Osservare il passato remoto dell' Universo

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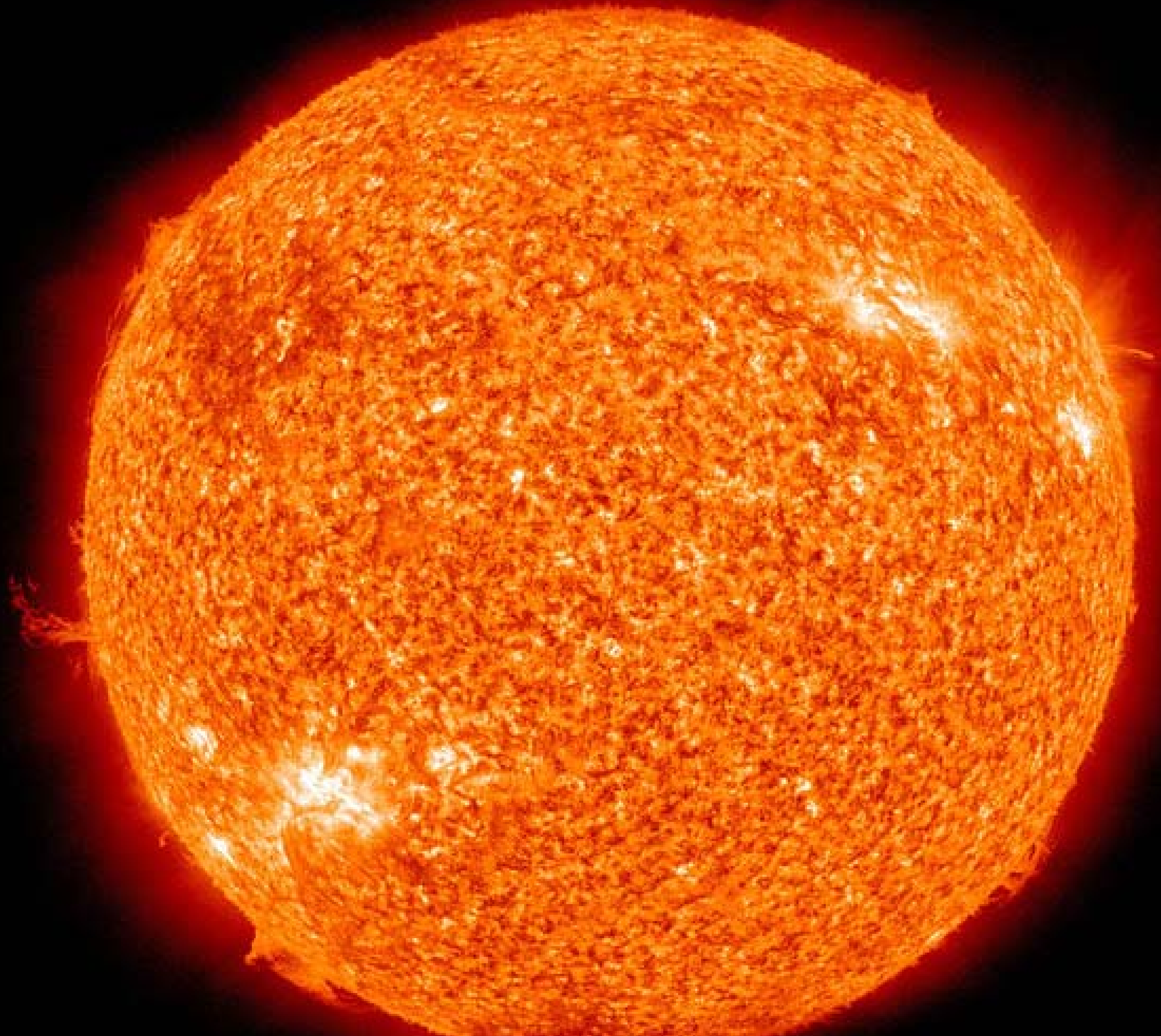
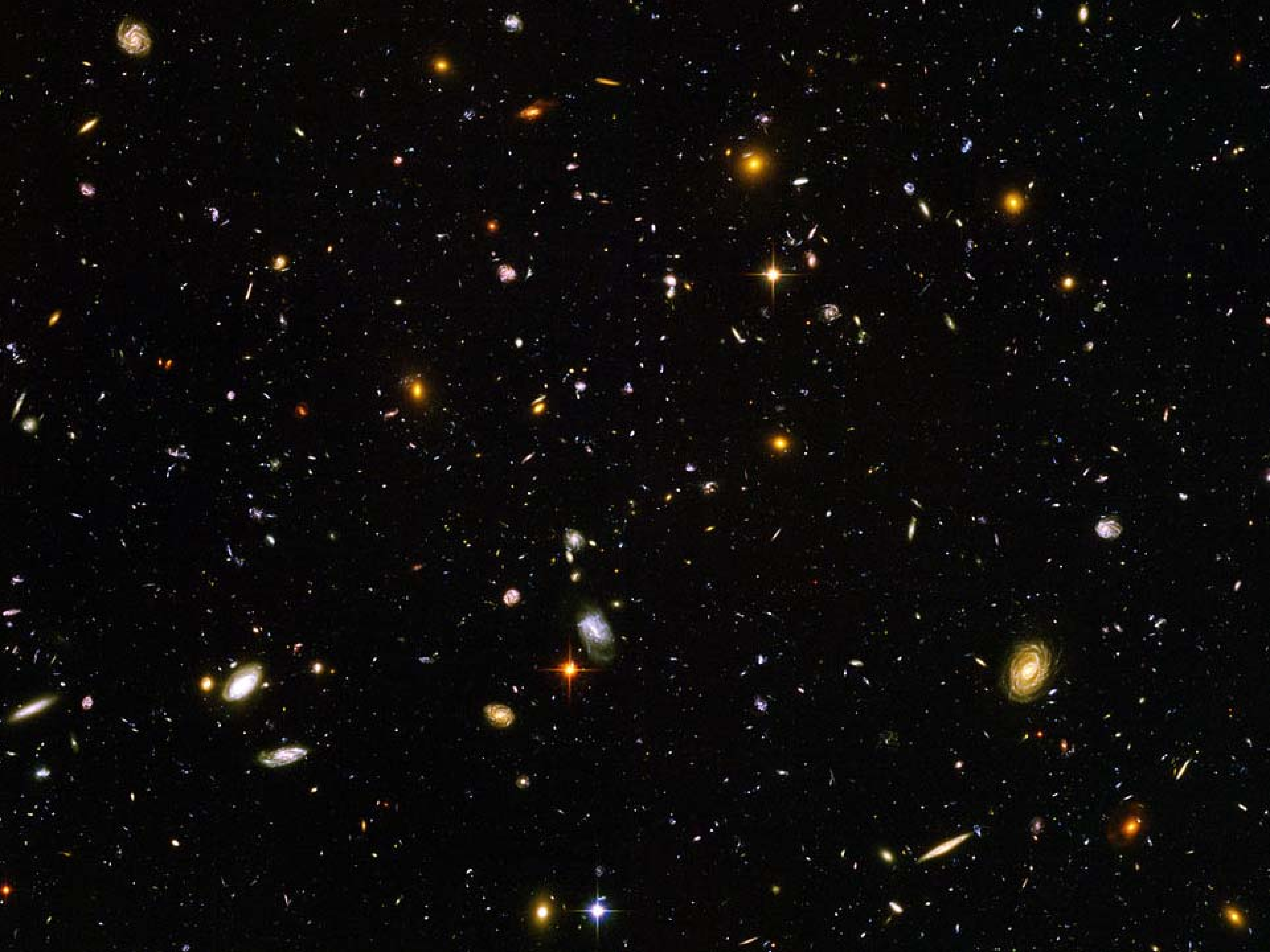
$c = 2.99792458 \times 10^8$ m/s

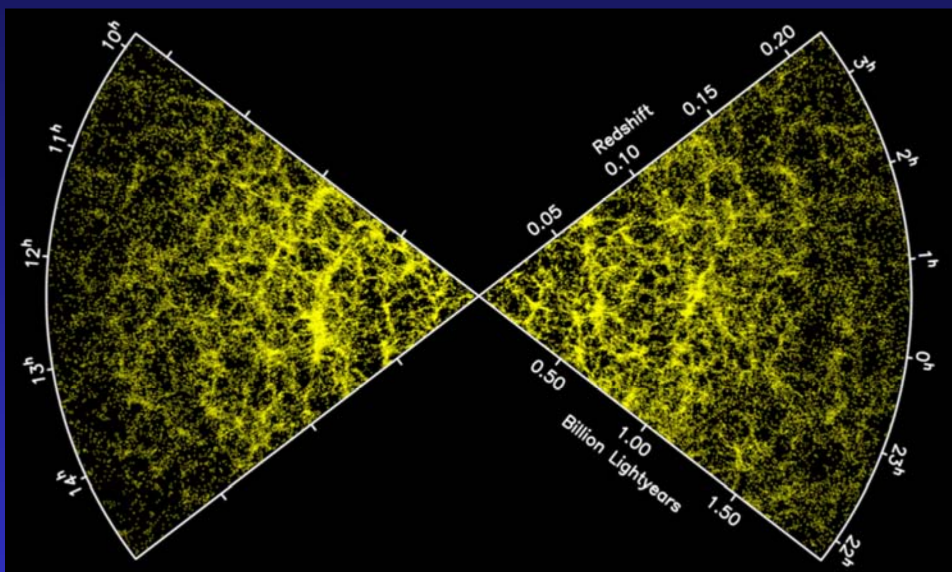
- La velocità della luce è elevatissima, ma non infinita
- Le distanze cosmiche sono enormi

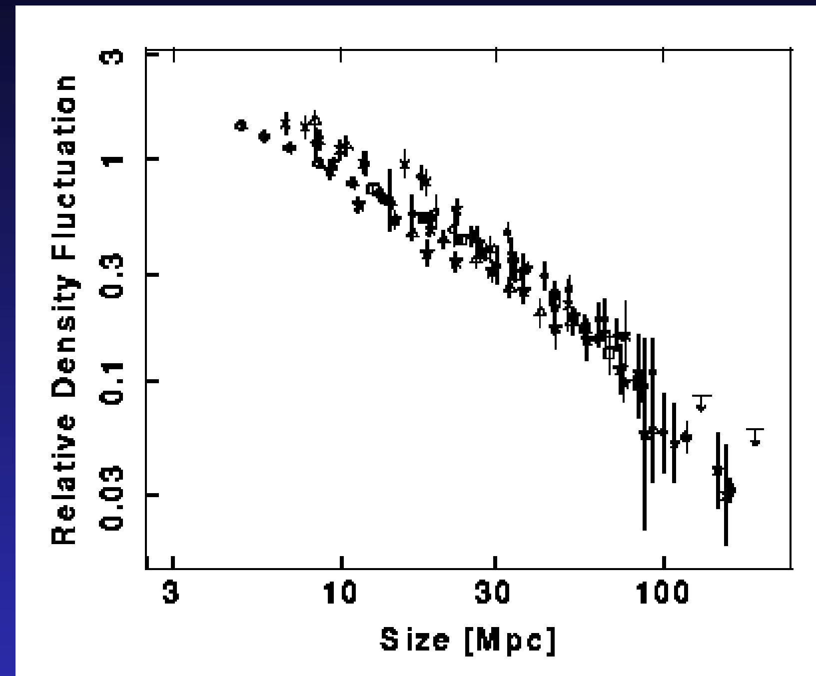
- Questi due fatti ci permettono di osservare il *passato* dell' universo, studiando luce che proviene da grandi distanze e quindi ci porta l' immagine della sorgente come era al momento dell' emissione.





Cataloghi tridimensionali della distribuzione delle galassie

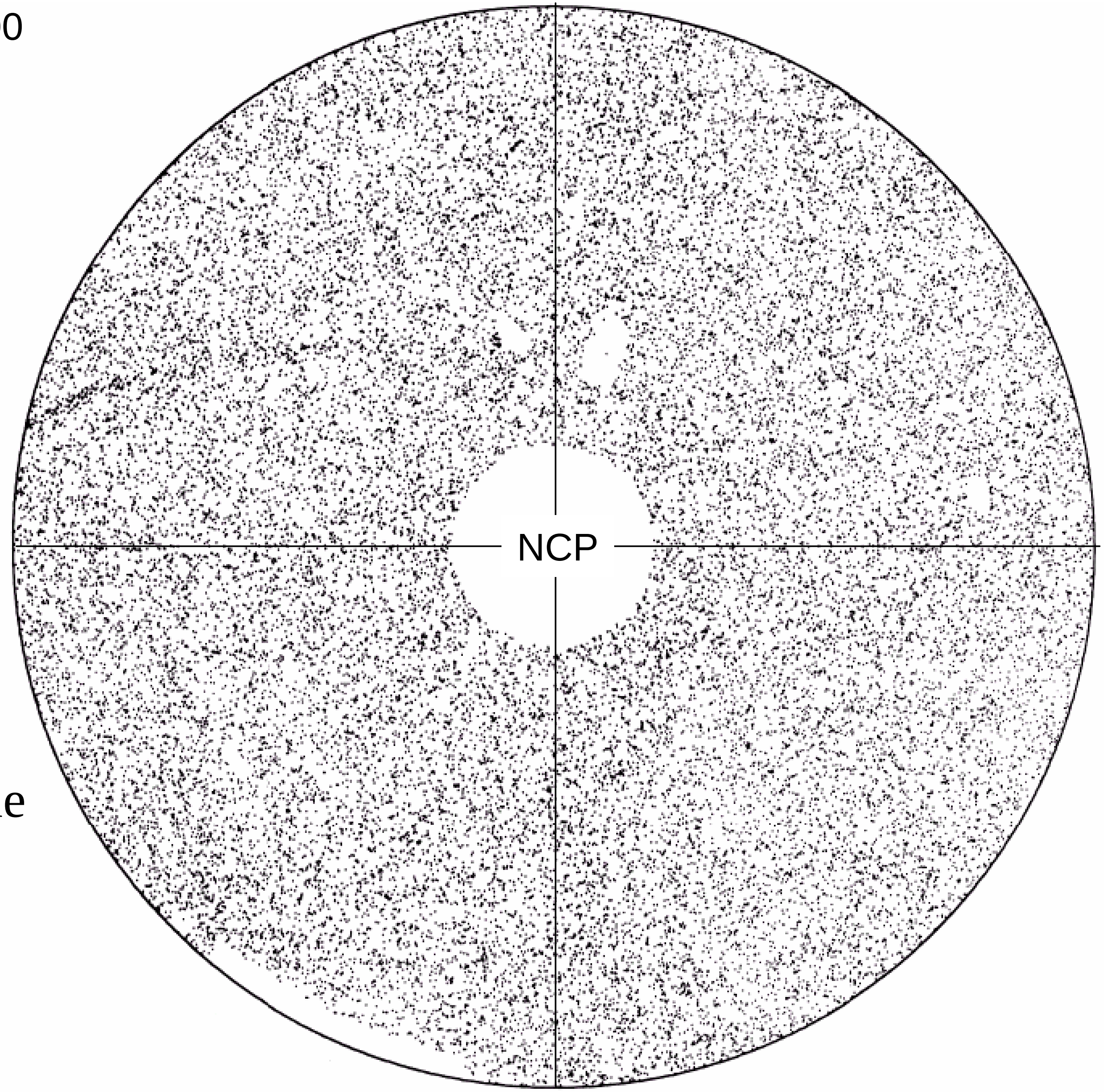




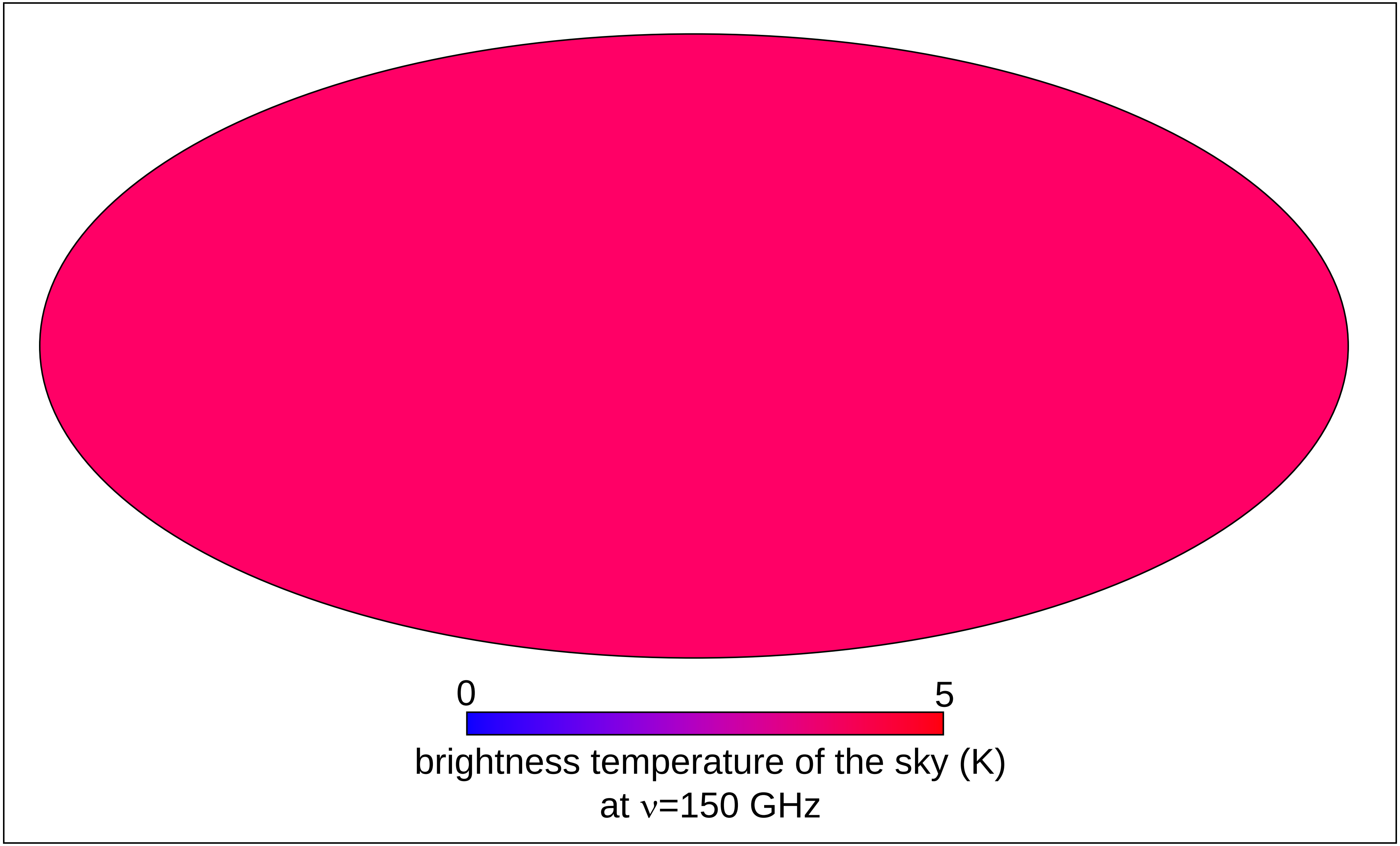
Peacock and Dodds
(1994, MNRAS, 267, 1020)

- La distribuzione 3D delle galassie è statisticamente omogenea, e lo è sempre di più se si considerano scale sempre più grandi.

Distribution of the 31000 brightest radio sources (λ=6 cm, Gregory and Condon 1991)
Northern hemisphere, equal-area projection

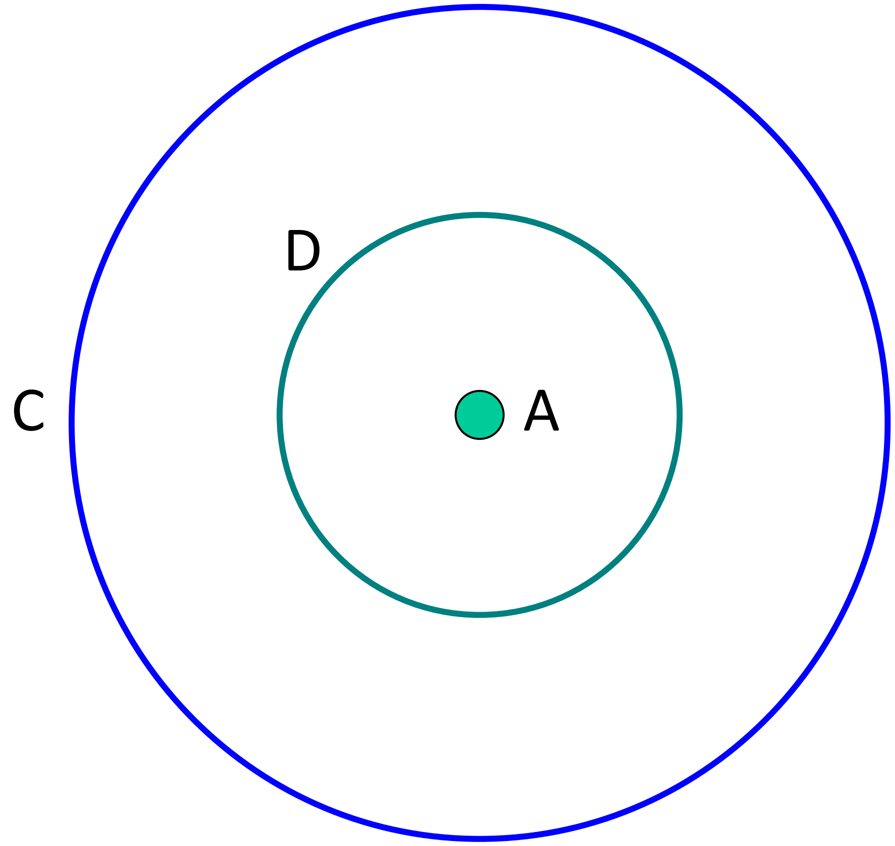


- L' omogeneità dell' universo a grandi scale è confermata dall' isotropia della distribuzione delle radiosorgenti lontane….

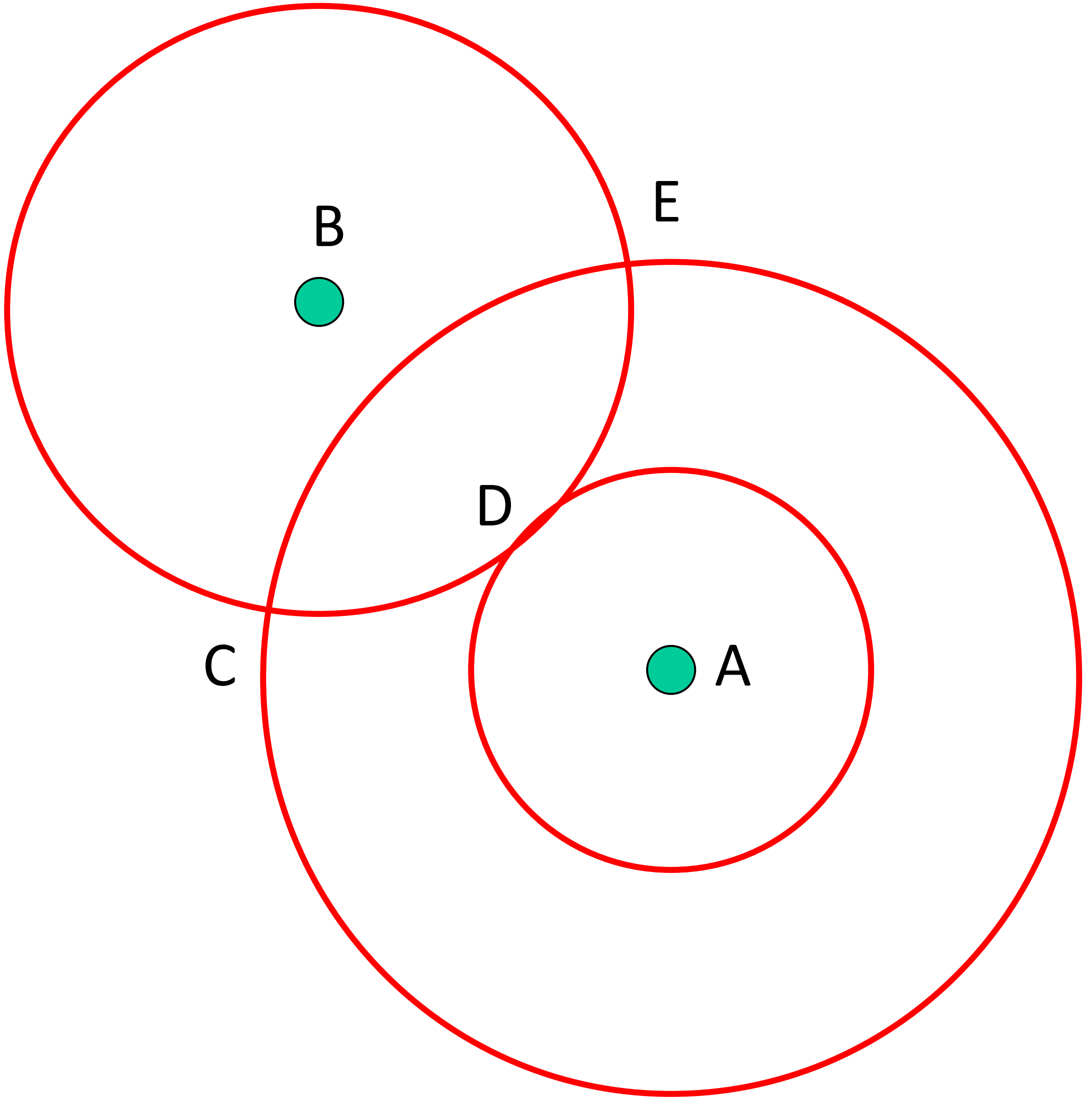


- … e dalla straordinaria isotropia del cielo nelle microonde.
- L' immagine del cielo più noiosa di tutte !

Principio Copernicano + isotropia = omogeneità



Principio Copernicano + isotropia = omogeneità



Cosa vedremo osservando ancora più lontano, e quindi sempre più indietro nel tempo ?

- Per rispondere si deve sapere se e come l' universo è cambiato al passare del tempo
- Si deve studiare la dinamica del sistema universo.
- Per prima cosa lo si deve modellizzare, e poi si devono applicare le appropriate leggi della dinamica per studiarne l' evoluzione.

Metodo

- Si usa un modello ultrasemplificato :
- Fluido omogeneo ed isotropo che riempie l’ universo (principio cosmologico)
- Funziona bene a grandi scale (background universe):
  - Isotropia delle radiogalassie
  - Isotropia del fondo cosmico di microonde
  - Principio Copernicano : non siamo speciali nell’ universo
  - 3D galaxy distribution surveys
- Forze in azione: gravitazione
- Teoria che descrive correttamente la dinamica : Relatività Generale (GR)

Ricetta dalla GR

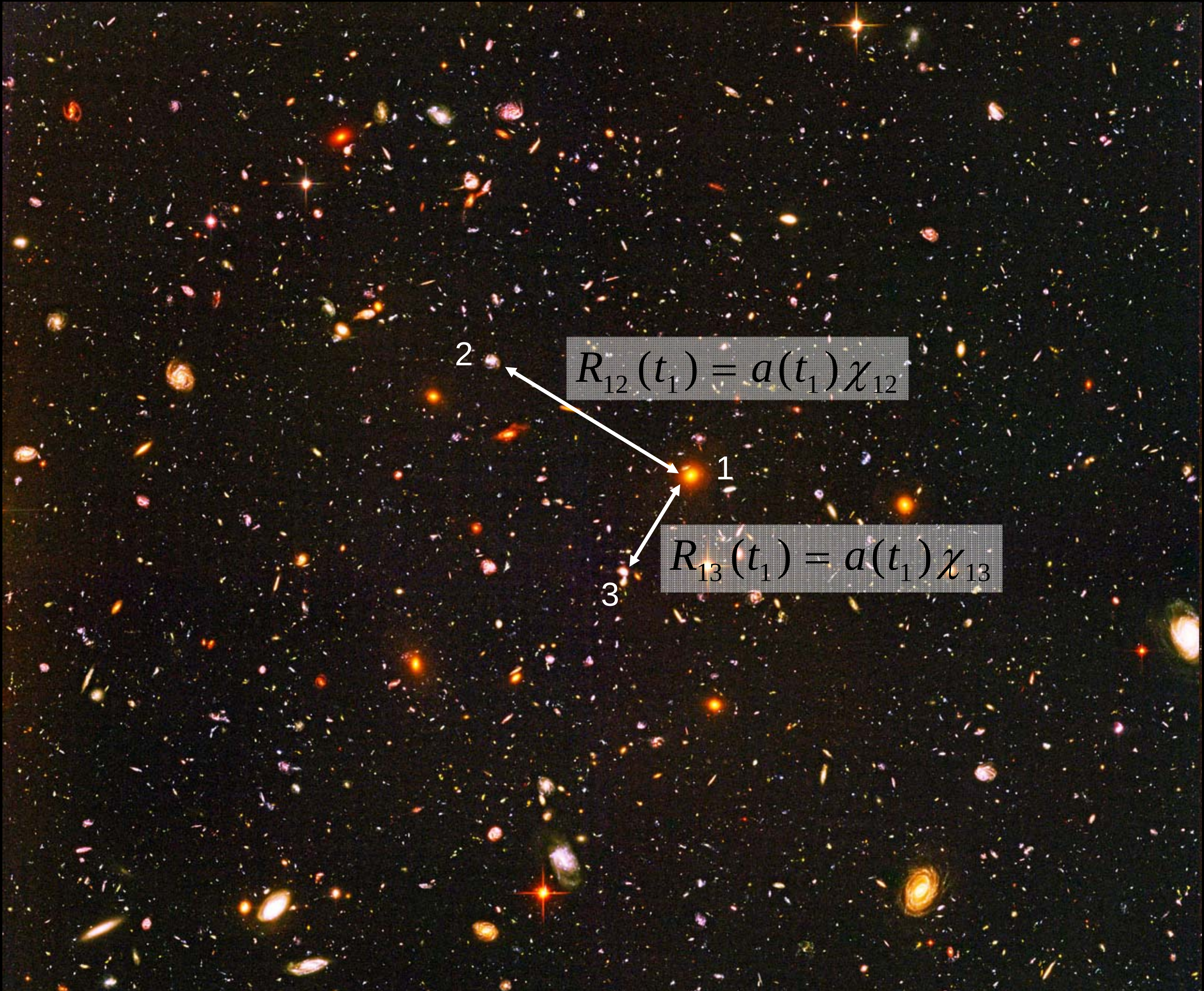
- Specificare la geometria (metrica), inserire il contenuto di massa-energia, e le equazioni di Einstein fanno il resto, determinando l' evoluzione del sistema.
- Nel nostro caso (4D = x,y,z,*i*ct):
  - Metrica euclidea (teorema di Pitagora in 4 dimensioni):

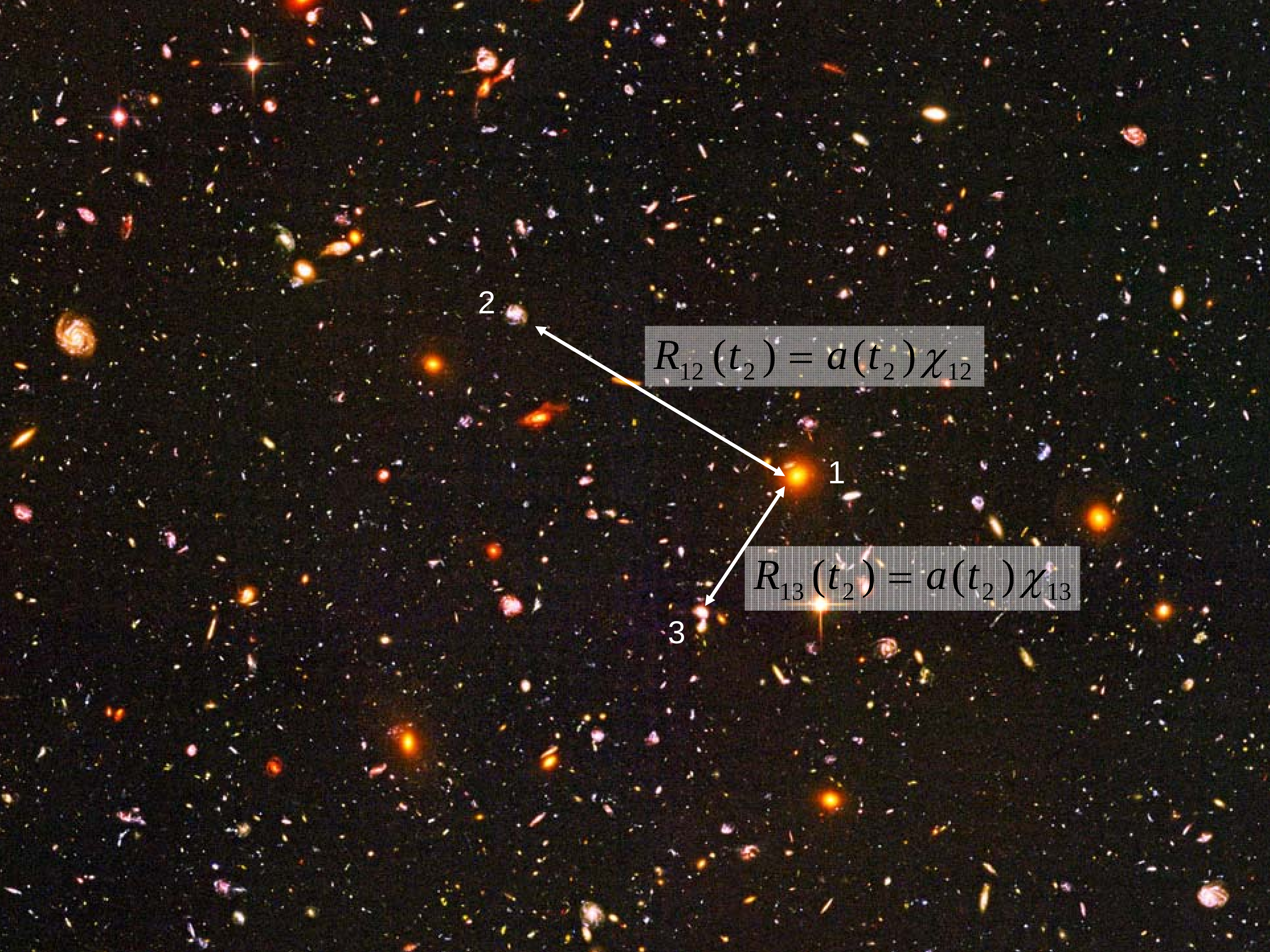
$$ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$$

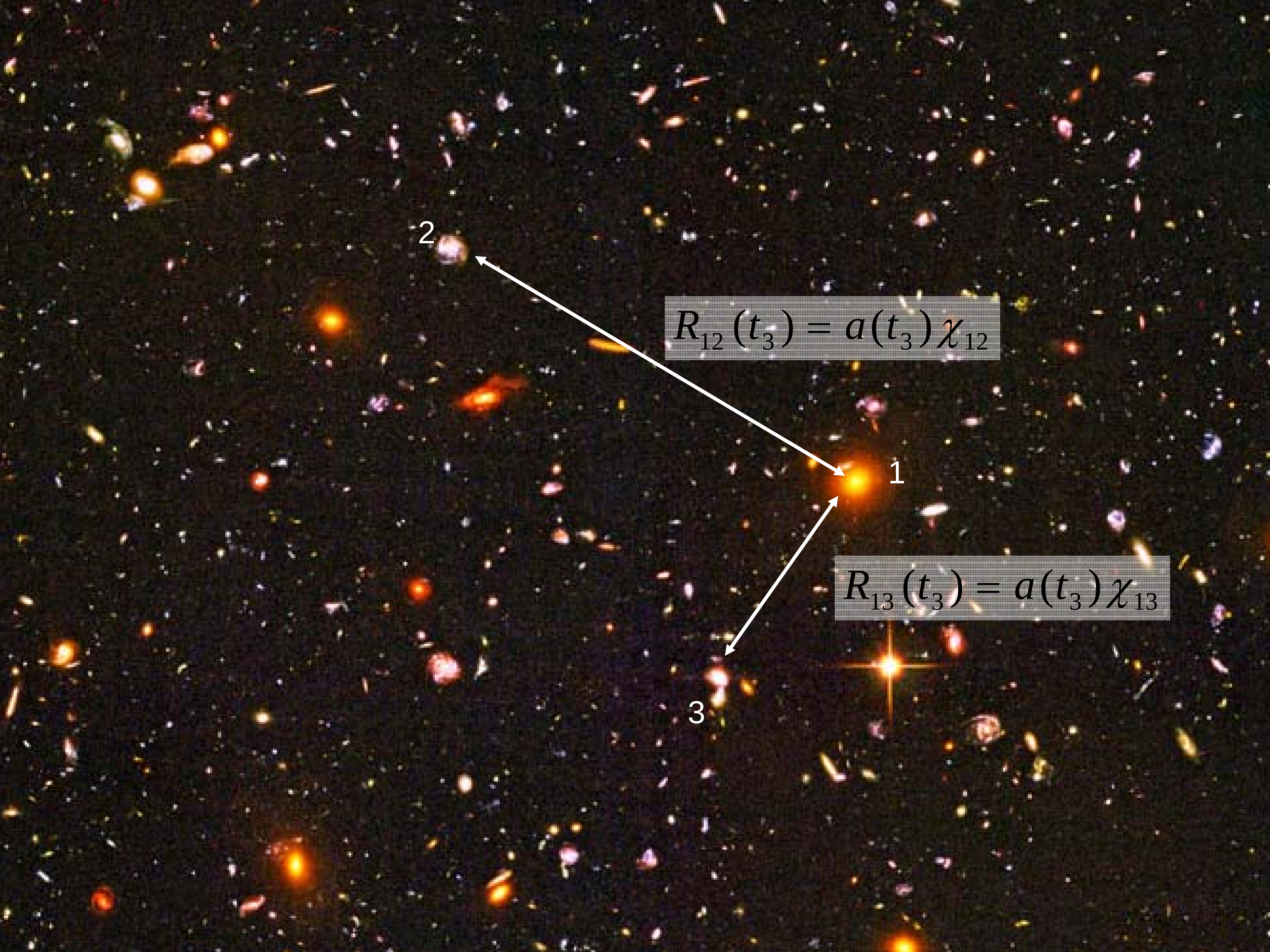
  - Metrica più generale omogena e isotropa (FRW):

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

  - Il fattore di scala *a(t)* permette di variare le dimensioni dell' universo mantenendo omogeneità ed isotropia: $R(t) = a(t)\chi$


2
$R_{12}(t_1) = a(t_1)\chi_{12}$
1
$R_{13}(t_1) = a(t_1)\chi_{13}$
3

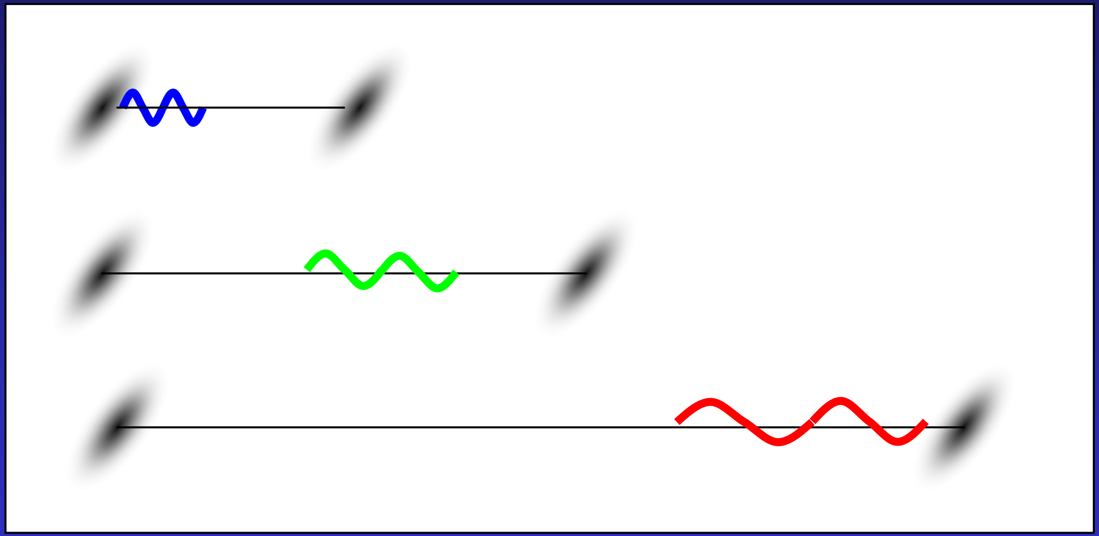

2
$R_{12}(t_2) = a(t_2)\chi_{12}$
1
$R_{13}(t_2) = a(t_2)\chi_{13}$
3


2
$R_{12}(t_3) = a(t_3)\chi_{12}$
1
$R_{13}(t_3) = a(t_3)\chi_{13}$
3

Redshift

- Se l' universo non è statico [$a=a(t)$] le lunghezze d' onda della luce cambiano durante il suo viaggio attraverso l' universo:

$$\frac{\lambda_{\text{det}}}{\lambda_{\text{em}}} = \frac{a(t_{\text{det}})}{a(t_{\text{em}})}$$



- In un universo in espansione si ha un allungamento delle lunghezze d' onda (redshift cosmologico)

Legge di Hubble

- Più una galassia è lontana
- Più tempo impiega la sua luce ad arrivarci
- Più si espande l' universo nel frattempo
- Più si allunga la lunghezza d' onda della luce durante il viaggio
- Più grande è il redshift

$$\frac{\lambda_{\mathrm{det}}}{\lambda_{\mathrm{em}}} = \frac{a(t_{\mathrm{det}})}{a(t_{\mathrm{em}})} > 1$$

$$z = \frac{\lambda_{\mathrm{det}} - \lambda_{\mathrm{em}}}{\lambda_{\mathrm{em}}}$$

- **z aumenta con la distanza**.
- Per piccole distanze (z<<1): Legge di Hubble:

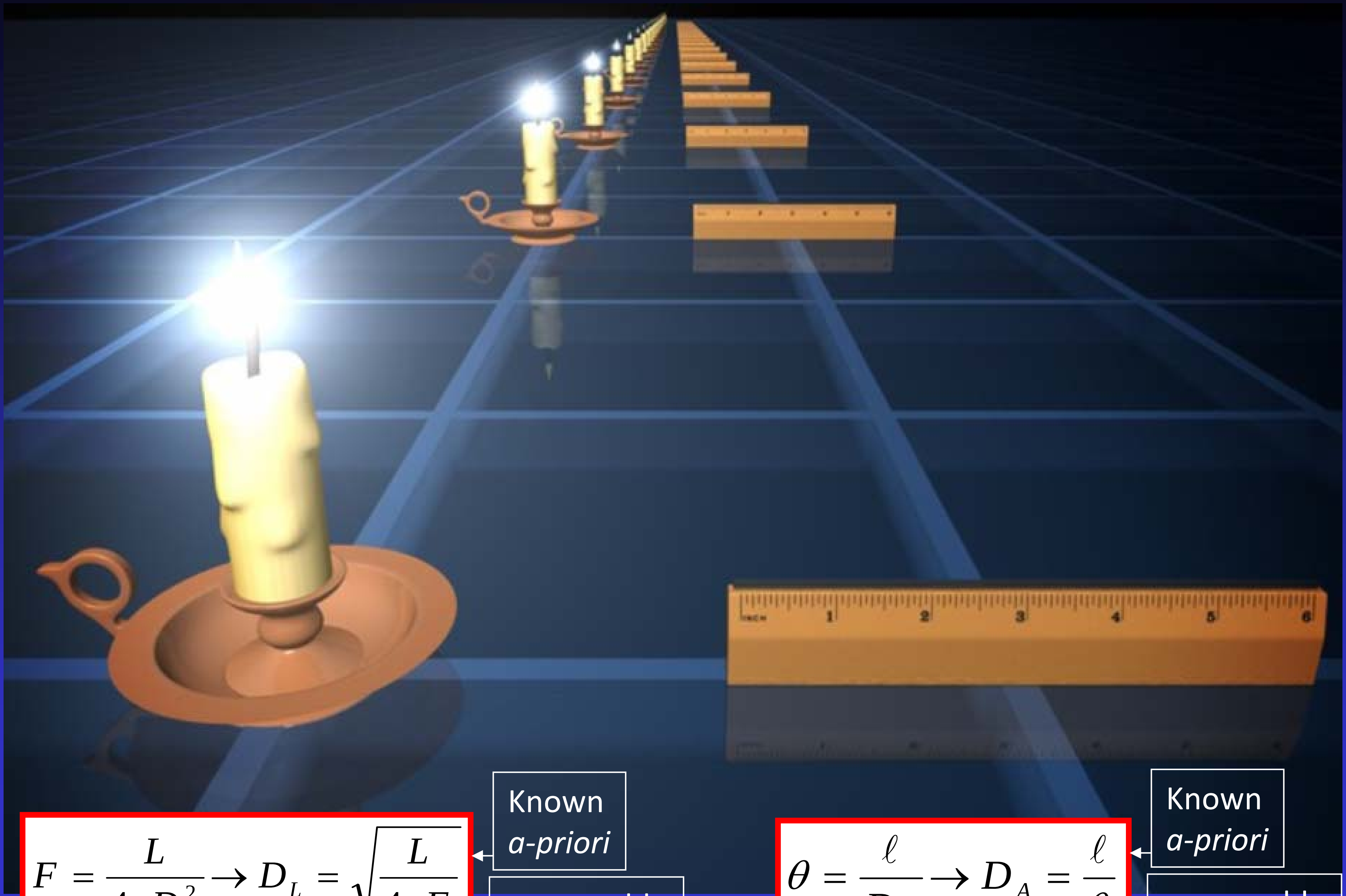
$$z = \left[\frac{H_o}{c}\right] D$$

Measurabile (misura diretta con uno spettrometro) → z

Una costante → H_o/c

Misurabile (indirettamente, usando Indicatori di distanza) → D

Distance Indicators



$$F = \frac{L}{4\pi D_L^2} \rightarrow D_L = \sqrt{\frac{L}{4\pi F}}$$

Known *a-priori*

measurable

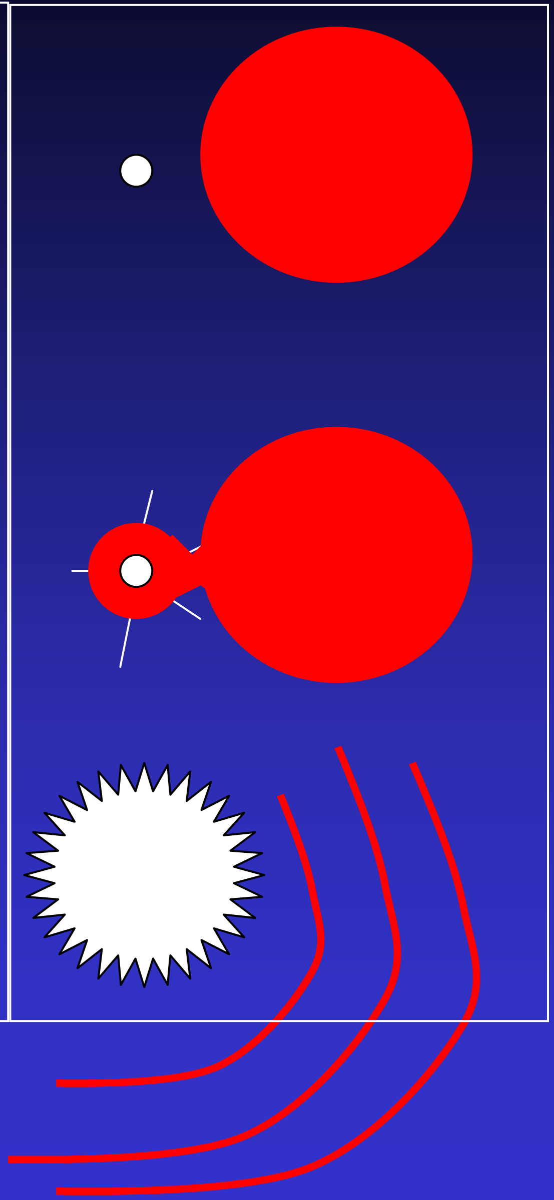
$$\theta = \frac{\ell}{D_A} \rightarrow D_A = \frac{\ell}{\theta}$$

Known *a-priori*

measurable

SNe1a

- Un fenomeno raro
- Sistema doppio : gigante rossa e nana bianca
- Il materiale della gigante rossa accresce la massa della nana bianca
- Quando la massa della nana bianca si avvicina alla massa di Chandrasekhar (1.4M_{sun}), la pressione interna non può più resistere all' autogravità e la stella implode, espellendo le parti più esterne.



