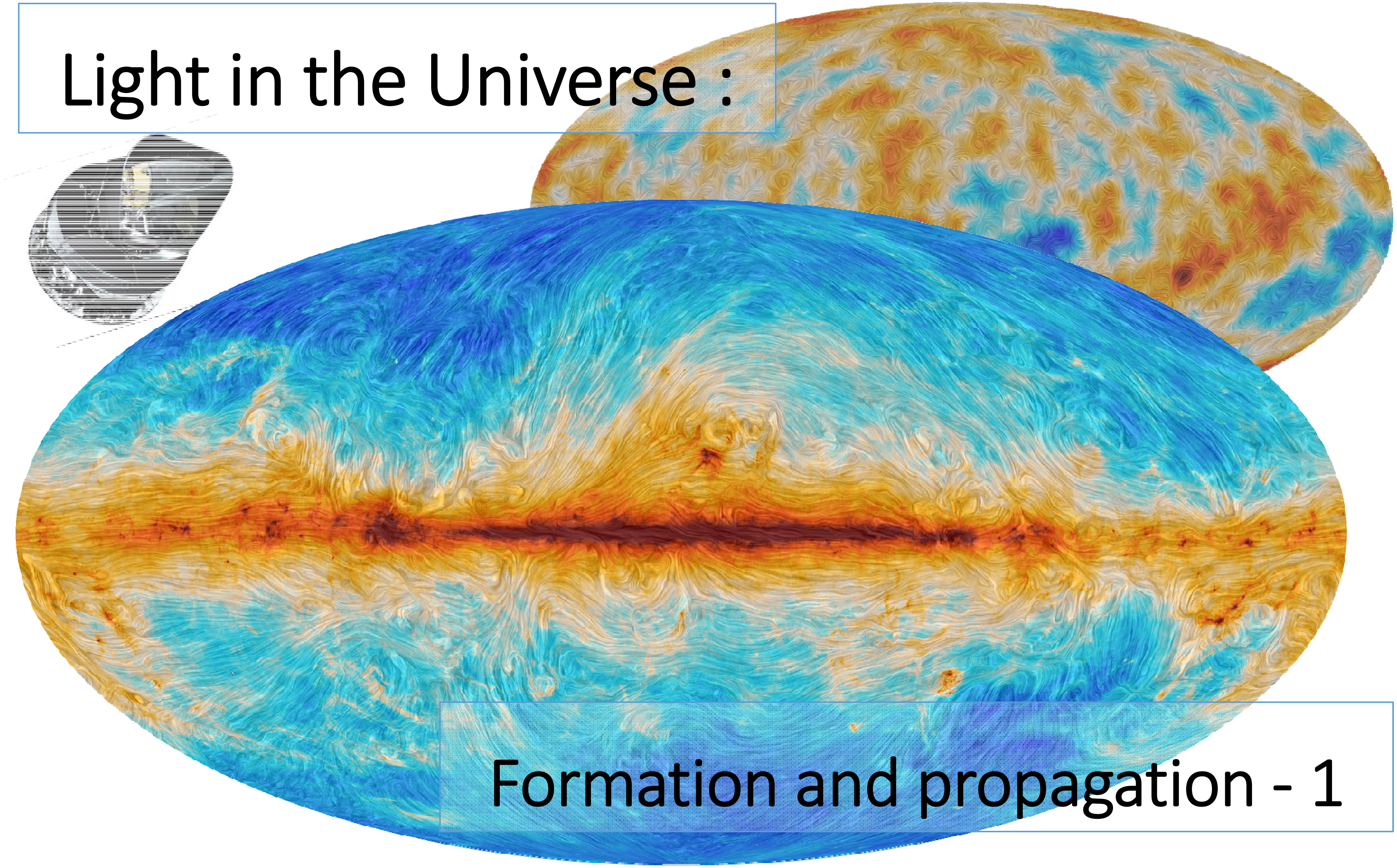
Light in the Universe :



Formation and propagation - 1

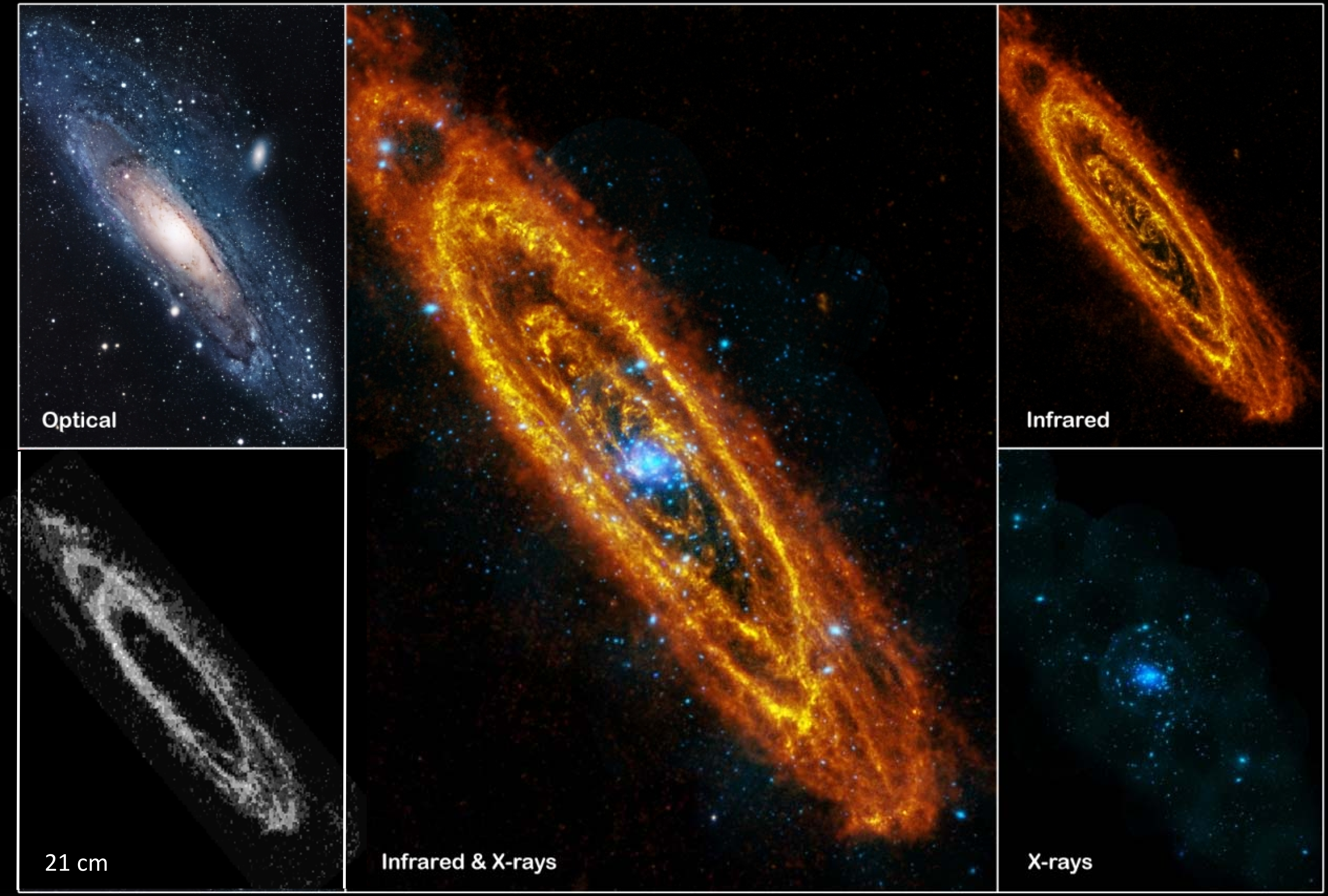
Paolo de Bernardis

Dipartimento di Fisica, Sapienza Università di Roma

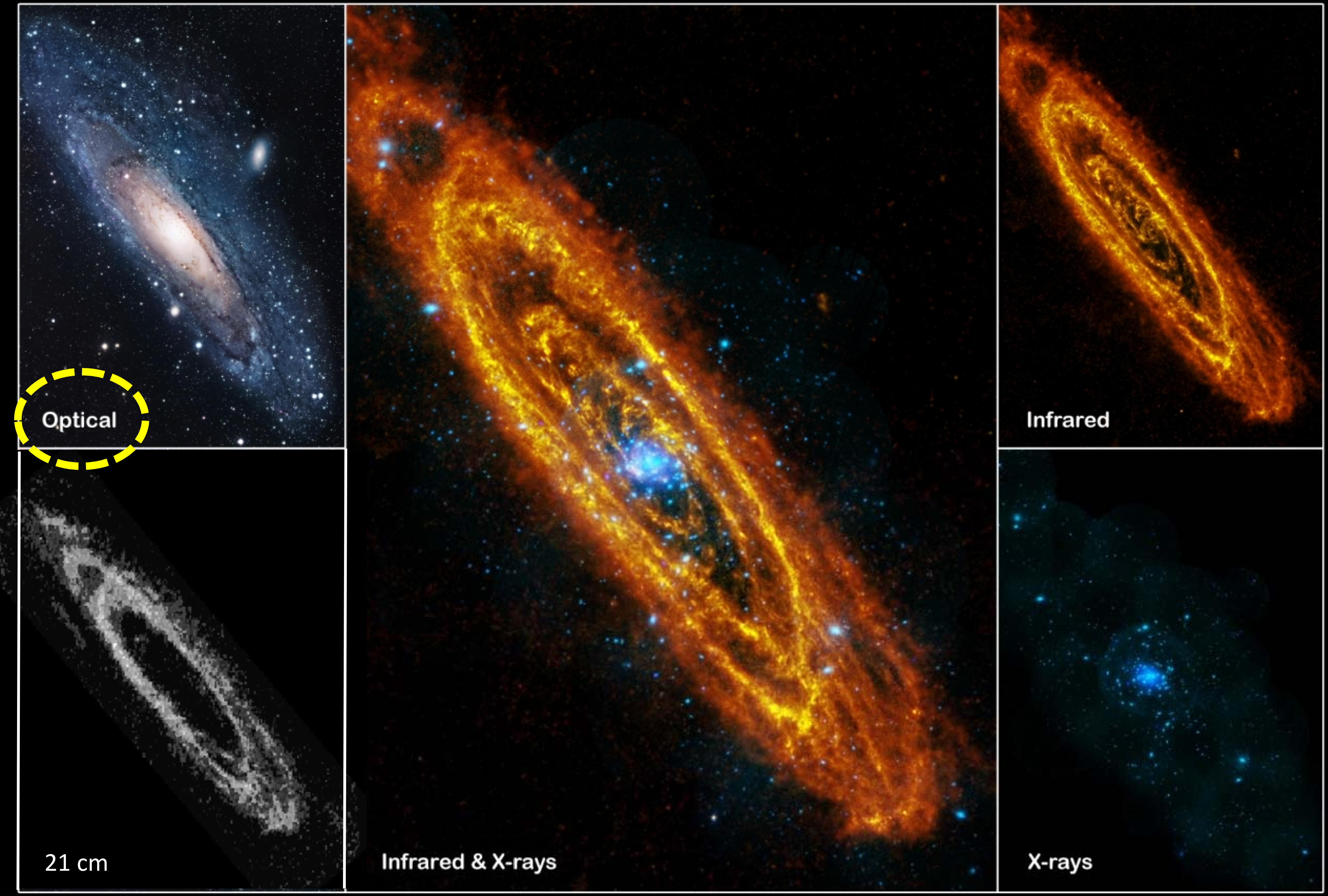
Winter College on Optics 2015 - Trieste, 9-20 February

Photons from the Universe

- Photons propagate for billions of light-years in the universe, carrying information on the distant, past cosmos.
- This very fact makes observational astronomy possible.
- 400 years of active astronomical observations have developed tools to collect and analyze photons from the universe in deep detail.
- What we know in Astrophyscis and Cosmology today is based by far mainly on these measurements.
- Over the whole EM spectrum:
  - Direction (Brightness Maps)
  - Energy distribution (Spectroscopy)
  - Polarization state (Polarimetry)
- The fidelity of the information carried by photons from the universe depends on
  - The wavaelength and the interaction with intervening matter (atmospheric, interstellar and intergalactic absorption and emission)
  - The expansion of the universe (cosmological redshift)
  - The interaction with intervening masses (gravitational lensing).



Understanding of a cosmic source requires observations across the whole EM spectrum

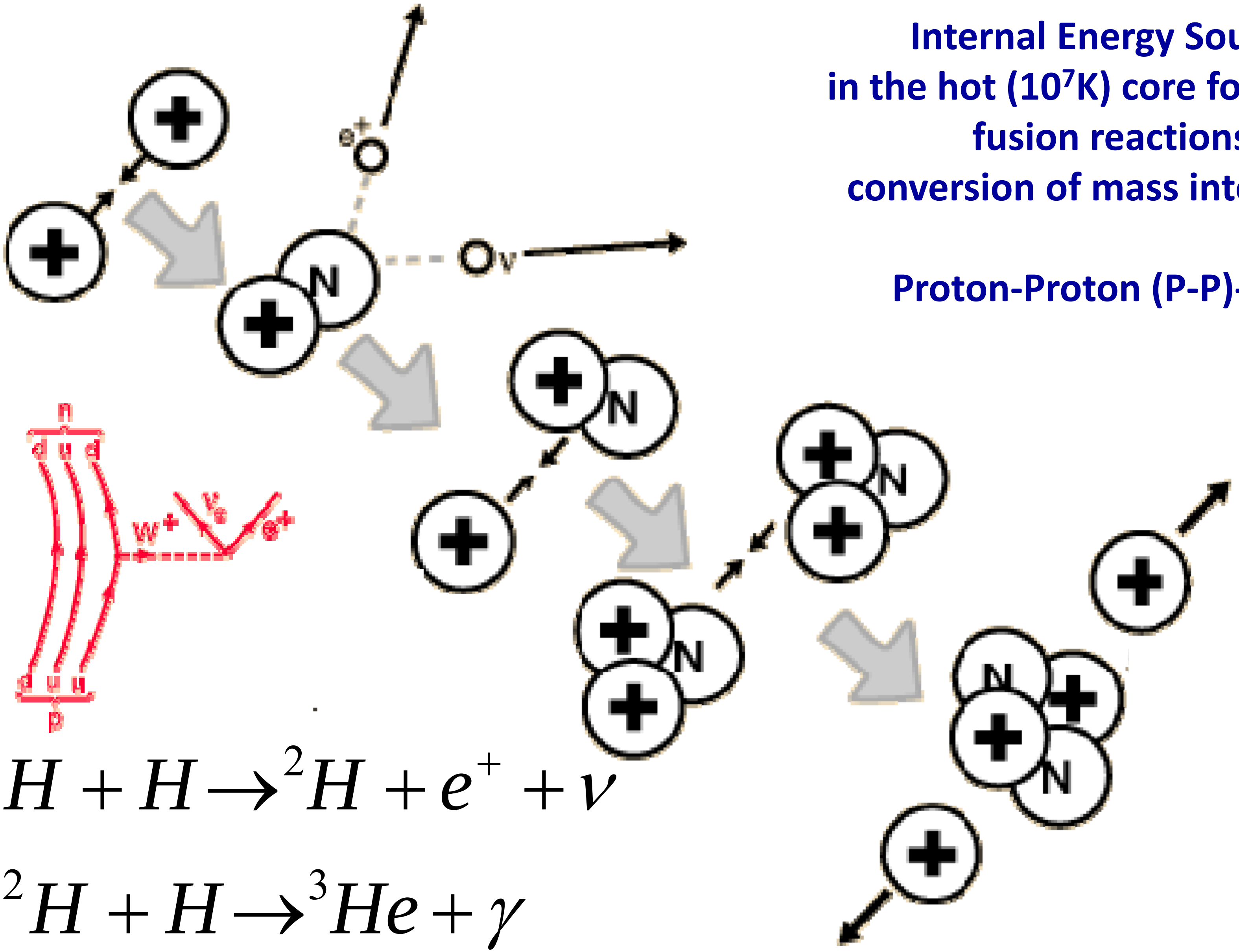


Understanding of a cosmic source requires observations across the whole EM spectrum

Stellar radiation

Internal Energy Source, in the hot (10^7K) core fo the star : fusion reactions, conversion of mass into energy

Proton-Proton (P-P)-chain

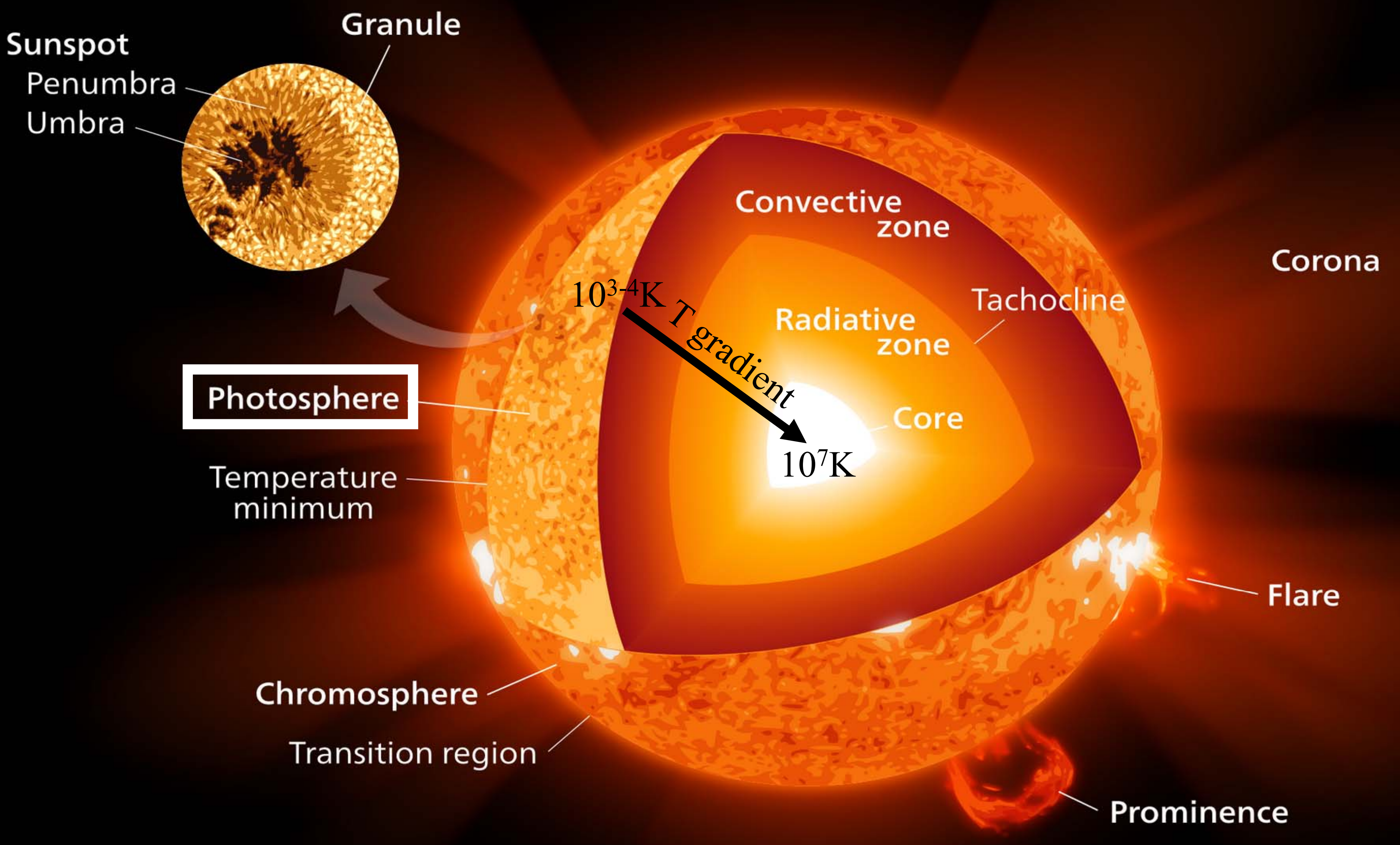


$$H + H \rightarrow {}^{2}H + e^{+} + \nu$$

$${}^{2}H + H \rightarrow {}^{3}He + \gamma$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + H + H$$

Thermalization through scattering / absorption



Photosphere = **semitransparent shell**, temperature T_s, optical depth $\tau(\nu)$

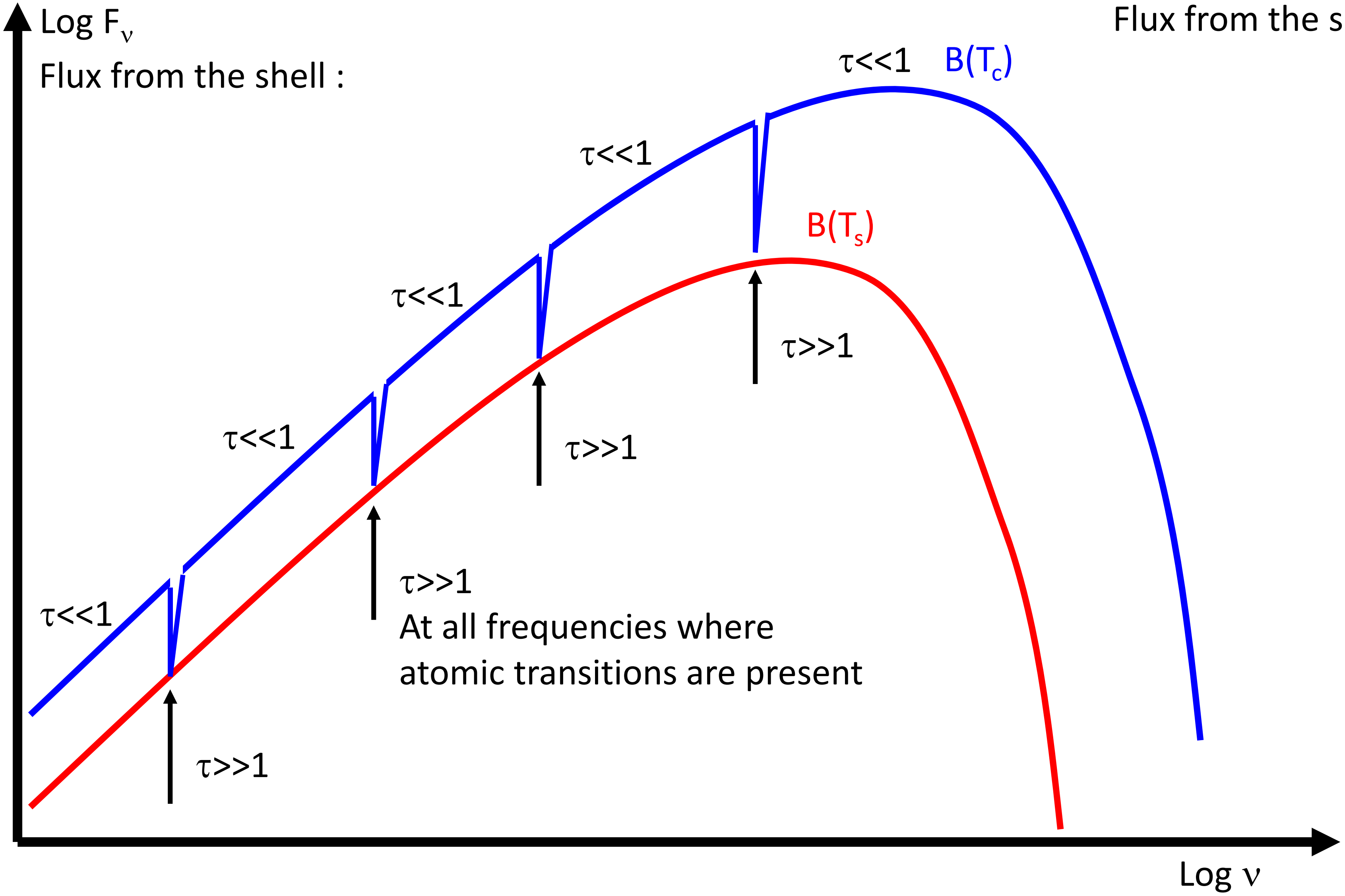
Internal = opaque core, temperature T_c and rising – high optical depth, BB spectrum

$$I_A = B(\nu,T_c)\, e^{-\tau} + B(\nu\ ,T_s)\left[1-e^{-\tau}\right]$$

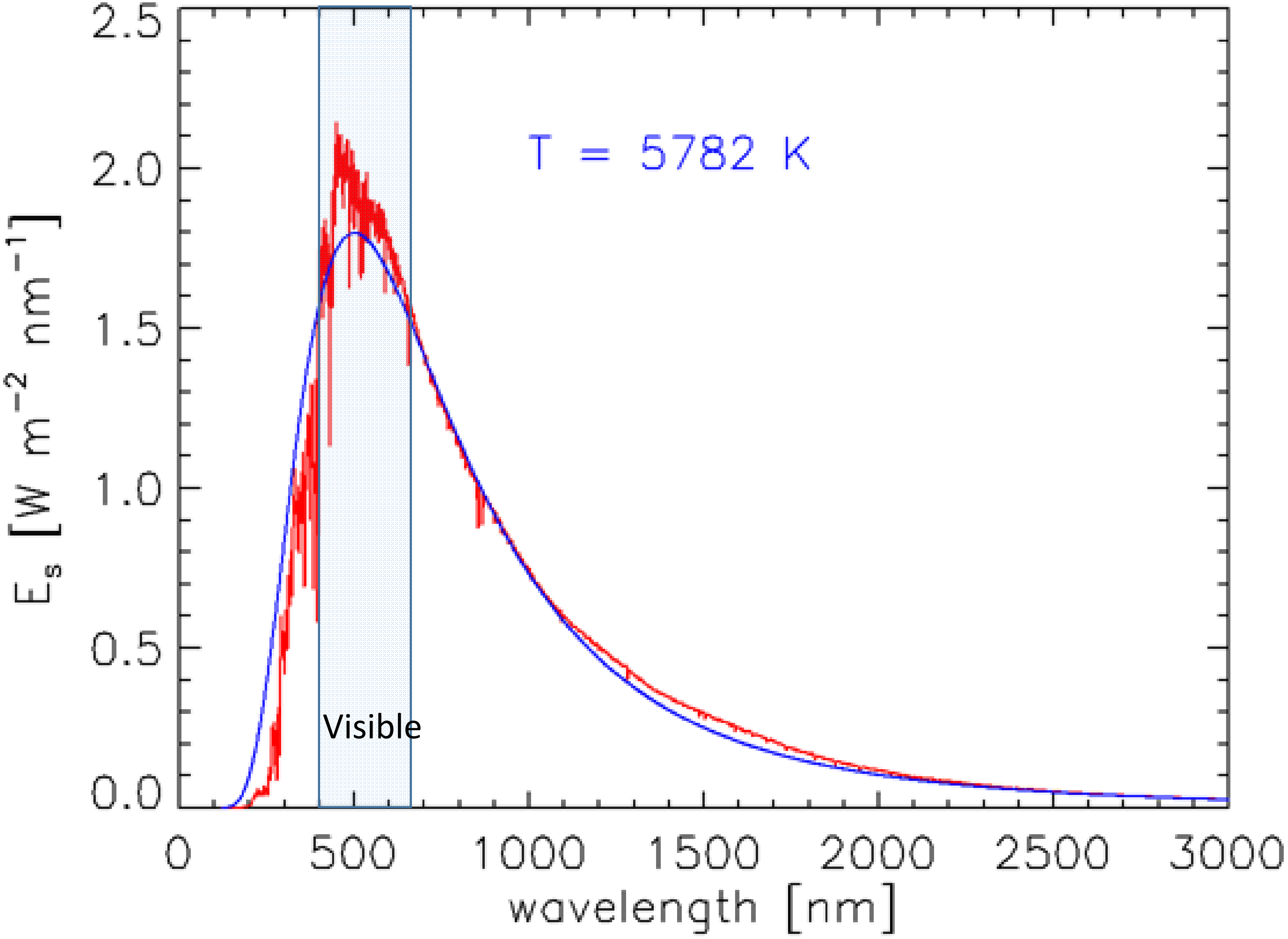
$$\tau \ll 1 \quad \Rightarrow \quad I_A = B(\nu,T_c) + \tau\, B(\nu\ ,T_s)$$

$$\tau \gg 1 \quad \Rightarrow \quad I_A = B(\nu\ ,T_s)$$

Flux from the shell



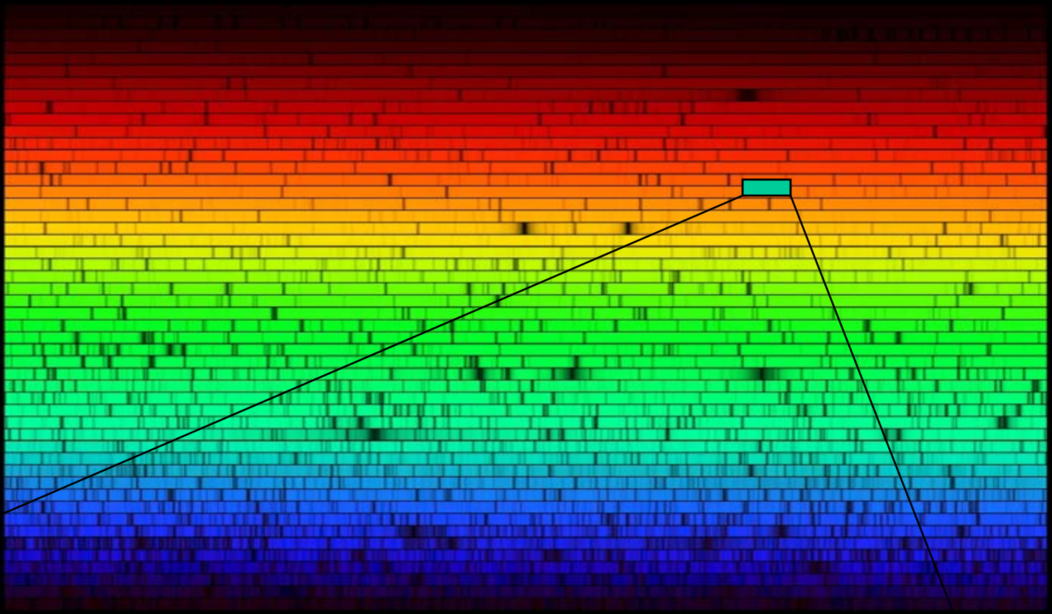
Specific flux from the sun (red curve) vs 5782K blackbody

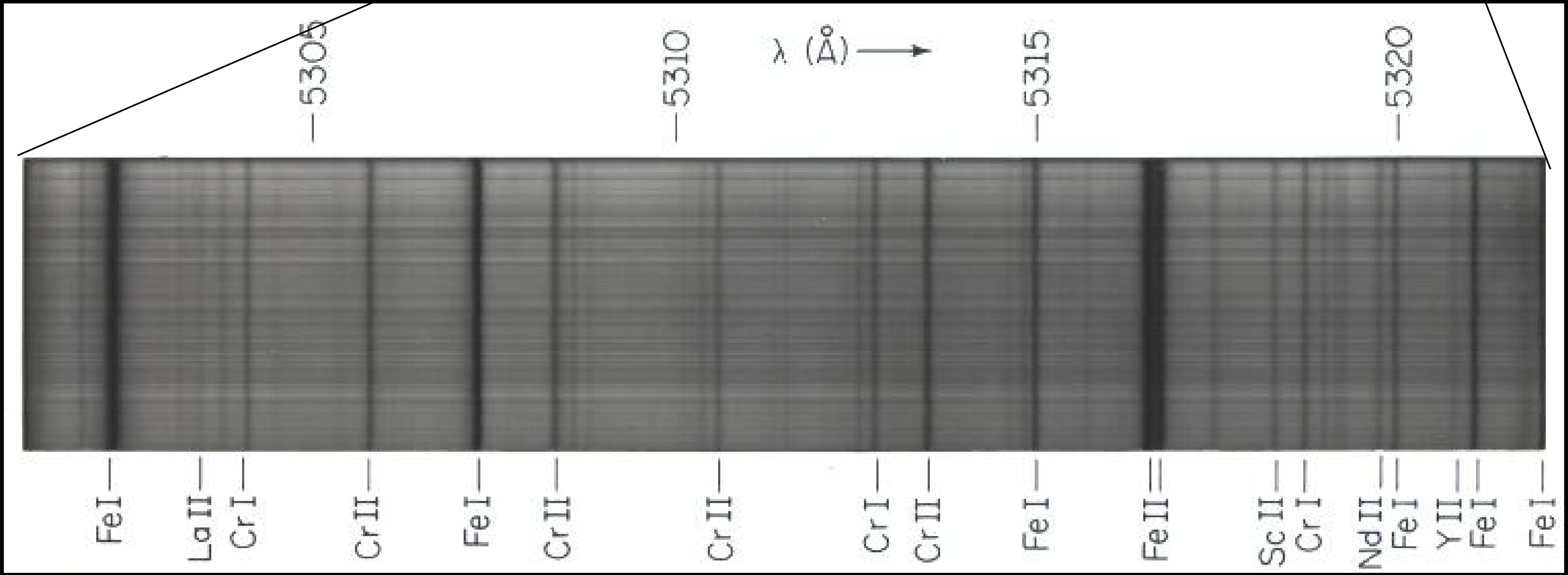


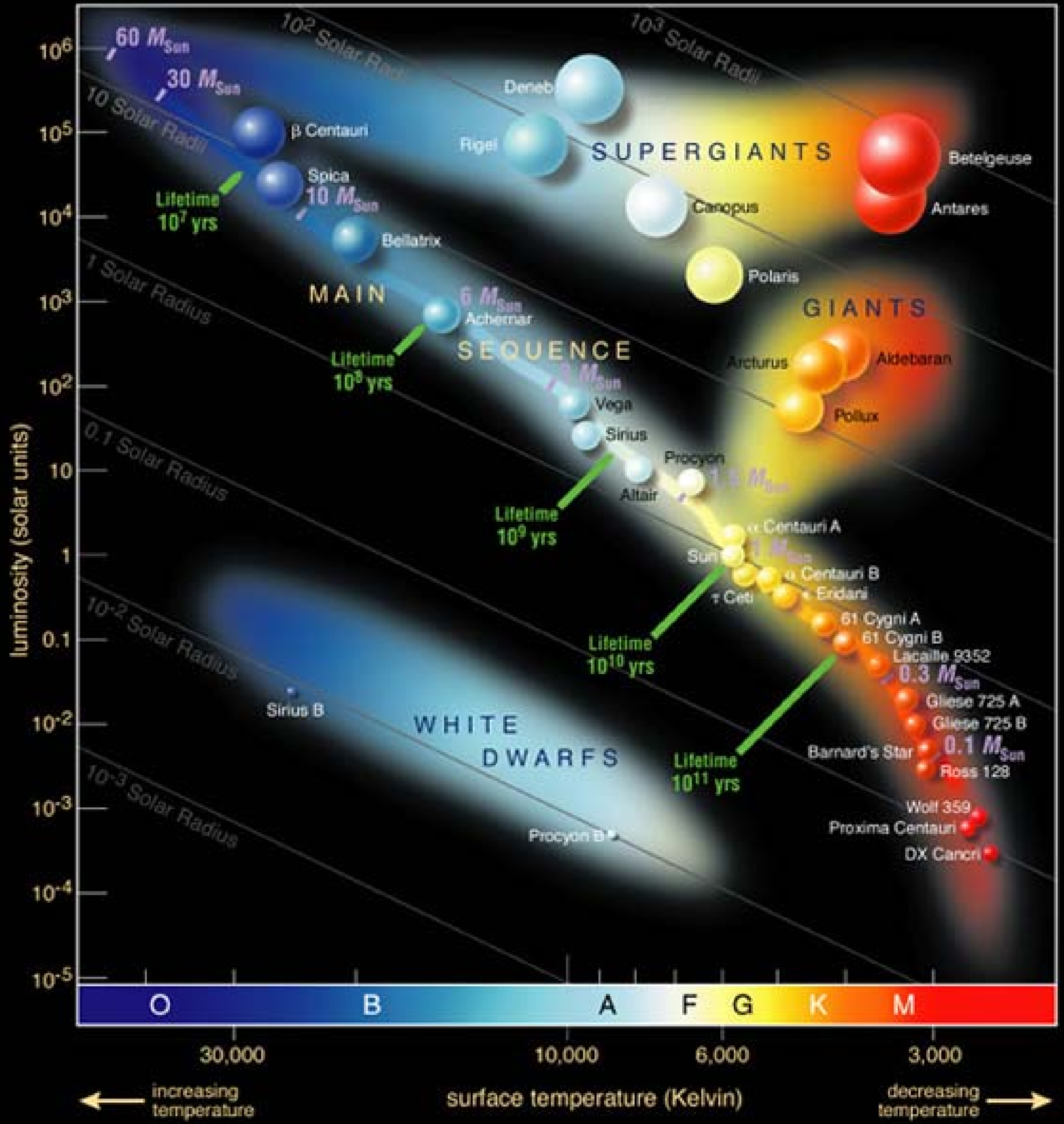
Stellar spectra :

Continuum (Blackbody)
+
absorption lines

from many different elements in the photosphere






$60\ M_{Sun}$
$30\ M_{Sun}$
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
Deneb
Rigel
SUPERGIANTS
Betelgeuse
β Centauri
Spica
$10\ M_{Sun}$
Lifetime 10^7 yrs
Canopus
Antares
Bellatrix
Polaris
1 Solar Radius
MAIN
$6\ M_{Sun}$
Achernar
GIANTS
SEQUENCE
Lifetime 10^8 yrs
$3\ M_{Sun}$
Arcturus
Aldebaran
Vega
Pollux
Sirius
0.1 Solar Radius
Procyon
Altair
$1.5\ M_{Sun}$
Lifetime 10^9 yrs
α Centauri A
$1\ M_{Sun}$
Sun
α Centauri B
τ Ceti
ε Eridani
10^{-2} Solar Radius
61 Cygni A
61 Cygni B
Lifetime 10^{10} yrs
Lacaille 9352
$0.3\ M_{Sun}$
Sirius B
Gliese 725 A
WHITE
Gliese 725 B
DWARFS
Barnard's Star
$0.1\ M_{Sun}$
Lifetime 10^{11} yrs
Ross 128
10^{-3} Solar Radius
Wolf 359
Proxima Centauri
Procyon B
DX Cancri
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Thermal Radiation

- There are many situations where matter is in local thermal equilibirim with radiation, or close to :
  - Photospheres of stars
  - Surface (or atmosphere) of planets
  - Clouds of interstellar dust
  - Early Universe
- In all these cases the emission is thermal: blackbody or similar.

