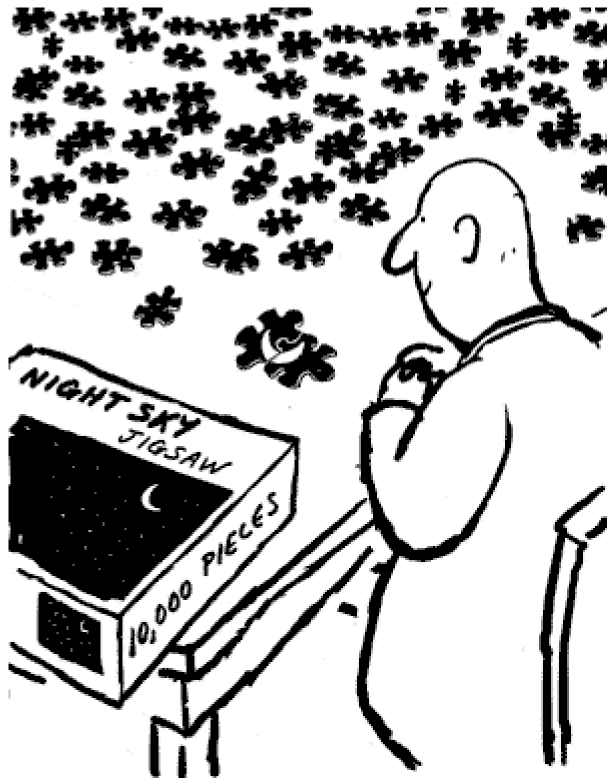
AS750 Observational Astronomy

Prof. Sebastian Lopez
Lecture 9

Observational limits



AS750 Observational Astronomy
Prof. Sebastian Lopez

Observational limits

0) Poisson! (quantum limitation)

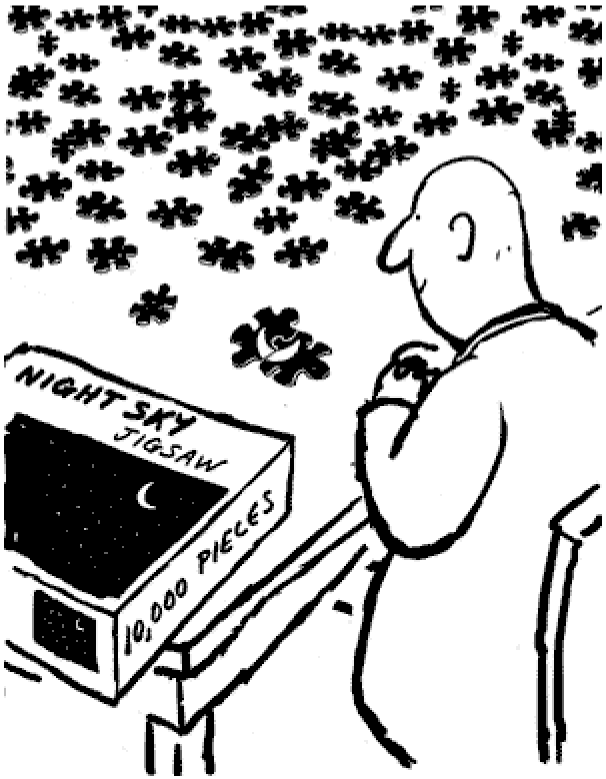
1) Diffraction limit

2) Detection (aperture) limit

   a)Simple case

   b)More realistic case

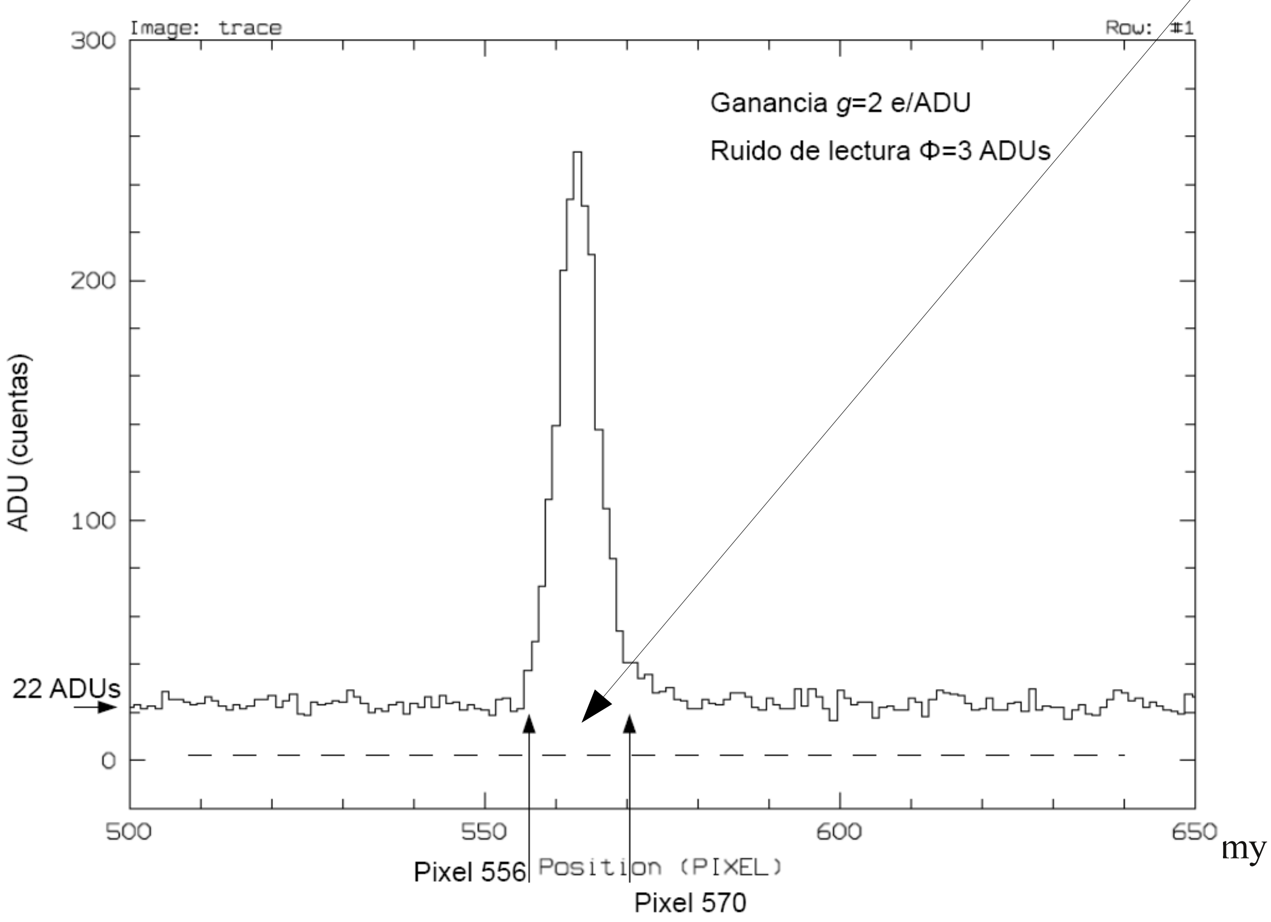
3) Atmosphere



Observational limits

2) Aperture limit (More realistic case)

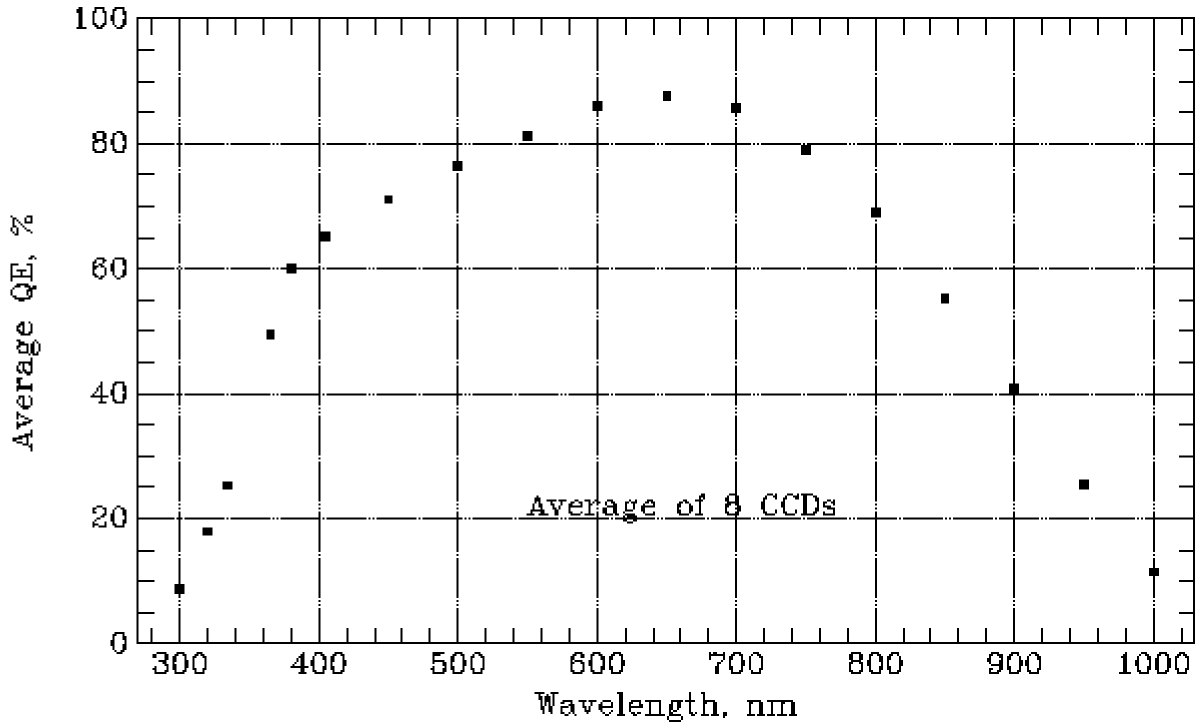
•Aperture has *m* pixels (1 arcsec^2)



Observational limits

2) Aperture limit (More realistic case)

