Microcosmo e Macrocosmo

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Lezioni della Cattedra Fermi

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Dipartimento di Fisica

Sapienza Università di Roma

Friedman's equation

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

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

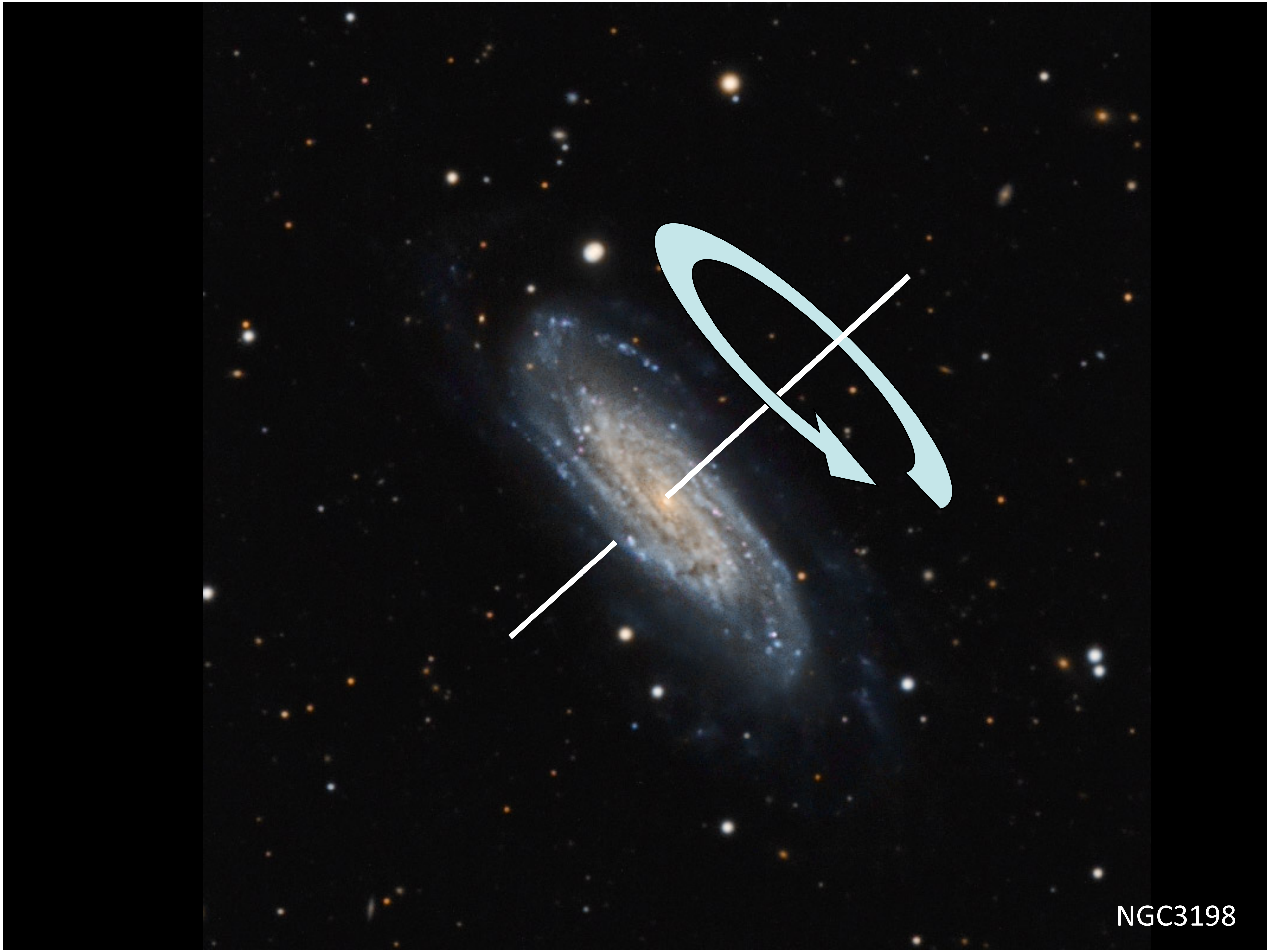
- The solution *a(t)* tells us how all the distances in the universe evolve with time (i.e. how the universe expands).
- To find the solution, we need to find empirically the mass energy densities ρ_{Ro} , ρ_{Mo} , ρ_Λ and from them the parameters Ω_{Ro} , Ω_{Mo} , Ω_Λ

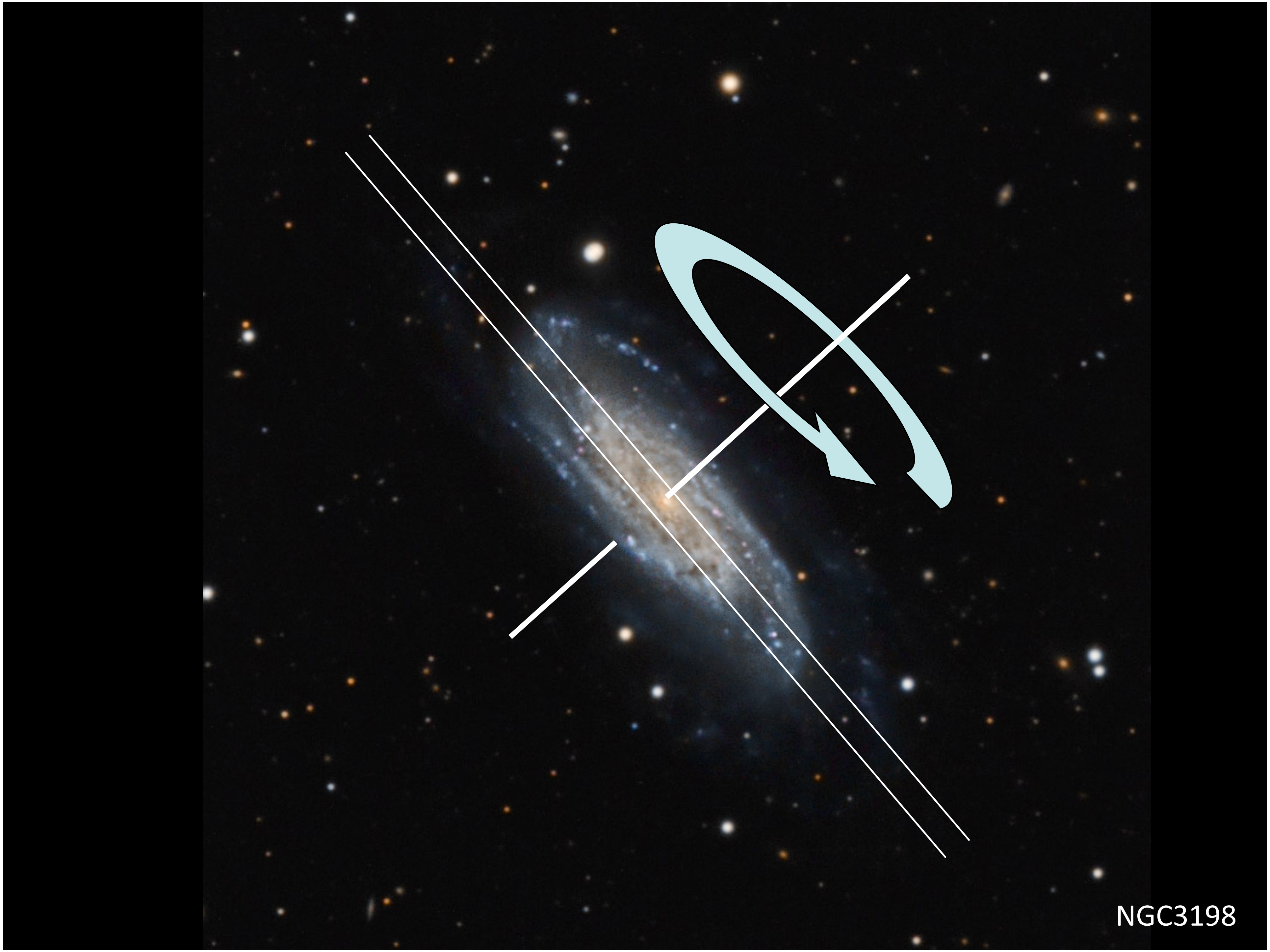
Dark Matter

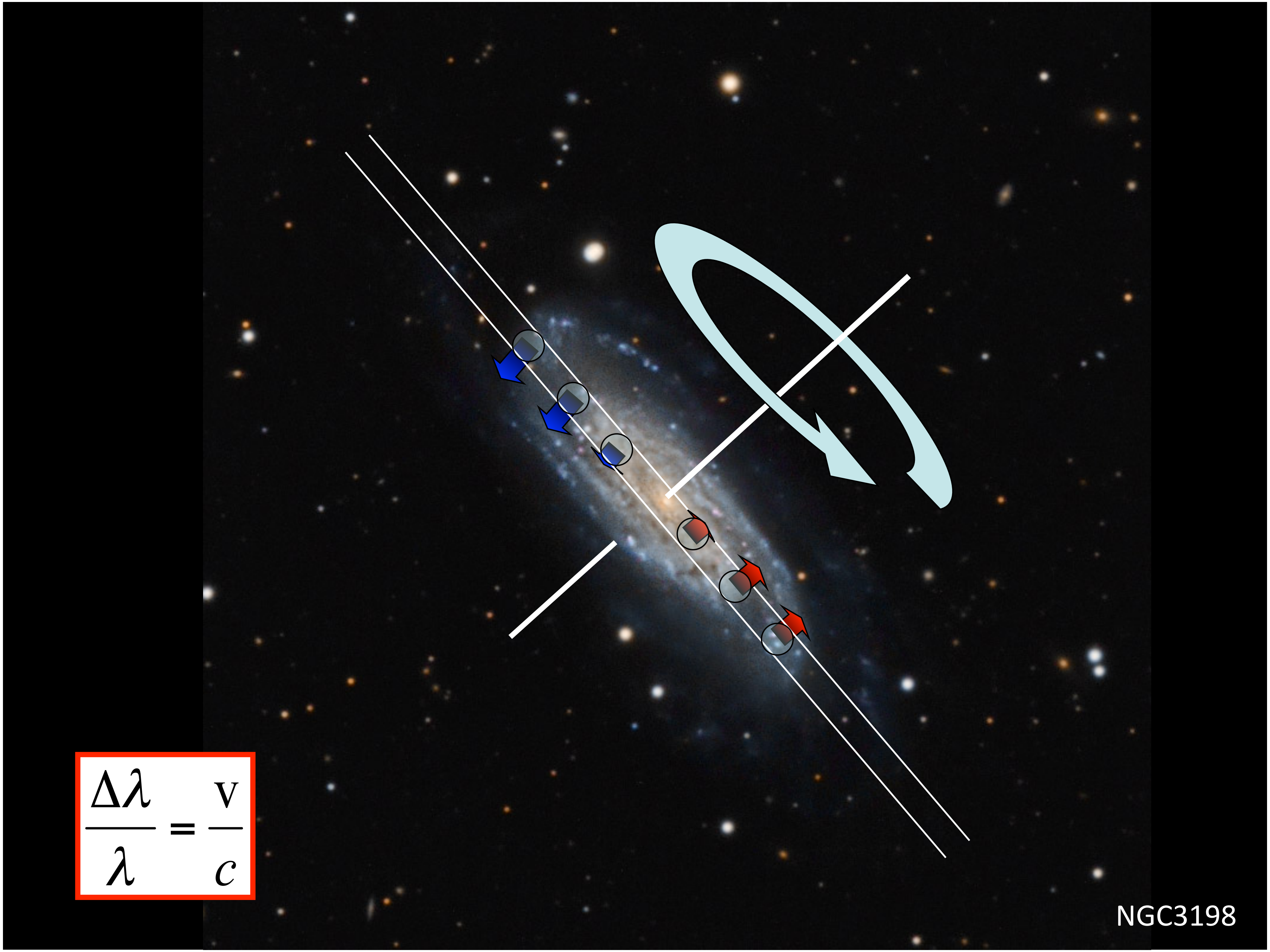
- Dark matter does not interact electromagnetically.
- We can measure it only through its gravitational interaction, which is much weaker than electromagnetic.
- The dynamics of stars in galaxies and of galaxies in clusters of galaxies cannot be explained without the presence of dark matter
- Additional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

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

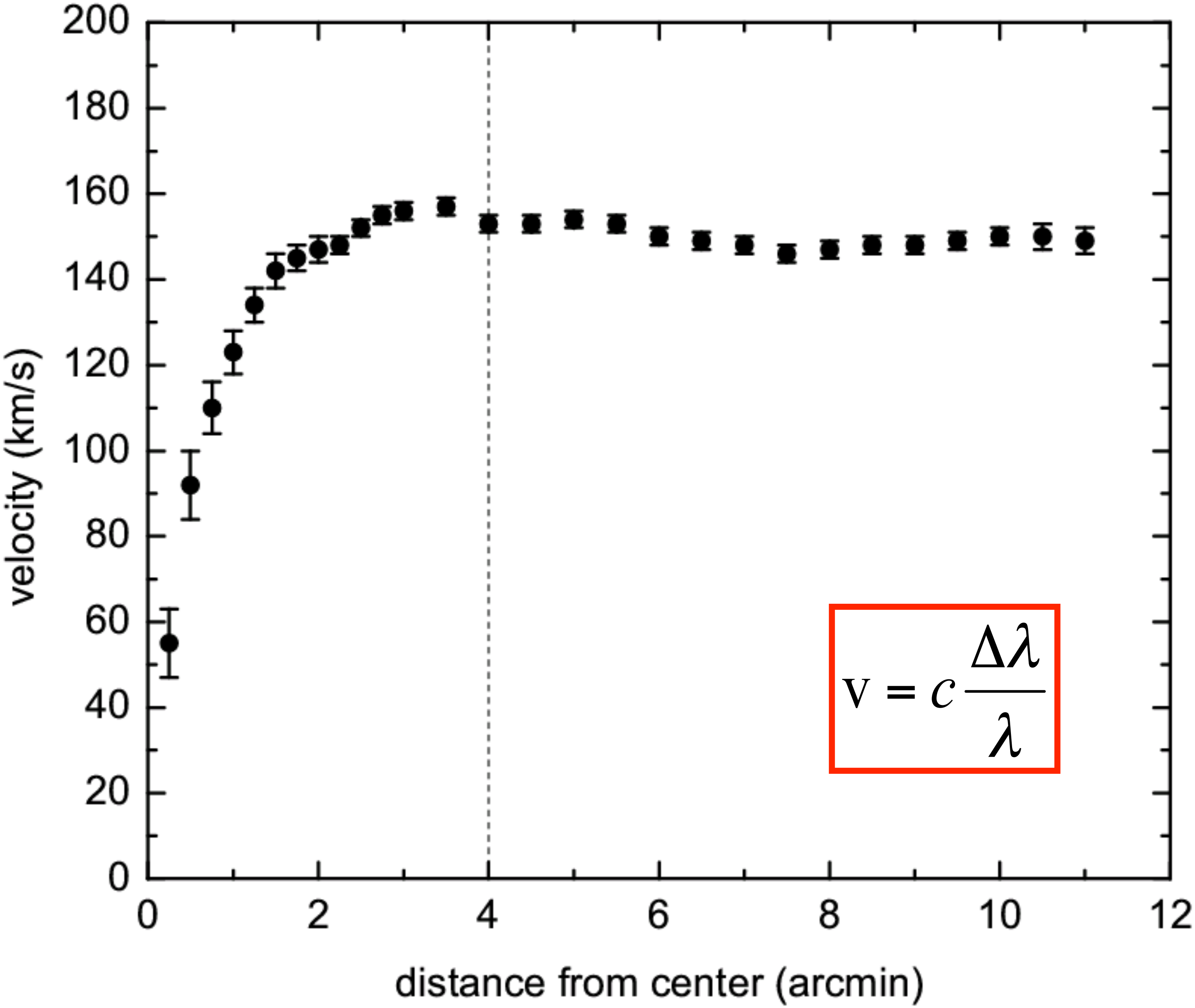

NGC3198


NGC3198

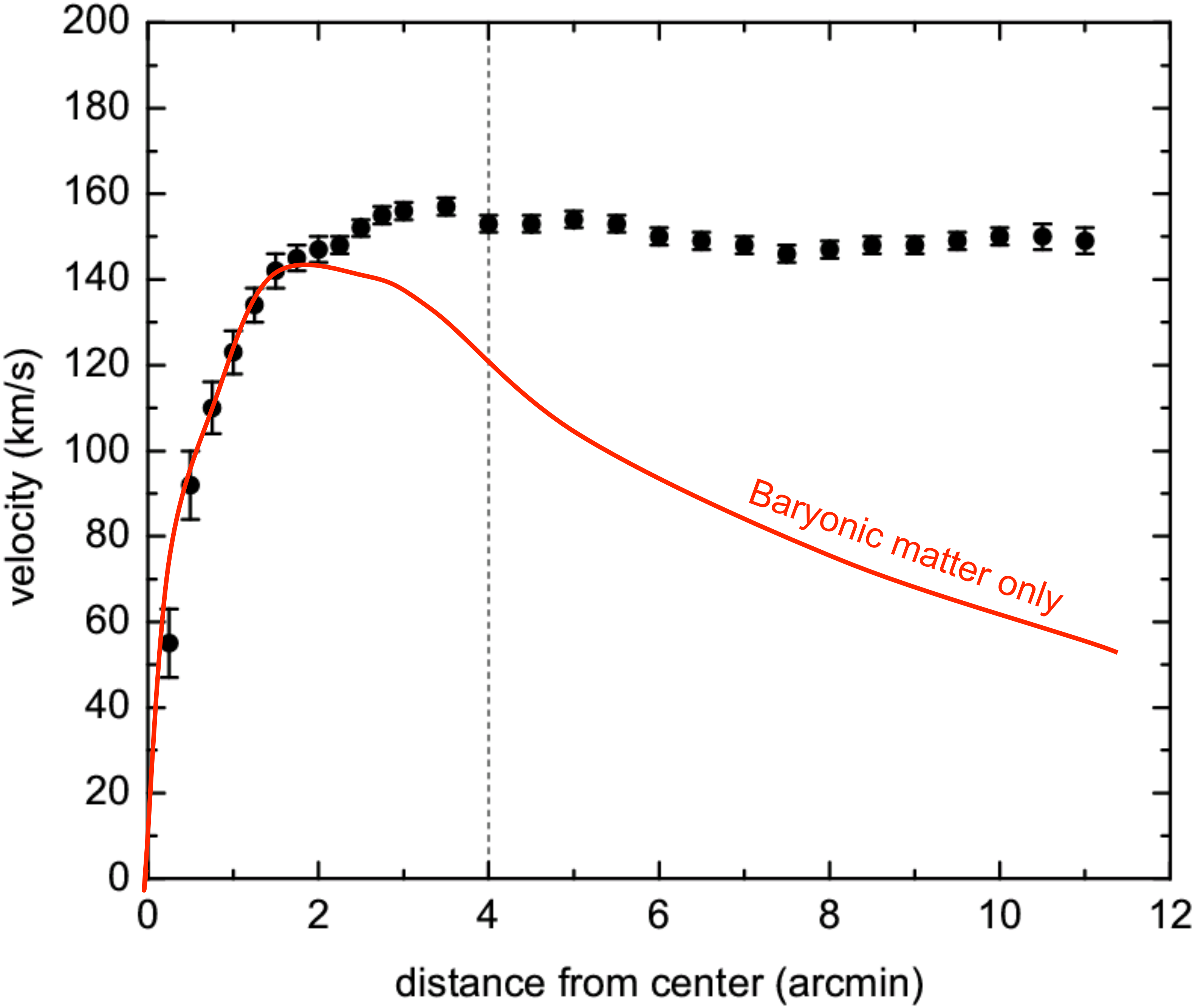

NGC3198



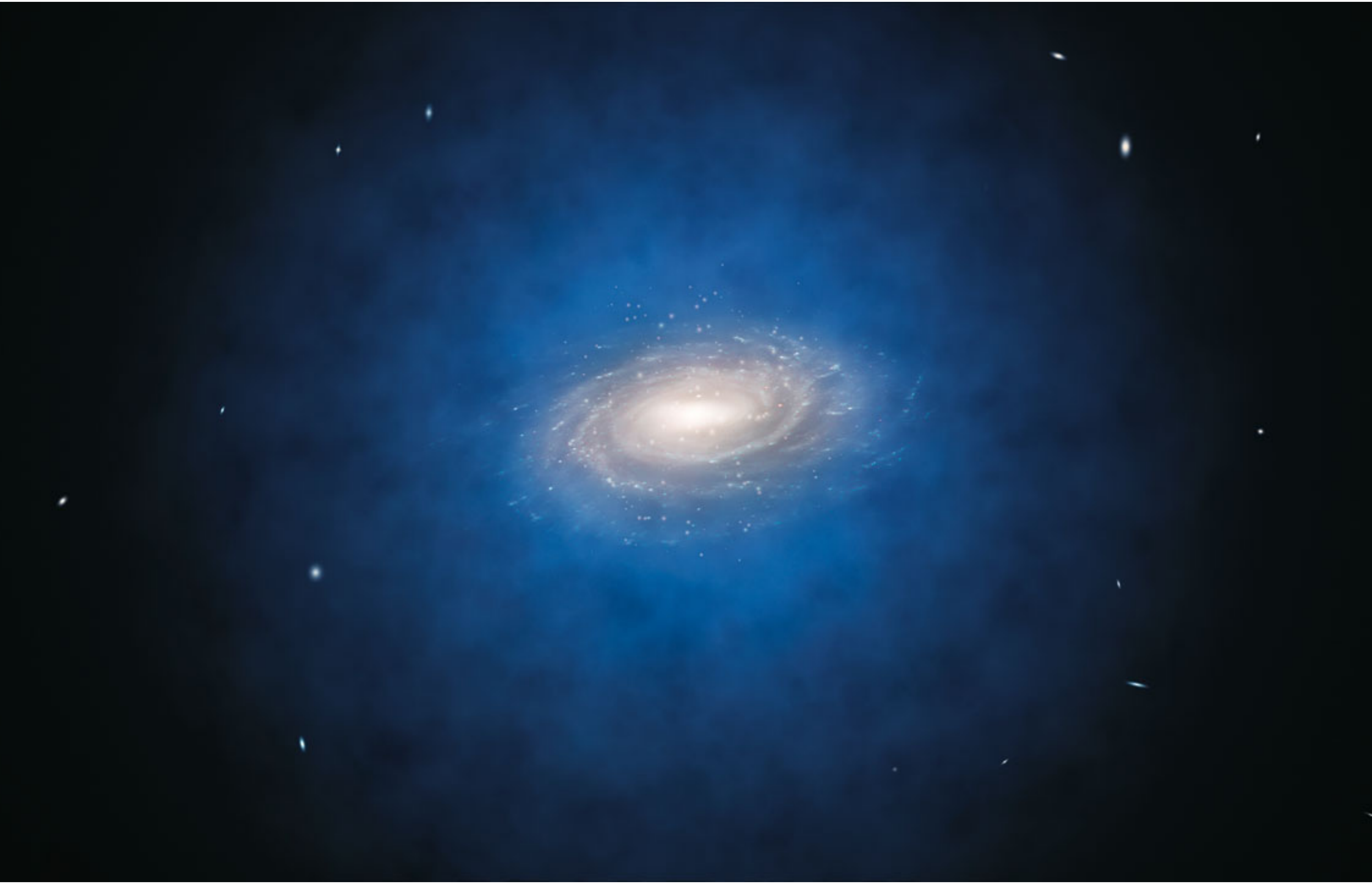
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$



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

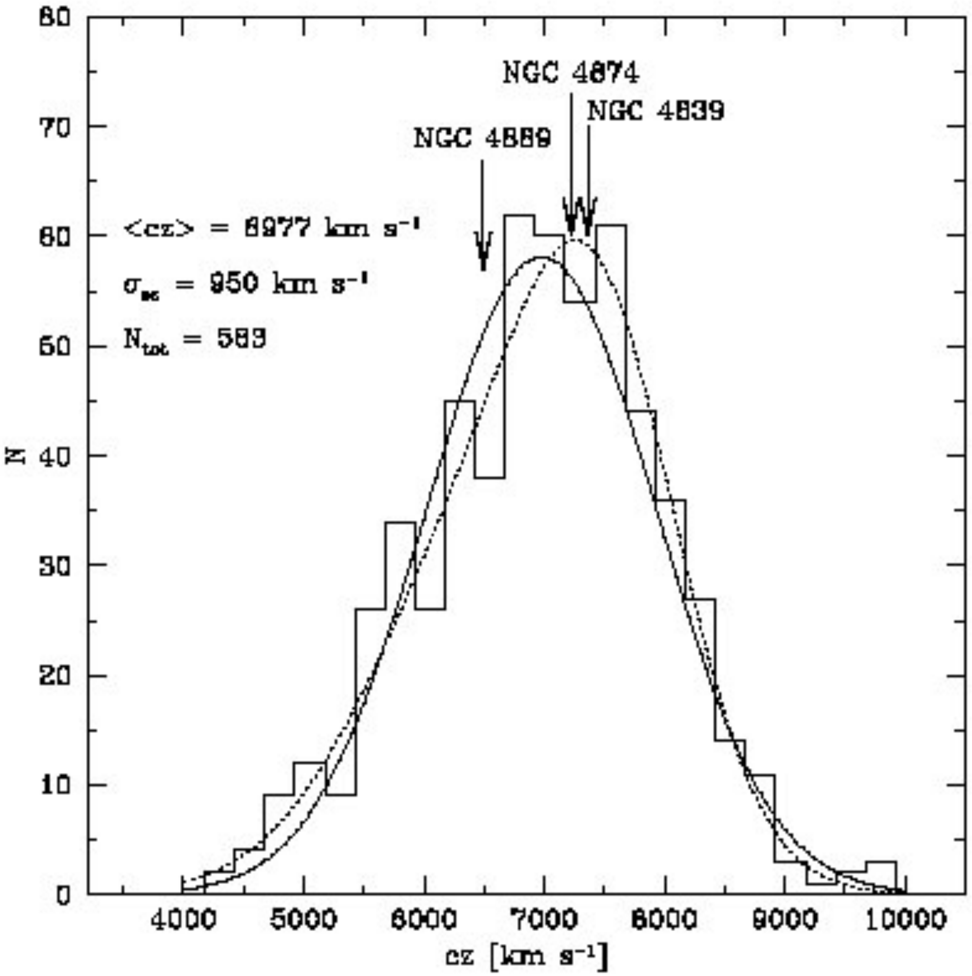


velocity (km/s)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
distance from center (arcmin)
Baryonic matter only



