Cosmic Microwave Background

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The Cosmic Microwave Background

- Is a very effective tool to investigate
  - the early universe
  - the formation of structures in the universe
  - fundamental physics.
- Has triggered the development of advanced experimental techniques in the mm/sub-mm range.
- Has still a huge discovery potential …

Schedule

1. CMB cosmology : the homogeneous isotropic universe and the CMB

2. The inhomogeneous universe and the CMB – new CMB observables

3. How to detect CMB photons – fundamental limits – detectors

4. Modulators, CMB experiments

5. The future of CMB research

Modern Cosmology

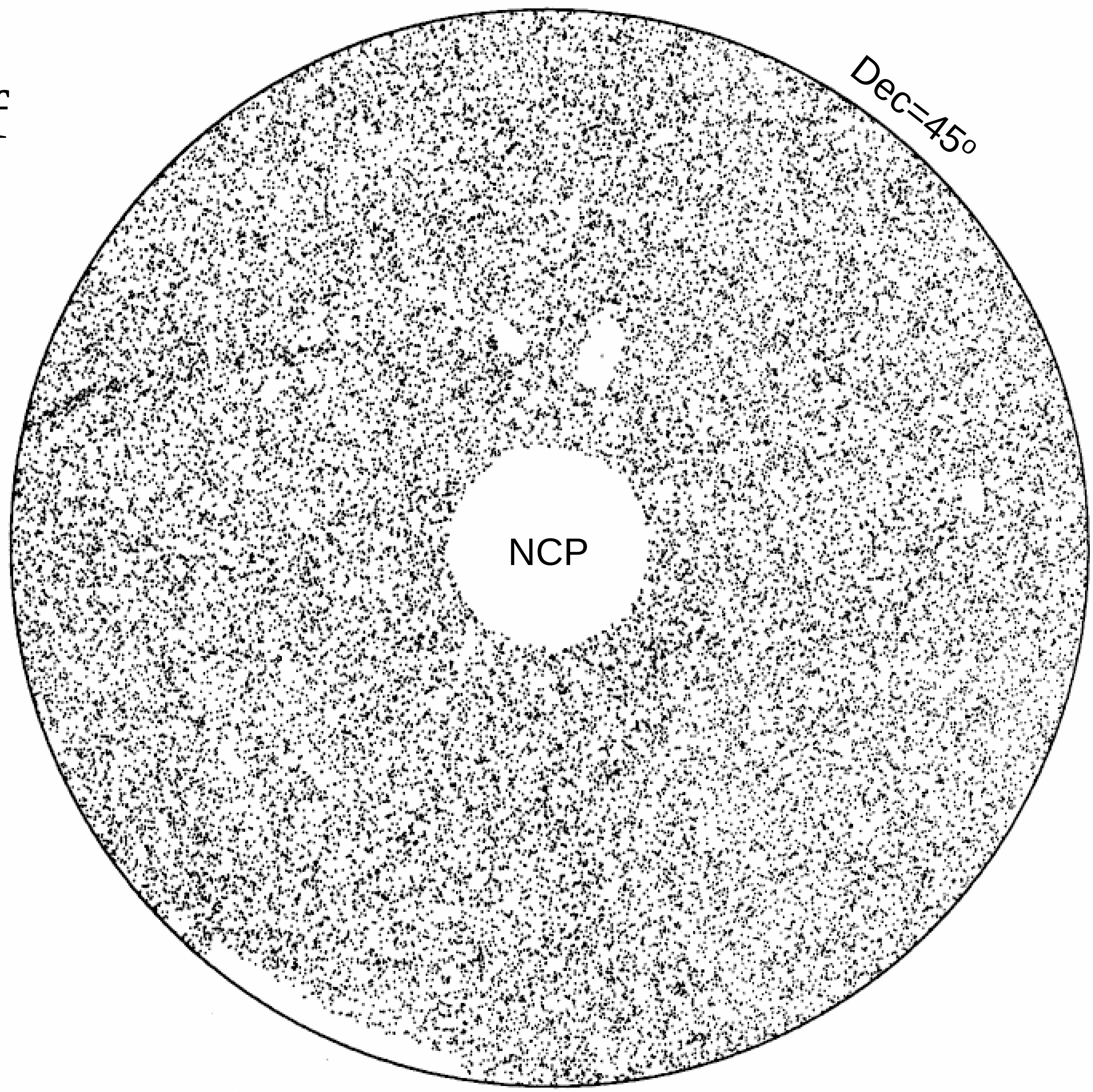
- Cosmology is the description of the Universe at large scales, and of its evolution.
- The Hot Big Bang model is based
  - on the Cosmological Principle
  - on general relativity (Einstein, Friedmann, ...)
  - on particle, nuclear, atomic physics (Gamow, ...)
- The observational evidences are
  - The expansion of the Universe
  - The measured abundances of light elements
  - The Cosmic Microwave Background

Modern Cosmology

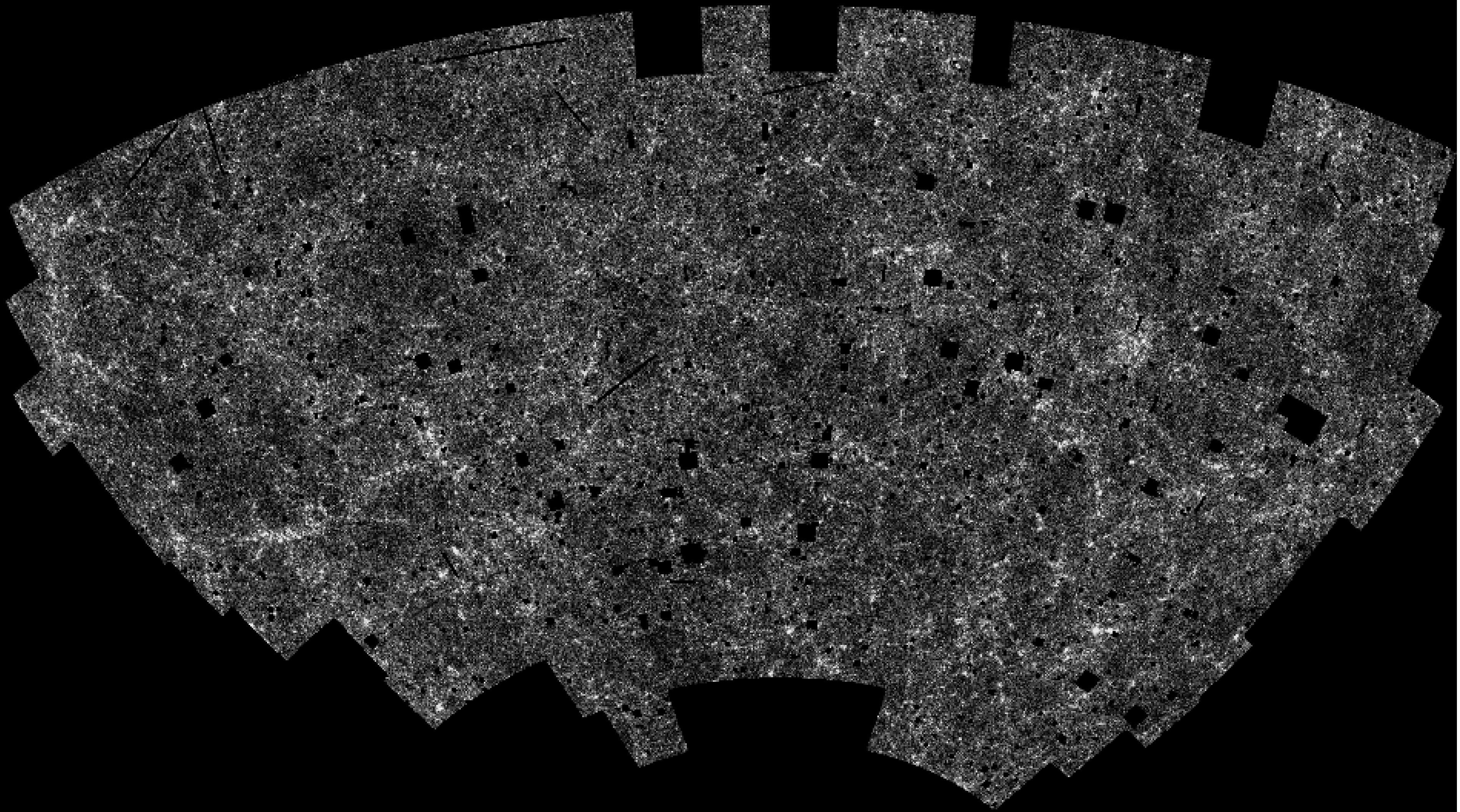
- If we believe that
  - we do not occupy a special position in the Universe, i.e. the Universe at large scales is the same everywhere
  - the Universe expands isotropically
  - the correct description of gravity is general relativity,
- then we get the FRW metric and then the Friedmann equation, describing the evolution of the scale factor.
- Empirical evidence for the above:

Projected distribution of distant radiogalaxies

- From Gregory & Condon 1991
- 31000 strong radiosources at λ=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)

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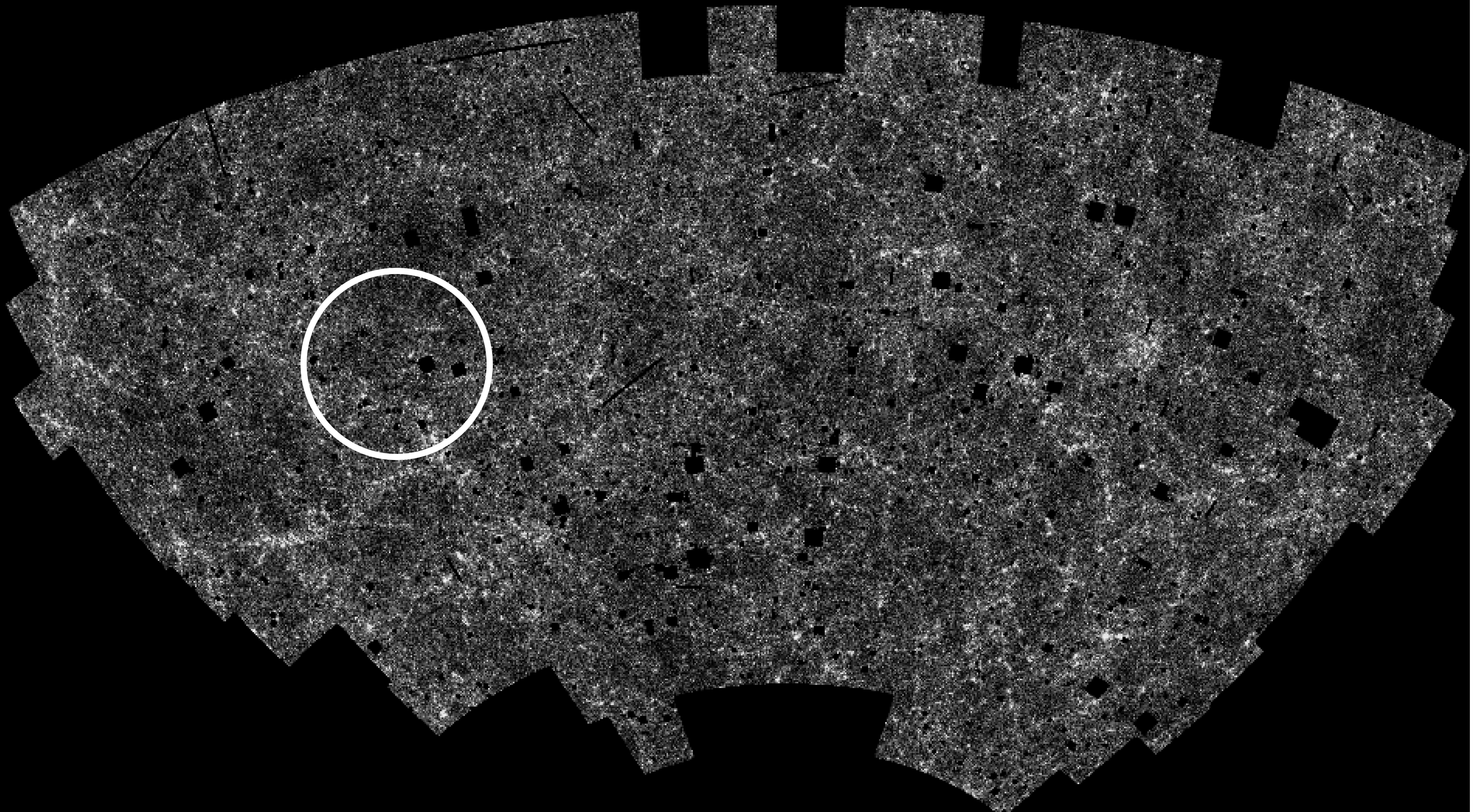

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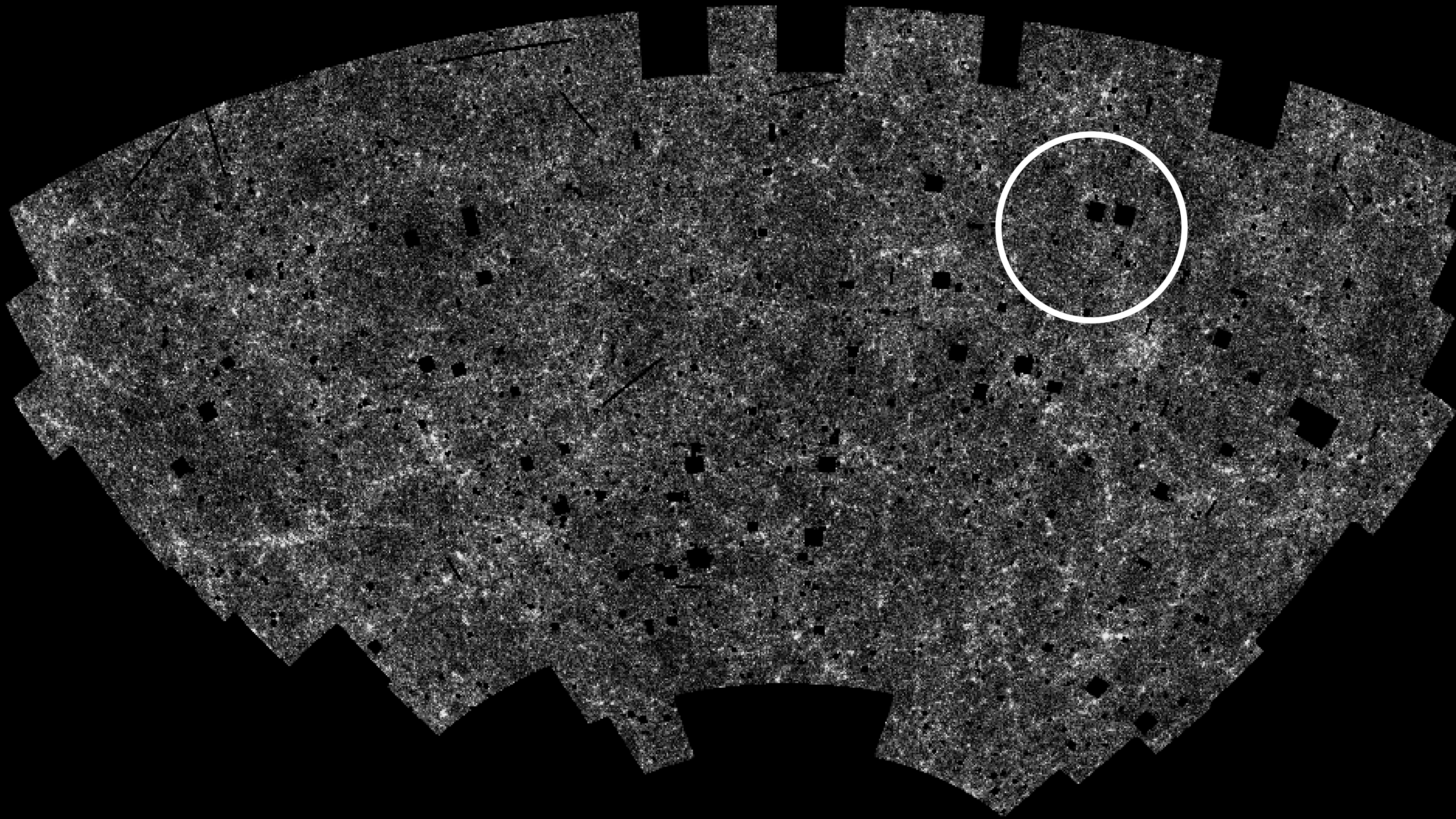

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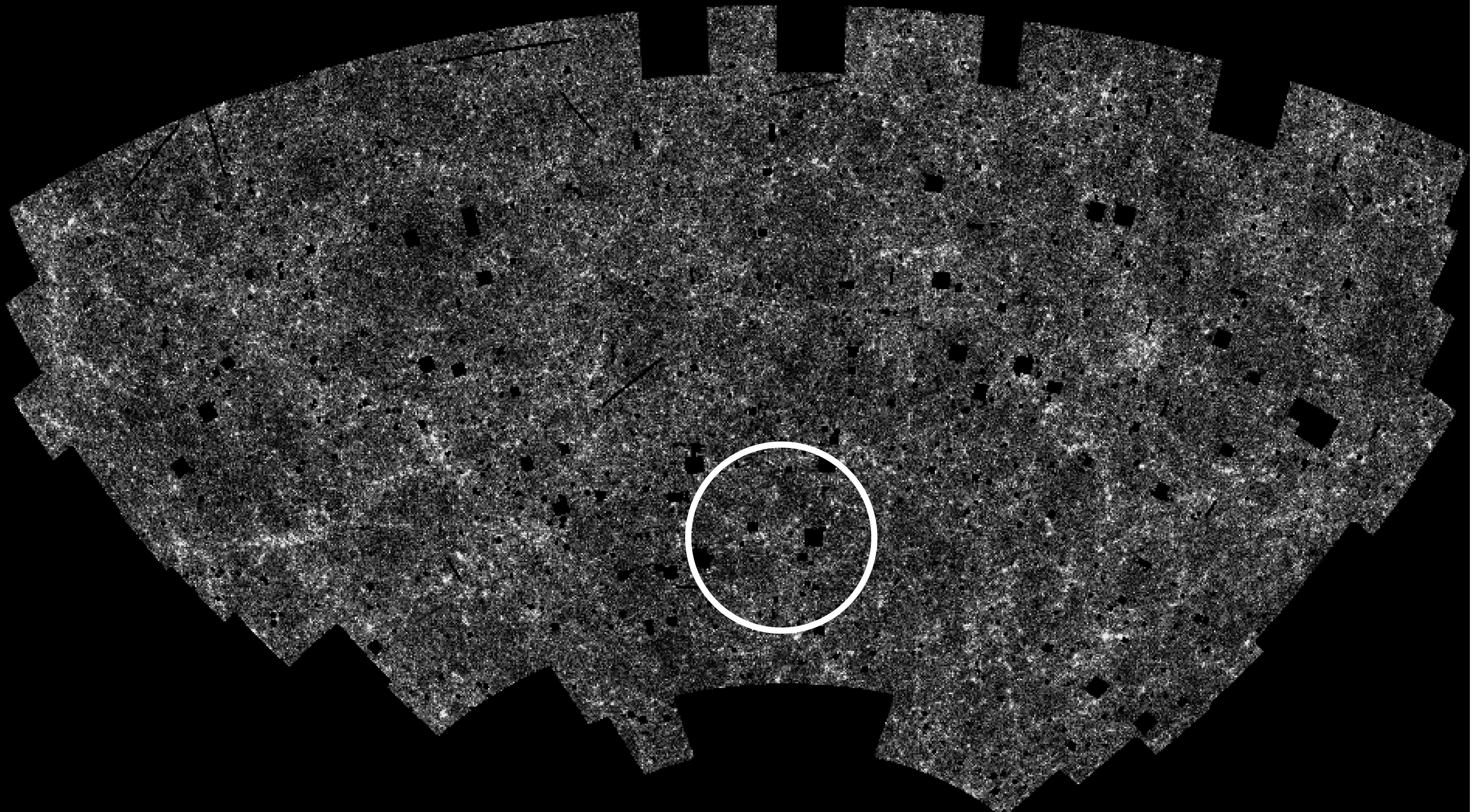