•Aperture has *m* pixels (1 $arcsec^2$)
•Detector has Quantum Efficiency QE



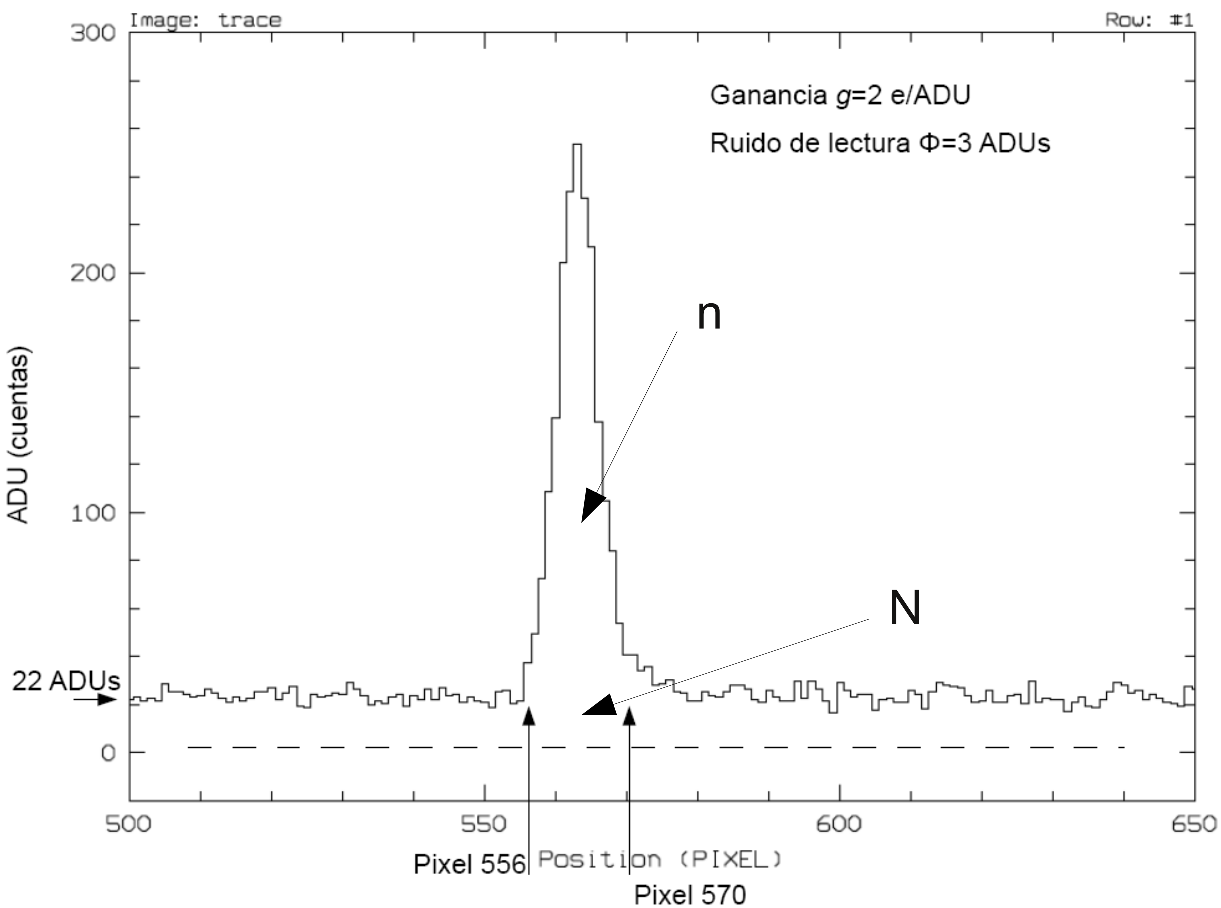
QE: percentage of photons that will produce a photo-electron on the CCD

QE of the red camera of the MIKE spectrograph on Clay @ LCO

Observational limits

2) Aperture limit (More realistic case)

- Aperture has *m* pixels (1 arcsec^2)
- Detector has Quantum Efficiency QE
- Read-out noise "Φ"



my

$$\frac{S}{N} = \frac{nq}{\sqrt{nq + Nq + \phi^2 m}}$$

Observational limits

2) Aperture limit (More realistic case)

- Aperture has *m* pixels (1 arcsec^2)
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$$\frac{S}{N}=\frac{nq}{\sqrt{nq+Nq+\phi^2 m}}$$

Homework: show that

$$t=\left(\frac{S}{N}\right)^2(1+r)\left[1+\left(1+\frac{4\phi^2 m}{\left(\frac{S}{N}\right)^2(1+r)^2}\right)^{1/2}\right]\frac{r}{2\mathrm{q}}\frac{1}{B}$$

where:

$$n=St\ ,\ N=Bt\ ,\ r\overset{\text{def}}{=}\frac{N}{n}$$

Observational limits

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$$n=St\ ,\ N=Bt\ ,\ r\overset{\text{def}}{=}\frac{N}{n}$$

Case 1: Ground-based telescope: $r\gg 1, N\gg\sqrt{\phi^2 m}\rightarrow t\approx\left(\frac{S}{N}\right)^2\frac{r^2}{2q}\frac{1}{B}$

Observational limits

2) Aperture limit (More realistic case)

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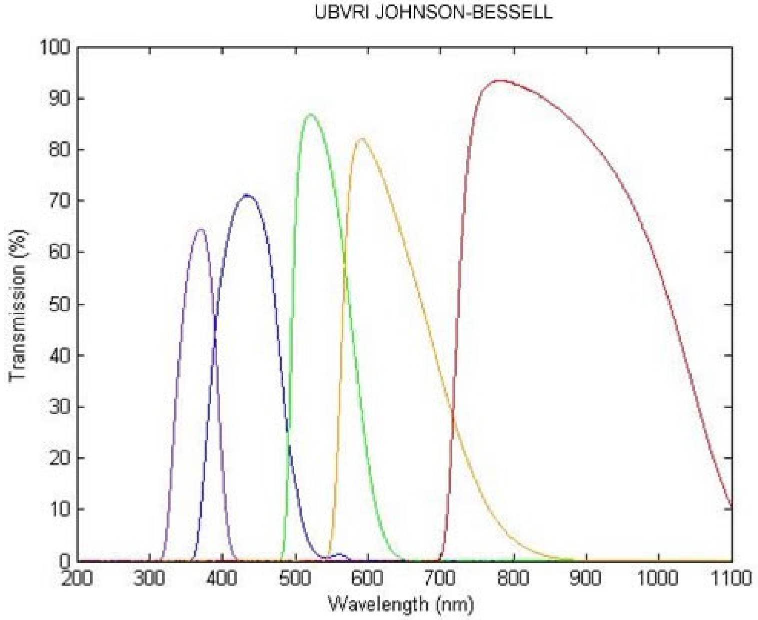
$$m_{star}(V) = 27, m_{sky}(V) = 22.5\, arcsec^{-2}, q = 0.8$$

Filter V is centered at 5300 Å and 500 Å wide. For the 3.6m telescope at La Silla, this sky brightness corresponds to B=30 photons per second per square arcsec.

Star magnitude in V



Observational limits

2) Aperture limit (More realistic case)

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$$m_{star}(V) = 27, m_{sky}(V) = 22.5\, arcsec^{-2}, q = 0.8$$

Let us suppose that the seeing conditions imply that 50% of the star photons are within 1 arcsec^2. Thus, in a 1 arcsec^2 aperture we have:

$$m_{star} - m_{sky} = -2.5 \log(F_{star} / F_{sky})$$

Observational limits

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$$m_{star} - m_{sky} = -2.5 \log(F_{star} / F_{sky})$$

$$27.0 - 22.5 = -2.5 \log(2n / N)$$

$$2 \times 10^{\frac{27.0-22.5}{2.5}} = N/n = r = 126$$

Observational limits

2) Aperture limit (More realistic case)

Case 1: Ground-based telescope: $r \gg 1, N \gg \sqrt{\phi^2 m} \rightarrow t \approx (\frac{S}{N})^2 \frac{r^2}{2q} \frac{1}{B}$

$$m_{star}(V) = 27, m_{sky}(V) = 22.5\, arcsec^{-2}, q = 0.8$$

$$2 \times 10^{\frac{27.0-22.5}{2.5}} = N/n = r = 126$$

$$B = 30\, s^{-1}$$

$$t = 330(\frac{S}{N})^2$$

Exposure time as a function of S/N

Observational limits

2) Aperture limit (More realistic case)

Case 1: Ground-based telescope: $r \gg 1, N \gg \sqrt{\phi^2 m} \rightarrow t \approx (\frac{S}{N})^2 \frac{r^2}{2q} \frac{1}{B}$

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$$B = 30\, s^{-1}$$

$$t = 330 (\frac{S}{N})^2$$

$$(\frac{S}{N}) = 5 \rightarrow t = 2.3\, h$$

Time necessary to reach S/N=5 on a mag=27 star using a 3.6m telescope .

Observational limits

2) Aperture limit (More reali

Case 1: Ground-based tele

$$m_{star}(V)=27, m_{sky}(V)=$$

$$2\times 10^{\frac{27.0-22.5}{2.5}} = N/n = r$$

$$B=30\,s^{-1}$$

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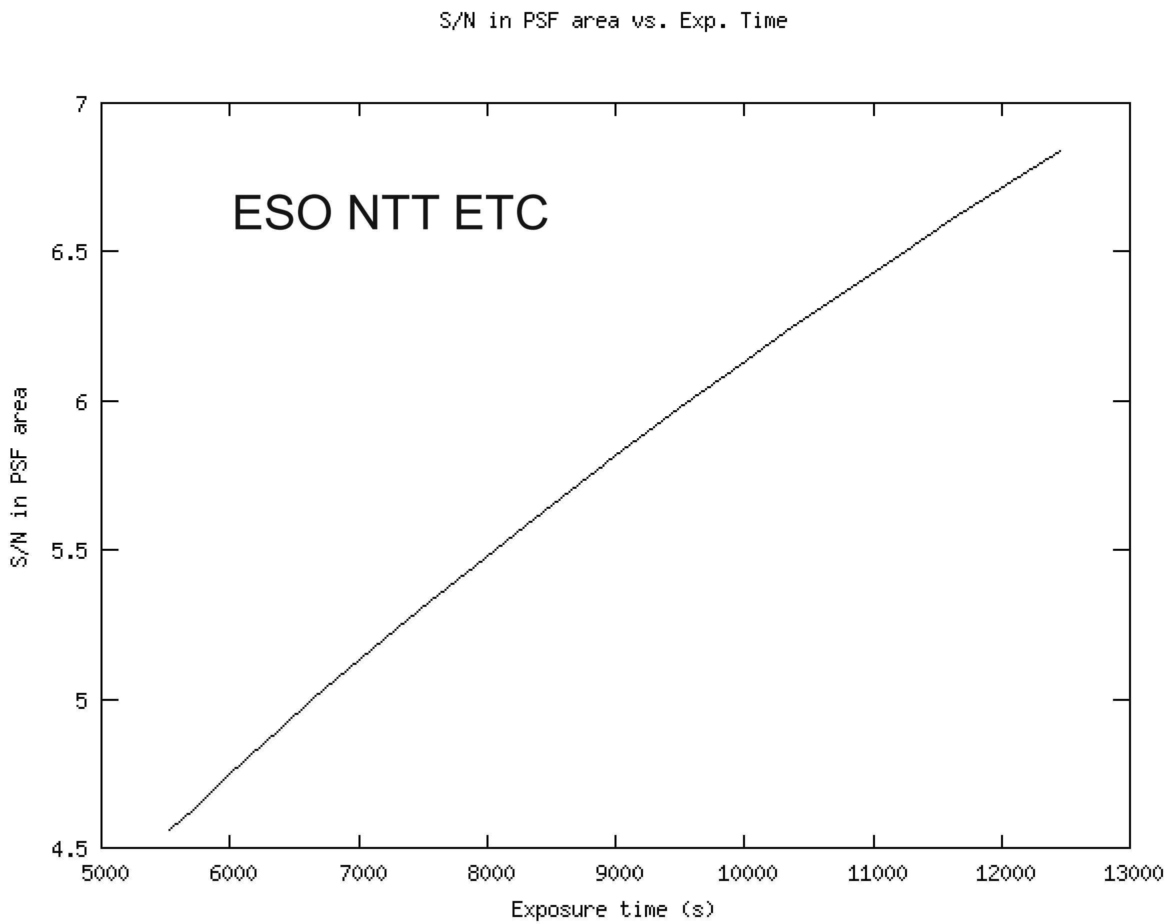


Time necessary to reach S/N=5 on a mag=27 star using a 3.6m telescope .

