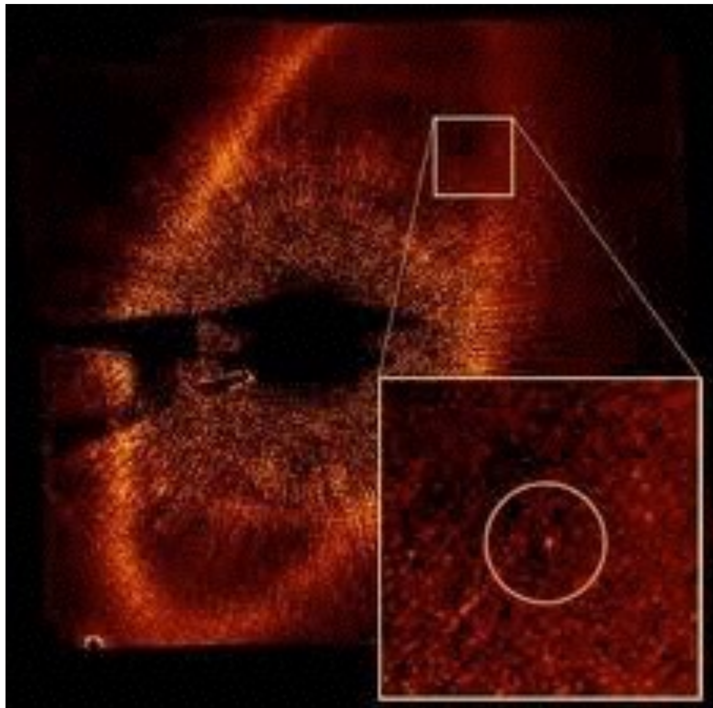
~ 10 weeks remaining

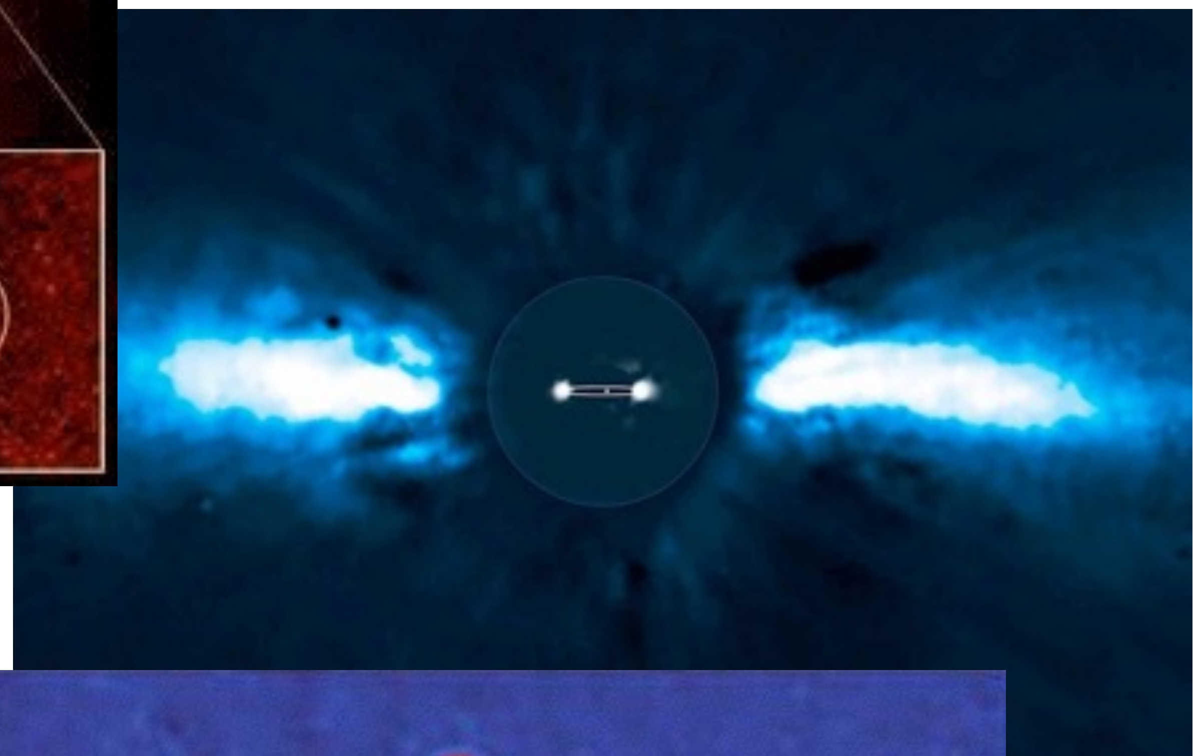
- Pick paper to present week of Feb 25th.
- TESS proposal due: March 14th ?
- GSC April 2nd
- RV proposal due April 4th ?
- JWST proposal due May 1st.

Direct Imaging

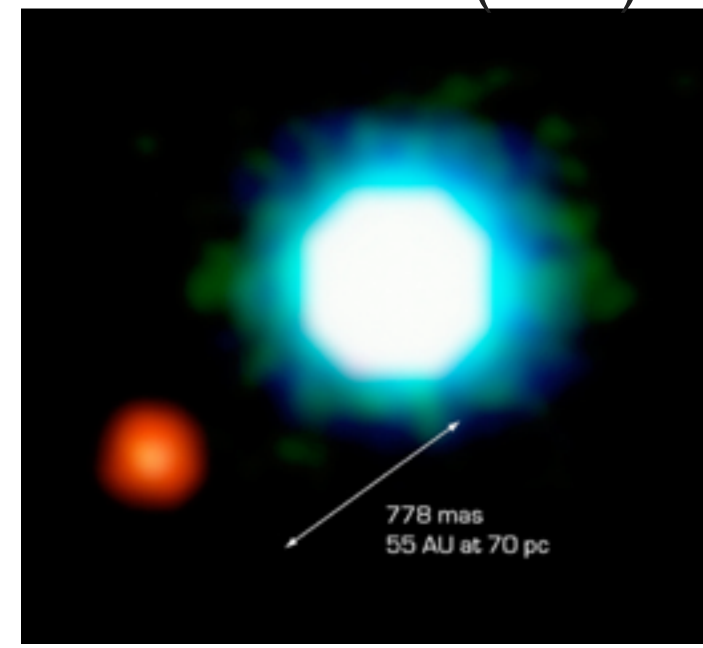
Kalas et al. (2008)

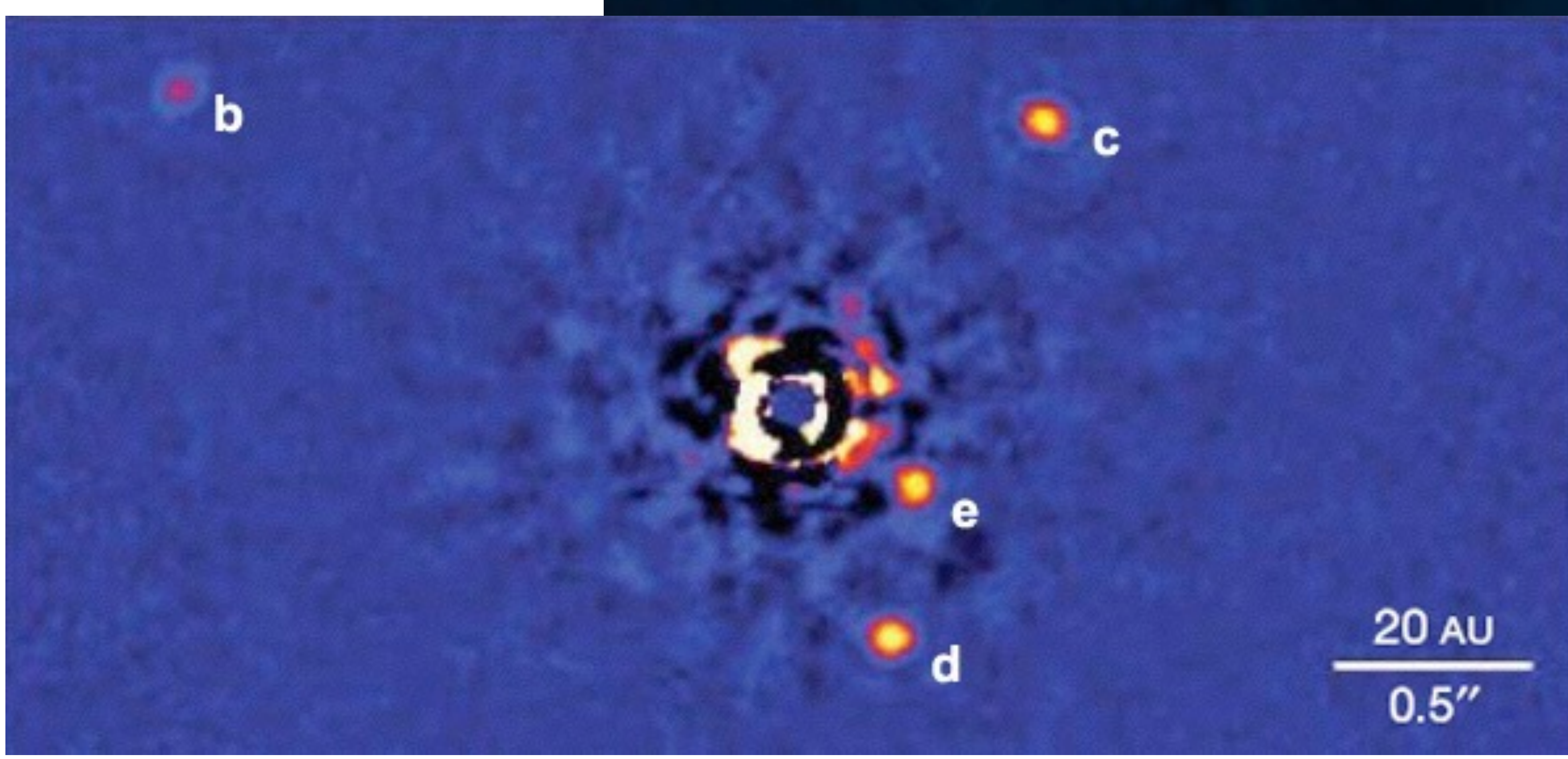


Lagrange et al. (2009)

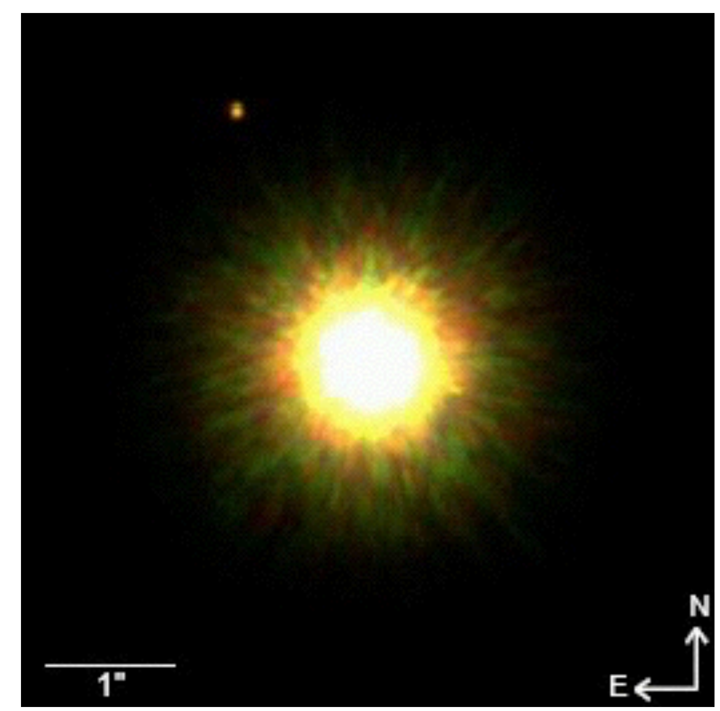


Chauvin et al. (2004)



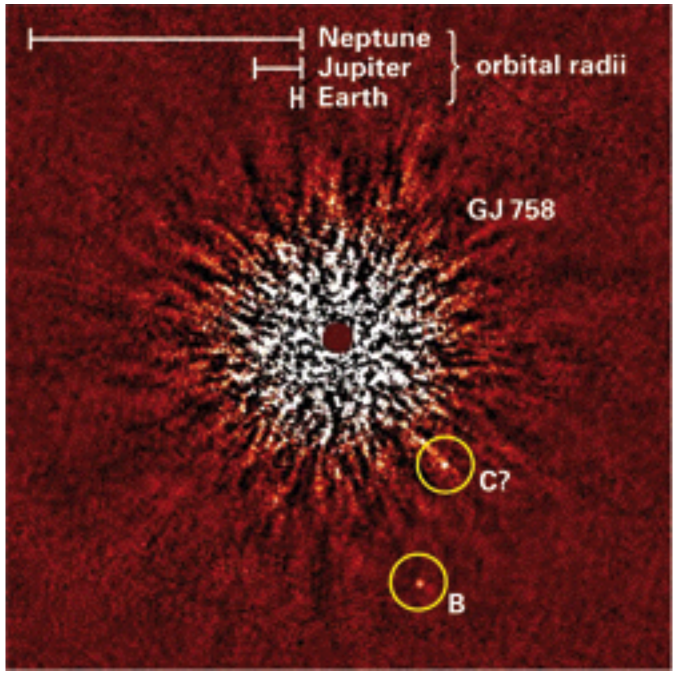


Marois et al. (2008,2010)

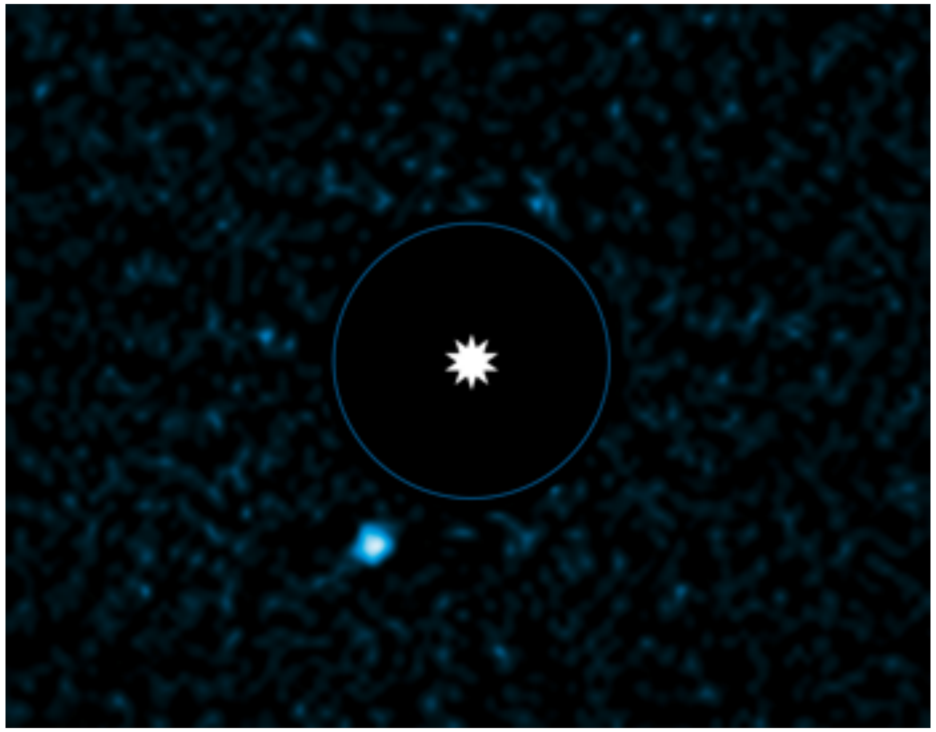


Lafrénière et al. (2010)

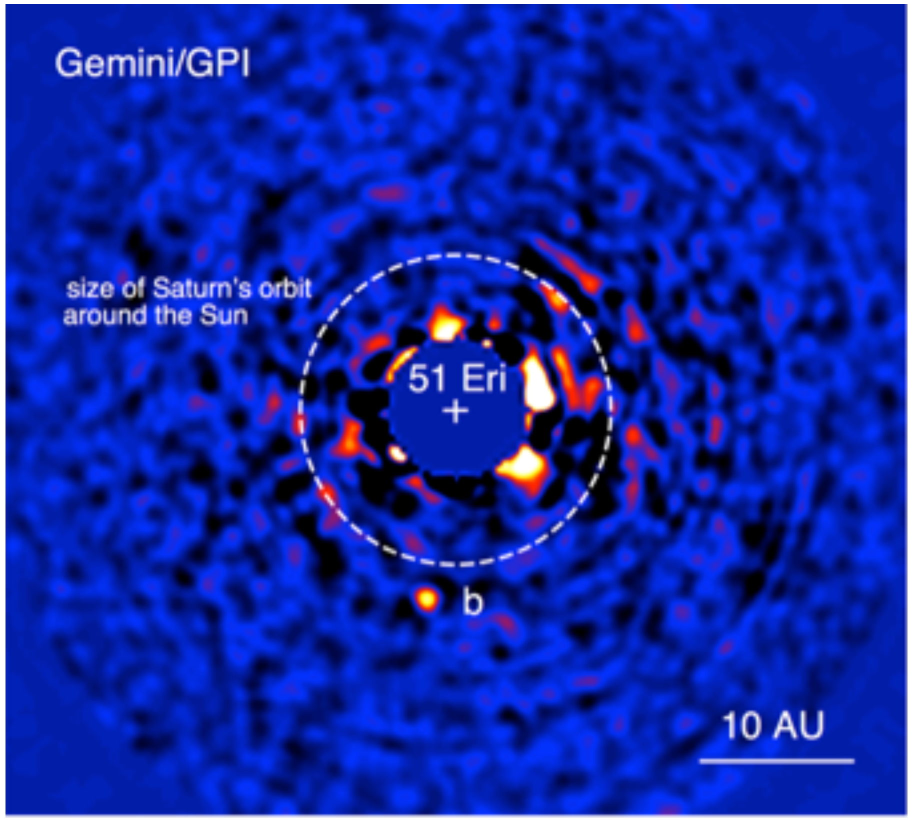
Direct Imaging



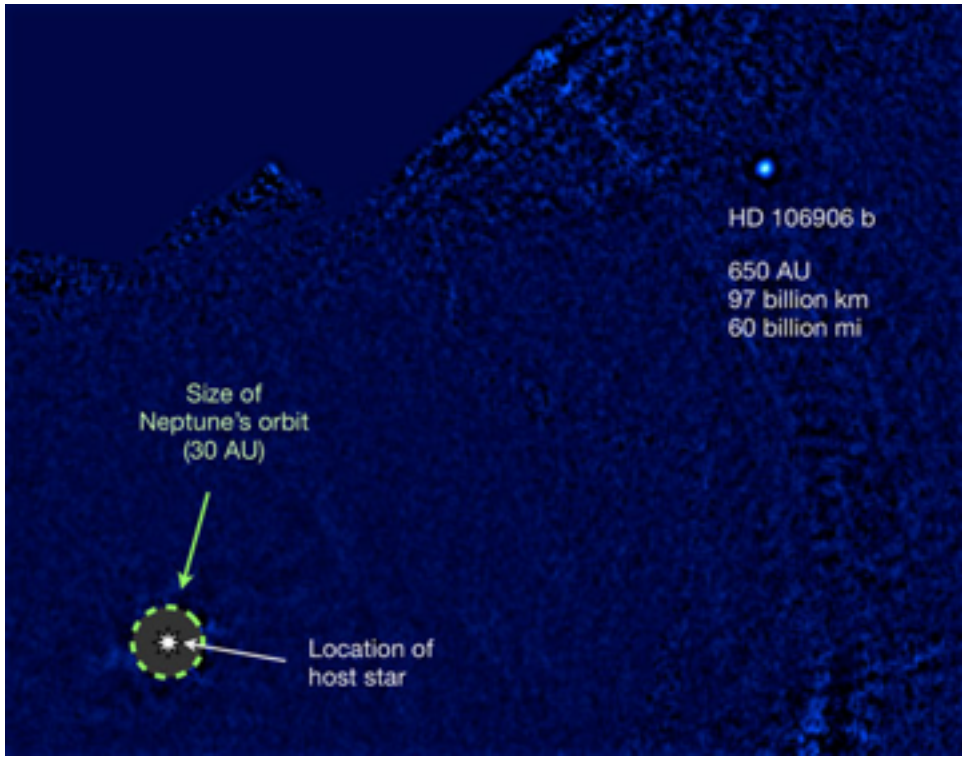
Thalaman et al. (2009)



Rameau et al. (2013)

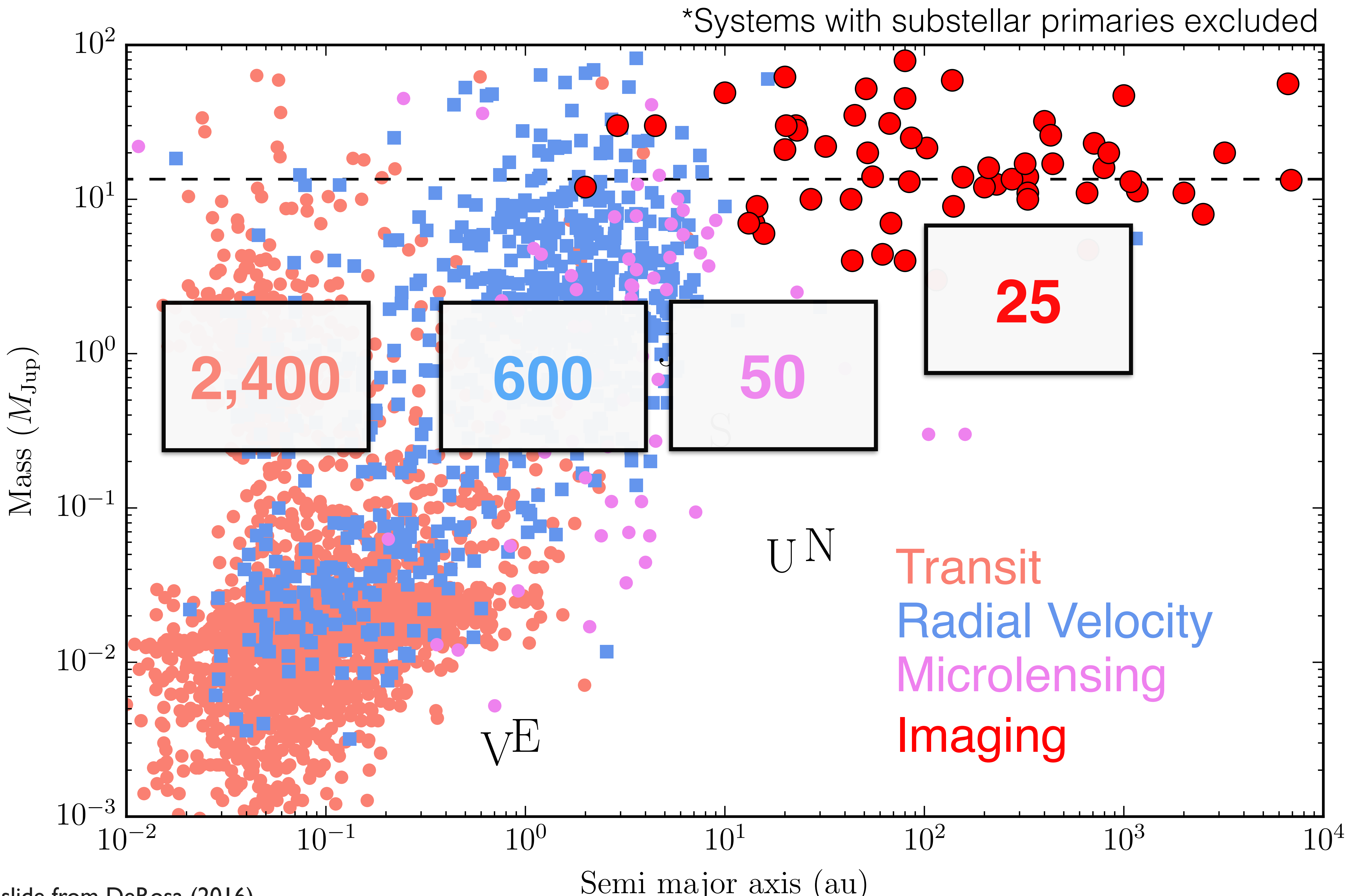


Macintosh et al. (2014)



Bailey et al. (2013)

Why bother?

