Astro 500

Techniques of Modern *Observational* Astrophysics

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Astro 500

- This course sets the foundation that will enable you to observe and process data to make expert astronomical measurements. To accomplish this we will establish
  - how instruments work;
  - how their design determines their science performance; and
  - the fundamentals of the measurement process.

- Attending the lectures and doing the homework are essential to learning the material.
- Readings are a resource to help you better understand the material. More on this in a moment.
- Specific examples of data analysis will often be given in terms of IRAF. Not necessarily the best, but widely available and free.
- Knowledge of IRAF helpful. Ability to program in some language essential.

Course Outline

1. Introduction
   - Overview
   - Fluxes & magnitudes,
   - Statistics & errors
2. Digital detectors
3. Telescopes, optics & observing

MX-1

4. Imaging cameras
5. Spectroscopy-I: dispersive systems
6. Spectroscopy-II: grating-dispersed spectrographs

MX-2

7. Spectroscopy-III: interferometry
8. 3D spectroscopy: current and future
9. Data processing and image analysis

MX-3

Syllabus

Class Website: http://www.astro.wisc.edu/~mab/education/astro500

- Course outline & schedule
- Handouts, lectures, homework and reading will be posted

Homework:

- ~5 problem sets due over the semester.
- Discuss problems with your classmates, but you must write up your own solutions.

Exams: Three midterm exams (in-class)

Grading:

Approximate weights for grading:

Homework	30%	Midterms	3 x 20%
Participation	10%		

Texts

Required:

o McLean, “Electronic Imaging in Astronomy,” Wiley

Recommended:

o Walker, “Astronomical Observations,” Cambridge University Press
o Schroeder, “Astronomical Optics,” Academic Press

Other Useful References:

o Kitchin, “Astrophysical Techiques,” Adam Hilger, Ltd
o Bevington & Robinson, “Data Reduction and Error Analysis for the Physical Sciences,” McGraw-Hill
o Gray, “The Observation and Analysis of Stellar Photospheres,” Cambridge
o Cox, “Allen’s Astrophysical Quantities,” Athlone Press
o Press et al., “Numerical Recipes,” Cambridge

paperback

stellar
astronomer?
get this one

Other material & credits

- Additional reading material will be provided as references in lectures and articles posted on web.
- Some lecture material kindly provided by M. Bolte (UCSC) & A. Sheinis (UW-Madison) and others cited along the way.

Lecture Outline

I. Introduction

- ✓ Course overview and summary
- Why astronomy is different
- Properties of light and astronomical information
- Astronomical foregrounds and backgrounds
- Large telescopes: overview

II. Fluxes & magnitude systems

- Luminosity & flux
- The *neper*: photons
- Magnitudes & magnitude errors
- Astronomical magnitude systems

Astronomy is different

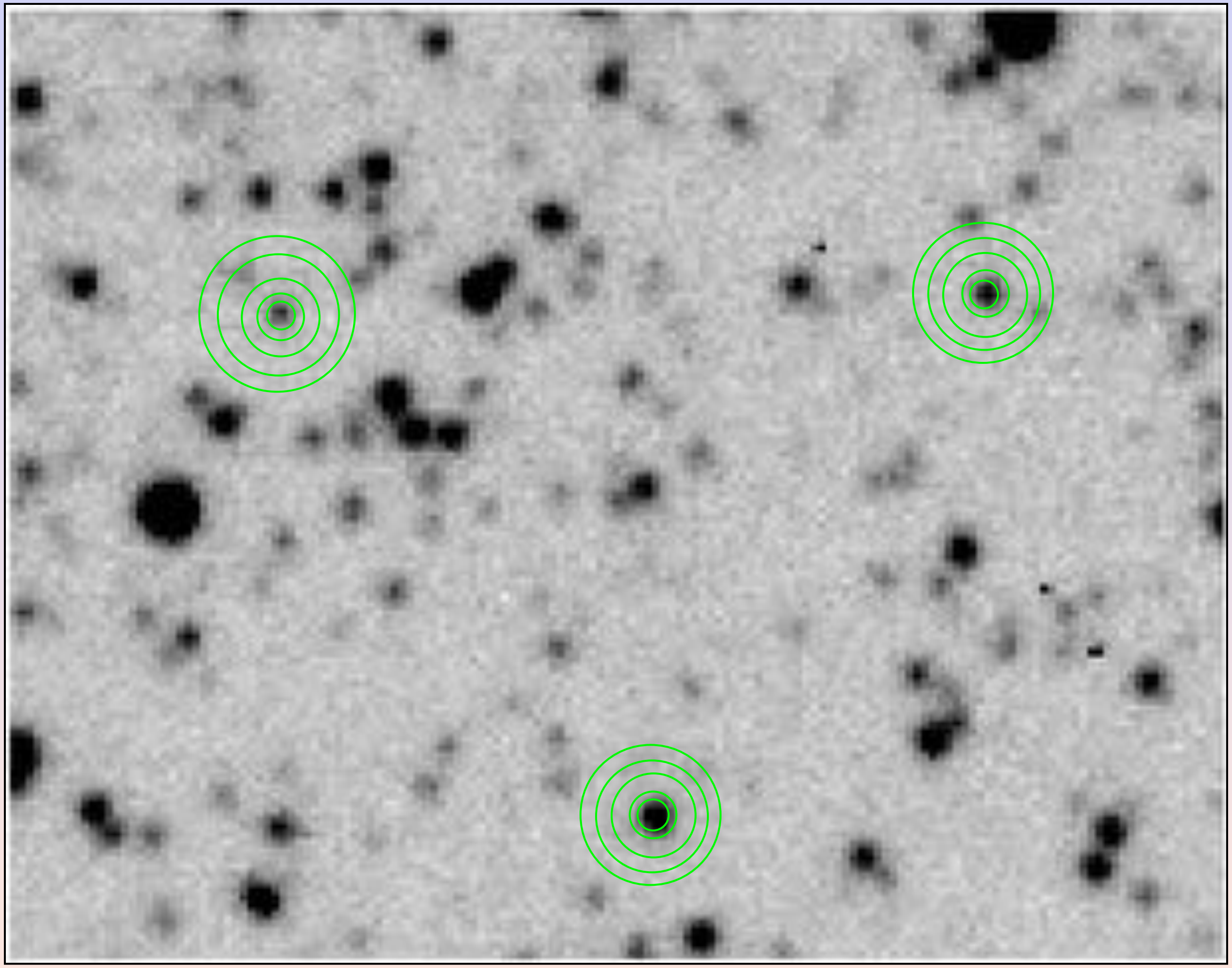
- Universe is both laboratory and specimen.
- We can only observe, no interaction: passive data collection.
- Have only the properties of light as information carrier
- Cannot measure *distances* directly, must infer from the measurement of light and astrophysically motivated inference.
- Limited to phenomena occurring in the past, but there is a time domain, i.e., repeat obserevations.
- Must take, and then interpret "snapshots."

- Telescopes and their instruments are our cameras.

Properties of light

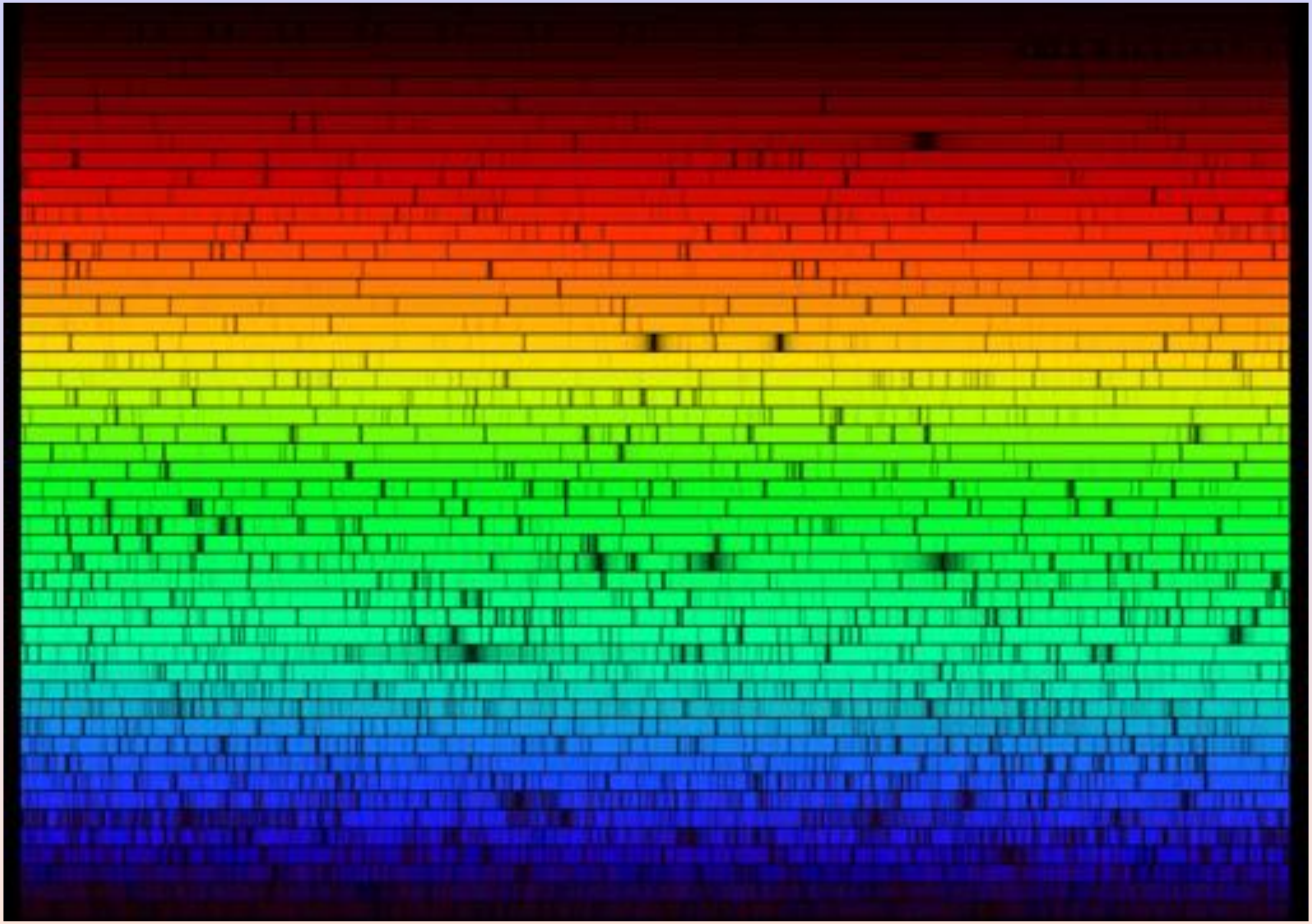
- Intensity: flux, irradiance, amplitude
- Position: Angle of arrival, image
- Color: wavelength(frequency)-dependent amplitude (spectral energy distribution)
- Angular momentum: spin, polarization
- Frequency (time): variability of any of the above
- Phase: interferometry (radio, adaptive optics)

