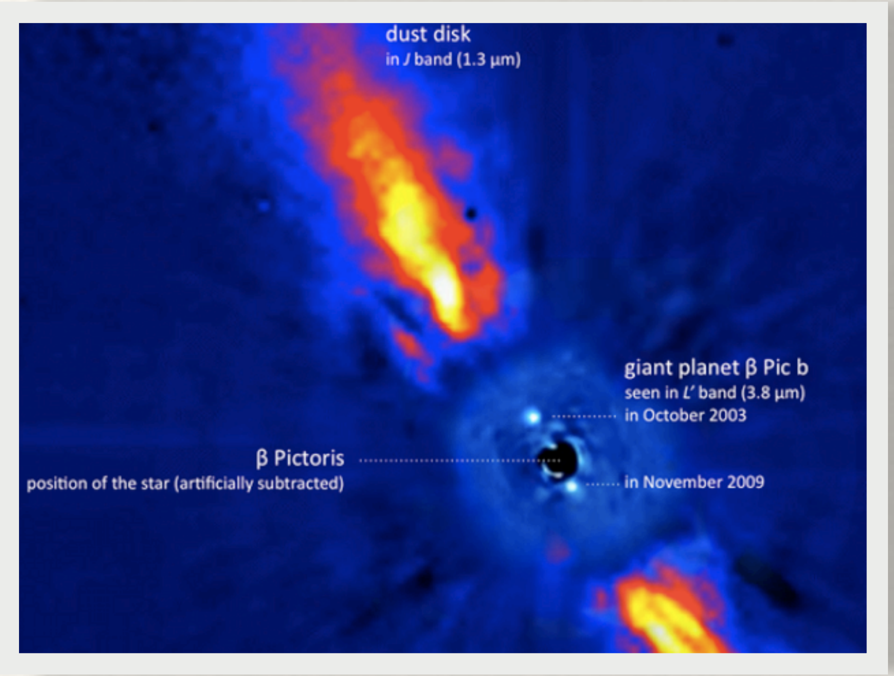
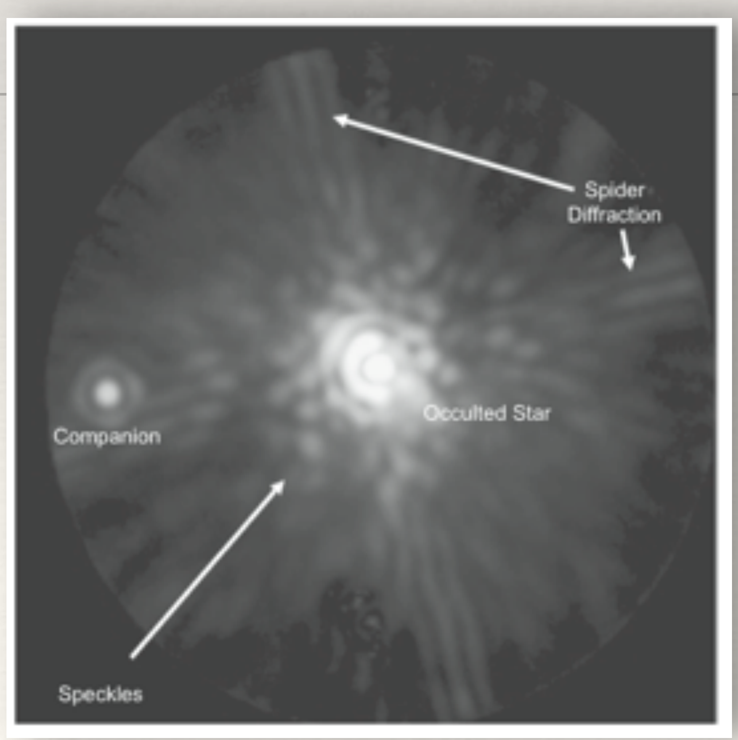


R. Claudi - INAF - Astronomical Observatory of Padova

DIRECT IMAGING OF EXTRASOLAR PLANETS

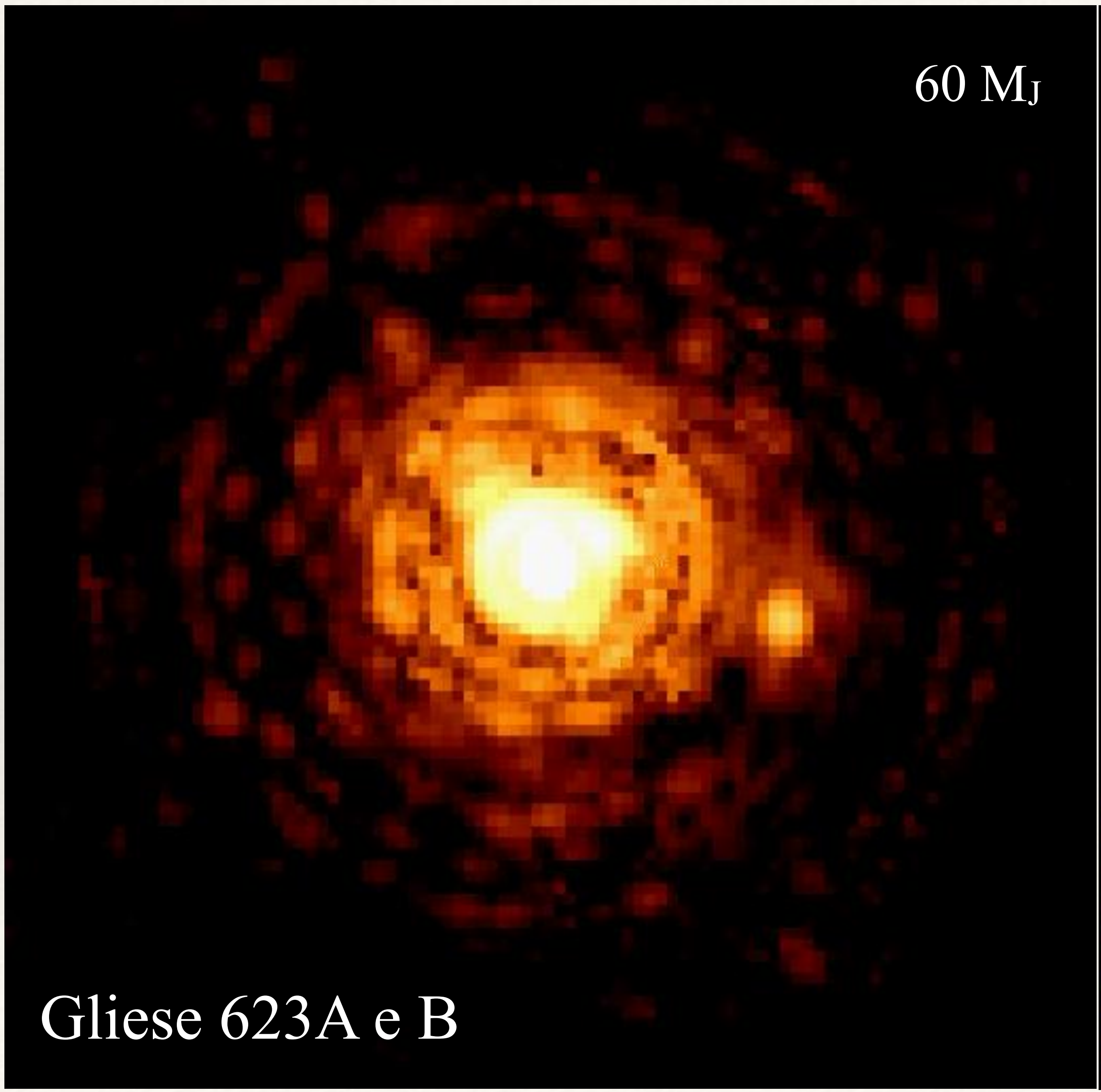
II: OBSERVATION ISSUES

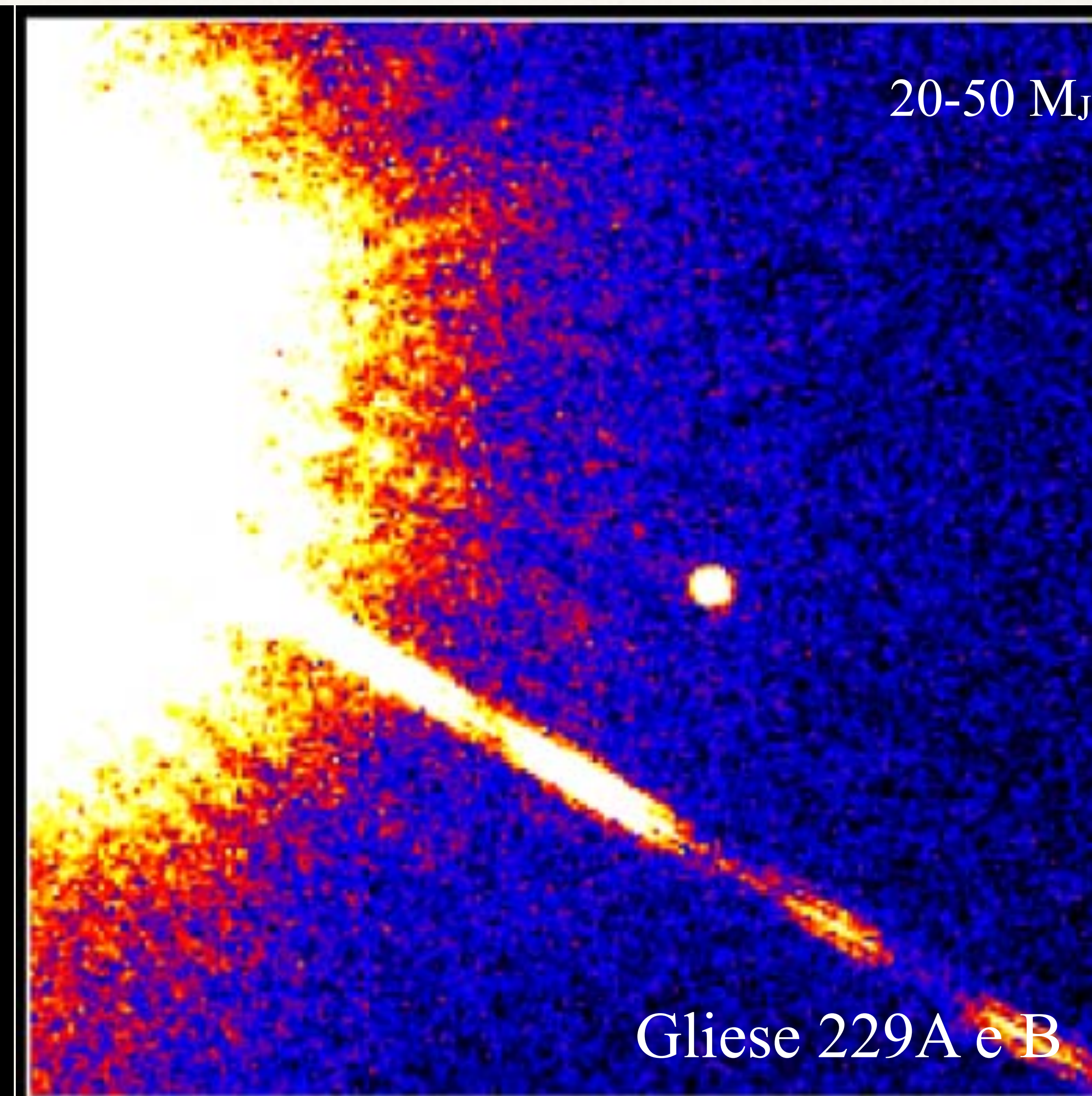


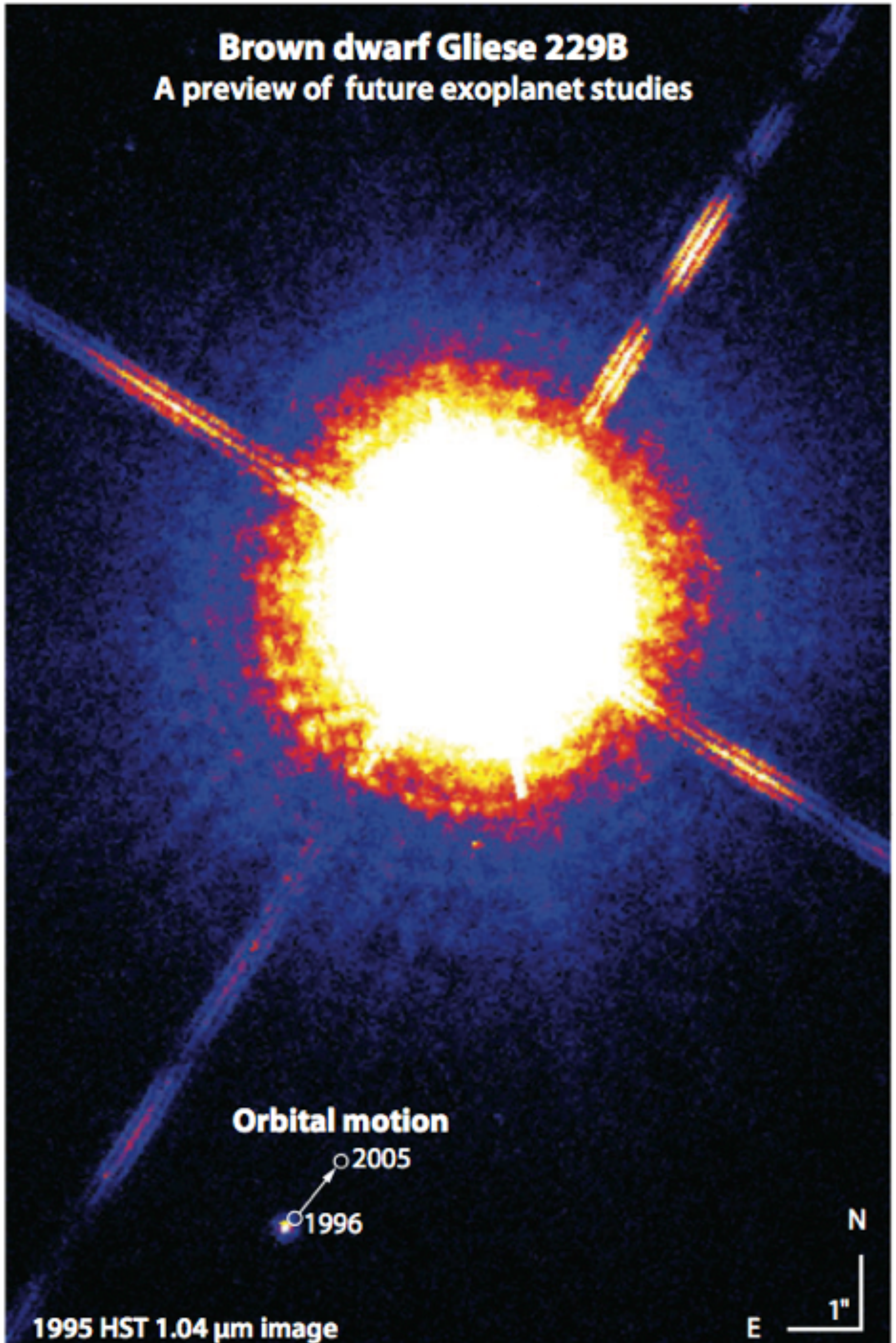
1st ADVANCED SCHOOL OF EXOPLANETARY SCIENCE
METHODS OF DETECTING EXOPLANETS
MAY 25-29, 2015 - VIETRI SUL MARE (SA)

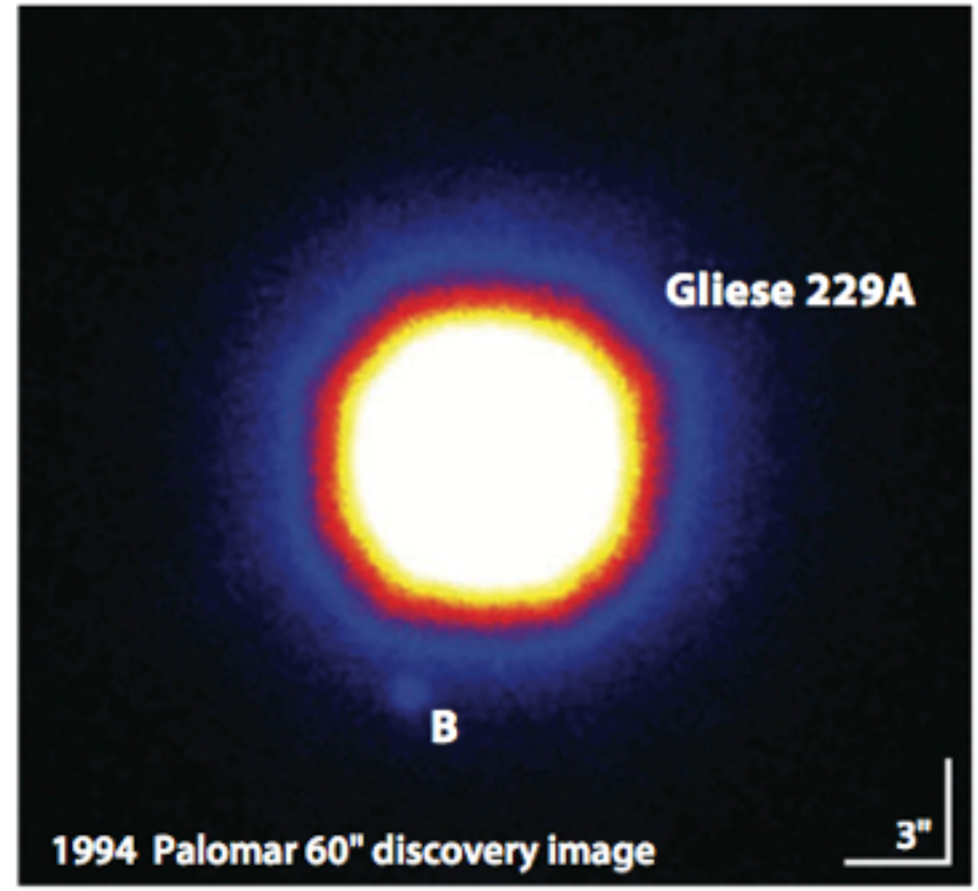
Observation Issues

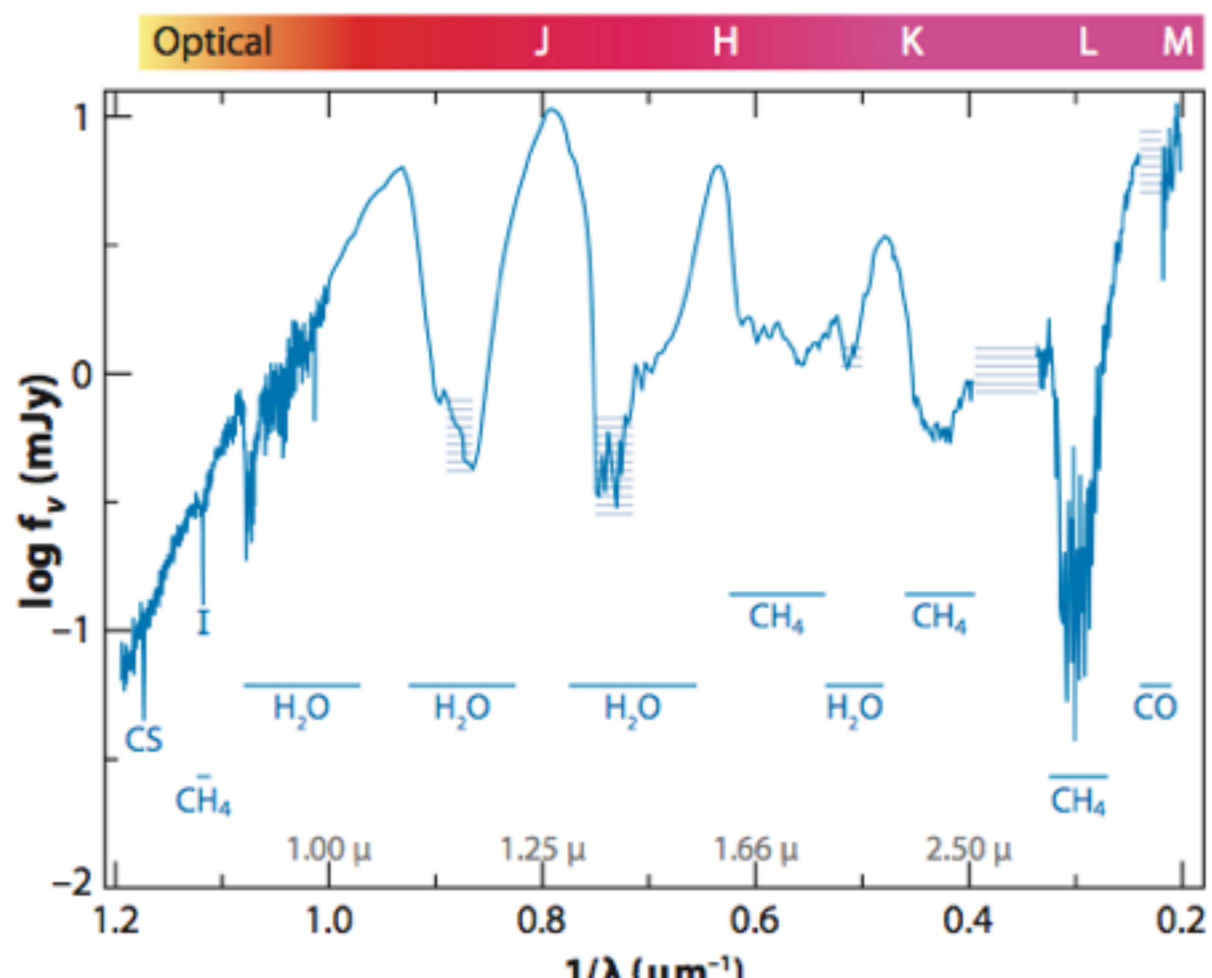
An already formed planet is smaller than a star. Jupiter has a diameter of $140x10^3$ km and its reflected light is very difficult to detect around an other star



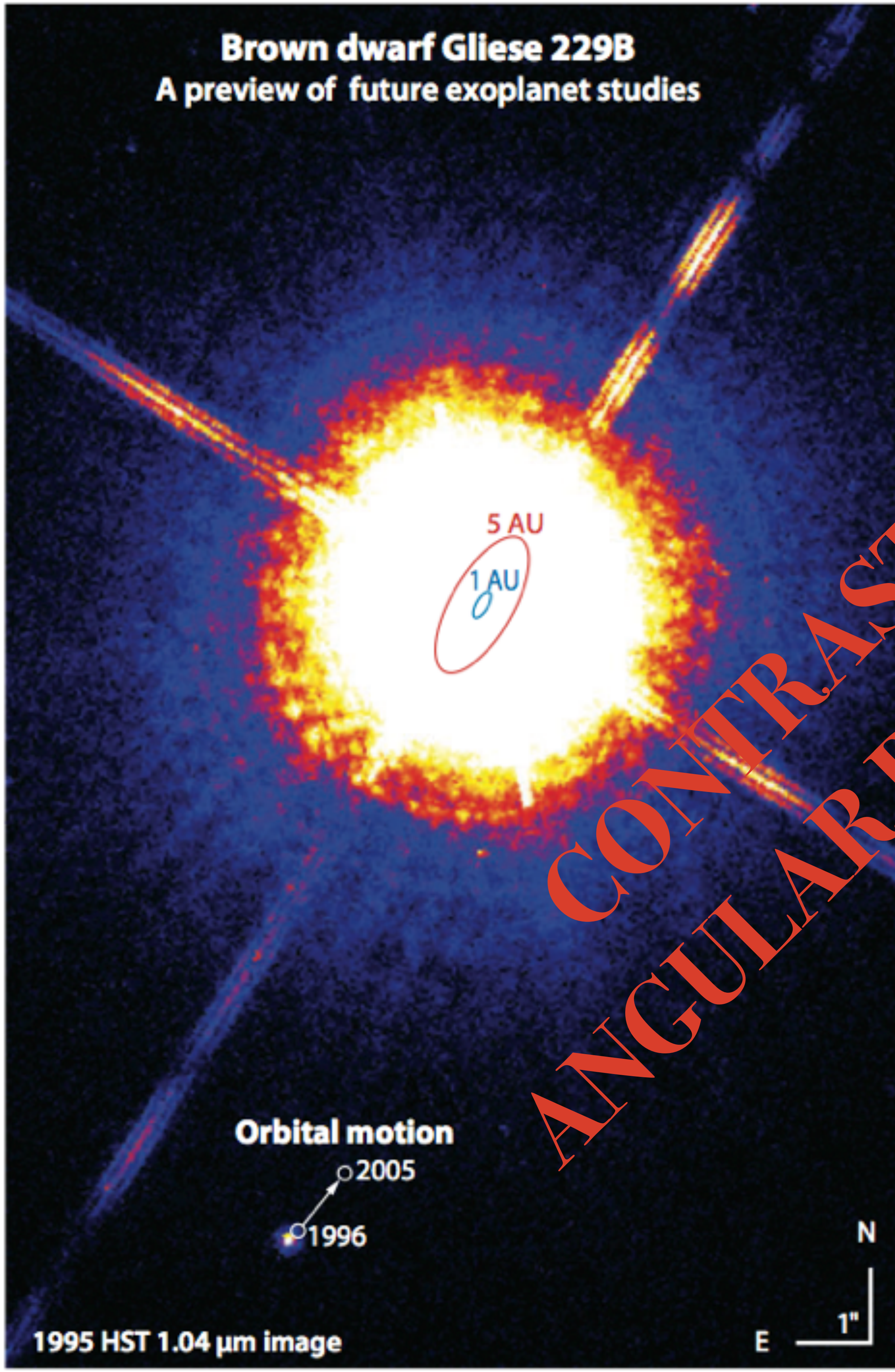


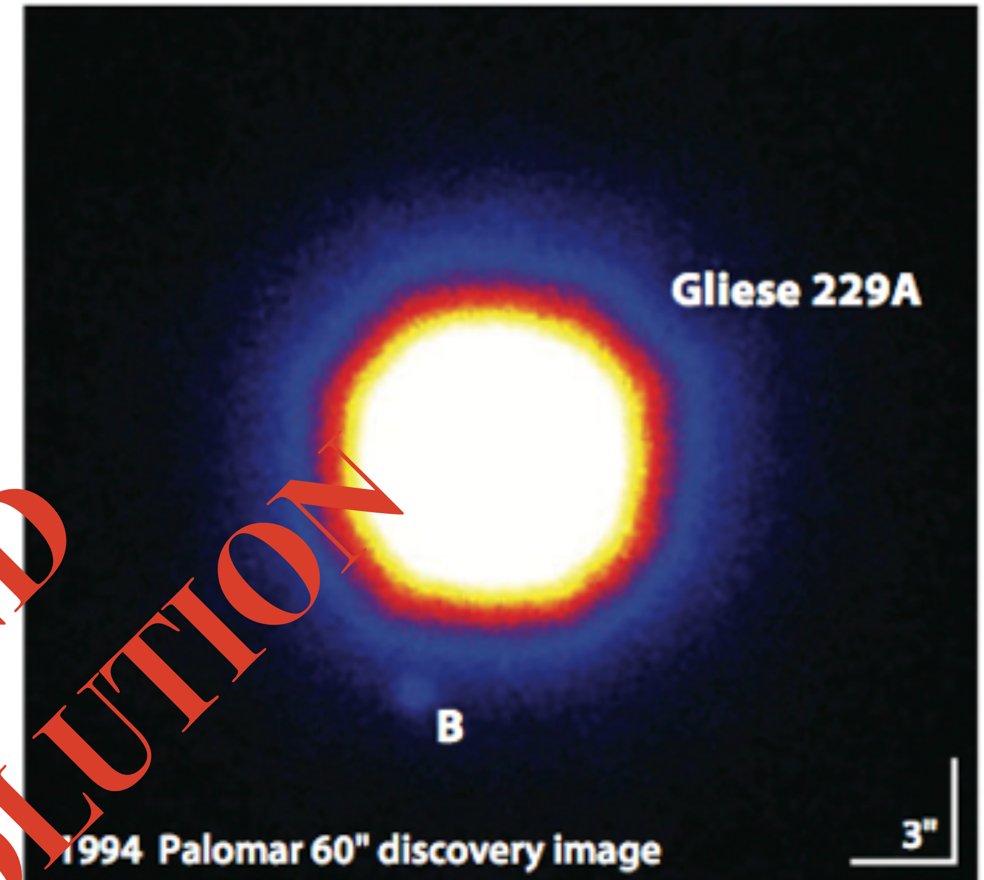

Brown dwarf Gliese 229B
A preview of future exoplanet studies
Orbital motion
2005
1996
N
E
1"
1995 HST 1.04 µm image