Blackbody Radiation

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

$$B(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{kT\lambda}}-1}$$

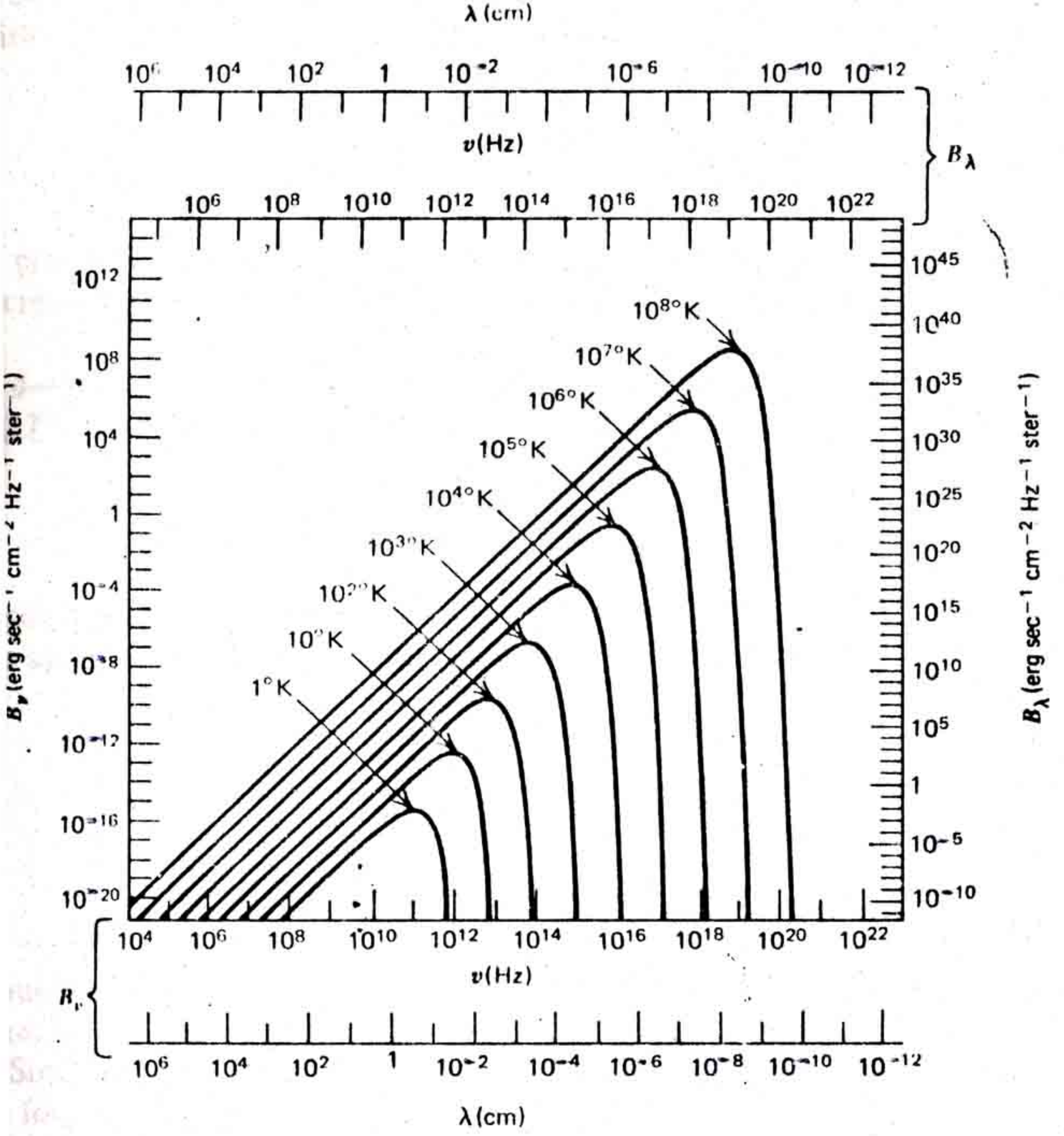
- Maximum brightness

$$\lambda_{\max}T=0.290\,cm\,K$$

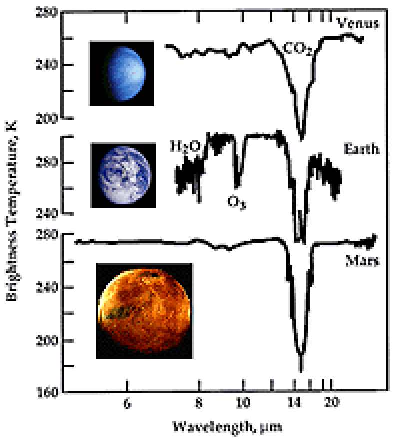
- Low frequency :

$$B(\nu,T)\approx\frac{2\nu^2}{c^2}kT$$

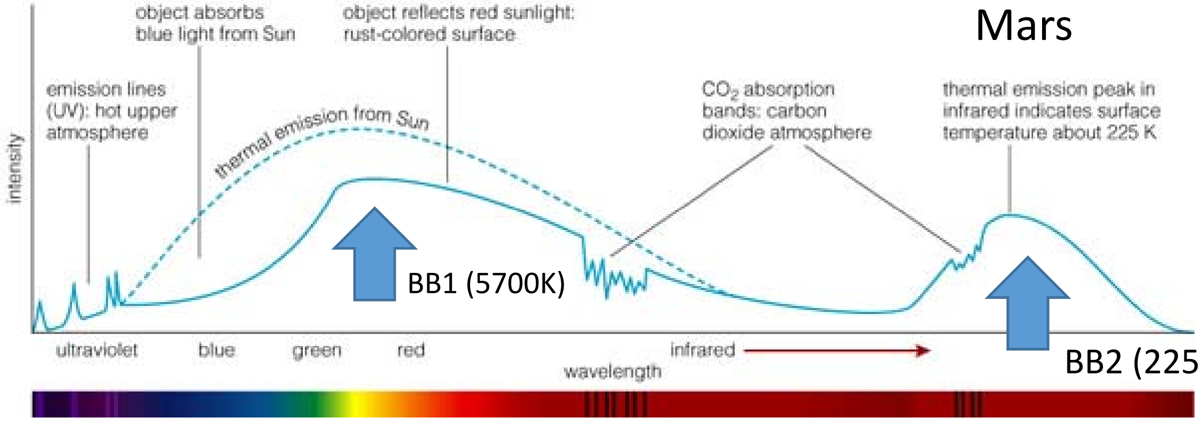
$$h\nu<<kT$$



Spectrum of planets



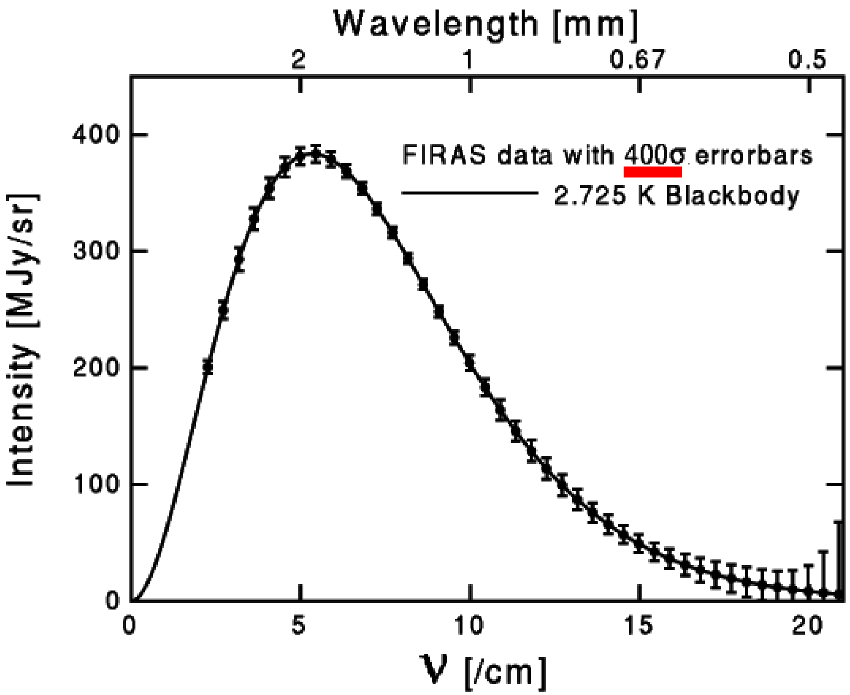
Mars



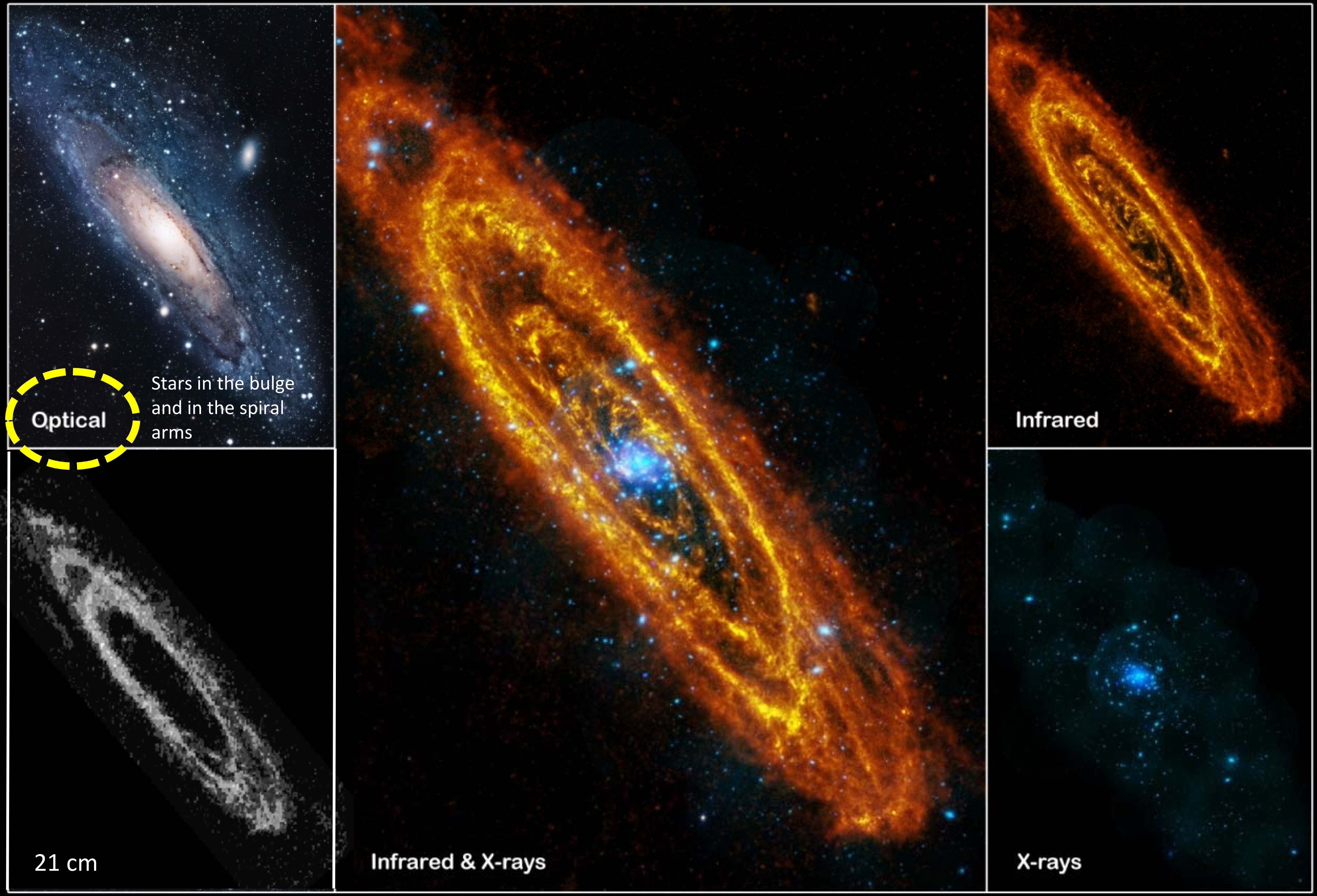
BB1 (5700K)

BB2 (225K)

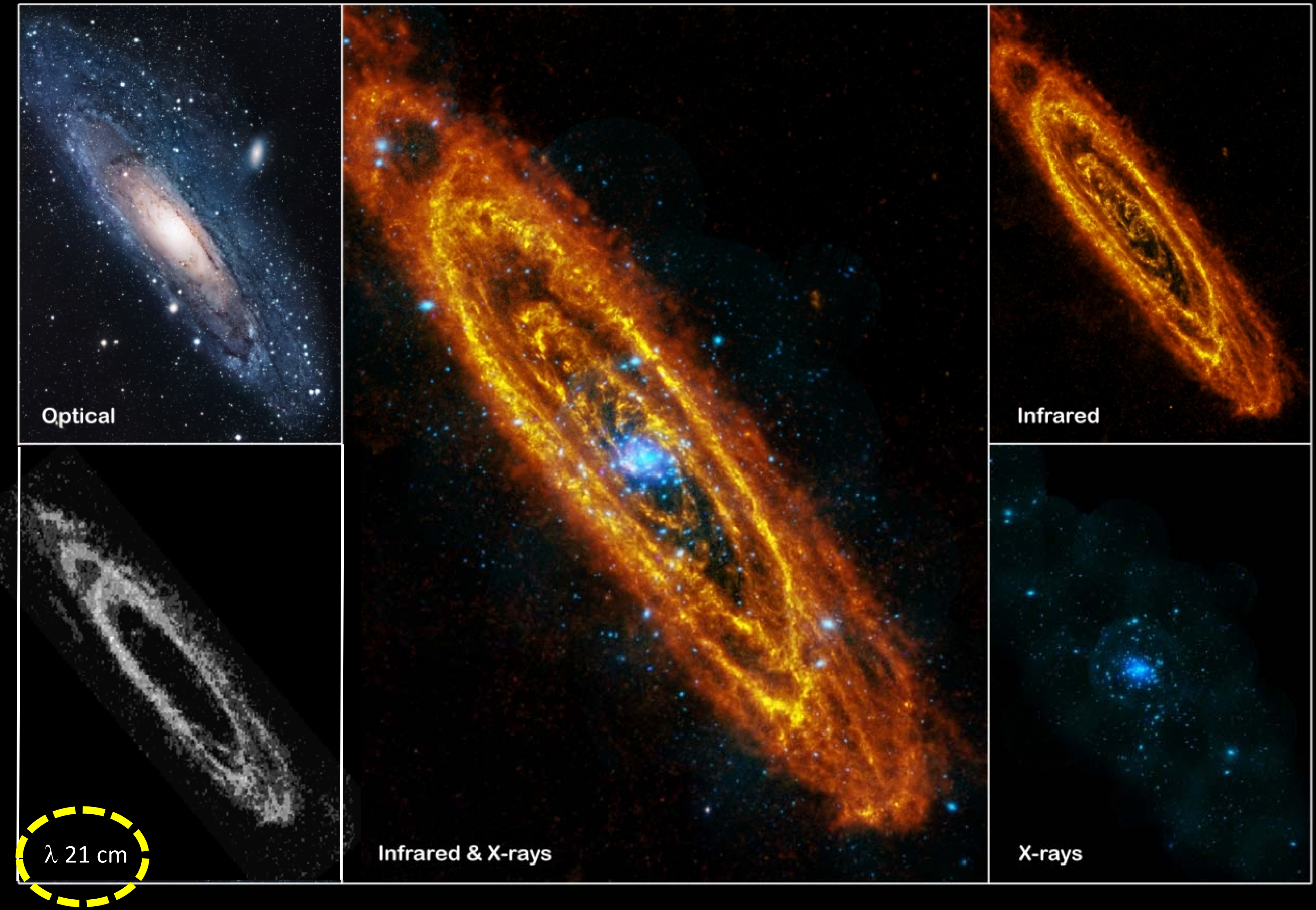
Spectrum of the Cosmic Microwave Background



BB3 (2.725K)



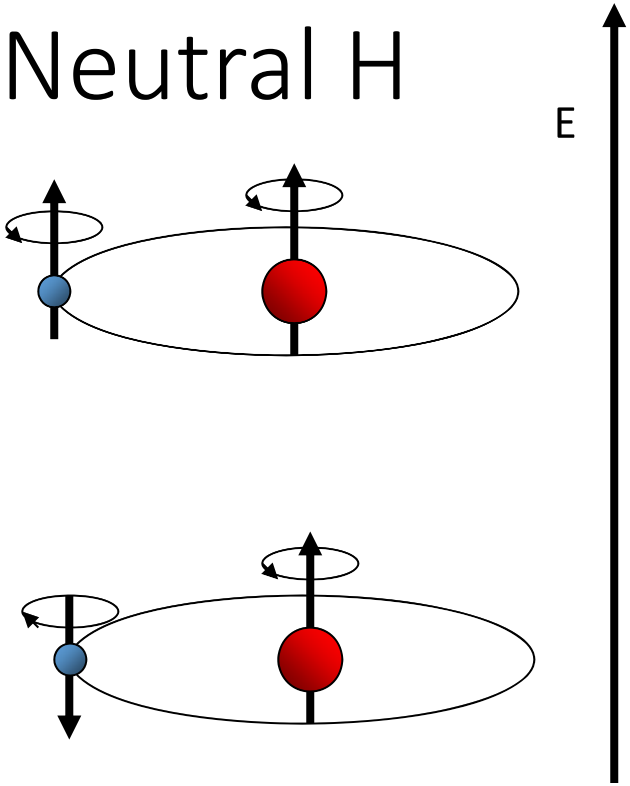
Understanding of a cosmic source requires observations across the whole EM spectrum



Understanding of a cosmic source requires observations across the whole EM spectrum

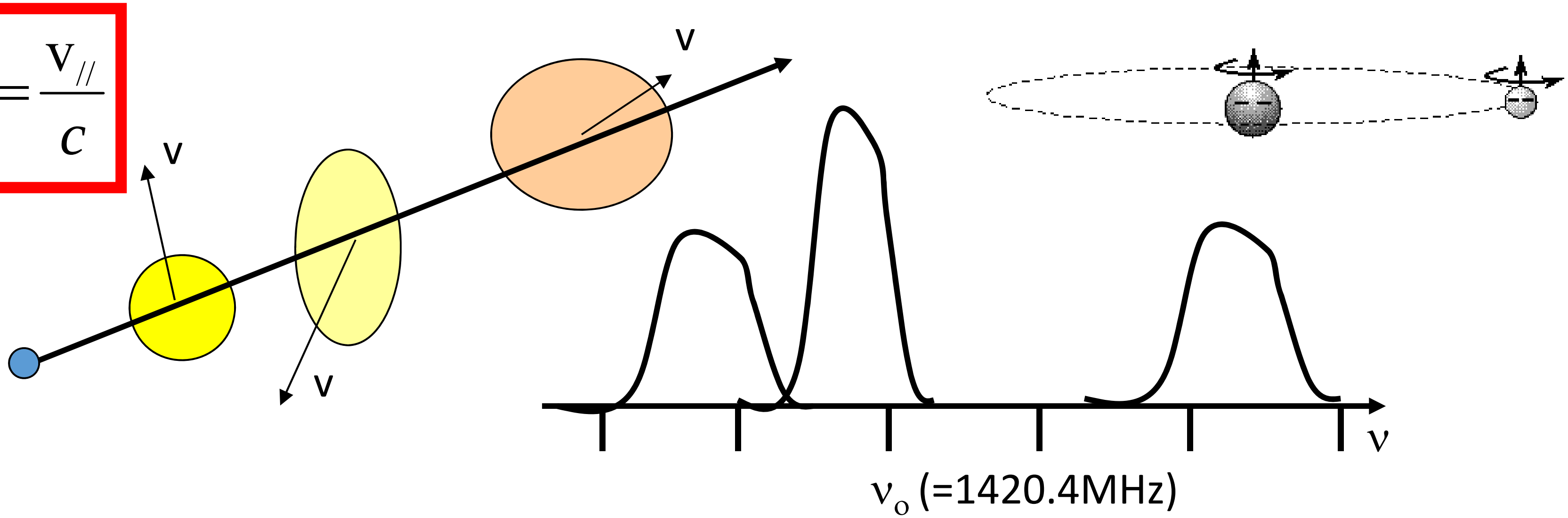
Neutral H

- Hydrogen is the most abundant element in the universe
- 3×10^9 solar masses of HI in our Galaxy, in optically thin clouds, with T between 30 and 80K, density from 100 to 800 cm^{-3}, masses from 1 to 100 M_{sun}.
- The best way to study neutral H (HI) is the spin-flip line at 21.1 cm (1420.4 MHz).
- This is a forbidden line, the lifetime of the excited state is million years, and is very difficult to study it in the laboratory.
- Despite of this, there are so many H atoms in any line of sight through our Galaxy, that a significant amount of 21 cm photons is produced continuously.
- The intrinsic width of the line is negligible, and the measured width is due to Doppler broadening



Neutral atomic Hydrogen creates 21 cm radiation

$$\boxed{\frac{\Delta\nu}{\nu_o} = \frac{v_{//}}{c}}$$



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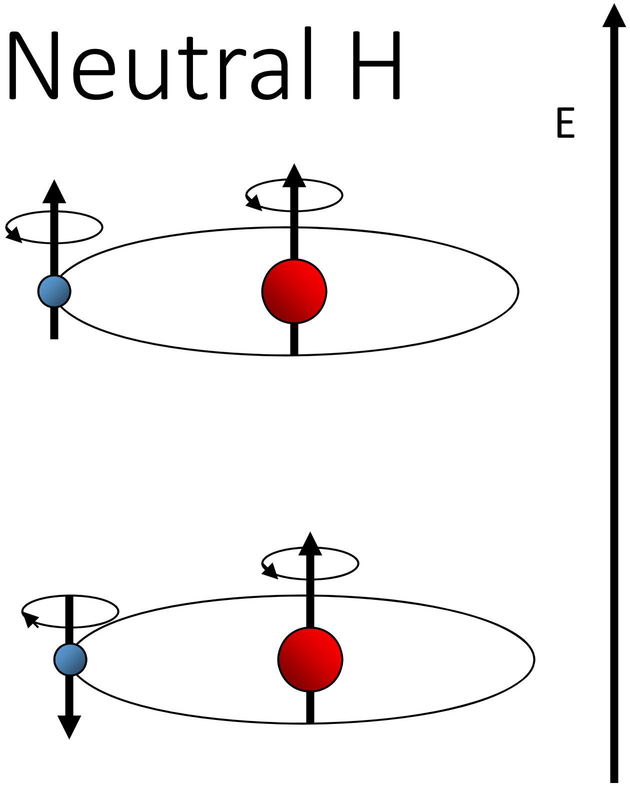

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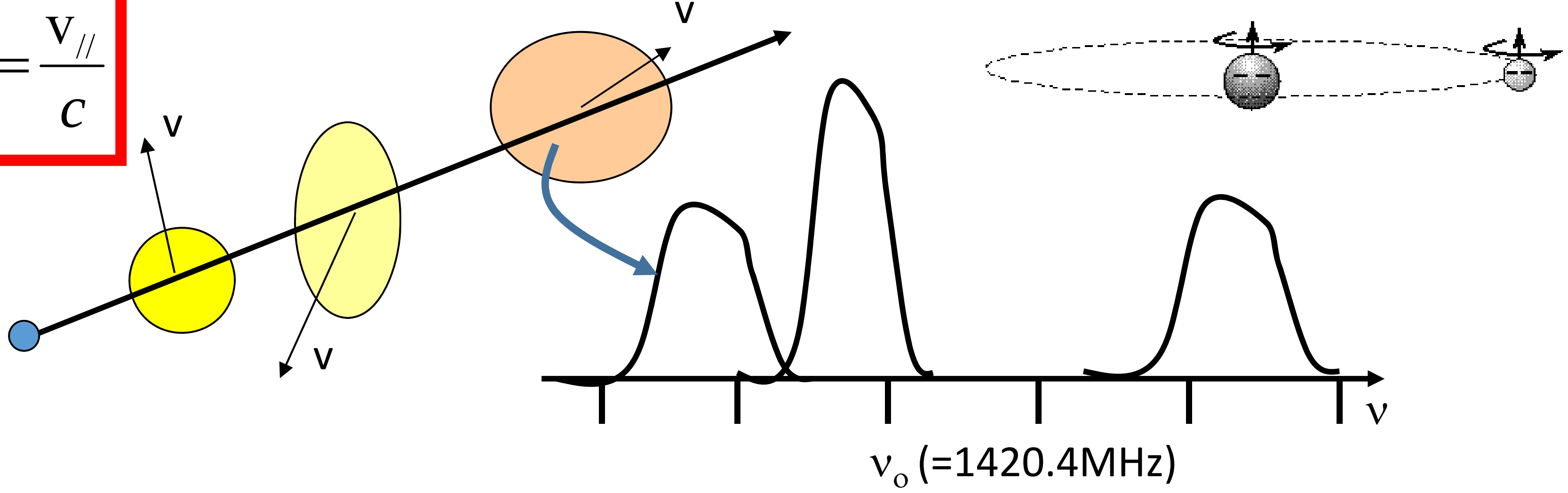

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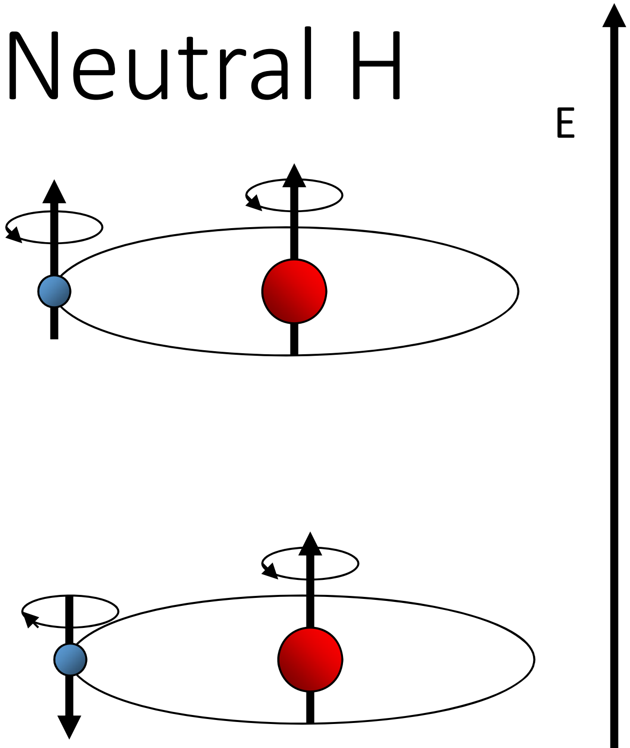

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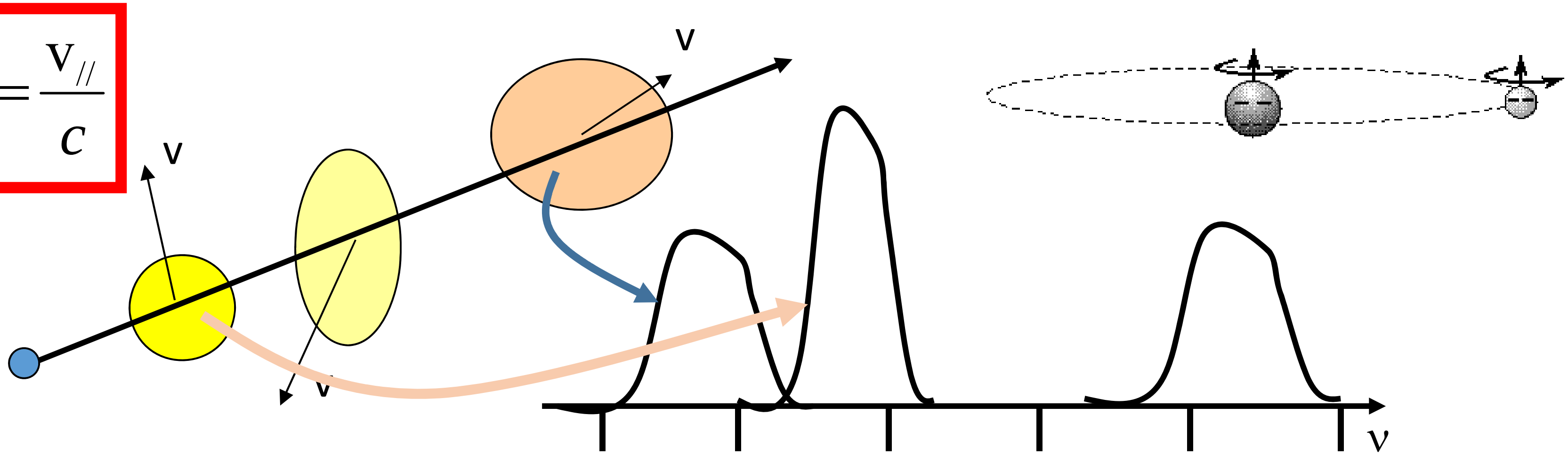

ν_o (=1420.4MHz)

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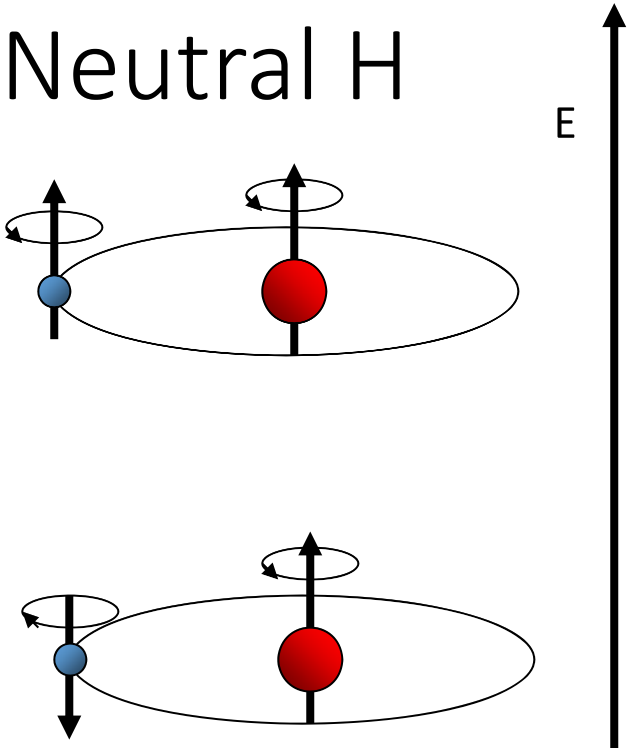