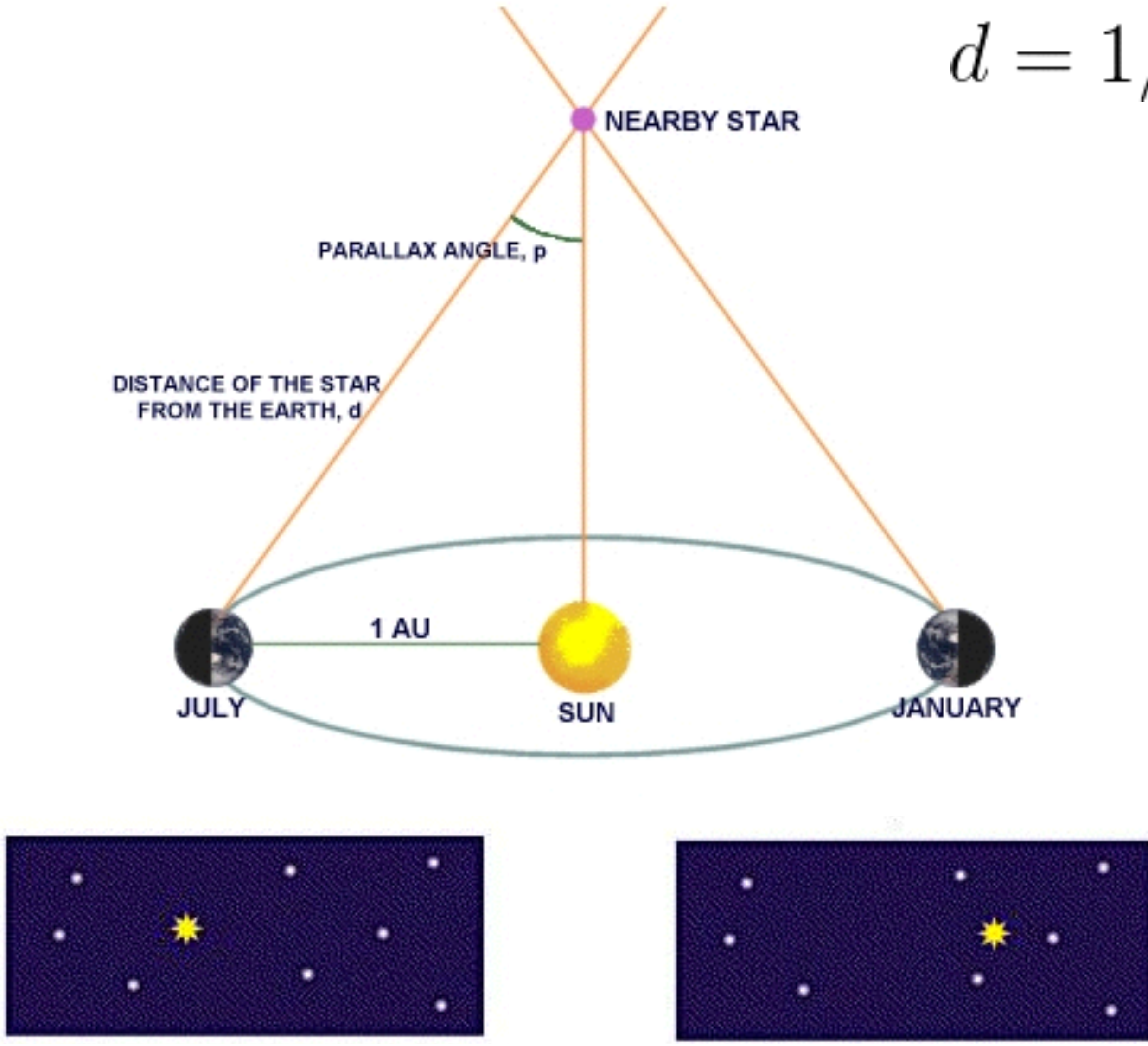


slide from DeRosa (2016)

The primary observables are:

- Separation (usually expressed in seconds of arc)
- Contrast (usually expressed as delta magnitude)

Quick Refresher on angles and magnitudes



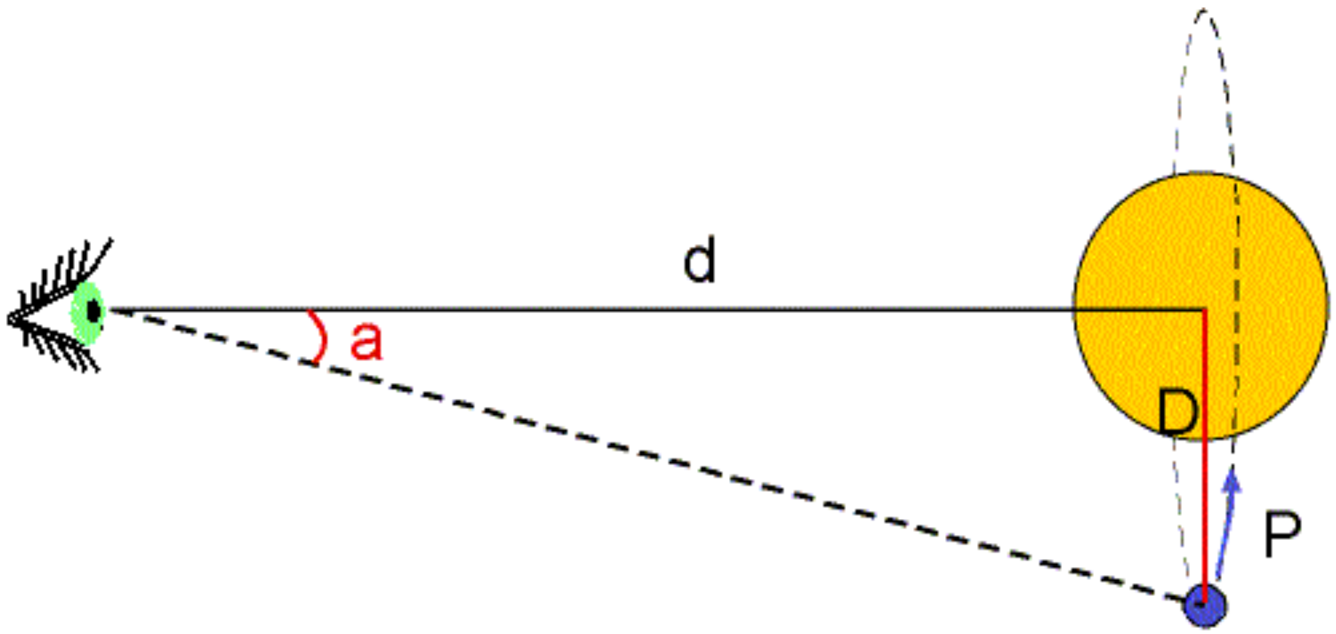
$$d = 1/p$$

distance d(parsecs)
parallax p(arc seconds)

primary resources for parallaxes: HIPARCOS (GAIA first data released, 2nd release in 2018) Various other near-IR parallax programs

usually find this stuff with VizieR online search

Quick Refresher on angles and magnitudes



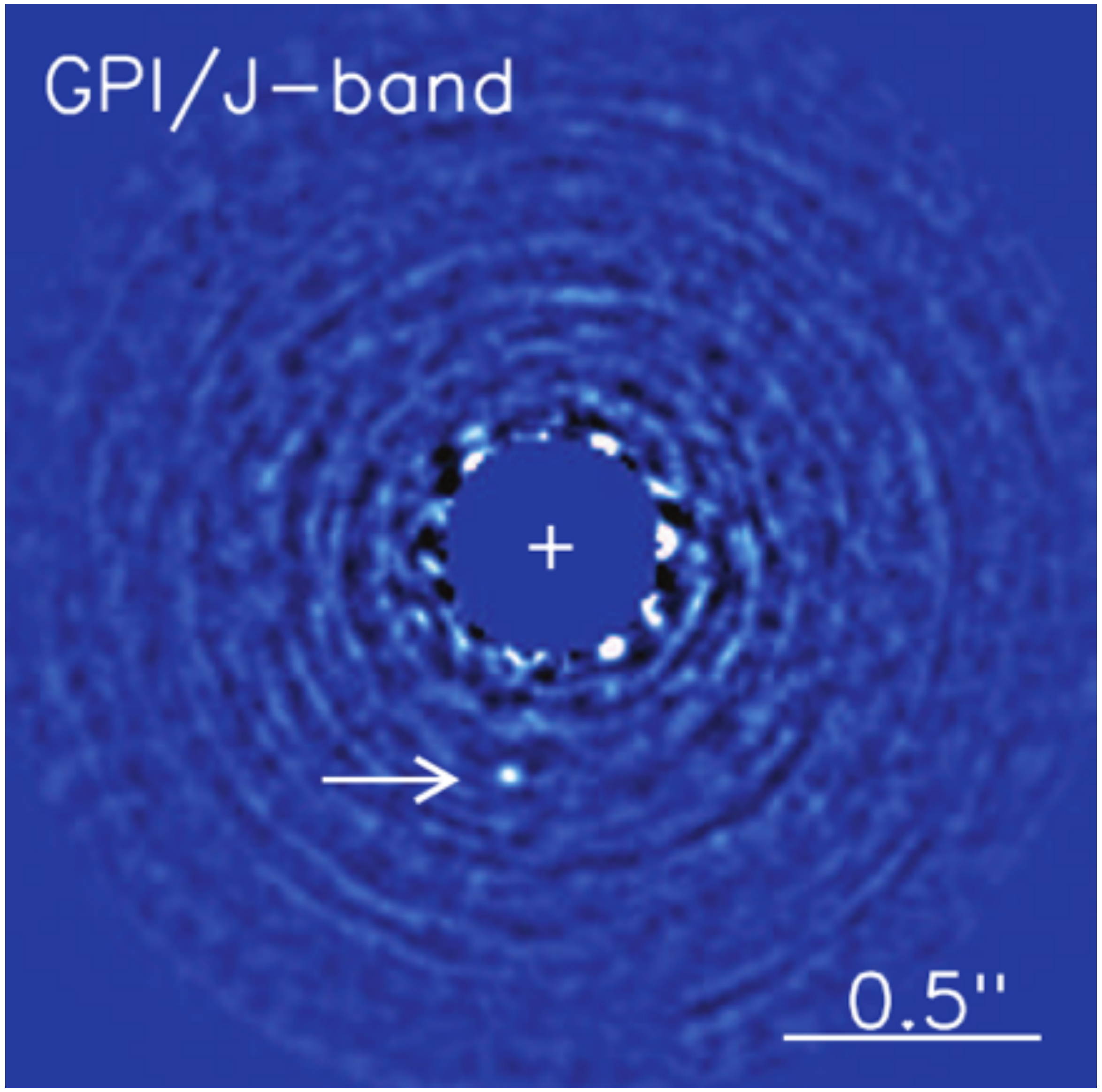
distance d(parsecs)
a (arc seconds)

$$a('') = D(\mathrm{AU})/d$$

$$D(\mathrm{AU}) = da$$

Quick Refresher on angles and magnitudes

How far is this planet from Earth, if the planet separation is 13 AU?

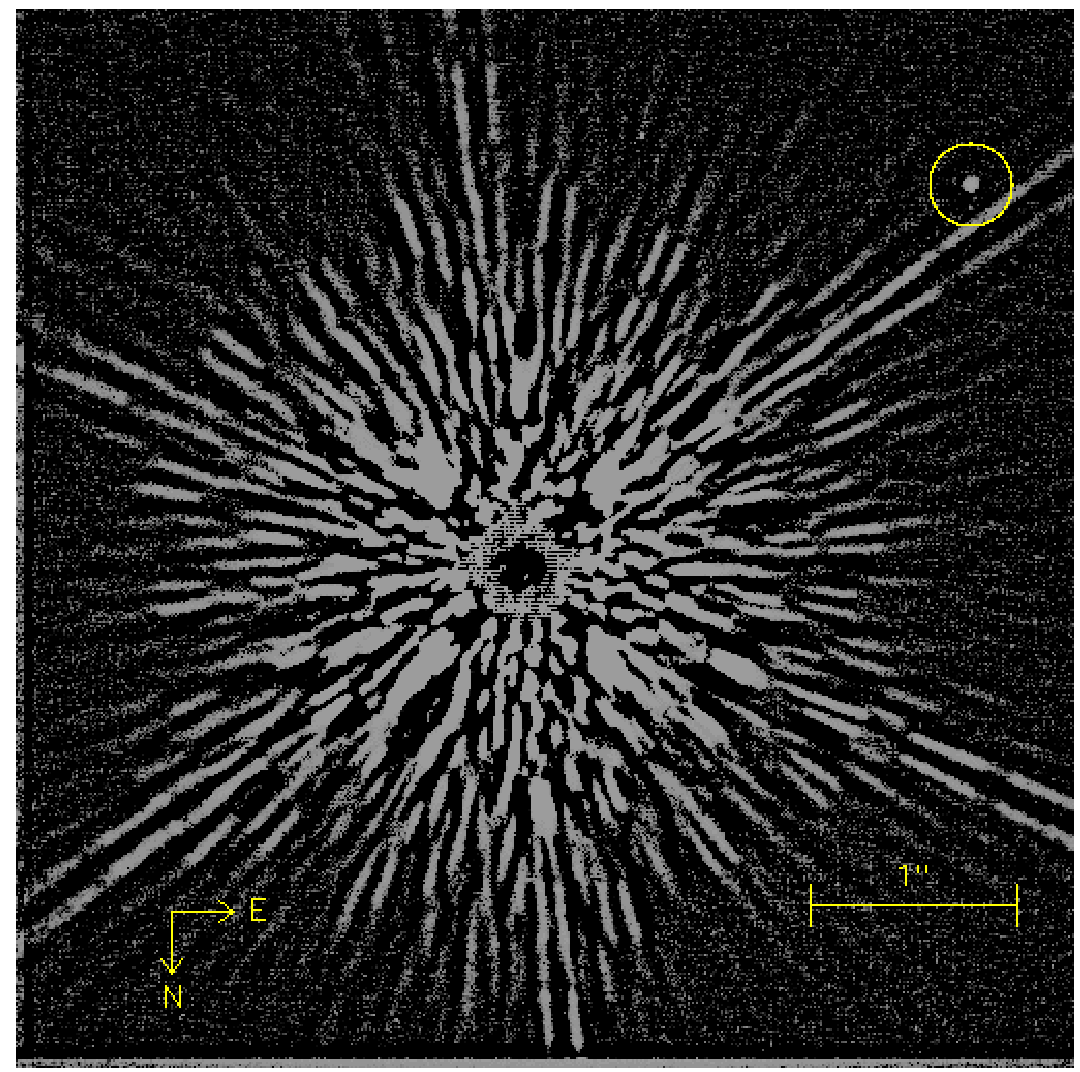


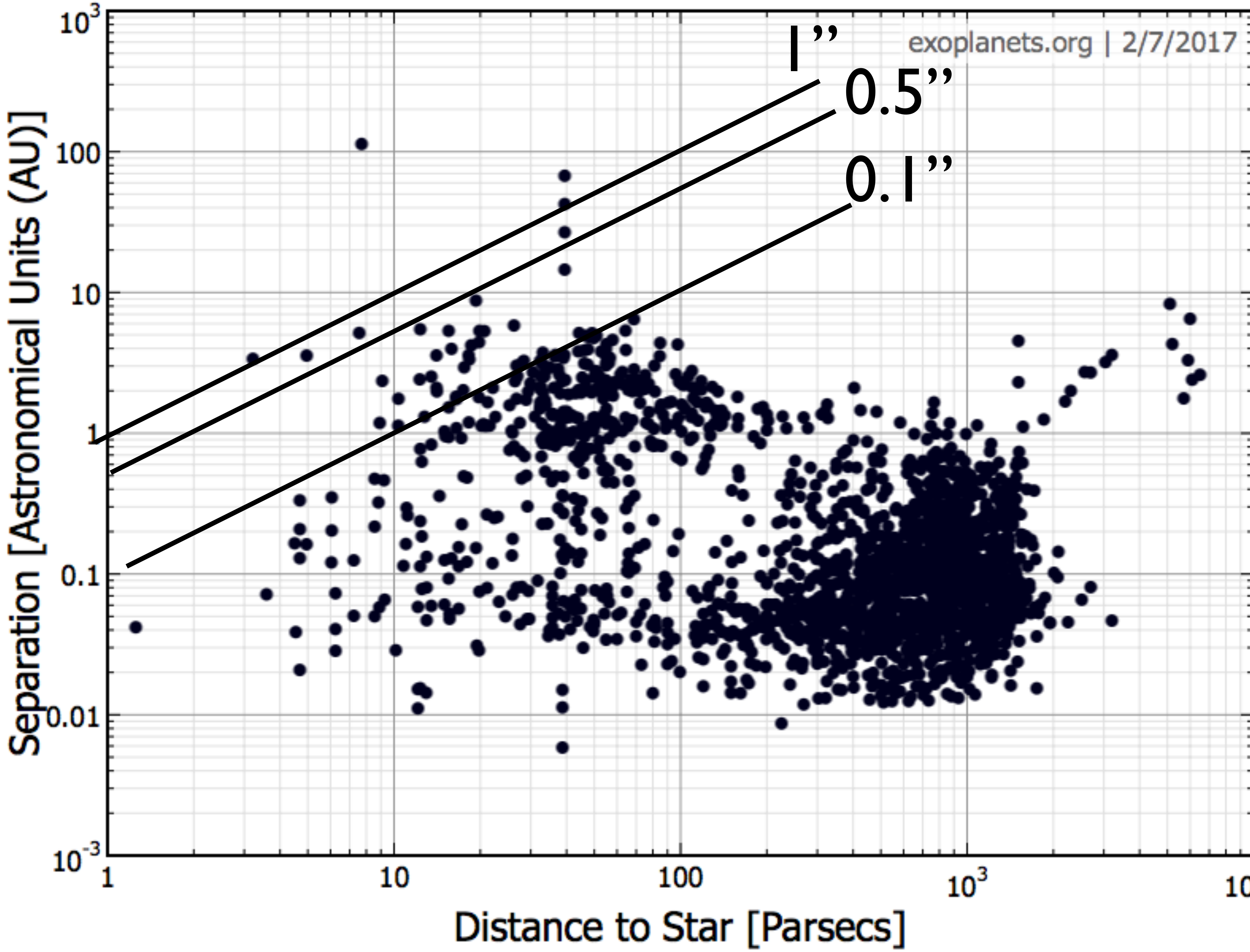
Quick Refresher on angles and magnitudes

in practice, measure separation in pixels
... then use pre-determined "plate scale"

NIRC2/Keck-2

Wavelength range	0.9-5.3 microns
Field of view	10x10 arcsec (narrow camera) 20x20 arcsec (medium camera) 40x40 arcsec (wide camera)
Pixel scale	0.009942 arcsec/pixel (+/- 0.00005") 0.019829 arcsec/pixel 0.039686 arcsec/pixel
Filters	z, Y, J, H, K, Ks, Kp, Lw, Lp, Ms, HeI, Pa_ H2O, PAH, Br_alpha, Br_alpha_cont