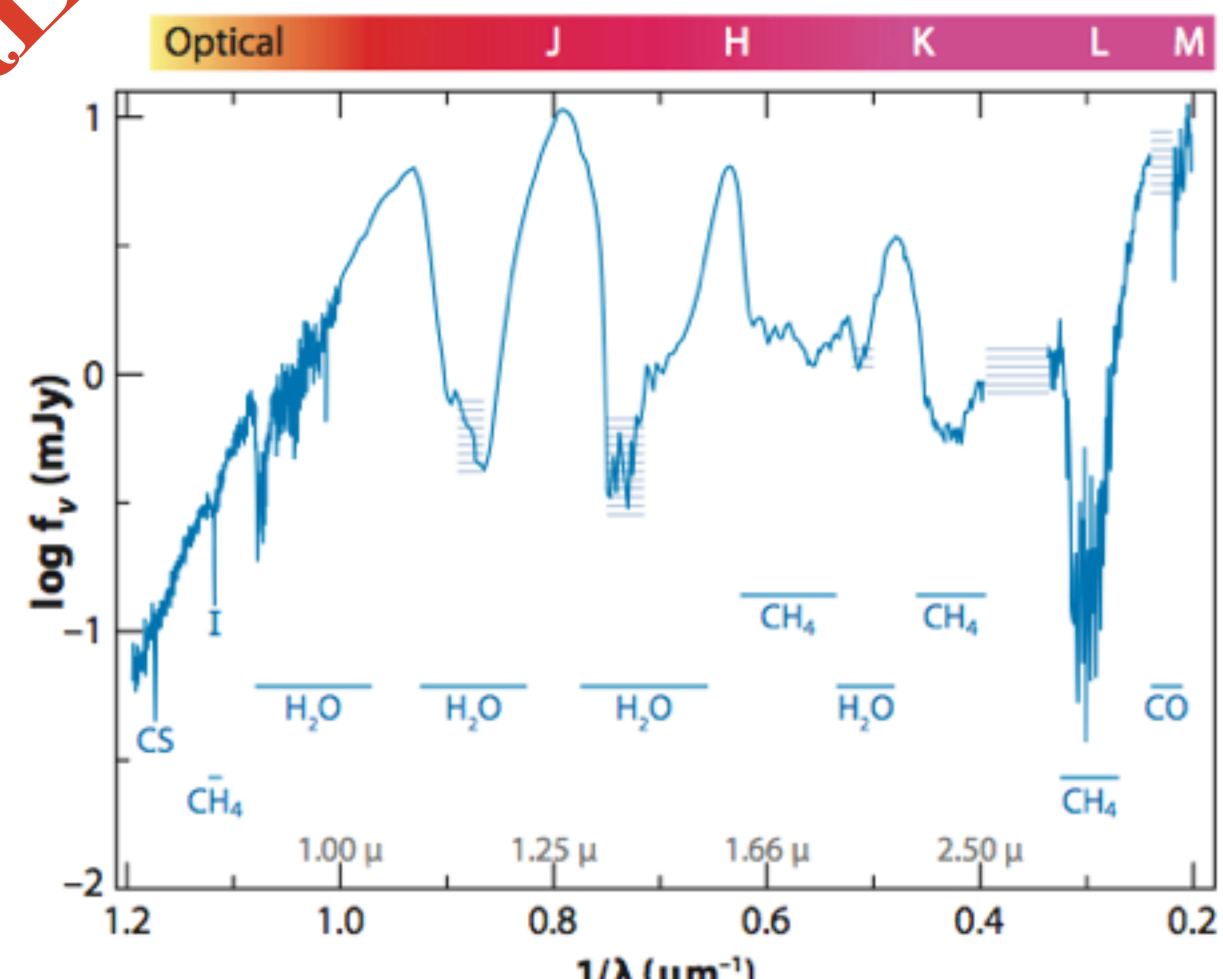

Gliese 229A
B
3"
1994 Palomar 60" discovery image


Optical
J
H
K
L
M
log f_v (mJy)
1
0
−1
−2
CS
CH4
I
H2O
H2O
H2O
H2O
CH4
CH4
CH4
CO
1.00 µ
1.25 µ
1.66 µ
2.50 µ
1.2
1.0
0.8
0.6
0.4
0.2
1/λ (µm⁻¹)

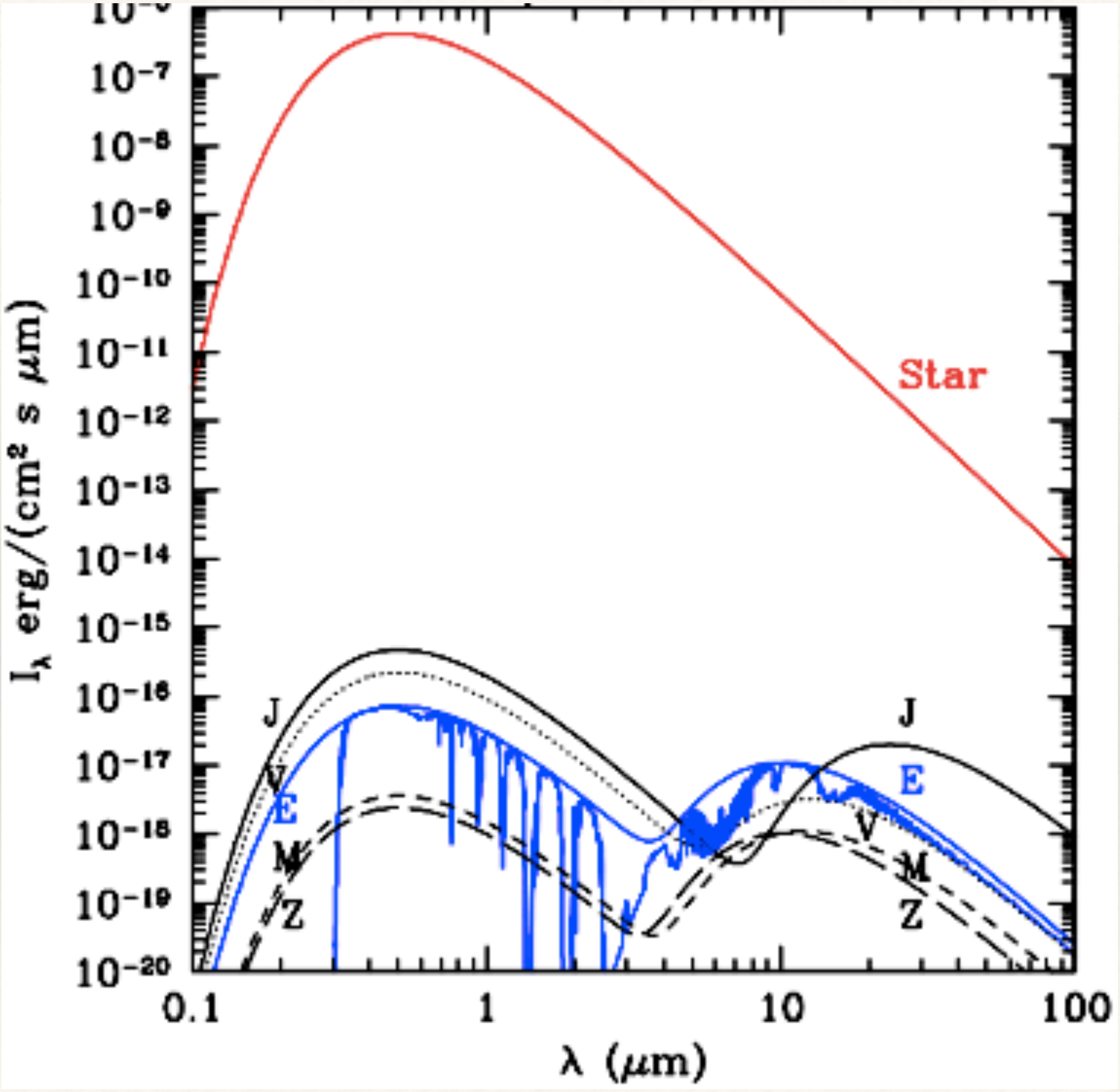
CONTRAST AND ANGULAR RESOLUTION







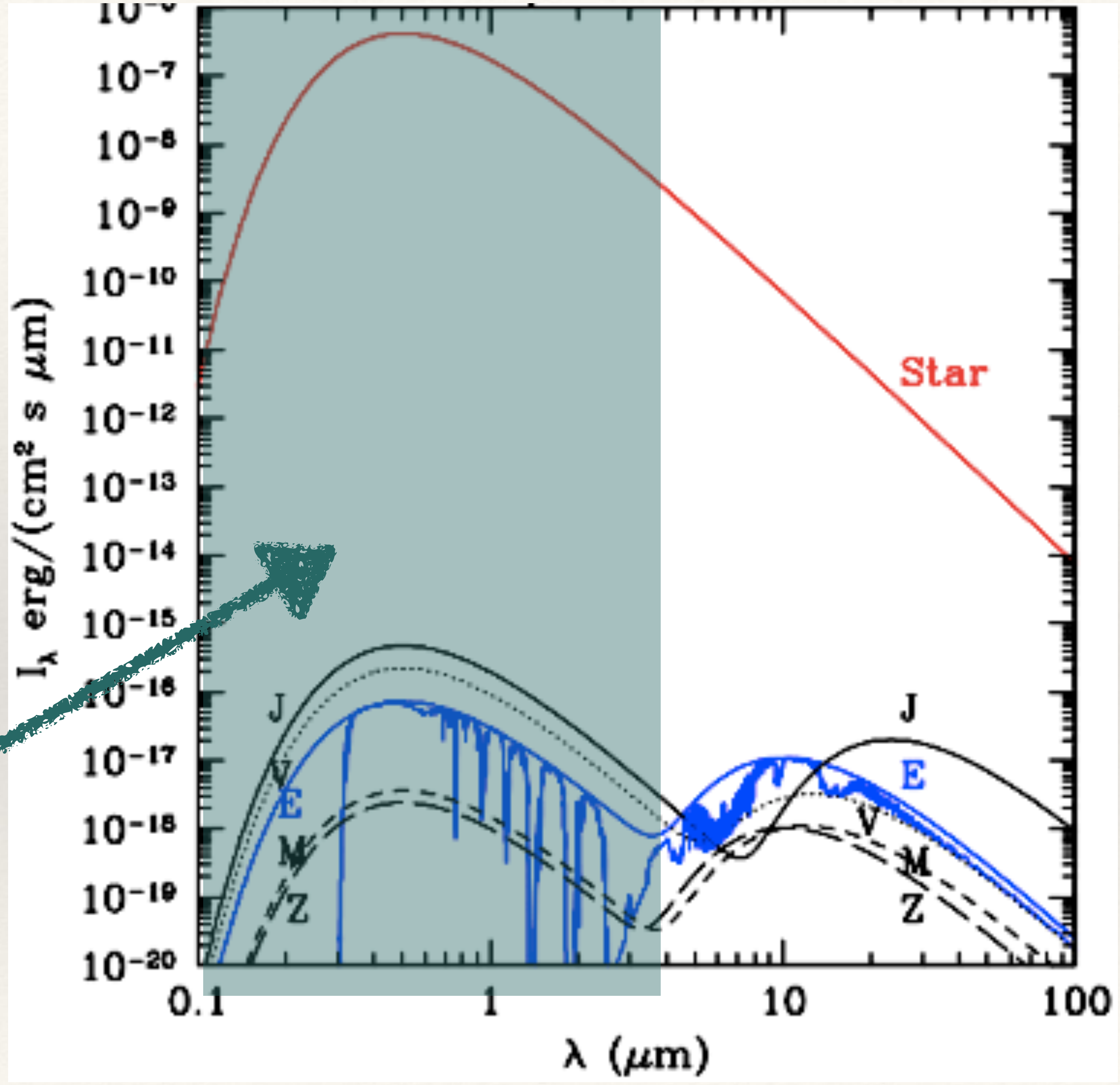
The Solar System to 10 pc



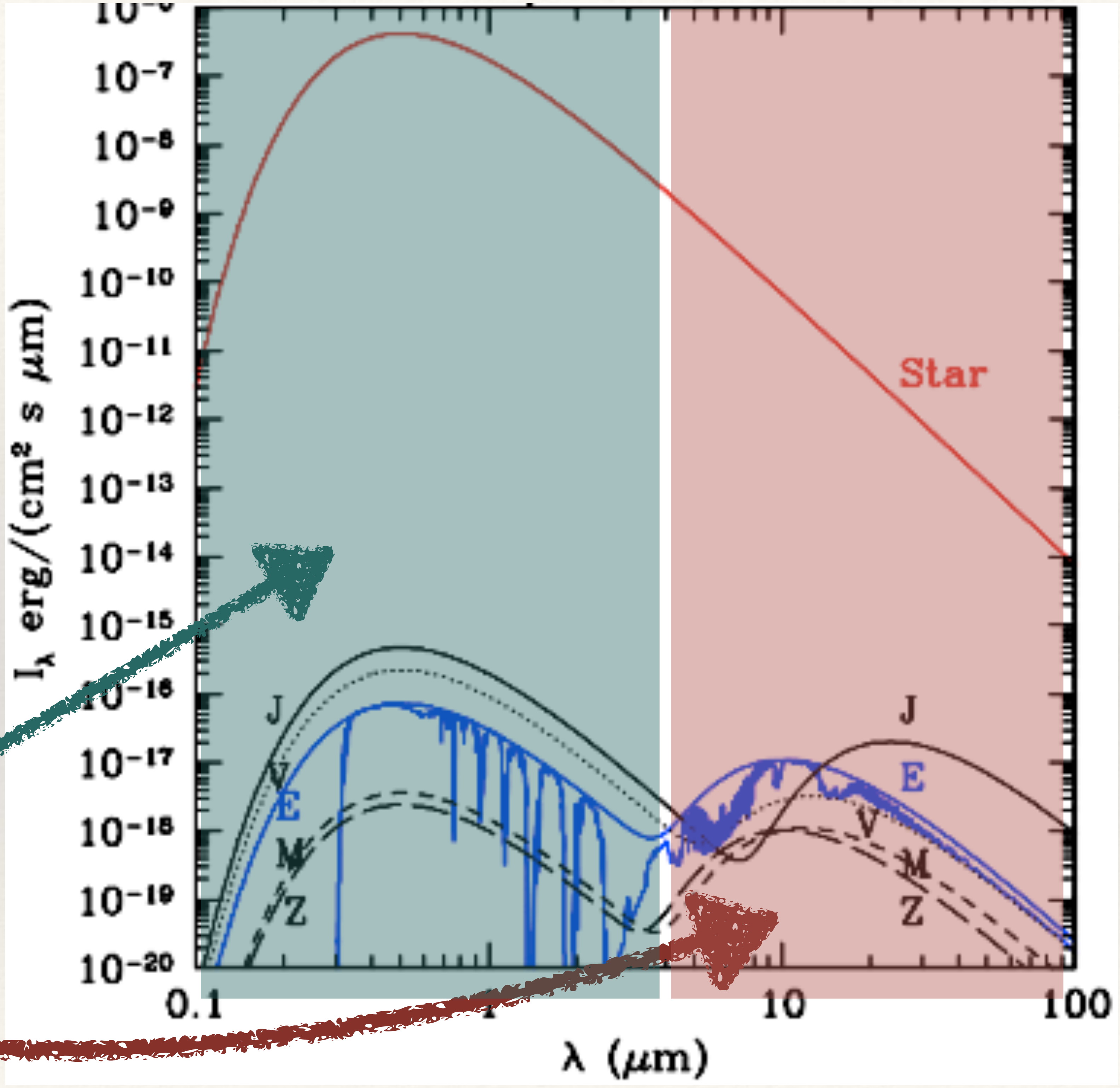
The Solar System to 10 pc

Reflected Flux
irradiated planets

$$F_p = a(\lambda,t).\varphi(t).\frac{r_p^2}{4d^2}B(\lambda,T_s).r_s^2$$



The Solar System to 10 pc



Reflected Flux
irradiated planets

$$F_p = a(\lambda,t).\varphi(t).\frac{r_p^2}{4d^2}B(\lambda,T_s).r_s^2$$

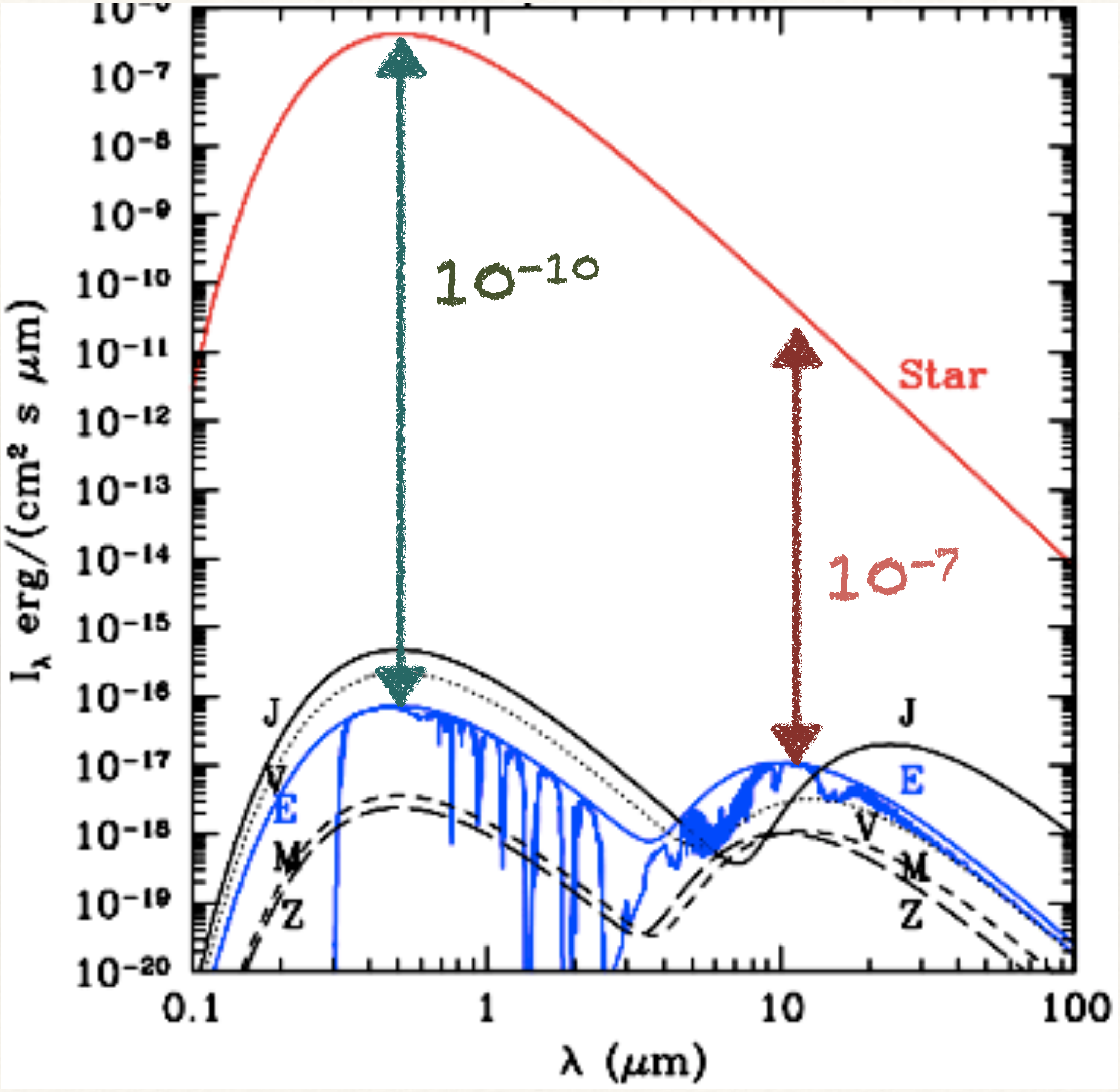
Intrinsic Flux
Self luminous planets

$$F_p = \varepsilon_{IR}.B(\lambda,Tp).r_p^2$$

The Solar System to 10 pc

Visible
Earth/Sun ~ 10^{-10}
Zodi not so bright

Infrared
Earth/Sun ~ 10^{-7}
Zodi bright



Albedo

Several definition.
It is mainly the fraction of impinging radiation that is reflected by the planetary surface.

Geometric Albedo: defined as the ratio of planet brightness at phase angle 0 to the brightness of a perfectly diffusing disk with the same position and apparent size as the planet. Generally be wavelength dependent.

Bond Albedo: defined as the ratio of total light (bolometric) reflected to the total light (bolometric) incident on the planet integrated over all wavelengths and planet

Planet	a (AU)	p (visible geom. alb.)	A_{bond} (Bond alb.)	T_{equil}* (K)	T_{eff}† (K)
Mercury	0.387	0.138	0.119	433	433
Venus	0.723	0.84	0.75	231	231
Earth	1.000	0.367	0.306	254	254
Moon	1.000	0.113	0.123	269	269
Mars	1.524	0.15	0.25	210	210
Jupiter	5.203	0.52	0.343	110	124.4
Saturn	9.543	0.47	0.342	81	95.0
Uranus	19.19	0.51	0.290	58	59.1
Neptune	30.07	0.41	0.31	46	59.3

$$T_{equil} = \left(\frac{1 - A_{Bond}}{4f}\right)^{1/4} \left(\frac{R}{a}\right)^{1/2} T_s$$

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$$T_{equil} = \left(\frac{1 - A_{Bond}}{4f}\right)^{1/4} \left(\frac{R}{a}\right)^{1/2} T_s$$

The effective temperature (T_{eff}) is different by the T_{eq} only in the case that the planet has an internal source of heating

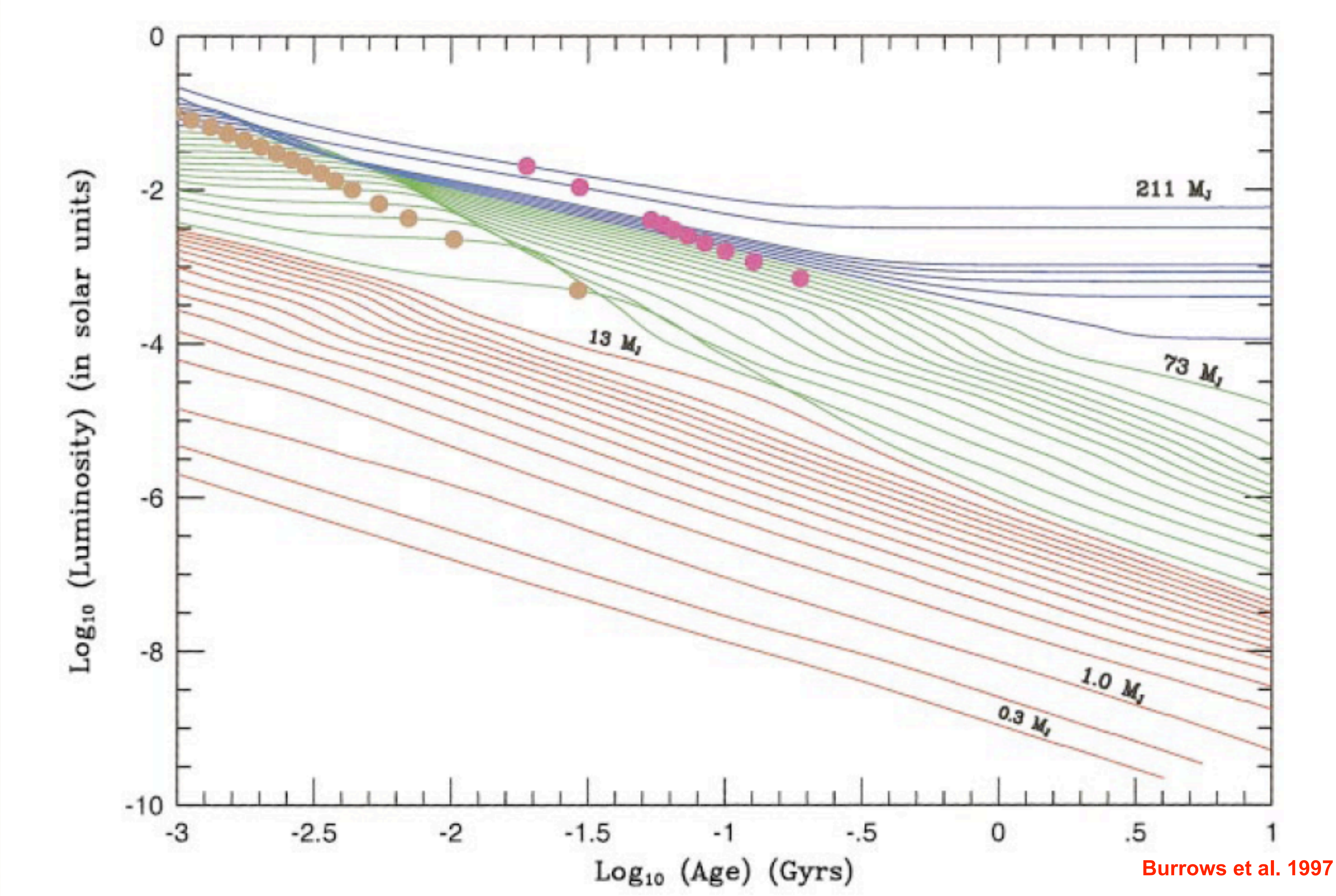
Star - Planet Contrast

$$Contrast = F_P / F_*$$

WARM PLANETS: the contrast is independent by the separation

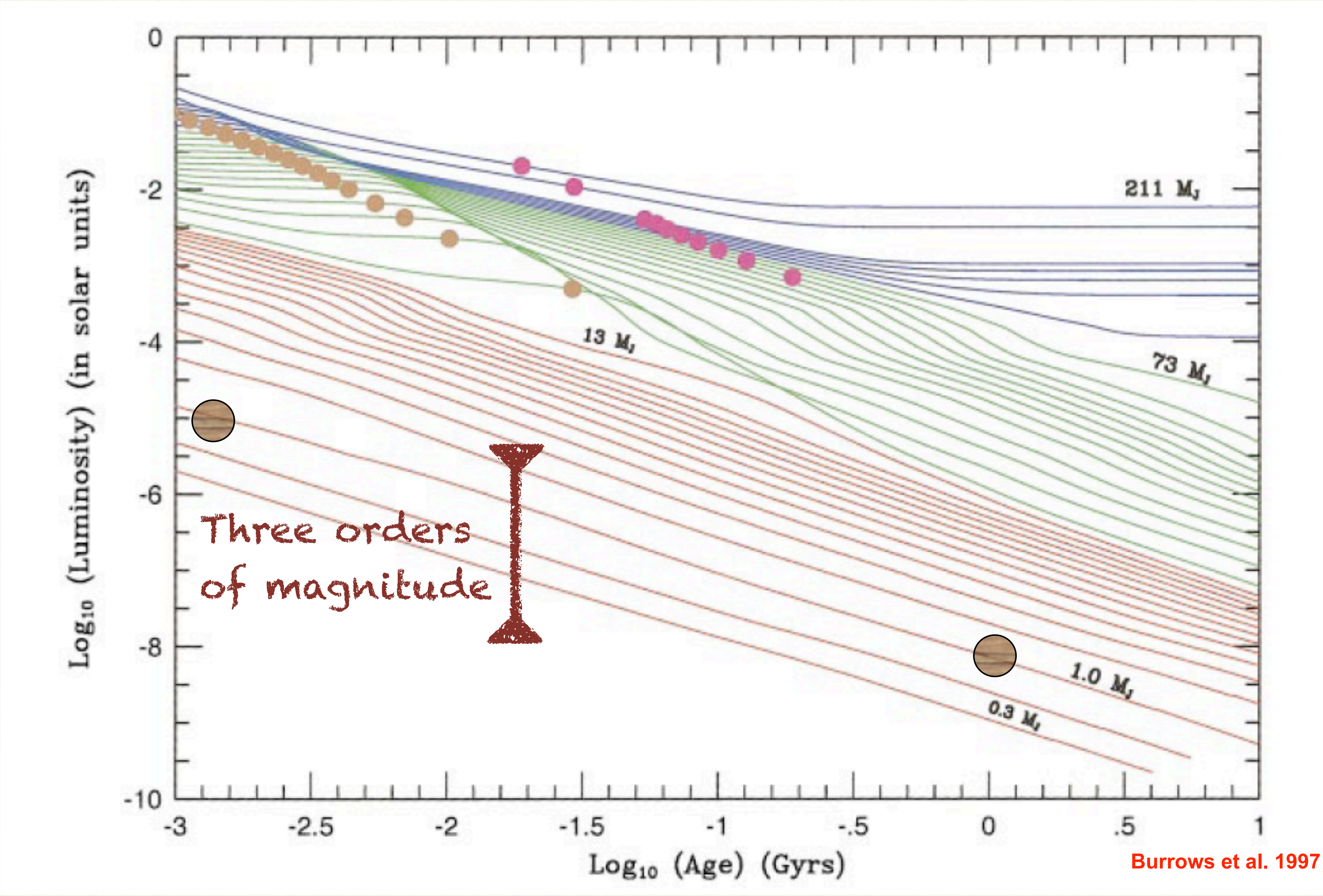
COLD PLANETS: the contrast is dependent by the separation (closer the planet brighter it'll be) and by the orbital phase. It is independent by the luminosity of the parent star, age and planetary mass.

