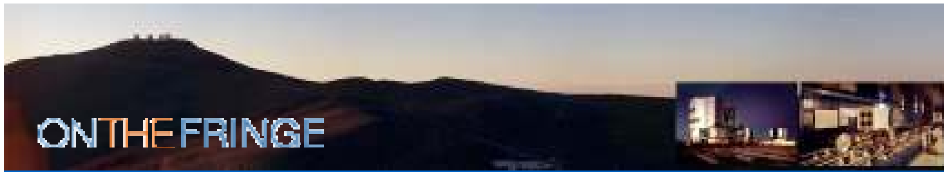
HST - AO - Coronography

Exoplanets and circumstellar disks:
Past and future science

G. Duchêne (Obs. Grenoble)

FOST

LAOG



Outline (2 classes)

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

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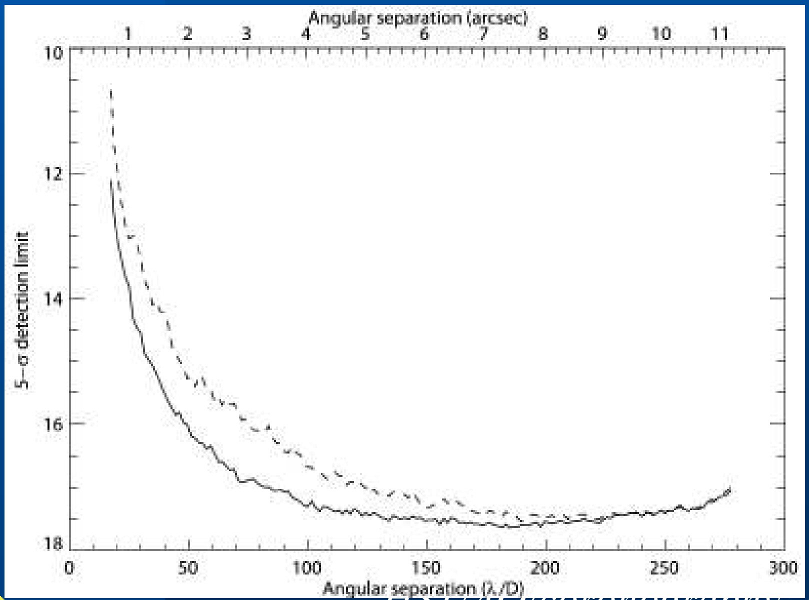
Coronography : Why and How?

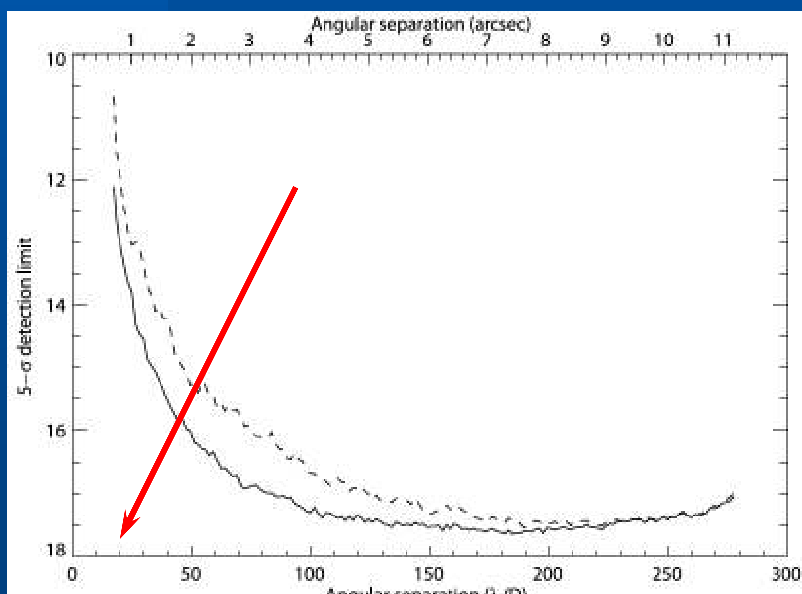
Need to improve contrast!

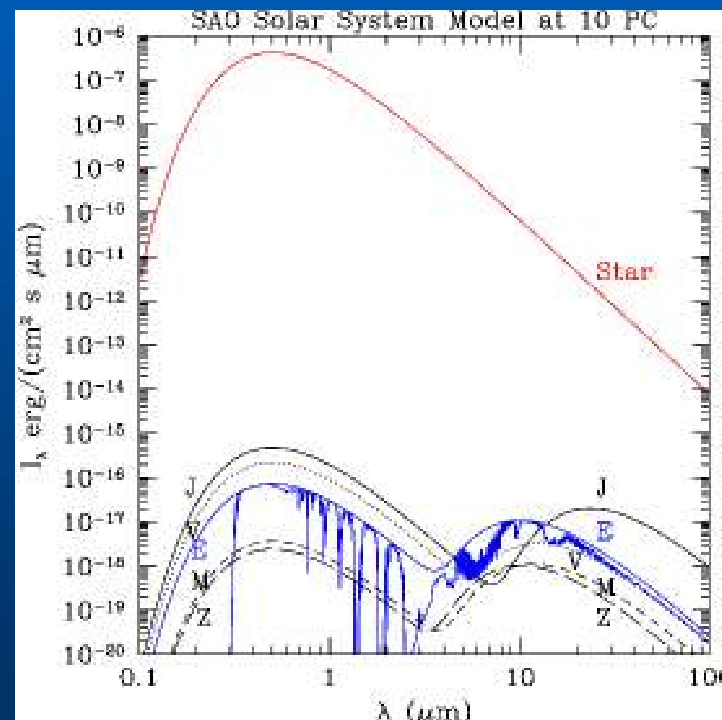
- Achievable contrast is not yet sufficient for planets (or disks)



Need to improve contrast!

- Achievable contrast is not yet sufficient for planets (or disks)
- Need to go inside!





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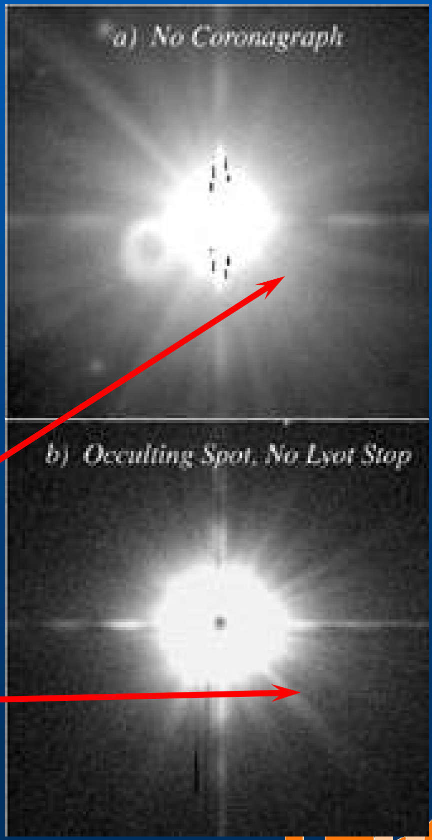
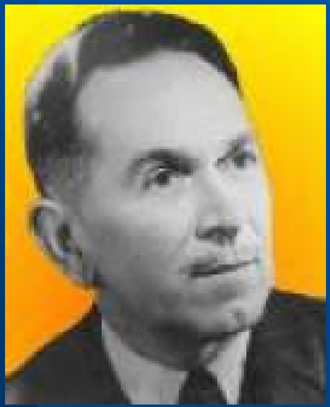


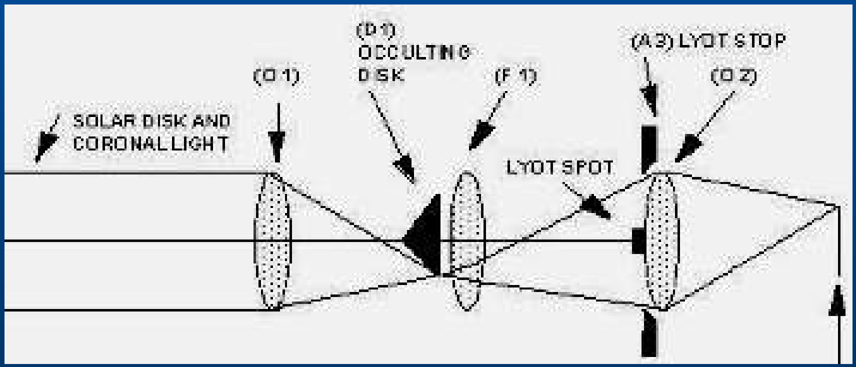
Block the central star!

- A simple idea to prevent saturation on detectors and go deeper
- However, just hiding it is not enough…
  - *Try the Sun with anything you can to hide it!*

Lyot coronography

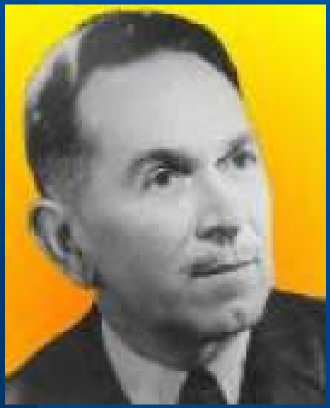
- 1930s design, dedicated for the Sun

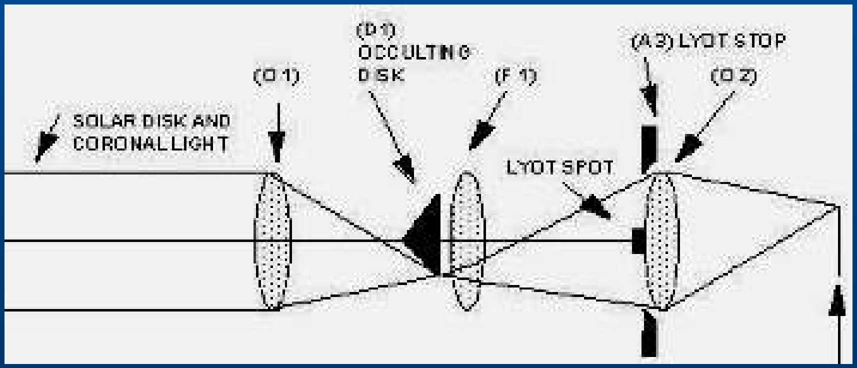




Lyot coronography

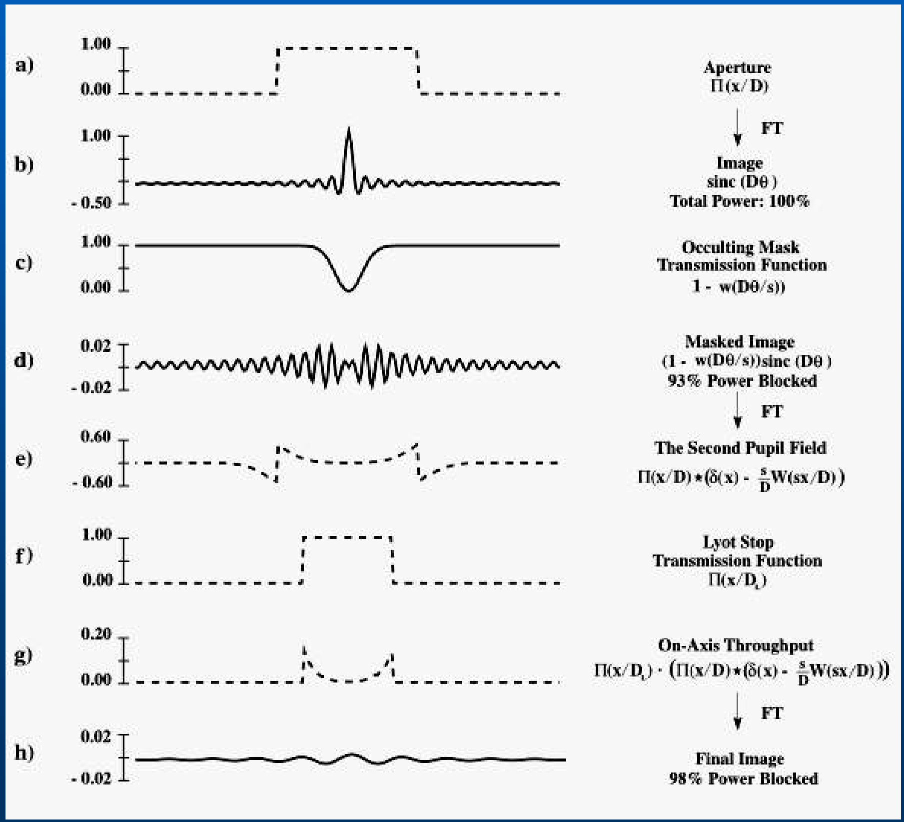
- 1930s design, dedicated for the Sun
- Key element: the Lyot stop!!
  - *Blocks scattered light*





Lyot coronography

- Optical concept:



——— *Image plane*

\- - - - - *Pupil (Fourier) plane*

Lyot coronography

- Optical concept:

Occulting mask

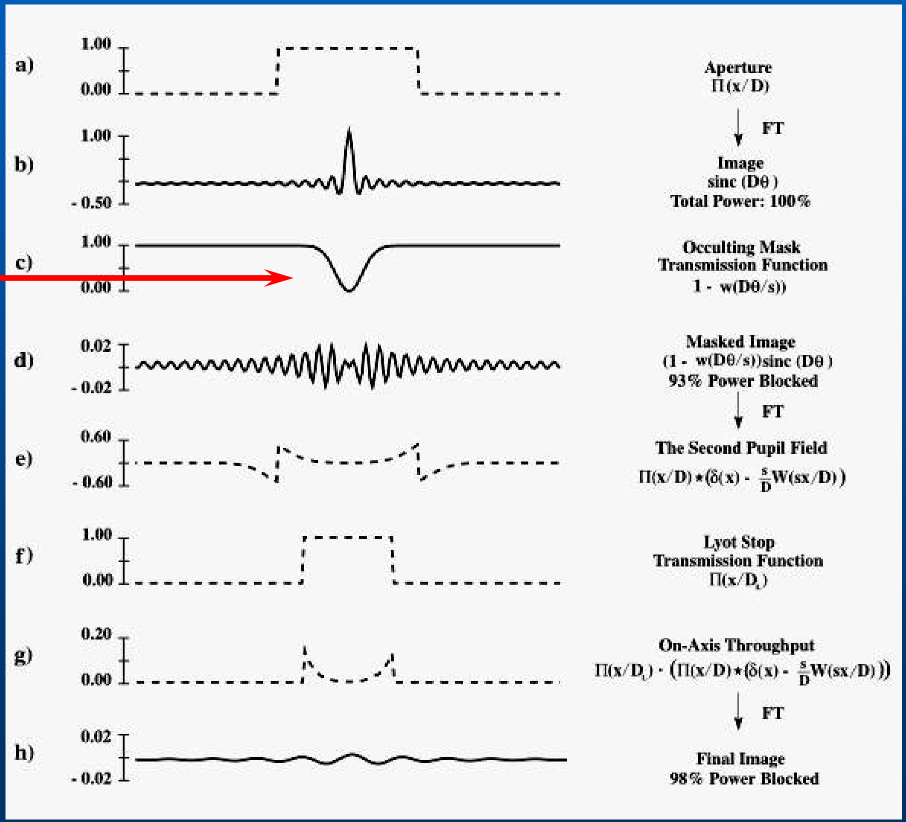


Image plane

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Lyot coronography

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Lyot stop

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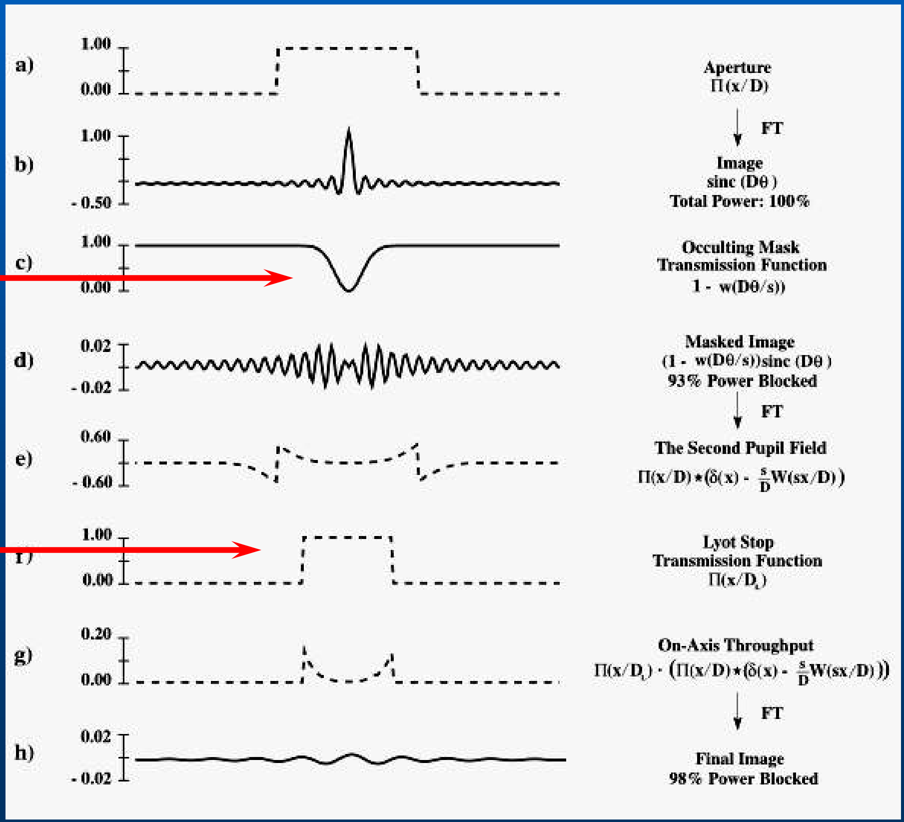

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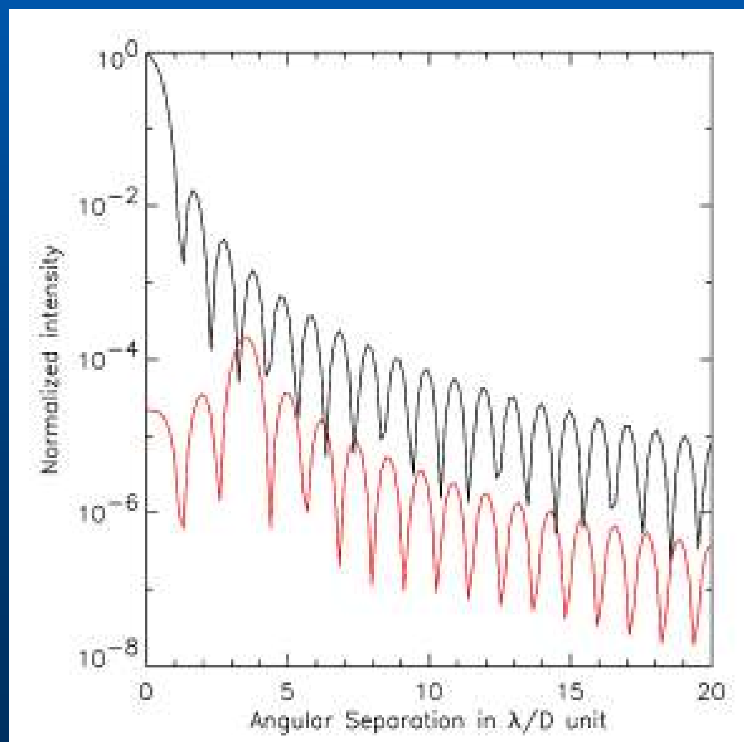
Lyot coronography

- Strong improvement on achievable contrast



Lyot coronography

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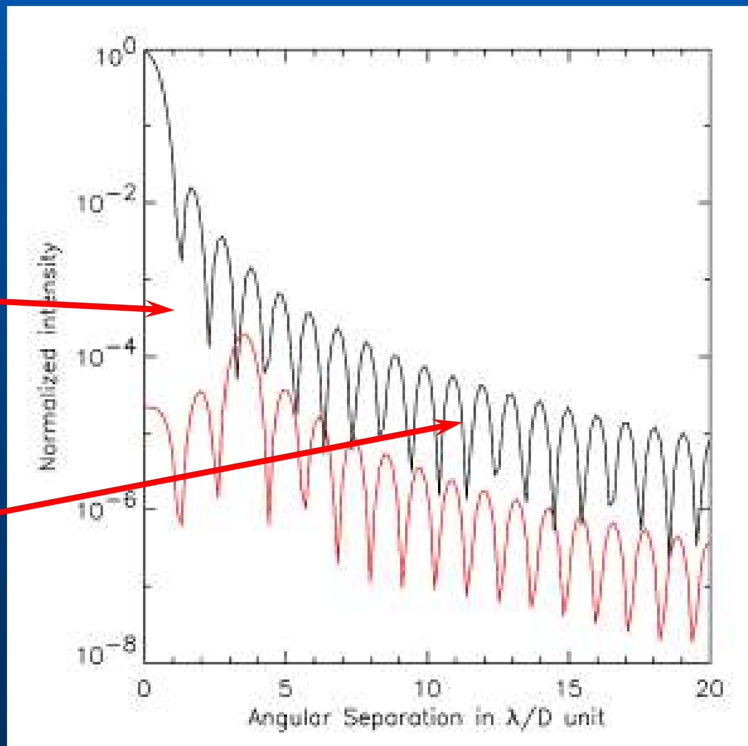
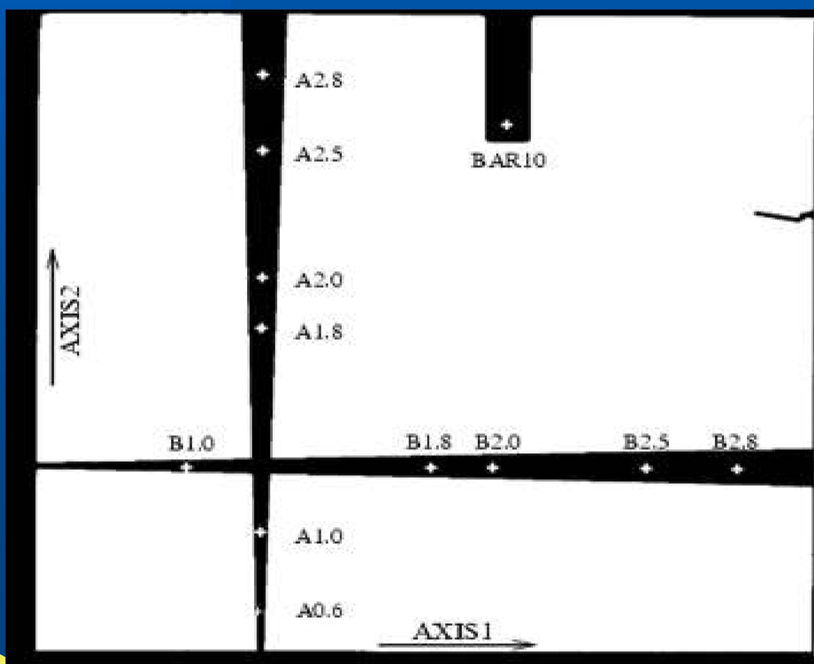
inside

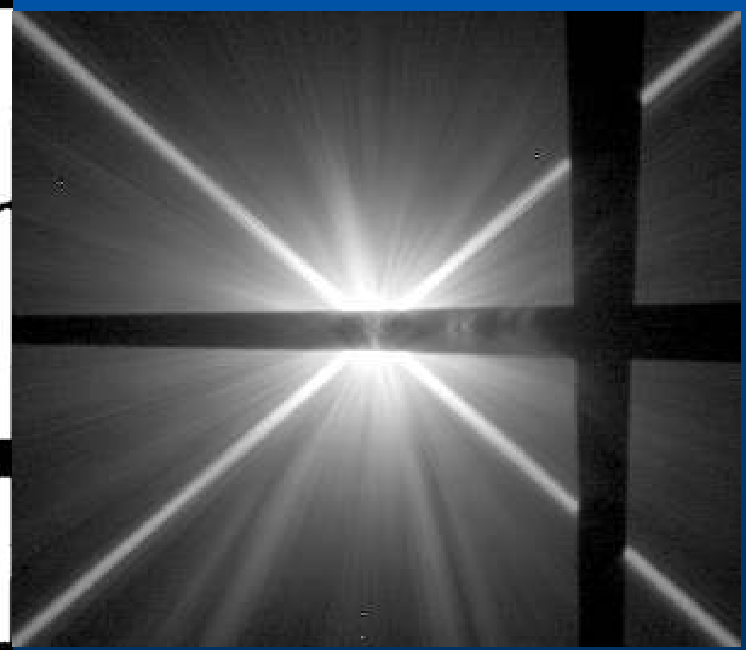
outside



Lyot coronography

- Occulting spot not always circular
  - *STIS wedge, allows range of spot sizes*





Modern coronographs

- HST and ground-based AO systems all have coronographic modes
- Typical occulting spot size: 0.3-3''

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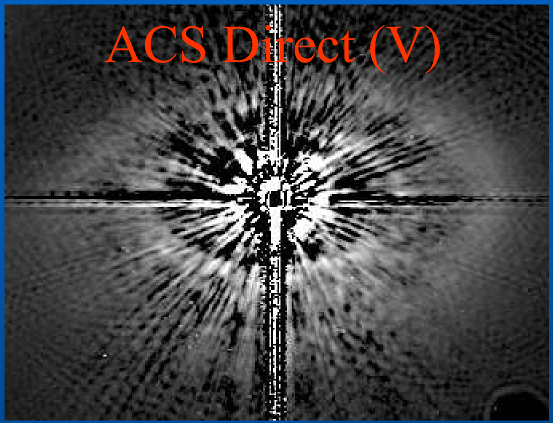
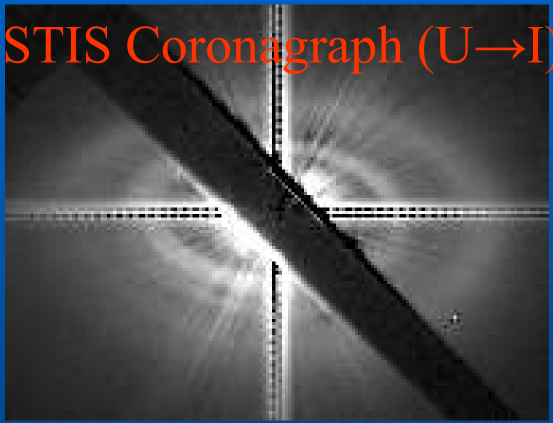
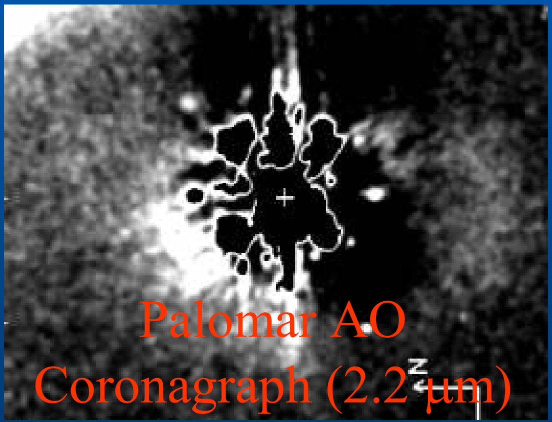
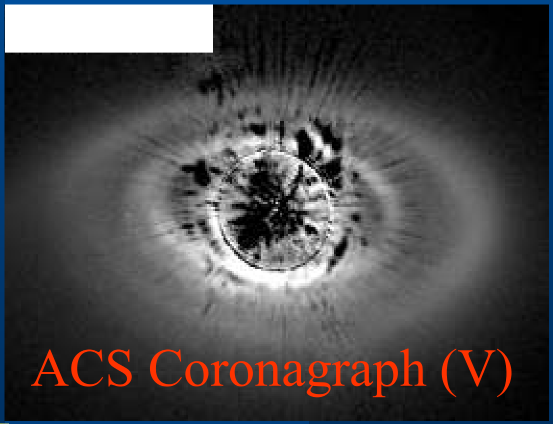
- HST and ground-based AO systems all have coronographic modes
- Typical occulting spot size: 0.3-3”
- Importance of space
  - *Stable PSF and ‘perfect’ positioning*
- Much more data from HST than ground-based AO