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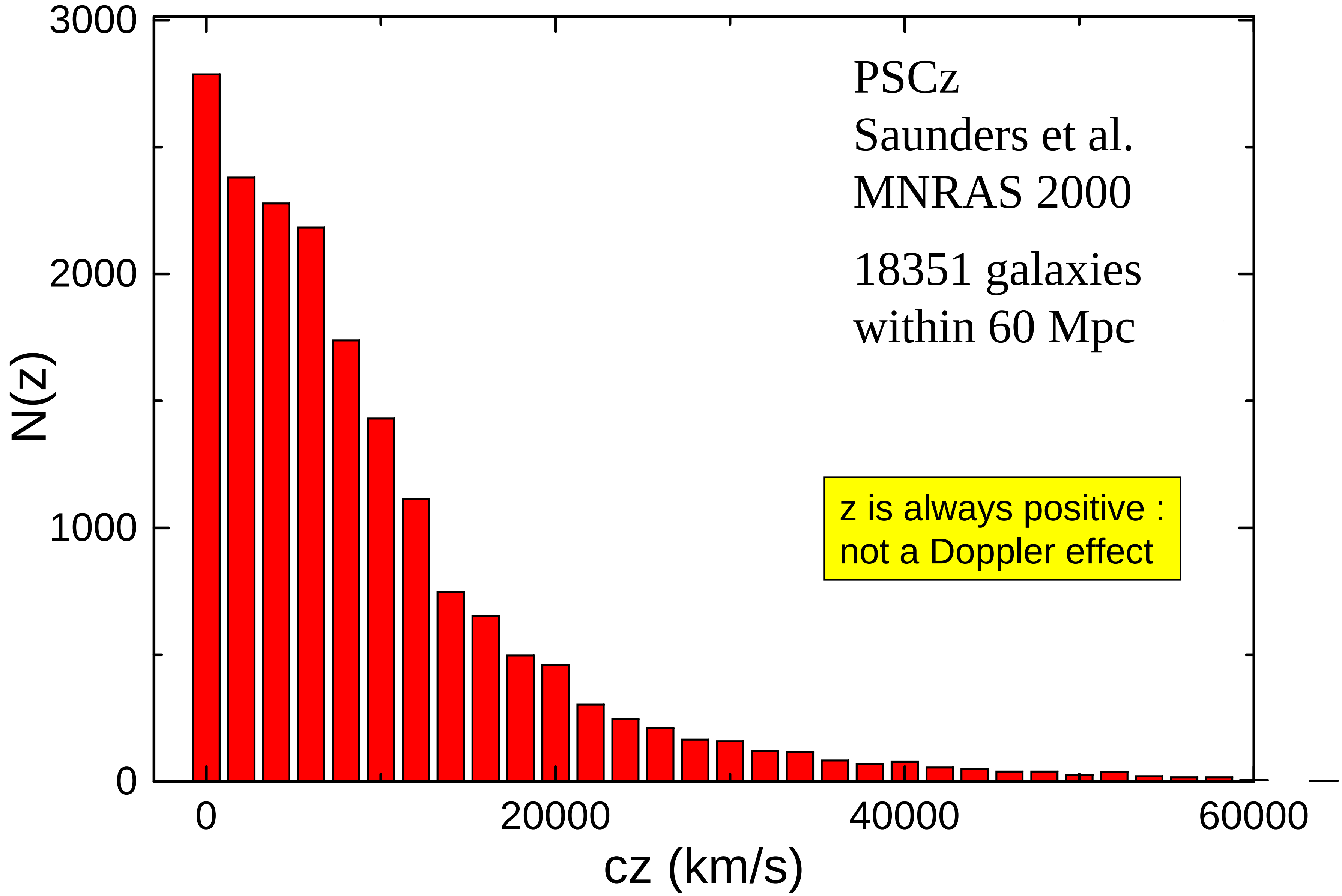
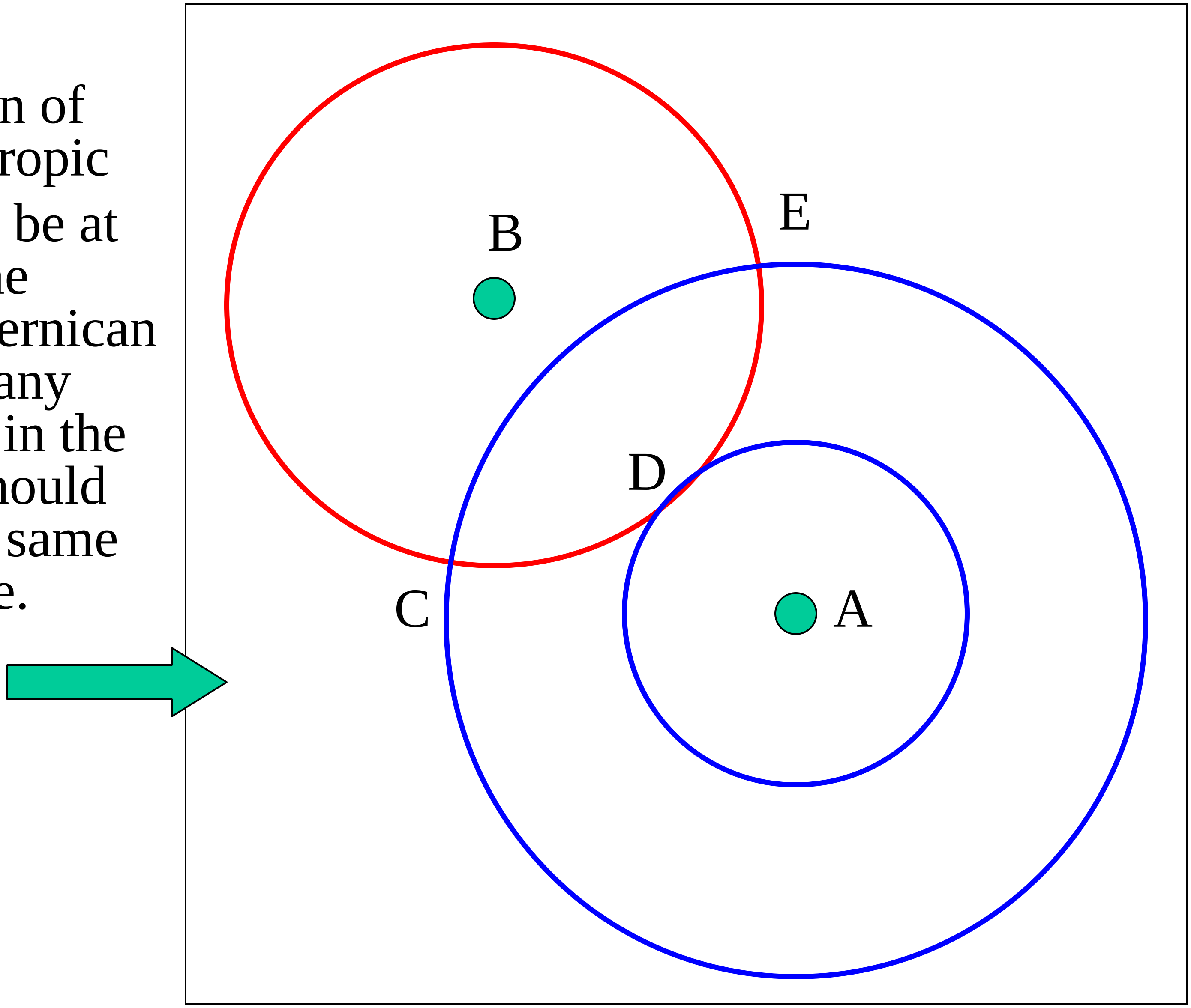
Cosmological Redshift of Galaxies

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



- 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 :

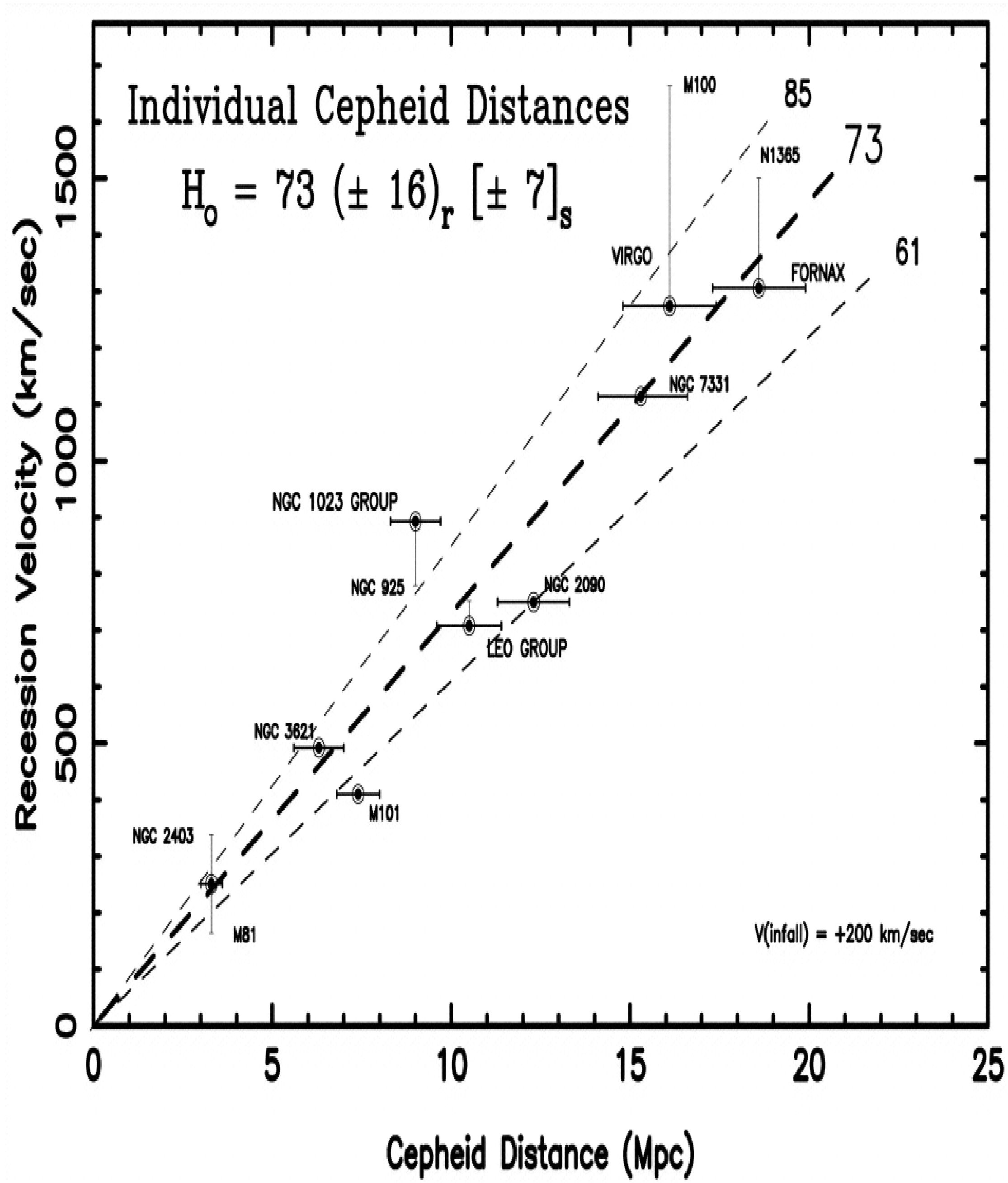


$$z = \frac{\lambda_{observed} - \lambda_{restframe}}{\lambda_{restframe}}$$

- Hubble's law from distant cepheid stars

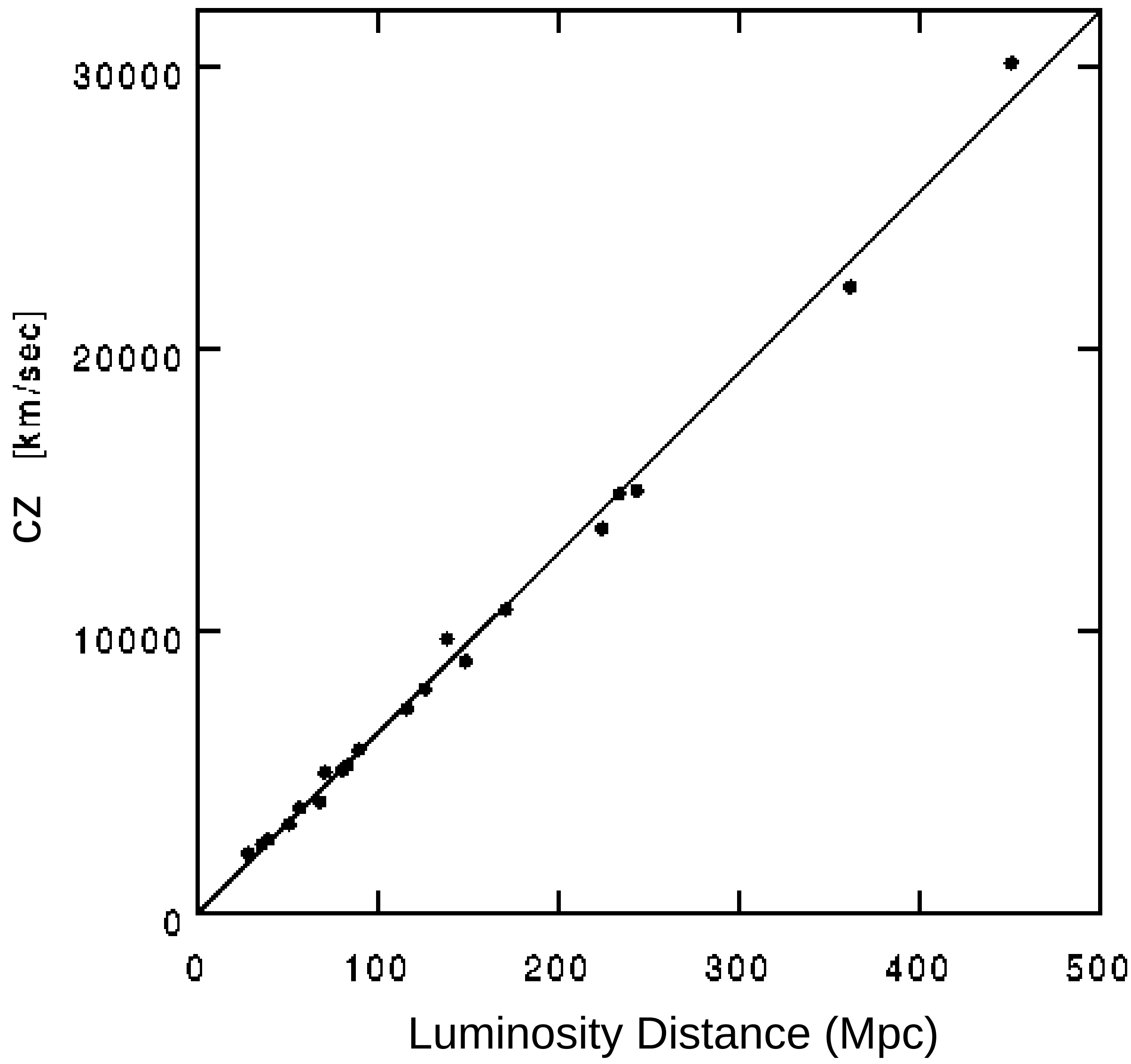
$$cz = H_o D$$

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



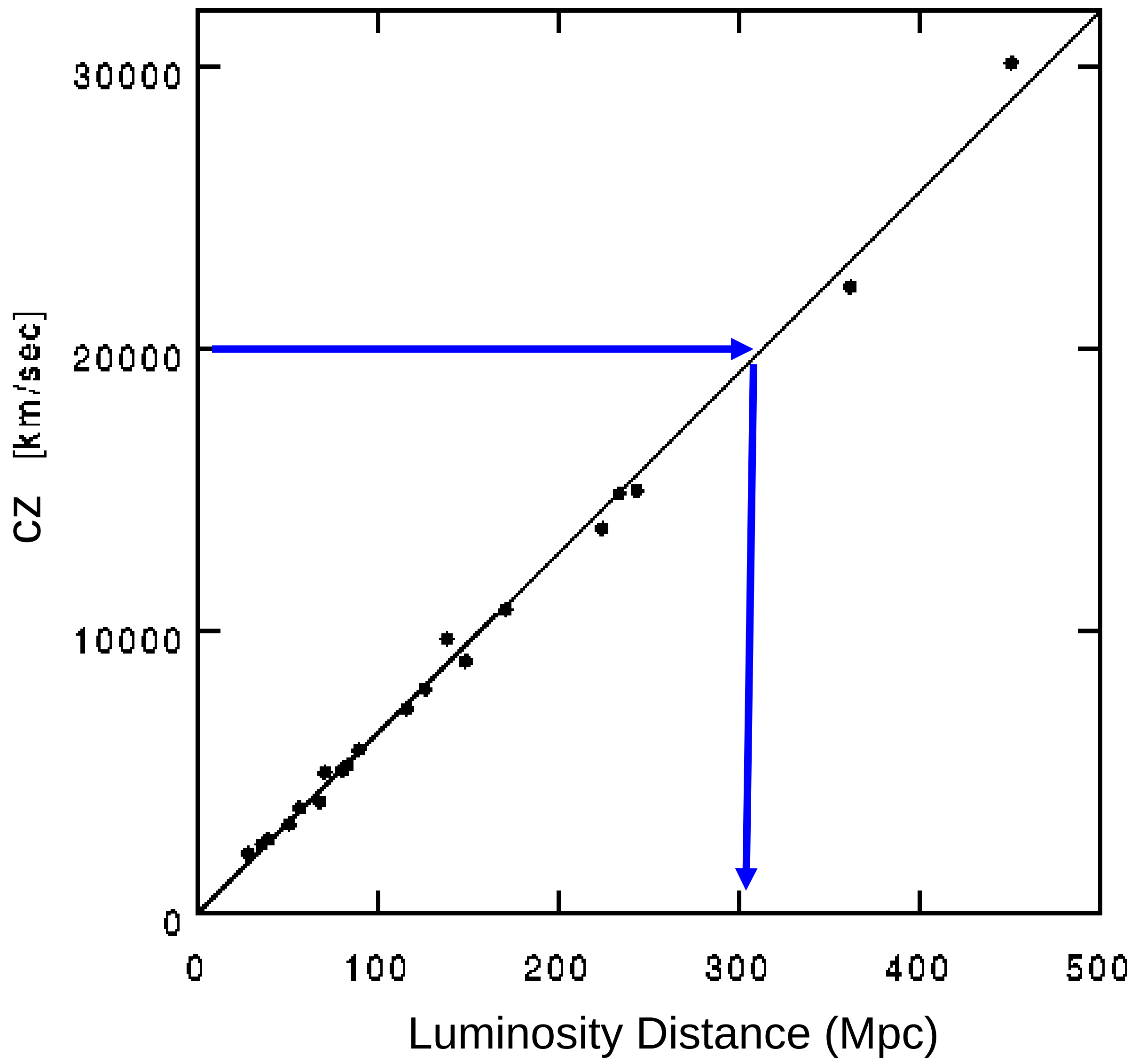
Madore B.F. et al., Ap.J. 515 29 (1999)

