Microcosmo e Macrocosmo

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Friedman's equation

- Einstein's equation, in the case of a homogenous isotropic universe, gives

$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4}+\frac{\Omega_{Mo}}{a^3}+\frac{(1-\Omega_o)}{a^2}+\Omega_\Lambda\right]$$

- The solution *a(t)* tells us how all the distances in the universe evolve with time (i.e. how the universe expands).
- To find the solution, we need to find empirically the mass energy densities ρ_{Ro} , ρ_{Mo} , ρ_Λ and from them the parameters Ω_{Ro} , Ω_{Mo} , Ω_Λ

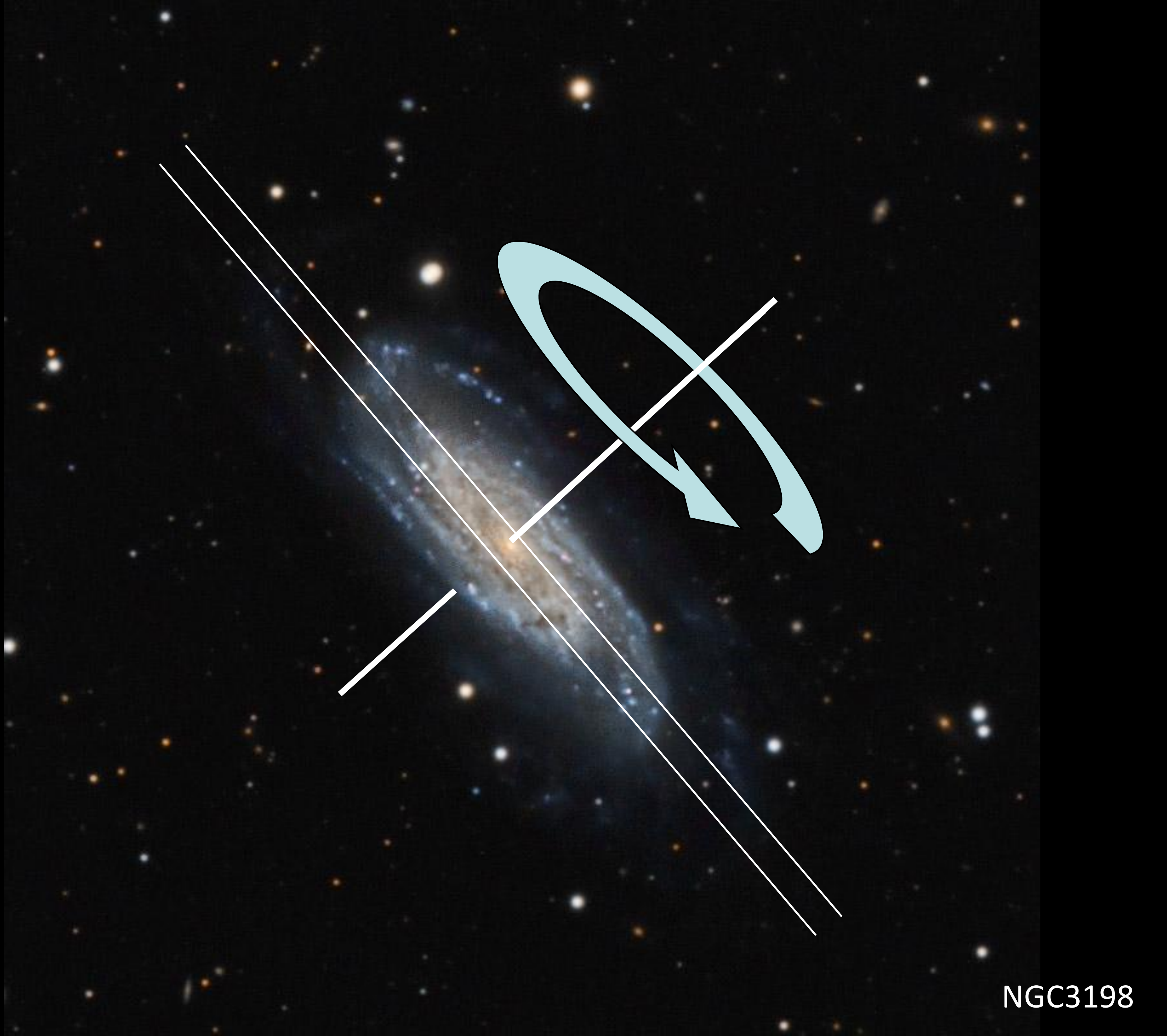
Dark Matter

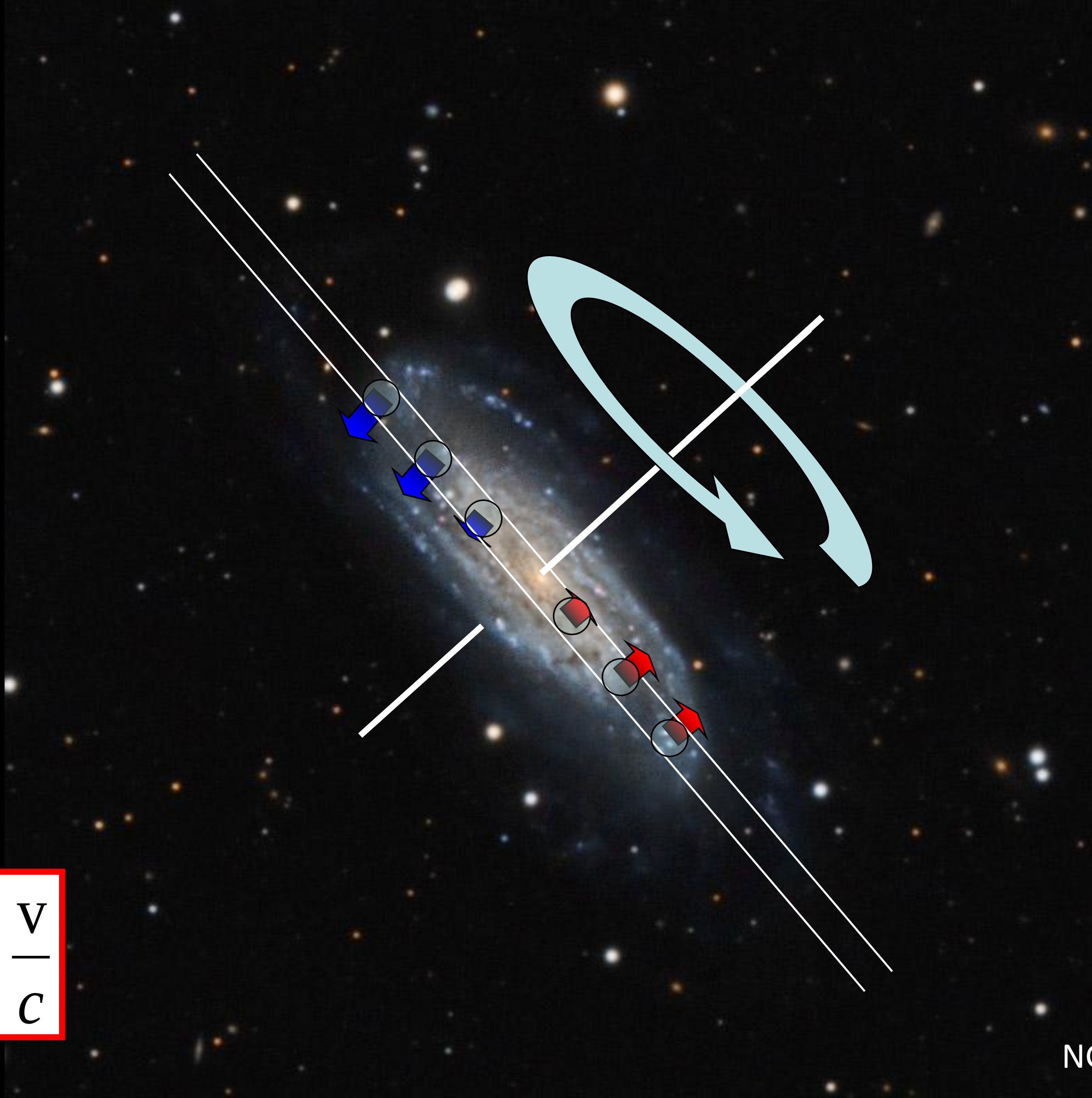
- Dark matter does not interact electromagnetically.
- We can measure it only through its gravitational interaction, which is much weaker than electromagnetic.
- The dynamics of stars in galaxies and of galaxies in clusters of galaxies cannot be explained without the presence of dark matter
- Additional evidence comes from gravitational lensing and other effects.

$$\Omega_{DMo} = (0.22 \pm 0.02)$$

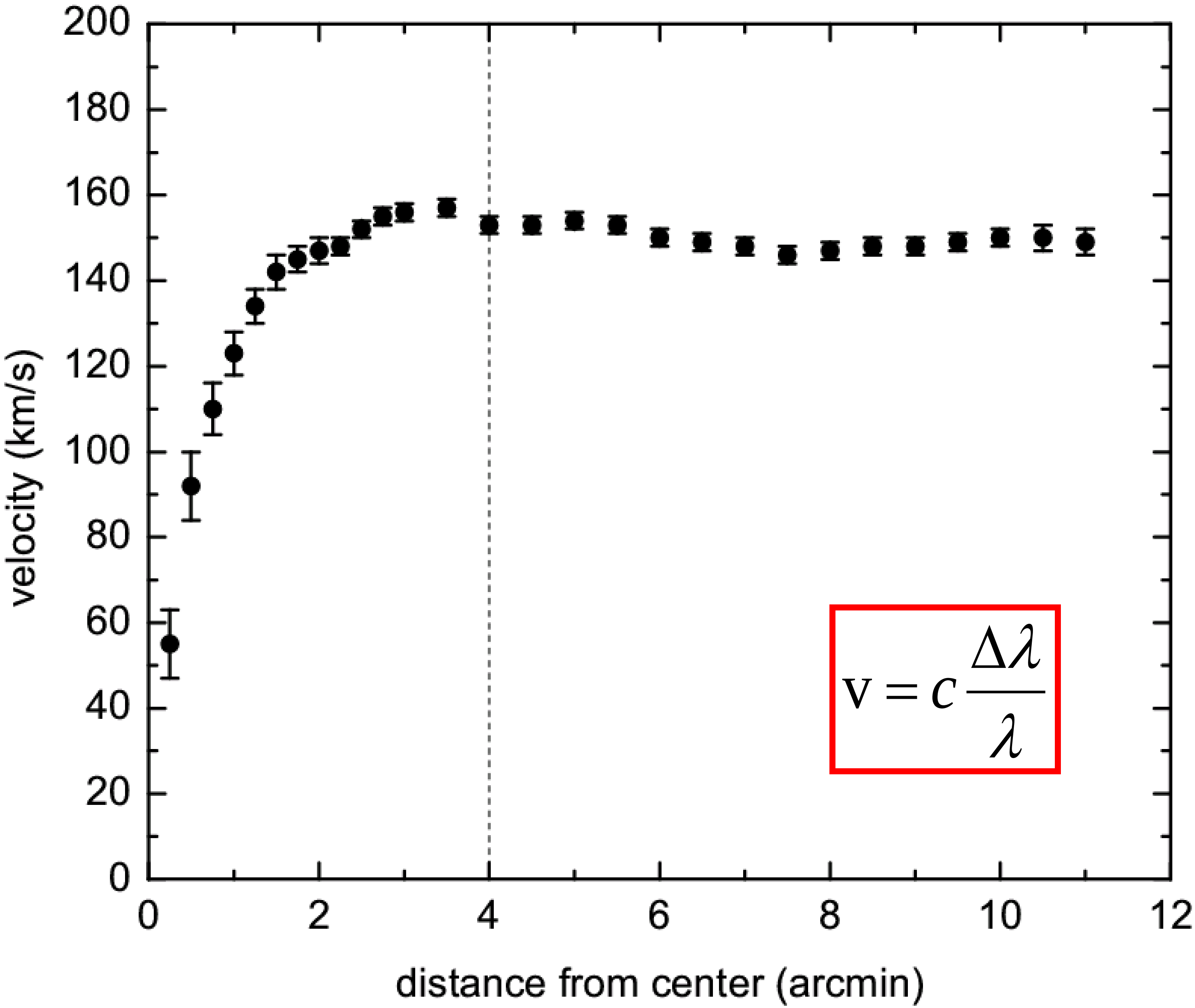
NGC3198

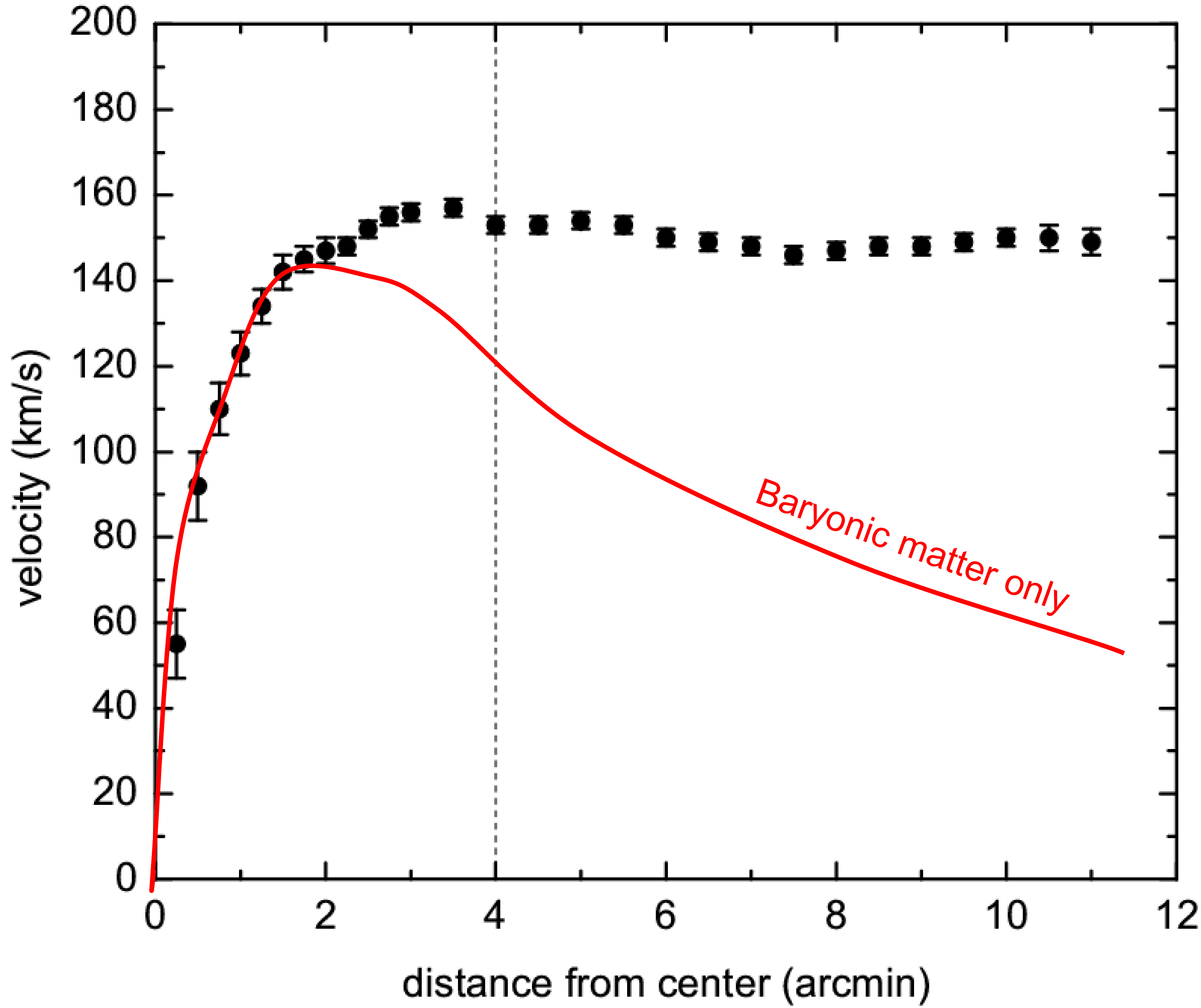

NGC3198


NGC3198



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

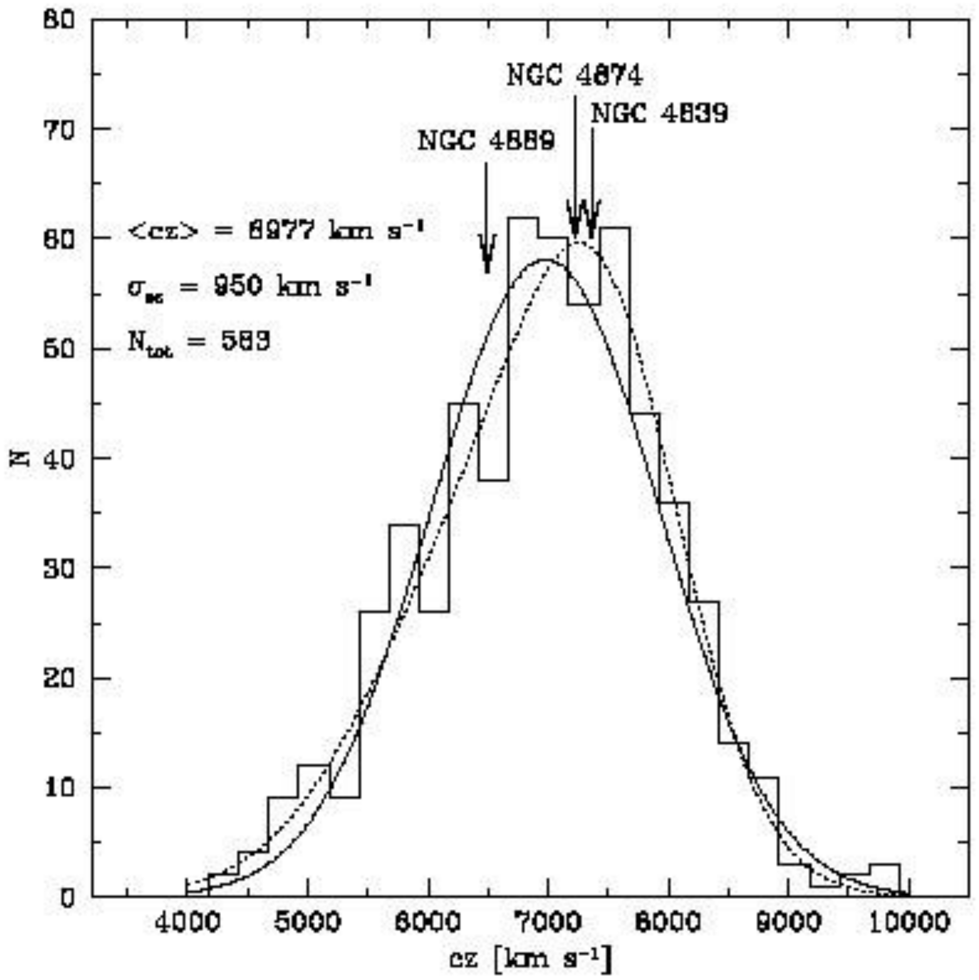

velocity (km/s)
distance from center (arcmin)
0
20
40
60
80
100
120
140
160
180
200
0
2
4
6
8
10
12
$v = c\dfrac{\Delta\lambda}{\lambda}$



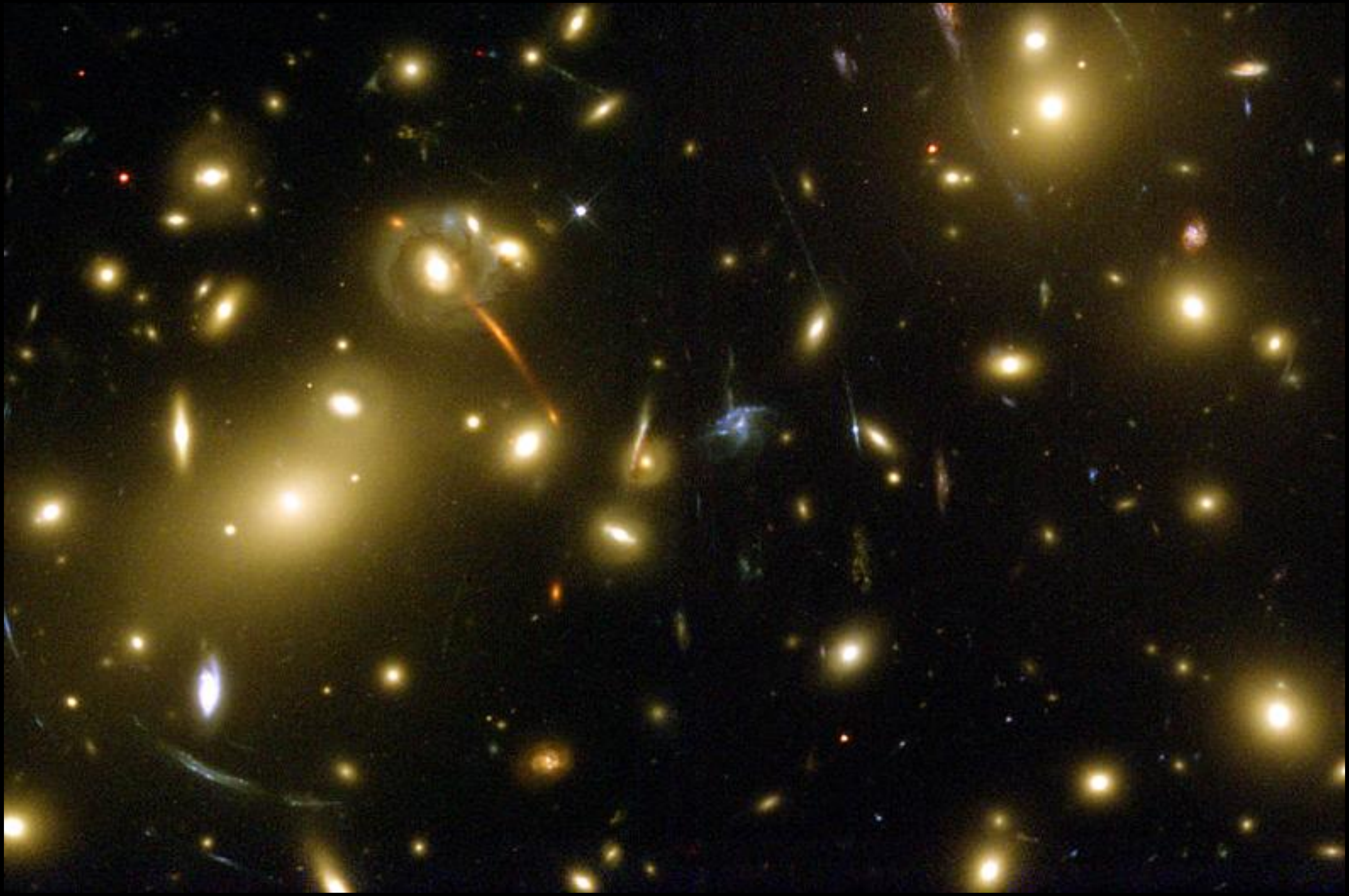
200
180
160
140
120
100
80
60
40
20
0
velocity (km/s)
0
2
4
6
8
10
12
distance from center (arcmin)
Baryonic matter only


