Fisica delle Particelle, Astrofisica & Cosmologia

- Breve storia dell'Universo:
  inflazione, BG, BBN, CMB, LSS
- Neutrini e oscillazioni
- Materia Oscura
- Energia Oscura
- Altri problemi aperti in fisica delle particelle

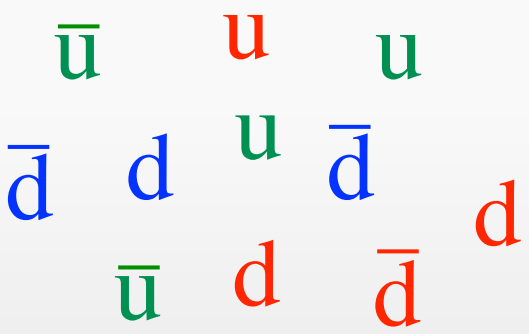
Marco CIRELLI [CNRS LPTHE Jussieu]

Bariogenesi & asimmetria barionica

(BAU)

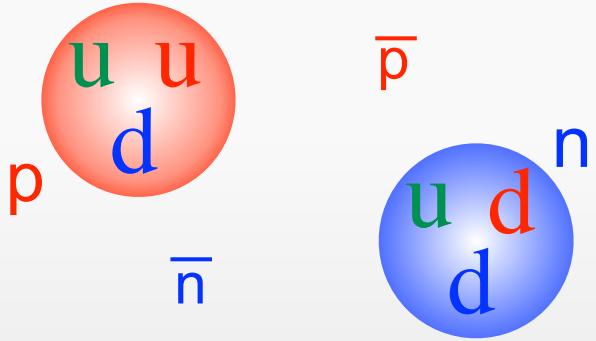
Bariogenesi

mare di quark (e antiquark) 'liberi'



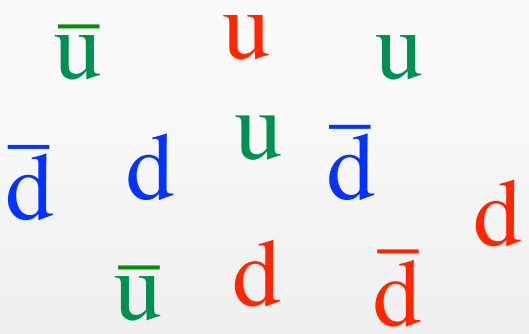
T ~ 1 GeV

barioni (e antibarioni)



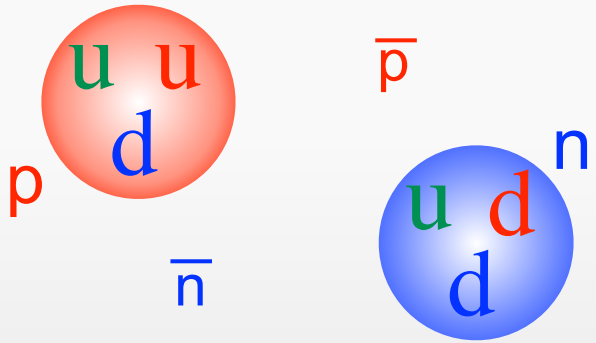
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

barioni (e antibarioni)



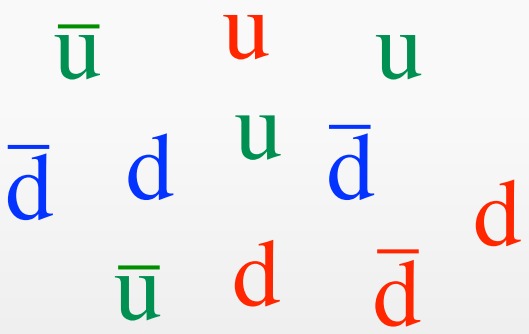
Problema: l'Universo sembra contenere solo materia (barioni)

- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN

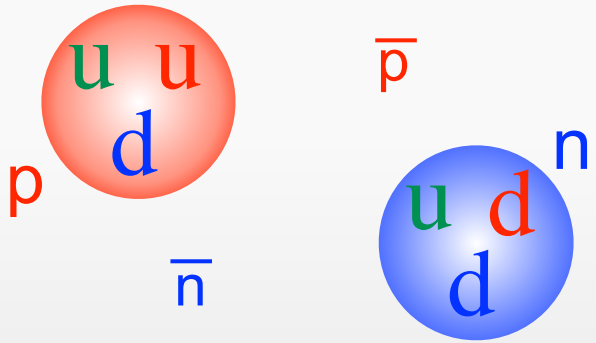
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

barioni (e antibarioni)



Problema: l'Universo sembra contenere solo materia (barioni)

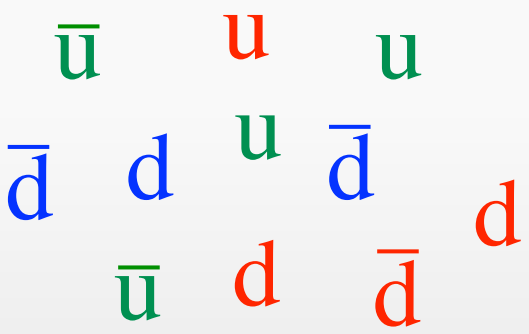
- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN

ma ci si aspetterebbe <u>simmetria</u>

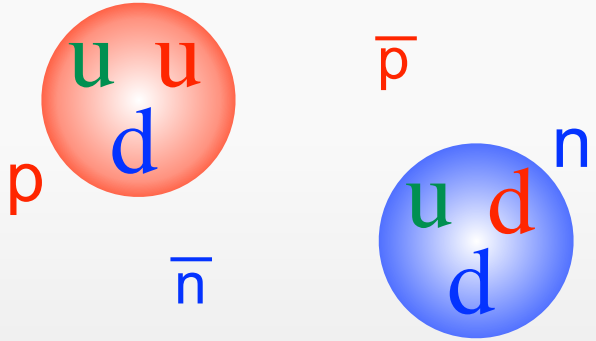
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

barioni (e antibarioni)

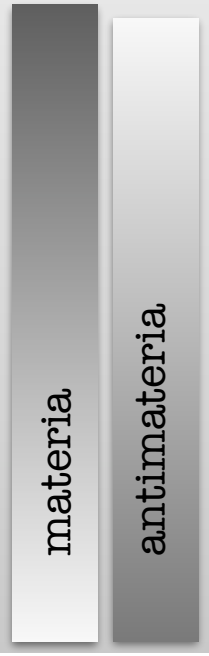


Problema: l'Universo sembra contenere solo materia (barioni)

- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

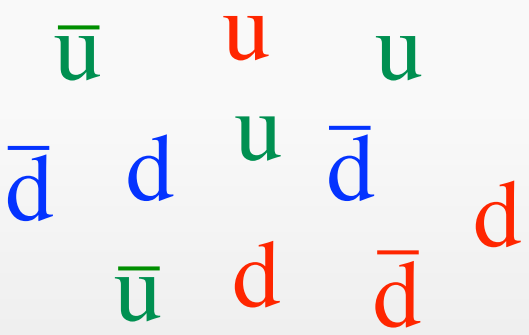
- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN

ma ci si aspetterebbe <u>simmetria</u>



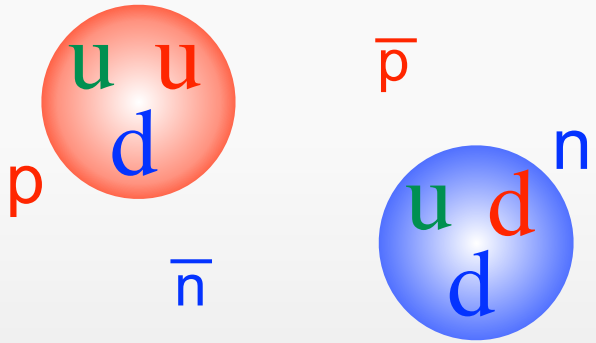
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

barioni (e antibarioni)

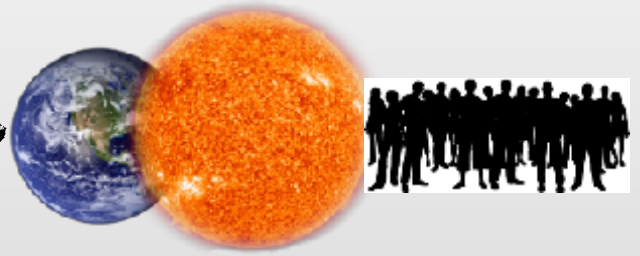


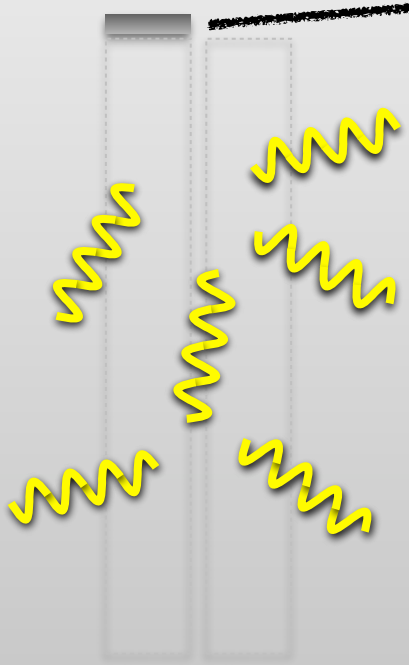
Problema: l'Universo sembra contenere solo materia (barioni)

- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN

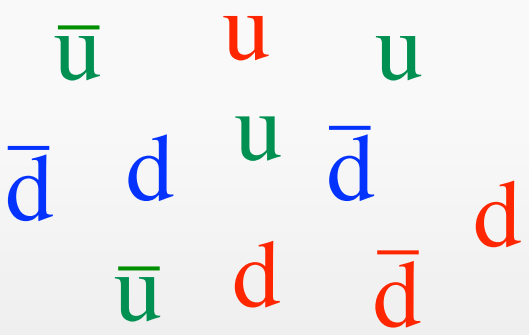
ma ci si aspetterebbe <u>simmetria</u>





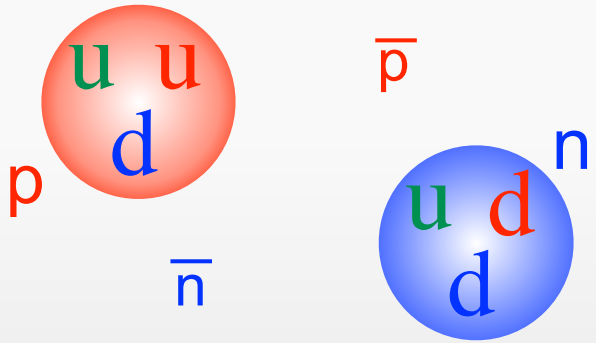
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

barioni (e antibarioni)