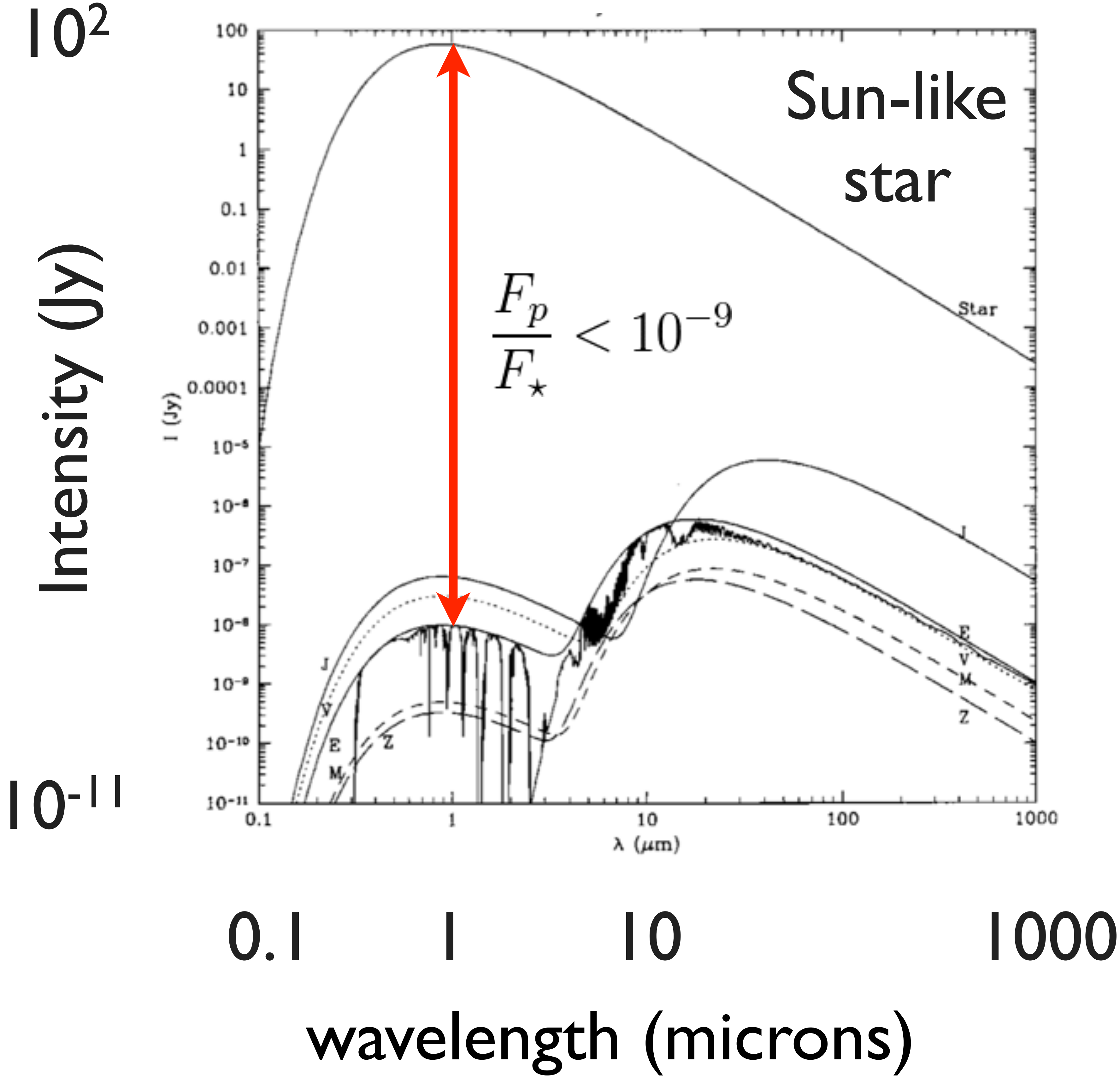


exoplanets.org | 2/7/2017
1"
0.5"
0.1"
Separation [Astronomical Units (AU)]
Distance to Star [Parsecs]
10^3
100
10
1
0.1
0.01
10^-3
1
10
100
10^3
10^4

The primary observables are:

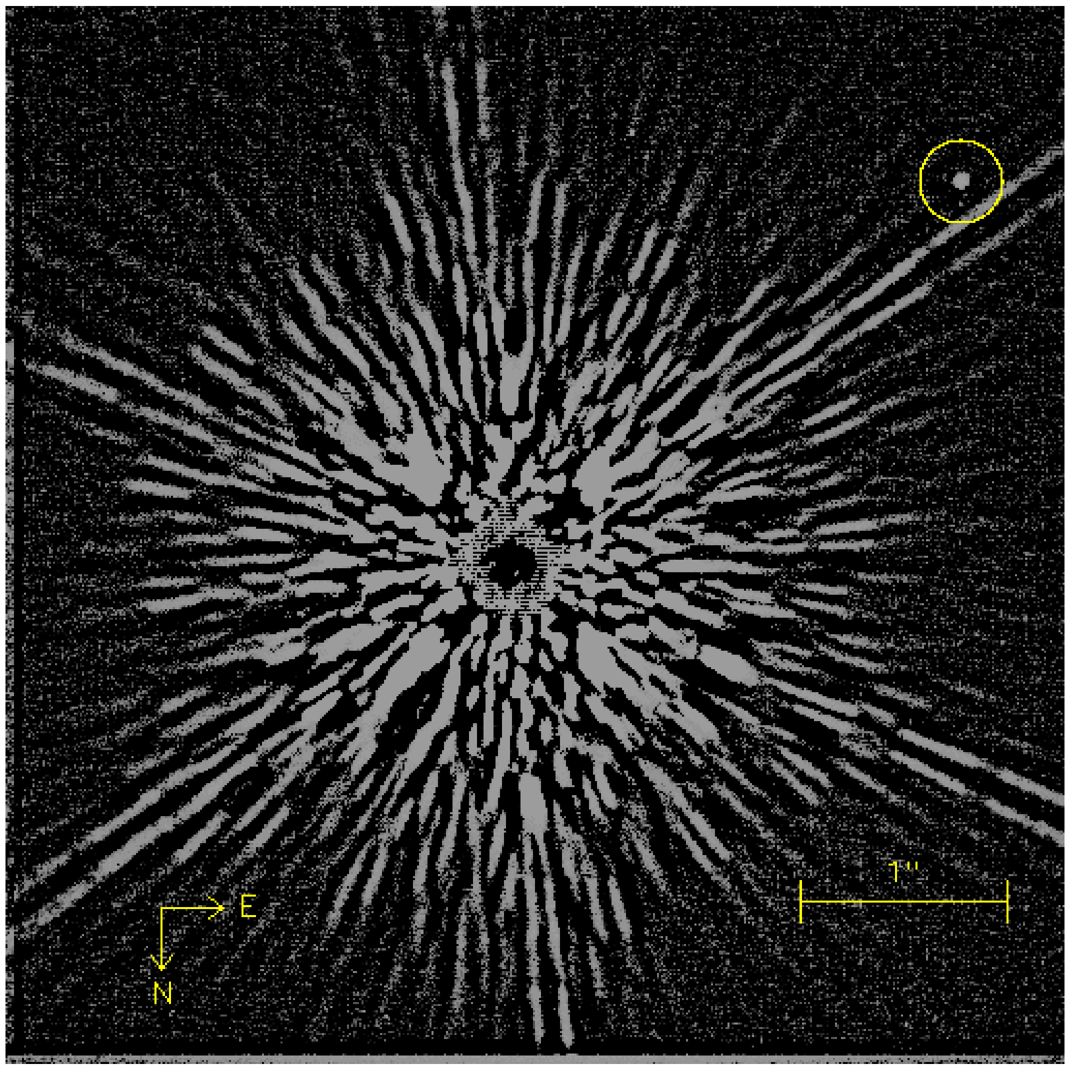
- Separation (usually expressed in seconds of arc)
- Contrast (flux ratio often expressed as delta magnitude)

“Contrast”



Sun-like star
$\frac{F_p}{F_\star} < 10^{-9}$
Intensity (Jy)
10^{2}
10^{-11}
wavelength (microns)
0.1
1
10
1000
Star
I (Jy)
λ (μm)

in practice, measure the “counts” ratio and piggyback off known magnitude of star



delta $m_K \sim 8$

Quick Refresher on angles and magnitudes

Magnitudes are evil and designed to confuse us -- especially theorists.

magnitudes

$$F = \frac{L}{4\pi d^2}$$

$$m_{\rm bol} = -2.5\log_{10}(L/4\pi d^2) + C$$

$$= -2.5\log_{10} L + 5\log_{10} d + C$$

$$M_{\rm bol} = -2.5\log_{10} L + 5\log_{10} 10 + C$$

$$m_{\rm bol} - M_{\rm bol} = 5\log_{10}(d/10\mathrm{pc})$$

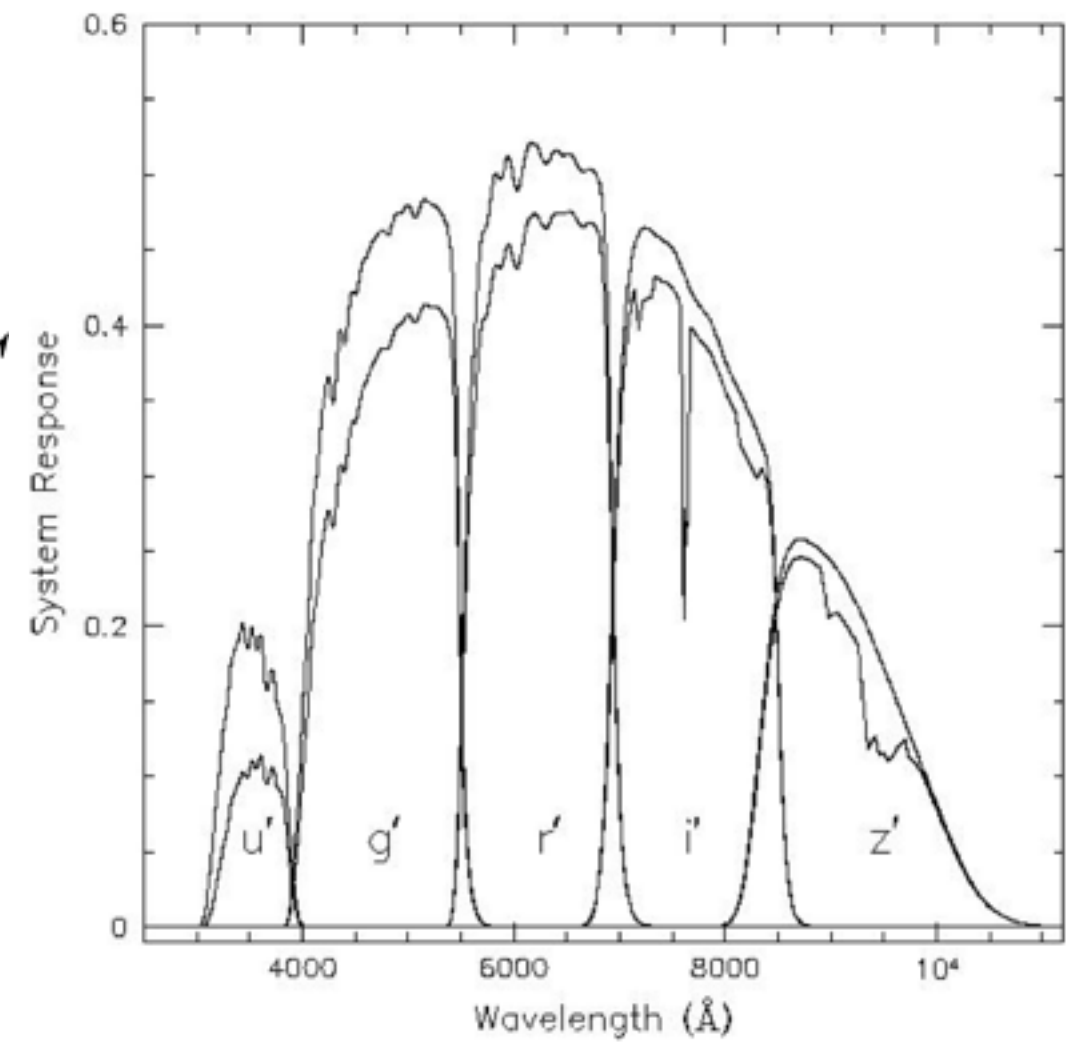
- L : total power output *over all wavelengths*
- F: bolometric flux
- m: apparent bolometric magnitude
- M: absolute bolometric

- In practice, we measure the flux over specific bands determined by the instrument (filters, etc.)

$$F_{\text{obs}} = \int_0^\infty f(\lambda) s(\lambda) d\lambda$$

$$m_V = -2.5 \log_{10} \left(\int_0^\infty f(\lambda) s_V(\lambda) d\lambda \right) + C$$

The constant depends on filter and normalization of the photometric system being used

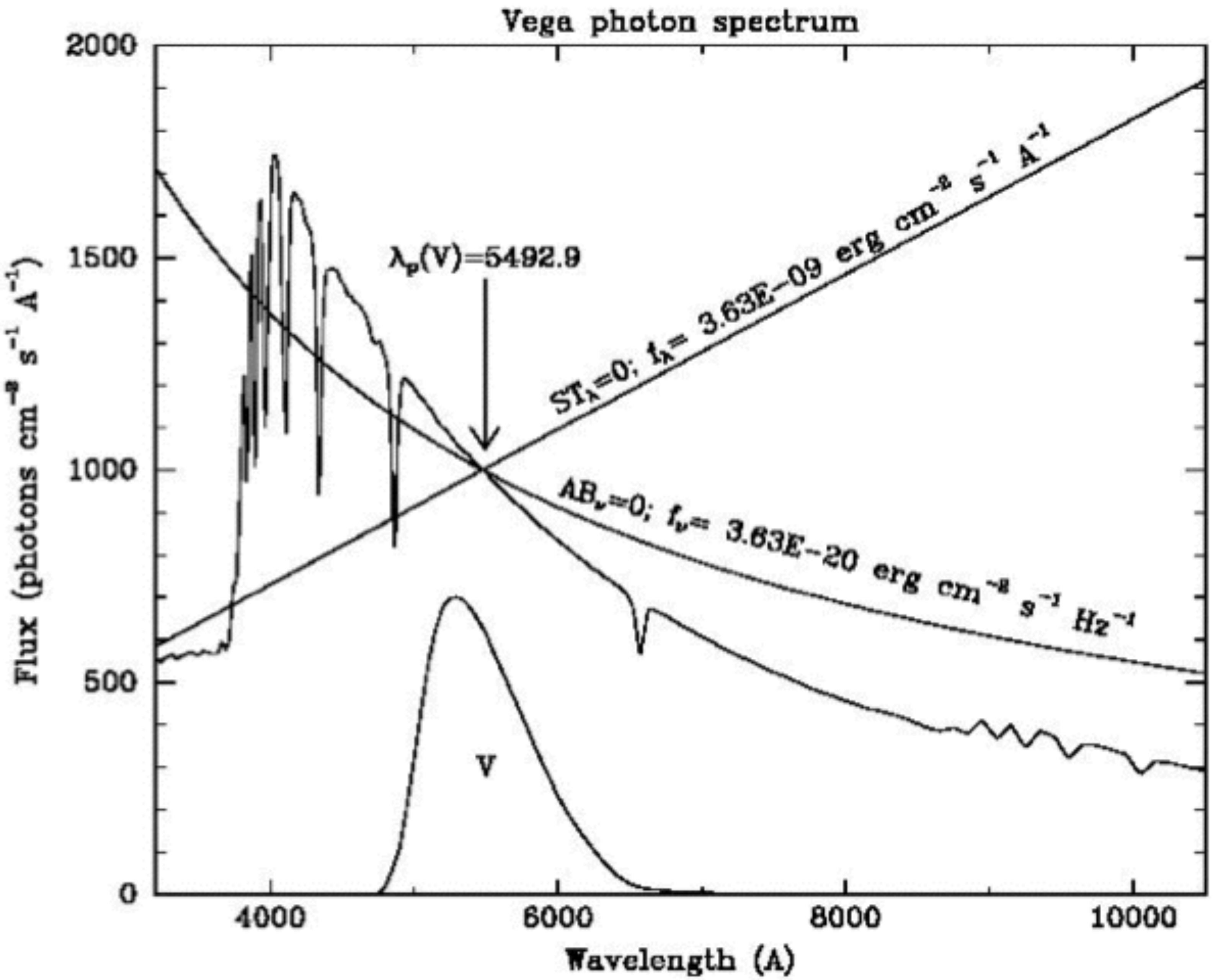


- many different filter sets: filter X at one telescope may not be the same as filter X at another!

- photometric systems have various normalizations (aka “zero-points”) with Vega’s spectrum being the most common

$$ZP = -2.5\log_{10}\left(\int_0^\infty f_{\rm Vega}(\lambda)s_V(\lambda)d\lambda\right)$$

- HST has their own (more sensible)



$$m(AB) = -2.5\log(F_\nu) - 48.60$$

$$m(ST) = -2.5\log(F_\lambda) - 21.10$$

Flux Density Conversion

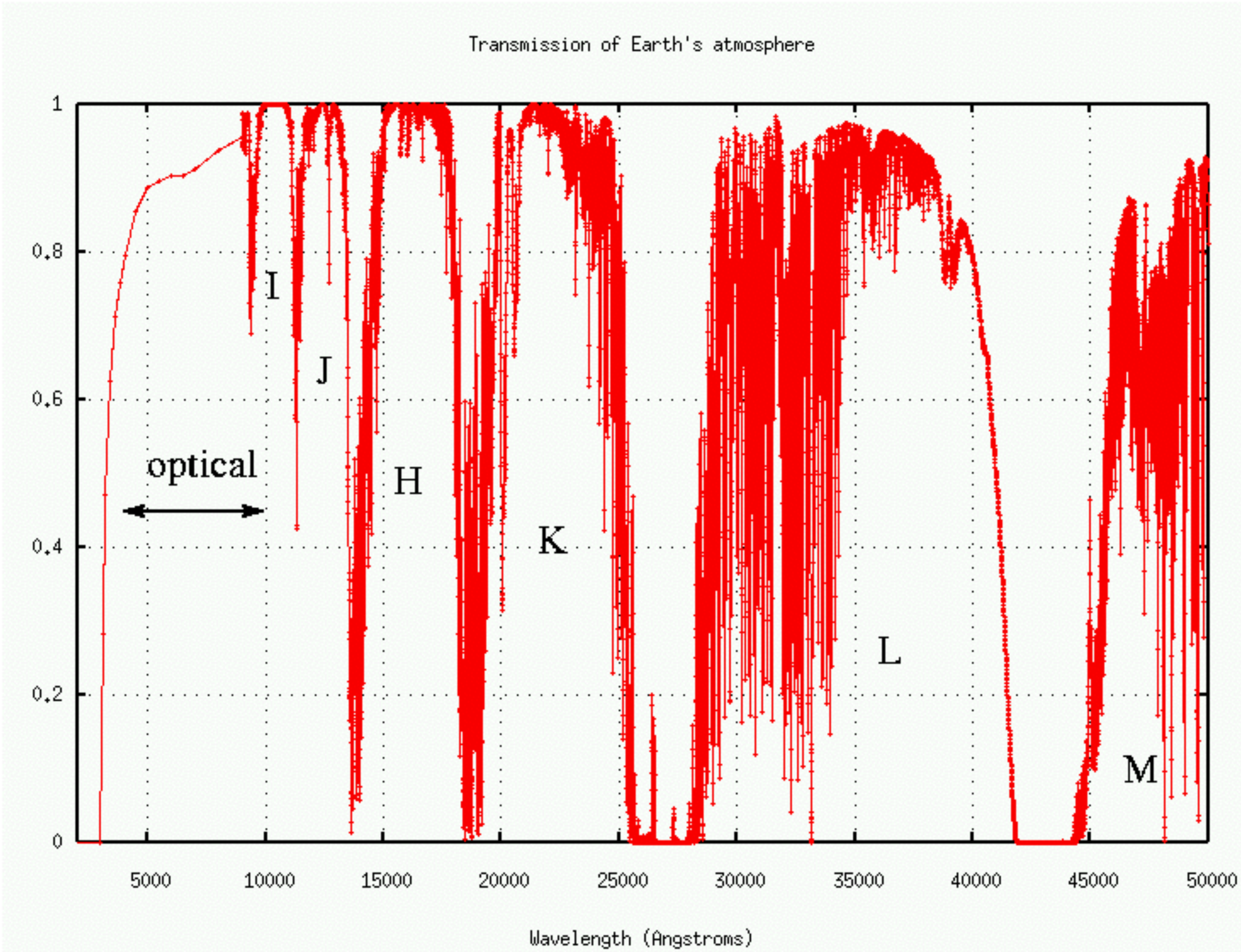
(E in keV; λ in Å)

