

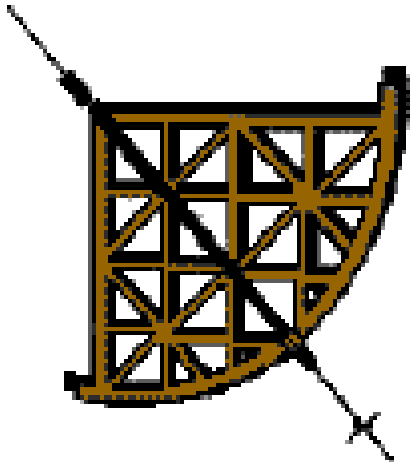
Introduzione alla Cosmologia Fisica Lezione 18

Il modello di Gamow, il satellite COBE, Boomerang. L'Universo piatto

Giorgio G.C. Palumbo

Università degli Studi di Bologna

Dipartimento di Astronomia



<http://oberon.roma1.infn.it/~boomerang>
<http://www.physics.ucsb.edu/~boom>

ASI
NASA
NSF
PNRA
PPARC

*A. Lange * Caltech*

ENEA

ING

IROE

*P. de Bernardis * La Sapienza*

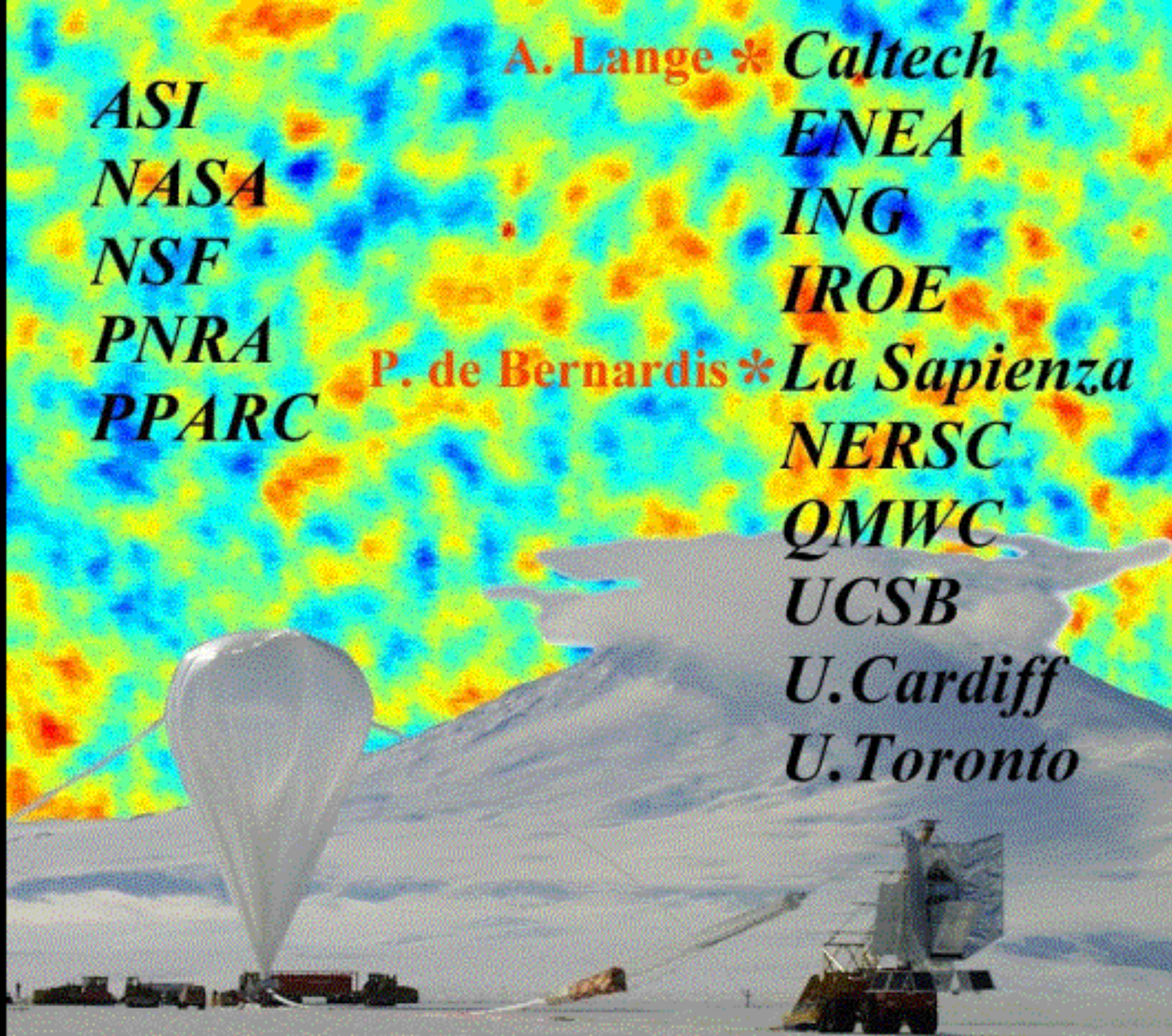
NERSC

QMWC

UCSB

U. Cardiff

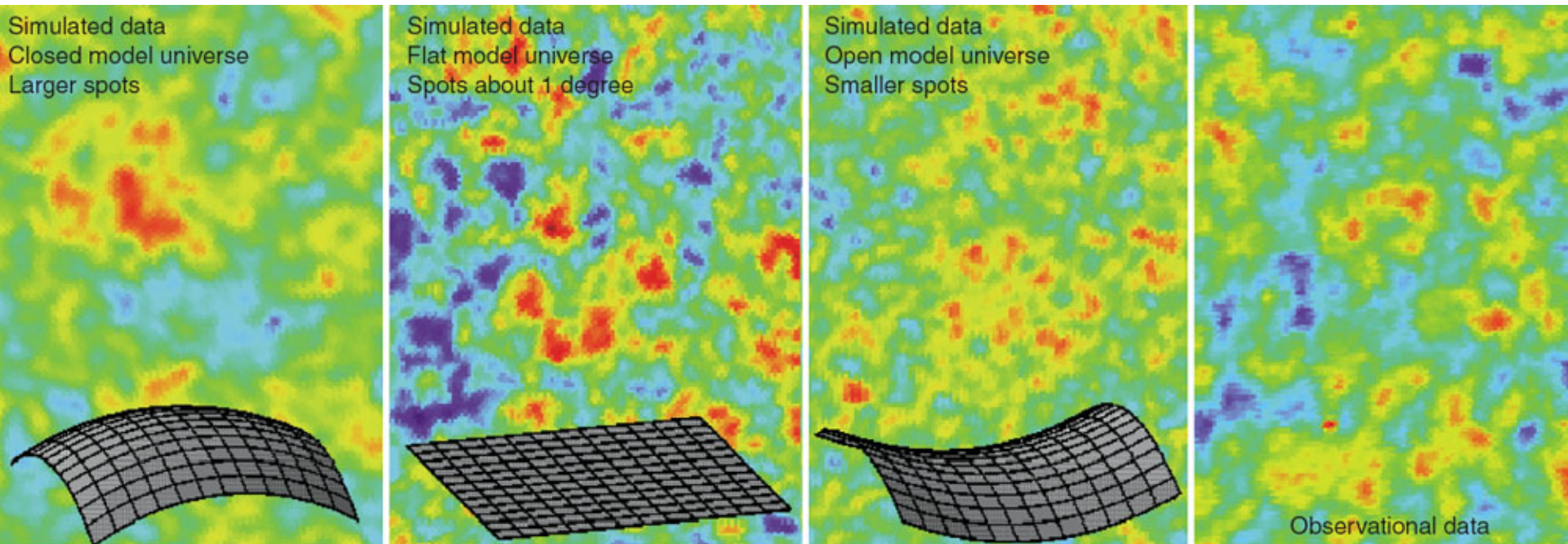
U. Toronto



1998-99

BOOMERanG-LDB

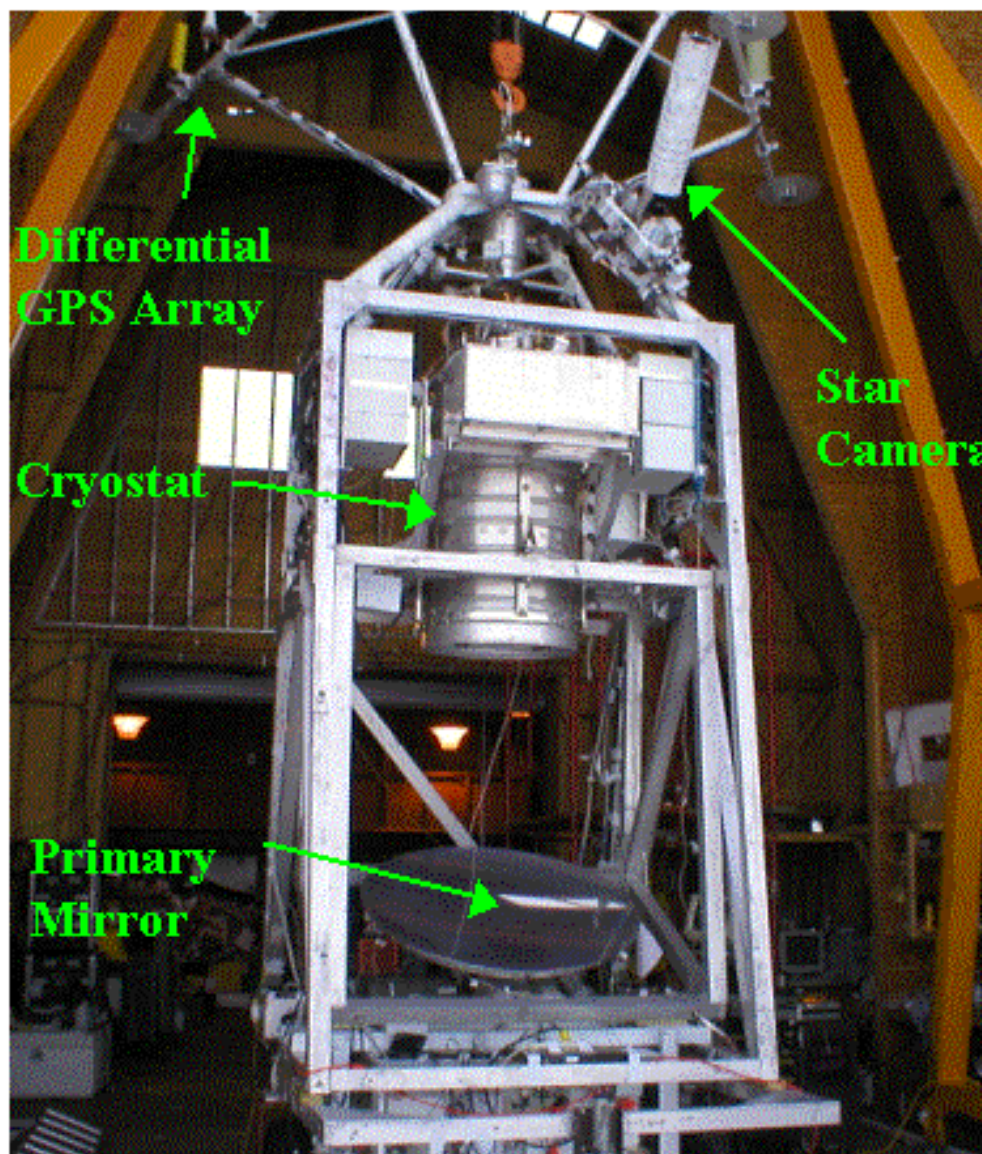
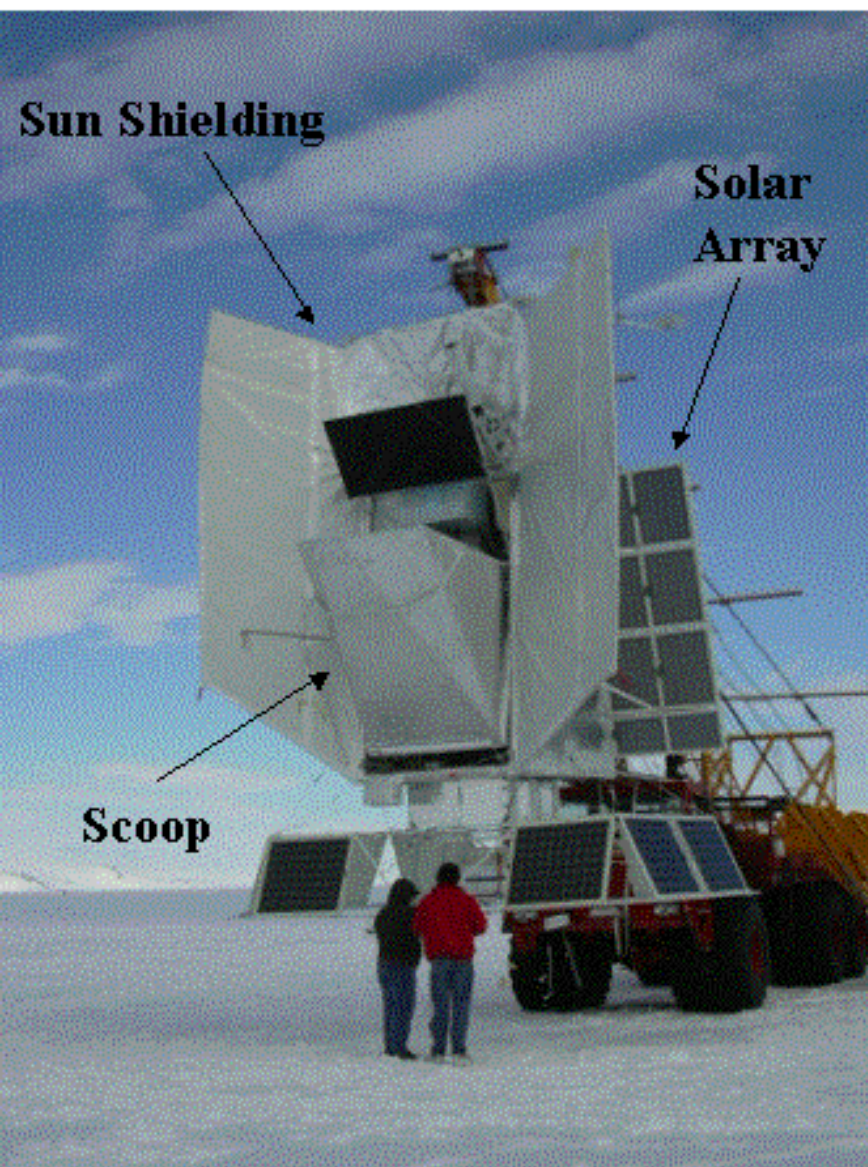
Variazioni angolari in temperatura del CMB (fondo cosmico a microonde) forniscono informazioni sulla geometria dell'Universo.



© 2006 Brooks/Cole - Thomson

Gran parte delle variazioni angolari hanno scale di 1 grado, indicano che l'Universo ha una geometria piatta

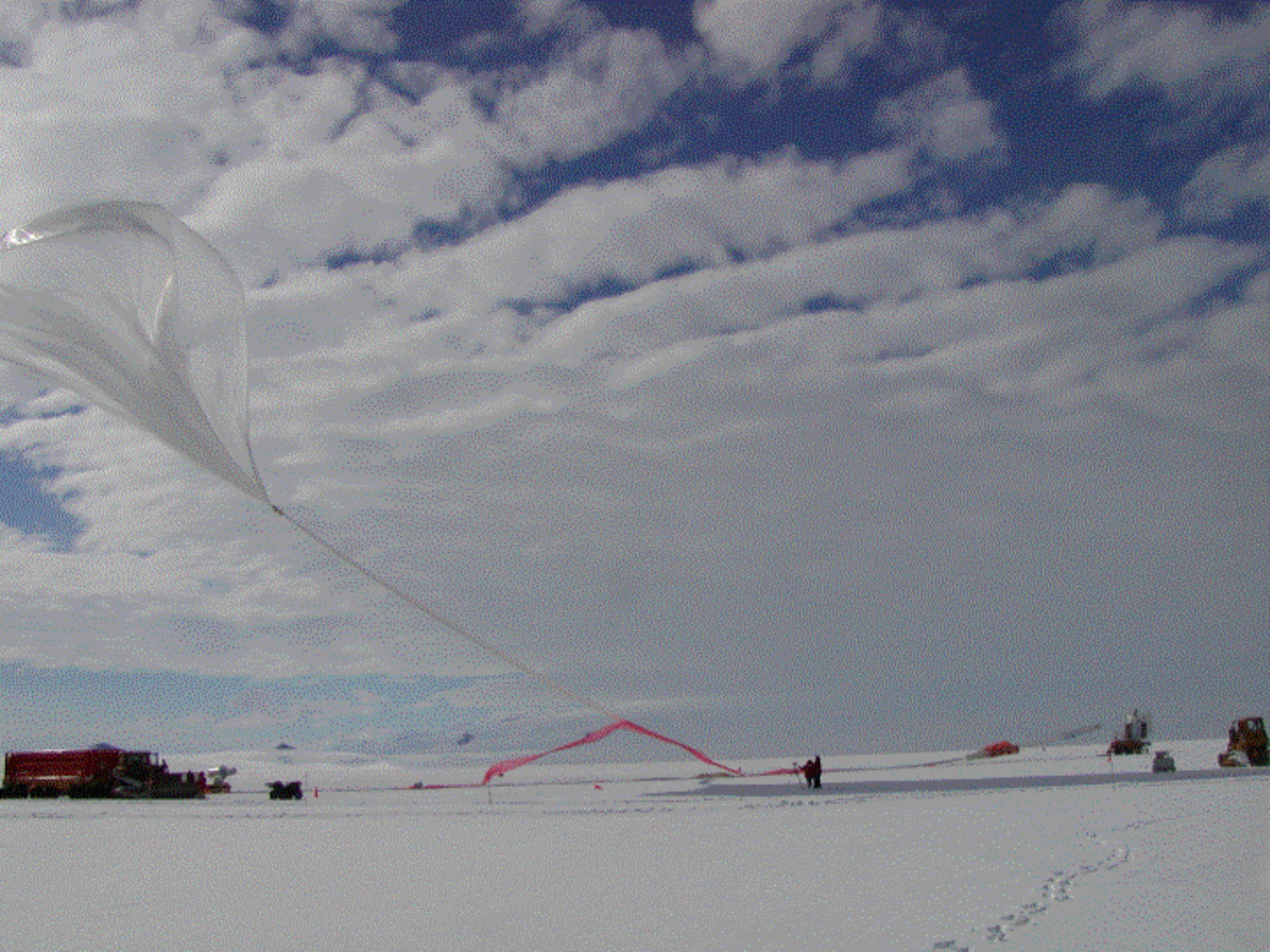
The BOOMERANG balloon-borne Telescope



Sensitive at 90, 150, 240, 410 GHz

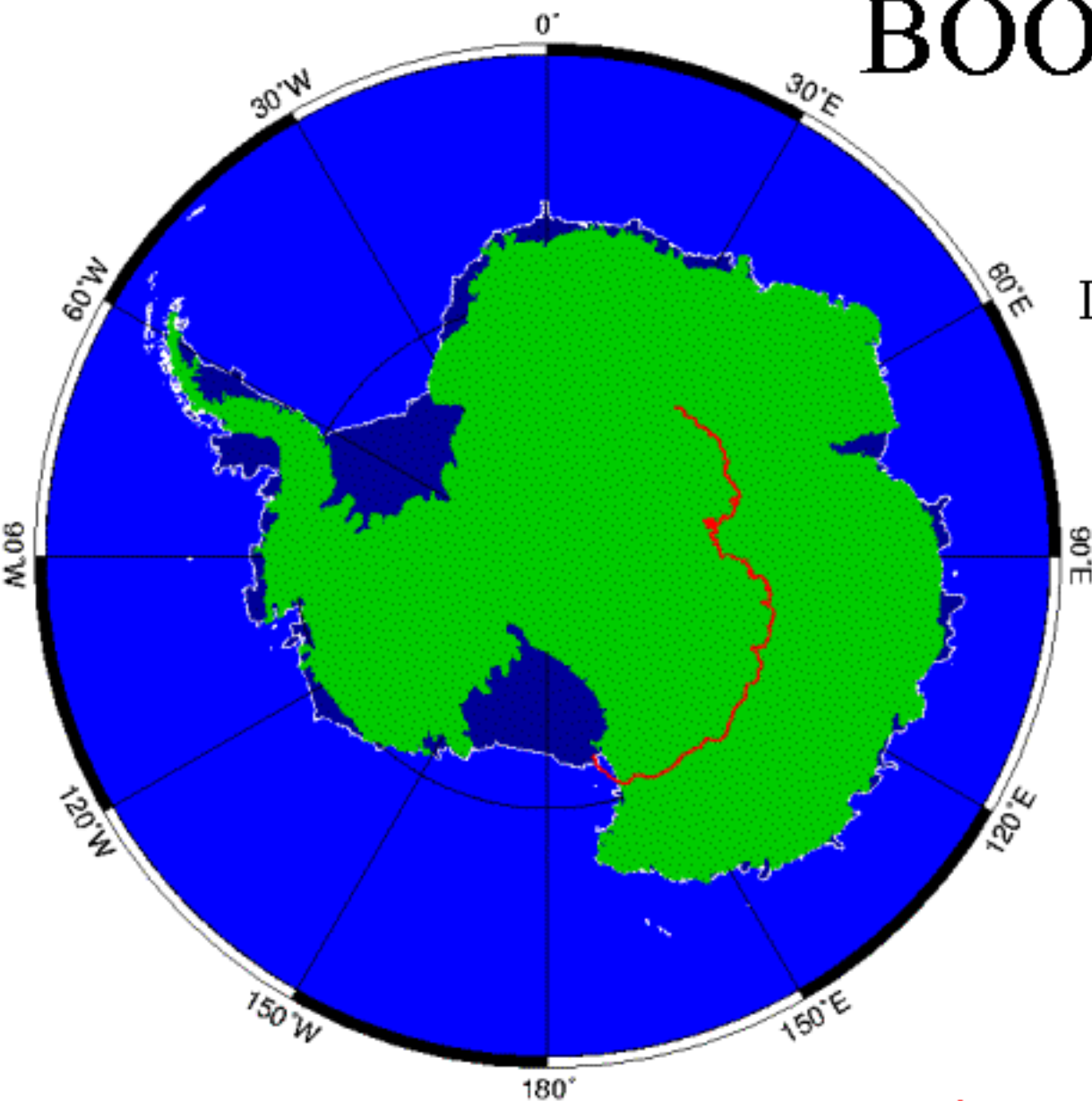


06/01/2003





BOOM03 Flight



Launched:

January 6, 2003

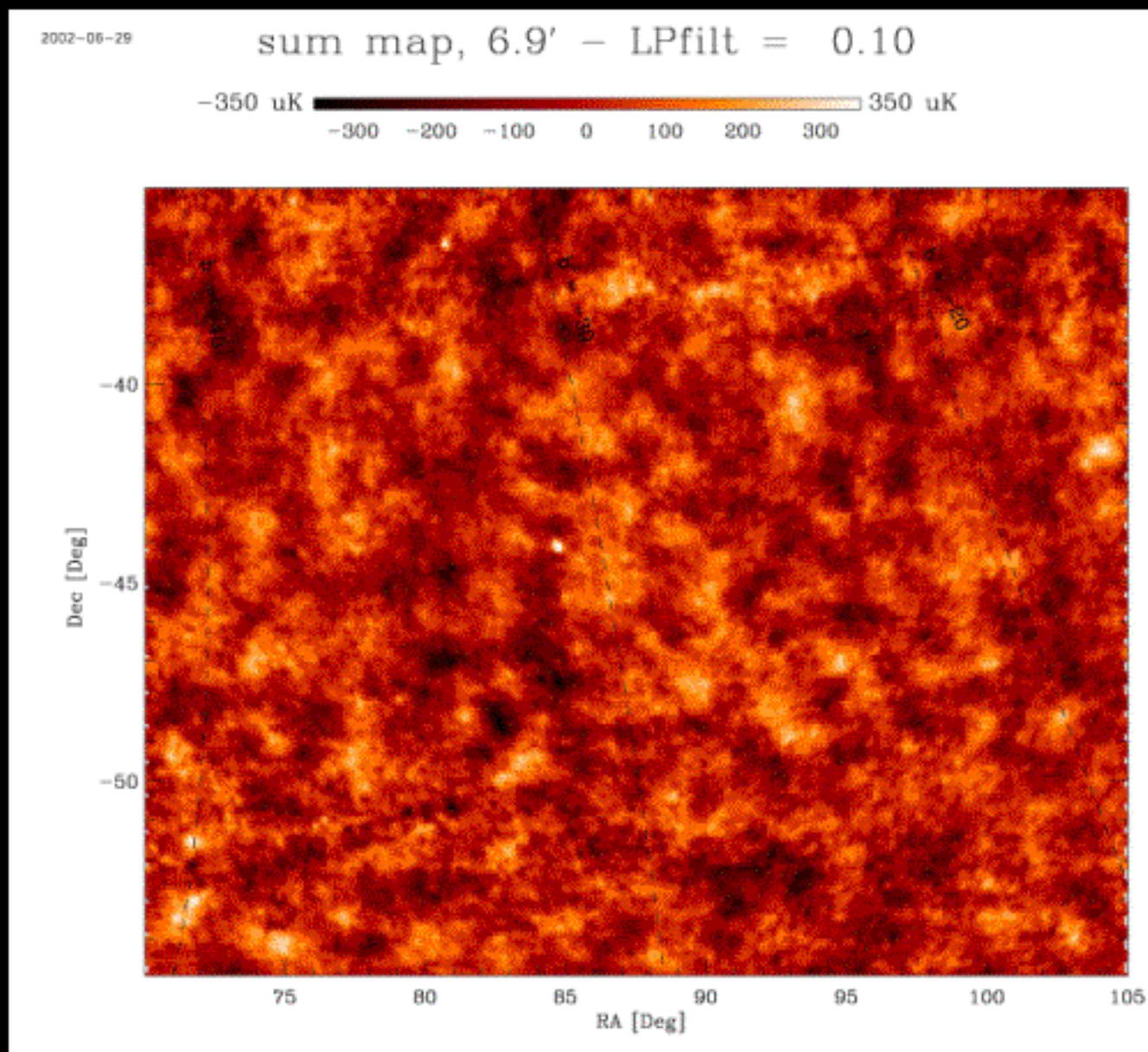
From:

McMurdo Station,
Antarctica

11.7 days of good data !!!

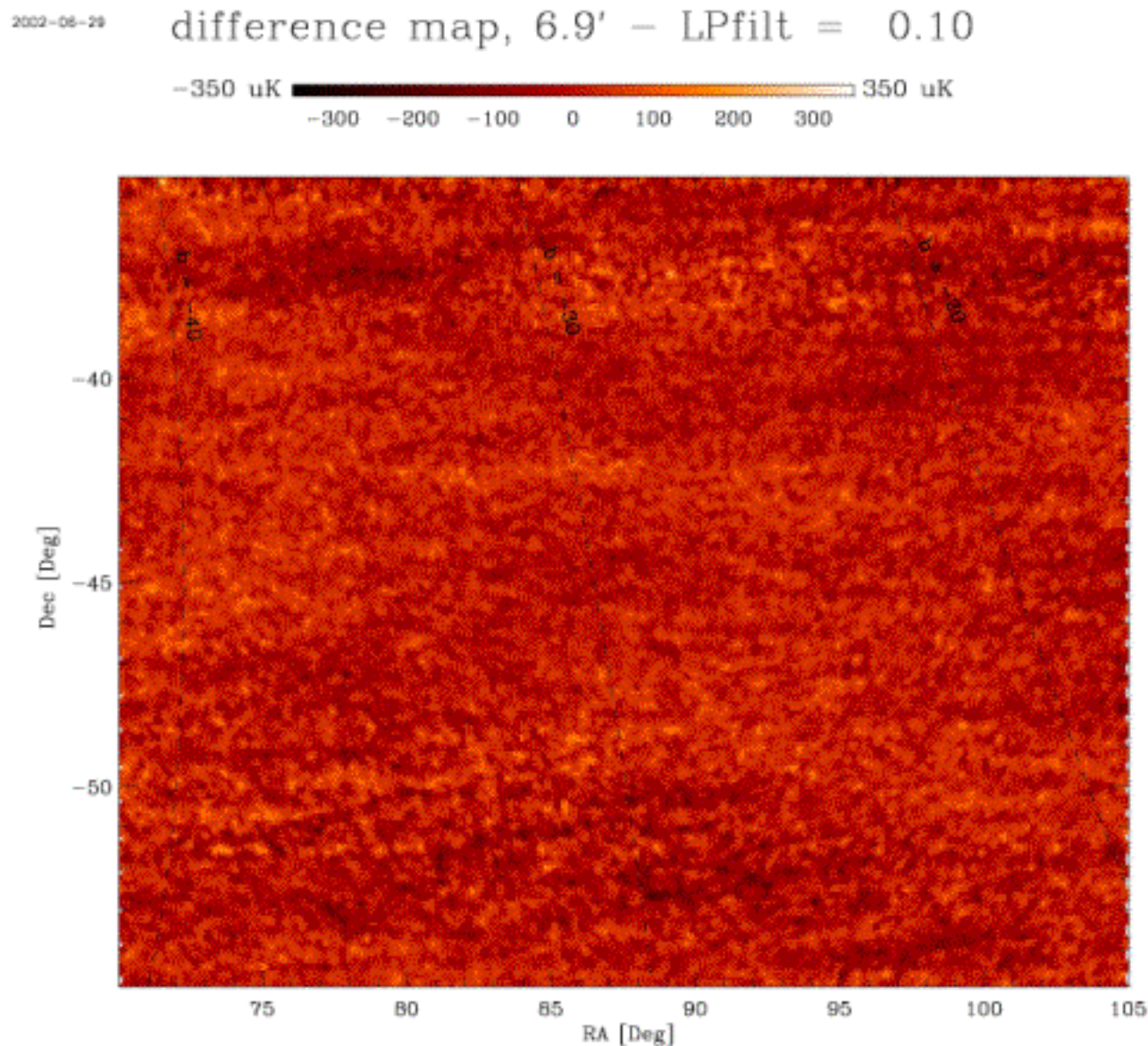
BOOMERanG

- **1998:** BOOMERanG mapped the temperature fluctuations of the CMB at sub-horizon scales ($<1^\circ$).
- The signal was well above the noise:

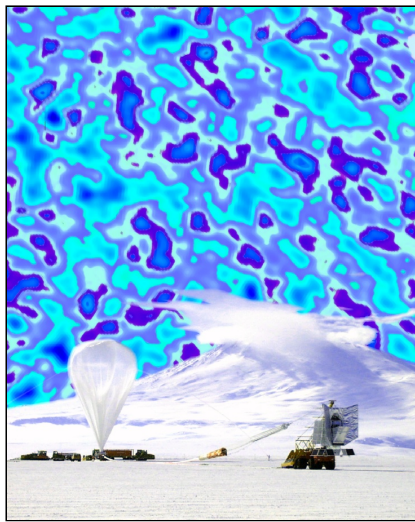


BOOMERanG

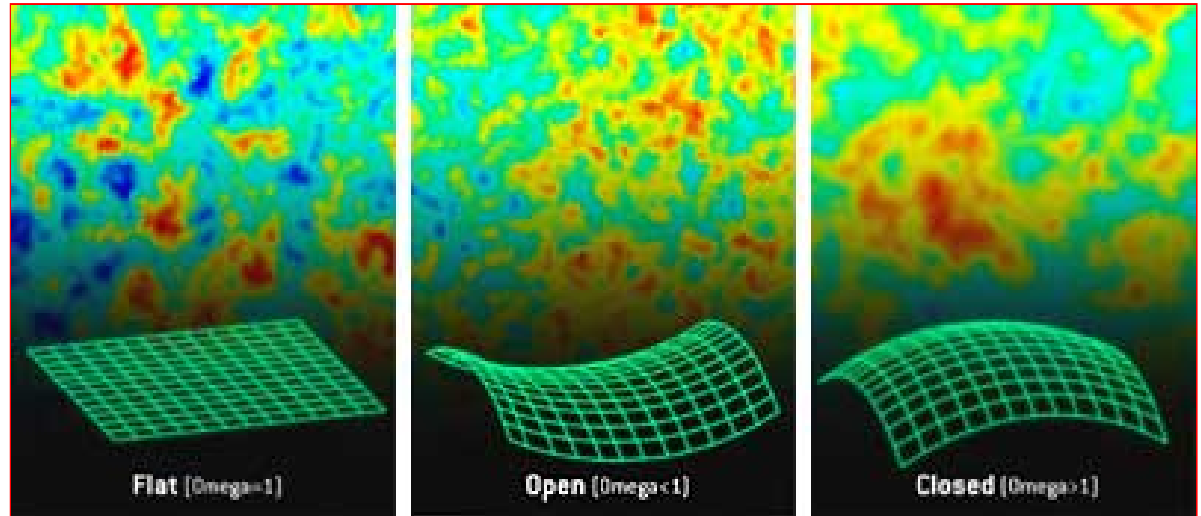
- **1998:**
BOOMERanG mapped the temperature fluctuations of the CMB at sub-horizon scales ($<1^\circ$).
- The signal was well above the noise:



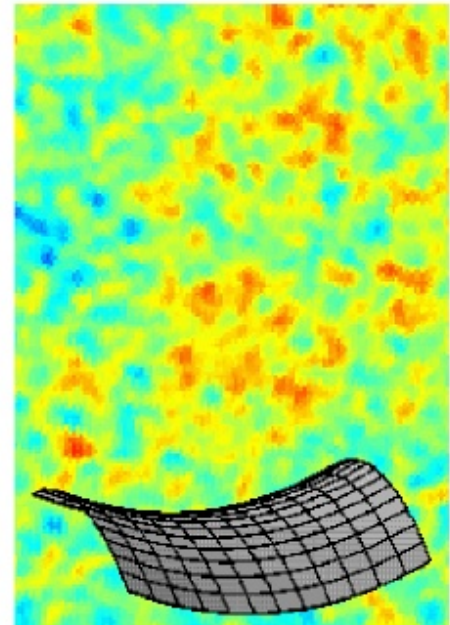
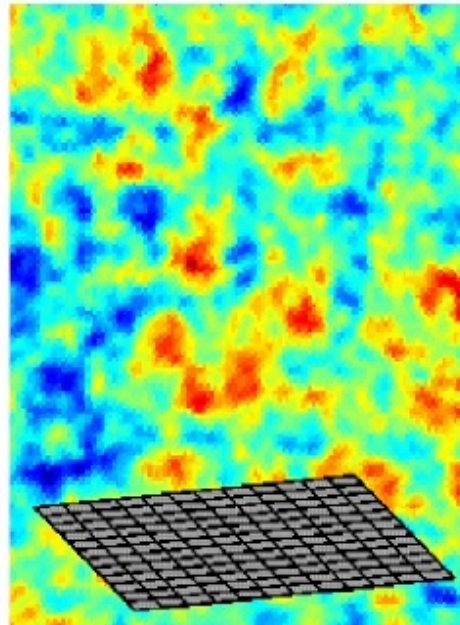
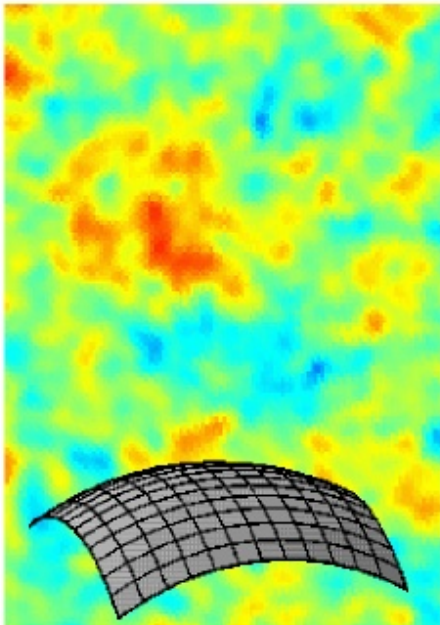
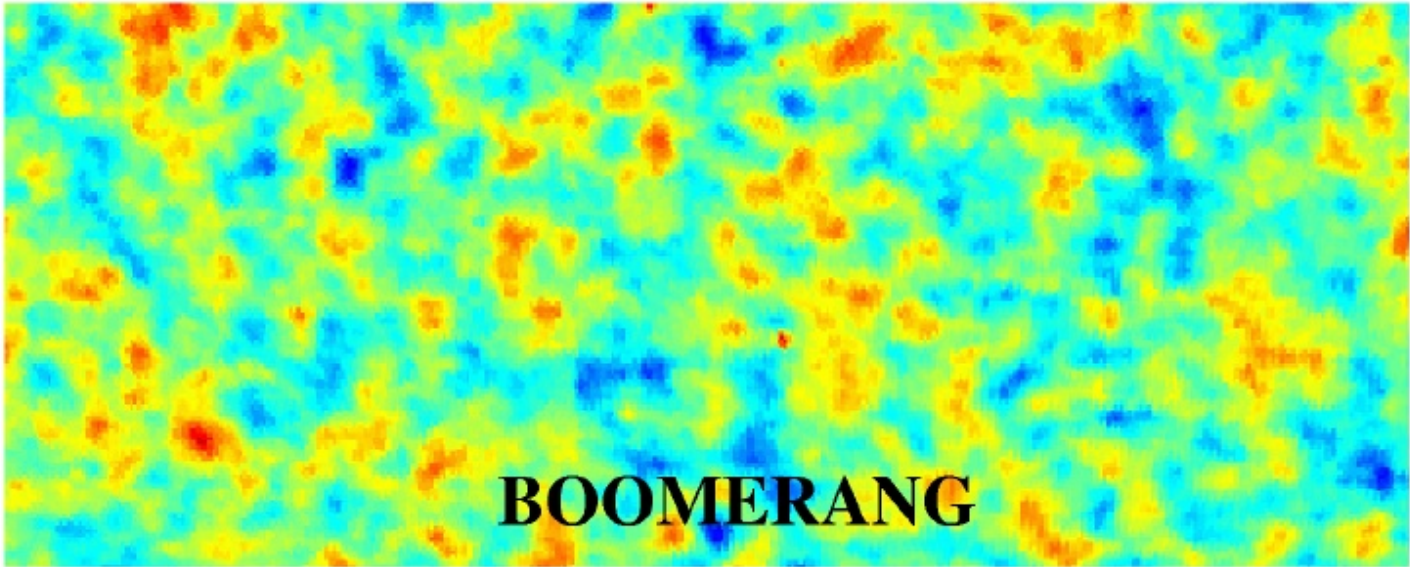
La geometria dell'universo



Boomerang

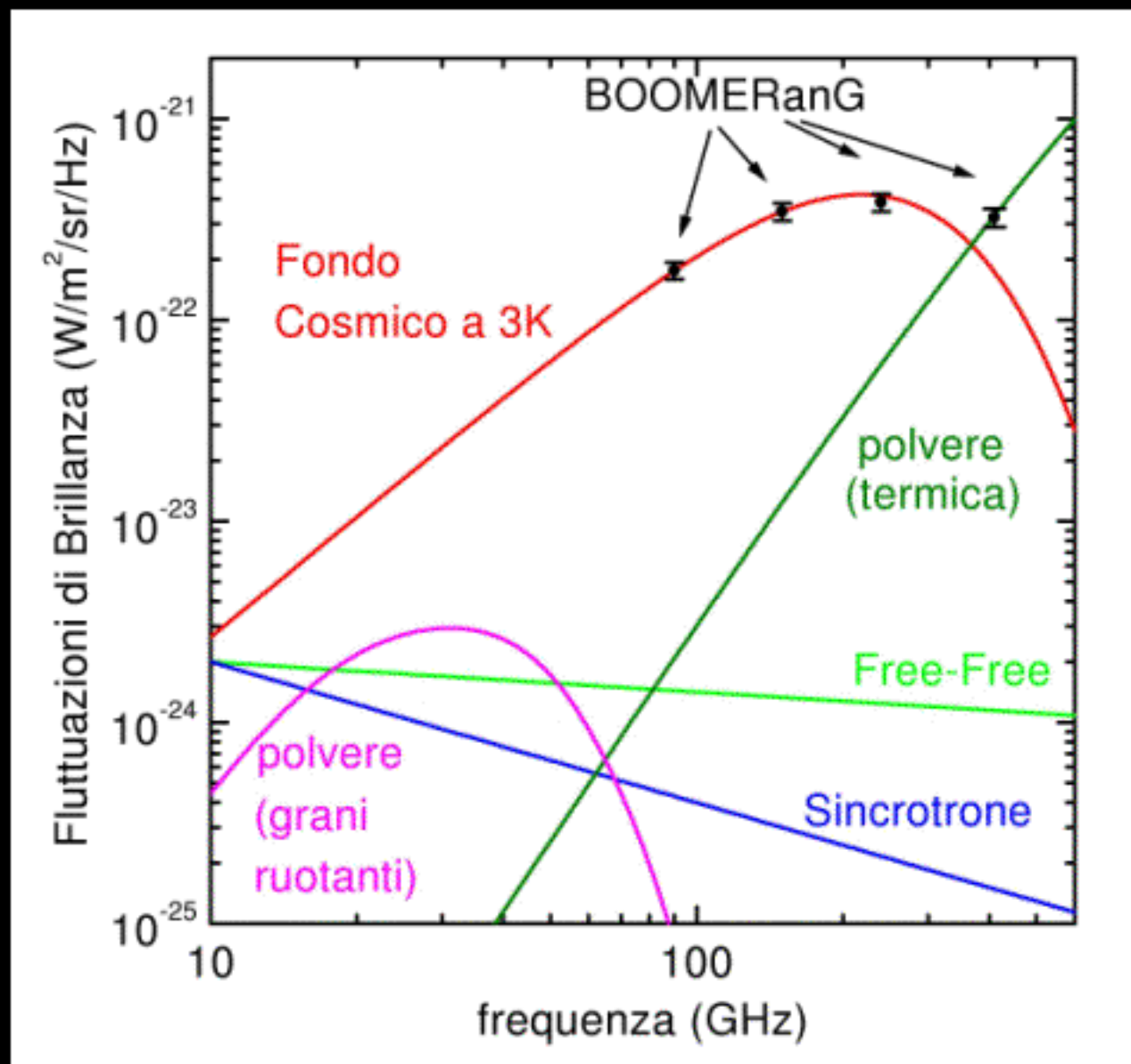


25°

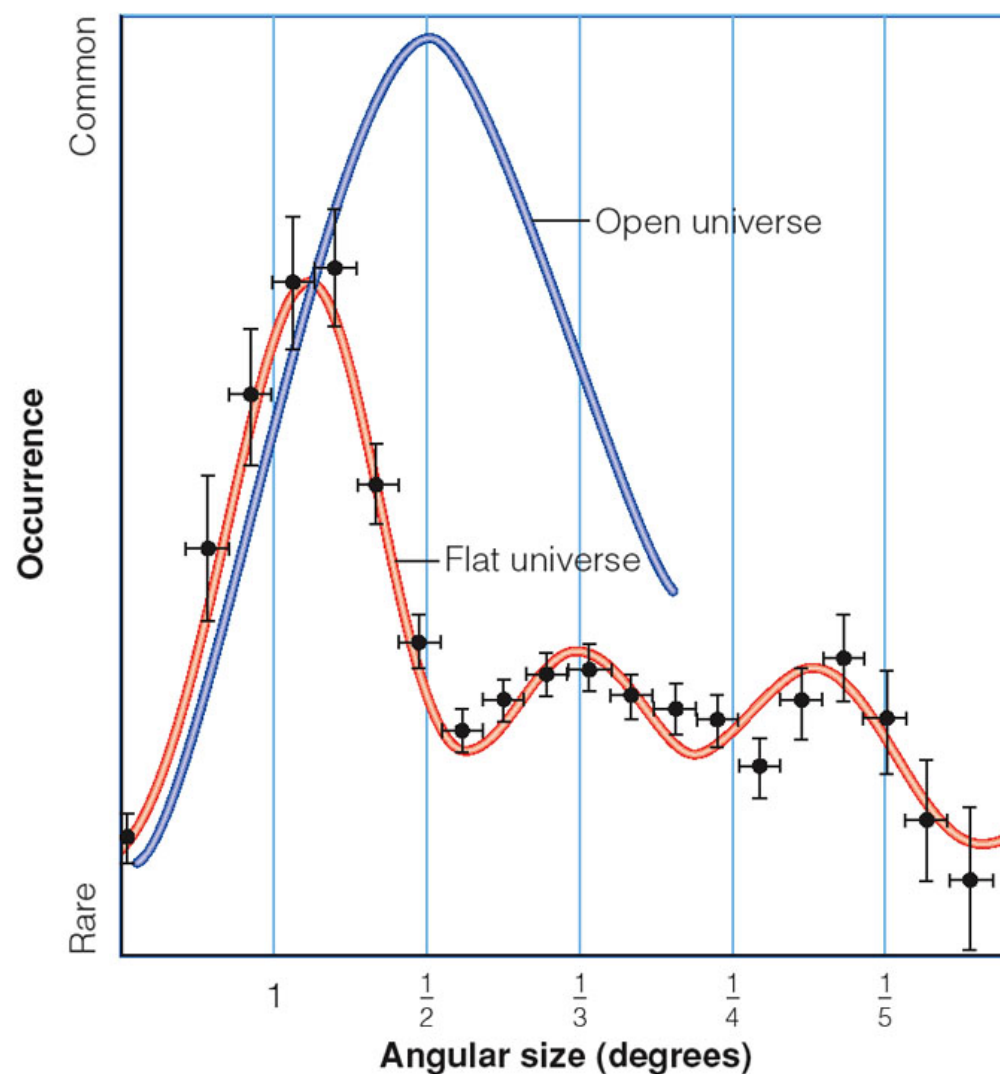


CMB and cosmology

- **1998:**
BOOMERanG mapped the temperature fluctuations of the CMB at sub-horizon scales ($<1^\circ$).
- The signal was well above the noise:

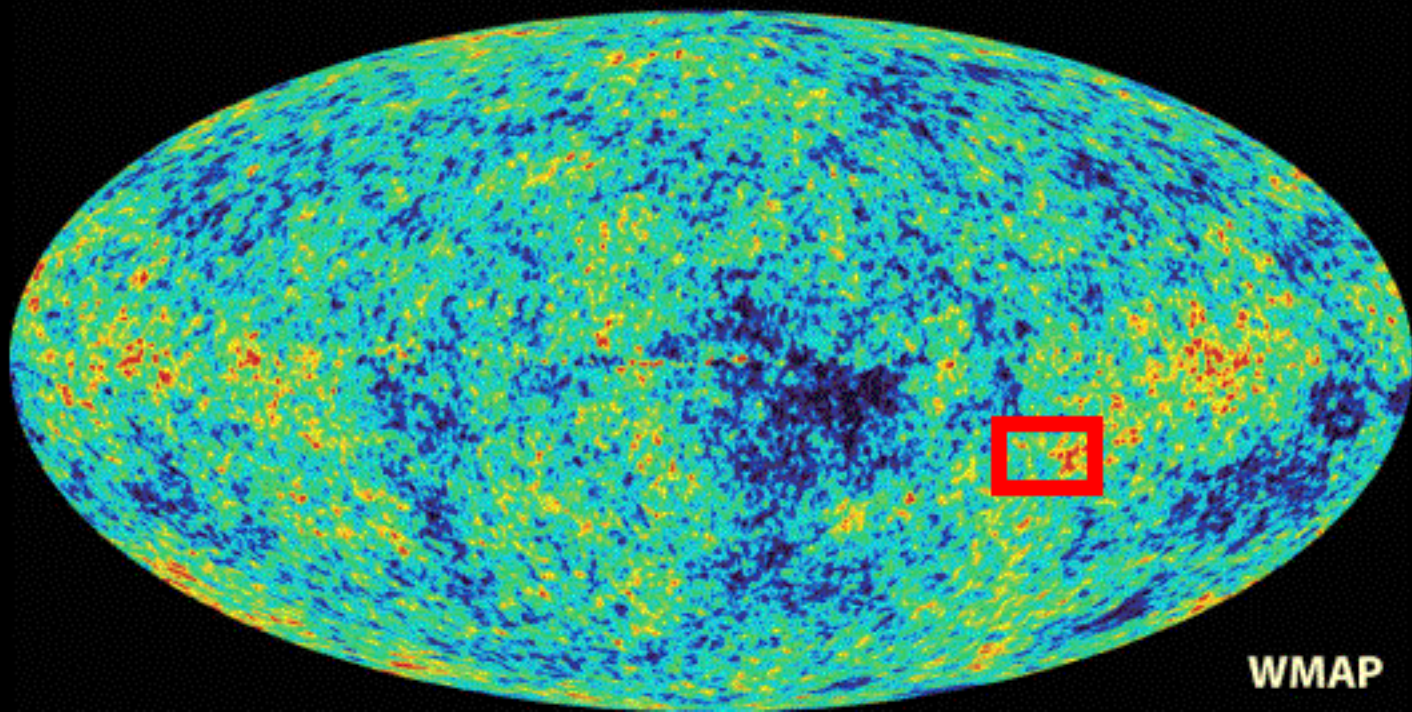
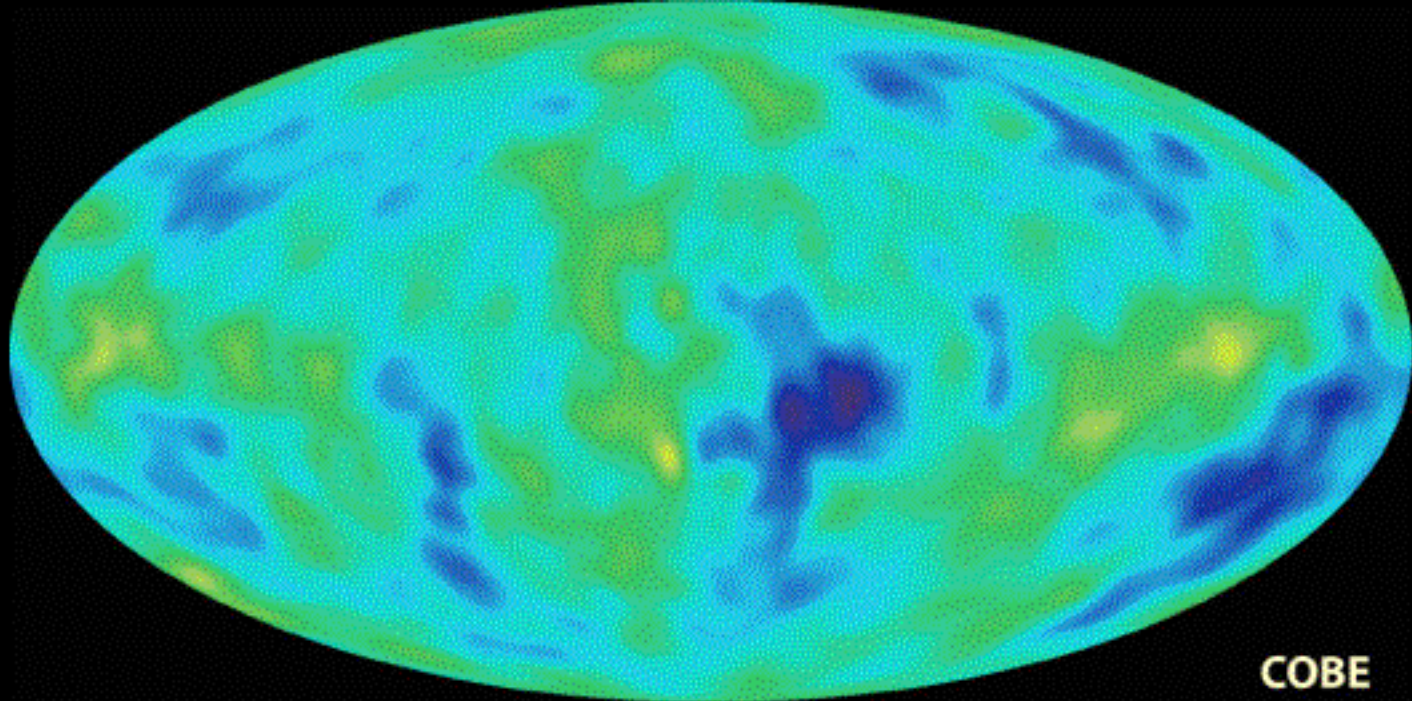


L'Universo è piatto!



© 2006 Brooks/Cole - Thomson

Se è piatto ha il 100% della densità critica!
Se è così la materia dovrebbe fornire tutta la densità



Cosmological Parameters

Compare with similar weak prior $0.5 < h < 0.9$

WMAP

(100% of the sky)

Bennett et al. 2003

- $\Omega = 1.02 \pm 0.02$
- $n_s = 0.99 \pm 0.04$ *
- $\Omega_b h^2 = 0.022 \pm 0.001$
- $\Omega_m h^2 = 0.14 \pm 0.02$
- $T = 13.7 \pm 0.2$ Gyr
- $\tau_{\text{rec}} = 0.166 \pm 0.076$

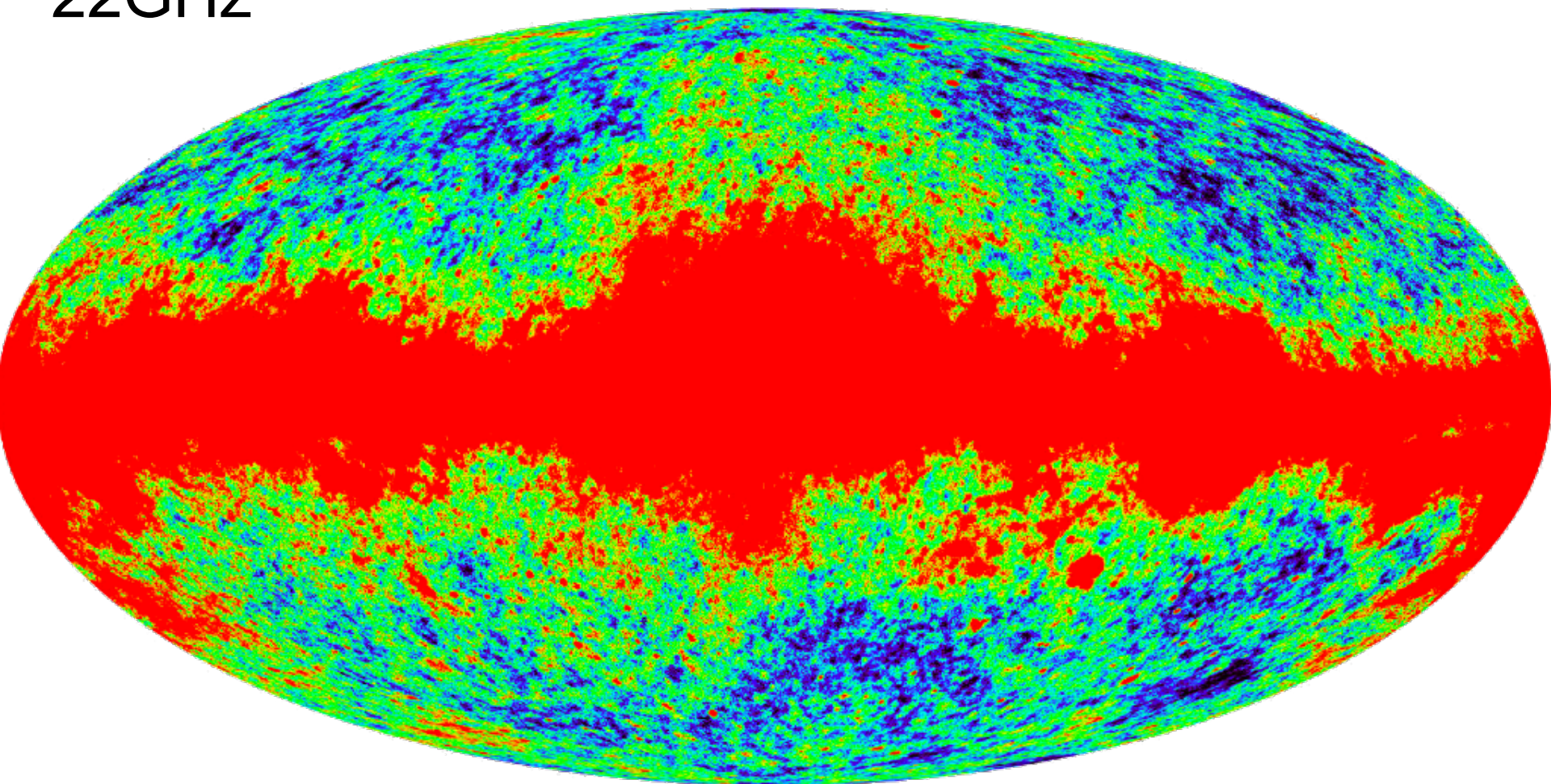
BOOMERanG

(4% of the sky)

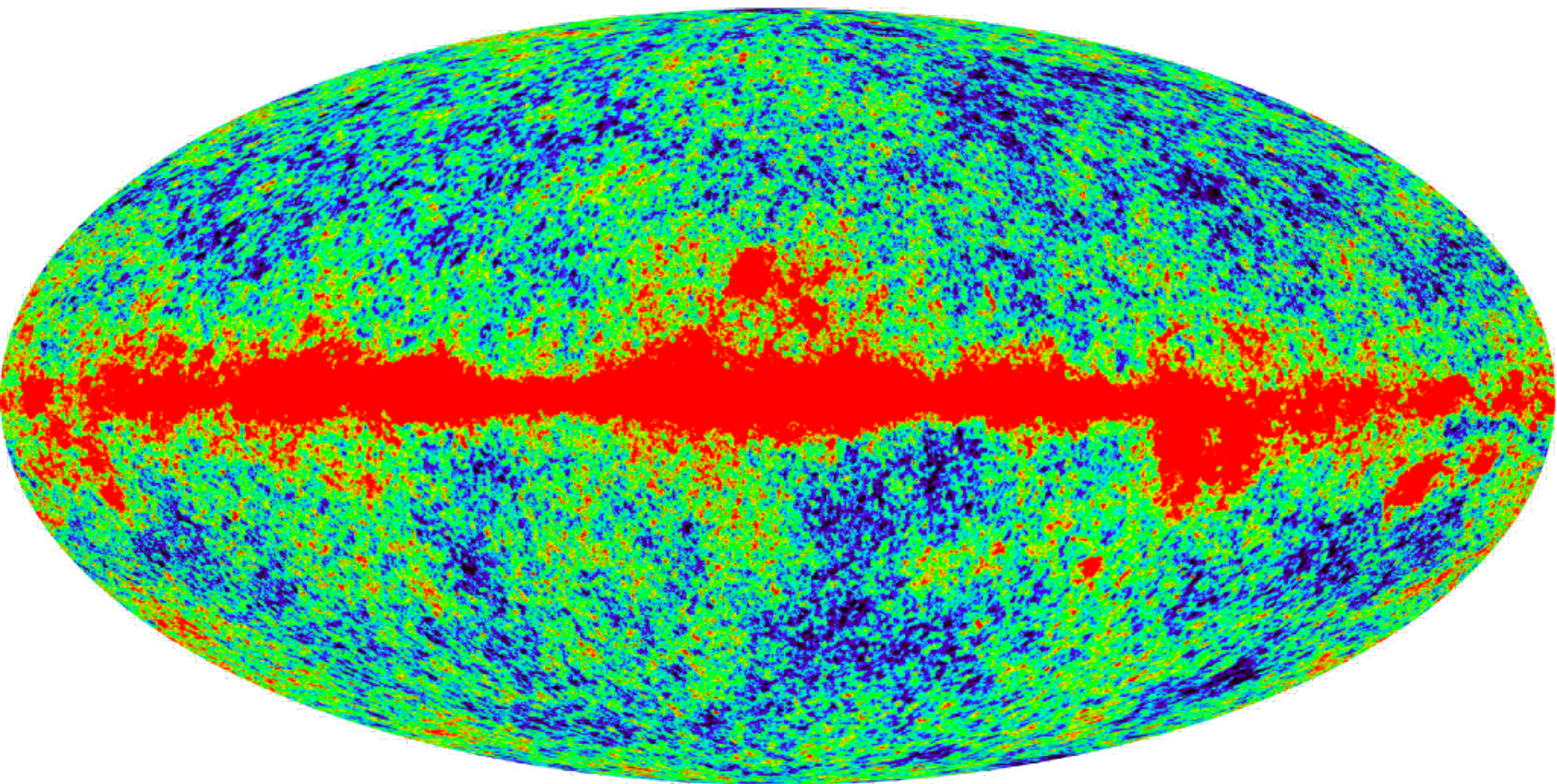
astro-ph/0212229

- $\Omega = 1.03 \pm 0.05$
- $n_s = 1.02 \pm 0.07$
- $\Omega_b h^2 = 0.023 \pm 0.003$
- $\Omega_m h^2 = 0.14 \pm 0.04$
- $T = 14.5 \pm 1.5$ Gyr