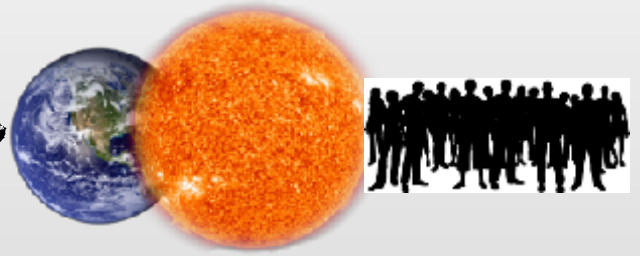


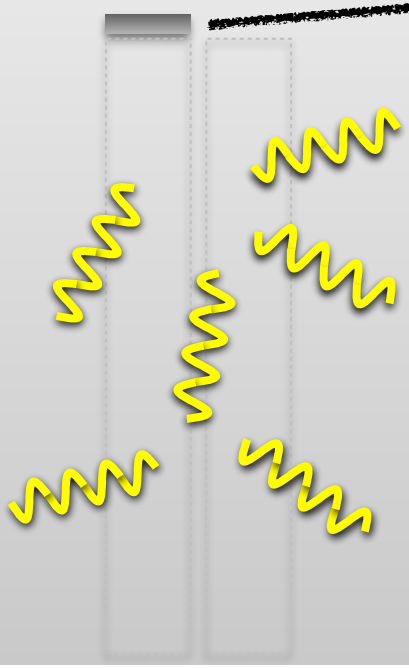
Problema: l'Universo sembra contenere solo materia (barioni)

- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN

ma ci si aspetterebbe <u>simmetria</u>

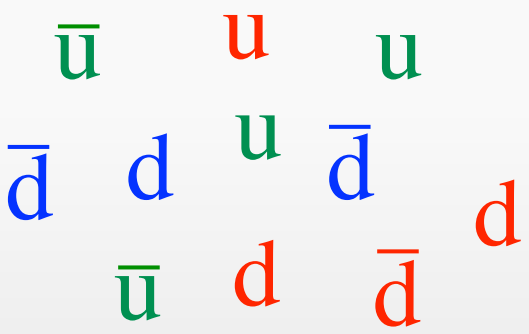




$$\eta = \frac{n_b - \bar{n}_b}{n_\gamma} = 6\ 10^{-10}$$

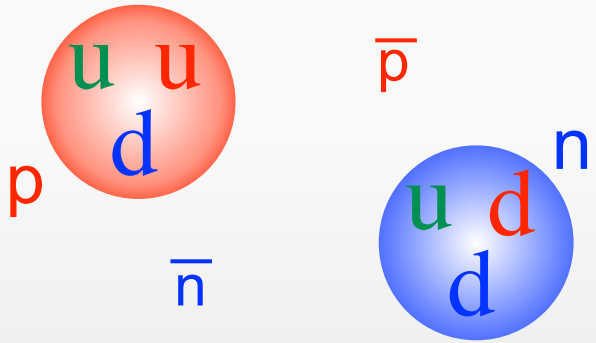
Bariogenesi

mare di quark (e antiquark) 'liberi'



T ~ 1 GeV

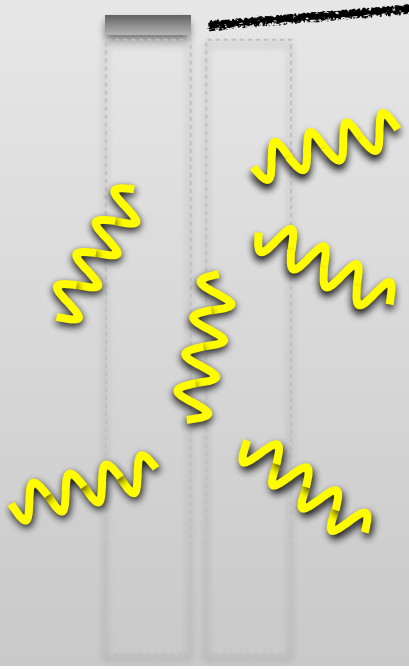
barioni (e antibarioni)



Problema: l'Universo sembra contenere solo materia (barioni)

- Terra, Sole, pianeti…
- domini di antimateria causerebbero annichilazione

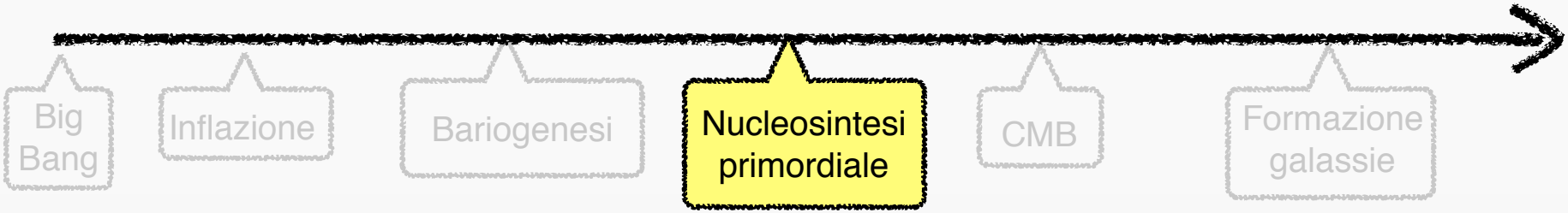
- la (poca) antimateria rilevata è prodotta dai raggi cosmici
- o al CERN



ma ci si aspetterebbe <u>simmetria</u>

$$\eta = \frac{n_b - \bar{n}_b}{n_\gamma} = 6\ 10^{-10}$$

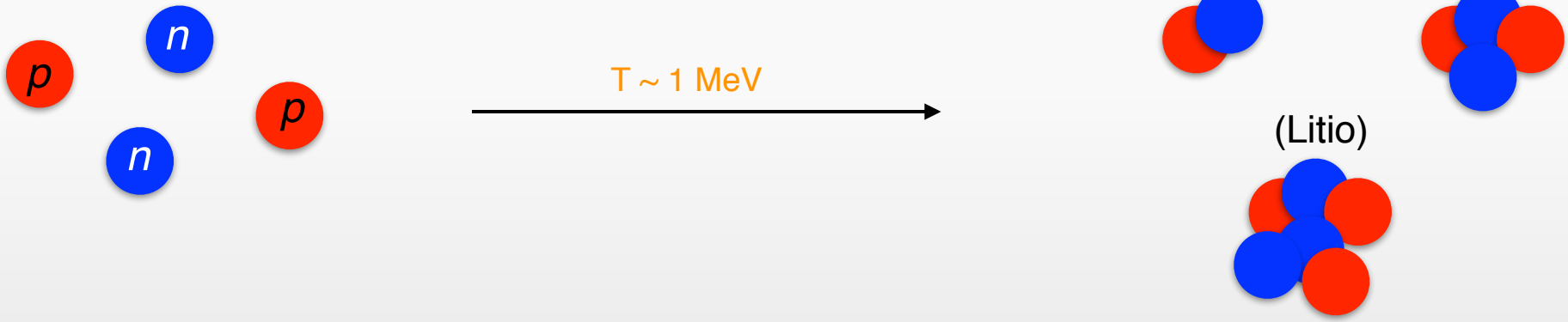
da dove viene l'<u>asimmetria</u>???



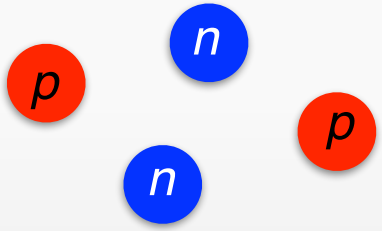
Nucleosintesi primordiale

(BBN)

Nucleosintesi primordiale

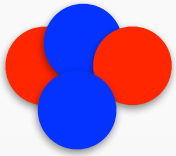


Nucleosintesi primordiale



Deuterio

Elio

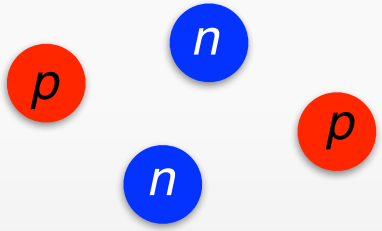


p: 938.3 MeV
n: 939.6 MeV
$\Delta m = 1.3$ MeV

p e^- $\leftrightarrow$ n ν

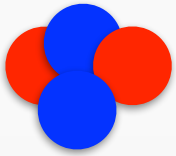
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale



Deuterio

Elio

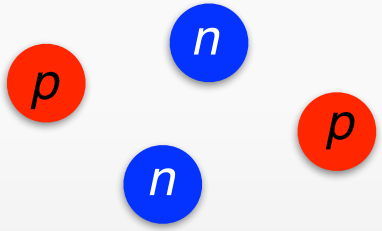


p: 938.3 MeV
n: 939.6 MeV
$\Delta m = 1.3$ MeV

$p\ e^- \leftrightarrow n\ \nu$

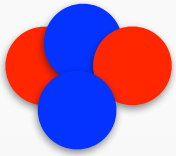
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale



Deuterio

Elio



p: 938.3 MeV
n: 939.6 MeV
$\Delta m = 1.3$ MeV

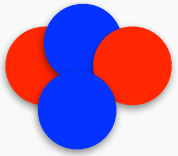
p e^- ↔ n ν

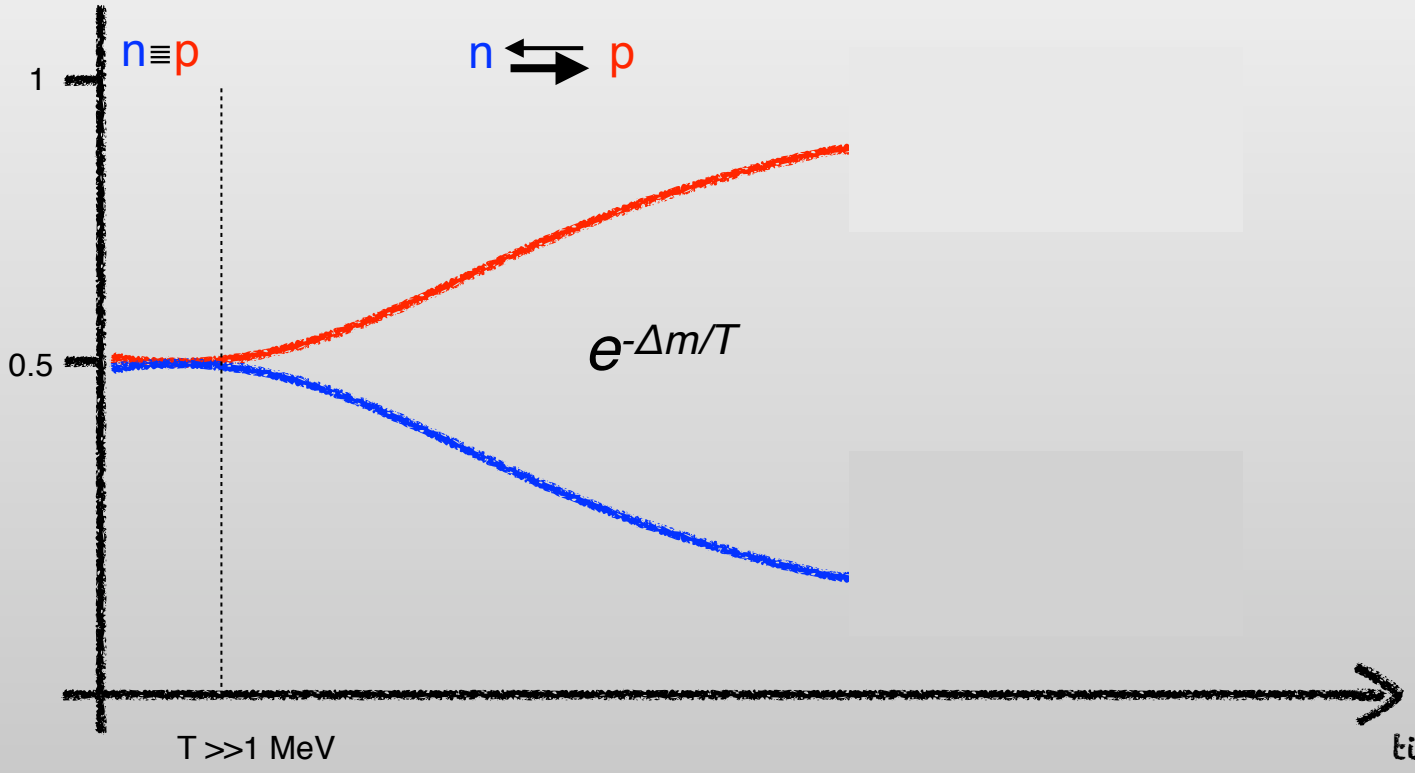
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
$\Delta m = 1.3$ MeV

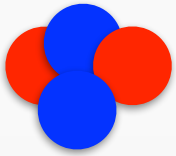
p e^- ↔ n ν

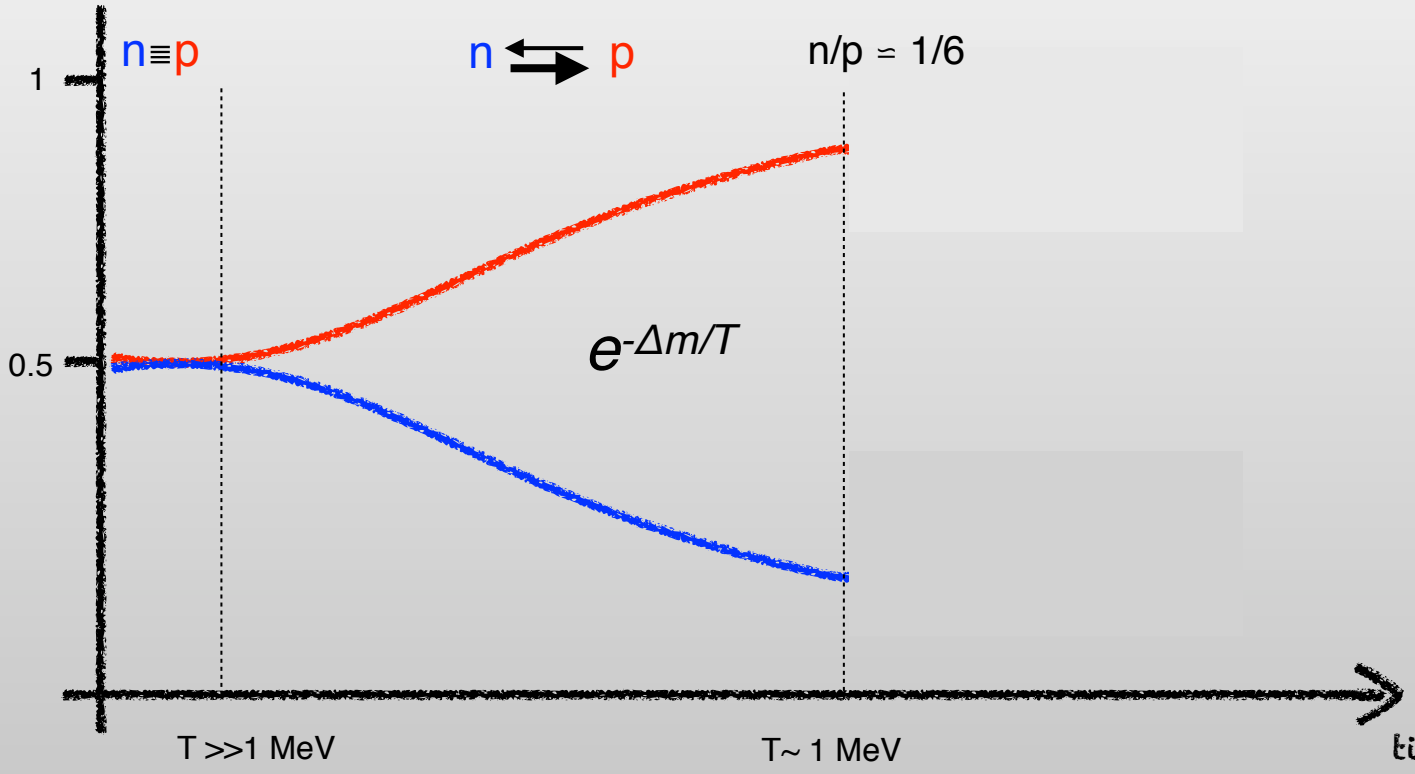
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
$\Delta m = 1.3$ MeV

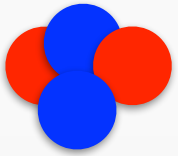
p e^- ↔ n ν

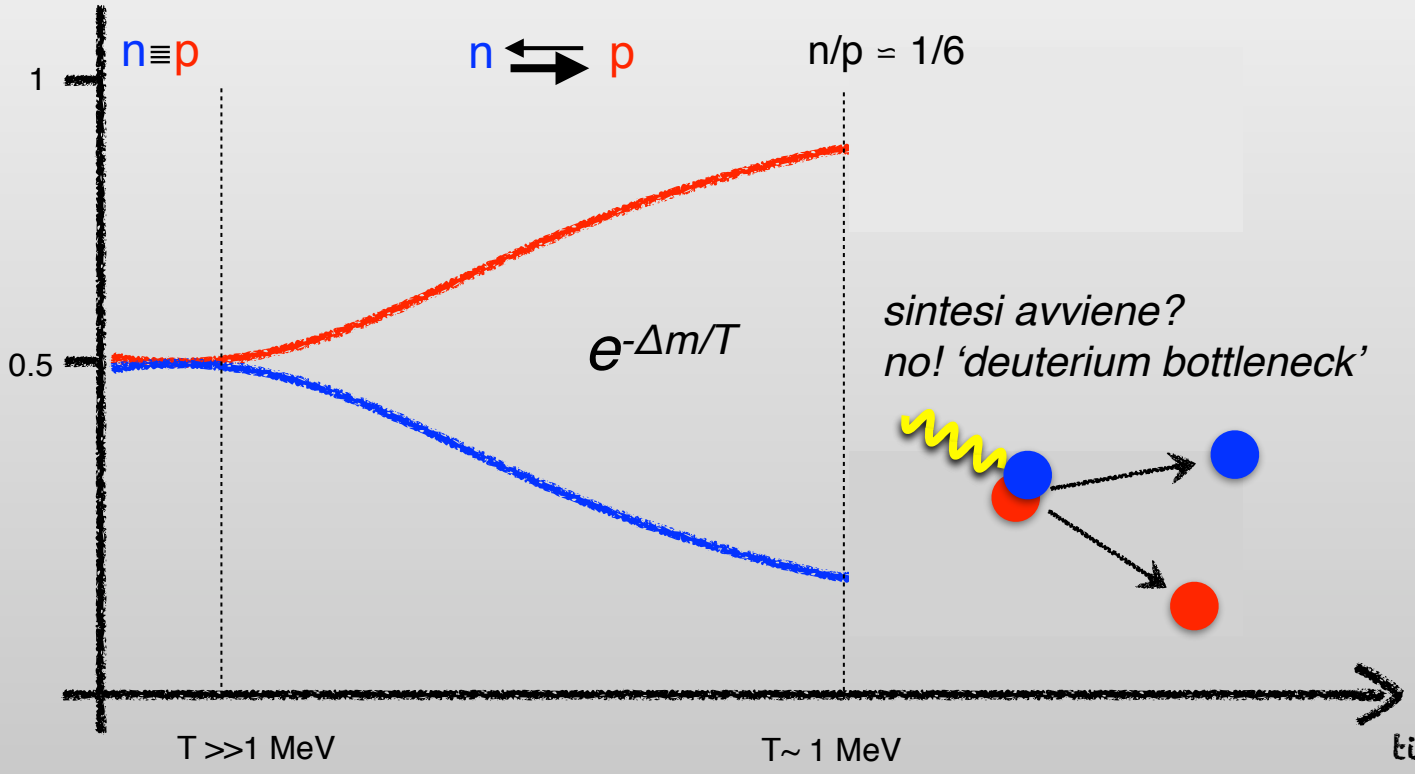
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

