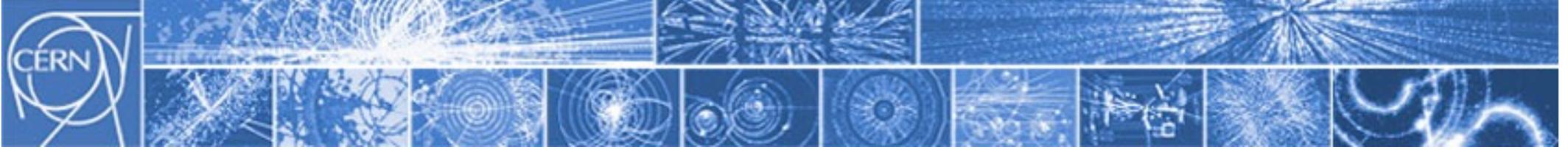
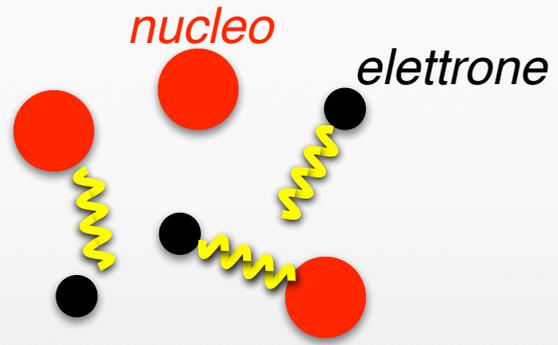


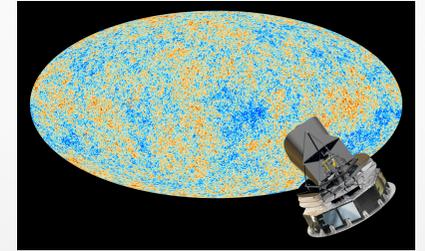
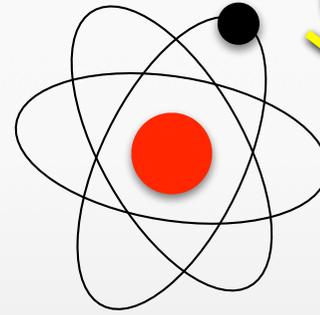
# **Radiazione Cosmica di fondo (Cosmic Microwave Background) (*CMB*)**

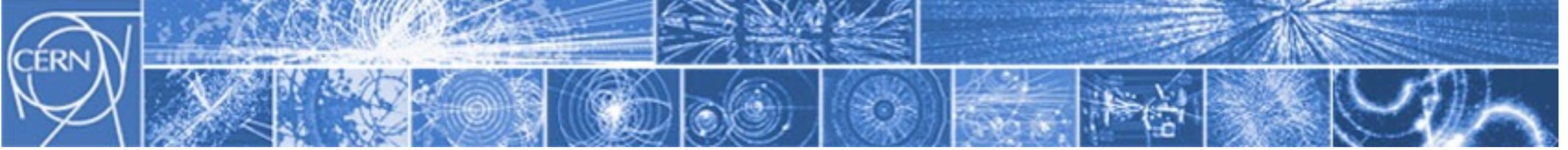


# CMB



'ricombinazione'

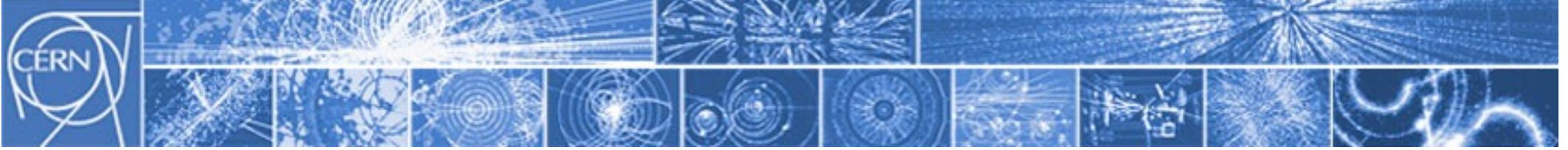




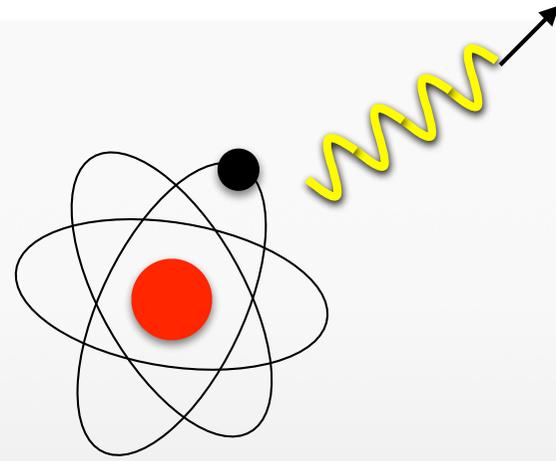
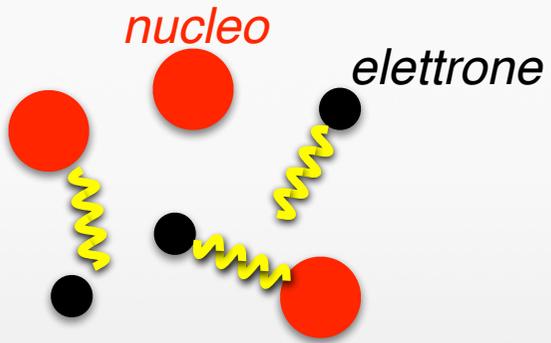
# CMB



Energia ionizzazione H: 13.6 eV



# CMB



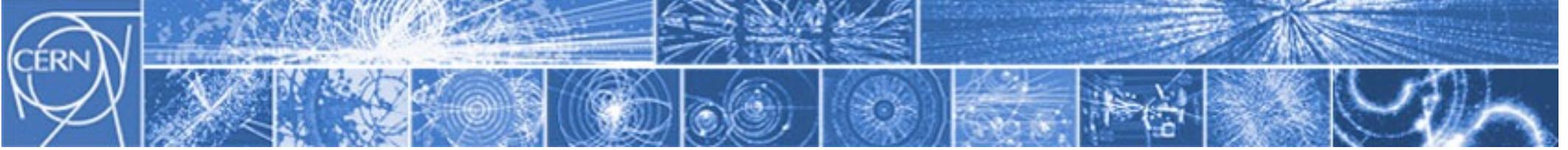
Energia ionizzazione H: 13.6 eV



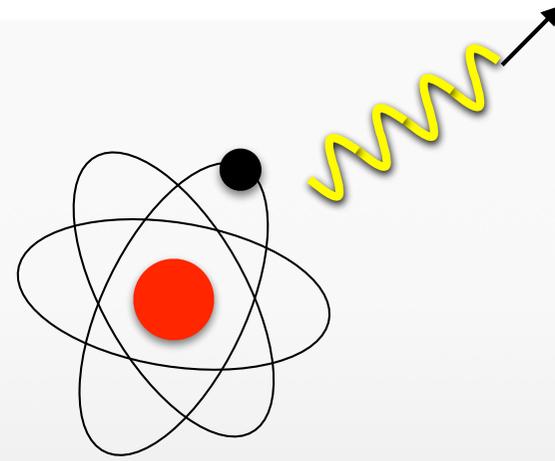
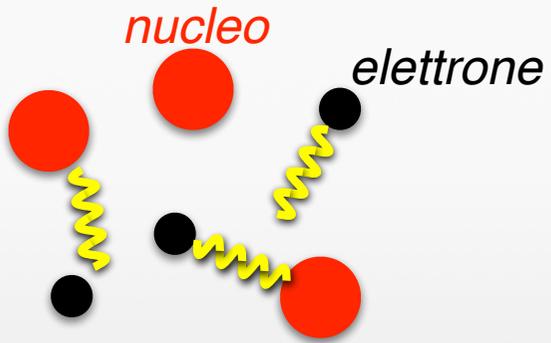
*'recombination bottleneck'*

Temperatura ricombinazione H: 0.25 eV

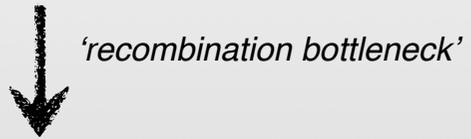
≈ 3000 K



# CMB

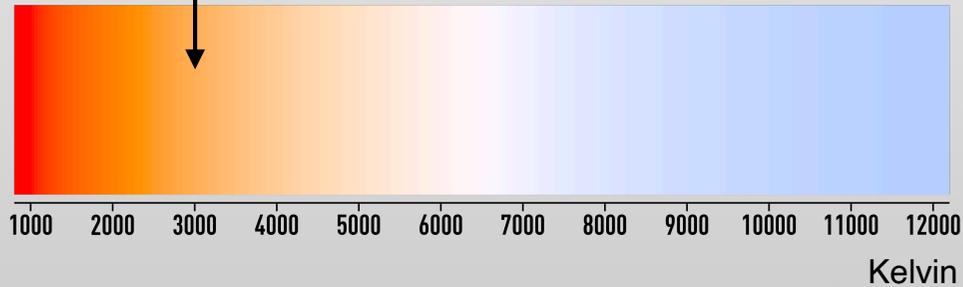


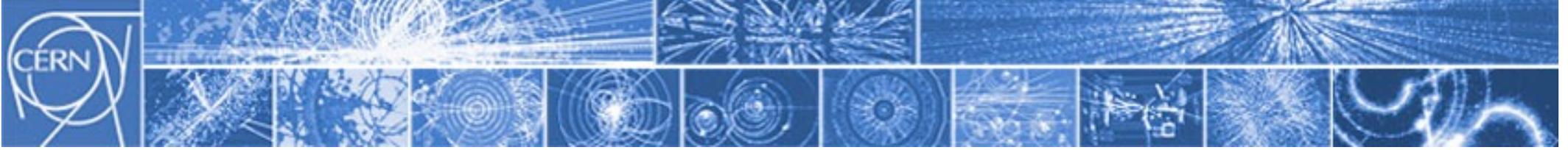
Energia ionizzazione H: 13.6 eV



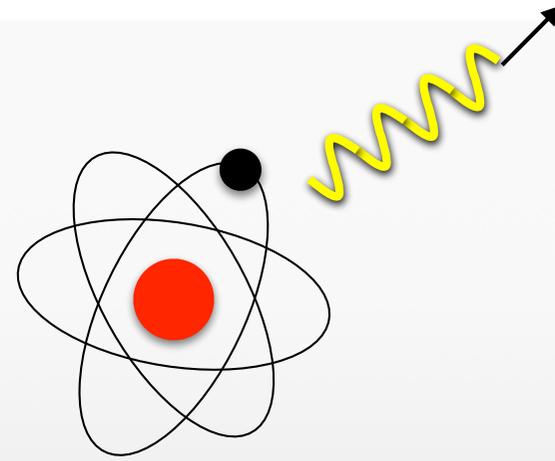
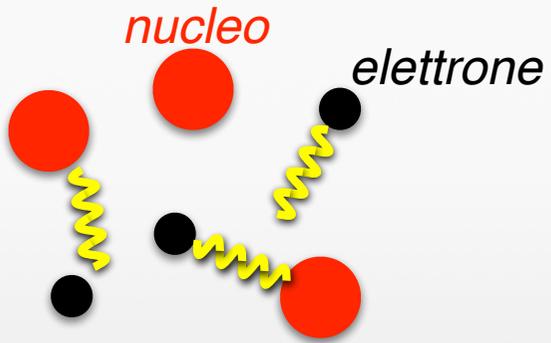
Temperatura ricombinazione H: 0.25 eV

$\approx 3000 \text{ K}$





# CMB



Energia ionizzazione H: 13.6 eV

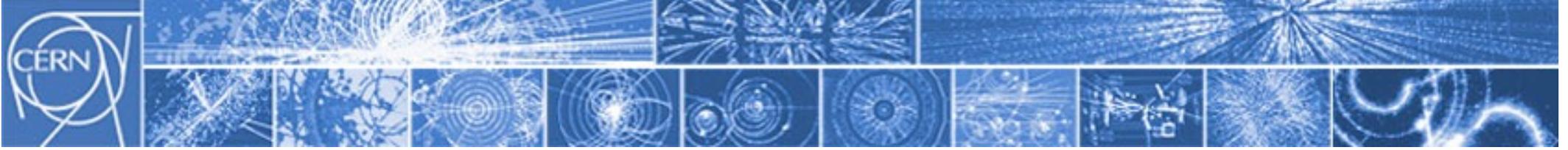


Temperatura ricombinazione H: 0.25 eV  
 $\approx 3000$  K

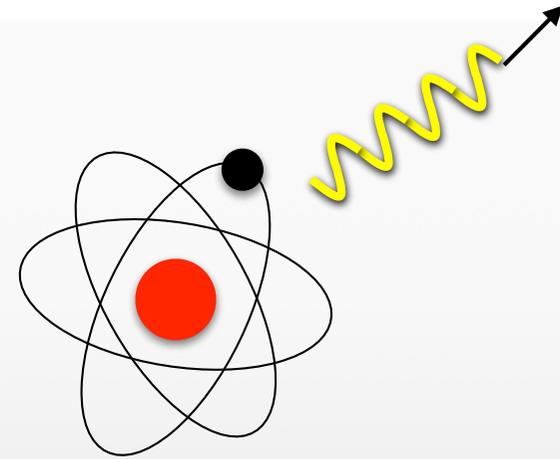
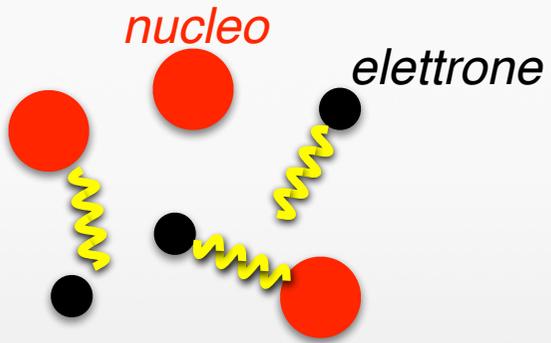


$z = 1100$

Temperatura oggi: 2.725 K



# CMB



Energia ionizzazione H: 13.6 eV

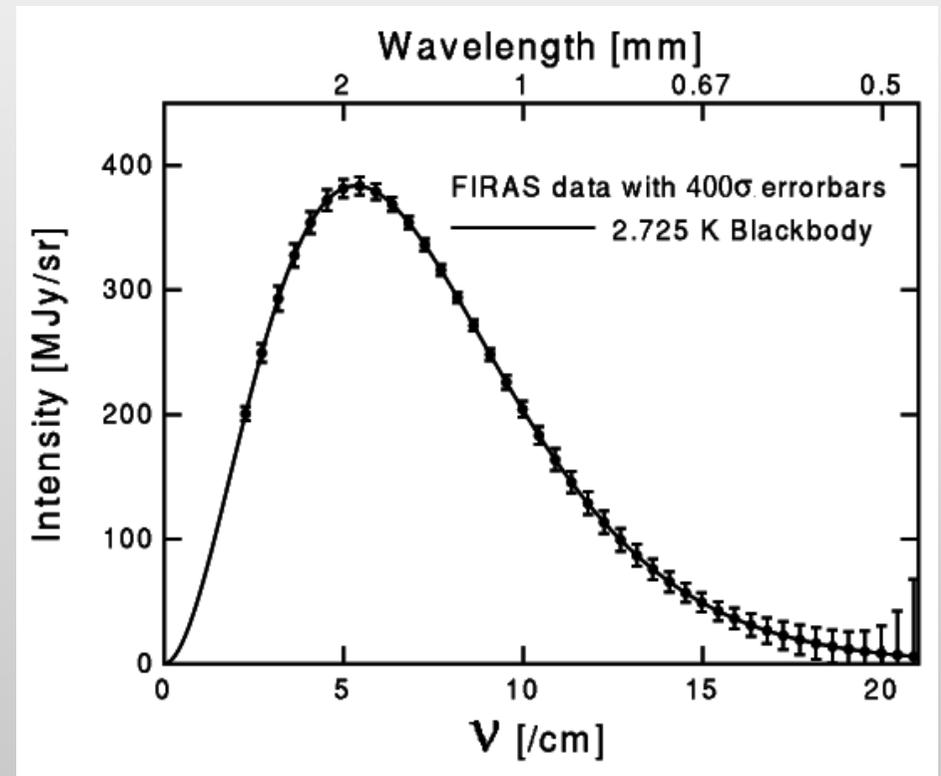


Temperatura ricombinazione H: 0.25 eV  
 $\approx 3000$  K

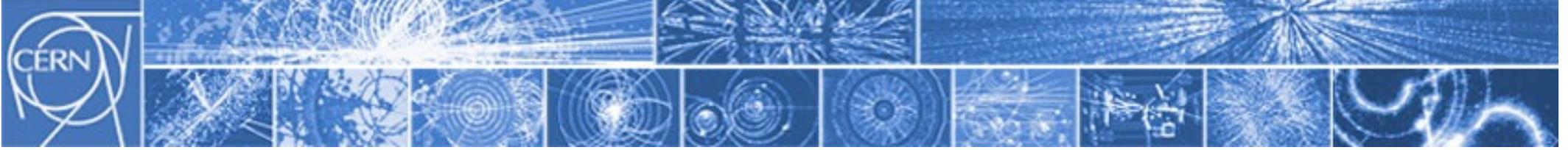


$z = 1100$

Temperatura oggi: 2.725 K

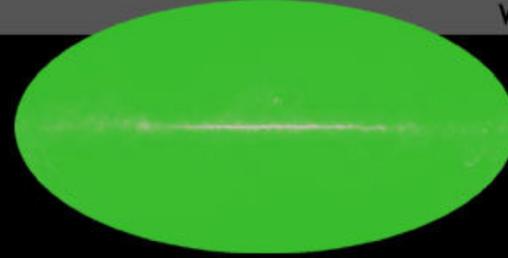
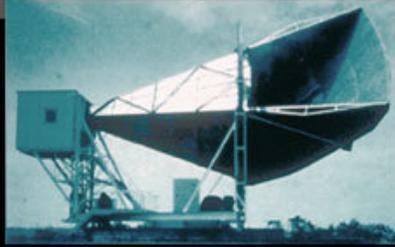


NB: 'Microwave' perché  $\lambda \sim 1$  mm, come il wifi, i GSM o il famoso forno (niente a che vedere con il micron, anche se, alla ricombinazione,  $\lambda \sim 1$   $\mu$ m!)