Images



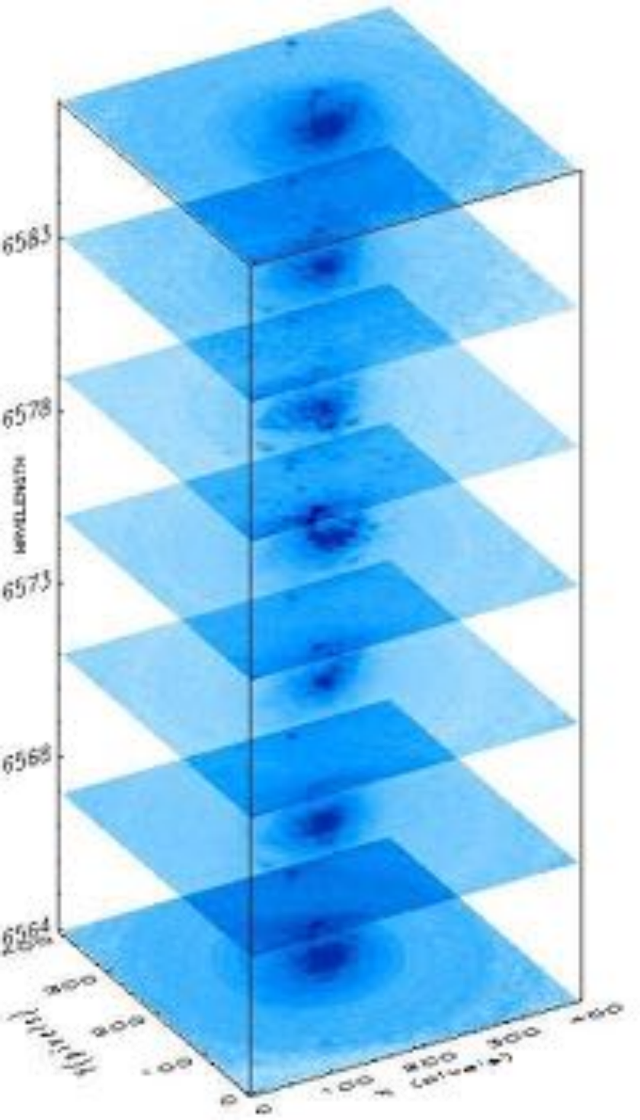
- Intensity
- Position
- Size & shape
- Color
- Polarization
- Variability

Stellar Spectra

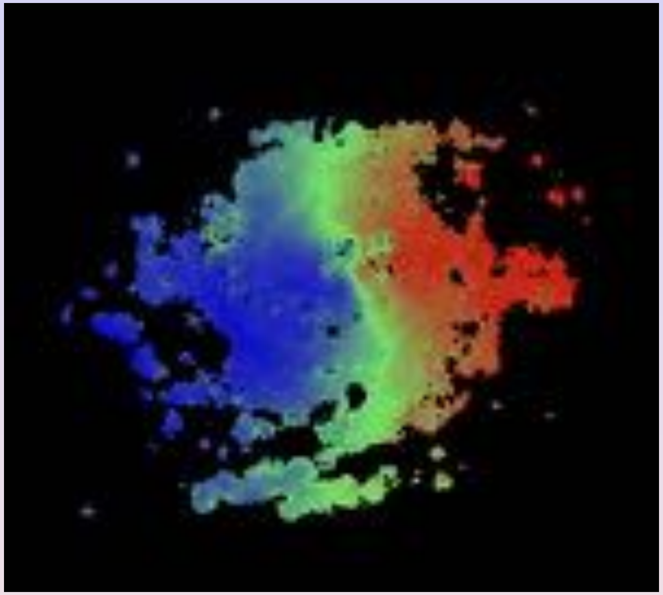


- Temperature
- Pressure
- Kinematics:
  - Rotation
  - Turbulence
  - Pulsation
- Abundances
- Variability

3D Spectra



Fabry-Perot data cube



Color-coded
velocity map

A few good numbers…

$\mathrm{m} \times 10^{-6} = \mathrm{cm} \times 10^{-4} = \mathrm{mm} \times 10^{-3} = \mu\mathrm{m} = \mathrm{nm} \times 10^{3} = \text{Å} \times 10^{4}$

- Solar black-body peak: 0.5μm, 500 nm, 5000 A
- Silicon band-gap (red-limit CCD): 1μm
- Thermal IR-limit: 2.3-2.4μm
- Wien's law: λ_{BB} (μm) = 2900/T(Kelvin)
- HI line-emission (neutral Hydrogen spin-flip):
  $\lambda = 21$ cm, $\nu = 1.4$ Ghz
- HII line-emission:

$B\alpha = 4.05 \mu\mathrm{m}$	Brackett
$P\alpha = 1.87\ \mu\mathrm{m}$	Paschen
$H\alpha = 656$ nm	Balmer
$H\beta = 486$ nm	
$Ly\alpha = 121.6$ nm	Lyman

…more good numbers later.

Foregrounds & Backgrounds

Foregrounds

- Airglow (molecular and thermal)

ground

- Atmospheric scattered light (solar & terrestrial)