TO → FROM ↓	S_ν(Jy)	$f_E\left(\frac{\text{photons}}{\text{cm}^2\,\text{sec keV}}\right)$	$f_\lambda\left(\frac{\text{photons}}{\text{cm}^2\,\text{sec Å}}\right)$	$F_\lambda\left(\frac{\text{erg}}{\text{cm}^2\,\text{sec Å}}\right)$	$F_\nu\left(\frac{\text{erg}}{\text{cm}^2\,\text{sec Hz}}\right)$
S_ν(Jy)	S_ν	$1.51 \times 10^3 S_\nu/E$	$1.51 \times 10^3 S_\nu/\lambda$	$3.00 \times 10^{-5} S_\nu/\lambda^2$	$10^{-23} S_\nu$
$f_E\left(\frac{\text{photons}}{\text{cm}^2\,\text{sec keV}}\right)$	$6.63 \times 10^{-4}\, E\, f_E$	f_E	$8.07 \times 10^{-2}\, E^2\, f_E$	$1.29 \times 10^{-10}\, E^3\, f_E$	$6.63 \times 10^{-27}\, E\, f_E$
$f_\lambda\left(\frac{\text{photons}}{\text{cm}^2\,\text{sec Å}}\right)$	$6.63 \times 10^{-4}\, \lambda\, f_\lambda$	$8.07 \times 10^{-2}\, \lambda^2\, f_\lambda$	f_λ	$1.99 \times 10^{-8}\, f_\lambda/\lambda$	$6.63 \times 10^{-4}\, \lambda\, f_\lambda$
$F_\lambda\left(\frac{\text{erg}}{\text{cm}^2\,\text{sec Å}}\right)$	$3.34 \times 10^{-4}\, \lambda^2\, F_\lambda$	$4.06 \times 10^{6}\, \lambda^3\, F_\lambda$	$5.03 \times 10^{7}\, \lambda\, F_\lambda$	F_λ	$3.34 \times 10^{-19}\, \lambda^2\, F_\lambda$
$F_\nu\left(\frac{\text{erg}}{\text{cm}^2\,\text{sec Hz}}\right)$	$10^{23}\, F_\nu$	$1.51 \times 10^{26}\, F_\nu/E$	$1.51 \times 10^{26}\, F_\nu/\lambda$	$3.00 \times 10^{18}\, F_\nu/\lambda^2$	F_ν

Key points:

- flux is weighted by filter response (can have significant structure)
- For Vega (and all A0V type stars) $m_i = m_j = m_V$ (for all i,j filters)
- "zero point" of system defined by Vega's spectrum
- in practice, you don't observe Vega, but rather sets of photometric "standard stars".
- In the Vega system, equal magnitudes do not necessarily have equal fluxes. (they do for ST and AB mags)
  - "colors" are delta magnitudes

common filters for direct imaging of exoplanets



The primary observables are:

- Separation (usually expressed in seconds of arc)
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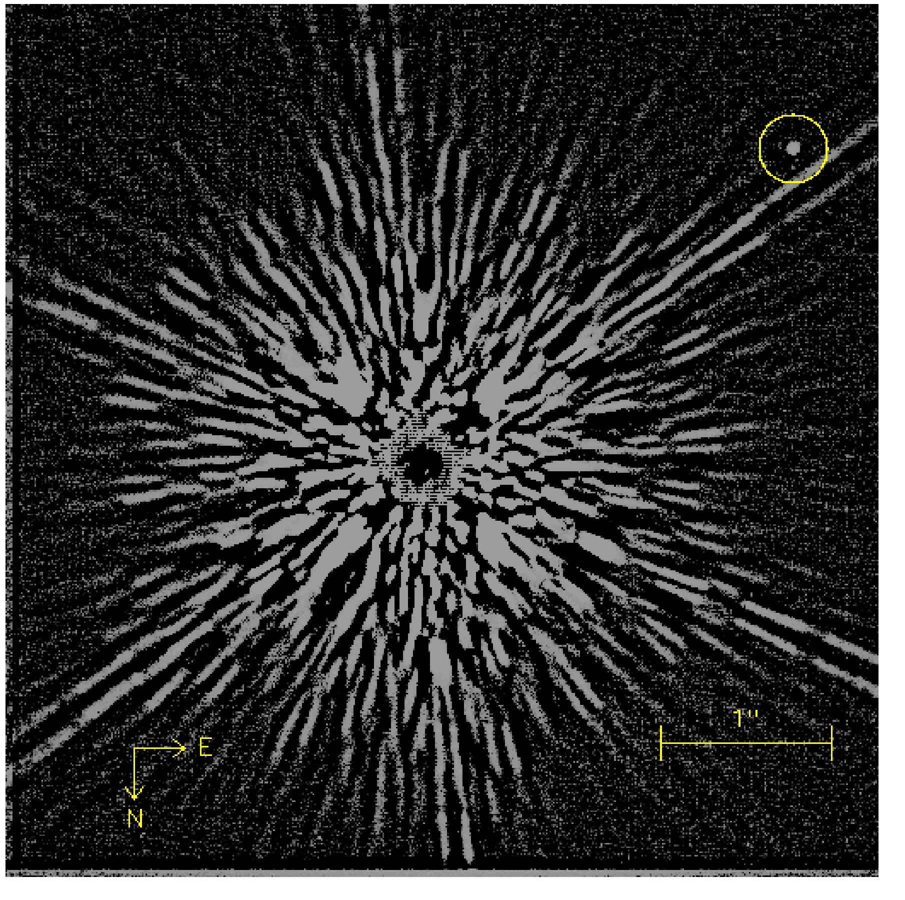


What you can directly infer:

- Orbital elements: P, a, e, w, T_o, i, and Ω
  …if you wait long enough

- With a and P, and estimate of M_s, you get M_p (Kepler's third law)

- Spectra or "colors" (reflected and emitted)
  → Atmospheric properties
  → M_p by comparing to models in the absence of a long enough time baseline to map the orbit

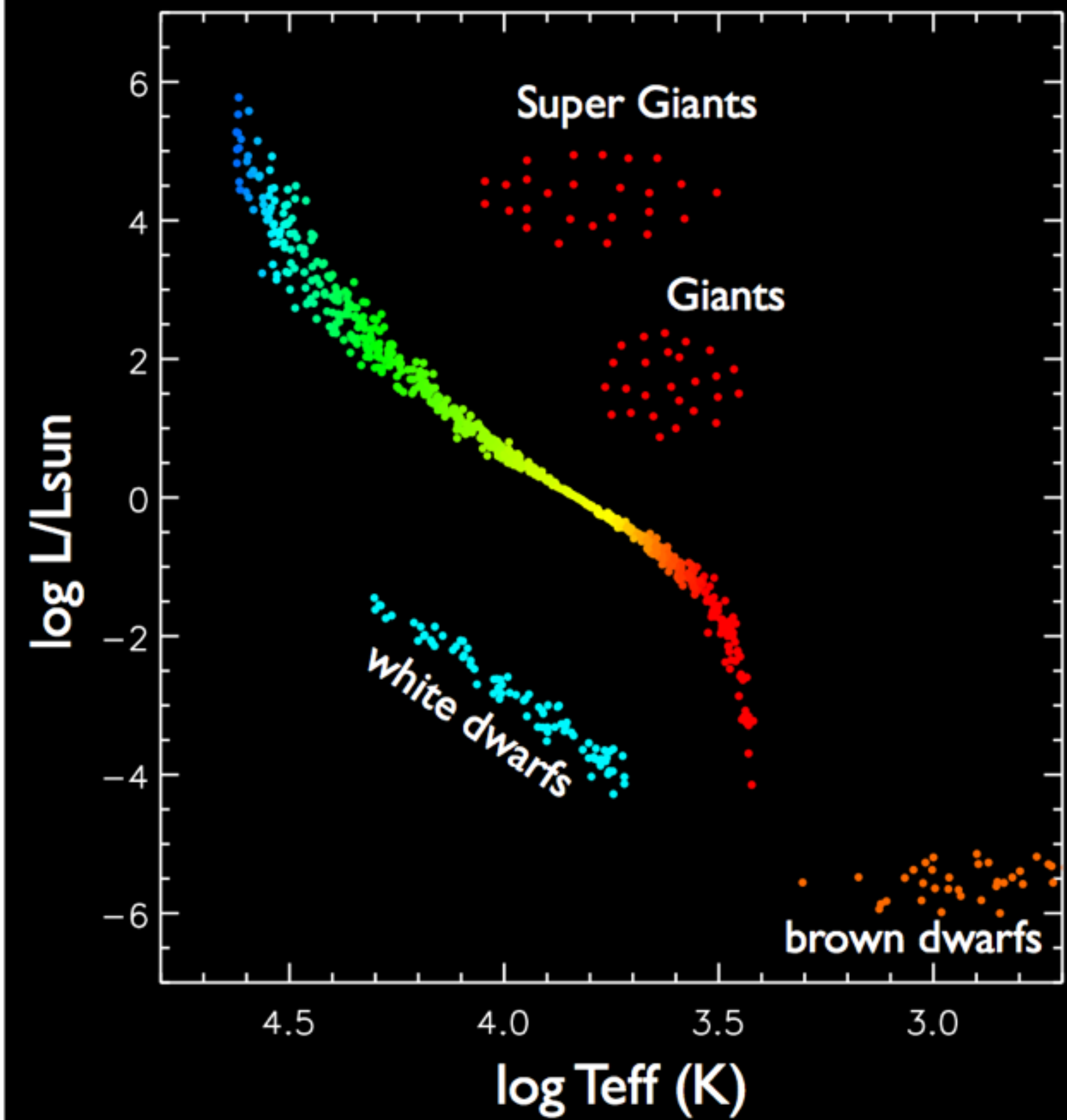
Astrophysical Considerations:

- maximize contrast by looking for red planets near blue stars
- maximize planet brightness by looking for young massive planets
- maximize separation by observing nearby stars
- minimize fore/background star confusion by observing nearby stars with large proper motions

