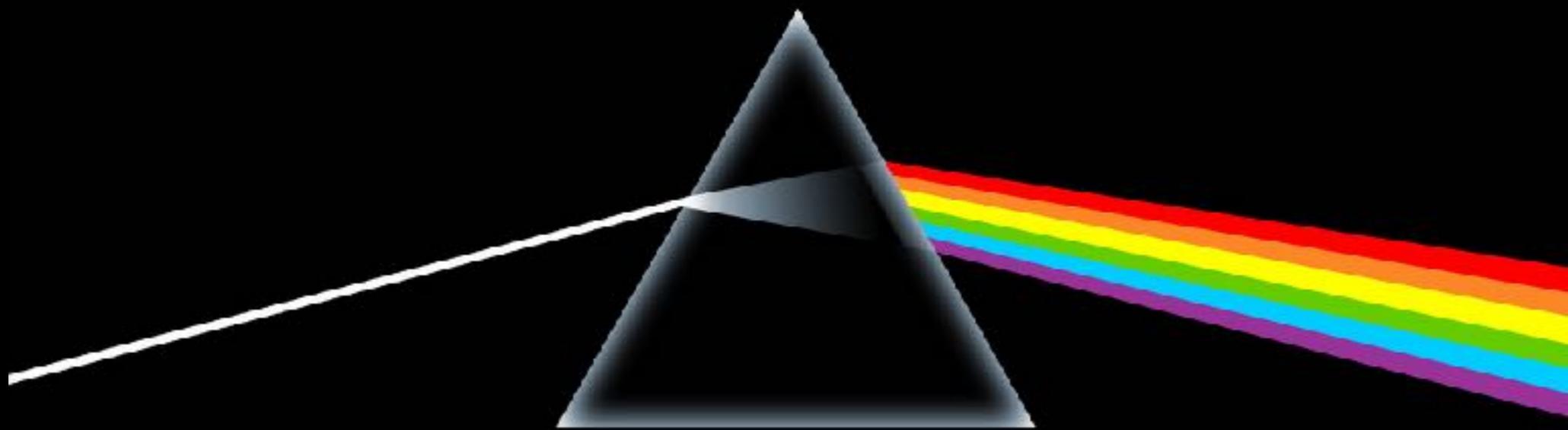


# Astronomy 503

# Observational Astronomy



Prof. Gautham Narayan

Lecture 03: Luminosities, Fluxes, Redshift

## History of astronomical discoveries

Malcolm Longair

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**Abstract** The wide diversity of routes to astronomical, astrophysical and cosmological discovery is discussed through a number of historical case studies. Prime ingredients for success include new technology, precision observation, extensive databases, capitalising upon discoveries in cognate disciplines, imagination and luck. Being in the right place at the right time is a huge advantage. The changing perspectives on the essential tools for tackling frontier problems and astronomical advance are discussed.

**Keywords** Astronomy · Astrophysics · Cosmology · Discovery · History

# Reading that may help with this week's homework

<https://arxiv.org/abs/1205.2064>

## 10 Statistical Methods for Astronomy

Eric D. Feigelson<sup>1,3</sup> · G. Jogesh Babu<sup>2,3</sup>

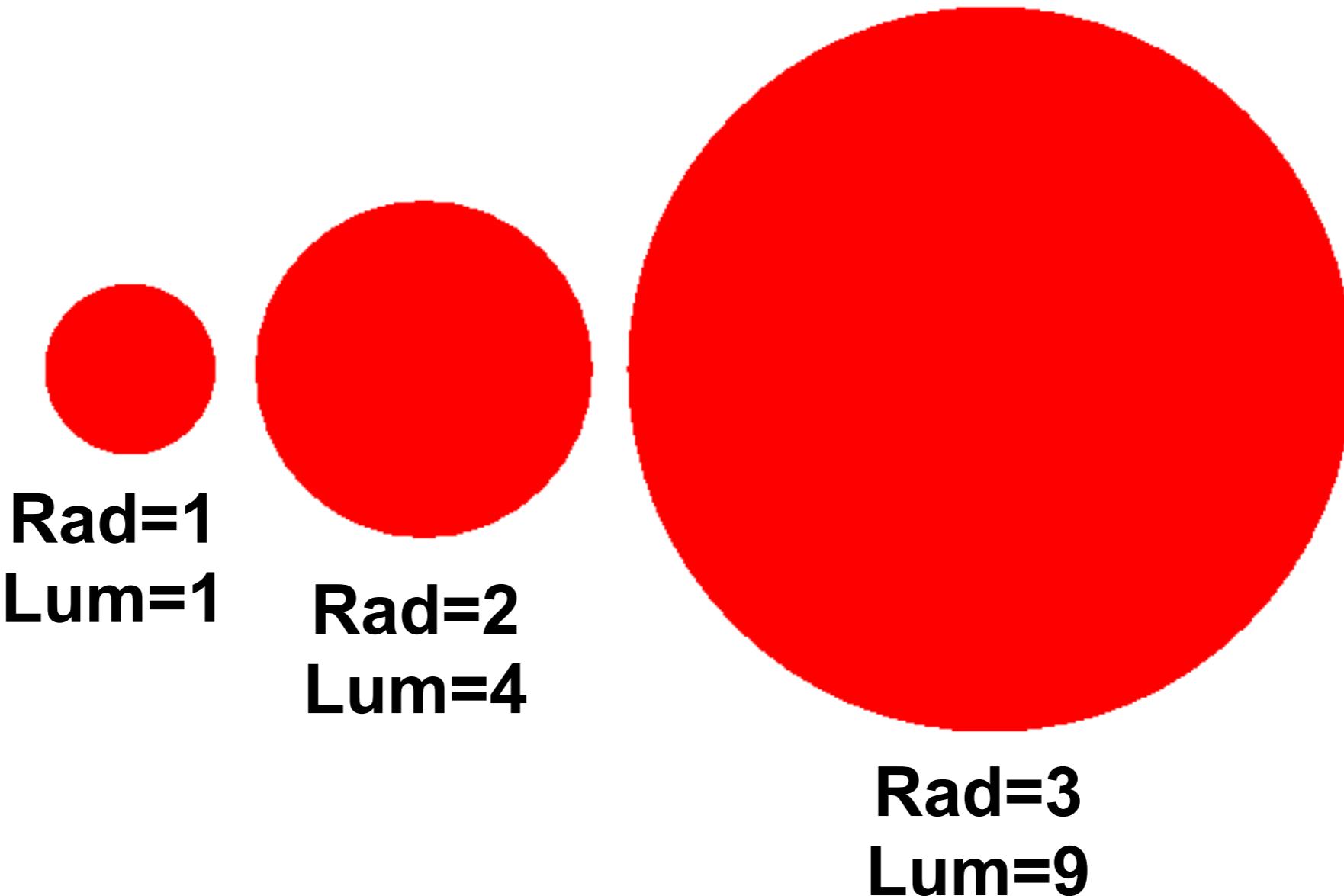
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<sup>3</sup>Center for Astrostatistics, The Pennsylvania State University, University Park, PA, USA

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# Bigger objects are brighter



**For stars of the same temperature,  
the larger the star, the greater the luminosity<sup>4</sup>**

# sizes from blackbodies

- How to measure a star's size? Stars are too far away to resolve, so we can't directly measure their sizes.
- However, we can use the Stefan-Boltzmann Law and solve for it !

$$L = 4\pi R^2 \sigma T^4$$

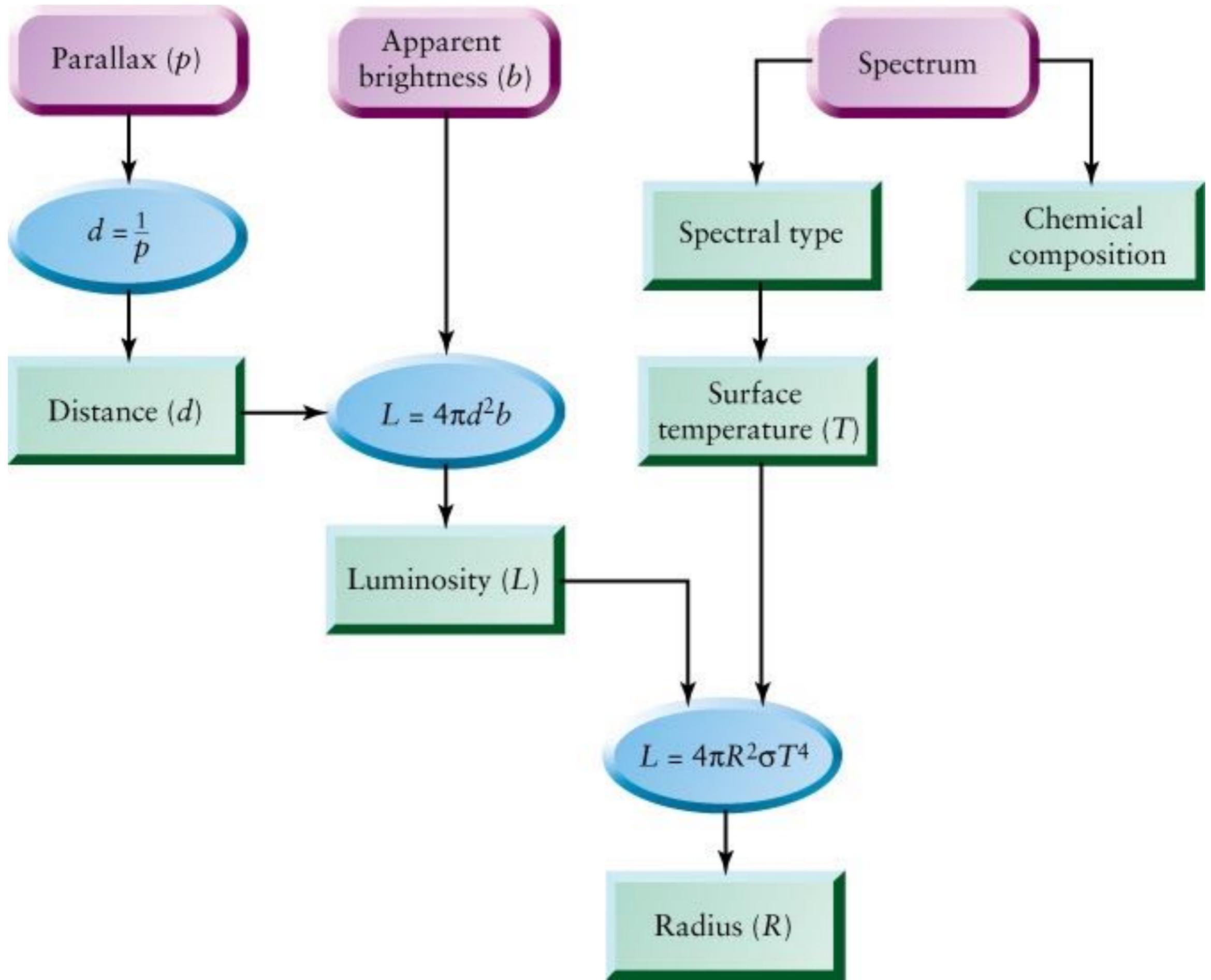
$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} = 5.67 \times 10^{-8} Js^{-1}m^{-2}K^{-4}$$

$$L \propto R^2 T^4$$

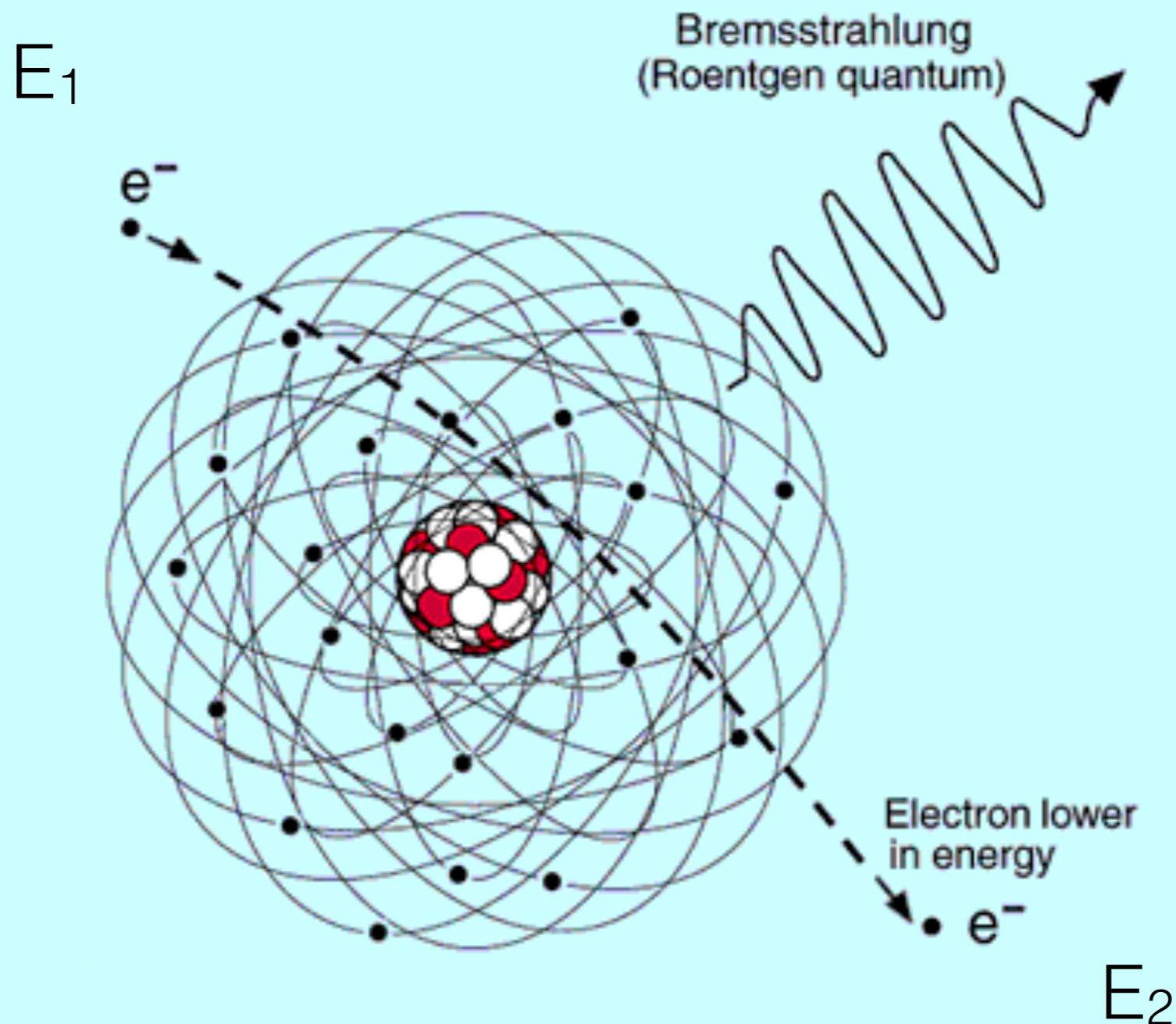
pi = ratio of a circle's circumference to its diameter  
c = the speed of light

k = Boltzmann constant relates a particle's energy to the temperature  
h = Planck constant is a quantum mechanical unit of energy

$$R \propto \frac{\sqrt{L}}{T^2}$$



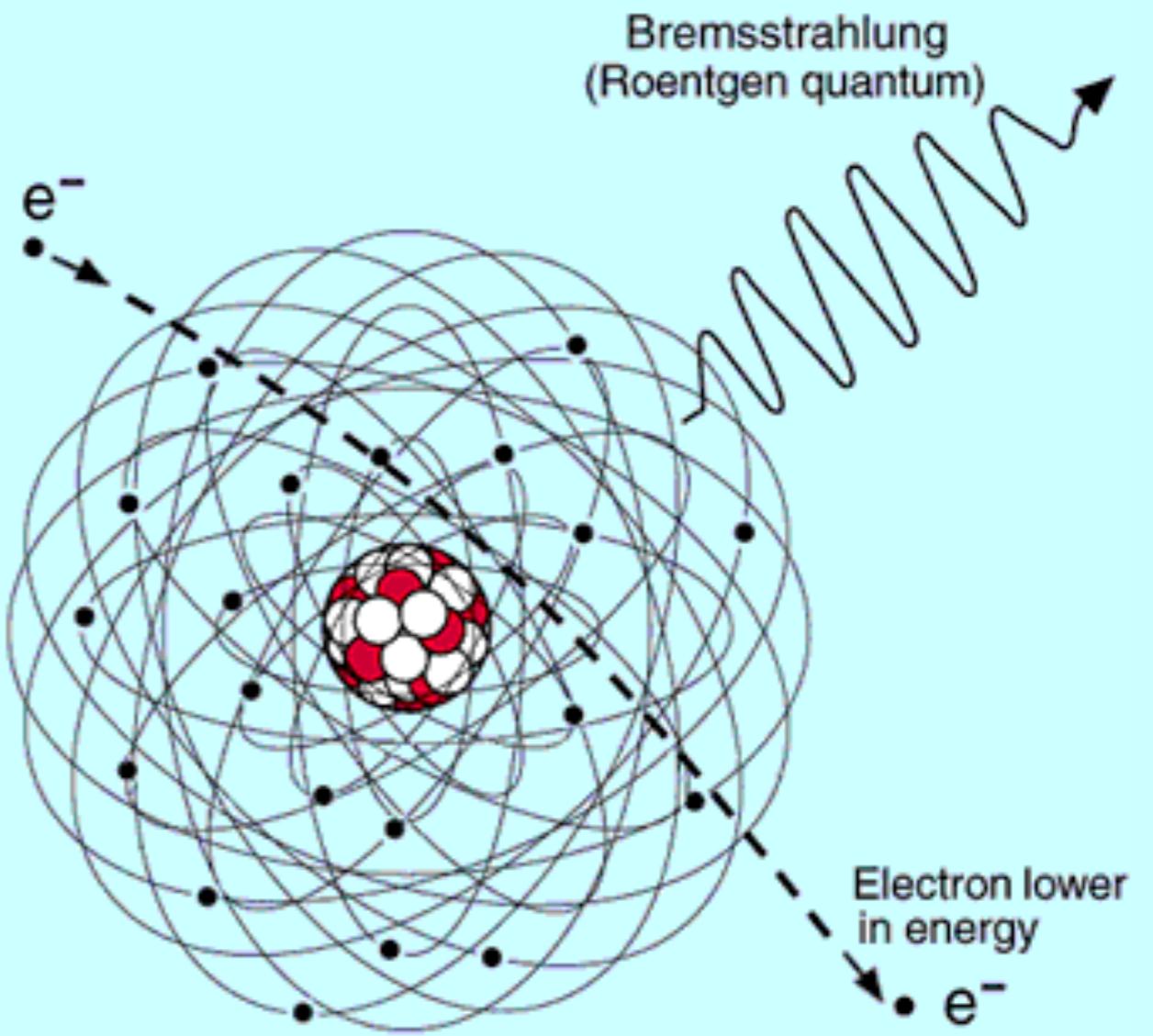
# Bremsstrahlung “Braking Radiation”



$$h\nu = E_1 - E_2$$

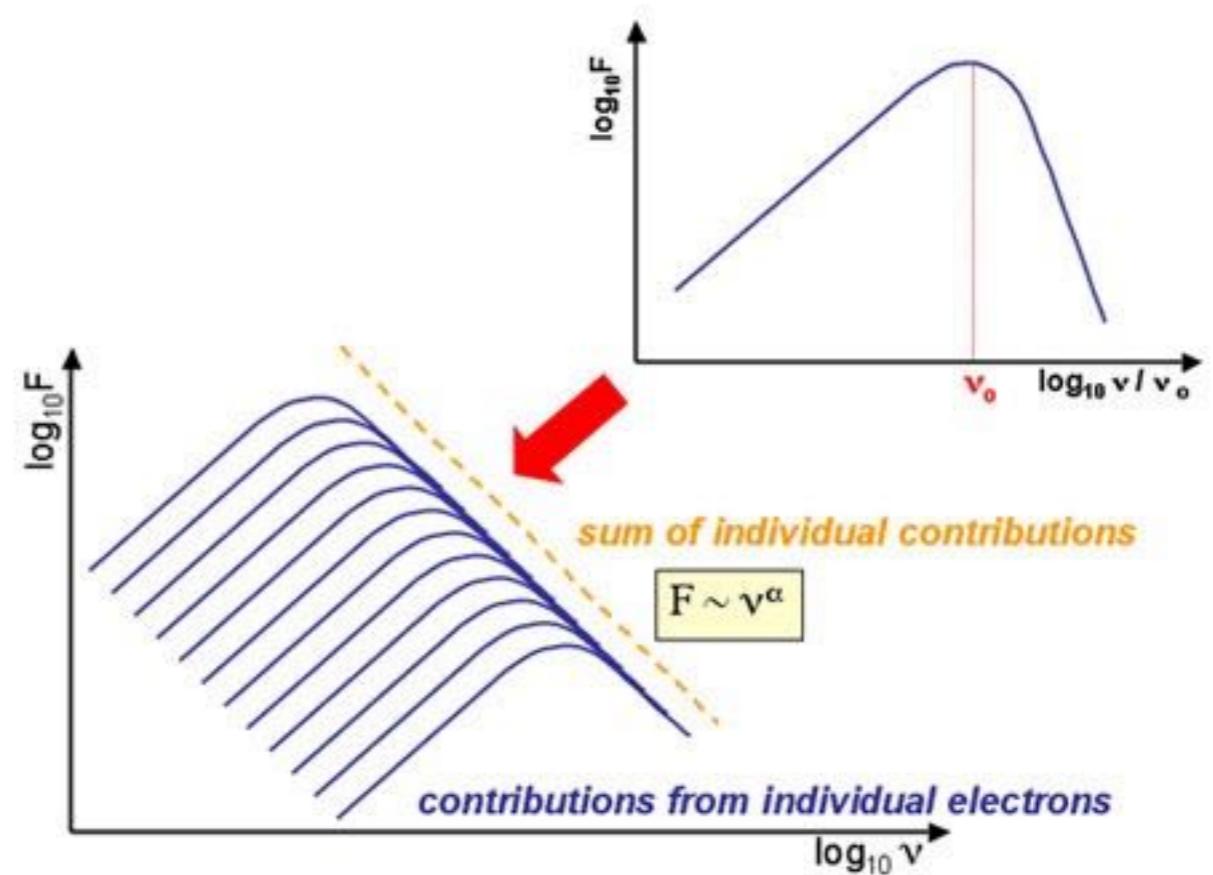
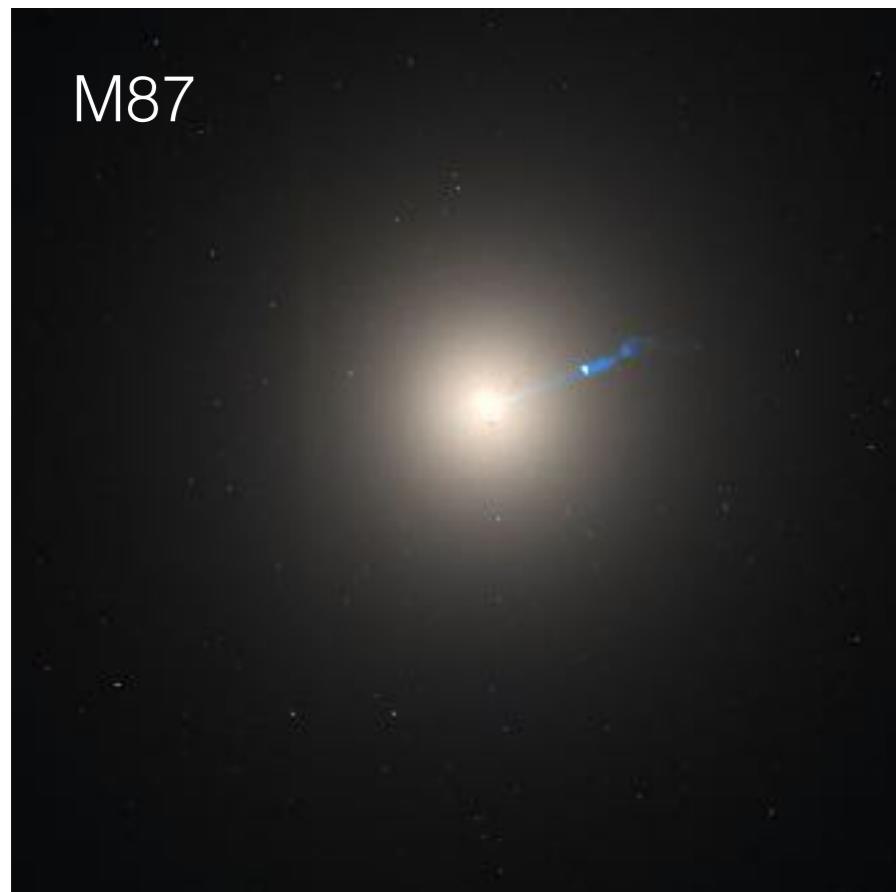
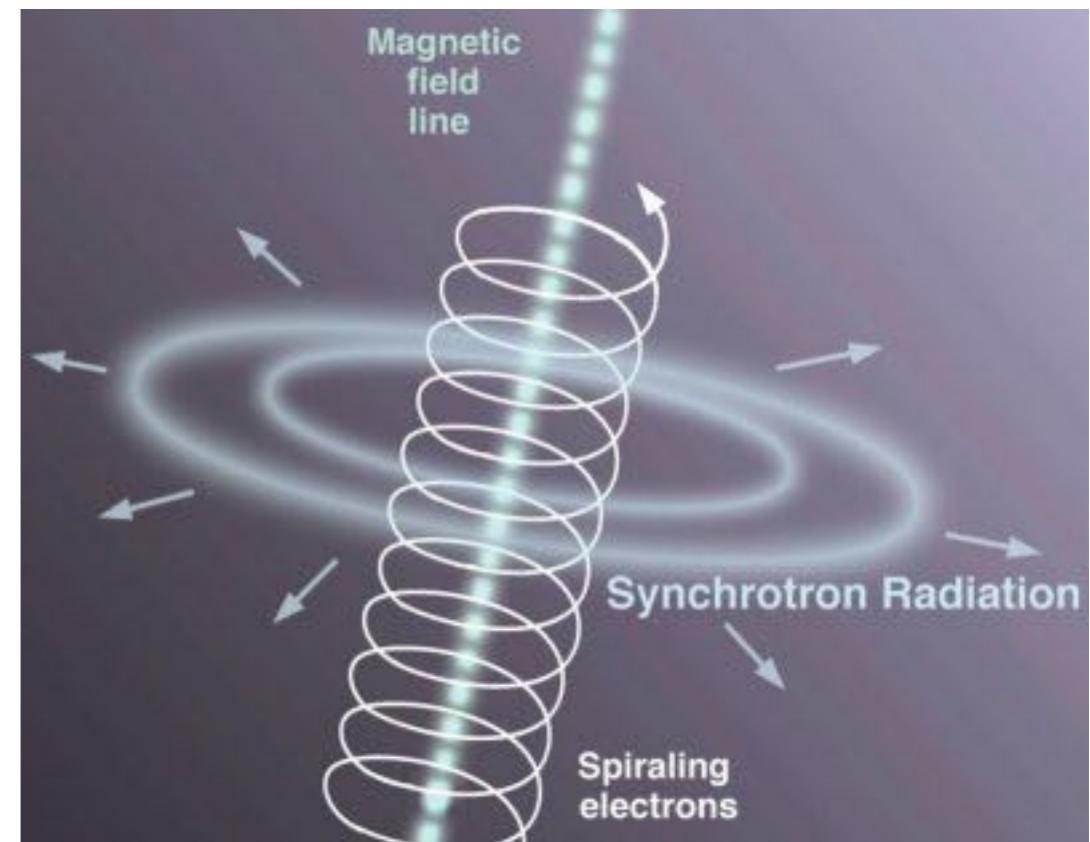
## free-free emission

- thermal bremsstrahlung
- free electrons scattering off ions
- free before, free after
- HII regions, star formation, proportional to thermal energy
- unpolarized

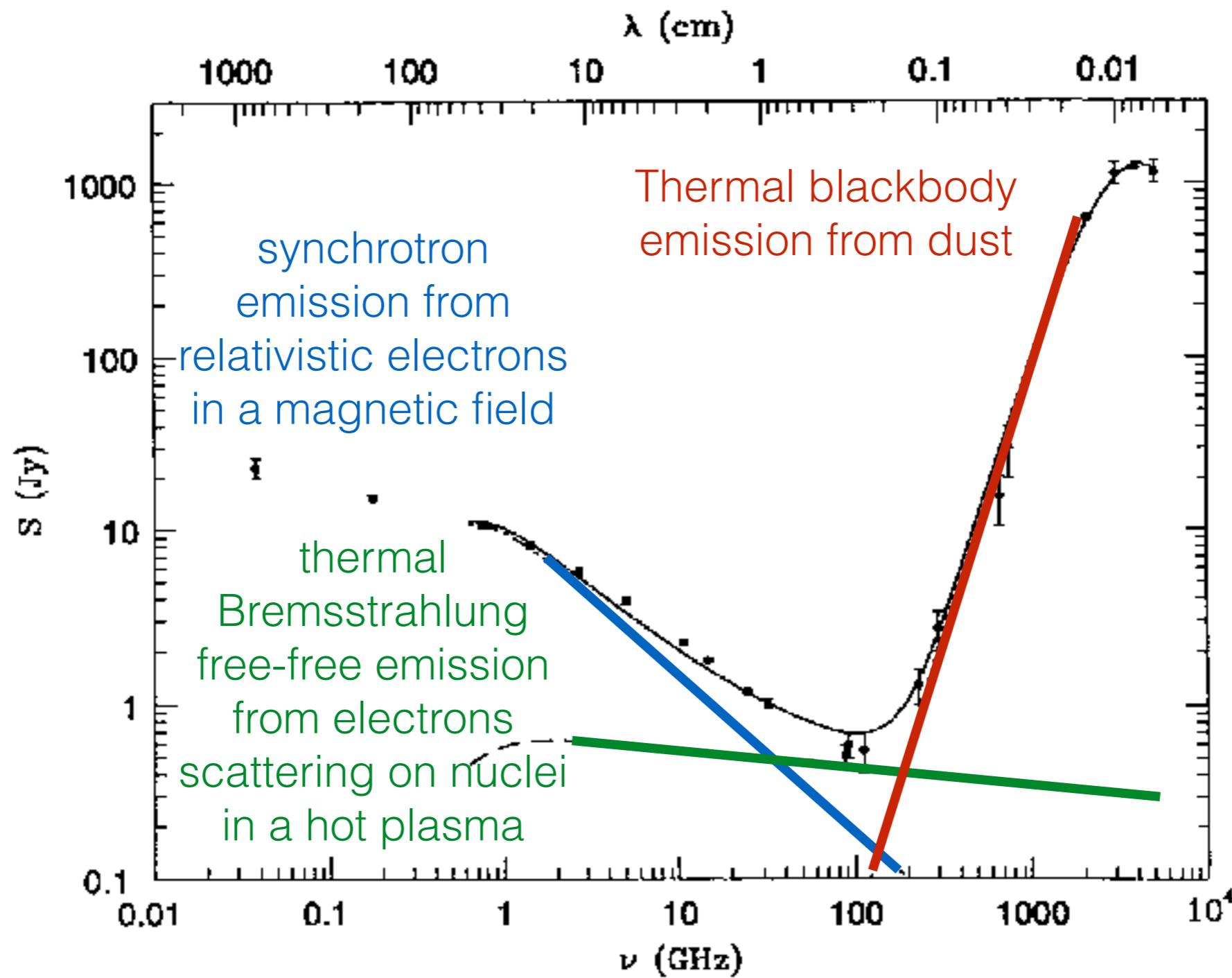


# Synchrotron emission

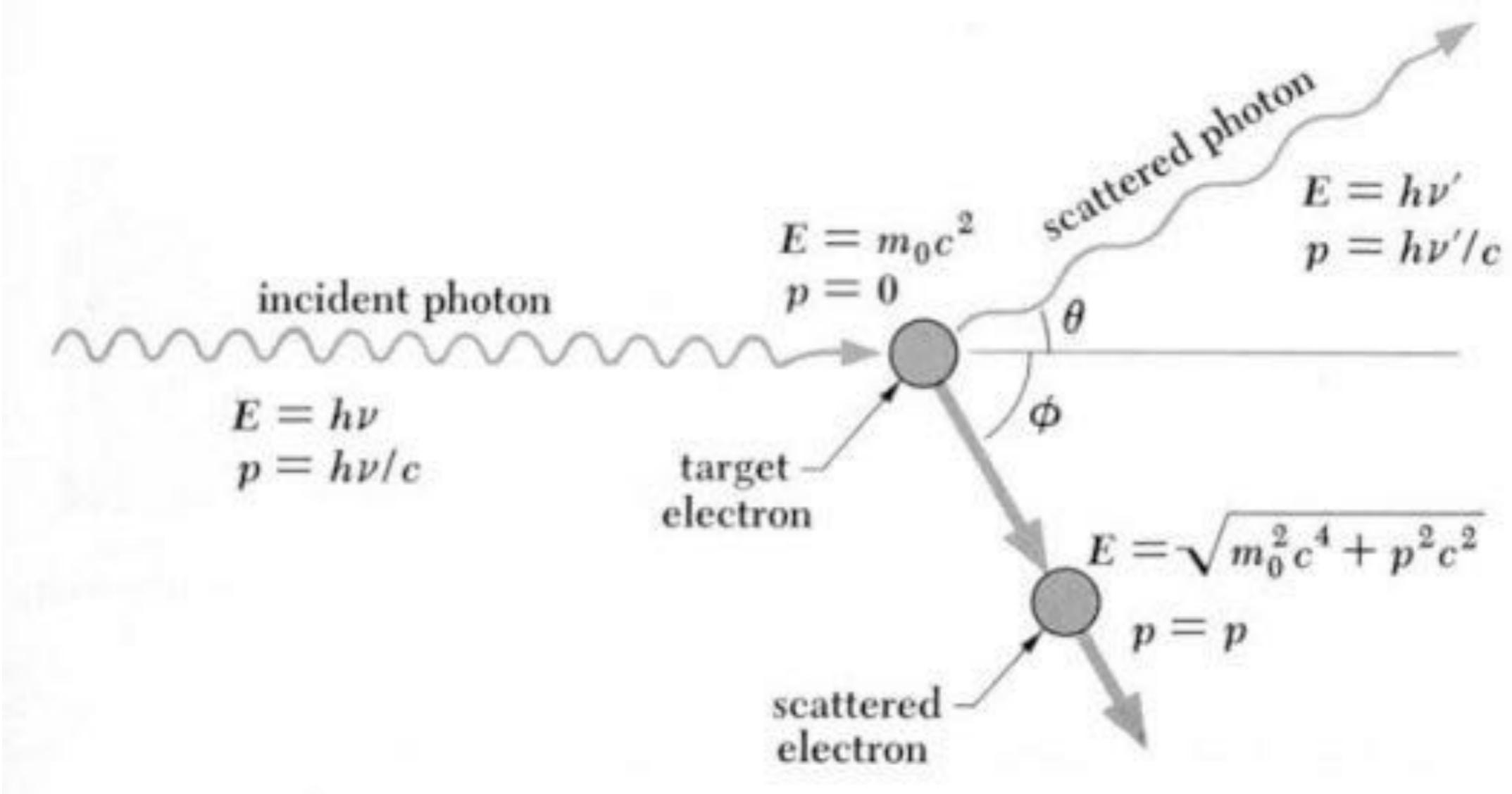
- Charged particles moving through magnetic fields
- Electrons produce broad spectrum, polarized light
- First detected in 1956 by Burbidge in M87