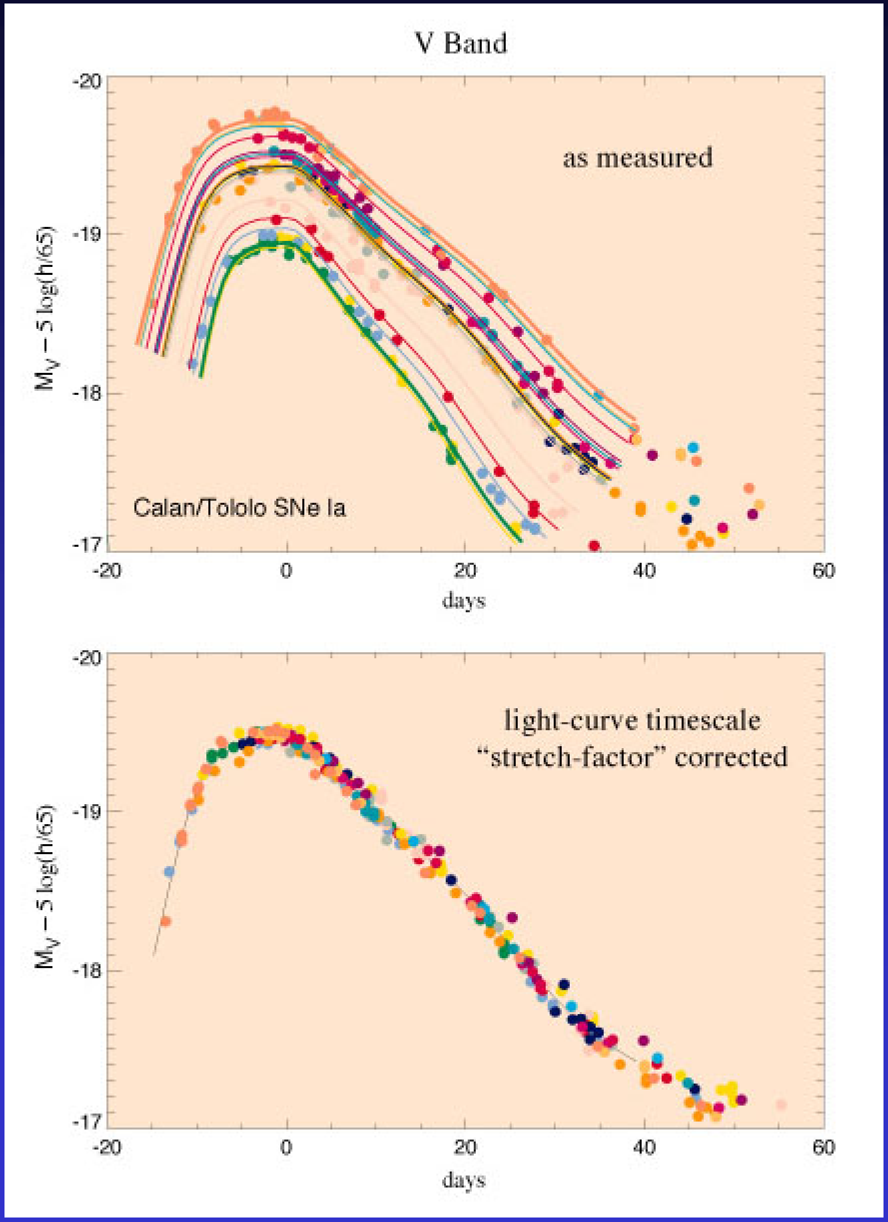
SNe1a

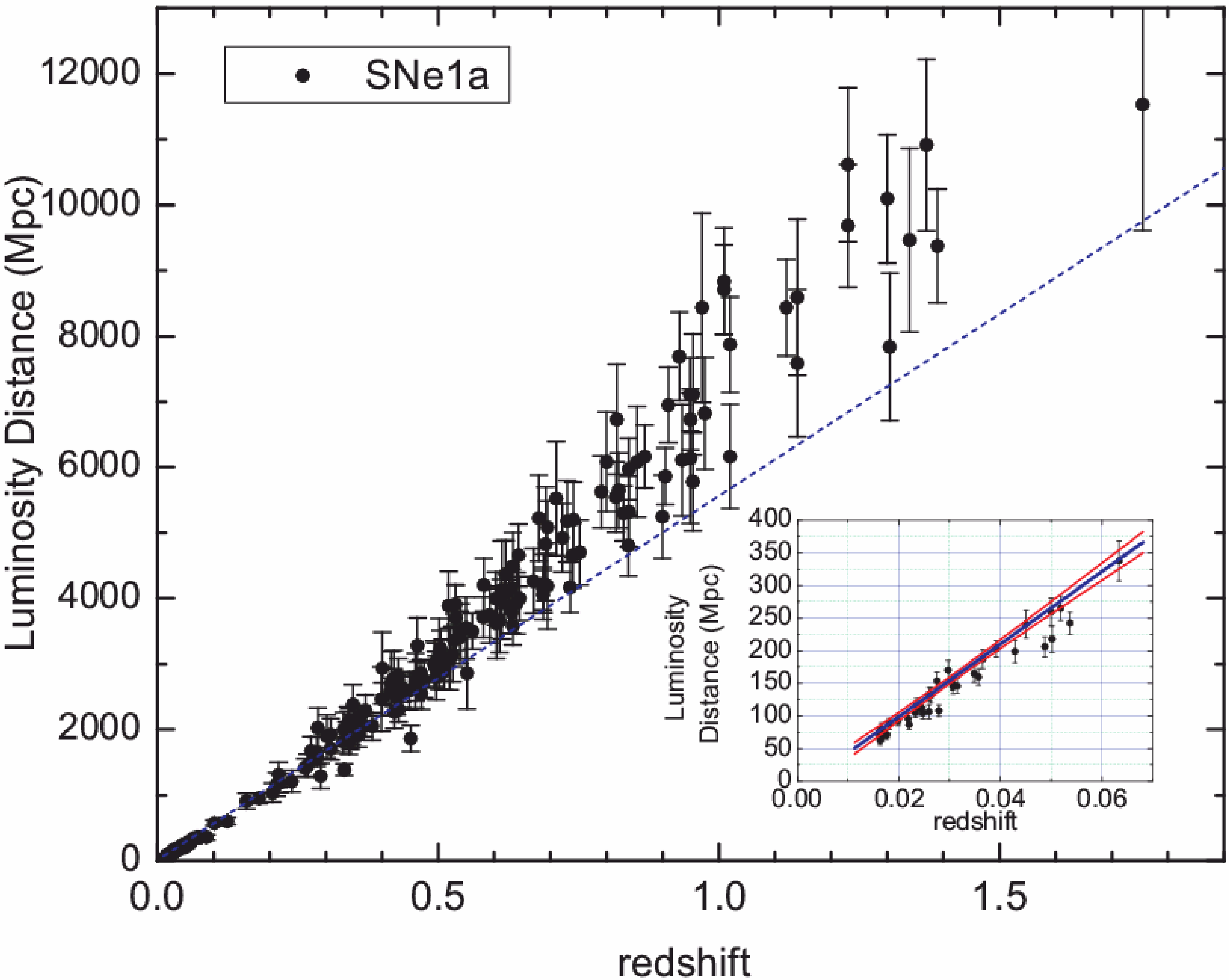
- La luminostià e la curva di luce che osserviamo sono il risultato del decadimento di nuclei radioattivi prodotti durante l' implosione della parte più interna della stella.

$^{56}Ni \rightarrow {}^{56}Co + \gamma$ (5.6 days)

$^{56}Co \rightarrow {}^{56}Fe + \gamma$ (79 days)

- Siccome la composizione e la massa iniziale sono le stesse per tutte le nane bianche vicino alla massa di Chandrasekar, la luminosità assoluta è circa la stessa per tutte le SN di questo tipo (SNe1a).
- Si devono applicare delle correzioni empiriche.





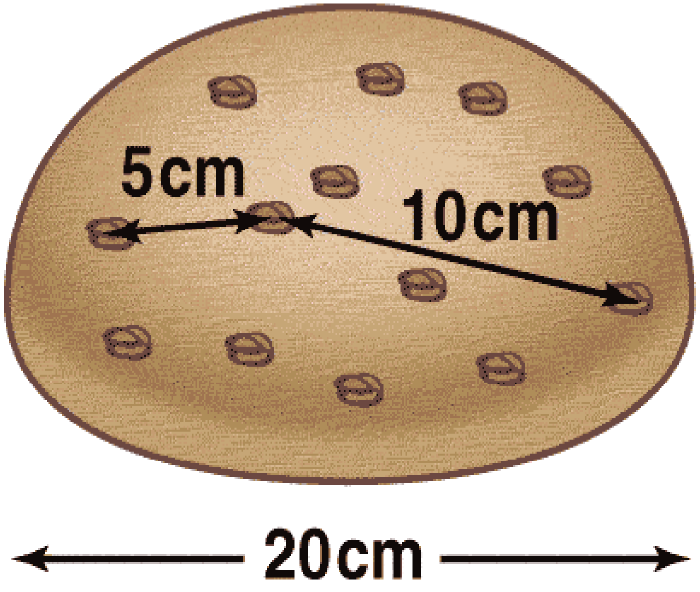
SNe1a
Luminosity Distance (Mpc)
redshift
0
2000
4000
6000
8000
10000
12000
0.0
0.5
1.0
1.5
Luminosity Distance (Mpc)
redshift
0
50
100
150
200
250
300
350
400
0.00
0.02
0.04
0.06

Costante di Hubble

- Usando le candele standard (SNe1a, ma anche variabili Cefeidi) si trova che la legge di Hubble è ben verificata a redshift < 1, e la costante di Hubble vale :

$$z = \left[\frac{H_o}{c}\right] D \quad \Longleftrightarrow \quad H_o = (74.3 \pm 2.1)\ \mathrm{km/s/Mpc}$$

- Una galassia ad una distanza di 1 Mpc (3.26 milioni di anni luce) recede da noi con una velocità di 74 km/s.
- Una galassia ad una distanza di 10 Mpc (32.6 milioni di anni luce) recede da noi con una velocità di 740 km/s.
- Non c’ è un centro in questa espansione generale dell’ universo.



MAP990404

L’ universo si sta espandendo

- E’ un risultato empirico, ed ha straordinarie conseguenze per la cosmologia
- Se si sta espandendo, in passato era più denso e più caldo.
- Per capire quantitativamente quanto, dobbiamo risolvere le equazioni della relatività generale che descrivono l’ evoluzione dell’ universo causata dalle forze gravitazionali in gioco.

Friedman's equation

- At this point we are in a position to write half of Einstein's equation (metric part) for an homogenous isotropic universe.
- To write the other half, we need to specify how much of the different possible forms of mass-energy densities is present in the universe, and how each contribution scales with the expansion of the universe:
  - Matter $\rho_M = \rho_{Mo} / a^3$
  - Radiation $\rho_R = \rho_{Ro} / a^4 \leftarrow n = n_o / a^3 \quad ; \quad E = h\nu = hc/\lambda \approx 1/a$
  - Cosmological Constant $\rho_\Lambda = \rho_{\Lambda o}$
- All densities are given in adimensional form, as a fraction of the critical density:

$$\rho_{co} = \frac{3H_o^2}{8\pi G} = (1.04 \pm 0.07) \times 10^{-29} \text{ g/cm}^3$$

$$\Omega_{io} = \frac{\rho_{io}}{\rho_{co}}$$

Friedman's equation

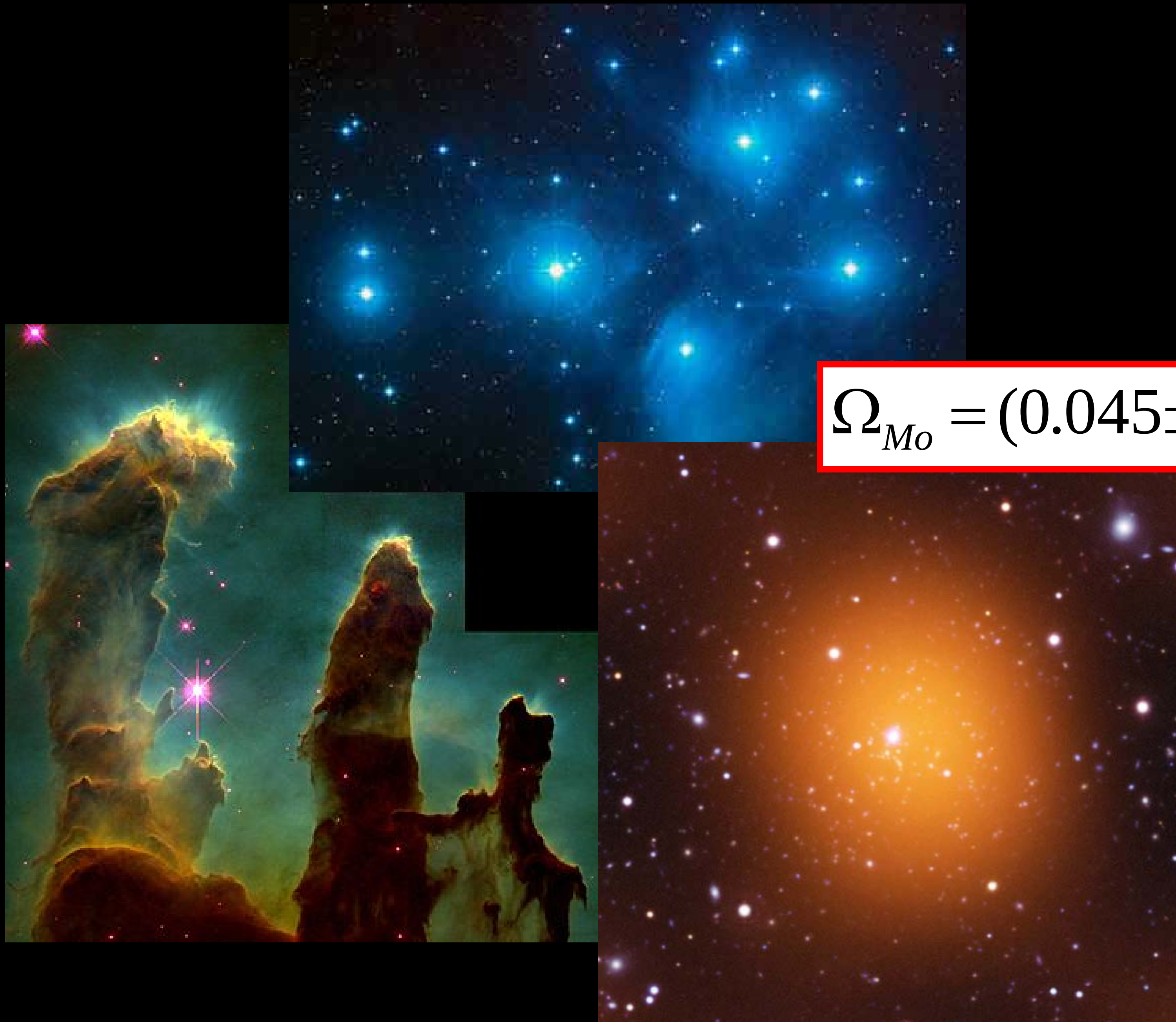
- Einstein's equation, in the case of a homogenous isotropic universe, gives

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

- 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

Baryonic Matter

- Baryonic matter interacts electromagnetically
- We can measure it because it emits, or absorbs, or scatters light and electromagnetic waves.
- Us, planets, stars, interstellar matter, galaxies, etc. contain baryonic matter.
- Measuring the luminosity, one can infer the mass responsible for such a luminosity.
- Most recent estimates: $\Omega_{Mo} = (0.045 \pm 0.003)$
- Consistent with primordial nucleosynthesis.
- A minor component of our universe.



$$\Omega_{Mo} = (0.045 \pm 0.003)$$

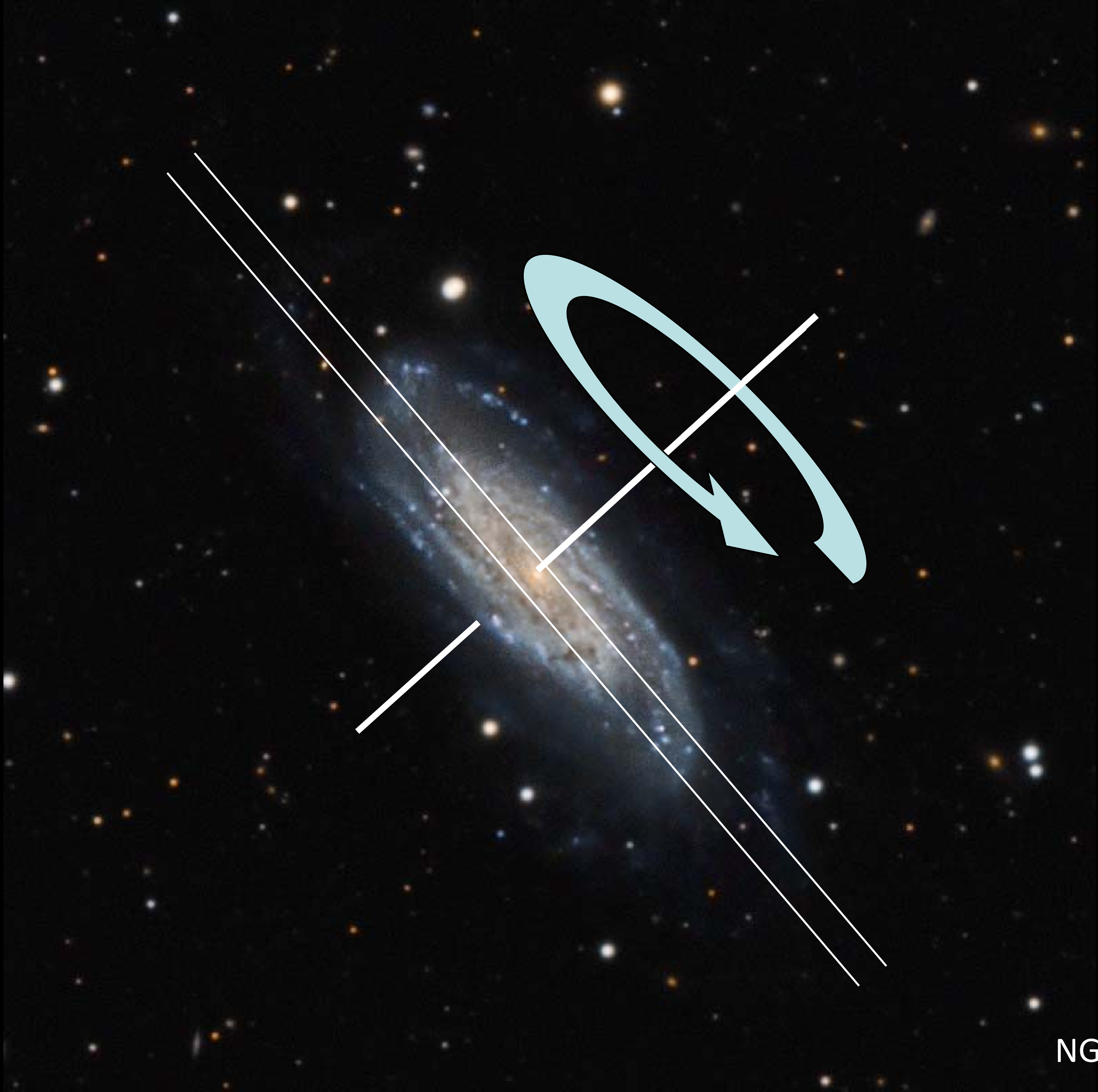
Dark Matter

- 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.

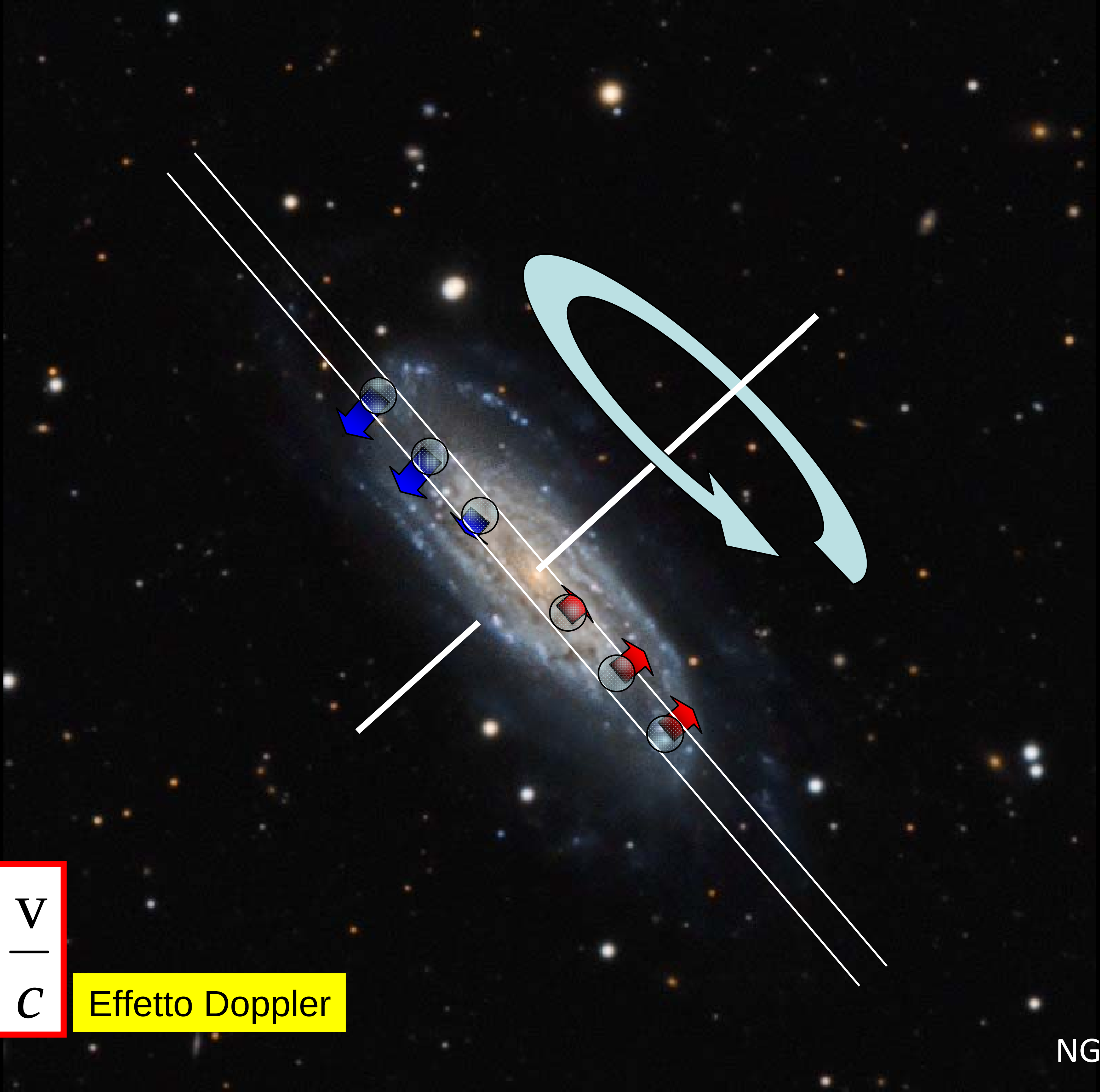
$$\Omega_{DMo} = (0.22 \pm 0.02)$$

NGC3198

NGC3198

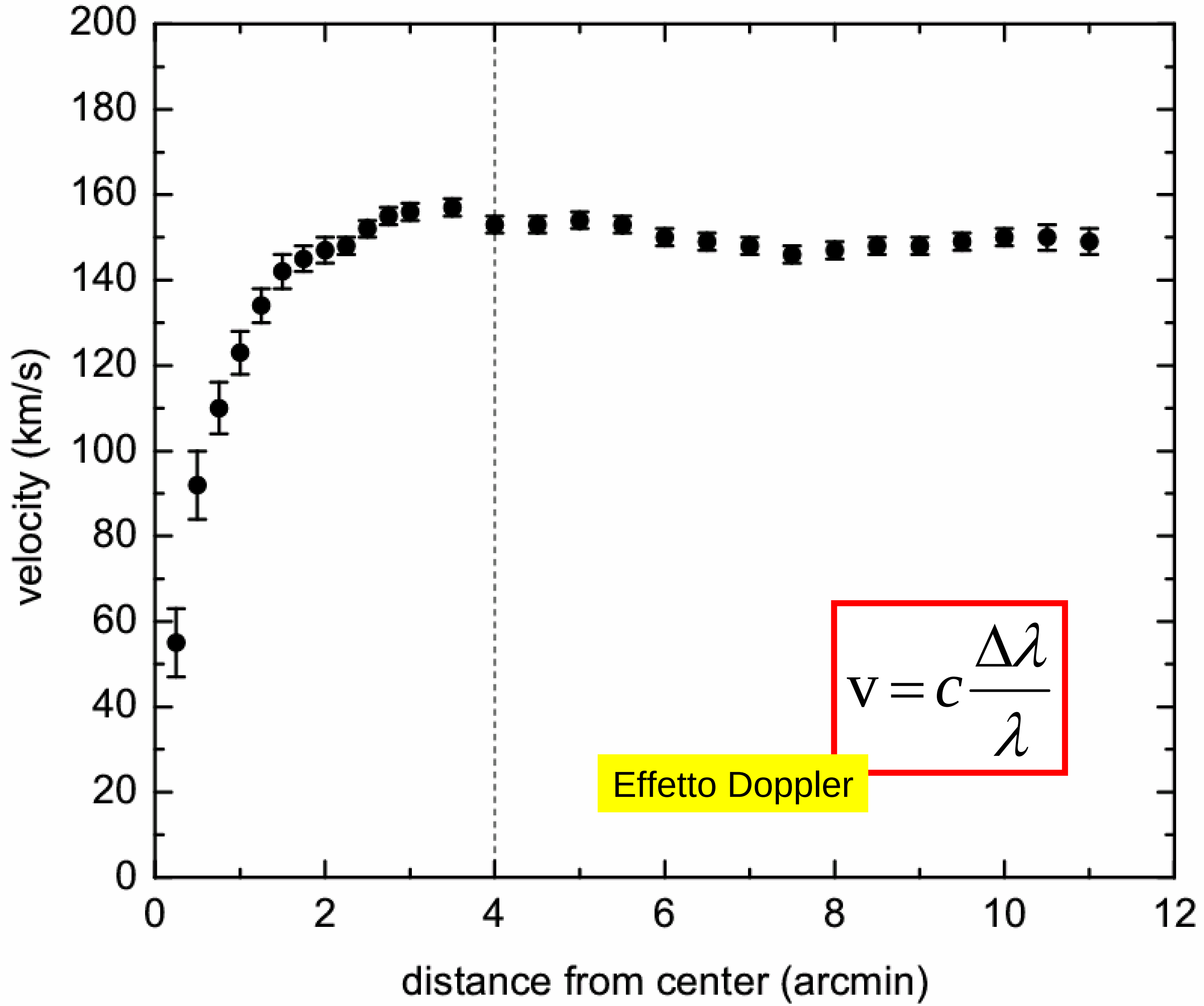


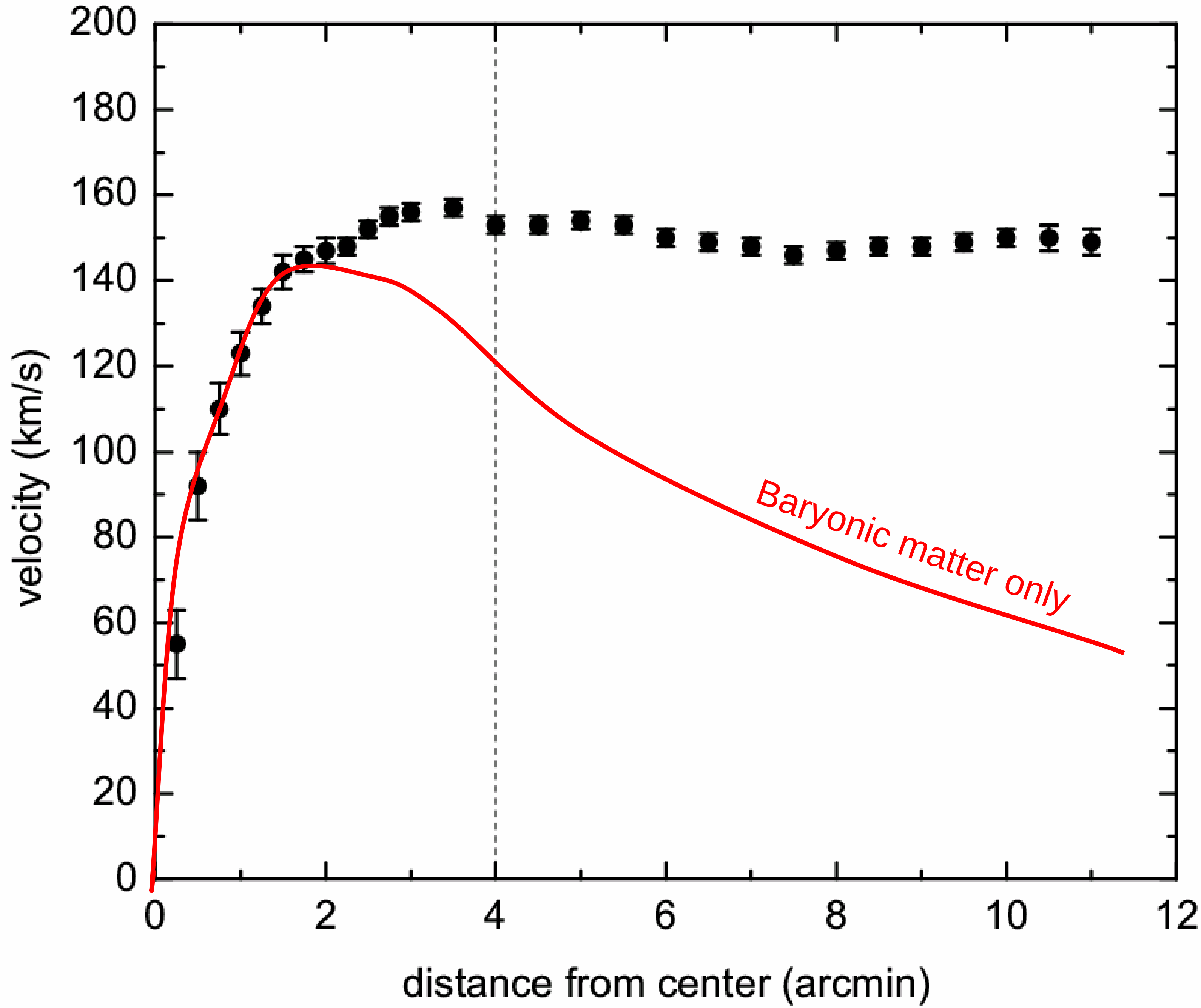
NGC3198



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

Effetto Doppler

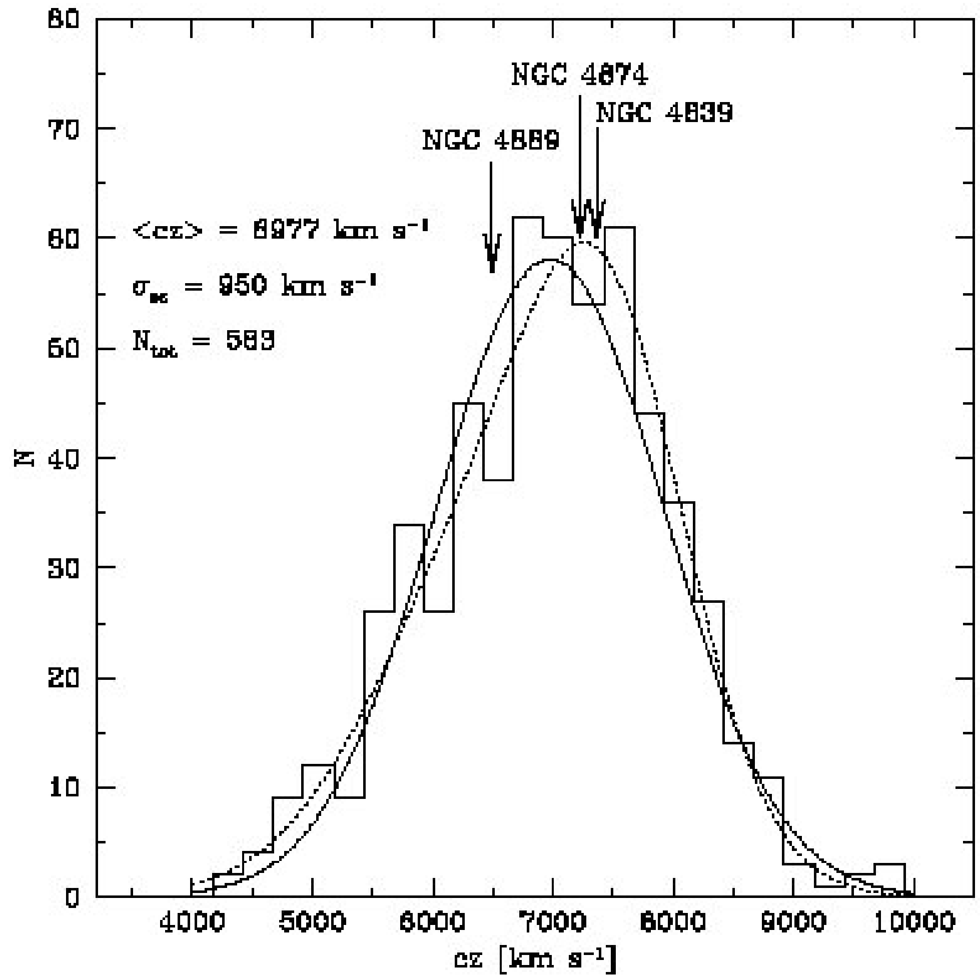

velocity (km/s)
distance from center (arcmin)
Effetto Doppler
$$v = c\frac{\Delta\lambda}{\lambda}$$



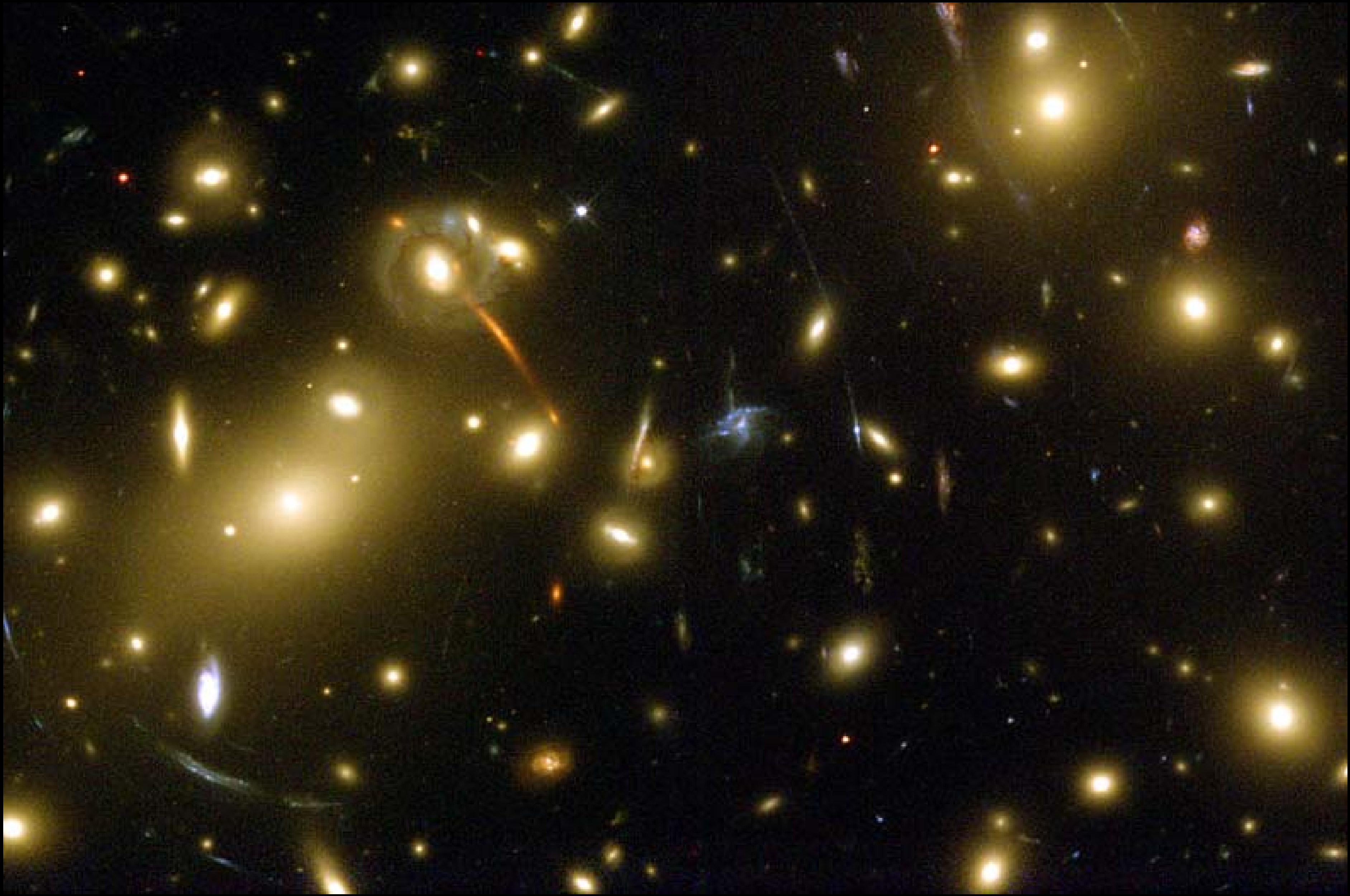
velocity (km/s)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
distance from center (arcmin)
Baryonic matter only


Coma

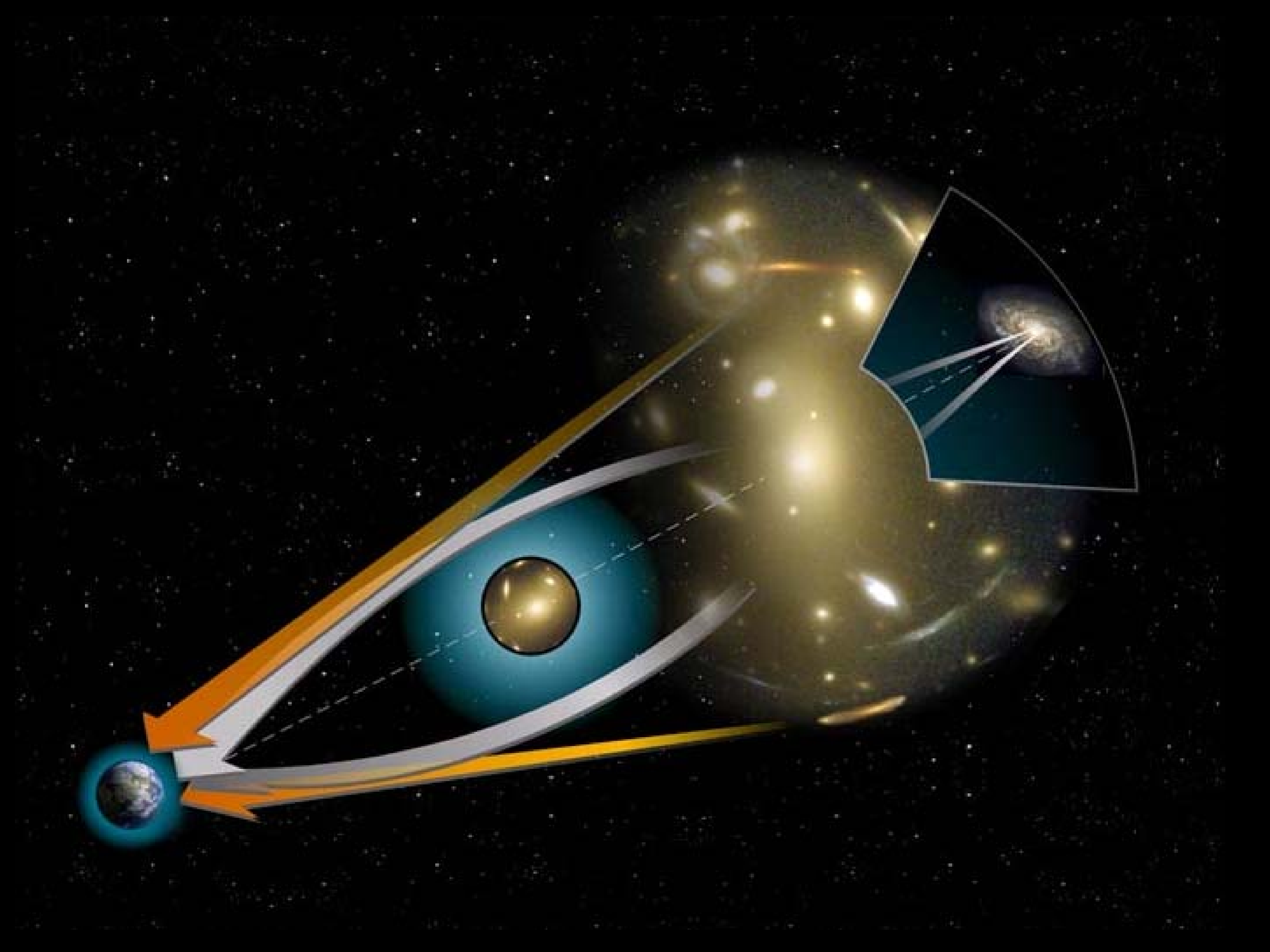
Figure 4.10— The distribution of radial velocities of all 583 identified Coma cluster galaxies ($4000 < cz < 10000$ km s^{-1}). The solid curve is a Gaussian with mean 6977 ± 53 km s^{-1} and standard deviation 950 ± 39 km s^{-1}. The dotted curve is the sum of two Gaussians with $\overline{cz_1} = 7501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