# CMB - storia

1965

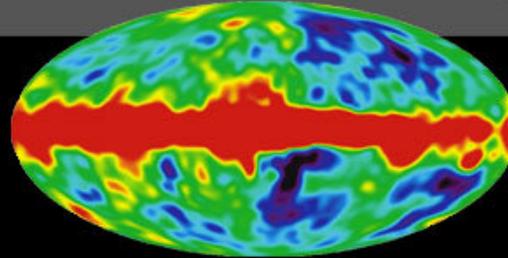


Penzias and Wilson

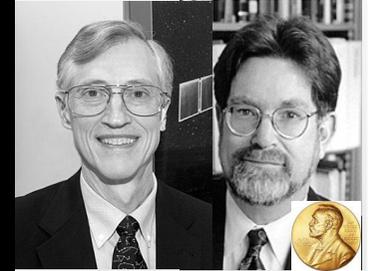


1978

1992

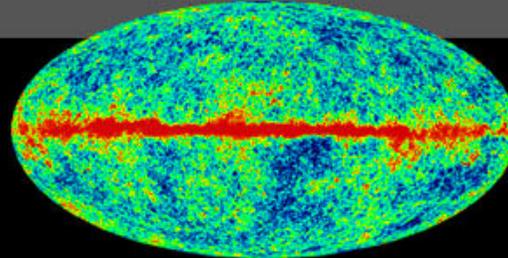
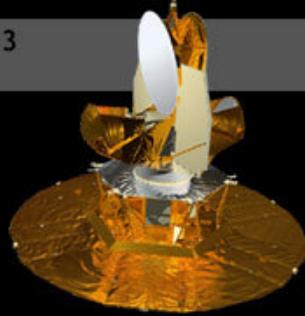


COBE



2006

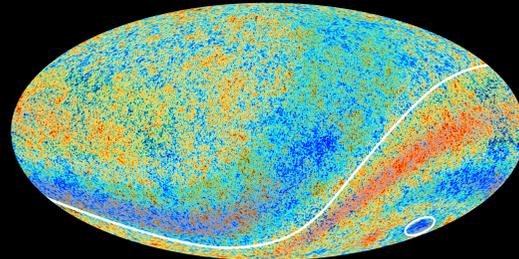
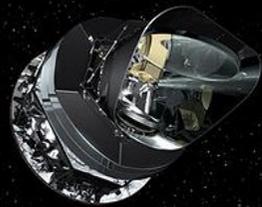
2003



WMAP

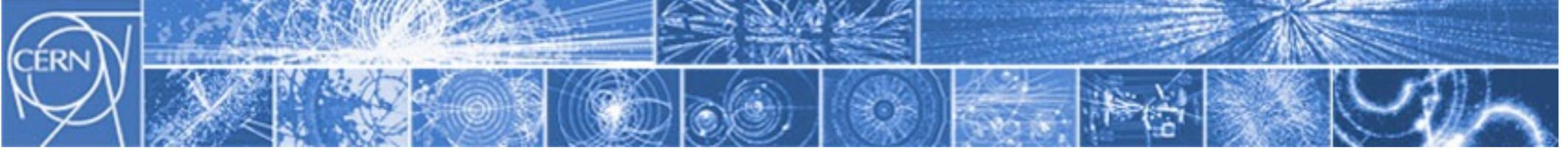


2013



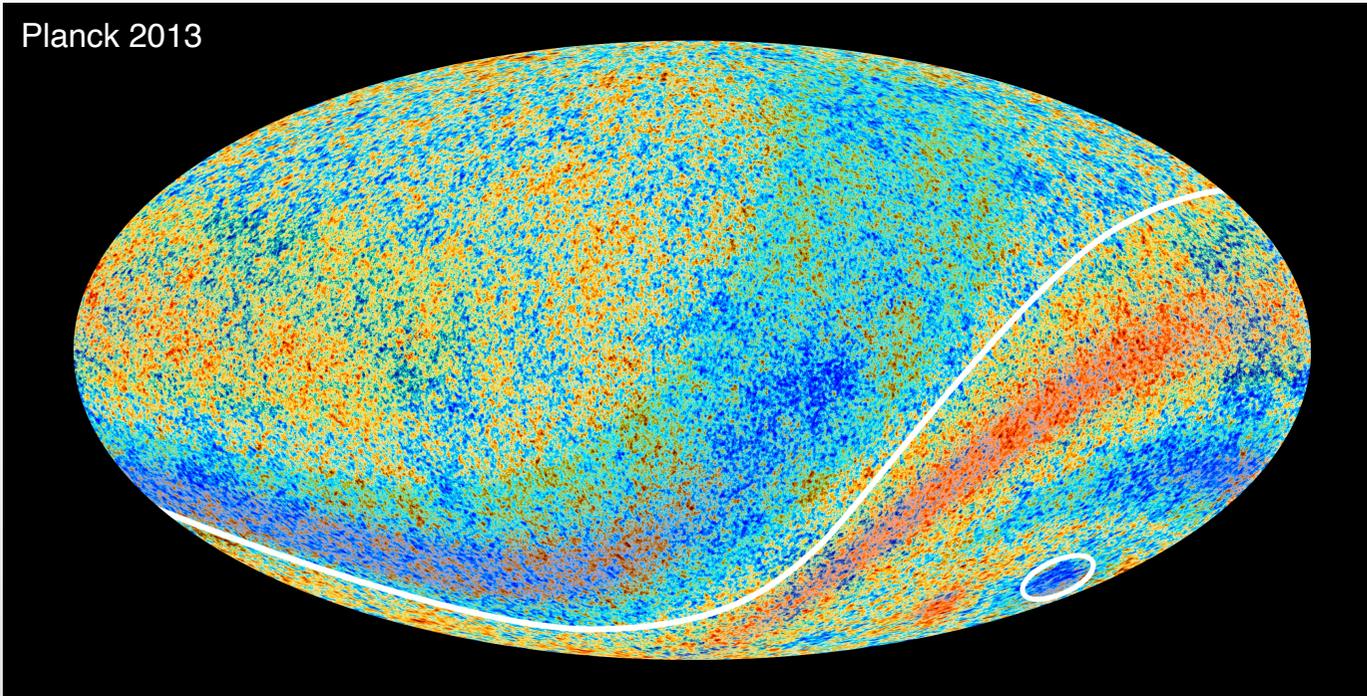
Planck

>200 scienziati  
IT+F+...



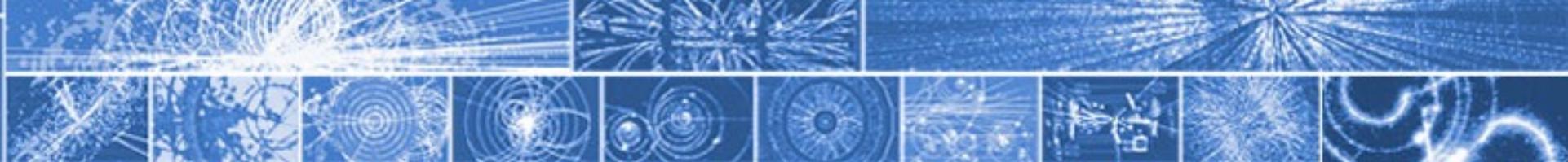
## CMB - fluttuazioni

Planck 2013



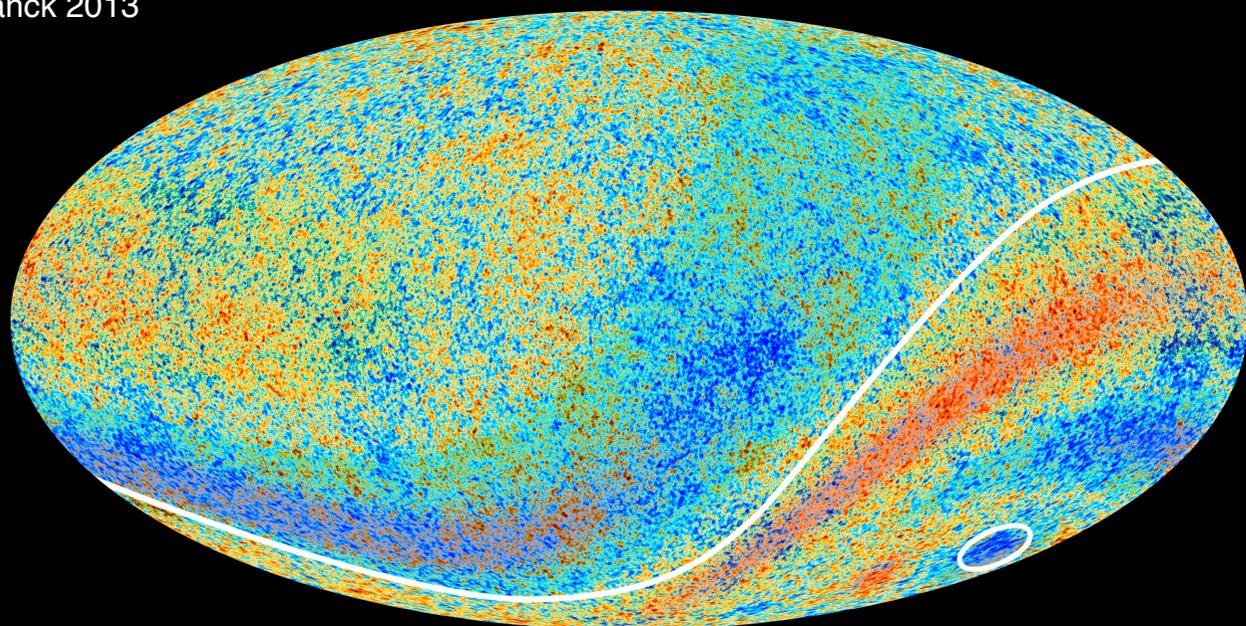
$$T = 2.725^{\circ} K$$

$$\frac{\delta T}{T} \sim 10^{-5}$$



# CMB - fluttuazioni

Planck 2013



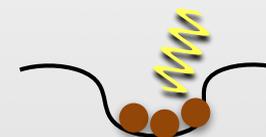
'cold spot'



maggiore densità  
maggiore perdita E  
(*'risalire la china'*)



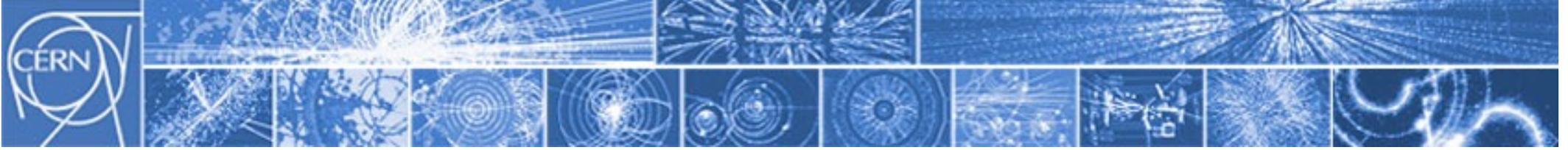
'hot spot'



minore densità  
minore perdita E

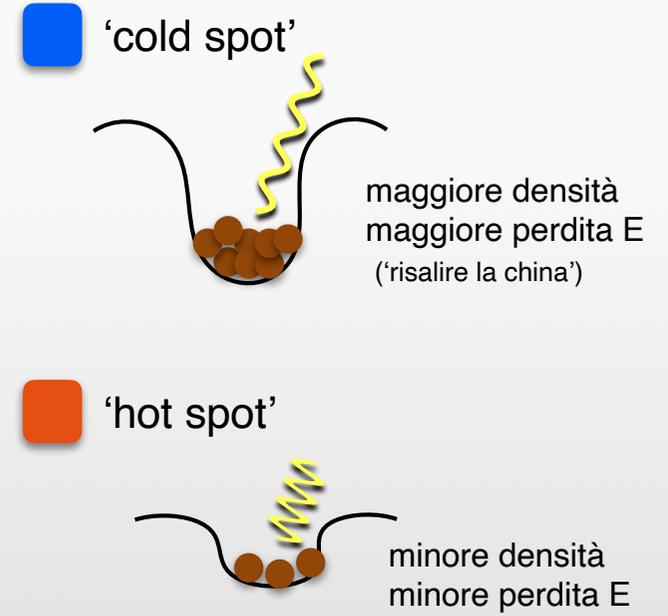
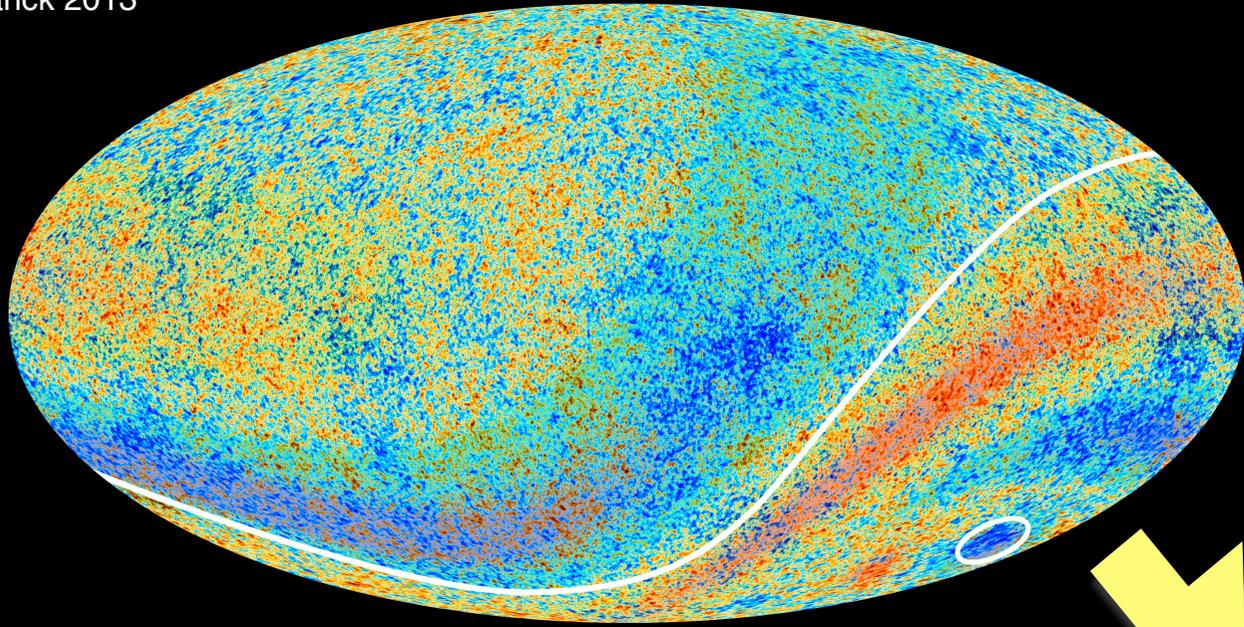
$$T = 2.725^{\circ} K$$