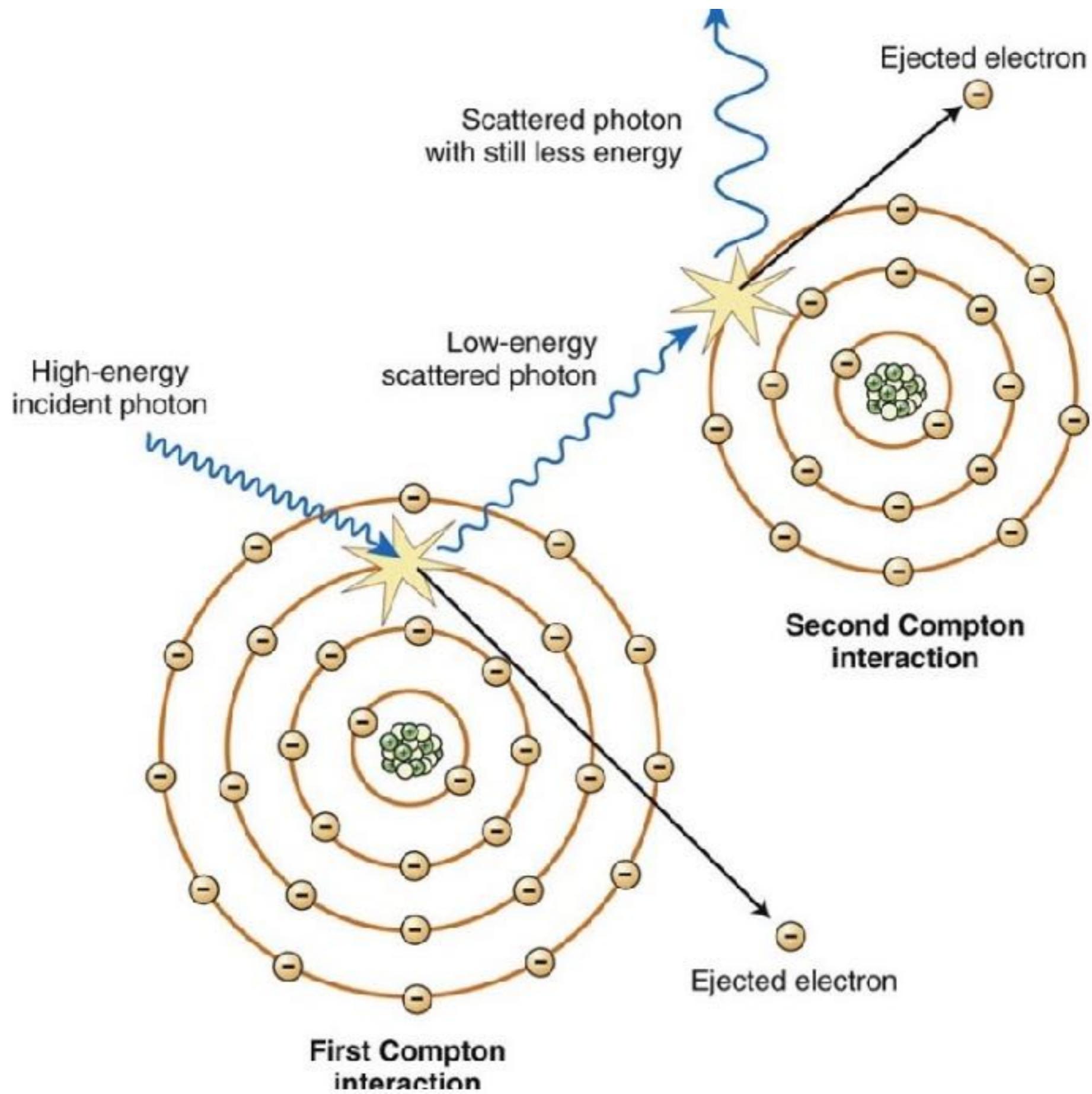


# M82

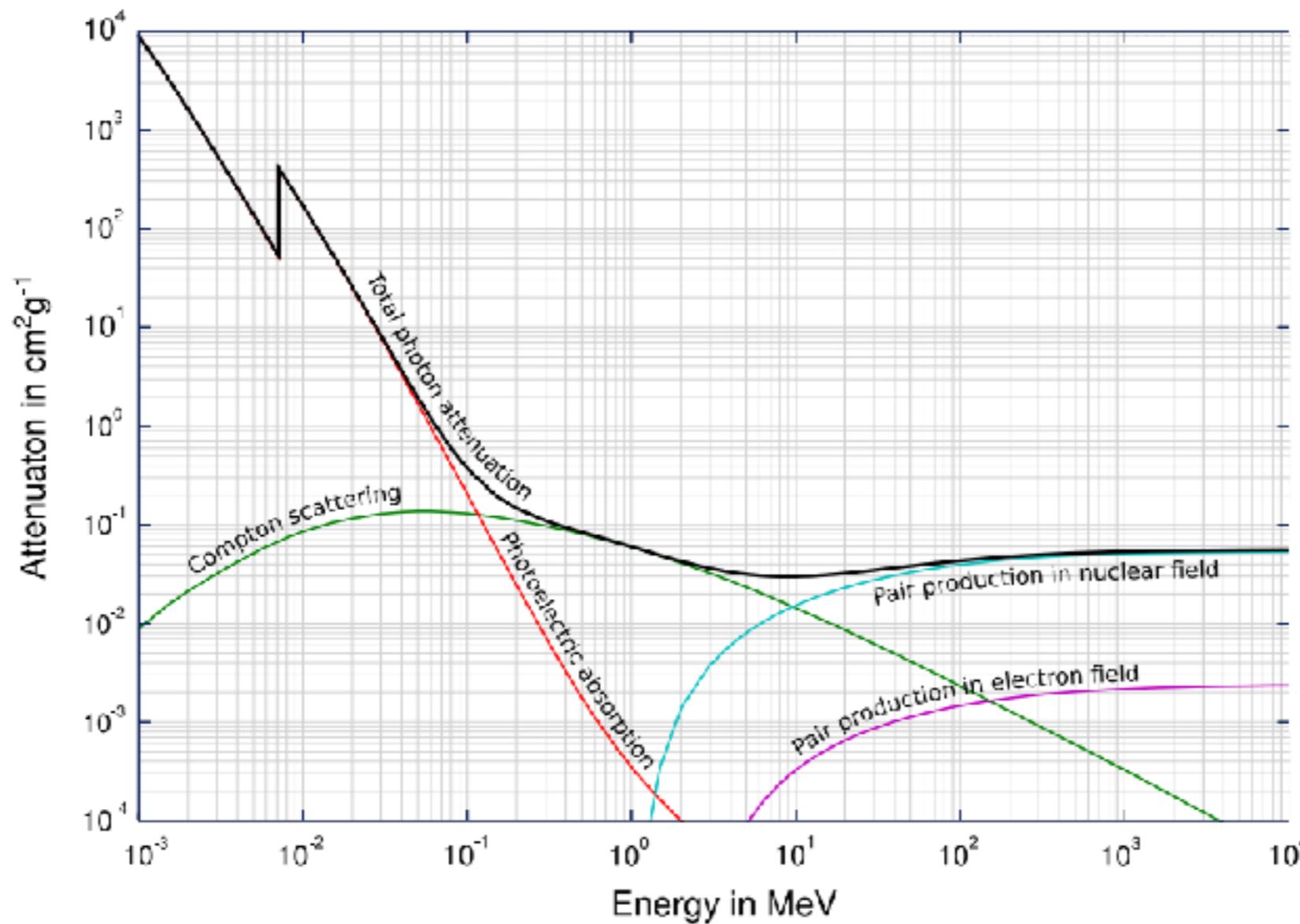


# Compton Scattering



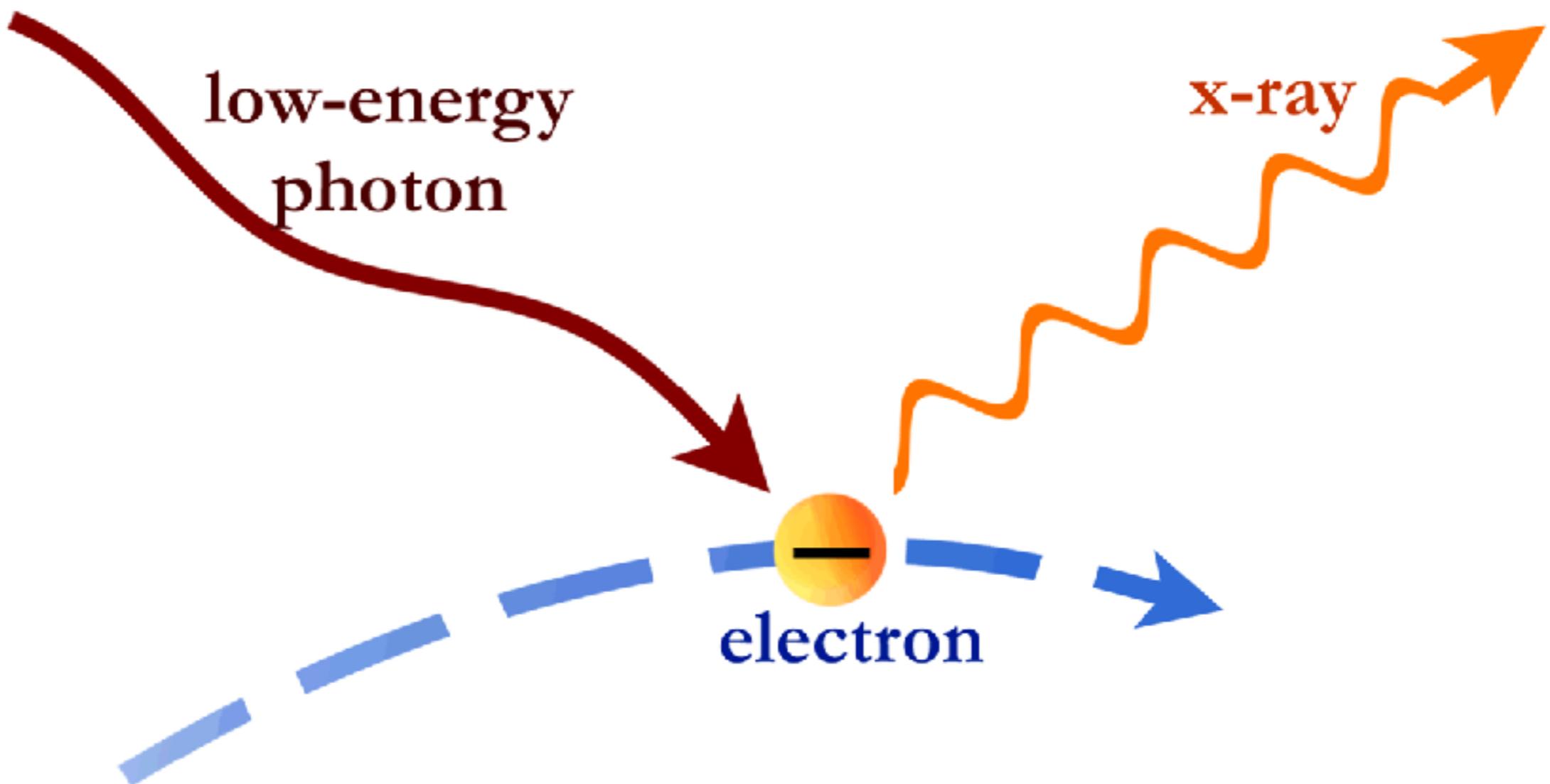


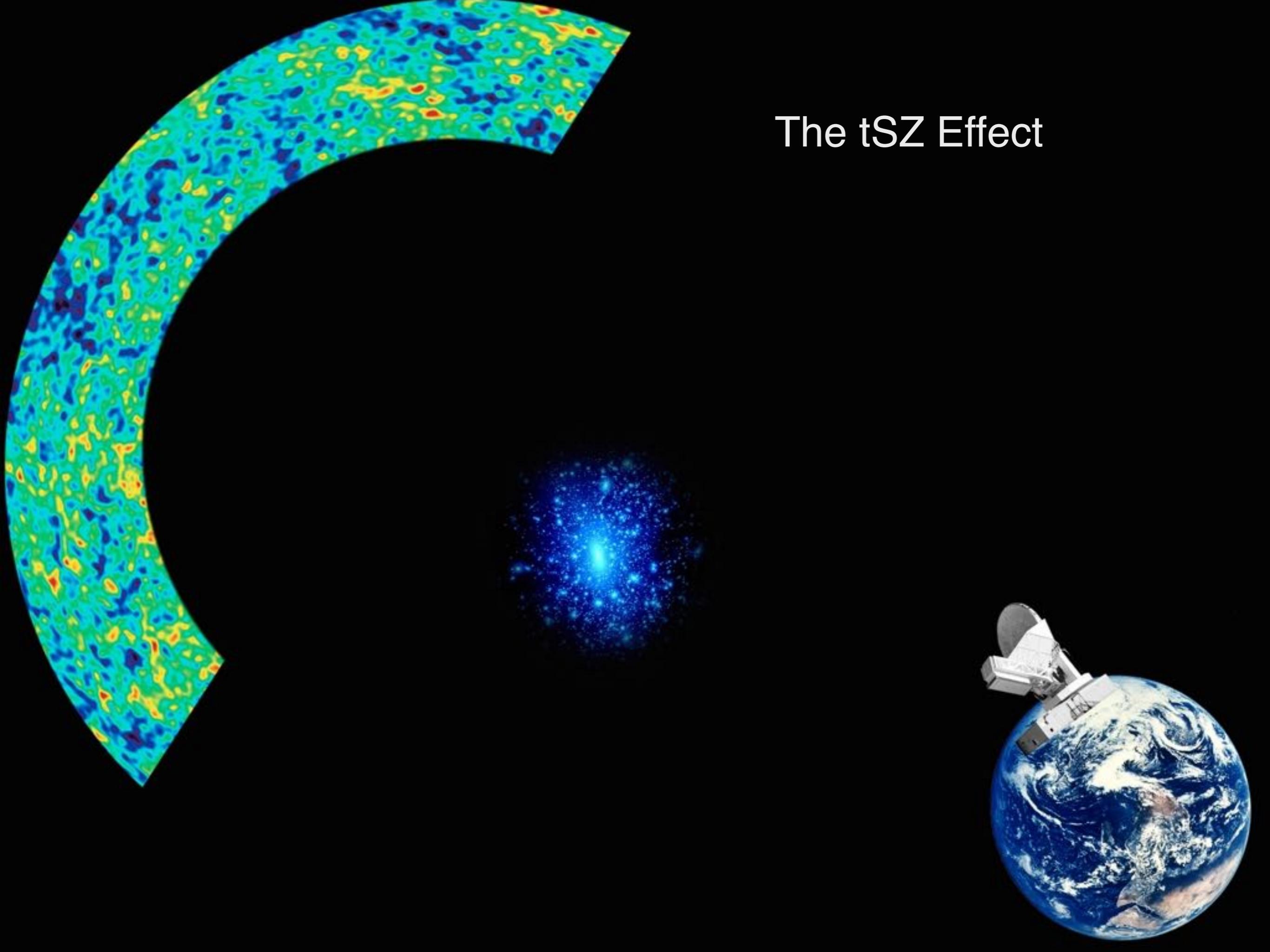
# Gamma Ray Cross Sections



At low energies, lots of scattering events, but low energy loss

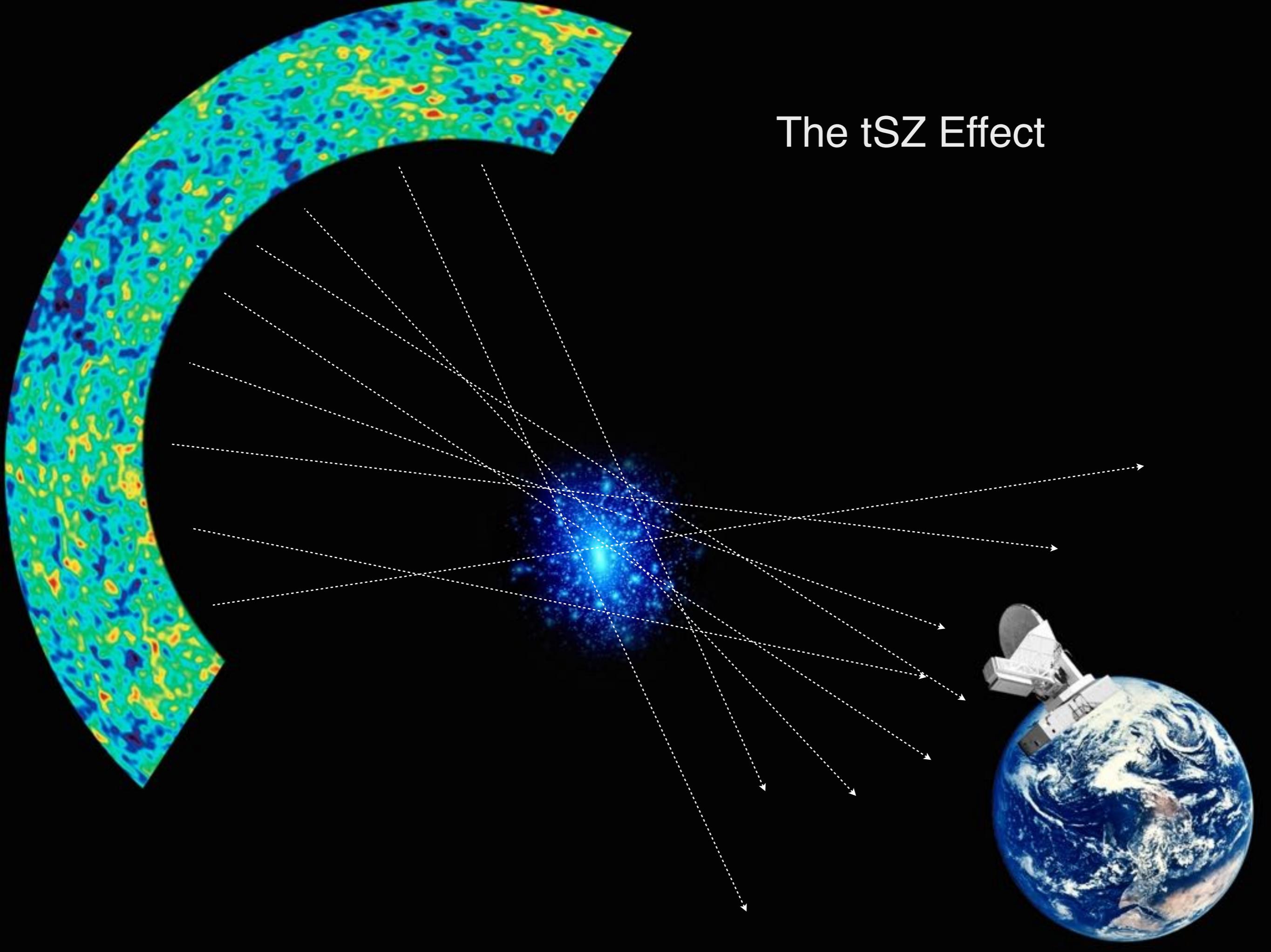
# Inverse Compton Scattering



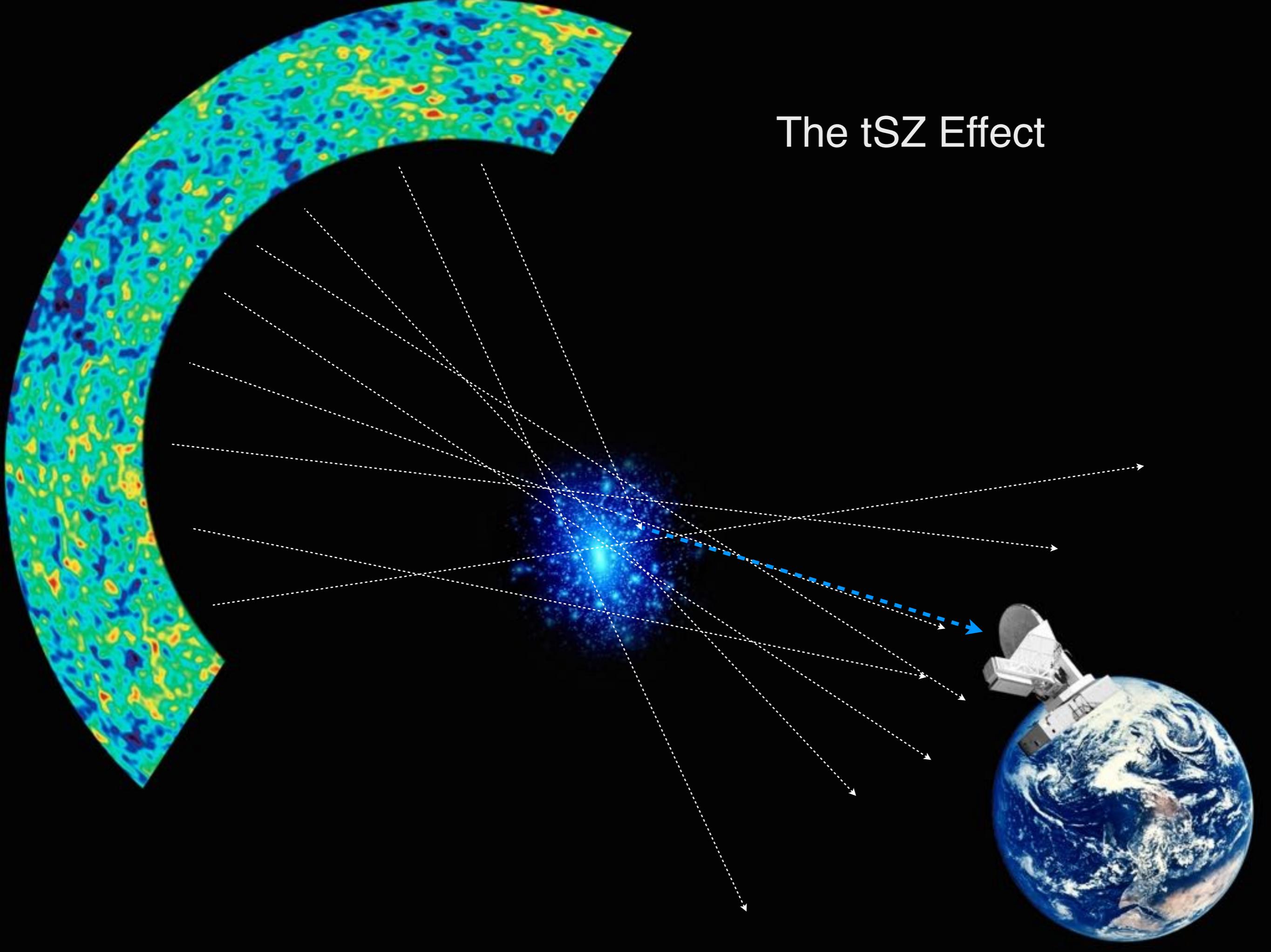


# The tSZ Effect

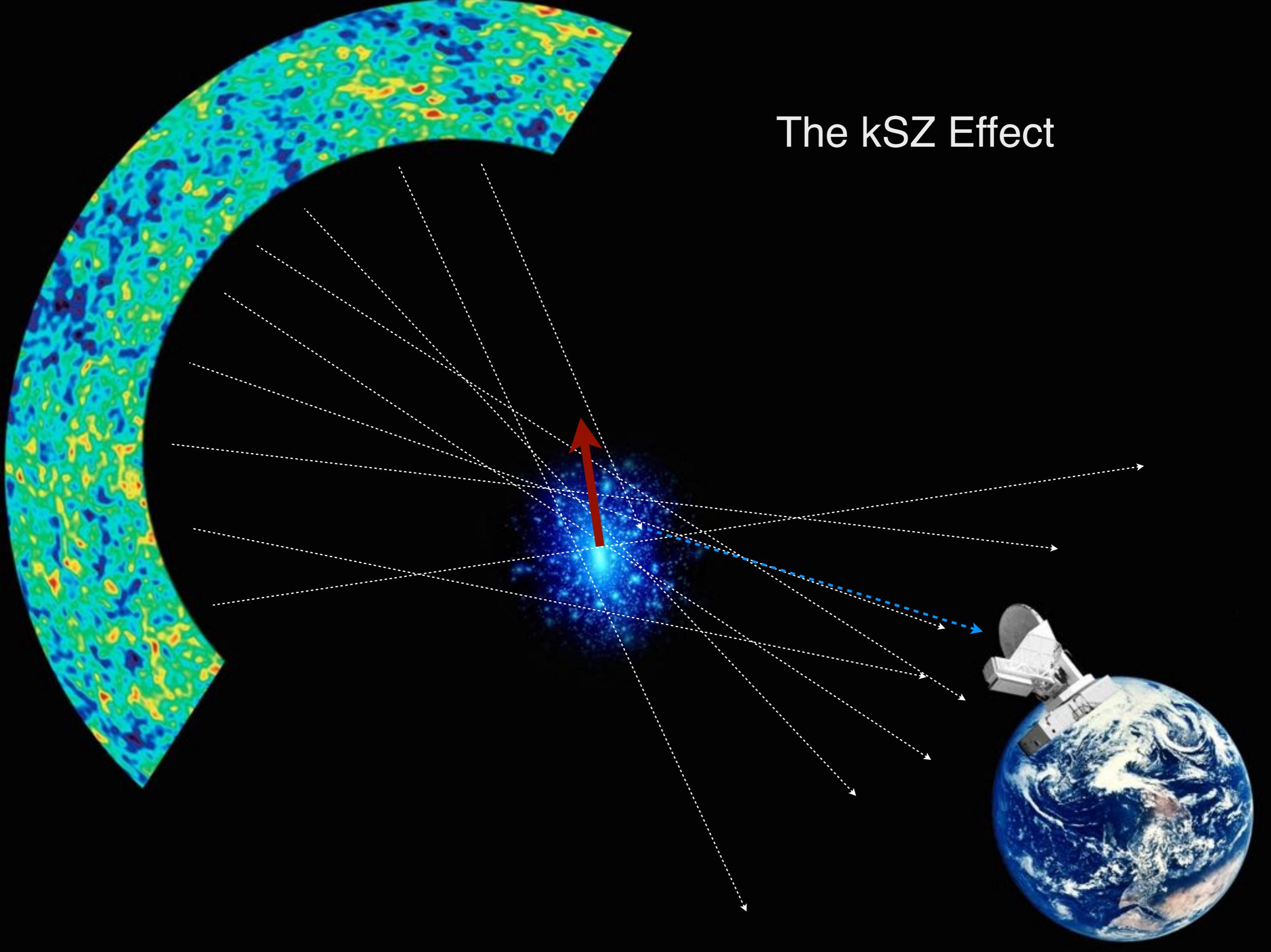
# The tSZ Effect



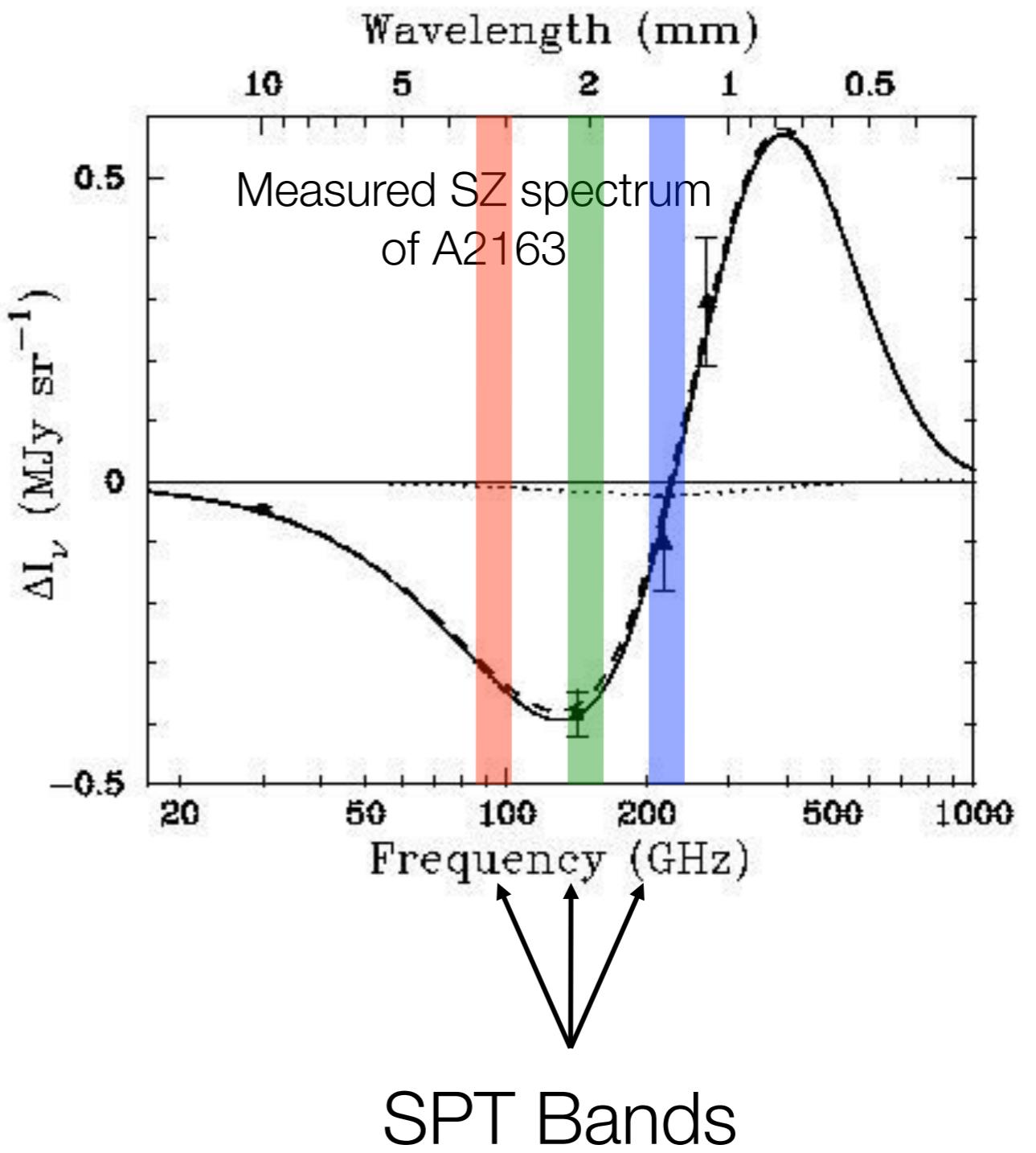
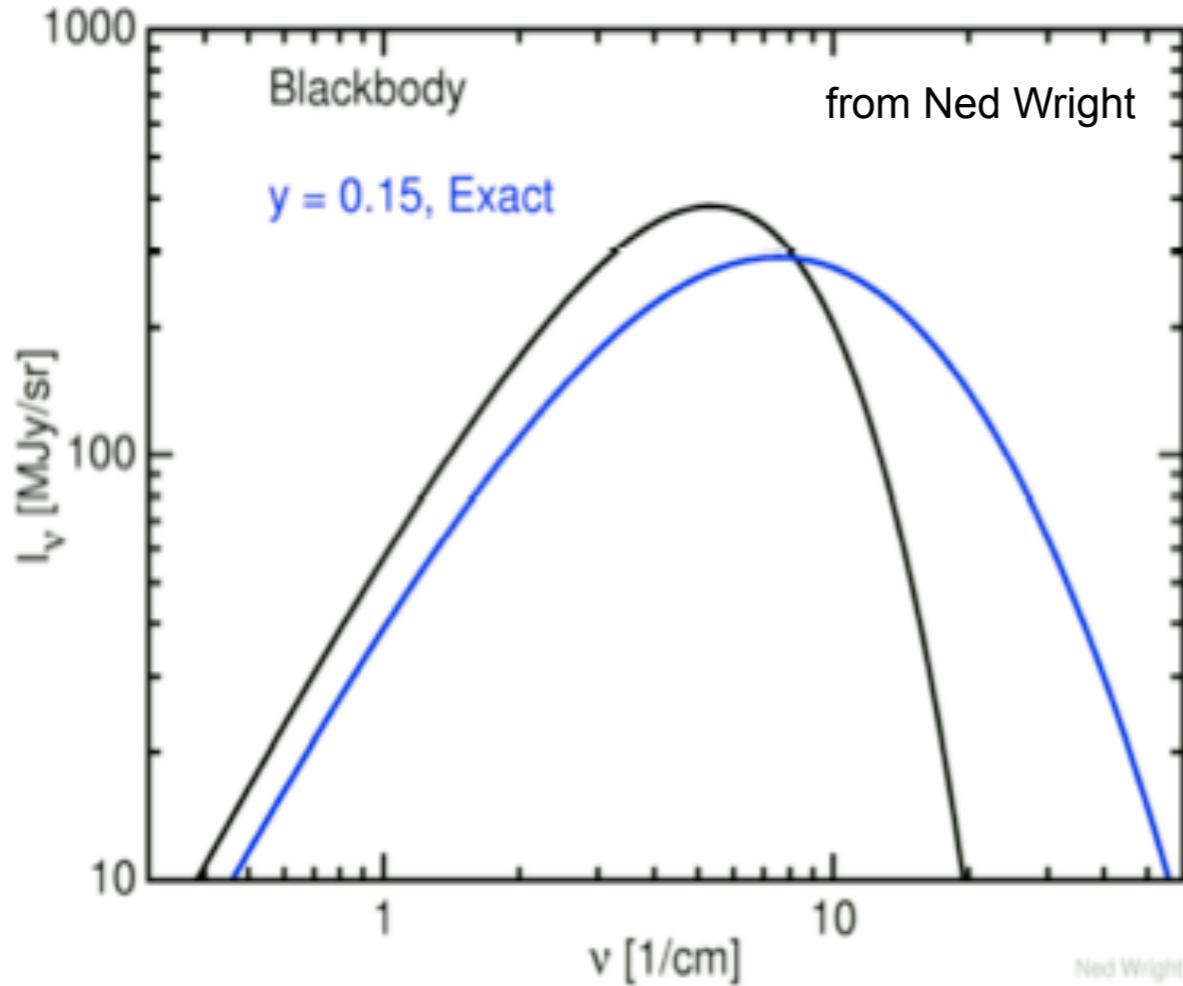
# The tSZ Effect