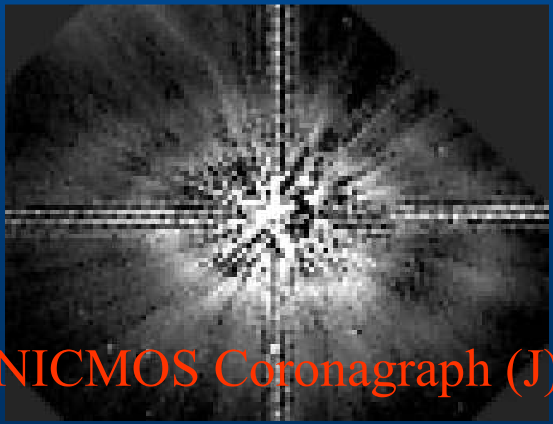
Modern coronographs



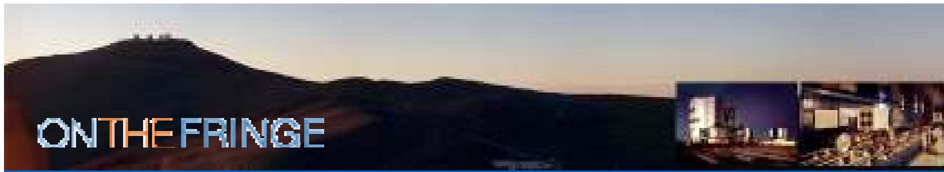






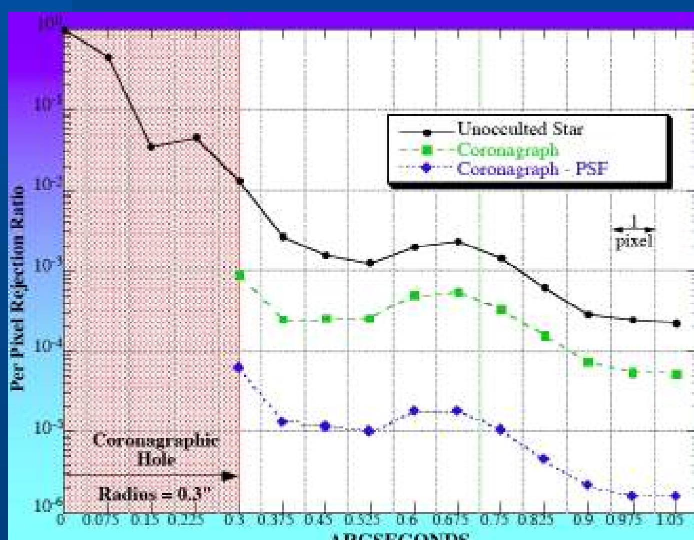


Courtesy: J. Krist



Modern coronographs

- Coronography can be combined with
  - *PSF subtraction*
  - *Roll subtraction, ADI*
  - *Polarization*



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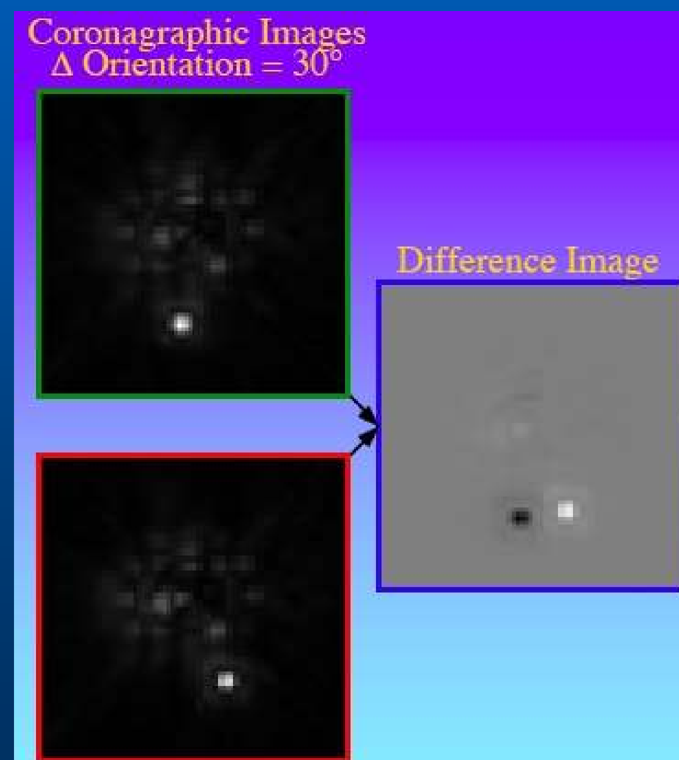

disks and planets

Improving on Lyot

- Residuals in coronographic images come from diffraction off sharp edges

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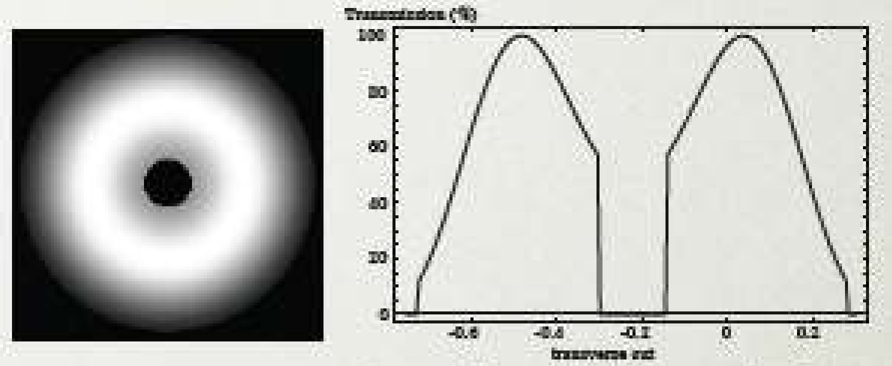
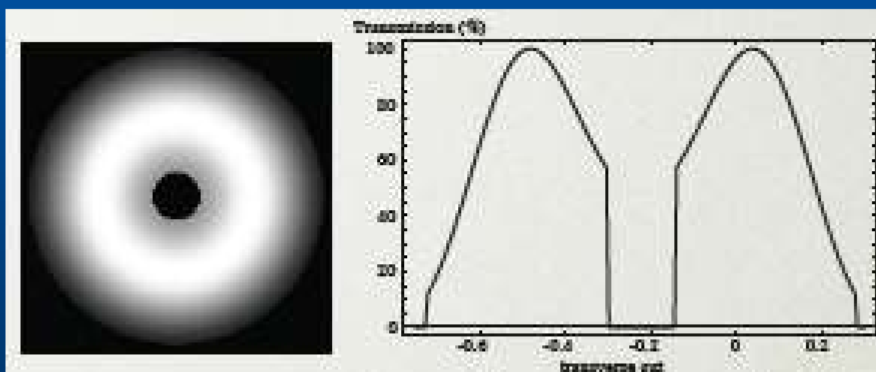


Apodizer transmission
Throughput 50%

Improving on Lyot

- Residuals in coronographic images come from diffraction off sharp edges
  - *Introduce a smoothing function*
  - *Apodization*
- Smoother profiles
- Lower resolution



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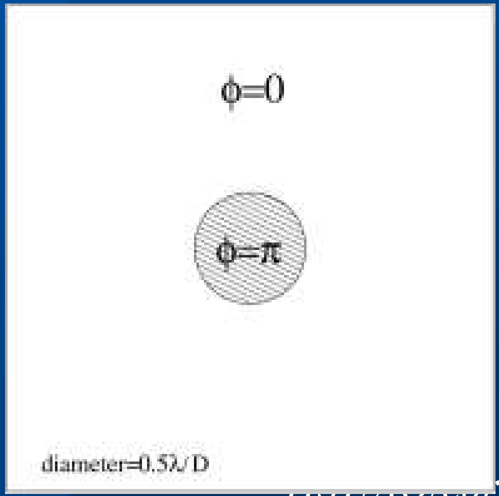
New coronograph designs

- Disk phase mask: cancel the star with itself (destructive interference)



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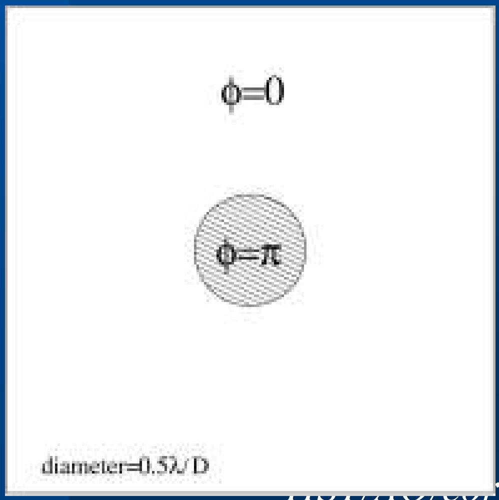
  - *Size of spot is selected to match fluxes*
  - *Size = 0.53 λ/D*



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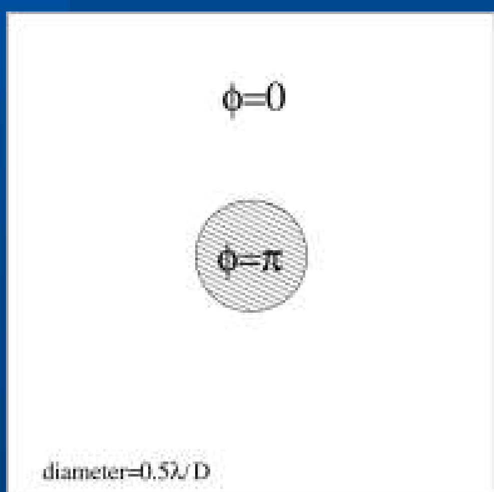
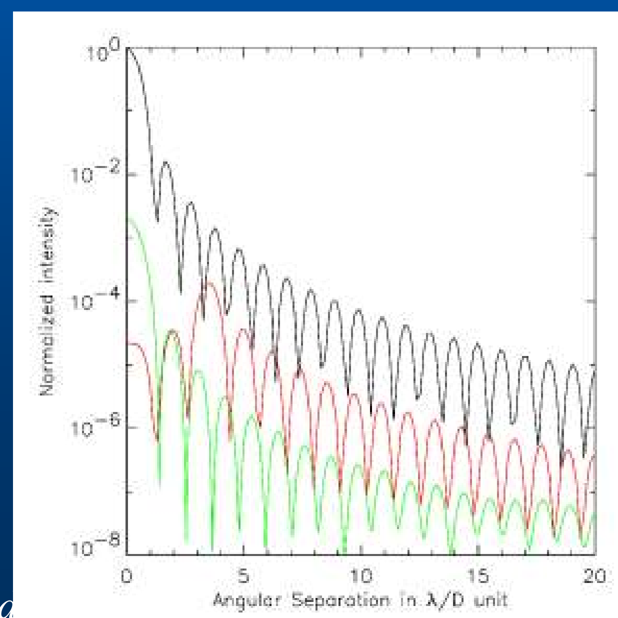
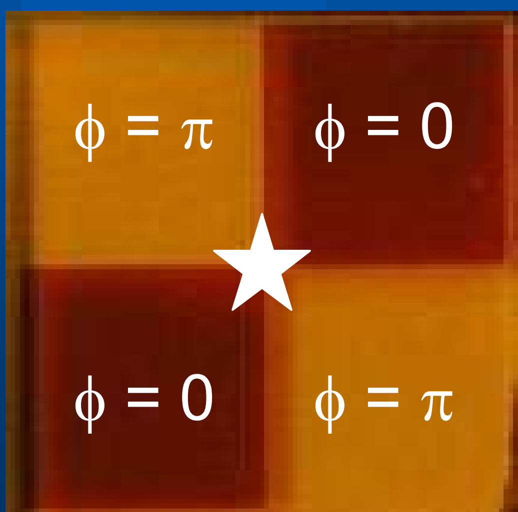




New coronograph designs

- 4-quadrant phase mask
  - *A different flavor of the same idea*



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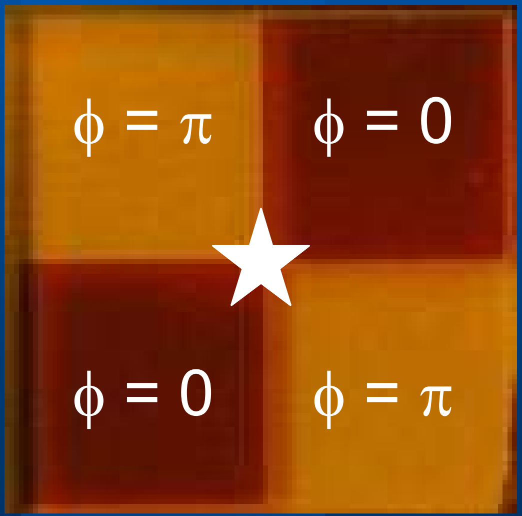

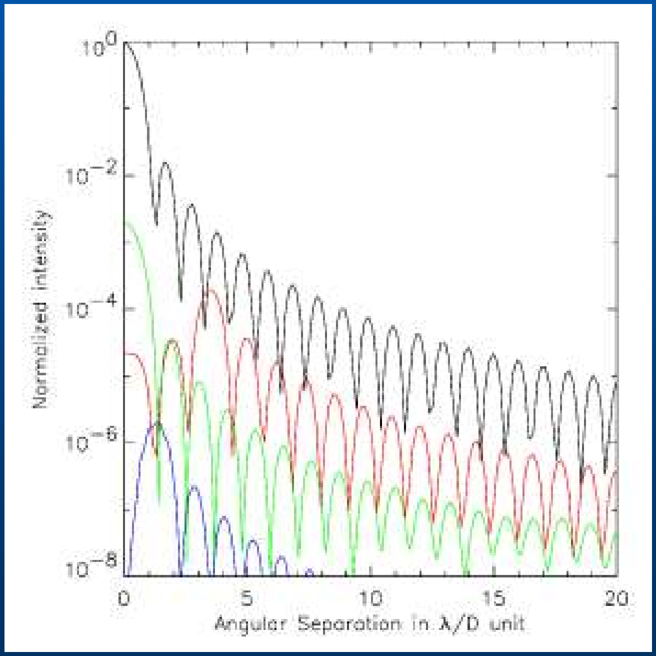

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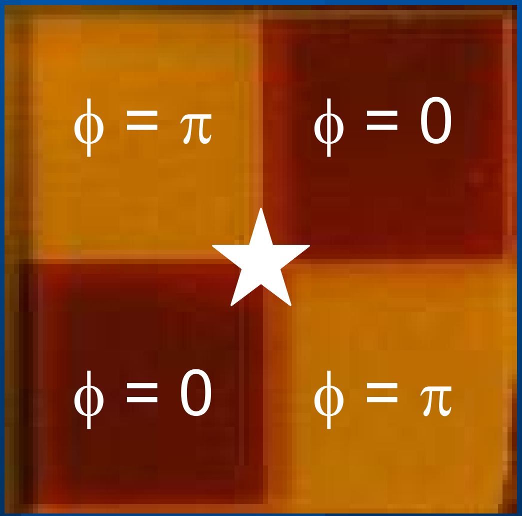
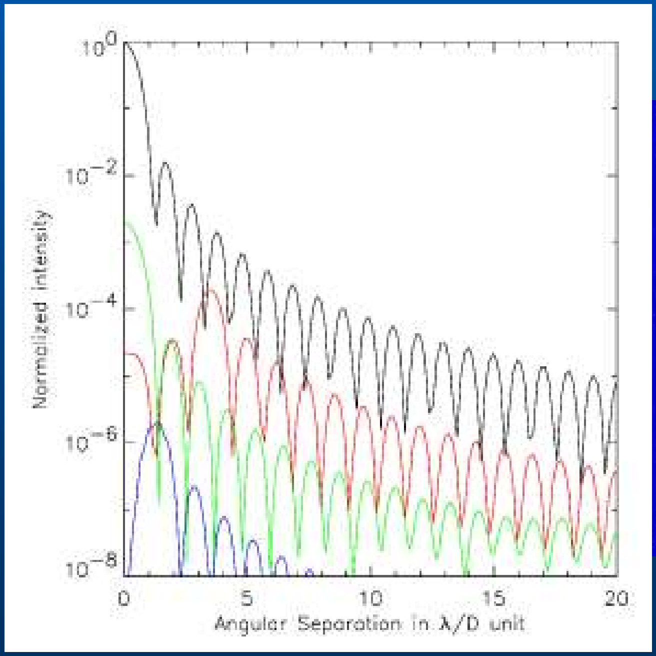
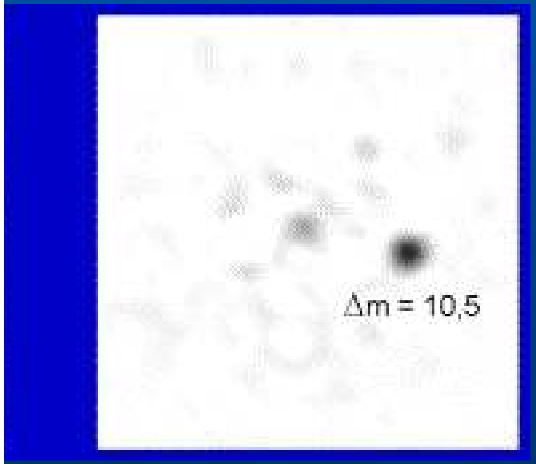


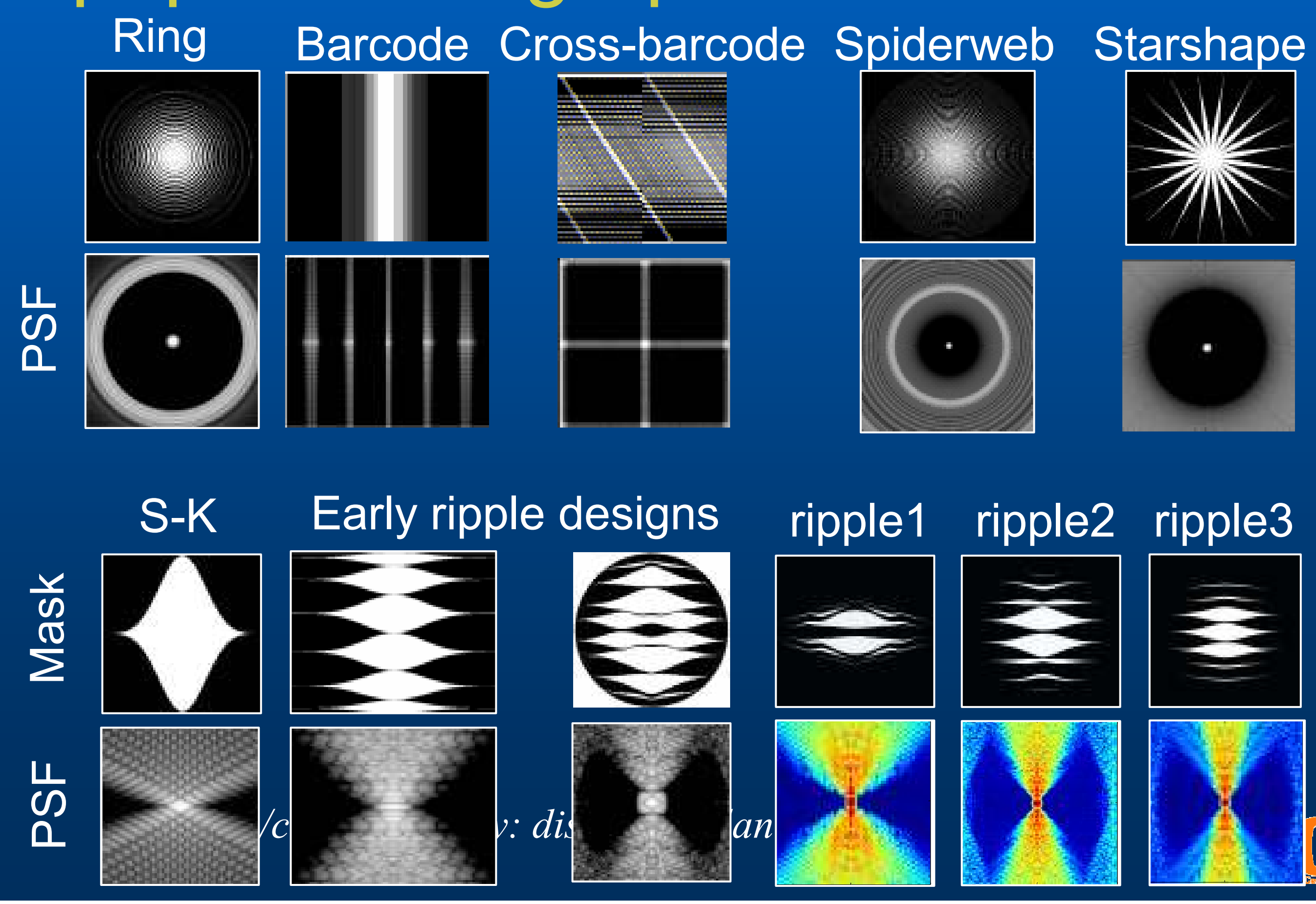




2 λ/D, in lab

New coronograph designs

- Shaped pupil coronographs



Coronography: limitations

- Fine design and alignment!

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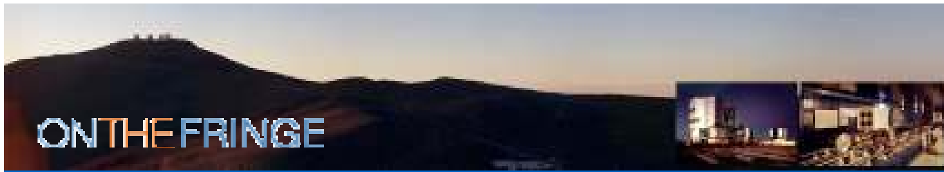
Aligned Lyot Stop

Misaligned Lyot Stop

Observed



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- Chromaticity of transmission optics!
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  - *Sensitivity?*

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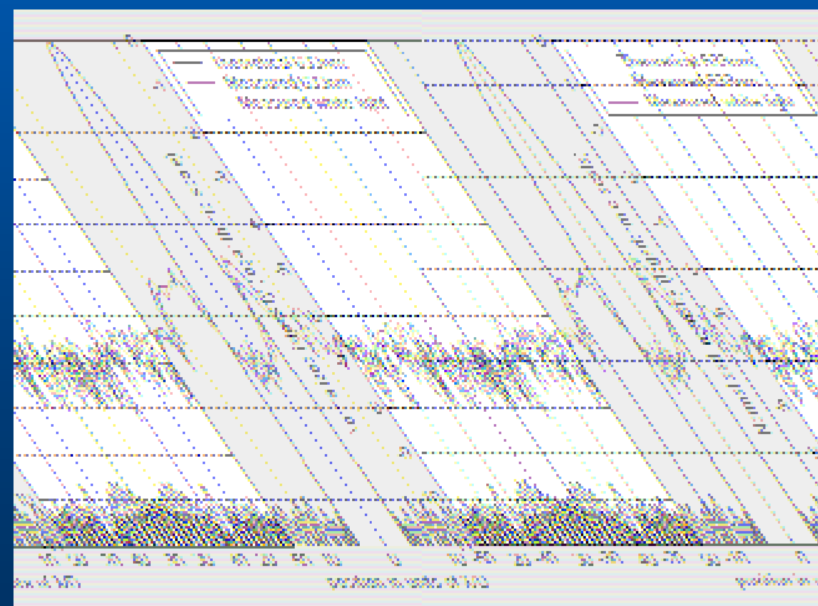

Coronography : Data processing

How to treat such datasets?

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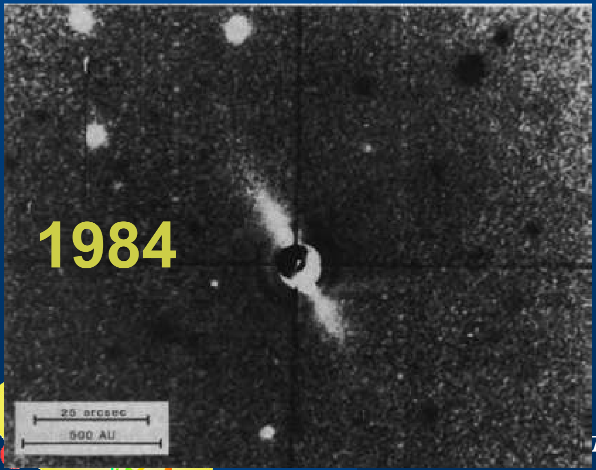
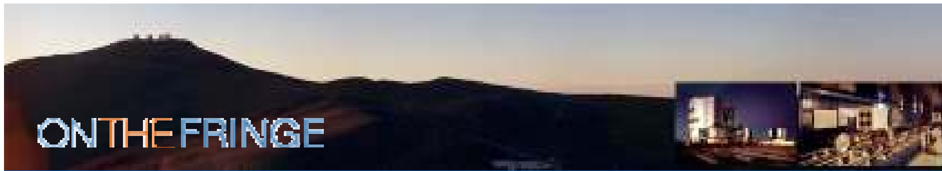
How to treat such datasets?