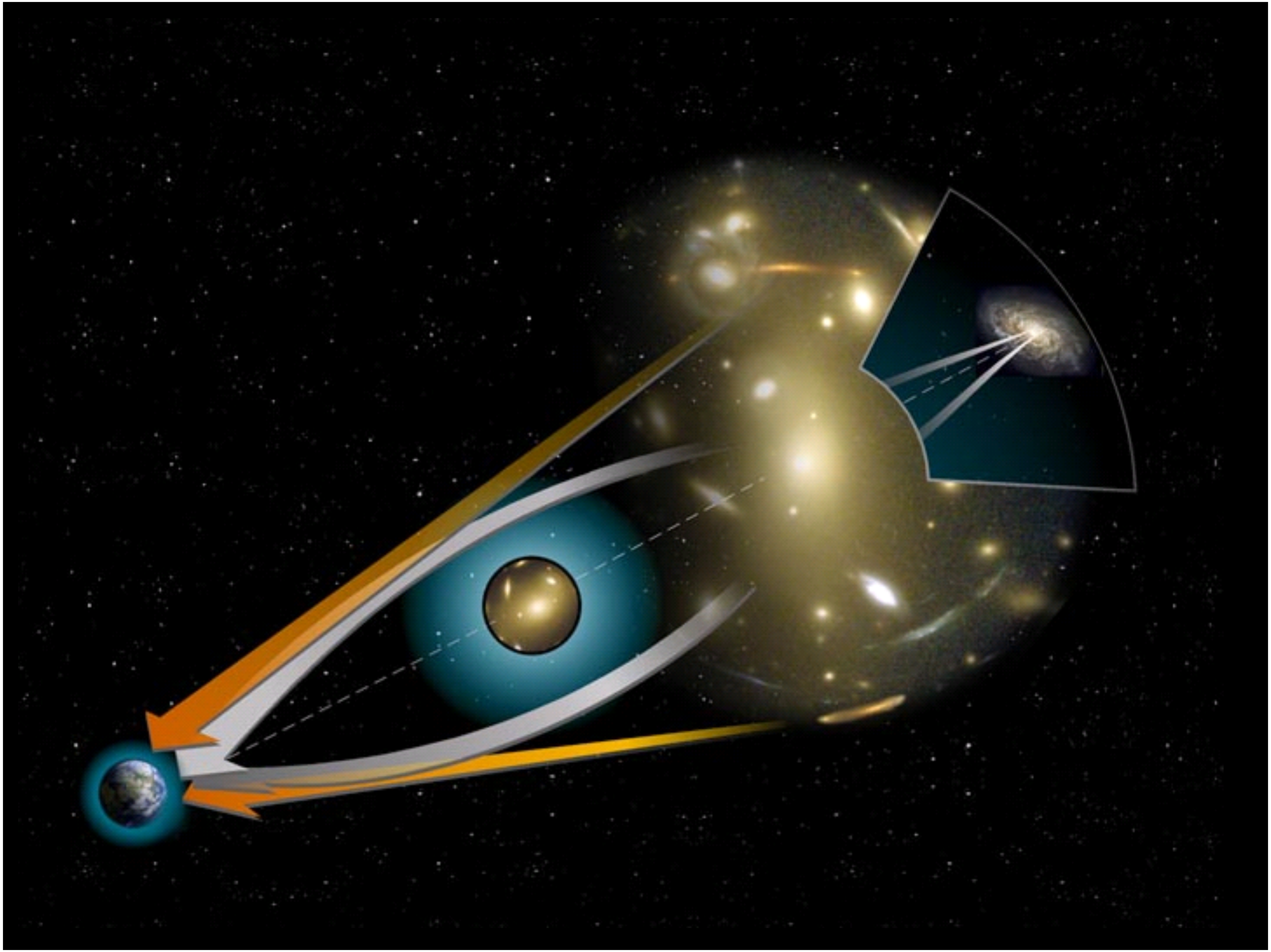

Coma

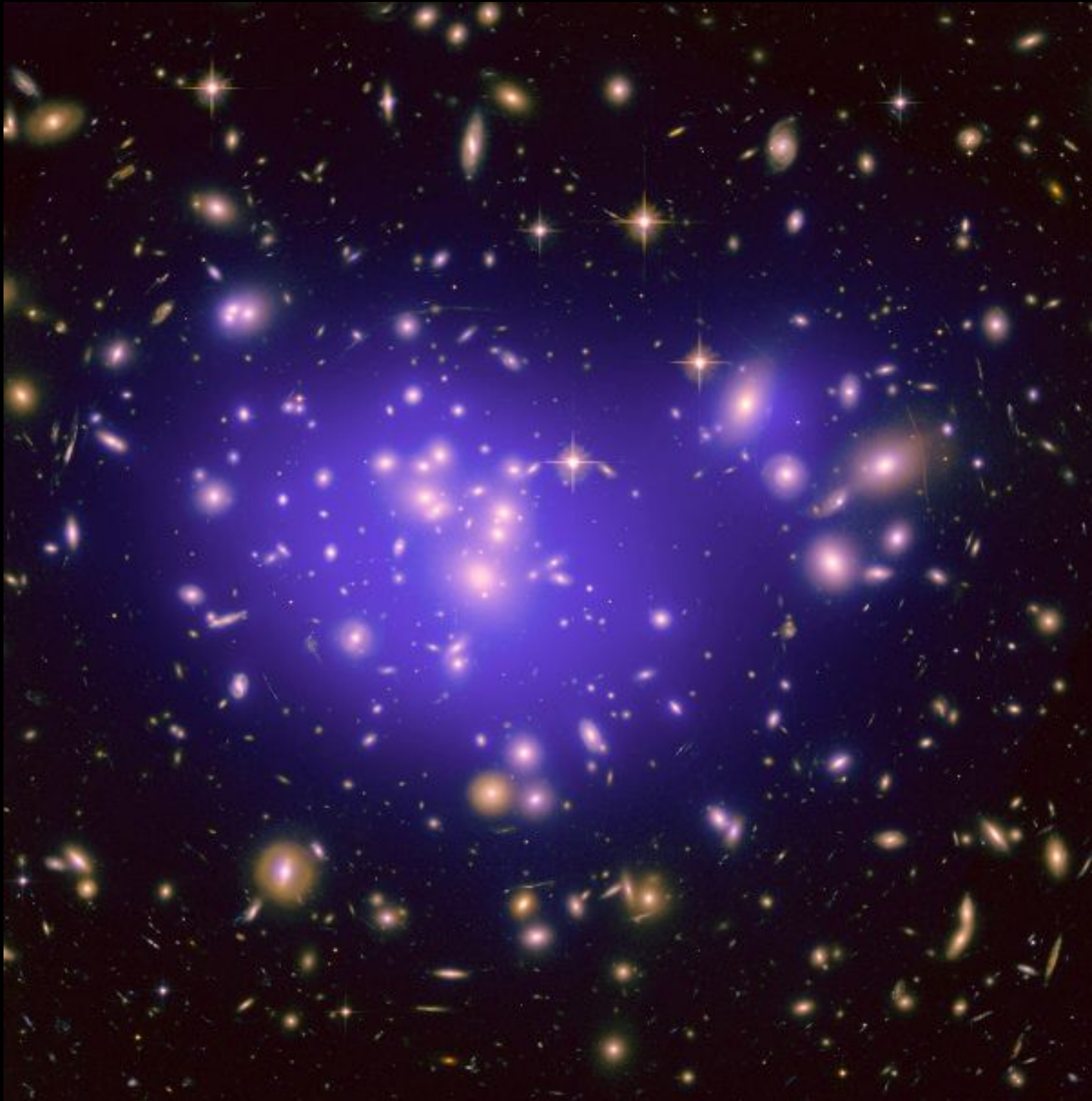
Figure 4.10— The distribution of radial velocities of all 583 identified Coma cluster galaxies ($4000 < cz < 10000$ km s^{-1}). The solid curve is a Gaussian with mean 6977 ± 53 km s^{-1} and standard deviation 950 ± 39 km s^{-1}. The dotted curve is the sum of two Gaussians with $\overline{cz_1} = 7501 \pm 187$ 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

A2218





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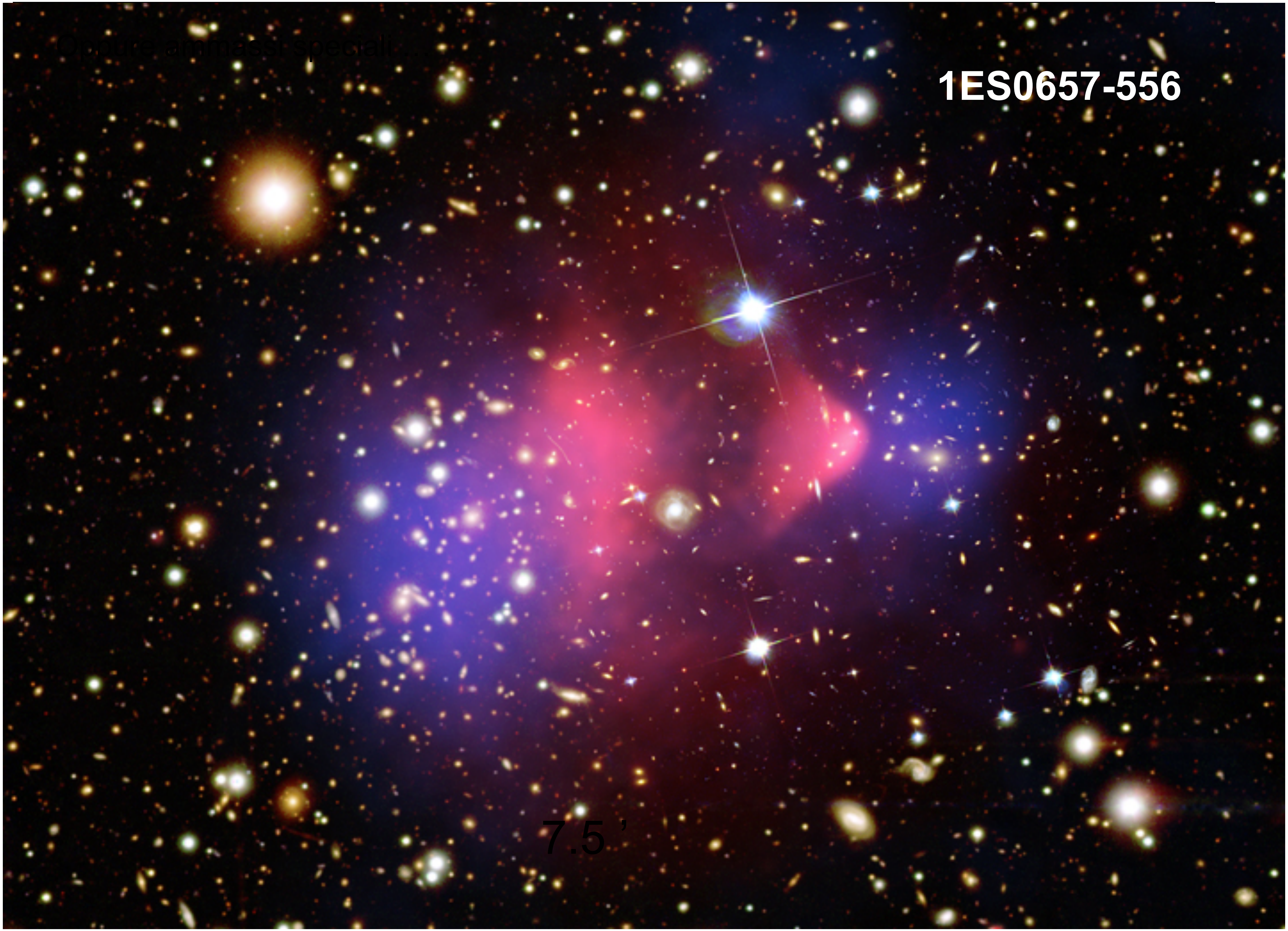
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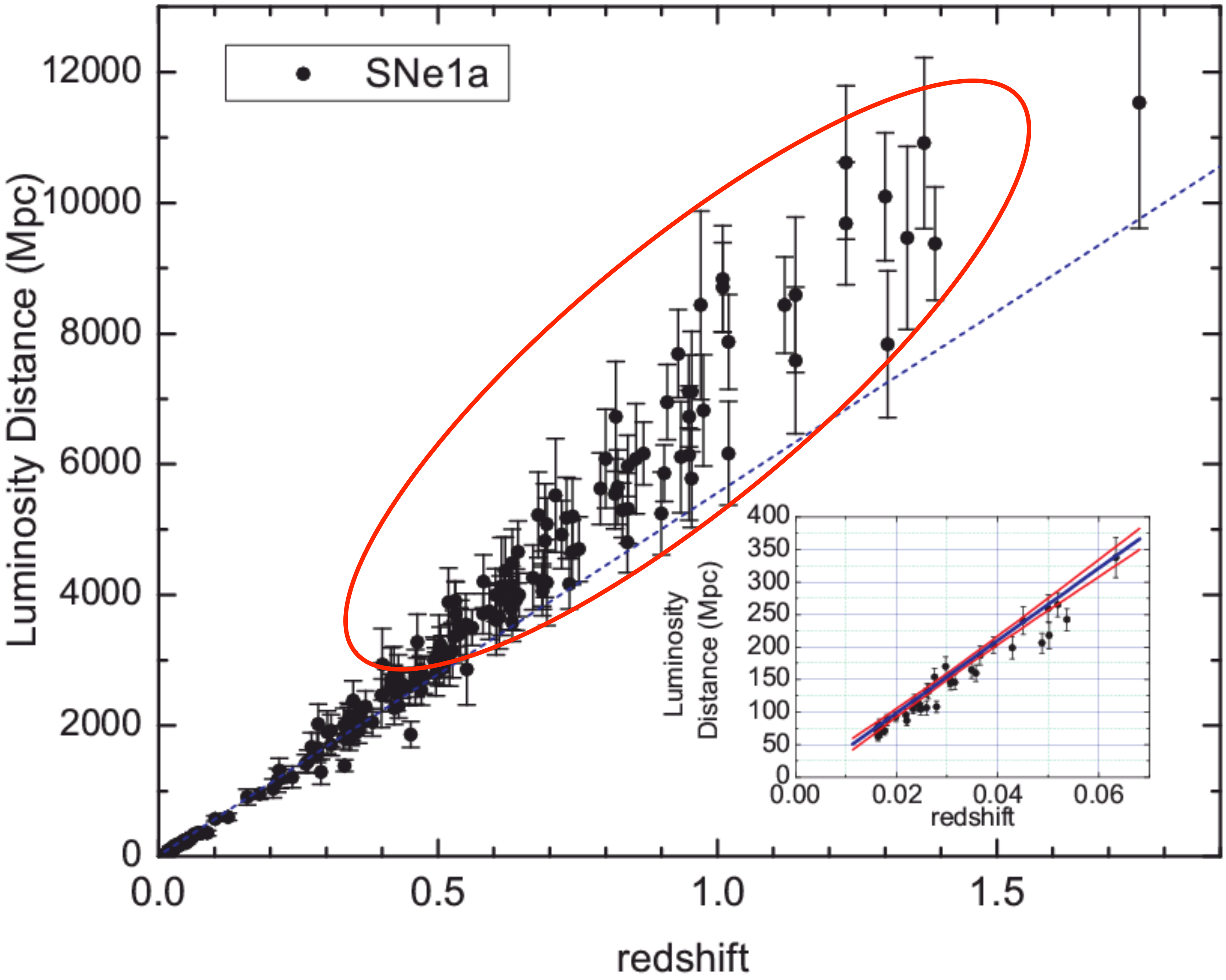


SNe1a
Luminosity Distance (Mpc)
12000
10000
8000
6000
4000
2000
0
0.0
0.5
1.0
1.5
redshift
400
350
300
250
200
150
100
50
0
0.00
0.02
0.04
0.06
Luminosity
Distance (Mpc)
redshift

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.

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

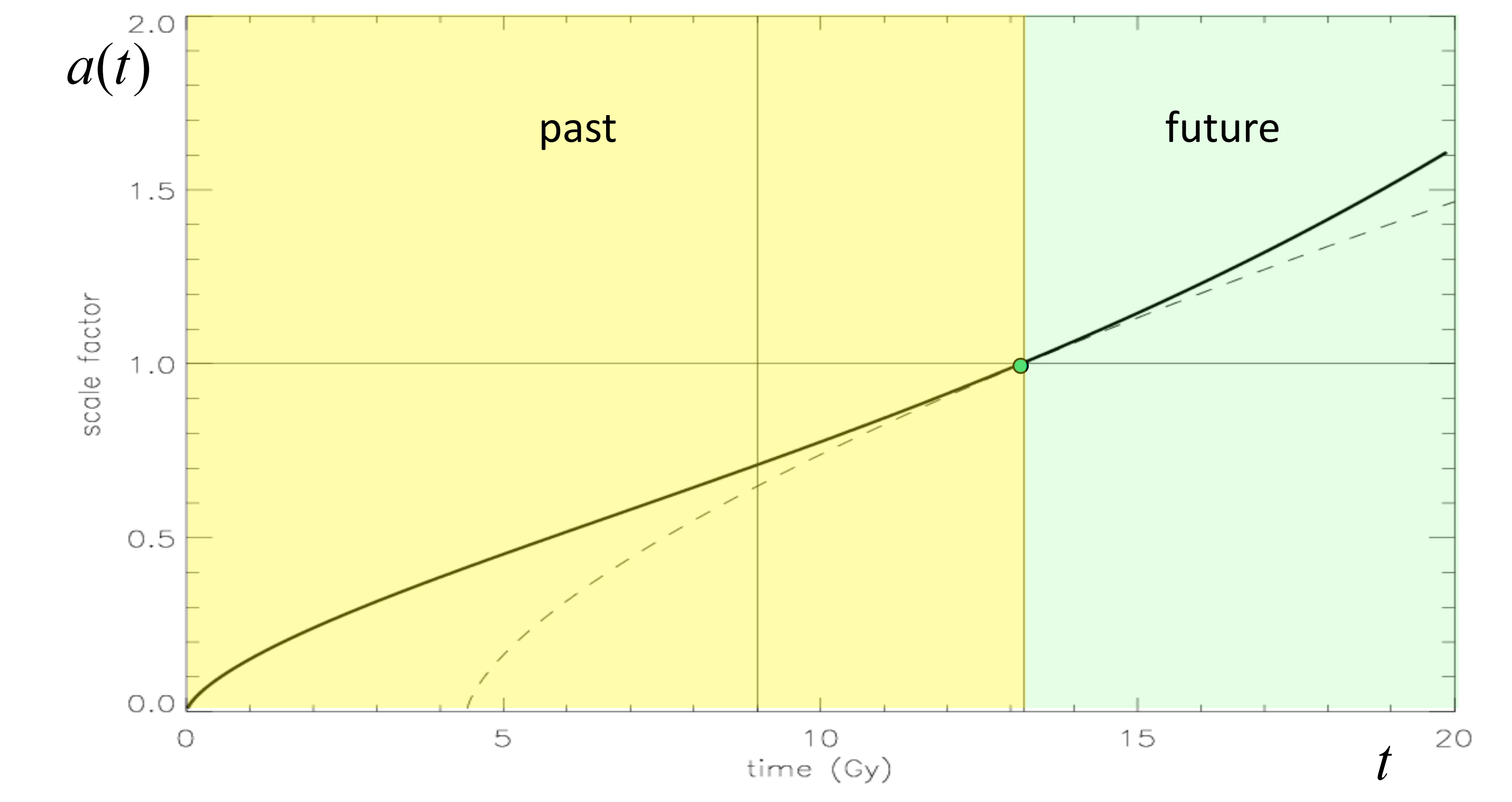
- I.e. the mass-energy density is consistent with the critical density, and there is no curvature of space.
- This result is confirmed and its accuracy is improved by measurements of the causal horizon at redshift 1100, using the cosmic microwave background:

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

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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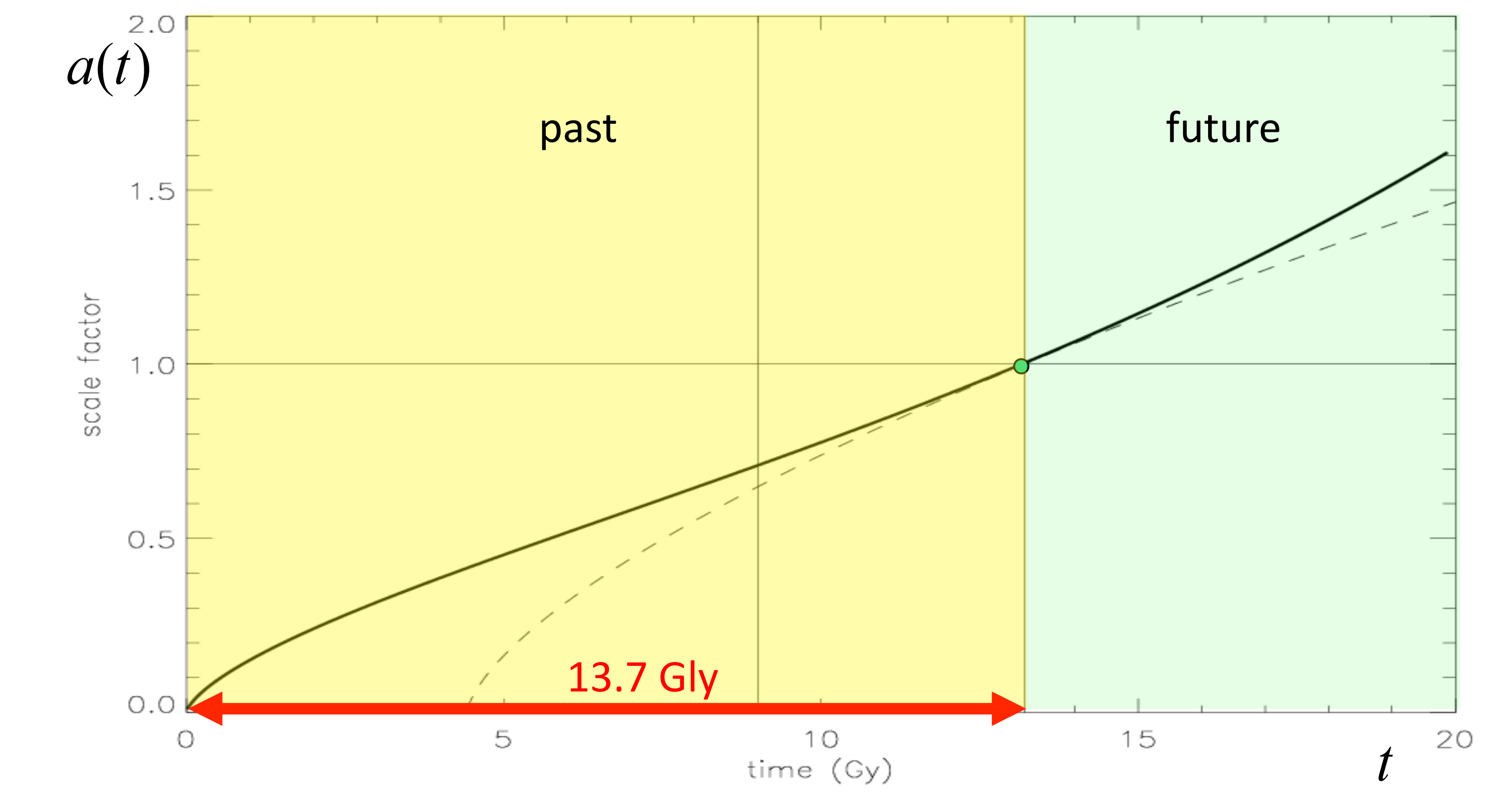

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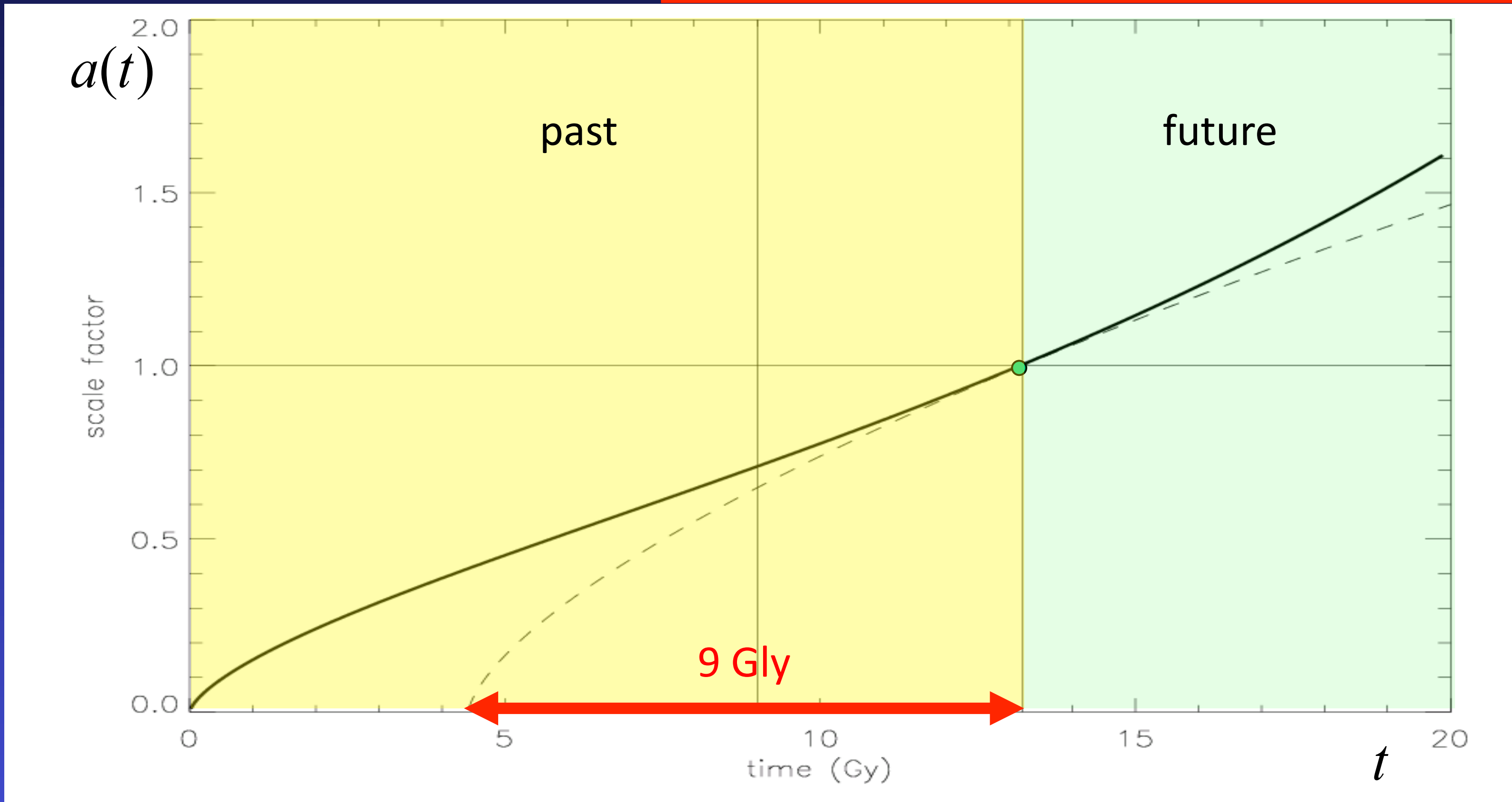


NGC 6397

Friedman's equation

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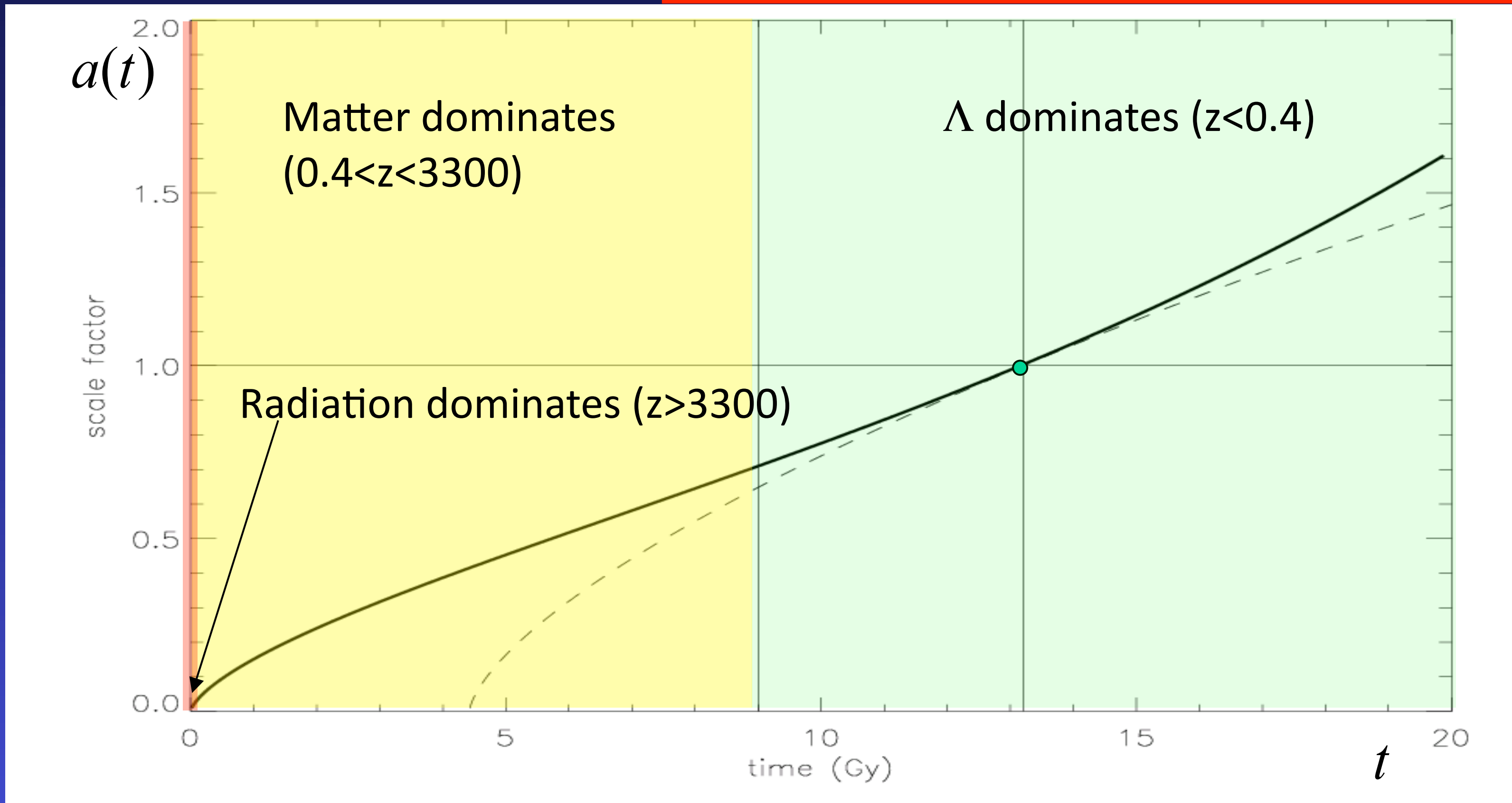
$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]$$