# The kSZ Effect

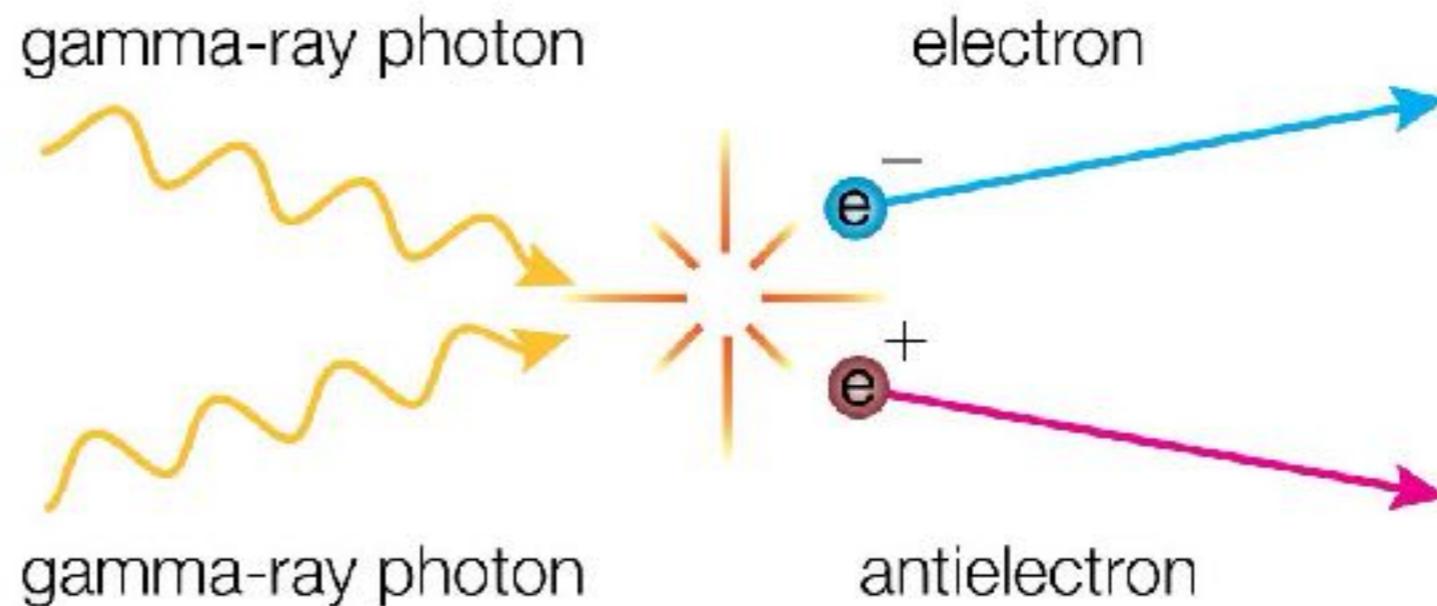


# Sunyaev-Zel'dovich Effect

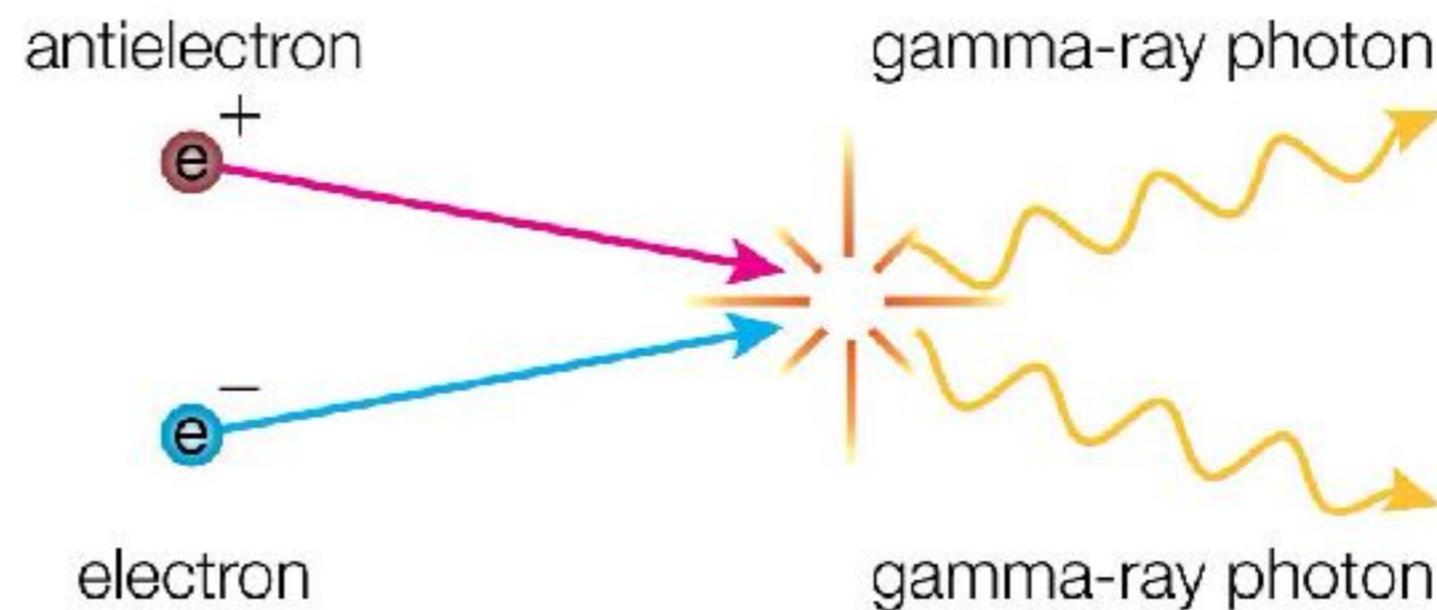


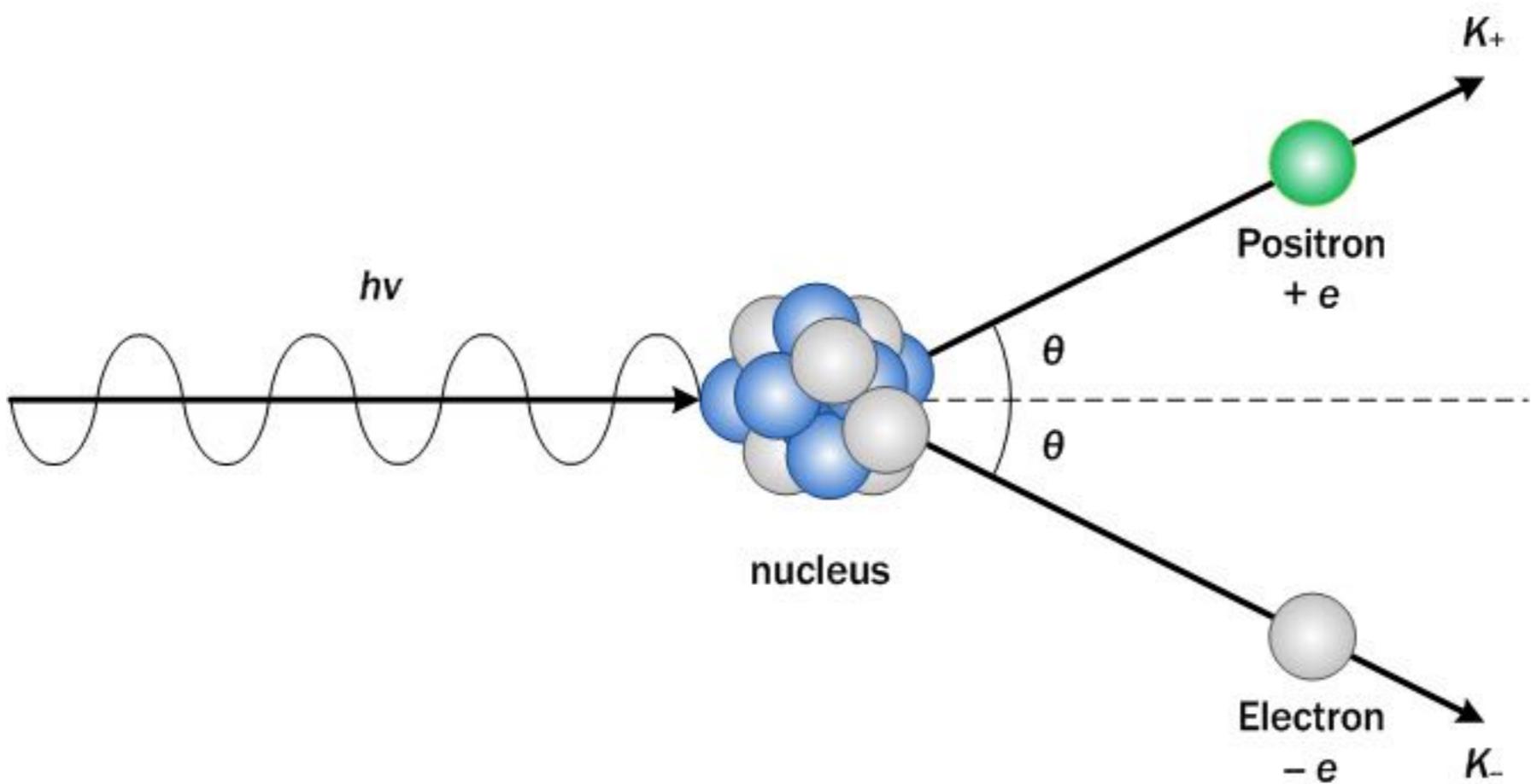
# Pair production

## Particle creation



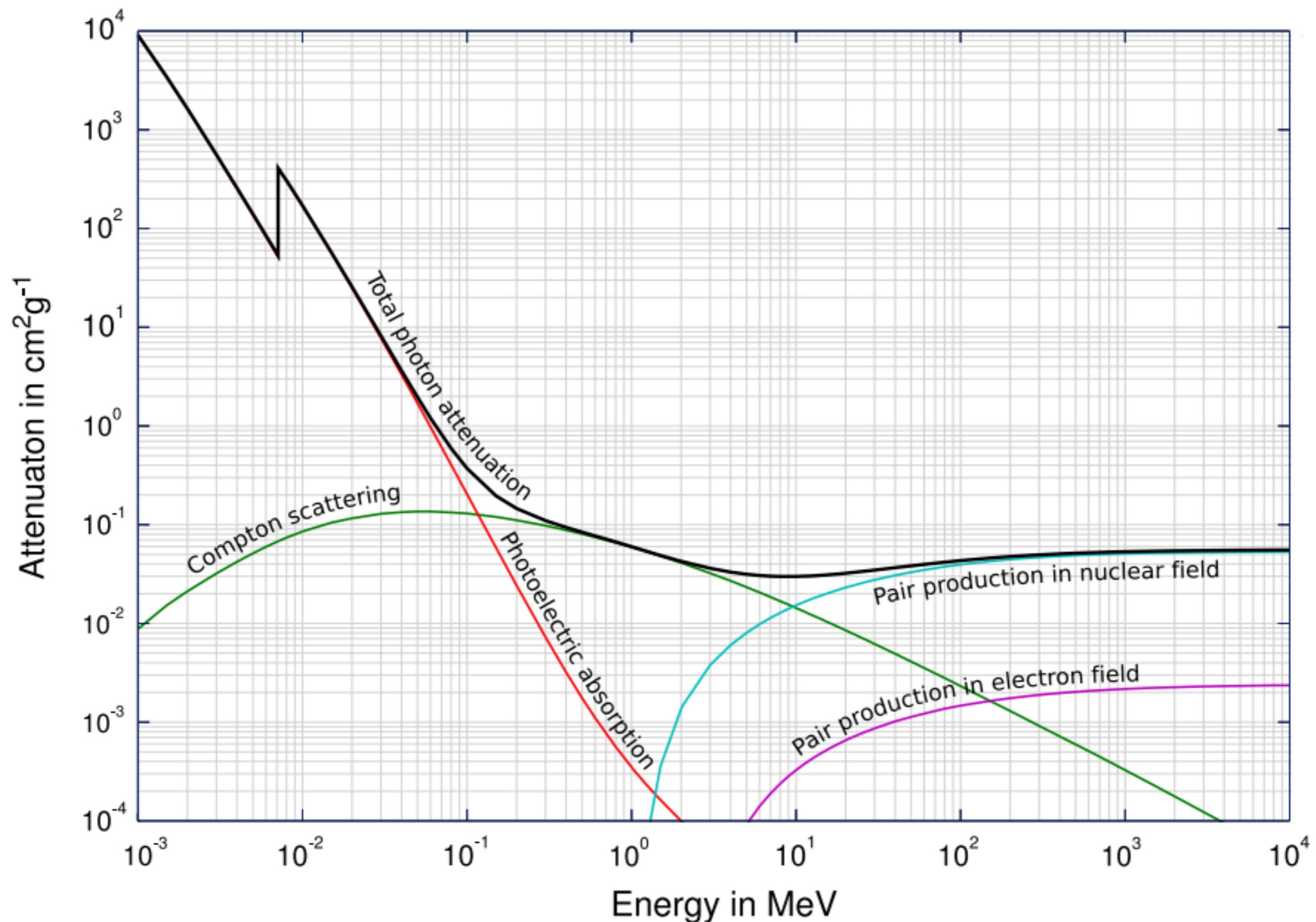
## Particle annihilation



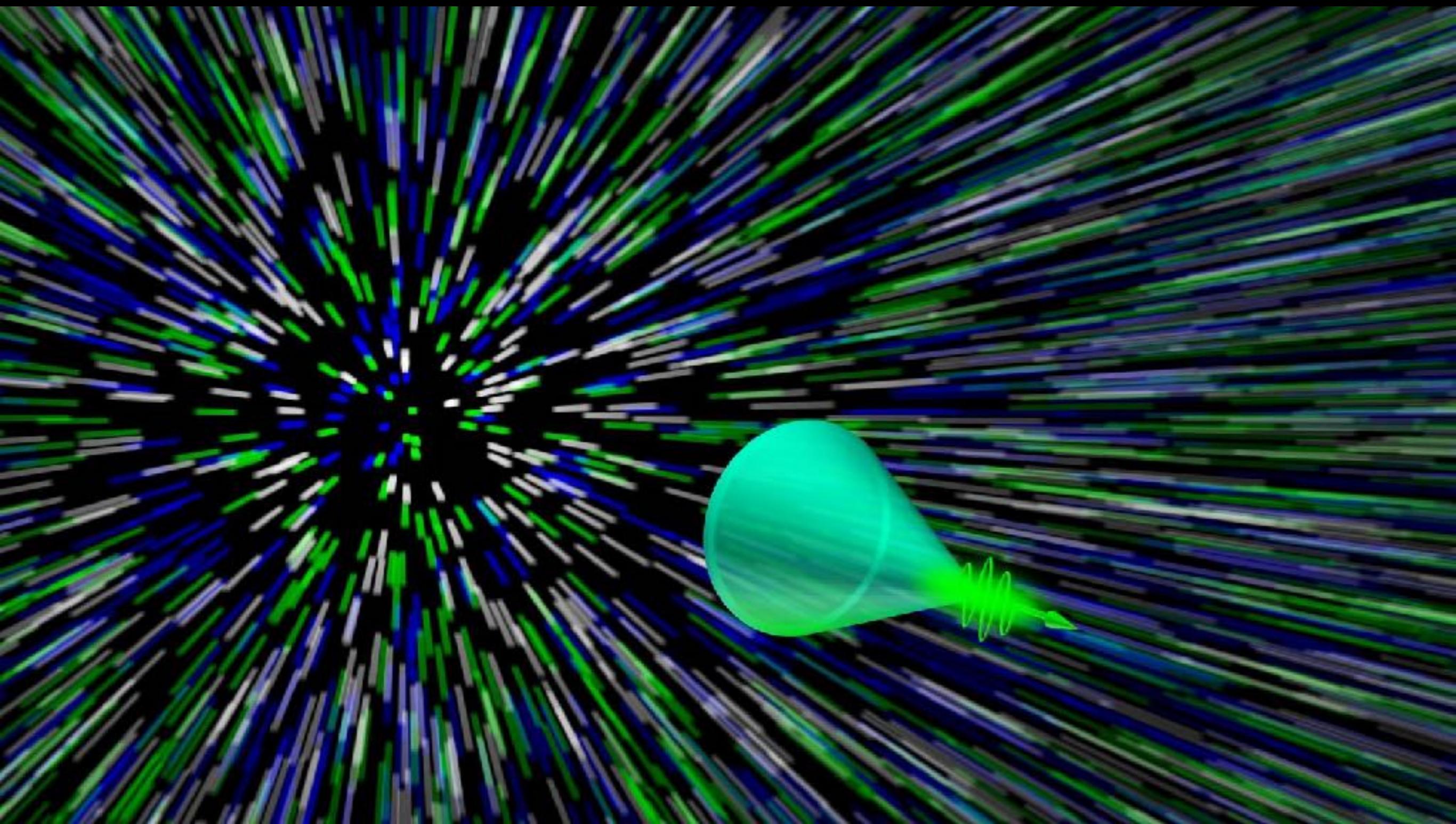


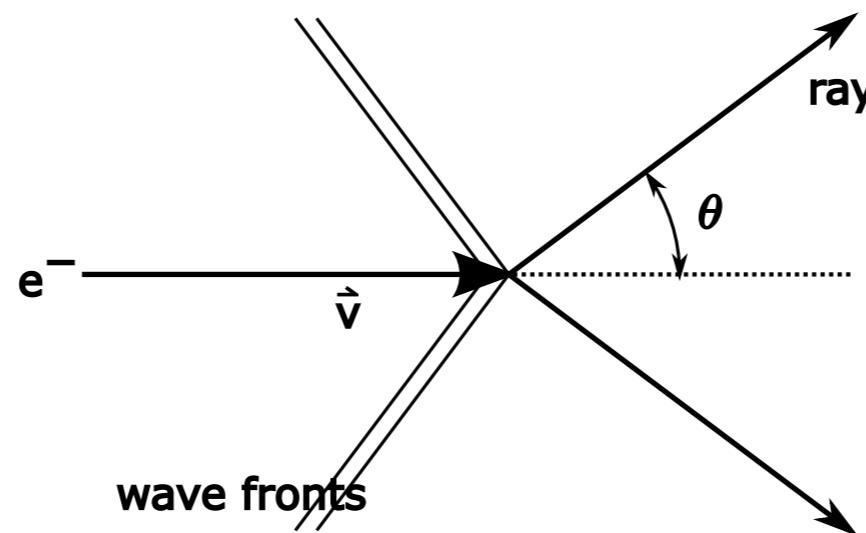


# Gamma Ray Cross Sections



Cherenkov





### Cerenkov light and Super Kamiokande

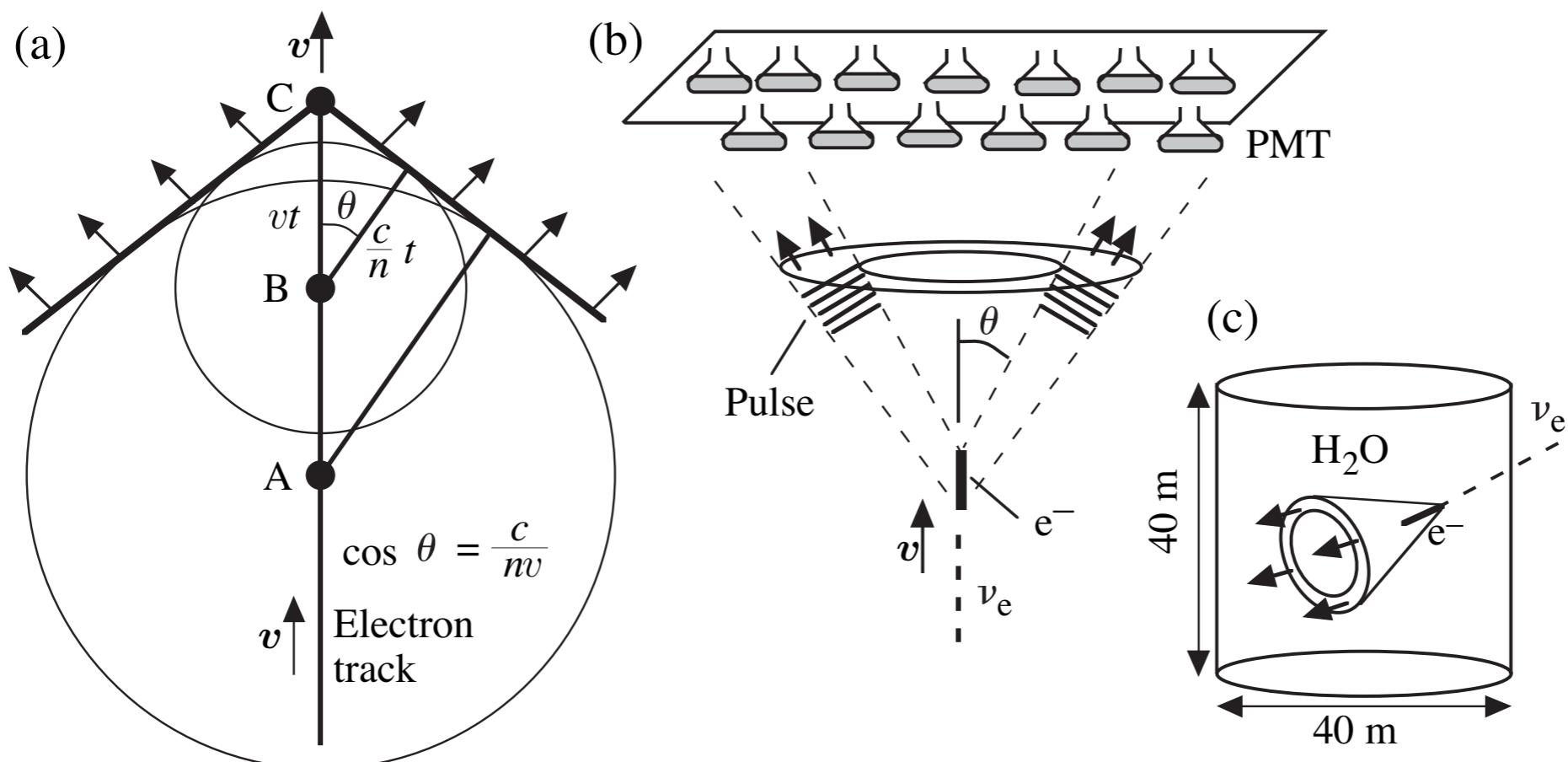
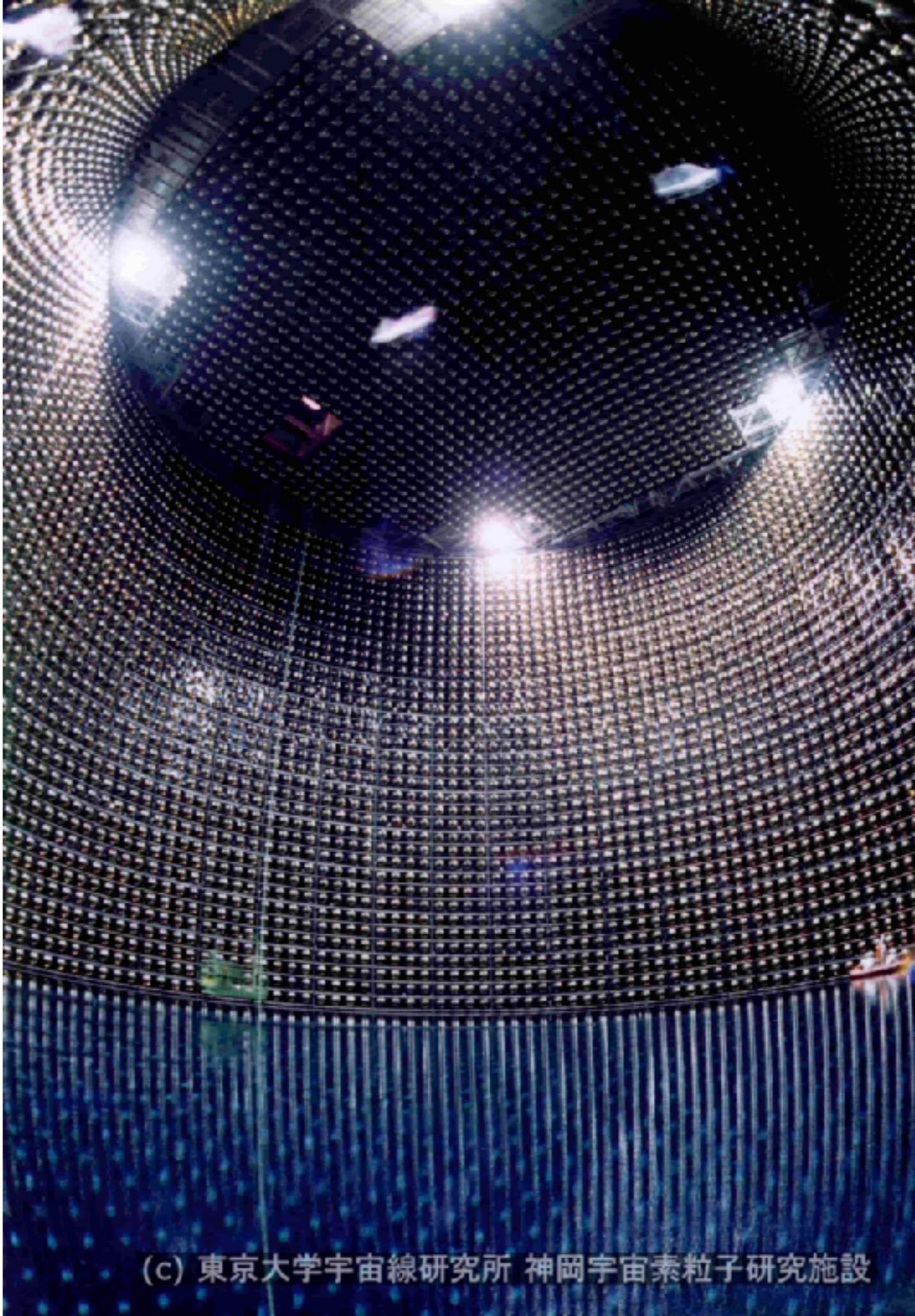


Fig. 12.2: Astronomy Methods (CUP), ©H. Bradt 2004

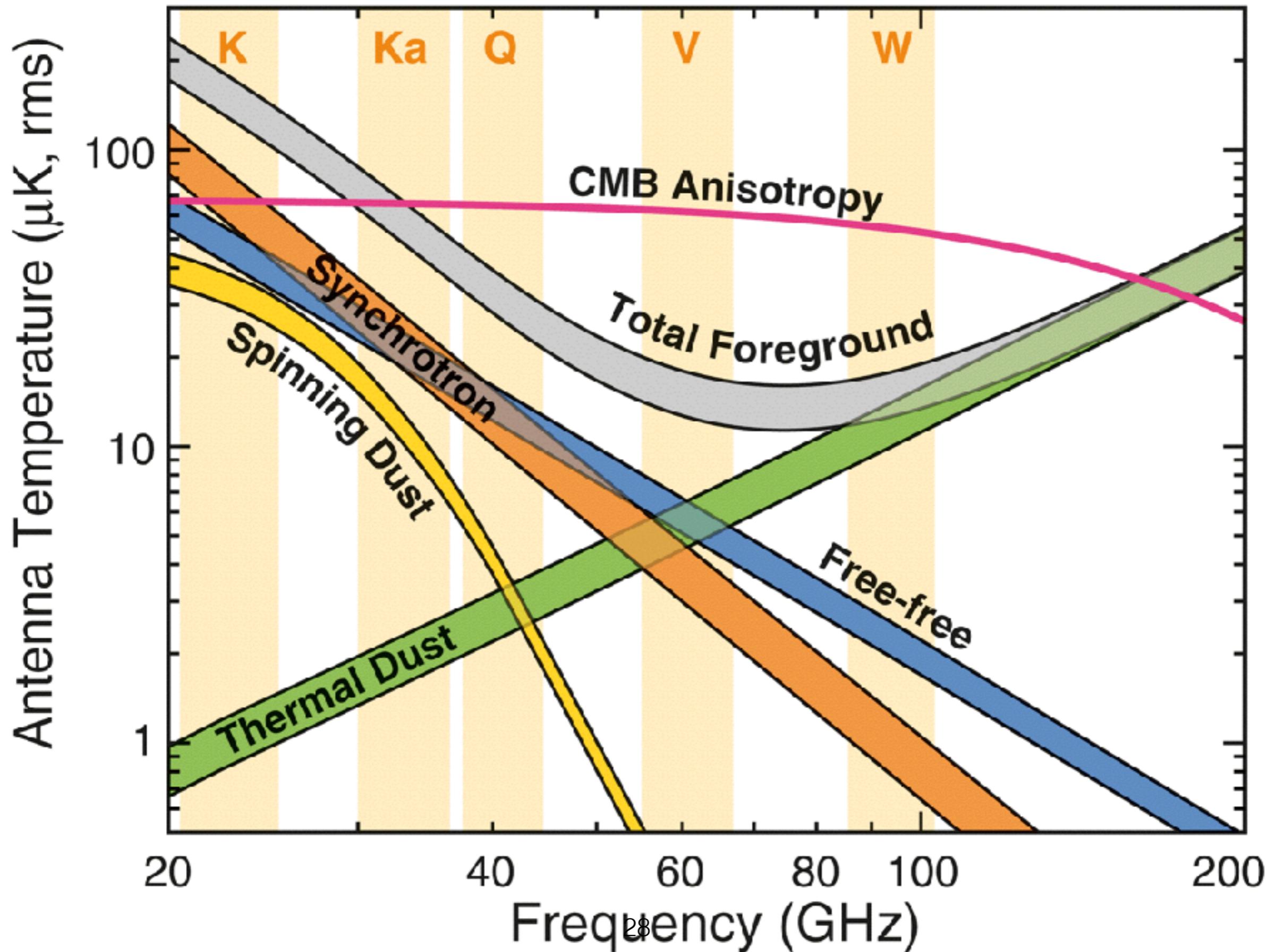


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

review of radiation processes:

- blackbody
- free-free
- synchrotron
- Compton-scattering
- pair-production
- Cherenkov

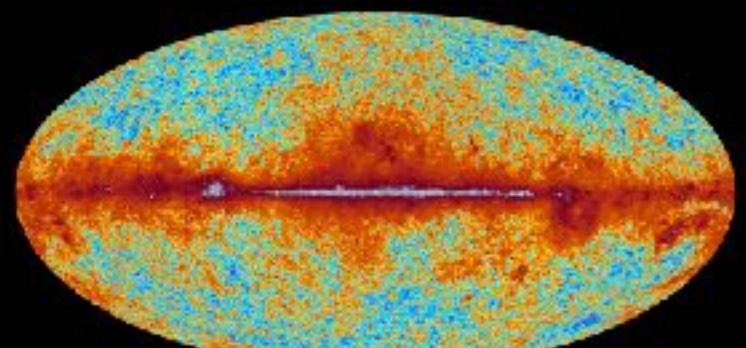
# Galactic Foregrounds and CMB



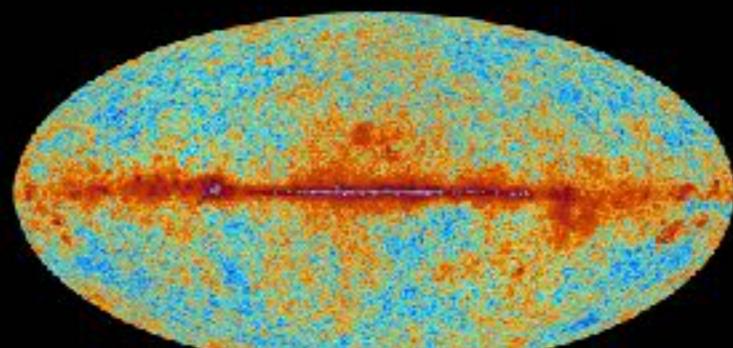


planck

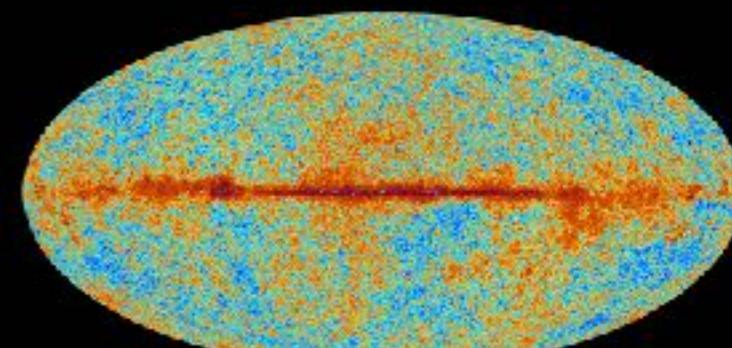
# *The sky as seen by Planck*



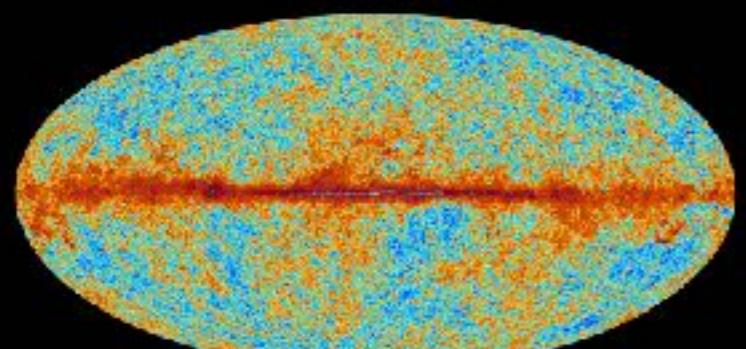
30 GHz



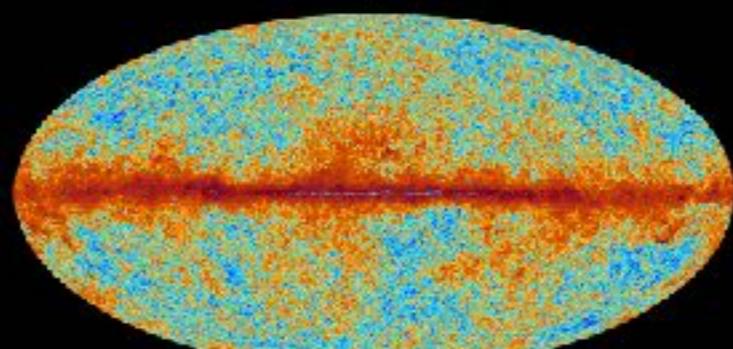
44 GHz



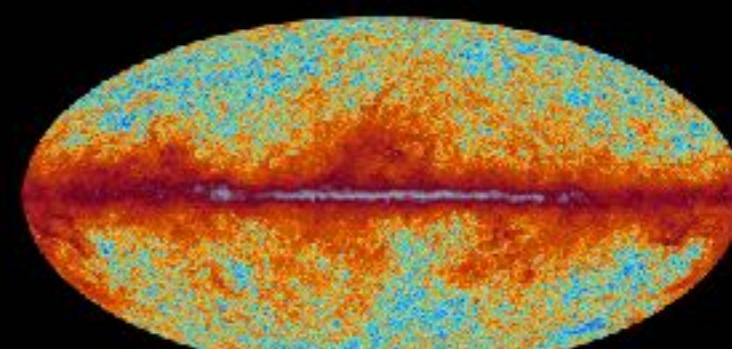
70 GHz



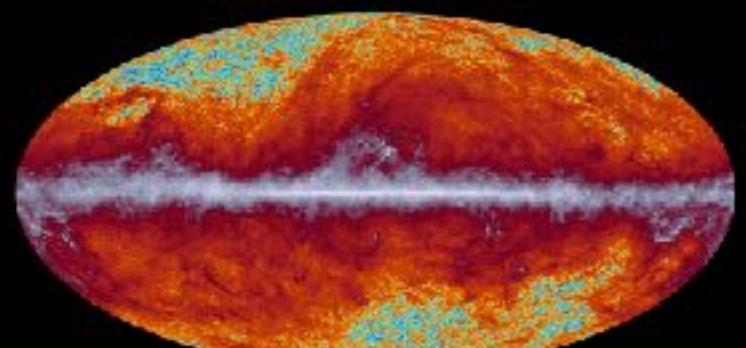
100 GHz



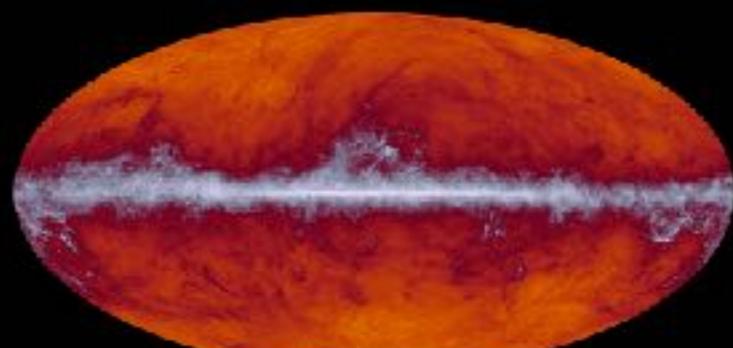
143 GHz



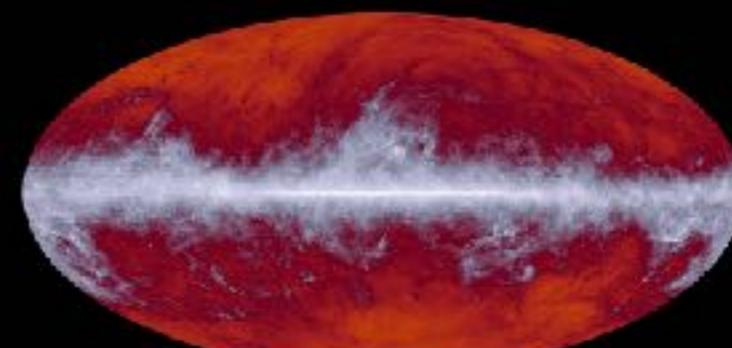
217 GHz



353 GHz

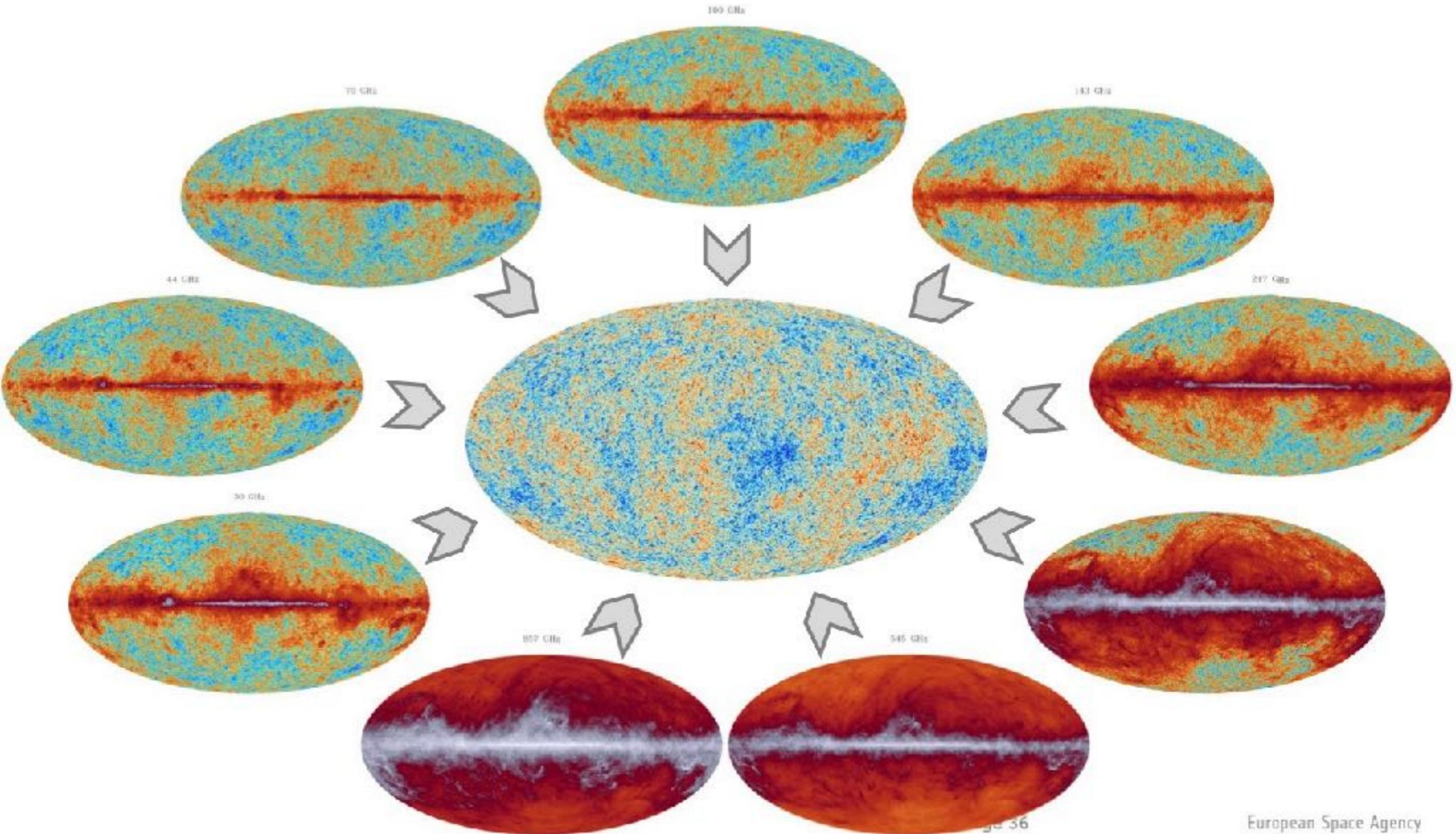


545 GHz



857 GHz

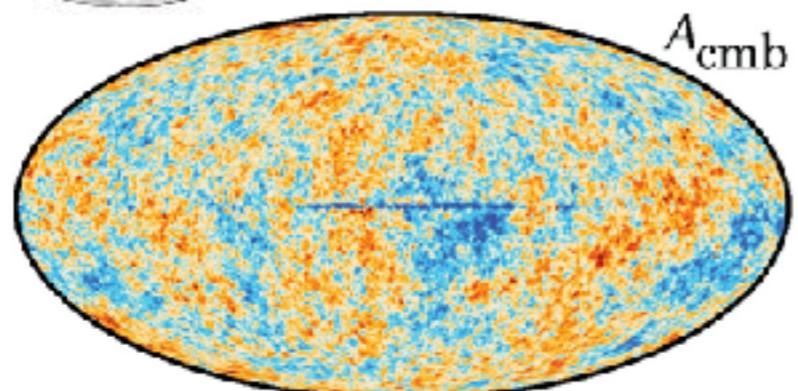
# Foregrounds



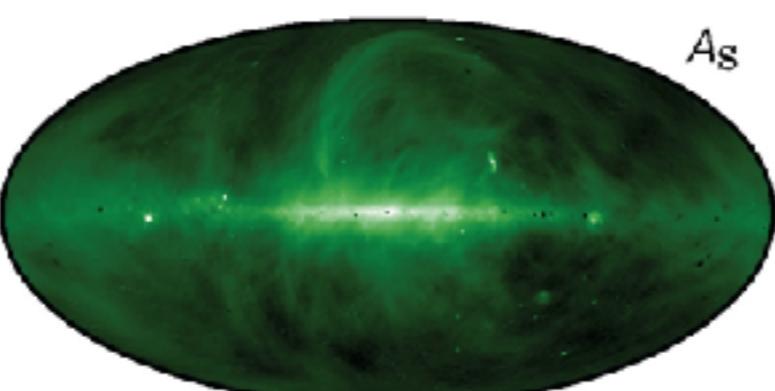
European Space Agency



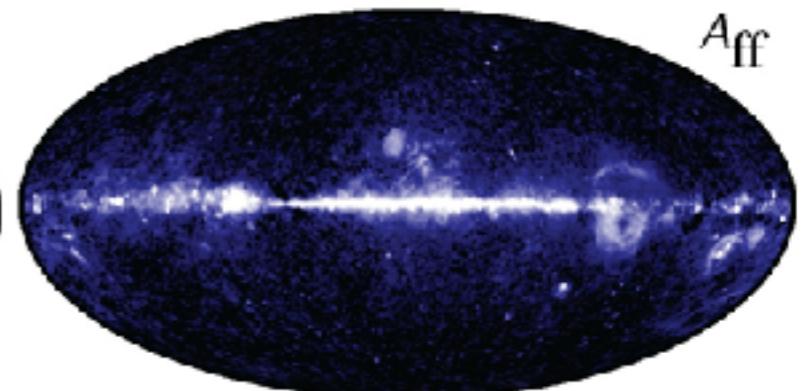
# Components on the sky from *Planck*



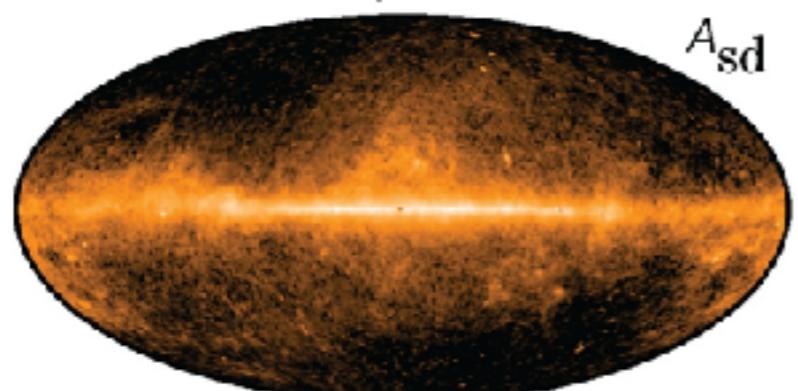
-250  $\mu\text{K}$  250



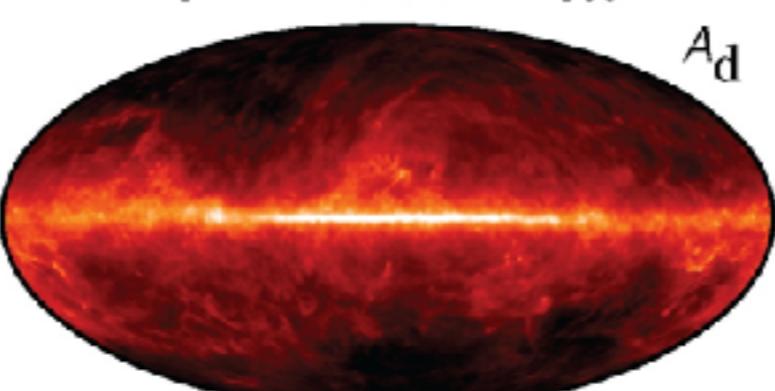
5 K @ 408 MHz 500



0  $\text{cm}^{-6}\text{pc}$  1000



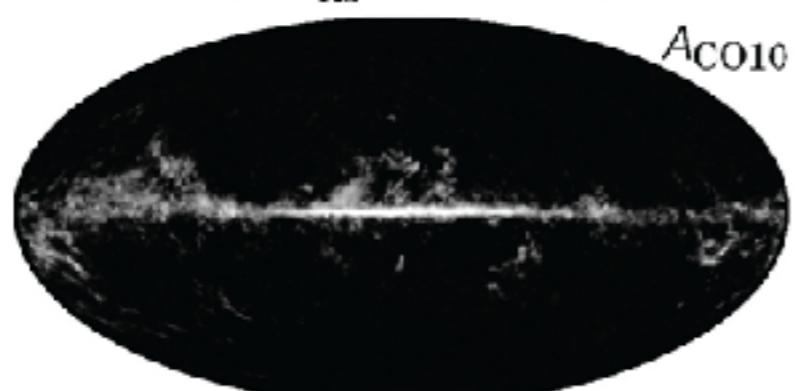
0.01 mK<sub>RJ</sub> @ 30 GHz 10



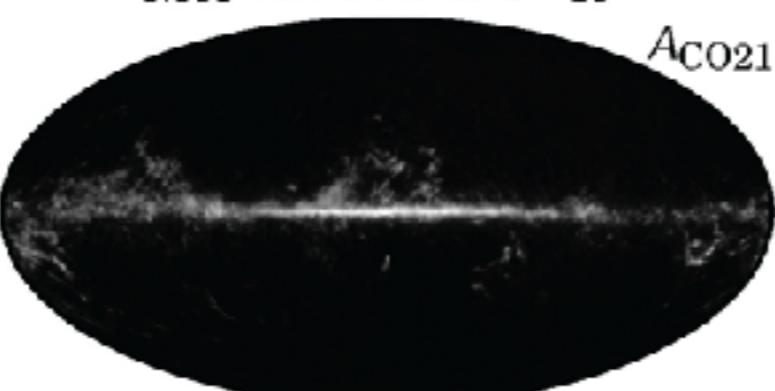
0.001 mK @ 545 GHz 10



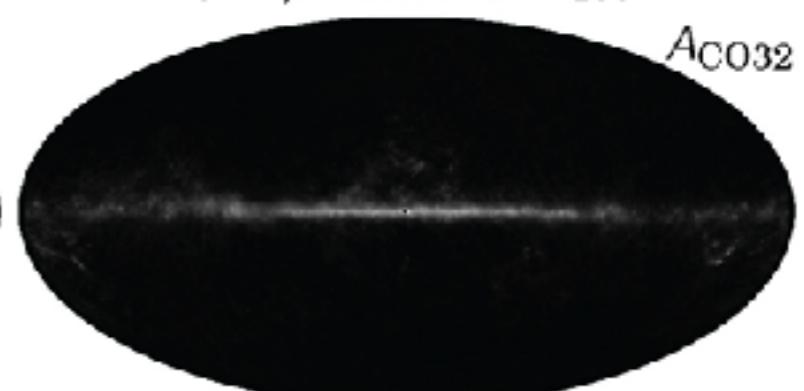
0  $\mu\text{K} @ 100\text{-ds1}$  100



0 K km/s 100



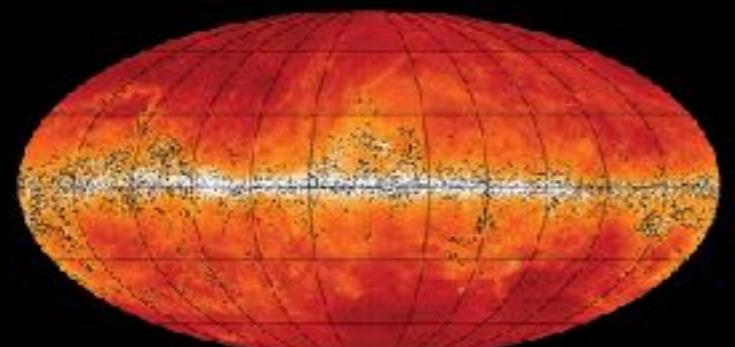
0 K km/s  
31



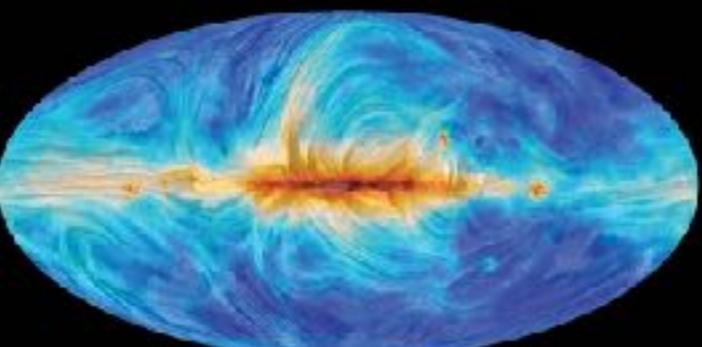
0 K km/s 100



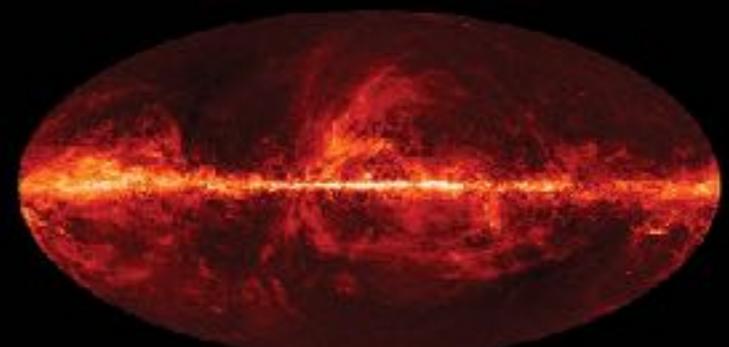
# High level data products from *Planck*



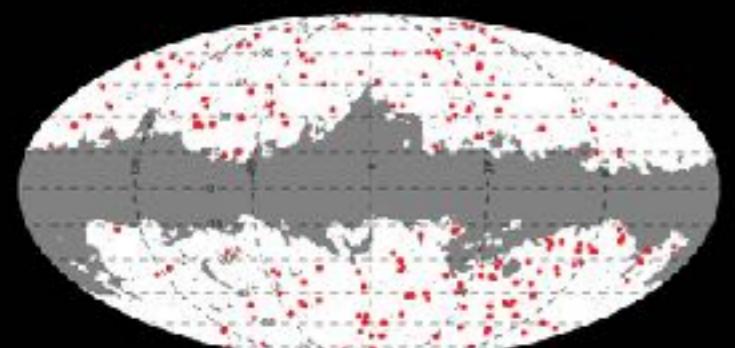
Galactic cold clumps



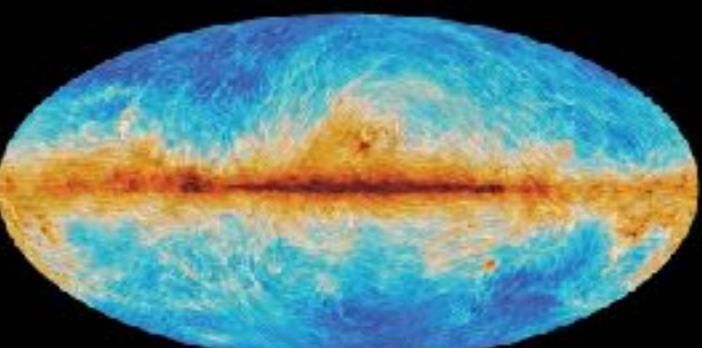
Magnetic field lines traced  
by synchrotron radiation at 30 GHz



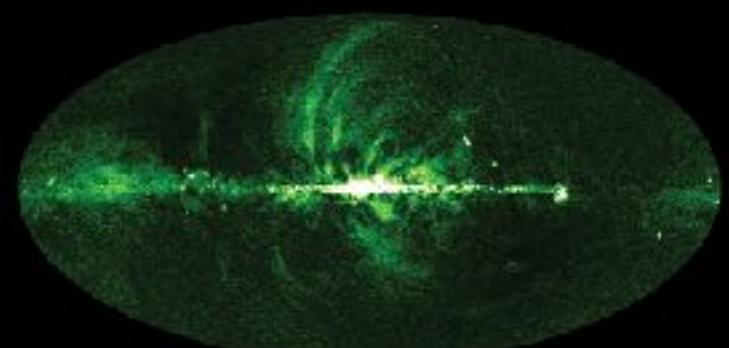
Polarised dust emission



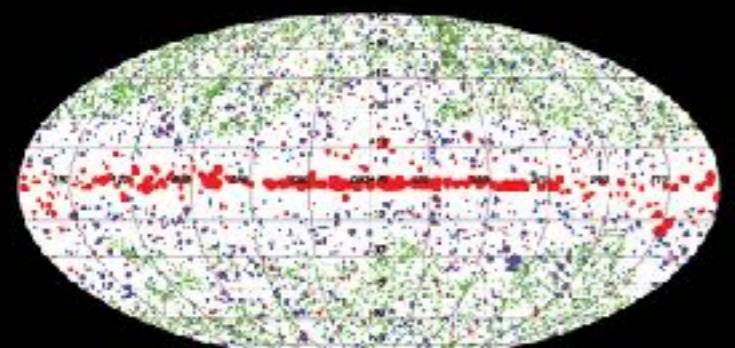
Galaxy clusters detected by  
the Sunyaev-Zeldovich effect



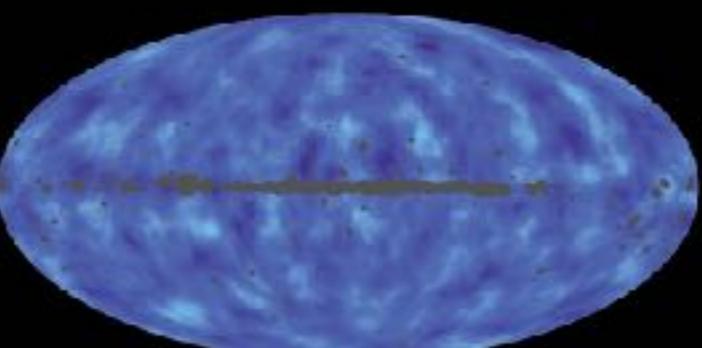
Magnetic field lines traced  
by dust emission at 353 GHz