- Hubble's law with Supernovae 1a

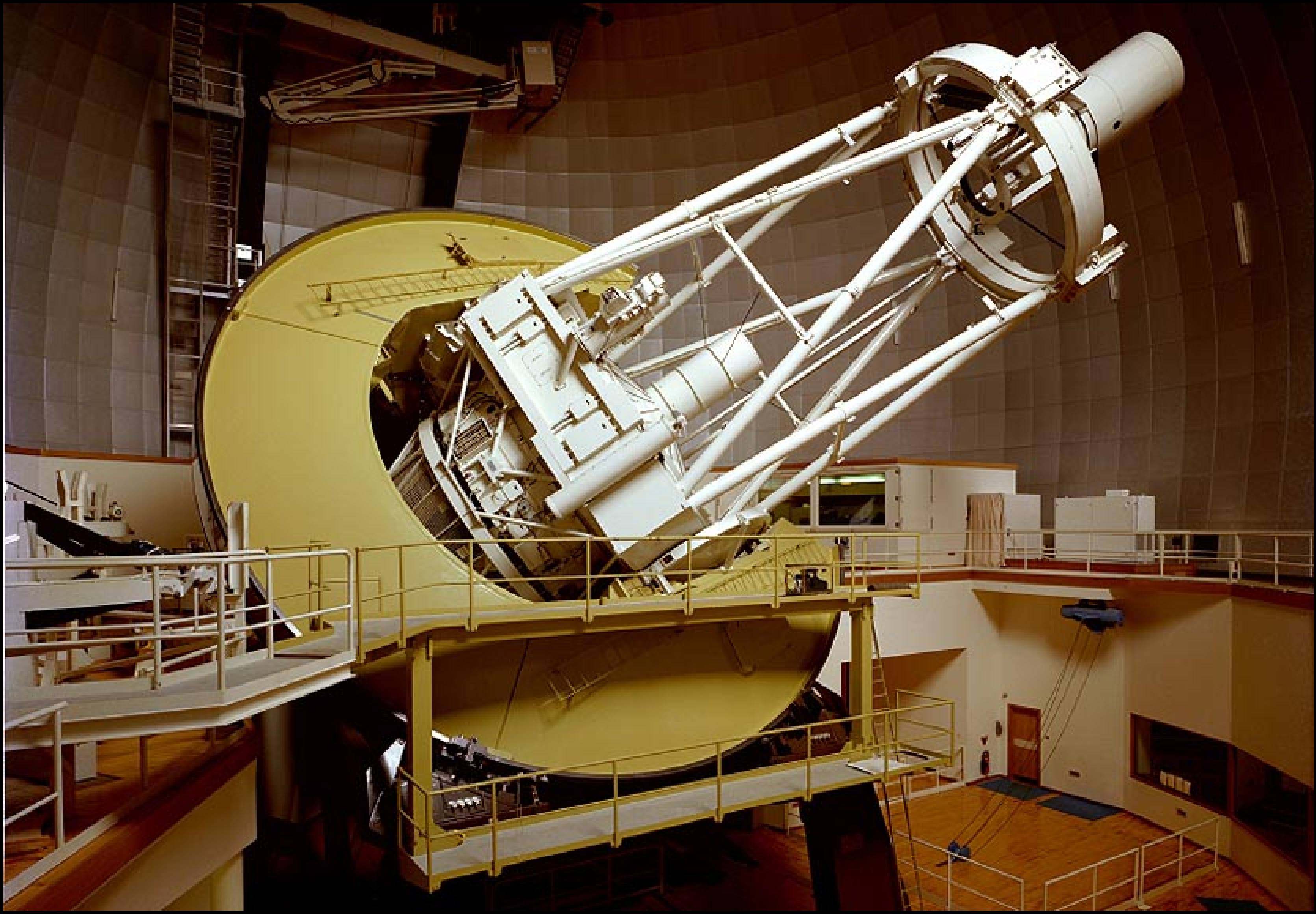


Riess et al. 1998

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

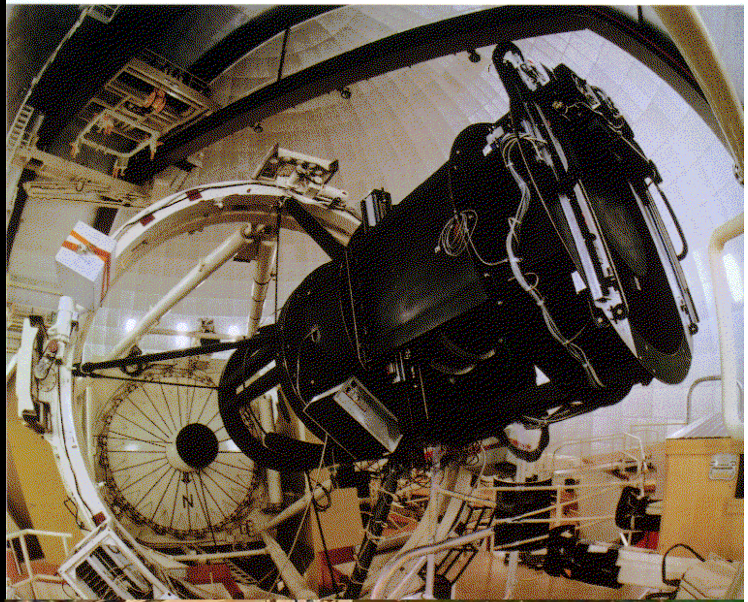


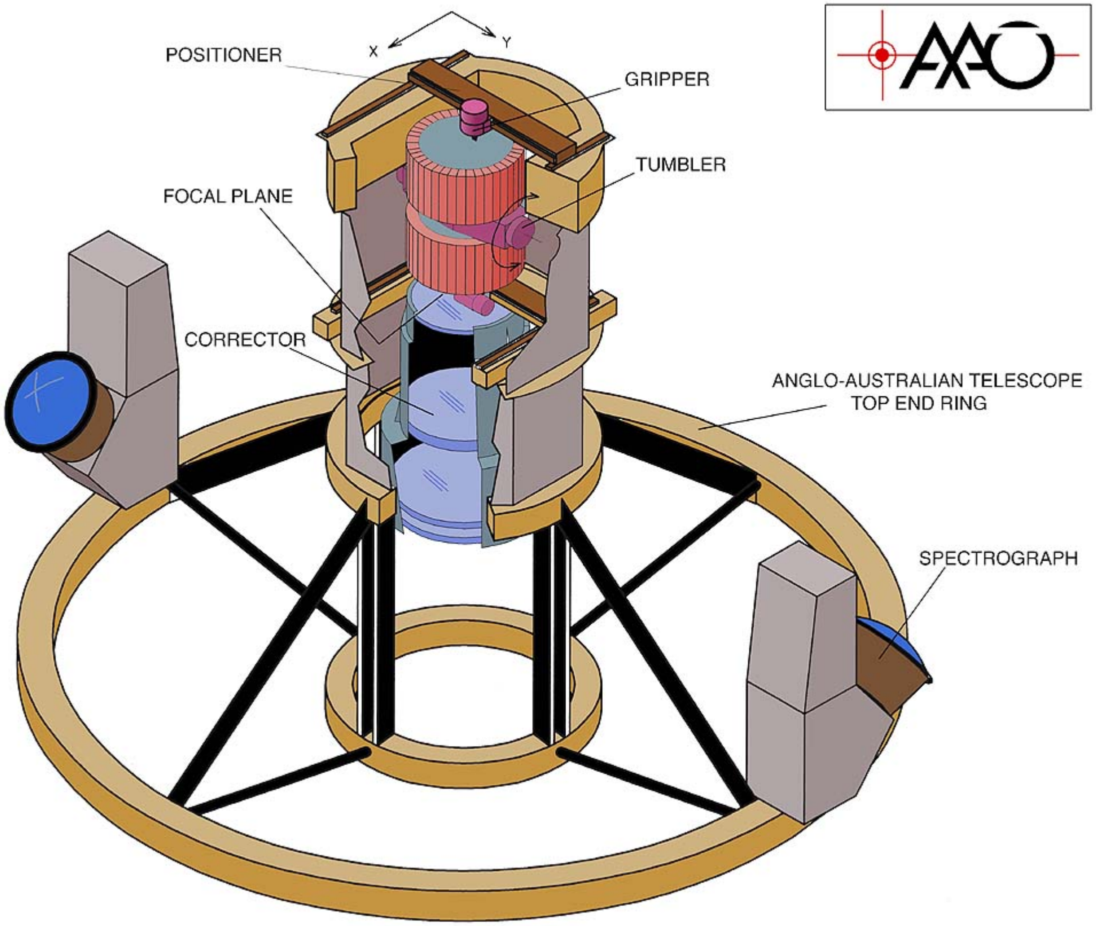
Il Telescopio Anglo-Australiano (4 m)