Coma

Figure 4.10— The distribution of radial velocities of all 583 identified Coma cluster galaxies ($4000 < cz < 10000$ km s^{-1}). The solid curve is a Gaussian with mean 6977 ± 53 km s^{-1} and standard deviation 950 ± 39 km s^{-1}. The dotted curve is the sum of two Gaussians with $\overline{cz_1} = 7501 \pm 187$ km s^{-1}, $\sigma_1 = 650 \pm 216$ km s^{-1} and $\overline{cz_2} = 6640 \pm 470$ km s^{-1}, $\sigma_2 = 1004 \pm 120$ km s^{-1} and gives a better fit to the observed distribution. The radial velocities of the three dominant galaxies are indicated.



http://www.ub.rug.nl/eldoc/dis/science/m.beijersbergen/c4.pdf



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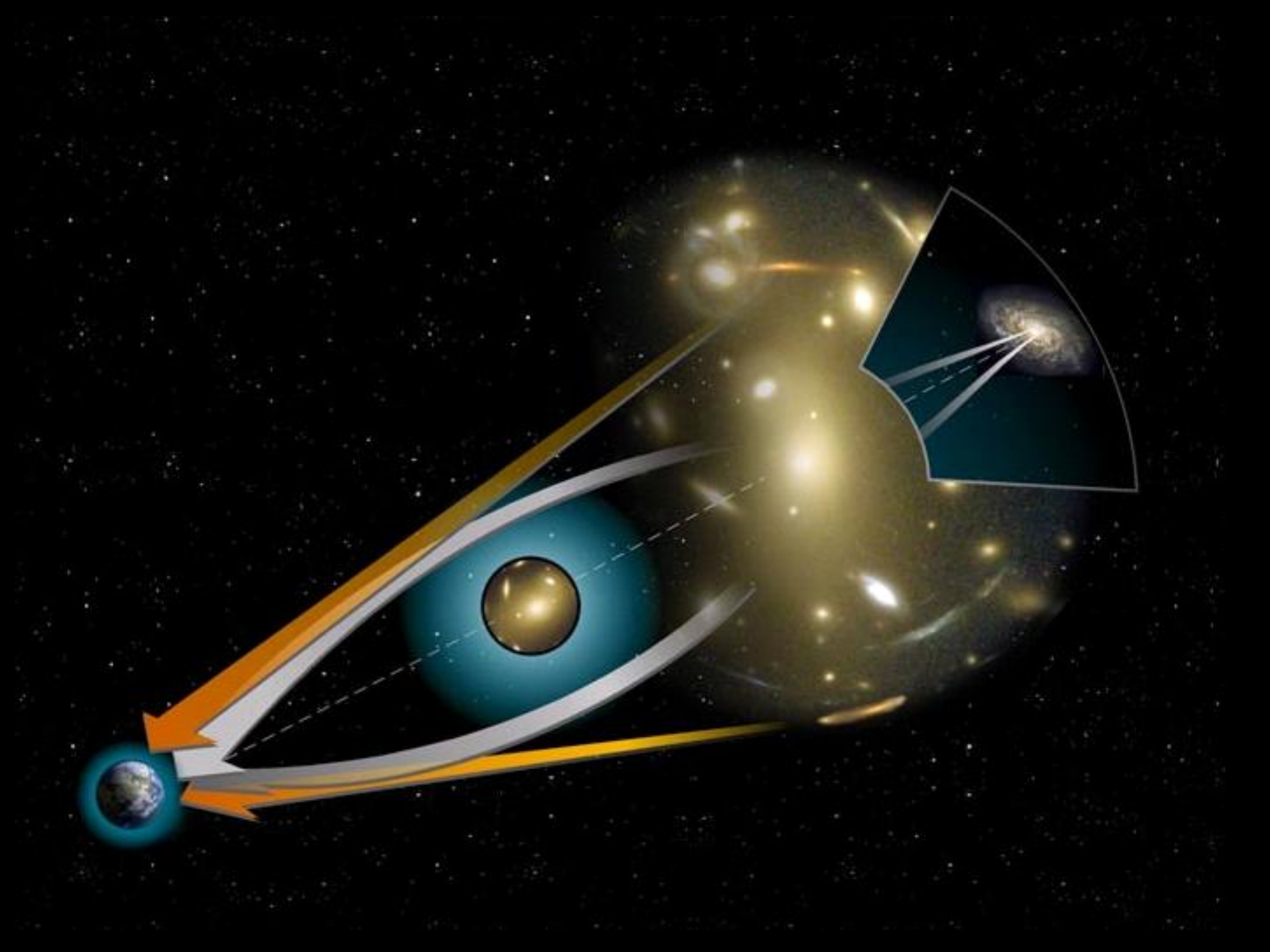
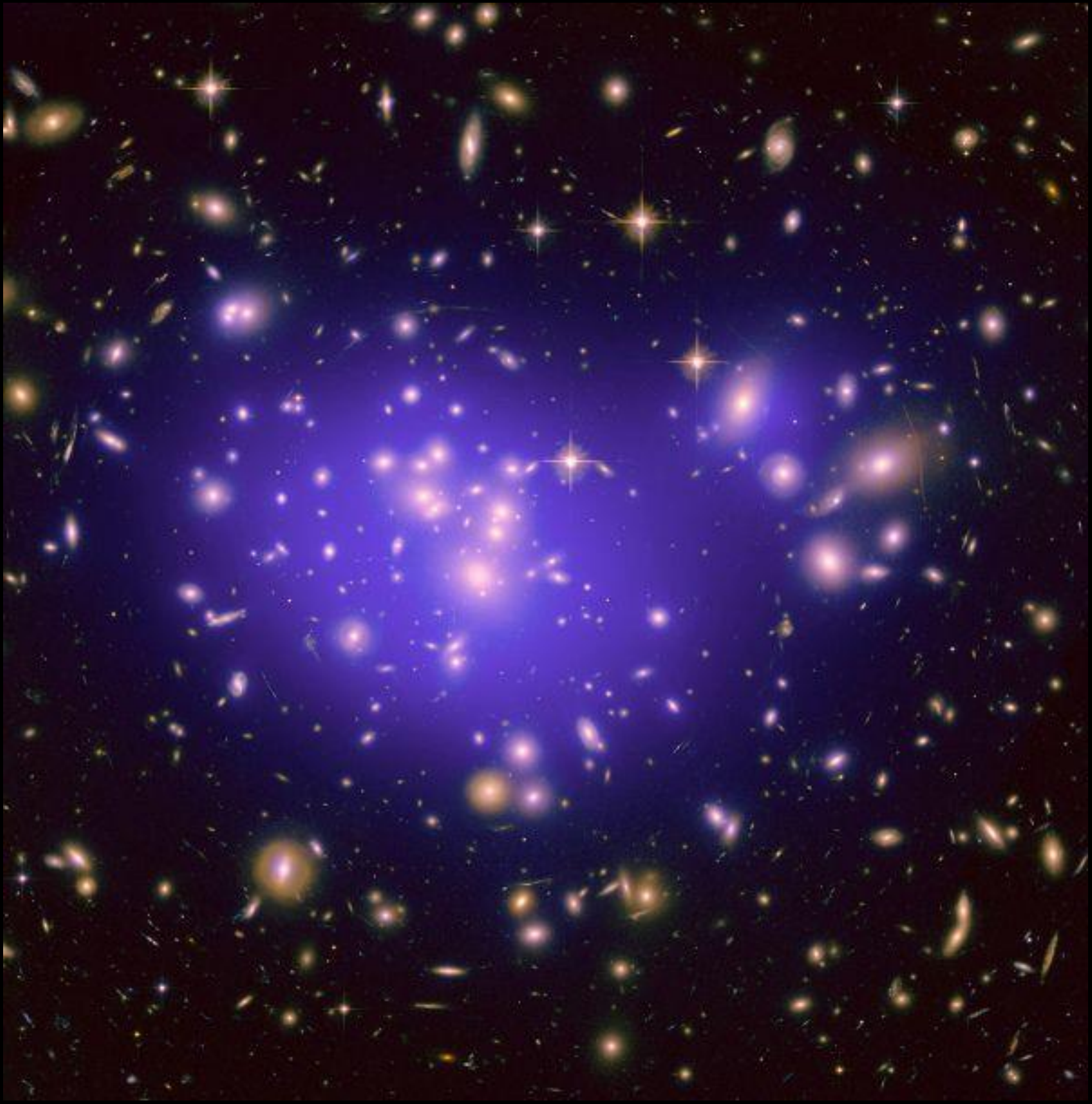
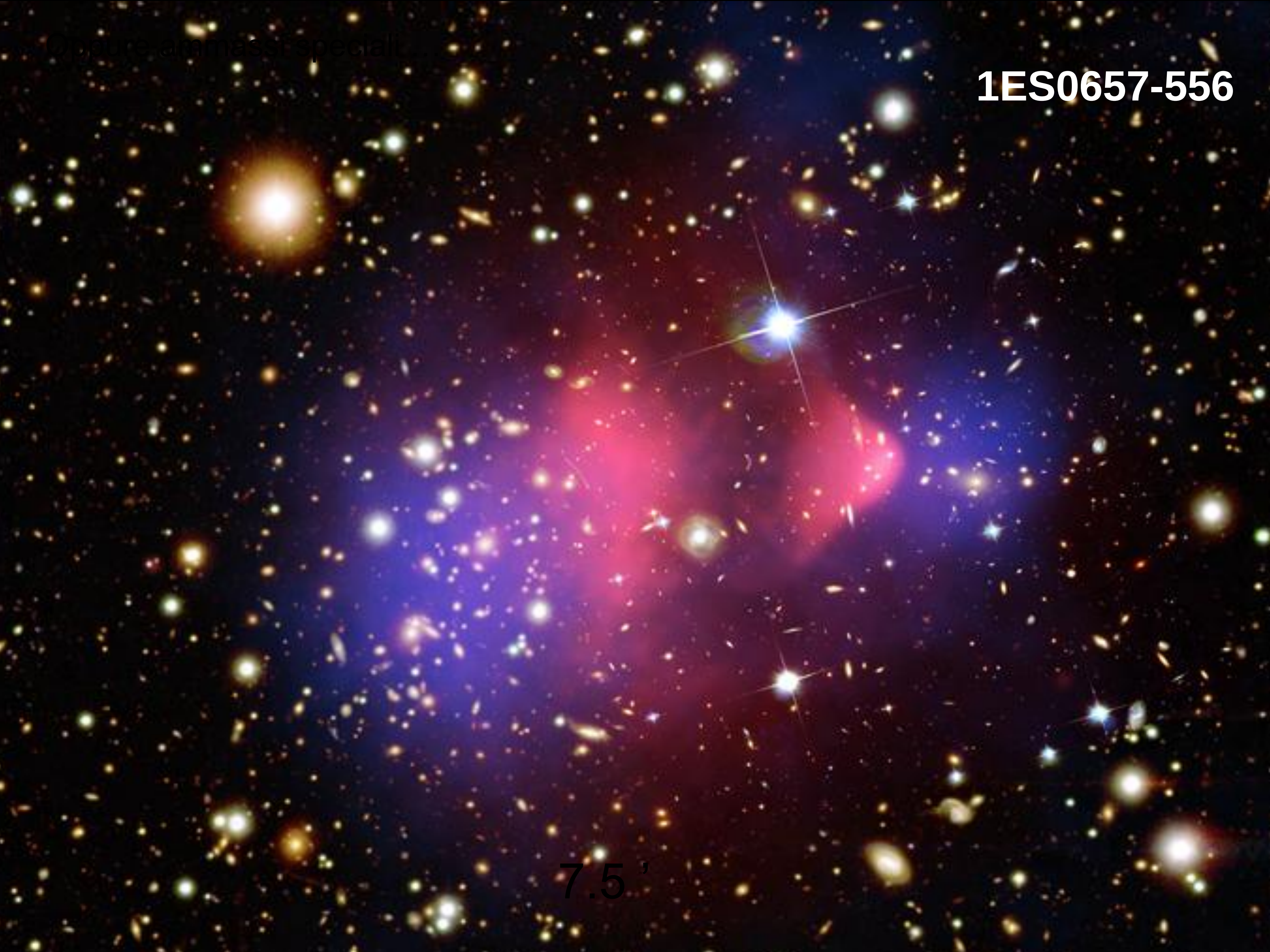
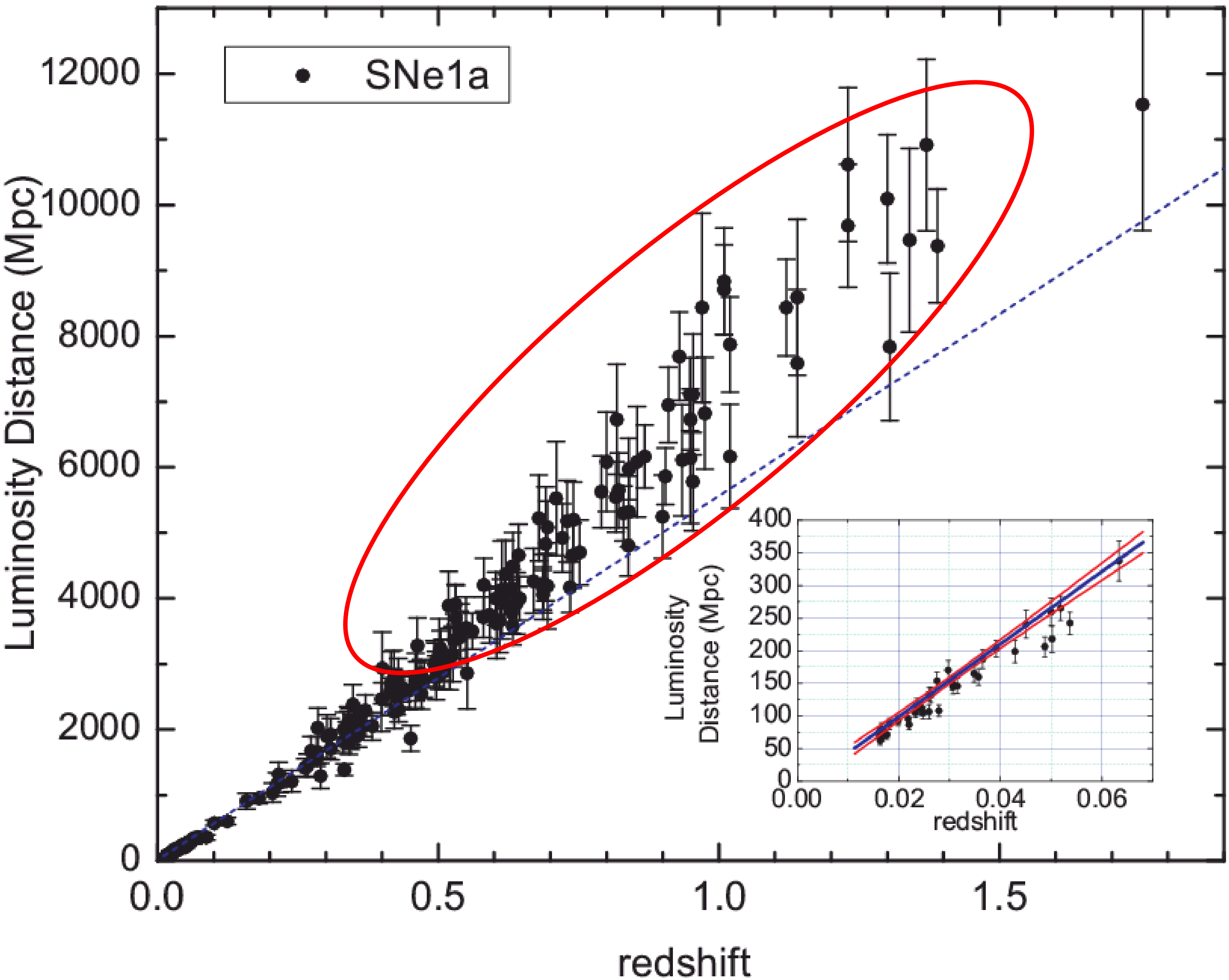




A1689

Oppure ammassi speciali…





SNe1a
Luminosity Distance (Mpc)
12000
10000
8000
6000
4000
2000
0
0.0
0.5
1.0
1.5
redshift
400
350
300
250
200
150
100
50
0
0.00
0.02
0.04
0.06
Luminosity Distance (Mpc)
redshift

Dark Energy

- Systematic weakness of distant (high redshift) SNe1a
- Can be explained by an accelerated expansion of the universe, so that they are more distant for a given redshift.
- From Friedman's equation, the only way is to have $\Omega_\Lambda > 0$.

$$\ddot{a} = H_o^2 \left[-\frac{\Omega_{Ro}}{a^3} - \frac{1}{2}\frac{\Omega_{Mo}}{a^2} + \Omega_\Lambda a \right]$$

- The best fit is $\Omega_\Lambda = (0.73 \pm 0.03)$
- This can be obtained from independent measurements as well (CMB, see below)

Radiation

- Light and electromagnetic waves fill the universe.
- Stellar radiation is not the most important radiation field present in the universe, since it dilutes far from stars.
- The cosmic microwave background is a perfect balckbody with a temperature T_o=2.725K filling the whole universe, so dominating over stellar and any other radiation at large scales.
- Its density today is negligible: $\Omega_{Ro} < 10^{-4}$
- However, early in the evolution of the universe, it dominated the energy density. In principle, it was light.

