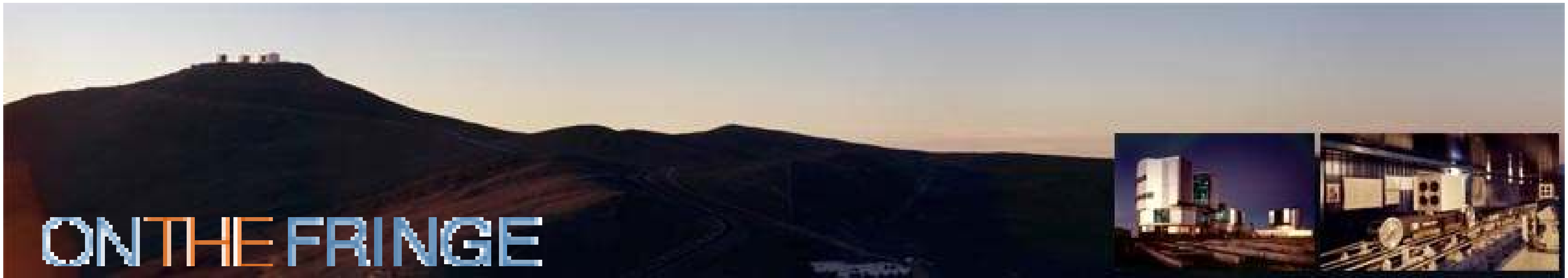


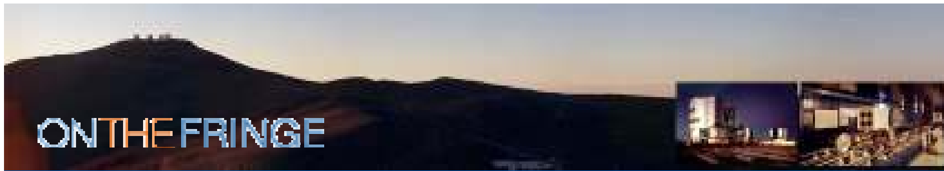
HST - AO - Coronography

Exoplanets and circumstellar disks: Past and future science

G. Duchêne (Obs. Grenoble)

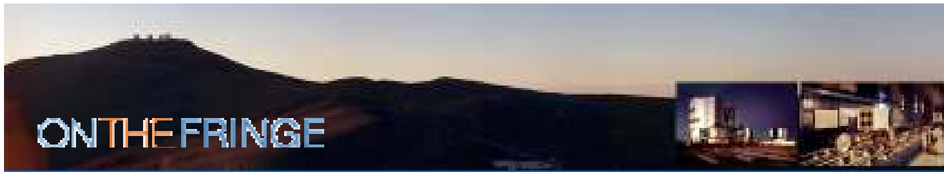
FOST

LAOG
Laboratoire d'AstrOphysique de Grenoble



Outline (2 classes)

- AO: why and how?
- AO: data processing
- Exoplanets: current observations
- Coronography: why and how?
- Disks: interpreting images
- The big picture (interferometry, ELTs)



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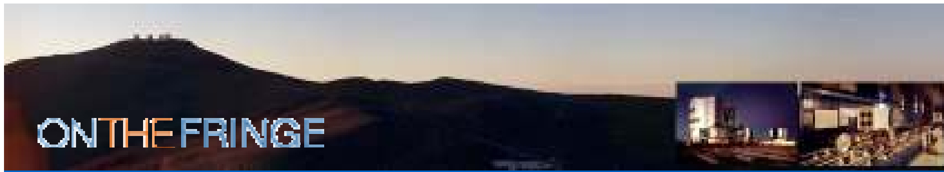
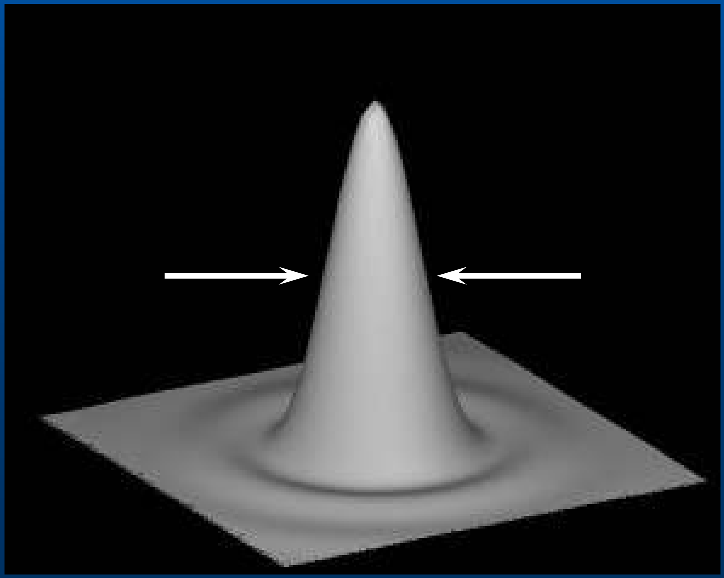


Adaptive Optics : Why and How?

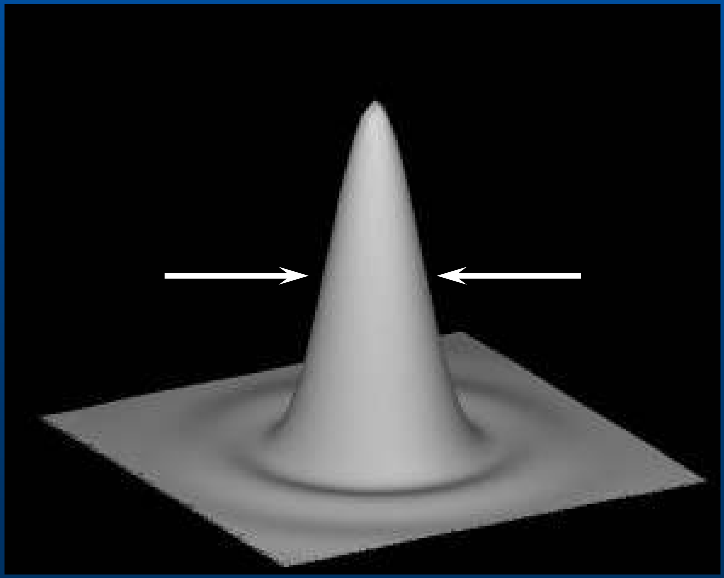
Observing with a telescope

- Back to basics: Fourier optics
  - *Telescope = circular pupil (usually)*
  - *Image of a point source = Airy function*



Observing with a telescope

- Back to basics: Fourier optics
  - *Telescope = circular pupil (usually)*
  - *Image of a point source = Airy function*
  - *Resolution: λ/D*
- Need for larger and larger telescopes!



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- Airy rings not seen in direct ground-based images

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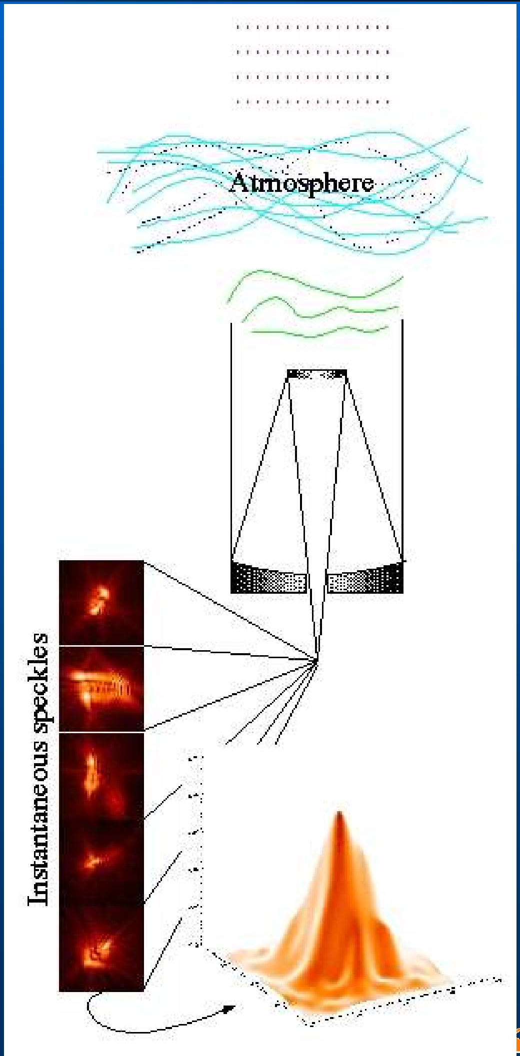
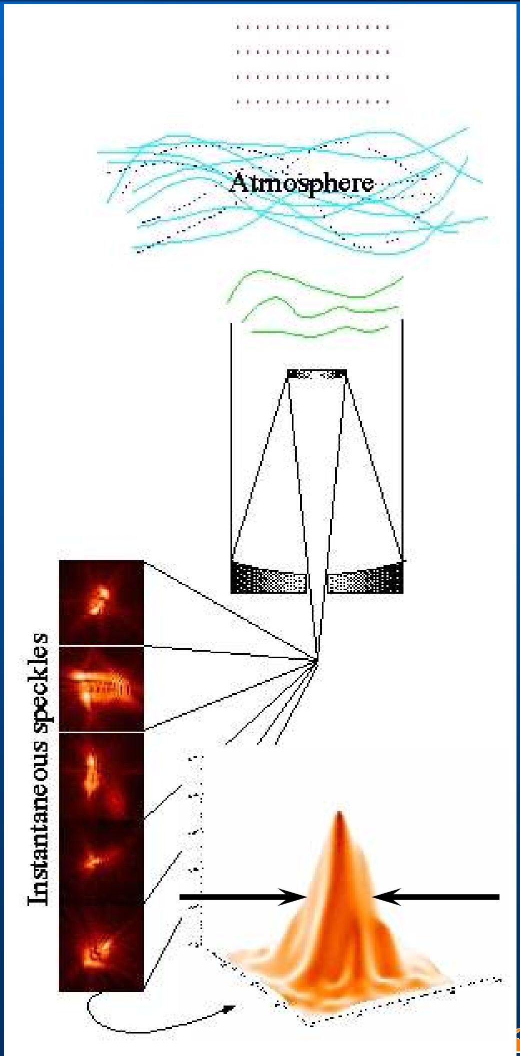
  - *Motion of air patches with different refractive index*



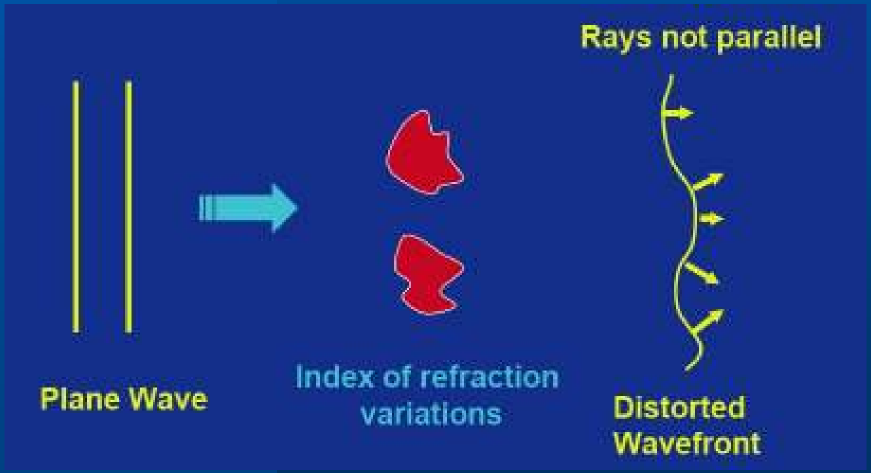
Why not in real images?

- Airy rings not seen in direct ground-based images
- Atmospheric turbulence!
  - *Motion of air patches with different refractive index*
- Seeing = time-averaged image of a point source
  - *Voigt profile (Gauss+Lorentz)*



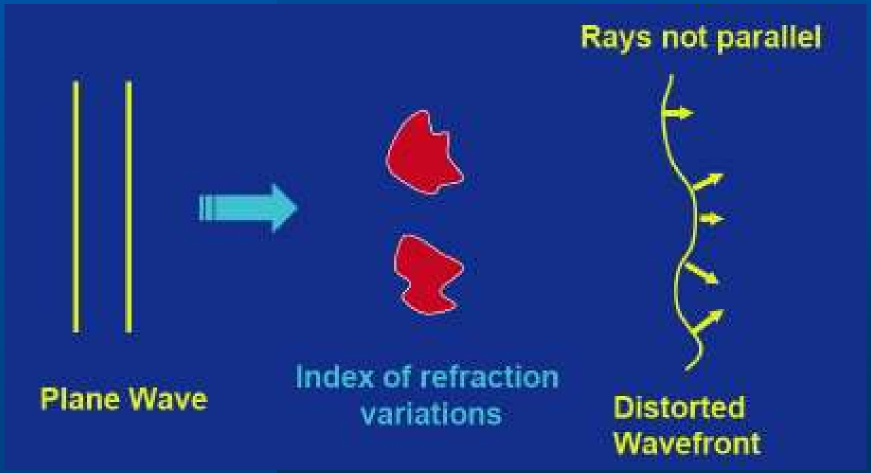
Atmosphere: a phase screen

- Refraction ⇒ distortion of incoming (planar) wavefront



Atmosphere: a phase screen

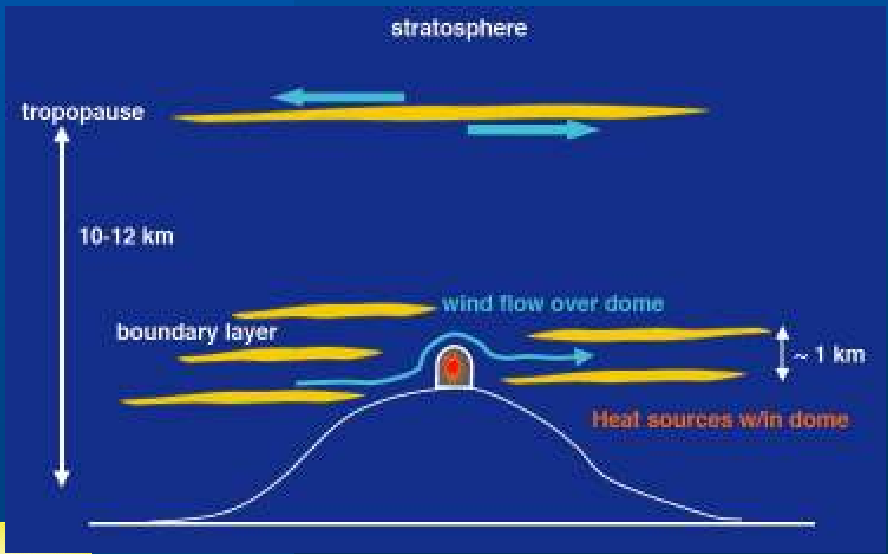
- Refraction ⇒ distortion of incoming (planar) wavefront
- Slope of wavefront ⇒ image shift



QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Atmospheric turbulence

- Strongly layered structure:
  - *Ground layer*
  - *A few km altitude*



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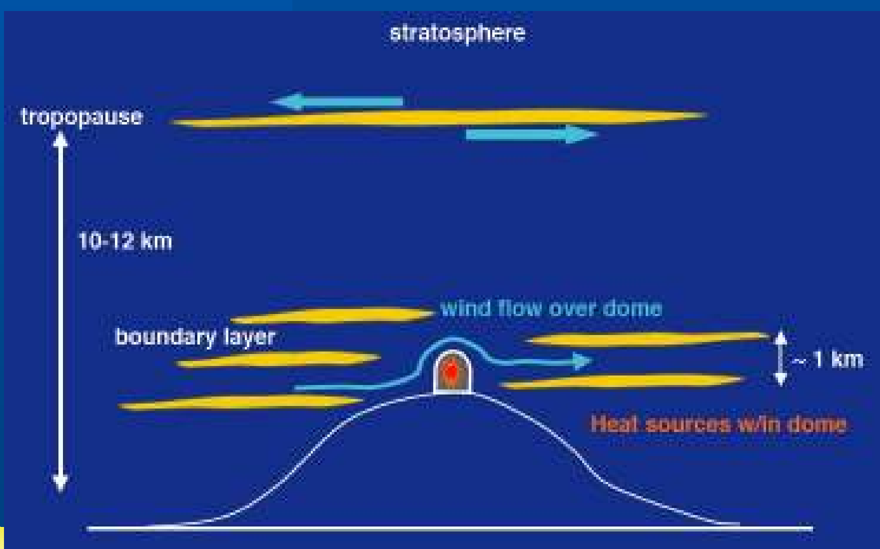
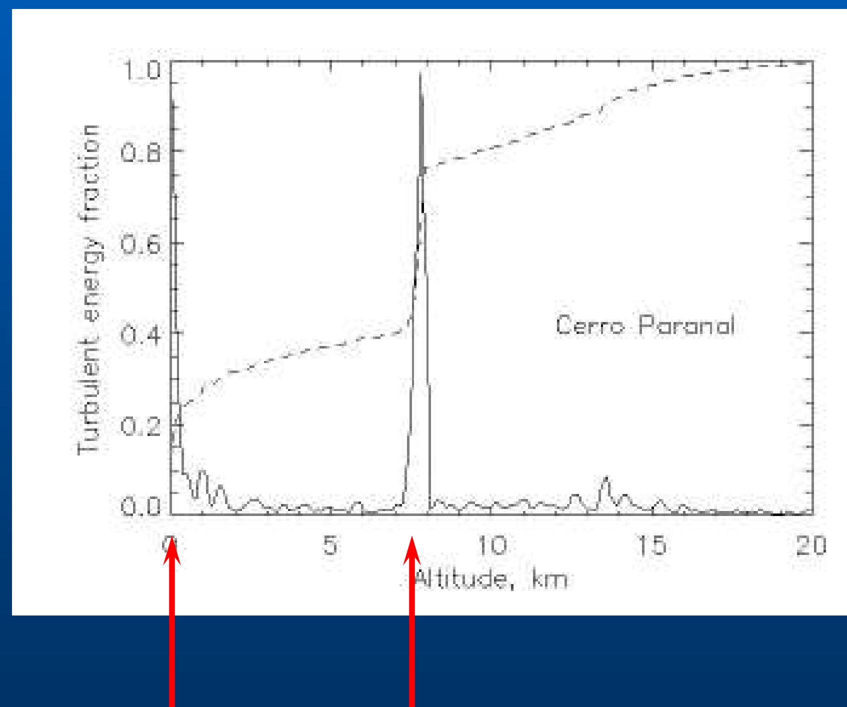
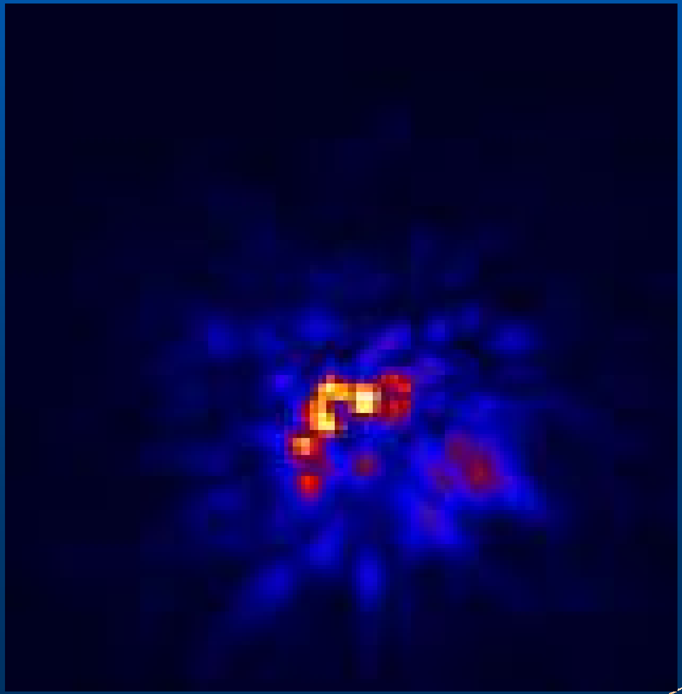




Atmospheric speckles

- A single short exposure (0.137s)
  - *Many diffraction-limited "speckles"*



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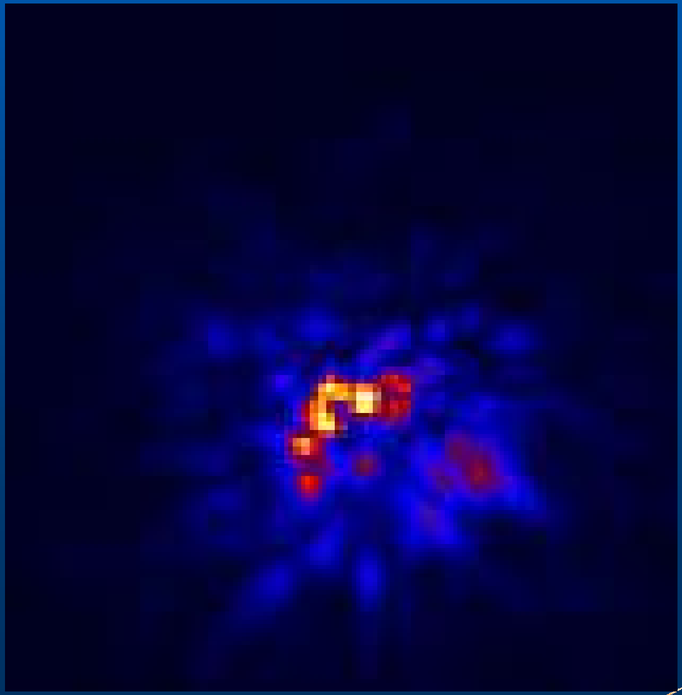
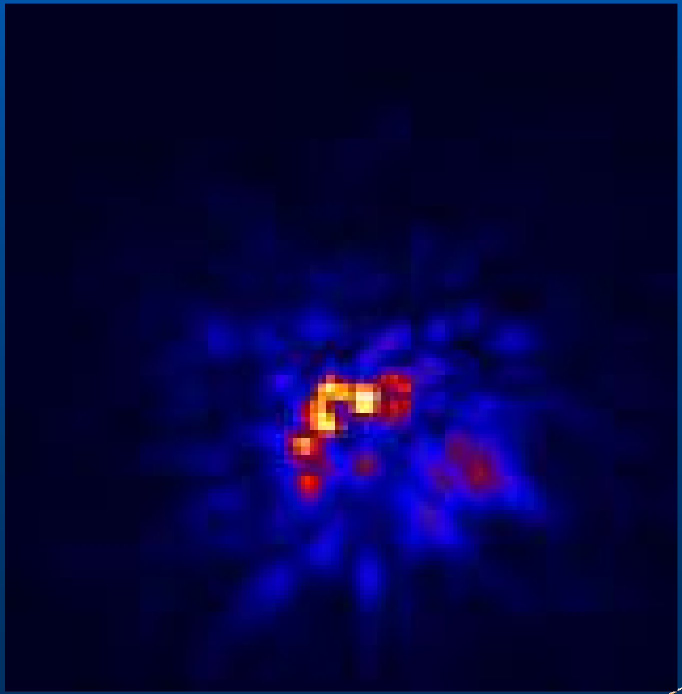
  - *Turbulence is very fast*



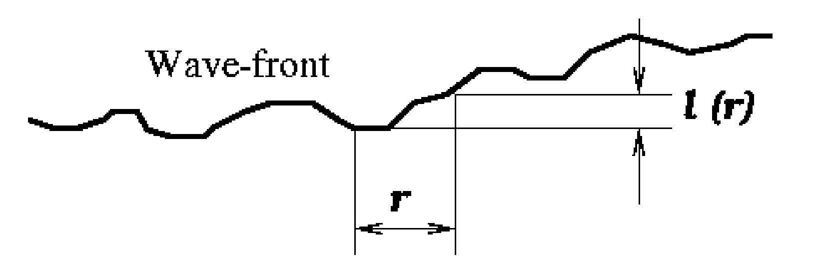
Atmospheric speckles

- A single short exposure (0.137s)
  - *Many diffraction-limited "speckles"*
- Lots of motion with time
  - *Turbulence is very fast*
- Average = seeing halo
- Obvious problem for interferometry!



Atmosphere: basic properties

- Some key parameters of turbulence:



Atmosphere: basic properties

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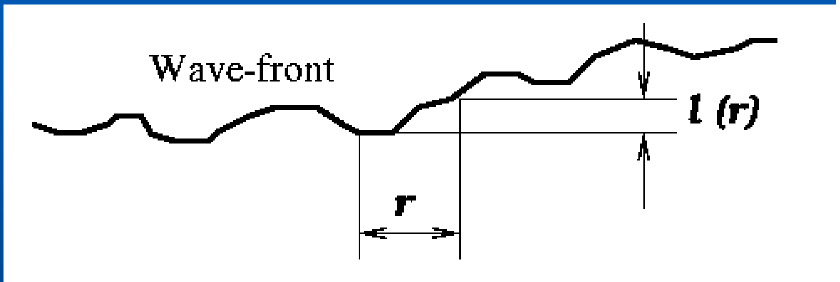
  - r_0 = *coherence length*



Atmosphere: basic properties

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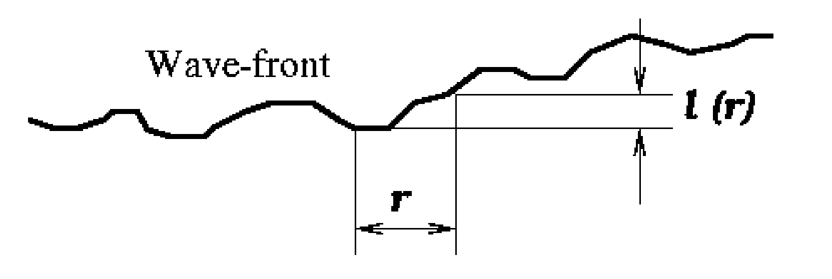

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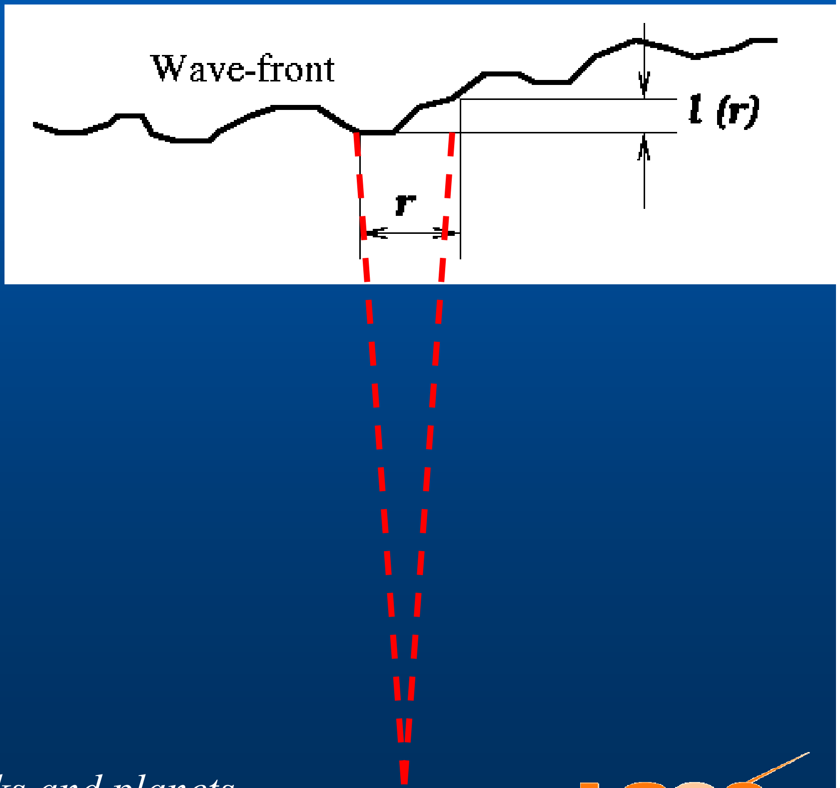
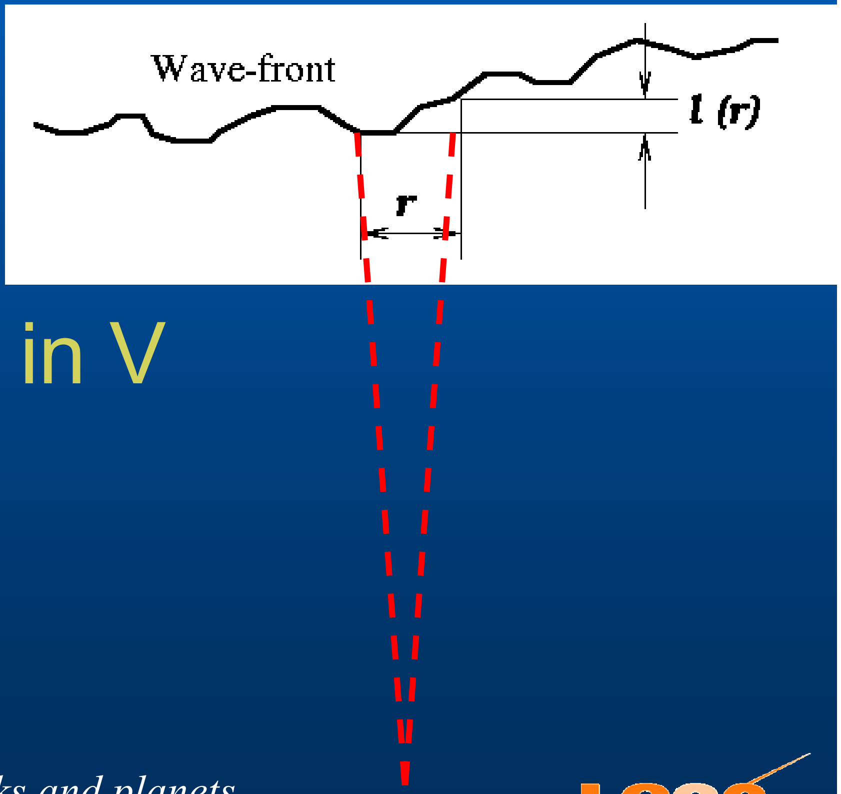


Atmosphere: basic properties

- Some key parameters of turbulence:
  - r_0 = *coherence length*
  - t_0 = *coherence time*
  - θ_0 = *anisoplatic angle*
- Typically r_0 = 10-20cm in V
  - t_0 = *few ms*
  - θ_0 = *few arcsec*



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- Strong dependence on wavelength:
  - $r_0 \propto \lambda^{6/5}$

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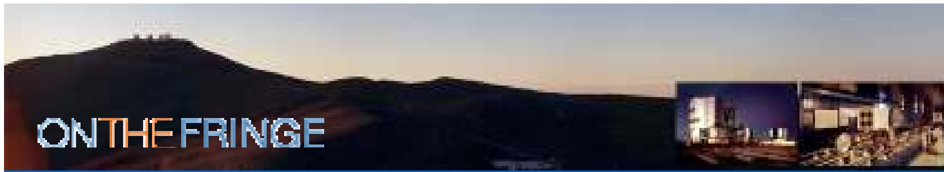