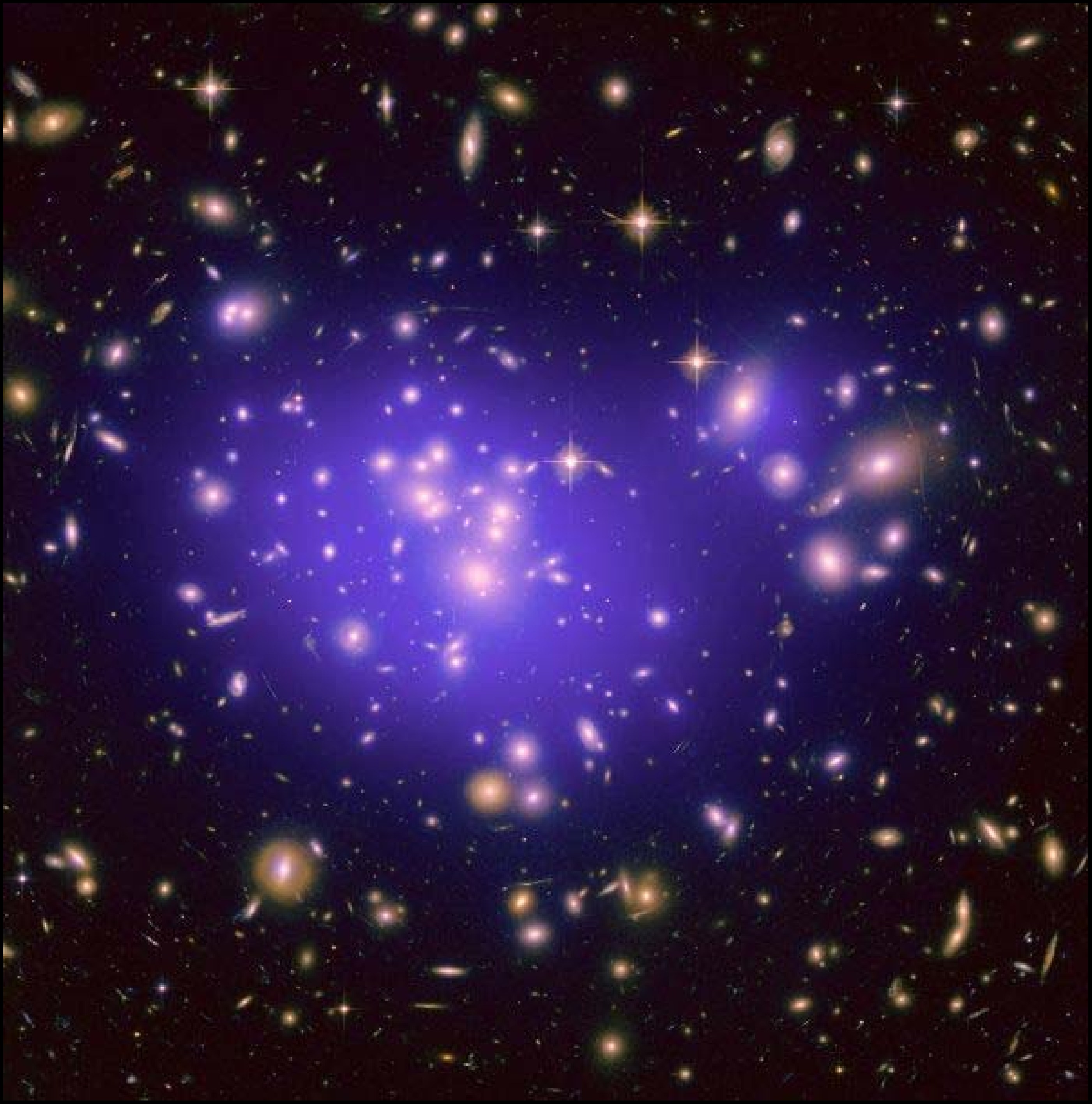


http://www.ub.rug.nl/eldoc/dis/science/m.beijersbergen/c4.pdf

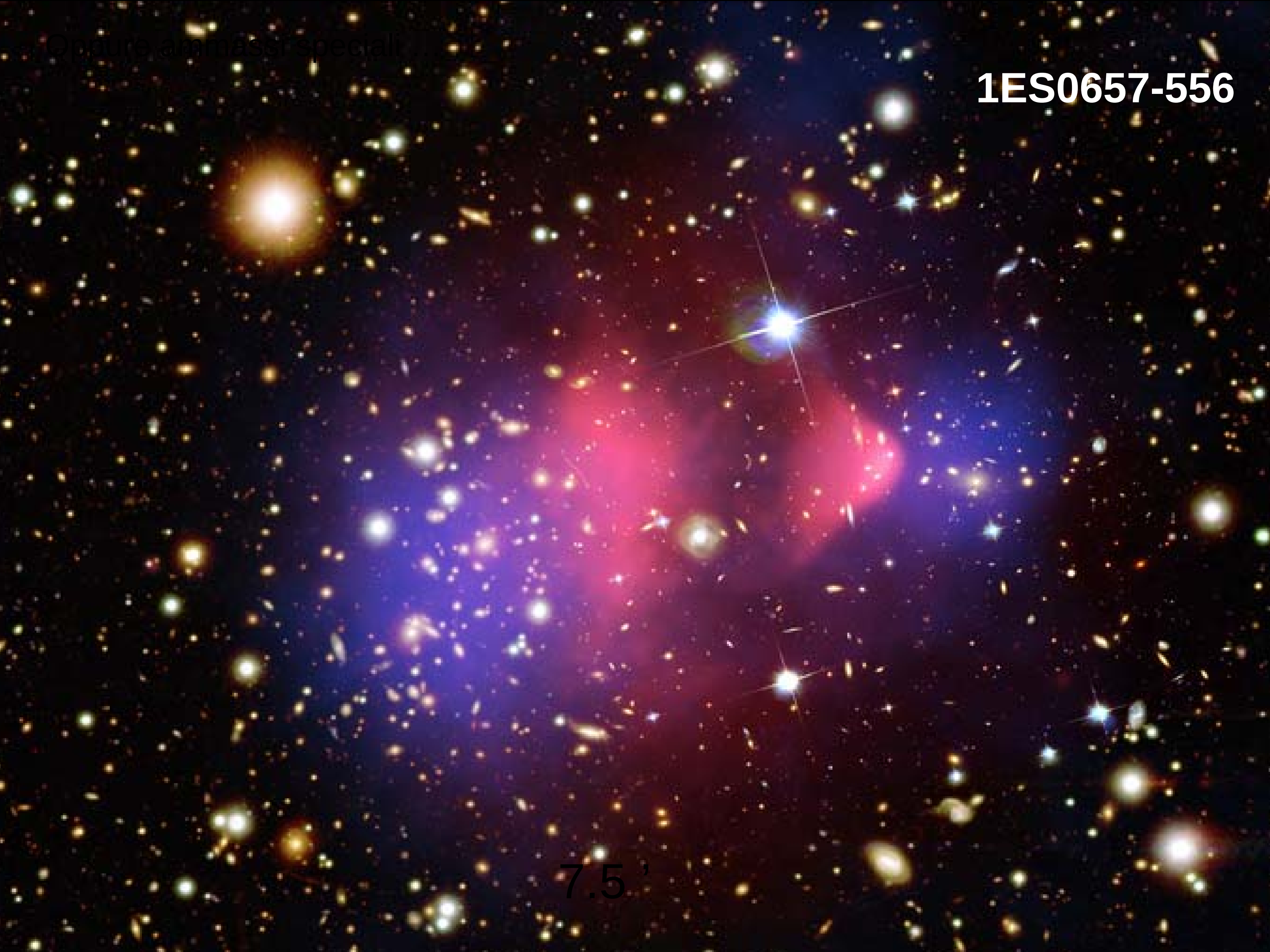


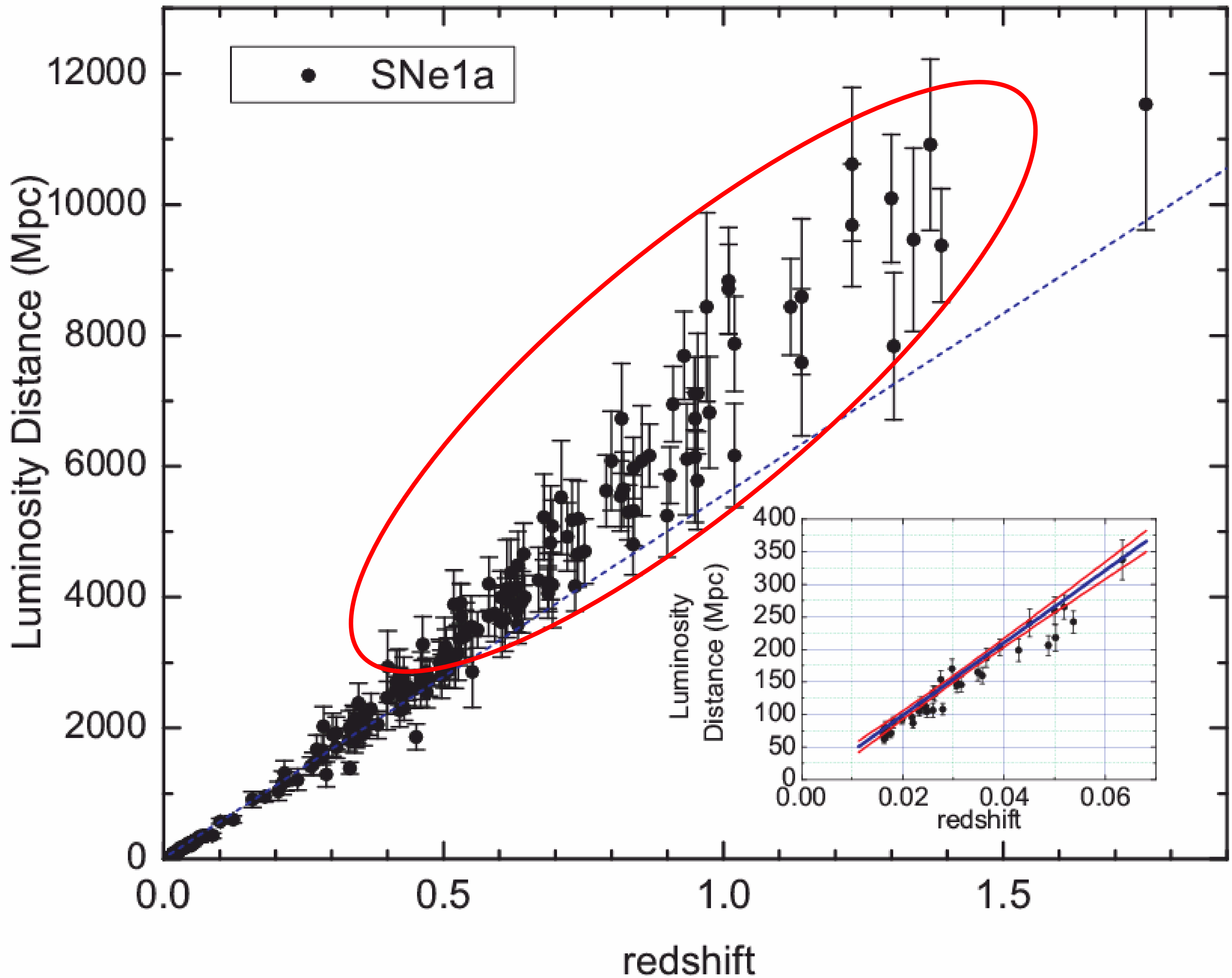
A2218





A1689


Oppure ammassi speciali…
1ES0657-556
7.5 ’



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

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

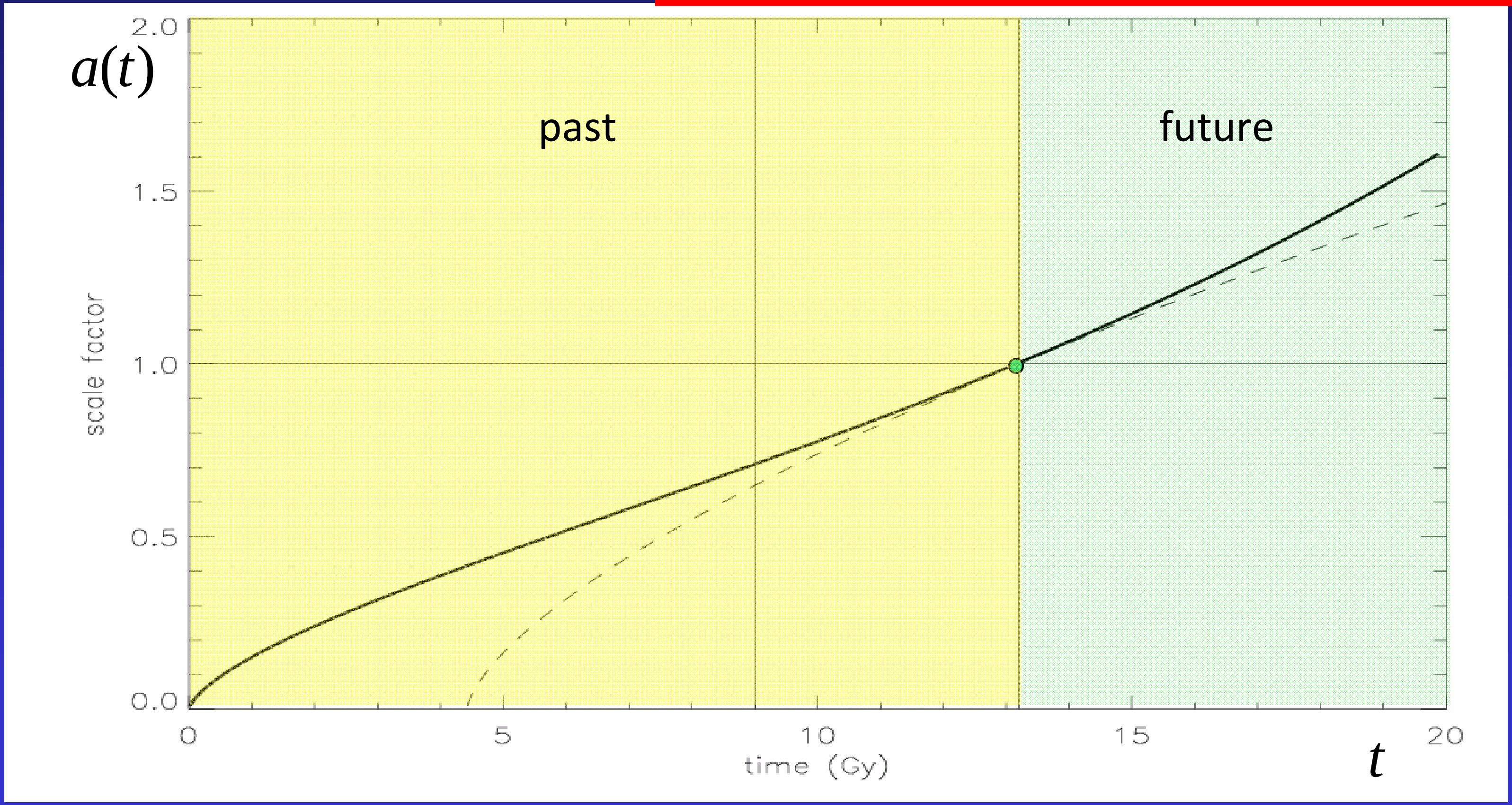
- I.e. the mass-energy density is consistent with the critical density, and there is no curvature of space.
- This result is confirmed and its accuracy is improved by measurements of the causal horizon at redshift 1100, using the cosmic microwave background:

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

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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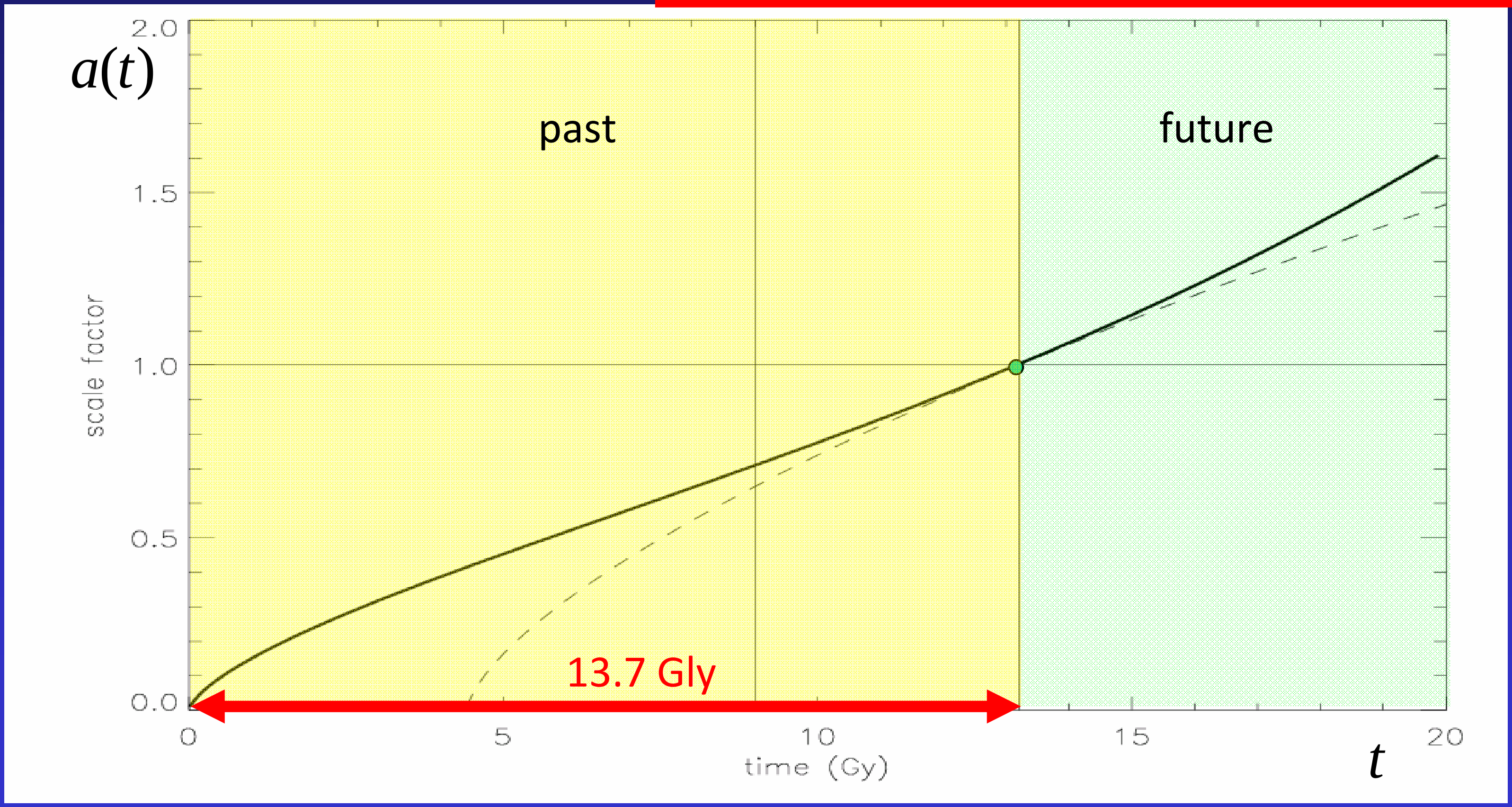

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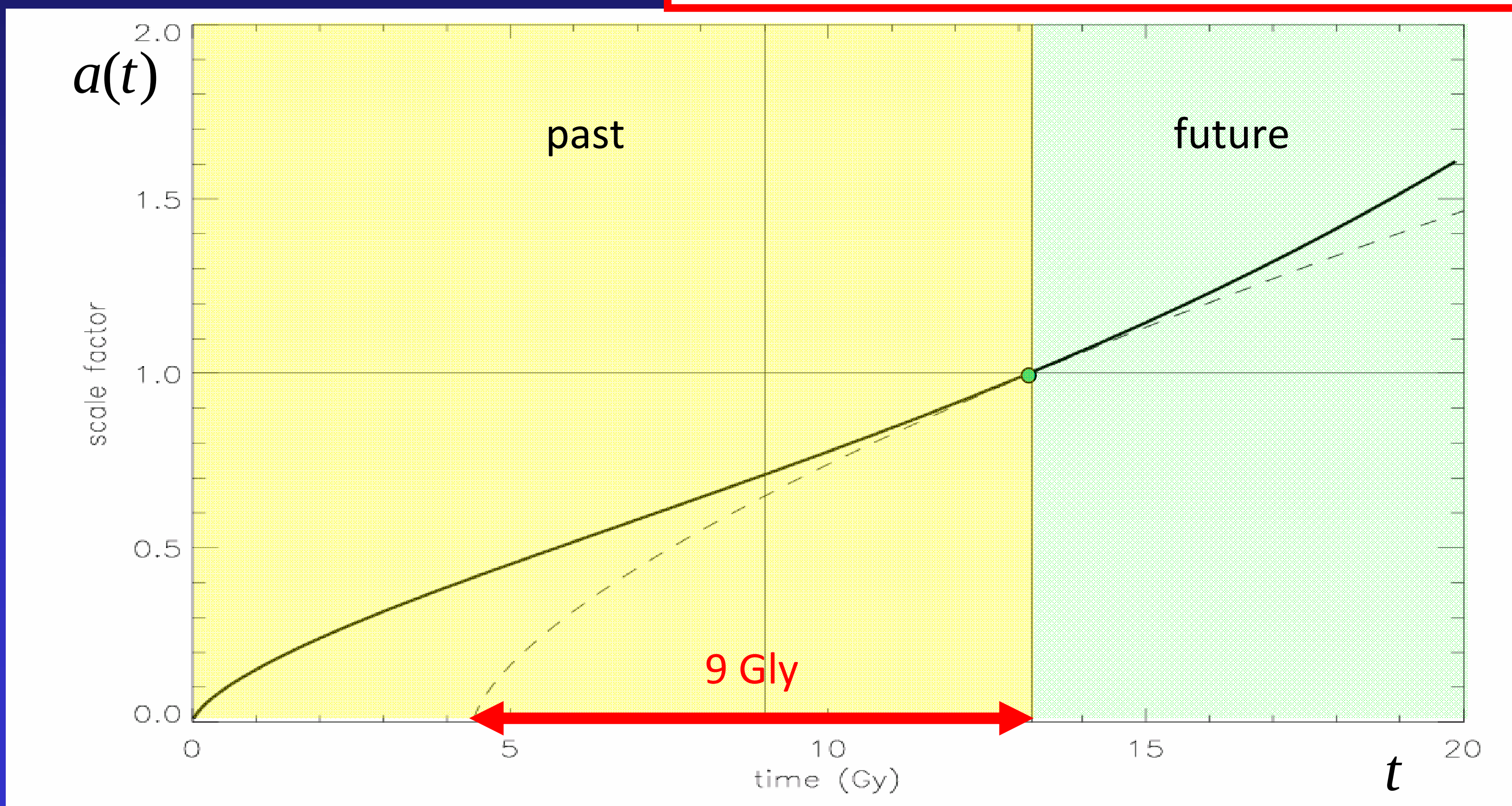


NGC 6397

Friedman's equation

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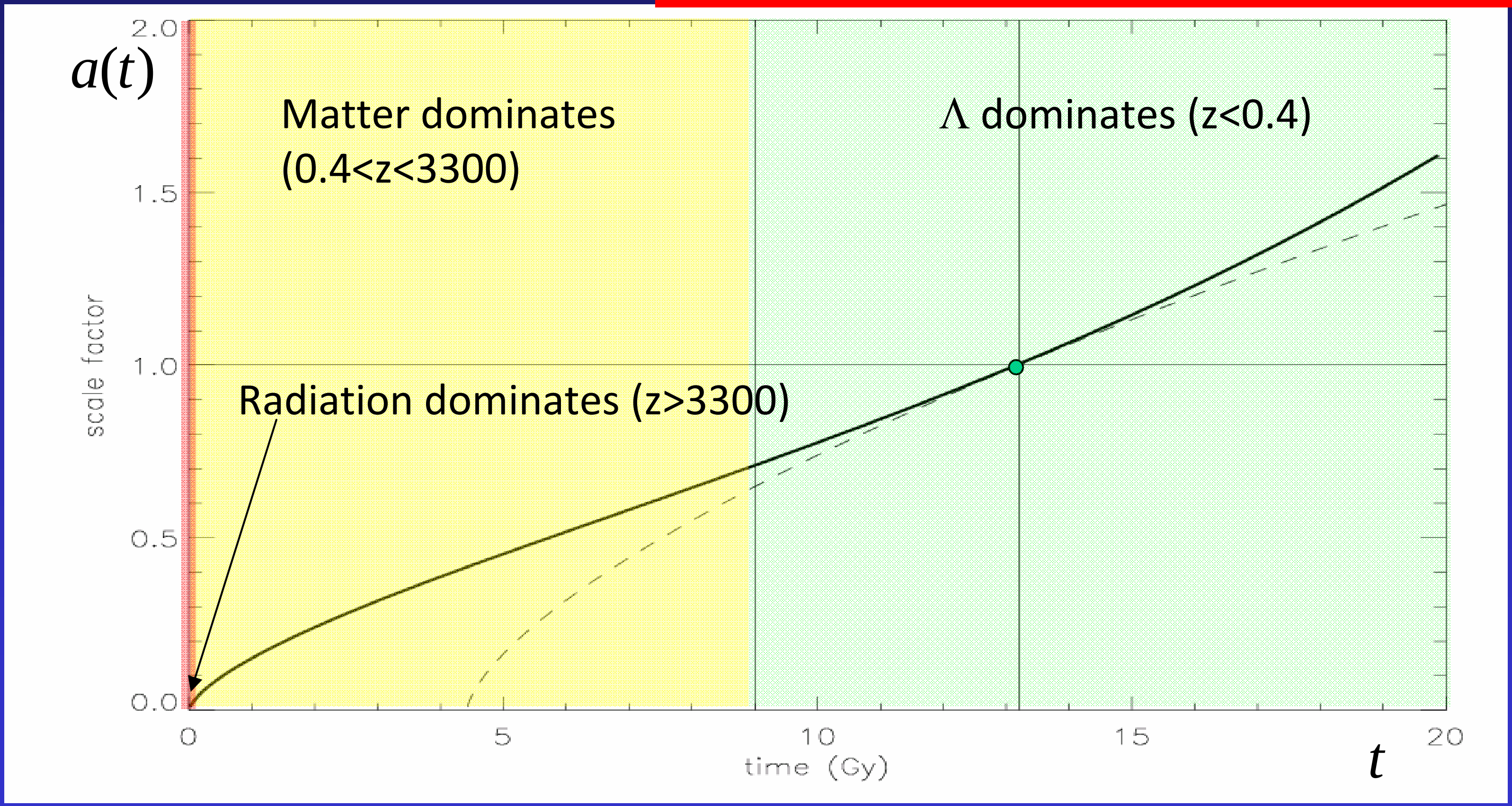

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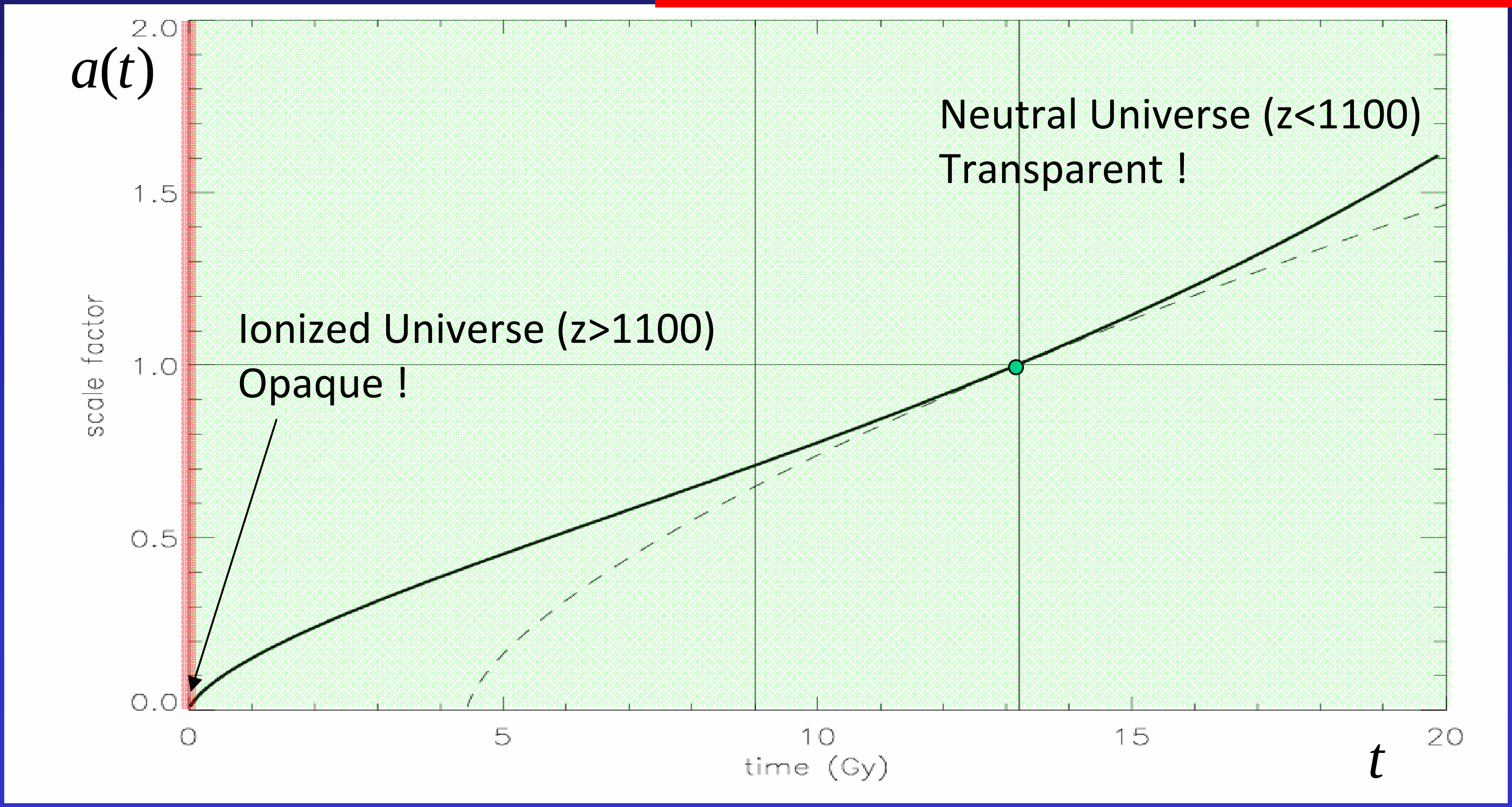
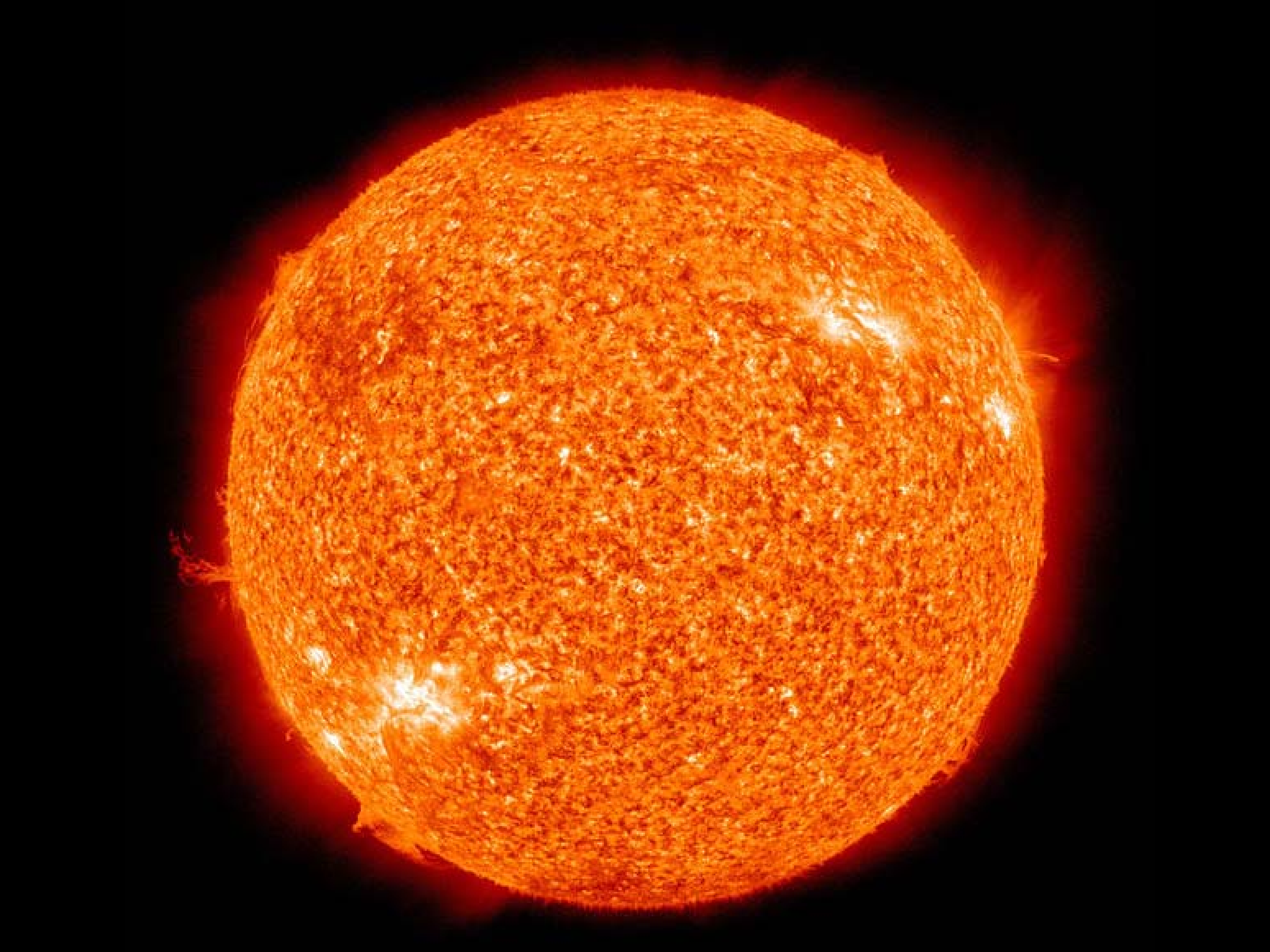
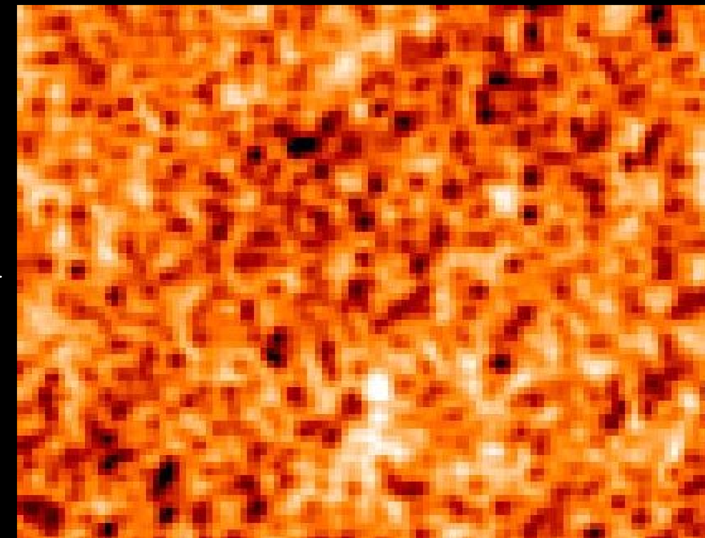




Granulazione solare

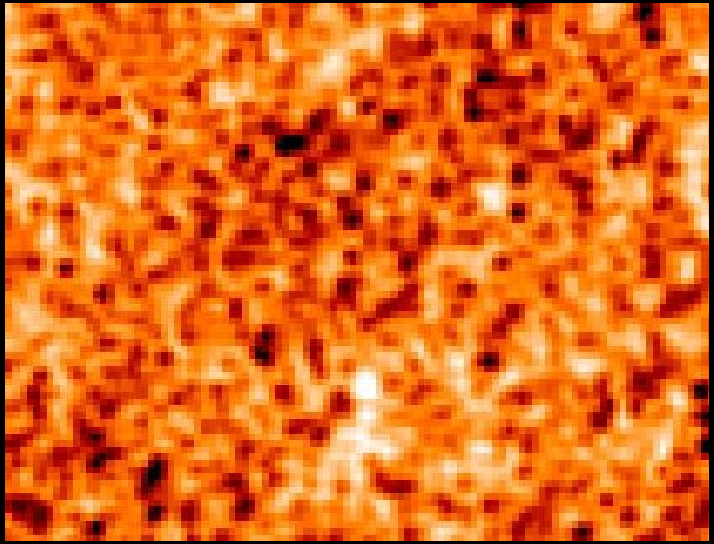


Gas incandescente
sulla superficie del
Sole (5500 K)

8 minuti luce

Qui, ora

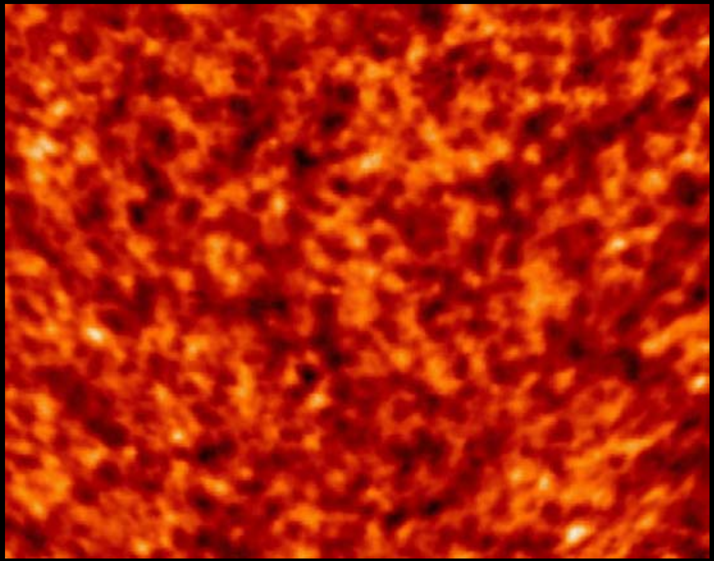
Granulazione solare



Gas incandescente sulla superficie del Sole (5500 K)

8 minuti luce

Qui, ora



Mappa di BOOMERanG dell’ Universo Primordiale

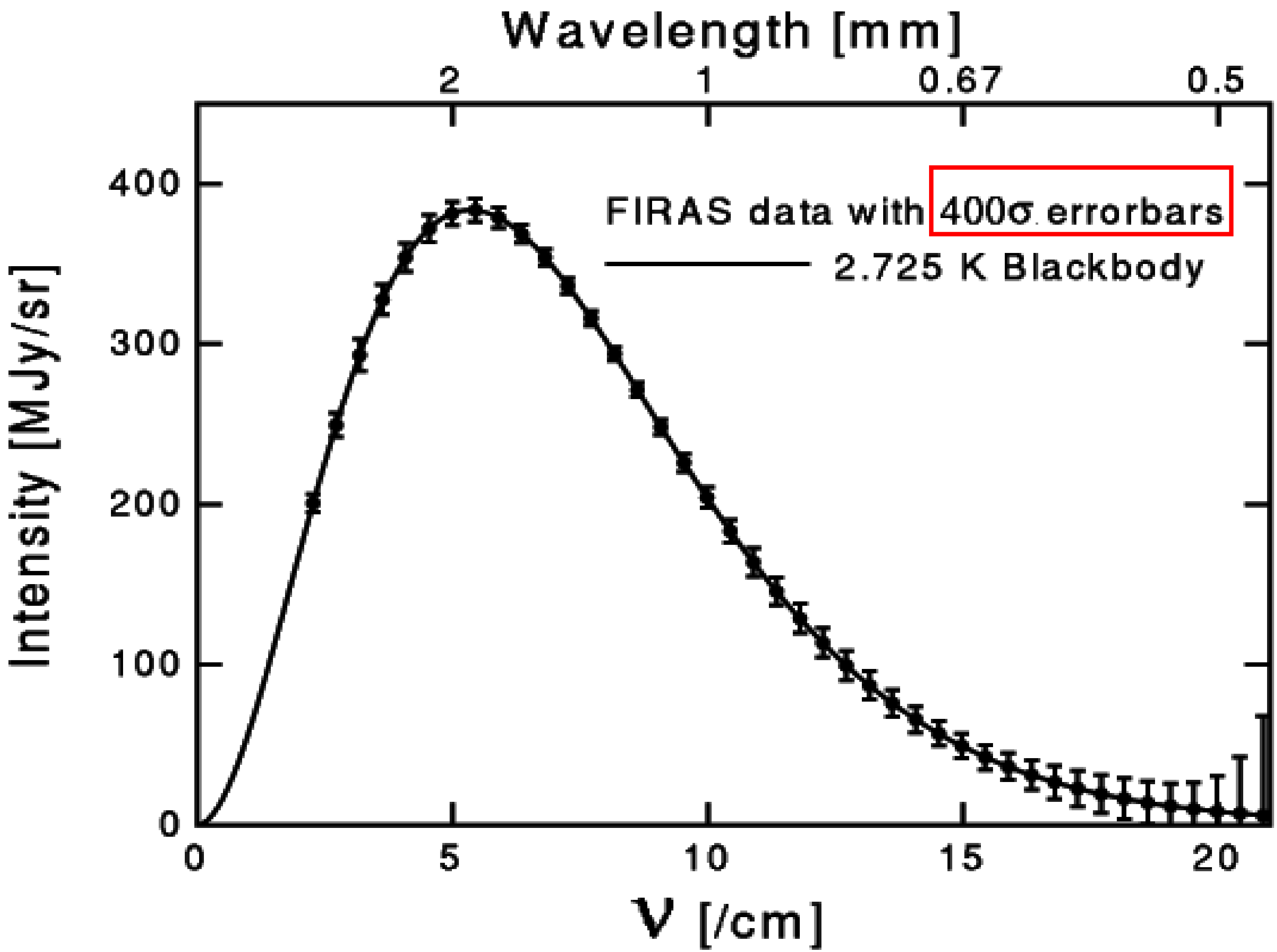
Gas incandescente nell’ universo primordiale (l’ universo diventa trasparente a 3000 K)

14 miliardi di anni luce

Qui, ora

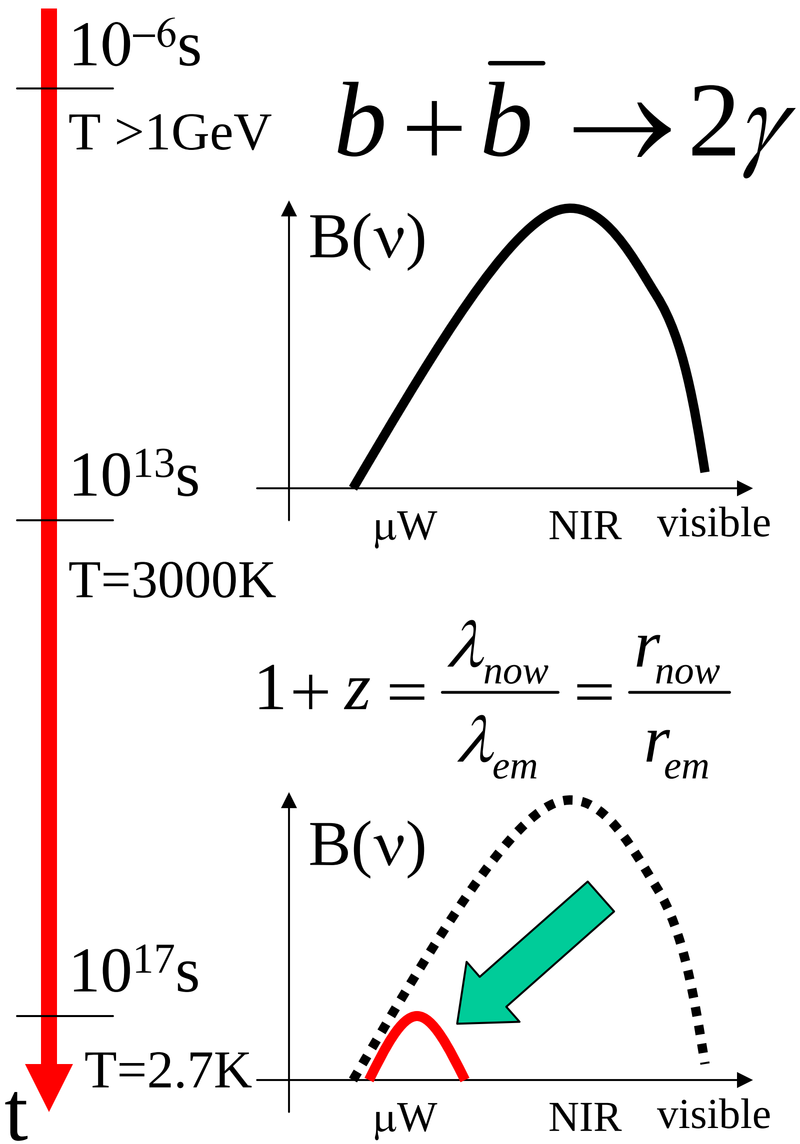
Fondo Cosmico di Microonde

- Osservando regioni di universo sempre più distanti, si arriva a sondare un’ epoca in cui l’ universo era talmente denso e caldo da essere ionizzato, e quindi opaco.
- Da questa barriera incandescente (simile alla superficie del sole) proviene luce che, a causa della successiva espansione dell’ universo, si trasforma in microonde che possono essere osservate ancora oggi.
- Il fondo cosmico di microonde, uno straordinario portatore di informazioni sulle primissime fasi dell’ espansione dell’ universo.