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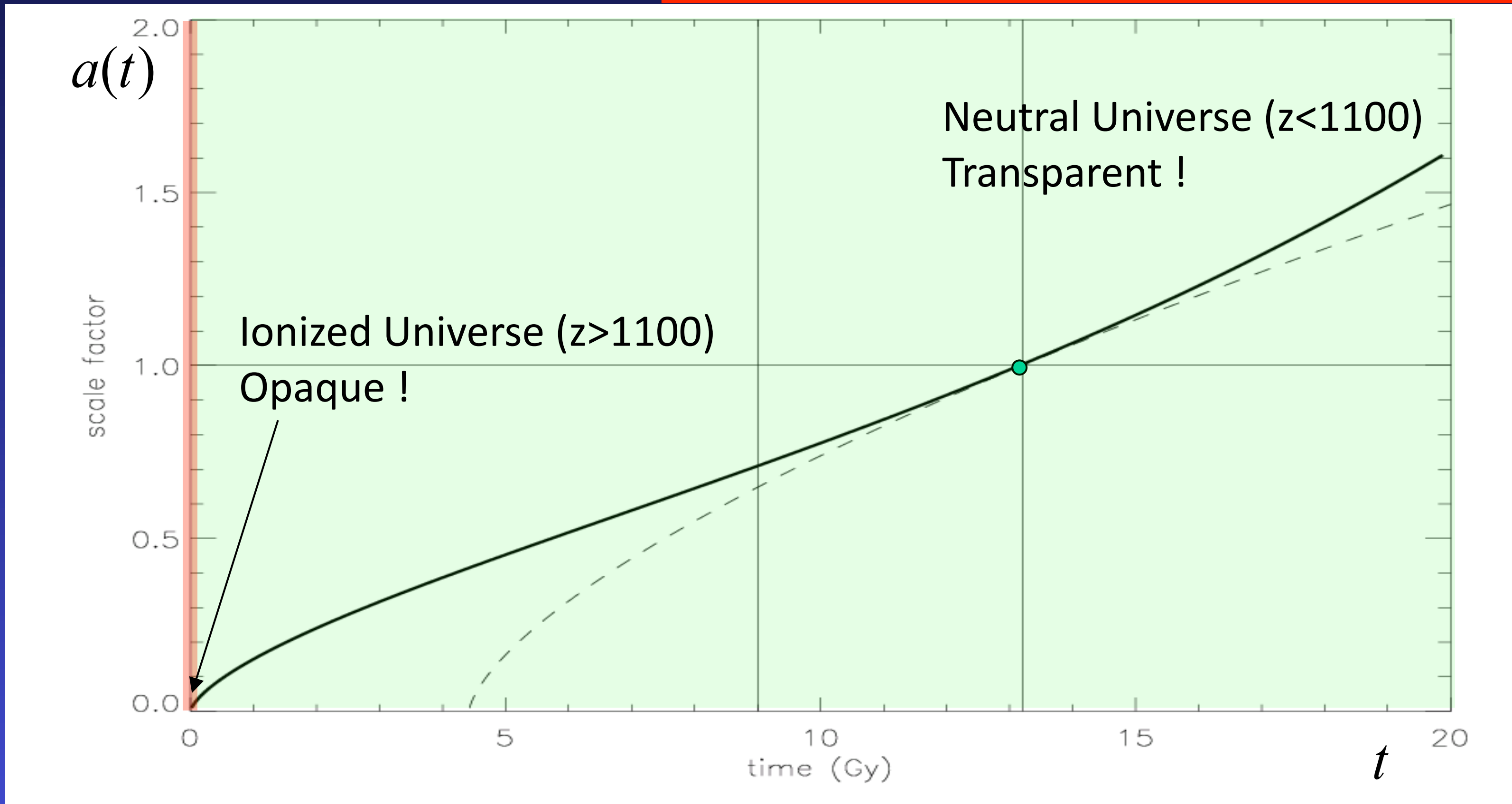
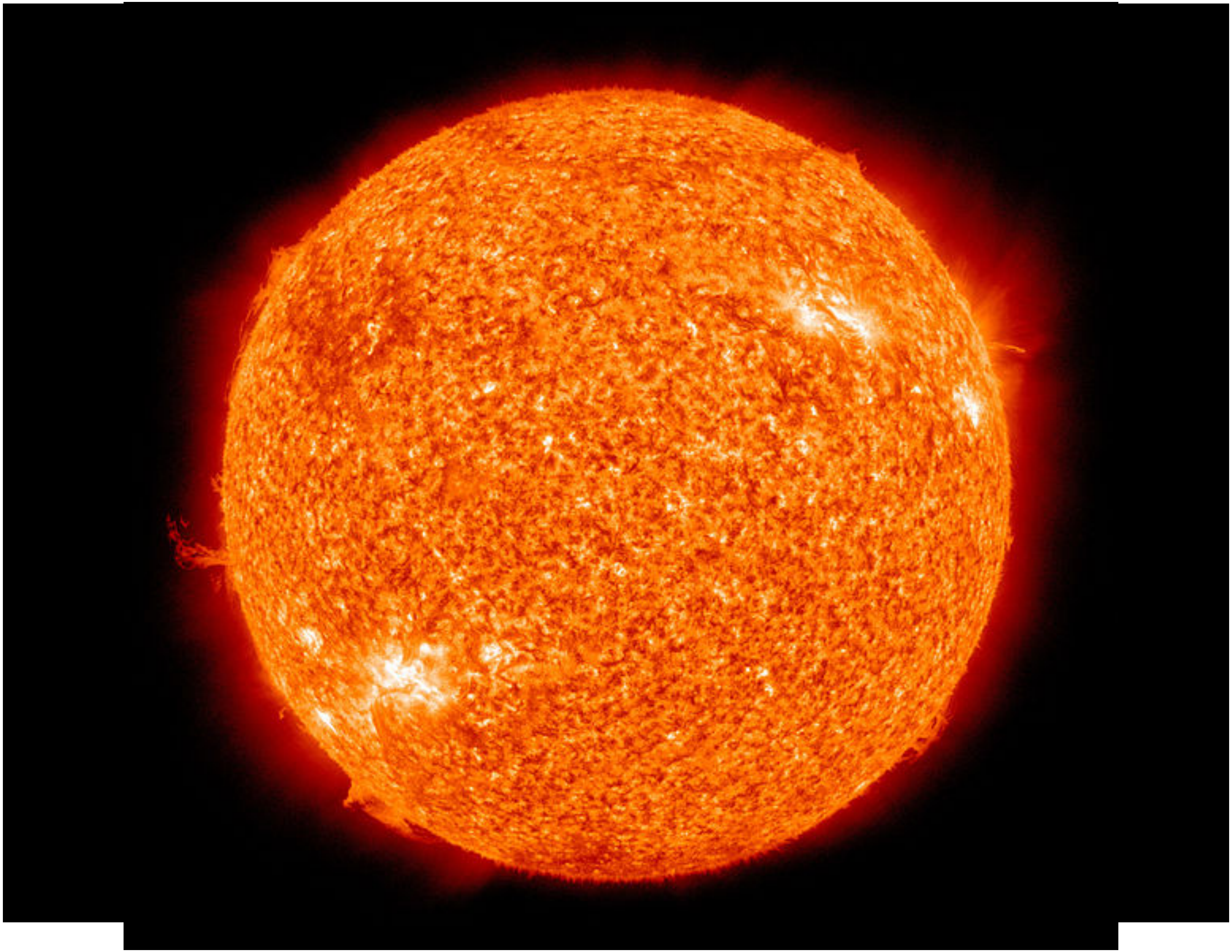
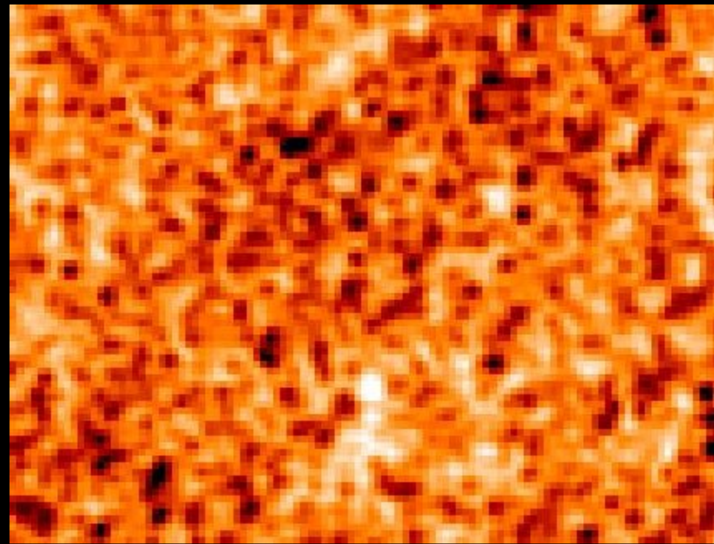




Granulazione solare

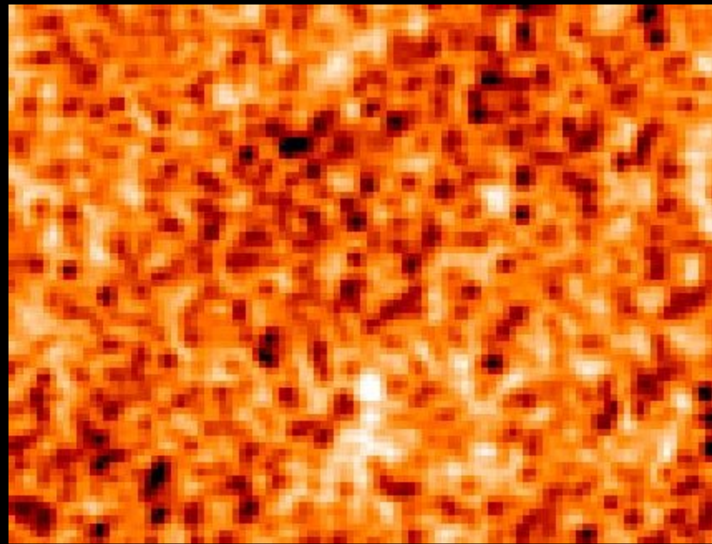


Gas incandescente
sulla superficie del
Sole (5500 K)

8 minuti luce

Qui, ora

Granulazione solare



Gas incandescente sulla superficie del Sole (5500 K)

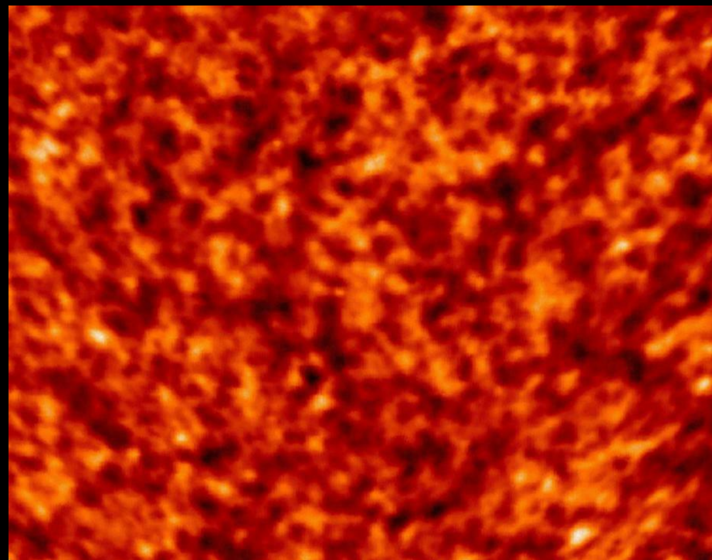
8 minuti luce

Qui, ora

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

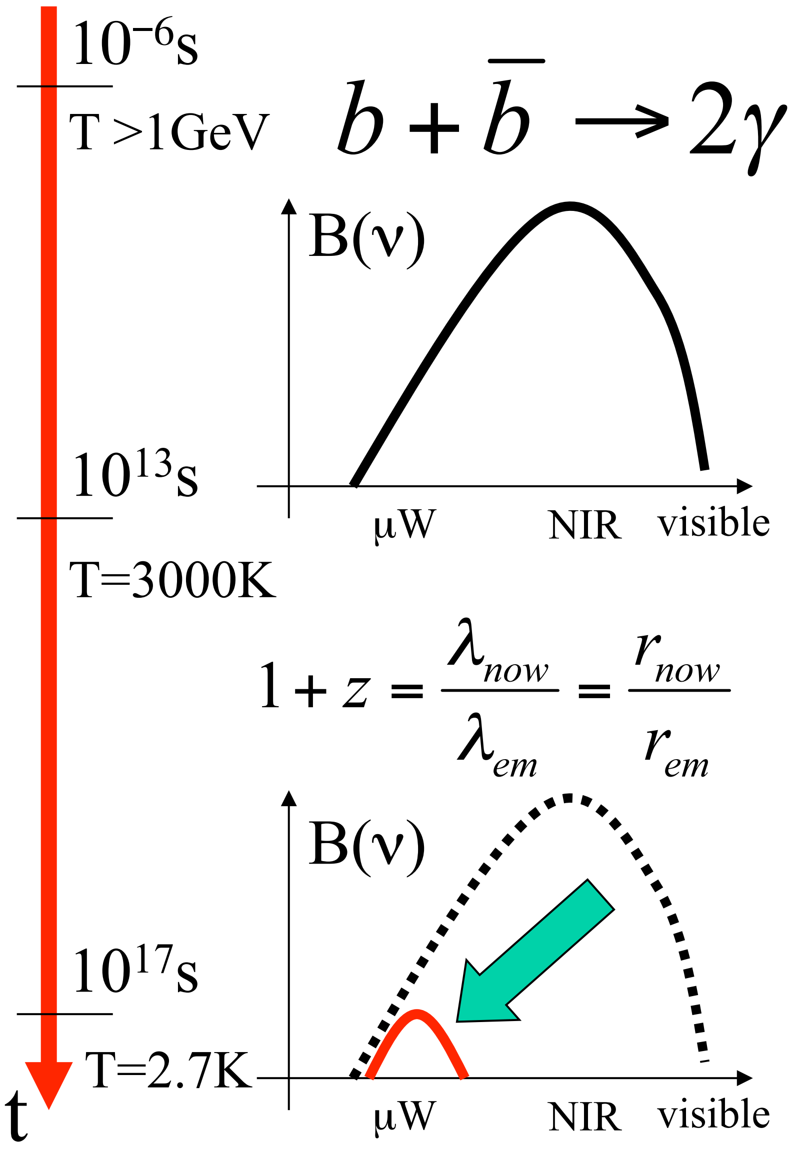
14 miliardi di anni luce

Qui, ora



Mappa di BOOMERanG dell' Universo Primordiale

What is the CMB



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

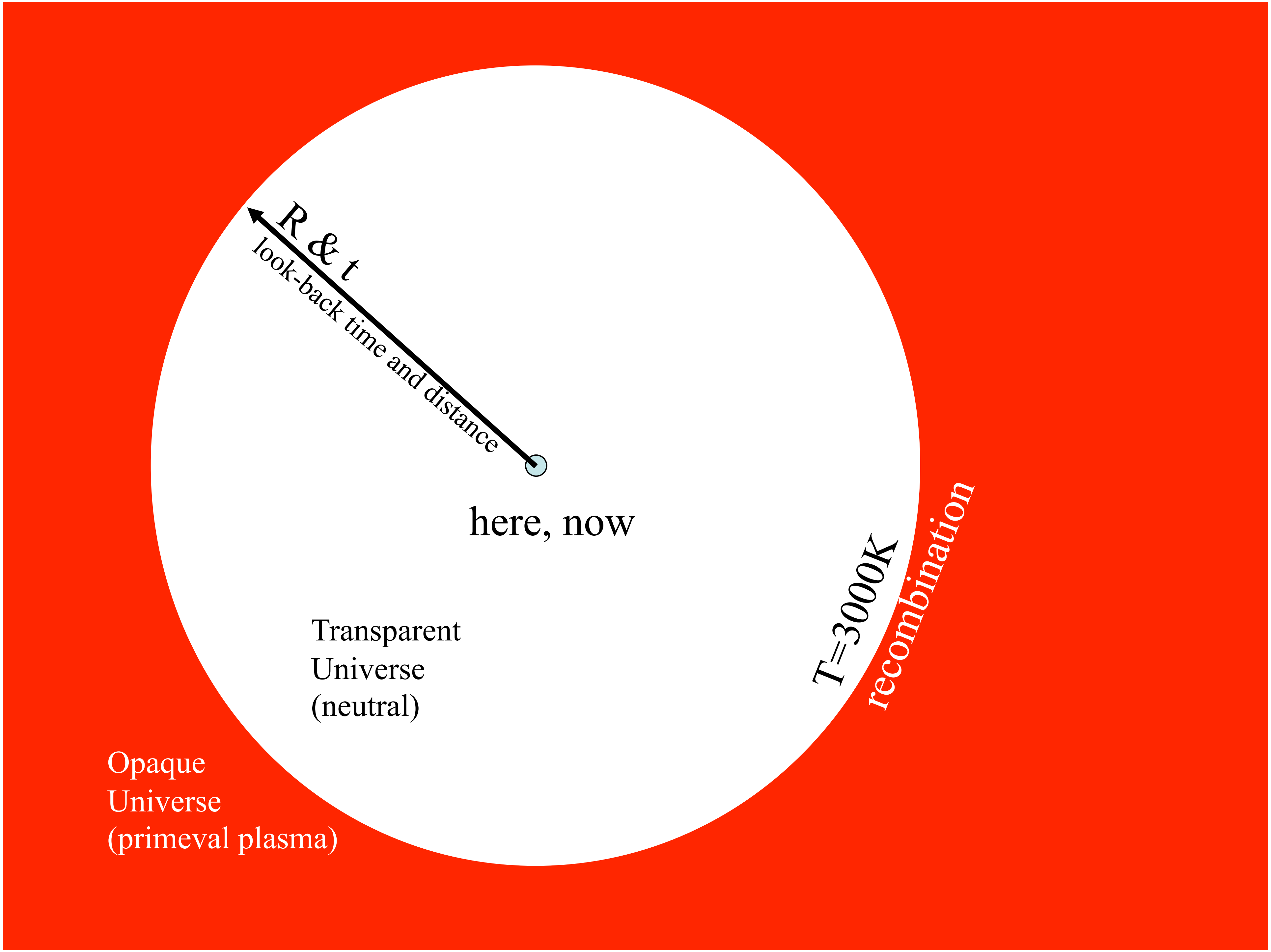
$$1 + z = \frac{\lambda_{now}}{\lambda_{em}} = \frac{r_{now}}{r_{em}}$$

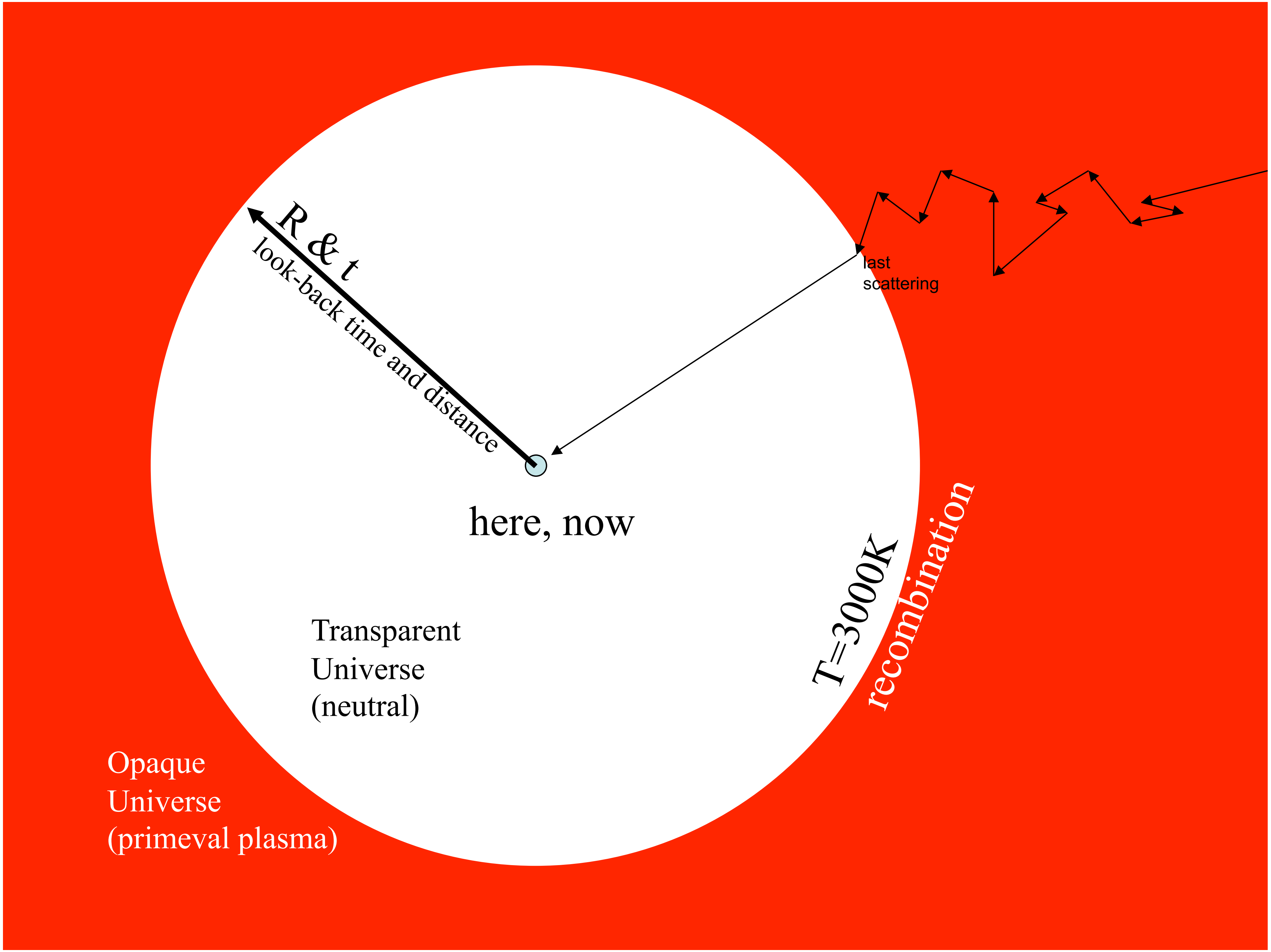
According to modern cosmology:

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**

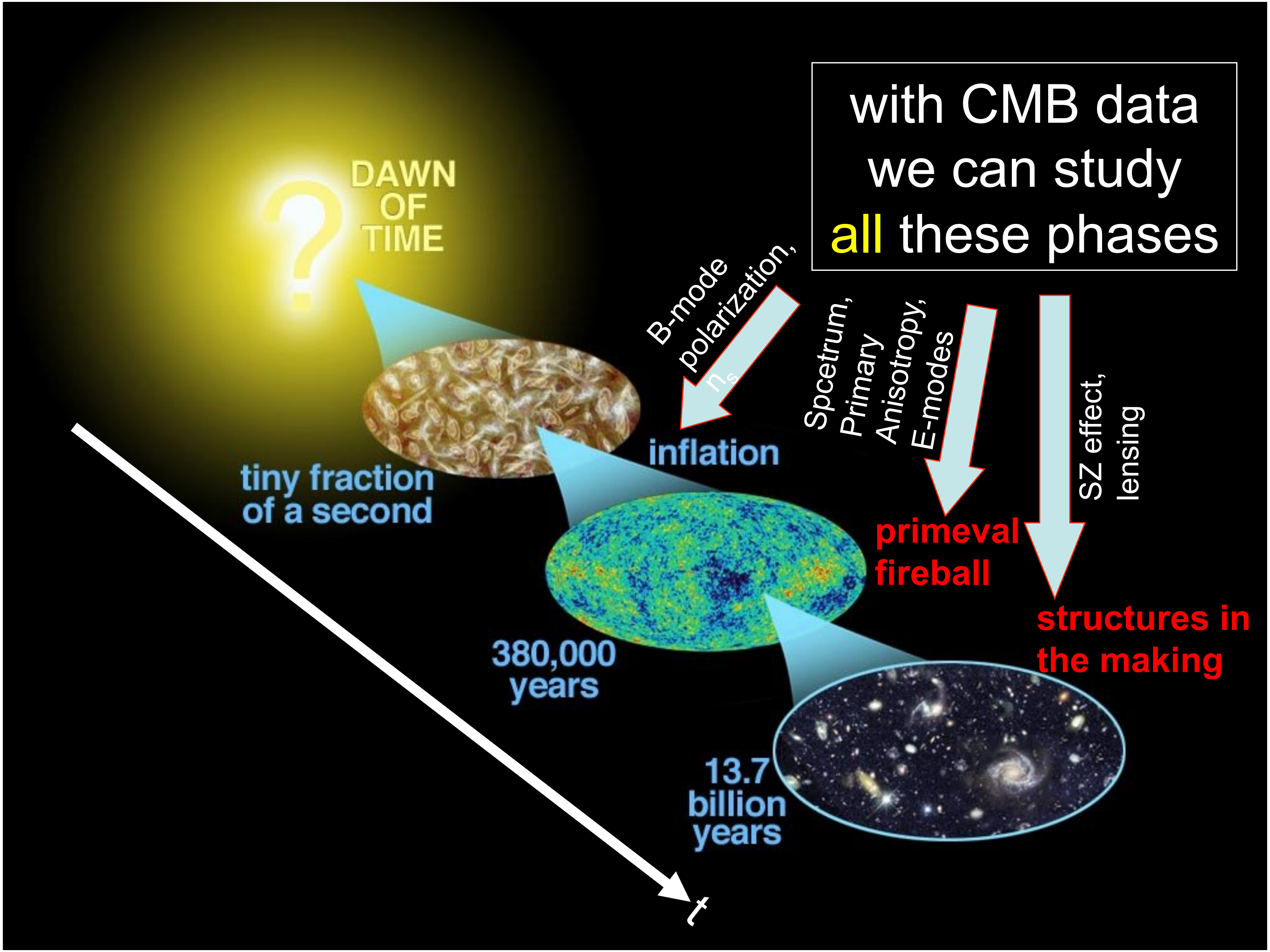
These photons carry
significant information
on the structure, evolution and
composition of our universe


R & t
look-back time and distance
here, now
Transparent Universe (neutral)
T=3000K
recombination
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
structures in the making
380,000 years
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:

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

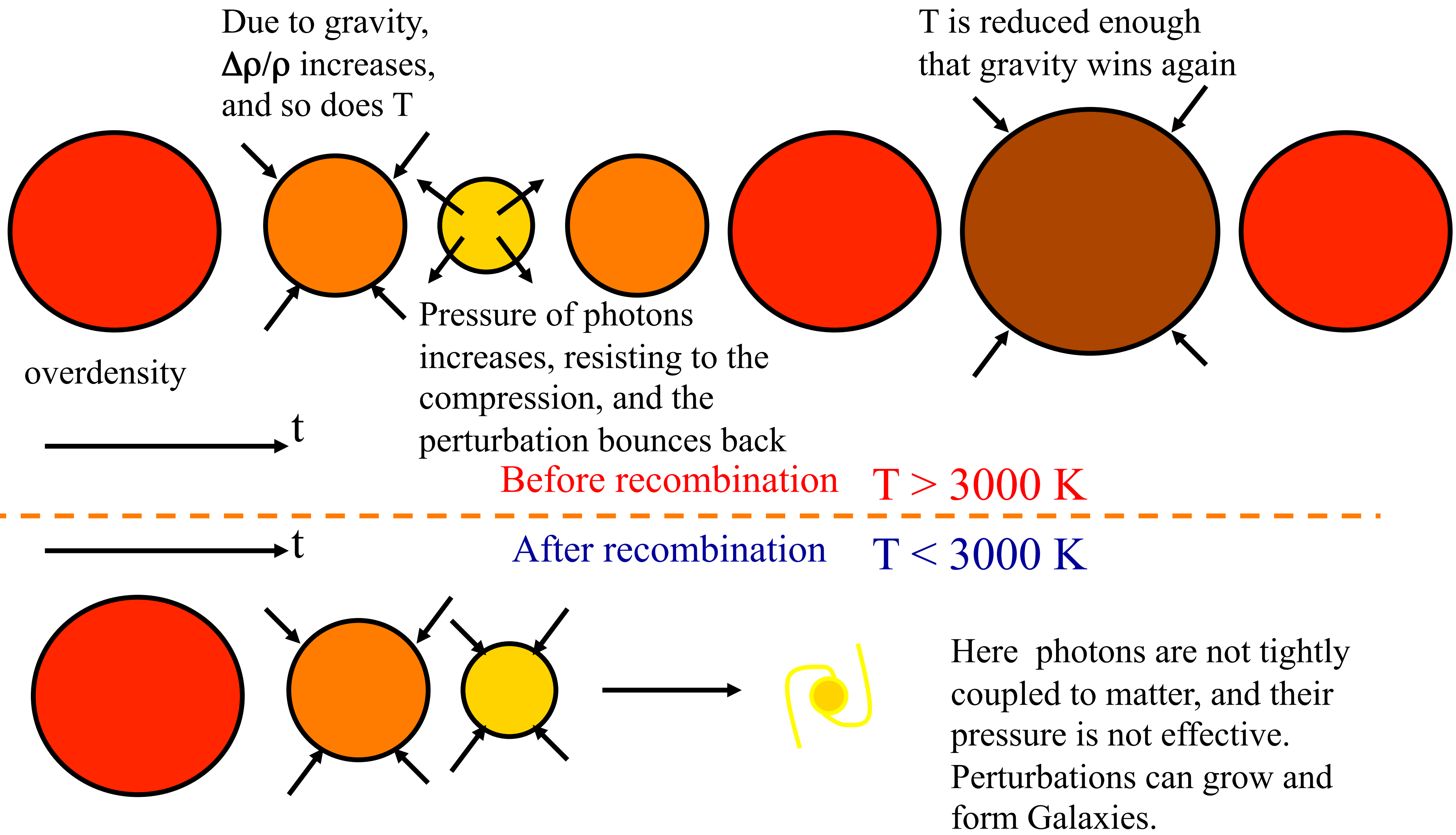
Sachs-Wolfe (gravitational redshift) — Photon density fluctuations — Doppler effect from velocity fields