Observational limits

2) Aperture limit (More realistic case)

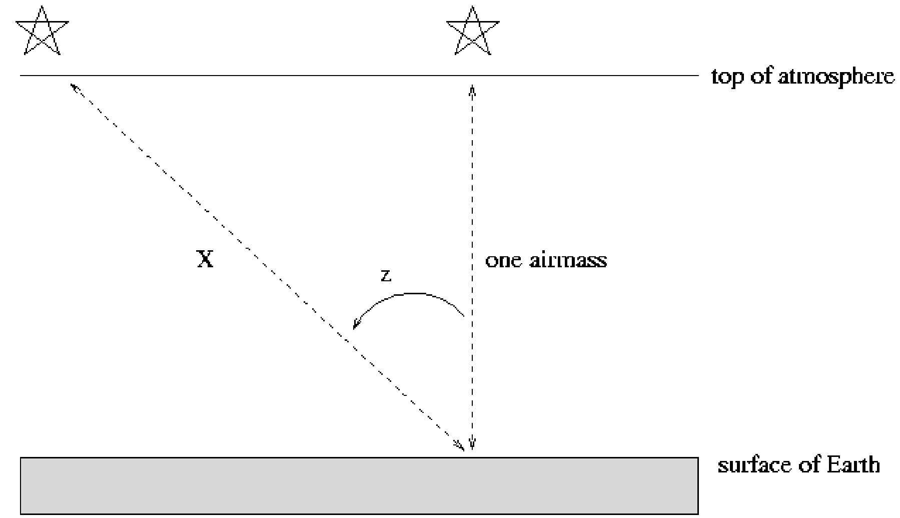
Case 2: Space-based telescope: $N \ll \sqrt{\phi^2 m} \rightarrow t \propto (\frac{S}{N})$

Observational limits

2) Atmosphere

Observational limits

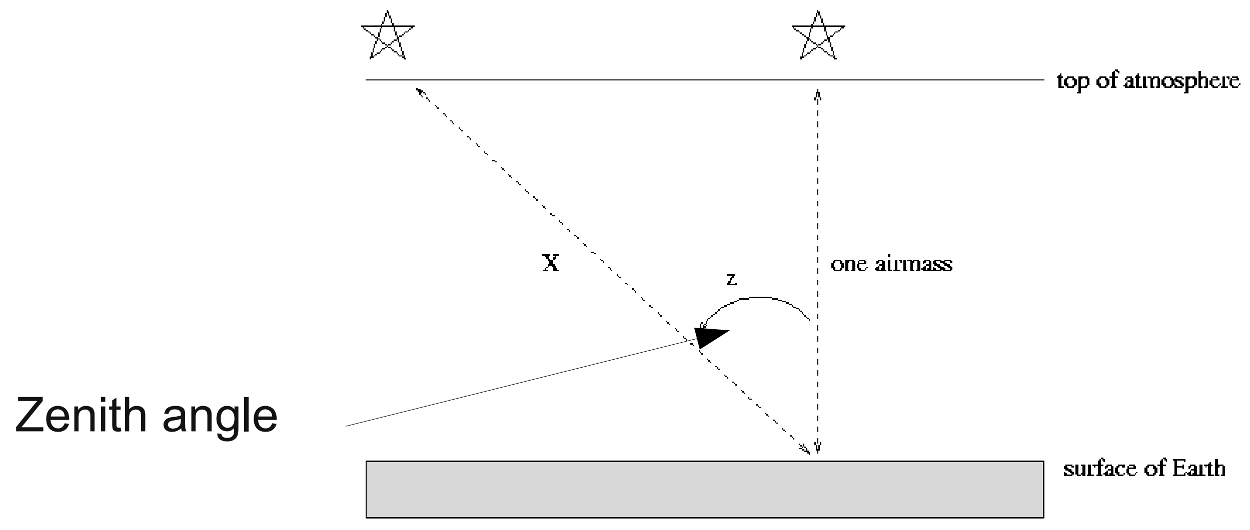
2) Atmosphere
a) "Airmass"



Dimming of star light due to extinction in the atmosphere

Observational limits

2) Atmosphere
a) "Airmass"

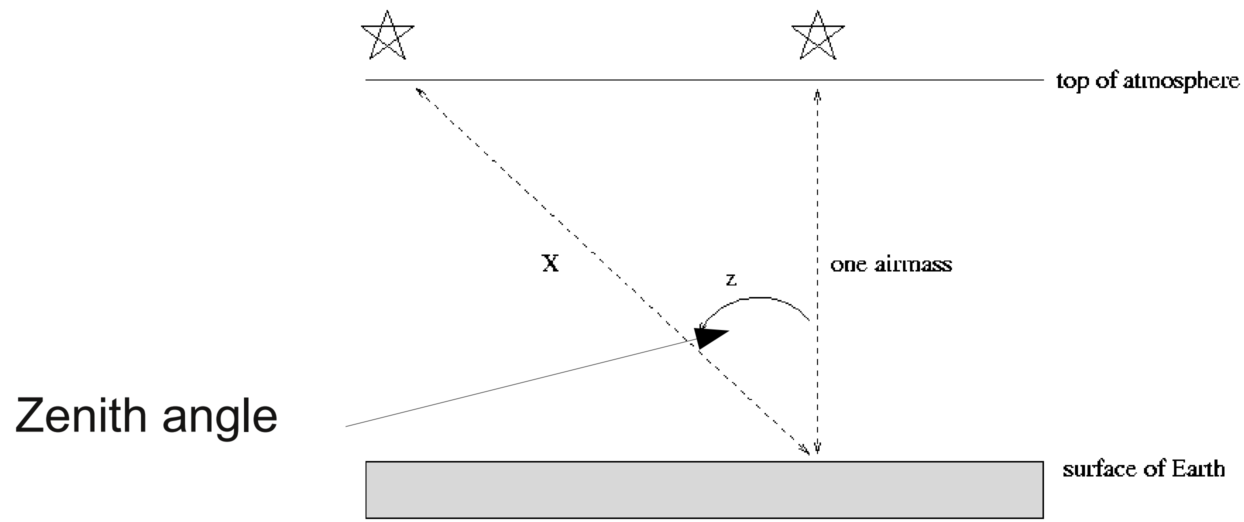


If we consider the earth and atmosphere to be flat, the number of airmasses light must traverse is given approximately by:

$$airmass\ X = \frac{one\ airmass}{\cos z} = (one\ airmass) \times sec\ z$$

Observational limits

2) Atmosphere
a) “Airmass”



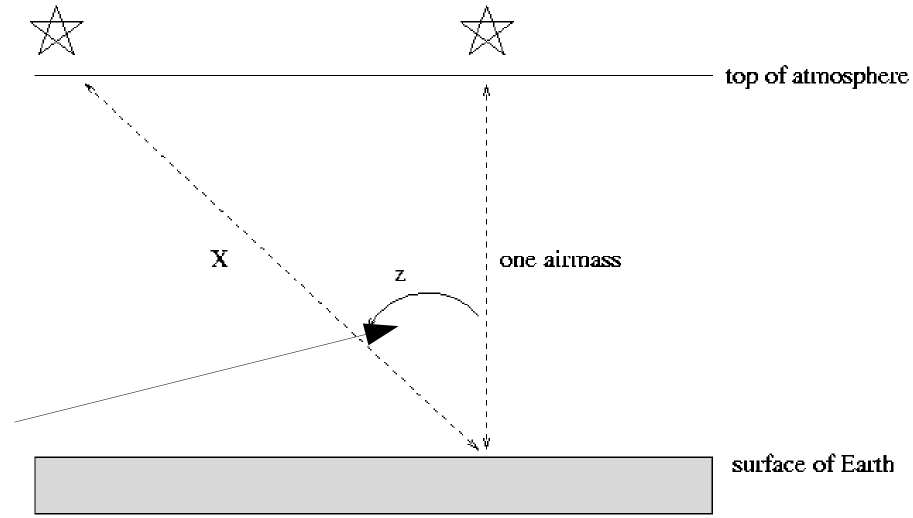
If we consider flux before and after crossing an air layer “dh”, in terms of extinction we have:

$$dF_{\lambda} = -k\, F_{\lambda}\, sec\, z\, |dh|$$

Extinction coefficient

Observational limits

2) Atmosphere
a) “Airmass”



Zenith angle

If we consider flux before and after crossing an air layer “dh”, in terms of extinction we have:

$$dF_{\lambda} = -k\, F_{\lambda}\, sec\, z \left| dh \right|$$

Integrating:

$$F_{\lambda} = F_0 \exp\left(-sec\, z \int_0^{\infty} k\, dh\right)$$

Observational limits

2) Atmosphere
a) "Airmass"

$$dF_\lambda = -k\, F_\lambda \sec z\, |dh|$$

$$F_\lambda = F_0 \exp\left(-\sec z \int_0^\infty k\, dh\right)$$

Apply log to have a magnitude scale:

$$m_\lambda = m_0 + \Delta m_0 \sec z$$

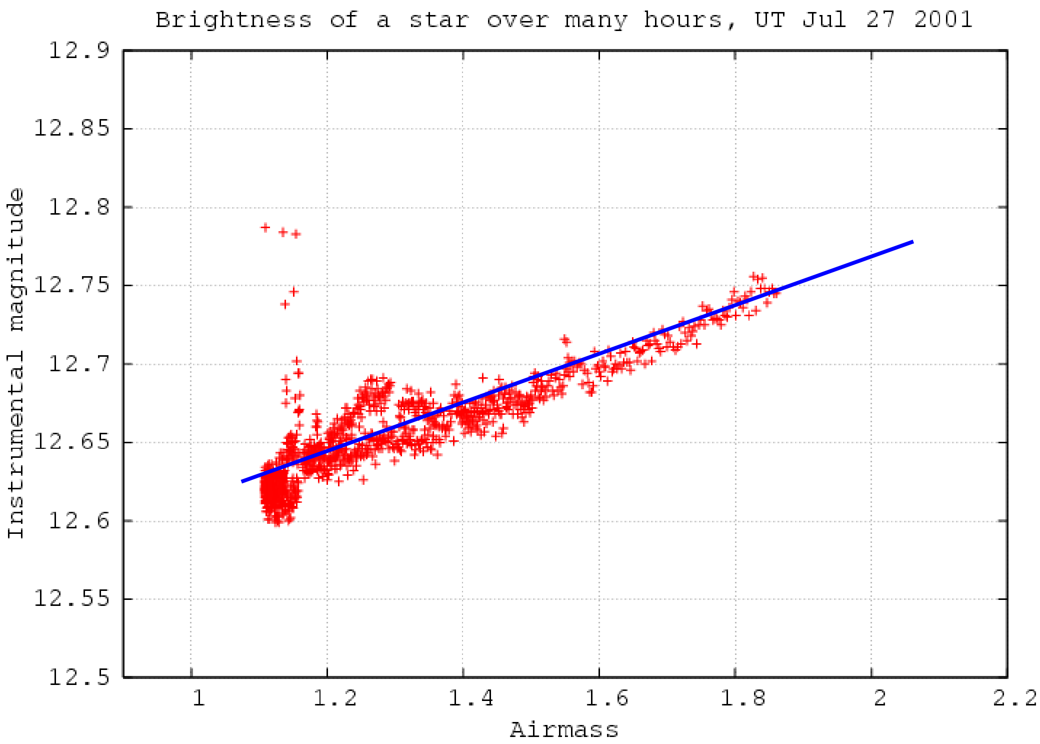
Observational limits

2) Atmosphere
a) "Airmass"

$$dF_\lambda = -k\, F_\lambda\, sec\, z\, |dh|$$

$$F_\lambda = F_0 \exp\left(-sec\, z \int_0^\infty k\, dh\right)$$

$$m_\lambda = m_0 + \Delta m_0\, sec\, z$$



Get this coefficients from the plot

Observational limits

2) Atmosphere
a) "Airmass"

Empirically::

$$m_\lambda = m_0 - \Delta m_0 M(z)$$

$$M(z) = sec\, z - 0.0018167(sec\, z - 1) - 0.002875(sec\, z - 1)^2 - 0.0008083(sec\, z - 1)^3$$

Observational limits

2) Atmosphere
a) “Airmass”

Empirically::

$$m_\lambda = m_0 - \Delta m_0 \, M(z)$$

$$M(z) = sec\,z - 0.0018167(sec\,z - 1) - 0.002875(sec\,z - 1)^2 - 0.0008083(sec\,z - 1)^3$$

Recommendation: observe as close as possible to the zenith!
(or at least avoid z>60°)