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  - r_0 = 15cm at 0.5 μm (~0.7" seeing)
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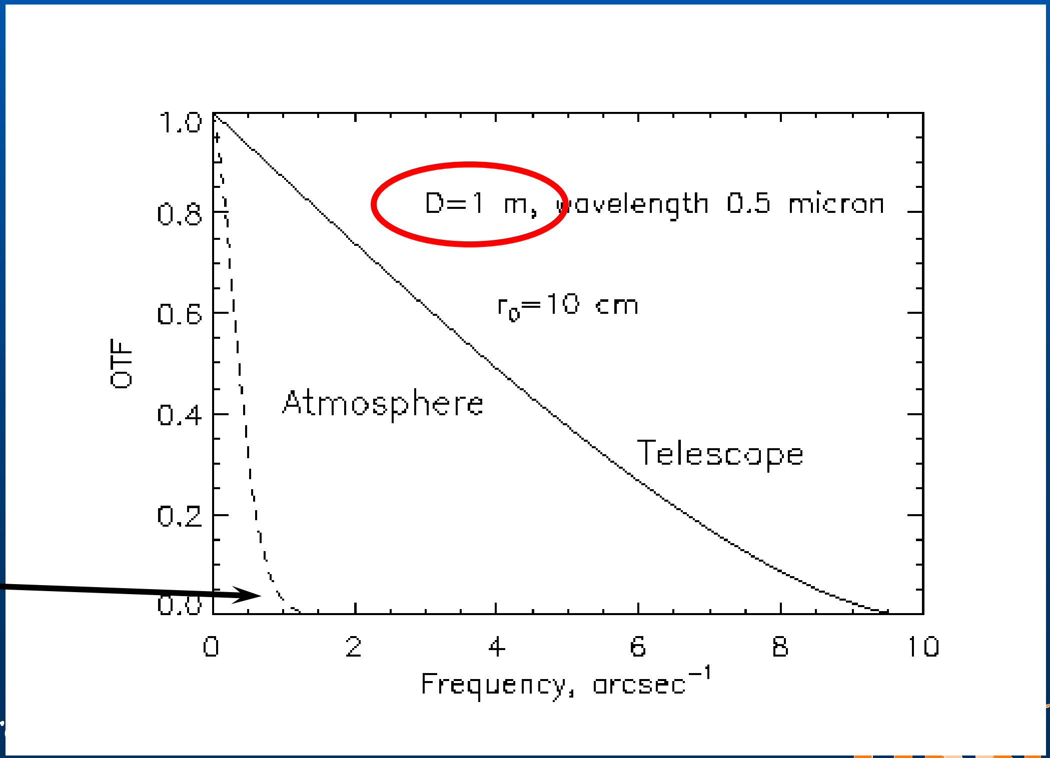
- Large telescopes are diffraction-limited in the mid-IR

Atmosphere: OTF

- In practice, atmosphere acts a low-pass filter in long integrations

Long integration



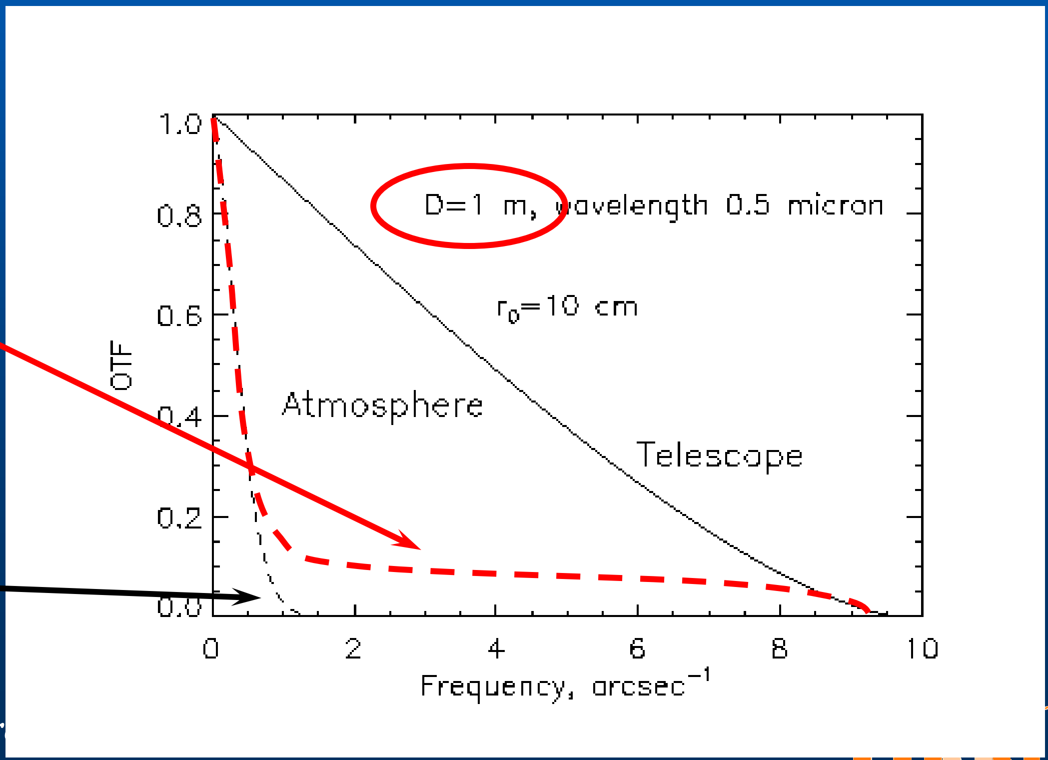
HST/AO/cor

Atmosphere: OTF

- In practice, atmosphere acts a low-pass filter in long integrations

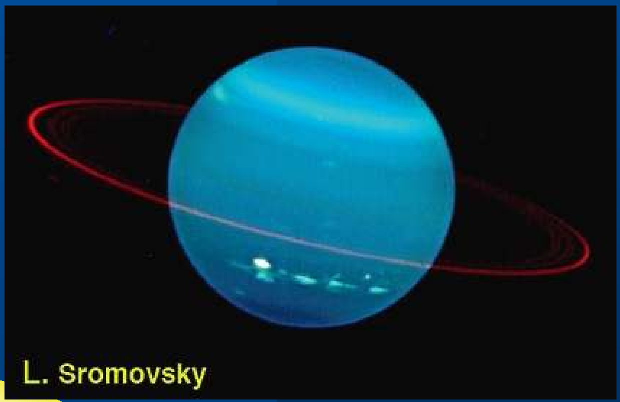
Short integration

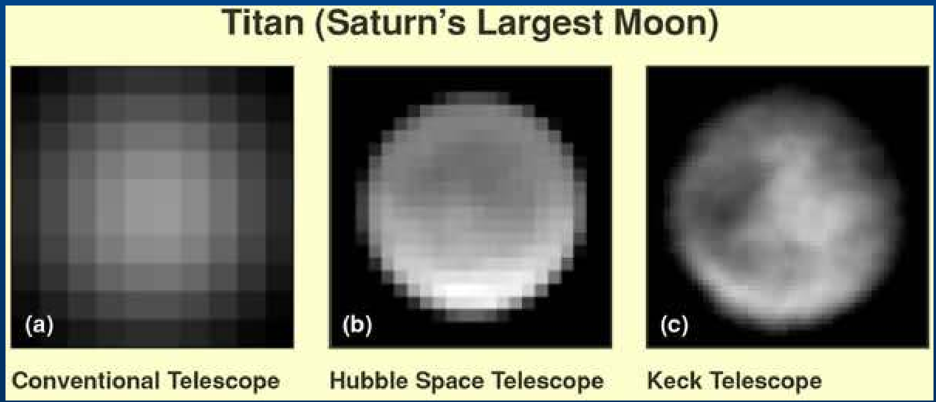
Long integration



Why do we care?

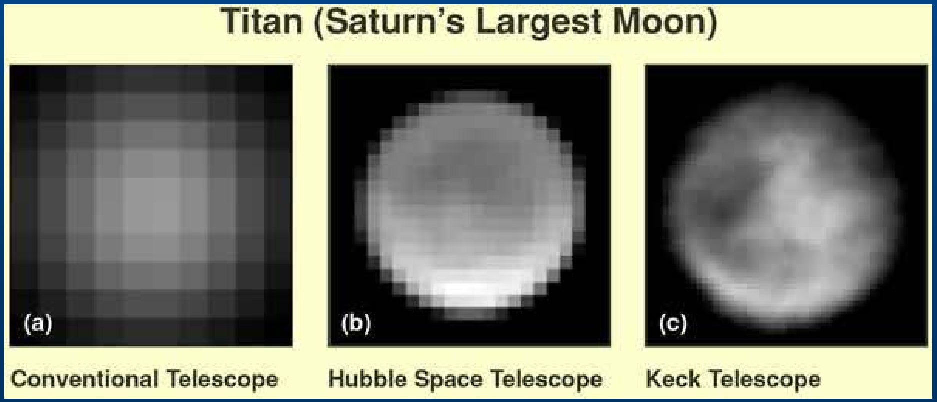
- Examples of seeing-limited science:
  - *From Solar System to distant galaxies!*





Why do we care?

- Examples of seeing-limited science:
  - *From Solar System to distant galaxies!*
- Most disks are 1'' across
  - *Need to beat the atmosphere!*



So what do we do?

- Place telescope above atmosphere
  - *Hubble Space Telescope*

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- Do very fast imaging to freeze the atmospheric turbulence
  - *Speckle interferometry*
- Correcting the atmosphere turbulence
  - *Adaptive optics*

Space-based imaging

- Problem solved (!!)

Space-based imaging

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- Advantage:
  - *Long-term stability of instruments*

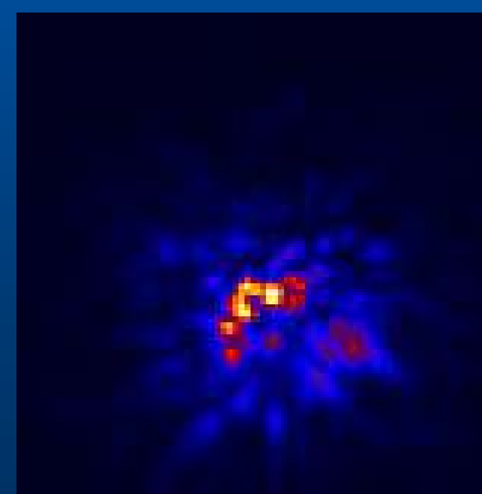
ONTHEFRINGE

Space-based imaging

- Problem solved (!!)
- Advantage:
  - *Long-term stability of instruments*
- Not necessarily the easiest thing to do:
  - *Very costly*
  - *'Small' telescopes (2.5m for HST)*
  - *Instrument not easily repairable (ACS ☹)*

Speckle interferometry: fake

- Need to obtain images very fast!
  - *Remember t_0 = few ms*



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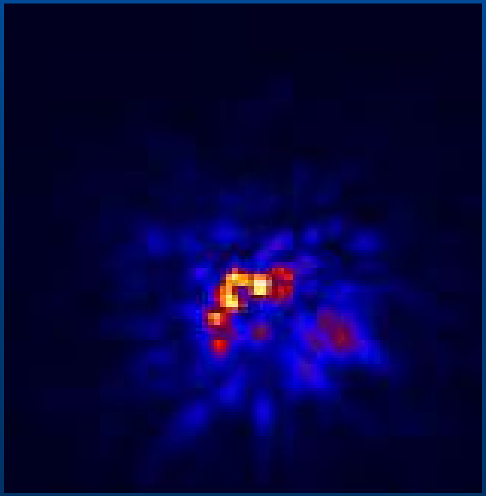
  - *Shift-and-add all frames*



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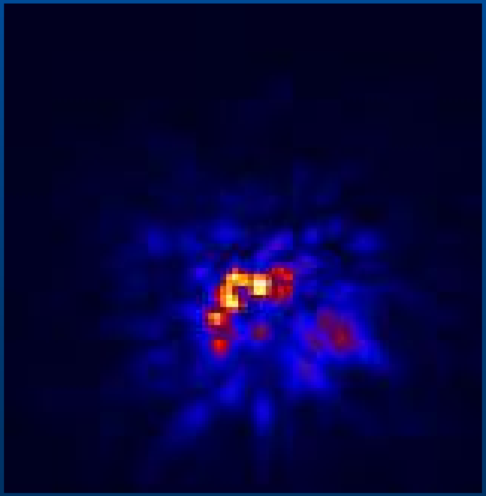
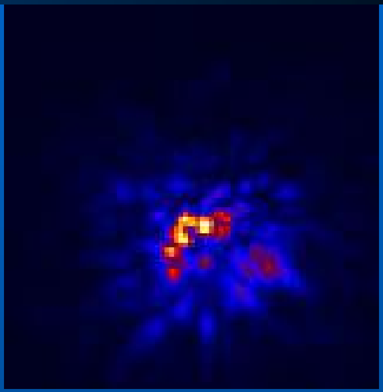
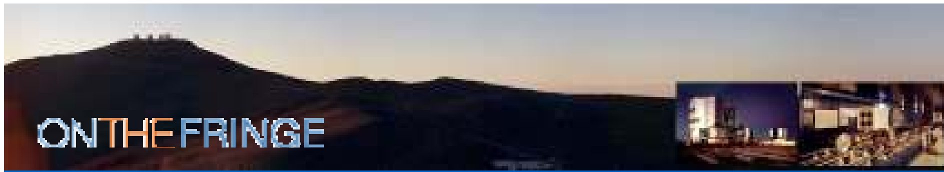
- Maintains diffraction limit!



Speckle interferometry: real

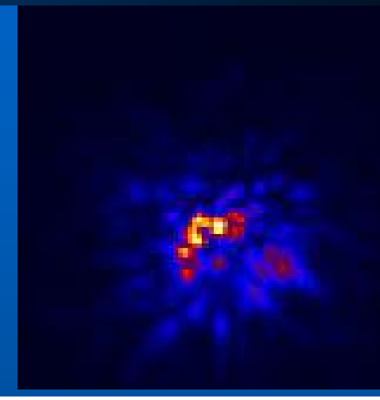
- Much better: Fourier Transform each frame and add all interferograms

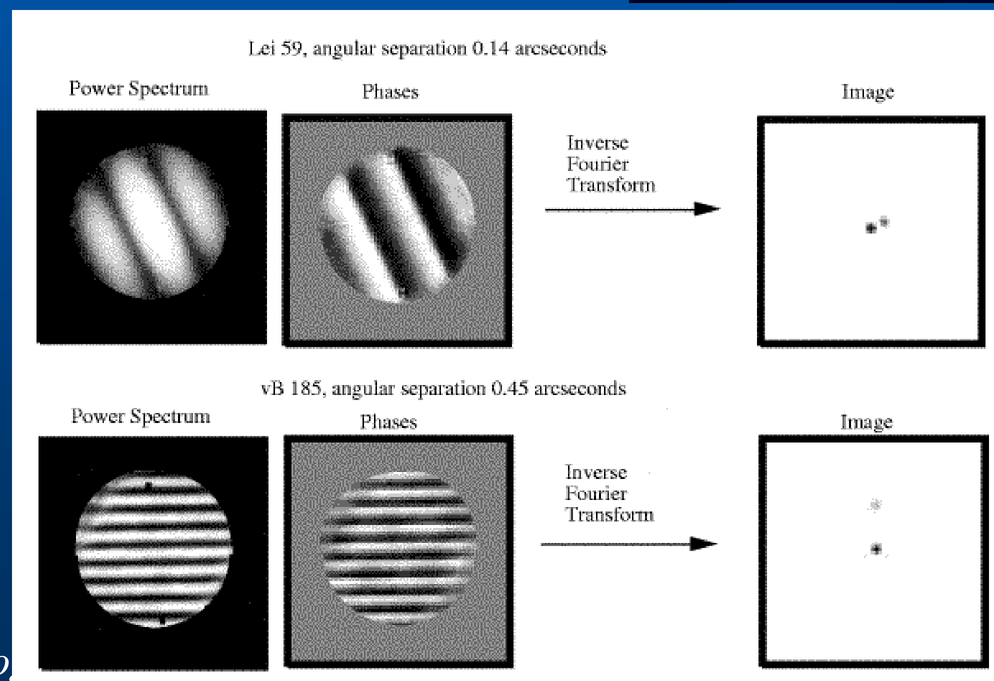




Speckle interferometry: real

- Much better: Fourier Transform each frame and add all interferograms
- Spatial shift ⇔ phase shift
  - *All speckles contribute!*



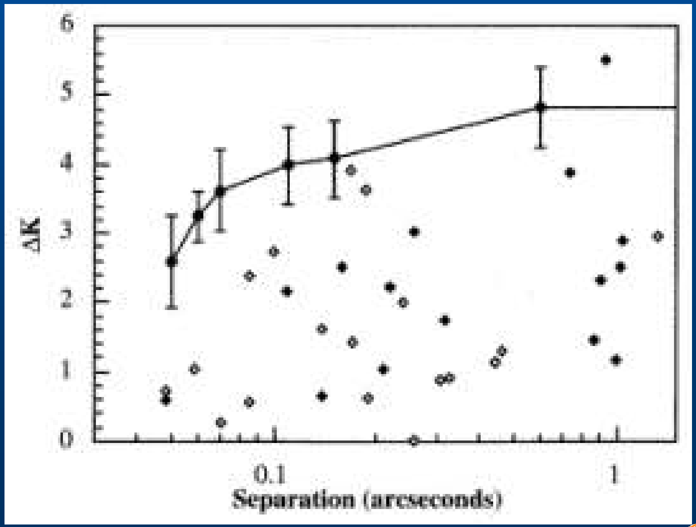


Speckle interferometry

- Advantages:
  - *Recovers highest spatial frequency*
  - *Can resolve down to λ/2D*

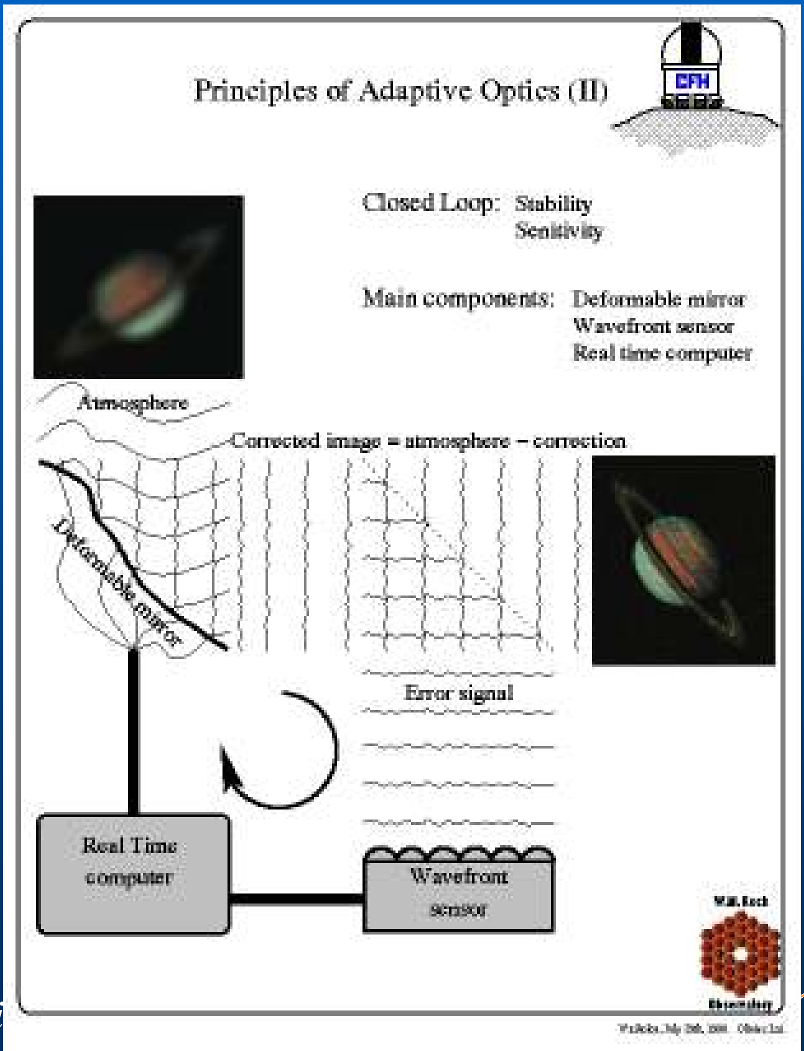
Speckle interferometry

- Advantages:
  - *Recovers highest spatial frequency*
  - *Can resolve down to λ/2D*
- Limitations:
  - *Low contrast (3-5 mag)*
  - *Very low efficiency*
    - *5' for 30s at Keck!!*



Adaptive optics: principles

- Real-time correction of turbulence!



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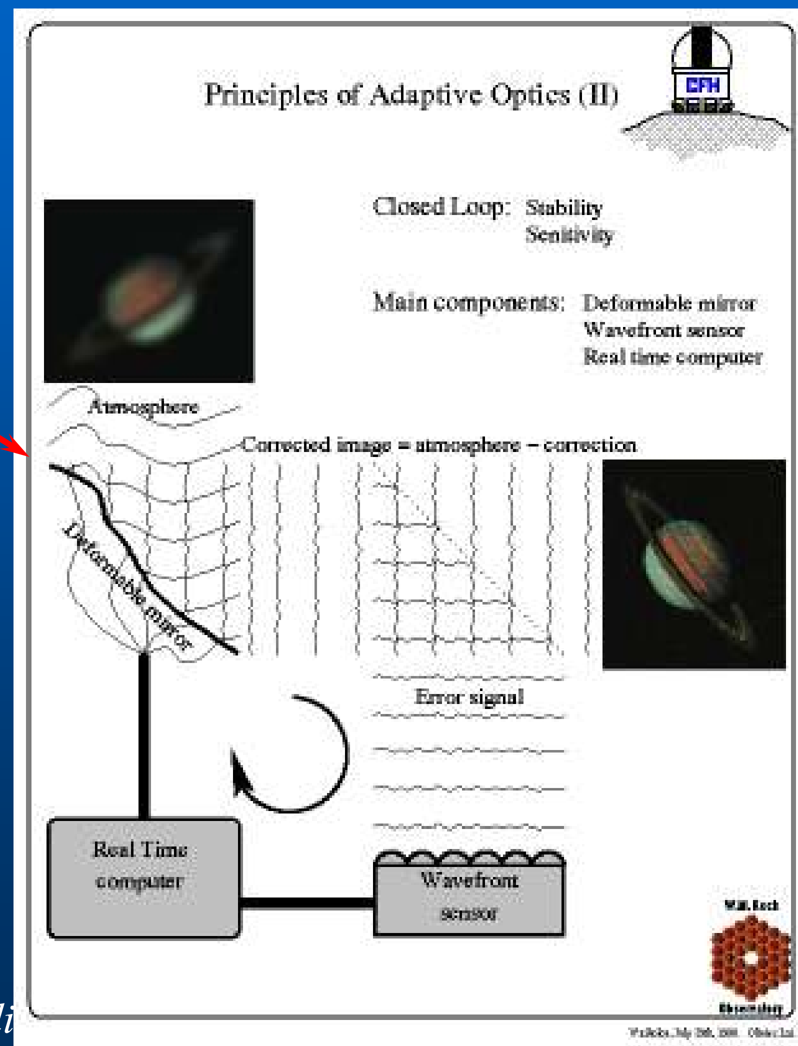

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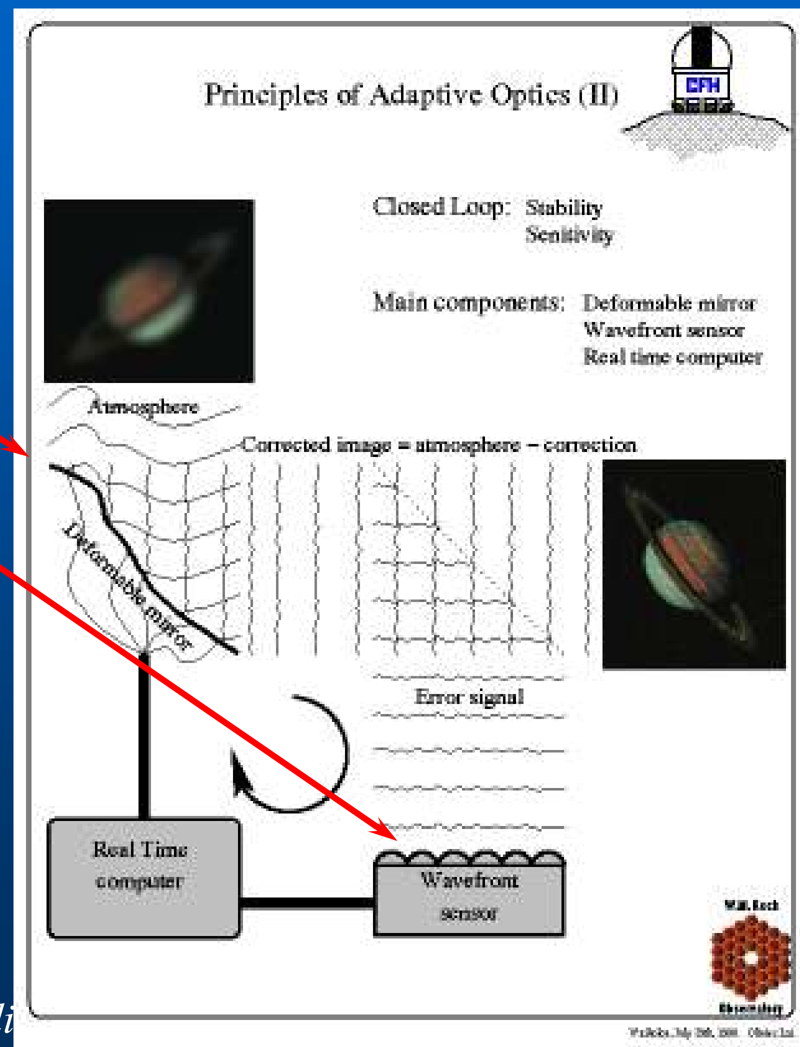

Adaptive optics: principles

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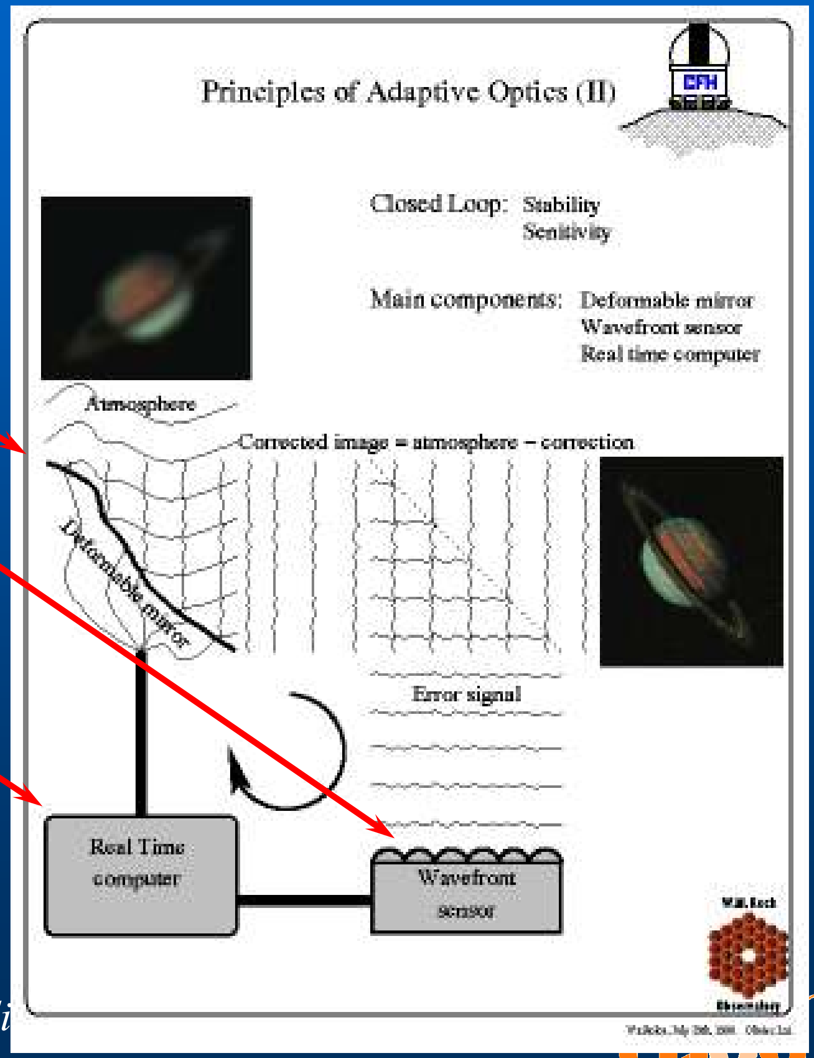
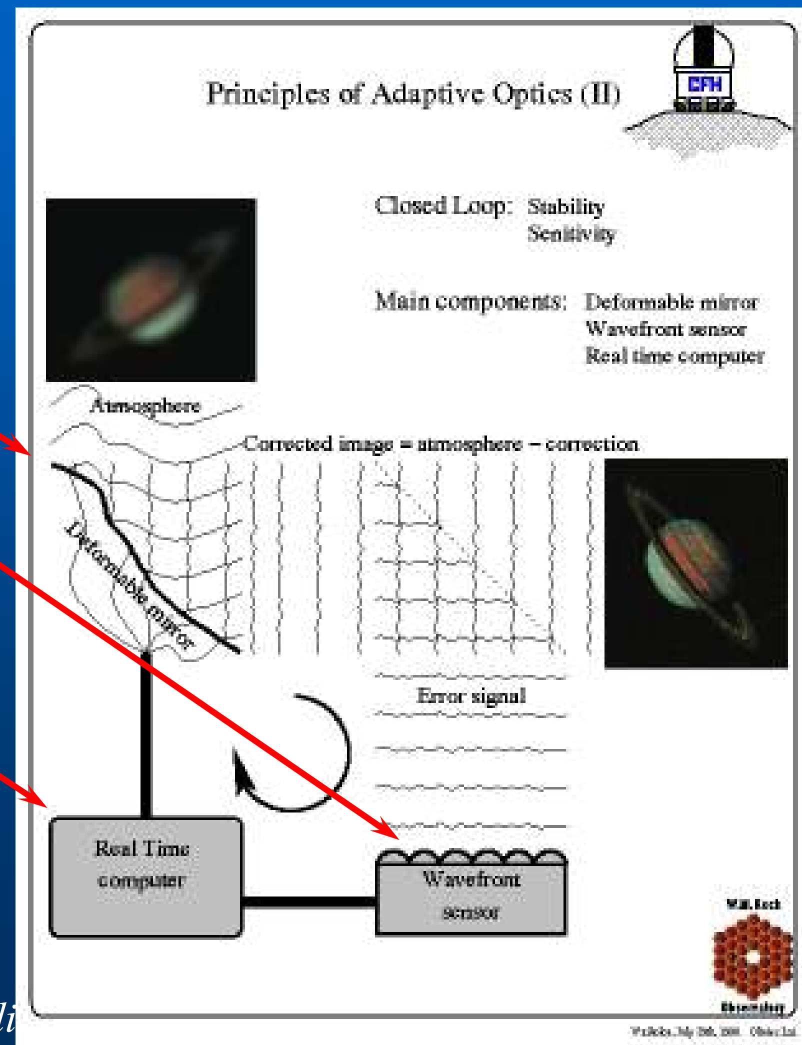
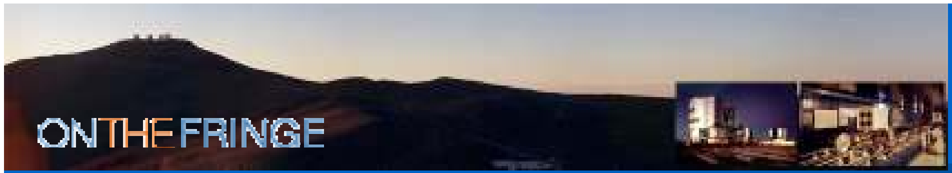
- Fast computer



Adaptive optics: principles

- Real-time correction of turbulence!
- Deformable mirror
- Wavefront sensor
- Fast computer
- Military: 1972!
- Astronomy: 1989…





Adaptive optics: principles

Incoming wavefront

Deformable mirror

Corrected wavefront

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Speckle cloud

Airy pattern!