Wavelength [mm]
2
1
0.67
0.5
FIRAS data with 400σ errorbars
2.725 K Blackbody
Intensity [MJy/sr]
400
300
200
100
0
0
5
10
15
20
ν [/cm]

What is the CMB



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

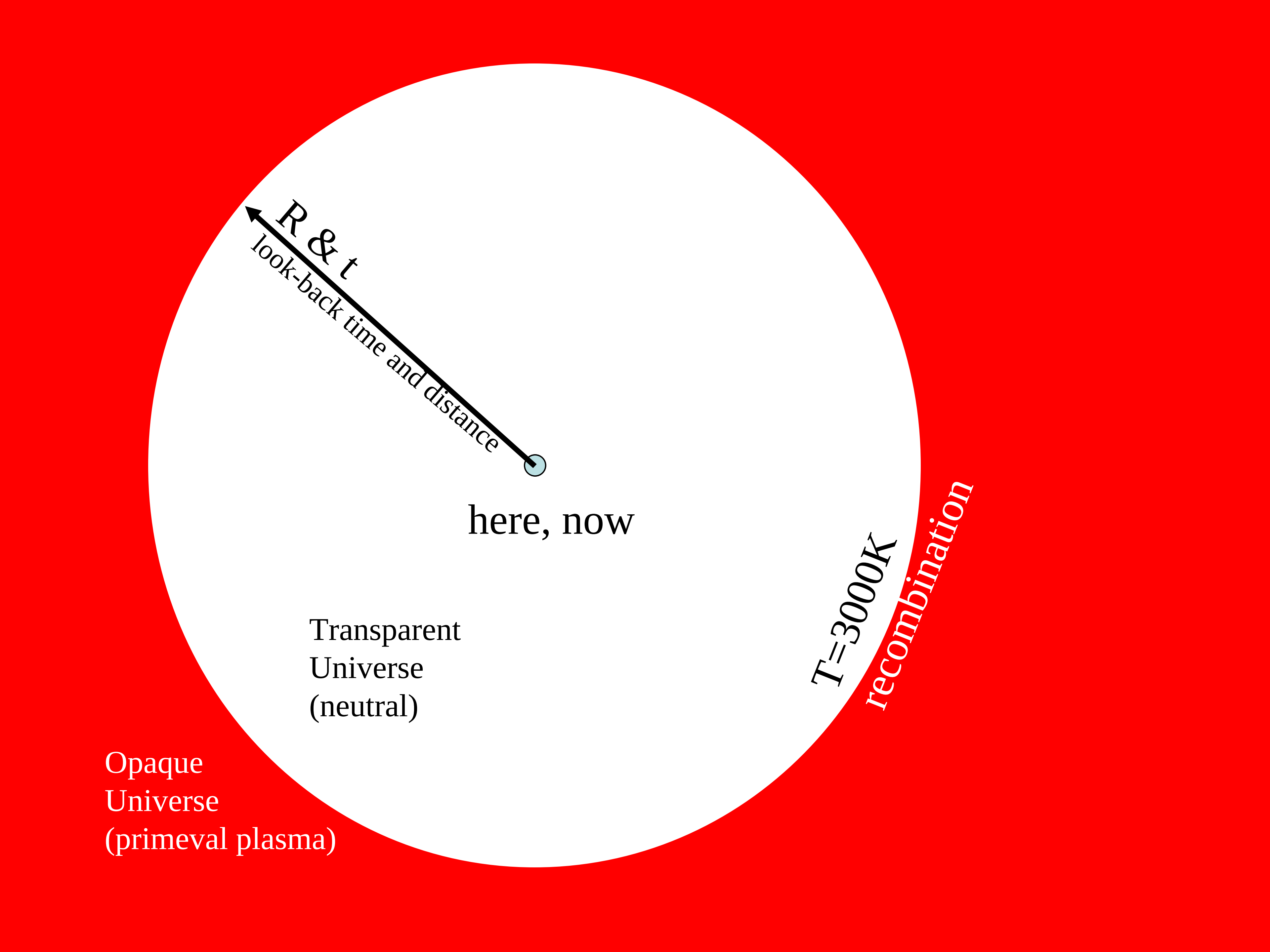
$$1 + z = \frac{\lambda_{now}}{\lambda_{em}} = \frac{r_{now}}{r_{em}}$$

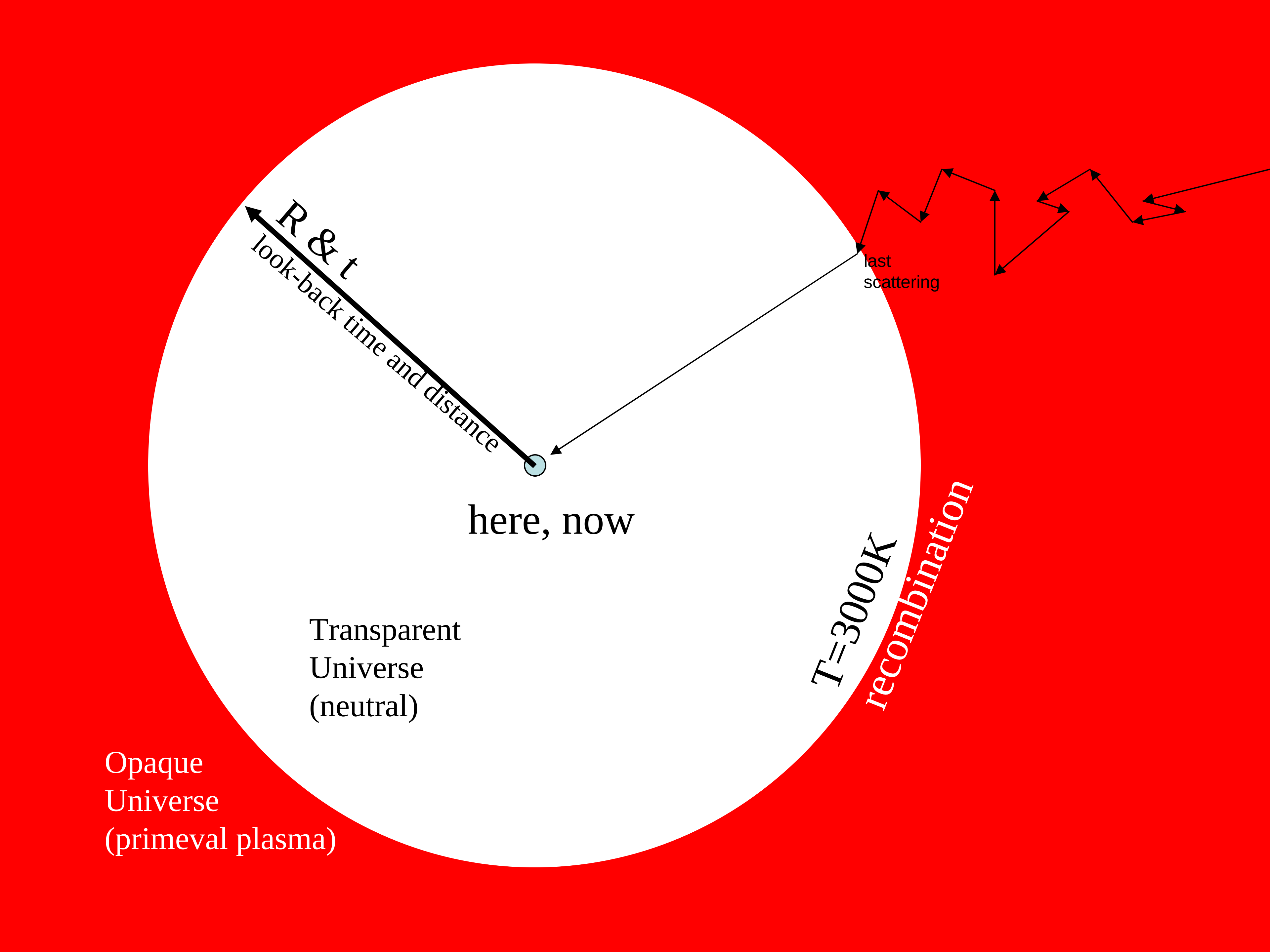
According to modern cosmology:

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/cm^3, ~1 meV**

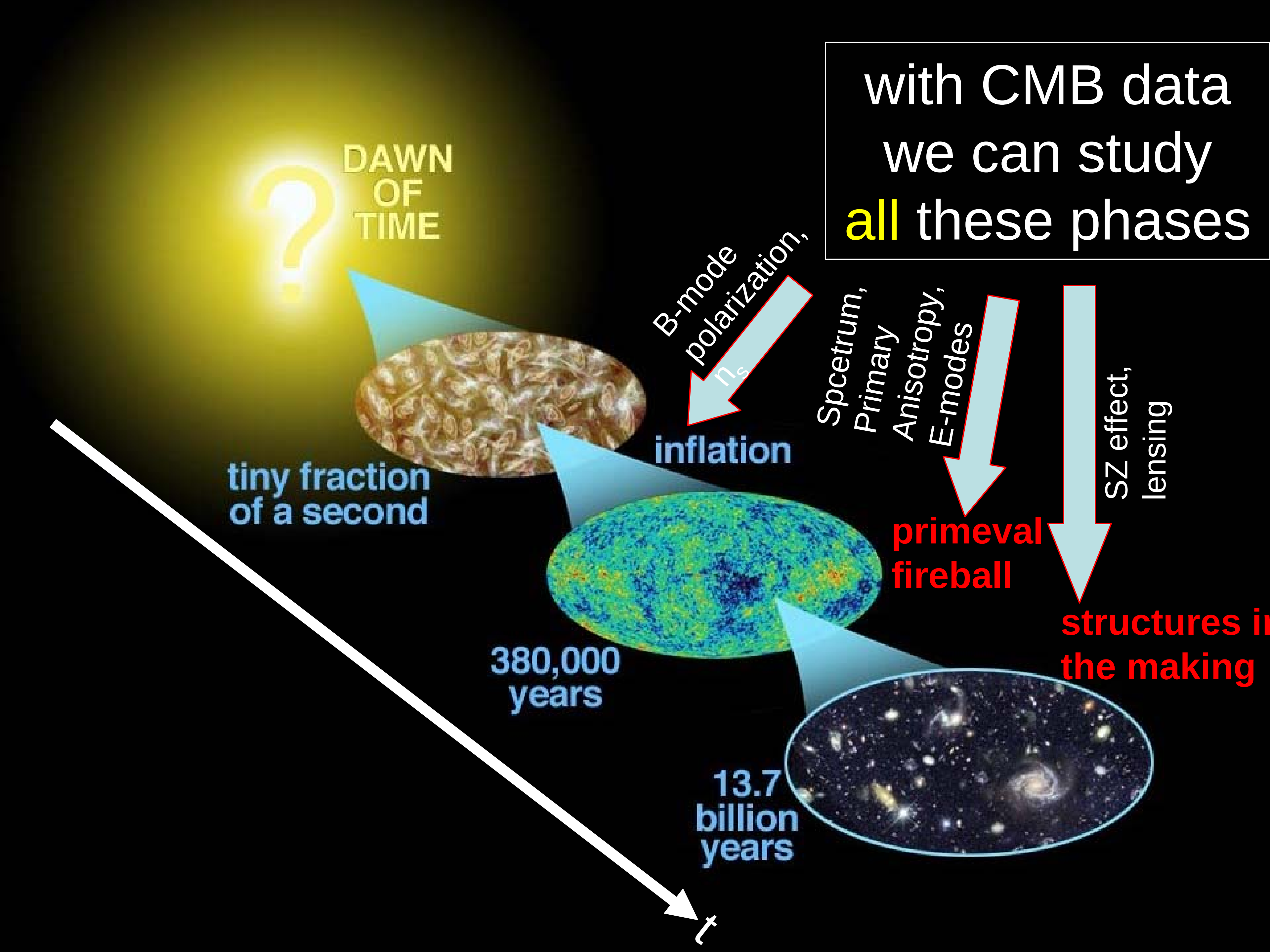
These photons carry
significant information
on the structure, evolution and
composition of our universe


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
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:

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

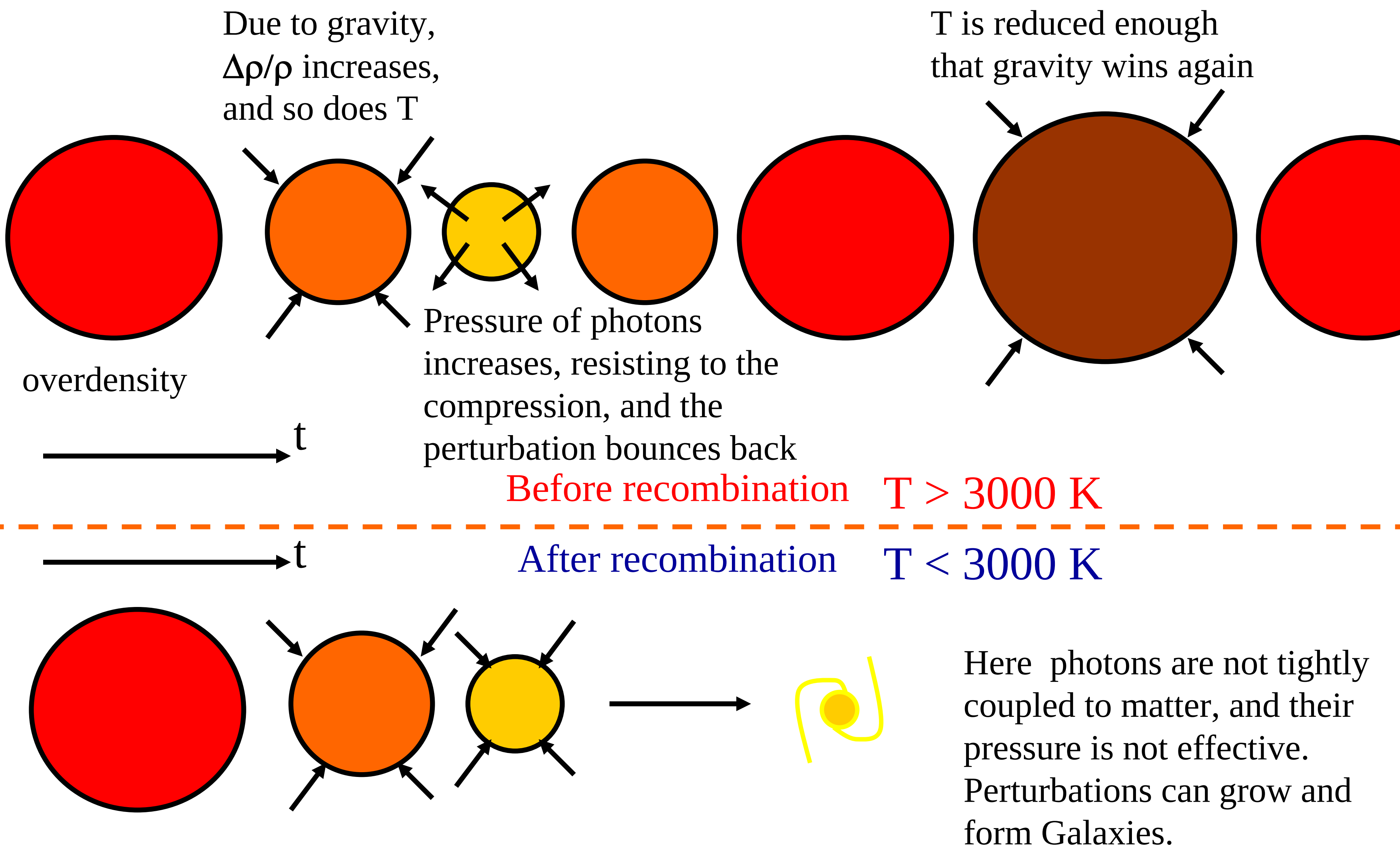
Sachs-Wolfe (gravitational redshift) | Photon density fluctuations | Doppler effect from velocity fields

- 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)

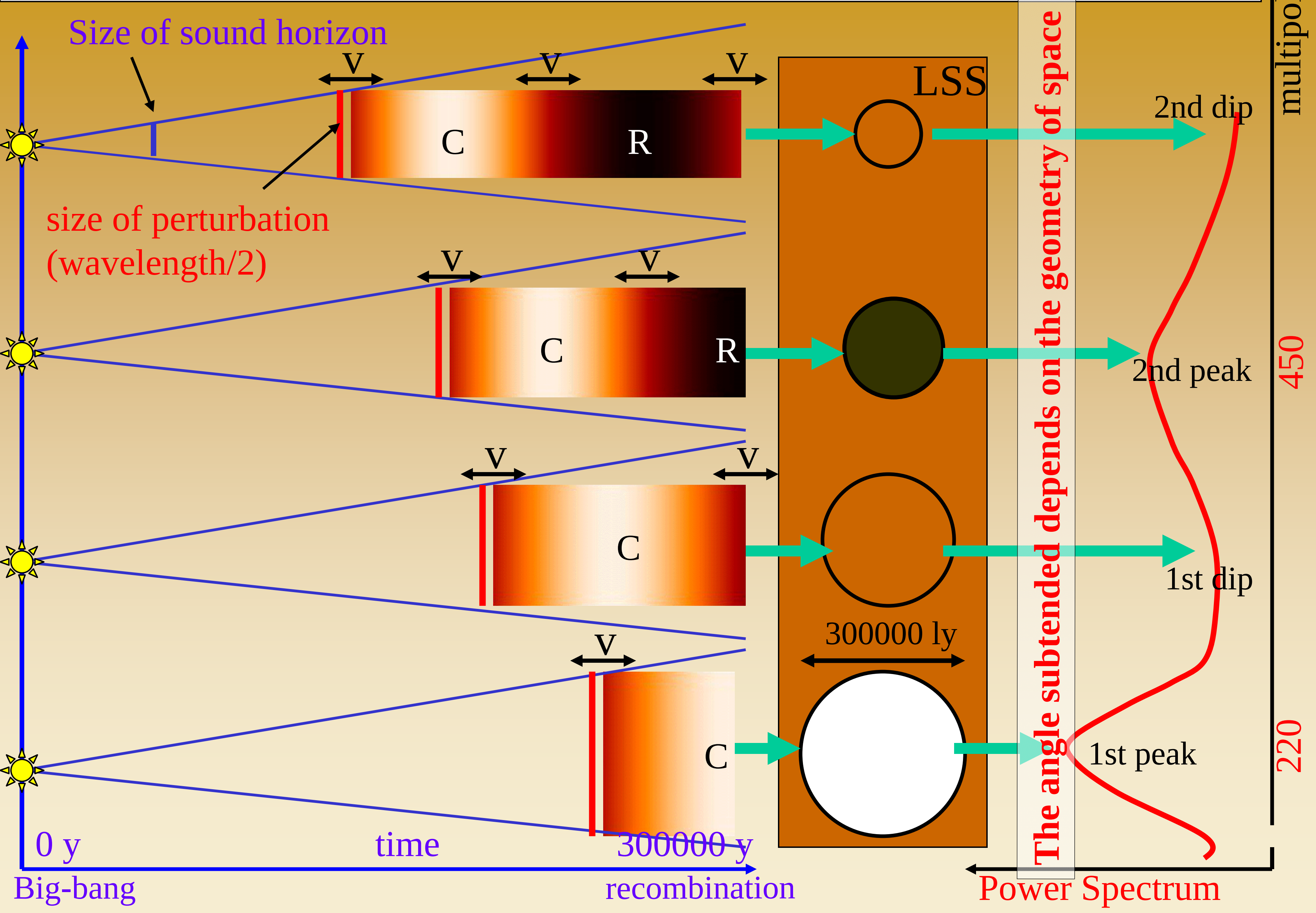
- The primeval plasma of photons and matter oscillates :
- self-gravity vs radiation pressure.
- We can measure the result of these oscillations as a weak anisotropy pattern in the image of the CMB.
- Statistical theory: all information encoded in the angular power spectrum of the image.

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.



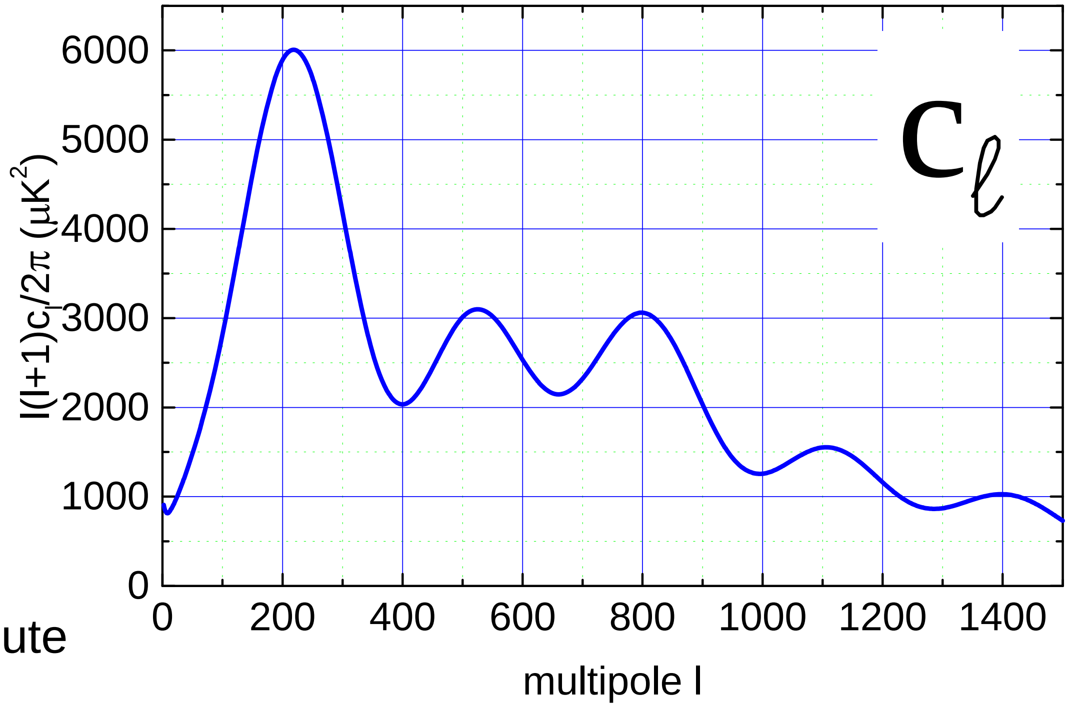
Expected power spectrum:

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

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

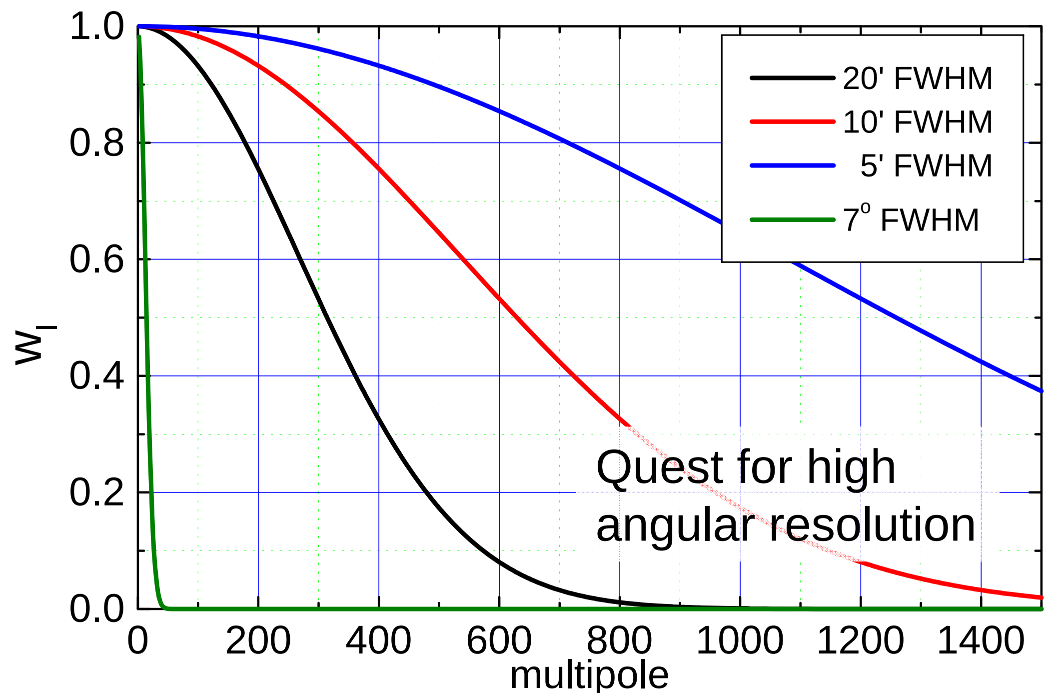
$$\langle \Delta T^2 \rangle = \frac{1}{4\pi} \sum_\ell (2\ell+1) c_\ell$$

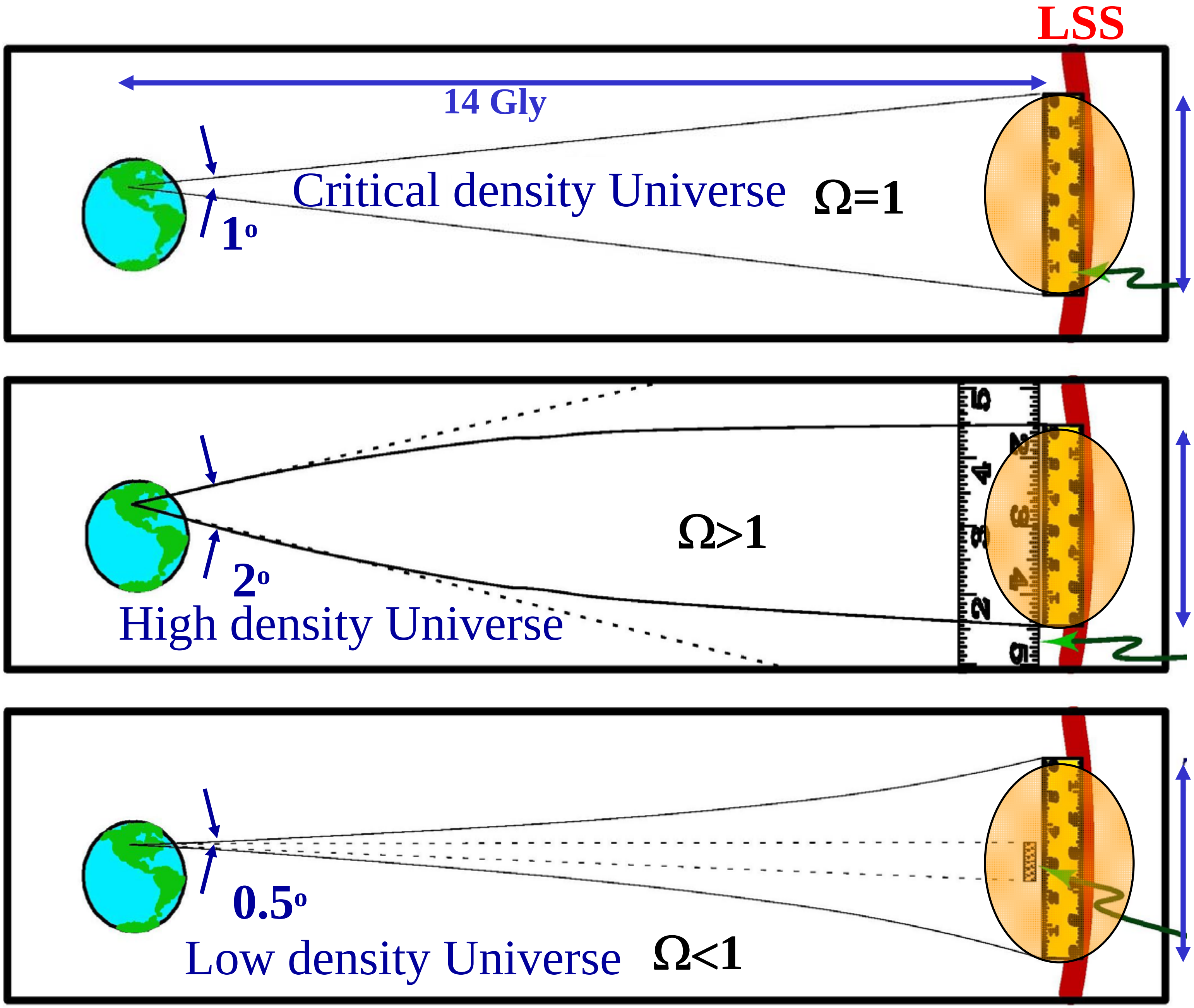
See e.g. http://camb.info to compute c_ℓ for a given cosmological model



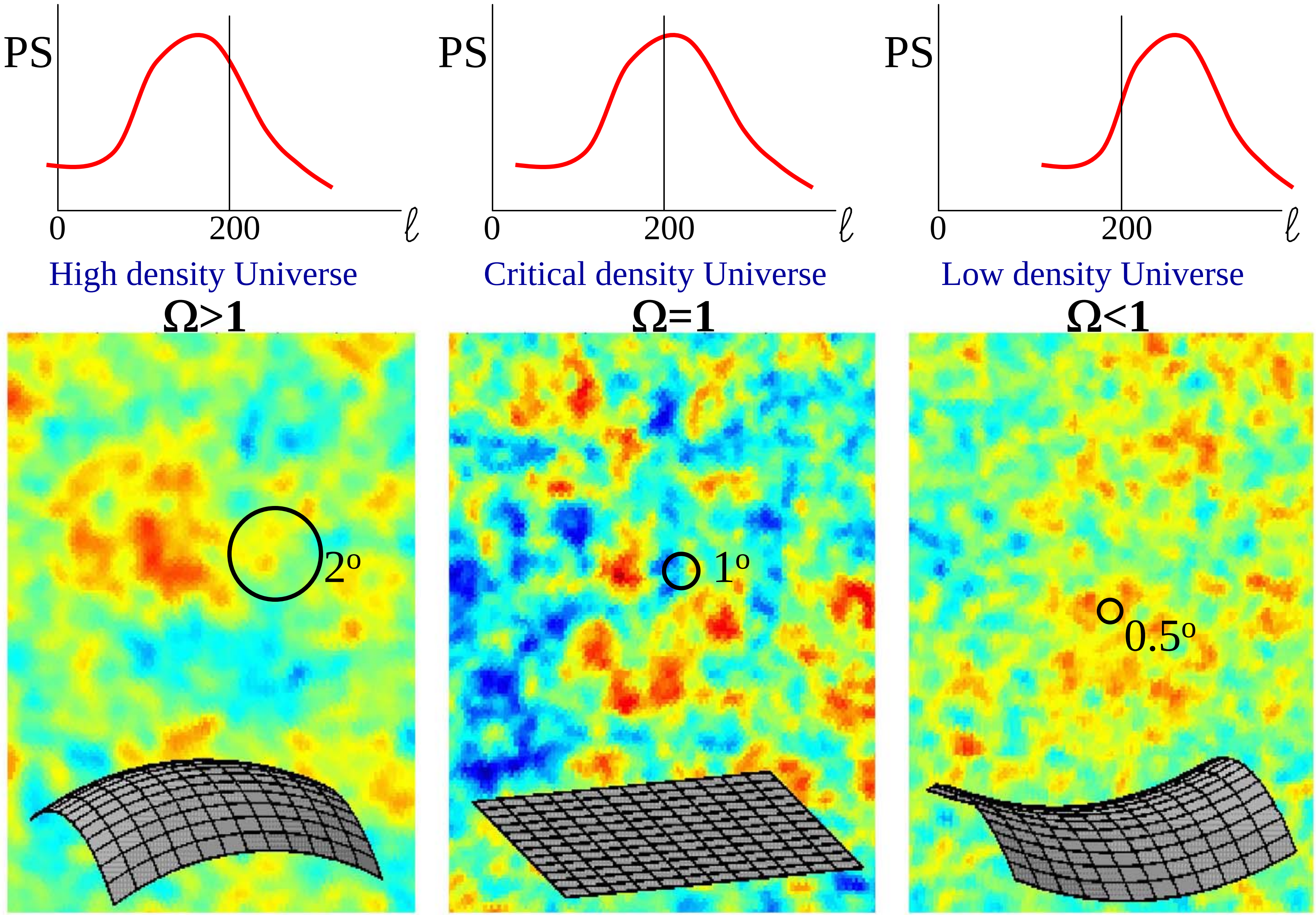
An instrument with finite angular resolution is not sensitive to the smallest scales (highest multipoles). For a gaussian beam with s.d. σ:

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





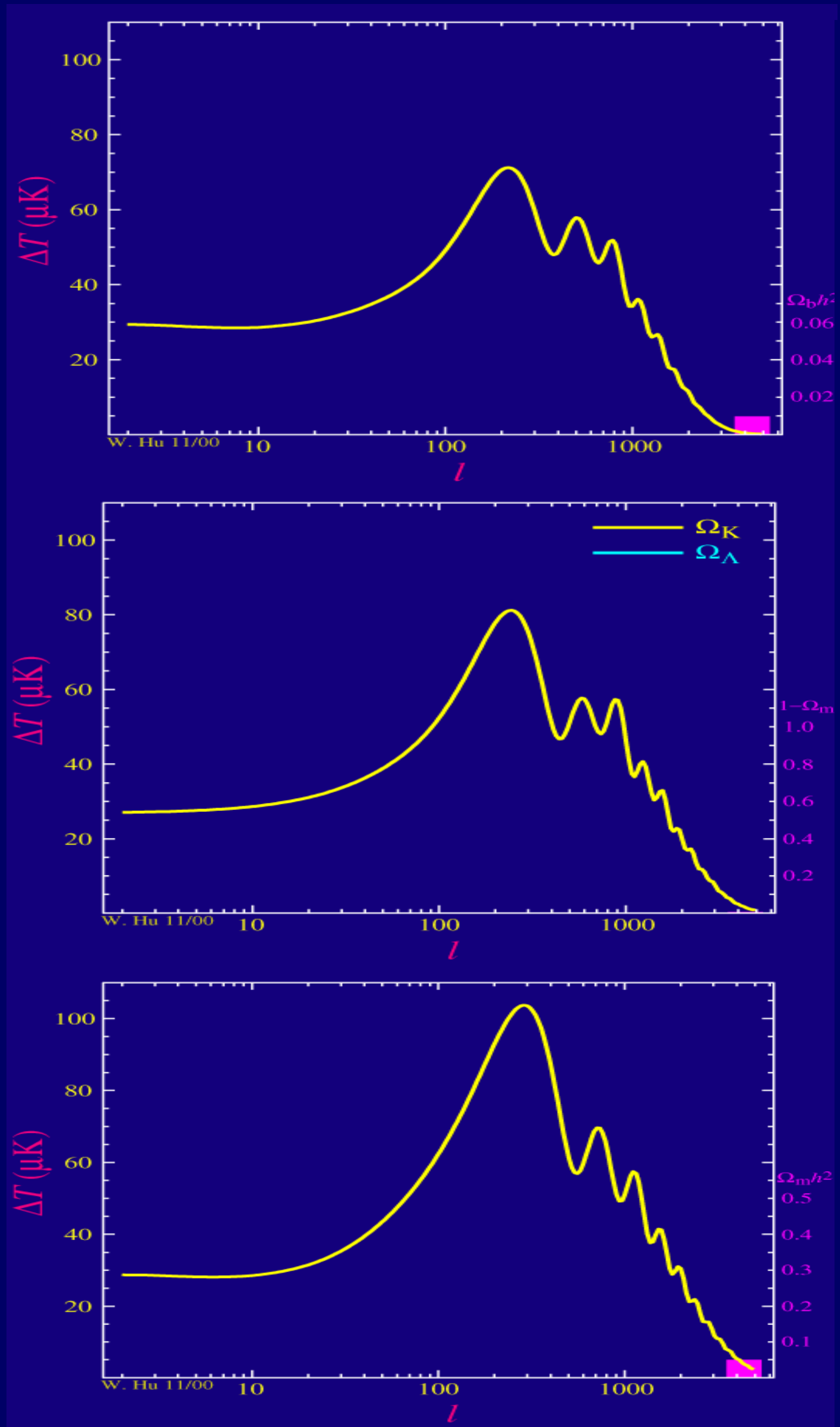
The image and PS are modified by the geometry of the universe



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

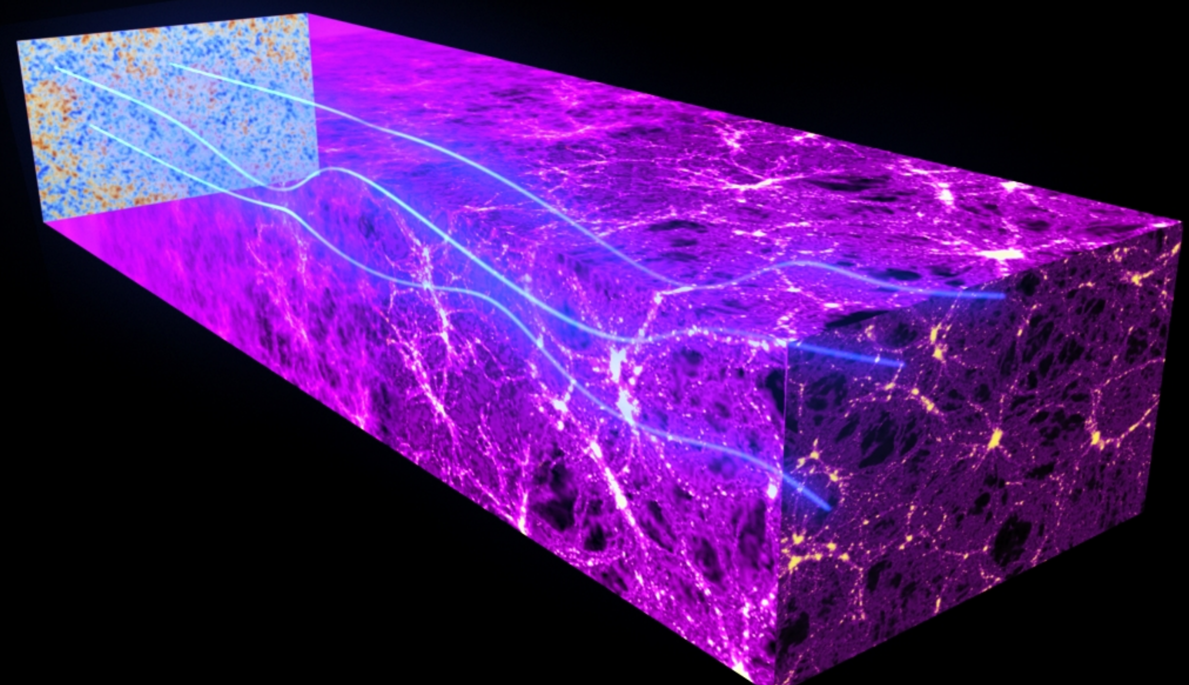
Composition

- 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.



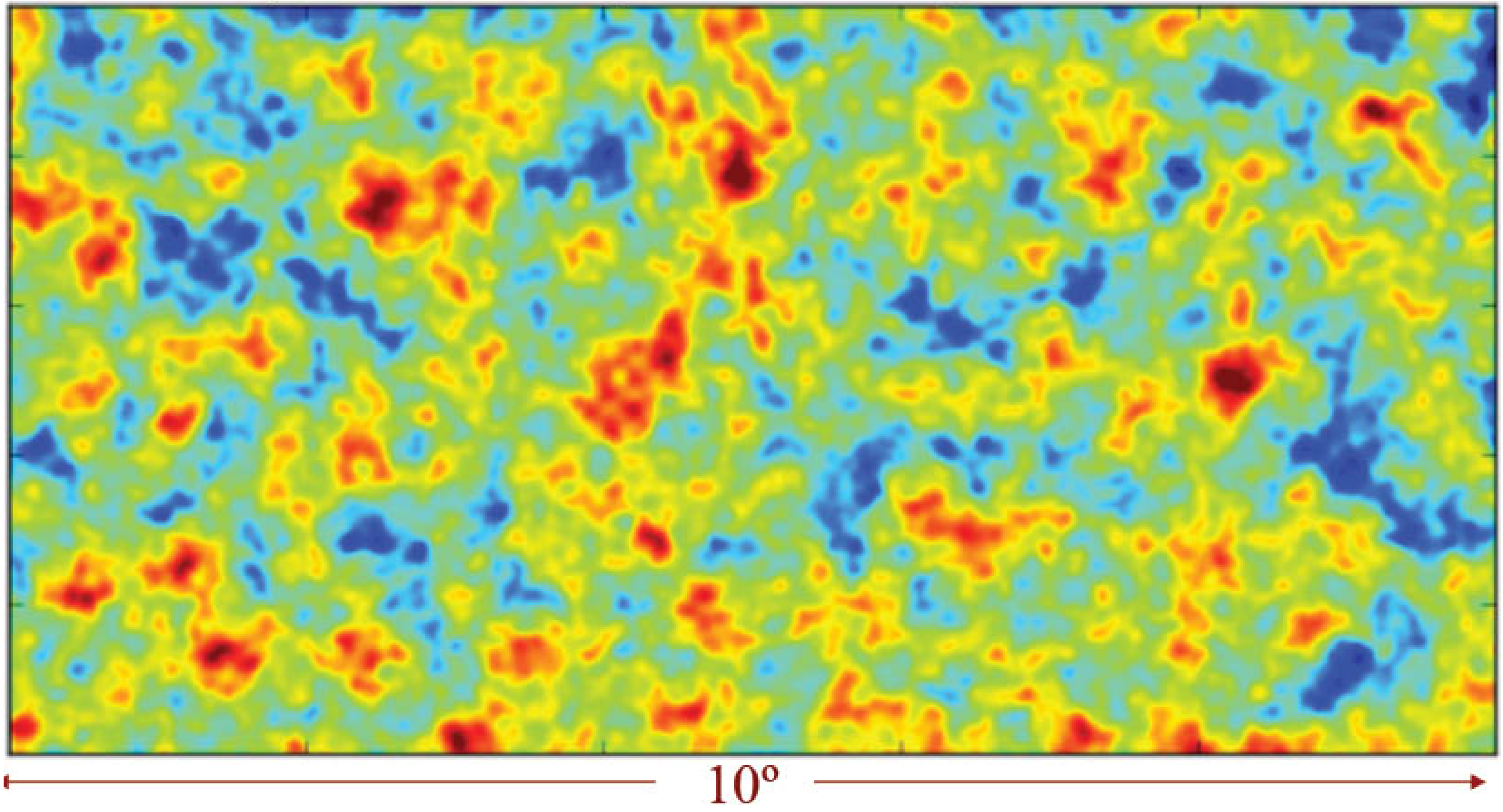
CMB anisotropy (lensing)

- 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.



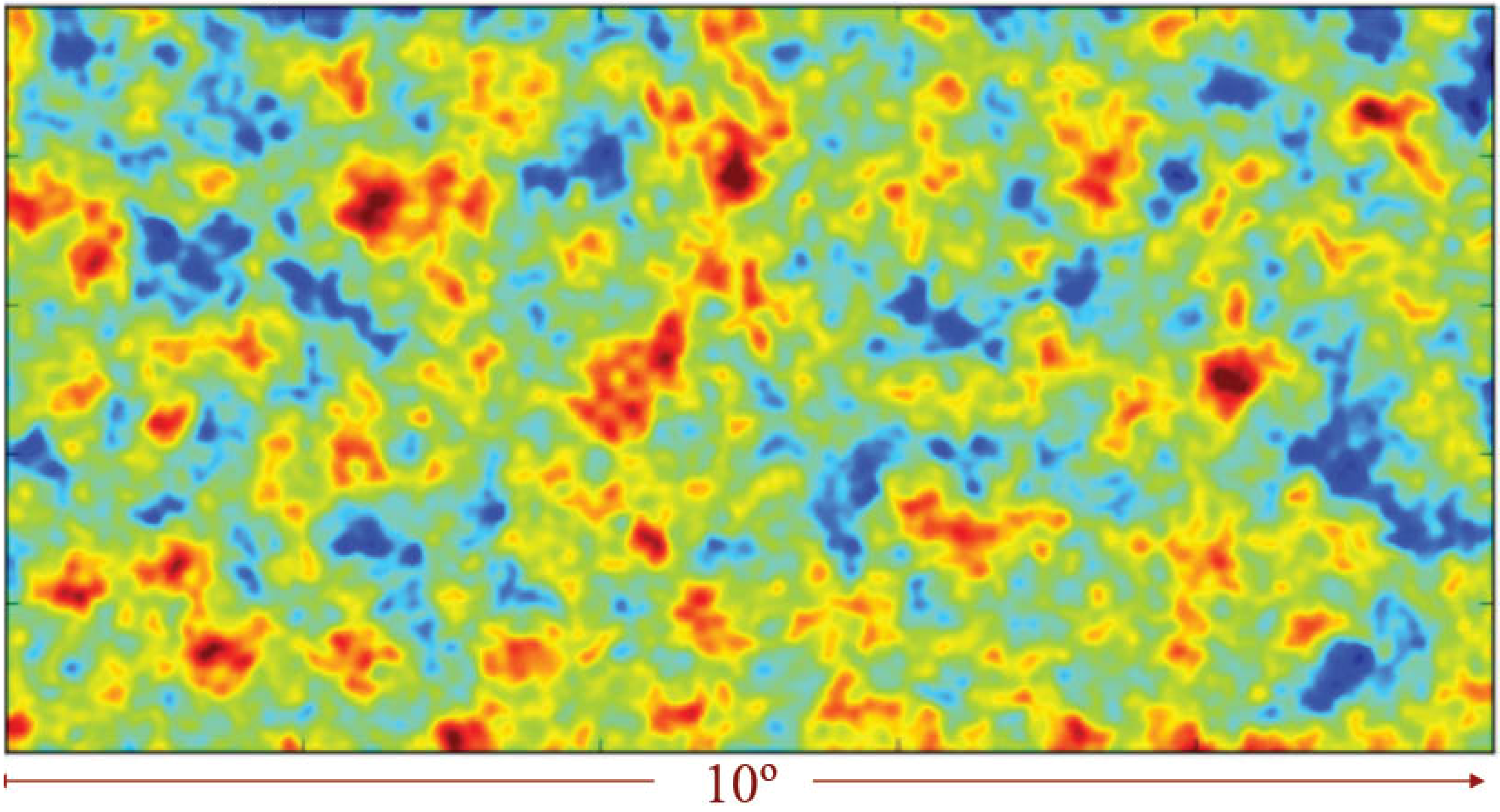
Typical deflection: 2.5’