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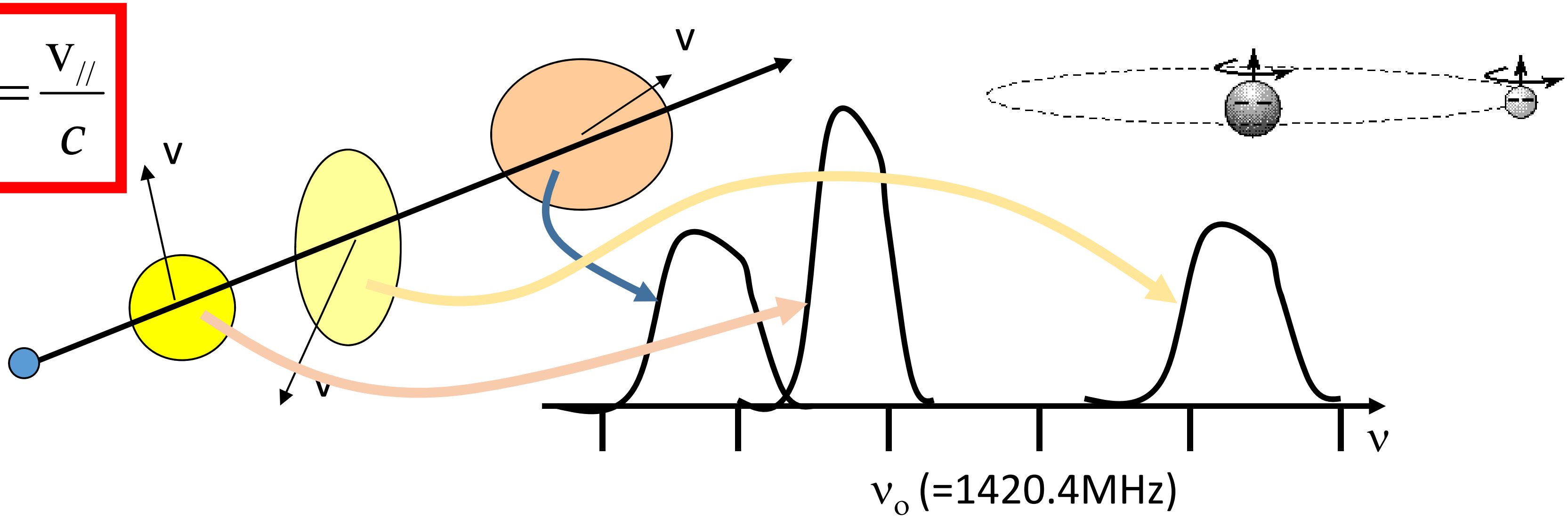
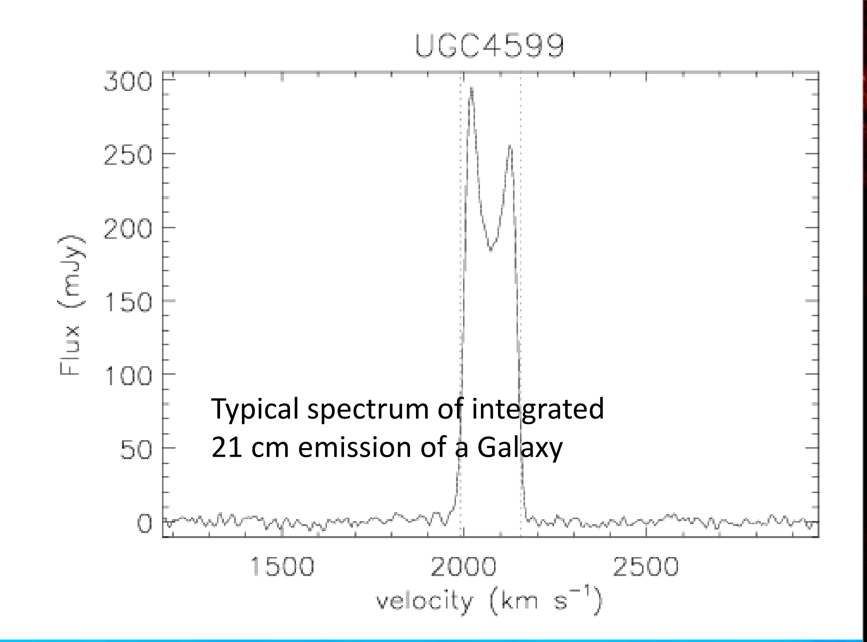
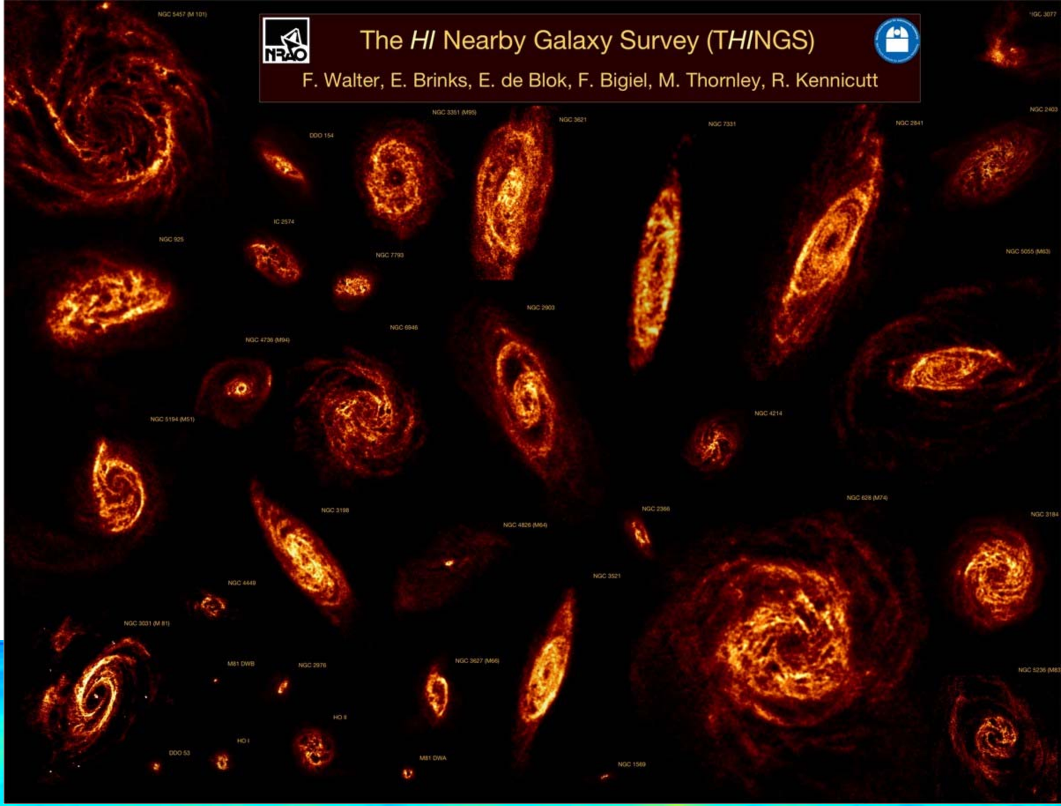
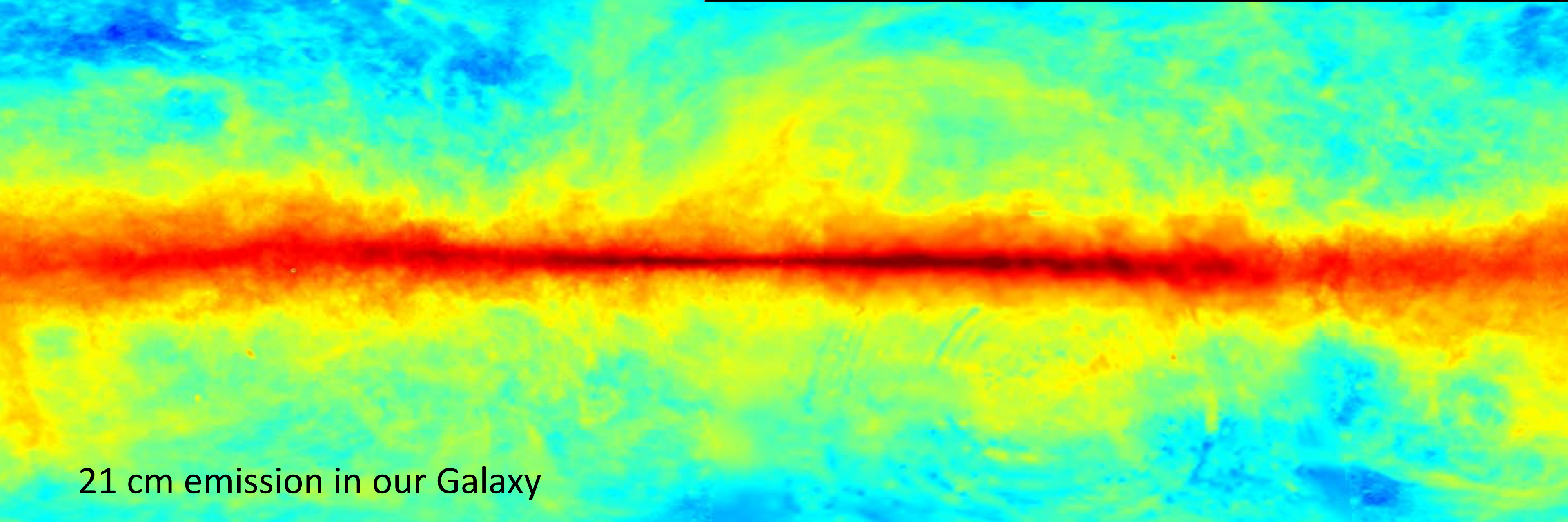




Typical spectrum of integrated 21 cm emission of a Galaxy

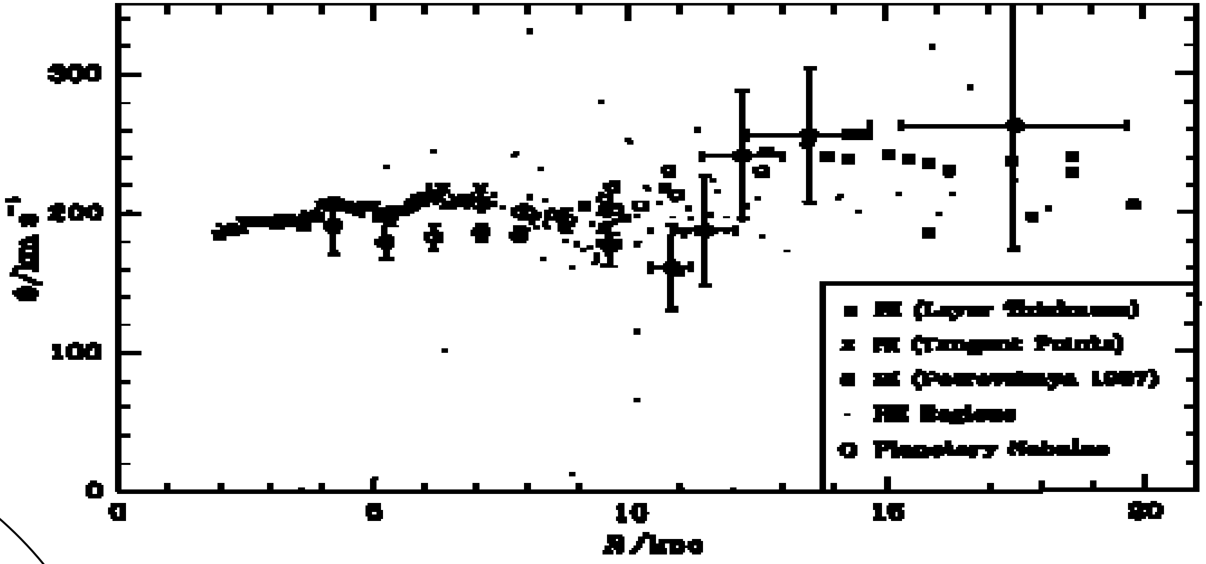




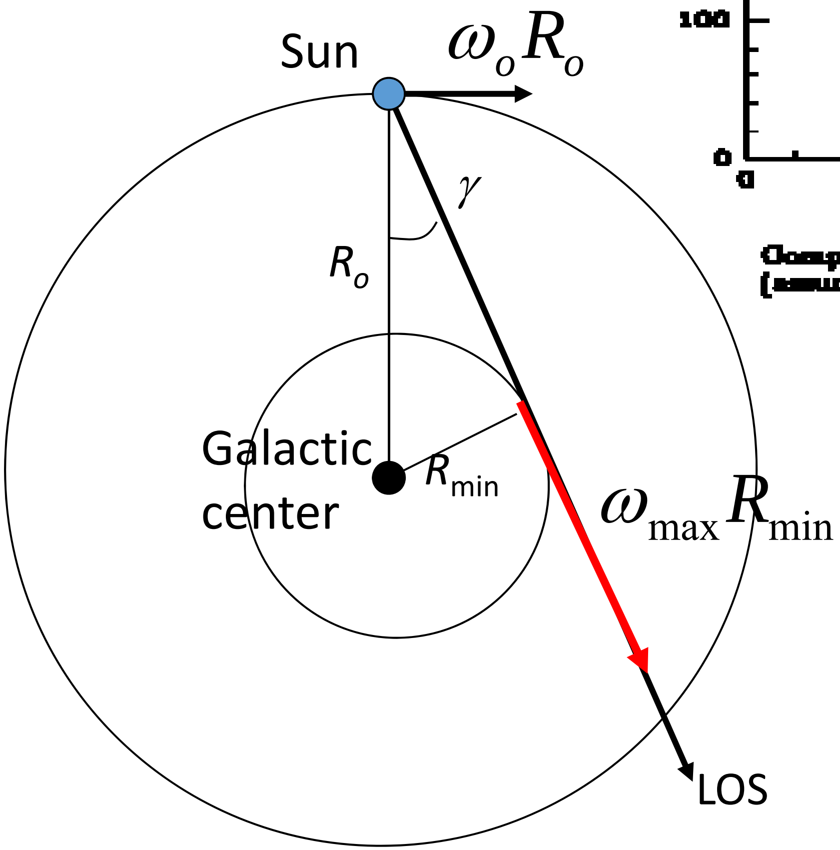
21 cm emission in our Galaxy

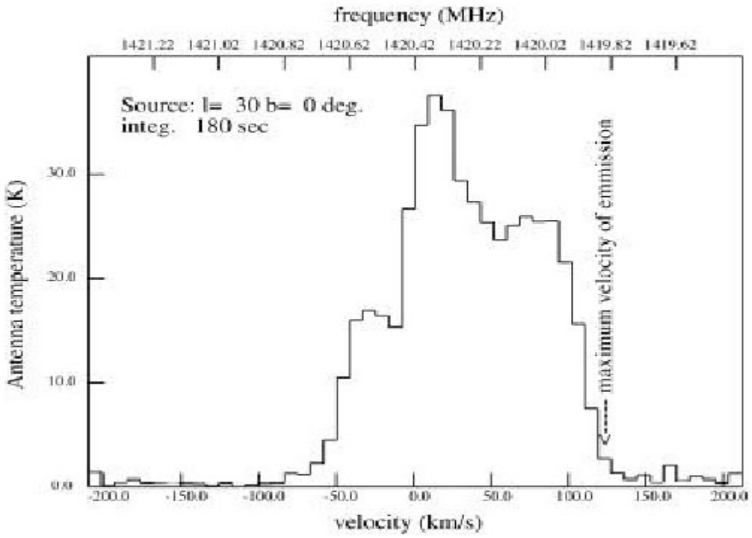
Rotation curve of our galaxy from 21cm line etc.

Contrary to Keplerian expectation, orbital velocity of matter high even at large distance from the center.



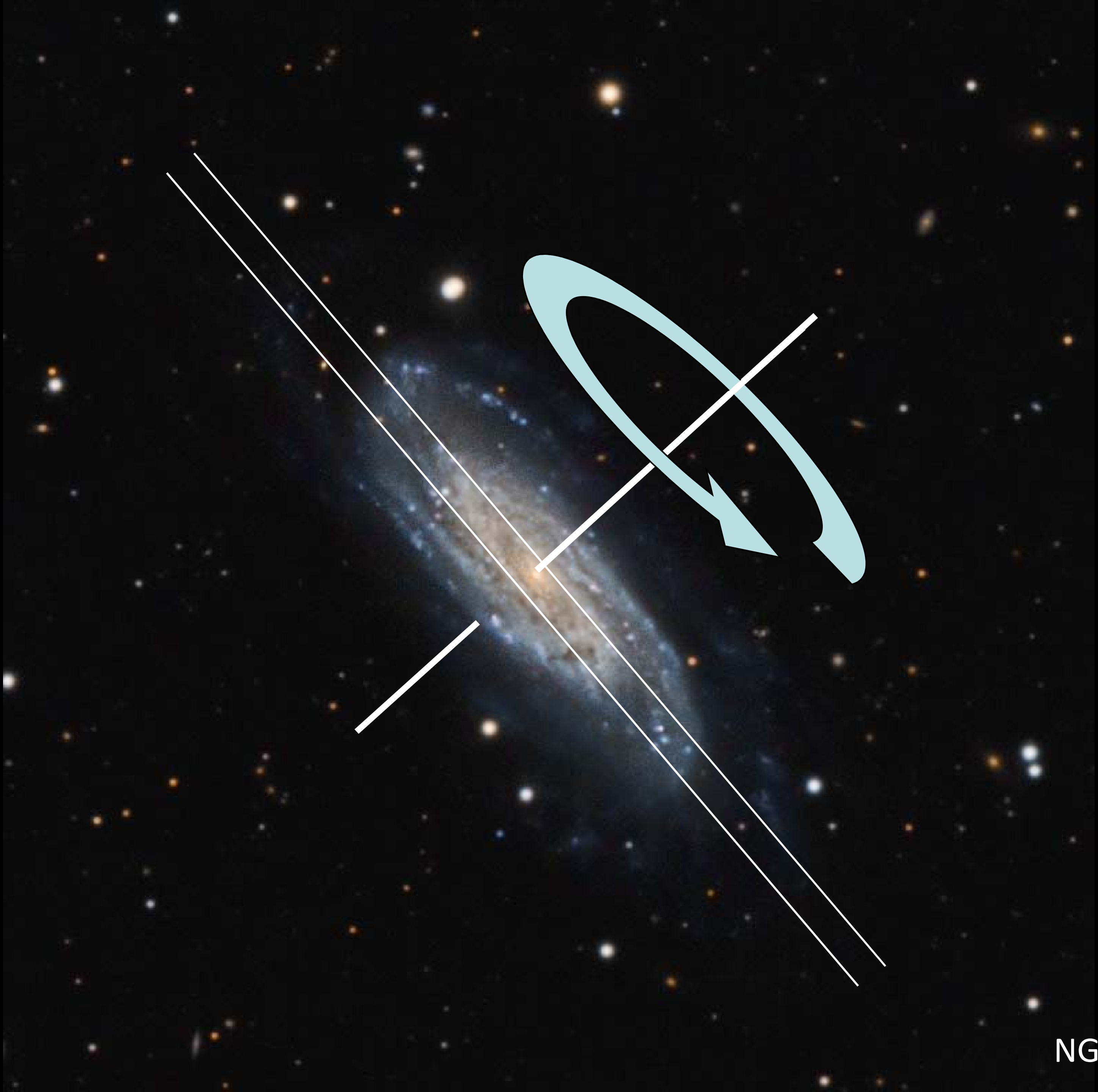
Comparison of the rotation curves calculated by all the methods discussed (assuming R_0 = 7.0 kpc and Θ_0 = 200 km s^{-1}).



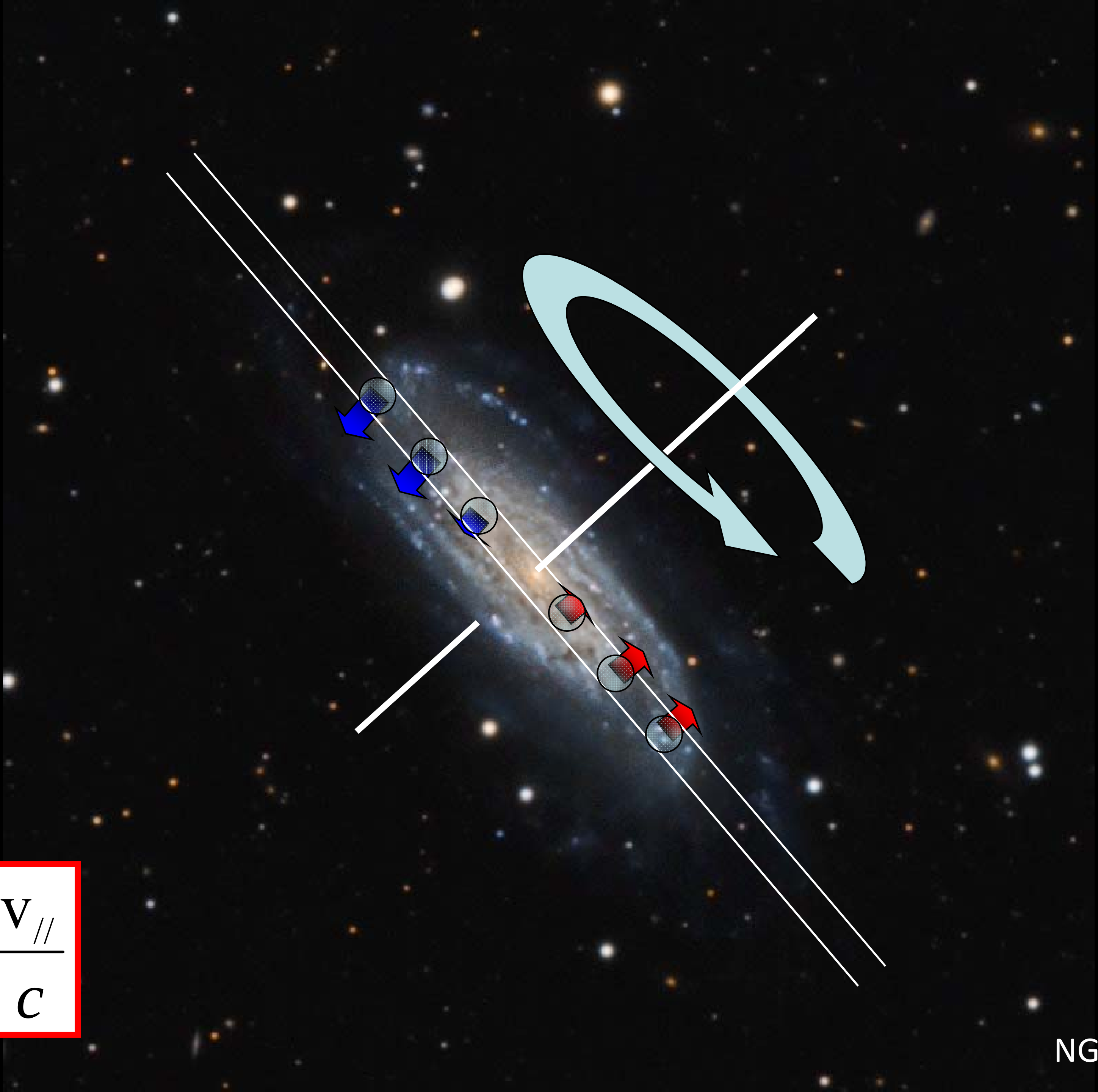


NGC3198

NGC3198



NGC3198

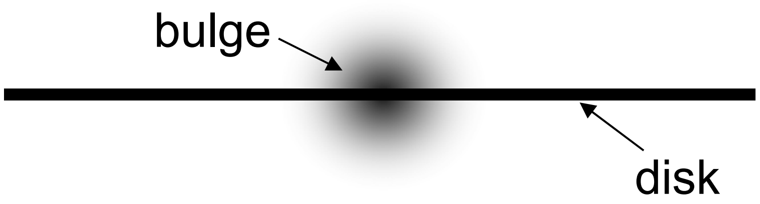


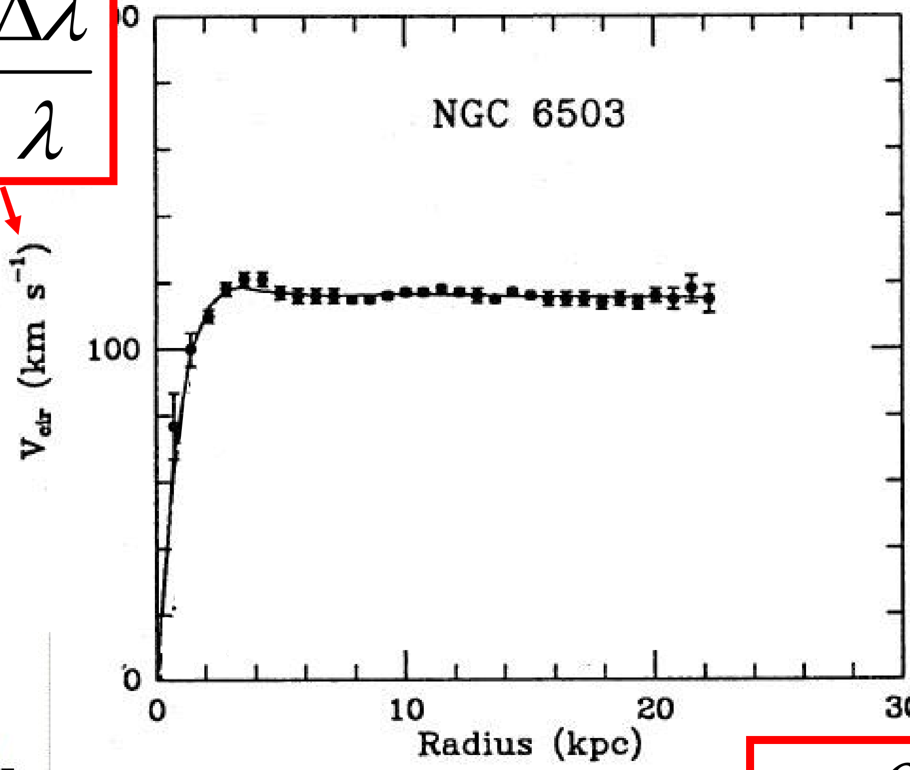
$$\boxed{\frac{\Delta\lambda}{\lambda} = \frac{v_{//}}{c}}$$

NGC3198

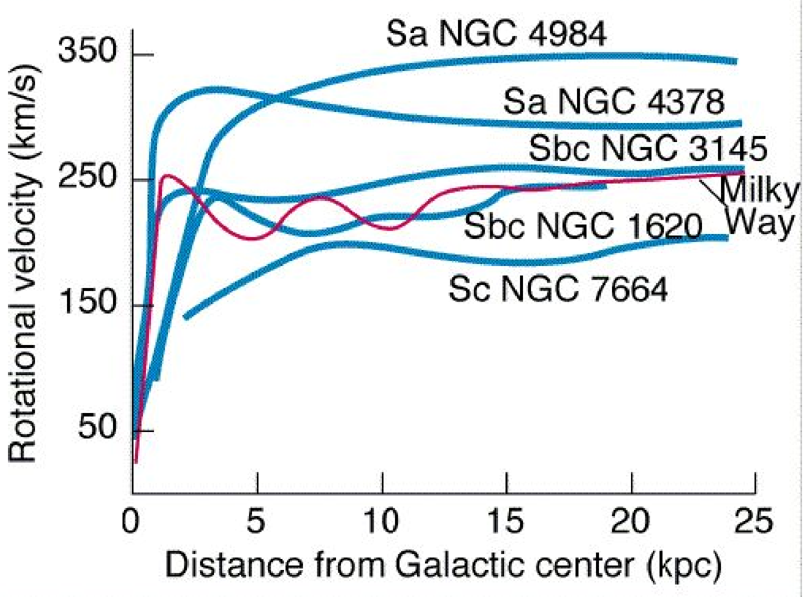
$$\boxed{v_{\mathrm{LOS}} = c\frac{\Delta\lambda}{\lambda}}$$

Edge-on spiral galaxy :

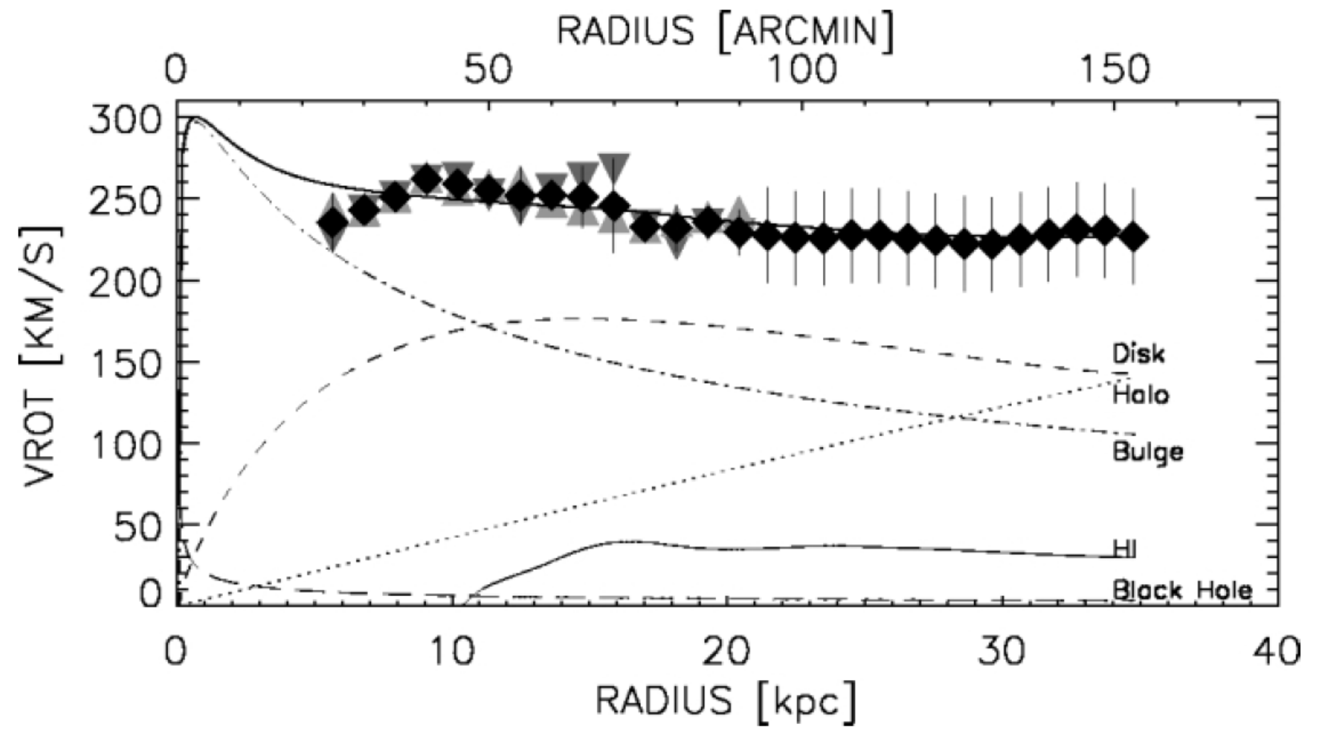




$$\boxed{r = \theta\, D}$$



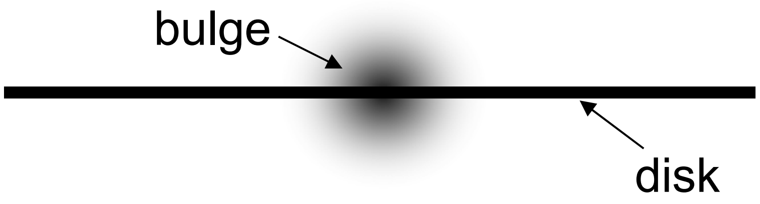
- All the rotation curves share the same basic trend (linear rise in the bulge region, approximately constant at larger distances)



M31

- Using 21 cm radiation the constant v trend at large distances is confirmed, at radii >> than the optical radius.