Adaptive optics

- Advantages:
  - *Obtain long exposures!*
  - *Can be high quality at long wavelength*

Adaptive optics

- Advantages:
  - *Obtain long exposures!*
  - *Can be high quality at long wavelength*
- Limitations:
  - *Technical/computing challenges*
  - *Need a bright reference (guide) star*
  - *No (little) visible light correction*

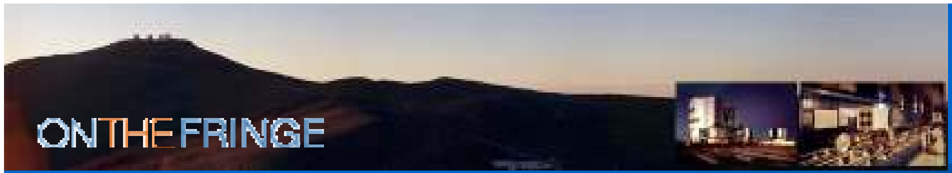
HST/AO/speckle interferometry

Visible wavelengths

High contrast images

Science goal

Highest spatial resolution



HST/AO/speckle interferometry

Visible wavelengths

Space Telescopes

High contrast images

Science goal

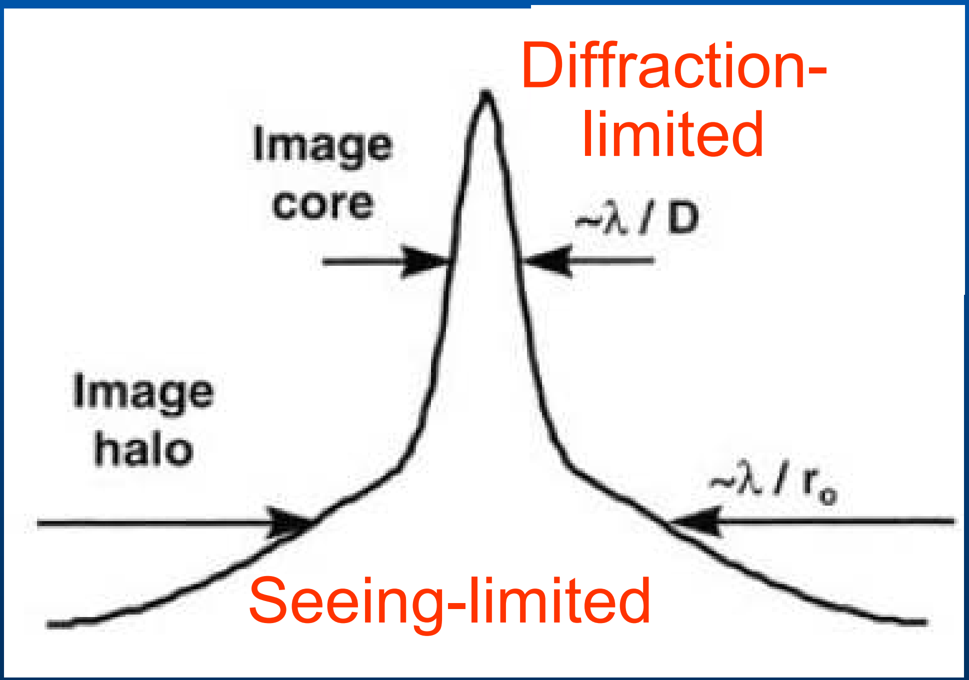
Ground-based Adaptive optics

Ground-based Speckle interferometry

Highest spatial resolution

Adaptive optics: quality

- Adaptive optics correction is always partial (limited bandwidth)
  - *Not as perfect as HST images*



Adaptive optics: quality

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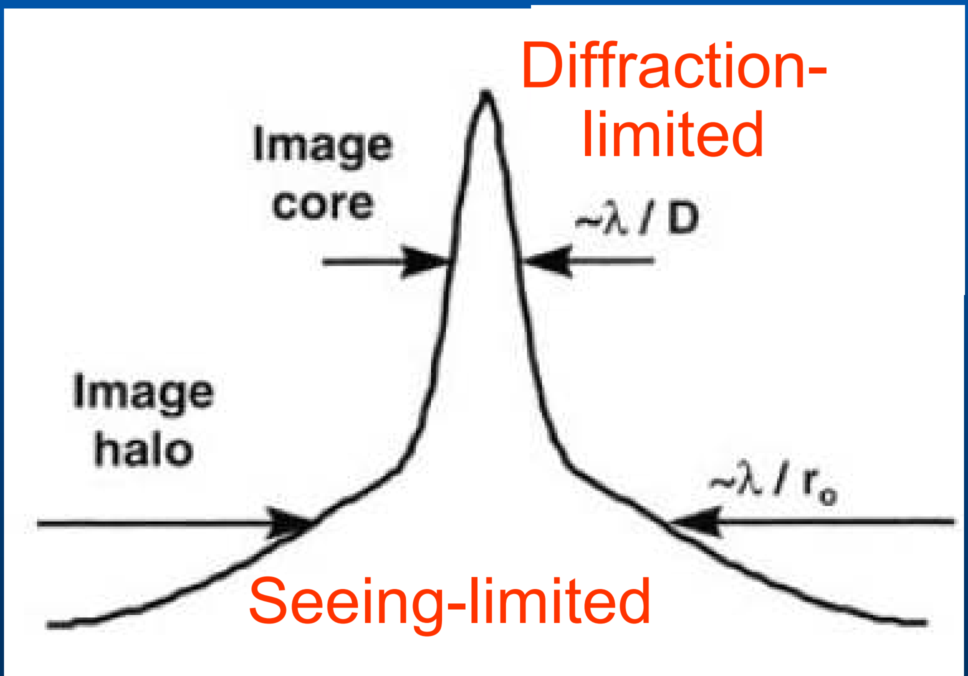
  - *Not as perfect as HST images*
- Problem for high contrast imaging



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- Measure of AO correction quality:
  - *Ratio of peak image to Airy peak of same total intensity*
  - *Strehl ratio*
    - *Range: 0-100%*

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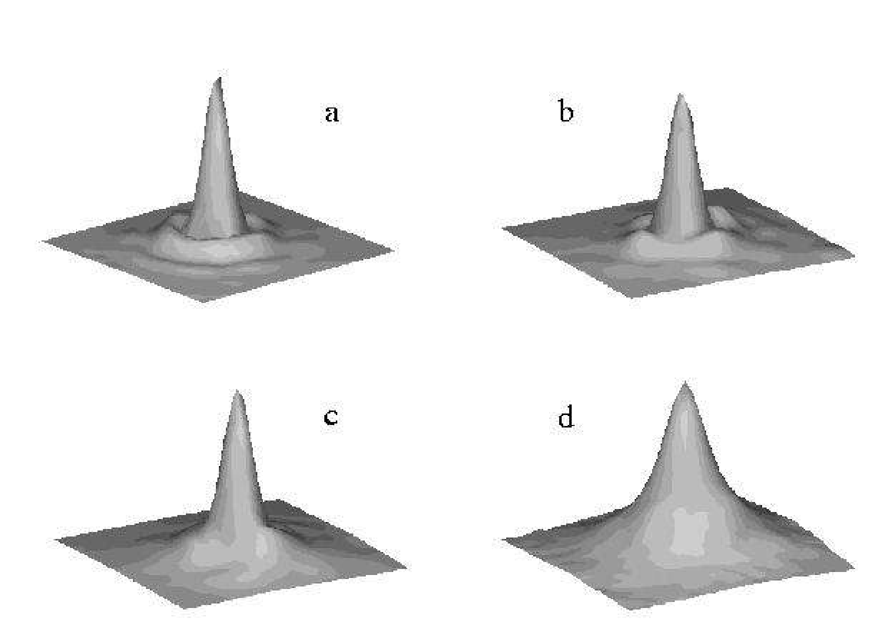
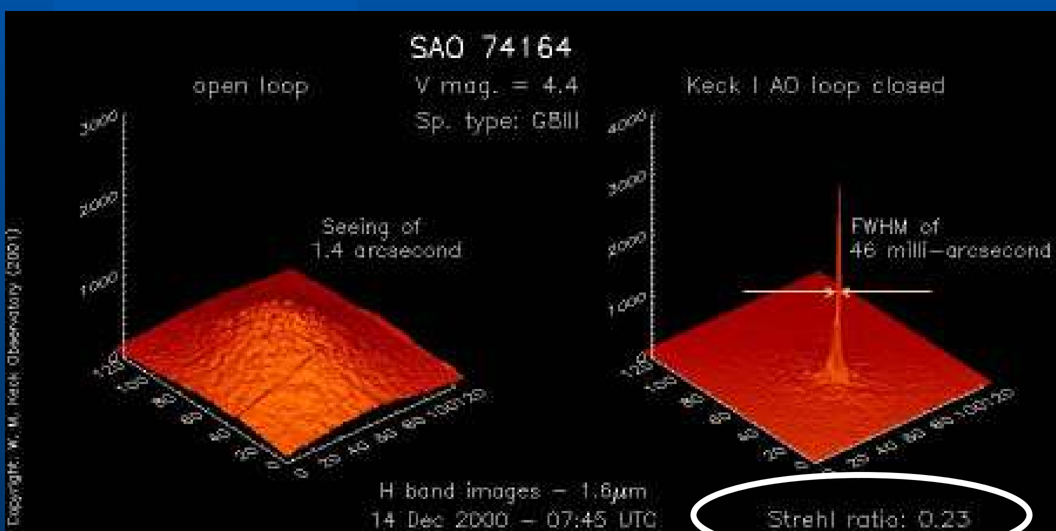
    - *Range: 0-100%*
- Images from ~10% to >50%

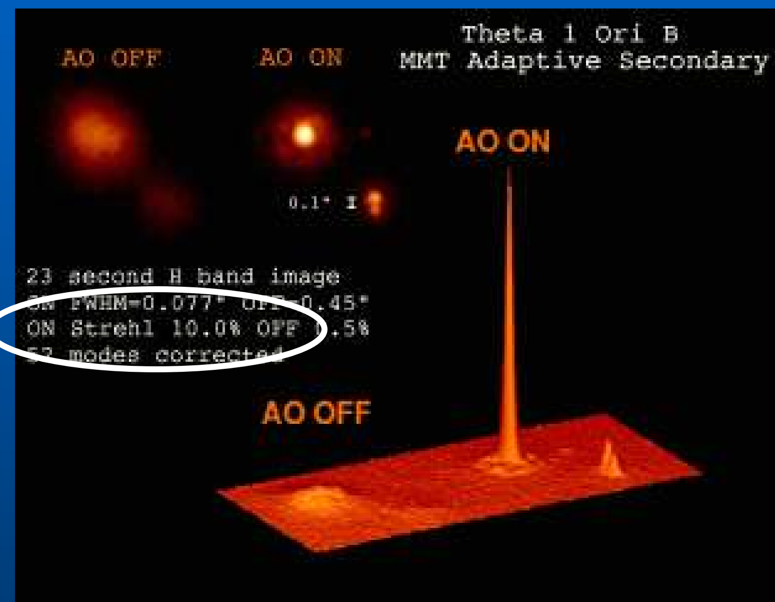


Adaptive optics: quality

- Strehl Ratio > ~10%

  ⇔ diffraction-limited





FOST

LAOG

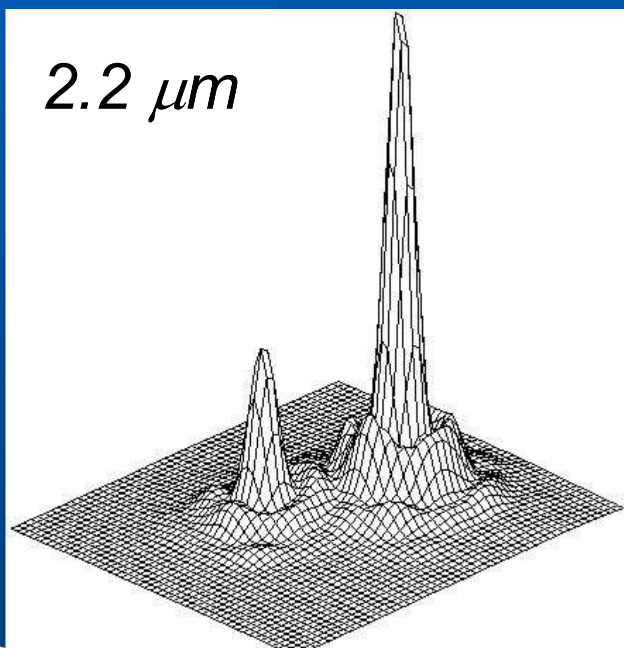
ON THE FRINGE

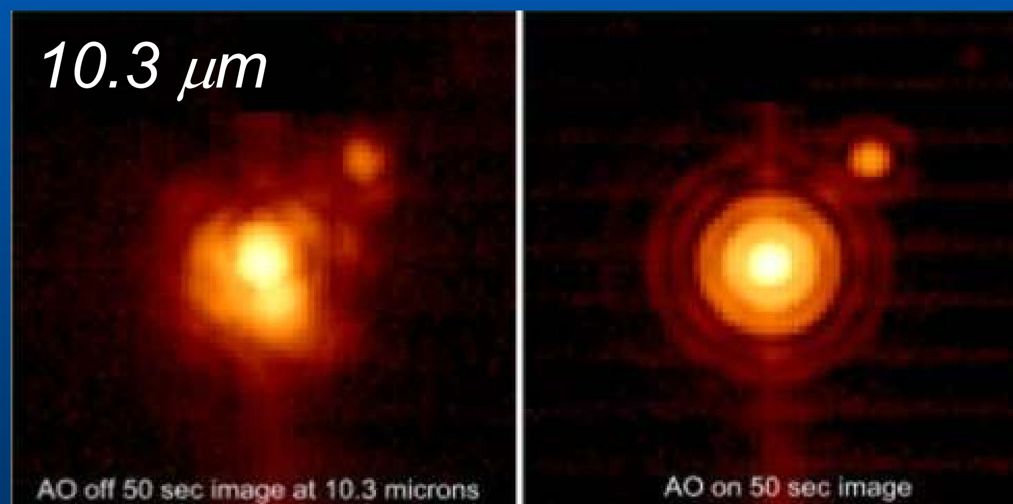
Adaptive optics: quality

- How good can it get?

Adaptive optics: quality

- How good can it get?
  - *SR~60% at 2 μm and up to 90-95% at 10 μm*





λ / r0 ~ λ / D in the MIR

Adaptive optics: anisoplatenism

- It is possible to guide off-axis
  - *AO correction depends on distance!*

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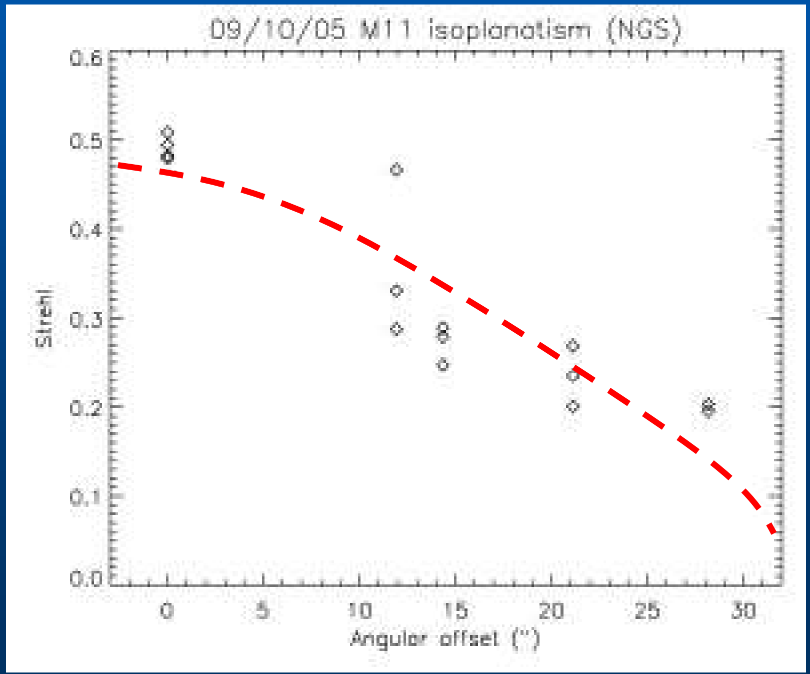
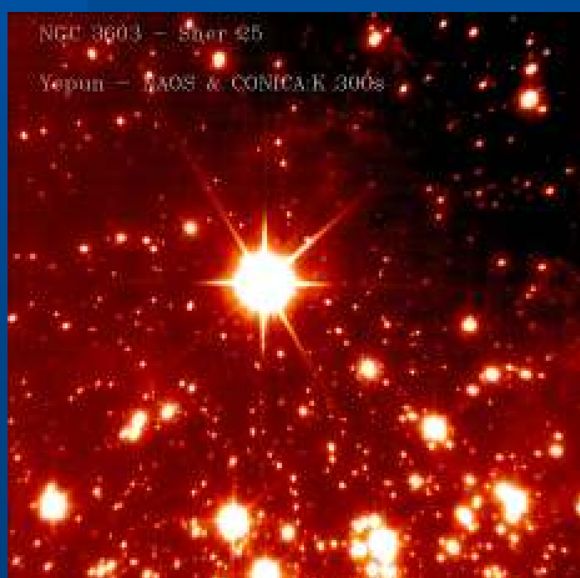
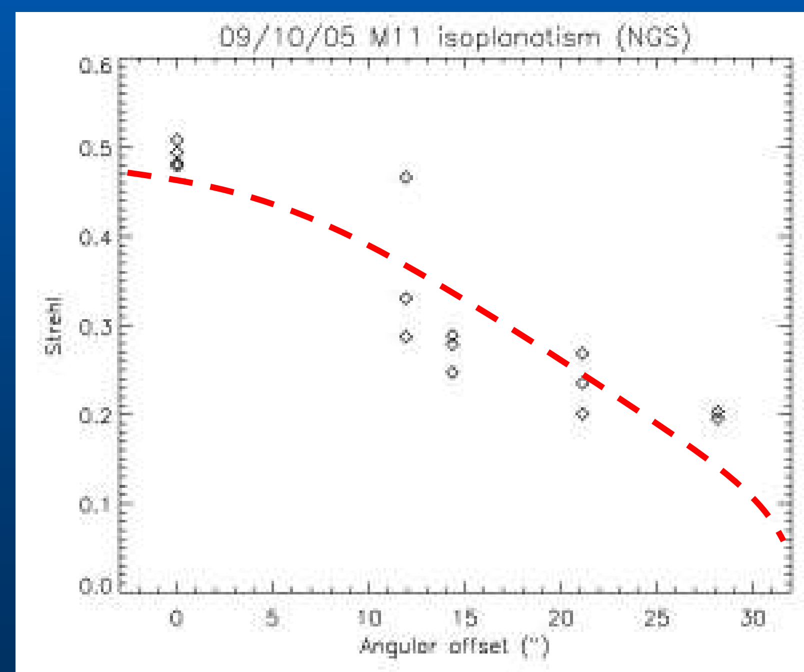


Adaptive optics: anisoplatenism

- It is possible to guide off-axis
  - *AO correction depends on distance!*
    - *Strehl ratio*
    - *Core shape*





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Adaptive optics: Zernike modes

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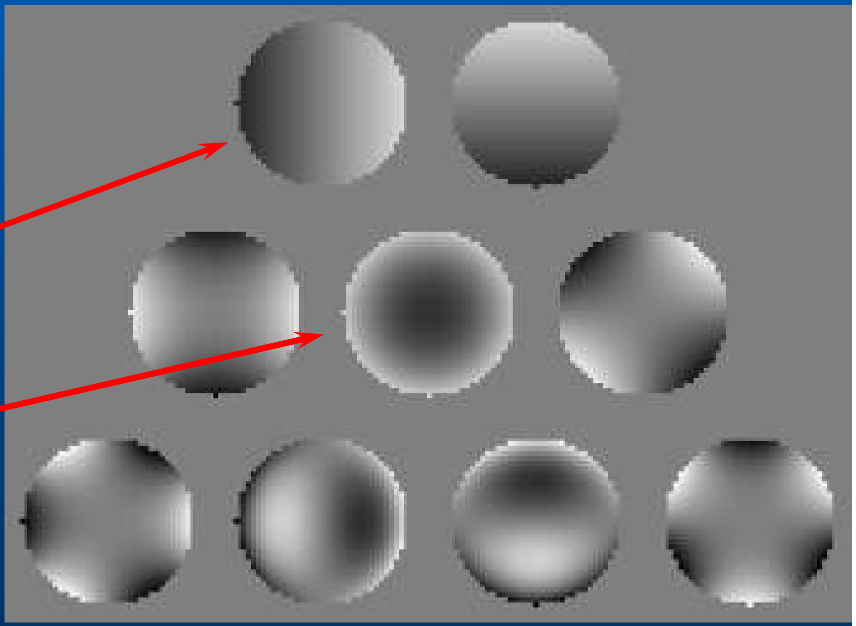
- In practice, measure WFS and determine shape to apply to DM
  - *Decomposition in independent "modes"*
- Zernike modes
  - *Tip-tilt*
  - *Defocus*
  - *etc…*



Adaptive optics: scaling

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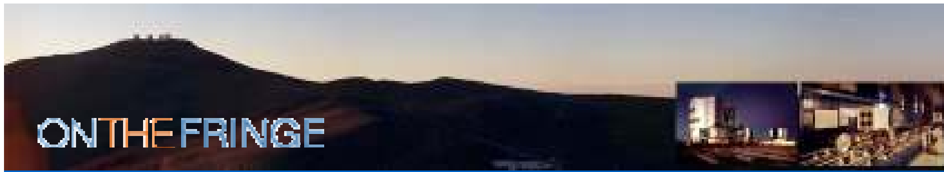

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  - *Roughly speaking: $N \sim (D/r0)^2$*
  - *With N actuators, can correct N modes*
    - *High-N allows high frequency correction*
- VERY difficult in optical!!
  - *Need thousands of (very fast) actuators*

Adaptive optics: scaling

- The chase is on worldwide for:
  - *Faster corrections*
  - *Higher N*

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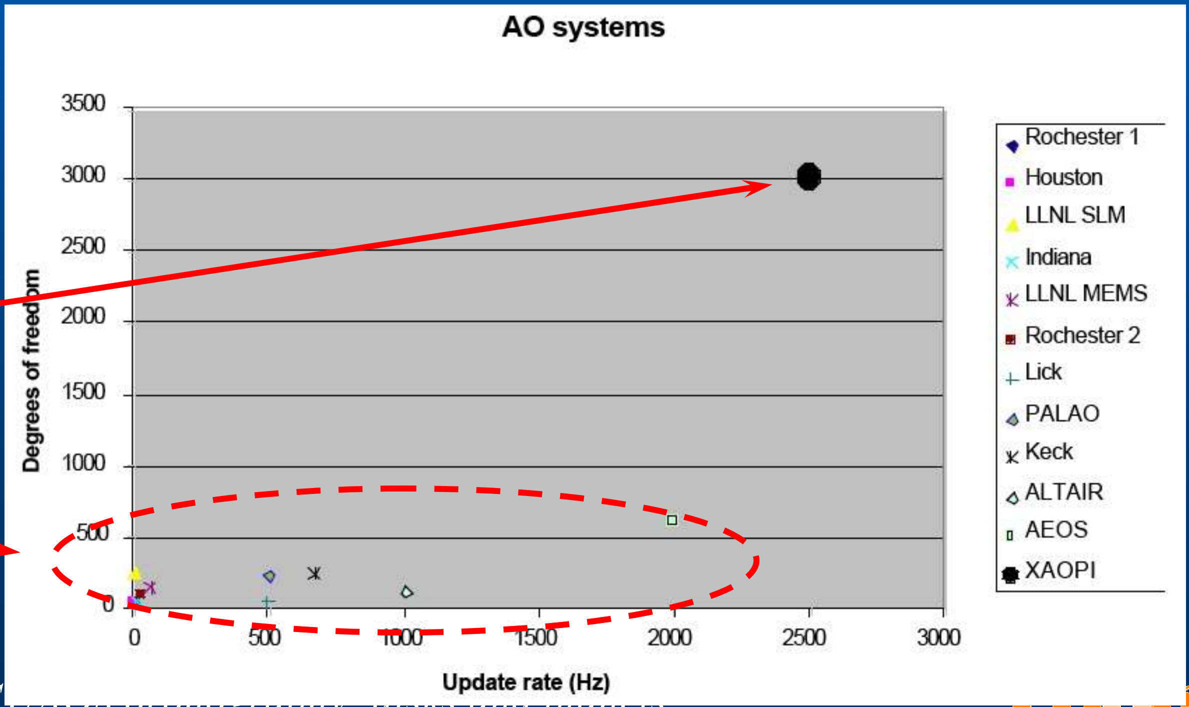
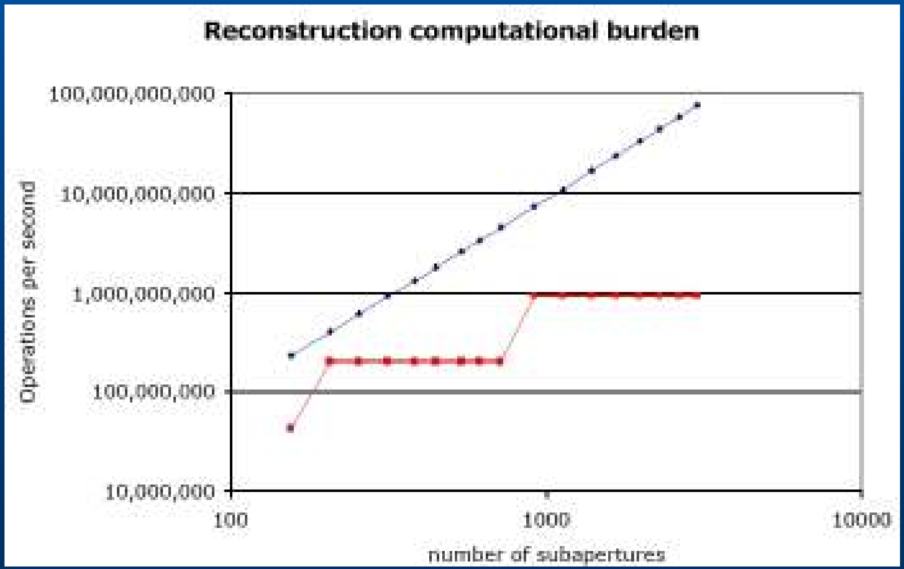
Next generation

Existing systems



Adaptive optics: scaling

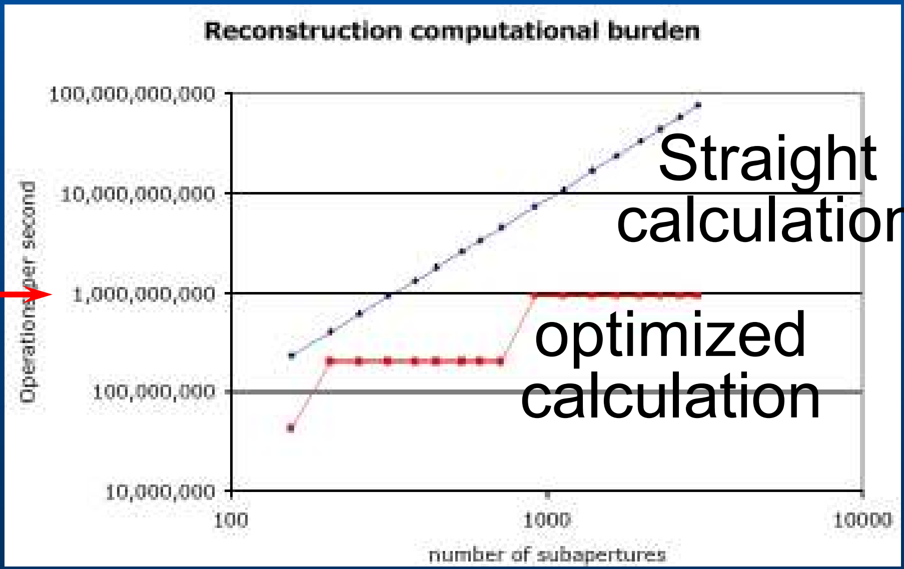
- More sensors/actuators and higher rate implies many more calculations!



Adaptive optics: scaling

- More sensors/actuators and higher rate implies many more calculations!
  - *Faster and faster real-time computers*
  - *Need for optimized methods!*

1 GFlop



WFS: Shack-Hartmann

- Wavefront slope ⇔ image displacement

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- Map the wavefront with series of lenslets
  - *Measure spatial displacement*
  - *Infer wavefront*
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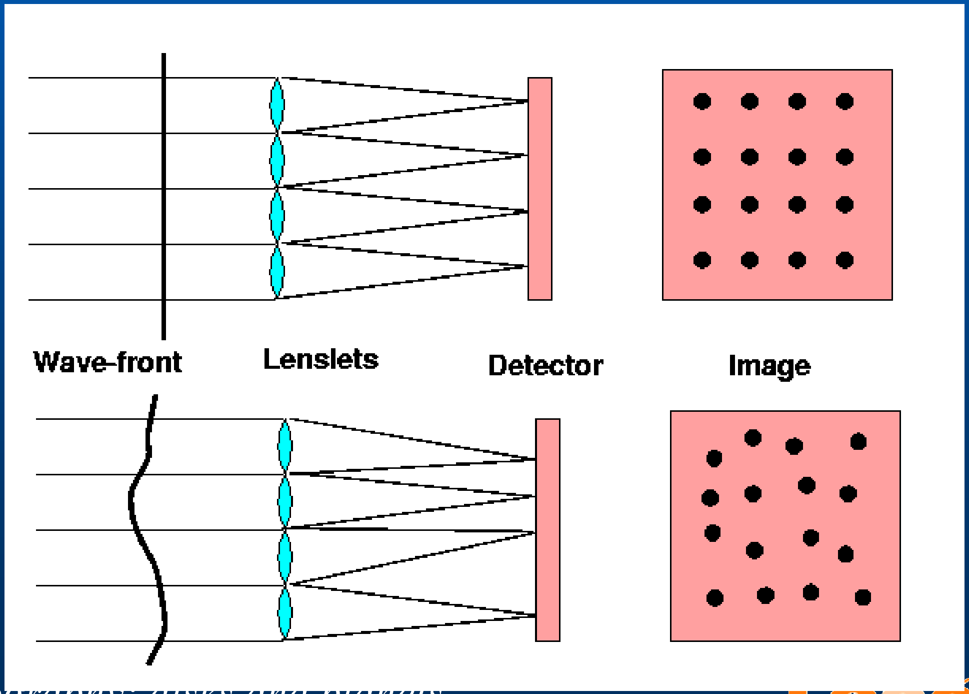

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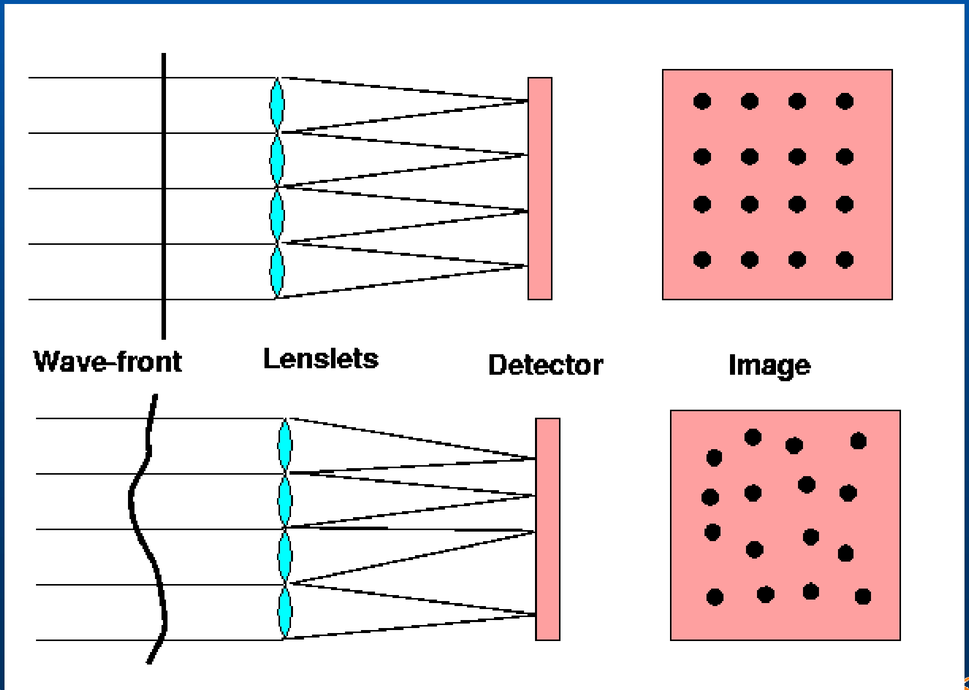
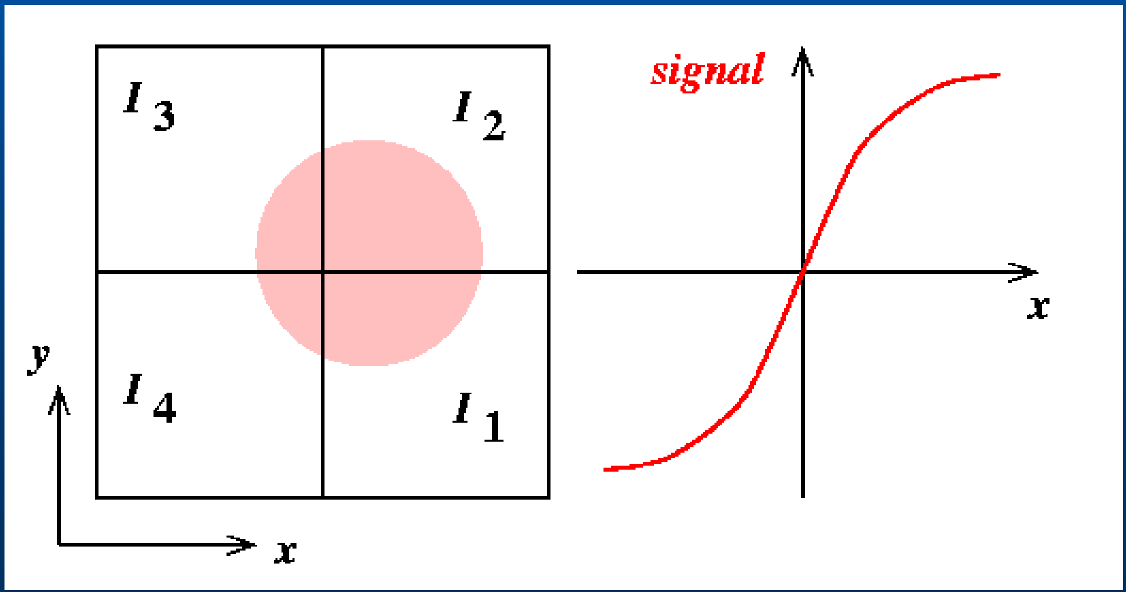