- Need to subtract remaining stellar flux
- Similar to AO images
  - *Regular PSF subtraction*
    - *Time/color constraints*
  - *Roll subtraction*
    - *Not possible on all telescopes*

Example: β Pictoris

Smith & Terrile (1984)





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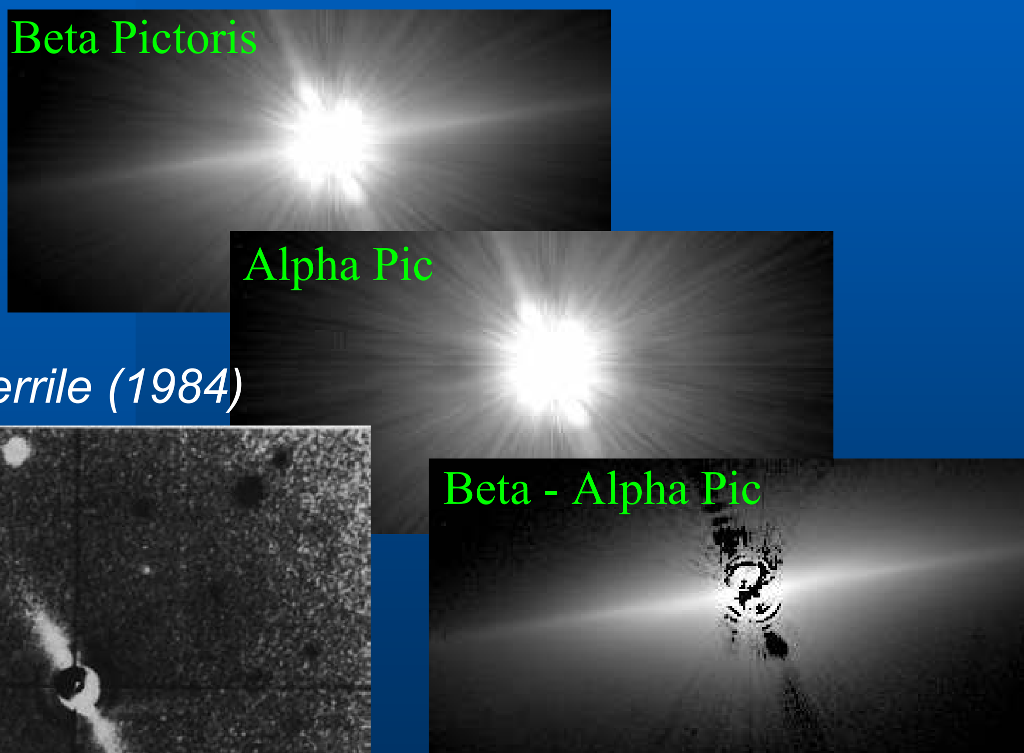

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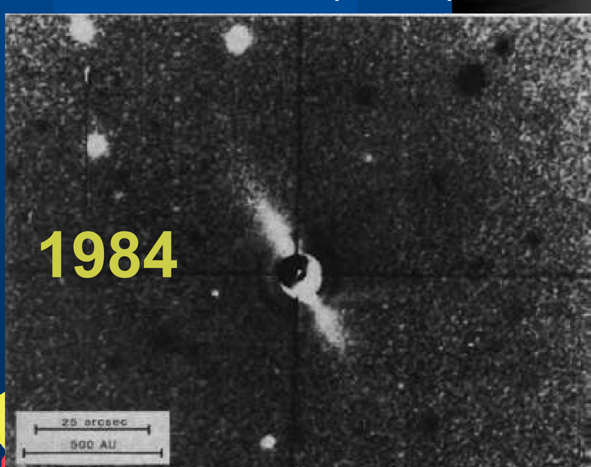

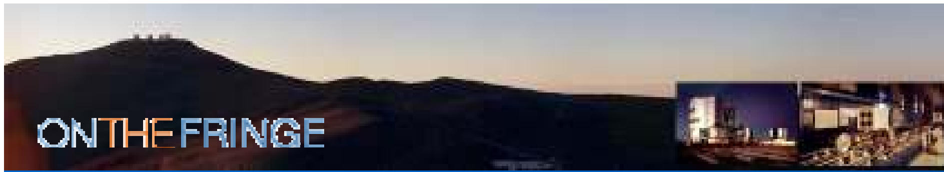

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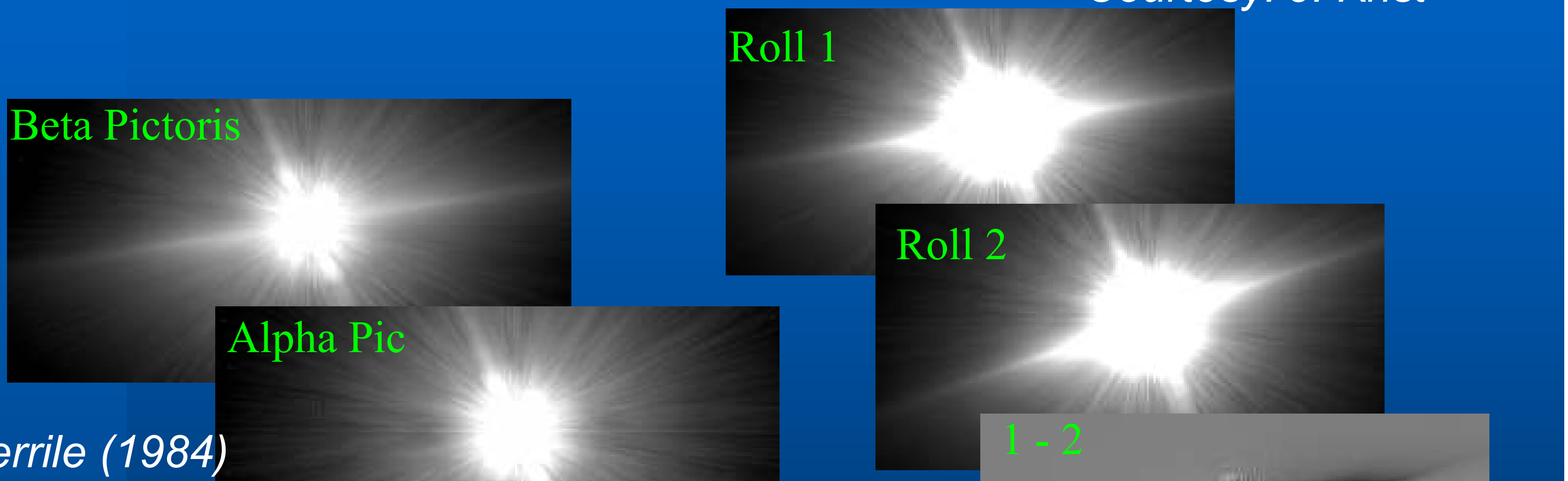

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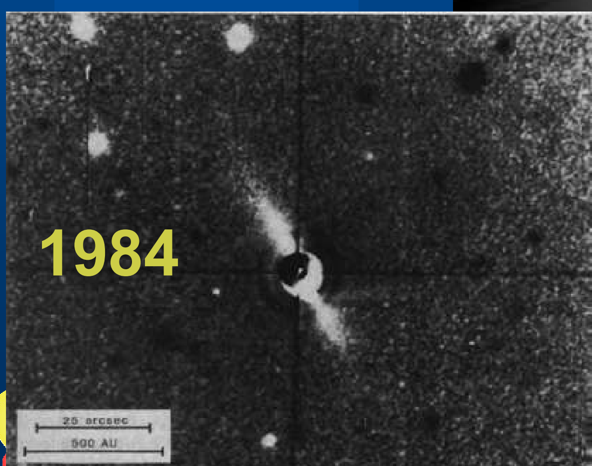
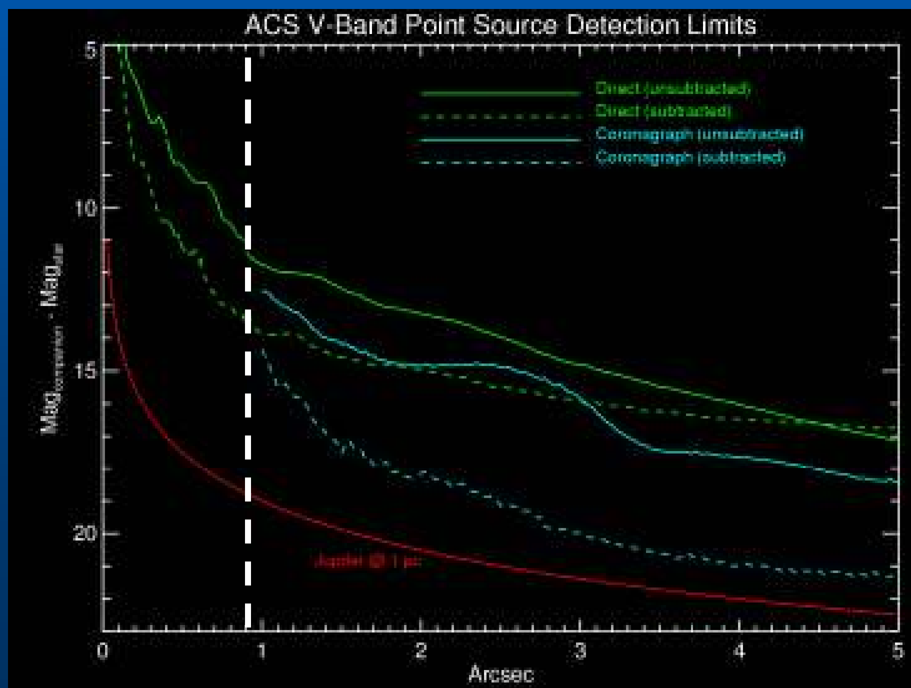


Contrast gain

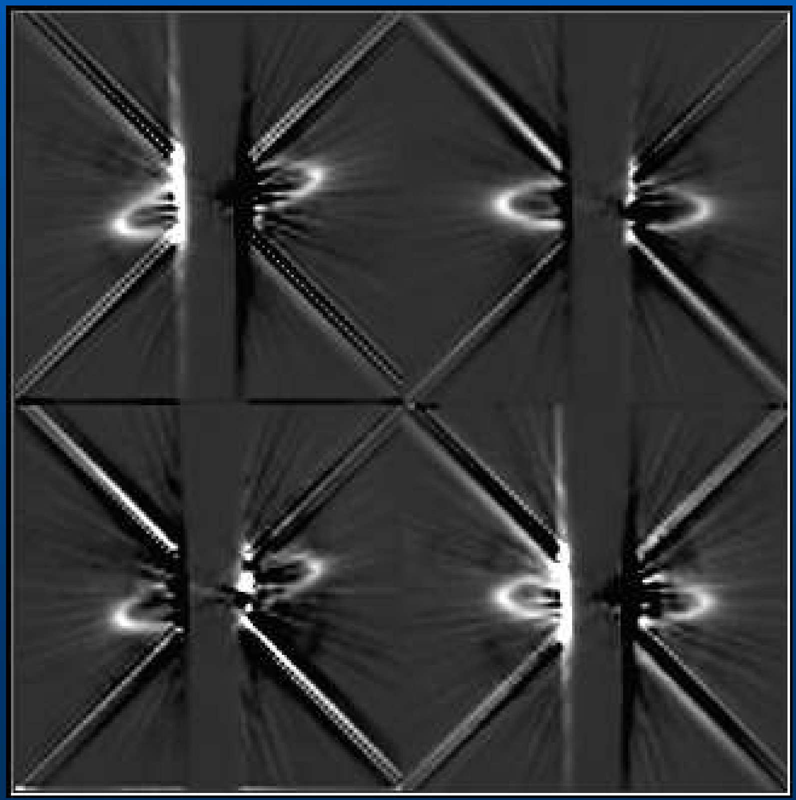
- Direct complementary images needed to probe the inner regions



HST/AO/coronography: disks and planets

Some little defects

- Need perfect centering and focusing



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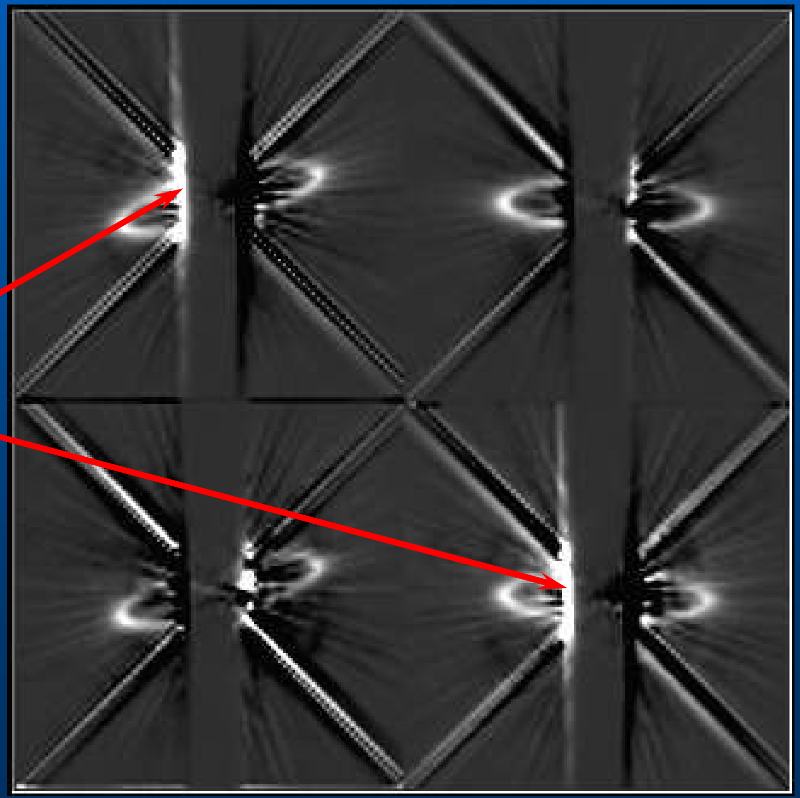

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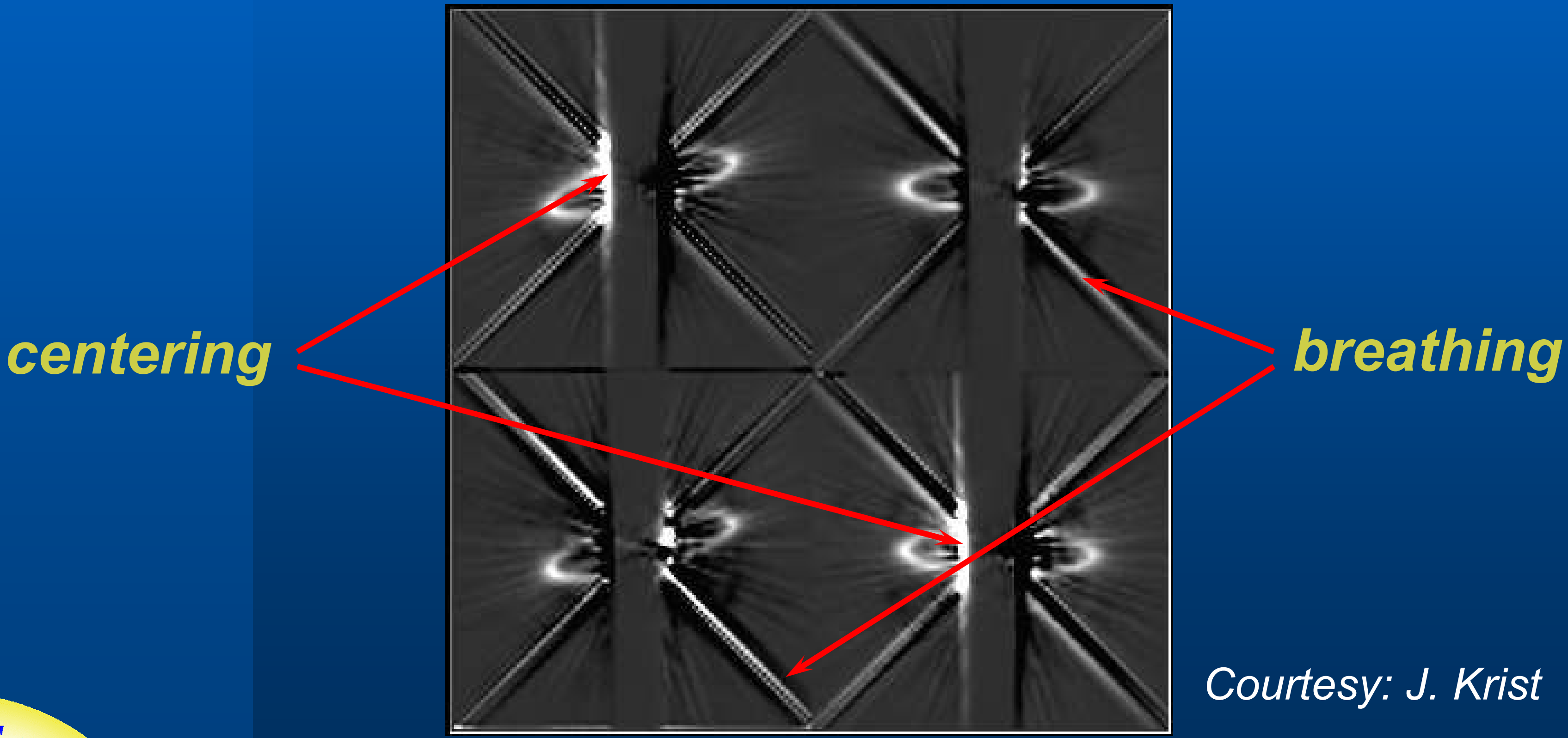

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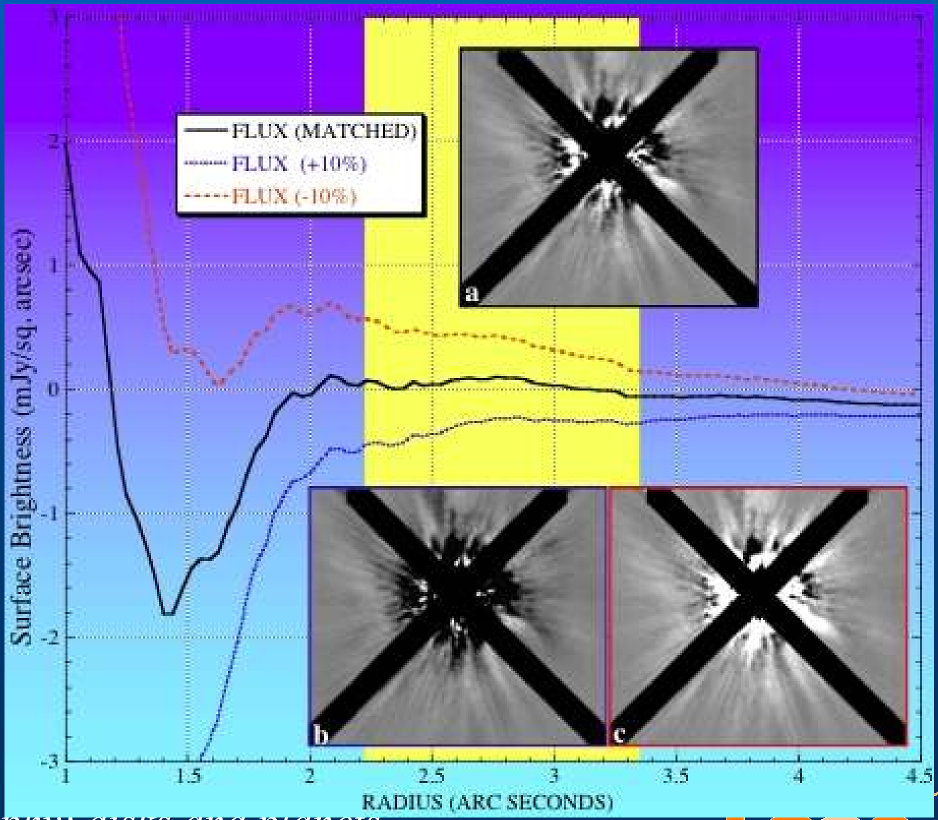

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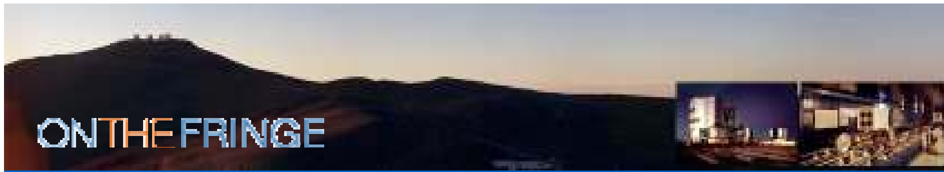

Science: Exoplanets (direct detection)

Exoplanets: basics

- Current state of the art
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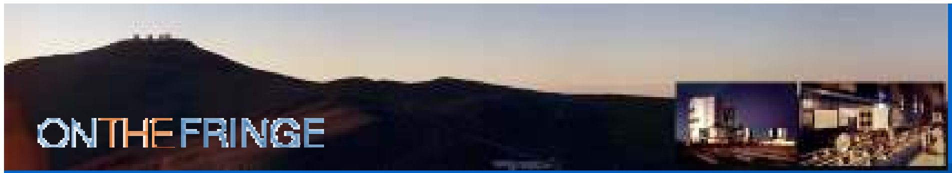

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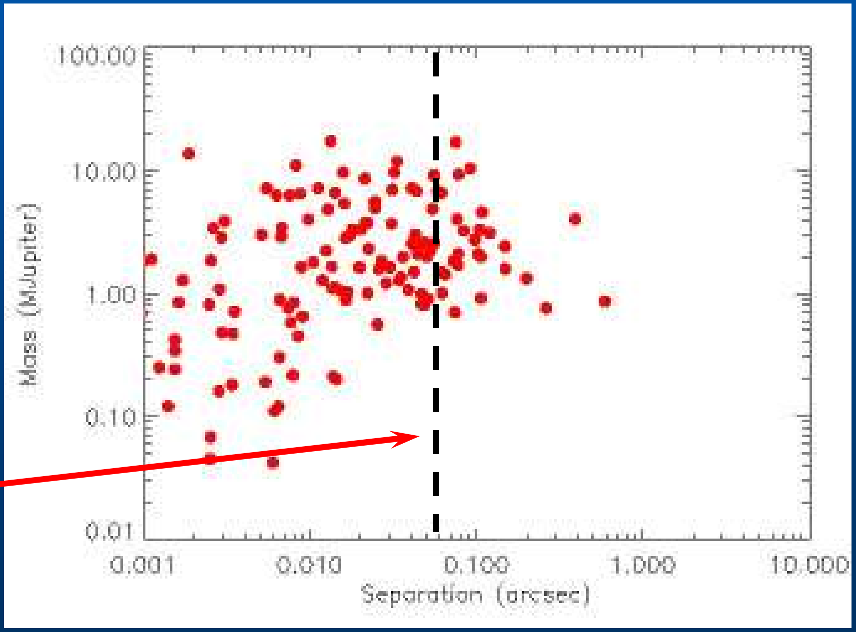
λ/d on 8m (2.2 μm)



Beuzit et al. (PPV)

HST/AO/coronography: disks and planets

FO4ST

LAOG

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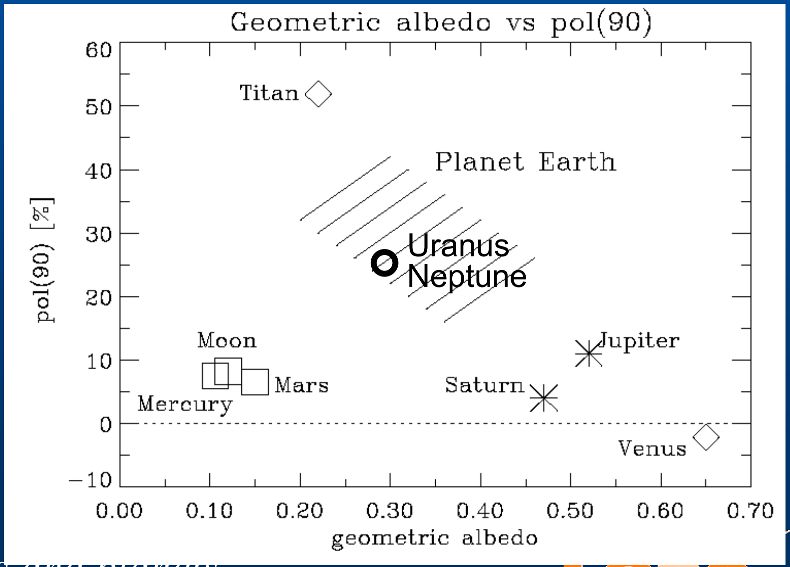

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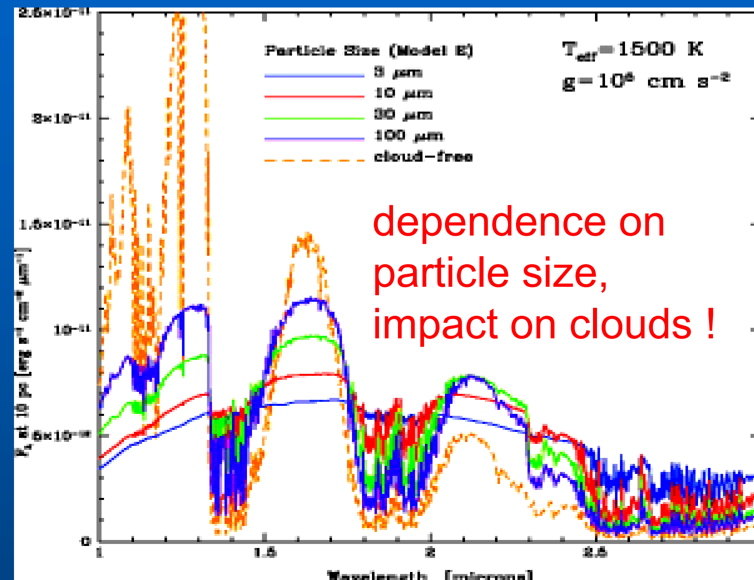

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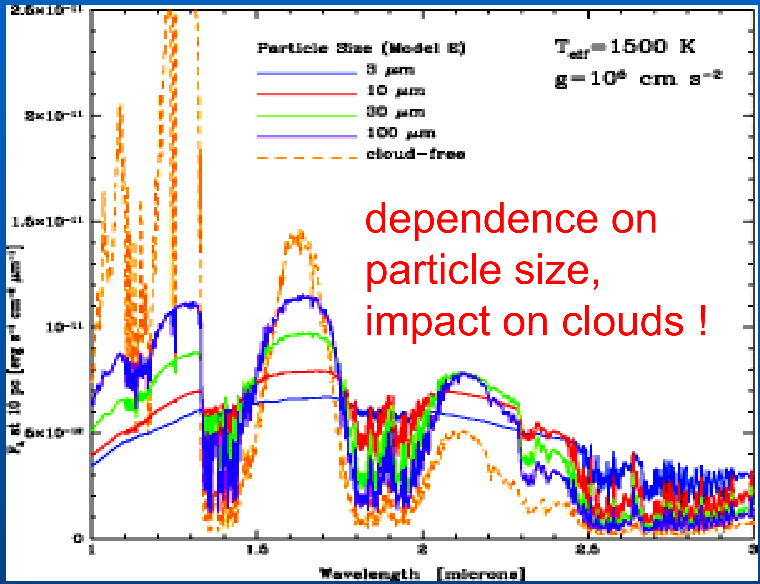
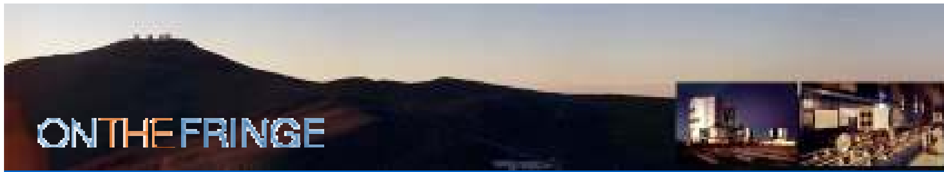
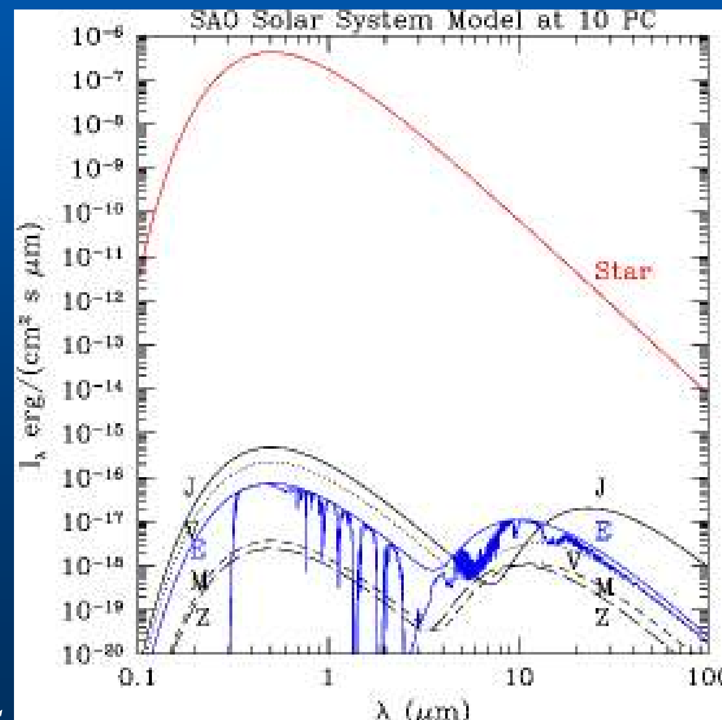
    - *Atmosphere (features)*
  - *Geology? Biology?*



