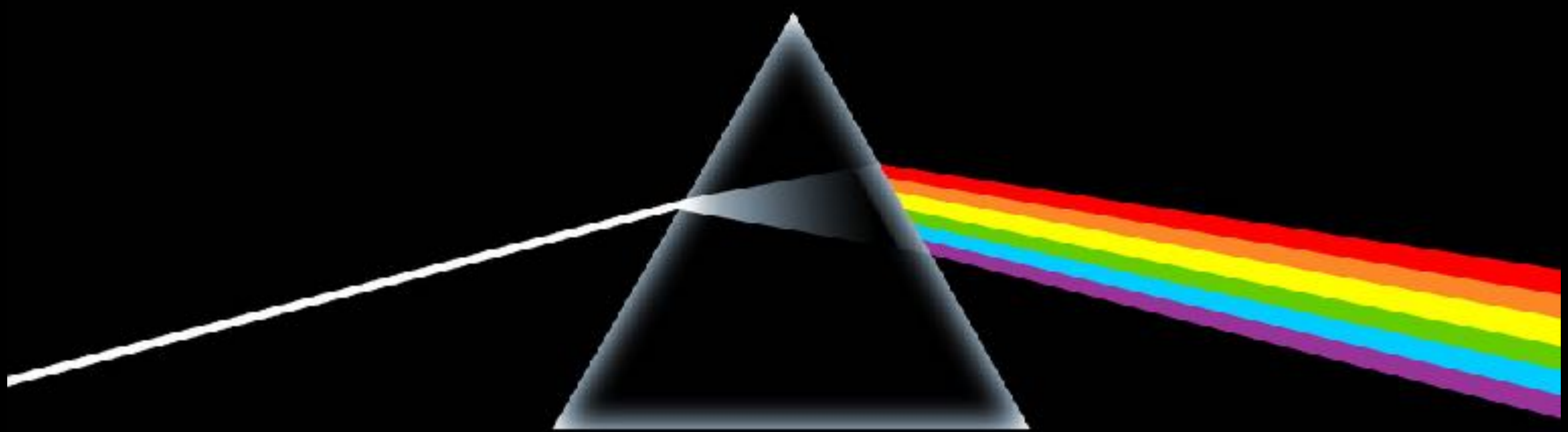
Astronomy 503
Observational Astronomy



Prof. Gautham Narayan

Lecture 03: Luminosities, Fluxes, Redshift

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REVIEW ARTICLE

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

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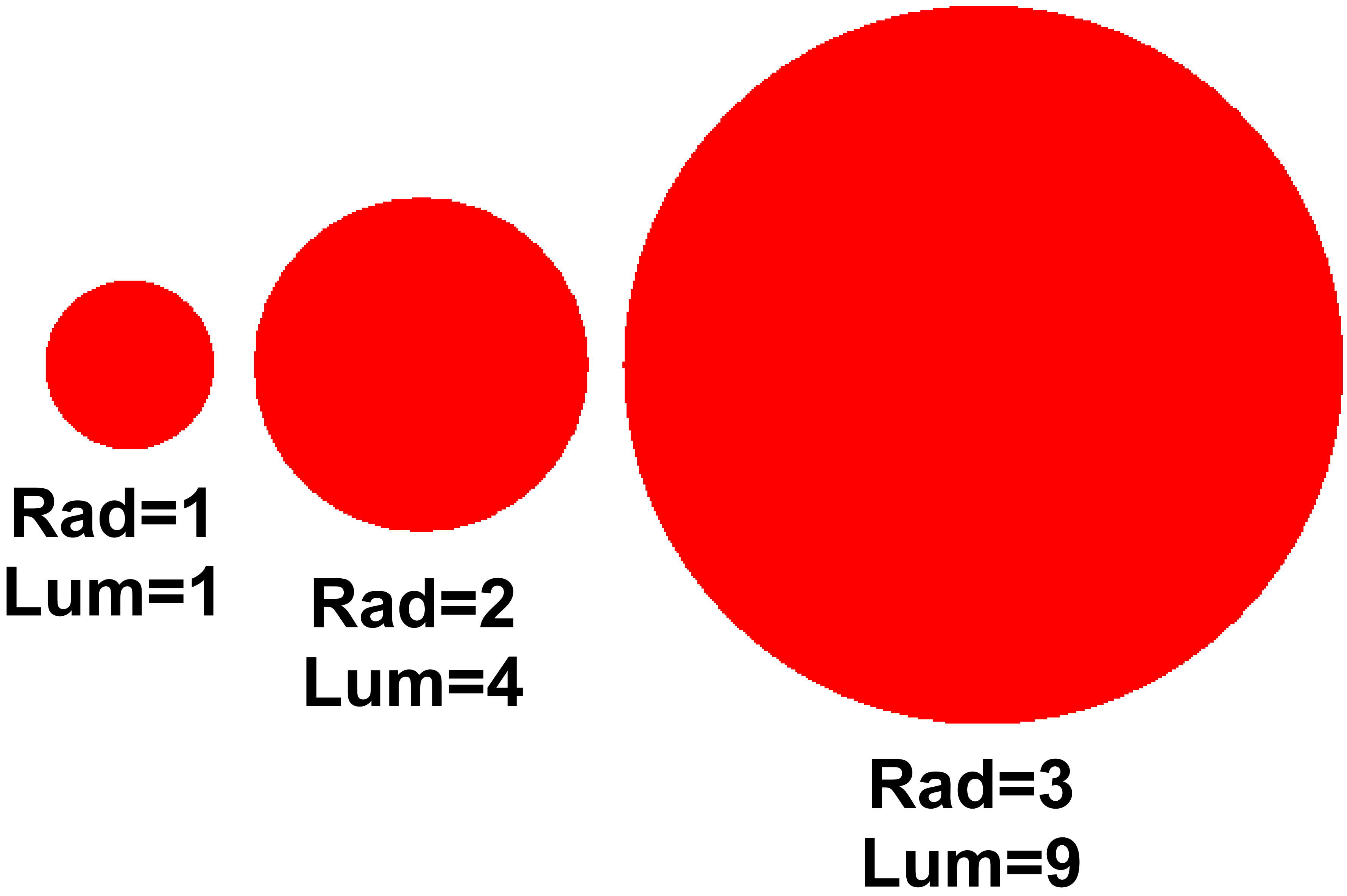
T.D. Oswalt, H.E. Bond (eds.), *Planets, Stars and Stellar Systems. Volume 2: Astronomical Techniques, Software, and Data*, DOI 10.1007/978-94-007-5618-2_10, © Springer Science+Business Media Dordrecht 2013

Bigger objects are brighter



For stars of the same temperature, the larger the star, the greater the luminosity

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 !

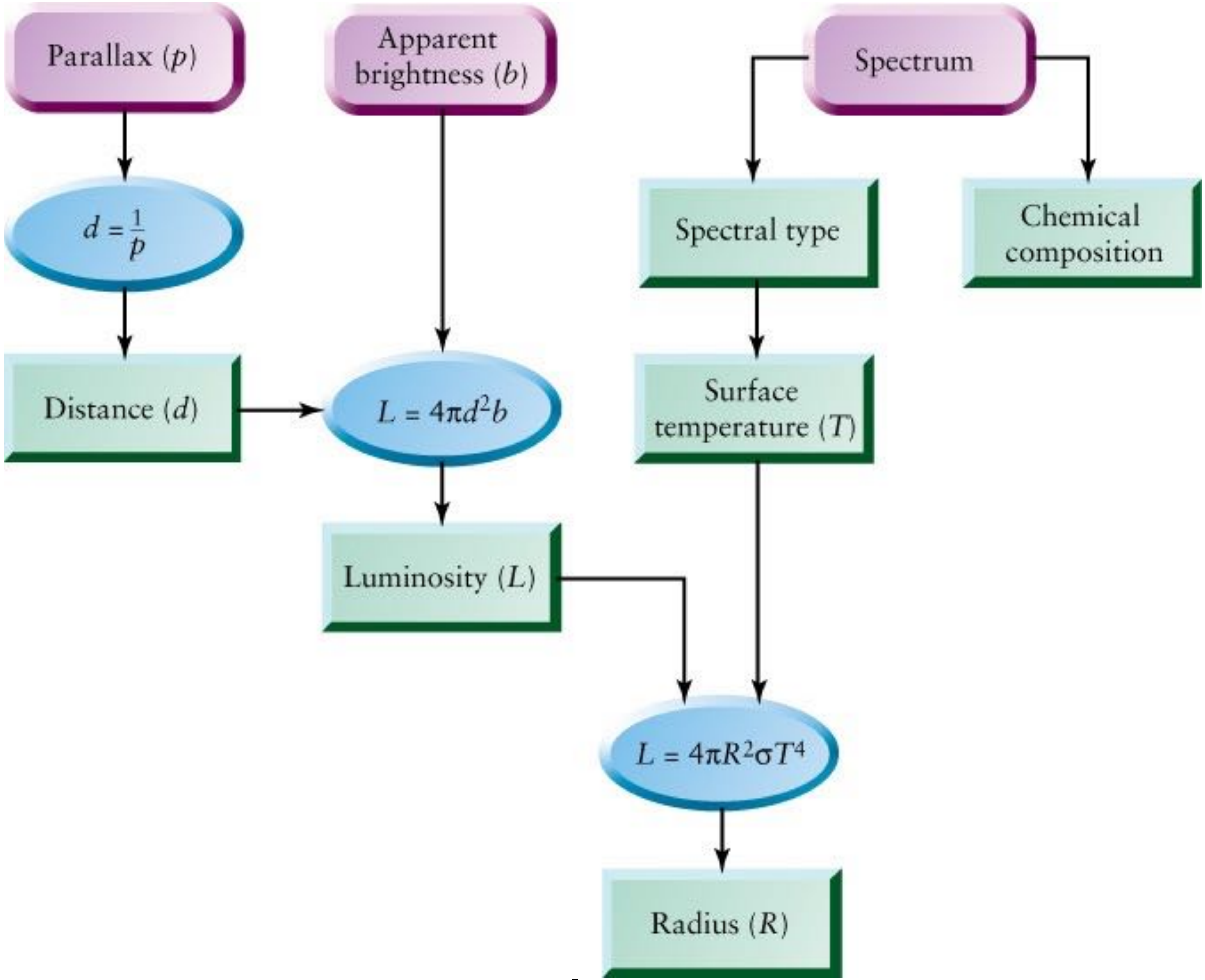
$$L = 4\pi R^2 \sigma T^4$$

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

pi = ratio of a circle's circumference to it's 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

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

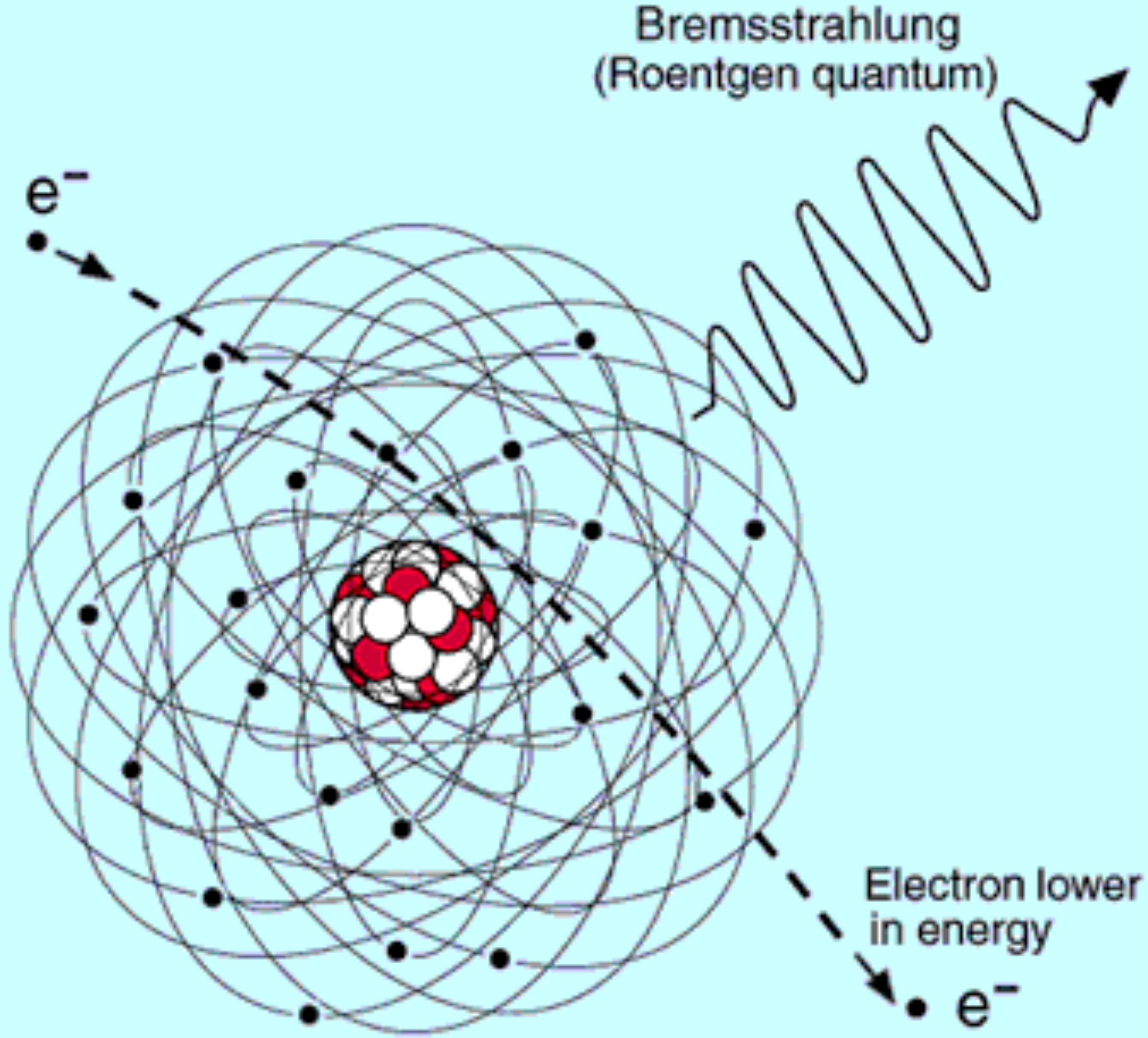
$$R \propto \frac{\sqrt{L}}{T^2}$$



Parallax (p)
Apparent brightness (b)
Spectrum
$d = \frac{1}{p}$
Spectral type
Chemical composition
Distance (d)
$L = 4\pi d^2 b$
Surface temperature (T)
Luminosity (L)
$L = 4\pi R^2 \sigma T^4$
Radius (R)

Bremsstrahlung “Braking Radiation”

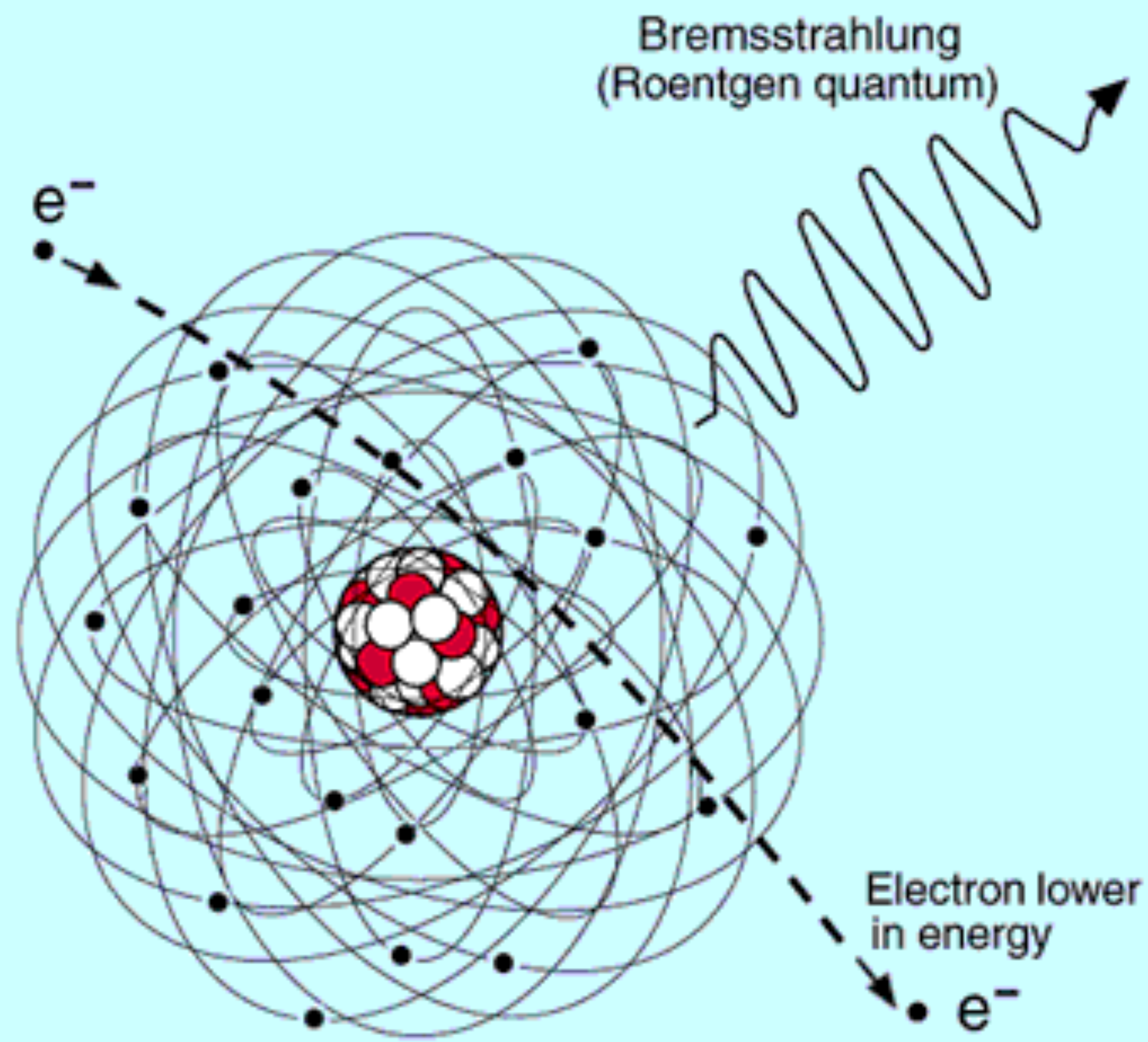
E_1



E_2

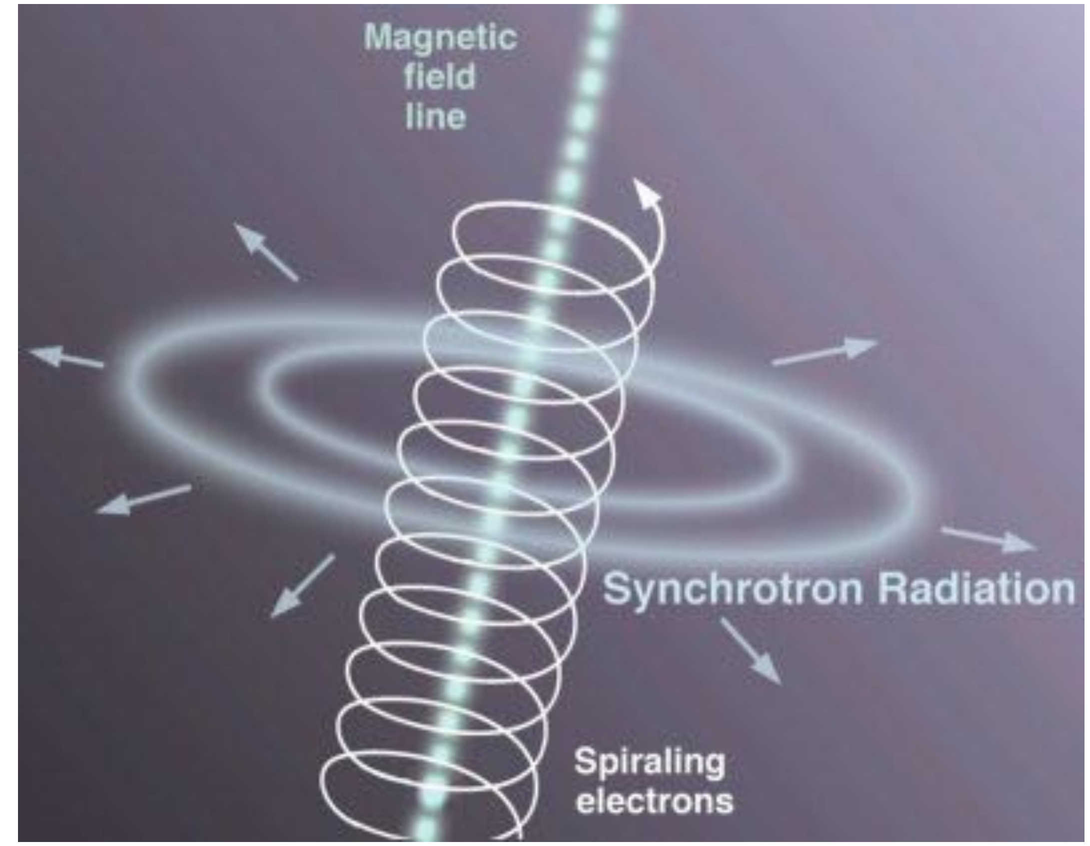
$$h\nu = E_1 - E_2$$

free-free emission

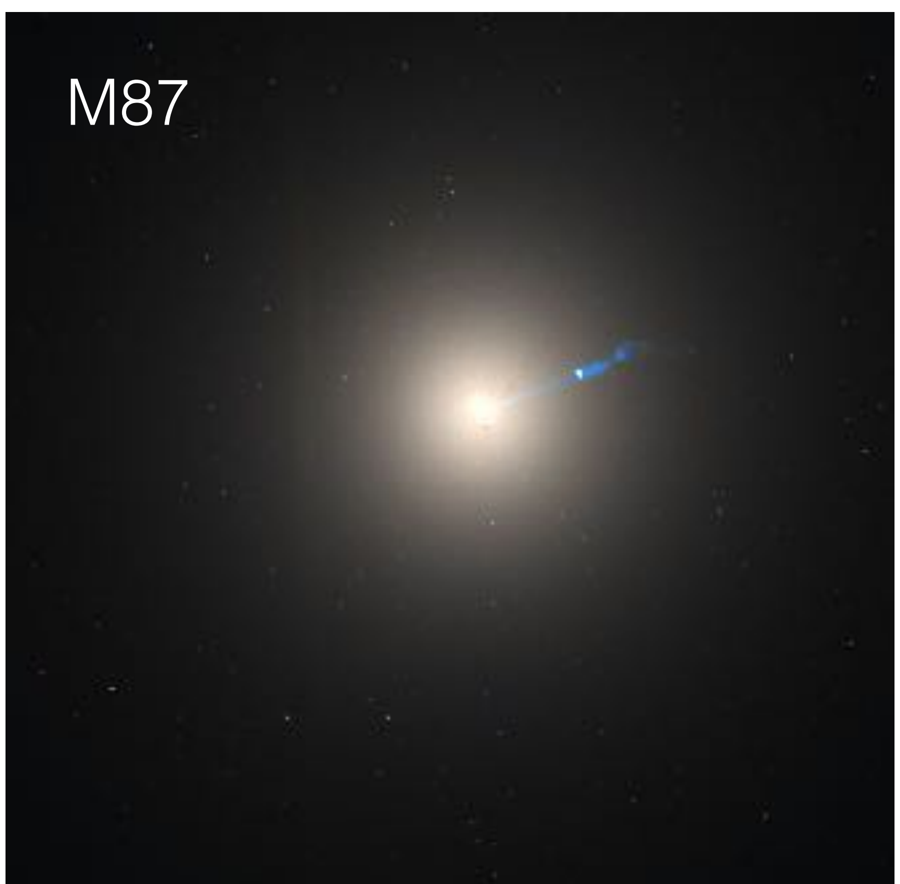


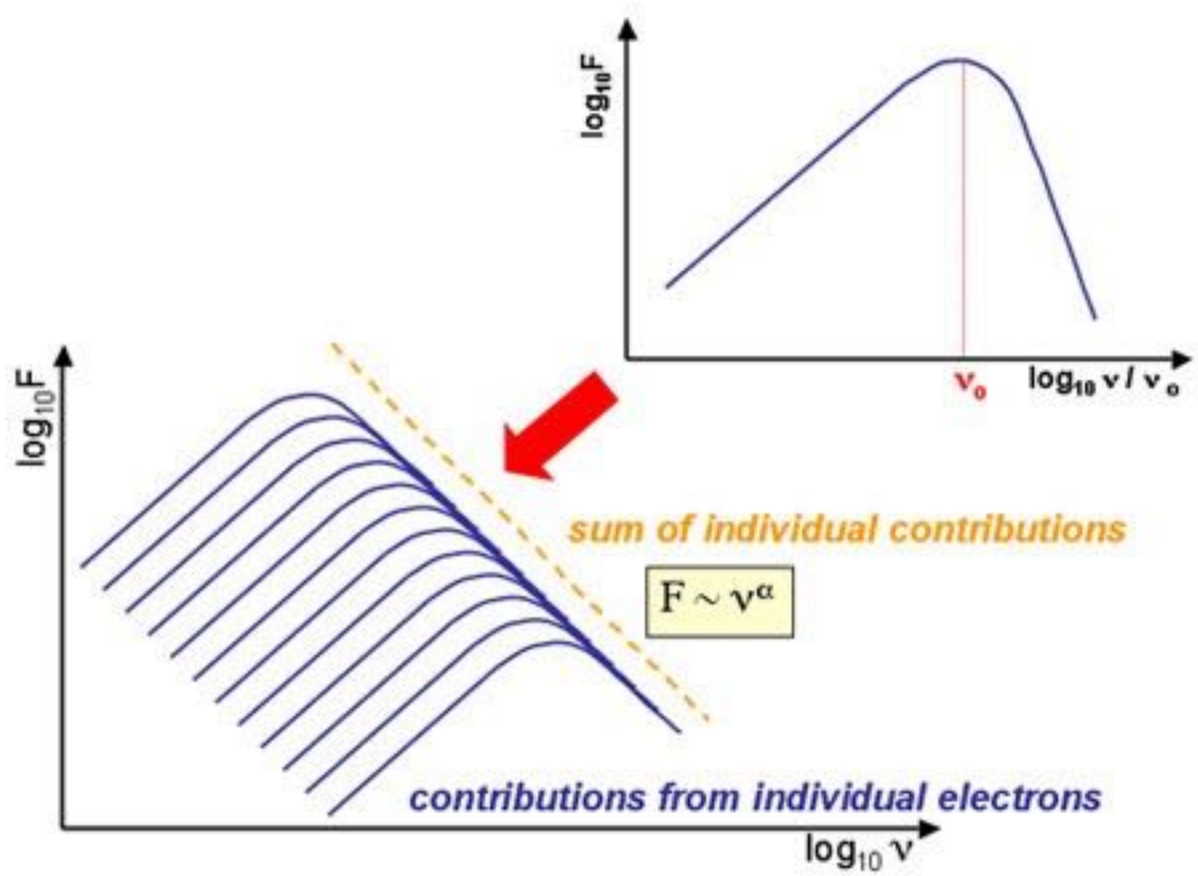
- thermal bremsstrahlung
- free electrons scattering off ions
- free before, free after
- HII regions, star formation, proportional to thermal energy
- unpolarized

Synchrotron emission

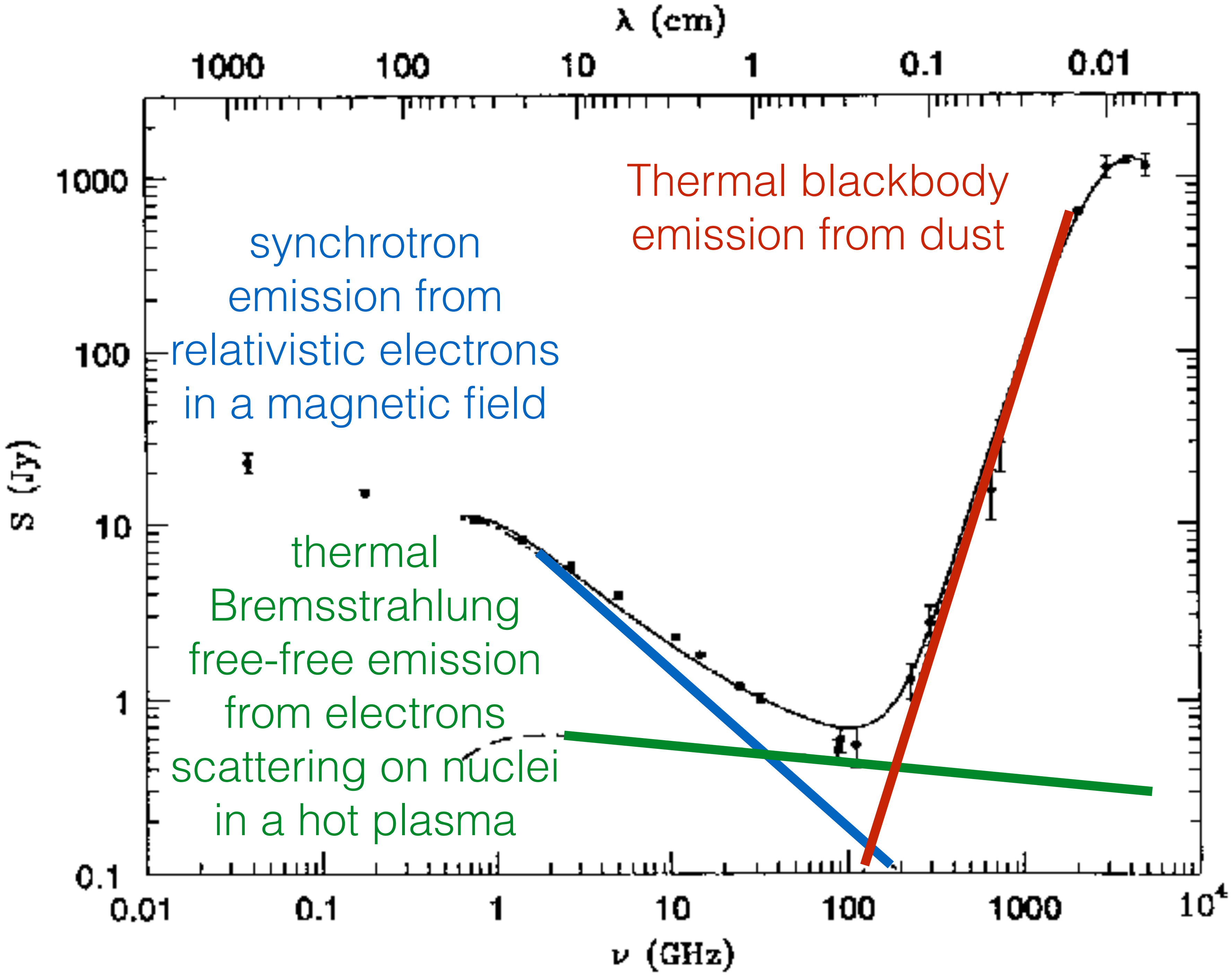


- Charged particles moving through magnetic fields
- Electrons produce broad spectrum, polarized light
- First detected in 1956 by Burbidge in M87