$N_{lenslet} < N_{actuators}$

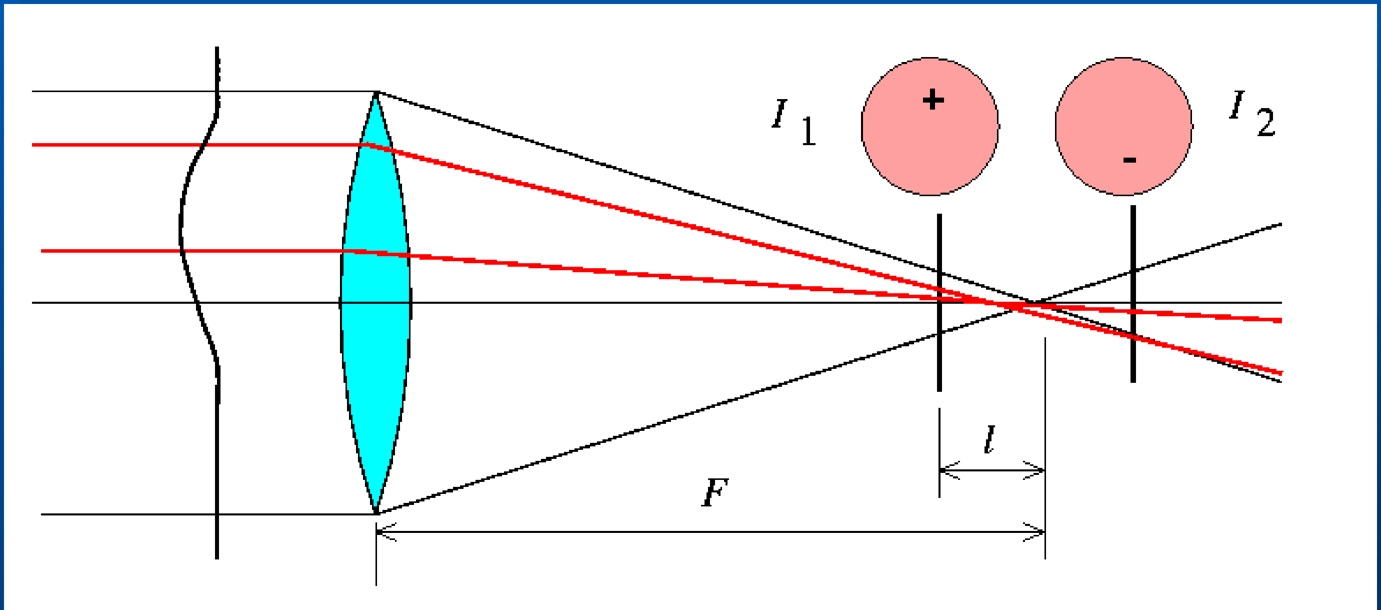
WFS: Shack-Hartmann

- Displacement measured on CCD
  - *4 pixels per lenslet*
  - *Linear combination of fluxes ⇒ offset*



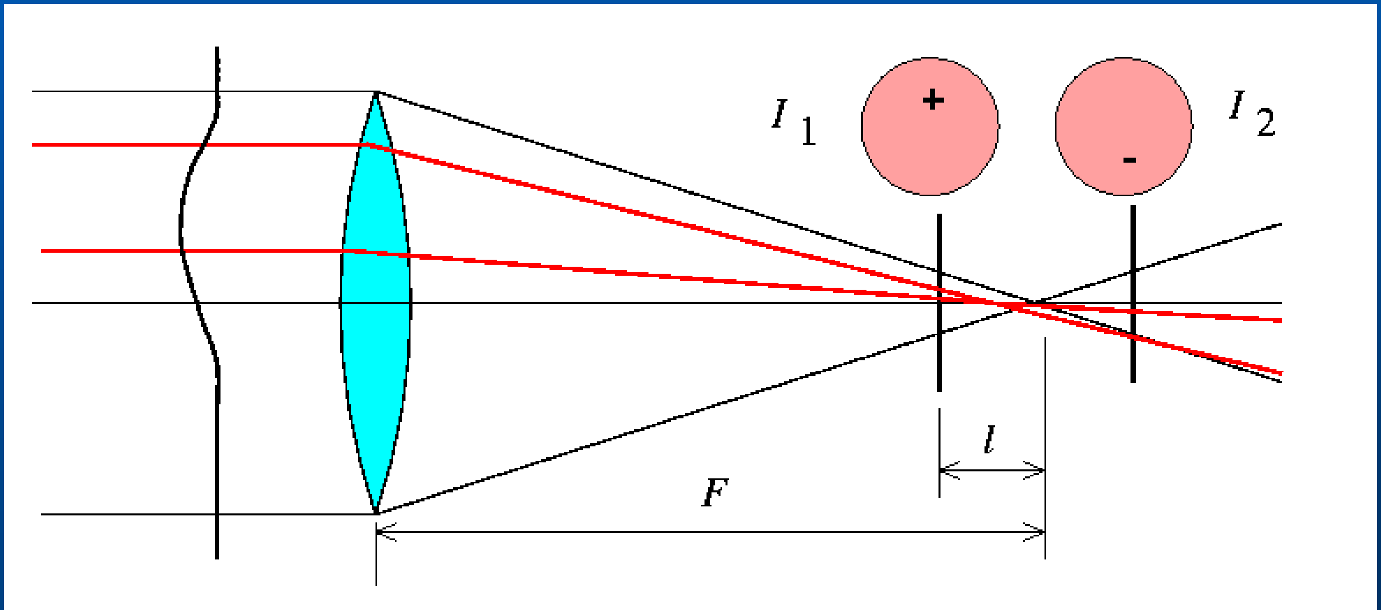
WFS: curvature

- Wavefront curvature ⇔ change of focus



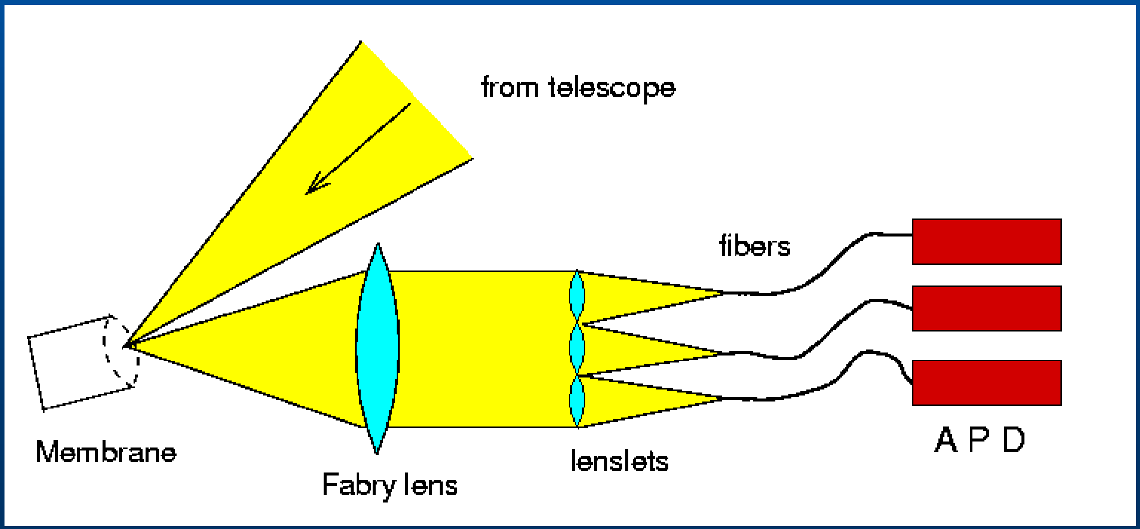
WFS: curvature

- Wavefront curvature ⇔ change of focus
  - *More/less flux ahead/past nominal focus*



WFS: curvature

- Vibrating membrane + photodiodes
  - *Measure flux around focus*
  - *Infer wavefront ⇒ modify DM*



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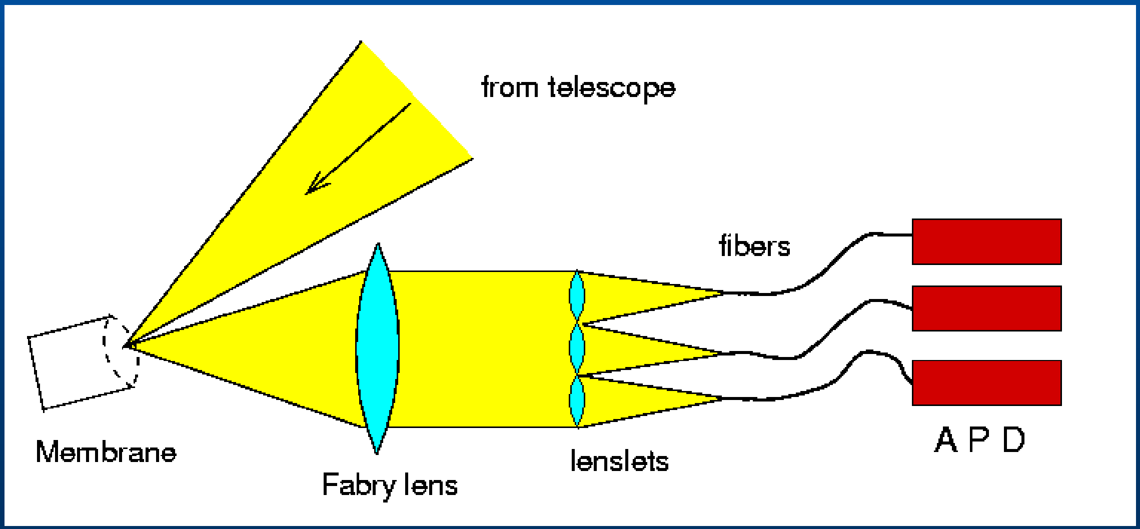

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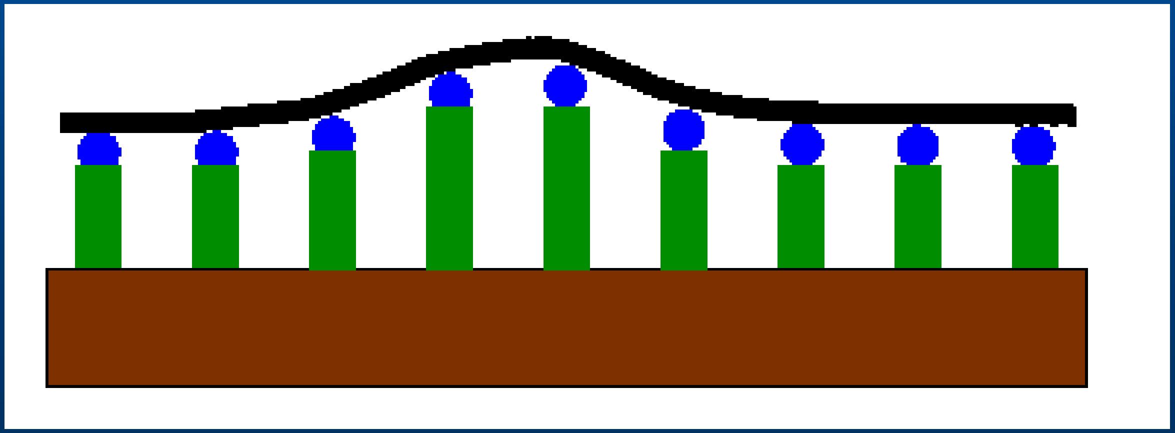
- Curvature system (F. Roddier)
  - *More light efficient*
- Shack-Hartmann (military)
  - *Can be scaled to large number of subapertures (e.g., large telescopes)*
- All planed systems are SH (or similar: pyramid sensor)

Deformable mirrors (I)

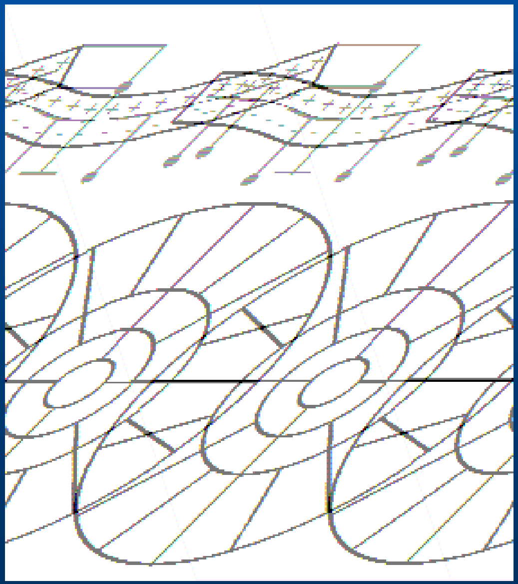
- The original design:
  - *Thin deformable mirror*
  - *Piezo-electric supports that can move up or down based on applied voltage*



ON THE FRINGE

Deformable mirrors (II)

- A minor variation:
  - *Bimorph crystal that bends depending on applied voltage (no mechanical support)*



Deformable mirrors (II)

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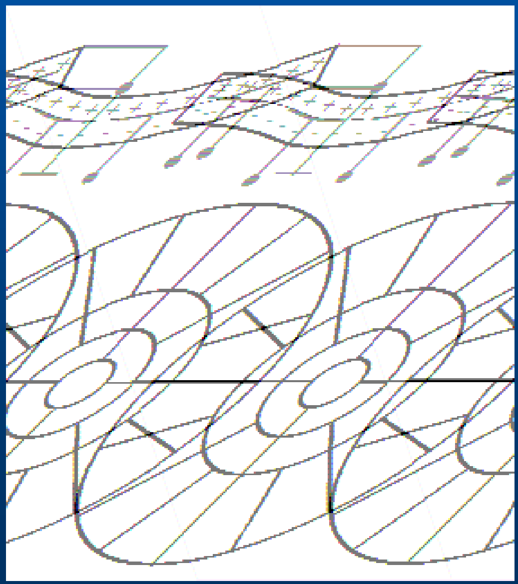
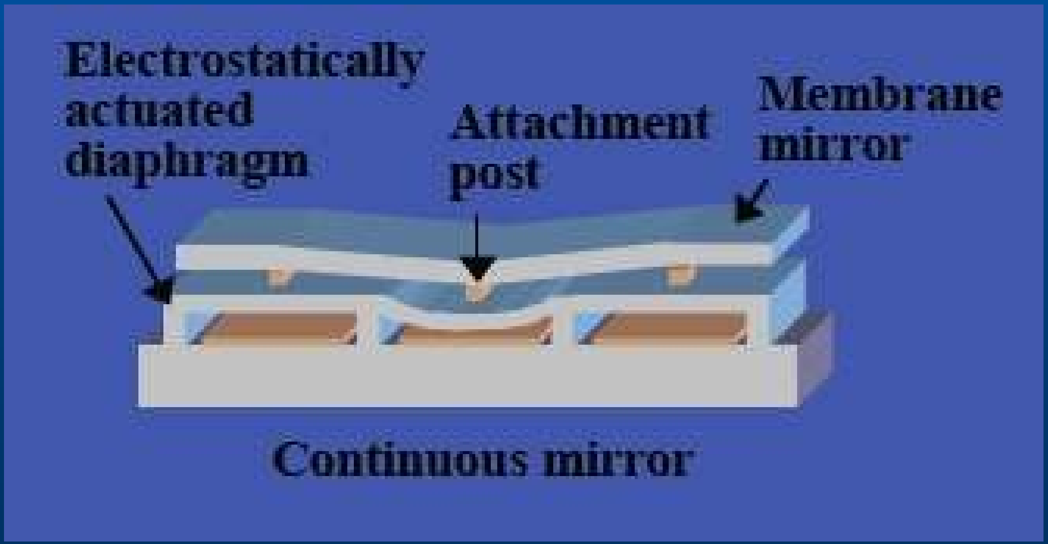
Amplitude: several μm

Frequency: several kHz



Deformable mirrors (III)

- The new generation:
  - *Micro-mirrors (MEMs) from communications*



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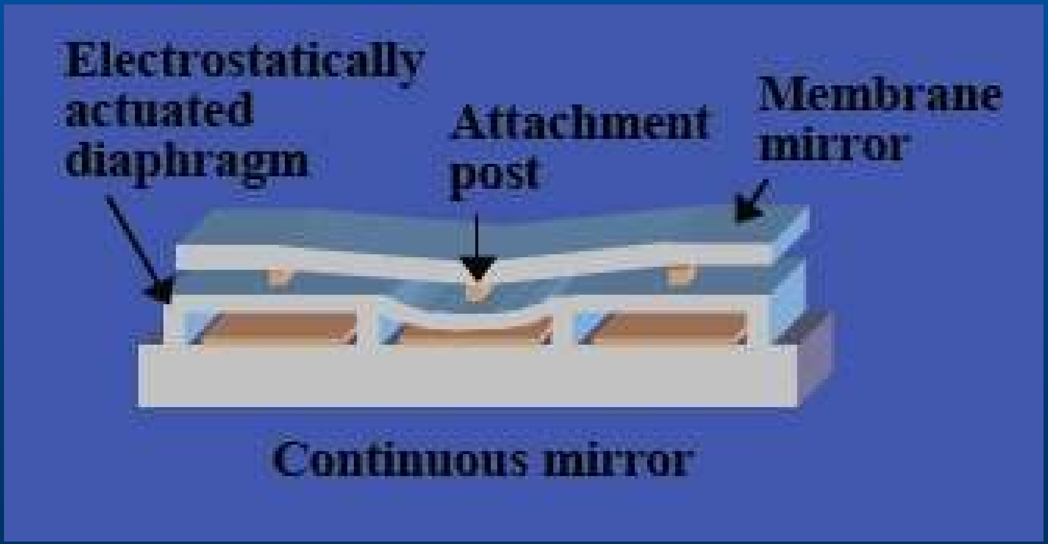

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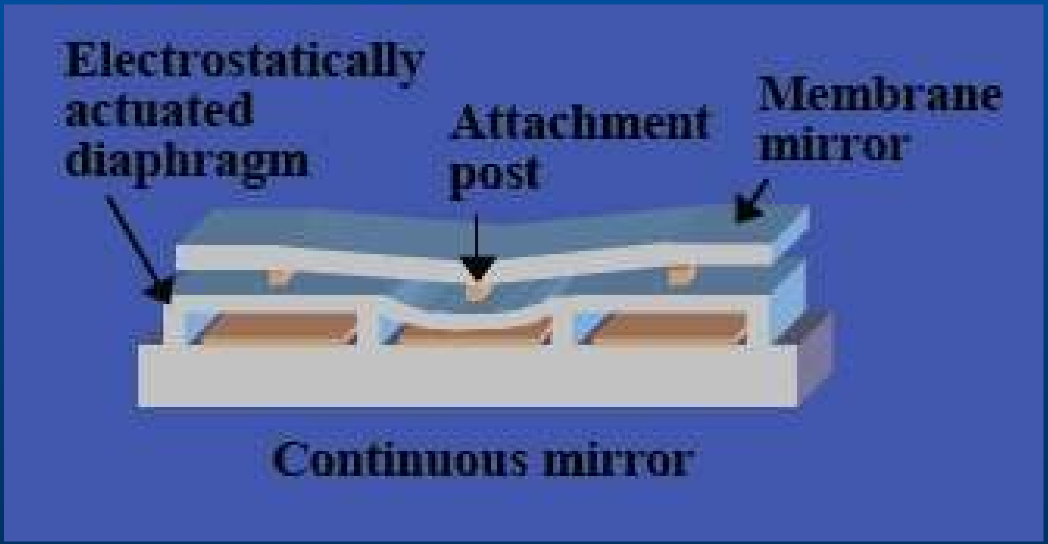
Still improving!



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Deformable mirrors (IV)

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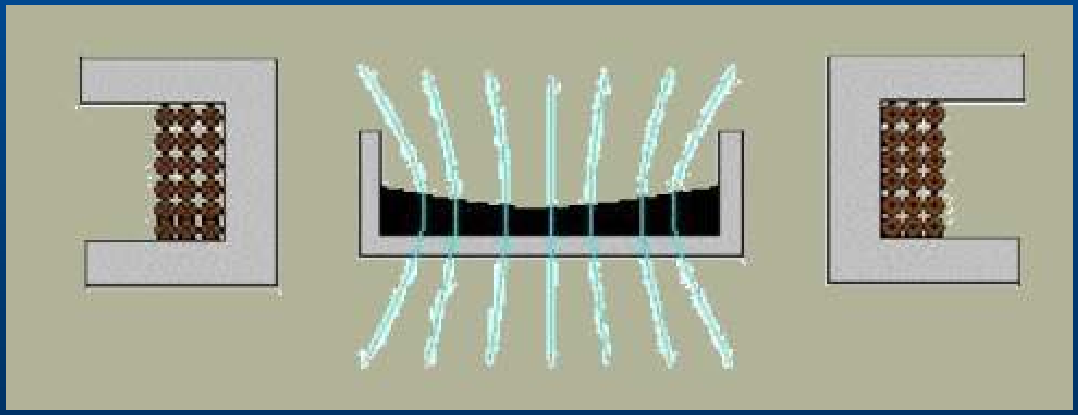

Deformable mirrors (IV)

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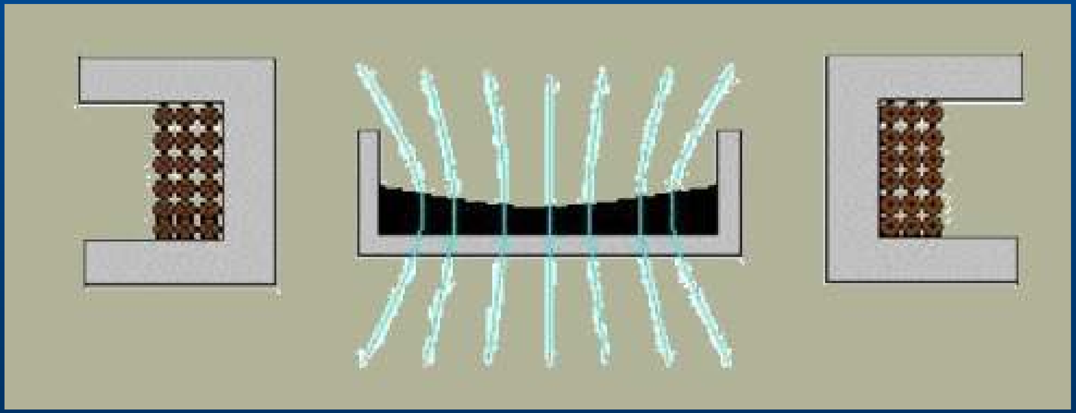
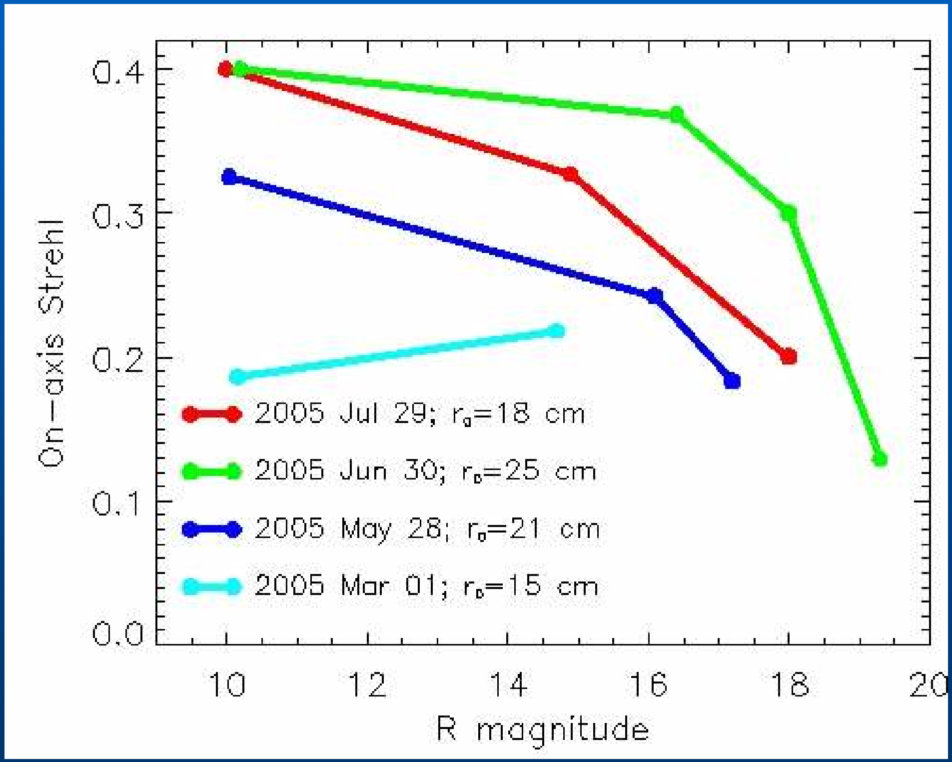
Other ideas to come!



Adaptive optics: performances

- **VLT/NAOS**

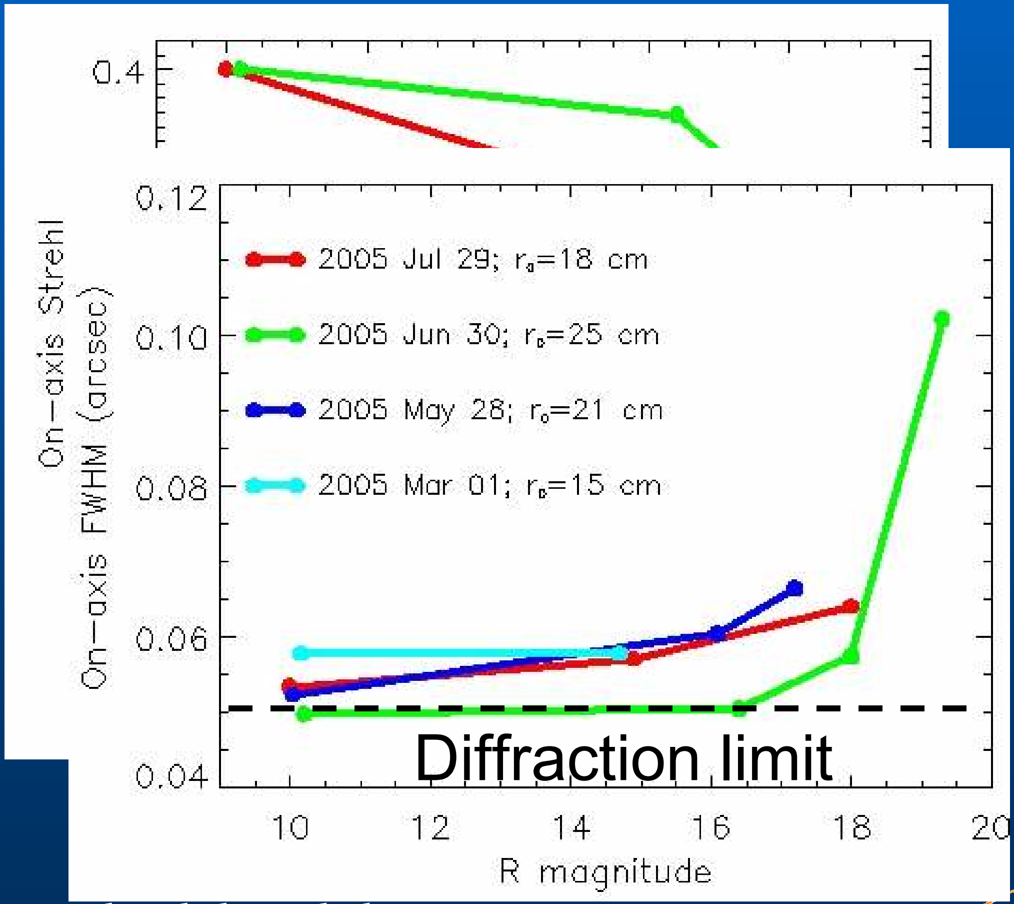


Adaptive optics: performances

- VLT/NAOS

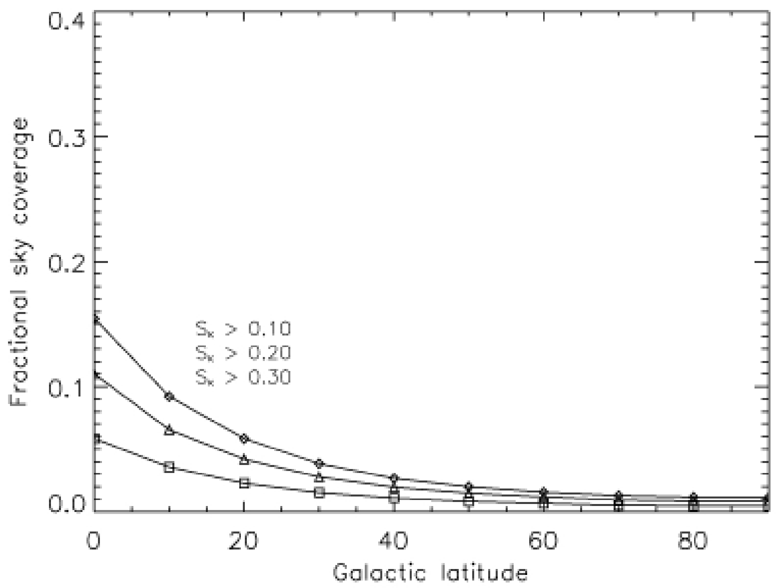
NAOS-CONICA at VLT YEPUN

ESO PR Photo 33I/01 (3 December 2001) © European Southern Observatory



Adaptive optics: limitations

- Need a bright star for AO correction
  - *Limited sky coverage*



Adaptive optics: limitations

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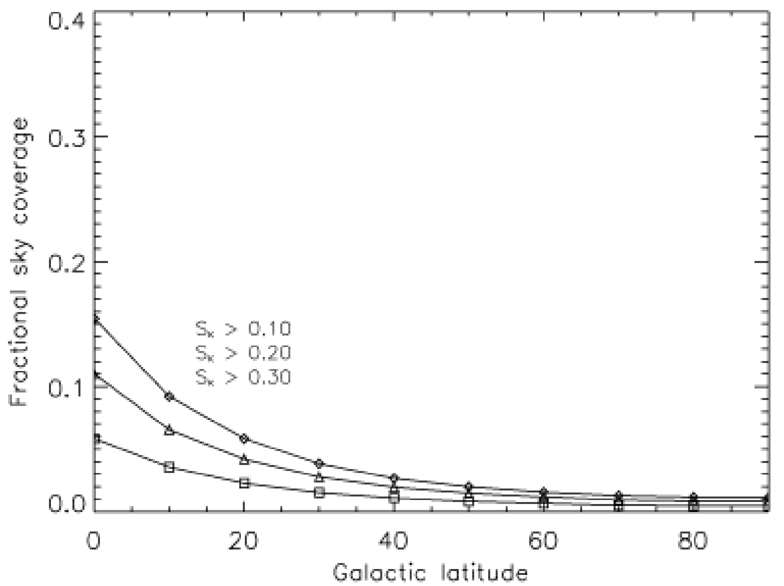
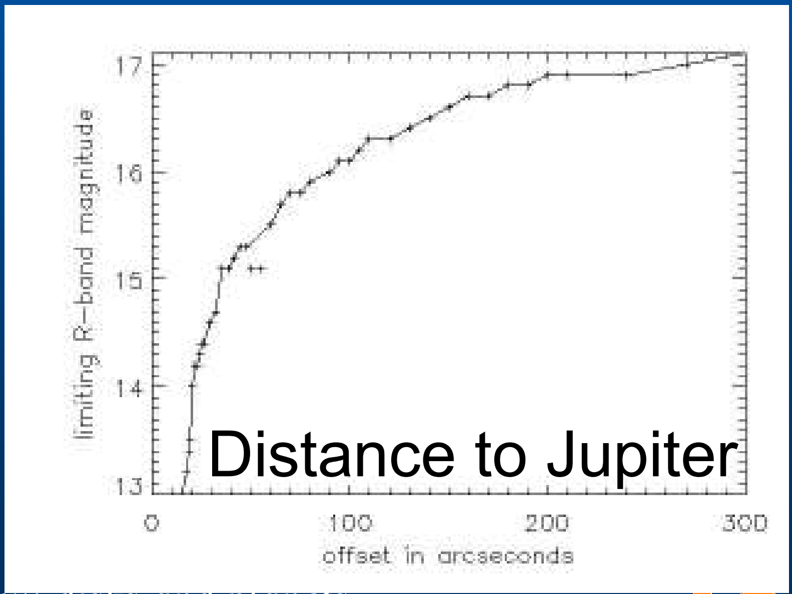
  - *Limited sky coverage*
- Sensitive to background (☠ Moon!)