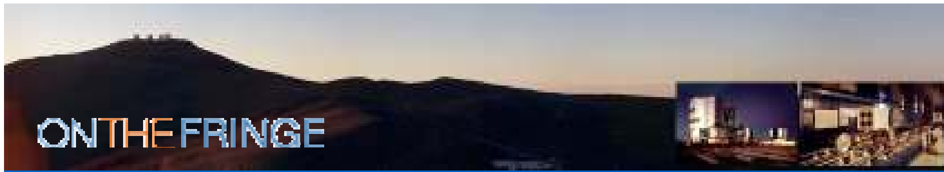


Search for wide planets

- Ongoing for ~15 years
  - *A high contrast challenge (10^6 - 10^9)*

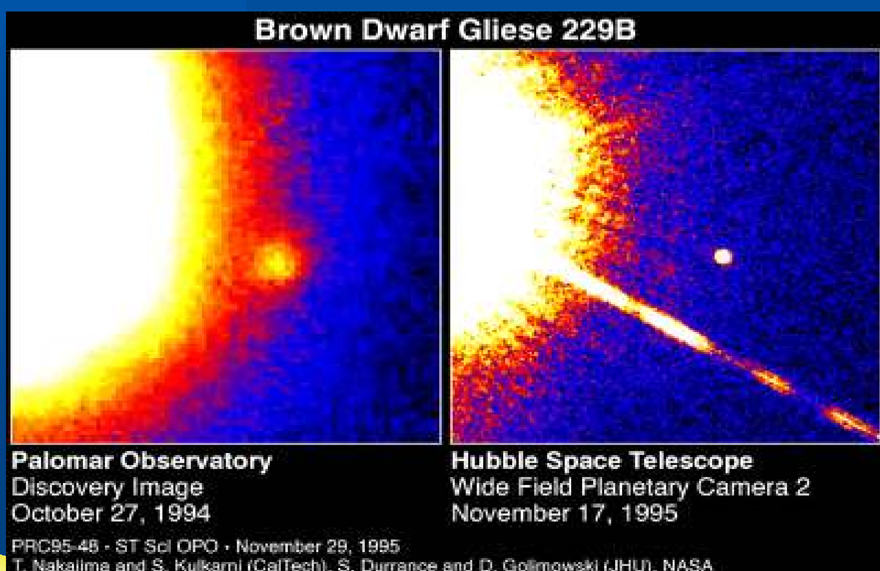


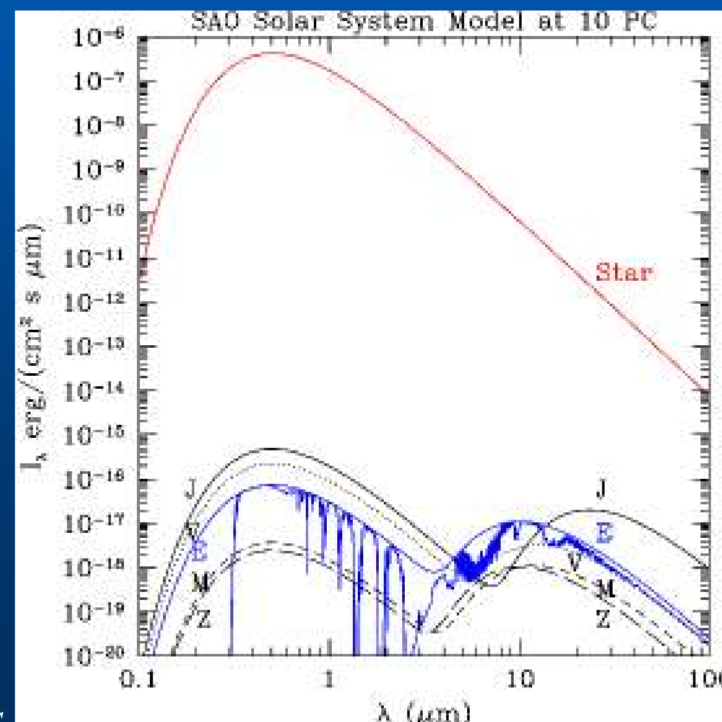
HST/AO/coronography: disks



Search for wide planets

- Ongoing for ~15 years
  - ➢ *A high contrast challenge (10^6 - 10^9)*
  - ➢ *A few BD companions*





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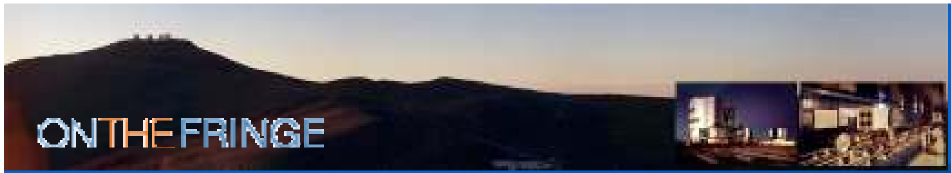

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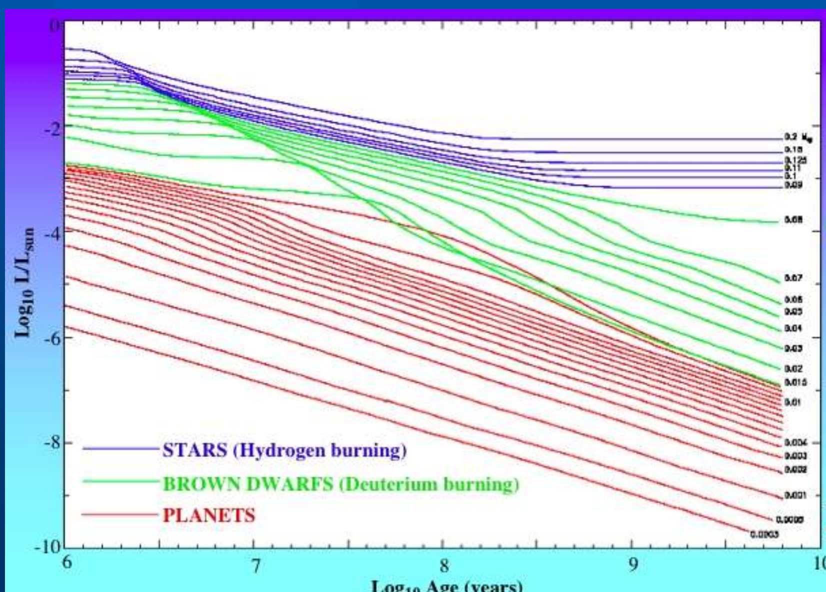

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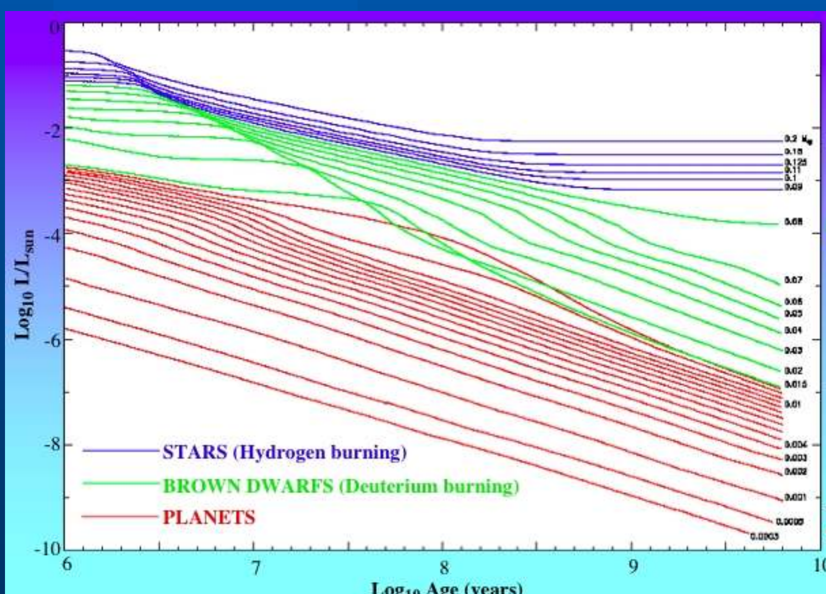

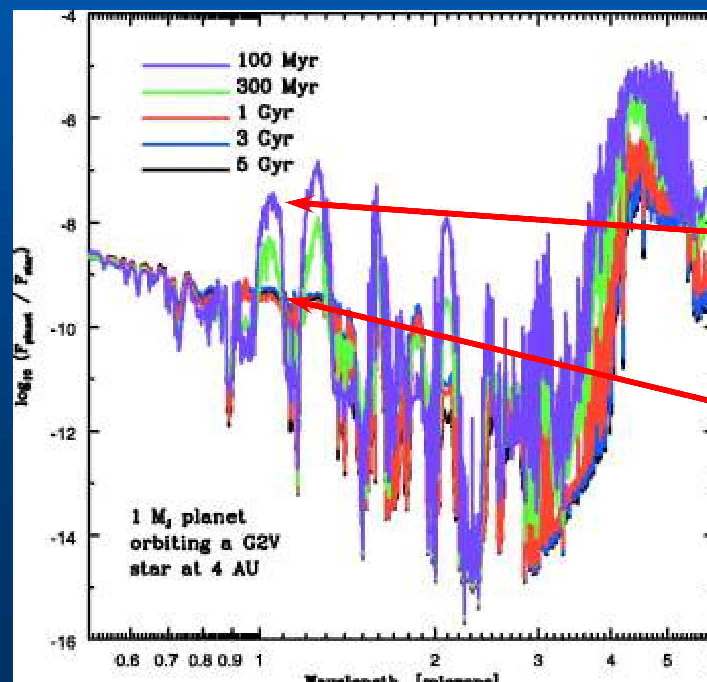

young

old

Burrows et al.

AB Pic

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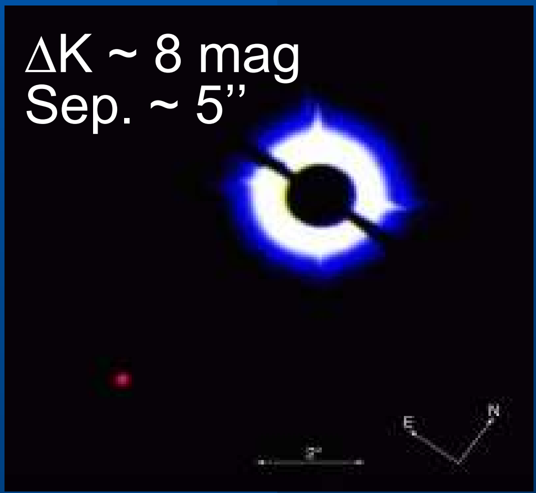

Chauvin et al. (2005)

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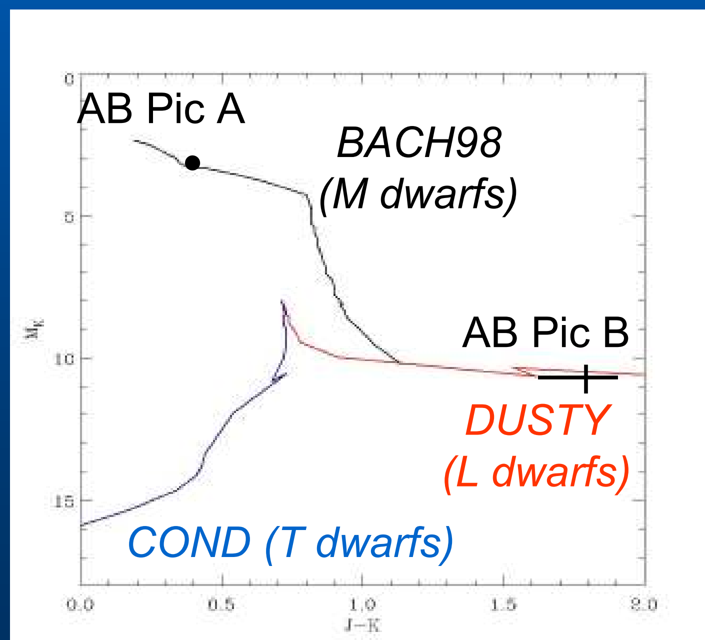
Chauvin et al. (2005)



FO4ST

LAOG

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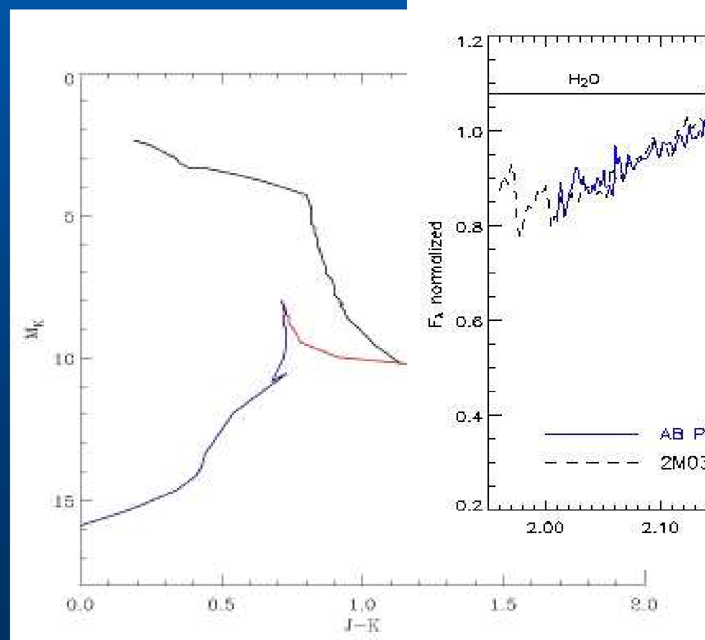

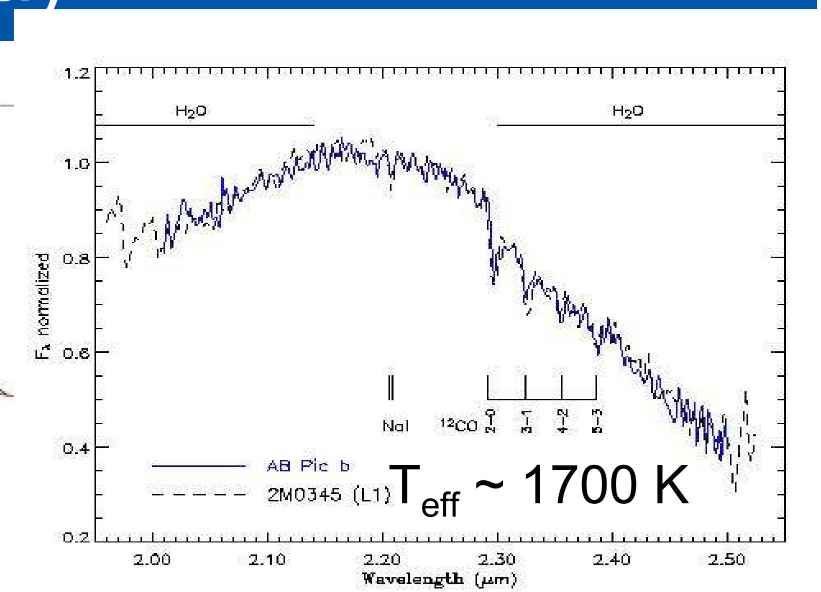

2MASSWJ 1207334-39325

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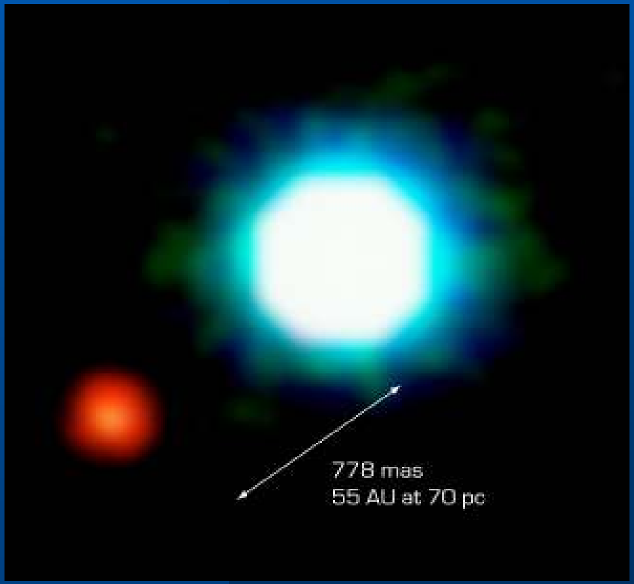

Chauvin et al. (2004)

2MASSWJ 1207334-39325

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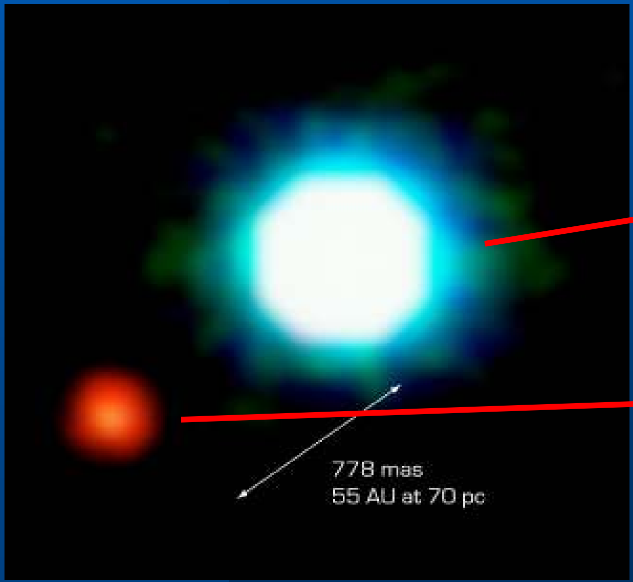
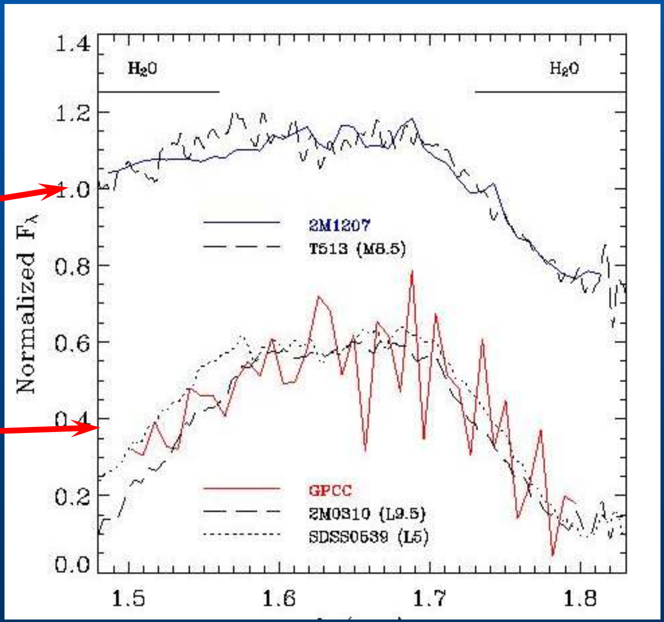
  - *T_{eff} ~ 1600K, 8 M_{Jup} companion*

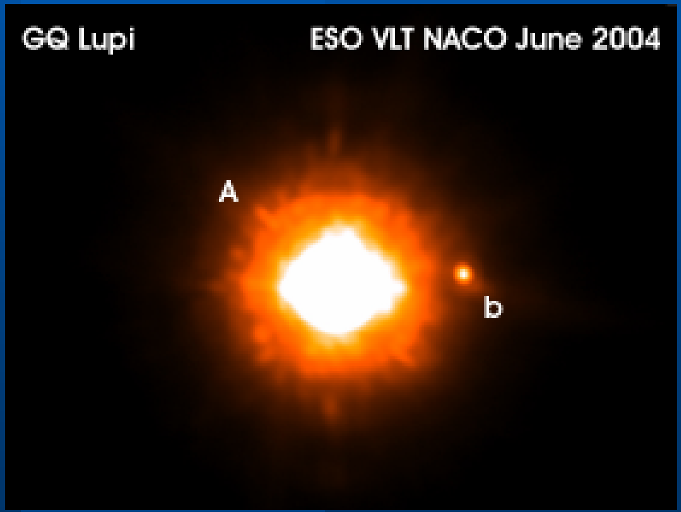




Chauvin et al. (2004)

GQ Lup

- An example of technical improvements!



Neuhauser et al. (2005)

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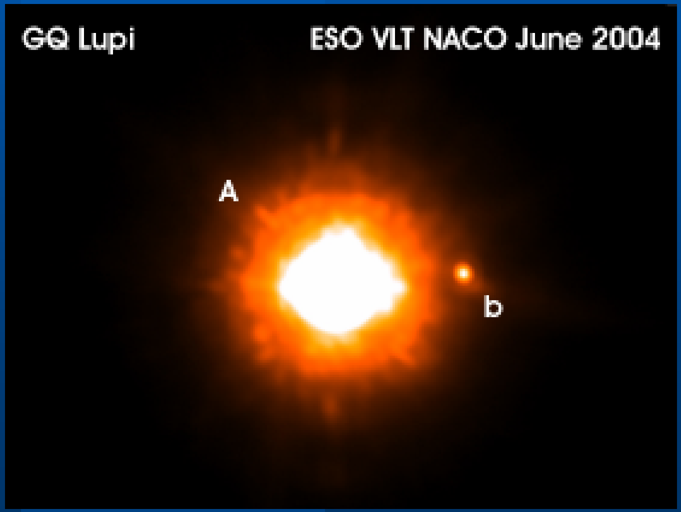

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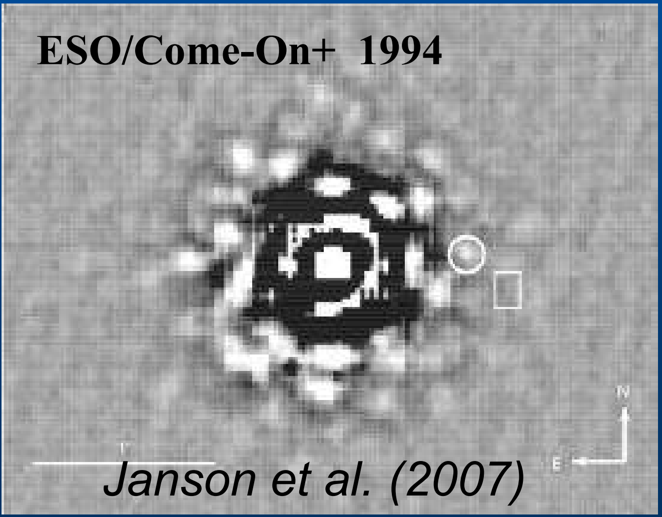
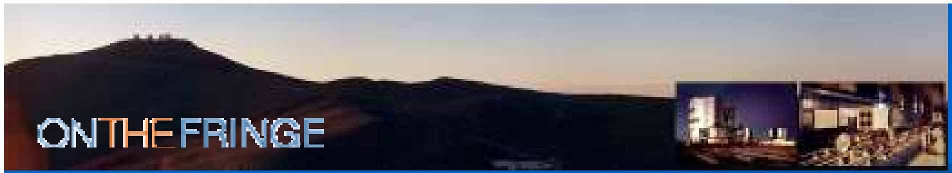


Janson et al. (2007)



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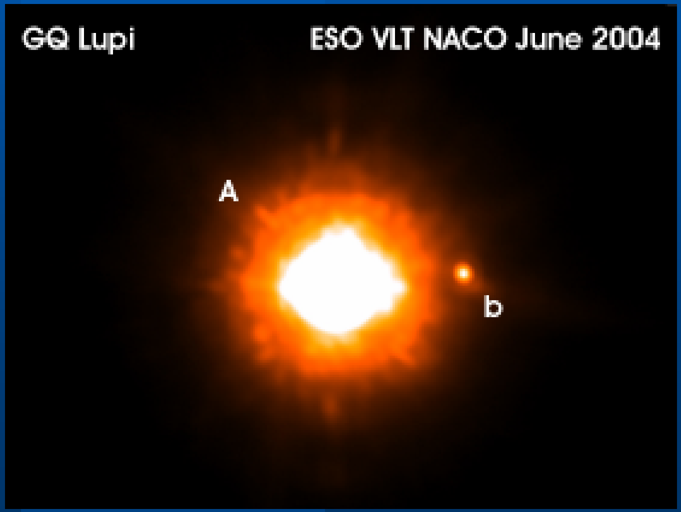
  - *~5 Myr-old 25 M_{Jup}*



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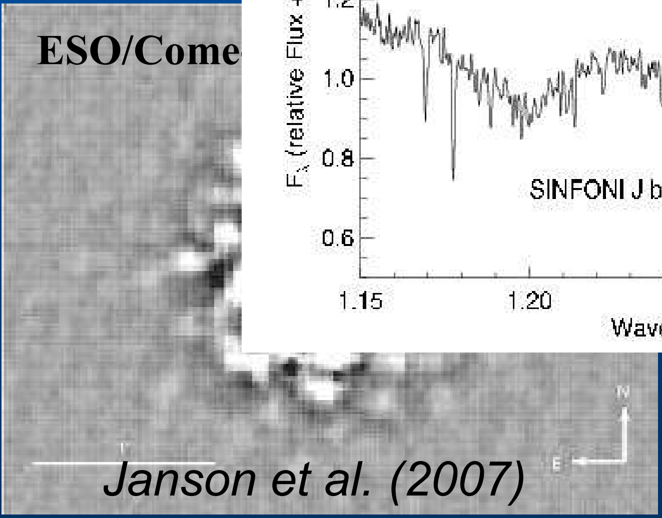

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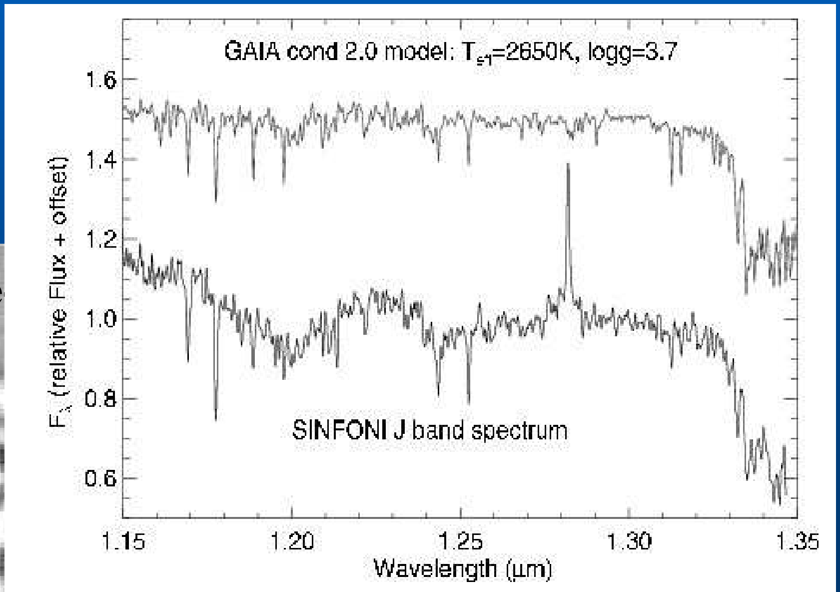

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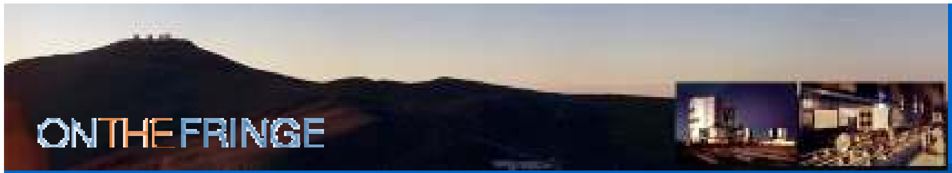
- Too far from their parent star to form in a disk through core accretion
  - *Are they really planets?*
- Similar to “free-floating” VLM objects in σ Ori, for instance
  - *Come very low-mass prestellar cores*
- No very low-mass objects found

What next?