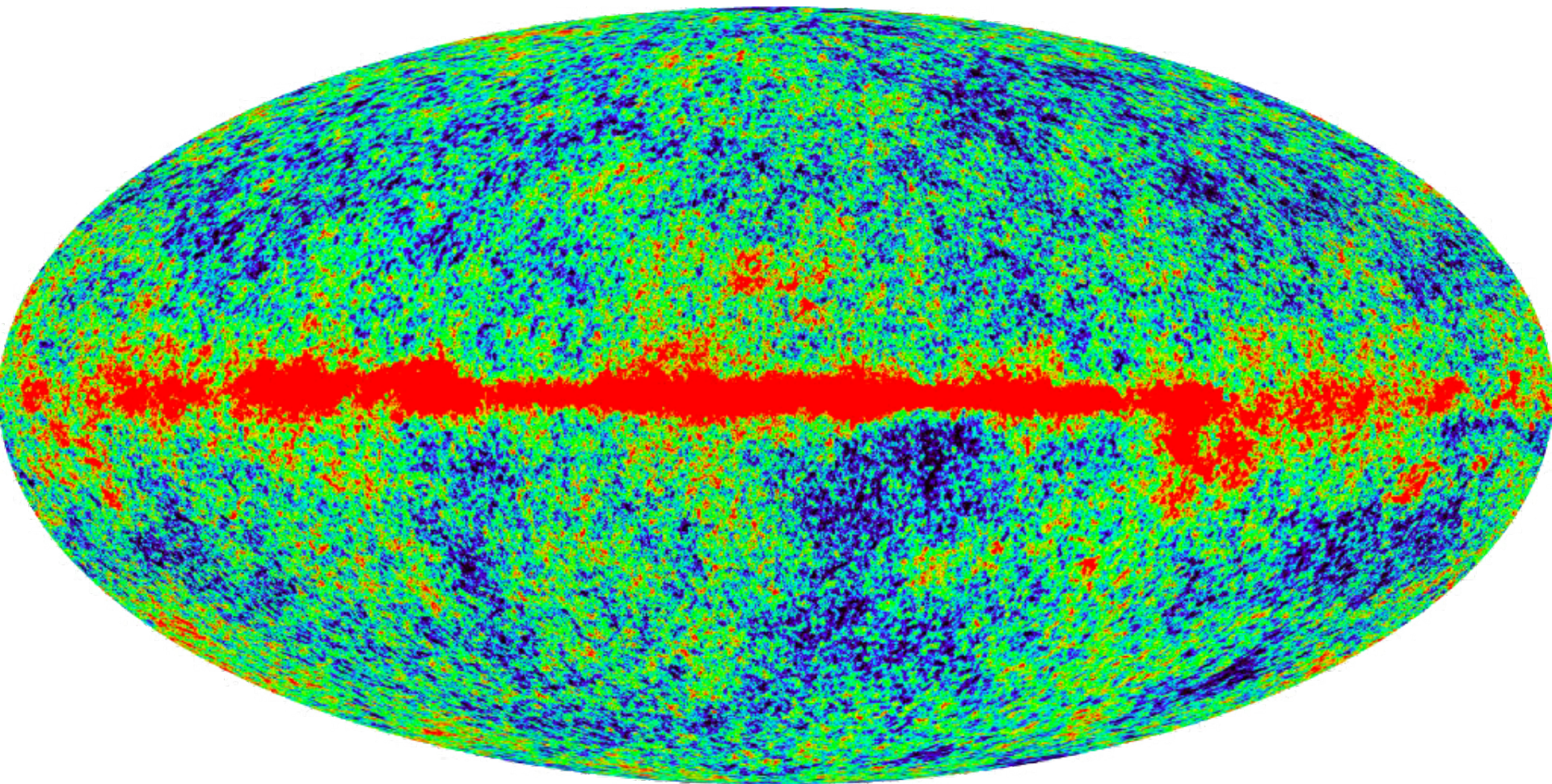
K
22GHz



Q 41GHz

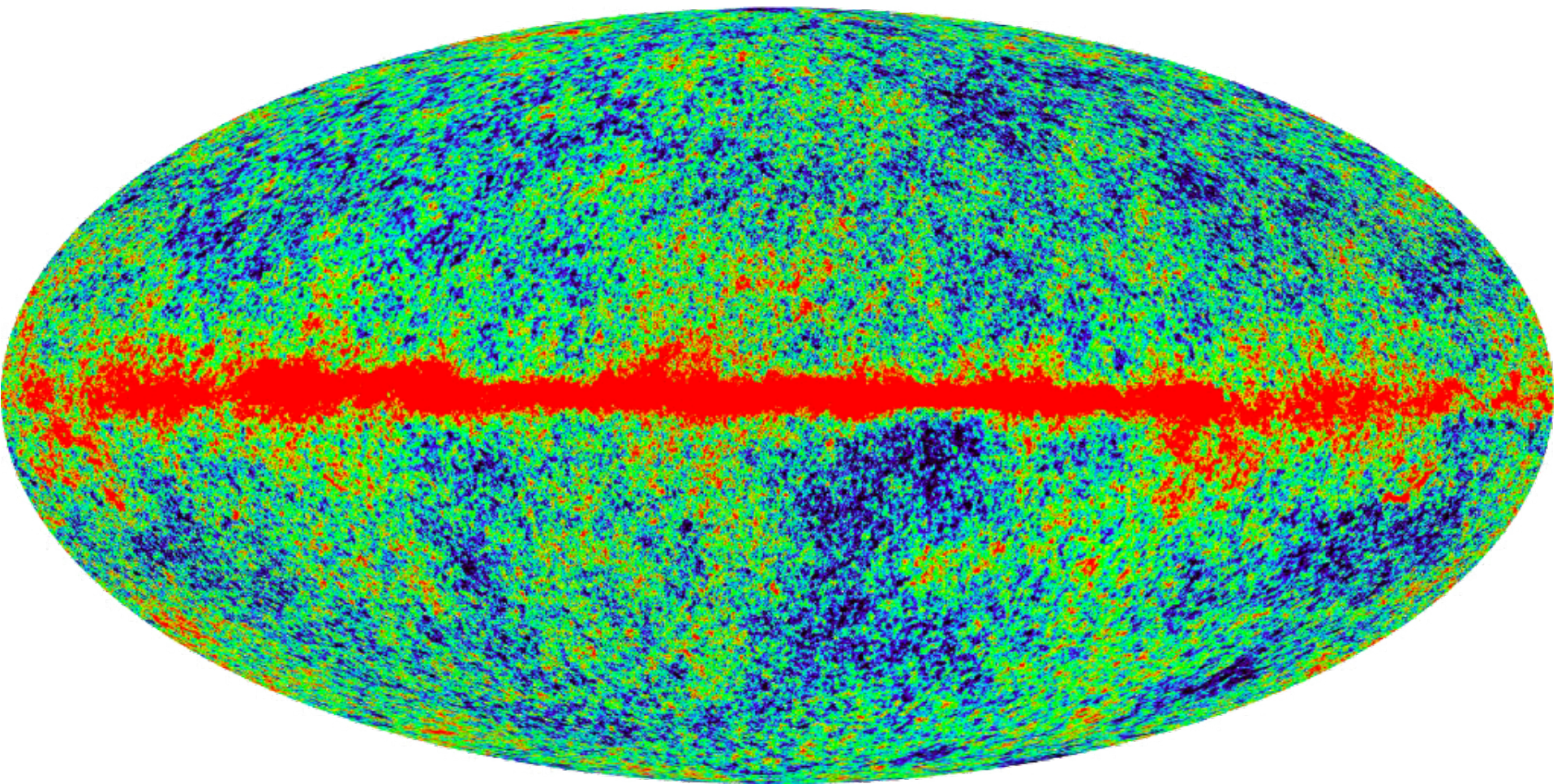


V 61 GHz

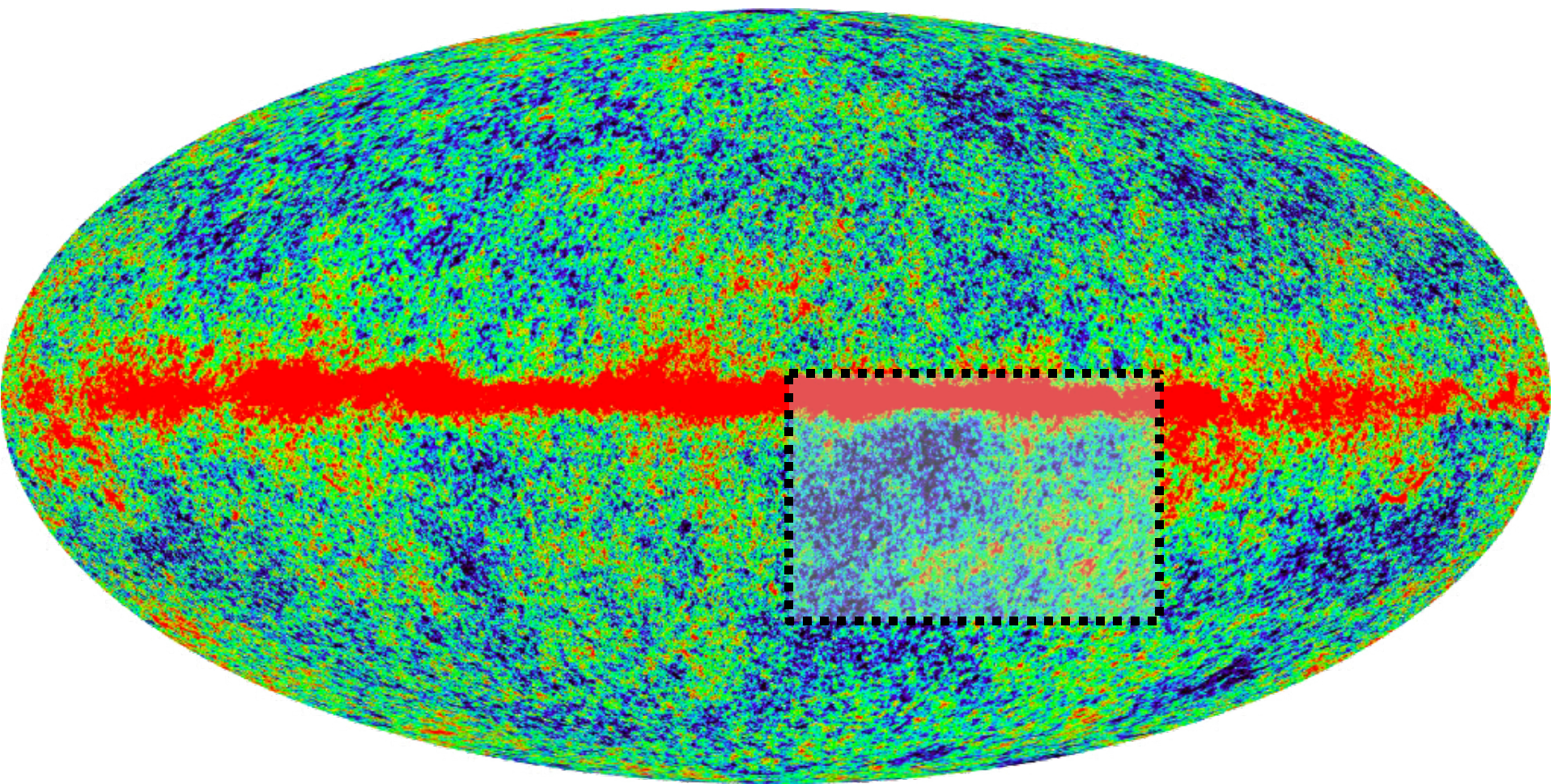


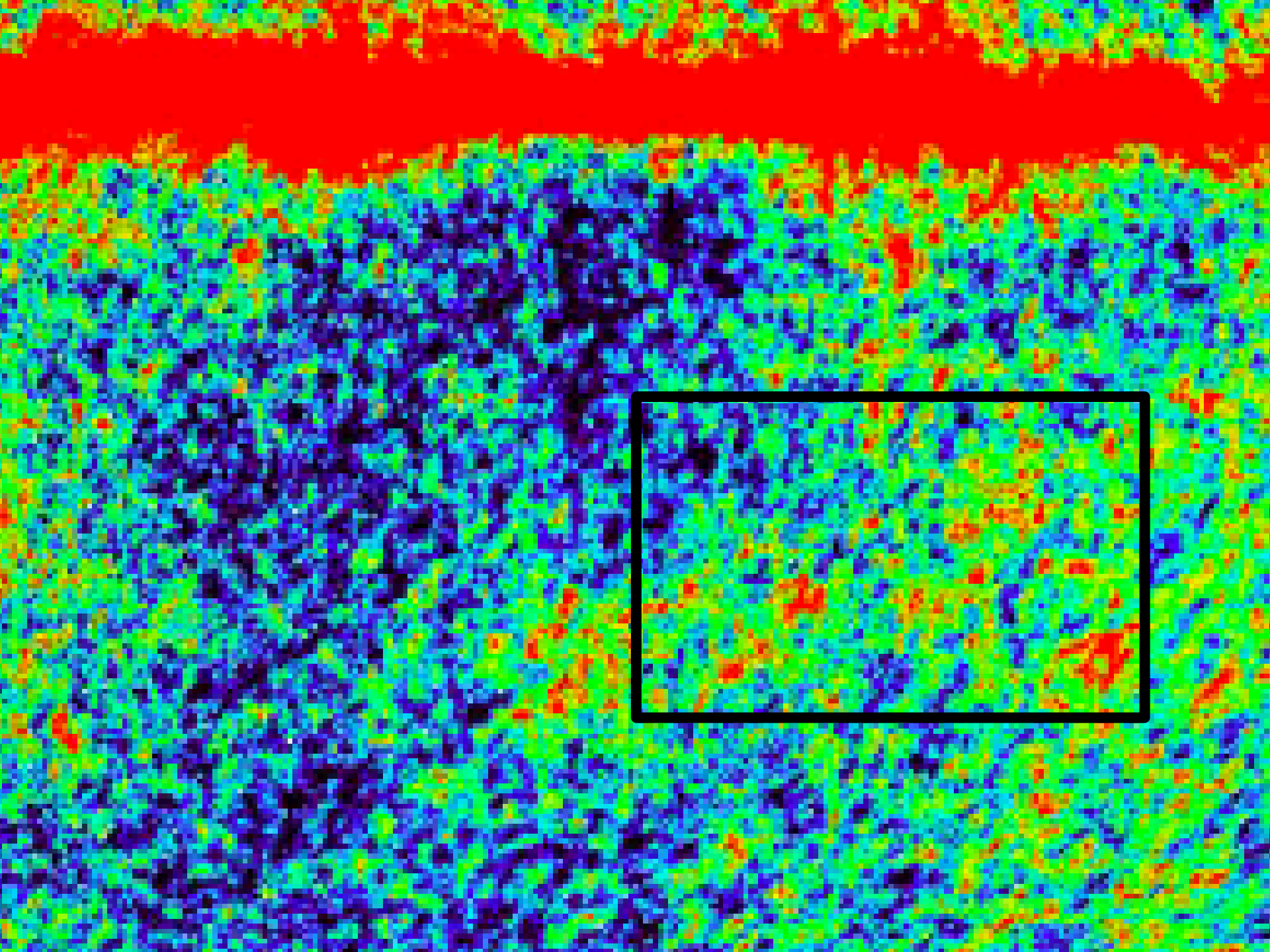
W 94 GHz

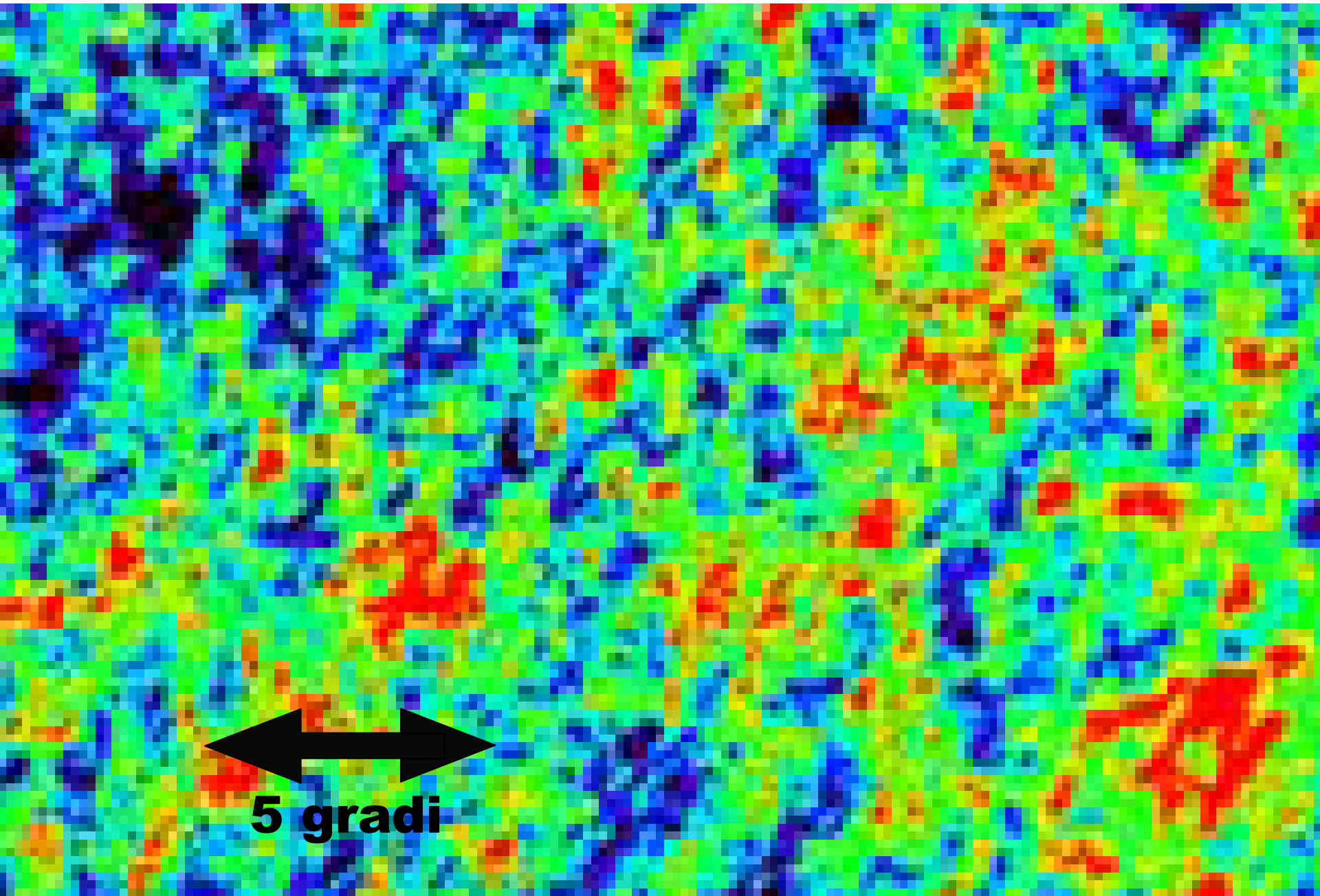
Sottratto il Dipolo



W 94GHz



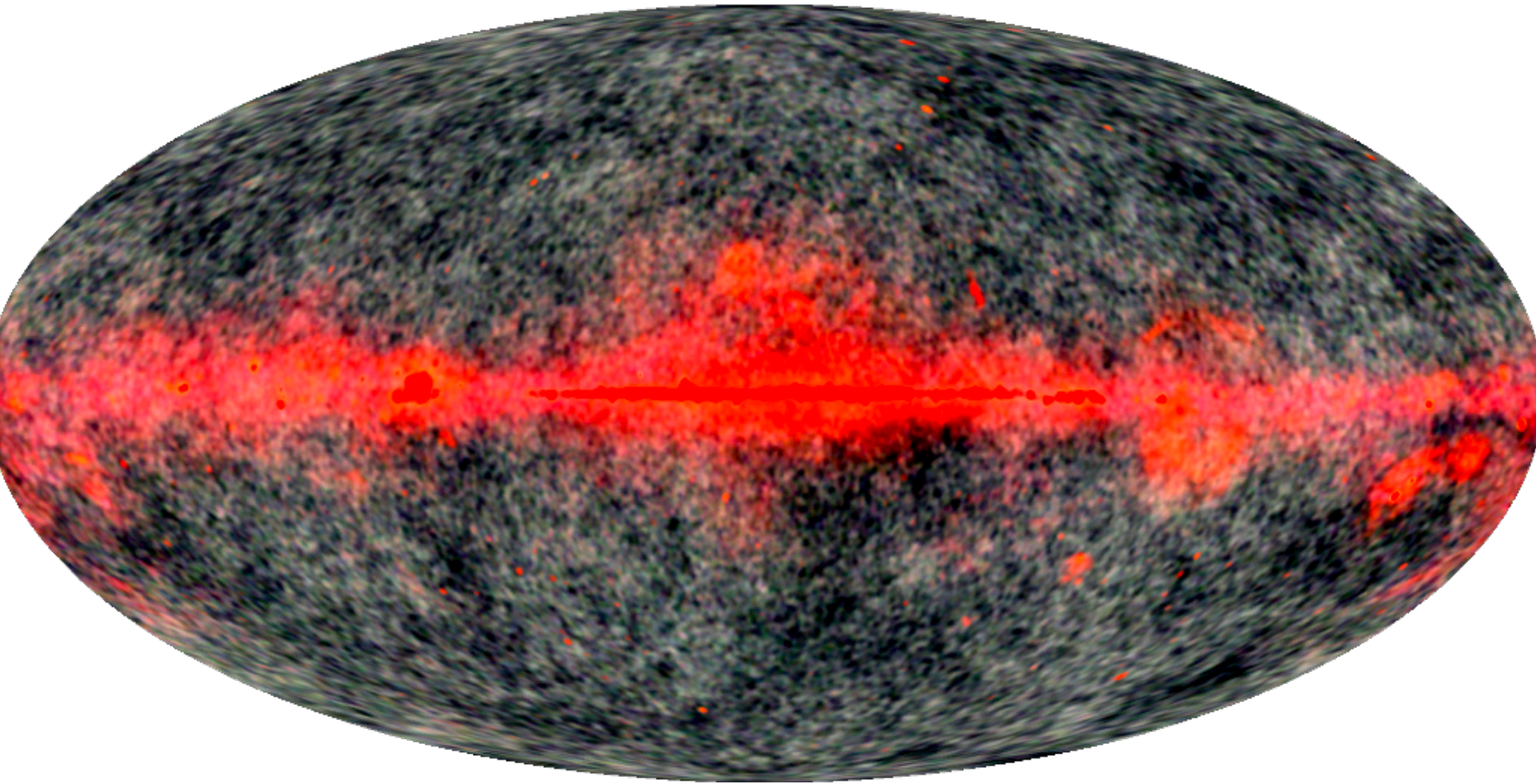




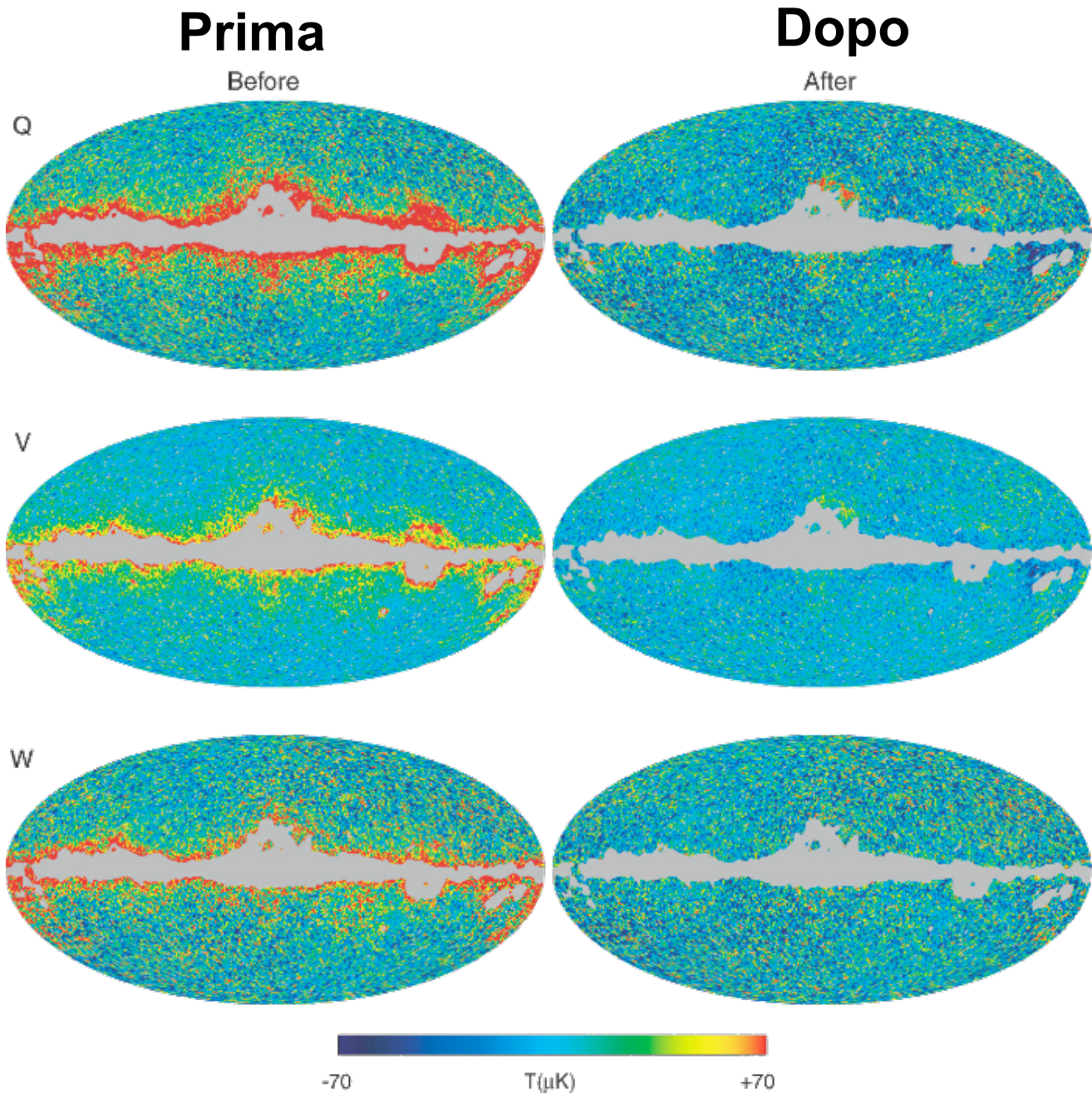
5 gradi

41, 61, 94 GHz Composizione Mappa di tutto il cielo

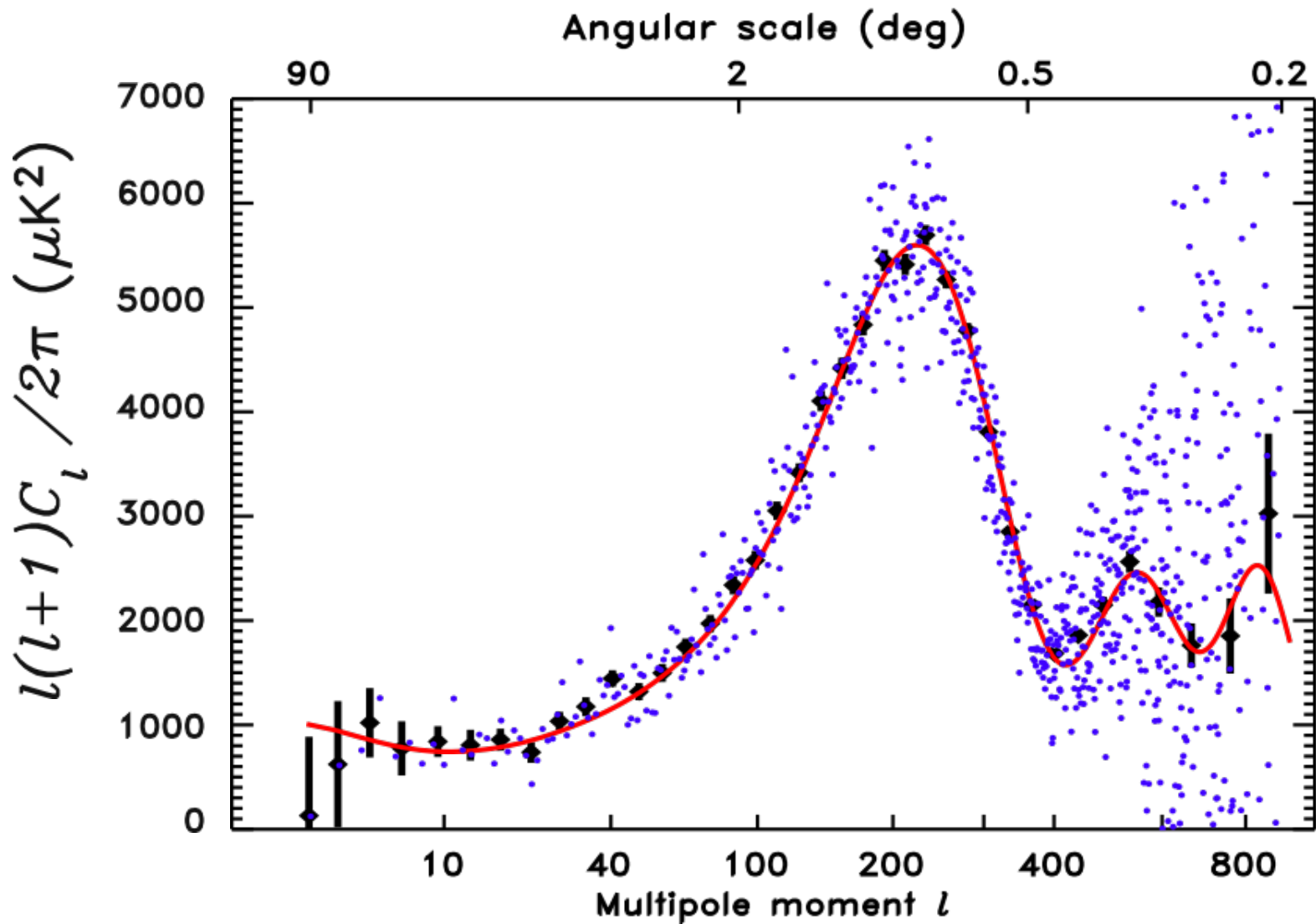
Sottratto il Dipolo



Sottrazione del
Foreground
analisi CMB

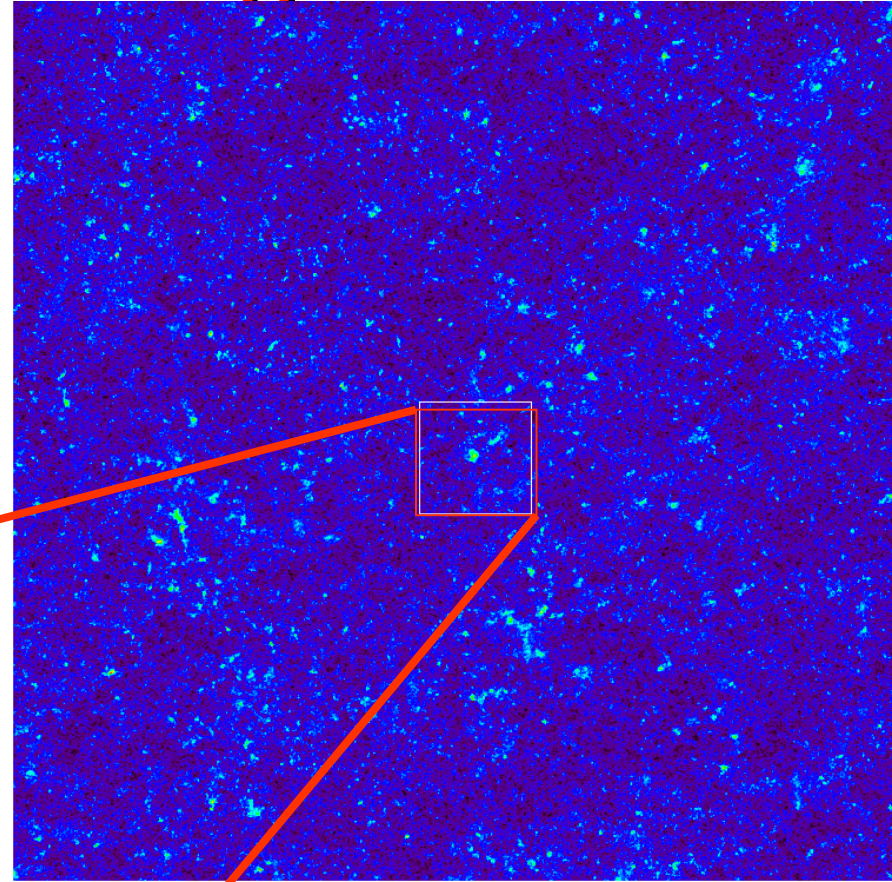
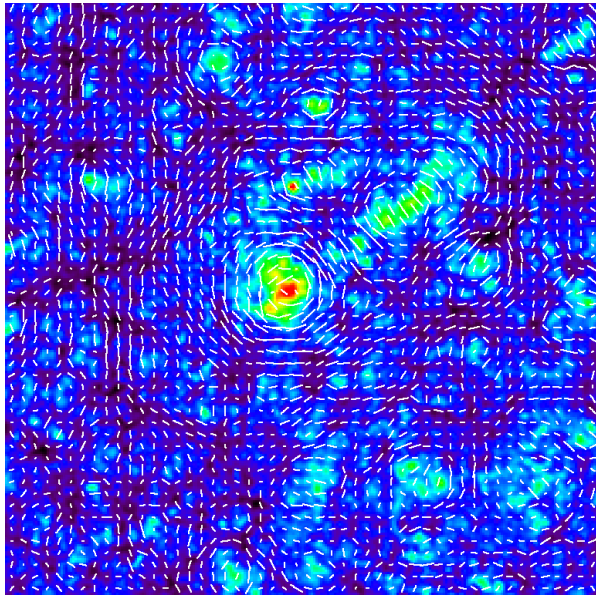


WMAP Angular Power Spectrum



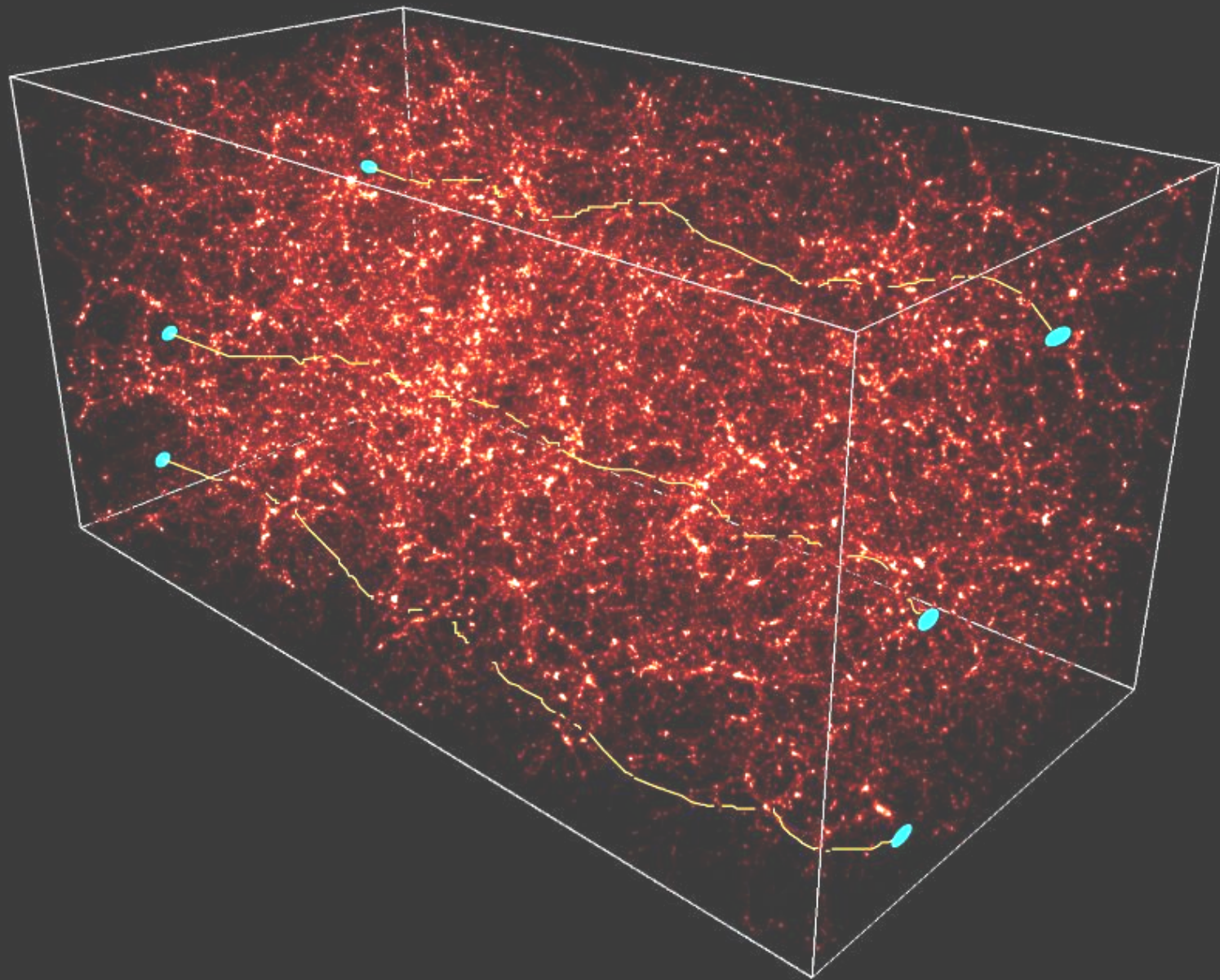
Lente gravitazionale Cosmologica debole

1 gado

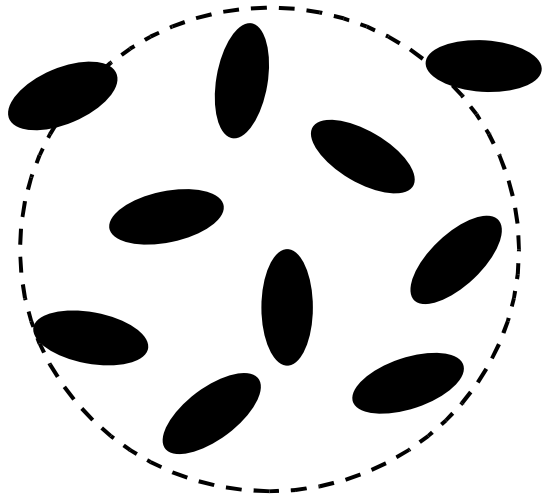


**immagine survey
a grande campo**

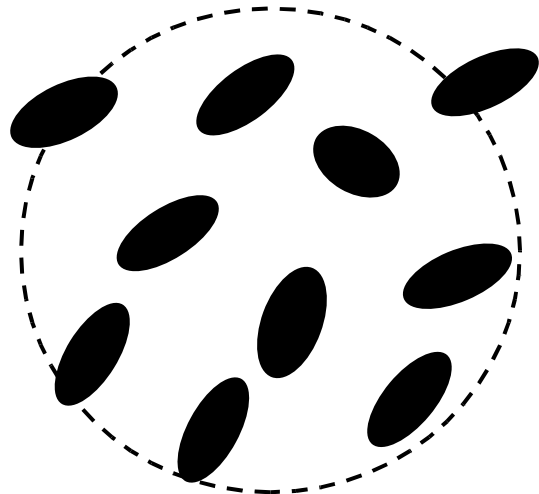
DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES



N Galassie



NO LENTE (allineamento casuale)



LENTE

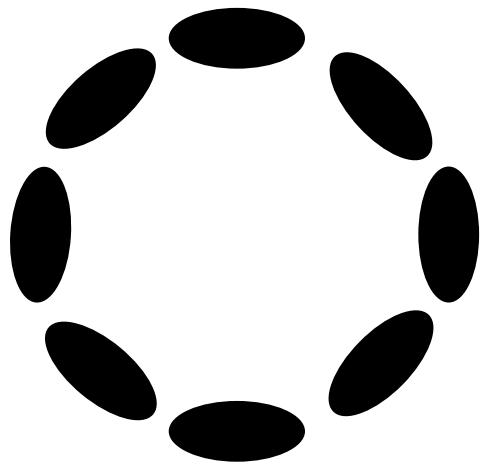
Stime di taglio

Forme medie

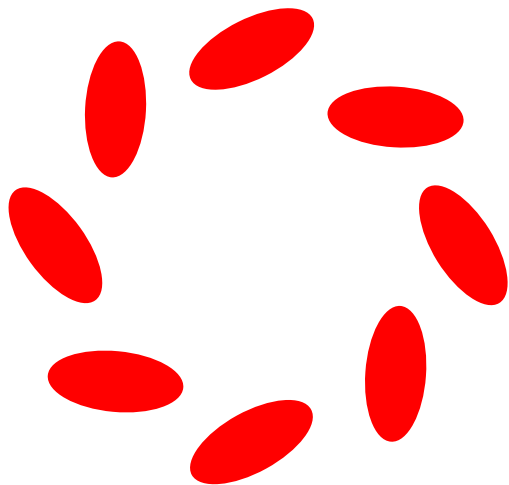
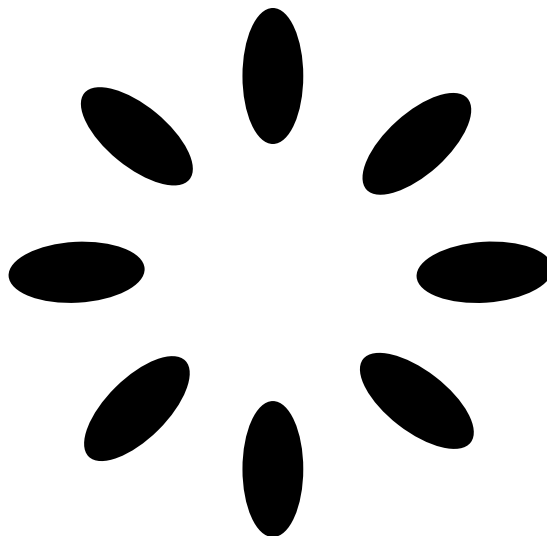
● $\langle e \rangle = 0$

● $\langle e \rangle \approx \gamma$

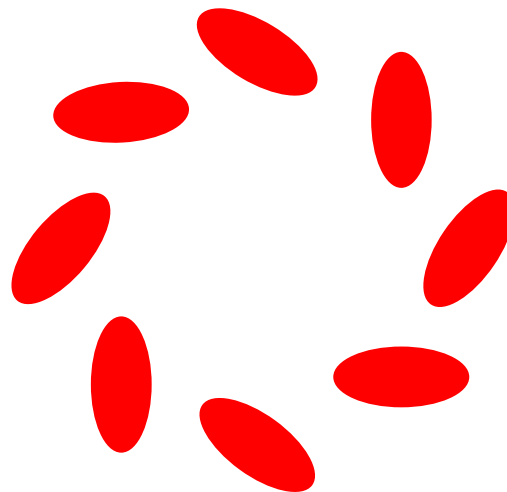
Ricerca di pattern nella mappa delle distorsioni



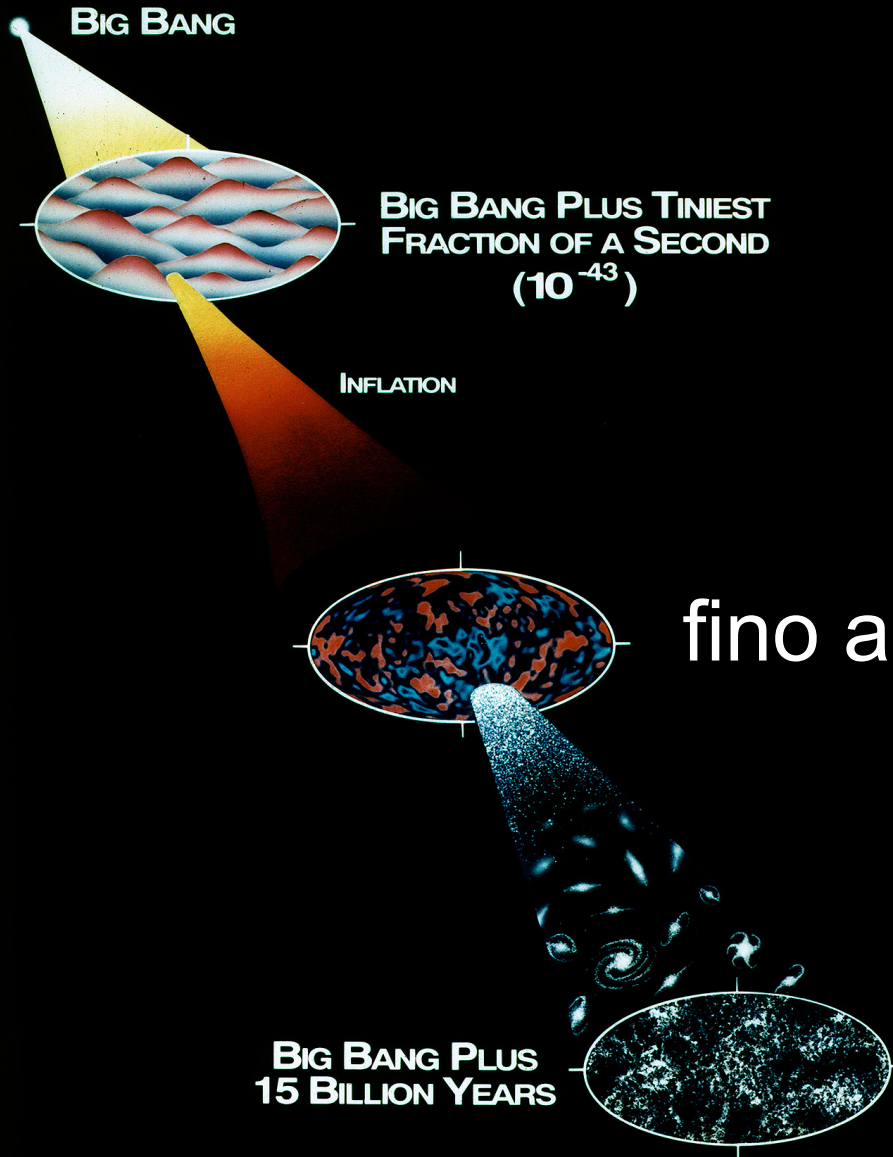
E mode



B mode



La storia dell'Universo



Universo caldo

Elettroni liberi

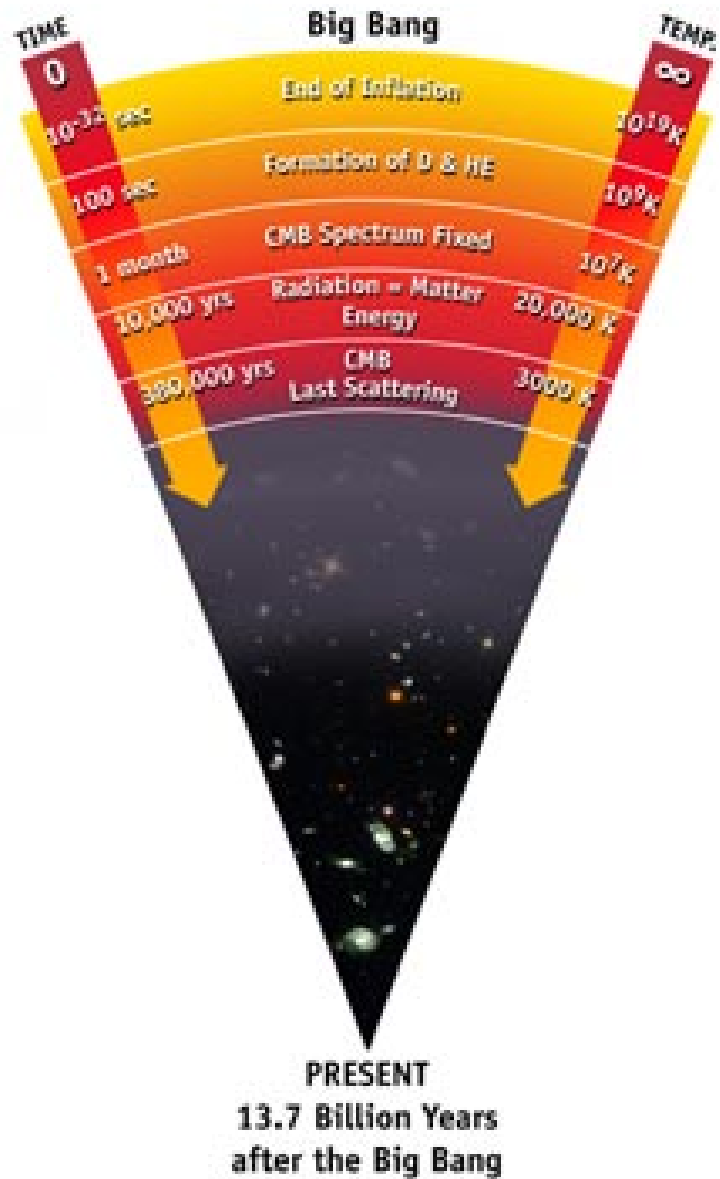
La luce scattera gli elettroni

fino a $\sim 380,000$ anni dopo il BE

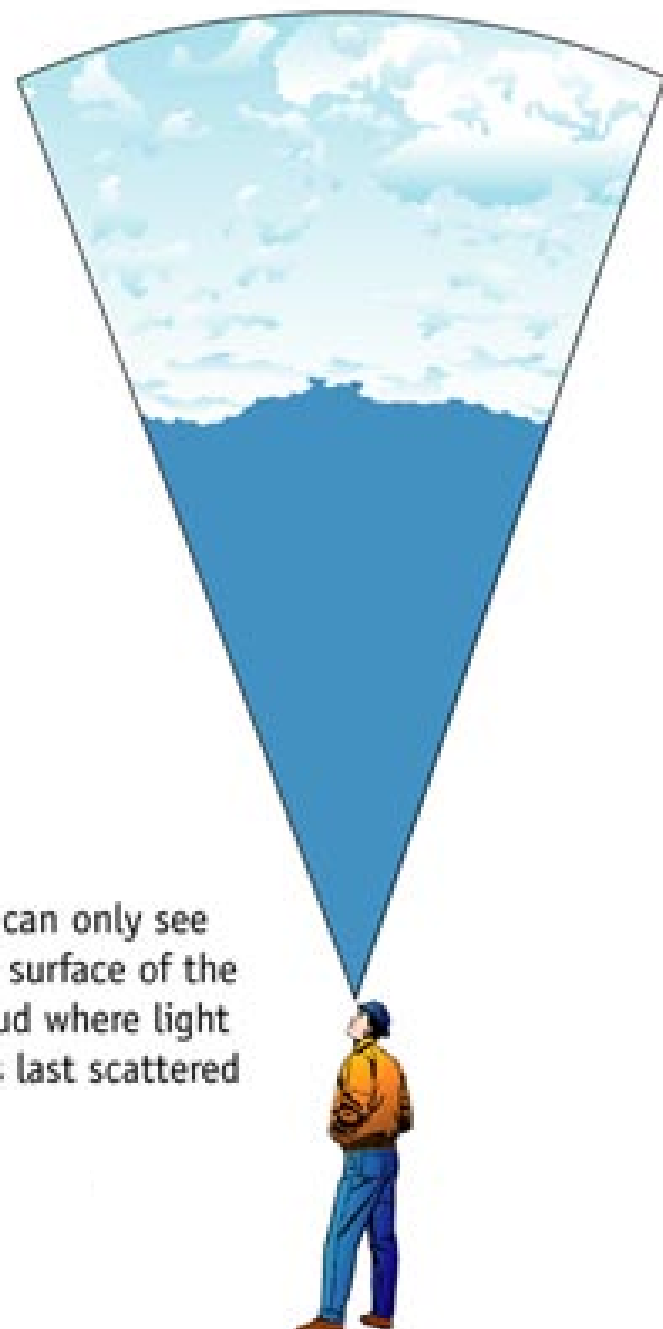
Universo più freddo

e^- e p^+ formano H

La luce viaggia libera



We can only see the surface of the cloud where light was last scattered



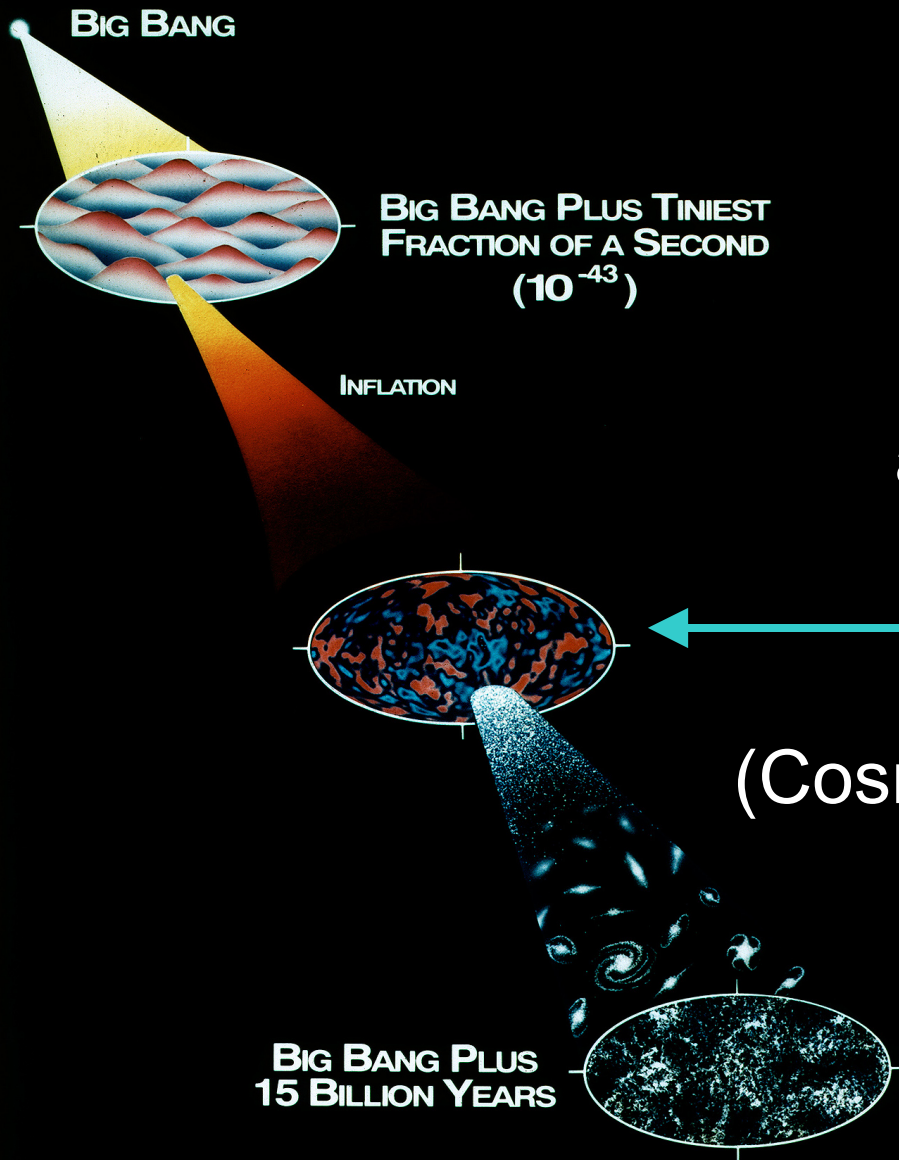


Immagine dell'Universo
a 380,000 anni dopo il BB

La CMB

(Cosmic Microwave Background)

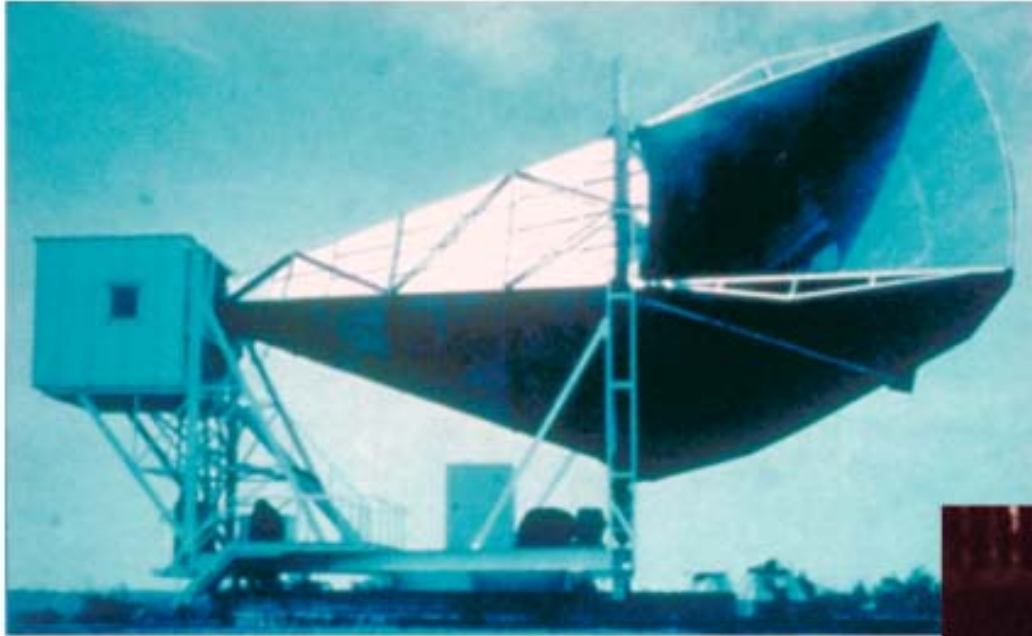
Perchè Microonde?

- La T dell'Universo era $\sim 3000^\circ \text{K}$ dopo 380,000 anni dal BB
- Luce visibile al massimo ($\sim 1\mu\text{m}$)

L'Universo si espande

- Causa del cambiamento di lunghezza d'onda della luce
- La Luce Visibile diventa microonde ($\sim 1\text{cm}$)

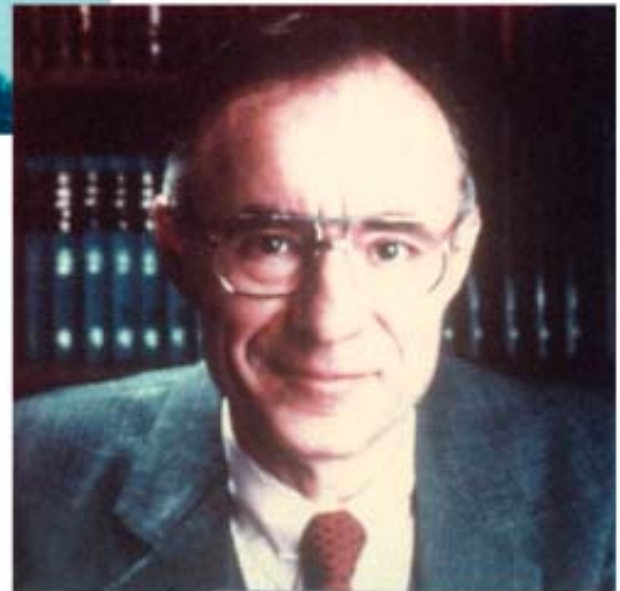
DISCOVERY OF COSMIC BACKGROUND



Microwave Receiver



Robert Wilson



Arno Penzias

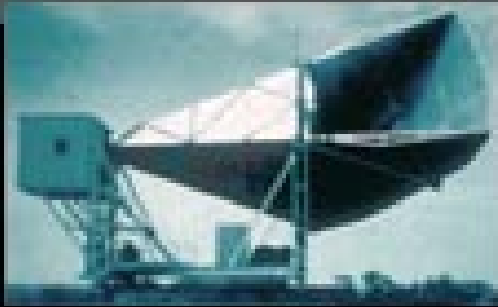
- 400 fotoni per cm cubico !



Storia delle osservazioni della CMB

1965

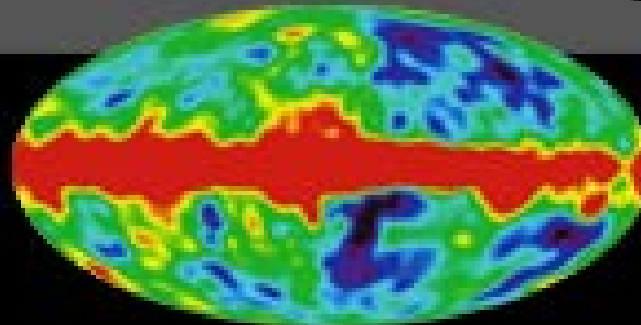
Penzias and
Wilson



Scoperta

1992

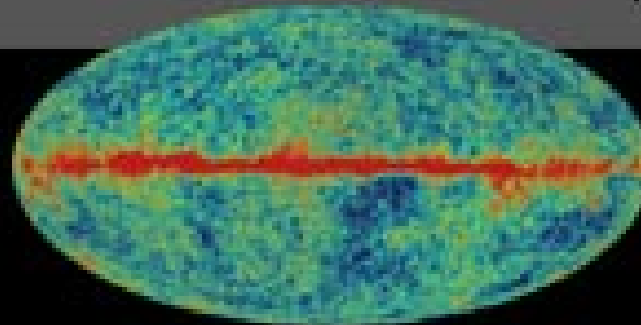
COBE



COBE

2003

WMAP



WMAP

1965

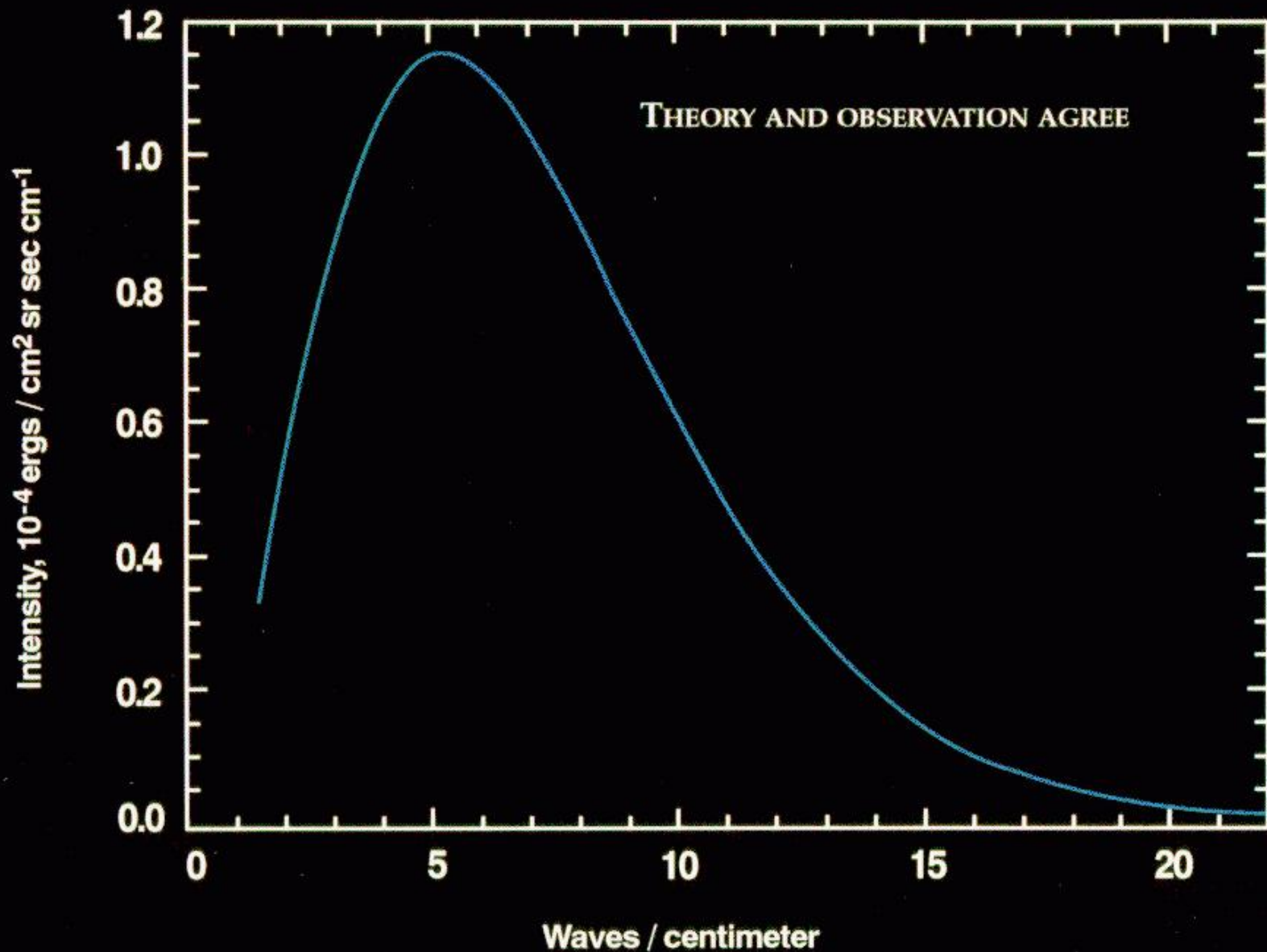
1992

2003

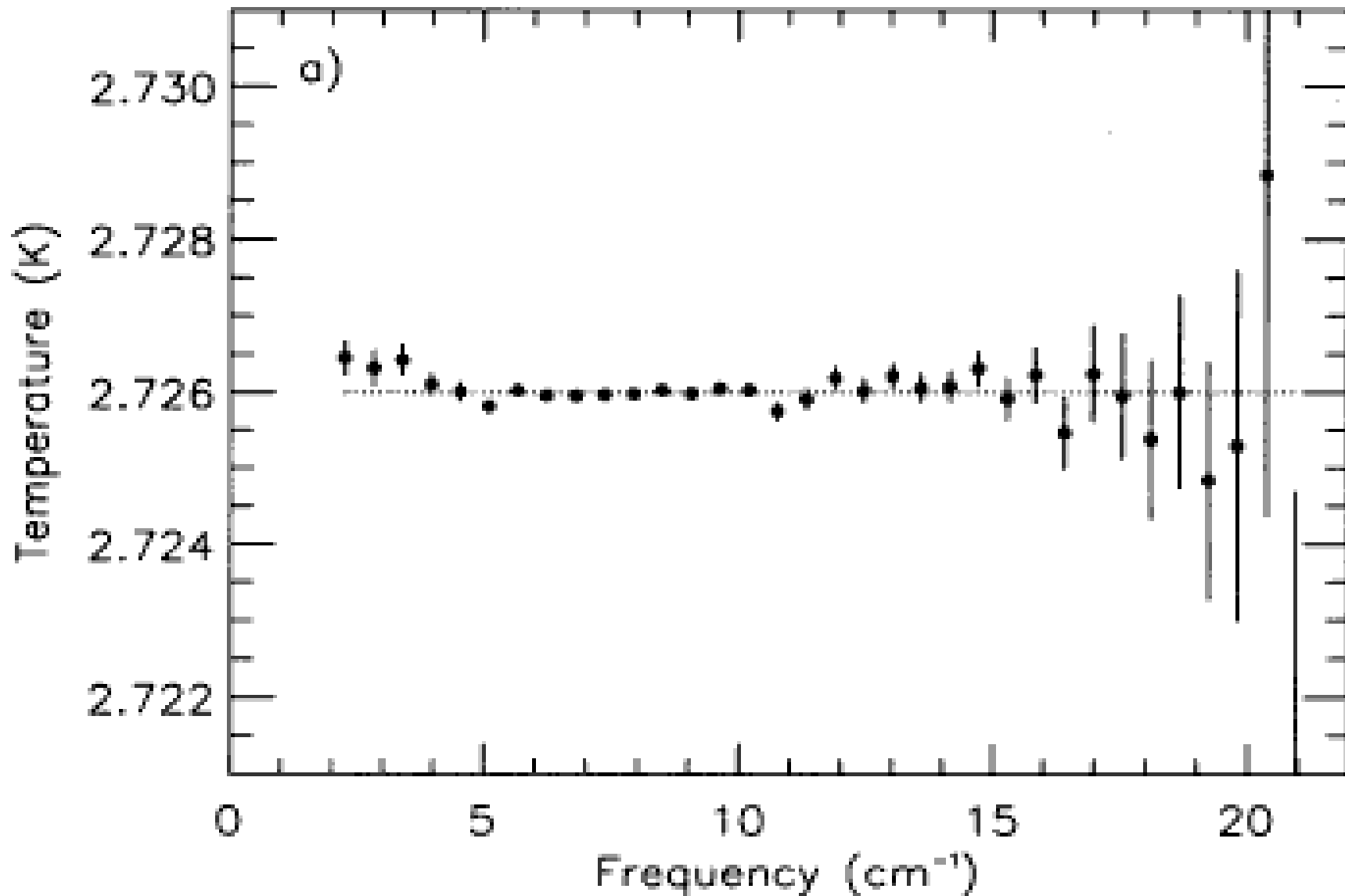
Lo spettro di frequenza

- Universo in equilibrio -> corpo nero
- Si osserva lo spettro di un perfetto corpo nero a 2.73K
- Si può connettere il numero di fotoni presenti oggi, protoni, 13.6 eV e ricavare $T_{\text{ricombinazione}}$
 - Da T_{CMB} oggi si ricava $z_{\text{ricombinazione}}$

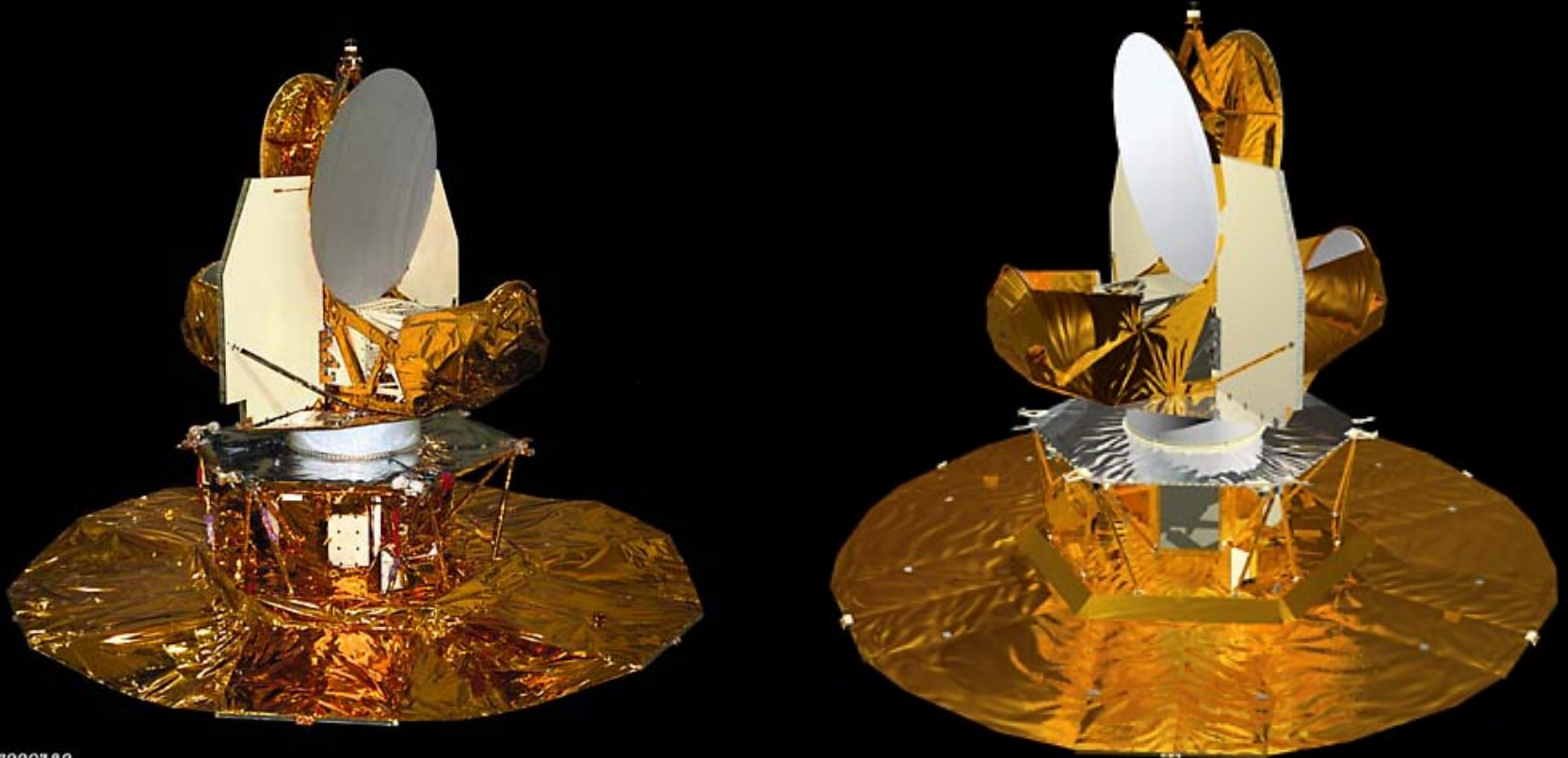
COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE



COBE: residui



The WMAP Satellite



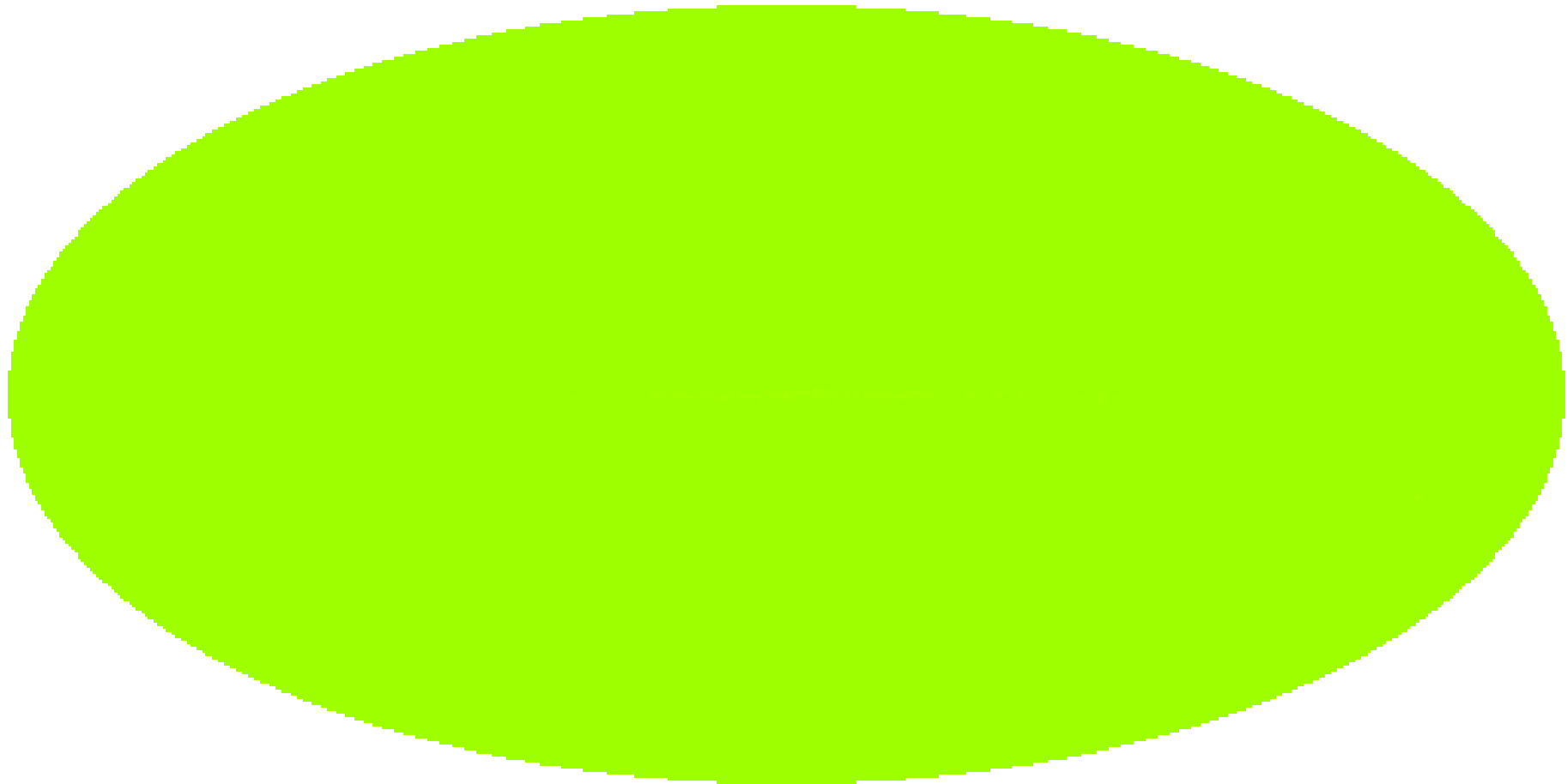
MAP990389

WMAP=Wilkinson Microwave Anisotropy Probe

Lancio giugno 2001



WMAP: cosa ha visto

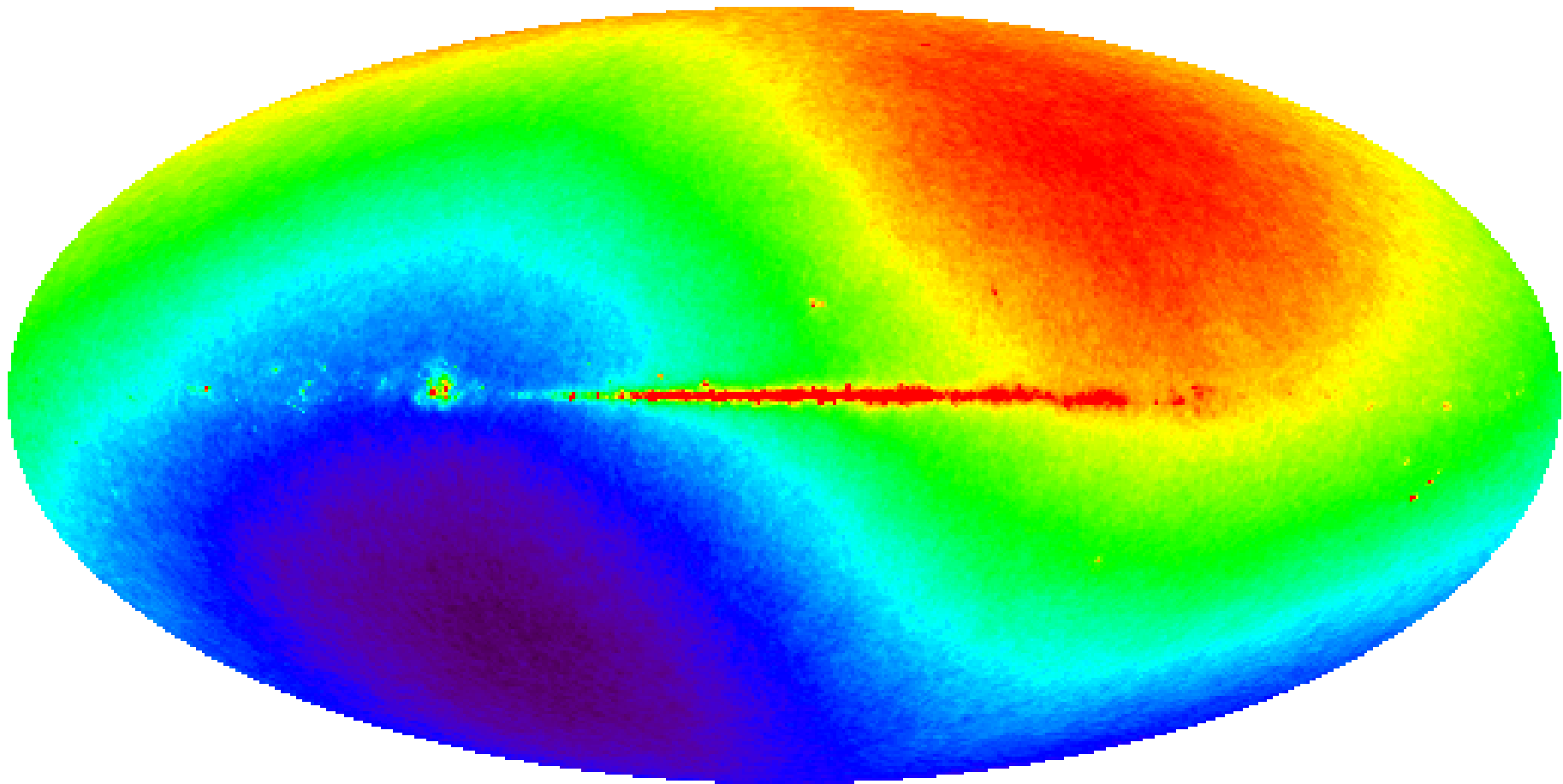


L'isotropia della CMB

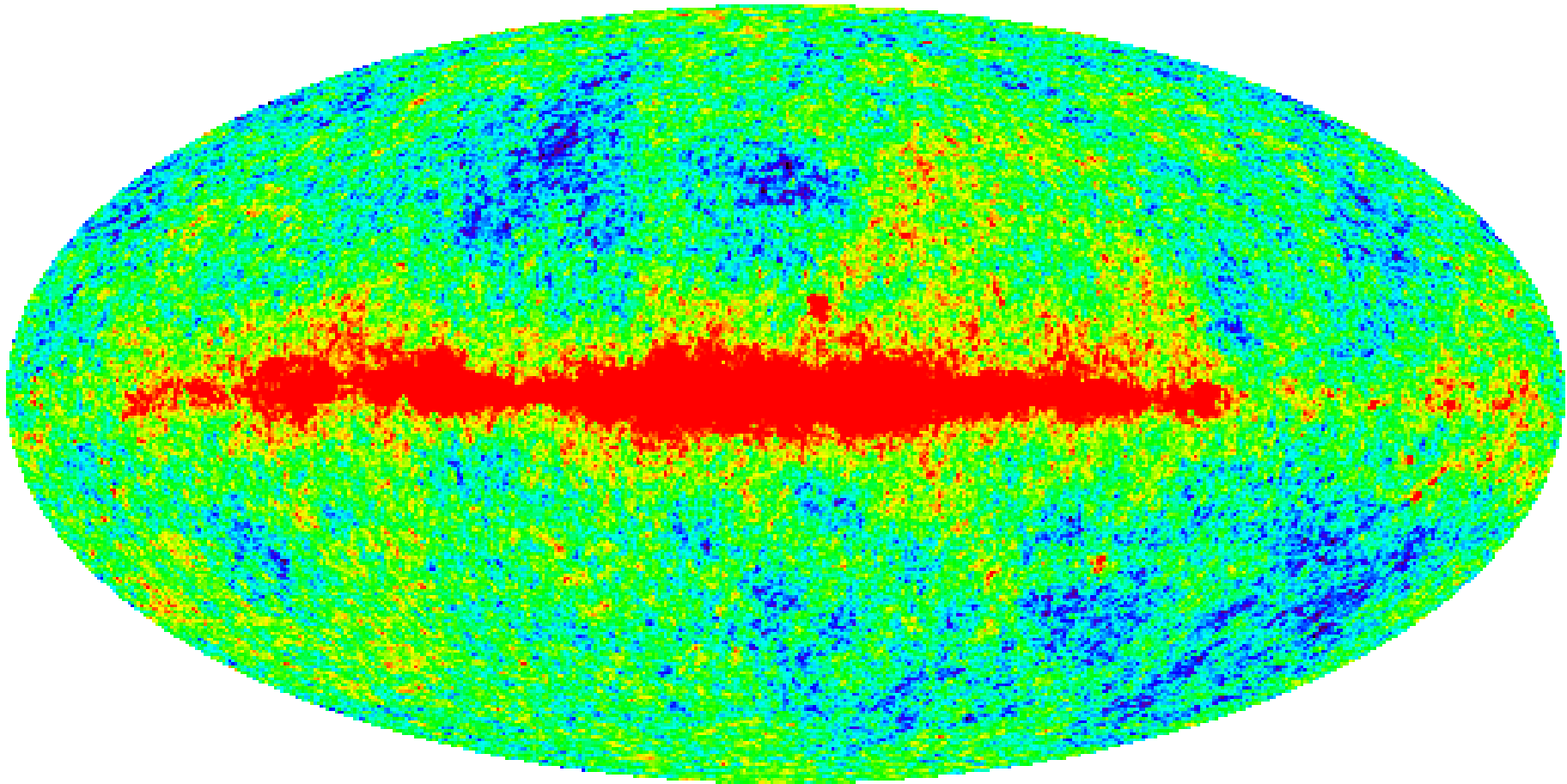
- CMB = istantanea dell'Universo a $z \sim 1000$
 - a $z \sim 1000$ l'Universo era omogeneo
- Comporta il 'Problema dell'orizzonte'
 - Dimensione dell'orizzonte $\sim c \times$ il tempo trascorso dal Big-Bang
 - orizzonte a $z \sim 1000$ è $\sim 1^\circ$ in cielo
 - Cielo a 0° e 180° non ancora 'connessi causalmente'
- 'Inflazione' introdotta per risolvere il problema
 - La rapida espansione estende la scala

La scala dei colori...

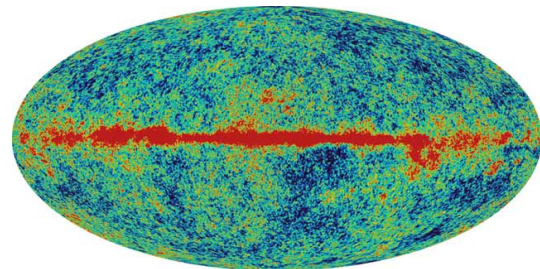
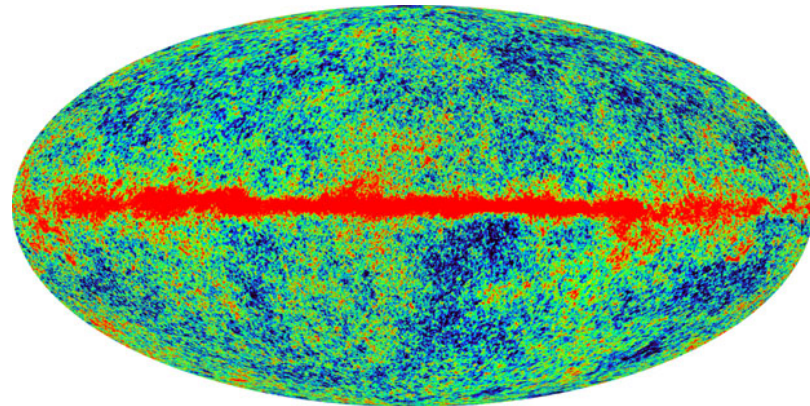
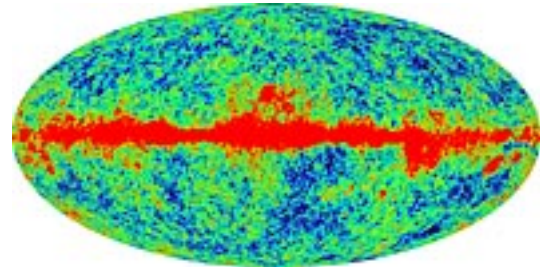
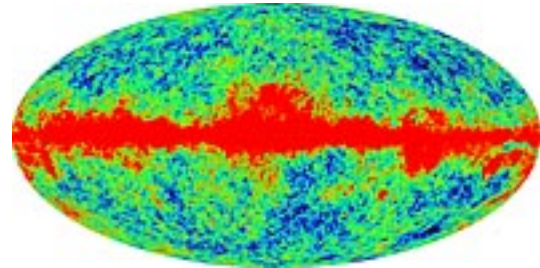
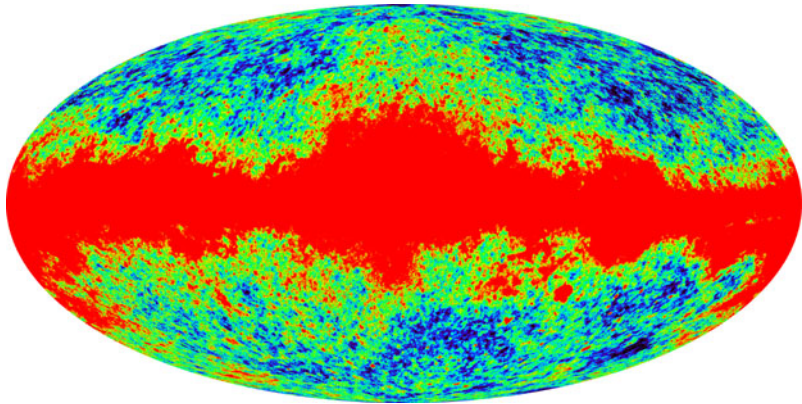
1 in 1000



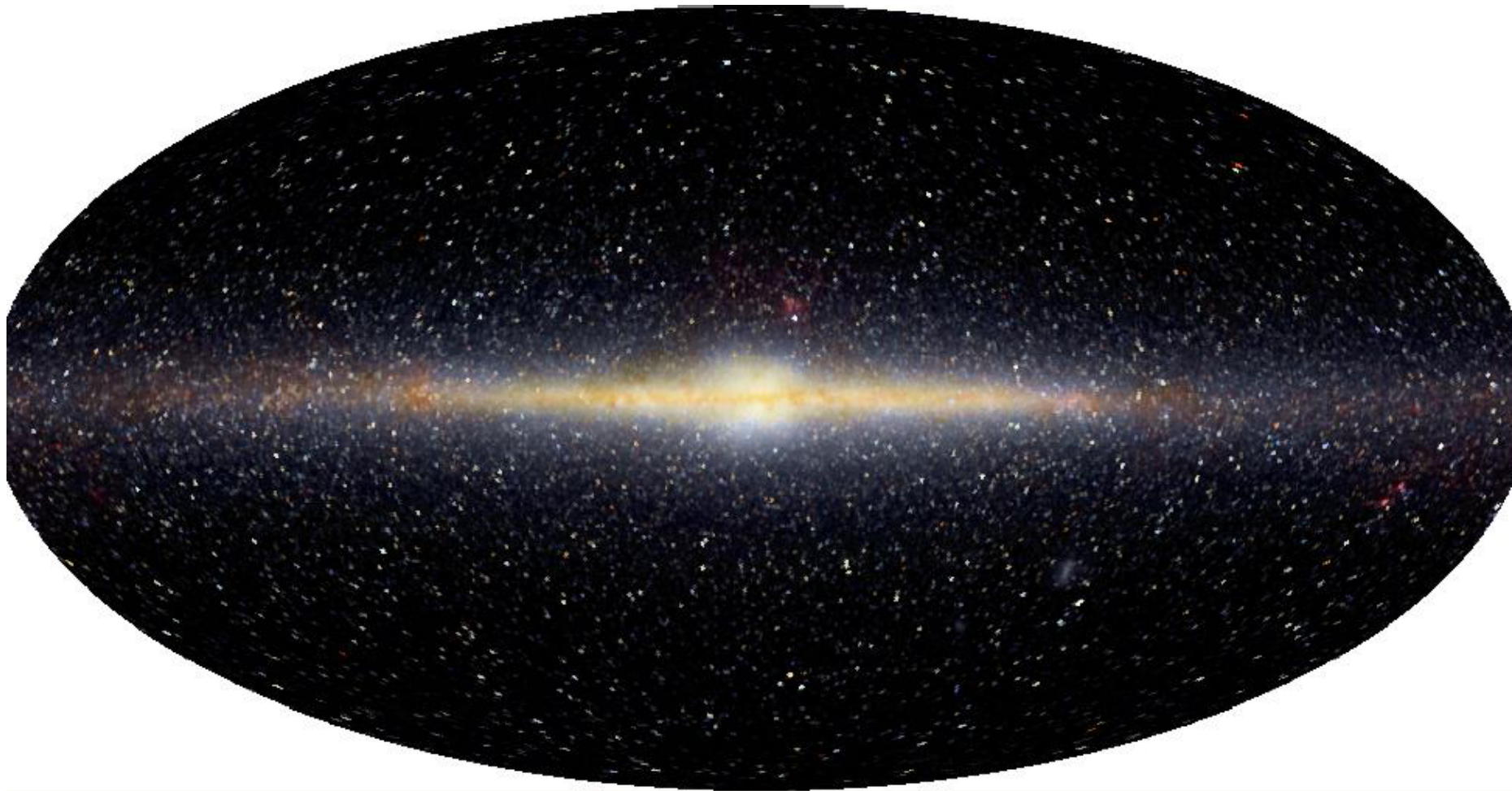
Rimuovere l'effetto del nostro moto attraverso la Galassia



Osservazioni in 5 bande di frequenze da 23 GHz a 90 GHz



Dobbiamo guardare attraverso la Galassia



La polvere nella Galassia è il segno più evidente

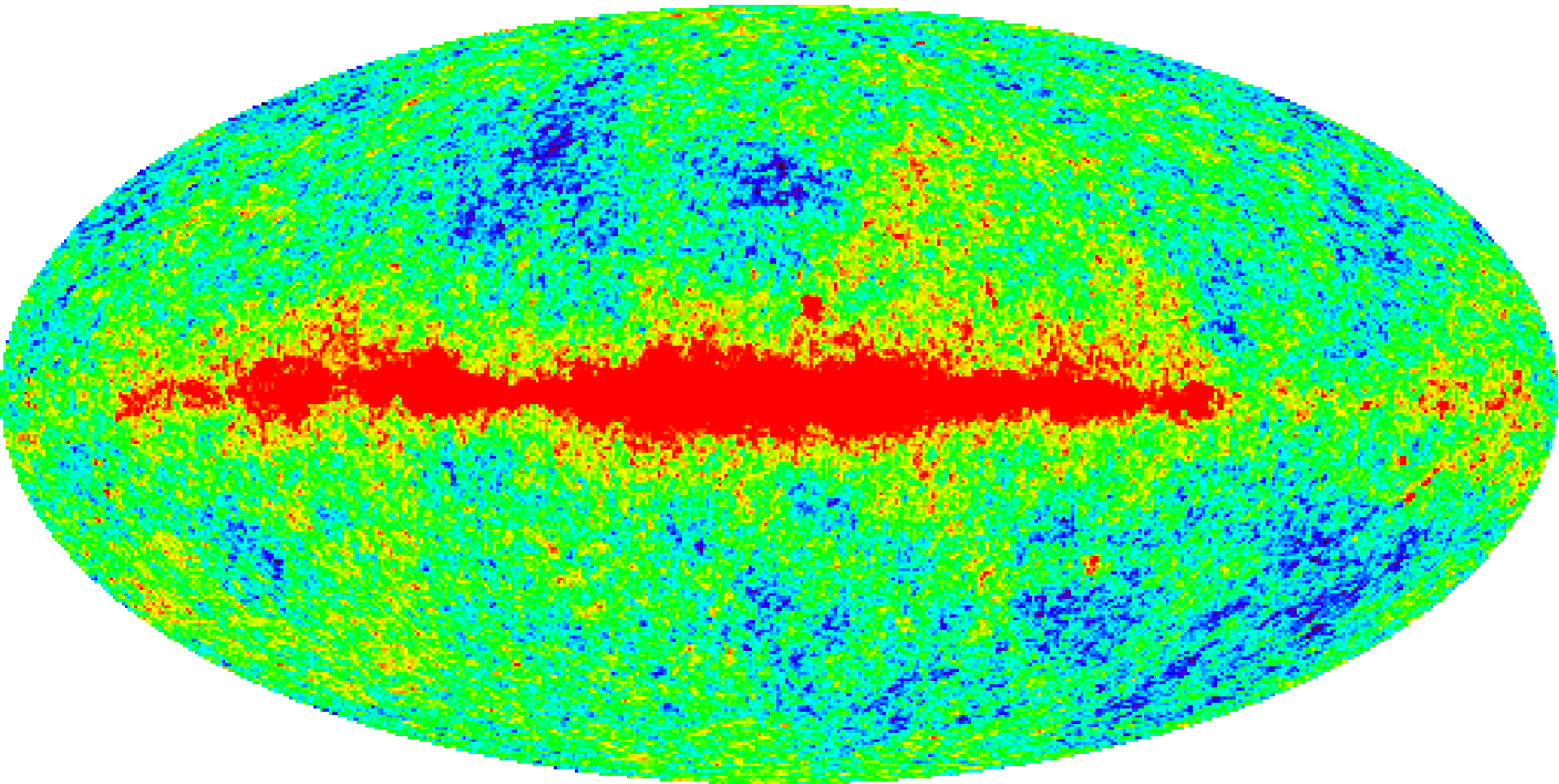
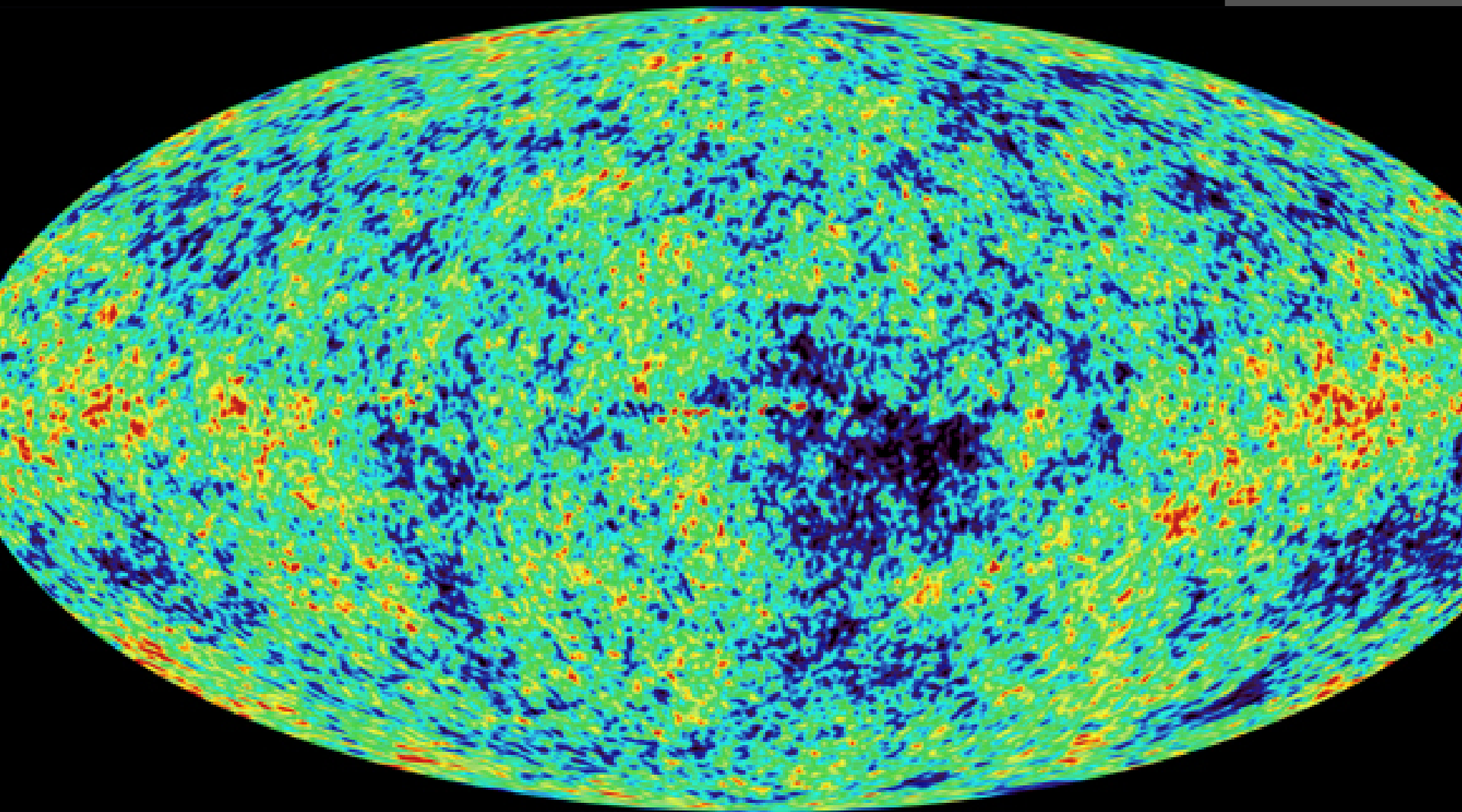
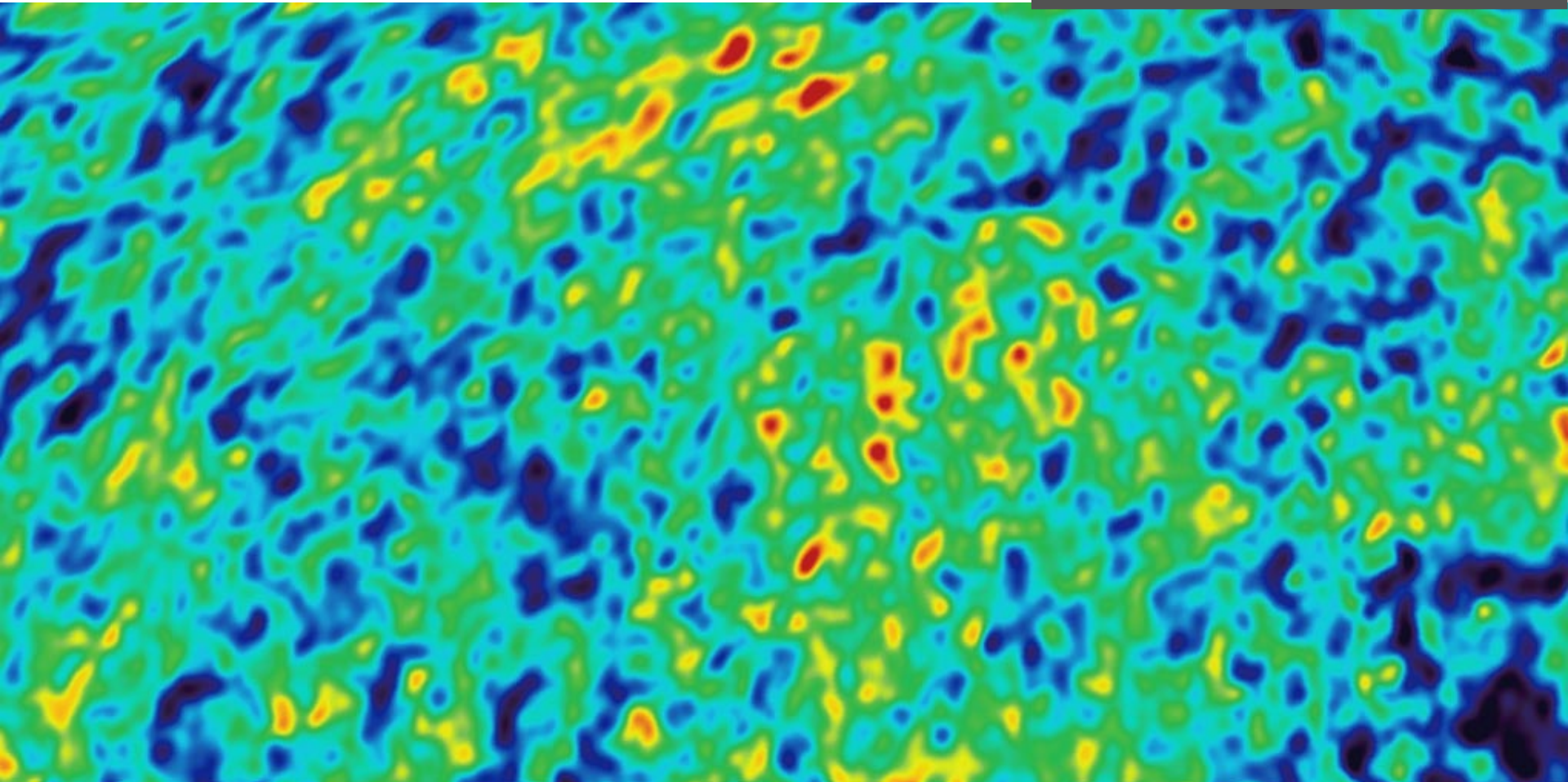


Immagine dell'Universo quando aveva
380,000 anni!