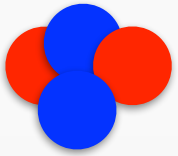
p e^- ↔ n ν

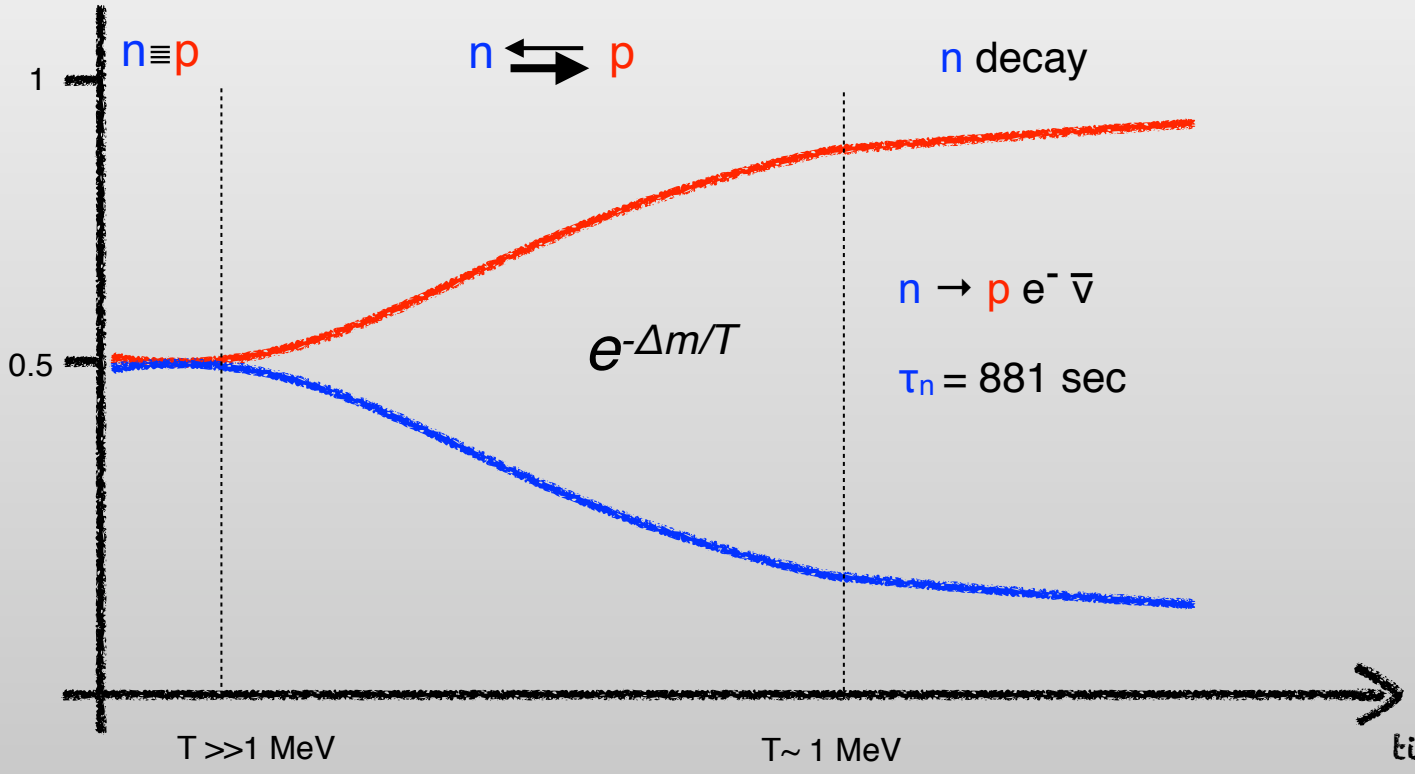
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

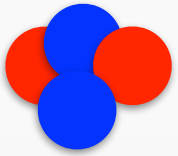
p e^- ↔ n ν

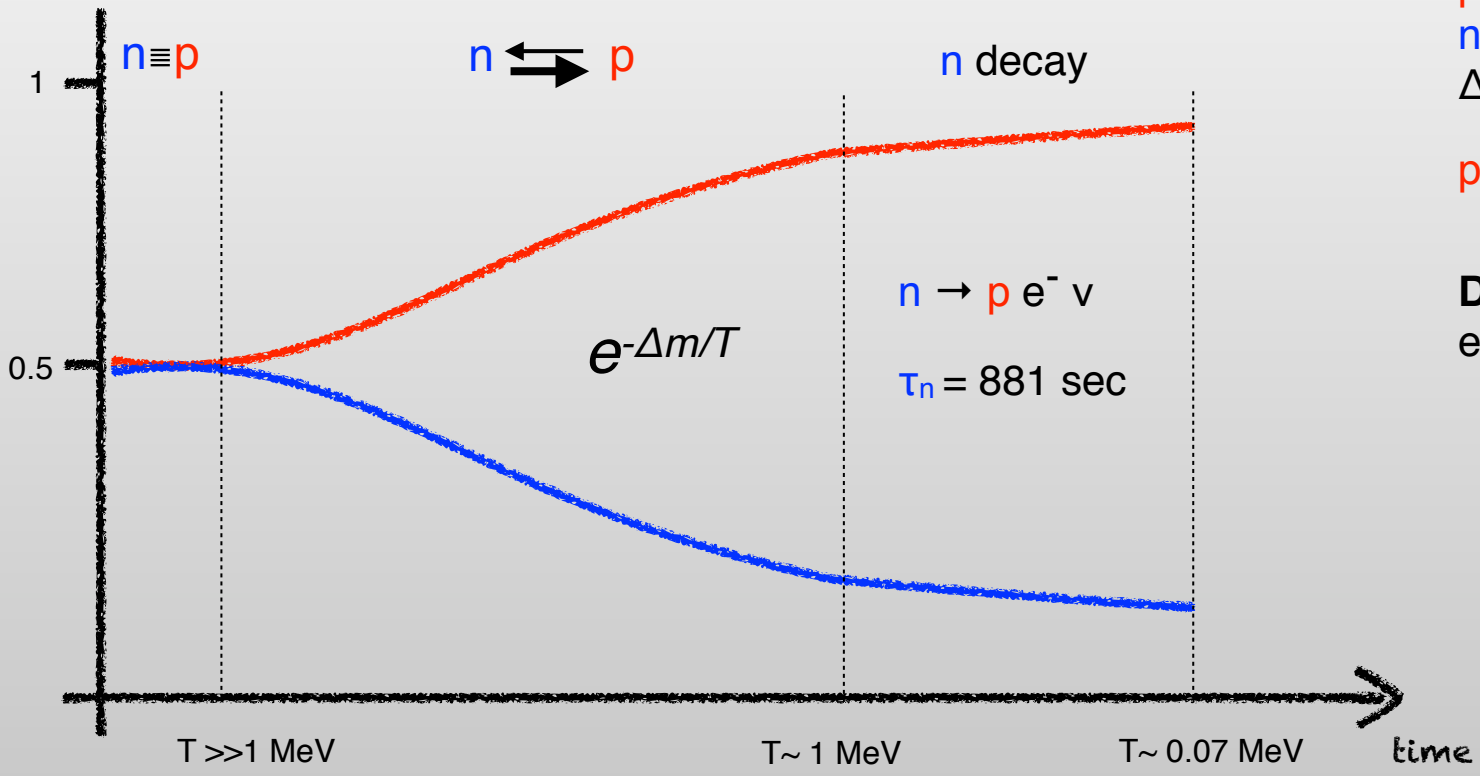
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