- Need even higher contrast at shorter separations

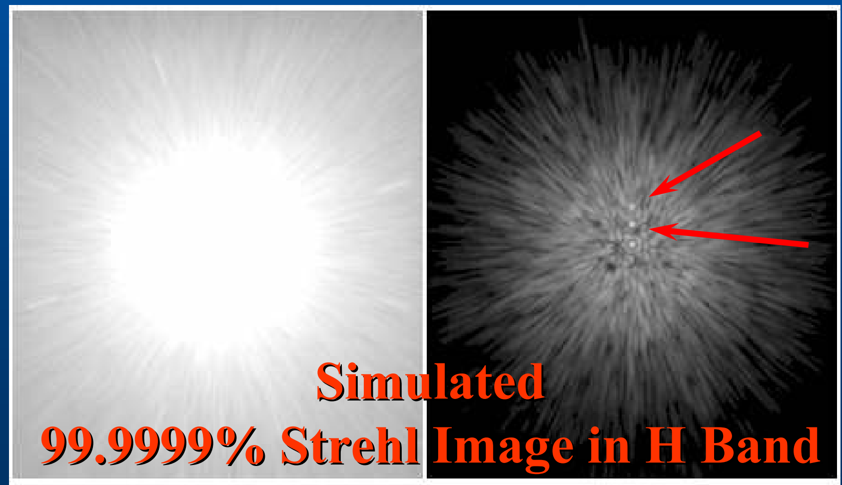


What next?

- Need even higher contrast at shorter separations
  - *Dedicated instruments (future AO)*

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

Simulated
95% Strehl in H band
8m telescope



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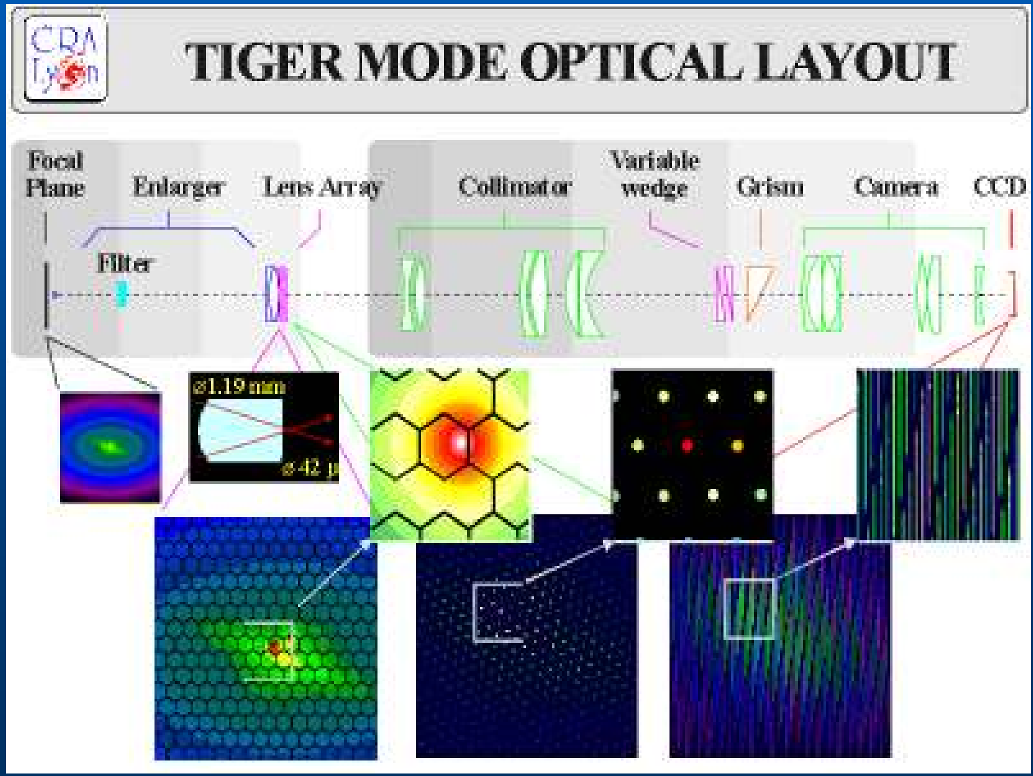
Lenslet array



Keck/OSIRIS

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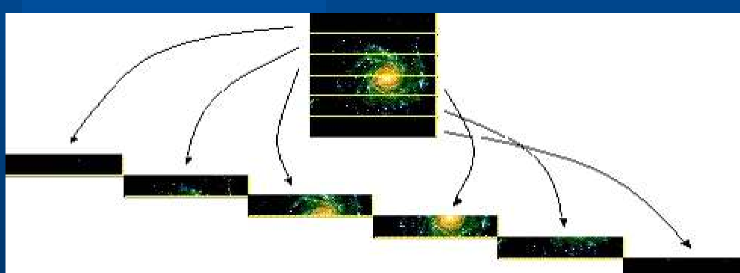
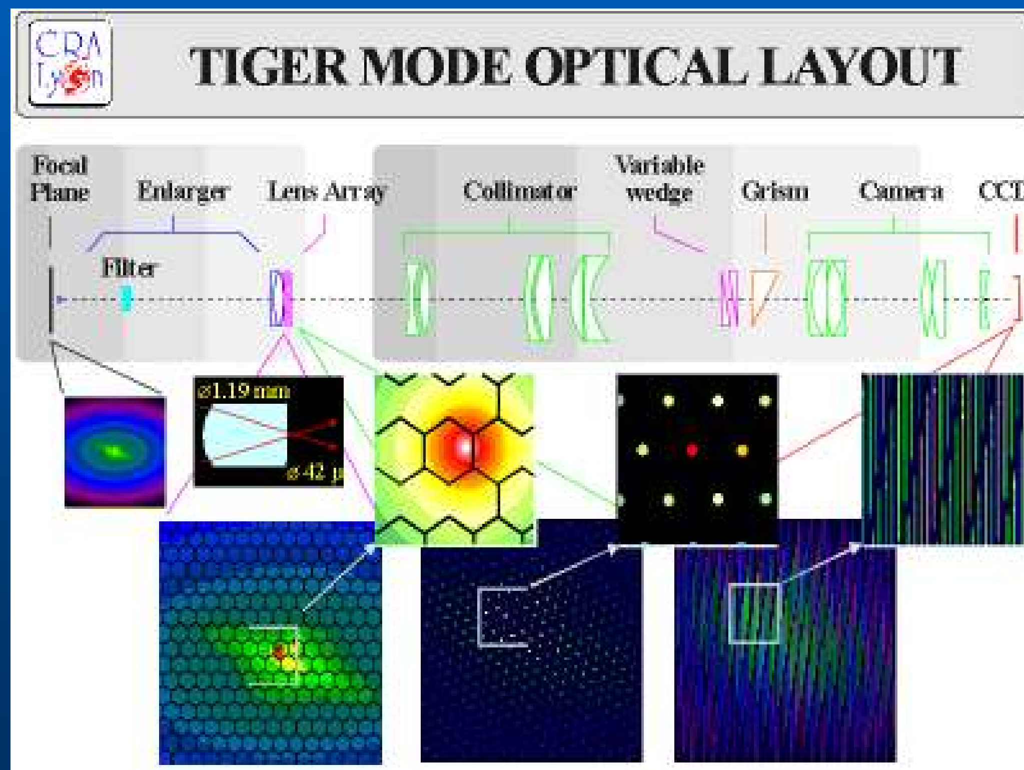
Lenslet array

Image slicing

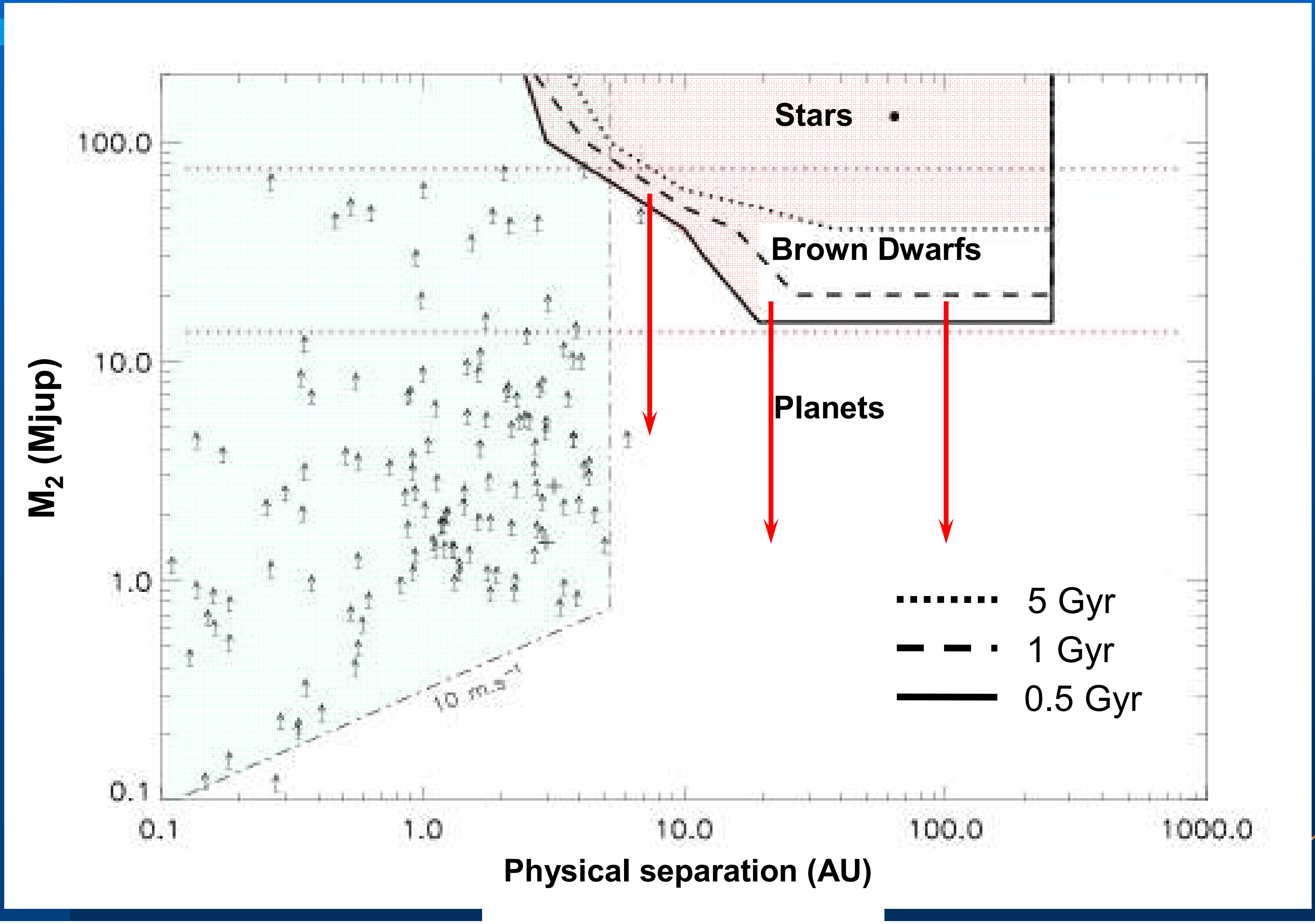


VLT/SINFONI

Keck/OSIRIS



Wait for a few years!!



Circumstellar disks : Scientific results

Coronography: a family picture

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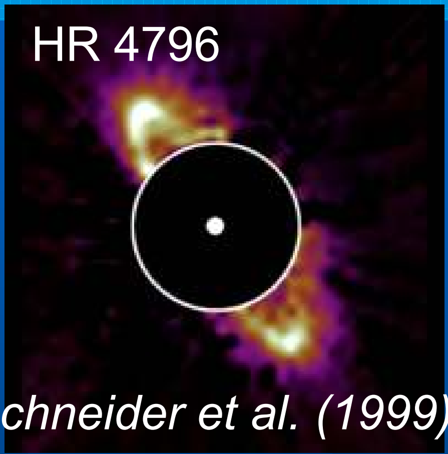

Schneider et al. (1999)

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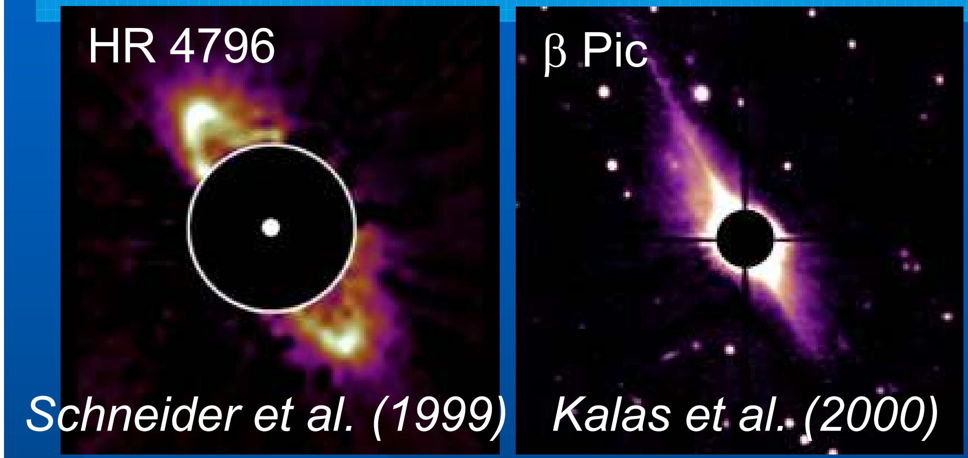

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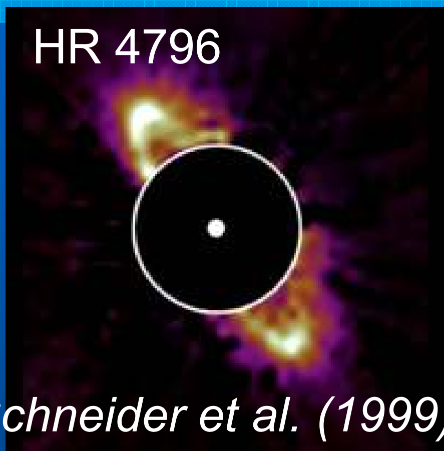

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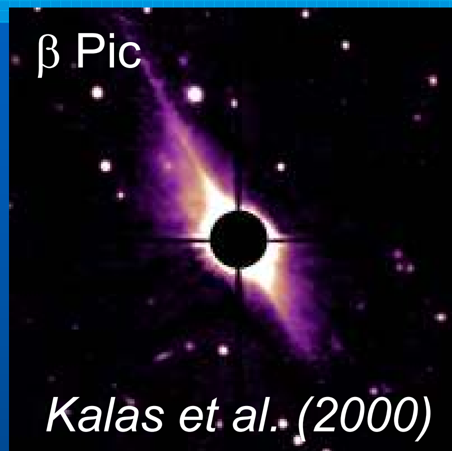
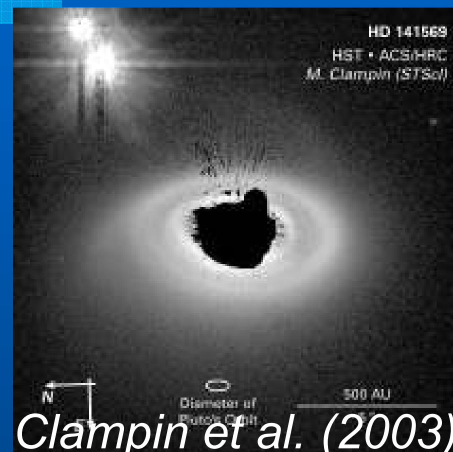


Kalas et al. (2000)



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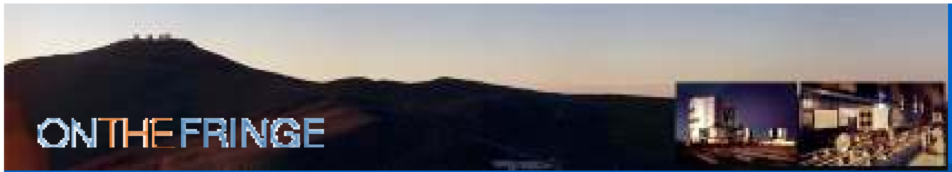

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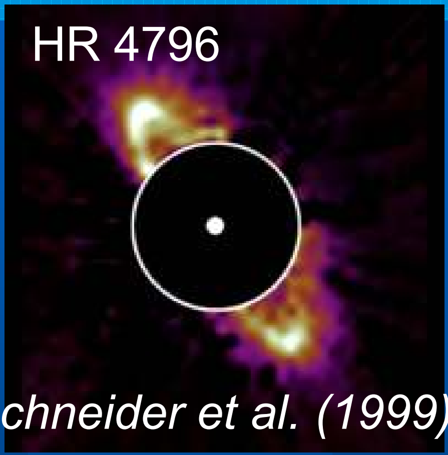

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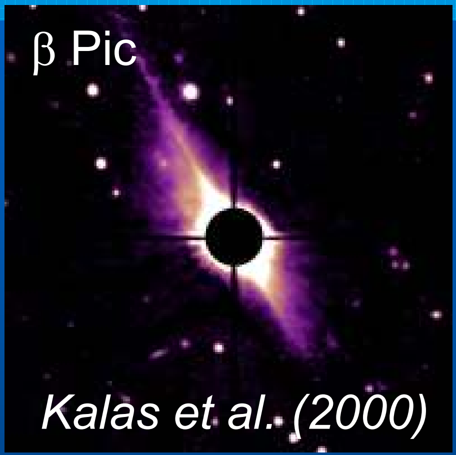

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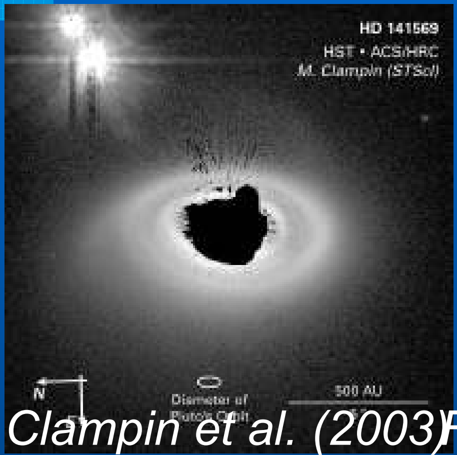

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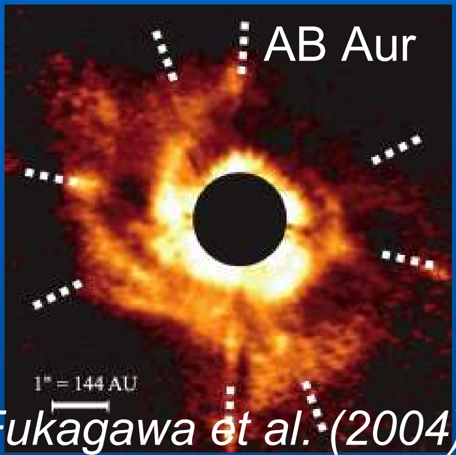
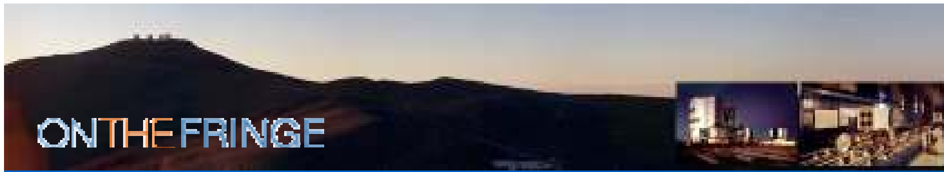


Fukagawa et al. (2004)



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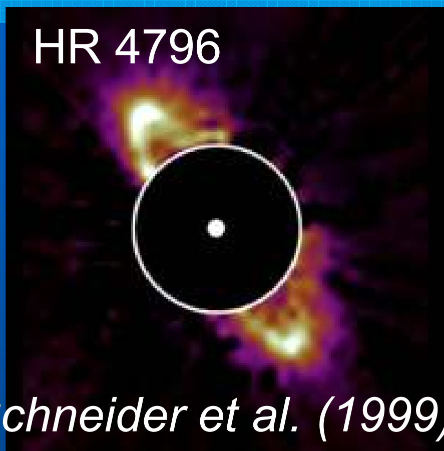

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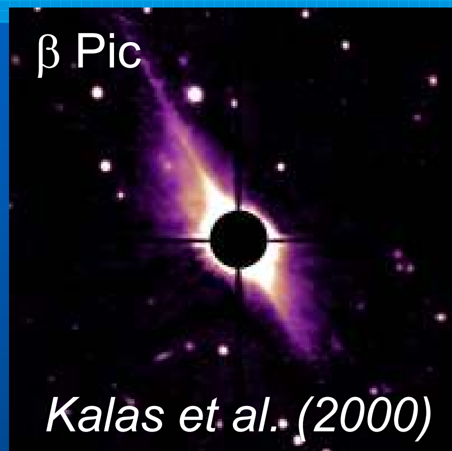

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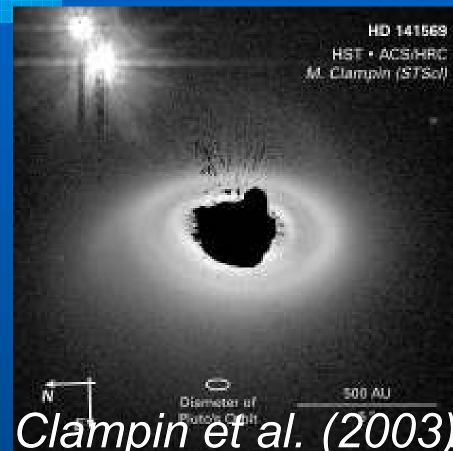

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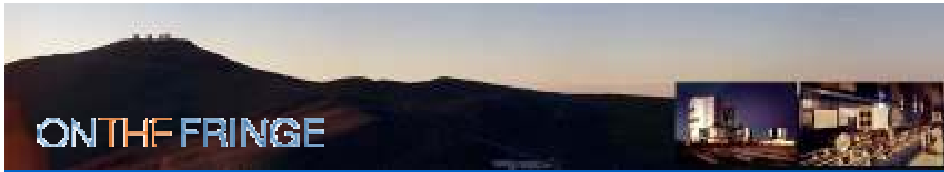

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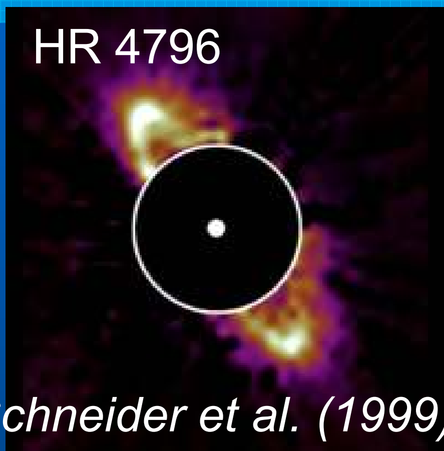

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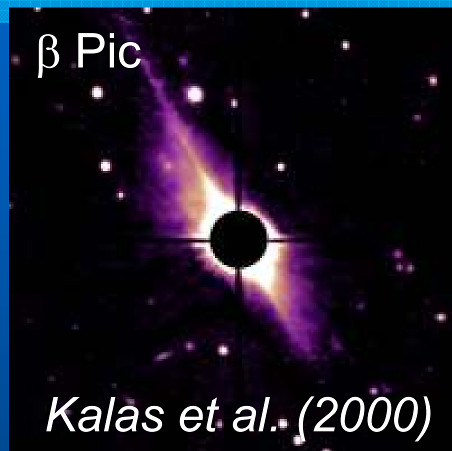

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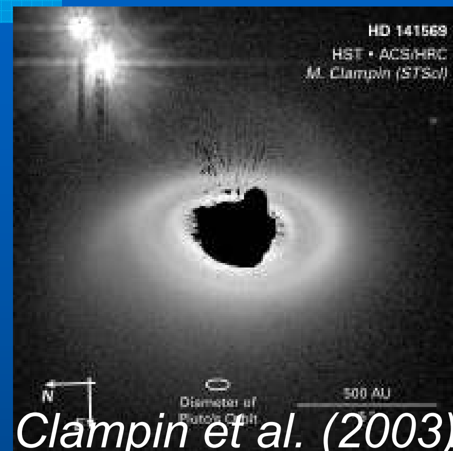

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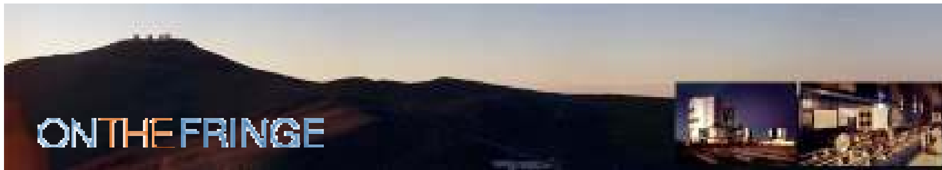

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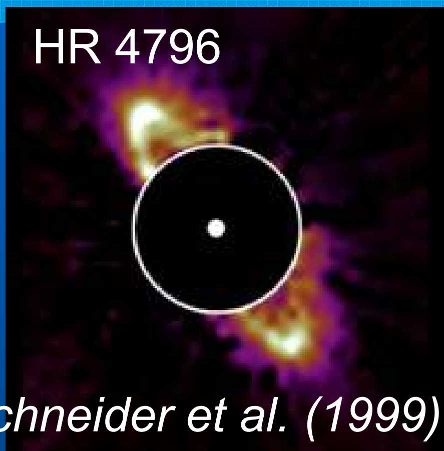

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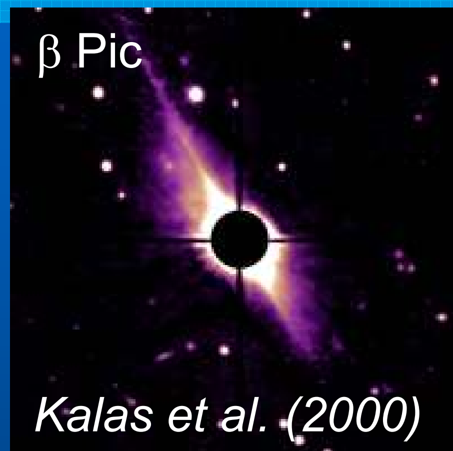

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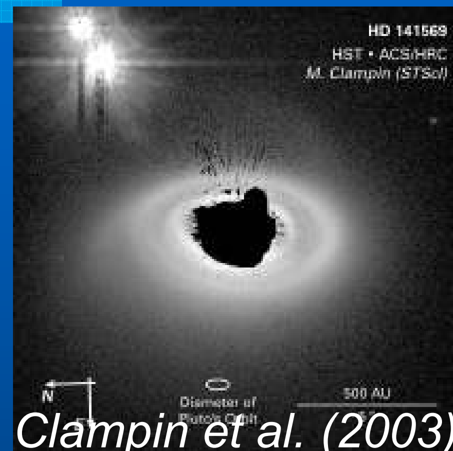

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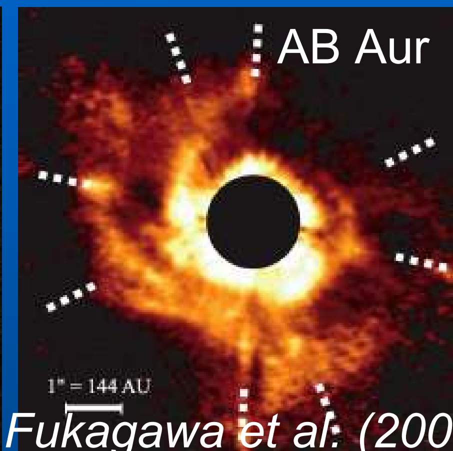