$$\frac{\delta T}{T} \sim 10^{-5}$$



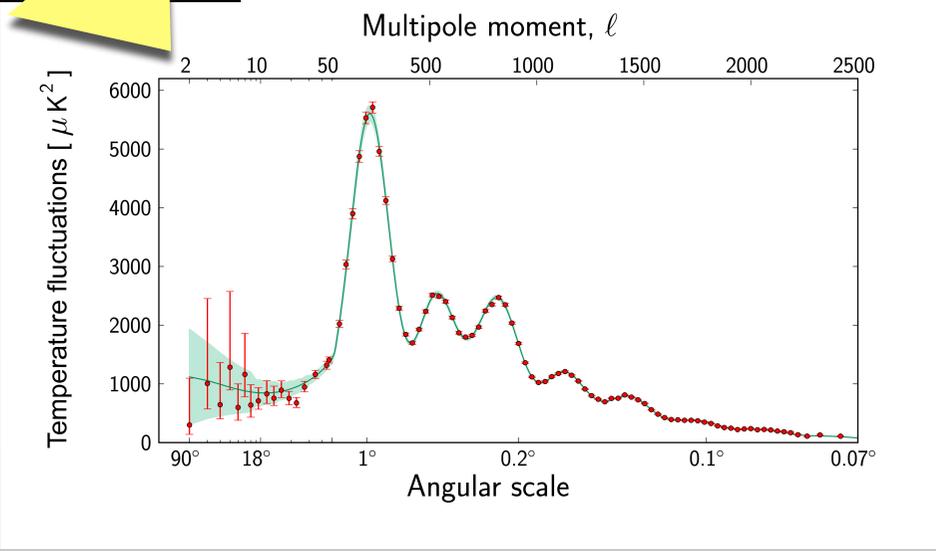
# CMB - fluttuazioni

Planck 2013

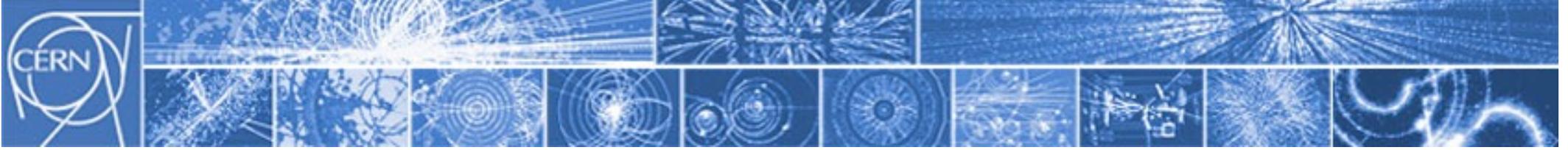


$$T = 2.725^\circ K$$

$$\frac{\delta T}{T} \sim 10^{-5}$$

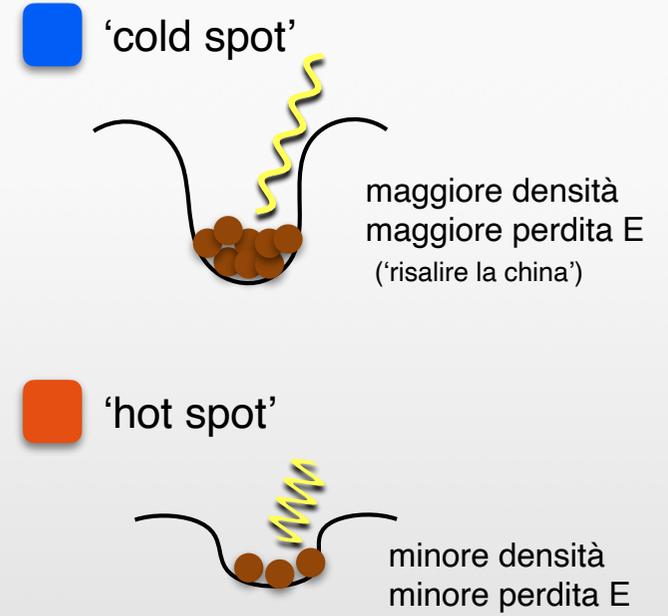
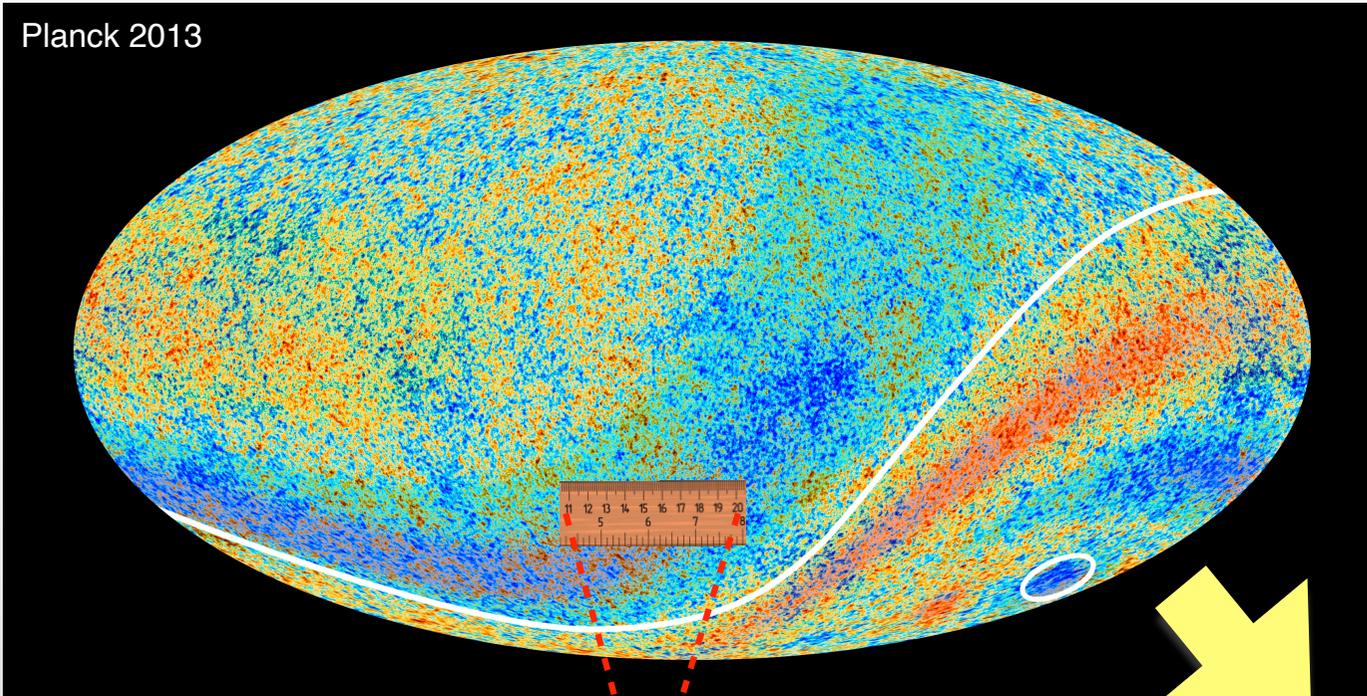


Spettro di potenza della CMB  
(CMB power spectrum)



# CMB - fluttuazioni

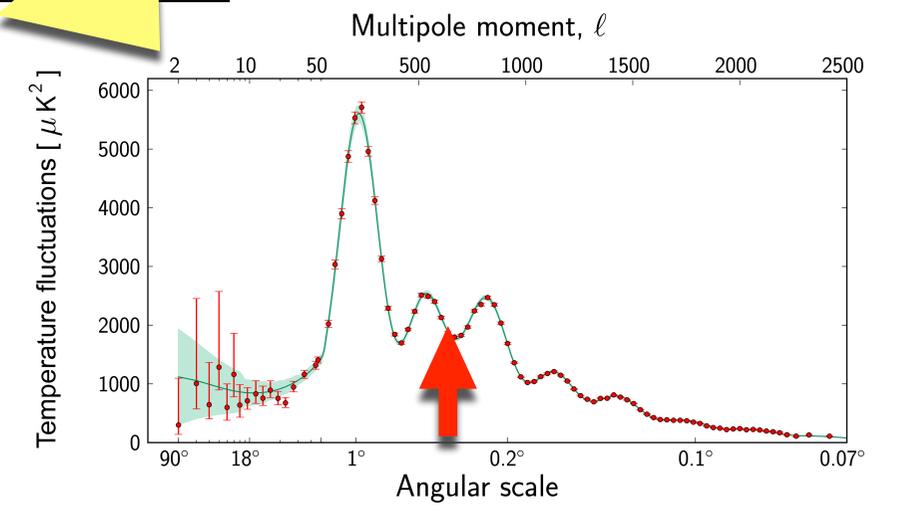
Planck 2013



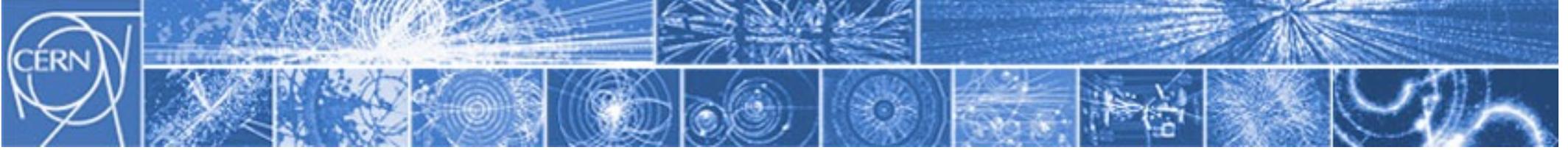
$$T = 2.725^{\circ} K$$

$$\frac{\delta T}{T} \sim 10^{-5}$$

0.5°

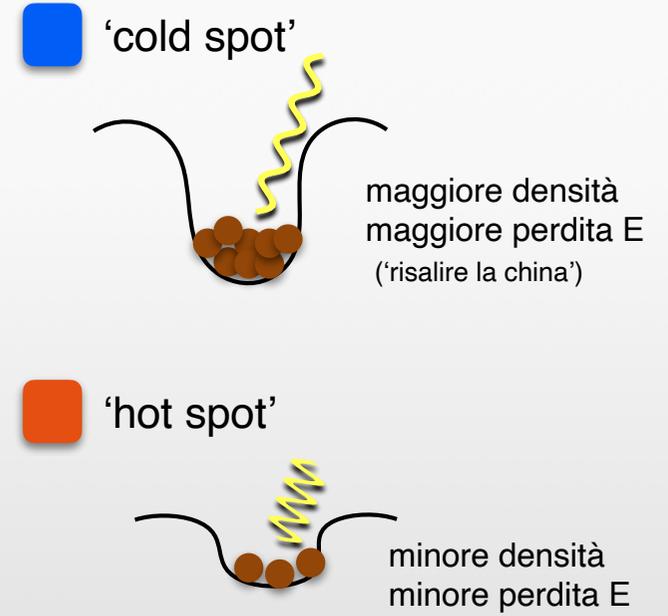
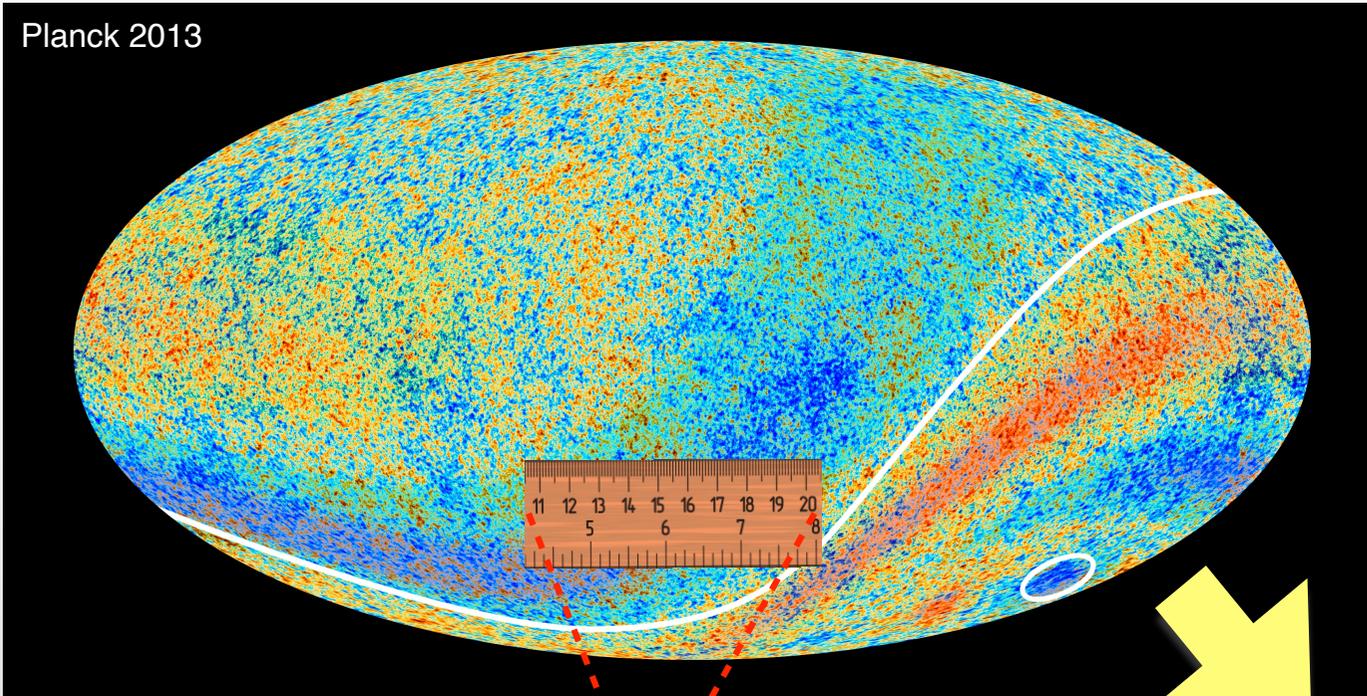


Spettro di potenza della CMB  
(CMB power spectrum)



# CMB - fluttuazioni

Planck 2013



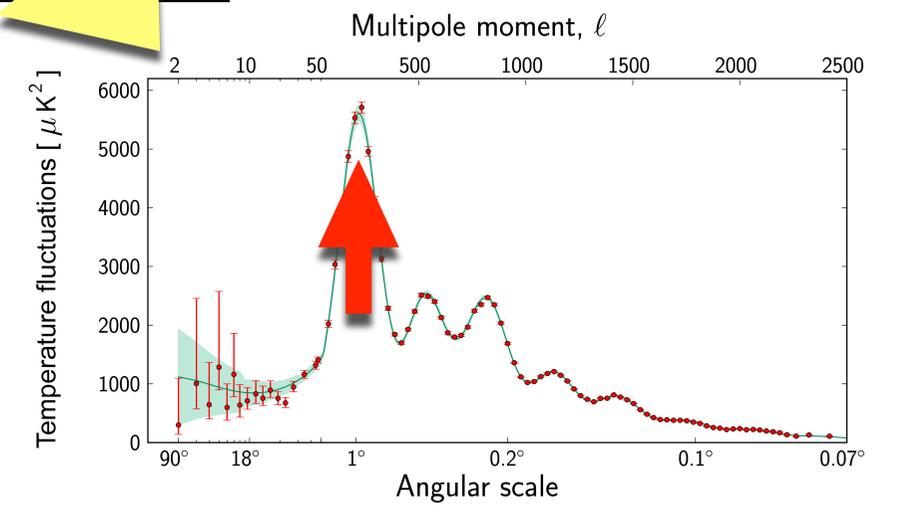
$$T = 2.725^{\circ}K$$

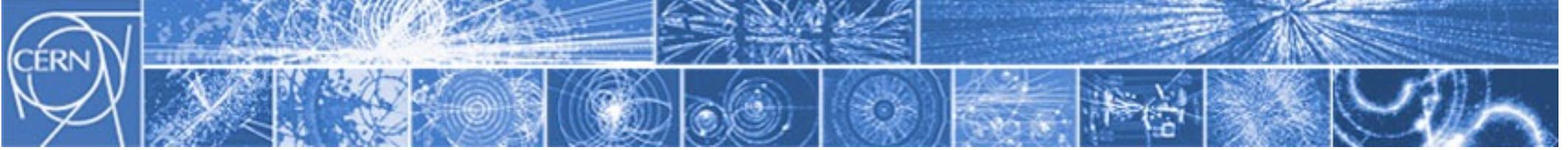
$$\frac{\delta T}{T} \sim 10^{-5}$$

1°

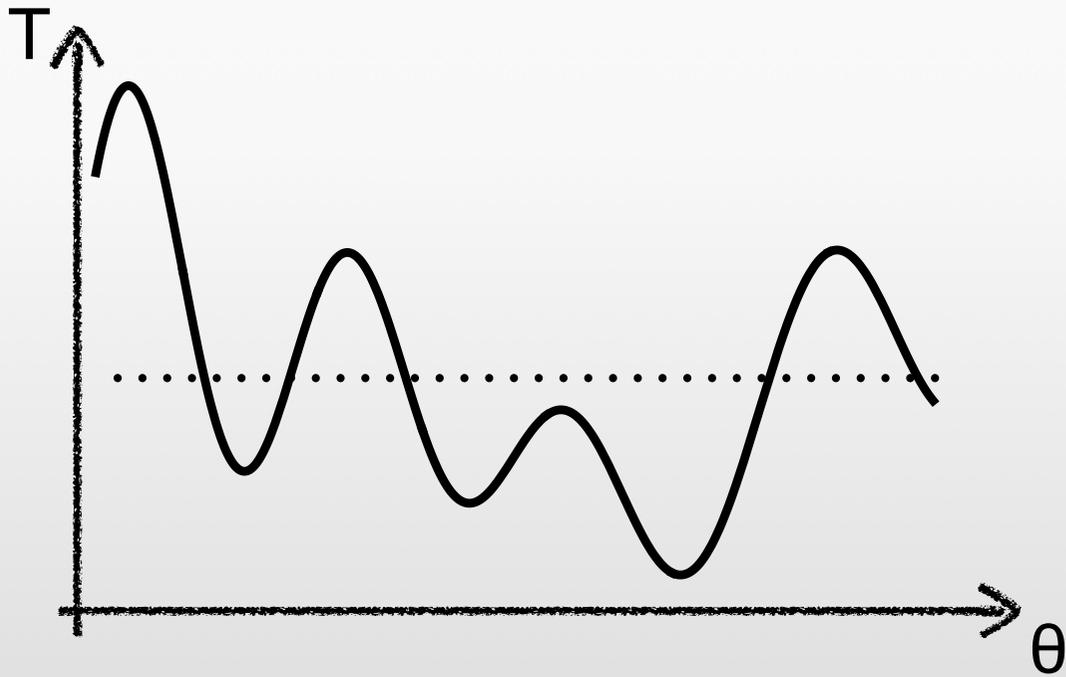


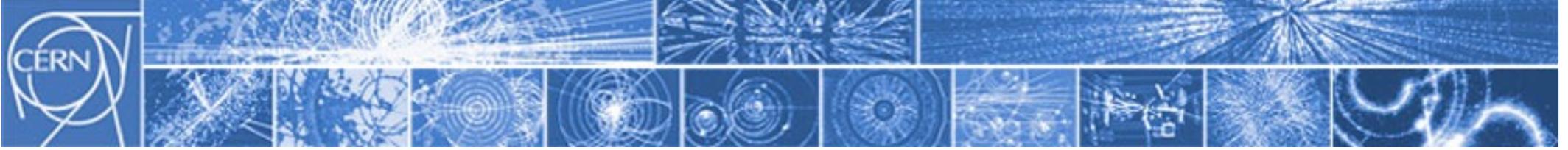
Spettro di potenza della CMB  
(CMB power spectrum)