ONTHEFRINGE

WFS: typical regime

- WFS usually work in (white) visible light
  - *Fast, low readout cameras*

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- Science camera usually works in NIR
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  - *Fast, low readout cameras*
- Science camera usually works in NIR
  - *Atmosphere too fast in visible*
  - *Simple separating dichroic*
- Strong requirement:
  - *Source must be (relatively) bright in visible*

WFS: using IR light

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- VLT/NACO offers an IR WFS

Dichroic Name	Reflected light to the WFS	Efficiency	Transmitted light to CONICA	Efficiency
VIS	V,R,I 0.45 – 0.95 μm	90%	J, H, K, L, M 1.05 – 5.0 μm	90%
N20C80	V,R,I,J,H,K 0.45 – 2.55 μm	20%	V, R, I, J, H, K 0.45 – 2.55 μm	80%
N90C10	V,R,I,J,H,K 0.45 – 2.55 μm	90%	V, R, I, J, H, K 0.45 – 2.55 μm	10%
JHK	I,J,H,K 0.80 – 2.55 μm	90%	L, M 2.8 – 5.5 μm	90%
K	K 1.9 – 2.55 μm	90%	V, R, I, J, H 0.45 – 1.8 μm	90%

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Useful if V-K > 5 mag →

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Adaptive optics: laser guide star

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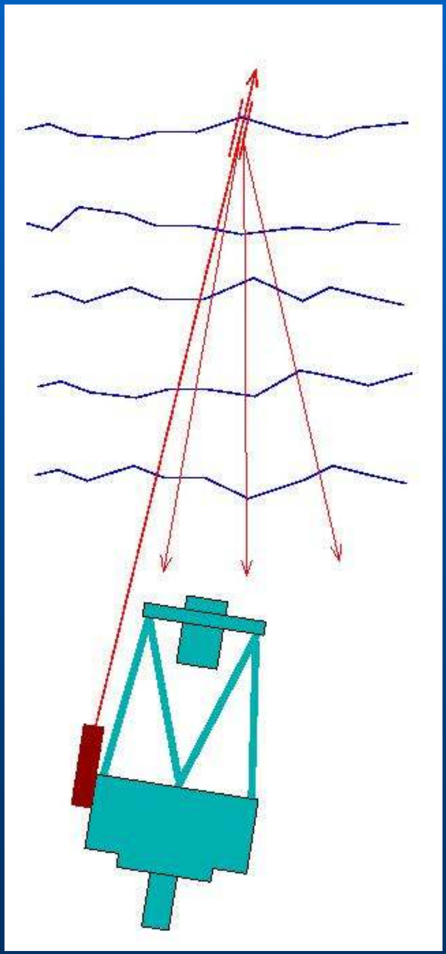
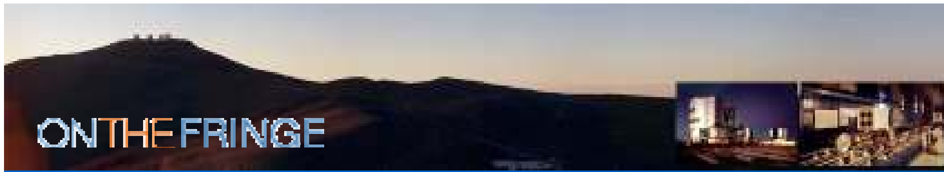
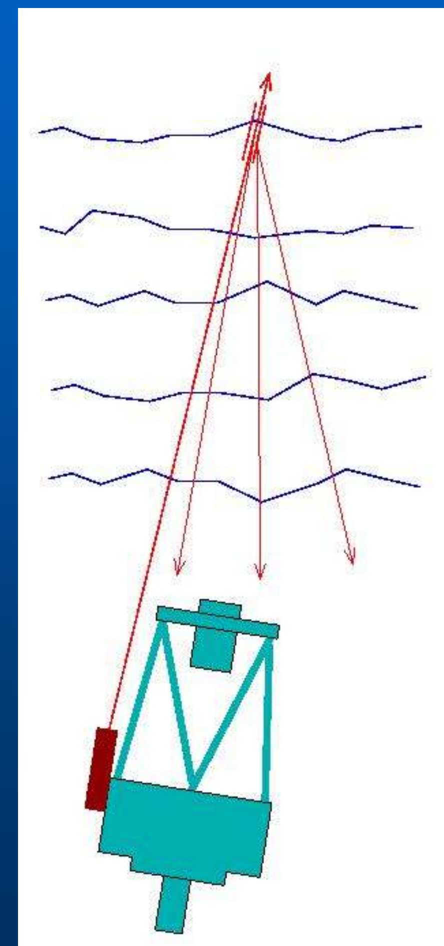
  - *Rayleigh Laser*



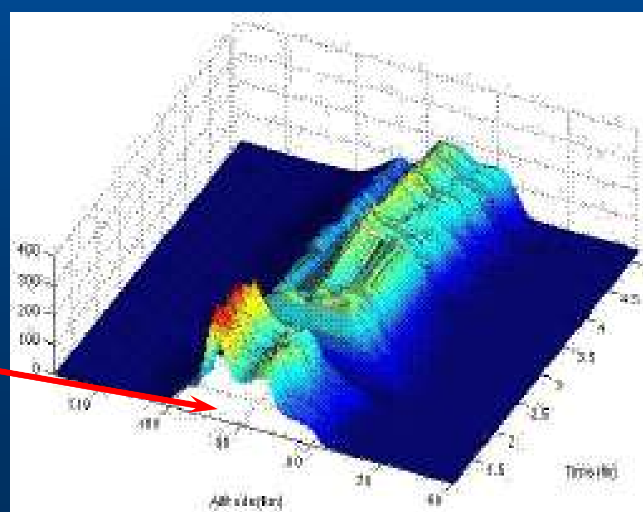


Adaptive optics: laser guide star

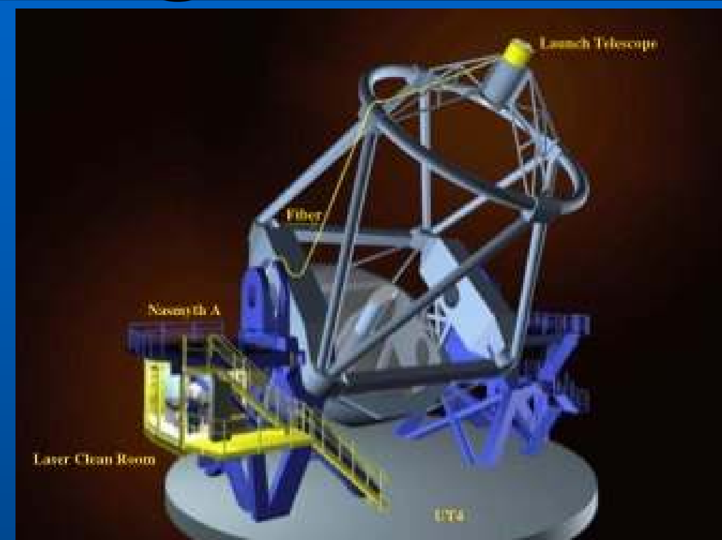
- Another option: create an artificial star!
  - ➢*Rayleigh Laser*
  - ➢*Sodium layer*

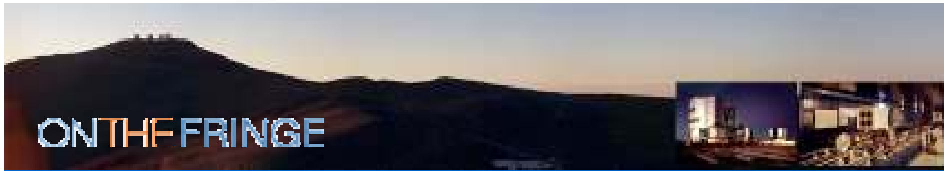


~90 km



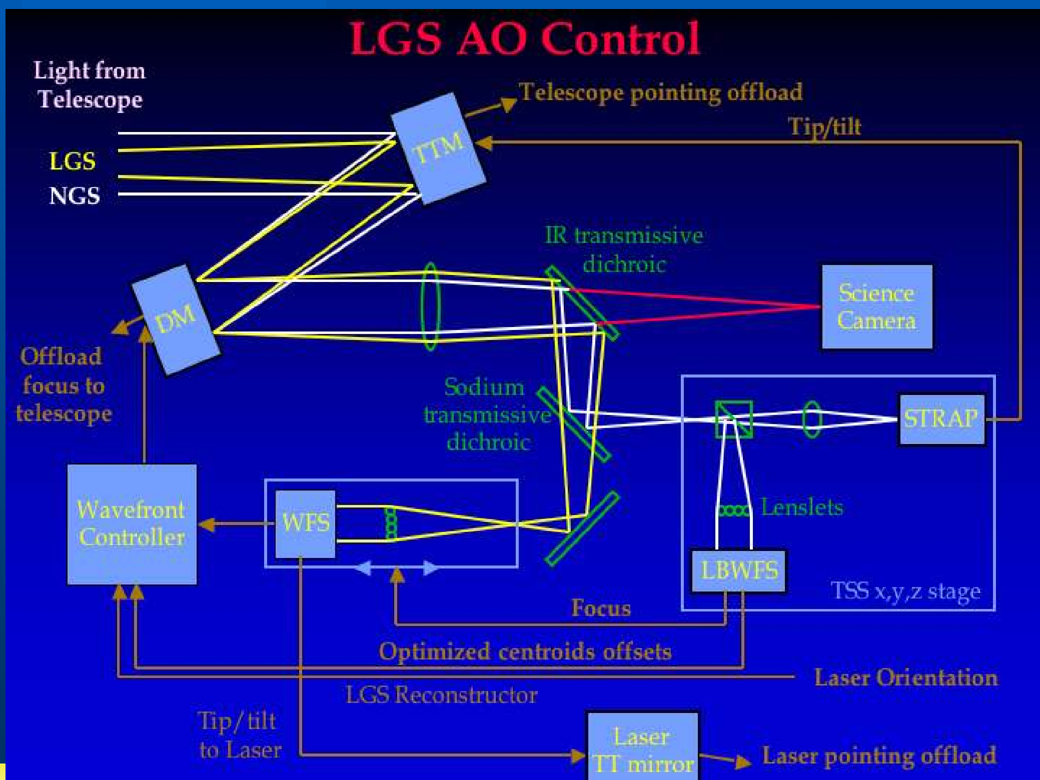
Adaptive optics: laser guide star

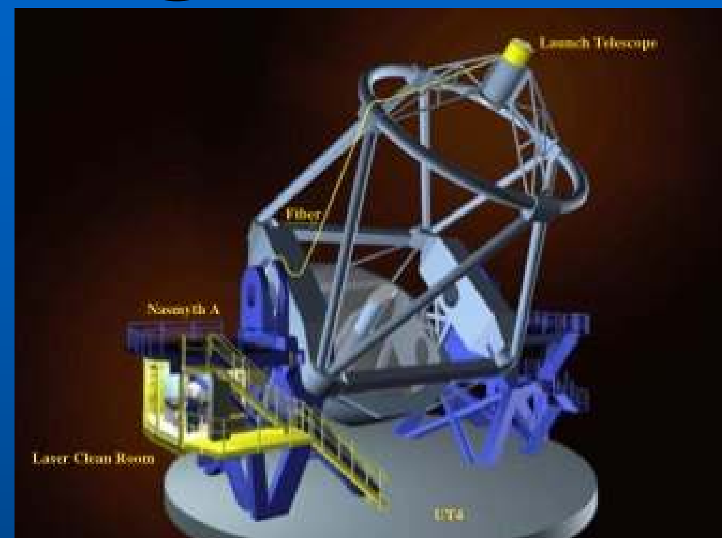




Adaptive optics: laser guide star

- More complex system!





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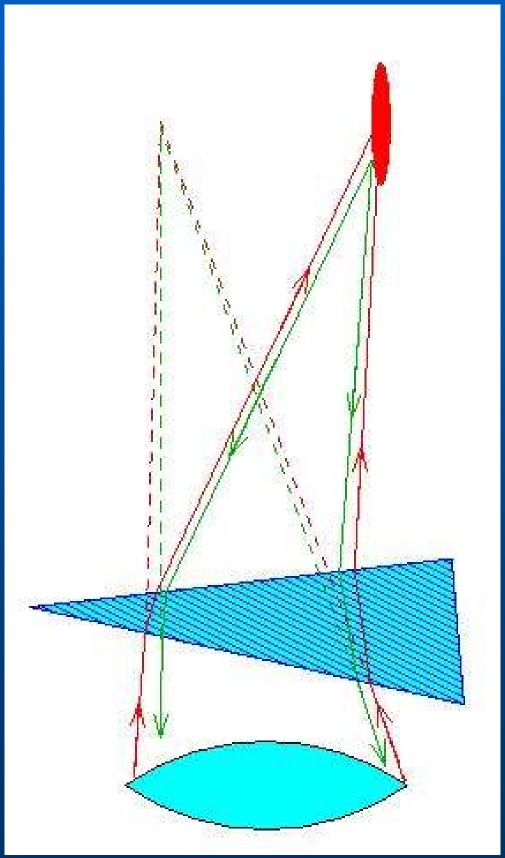
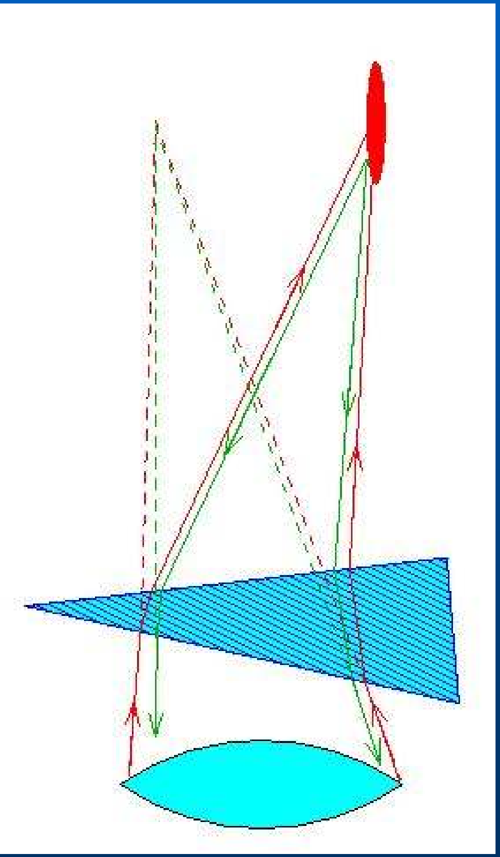


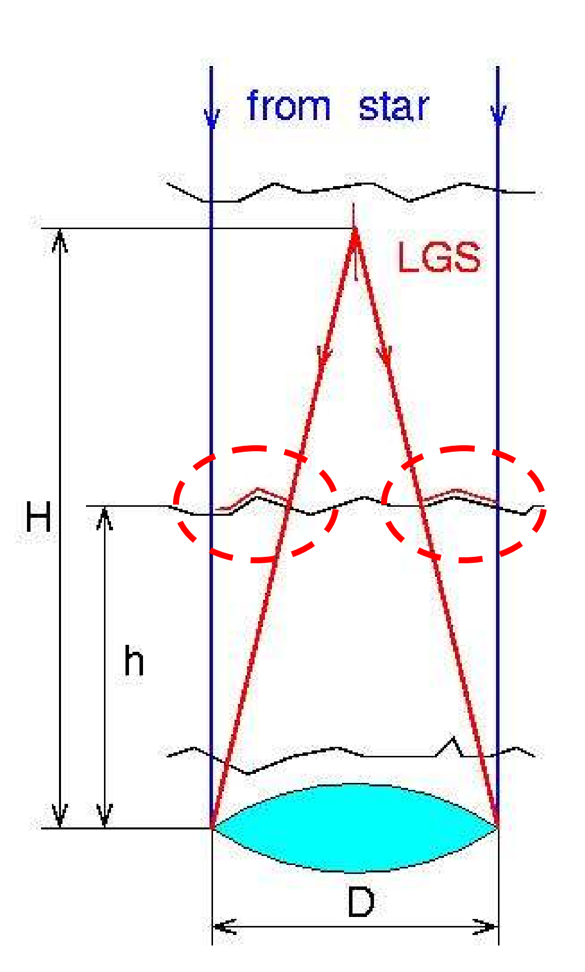
Adaptive optics: laser guide star

- And this does not solve all problems…
- Light propagates the same way up and down
  - *No measurement of tip-tilt!*
- Still needs a (fainter) reference star for tip-tilt



Adaptive optics: laser guide star

- Another problem: not all turbulence is corrected
  - ➢ *'cone effect'*



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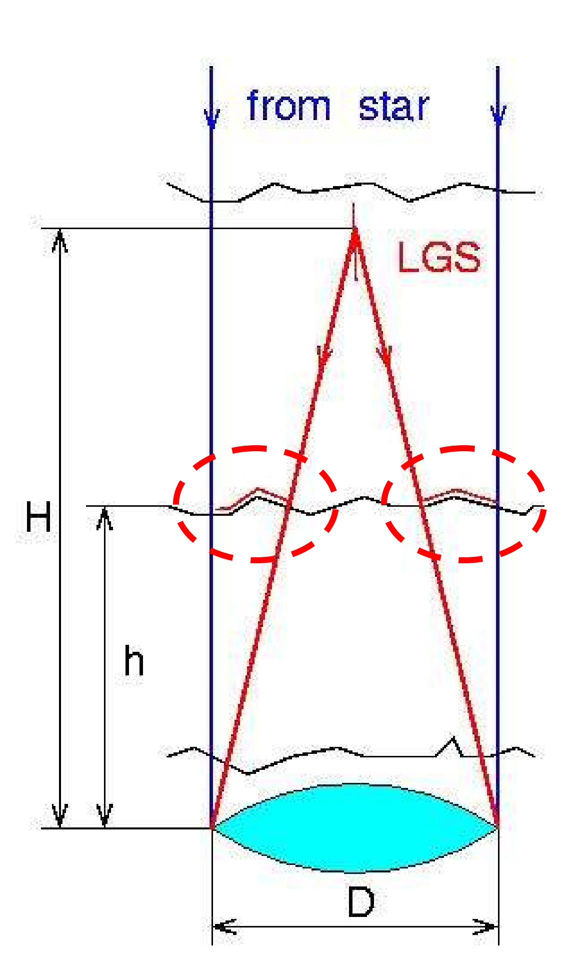
- Crucial for future large telescopes (30m+)



Adaptive optics: laser guide star

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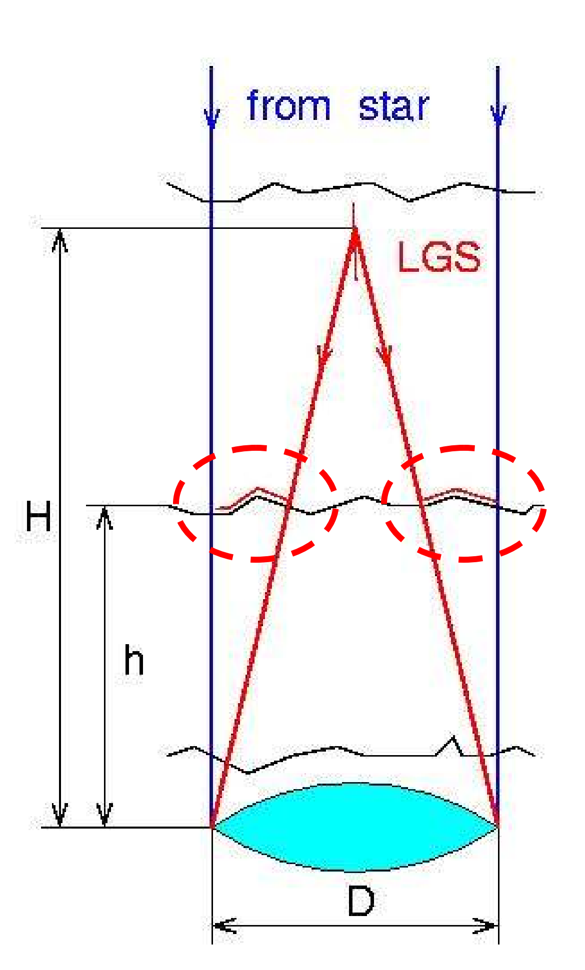
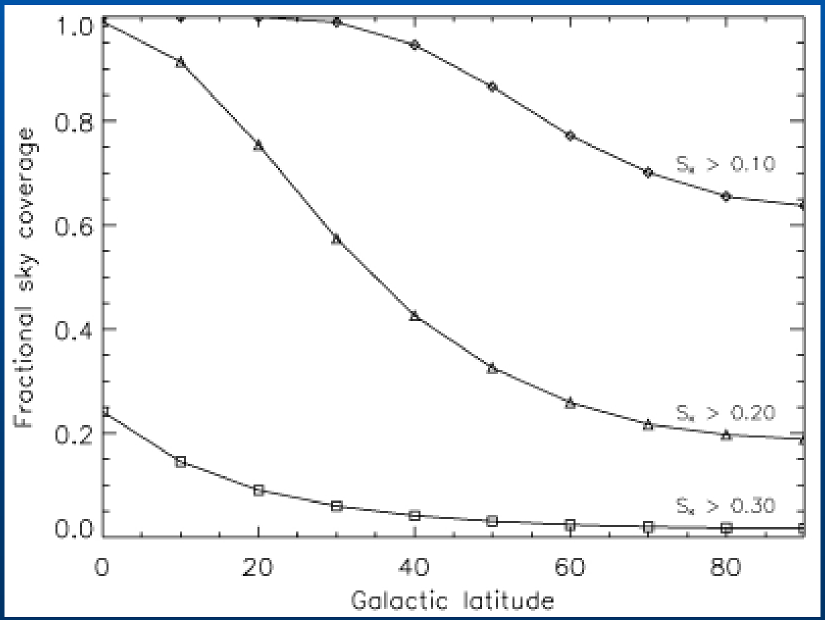
- NB: elongation of spot is not negligible either…



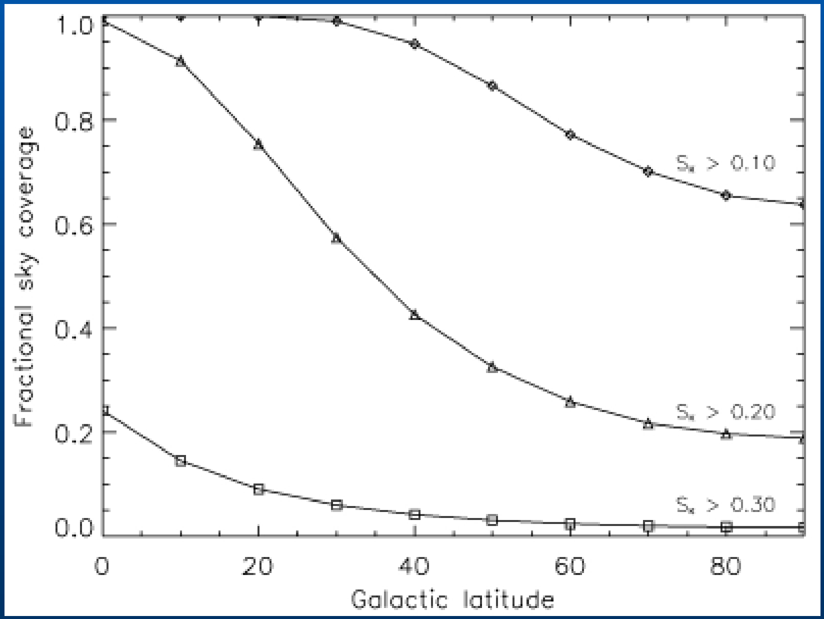
Adaptive optics: laser guide star

- Notwithstanding these problems, LGS is still a major improvement!
  - *Faint targets*
  - *Sky coverage*



Adaptive optics: laser guide star

- Notwithstanding these problems, LGS is still a major improvement!
  - ➢ *Faint targets*
  - ➢ *Sky coverage*
- All major observatory has/plans an LGS



Adaptive optics: next generation

- Best now: Lyot Project on AEOS
  - *3.6 m telescope atop Haleakela (Maui)*
  - *941 actuator AO system*
  - *80-90% Strehl at H-Band*

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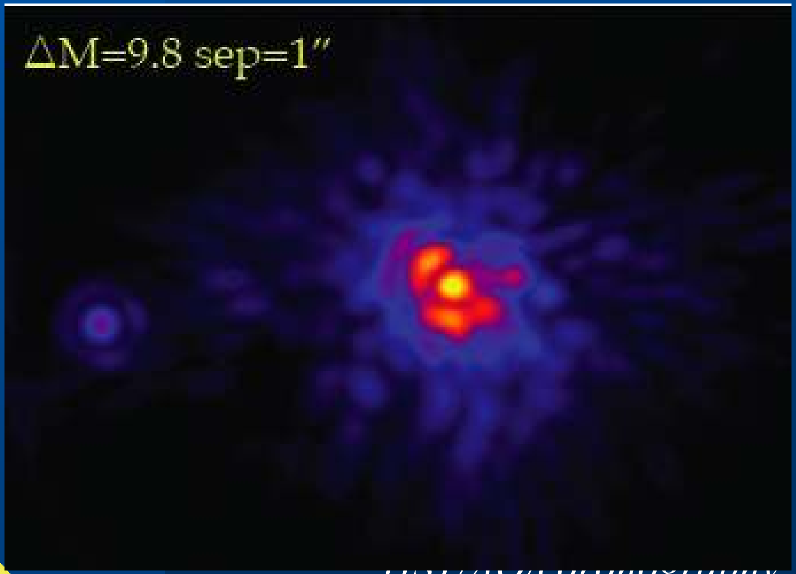

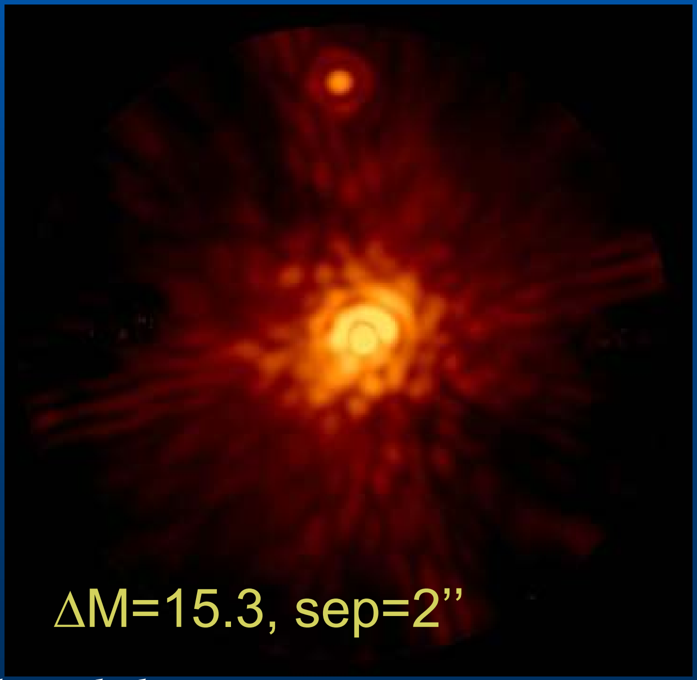

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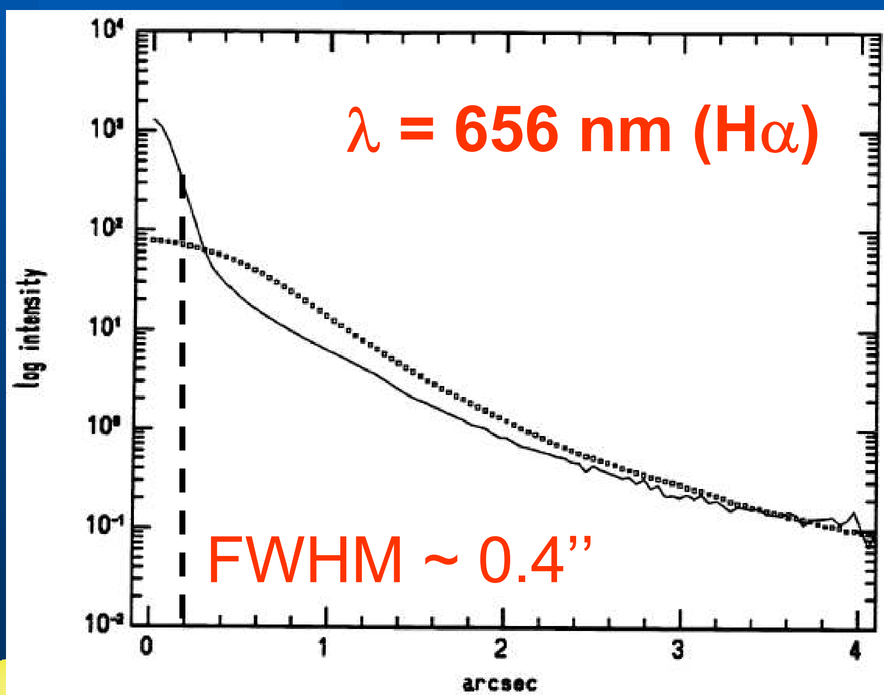
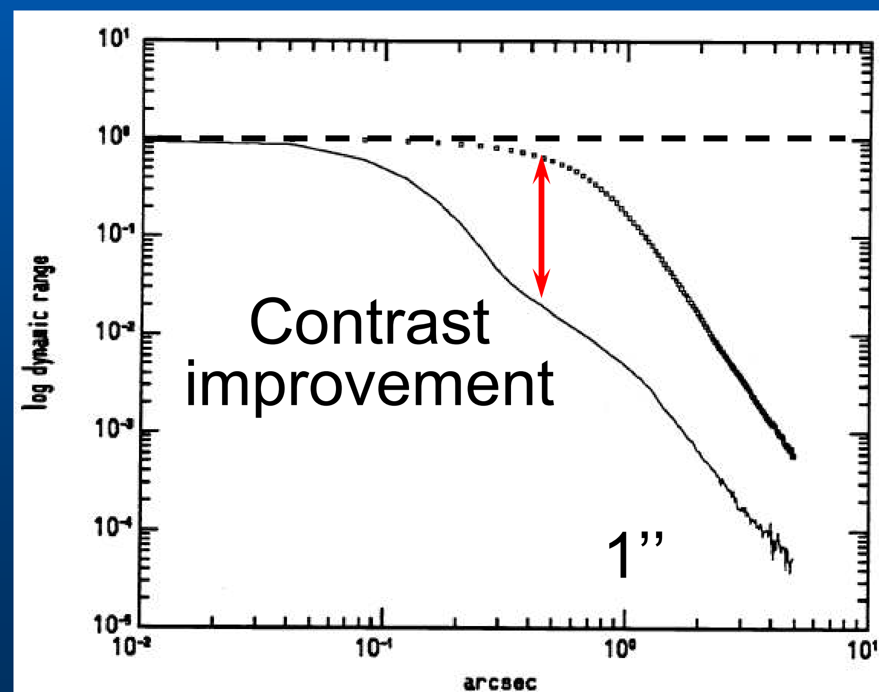
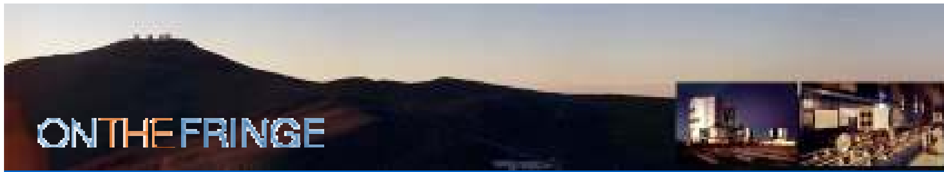
Adaptive optics: next generation