Fukagawa et al. (2004)

Fitzgerald et al. (2007)

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Grady et al. (2001)

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- ‘Natural’ coronograph

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  - *Edge-on disks*

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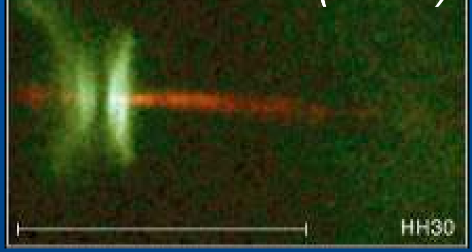

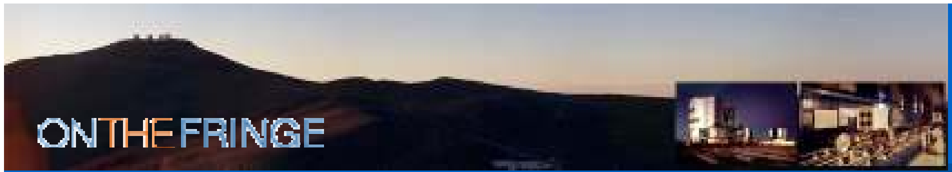

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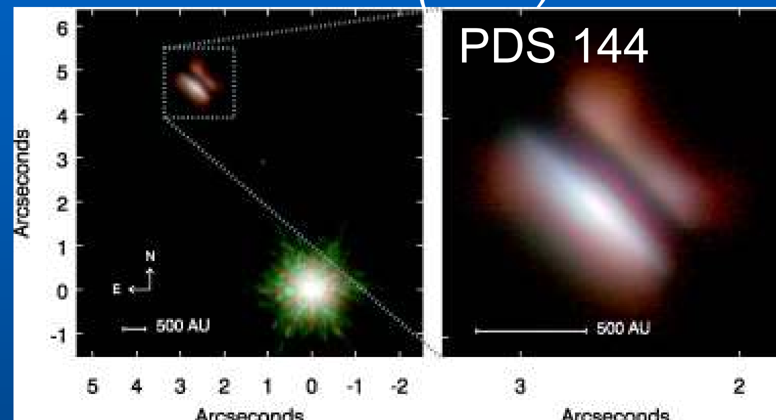
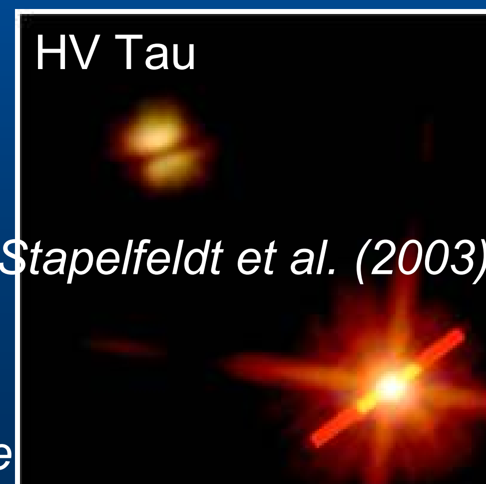
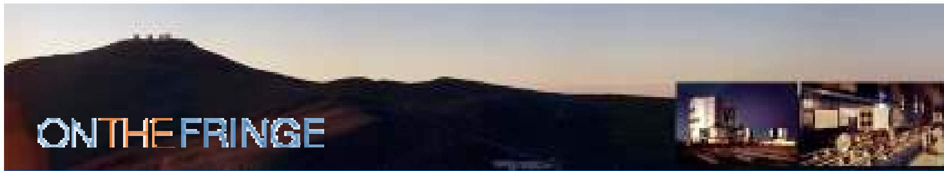




Stapelfeldt et al. (2003)

Courtesy: C. McCabe



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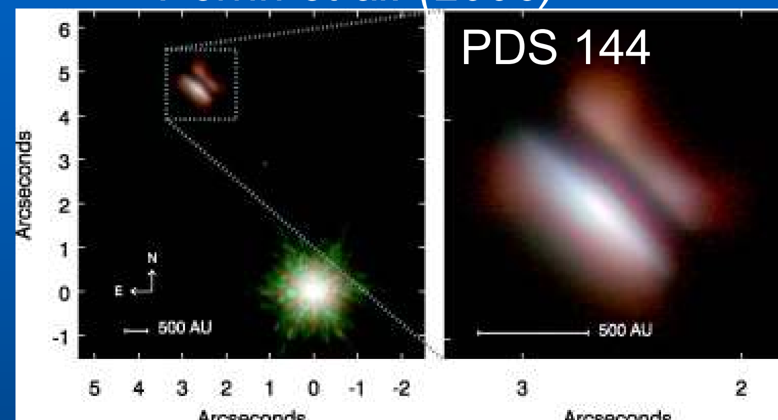
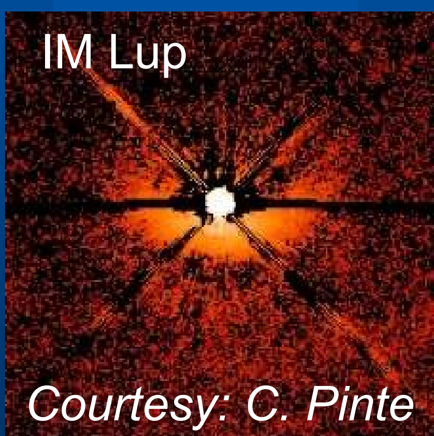


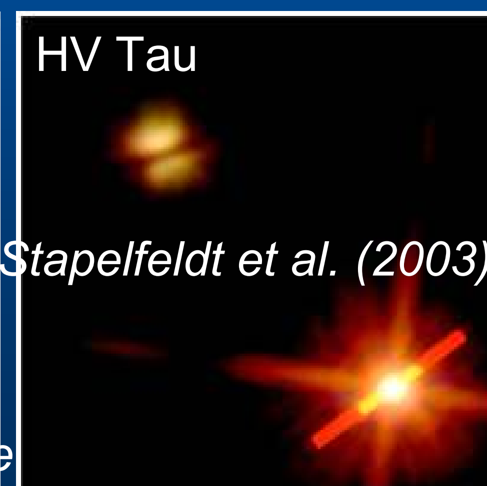
Burrows et al. (1996)



Courtesy: C. Pinte

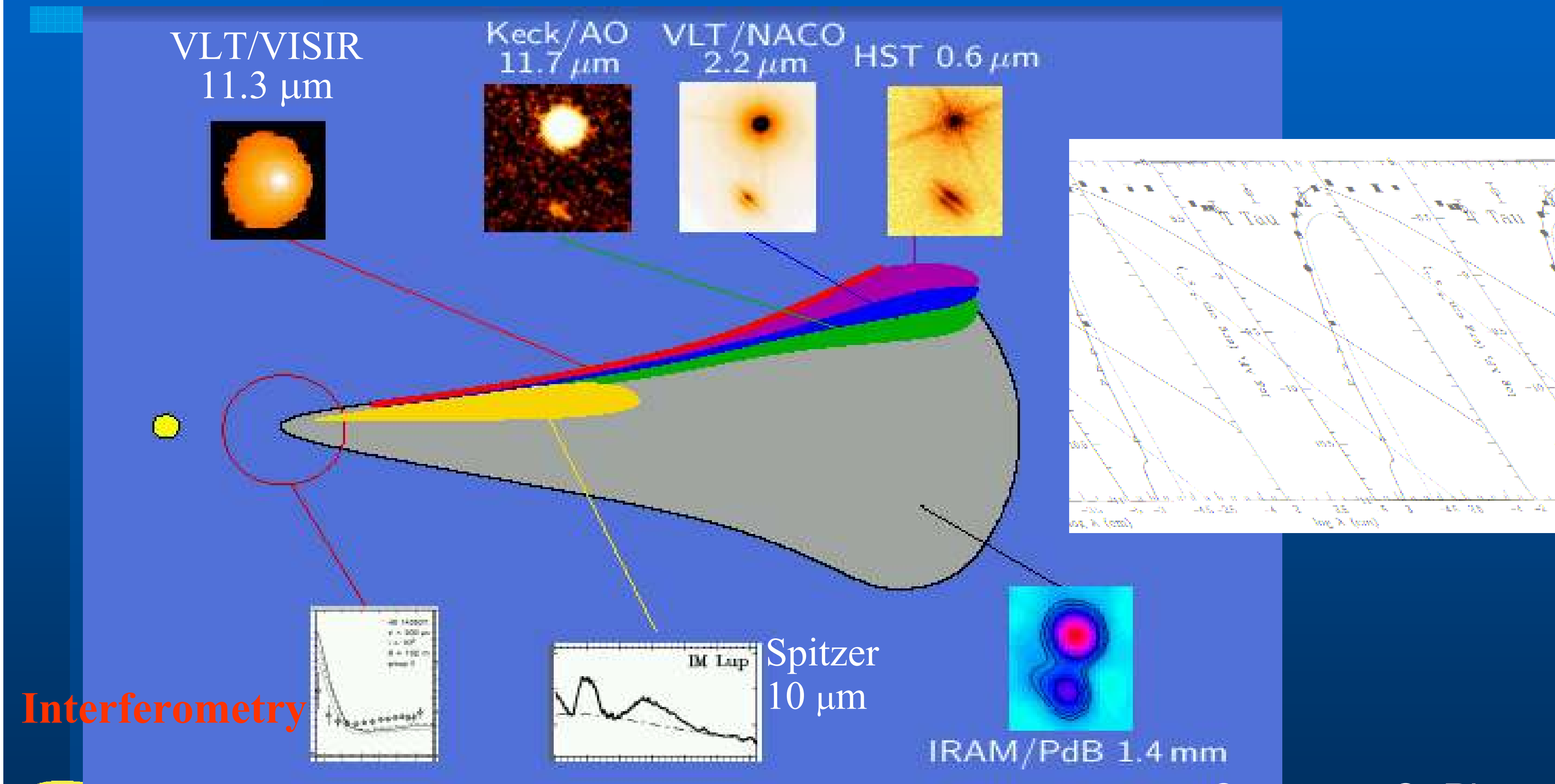
Krist et al. (2005)

Courtesy: C. McCabe



Stapelfeldt et al. (2003)

What type of observations?



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HST/AO/coronography: disks and planets

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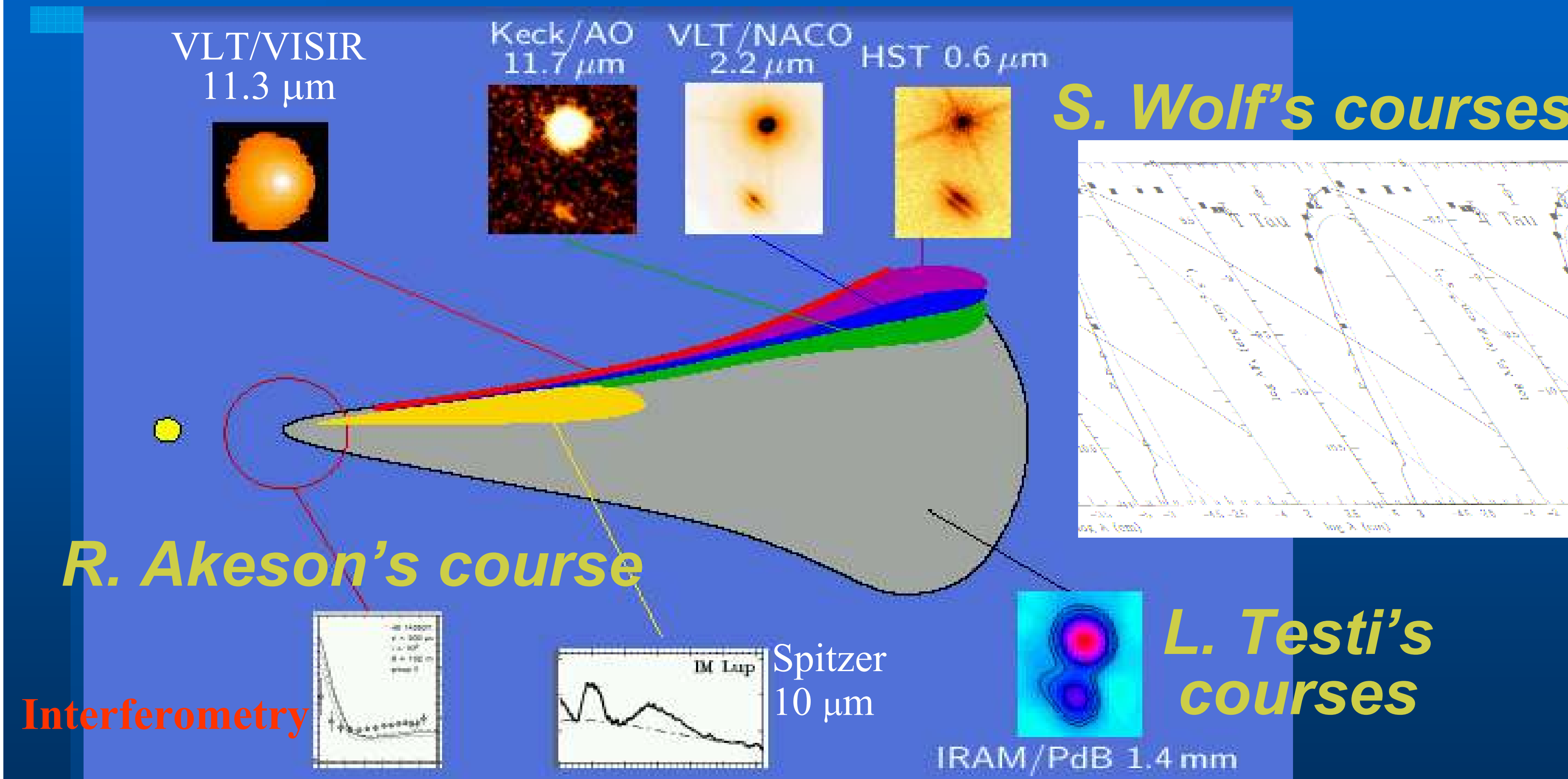

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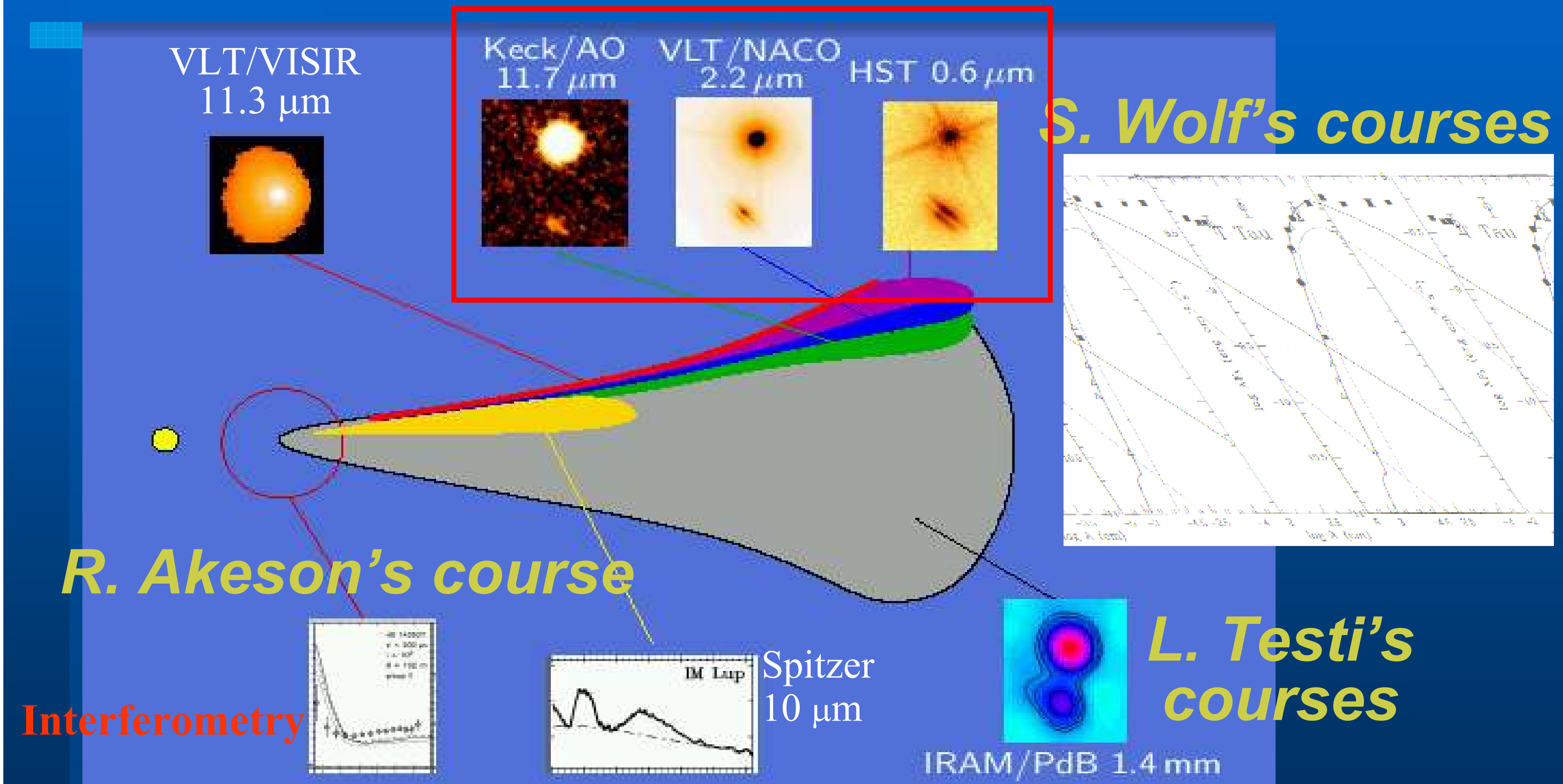

HST/AO/coronography: disks and planets

Interpreting disk images

- Images are very important but need to be quantitatively analyzed
  - *Obtaining an image is a not a goal in itself*

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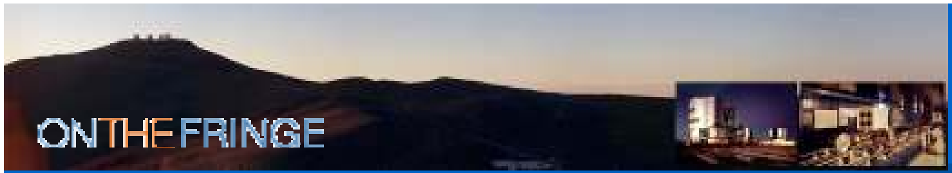
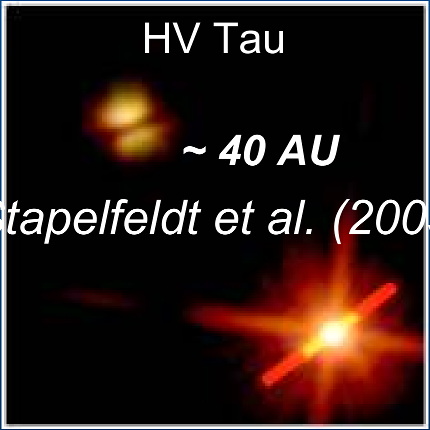
  - *Obtaining an image is a not a goal in itself*
- This usually requires exact radiative transfer modeling
  - *If possible in conjunction with SED…*
  - *See S. Wolf's lectures*

Basic parameters



Basic parameters

- Disk radii: 10s to 1000s of AU



Stapelfeldt et al. (2003)

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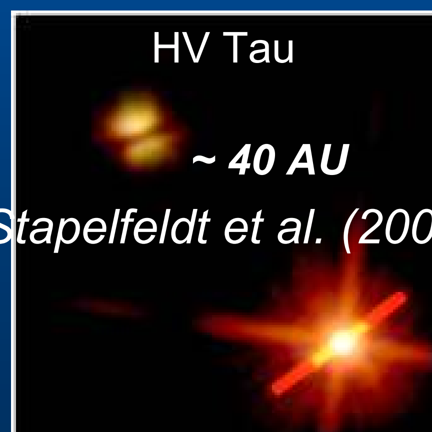

Stapelfeldt et al. (2003)

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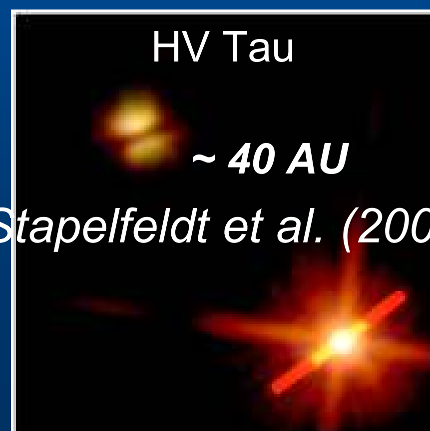
Basic parameters

- Disk radii: 10s to 1000s of AU
- Disk height: H/R ~ 0.1
- Masses cannot be easily determined
  - *Young disks are optically thick…*
  - *Radio regime!*
    - – *L Testi's courses*



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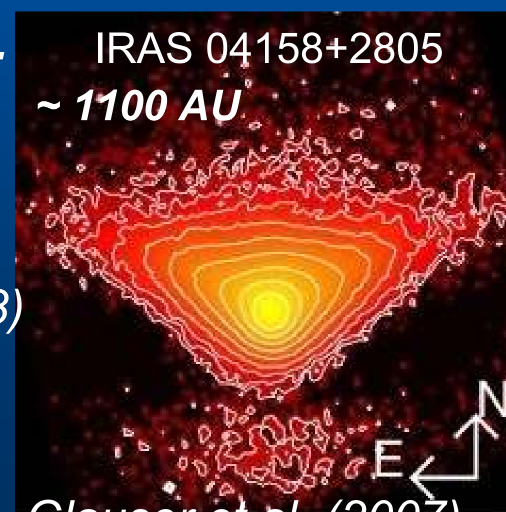
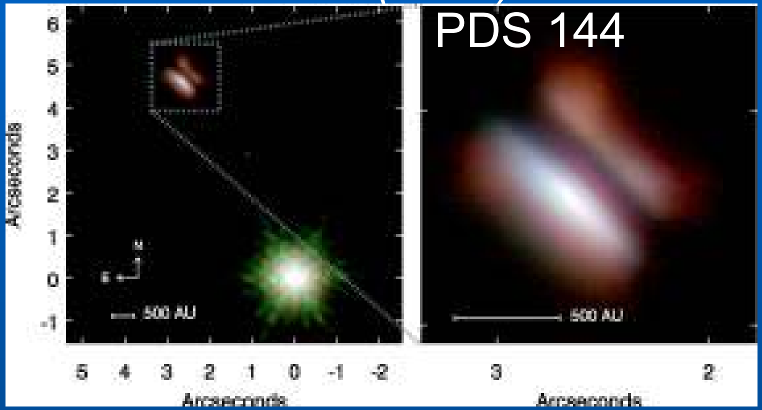


Glauser et al. (2007)

Structural information

- Flared geometry
  - *Hydrostatic equilibrium*

Perrin et al. (2006)



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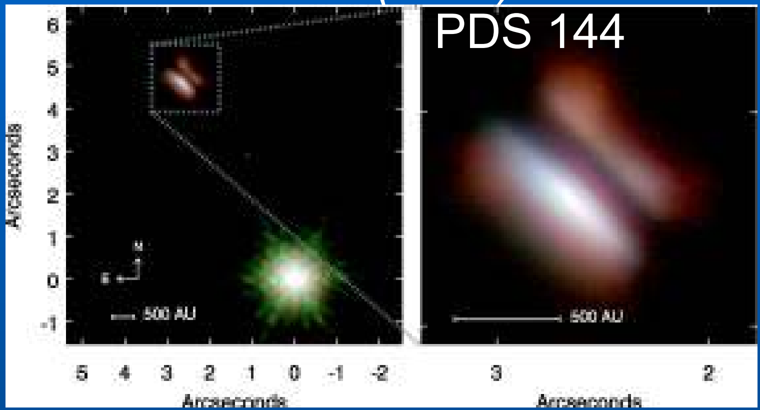

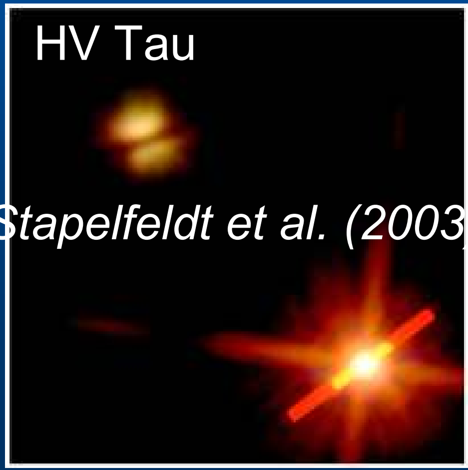

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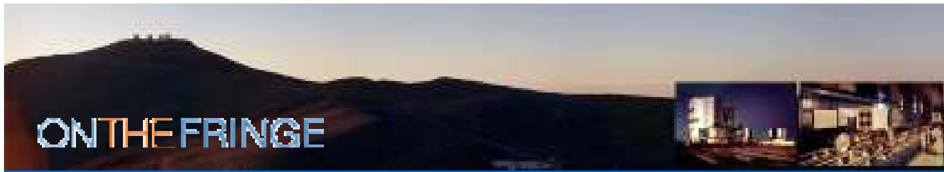
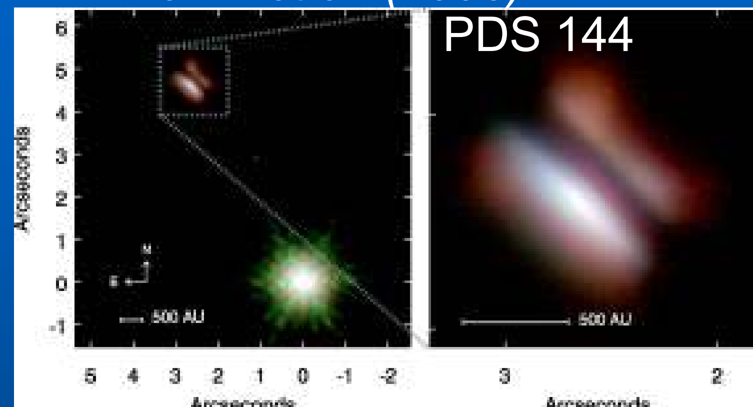
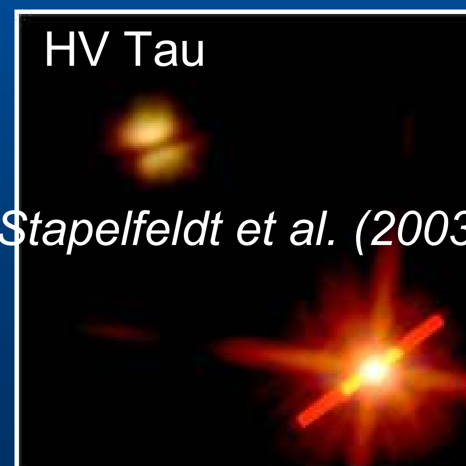


Structural information

- Flared geometry
  - ➢ *Hydrostatic equilibrium*
- Truncation in binaries?
- Presence of spiral arms
  - ➢ *Companions? Instability?*

Perrin et al. (2006)