$$\sigma T_{\rm eff}^4 = \int F_\lambda d\lambda$$

$$L_{\rm bol} = 4\pi R^2 \sigma T_{\rm eff}^4$$

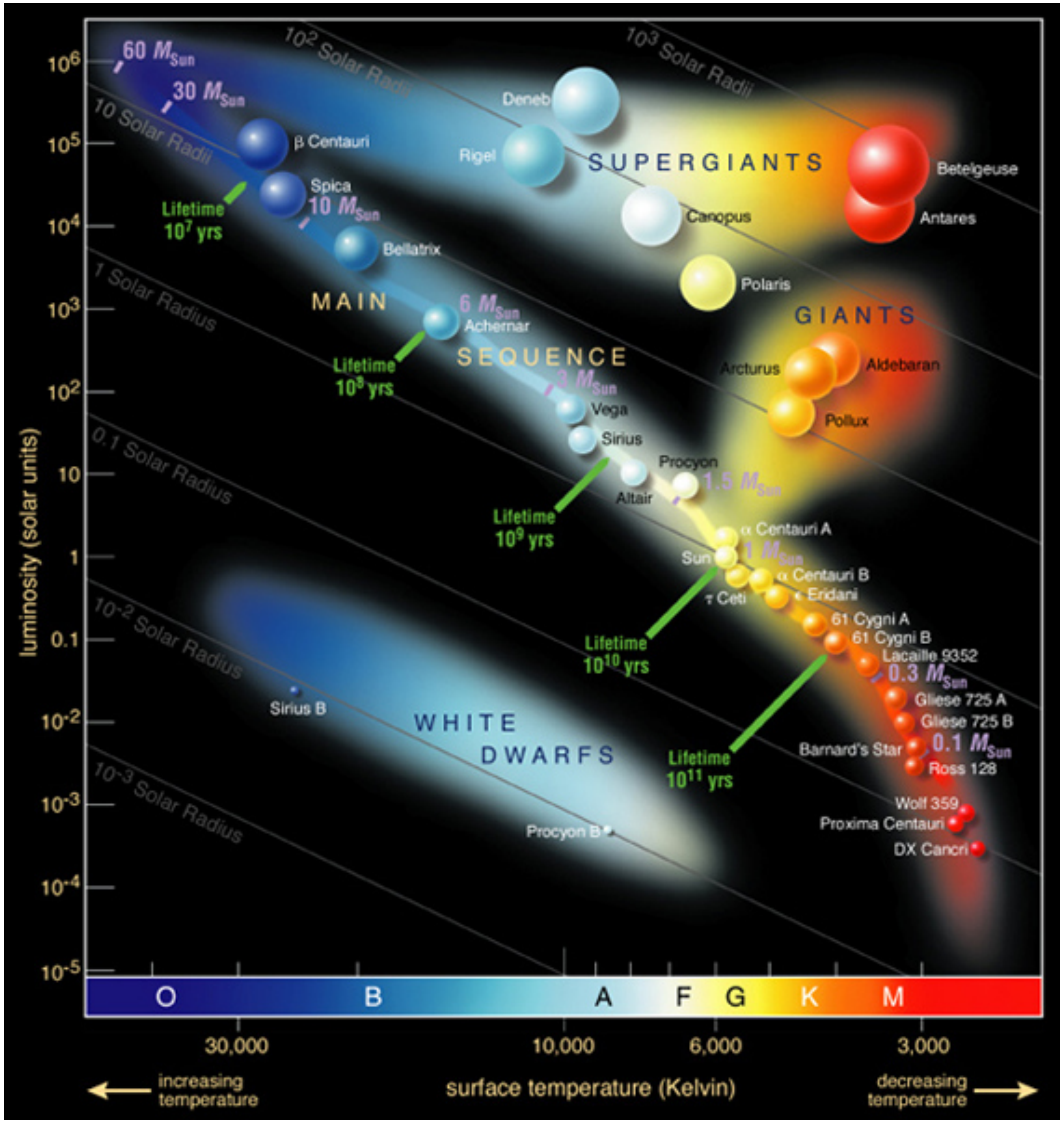
HR diagram



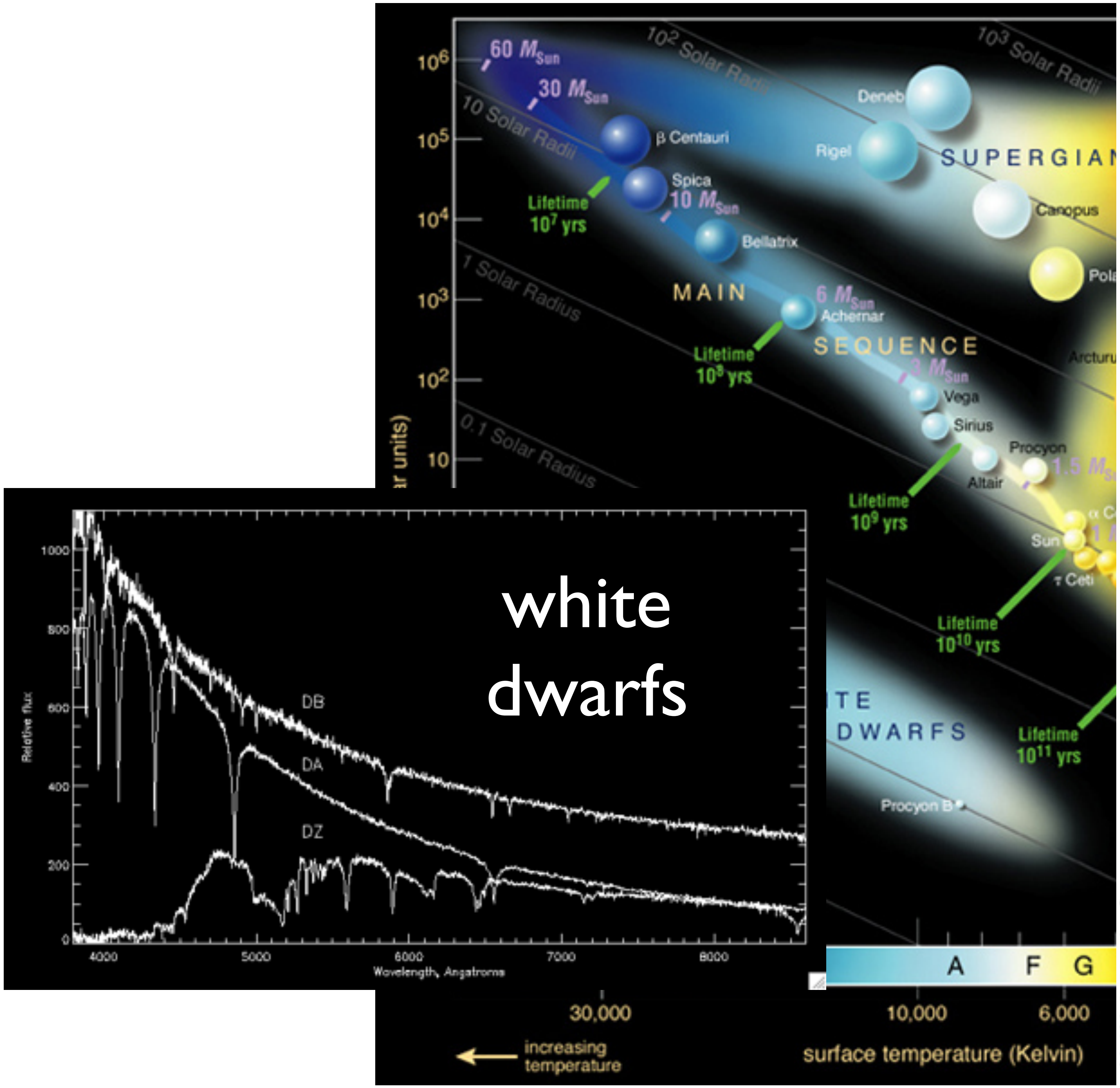
Blue Red

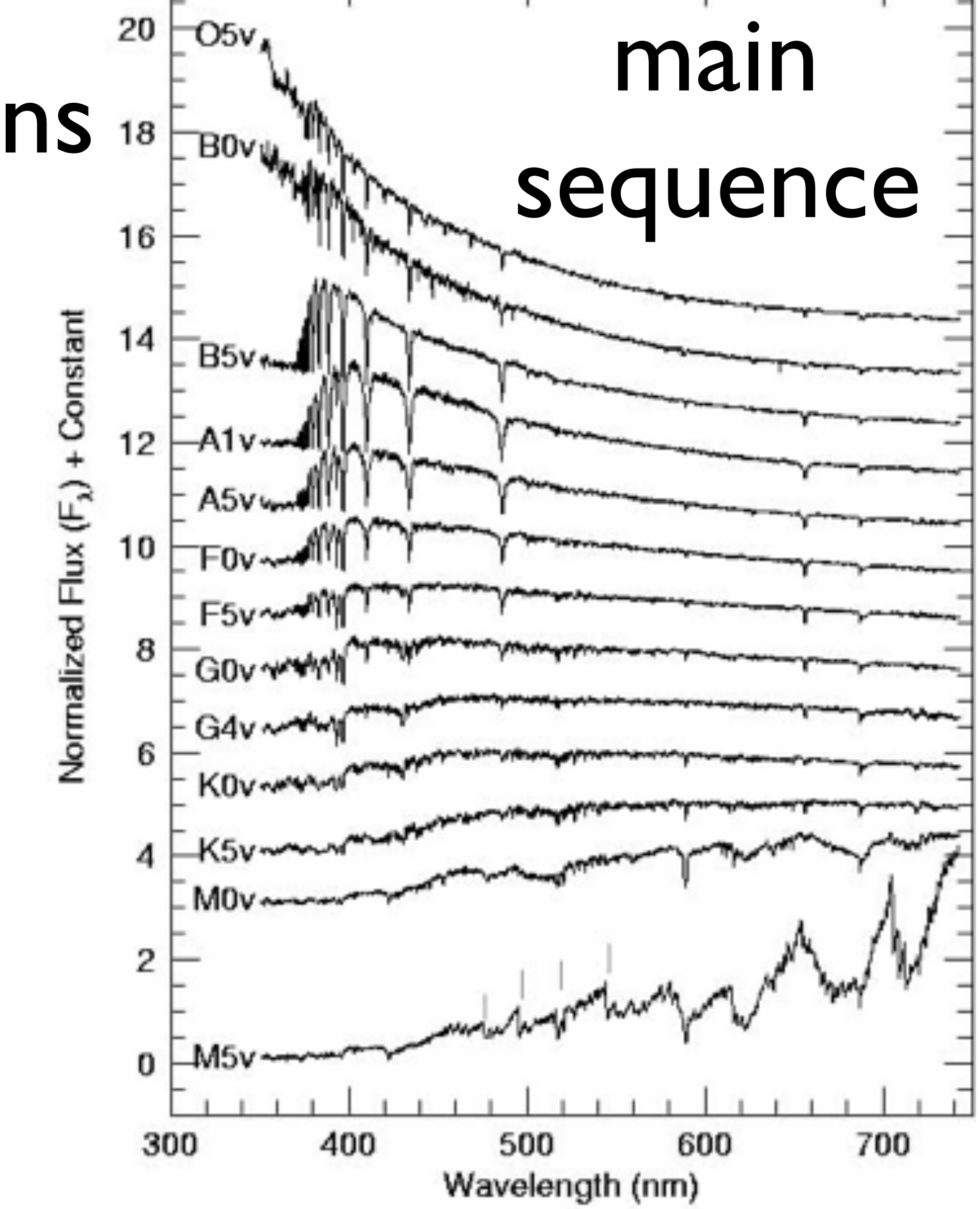
short lived

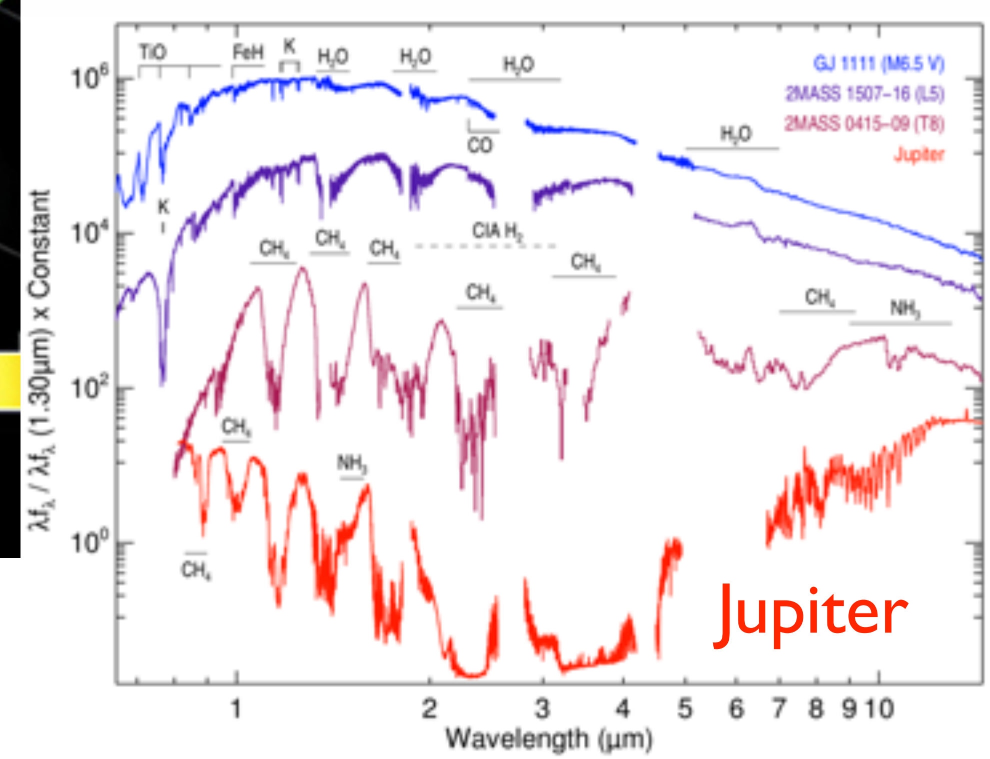
long lived



Spectral Energy Distributions



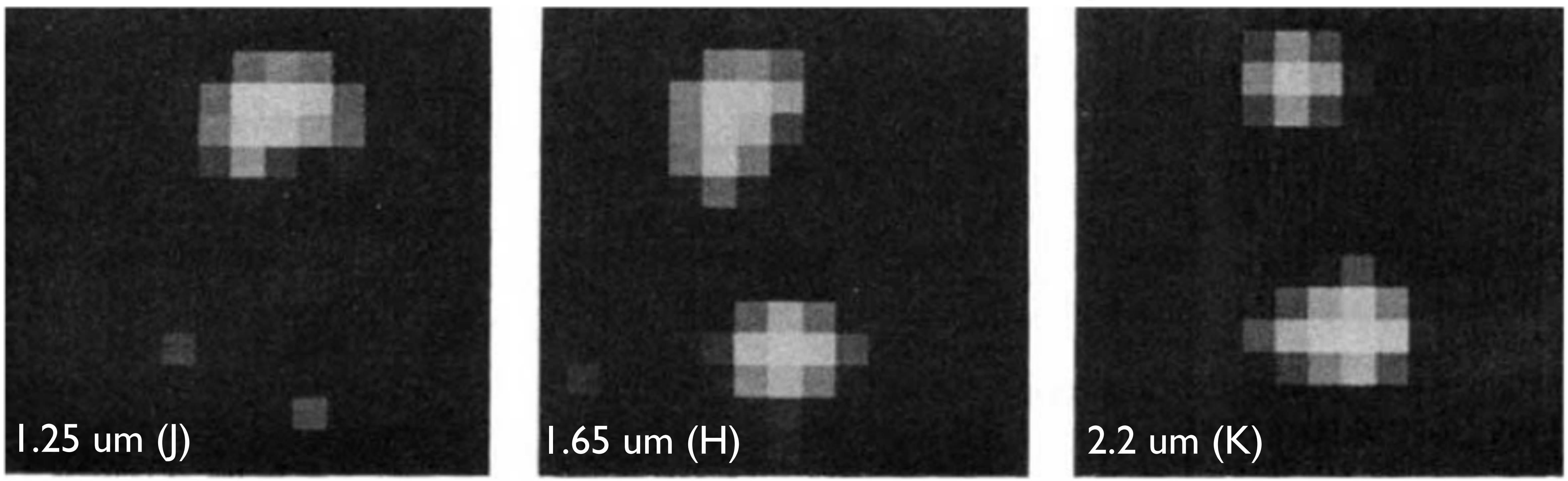




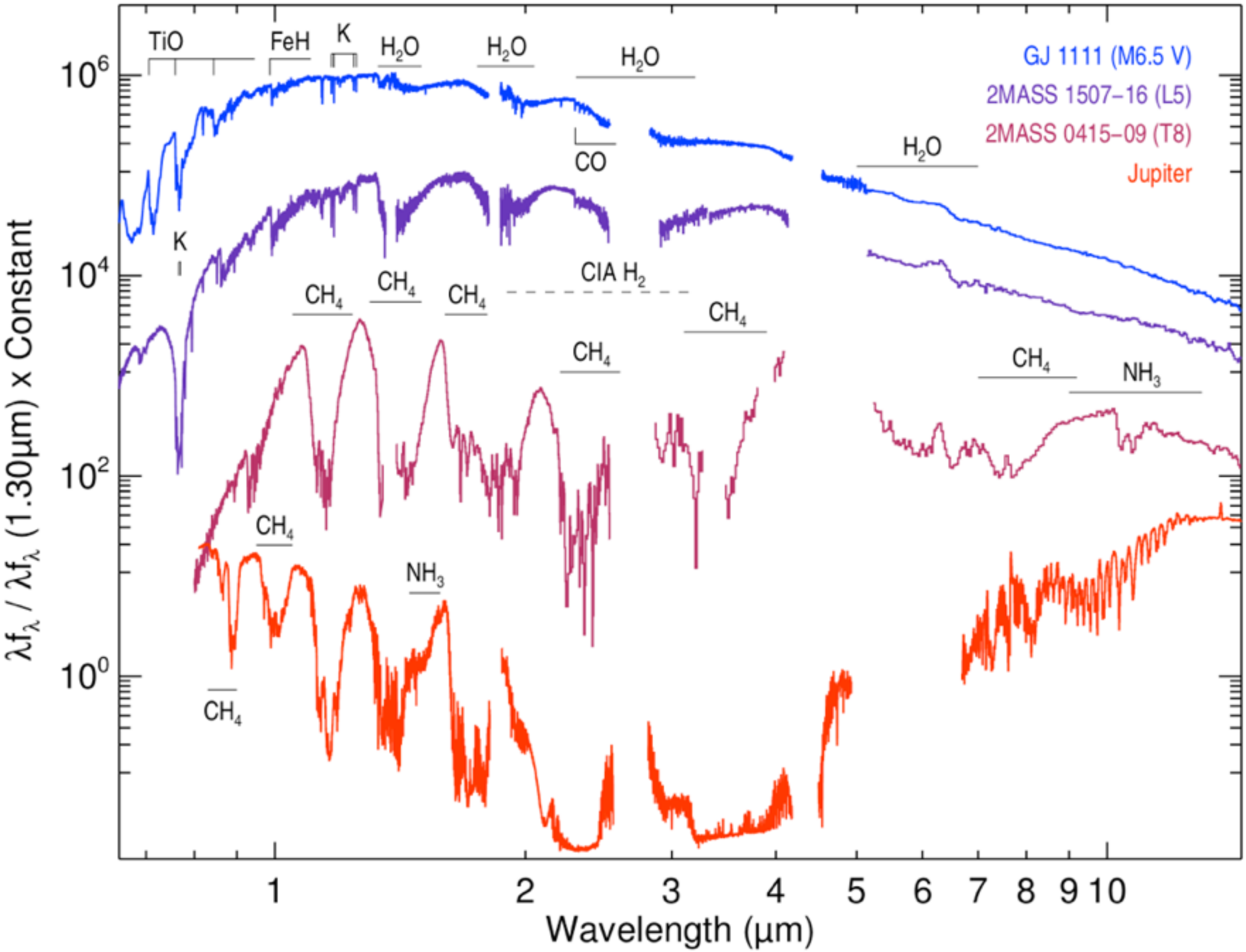
Early "direct imaging" results:

GD165AB (brown dwarf + white dwarf)

(Becklin & Zuckerman 1988)

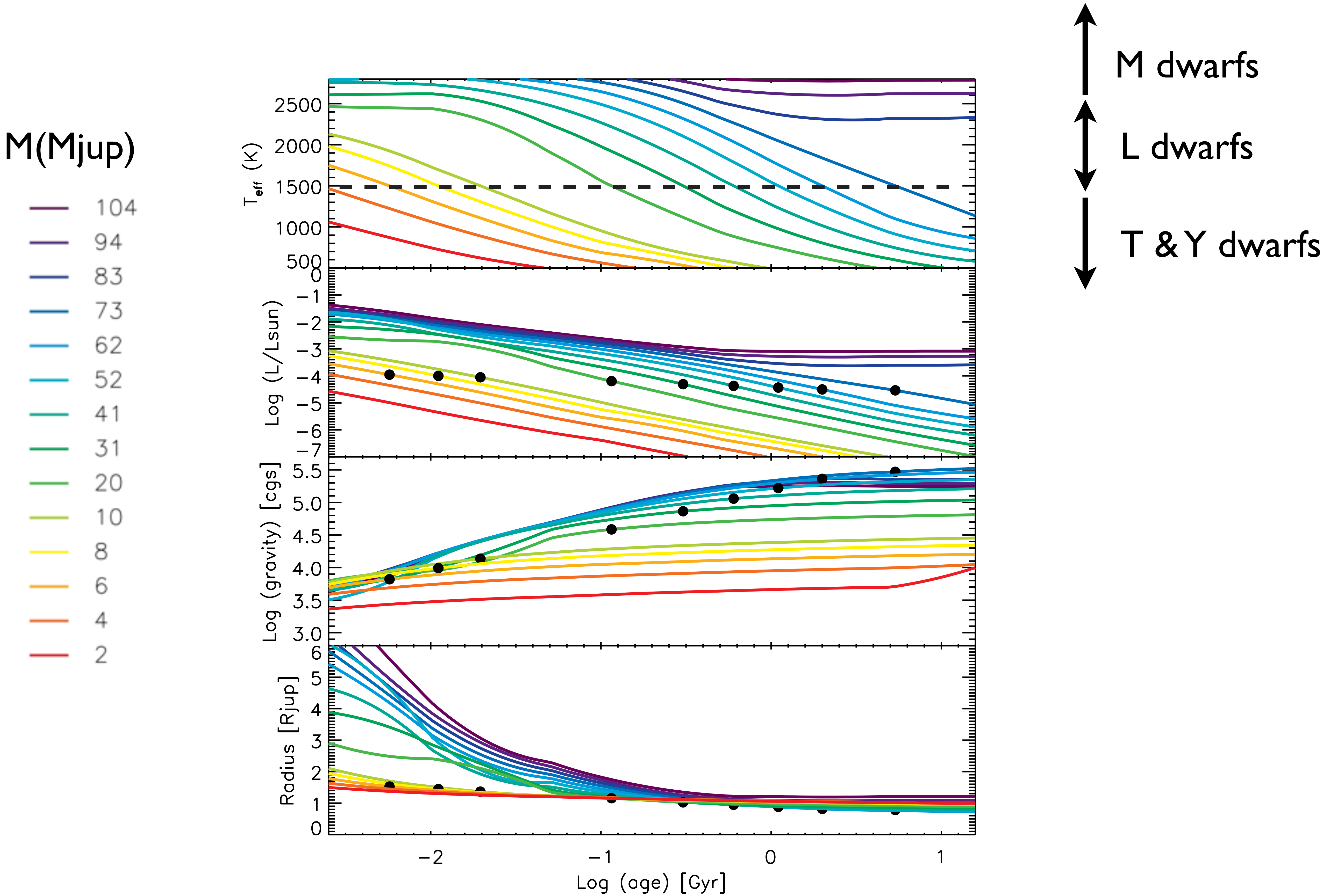


~ 7 arcsec



(credit: Mike Cushing)

Brown Dwarf /Giant Planet Evolution:

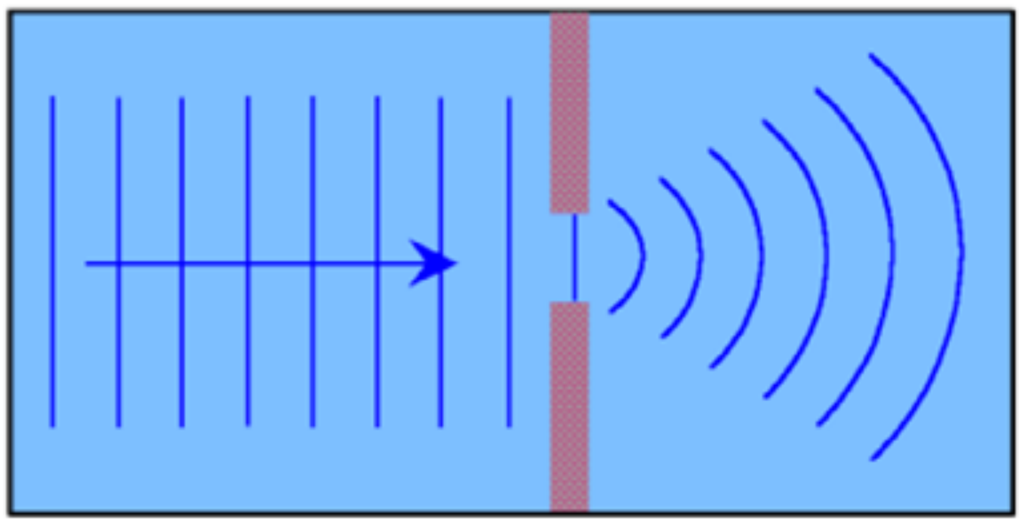


Baraffe et al. 2003

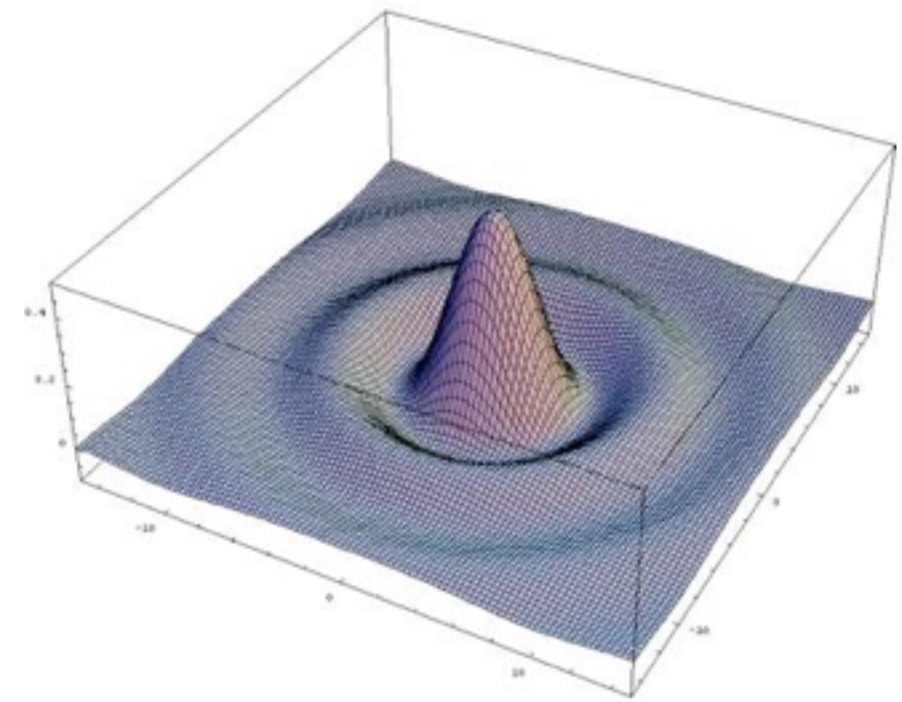
Practical Considerations:

- Telescope diffraction
- Atmospheric turbulence
- Starlight suppression
- Instrumental speckles
- Zodiacal light

Telescope Diffraction



Plane wave of light converted to a spherical wave after passing through a circular aperture.



"Airy pattern"

The angle from the center to the first minimum is:

$$\theta_{zero,\,0} \approx 1.22\ \lambda / D$$

The width (FWHM) of the central peak is:

$$\theta_{FWHM,\,0} \approx \lambda / D$$

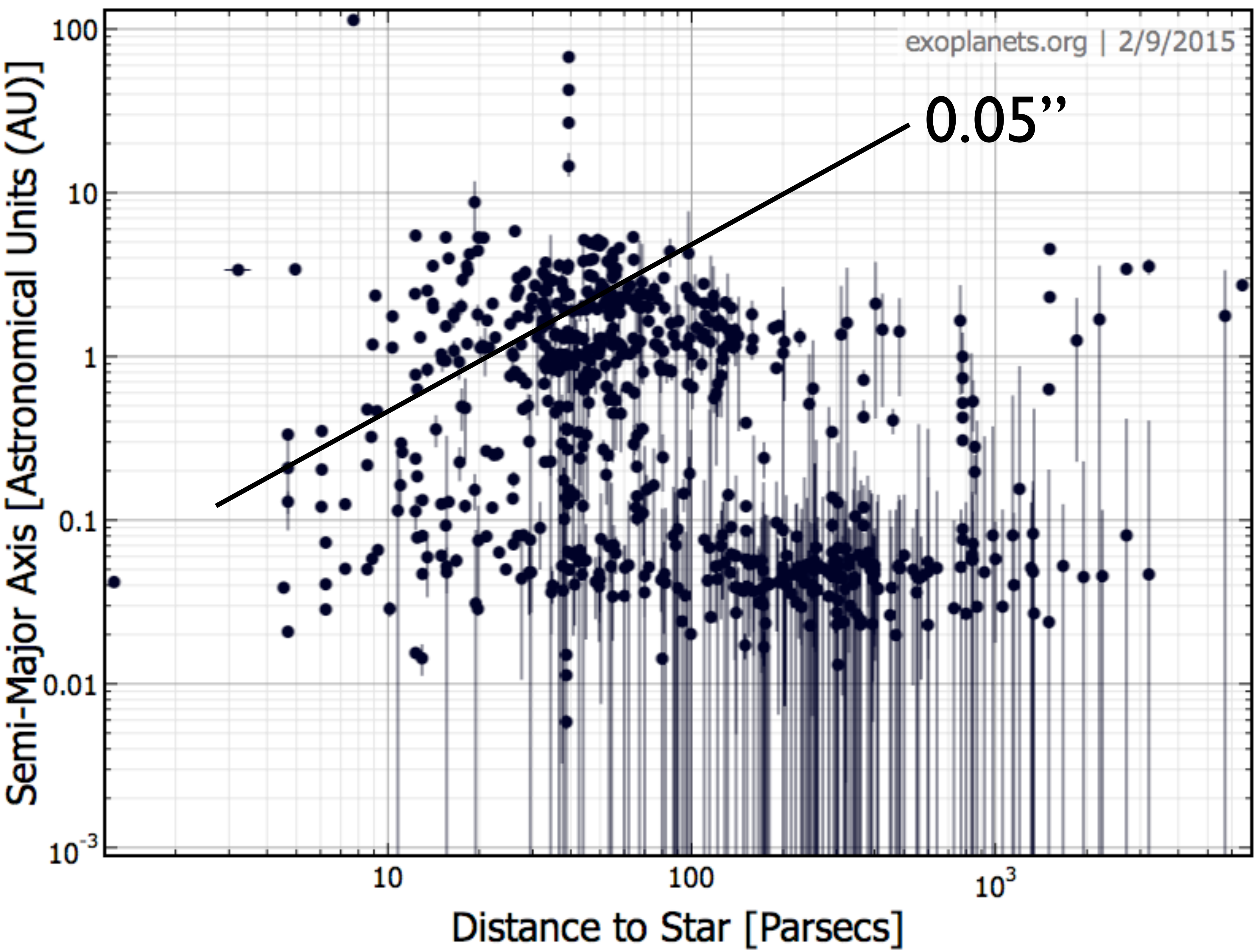
Example (diffraction limit)

- Hubble Space Telescope: D = 2.4m in the optical (0.5 microns)

$$\theta(radians) = 1.22\frac{\lambda}{D} = \frac{1.22 \times 5000\mathring{A}}{2.4m} = \frac{6100 \times 10^{-8}cm}{240cm}$$