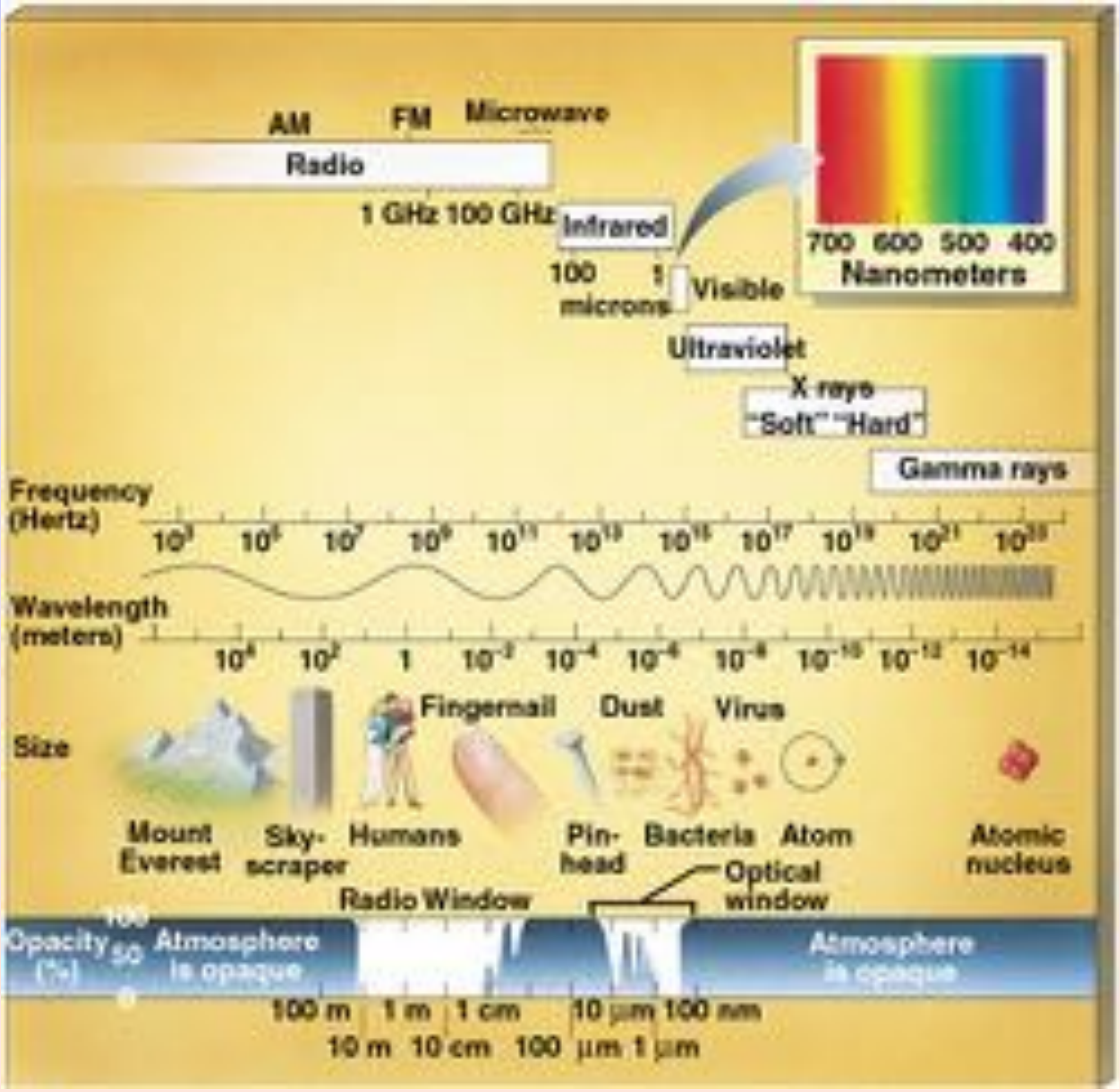
space

- Zodiacal light (solar light scattered off interstallar dust)
- Galactic stars and gas
- Nearby galaxies
- Distant galaxies
- CMBR

Backgrounds

Emission

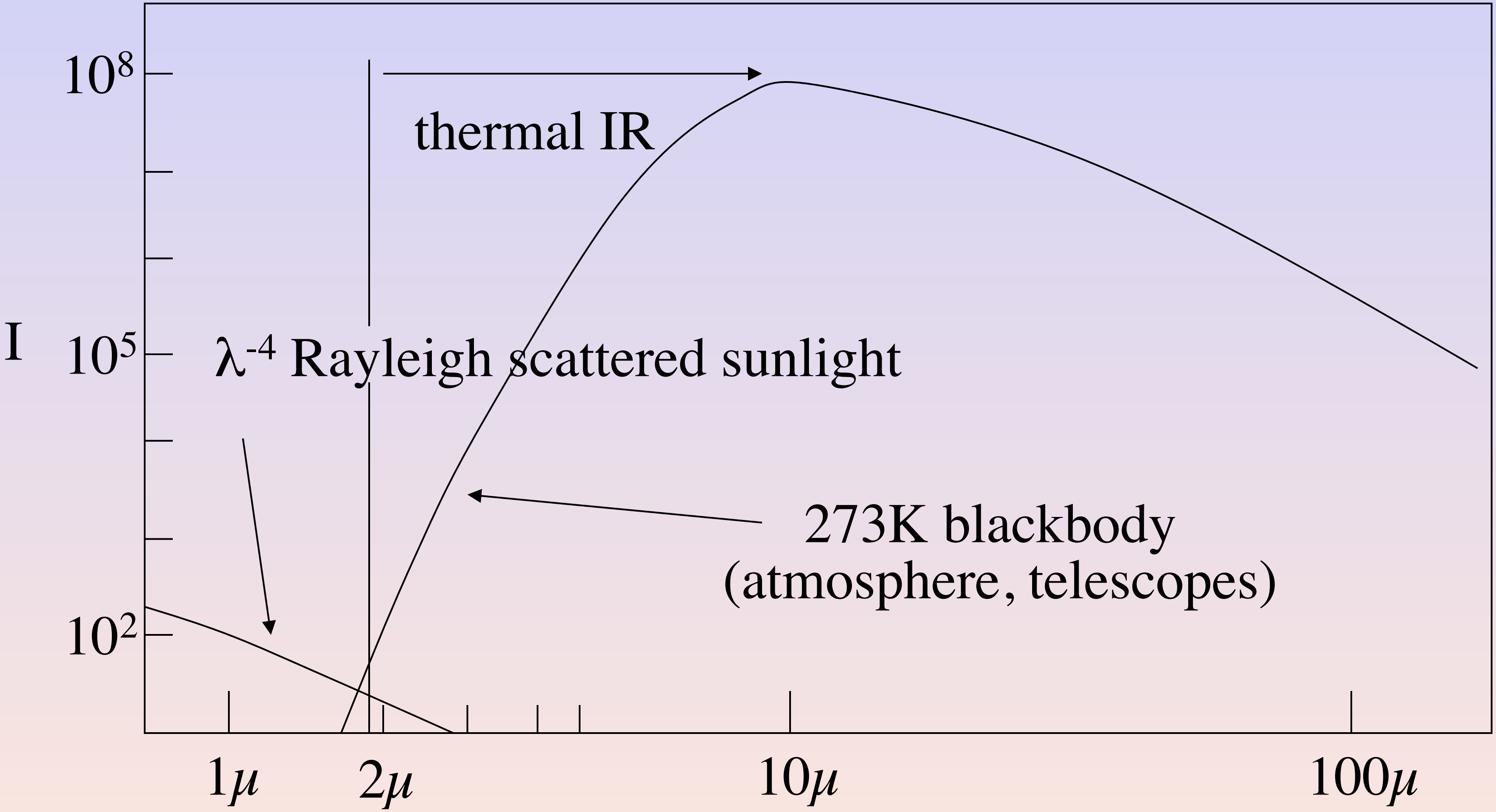
Foregrounds: extinction too!



Scattering & absorption

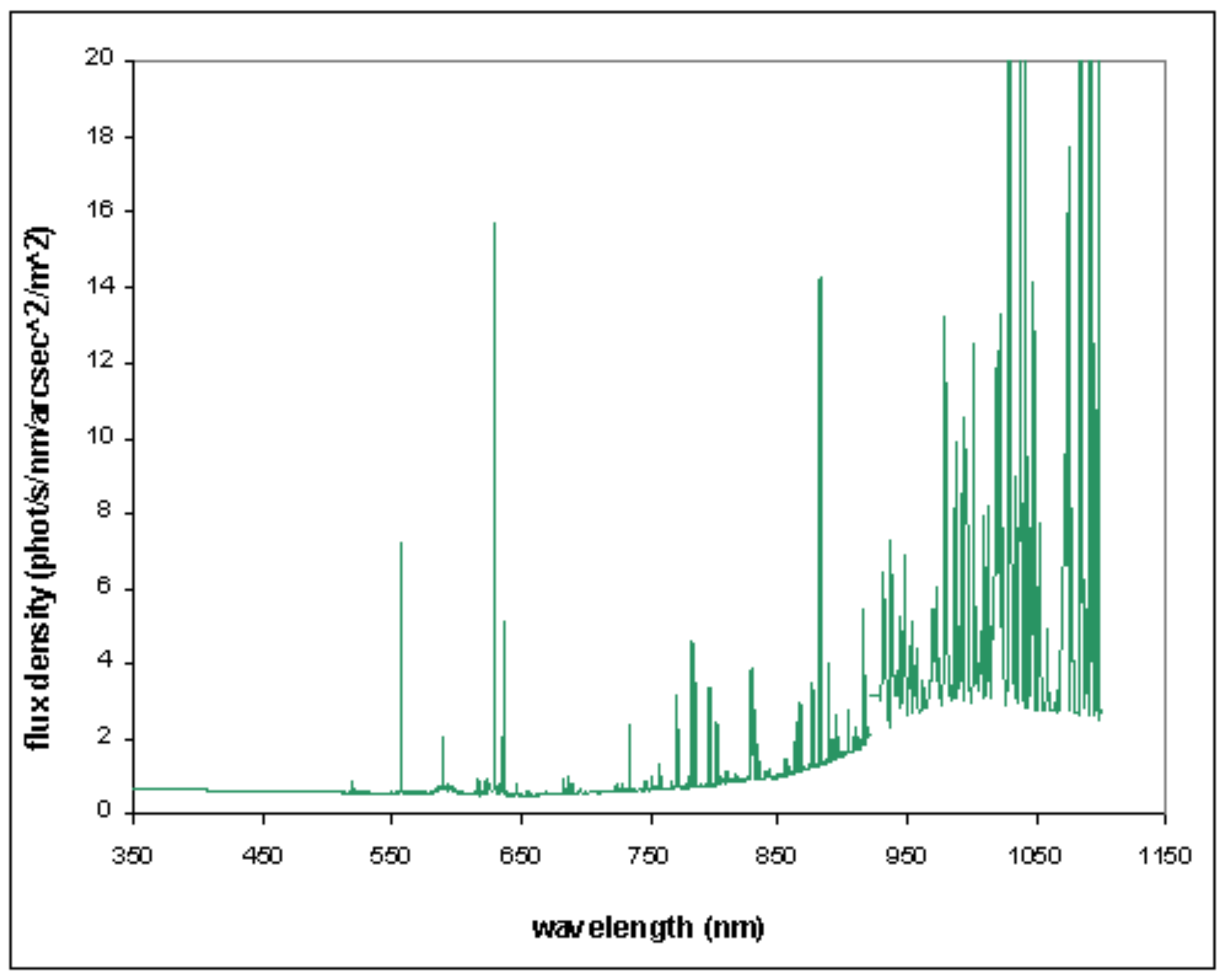
- Atmosphere
- Galactic dust & gas
- Distant galaxies
- Intergalactic dust & gas