- 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)

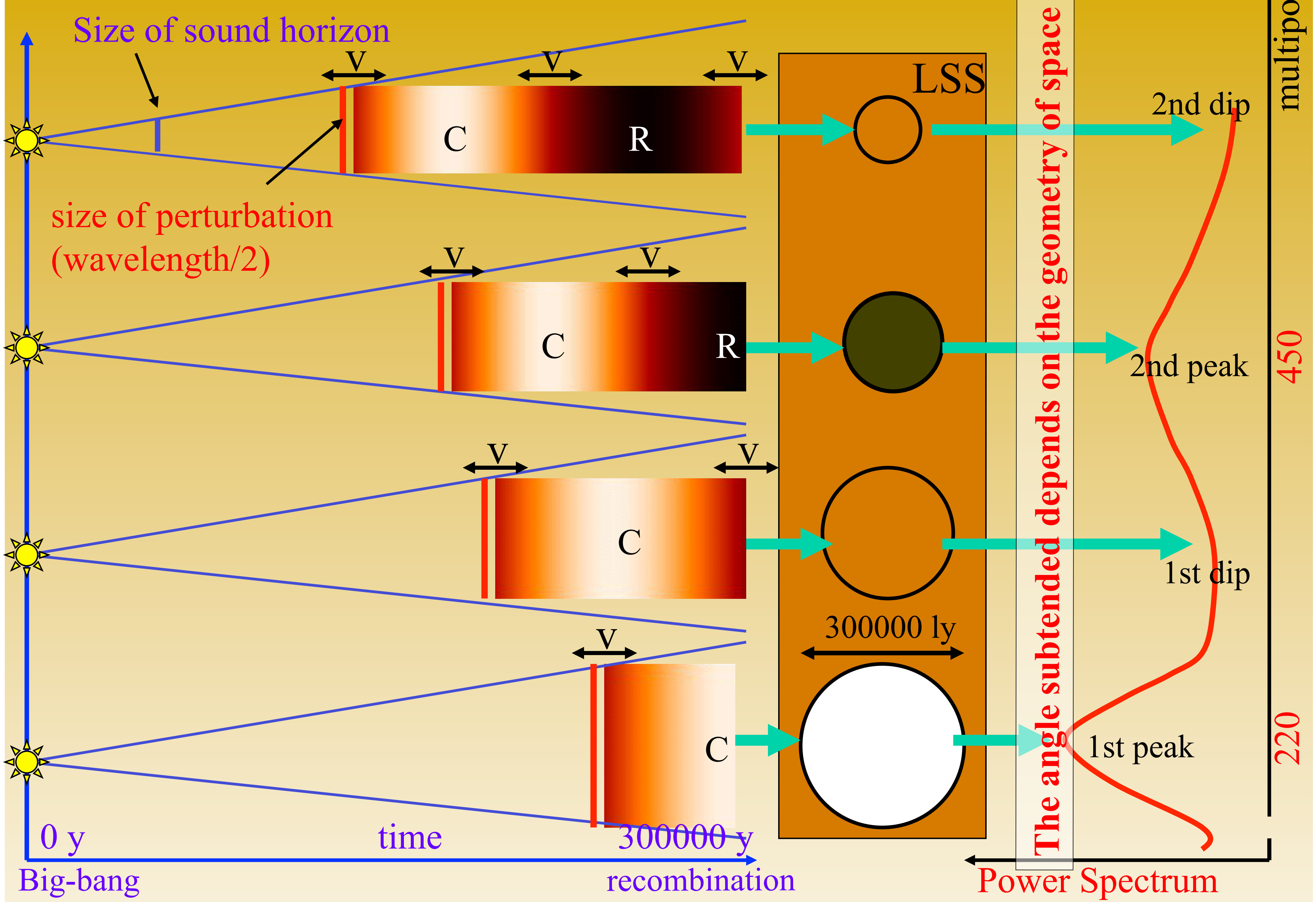
- The primeval plasma of photons and matter oscillates :
- self-gravity vs radiation pressure.
- We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
- Statistical theory: all information encoded in the angular power spectrum of the image.

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.



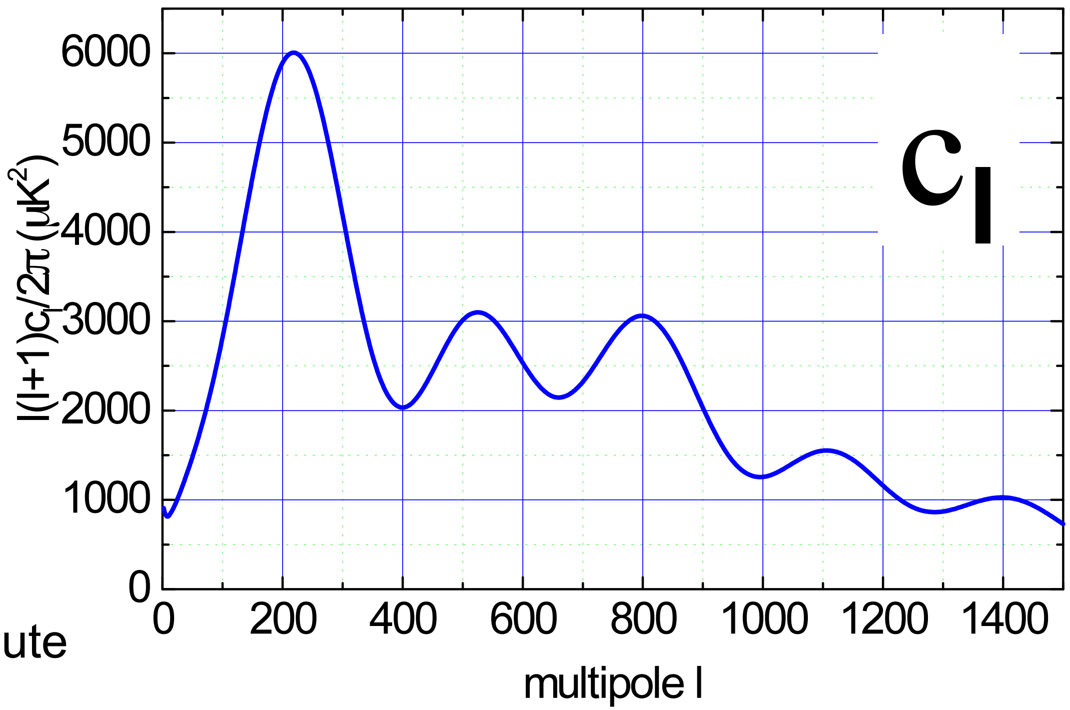
Expected power spectrum:

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

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

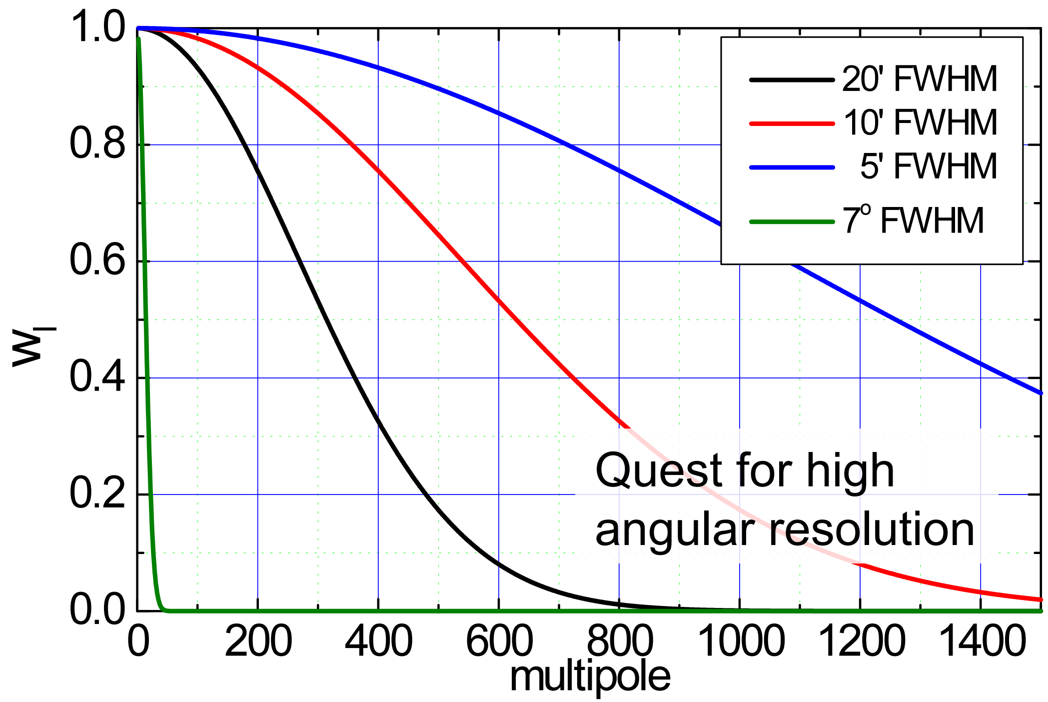
$$\left\langle \Delta T^2 \right\rangle = \frac{1}{4\pi} \sum_\ell (2\ell+1) c_\ell$$

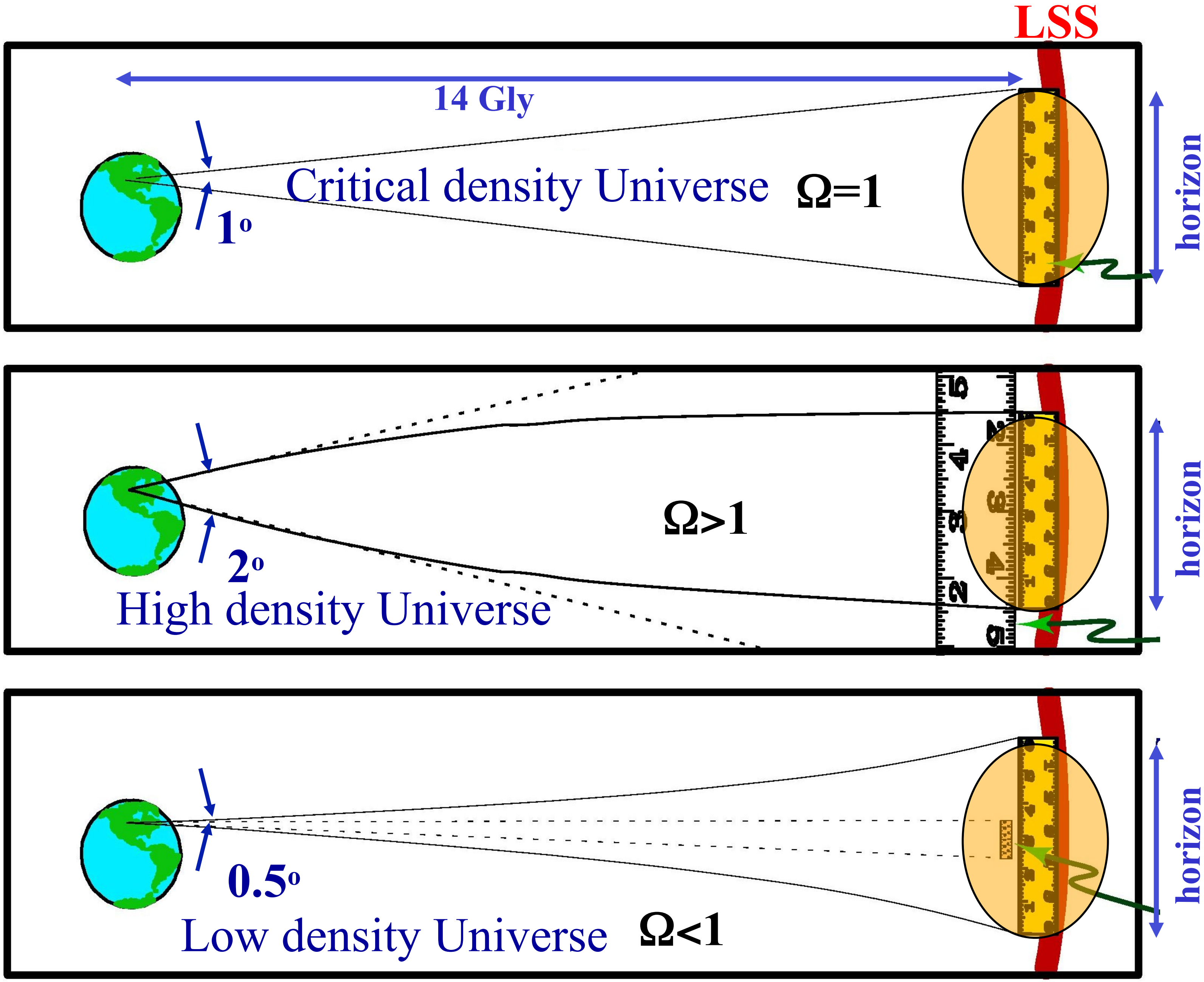
See e.g. http://camb.info to compute c_l for a given cosmological model



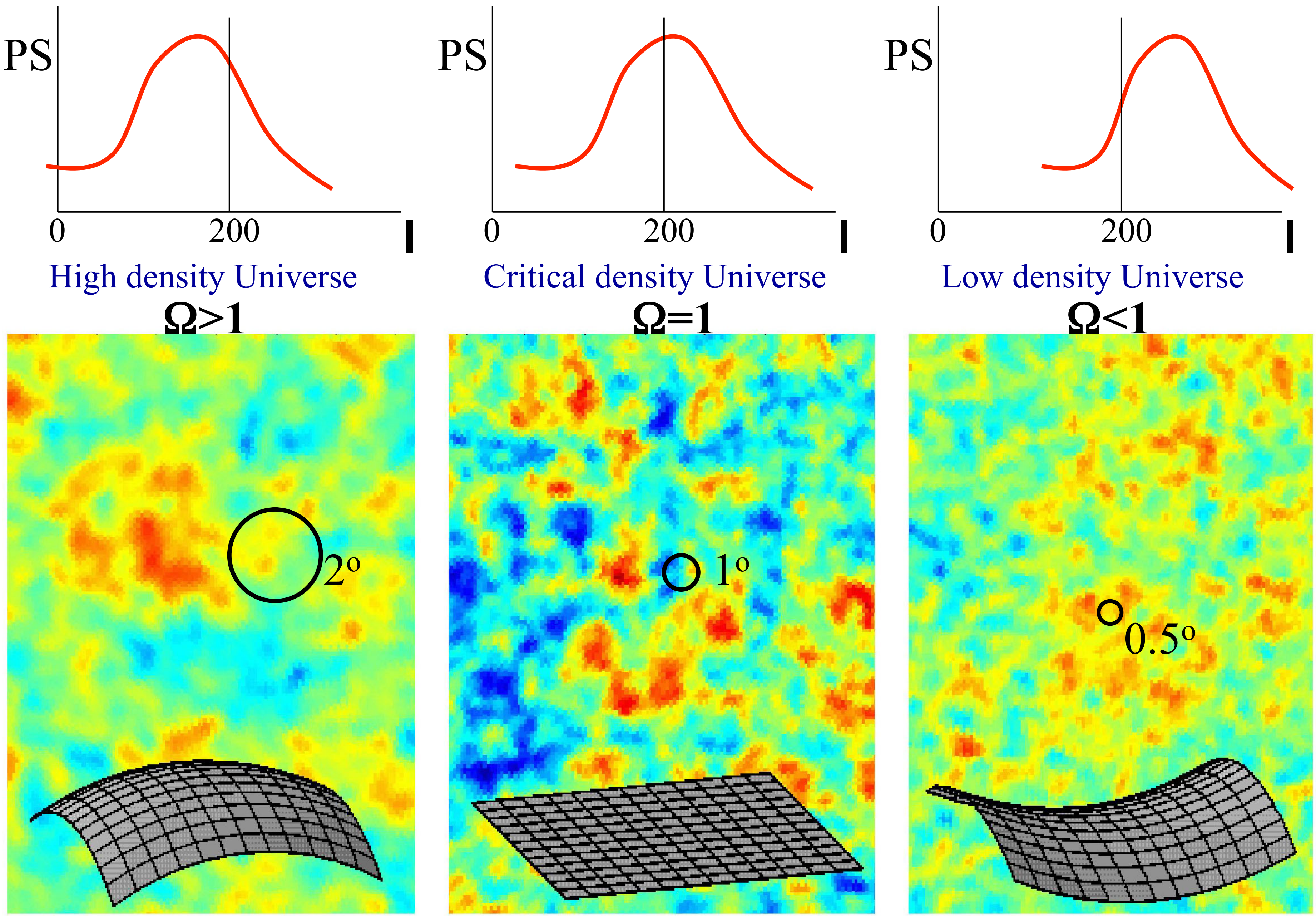
An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

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





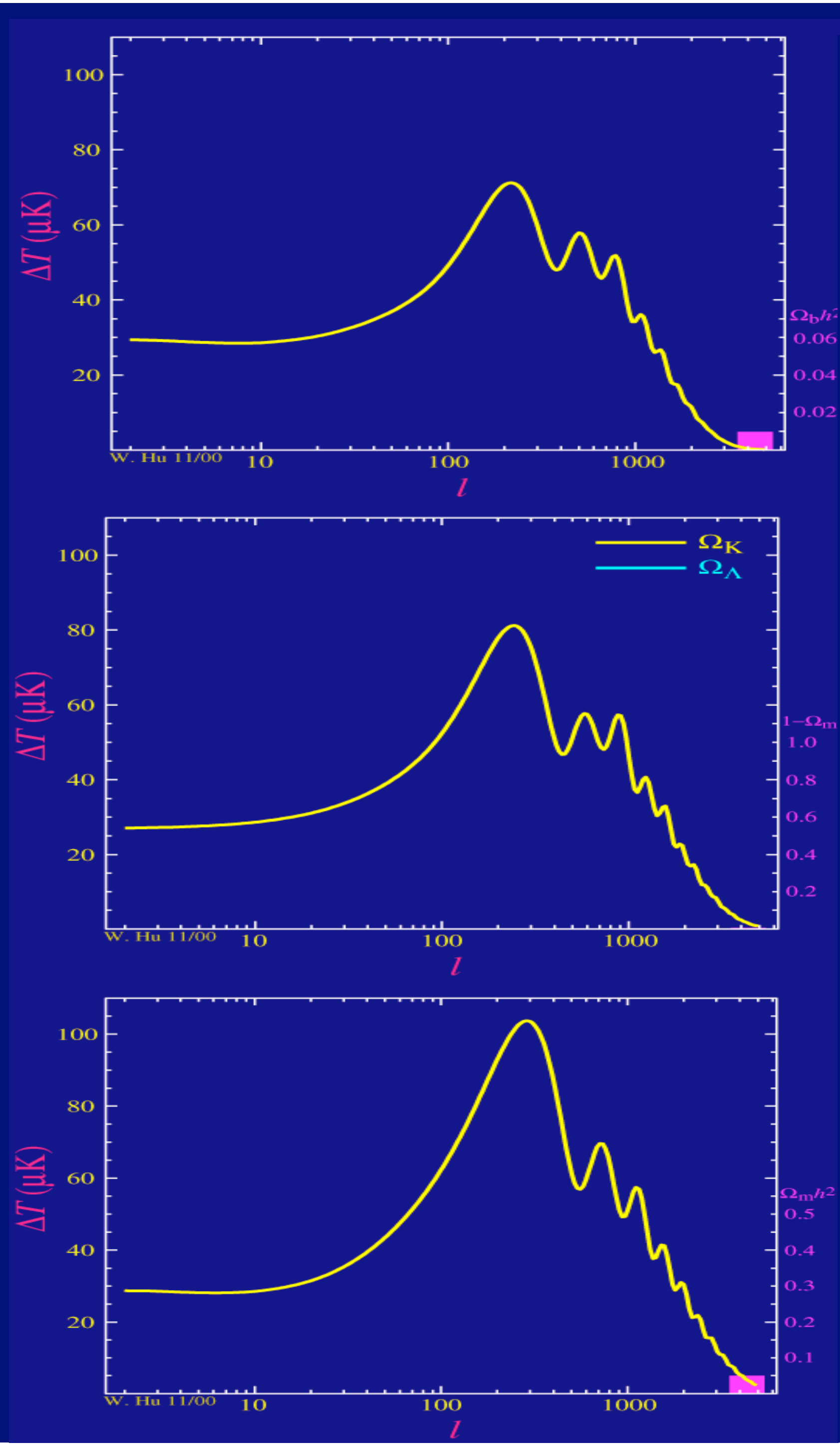
The image and PS are modified by the geometry of the universe



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

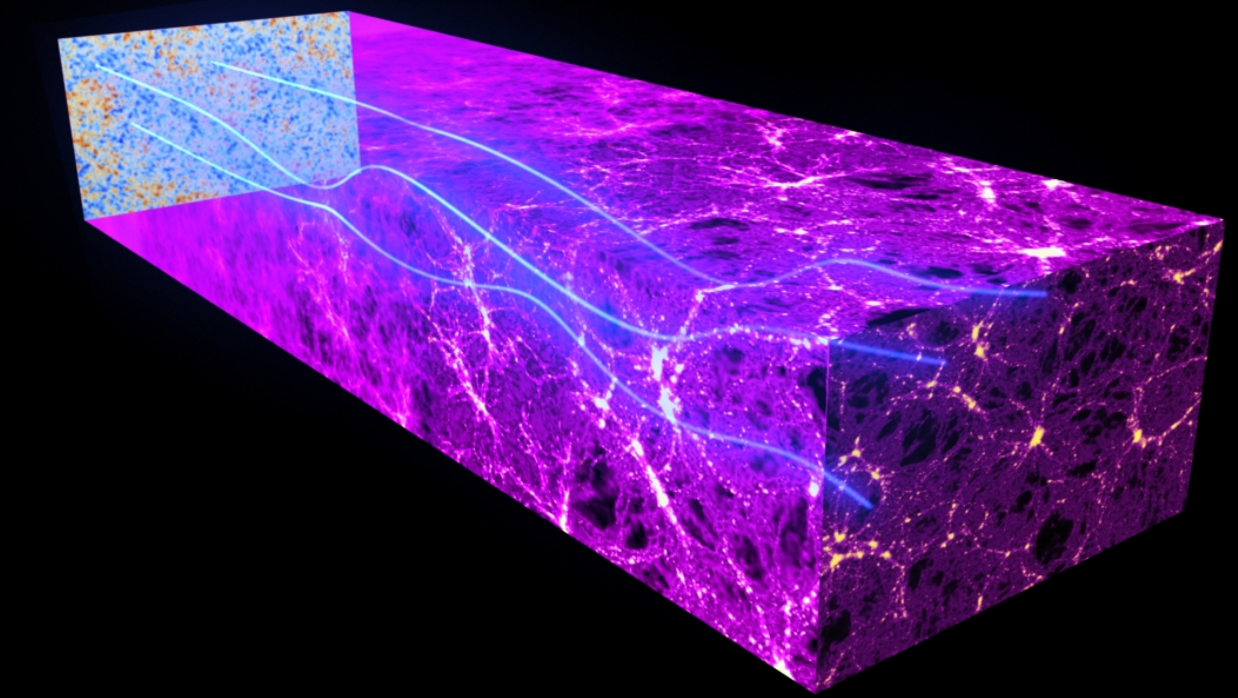
Composition

- 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.



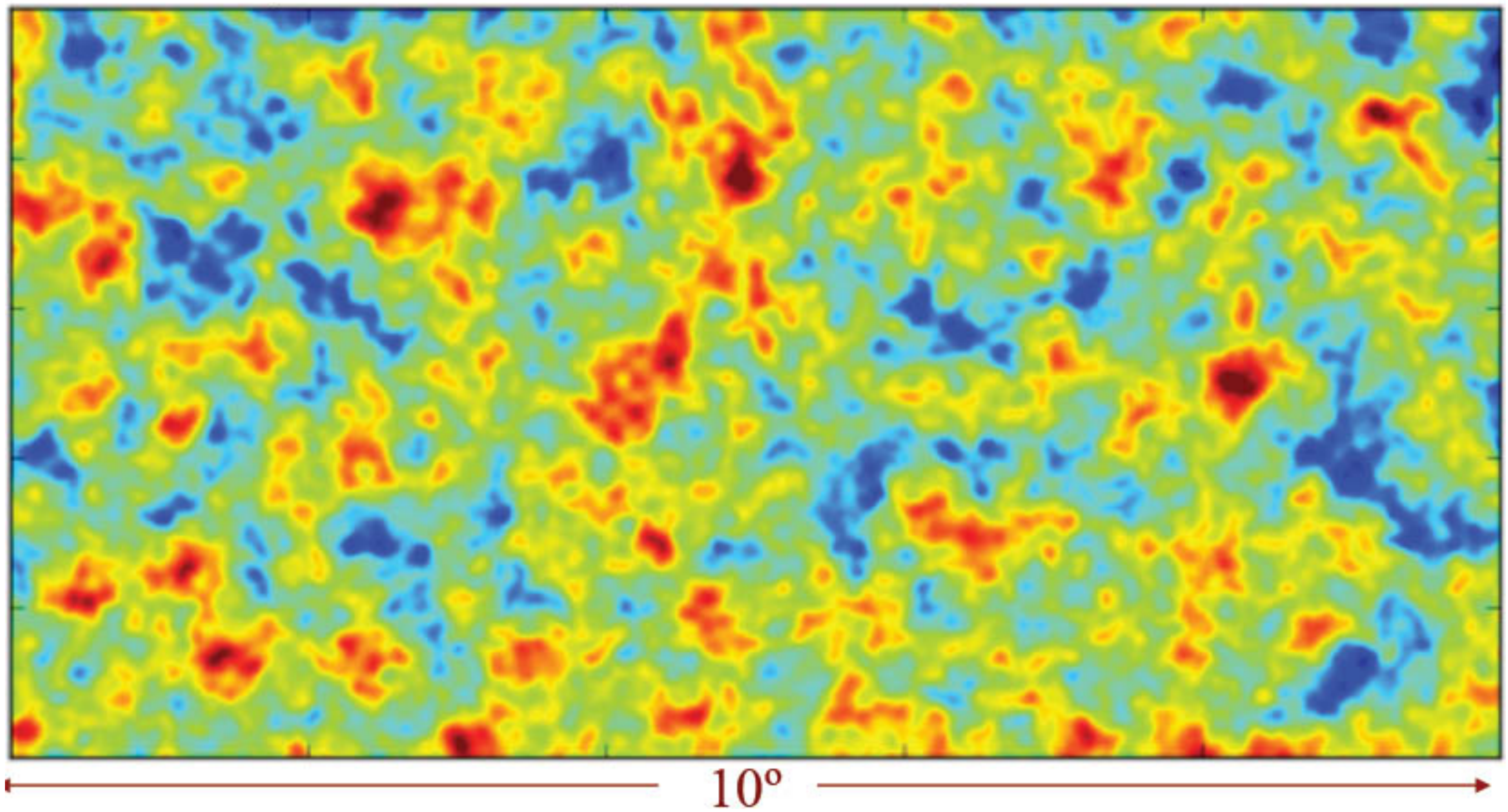
CMB anisotropy (lensing)

- 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.