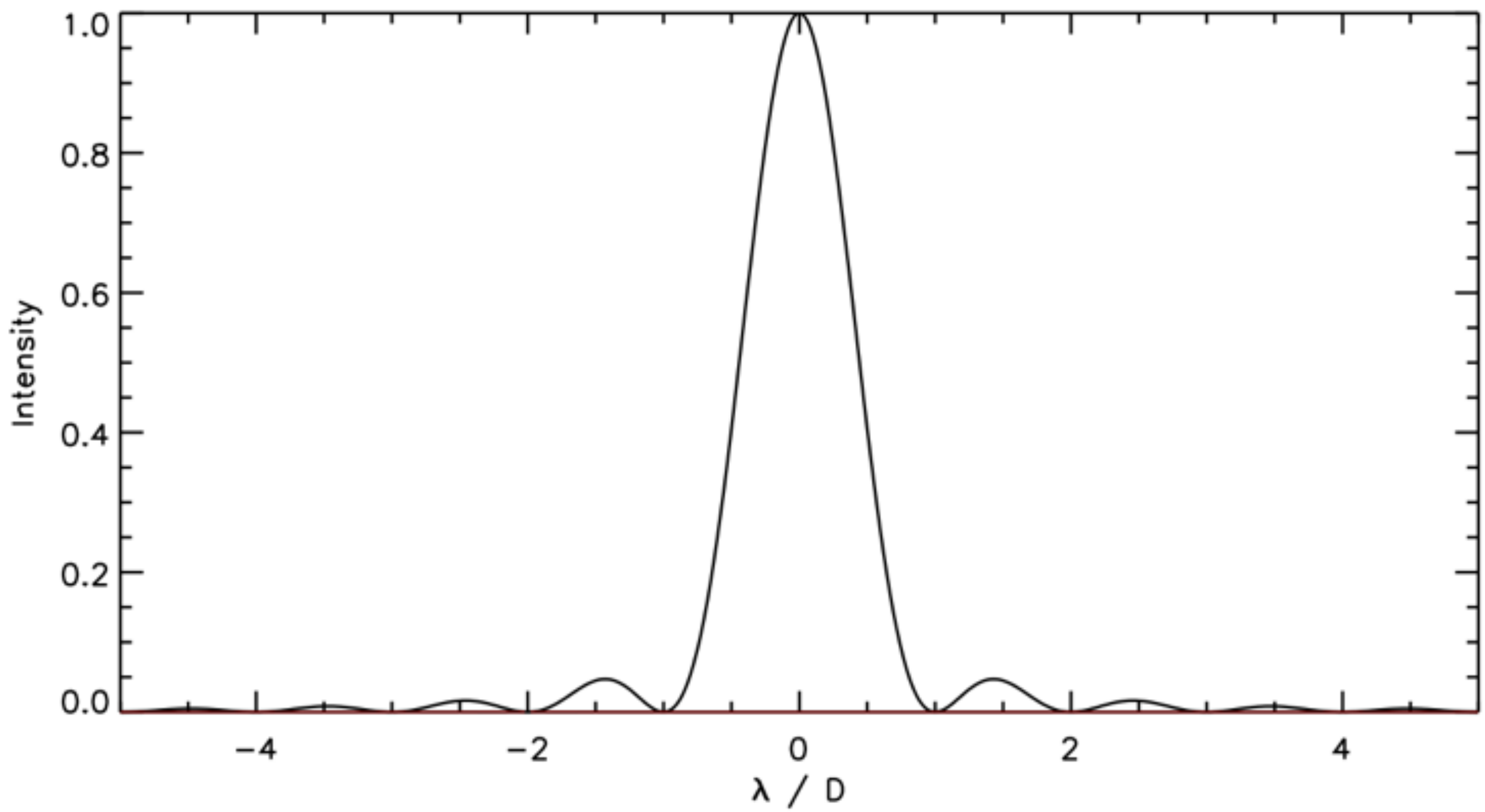
$$= 2.54 \times 10^{-7} radians$$

$$= 2.54 \times 10^{-7} radians \times \frac{1''}{4.85 \times 10^{-6}} = 0.05''$$



exoplanets.org | 2/9/2015
0.05''
Semi-Major Axis [Astronomical Units (AU)]
100
10
1
0.1
0.01
10^{-3}
10
100
10^3
Distance to Star [Parsecs]

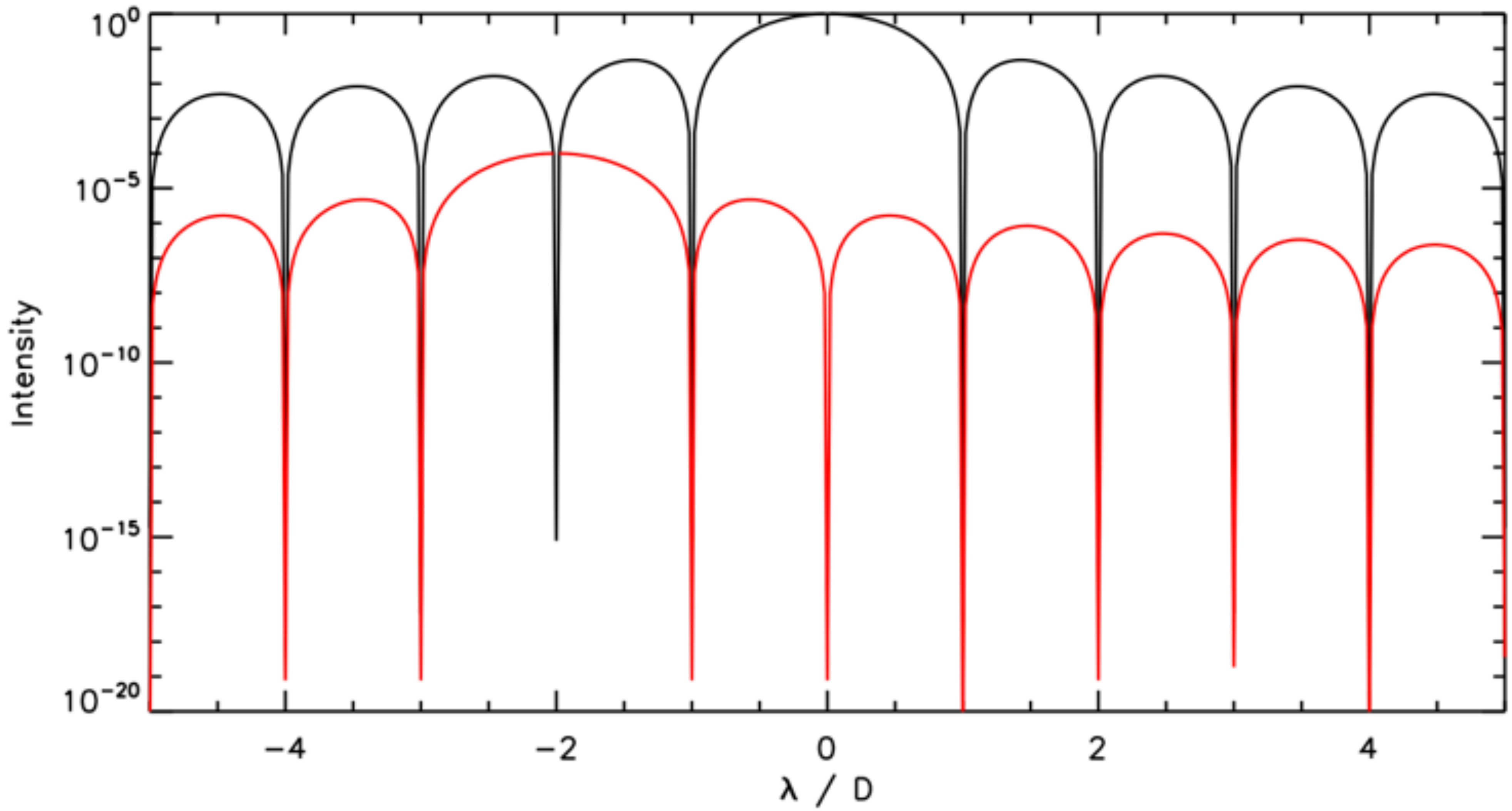
Telescope Diffraction



There is a second peak at -2λ/D with contrast of 10^{-4}

Can you see it?

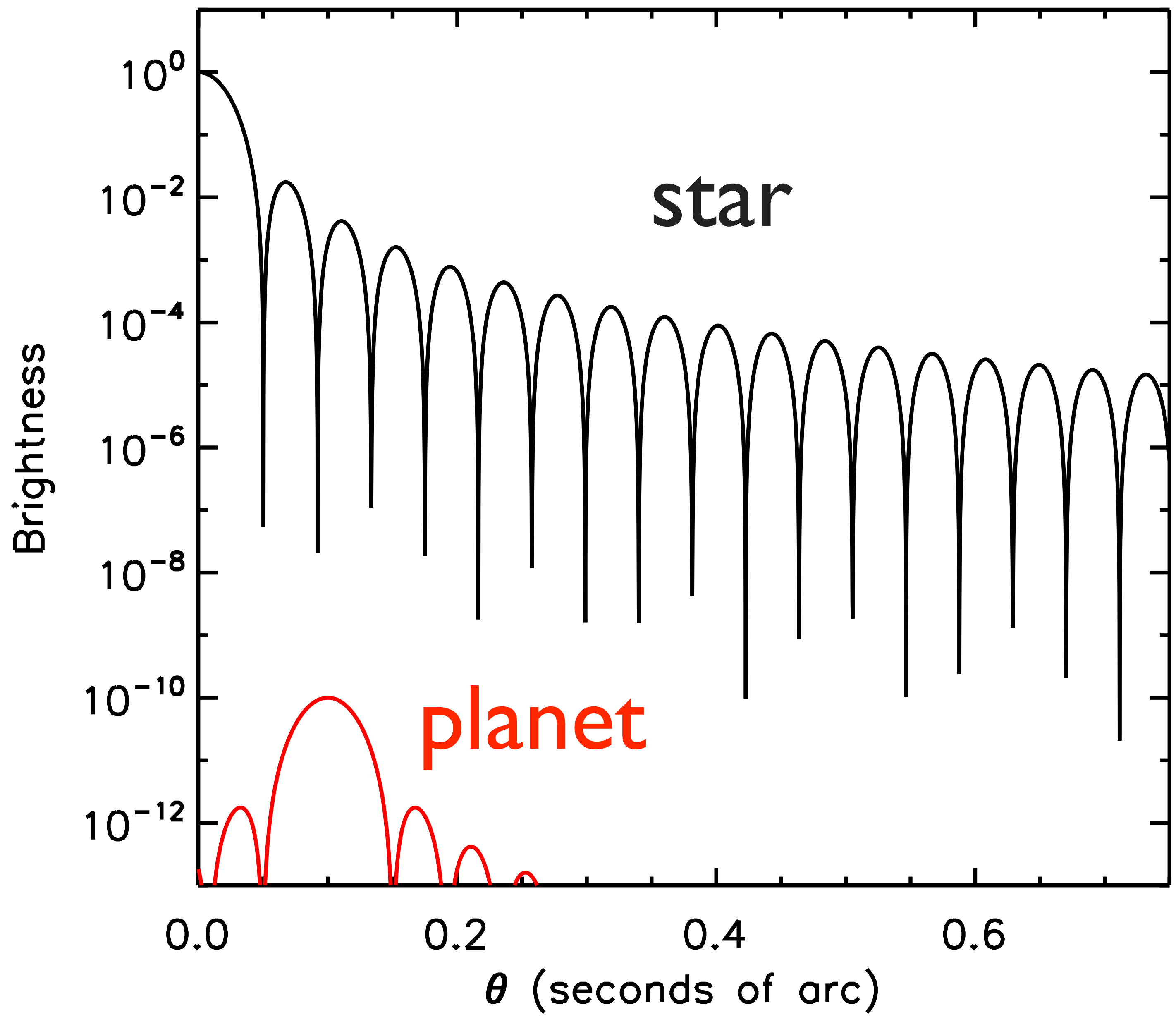
Telescope Diffraction



There is a second peak at -2λ/D with contrast of 10^{-4}

Can you see it?

How do we remove the star light, while preserving that from the planet?



Basic Tools

- **Adaptive Optics**
- **Coronagraphs**
- **Differential Imaging**
- **Post-processing of images**

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)

Terminology

- **Contrast**: ratio of the peak of the stellar PSF to the noise at the planet location
- **Inner Working Angle**: smallest angle on the sky at which the required contrast is achieved (and planet flux is reduced by no more than 50% relative to other angles)
- **Throughput**: ratio of the open telescope area remaining, after high-contrast is achieved.
- **Bandwidth**: wavelength at which high contrast is achieved
- **Sensitivity**: degree to which contrast is degraded in the presence of aberrations.

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)

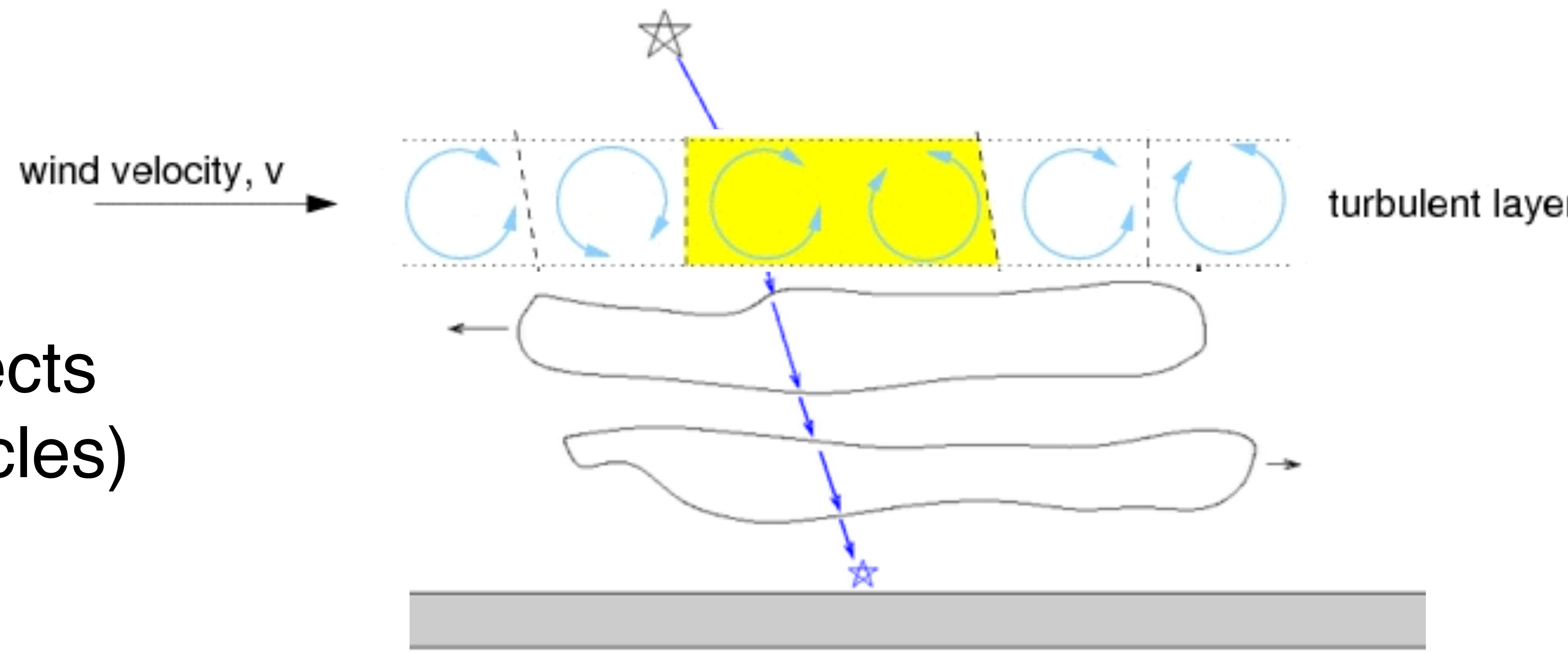
Terminology

- **AO**: adaptive optics
- **DM**: deformable mirror
- **Speckles**: (random and quasi-static) “copies” of the same star, randomly offset (short timescales, ms) and quasi-static aberrations caused by imperfect optics (longer timescales, minutes to hours).
- **Strehl ratio**: ratio of the peak intensity to that of a perfect image.

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)

Atmospheric Turbulence

- convection
- wind shear
- ground-layer effects (wind over obstacles)

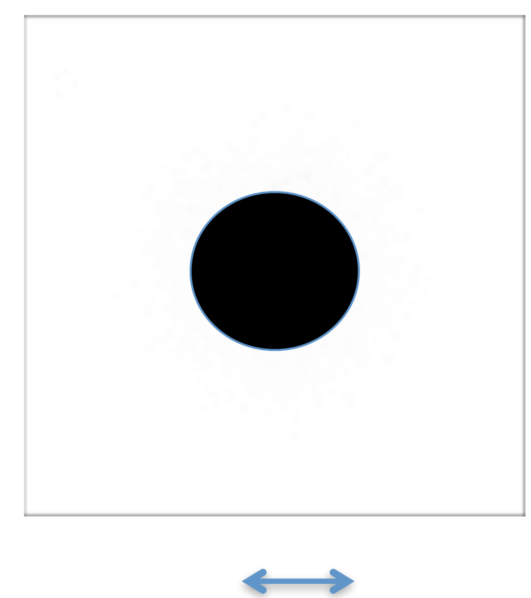


Atmospheric Turbulence

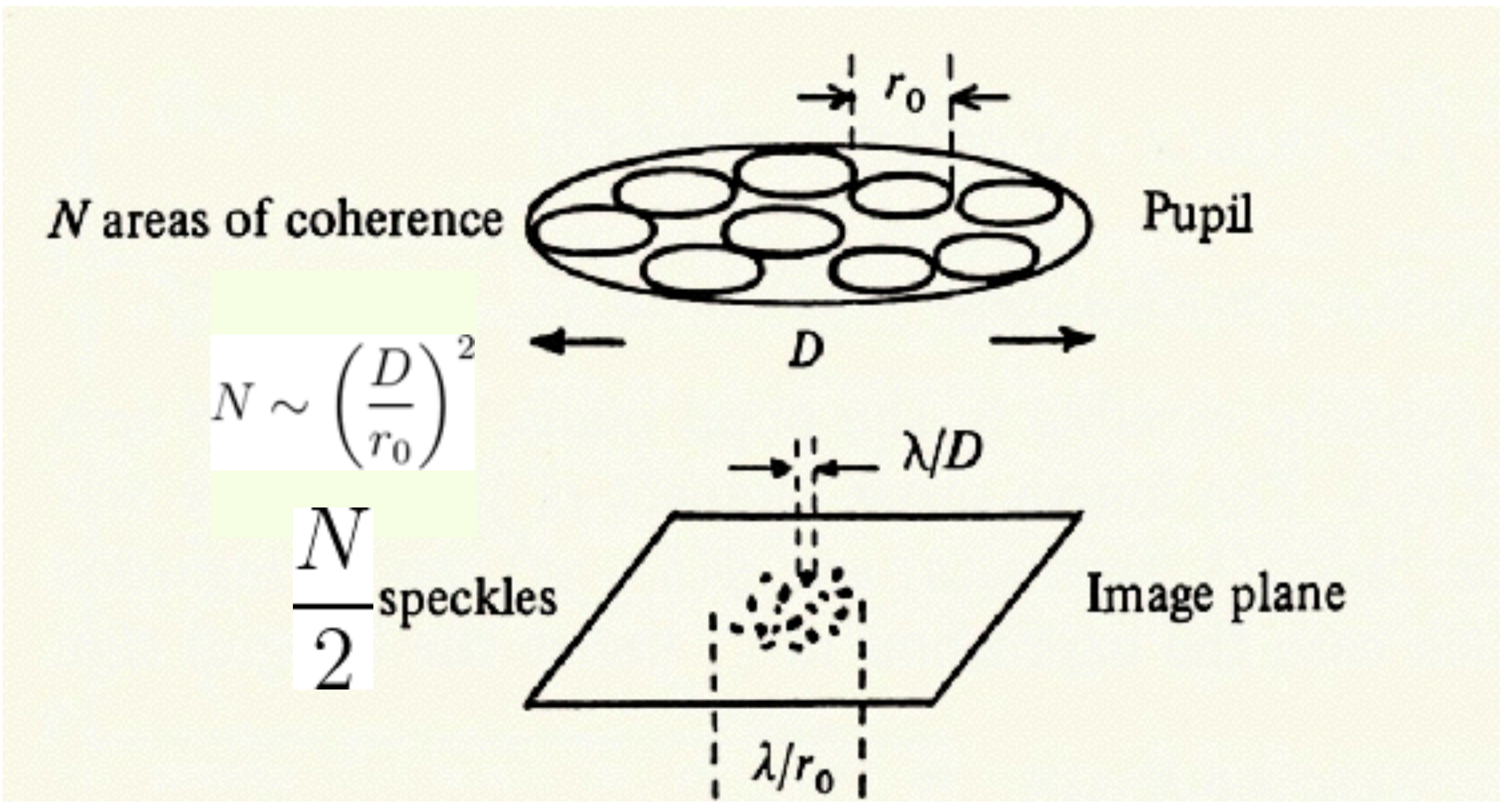
seeing and speckles

Very short timescale

Averaged over > a few seconds



approx 1”



$$r_0 \propto \lambda^{6/5}$$

$$\theta_{\text{seeing}} \propto \lambda/r_o \propto \lambda^{-1/5}$$

$$\theta_{\text{dif}} \propto \lambda$$

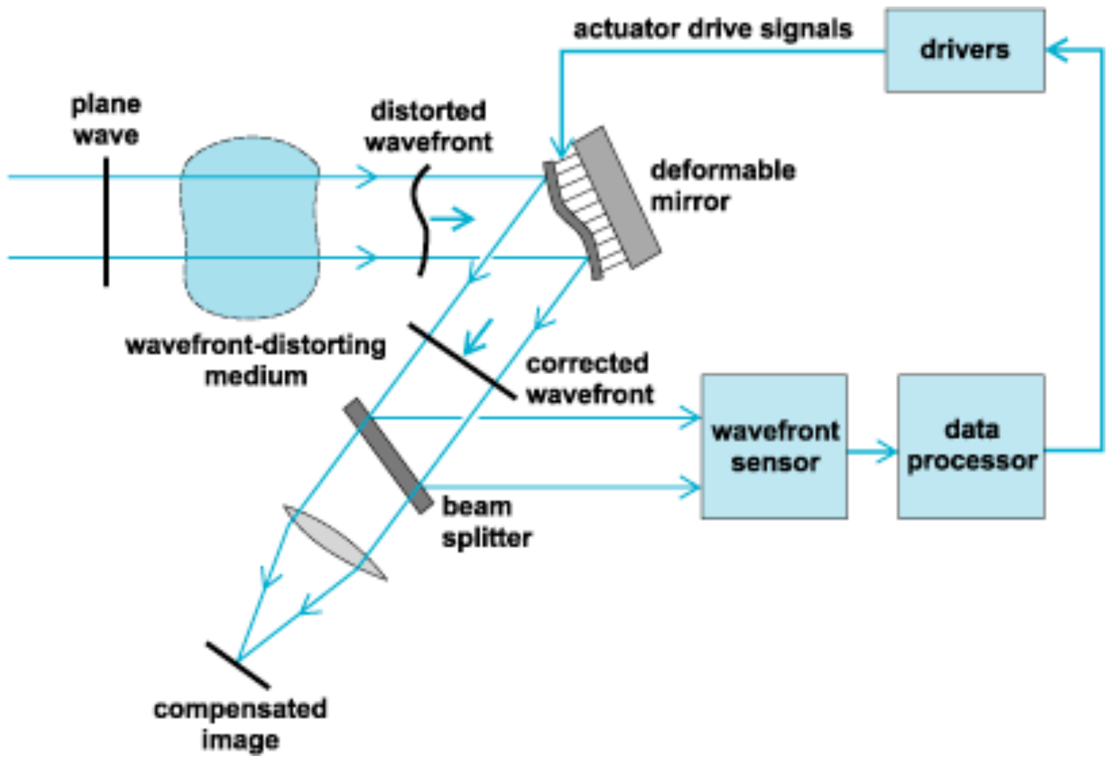
r0 = "Fried parameter"