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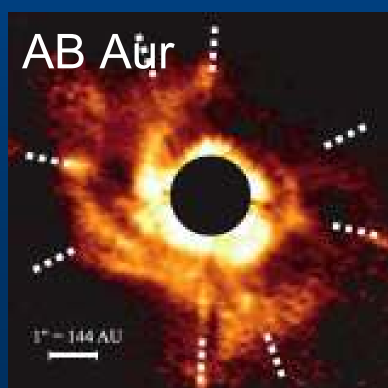
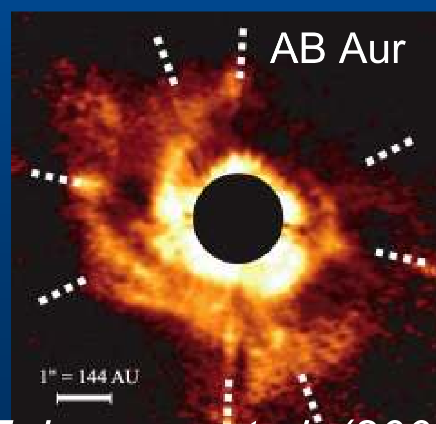


Structural information

- A word of caution about asymmetries:
  - ***What you see is not what you have!***

Grady et al. (2001)



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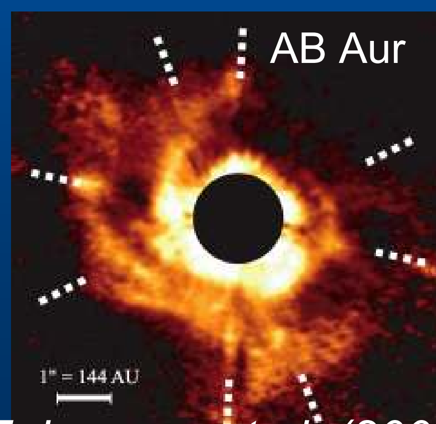

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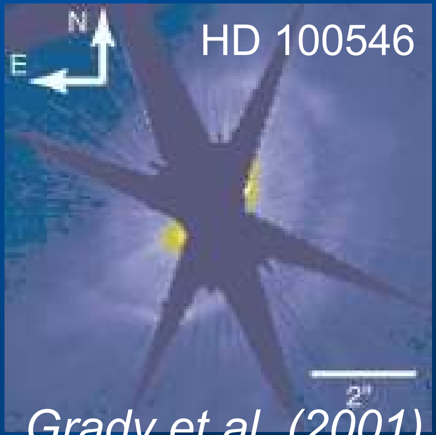

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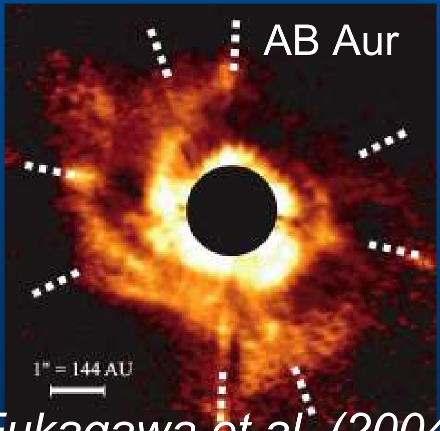

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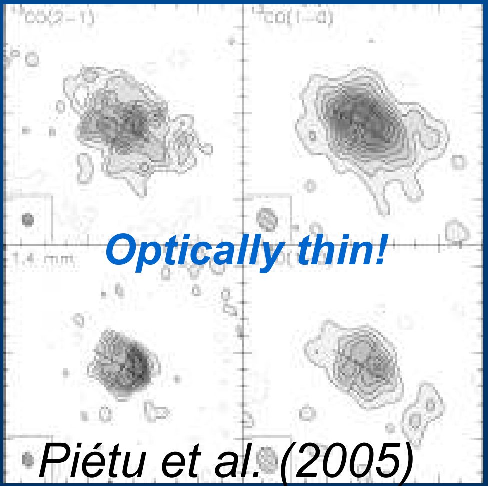
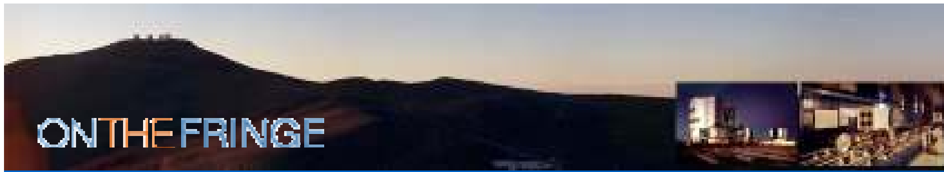


Piétu et al. (2005)

Dust information

- We receive scattered stellar photons
- Scattering depends on $\lambda/2\pi a$



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    - *Large grains scatter forward*
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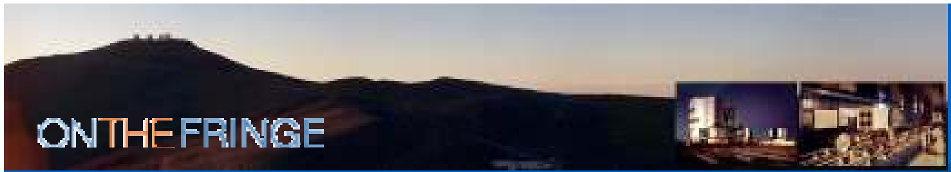

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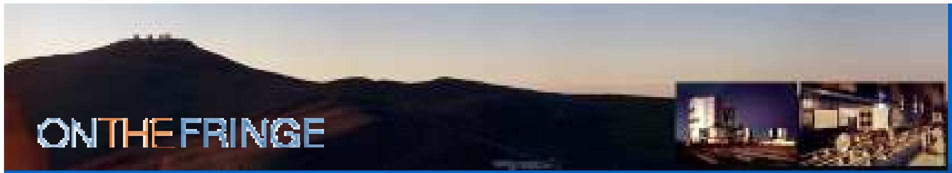

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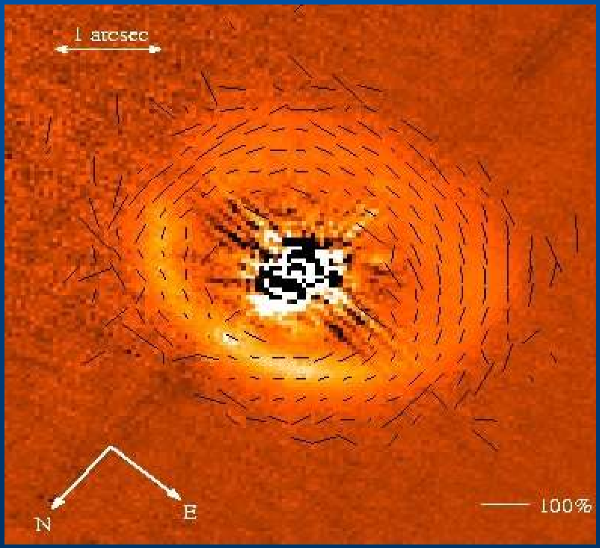
- Scattering also depends on geometry

Dust information

- An exemple: the GG Tau ring

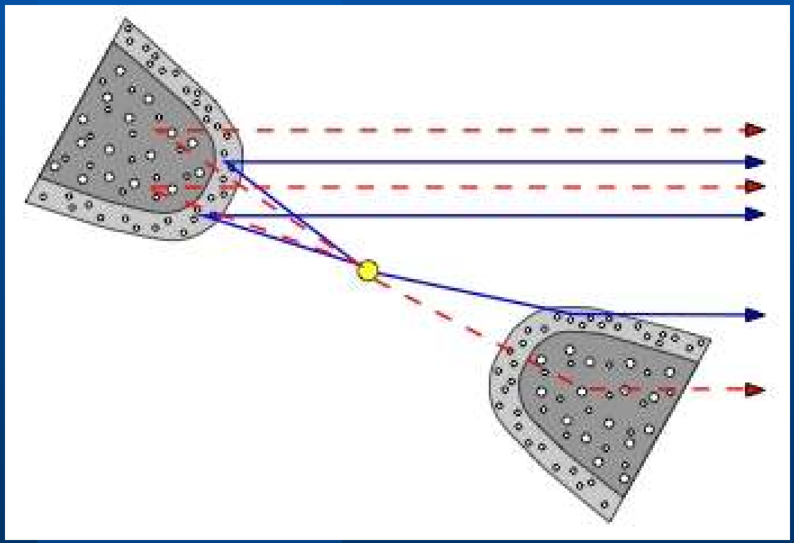


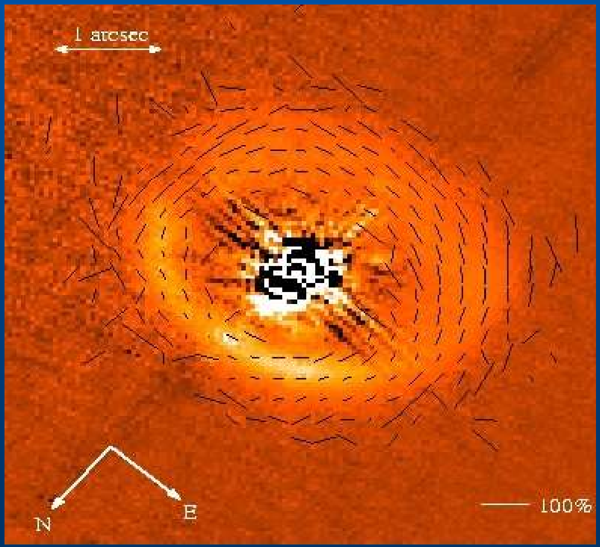
Silber et al. (2000)

ON THE FRINGE

Dust information

- An exemple: the GG Tau ring
  - *A case where $\lambda < 2\pi a$ ('large' grains)*





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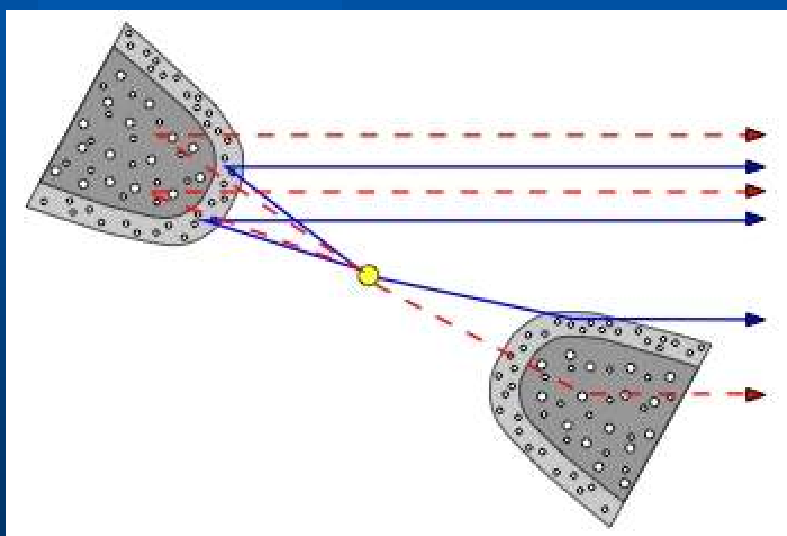

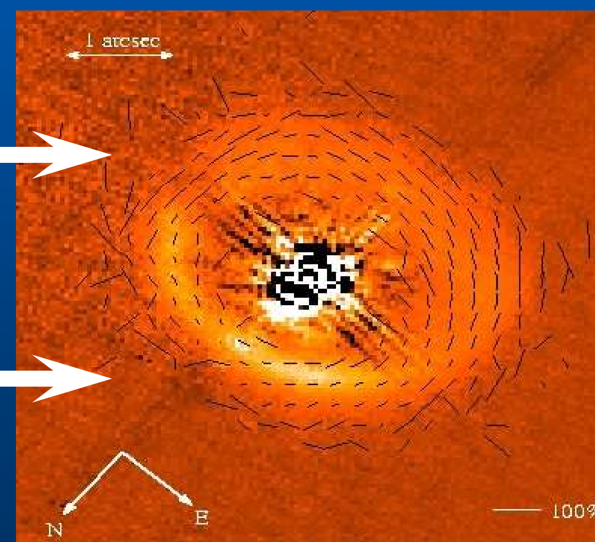

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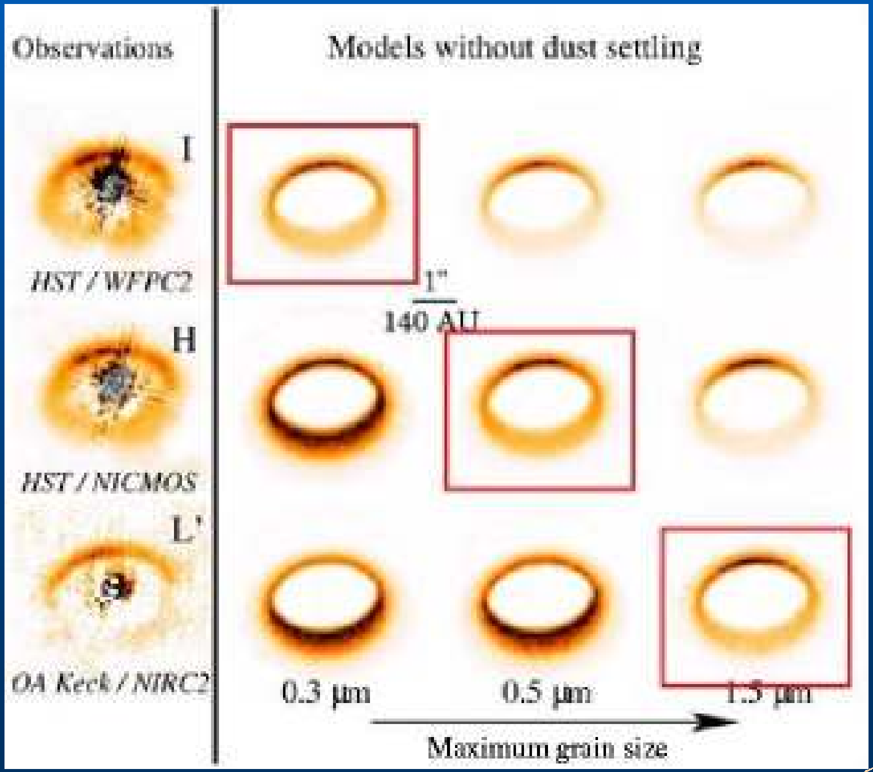
- Basic strategy: image same disk over a wide range of wavelengths
  - *Each image probes a different grain size*

Dust information

- Basic strategy: image same disk over a wide range of wavelengths
  - *Each image probes a different grain size*
- Dust opacity decreases at longer wavelengths (reddening)
  - *Longer wavelength images probe deeper layers of the disk!*

Back to the GG Tau ring

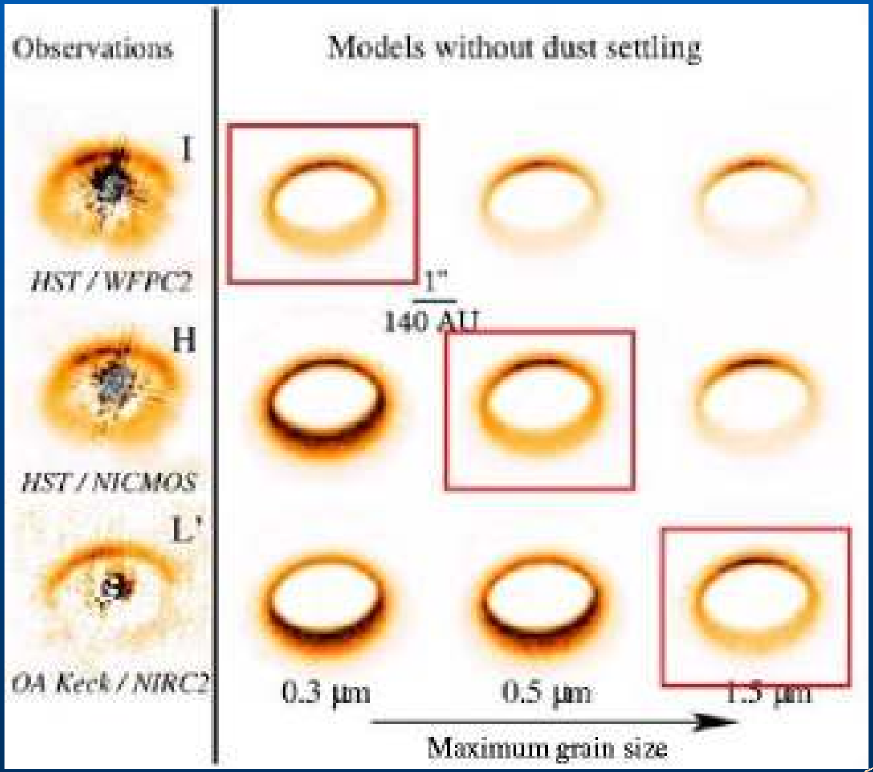
- The longer the wavelength, the larger the required a_{max}



Duchêne et al. (2004)

Back to the GG Tau ring

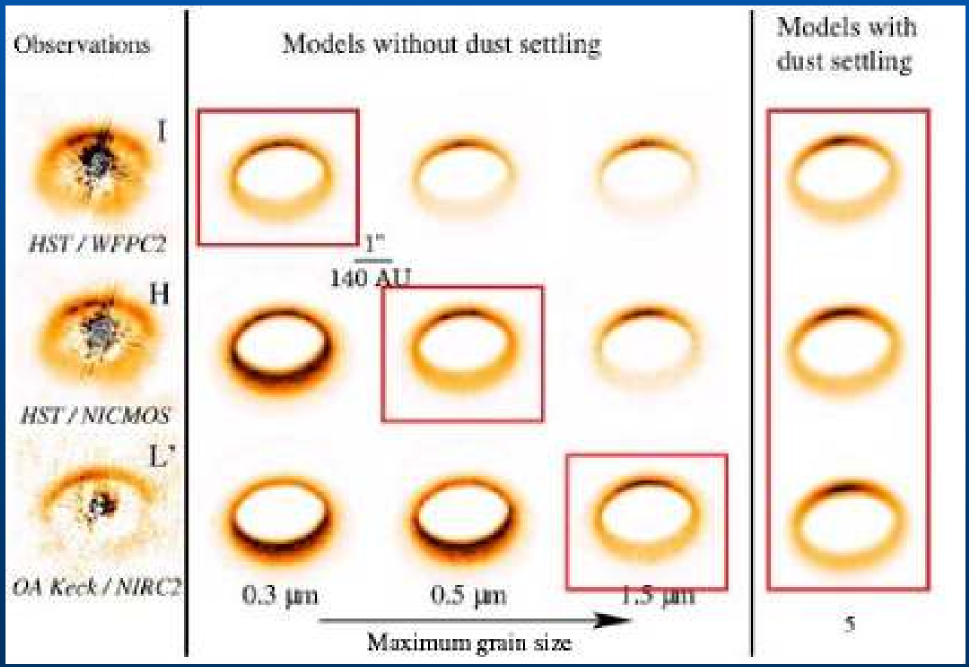
- The longer the wavelength, the larger the required a_{max}
- Suggests a layered structure with larger grains inside
  - *Dust sedimentation?*
  - *Gas/dust drag?*



Duchêne et al. (2004)

Back to the GG Tau ring

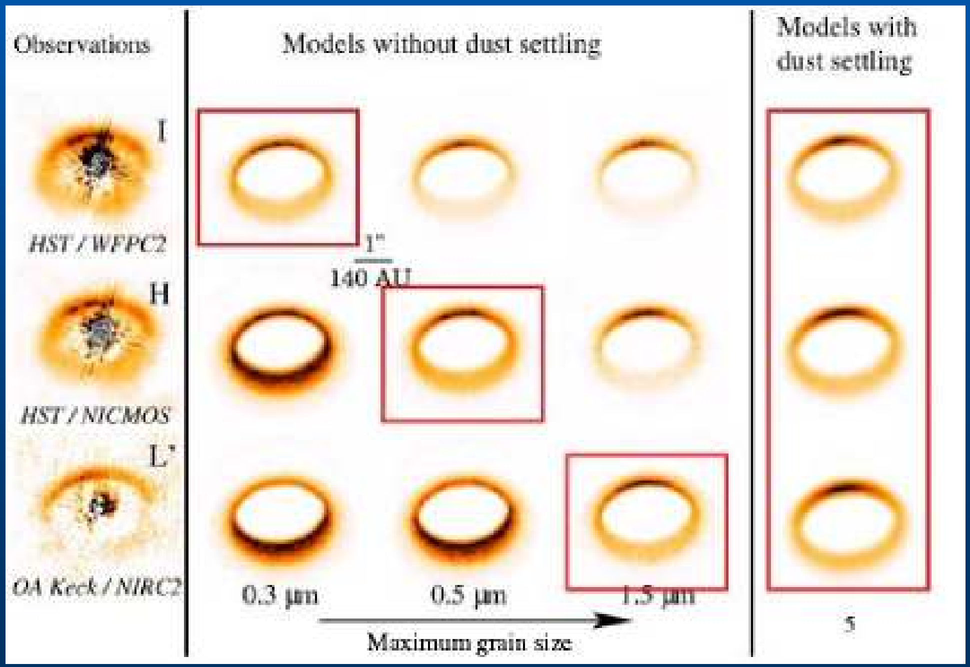
- Vertical AND radial stratification can account for all observations



Pinte et al. (2007)

Back to the GG Tau ring

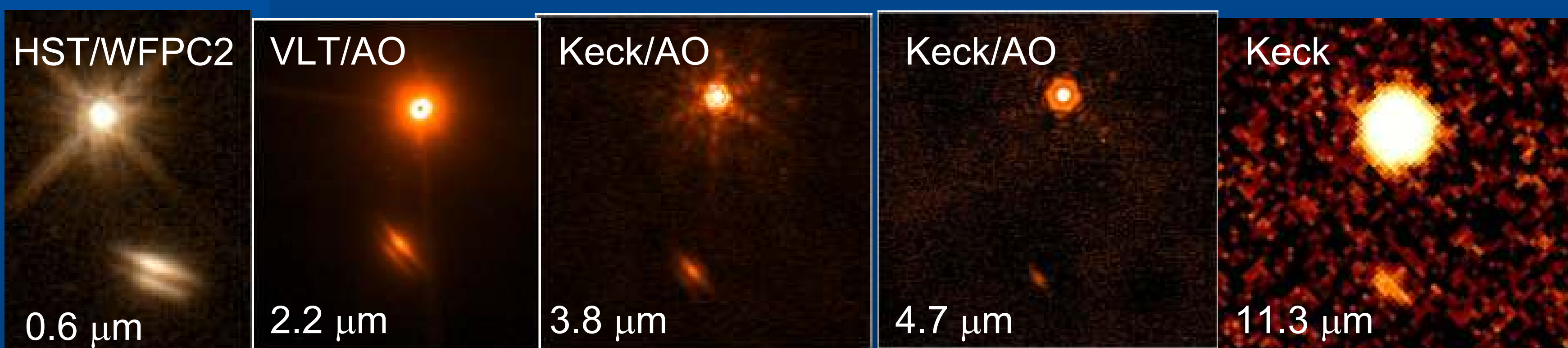
- Vertical AND radial stratification can account for all observations
- Supported by hydrodynamical (two-fluids) simulations of the ring



Pinte et al. (2007)

How wide a wavelength range?

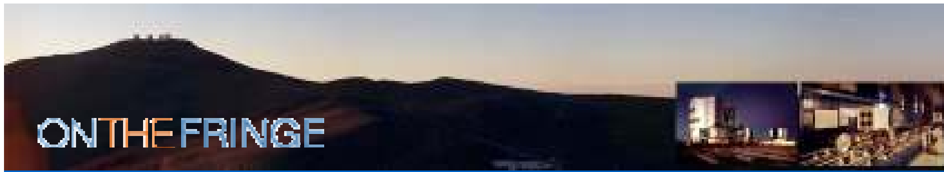
- The edge-on disk around HK Tau B has been observed over a factor of 20 in λ



Stapelfeldt et al. (1998)

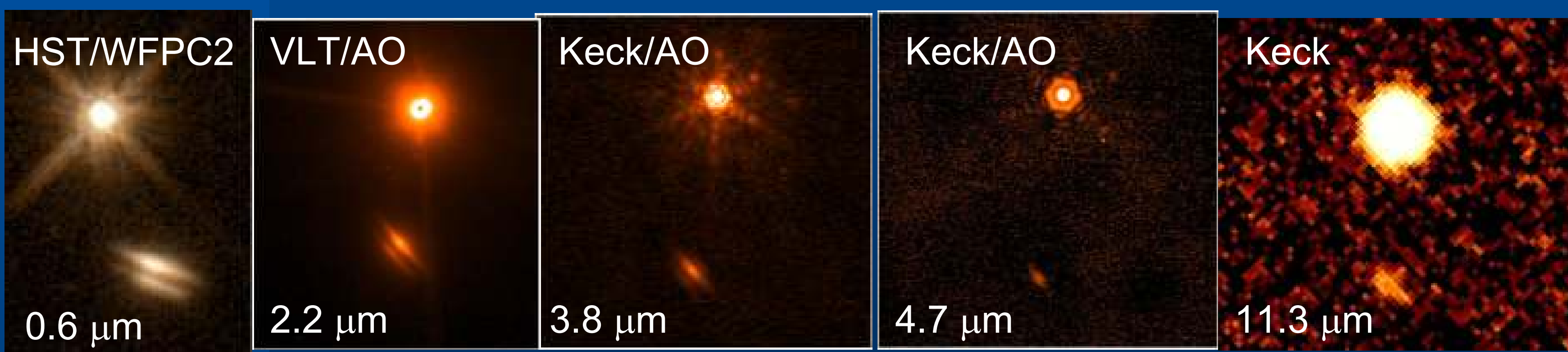
Courtesy: C. McCabe

McCabe et al. (2003)



How wide a wavelength range?

- The edge-on disk around HK Tau B has been observed over a factor of 20 in λ
- Well-mixed power law size distribution is definitely excluded; large grains needed!