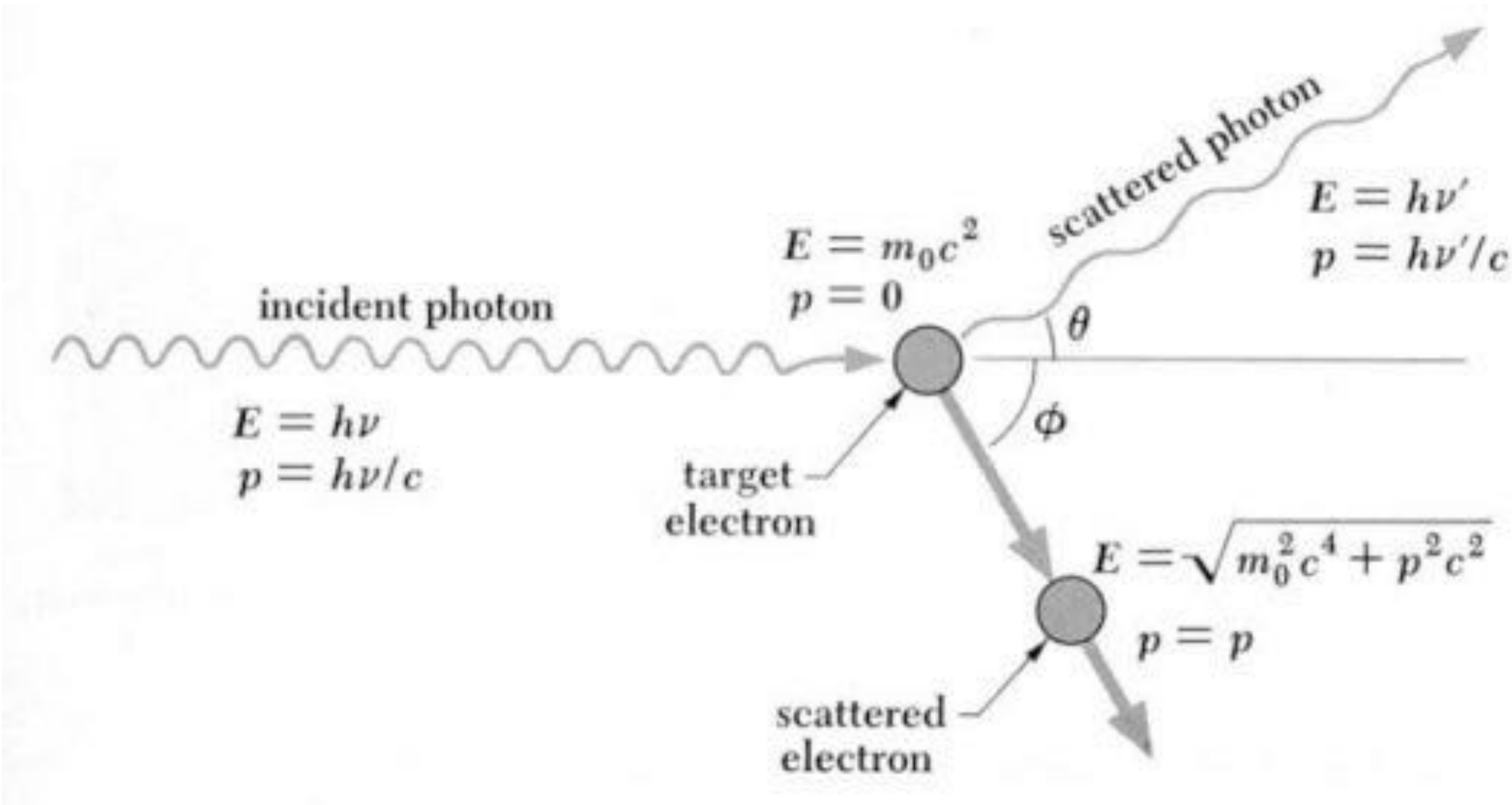


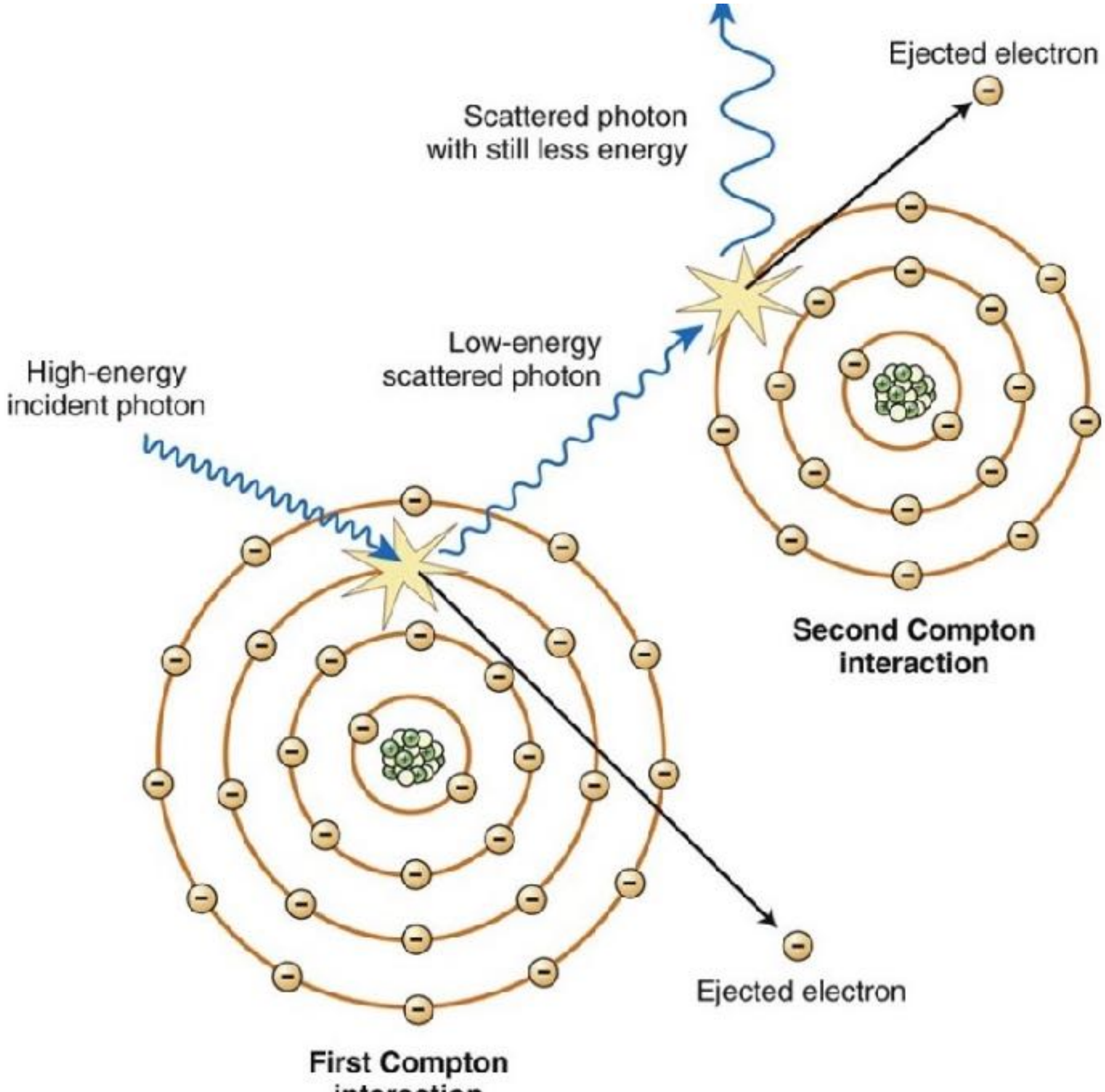


M82

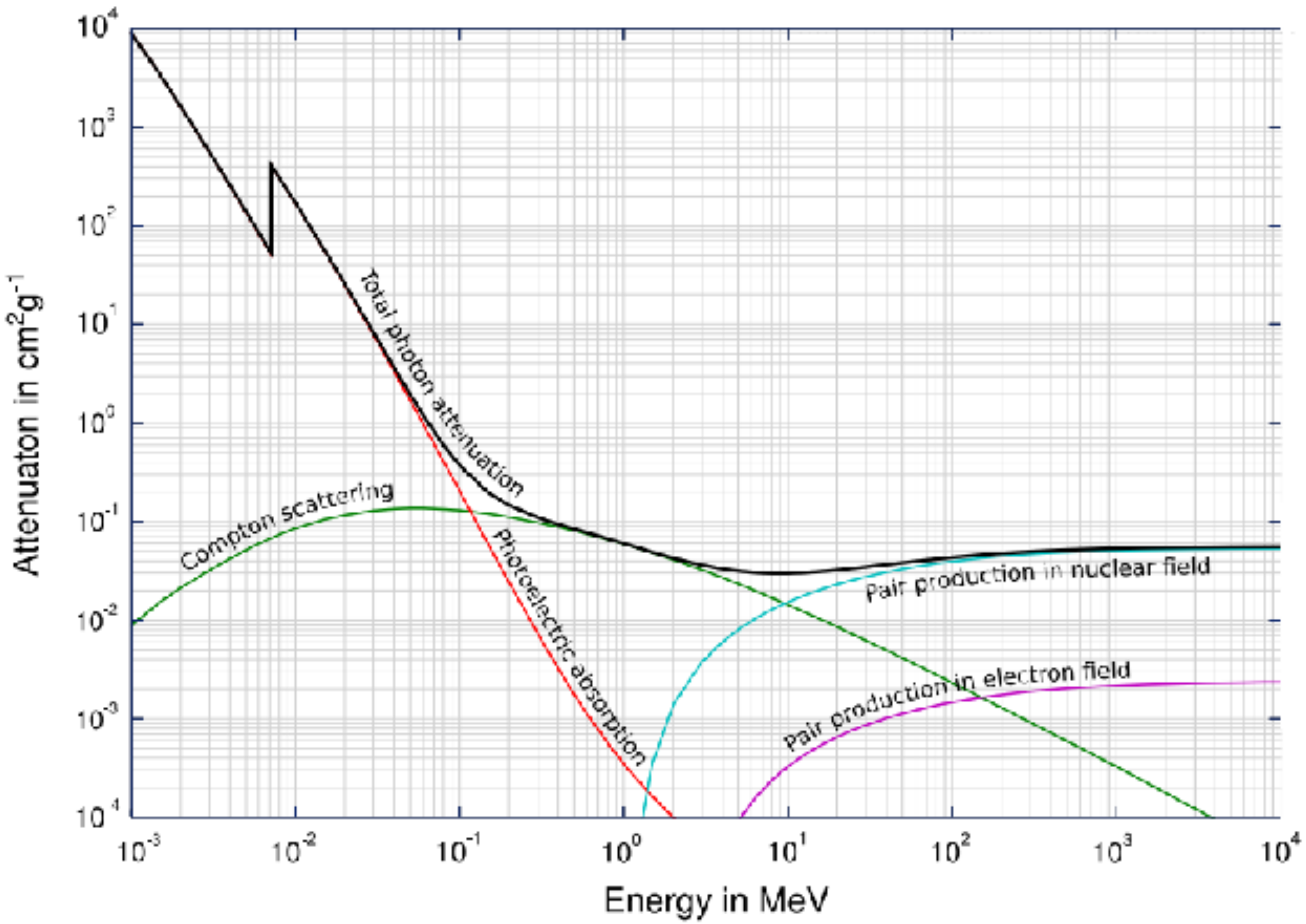

λ (cm)
1000
100
10
1
0.1
0.01
1000
100
10
1
0.1
S (Jy)
0.01
0.1
1
10
100
1000
10^4
ν (GHz)
Thermal blackbody
emission from dust
synchrotron
emission from
relativistic electrons
in a magnetic field
thermal
Bremsstrahlung
free-free emission
from electrons
scattering on nuclei
in a hot plasma

Compton Scattering



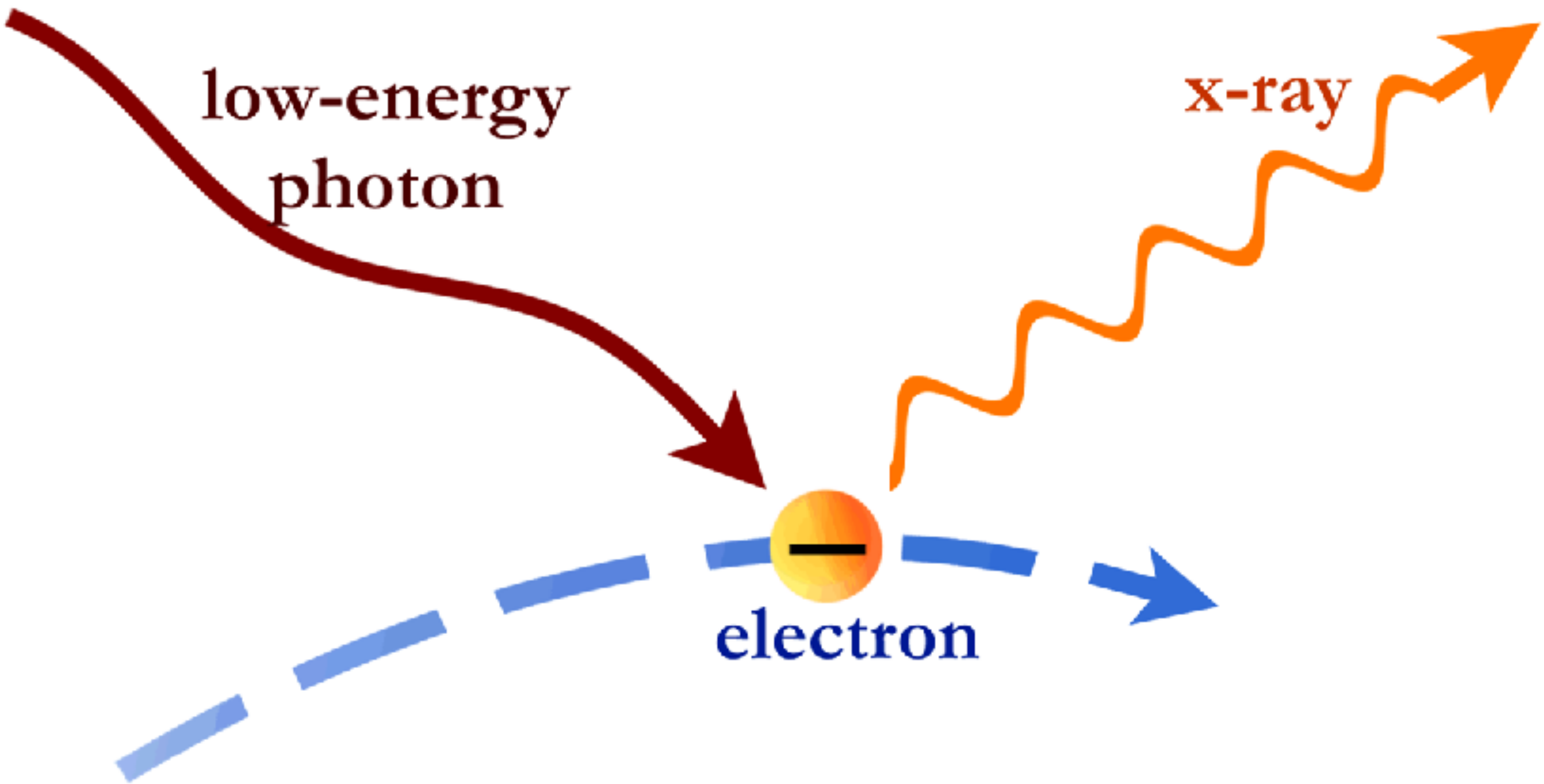

Ejected electron
Scattered photon
with still less energy
Low-energy
scattered photon
High-energy
incident photon
Second Compton
interaction
Ejected electron
First Compton
interaction