- Best now: Lyot Project on AEOS
  - *Substantial correction in the visible*







Adaptive optics: next generation

- Goal SR = 95% or more
  - *VLT/SPHERE, Gemini/GPI*

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

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AO: different context (I)

- AO is not used only for distant stars

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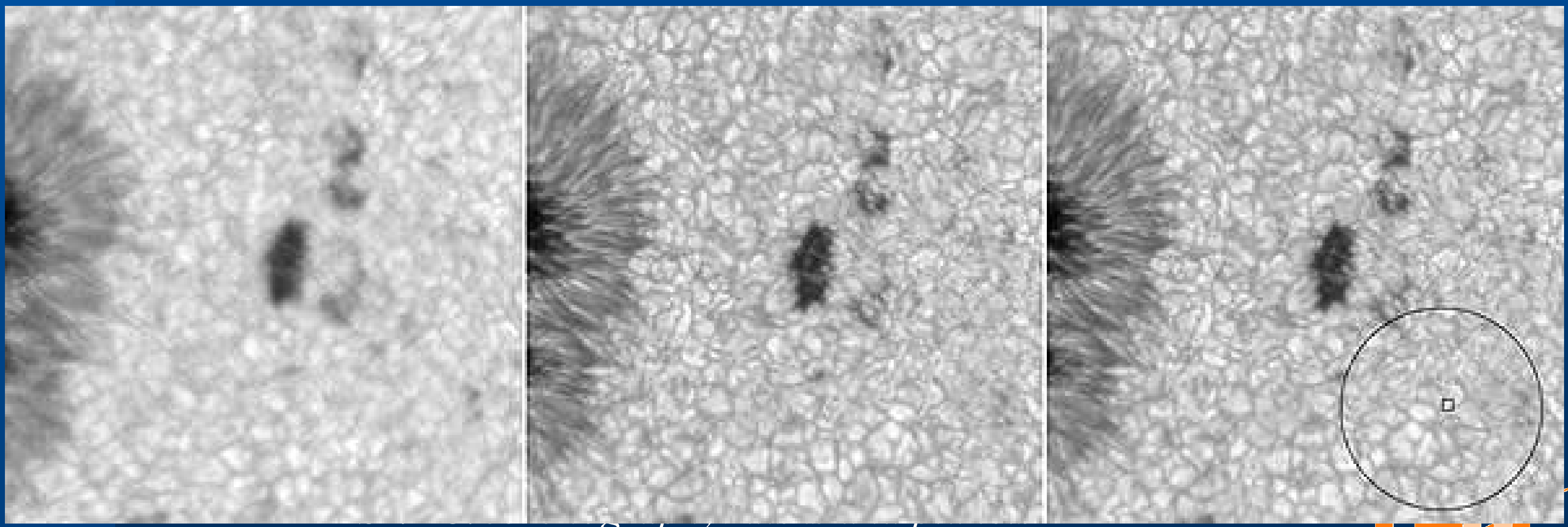
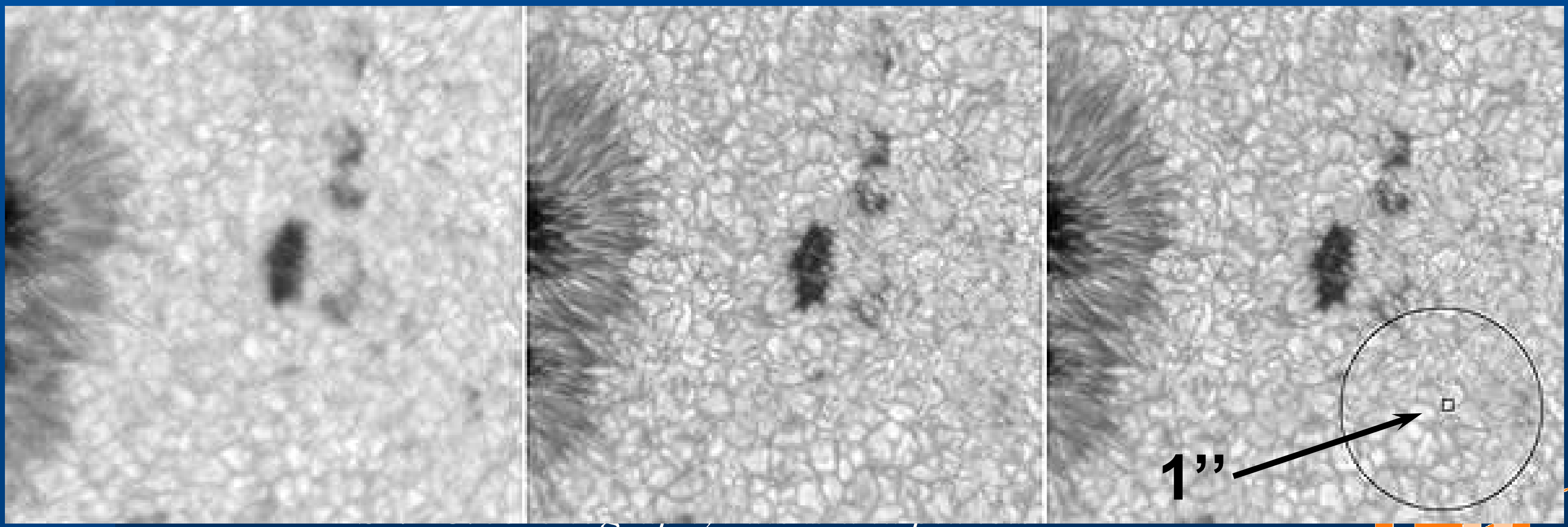
- AO is not used only for distant stars
  - *Sun observation also suffer from turbulence (even more!)*



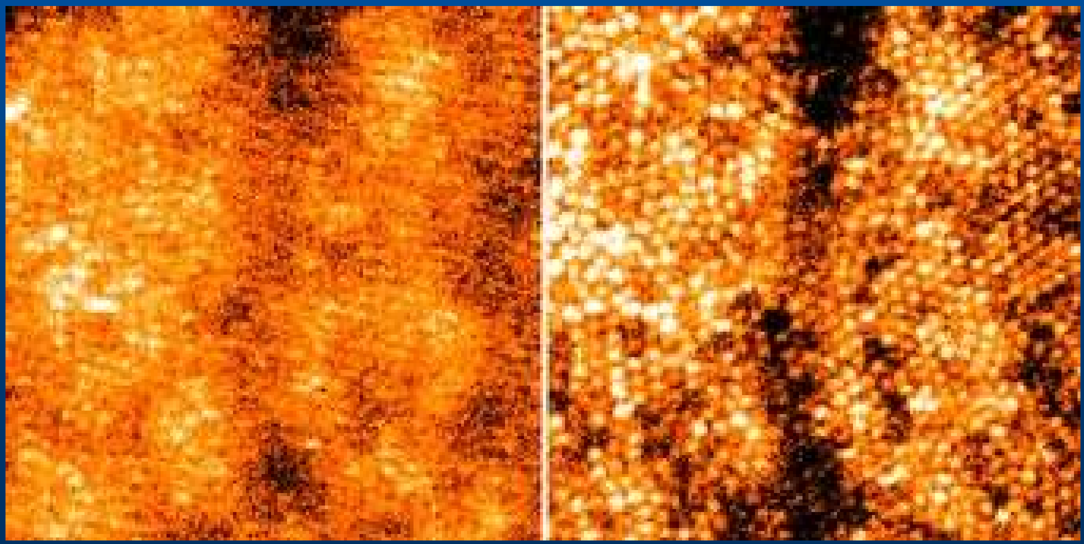
AO: different context (I)

- AO is not used only for distant stars
  - *Sun observation also suffer from turbulence (even more!)*
  - *'guide source': solar granulation!*



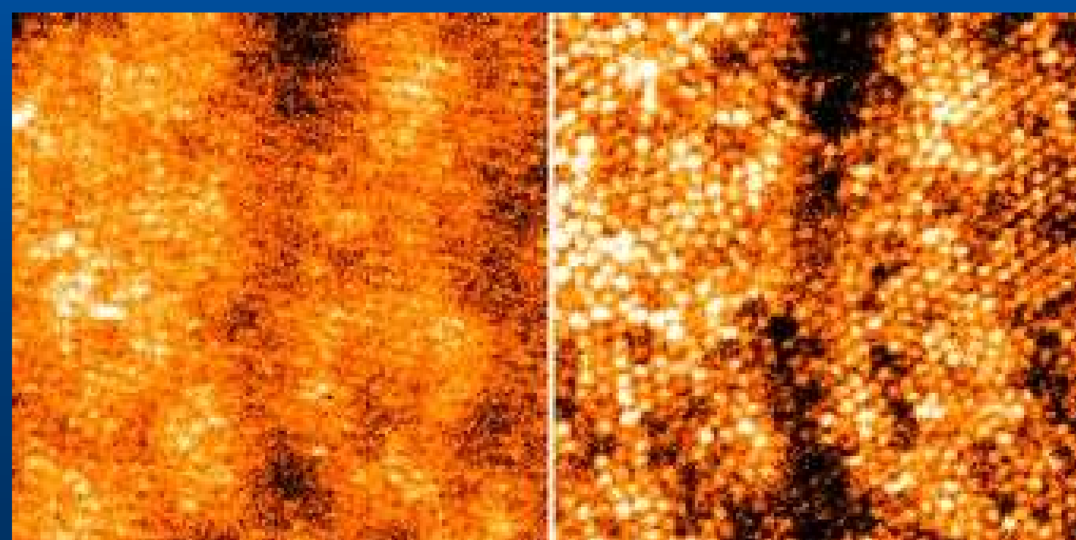
AO: different context (II)

- AO is also used to image the eye



AO: different context (II)

- AO is also used to image the eye
  - *Correct for imperfections in eyeball*
  - *Different set of constraints (larger stroke, slower rate)*



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- AO is also used to image the eye
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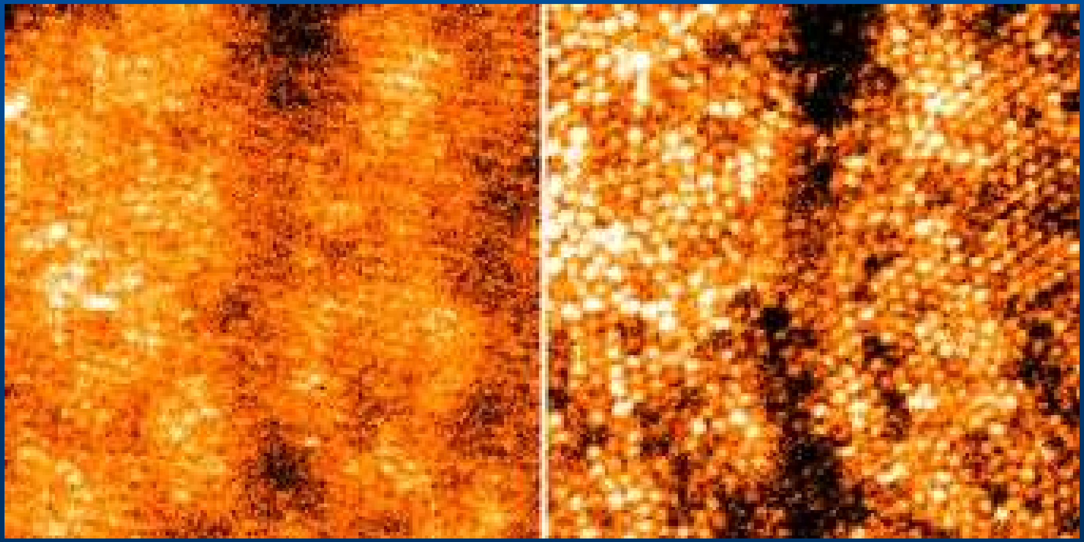
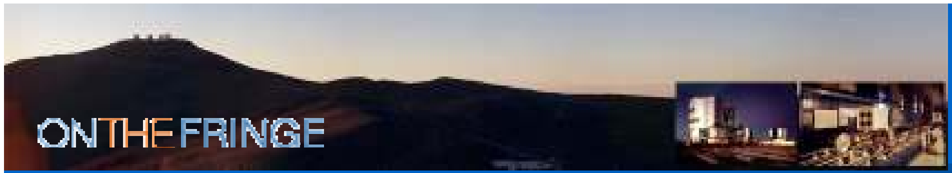
Used for eye surgeries!





Adaptive Optics : Data processing

HST/AO imaging data

- Images are images…
- Same basic reduction steps

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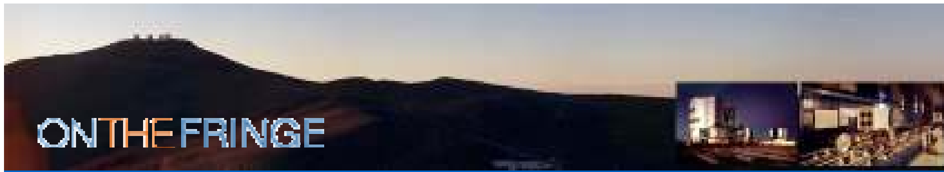


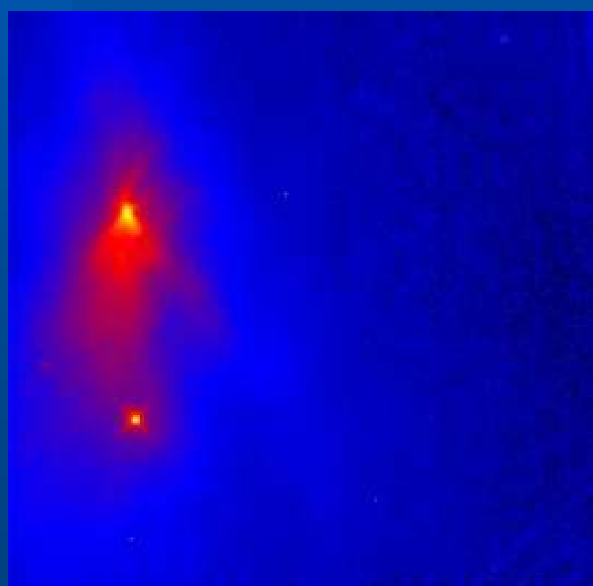
HST/AO imaging data

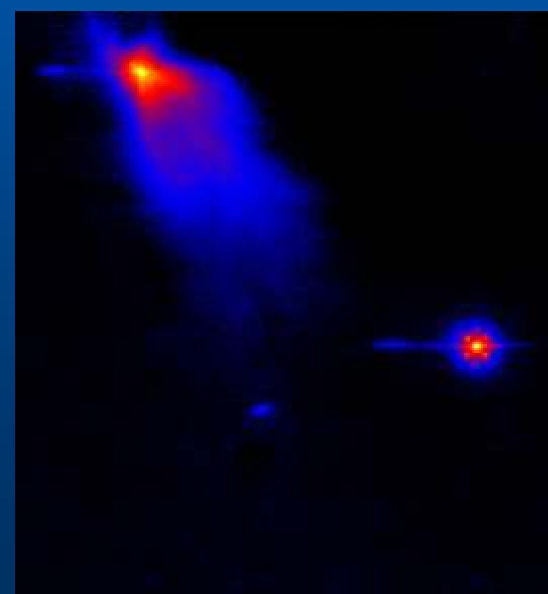
- Images are images…
- Same basic reduction steps
- If sufficient for scientific purposes, aperture photometry is OK
  - *Watch for aperture corrections!*
- Most of the time PSF fitting or subtraction is needed, or deconvolution

ON THE FRINGE

HST/AO imaging data

- HST *vs* AO: an example

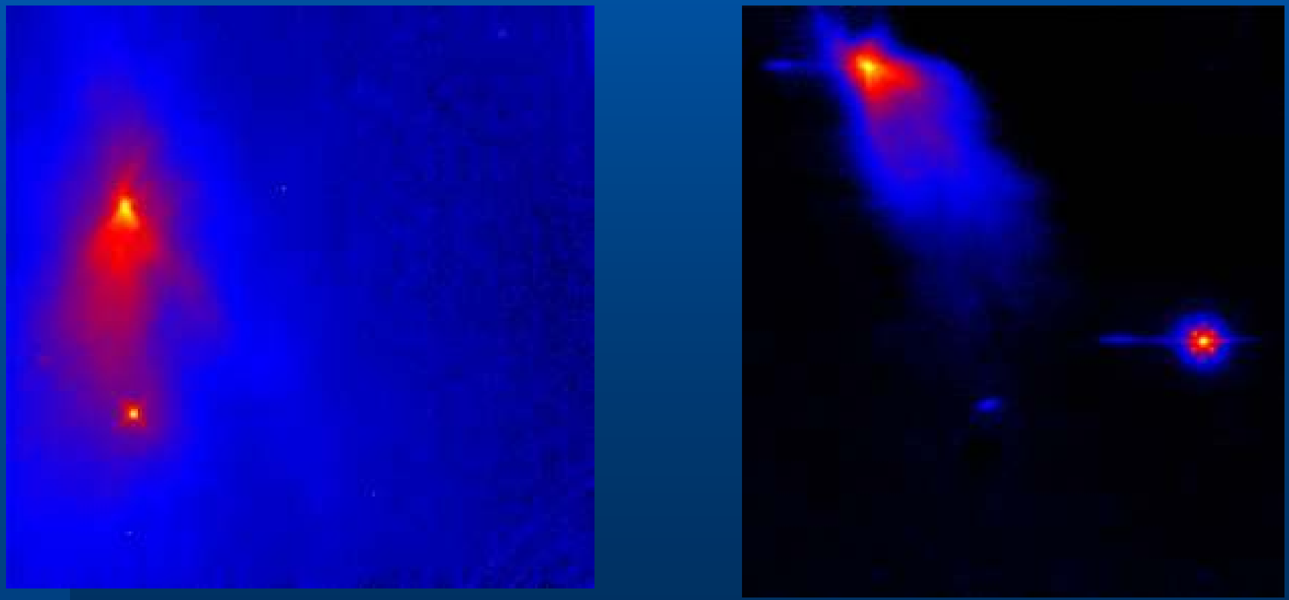




HST/AO/coronography: disks and planets

HST/AO imaging data

- HST *vs* AO: an example
  - *AO has higher resolution but more complex PSF and higher background*



ONTHEFRINGE

HST PSF fitting

- It can be useful to fit a PSF:
  - *To remove a star and search for faint object around it*
  - *For tight binary systems*

HST PSF fitting

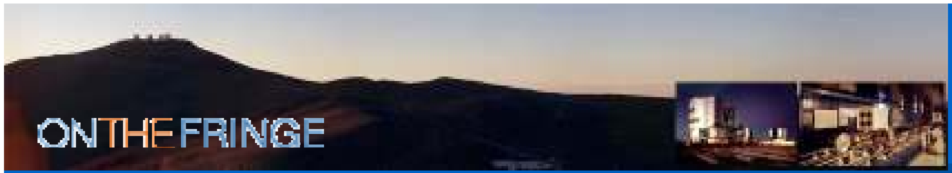
- It can be useful to fit a PSF:
  - *To remove a star and search for faint object around it*
  - *For tight binary systems*
- Relatively easy for HST
  - *Tinytim (OK for simple analysis)*
  - *Subsequent orbit (better accuracy)*

Adaptive optics PSF

- Things are more complicated for AO

Adaptive optics PSF

- Things are more complicated for AO
- Depends on
  - *Guide star (brightness, color)*
  - *Distance to guide star*
  - *Atmospheric conditions*
  - *Airmass*



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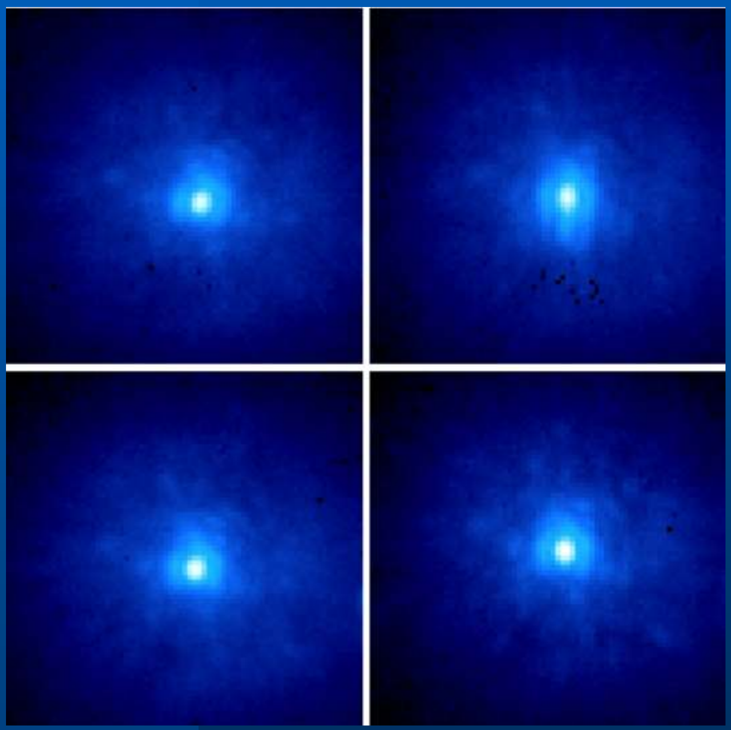
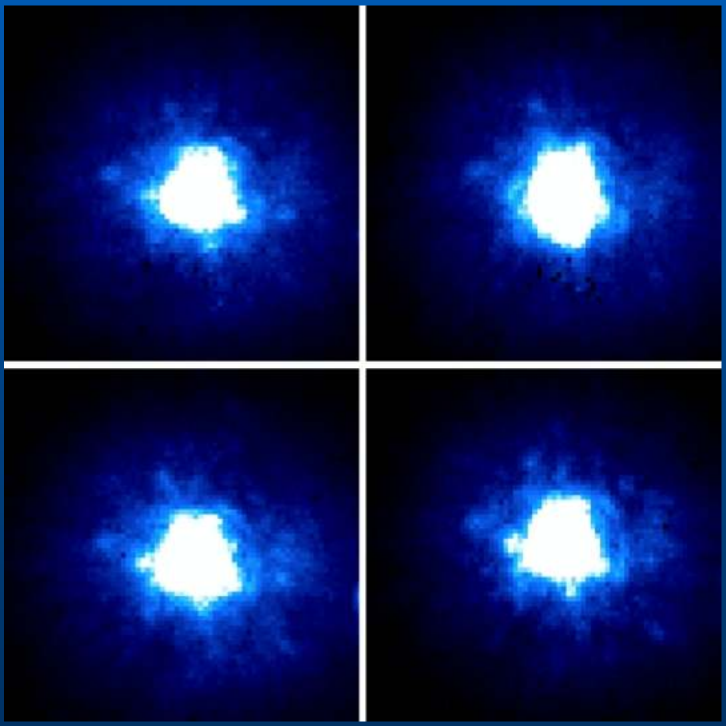
- Things are more complicated for AO
- Depends on
  - *Guide star (brightness, color)*
  - *Distance to guide star*
  - *Atmospheric conditions*
  - *Airmass*
  - *TIME!!!*

AO PSF: variability

- 4 images taken in a 20s sequence





ONTHEFRINGE

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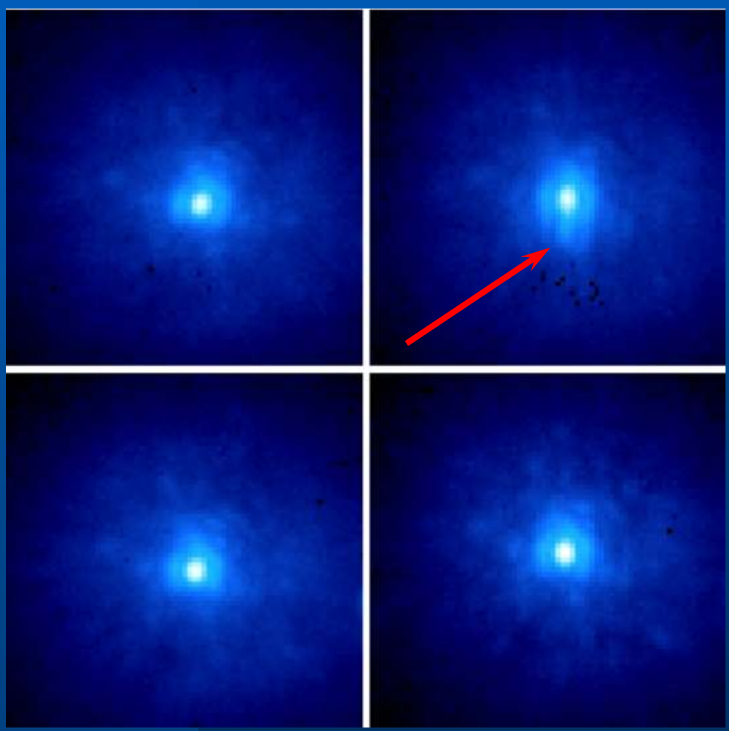
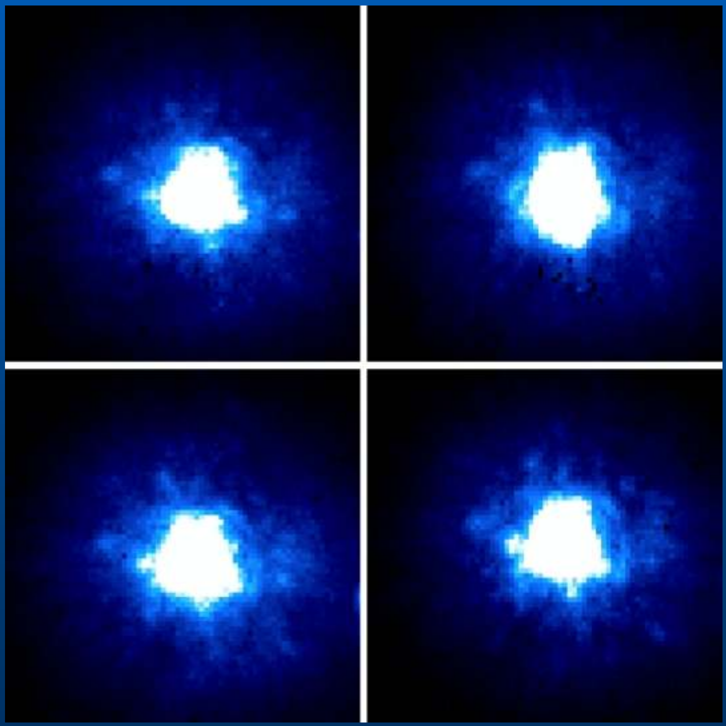




AO PSF: variability

- As a function of time:
  - *Strehl ratio varies*
  - *Specific mode correction varies*
  - *Speckle pattern changes*

AO PSF: variability

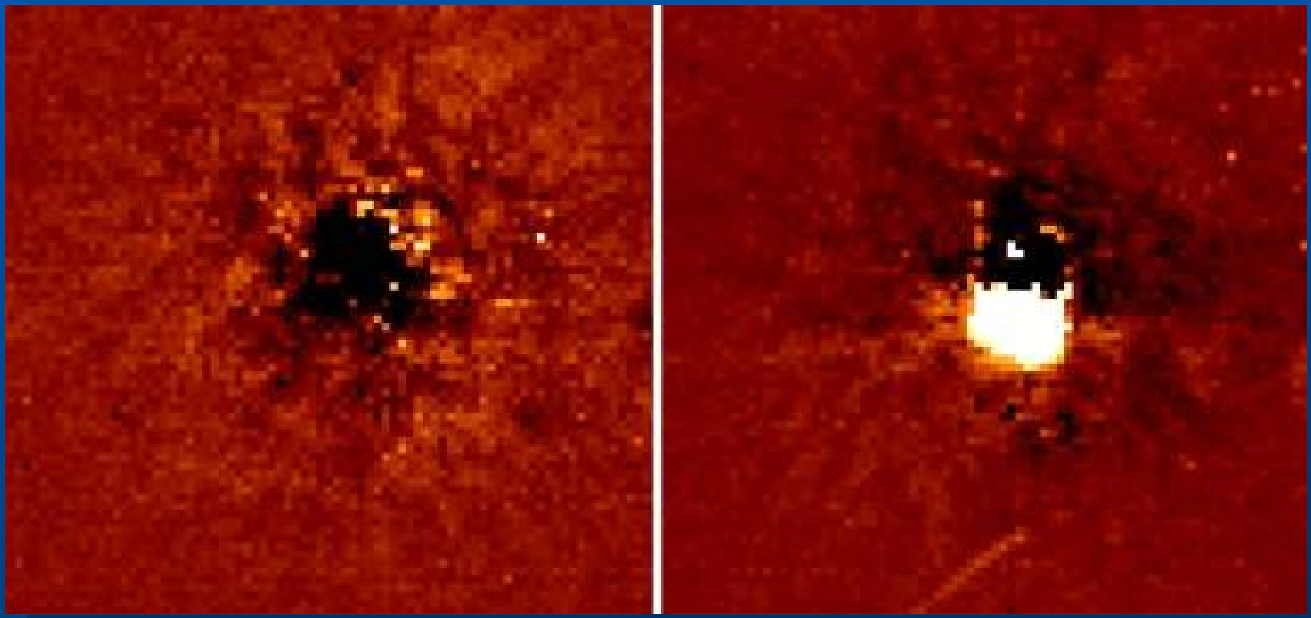
- As a function of time:
  - *Strehl ratio varies*
  - *Specific mode correction varies*
  - *Speckle pattern changes*
- Rule of thumb:
  - *Close in time (simultaneous!)*
  - *Similar colors/brightness*

AO PSF: variability

- … but that’s not enough!

AO PSF: variability

- … but that's not enough!
- Same star, ~10s time difference!