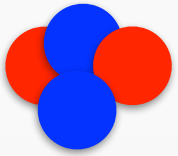
p e^- ↔ n ν

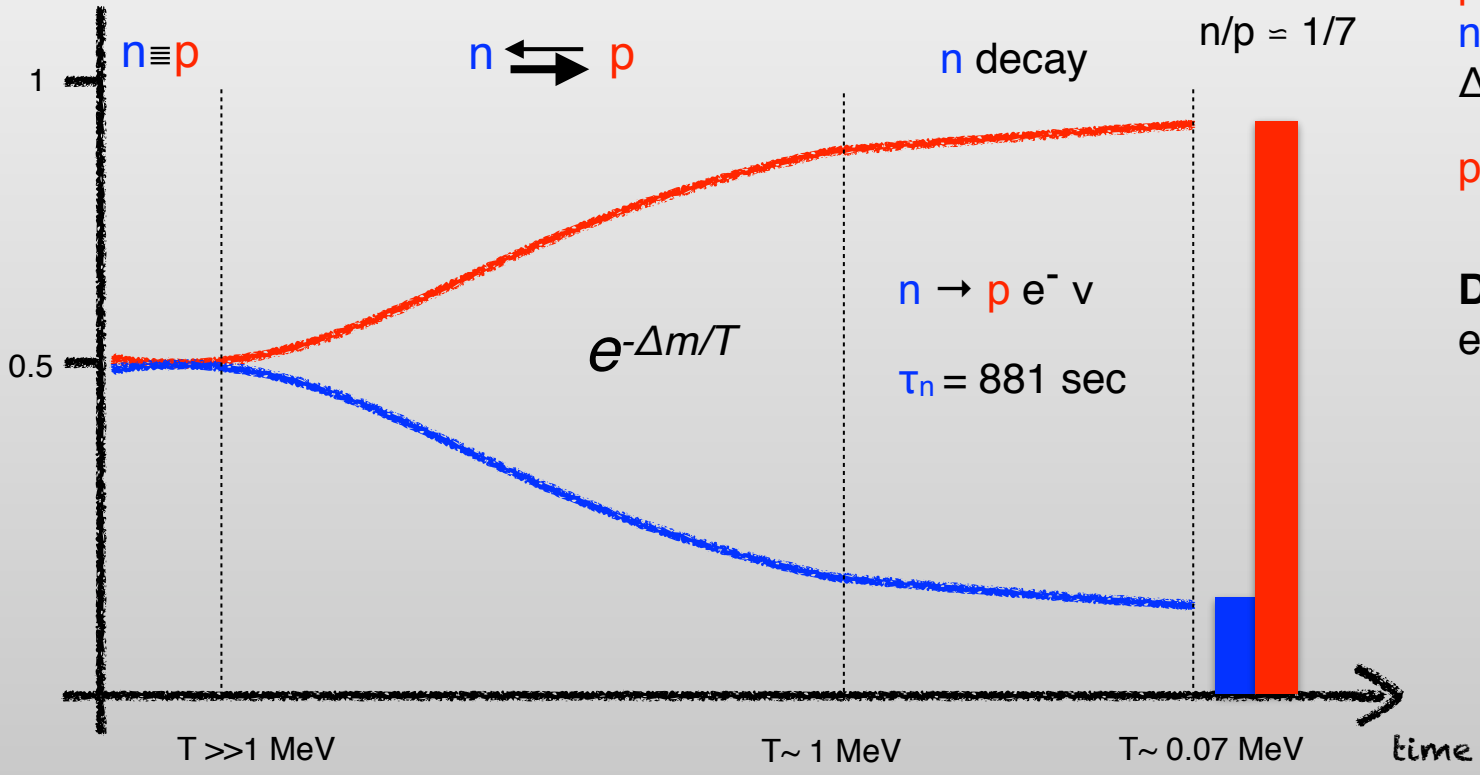
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio





p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

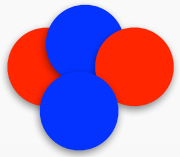
p e^- ↔ n ν

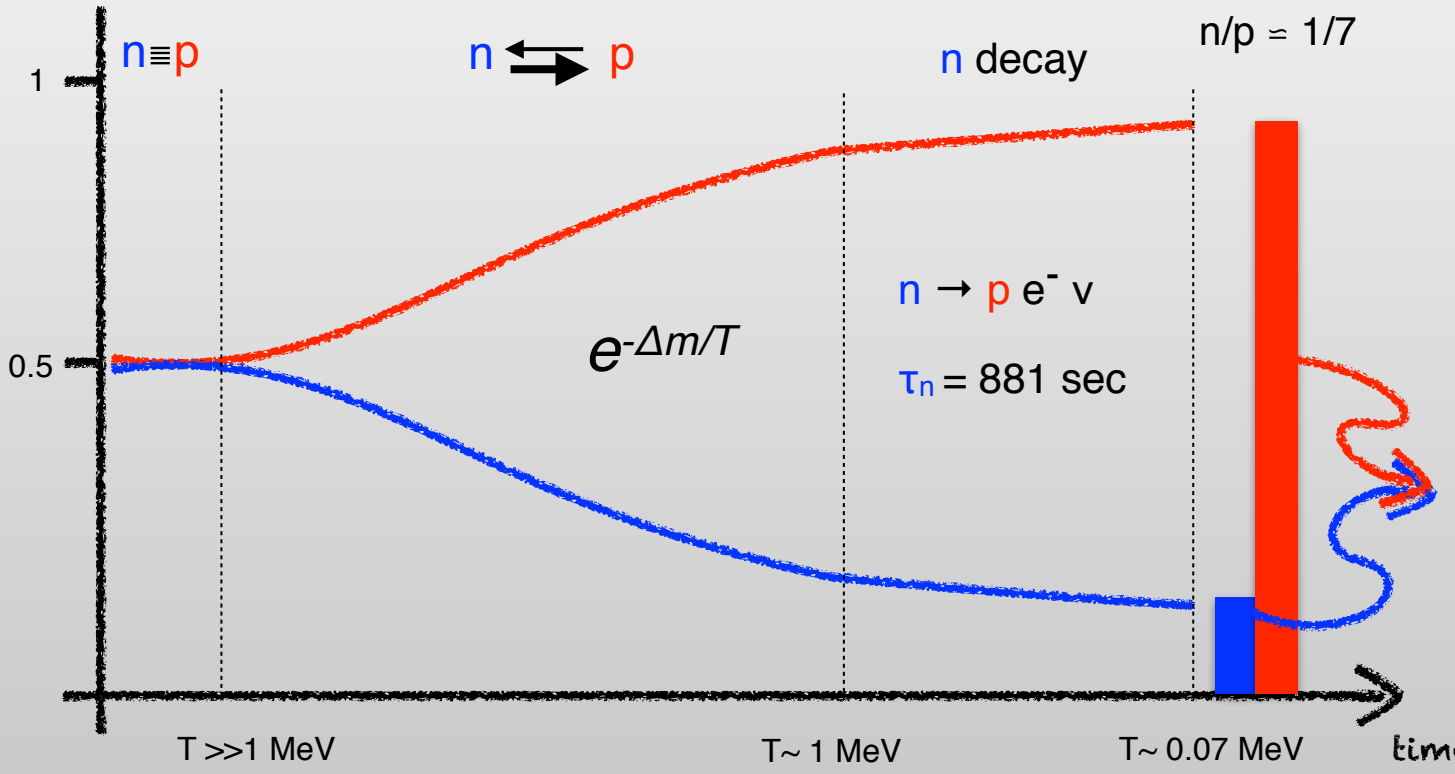
D: 1876.12 MeV
energia legame **D**: ~2 MeV

Nucleosintesi primordiale

Deuterio

Elio

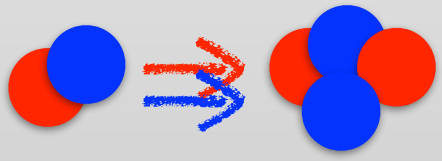




p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

p e^- ↔ n ν

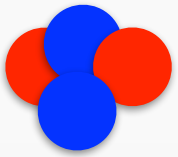
D: 1876.12 MeV
energia legame **D**: ~2 MeV