Edge-on galaxy :



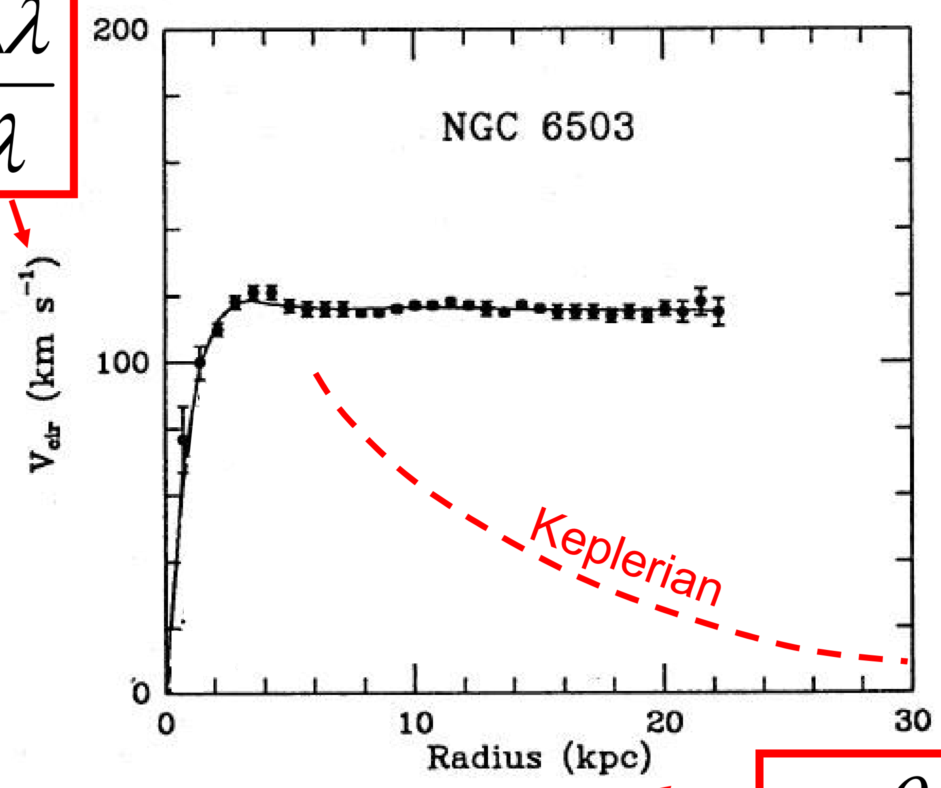
If the mass density has a spherical symmetry (as in the bulge of the galaxy)

$$v = \sqrt{\frac{GM(<r)}{r}}$$

From the bulge only, the velocity of a test star at $r > r_b$ would be Keplerian

$$v = \sqrt{\frac{GM_b}{r}}$$

$$\boxed{v = c\frac{\Delta\lambda}{\lambda}}$$



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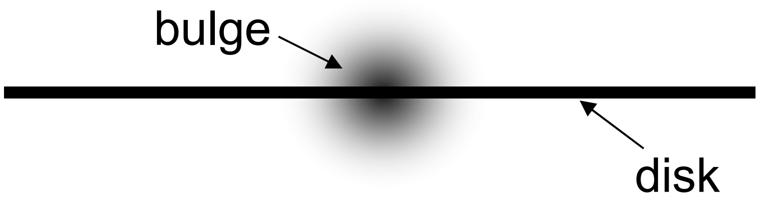

If the mass density has a spherical symmetry (as in the bulge of the galaxy)

$$\mathrm{v} = \sqrt{\frac{GM(<r)}{r}}$$

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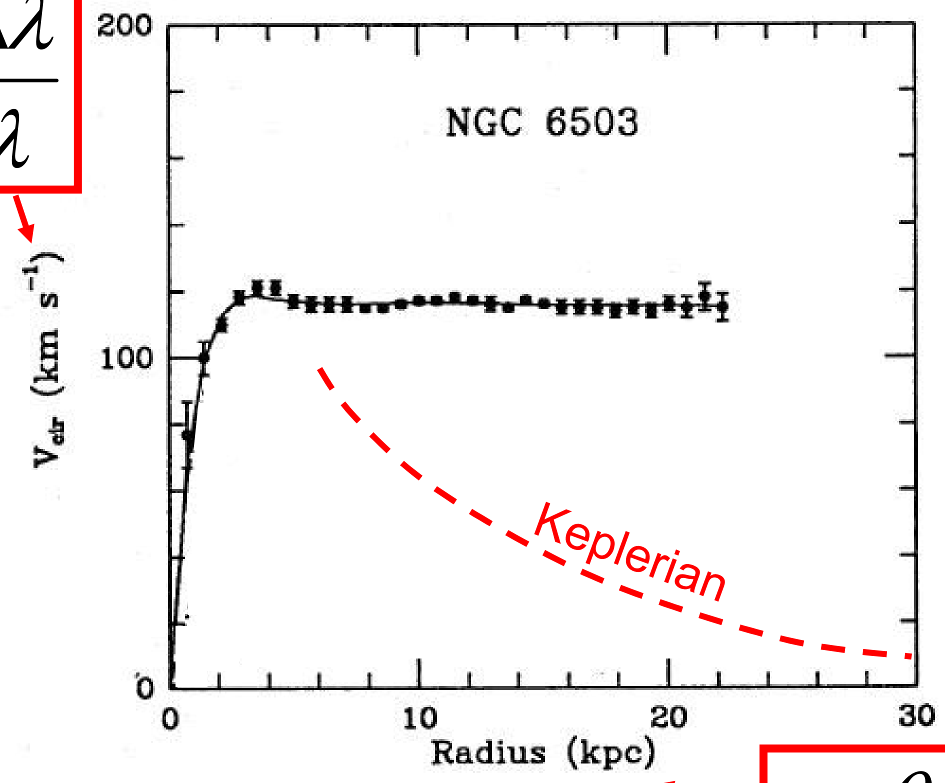
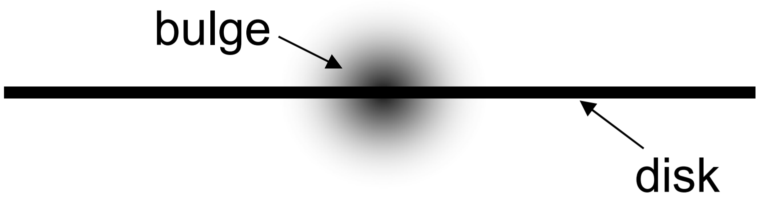


$$\boxed{\mathrm{r} = \theta\, D}$$

It can be shown that in the presence of an exponential disk with scale radius r_d the combined effect of bulge + disk is still Keplerian :

$$\boxed{\mathrm{v} \approx \frac{1}{\sqrt{r}}\ ; \quad r > 3r_d}$$

Edge-on galaxy :



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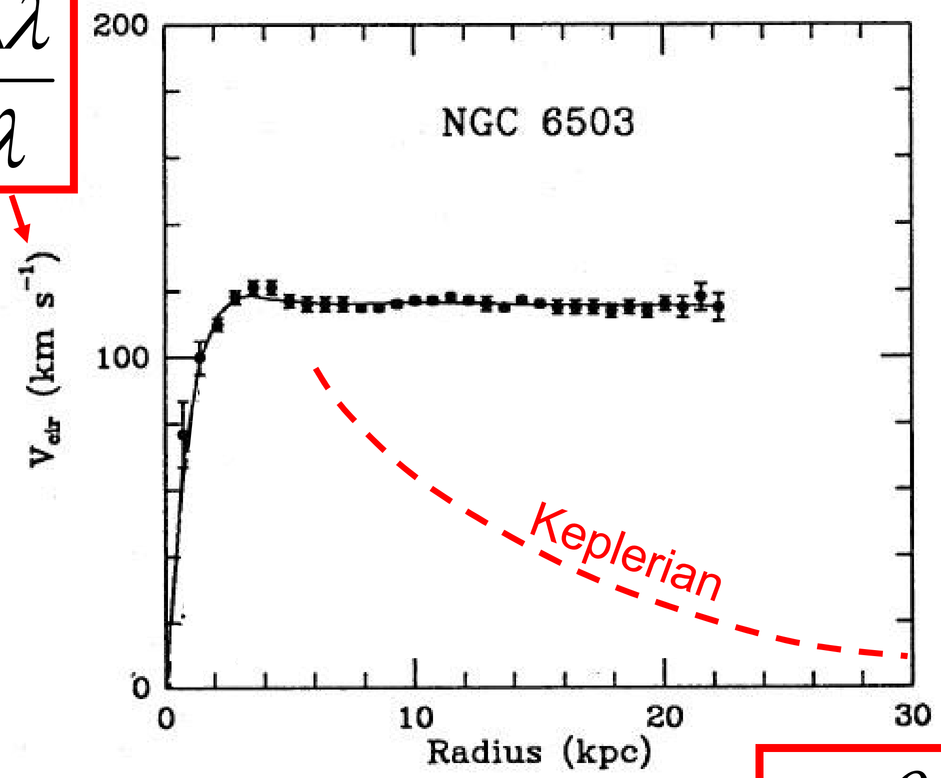
$$\boxed{v = c\frac{\Delta\lambda}{\lambda}}$$



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It can be shown that in the presence of an exponential disk with scale radius r_d the combined effect of bulge + disk is still Keplerian :

$$\boxed{v \approx \frac{1}{\sqrt{r}} \quad ; \quad r > 3r_d}$$

THIS DOES NOT FIT THE MEASURED DATA !

- Two main interpretations:
  - The mass of the galaxy is dominated by an approximately spherical dark halo, much larger than the optical radius, and with density falling as $1/r^2$ at large radii. In fact, in this case

$$M(<r) = \int_0^r 4\pi r^2 \rho(r)\,dr \propto r$$

$$\longrightarrow \quad \mathrm{v}(r) = \sqrt{\frac{GM(<r)}{r}} \propto \text{constant}$$

  - Gravity deviates from Newton’s law at extremely low accelerations (i.e. at large distances in galaxies) (Milgrom, MOND theory).

Dark Matter

- The luminosity of spiral galaxies falls off exponentially wirh r ; the luminosity of elliptical galaxies falls off as $1/r^4$.
- So, luminous matter cannot produce the observed constant rotation curves at large radii.
- The total luminous mass is much less than the mass required from the relation

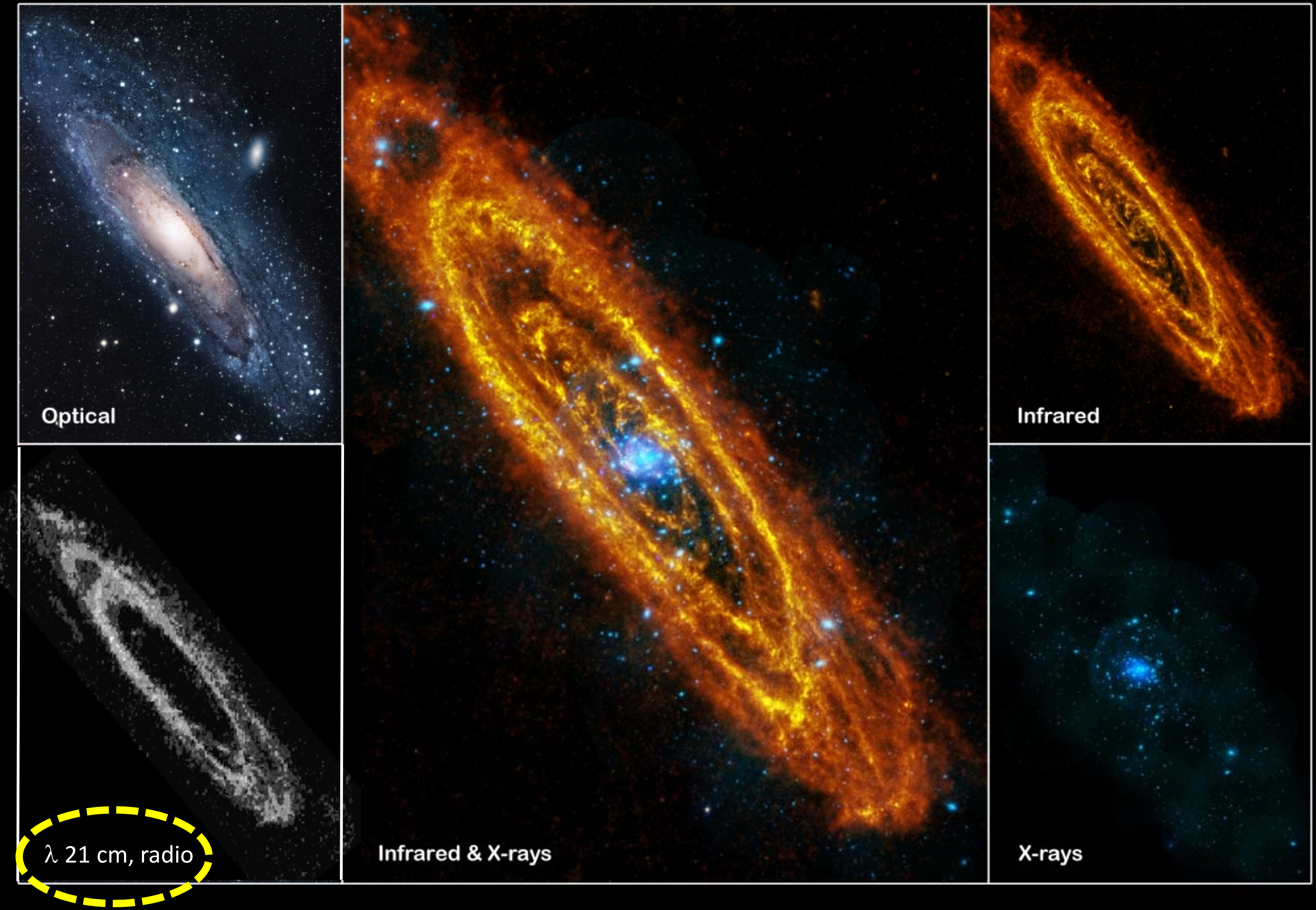
$$\mathrm{v} = \sqrt{\frac{GM(<r)}{r}} \quad \rightarrow \quad M(<r_{\max}) = \frac{r_{\max}\mathrm{v}_{\max}^2}{G}$$

- Typical numbers (confirmed also by the analysis of the motion of satellite galaxies):

$$\begin{aligned} &M(<200\,kpc) \approx 2\times 10^{12} M_{sun} \\ &L \approx 2\times 10^{10} L_{sun} \end{aligned} \quad \Rightarrow \quad \gamma = \frac{M_{Sp}}{L_{Sp}} \approx 100\frac{M_{sun}}{L_{sun}} = 100\gamma_{sun}$$

- Stars in spiral galaxies have an average mass to light ratio $\gamma<5\gamma_{sun}$. So the required mass has to be **dark**.
- Luminous matter can account for at most 5% of the total mass.

Blue = non-baryonic, dark matter halo
White = baryonic matter



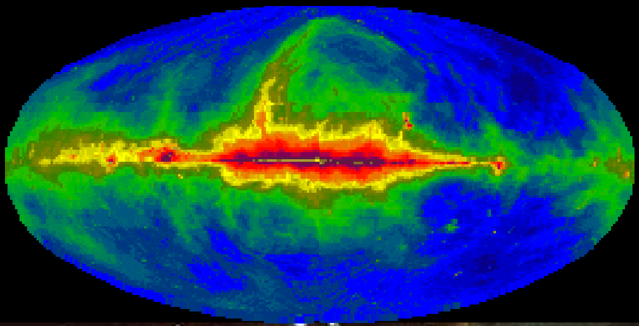
Understanding of a cosmic source requires observations across the whole EM spectrum

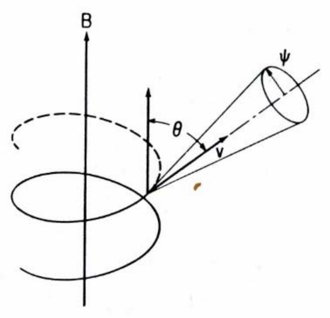
Galactic Synchrotron

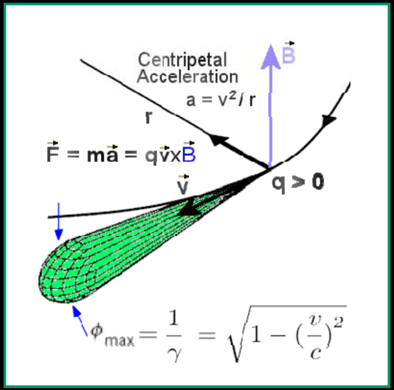
$$I(\nu) \approx \nu^{\alpha}$$

$$\alpha \approx -0.8 \pm 0.1$$

- Due to free electrons spiraling the in magnetic field of our Galaxy
- Continuum spectrum, depends on energy spectrum of electrons
- Significantly polarized (linear & circular)

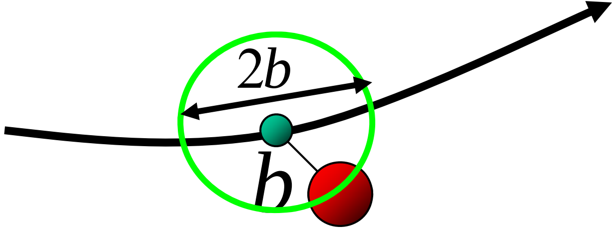


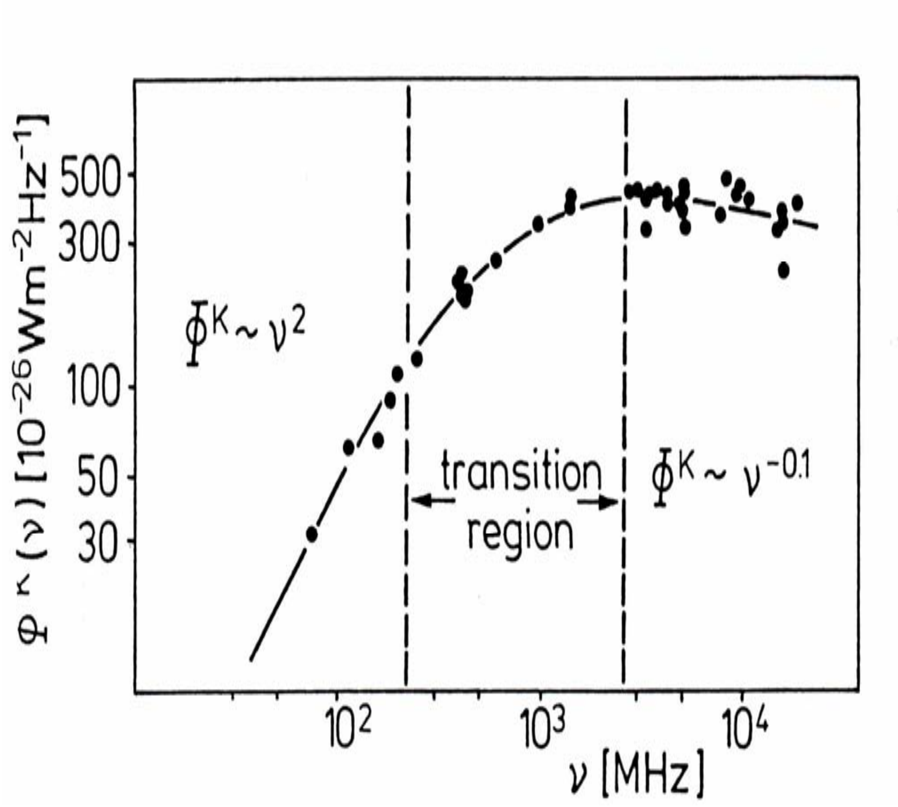


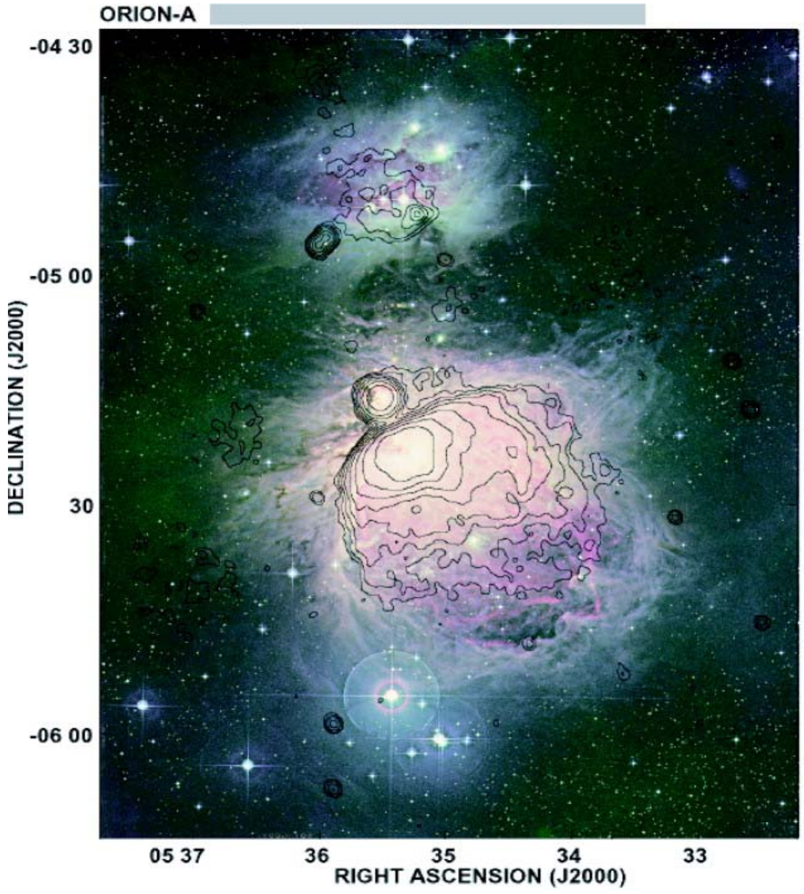


Free-Free Radiation

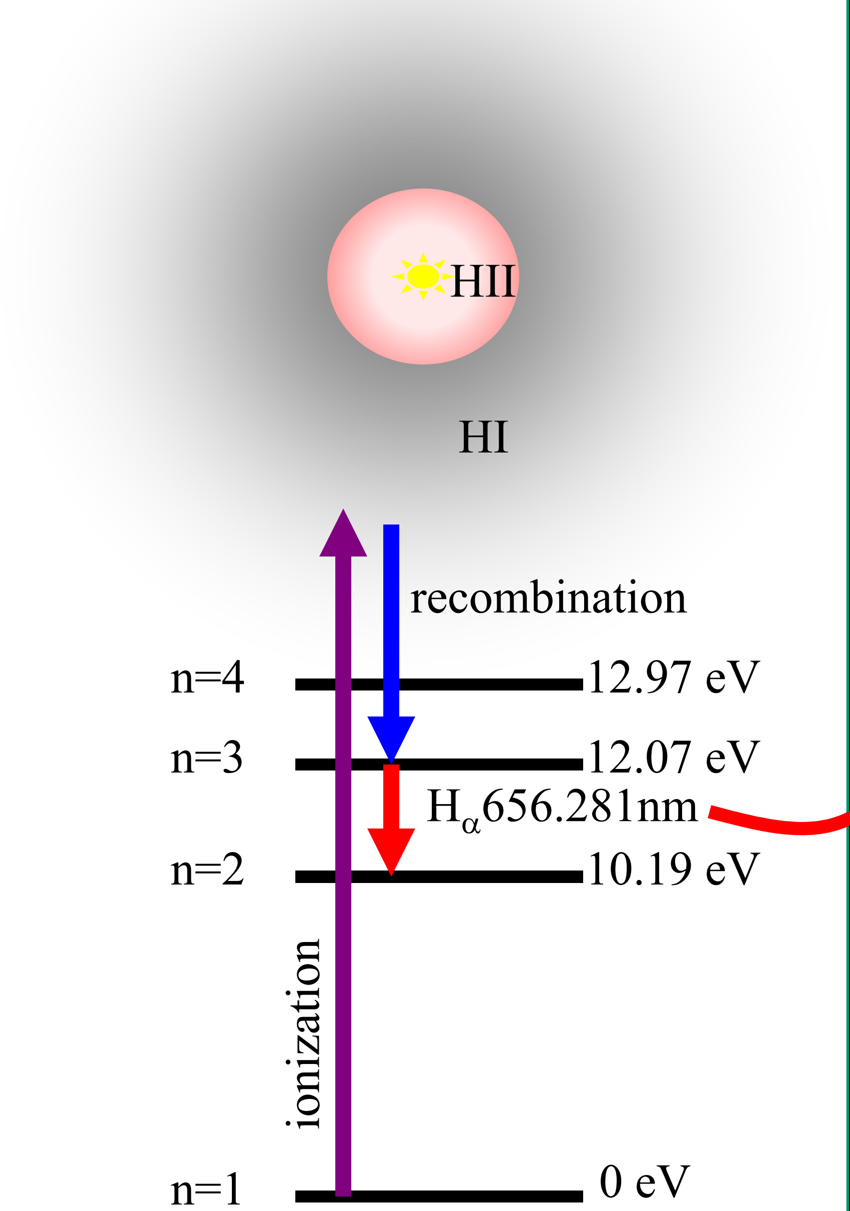
- Due to free electrons scattering against protons
- Continuum spectrum
- not polarized
- Evident in HII regions







HII regions



HII

HI

recombination

ionization

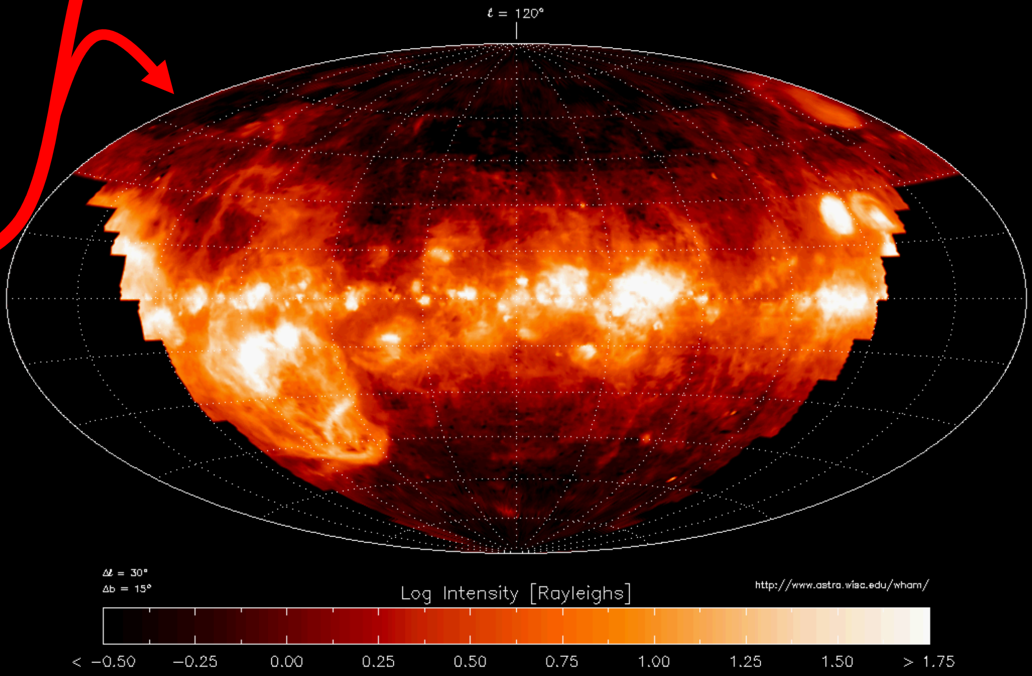
n=4 12.97 eV

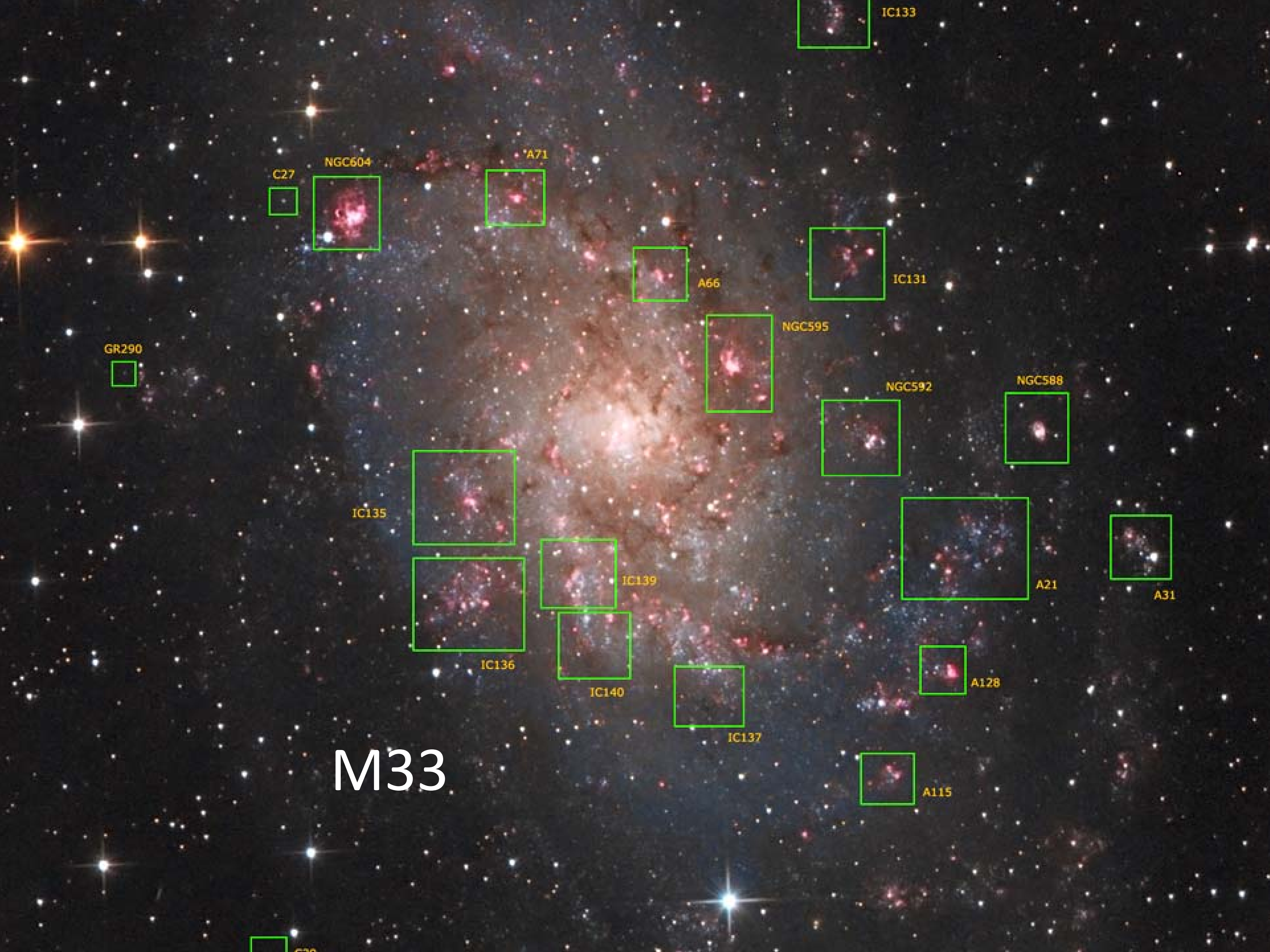
n=3 12.07 eV

H_α656.281nm

n=2 10.19 eV

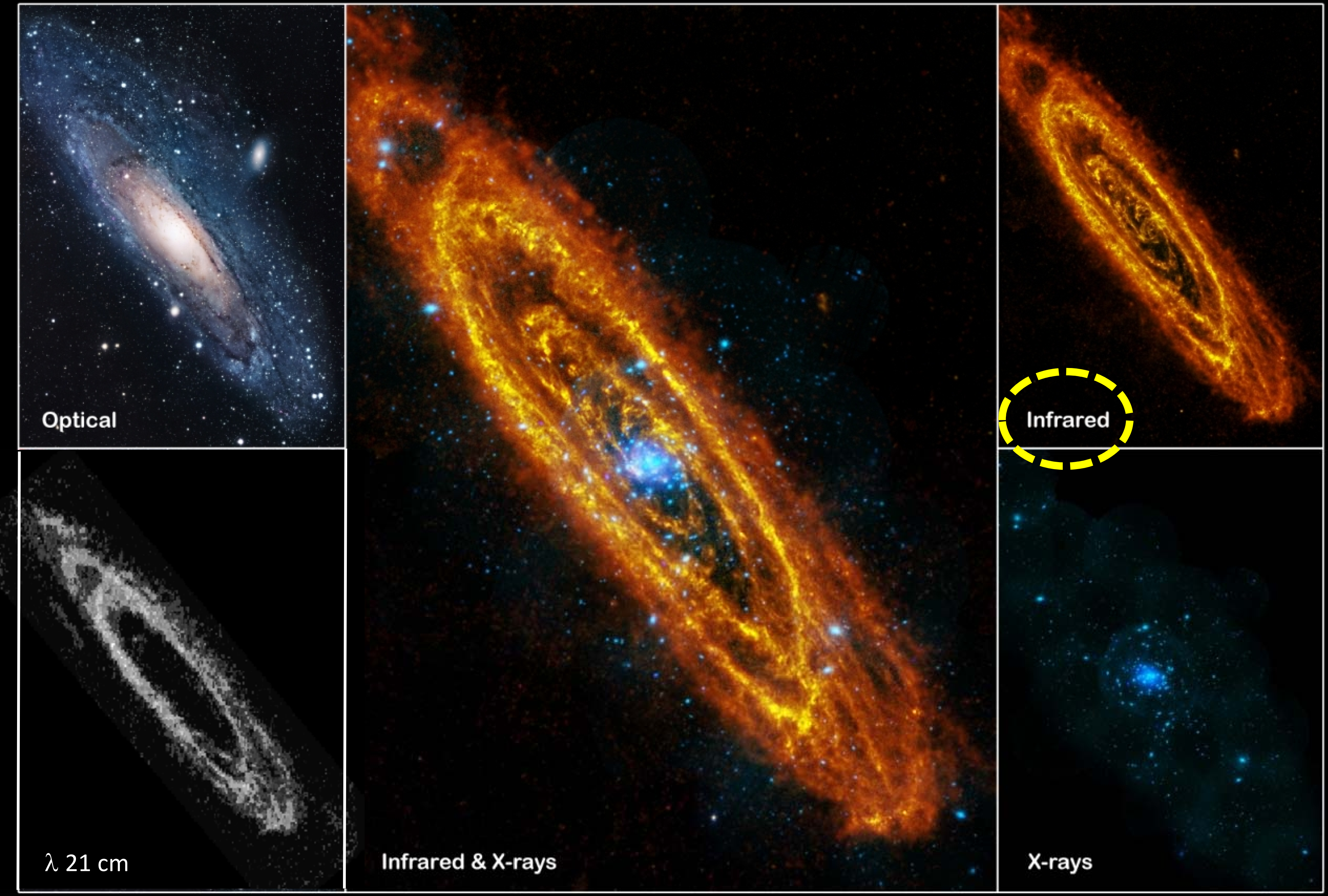
n=1 0 eV





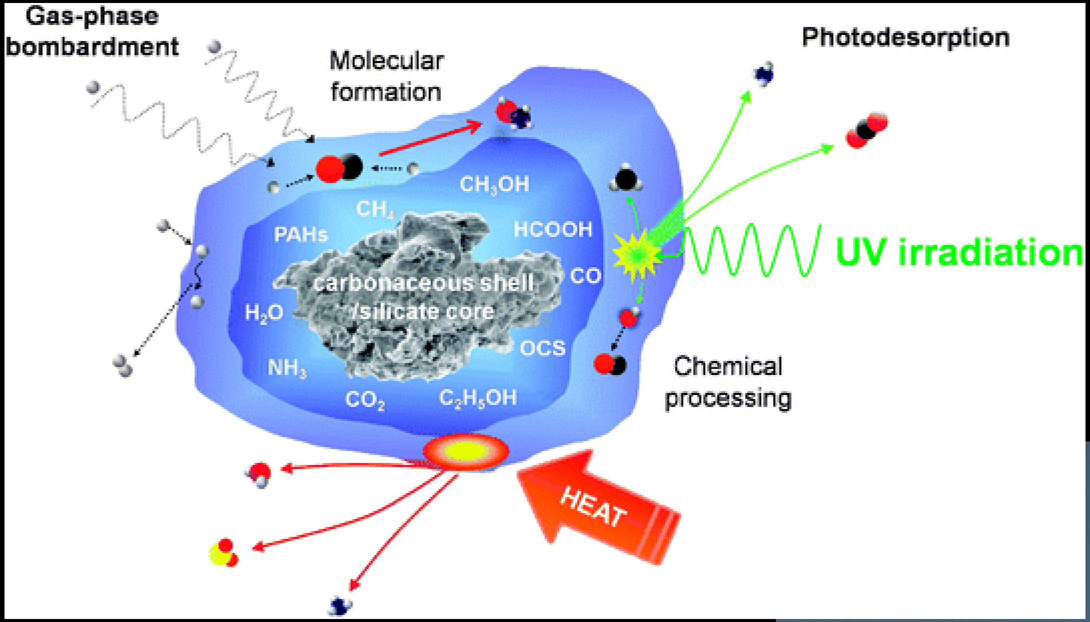
M33

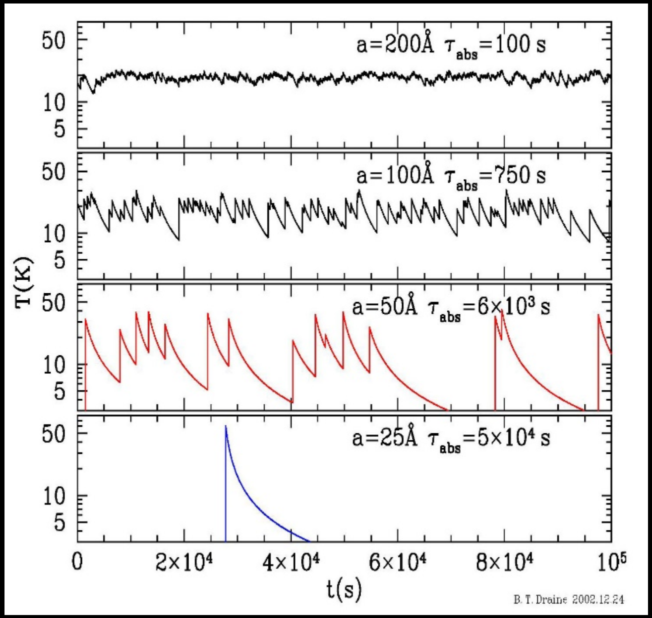
IC133
A71
NGC604
C27
A66
IC131
NGC595
GR290
NGC592
NGC588
IC135
IC139
A21
A31
IC136
IC140
A128
IC137
A115