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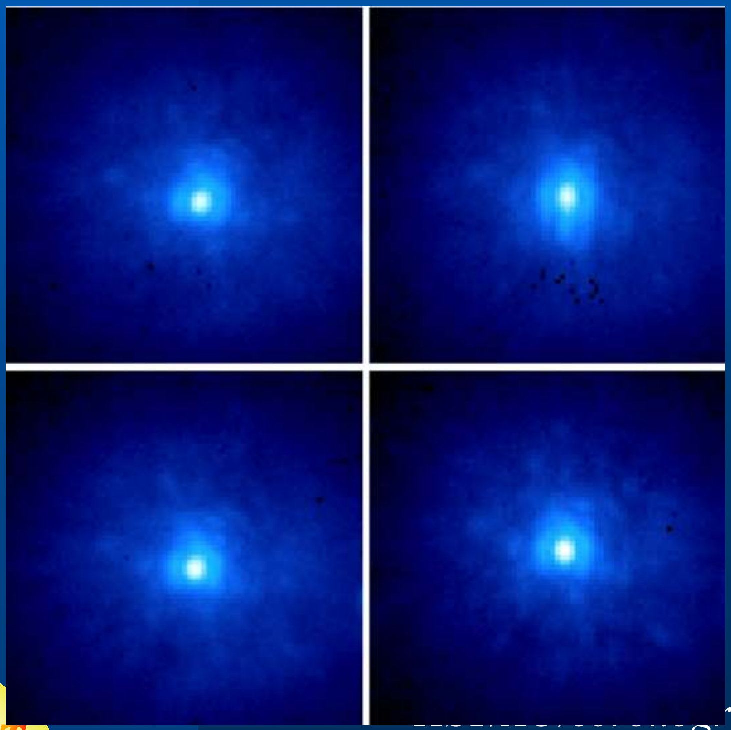
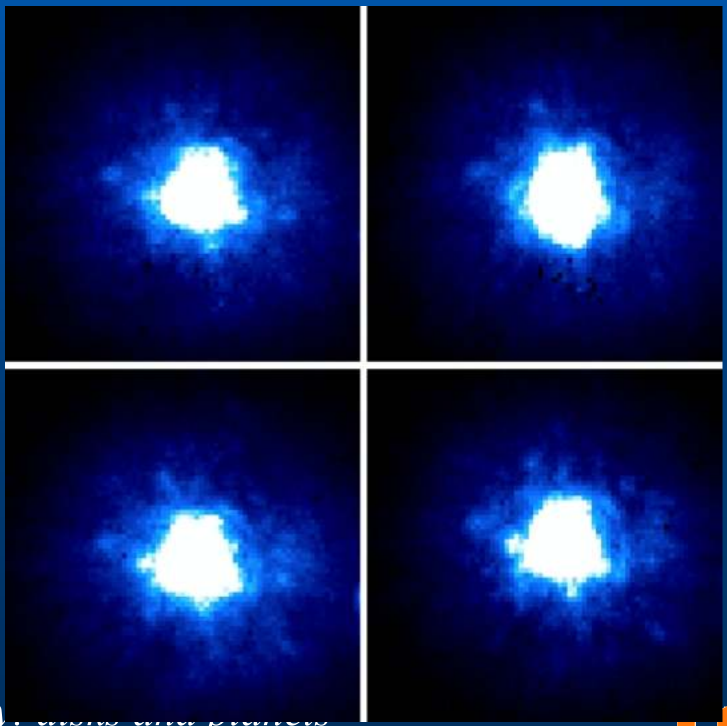
- Create a database of PSFs with many observations and search through it
- Long time difference doesn't matter as long as it works!
- NB: curvature systems give good estimate of PSF

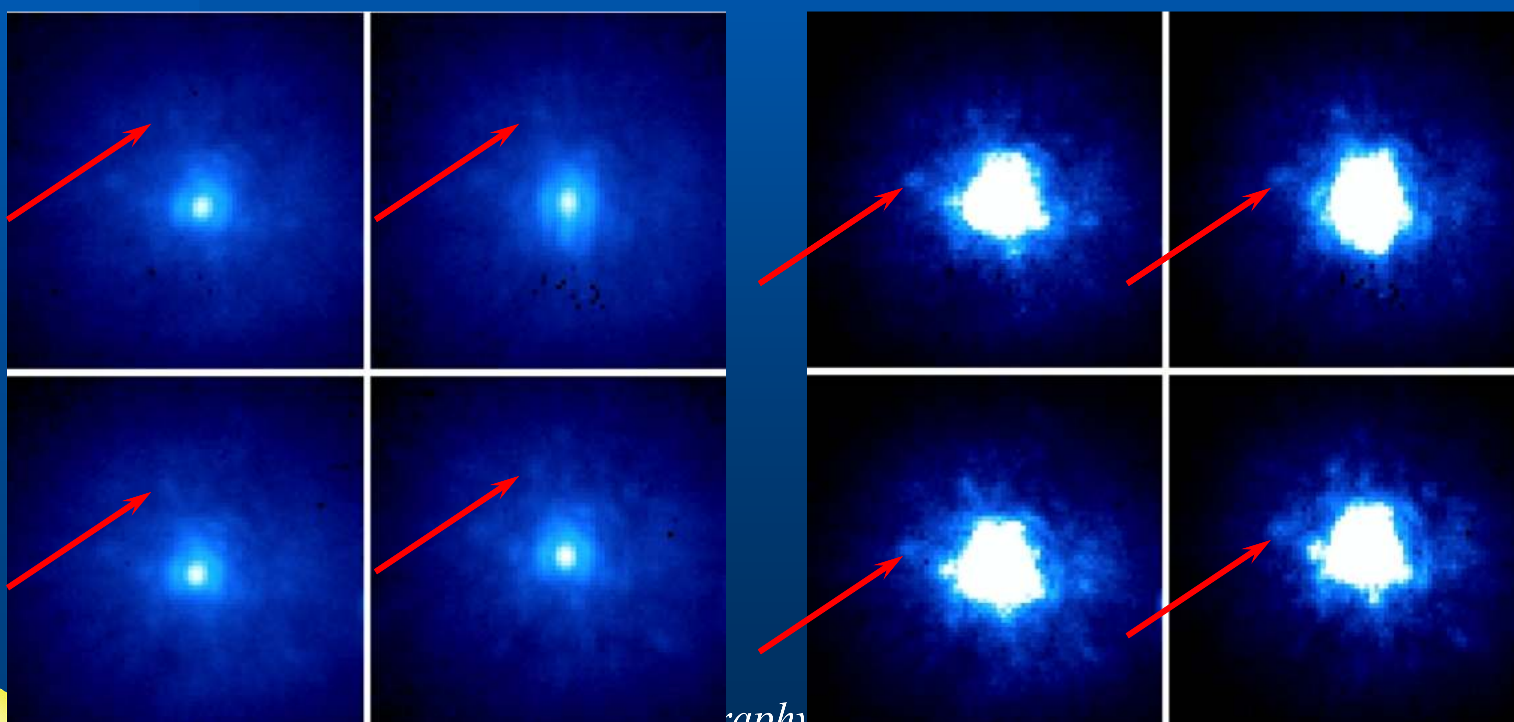
AO PSF: variability





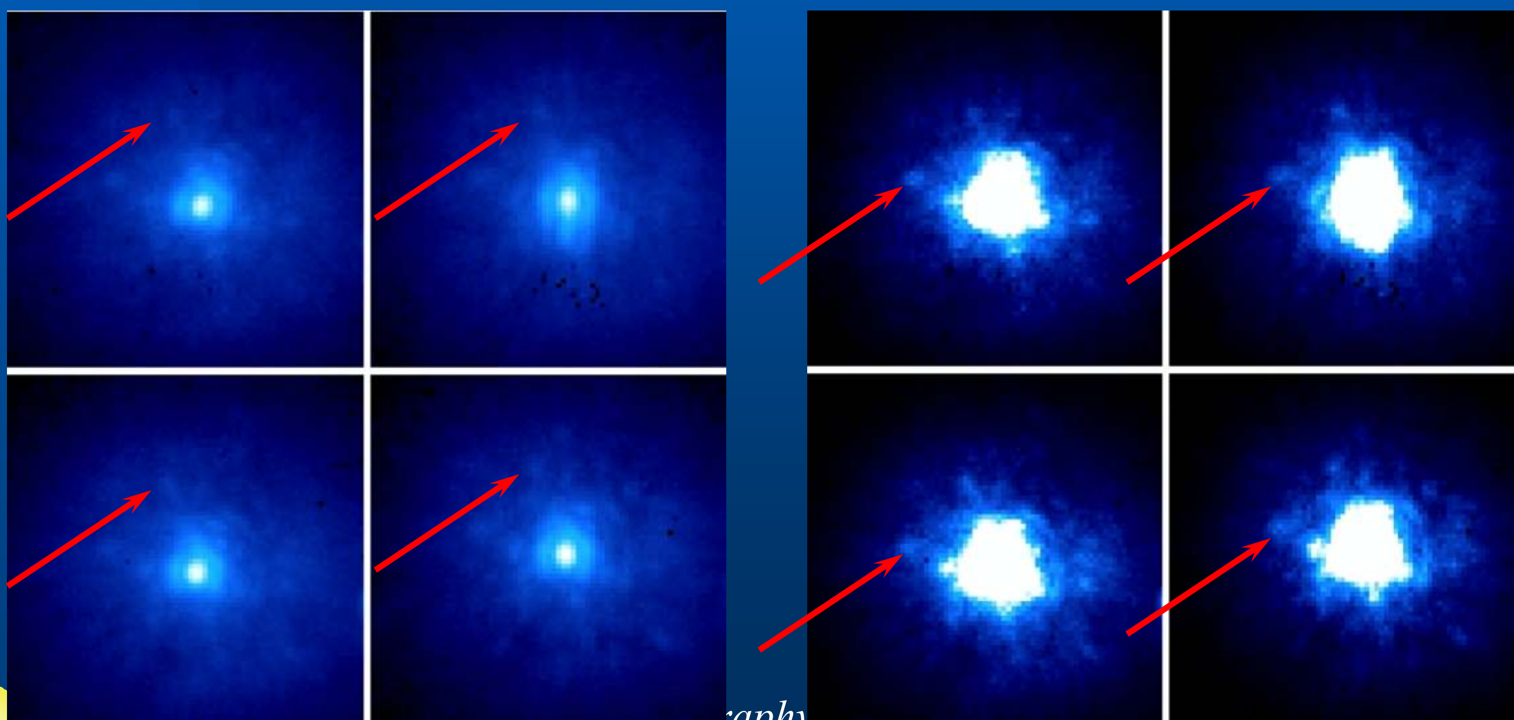
AO PSF: variability

- Some speckle can live a ‘long time’



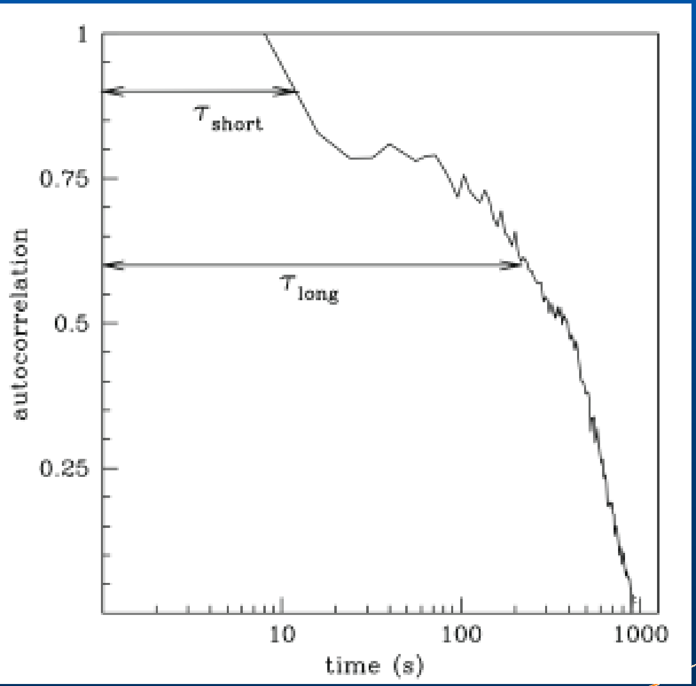
AO PSF: variability

- Some speckle can live a ‘long time’
  - *Semi-static speckles*



AO PSF: variability

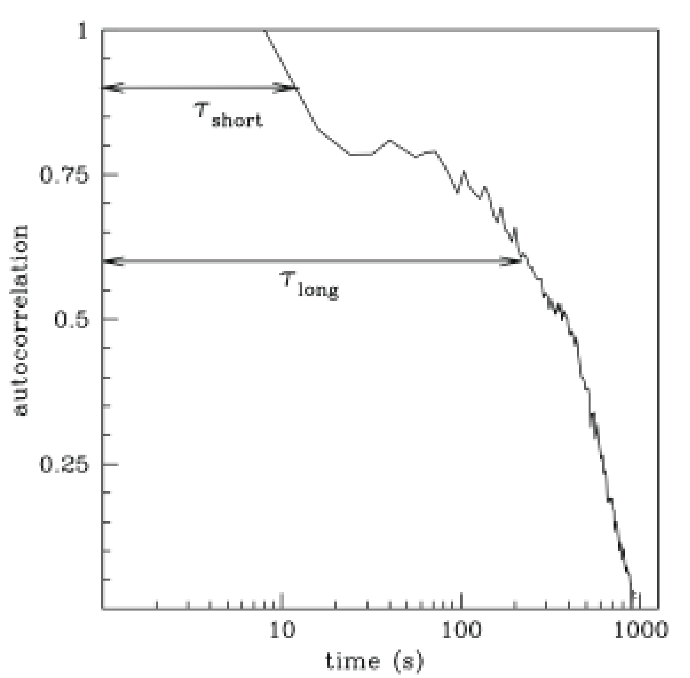
- These features can live several minutes



ONTHEFRINGE

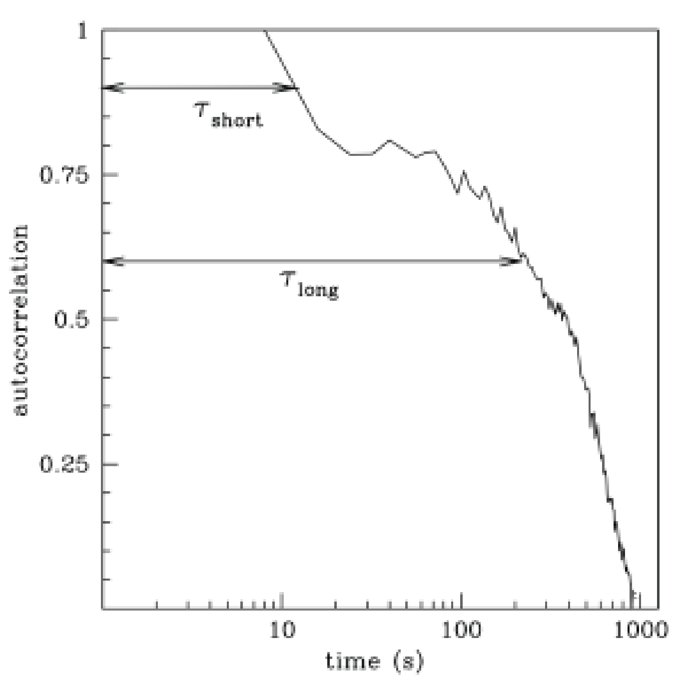
AO PSF: variability

- These features can live several minutes
- Easy to be confused with actual faint companions



AO PSF: variability

- These features can live several minutes
- Easy to be confused with actual faint companions
- Potential danger for systematic searches
  - *Need to get rid of them!!*



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  - *Always on Airy ring!*
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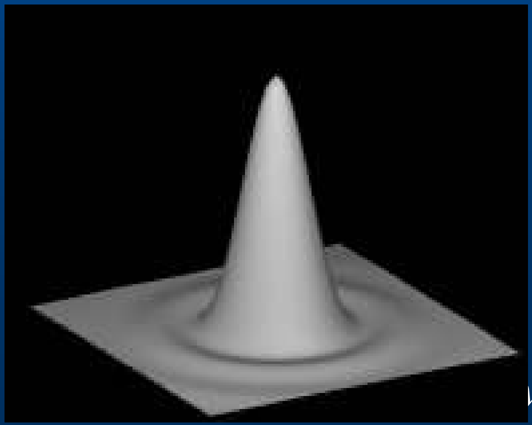
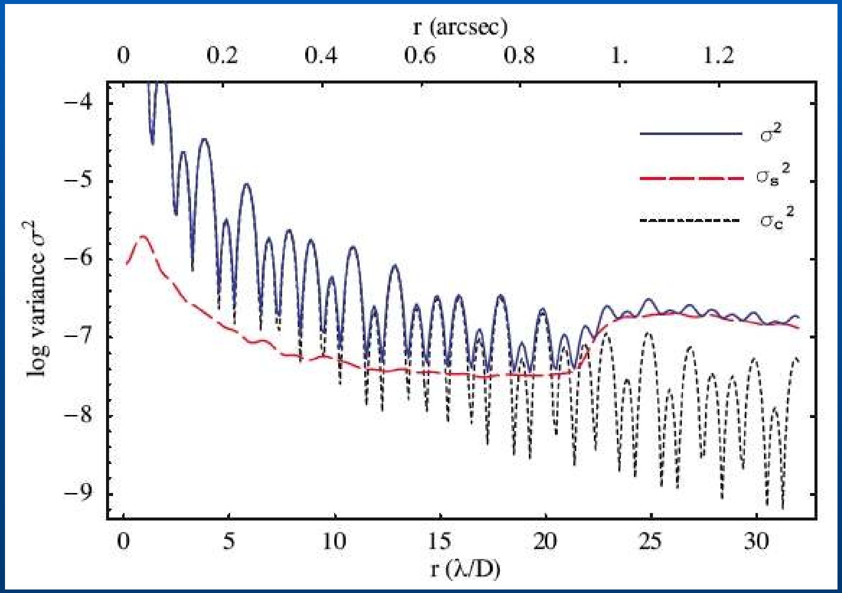
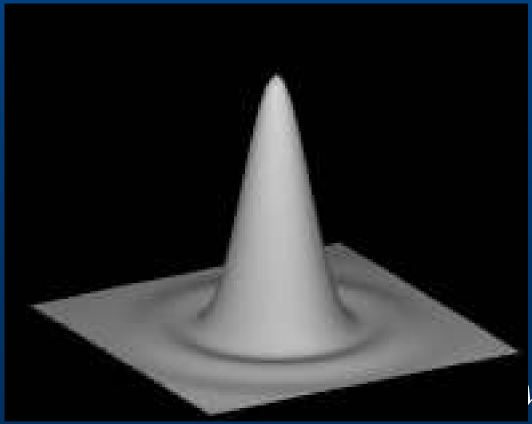


AO PSF: variability

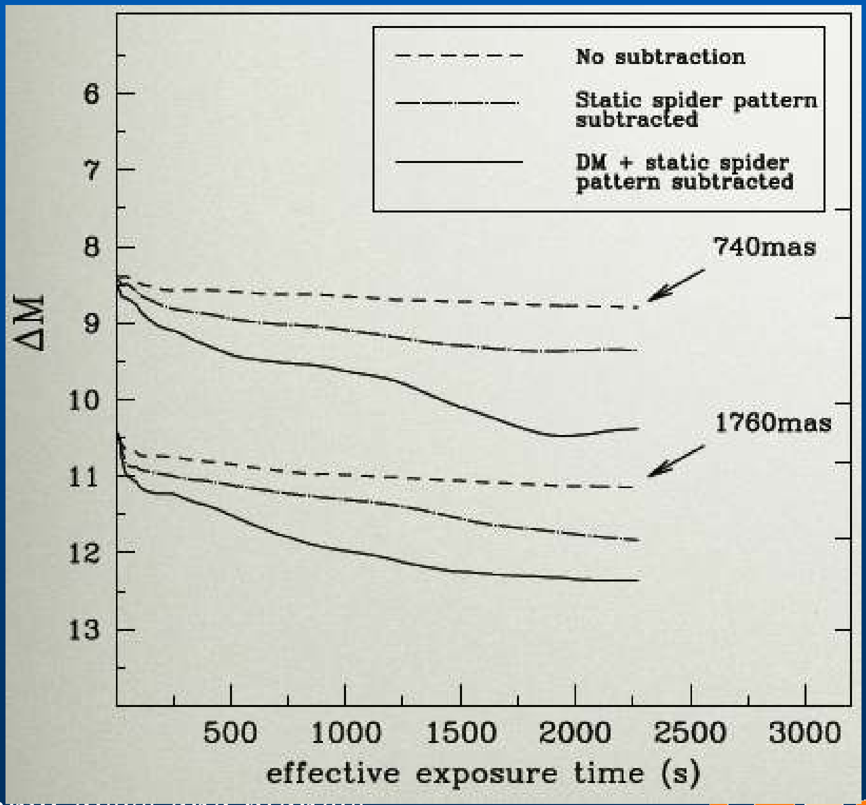
- Problem: they are not randomly located
  - *Always on Airy ring!*
  - *'Pinned speckles'*
- One can't average them out!!!





AO PSF: variability

- In other word, adding more data will not help us here…



AO PSF: variability

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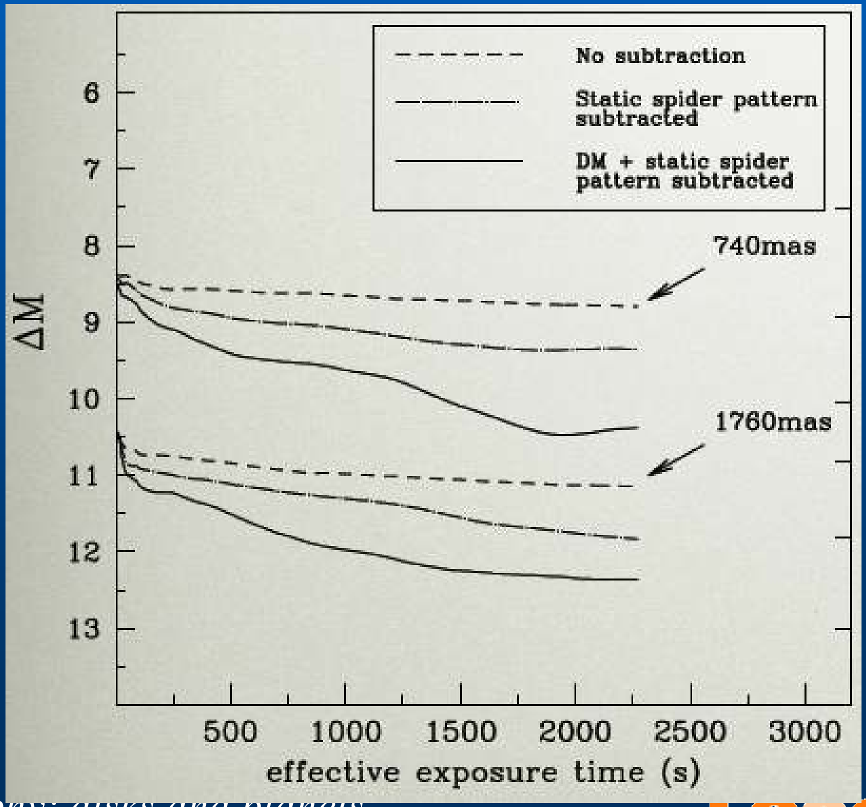
Unusual behavior

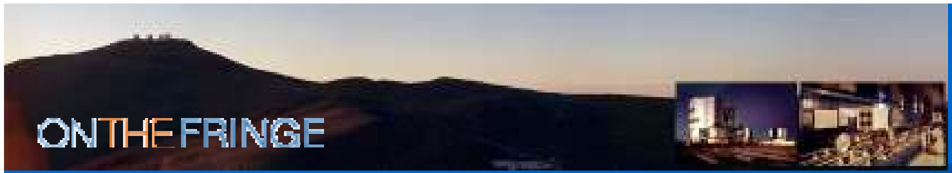
↓

Specific techniques



Improving PSF subtraction

- Simply subtracting a PSF is not enough
  - *Need a more sophisticated method!*



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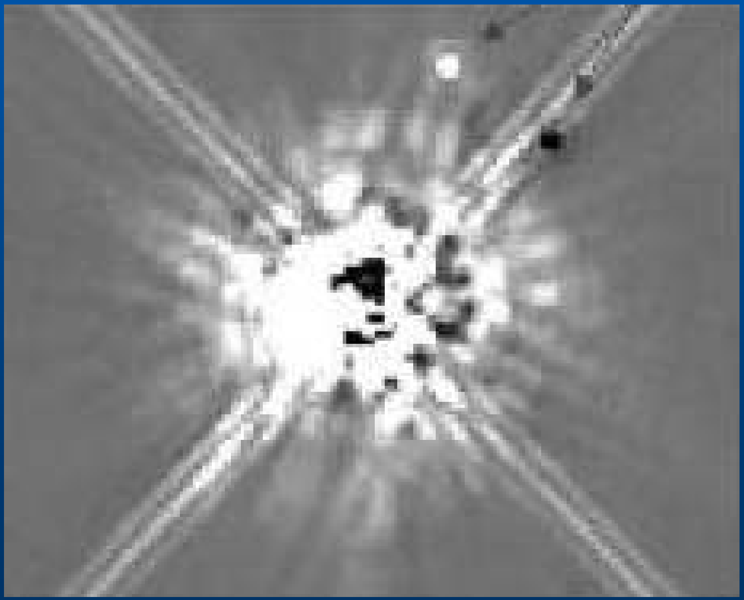
Improving PSF subtraction

- Simply subtracting a PSF is not enough
  - *Need a more sophisticated method!*
- HST: roll subtraction
  - *2 visit with different telescope orientation*
  - *PSF features fixed*
  - *Real companions move!*



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- AO-equivalent of HST roll subtraction?

Improving PSF subtraction

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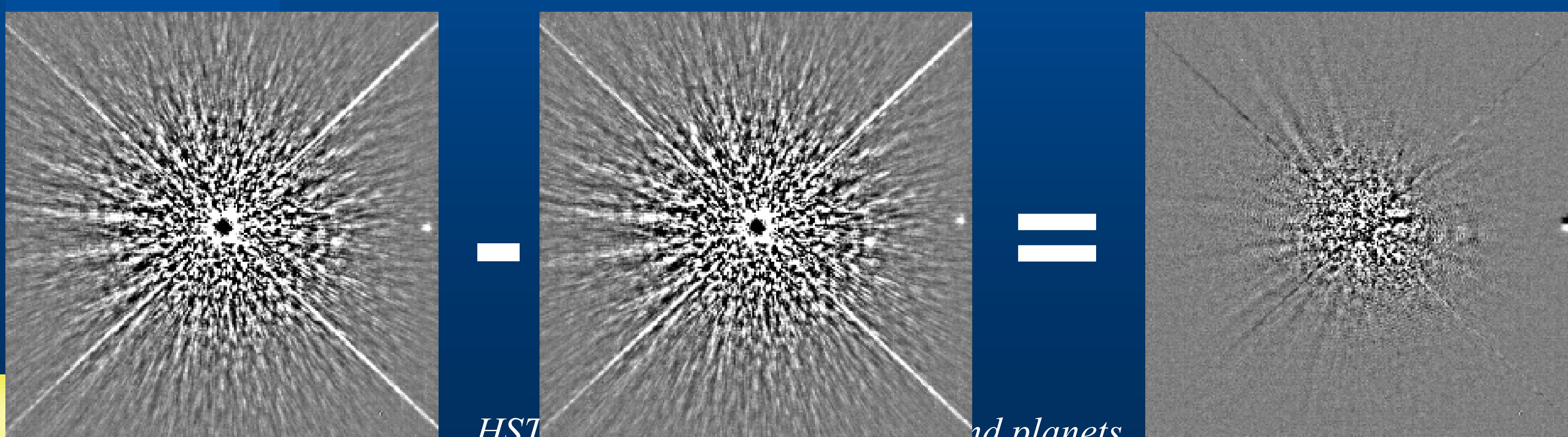
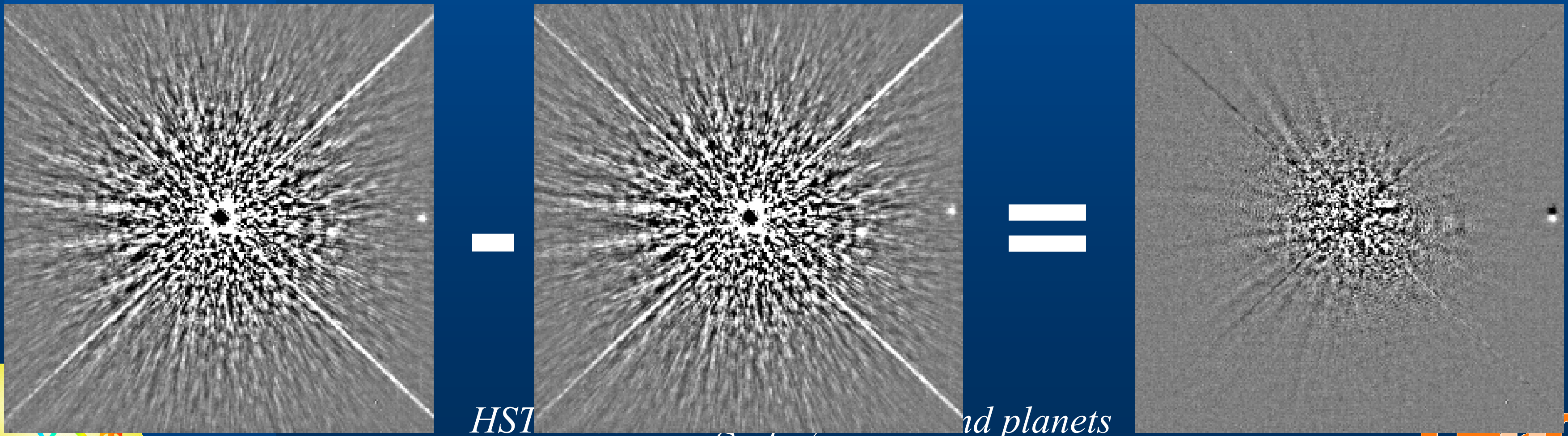
  - *Angular Differential Imaging (ADI)*



Improving PSF subtraction

- AO-equivalent of HST roll subtraction?
  - *Angular Differential Imaging (ADI)*
- Not possible everywhere
  - *Need to rotate field but not pupil*



Improving PSF subtraction

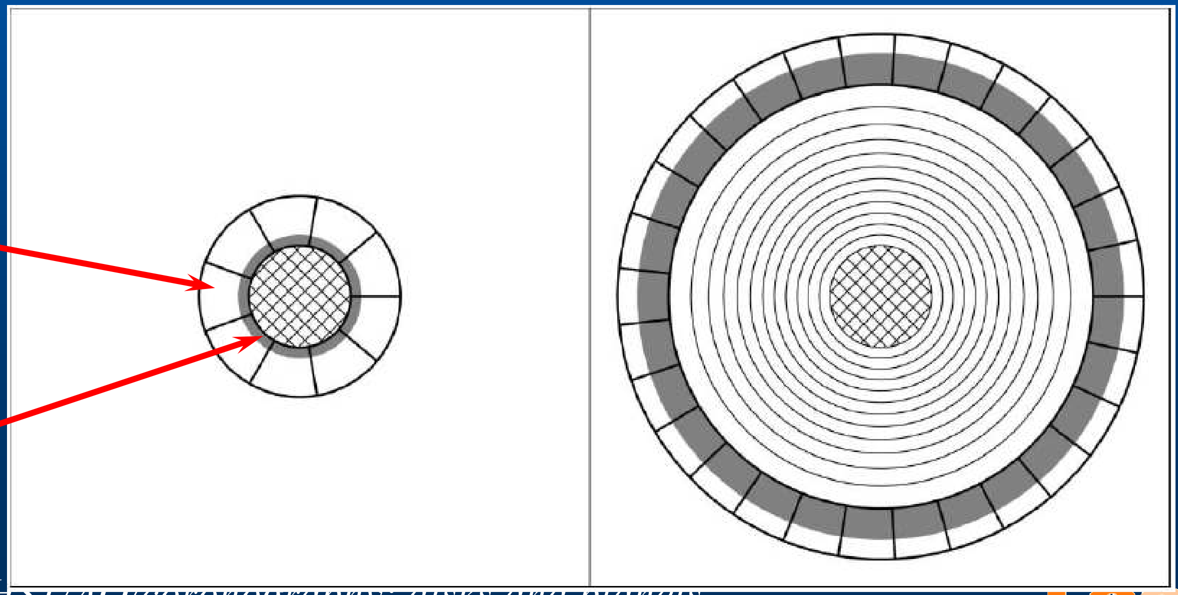
1. remove a smooth axisymmetric pattern from all images

Improving PSF subtraction

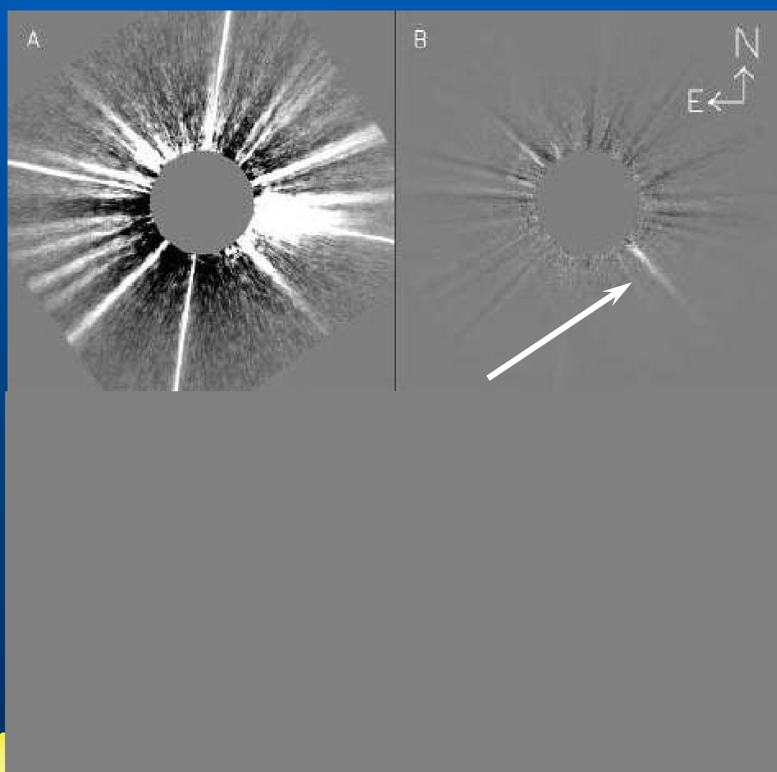
1. remove a smooth axisymmetric pattern from all images
2. a local estimate from all other rotated images

Fitting region

Subtraction region

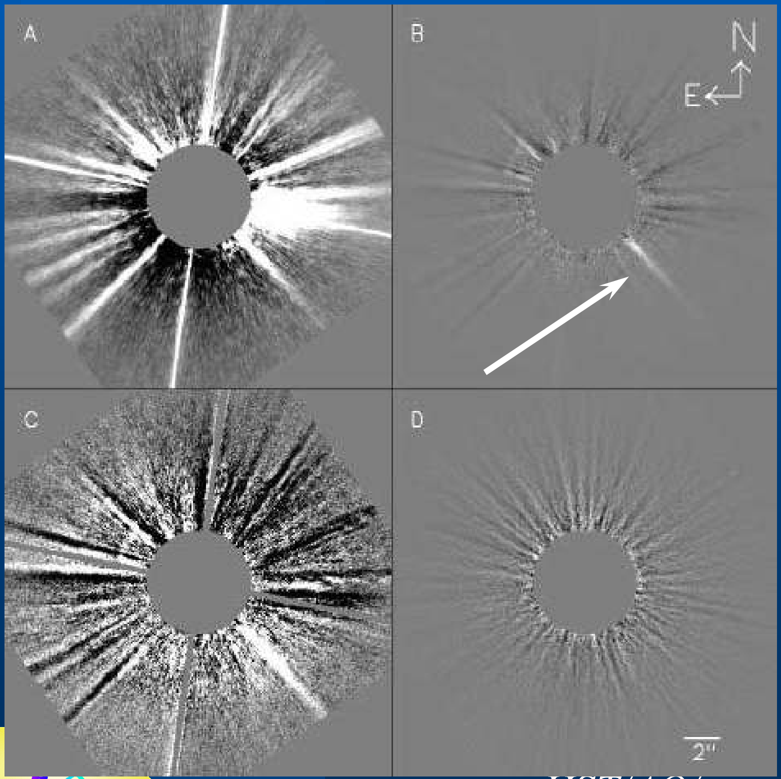


Improving PSF subtraction



Improving PSF subtraction

- Finally, add up al images for net gain!