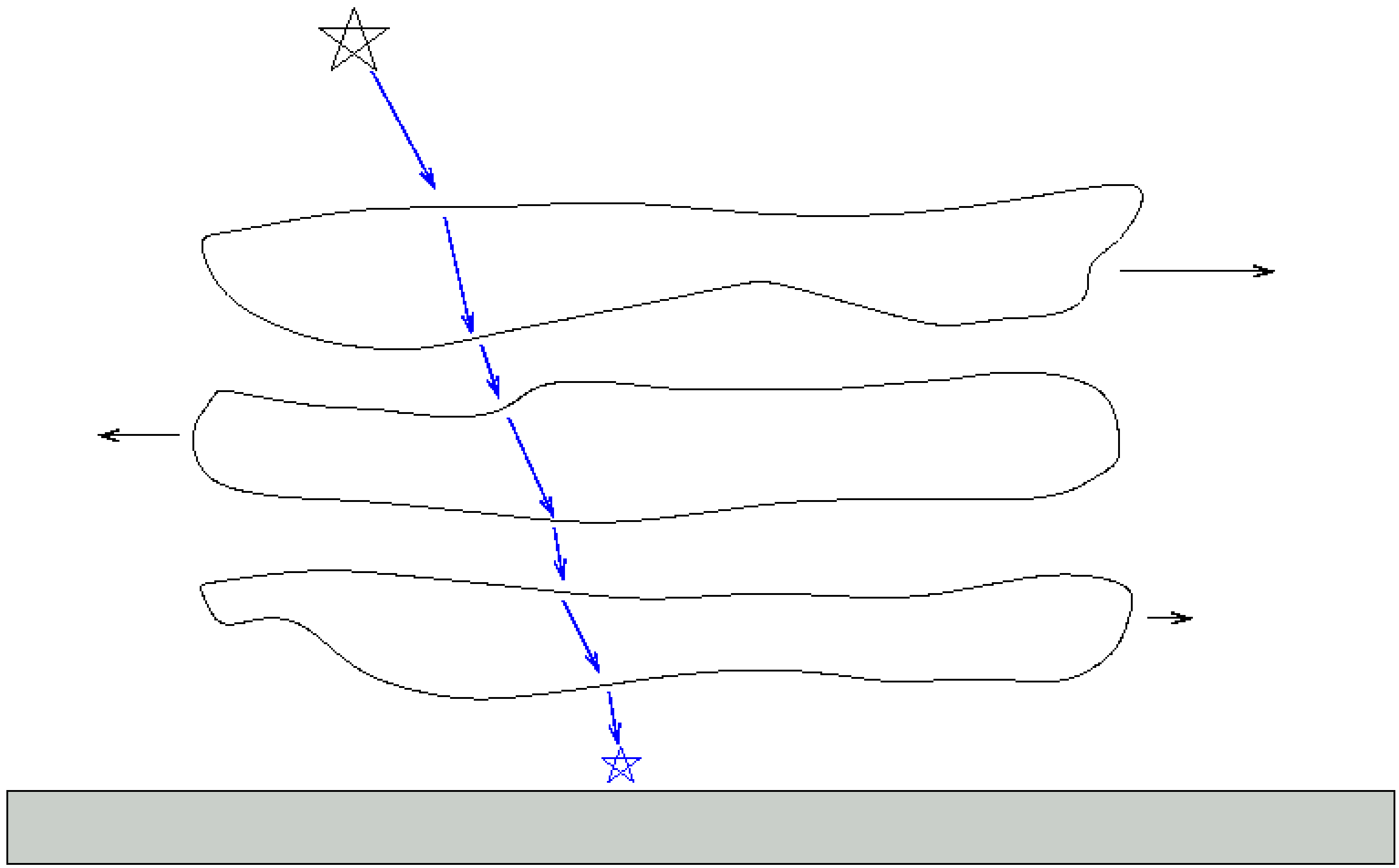
Observational limits

Hourly Airmass Table for Q1355 for Mar 14, 2010

```
*** Hourly airmass for Q1355 ***

Epoch 1950.00: RA  13 55 00.0, dec -22 57 00
Epoch 2010.20: RA  13 58 21.8, dec -23 14 34

At midnight: UT date 2010 Mar 15, Moon 0.01 illum, 131 degr from obj

  Local      UT      LMST      HA     secz   par.angl. SunAlt MoonAlt

  19 00    23 00     5 47    -8 11   (down)  -131.0     -0.6    ...
  20 00     0 00     6 47    -7 11   (down)  -123.7    -13.6    ...
  21 00     1 00     7 47    -6 11    6.498  -118.1     ...     ...
  22 00     2 00     8 47    -5 11    2.755  -113.8     ...     ...
  23 00     3 00     9 48    -4 11    1.784  -110.6     ...     ...
   0 00     4 00    10 48    -3 11    1.365  -108.6     ...     ...
   1 00     5 00    11 48    -2 10    1.152  -108.7     ...     ...
   2 00     6 00    12 48    -1 10    1.045  -114.6     ...     ...
   3 00     7 00    13 48    -0 10    1.006  -159.8     ...     ...
   4 00     8 00    14 48     0 50    1.025   120.9     ...     ...
   5 00     9 00    15 49     1 50    1.107   109.6     ...     ...
   6 00    10 00    16 49     2 50    1.277   108.3    -10.2    ...
```

Observational limits

2) Atmosphere
a) “Seeing”

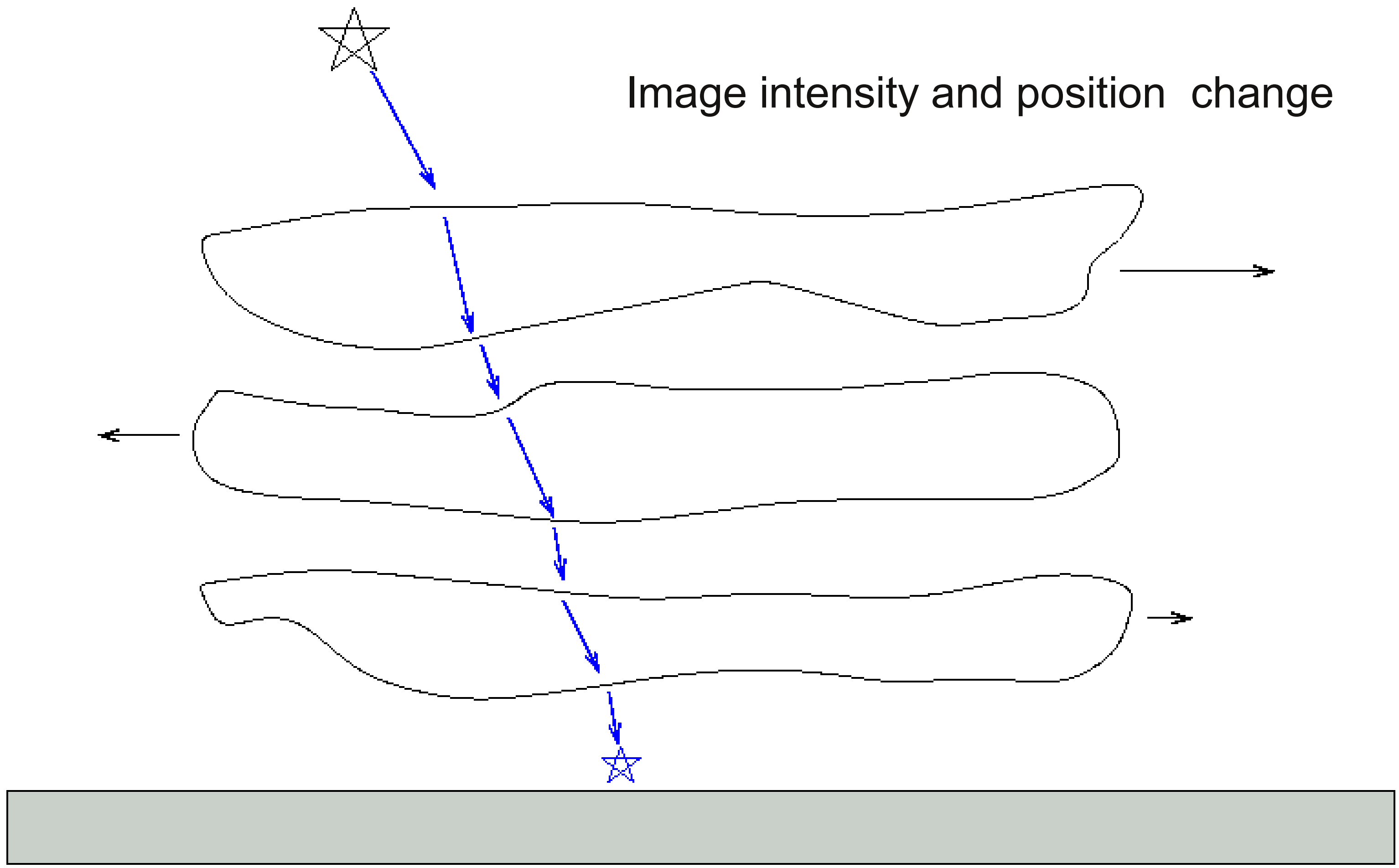


Observational limits

2) Atmosphere
a) "Seeing"

Atmospheric layers move differentially at different time and spatial scales. This produces rapid variations in the airmass and refraction index.

Image intensity and position change

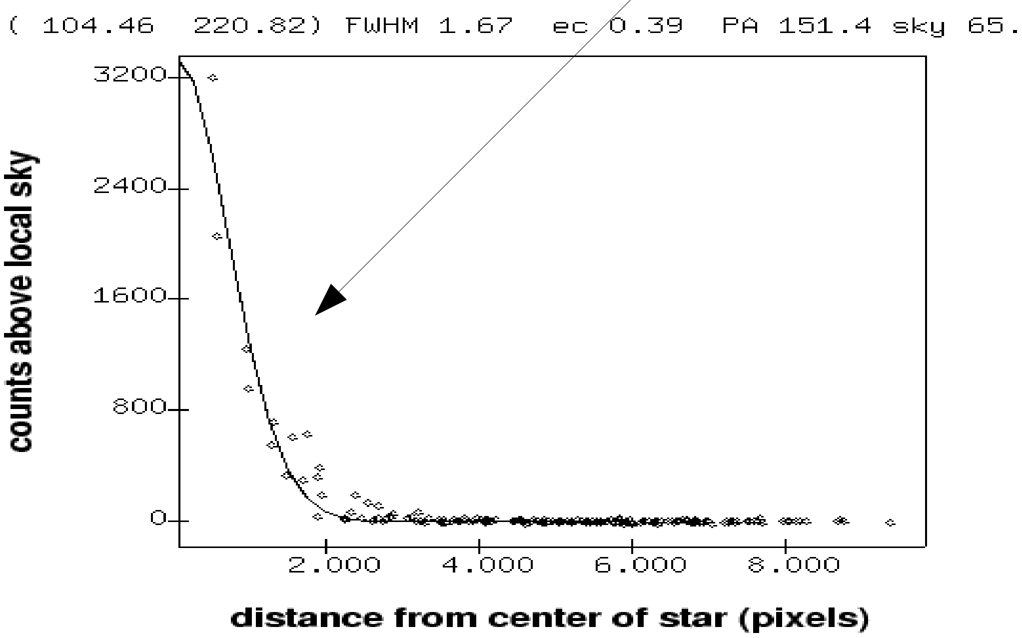


Observational limits

2) Atmosphere
a) “Seeing”