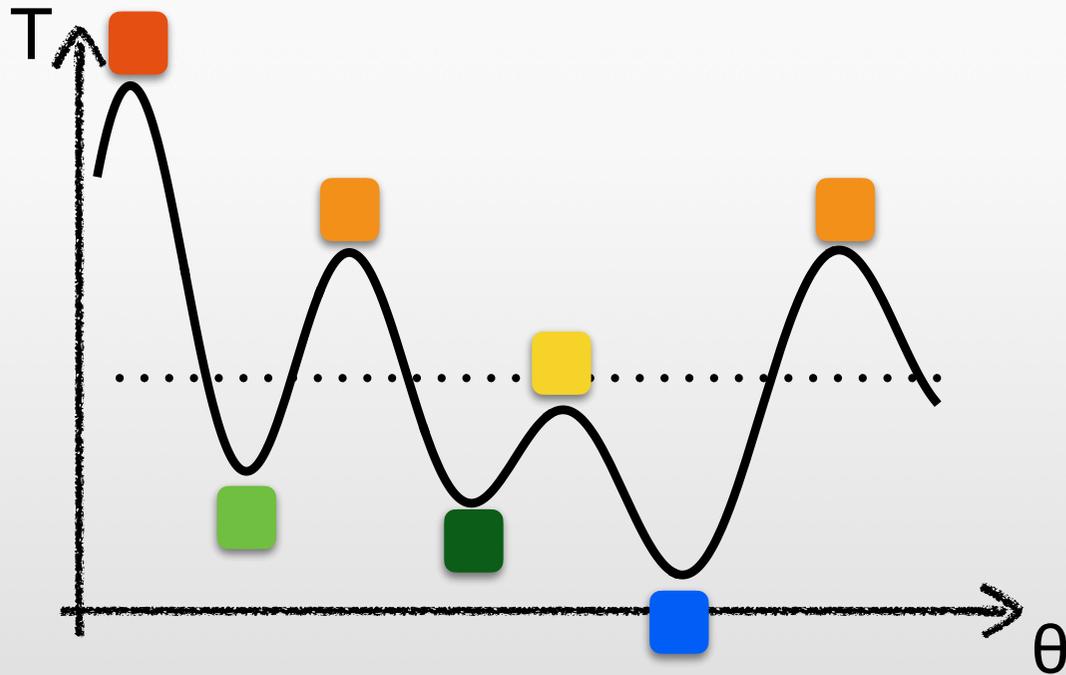


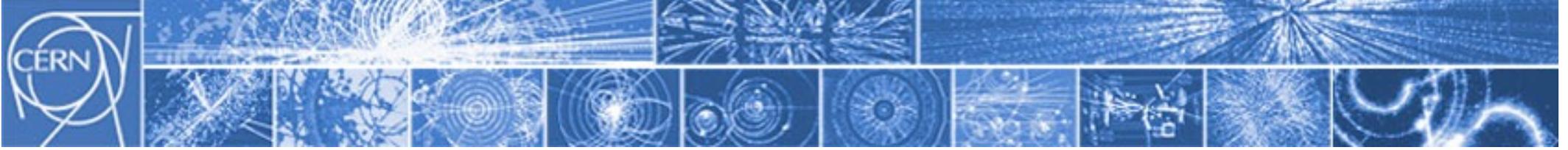
## Trasformata di Fourier *for dummies*



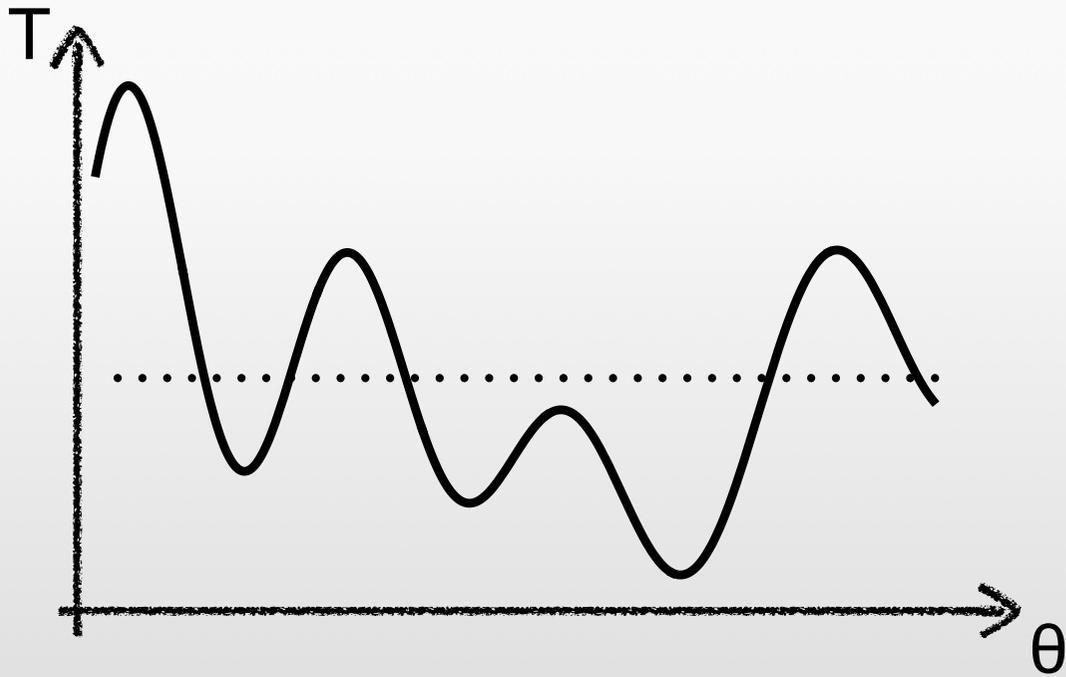


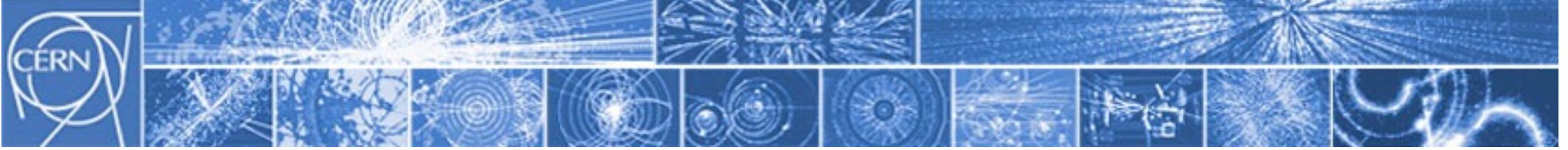
## Trasformata di Fourier *for dummies*



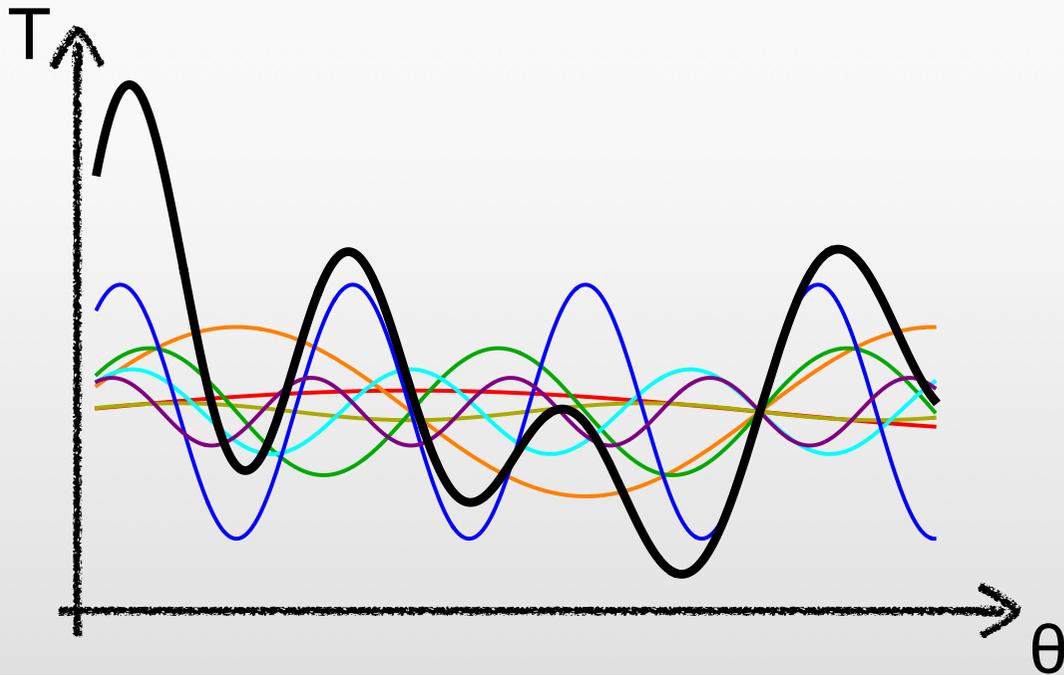


## Trasformata di Fourier *for dummies*

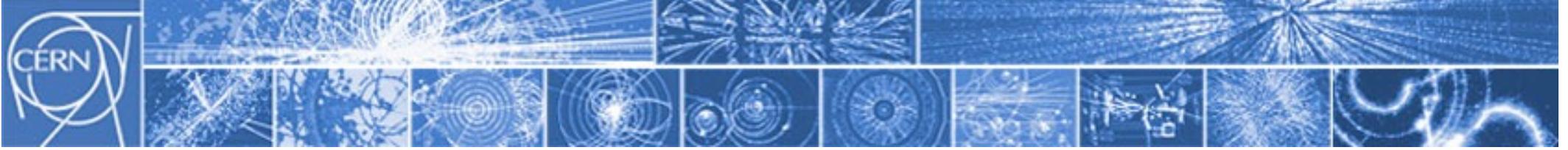




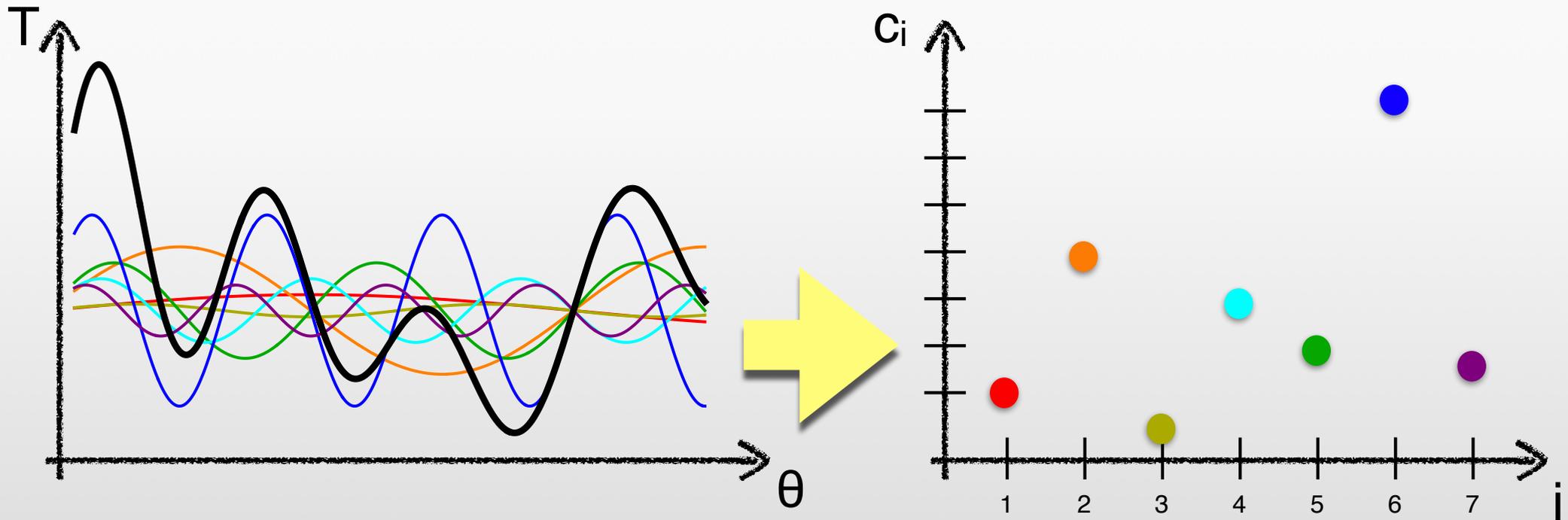
## Trasformata di Fourier for dummies



$$\sum_{i=1}^7 c_i \sin\left(\frac{i}{2}\theta\right)$$

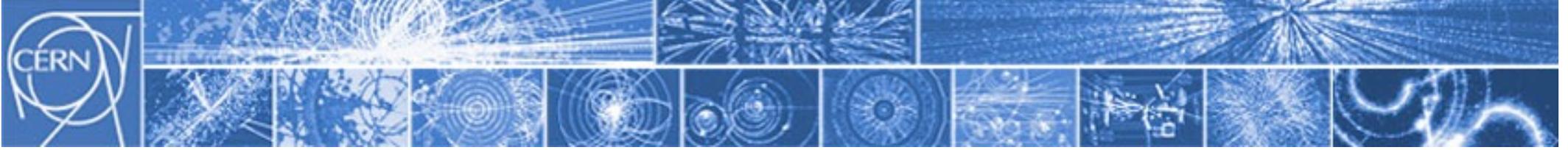


# Trasformata di Fourier for dummies

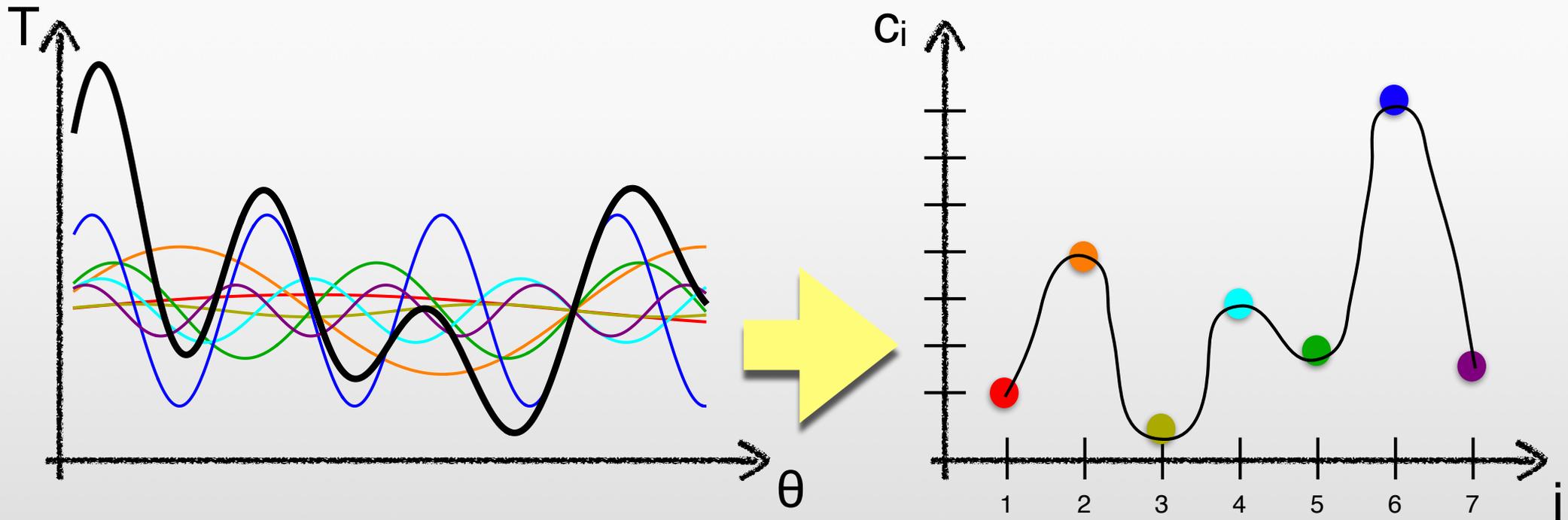


$$\sum_{i=1}^7 c_i \sin\left(\frac{i}{2}\theta\right)$$

- $c_1 = 0.5$
- $c_2 = 2$
- $c_3 = 0.2$
- $c_4 = 1.5$
- $c_5 = 1$
- $c_6 = 3$
- $c_7 = 0.8$

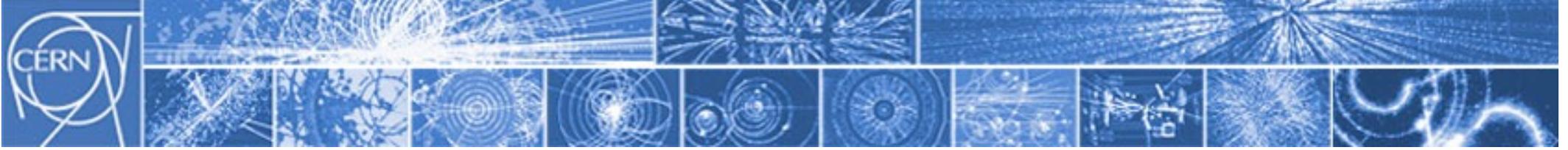


# Trasformata di Fourier for dummies

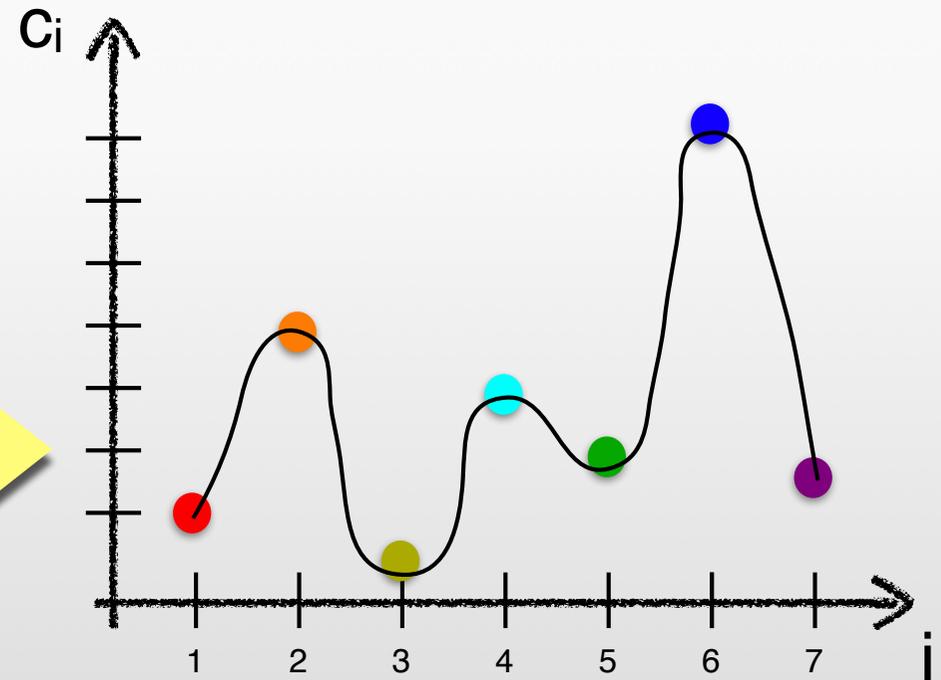
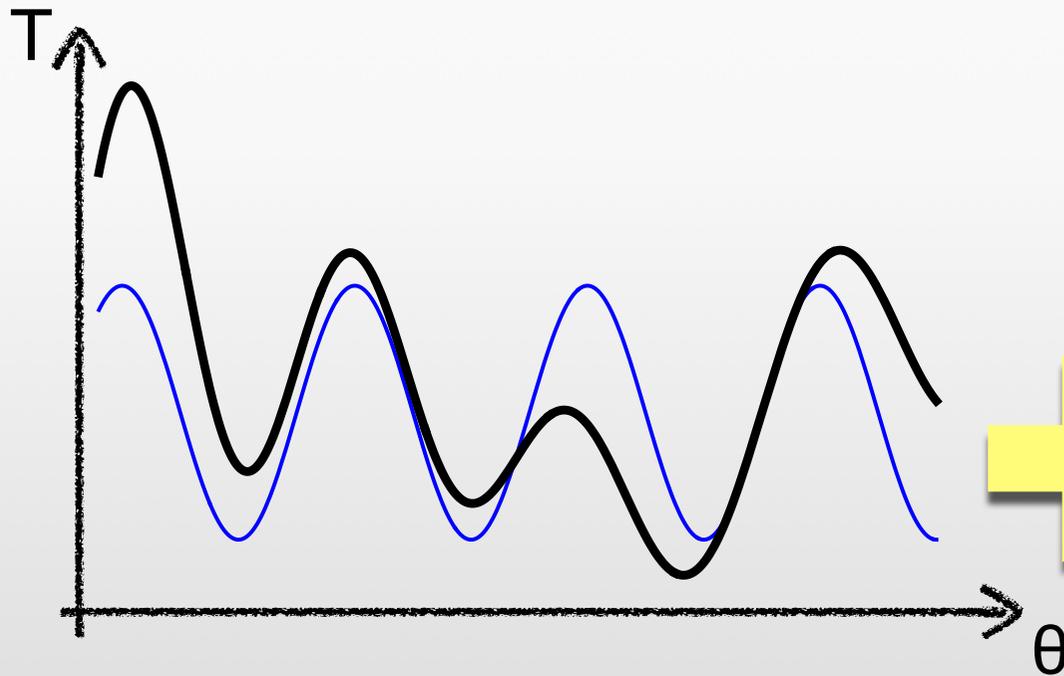


$$\sum_{i=1}^7 c_i \sin\left(\frac{i}{2}\theta\right)$$

- $c_1 = 0.5$
- $c_2 = 2$
- $c_3 = 0.2$
- $c_4 = 1.5$
- $c_5 = 1$
- $c_6 = 3$
- $c_7 = 0.8$