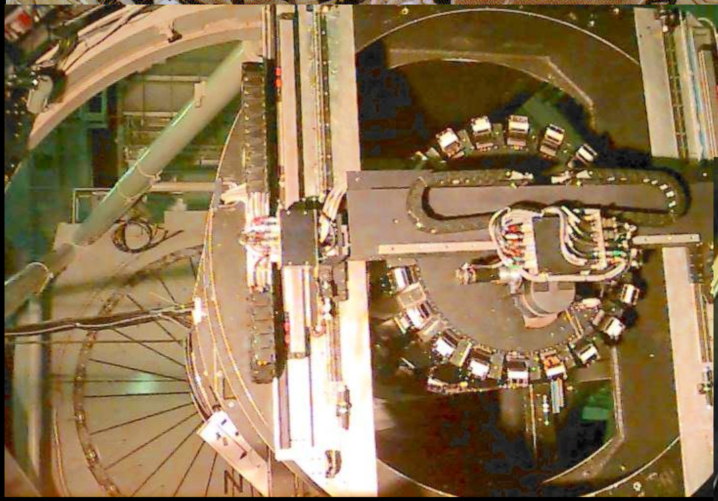


ANGLO-AUSTRALIAN TELESCOPE

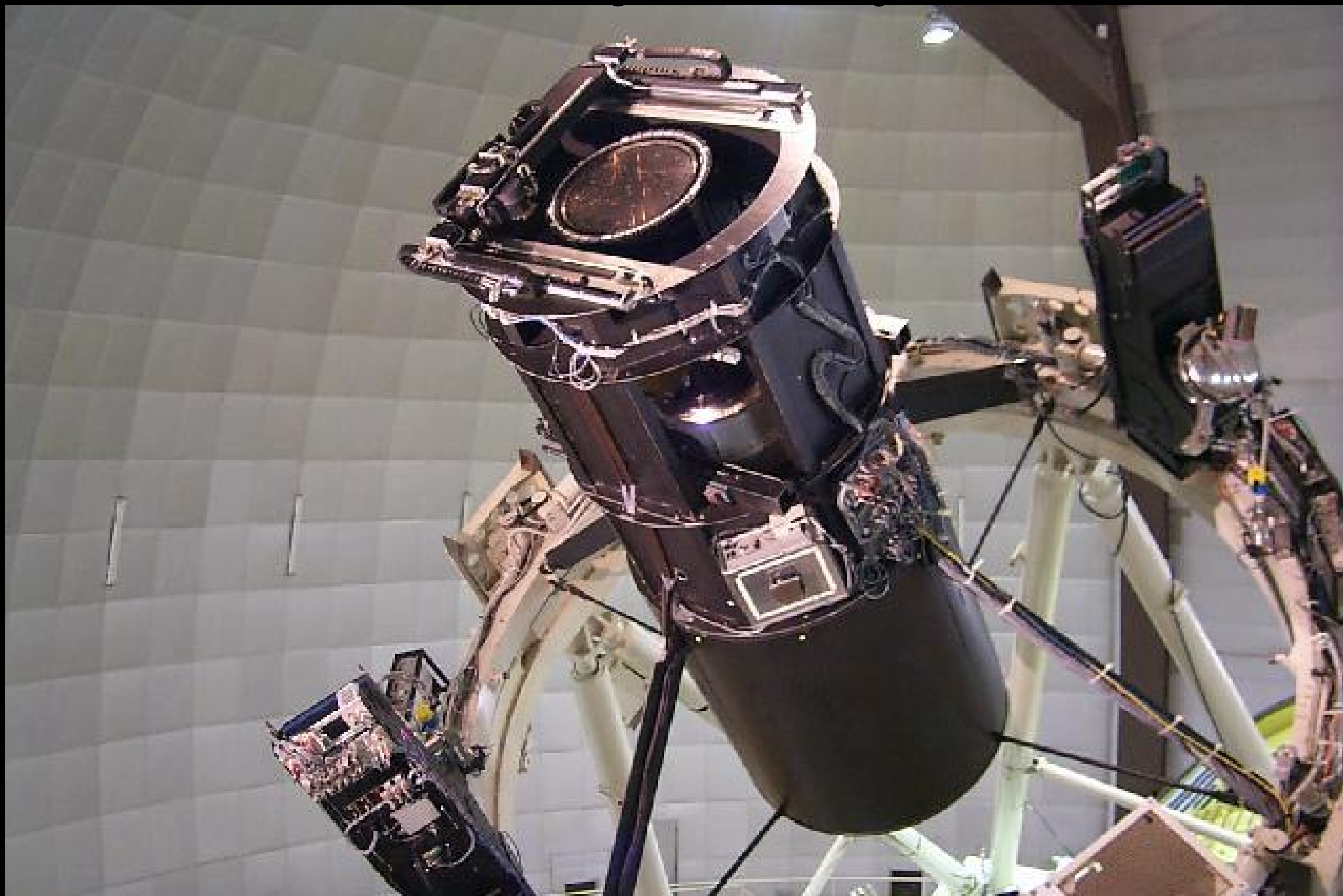
TWO-DEGREE FIELD FACILITY



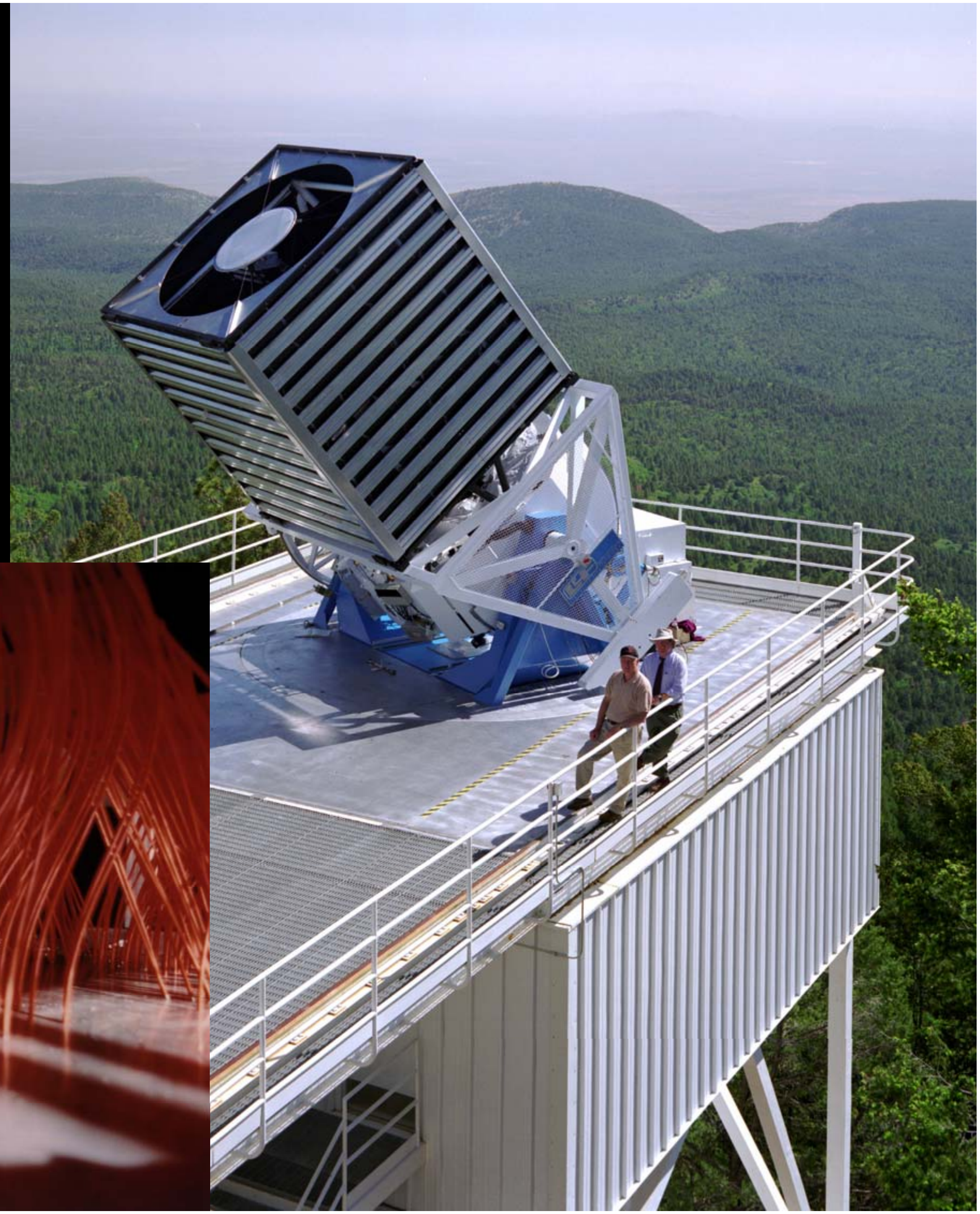


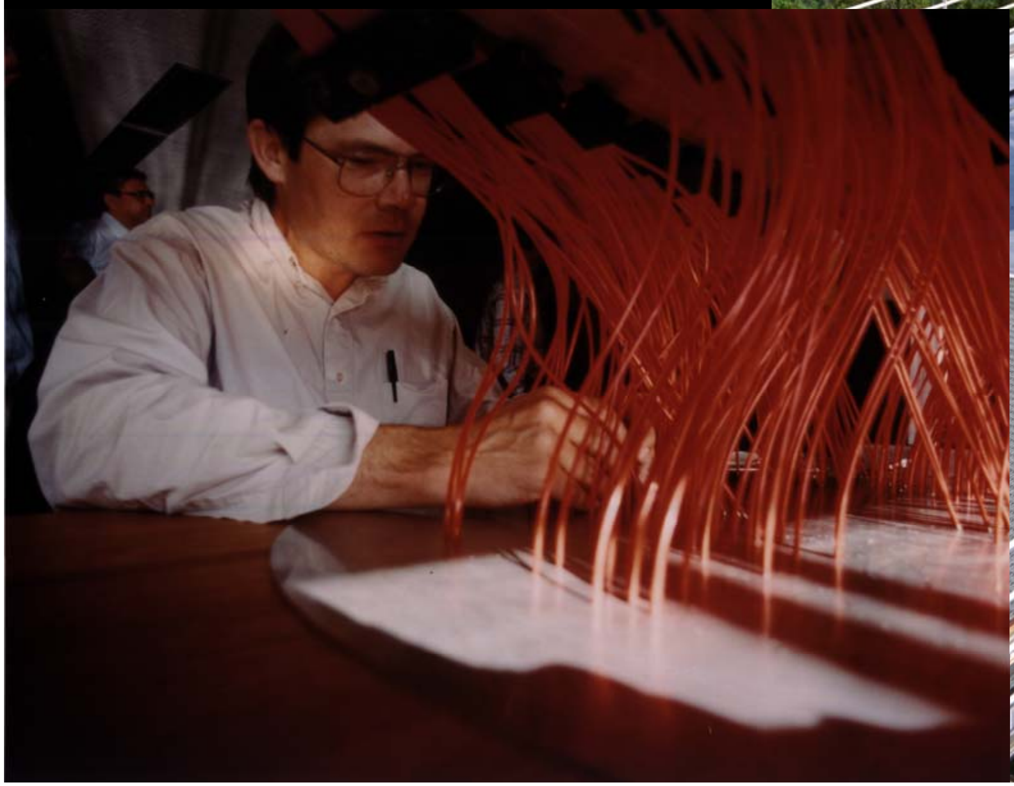


Uno spettrometro a fibre ottiche automatizzato



- Sloan Digital Sky Survey
- Telescopio dedicato e spettrometro a fibre ottiche.
- Piu’ di 1 milione di galassie !





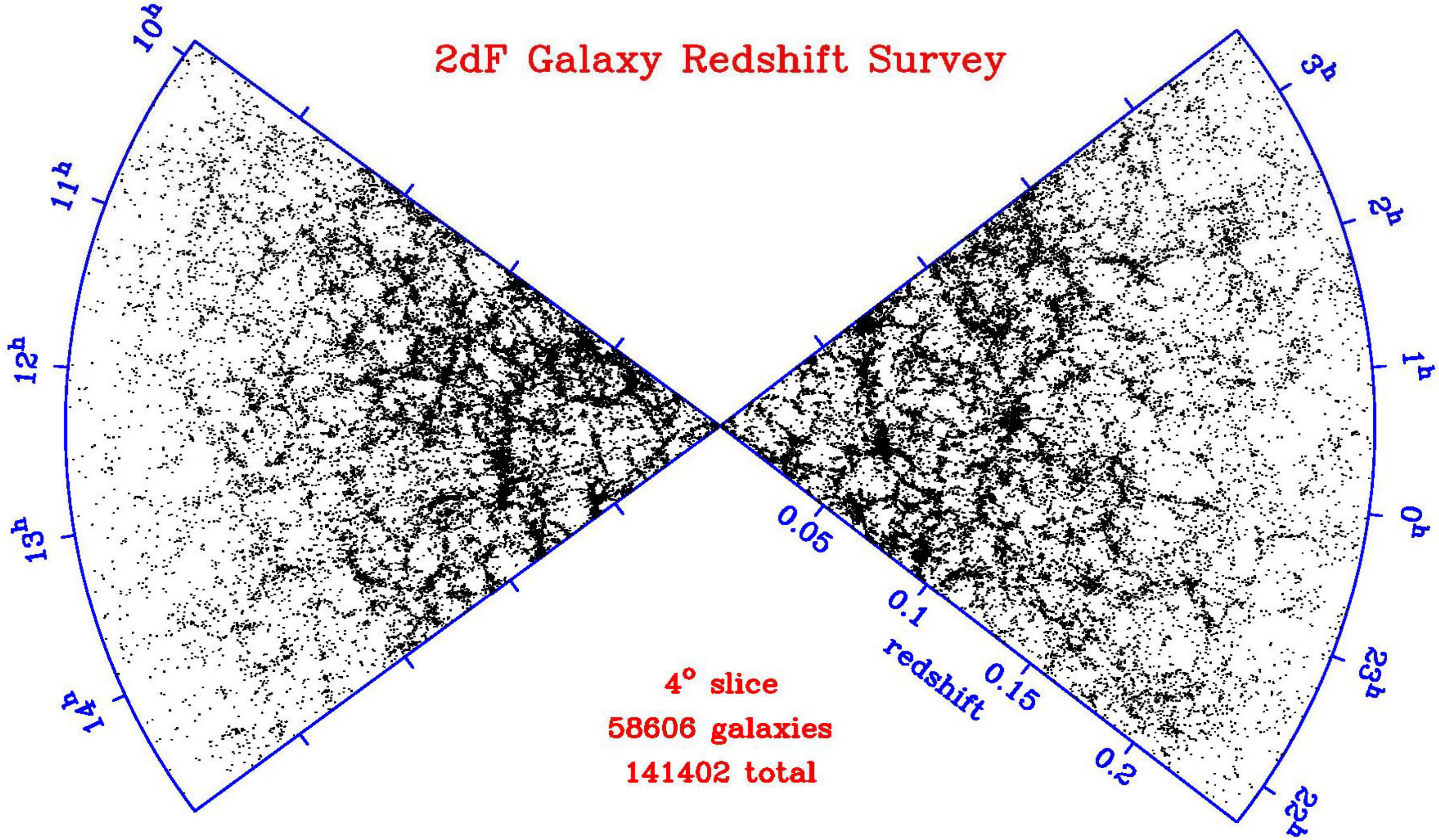
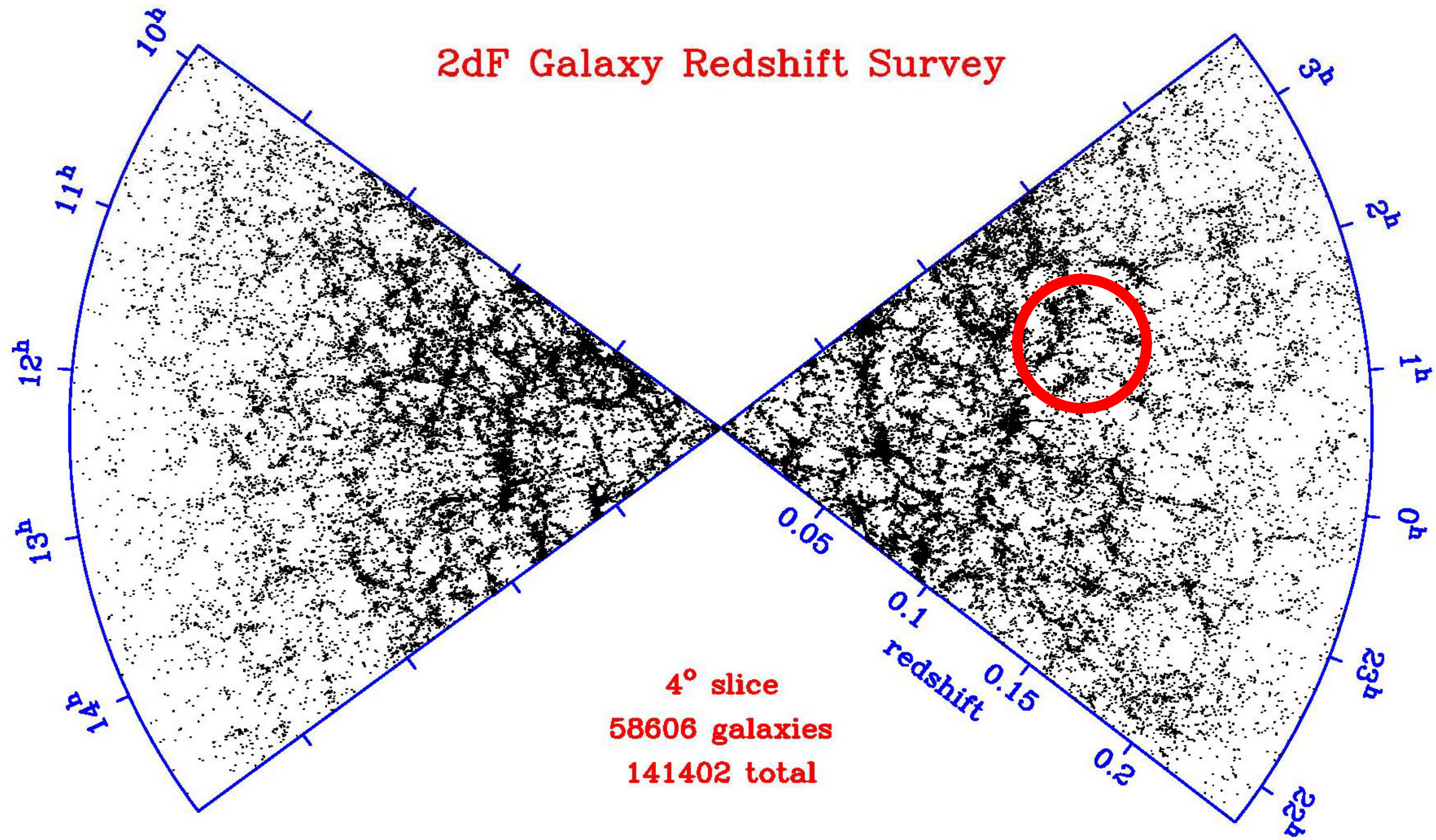


FIGURE 2. The distribution of galaxies in part of the 2dFGRS, drawn from a total of 141,402 galaxies: slices 4° thick, centred at declination −2.5° in the NGP and −27.5° in the SGP. Not all 2dF fields within the slice have been observed at this stage, hence there are weak variations of the density of 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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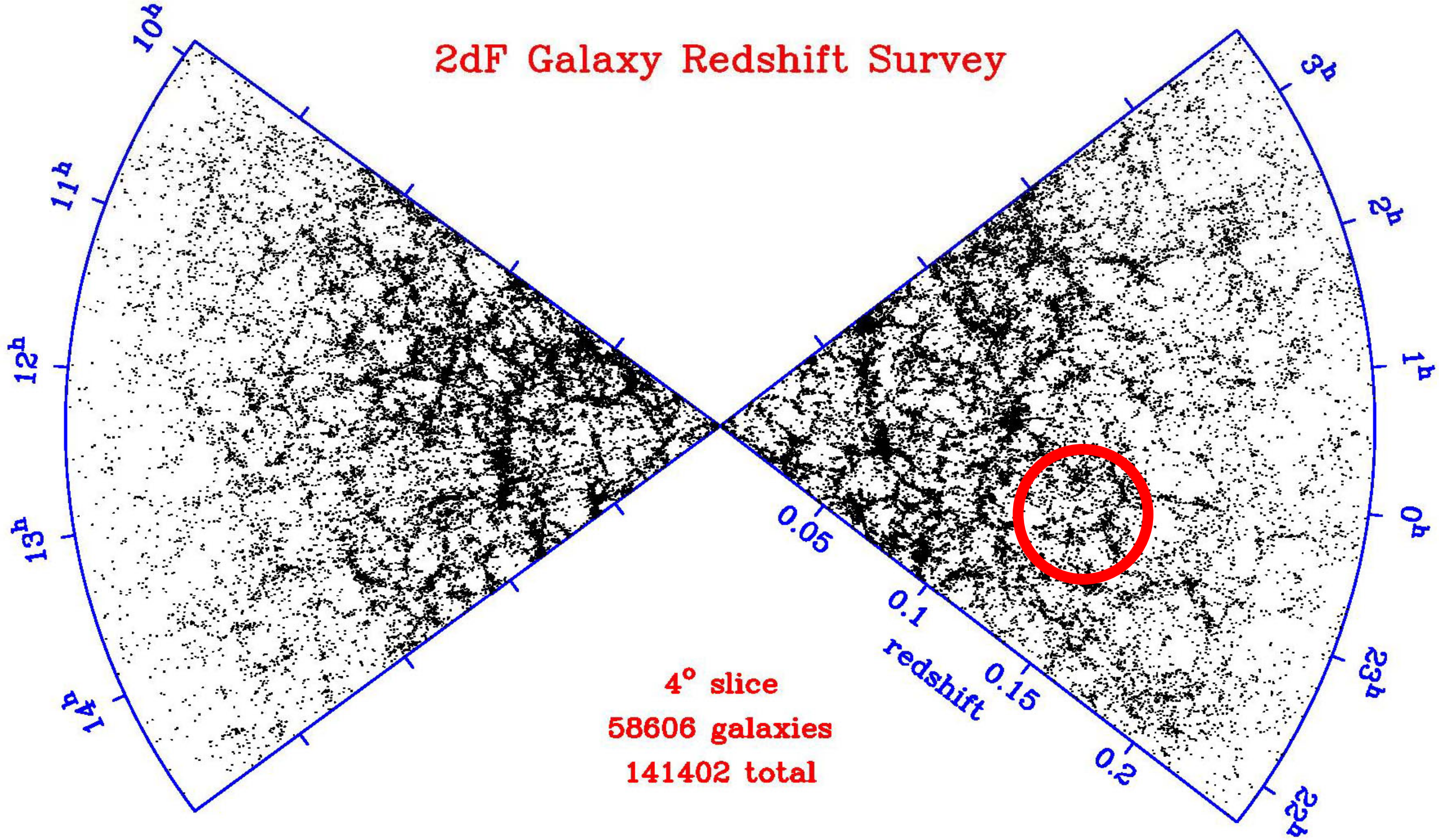

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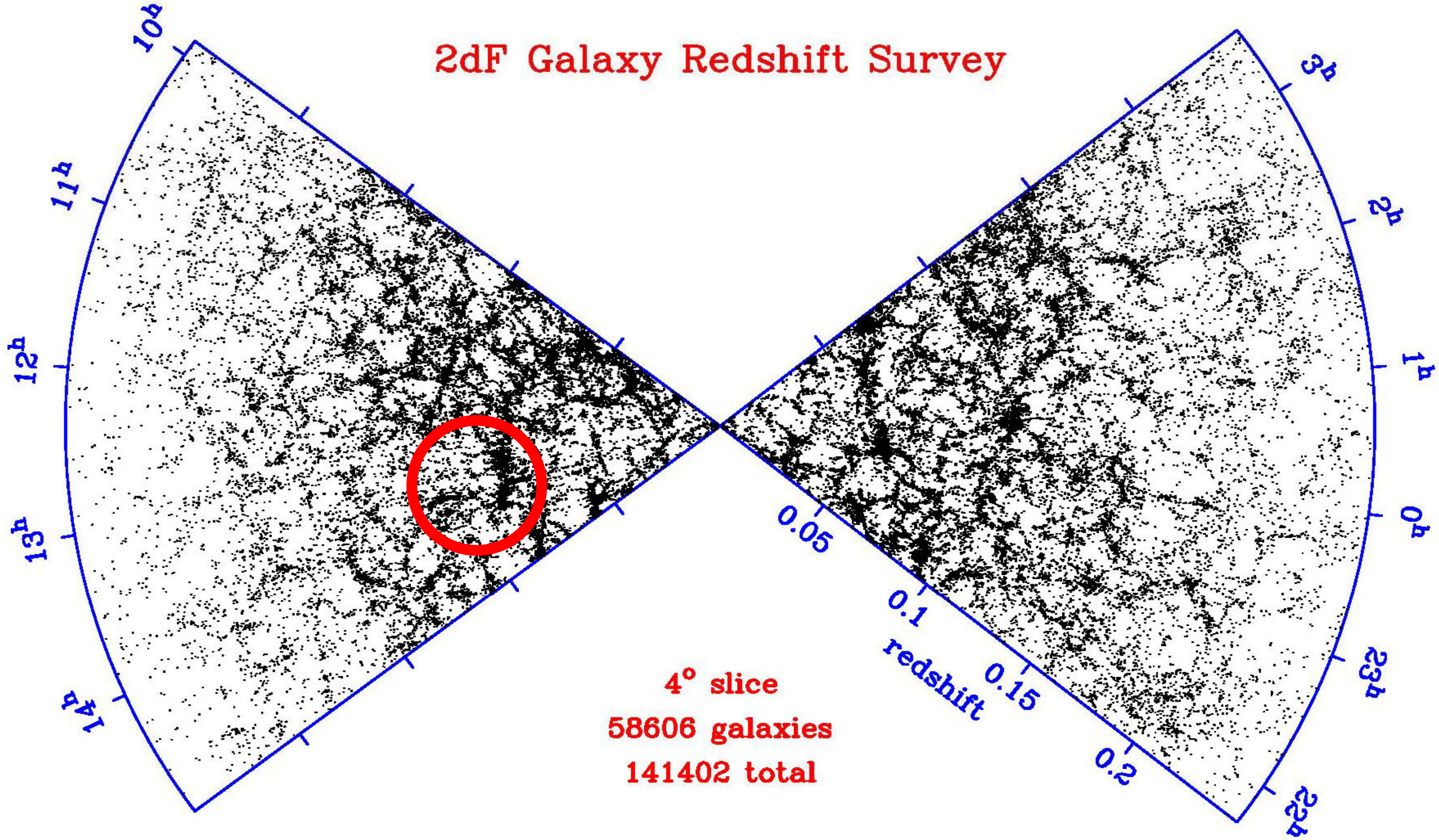

