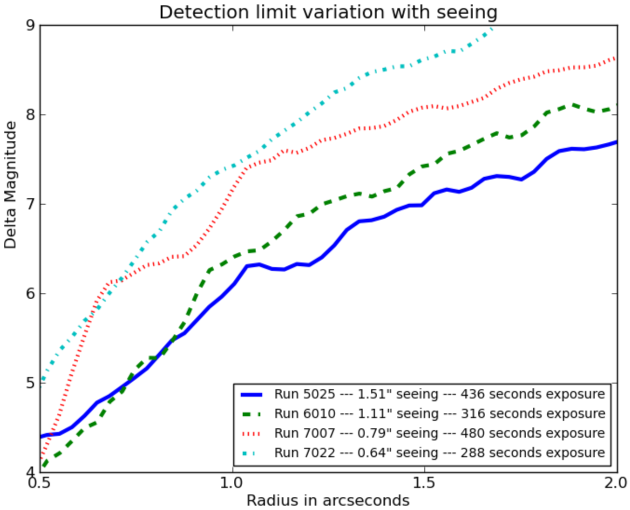


# Applications

- Stellar binarity surveys



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- High resolution surveys (e.g. microlensing in crowded field)
- Cheap high resolution follow-up (stellar transits, etc)
- Planetary imaging
- Potentially better faint limits that conventional imagers in future? (esp. for bright sky)

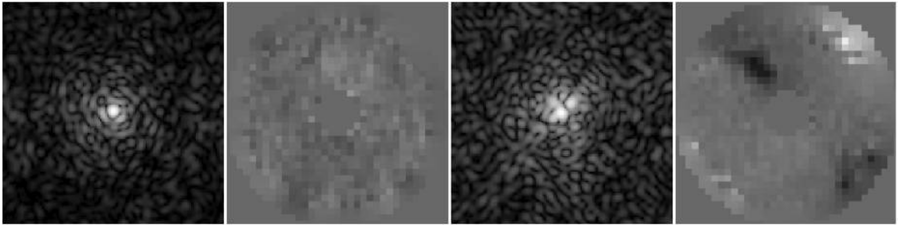
But still limited to smaller telescopes.

# Outline

1. Atmospheric effects
2. High spatial resolution astronomy
3. Adaptive optics
4. Lucky imaging
5. **Lucky imaging + AO**

# Lucky + AO

Adaptive optics systems are not stable.



*Gladysz et al., 2008*

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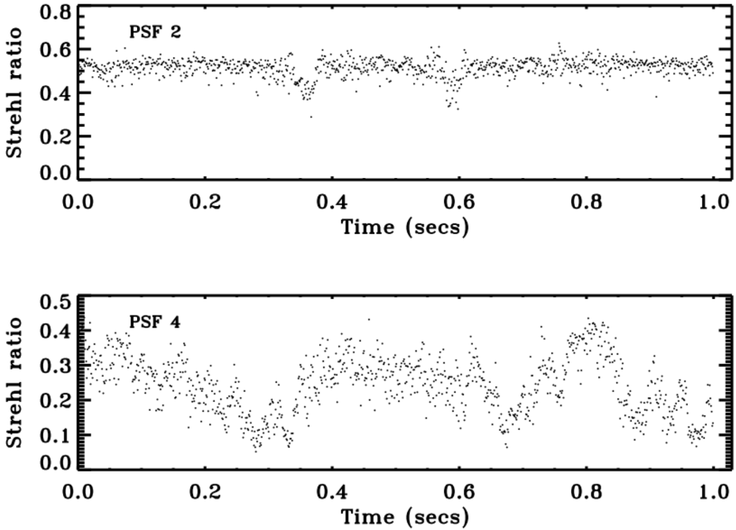


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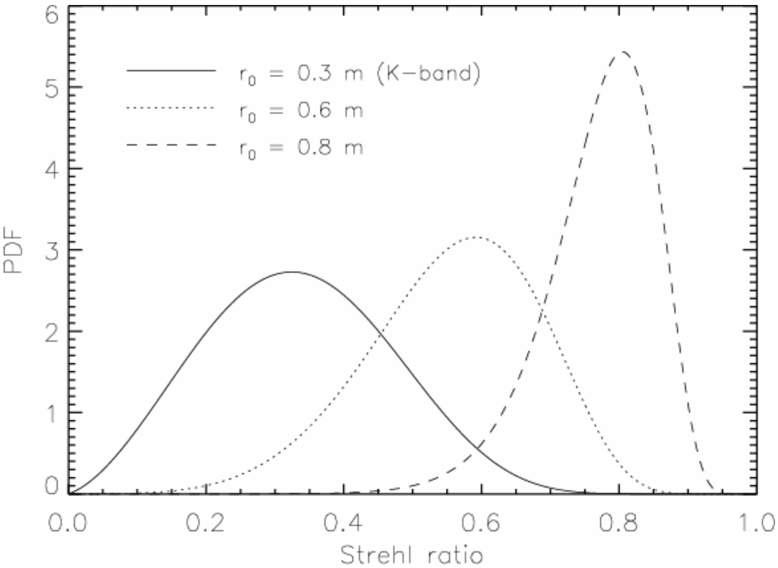