Low mass object luminosity evolution



Burrows et al. 1997

Low mass object luminosity evolution



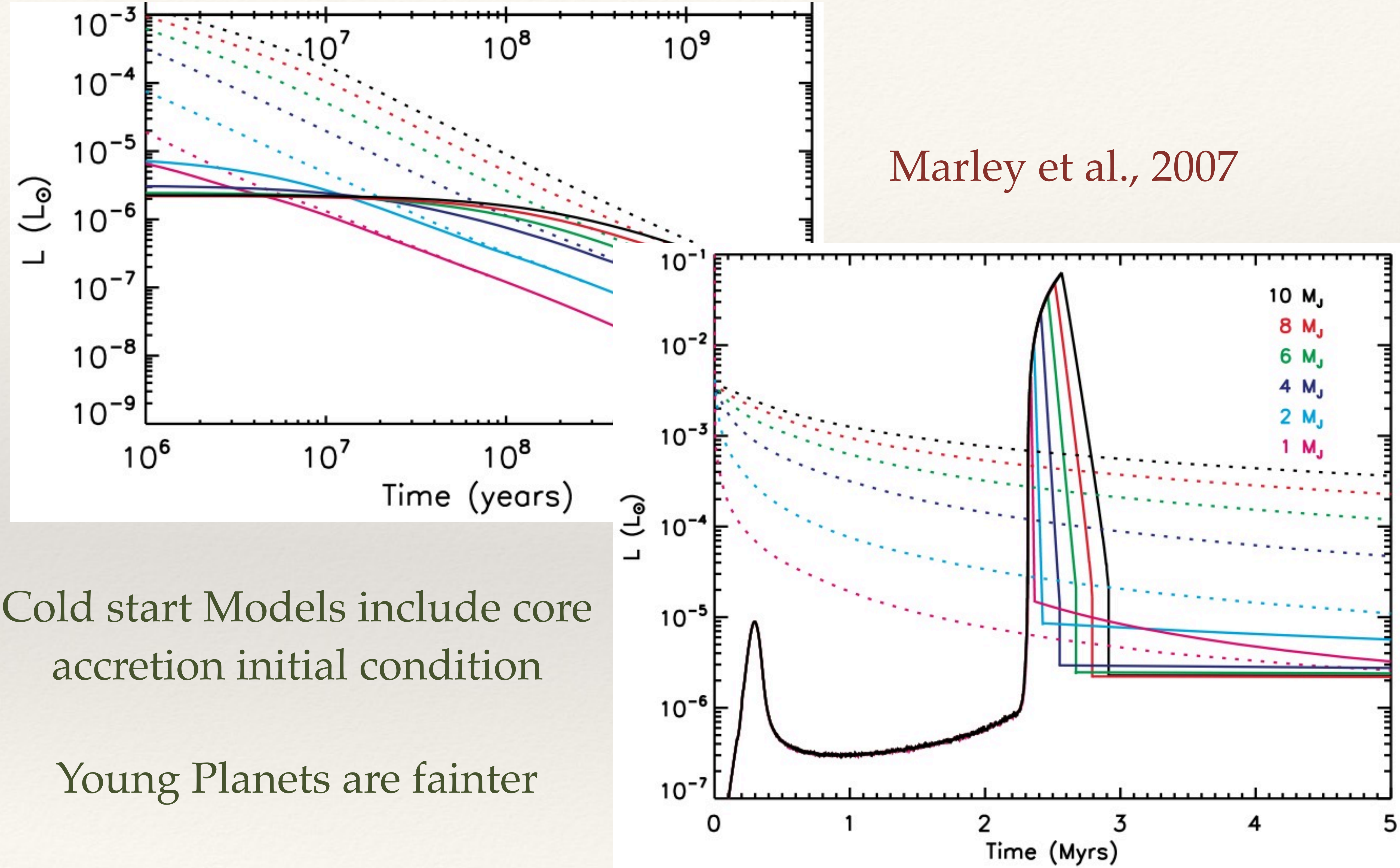
Theoretical Model Compilations

Table 1. COND isochrones for 0.1 Gyr.

$m/M_\odot$	T_{eff}	$\log L/L_\odot$	$R/R_\odot$	$\log g$	M_V	M_R	M_I	M_J	M_H	M_K	$M_{L'}$	M_M
0.0005	240.	−7.418	0.114	3.020	41.98	37.51	34.00	28.42	26.59	37.66	19.57	17.64
0.0010	309.	−6.957	0.117	3.300	32.58	28.68	25.89	22.43	22.38	29.11	17.41	15.69
0.0020	425.	−6.383	0.120	3.580	29.69	25.62	22.79	20.05	19.76	23.13	15.94	14.55
0.0030	493.	−6.112	0.121	3.746	28.71	24.48	21.66	18.88	18.57	20.88	15.21	13.93
0.0040	563.	−5.880	0.122	3.869	28.09	23.77	20.95	17.95	17.71	19.35	14.59	13.50
0.0050	630.	−5.686	0.122	3.965	27.65	23.25	20.44	17.23	17.02	18.15	14.06	13.14
0.0060	688.	−5.534	0.121	4.048	27.36	22.92	20.09	16.71	16.51	17.26	13.67	12.83
0.0070	760.	−5.365	0.121	4.117	27.03	22.55	19.74	16.16	16.01	16.38	13.26	12.55
0.0080	816.	−5.246	0.120	4.180	26.77	22.28	19.49	15.76	15.65	15.79	12.97	12.35
0.0090	886.	−5.103	0.120	4.232	26.45	21.96	19.19	15.32	15.23	15.16	12.63	12.13
0.0100	953.	−4.978	0.120	4.279	26.10	21.66	18.92	14.94	14.86	14.69	12.34	11.96
0.0120	1335.	−4.332	0.129	4.297	23.53	19.44	16.79	13.20	12.97	12.76	10.90	11.17
0.0150	1399.	−4.281	0.124	4.424	23.30	19.24	16.46	13.05	12.82	12.65	10.83	11.15
0.0200	1561.	−4.110	0.122	4.569	22.30	18.55	16.08	12.60	12.34	12.17	10.53	10.99
0.0300	1979.	−3.668	0.126	4.715	19.96	16.80	14.48	11.52	11.20	10.90	9.82	10.38
0.0400	2270.	−3.386	0.132	4.797	18.46	15.63	13.31	10.89	10.52	10.19	9.39	9.84
0.0500	2493.	−3.167	0.141	4.837	17.09	14.77	12.53	10.43	10.02	9.71	9.04	9.37
0.0600	2648.	−3.008	0.150	4.863	16.08	14.12	12.01	10.10	9.68	9.37	8.78	9.03
0.0700	2762.	−2.879	0.160	4.874	15.33	13.59	11.60	9.82	9.39	9.10	8.55	8.75
0.0720	2782.	−2.856	0.162	4.875	15.20	13.50	11.53	9.77	9.34	9.05	8.51	8.70
0.0750	2809.	−2.821	0.166	4.875	15.01	13.36	11.42	9.69	9.26	8.97	8.44	8.63
0.0800	2846.	−2.776	0.170	4.880	14.77	13.18	11.29	9.60	9.16	8.87	8.36	8.53
0.0900	2910.	−2.689	0.180	4.884	14.34	12.85	11.03	9.40	8.96	8.68	8.19	8.35
0.1000	2960.	−2.617	0.189	4.887	14.02	12.58	10.82	9.24	8.80	8.52	8.05	8.19

Baraffe et al. 2003

But … someone disagrees …

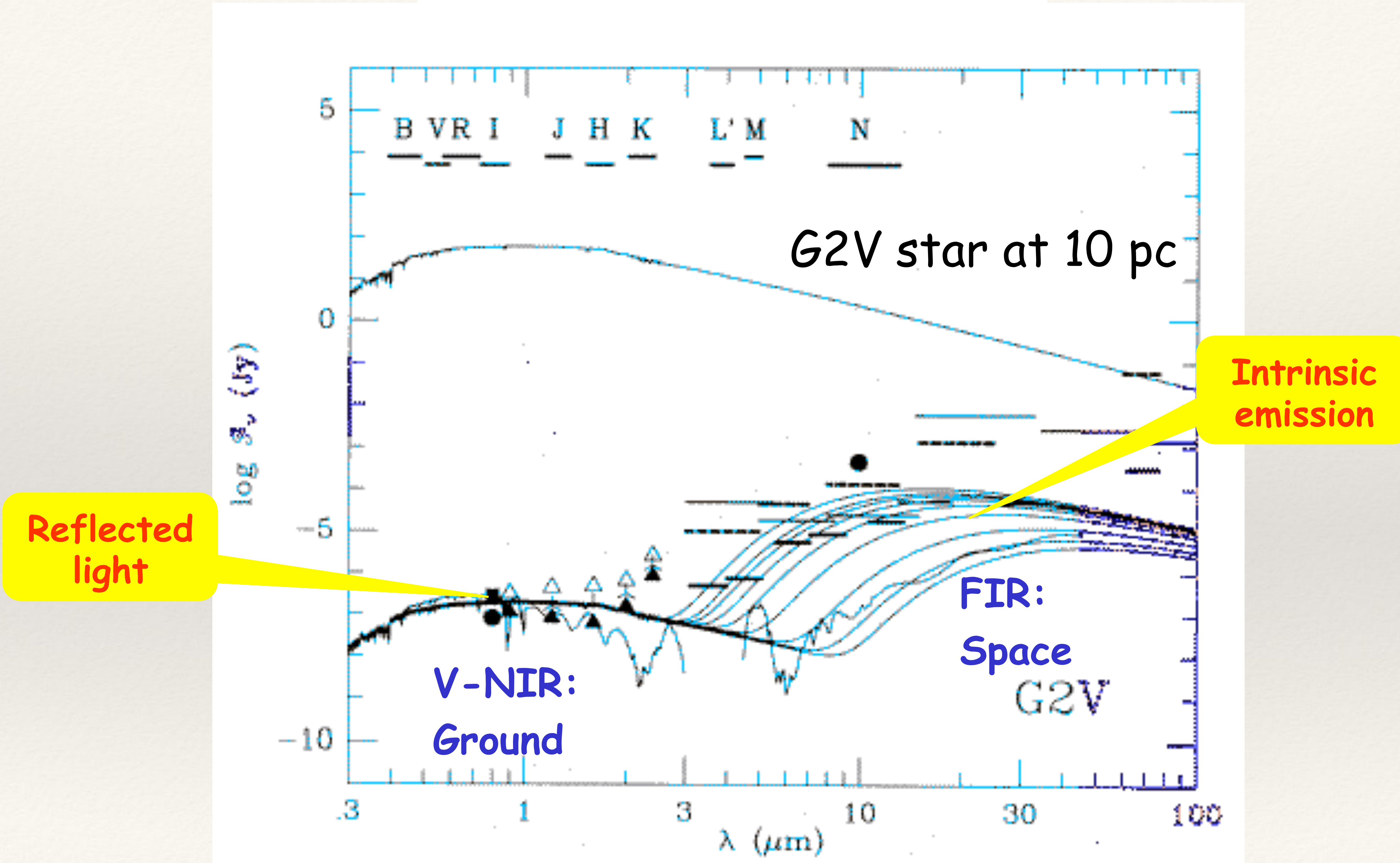


Marley et al., 2007

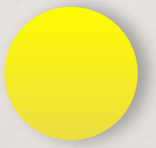
Cold start Models include core accretion initial condition

Young Planets are fainter

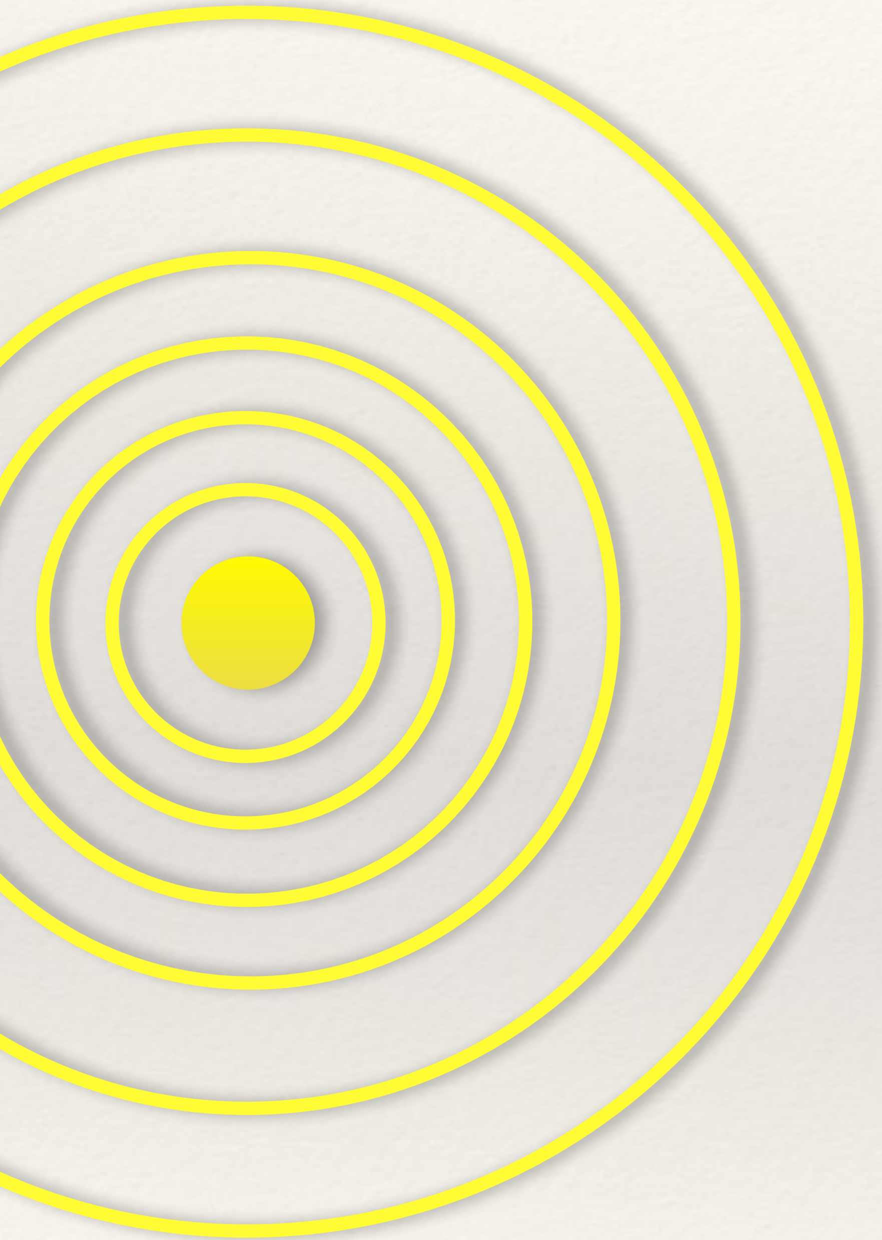
Wavelength Range Selection



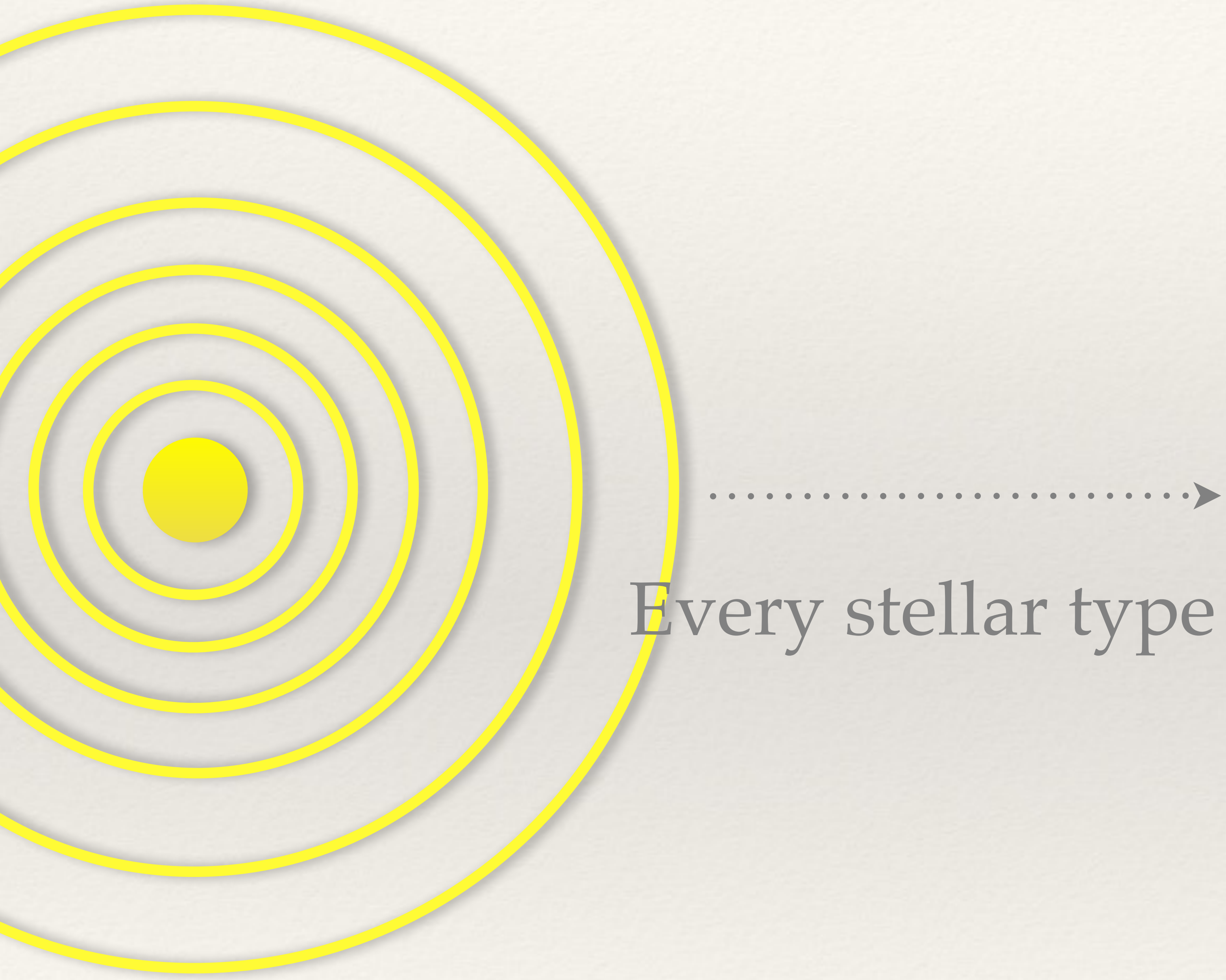
Diffraction/Wavefront



Diffraction/Wavefront

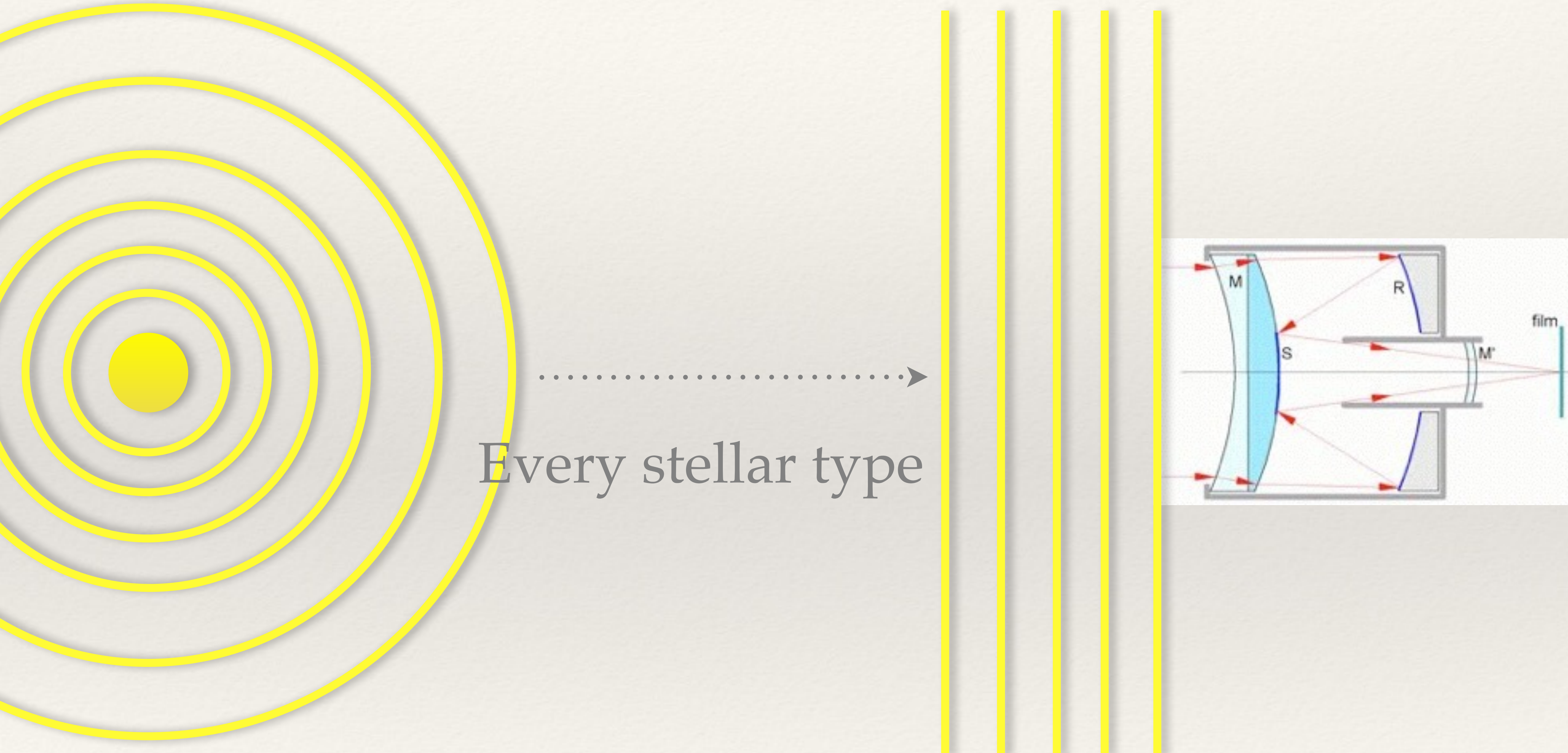


Diffraction/Wavefront



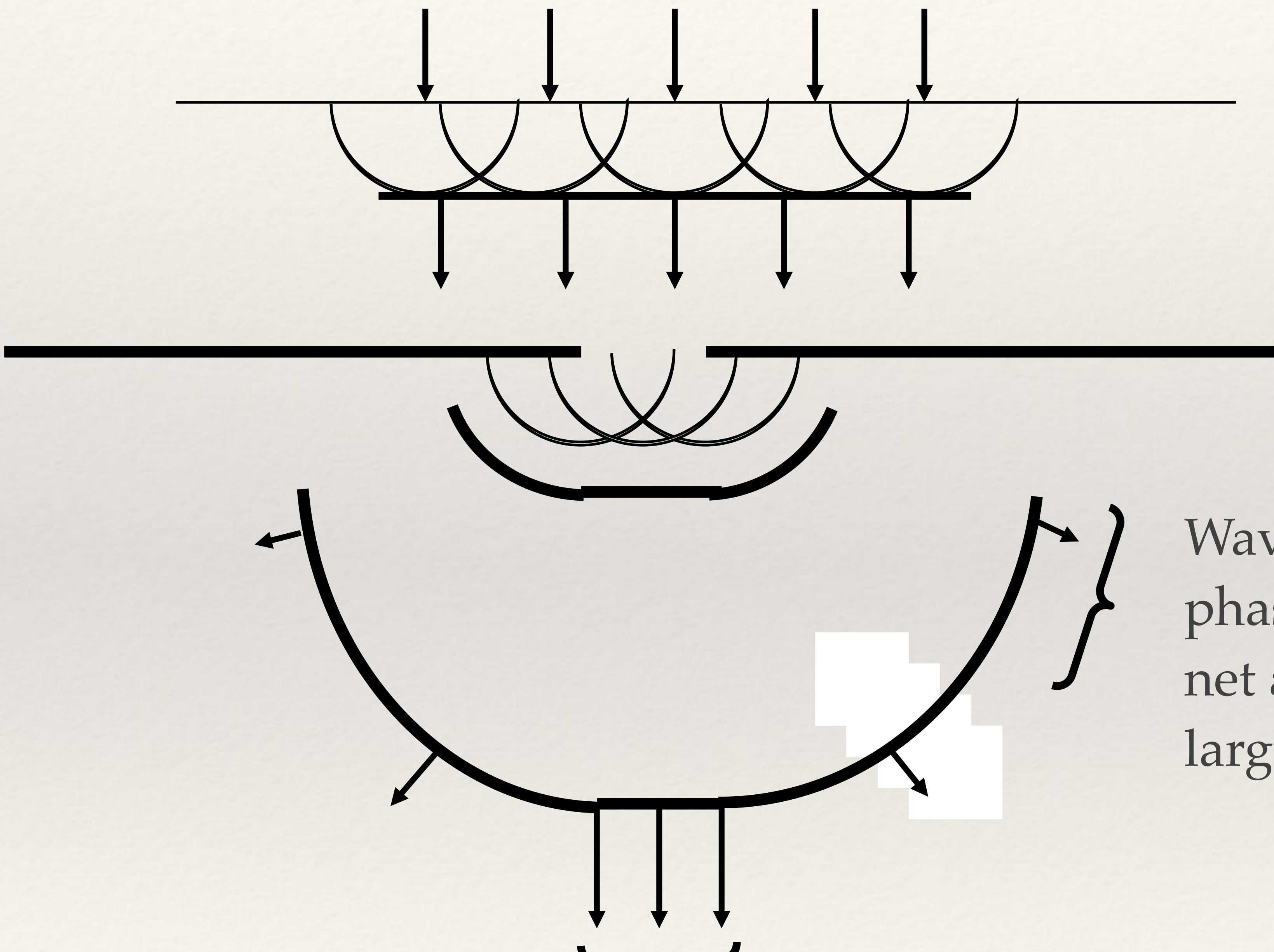
Every stellar type

Diffraction/Wavefront



Huygens wavelets

Portion of large, spherical wavefront from distant atom.

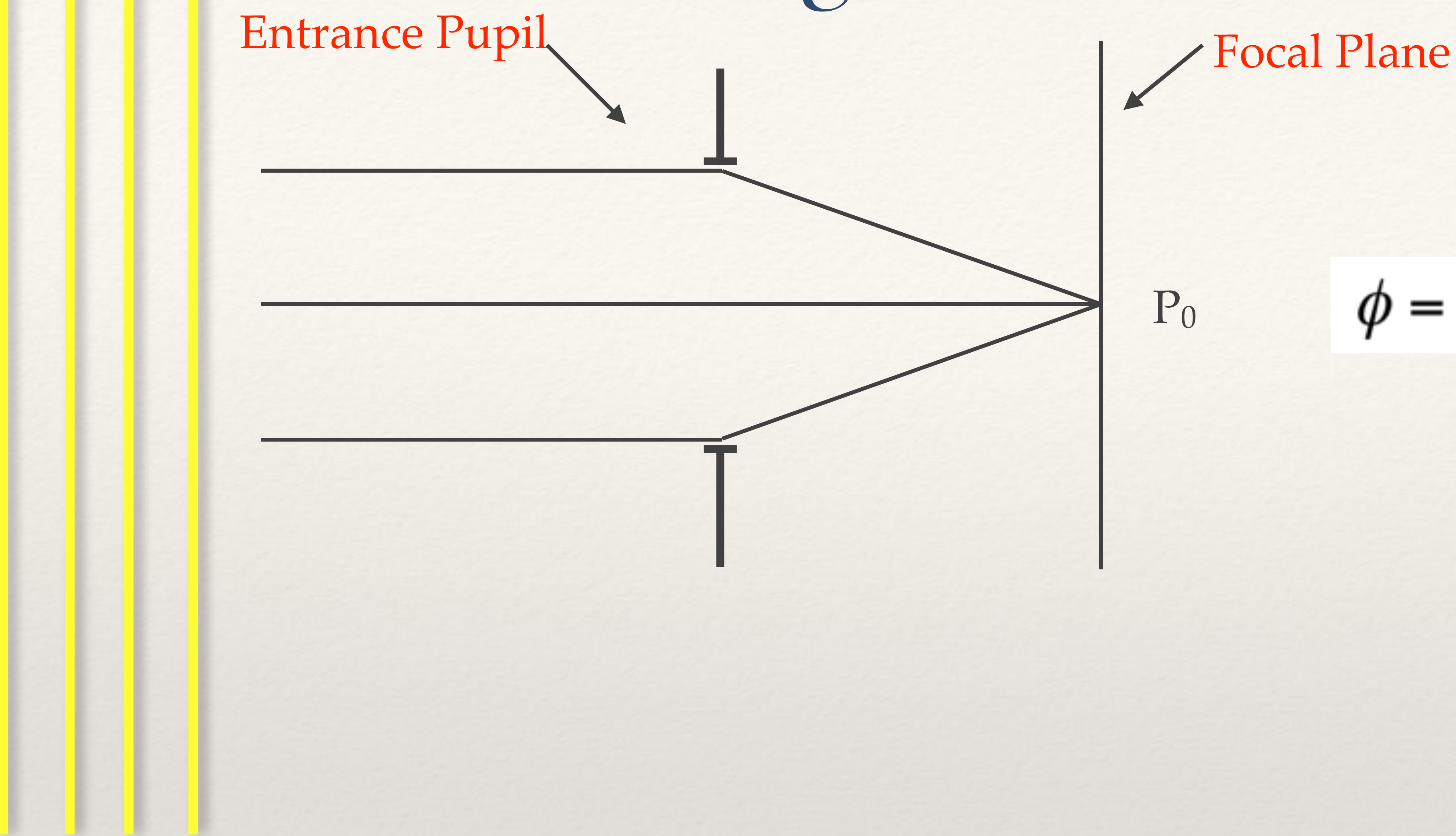


Blocking screen, with slit.

Wavelets add with various phases here, reducing the net amplitude, especially at large angles.