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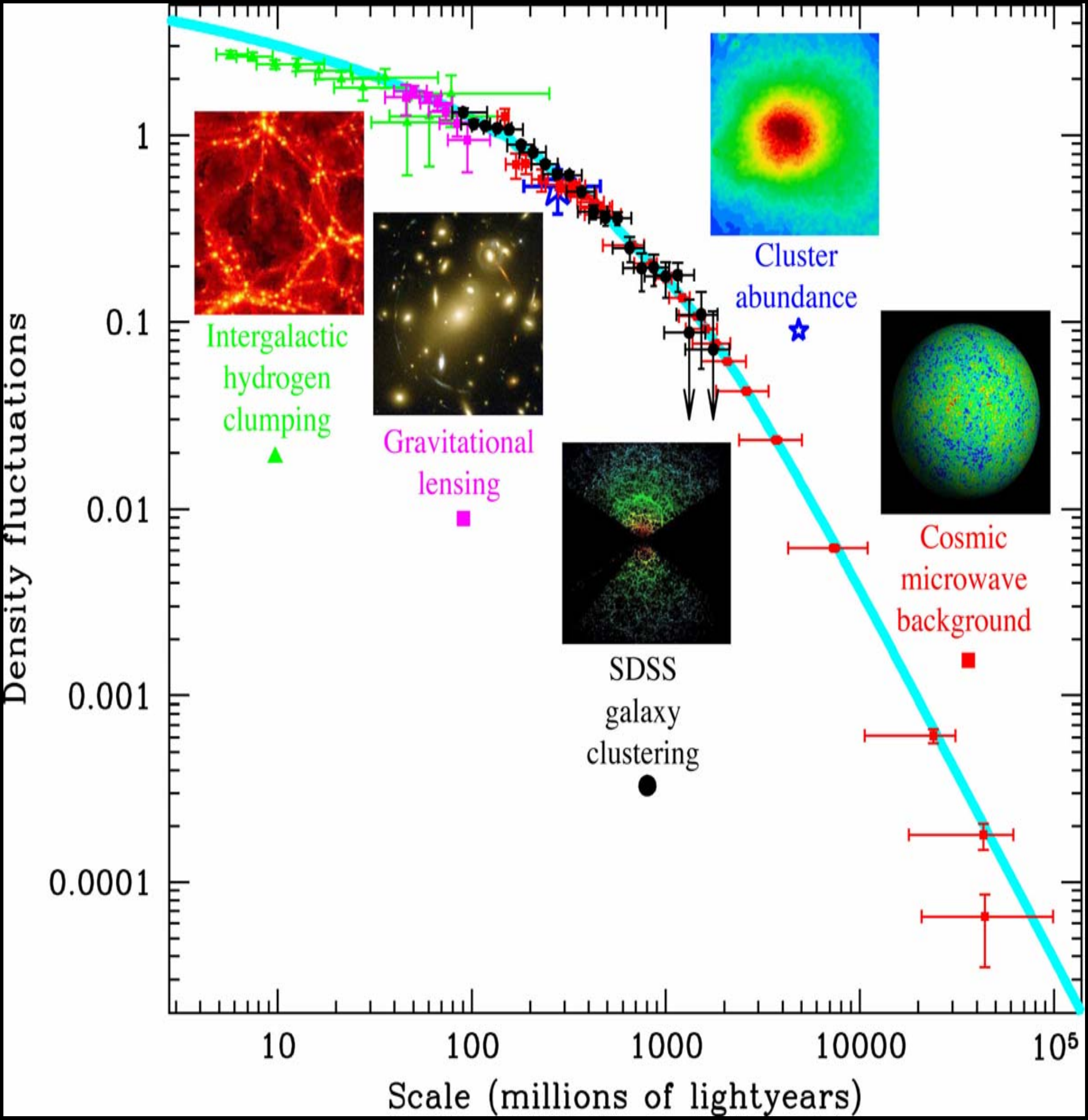
- The universe at large scales is statistically isotropic and homogeneous.

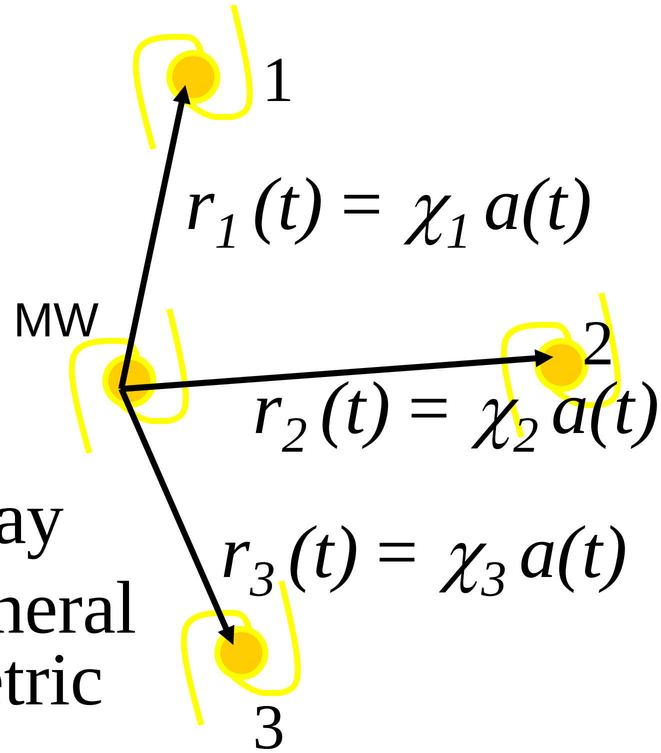
- Confirmed by the fact that if we increase the sampling volume, the rms galaxy density fluctuation decreases.



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 observer : r = physical distance χ = comoving distance $a(t)$ = scale factor = 1 today



- FRW metric: the most general homogenous isotropic metric

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

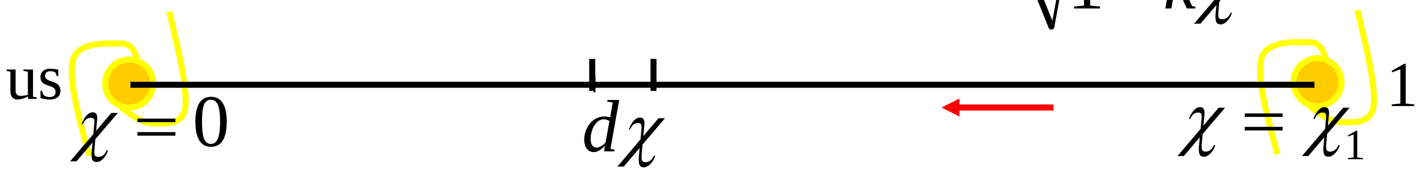
- $1/k$ = curvature of space
- In this metric, the redshift of distant sources is naturally predicted, if the universe is expanding.

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,

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

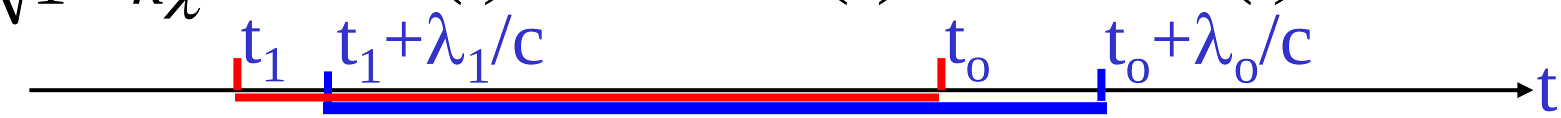
- Assuming *ds*=0 for photons, $cdt = a(t)\dfrac{d\chi}{\sqrt{1-k\chi^2}}$



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

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



- 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. So we get

Redshift of the source

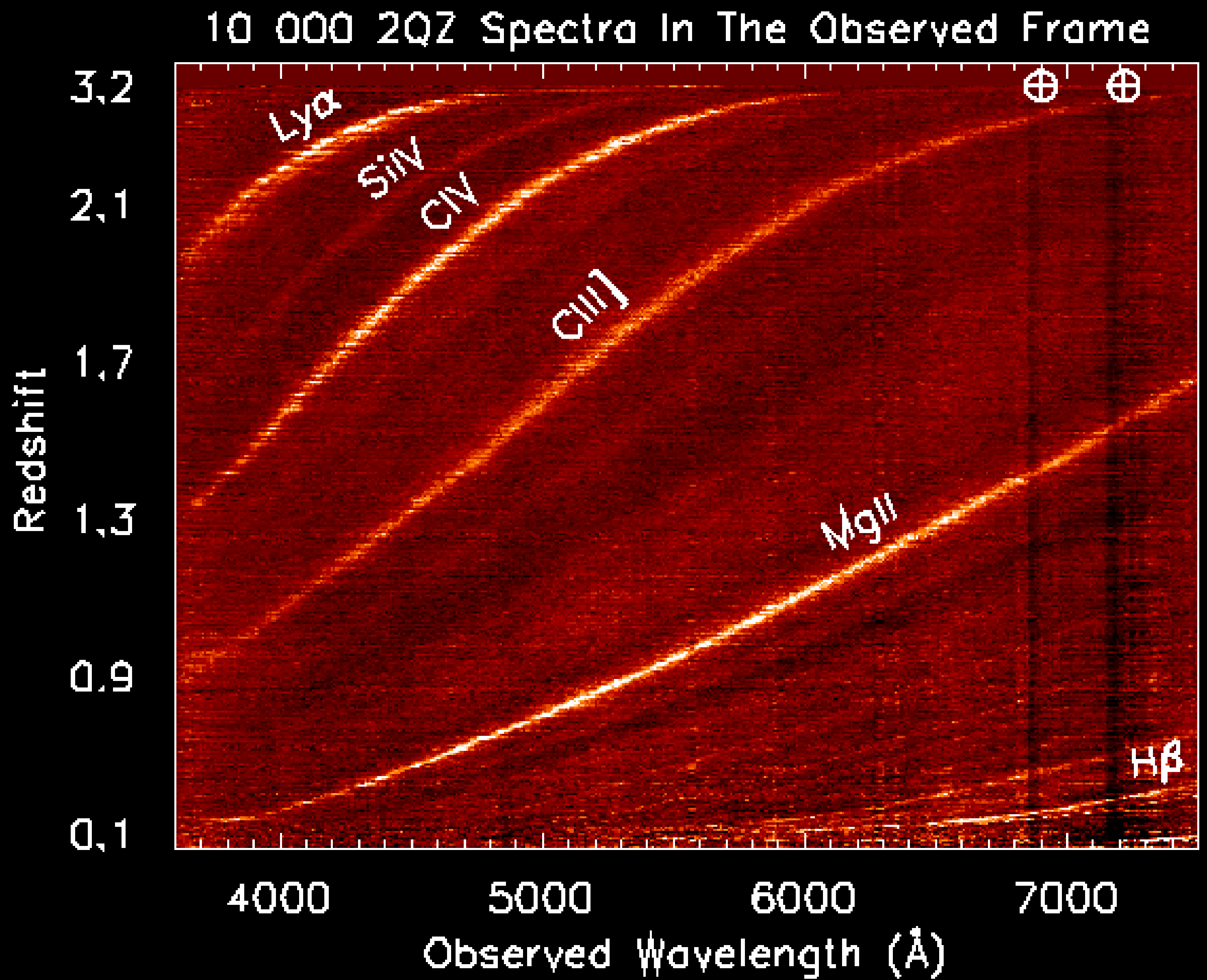
$$\frac{c}{a(t_1)}\frac{\lambda_1}{c} = \frac{c}{a(t_o)}\frac{\lambda_o}{c} \Rightarrow \frac{a(t_o)}{a(t_1)} = \frac{\lambda_o}{\lambda_1} \underset{def}{=} (1+z_1)$$

- 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**.

Expansion of the Universe

- We have started from the empirical finding that redshifts of galaxies are a measure of their distance from us (Hubble's law).
- Now we know that cosmological redshift is due to the expansion of the universe, and Hubble's law is a necessary consequence of this :
- Increasing the distance of a galaxy increases the time required for photons to reach us, meanwhile the scale factor has more time to increase, and, consequently, the redshift increases.

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.



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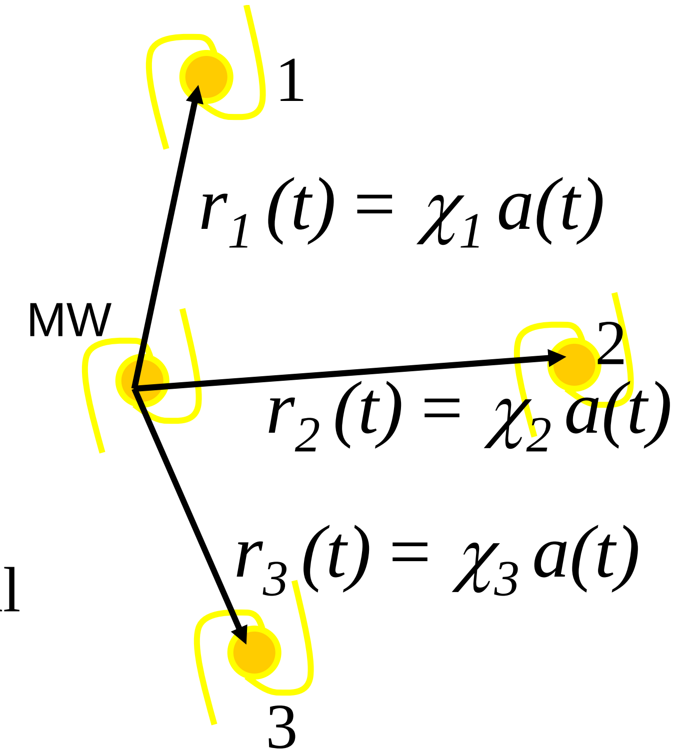


$$(ds)^2 = c^2 dt^2 - a^2(t)\left[\left(\frac{d\chi}{\sqrt{1-k\chi^2}}\right)^2 - (\chi d\theta)^2 - (\chi \sin\theta d\varphi)^2\right]$$

- $1/k^2$ = curvature of space
- If we want to know how the universe expands, we need to integrate the Einstein Field Equations

Curvature Tensor (derived from the metric of the universe)

$$G = -\frac{8\pi G}{c^4} T$$

Stress-energy tensor (describes the energy content of the universe)

Energy density

- Matter : $\rho_m = \rho_{mo} a^{-3}$

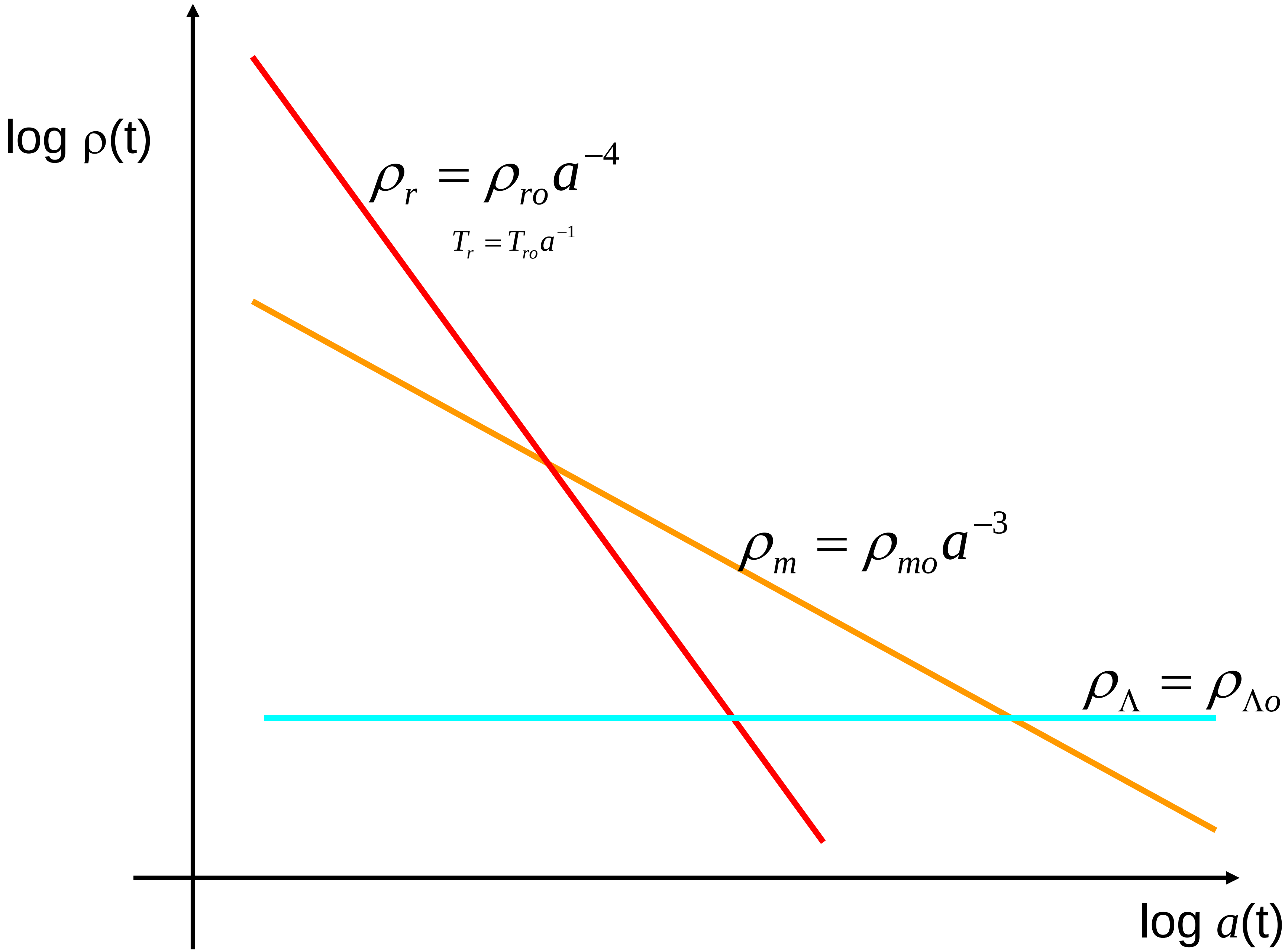
- Radiation : $\rho_r = n_r h\nu = n_r \dfrac{hc}{\lambda} = n_{ro} a^{-3} \dfrac{hc}{\lambda_o a} = \rho_{ro} a^{-4}$