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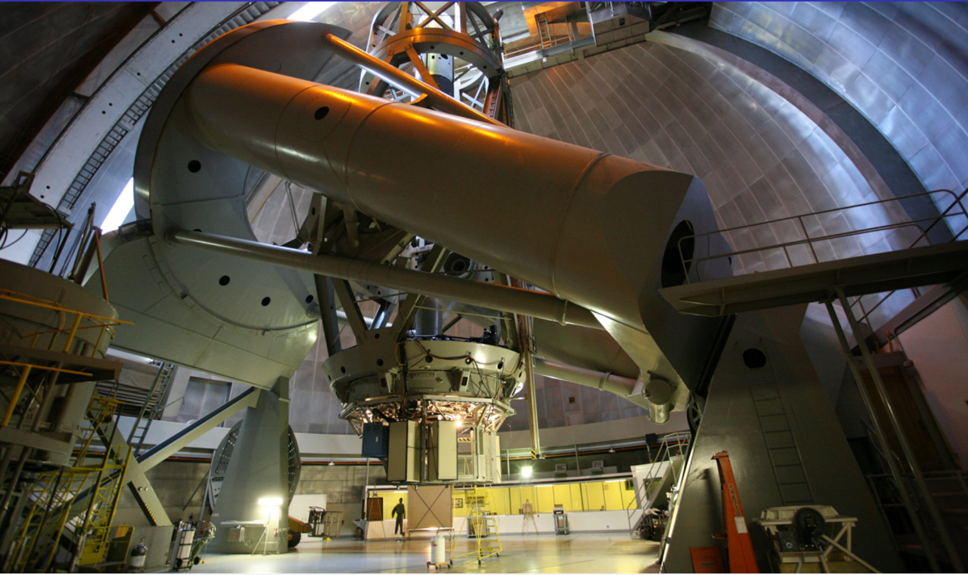
# Lucky at Mt. Palomar



*Law et al., 2009*

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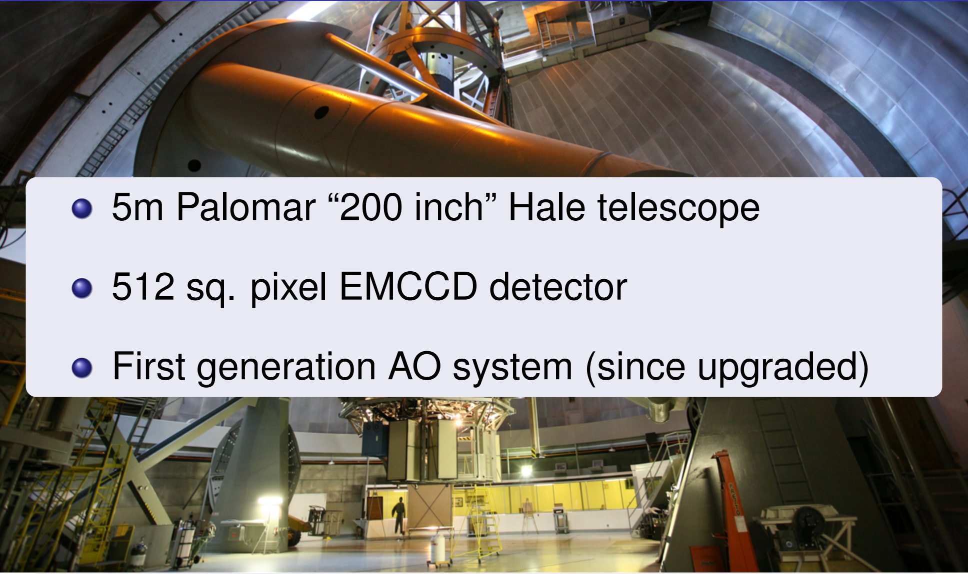
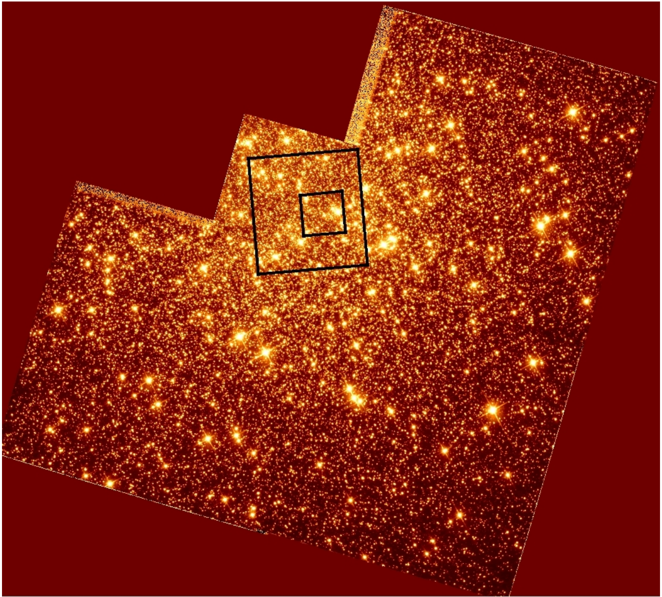