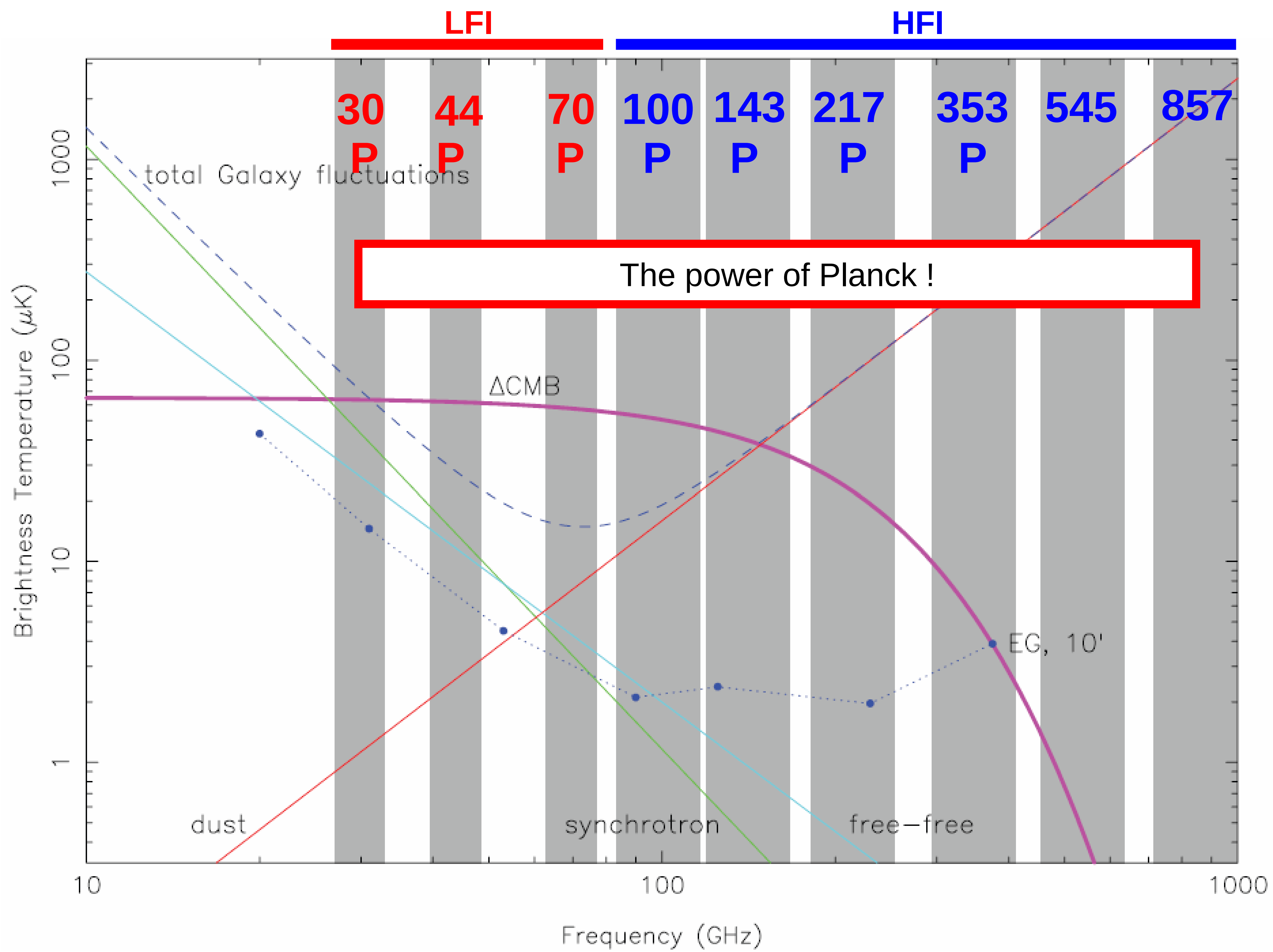
intrinsic CMB anisotropy

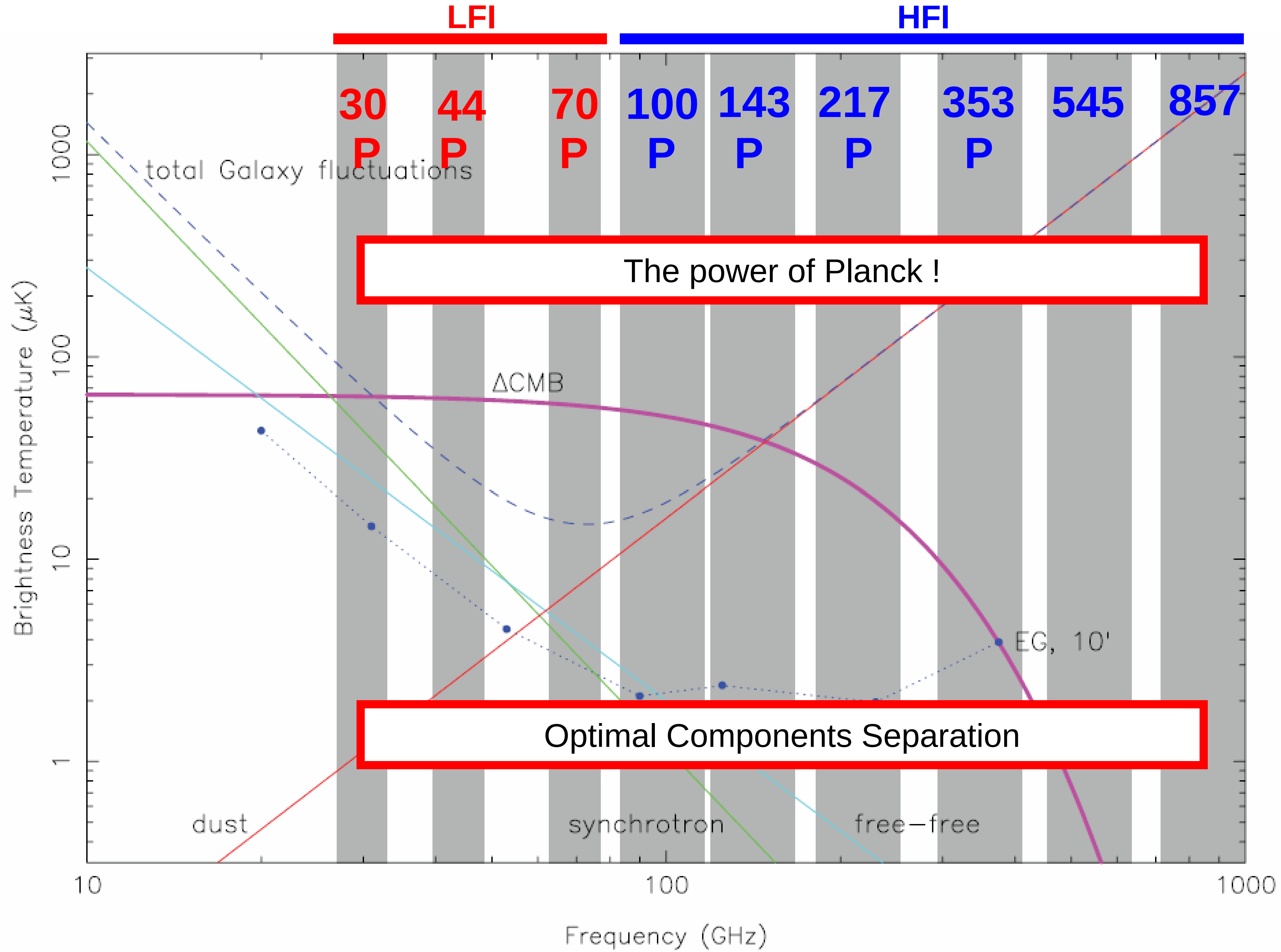


Typical deflection: 2.5’

lensed CMB anisotropy




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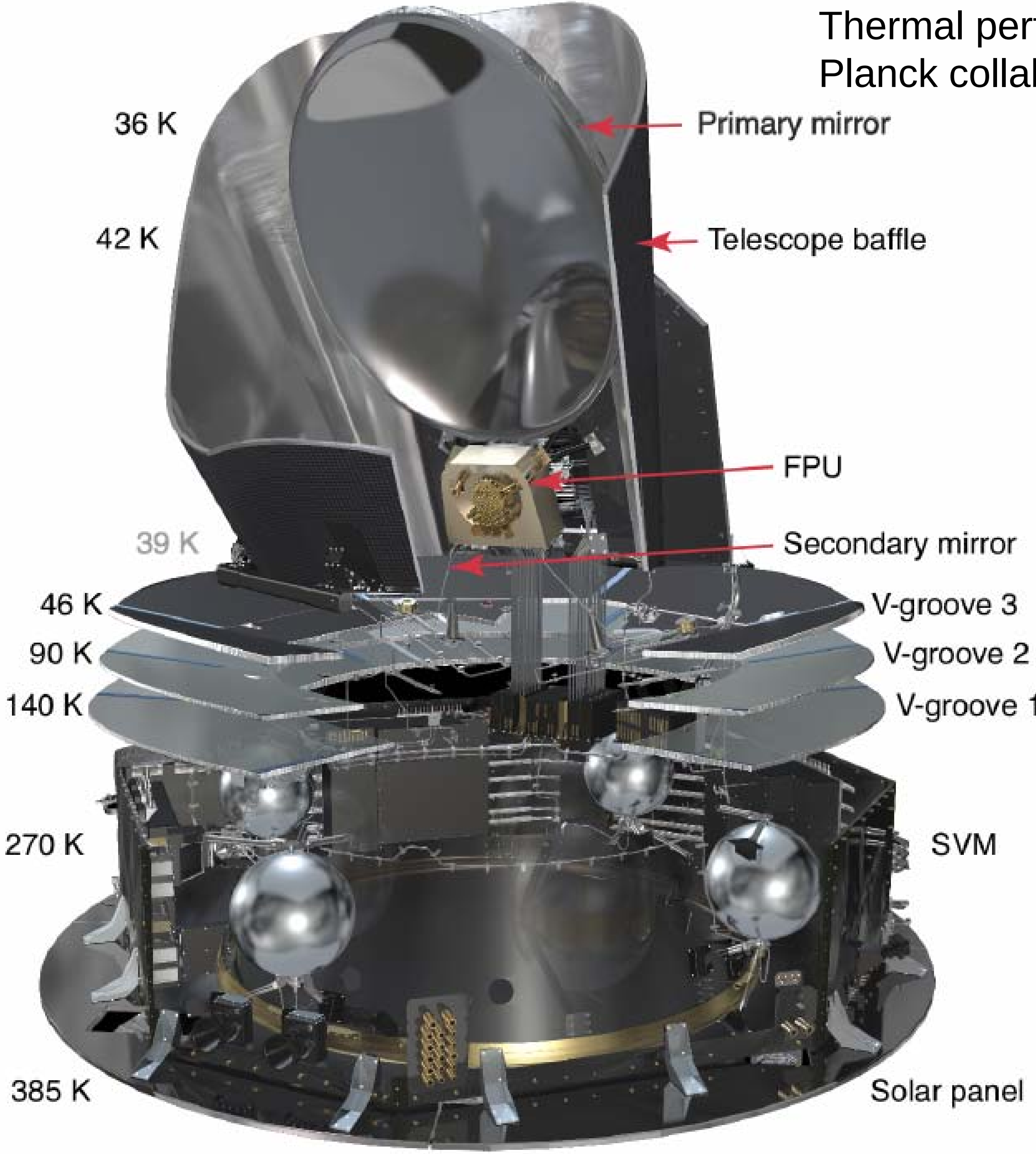
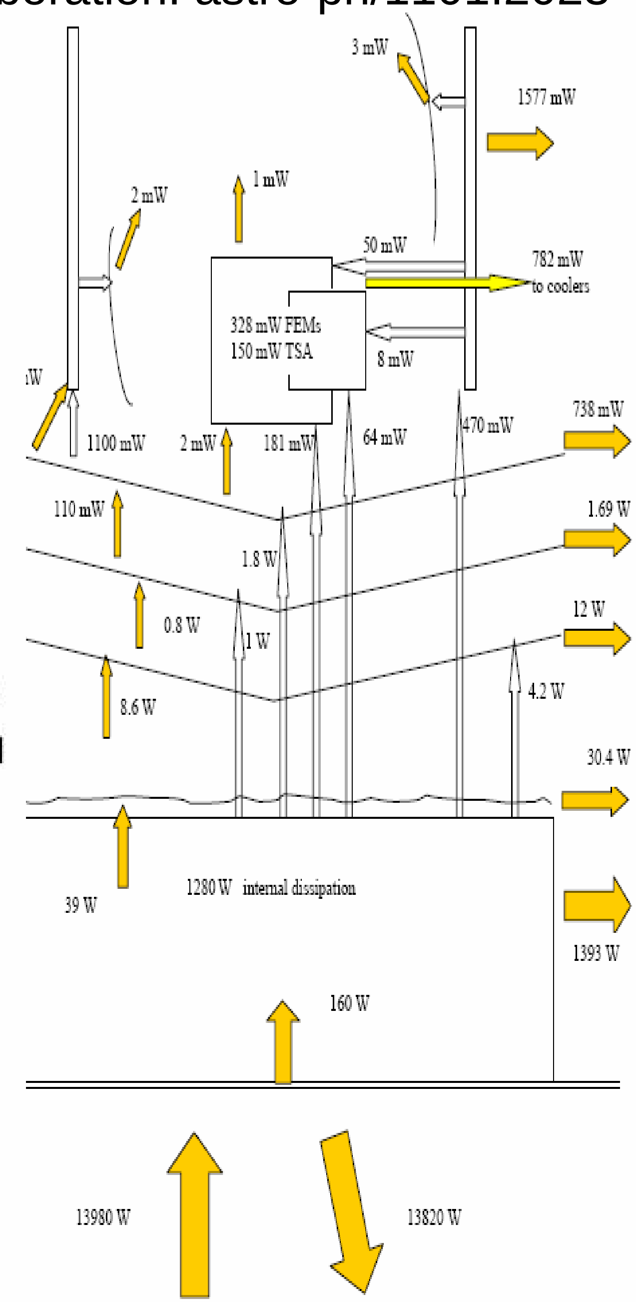
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

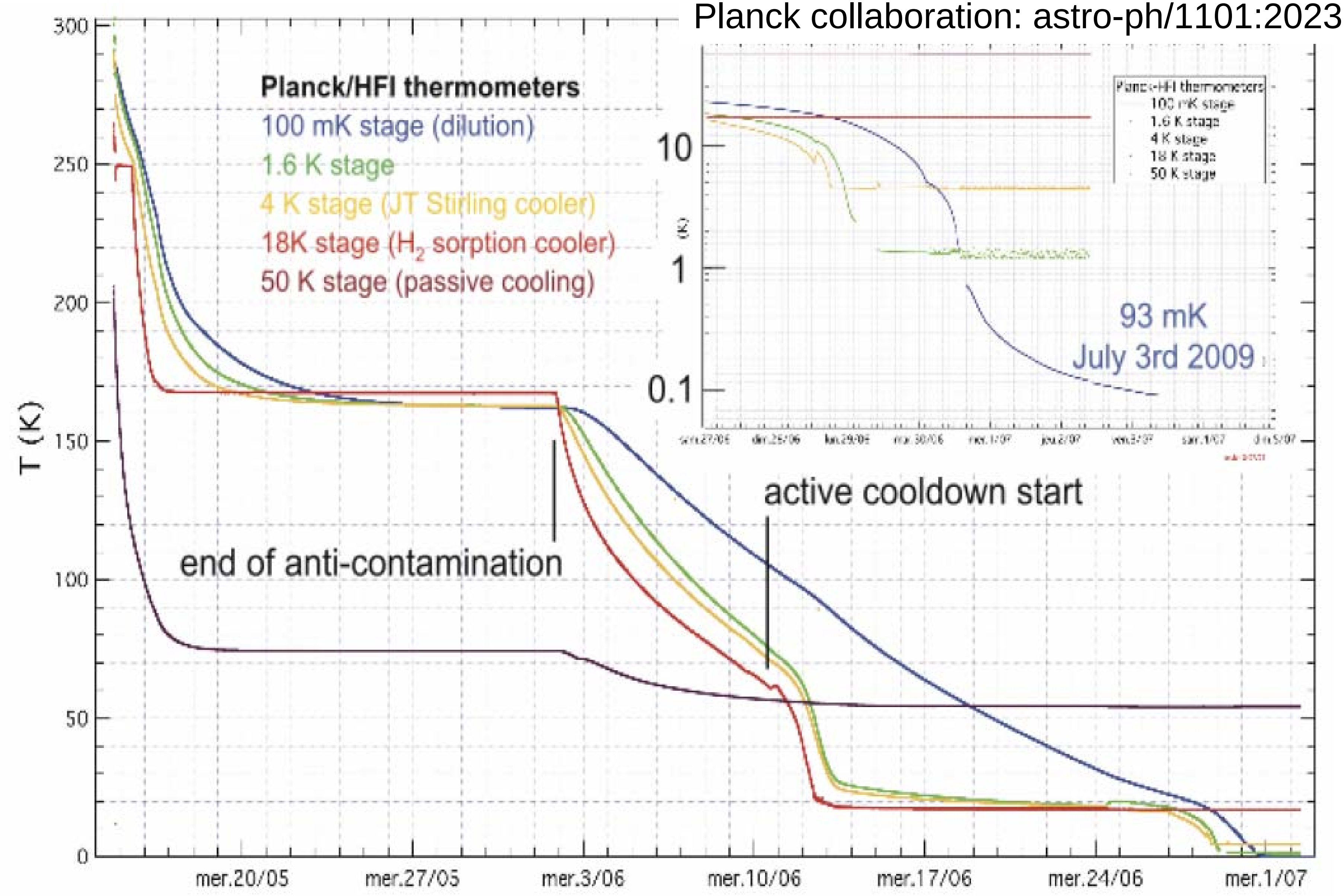
14 / May / 2009

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.

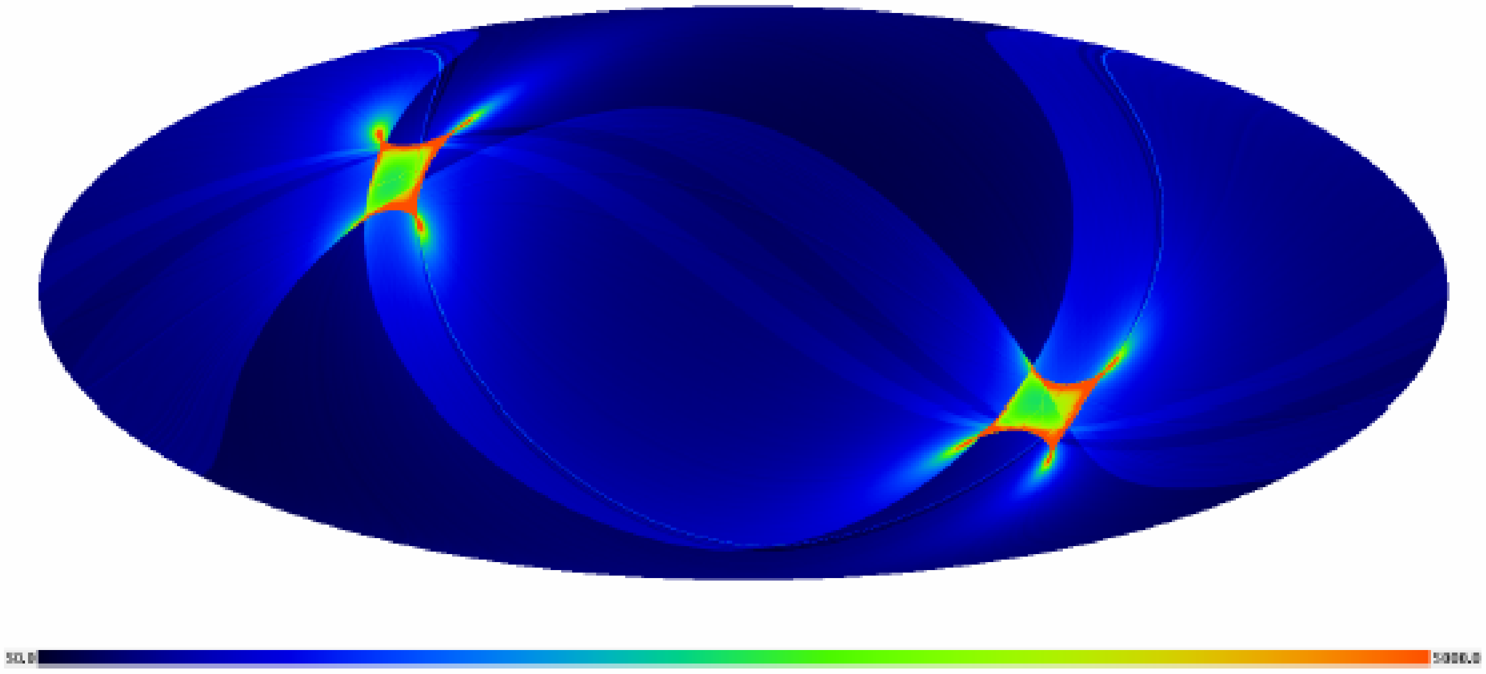
	30 GHz	100 GHz	545 GHz	
Mean[a]	2293	4575	2278	sec deg^2
Minimum	440	801	375	sec deg^2
$<$ half Mean[b]	14.4	14.6	15.2	%
$> 4\times$ Mean[c]	1.6	1.5	1.2	%
$> 9\times$ Mean[d]	0.41	0.42	0.41	%

[a] Mean over the whole sky of the integration time cumulated for all detectors (definition as in Table 3) in a given frequency channel.

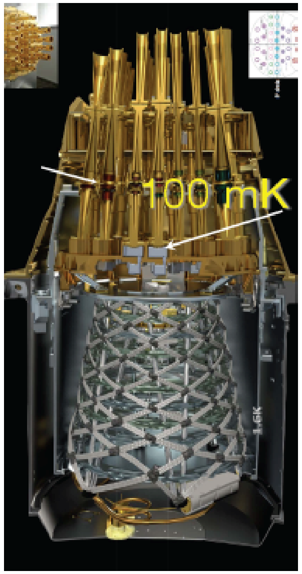
[b] Fraction of the sky whose coverage is less than half the Mean.

[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

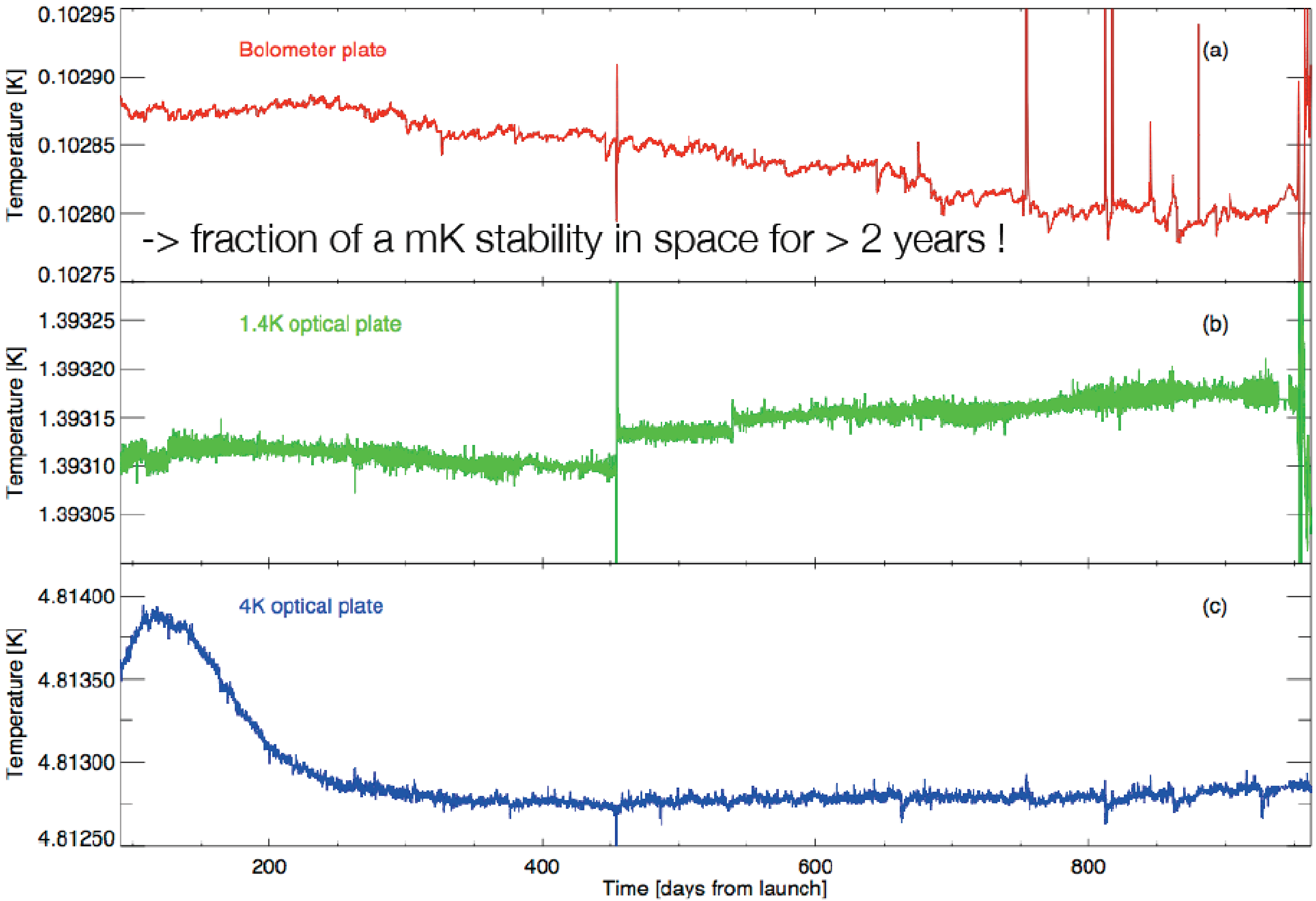
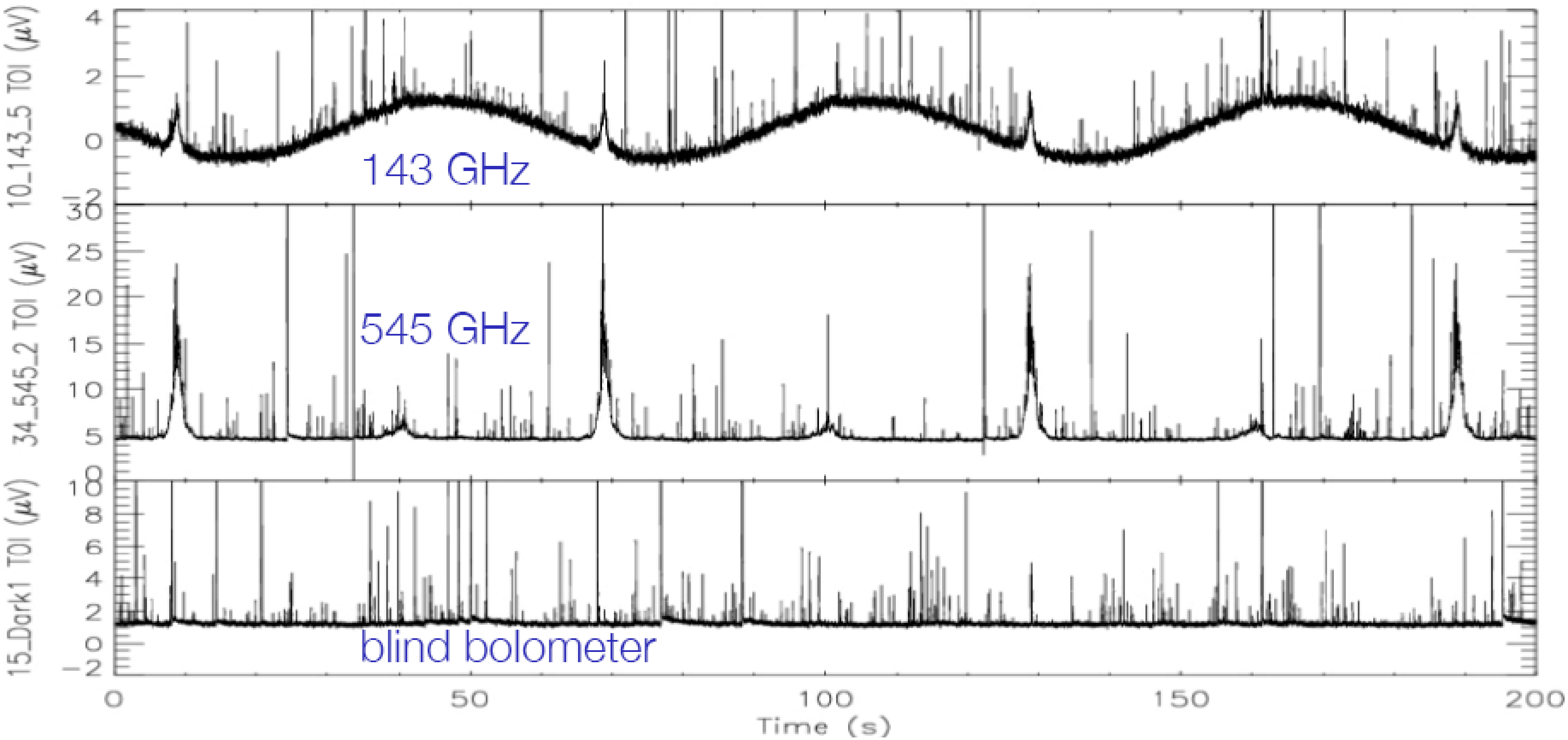


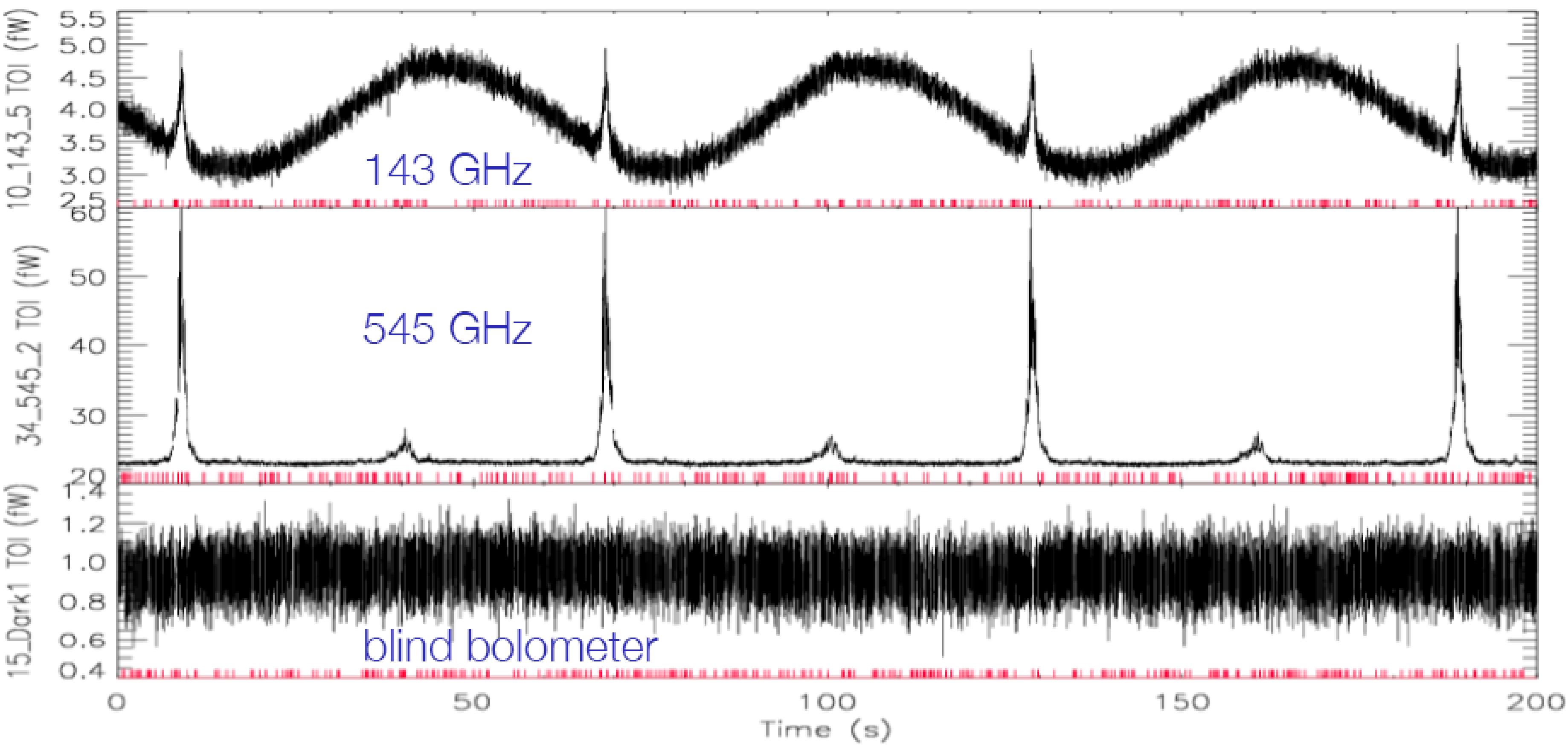
Fig. 7. The impressive stability of the HFI thermal stages during operations. Shown is the temperature evolution of the bolometer stage (*top*), the 1.6 K optical filter stage (*middle*) and the 4-K cooler reference load stage (*bottom*). The horizontal axis displays days since the beginning of the nominal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

Raw HFI data

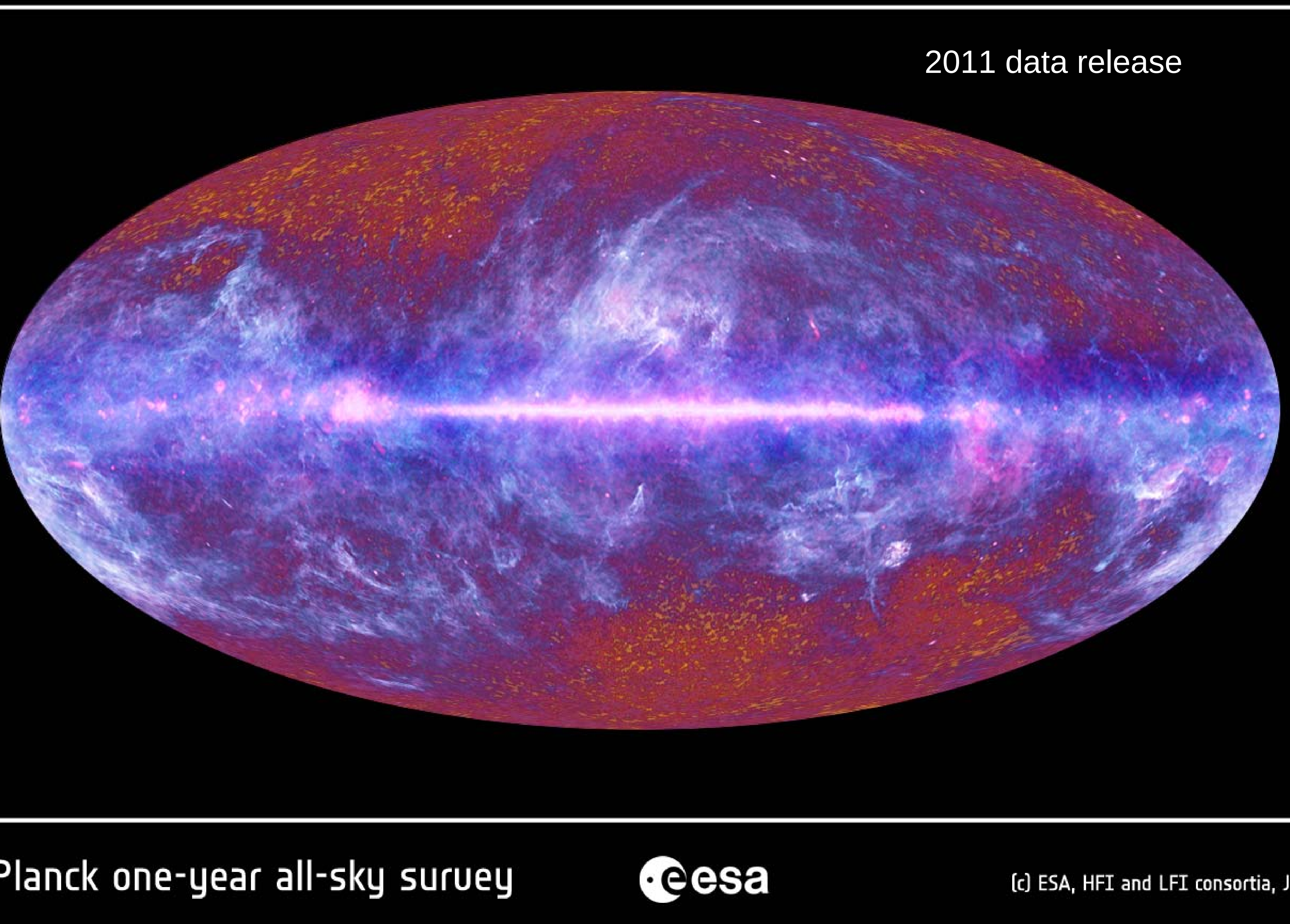


10_143_5 TOI (μV)
34_545_2 TOI (μV)
15_Dark1 TOI (μV)
143 GHz
545 GHz
blind bolometer
Time (s)

De-spiked HFI data



<20% of data flagged


2011 data release
Planck one-year all-sky survey
(c) ESA, HFI and LFI consortia, J

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
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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
- 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

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Power Spectra, cosmological parameters

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Photon propagation effects

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Constraints on cosmology

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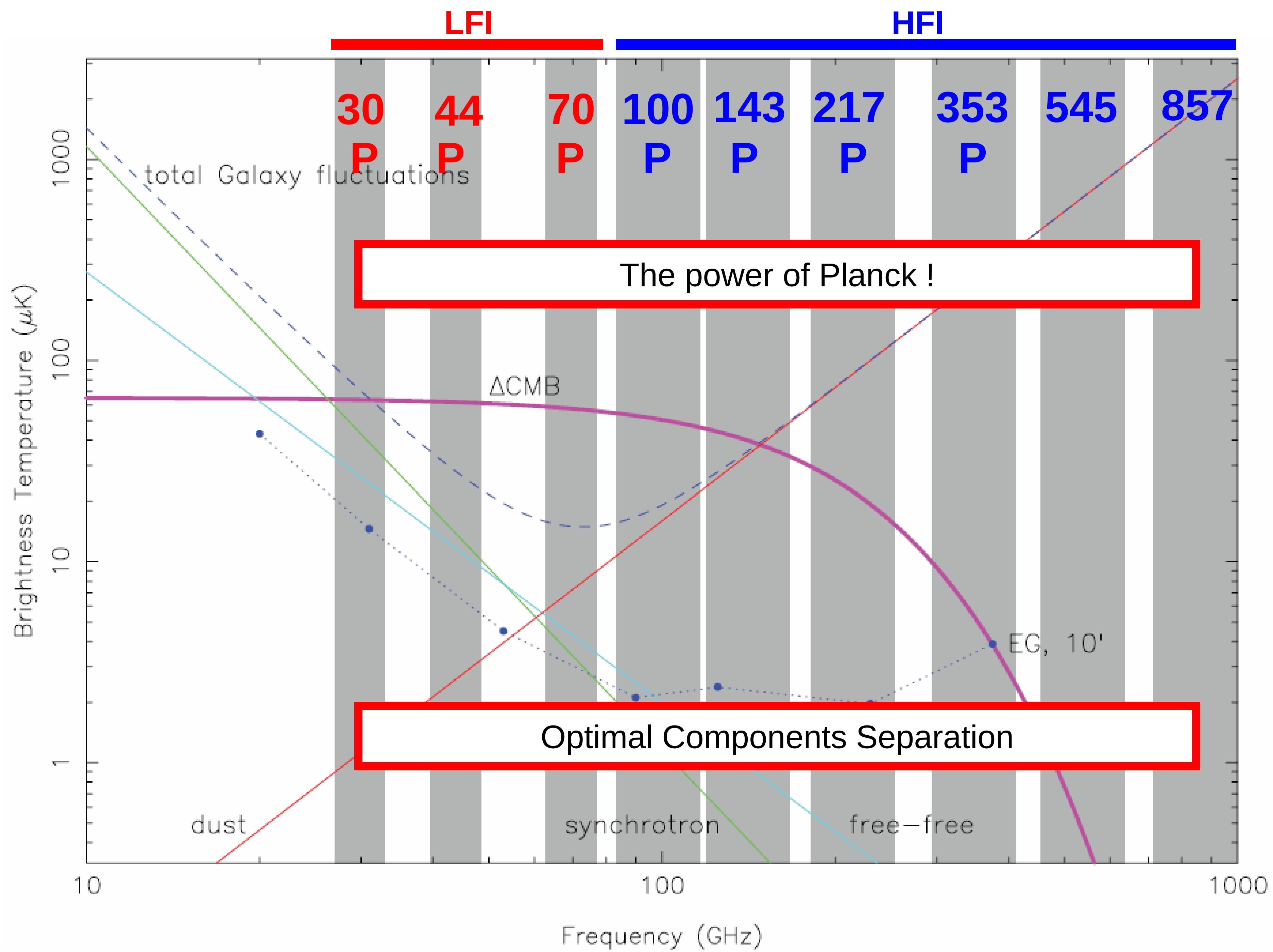

LFI
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30 P
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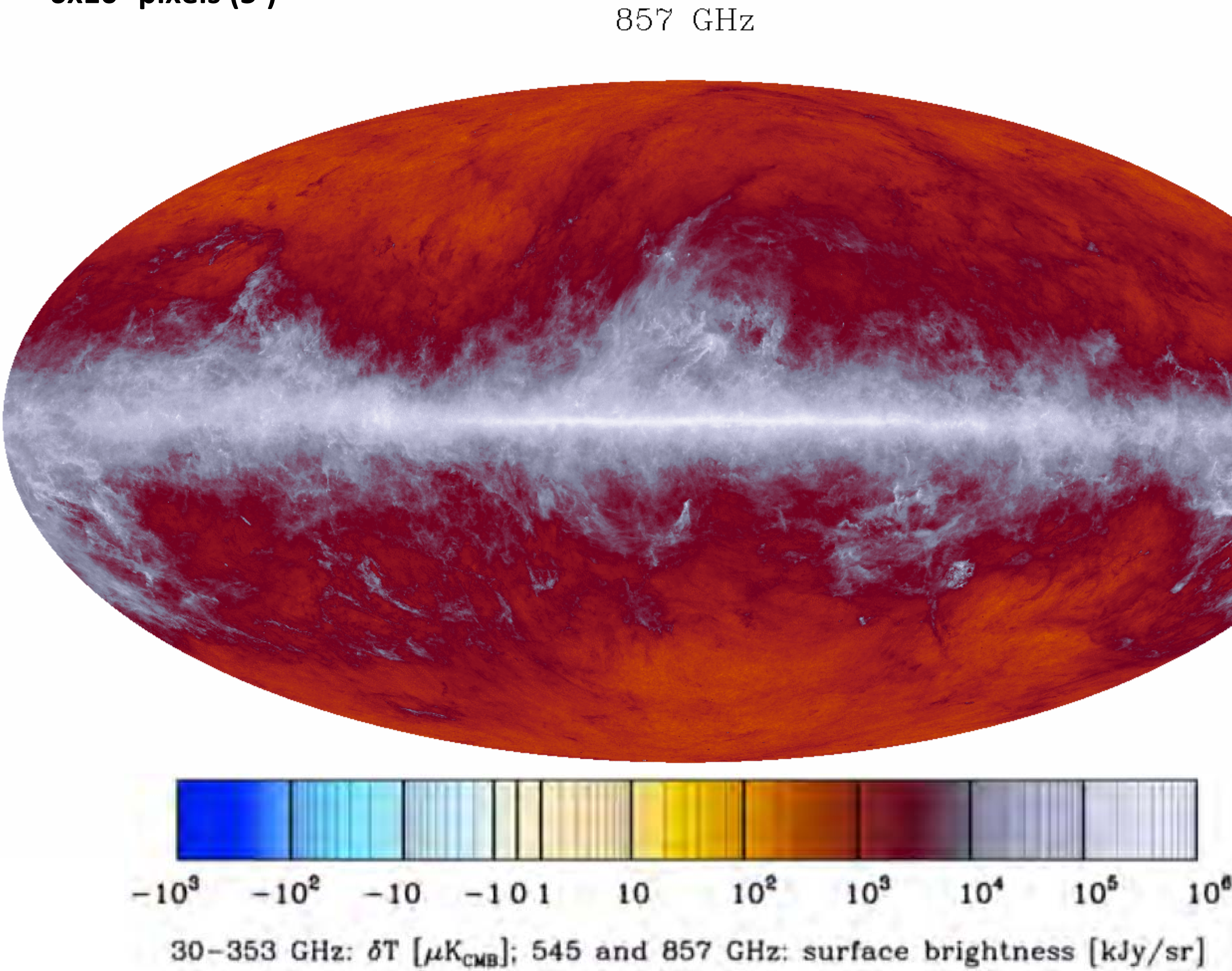
total Galaxy fluctuations
The power of Planck !
ΔCMB
EG, 10'
Optimal Components Separation
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

$6x10^6$ pixels (5')

Planck Legacy Maps



components separation

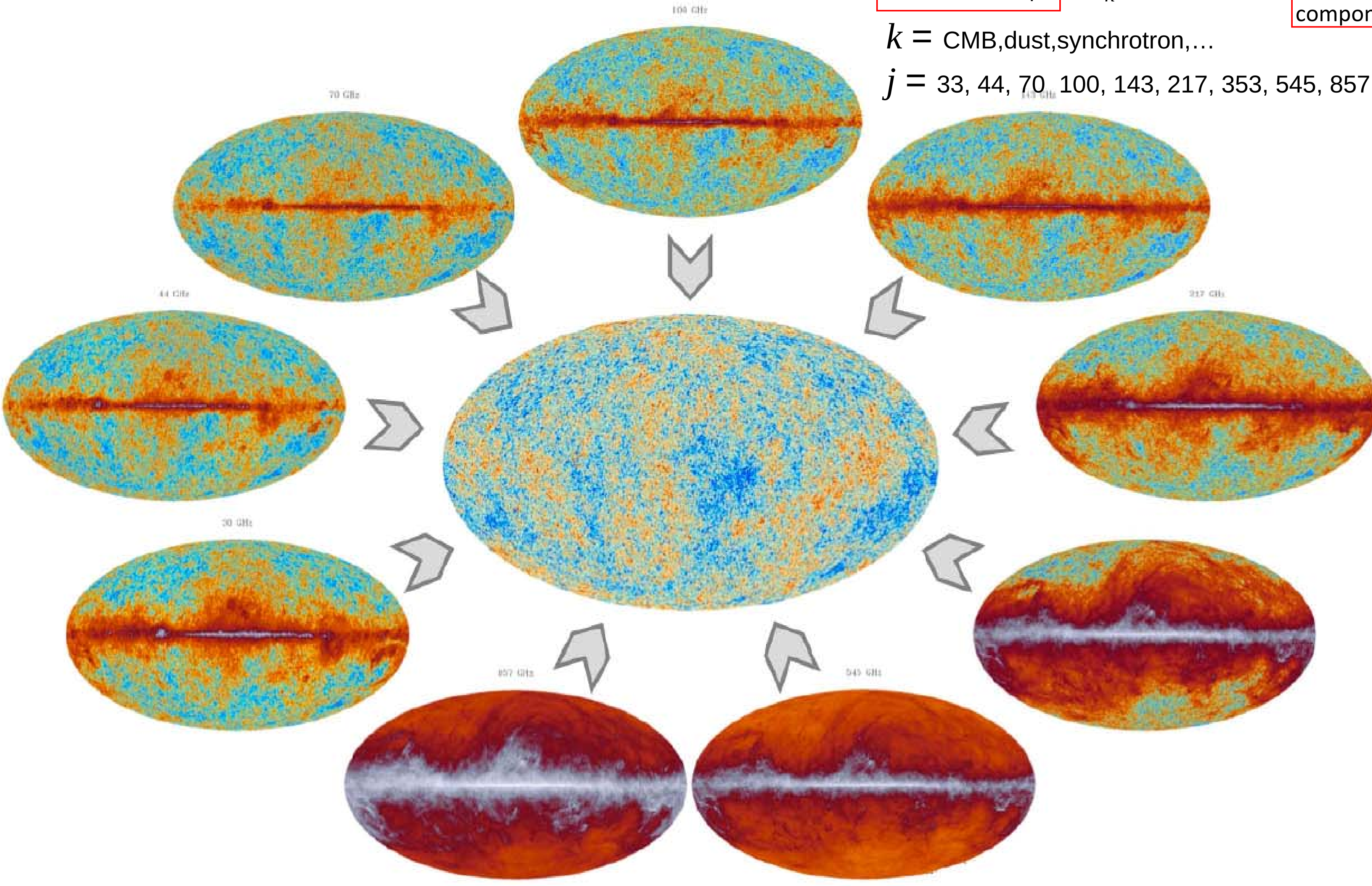
$$\Delta T(\nu_j,\ell,b)=\sum_k a_k(\nu_j,\ell,b)C_k(\ell,b)$$