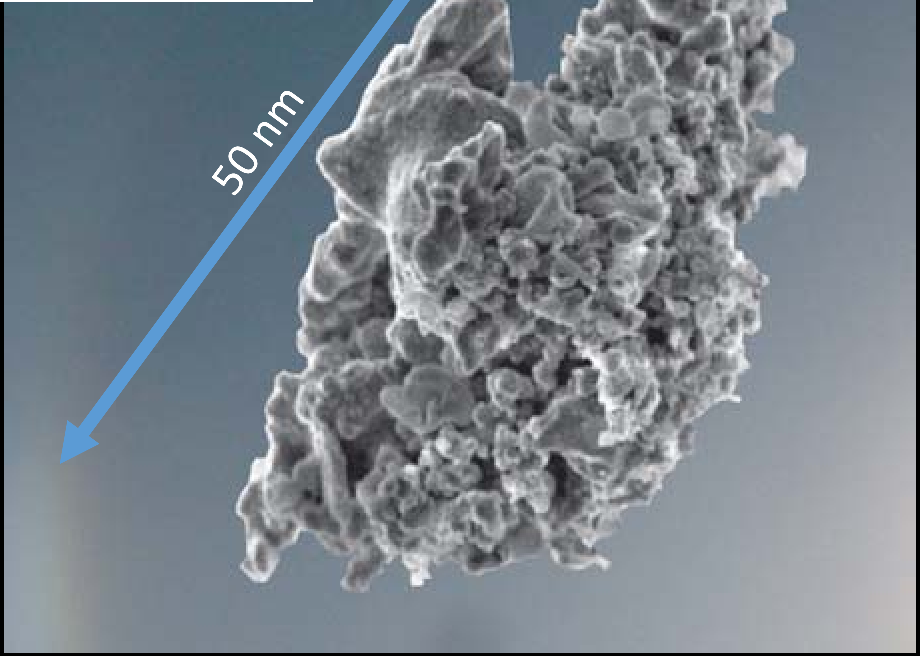
Understanding of a cosmic source requires observations across the whole EM spectrum

Interstellar dust grains

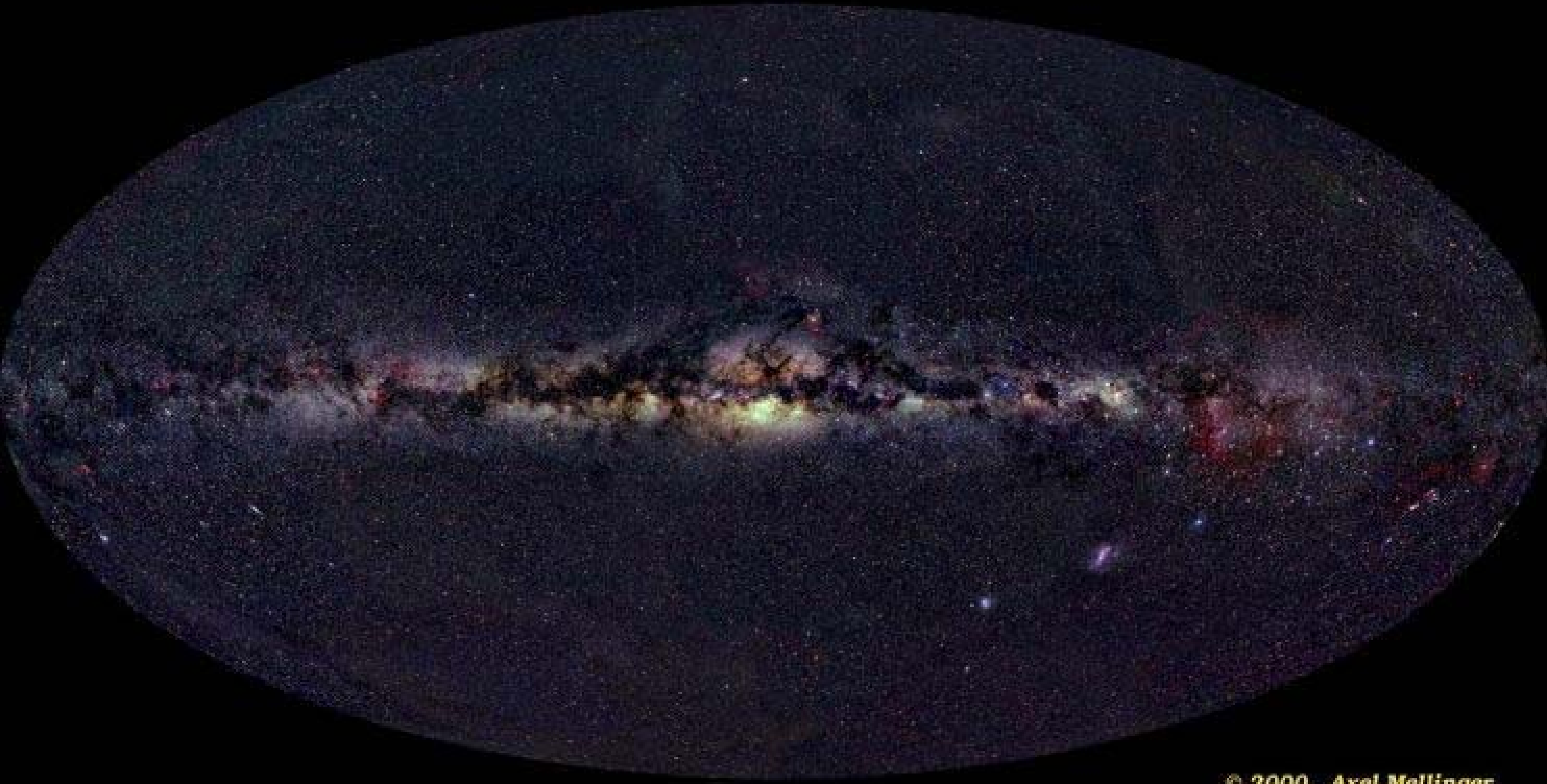




B. T. Draine 2002.12.24

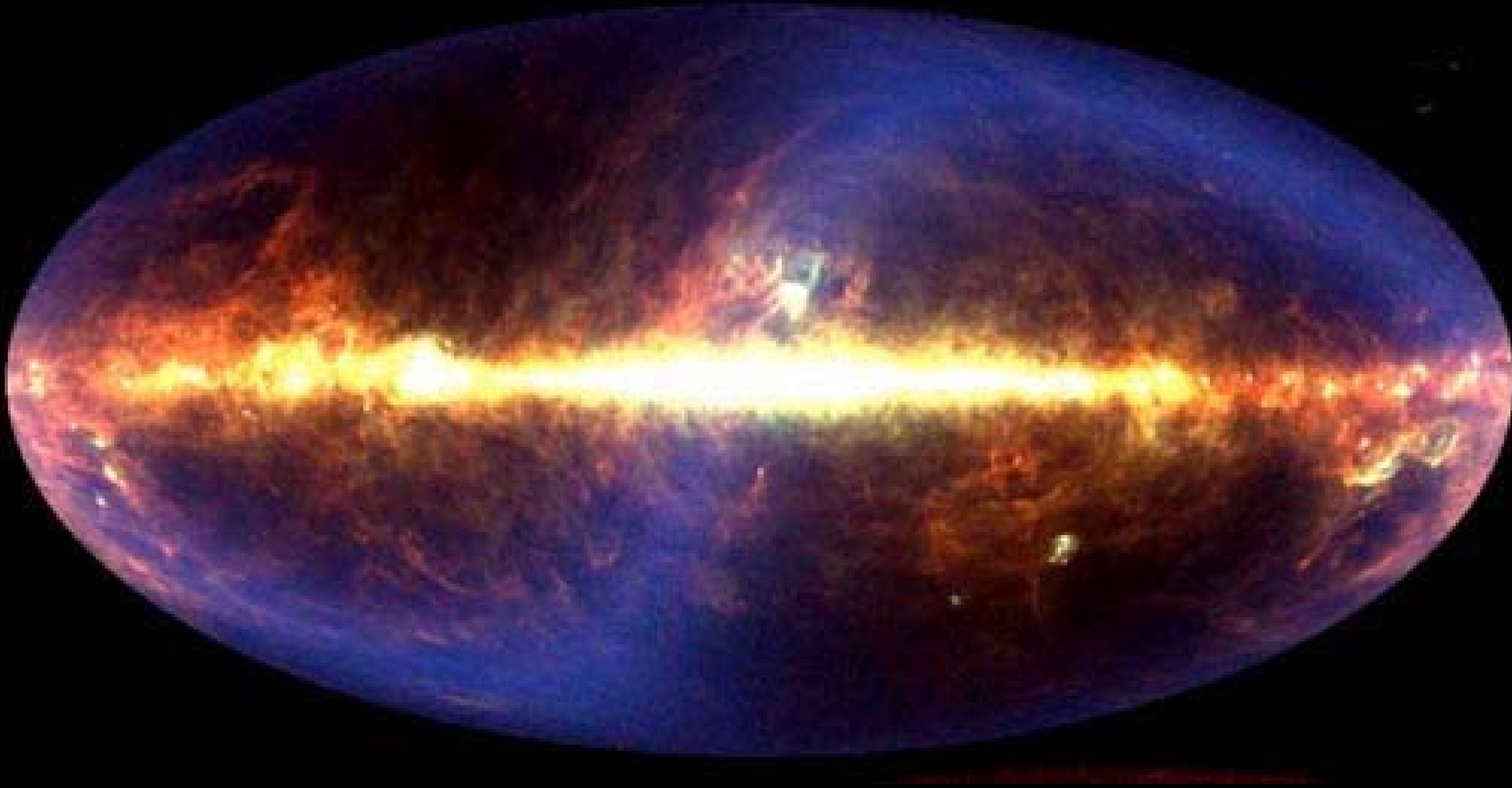


- Dust grains absorbing visible light ….



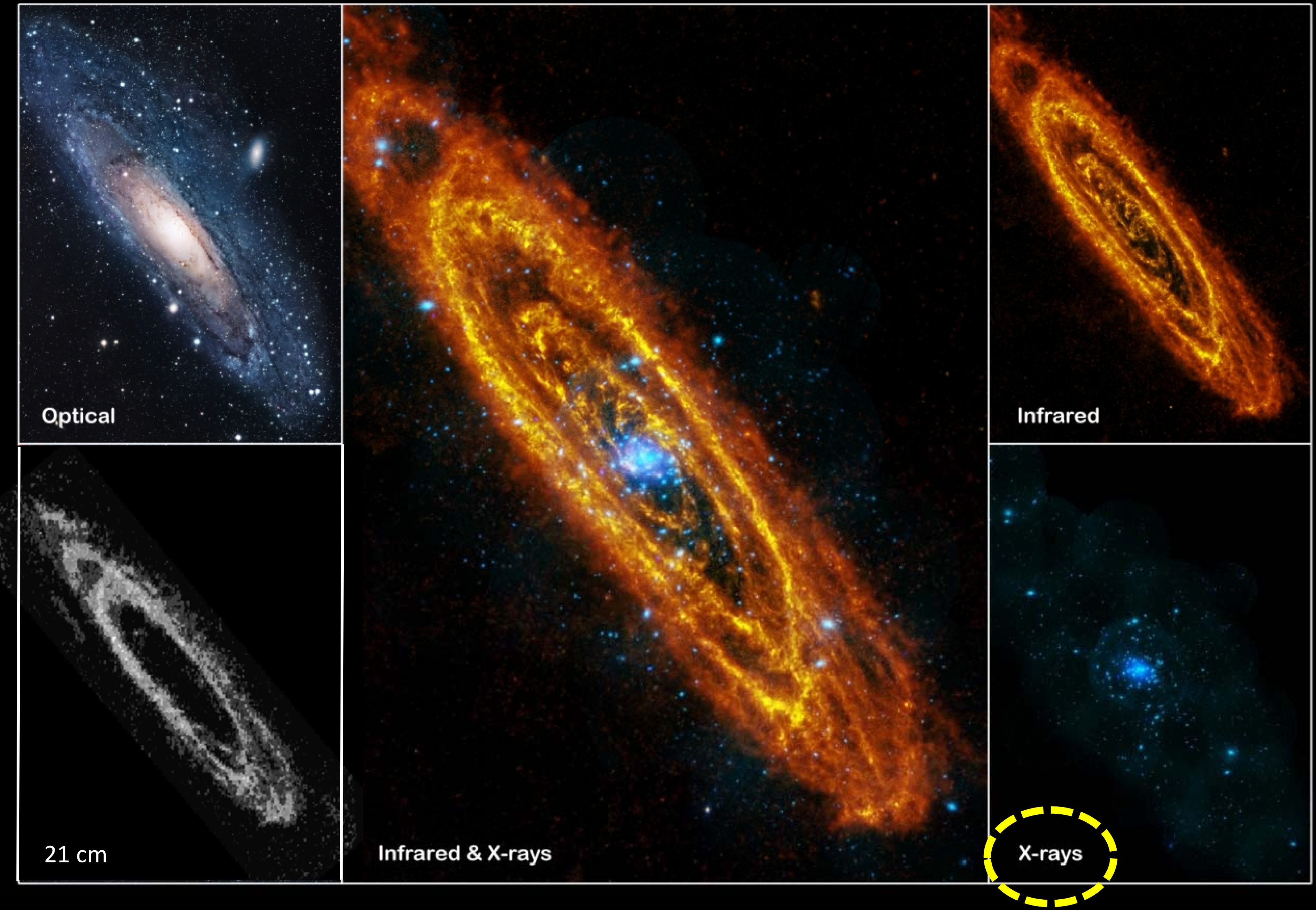
© 2000, Axel Mellinger

- … and emitting thermal / far IR



- absorbing visible light ….

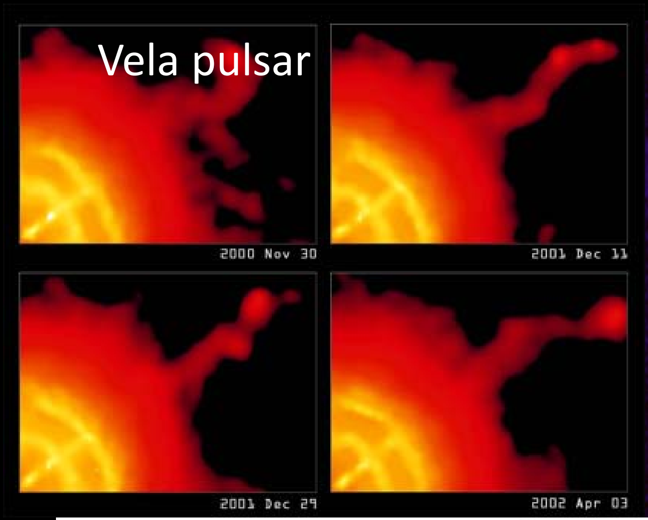
… and emitting thermal / far IR

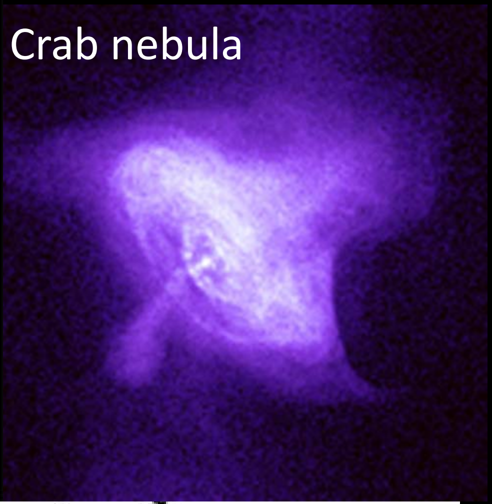


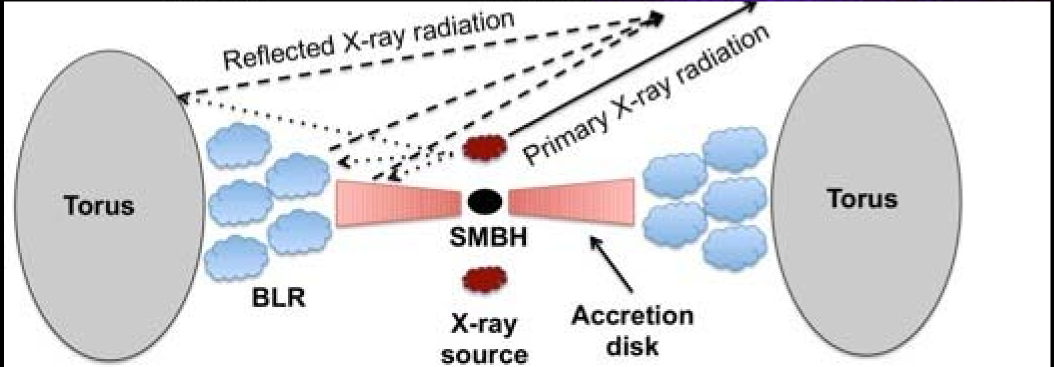
Understanding of a cosmic source requires observations across the whole EM spectrum

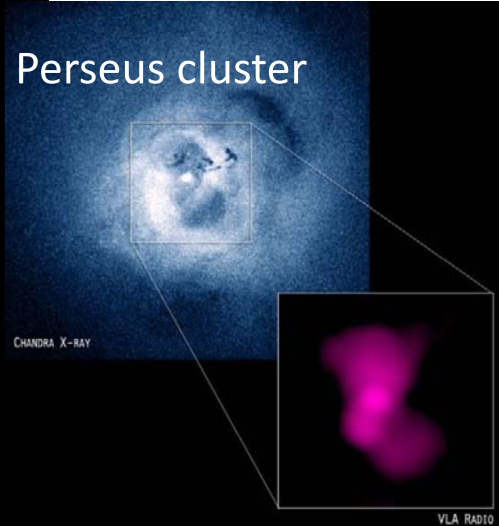
X-rays

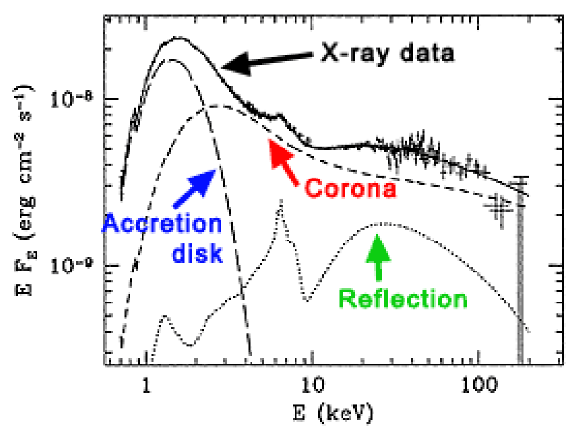
- X-rays come from extremely hot gasses, 10^6-10^8K.
- Mainly in compact stars, such as neutron stars or black holes : material falling into a black hole is heated by friction in the extremely strong gravitational field
- Also, intergalactic gas is heated to very high T in the deep gravitational potential well of galaxy clusters





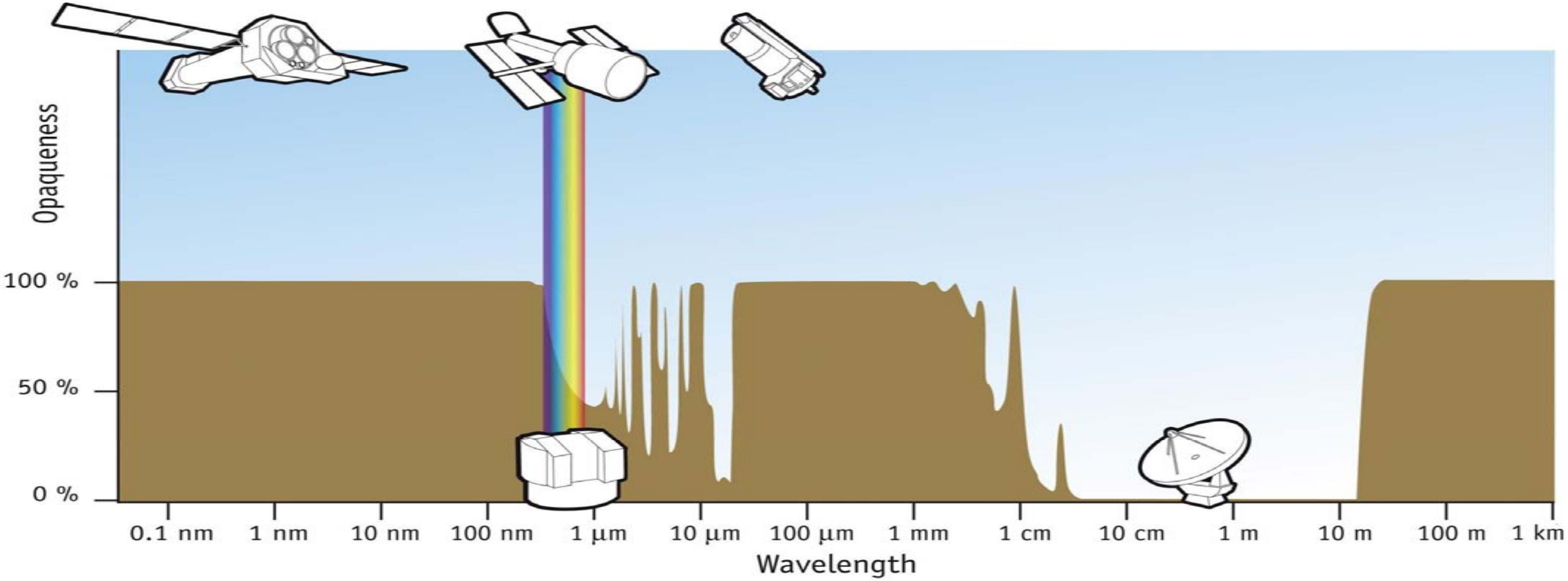




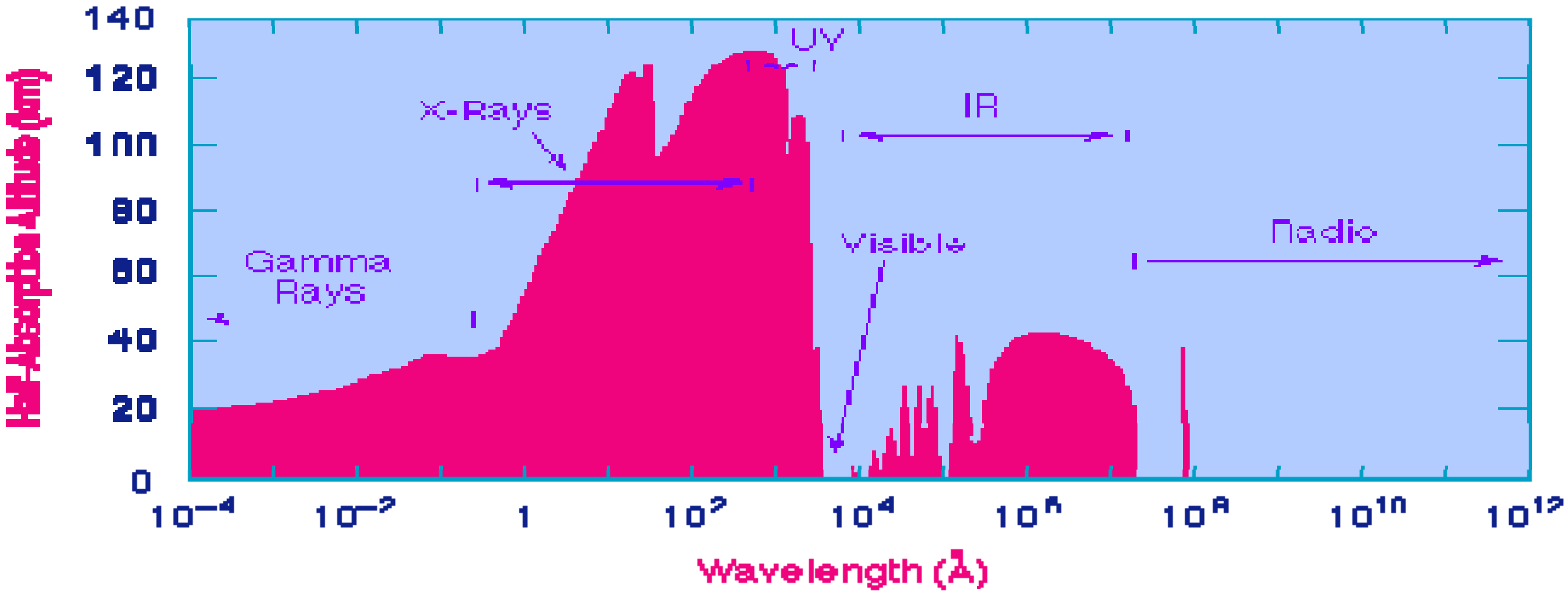


Propagation effects

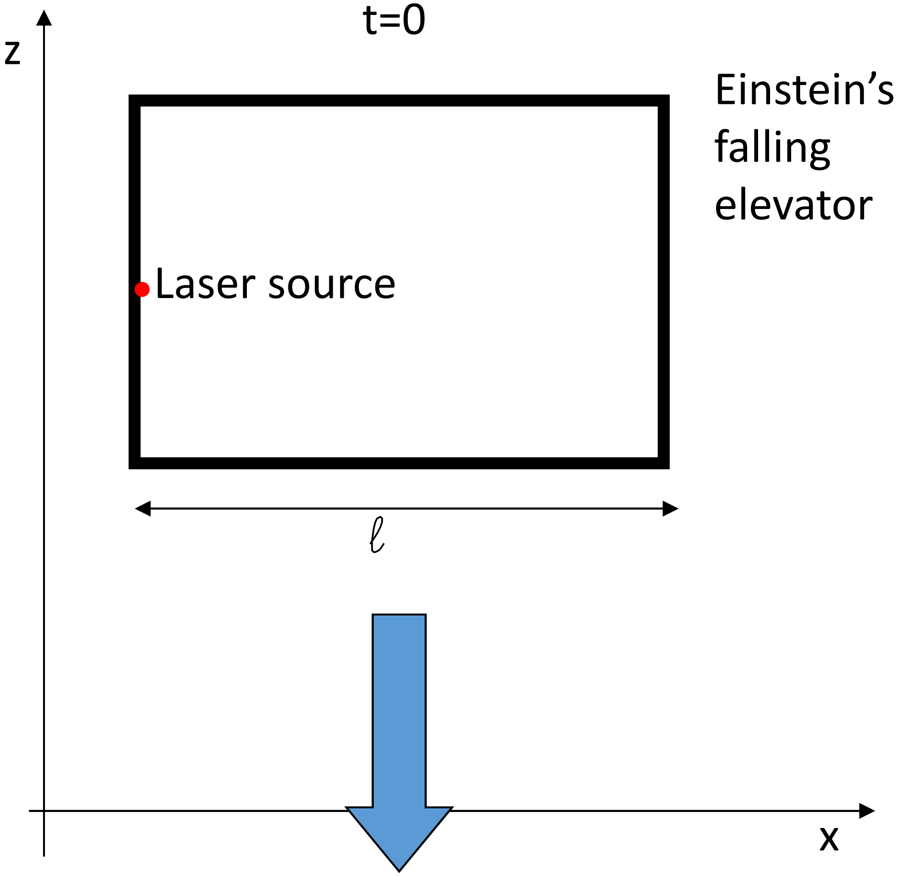
- Absorption / emission / scattering in the Earth atmosphere
- Absorption / scattering / emission in the universe
- Lensing
- Redshift



γ-rays X-rays UV V NIR FIR µ-waves radio radio

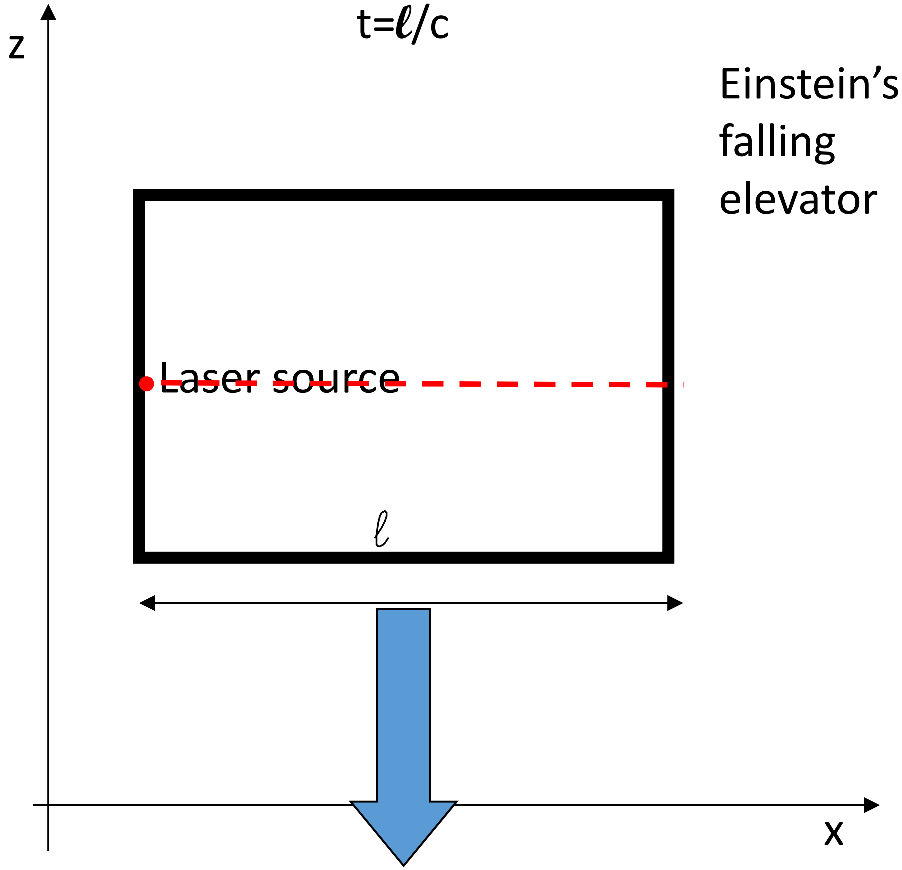


Bending of light in a gravitational field



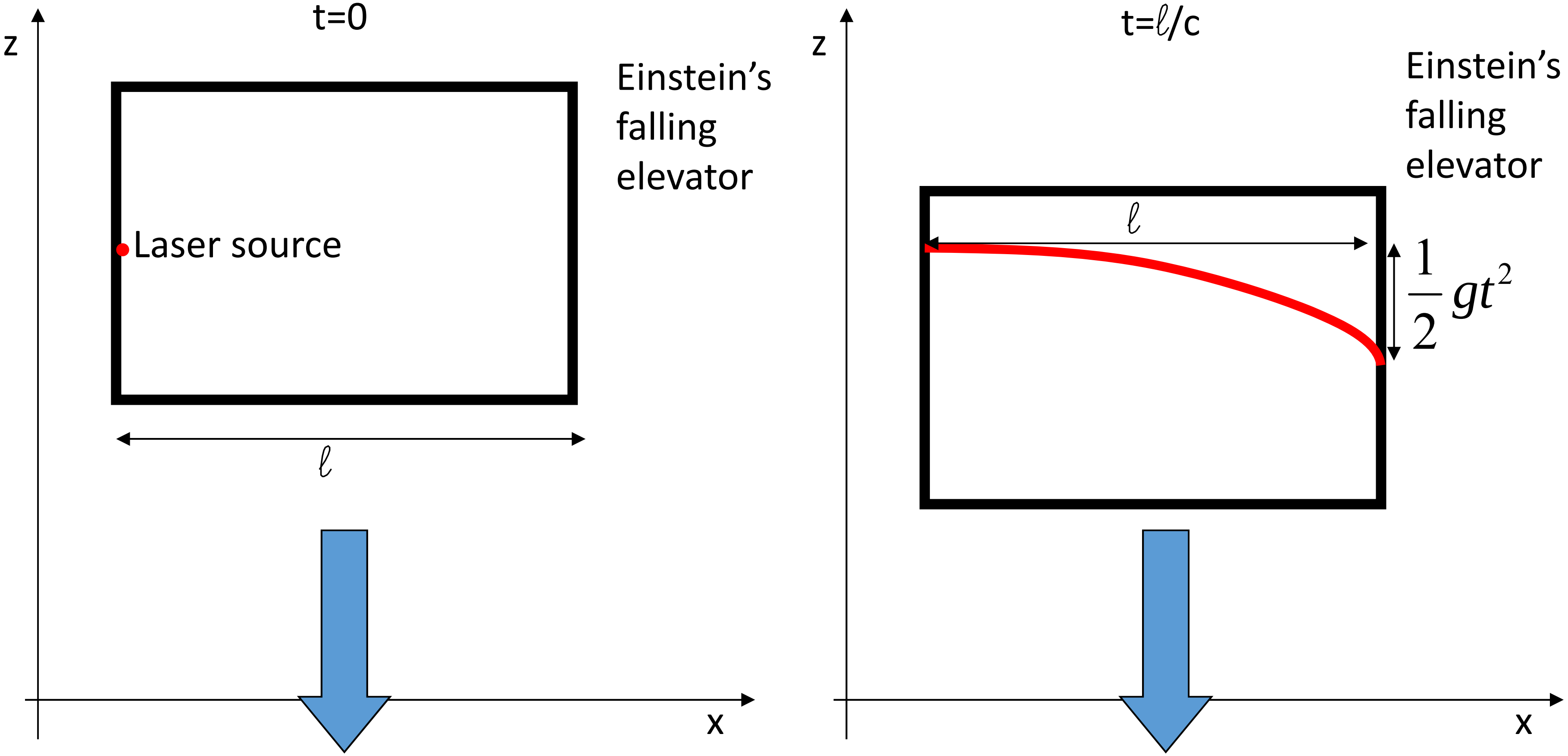
- The observer in the feee-falling elevator does not feel gravity, and will see the laser beam propagating at constant height wrt the floor.