Telescopes with diameter > r0 are "seeing" limited with resolution comparable to telescope with D = r0

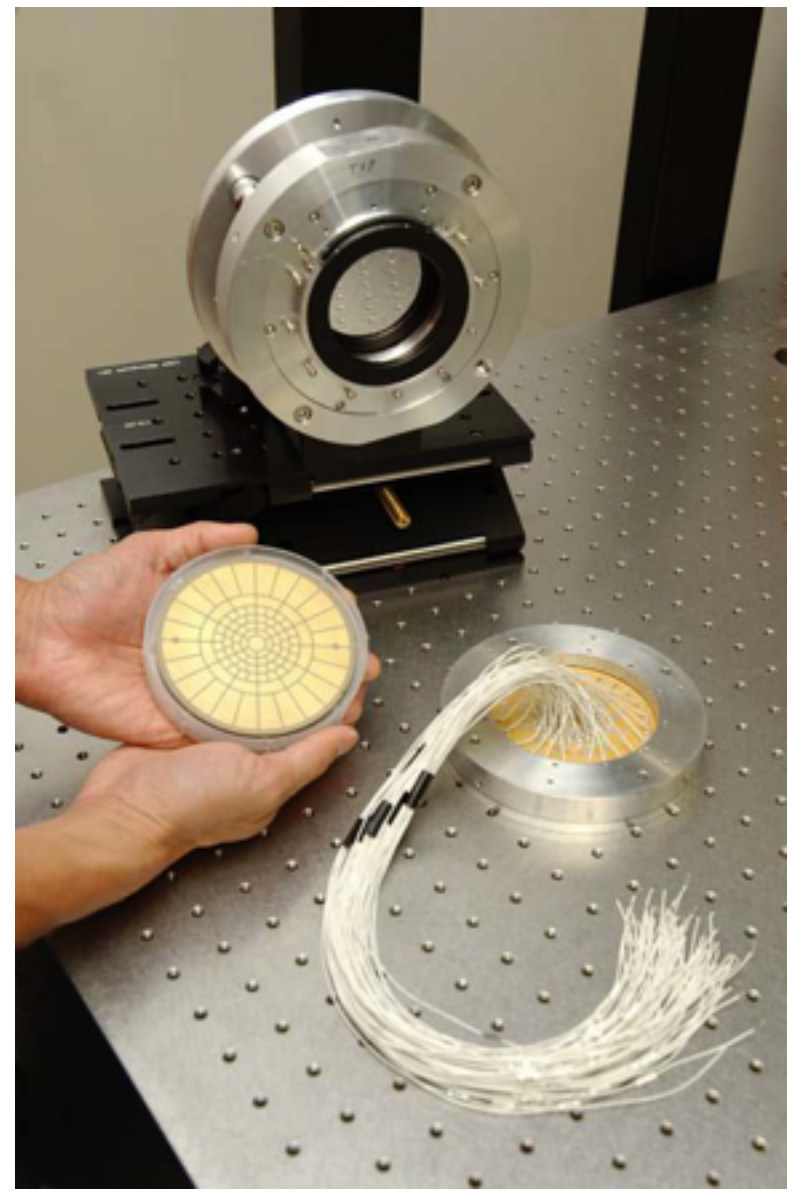
r0 ~ 10 cm in the optical and ~ 70 cm in the infrared.

At longer wavelengths, the relative differences between the seeing limit and diffraction limit become less important.

Atmospheric Turbulence

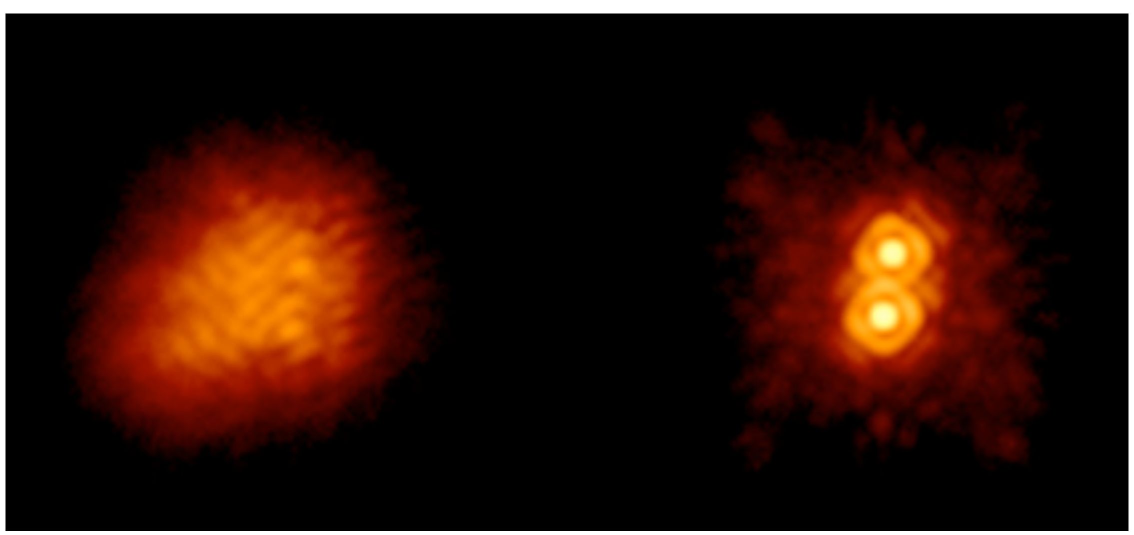


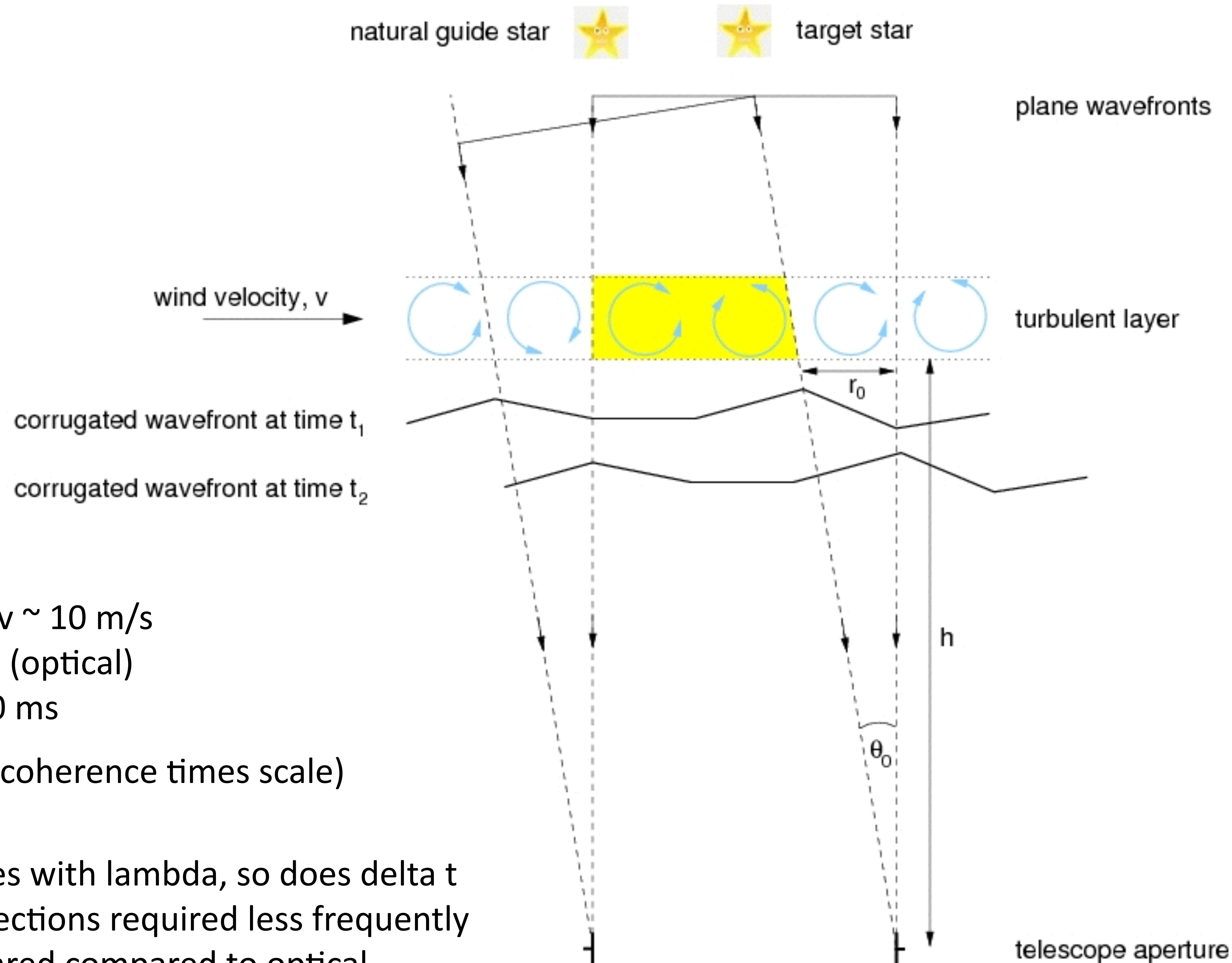
Correction for wavefront errors with adaptive optics (AO)



AO off

AO on



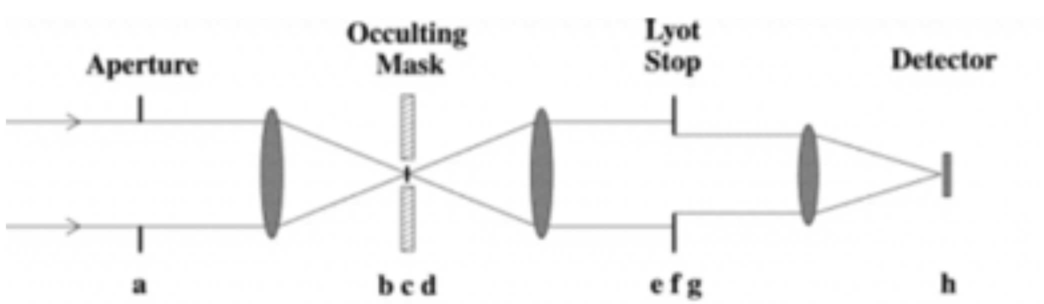


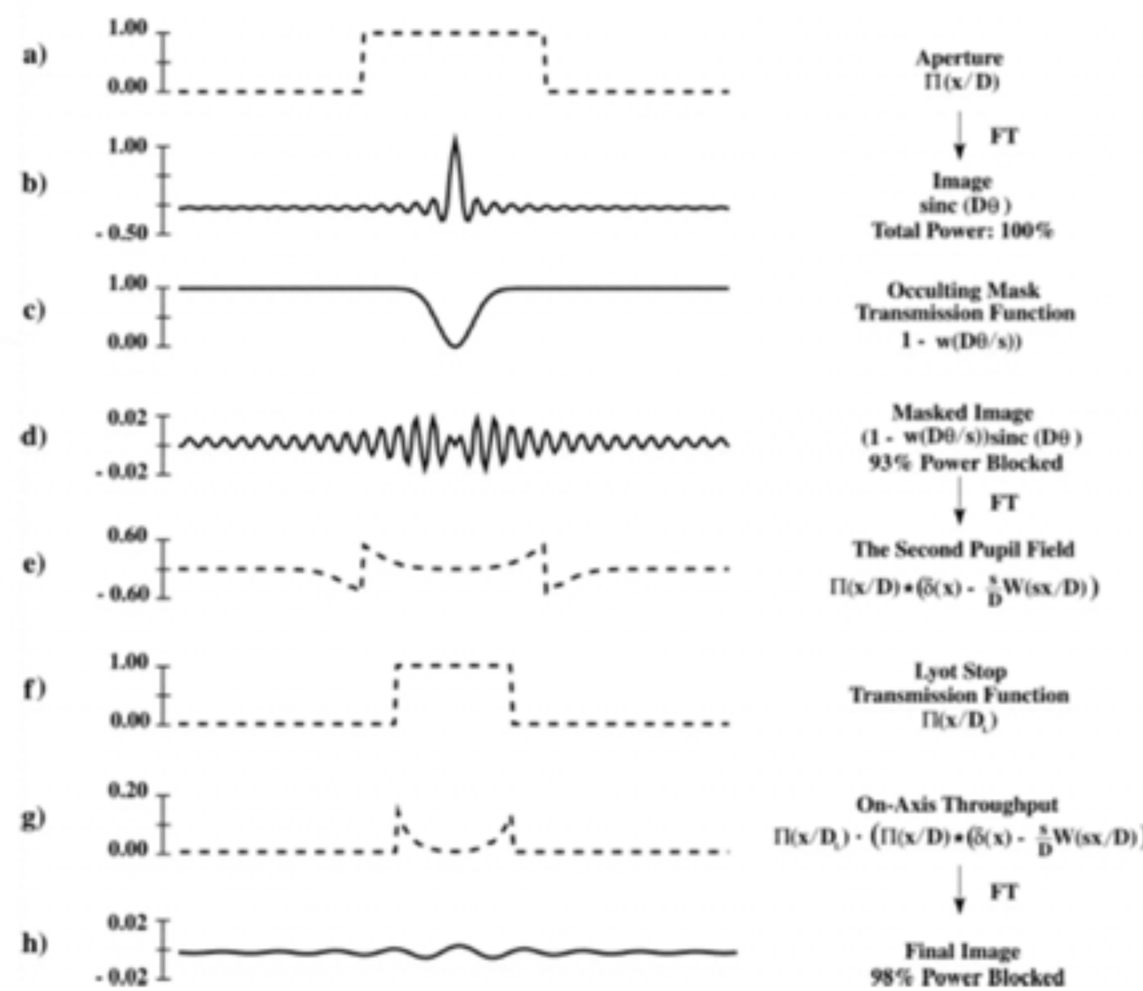
Example: v ~ 10 m/s
r0 ~ 10 cm (optical)
t2 - t1 ~ 10 ms

(this is the coherence times scale)

r0 increases with lambda, so does delta t
... AO corrections required less frequently
in the infrared compared to optical.

LYOT CORONAGRAPH STEP BY STEP





see move: https://www.youtube.com/watch?v=zkTHuqiH_1Y

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)

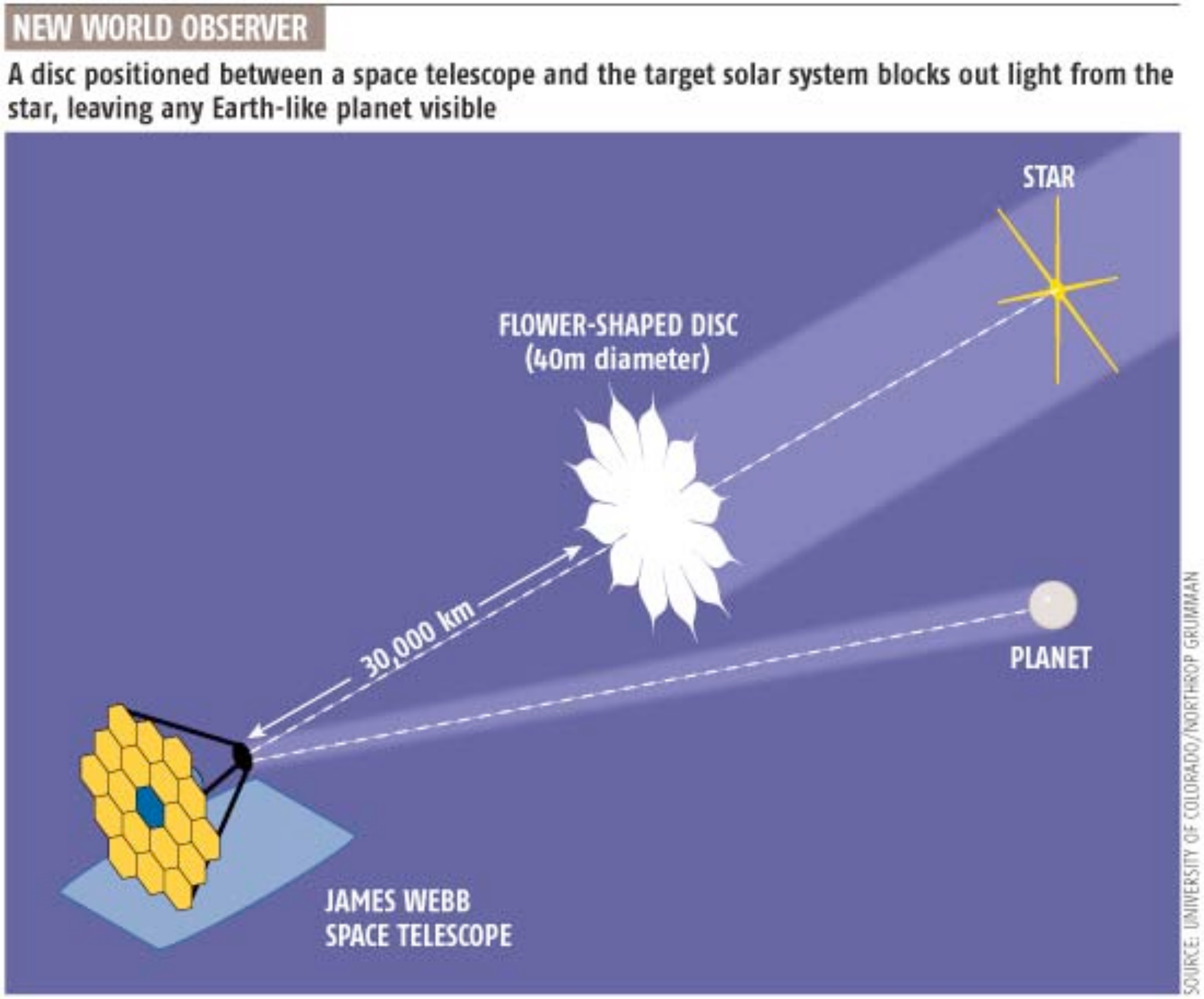
Starlight Suppression

Coronograph:

Invented by Bernard Lyot in 1933 to observe the corona of the sun (contrast = 10^{-6})

Internal (e.g., Lyot) and External (star shade) occulter versions

Star Shade (external occulter)

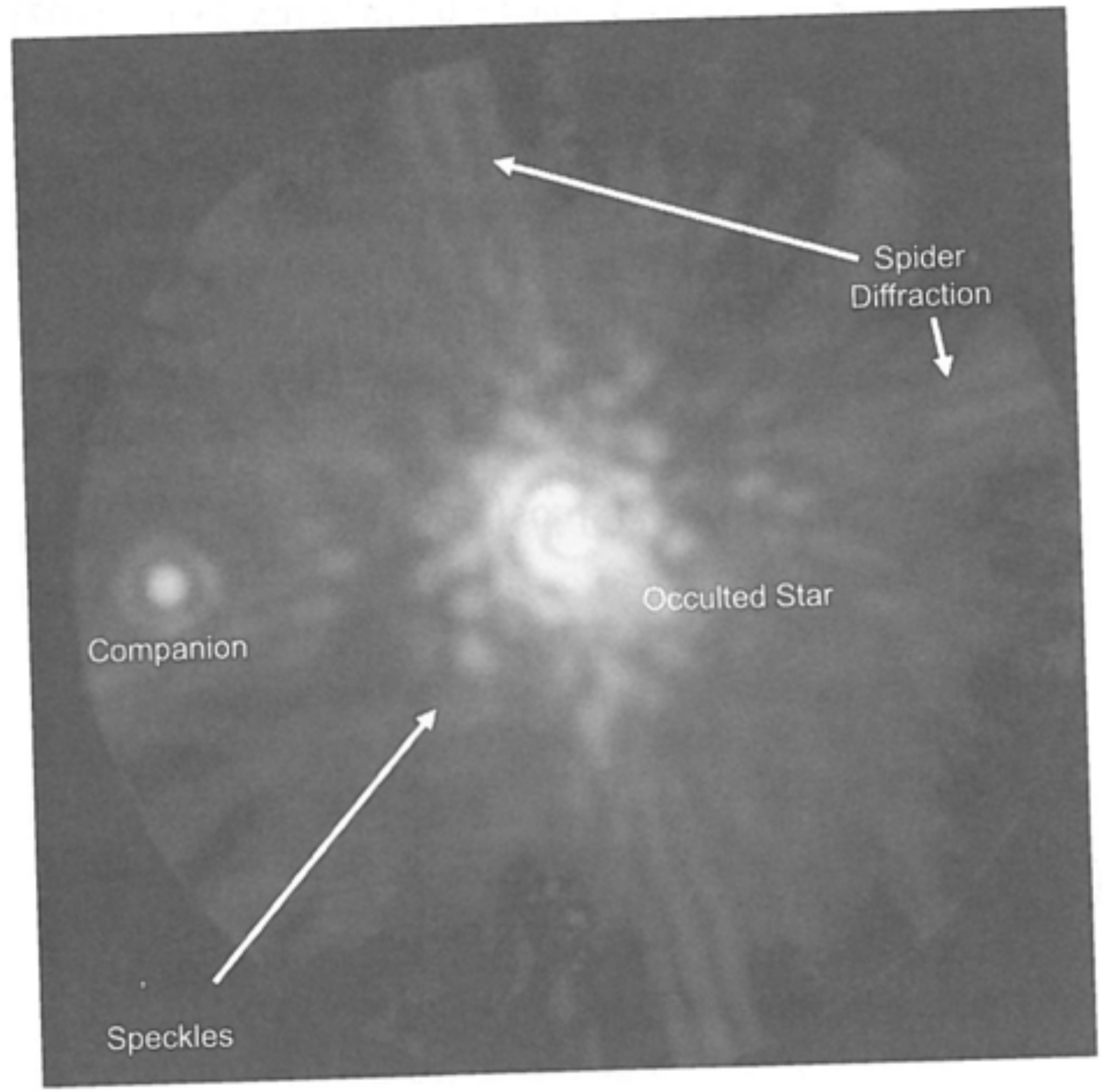


Must be ~40 m across with 0.2mm tolerances for contrasts of 10^{-10}

Starlight Suppression

Imperfections in the optical system will lead to wavefront errors that manifest as speckles.