FWHM ~ “seeing” ~ 3.7 arcsec

Ground telescope

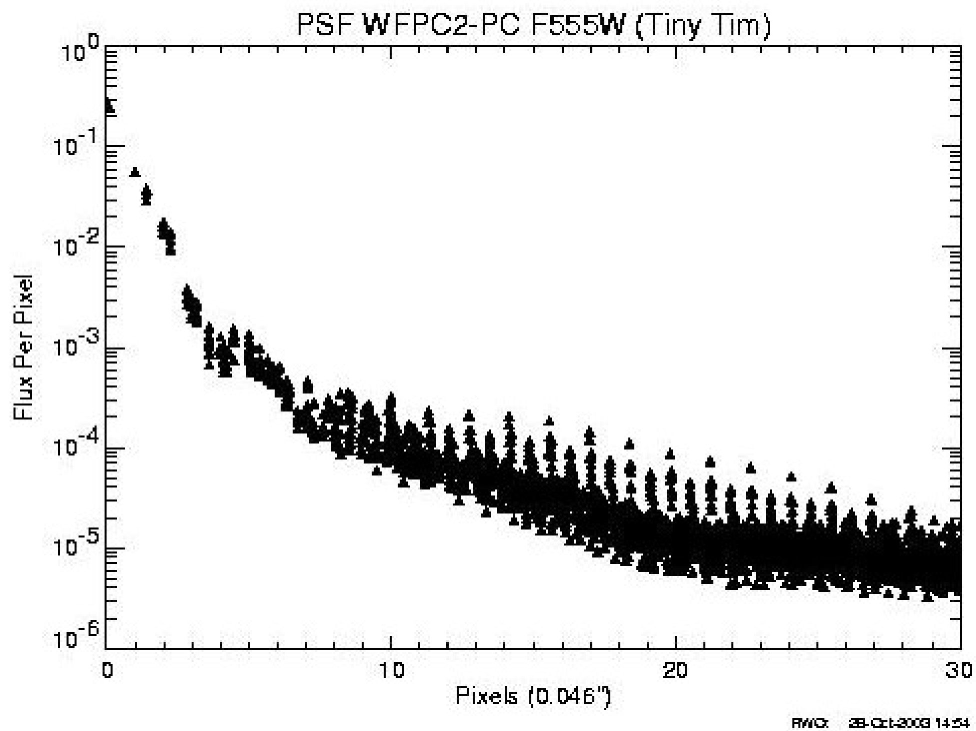


Observational limits

2) Atmosphere
a) “Seeing”

FWHM ~ 0.25 arcsec!

Space telescope

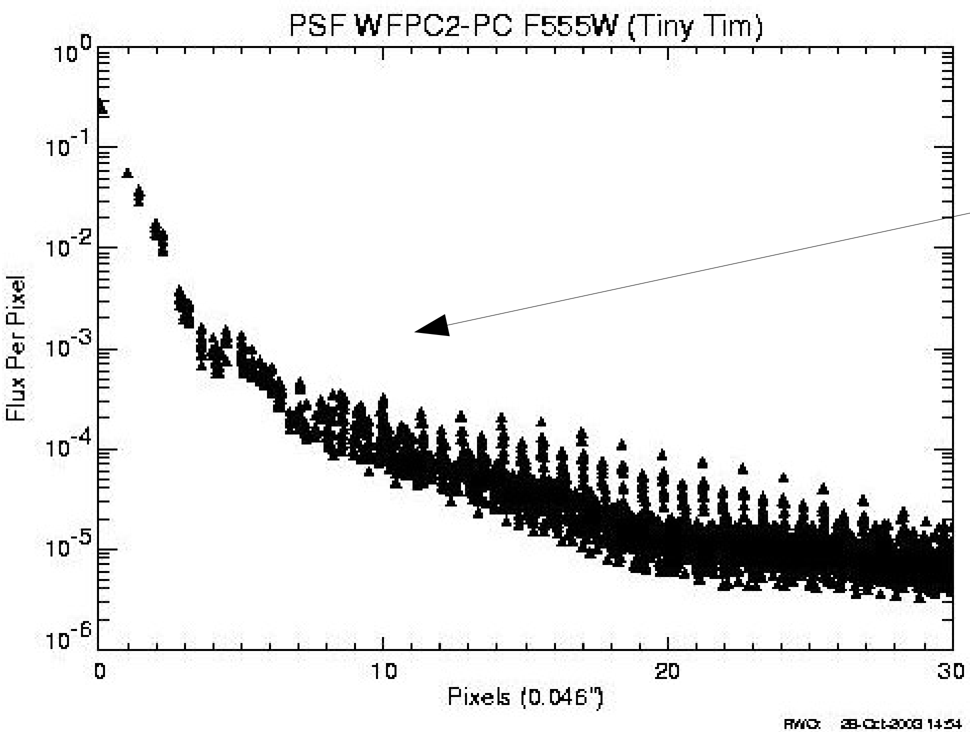


Observational limits

2) Atmosphere
a) “Seeing”

FWHM ~ 0.25 arcsec!

Space telescope

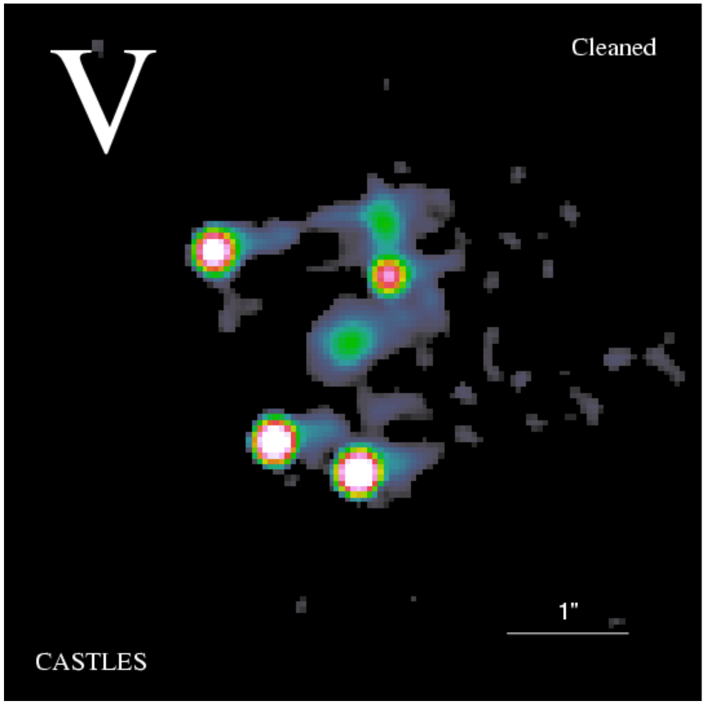


Point-Spread Function (PSF).
Usually approximated by a Gaussian,
But this is optics-dependent
(Moffat function)

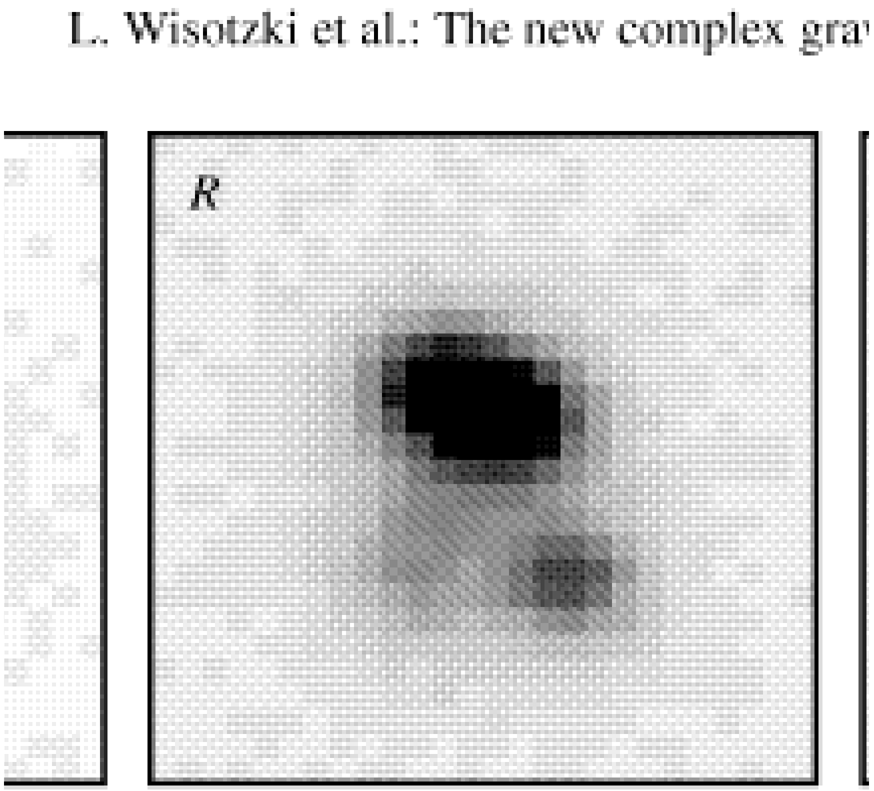
Observational limits

2) Atmosphere
a) “Seeing”

Gravitationally lensed QSO HE0230-2130



CASTLES Survey

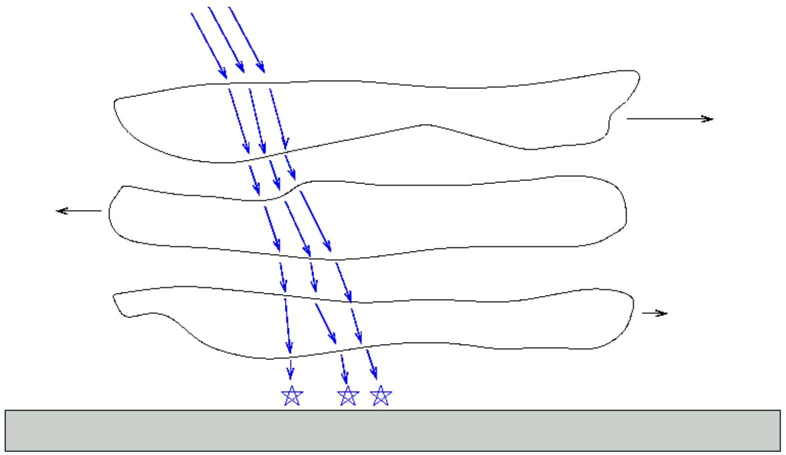


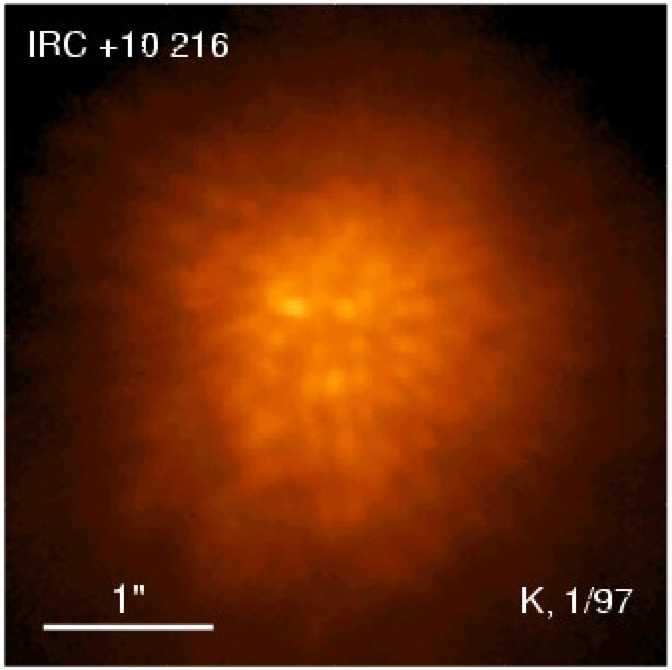
CTIO 1.5m, seeing~1 arcsec

Observational limits

2) Atmosphere
a) "Seeing"