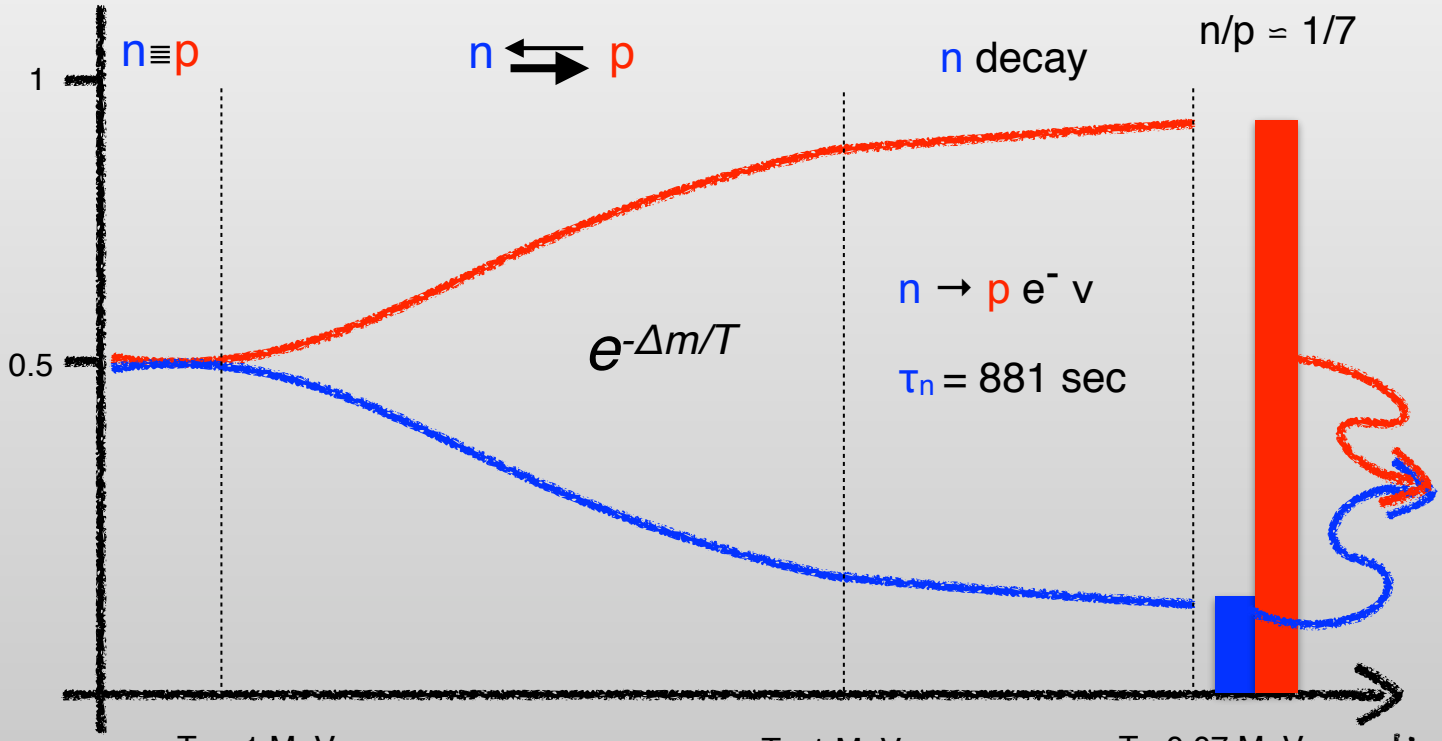


Nucleosintesi primordiale

Deuterio

Elio

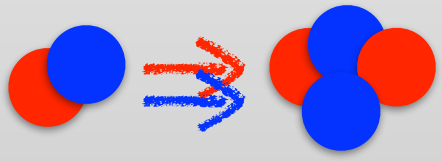




p: 938.3 MeV
n: 939.6 MeV
Δm = 1.3 MeV

p e^- ↔ n ν

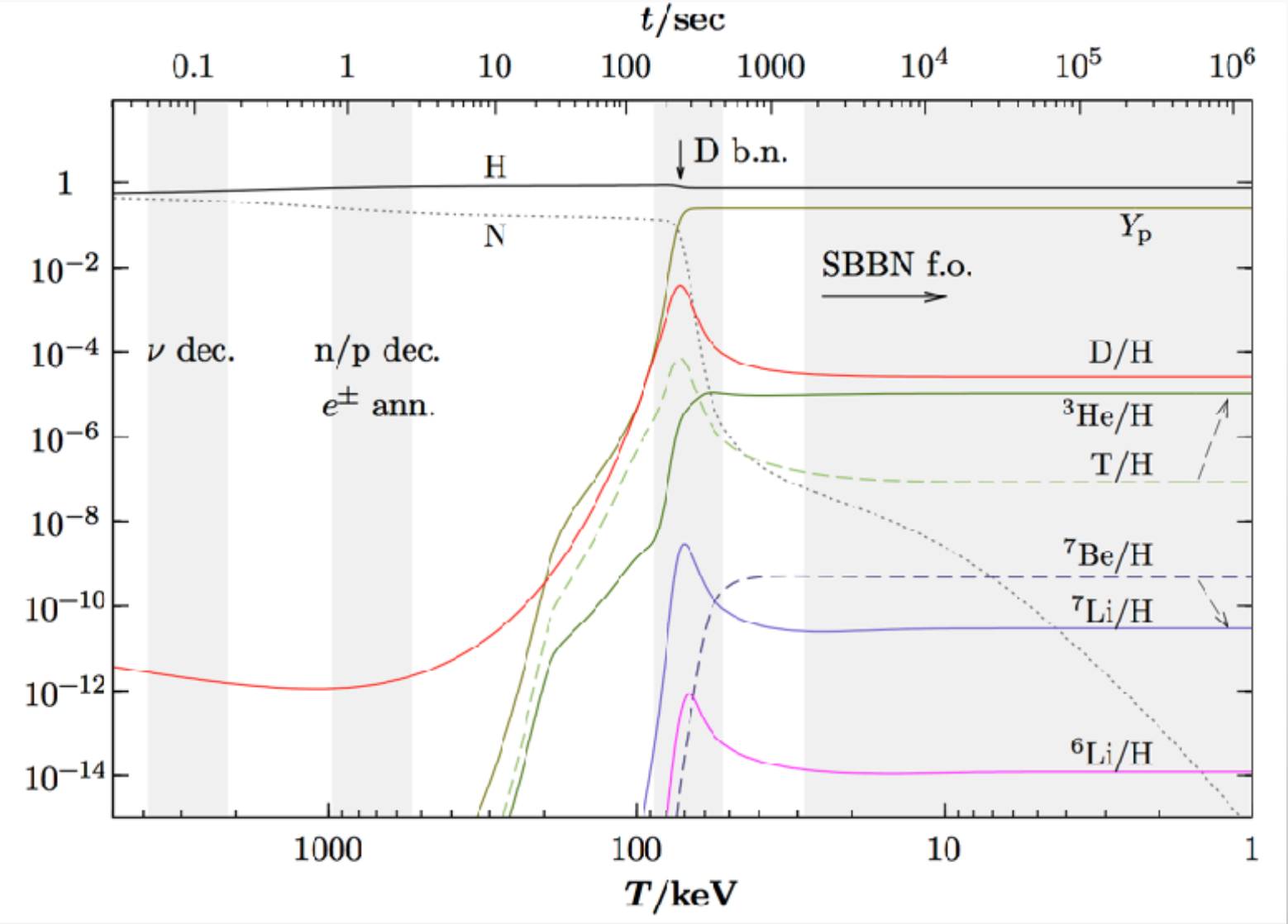
D: 1876.12 MeV
energia legame **D**: ~2 MeV



previsione:
^{4}He = 25%
osservazioni:
^{4}He = 24.9% ± 0.9%

Alpher, Bethe, Gamow 1948

Produzione degli altri elementi leggeri:



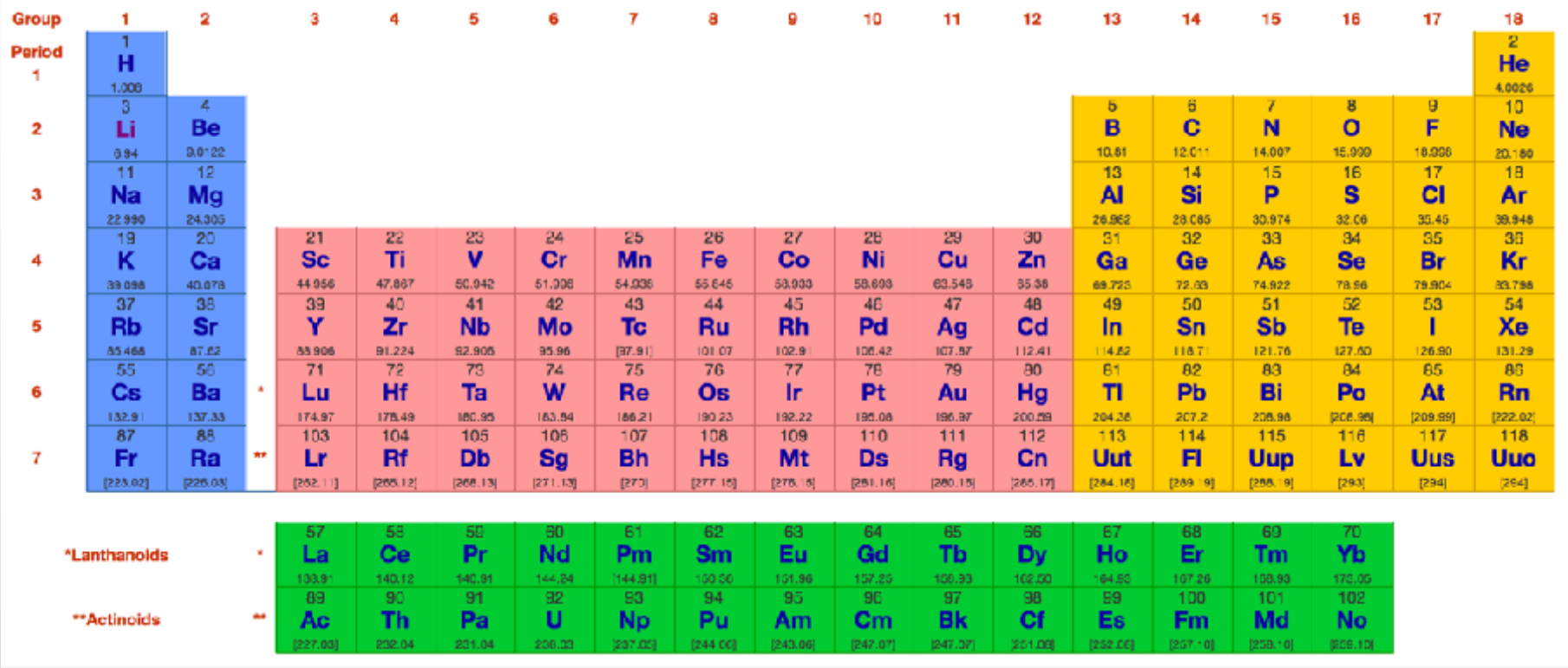
Pradler, Pospelov 1011.1054

predizioni su 14 ordini di grandezza!

verificate (eccetto ^{7}Li)

[come se una teoria economica potesse predire correttamente il PIL degli USA (17 trilioni) e il contenuto del portafoglio di tua nonna, con una precisione di 10 centesimi di euro]

Come sono prodotti tutti gli altri elementi?

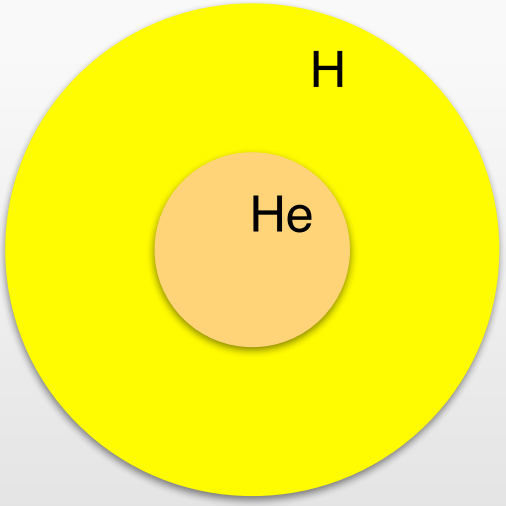


Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare

Come sono prodotti tutti gli altri elementi?