# Trasformata di Fourier for dummies



$$\sum_{i=1}^7 c_i \sin\left(\frac{i}{2}\theta\right)$$

$$c_1 = 0.5$$

$$c_2 = 2$$

$$c_3 = 0.2$$

$$c_4 = 1.5$$

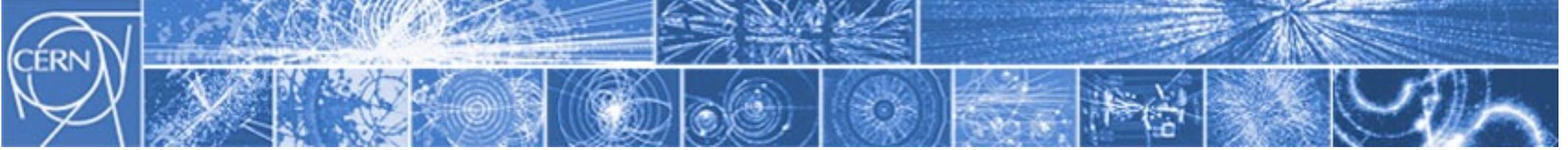
$$c_5 = 1$$

$$c_6 = 3$$

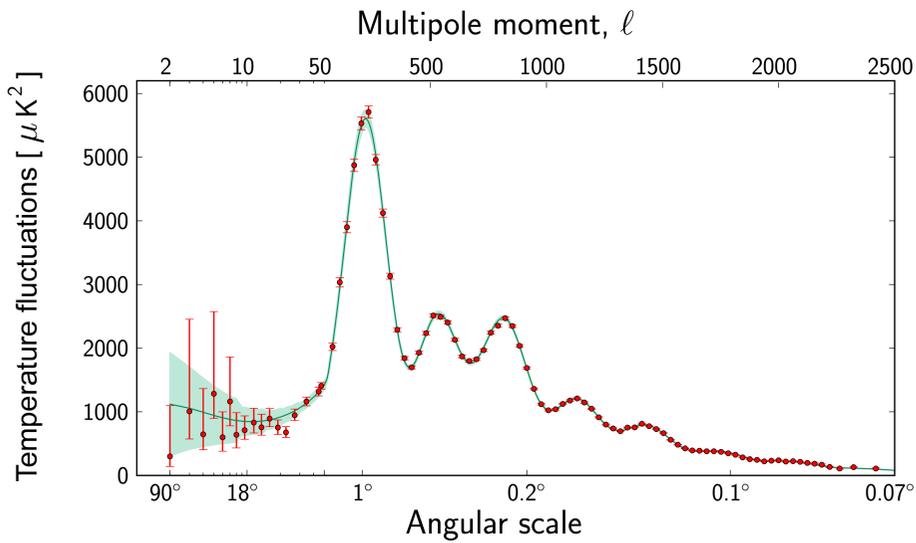
$$c_7 = 0.8$$

statisticamente, i picchi sono 'spesso' separati dal periodo blu:

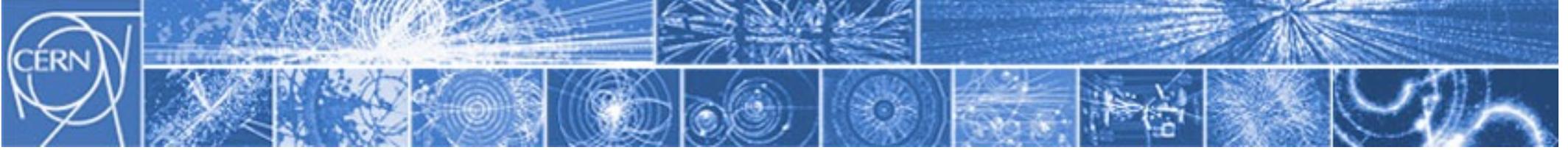
'elevata potenza' per il modo  $i=6$



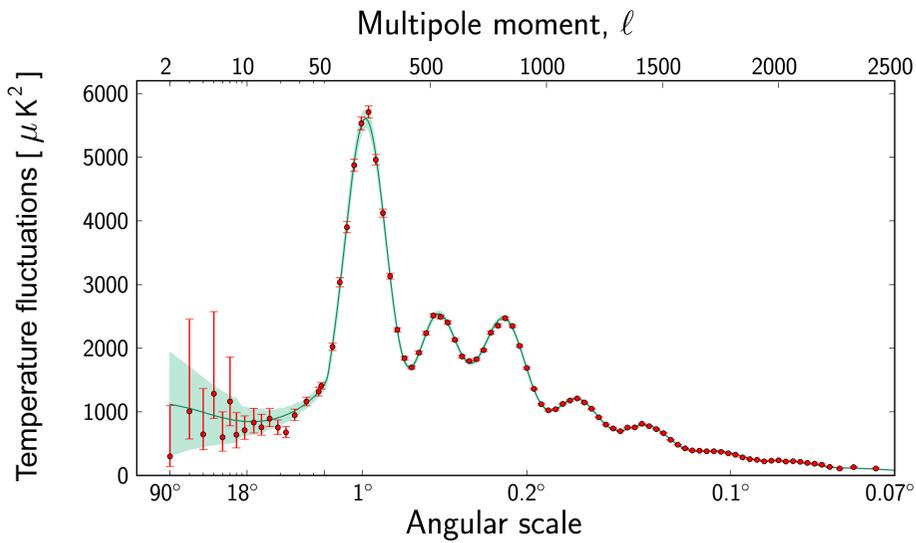
# CMB - fluttuazioni



Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo



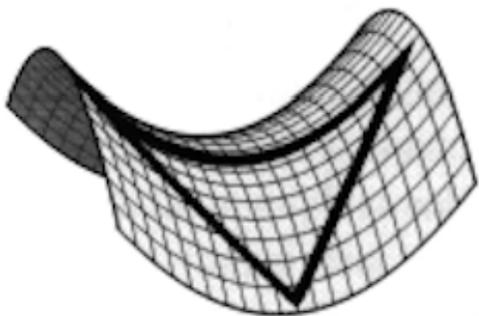
# CMB - fluttuazioni



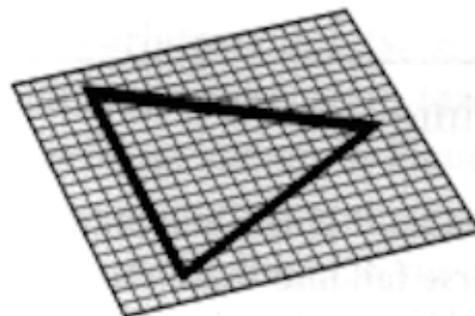
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

E.g.: curvatura dell'Universo

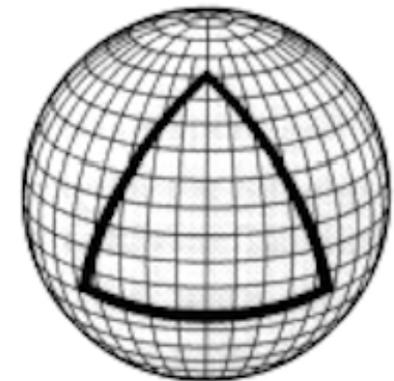
(somewhat oversimplified, but ok)



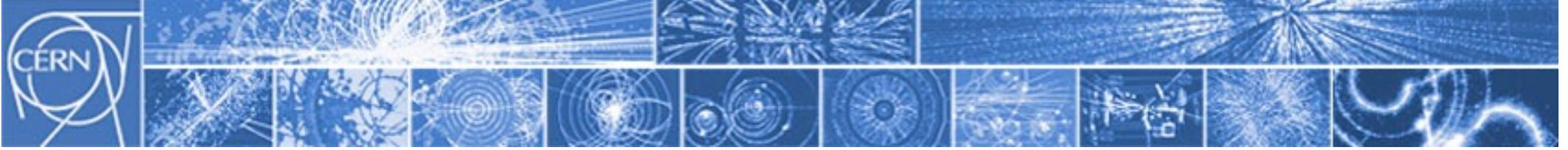
Negative Curvature



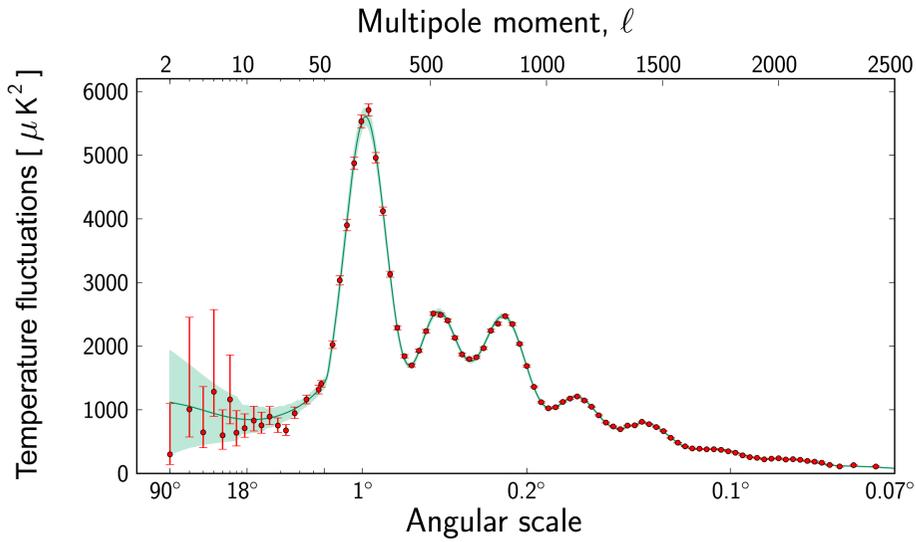
Flat Curvature



Positive Curvature

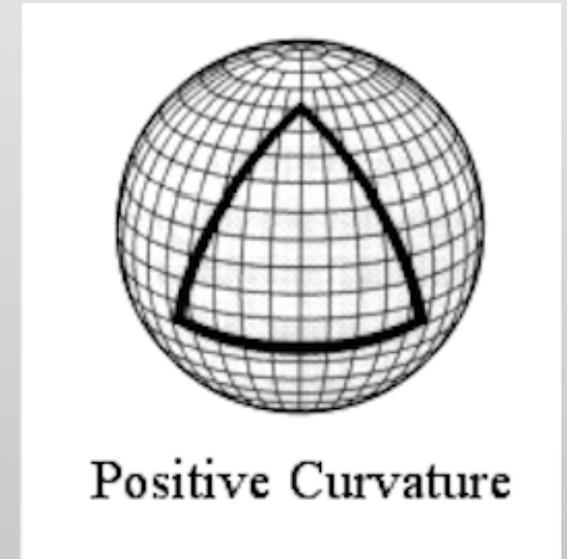
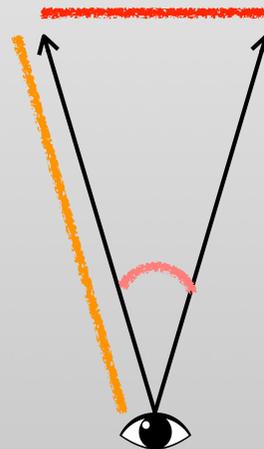
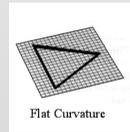


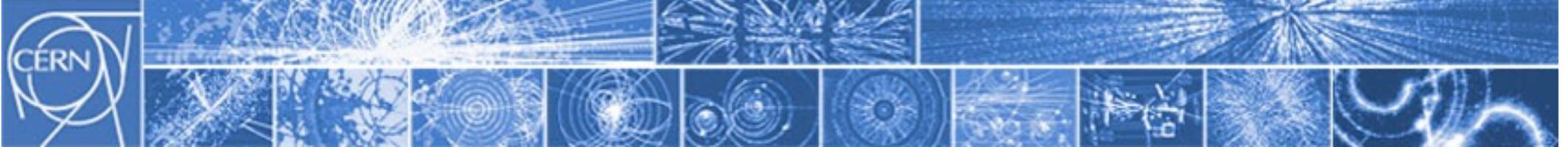
# CMB - fluttuazioni



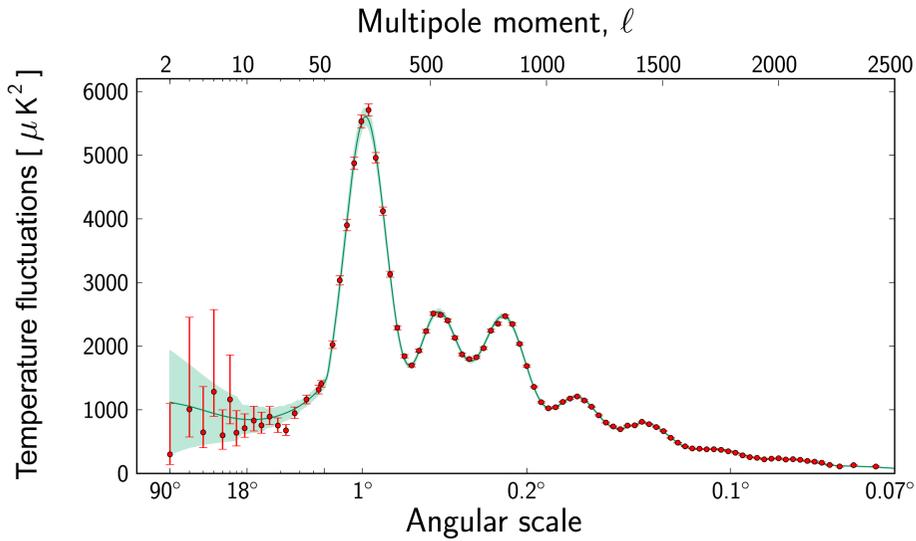
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

E.g.: curvatura dell'Universo



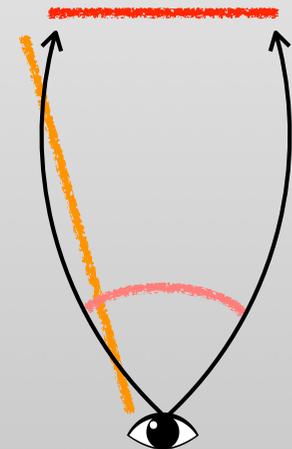
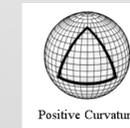
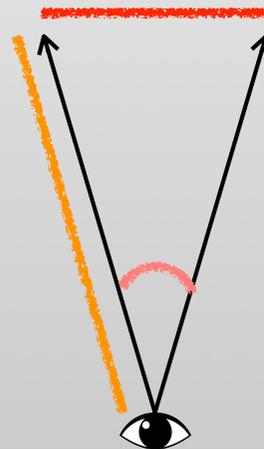
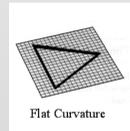


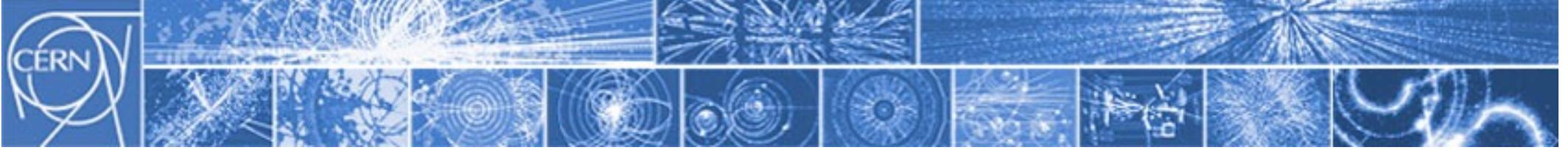
# CMB - fluttuazioni



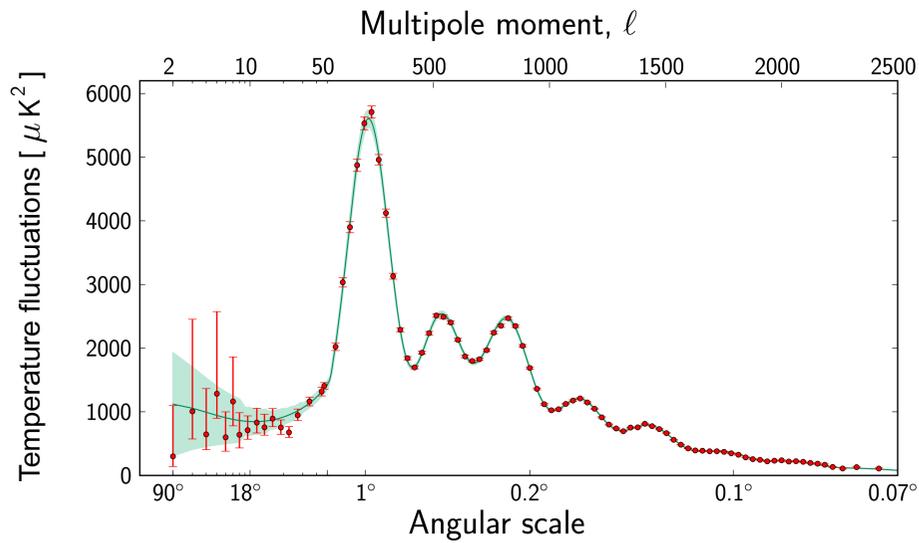
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