Bending of light in a gravitational field



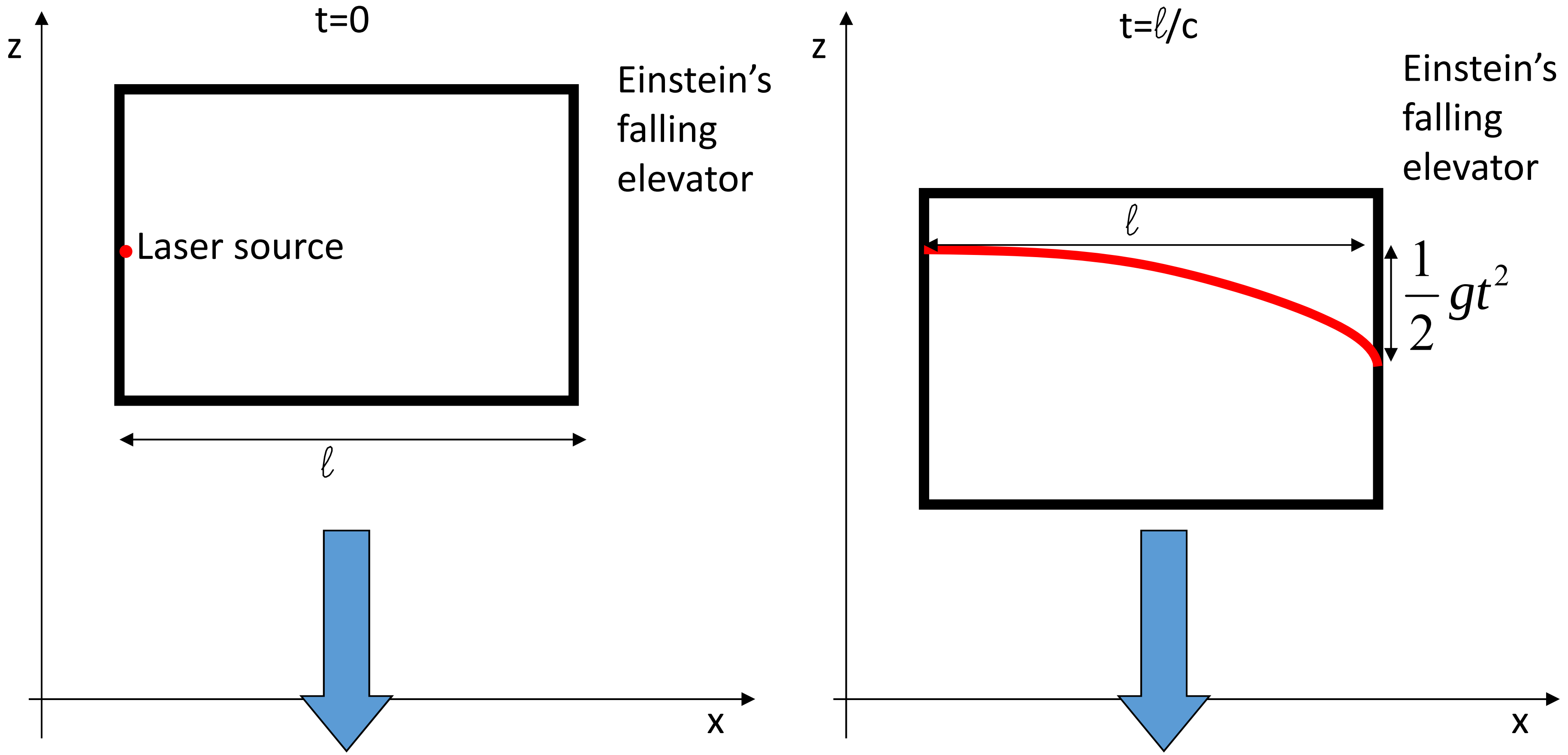
- The observer in the feee-falling elevator does not feel gravity, and will see the laser beam propagating at constant height wrt the floor while falling.

Bending of light in a gravitational field



- The observer in the feee-falling elevator does not feel gravity, and will see the laser beam propagating at constant height wrt the floor.
- The observer at rest outside (feeling gravity) will see the same outcome of the experiment, which means that the laser beam is deflected down in his reference frame.

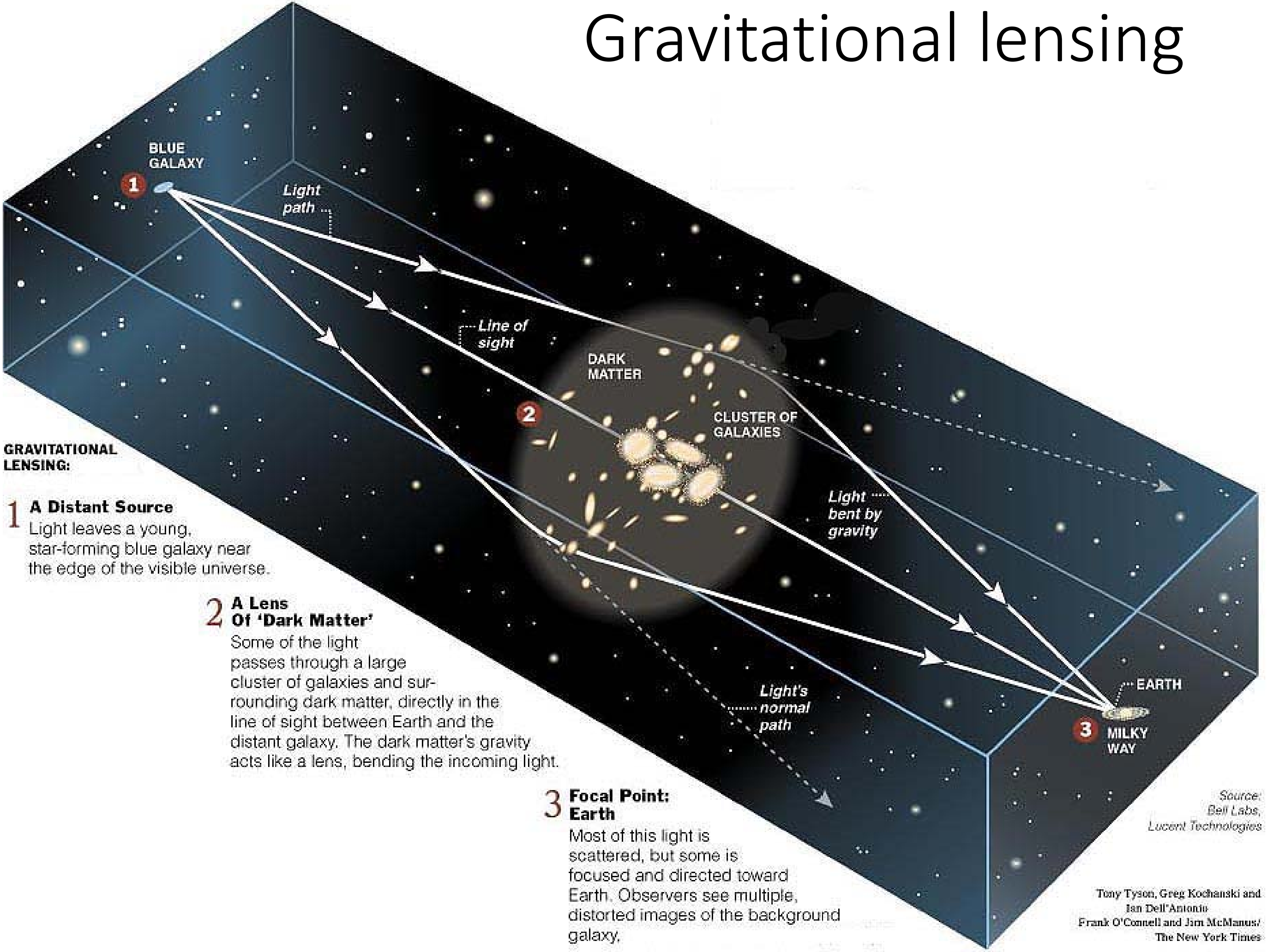
Bending of light in a gravitational field



- The observer in the feee-falling elevator does not feel gravity, and will see the laser beam propagating at constant height wrt the floor.
- The observer at rest outside (feeling gravity) will see the same outcome of the experiment, which means that the laser beam is deflected down in his reference frame: **the presence of gravity deflects light rays.**

$$\varphi \approx \frac{\frac{1}{2}gt^2}{\ell} \approx \frac{g\ell}{c^2} \approx \frac{10m/s^2 \times 10m}{\left(3\times 10^8 m/s\right)^2} \approx 10^{-15}\,rad \approx 2\times 10^{-10}\,arcsec$$

Gravitational lensing



GRAVITATIONAL LENSING:

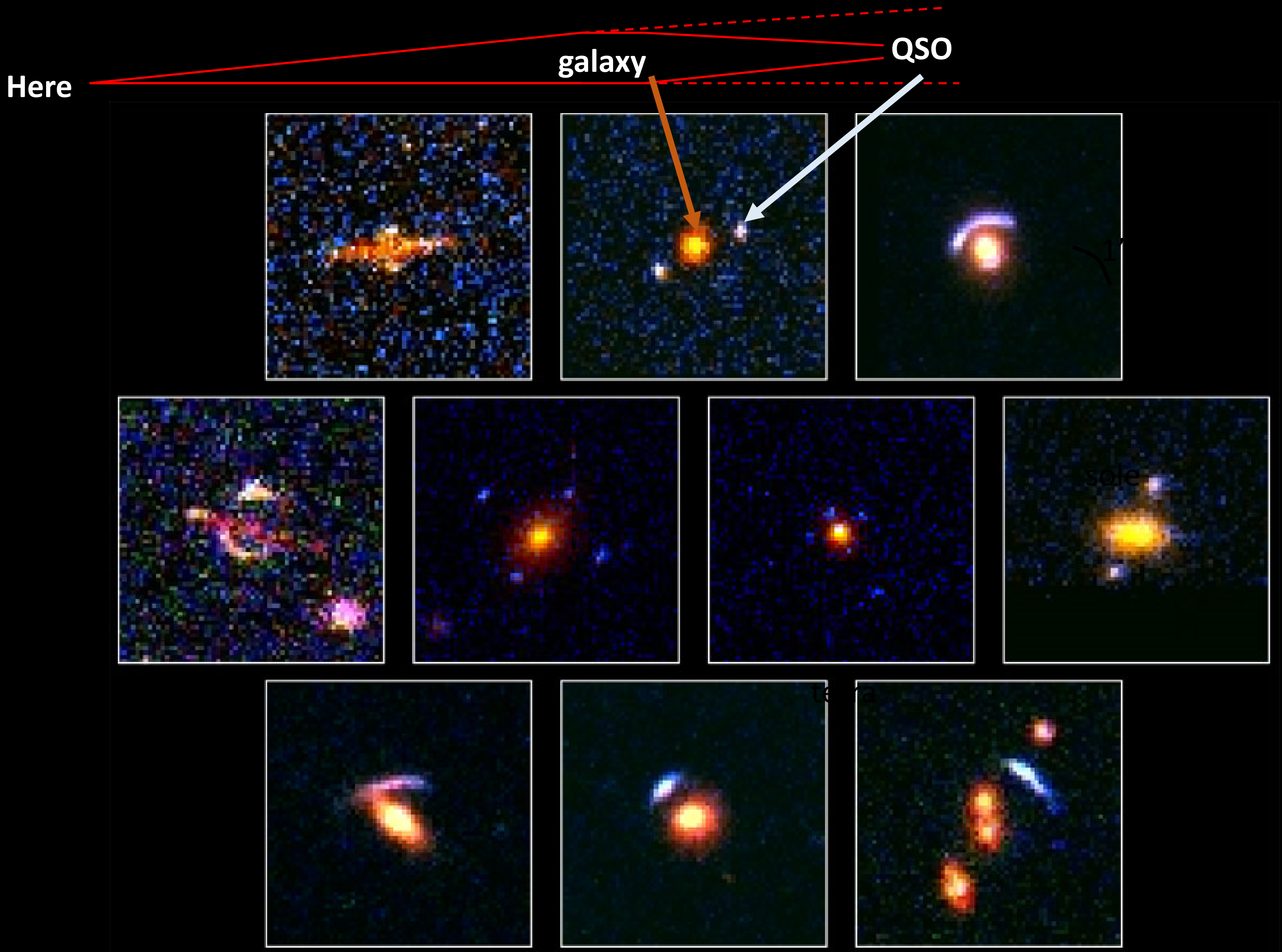
1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/
The New York Times

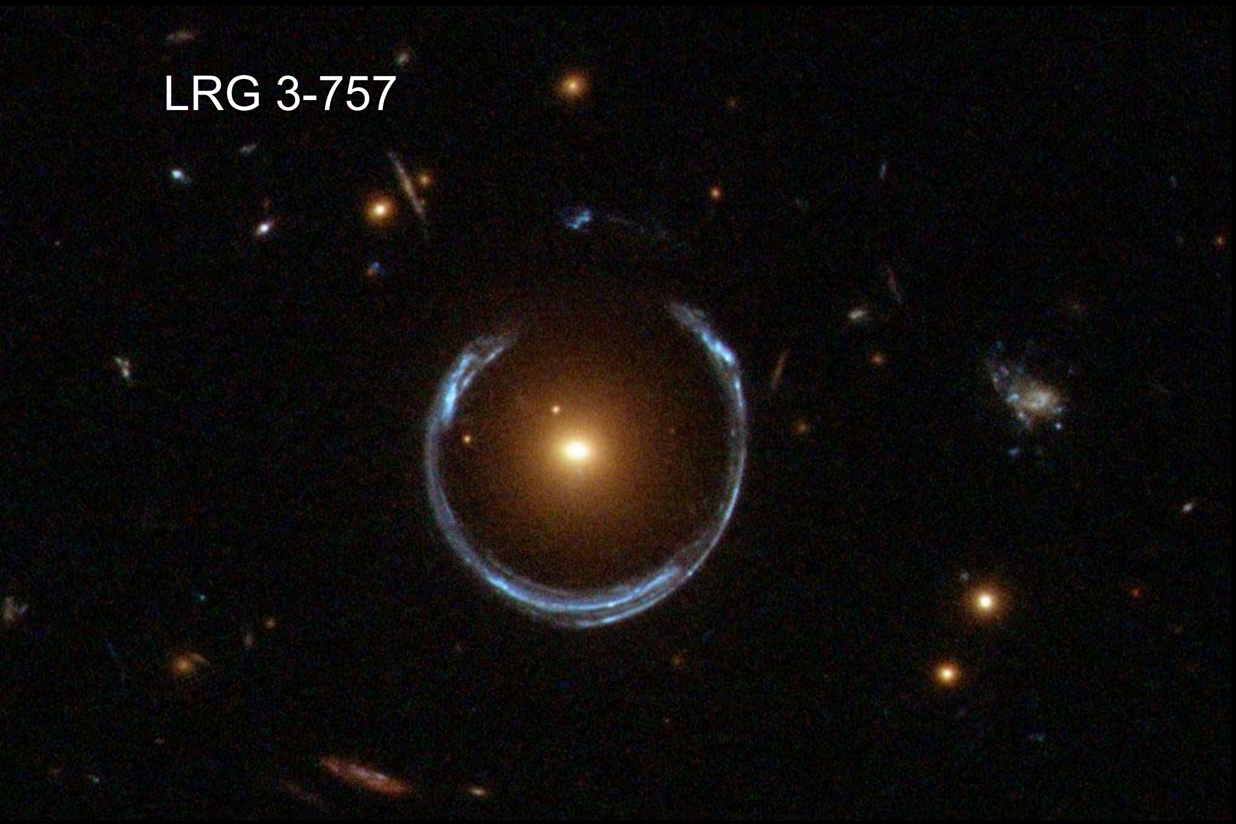


Gallery of Gravitational Lenses

PRC99-18 • STScI OPO • K. Ratnatunga (Carnegie Mellon University) and NASA

HST • WFPC2

Gravitational deflection of light



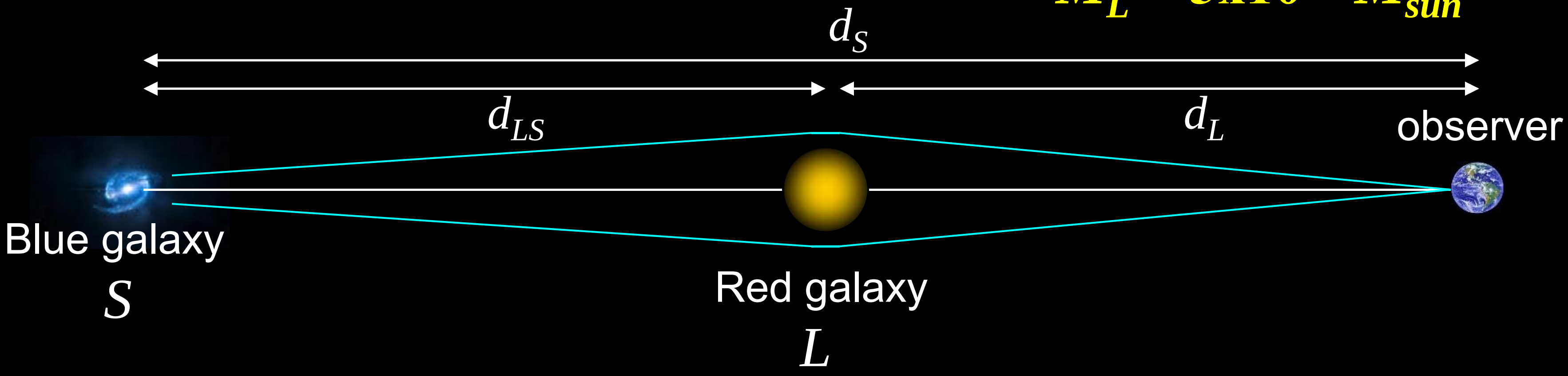
$$\theta_E = \sqrt{\frac{4GM_L}{c^2}\frac{d_{LS}}{d_L d_S}}$$

M_L can be computed from measured data :

Angular diameter distances are estimated from the measured redshifts of L and S

θ_E is estimated from the image

$M_L = 5\text{x}10^{12}\ M_{sun}$

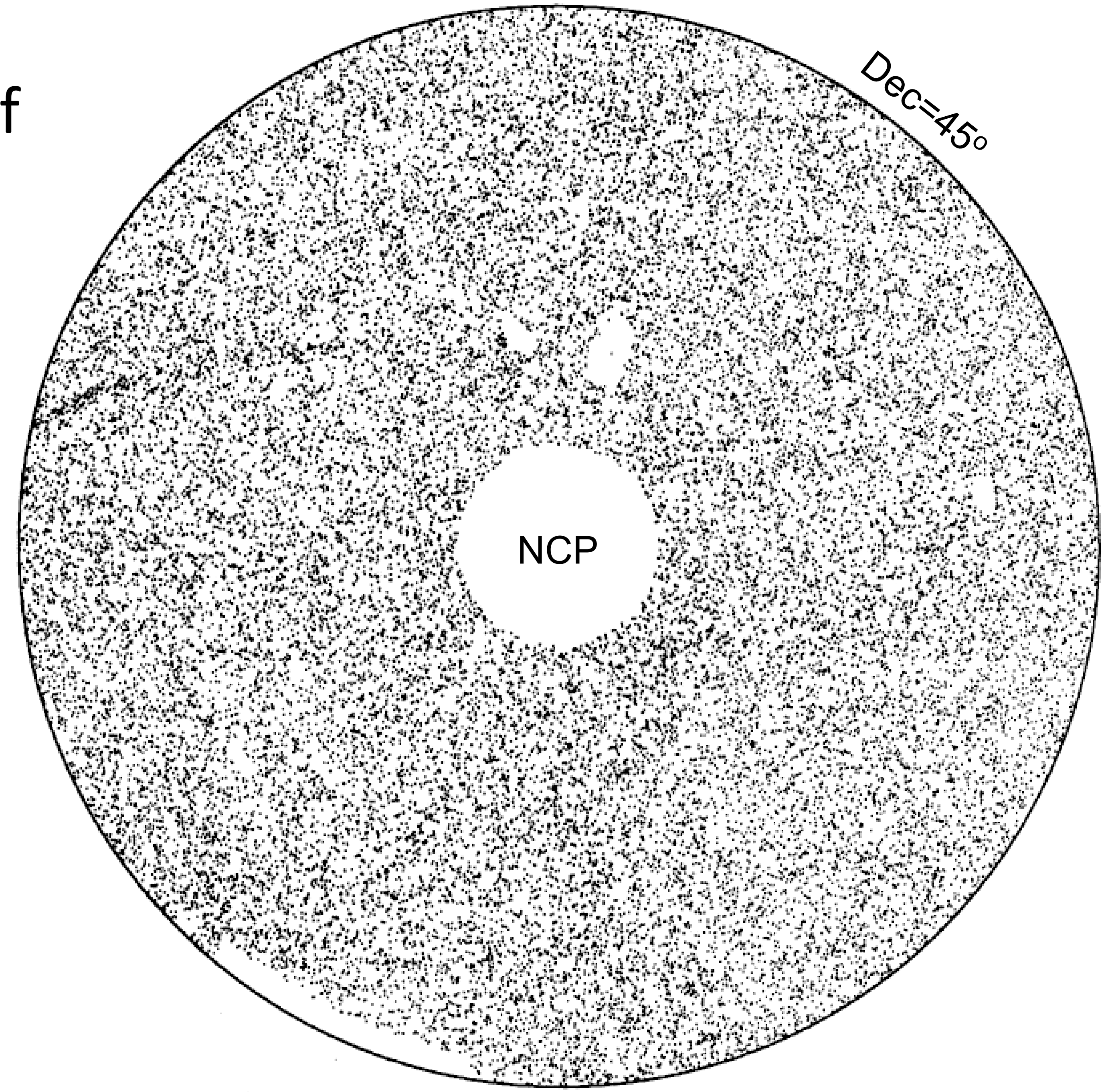


Cosmology: the universe at the largest scales

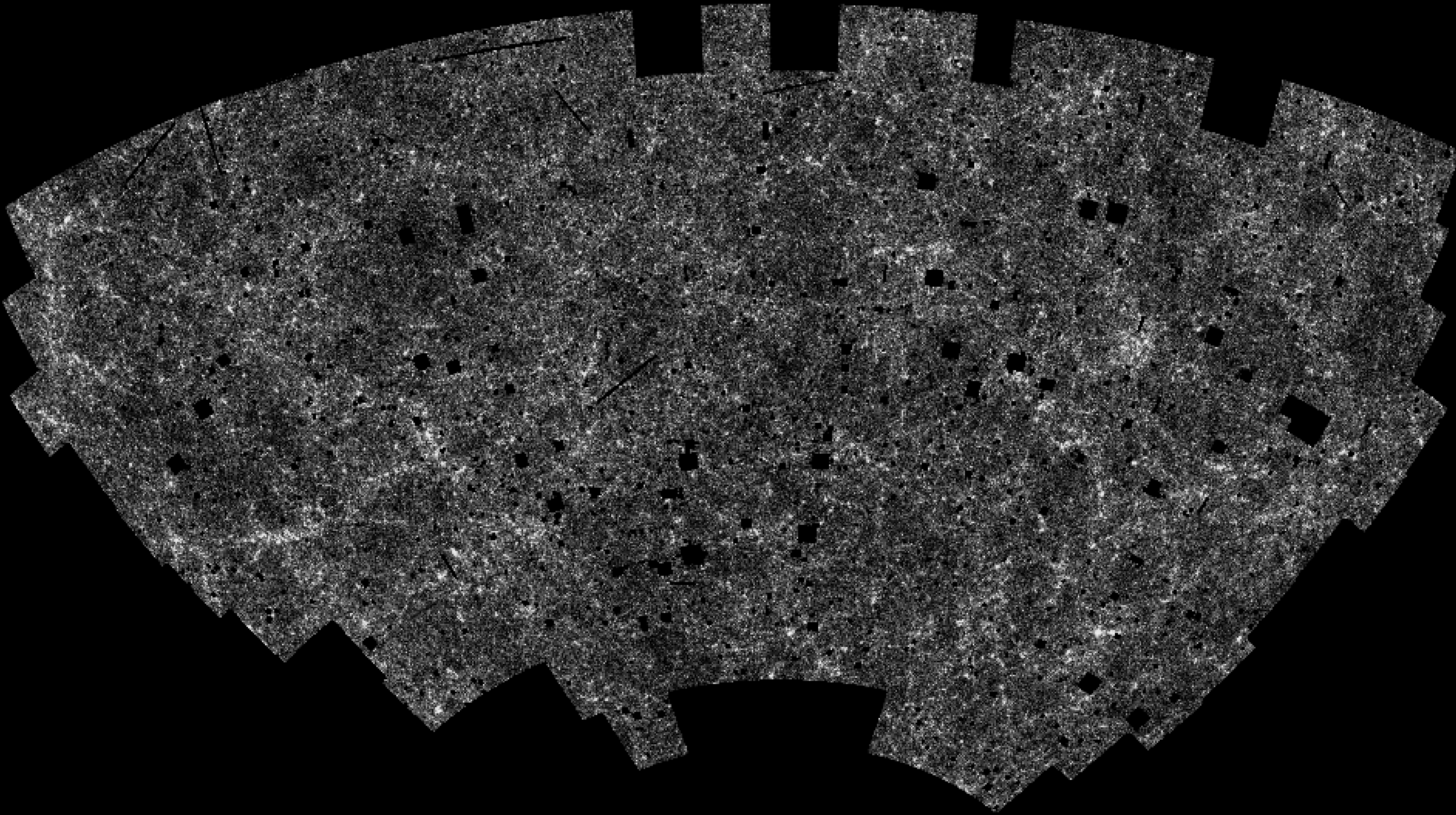
- If we believe that
  - we do not occupy a special position in the Universe, i.e. the Universe at large scales is the same everywhere
  - The universe at large scales is isotropic around us
  - The correct description of gravity (the only force active at cosmological scales) is general relativity,
- then we get the FRW metric, describing the geometry of space in an isotropic homogenous medium, and allowing for expansion or contraction, described by a scalar scale factor, and we can study the evolution of the medium
- Empirical evidence for the above:

Projected distribution of distant radiogalaxies

- From Gregory & Condon 1991
- 31000 strong radiosources at l=6cm
- Sampling rare objects one gets good Poissonian **isotropy**

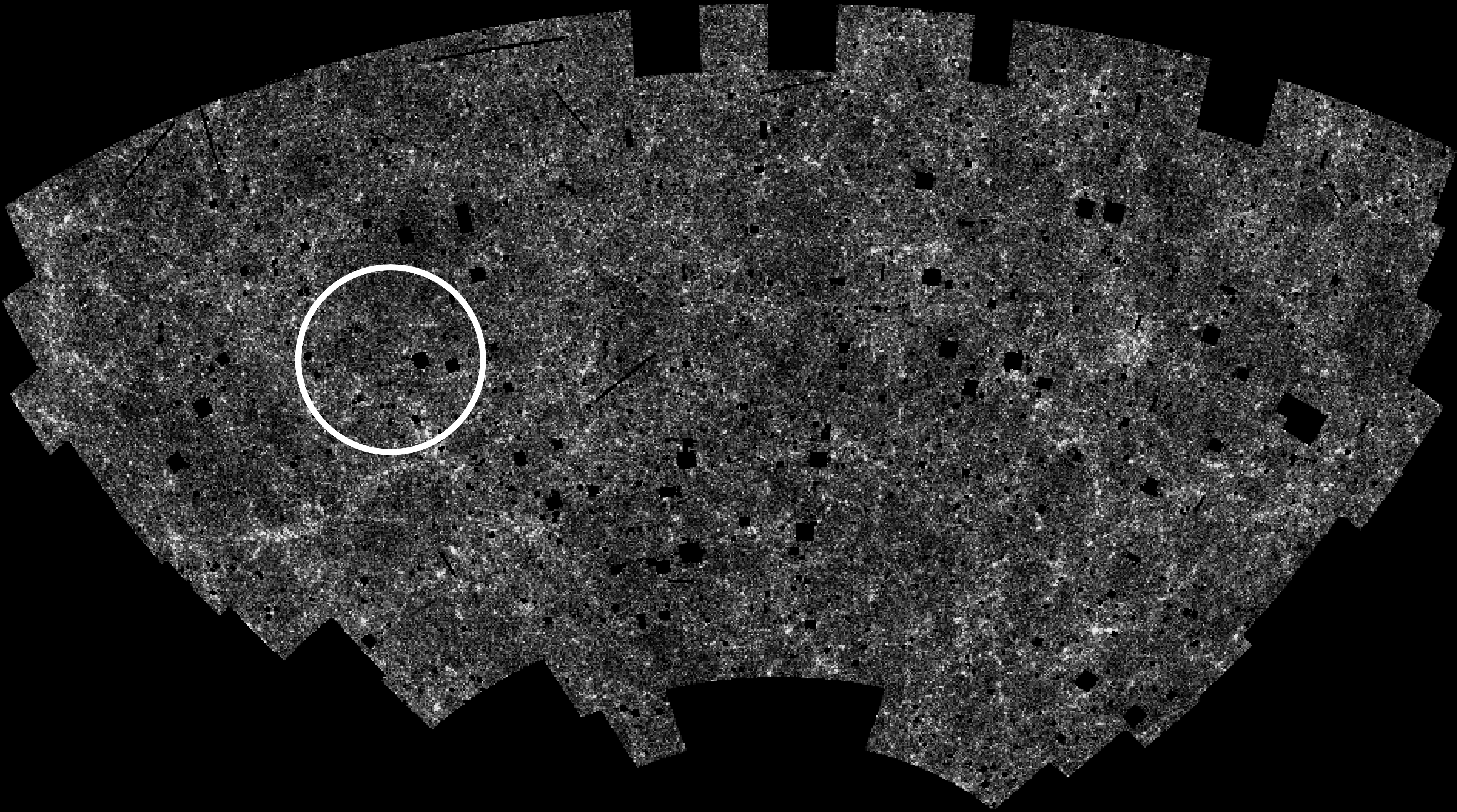


Projected Distribution of Galaxies



APM (Automatic Plate Machine) survey, 10^6 galaxies
About 1/10 of the sky (circa 1985)