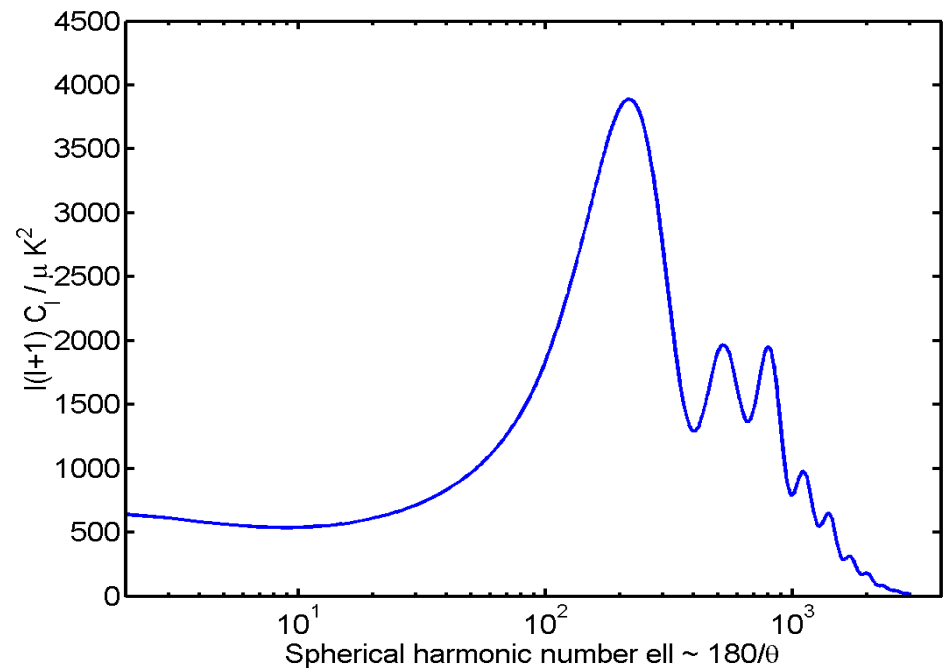
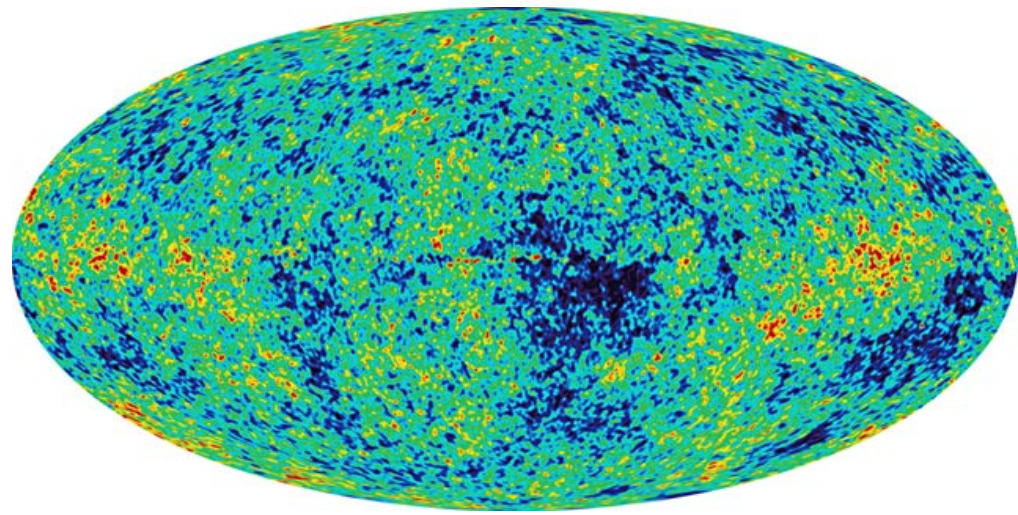


Esiste una scala caratteristica
a ~ 1 grado



Proprietà Statistiche

- Trasformazione in armoniche sferiche
- ~ trasformate di Fourier
- Quantificazione della rugosità su scale diverse



Cosa sono le C_ℓ ?

- Qualitativamente: \sim potenza in ogni modo di Fourier
- Quantitativamente:

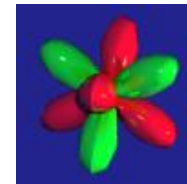
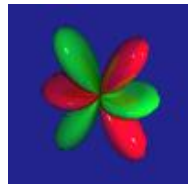
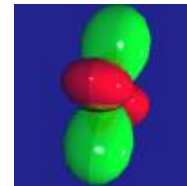
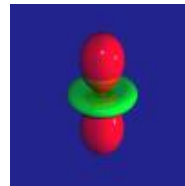
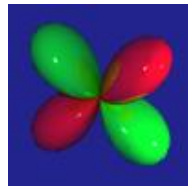
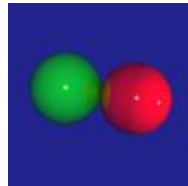
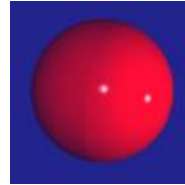
$$T_{\text{CMB}} = 2.726K$$

$$\Delta T(\theta, \phi) = T(\theta, \phi) - T_{\text{CMB}}$$

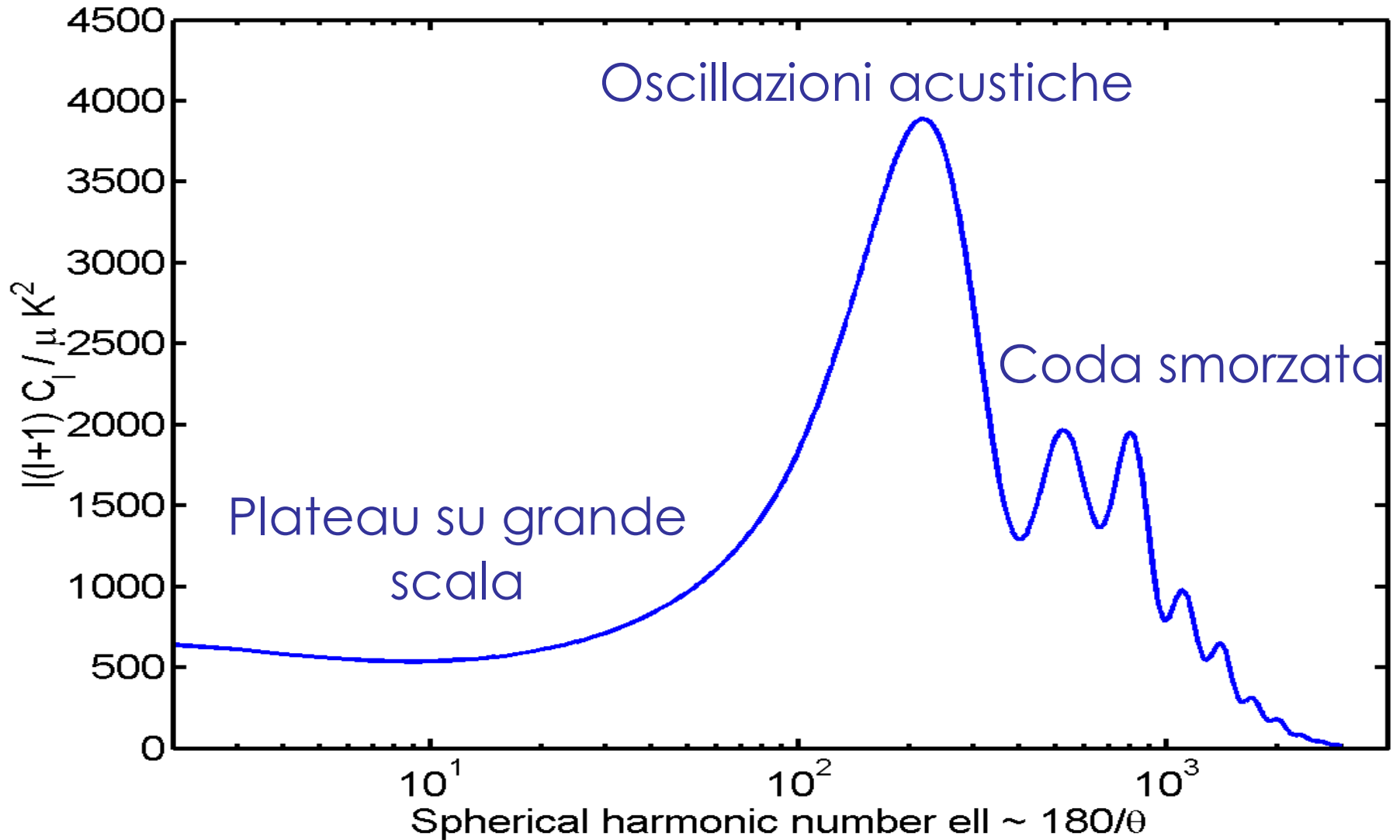
$$a_{\ell m} = \int \frac{\Delta T(\theta, \phi)}{T_{\text{CMB}}} Y_{\ell m}(\theta, \phi) d\Omega$$

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

Armoniche Sferiche



3 regimi dello spettro di potenza della CMB



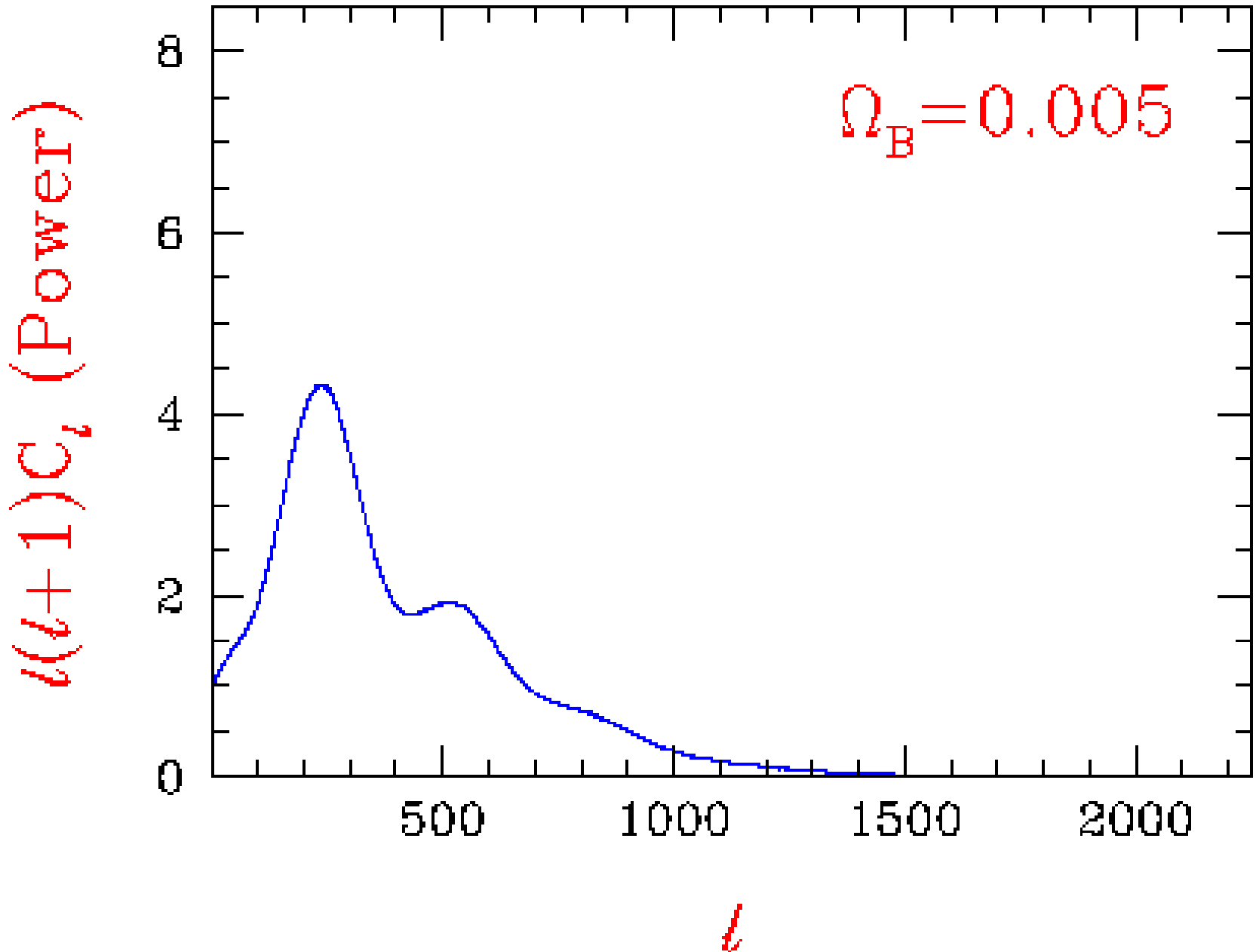
Parametri Cosmologici



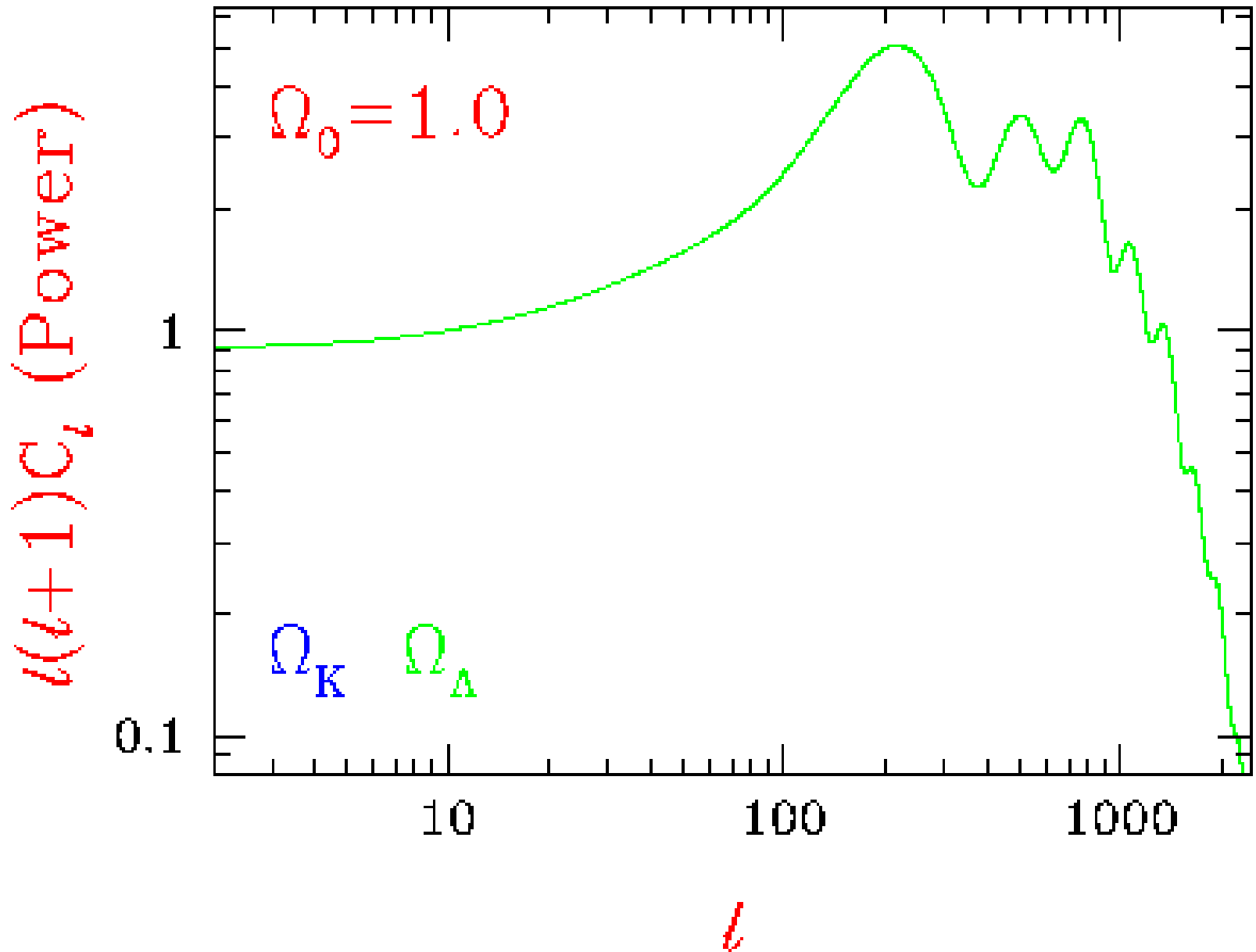
- Contenuto dell'Universo: $\Omega_b, \Omega_{DM}, f_v, \Omega_\Lambda, w(z)$
- Dinamica dell'Universo: H_0
- Rugosità: $\sigma_8, n_s(k)$
- Onde gravitazionali primordiali: A_t, n_t
- Quando si sono formate le prime stelle: z_{re}
- Altro : WDM, isocurvatura, non-Gaussianità...

Ogni parametro ha un effetto sulla CMB

Aumento della densità Barionica



Diminuzione della densità di Materia



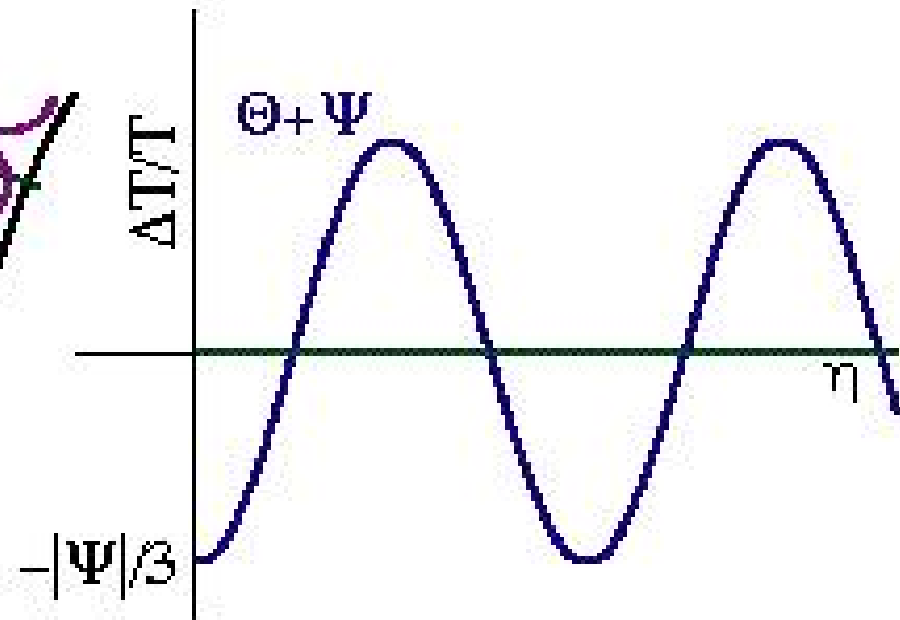
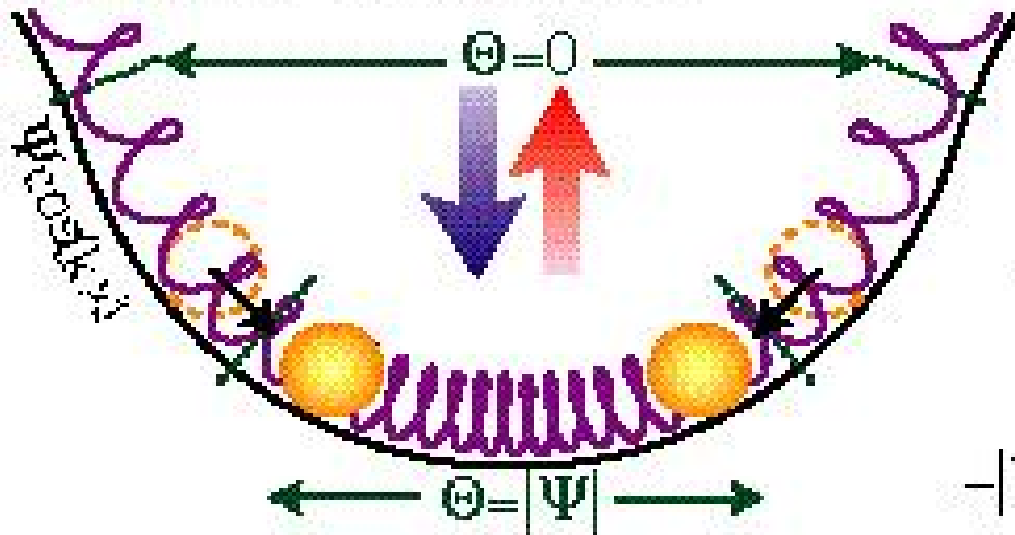
Significato dei picchi: posizione del 1^{mo} picco

- Un fluido in oscillazione causa strutture a picchi
- Curvatura dell'Universo -> posizione dei picchi

Fluido oscillante

- Fluido di fotoni-barioni oscilla nella buca di potenziale della DM

Acoustic Oscillations



- Le grandi scale oscillano più lentamente

Una analogia

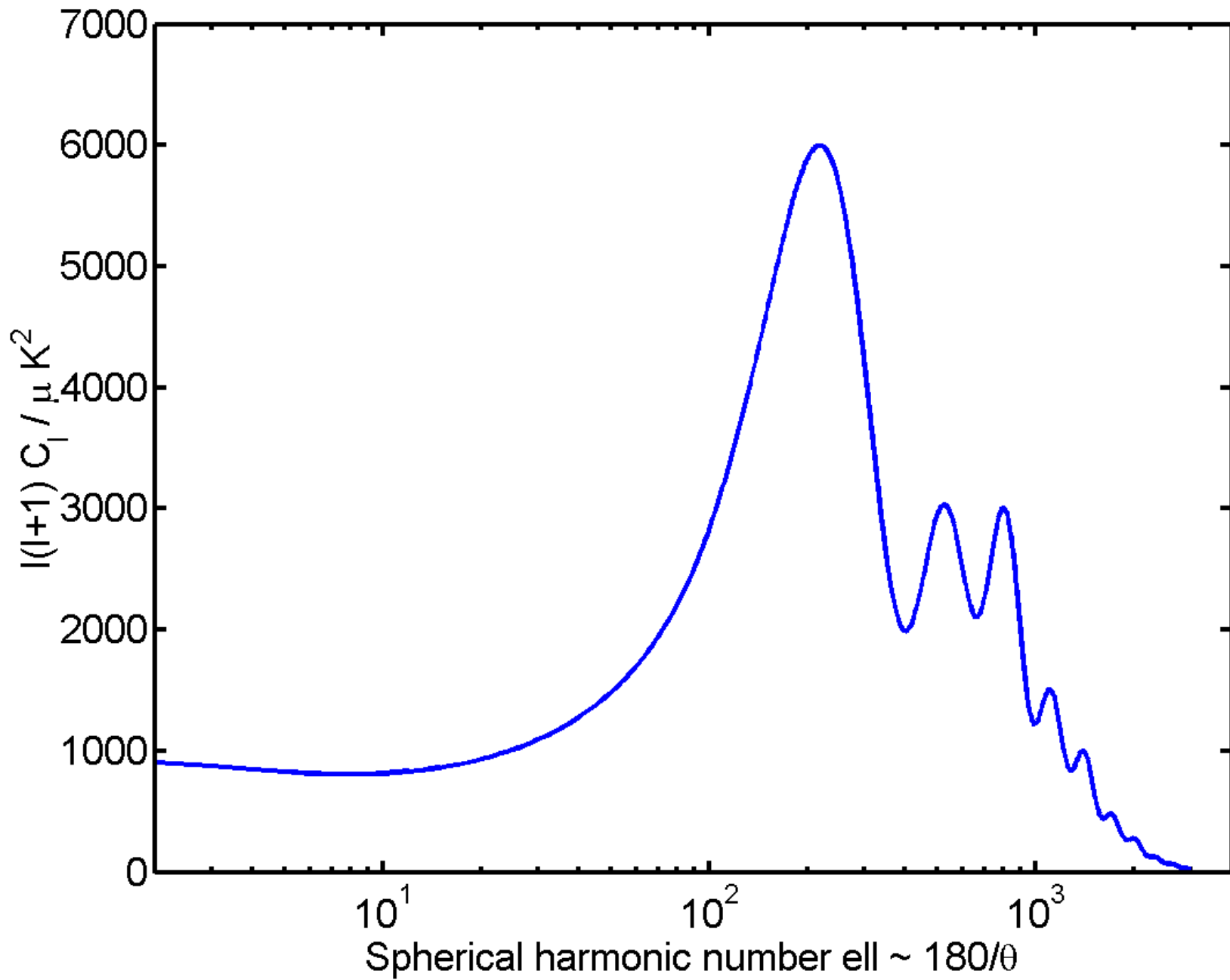
- Lascia cadere molte palline elastiche da diverse altezze e aspetta 5 minuti
- Le palline che cadono da più basso rimbalzano più volte
- Quelle che cadono dal punto più alto nei 5 minuti non raggiungono neppure il terreno
- C'è una pallina che appena ce la fa a toccare terra nel tempo a disposizione

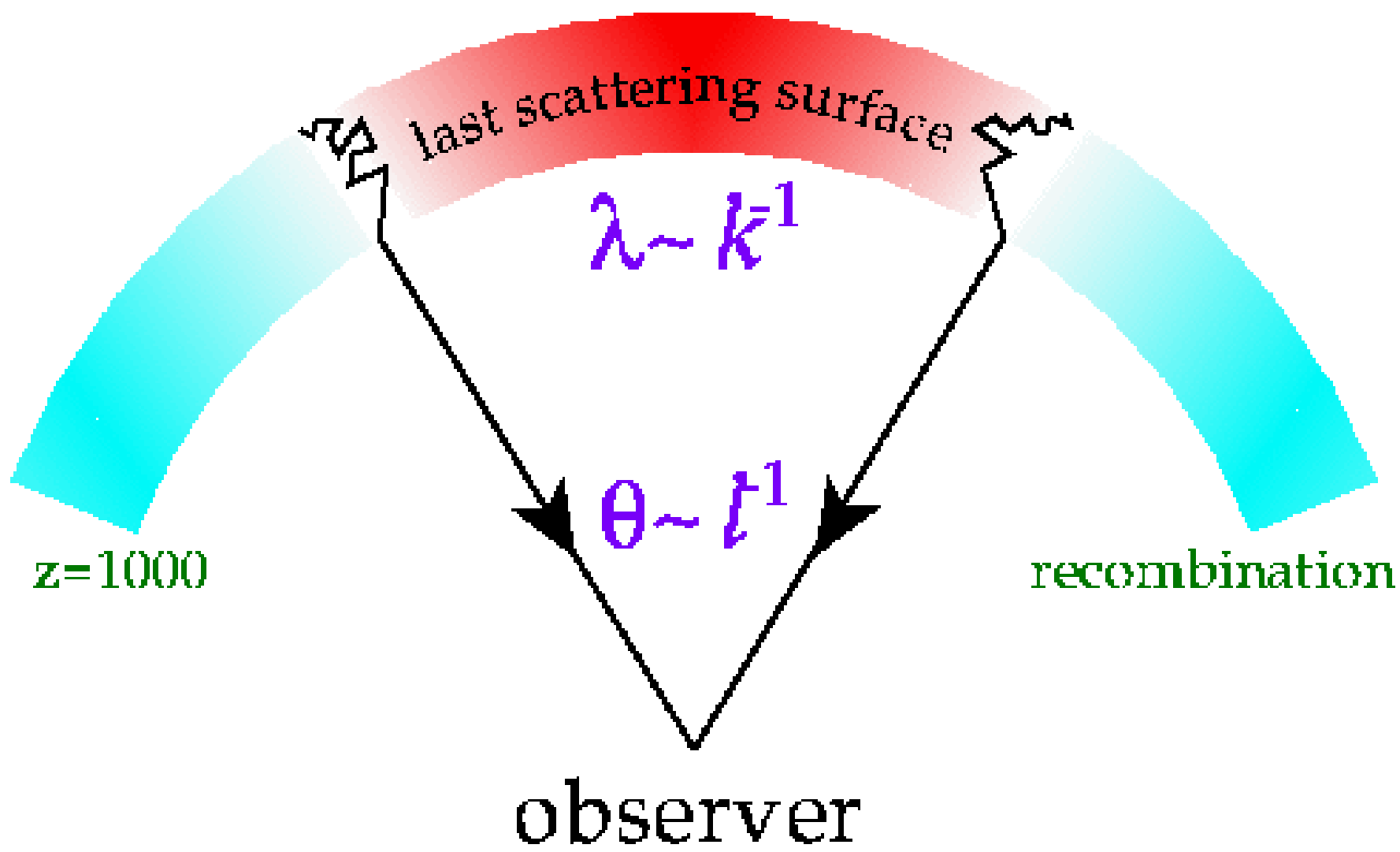
Nesso con la cosmologia

- Palline elastiche
- 5 minuti
- Rimbalzi
- Iniziale altezza della pallina che appena ce la fa a toccare terra
- Fluido oscillanti di fotoni-barioni
- Età dell'Universo al tempo della ricombinazione
- Picchi nel grafico CMB
- Posizione del primo picco