Gamma Ray Cross Sections

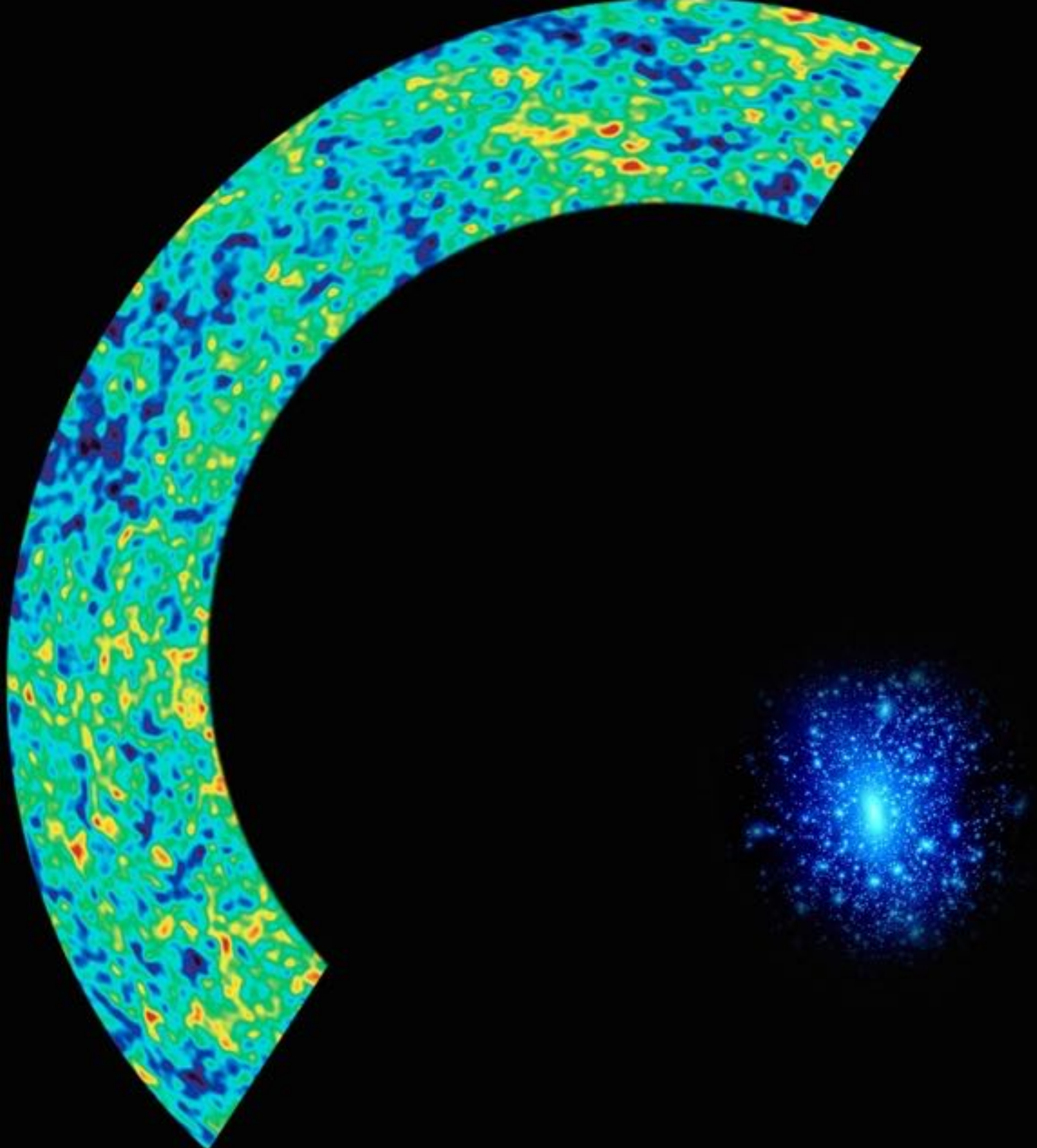


At low energies, lots of scattering events, but low energy loss

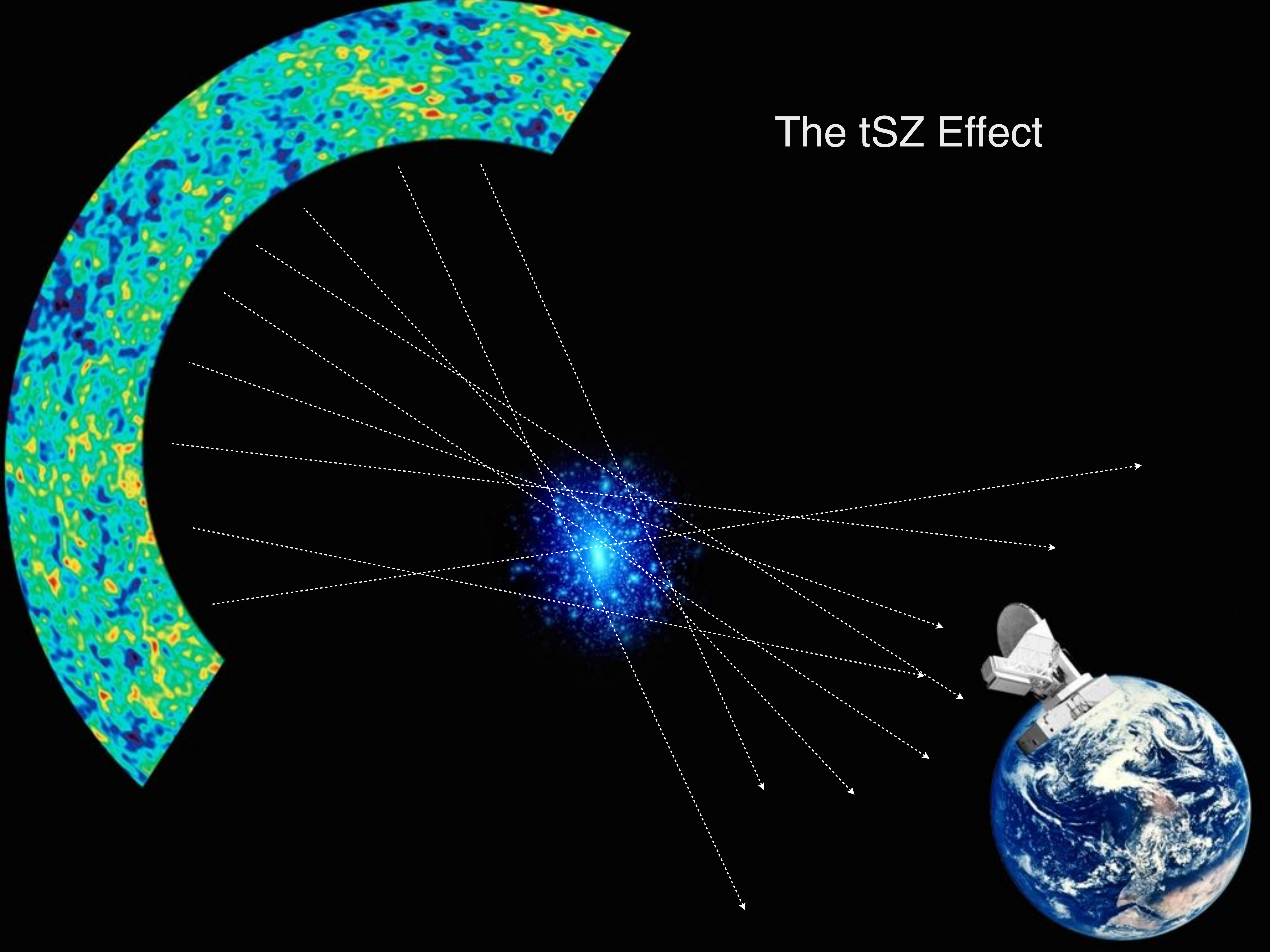
Inverse Compton Scattering



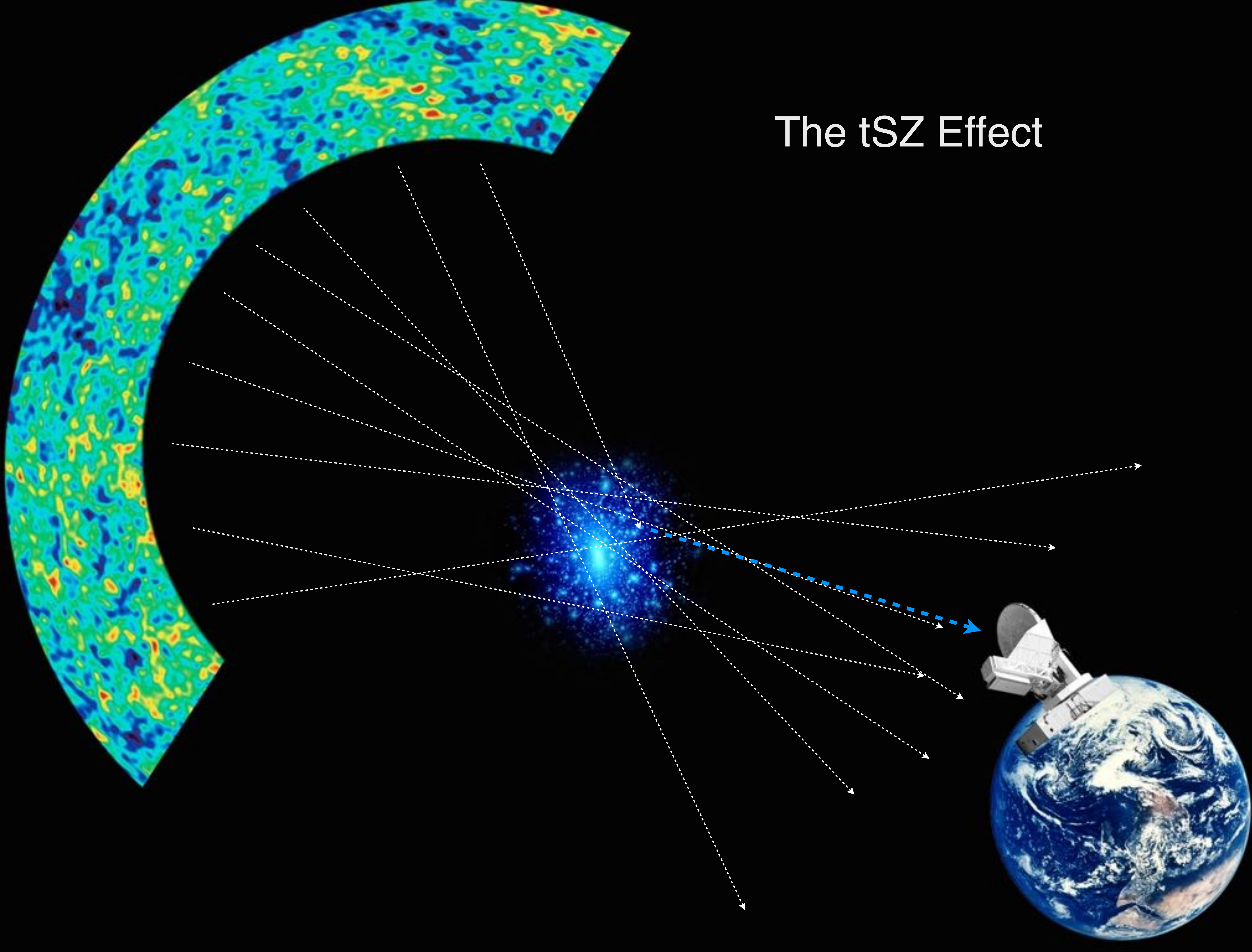
The tSZ Effect



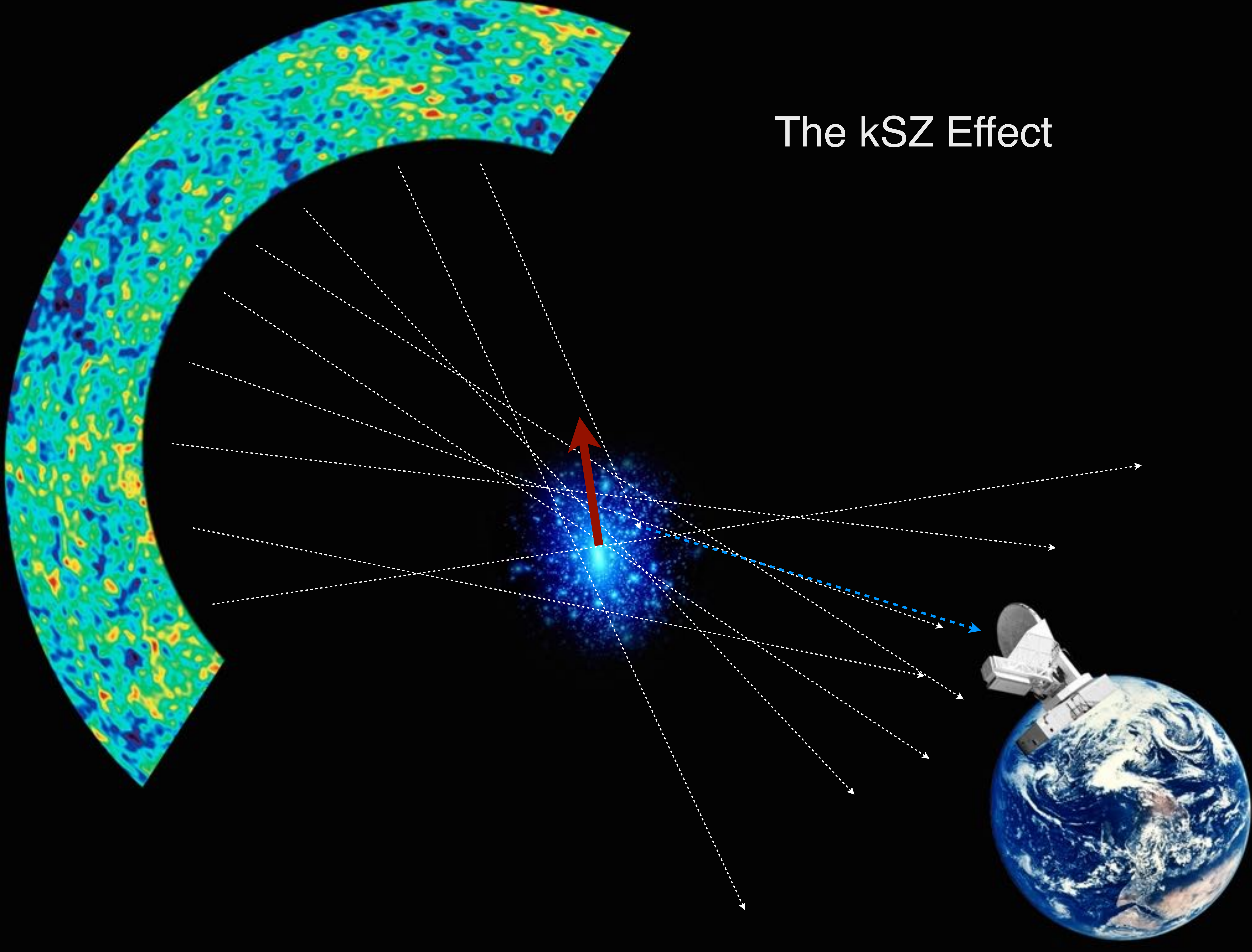
The tSZ Effect



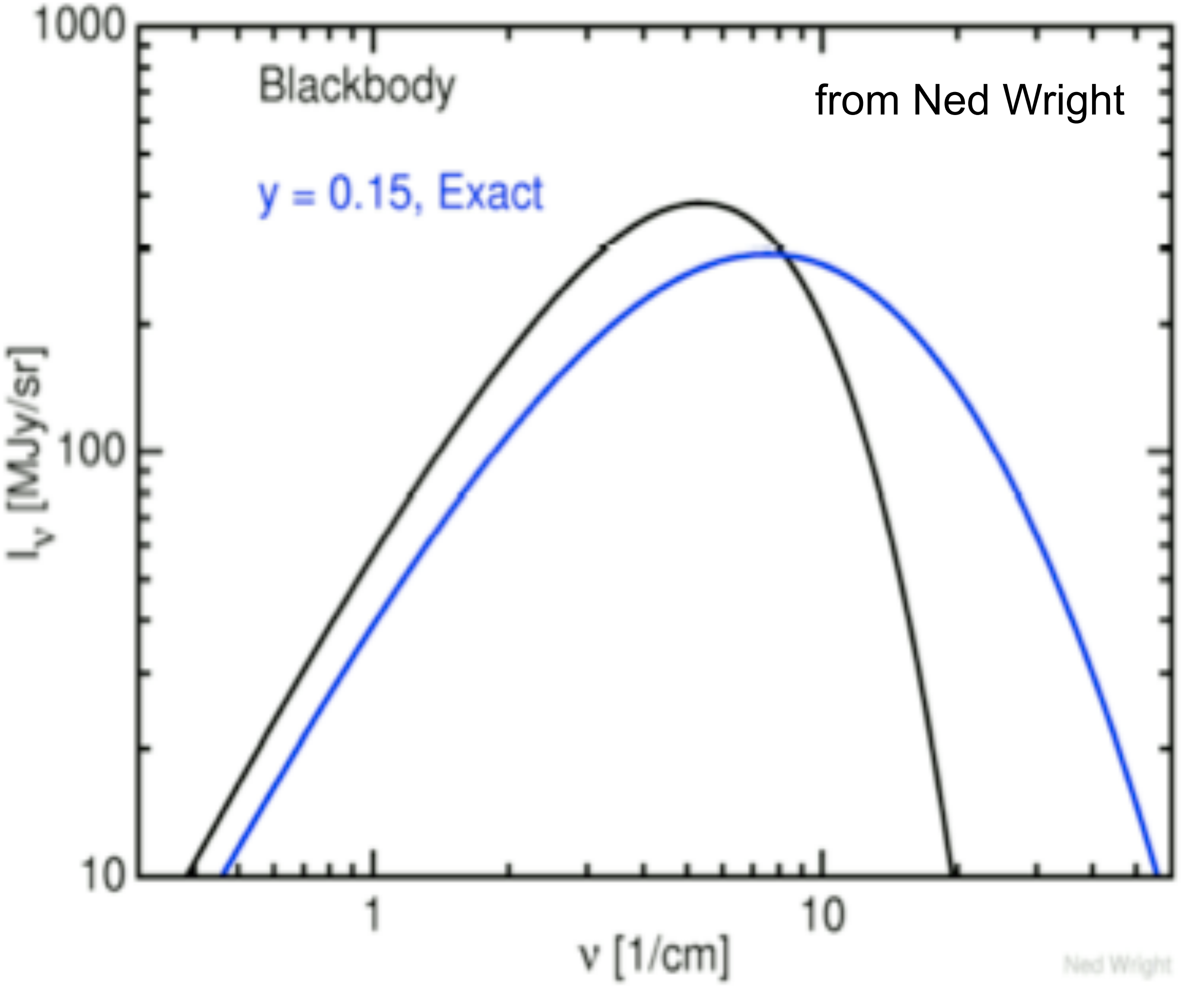
The tSZ Effect

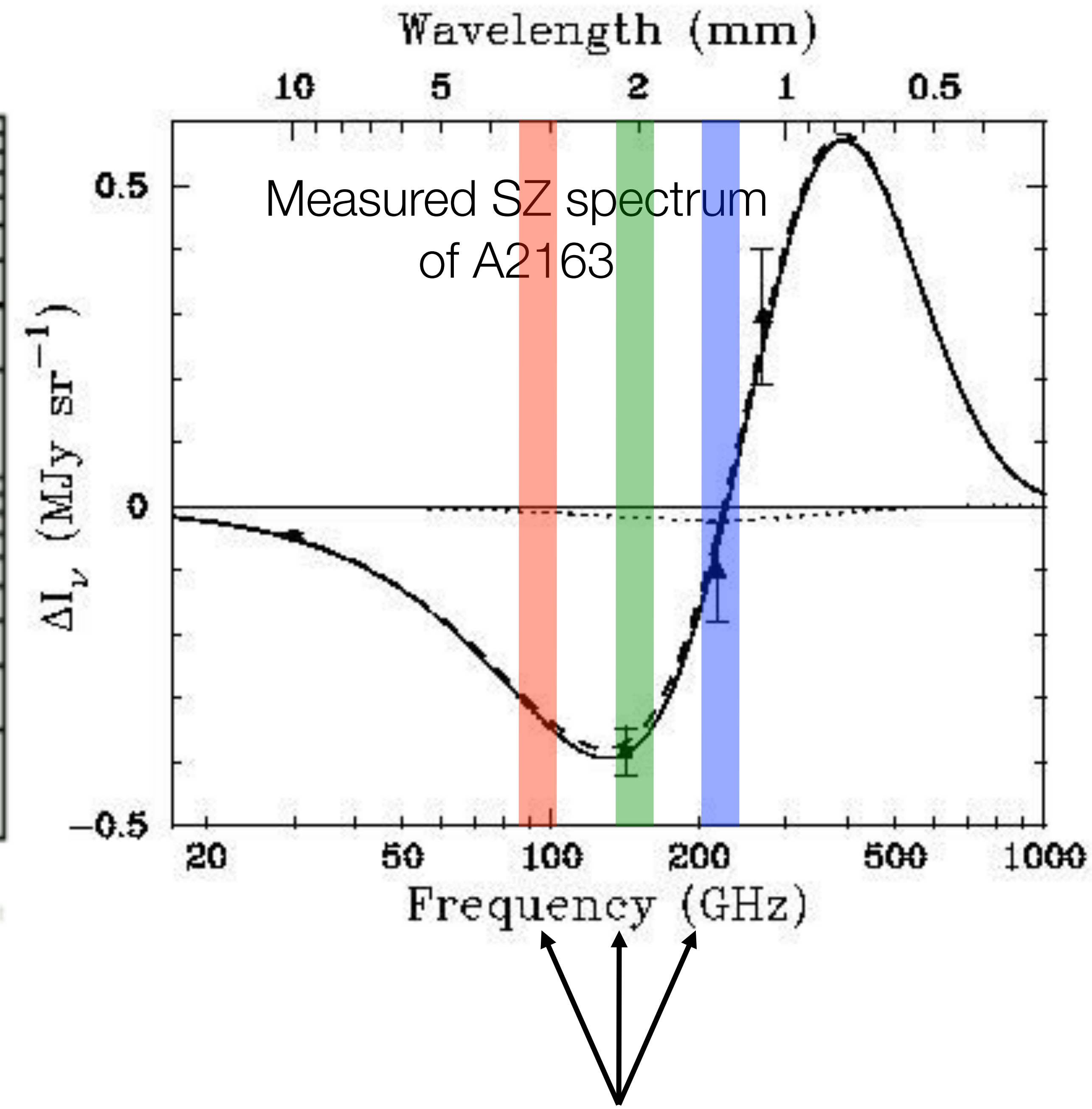


The kSZ Effect



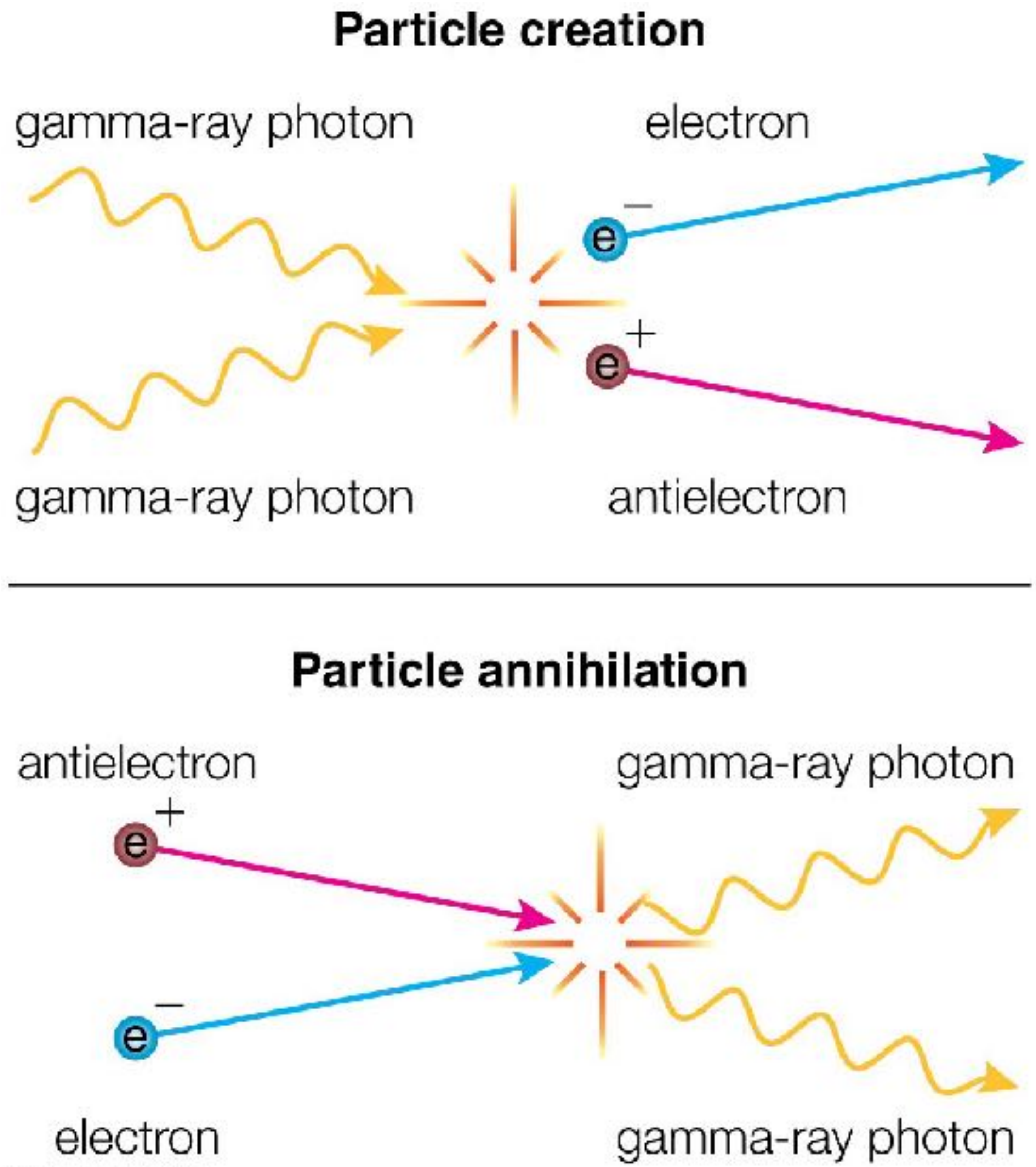
Sunyaev-Zel’dovich Effect

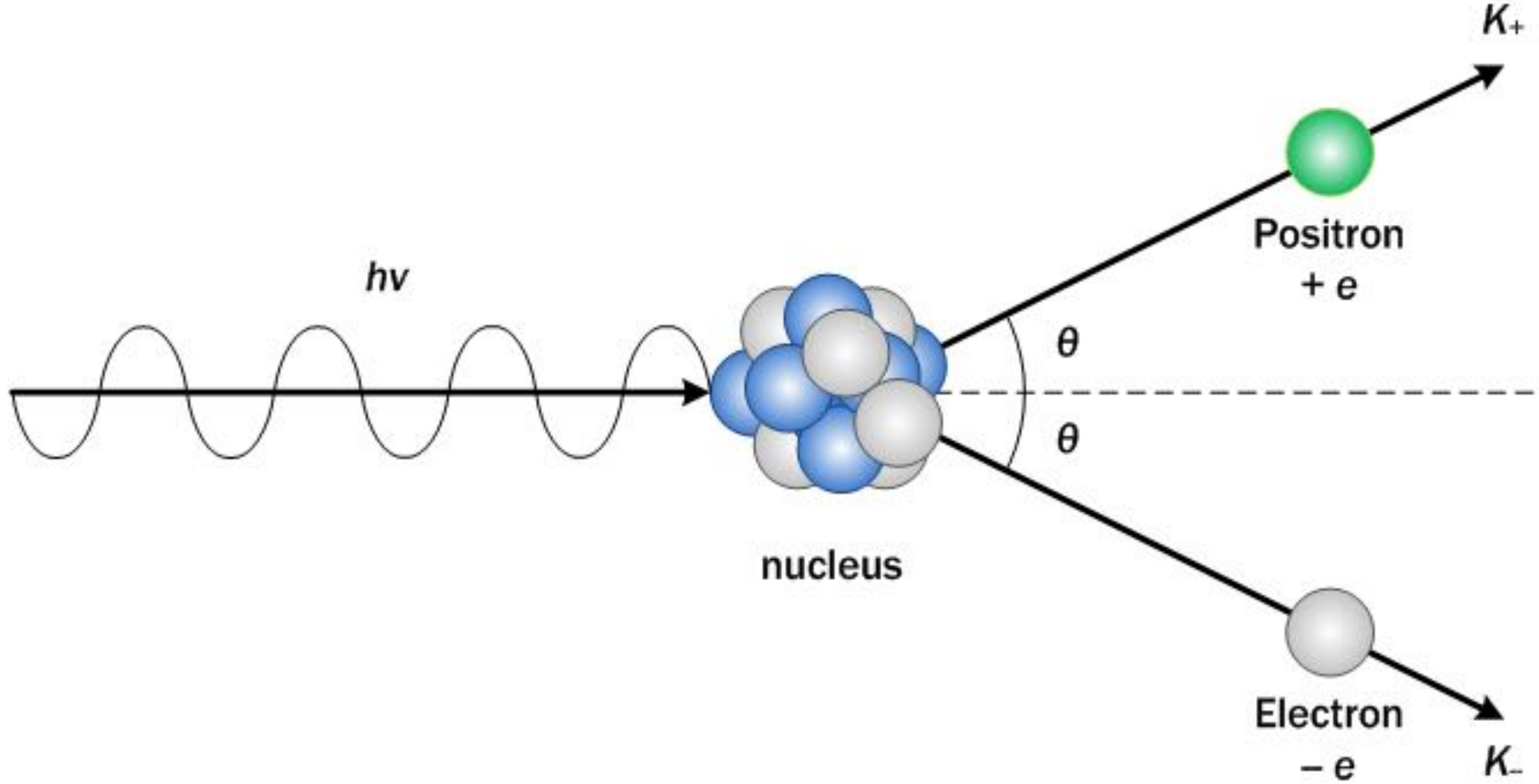




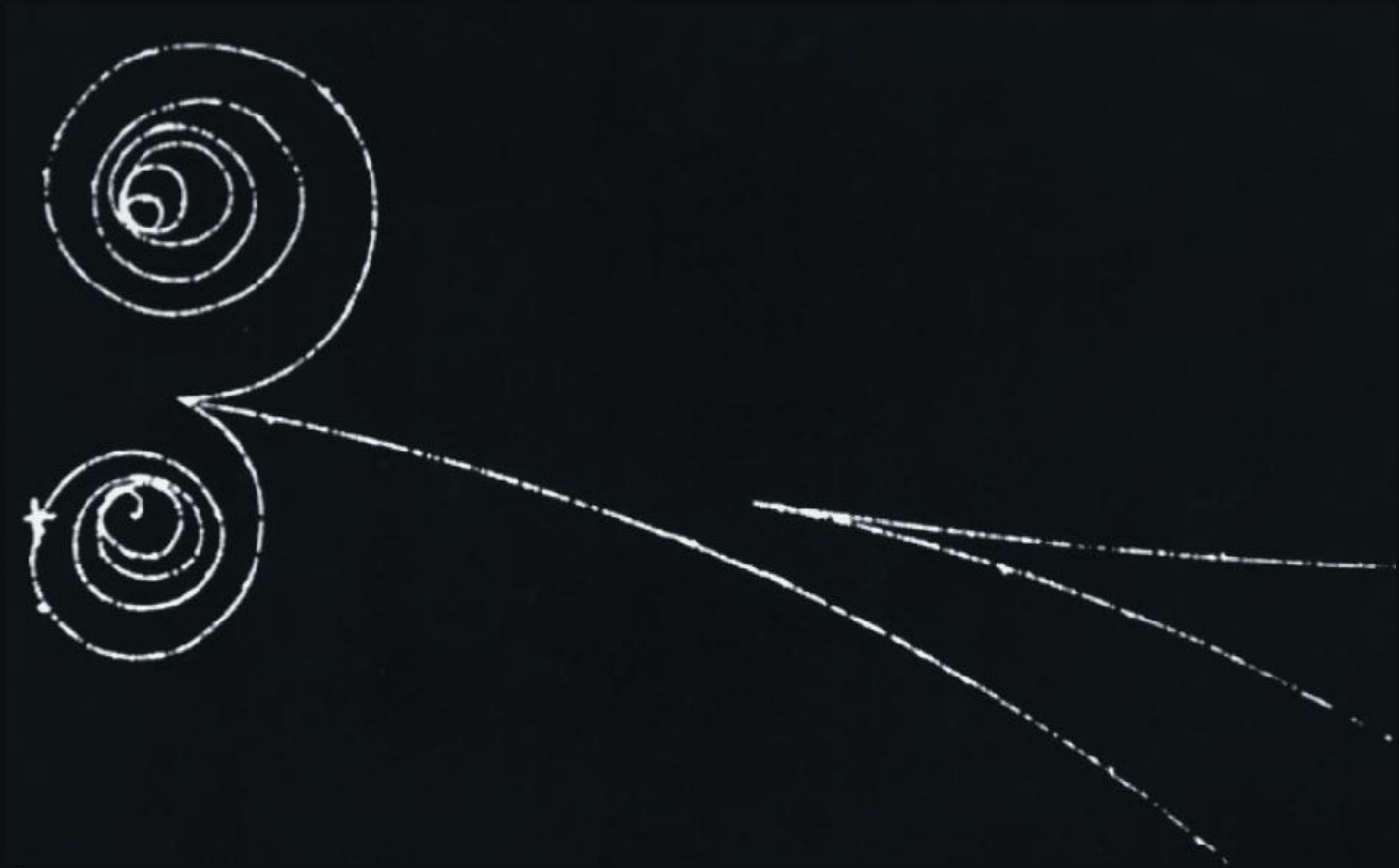
SPT Bands

Pair production

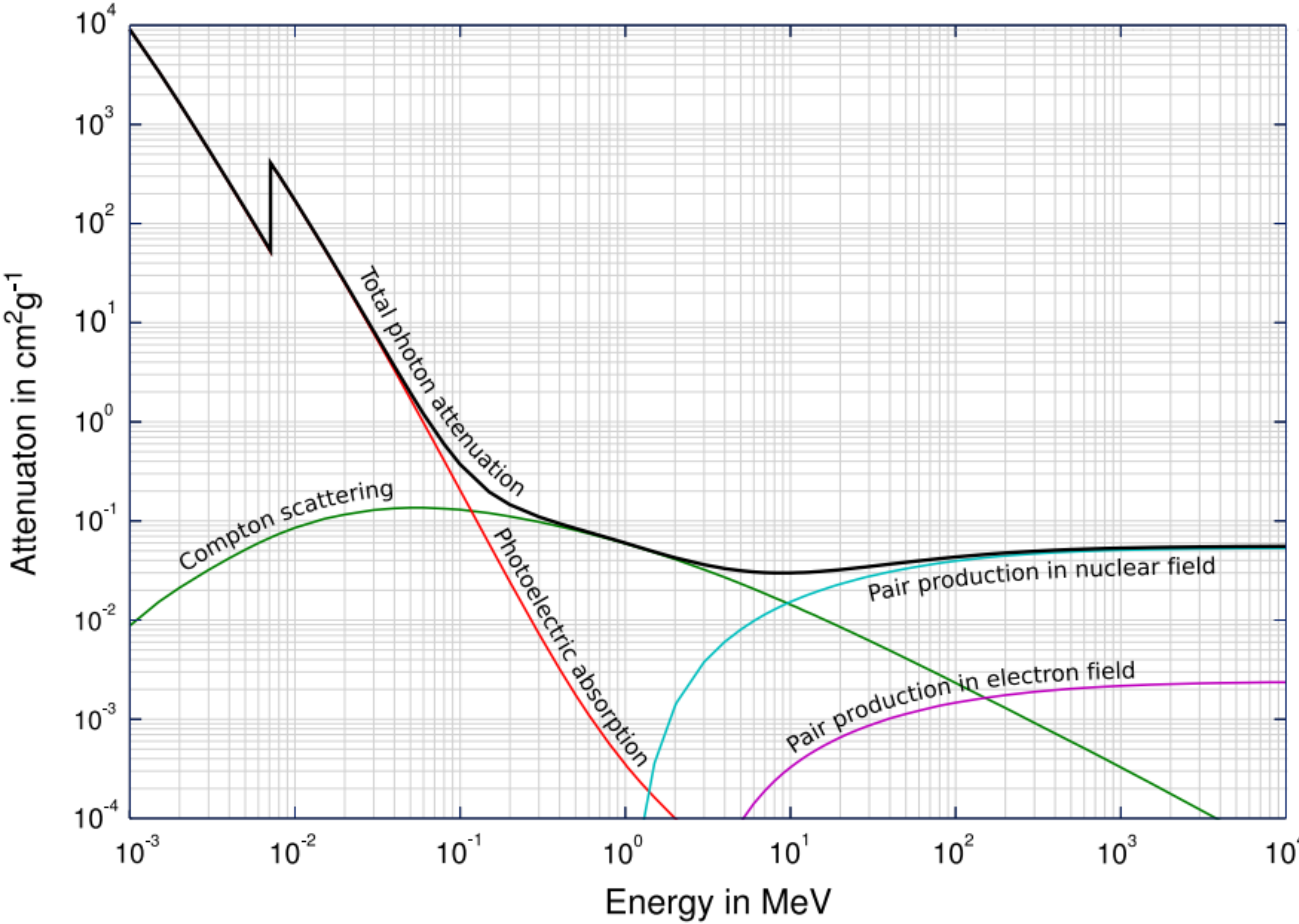




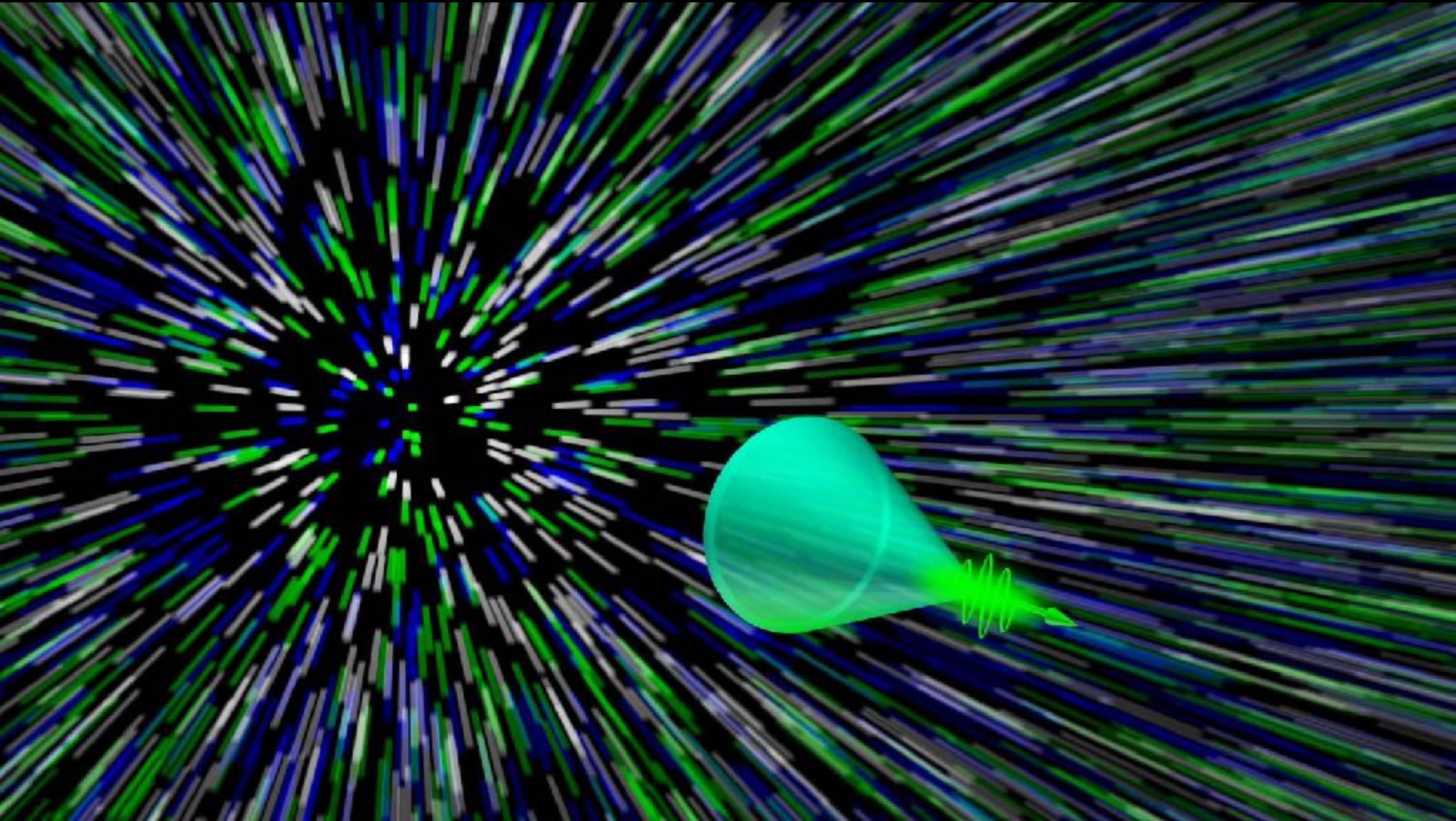
$h\nu$
nucleus
θ
θ
Positron
$+e$
K_+
Electron
$-e$
K_-