Projected Distribution of Galaxies



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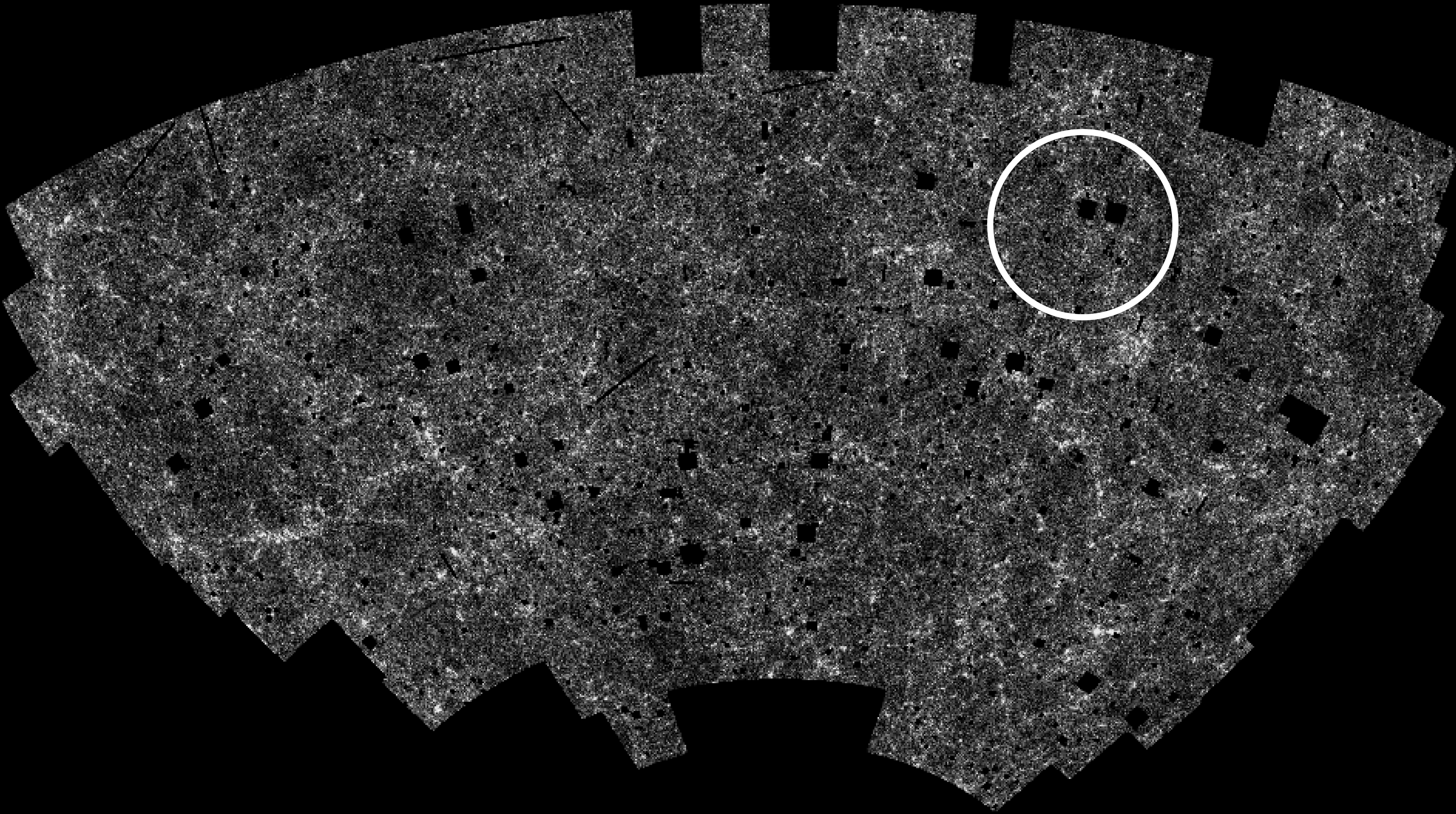
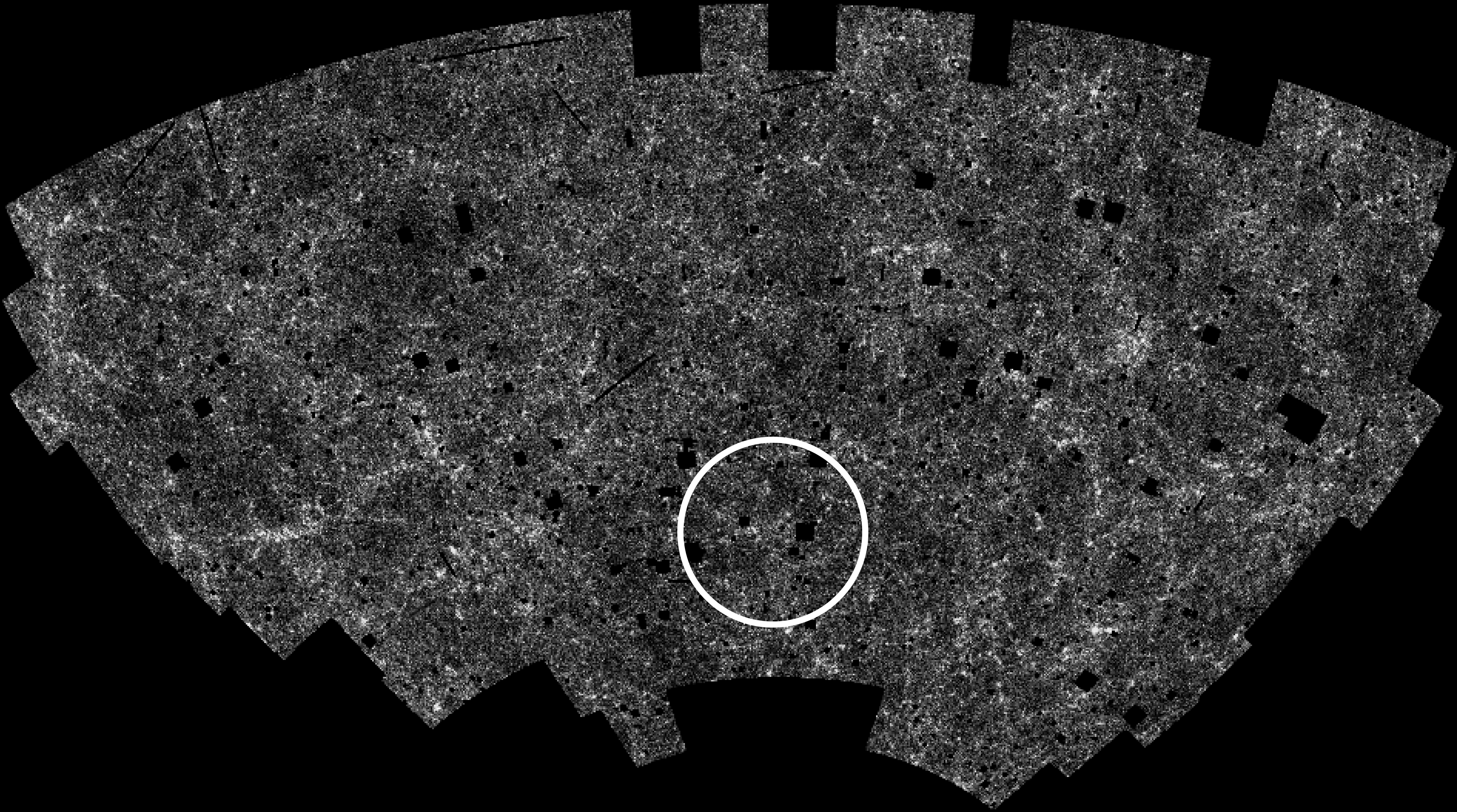


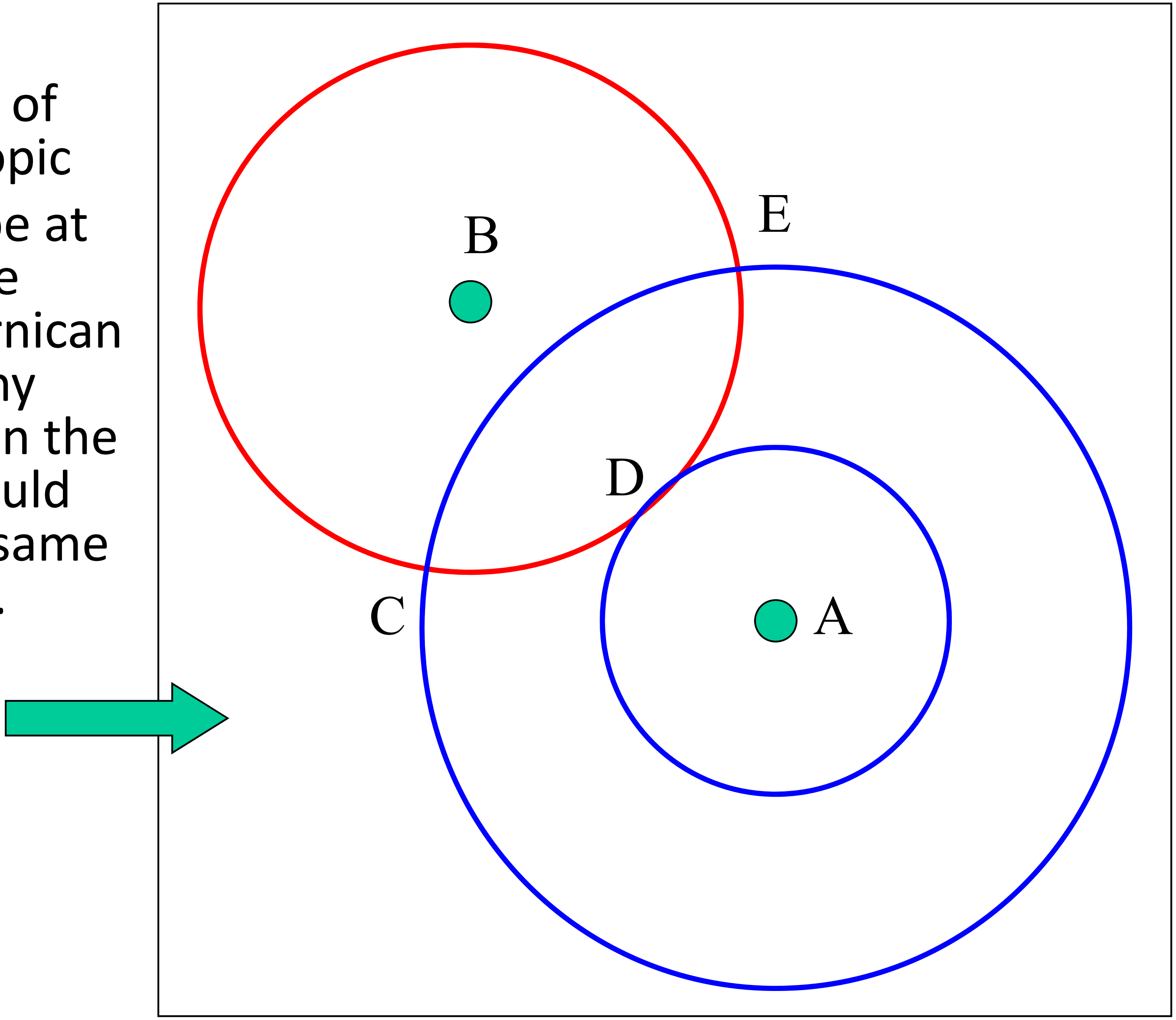
APM (Automatic Plate Machine) survey, 10^6 galaxies
About 1/10 of the sky (circa 1985)

Projected Distribution of Galaxies



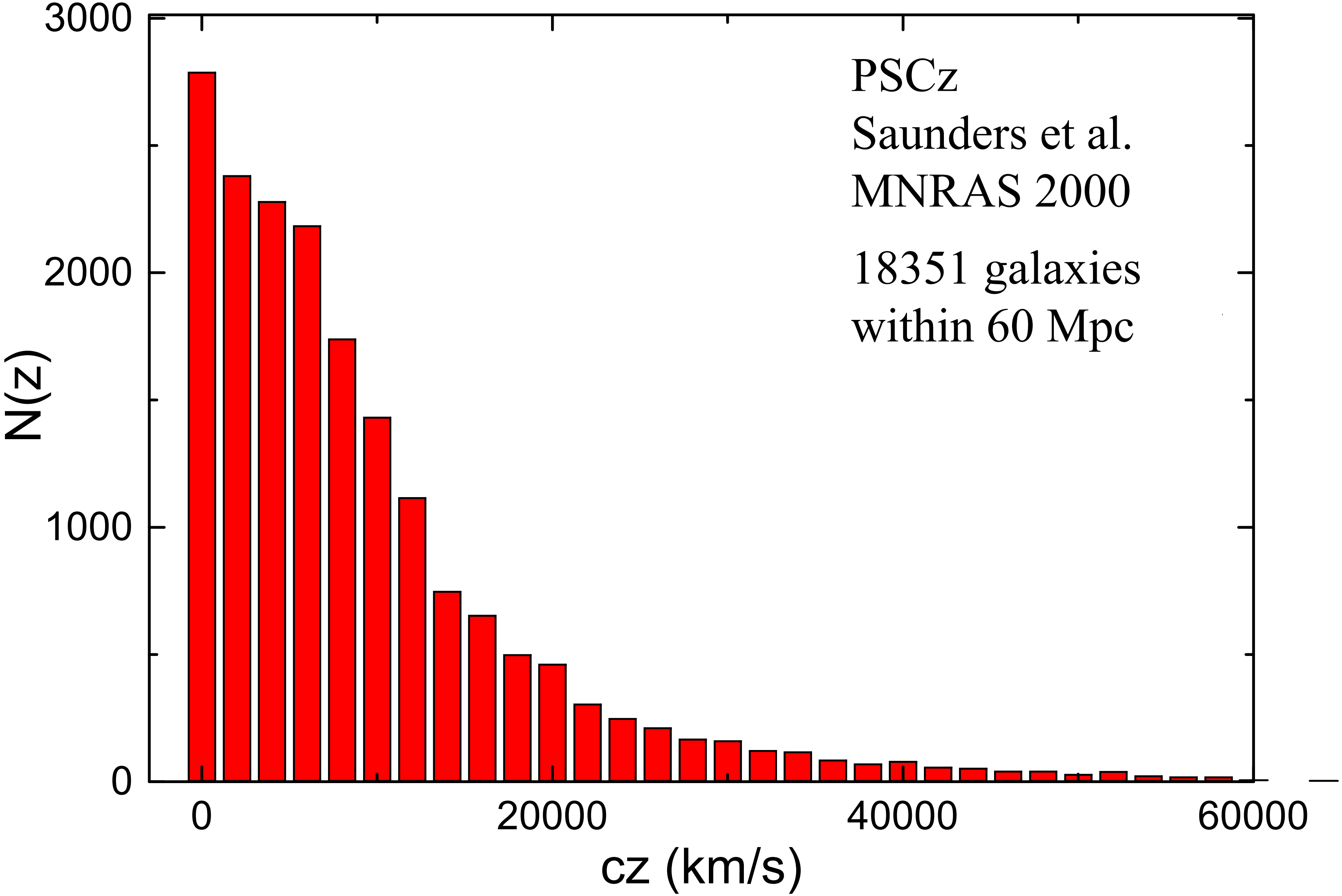
APM (Automatic Plate Machine) survey, 10^6 galaxies
About 1/10 of the sky (circa 1985)

- The distribution of galaxies is isotropic
- We (A) cannot be at the center of the Universe (Copernican priniciple), so any other observer in the universe (B) should experience the same isotropy we see.
- This implies homogeneity :



Cosmological Redshift of Galaxies

$$z = \frac{\lambda_{observed} - \lambda_{restframe}}{\lambda_{restframe}}$$

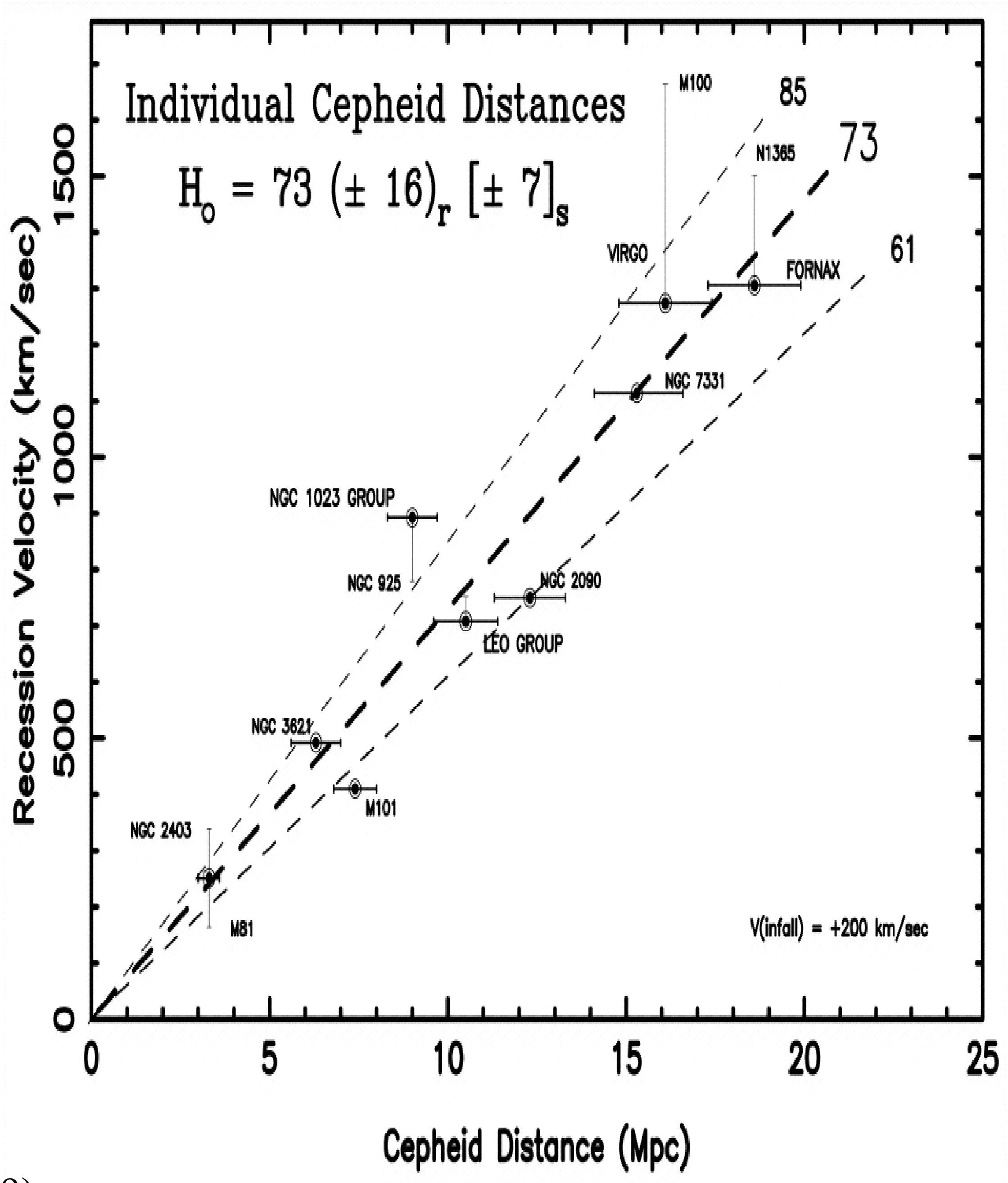


$$z = \frac{\lambda_{observed} - \lambda_{restframe}}{\lambda_{restframe}}$$

- Hubble's law from distant cepheid stars

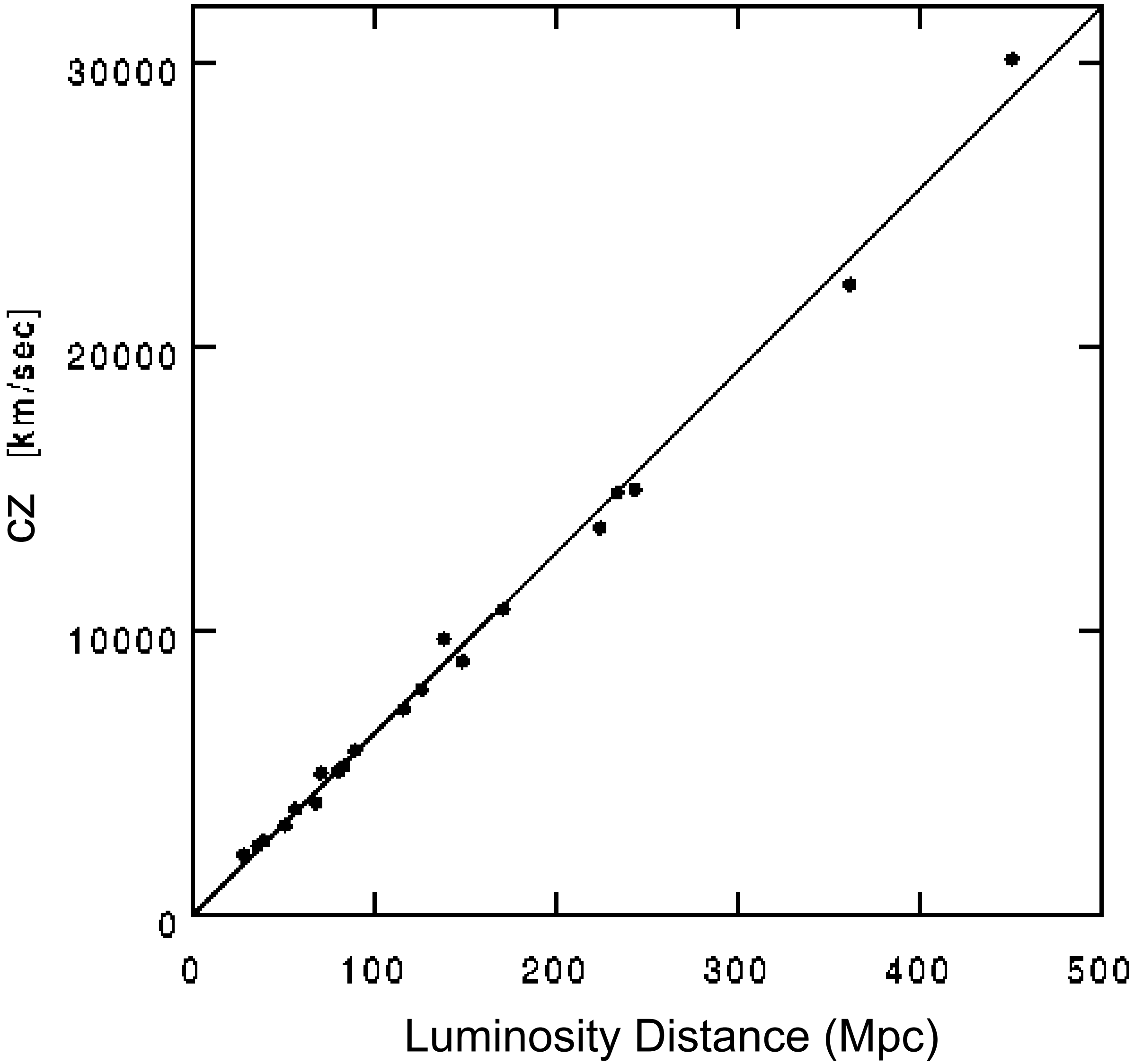
$$cz = H_o D$$

- The redshift z is an empirical measure of the distance D at cosmological scales



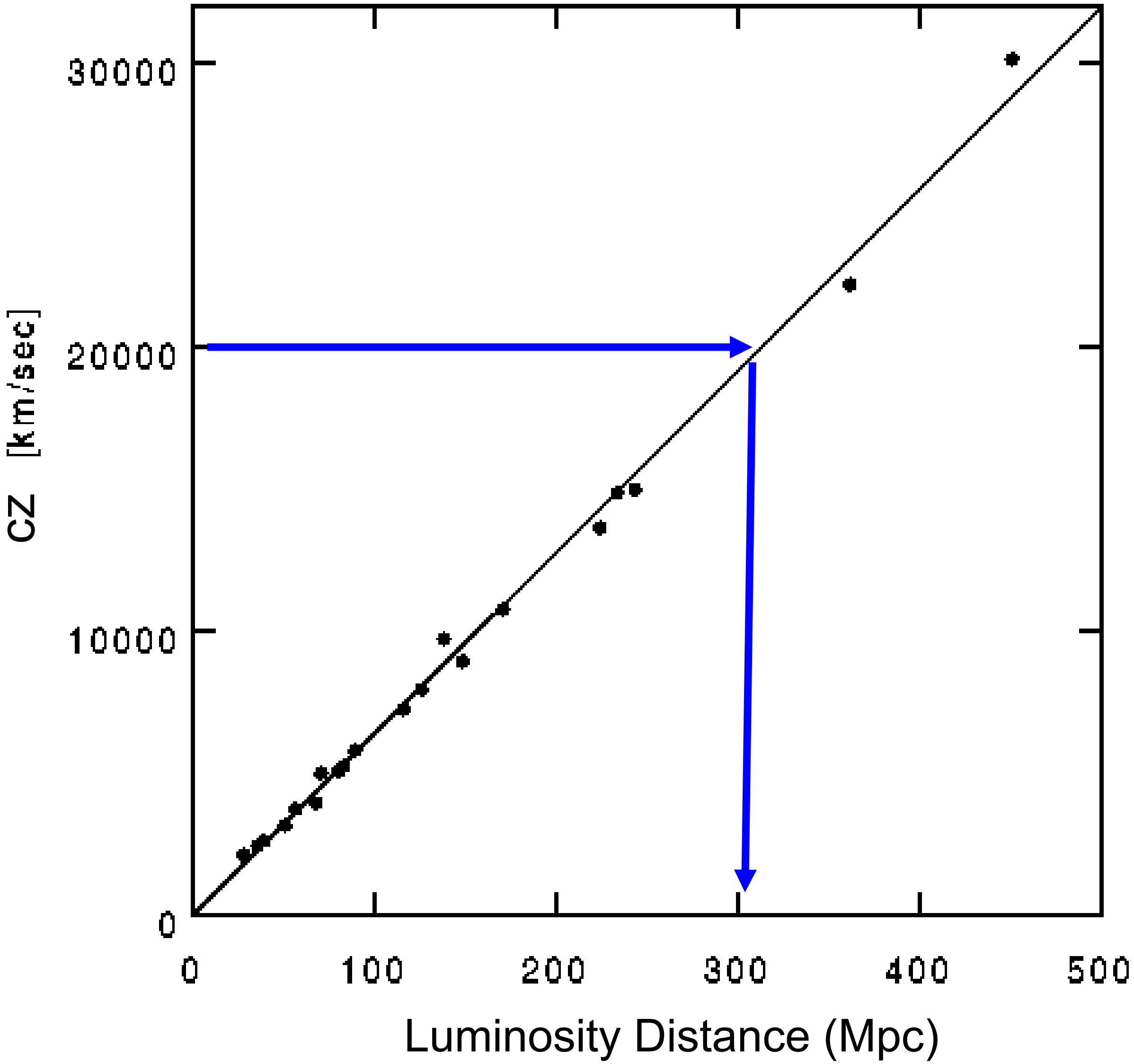
Madore B.F. et al., Ap.J. 515 29 (1999)

- Hubble’s law with Supernovae 1a

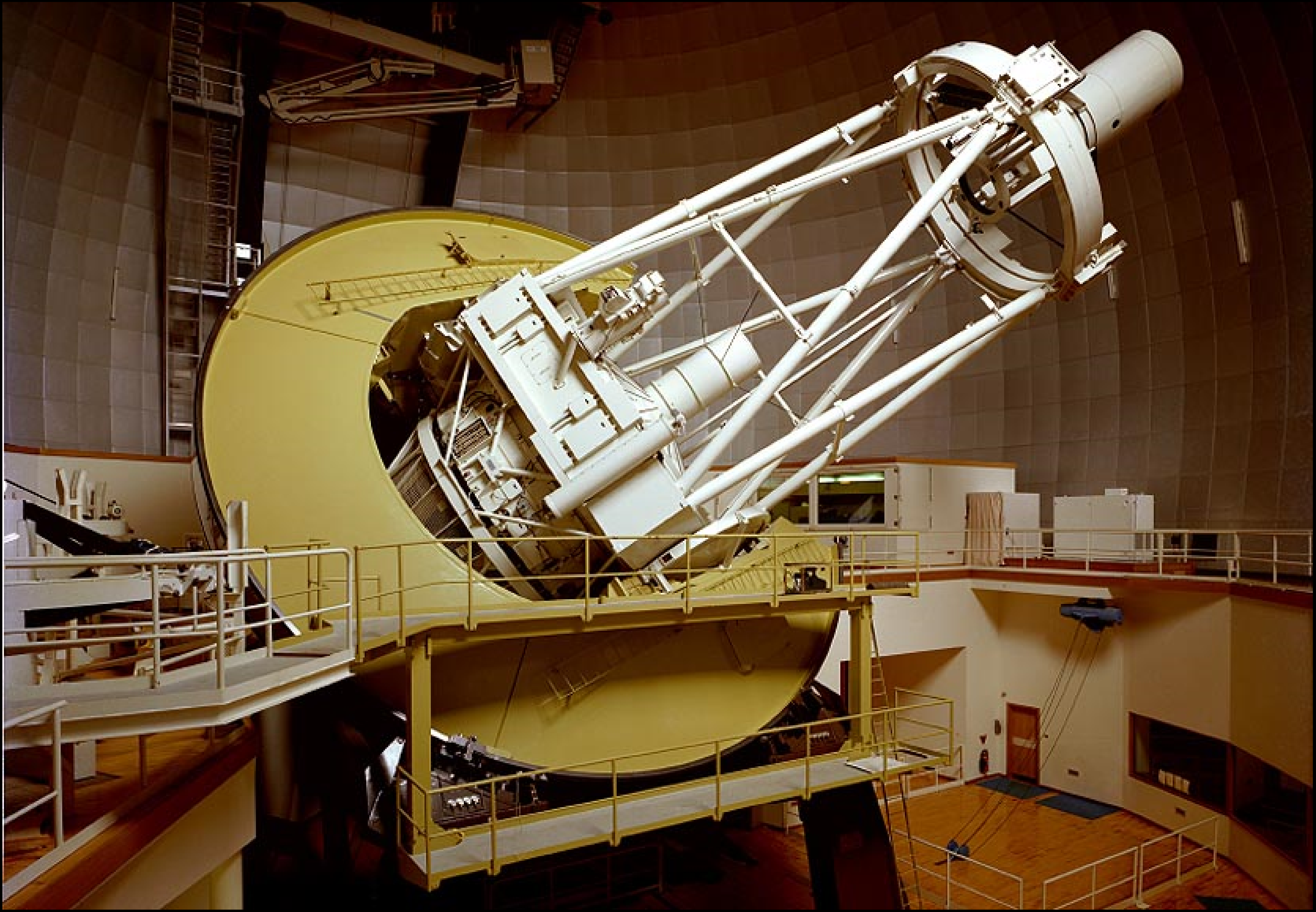


Riess et al. 1998

- Redshift as a distance indicator
- This can be done on very large samples of galaxies using redshift survey machines:

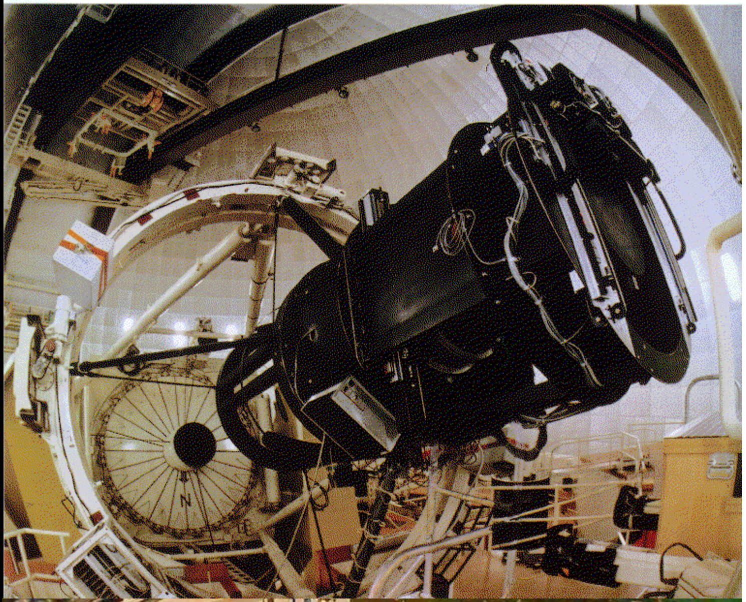


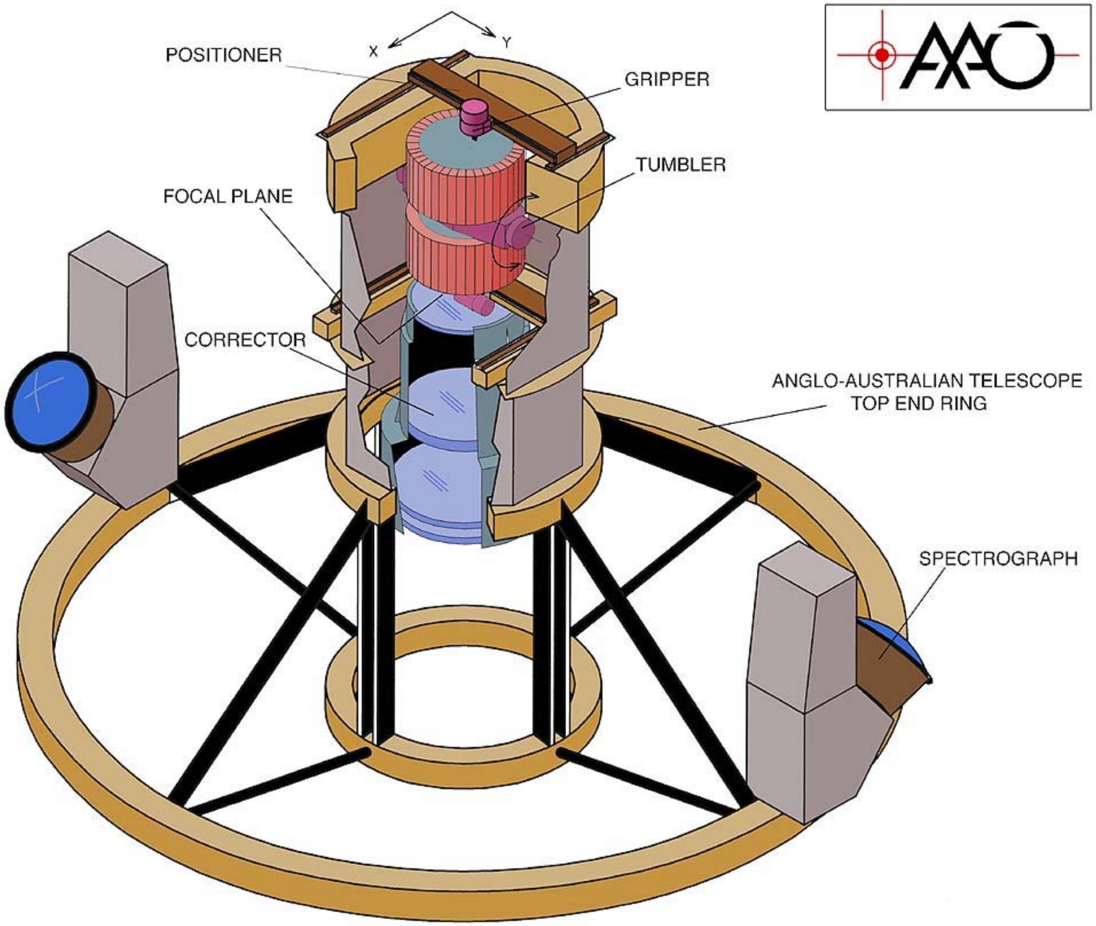
Anglo-Australian Telescope (4 m)



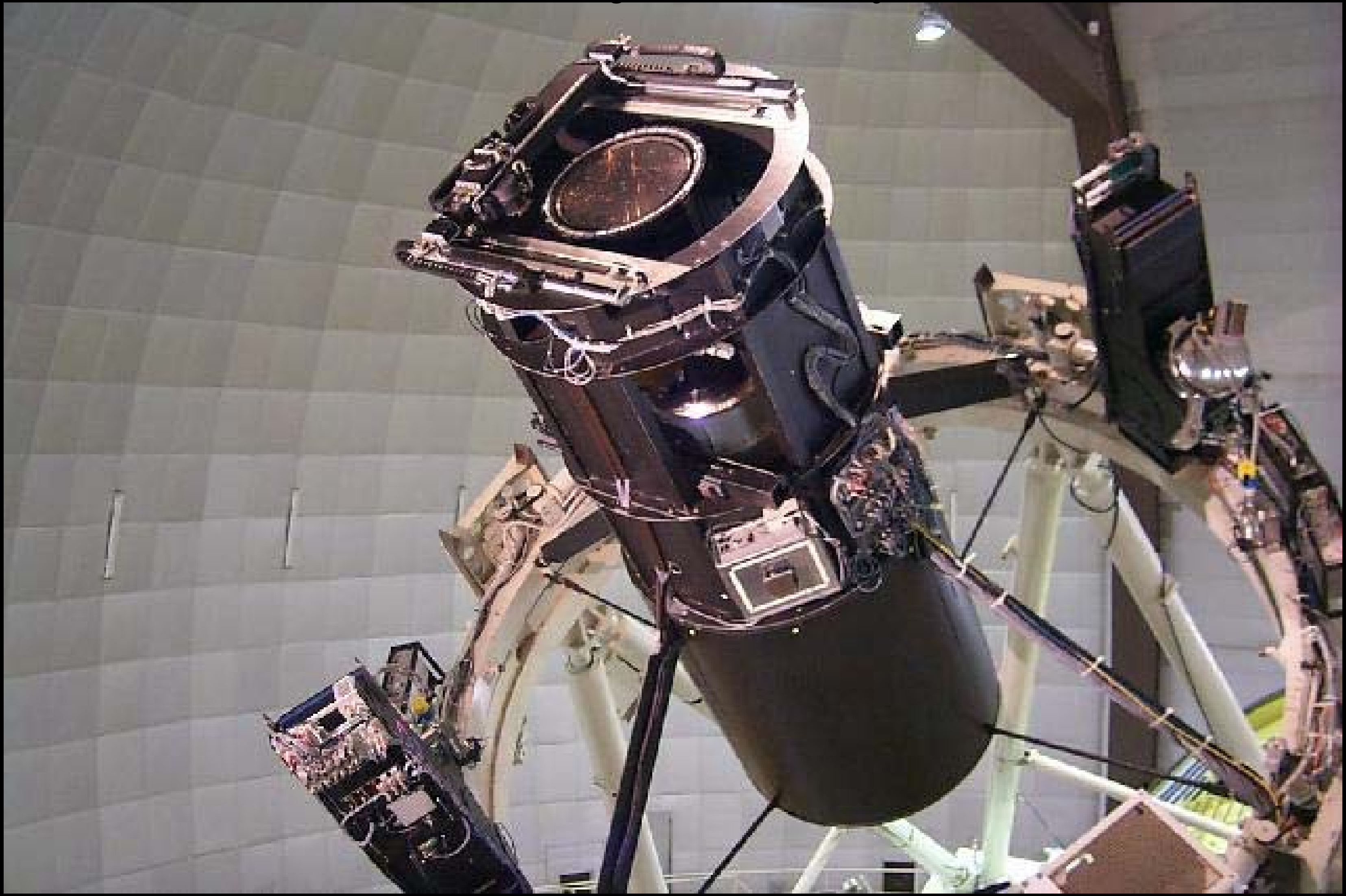
ANGLO-AUSTRALIAN TELESCOPE

TWO-DEGREE FIELD FACILITY

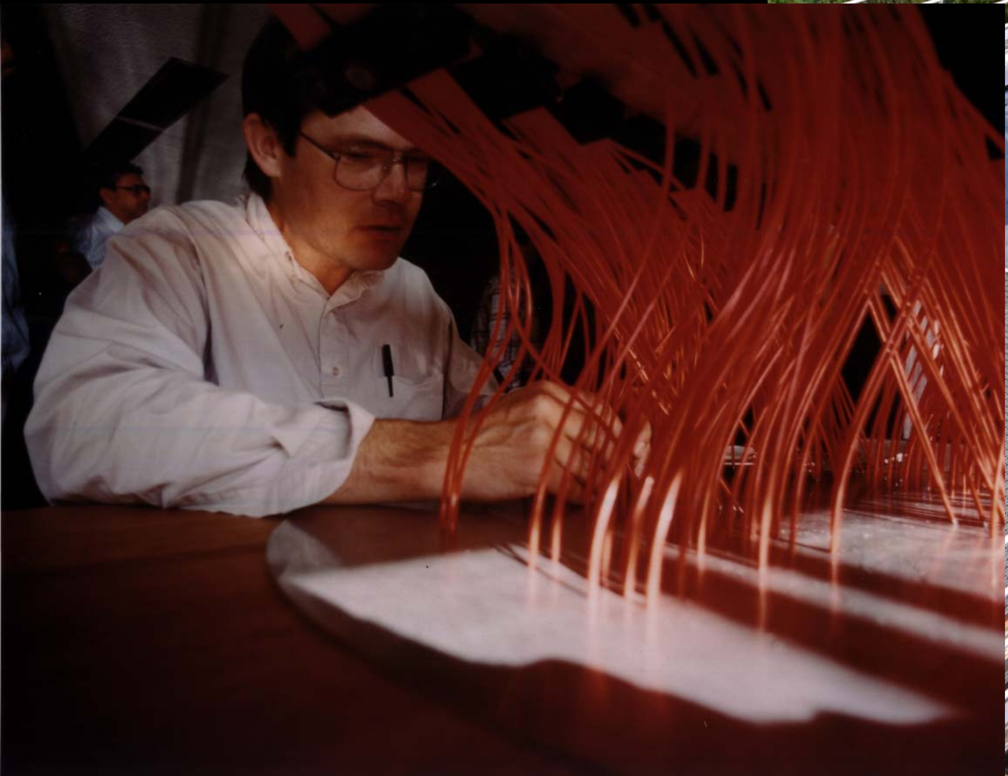




Robotized optical fiber spctrometer



- Sloan Digital Sky Survey
- Dedicated telescope with optical fibers spectrometer
- Measured redshift s for more than 10^6 galaxies !