Terrestrial Foregrounds

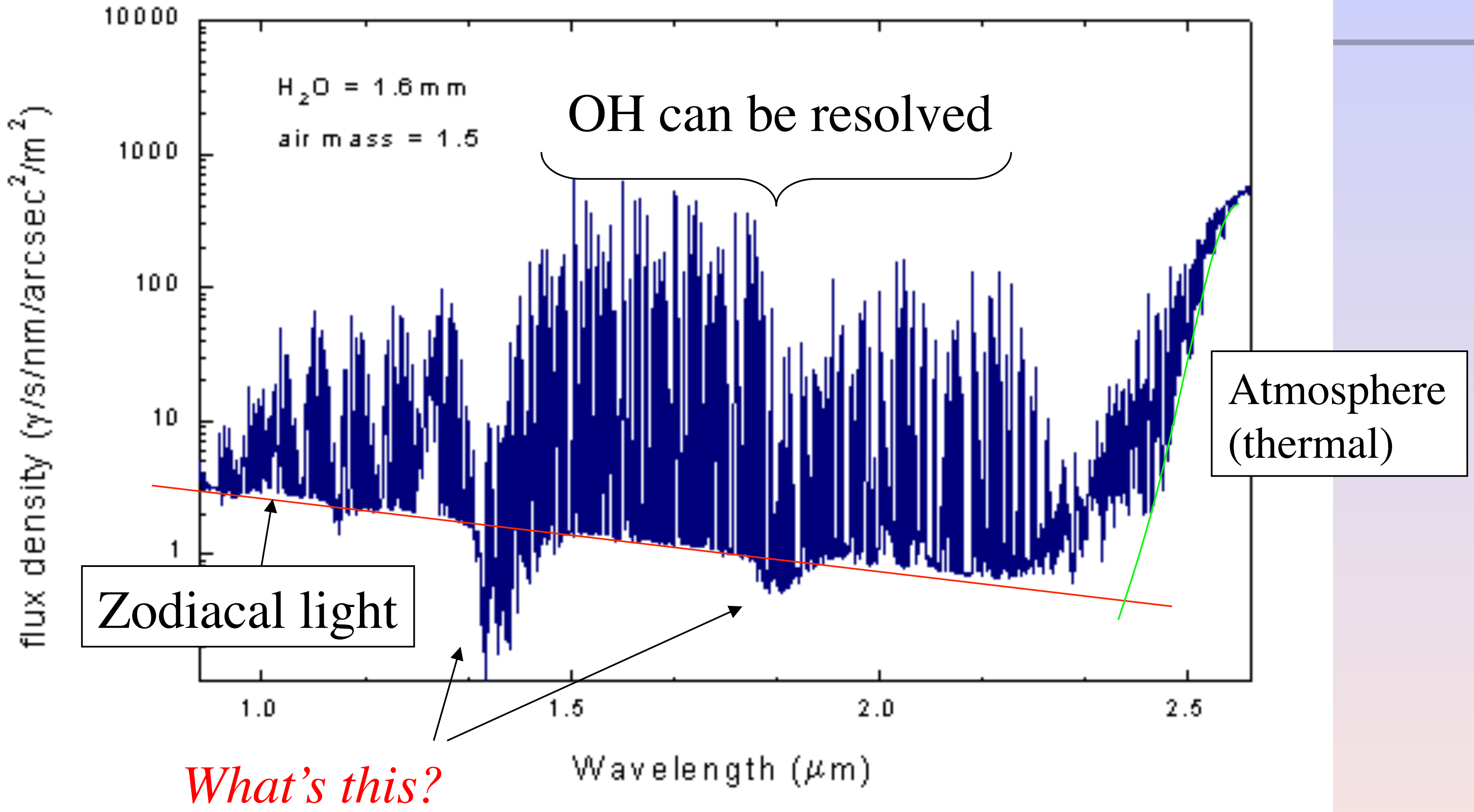


Scattered light and thermal emission

Terrestrial Foregrounds



Atmospheric molecular emission: time, position, and λ dependent



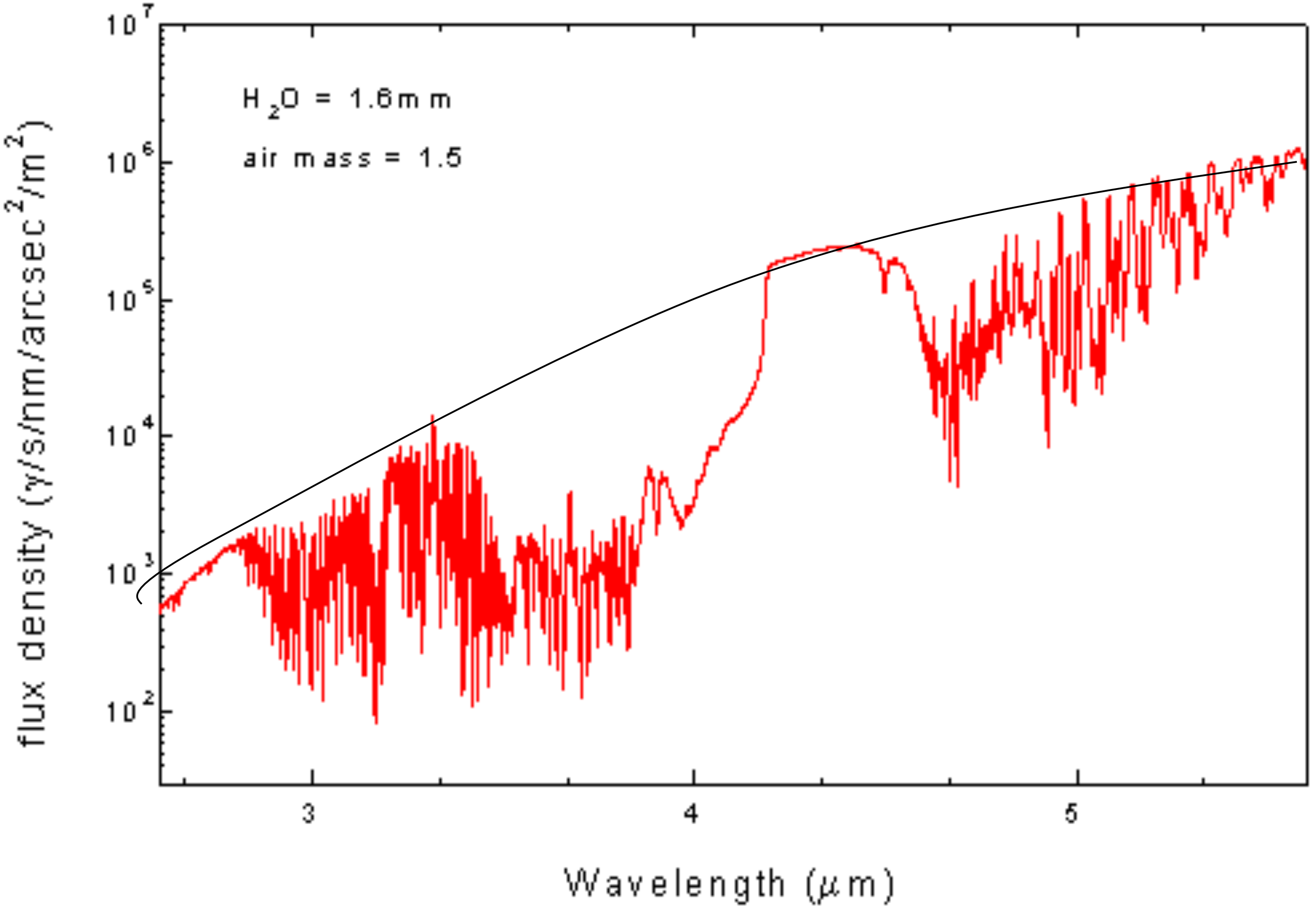
OH can be resolved

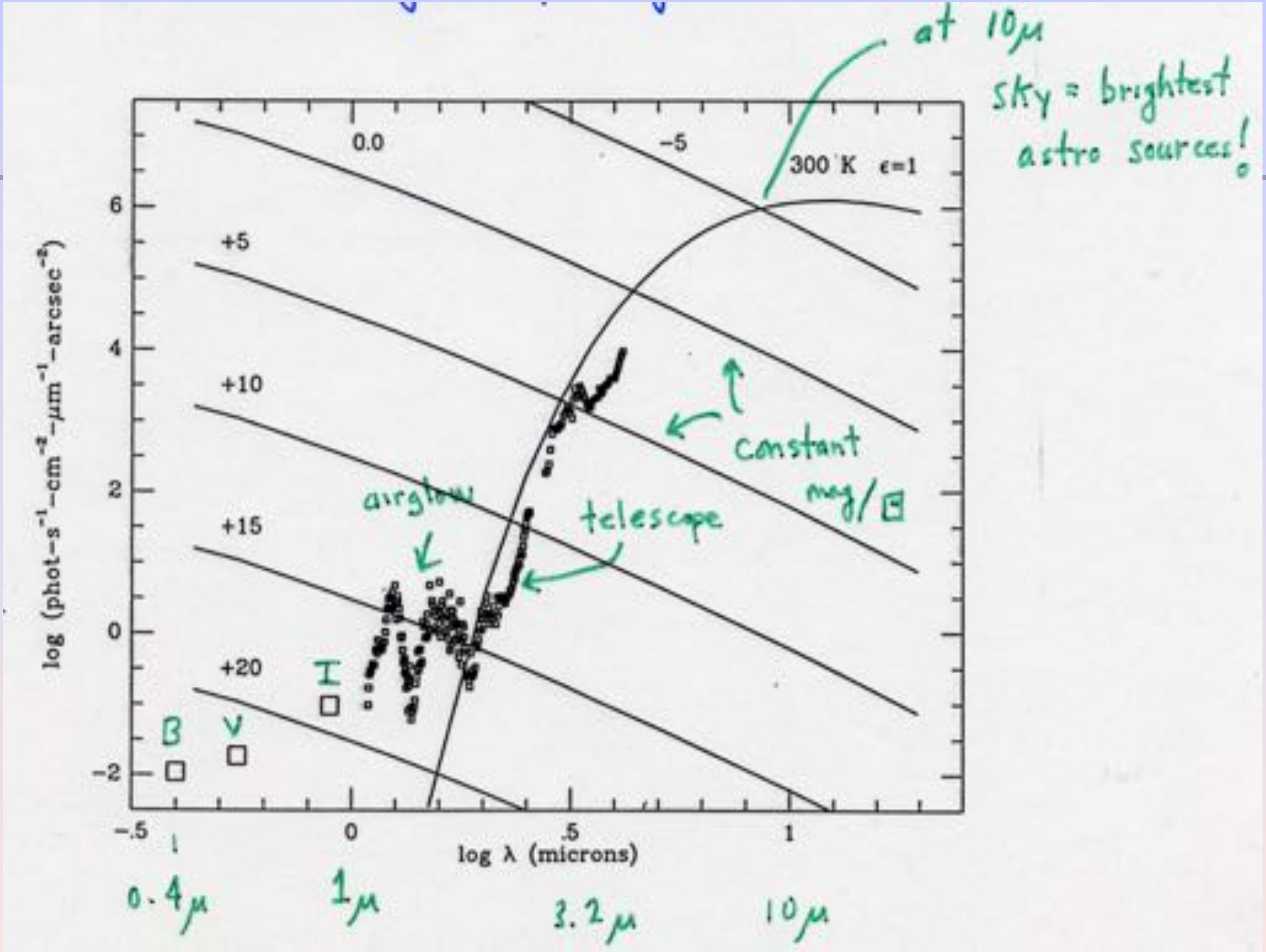
Atmosphere (thermal)

Zodiacal light

What's this?

Note vertical scales on plots!





at 10μ sky = brightest astro sources!

constant mag/□

LargeTelescopes

- Light buckets …

- Only two (Keck I and II) available in the 90’s
- Several available at the turn of the century (the 4 VLT units, Gemini North and South, Subaru, HET)
- Three more on-line now: SALT, LBT, GTC
- and building begun already for 30-50m telescopes...

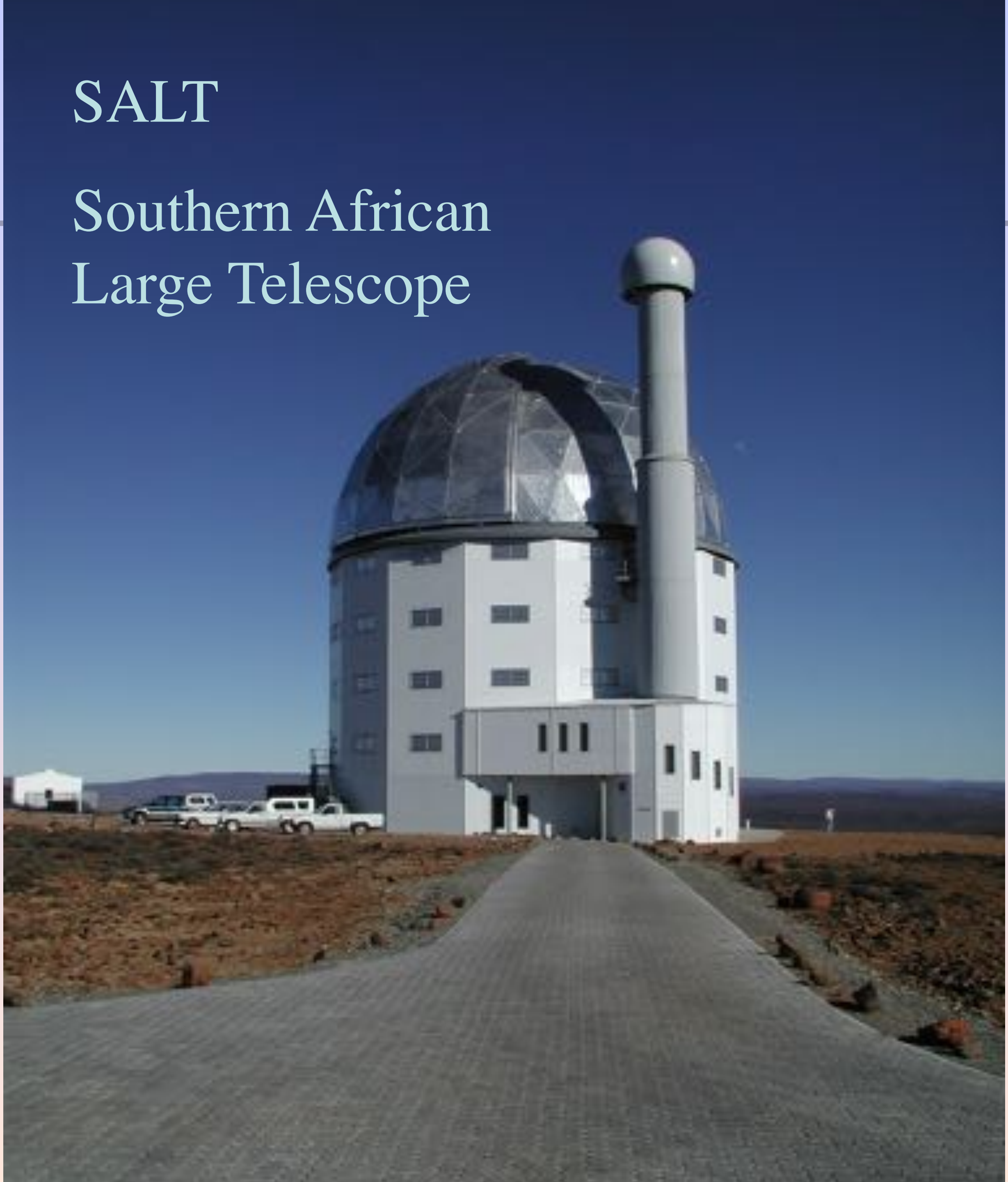
Telescopes: D≥5m

Table 1.1

Name	Diameter	Nationality of Sponsors	Site	Built
(SALT)	11.0 m	South Africa, USA, UK, Germany, Poland, New Zealand	South Africa	2005
(GTC)	10.4 m	Spain	Roque de los Muchachos Observatory, Canary Islands	2005
Keck 1	9.8 m	USA	Mauna Kea Observatory, Hawaii	1993
Keck 2	9.8 m	USA	Mauna Kea Observatory, Hawaii	1996