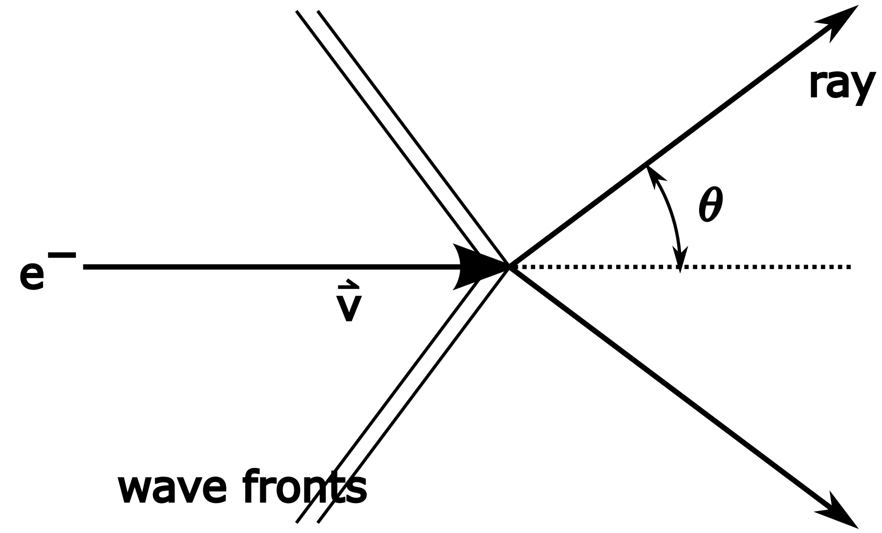


Gamma Ray Cross Sections



Cherenkov





Cerenkov light and Super Kamiokande

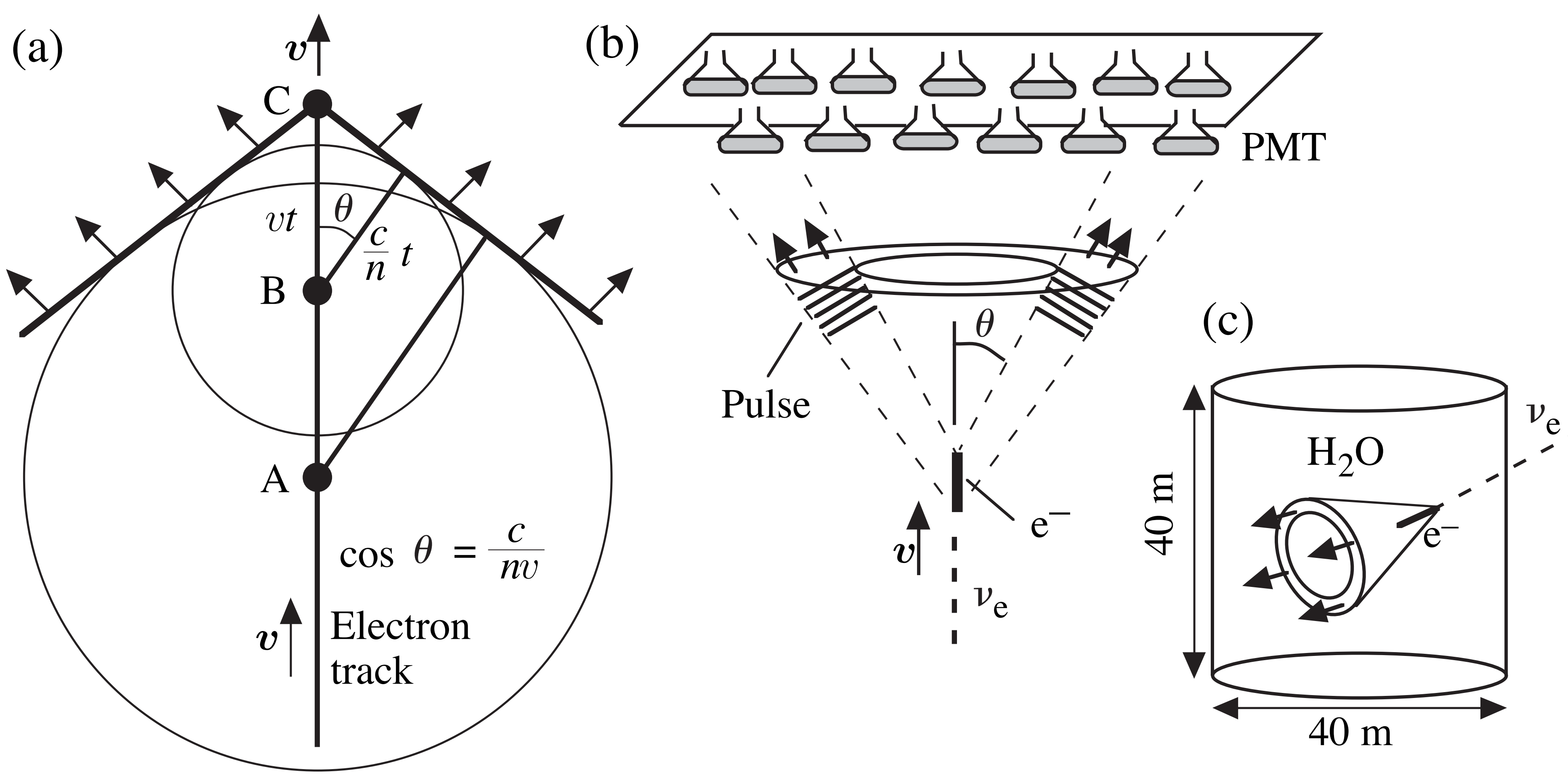
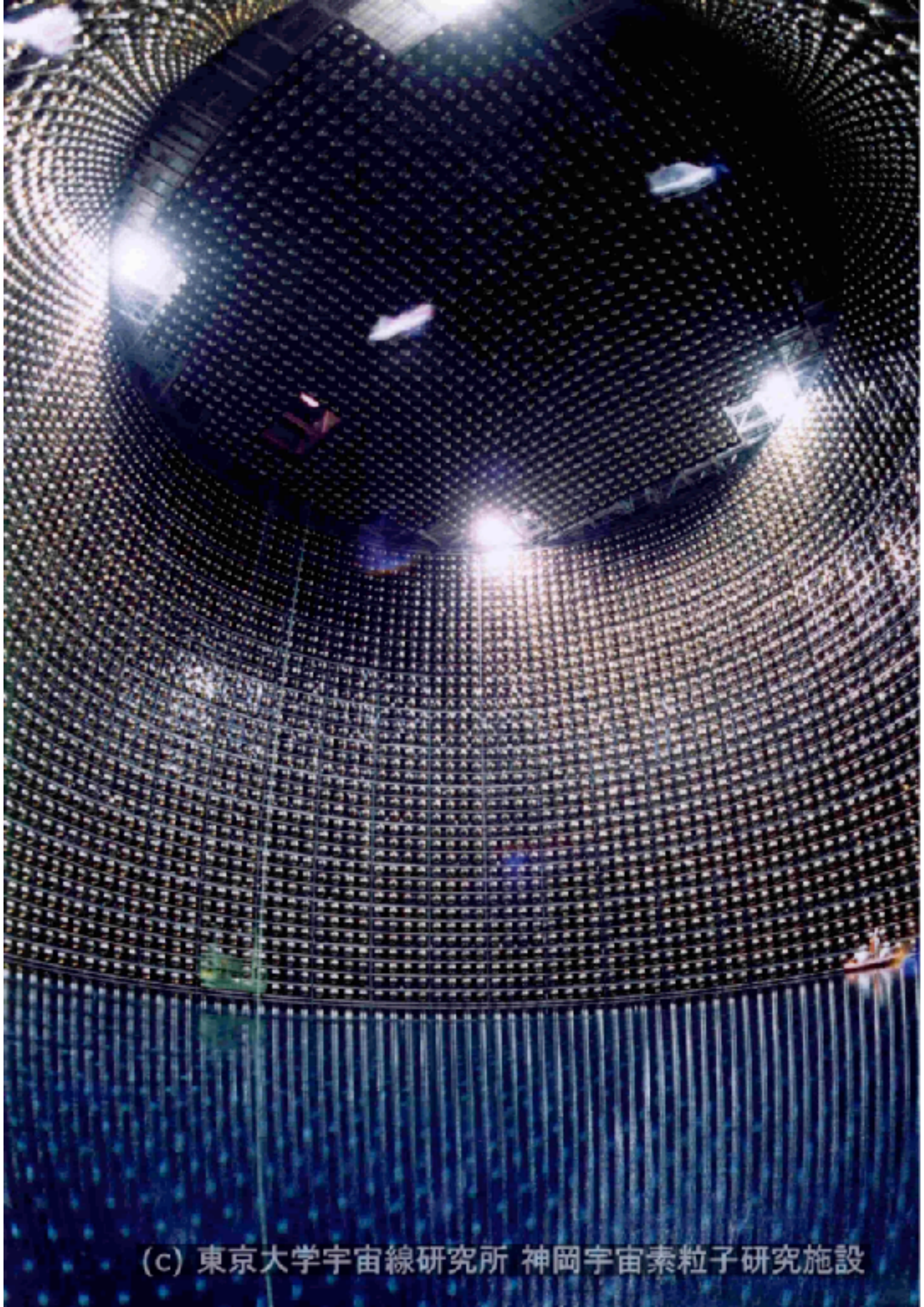


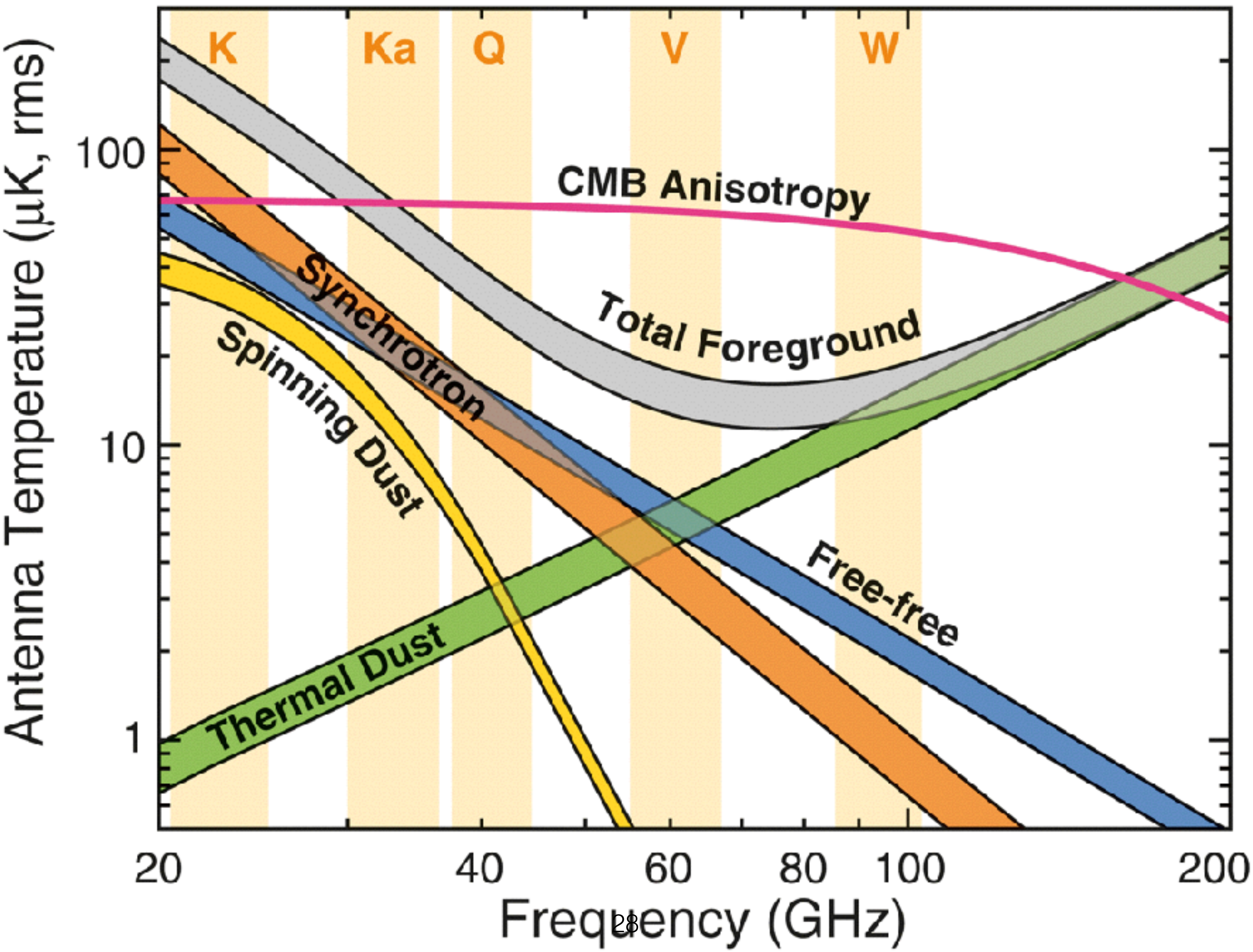
Fig. 12.2: Astronomy Methods (CUP), ©H. Bradt 2004


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

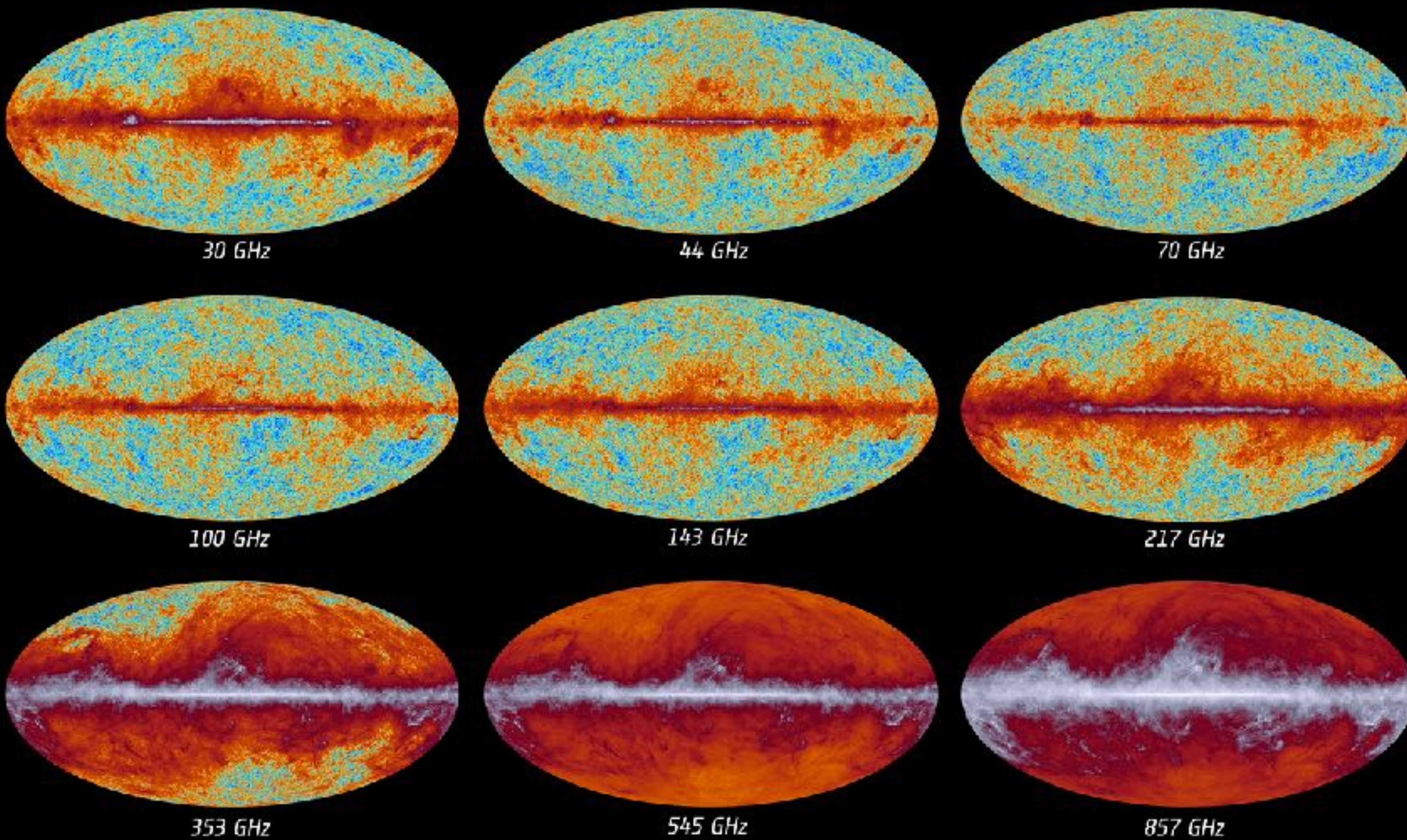
review of radiation processes:

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

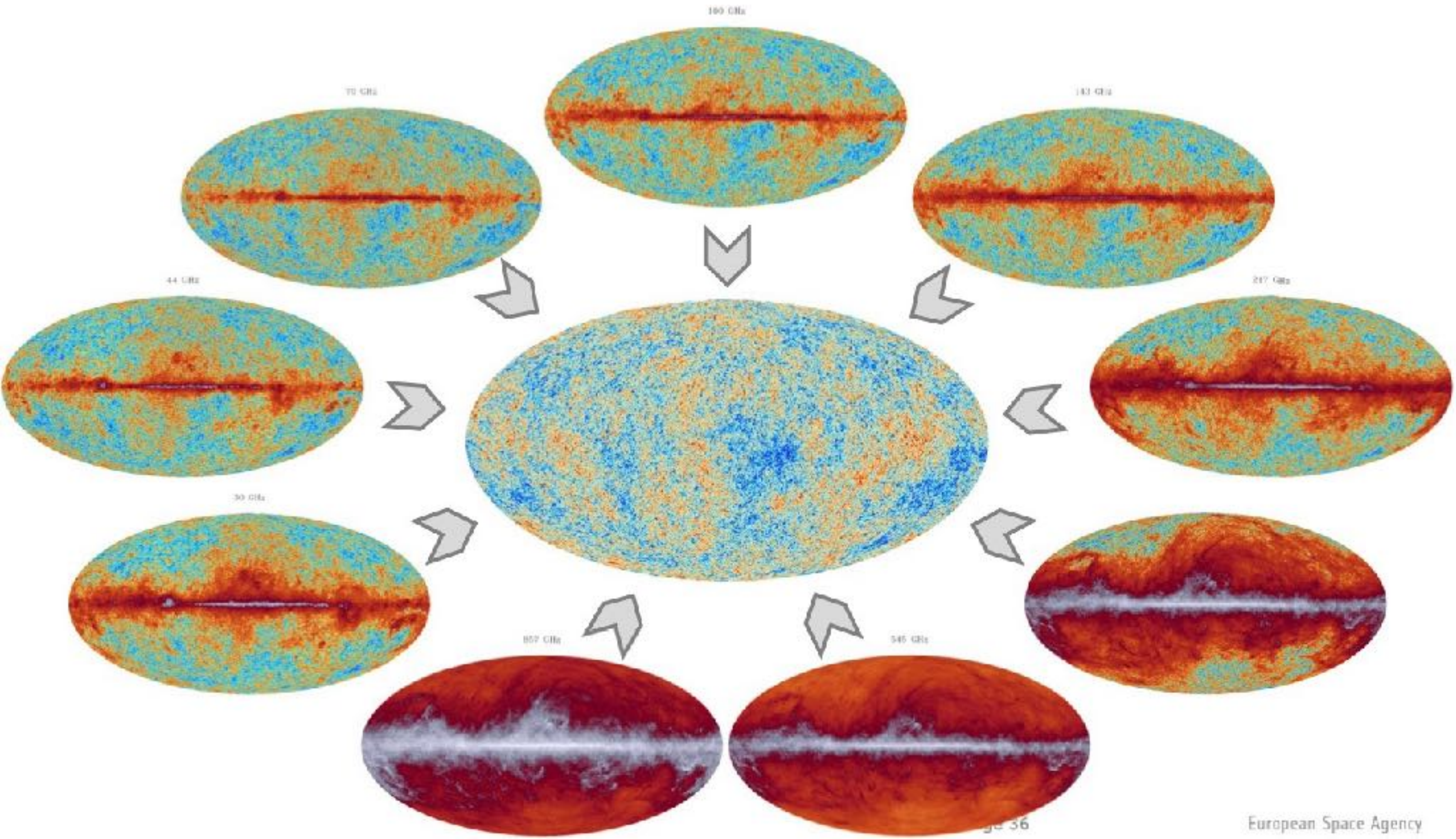
Galactic Foregrounds and CMB

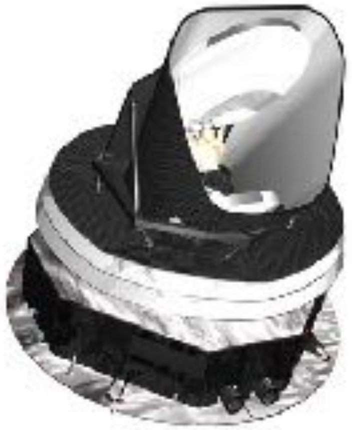


The sky as seen by Planck

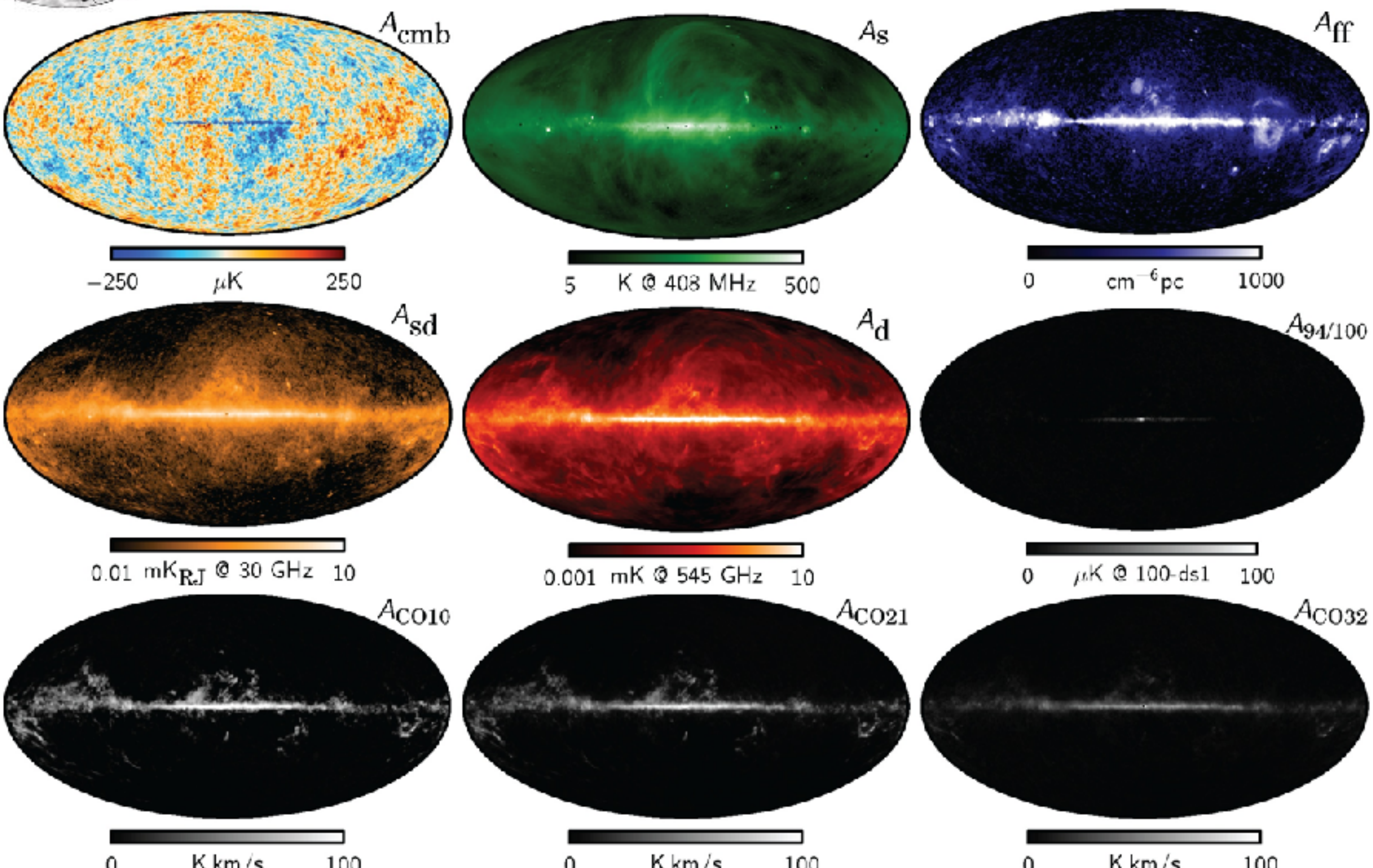


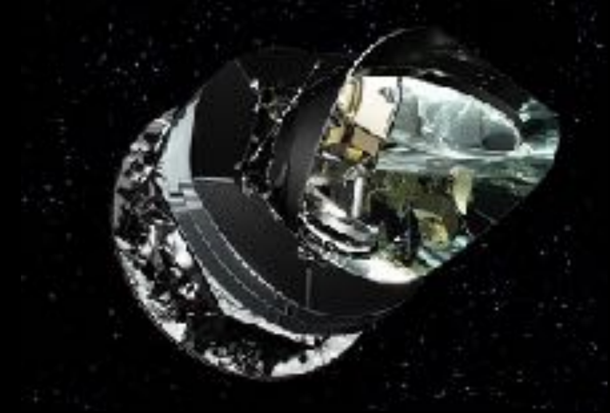
Foregrounds



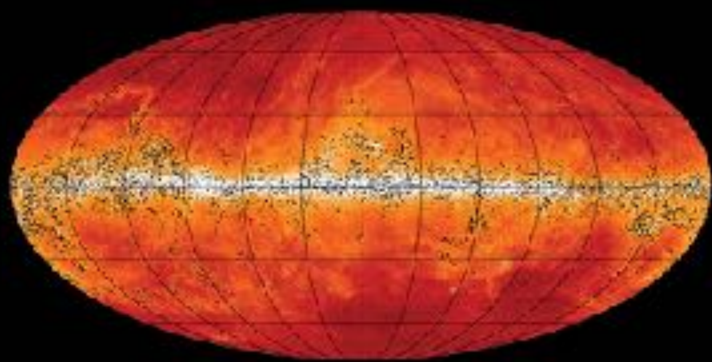


Components on the sky from *Planck*

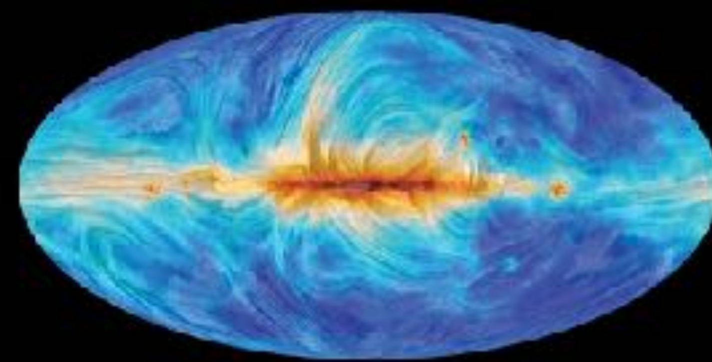




High level data products from *Planck*

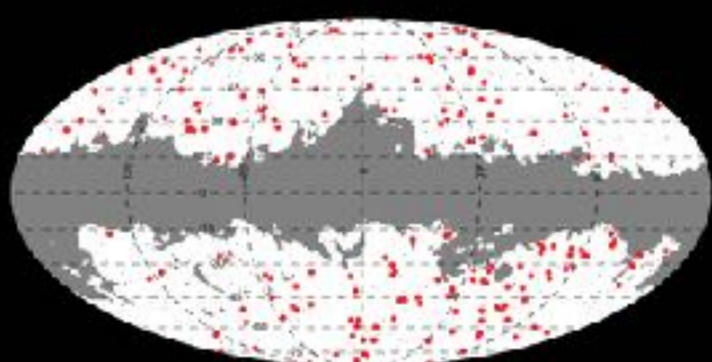


Galactic cold clumps

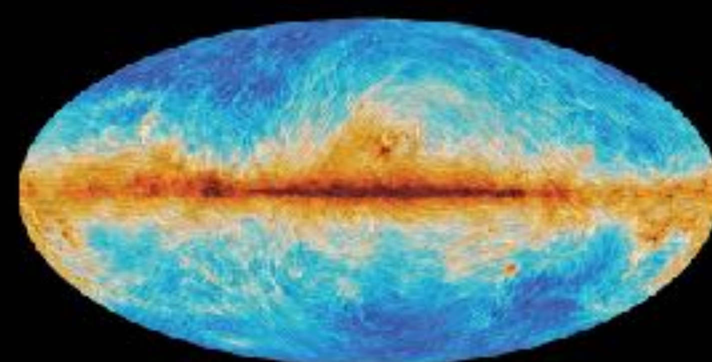


Magnetic field lines traced by synchrotron radiation at 30 GHz

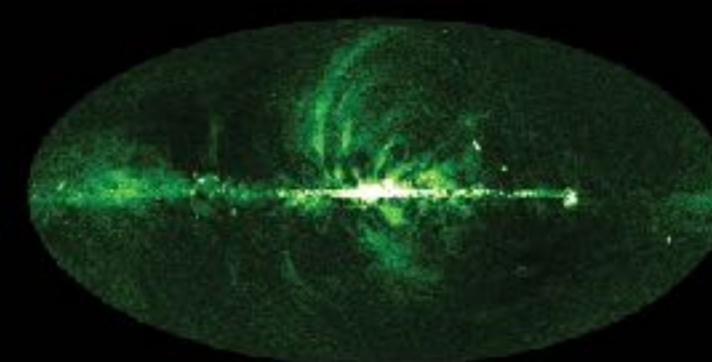
Polarised dust emission



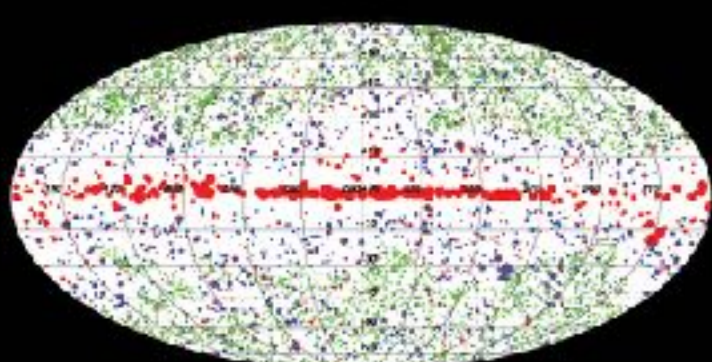
Galaxy clusters detected by the Sunyaev-Zeldovich effect



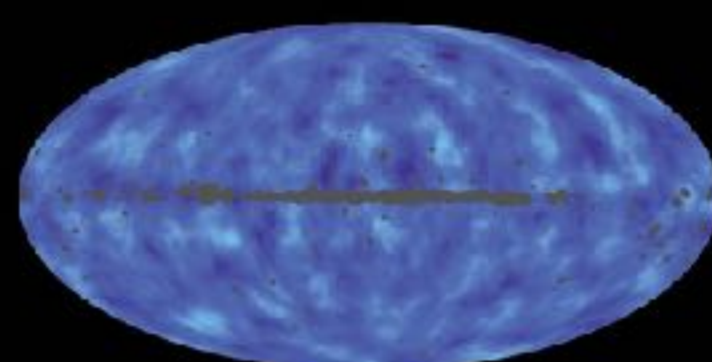
Magnetic field lines traced by dust emission at 353 GHz