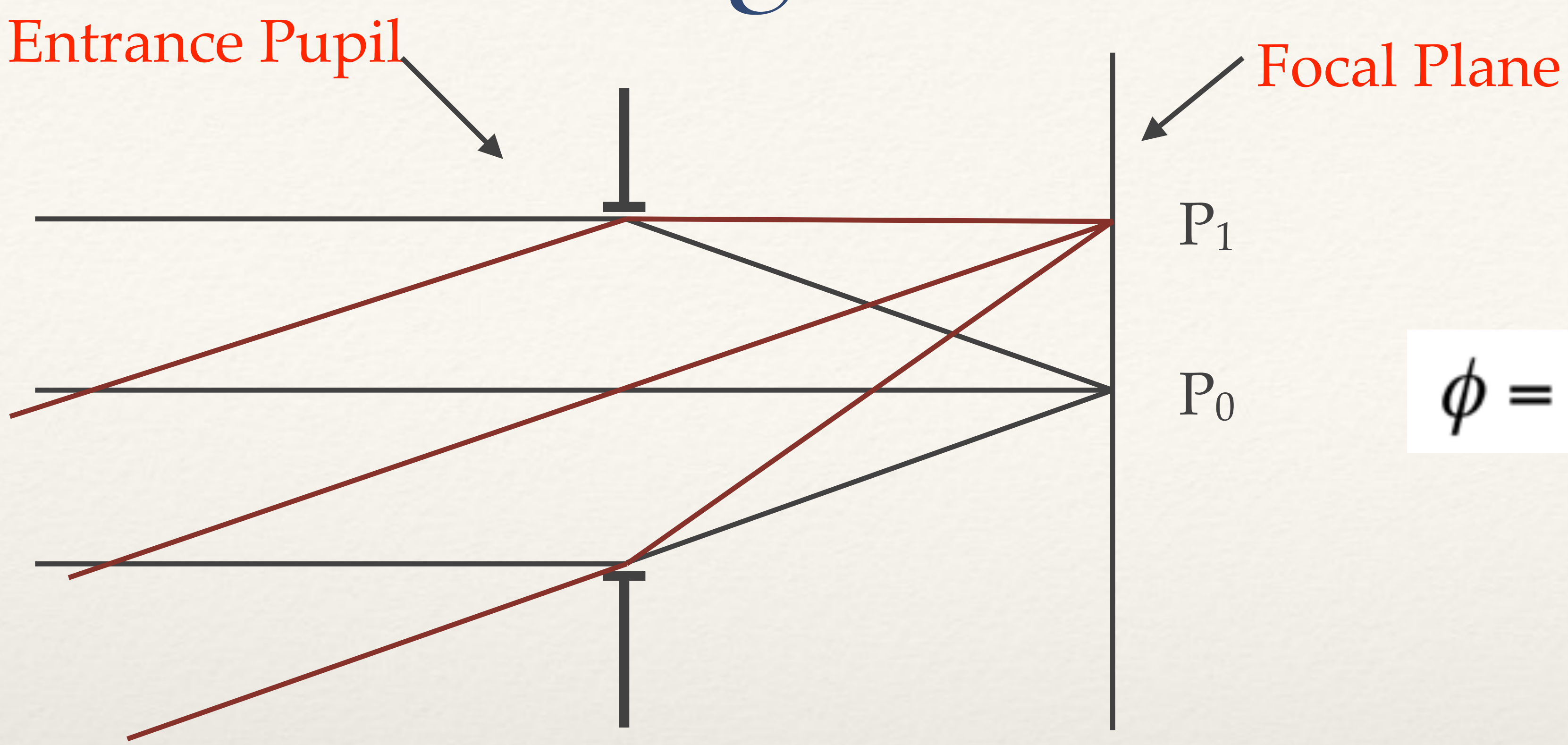
Wavelets align here, and make nearly flat wavefront, as expected from geometric optics.

Image Formation: I



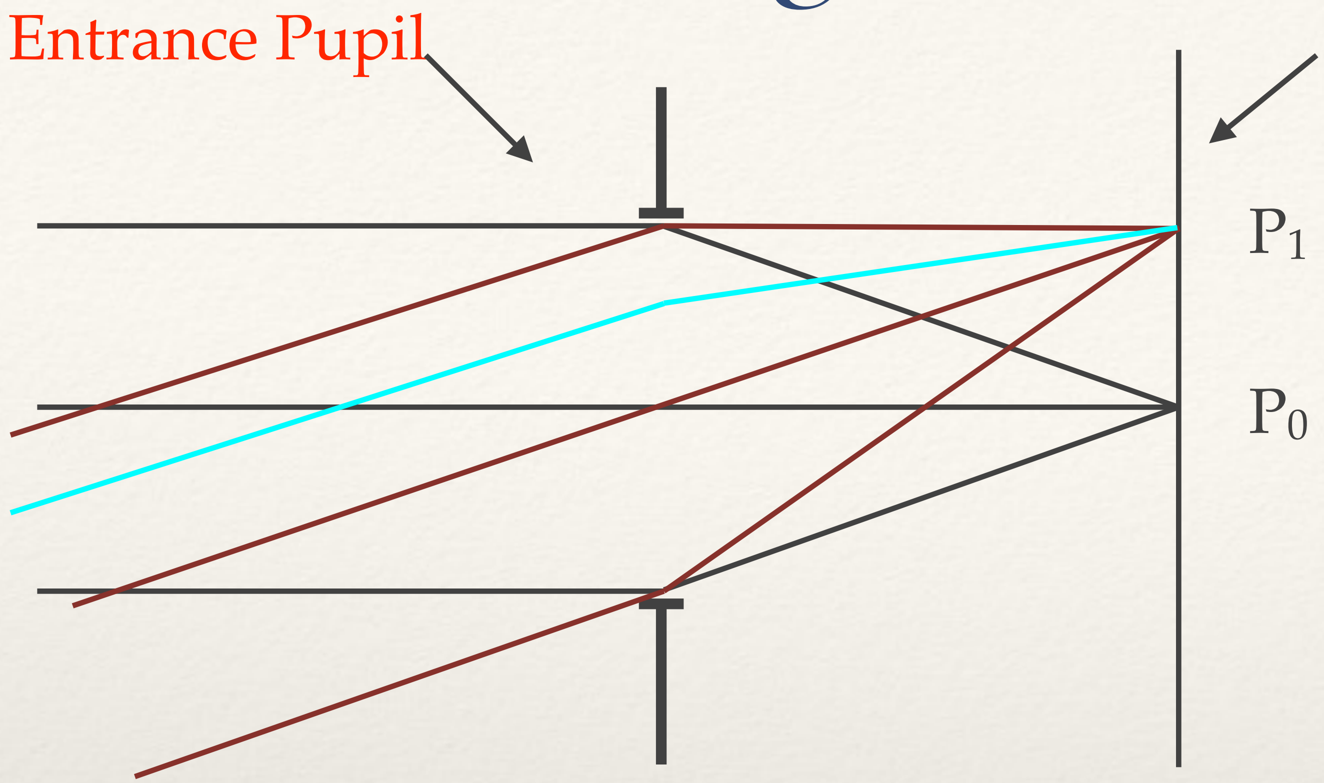
$$\phi = 0$$

Image Formation: I



$$\phi = 0$$

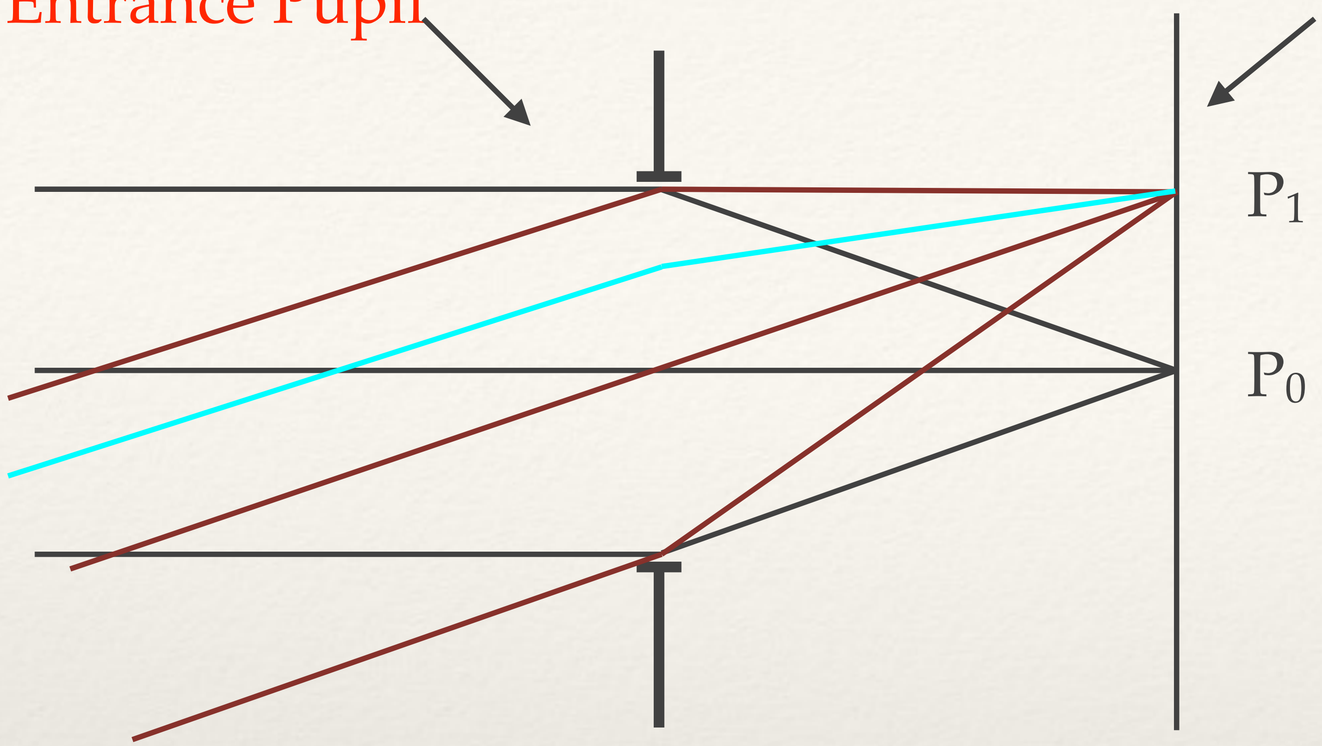
Image Formation: I



$$\phi_1(x_1) = 2\pi x_1 \sin(\theta_2) / \lambda$$

$$\phi = 0$$

Image Formation: I



$$\phi_1(x_1) = 2\pi x_1 \sin(\theta_2)/\lambda$$

$$\phi = 0$$

$$A_2(\theta_2) = \sum(wavelets) = \int_D A_1(x_1) e^{i\phi_1(x_1)} dx_1 / D$$

FRESNEL

$$\phi_1(x_1) = 2\pi x_1 \sin(\theta_2)/\lambda$$

High Order Terms
More exact but also more complicate handling

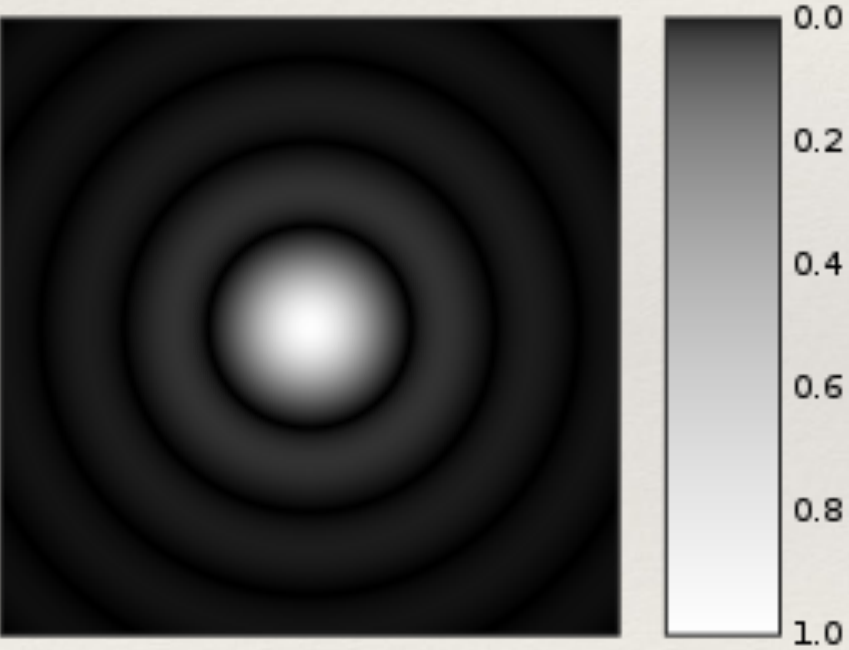
FRAUNHOFER

$$\sin\theta \sim \theta$$

Simpler Handling

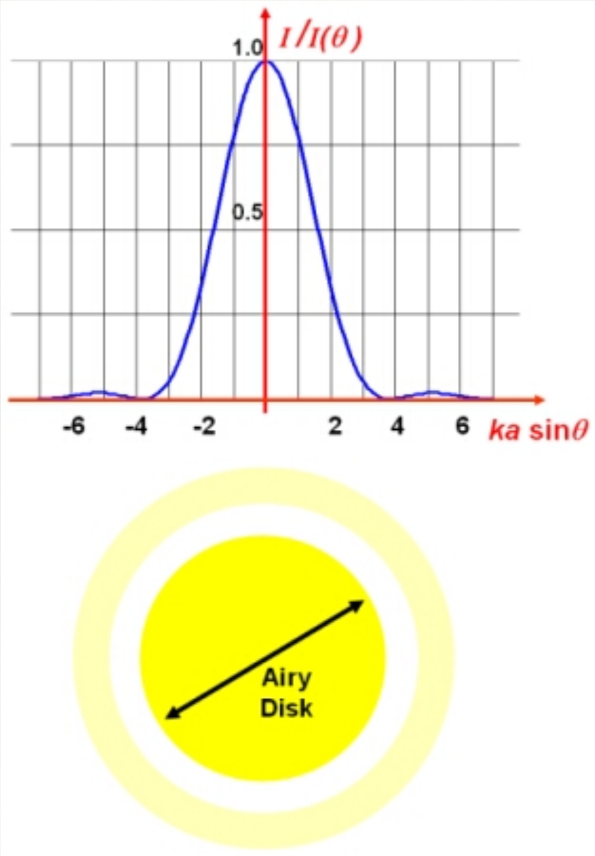
Image Formation: II

$$A_2(\theta) = \int_{-D/2}^{D/2} e^{i2\pi\theta x_1/\lambda}\, dx_1 = \frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda} D$$



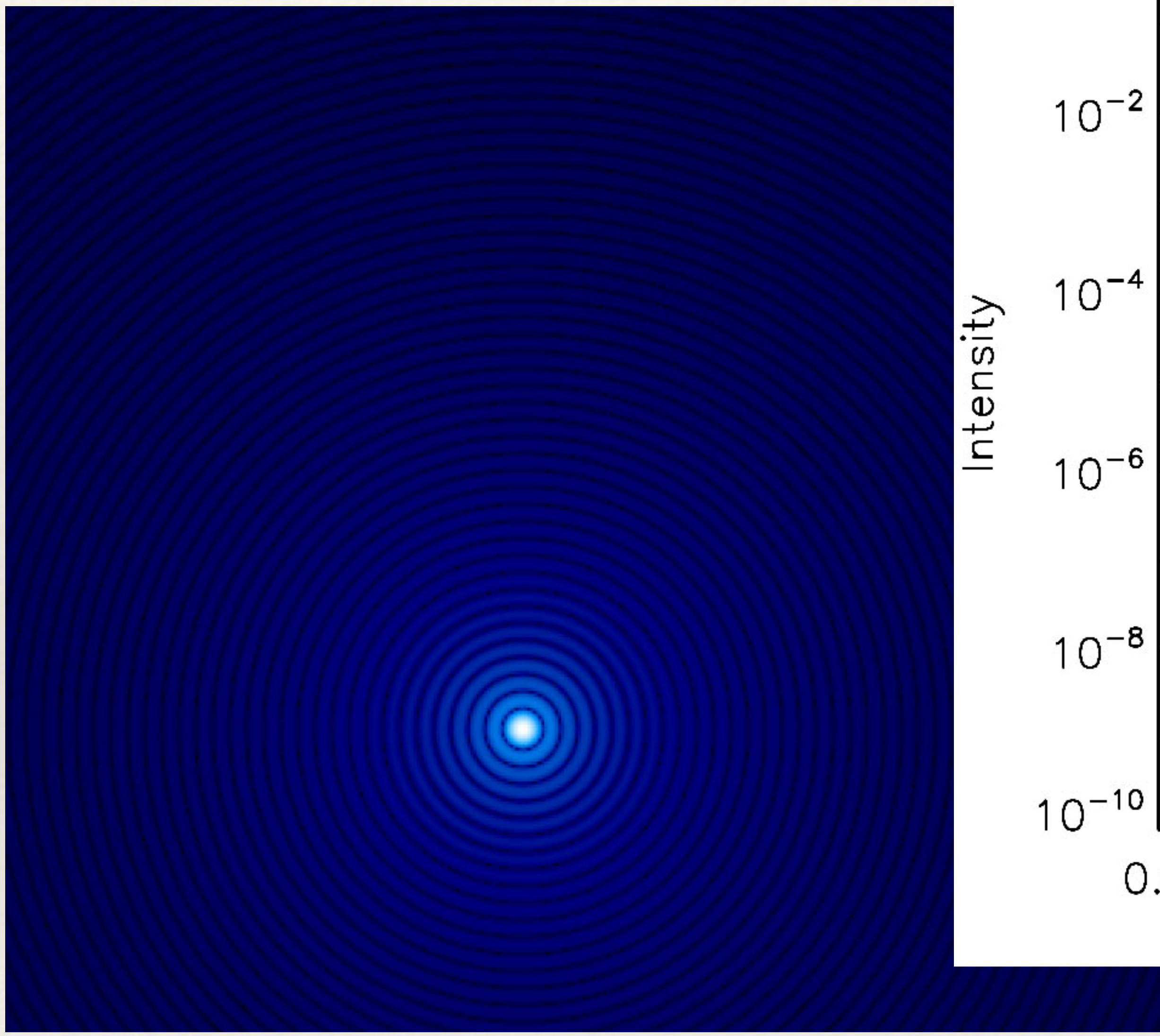
$$I_2(\theta) = \left[\frac{\sin(\pi\theta D/\lambda)}{\pi\theta D/\lambda}\right]^2 D^2$$