$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]$$

Density Parameter

- The total mass-energy density is the sum of all the components analyzed above.

$$\Omega_o = \Omega_{Ro} + \Omega_{Mo} + \Omega_{DMo} + \Omega_\Lambda \approx 1$$

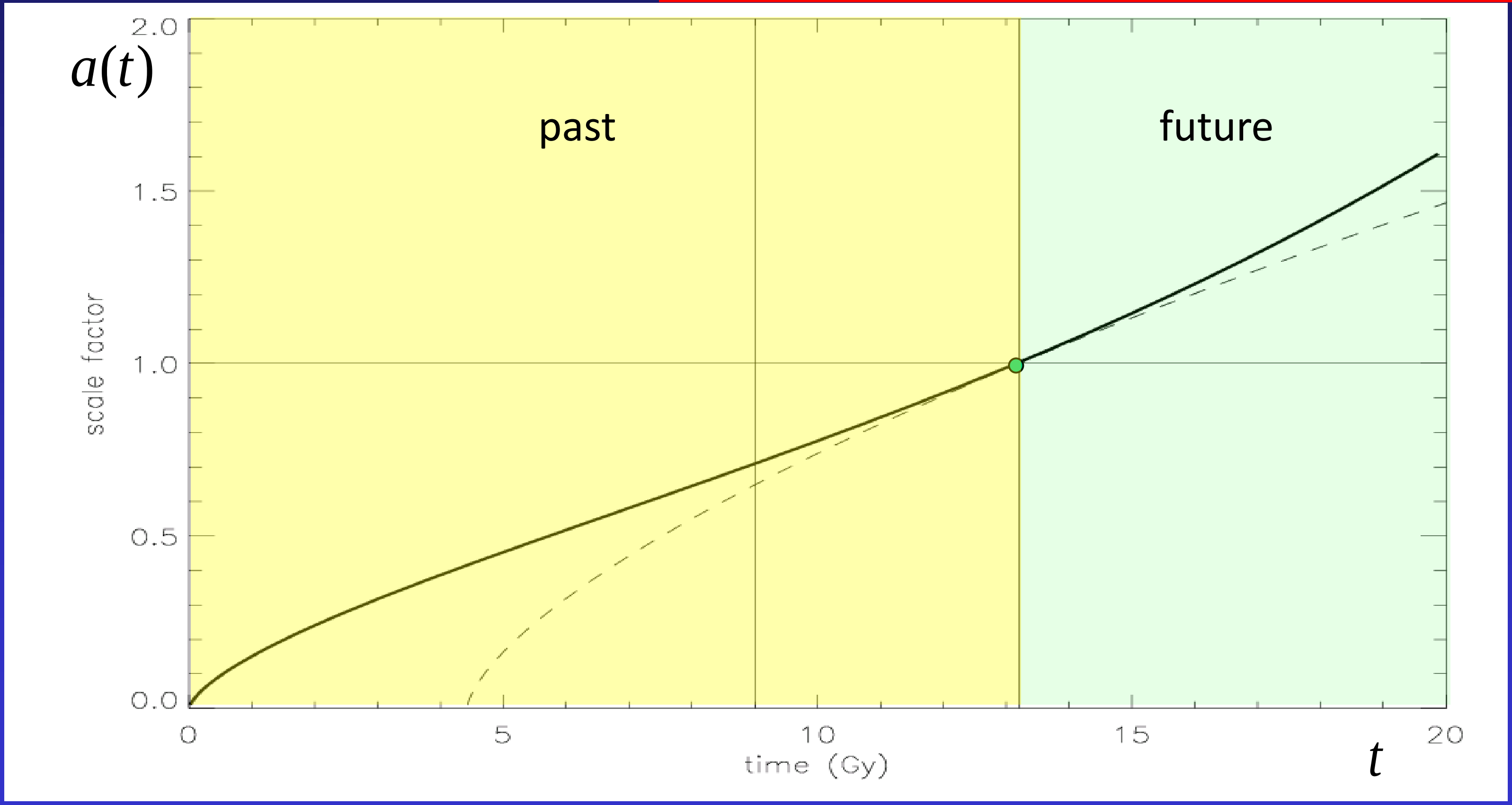
- I.e. the mass-energy density is consistent with the critical density, and there is no curvature of space.
- This result is confirmed and its accuracy is improved by measurements of the causal horizon at redshift 1100, using the cosmic microwave background:

$$\Omega_o = (1.02 \pm 0.02)$$

Friedman's equation

- We know all the parameters, so we can solve the equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4}+\frac{\Omega_{Mo}}{a^3}+\frac{(1-\Omega_o)}{a^2}+\Omega_\Lambda\right]$$



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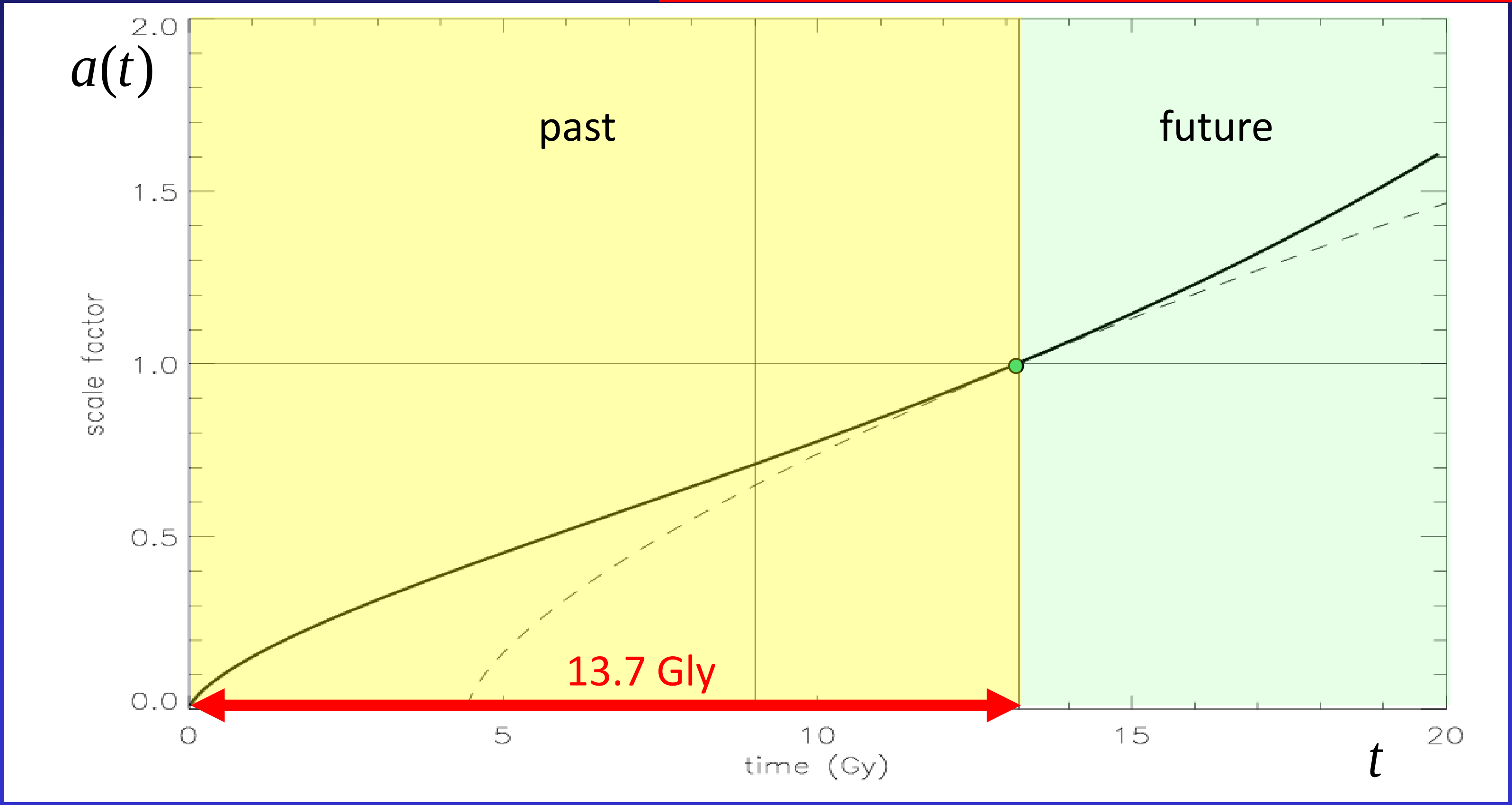

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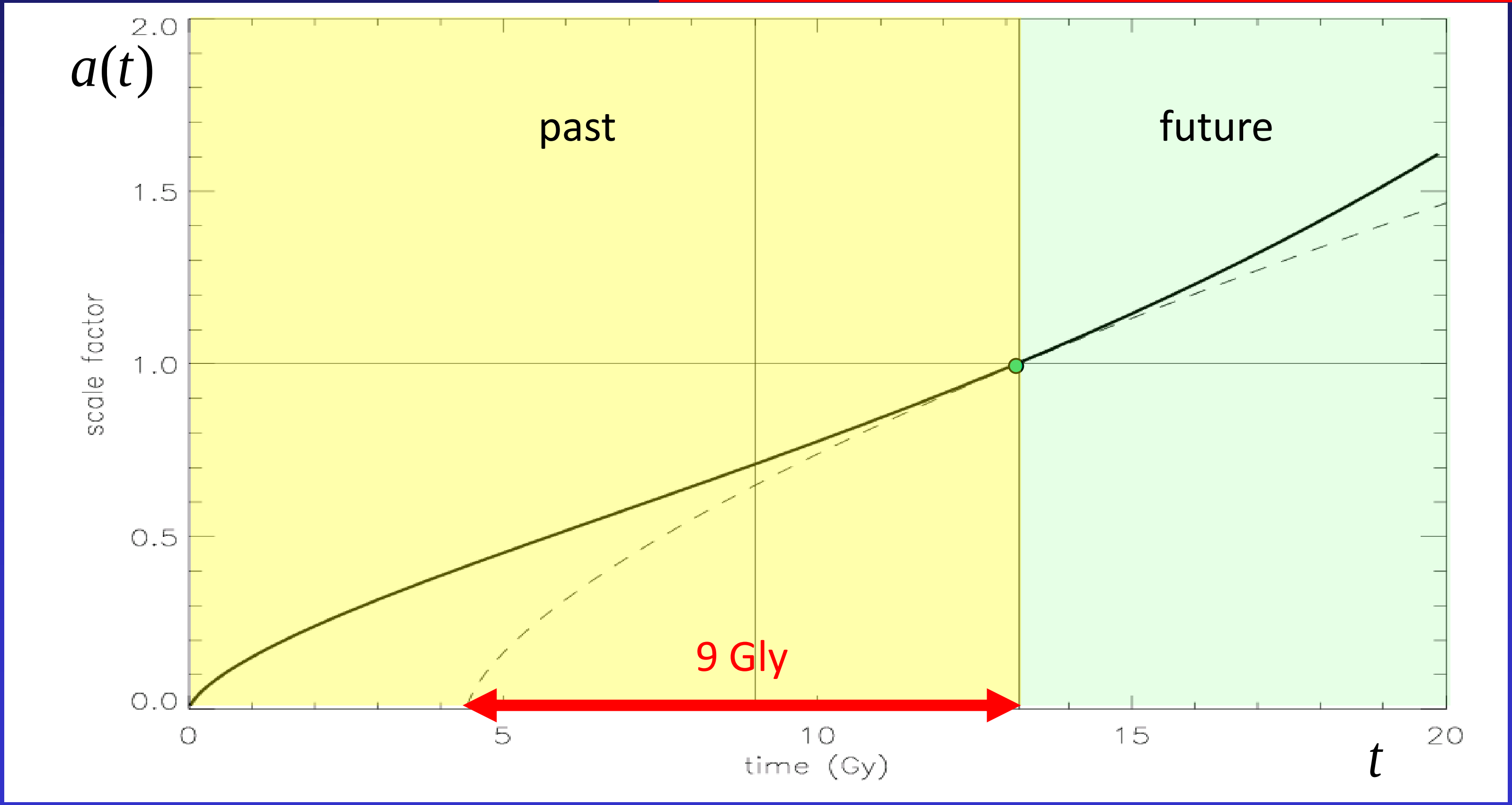
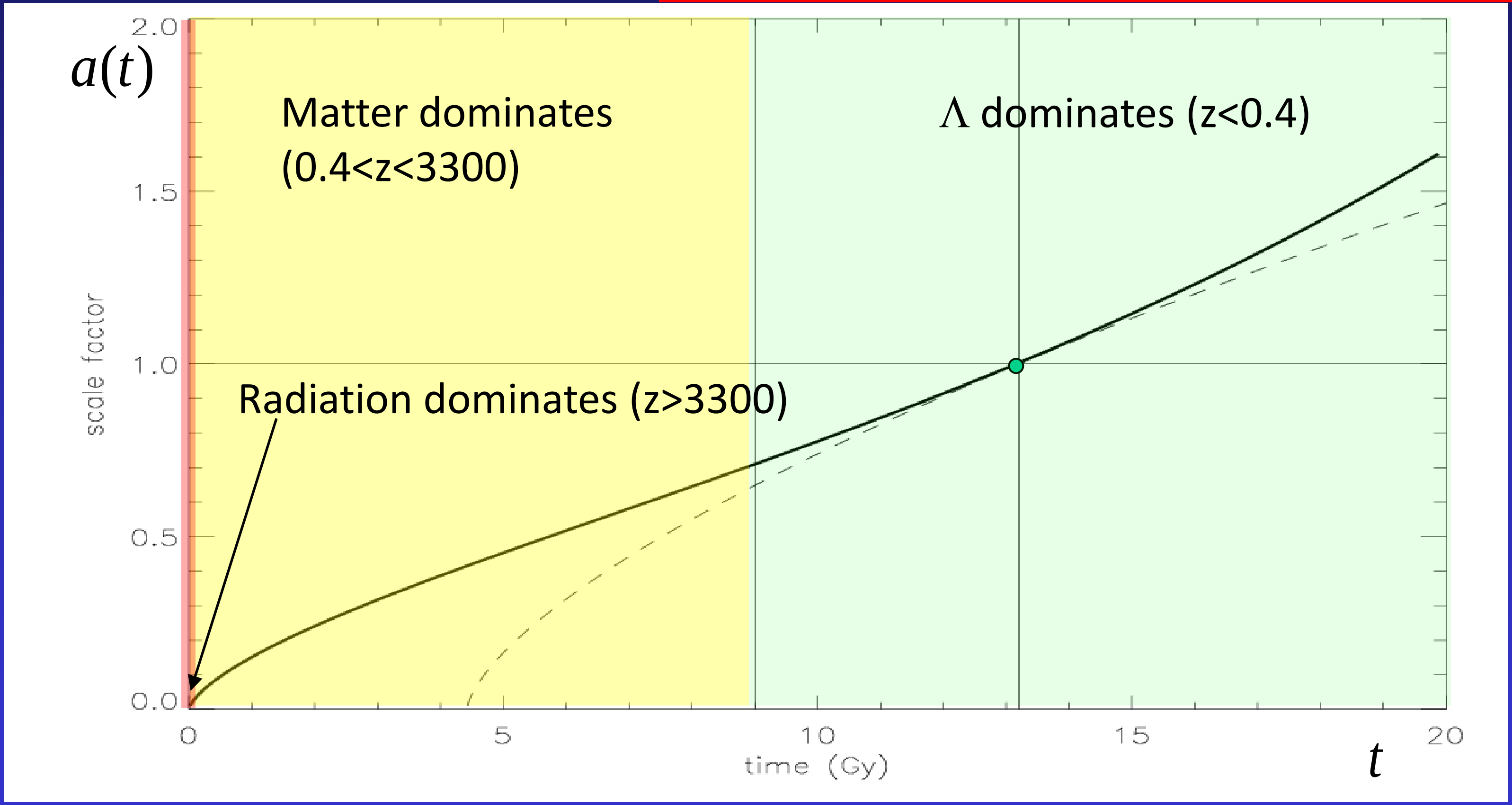



NGC 6397

Friedman's equation

- We know all the parameters, so we can solve the equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]$$



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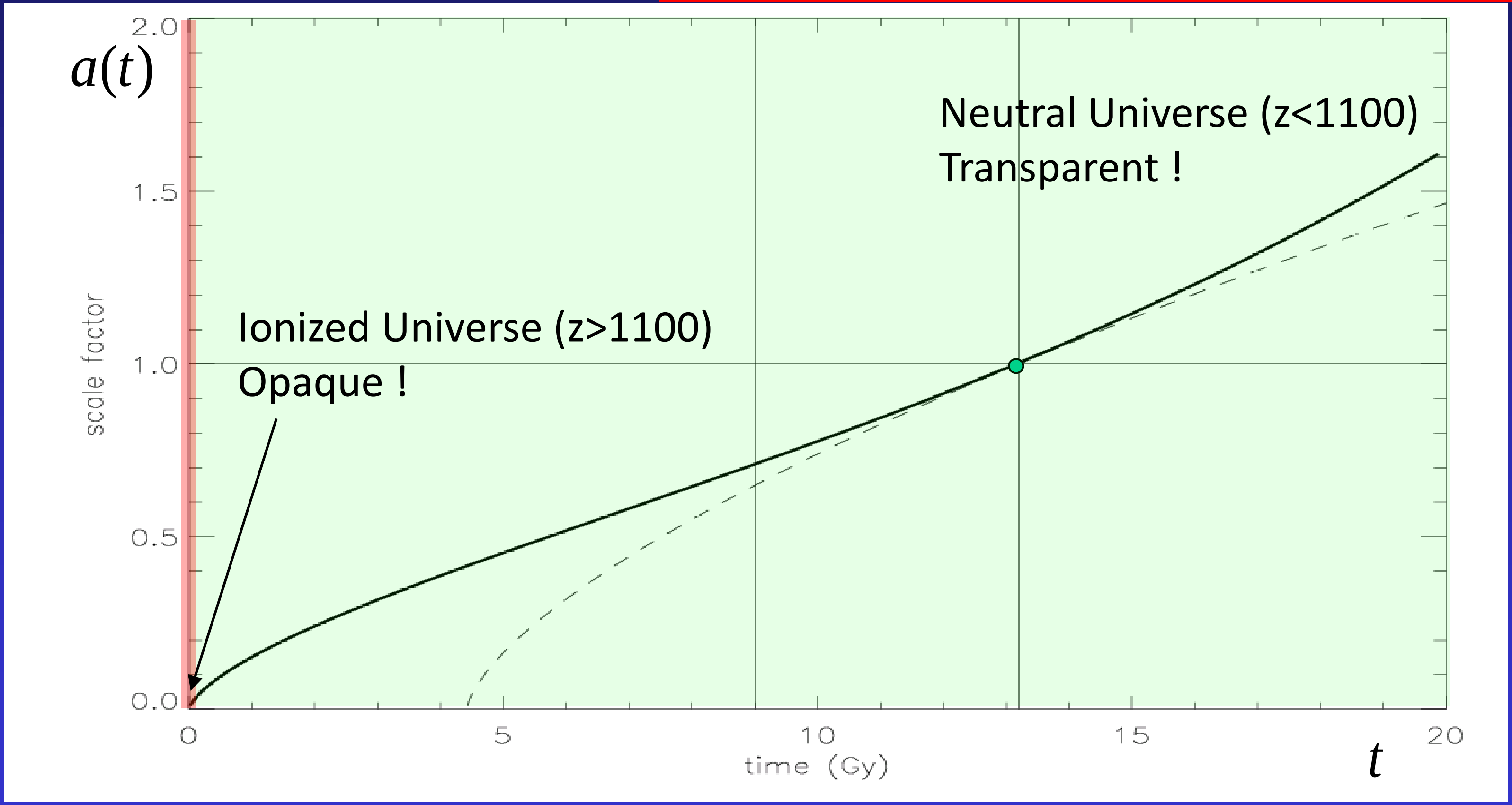
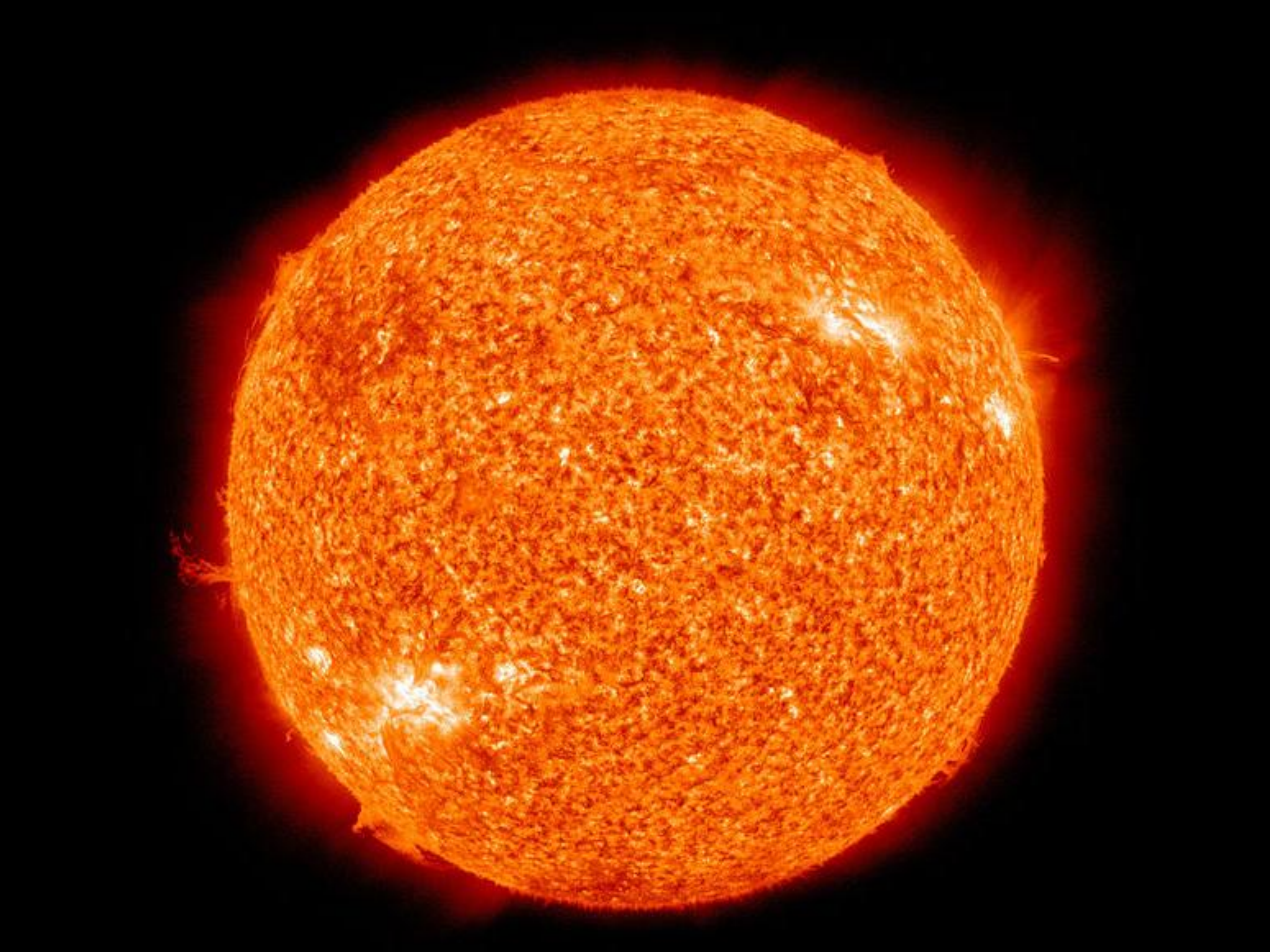
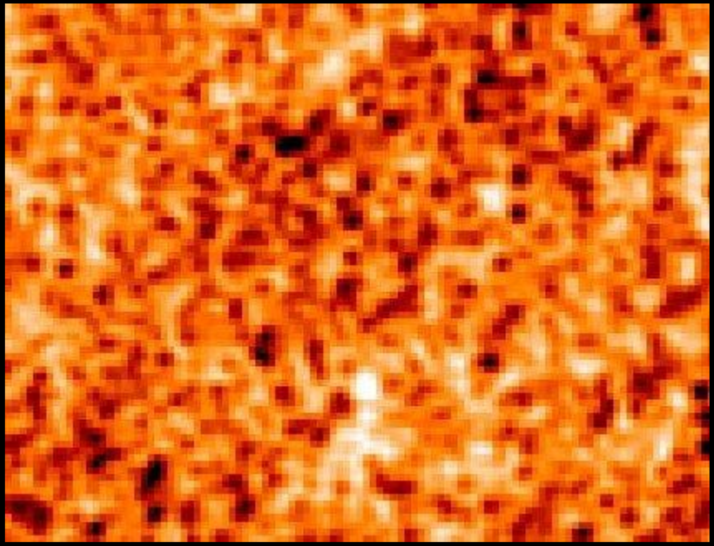