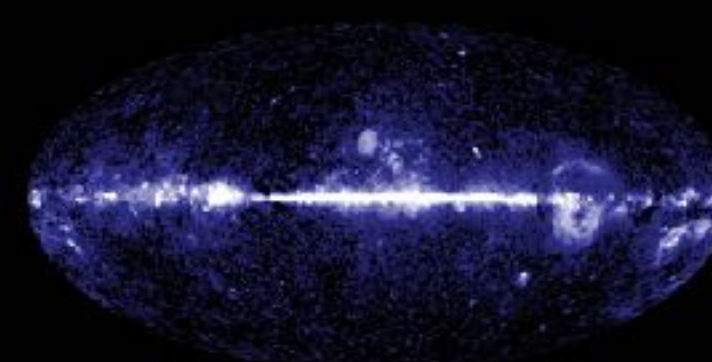
Polarised synchrotron emission



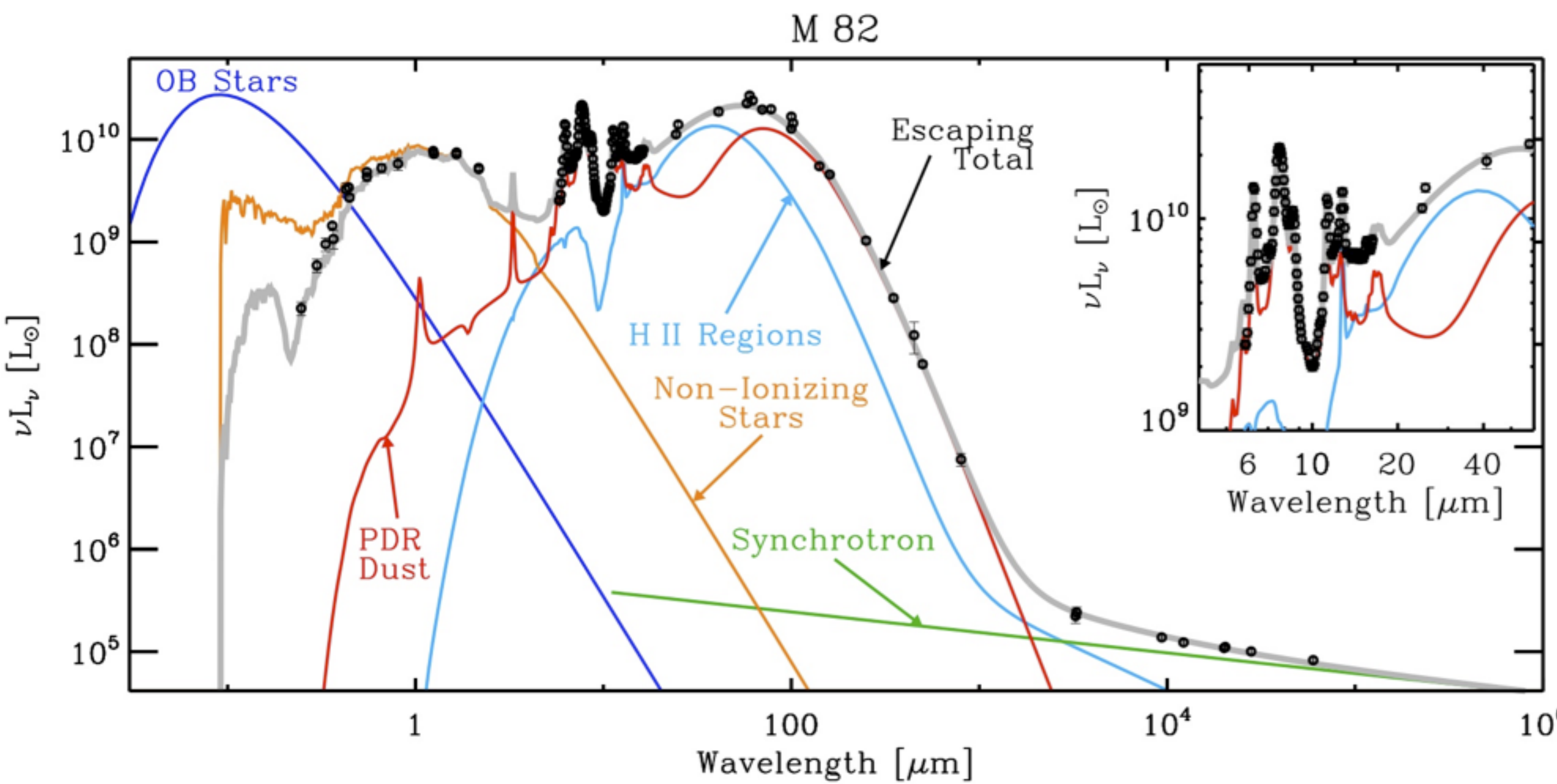
Compact sources



Gravitational-lensing potential — a tracer of dark matter structures



Line radiation from carbon monoxide gas

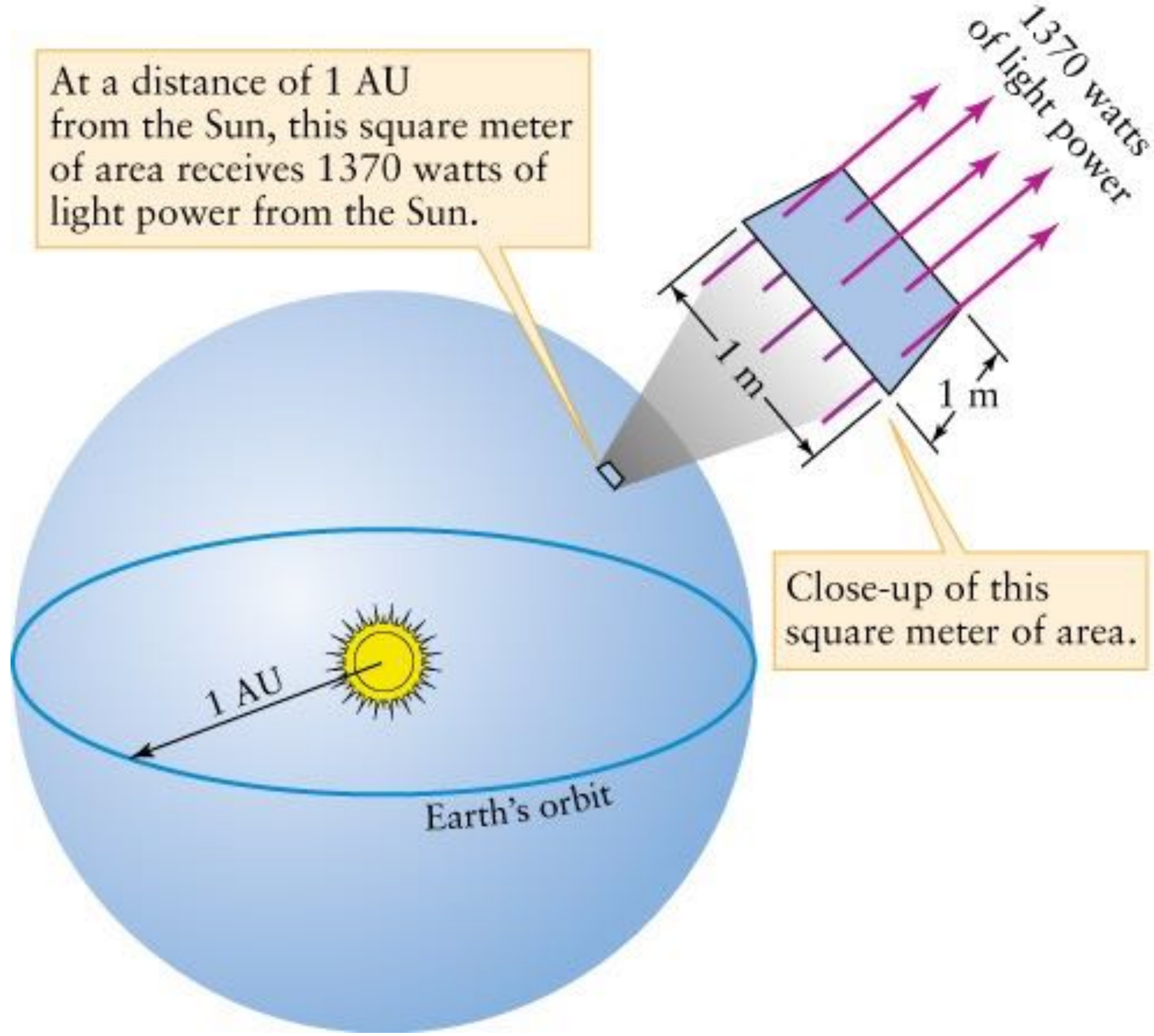


Galliano, Dwek & Chanial 2008

Flux and Luminosity

- **Flux** = the amount of power falling within a given area [W/m^2]

- **Luminosity** = the brightness of an object (like wattage of a lightbulb) [W]



Luminosity (L)

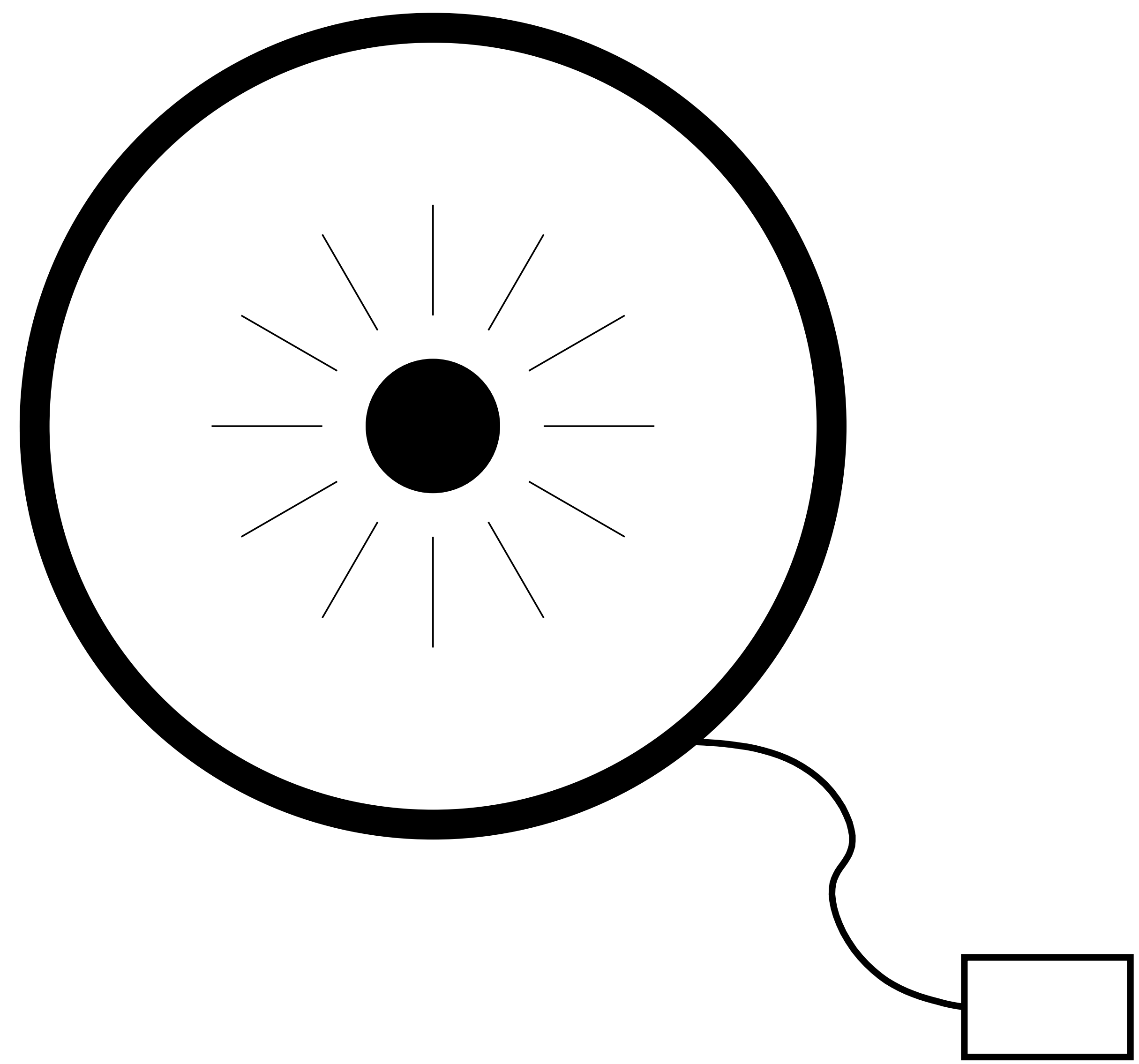
- A source's luminosity is the **power** that it emits in radiation.
- SI units are W.
- Also used are erg $s^{-1} \equiv 10^{-7}$ W

- 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 ~1 W

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



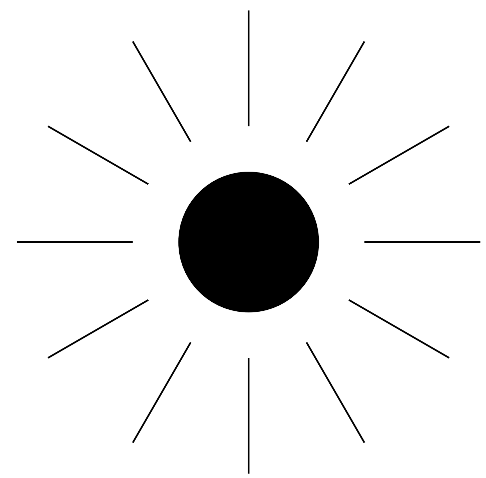
$$E = \int L \, dt$$

Flux (ϕ)

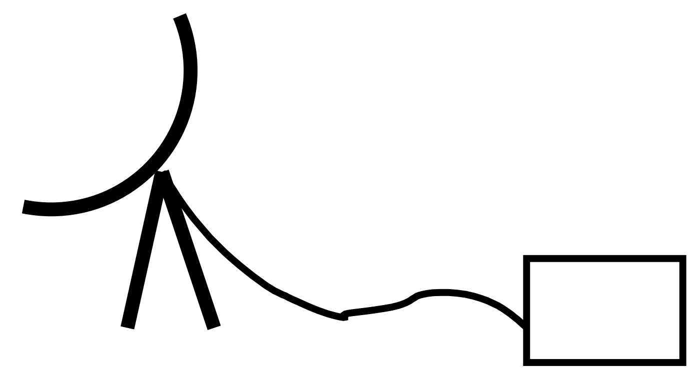
- The flux of a source is the power received **per unit area**.

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

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



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



$$E = \iint \phi \, \mathrm{d}t \, \mathrm{d}A$$

Flux Density (F_ν)

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

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

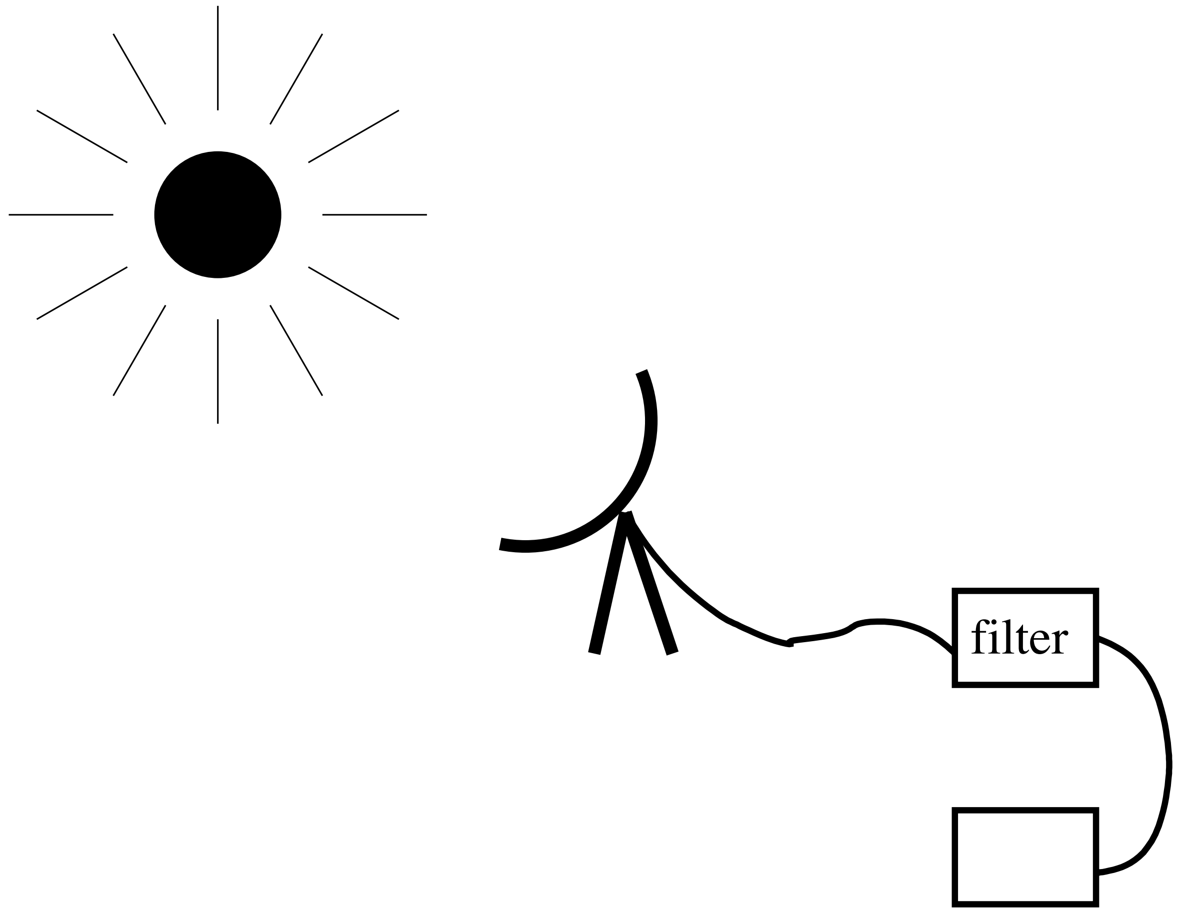
$\Delta\nu = \nu_2 - \nu_1$ is the bandwidth

- Also called specific flux - 'specific' refers to Hz^{-1}.

- NB Astronomers often say 'flux' when they mean 'flux density'

- SI units are $\mathrm{W m^{-2} Hz^{-1}}$

- Also used are $\mathrm{Jy} \equiv 10^{-26}\ \mathrm{W m^{-2} Hz^{-1}}$



$$E = \iiint F_\nu \, \mathrm{d}\nu \, \mathrm{d}A \, \mathrm{d}t$$

(units for a point source)

Specific Intensity, Surface Brightness (I_ν)

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

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

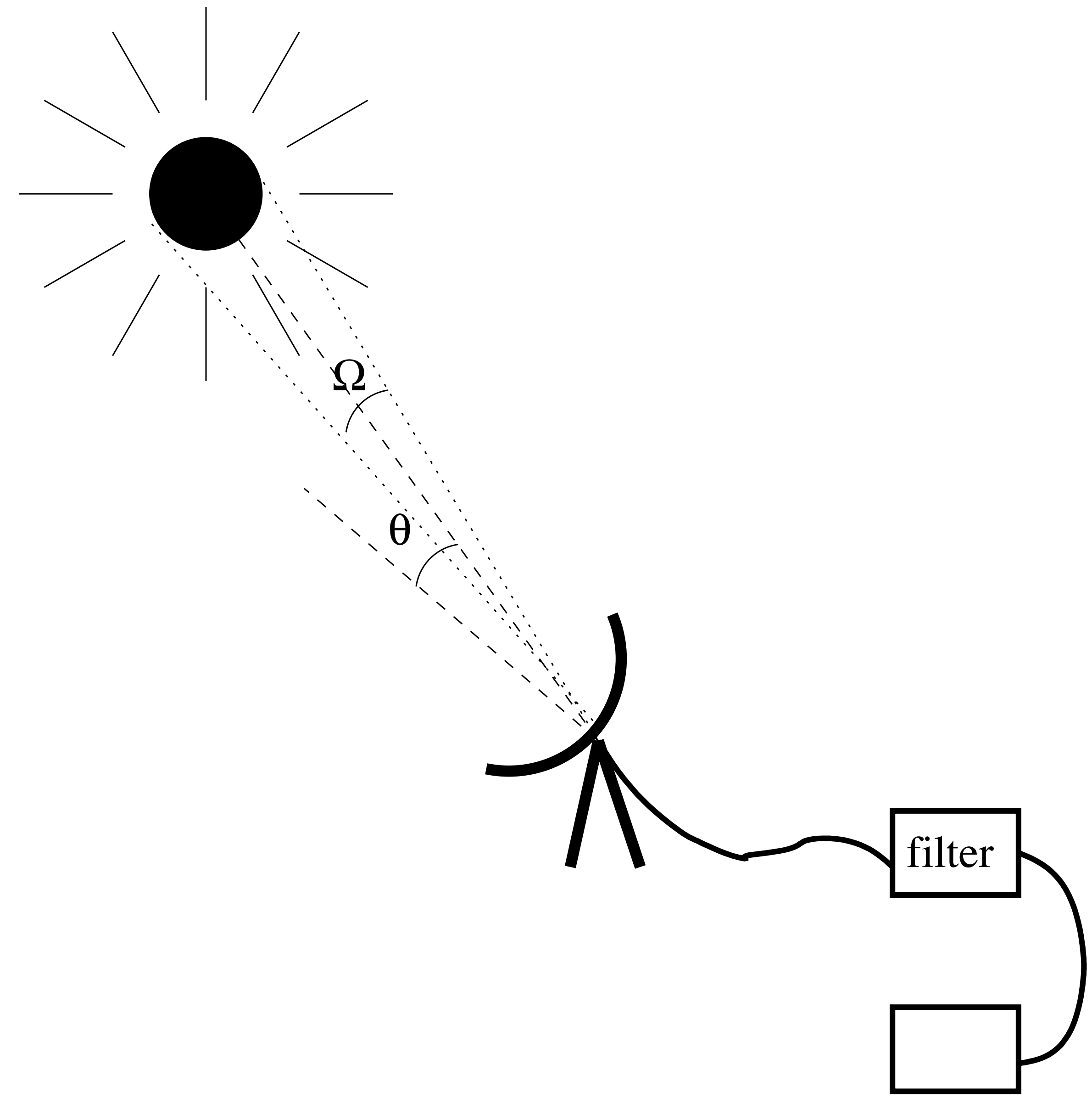
$\Rightarrow F_\nu$ at surface of a spherical source $= \pi I_\nu$

- Specific intensity is independent of distance.
- Also define the mean intensity J_ν

$$J_\nu = \tfrac{1}{4\pi} \int_{4\pi} I_\nu \mathrm{d}\Omega$$

- An *isotropic* radiation field is one where I_ν is independent of angle, so $J_\nu = I_\nu$.

- Units are $\mathrm{Wm^{-2}Hz^{-1}sr^{-1}}$



(units for a diffuse source)

$$E = \int\iiint I_\nu \cos\theta \, \mathrm{d}\nu \, \mathrm{d}\Omega \, \mathrm{d}A \, \mathrm{d}t$$

Calculating F_ν and I_ν for a blackbody

- The specific intensity of a black-body is given by the Planck function, B_ν

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

A derivation of B_ν is given in the appendix.

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

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

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_ν (source) = 3.02 x 10^{-17} $\mathrm{Wm^{-2}Hz^{-1}sr^{-1}}$. (We are in the Rayleigh-Jeans region)

F_ν (source) = I_ν (source) x $\Omega_{(source)}$ = 2.2 x 10^{-27} $\mathrm{Wm^{-2}Hz^{-1}}$ = 0.22 Jy.

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

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)

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

units of watts per square meter per Hz

Calculating F_ν and I_ν for a blackbody

- The specific intensity of a black-body is given by the Planck function, B_ν

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

A derivation of B_ν 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_ν (source) = 3.02×10^{-17} $Wm^{-2}Hz^{-1}sr^{-1}$. (We are in the Rayleigh-Jeans region)

F_ν (source) = I_ν (source) x $\Omega_{(source)}$ = 2.2×10^{-27} $Wm^{-2}Hz^{-1}$ = 0.22 Jy.

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

Determining Ω

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

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

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 $F_\nu = I_\nu \, \Omega_{(source)}$ (as in the previous example).
- Another simple case is if the source has constant specific intensity inside the beam; the integration then gives $I_\nu \, \Omega_{(beam)}$ where $\Omega_{(beam)}$ is the effective beam solid angle. The effective beam solid angle for a Gaussian beam of FWHM θ_{FWHM} is $\Omega_{(beam)} = \theta^2_{FWHM} \frac{\pi}{4\ln 2}$

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

I_ν (CMB) = 3.02 x 10^{-20} $Wm^{-2}Hz^{-1}sr^{-1}$. (We are in the Rayleigh-Jeans region)

F_ν(CMB) = I_ν (CMB) x $\Omega_{(beam)}$ = 2.9 x 10^{-27} $Wm^{-2}Hz^{-1}$ = 0.29 Jy.

($\Omega_{(beam)}$ = (1/60 x π/180)^2 x 1.13)

Summary of Key Points

- Flux density, F_ν, is power per unit area per unit *frequency*, measured in $\mathrm{Jy} \equiv 10^{-26}\mathrm{Wm}^{-2}\mathrm{Hz}^{-1}$

- Specific intensity, I_ν 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 Ω is often either $\Omega_{(\mathrm{source})}$ or $\Omega_{(\mathrm{beam})}$ 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

$$F_\lambda = F_\nu \cdot \frac{\nu^2}{c} \tag{6}$$

for $\lambda = c/\nu$.

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

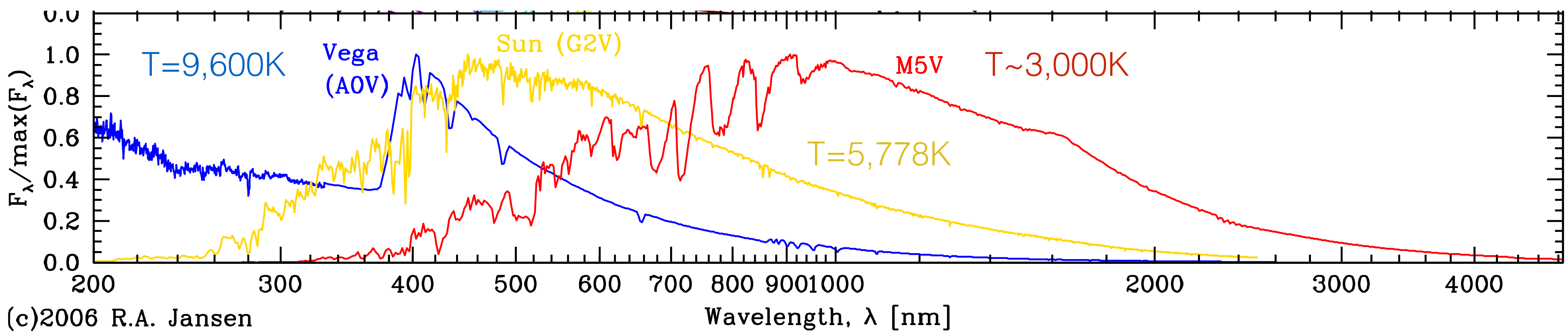
Definitions

- 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	$6x10^{10}$	
full Moon	-13	$1.6x10^{5}$	
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	$4x10^{-3}$	limit of human eye
Neptune	8	$6x10^{-4}$	
	10	$1x10^{-4}$	binoculars
quasar	13	$6x10^{-6}$	6" telescope
	27	$1.6x10^{-11}$	8m-class telescope
	32	$1.6x10^{-13}$	HST

Absolute Magnitudes

- There is also a magnitude system that is "absolute" and calibrated to Janskys. This is $\mathbf{m_{AB}}$
- 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.