E.g.: curvatura dell'Universo





# CMB - fluttuazioni

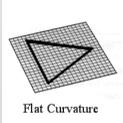
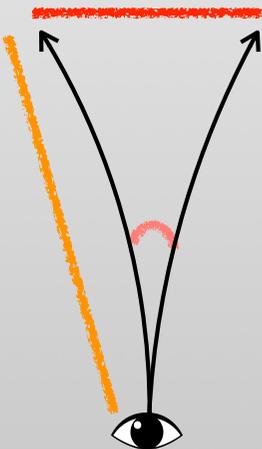


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

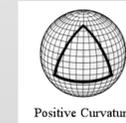
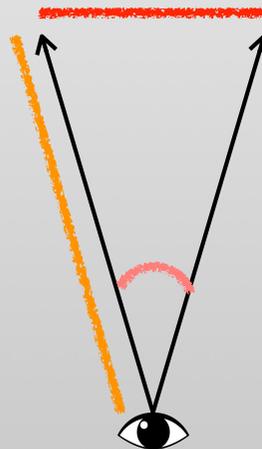
E.g.: curvatura dell'Universo



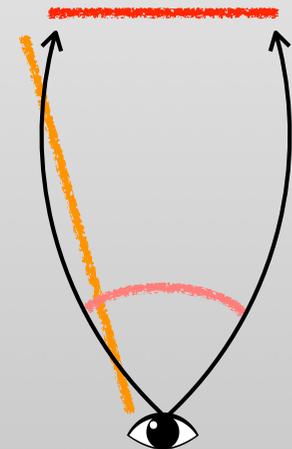
Negative Curvature

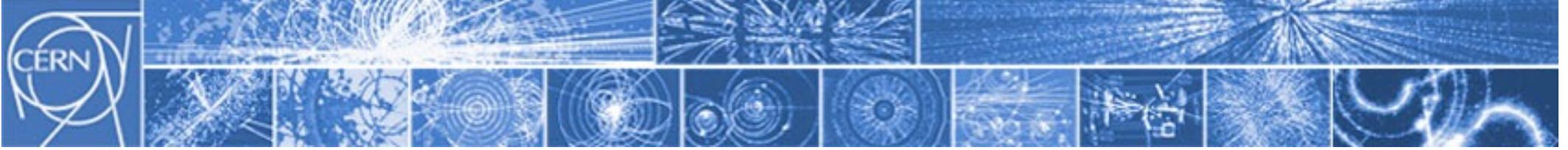


Flat Curvature

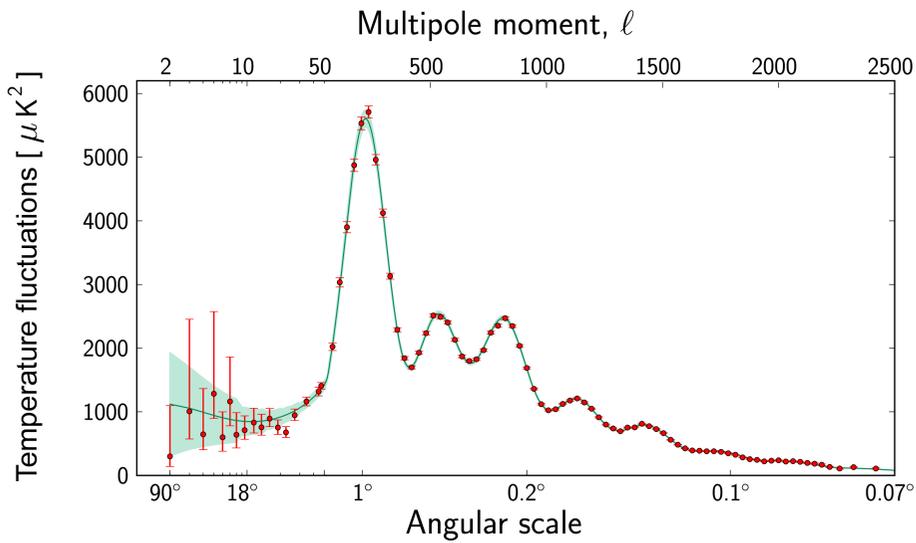


Positive Curvature





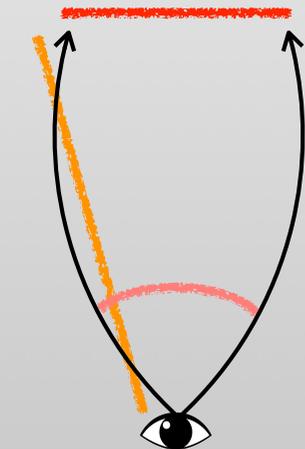
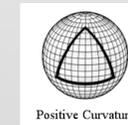
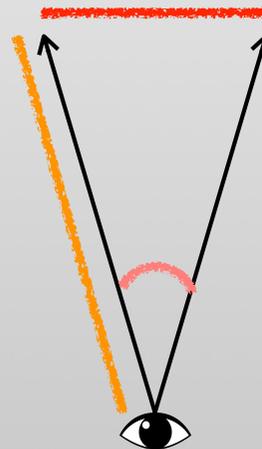
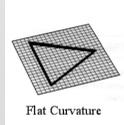
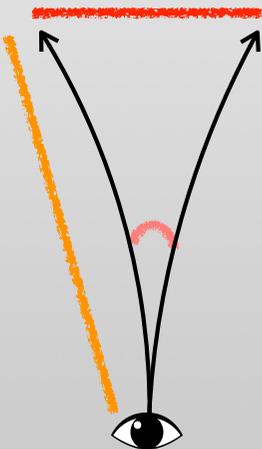
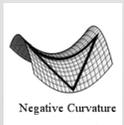
# CMB - fluttuazioni

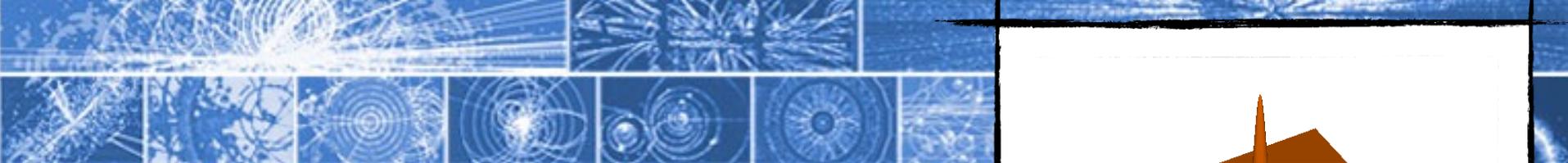


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

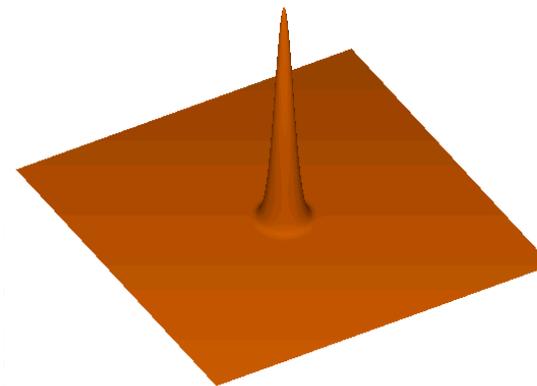
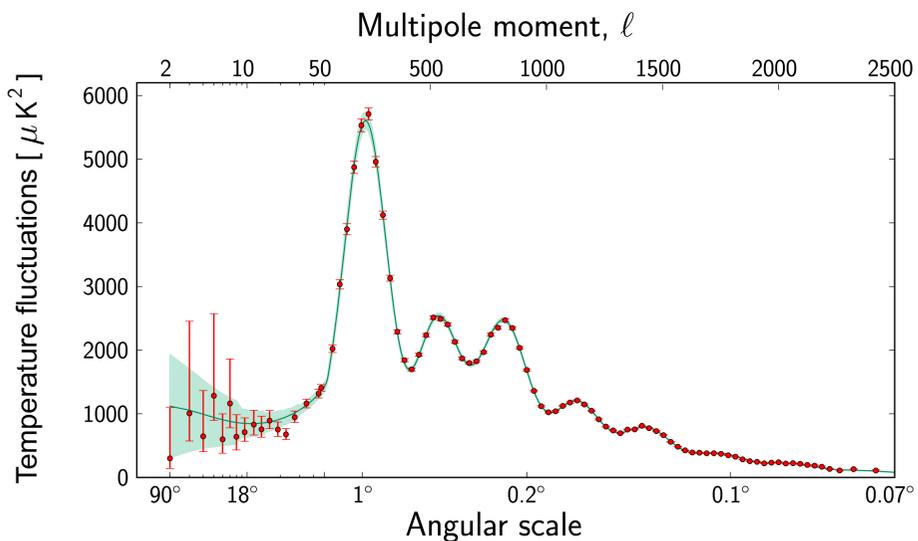
E.g.: curvatura dell'Universo

 lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione





# CMB - fluttuazioni

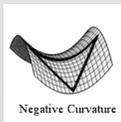


Lo spettro di un'eccezionale sulle proprietà

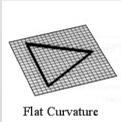
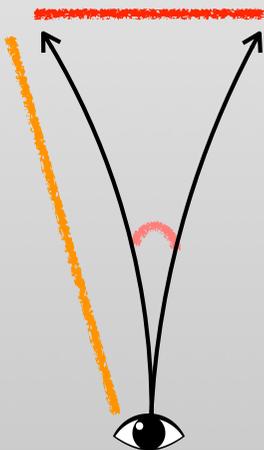
E.g.: curvatura dell'Universo



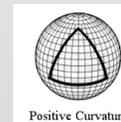
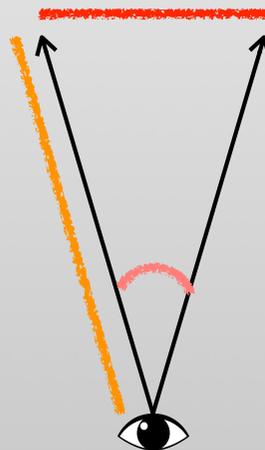
lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione



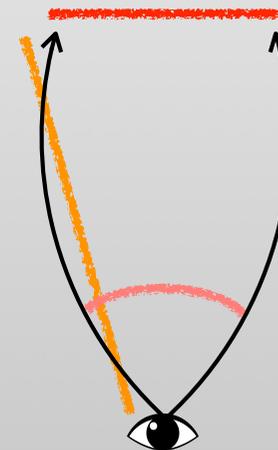
Negative Curvature



Flat Curvature

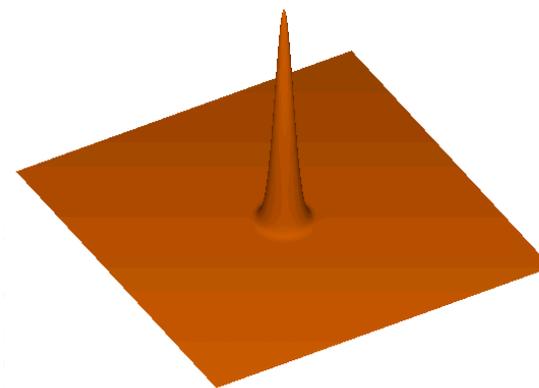
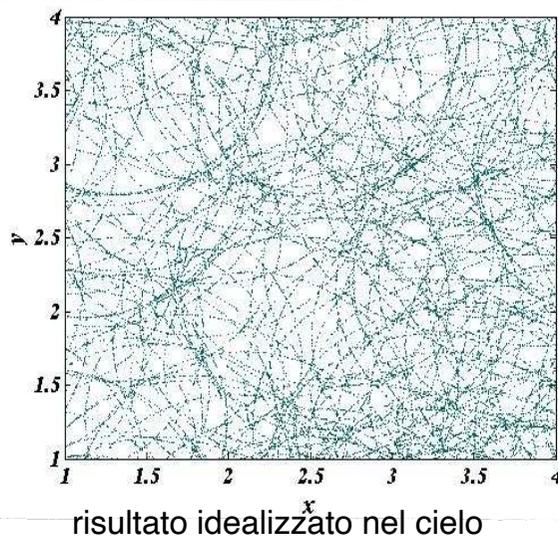
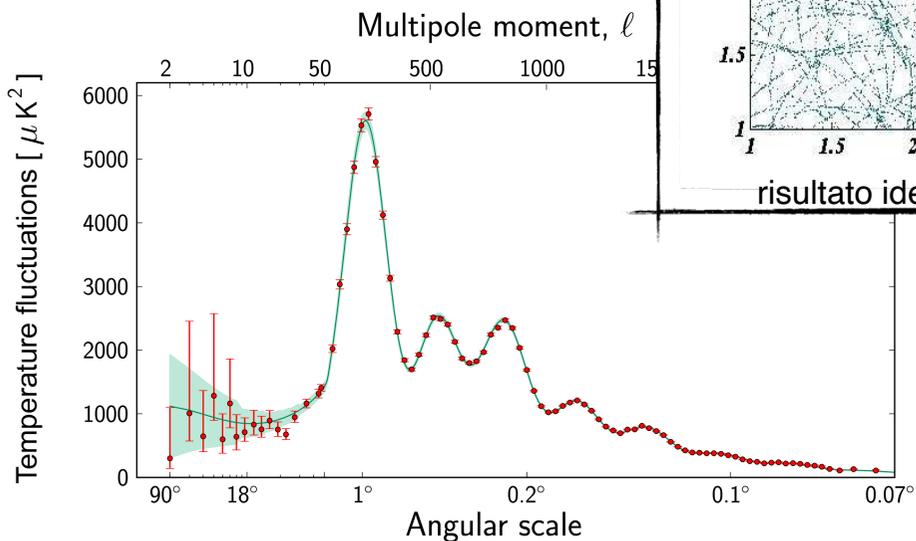


Positive Curvature





# CMB - fluttuazioni

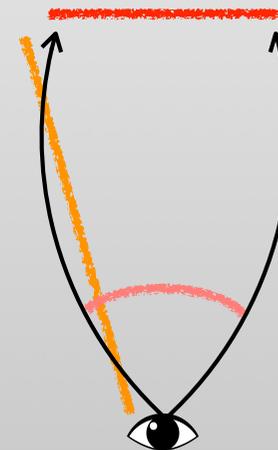
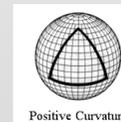
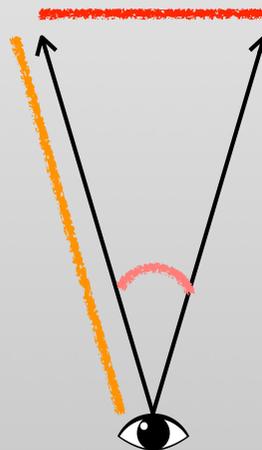
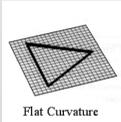
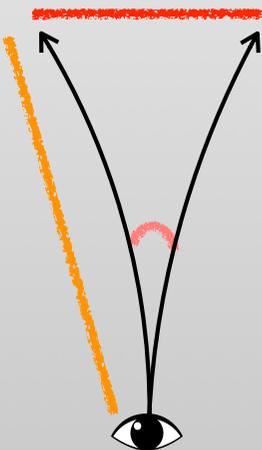
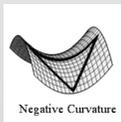


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## E.g.: curvatura dell'Universo

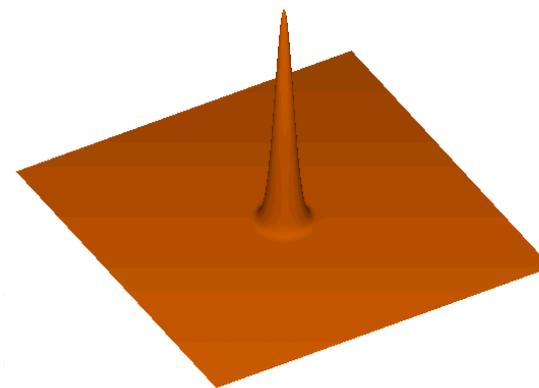
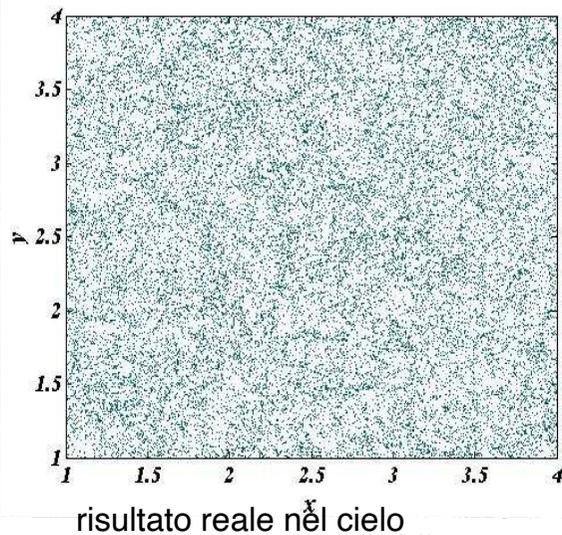
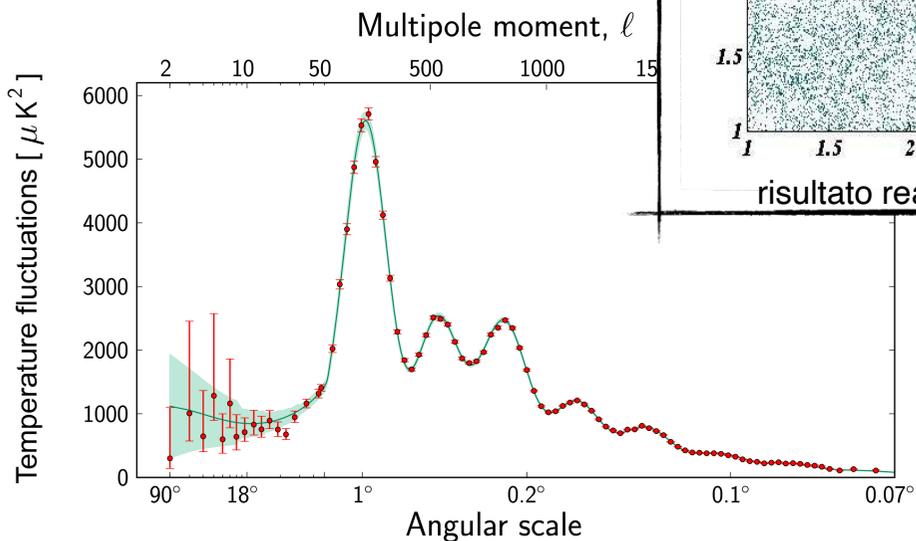


lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione





# CMB - fluttuazioni

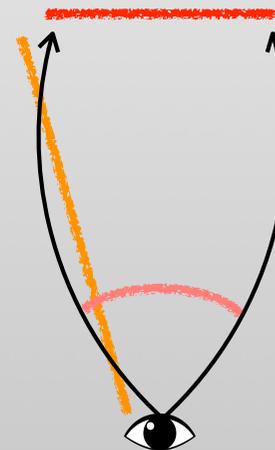
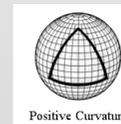
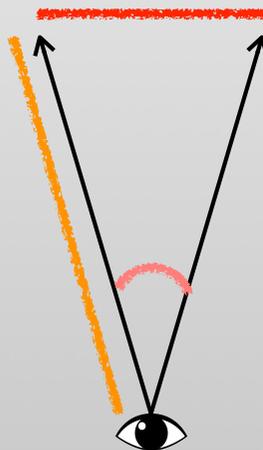
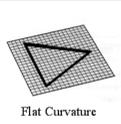
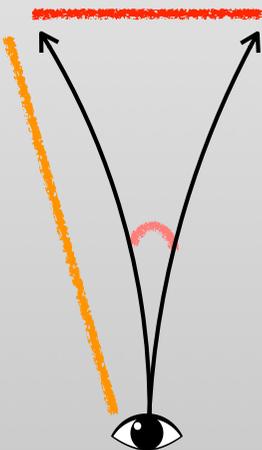
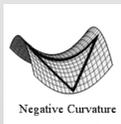