(HET)	9.2 m	USA, Germany	McDonald Observatory, Texas	1997
(LBT)	2x8.4 m	USA, Italy, Germany	Mount Graham Arizona	2004
Subaru (NLT)	8.3 m	Japan	Mauna Kea Observatory, Hawaii	1999
VLT 1 (Antu)	8.2 m	ESO Countries (European + Chile)	Paranal Observatory, Chile	1998
VLT 2 (Kueyen)	8.2 m	ESO Countries (European + Chile)	Paranal Observatory, Chile	1999
VLT 3 (Melipal)	8.2 m	ESO Countries (European + Chile)	Paranal Observatory, Chile	2000
VLT 4 (Yepun)	8.2 m	ESO Countries (European + Chile)	Paranal Observatory, Chile	2001
Gemini North	8.1 m	USA, UK, Canada, Chile, Australia,	Mauna Kea Observatory, Hawaii	1999
Gemini South	8.1 m	USA, UK, Canada, Chile, Australia,	Cerro Tololo Observatory, Chile	2001
MMT	6.5 m	USA	Fred Lawrence Whipple Observatory, Arizona	1999
Magellan 1	6.5 m	USA	Las Campanas Observatory, Chile	2000
Magellan 2	6.5 m	USA	Las Campanas Observatory, Chile	2002
BTA-6	6 m	Russia	Zelenchukskaya, Caucasus	1976
Large Zenith Telescope (LZT)	6 m	Canada, France	Maple Ridge, British Columbia	2003
Hale Telescope	5 m	USA	Palomar Observatory, California	1948