Granulazione solare

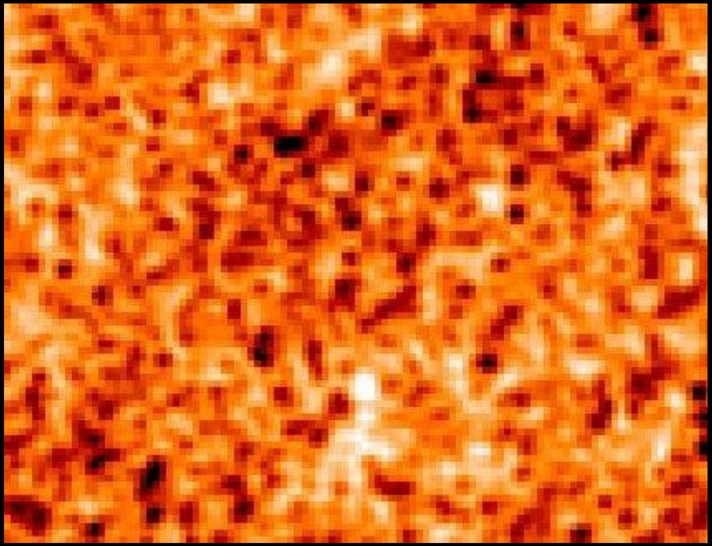


Gas incandescente sulla superficie del Sole (5500 K)

8 minuti luce

Qui, ora

Granulazione solare



Gas incandescente sulla superficie del Sole (5500 K)

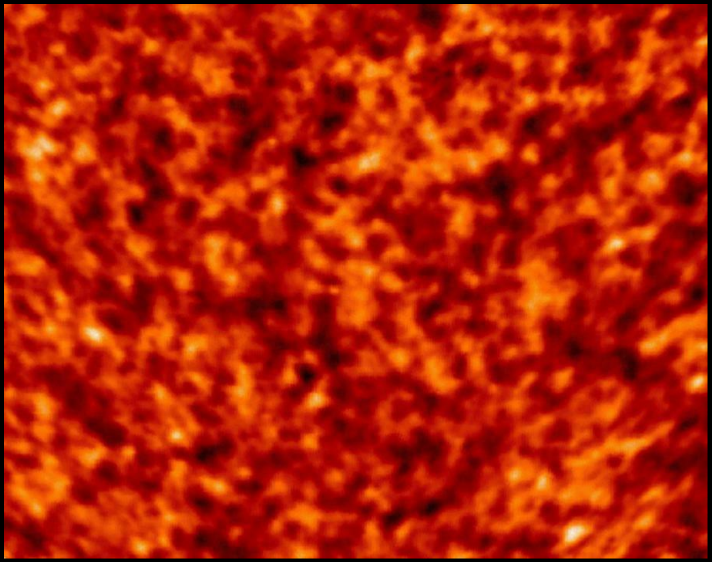
8 minuti luce

Qui, ora

Gas incandescente nell’ universo primordiale (l’ universo diventa trasparente a 3000 K)

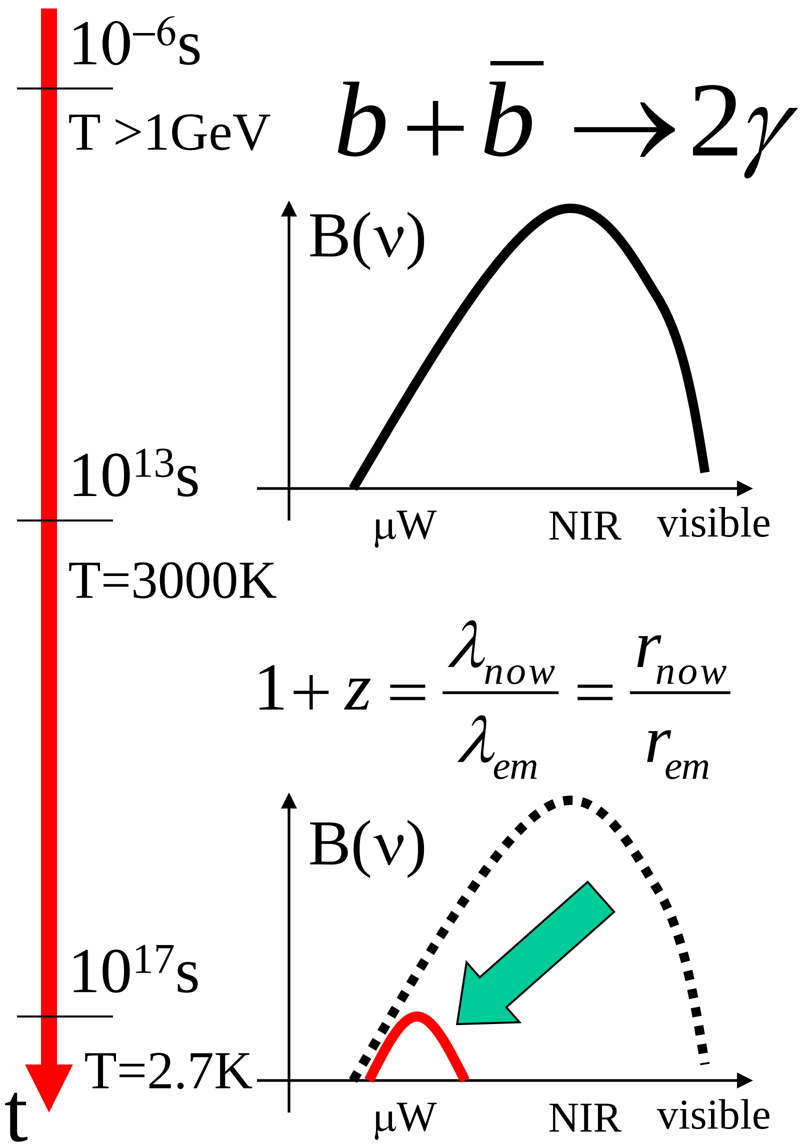
14 miliardi di anni luce

Qui, ora



Mappa di BOOMERanG dell’ Universo Primordiale

What is the CMB

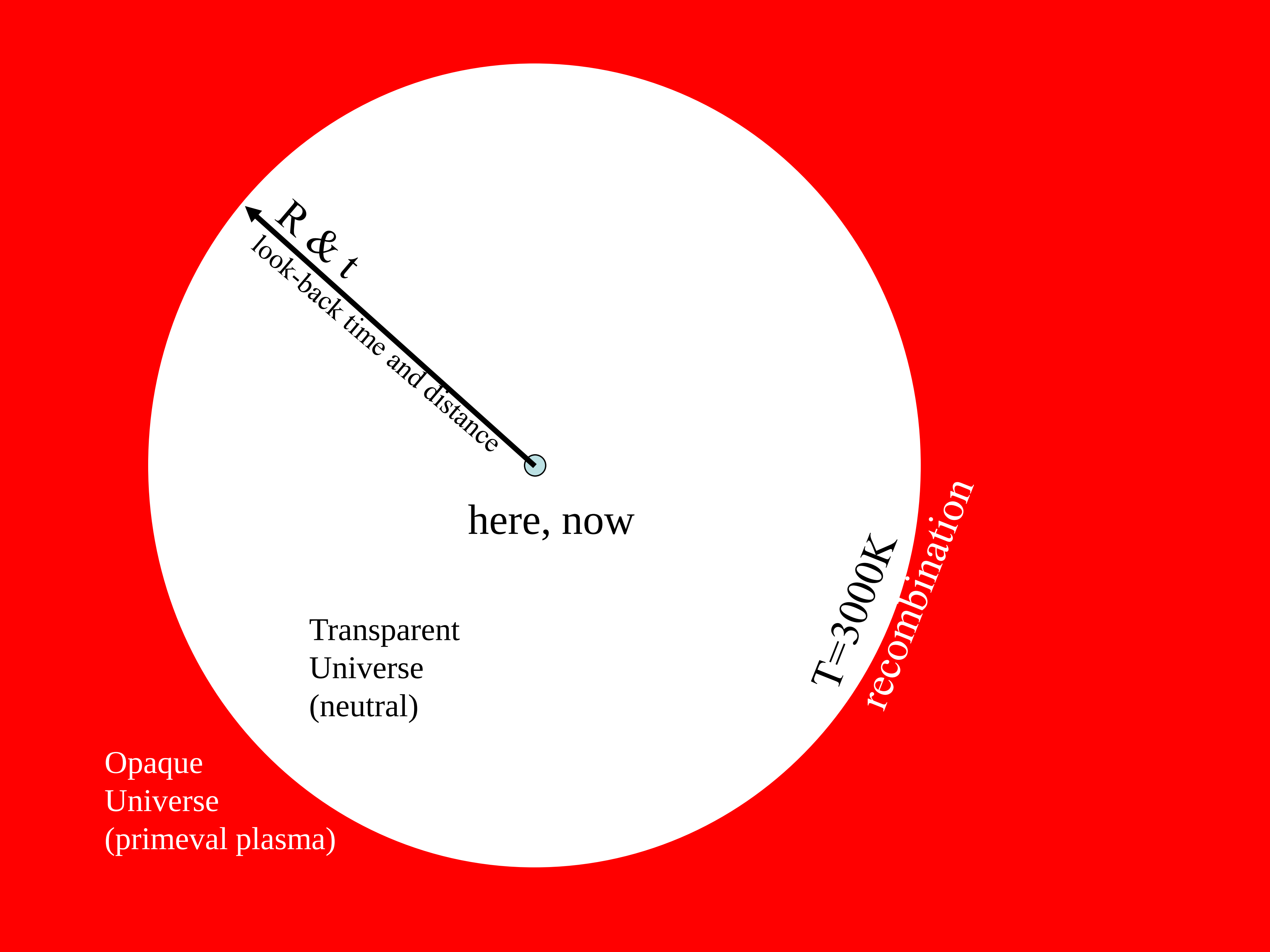


According to modern cosmology:

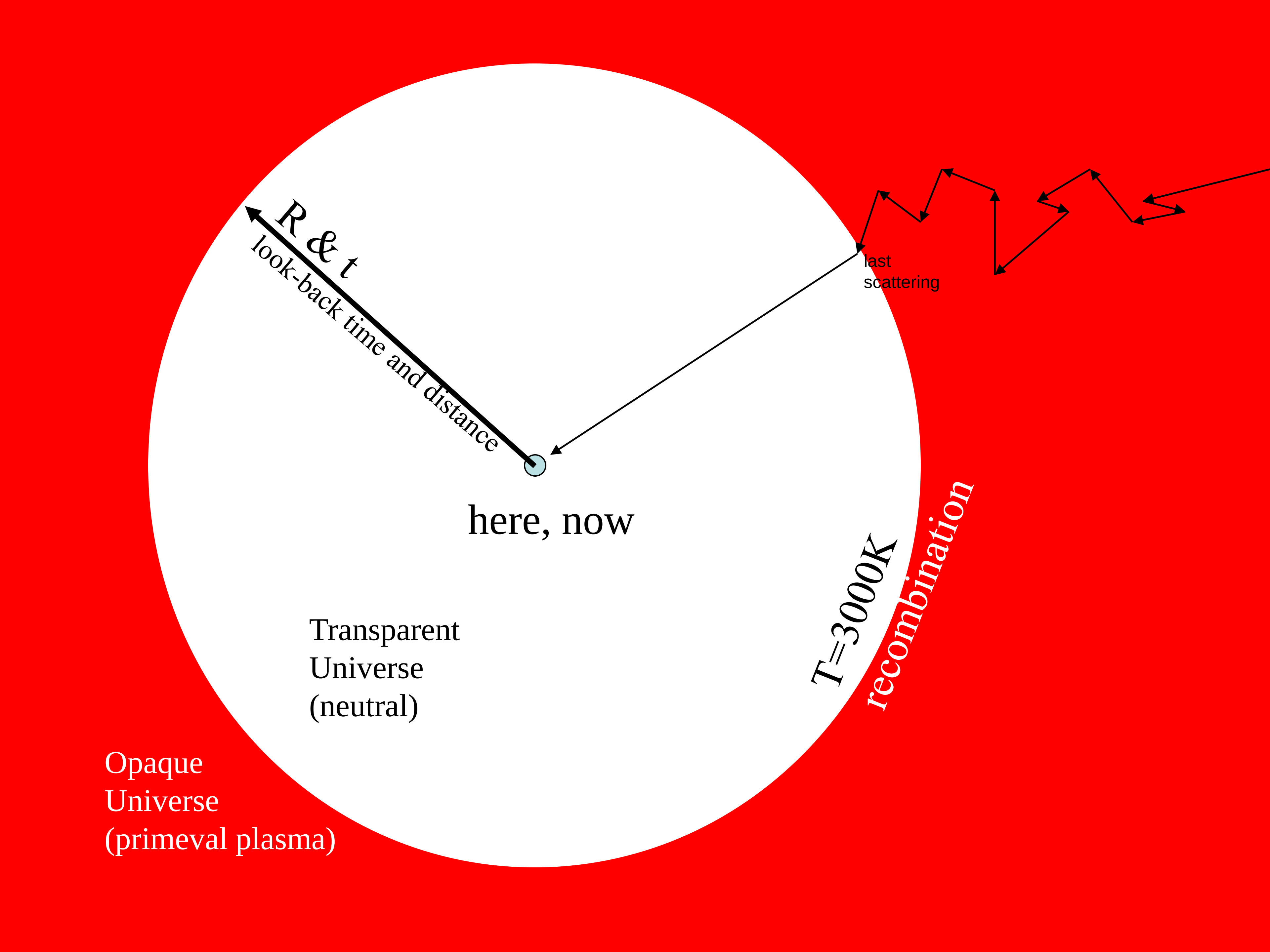
An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 μs after the Big Bang ($10^9\gamma$ for each baryon)
- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Redshifted** to microwave frequencies **and diluted** in the subsequent 14 Gyrs of expansion of the Universe
- **Today: 410γ/cm³, ~1 meV**

These photons carry
significant information
on the structure, evolution and
composition of our universe

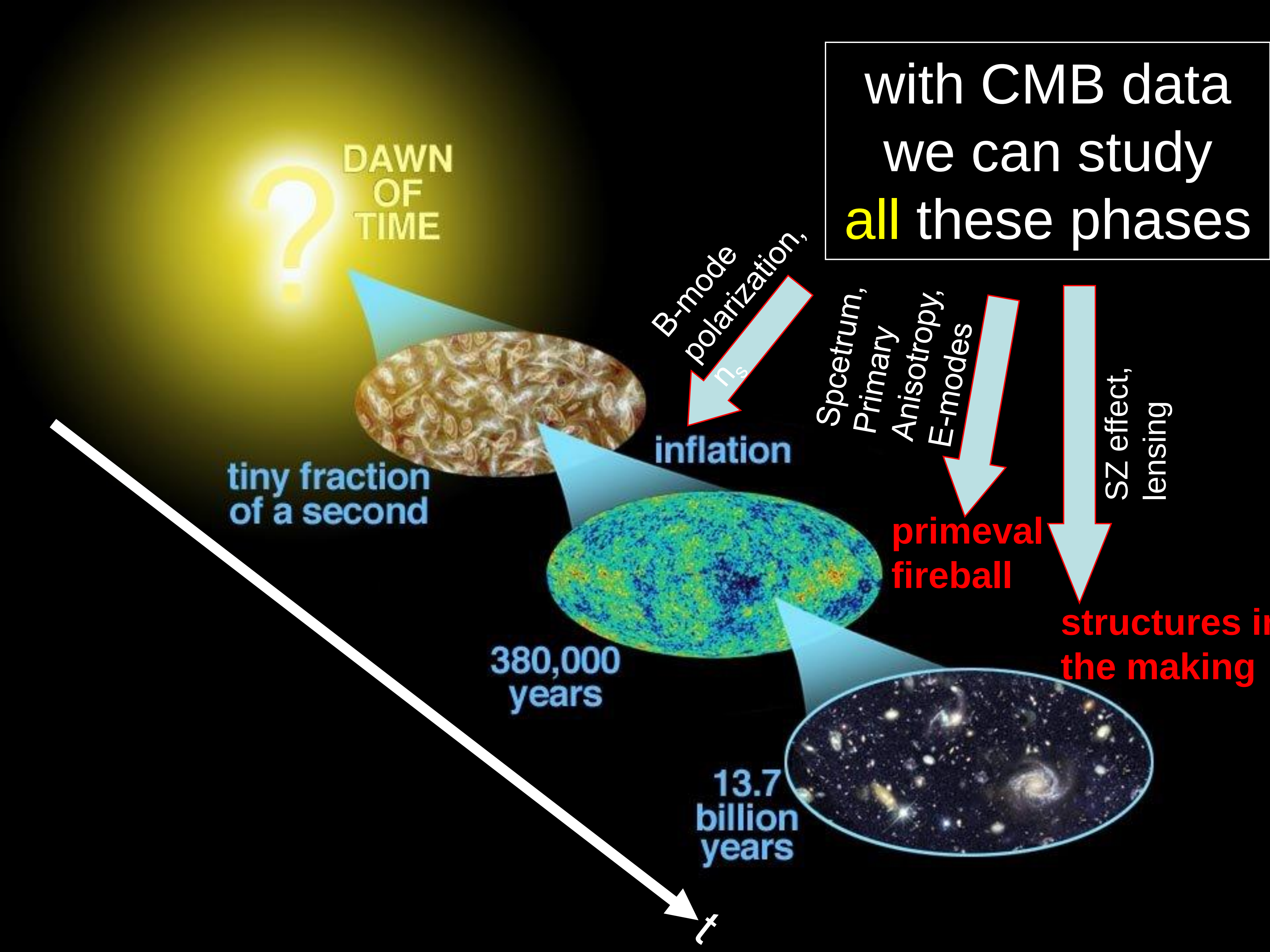


R & t
look-back time and distance
here, now
T=3000K
recombination
Transparent
Universe
(neutral)
Opaque
Universe
(primeval plasma)


R & t
look-back time and distance
last
scattering
here, now
T=3000K
recombination
Transparent
Universe
(neutral)
Opaque
Universe
(primeval plasma)

The spectrum

- CMB photons are produced when matter and radiation are in tight thermal equilibrium (Thomson scattering in the primeval plasma)
- The spectrum of the CMB has to be a blackbody.
- The expansion of the universe preserves the shape of a blackbody spectrum, while its temperature decreases as the inverse of the scale factor.
- Measuring a blackbody spectrum of the CMB, we can prove the existence of a primeval fireball phase of the universe.
- To be consistent with the primordial abundance of light elements, a temperature of a few K is expected (Gamow)


with CMB data we can study all these phases
DAWN OF TIME
B-mode polarization, n_s
Spcetrum, Primary Anisotropy, E-modes
SZ effect, lensing
inflation
tiny fraction of a second
primeval fireball
380,000 years
structures in the making
13.7 billion years
t

CMB anisotropy (intrinsic)

- Different physical effects, all related to the *small* density fluctuations $\delta\rho/\rho$ present 380000 yrs after the big bang (recombination) produce CMB Temperature fluctuations:

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\varphi}{c^2} + \frac{1}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} - \frac{\vec{\mathrm{v}}}{c}\cdot\vec{n}$$