Speckle interferometry



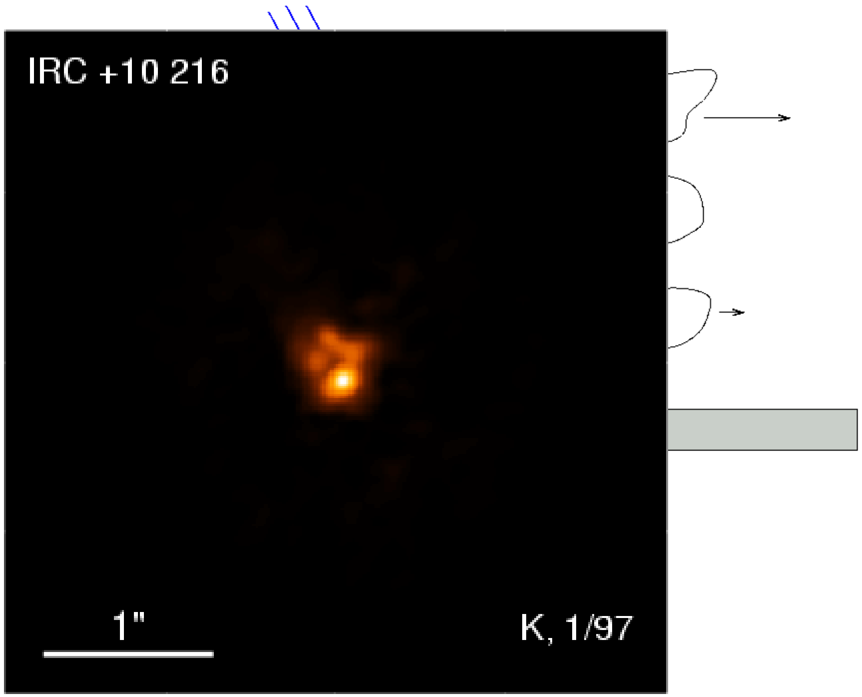


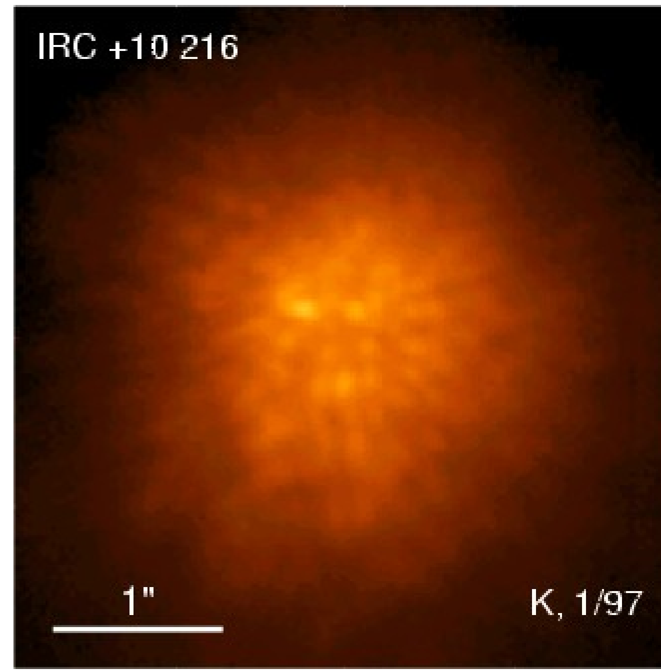
Speckles pattern

Observational limits

2) Atmosphere
a) “Seeing”

Speckle interferometry





Deconvolved image

Observational limits

2) Atmosphere

a) "Seeing"

Approximation for seeing

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6}$$

Observational limits

2) Atmosphere
a) "Seeing"

Approximation for seeing

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6}$$

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6} \gg 206265 \left(\frac{\lambda}{D} 1.22\right)$$

Observational limits

2) Atmosphere
a) "Seeing"

Approximation for seeing

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6}$$

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6} \gg 206265 \left(\frac{\lambda}{D} 1.22\right)$$

$$\alpha_{FWHM} \propto \lambda^{-0.2} sec\, z^{0.6} \propto 206205 \frac{\lambda}{r_0}$$

Fried parameter, approx 10cm

Observational limits

2) Atmosphere
a) “Seeing”

Some other concepts you will see at some point:
- •Characteristic length (Fried parameter)
- •Strehl ratio: peak PSF/peak Diff. Limit
- •80% energy diameter

Observational limits

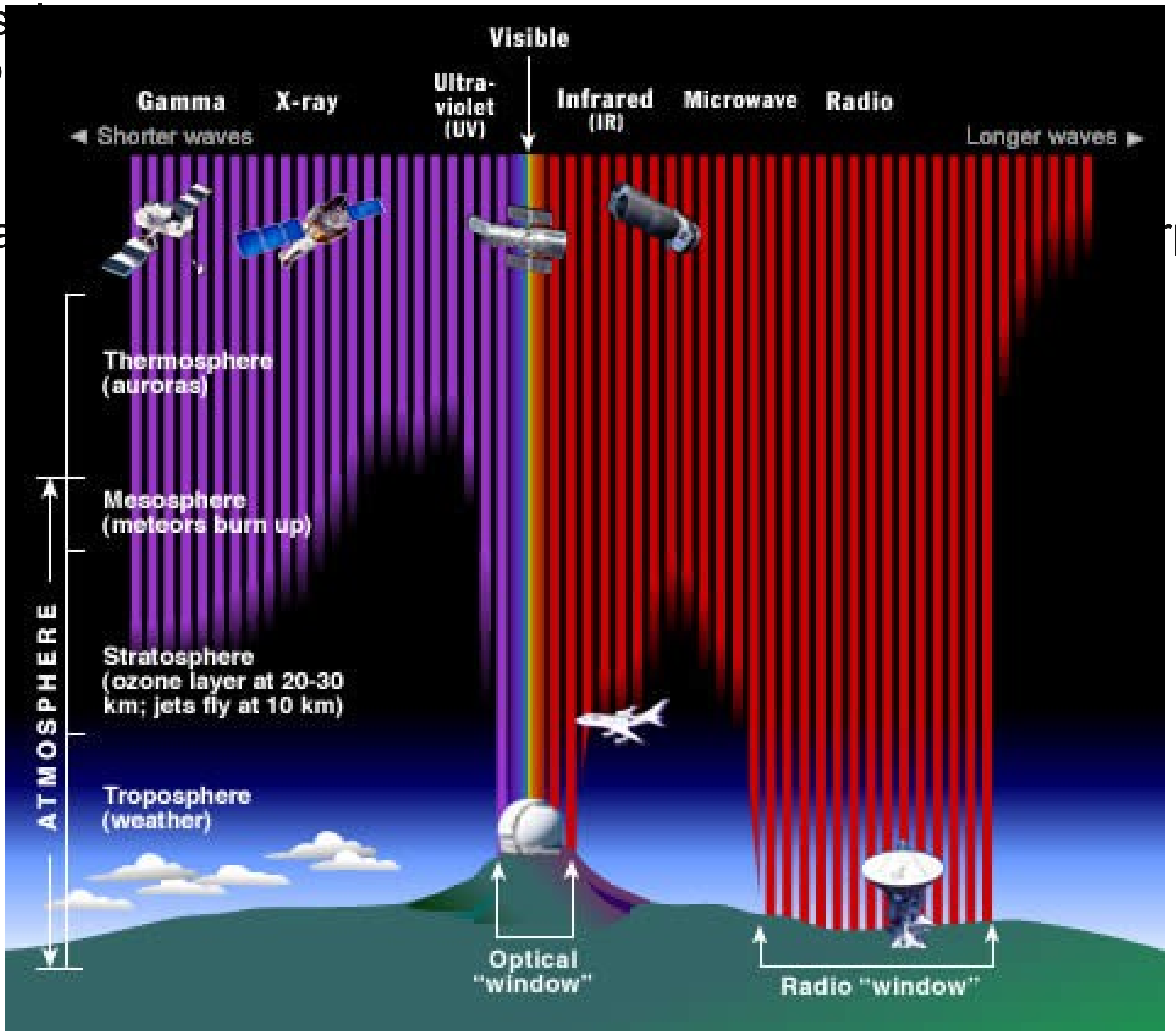
2) Atmosphere
b) “Absorption”

Scattering (eg. Rayleigh scattering by air molecules) and absorption..

Observational limits

2) Atmos
b) "Abso

Sca ... rption..



Observational limits

2) Atmos
b) “Abso

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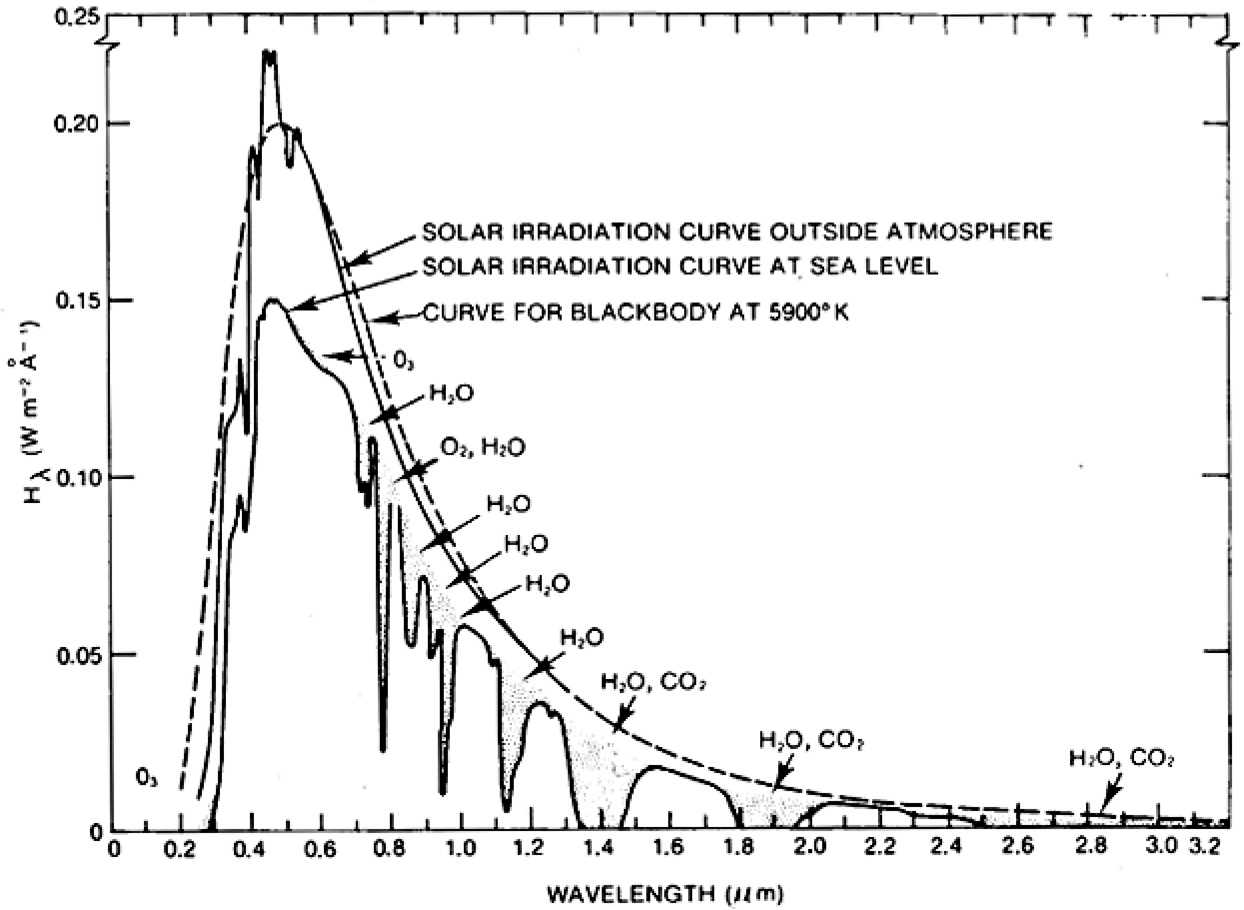
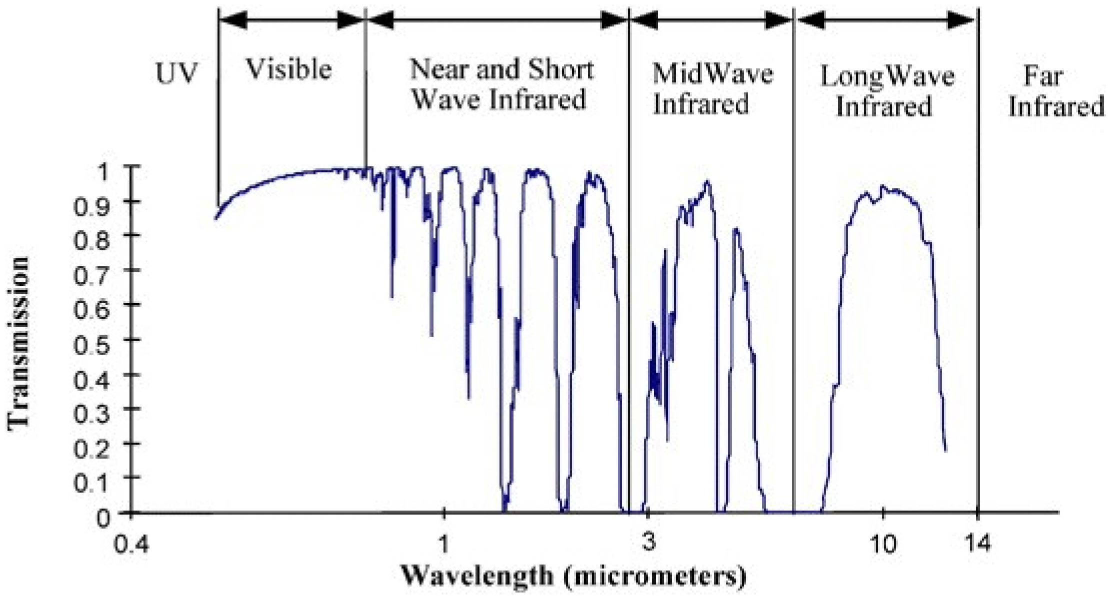