Primo picco acustico

- Considera la scala in cui c'è stato appena il tempo dal Big-Bang di collassare per gravità
- È alla massima $T \Rightarrow$ punto più caldo
- Scala = velocità del collasso x tempo a disposizione
 - ~ velocità del suono x età dell'Universo a $z \sim 1000$
 - ~ $200 (\Omega_m h^2)$ Mpc comoventi
 - ~ **1 grado**





last scattering surface

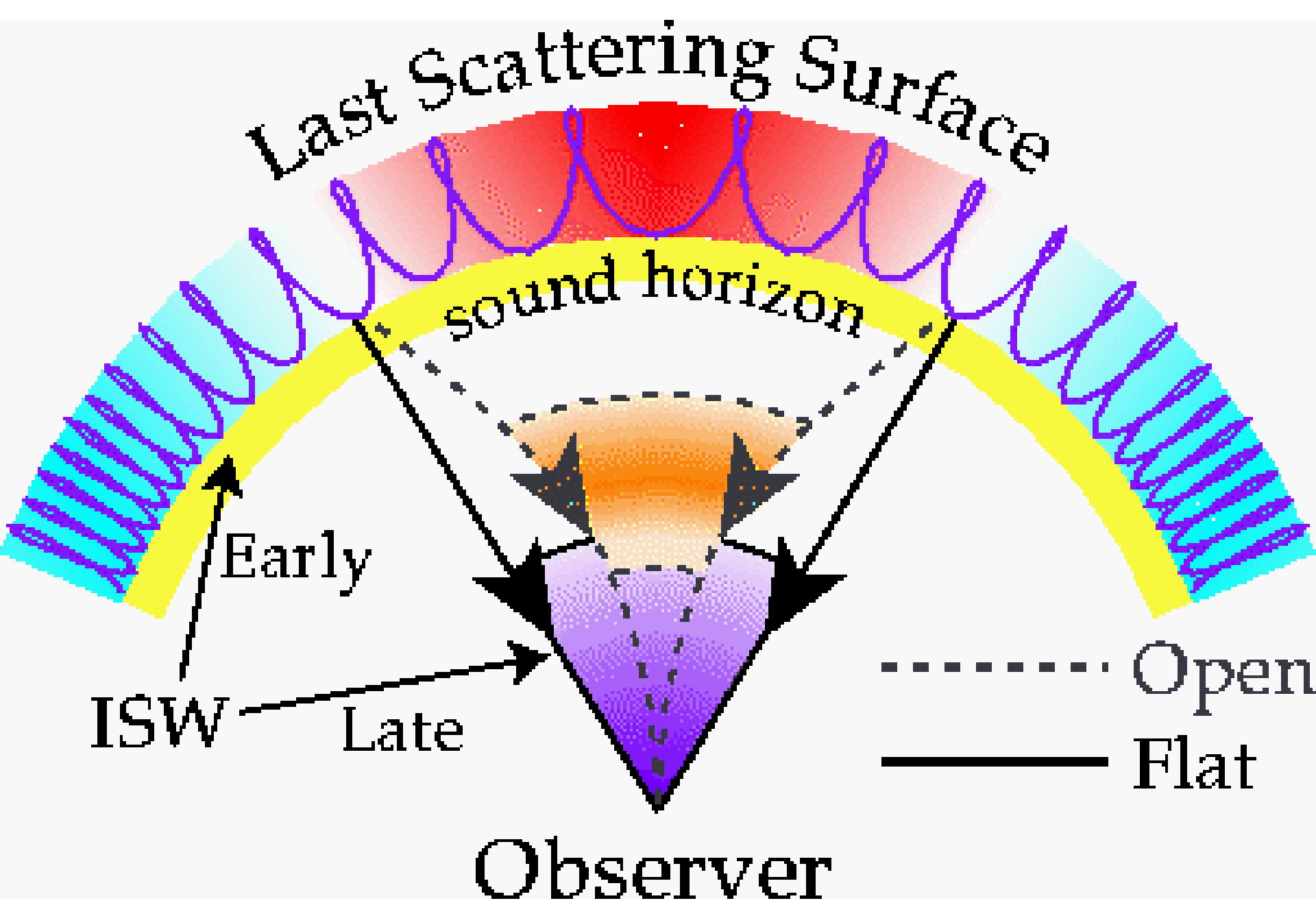
$$\lambda \sim k^{-1}$$

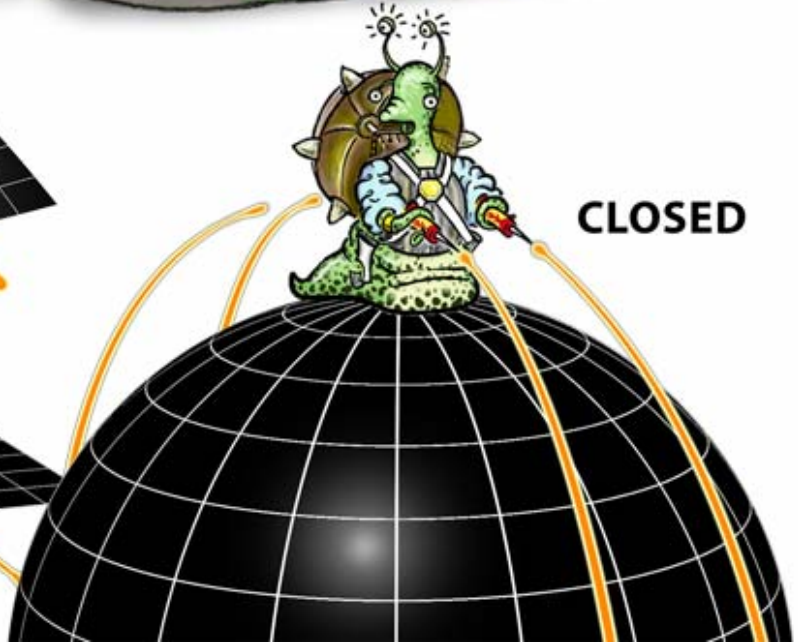
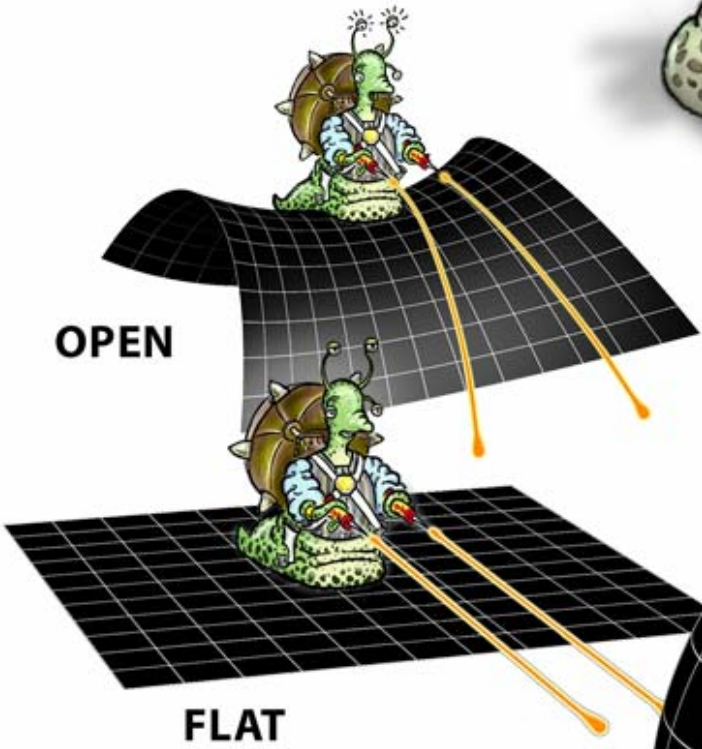
$$\theta \sim l^{-1}$$

z=1000

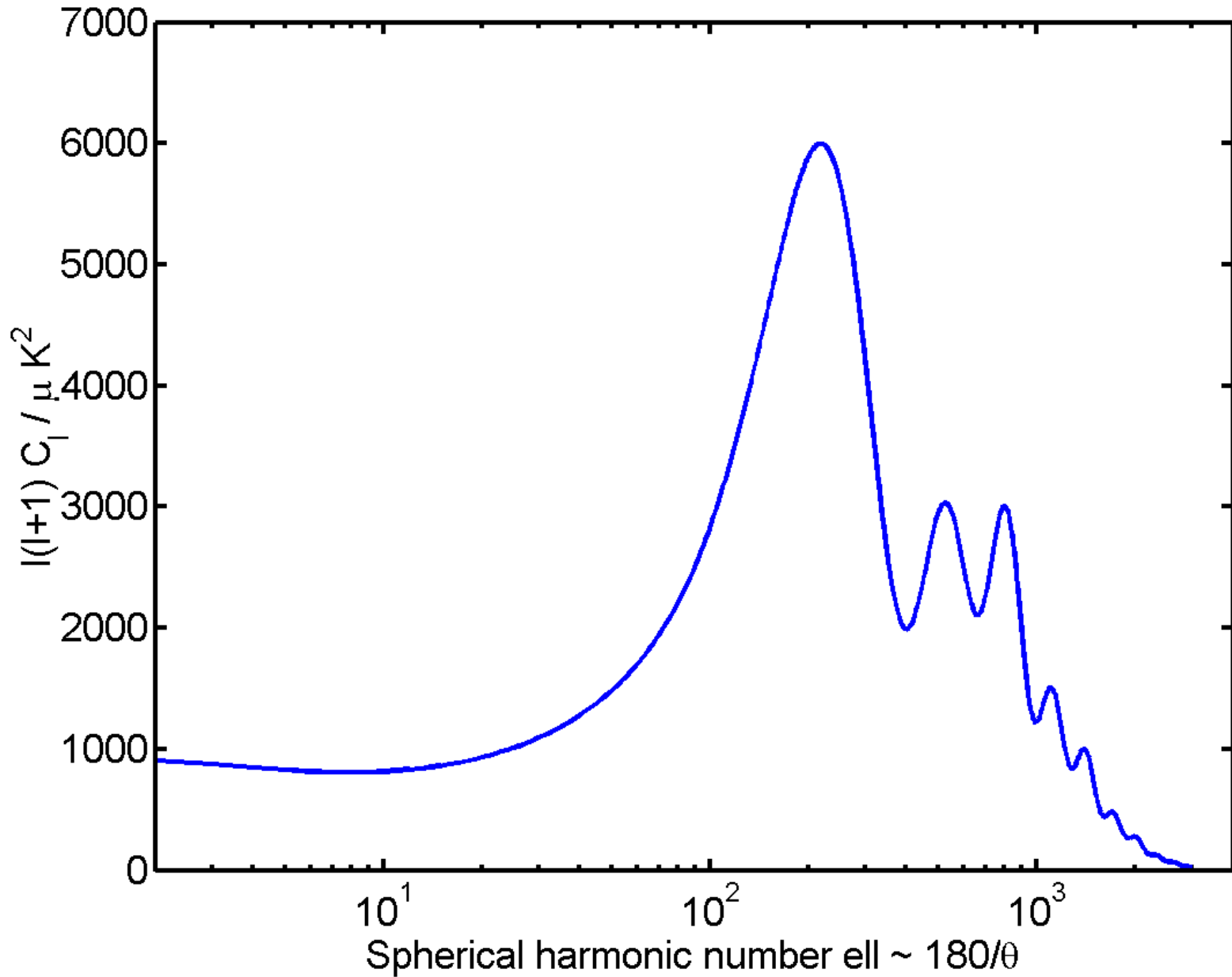
recombination

observer

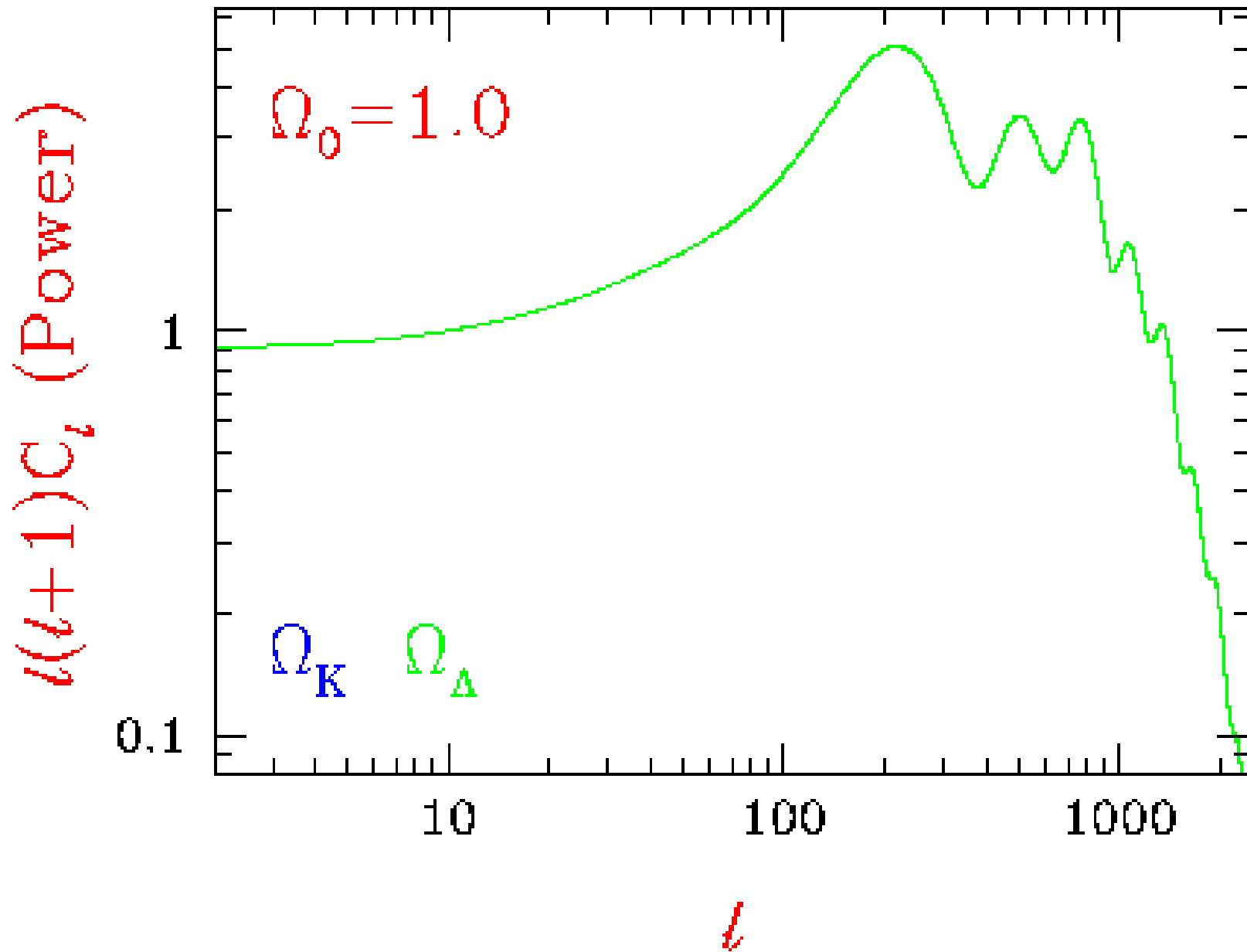


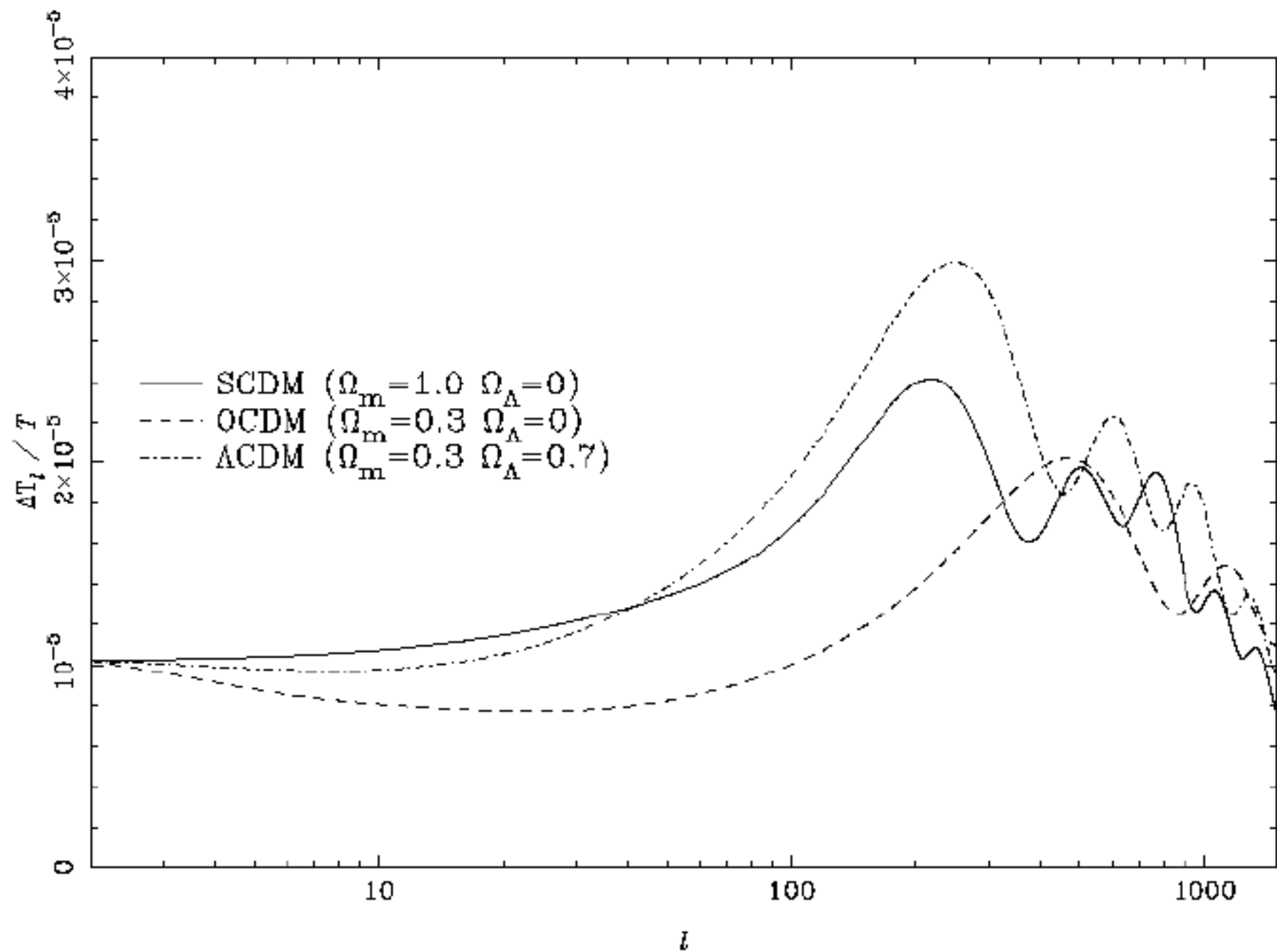


In che direzione muoverà il picco?



Piatto \rightarrow Aperto
Picco si sposta verso destra

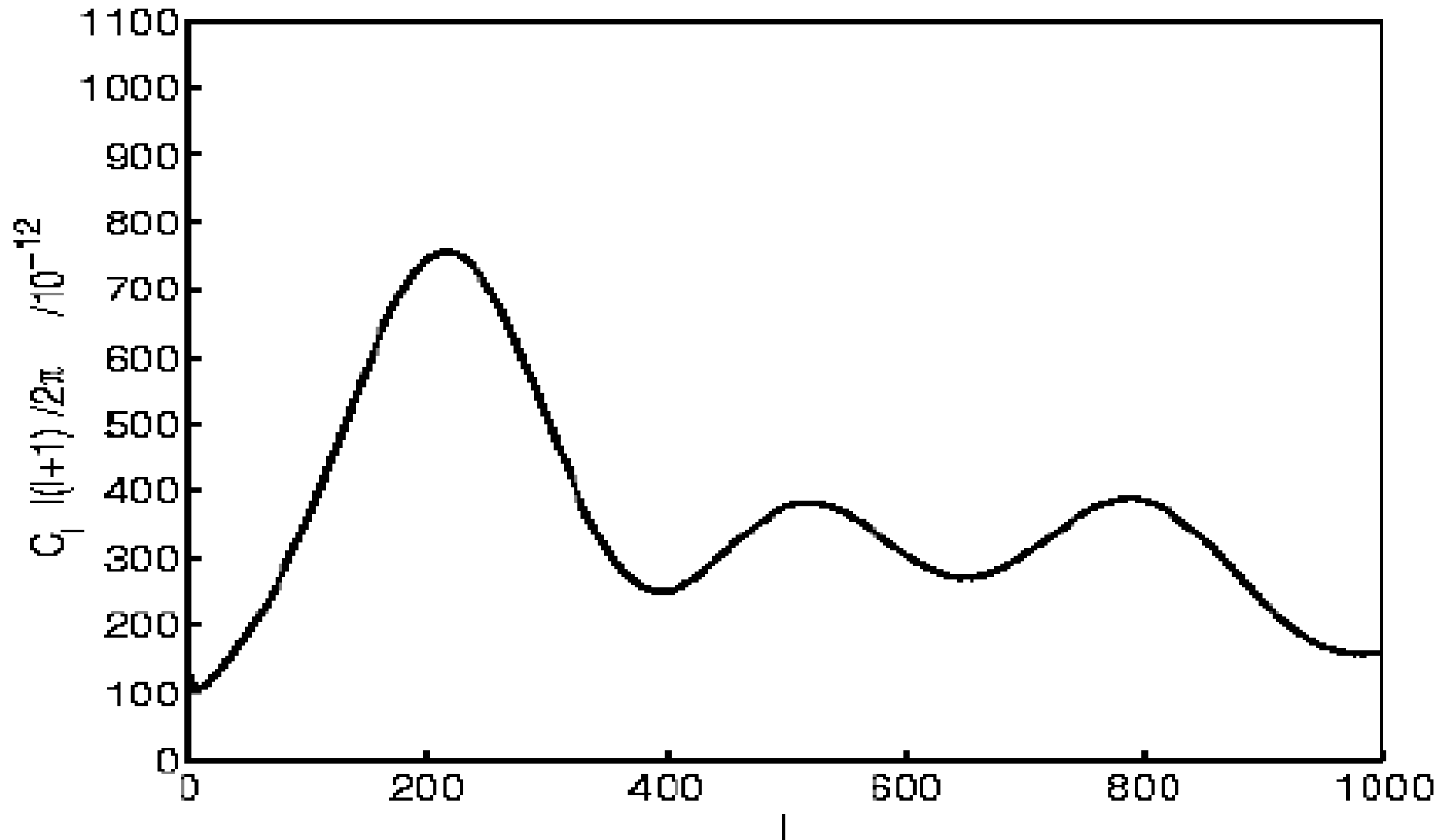


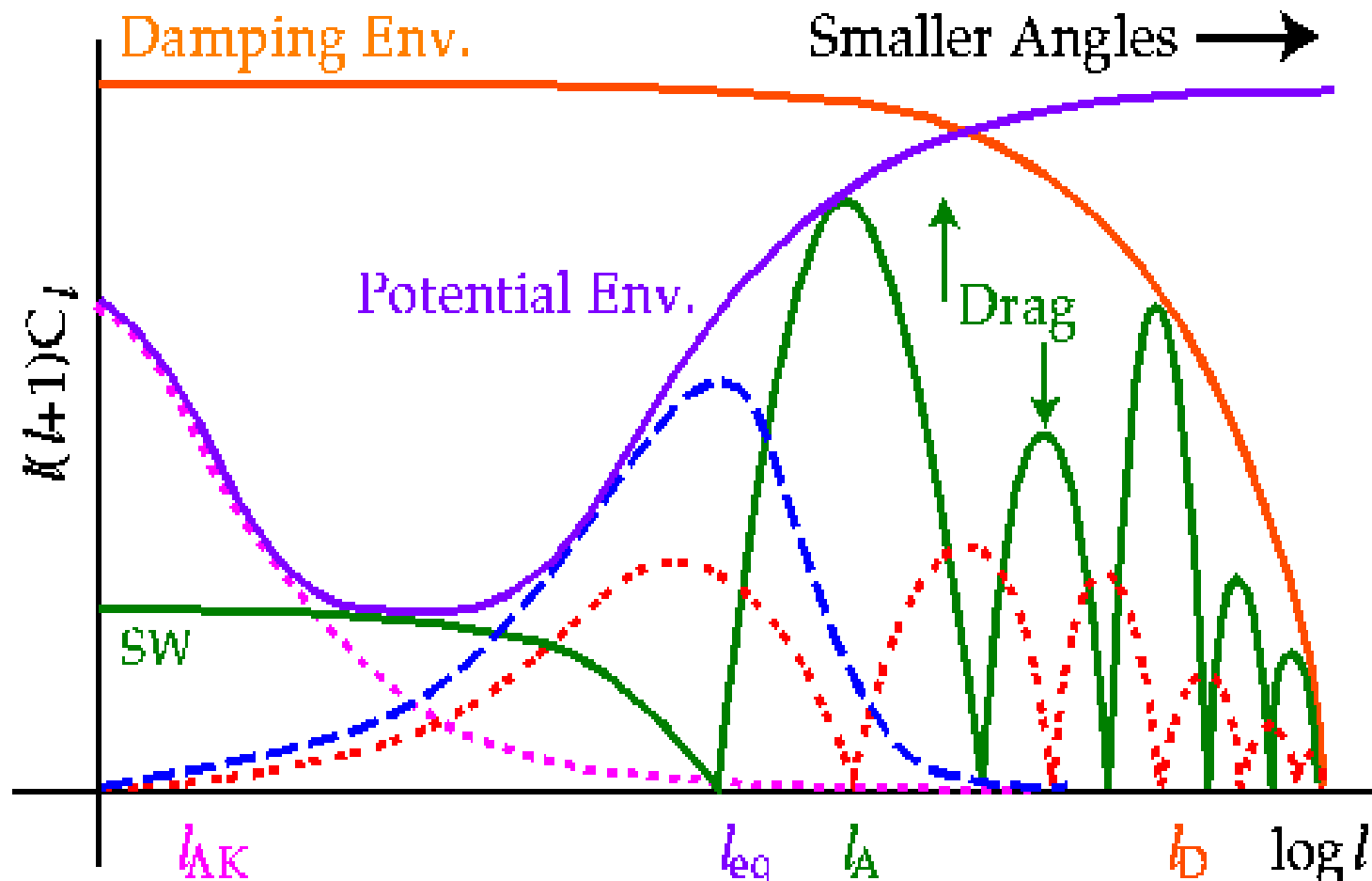


Picchi secondari

- Il grafico è \sim FT di $(T(\theta) - (T)_{\text{media}})$
- Secondo picco = collasso, espande al max
- Terzo picco = collasso, espansione, collasso
- etc..
- Ci si aspetta che i picchi siano egualmente spazati in l

Grafico con assi lineari





| | Ω_K | Ω_A | $\Omega_0 h^2$ | $\Omega_B h^2$ | |
|----------|------------|------------|----------------|----------------|---------------------|
| l_K | ↑ | ↑ | ● | ● | ● - - - ● Late ISW |
| l_{eq} | ↑ | ↓ | ↑ | ● | ● - - - ● Early ISW |
| l_A | ↑ | ↓ | ↓ | ↑ | ● — ● Eff. Temp. |
| l_D | ↑ | ↓ | ↓ | ↑ | ● - - - ● Doppler |

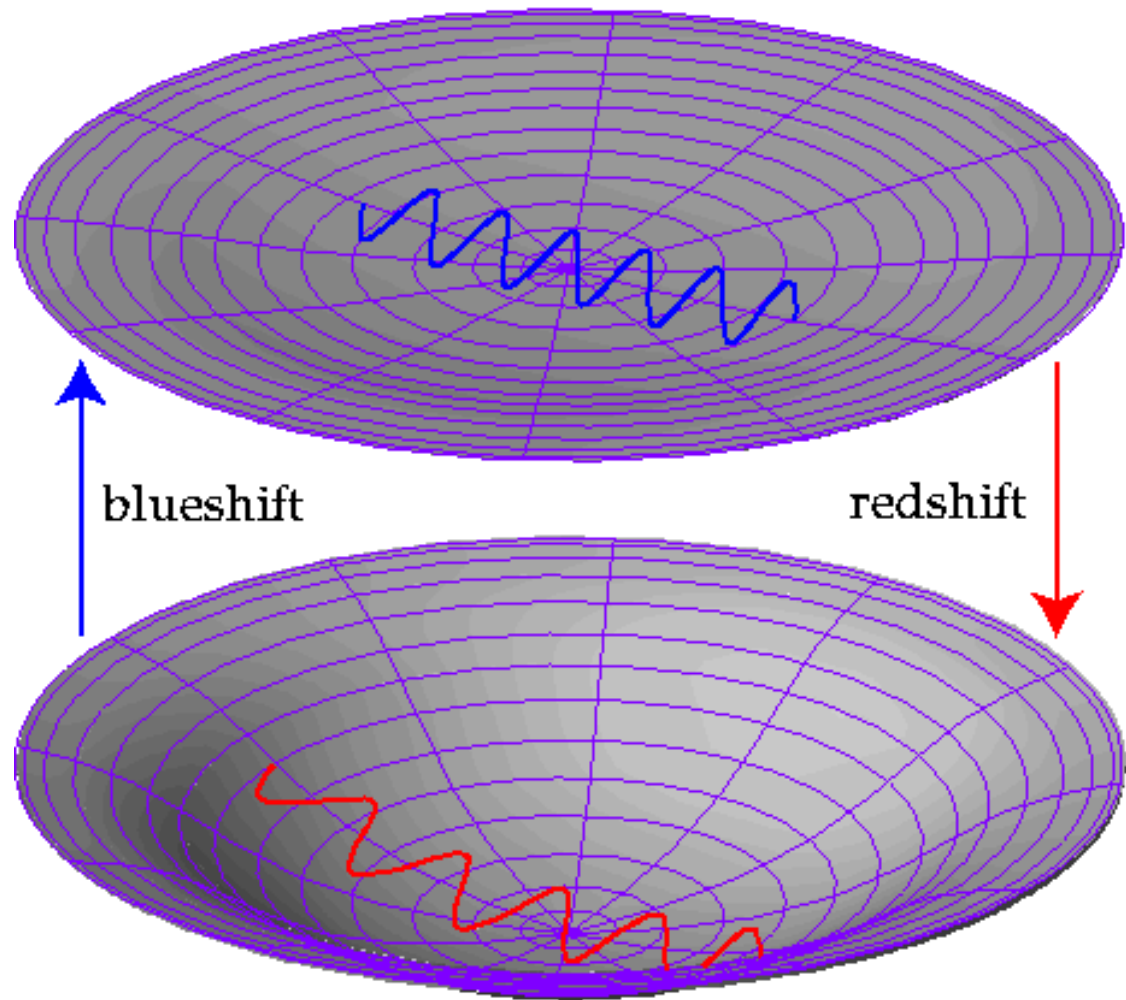
Su scale maggiori: effetto Sachs-Wolfe

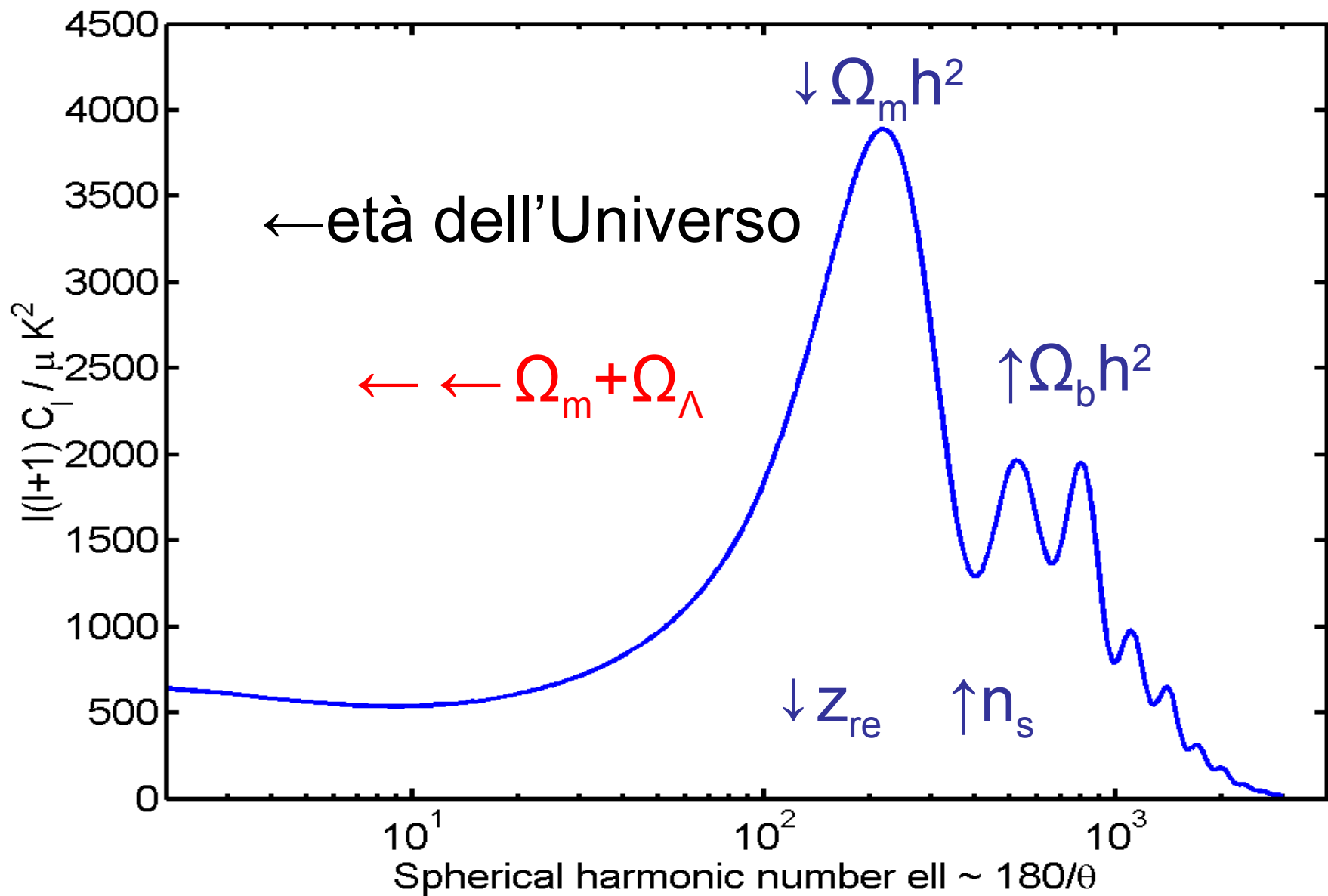
- Buca di potenziale gravitazionale dovuta a DM
 - Segue lo spettro di potenza della materia su grande scala
- Fotoni escono dalla buca di potenziale
 - redshift: gravitazionale freddo \rightarrow buca profonda
 - $\Delta v / v \sim \Delta T / T \sim \Delta \Phi / c^2$
- GR
 - fattore $2/3 \sim$ buca profonda, t è più piccola \rightarrow più calda
 - $\Delta T / T = 1/3 \Delta \Phi / c^2$

ISW

Dilation Effect

- Effetto Sachs-Wolfe integrato
- Dovuto ai fotoni che viaggiano attraverso le strutture che collassano
- Aumenta la potenza a piccoli ℓ in C_{ℓ}^{TT}

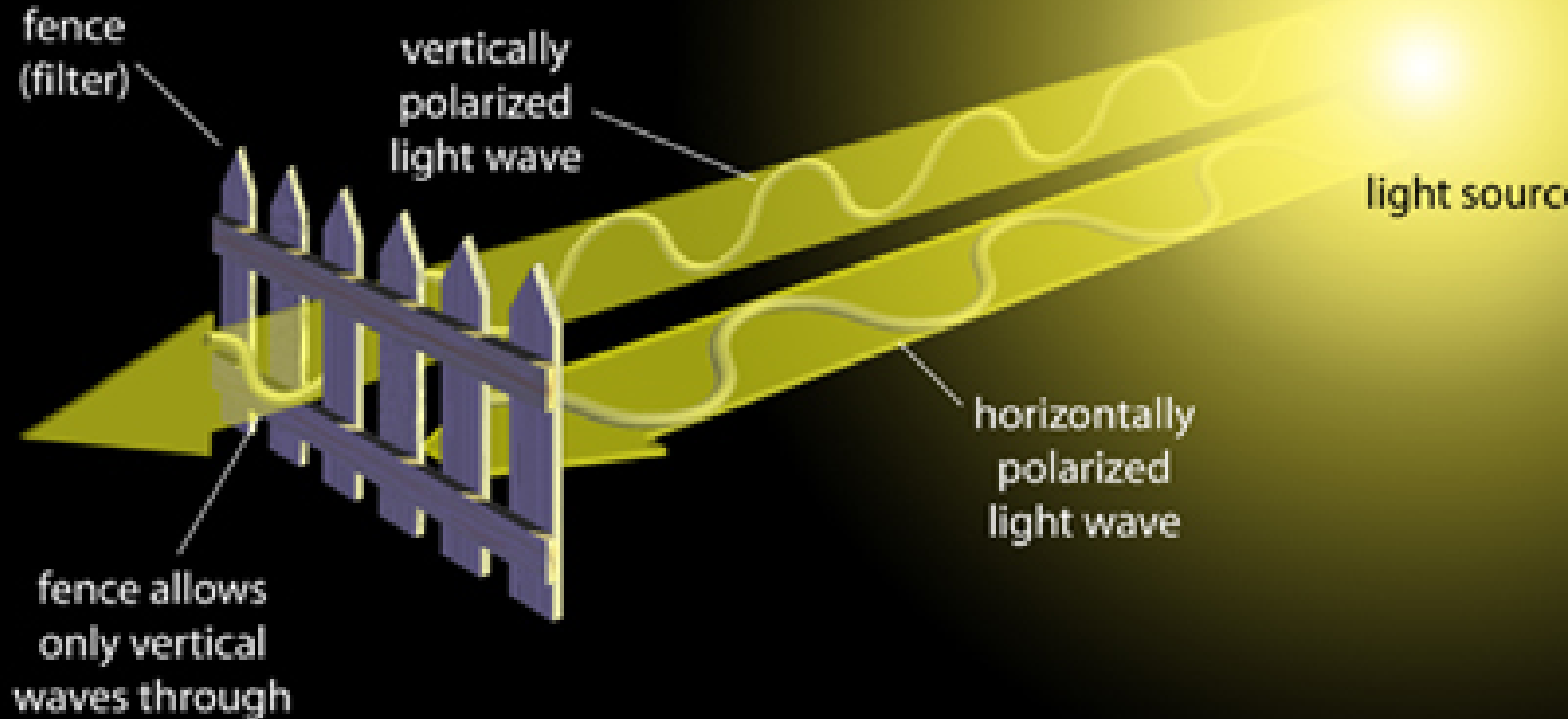




Polarizzazione della CMB

- Misure dell'angolo e mag. di polarizzazione in ciascun punto del cielo
- Scomporli in 2 mappe: E e B
 - E equivale ai contorni di livello su una mappa
 - B è come acqua che sgorga attraverso uno scarico
- Può essere correlato con il segnale non-polarizzato
 - possibile spettro di potenza: TT, TE, TB, EE, EB, BB
 - Ci si aspetta TB e EB = zero a causa della parità