Measured maps

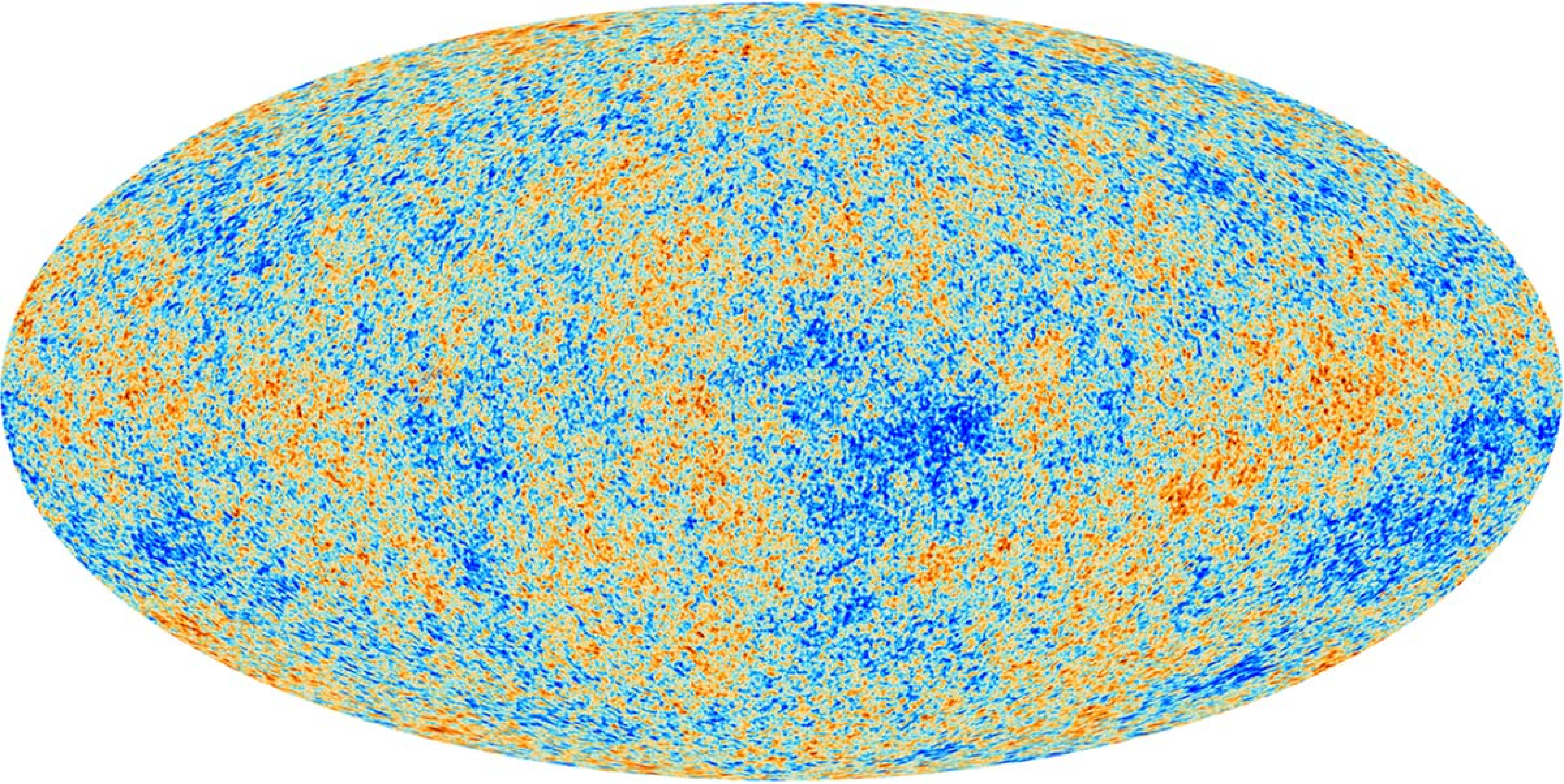
physical components

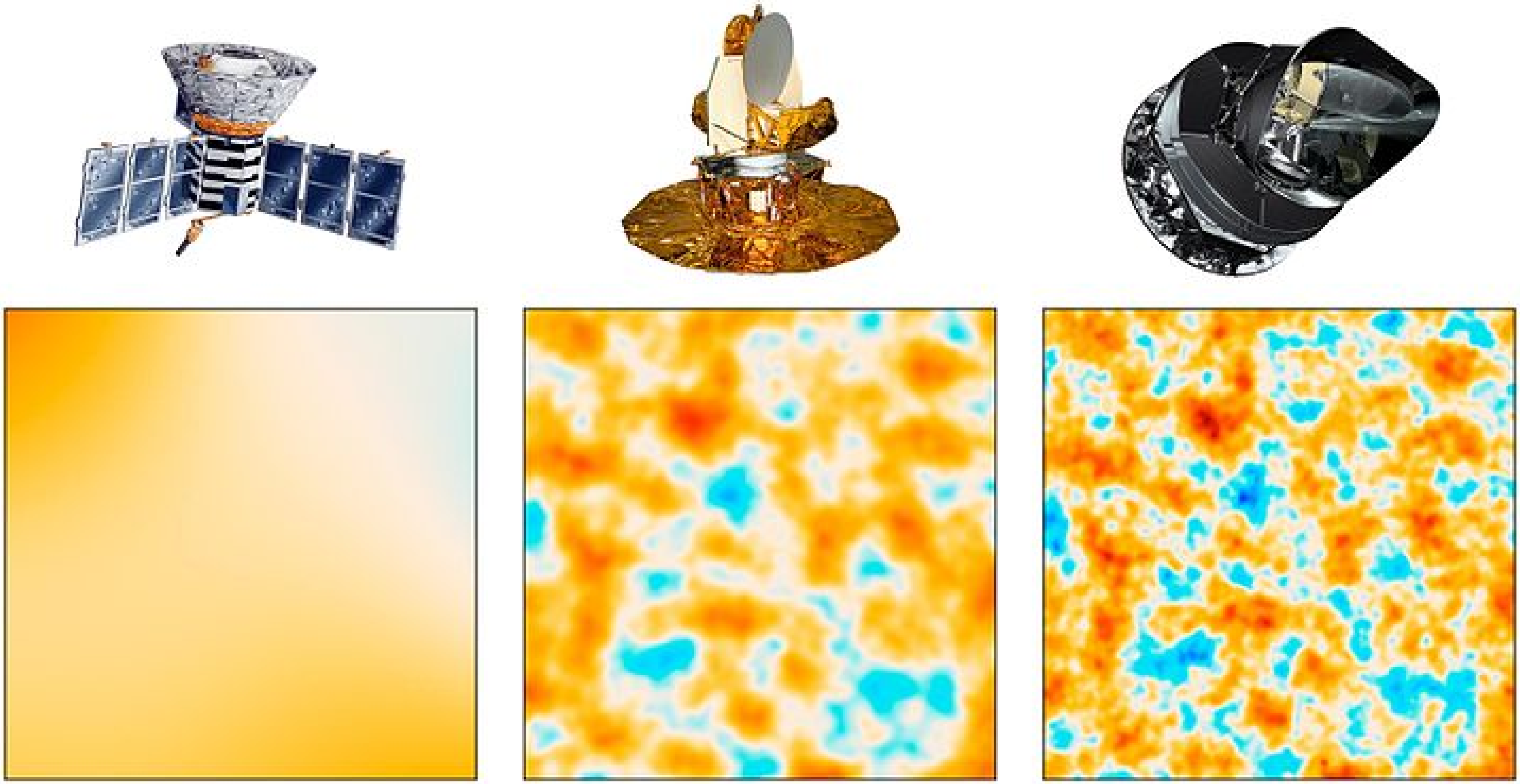
$k =$ CMB,dust,synchrotron,…

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



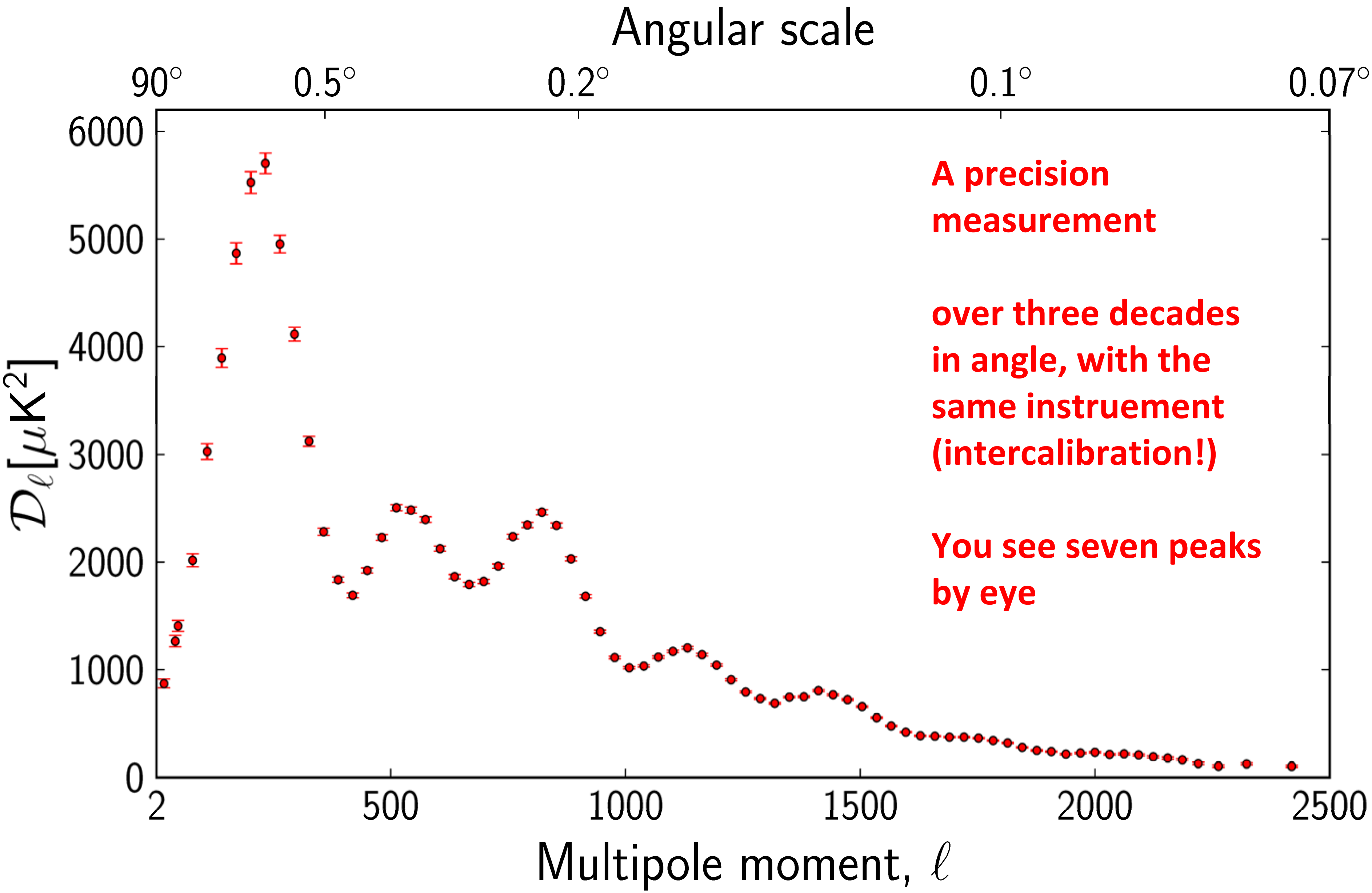
The CMB component





COBE WMAP Planck

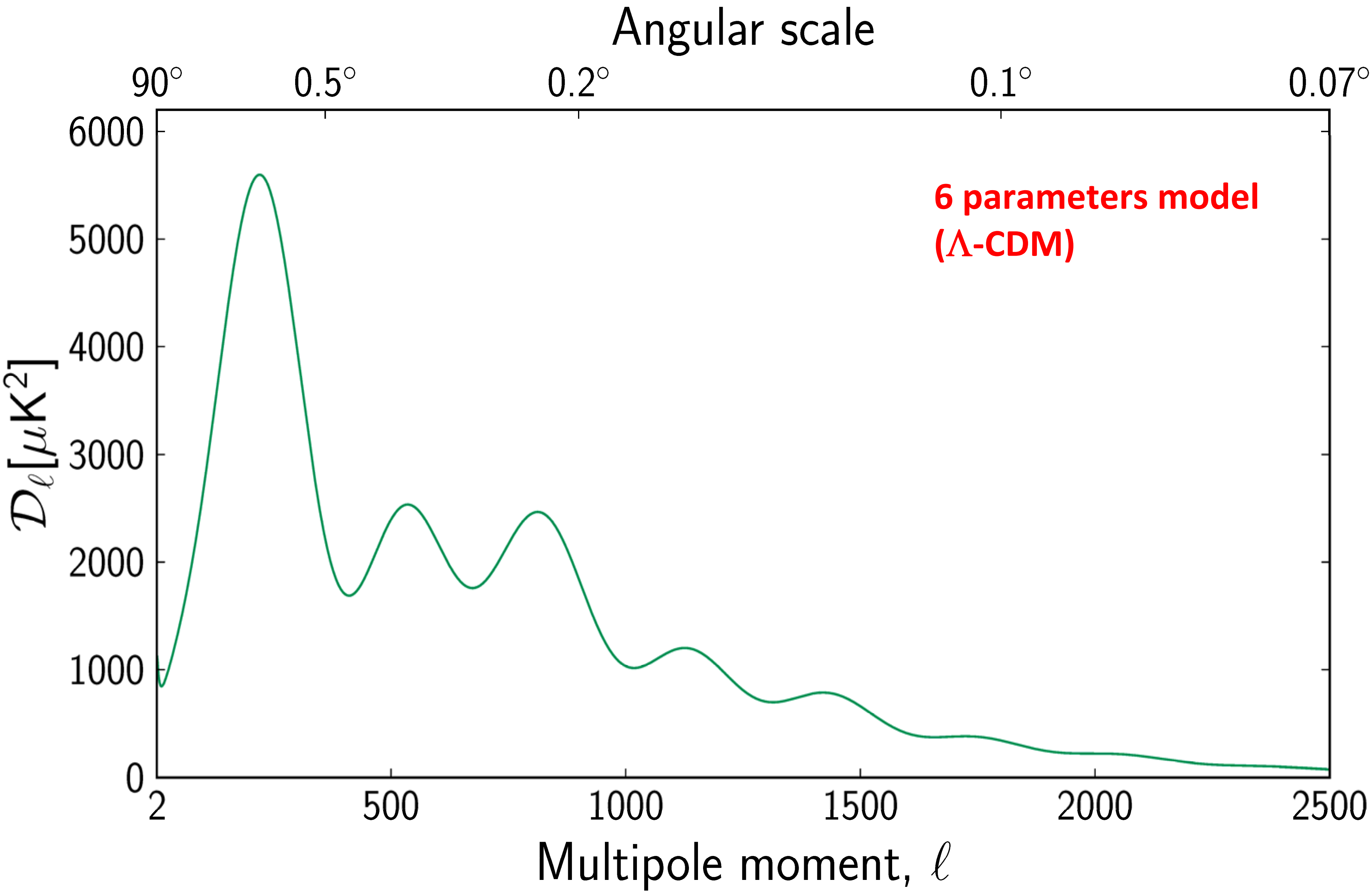
Best angular resolution
Best control of foregorunds

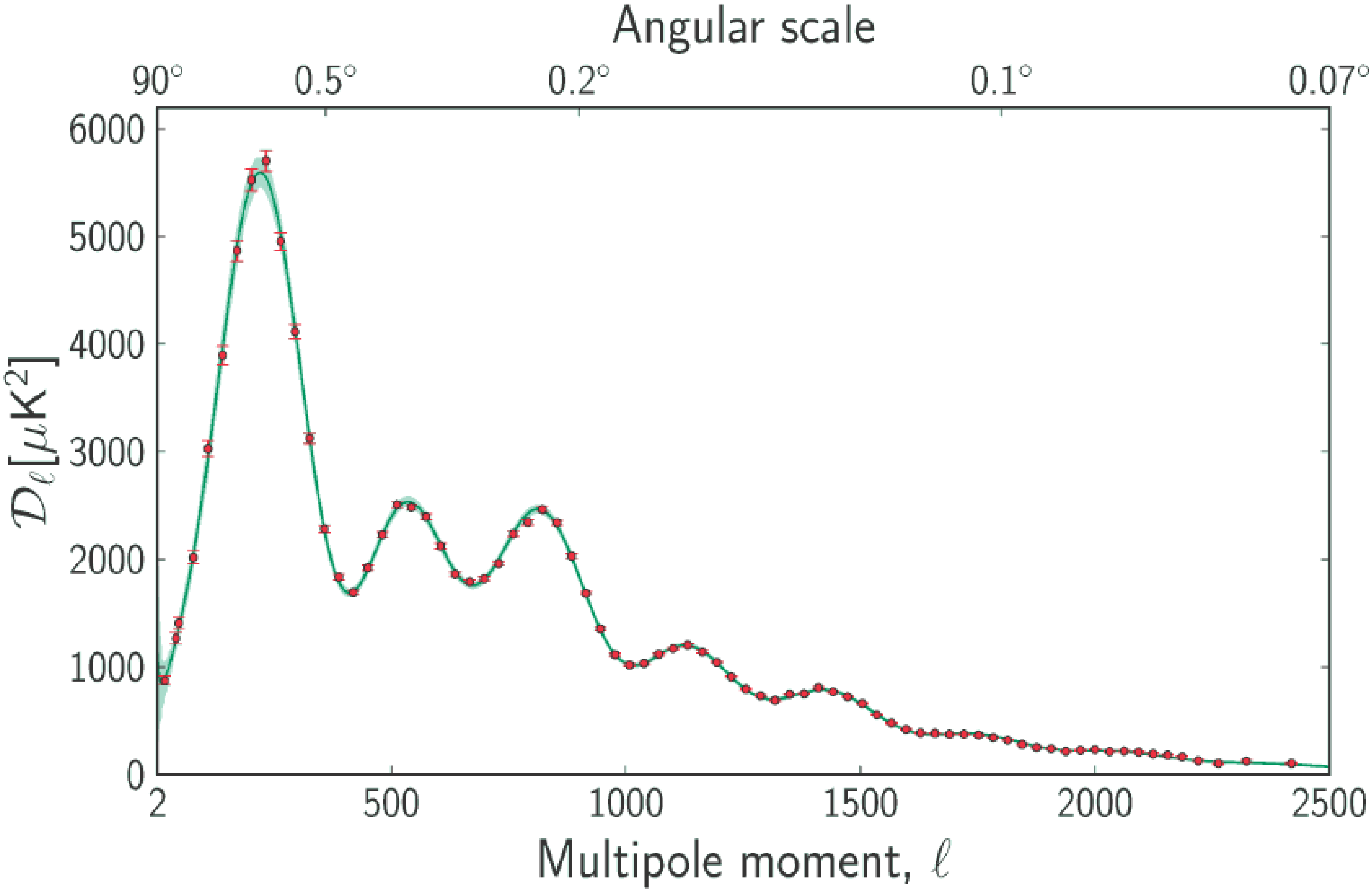


A precision measurement

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

You see seven peaks by eye

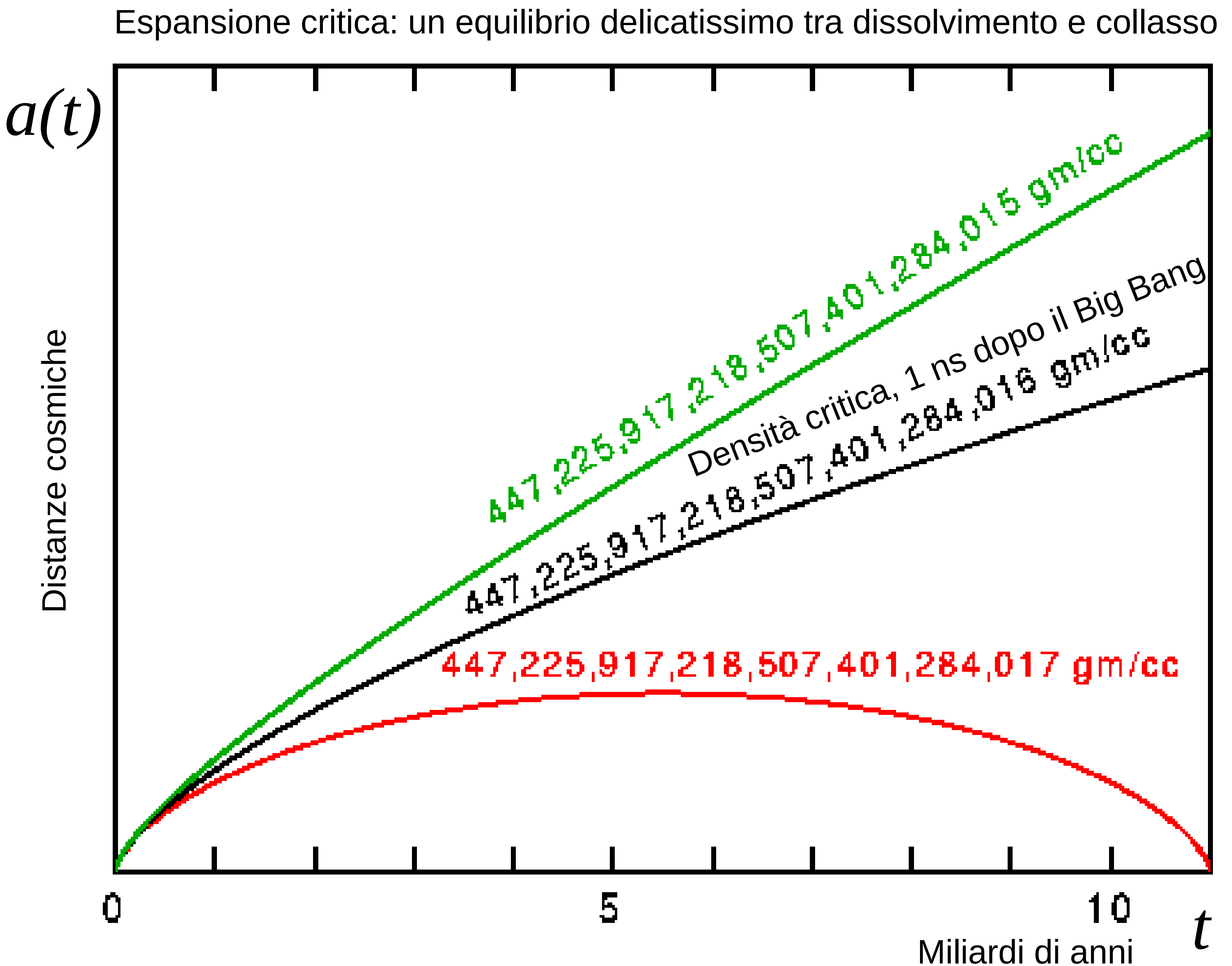

Angular scale
90°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
500
1000
1500
2000
2500
Multipole moment, ℓ
6 parameters model
(Λ-CDM)



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

Paradosso della Piattezza

- Se i fotoni si sono propagati lungo linee rette dalla ricombinazione fino a noi, allora l' universo ha una geometria euclidea.
- Ma secondo le equazioni di Einstein, questa geometria si verifica solo se la densità totale di massa-energia dell' universo ha un valore molto preciso: la densità critica (10^{-29} g/cm^3).
- Quindi abbiamo pesato l' universo !
- Ma quello della densità critica è uno spartiacque tra evoluzioni dell' universo estremamente diverse !
- Chi ha regolato così precisamente la densità ?
- Paradosso della piattezza.

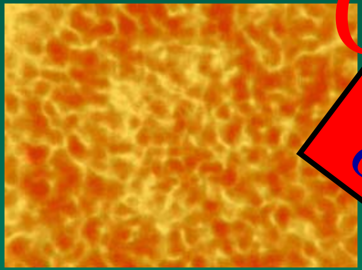

Espansione critica: un equilibrio delicatissimo tra dissolvimento e collasso
a(t)
Distanze cosmiche
447,225,917,218,507,401,284,015 gm/cc
Densità critica, 1 ns dopo il Big Bang
447,225,917,218,507,401,284,016 gm/cc
447,225,917,218,507,401,284,017 gm/cc
0
5
10
t
Miliardi di anni

Altri paradossi … e una soluzione

- Perché non ci sono monopoli magnetici ?
- Perché le piccole fluttuazioni di temperatura del fondo cosmico, oltre ad essere piccole, sono Gaussiane e Invarianti di scala ?
- Chi ha generato le prime strutture cosmiche ?

- C' è una ipotesi affascinante che spiegherebbe questi paradossi e risponderebbe a queste domande.
- E' affascinante perché collega il cosmo con il microcosmo…
- E' l' ipotesi dell' Inflazione Cosmica

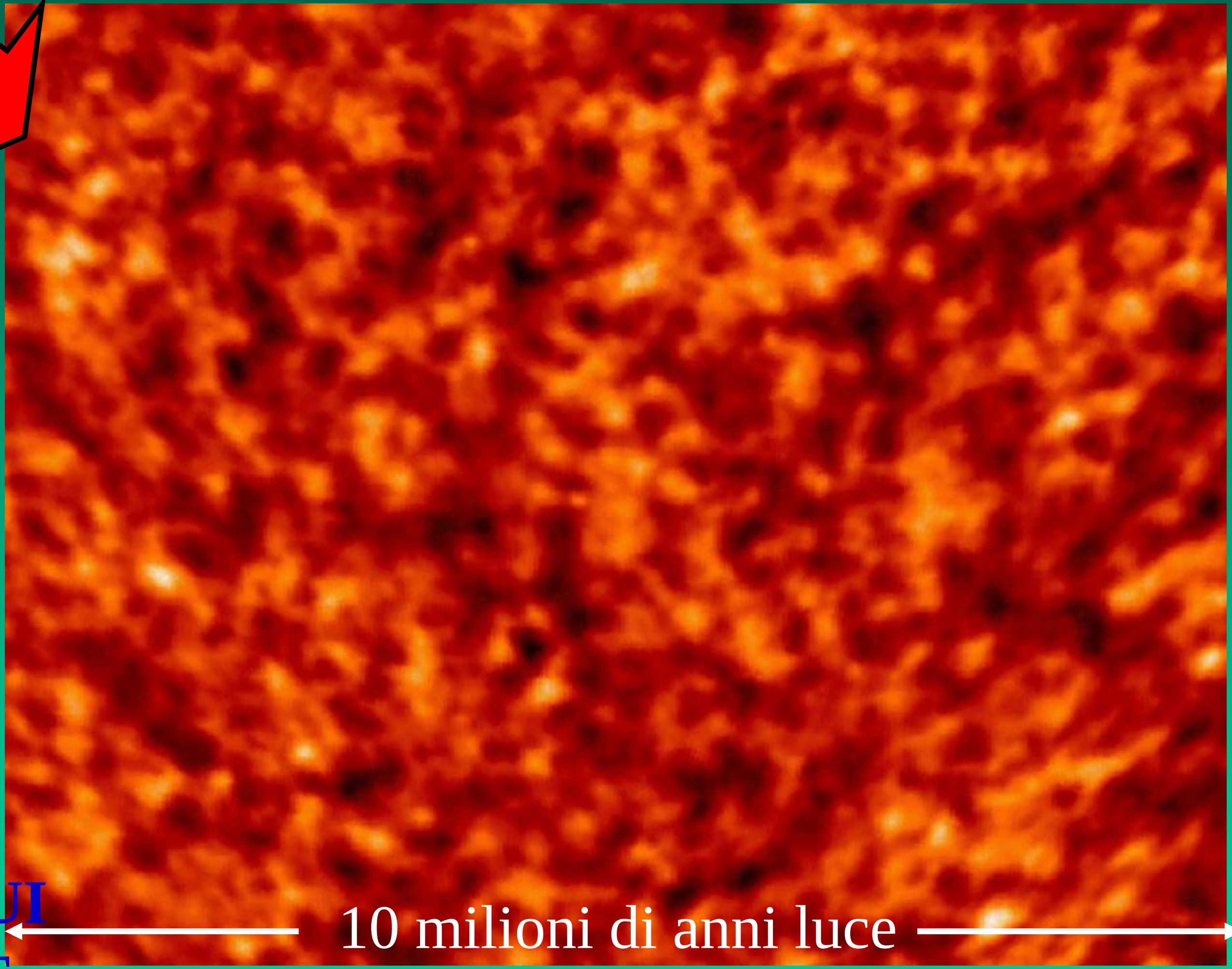
Chi crea le strutture ? Inflation !



Inflazione Cosmica

Dimensioni subatomiche
$t=10^{-32}$s
Fluttuazioni quantistiche del campo di energia primordiale

Energie tipiche:
10^{16} GeV
(100 milioni di miliardi di milardi di eV)



10 milioni di anni luce
t=380000 anni
Fluttuazioni di densita’ illuminate dalla luce del fondo cosmico

UNA FINESTRA SUI PRIMI ISTANTI E SULLA FISICA DELLE ALTISSIME ENERGIE

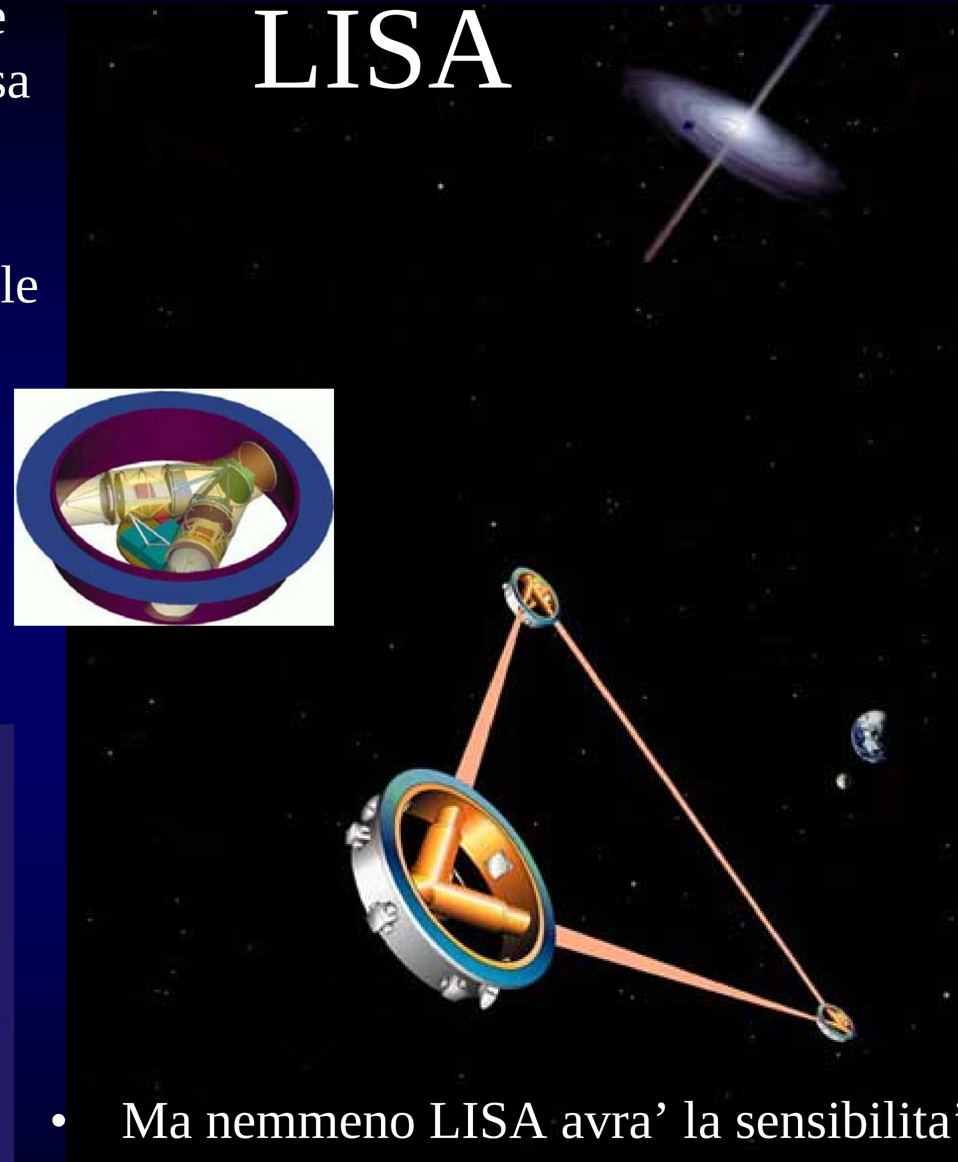
Previsioni dell’ inflazione cosmica:

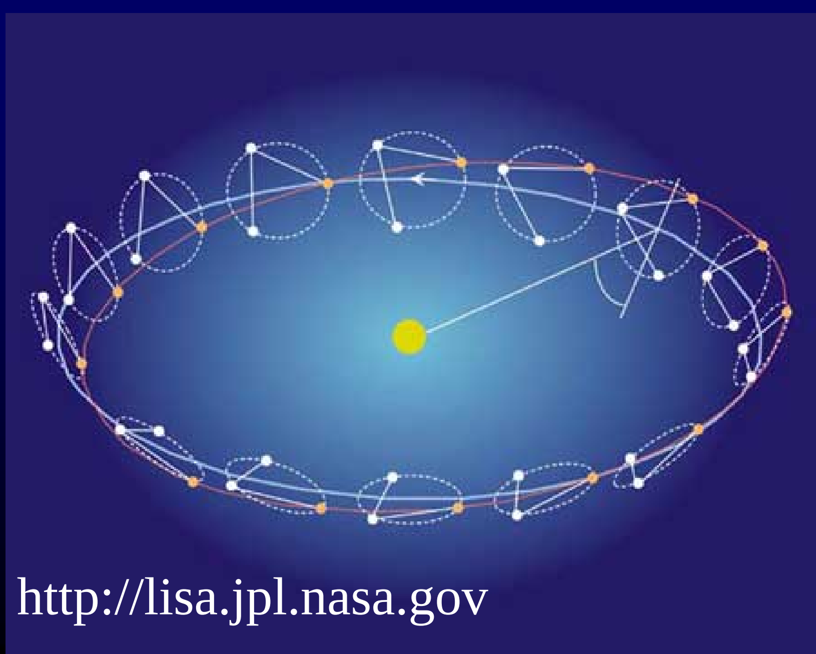
- La geometria a grande scala deve essere euclidea, perché quasiasi curvatura dello spazio antecedente si stira durante l’ inflazione
- Le fluttuazioni di densita’ devono essere uguali a tutte le scale (origine quantistica)
- Le fluttuazioni di temperatura devono essere gaussiane (origine quantistica)
- Durante l’ espansione inflazionaria si generano onde gravitazionali stocastiche

L’ ultima previsione e’ tutta da verificare.

LISA

- Le onde gravitazionali non sono state ancora misurate direttamente. Ma si sa da misure indirette che esistono.
- L' interferometro spaziale LISA misurera' tra qualche anno quelle delle stelle binarie presenti nella nostra Galassia, e quelle generate da buchi neri massicci in galassie distanti.
- Sara' una ulteriore conferma della teoria della Relativita' Generale !





- Ma nemmeno LISA avra' la sensibilita' per misurare le onde gravitazionali primordiali prodotte durante l' inflazione cosmica.

- http://lisa.jpl.nasa.gov

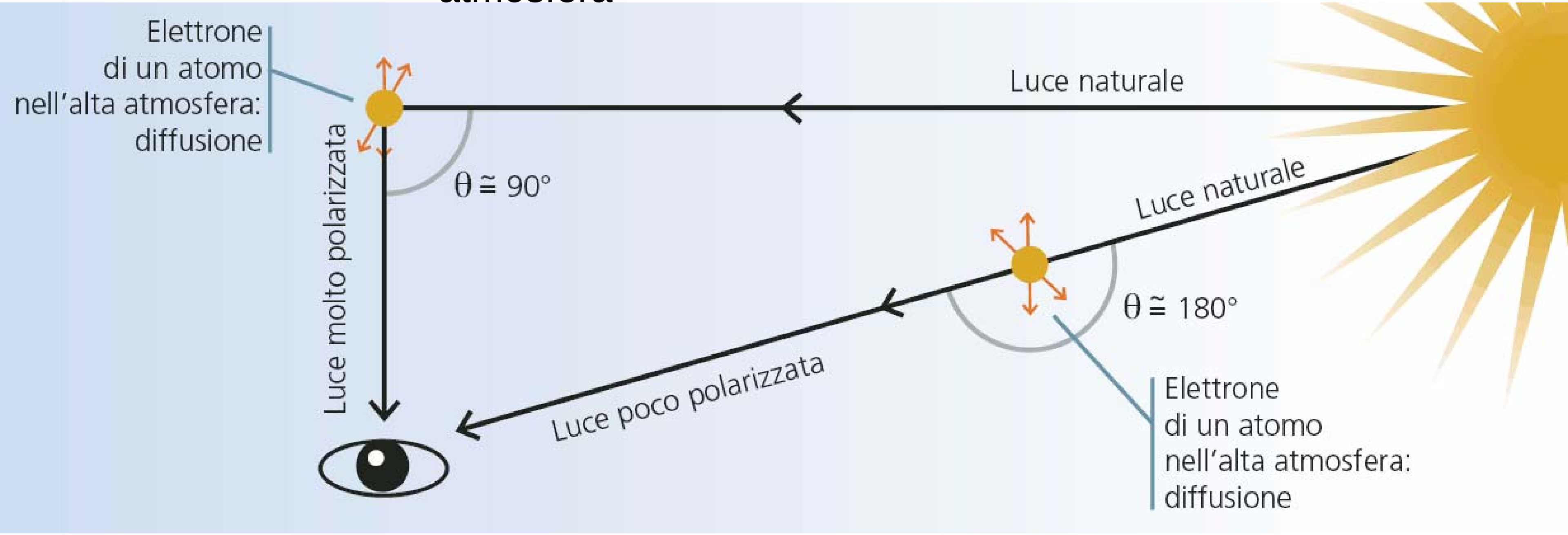
- **Ma queste perturbazioni interagiscono con il fondo cosmico a microonde, generando una debole polarizzazione lineare rotazionale dei suoi fotoni.**
- **Il segnale e' piccolissimo, meno di un decimo di miliardesimi di grado, e mischiato ad una componente irrotazionale piu' grande (pochi milionesimi di grado).**

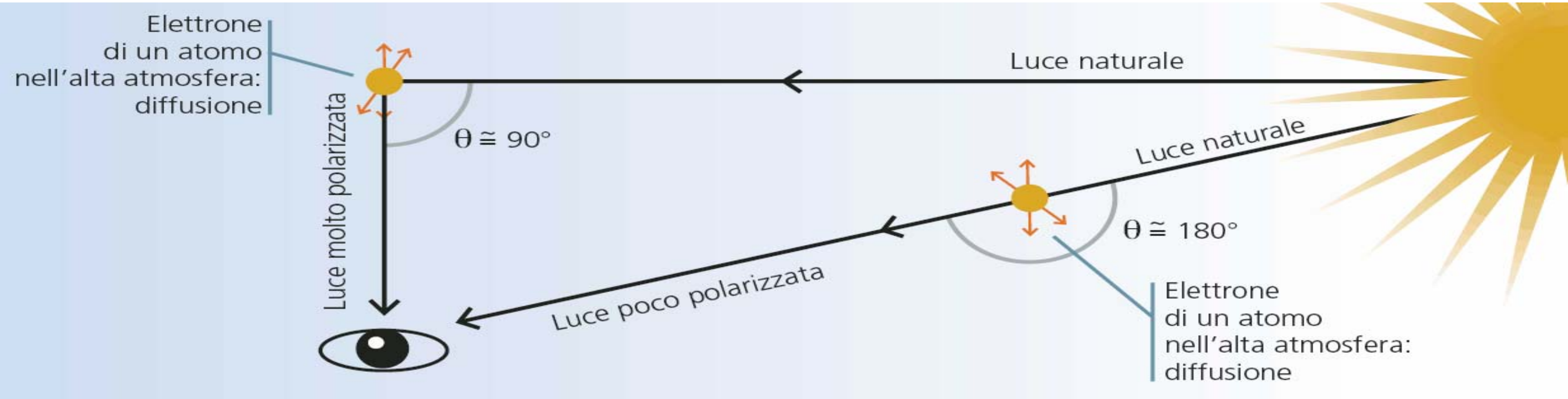
Polarizzazione della luce: direzione preferenziale di oscillazione del campo elettromagnetico

La luce blu del cielo è polarizzata

- La usavano i Vichinghi per trovare la rotta nei lunghi crepuscoli solare, usando la “pietra del sole”, lo spato d’ Islanda
- La usano le api per orientarsi e ritrovare l’ alveare
- La usiamo noi con il filtro polarizzatore quando nelle fotografie si vogliono far risaltare le nubi (non polarizzate) contro il cielo blu

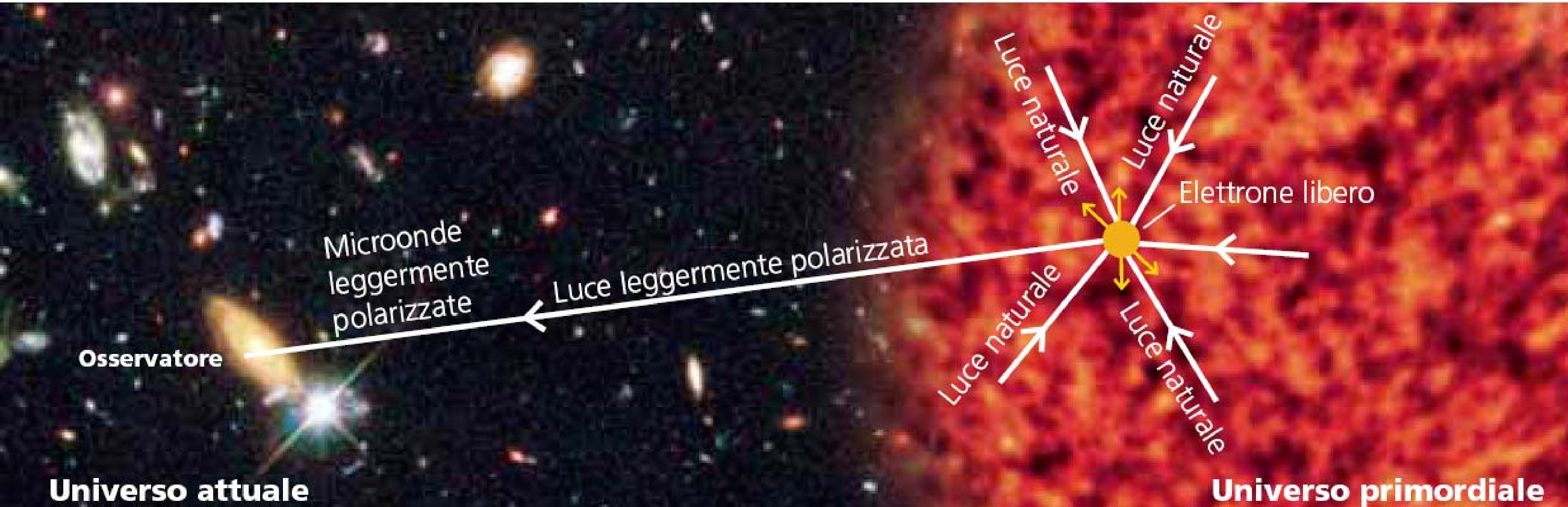
E’ polarizzata perché diffusa (deviata) dagli elettroni dell’ alta atmosfera

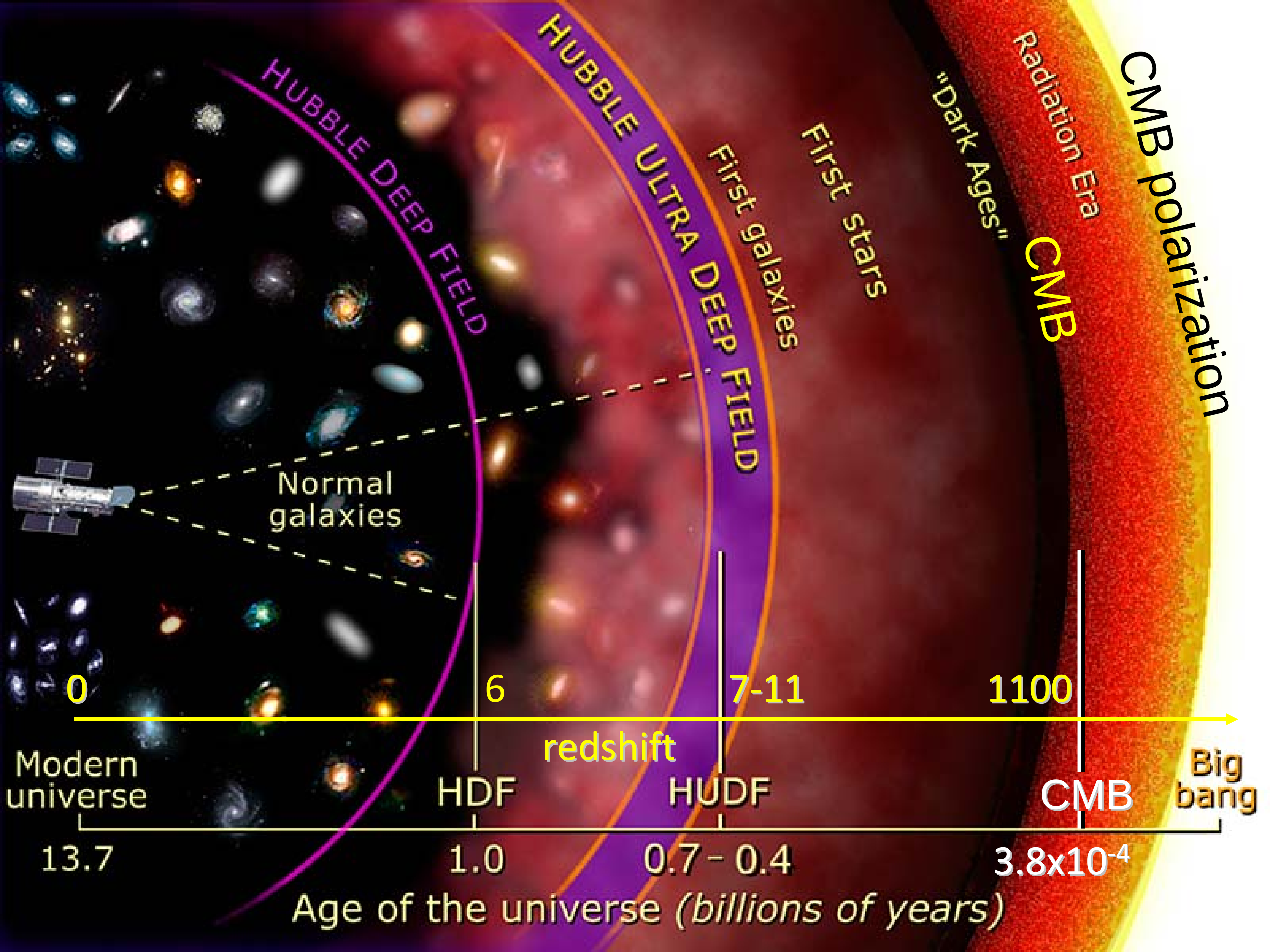




Per i fotoni che provengono dall' universo primordiale avviene un fenomeno simile: sono anche essi deviati dagli elettroni, e se il mezzo è inomogeneo, nasce una debole polarizzazione.