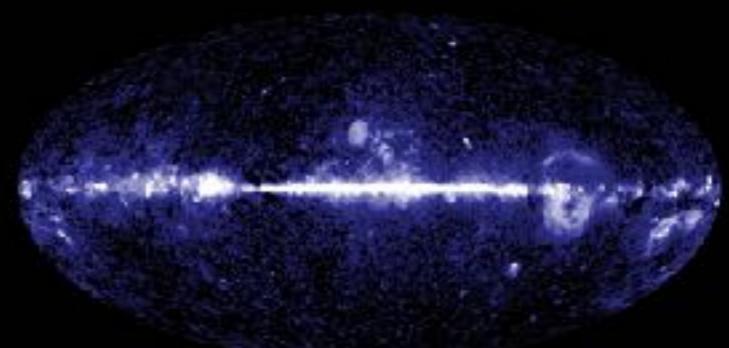
Polarised synchrotron emission



Compact sources

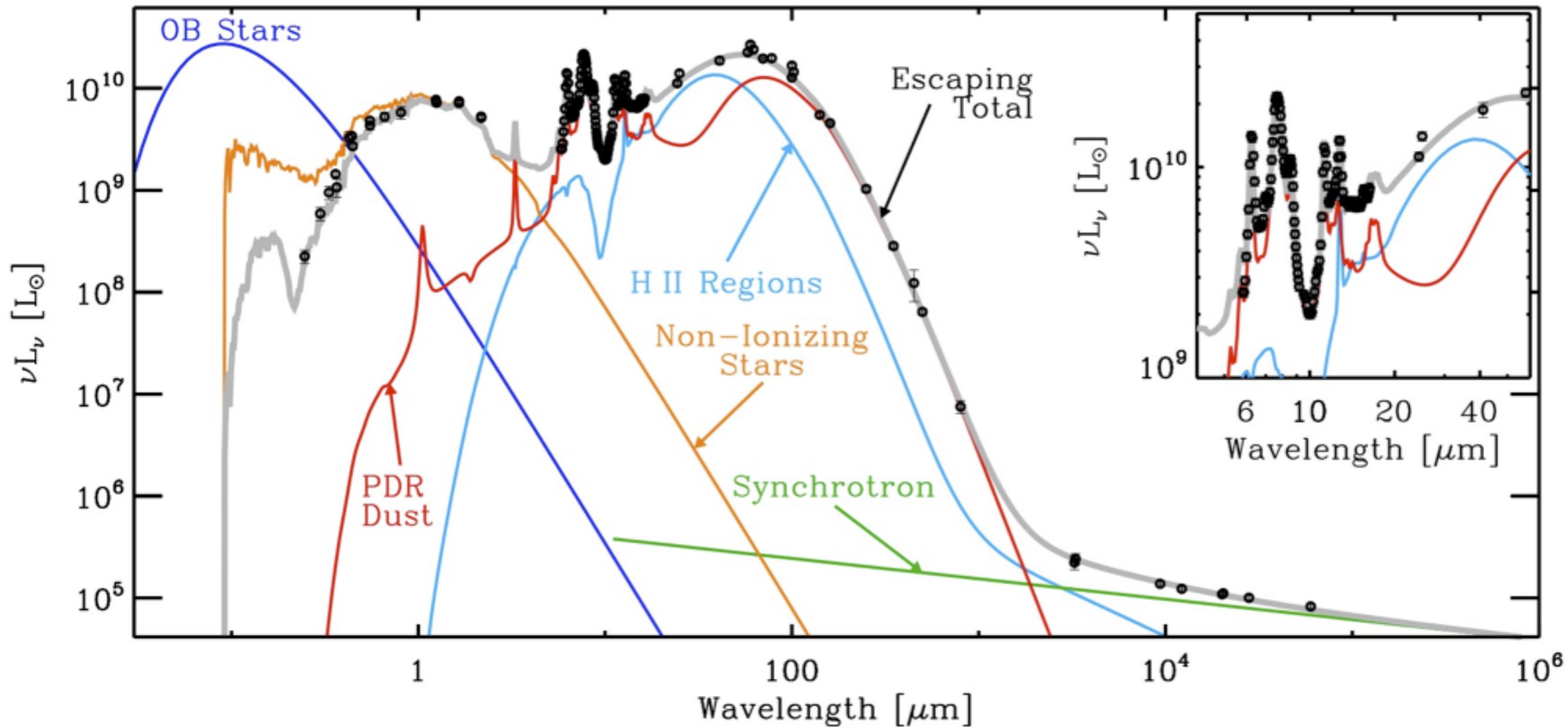


Gravitational-lensing potential –  
a tracer of dark matter structures



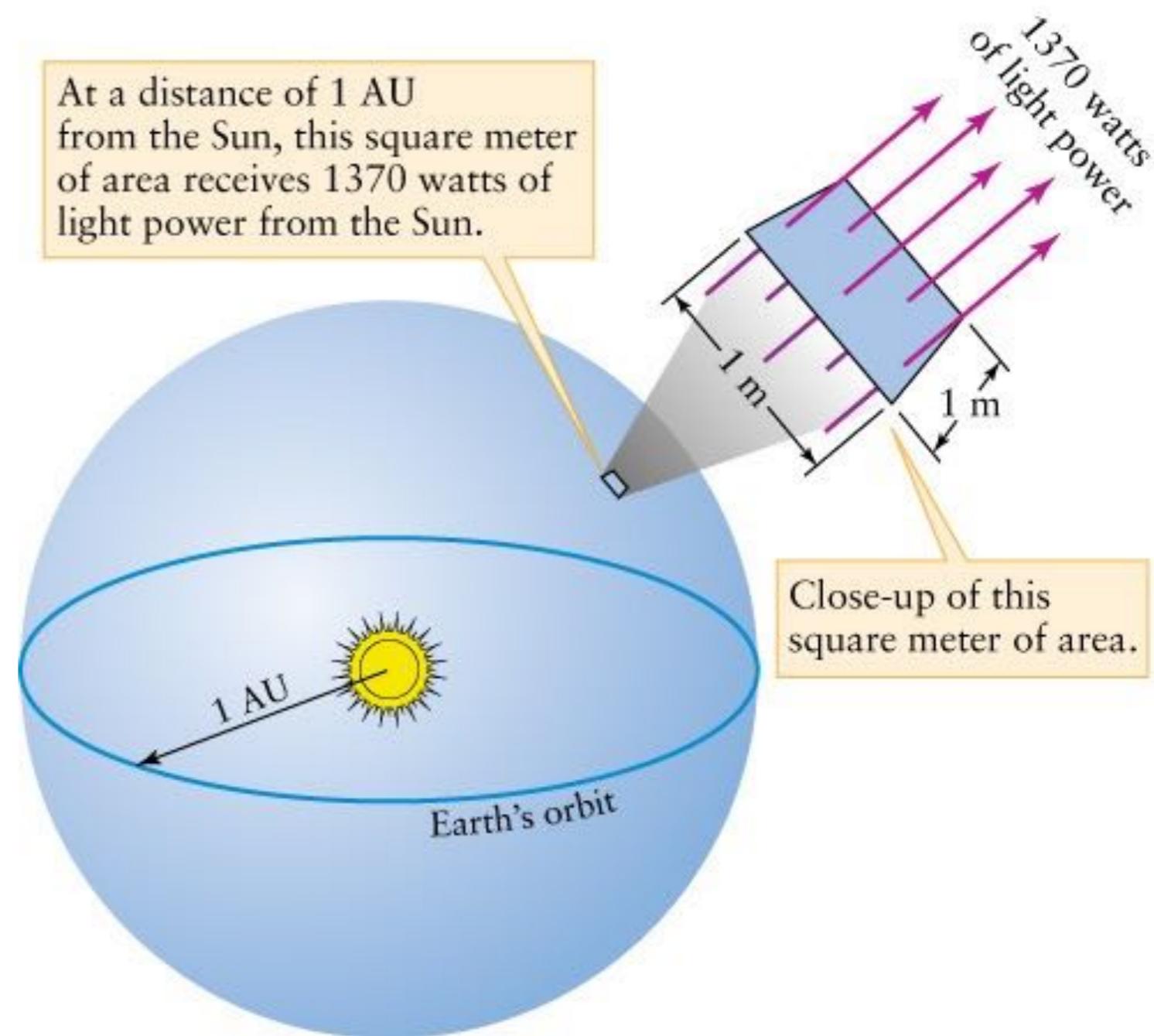
Line radiation from carbon monoxide gas

M 82



# Flux and Luminosity

- **Flux** = the amount of power falling within a given area [ $\text{W/m}^2$ ]
- **Luminosity** = the brightness of an object (like wattage of a lightbulb) [W]



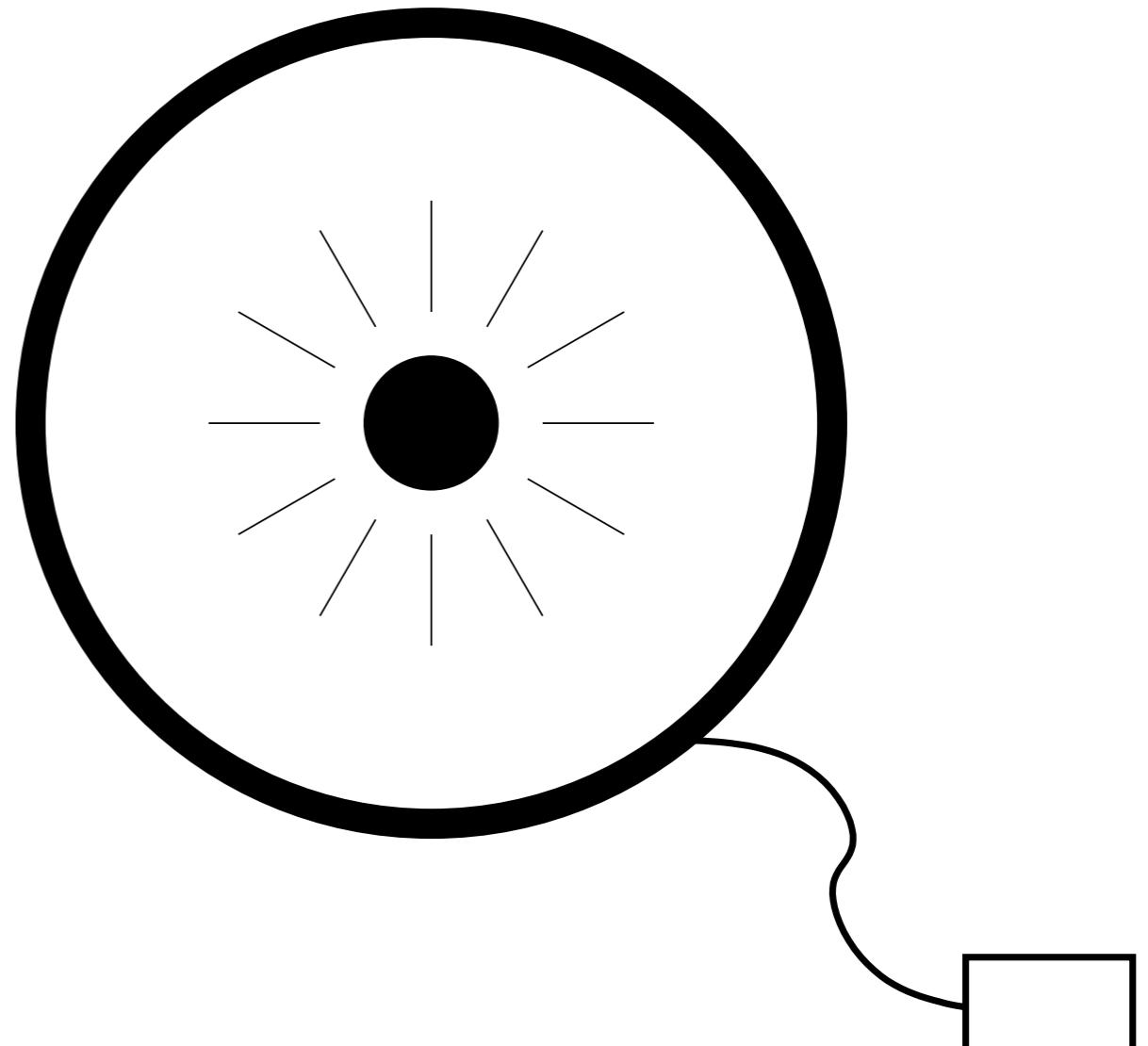
# Luminosity ( $L$ )

- A source's luminosity is the **power** that it emits in radiation.
- SI units are W.
- Also used are  $\text{erg s}^{-1} \equiv 10^{-7} \text{ W}$
- Have to define a frequency range

e.g. the total (or bolometric) luminosity of a lightbulb is 50 W

the luminosity in the visible range is only  $\sim 1 \text{ W}$

- For a spherical blackbody source
- $$L = 4\pi R^2 \sigma T^4$$



$$E = \int L \, dt$$

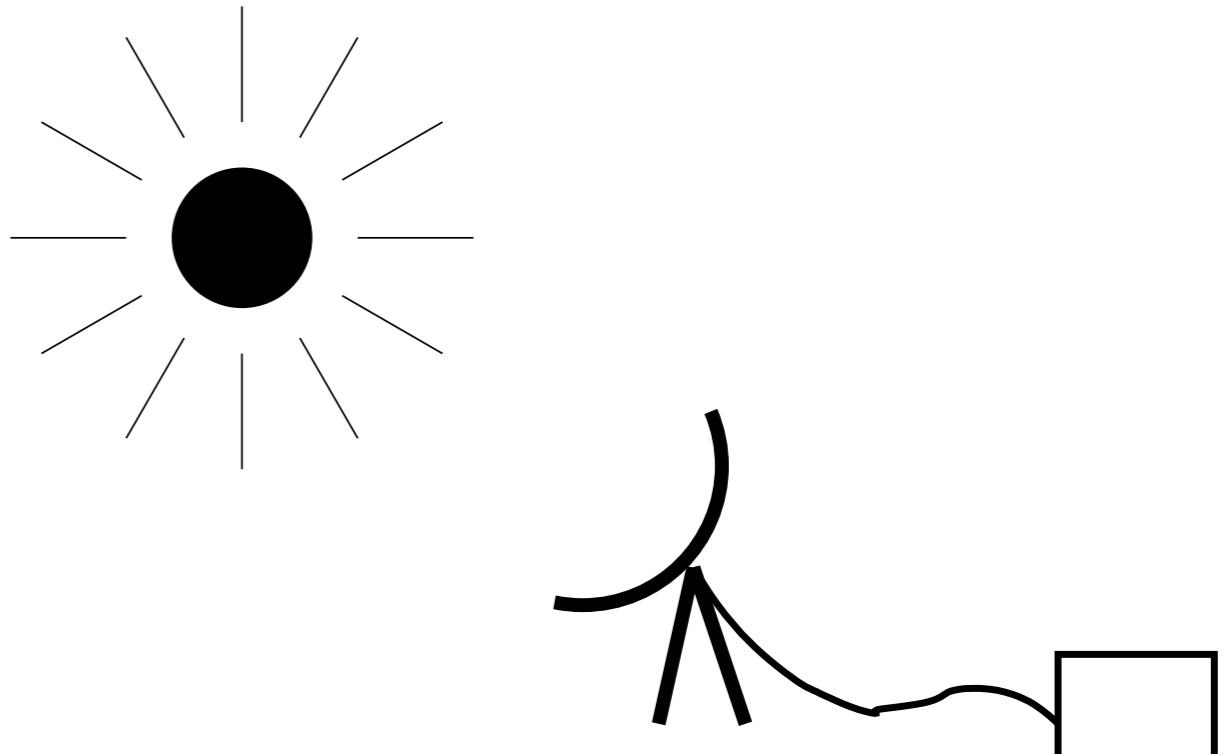
# Flux ( $\phi$ )

- The flux of a source is the power received **per unit area**.

The flux from a uniform spherical source at distance  $d$  is given by

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

- SI units are  $\text{Wm}^{-2}$ .
- e.g. Flux from a light bulb at a distance of 10 m is  $0.04 \text{ Wm}^{-2}$



$$E = \iint \phi \, dt \, dA$$

# Flux Density ( $F_\nu$ )

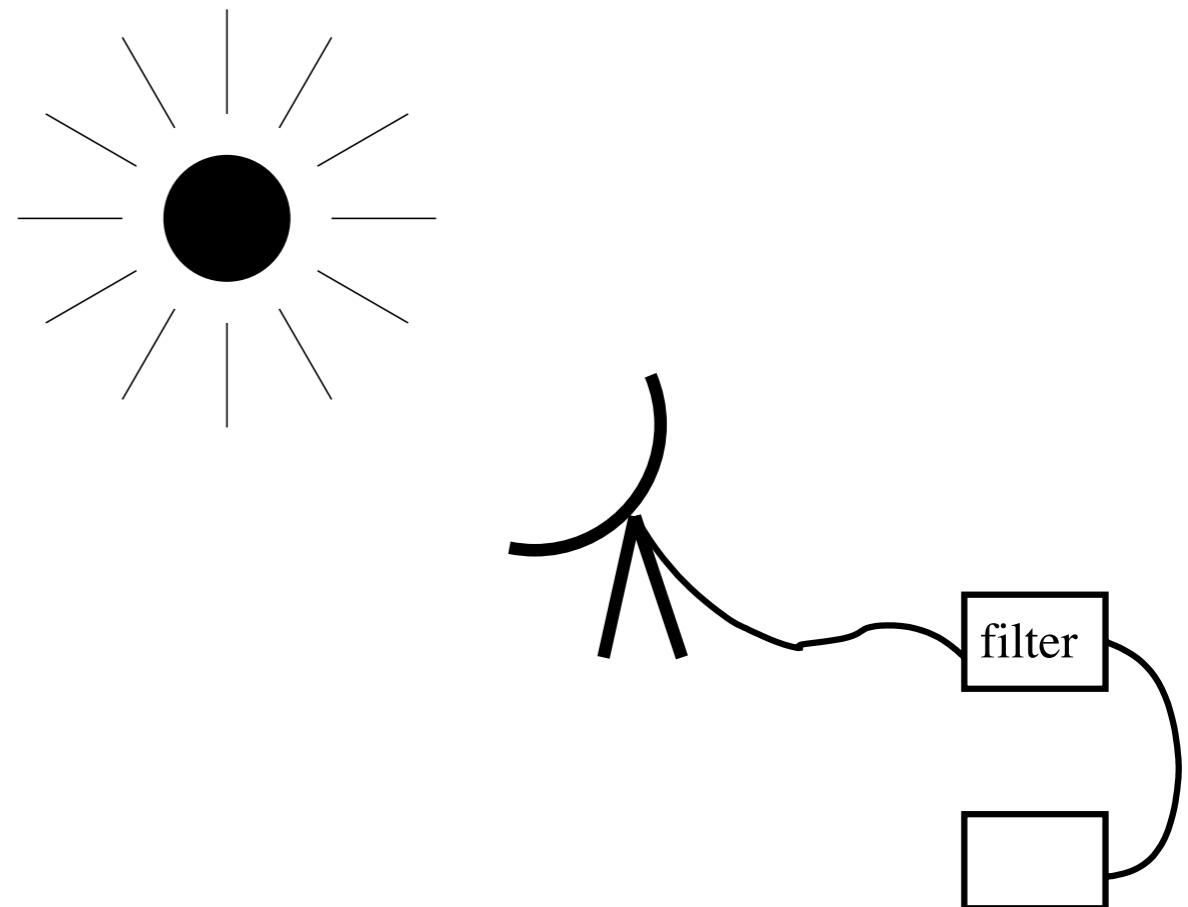
- Flux density is the power received per unit area **per unit frequency**. Flux is the integral of flux density with respect to frequency.

$$\phi = \int_{\nu_1}^{\nu_2} F_\nu \, d\nu$$

$\Delta\nu = \nu_2 - \nu_1$  is the bandwidth

- Also called specific flux - ‘specific’ refers to  $\text{Hz}^{-1}$ .
- NB Astronomers often say ‘flux’ when they mean ‘flux density’
- SI units are  $\text{W m}^{-2} \text{Hz}^{-1}$
- Also used are  $\text{Jy} \equiv 10^{-26} \text{ W m}^{-2} \text{Hz}^{-1}$

(units for a point source)



$$E = \iiint F_\nu \, d\nu \, dA \, dt$$

# Specific Intensity, Surface Brightness ( $I_\nu$ )

- Specific intensity (or surface brightness) is the power received (or emitted) per unit area per unit frequency **per unit solid angle**.

$$F_\nu = \int I_\nu \cos \theta \, d\Omega$$

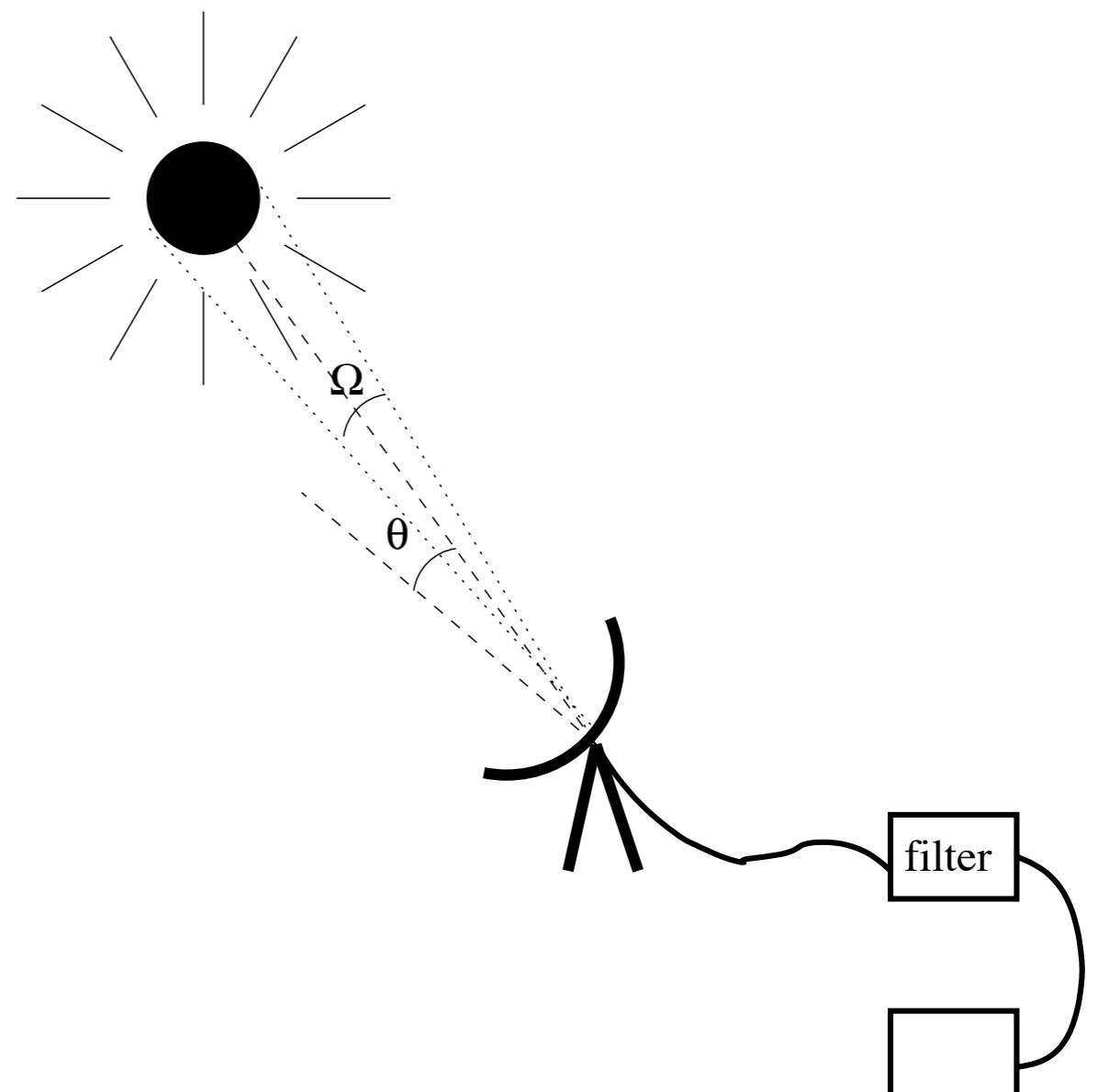
$$\Rightarrow F_\nu \text{ at surface of a spherical source} = \pi I_\nu$$

- Specific intensity is independent of distance.
- Also define the mean intensity  $J_\nu$

$$J_\nu = \frac{1}{4\pi} \int_{4\pi} I_\nu \, d\Omega$$

- An *isotropic* radiation field is one where  $I_\nu$  is independent of angle, so  $J_\nu = I_\nu$  .
- Units are  $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$

(units for a diffuse source)



$$E = \iiint I_\nu \cos \theta \, d\nu \, d\Omega \, dA \, dt$$

# Calculating $F_\nu$ and $I_\nu$ for a blackbody

- The specific intensity of a black-body is given by the Planck function,  $B_\nu$

$$I_\nu = B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{(\exp \frac{h\nu}{kT} - 1)} \left( = \frac{F_\nu}{\Omega} \quad \text{for a uniform brightness source} \right)$$

A derivation of  $B_\nu$  is given in the appendix.

- In the Rayleigh-Jeans region where  $h\nu \ll kT$

$$I_\nu = B_\nu = \frac{2kT}{\lambda^2}$$

e.g. A black-body source of angular radius 1 arcsec and temperature 2700 K is observed by a telescope with a beam FWHM = 1 arcmin at 1GHz.

$I_\nu(\text{source}) = 3.02 \times 10^{-17} \text{ Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ . (We are in the Rayleigh-Jeans region)

$F_\nu(\text{source}) = I_\nu(\text{source}) \times \Omega_{(\text{source})} = 2.2 \times 10^{-27} \text{ Wm}^{-2}\text{Hz}^{-1} = 0.22 \text{ Jy}$ .

( $\Omega_{(\text{source})} = \pi(1/3600 \times \pi/180)^2$  )

# Luminosity

spectral radiance for a blackbody:

$$B(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT}) - 1}$$

Flux Density (or monochromatic flux)  
(sometimes called the spectral irradiance)

$$S = \int \int_{\text{source}} B(\theta, \phi) d\Omega \quad [\frac{W}{m^2 \cdot Hz}]$$

units of watts per square meter per Hz

# Calculating $F_\nu$ and $I_\nu$ for a blackbody

- The specific intensity of a black-body is given by the Planck function,  $B_\nu$

$$I_\nu = B_\nu = \frac{2h\nu^3}{c^2} \frac{1}{(\exp \frac{h\nu}{kT} - 1)} \left( = \frac{F_\nu}{\Omega} \quad \text{for a uniform brightness source} \right)$$

A derivation of  $B_\nu$  is given in the appendix.

- In the Rayleigh-Jeans region where  $h\nu \ll kT$

$$I_\nu = B_\nu = \frac{2kT}{\lambda^2}$$

e.g. A black-body source of angular radius 1 arcsec and temperature 2700 K is observed by a telescope with a beam FWHM = 1 arcmin at 1GHz.

$I_\nu(\text{source}) = 3.02 \times 10^{-17} \text{ Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ . (We are in the Rayleigh-Jeans region)

$F_\nu(\text{source}) = I_\nu(\text{source}) \times \Omega_{(\text{source})} = 2.2 \times 10^{-27} \text{ Wm}^{-2}\text{Hz}^{-1} = 0.22 \text{ Jy}$ .

( $\Omega_{(\text{source})} = \pi(1/3600 \times \pi/180)^2$  )

# Determining $\Omega$

- In general the integration for calculating the received flux density from the specific intensity using

$$F_\nu = \int I_\nu \cos \theta \, d\Omega$$

is not trivial since it must take into account the telescope's response function, also called the beam.

- If the source is much smaller than the telescope's beam then this makes a negligible difference and  $F_\nu = I_\nu \Omega_{(\text{source})}$  (as in the previous example).
- Another simple case is if the source has constant specific intensity inside the beam; the integration then gives  $I_\nu \Omega_{(\text{beam})}$  where  $\Omega_{(\text{beam})}$  is the effective beam solid angle. The effective beam solid angle for a Gaussian beam of FWHM  $\theta_{\text{FWHM}}$  is  $\Omega_{(\text{beam})} = \theta_{\text{FWHM}}^2 \frac{\pi}{4 \ln 2}$

Extending the previous example: the telescope also picks up radiation from the 2.7 K Cosmic Microwave Background .

$$I_\nu (\text{CMB}) = 3.02 \times 10^{-20} \text{ Wm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}. \text{ (We are in the Rayleigh-Jeans region)}$$

$$F_\nu (\text{CMB}) = I_\nu (\text{CMB}) \times \Omega_{(\text{beam})} = 2.9 \times 10^{-27} \text{ Wm}^{-2}\text{Hz}^{-1} = 0.29 \text{ Jy.}$$

$$(\Omega_{(\text{beam})} = (1/60 \times \pi/180)^2 \times 1.13)$$

# Summary of Key Points

- Flux density,  $F_\nu$ , is power per unit area per unit *frequency*, measured in  $\text{Jy} \equiv 10^{-26} \text{Wm}^{-2}\text{Hz}^{-1}$
- Specific intensity,  $I_\nu$ , is flux density per unit *solid angle*. It is independent of distance.
- For blackbody sources  $I_\nu = B_\nu$  (Planck function).
- For uniform sources  $F_\nu = I_\nu \Omega$  where  $\Omega$  is often either  $\Omega_{(\text{source})}$  or  $\Omega_{(\text{beam})}$  for compact or extended sources respectively.
- A source's polarisation can be characterised by its Stoke's parameters.  $I$  gives the total flux.  $Q$  and  $U$  give the degree of linear polarisation,  $V$  the degree of circular polarisation.

- You can convert between  $F_{\nu}$  and  $F_{\lambda}$  - just make sure to do so consistently
- Narayan et al. (2019), Sec. 4.3 if you need a slightly more detailed version than is in these slides

$$F_{\lambda} = F_{\nu} \cdot \frac{\nu^2}{c} \quad (6)$$

for  $\lambda = c/\nu$ .

$$\langle F_{\lambda}^p \rangle = \frac{\int_0^{\infty} \lambda \cdot F^p(\lambda) \cdot R(\lambda) \cdot d\lambda}{\int_0^{\infty} \lambda \cdot R(\lambda) \cdot d\lambda}. \quad \langle F_{\nu}^p \rangle = \frac{\int_0^{\infty} \nu^{-1} \cdot F^p(\nu) \cdot R(\nu) \cdot d\nu}{\int_0^{\infty} \nu^{-1} \cdot R(\nu) \cdot d\nu}$$

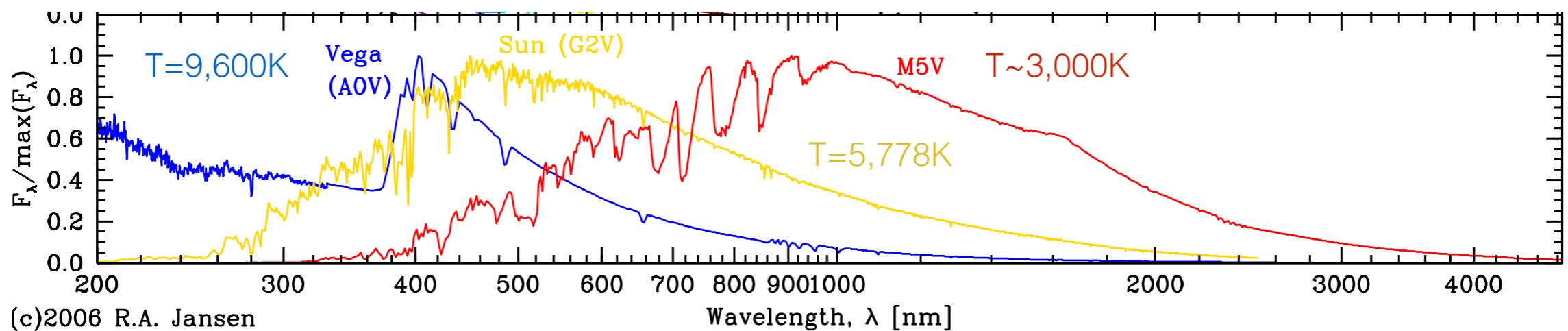
# Definitions

- Intrinsic/absolute Luminosity
- Observed Luminosity
- Apparent Brightness
- Flux
- Magnitude

# Magnitudes

- In general, magnitudes match our eye's sensitivities.
- Standard relative to **Vega**. Why Vega?

$$\Delta m = m_1 - m_2 = -2.5 \log_{10} \frac{F_1}{F_2}$$



- note that a magnitude difference is equivalent to a flux ratio.
- Calibration is difficult ! Relative calibration can be good in some cases because you simply take an image of a standard star, reference it to Vega, and normalize everything.
- Turns out Vega is slightly variable and also has a debris disk. It's also not always visible.

# Calibrating stars is hard.



Figure 4. The observing telescope (right) and collimated laser for horizontal extinction (left) on the ridge at Mt. Hopkins. The calibration source was located in the support building in the background.

The field calibration source consists of a 50 mm diameter integrating sphere with a 1 mm diameter aperture. The sphere is illuminated by a 10 W quartz tungsten halogen (QTH) lamp. A second

# relative magnitudes for reference and intuition

Object	magnitude	relative flux	instrument
Sun	-27	$6 \times 10^{10}$	
full Moon	-13	$1.6 \times 10^5$	
SN 1006	-7	631	
SN 1572	-4	40	limit of eye in daytime
Jupiter, Mars	-3	16	
Vega, Saturn	0	1	
Polaris	2	0.16	
	6	$4 \times 10^{-3}$	limit of human eye
Neptune	8	$6 \times 10^{-4}$	
	10	$1 \times 10^{-4}$	binoculars
quasar	13	$6 \times 10^{-6}$	6" telescope
	27	$1.6 \times 10^{-11}$	8m-class telescope
	32	$1.6 \times 10^{-13}$	HST

# Absolute Magnitudes

- There is also a magnitude system that is "absolute" and calibrated to Janskys. This is **m<sub>AB</sub>**
- This became popular with SDSS in the late 1990s and is predominant today. It can be the source of great confusion, however!
- To convert to vega to AB magnitudes you need to know some zero point corrections. I always keep a cheat sheet. You can google these.

$$g = g(\text{AB}) + 0.013$$

$$r = r(\text{AB}) + 0.226$$

$$i = i(\text{AB}) + 0.296$$

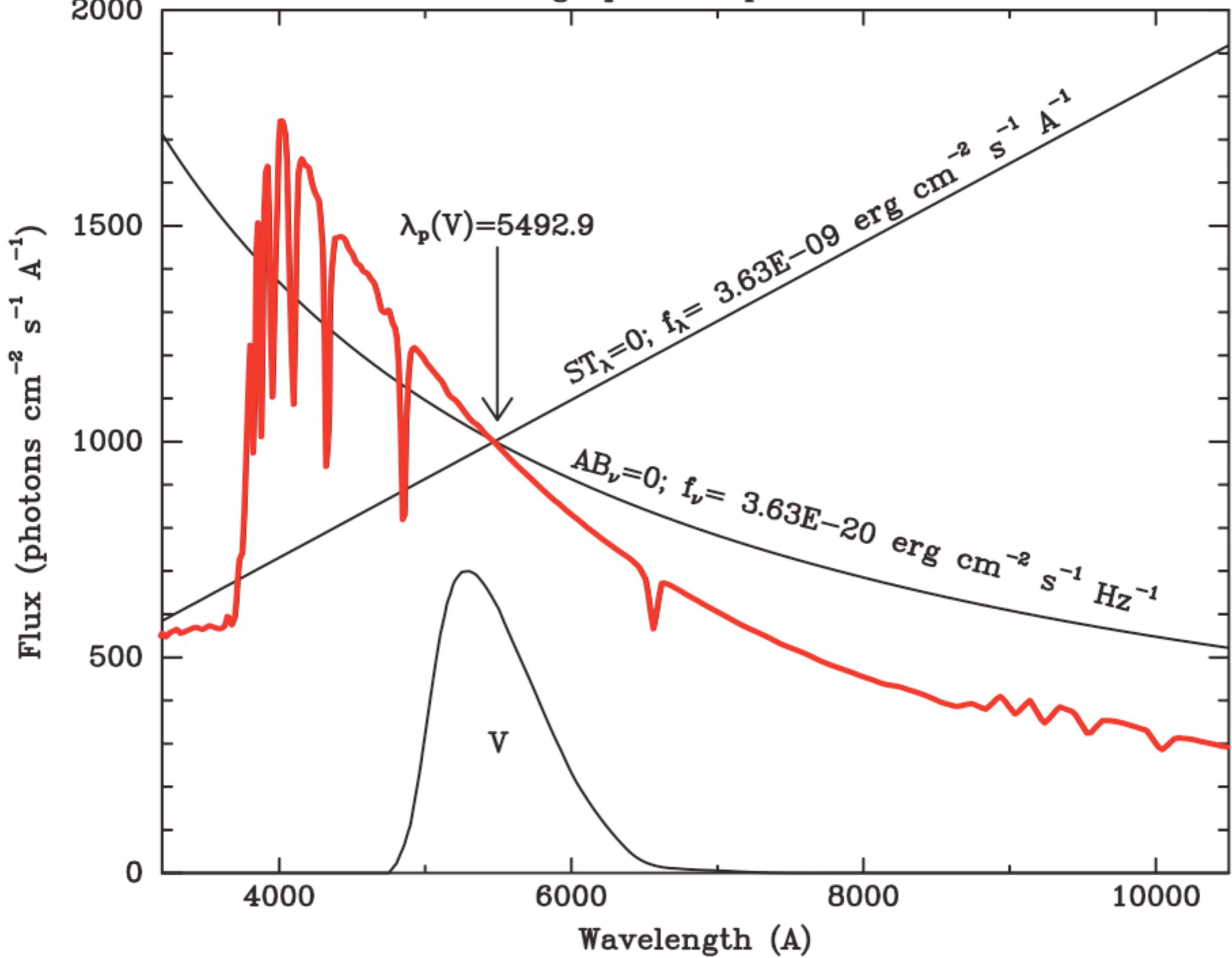
- To convert m<sub>AB</sub> to fluxes, use these:

$$m_{\text{AB}} = 23.9 - 2.5 \log_{10}(\mu\text{Jy})$$

$$S_\nu[\mu\text{Jy}] = 10^6 \cdot 10^{23} \cdot 10^{(-m_{\text{AB}}+48.6)/2.5} = 10^{(23.9-m_{\text{AB}})/2.5}$$

$$S_\nu[m\text{Jy}] = 10^{(16.4-m_{\text{AB}})/2.5}$$

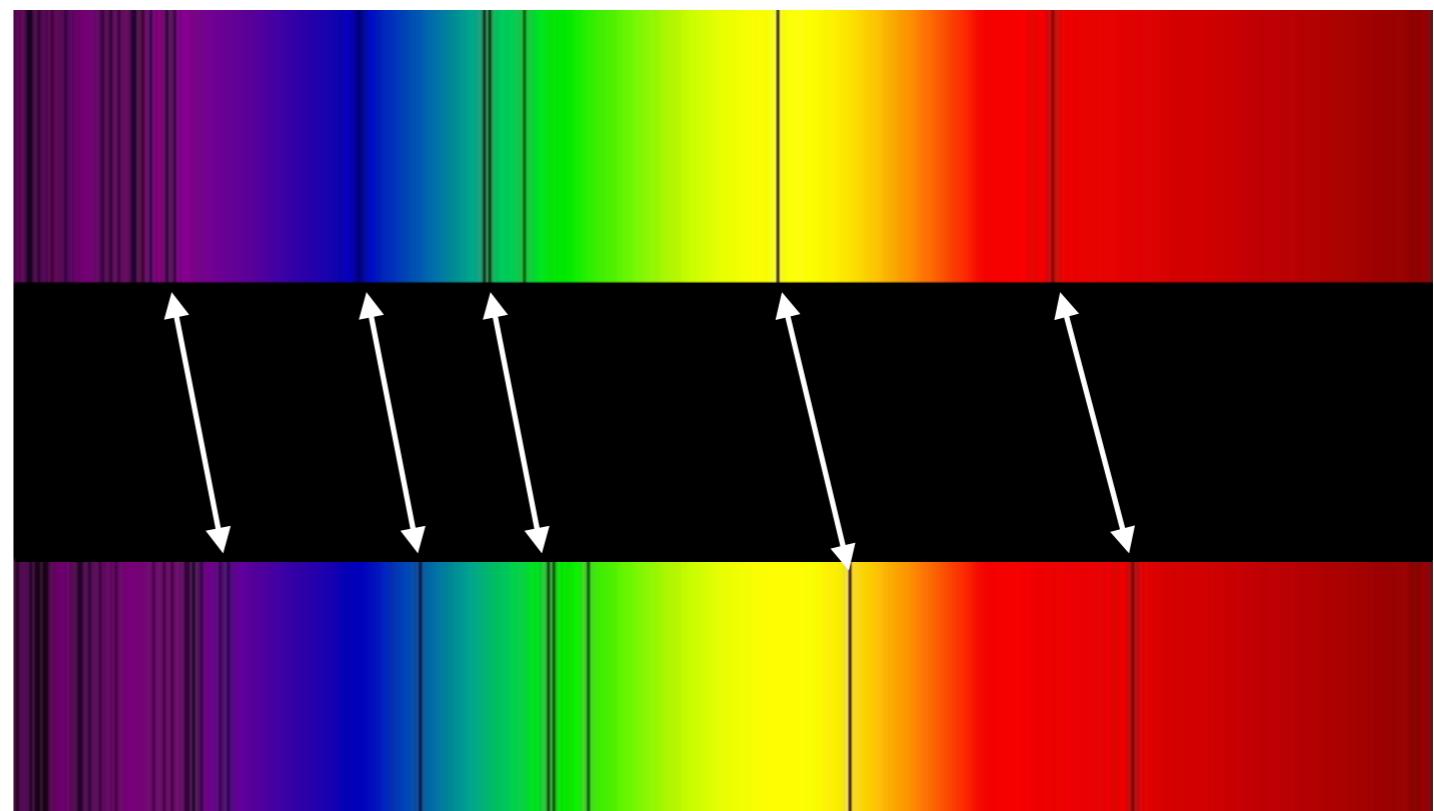
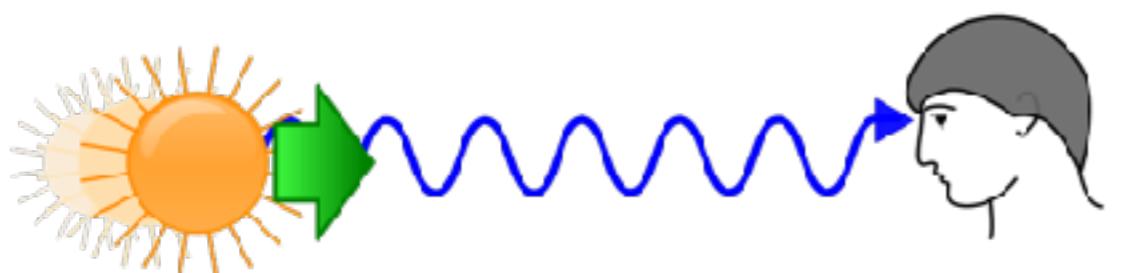
# Vega photon spectrum