WIYN Telescope

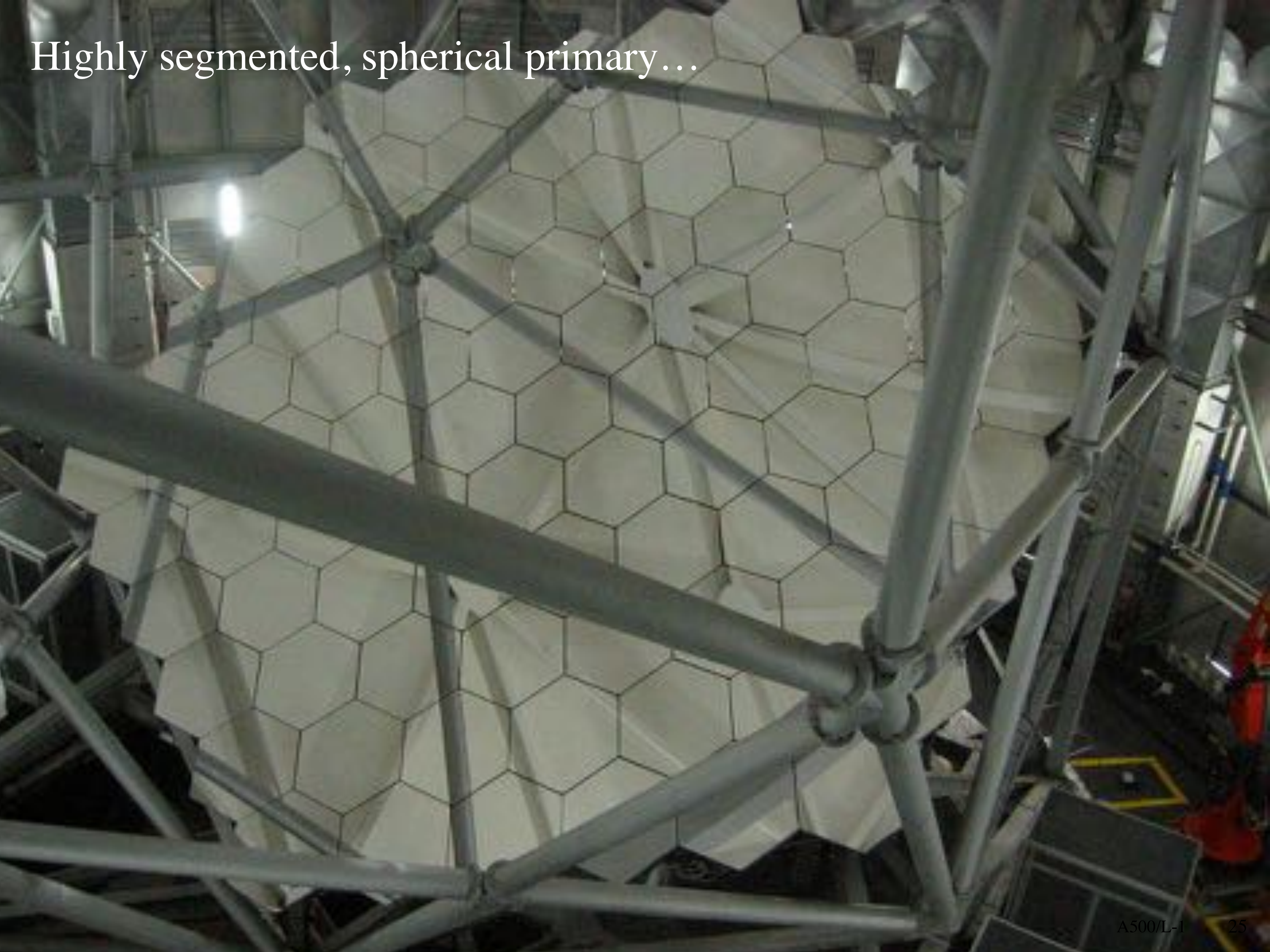
monolithic spin-cast 3.5m

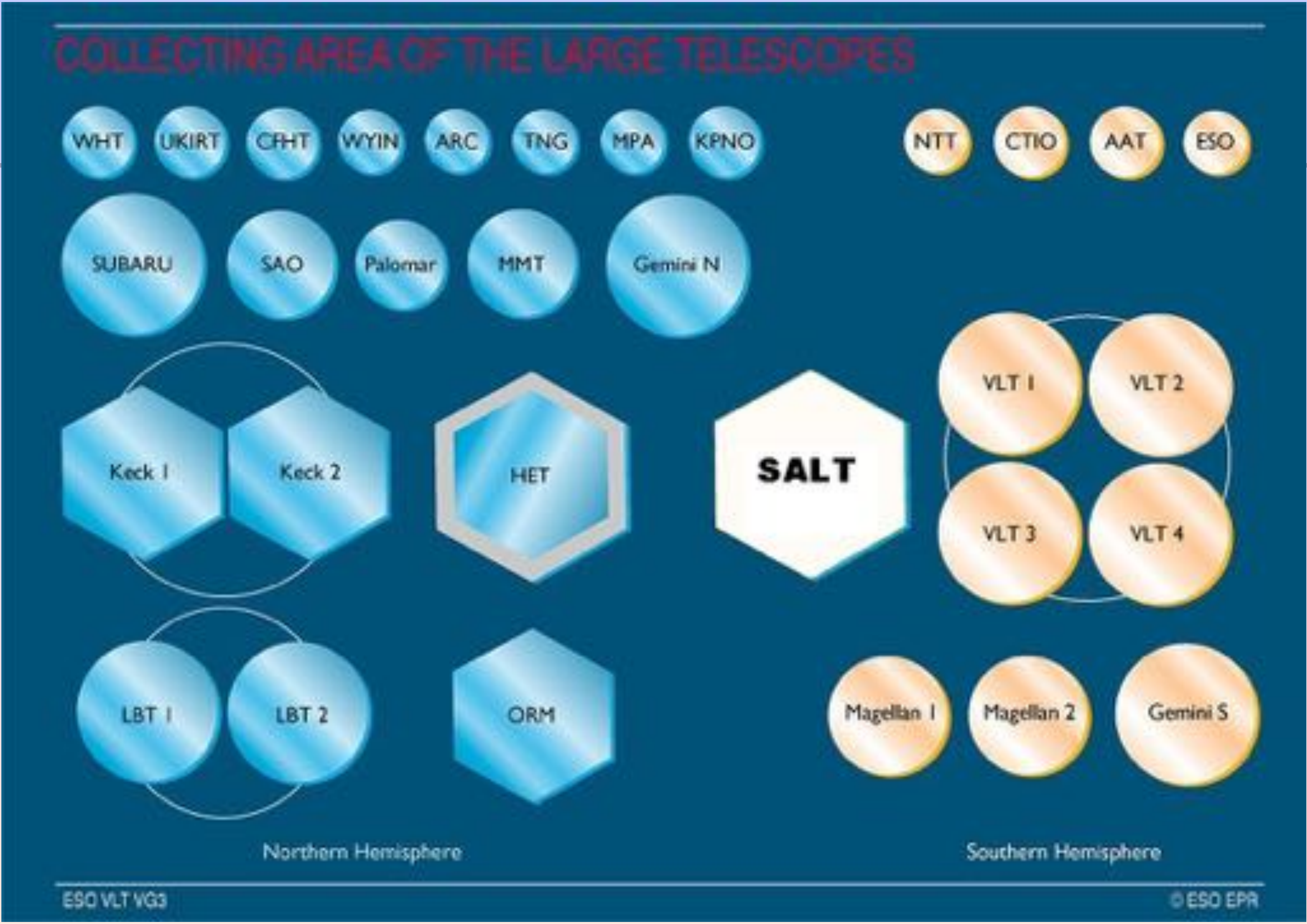


SALT

Southern African Large Telescope

Highly segmented, spherical primary…



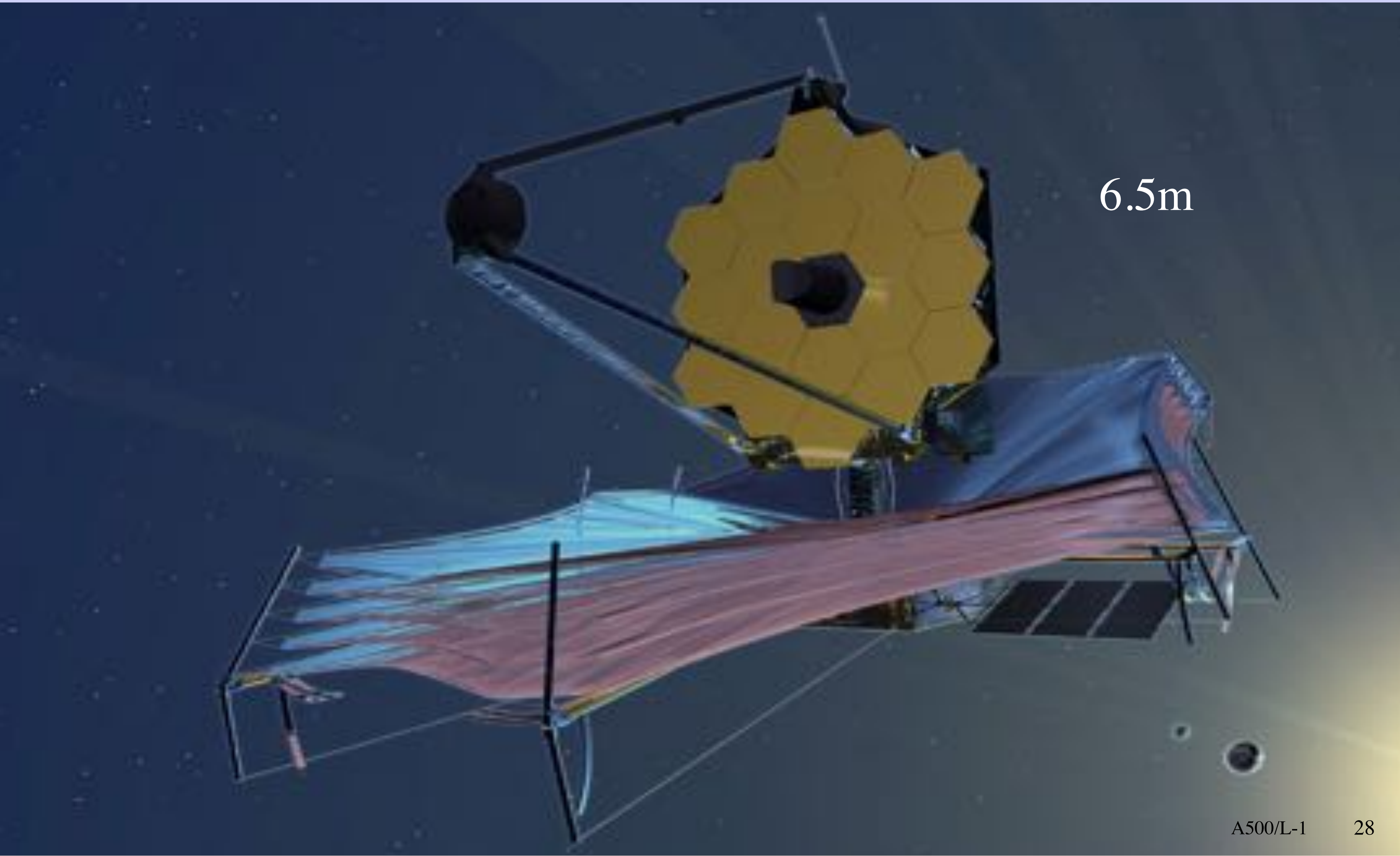

COLLECTING AREA OF THE LARGE TELESCOPES
WHT
UKIRT
CFHT
WYIN
ARC
TNG
MPA
KPNO
NTT
CTIO
AAT
ESO
SUBARU
SAO
Palomar
MMT
Gemini N
Keck 1
Keck 2
HET
SALT
VLT 1
VLT 2
VLT 3
VLT 4
LBT 1
LBT 2
ORM
Magellan 1
Magellan 2
Gemini S
Northern Hemisphere
Southern Hemisphere
ESO VLT VG3
© ESO EPR

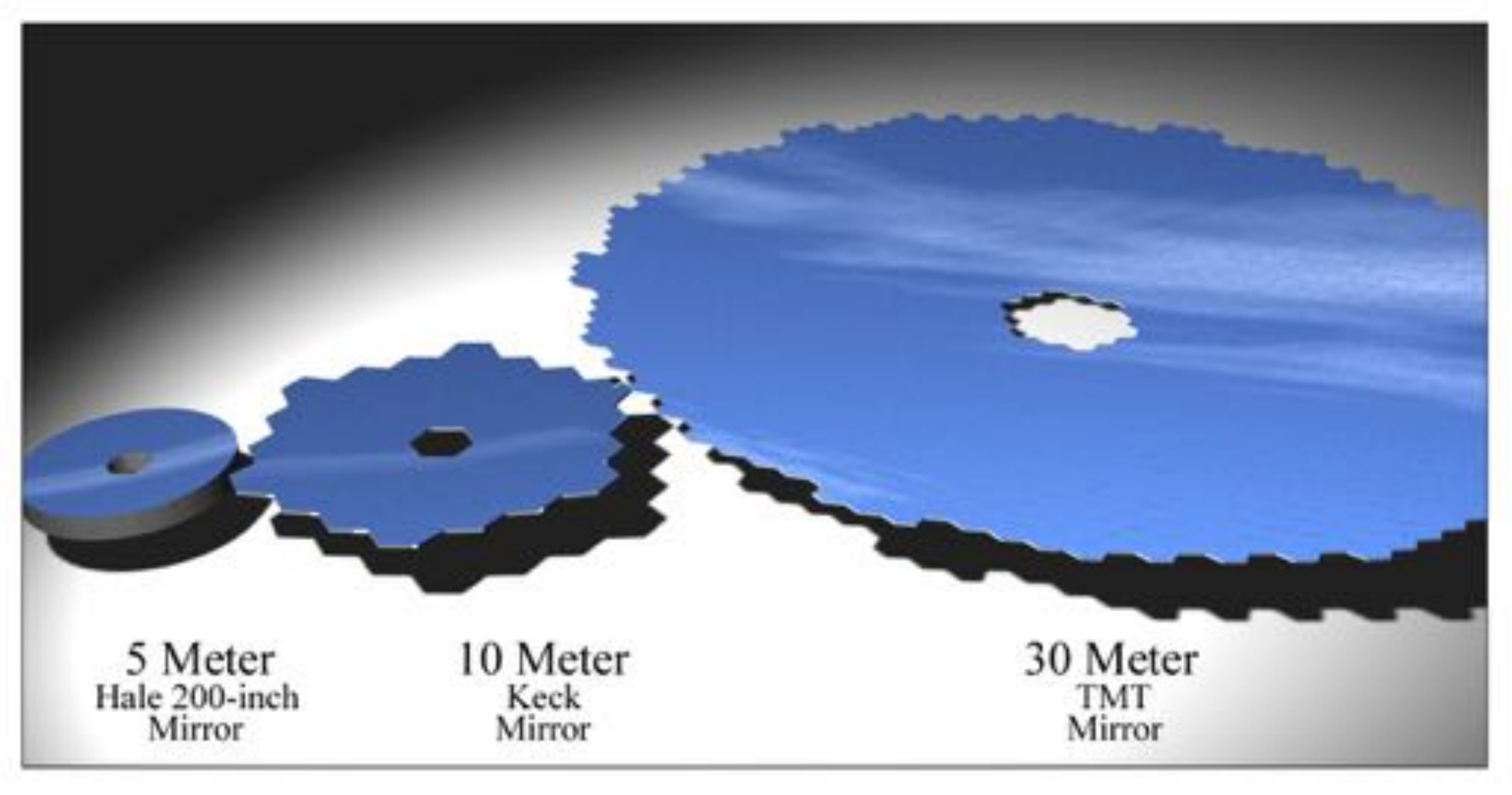
Future instruments

Ground-based 30m-class telescopes (TMT)

Future instruments

Space-based instruments: JWST




5 Meter
Hale 200-inch
Mirror
10 Meter
Keck
Mirror
30 Meter
TMT
Mirror

For next time:

Take a look at the texts :
Start the reading
Evaluate and purchase

Recall: properties of light

- Intensity, flux, irradiance, amplitude
- Angle of arrival, position, image
- Wavelength, frequency, color
- Angular momentum, spin, polarization
- Time variation (in some cases)
- Phase (interferometry, radio, AO)

Total E/t = Luminosity (L)

$$dE = L(t)dt$$

$$dE = L_\upsilon(t)d\upsilon\, dt$$

$$dE = L_\lambda(t)d\lambda\, dt$$

L_λ, L_ν = specific luminosity

All of the above are in units of energy flow per unit time, not photon flow rate.

Apparent Flux

$$dE_A = f_\upsilon \, dA \, d\upsilon \, dt$$

$$dE = f_\upsilon (4\pi R^2) \, d\upsilon \, dt = L_\upsilon \, d\upsilon \, dt$$

$$\therefore \quad f_\upsilon = \frac{L_\upsilon}{(4\pi R^2)}$$

and similarly for L_λ and f_λ. Again, all of the above are in units of energy flow per unit time, not photon flow rate.

- Flux is energy incident on some area dA of the Earth's surface.
- Flux is not conserved and falls off as R^{-2} for a point source.