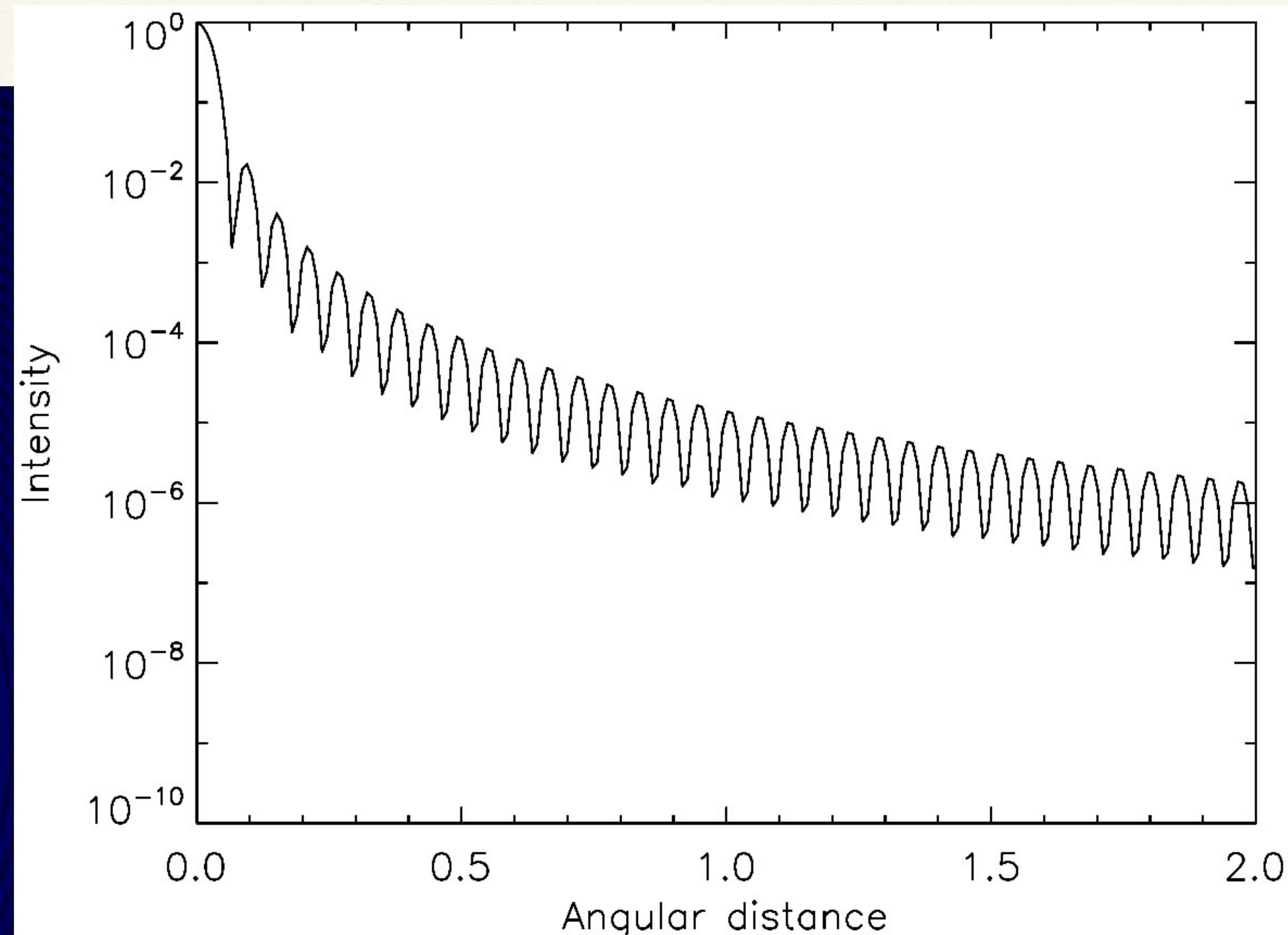
$$\theta \simeq 1.22\frac{\lambda}{D}$$



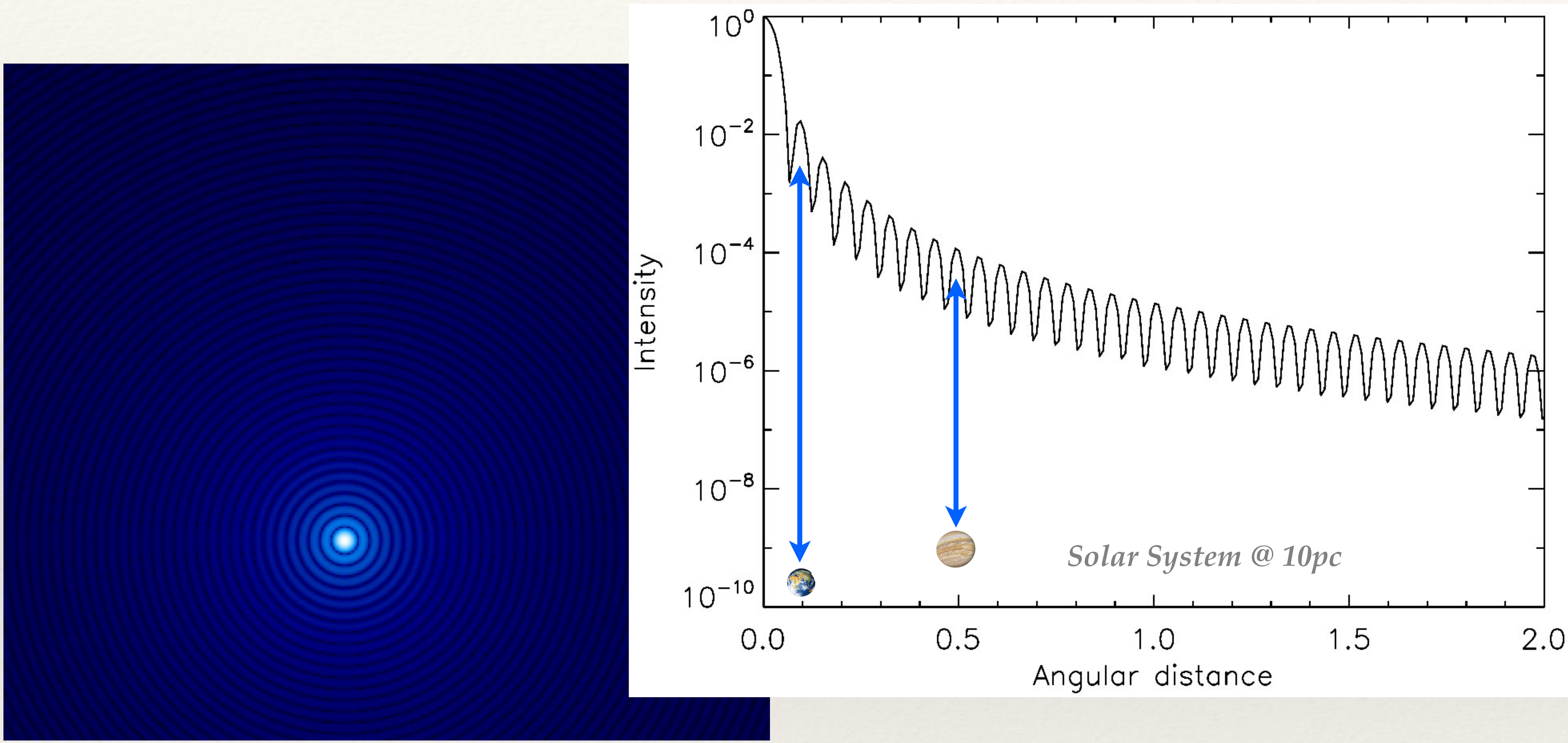
Diffraction

Diffraction

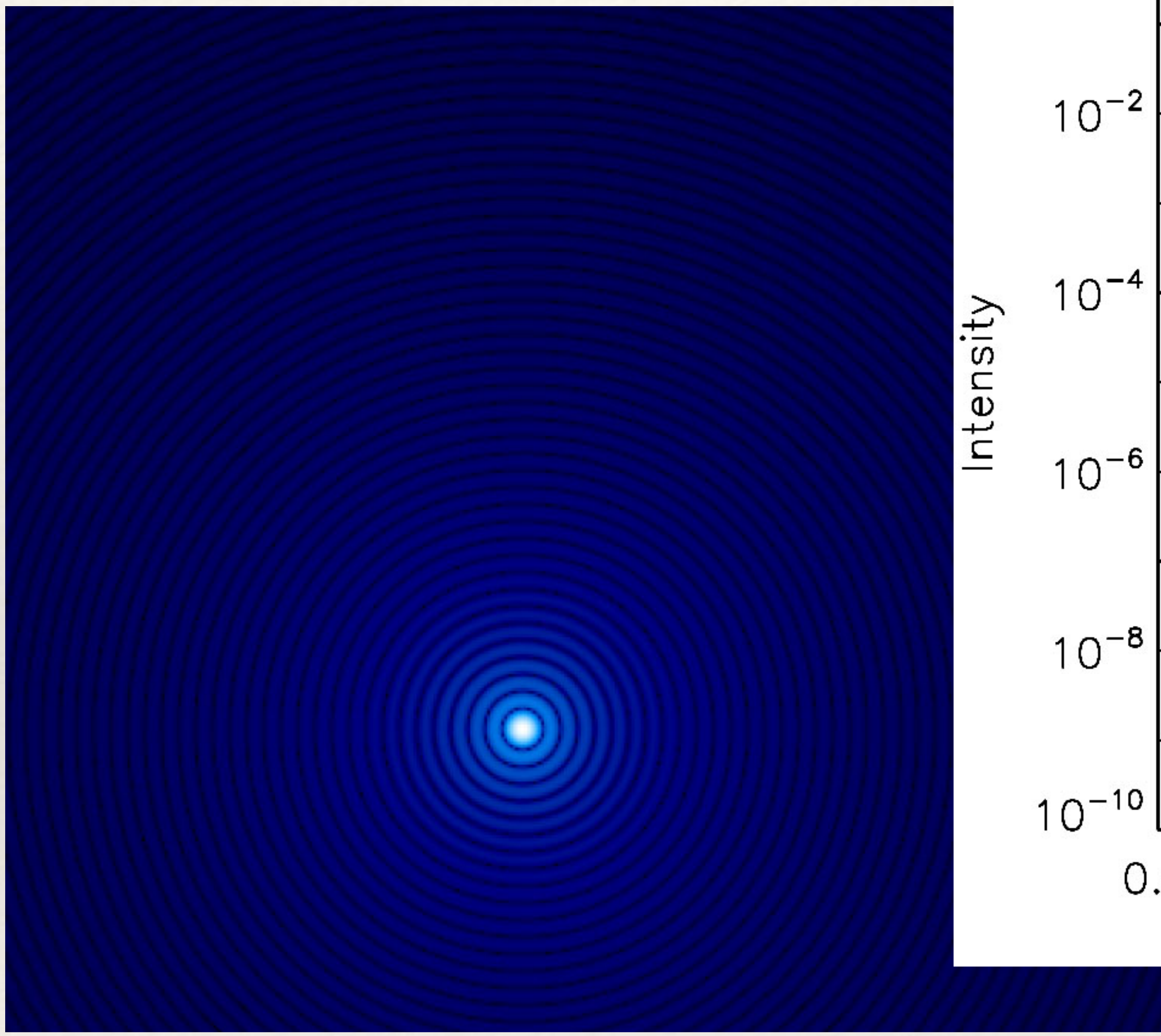


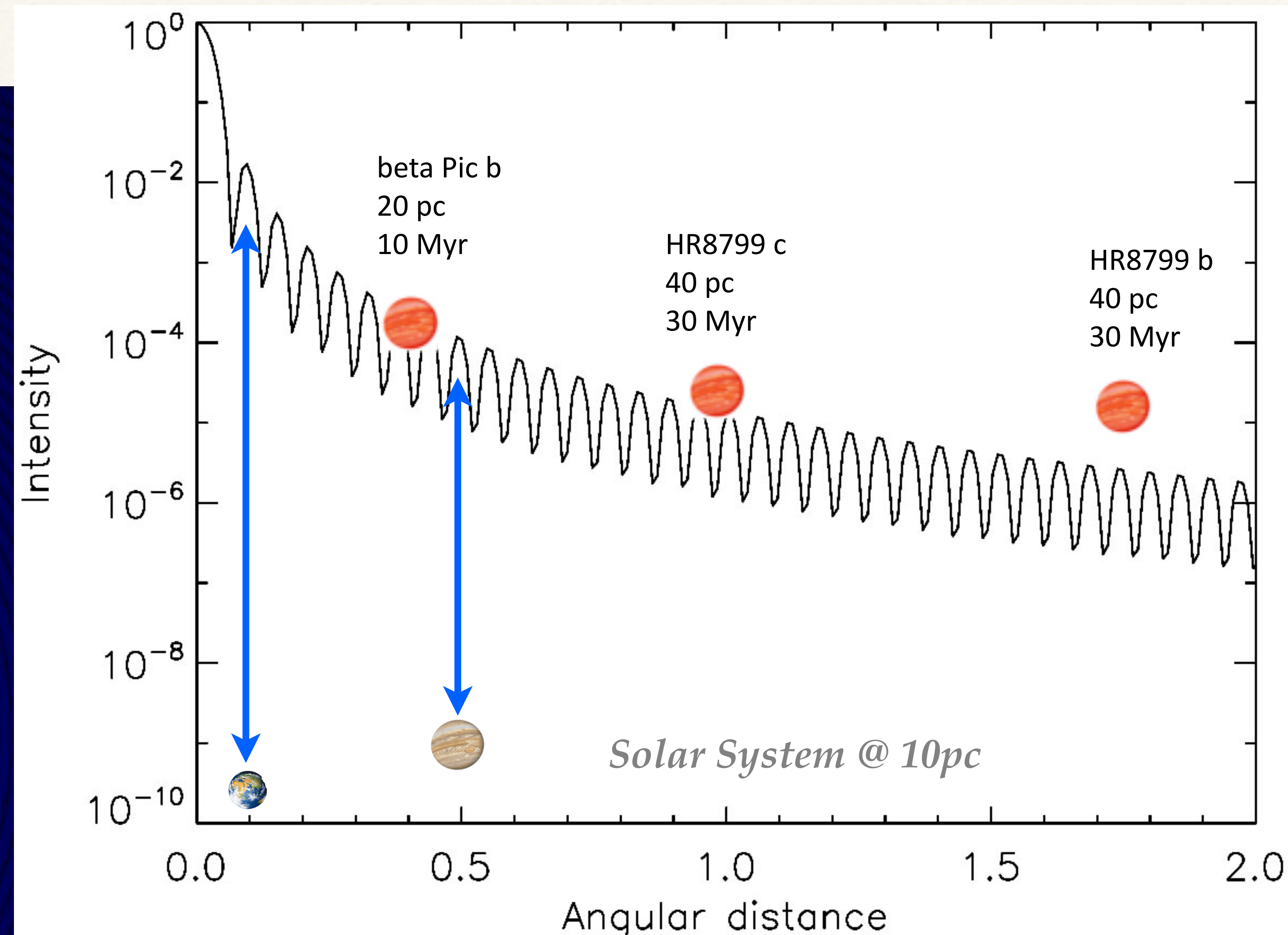


Diffraction



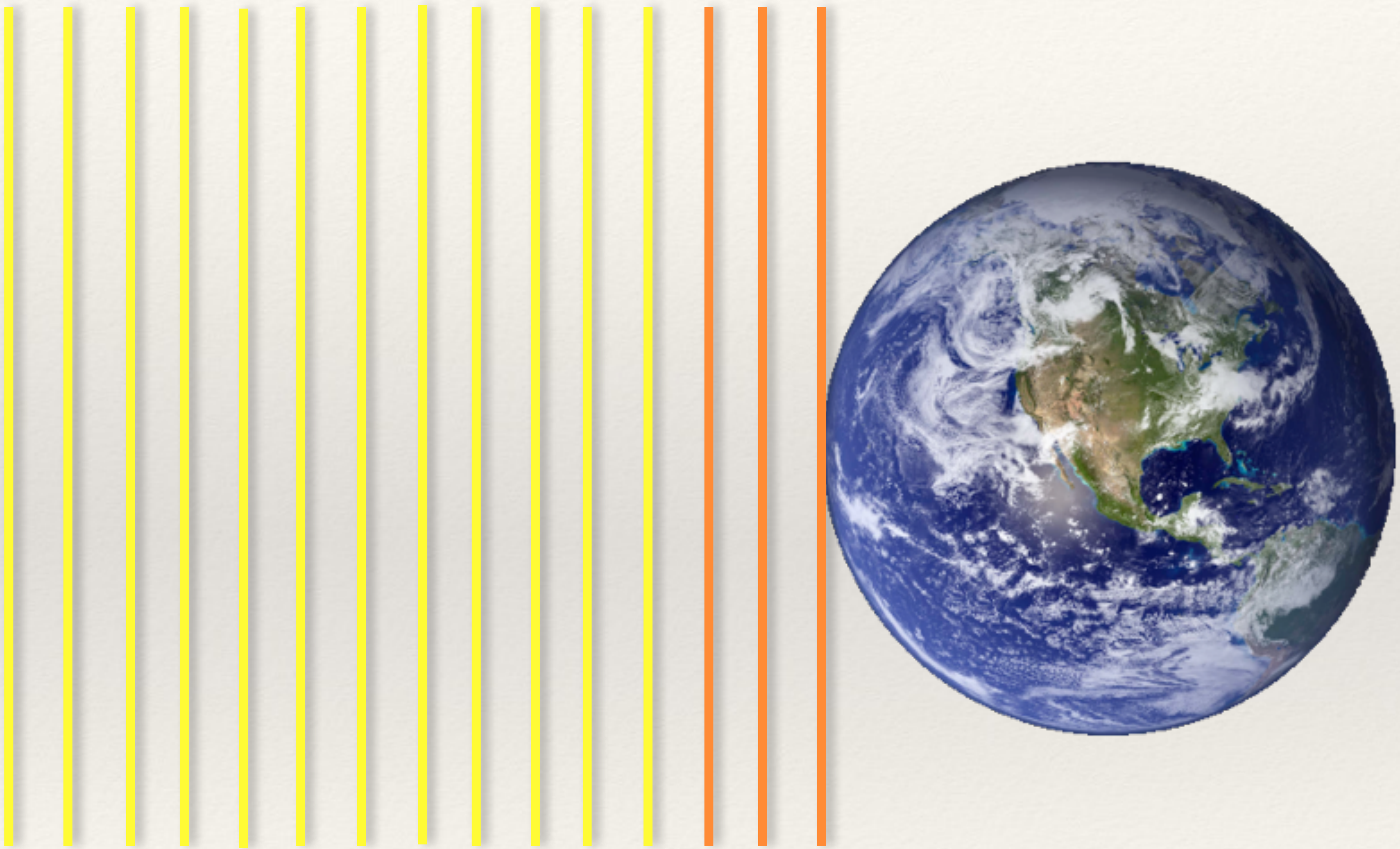
Diffraction





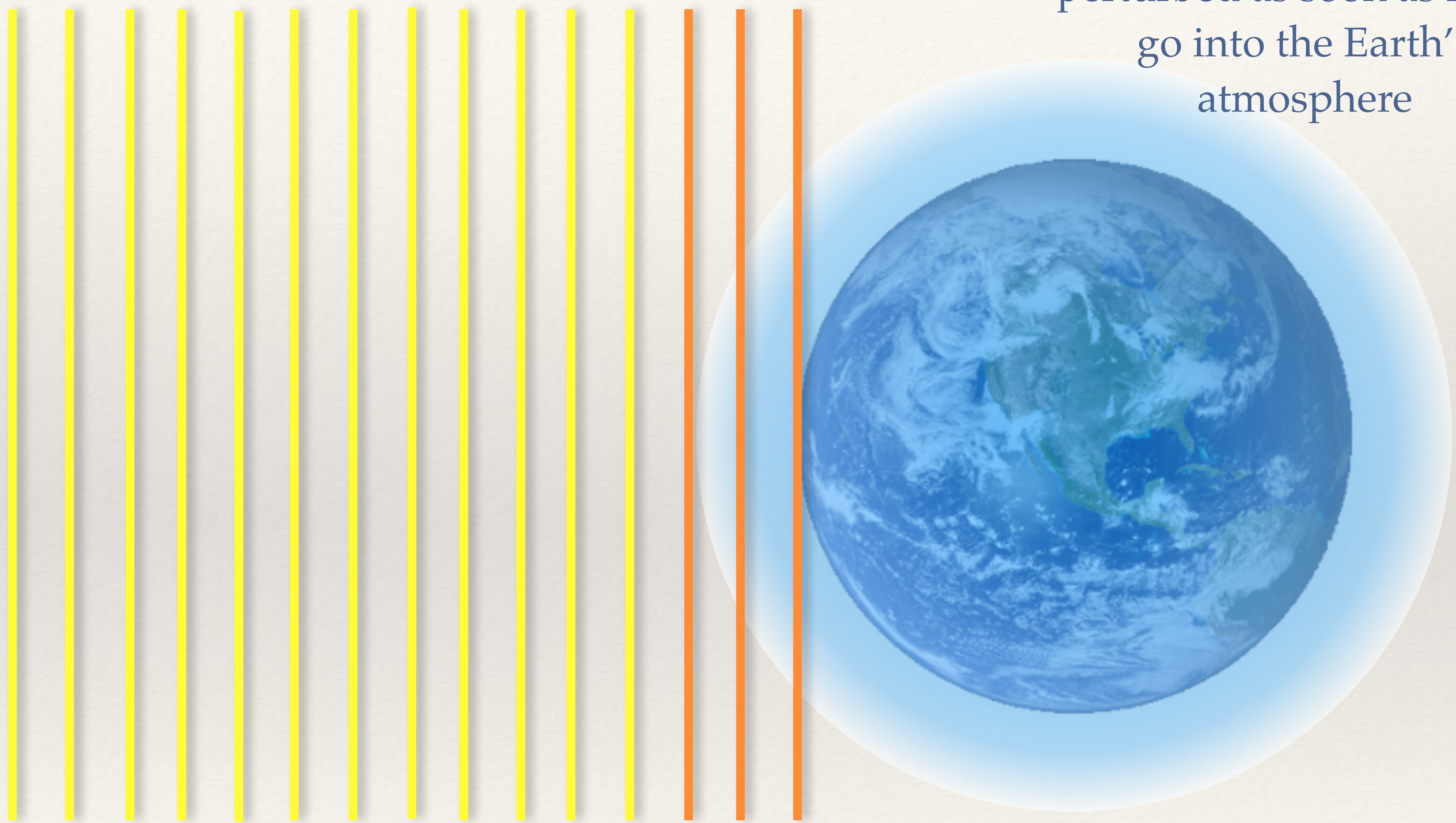
Atmospheric Turbulence

Atmospheric Turbulence



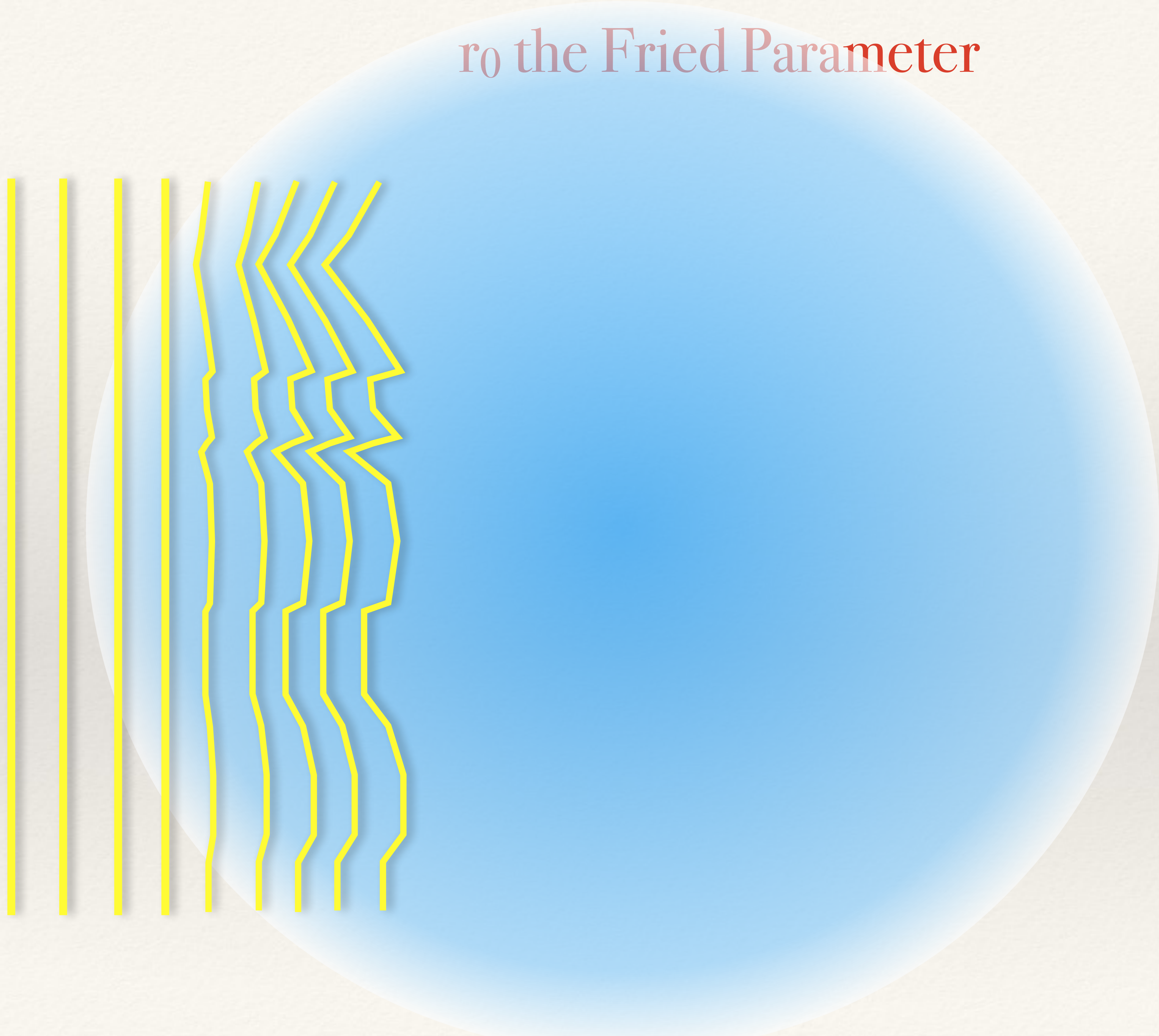
Atmospheric Turbulence

The wavefront will be perturbed as soon as it will go into the Earth's atmosphere



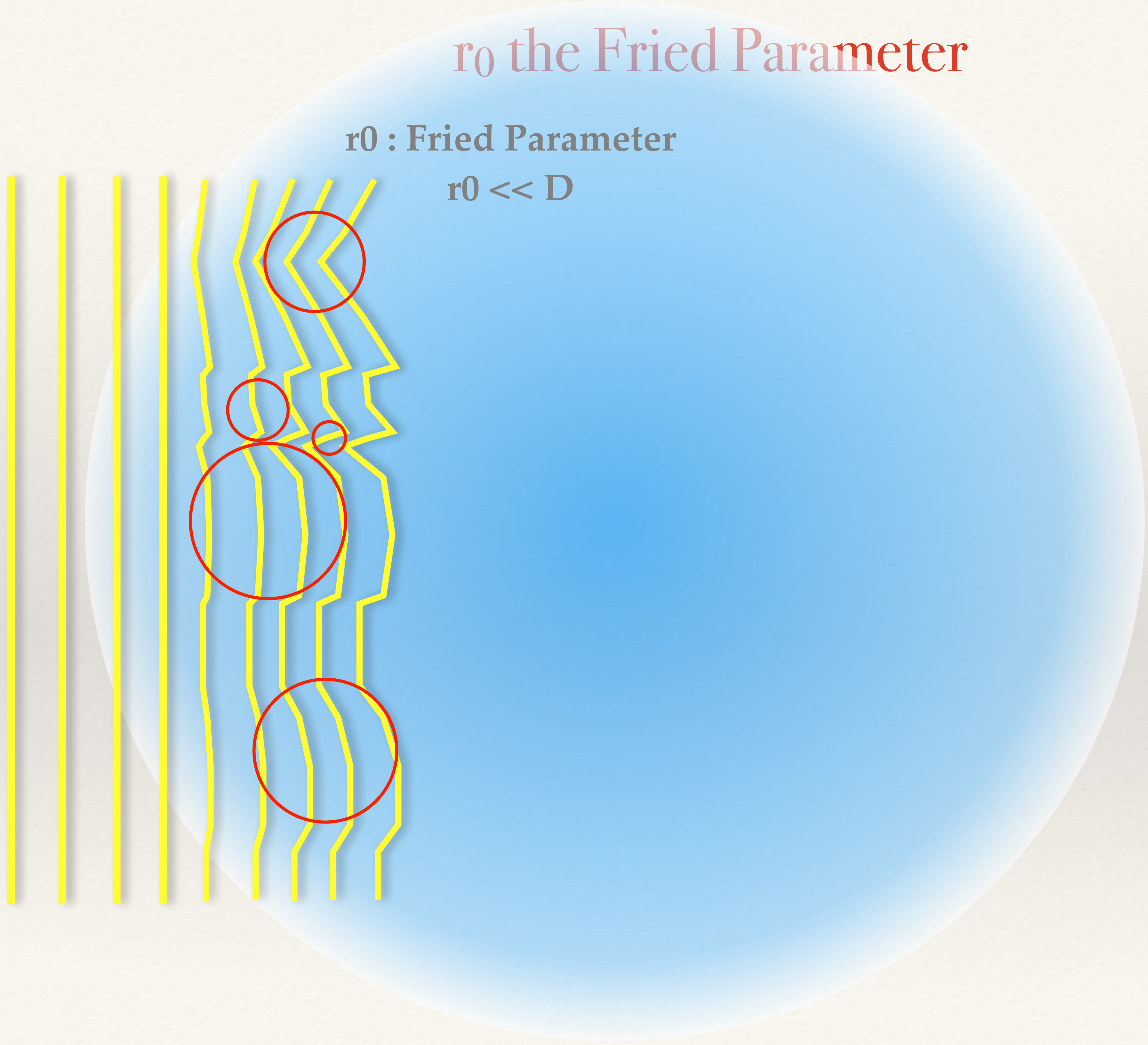
Atmospheric Turbulence:

r_0 the Fried Parameter



Atmospheric Turbulence:

r_0 the Fried Parameter

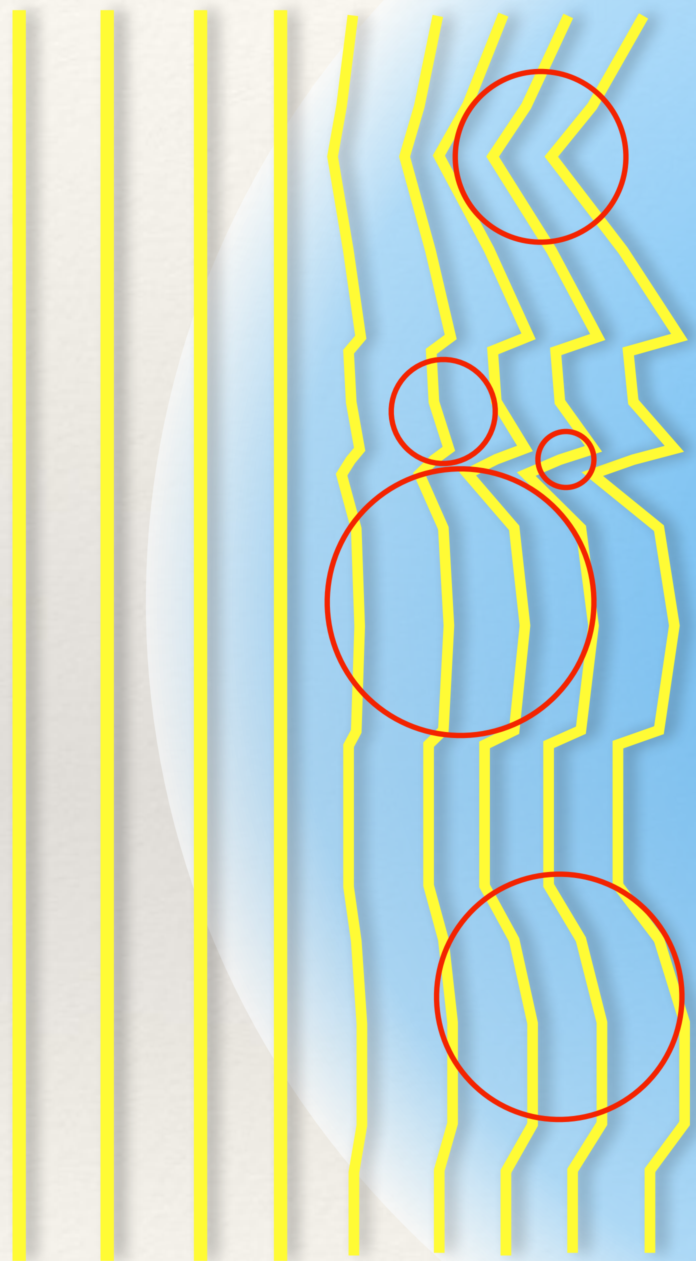


Atmospheric Turbulence:

r_0 the Fried Parameter

r0 : Fried Parameter

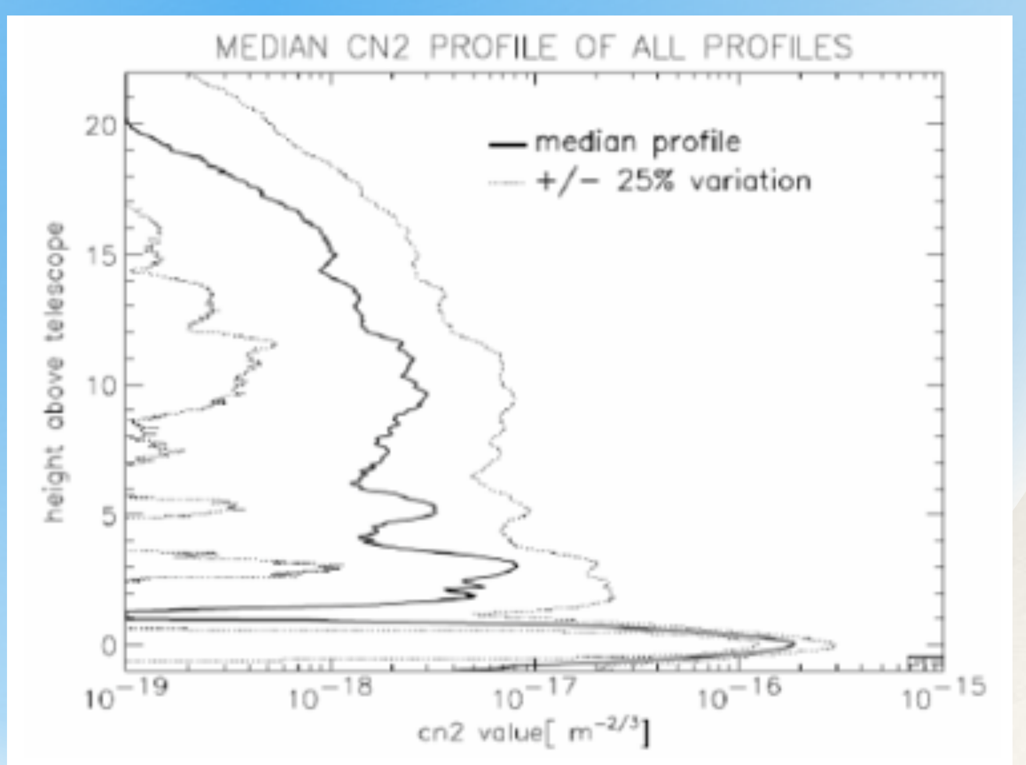
r0 << D



Zenith Angle: 0 to the Zenit, π/2 to the Horizon

$$r_0 \propto \left[\lambda^{-2}(\cos\gamma)^{-1}\int C_n^2(z)\,dz\right]^{-3/5}$$

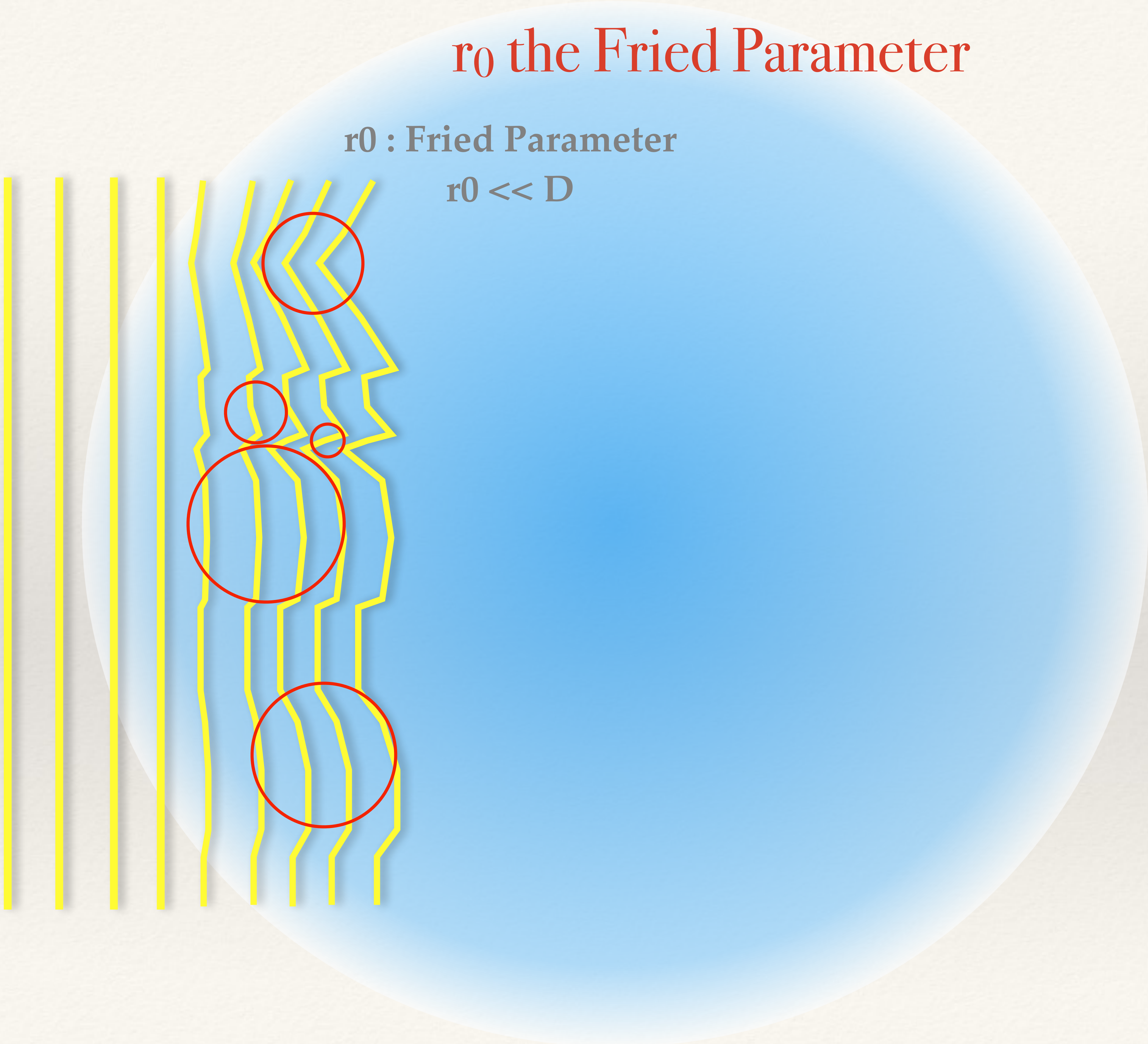
Refractive index structure constant



r_0~10cm

Atmospheric Turbulence:

r_0 the Fried Parameter

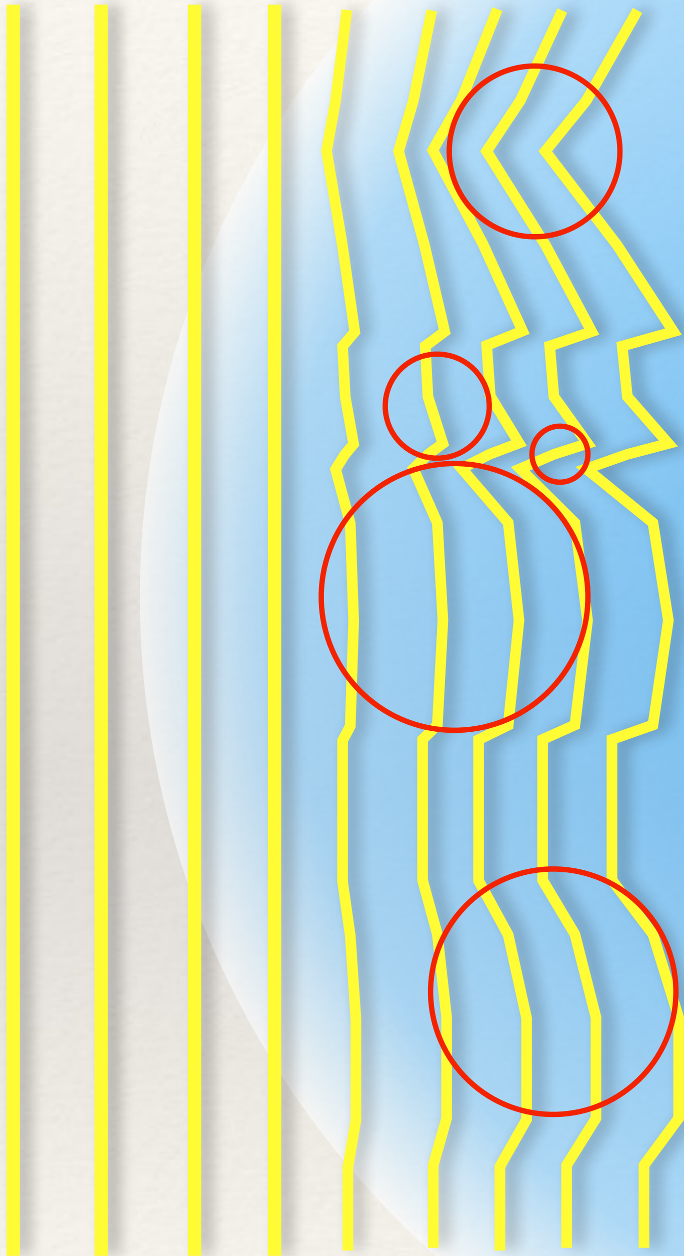


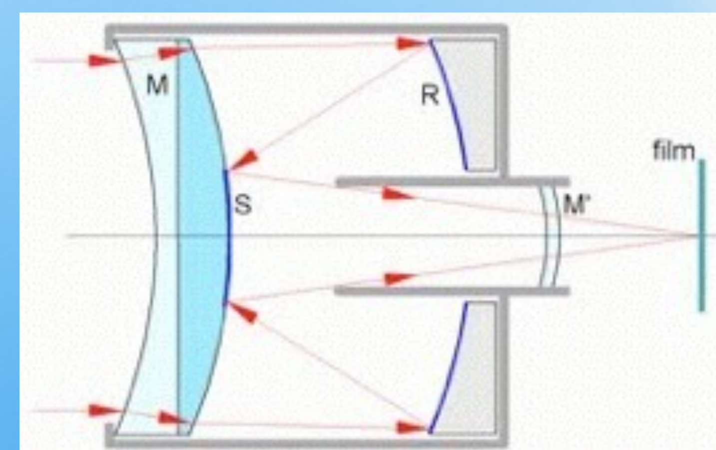
Atmospheric Turbulence:

r_0 the Fried Parameter

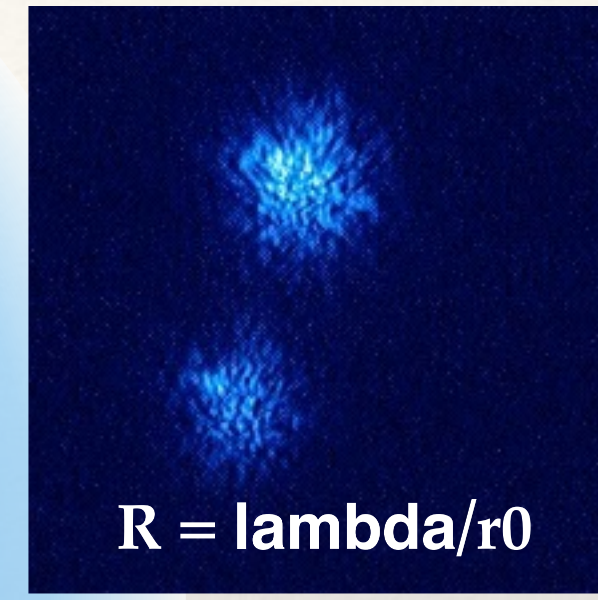
r0 : Fried Parameter

r0 << D





Speckles Formation

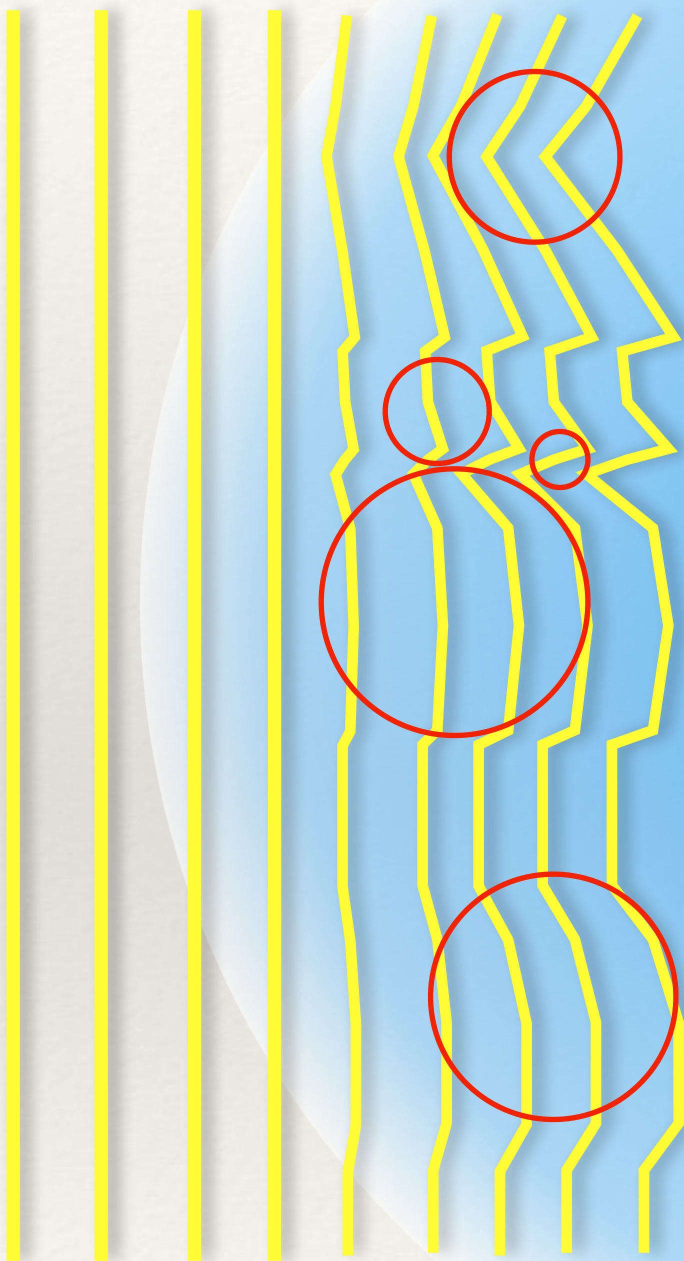


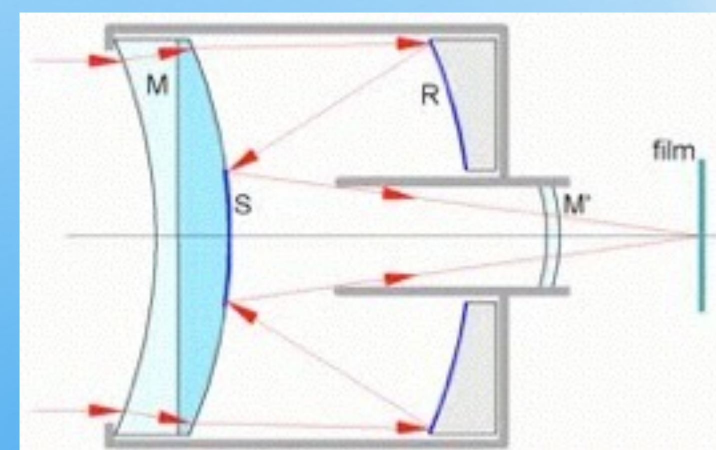
Atmospheric Turbulence:

r_0 the Fried Parameter

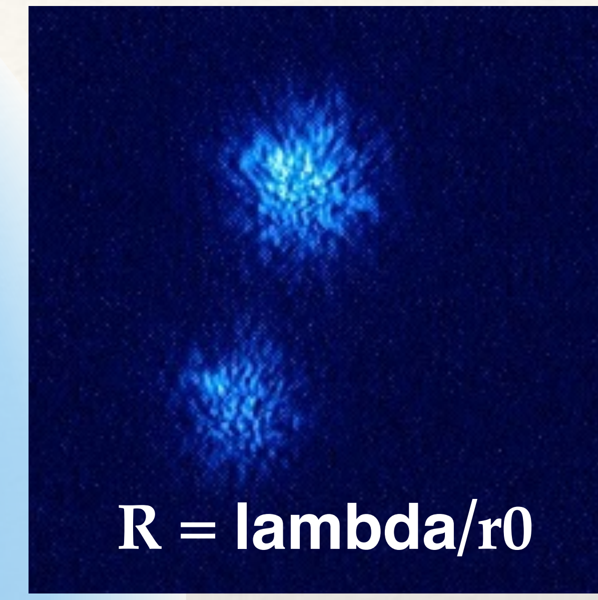
r0 : Fried Parameter

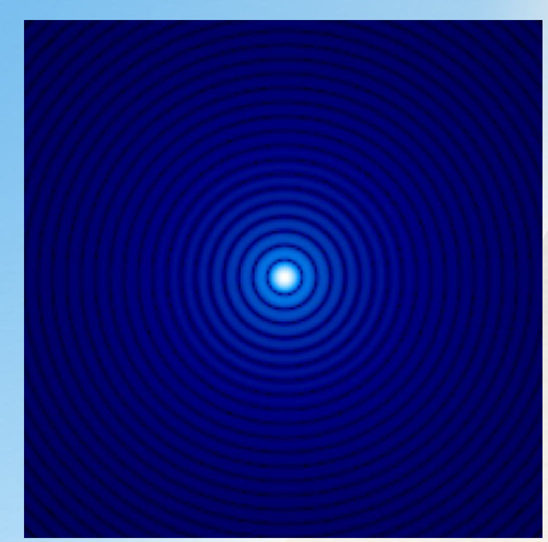
r0 << D





Speckles Formation



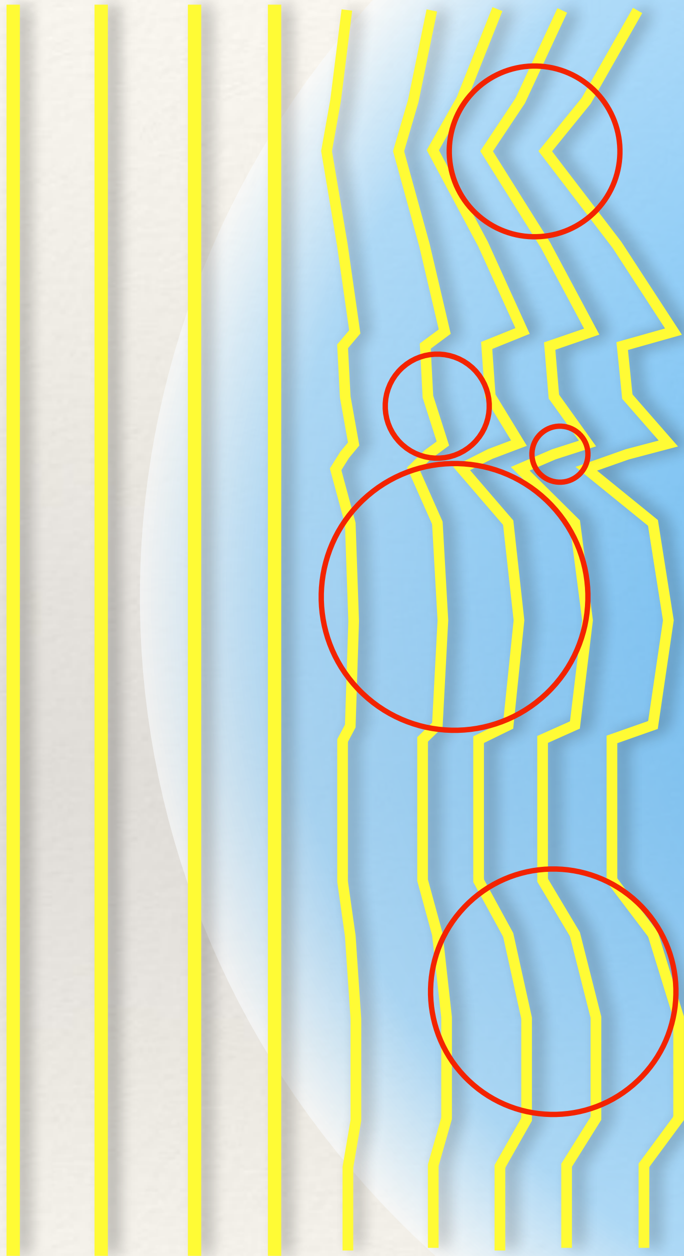


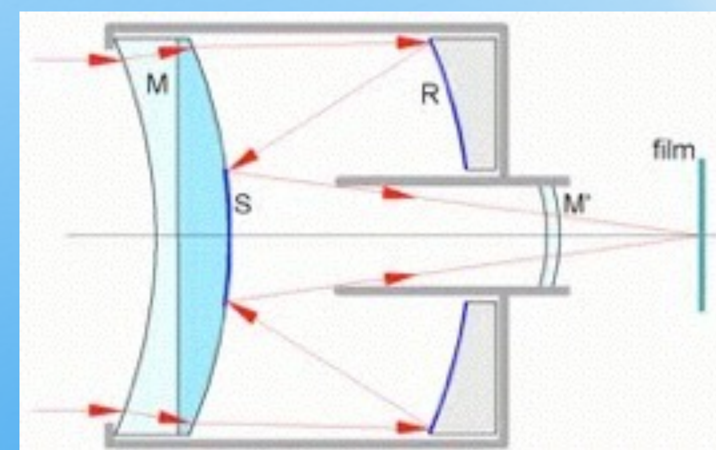
Atmospheric Turbulence:

r_0 the Fried Parameter

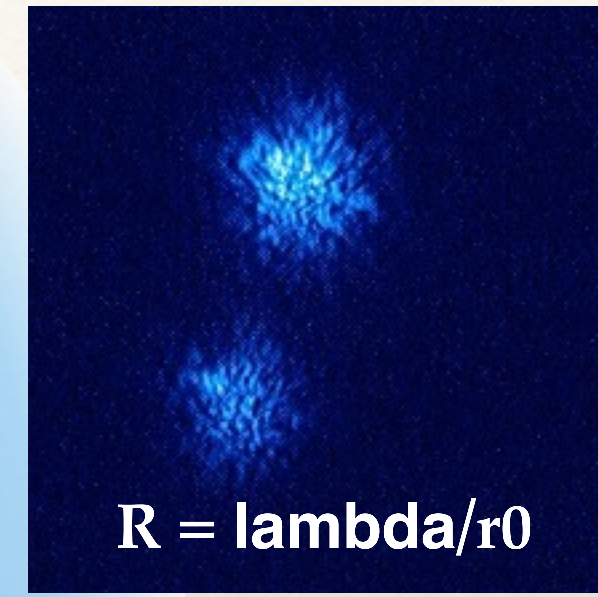
r0 : Fried Parameter

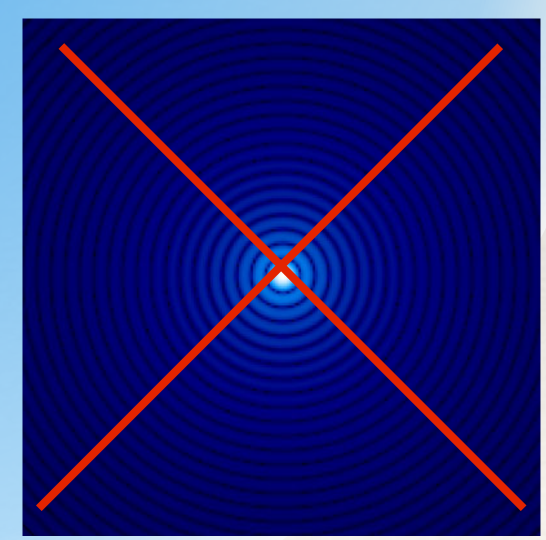
r0 << D





Speckles Formation





Speckles Formation

…suppose that the wavefront incident on telescope is advanced by a phase step ϕ/2 on one half of the pupil and delayed by ϕ/2 on the other half, the electric field amplitude will be given by:

$$A_2(\theta) = \int_0^{+D/2} e^{+i\phi/2} e^{i2\pi x_1\theta/\lambda}\, dx + \int_{-D/2}^{0} e^{-i\phi/2} e^{i2\pi x_1\theta/\lambda}\, dx$$

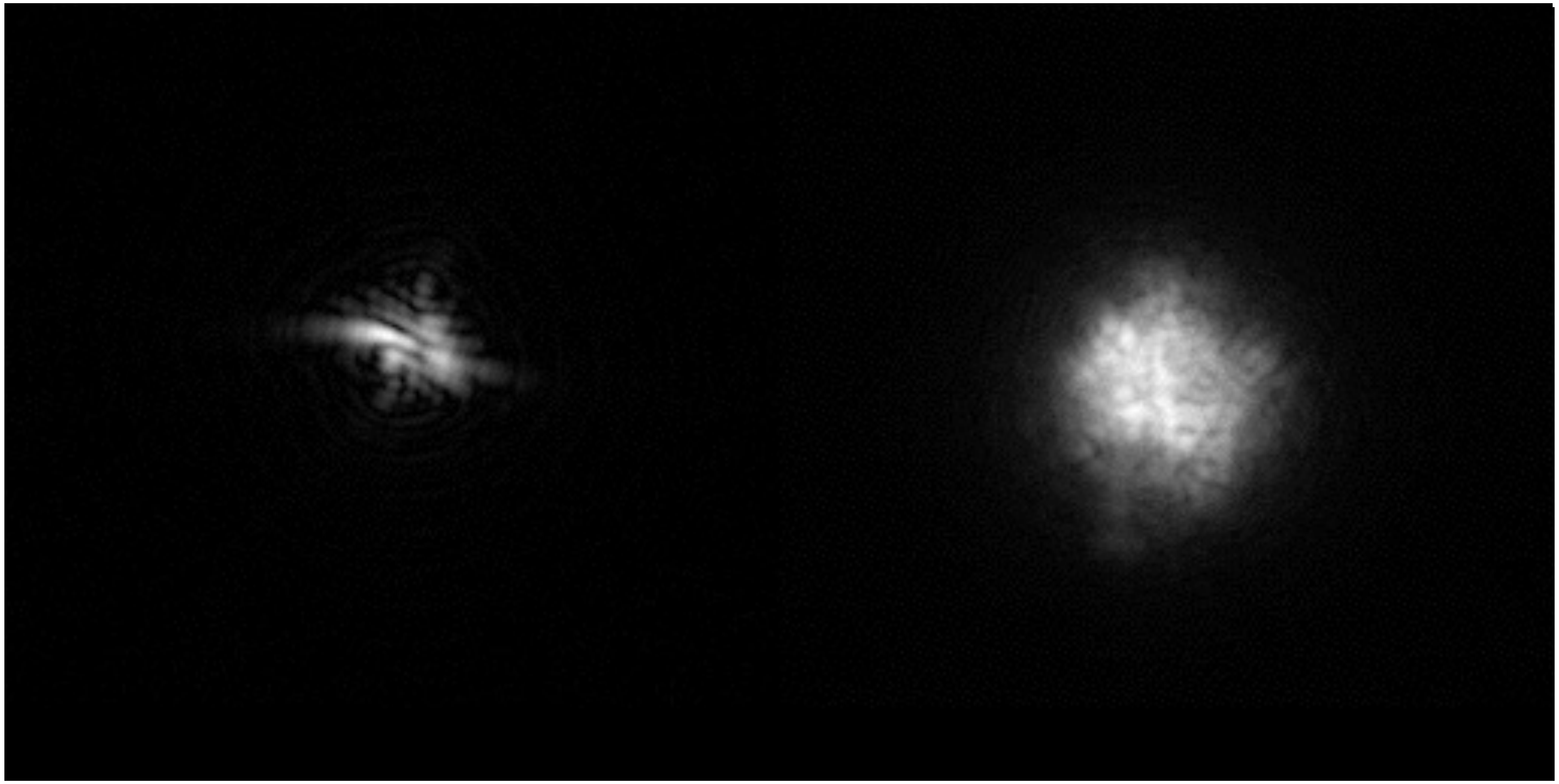
$$A_2(\theta) = \frac{\sin(\pi D\theta / 2\lambda)}{\pi D\theta / 2\lambda} \cos(\pi D\theta / 2\lambda + \phi / 2) D$$

$$A_2(\theta, \phi = \pi) = \frac{\sin^2(\pi D\theta / 2\lambda)}{\pi D\theta / 2\lambda} D$$

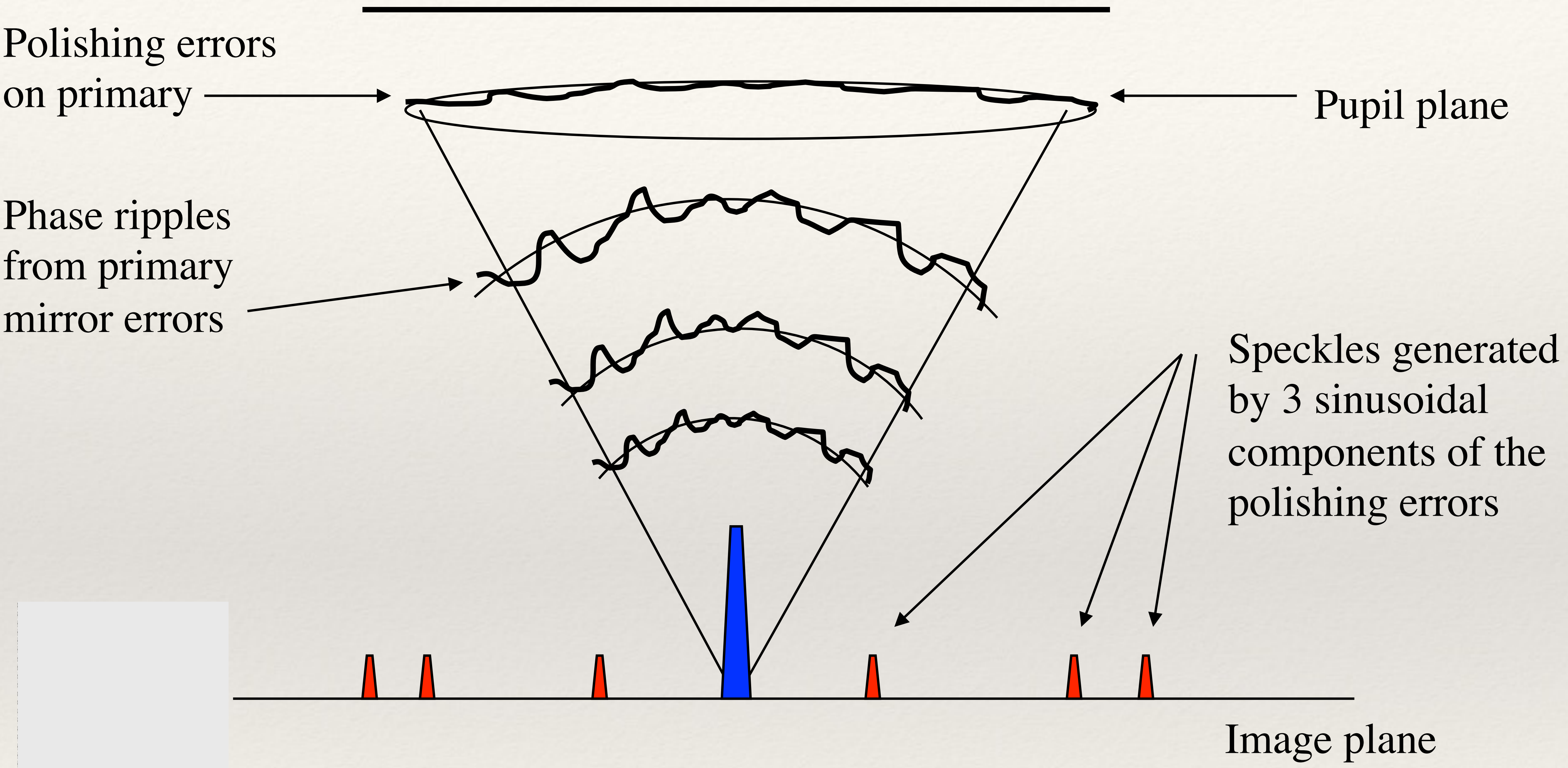
Which is a pair of peaks (speckles), each similar in width to the original peak and separated by about twice that width

Speckles

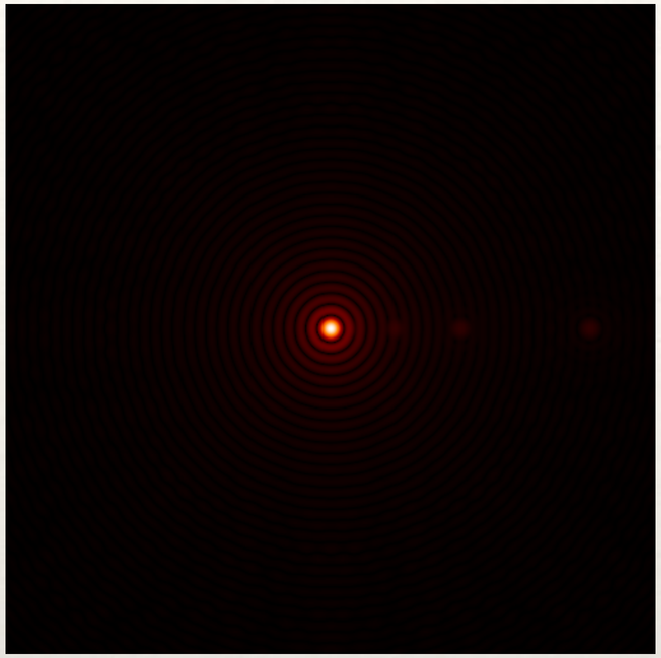
Speckles



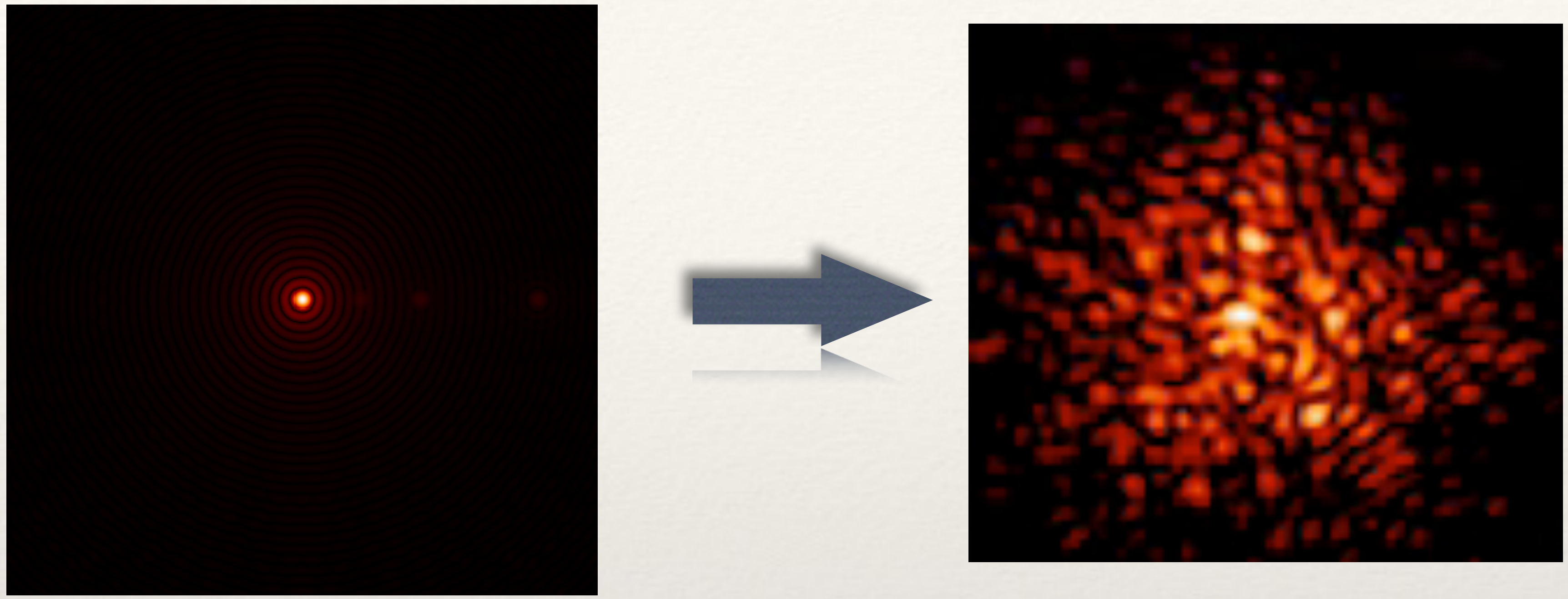
Speckles … not only from the atmosphere…