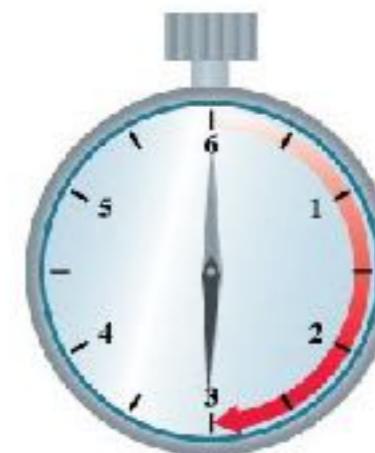
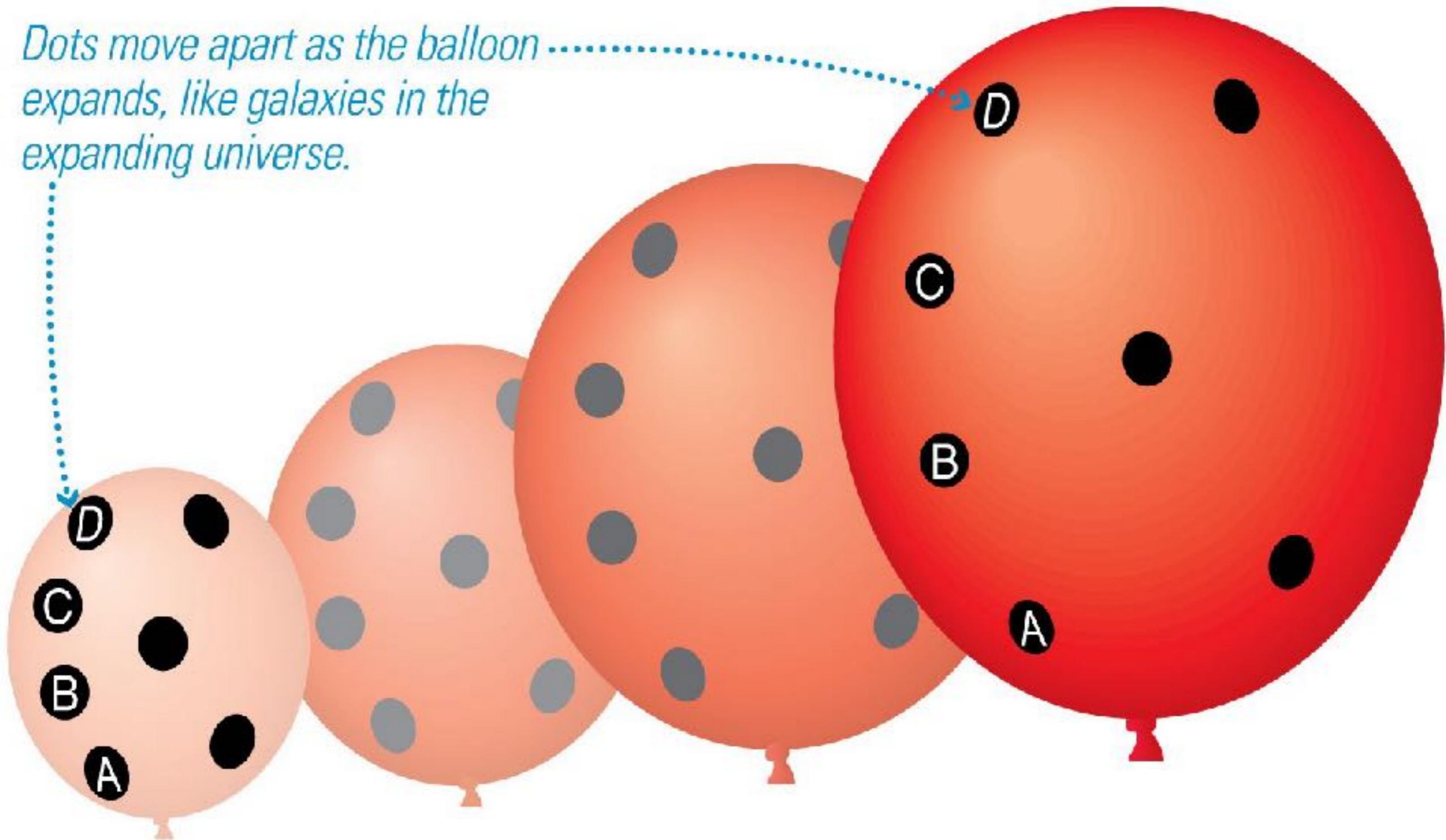
# Distance

- Historically, the most difficult parameter to measure in Astronomy
- apparent magnitude,  $m$  = how bright it appears
- absolute magnitude,  $M$  = how bright it would be at 10 pc, 32.6 ly
- distance modulus:  $m - M = 5(\log_{10}d - 1)$
- $d$  is in pc

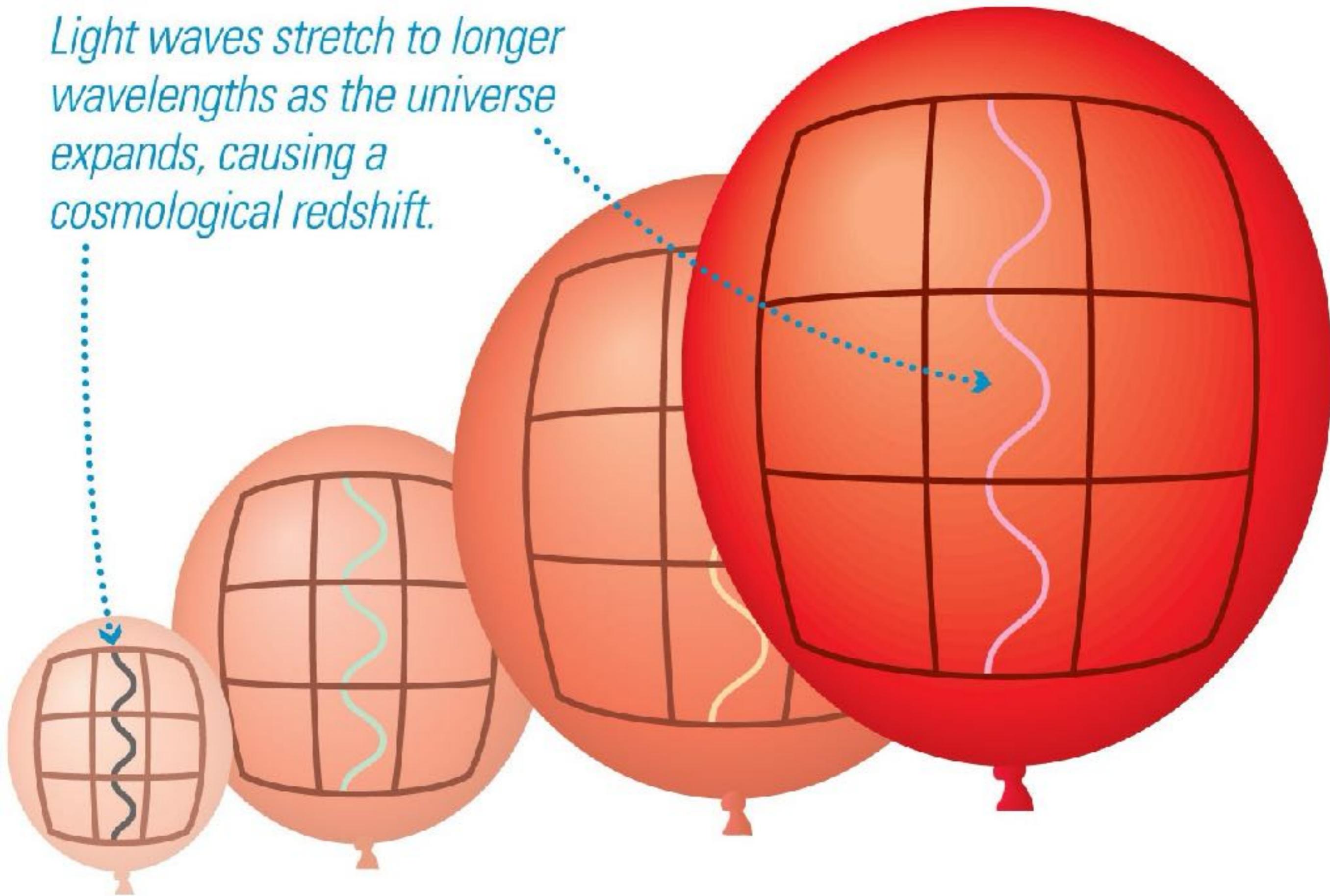
# Doppler Shift



*Dots move apart as the balloon .....  
expands, like galaxies in the  
expanding universe.*



*Light waves stretch to longer wavelengths as the universe expands, causing a cosmological redshift.*



# Redshift

Cosmological redshift is due to the expansion of the universe

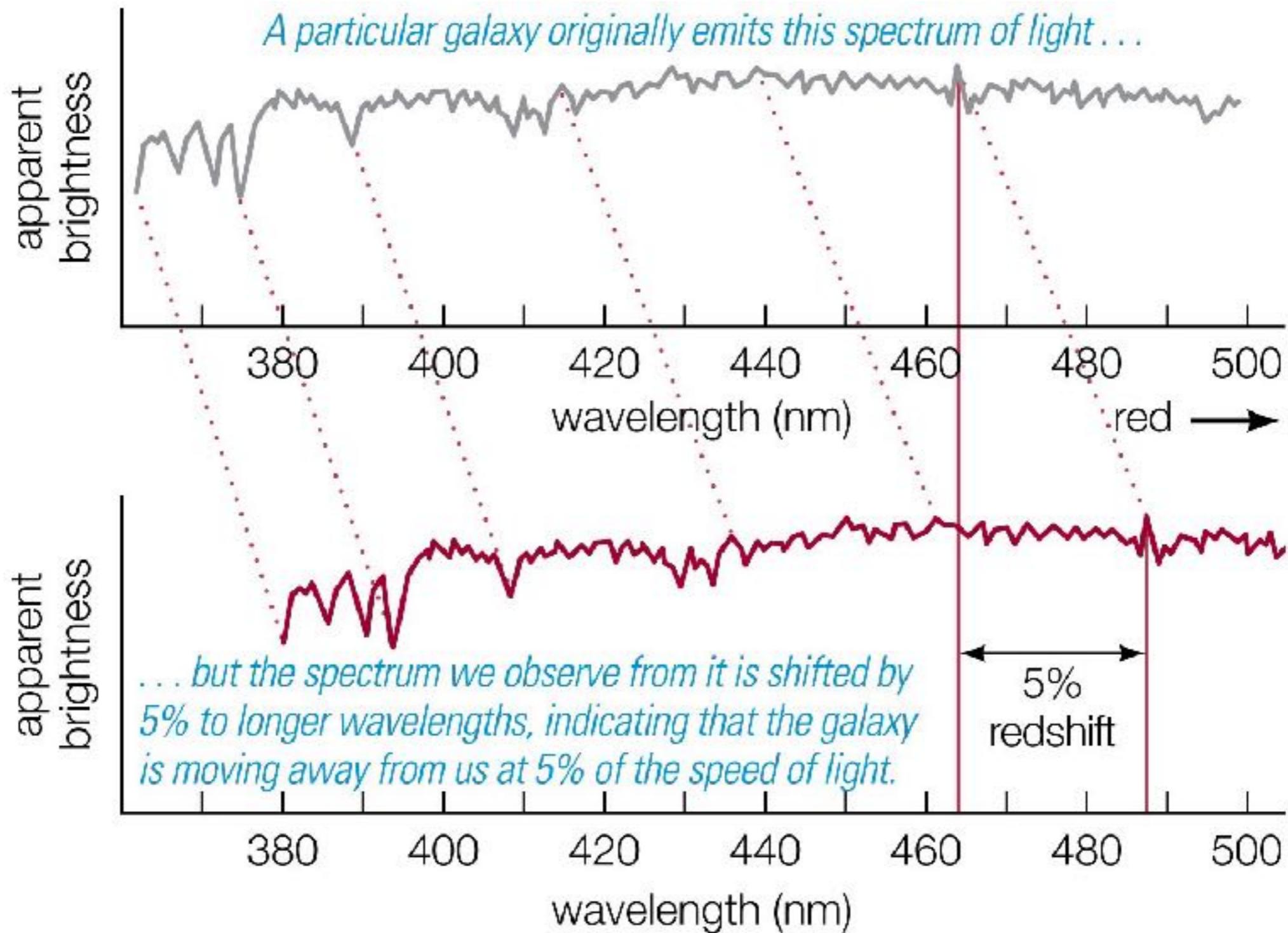
$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

$$1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}}$$

$$z = \frac{\nu_{\text{emit}} - \nu_{\text{obs}}}{\nu_{\text{obs}}}$$

$$1 + z = \frac{\nu_{\text{emit}}}{\nu_{\text{obs}}}$$

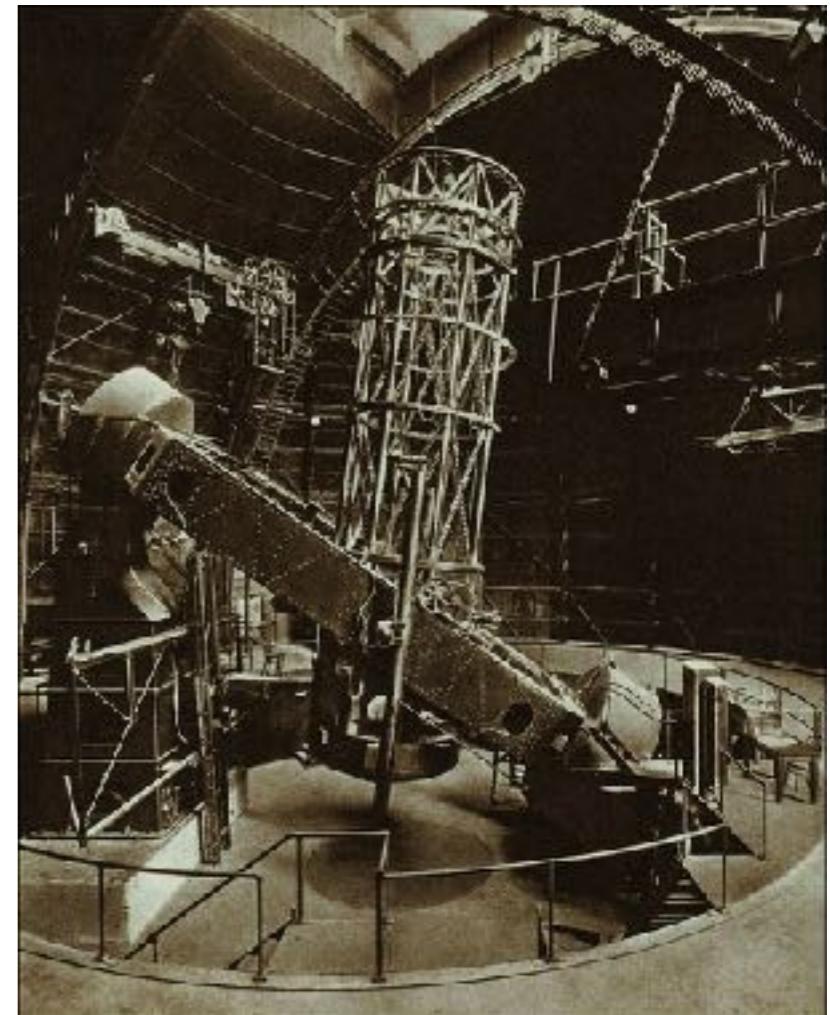
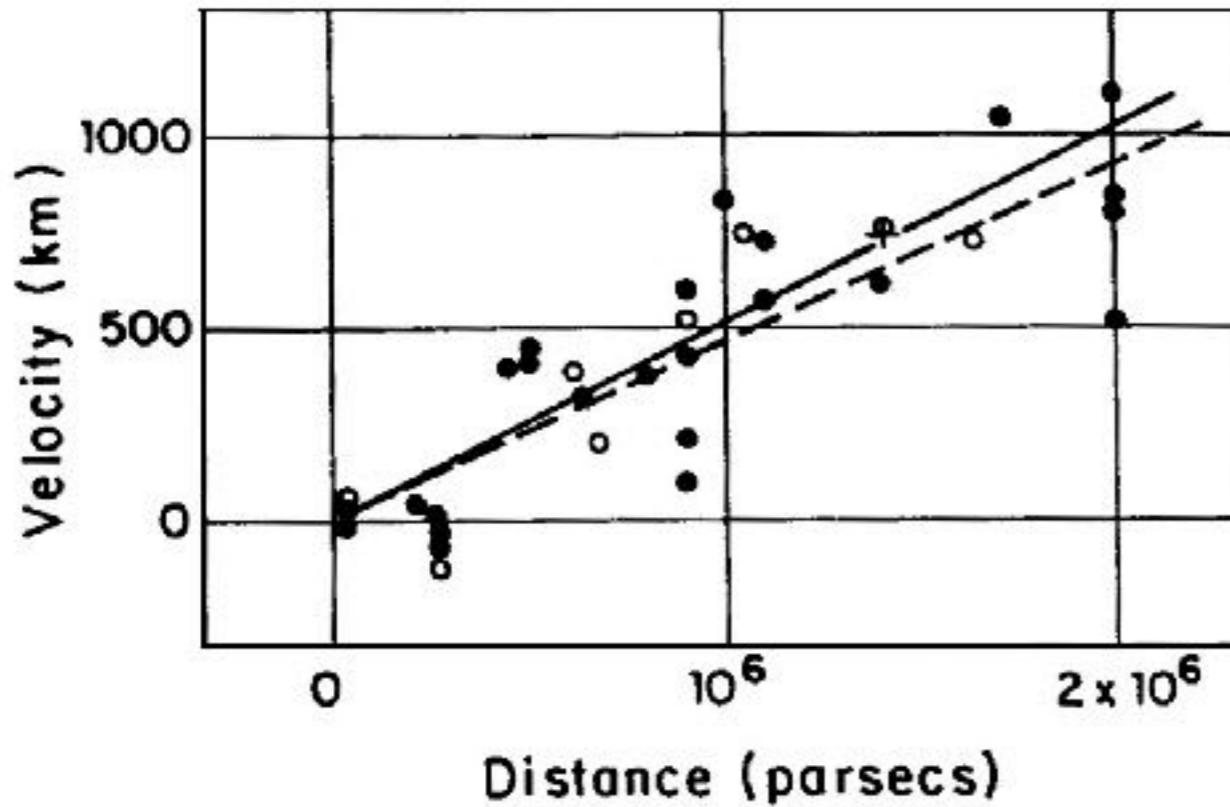
The percentage at which the wavelength of light has been shifted.

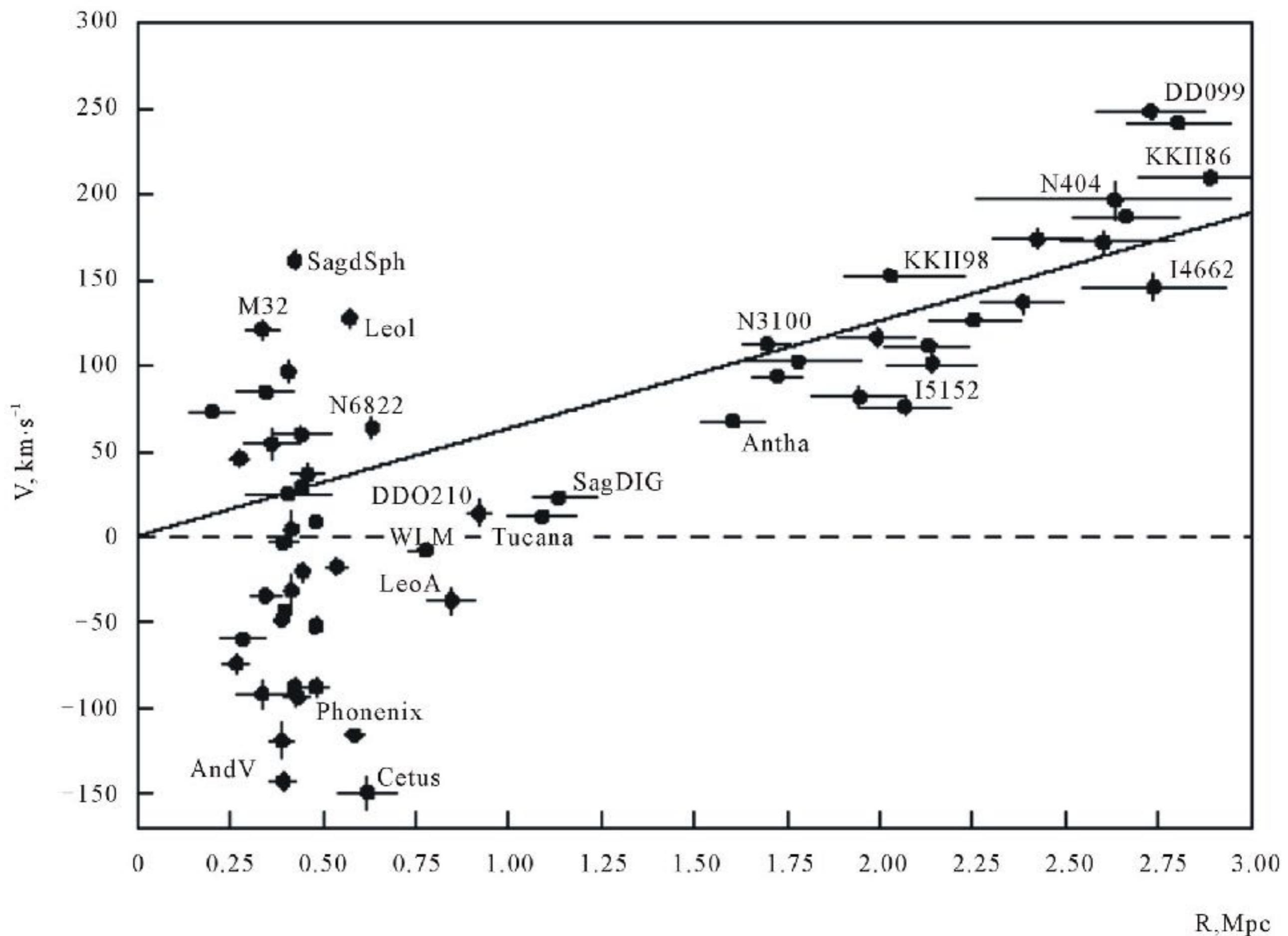


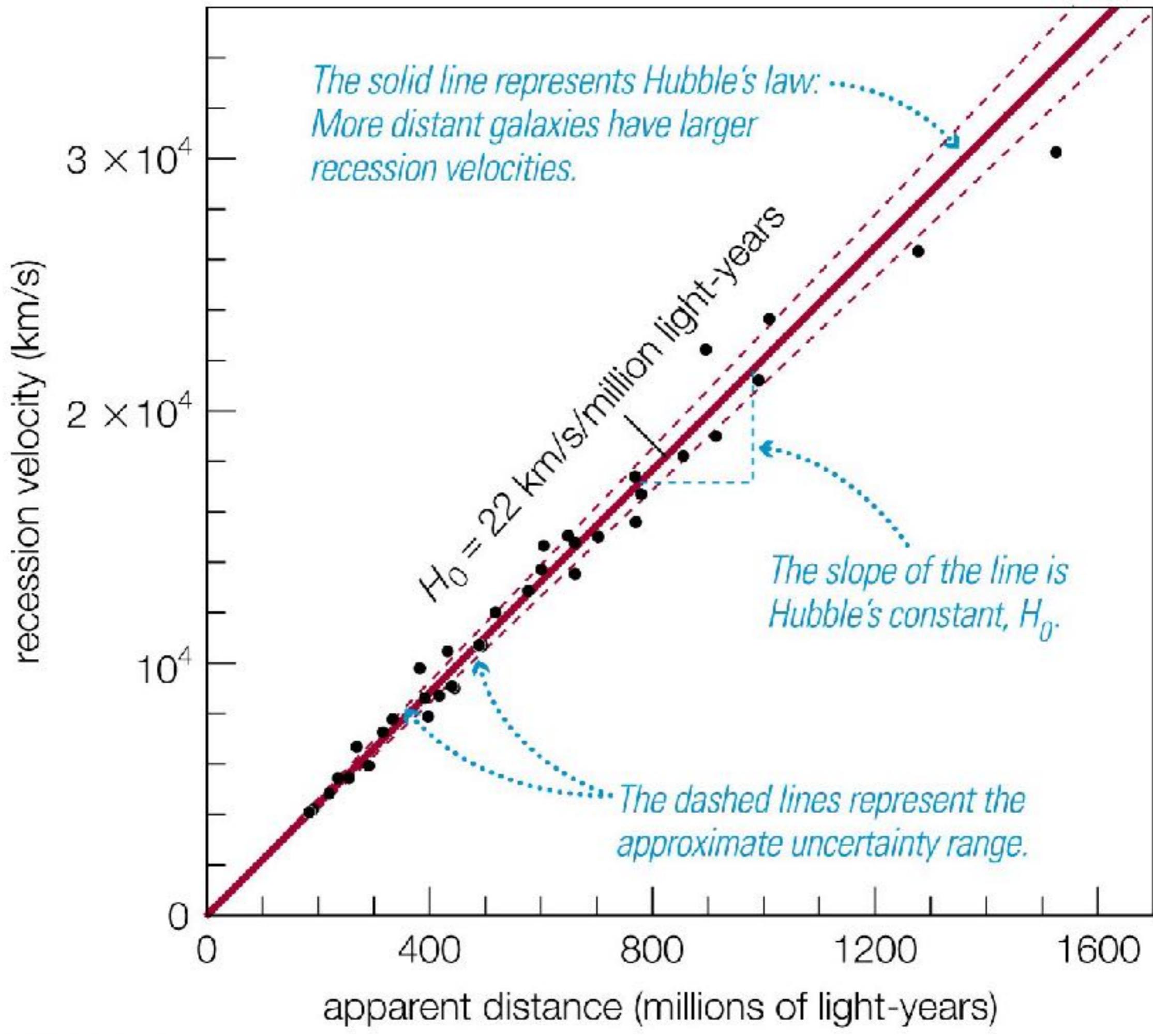
$$z = 0.05$$

# The Universe is Expanding

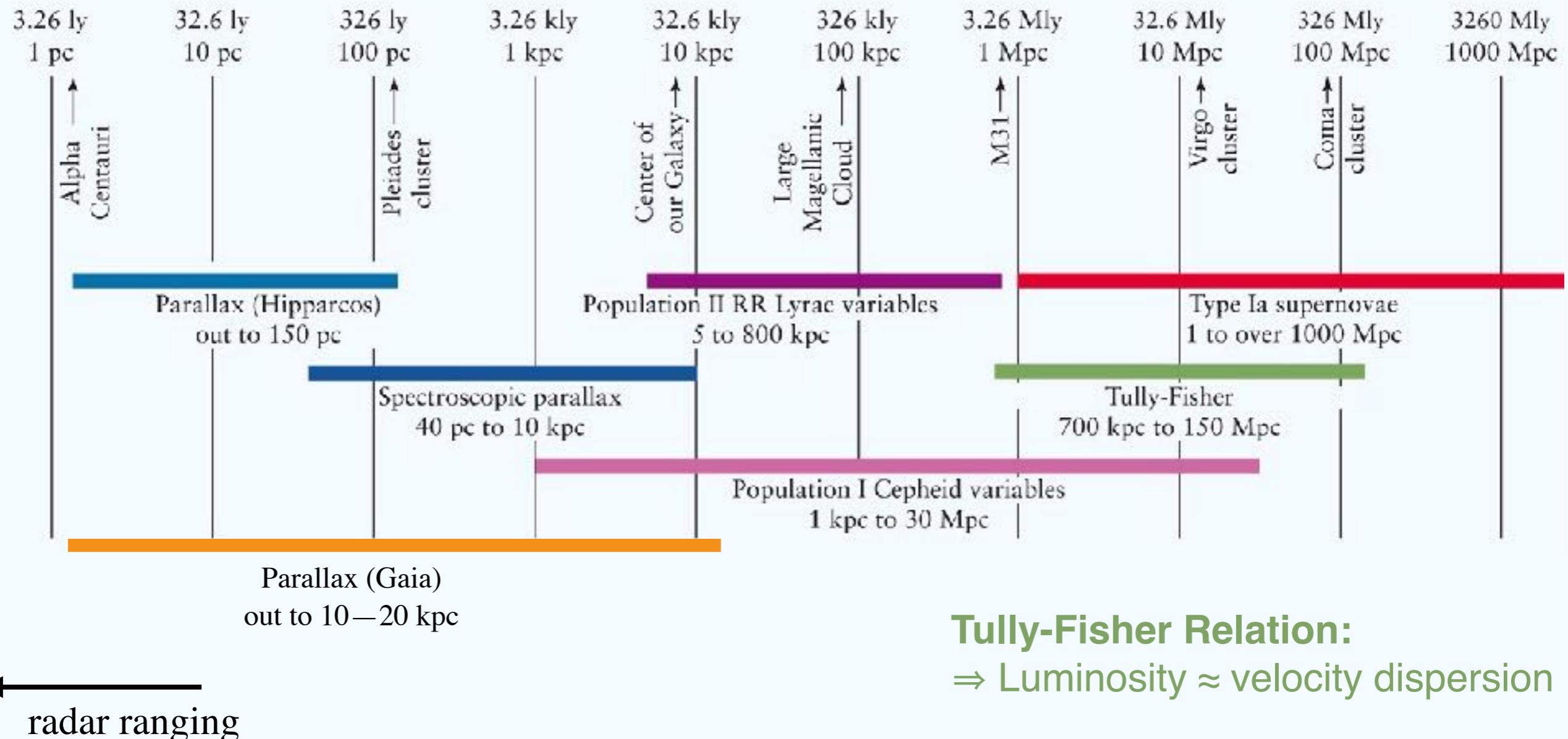
- In 1922 Edwin Hubble determined the distance to the nebulae by observing cepheid variable stars.
- He used the 100-inch Hooker Telescope on Mt. Wilson, which was the most powerful telescope on Earth from 1917 —1948
- Hubble combined his distance measurements with redshift velocity measurements from Vesto Slipher.
- In 1924 he published his results in the *New York Times*
- In 1929 he reported the "redshift distance law of galaxies" thereby demonstrating that the Universe, once assumed to be unchanging, was expanding







# The Cosmic Distance Ladder



**Tully-Fisher Relation:**  
⇒ Luminosity  $\approx$  velocity dispersion



## A Comprehensive Measurement of the Local Value of the Hubble Constant with $1 \text{ km s}^{-1} \text{ Mpc}^{-1}$ Uncertainty from the Hubble Space Telescope and the SH0ES Team

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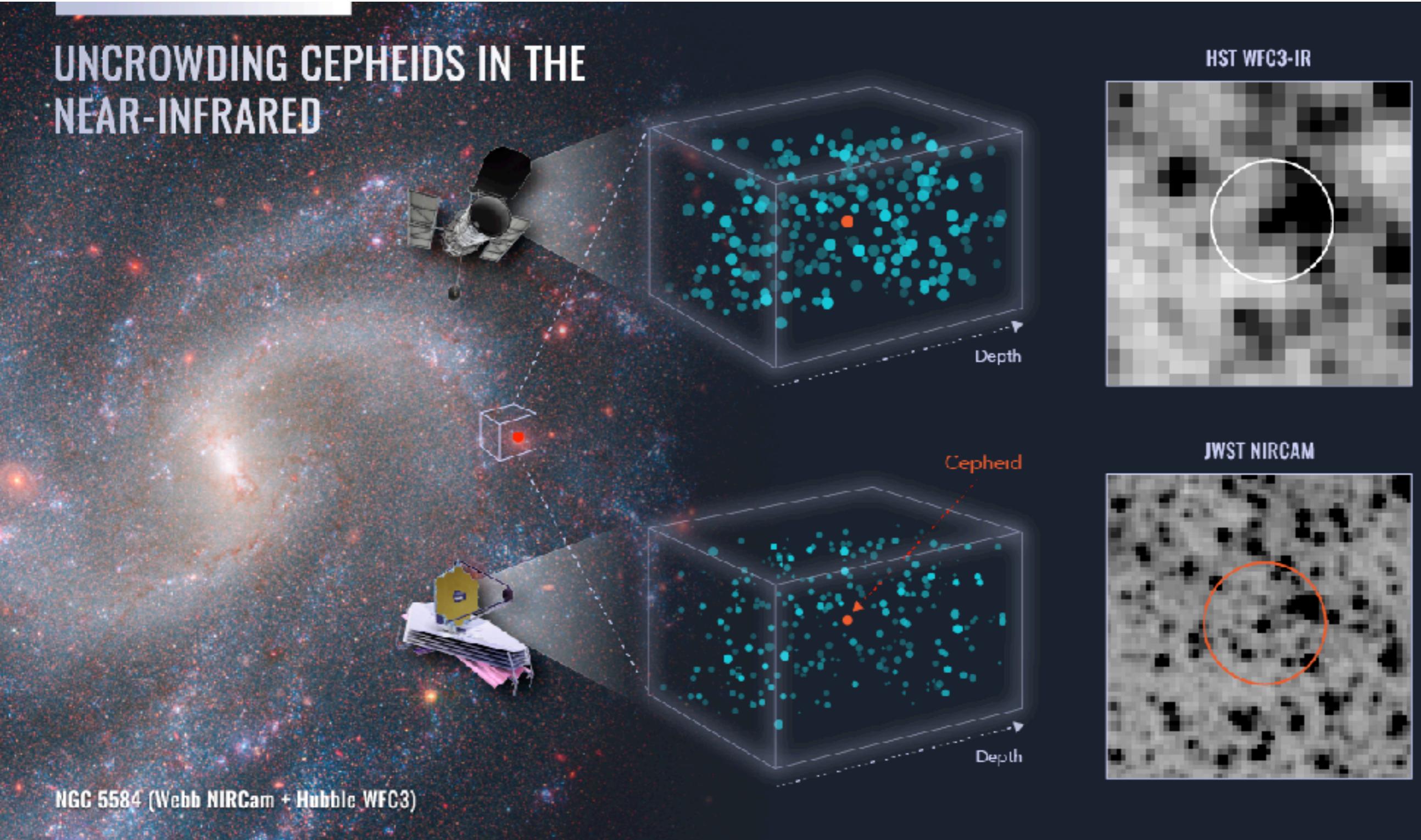
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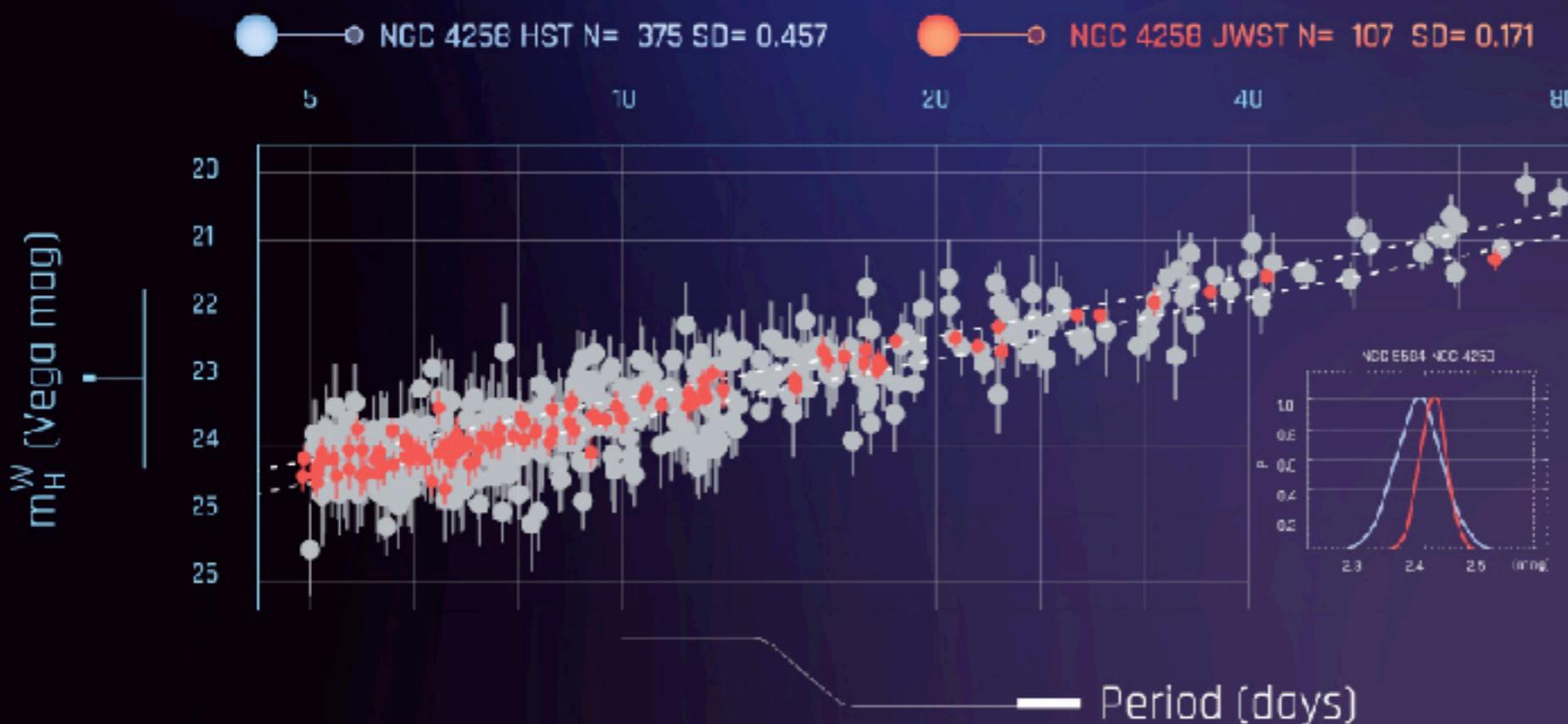
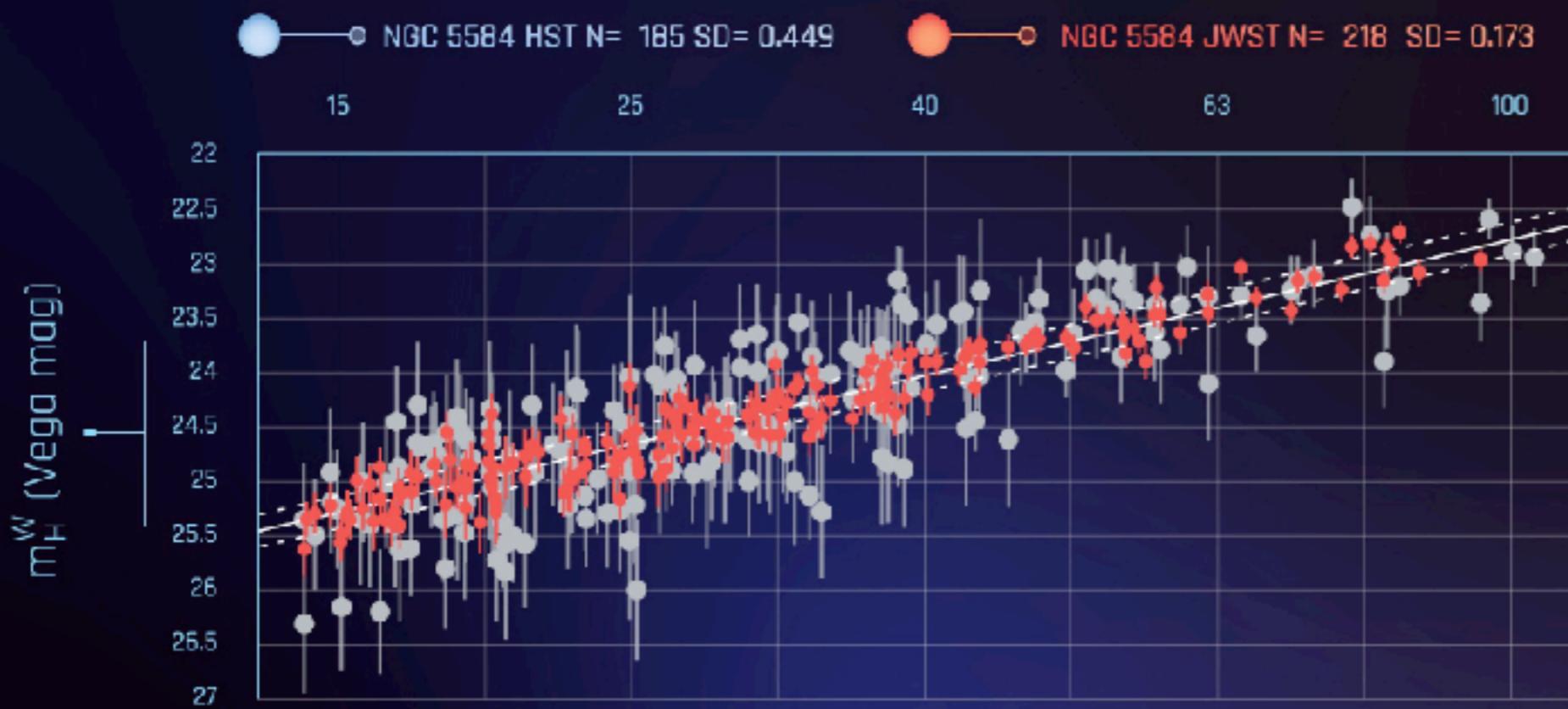
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# UNCROWDING CEPHEIDS IN THE NEAR-INFRARED