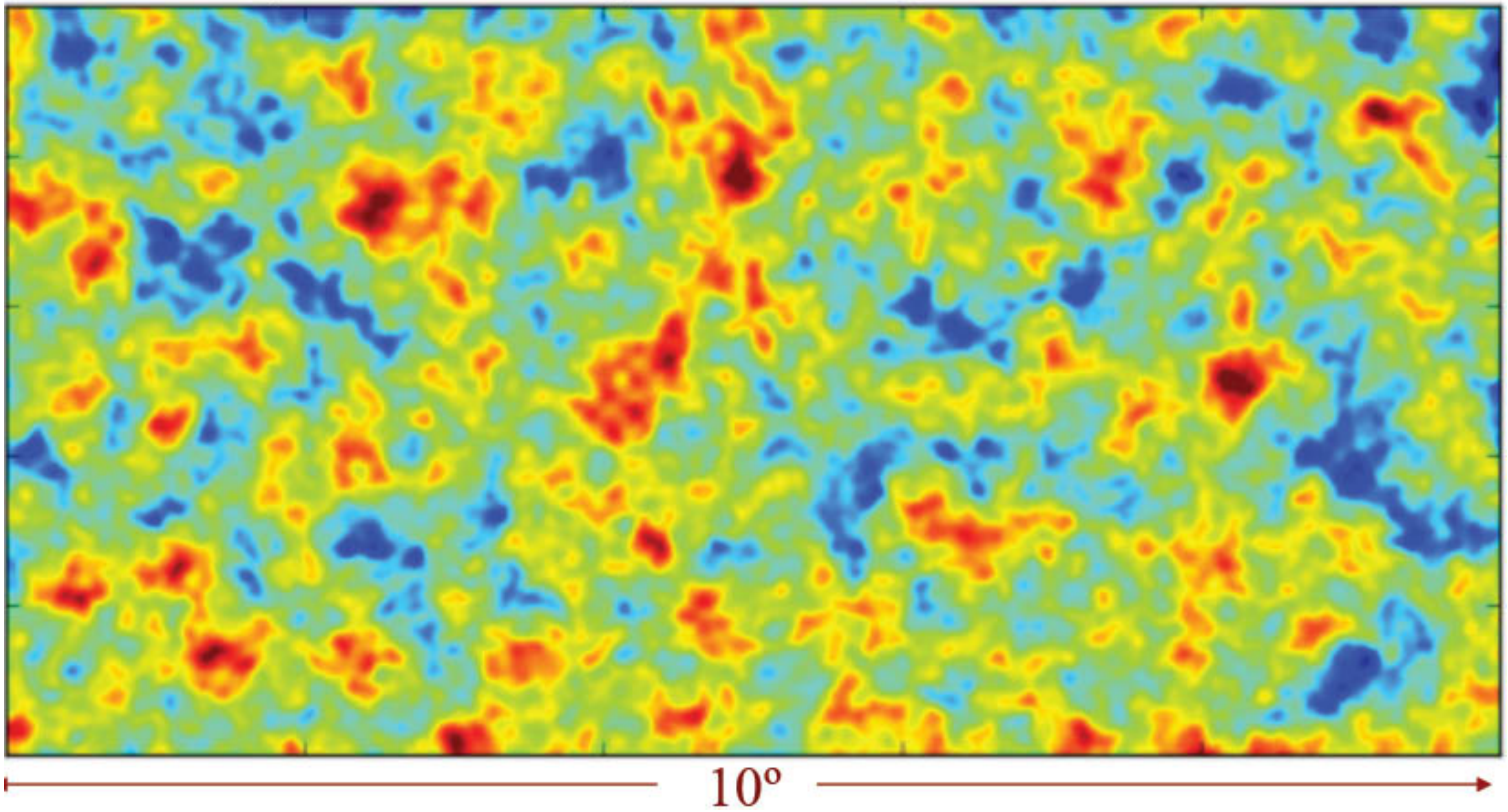
Typical deflection: 2.5’

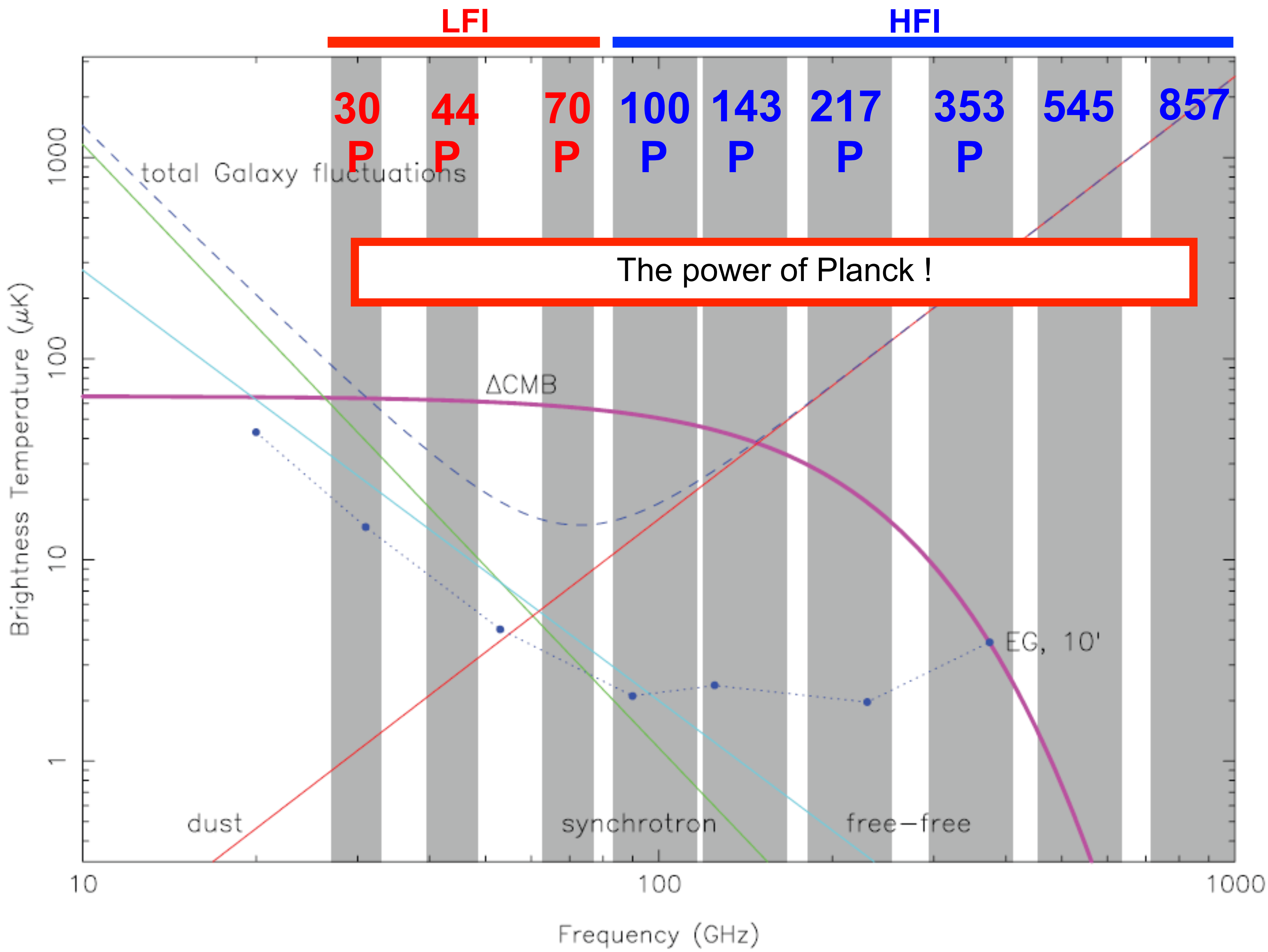
intrinsic CMB anisotropy

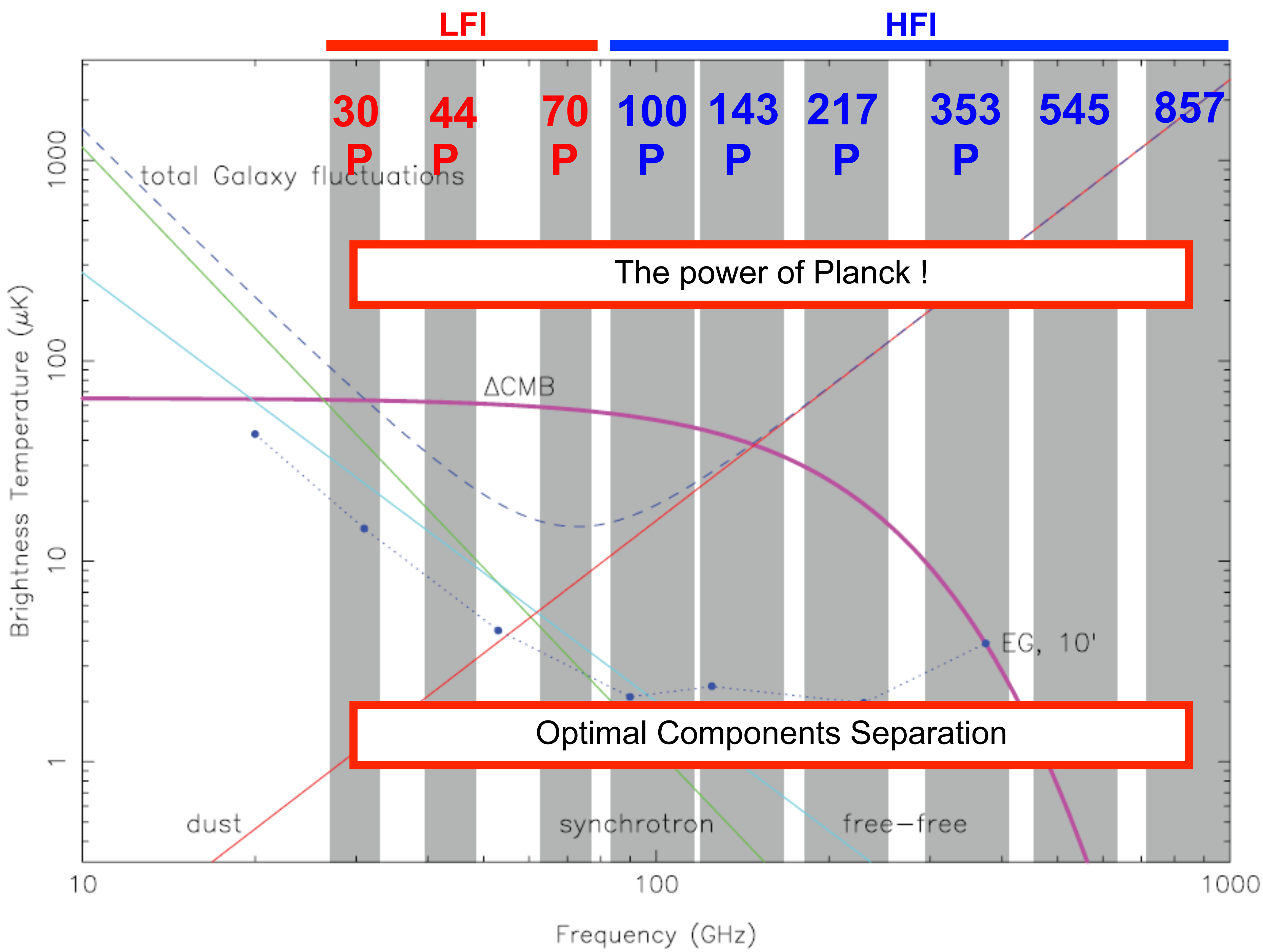


Typical deflection: 2.5’

lensed CMB anisotropy



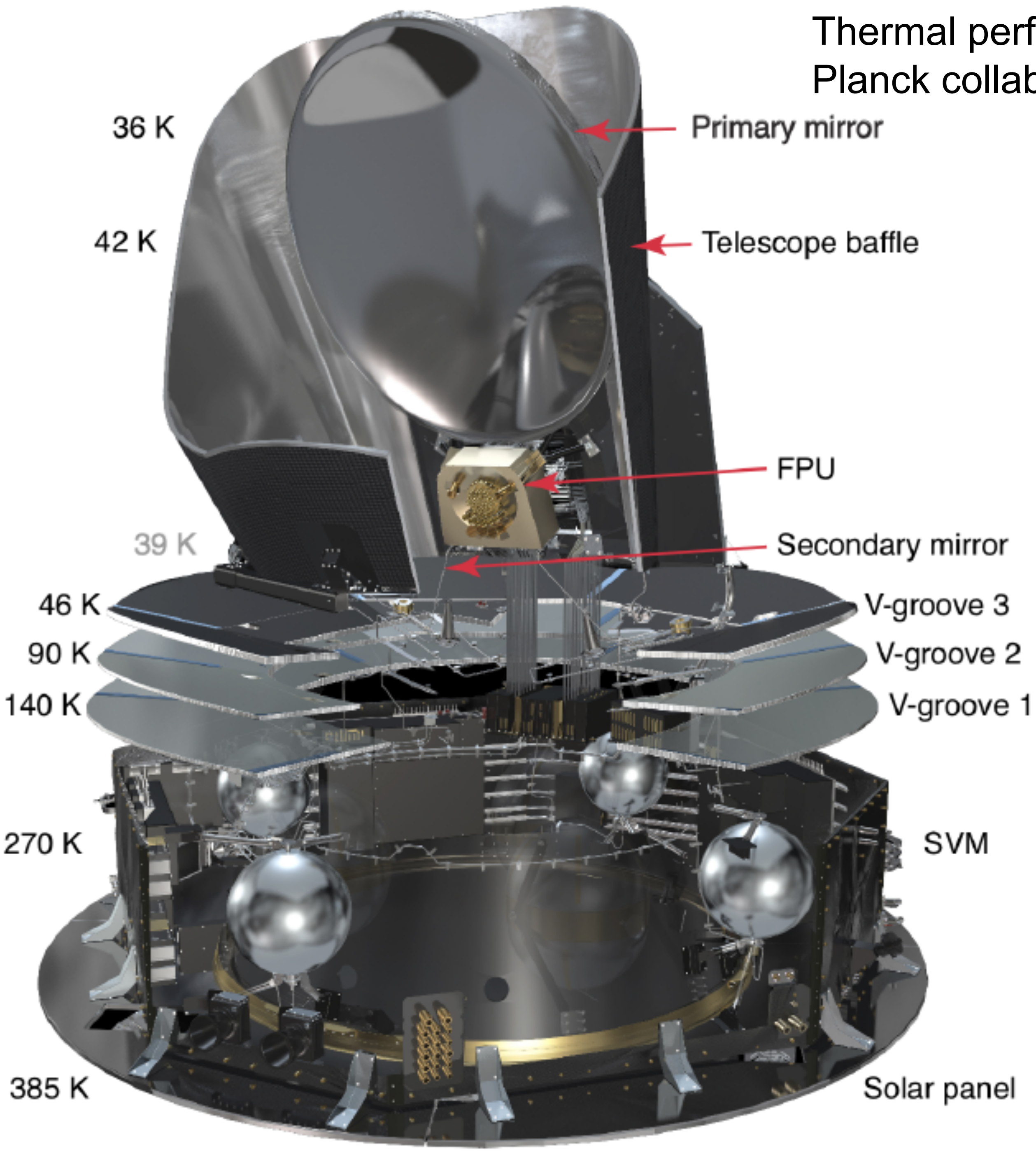

LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
The power of Planck !
total Galaxy fluctuations
ΔCMB
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
Frequency (GHz)
1
10
100
1000
10
100
1000

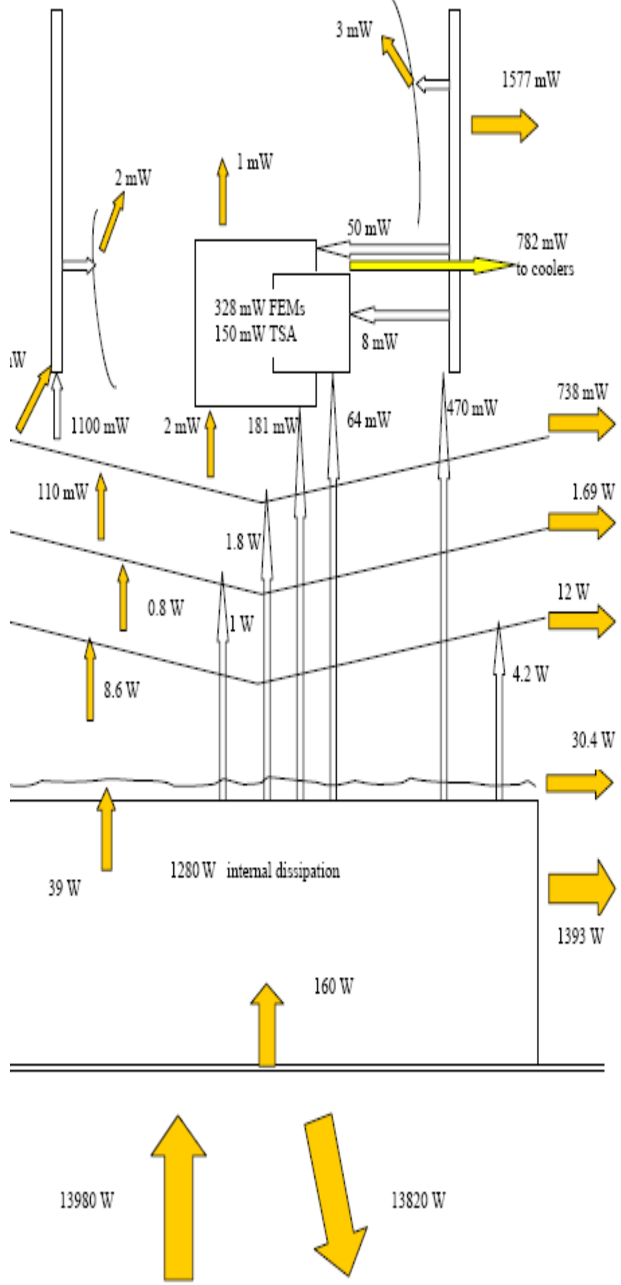


LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
total Galaxy fluctuations
The power of Planck !
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

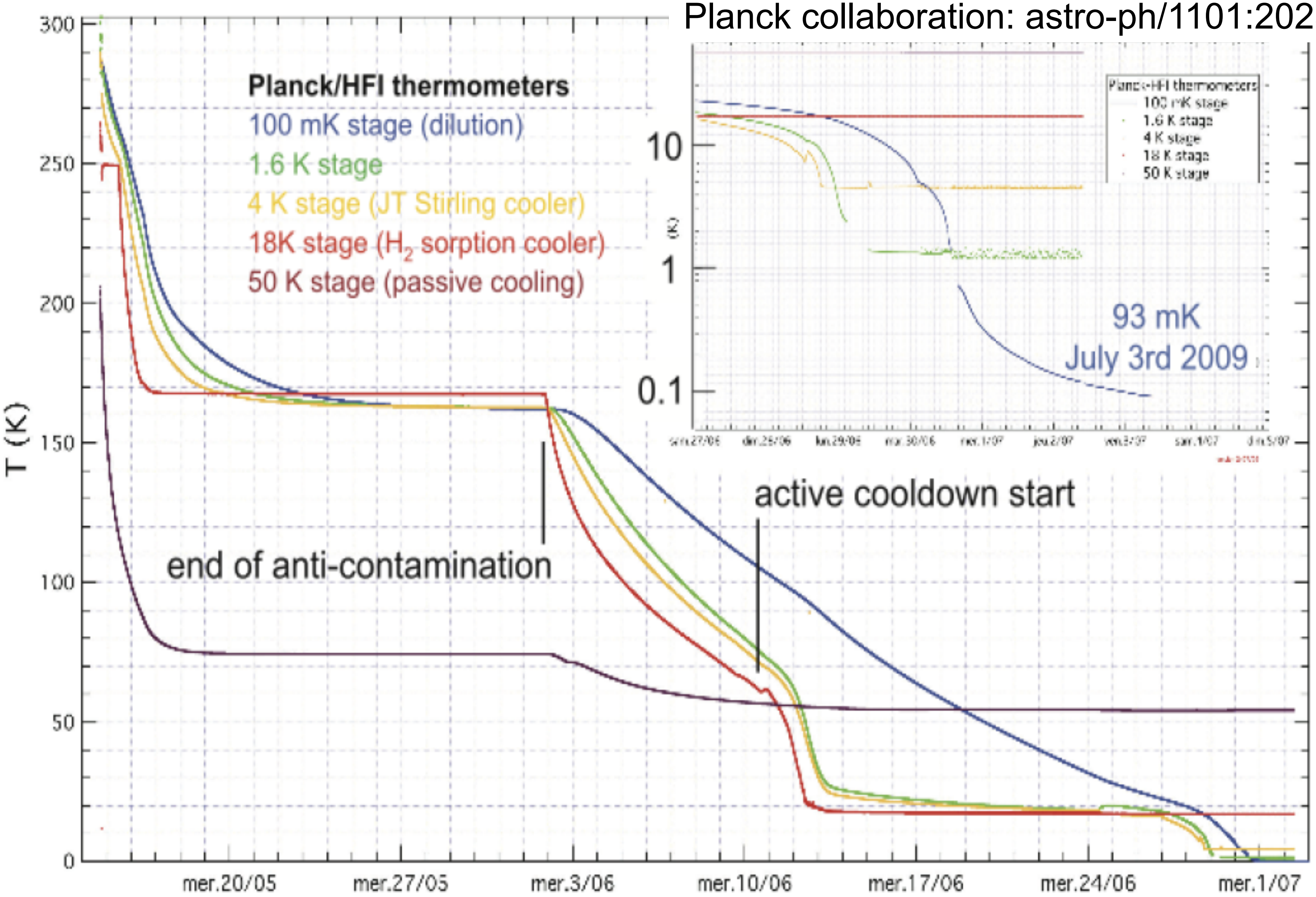
14 / May / 2009

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





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

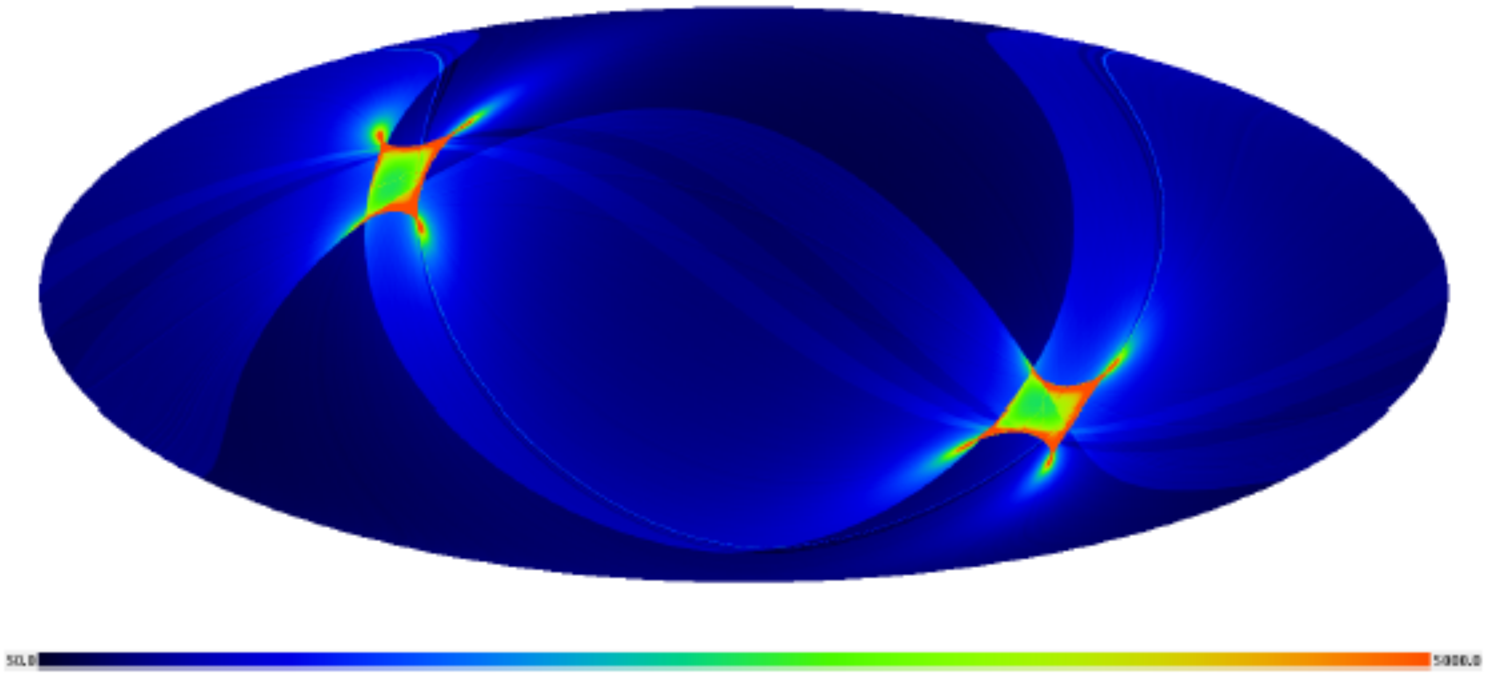


Mission :
Planck collaboration: astro-ph/1101:2022

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× Mean[c]	1.6	1.5	1.2	%
> 9× 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

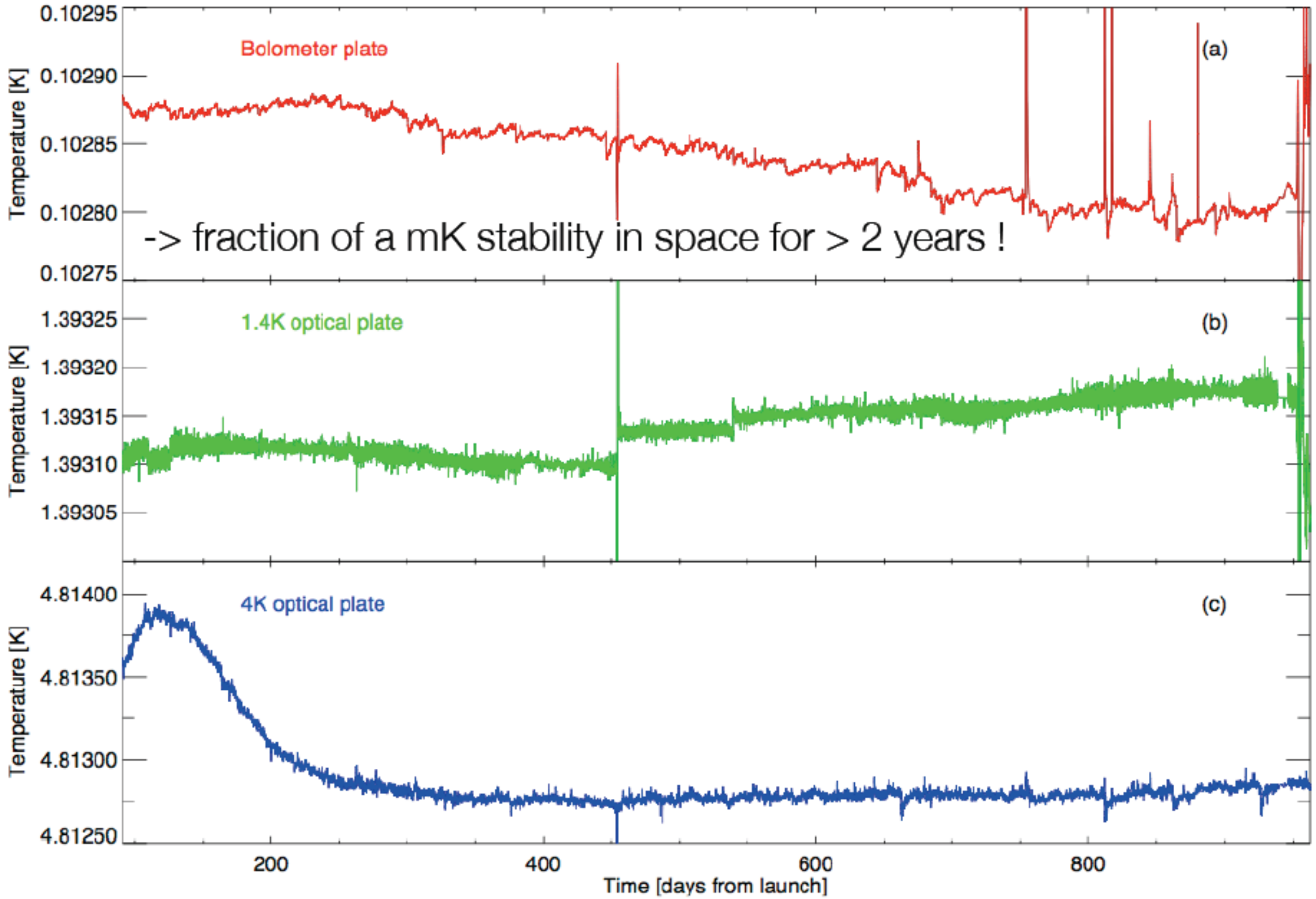
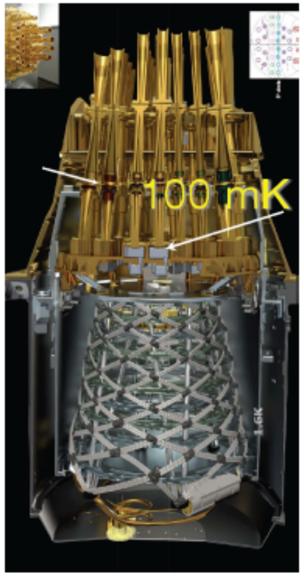
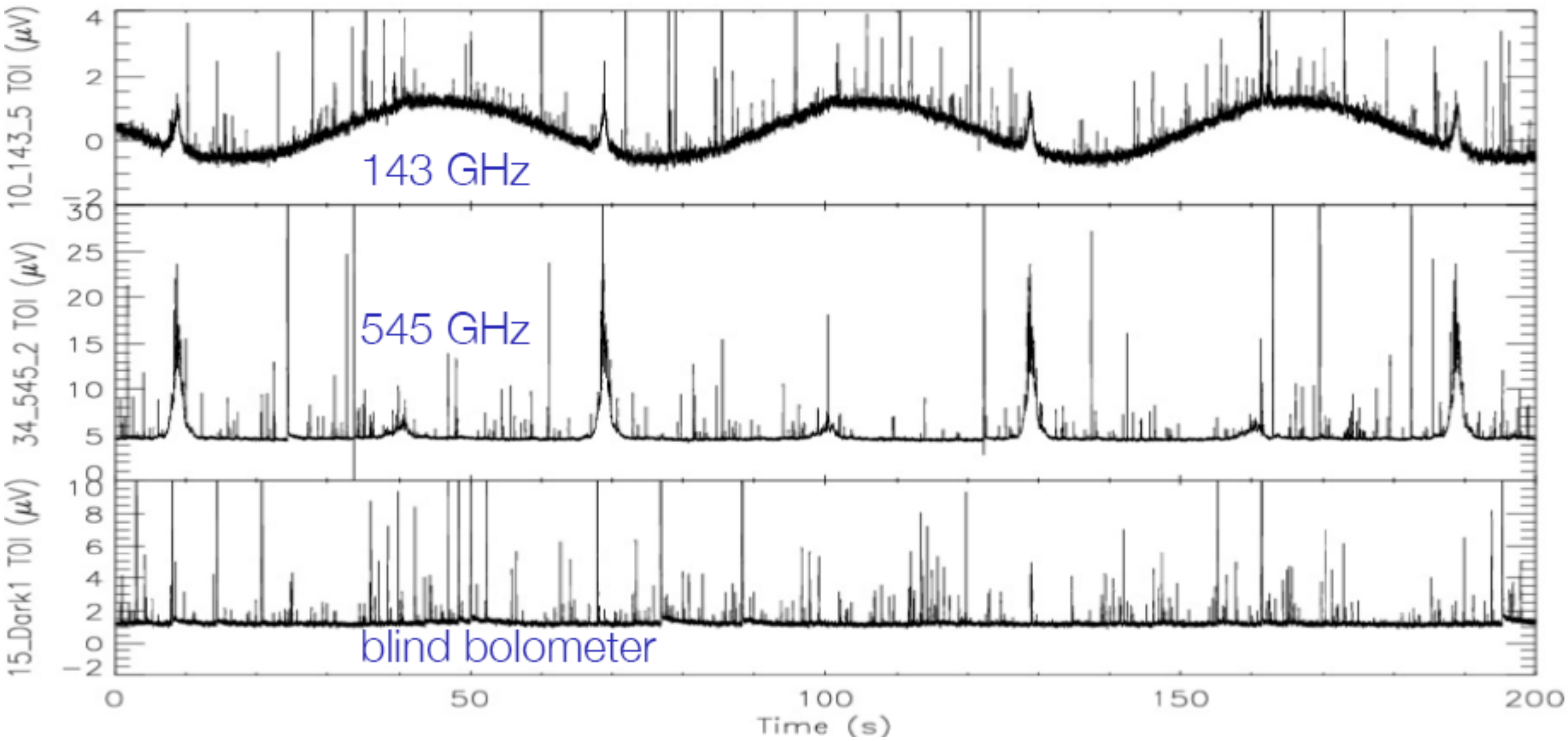


Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal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



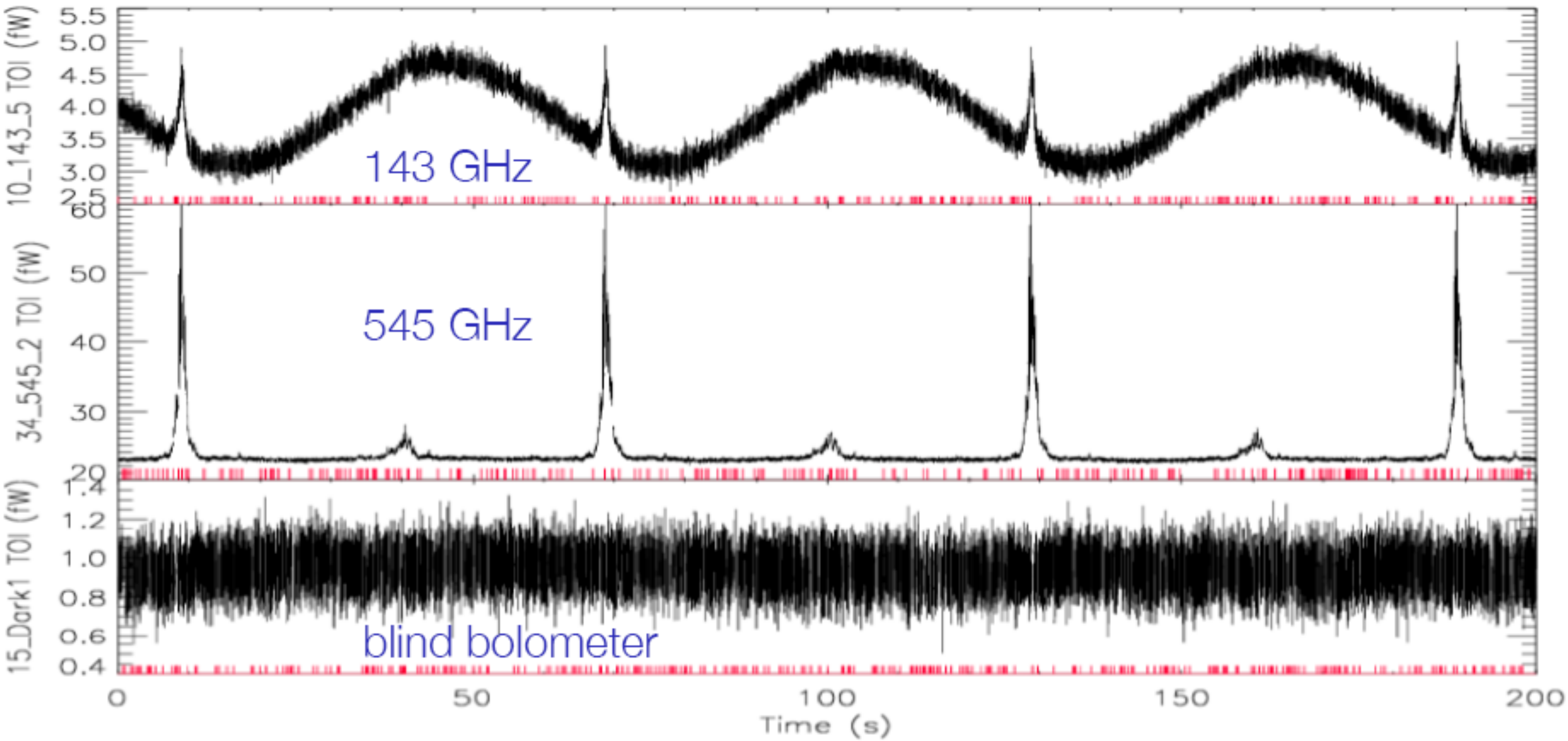
Cryostat:
dilution He3/He4

Raw HFI data



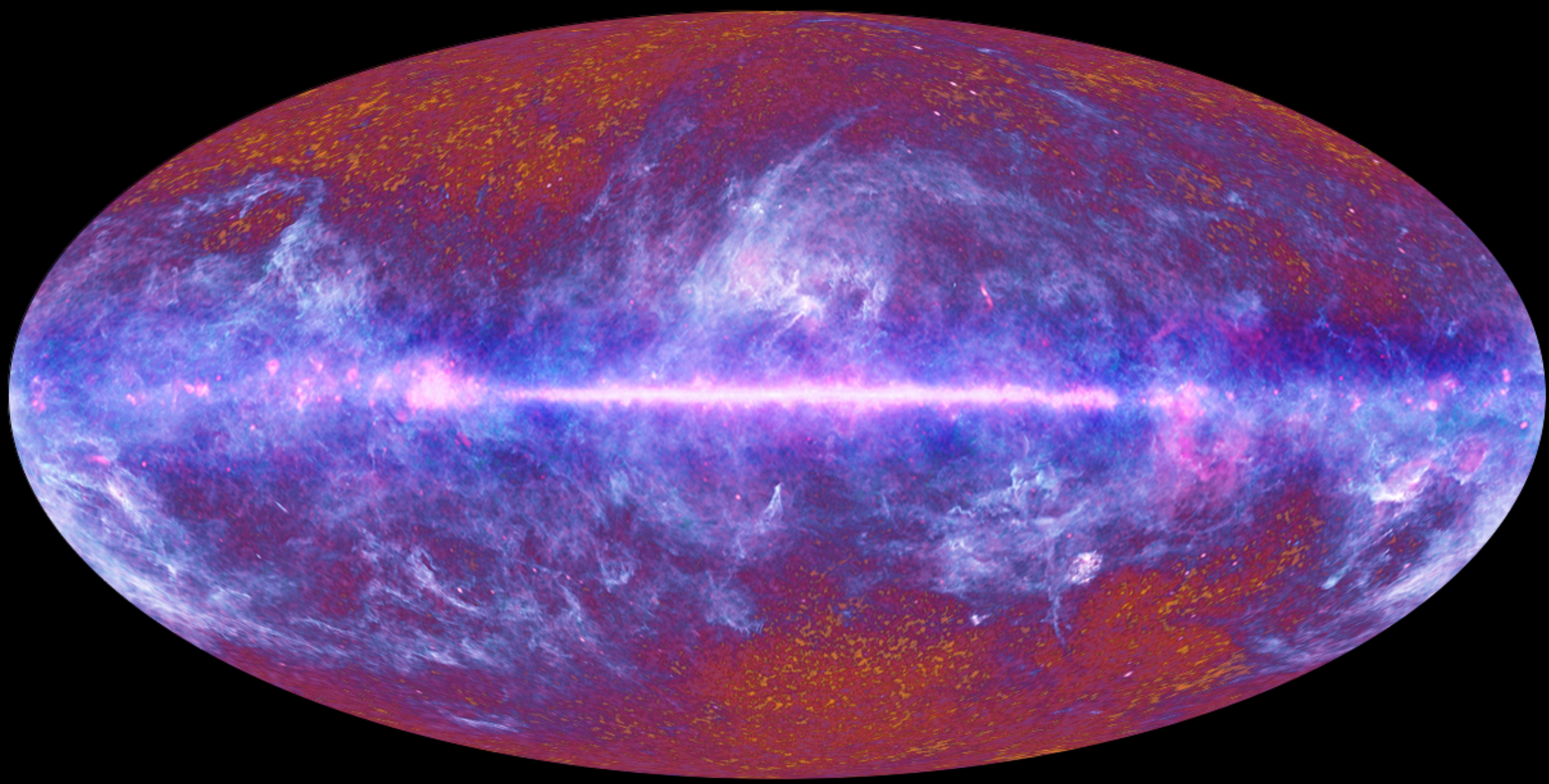
10_143_5 TOI (μV)
34_545_2 TOI (μV)
15_Dark1 TOI (μV)
143 GHz
545 GHz
blind bolometer
Time (s)

De-spiked HFI data



<20% of data flagged

2011 data release



The Planck one-year all-sky survey

esa

The 2013 Planck results

- Planck 2013 results. I. Overview of products and results
- Planck 2013 results. II. Low Frequency Instrument data processing
- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
- Planck 2013 results. VI. High Frequency Instrument data processing
- Planck 2013 results. VII. HFI time response and beams
- Planck 2013 results. VIII. HFI calibration and mapmaking
- 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
- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters
- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
- Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation
- Planck 2013 results. XIX. The integrated Sachs-Wolfe effect
- Planck 2013 results. XX. Cosmology from Sunyaev- Zeldovich cluster counts
- Planck 2013 results. XXI. All-sky Compton-parameter map and characterization
- Planck 2013 results. XXII. Constraints on inflation
- Planck 2013 results. XXIII. Isotropy and statistics of the CMB
- Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity
- Planck 2013 results. XXV. Searches for cosmic strings and other topological defects
- Planck 2013 results. XXVI. Background geometry and topology of the Universe
- Planck 2013 results. XXVII. Special relativistic effects on the CMB dipole
- Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources
- Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources
- Planck 2013 results. Explanatory supplement

29 papers (+1 to come on CIB);
800+ pages
1 Explanatory Supplement
all products available online

The 2013 Planck results

Instruments, processing, systematic effects

- Planck 2013 results. I. Overview of products and results
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Components separation

- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
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Power Spectra, cosmological parameters

- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters

Photon propagation effects

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The Sunyaev-Zeldovich effect

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Constraints on cosmology

- Planck 2013 results. XXII. Constraints on inflation
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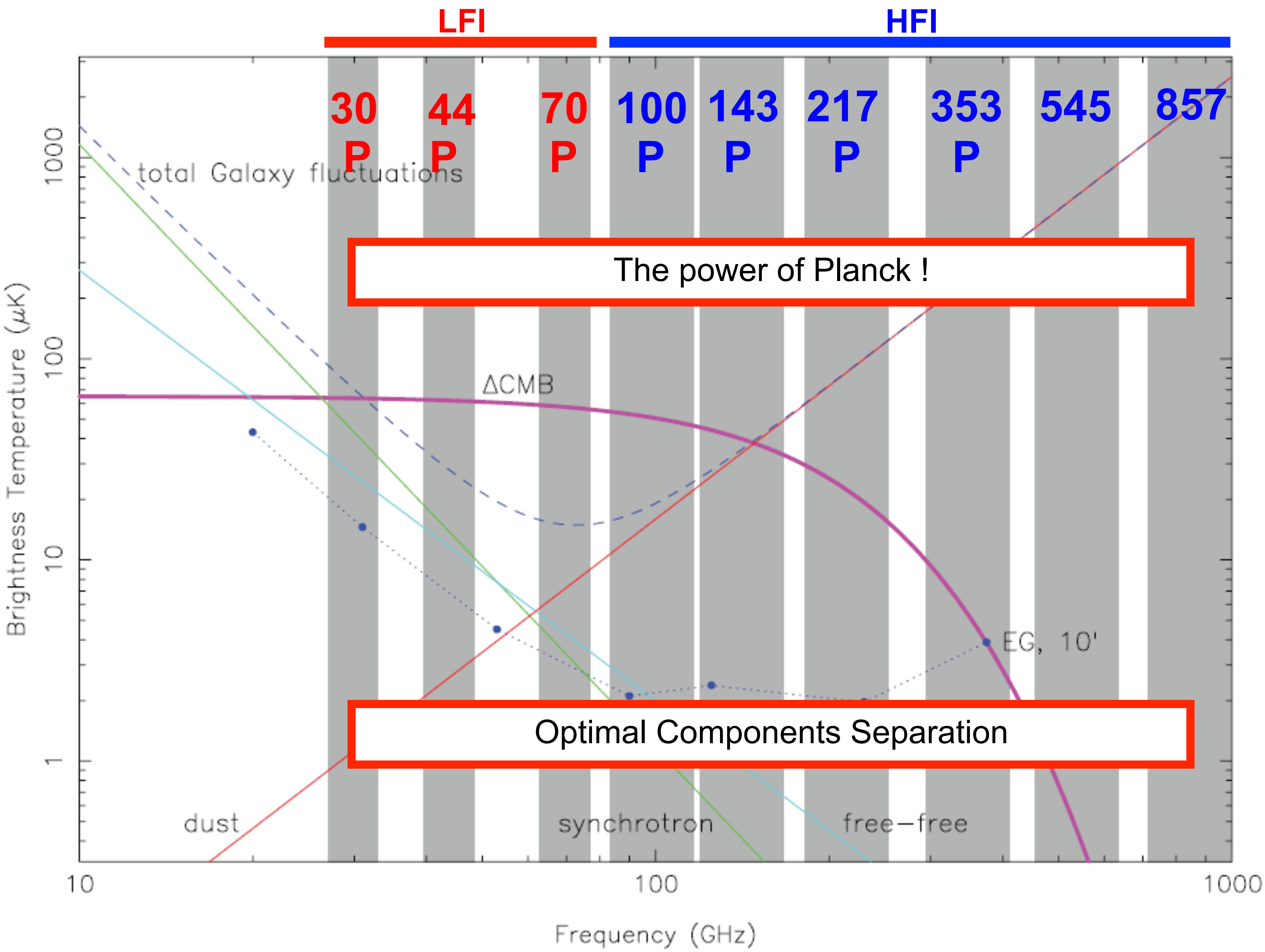
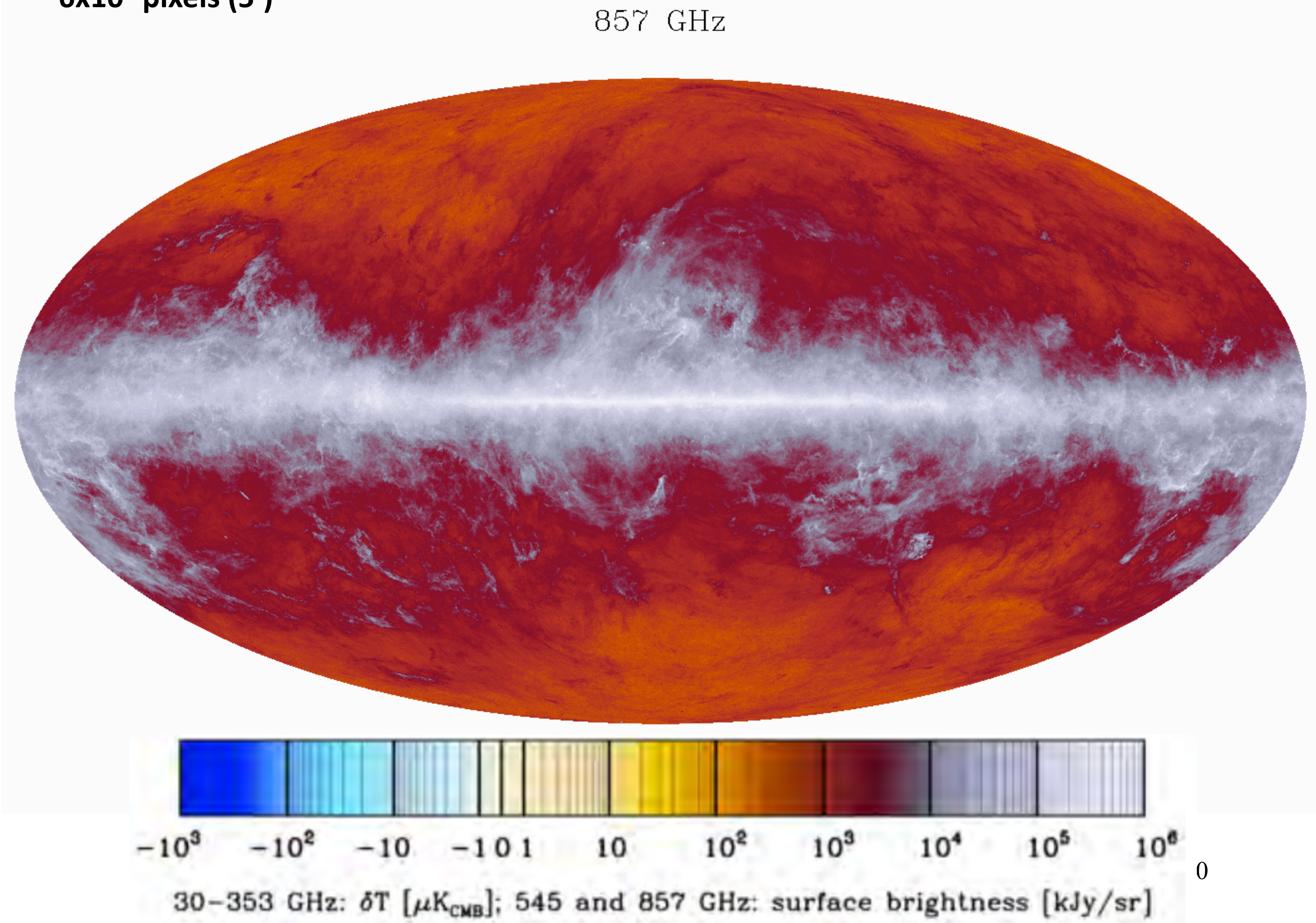


LFI
HFI
30 P
44 P
70 P
100 P
143 P
217 P
353 P
545
857
total Galaxy fluctuations
The power of Planck !
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1
10
100
1000
10
100
1000
Frequency (GHz)

6x10^6 pixels (5')