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Older disks: debris disks

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- After planetary system formation, dust grains are produced in collisions
- The 'end result' of planet formation that we can compare to the younger disks
  - *Structure: evidence for planets?*
  - *Dust properties: processing?*

Debris disks: structure

- Observed asymmetries are intrinsic
  - *Tracers of planetary systems?*

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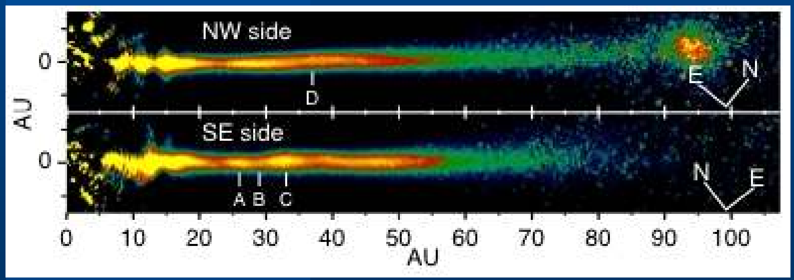

Fitzgerald et al. (2007)

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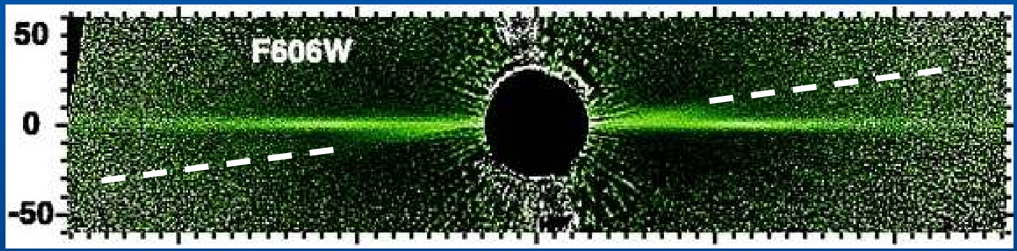
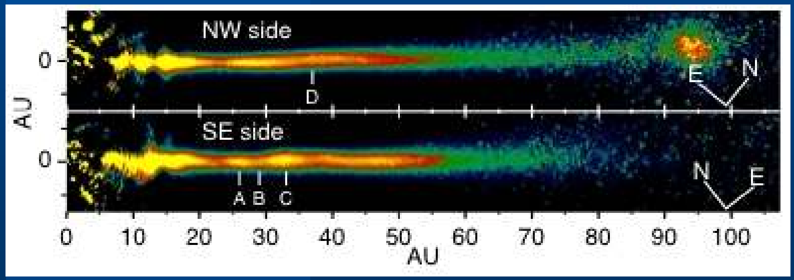


Golimowski et al. (2007)



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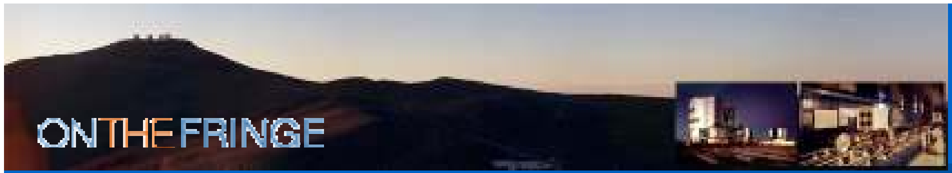

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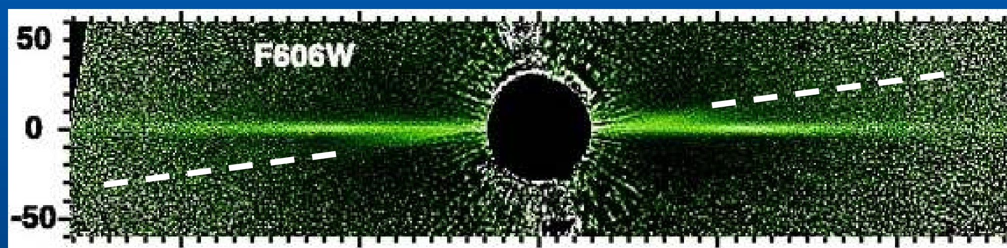

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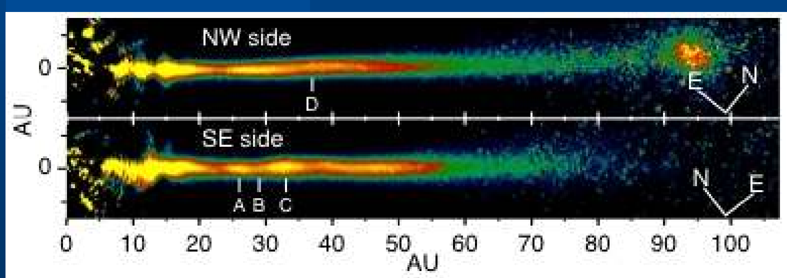

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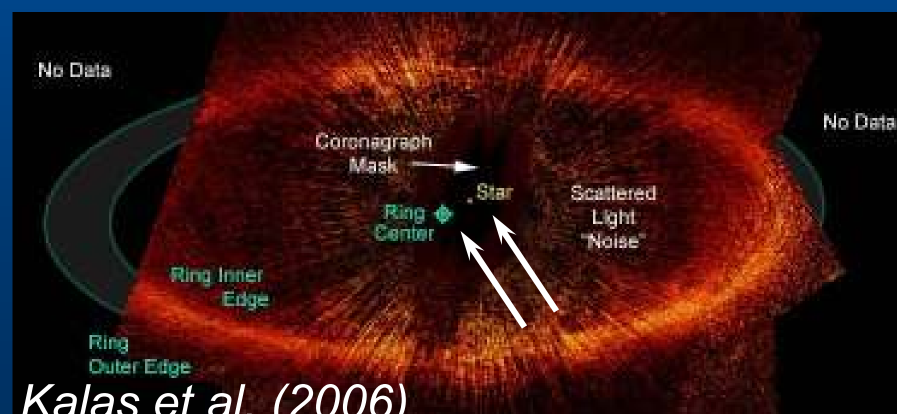


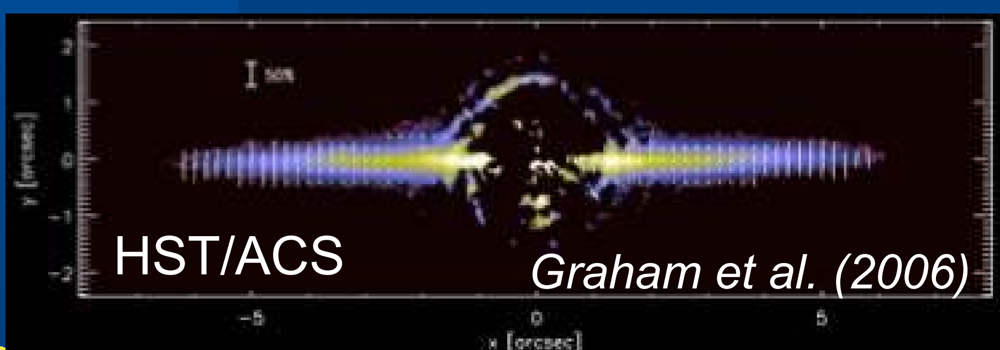
Kalas et al. (2006)

Debris disks: dust grains

- The AU Mic edge-on disk:

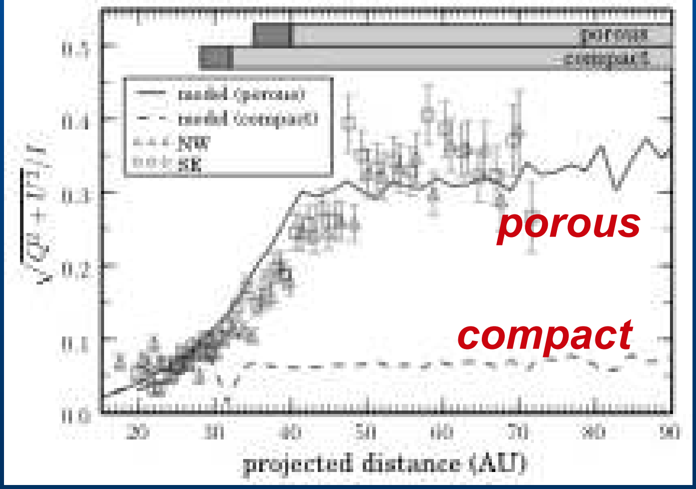
Debris disks: dust grains

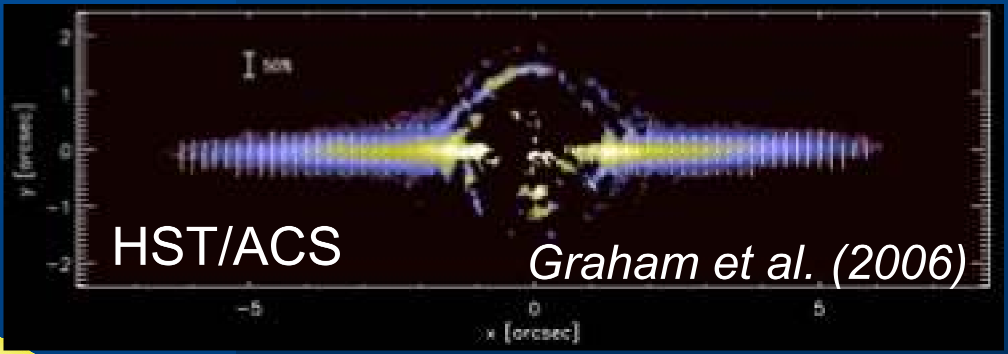
- The AU Mic edge-on disk:
  - *Linear polarization ~ 40%*
  - *Need very small grains*
    - $a_{min} < 0.1\ \mu m$



Debris disks: dust grains

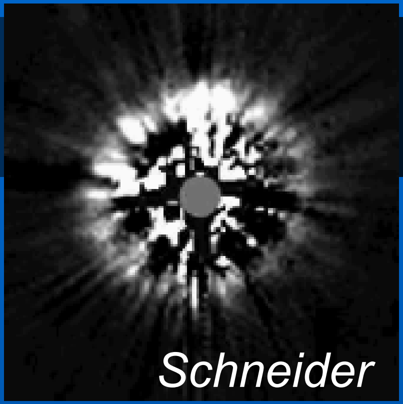
- The AU Mic edge-on disk:
  - *Linear polarization ~ 40%*
  - *Need very small grains*
    - – $a_{min} < 0.1\ \mu m$
  - *Grains must be porous!!*





Debris disks: dust grains

- Another debris disk: HD 181327



Schneider et al. (2006)

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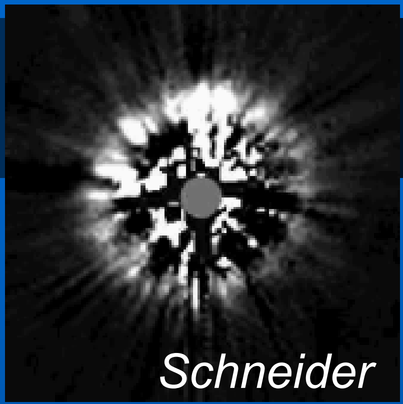

Schneider et al. (2006)

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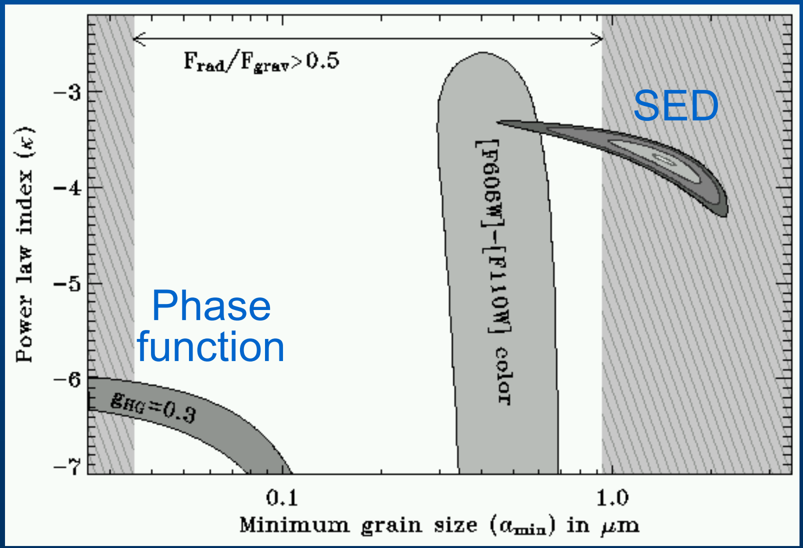

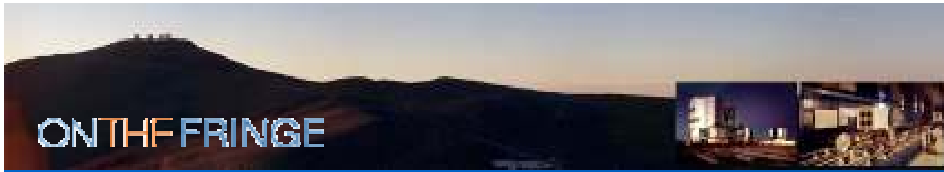

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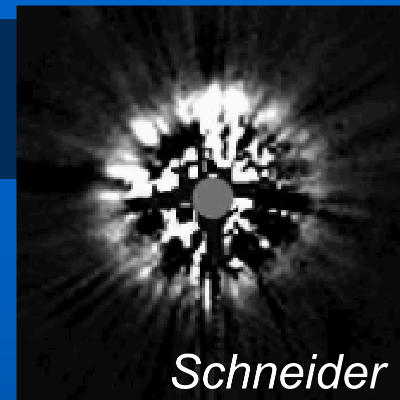

Schneider et al. (2006)

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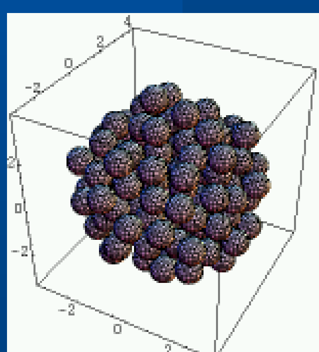
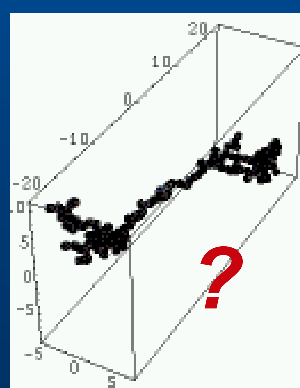
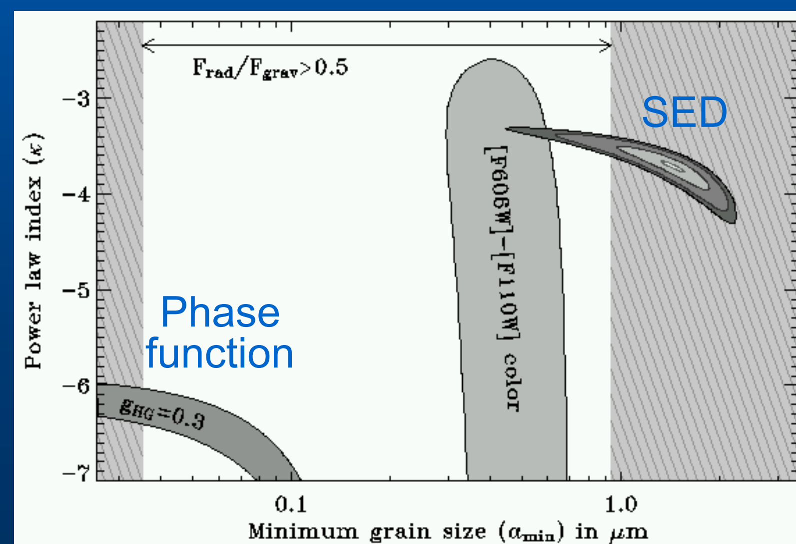
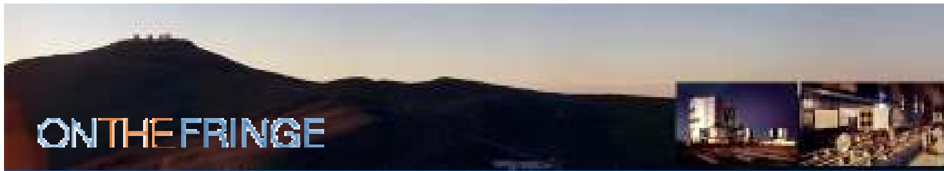
- All observables cannot be explained simultaneously with spherical grains
  - *Fluffy aggregates?*



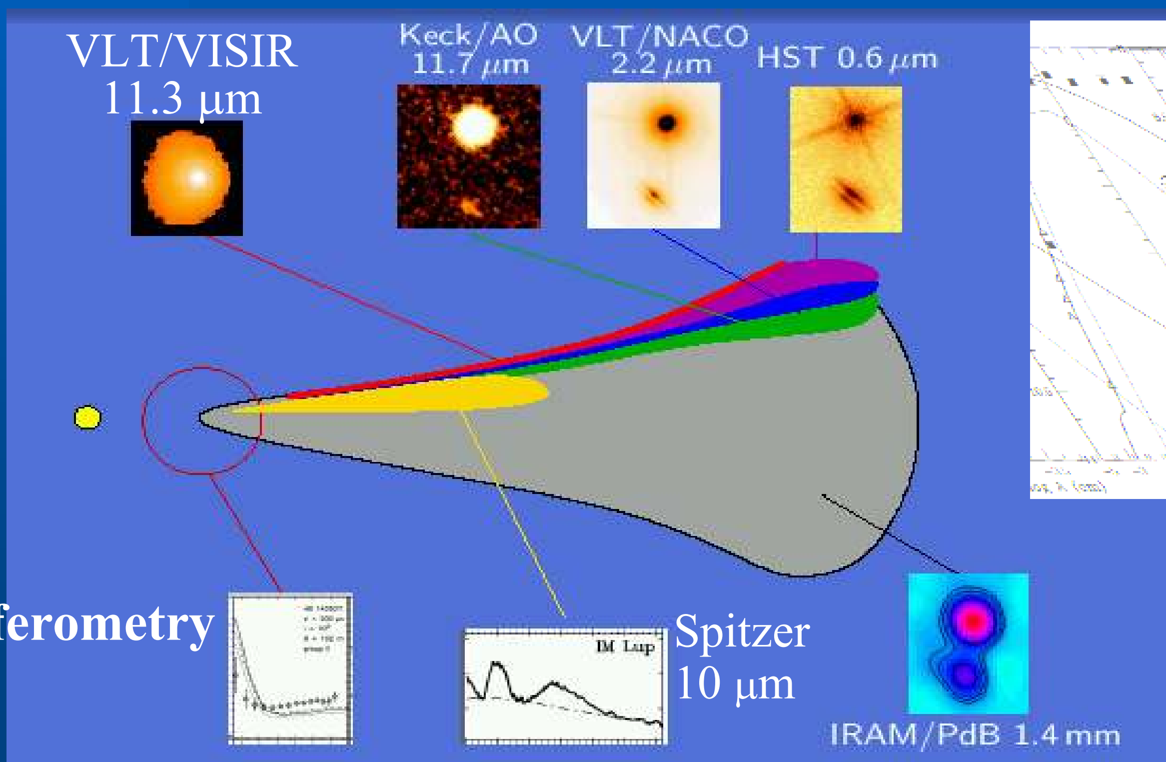
vs

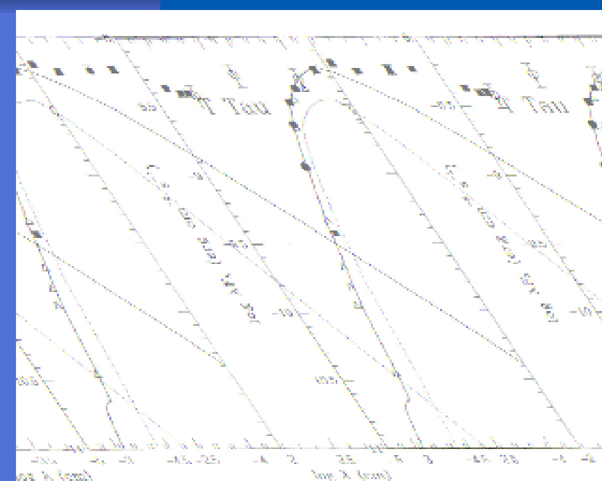






Studying circumstellar disks



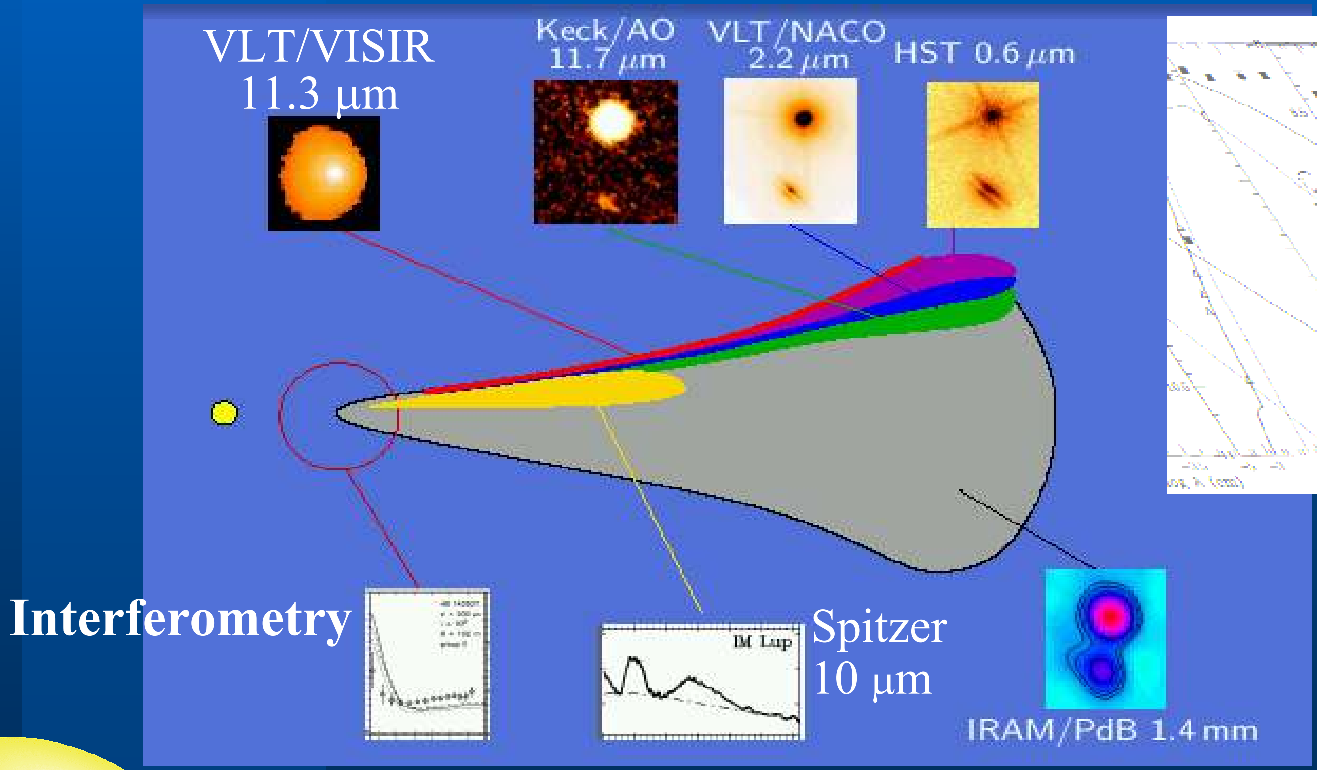


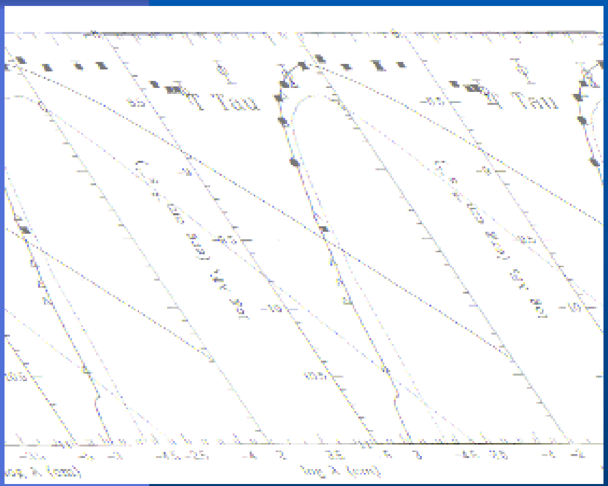
Courtesy:
C. Pinte

HST/AO/coronography: disks and planets

Studying circumstellar disks

- All observations are complementary!





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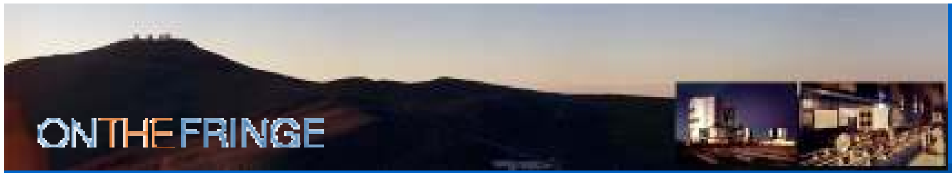

The big picture : Interferometry & ELTs

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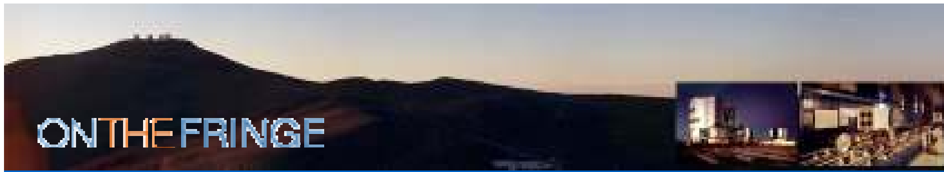
How about interferometry?

- Different part of parameter space!
- Inner regions of disks
  - *See R. Akeson's course*
- Radial dependence of dust properties
  - *Processing at high temperature*
- Shape of inner rim
  - *Effect of strong illumination*



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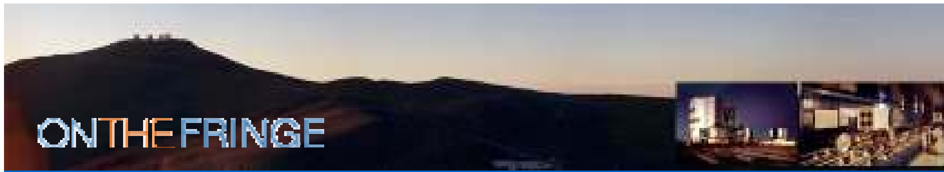

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  - *See N. Santos' courses*

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  - *Complex (MC)AO systems required*
  - *Extremely competitive (large teams)*

ONTHEFRINGE

The big picture

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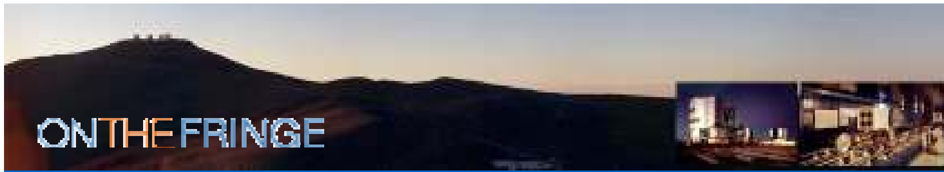
- Start with HST/AO imaging
- Follow-up with interferometry
- Get nice images with ELTs / 'interferometric imagers'



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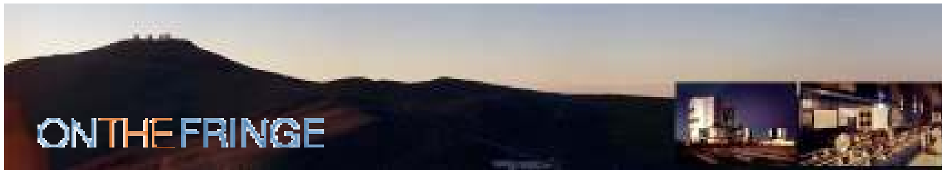

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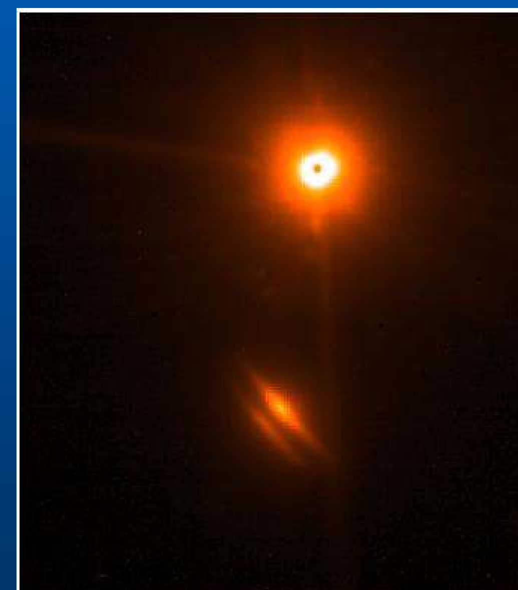

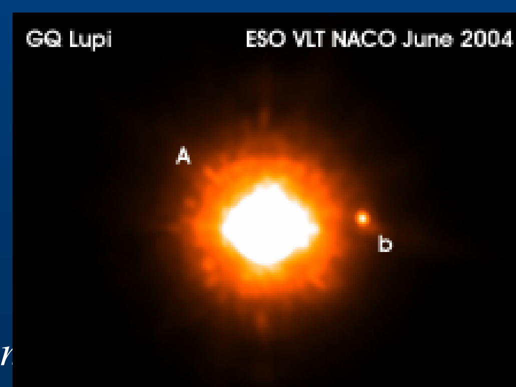

HST/AO/coron