  Note that, for a blackbody,

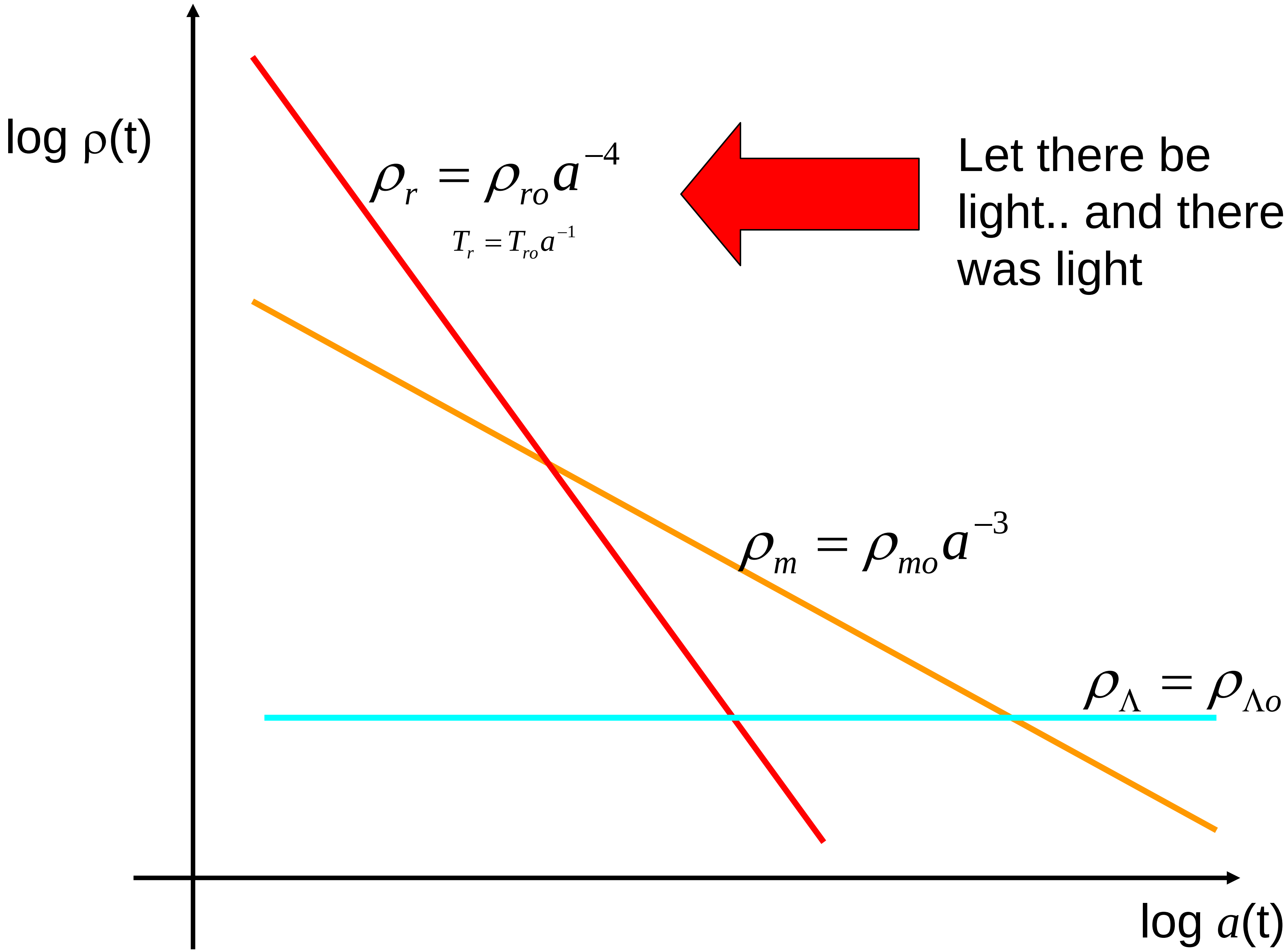
$$\rho_{rBB} = \sigma T_r^4 \quad \rightarrow \quad T_r = T_{ro} a^{-1}$$

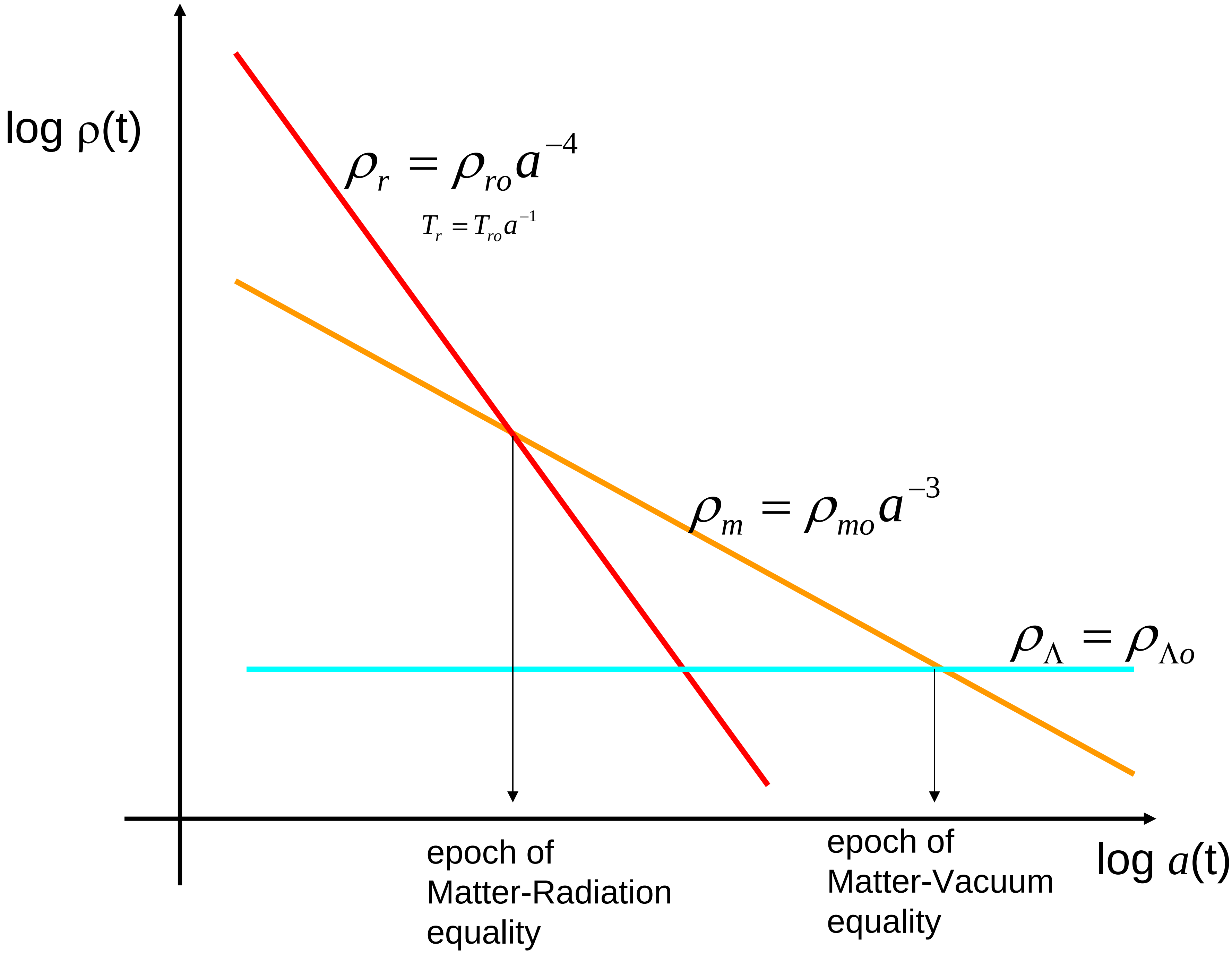
- Cosmological Constant :

$$\rho_\Lambda = \rho_{\Lambda o}$$

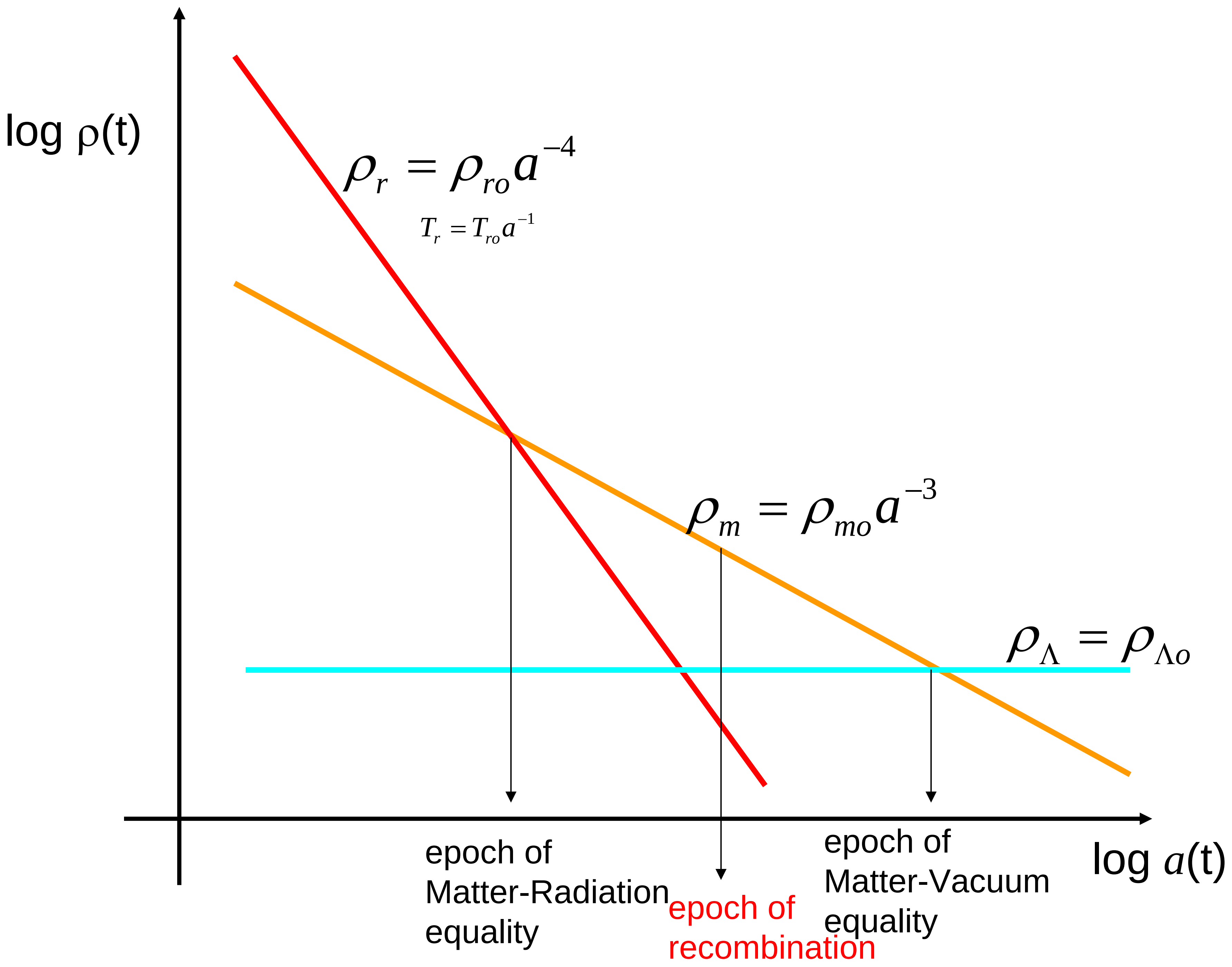


log ρ(t)
$\rho_r = \rho_{ro} a^{-4}$
$T_r = T_{ro} a^{-1}$
$\rho_m = \rho_{mo} a^{-3}$
$\rho_\Lambda = \rho_{\Lambda o}$
log a(t)


log ρ(t)
$\rho_r = \rho_{ro} a^{-4}$
$T_r = T_{ro} a^{-1}$
Let there be light.. and there was light
$\rho_m = \rho_{mo} a^{-3}$
$\rho_\Lambda = \rho_{\Lambda o}$
log a(t)



log ρ(t)
$\rho_r = \rho_{ro} a^{-4}$
$T_r = T_{ro} a^{-1}$
$\rho_m = \rho_{mo} a^{-3}$
$\rho_\Lambda = \rho_{\Lambda o}$
epoch of Matter-Radiation equality
epoch of Matter-Vacuum equality
log a(t)



log ρ(t)
$\rho_r = \rho_{ro} a^{-4}$
$T_r = T_{ro} a^{-1}$
$\rho_m = \rho_{mo} a^{-3}$
$\rho_\Lambda = \rho_{\Lambda o}$
log a(t)
epoch of Matter-Radiation equality
epoch of recombination
epoch of Matter-Vacuum equality

Primeval Fireball

- If the Universe is expanding, it was denser and hotter in the past.
- Both matter and radiation were hotter in the past, when the scale factor was smaller.
- In a sufficiently early phase of the Universe, the temperature of matter was so high that matter (H) was ionized. As a consequence, Thomson scatterings where so frequent to keep matter and radiation in thermal equilibrium.
- This early phase is called the **Primeval Fireball**
- The universe was full of ionized matter and radiation in thermal equilibrium (blackbody radiation).
- This primeval fireball phase ended when the universe cooled down enough to allow the combination of electrons and protons in hydrogen atoms: this is the so called **recombination** epoch.

The cosmic Blackbody

- Blackbody radiation present in the primeval fireball should still be present in the universe.
- And should still have a blackbody spectrum, with a temperature reduced by the ratio of the scale factor now and the scale factor when radiation was released, i.e. at recombination.
- In fact :

Evolution of a blackbody spectrum in an expanding universe.

- Specific energy density of a blackbody:

$$u_\nu = \frac{8\pi\nu^2}{c^3} h\nu \frac{1}{e^{h\nu/kT}-1} = \frac{8\pi h\nu^3}{c^3\left(e^{h\nu/kT}-1\right)}$$

$$u_\lambda = \frac{dE}{d\lambda} = \frac{dE}{d\nu}\frac{\nu}{\lambda} = u_\nu \frac{\nu}{\lambda} = \frac{8\pi h\nu^4}{\lambda c^3\left(e^{h\nu/kT}-1\right)} = \frac{8\pi hc}{\lambda^5\left(e^{hc/\lambda kT}-1\right)}$$

- So the energy density is $u_\lambda d\lambda = \frac{8\pi hc}{\lambda^5\left(e^{hc/\lambda kT}-1\right)} d\lambda$

- Due to the expansion and the redshift: $\frac{\lambda}{\lambda_o} = \frac{a}{a_o}$; $\frac{u_\lambda d\lambda}{u_{\lambda_o} d\lambda_o} = \left[\frac{a}{a_o}\right]^4$

Evolution of a blackbody spectrum in an expanding universe

$$u_{\lambda_o} d\lambda_o = \left[\frac{a}{a_o}\right]^4 u_\lambda d\lambda = \left[\frac{a}{a_o}\right]^4 \frac{8\pi hc}{\lambda_o^5 \left[\frac{a}{a_o}\right]^5 \left(e^{hc/\lambda_o\left[\frac{a}{a_o}\right]kT} - 1\right)} d\lambda_o \left[\frac{a}{a_o}\right]$$