Planck Legacy Maps



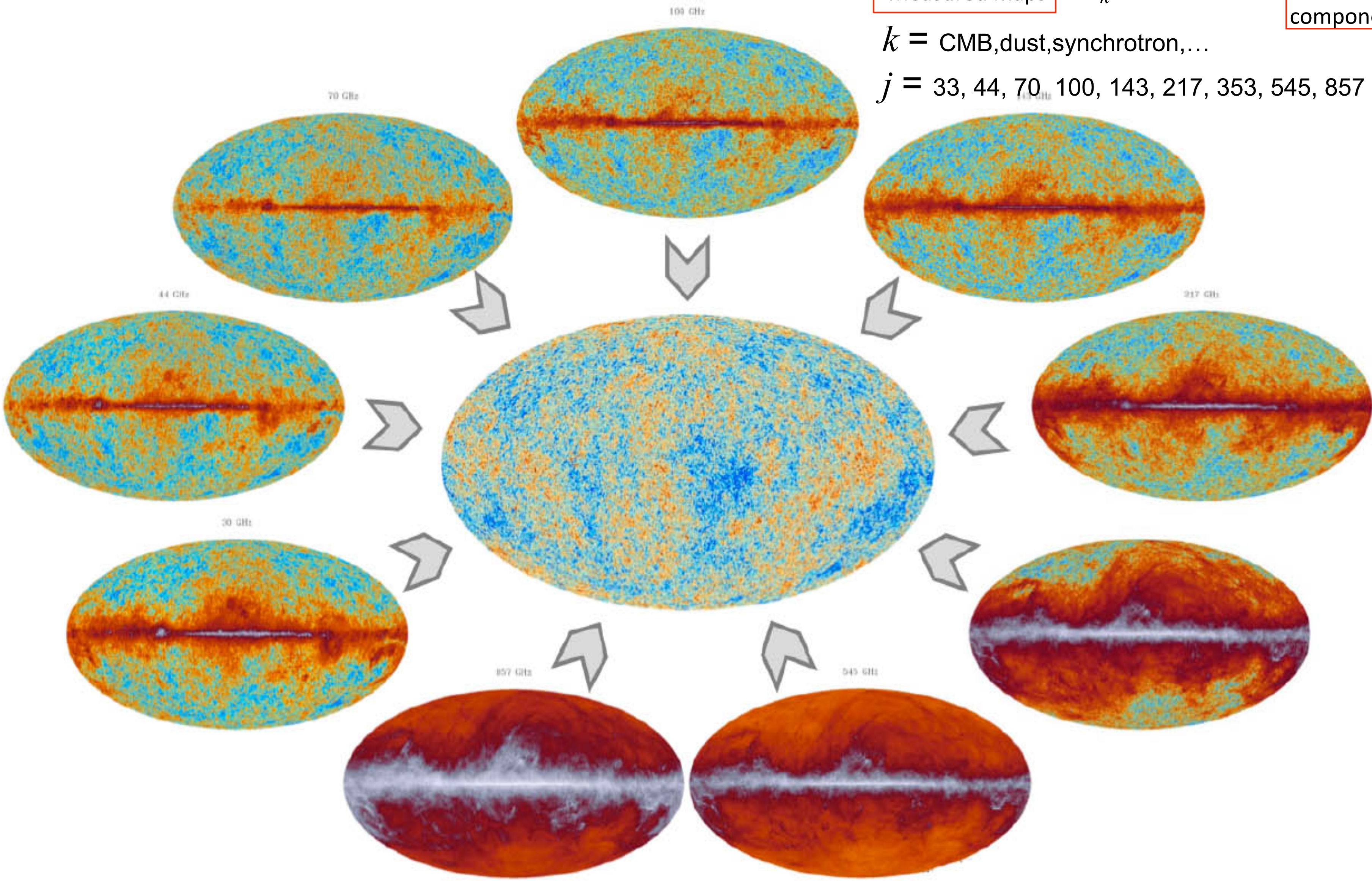
components separation

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

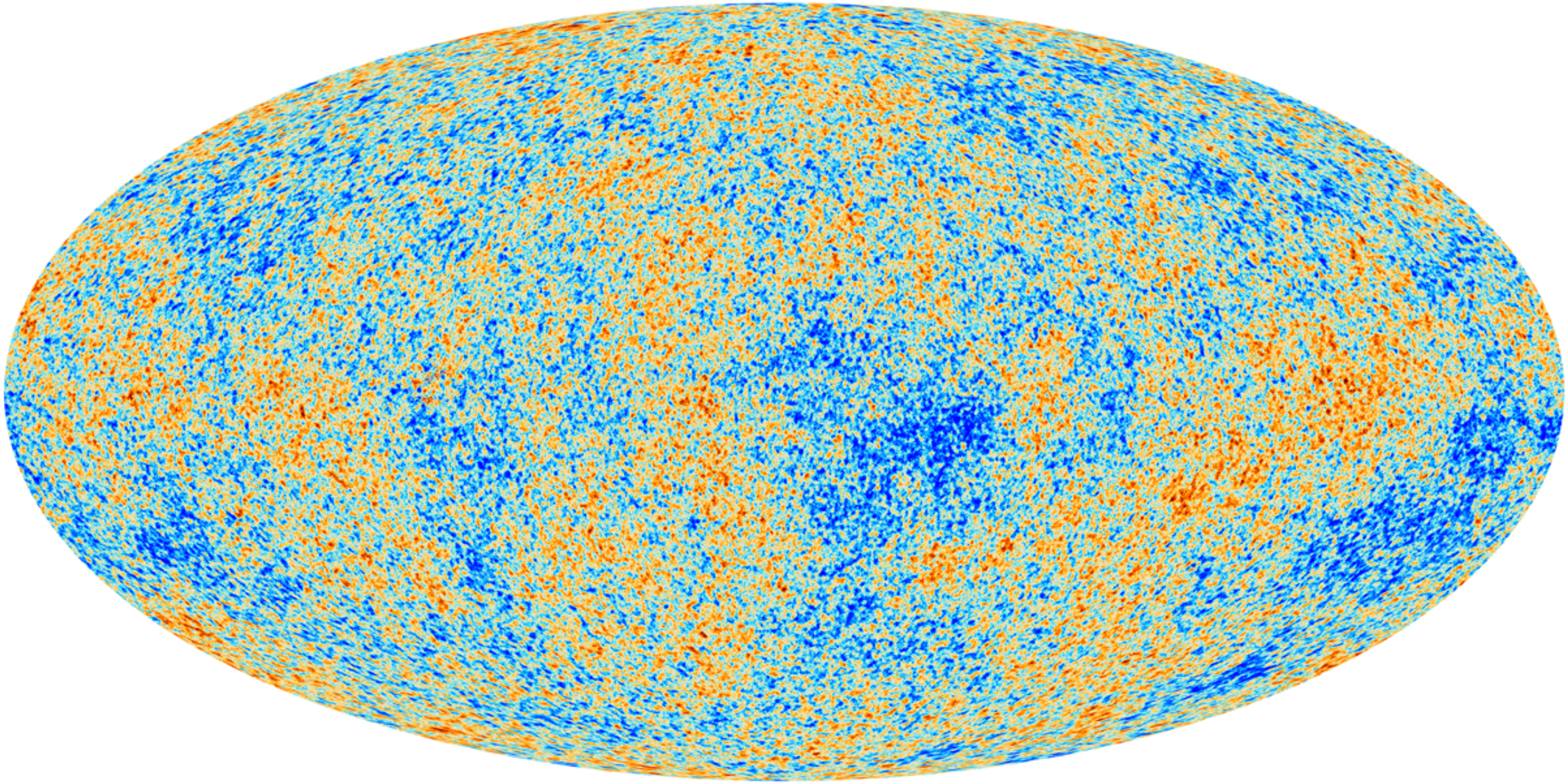
Measured maps — physical components

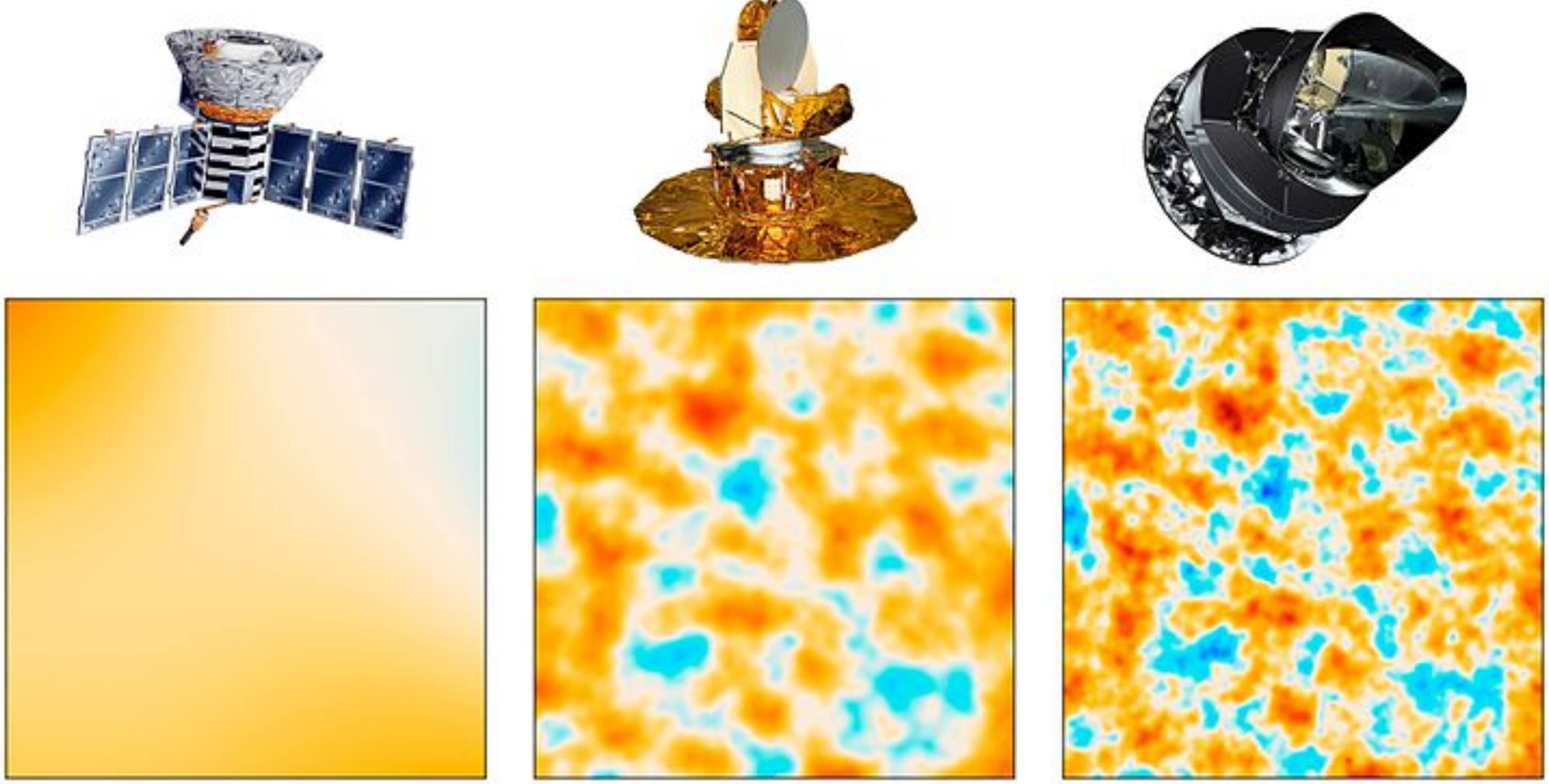
k = CMB,dust,synchrotron,…

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



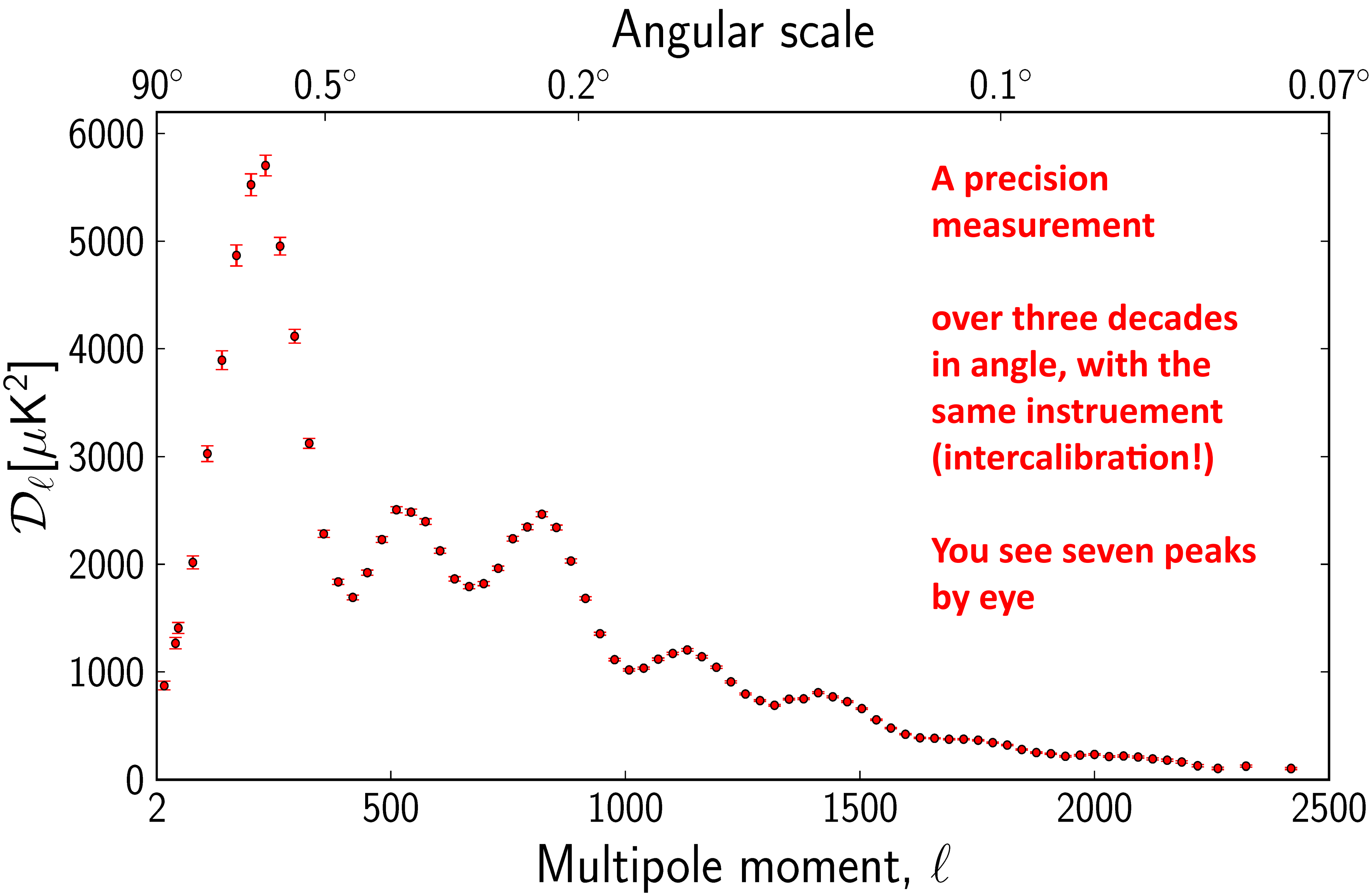
The CMB component





COBE WMAP Planck

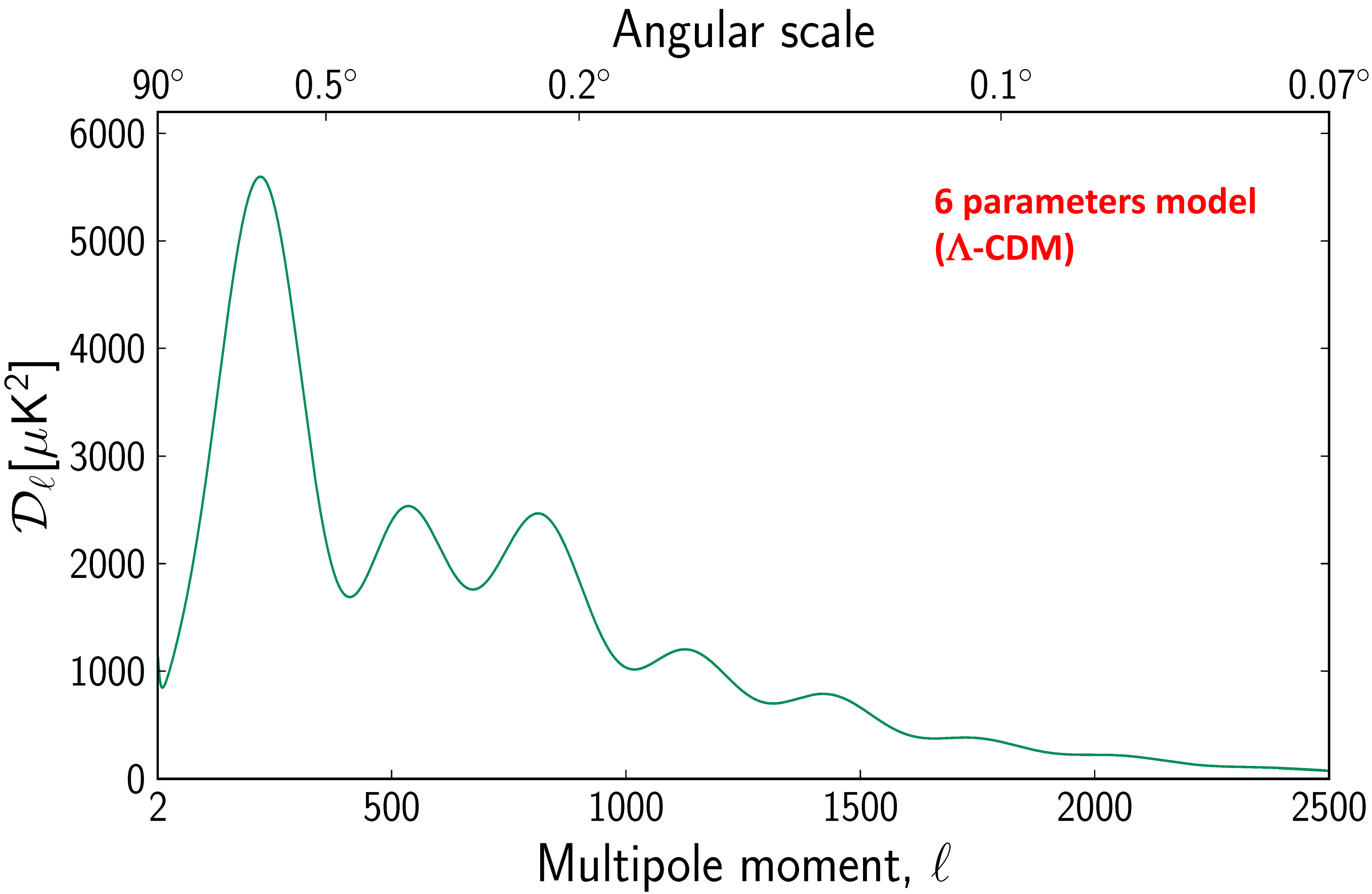
Best angular resolution
Best control of foregorunds

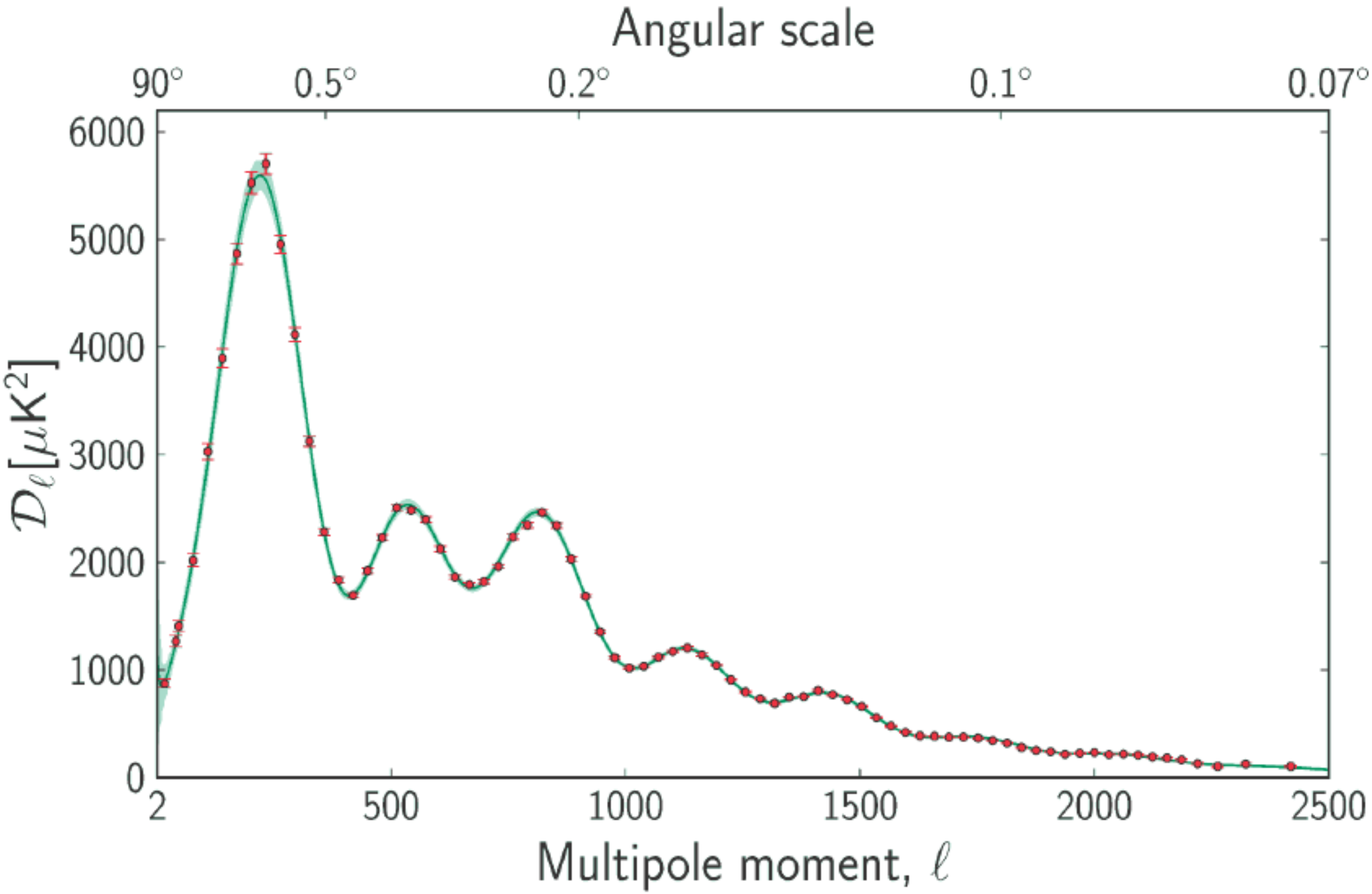


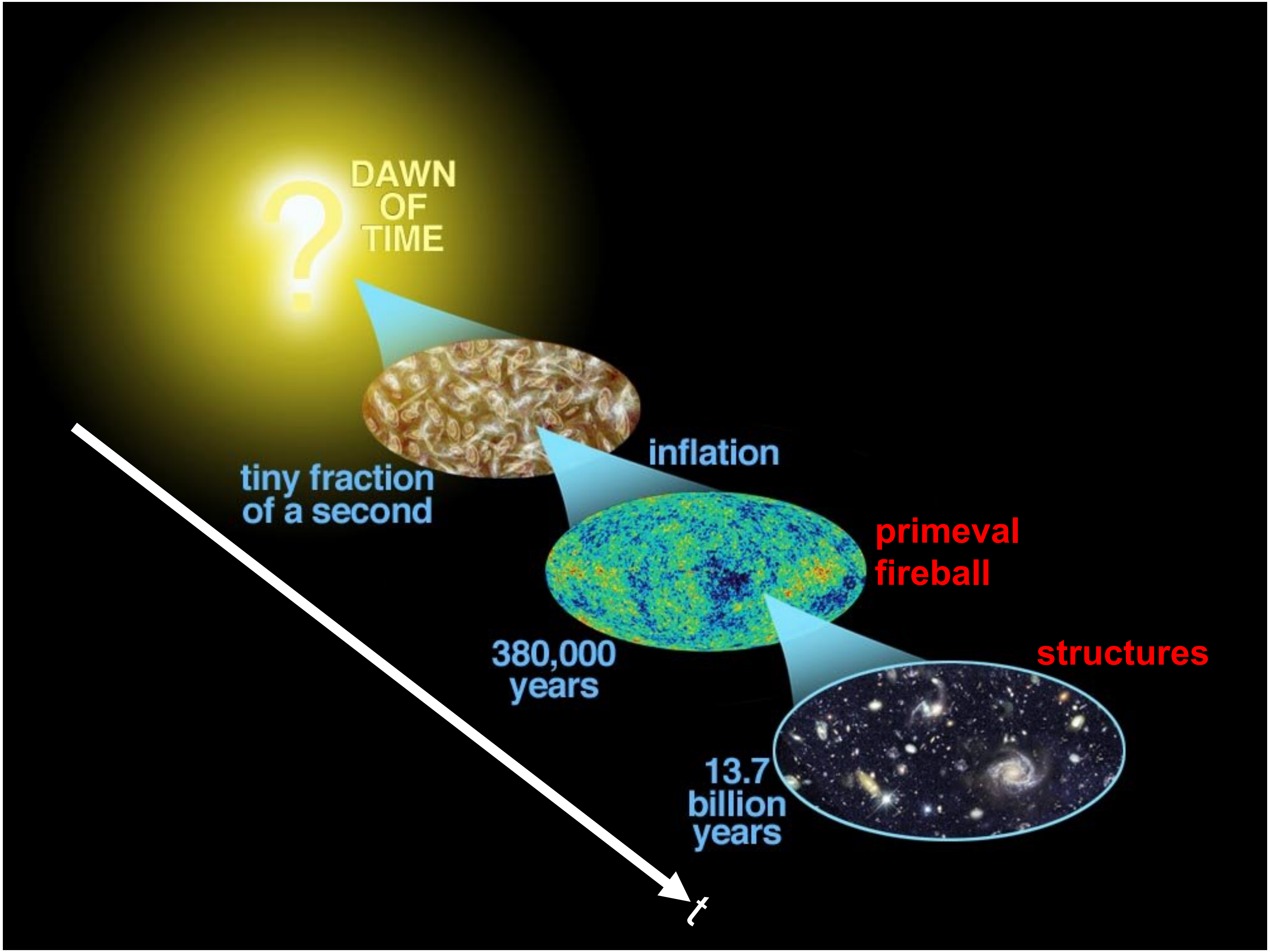
A precision measurement

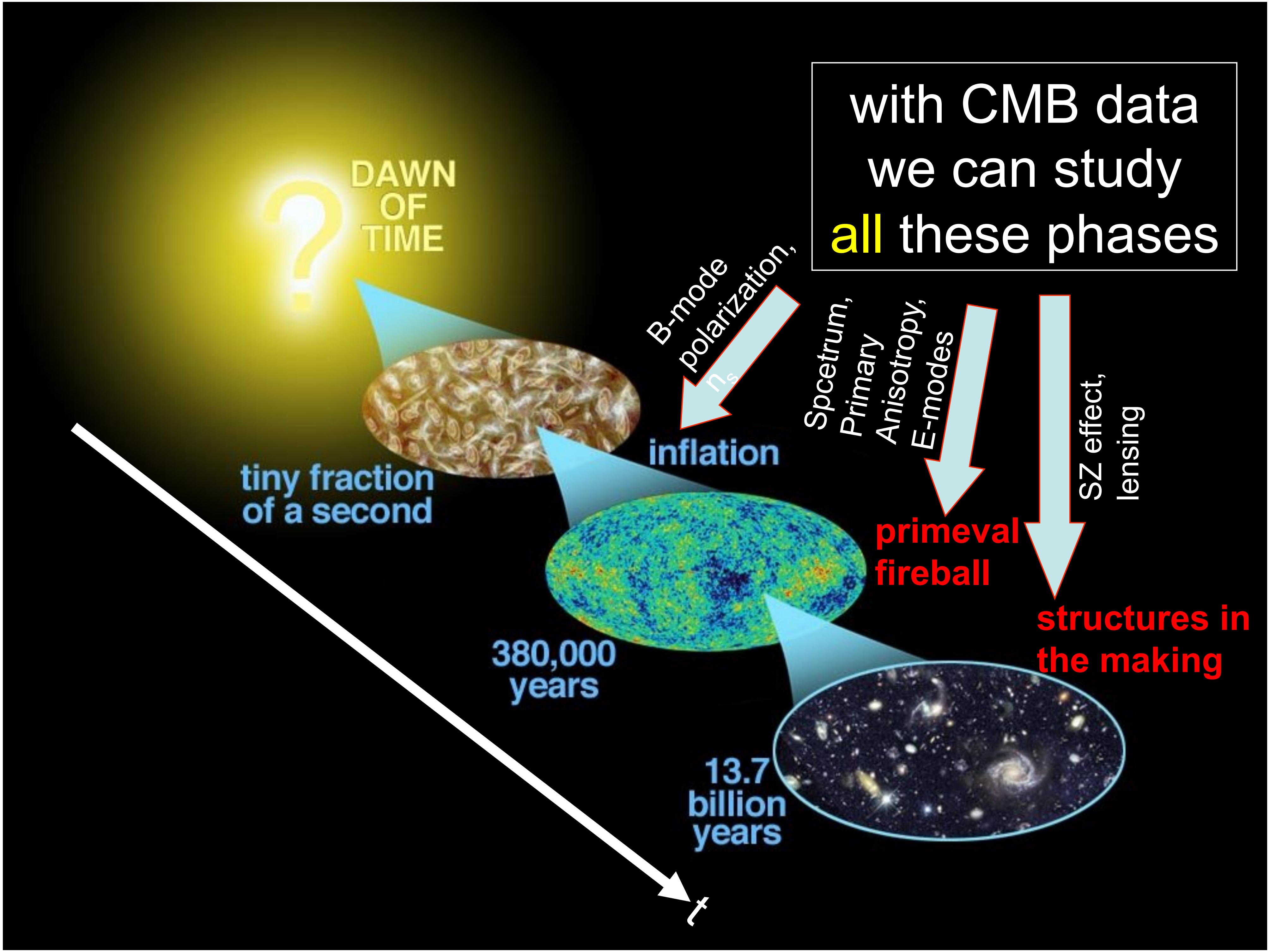
over three decades in angle, with the same instruement (intercalibration!)

You see seven peaks by eye


Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ
6 parameters model
(Λ-CDM)


Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ

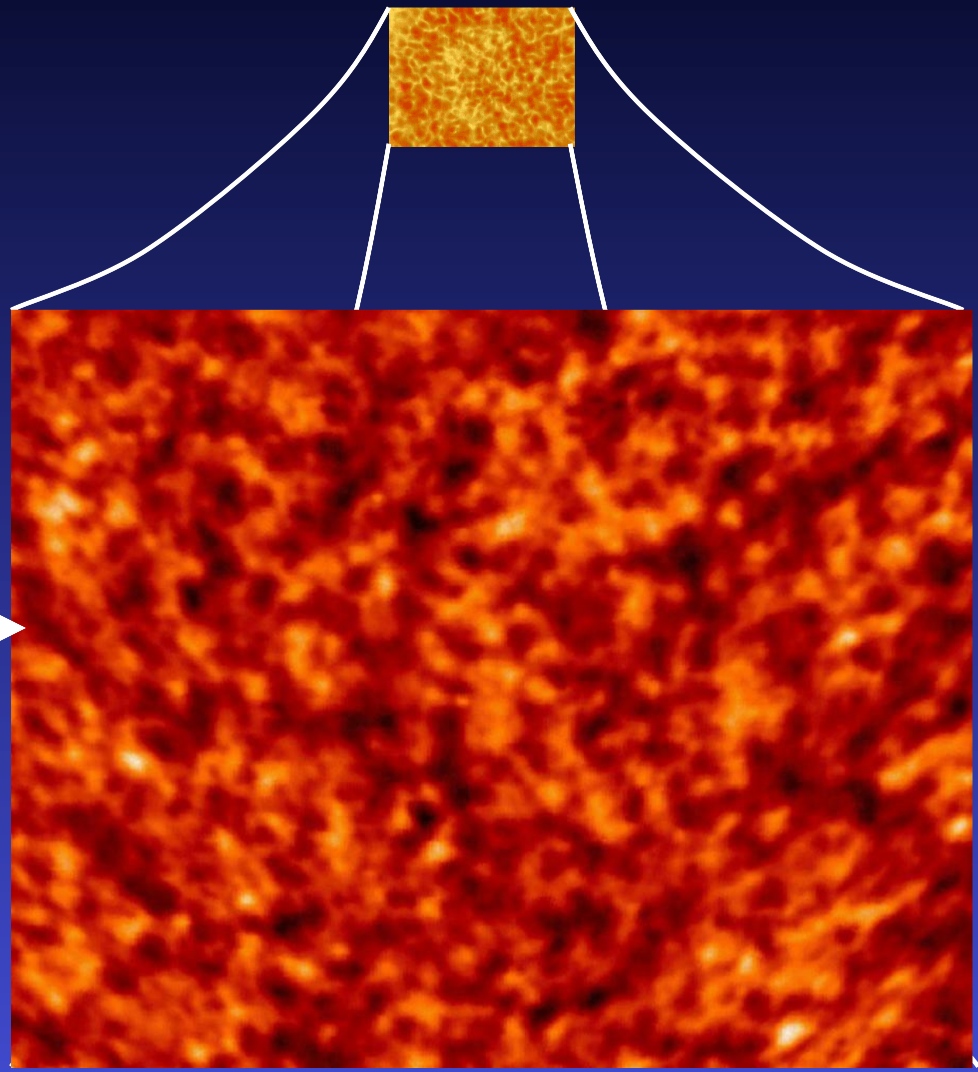

DAWN OF TIME
inflation
tiny fraction of a second
primeval fireball
380,000 years
structures
13.7 billion years
t



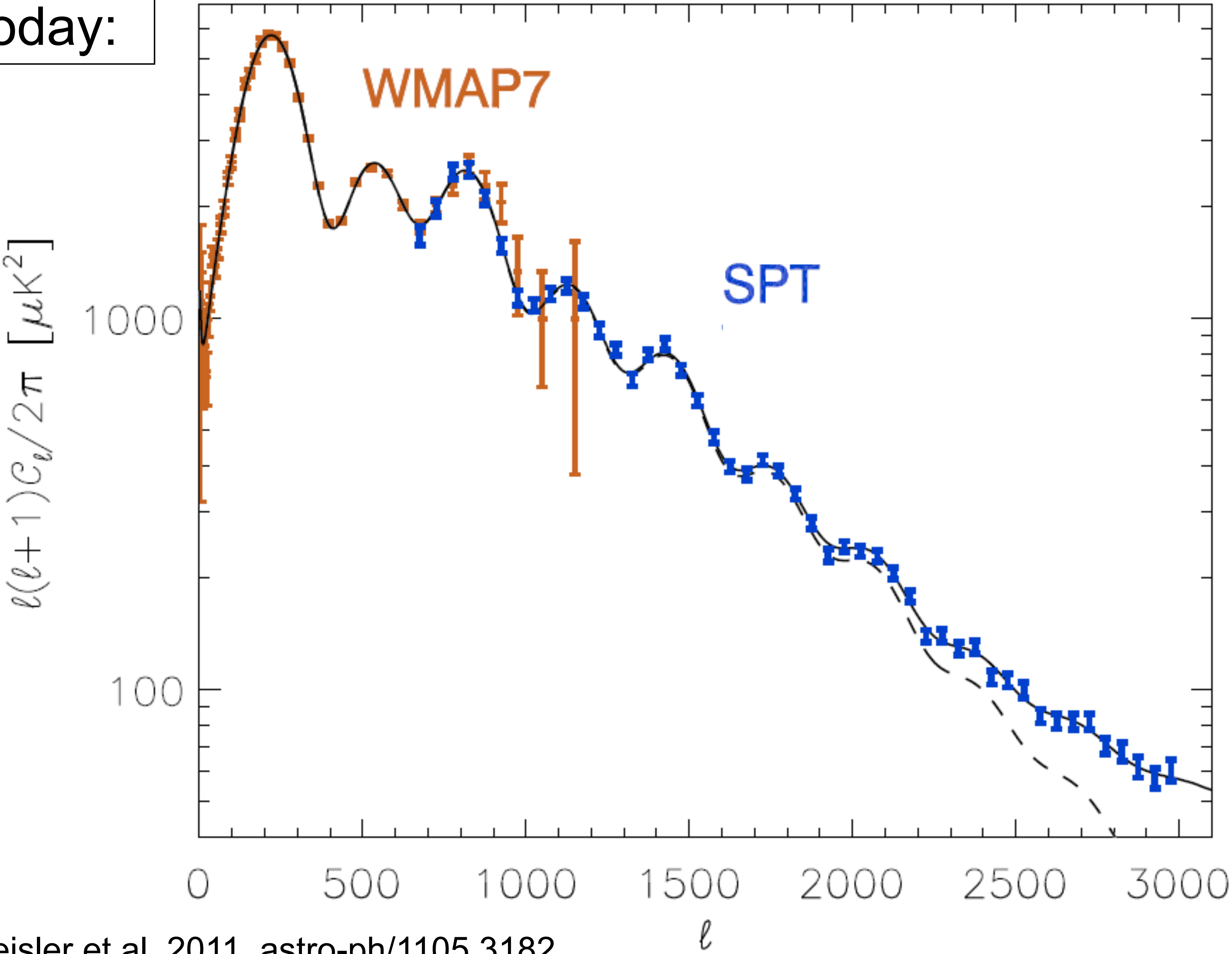
with CMB data we can study all these phases
DAWN OF TIME
?
B-mode polarization, n_s
Spcetrum, Primary Anisotropy, E-modes
SZ effect, lensing
inflation
tiny fraction of a second
primeval fireball
structures in the making
380,000 years
13.7 billion years
t

Inflation: a predictive theory

- Space is flat, geometry is Euclidean
- Quantum fluctuations at microscopic scales in the pre-inflation era produce density fluctuations at cosmological scales in the post inflation era.
- These are gaussian and almost scale-invariant
- These grow gravitationally, oscillate, produce CMB anistropy
- Very precise characteristics of CMB anisotropy.