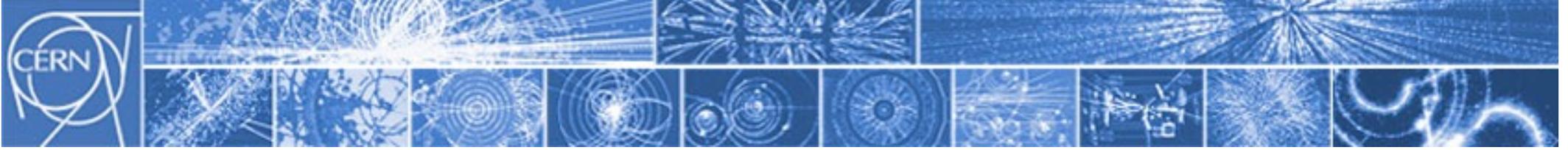
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## E.g.: curvatura dell'Universo

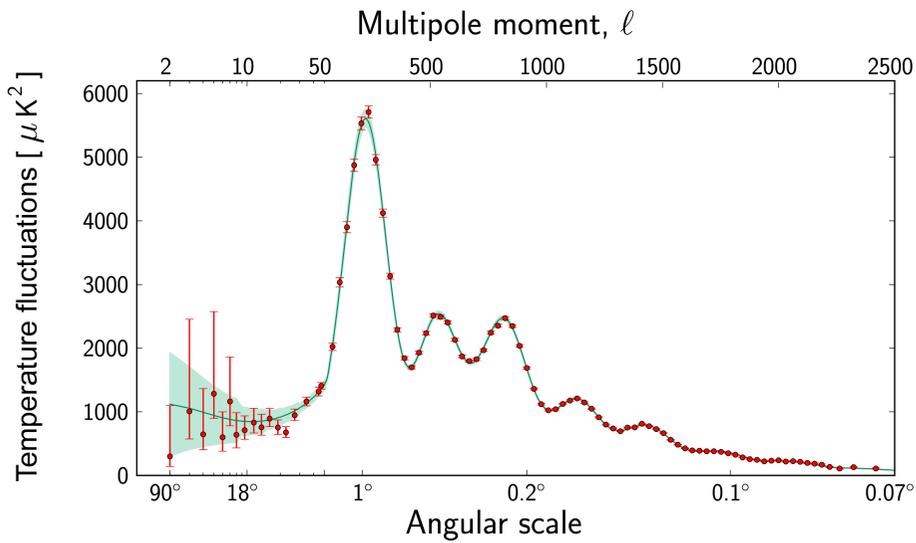


lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione





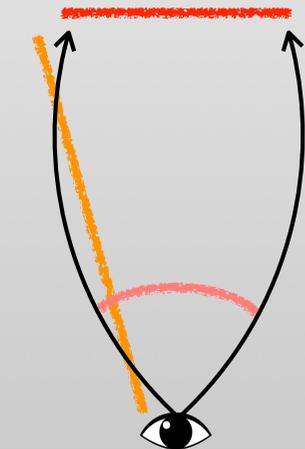
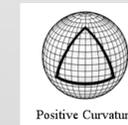
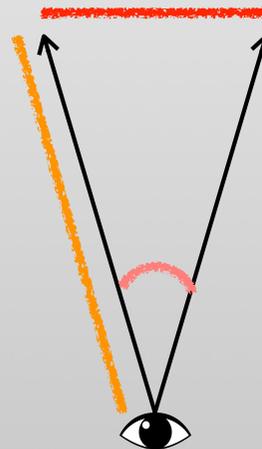
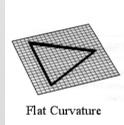
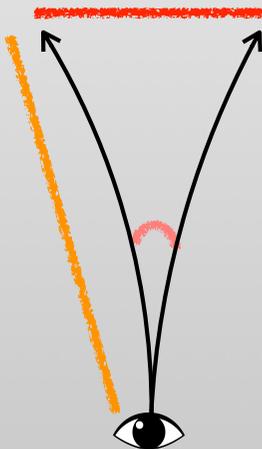
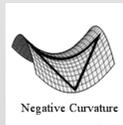
# CMB - fluttuazioni

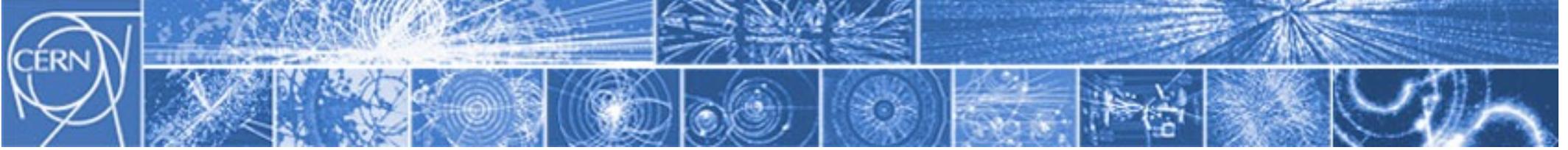


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

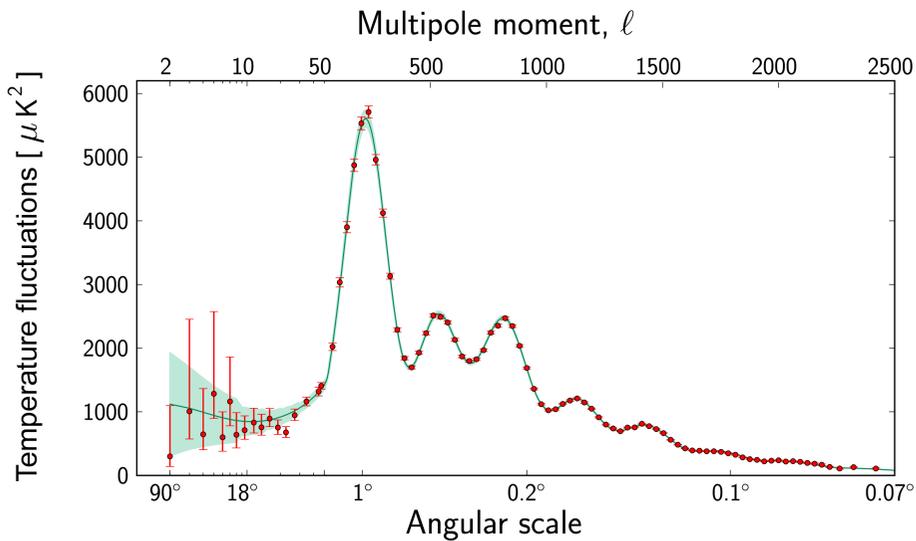
E.g.: curvatura dell'Universo

-  lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione
-  distanza nota: la distanza percorsa dai fotoni CMB fino ad oggi





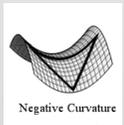
# CMB - fluttuazioni



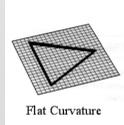
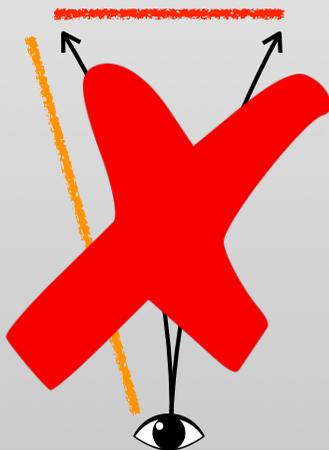
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

E.g.: curvatura dell'Universo

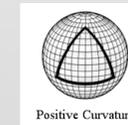
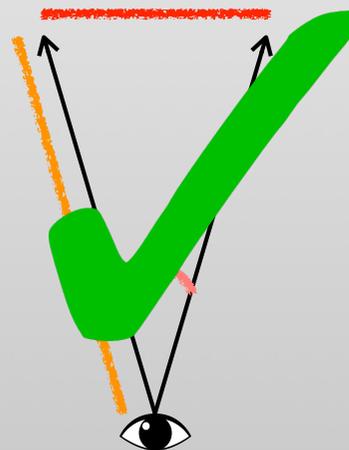
-  lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione
-  distanza nota: la distanza percorsa dai fotoni CMB fino ad oggi



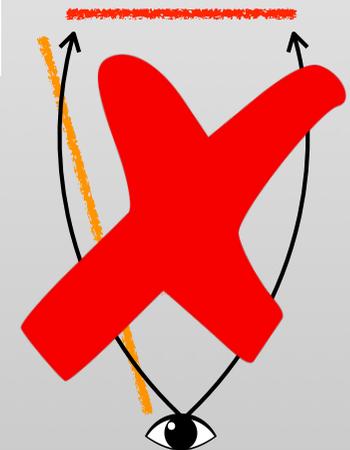
Negative Curvature

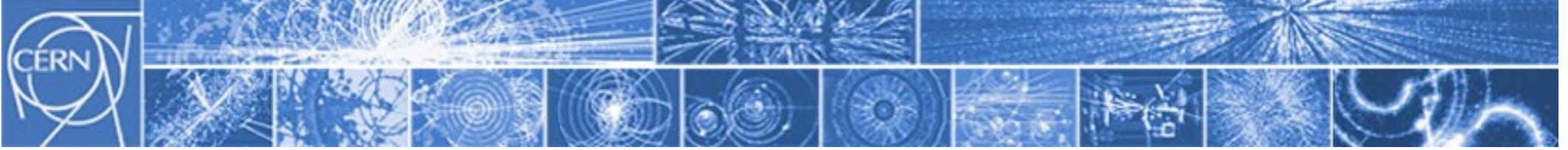


Flat Curvature

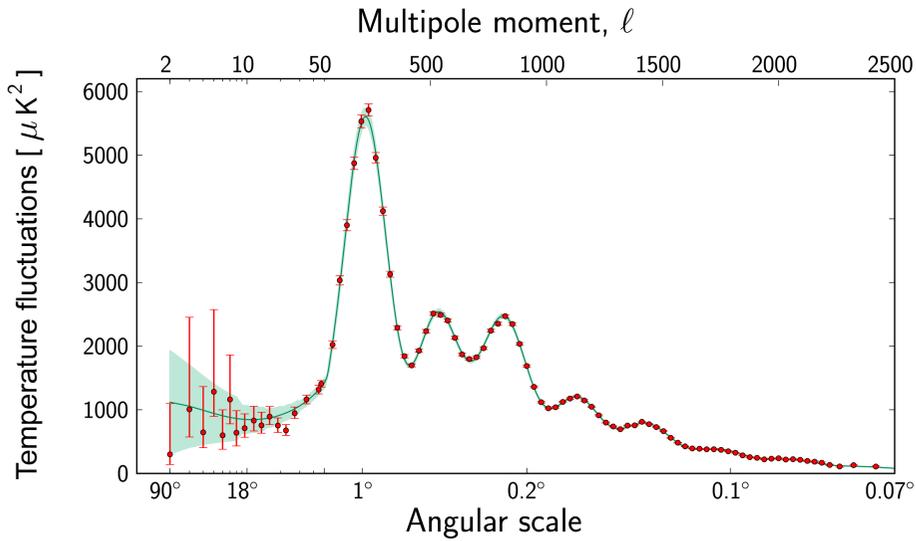


Positive Curvature





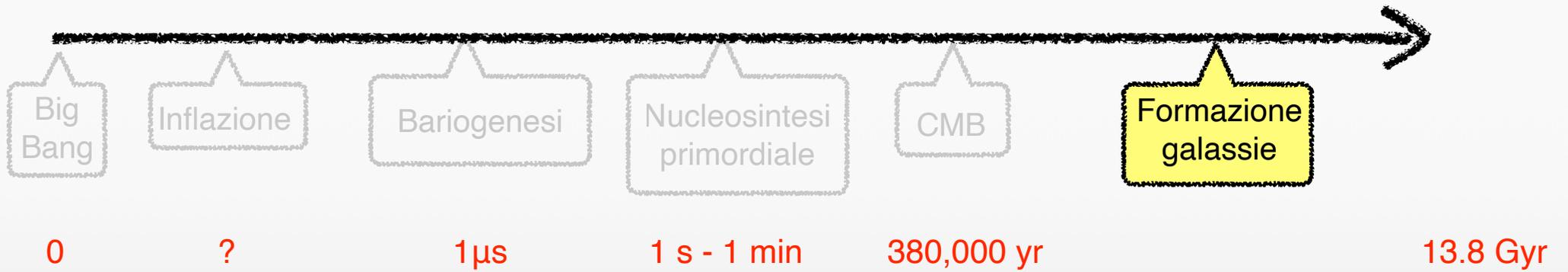
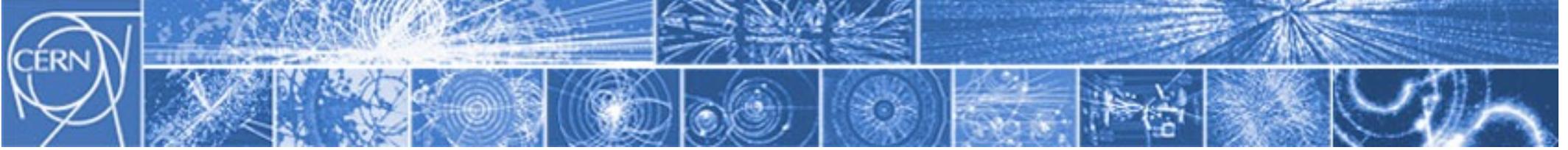
# CMB - fluttuazioni



Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

Parameter	TT+lowP 68 % limits
$\Omega_b h^2$	$0.02222 \pm 0.00023$
$\Omega_c h^2$	$0.1197 \pm 0.0022$
$100\theta_{MC}$	$1.04085 \pm 0.00047$
$\tau$	$0.078 \pm 0.019$
$\ln(10^{10} A_s)$	$3.089 \pm 0.036$
$n_s$	$0.9655 \pm 0.0062$
$H_0$	$67.31 \pm 0.96$
$\Omega_\Lambda$	$0.685 \pm 0.013$
$\Omega_m$	$0.315 \pm 0.013$
$\Omega_m h^2$	$0.1426 \pm 0.0020$
$\Omega_m h^3$	$0.09597 \pm 0.00045$
$\sigma_8$	$0.829 \pm 0.014$
$\sigma_8 \Omega_m^{0.5}$	$0.466 \pm 0.013$
$\sigma_8 \Omega_m^{0.25}$	$0.621 \pm 0.013$
$z_{re}$	$9.9^{+1.8}_{-1.6}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$
$10^9 A_s e^{-2\tau}$	$1.880 \pm 0.014$
Age/Gyr	$13.813 \pm 0.038$
$z_*$	$1090.09 \pm 0.42$
$r_*$	$144.61 \pm 0.49$
$100\theta_*$	$1.04105 \pm 0.00046$
$z_{drag}$	$1059.57 \pm 0.46$
$r_{drag}$	$147.33 \pm 0.49$
$k_D$	$0.14050 \pm 0.00052$
$z_{eq}$	$3393 \pm 49$