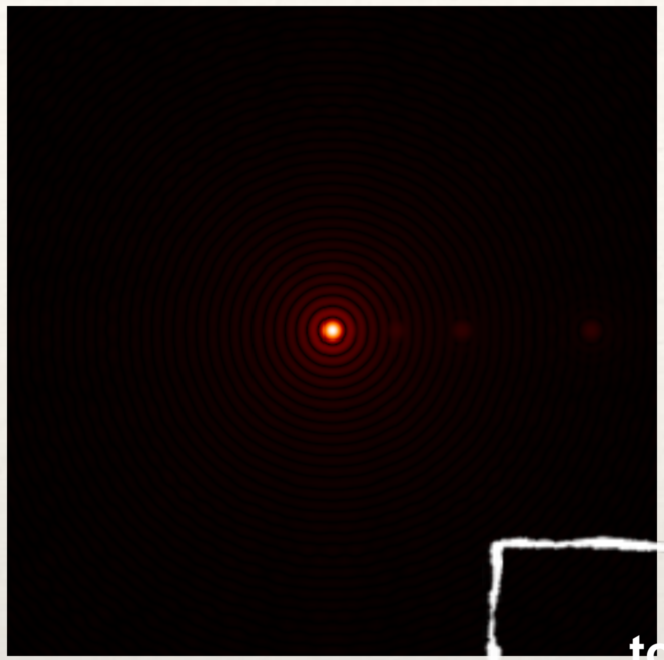
point
source

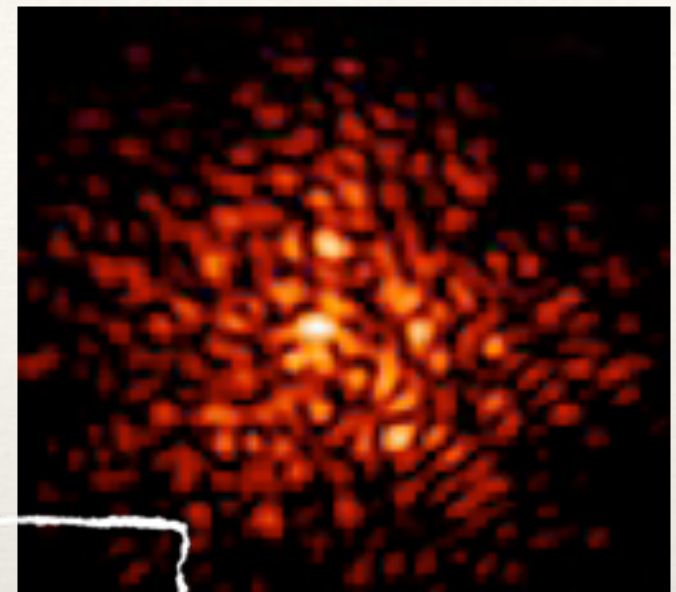


point source



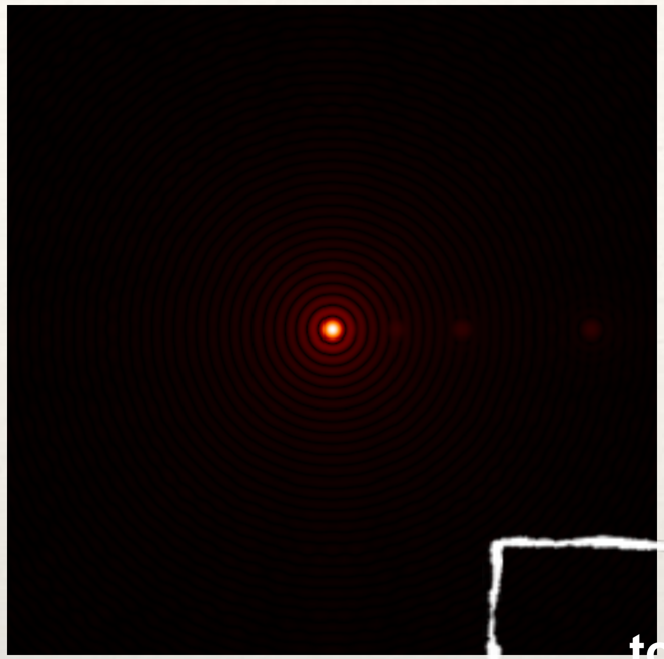
point source

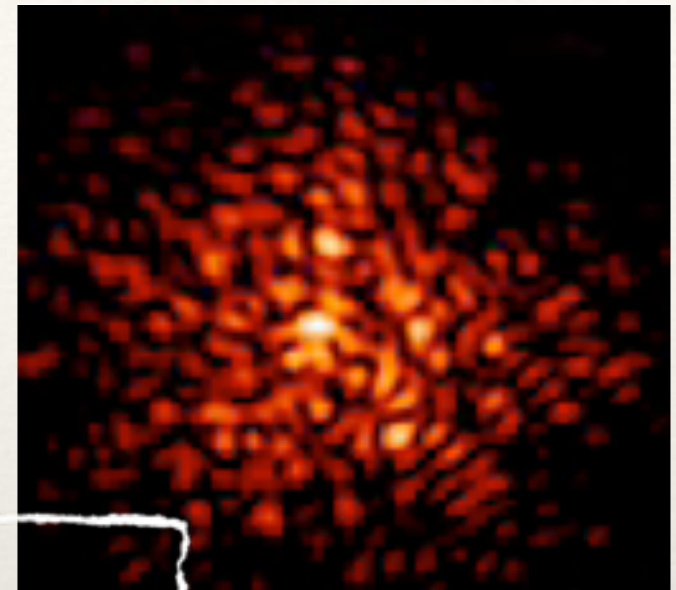




r0 is a few cm
to be compared with
telescope diameter (a few m)

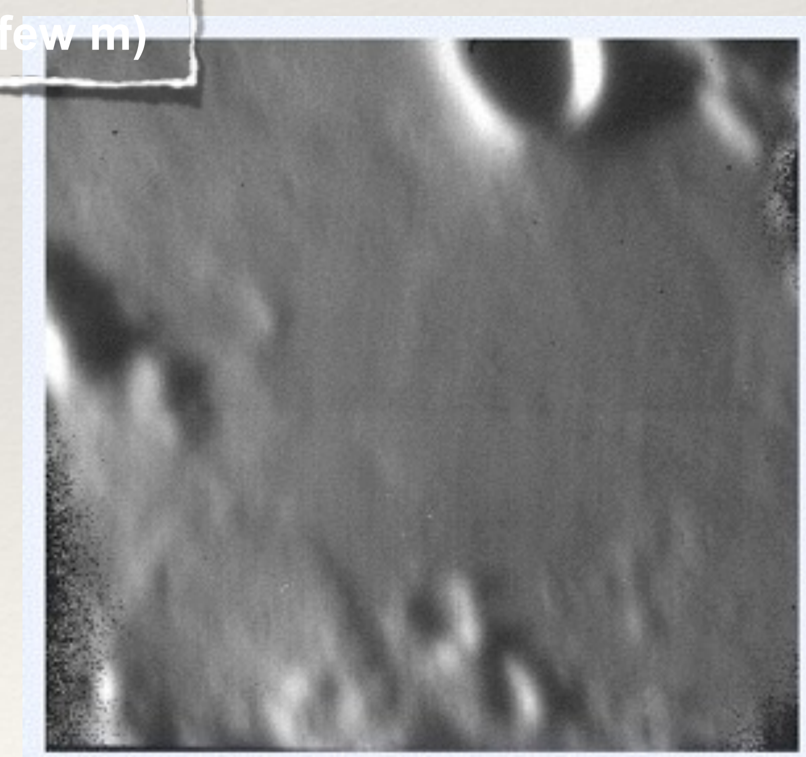
point source



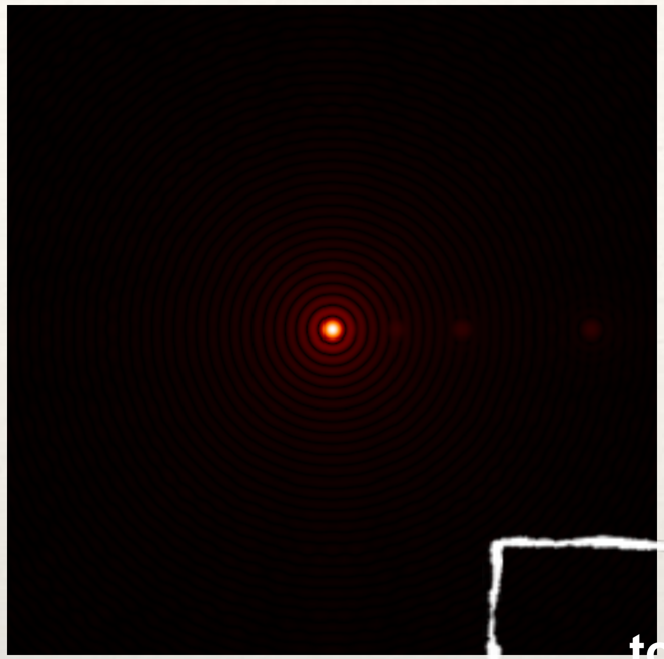


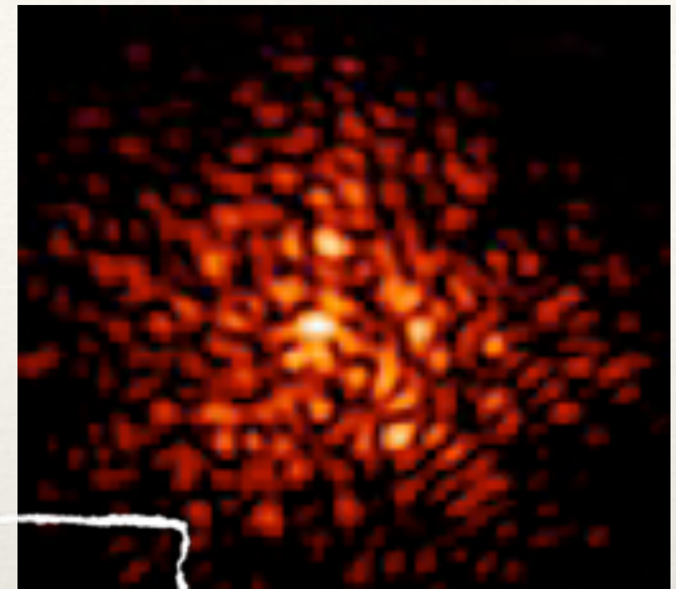
r0 is a few cm
to be compared with
telescope diameter (a few m)

extended object



point source





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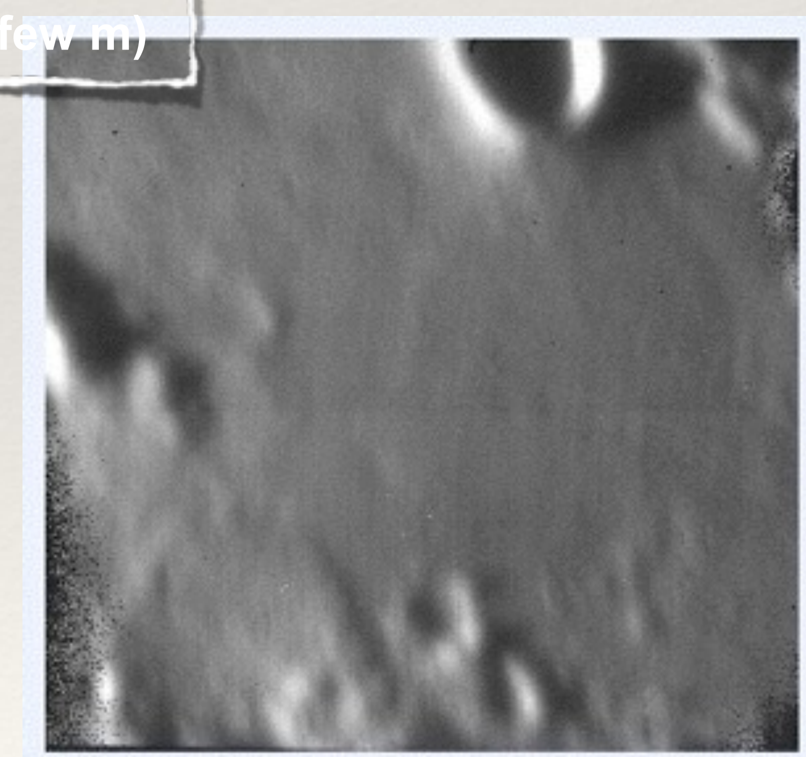
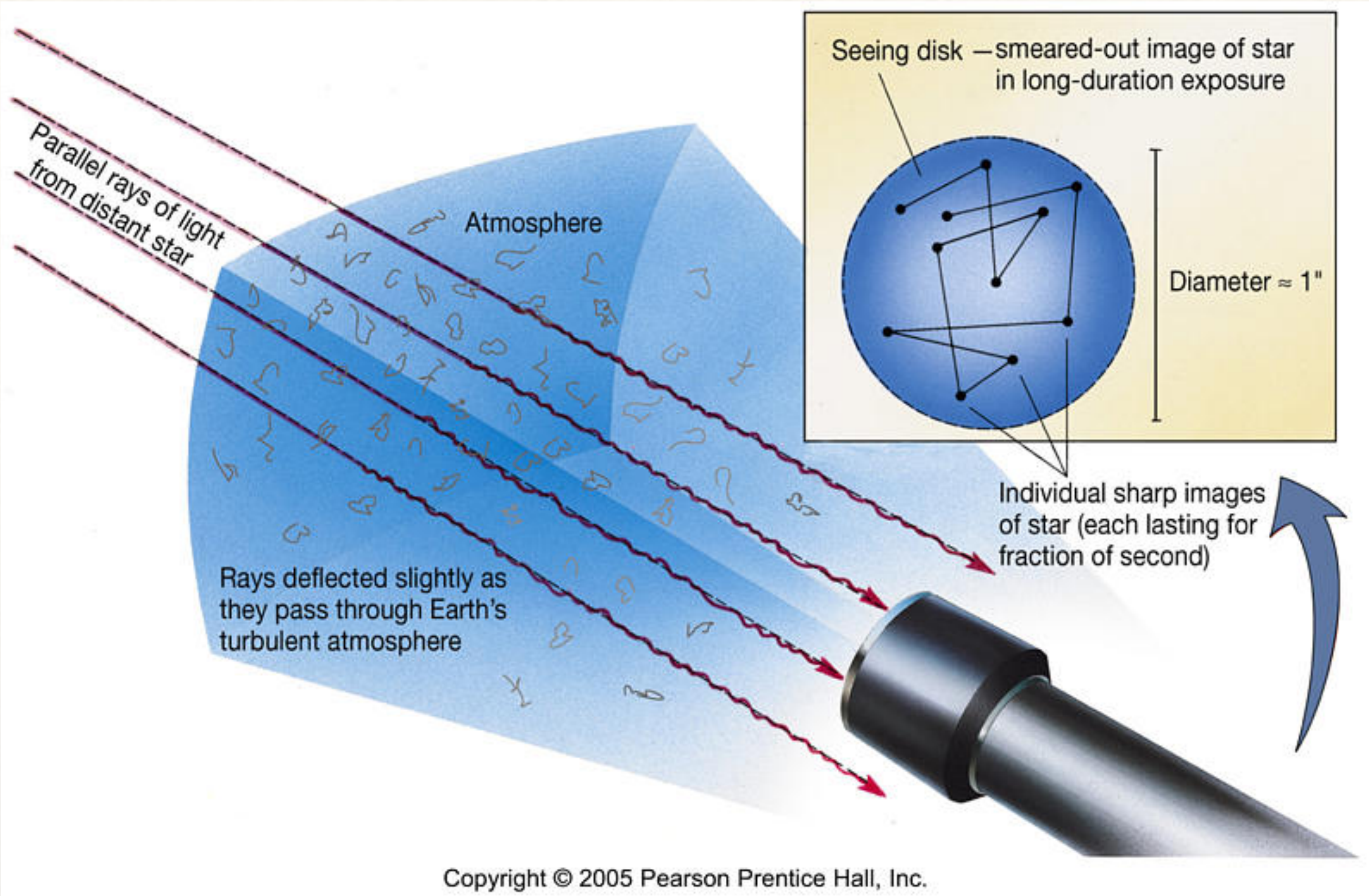
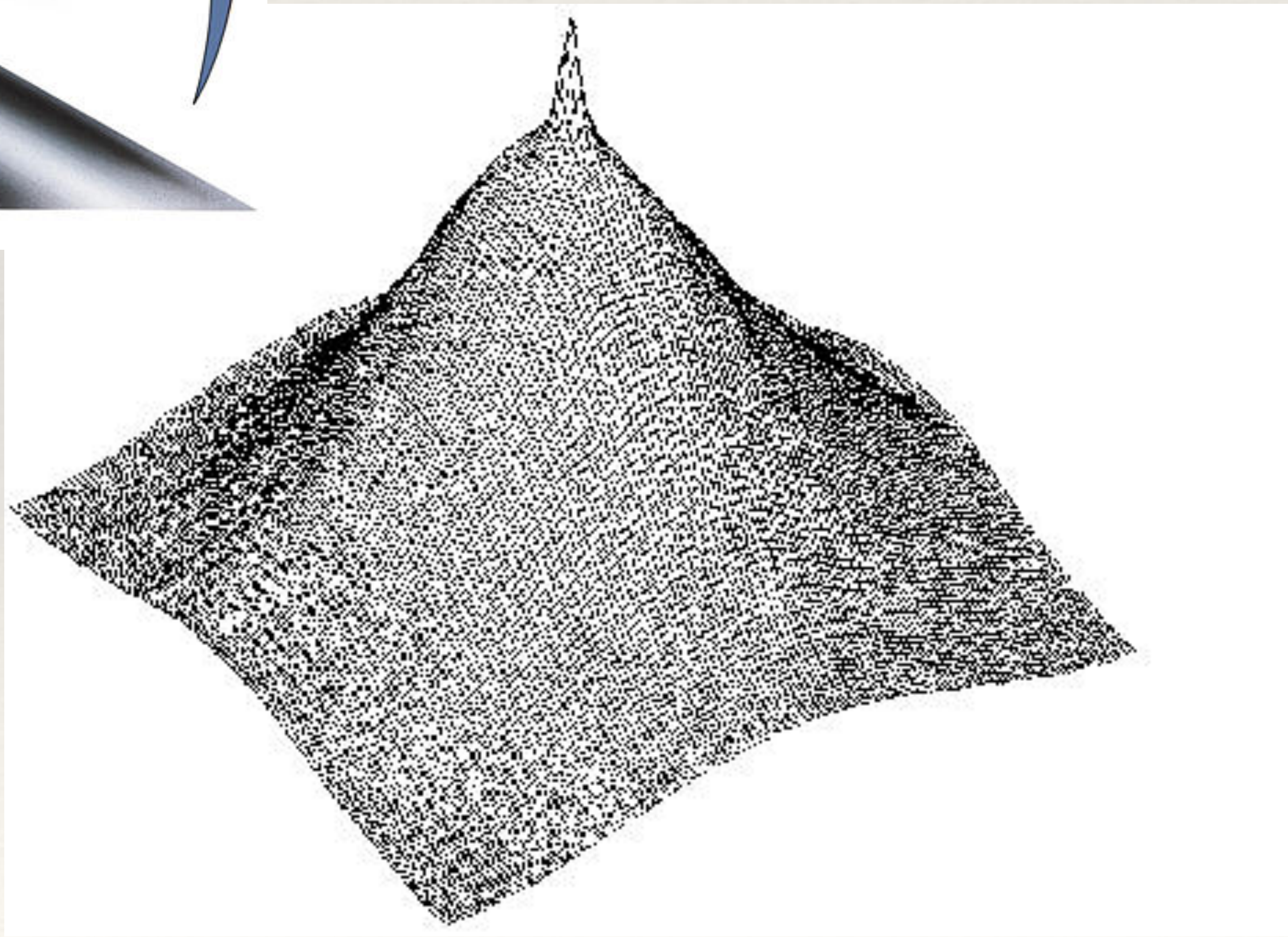
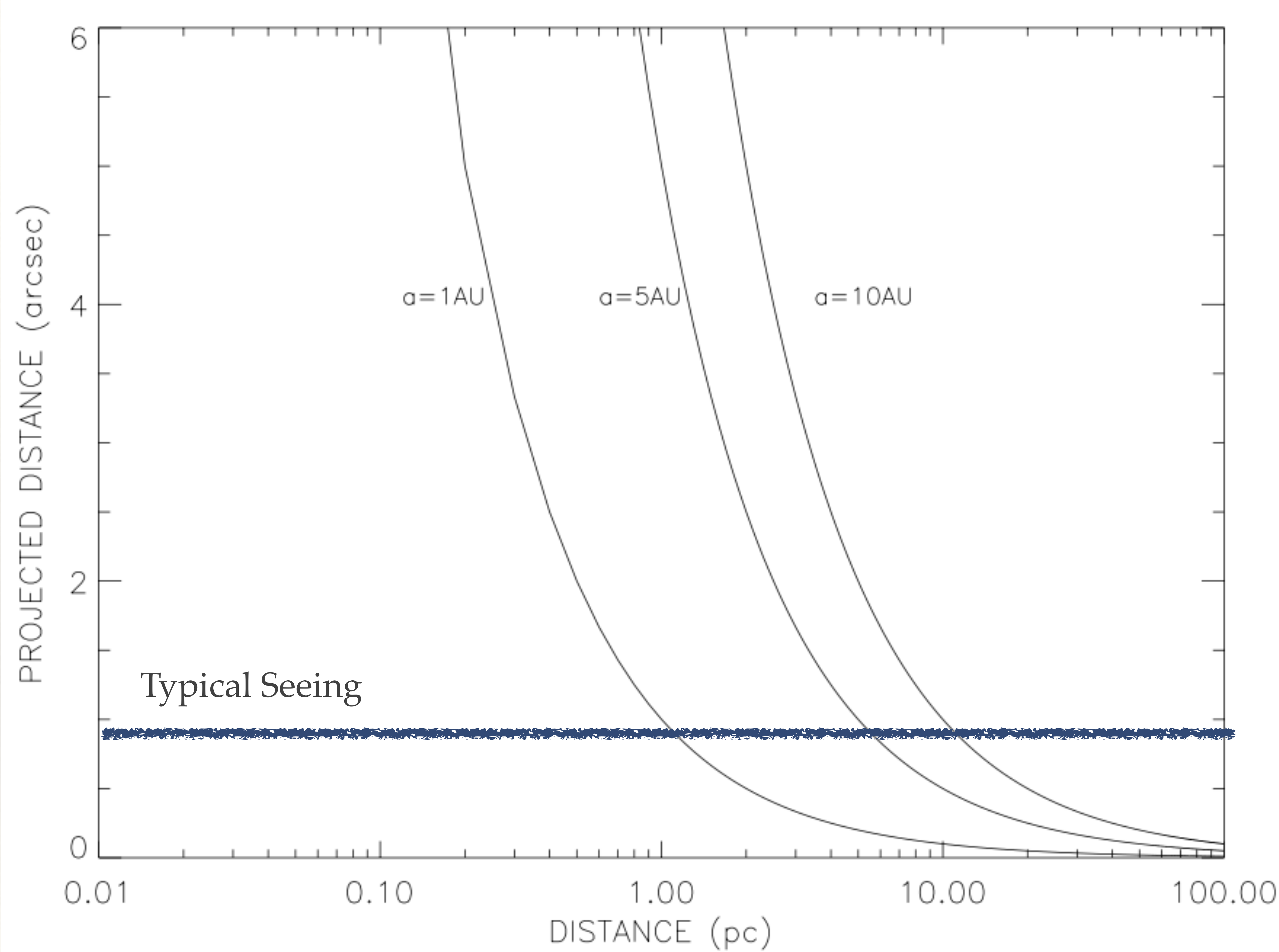


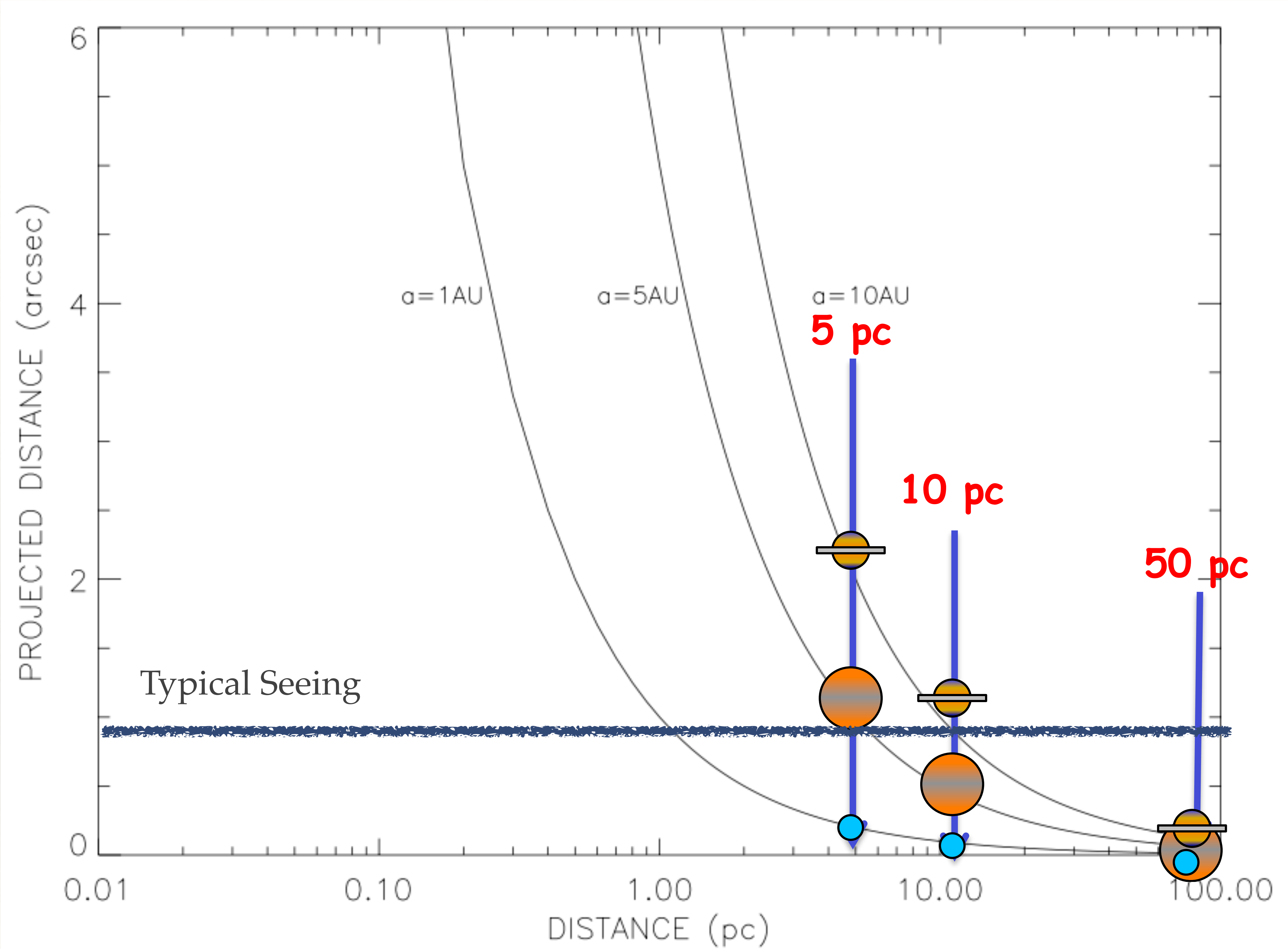
The Reality: Seeing Disk



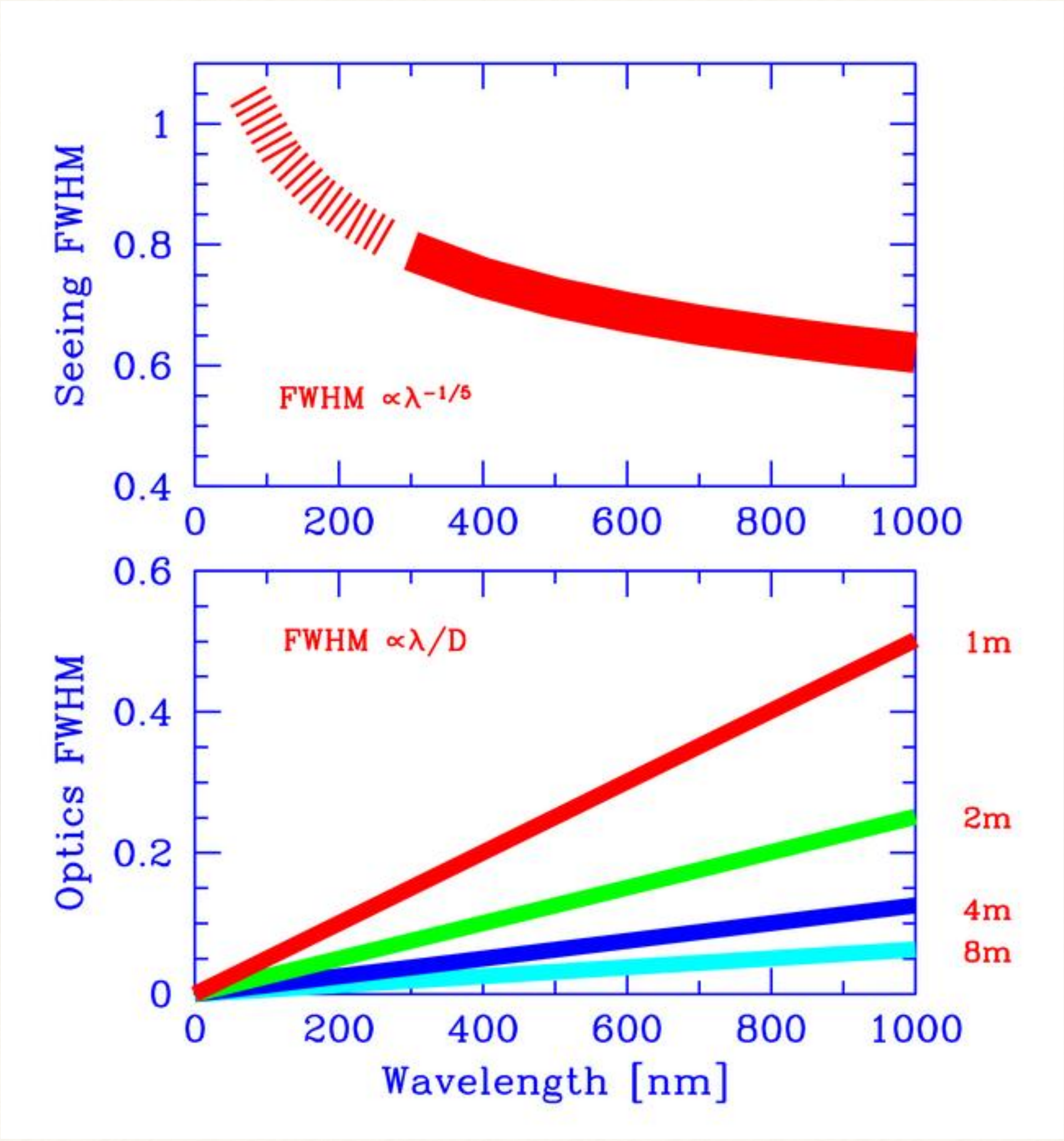




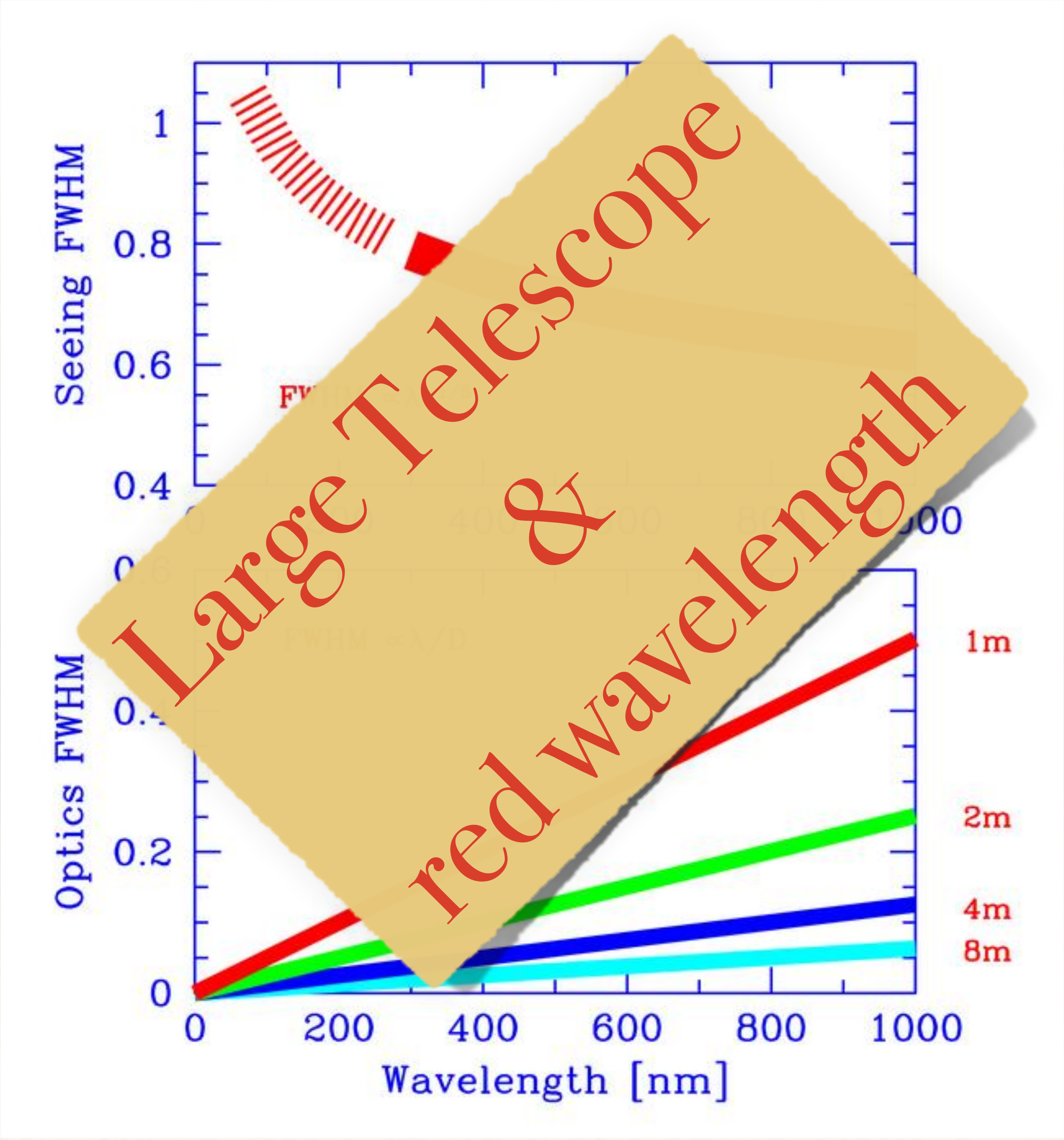
PROJECTED DISTANCE (arcsec)
6
4
2
0
a=1AU
a=5AU
a=10AU
Typical Seeing
0.01
0.10
1.00
10.00
100.00
DISTANCE (pc)