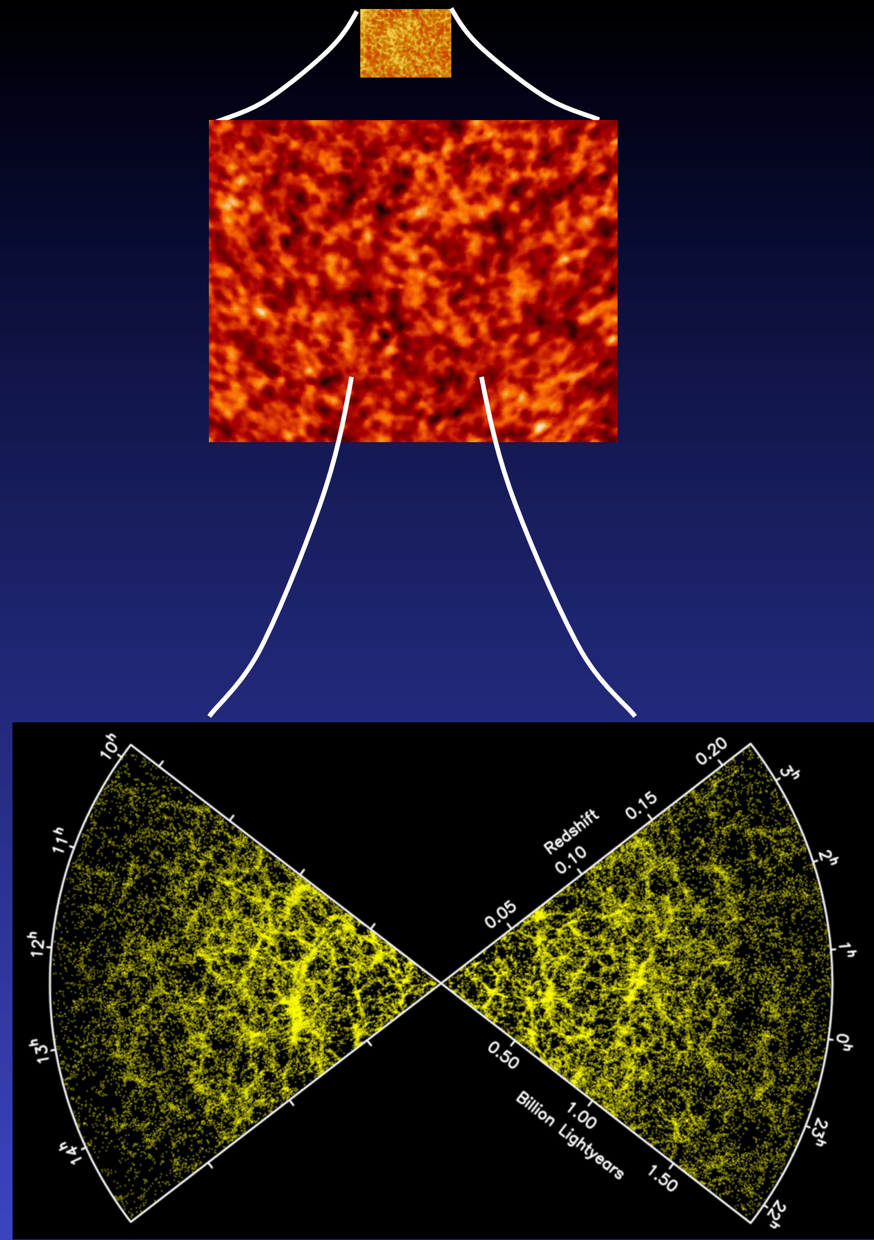


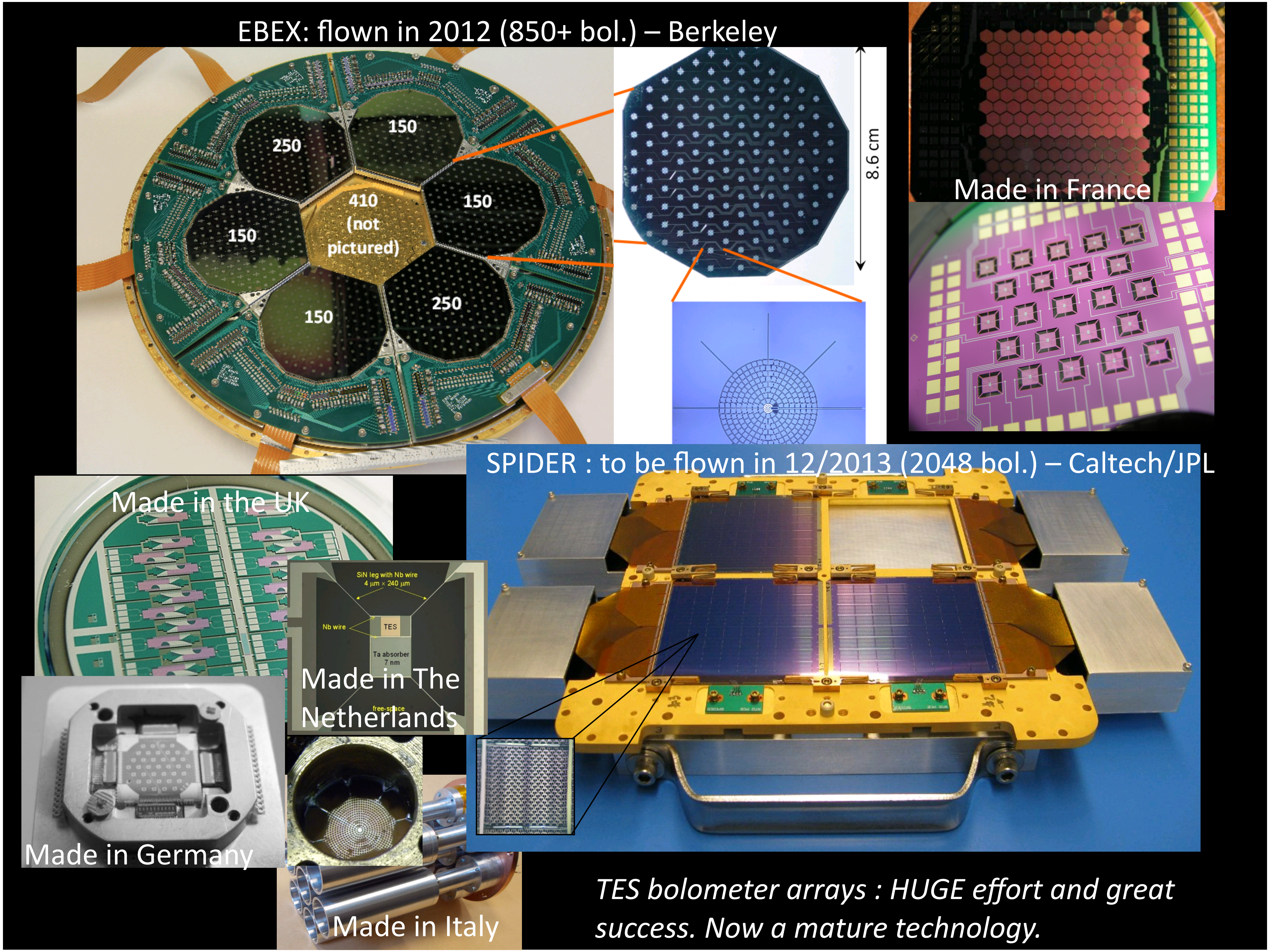
Today:



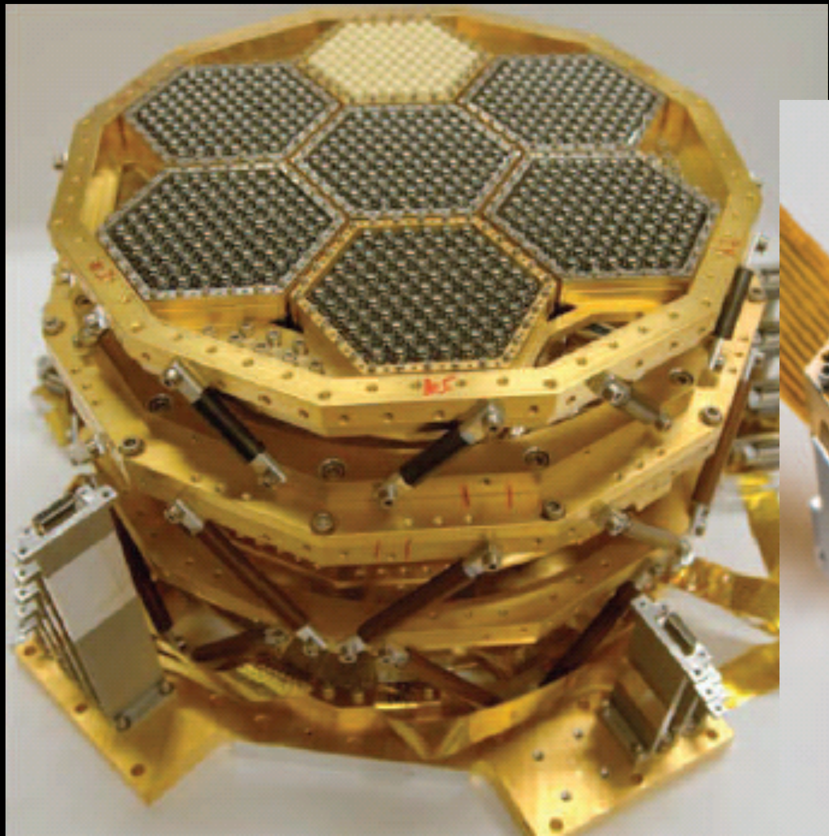
Keisler et al. 2011, astro-ph/1105.3182

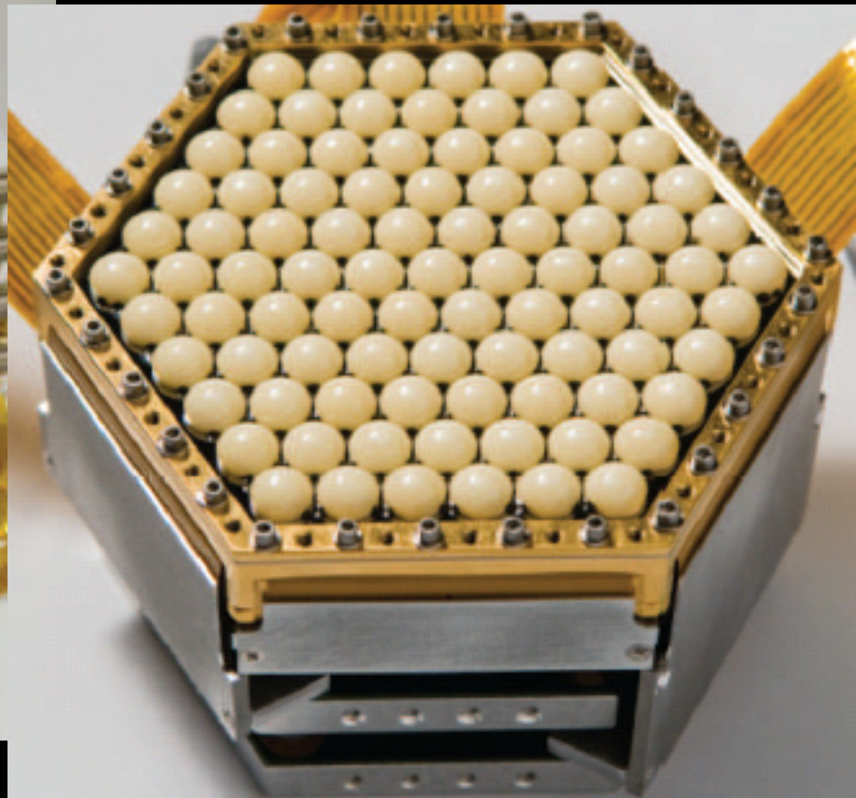
- Space is flat, geometry is Euclidean
- Quantum fluctuations at microscopic scales in the pre-inflation era produce density fluctuations at cosmological scales in the post inflation era.
- These are gaussian and almost scale-invariant
- These grow gravitationally, oscillate, produce CMB anistropy
- and eventually the large scale structure in the universe.
- The ultra-fast expansion produces gravitational waves and polarization of the CMB.




EBEX: flown in 2012 (850+ bol.) – Berkeley
250
150
410
(not
pictured)
150
150
150
250
8.6 cm
Made in France
SPIDER : to be flown in 12/2013 (2048 bol.) – Caltech/JPL
Made in the UK
SiN leg with Nb wire
4 µm × 240 µm
Nb wire
TES
Ta absorber
7 nm
Made in The
Netherlands
Made in Germany
Made in Italy
TES bolometer arrays : HUGE effort and great
success. Now a mature technology.

The trend :



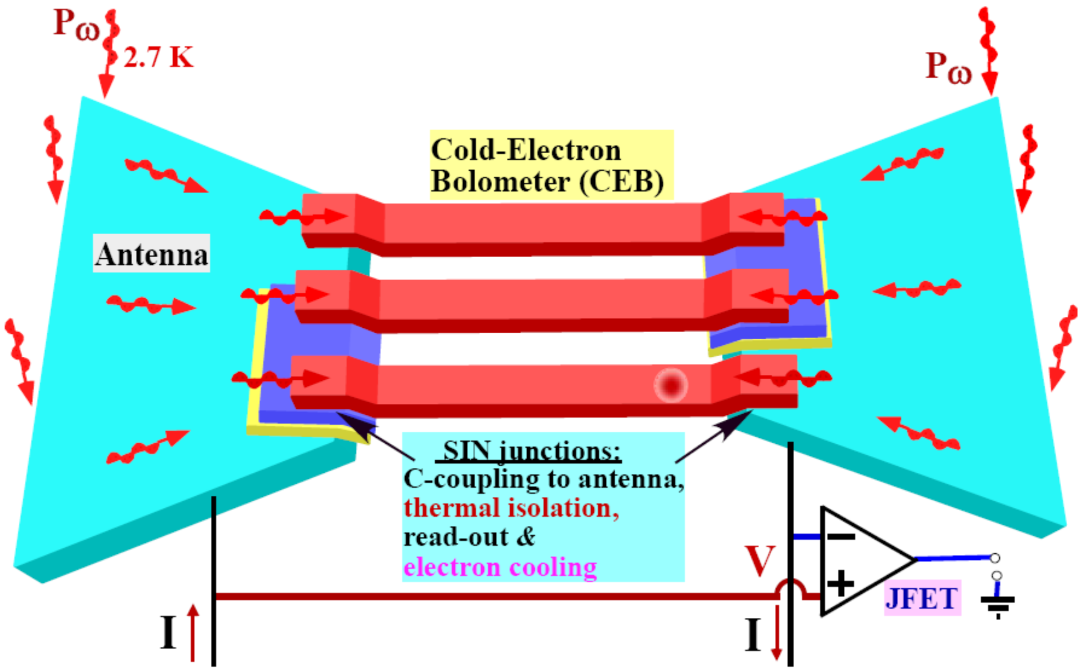


- Large arrays of multichroic pixels: 6000+ detectors for polarbear2, SPTpol, litebird …
- ESA ITT for compact focal planes (Maynooth)

2)

Improving over TES bolometers ?

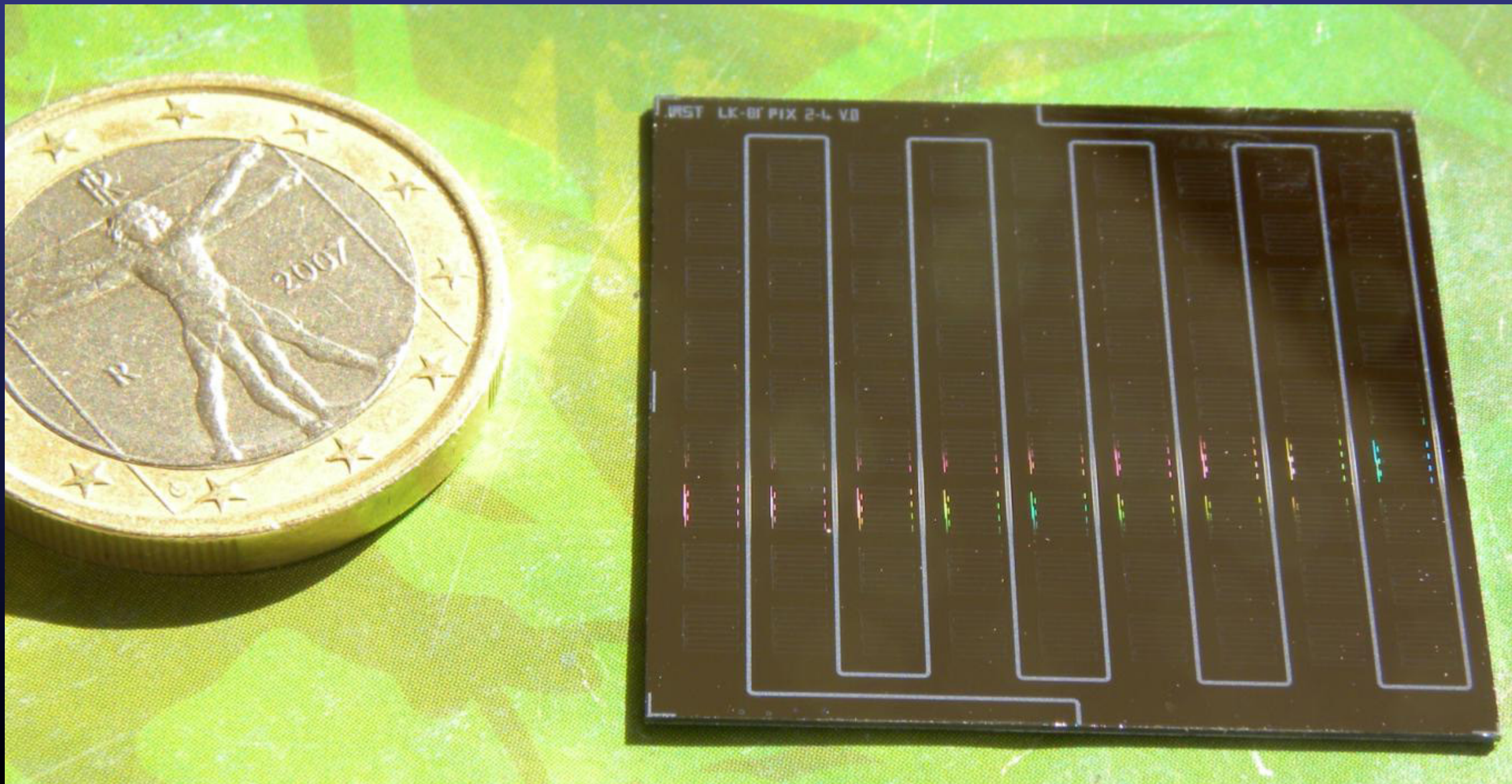
- KIDs & CEBs !
- KIDs made in Cardiff, Grenoble, Rome/TN etc.
- CEBs made in Chalmers



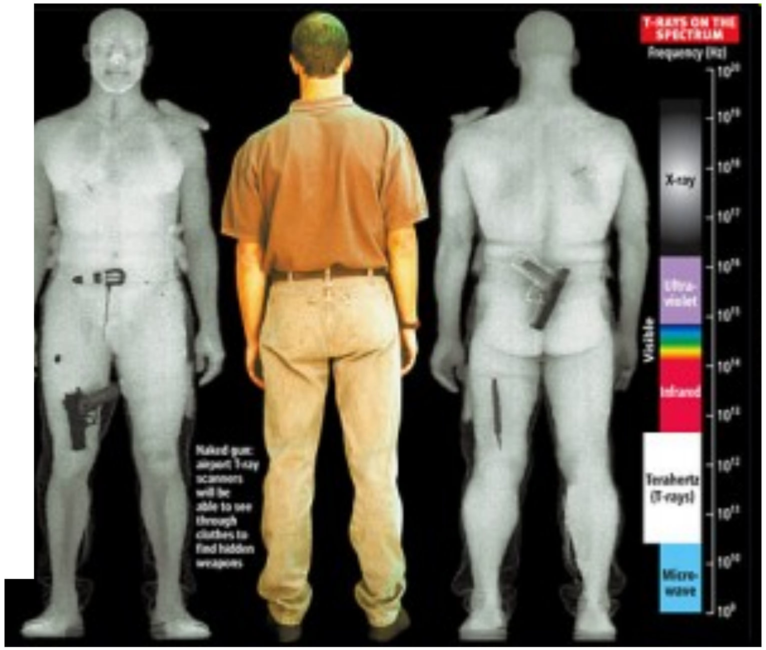
Very insensitive to CR hits (sensing electrons are confined in a sub-μm sized junction, and effectively decoupled from the lattice)
Kuzmin et al. 2010

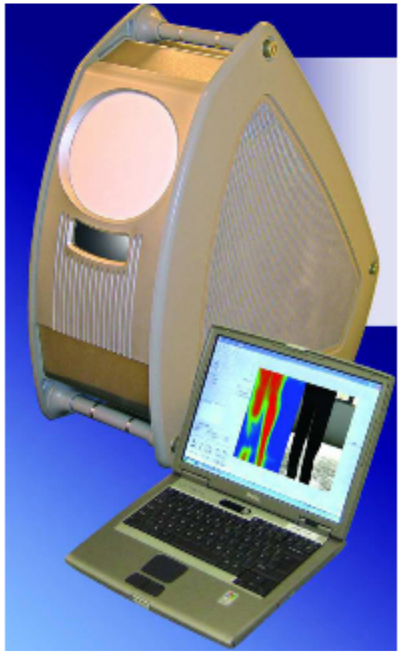
KIDs

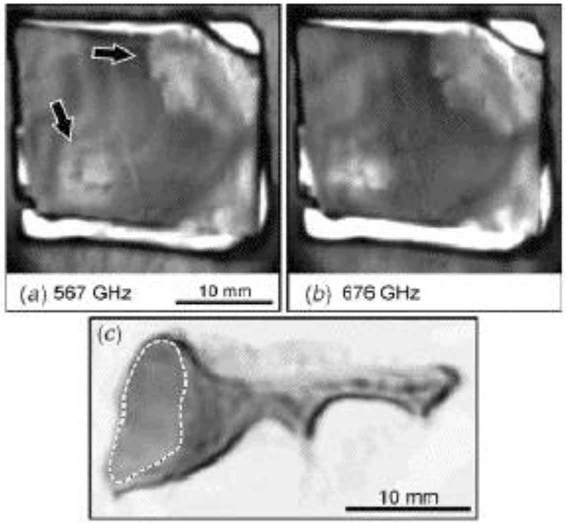
- You heard about the great results of the Grenoble group with kinetic inductance detectors at the IRAM dish (NIKA).
- However, CMB BLIP is not reached yet, and standard KIDs are very sensitive to CR hits.
- KIDs are easier than TES to build, at least in the ground based versions.
- Space-based version still to be developed, and significant added complexity.

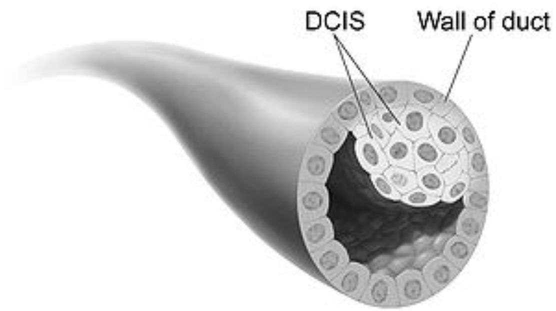


KIDs array made in Italy (Calvo et al. 2010)



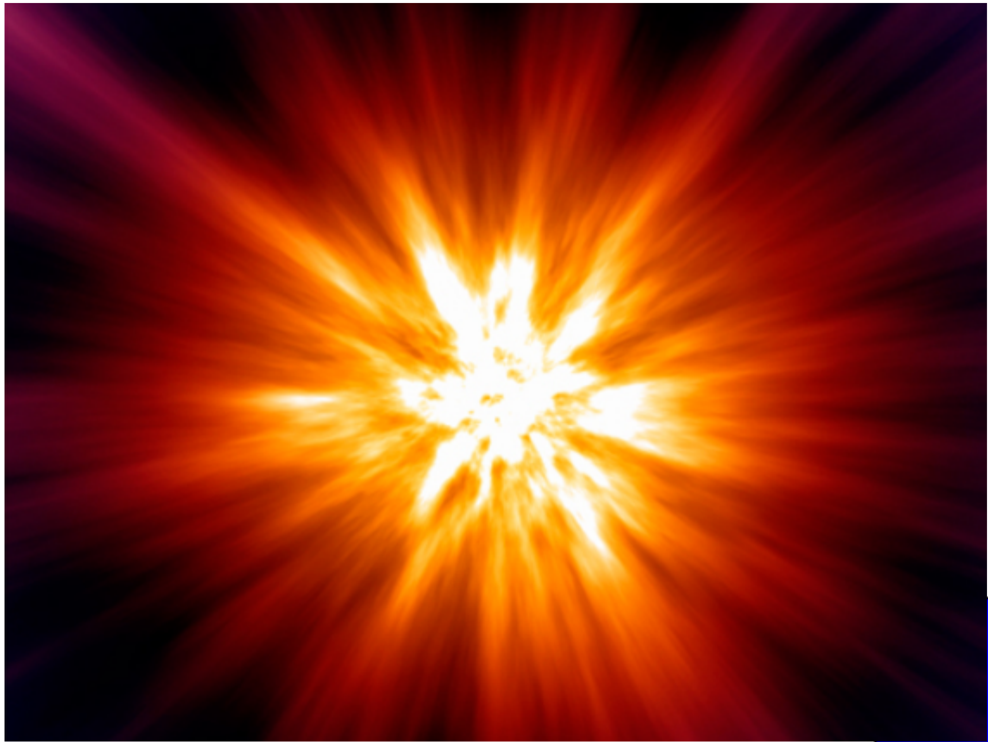






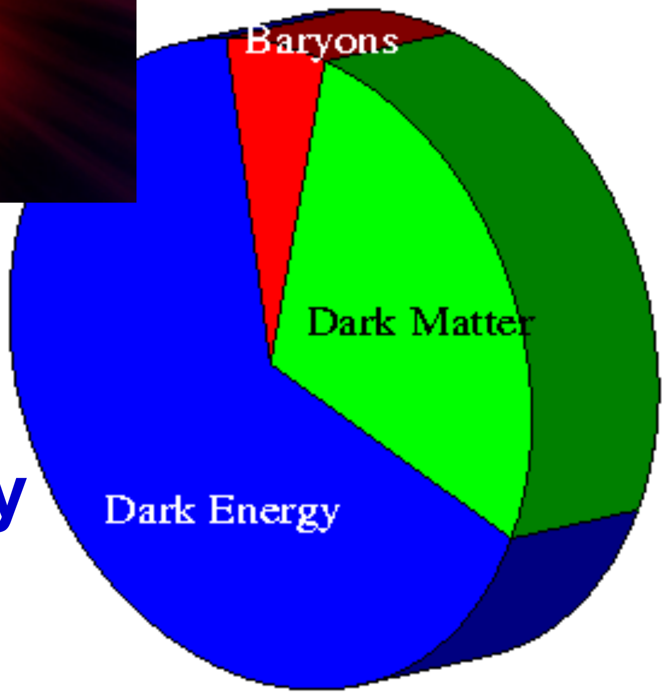
National Cancer Institute

Enigmas in cosmology, today.
(or in fundamental physics ?)



Inflation

?



? Dark Energy 74%

Dark Matter 22%

?