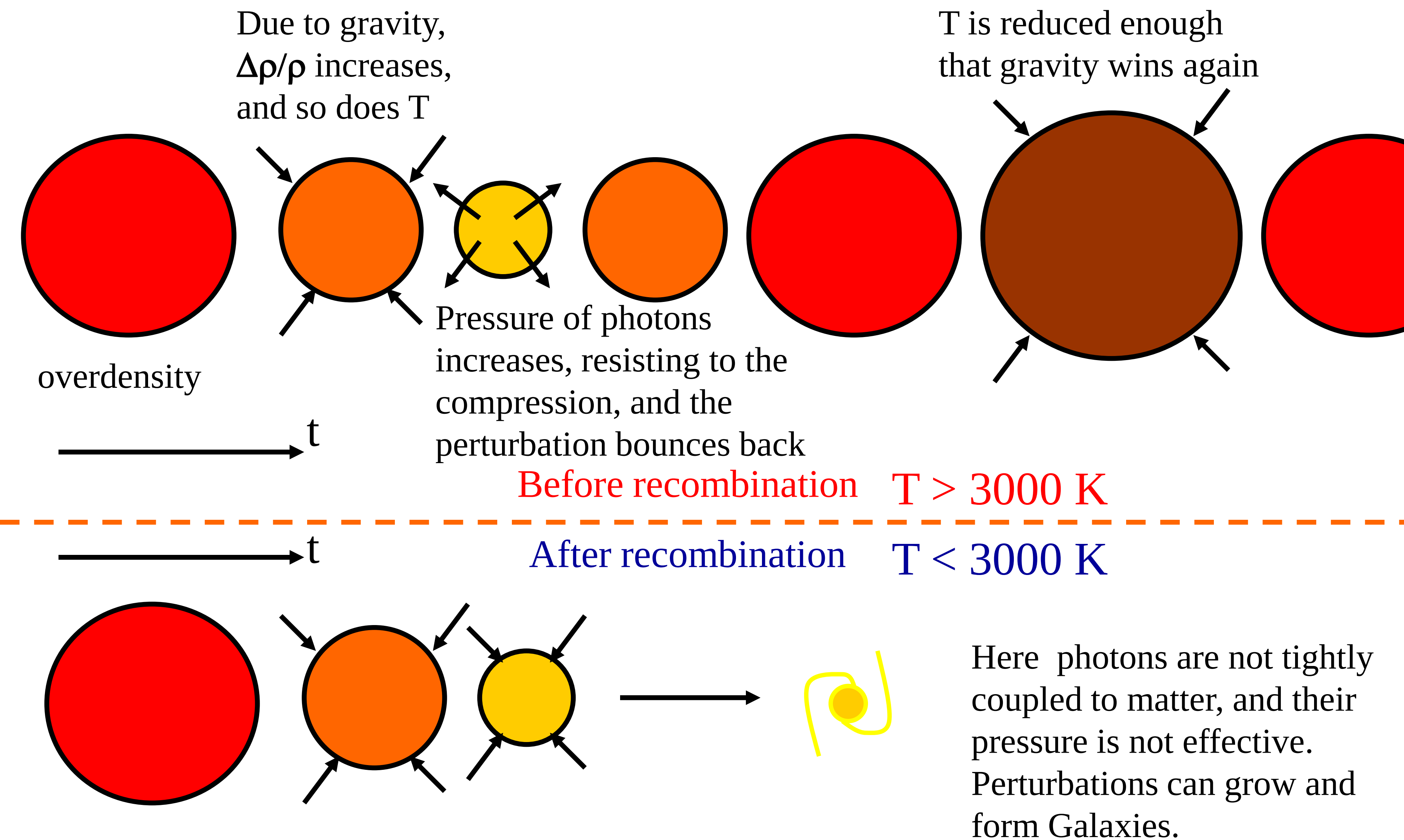
Sachs-Wolfe (gravitational redshift)	Photon density fluctuations	Doppler effect from velocity fields

- Scales larger than the horizon are basically frozen in the pre-recombination era. Flat power spectrum of $\delta T/T$ at large scales.
- Scales smaller than the horizon undergo acoustic oscillations during the primeval fireball. Acoustic peaks in the power spectrum of $\delta T/T$ at sub-degree scales.

CMB anisotropy (intrinsic)

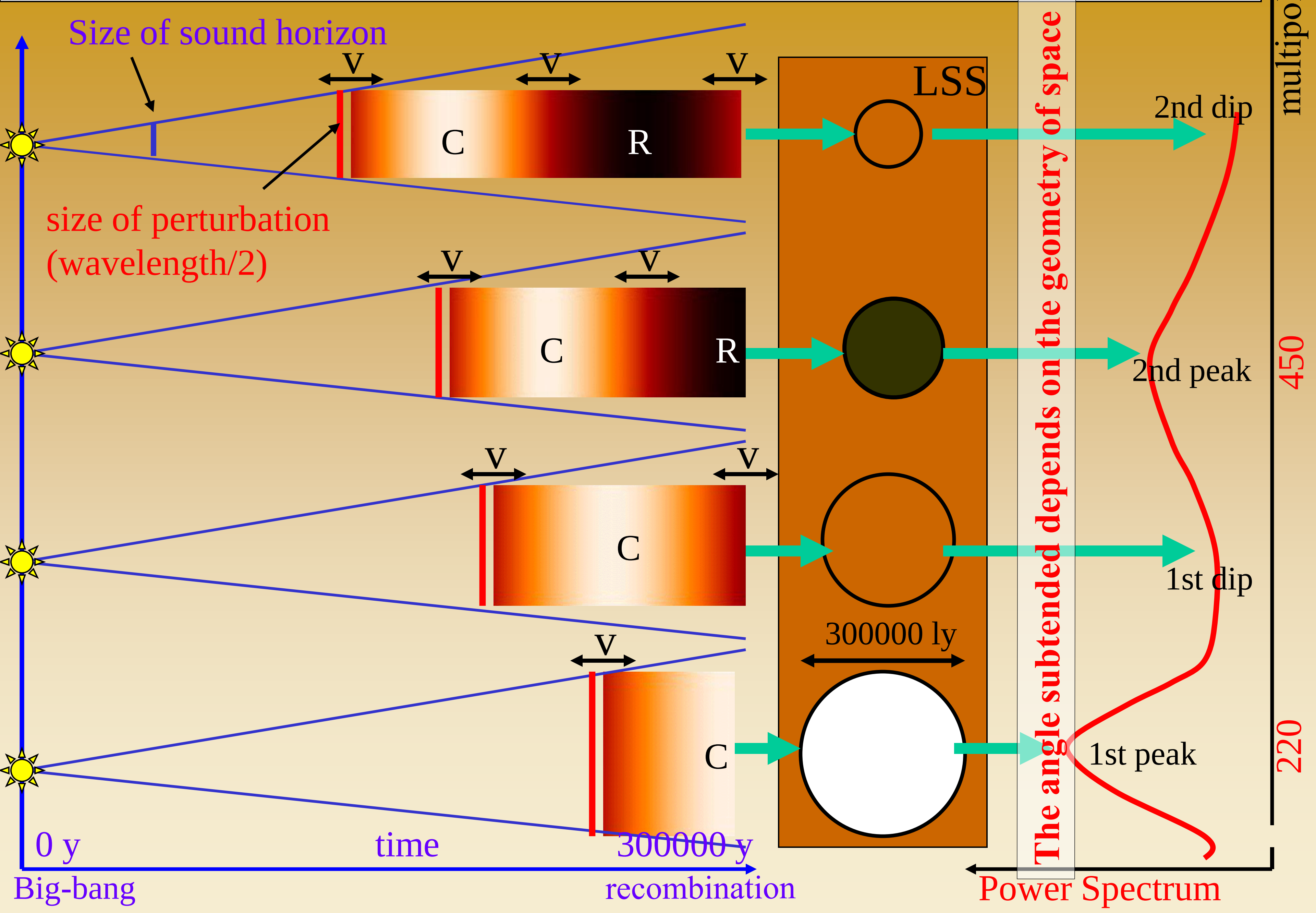
- The primeval plasma of photons and matter oscillates :
- self-gravity vs radiation pressure.
- We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
- Statistical theory: all information encoded in the angular power spectrum of the image.

Density perturbations ($\Delta\rho/\rho$) were **oscillating** in the primeval plasma (as a result of the opposite effects of gravity and photon pressure).



After recombination, density perturbation can **grow** and create the hierarchy of structures we see in the nearby Universe.

In the primeval plasma, photons/baryons density perturbations start to oscillate only when the sound horizon becomes larger than their linear size . Small wavelength perturbations oscillate faster than large ones.



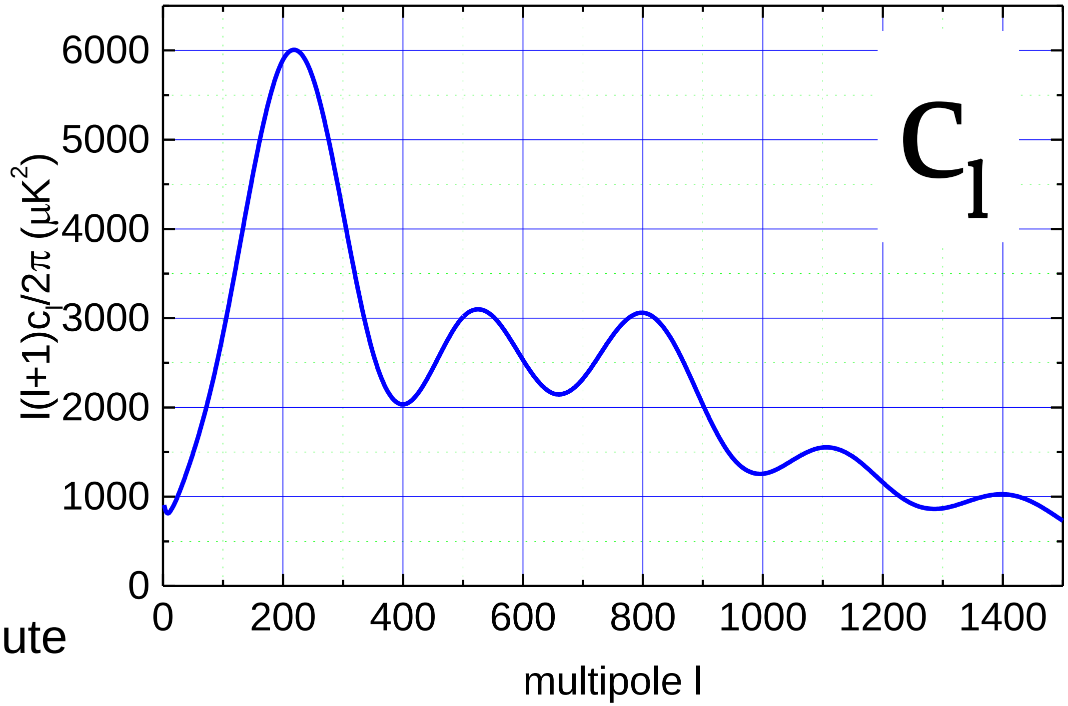
Expected power spectrum:

$$\Delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta,\varphi)$$

$$c_\ell = \langle a_{\ell m}^2 \rangle$$

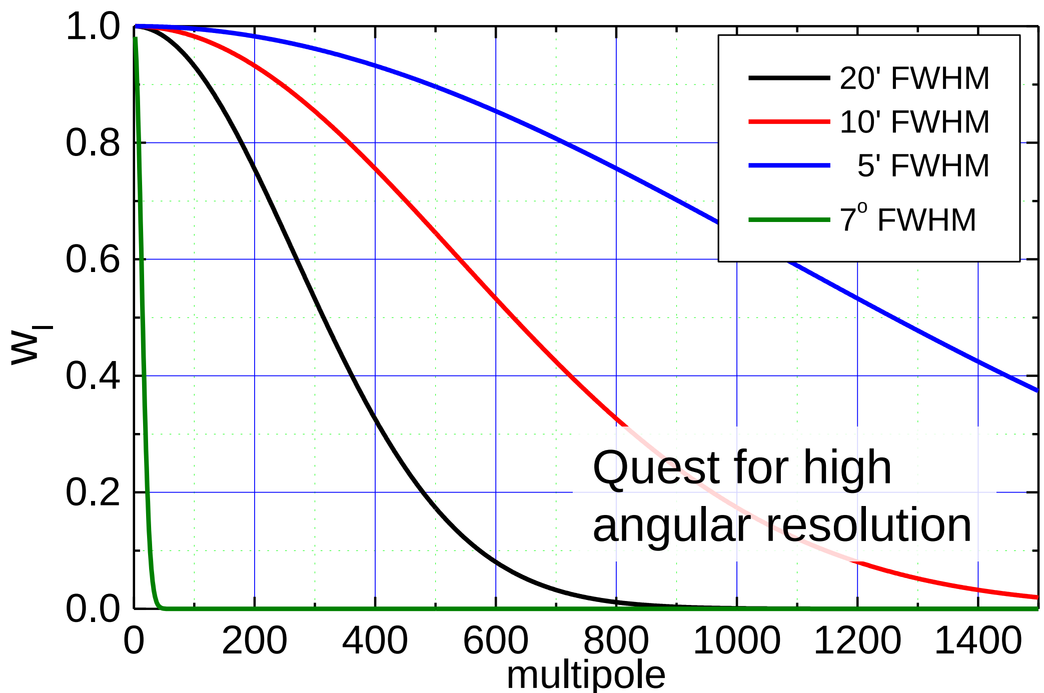
$$\langle \Delta T^2 \rangle = \frac{1}{4\pi} \sum_\ell (2\ell+1) c_\ell$$

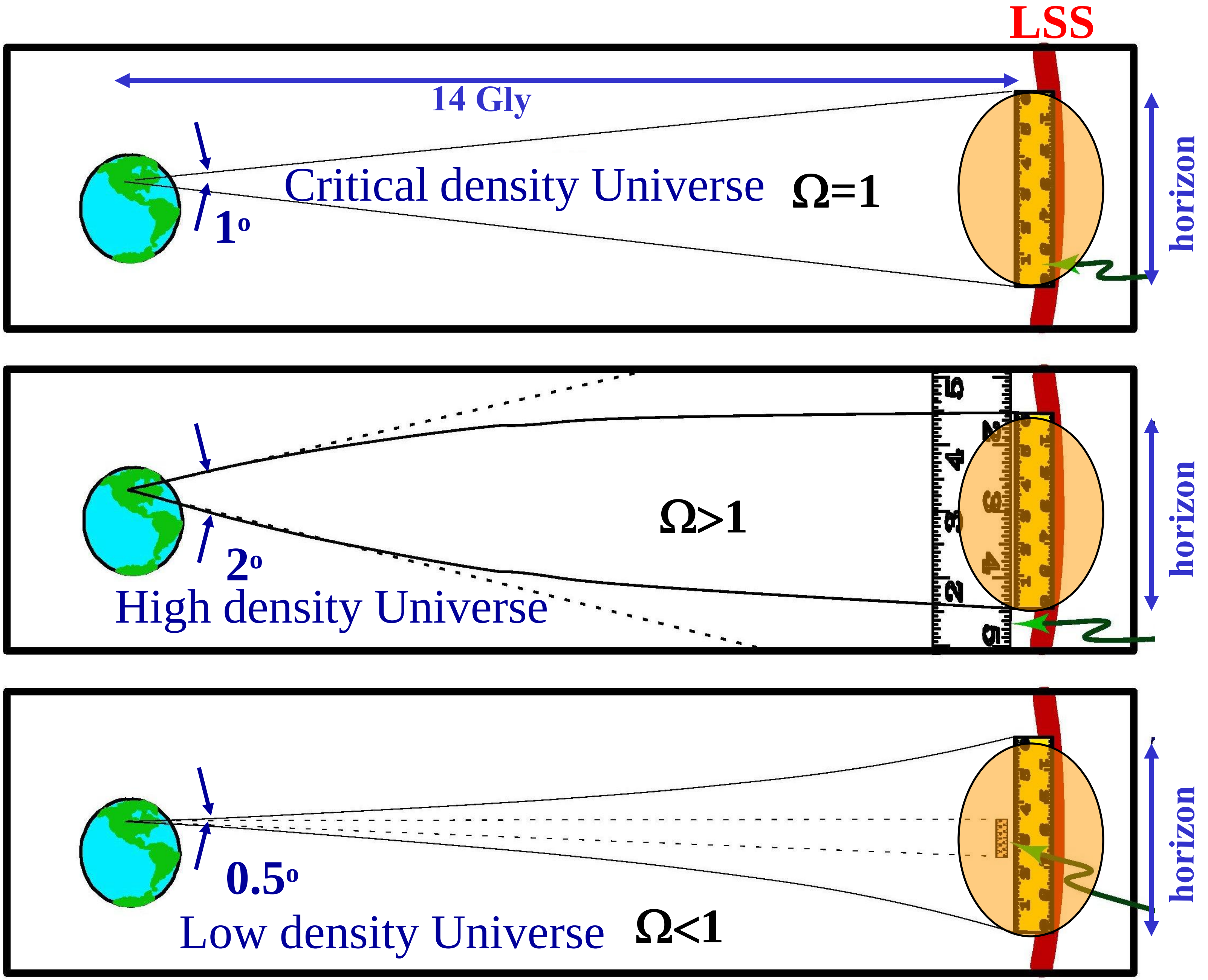
See e.g. http://camb.info to compute c_l for a given cosmological model



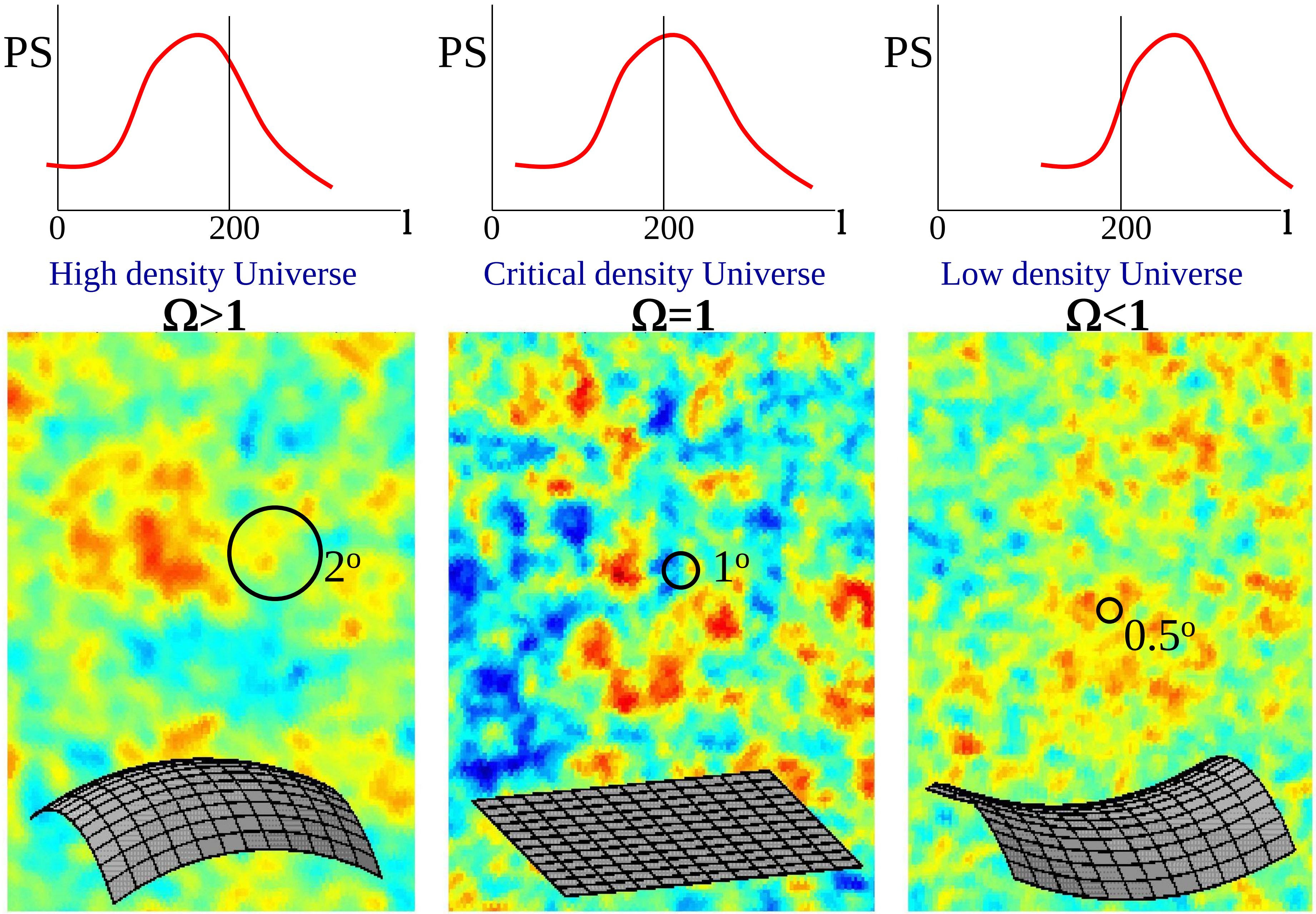
An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

$$w_\ell^{LP} = e^{-\ell(\ell+1)\sigma^2}$$





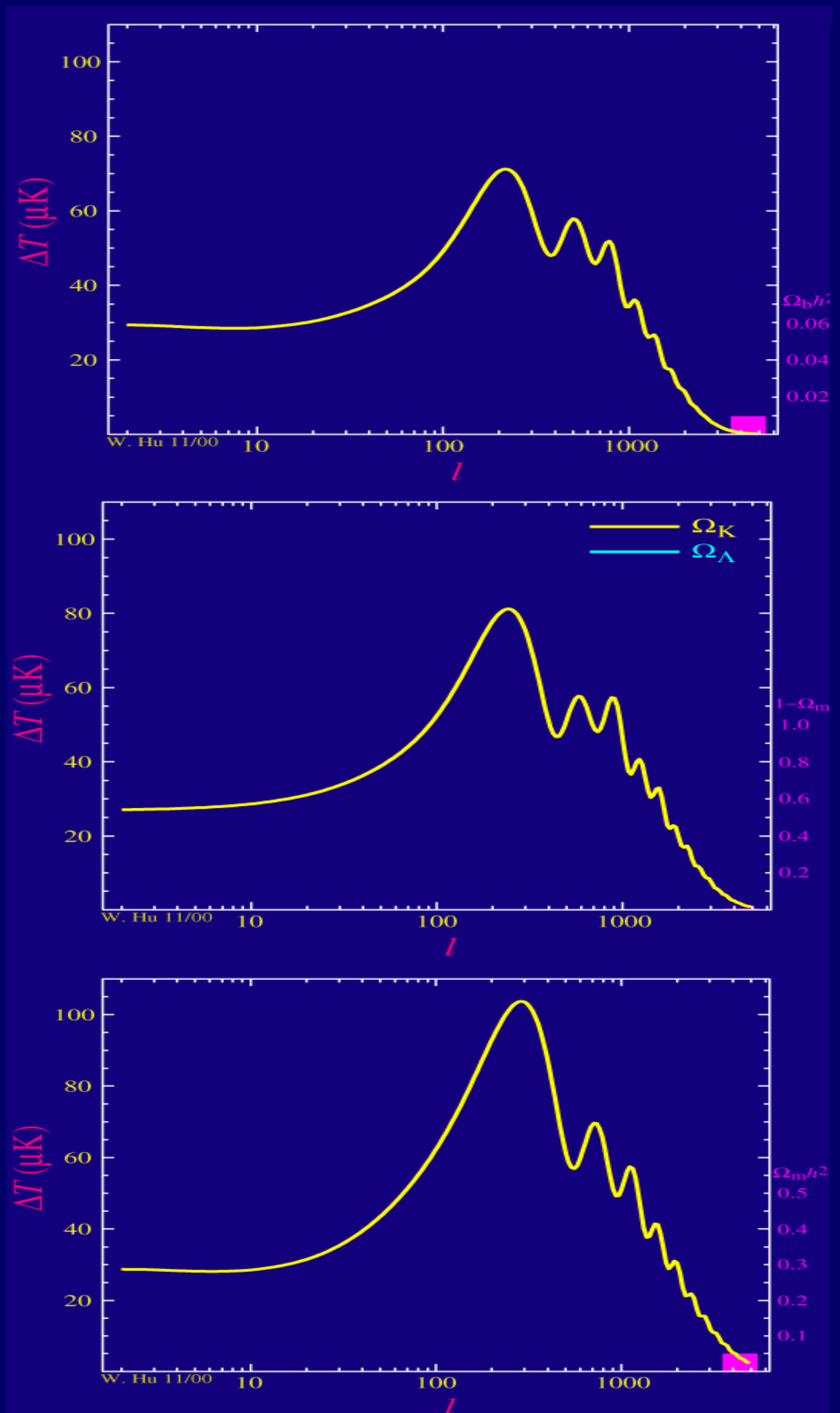
The image and PS are modified by the geometry of the universe



The mass-energy density of the Universe can be measured in this way.