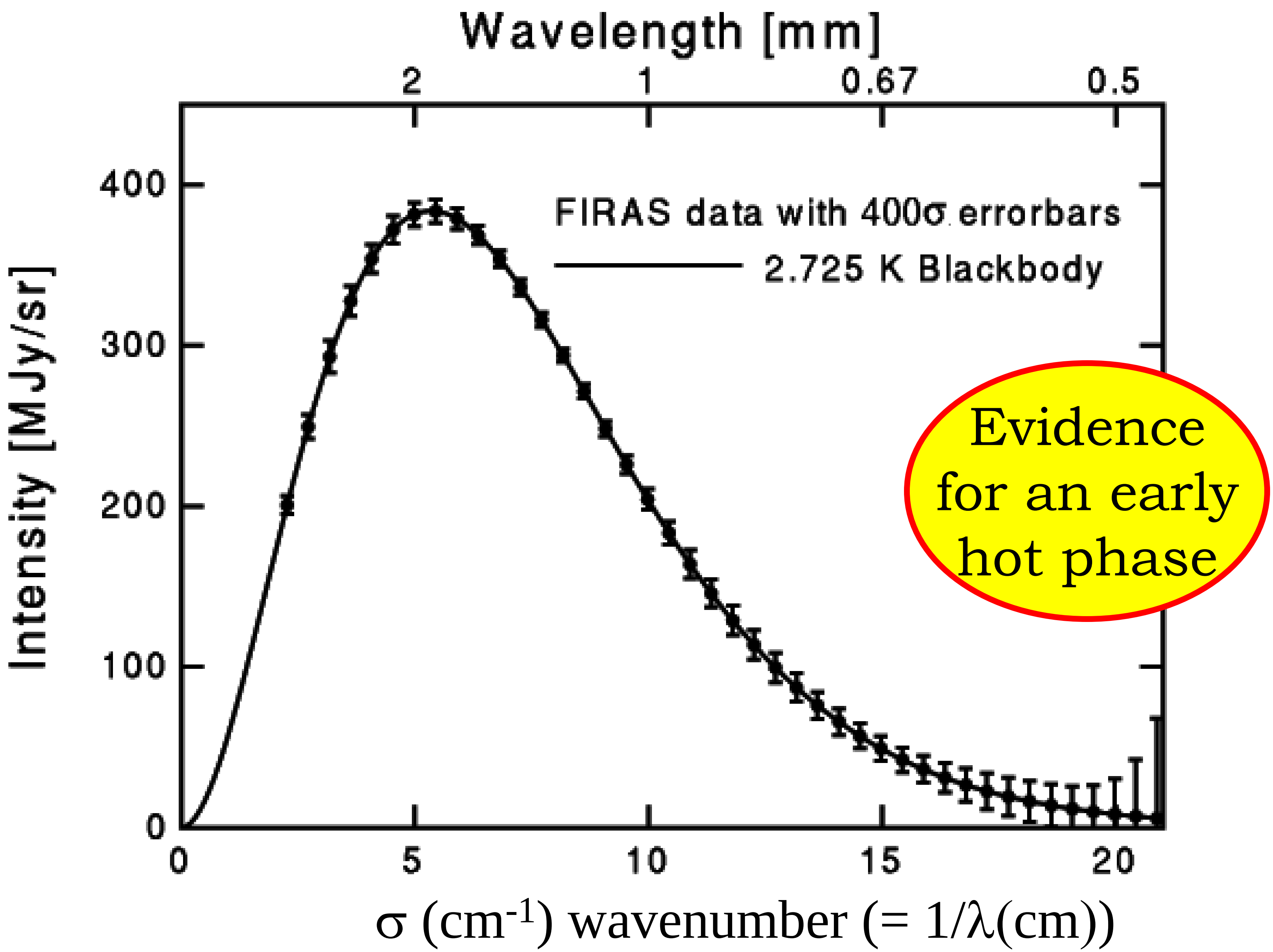
$$\Rightarrow \quad u_{\lambda_o} d\lambda_o = \frac{8\pi hc}{\lambda_o^5 \left(e^{hc/\lambda_o\left[\frac{a}{a_o}\right]kT} - 1\right)} d\lambda_o$$

$$u_{\lambda_o} d\lambda_o = \frac{8\pi hc}{\lambda_o^5 \left(e^{hc/\lambda_o kT_o} - 1\right)} d\lambda_o$$

$$T = T_o \frac{a_o}{a}$$

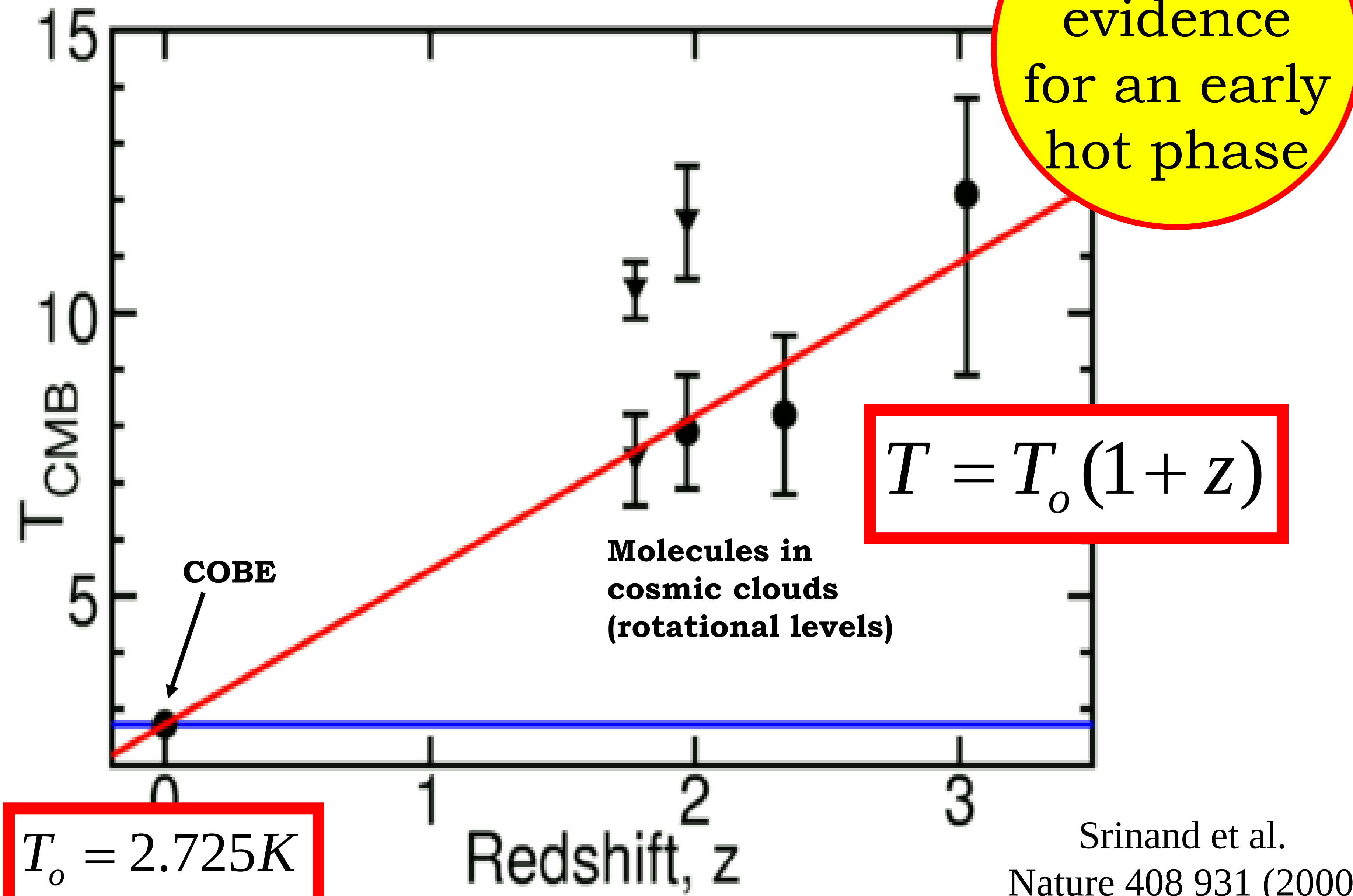
- A blackbody spectrum remains a blackbody, but its temperature scales as the inverse of the scale-factor.

- The photons of the primeval fireball should still be around, as a low-temperature blackbody.



Wavelength [mm]
2
1
0.67
0.5
Intensity [MJy/sr]
400
300
200
100
0
5
10
15
20
FIRAS data with 400σ errorbars
2.725 K Blackbody
Evidence for an early hot phase
σ (cm-1) wavenumber (= 1/λ(cm))

Primeval Fireball



$$T = T_o(1+z)$$

$$T_o = 2.725K$$

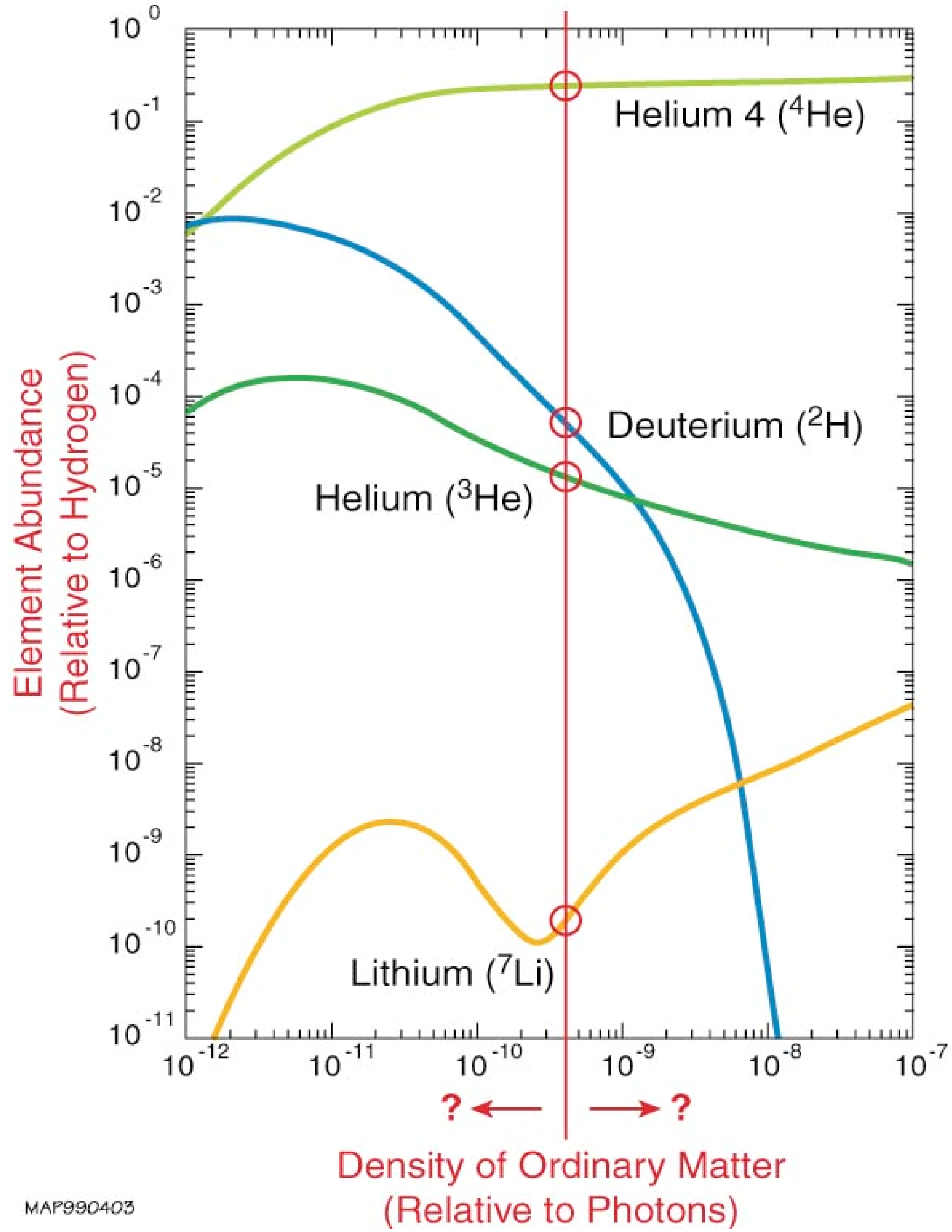
Srinand et al.
Nature 408 931 (2000)

CMB and cosmology

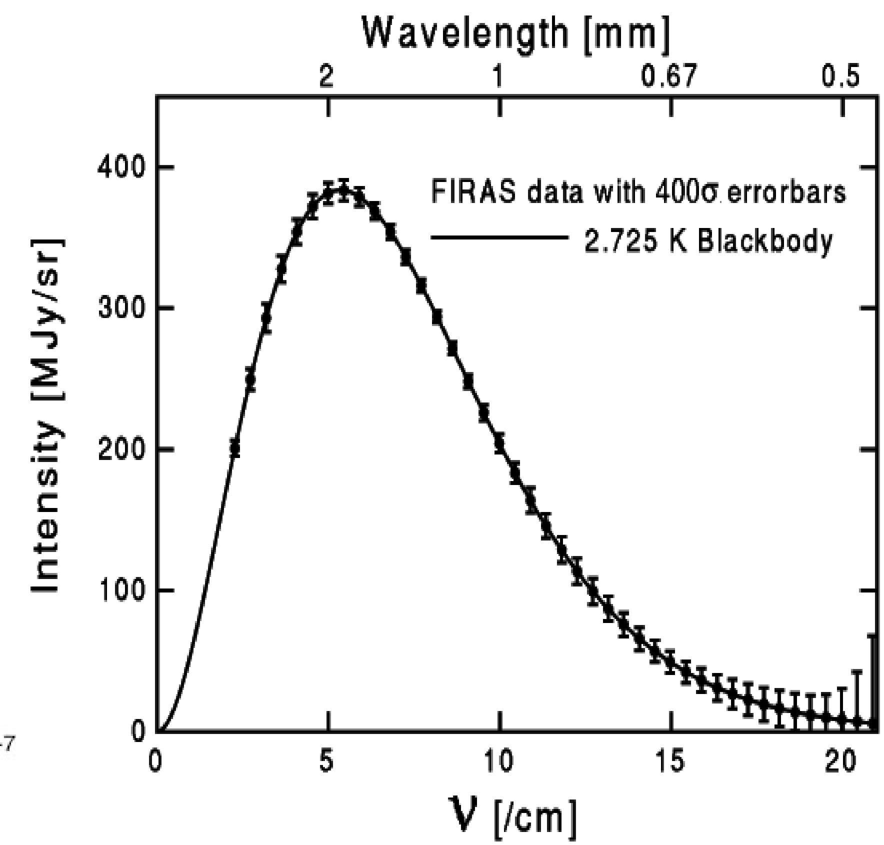
- We will see later how these measurements have been obtained.
- Now let’s stress how important for cosmology is the presence of the Cosmic Microwave Backgorund, and how this radiation formed, according to modern cosmology.
- A blackbody with T=2.725K consists of 400 γ/cm^3 . This is a density way higher than the average density of matter in the universe. **About 10^9 times higher**. CMB photons are the most abundant particels in the universe.
- The BB nature of the CMB is a **direct confirmation that the universe underwent a hot early phase**.
- There is no other way to produce such a perfect blackbody spectrum, filling the sky with an almost perfect isotropy.
- We need to investigate when was formed, and when was released.

Nucleosynthesis and the CMB

- At an even earlier phase, the temperature was high enough that nuclear reactions produced light elements starting from a plasma of simple particles (nucleosynthesis).
- The observed primordial abundance of light elements can be produced only if an abundant background of photons is present (10^9 γ/baryon). (G.Gamow).
- This background is observed today as the Cosmic Microwave Background.



Synergic Evidences for an early hot phase



Recombination epoch

- Here the primeval plasma cools down enough to allow the formation of the first hydrogen atoms.
- electrons and protons can combine if the energy of the photons of the primeval fireball is less than the binding energy, which, for the fundamental state of H is B=13.6eV.
- So one would naively say that the temperature of matter and radiation has to be less than T=B/k=156000K
- However, in a blackbody distribution, there is a tail of photons with energy much higher than the average energy. Since the number of photons is so high with respect to the number of particels, the temperature has to be much less than 156000K.
- The equilibrium between elettrons, protons, H atoms is described by Saha's equation, which can be found from the equilibirum distributions:

$$n_i \cong g_i \left(\frac{m_i kT}{2\pi h^2} \right)^{3/2} e^{(\mu_i - m_i c^2)/kT}$$

- where *i*=e,p,H. Equilibrium mantained by $p + e \leftrightarrow H + \gamma$

Recombination epoch

$$n_i \cong g_i \left(\frac{m_i kT}{2\pi h^2} \right)^{3/2} e^{(\mu_i - m_i c^2)/kT} \qquad\qquad p + e \leftrightarrow H + \gamma$$

- To balance the chemical potentials we have $\mu_e + \mu_p = \mu_H$.
- Expressing μ_i with n_i, and defining the hydrogen binding energy as $B=(m_p+m_e-m_H)c^2$ we find Saha's equation:

$$\frac{n_H}{n_p n_e} \cong \left(\frac{h^2}{2\pi m_e kT} \right)^{3/2} e^{B/kT}$$

- We define η as the ratio of baryons to photons $\eta = n_b/n_\gamma \sim 5 \times 10^{-10}$, and x as the ionized fraction $x = n_e/n_b = n_p/n_b$ so we can write $n_p = n_e = x n_b = x \eta n_\gamma$ and $n_H = (1-x) n_b = (1-x) \eta n_\gamma$

Recombination epoch

- Inserting the definitions above into Saha's equation we find

$$\frac{1-x}{x^2} \cong n_\gamma \eta \left(\frac{h^2}{2\pi m_e kT} \right)^{3/2} e^{B/kT}$$

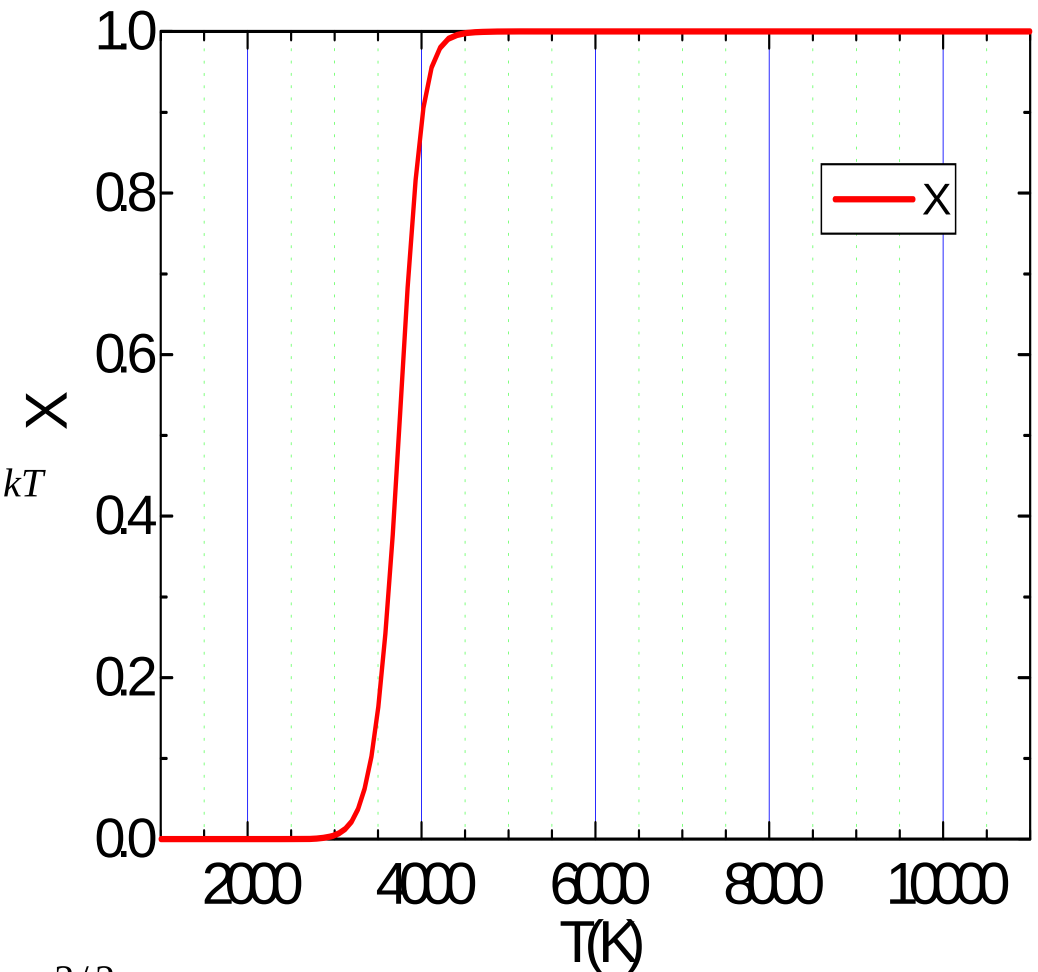
but $n_\gamma = n_{\gamma o} (T / T_o)^3$ so

$$\frac{1-x}{x^2} \cong n_{\gamma o} \eta \left(\frac{h^2 (T / T_o)}{2\pi m_e kT_o} \right)^{3/2} e^{B/kT}$$

whose solution is

$$x = \frac{\sqrt{1+4f(T)}-1}{2f(T)}$$

with $\quad f(T) = n_{\gamma o} \eta \left(\frac{h^2 (T / T_o)}{2\pi m_e kT_o} \right)^{3/2} e^{B/kT}$



Recombination epoch

- Since η is very small, the actual temperature if recombination is T_{rec}~3000K , not 156000K. So

$$(1+z_{rec})=a_o/a_{rec}=T_{rec}/T_o \sim 3000/2.725 \sim 1100$$

- **Recombination happened when all lengths were 1100 times smaller than today.**
- To convert this into a time, we need to find *a(t)*.
- We need to notice, also, that Saha's equation is valid only in thermodynamic equilibrium, i.e. as long as the reaction

$$p + e \leftrightarrow H + \gamma$$

is active.