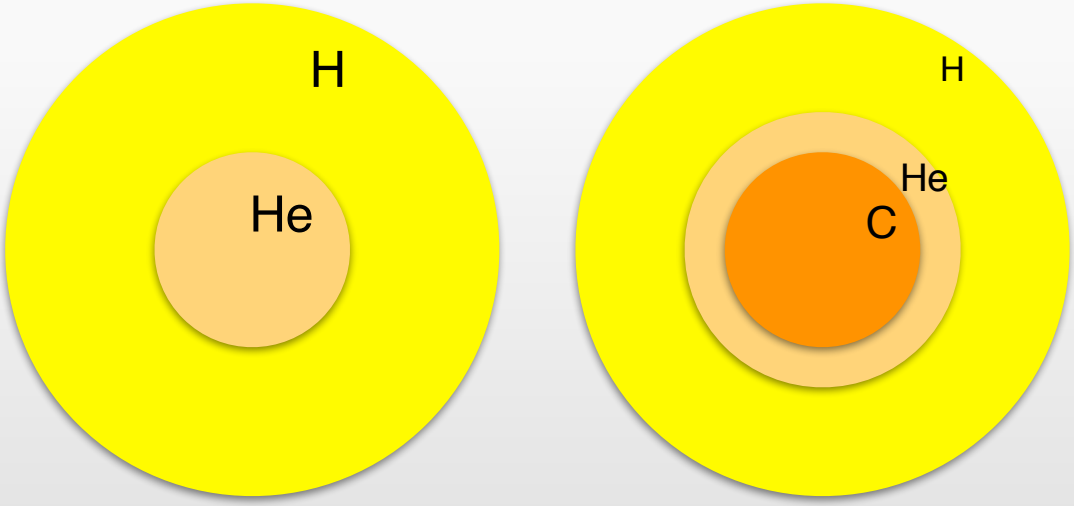
Nucleosintesi stellare



$4\,H \rightarrow {}^{4}He + \textit{energy}$

Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare



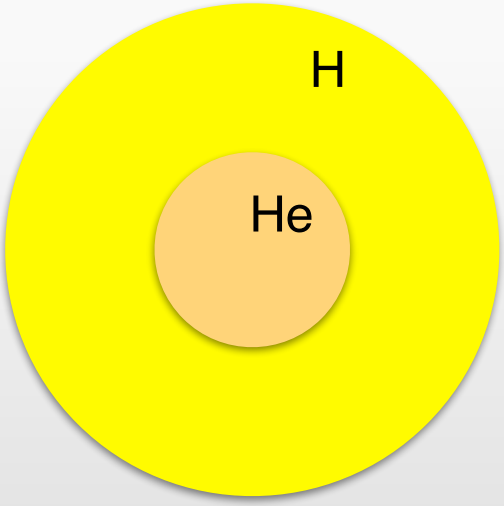
4 H→^{4}He + *energy*

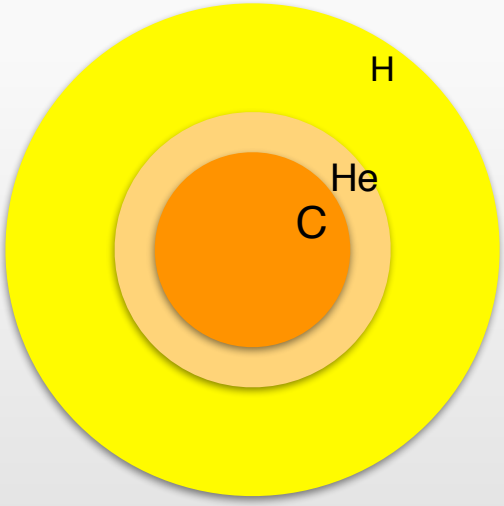
3 ^{4}He→^{12}C + *energy*

Fusione nucleare produce nuclei pesanti
e fornisce pressione di sostegno

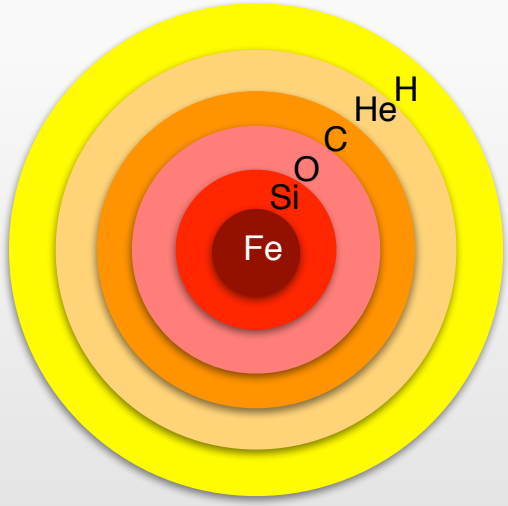
Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare





.....

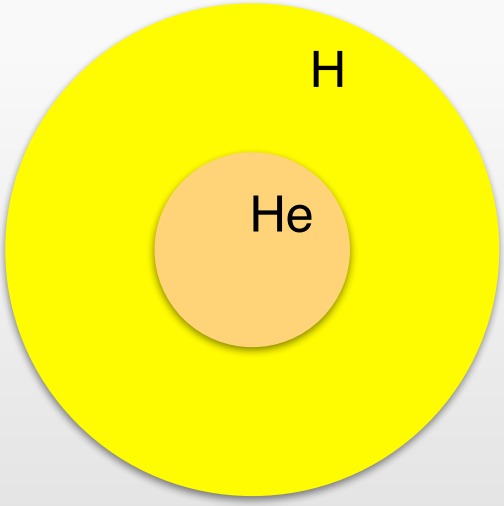


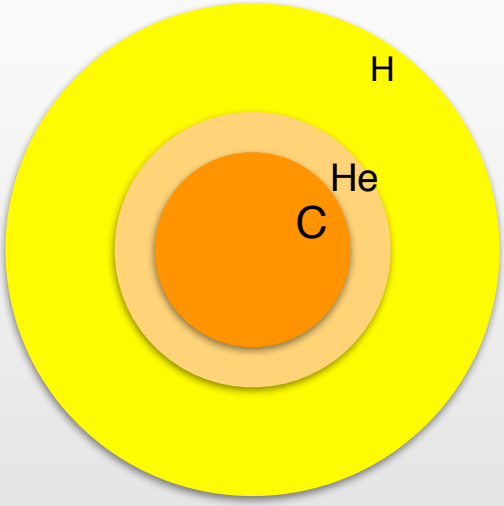
$4\ H \rightarrow {}^{4}He + \textit{energy}$ $3\ {}^{4}He \rightarrow {}^{12}C + \textit{energy}$

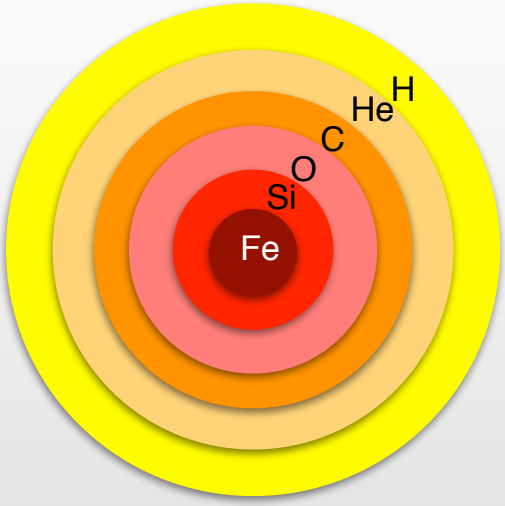
Fusione nucleare produce nuclei pesanti
e fornisce pressione di sostegno

Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare



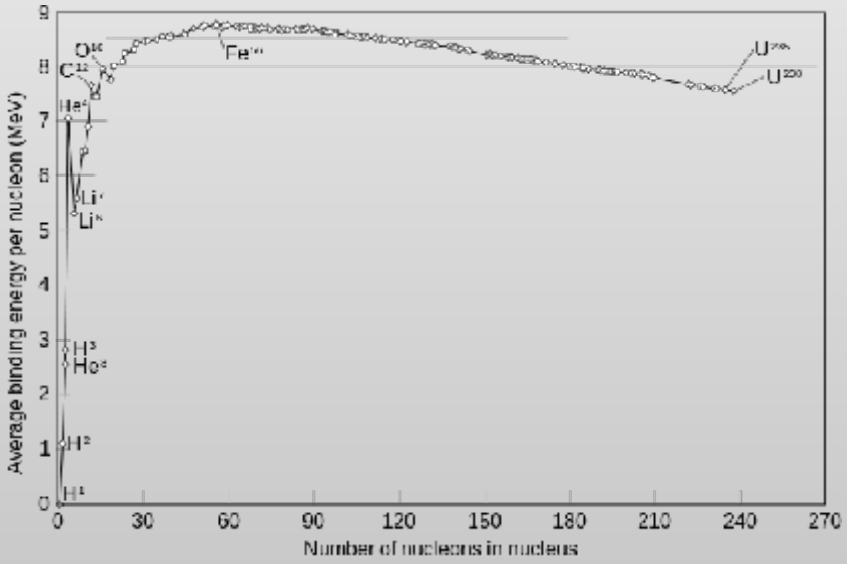




4 H→^{4}He + *energy*

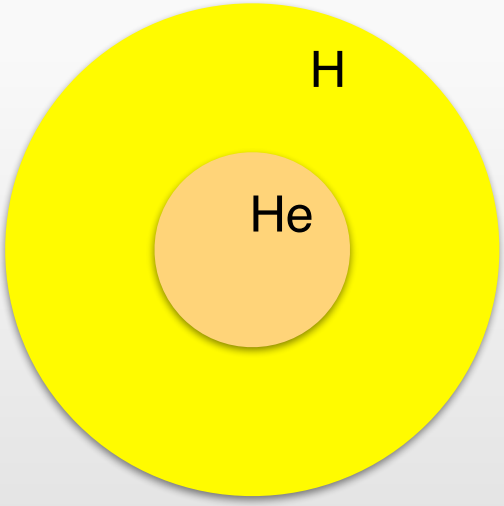
3 ^{4}He→^{12}C + *energy*

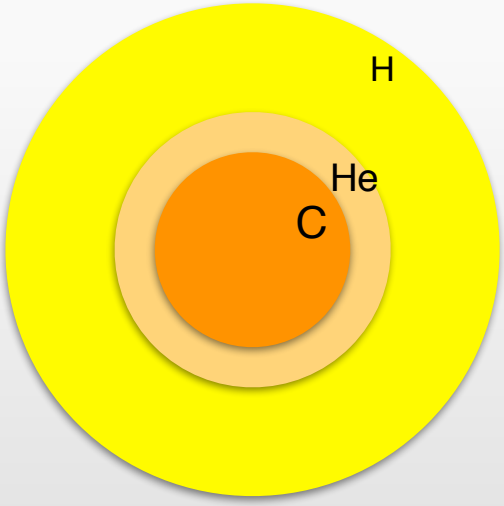
Fusione nucleare produce nuclei pesanti
e fornisce pressione di sostegno