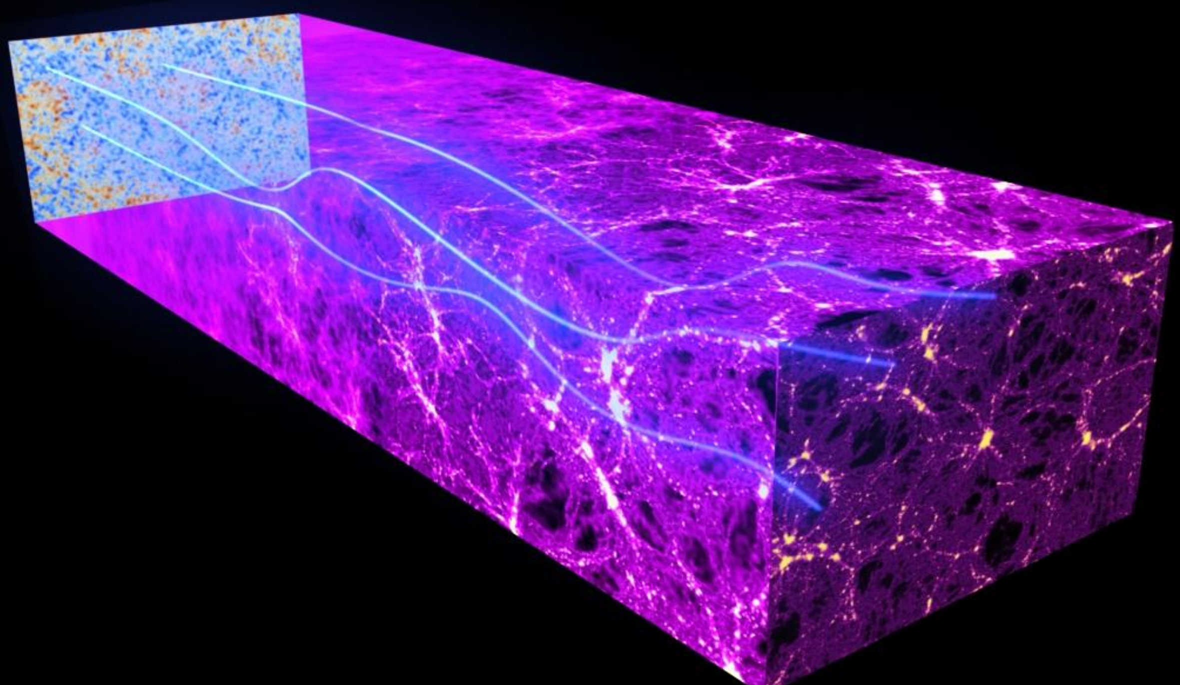
Composition

- The composition of the universe (baryons, dark matter, dark energy) affects the shape of the power spectrum.
- Accurate measurements of the power spectrum allow to constrain the energy densities of the different components of the universe.



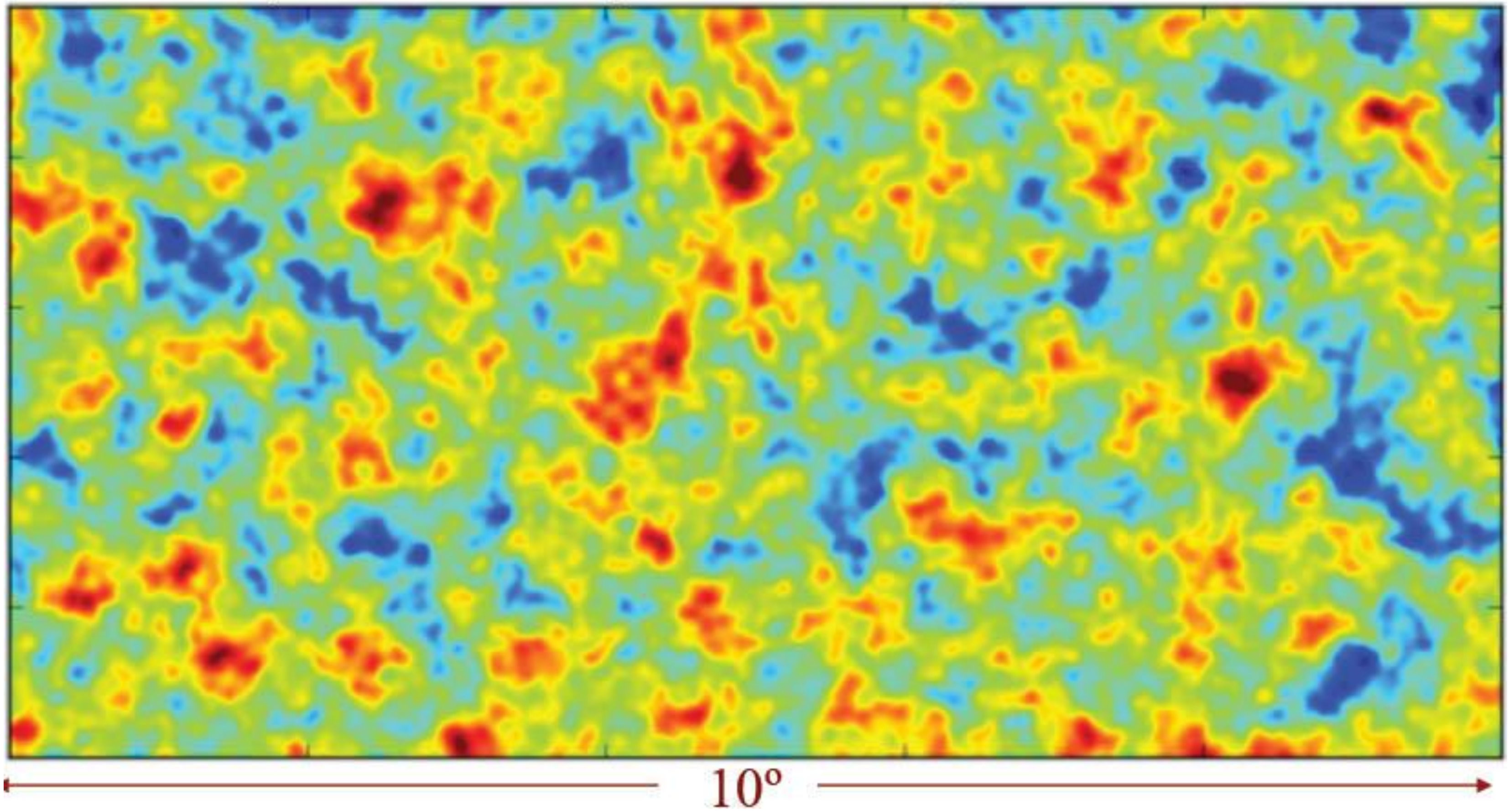
CMB anisotropy (lensing)

- Photons travelling in the universe for 13.7 Gly interact with massive structures, and are deflected (gravitational lensing)
- The result is a modified image of CMB anisotropy, which can be analyzed to study the distribution of mass (mainly dark matter) all the way to recombination.