Sources include: the support structure for the secondary mirror, an obscured aperture, a segmented primary mirror, imperfect pointing, imperfect coronagraph masking, and imperfect optical surfaces.

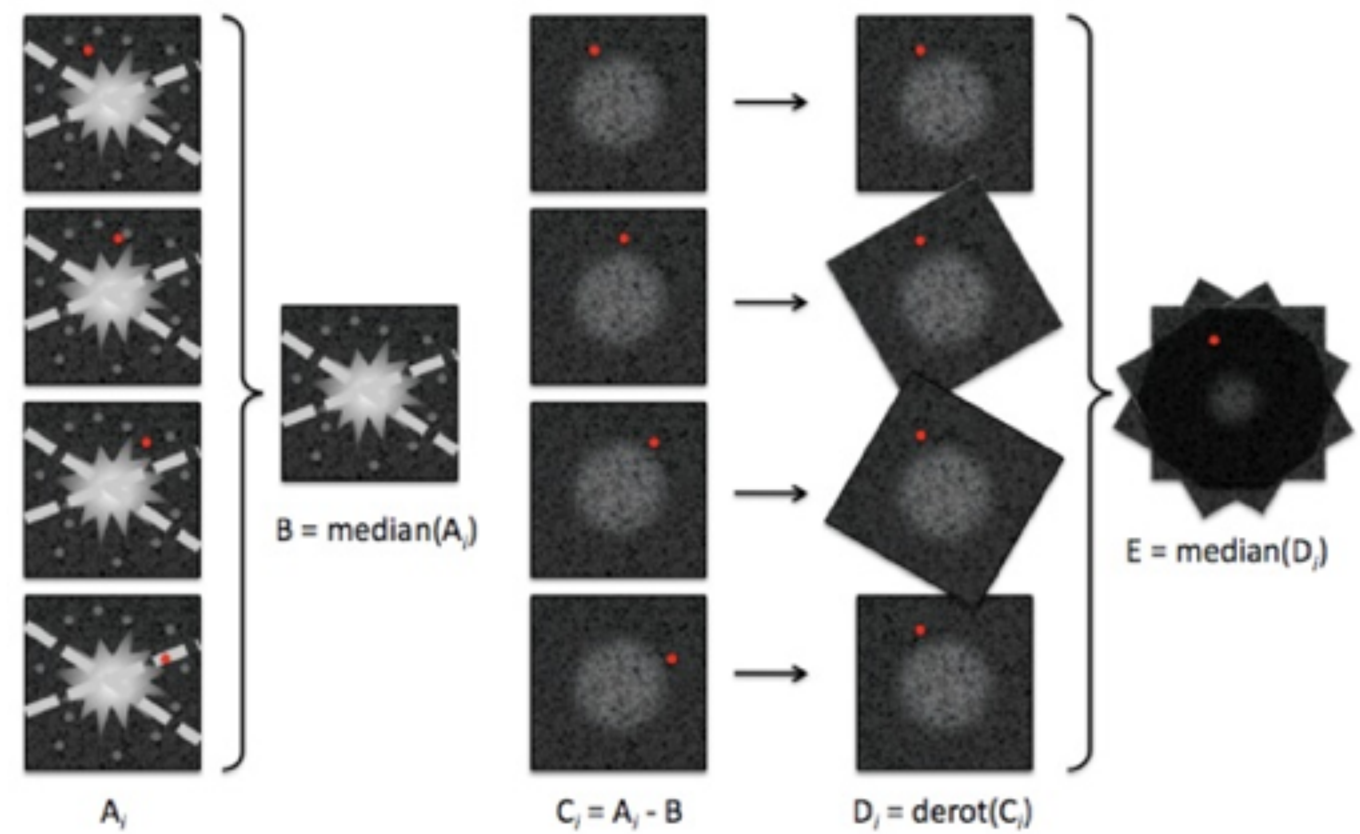


Post-processing (speckle suppression)

Techniques for removal:

- **Angular Differential Imaging**
- **Chromatic Speckle Suppression**

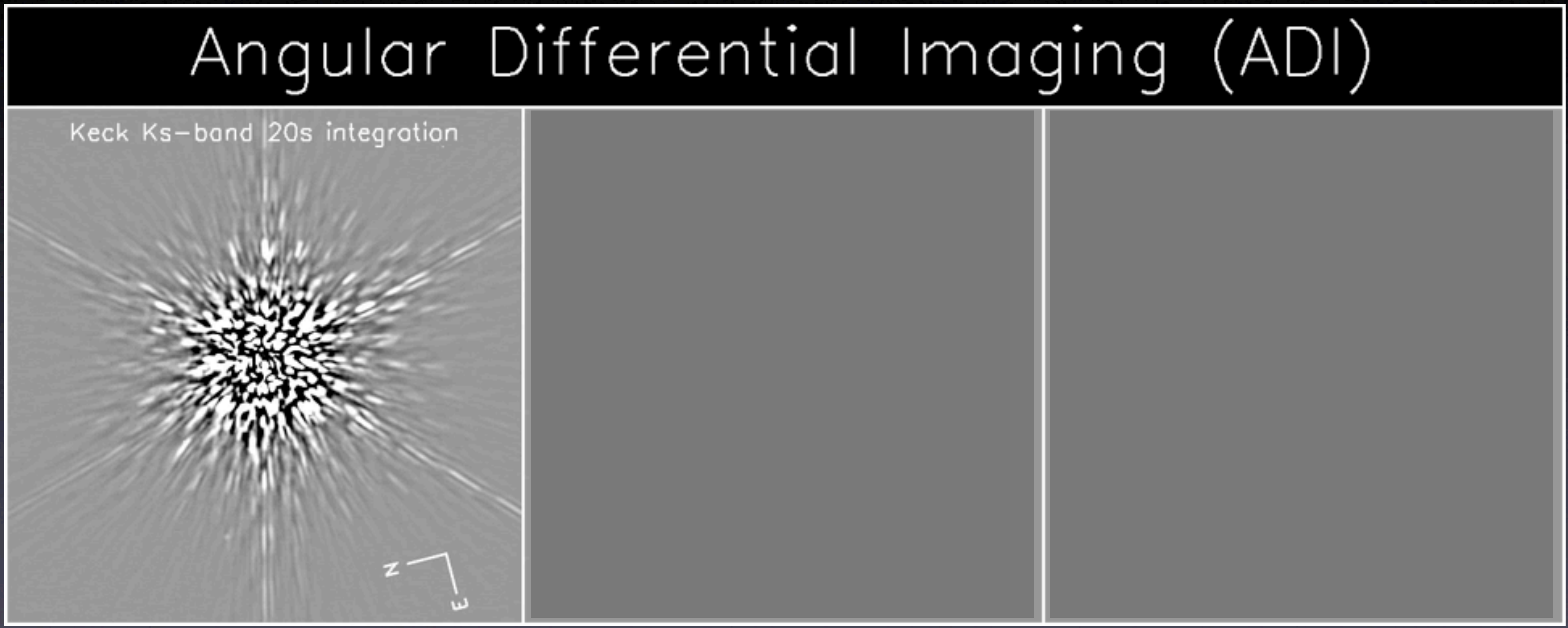
ADI



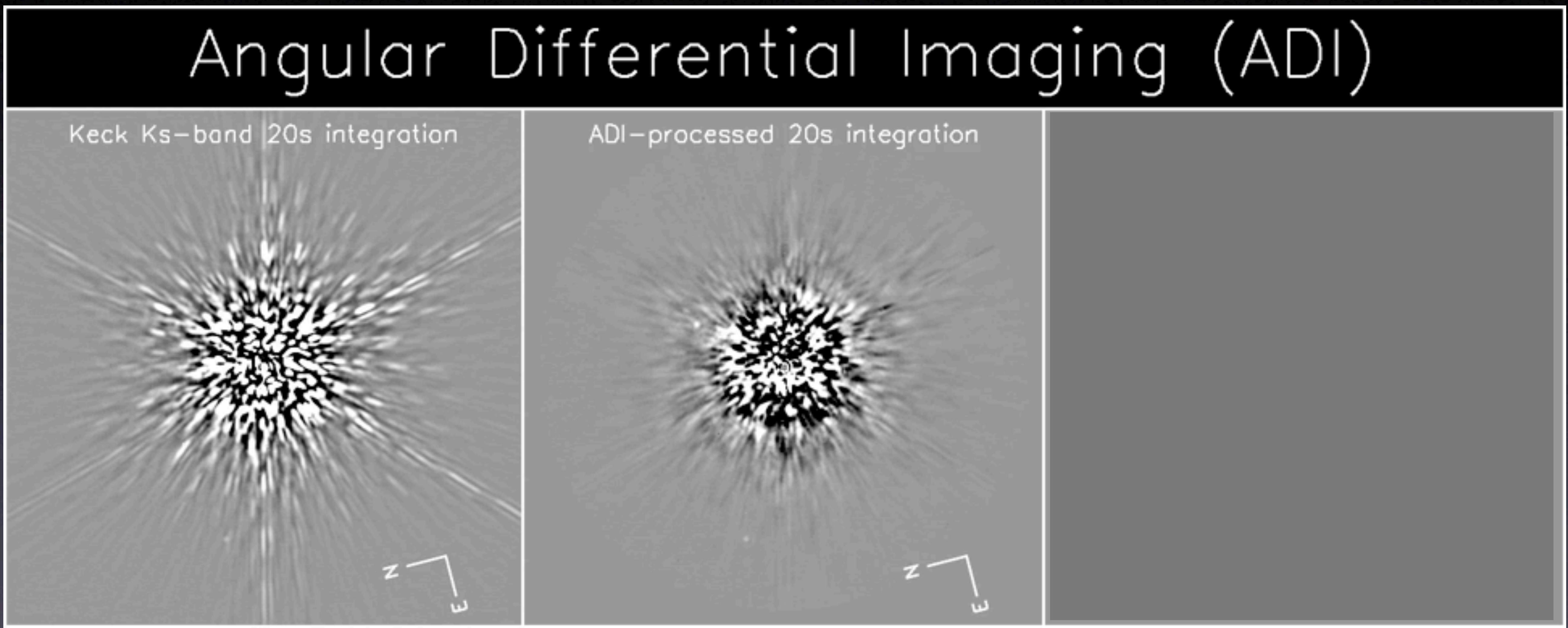
Instrument speckles will rotate with the telescope, while stars/planets will not

Marois et al. 2006, ApJ, 641, 556

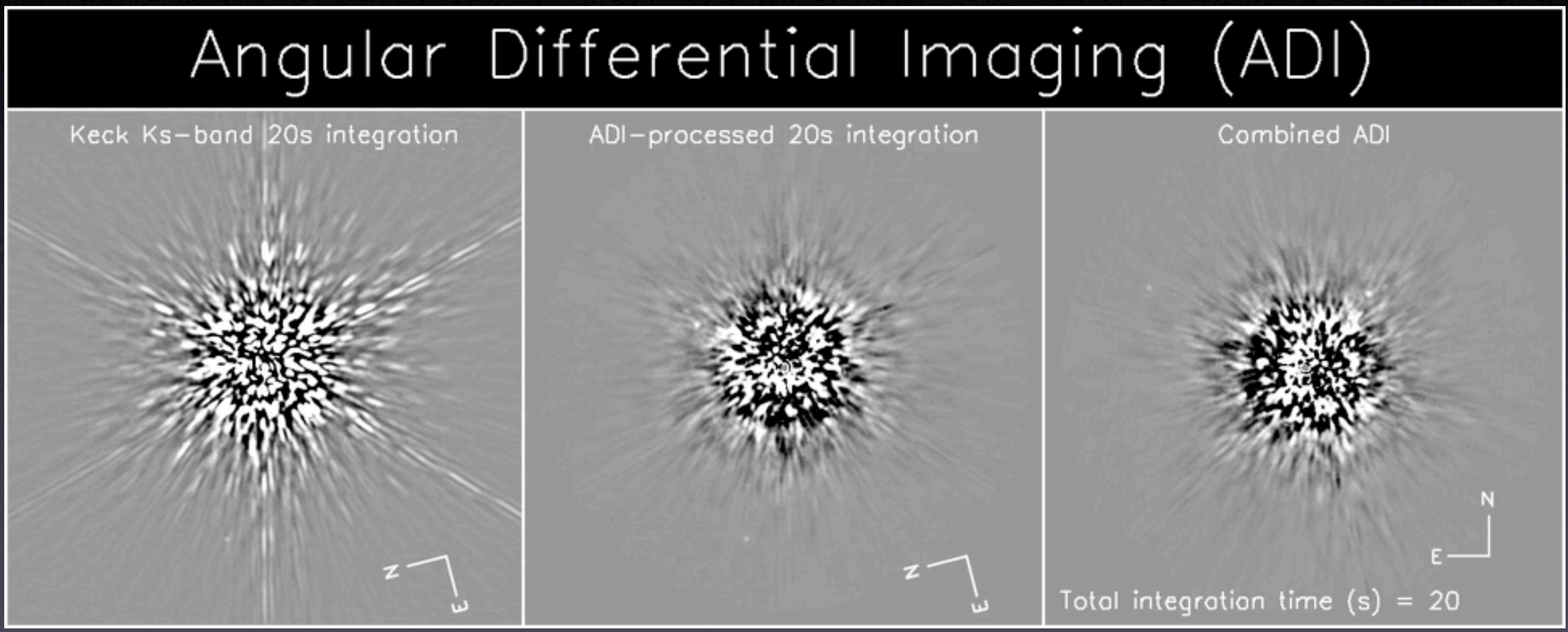
Clever data processing ...

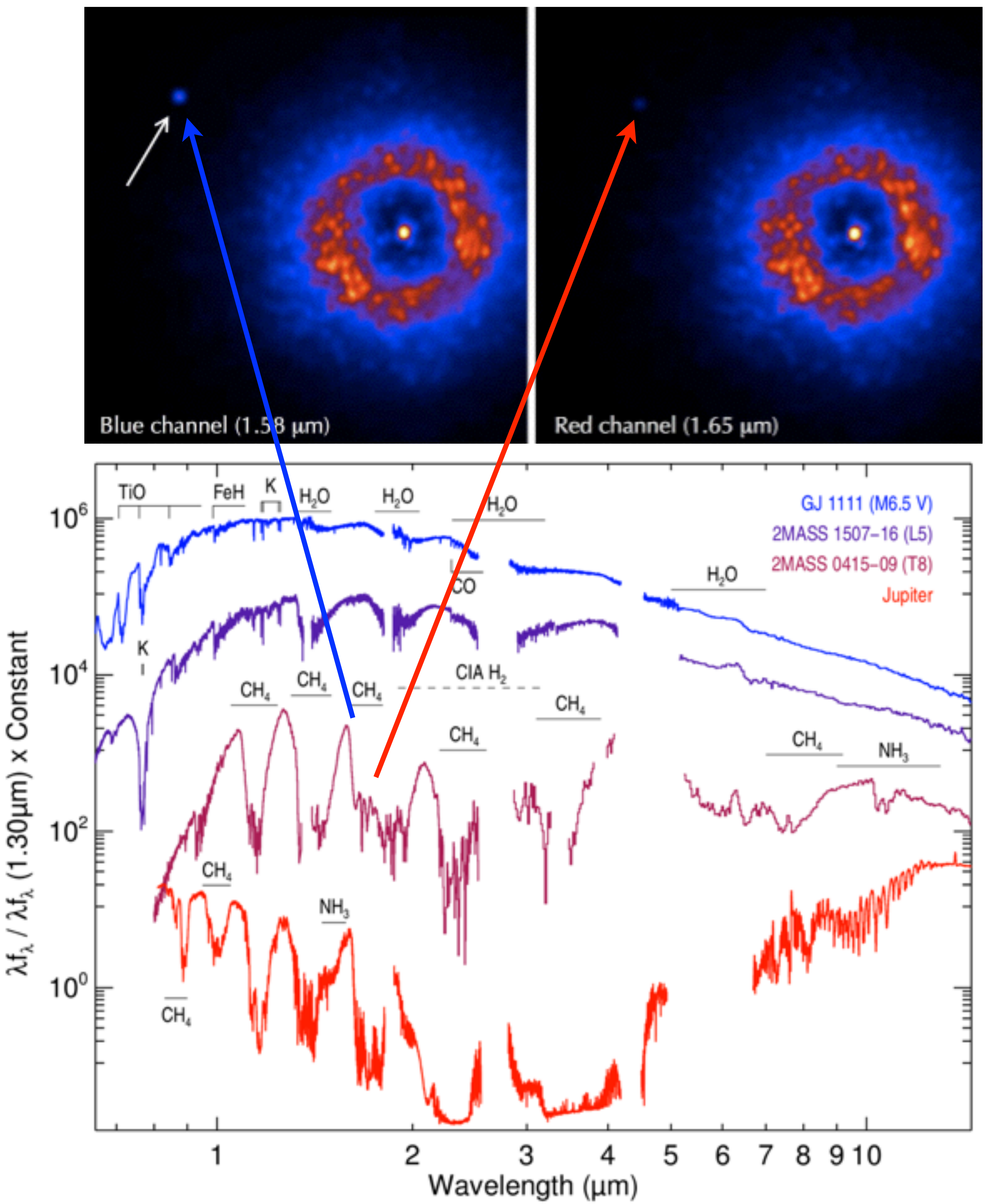


Clever data processing ...



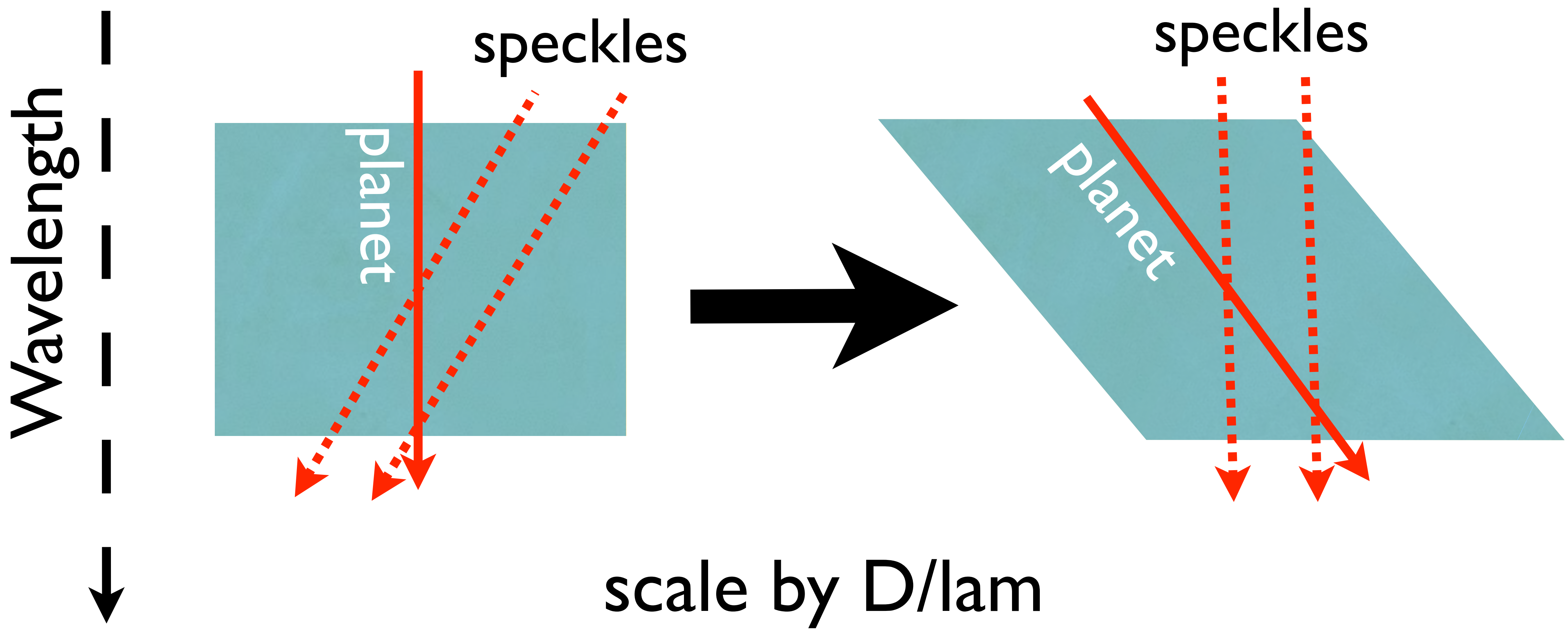
Clever data processing ...





Simultaneous
differential imaging

Speckle Removal



see also Sparks & Ford (2002)