➢ *What about extended sources?*

Flux Units

- Flux (f_ν): measured in Janskys
  - 1 Jy = 10^{-26} W m^{-2} Hz^{-1}= 10^{-23} erg sec^{-1} cm^{-2} Hz^{-1}
- Flux (f_λ): measured in ergs s^{-1} cm^{-2} $Å^{-1}$ (cgs units)
- Photon flux (f_γ) is useful for calculating signal-to-noise (counting statistics):
  - Define *neper* = $\Delta\lambda/\lambda = \Delta\nu/\nu = \Delta\ln\nu$
  - The photon flux is:
    - o photons sec^{-1} cm^{-2} $neper^{-1}$ = f_ν/h
    - o where h=6.6256 x 10^{-27} erg sec
  - Useful identify:

1 microJy = μJy = 15.1 photons sec^{-1} m^{-2} $neper^{-1}$

Apparent magnitudes

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{f_1}{f_2}\right) = -a\ln\left(\frac{f_1}{f_2}\right)$$

f_n: the apparent flux of object n.

$$a = 2.5\log_{10} e = 1.08574$$

Pogson's ratio (MNRAS, 1856, 17, 12)

$$m = -2.5\log_{10}\left(\frac{f_1}{f_0}\right) + m_0$$

Will drop "10" here on out.

m_0 : zeropoint of the magnitude system

$f = f_0$ dexp[-0.4(m-m_0)] ← how to get your money back

Absolute Magnitudes

$$m_\lambda - M_\lambda = 5\log_{10} d - 5 + A_\lambda$$

$$\therefore \quad \frac{f_1}{f_2} = \left(\frac{d_2}{d_1}\right)^2$$

- Absolute magnitude is the apparent magnitude that would be observed if the object were at a distance, d, of 10 pc.
- A_λ is the total extinction due to interstellar dust, in magnitudes, typically take to be only the Galactic foreground screen (Burstein & Heiles 1982, AJ, 87, 1165; Schlegel et al. 1998, ApJ, 500, 525):
  - $f = f_0 \exp(-\tau_\lambda)$,
  - $A_\lambda = 1.086\ \tau_\lambda = -2.5 \log(f/f_0)$

HI →

← IRAS

See nedwww.ipac.caltech.edu/help/extinction_law_calc.html

Absolute Magnitudes

- For extragalactic observers: *d* in Mpc, plus the so-called k-correction, κ, which accounts for effects of the cosmological expansion
  1) effects of redshifting the rest-frame spectrum in the observed band-pass; and
  2) photon dilution.

$$\boxed{m_\lambda - M_\lambda = 5\log_{10} d + 25 + A_\lambda + \kappa_\lambda}$$

See, e.g.: Schneider, Gunn & Hoessel (1983, ApJ, 264, 337)

Magnitude Errors: S/N ⇔ δmag

$$
\begin{aligned}
m \pm \delta(m) &= m_o - 2.5\log(S \pm N) \\
&= m_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right] \\
&= \underbrace{m_o - 2.5\log(S)}_{\mathrm{m}} - \underbrace{2.5\log(1 \pm \tfrac{N}{S})}_{\delta\mathrm{m}}
\end{aligned}
$$

What happens when S/N<1 ?

$$
\begin{aligned}
\delta(m) &\approx 2.5\log\left(1 + \tfrac{1}{S/N}\right) \\
&= \frac{2.5}{2.3}\left[\tfrac{N}{S} - \tfrac{1}{2}\left(\tfrac{N}{S}\right)^2 + \tfrac{1}{3}\left(\tfrac{N}{S}\right)^3 - \ldots\right] \\
&\approx 1.086\left(\tfrac{N}{S}\right)
\end{aligned}
$$

Note: in log +/- not symmetric

Fractional error

This is the basis of people referring to +/- 0.02mag error as “2%”

An alternate magnitude scheme

- **The inverse hyperbolic sine**: Lupton et al. (1999, AJ, 118, 1406)
- Replace log with asinh (i.e., $\sinh^{-1}$)
- Invented to handle errors at low S/N

Definition of asinh mag (μ):

$$m = m_0 - 2.5 \log f \,,$$

$$x \equiv f/f_0,$$

$$\mu(x) \equiv -a\left[\sinh^{-1}\left(\frac{x}{2b}\right) + \ln b\right] .$$

Limiting behaviour:

$$\lim_{x \to \infty} \mu(x) = -a \ln x = m \,, \quad \lim_{x \to 0} \mu(x) = -a\left(\frac{x}{2b} + \ln b\right) .$$

$$\begin{aligned} \mu &= (m_0 - 2.5 \log b') - a \sinh^{-1}(f/2b') \\ &\equiv \mu(0) - a \sinh^{-1}(f/2b') \,, \end{aligned}$$

$$\mathrm{Var}(\mu) = \frac{a^2\sigma'^2}{4b'^2 + f^2} \approx \frac{a^2\sigma'^2}{4b'^2} \,,$$

- $a = 2.5 \log e$
- b is a softening parameter that depends on data noise properties -- *this is the boon and the problem*.

Asinh magnitudes: Noise Properties

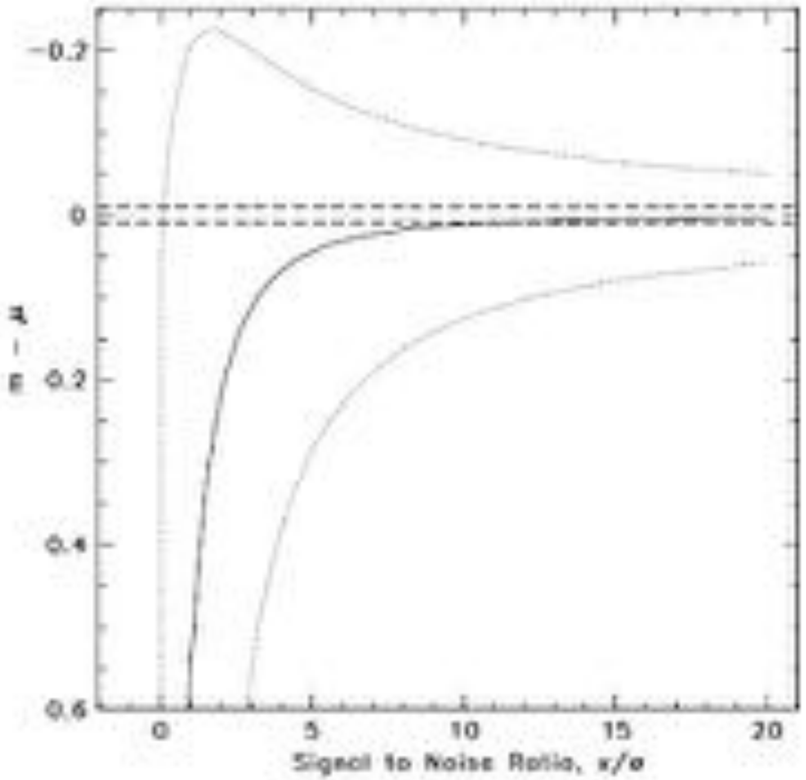


FIG. 1.—Behavior of $m - \mu$ as a function of signal-to-noise ratio x/σ. The solid line is the value of $m - \mu$ and the region between the dotted lines corresponds to the $\pm 1\ \sigma$ error region for m. The dashed lines are drawn at ± 0.01.

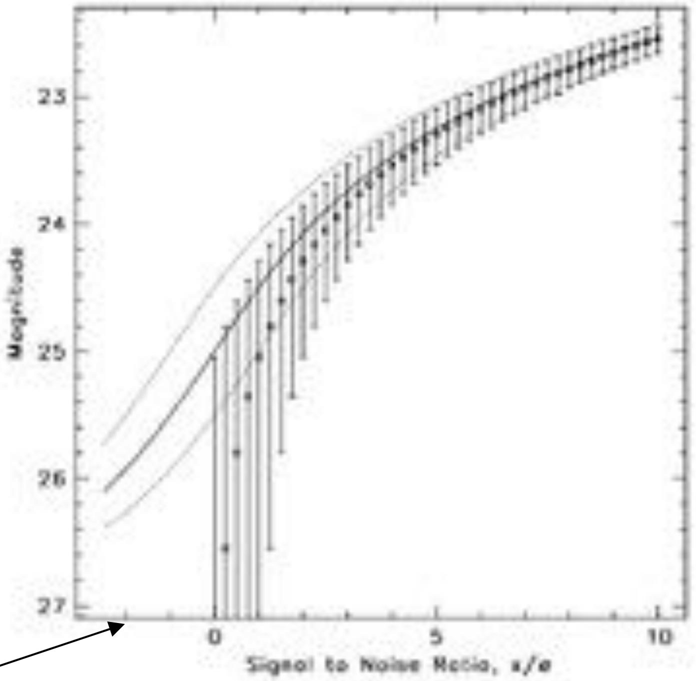


FIG. 2.—Behavior of m and μ and their respective errors as a function of signal-to-noise ratio x/σ. The solid line is the value of μ, and the region between the dotted lines its $\pm 1\ \sigma$ error region; the points with error bars are the classical magnitudes m. We have arbitrarily chosen a zero point of $\mu = 25.0$ for an object with no flux. One other feature of our modified magnitudes is apparent from this figure, namely, that the error band on μ is nearly symmetrical, while the errors in m are strongly skewed at faint magnitudes. For signal-to-noise ratios of less than about 2, $m - \mu$ exceeds the value $0.52\ [\mathrm{Var}(m)]^{1/2}$ quoted in the main body of the paper; this is because of the breakdown of the linear approximation used to calculate m's variance.

Note: negative fluxes “allowed” for asinh