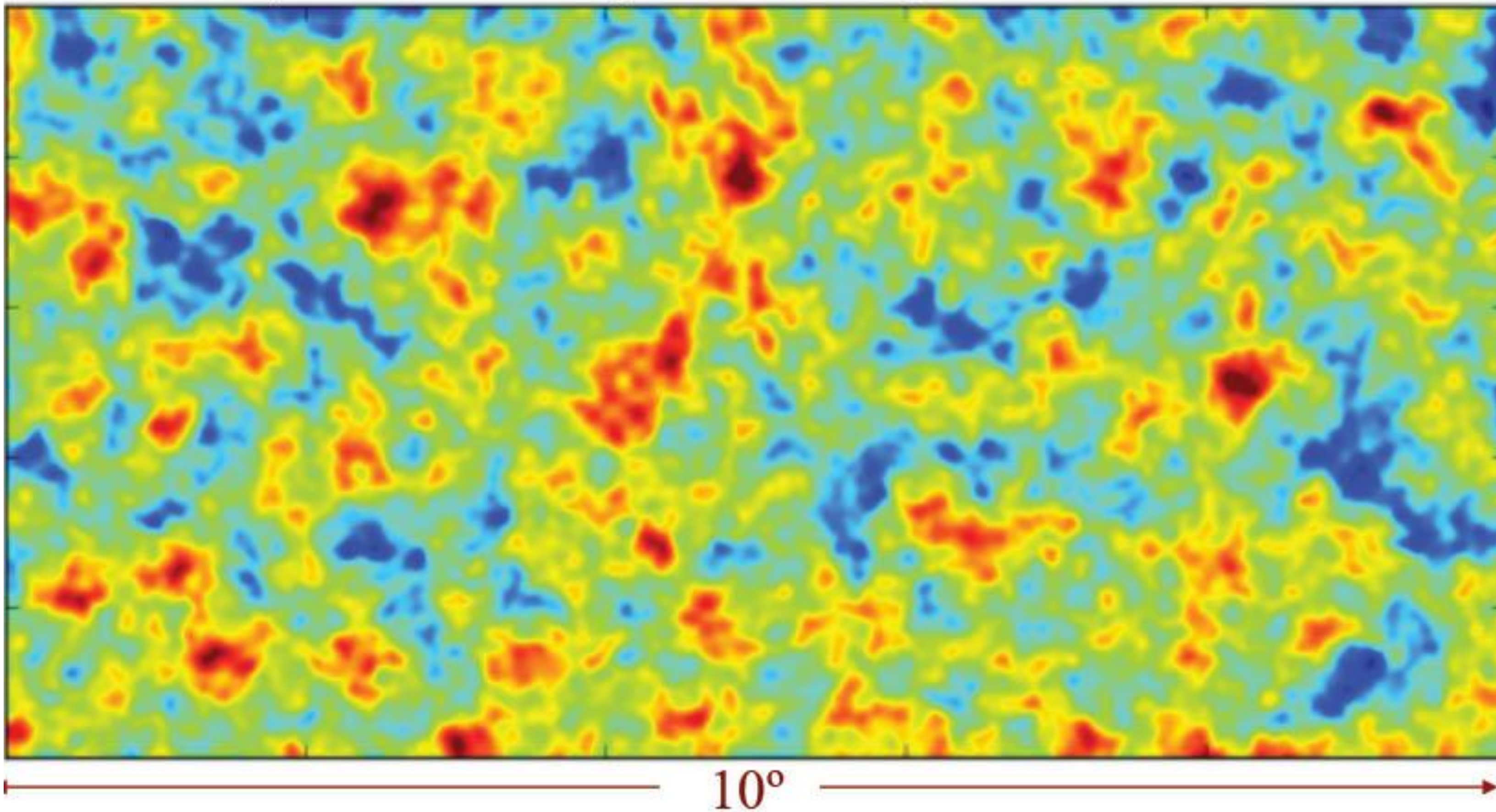
Typical deflection: 2.5′

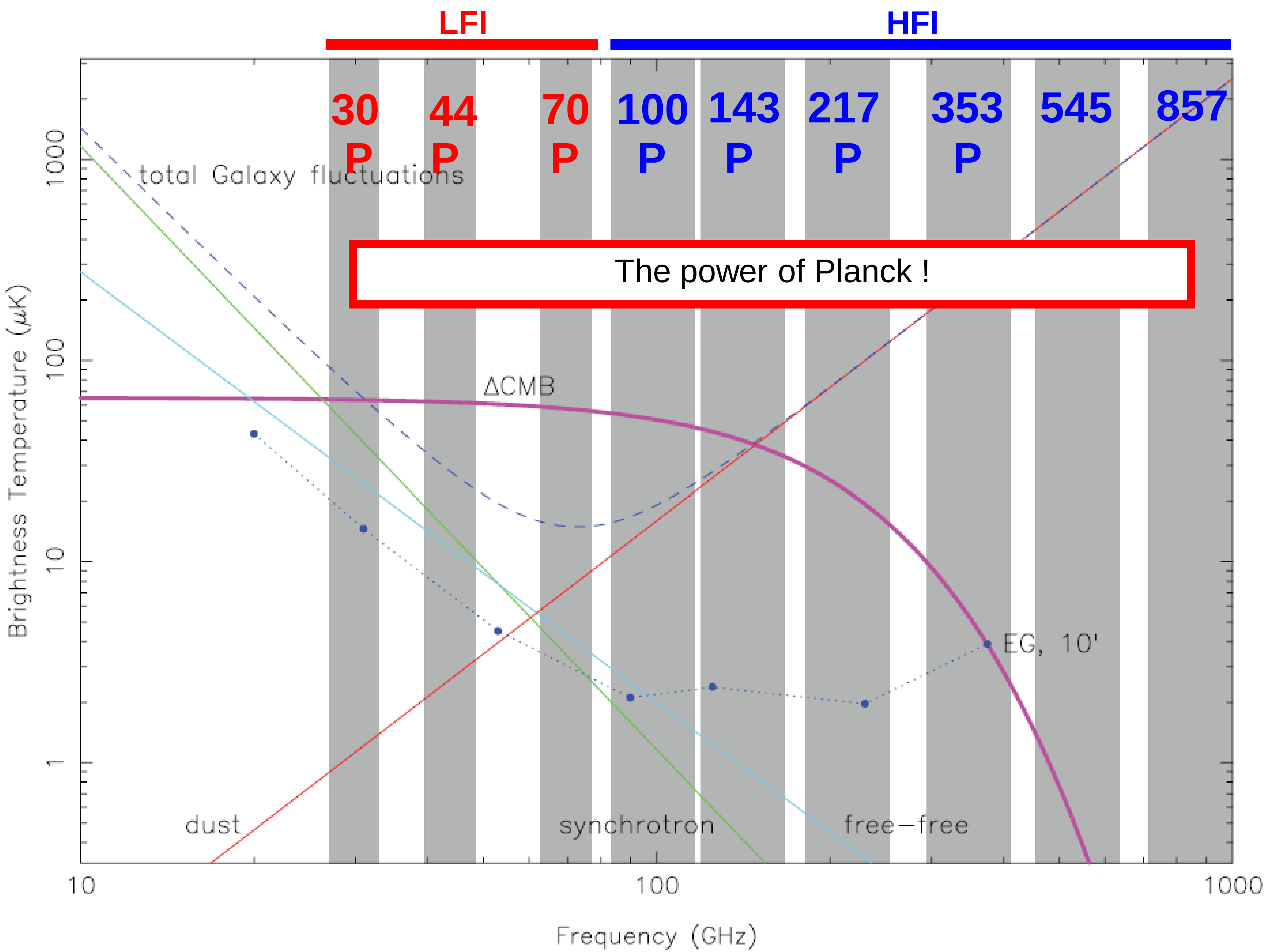
intrinsic CMB anisotropy

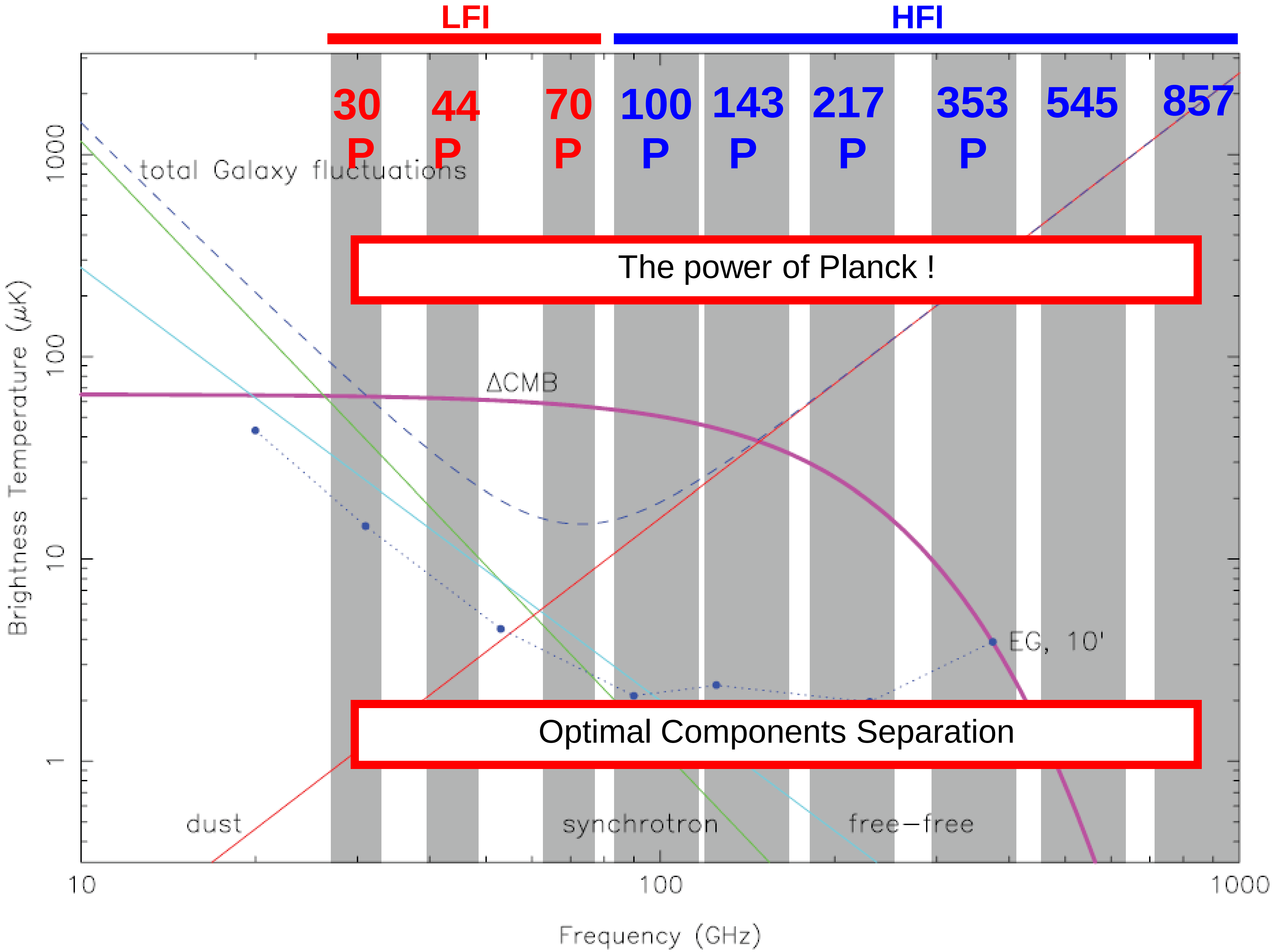


Typical deflection: 2.5′

lensed CMB anisotropy




LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
The power of Planck !
total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
Frequency (GHz)
1000
100
10
1
10
100
1000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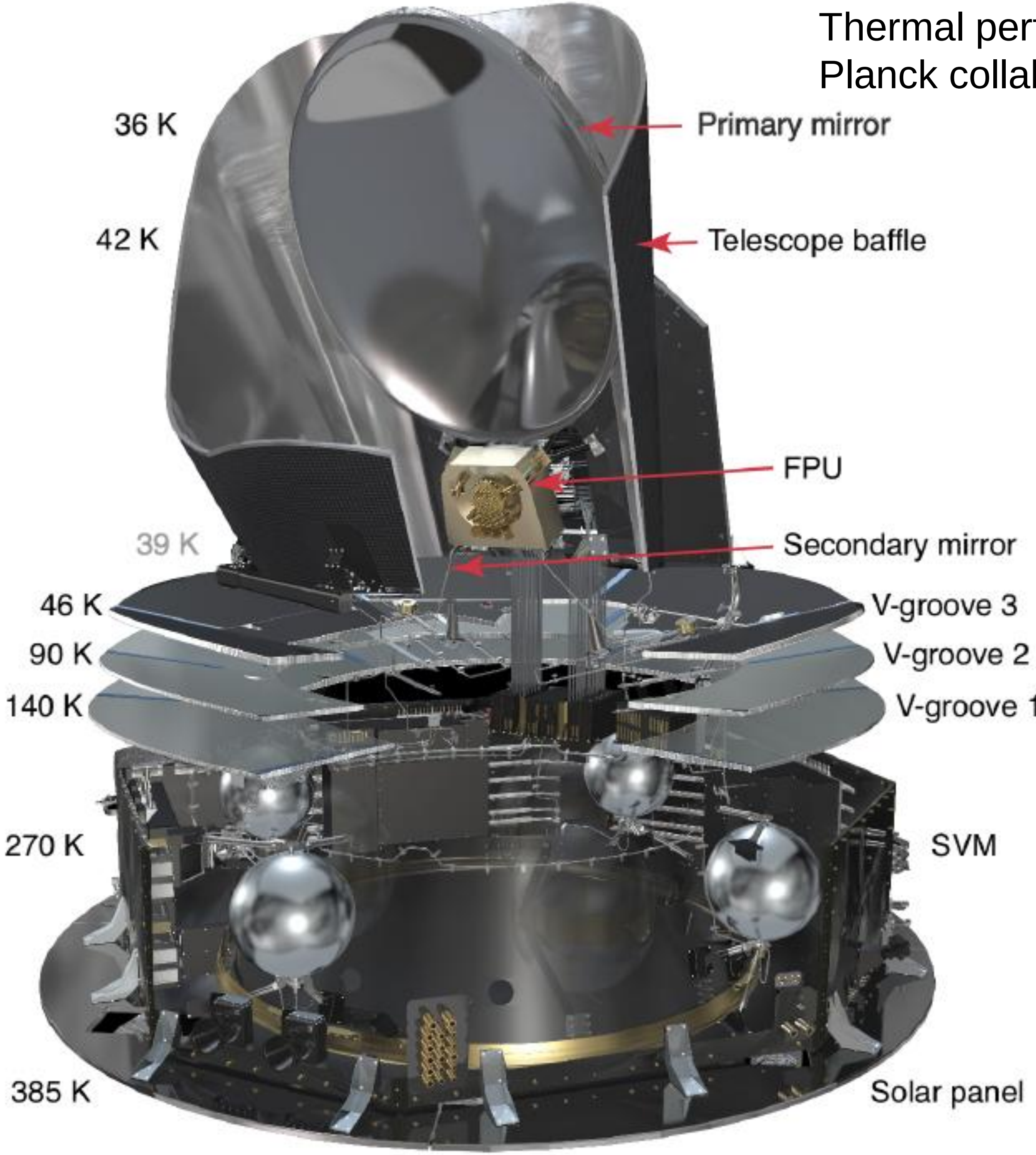
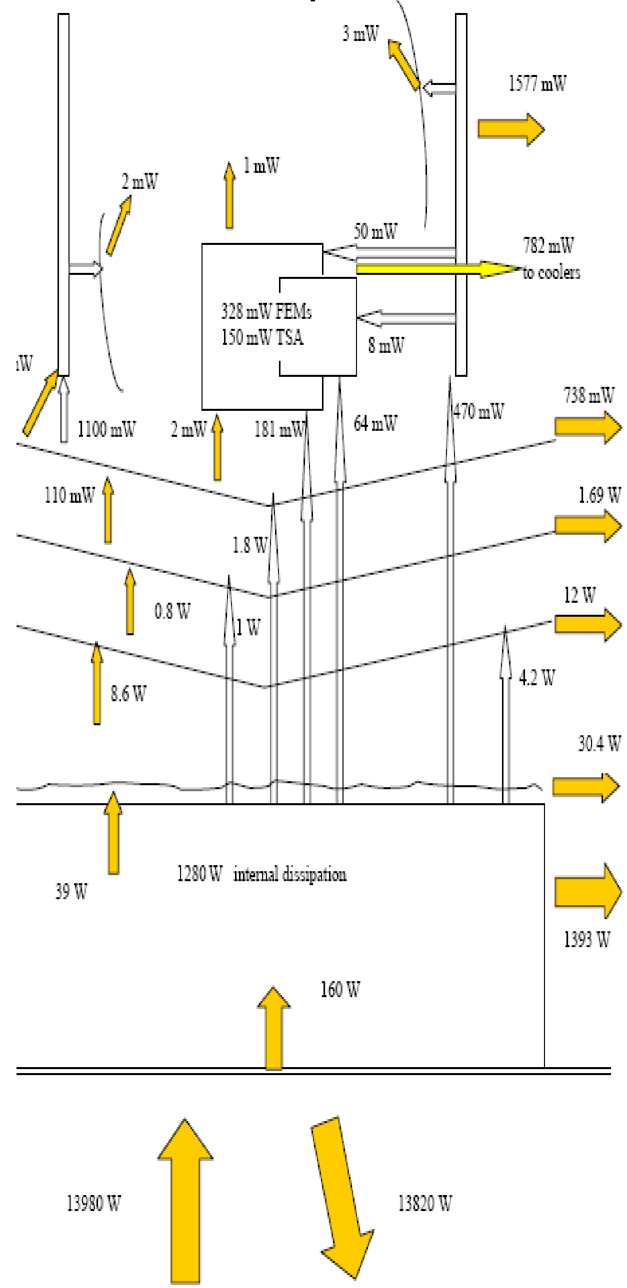
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

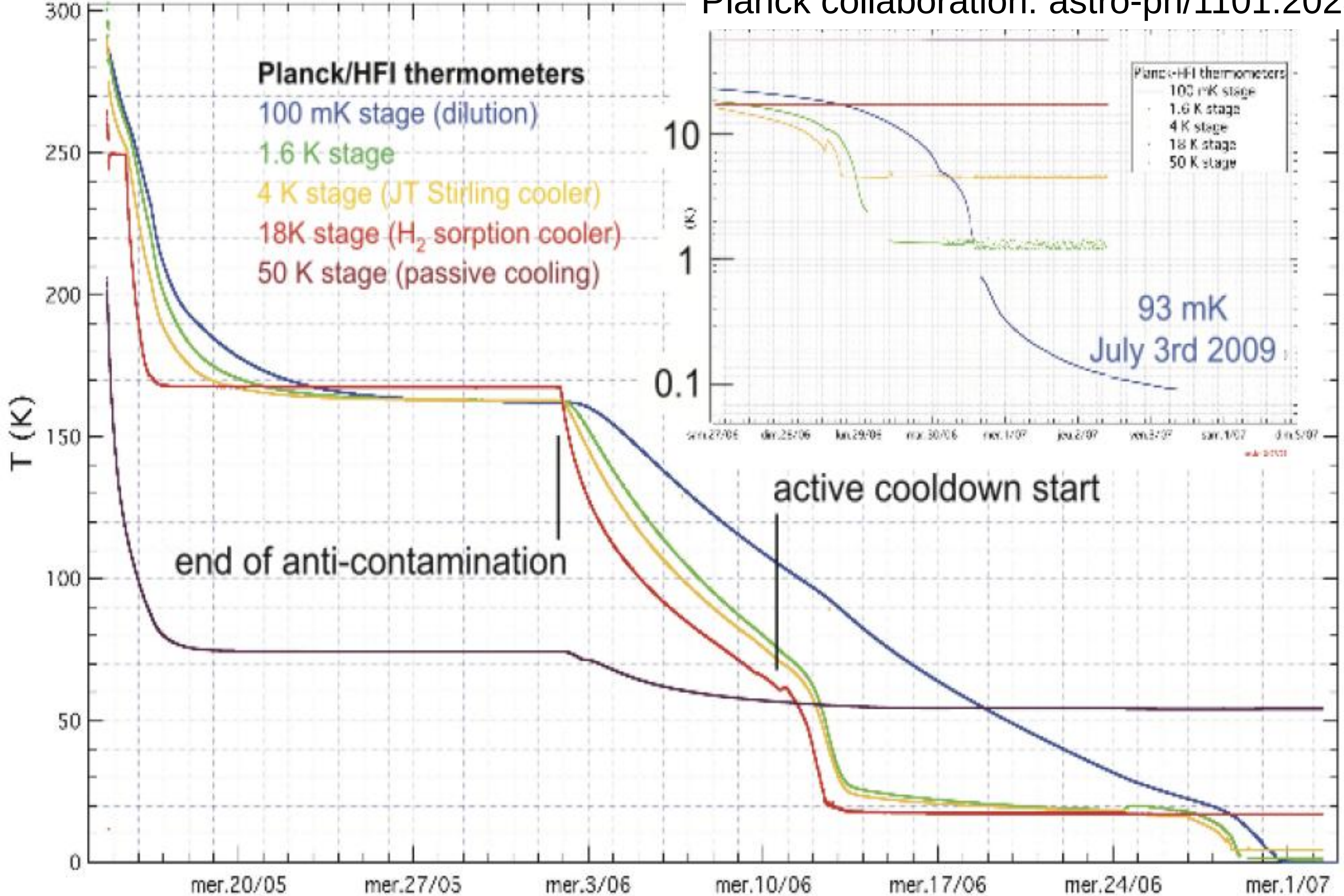
14 / May / 2009

Thermal performance :
Planck collaboration: astro-ph/1101:2023





Thermal performance :
Planck collaboration: astro-ph/1101:2023

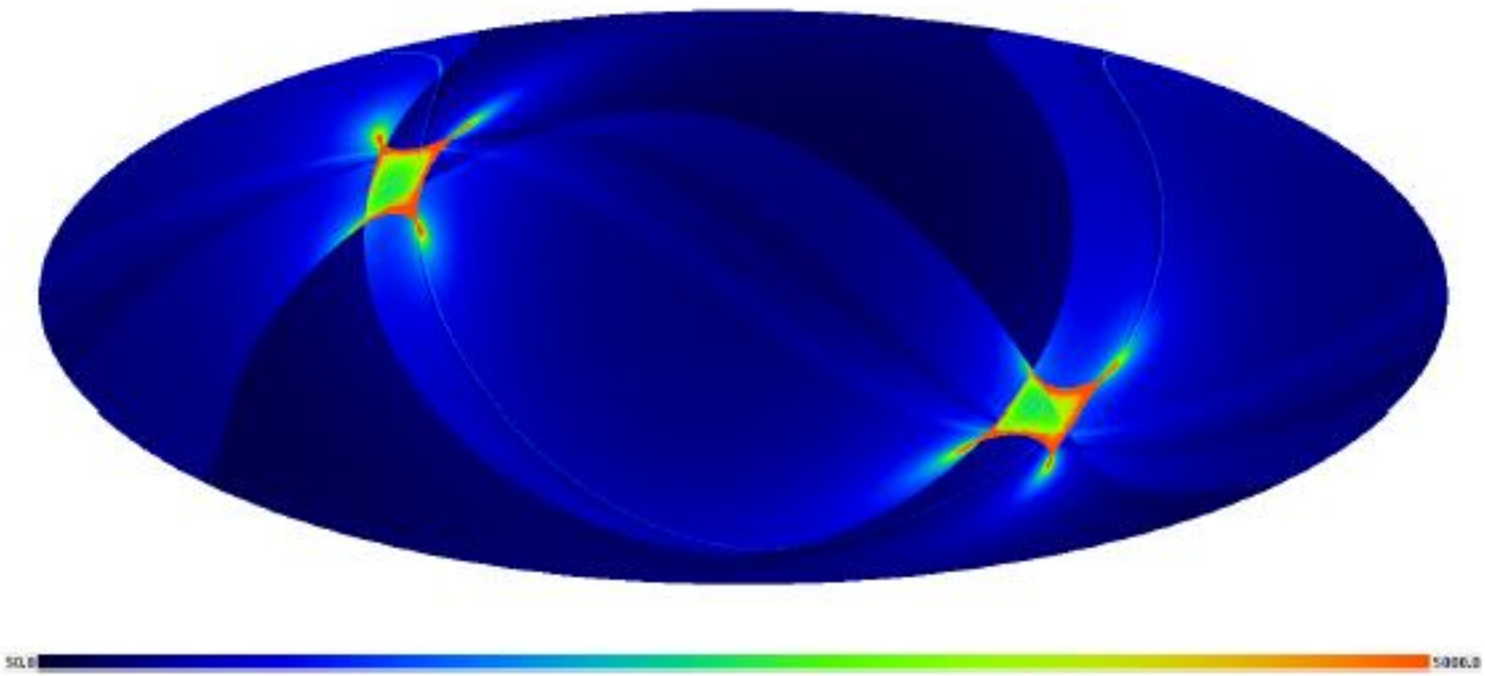


Mission :
Planck collaboration: astro-ph/1101:2022

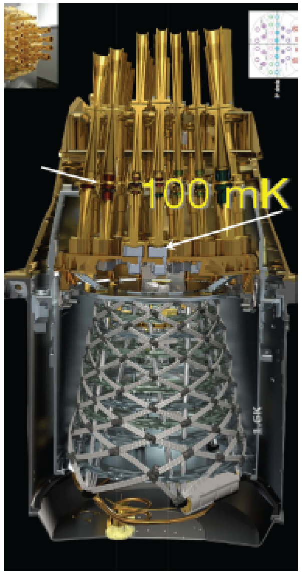
Table 1. *Planck* coverage statistics.

	30 GHz	100 GHz	545 GHz	
Mean[a]	2293	4575	2278	sec deg^2
Minimum	440	801	375	sec deg^2
$<$ half Mean[b]	14.4	14.6	15.2	%
$> 4\times$ Mean[c]	1.6	1.5	1.2	%
$> 9\times$ Mean[d]	0.41	0.42	0.41	%

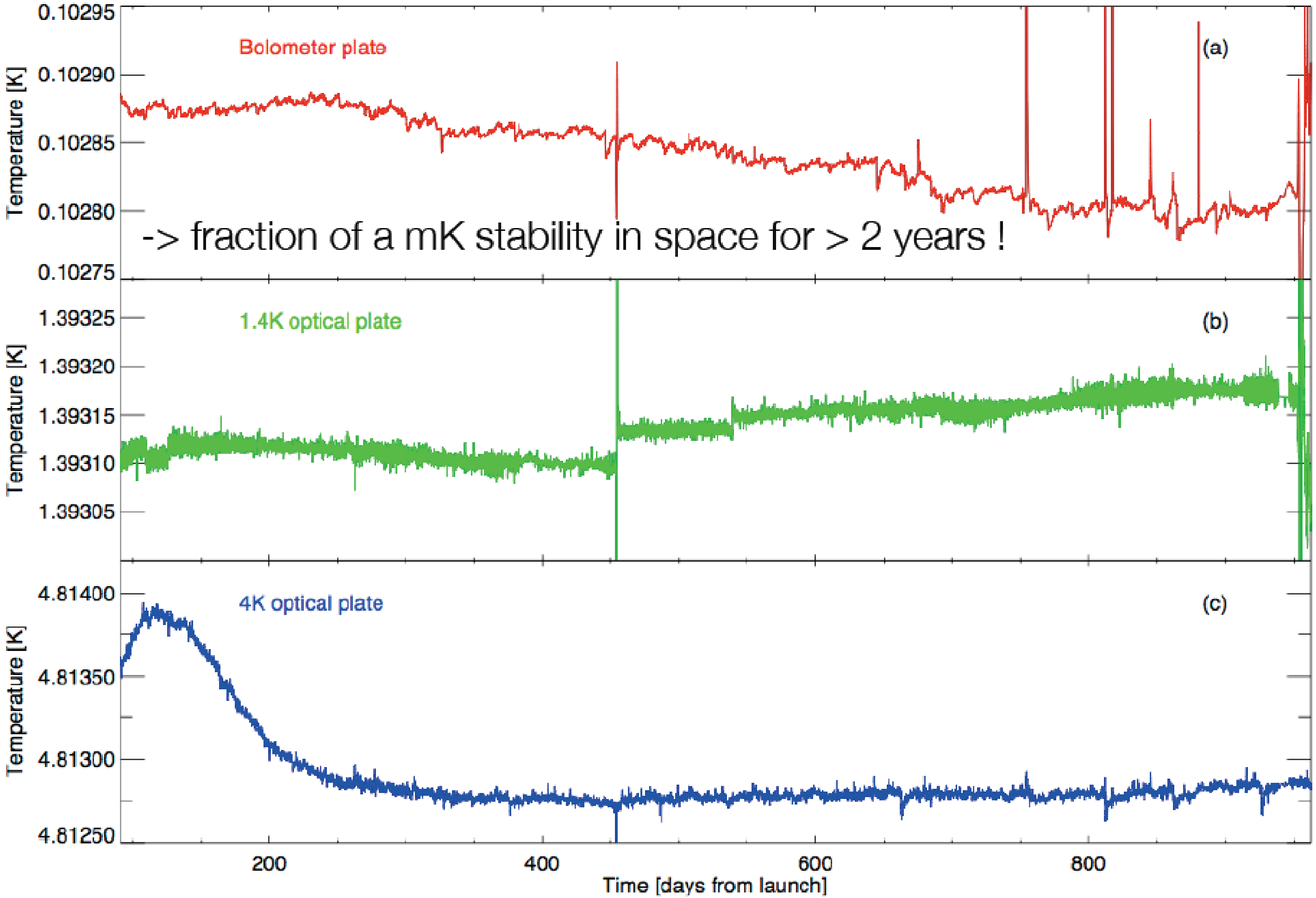
[a] Mean over the whole sky of the integration time cumulated for all detectors (definition as in Table 3) in a given frequency channel.
[b] Fraction of the sky whose coverage is less than half the Mean.
[c] Fraction of the sky whose coverage is larger than four times the Mean.
[d] Fraction of the sky whose coverage is larger than nine times the Mean.



A very **stable** environment



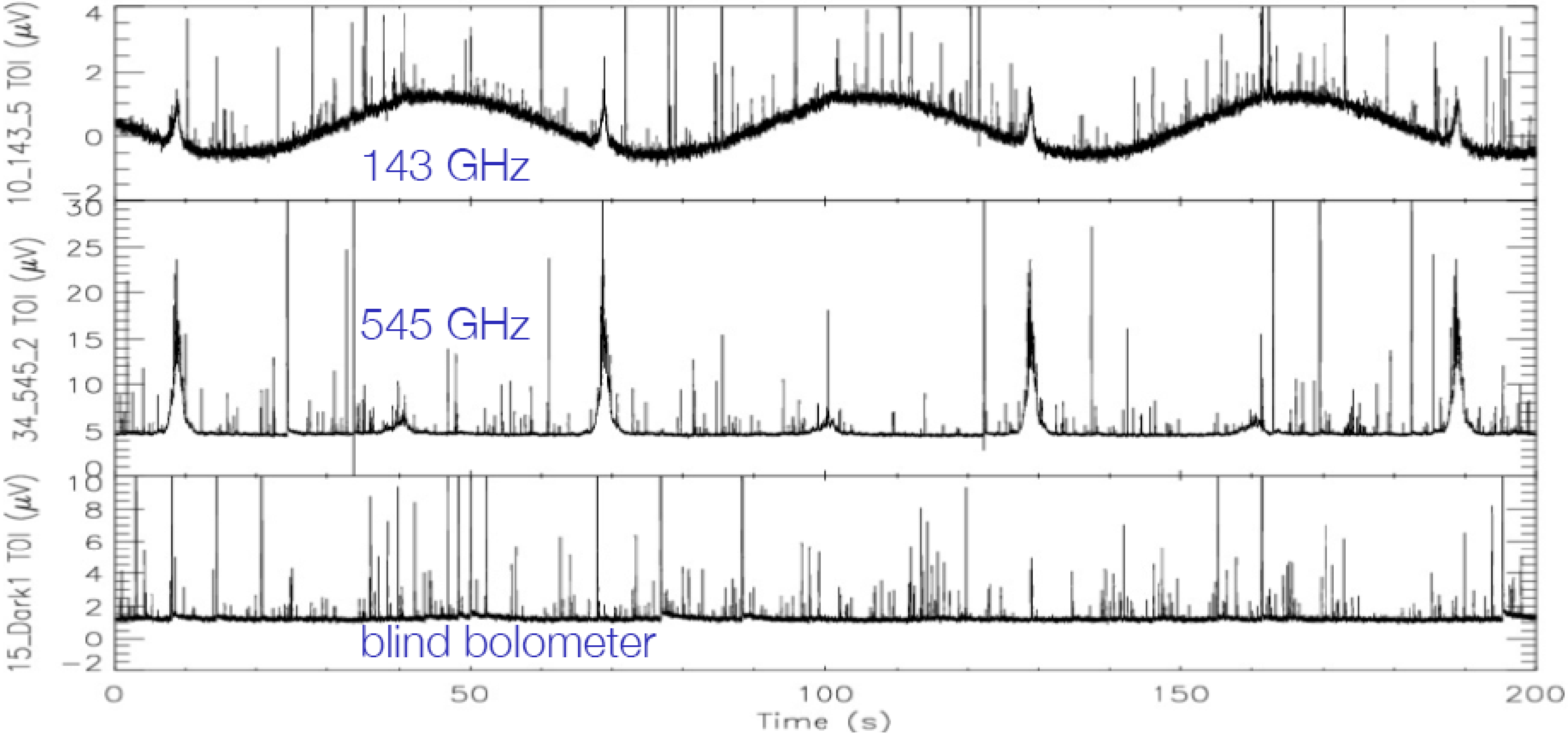
Cryostat:
dilution He3/He4



-> fraction of a mK stability in space for > 2 years !