6
4
2
0
PROJECTED DISTANCE (arcsec)
a=1AU
a=5AU
a=10AU
5 pc
10 pc
50 pc
Typical Seeing
0.01
0.10
1.00
10.00
100.00
DISTANCE (pc)

Diffraction vs Seeing



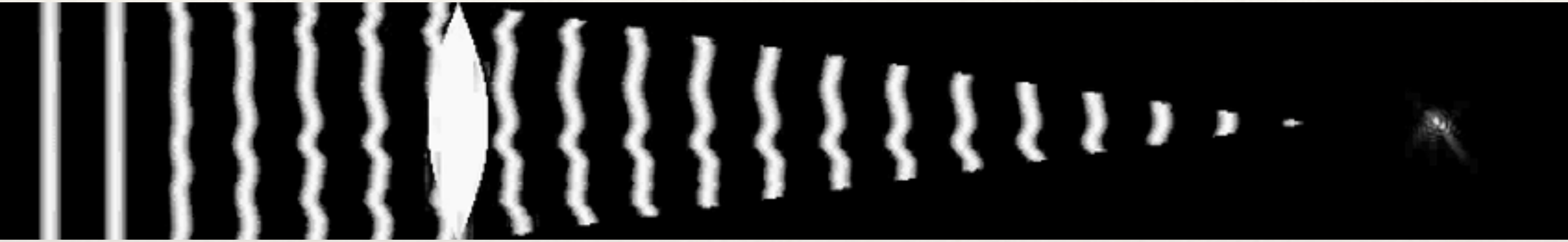
Diffraction vs Seeing



High **Angular** Resolution

- ☑ **Space** telescope
- ☑ **10m-**telescopes + AO system

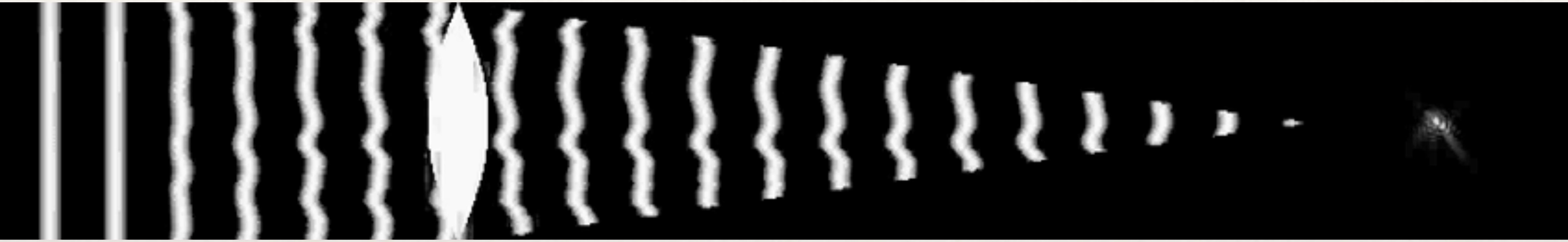
… but we have to remind that …



… turbulence evolution with time. Typical time:~ some milli seconds

correction need systems more rapid than kHz

… but we have to remind that …



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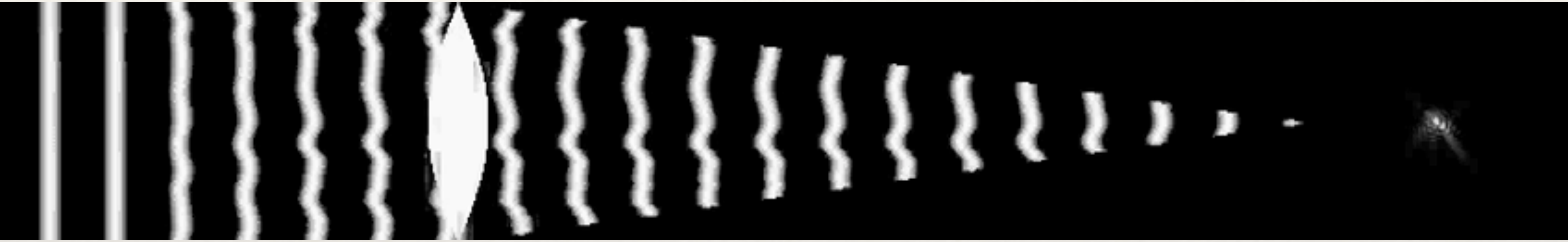
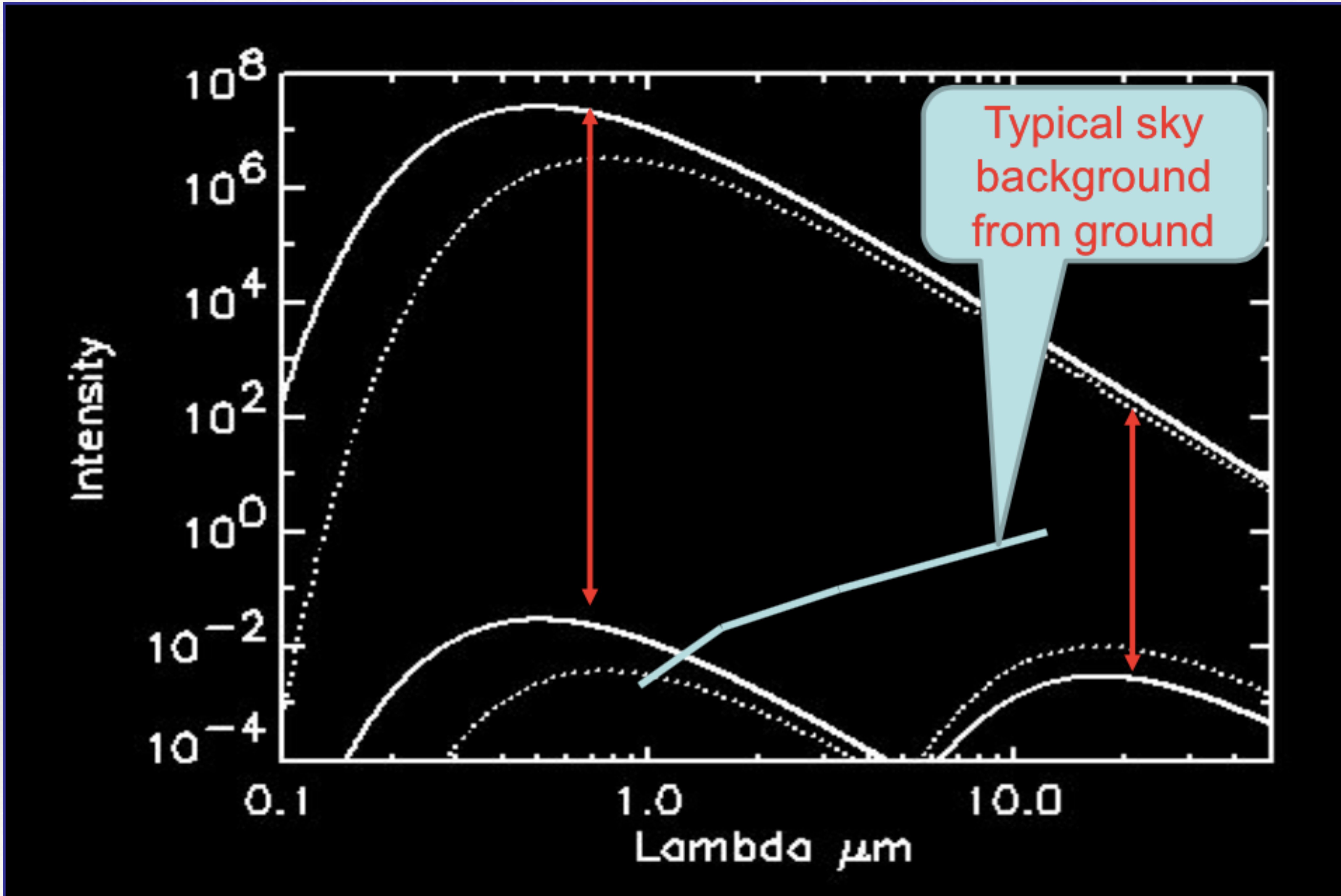


… turbulence evolution with time. Typical time:~ some milli seconds

correction need systems more rapid than kHz

… and also the following source of noise:

- Instrumental noise
  - Flat Field errors
  - Instrumental Background
- Stellar Noise
  - Photon Noise
  - Speckle noise
- Sky Background
  - Larger at longer wavelength

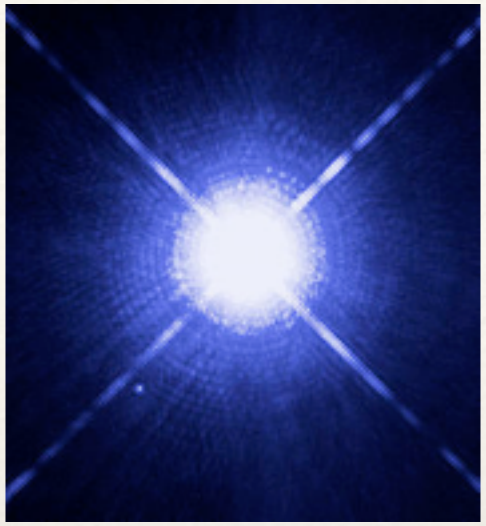


Typical sky background from ground
Intensity
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
0.1
1.0
10.0
Lambda μm

… going to the the space is better!?

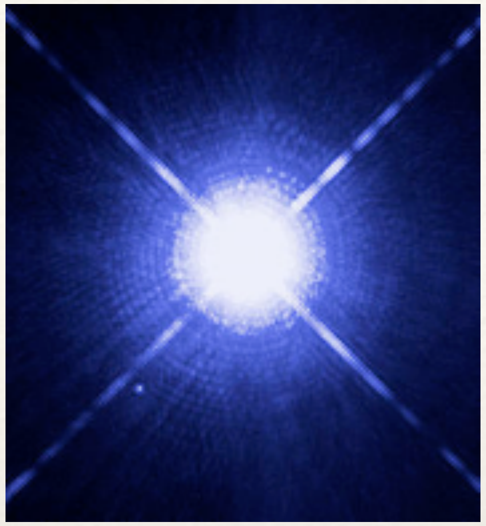
… going to the the space is better!?

… going to the the space is better!?



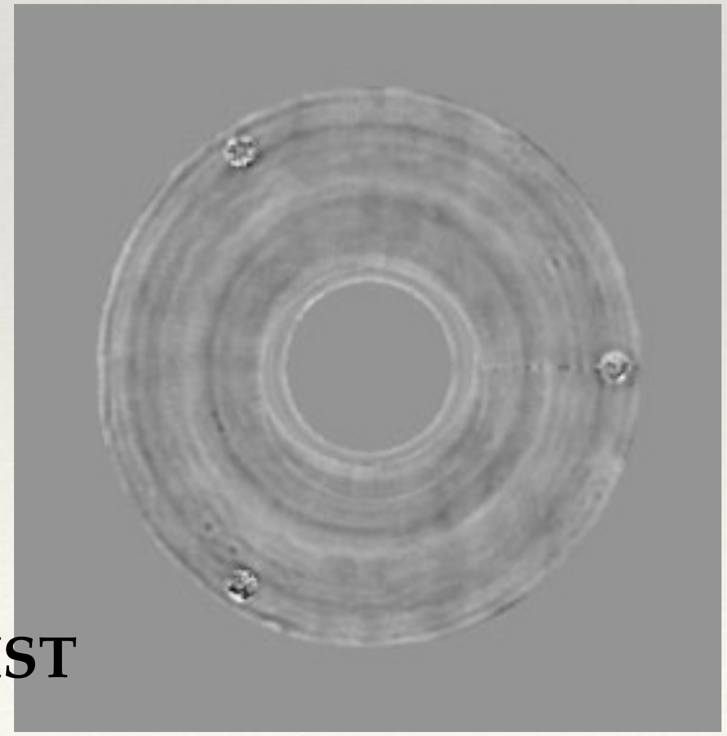
WOW! it seems better ..
Doesn't it?

… going to the the space is better!?



WOW! it seems better ..
Doesn't it?

However optics are not perfect



aberrations HST

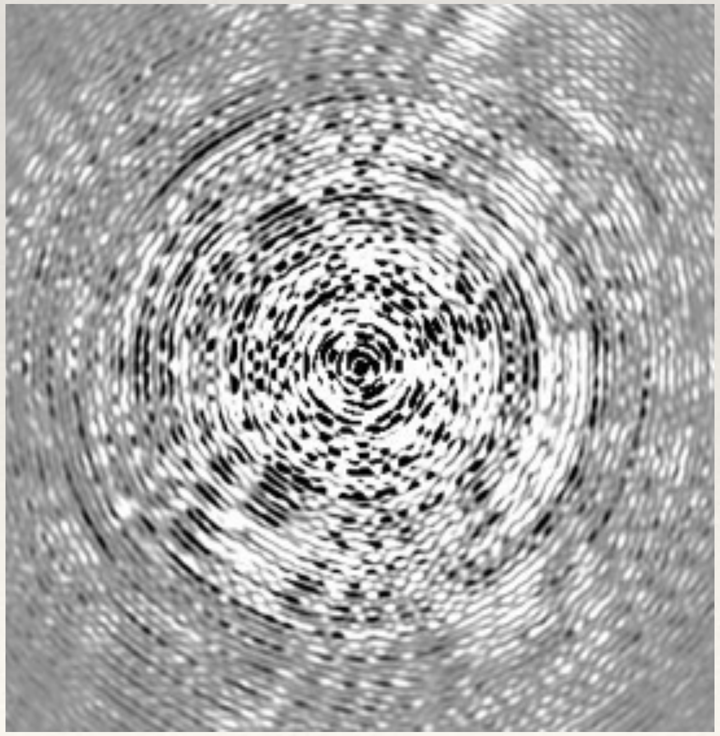


image speckles HST

In summary …

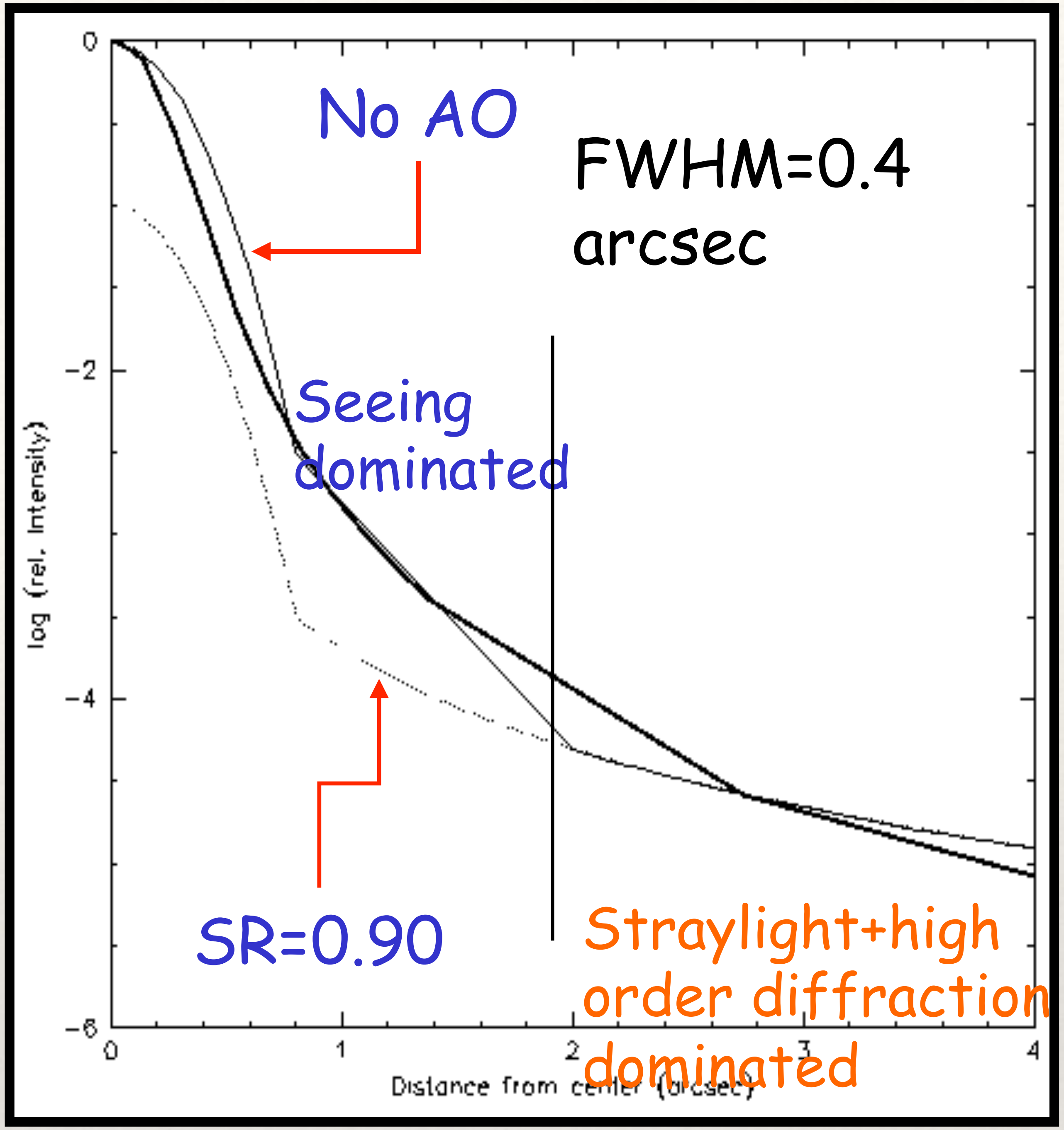
PSF is the convolution of two main components:

– Flat but not infinite wavefront (limited pupil size): diffraction peak (Airy disk) usually expressed in units of lambda/D narrower PSF for larger telescopes

– Perturbations with respect to flat wavefront. Speckles: correspond to a sinusoidal wavefront pattern. It is essentially a diffraction image offset with respect to the center (depending on the frequency of the sinusoid over the pupil: tilt on the pupil -> shift on focal plane)

HIGH CONTRAST IMAGING

PROBLEMS AND TECHNIQUES



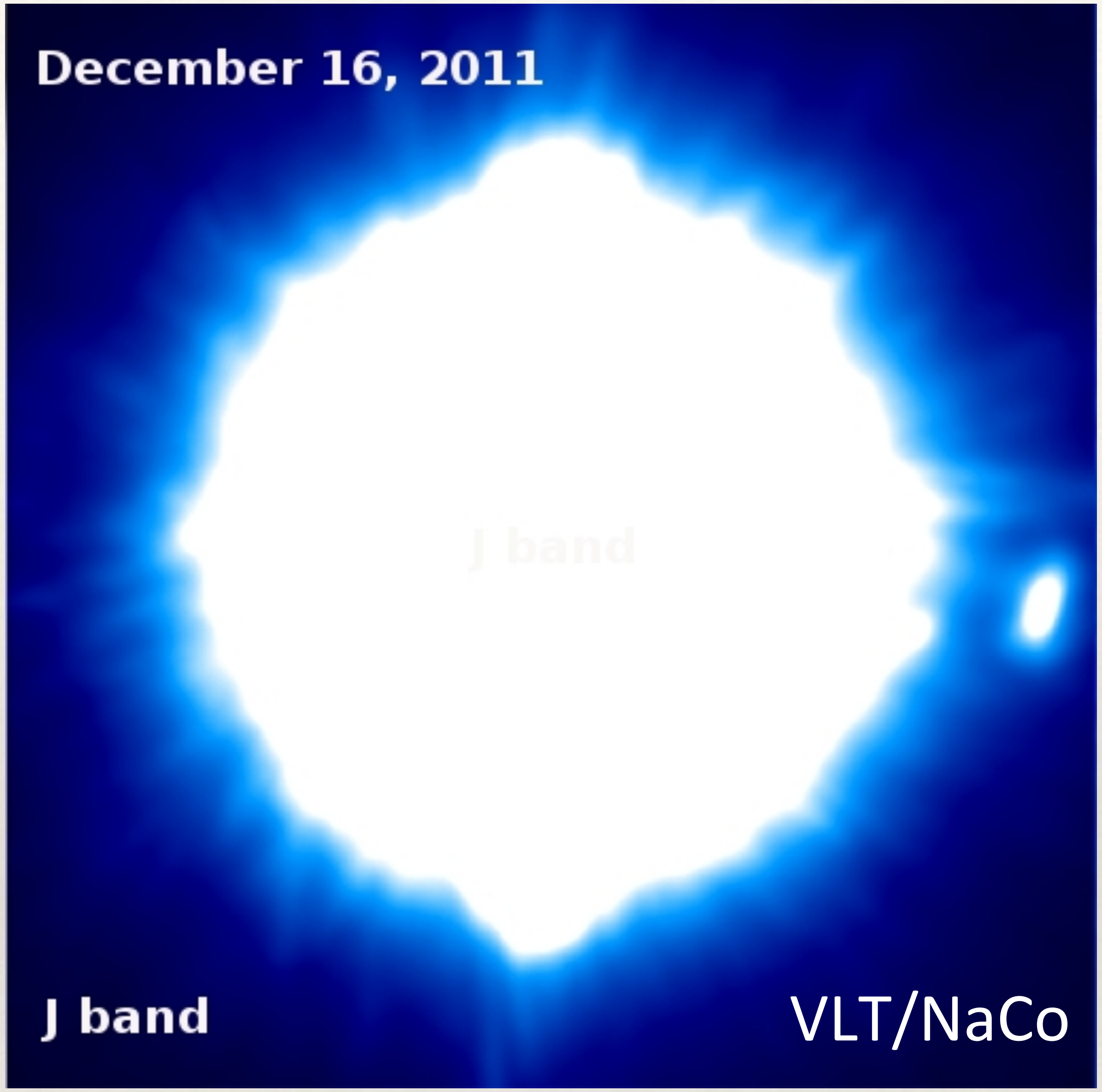
Atmosphere + speckles

- ☑ Adaptive Optics
- ☑ Differential Imaging

Diffraction

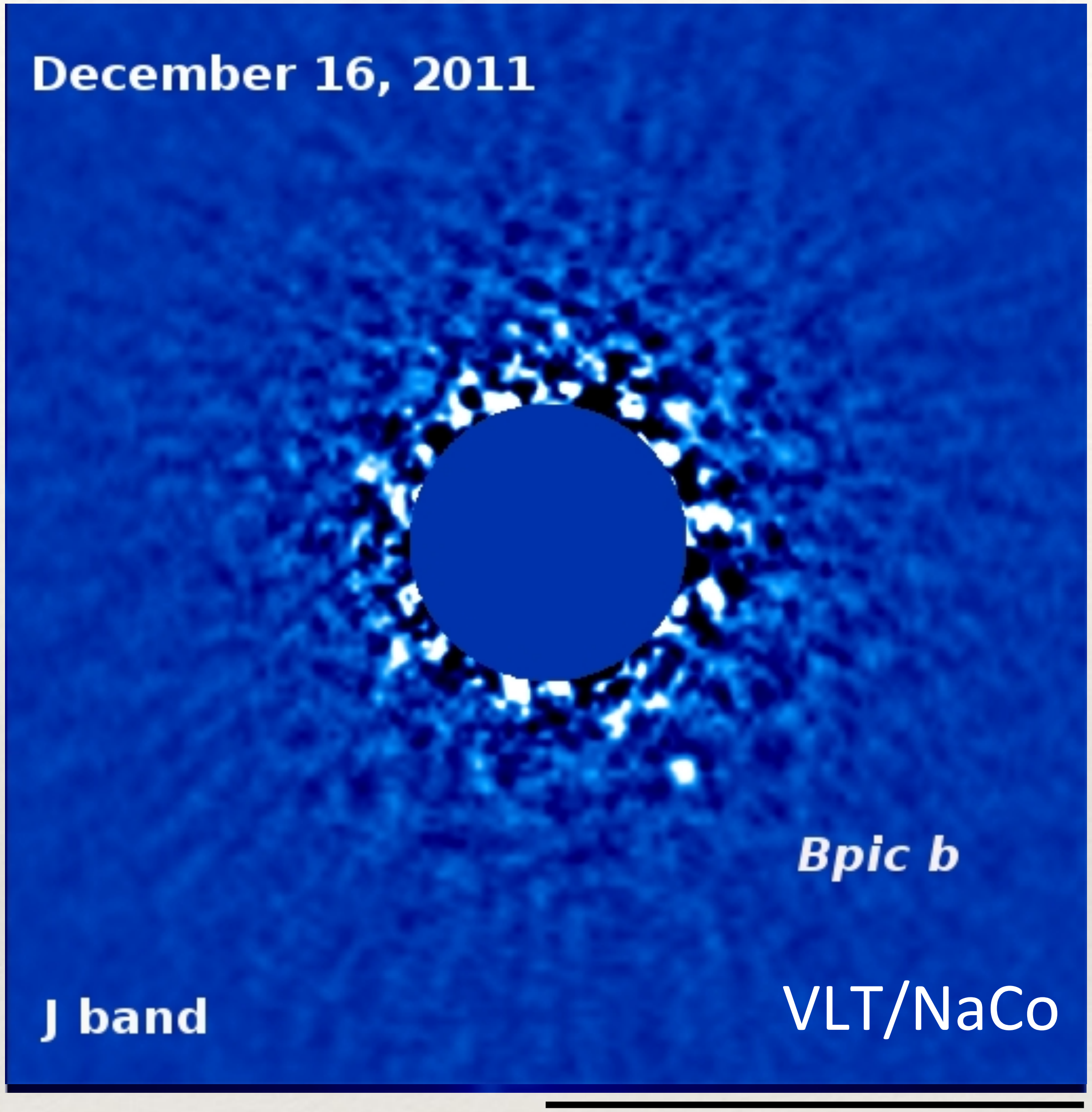
- ☑ Coronography (Lyot, Apodizing Masks)
- ☑ Interferometry (Nulling, 4-quadrant)

High Contrast Image at inner angle



1“ (i.e 19AU@19pc)

High Contrast Image at inner angle



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