Polarization: How It Works

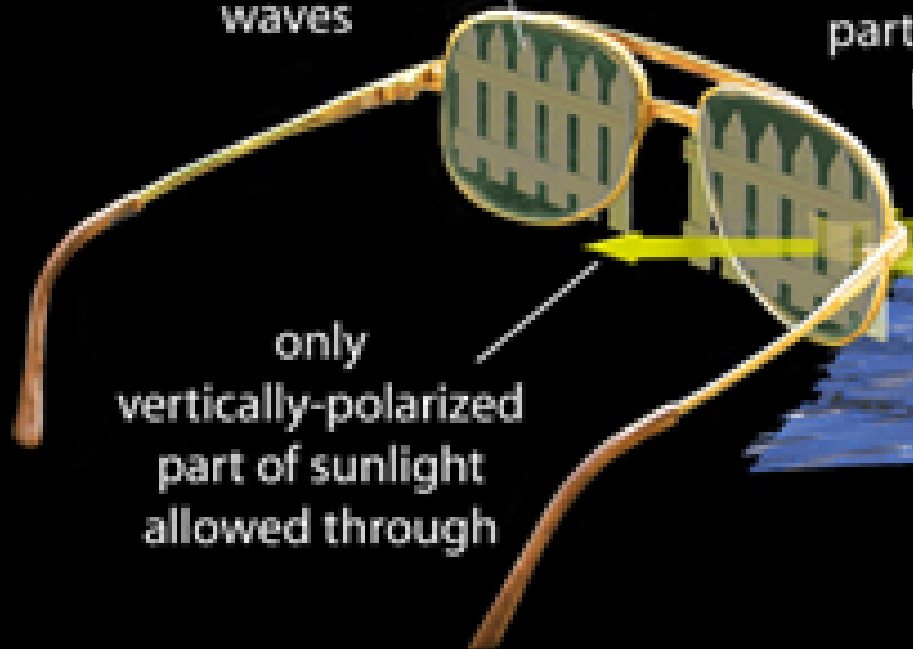


like the fence.

waves through

how we see it...

like the fence,
lenses of
polarized sunglasses
accept only vertical
waves



only
vertically-polarized
part of sunlight
allowed through

partially-polarized
light from
scattering



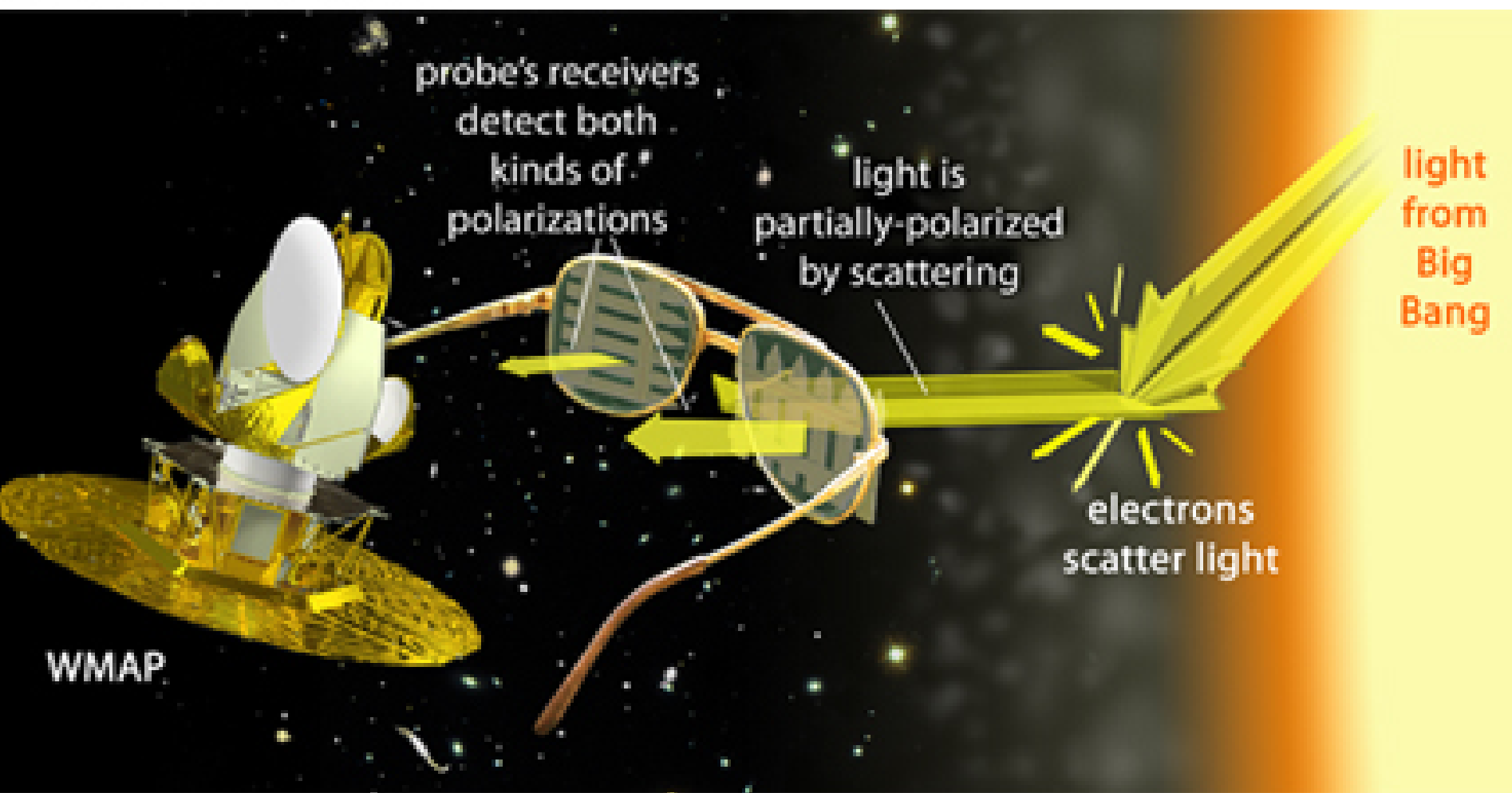
Sun

unpolarized
natural
light

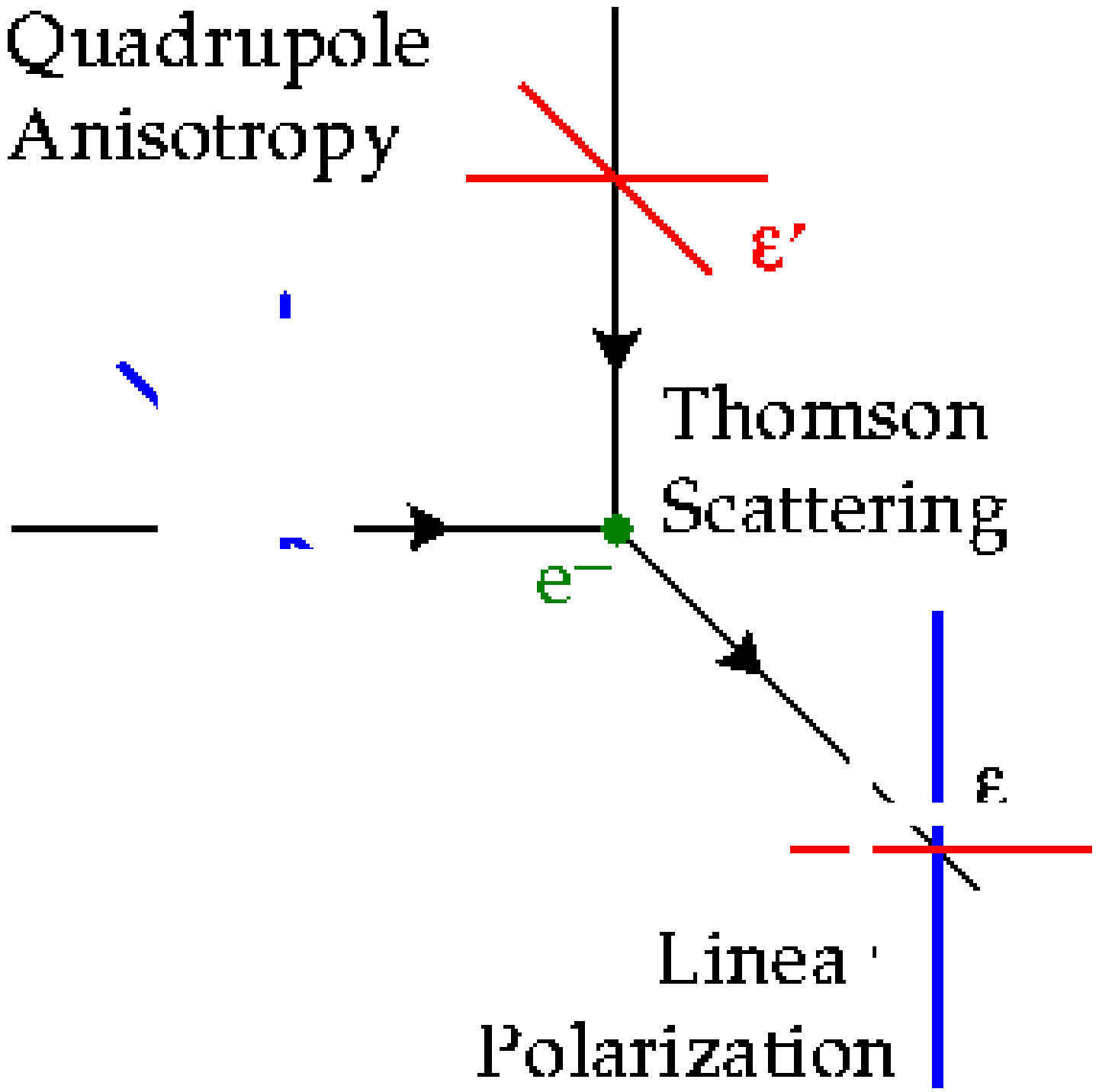
water

viewer's eye

How WMAP sees it...



Quadrupole
Anisotropy



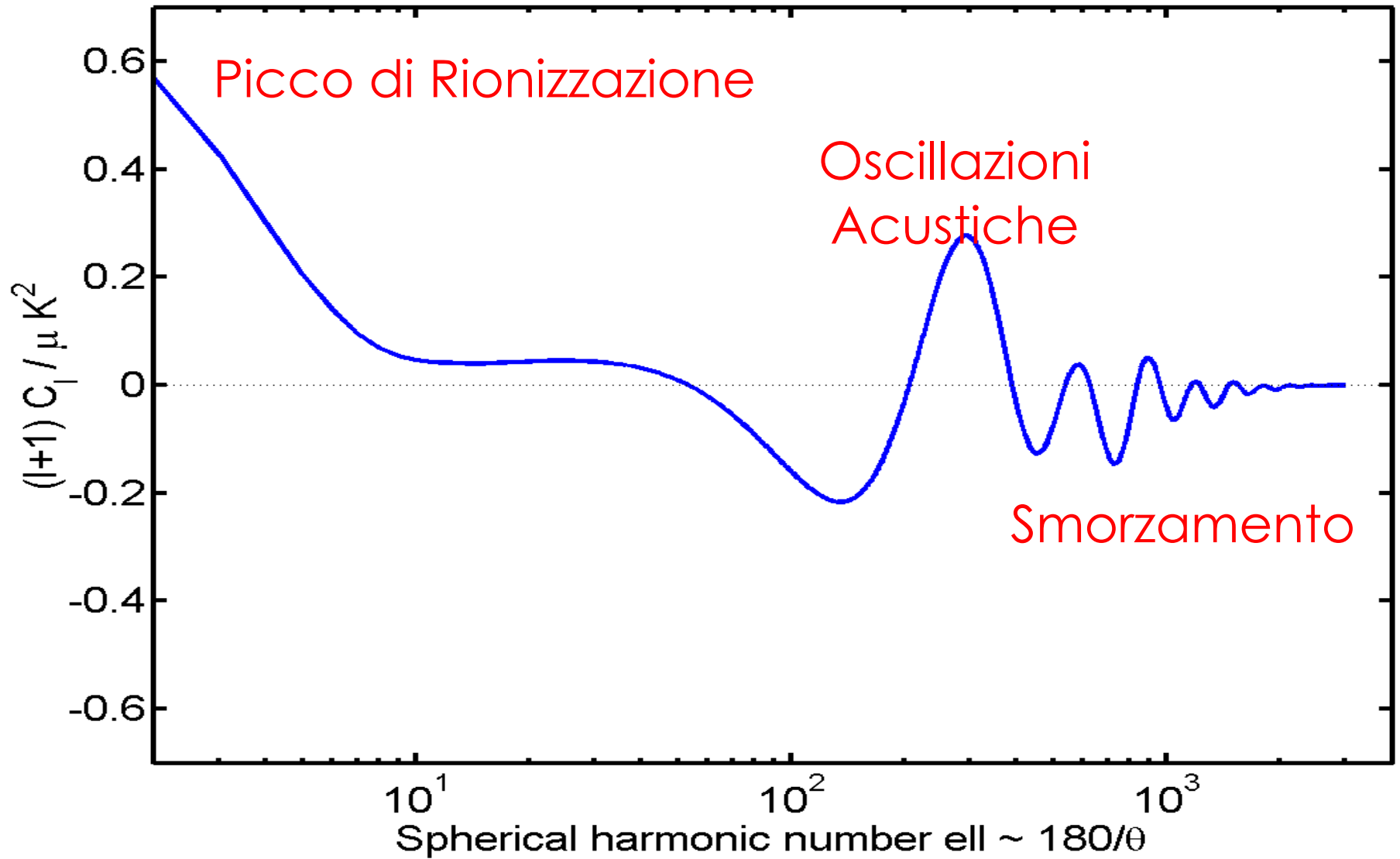
Thomson
Scattering

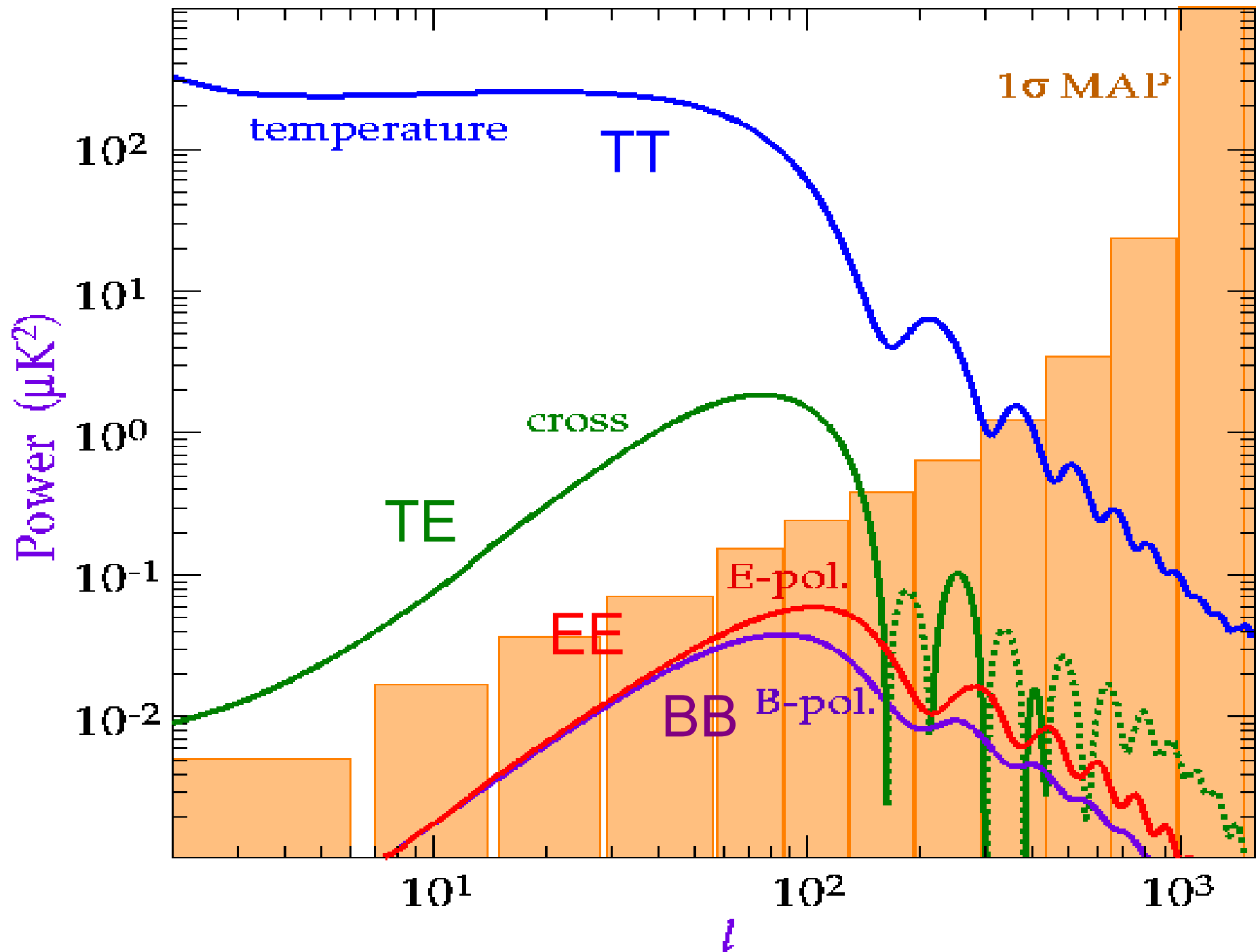
e^-

ϵ

Linea
Polarization

3 regimi di polarizzazione CMB





CMB spettro di potenza: oscillazioni acustiche

- Effetto dominante è la velocità dei barioni
- Le velocità sono massime quando il contrasto di densità è minimo
- La Polarizzazione è fuori fase con i picchi acustici
- Misura gli stessi parametri cosmologici TT.
Assunzioni per il test

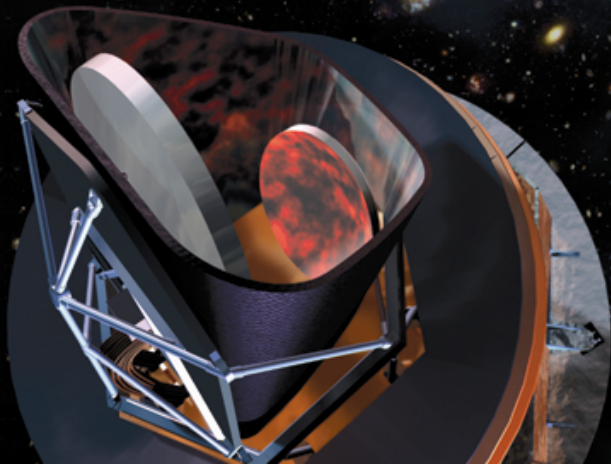
Risultati da WMAP



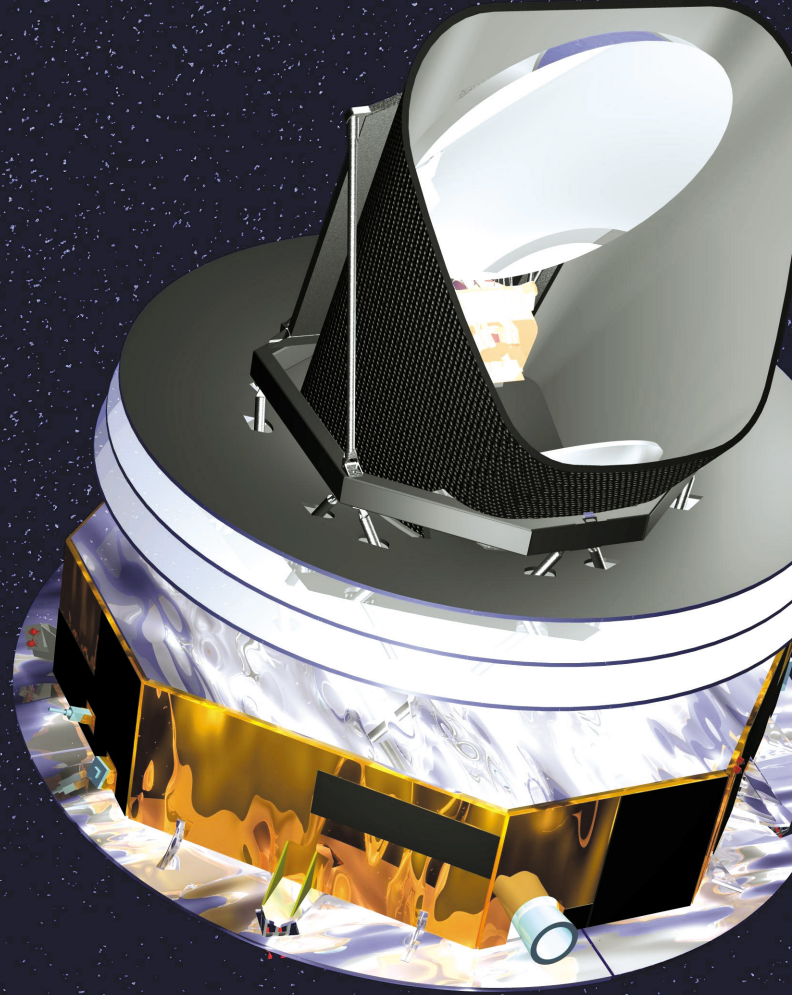


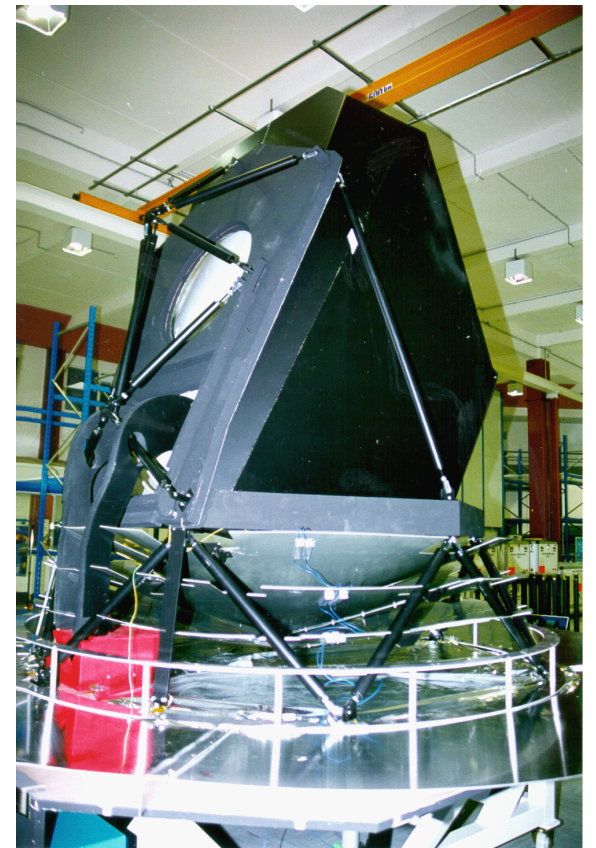
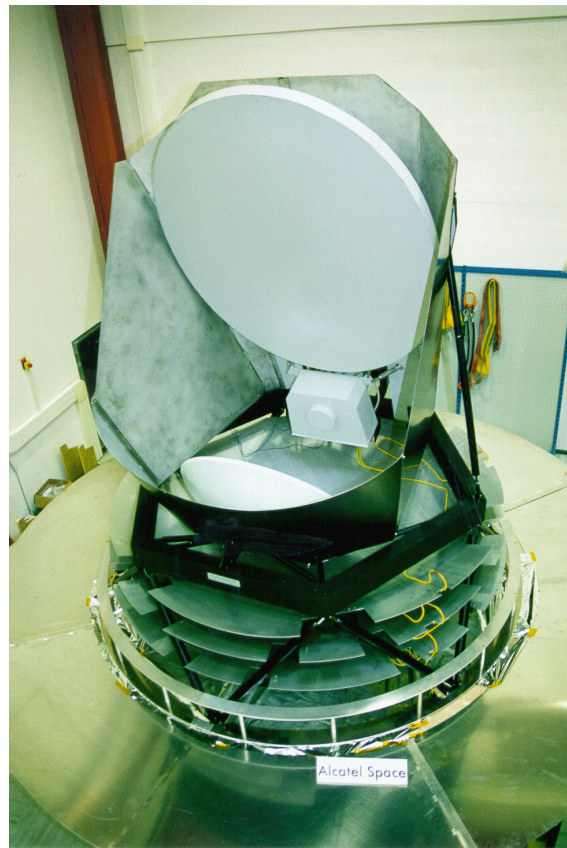
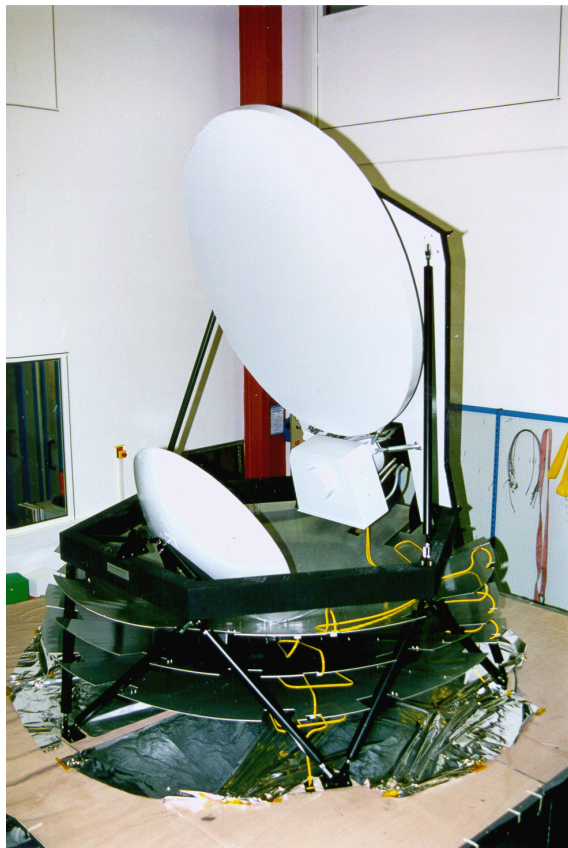
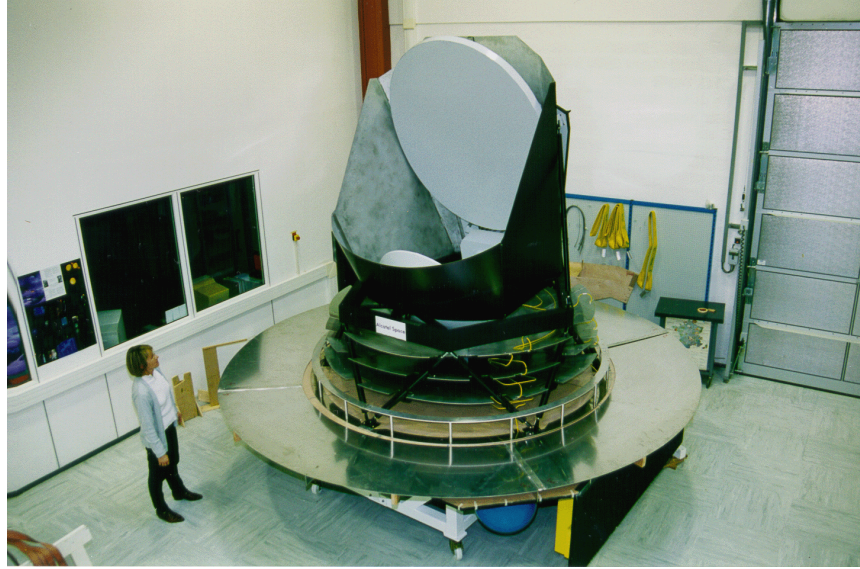
PLANCK

Looking back to the dawn of time
Un regard vers l'aube du temps



<http://sci.esa.int/planck>





Angular Scale

90°

2°

0.5°

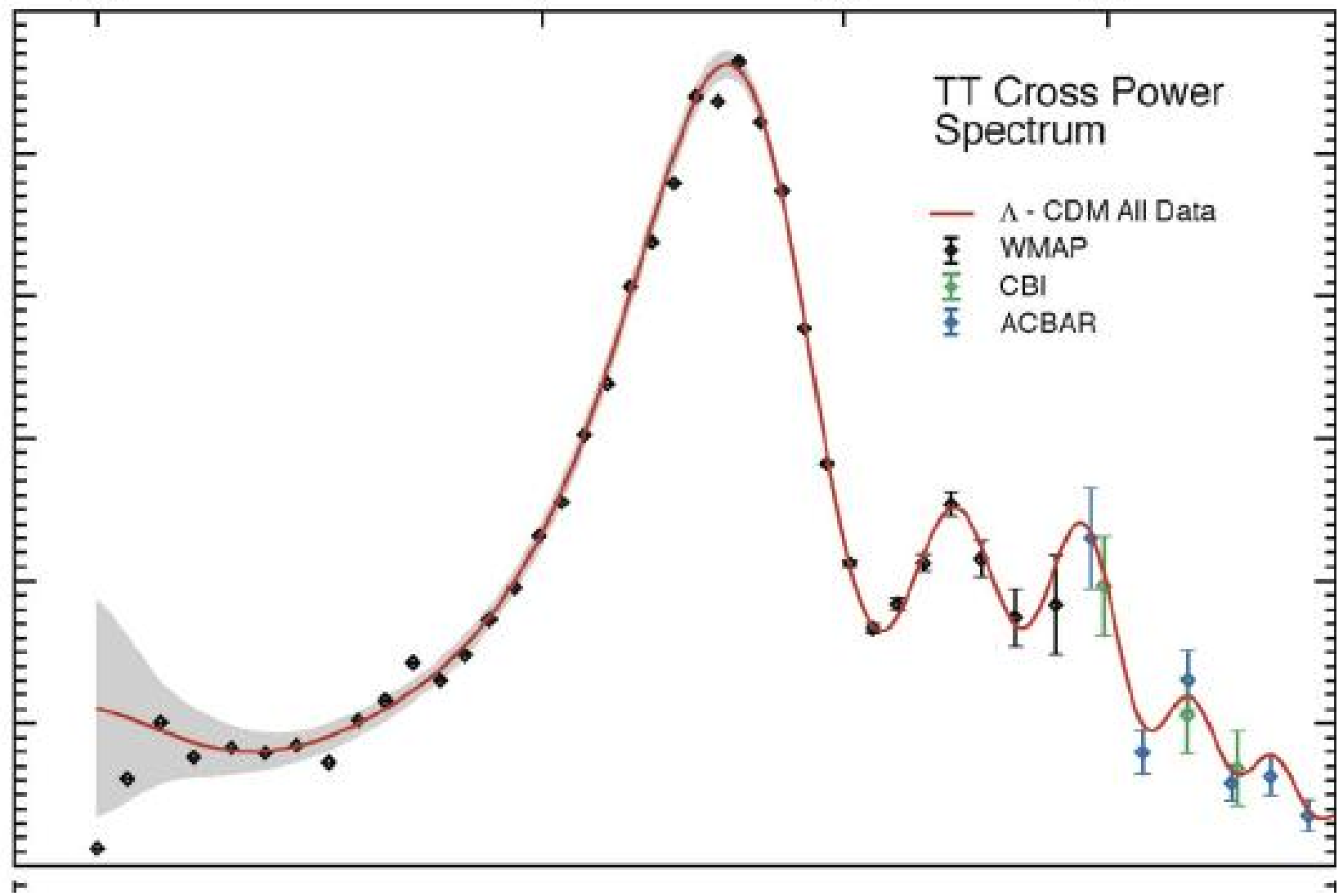
0.2°

6000
5000
4000
3000
2000
1000
0

$l(l+1)C_l/2\pi$ (μK^2)

TT Cross Power Spectrum

- Λ - CDM All Data
- ◼ WMAP
- ◼ CBI
- ◼ ACBAR



Il sacro Graal, Big-Bang

- Perché misurare EE?
 - Modelli di isocurvatura
 - Sviluppa tecnologie per il BB
- BB primordiale \leftrightarrow onde gravitazionali primordiali
- Predette da alcuni modelli di inflazione
 - Predette inesistenti dai modelli ekpyrotici
- Serie difficoltà
 - Il segnale previsto è piccolo
 - contaminazione da lensing gravitazionale