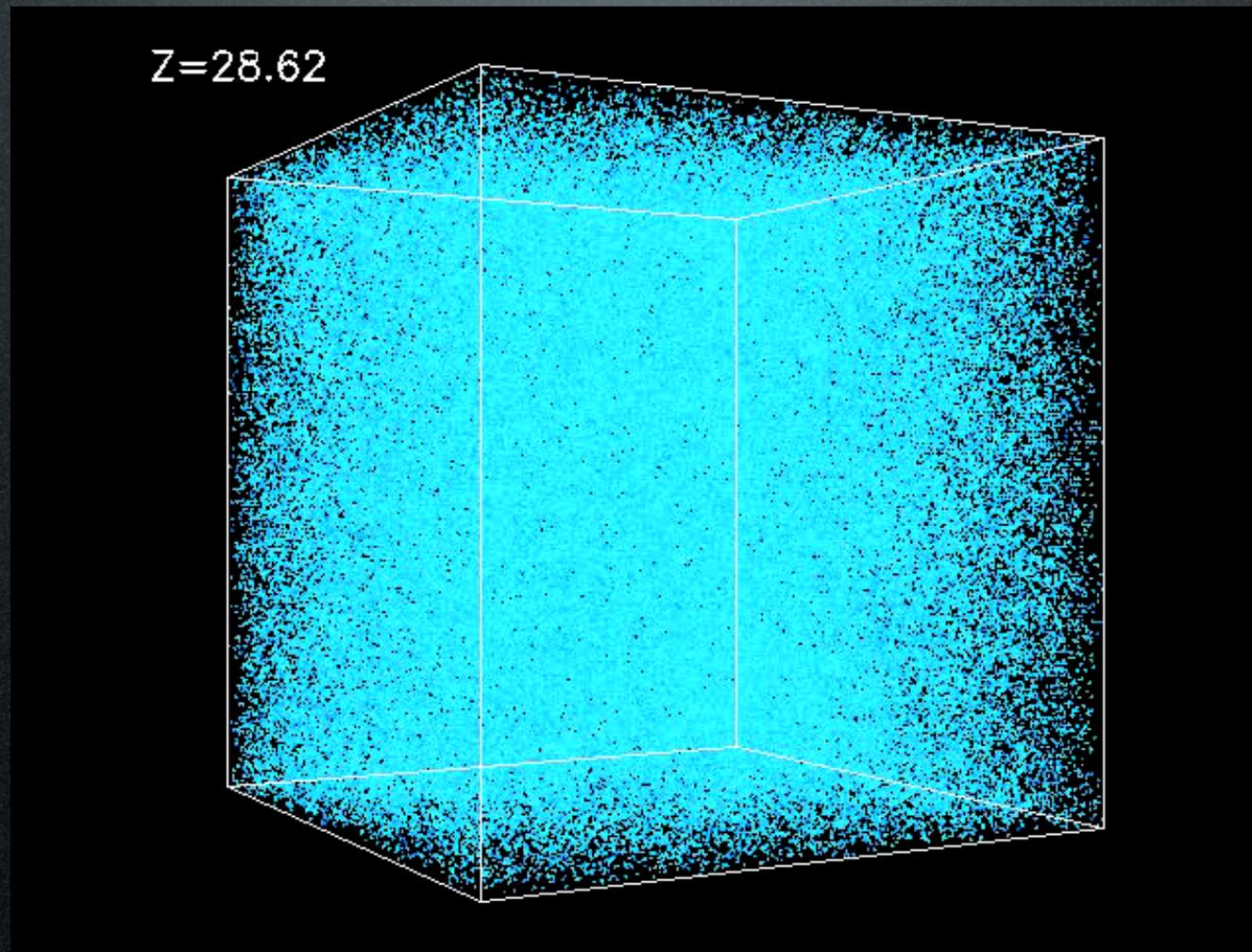




# Formazione Galassie, Ammassi (*LSS formation*)

# DM N-body simulations

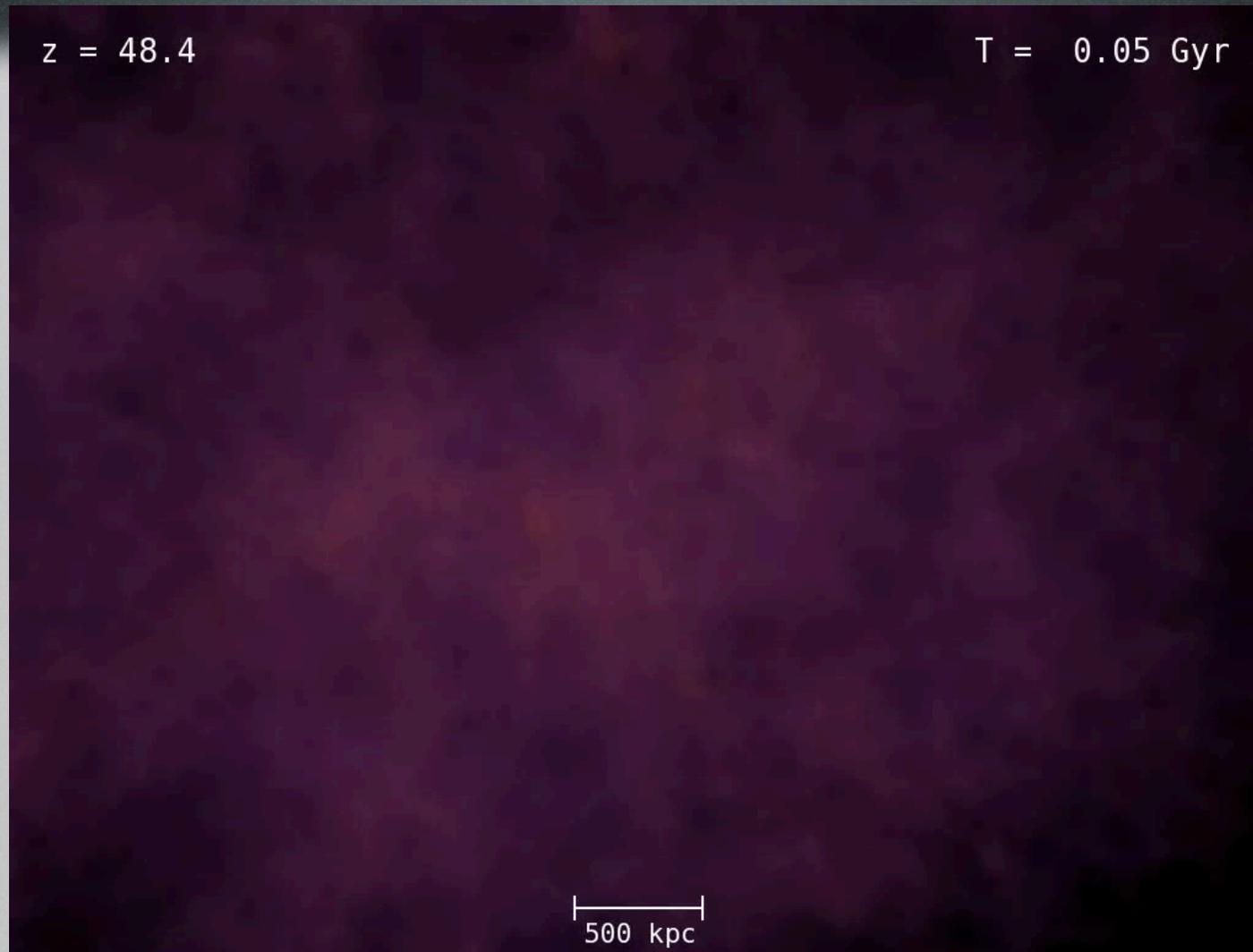
$2 \times 10^6$  CDM particles, 43 Mpc cubic box



# DM N-body simulations

Aquarius project of the VIRGO coll.:

$1.5 \cdot 10^9$  CDM particles, single galactic halo



# Simulations with baryons?

Illustris simulation:

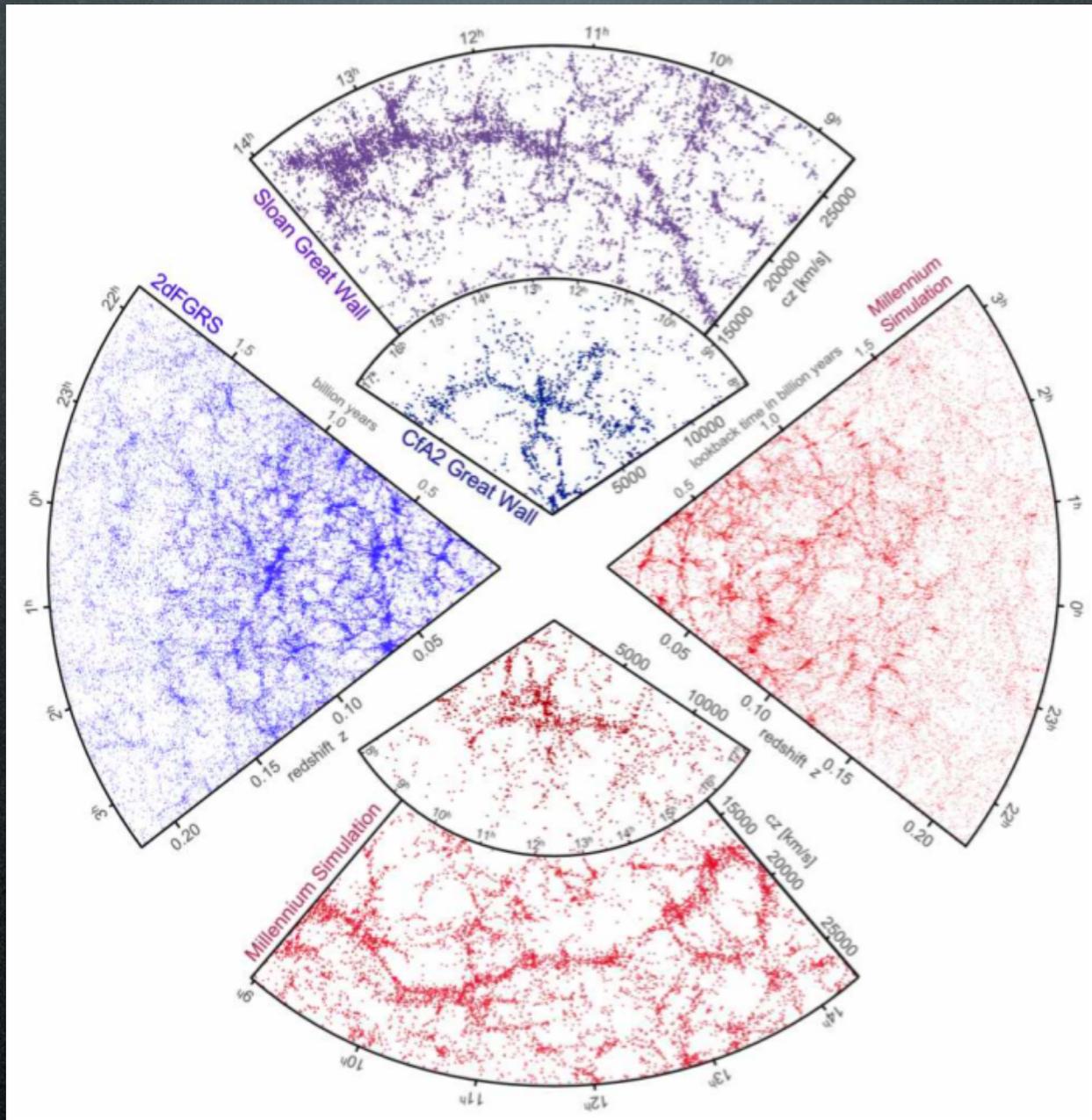
up to  $1.8 \cdot 10^{10}$  CDM particles/hydro cells, 100 Mpc cubic box



# DM N-body simulations

2dF:  $2.2 \times 10^5$  galaxies

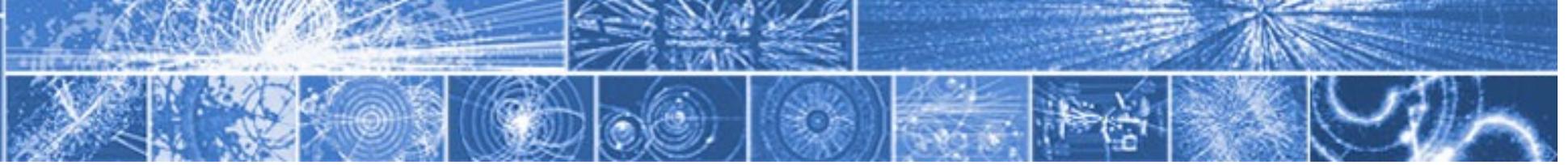
SDSS:  $10^6$  galaxies,  
2 billion yr



Of course, you have to  
infer galaxies within the  
DM simulation

Springel, Frenk, White, Nature 440 (2006)

Millennium:  
 $10^{10}$  particles,  
 $500 h^{-1}$  Mpc



*(non in scala!)*

?

$10^{15}$  GeV

1 GeV

1 MeV

1 eV

Big Bang

Inflazione

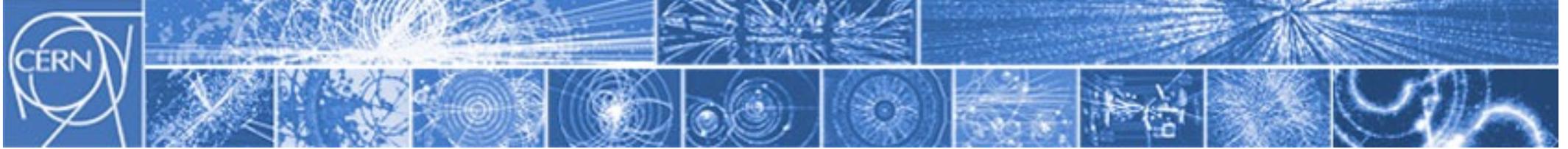
Bariogenesi

Nucleosintesi  
primordiale

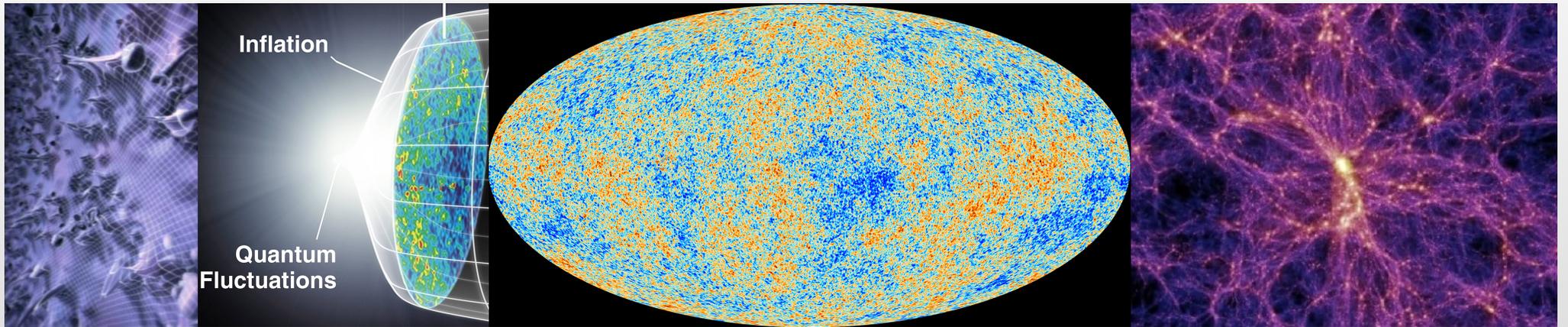
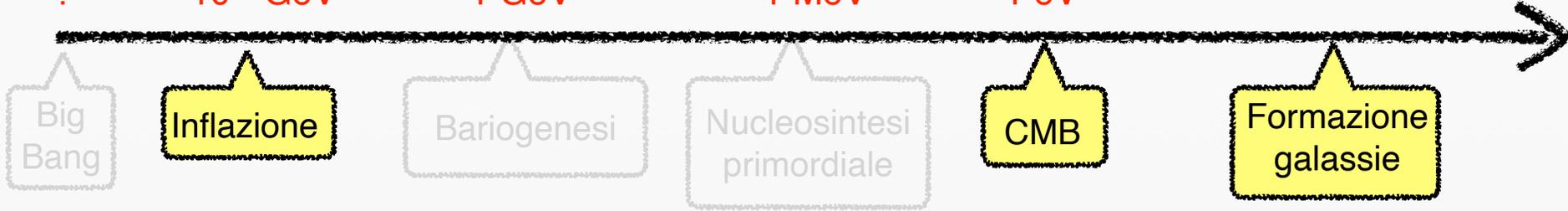
CMB

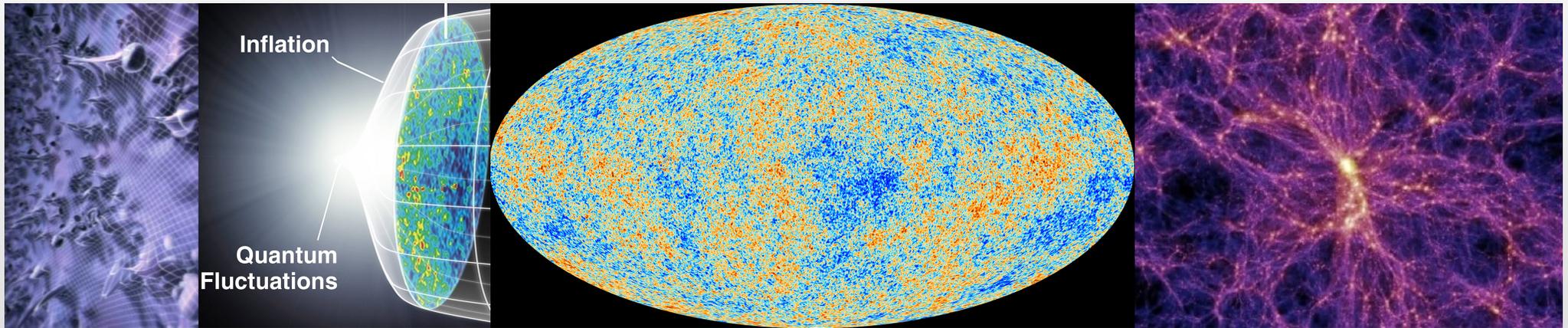
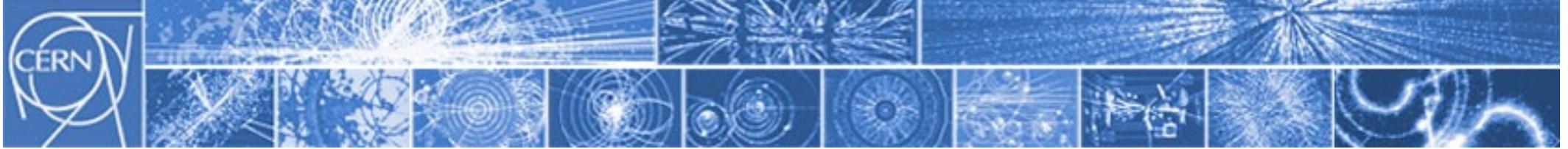
Formazione  
galassie





?       $10^{15}$  GeV      1 GeV      1 MeV      1 eV      (non in scala!)





*According to inflation, the more than 100 billion galaxies, sparkling throughout space like heavenly diamonds, are nothing but quantum mechanics writ large across the sky. To me, this realization is one of the greatest wonders of the modern scientific age.*

**Brian Greene**