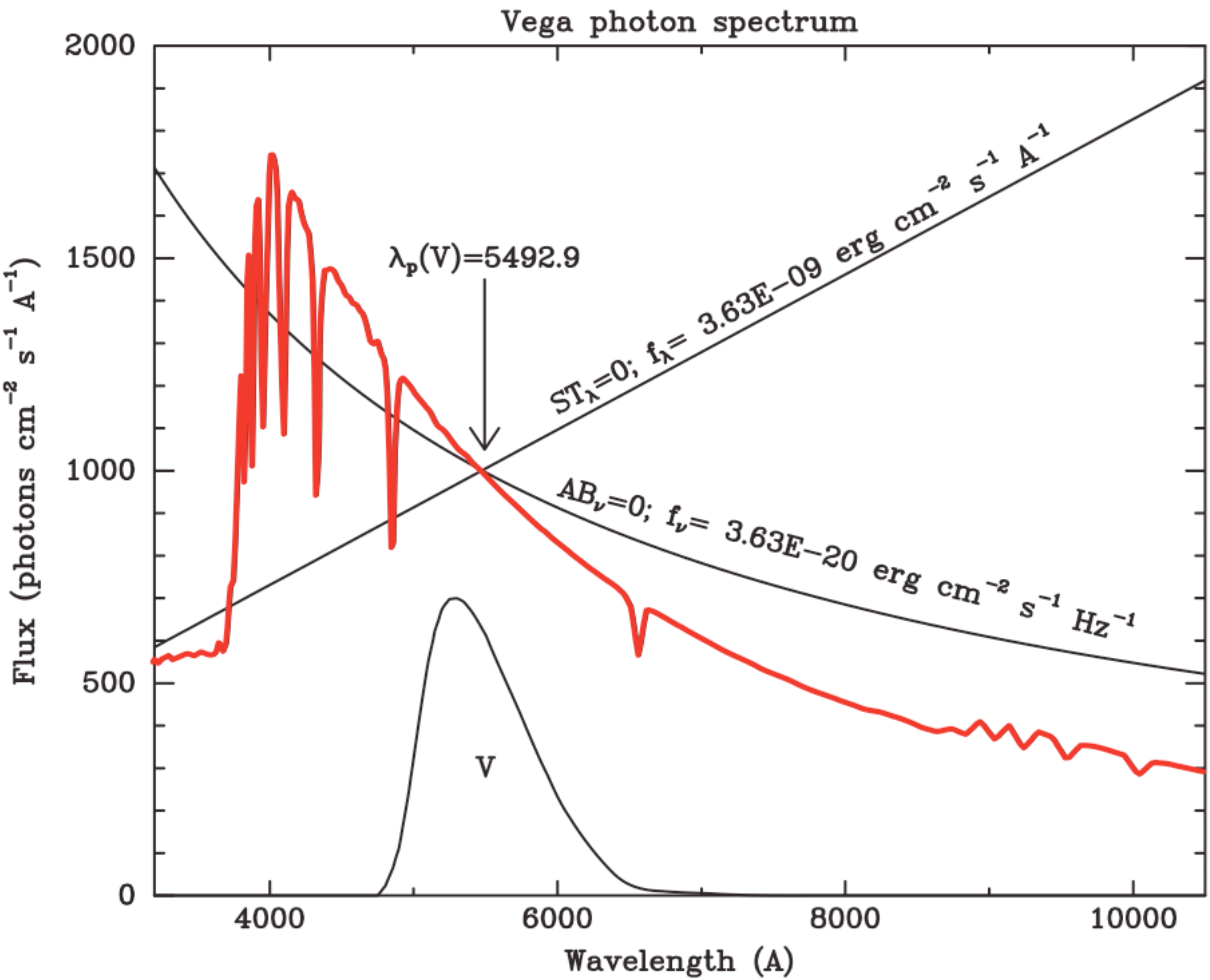
$$g = g(AB) + 0.013$$
$$r = r(AB) + 0.226$$
$$i = i(AB) + 0.296$$

- To convert m_{AB} to fluxes, use these:

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

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

$$S_\nu[mJy] = 10^{(16.4-m_{\mathrm{AB}})/2.5}$$



Vega photon spectrum
2000
1500
1000
500
0
Flux (photons cm^{-2} s^{-1} A^{-1})
4000
6000
8000
10000
Wavelength (A)
λ_p(V)=5492.9
ST_λ=0; f_λ= 3.63E−09 erg cm^{-2} s^{-1} A^{-1}
AB_ν=0; f_ν= 3.63E−20 erg cm^{-2} s^{-1} Hz^{-1}
V

Distance

- Historically, the most difficult parameter to measure in Astronomy

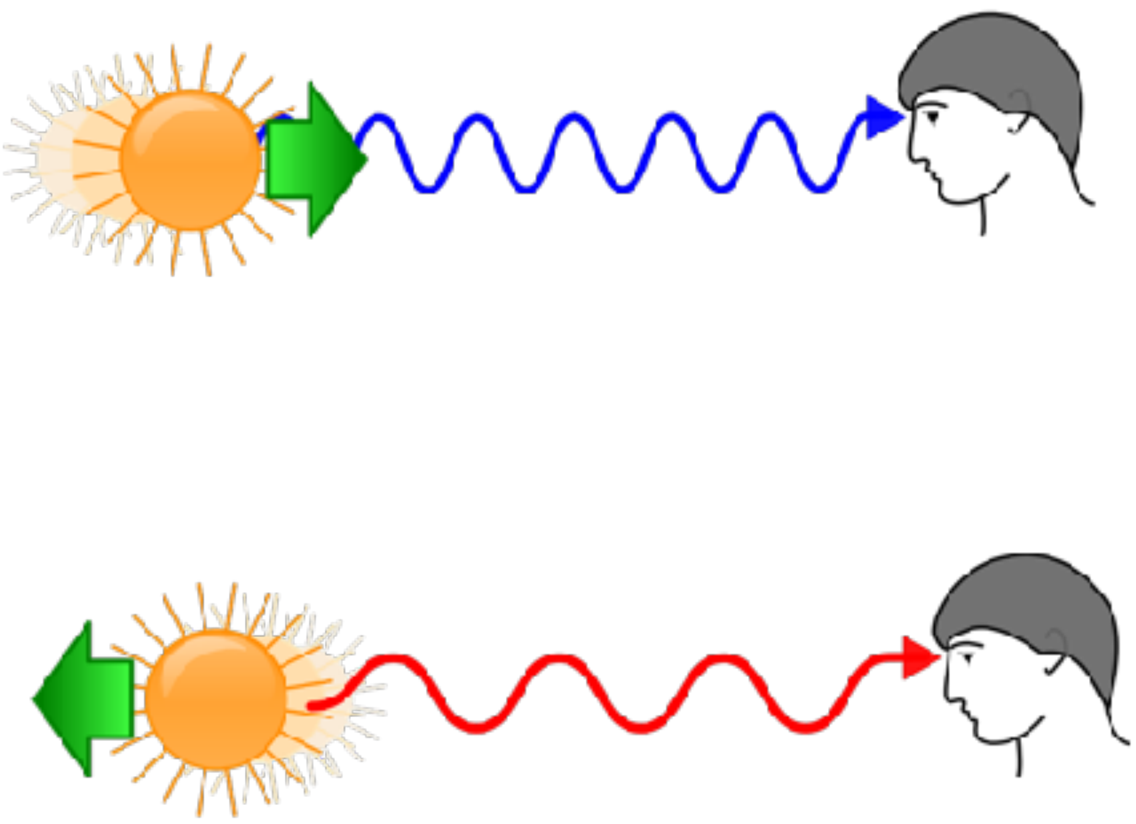
- apparent magnitude, m = how bright it appears

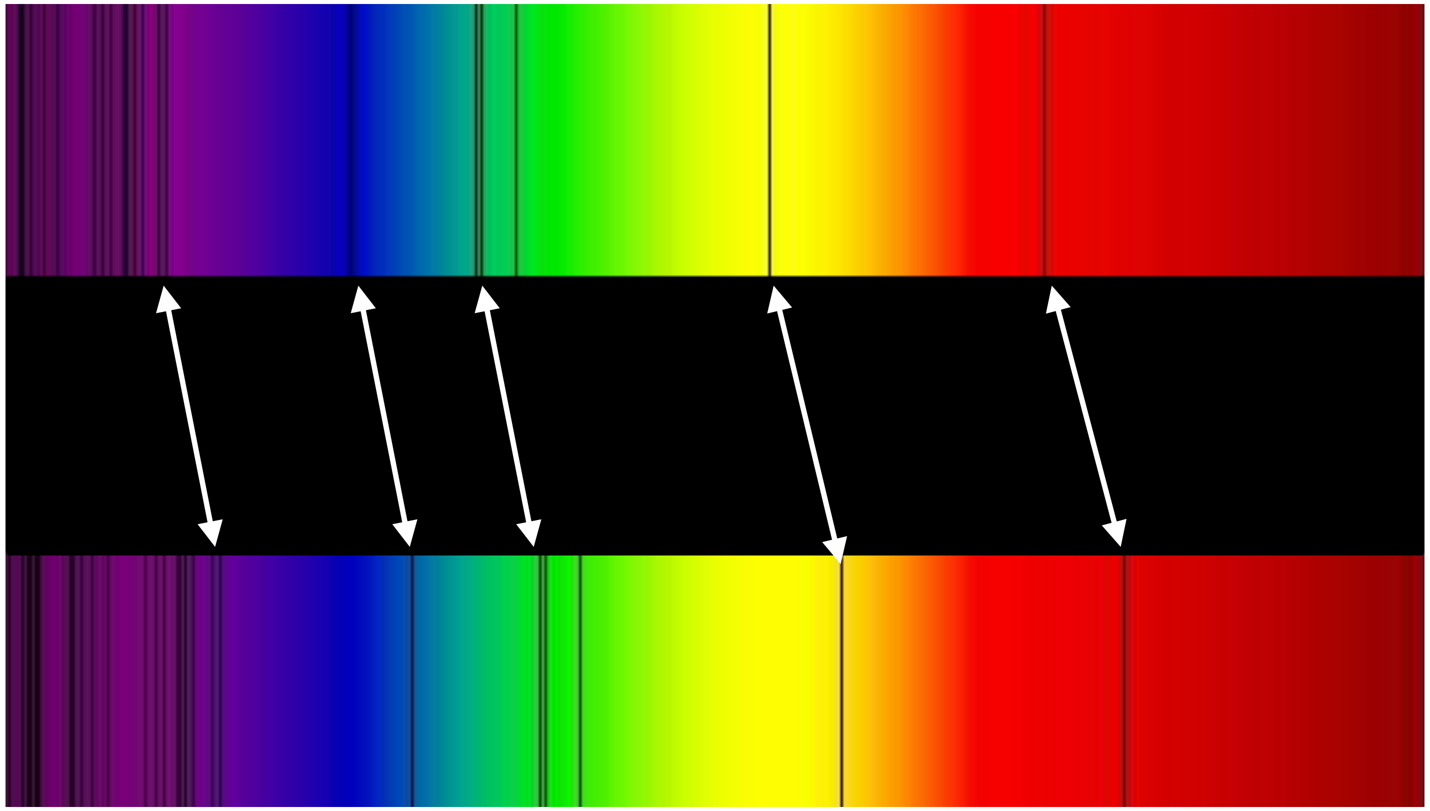
- absolute magnitude, M = how bright it would be at 10 pc, 32.6 ly

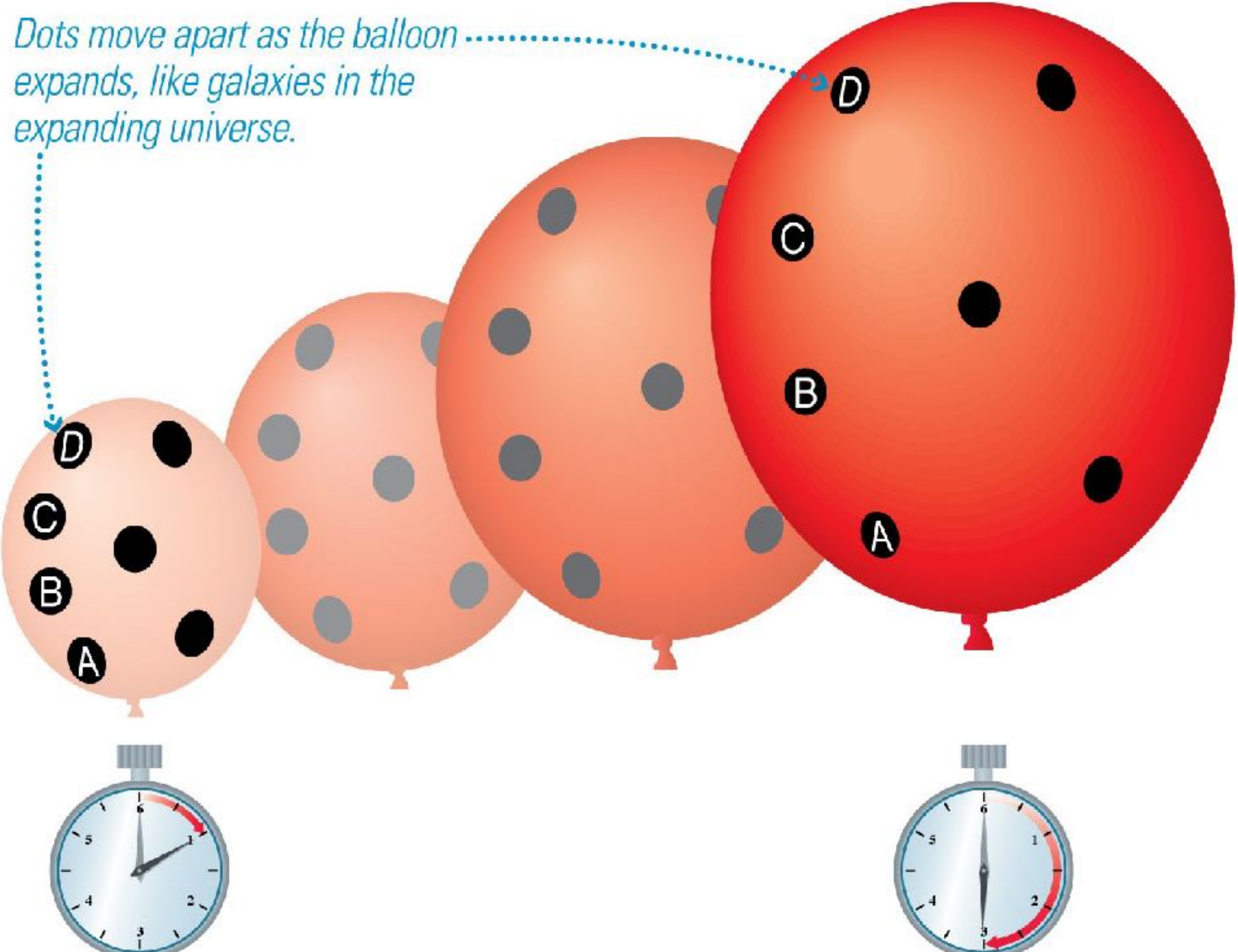
- distance modulus: $m - M = 5(\log_{10}d - 1)$

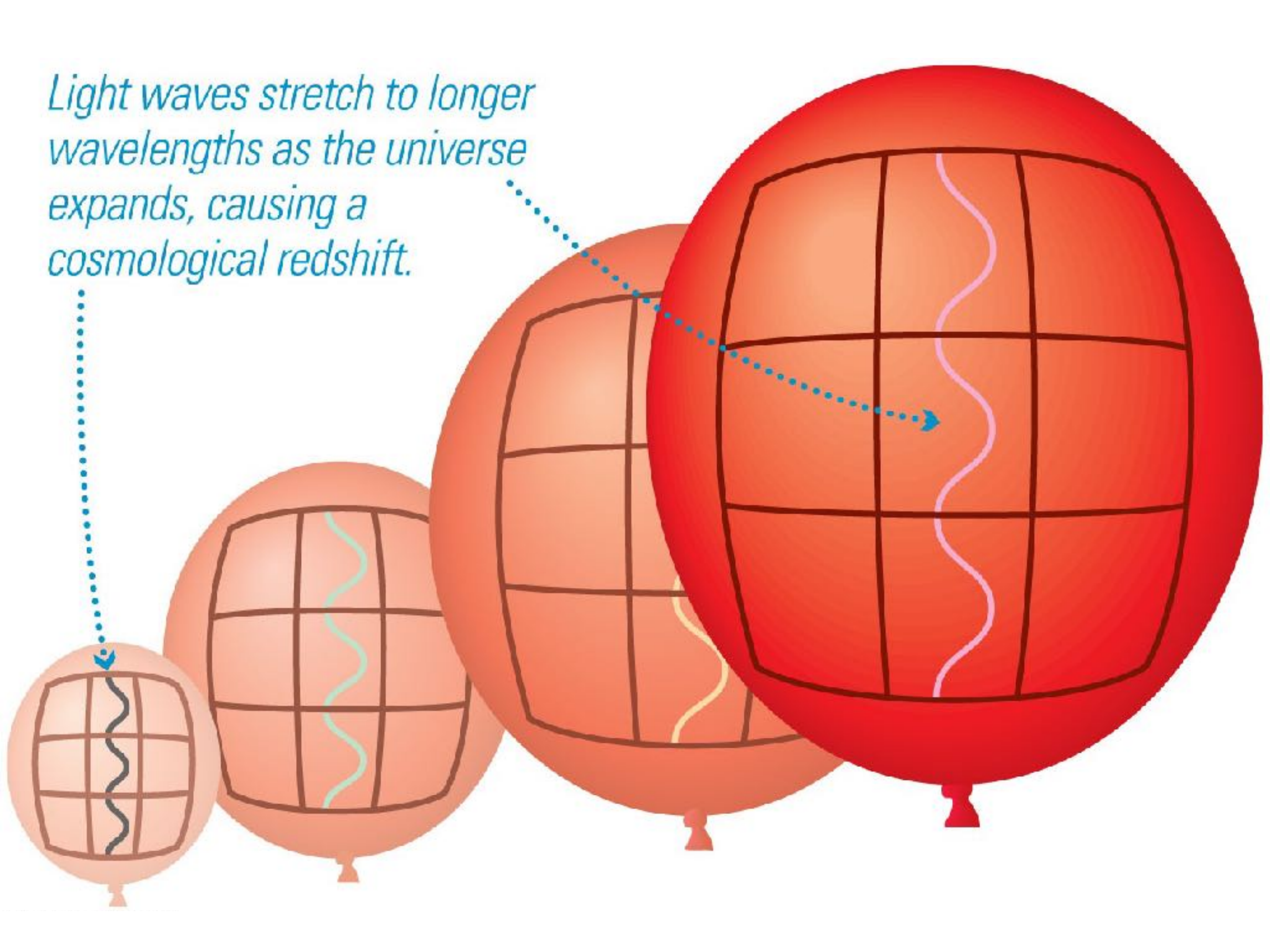
- d is in pc

Doppler Shift






Dots move apart as the balloon expands, like galaxies in the expanding universe.
D
C
B
A
D
C
B
A


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

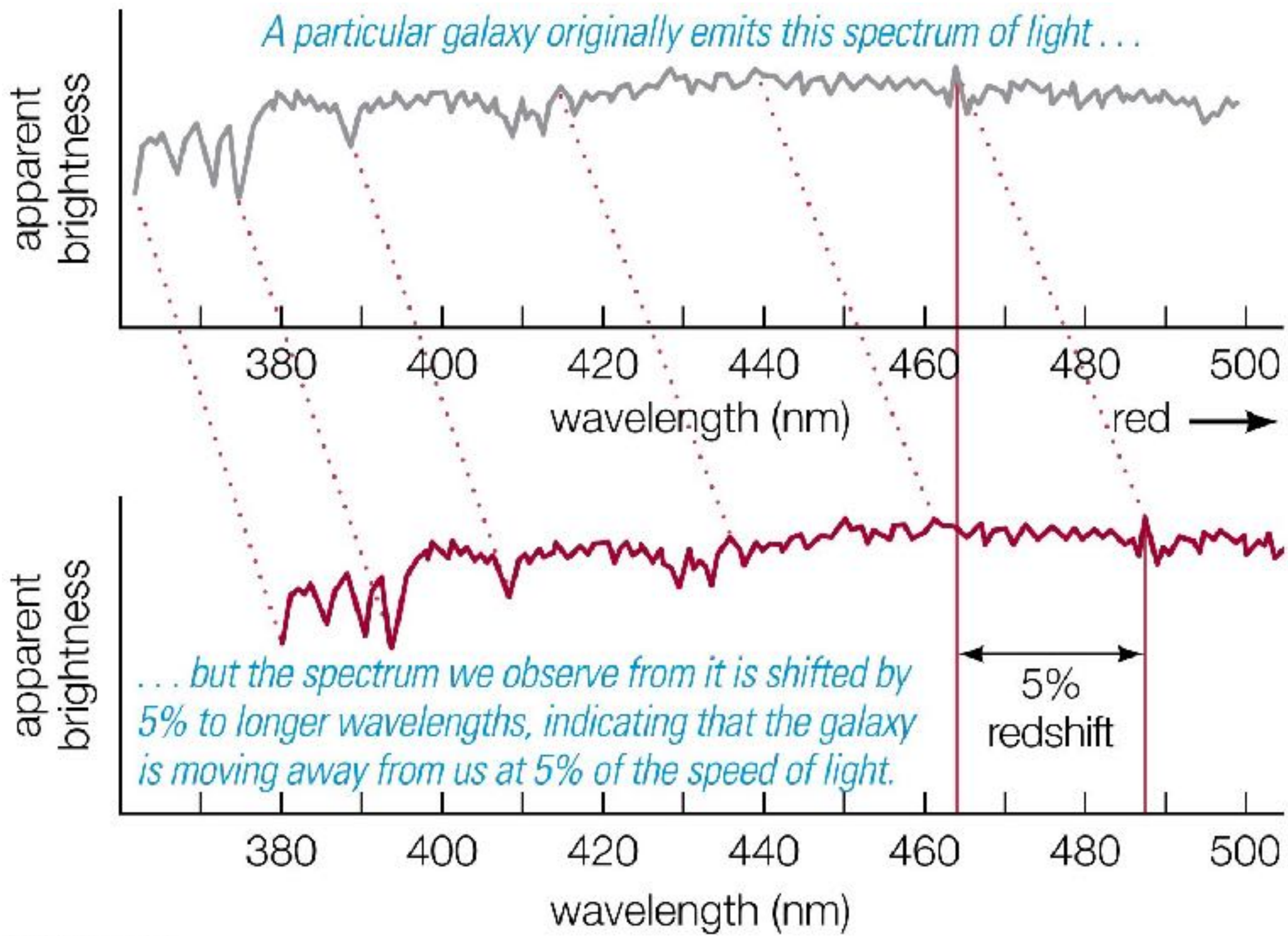
$$z = \frac{\lambda_{\mathrm{obs}} - \lambda_{\mathrm{emit}}}{\lambda_{\mathrm{emit}}}$$

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

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

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

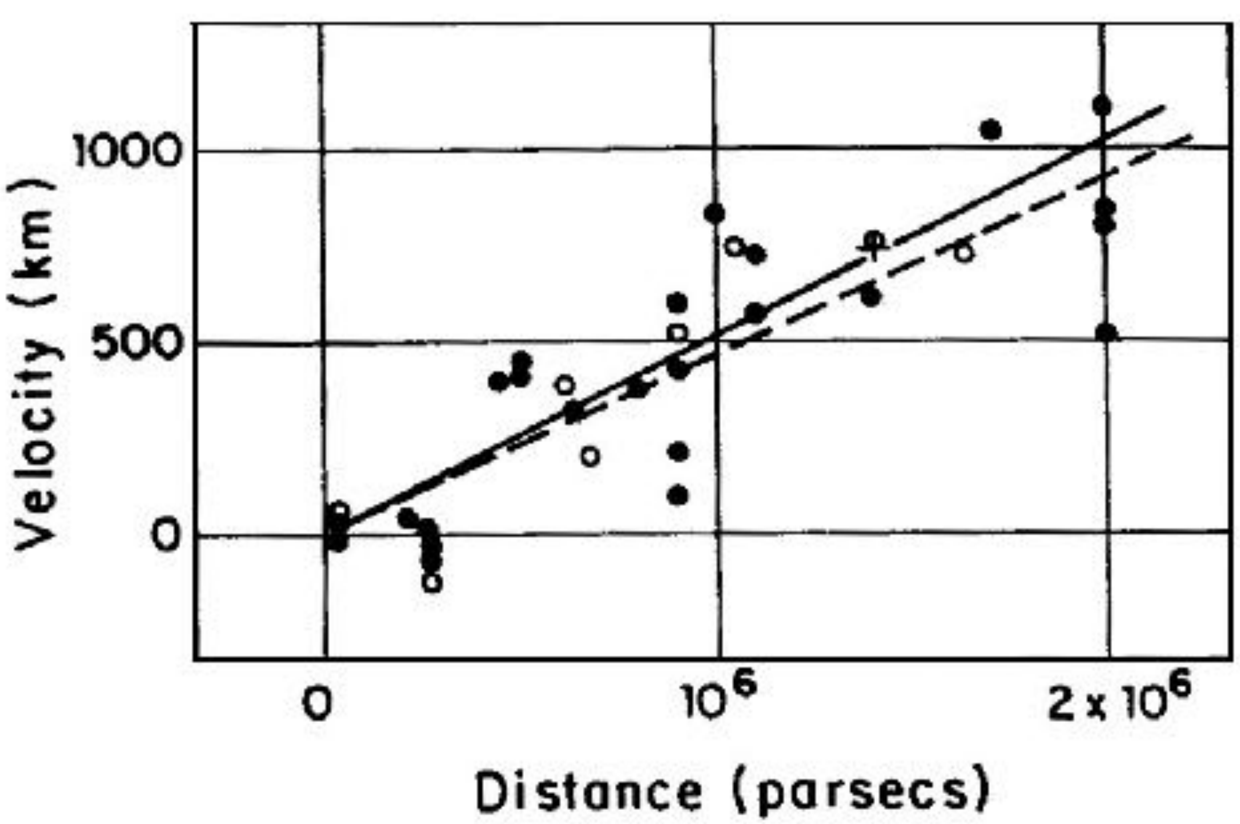
The percentage at which the wavelength of light has been shifted.

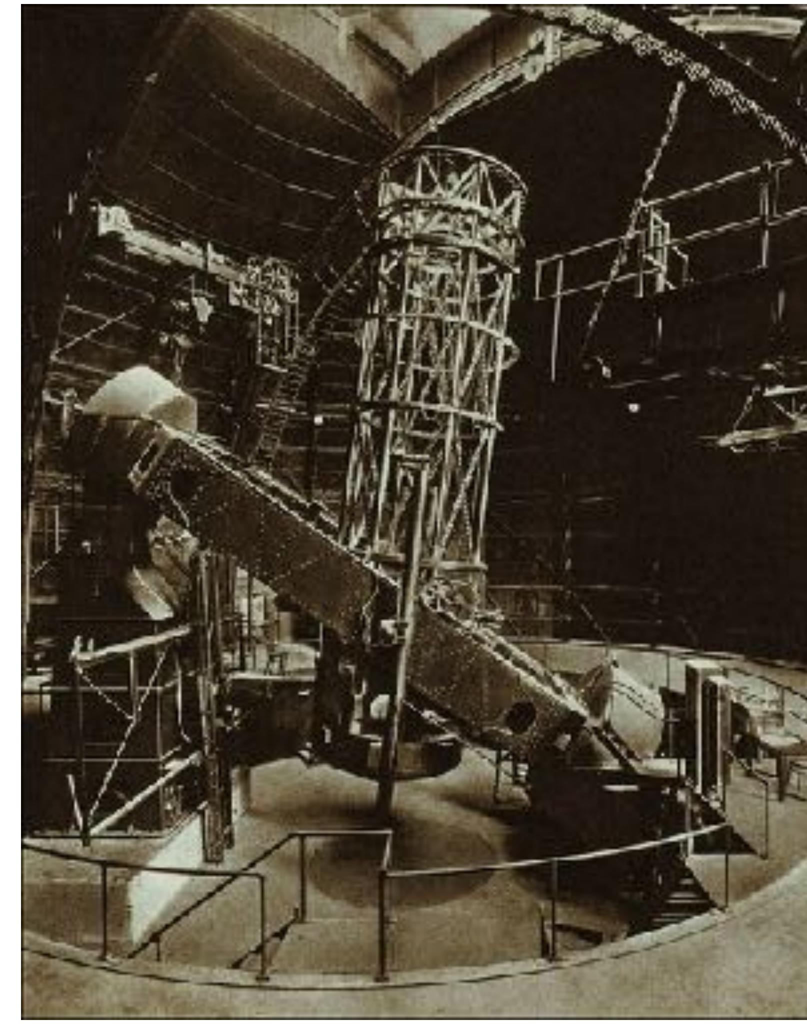

A particular galaxy originally emits this spectrum of light . . .
apparent brightness
380
400
420
440
460
480
500
wavelength (nm)
red
. . . but the spectrum we observe from it is shifted by 5% to longer wavelengths, indicating that the galaxy is moving away from us at 5% of the speed of light.
5% redshift
apparent brightness
380
400
420
440
460
480
500
wavelength (nm)

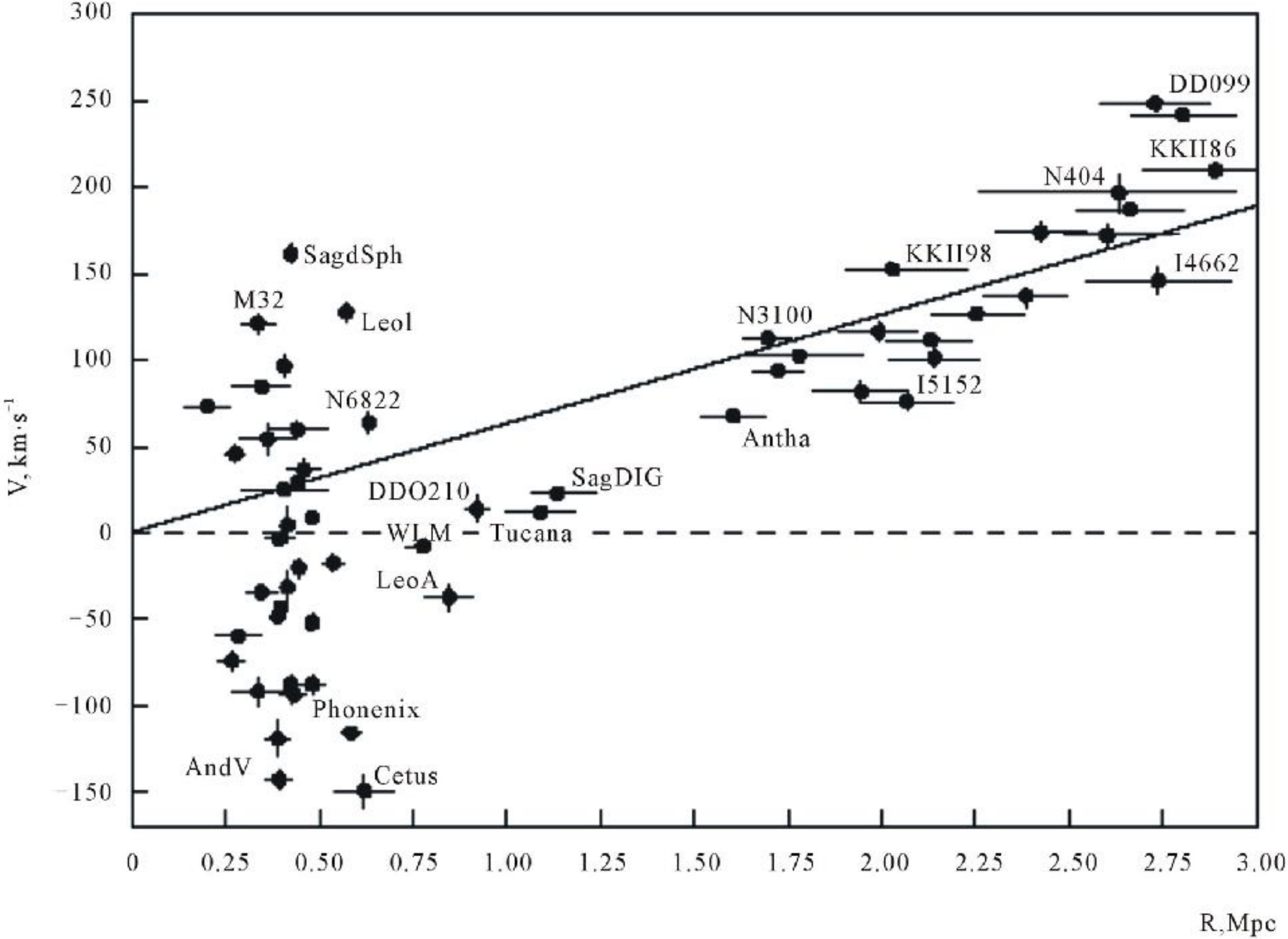
$z = 0.05$

The Universe is Expanding

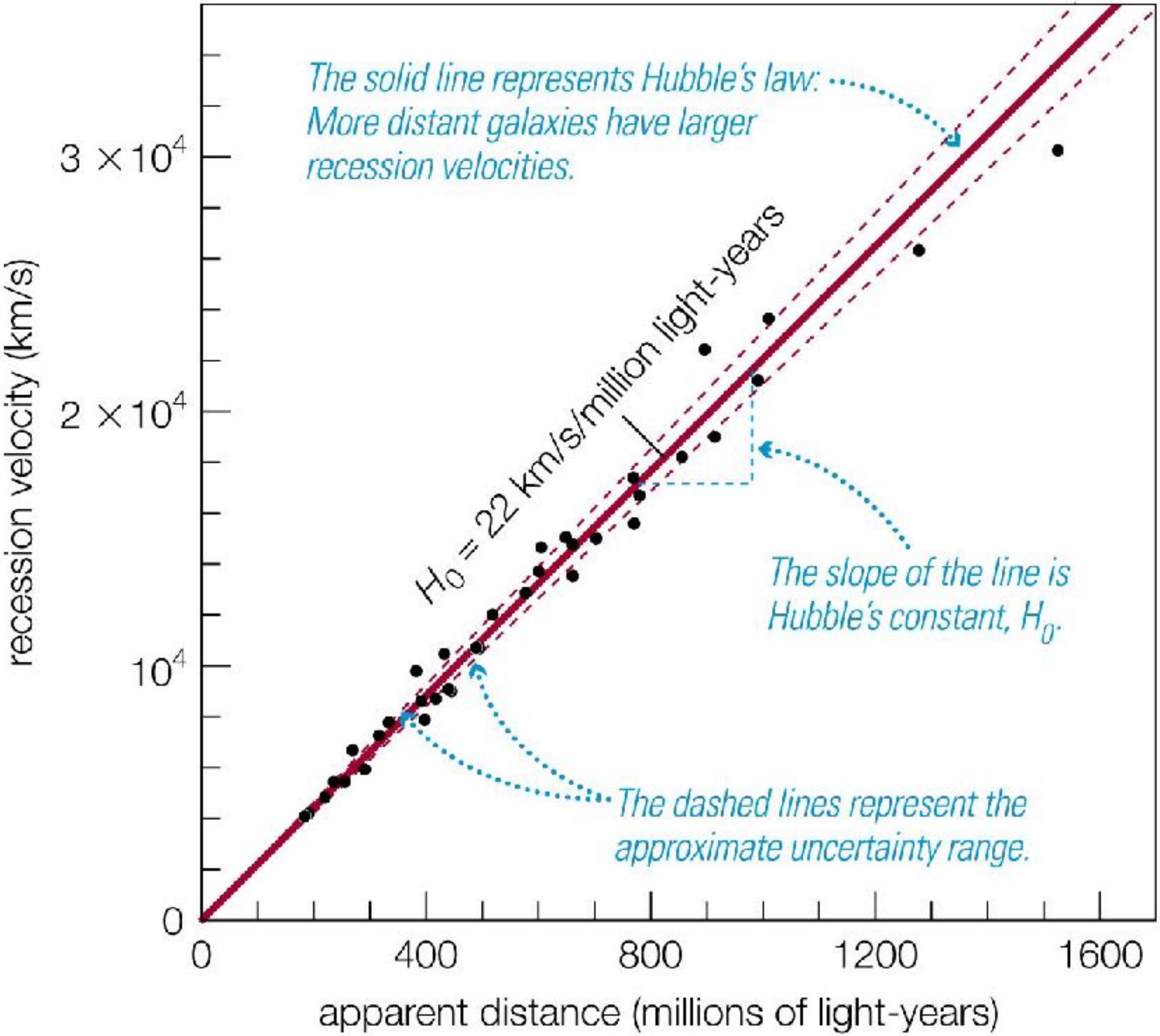
- In 1922 Edwin Hubble determined the distance to the nebulae by observing cepheid variable stars.
- He used the 100-inch Hooker Telescope on Mt. Wilson, which was the most powerful telescope on Earth from 1917—1948
- Hubble combined his distance measurements with redshift velocity measurements from 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