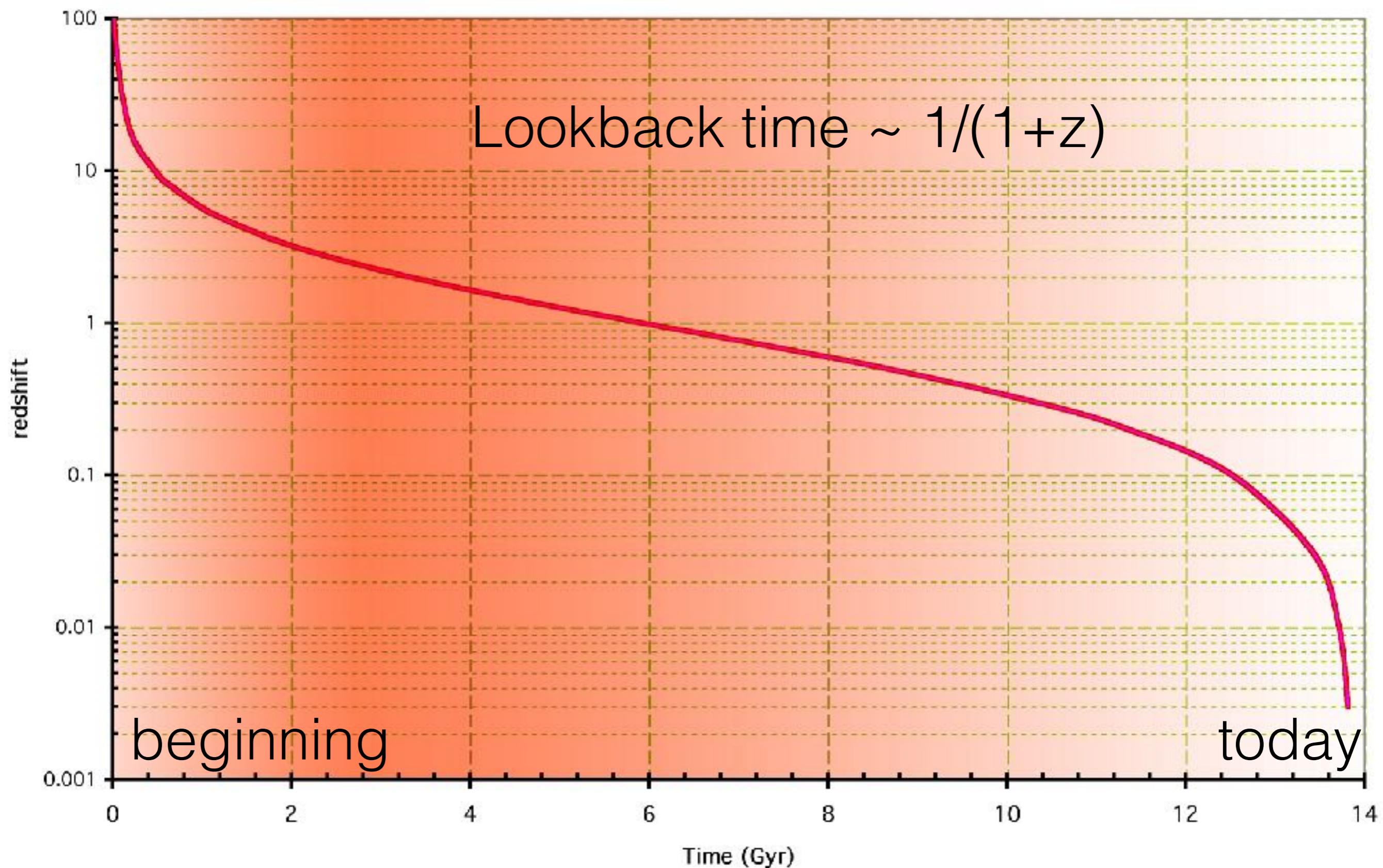


Cepheid crowding  
from Riess et al.  
2023

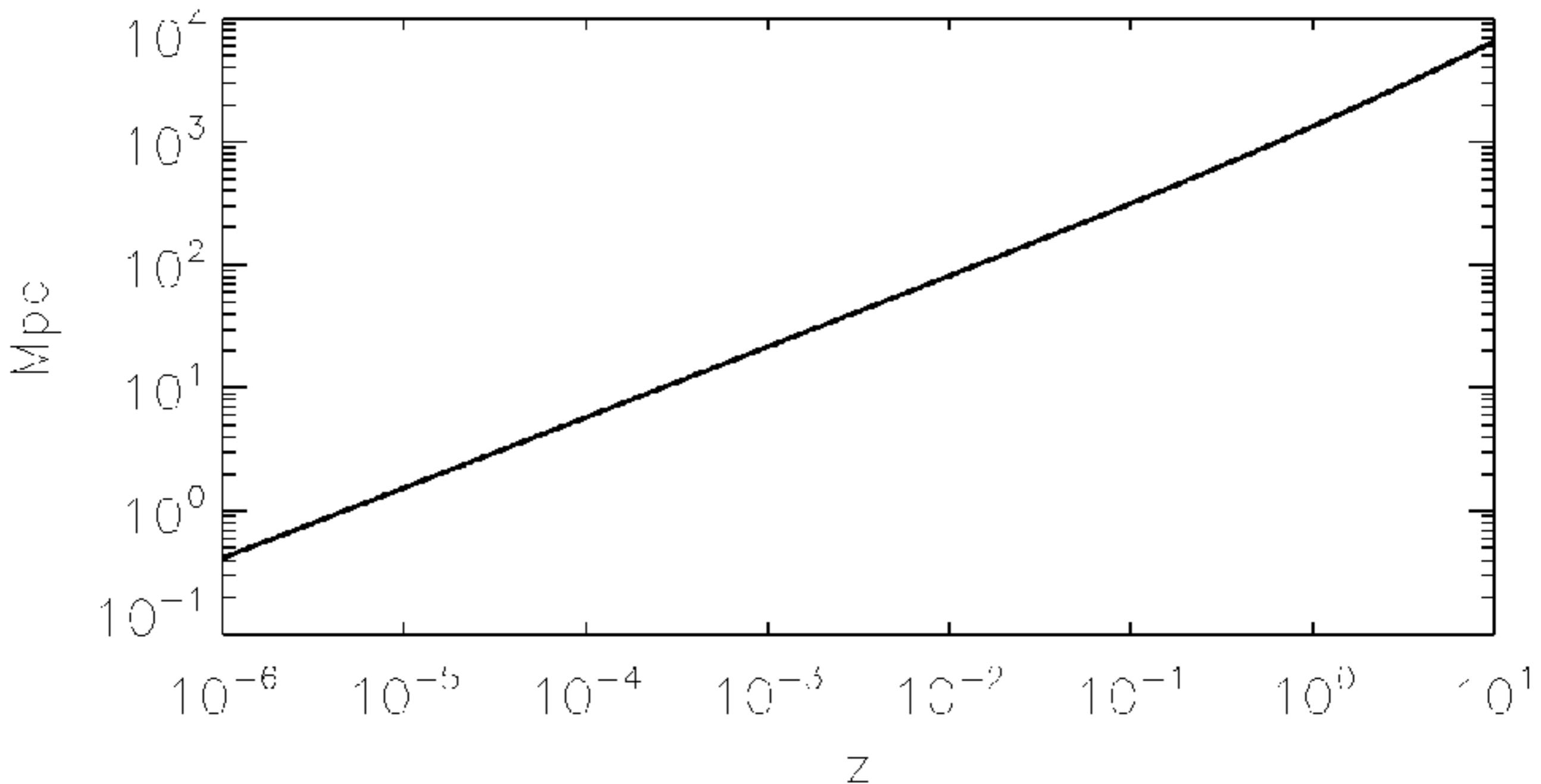


Cepheid crowding  
from Riess et al.  
2023

$H_0 = 68 \text{ km/s/Mpc}$ ,  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$



# physical distance v. redshift

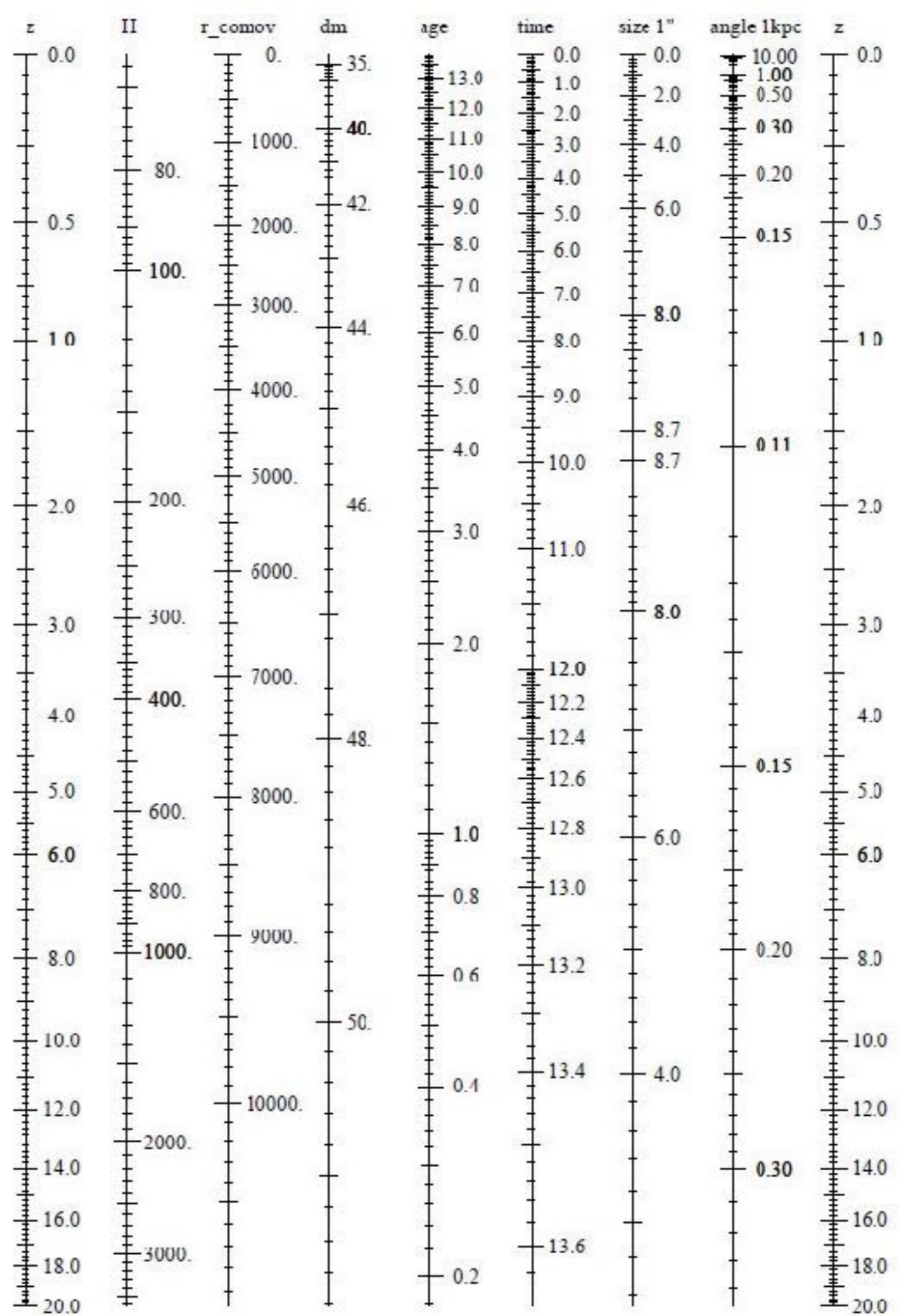




**Table 25-1 Redshift and Distance**

Redshift $z$	Recessional velocity $v/c$	Distance at which we see the object		Present distance to the object (comoving radial distance)	
		(Mpc)	( $10^9$ ly)	(Mpc)	( $10^9$ ly)
0	0	0	0	0	0
0.1	0.095	384	1.25	403	1.32
0.2	0.180	721	2.35	790	2.58
0.3	0.257	1020	3.32	1160	3.79
0.4	0.324	1280	4.17	1510	4.94
0.5	0.385	1510	4.93	1850	6.04
0.75	0.508	2070	6.48	2620	8.54
1	0.600	2350	7.65	3290	10.7
1.5	0.724	2840	9.26	4390	14.3
2	0.800	3160	10.3	5250	17.1
3	0.882	3520	11.5	6500	21.2
4	0.923	3710	12.1	7370	24.0
5	0.946	3830	12.5	8010	26.1
10	0.984	4060	13.2	9790	31.9
Infinite	1	4210	13.7	14500	47.4

This table assumes a Hubble constant  $H_0 = 73 \text{ km/s/Mpc}$ , a matter density parameter  $\Omega_m = 0.24$ , and a dark energy density parameter  $\Omega_\Lambda = 0.76$  (see Chapter 26). The distance at which we see the object (in light-years) is equal to the light travel time in years. The present distance to the object is the distance  $d$  to be used in the Hubble law,  $v = H_0 d$ .



# Ned Wright's Cosmology Calculator:

<http://www.astro.ucla.edu/~wright/CosmoCalc.html>

The screenshot shows a web browser window with the URL <http://www.astro.ucla.edu/~wright/CosmoCalc.html> in the address bar. The page content is as follows:

**Enter values, hit a button**

69.6	$H_0$
0.286	$\Omega_M$
3	$z$
<input type="radio"/> Open	<input type="radio"/> Flat
0.714	$\Omega_{vac}$
<input type="radio"/> General	

**For  $H_0 = 69.6$ ,  $\Omega_M = 0.286$ ,  $\Omega_{vac} = 0.714$ ,  $z = 3.000$**

- It is now 13.721 Gyr since the Big Bang.
- The age at redshift  $z$  was 2.171 Gyr.
- The [light travel time](#) was 11.549 Gyr.
- The [comoving radial distance](#), which goes into Hubble's law, is 6481.3 Mpc or 21.139 Gly.
- The comoving volume within redshift  $z$  is 1140.389 Gpc<sup>3</sup>.
- The [angular size distance  \$D\_A\$](#)  is 1620.3 Mpc or 5.2846 Gly.
- This gives a scale of 7.855 kpc/".
- The [luminosity distance  \$D\_L\$](#)  is 25924.3 Mpc or 84.554 Gly.

1 Gly = 1,000,000,000 light years or  $9.461 \times 10^{26}$  cm.  
1 Gyr = 1,000,000,000 years.  
1 Mpc = 1,000,000 parsecs =  $3.08568 \times 10^{24}$  cm, or 3,261,566 light years.

[Tutorial: Part 1 | Part 2 | Part 3 | Part 4](#)  
[FAQ](#) | [Age](#) | [Distances](#) | [Bibliography](#) | [Relativity](#)

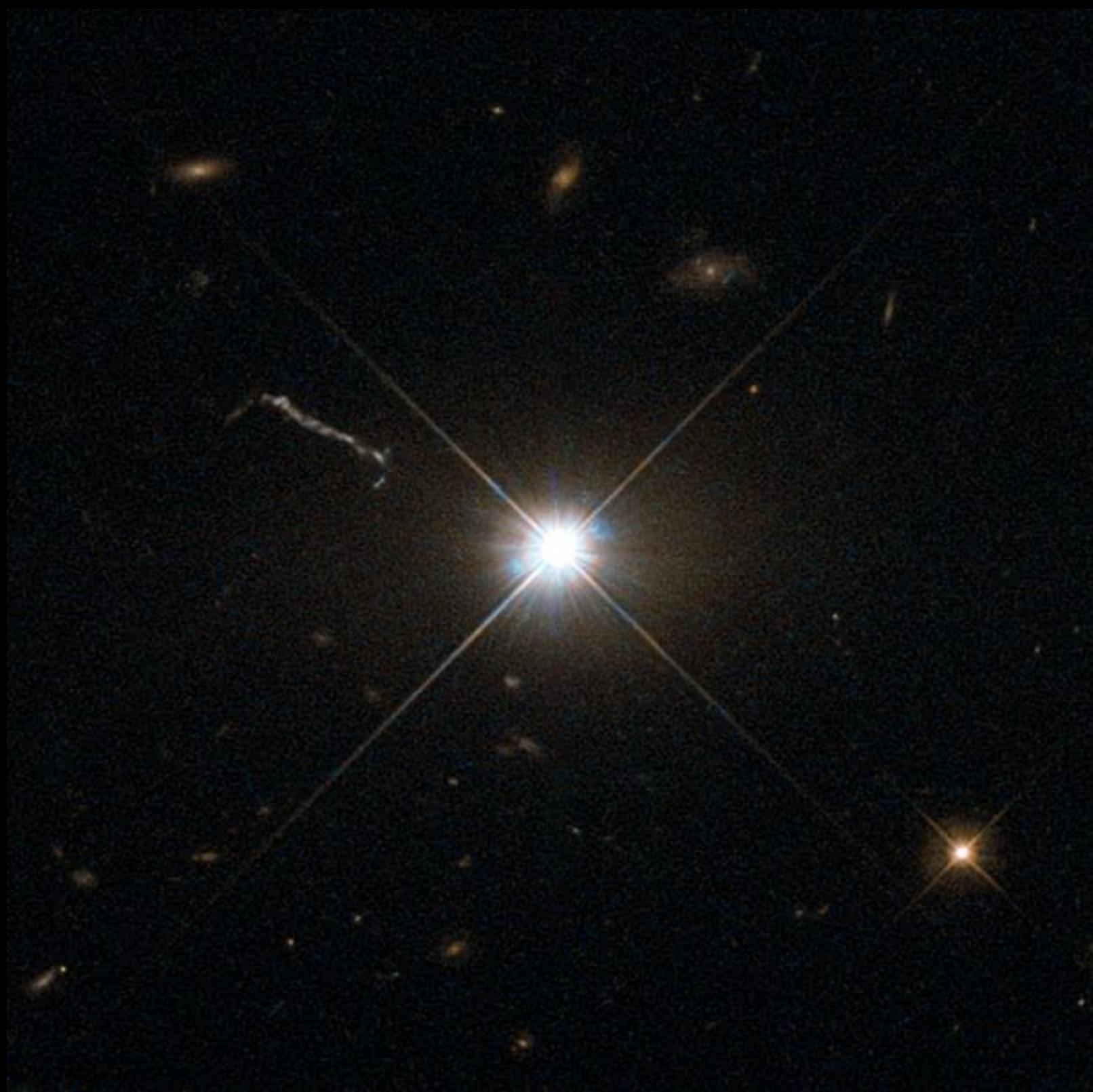
See the [advanced](#) and [light travel time](#) versions of the calculator.

[James Schombert](#) has written a [Python version](#) of this calculator.

[Ned Wright's home page](#)

© 1999-2016 [Edward L. Wright](#). If you use this calculator while preparing a paper, please cite [Wright \(2006, PASP, 118, 1711\)](#). Last modified on 04/25/2016 00:27:11

# Quasar 3C 273

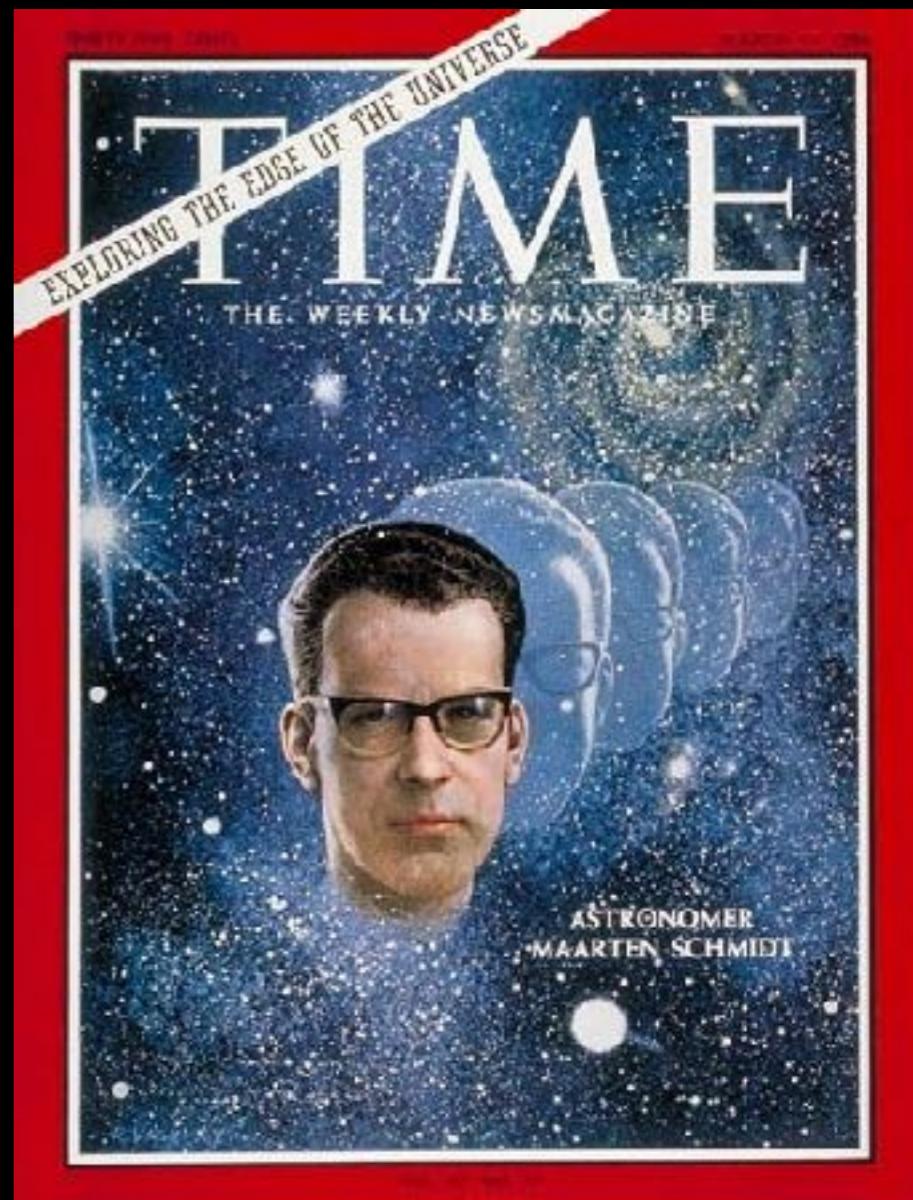


# Quasar 3C 273



Allan Sandage

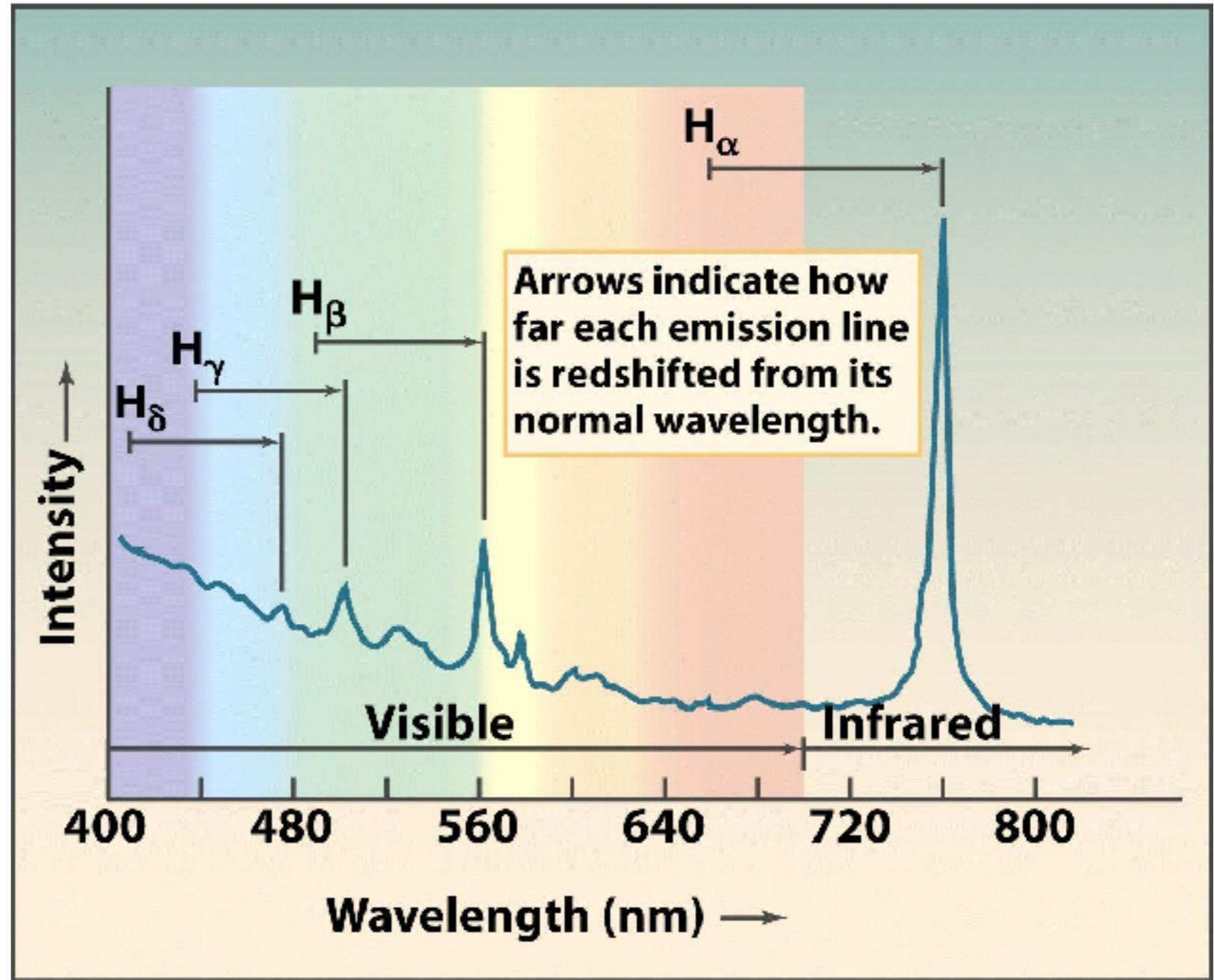
- The first quasars (3C 48 and 3C 273) were discovered in the early 1960s by Allan Sandage at Carnegie. (U. of Illinois '48). He was a graduate student of Edwin Hubble and Walter Baade at Caltech.
- Most quasars were radio sources with no corresponding visible object. They have “strange redshifts” corresponding to no known emission lines.
- Were they nearby objects or distant objects as implied by their redshift? One strong argument against them being at cosmological distances was that they implied mass–energy conversion processes (~10%) that were far in excess of nuclear fusion (0.7%).
- Quasars were much more common in the early universe. This discovery by Maarten Schmidt in 1967 was early strong evidence against the Steady State cosmology of Fred Hoyle, and in favor of the Big Bang cosmology.



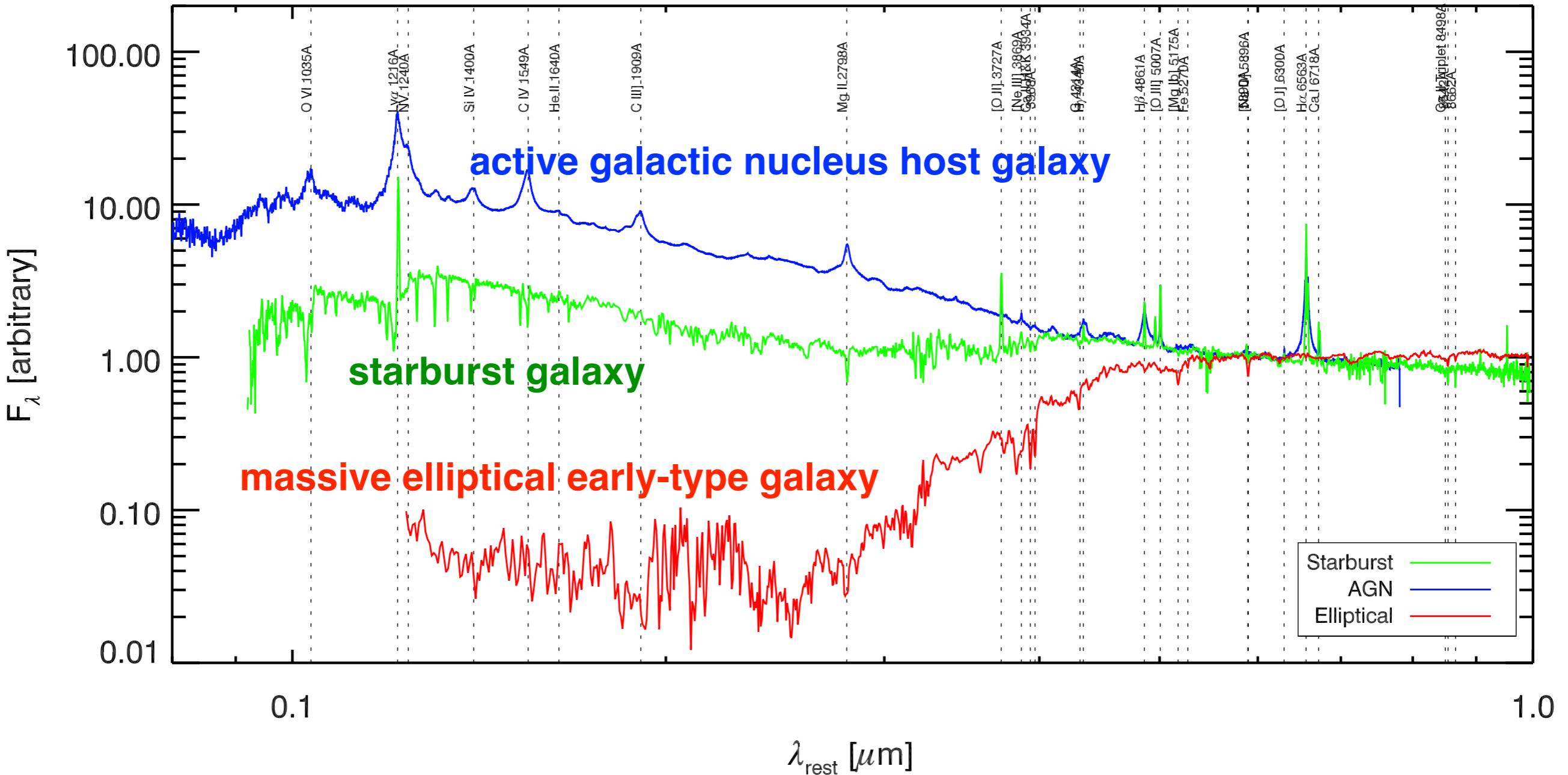
# Light from quasars is highly redshifted!

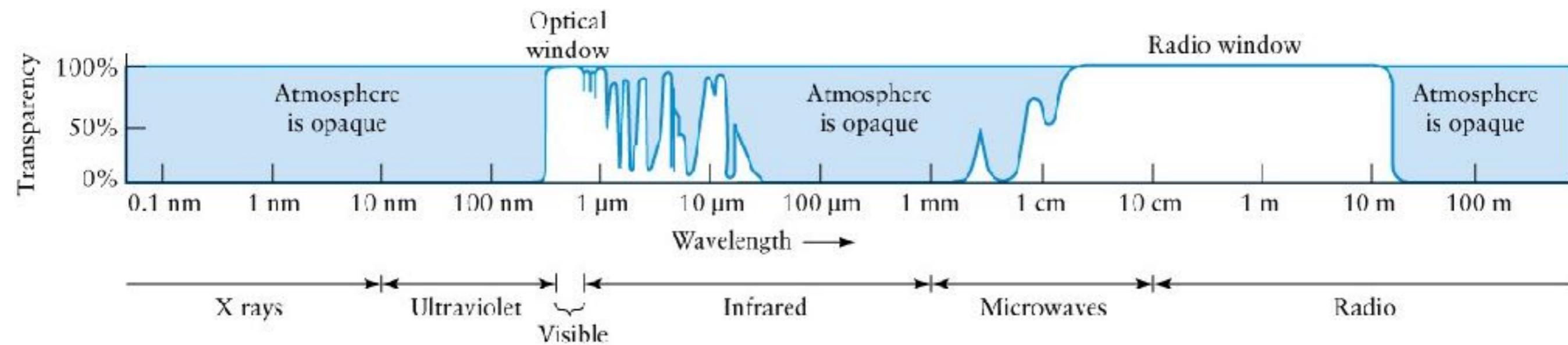
Quasar 3C273  
is receding  
from us at 16%  
the speed of  
light.  
That  
corresponds to  
 $z=0.158$