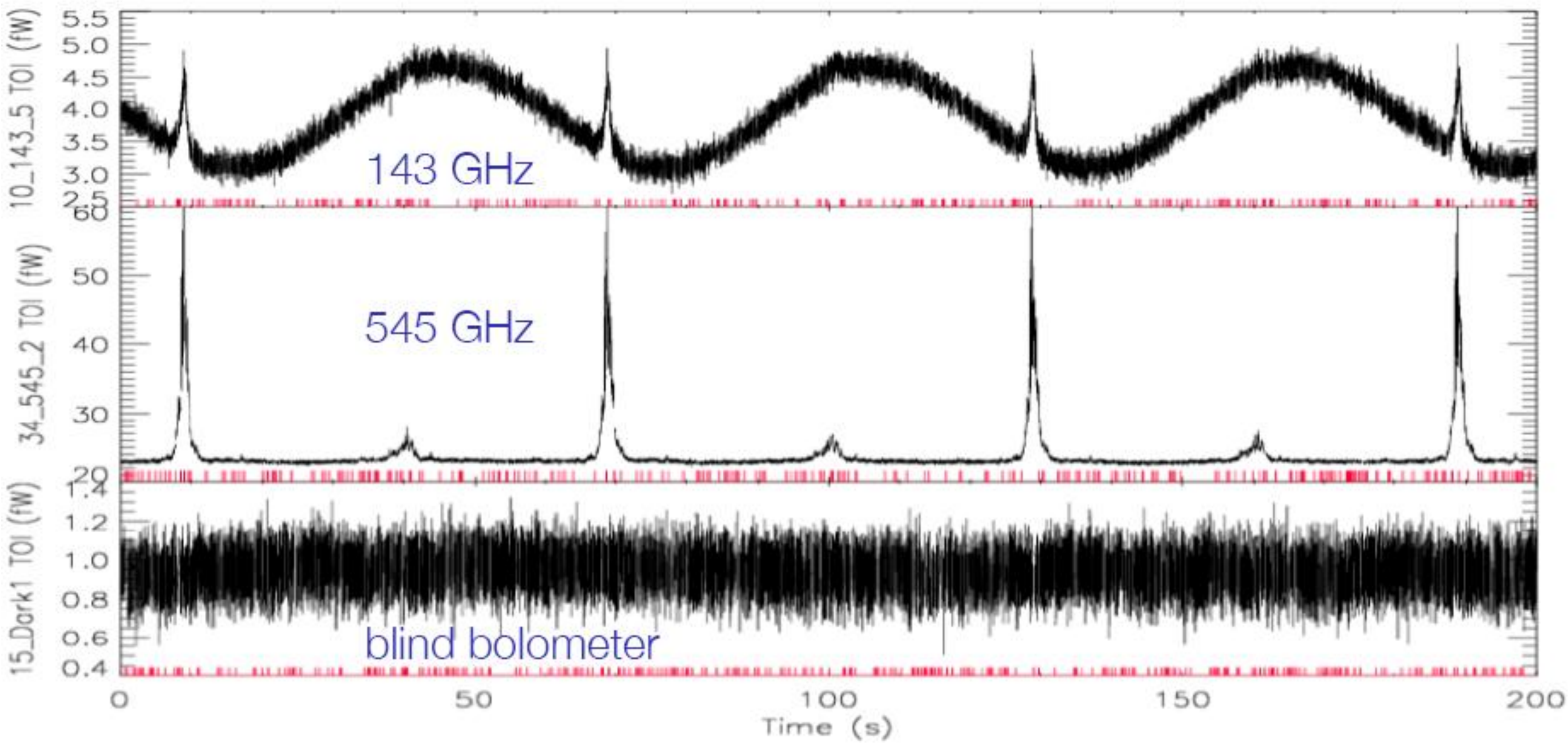
Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal mission.

Raw HFI data



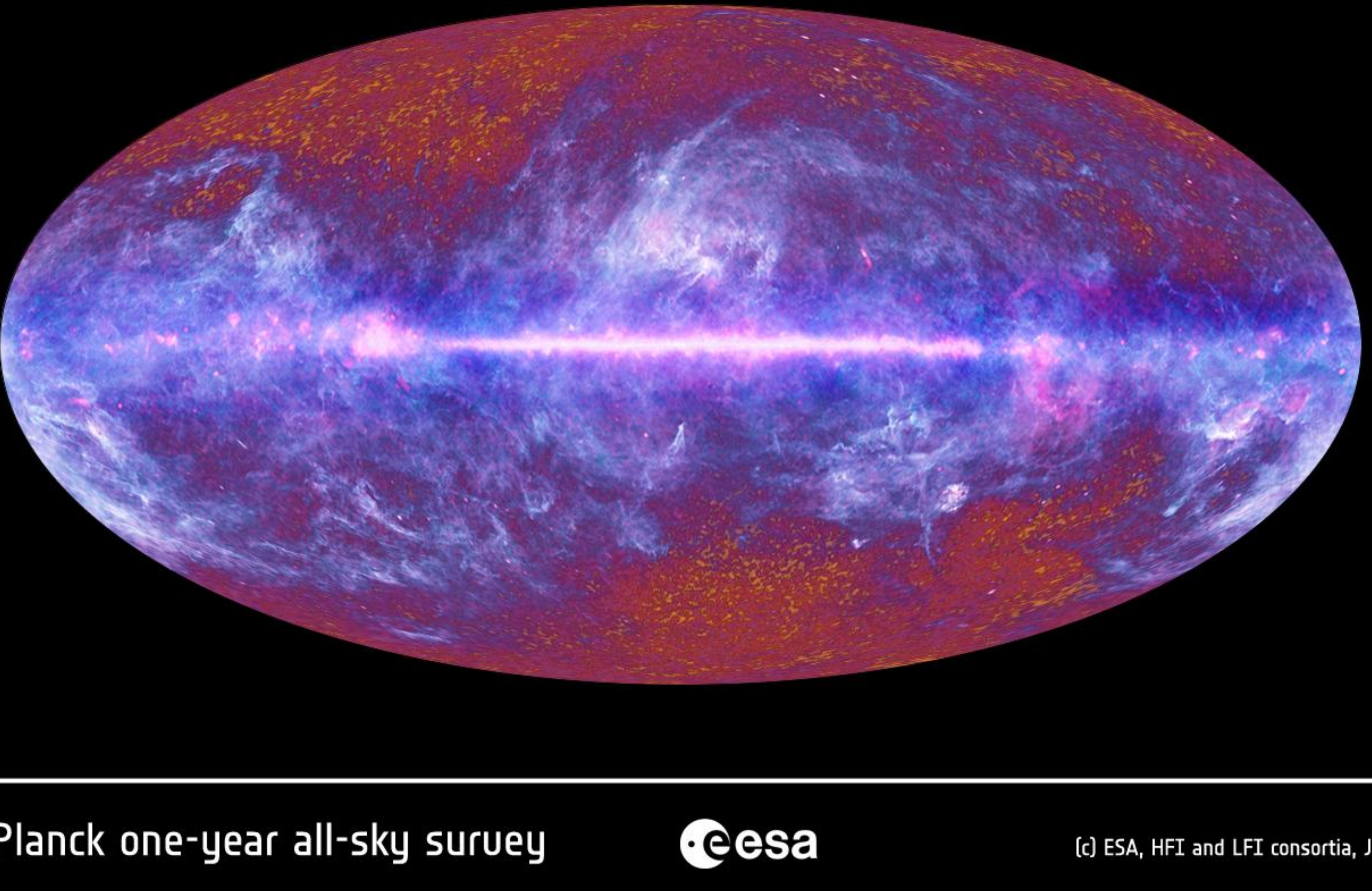
143 GHz
545 GHz
blind bolometer
10_143_5 TOI (μV)
34_545_2 TOI (μV)
15_Dark1 TOI (μV)
Time (s)
0
50
100
150
200

De-spiked HFI data



<20% of data flagged

2011 data release



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- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
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- Planck 2013 results. IX. HFI spectral response
- Planck 2013 results. X. HFI energetic particle effects
- Planck 2013 results. XI. Consistency of the data
- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
- Planck 2013 results. XIV. Zodiacal emission
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Components separation

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Power Spectra, cosmological parameters

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- Planck 2013 results. XVI. Cosmological parameters

Photon propagation effects

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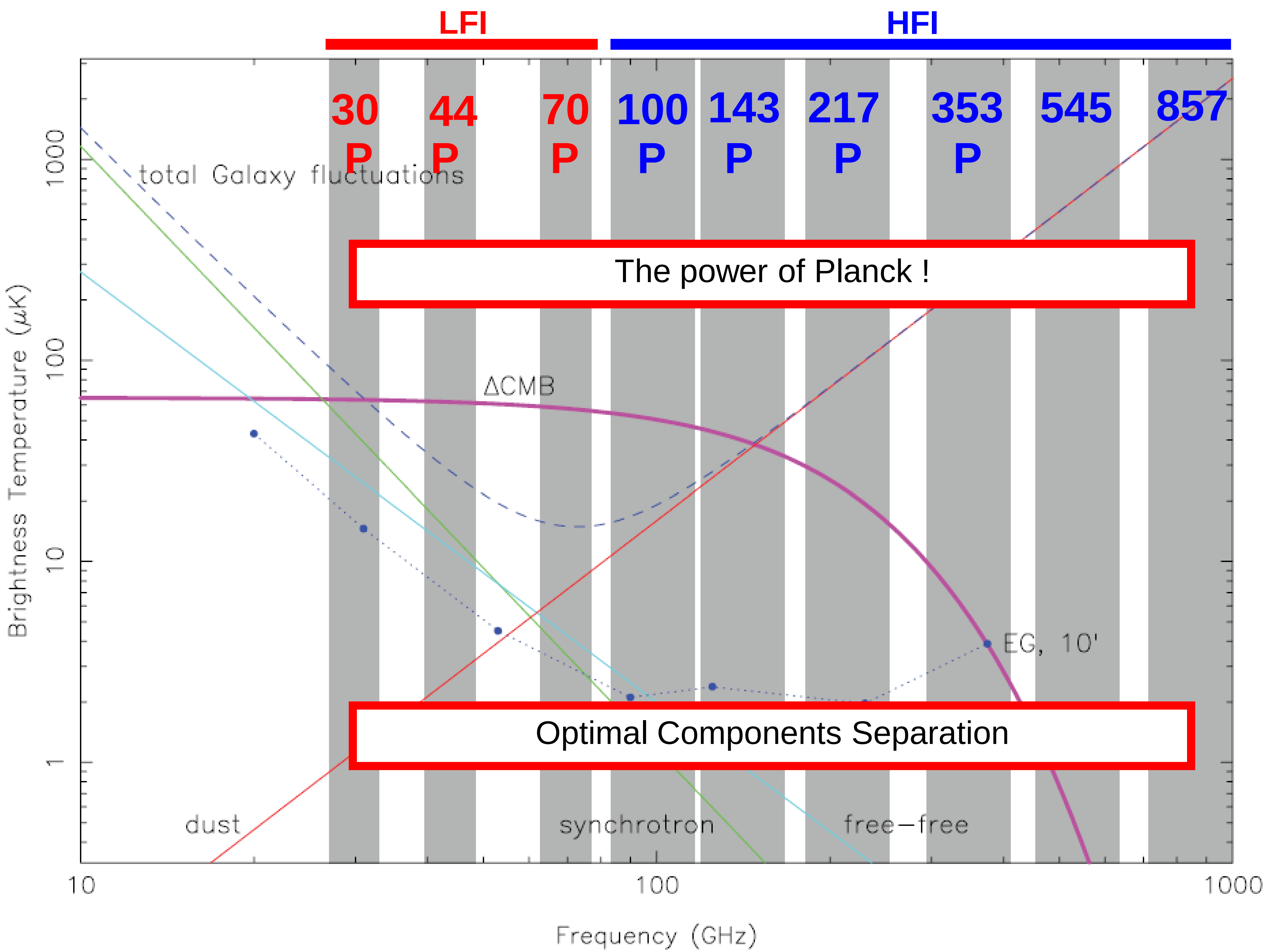
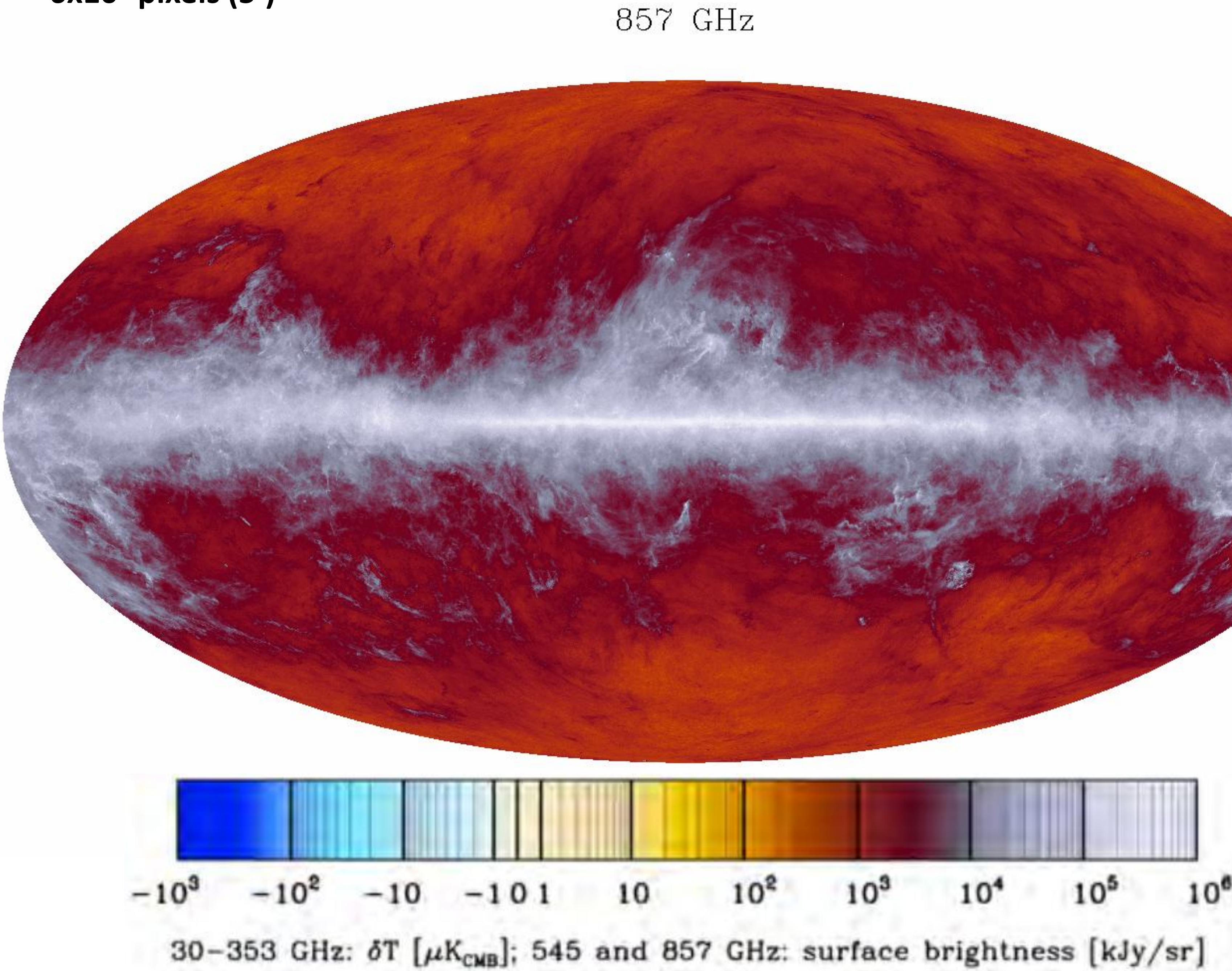

LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
total Galaxy fluctuations
The power of Planck !
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

6x10^6 pixels (5')

Planck Legacy Maps



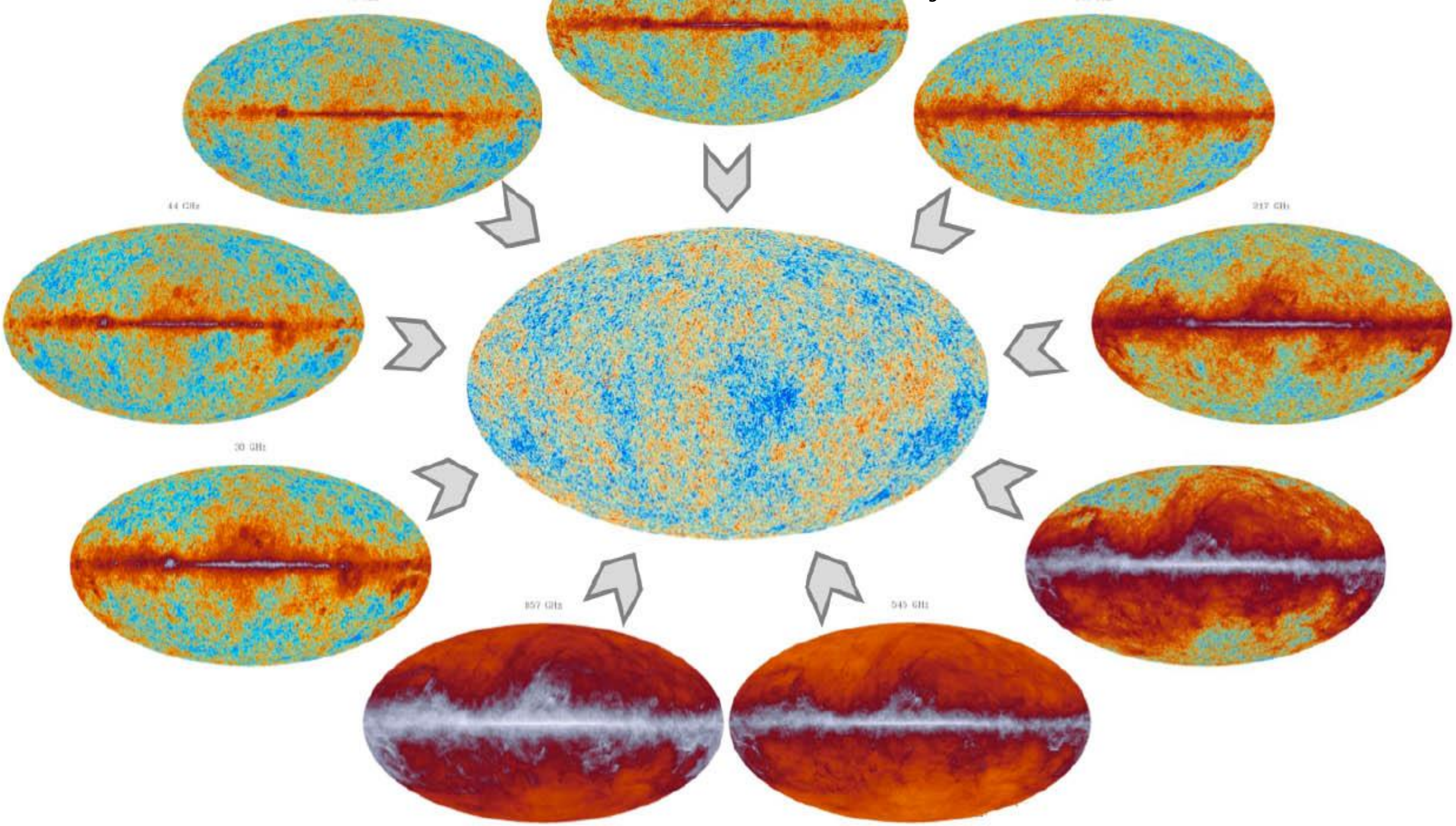
components separation

$$\Delta T(\nu_j, \ell, b) = \sum_k a_k(\nu_j, \ell, b) C_k(\ell, b)$$

Measured maps — physical components

k = CMB,dust,synchrotron,…

j = 33, 44, 70, 100, 143, 217, 353, 545, 857 GHz



The CMB component