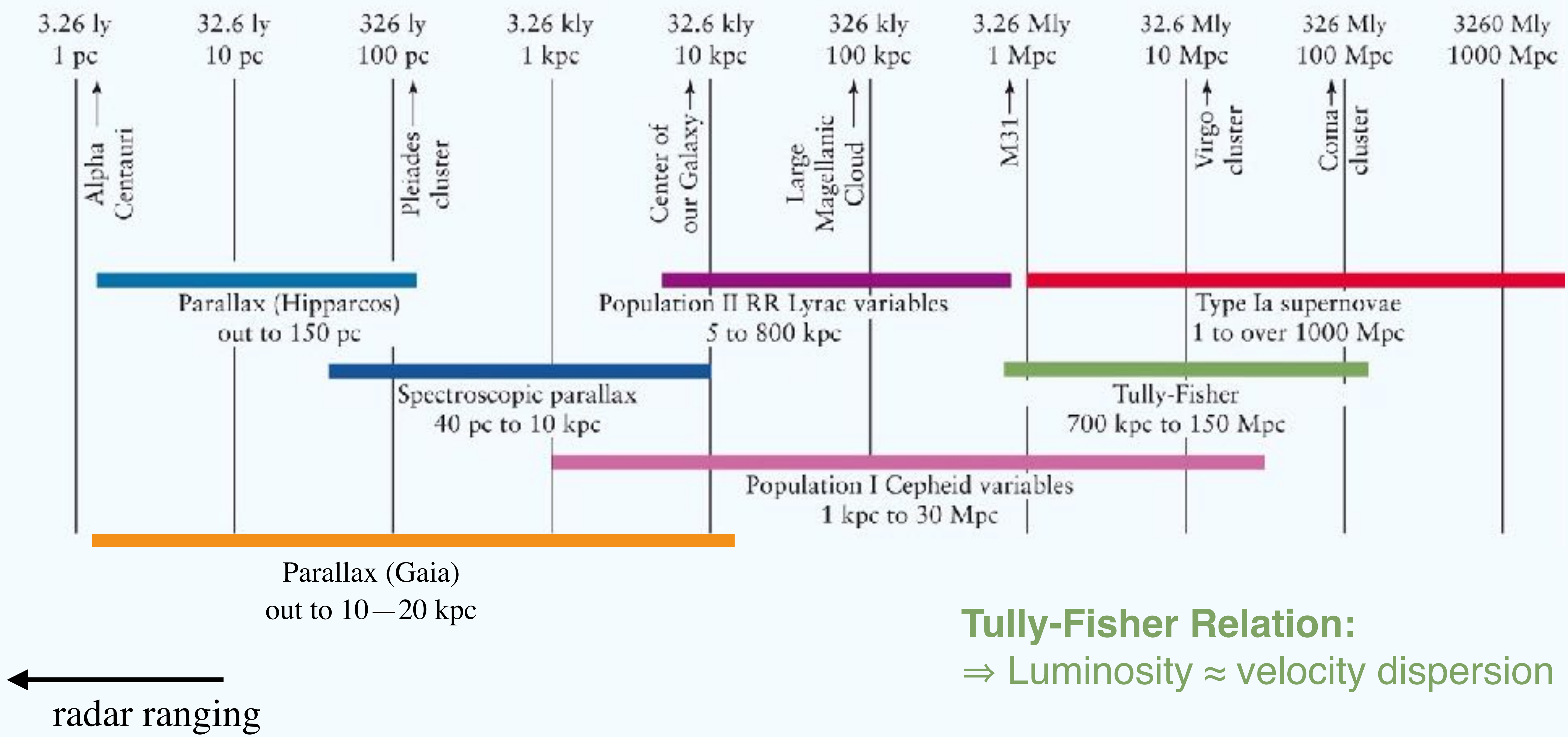


300
250
200
150
100
50
0
-50
-100
-150
V, km·s⁻¹
0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
R,Mpc
DD099
KKII86
N404
KKII98
I4662
N3100
I5152
Antha
SagdSph
M32
LeoI
N6822
SagDIG
DDO210
WLM
Tucana
LeoA
Phonenix
AndV
Cetus



The solid line represents Hubble's law: More distant galaxies have larger recession velocities.
$H_0 = 22$ km/s/million light-years
The slope of the line is Hubble's constant, H_0.
The dashed lines represent the approximate uncertainty range.
recession velocity (km/s)
3×10^4
2×10^4
10^4
0
0
400
800
1200
1600
apparent distance (millions of light-years)

The Cosmic Distance Ladder



Tully-Fisher Relation:

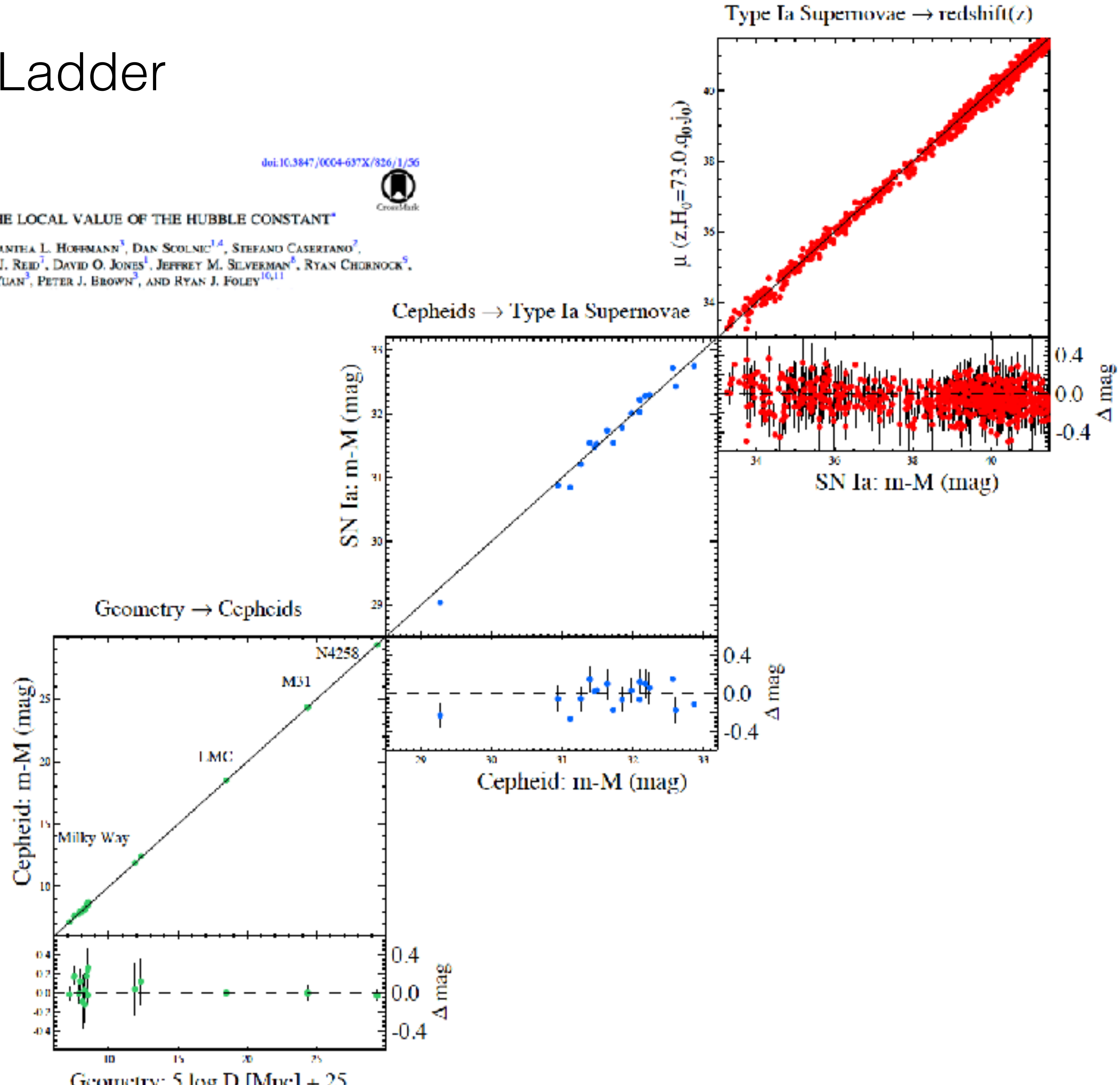
⇒ Luminosity ≈ velocity dispersion

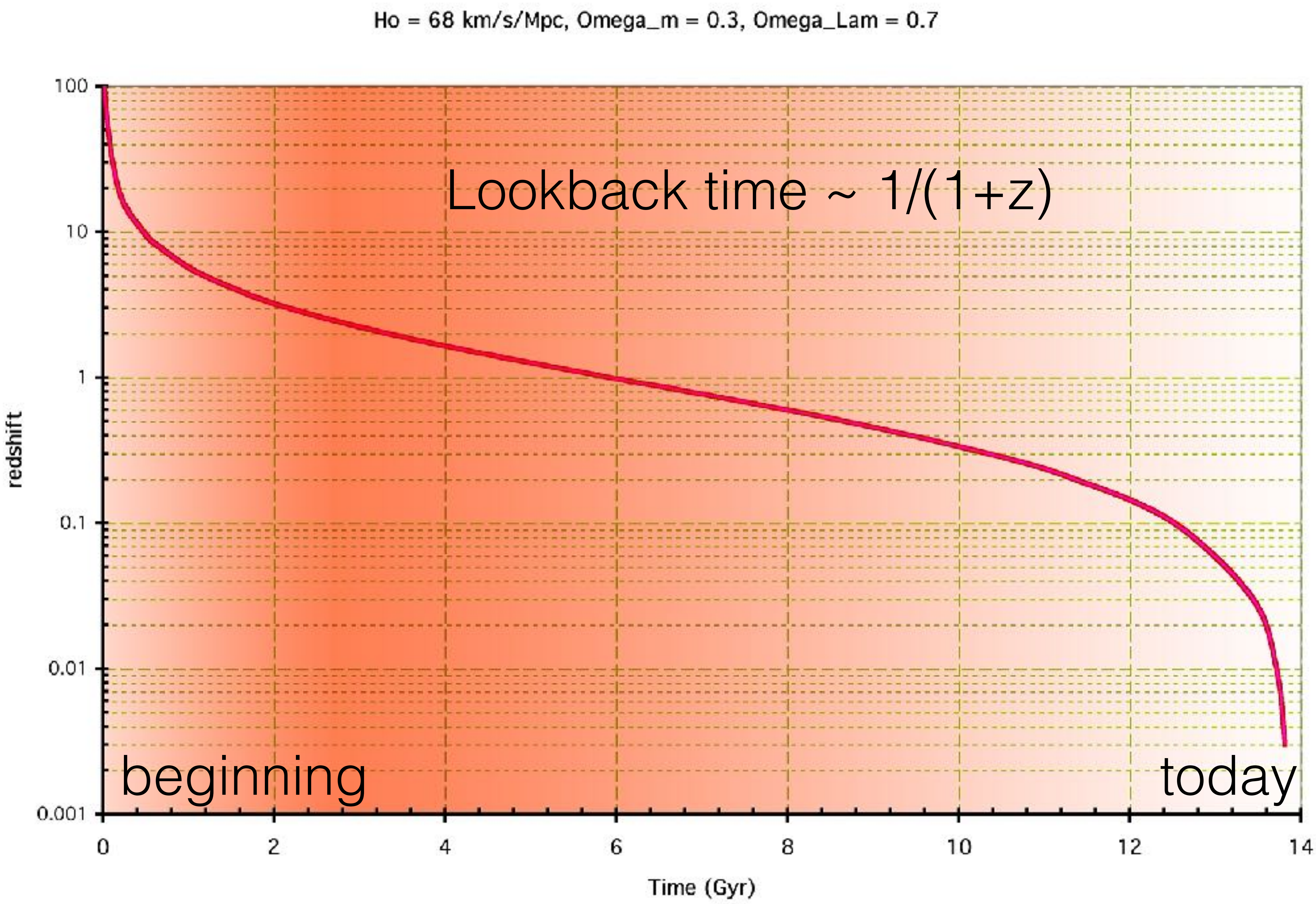
The Distance Ladder

The Astrophysical Journal, 826:56 (31pp), 2016 July 20 doi:10.3847/0004-637X/826/1/56

A 2.4% DETERMINATION OF THE LOCAL VALUE OF THE HUBBLE CONSTANT*

Adam G. Riess[1,2], Lucas M. Macri[3], Samantha L. Hoffmann[1], Dan Scolnic[1,4], Stefano Casertano[2], Alexei V. Filippenko[5], Brad E. Tucker[5,6], Mark J. Reid[7], David O. Jones[1], Jeffrey M. Silverman[8], Ryan Chornock[9], Peter Challis[7], Wenlong Yuan[3], Peter J. Brown[3], and Ryan J. Foley[10,11]





Ho = 68 km/s/Mpc, Omega_m = 0.3, Omega_Lam = 0.7
Lookback time ~ 1/(1+z)
beginning
today
redshift
100
10
1
0.1
0.01
0.001
Time (Gyr)
0
2
4
6
8
10
12
14

physical distance v. redshift

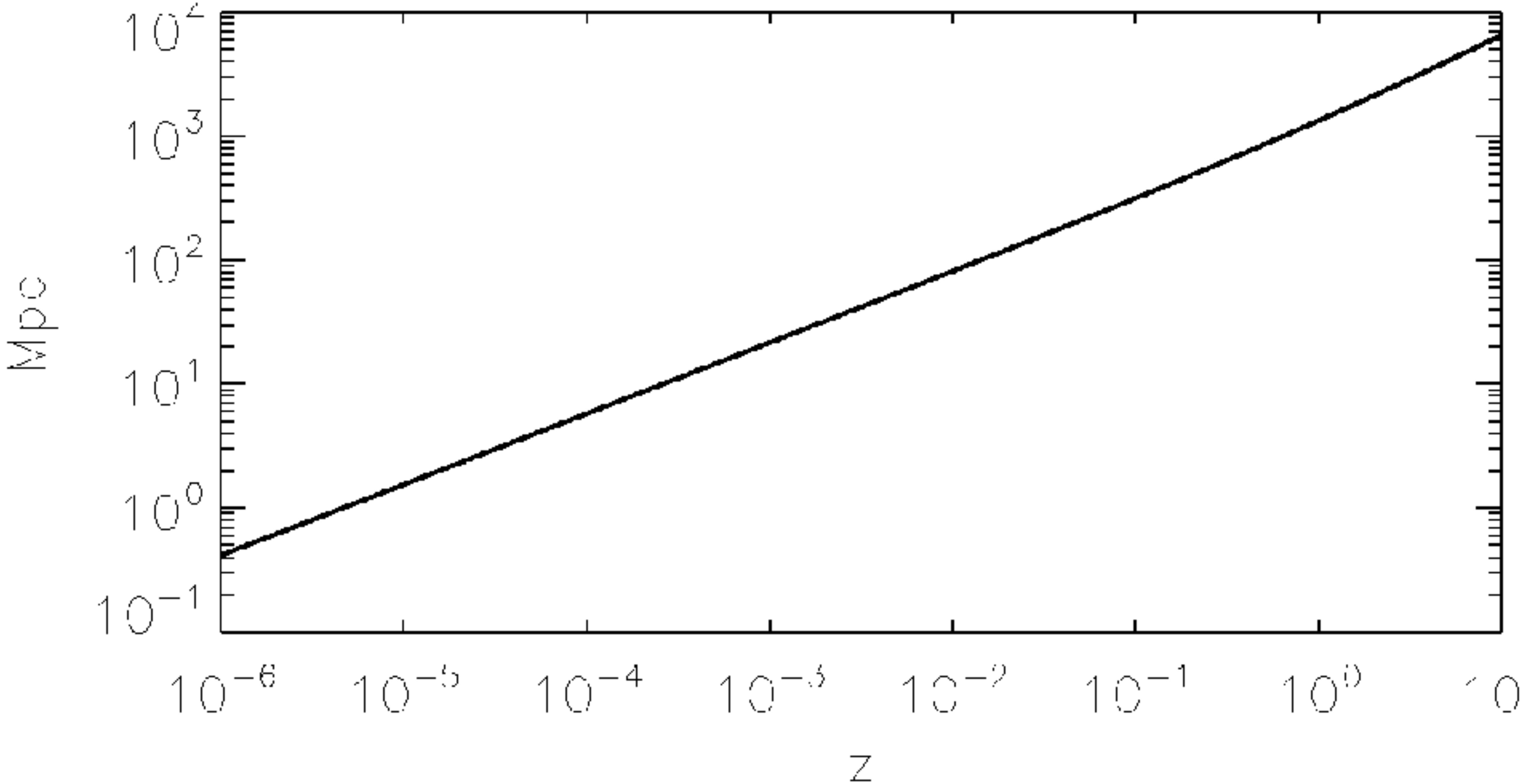
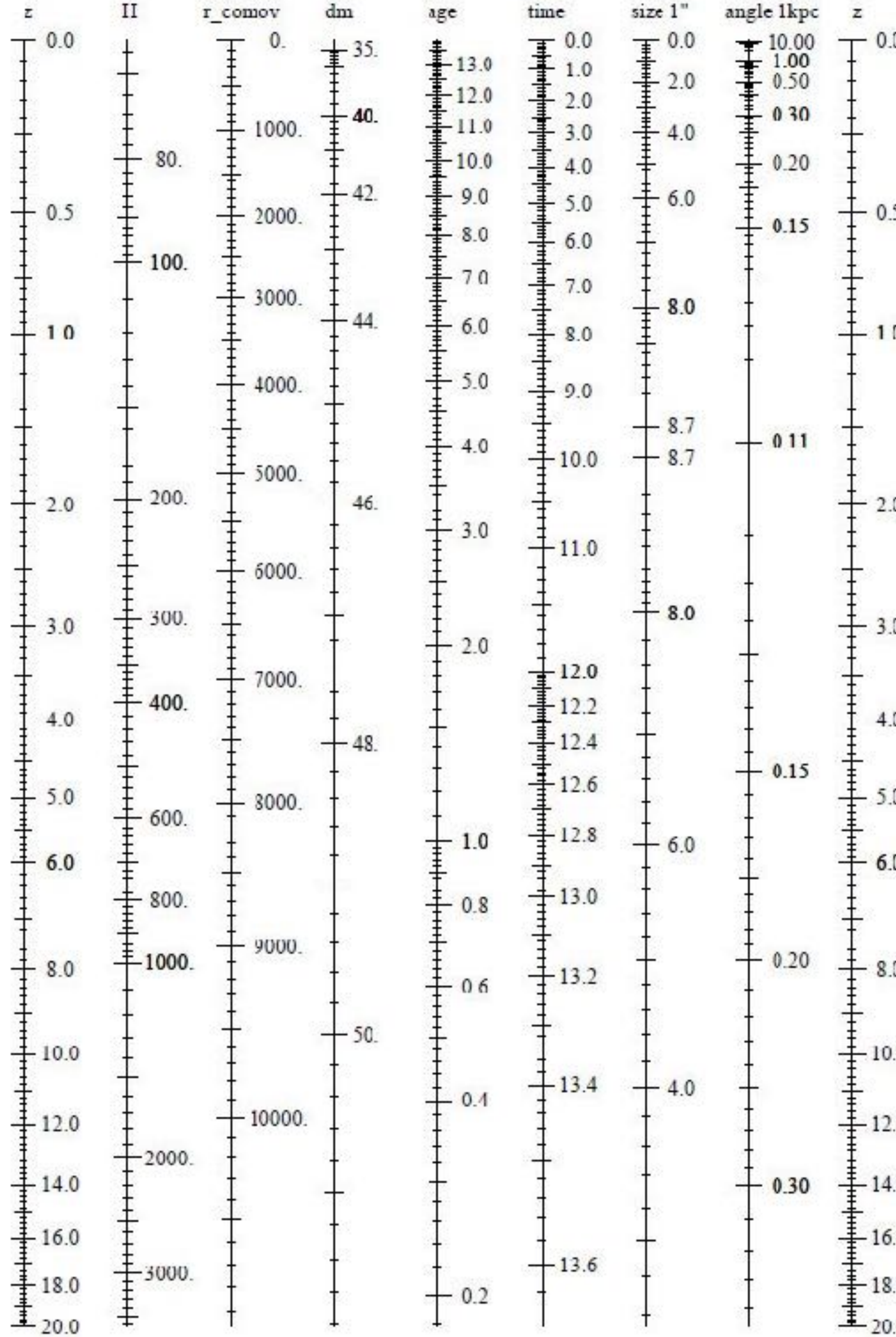


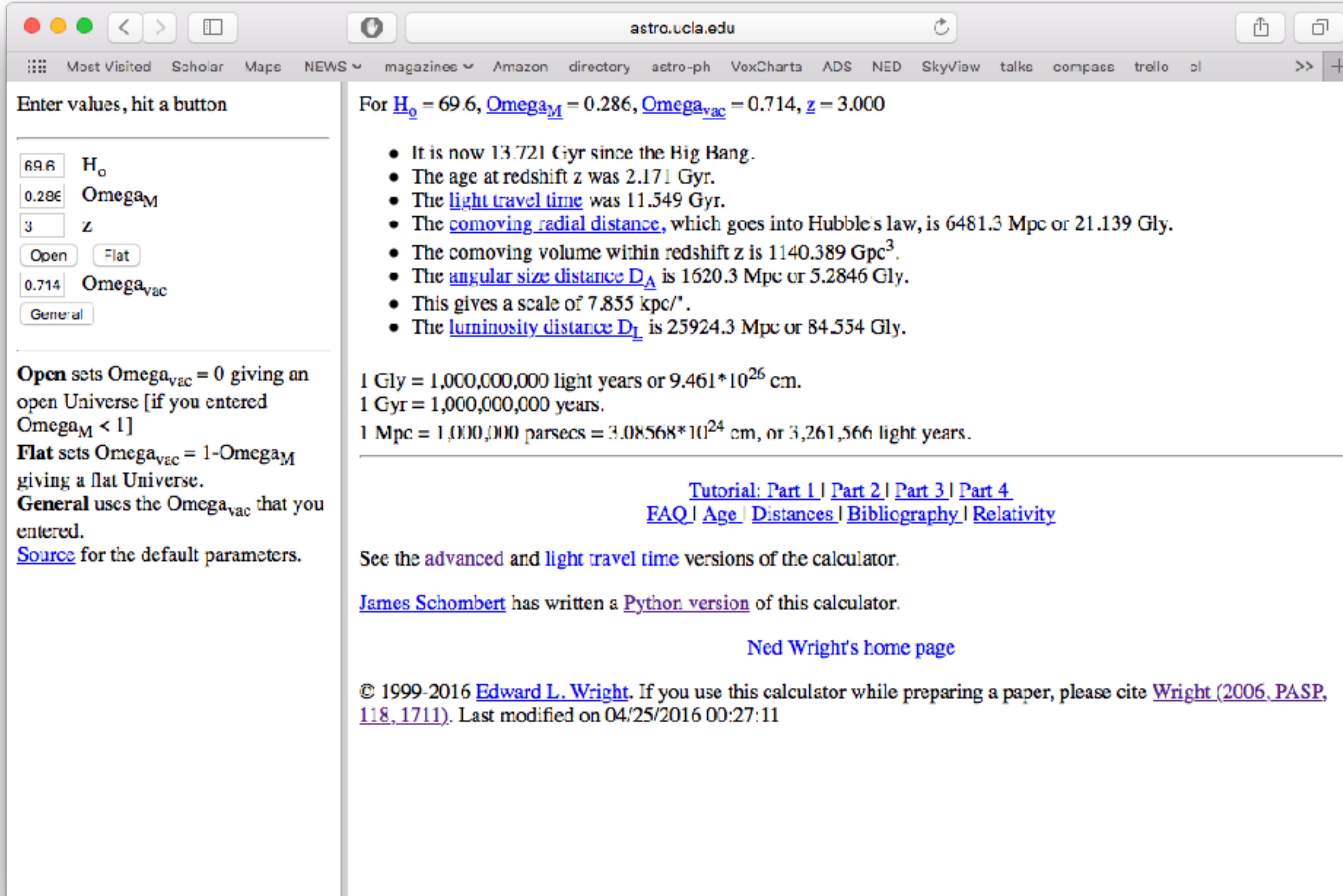
Table 25-1 Redshift and Distance

Redshift z	Recessional velocity v/c	Distance at which we see the object (Mpc)	Distance at which we see the object (10^9 ly)	Present distance to the object (comoving radial distance) (Mpc)	Present distance to the object (comoving radial distance) (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

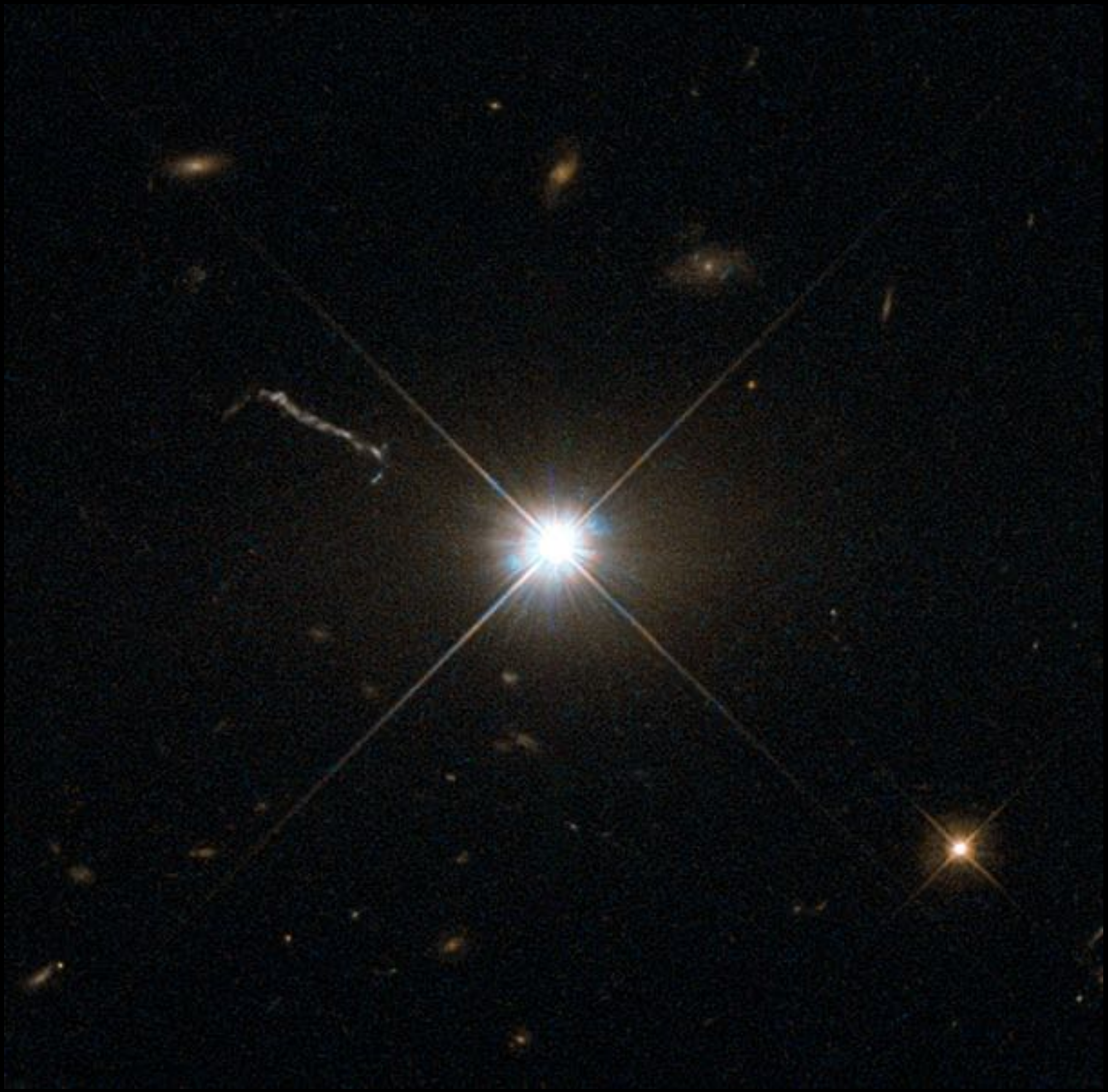
This table assumes a Hubble constant $H_0 = 73$ km/s/Mpc, a matter density parameter $\Omega_m = 0.24$, and a dark energy density parameter $\Omega_\Lambda = 0.76$ (see Chapter 26). The distance at which we see the object (in light-years) is equal to the light travel time in years. The present distance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


z
0.0 0.5 1.0 2.0 3.0 4.0 5.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0
II
80. 100. 200. 300. 400. 600. 800. 1000. 2000. 3000.
r_comov
0. 1000. 2000. 3000. 4000. 5000. 6000. 7000. 8000. 9000. 10000.
dm
35. 40. 42. 44. 46. 48. 50.
age
13.0 12.0 11.0 10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.8 0.6 0.4 0.2
time
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 12.2 12.4 12.6 12.8 13.0 13.2 13.4 13.6
size 1"
0.0 2.0 4.0 6.0 8.0 8.7 8.7 8.0 6.0 4.0
angle 1kpc
10.00 1.00 0.50 0.30 0.20 0.15 0.11 0.15 0.20 0.30
z
0.0 0.5 1.0 2.0 3.0 4.0 5.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0