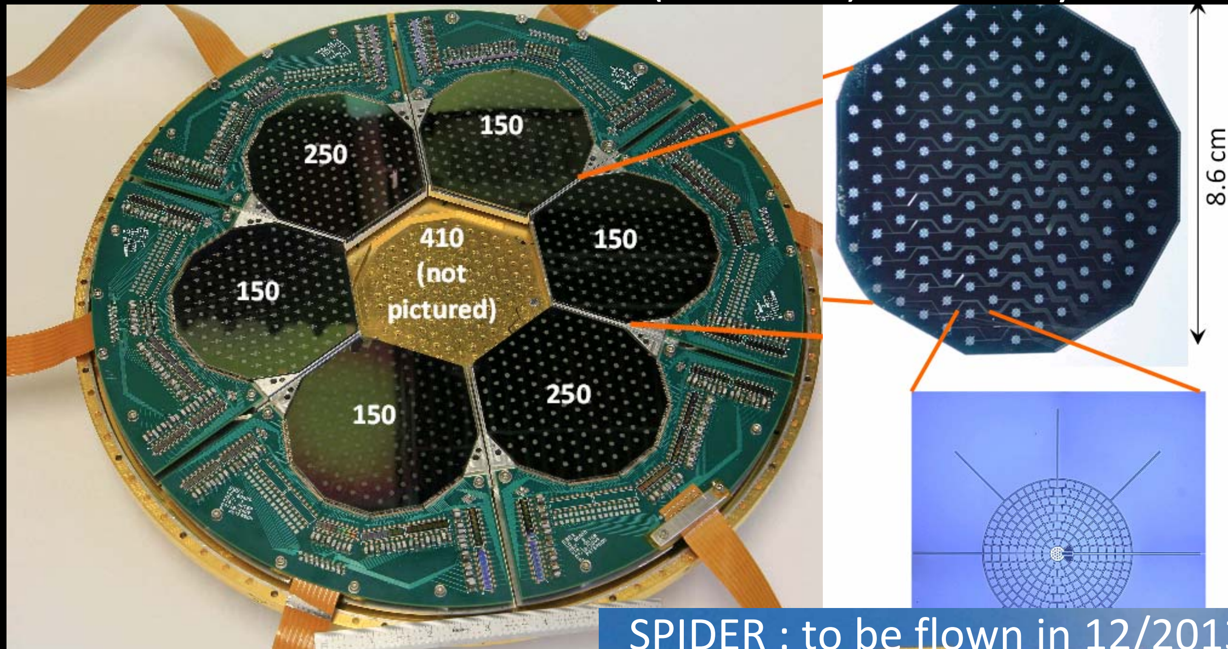
L' inomogeneità può essere dovuta a fluttuazioni di densità, ma anche alle onde gravitazionali prodotte dall' inflazione cosmica, se c'è stata.

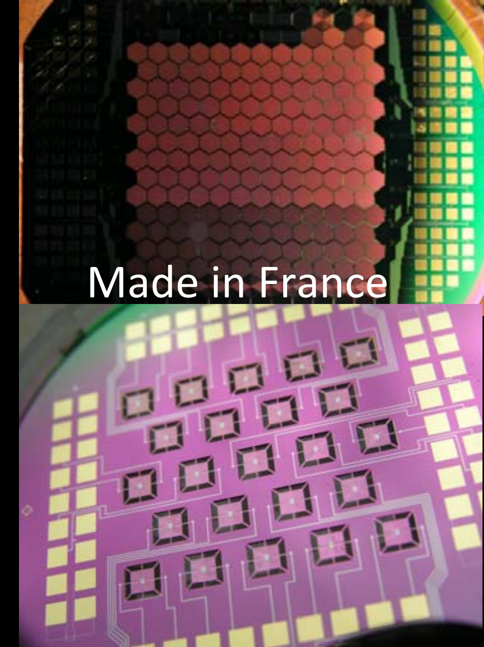


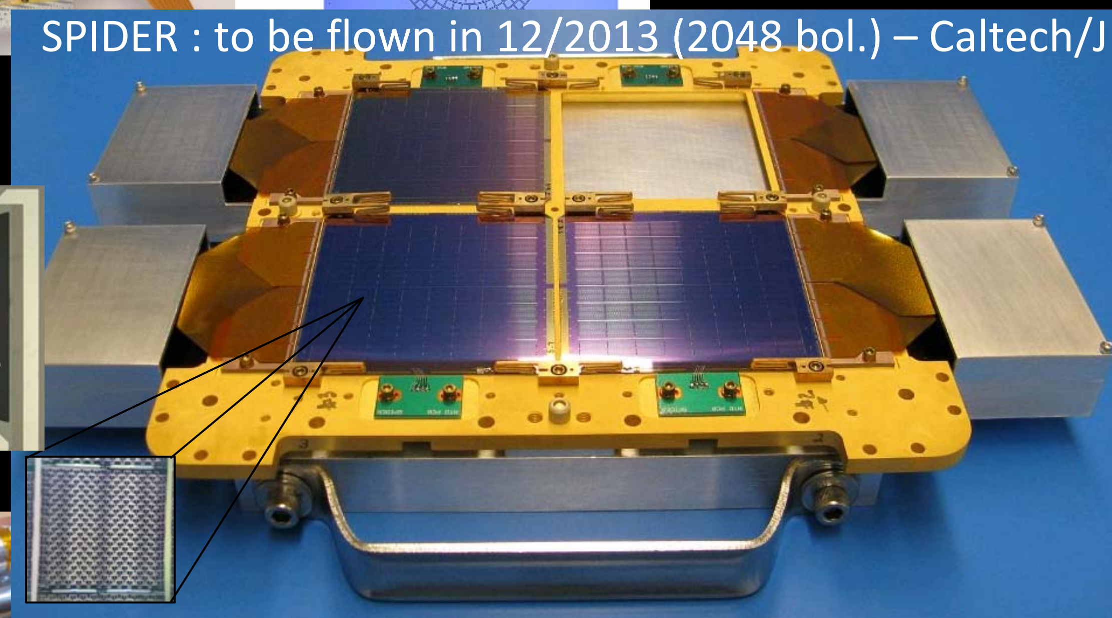


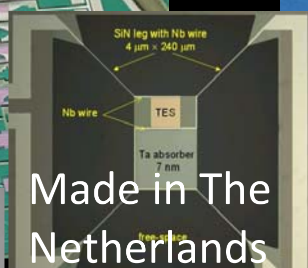
HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
CMB
CMB polarization
Normal galaxies
0
6
7-11
1100
redshift
Modern universe
HDF
HUDF
CMB
Big bang
13.7
1.0
0.7 – 0.4
3.8x10-4
Age of the universe (billions of years)

EBEX: flown in 2012 (850+ bol.) – Berkeley



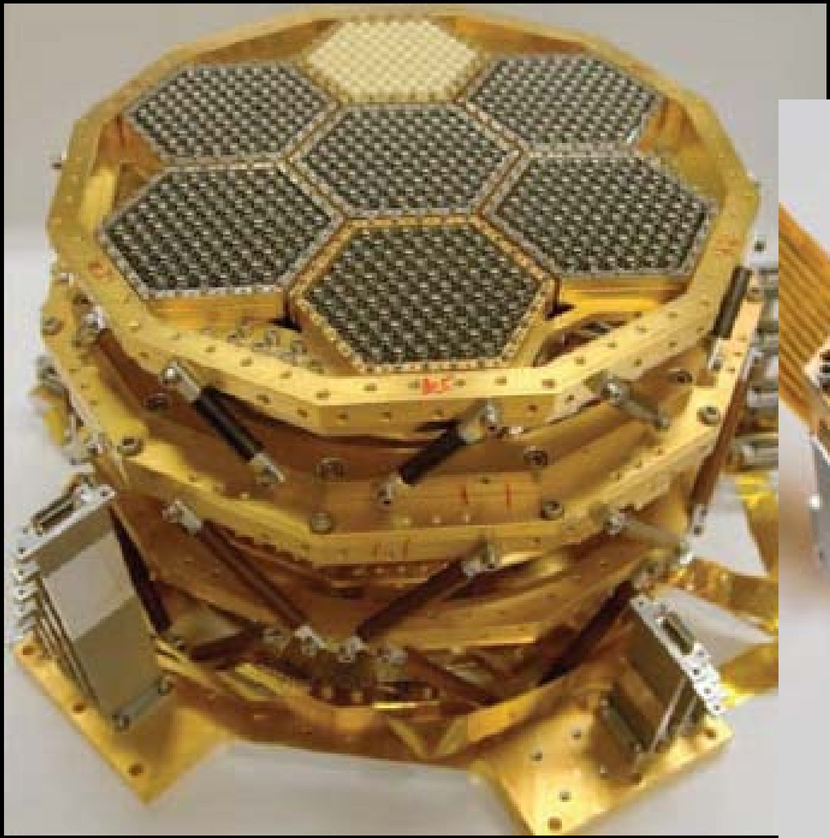


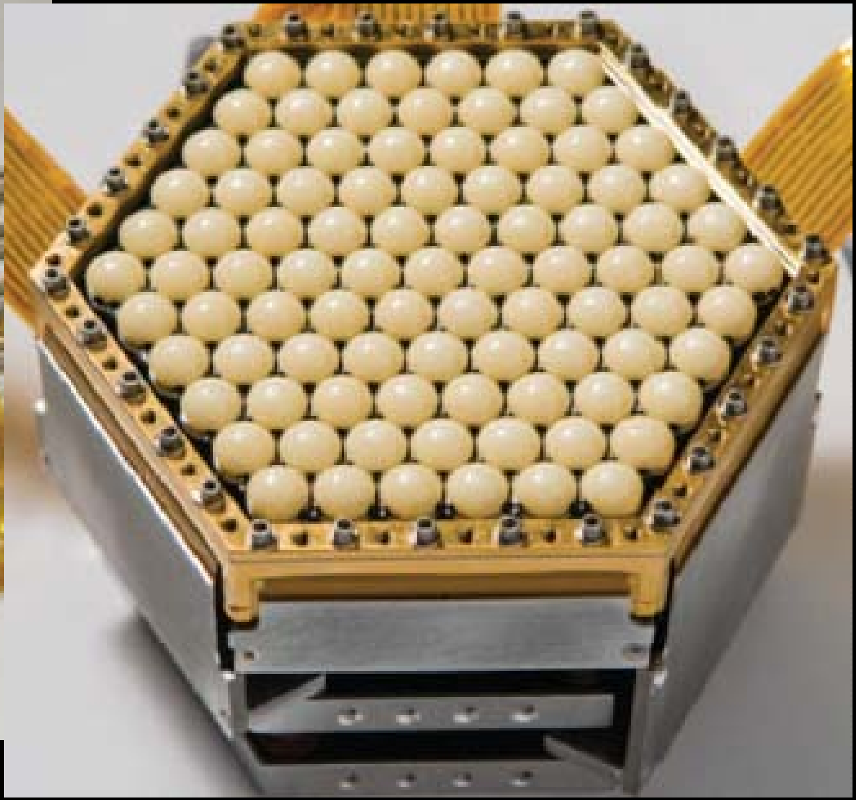




TES bolometer arrays : HUGE effort and great success. Now a mature technology.

The trend :

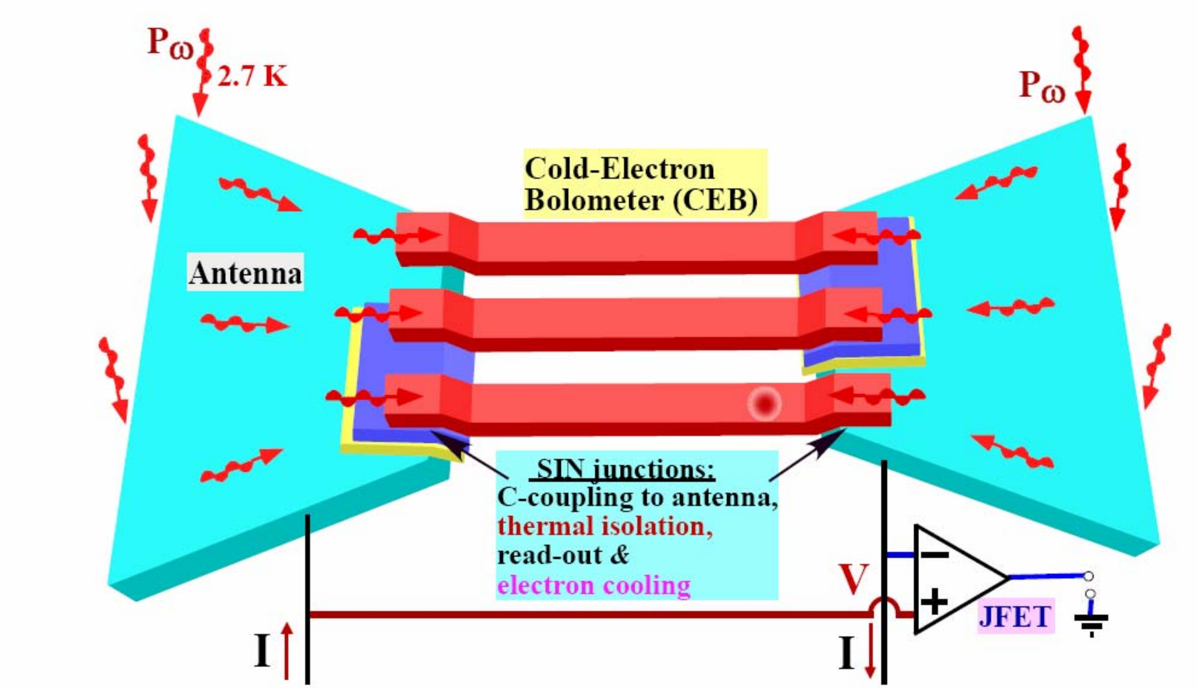




- Large arrays of multichroic pixels: 6000+ detectors for polarbear2, SPTpol, litebird …
- ESA ITT for compact focal planes (Maynooth)

Improving over TES bolometers ?

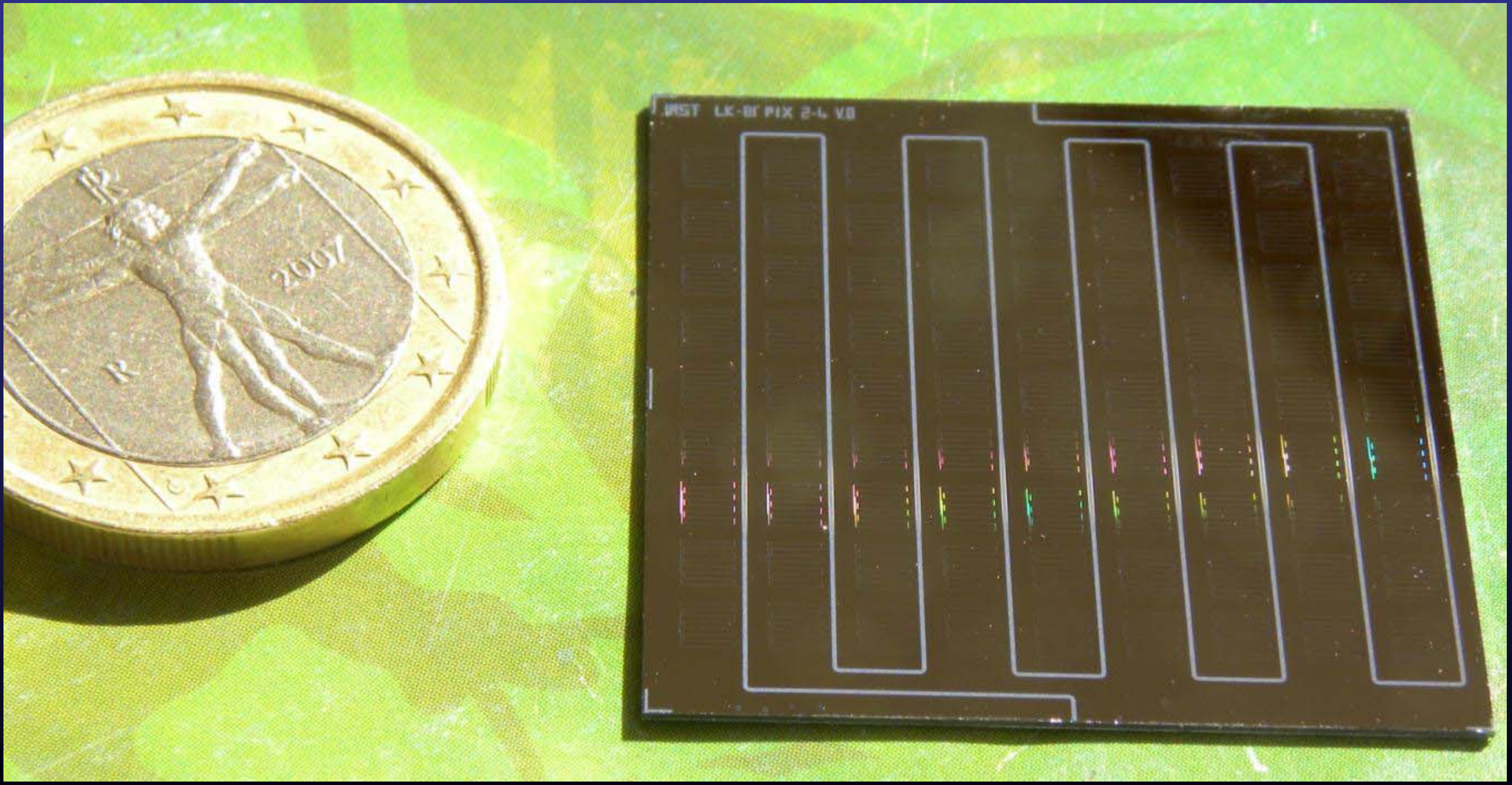
- KIDs & CEBs !
- KIDs made in Cardiff, Grenoble, Rome/TN etc.
- CEBs made in Chalmers



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

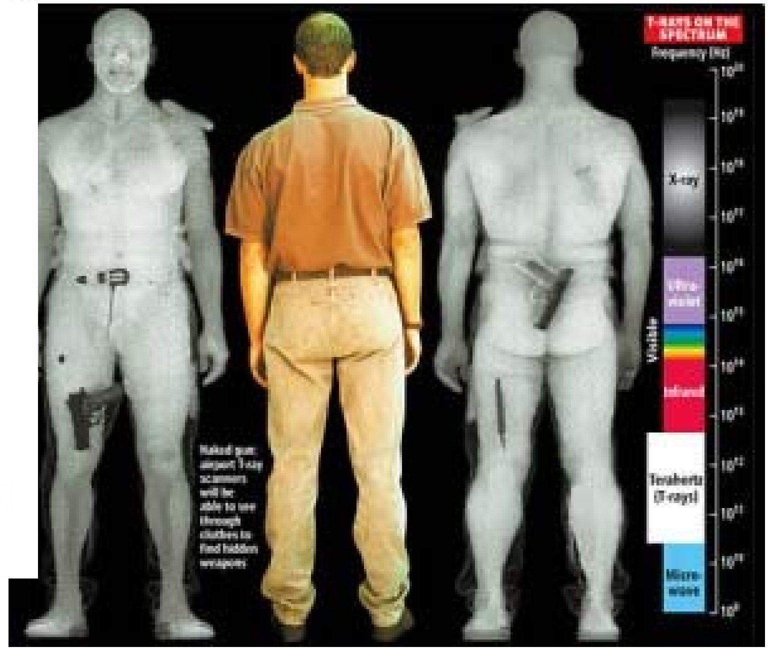
KIDs

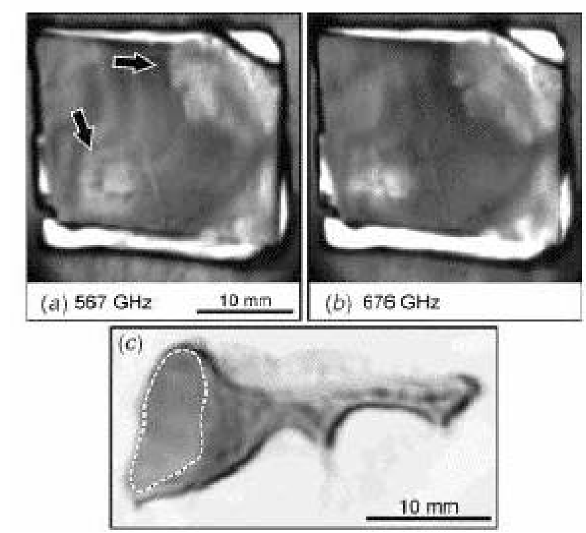
- You heard about the great results of the Grenoble group with kinetic inductance detectors at the IRAM dish (NIKA).
- However, CMB BLIP is not reached yet, and standard KIDs are very sensitive to CR hits.
- KIDs are easier than TES to build, at least in the ground based versions.
- Space-based version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

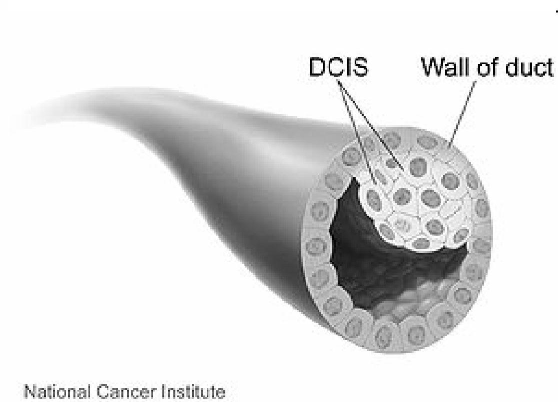


KIDs array made in Italy (Calvo et al. 2010)

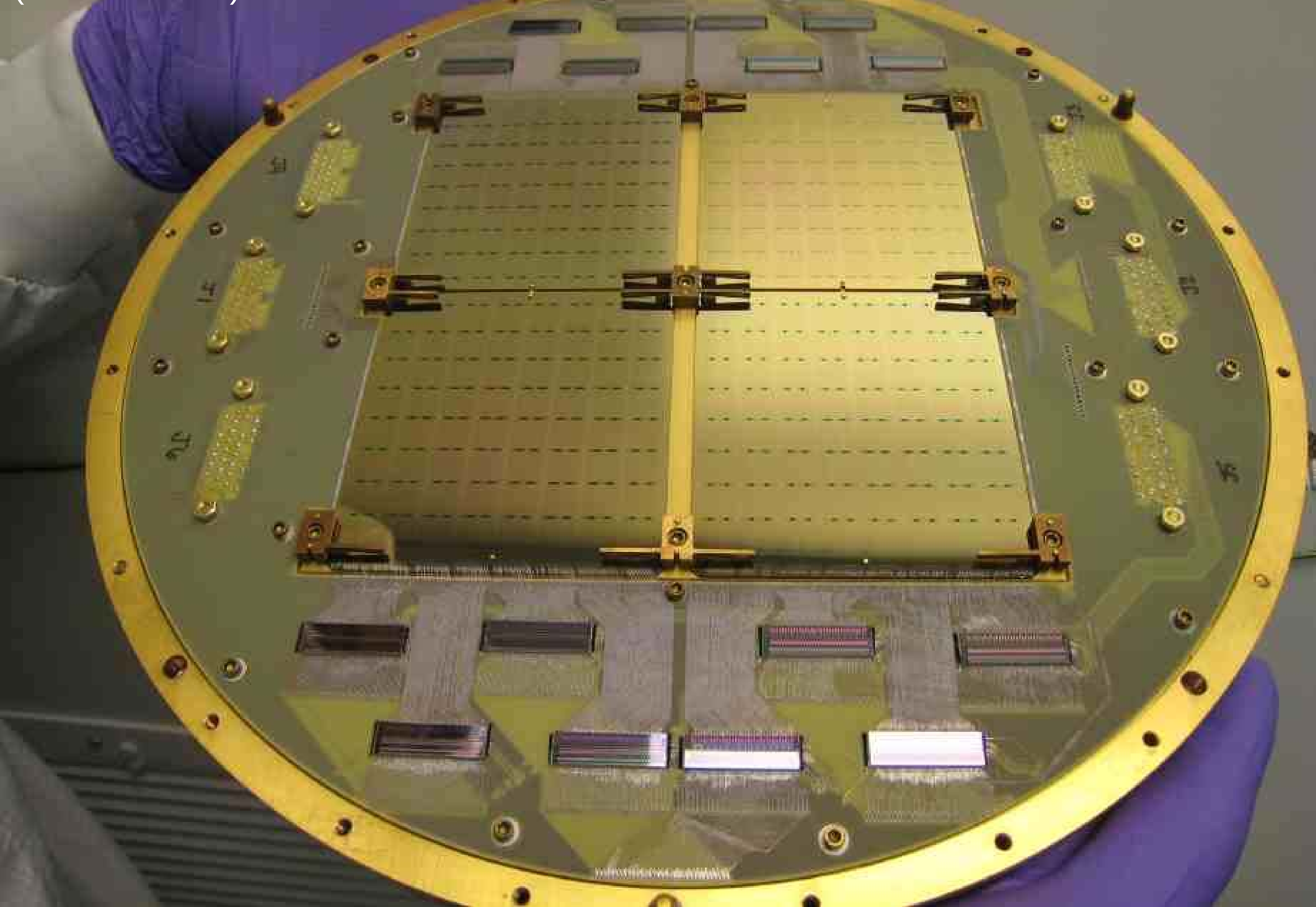

ProVision


T-RAYS ON THE SPECTRUM
Frequency (Hz)
X-ray
Ultra-violet
Visible
Infrared
Terahertz (T-rays)
Micro-wave
Naked gun: airport T-ray scanners will be able to see through clothes to find hidden weapons

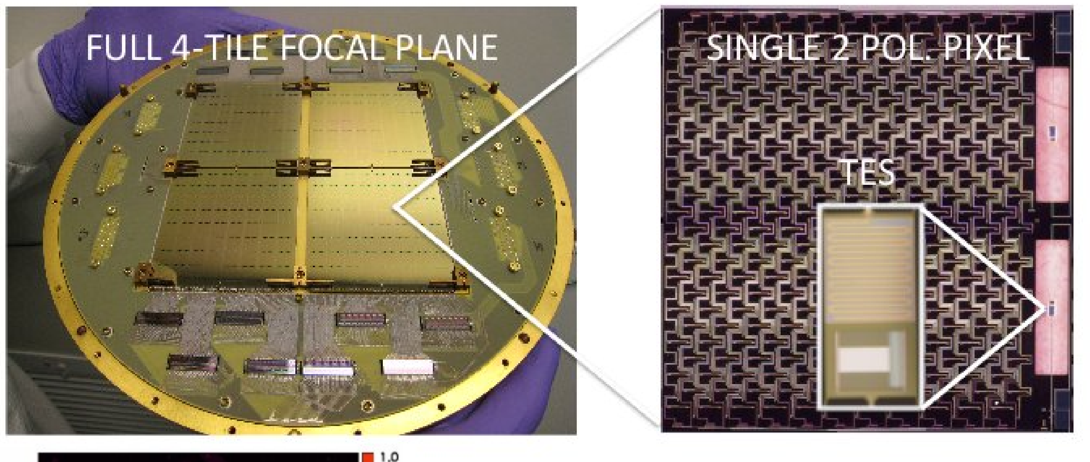

(a) 567 GHz
10 mm
(b) 676 GHz
(c)
10 mm

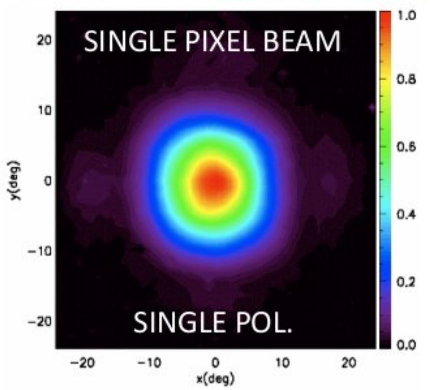

DCIS
Wall of duct
National Cancer Institute

Large Number of Detectors for Sensitivity : TES bolometers with phased-array antennas (Caltech + JPL) for BICEP2



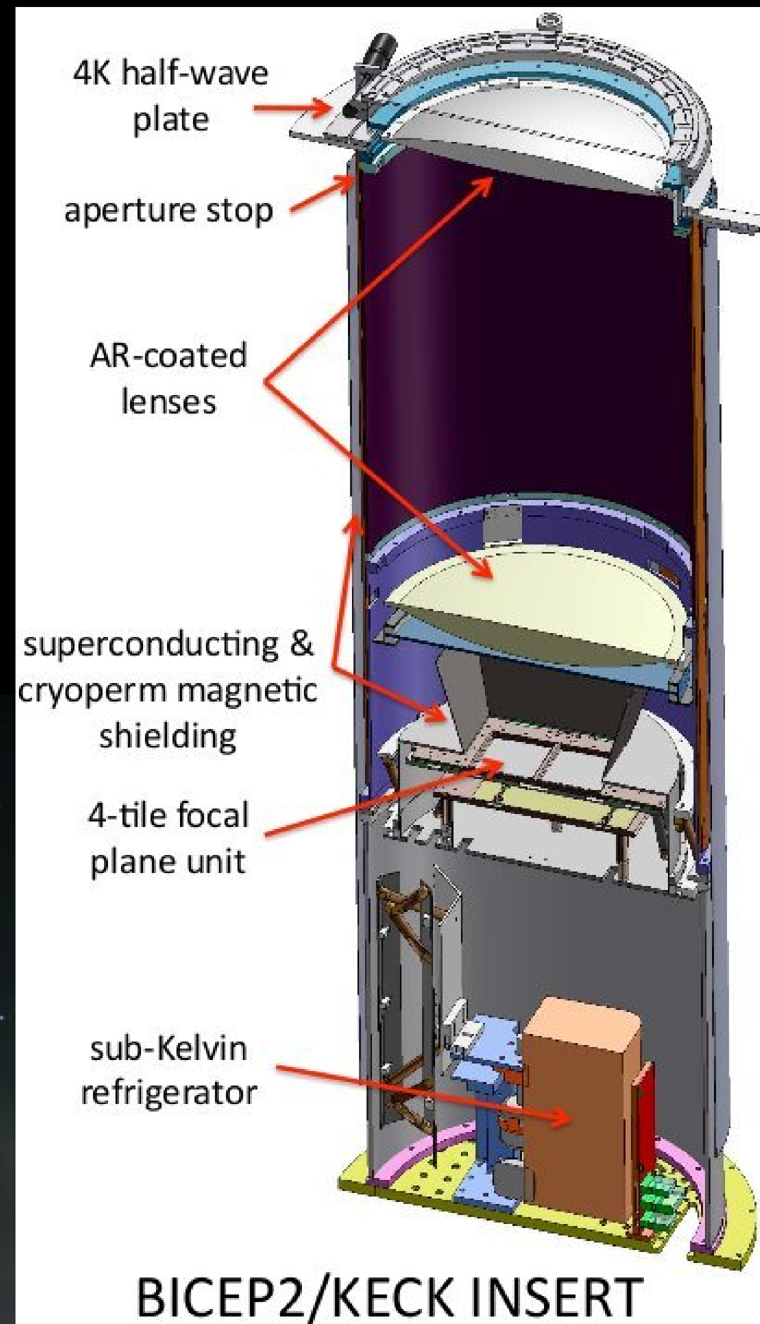
BICEP2/KECK (south pole)

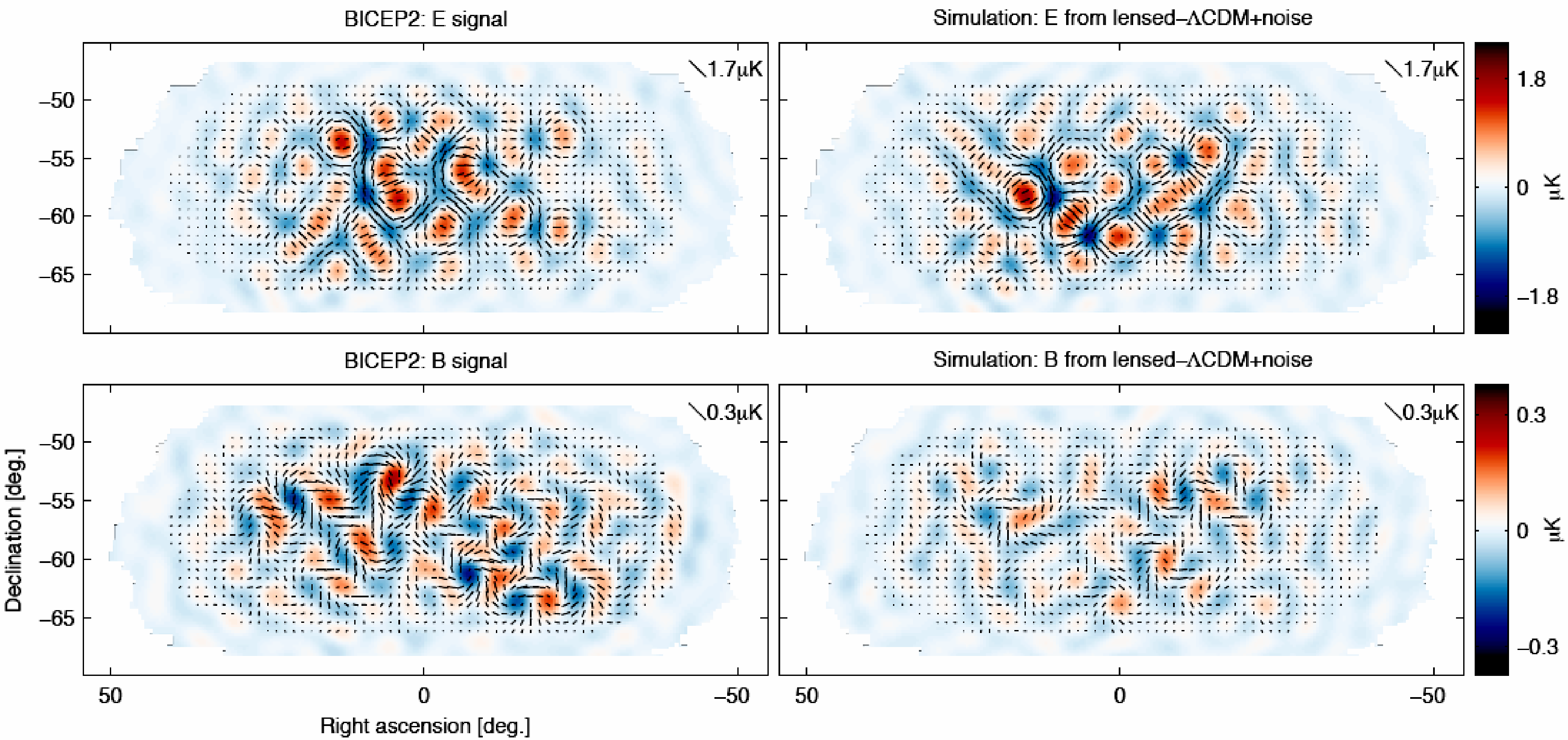




3 dark winters of integration
In the best sky spot (<1000 sq. deg)

BICEP2 : single frequency 150 GHz

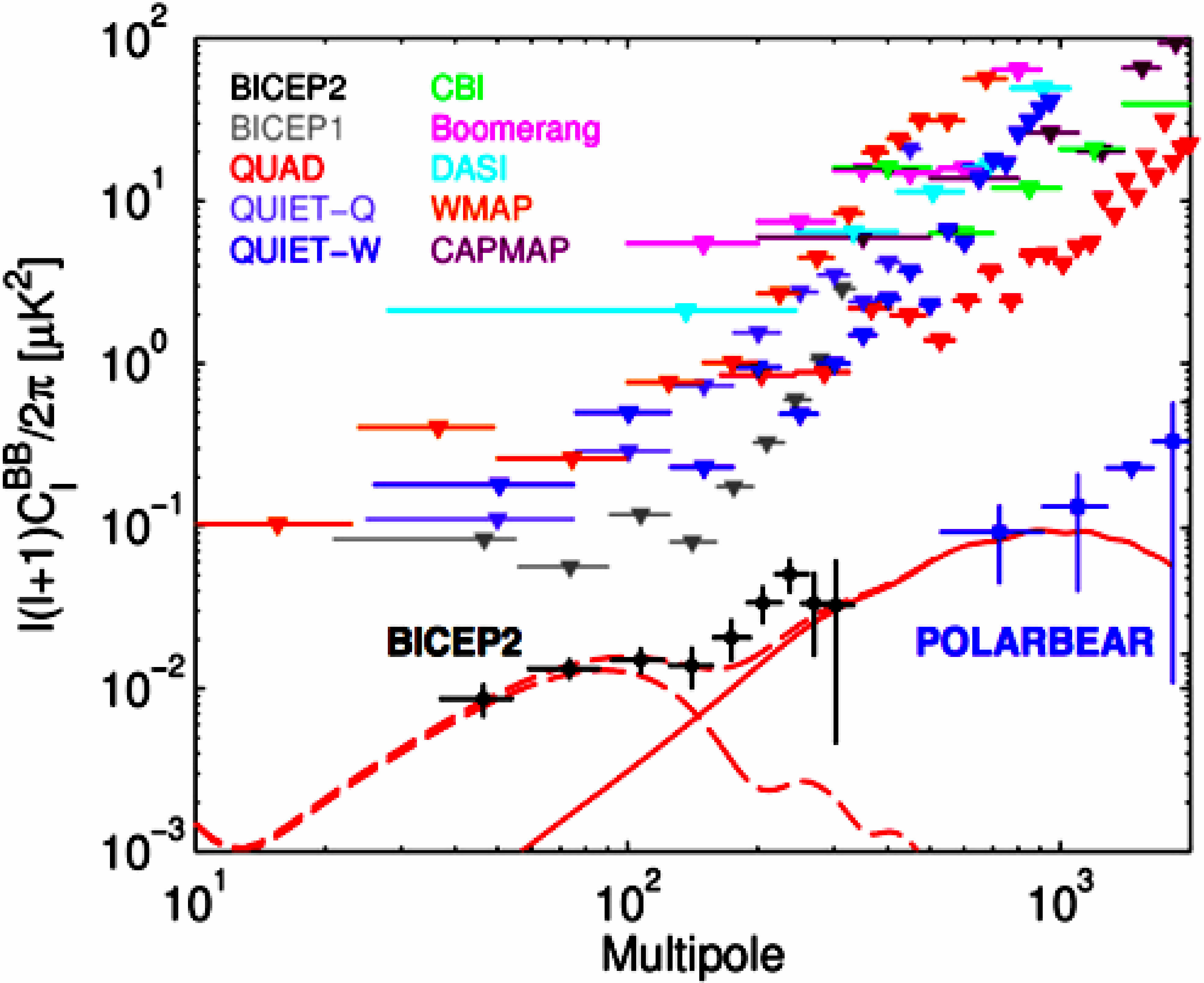




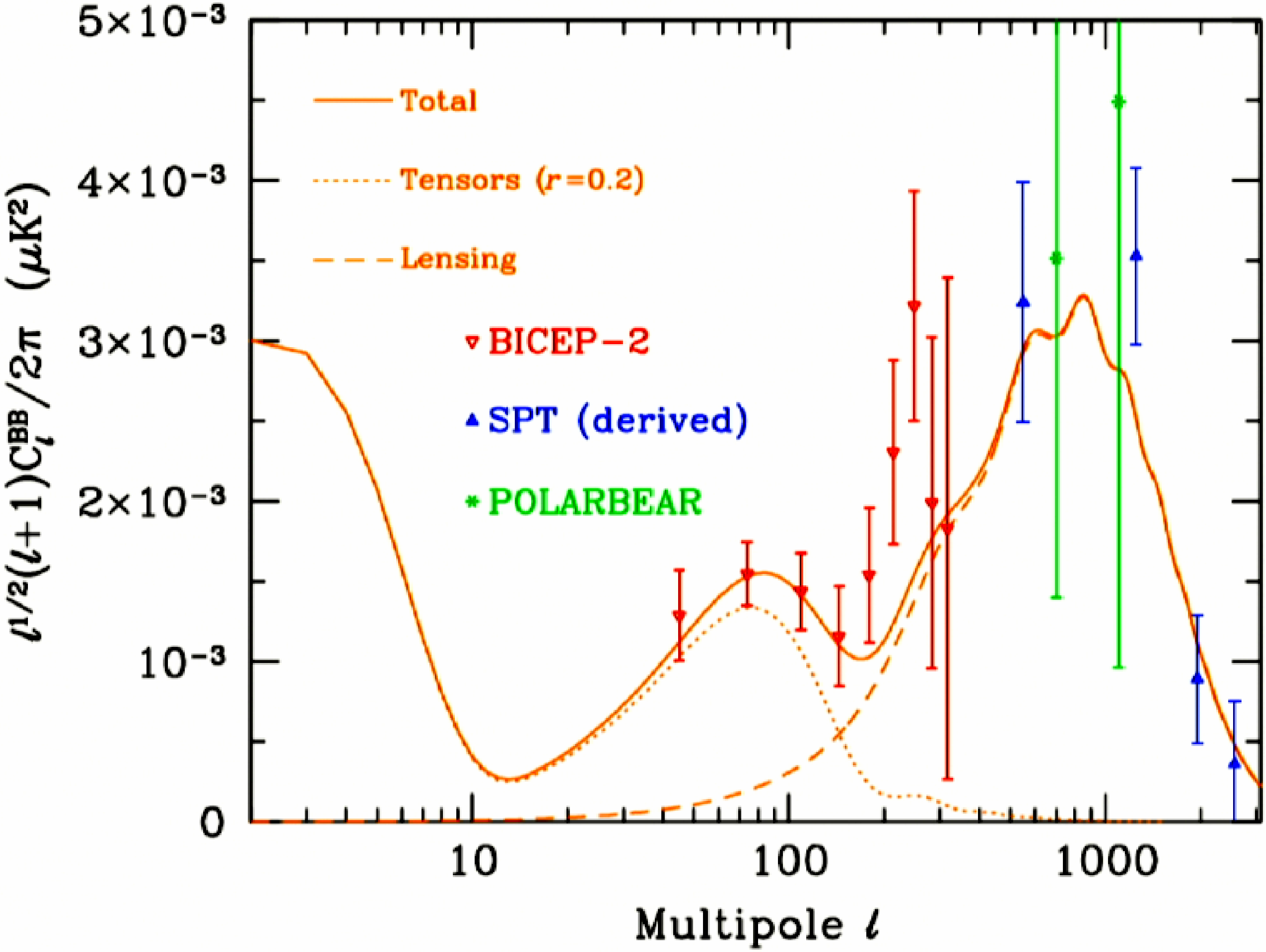
BICEP2 @ south pole :

- 3 dark winters of integration with hundreds of polarization-sensitive bolometers
- Extremely deep map (87 nK deg) of the lowest foreground intensity patch in the sky
- Single frequency (150 GHz)

see astro-ph/1403-3985 and astro-ph/1403-4302



BICEP2
BICEP1
QUAD
QUIET-Q
QUIET-W
CBI
Boomerang
DASI
WMAP
CAPMAP
BICEP2
POLARBEAR
$l(l+1)C_l^{BB}/2\pi$ [μK^2]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
Multipole

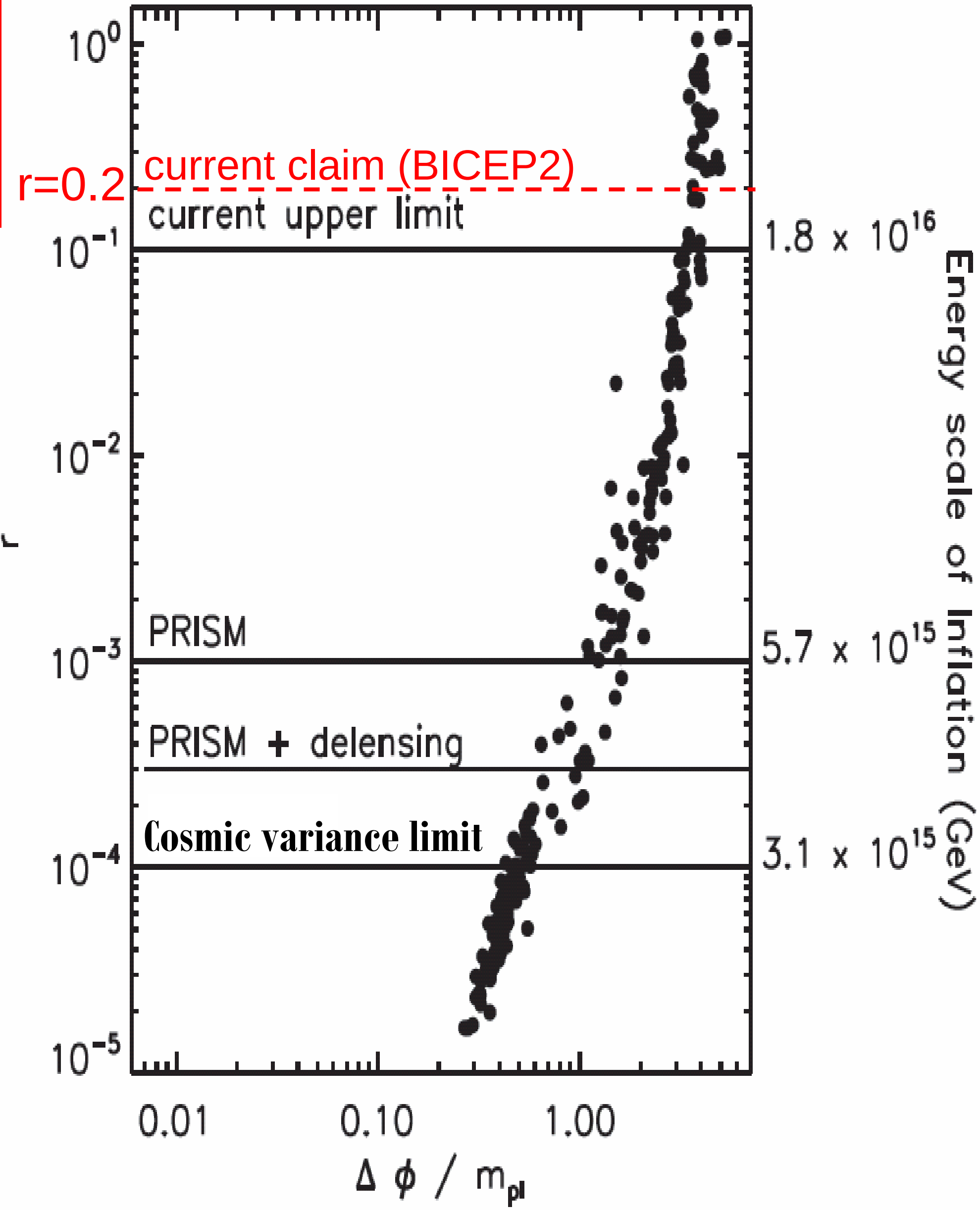


5×10⁻³
4×10⁻³
3×10⁻³
2×10⁻³
10⁻³
0
Total
Tensors (r=0.2)
Lensing
BICEP-2
SPT (derived)
POLARBEAR
ℓ^{1/2}(ℓ+1)C_ℓ^{BB}/2π (μK²)
10
100
1000
Multipole ℓ

BICEP2 results: potentially a huge impact on Cosmology and Fundamental Phsyics

IF the detected B-modes are generated by cosmic inflation:

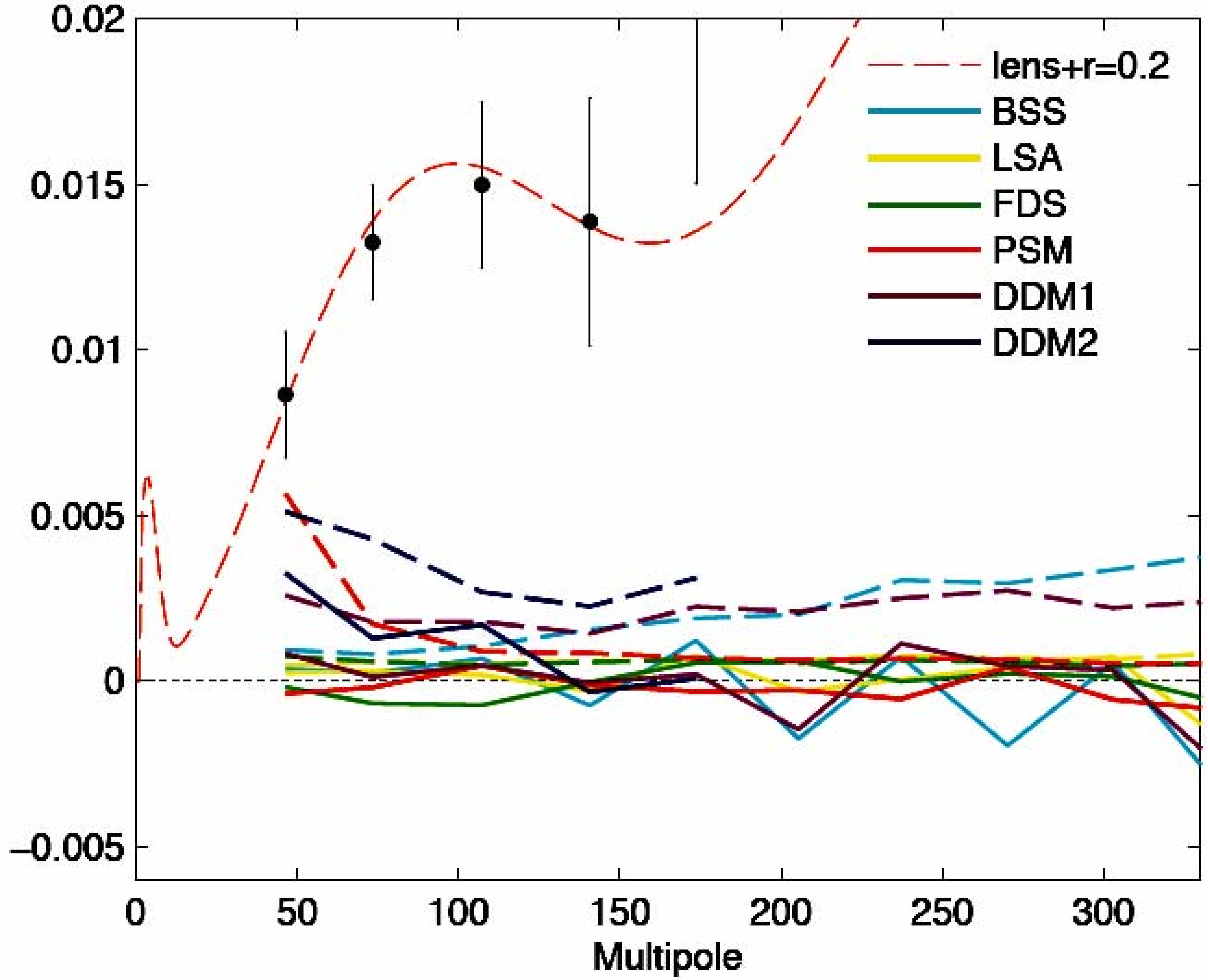
- What has been measured is the result of pre-inflationary quantum fluctuations in the spacetime metric
- The energy-scale of inflation is $2x10^{16}$ GeV (quite precise !)
- We can reject several classes of inflation models
- With new instruments and more precise measurements of B-modes we can constrain other parameters of inflation
- high-energy theory is to construct models of new physics near the Planck scale that include inflation.
- knowing the slope of the spectrum of tensor perturbations would provide a new observational constraint of physics in this energy range that CANNOT be probed by any other means



However …

- Extraordinary discoveries require extraordinary evidence
- **Is the BICEP2 B-modes signal really in the sky ?** My personal opinion is YES, despite of the tiny level, there is more than enough evidence for this in the papers. A systematics paper will be published soon, to fully convince.
- **Is the BICEP2 B-modes signal really primordial ?** My personal opinion is that these is NOT enough evidence for this in the papers.