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$

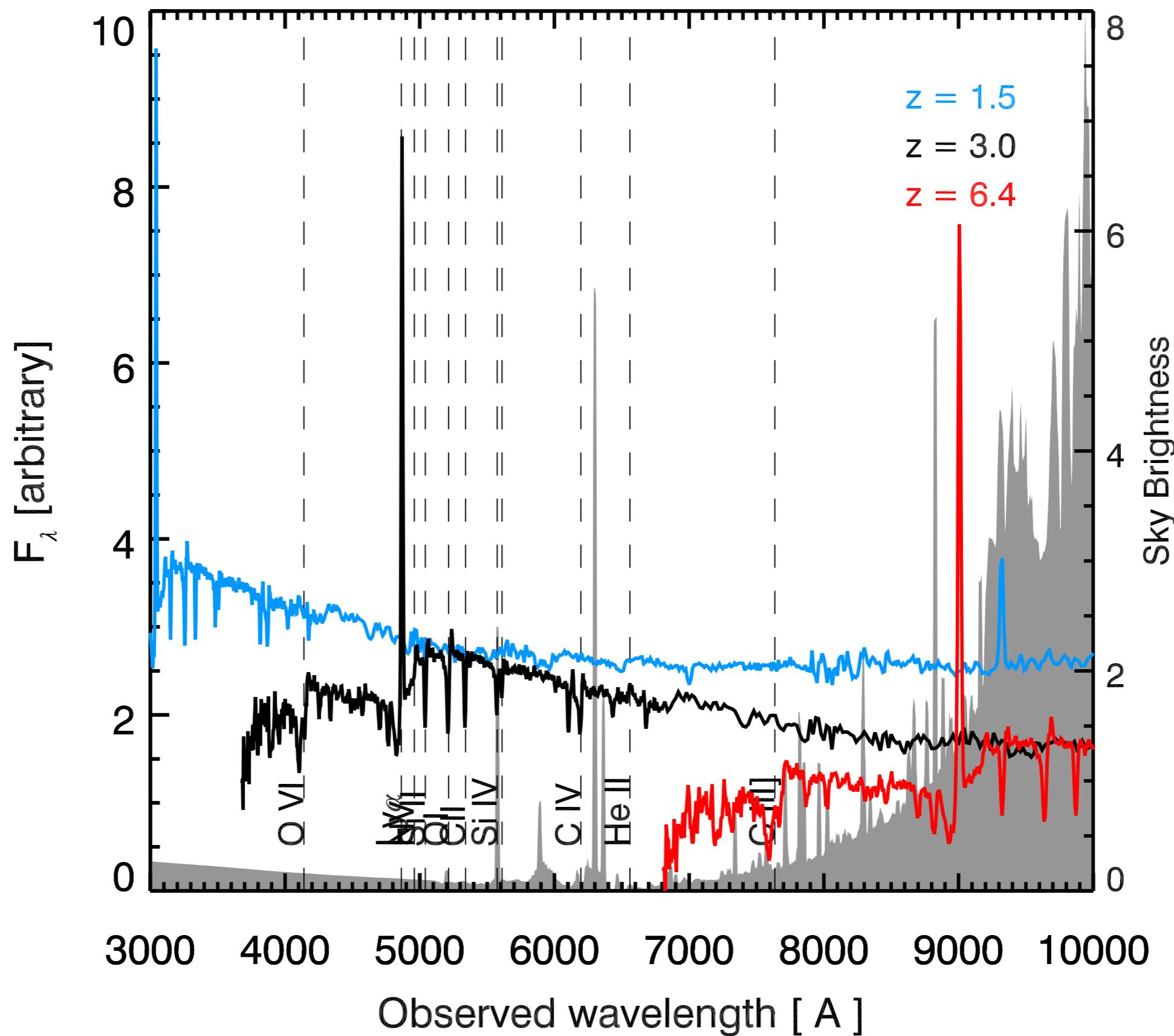


## Optical SED by Galaxy type

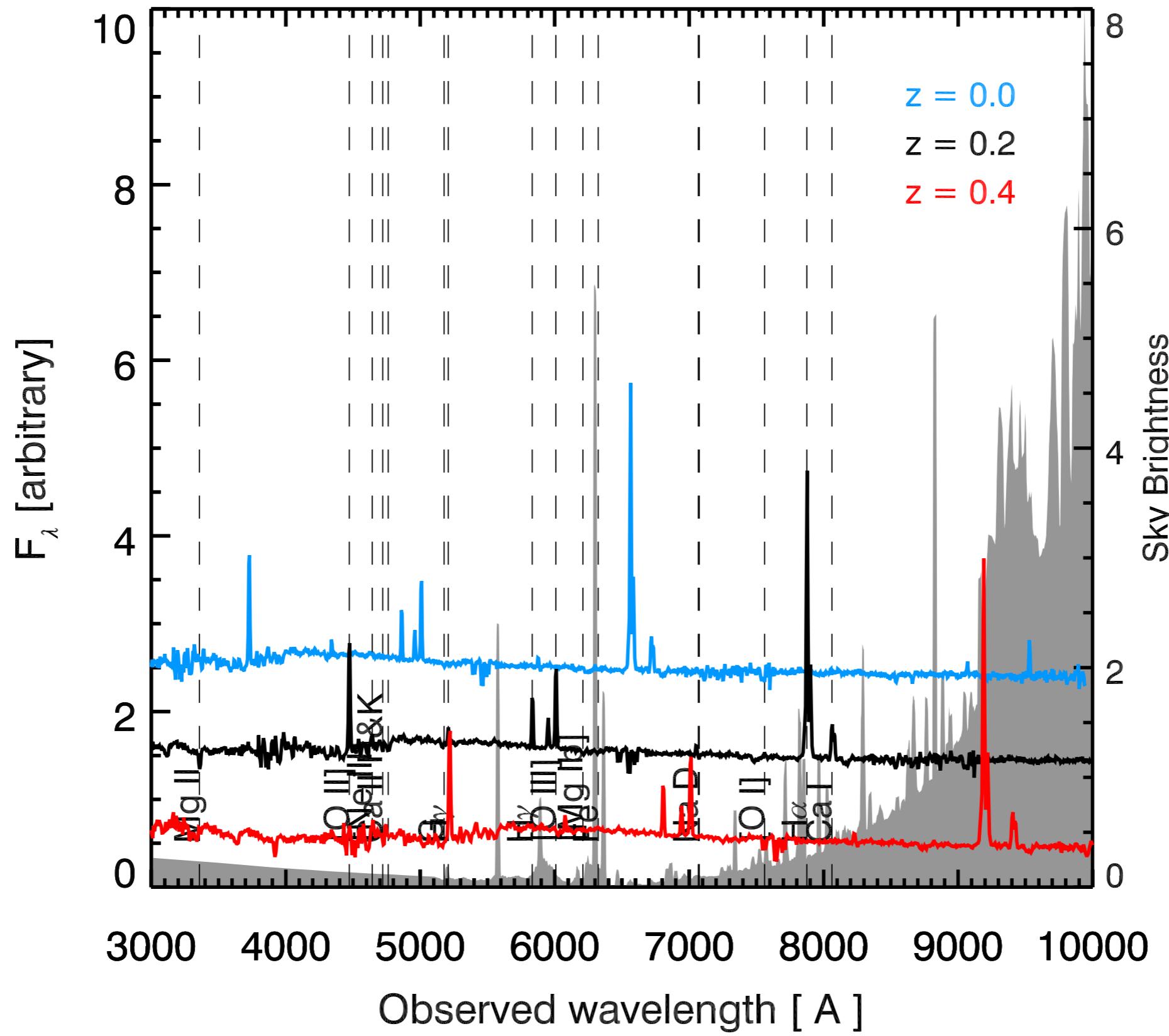




# Ly-a in an optical spectrograph

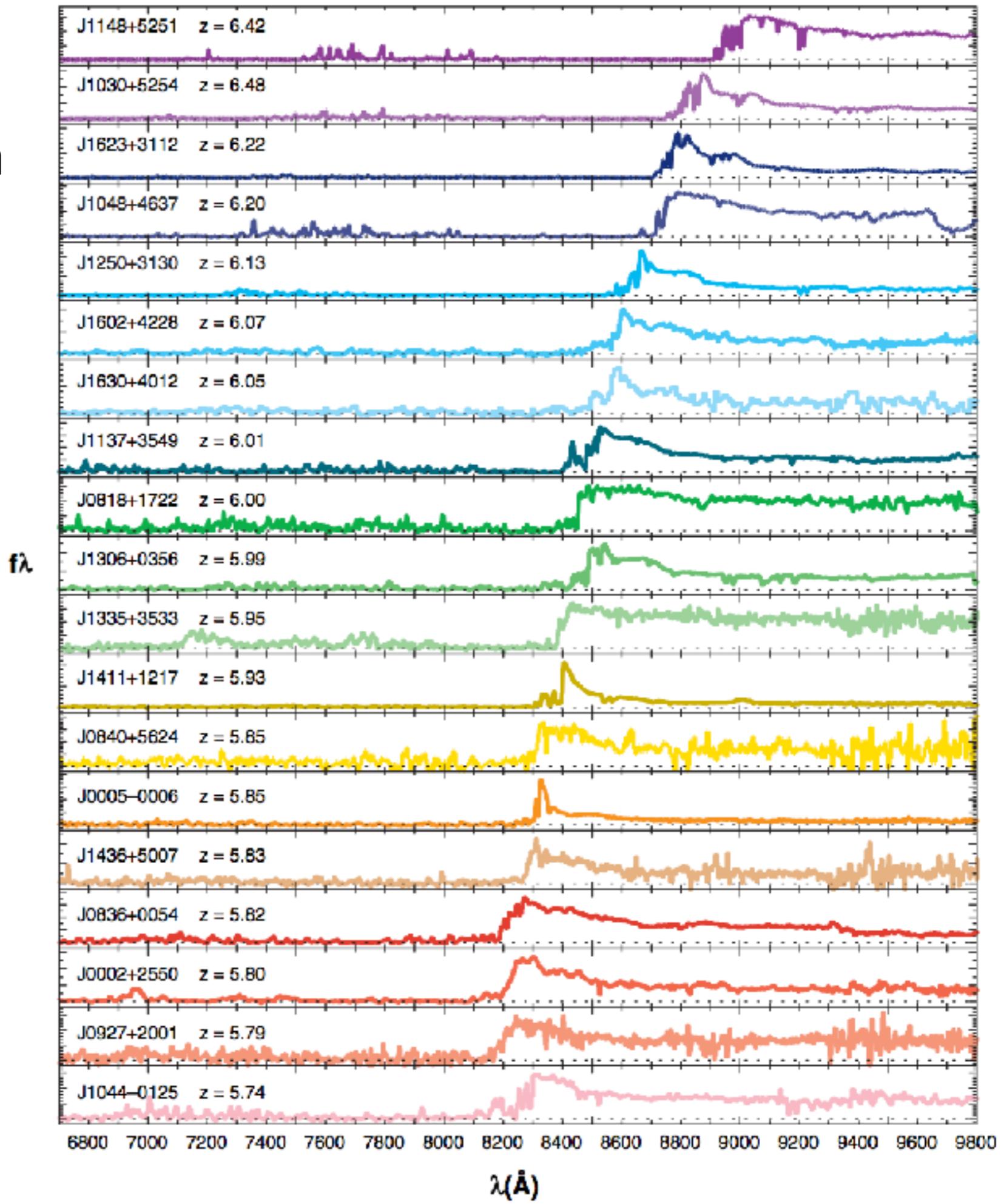


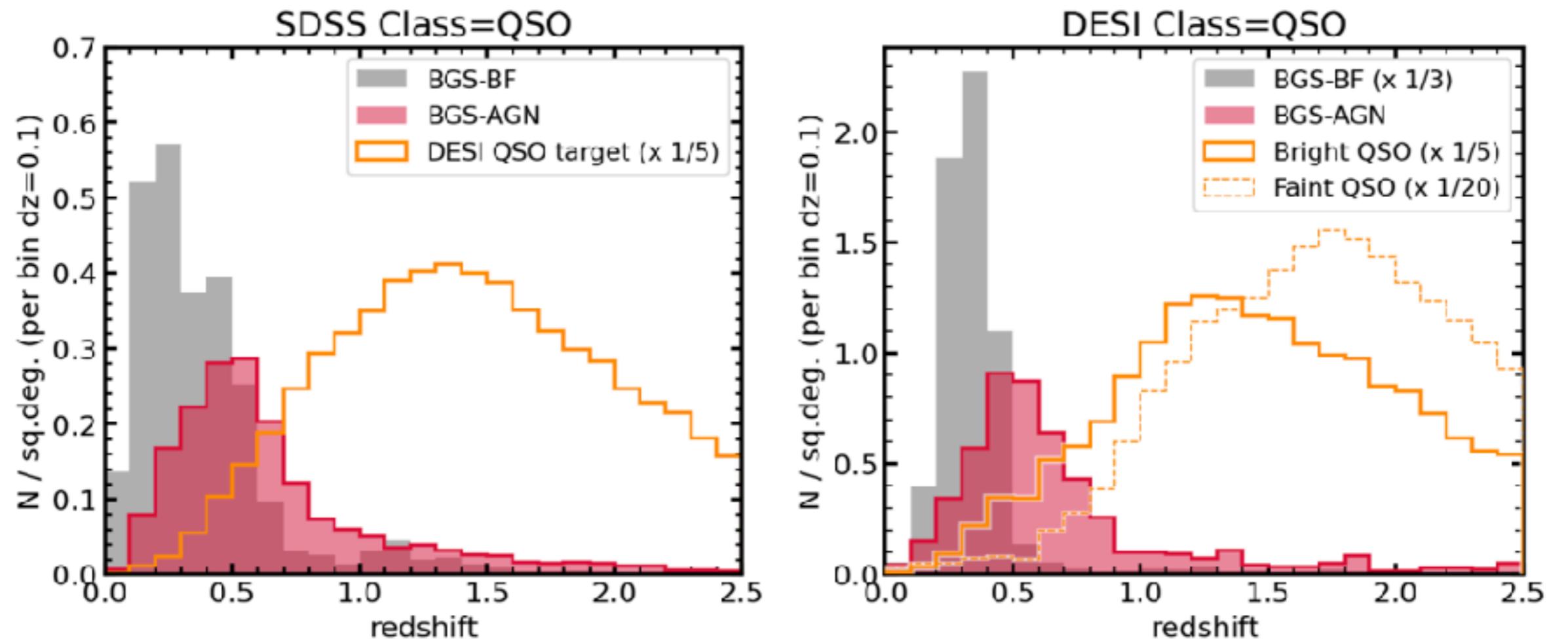
# H-a in an optical spectrograph



# Quasars in SDSS

More than 200,000 known

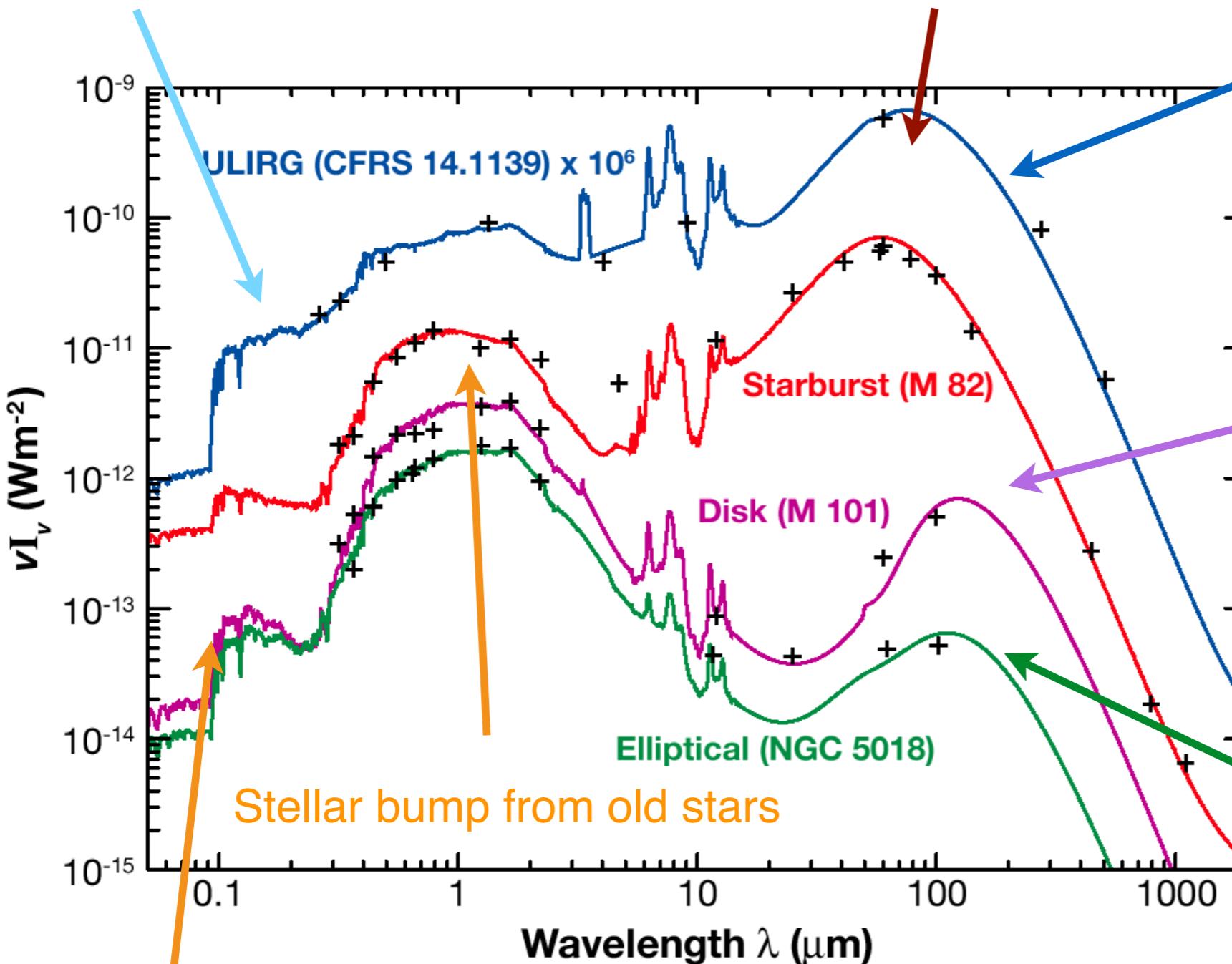




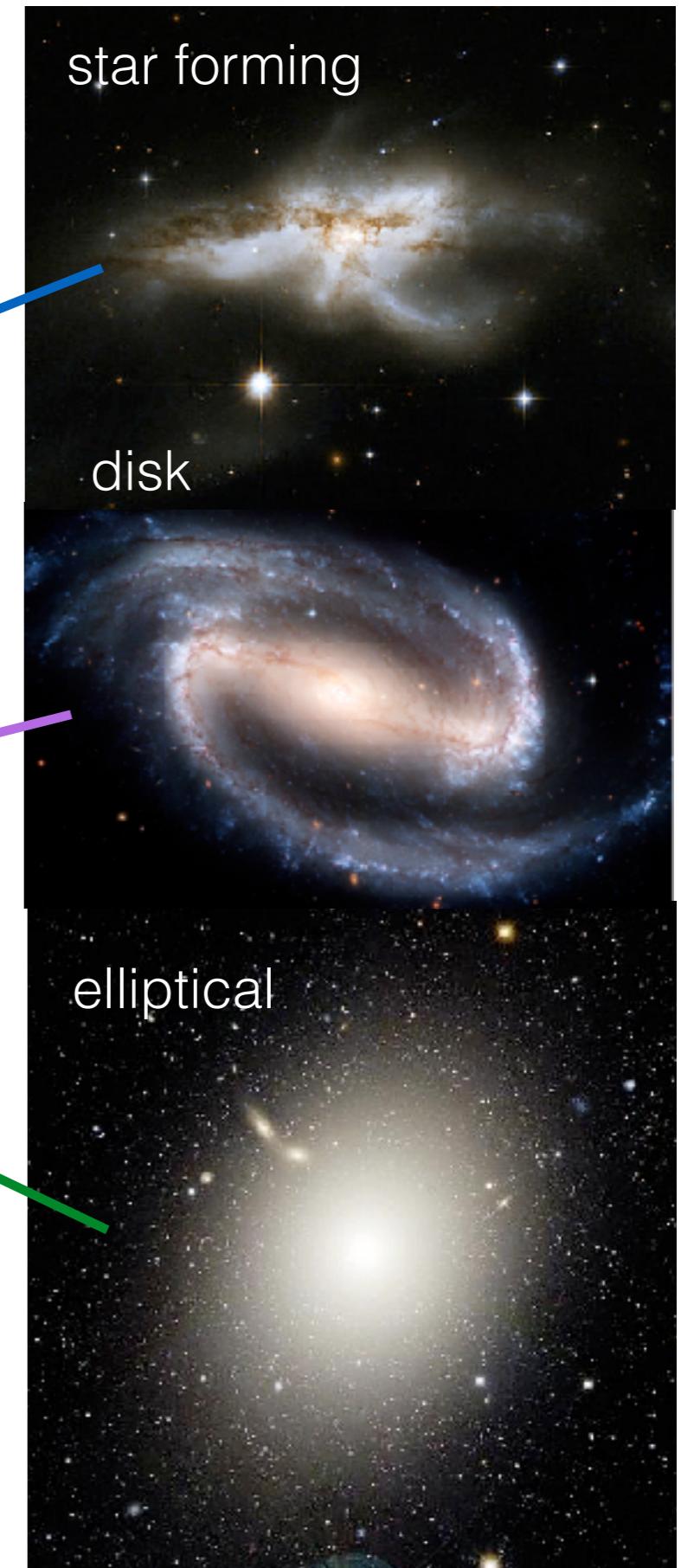
**Figure 11.** Redshift distributions as predicted from the SDSS QSOs (left-hand panel), and as observed with DESI SV3 (right-hand panel) for the QSO spectral type. In both panels, the population that fulfills the selection criteria for the BGS-BF sample is shown in gray while the BGS-AGN sample is shown in red. On the right-hand side panel, the distribution of QSOs from the BGS-BF sample was scaled down by a factor of three. We attribute the much larger number density to the difference in magnitude limits for SDSS and DESI. This figure truncates the tail of the distribution at  $z = 2.5$  to focus on the bulk of the sample. Nine additional BGS-AGN QSOs at  $2.5 < z < 3.3$  are included in Figure 13, which shows the complete sample of 519 unique BGS AGN targets in SV3. To compare with higher redshift QSOs, we add the redshift distribution for objects selected as DESI QSO targets in orange histograms. The solid orange histograms are QSO targets that meet the magnitude limits of the BGS sample. On the right-hand side, we further show QSO targets fainter than BGS with a dashed orange histogram scaled by a factor of 20 due to the high target density.

# Spectral Energy Densities of Galaxies

UV radiation absorbed by dust

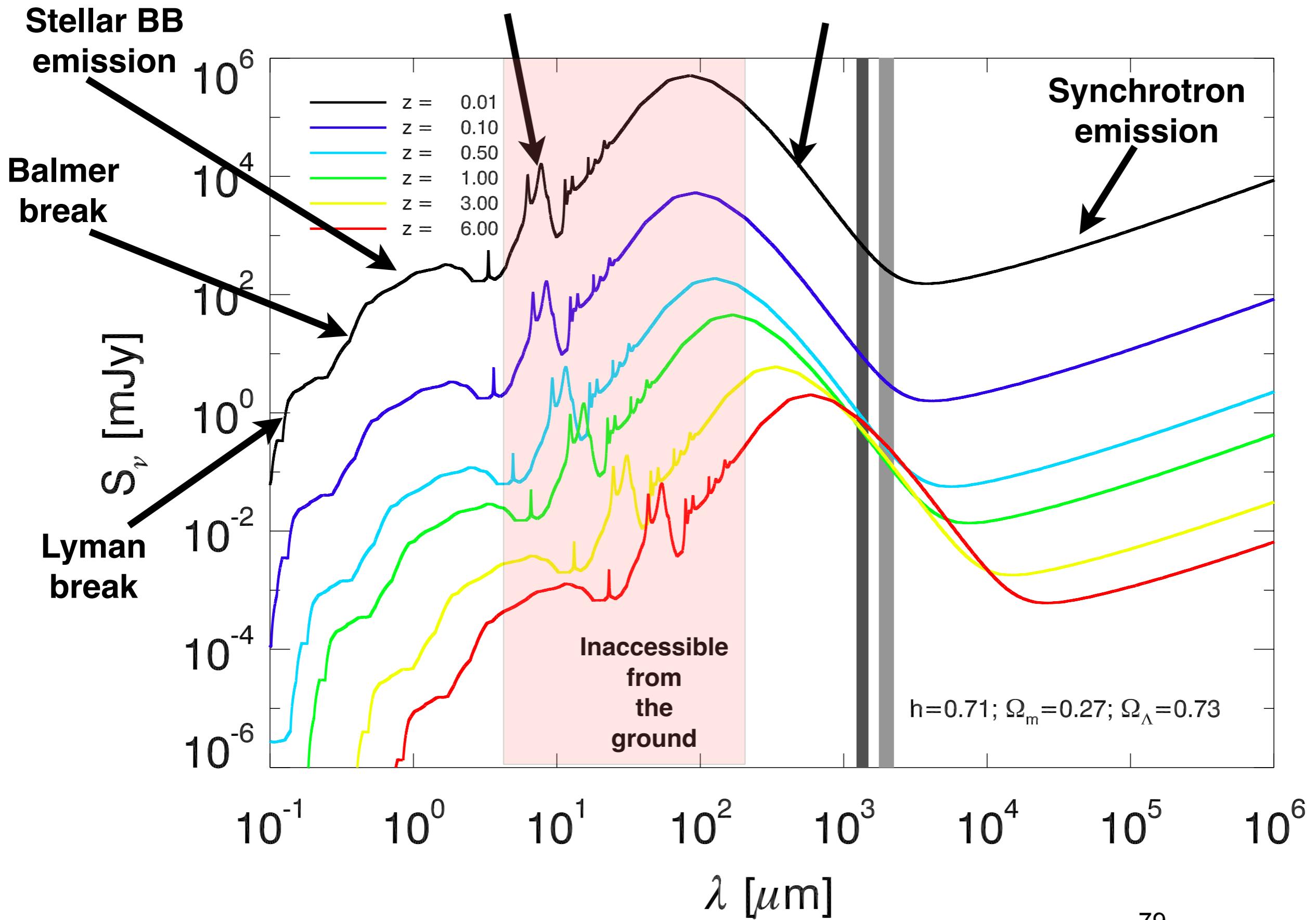


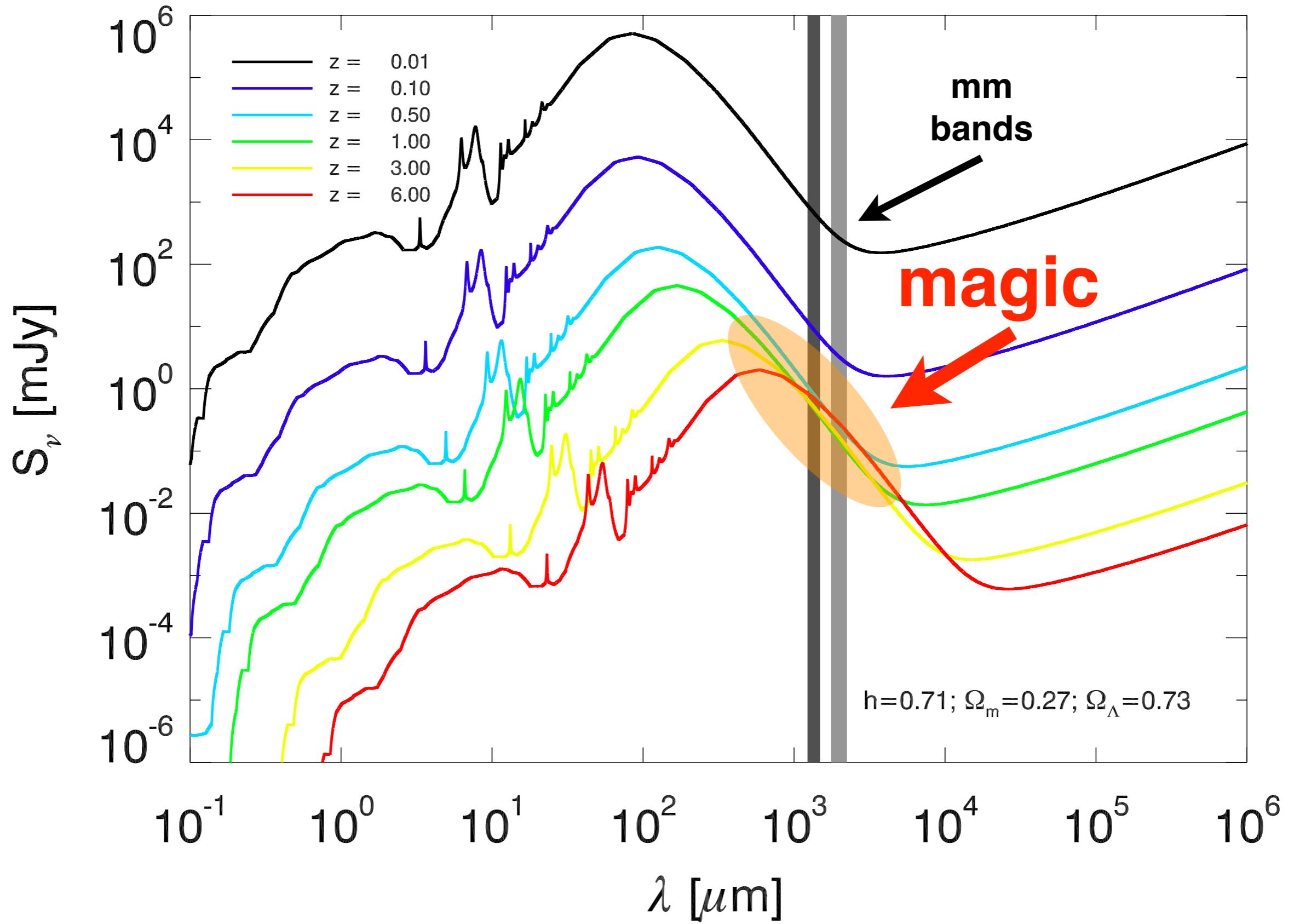
Lagache+ 2005



## PAH lines

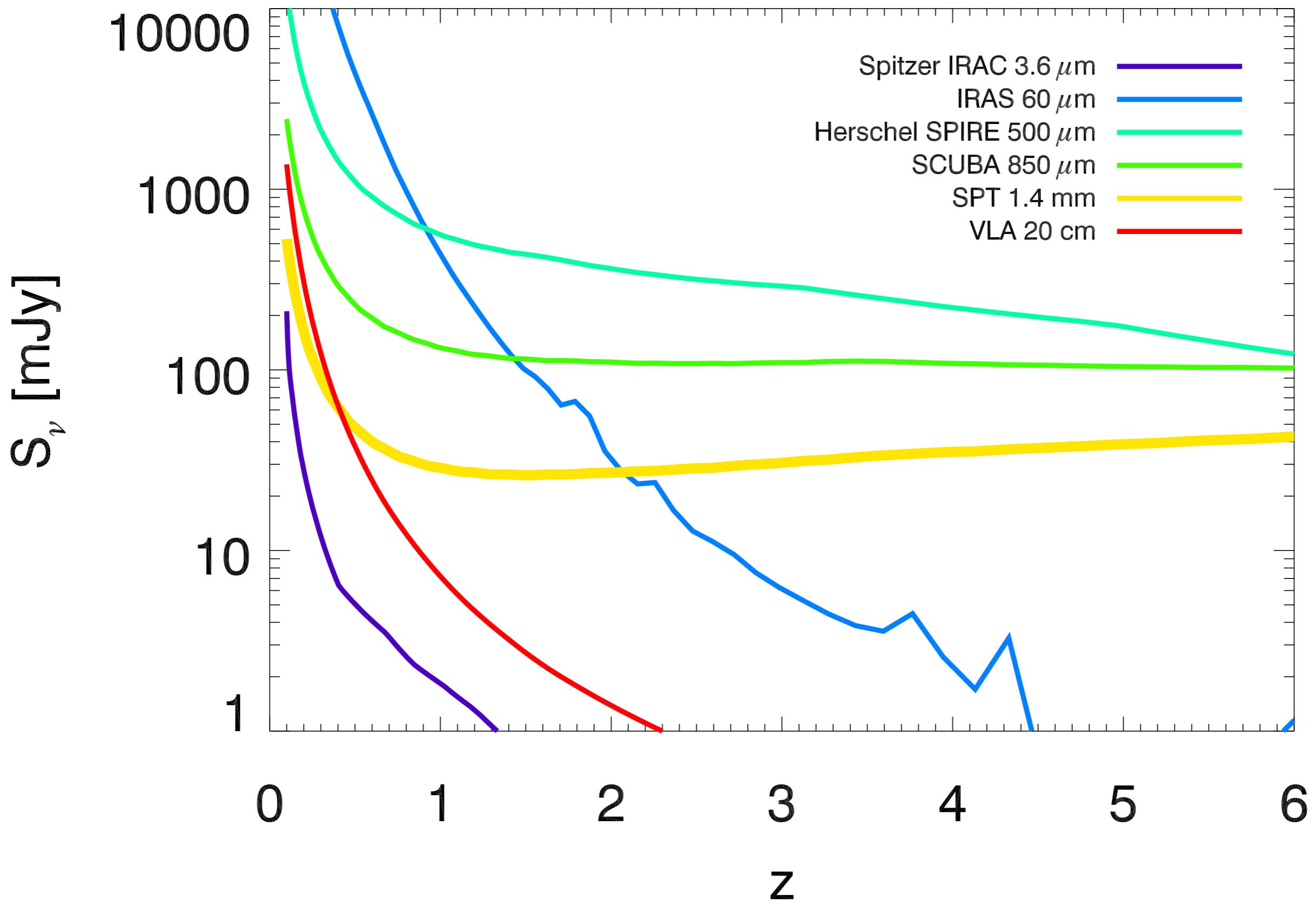
## R-J side of modified BB emission from dust





# Sub-mm magic and the k-correction

## Arp 220 Flux Density v. Redshift



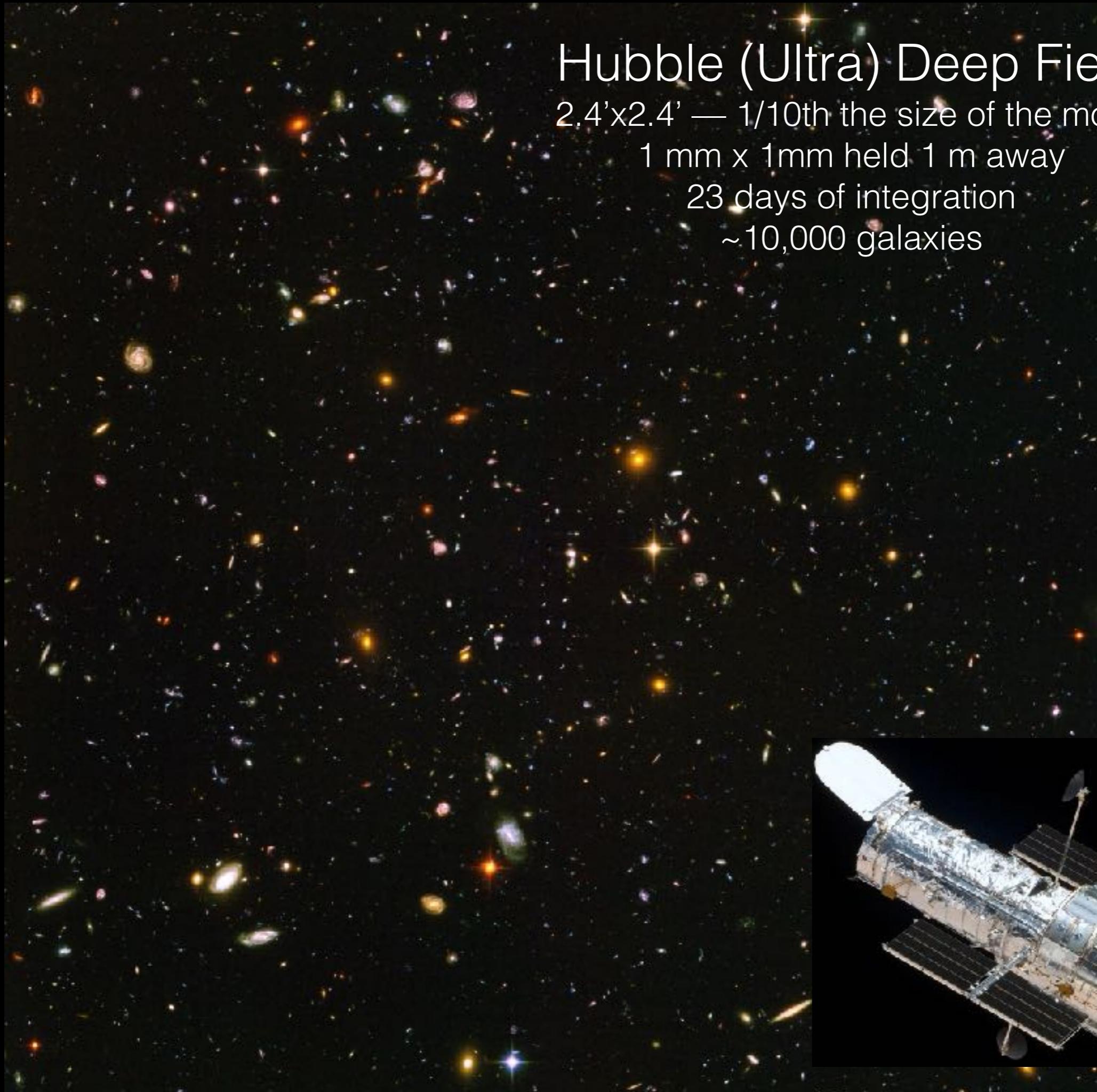
# Hubble (Ultra) Deep Field

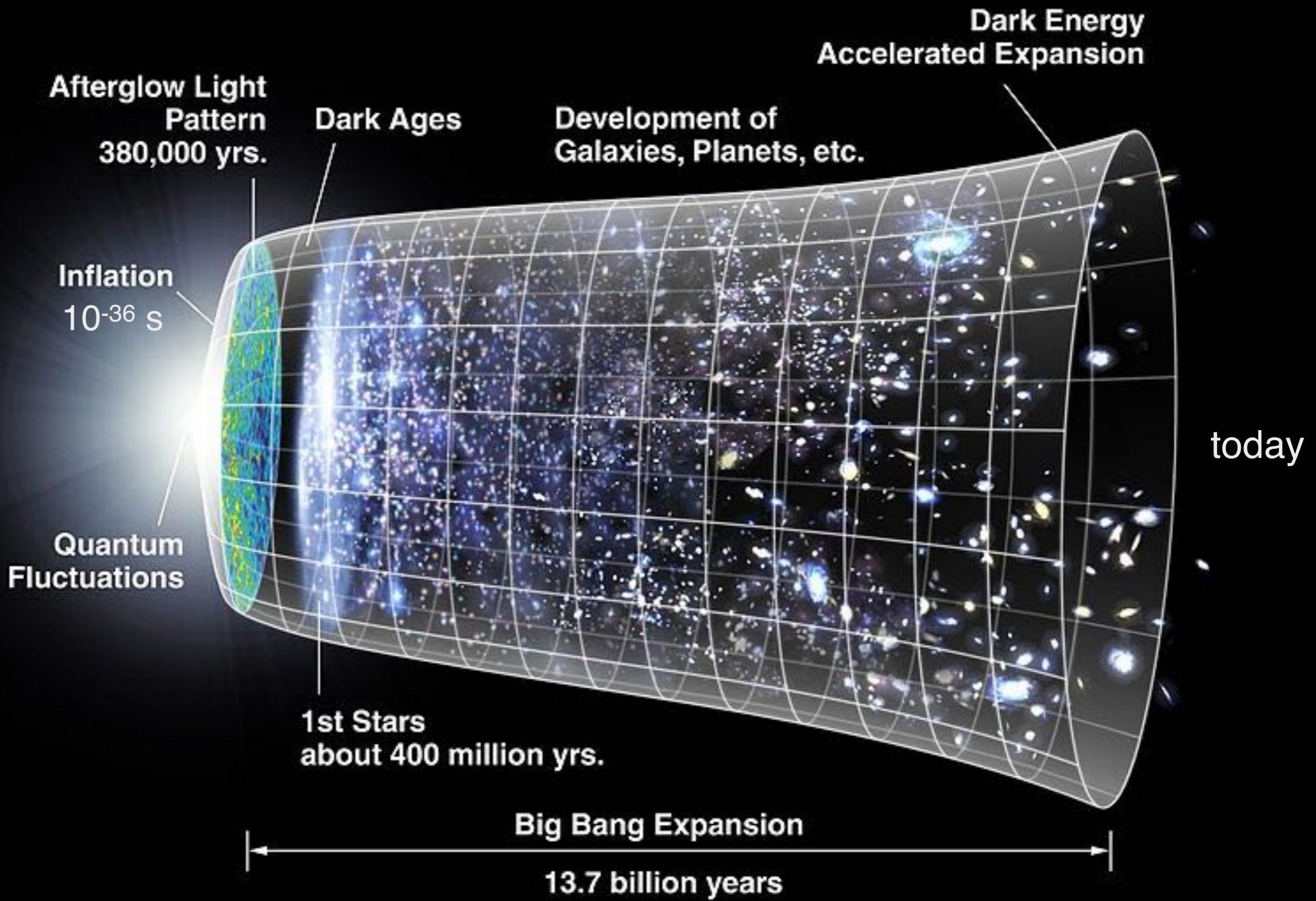
2.4'x2.4' — 1/10th the size of the moon

1 mm x 1mm held 1 m away

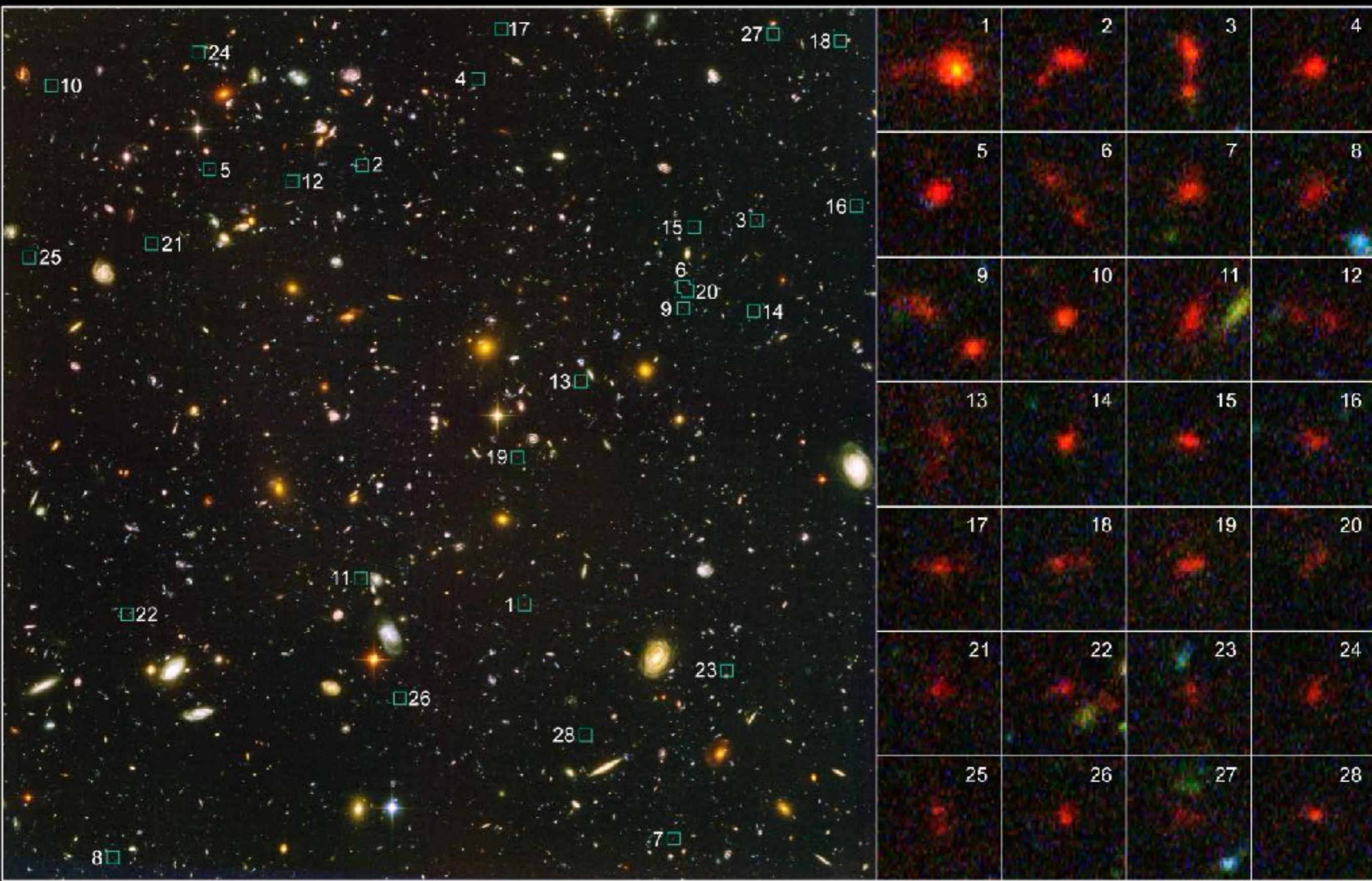
23 days of integration

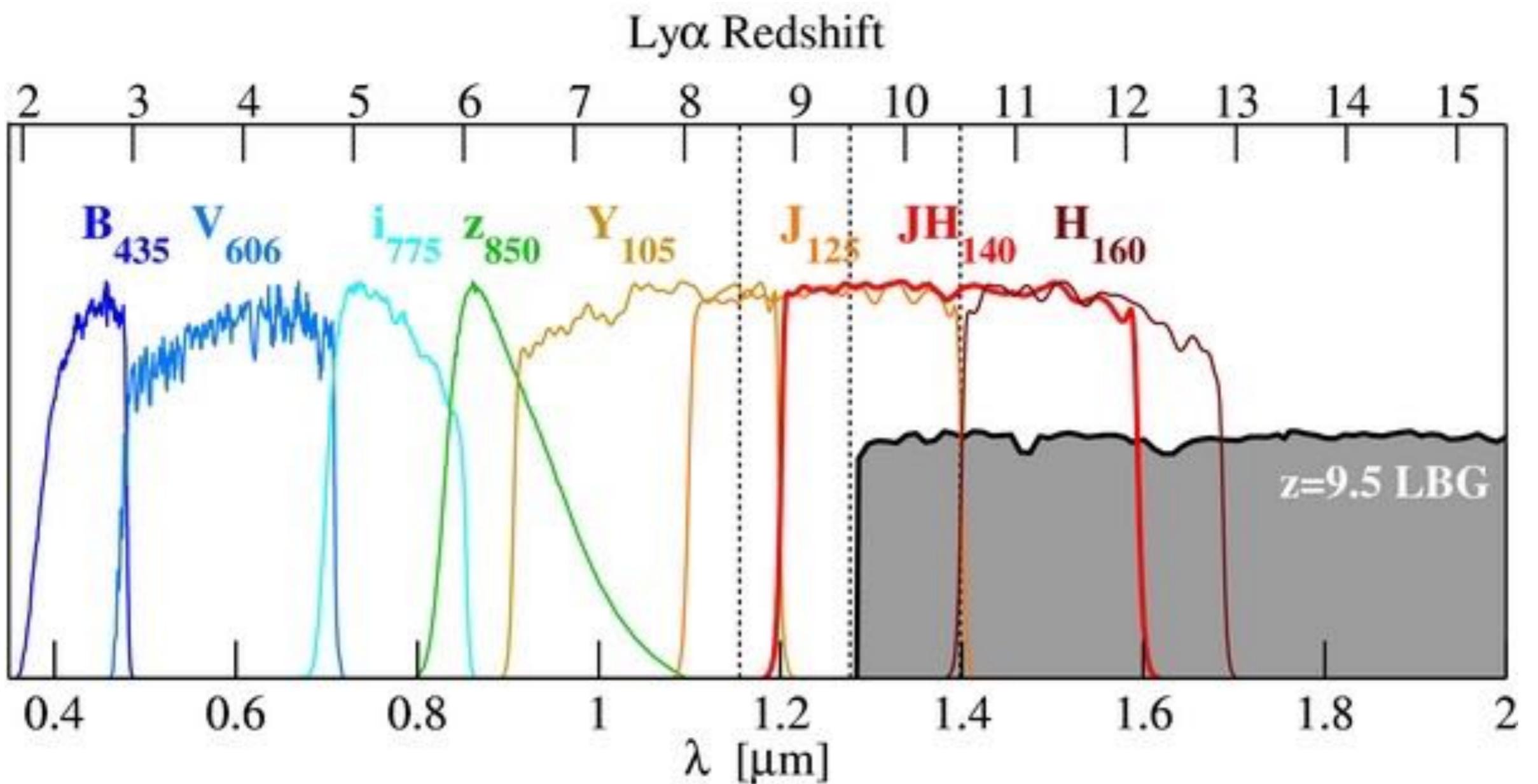
~10,000 galaxies



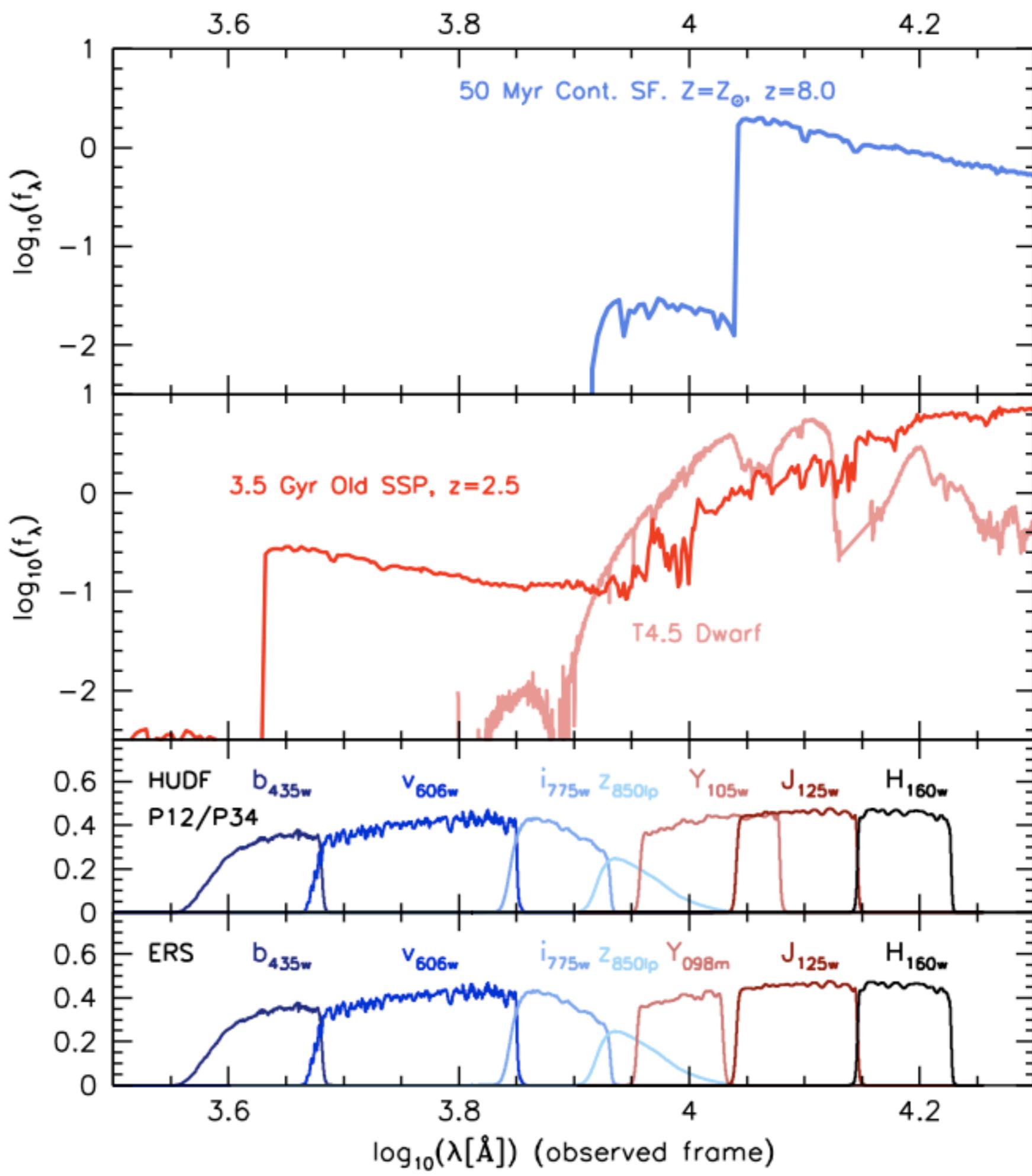


# $z \sim 7$ galaxies in the Hubble Ultra Deep Field





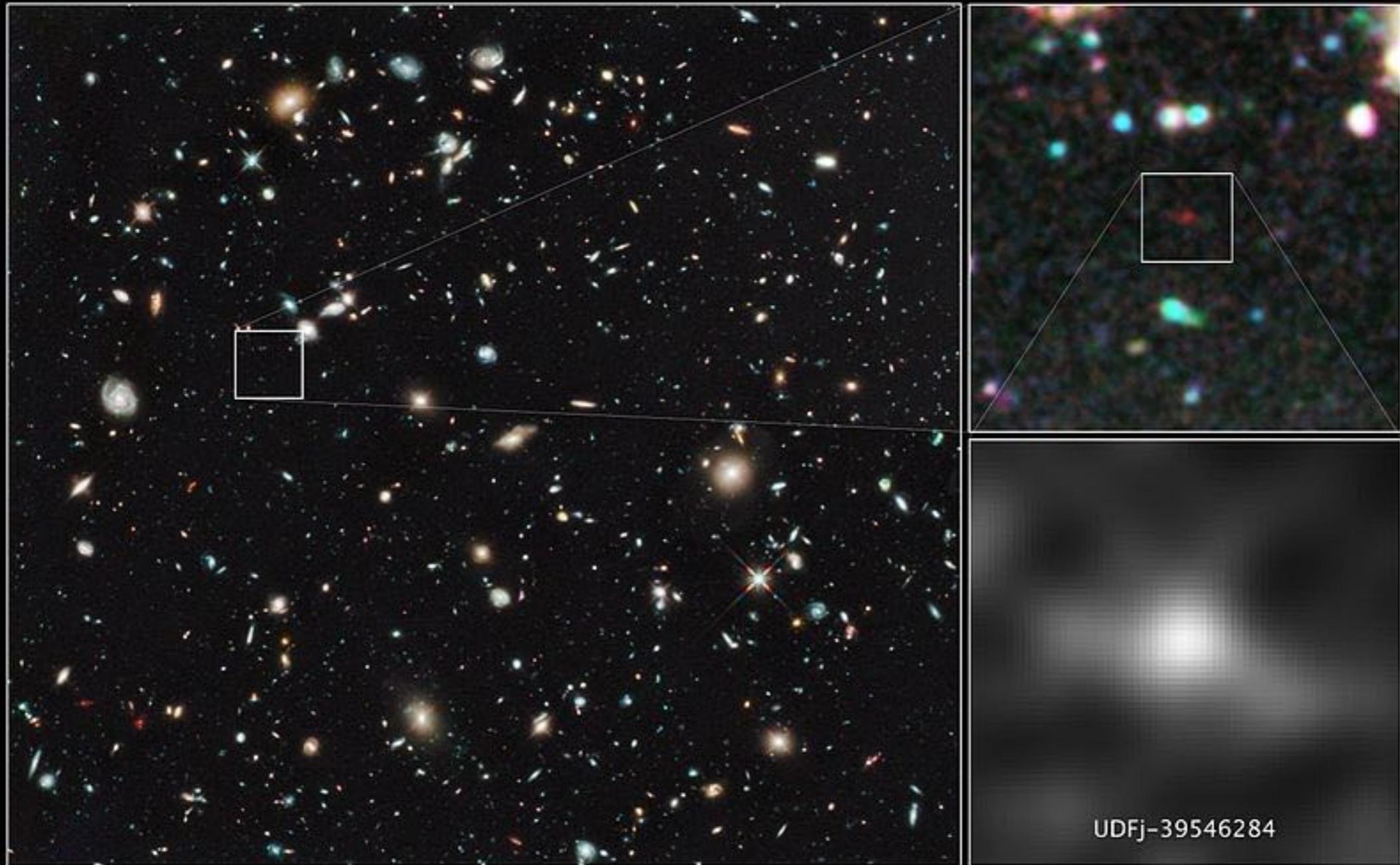
Your homework #1 has you able to calculate magnitudes for sources, but it's incomplete - in particular, we haven't talked about the concept of "Significance" or "uncertainty" yet.