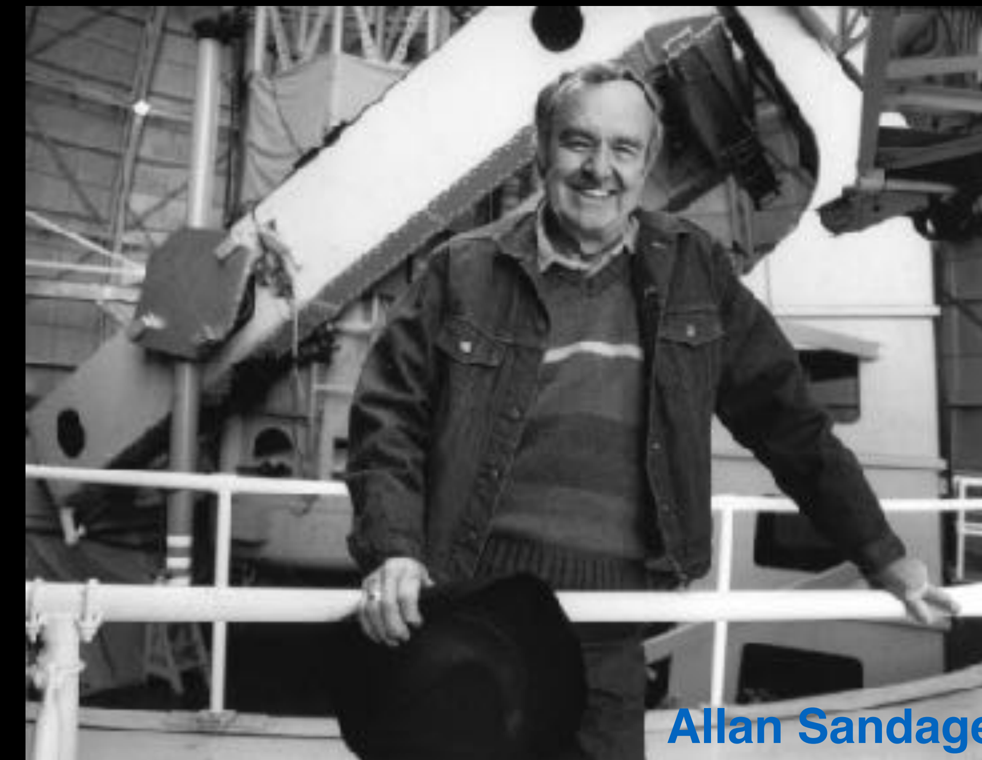
Ned Wright's Cosmology Calculator: http://www.astro.ucla.edu/~wright/CosmoCalc.html

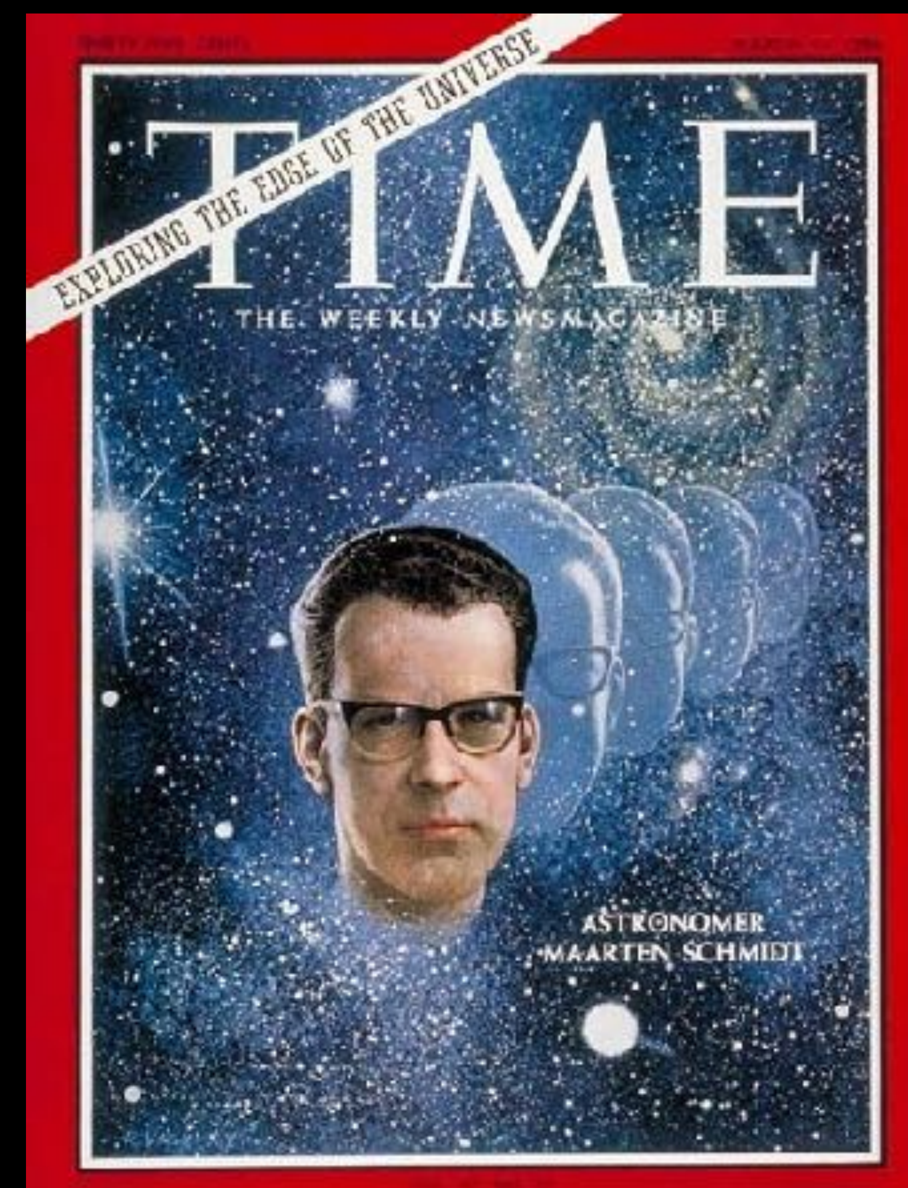


Quasar 3C 273



Quasar 3C 273



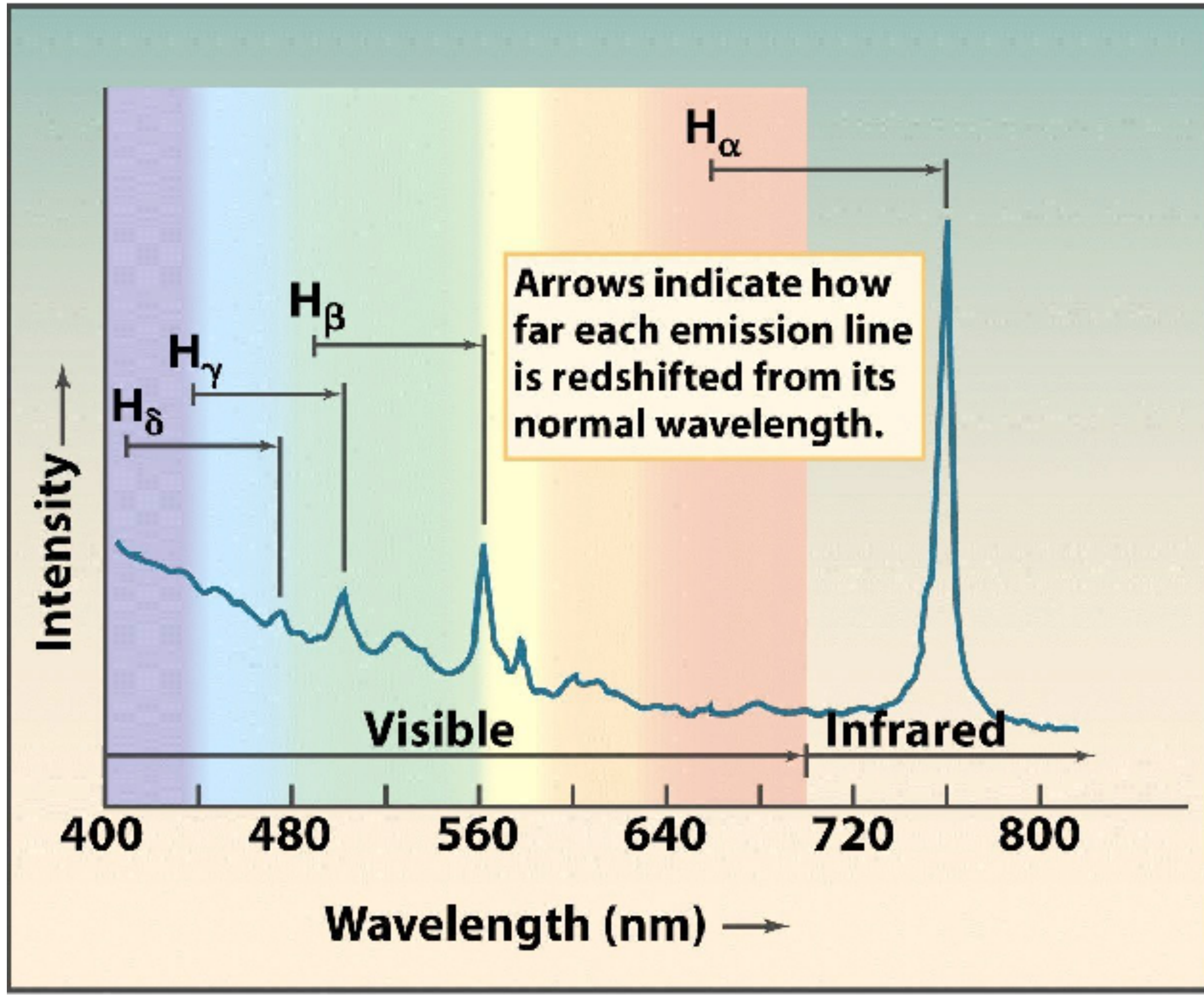


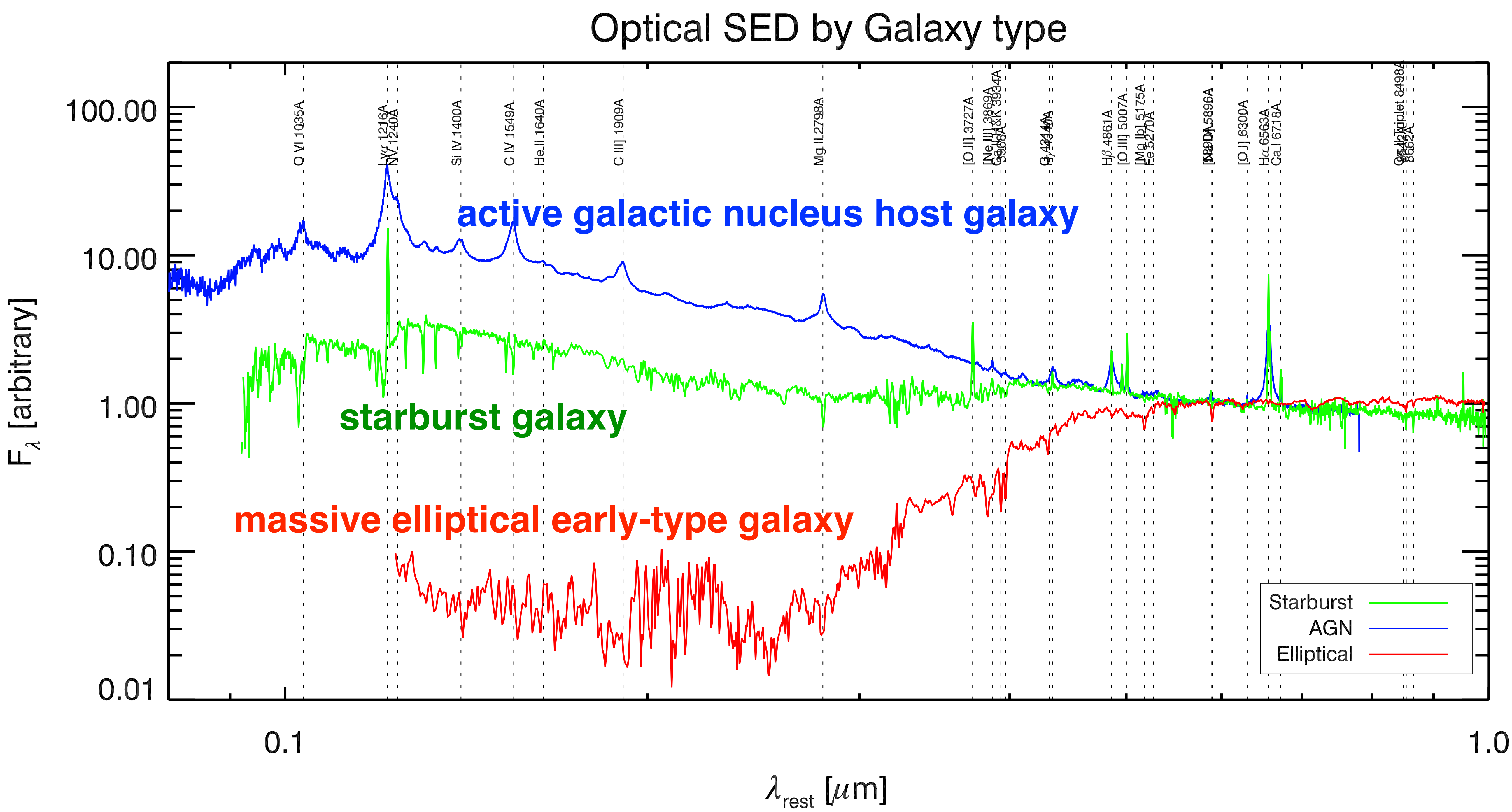
- The first quasars (3C 48 and 3C 273) were discovered in the early 1960s by Allan Sandage at Carnegie. (U. of Illinois ’48). He was a graduate student of Edwin Hubble and Walter Baade at Caltech.
- Most quasars were radio sources with no corresponding visible object. They has “strange redshifts” corresponding 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!

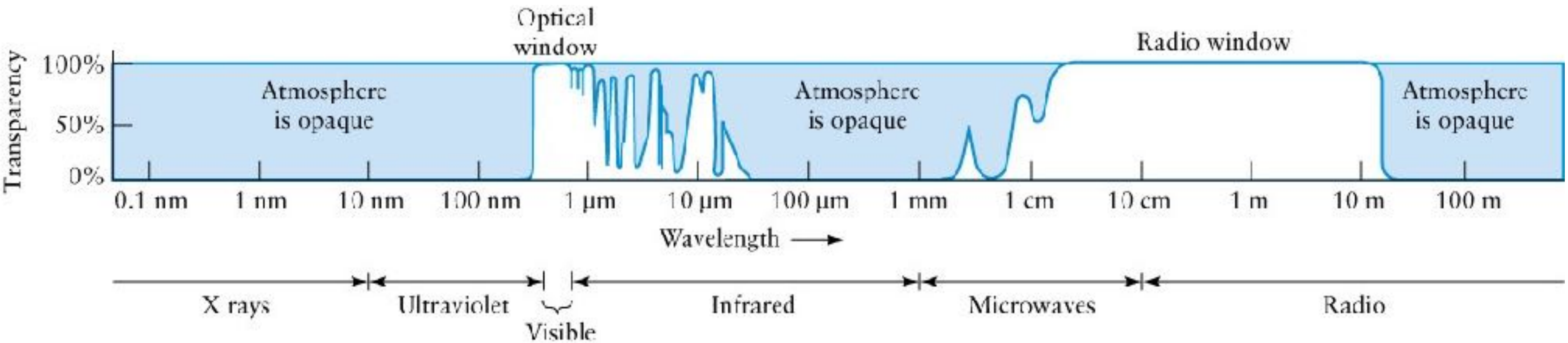
Quasar 3C273 is receding from us at 16% the speed of light. That corresponds to z=0.158

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

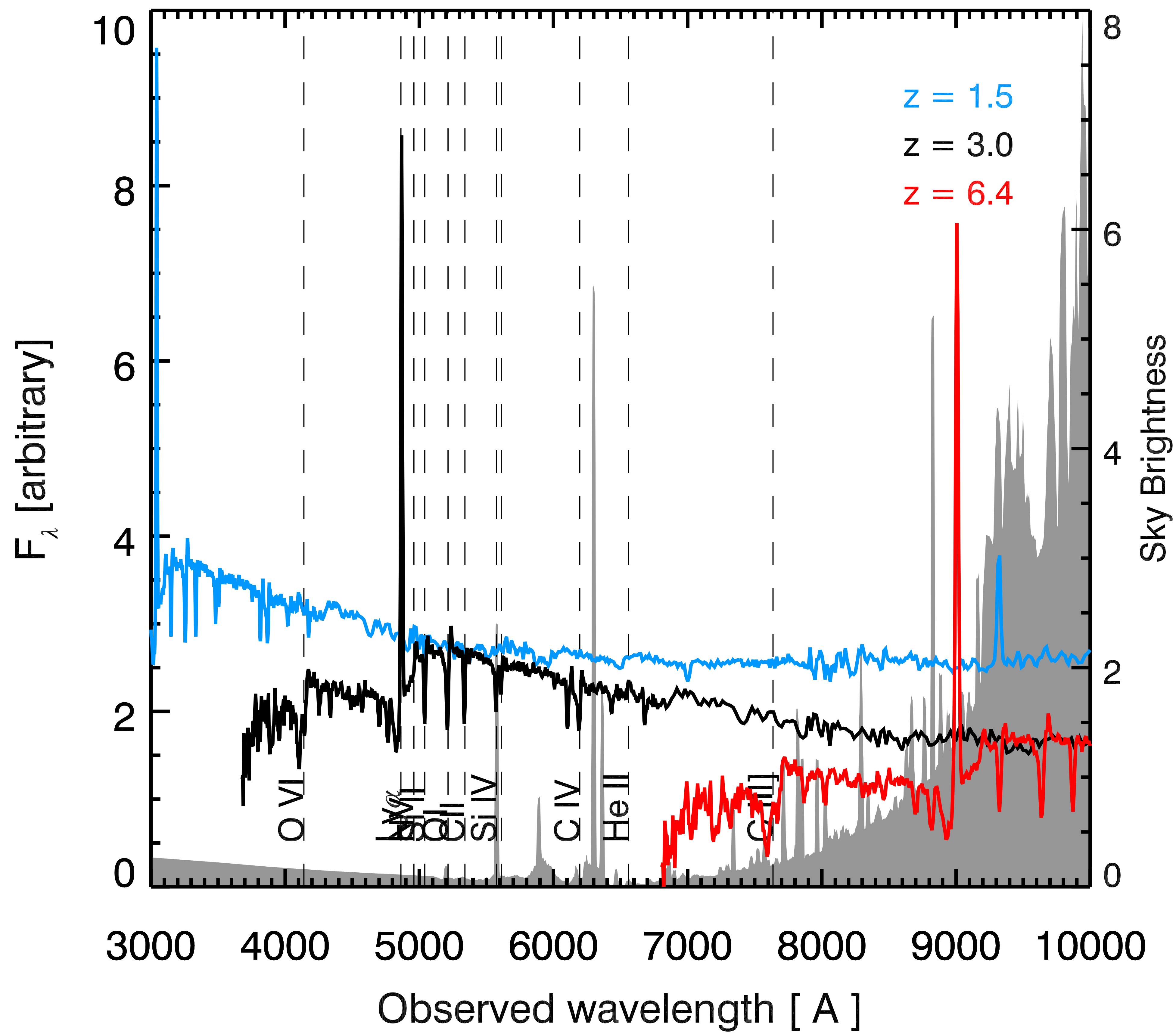




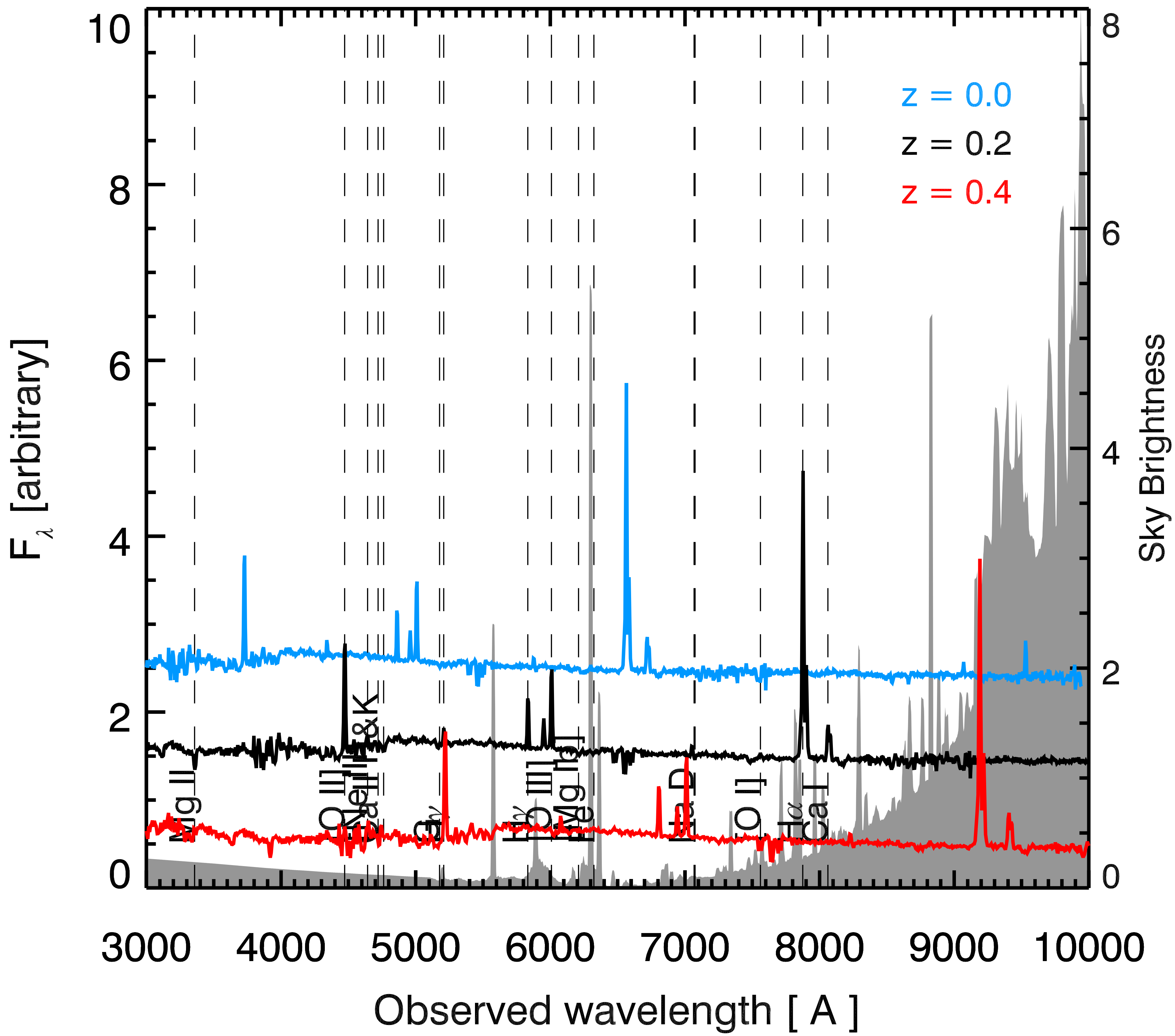
Optical SED by Galaxy type
active galactic nucleus host galaxy
starburst galaxy
massive elliptical early-type galaxy
Starburst
AGN
Elliptical
100.00
10.00
1.00
0.10
0.01
0.1
1.0
F_λ [arbitrary]
λ_rest [μm]
O VI 1035A
Lyα 1216A
NV 1240A
Si IV 1400A
C IV 1549A
He II 1640A
C III] 1909A
Mg II 2798A
[O II] 3727A
[Ne III] 3869A
Hβ 4861A
[O III] 5007A
[O I] 6300A
Hα 6563A
Ca I 6718A


Optical window
Radio window
Transparency
100%
50%
0%
Atmosphere is opaque
Atmosphere is opaque
Atmosphere is opaque
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
Wavelength
X rays
Ultraviolet
Visible
Infrared
Microwaves
Radio

Ly-α in an optical spectrograph

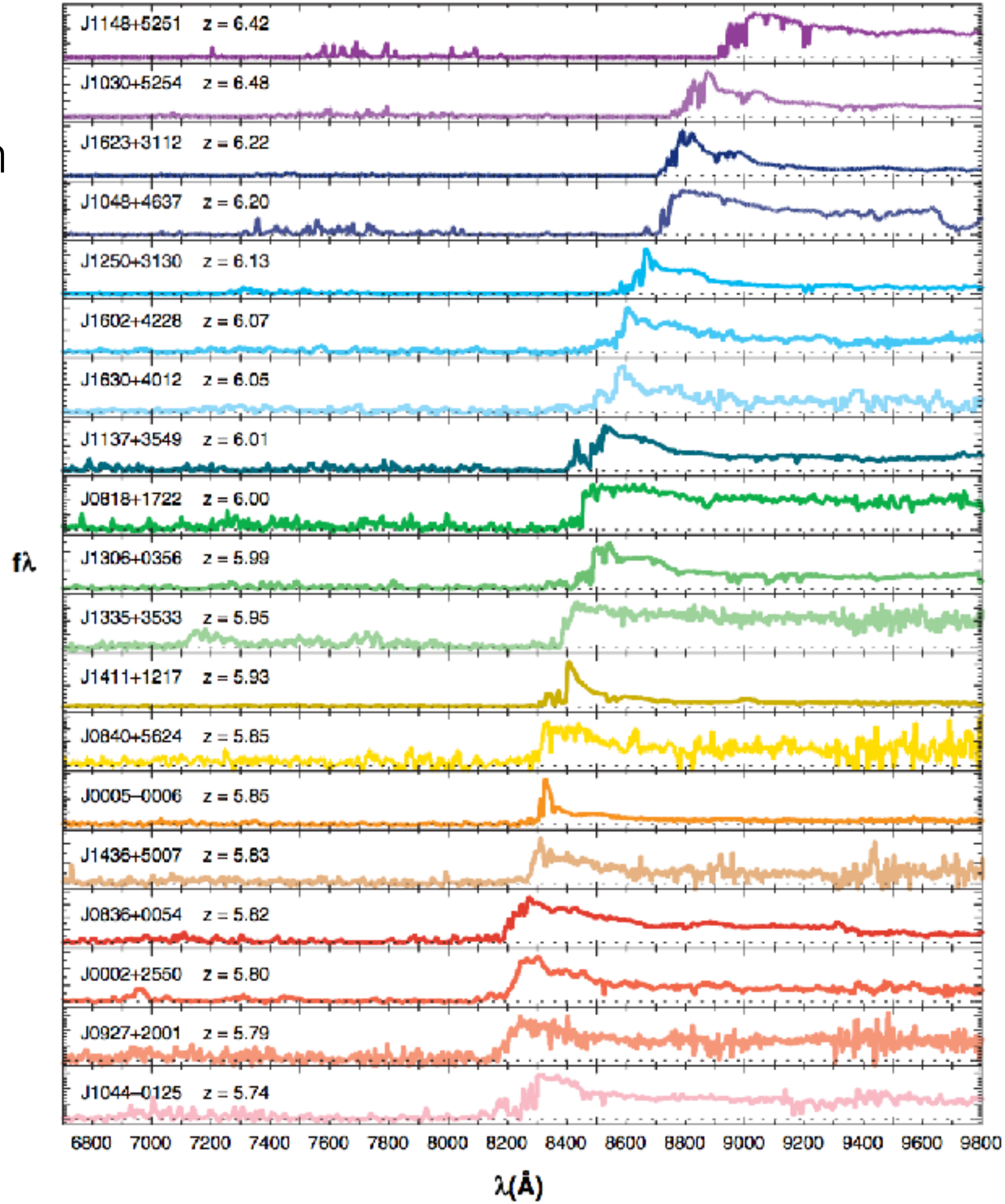


H-α in an optical spectrograph



Quasars in SDSS

More than 200,000 known



Most distant astronomical object