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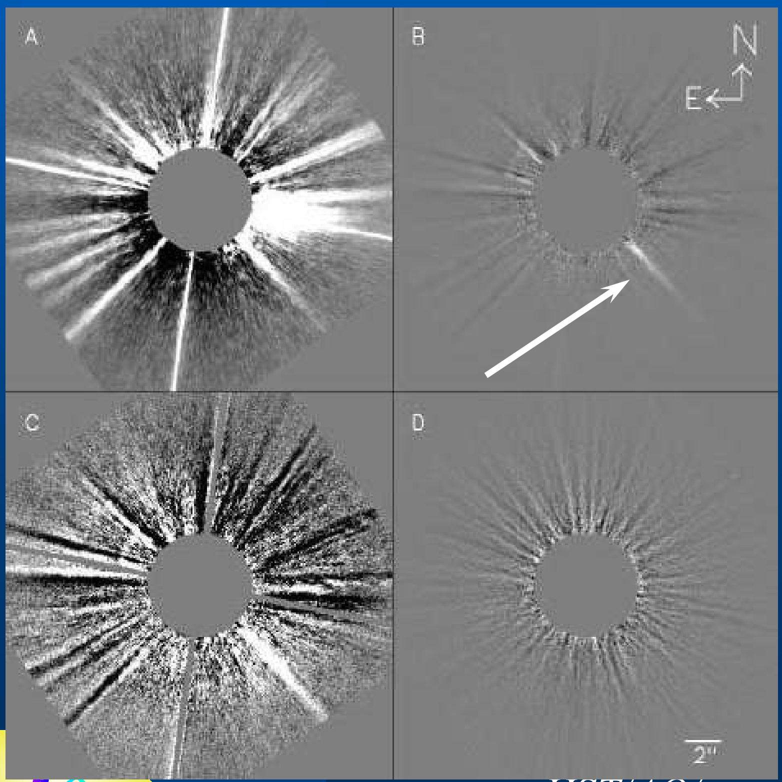
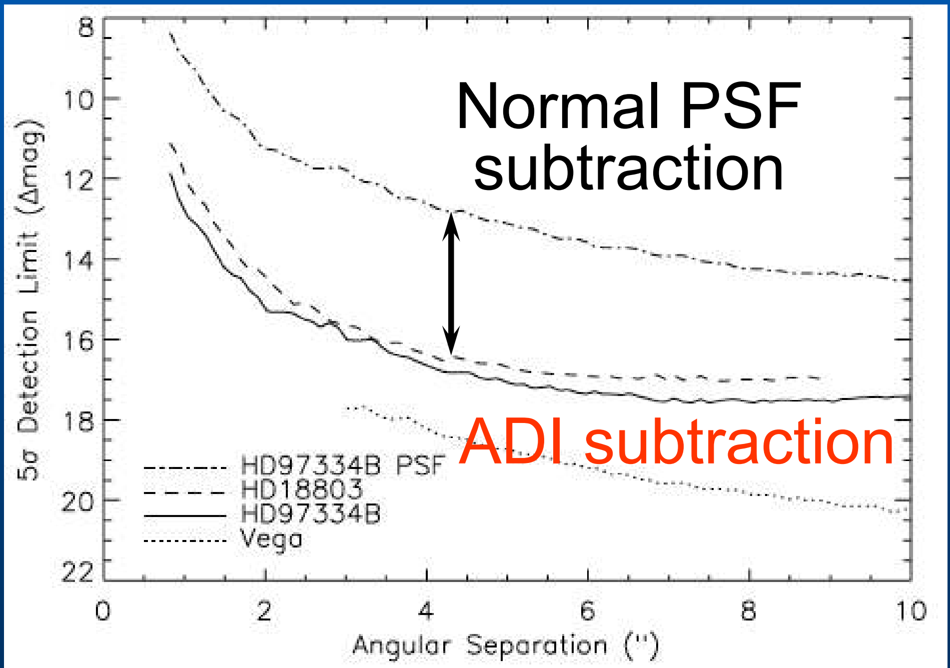
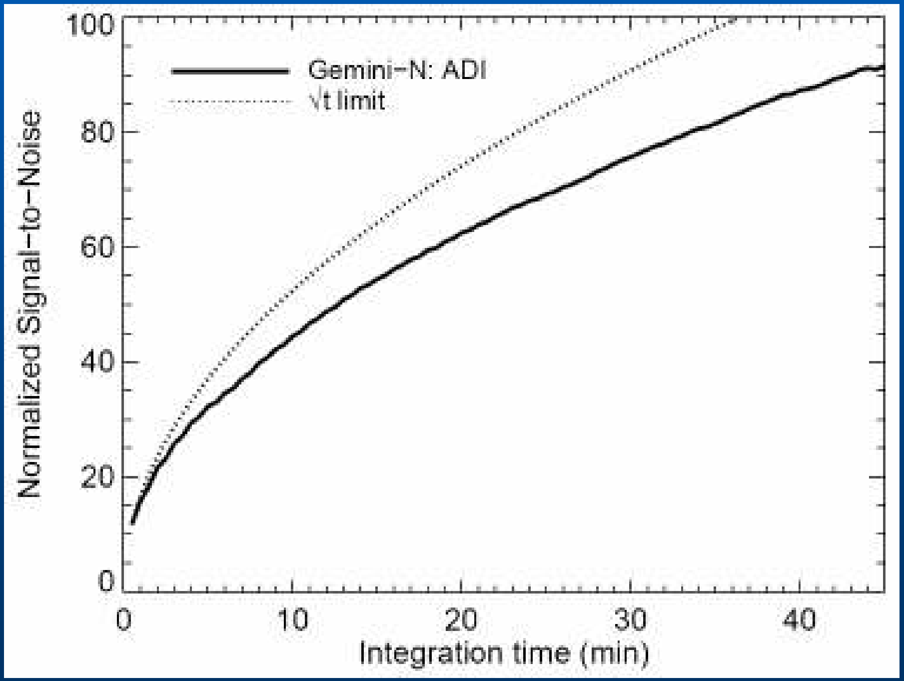




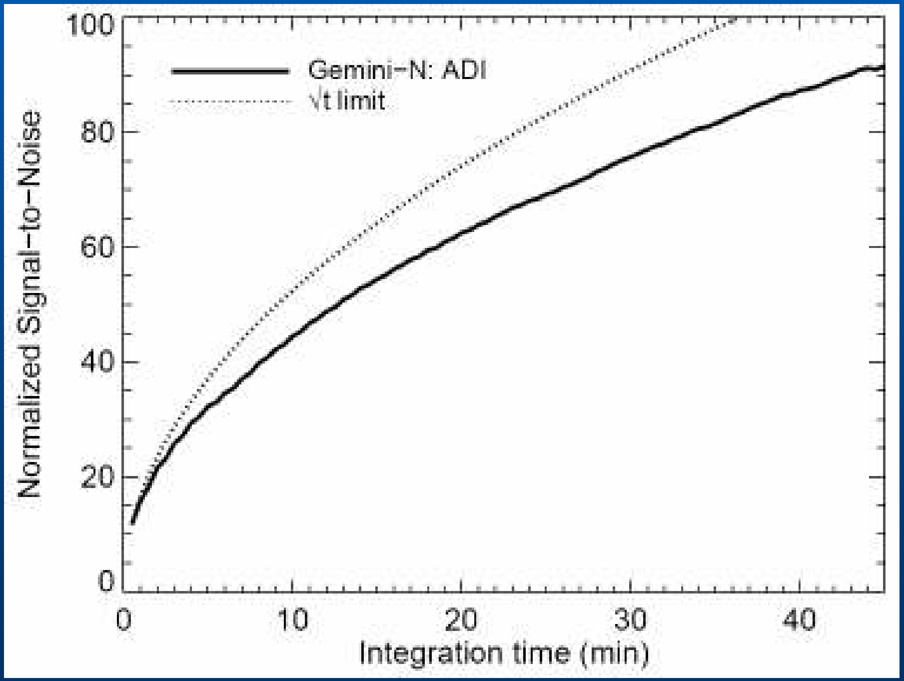
Improving PSF subtraction

- With this technique, noise is again close to photon noise
- SNR ∝ $t^{1/2}$



Improving PSF subtraction

- With this technique, noise is again close to photon noise
- SNR $\propto t^{1/2}$
- Different flavors of ADI, improvements with experience!



Alternative: use λ dependence

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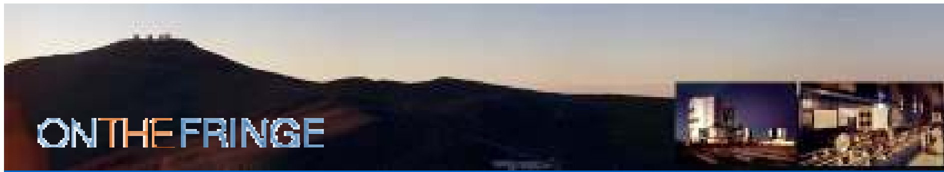
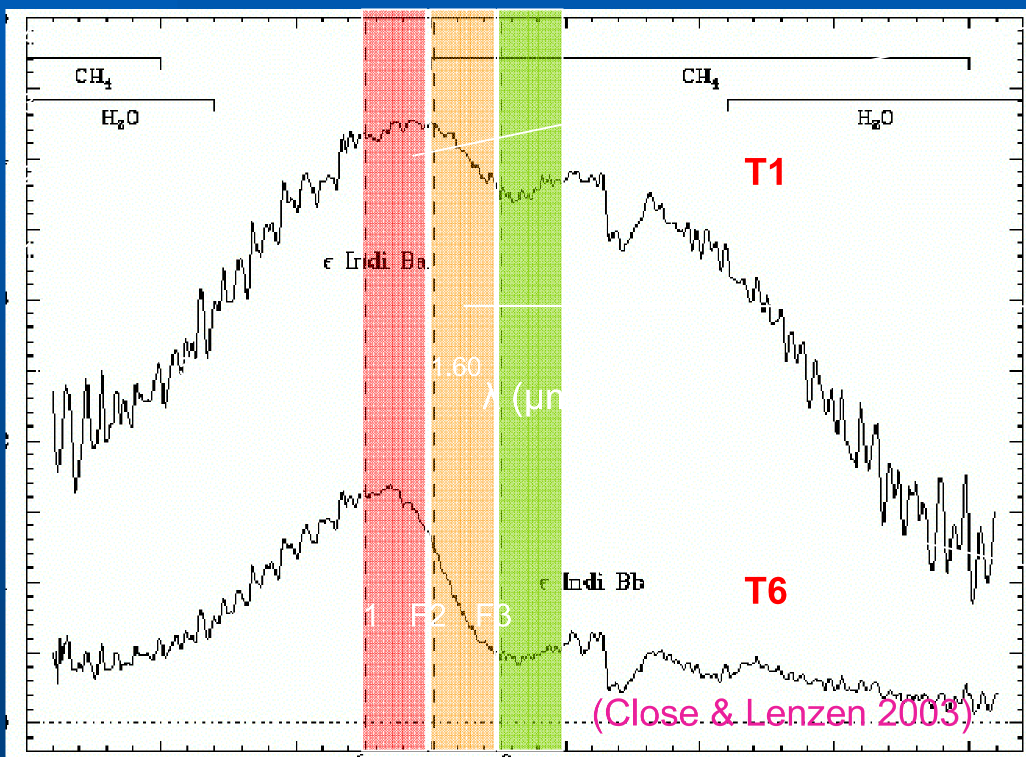
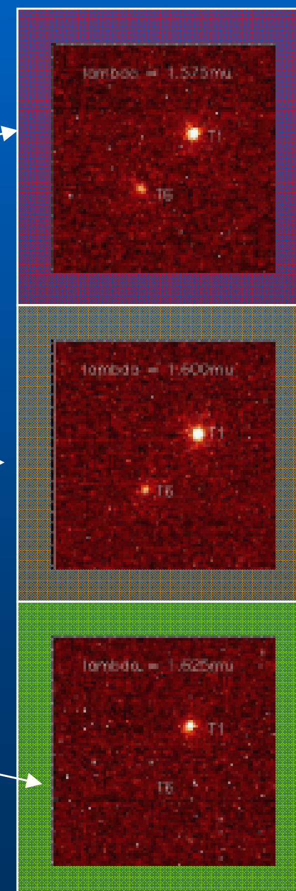
- Speckles are diffraction features
  - *Their location varies with wavelength!*
- On the other hand, real companions do not move…
- It should be easy to disentangle!
- This is the basis for Simultaneous Differential Imaging (SDI)

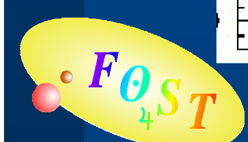


Use wavelength dependence

- Well-selected filters: methane

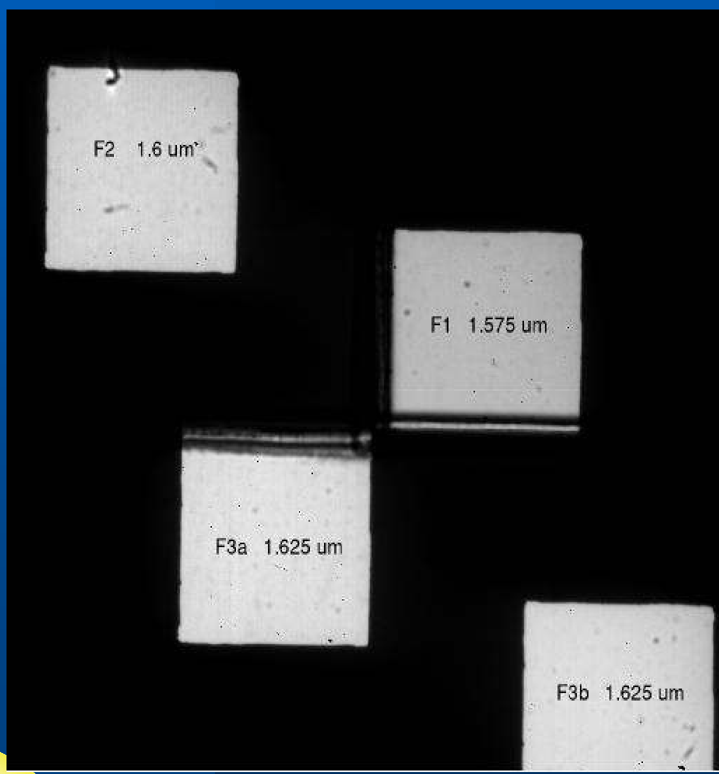






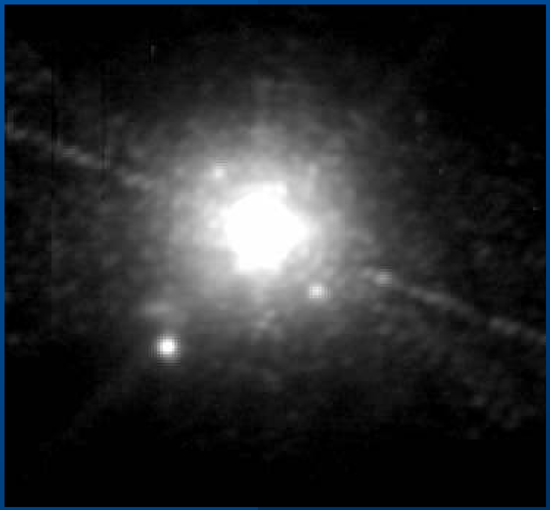
SDI at VLT/NACO

- SDI now offered as a NACO mode



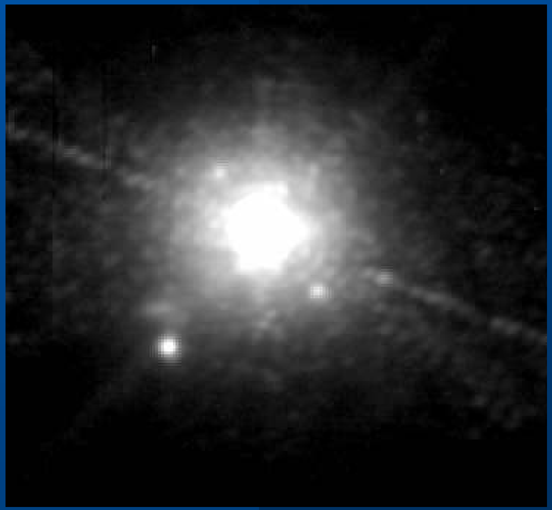
SDI at VLT/NACO

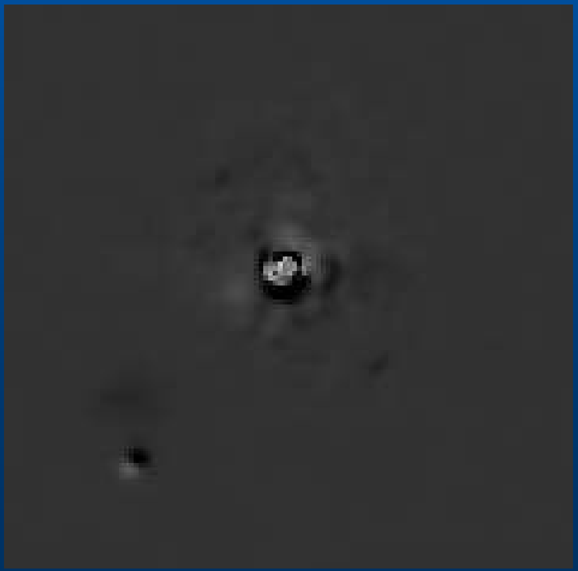
- Select 2 frames and 'stretch' one of them radialy to compensate for $\Delta\lambda$



SDI at VLT/NACO

- Select 2 frames and 'stretch' one of them radialy to compensate for $\Delta\lambda$
- Adjust flux and subtract!





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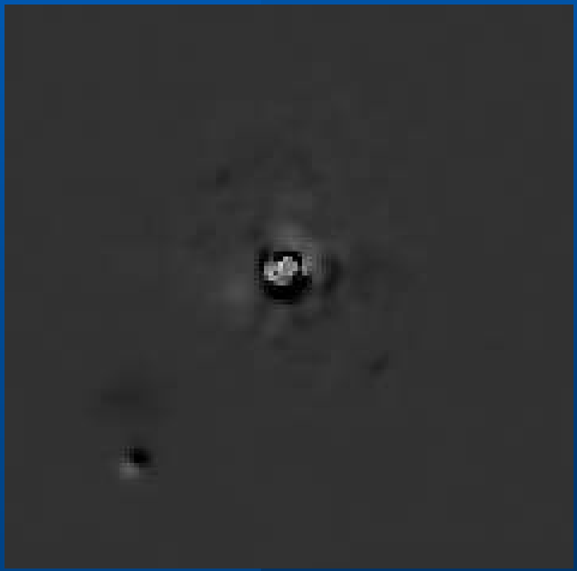
SDI at VLT/NACO

- Even better: combine SDI and ADI
  - *Take advantage of both techniques*



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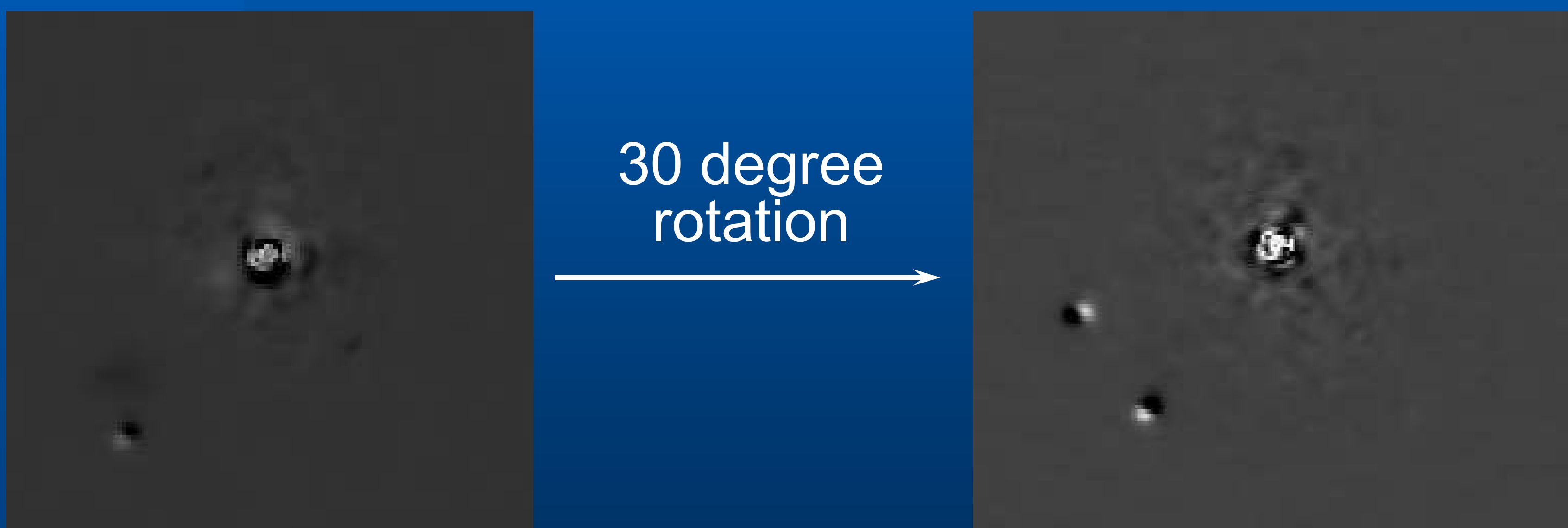

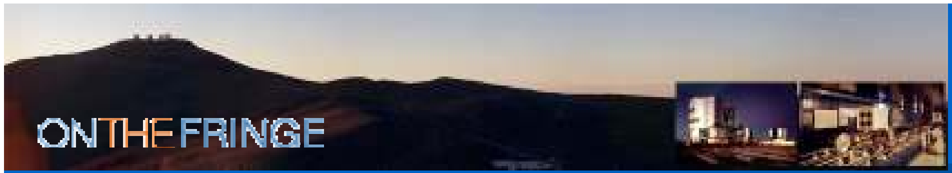

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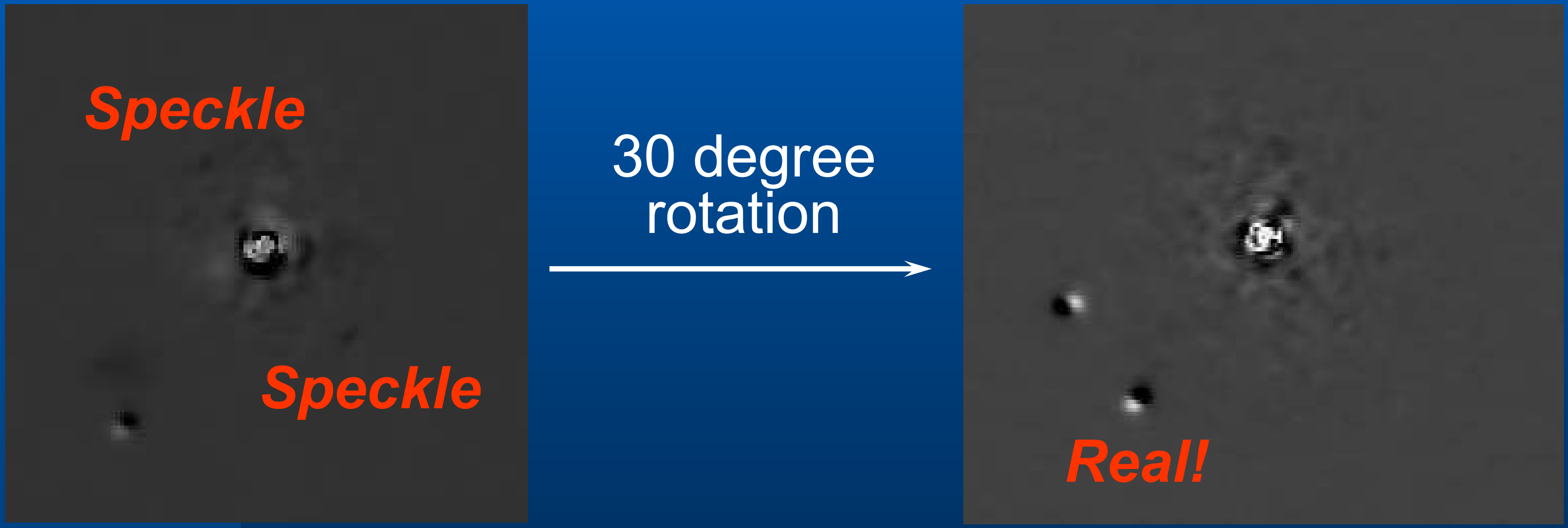

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- Use linear polarization!
  - *Dual beam to avoid losing 50% of light…*

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Can we improve even more?

- Use linear polarization!
  - *Dual beam to avoid losing 50% of light…*
- Starlight is un-polarized whereas planets or disks are polarized
- Not a natural thing to do, but it does improve contrast substantially
  - *Planned for all next generation AO systems*

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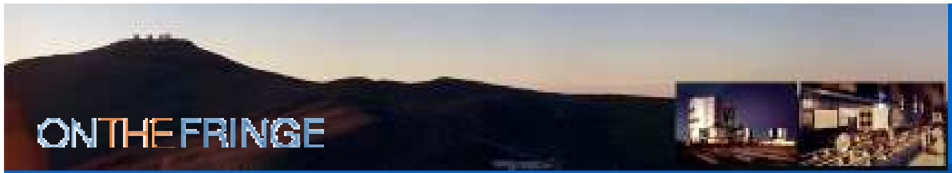
- There is a technique, designed for over 75 years, to improve contrast
  - *Coronography!*

Can we improve even more?

- There is a technique, designed for over 75 years, to improve contrast
  - *Coronography!*
- Can be combined with alll these techniques
- See tomorrow's course



Beyond imaging…

- Characterization of planets implies spectroscopy (see tomorrow’s course)

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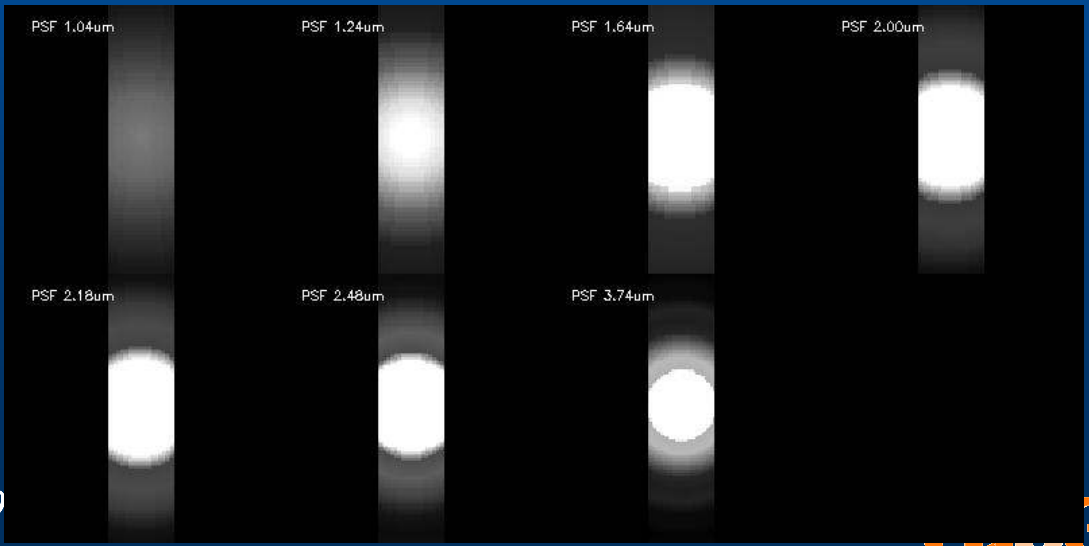

HST/AO

Beyond imaging…

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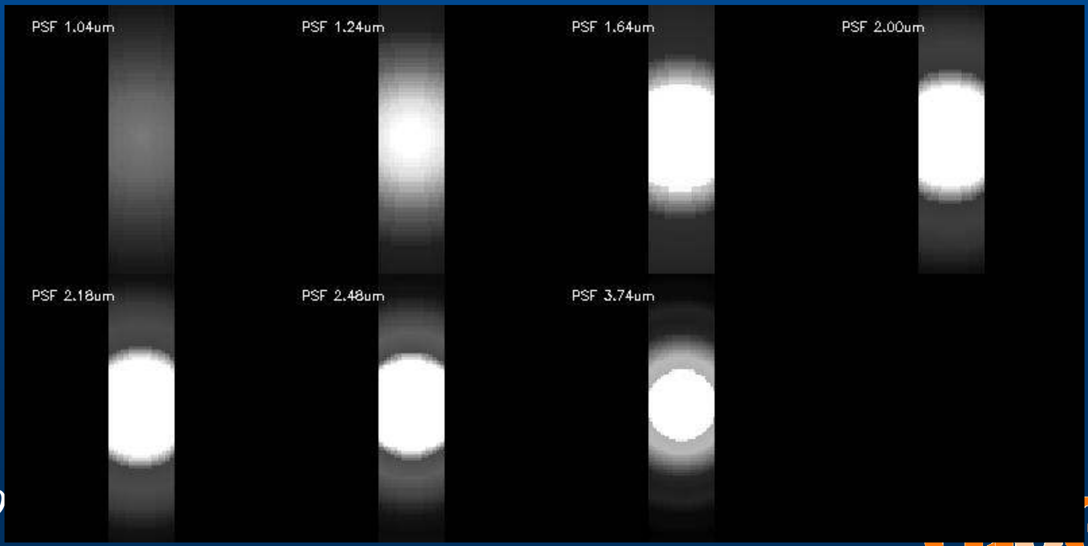
Integral Field Spectroscopy is needed



HST/AO

A quick bibliography

- Speckle interferometry
  - *Labeyrie (1970), Patience et al. (1998)*
- Adaptive Optics
  - *Textbooks by F. Roddier, or J. Hardy, or R. Tyson*
  - *http://cfao.ucolick.org ⇒ many links worldwide*
- Angular Differential Imaging
  - *Marois et al. (2006), Lafrenière et al. (2007)*
- Simultaneous Differential Imaging
  - *Racine et al. (1999)*
  - *Lenzen et al. (2004), Marois et al. (2004)*