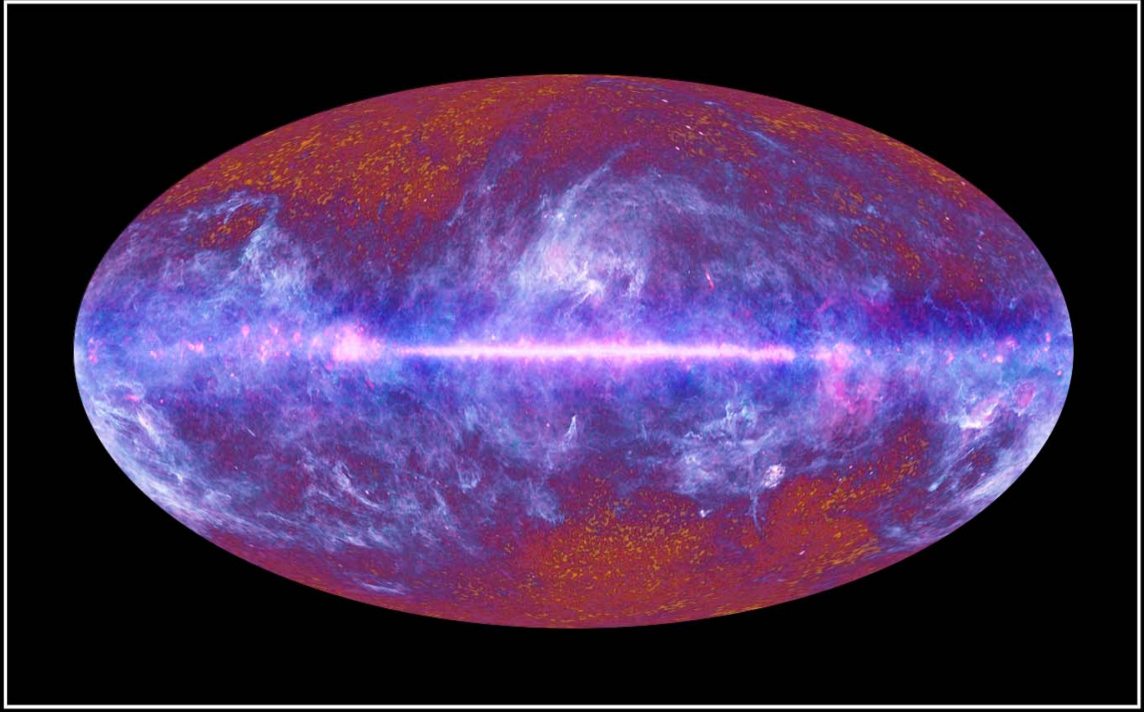
From BICEP2 paper :



Models for the foregorund signal (mainly interstellar dust)

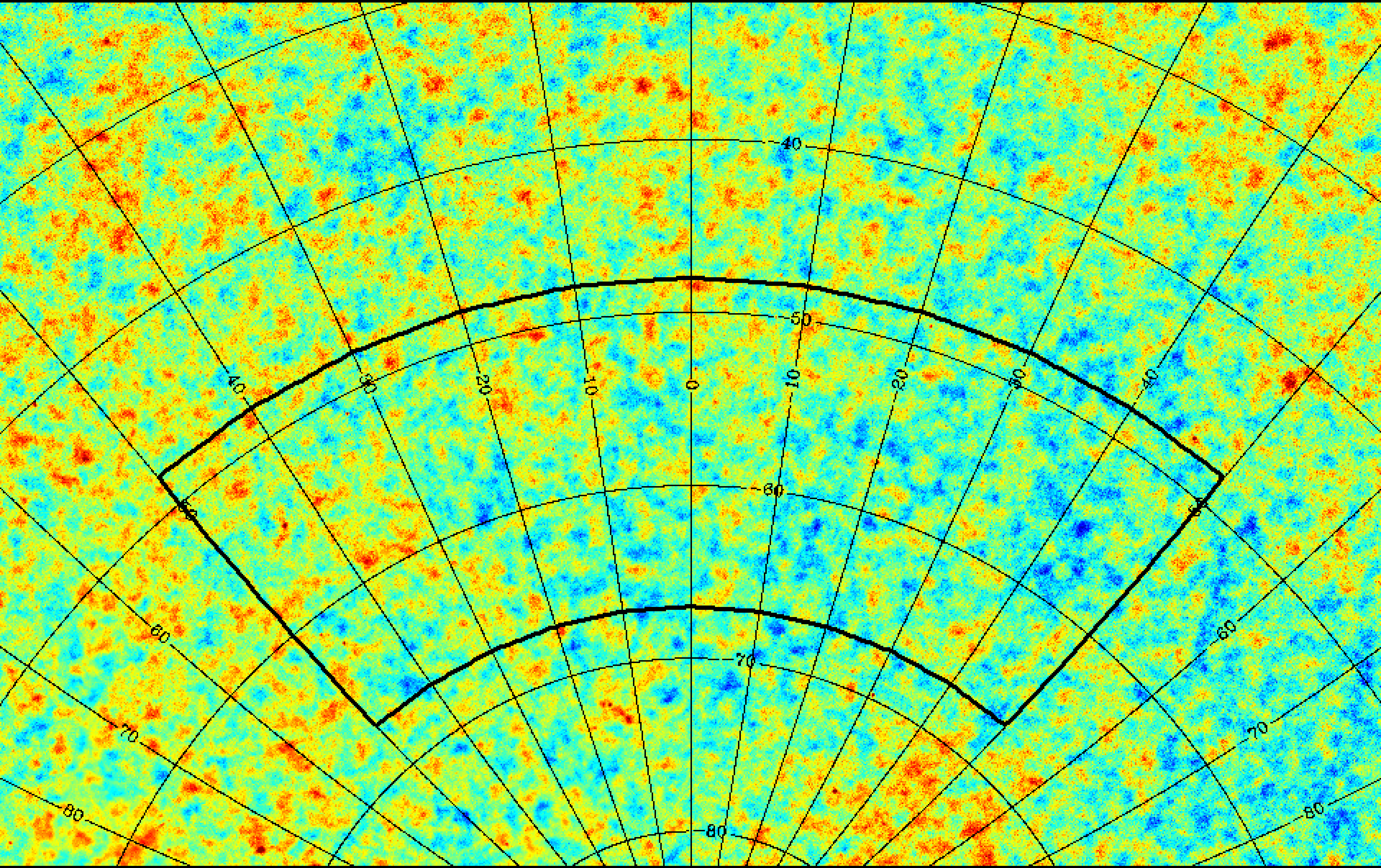
Interstellar dust polarization

- Interstellar dust grains are elongated and aligned in the magnetic field of our Galaxy
- Dust grains are heated by UVs from stars, and re-emit as grey-body sources in the FIR, with a temperature of 20-30K.
- Due to the alignement, the emission is polarized.
- The polarization fraction depends on the degree of alignment and on the coherence of the B-field along the line of sight



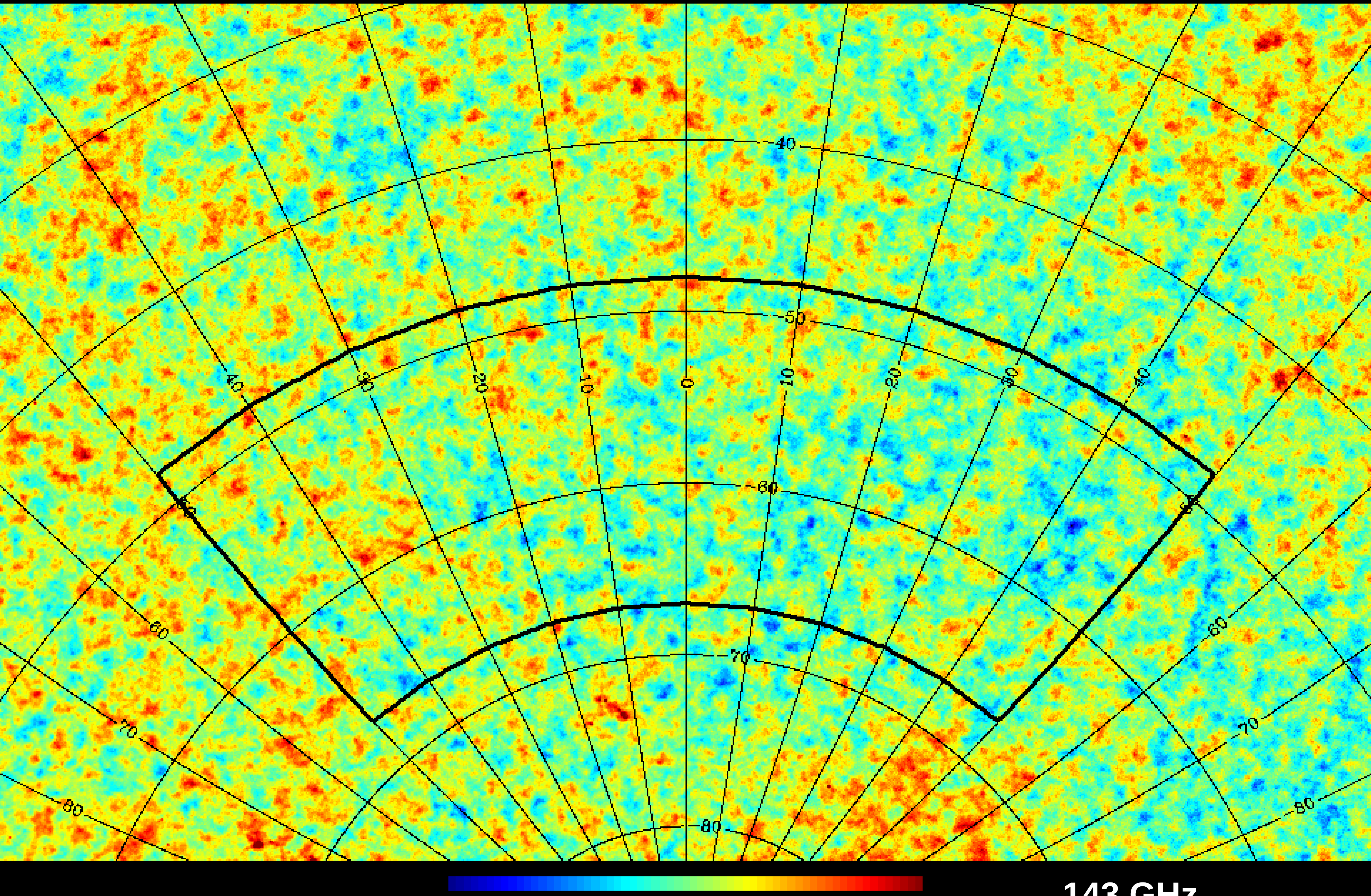
The Planck one-year all-sky survey · esa · (c) ESA, HFI and LFI consortia, July 2010

- In high-latitude regions the line of sight crosses only one or a few thin dust clouds, where the magnetic field is likely to be coherent. So lower dust intensity does not imply necessarily low dust polarization.
- Planck polarization data at 340 GHz are very sensitive to polarized dust.
- Other data are very scarce and there are no data are available in the region observed by BICEP2.



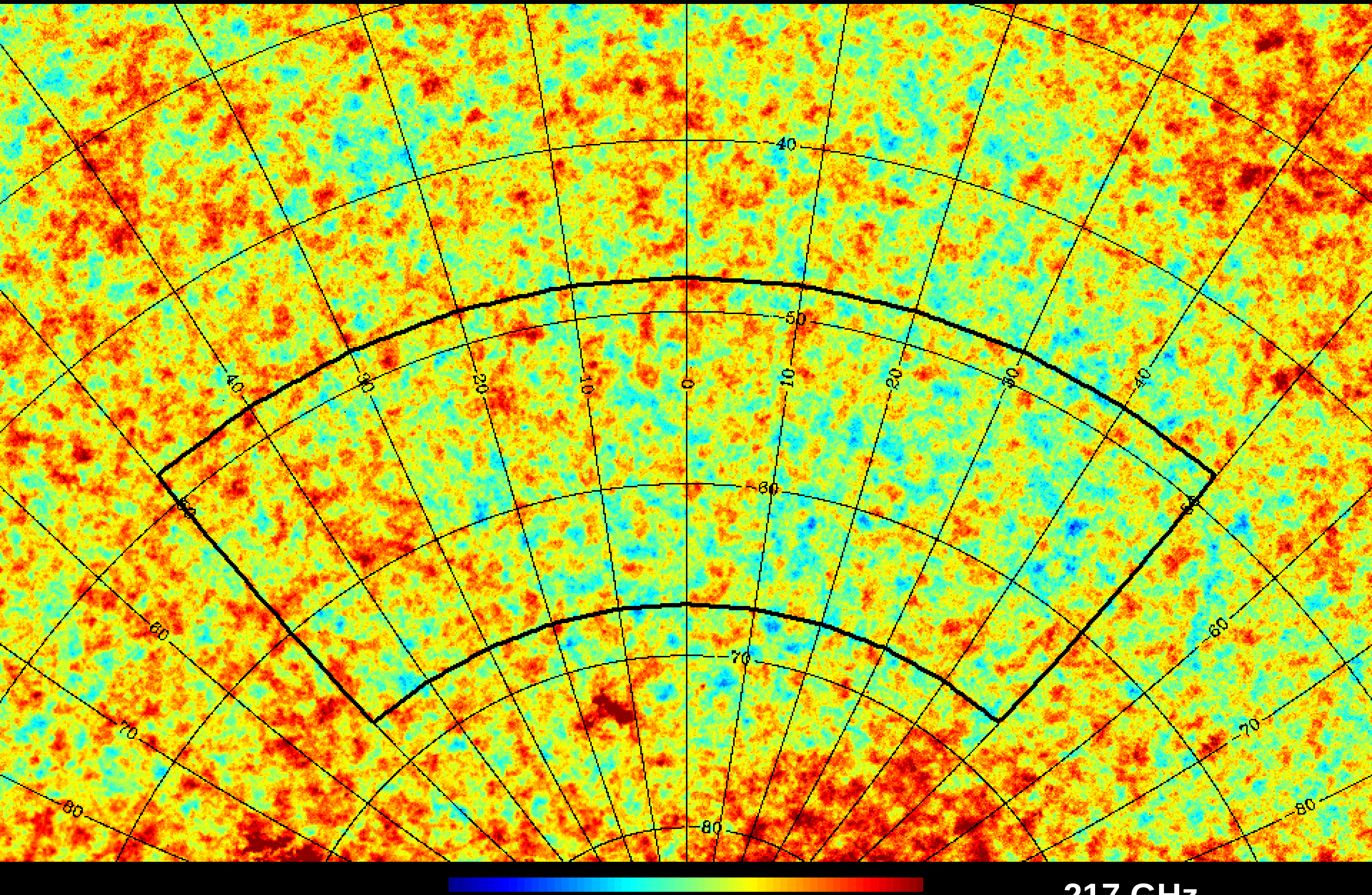
100 GHz

Planck data in the BICEP2 region



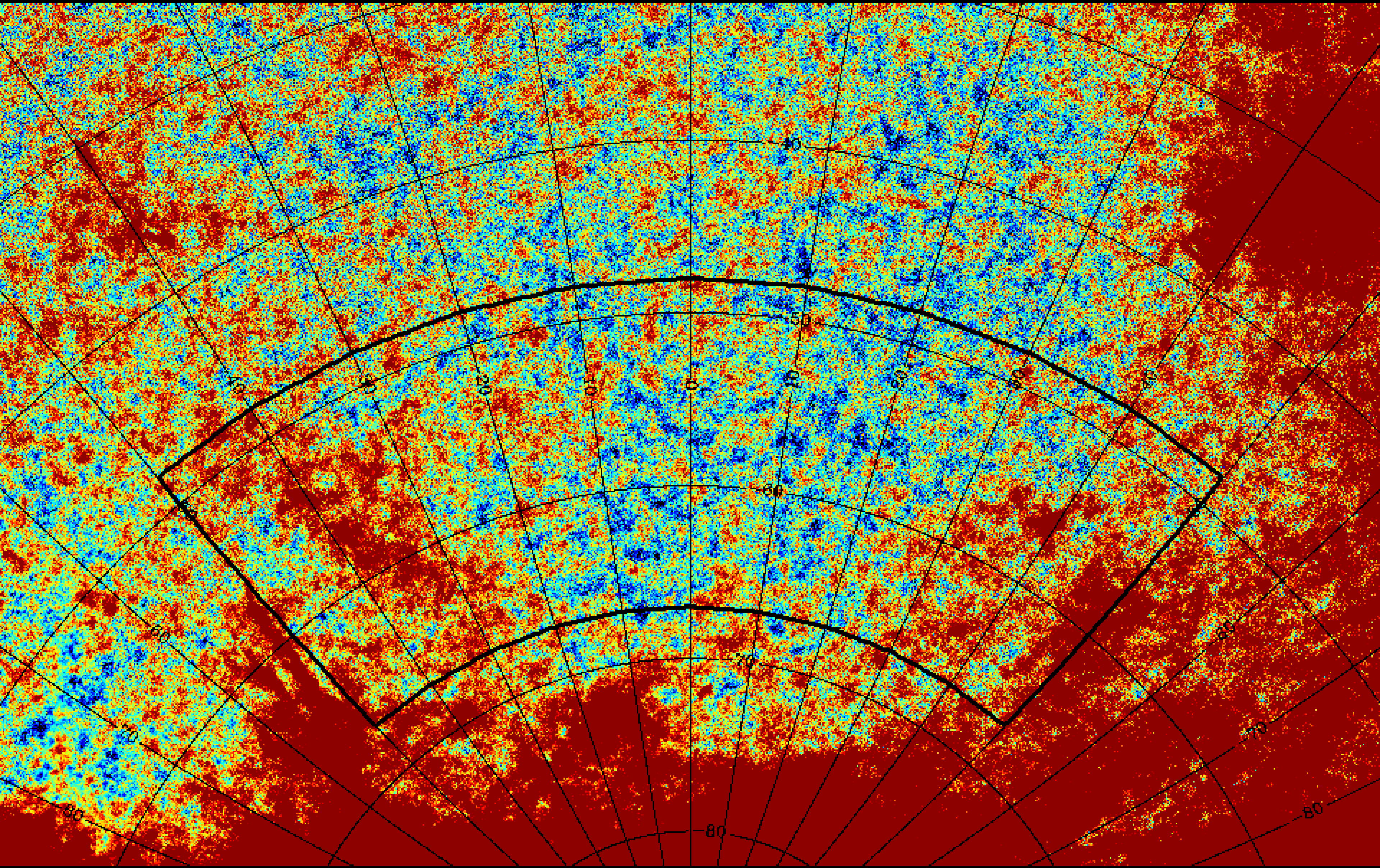
143 GHz

Planck data in the BICEP2 region



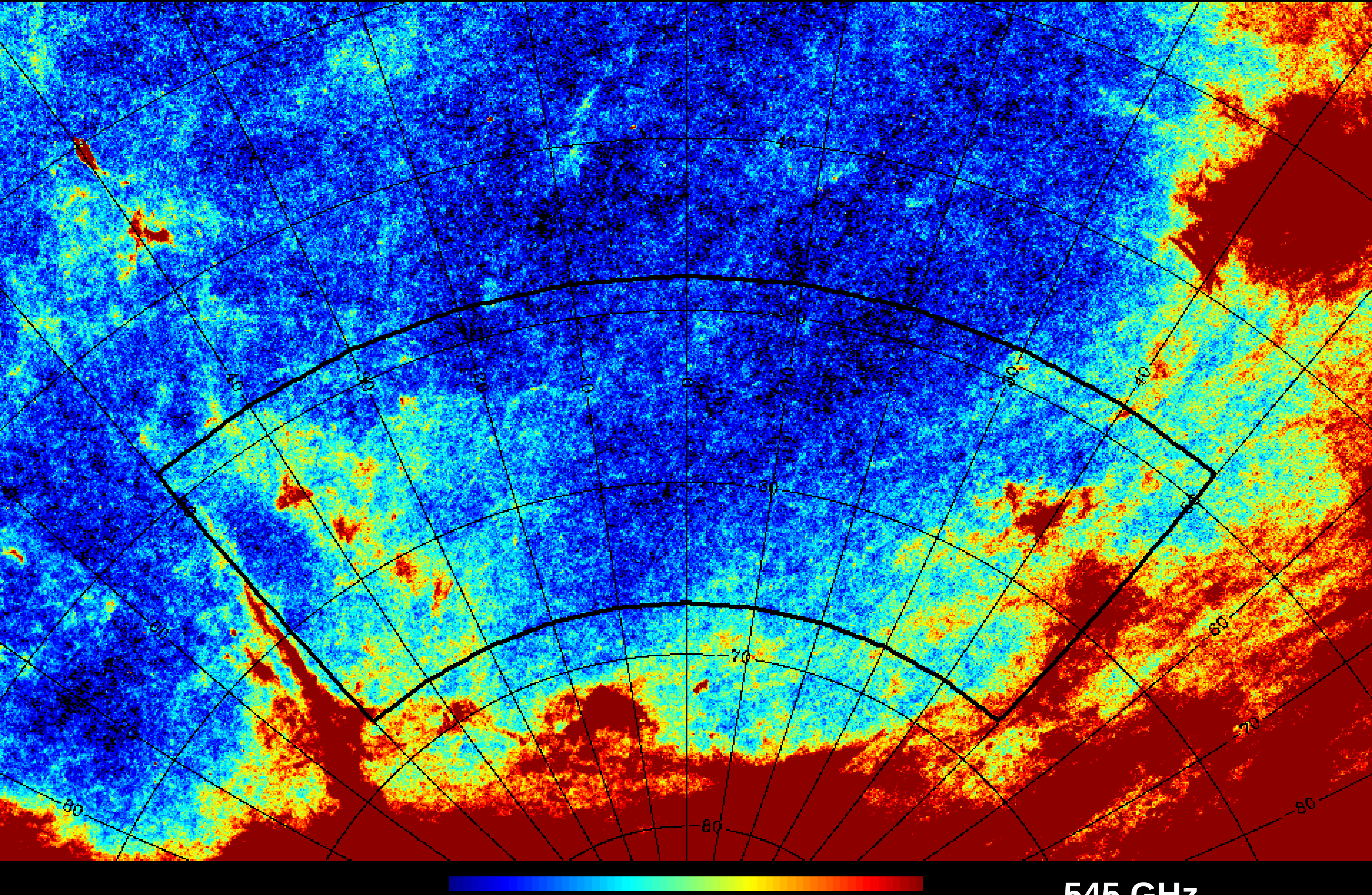
217 GHz

Planck data in the BICEP2 region



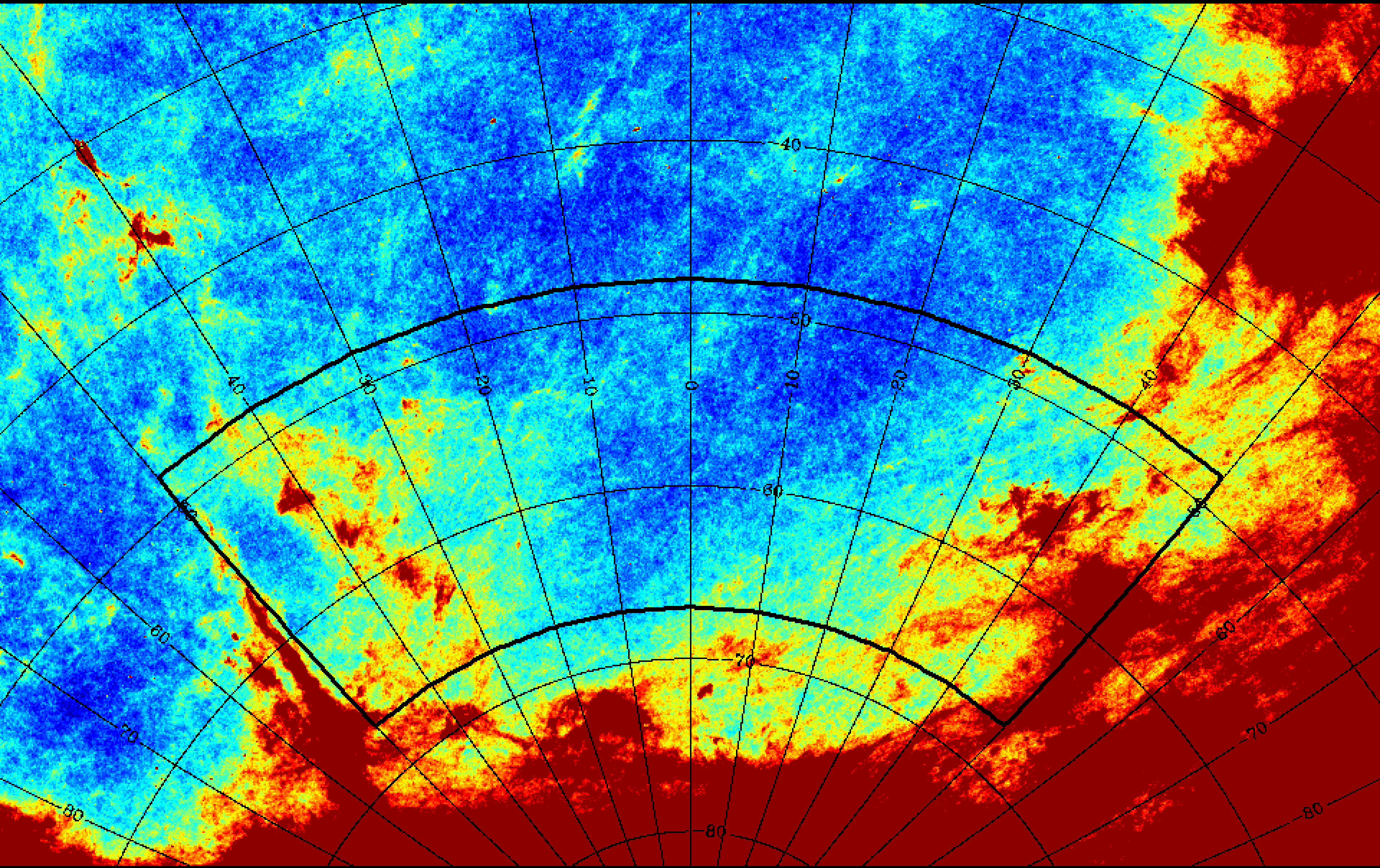
353 GHz

Planck data in the BICEP2 region



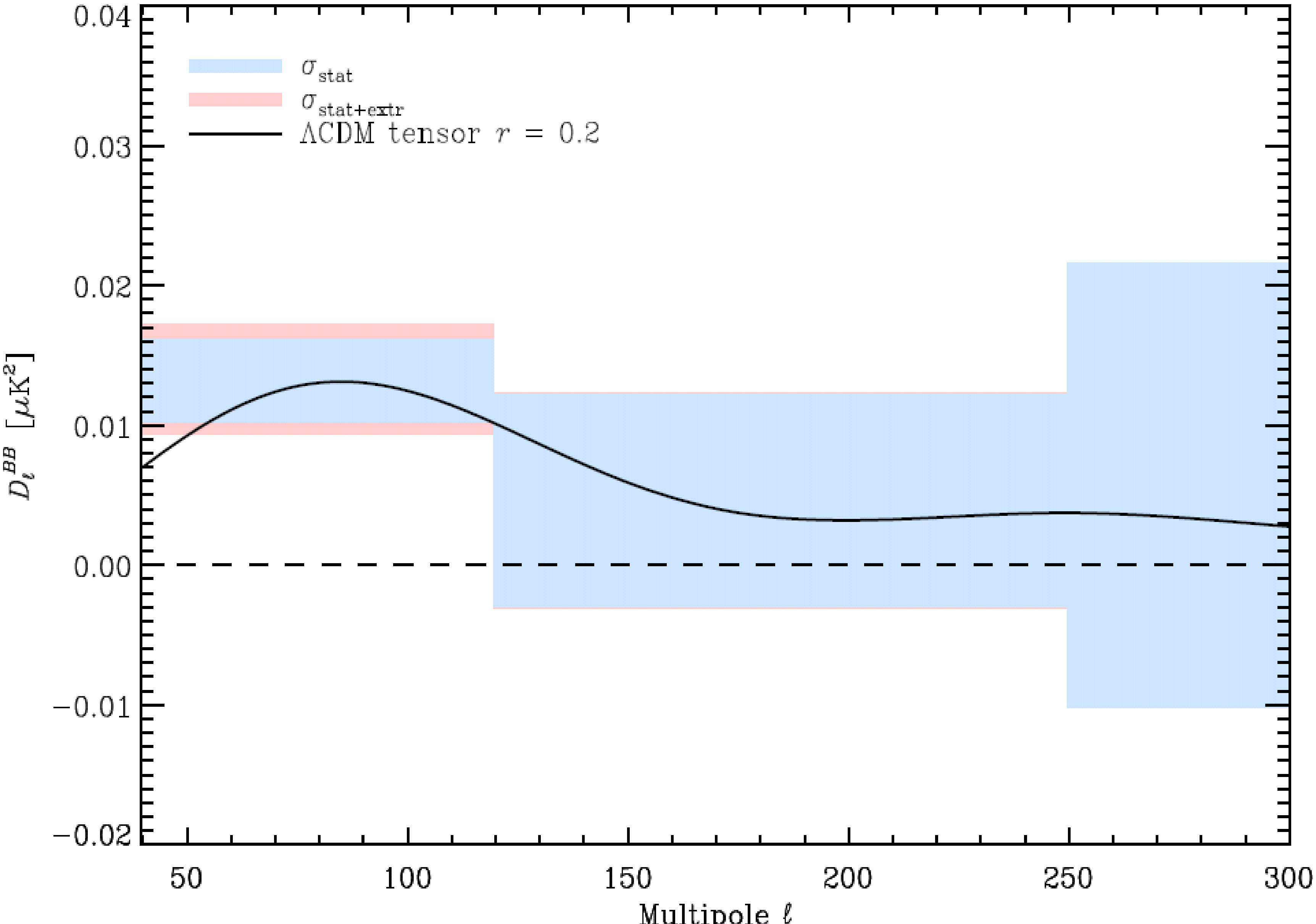
545 GHz

Planck data in the BICEP2 region



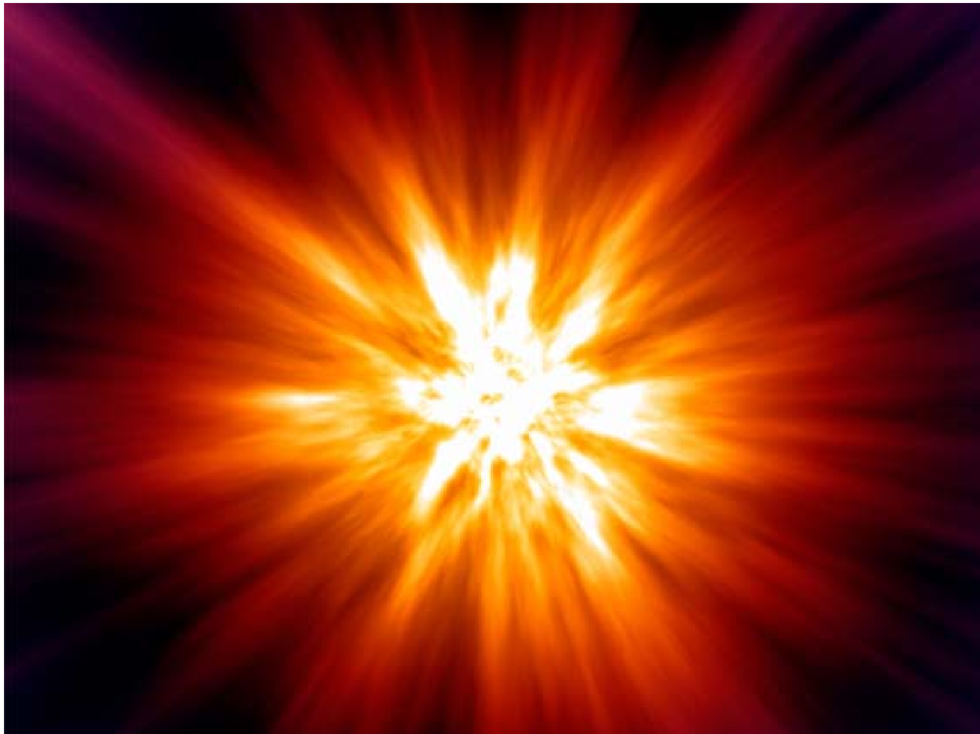
857 GHz

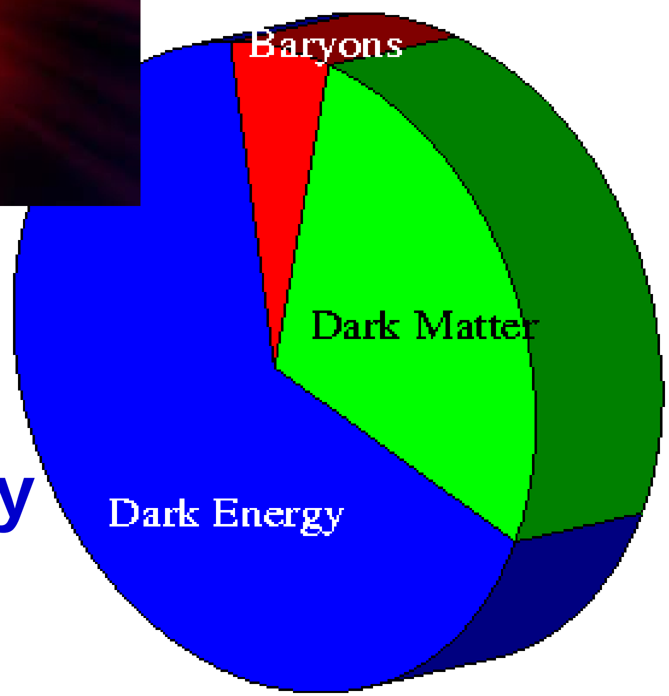
Planck data in the BICEP2 region



0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
50
100
150
200
250
300
Multipole ℓ
D_ℓ^{BB} [μK^2]
$\sigma_{\rm stat}$
$\sigma_{\rm stat+extr}$
ΛCDM tensor r = 0.2

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





Inflation

?

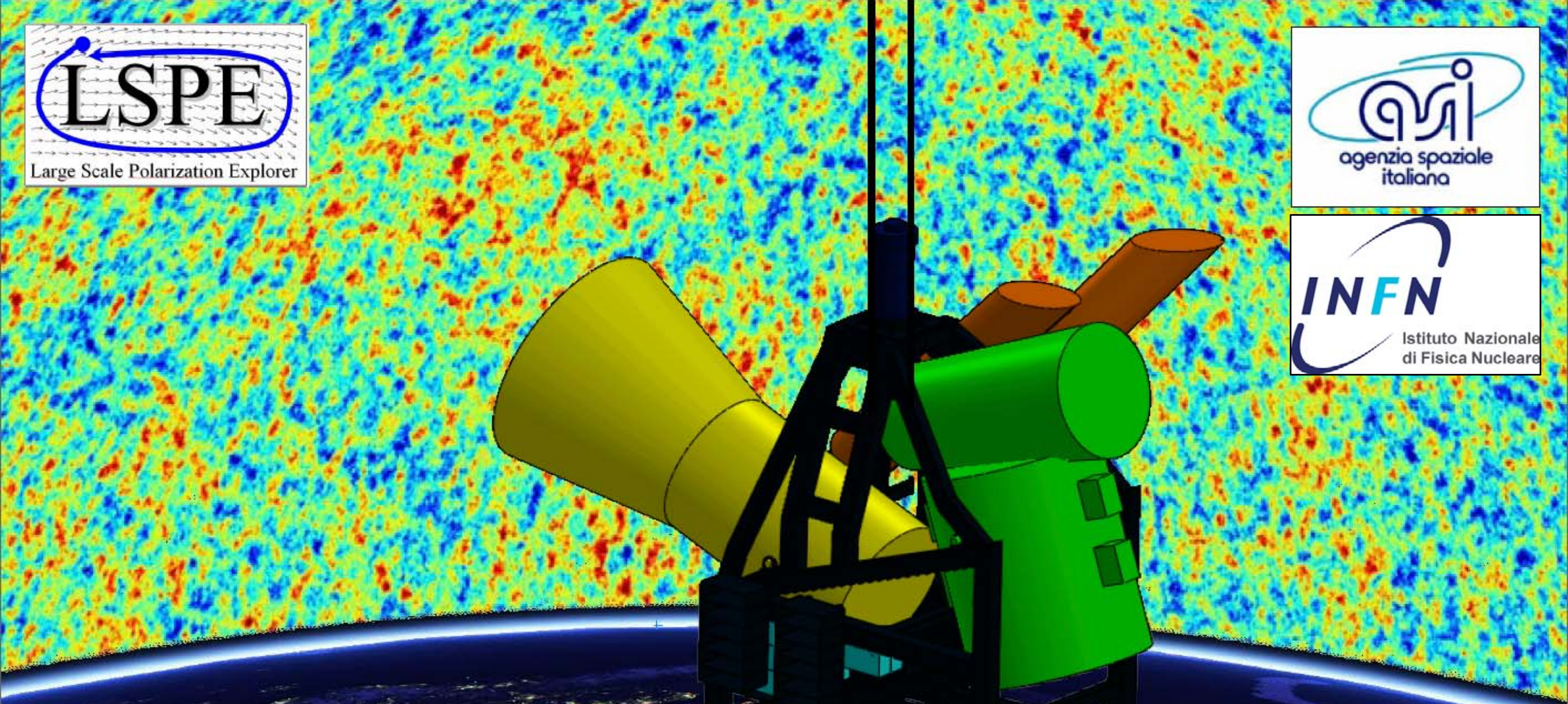
Dark Energy 74%

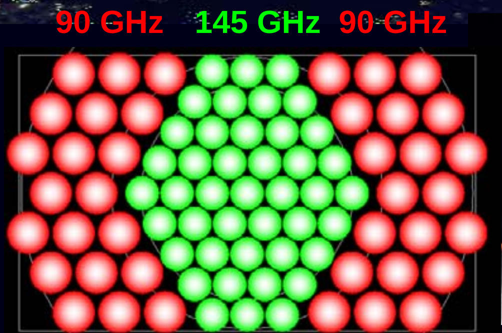
?

Dark Matter 22%

?

Large Scale Polarization Explorer





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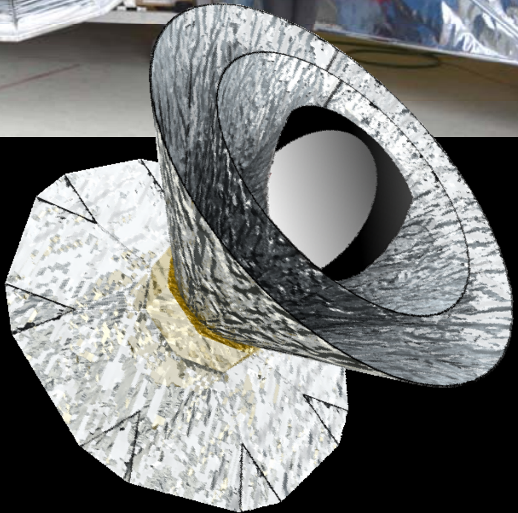
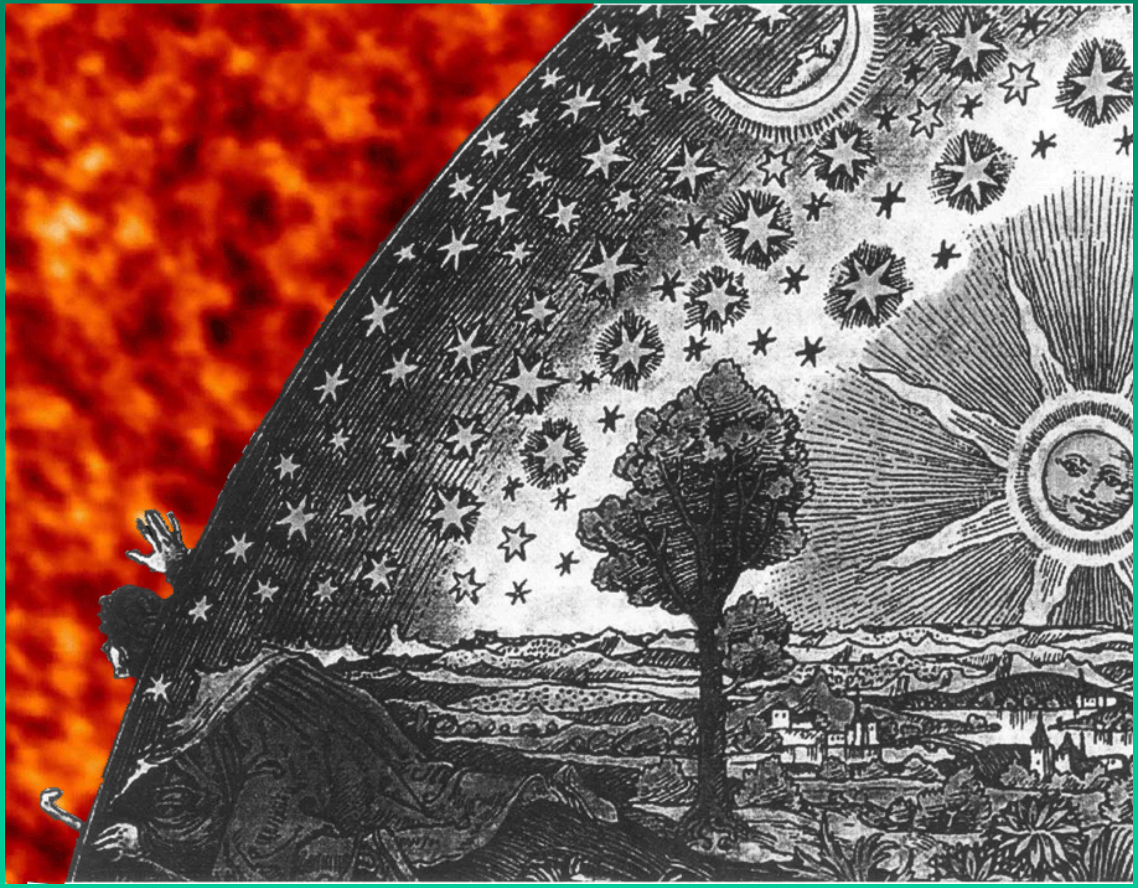
Progress linked to technology development c): angular resolution

- Planck: 1.5m aperture, 5' resolution @300 GHz
- OLIMPO: 2.6m, 4'-1' resolution 140-600 GHz
- SPT: 10m, 1' resolution @140 GHz
- COrE: 1' resolution @600 GHz
- PRISM: sub-arcmin @300 GHz



Forse la polarizzazione del fondo cosmico a microonde ci svelerà cosa accadde nei primi attimi …

C’è ancora moltissimo da fare per arrivarci.



Per saperne di più ....