UDFy-38135539

2010 z=8.6

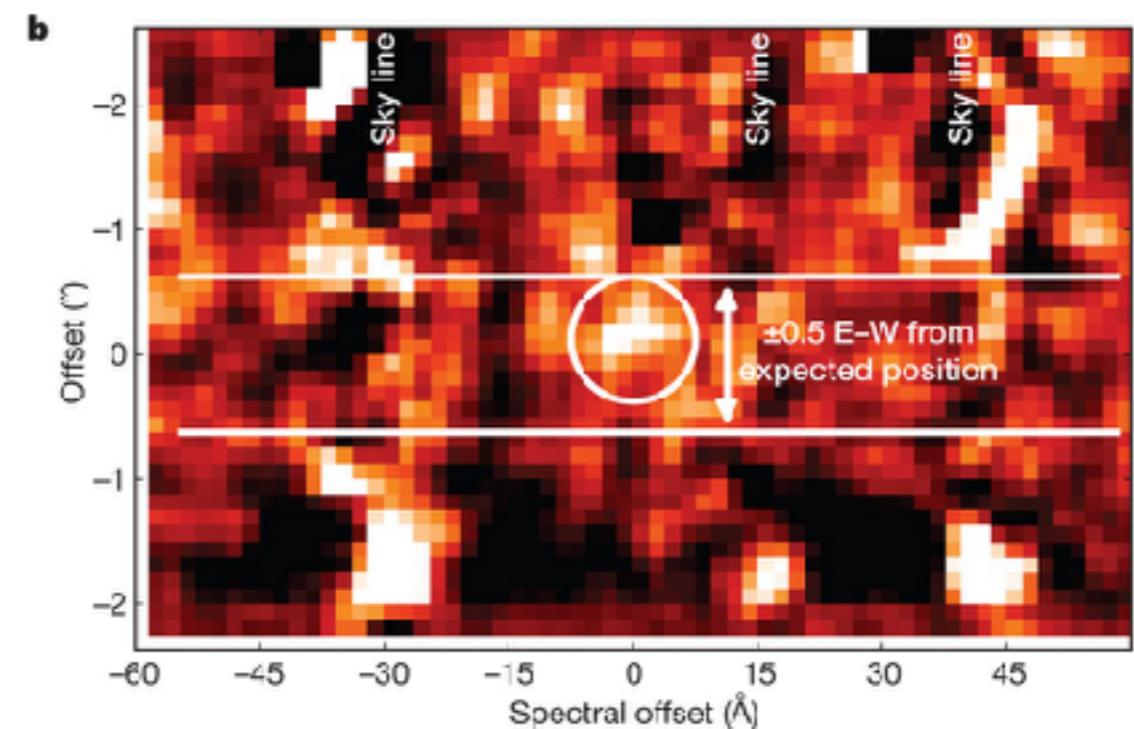
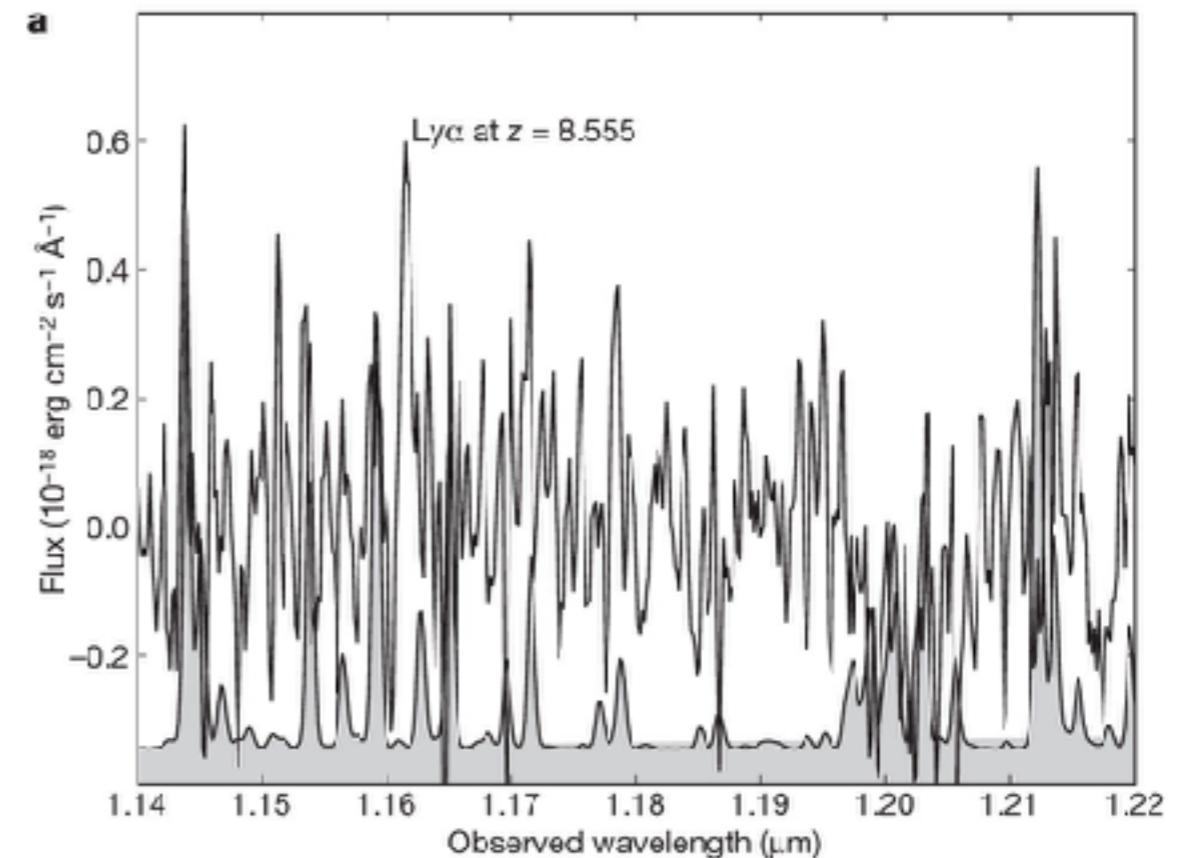
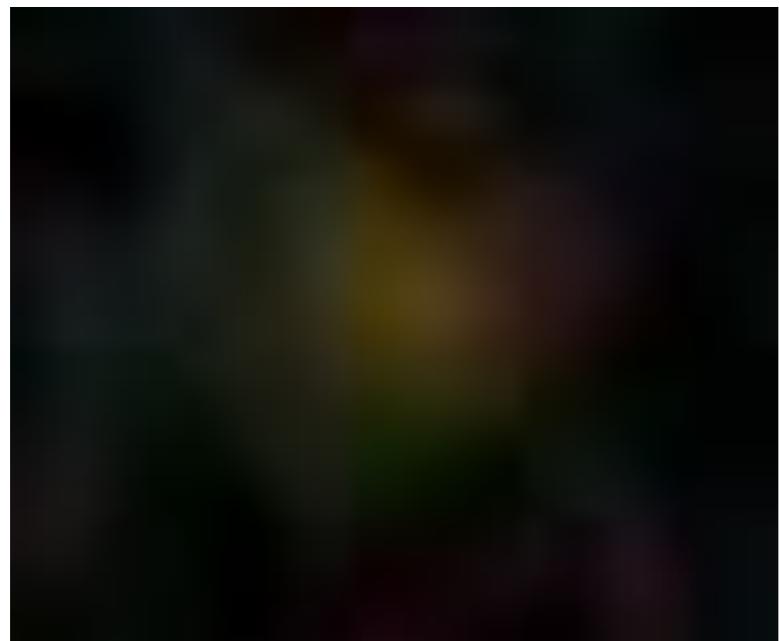
most distant “spectroscopically confirmed” object



# UDFy-38135539

2010 z=8.6

most distant “spectroscopically confirmed” object

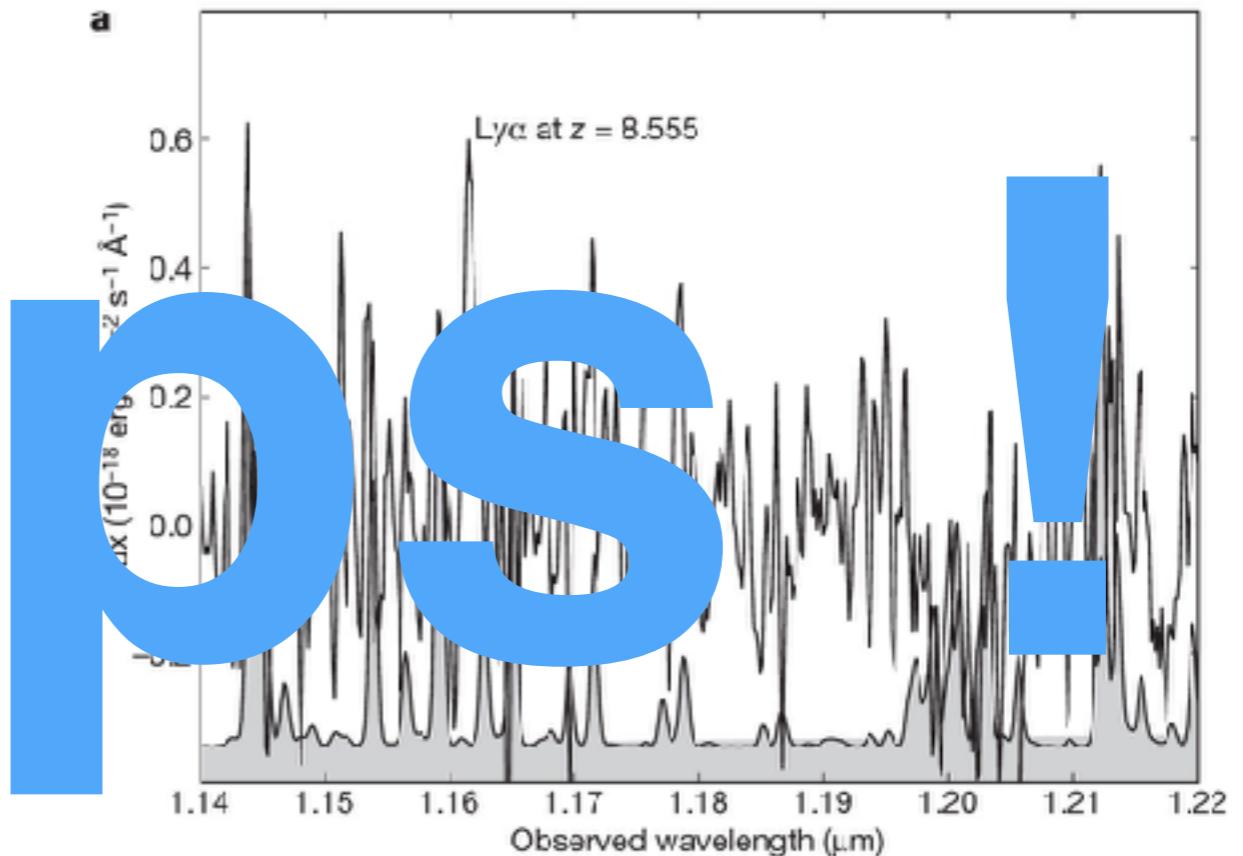


UDFy-38135539

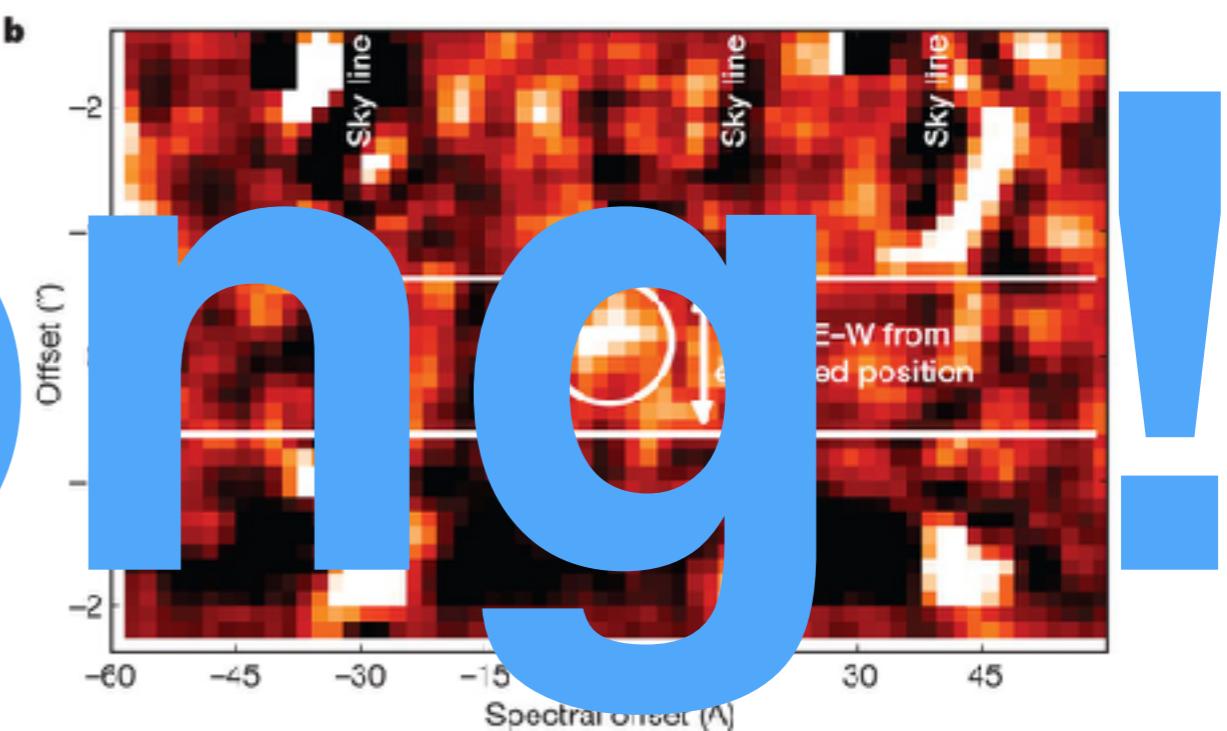
2010 z=8.6

most distant “spectroscopically confirmed” object

Ooops!



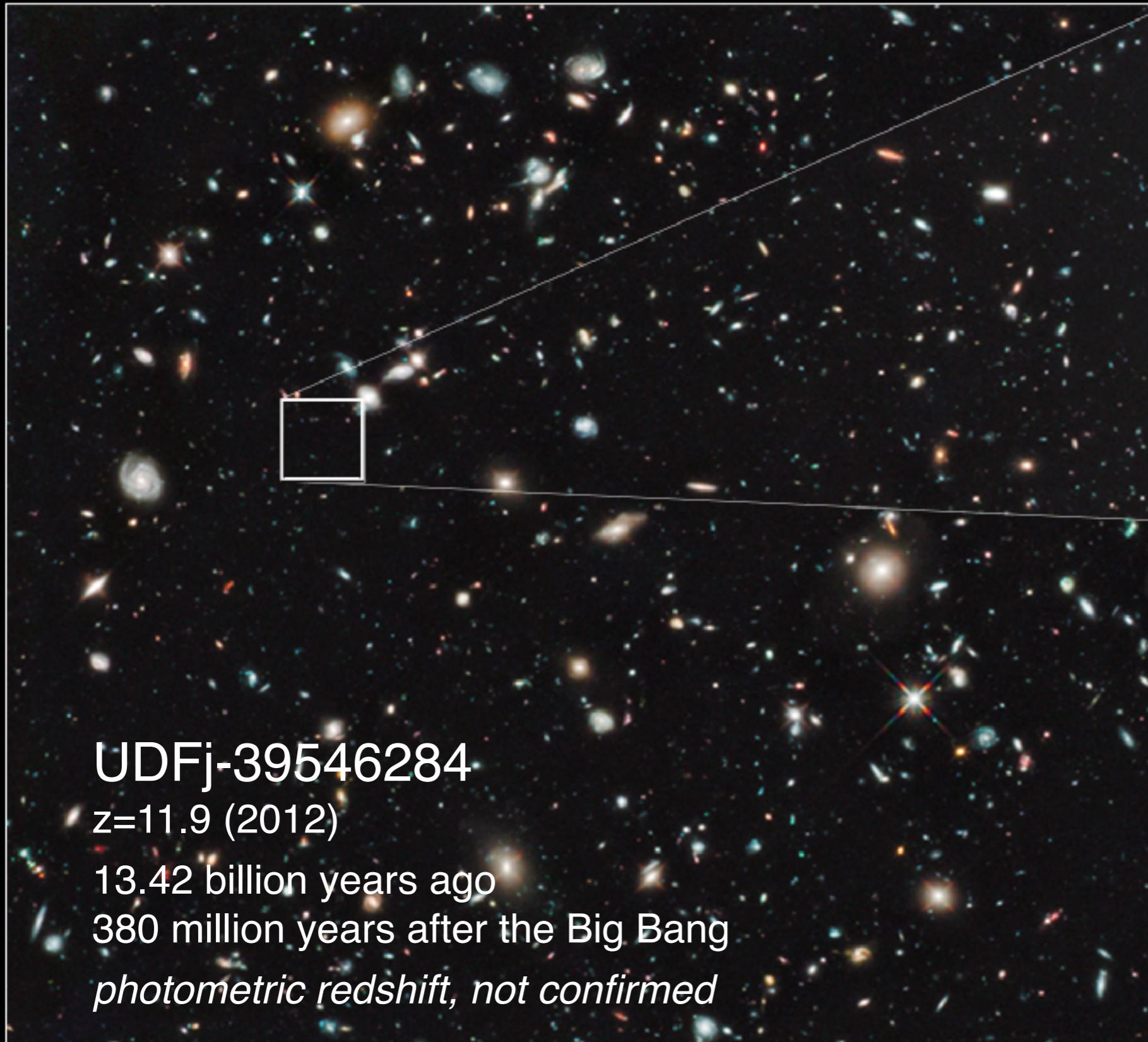
Wrong!



Getting from potential high-z source to confirmed high-z source needs two things

- 1) more data
- 2) better data

## Hubble Ultra Deep Field 2009-2010



**UDFj-39546284**

$z=11.9$  (2012)

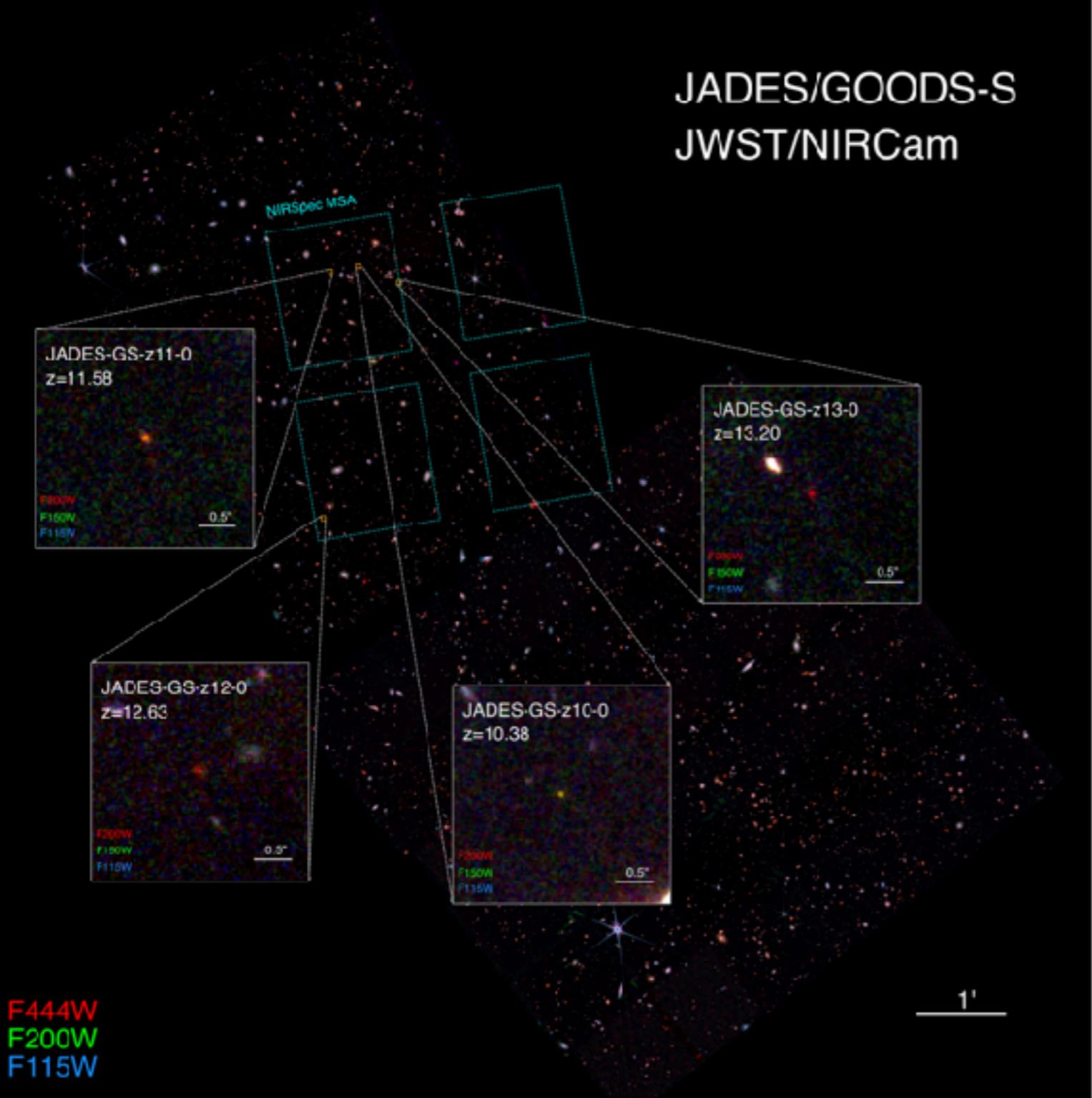
13.42 billion years ago

380 million years after the Big Bang

*photometric redshift, not confirmed*

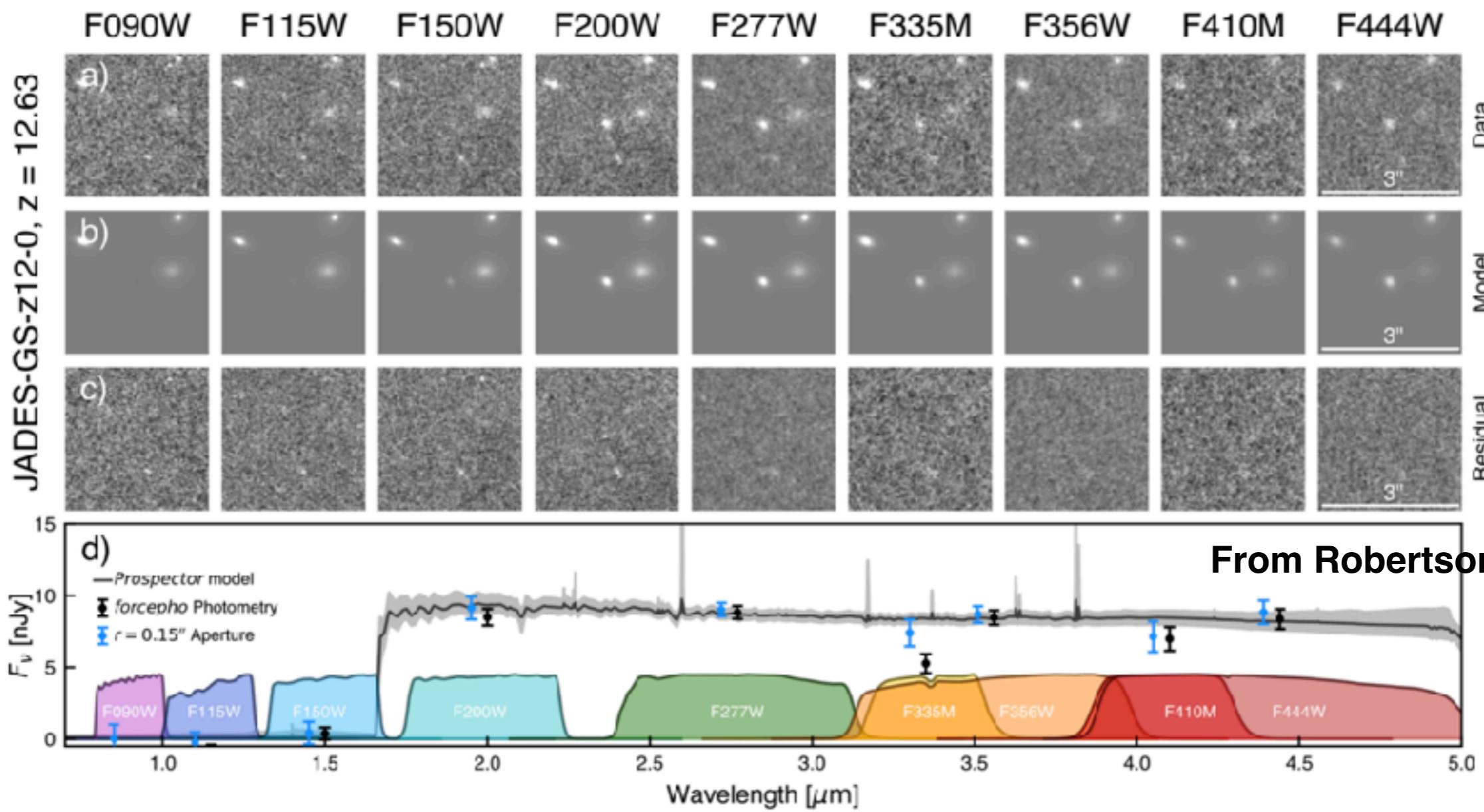
UDFj-39546284

JADES/GOODS-S  
JWST/NIRCam



From Robertson et al.,  
2022

**Fig. 1| Distant galaxies selected and confirmed by the JWST JADES program.** From the JWST NIRCam imaging at wavelengths  $\lambda \approx 0.8 - 5 \mu\text{m}$  (F444W-F200W-F115W shown as a colour mosaic, a), galaxies with photometrically-determined redshift estimates of  $z_{\text{phot}} > 10$  were selected for JWST NIRSpec MSA follow-up (footprint in cyan). An initial sample of four  $z > 10$  galaxies (F200W-F150W-F115W thumbnails, b-e) was spectroscopically confirmed by ref. 37 at redshifts  $z \sim 10.4-13.2$ . The most distant galaxies at  $z=13.20$  and  $z=12.63$  are newly discovered by JADES NIRCam imaging, while the  $z=10.38$  and  $z=11.58$  galaxies confirm previous photometric redshift estimates from the literature. The yellow-orange-red colours reflect the absorption of the F115W and F150W fluxes of these distant galaxies by the intervening intergalactic medium.

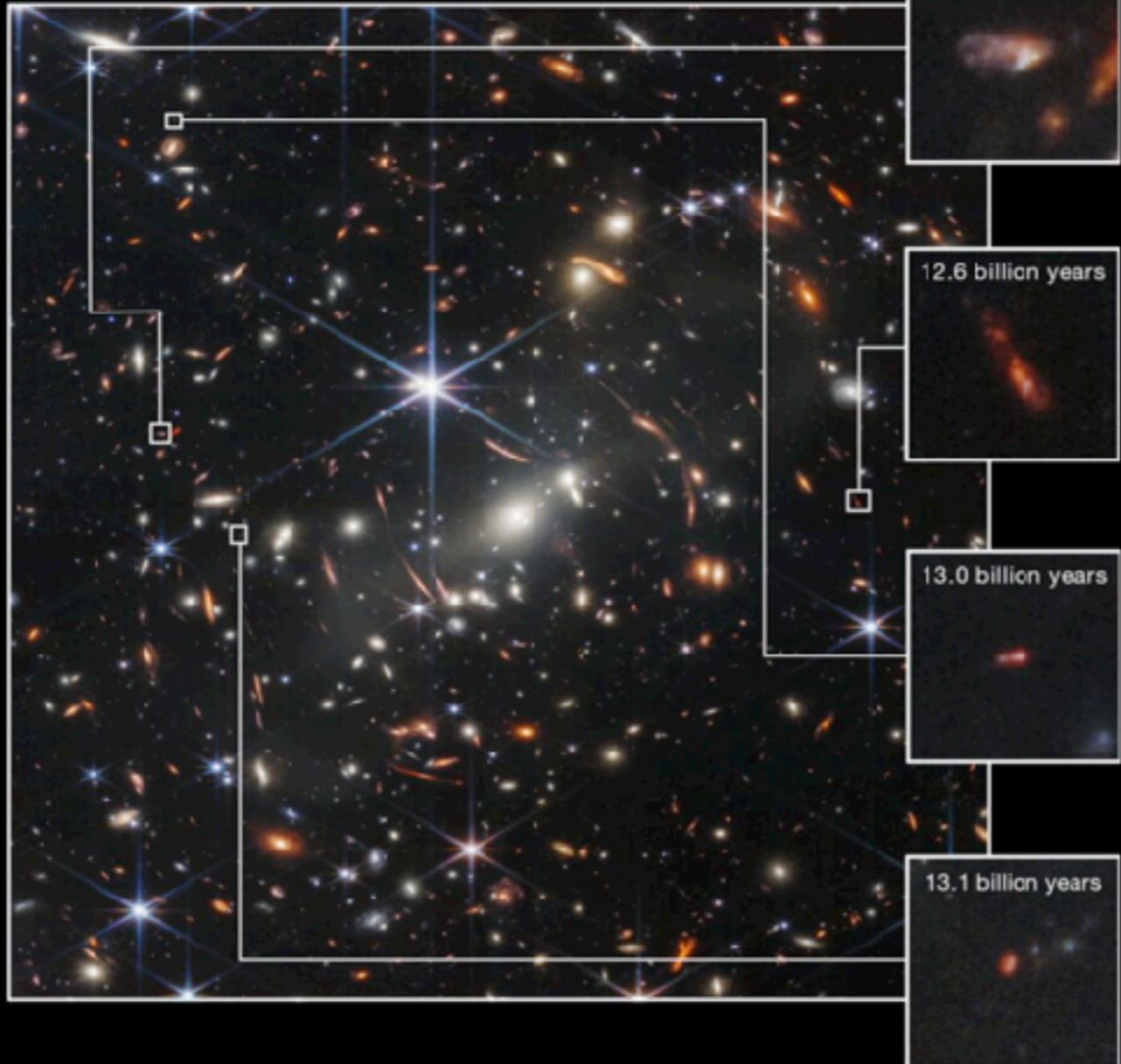


**Fig. 2| Precision photometry and spectral energy distribution (SED) modelling of JADES-GS-z12-0.** The sources detected by the JADES photometric pipeline are supplied to the *forcepho* scene modelling code, which then fits surface brightness profile models to the flux image of the object and its neighbours (a) in all NIRCam bands (columns, and filter curves in d) simultaneously. This method allows for the construction of accurate models of the observations (b) that leave only slight residuals (c) relative to the data. The source fluxes are then used as constraints for SED fitting (maximum likelihood fit to the  $N=6$  detections, line in d with  $1\sigma$  s.d. marginalised credibility interval as shaded region) to the photometry (points show mean values with  $1\sigma$  s.d. error bars, including *forcepho* photometry in black and  $r=0.15''$  aperture photometry in blue with an offset for clarity), which in turn constrain the physical galaxy properties. The postage stamps are  $3'' \times 3''$ , or about  $13 \text{ kpc} \times 13 \text{ kpc}$  at redshift  $z=10$ .

GALAXY CLUSTER SMACS 0723

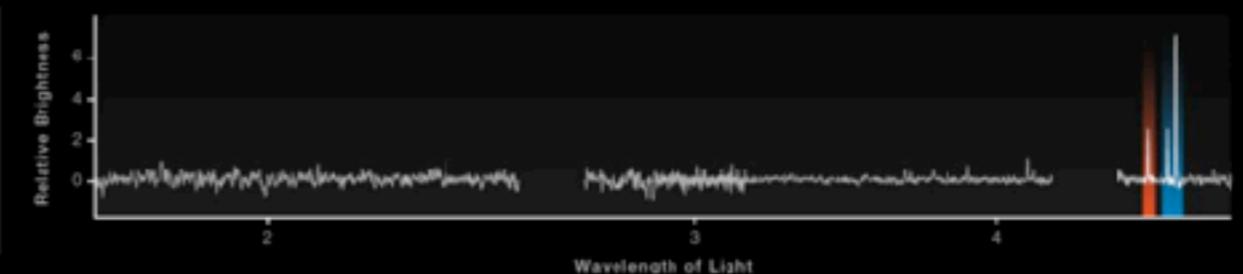
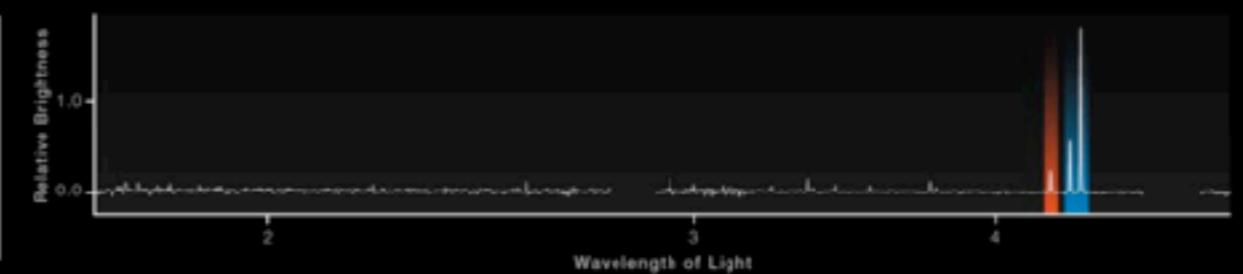
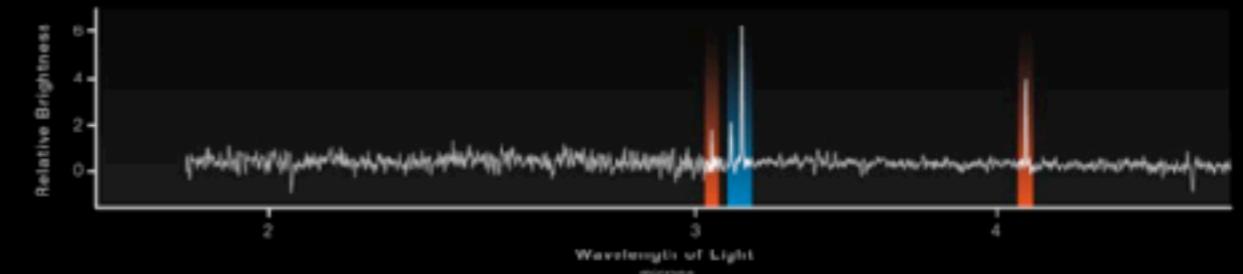
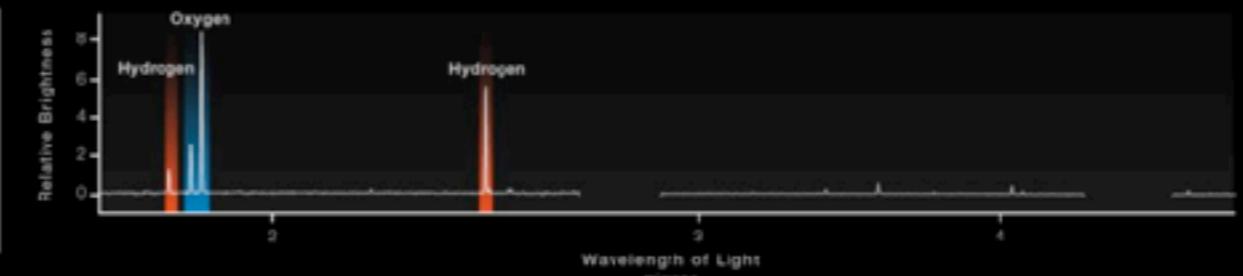
# WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE

NIRCam Imaging



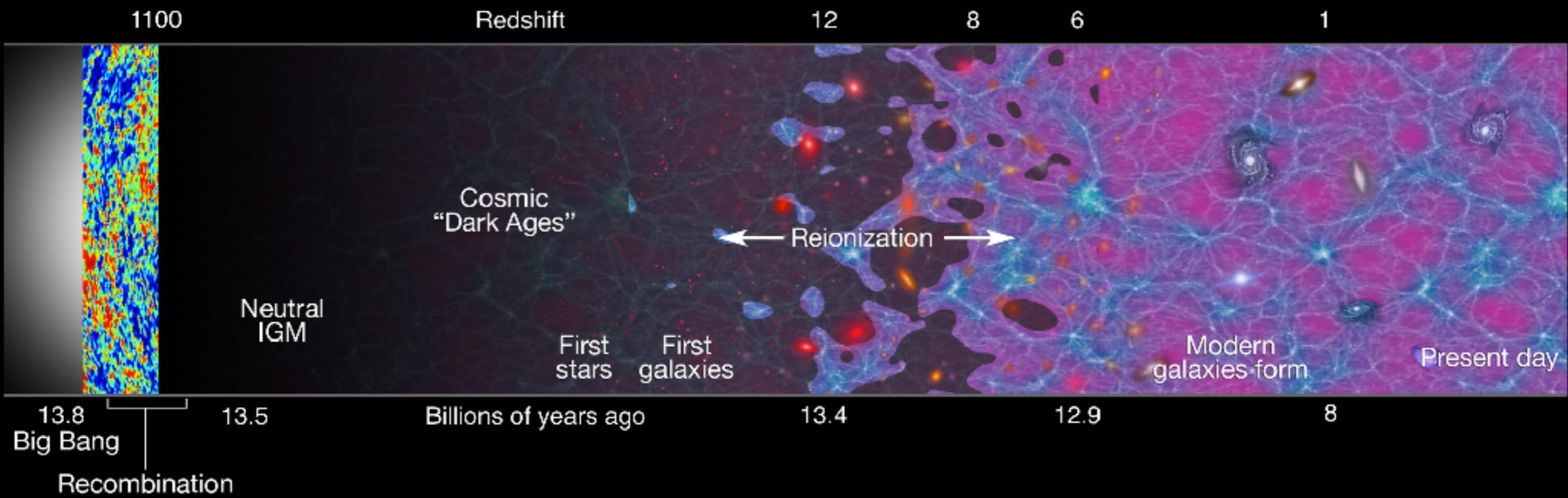
NIRSpec Microshutter Array Spectroscopy

Lowest redshift



Highest redshift

**WEBB**  
SPACE TELESCOPE



# Hubble Probes the Early Universe