- This will not be active anymore once most of the electrons and protons have combined into *H* atoms: when their density will be low enough, the reaction rate will be too low compared to the expansion, which separates particles preventing reactions. So we expect a small residual ionization to survive (residual x is around 10^{-4})

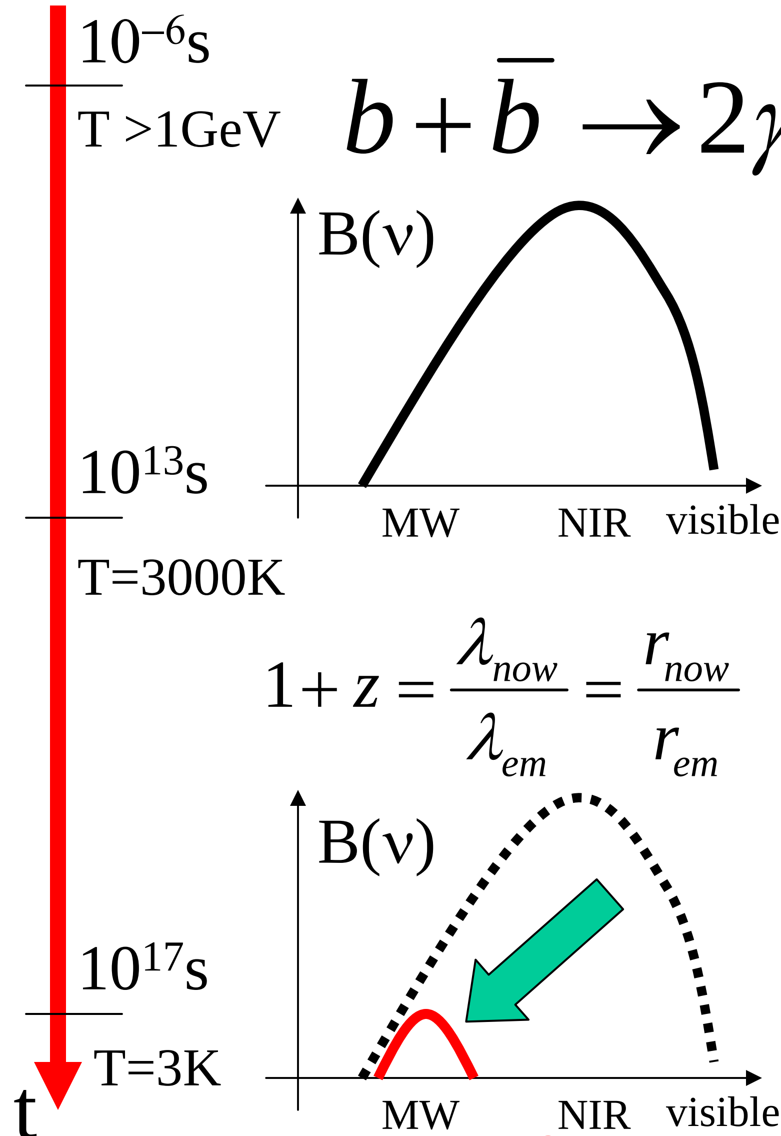
Recombination epoch

- Since η is very small, the actual temperature if recombination is T_{rec}~3000K , not 156000K. So $(1+z_{rec})=T_{rec}/T_o \sim 1100$.
- **Recombination happened when all lengths were 1100 times smaller than today.**
- When most protons and electrons combine, interactions of photons and matter become so rare that the universe becomes transparent. (The cross-section of a Hydrogen atom is 1800 times smaller than the Thomson cross-section. Basically, most CMB photons do not interact with matter anymore, before reaching our CMB telescopes.

- Note: **We can make astronomical observations using electromagnetic radiation only within a sphere whose radius is as large as the look-back distance to recombination.**
- We cannot measure anything more distant than that, since the Universe was not transparent before recombination. It was completely opaque, like the interior of the sun.

- So we really need to find *a(t)*

What is the CMB



$$b + \bar{b} \rightarrow 2\gamma$$

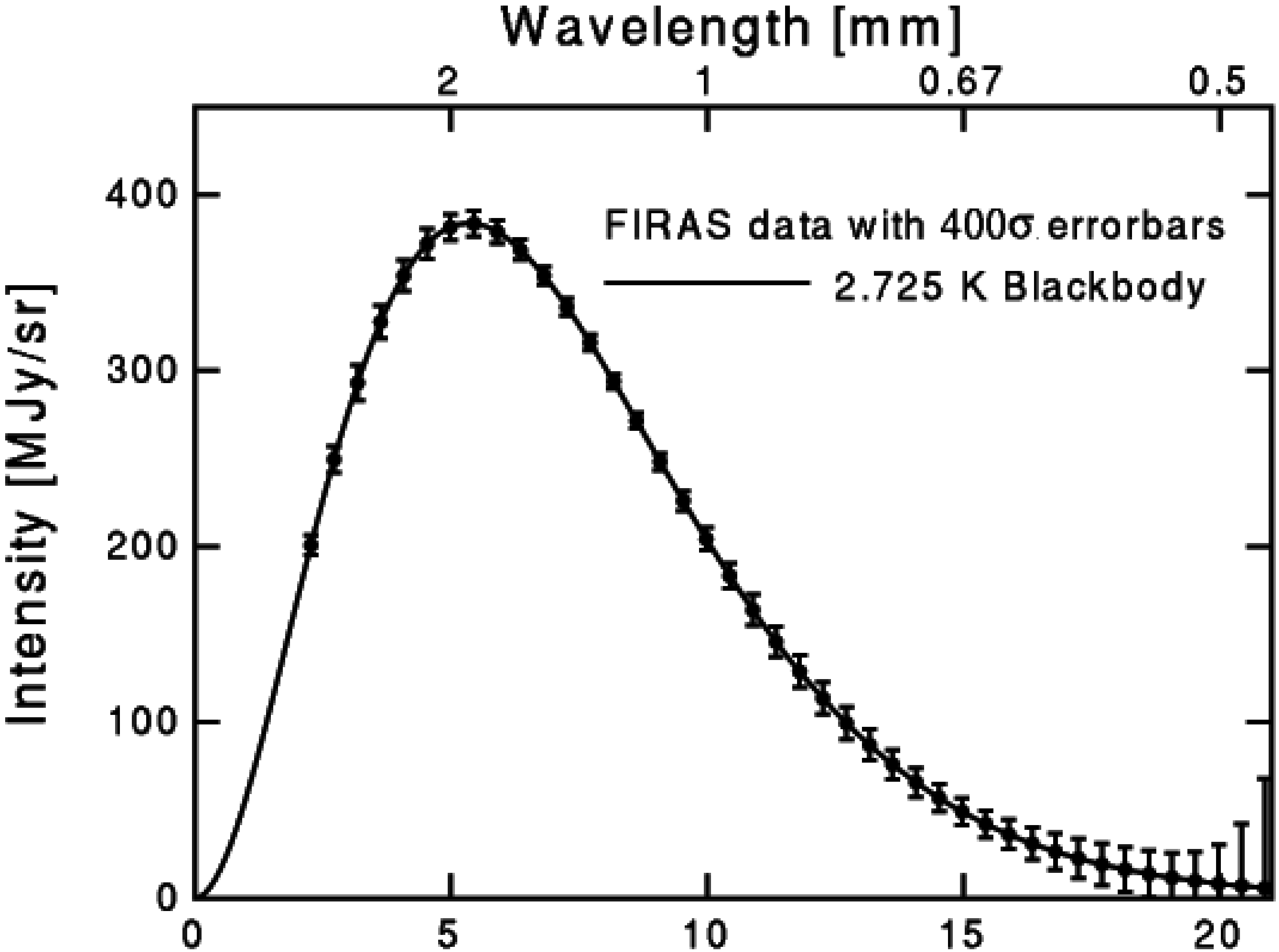
$$1 + z = \frac{\lambda_{now}}{\lambda_{em}} = \frac{r_{now}}{r_{em}}$$

Today 400γ/cm^3

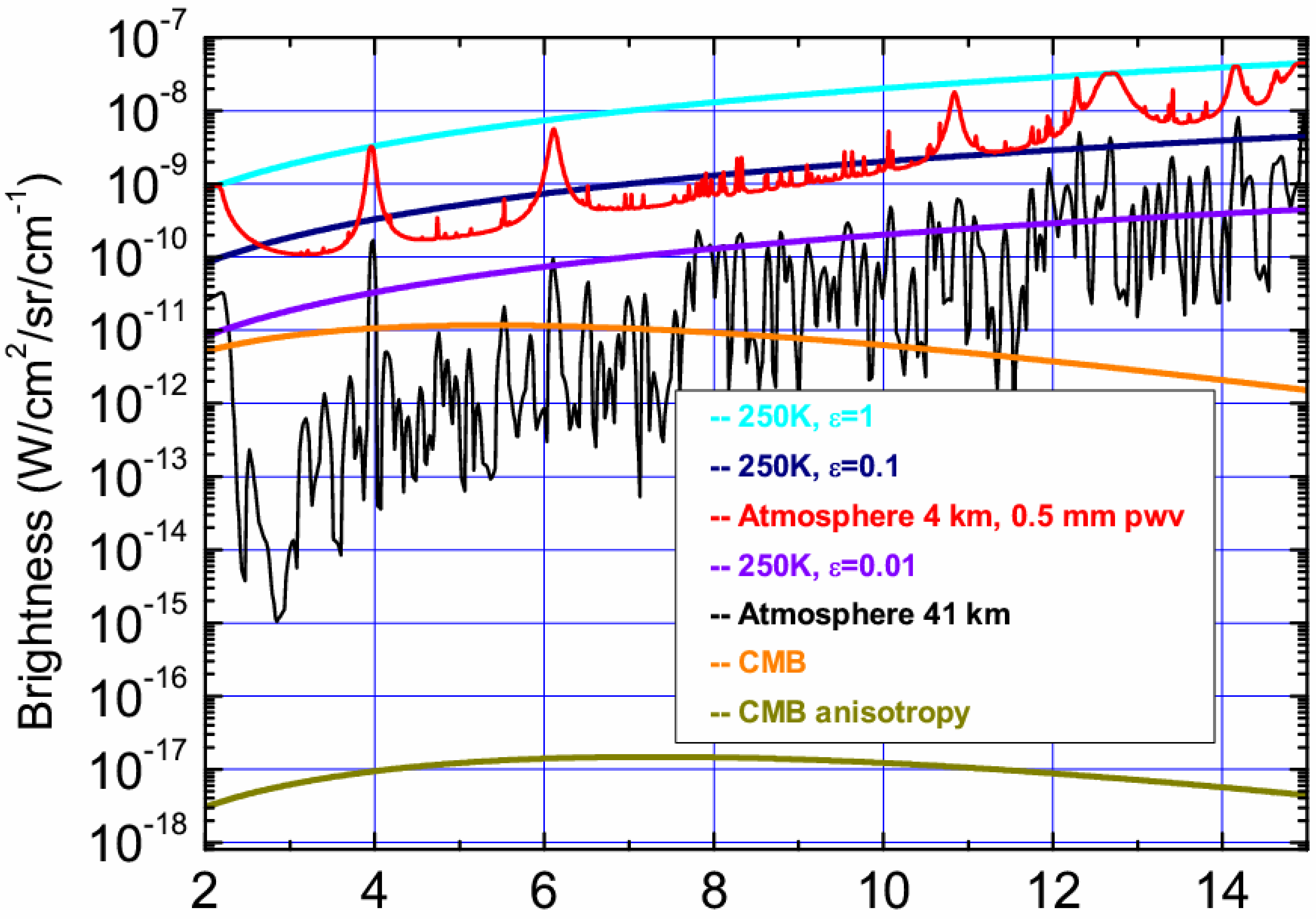
According to modern cosmology:

An abundant background of photons filling the Universe.

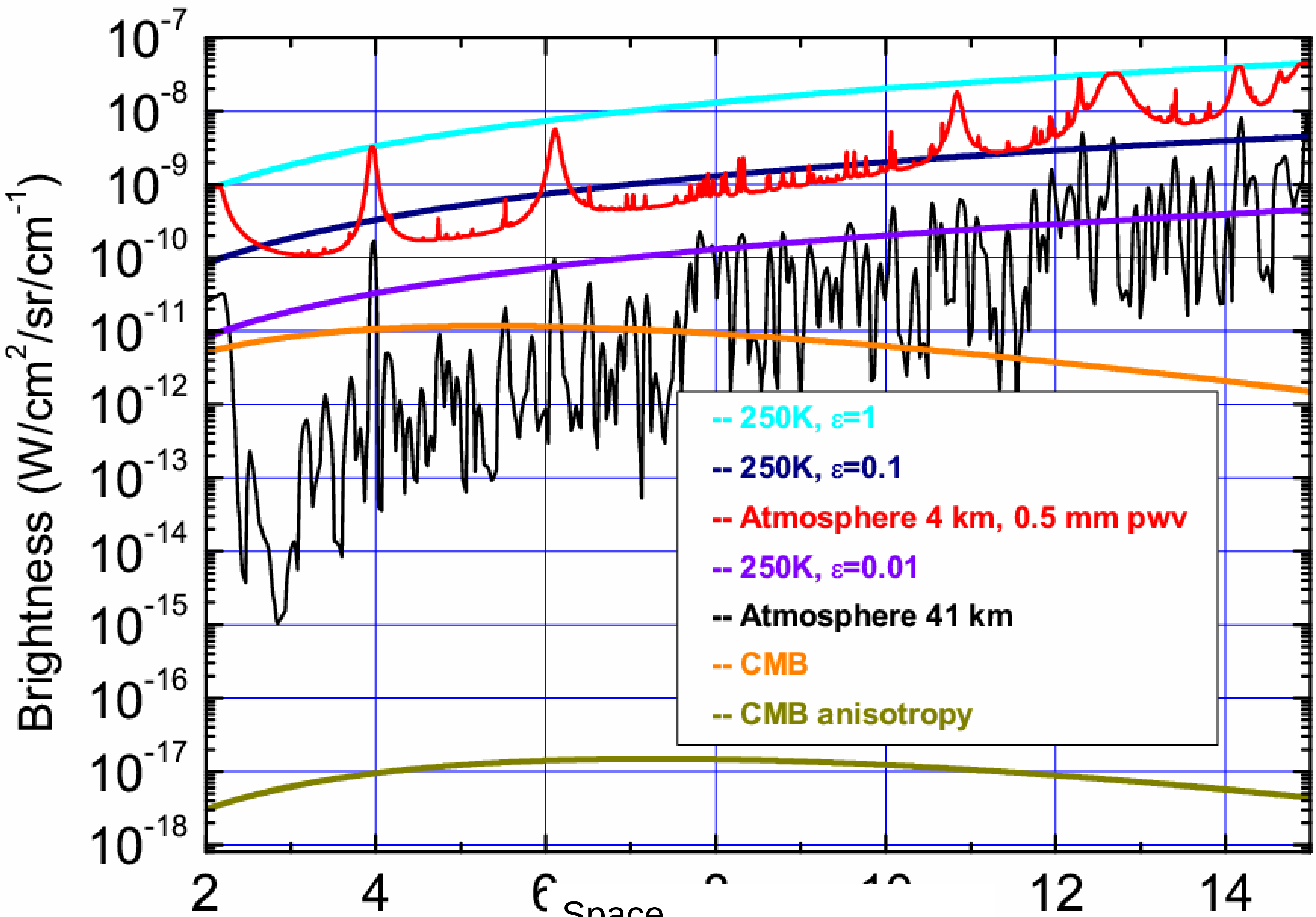
- **Generated** in the very early universe, less than 4 μs after the Big Bang (10^9γ for each baryon) from a small $b - \bar{b}$ asymmetry
- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Redshifted** to microwave frequencies (z_{CMB}=1100) **and diluted** in the subsequent 14 Gyrs of expansion of the Universe



σ (cm^{-1}) wavenumber (= 1/λ(cm))



Environment !



Environment !

Space

Cryogenics