- 5m Palomar “200 inch” Hale telescope
- 512 sq. pixel EMCCD detector
- First generation AO system (since upgraded)

*Law et al., 2009*

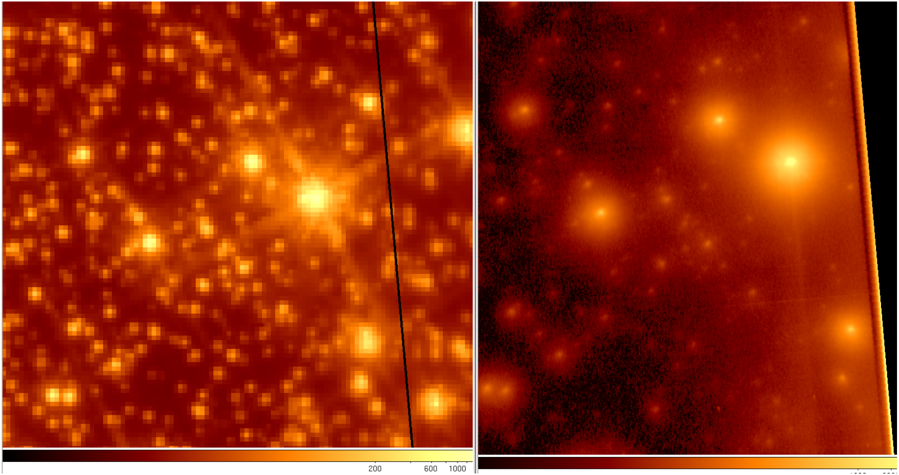
# Lucky at Mt. Palomar

Field of view:



# Lucky at Mt. Palomar

Comparison with HST:



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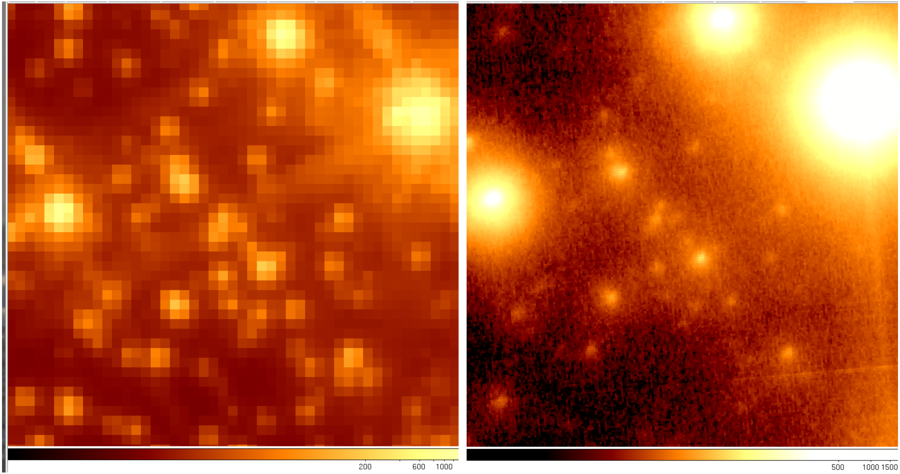

# Lucky + AO: Applications

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- Exoplanet direct imaging (See e.g Gladysz 2010)
- Resolving close stars (Kervella 2009)
- Cheap visible wavelength AO on 4m class telescopes
- Expanding AO sky coverage

# Summary

- Standard lucky imaging can now go wide and faint
- This gives HST class capabilities at very low cost
- EMCCD's are pretty good and still improving
- AO astronomers should consider fast imaging to get the most from their systems