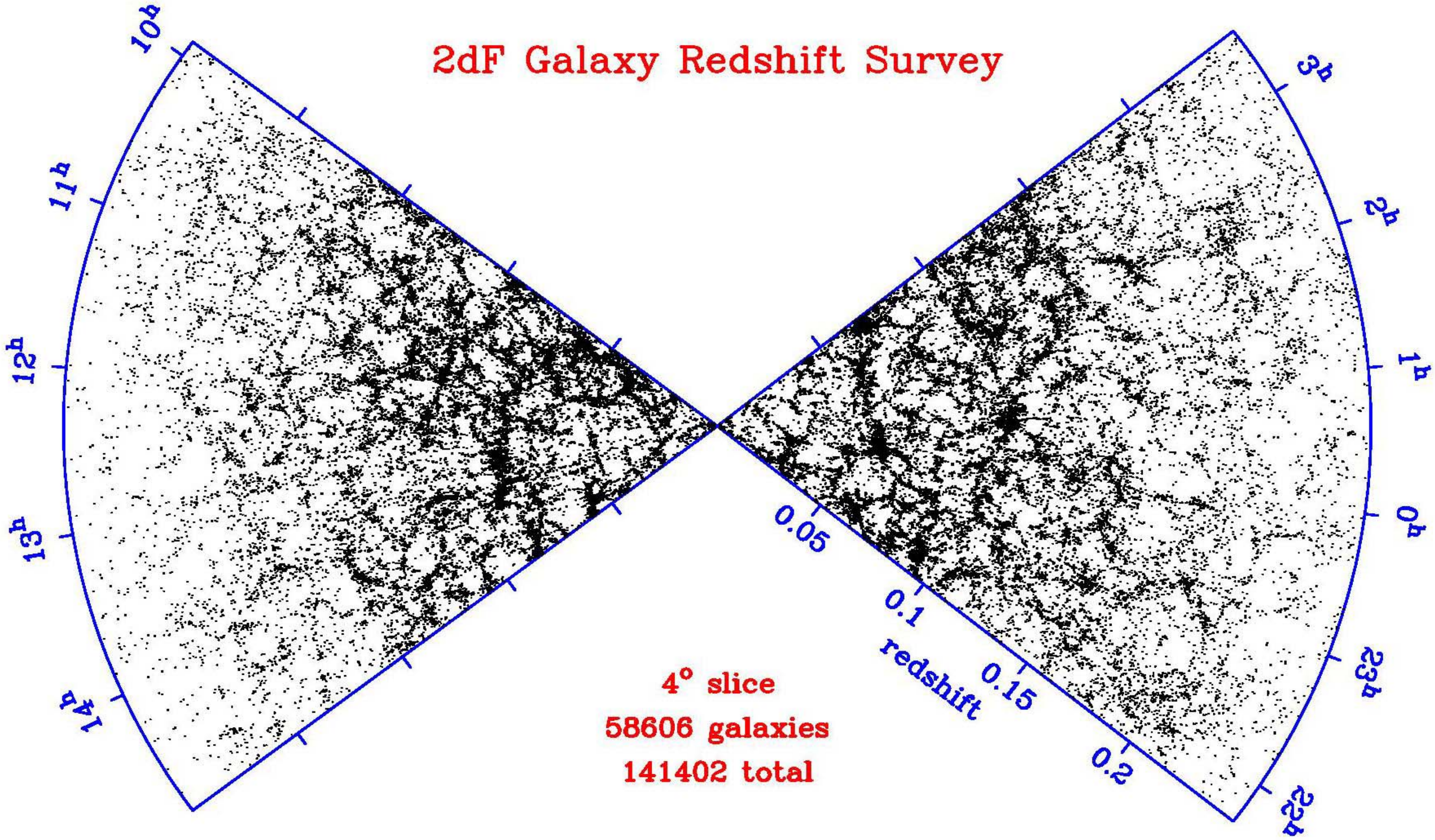
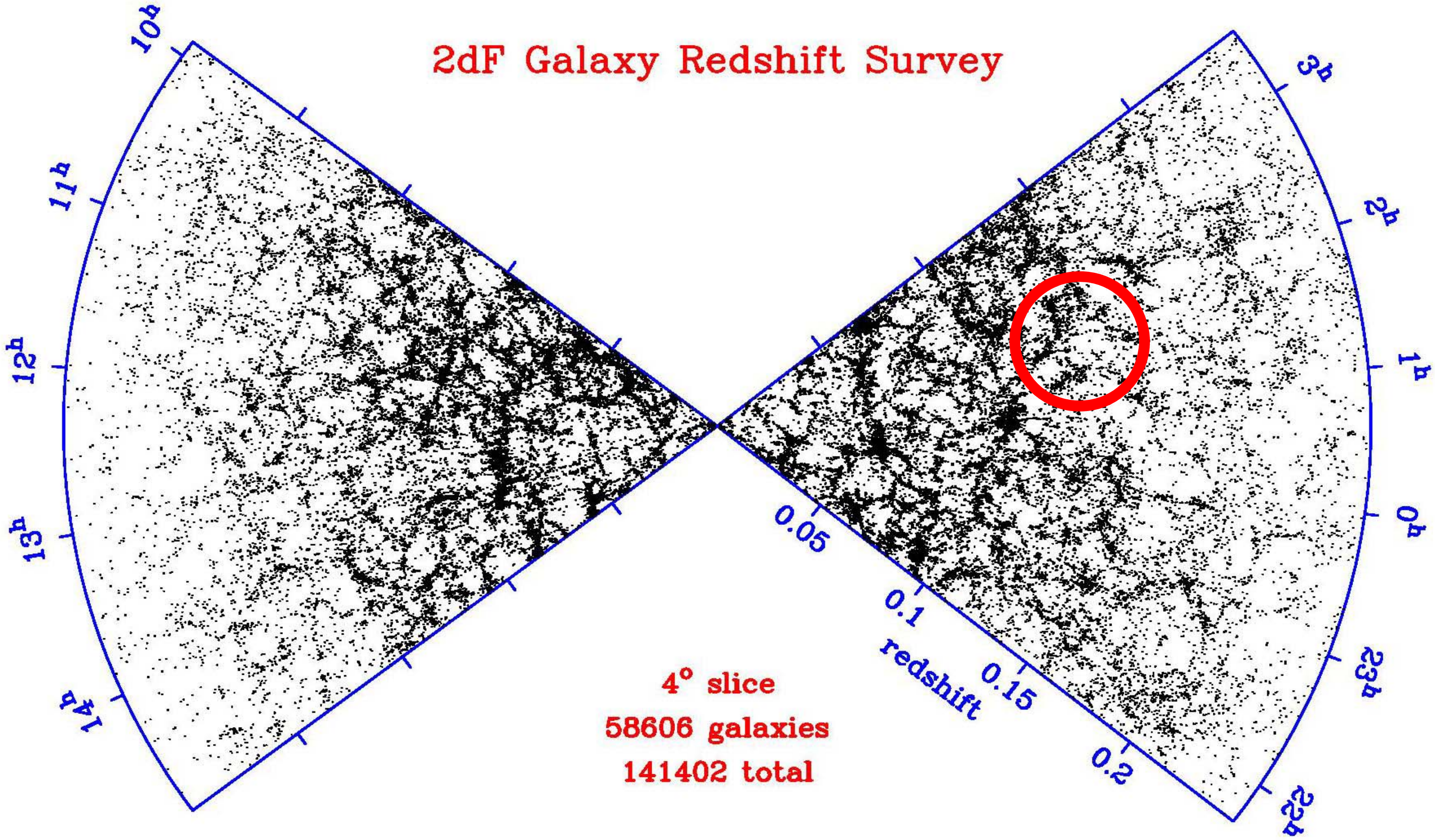


FIGURE 2. The distribution of galaxies in part of the 2dFGRS, drawn from a total of 141,402 galaxies: slices 4° thick, centred at declination −2.5° in the NGP and −27.5° in the SGP. Not all 2dF fields within the slice have been observed at this stage, hence there are weak variations of the density of sampling as a function of right ascension. To minimise such features, the slice thickness increases to 7.5° between right ascension 13.1^h and 13.4^h. This image reveals a wealth of detail, including linear supercluster features, often nearly perpendicular to the line of sight. The interesting question to settle statistically is whether such transverse features have been enhanced by infall velocities.



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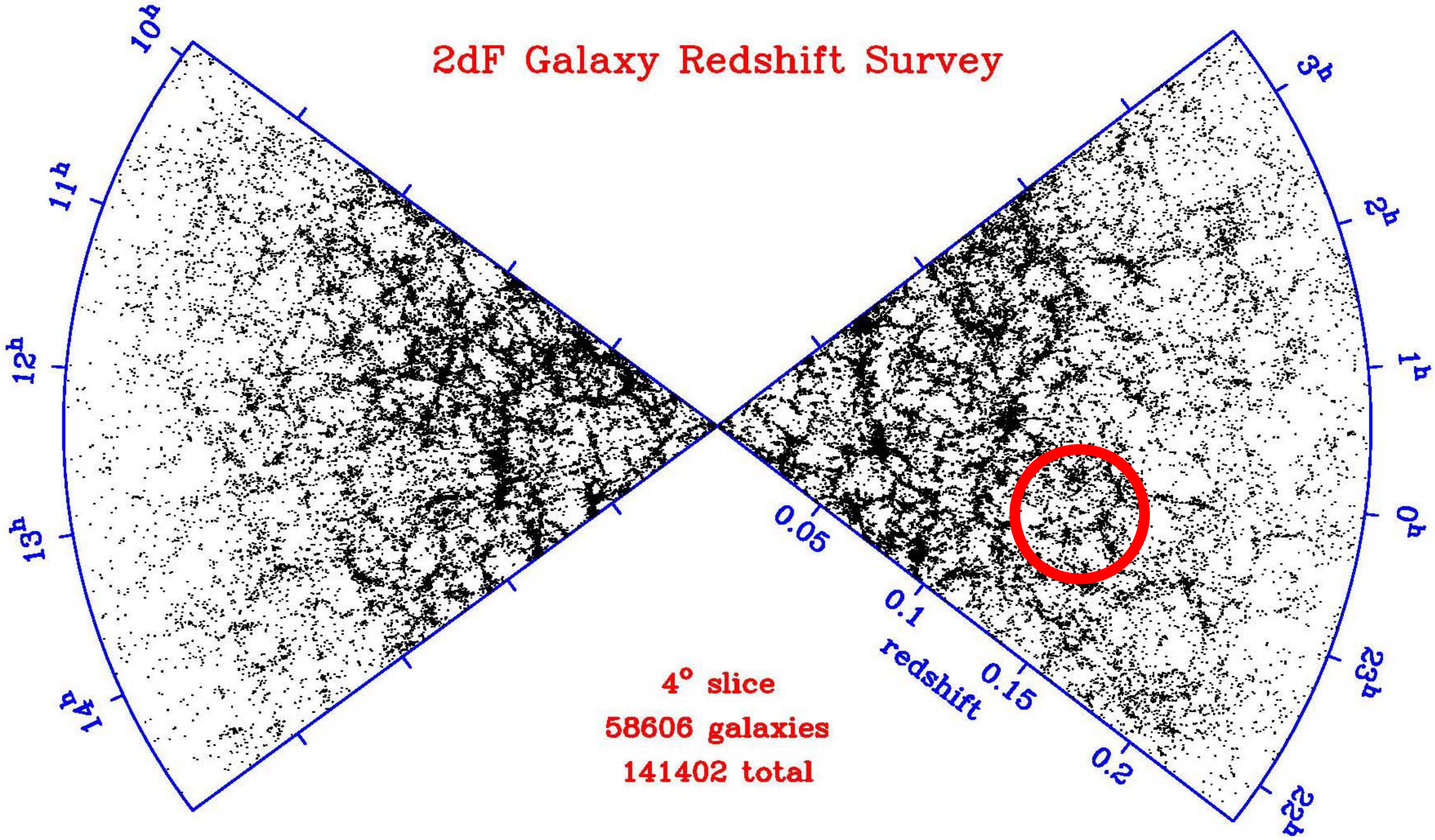

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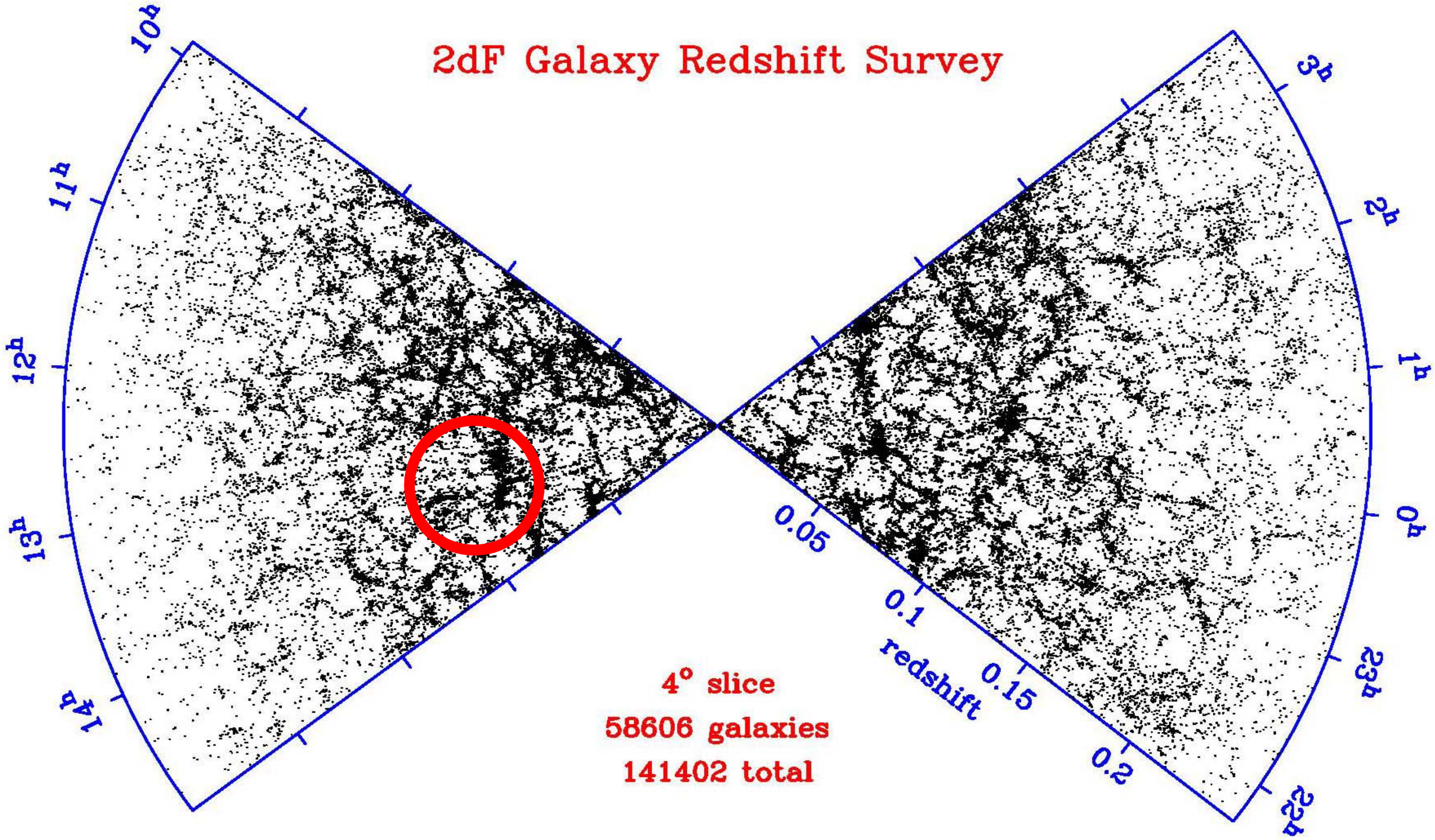

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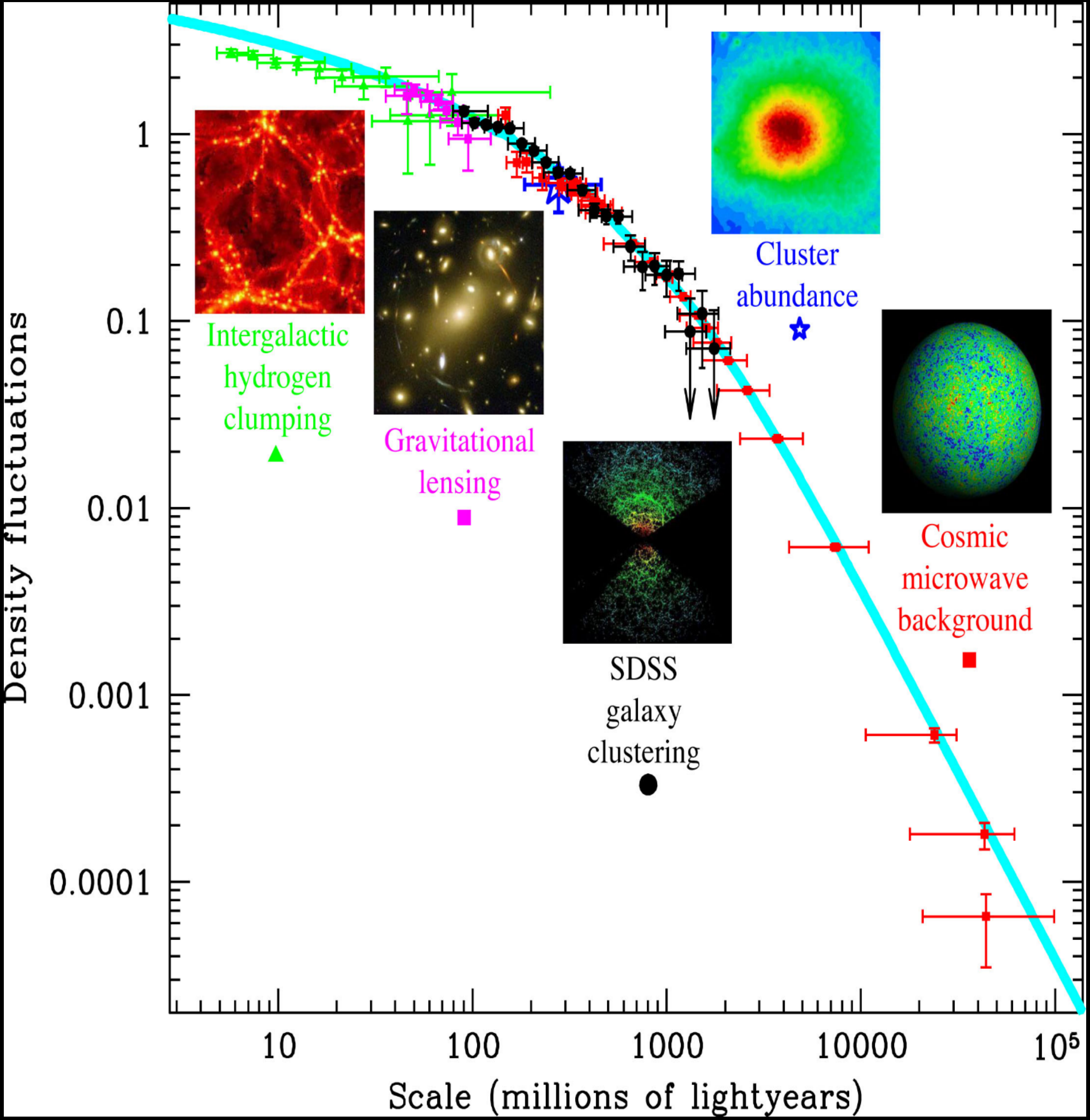
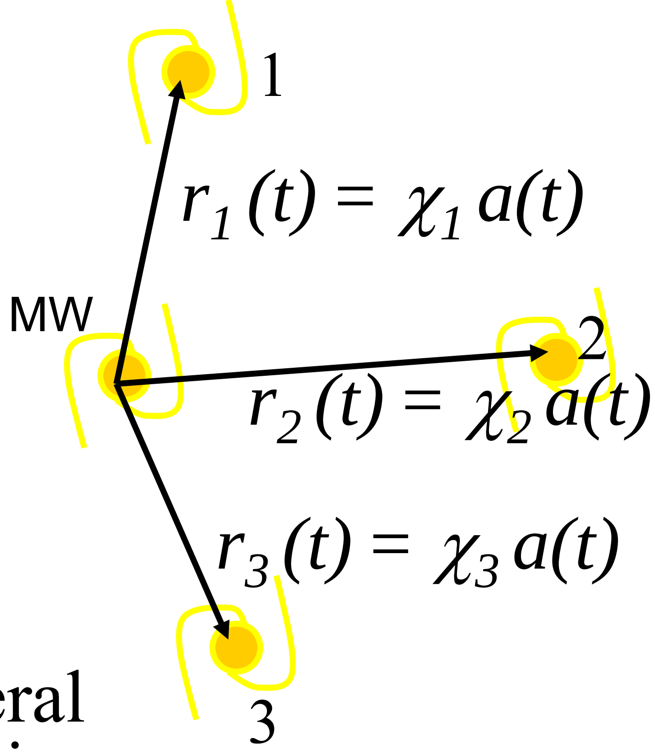
- The universe at large scales is statistically isotropic and homogeneous.

- Confirmed by the fact that if we increase the sampling volume, the rms galaxy density fluctuation decreases.



http://www.sdss.org/news/releases/20031028.powerspectrum.html

- The universe at large scales is statistically isotropic and homogeneous.
- However, the universe does not have to be static (and cannot, according to general relativity)
- An isotropic expansion or contraction preserves isotropy and homogeneity.



- Isotropic expansion
  or contraction :
  for every galaxy *i* :
  r_i = physical distance
  χ_i = comoving distance
  $a(t)$ = common scale factor
  conventionally a=1 today
- FRW metric: the most general homogenous isotropic metric

$$(ds)^2 = c^2 dt^2 - a^2(t)\left[\left(\frac{d\chi}{\sqrt{1-k\chi^2}}\right)^2 - (\chi d\theta)^2 - (\chi \sin\theta d\varphi)^2\right]$$

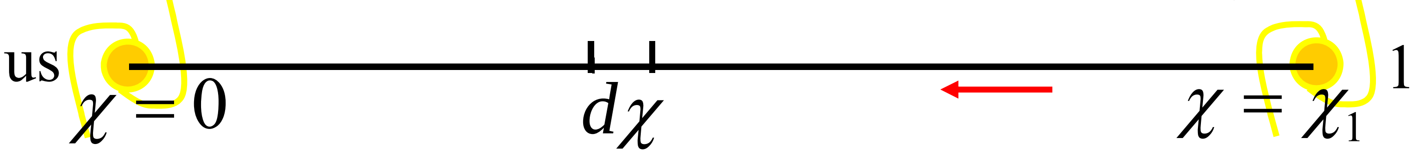
- $1/k$ = curvature of space
- In this metric, the redshift of distant sources is naturally predicted, if the universe is expanding.

Cosmological Redshift

- In an expanding universe the wavelengths of photons expand in the same way as all other lengths (*a(t)*).
- Consider a source at distance $R(t)=a(t)\,\chi_1$ (comoving coordinate χ_1)
- Photons emitted from the source propagate radially towards us along coordinate χ, occupying sequentially all coordinates between χ_1 and 0.
- From the FRW metric, with radial propagation:

$$(ds)^2 = c^2dt^2 - a(t)^2\left[\left(\frac{d\chi}{\sqrt{1-k\chi^2}}\right)^2 + \cancel{(\chi d\theta)^2} + \cancel{(\chi \sin\theta d\varphi)^2}\right]$$

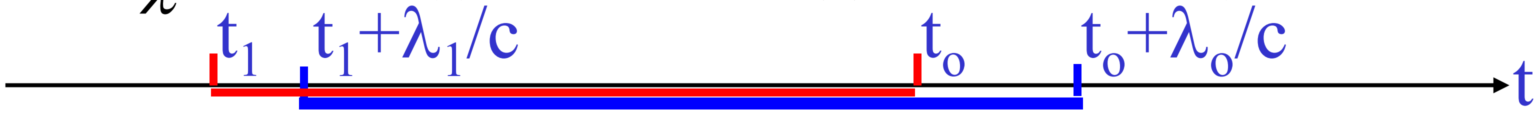
- Assuming *ds*=0 for photons (v=c), $cdt = a(t)\dfrac{d\chi}{\sqrt{1-k\chi^2}}$



Cosmological Redshift

- Consider a first crest of the EM wave emitted at time t_1 and received at time t_o; the next crest is emitted at $t_1+\lambda_1/c$ and received at $t_o+\lambda_o/c$. Since χ_1 is constant, we have that

$$\int_0^{\chi_1} \frac{d\chi}{\sqrt{1-k\chi^2}} = \int_{t_1}^{t_o} \frac{c\,dt}{a(t)} = \int_{t_1+\lambda_1/c}^{t_o+\lambda_o/c} \frac{c\,dt}{a(t)} \Rightarrow \int_{t_1}^{t_1+\lambda_1/c} \frac{c\,dt}{a(t)} = \int_{t_o}^{t_o+\lambda_o/c} \frac{c\,dt}{a(t)}$$



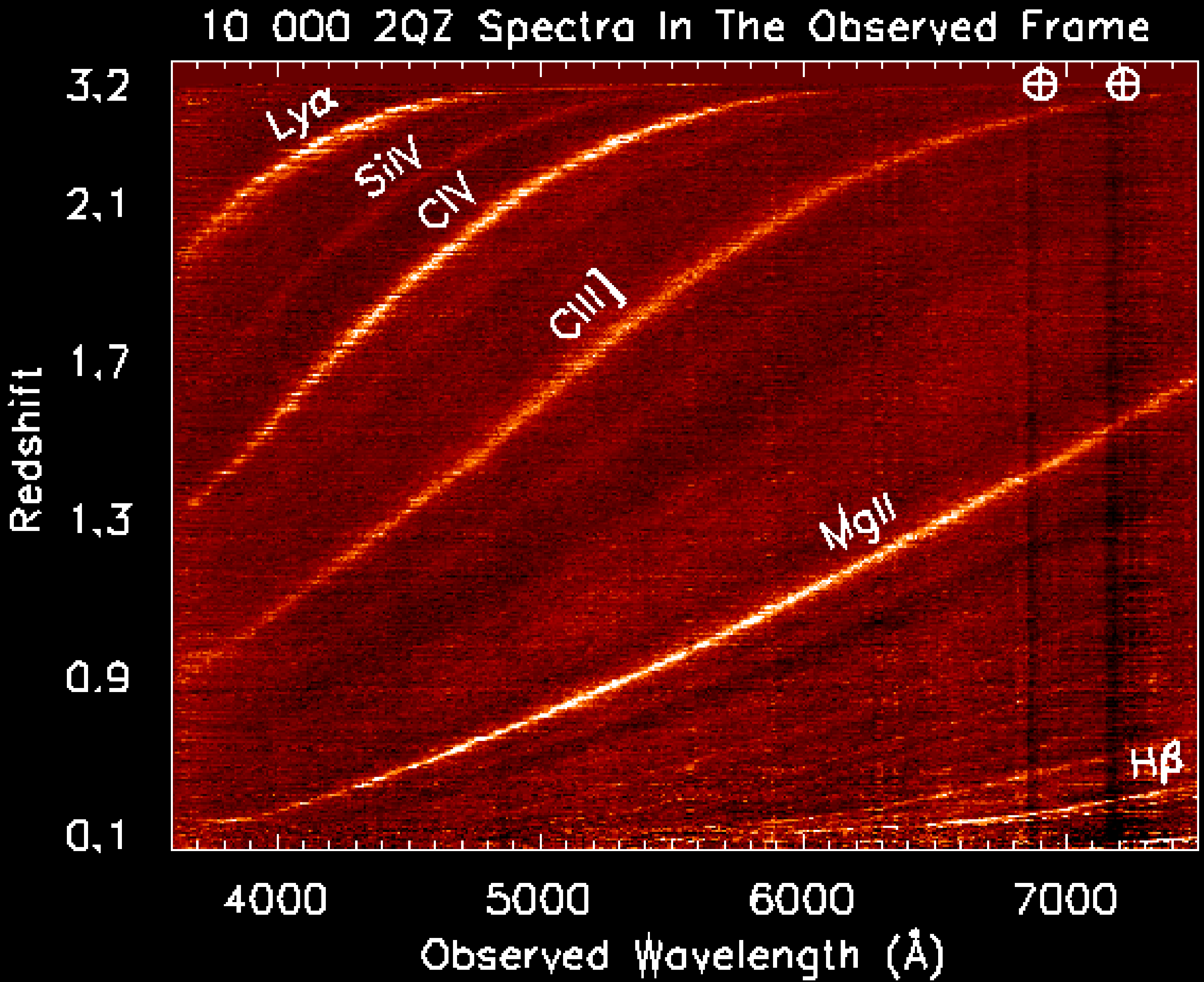
- However, the times λ_o/c e λ_1/c are both $\ll H_o^{-1}$, the typical timescale for of $a(t)$. So we can safely consider $a(t)$ as constant in the integrals, and we get

Redshift of the source

$$\frac{c}{a(t_1)}\frac{\lambda_1}{c} = \frac{c}{a(t_o)}\frac{\lambda_o}{c} \Rightarrow \frac{a(t_o)}{a(t_1)} = \frac{1}{a(t_1)} = \frac{\lambda_o}{\lambda_1} \underset{def}{=} (1+z_1)$$

- The wavelengths of photons elongate in the same way as all other cosmological distances, following the same scale factor $a(t)$. In particular, **redshift implies expansion**.

10000 optical spectra of QSOs (with important emission lines) as measured from the 2dF survey, plotted in vs the observed wavelengths. The redshift scale is not linear.



$$v = c$$

Observing far = observing the past

$$\lambda_{obs}/\lambda_{em} = 1 + z = 1/a_{em}$$

In an expanding universe $a_{em} < 1$

Observing far = measuring long λs