Observational limits

2) Atmosphere
b) "Absorption"

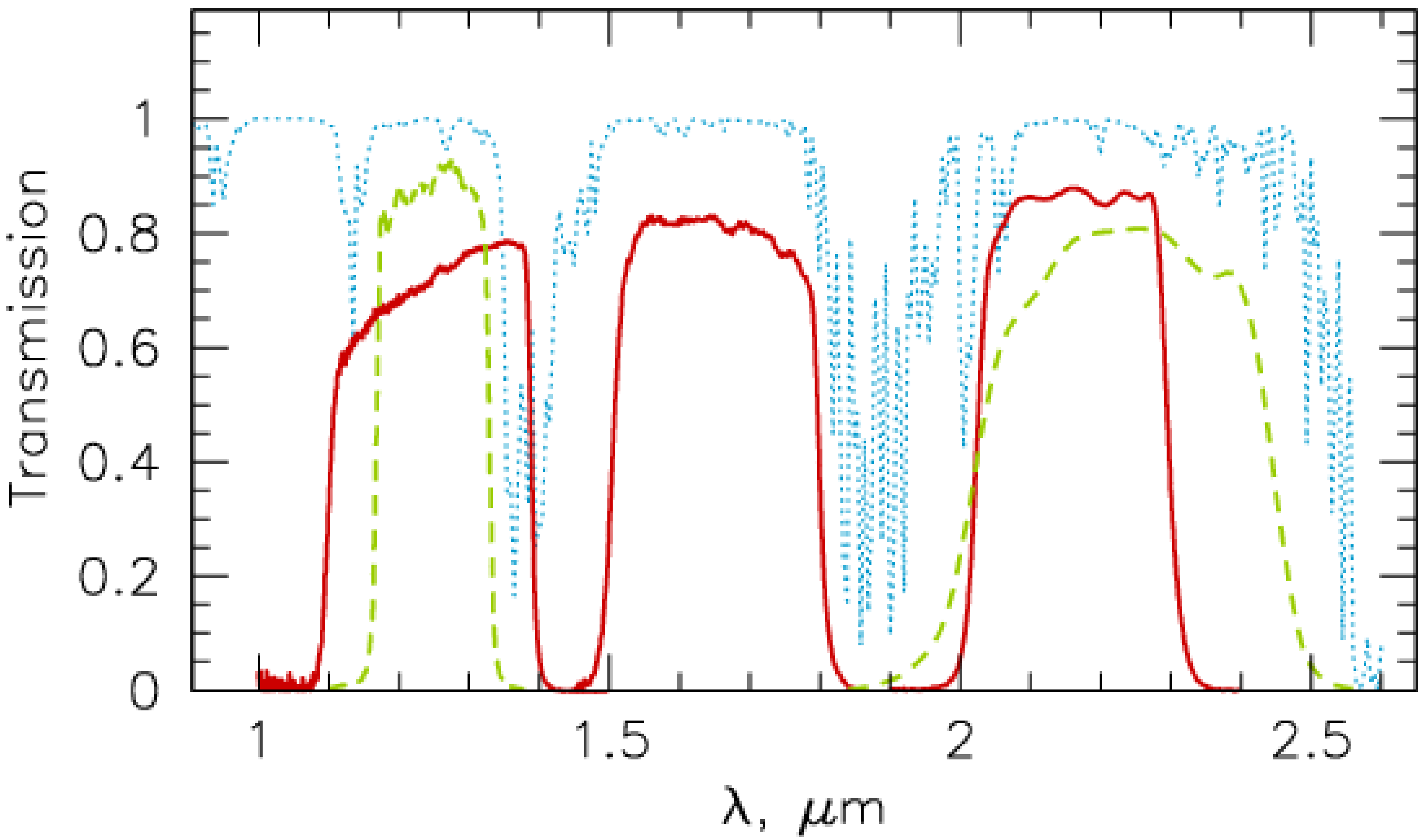
Transmission bands.



Observational limits

2) ʻʻ . ˈ
b)

SOFI/NTT mid-IR filters



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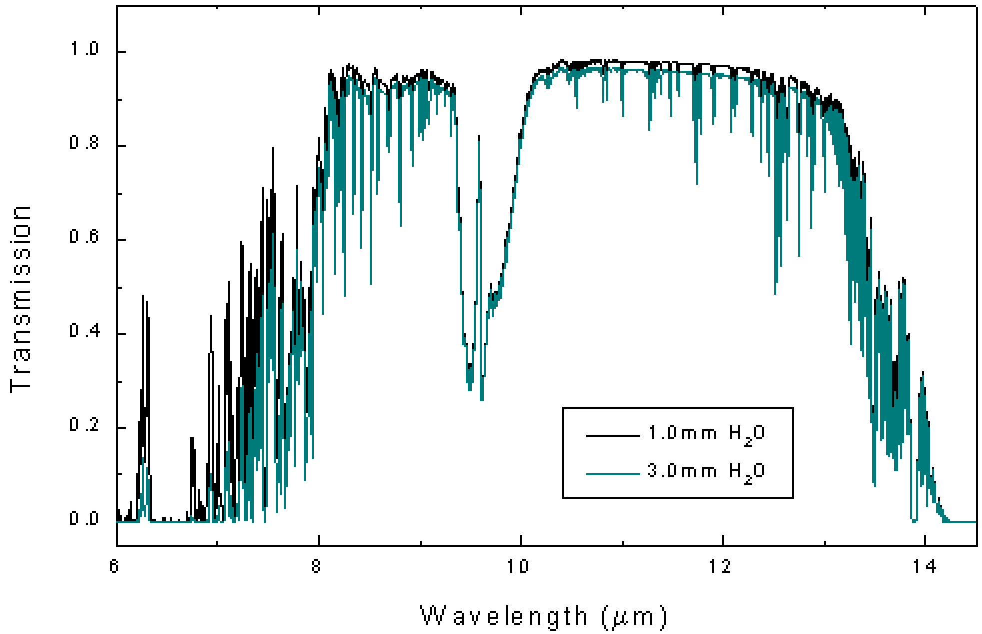
Observational limits

2) Atmosphere
b) “Absorption”

Water vapor dangerous for IR astronomy!.

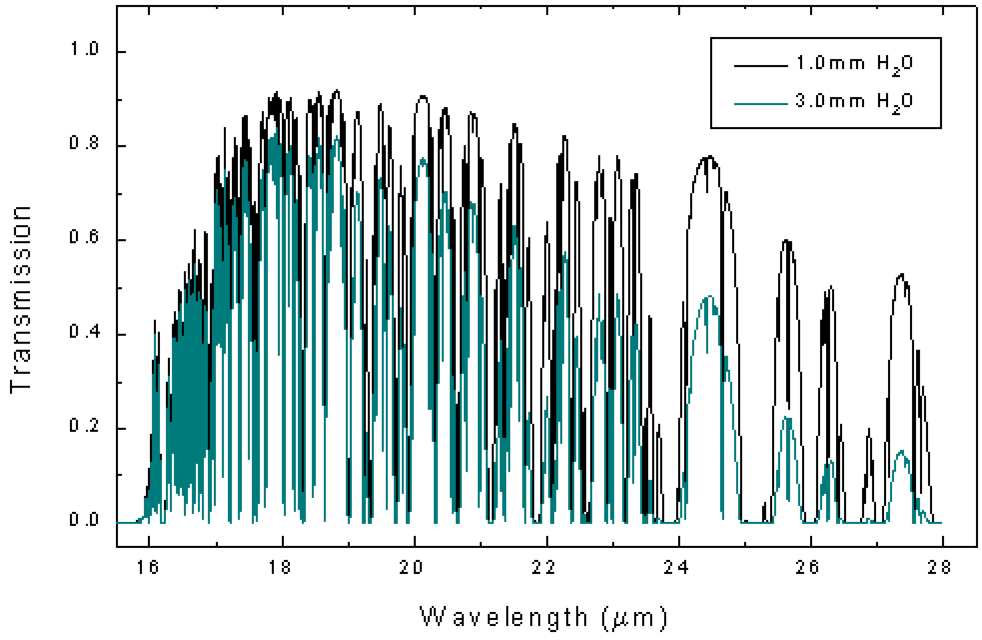


Mauna Kea water vapor transmission

Observational limits

2) Atmosphere
b) "Absorption"

Water vapor dangerous for IR astronomy!.



Mauna Kea water vapor transmission

Observational limits

2) Atmosphere
c) “Sky brightness”

Skybrightness depends on:
•Scattered sun and moon light
•Airglow (eg., auroras)
•Air pollution

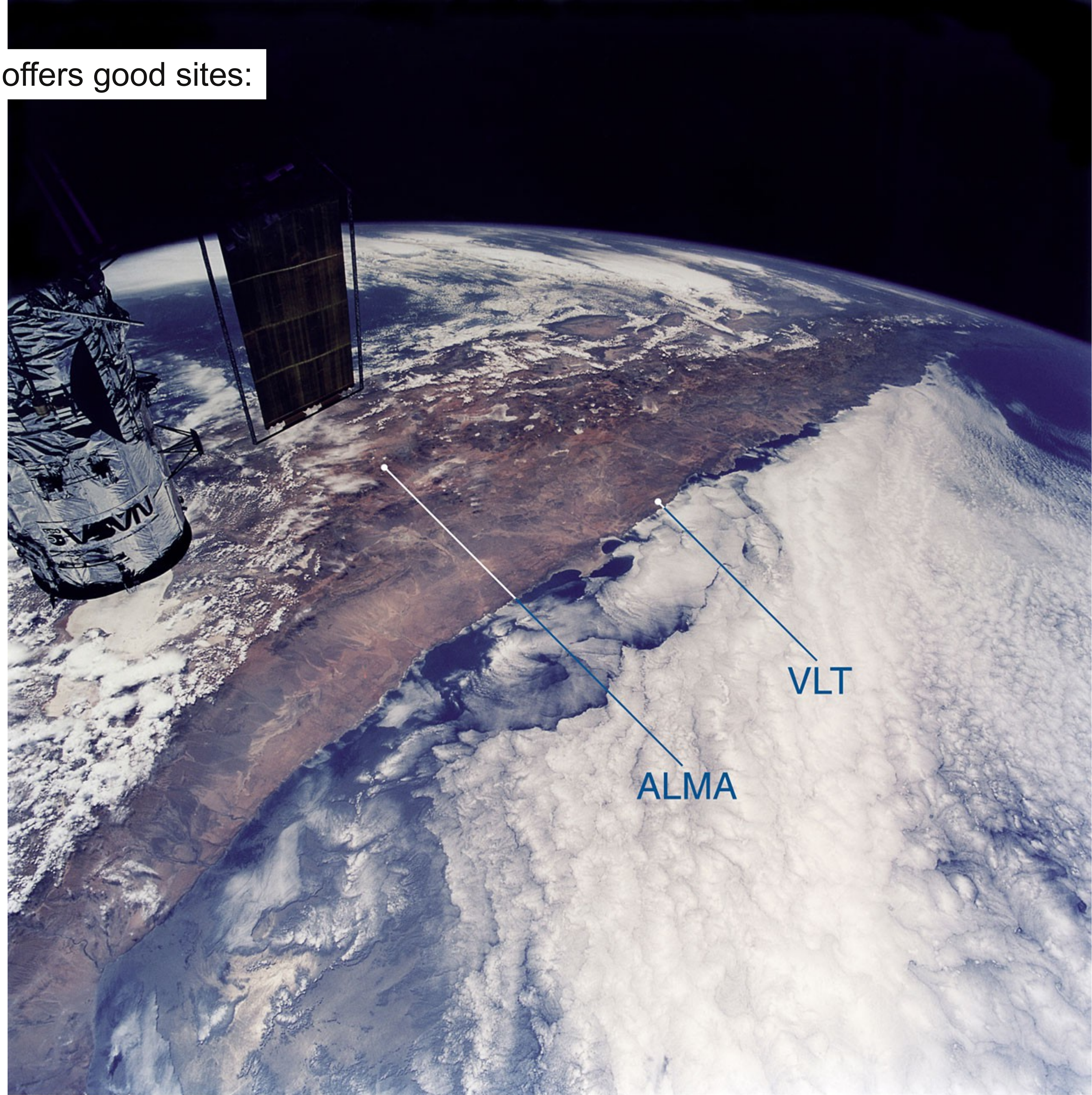
Observational limits

2) Atmosphere
c) “Sky brightness”

Days from new moon	Sky Brightness					
	U	B	V	R	I	z
0	22.0	22.7	21.8	20.9	19.9	18.8
3	21.5	22.4	21.7	20.8	19.9	18.8
7	19.9	21.6	21.4	20.6	19.7	18.6
10	18.5	20.7	20.7	20.3	19.5	18.3
14	17.0	19.5	20.0	19.9	19.2	18.1

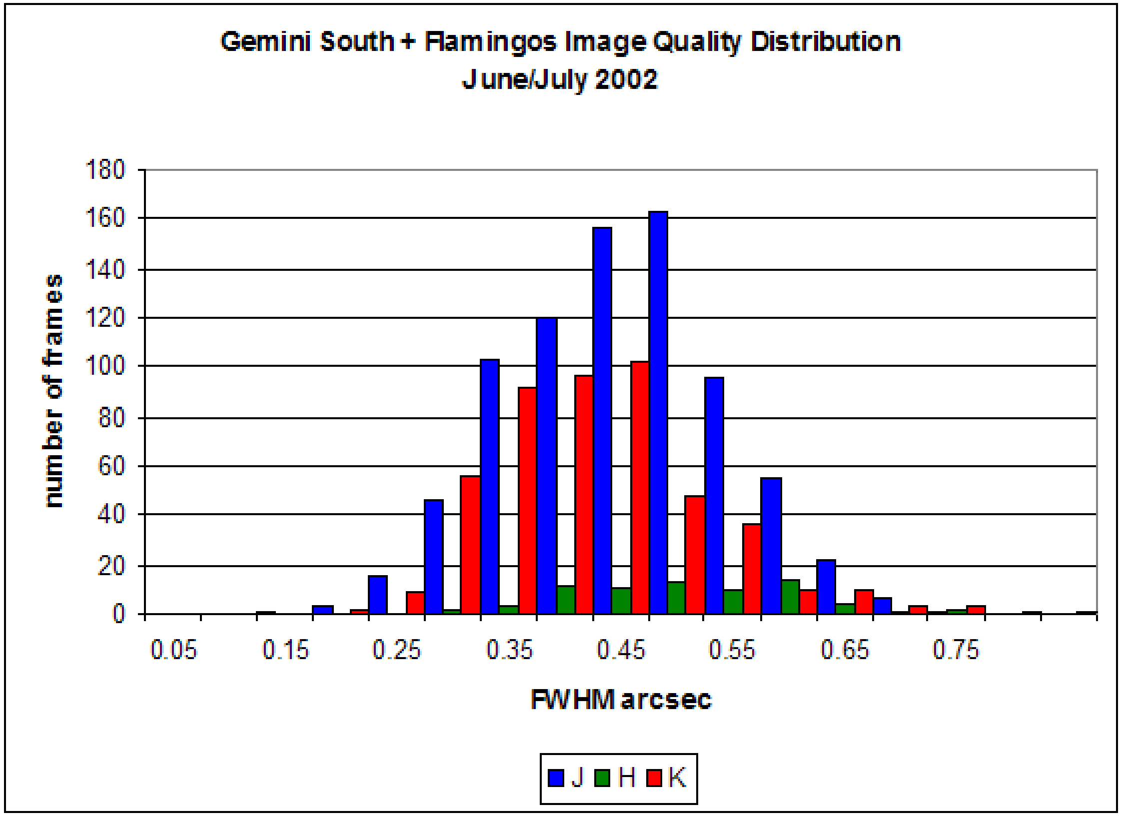
Sky surface brightness at La Silla

Why northern Chile offers good sites:

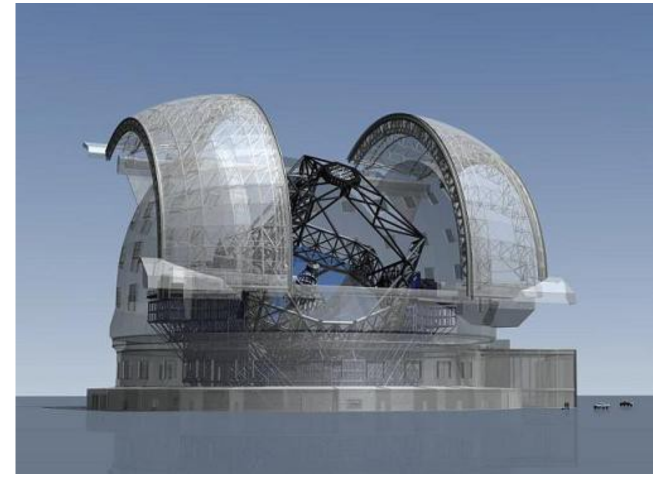


Observational limits

Why northern Chile offers good sites:



Observational limits



Conditions for a good astronomical site:

•Clear skies

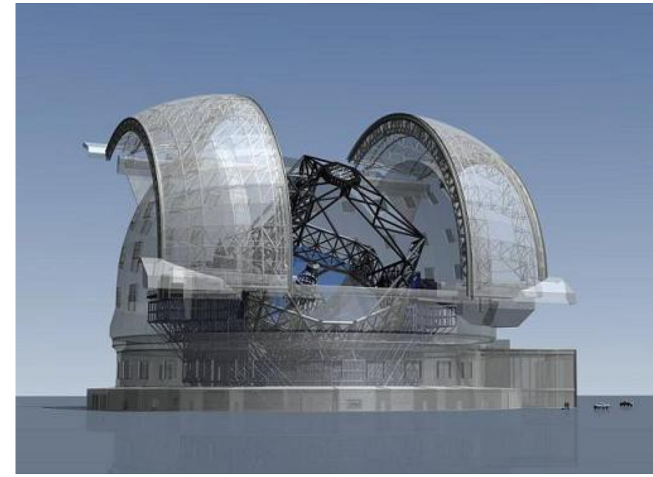
•Good seeing

•Dark skies

•Little water vapor

•Little radio pollution

Observational limits



Conditions for a good astronomical site:

•Clear skies

•Good seeing

•Dark skies

•Little water vapor

•Little radio pollution

Good sites are therefore: high, far from cities, and lie over the thermal Inversion layer

Observational limits

Conditions for

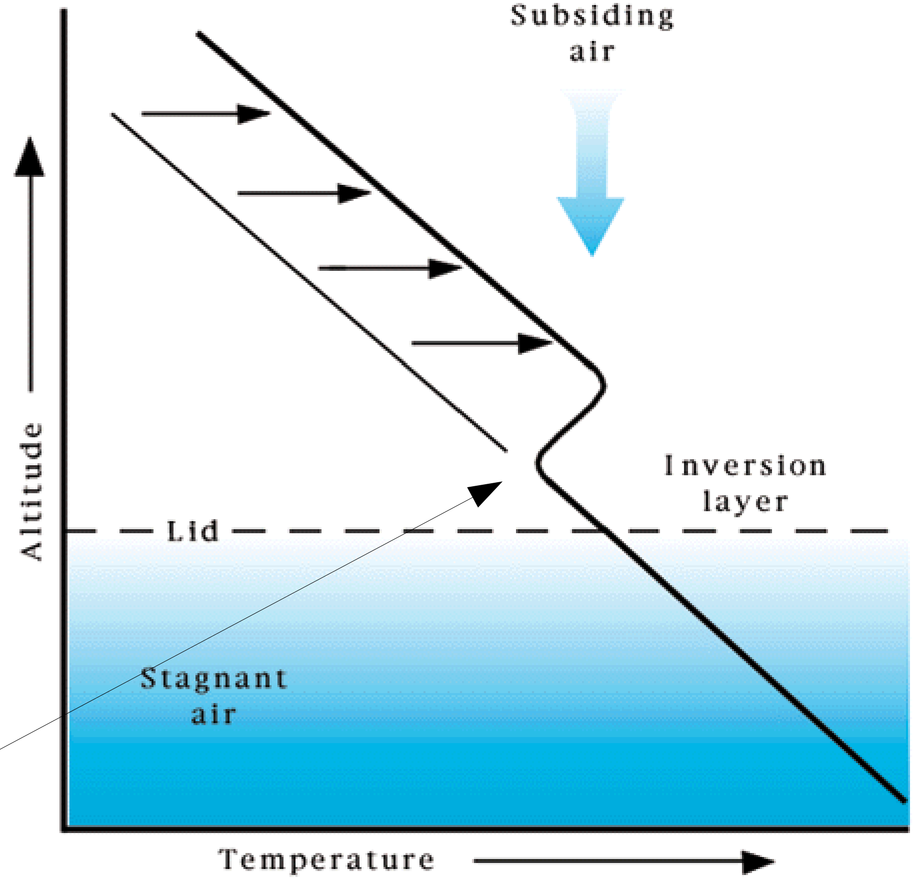
•Clear skies

•Good seeing

•Dark skies

•Little water va

•Little radio po



Good sites ar ... hermal
Inversion laye

Here is where most clouds form