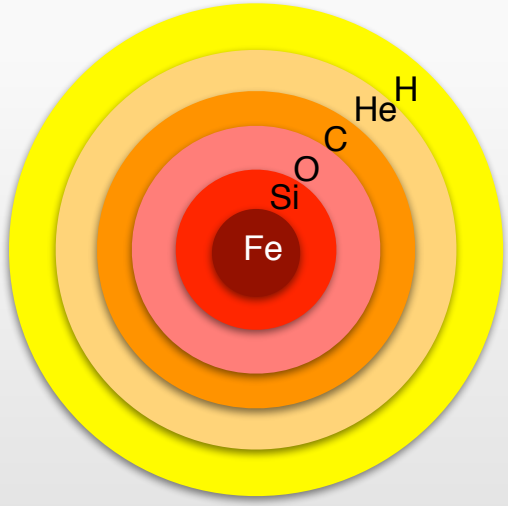


Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare





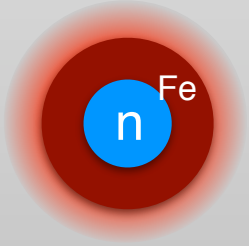


4 H→^{4}He + *energy*

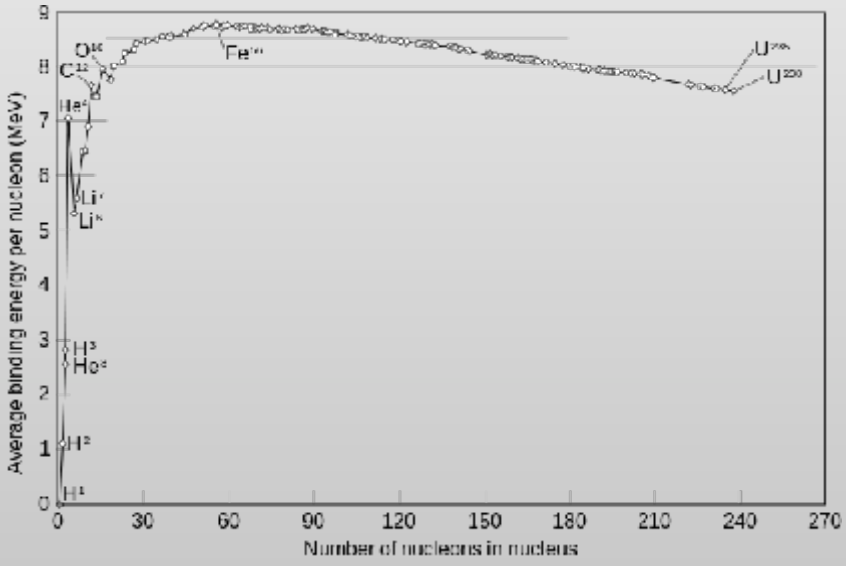
3 ^{4}He→^{12}C + *energy*

Fusione nucleare produce nuclei pesanti
e fornisce pressione di sostegno

Nucleosintesi nelle supernovae

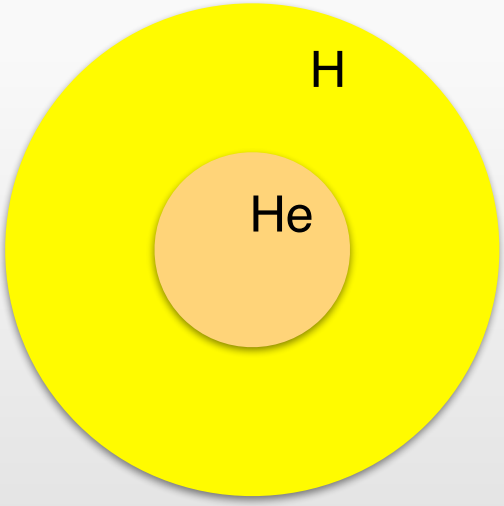


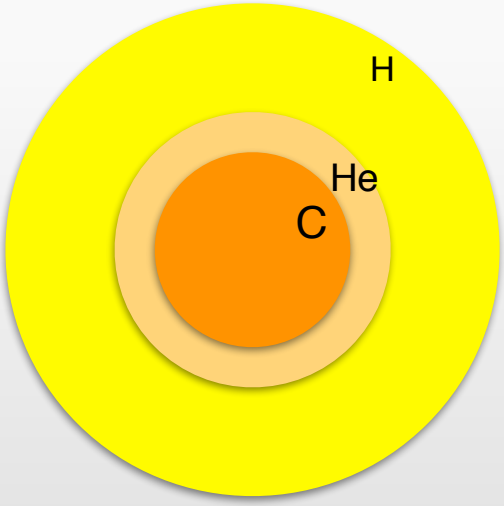
Appena prima dell'esplosione,
neutronizzazione del nocciolo e
cattura rapida di neutroni



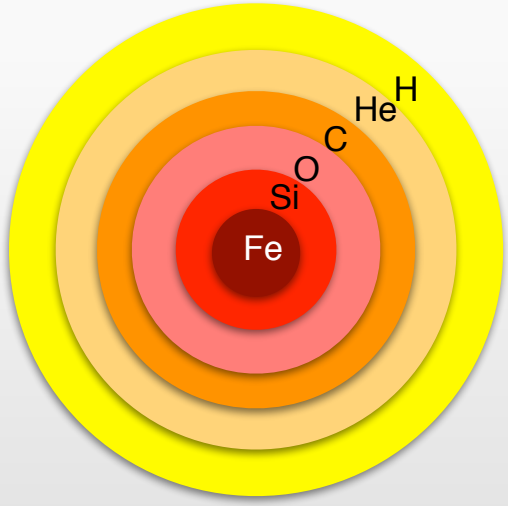
Come sono prodotti tutti gli altri elementi?

Nucleosintesi stellare





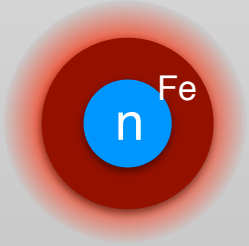
.....



$4\ H \rightarrow {}^{4}He + \textit{energy}$ $3\ {}^{4}He \rightarrow {}^{12}C + \textit{energy}$

Fusione nucleare produce nuclei pesanti
e fornisce pressione di sostegno

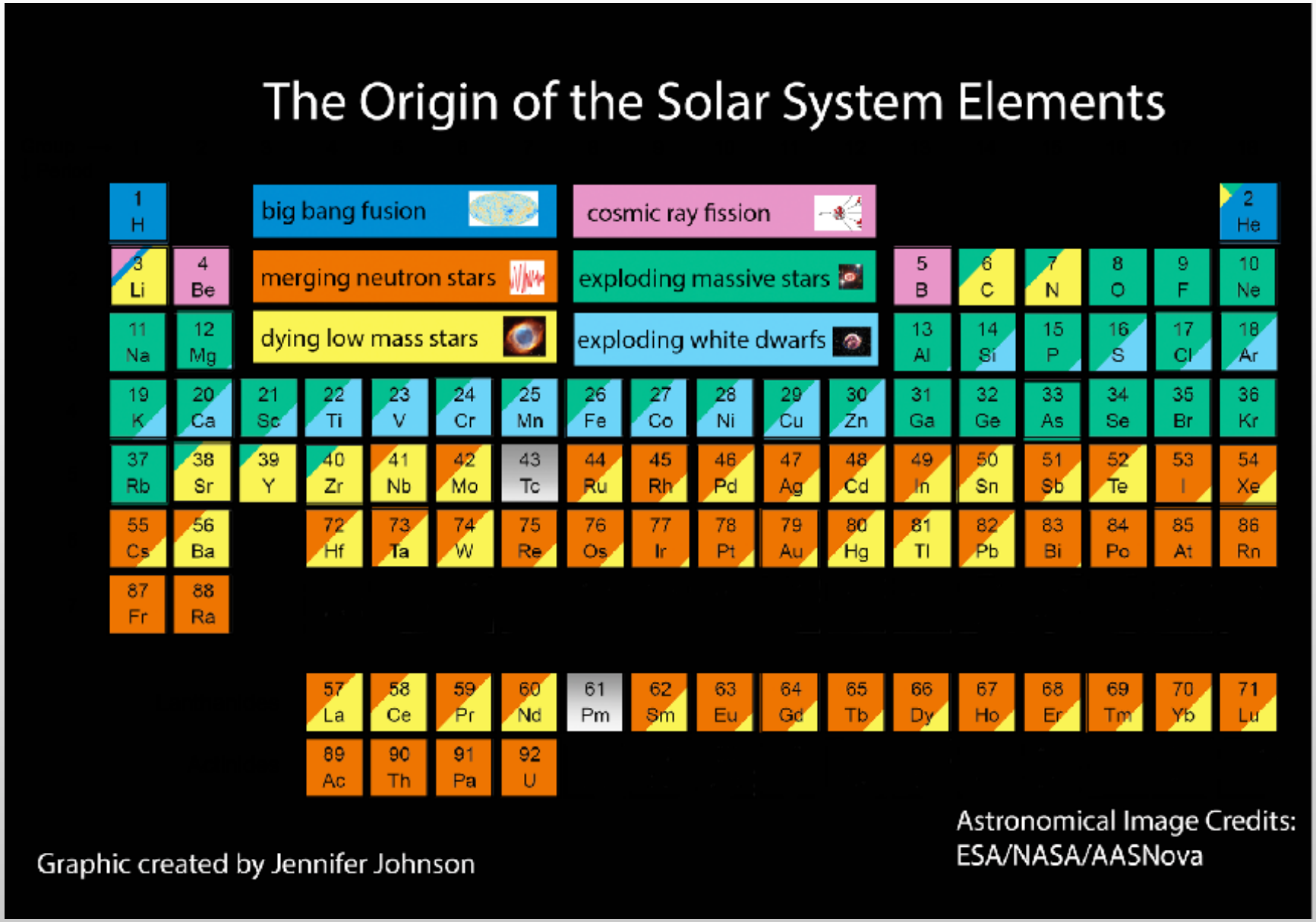
Nucleosintesi nelle supernovae



Appena prima dell'esplosione,
neutronizzazione del nocciolo e
cattura rapida di neutroni

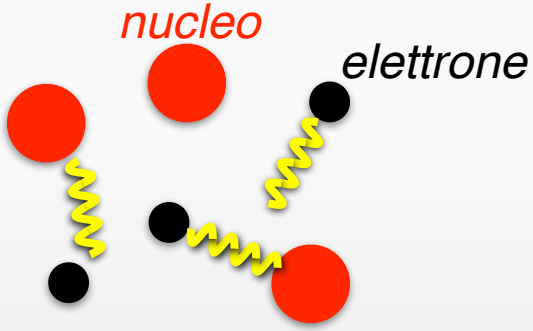
The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff.
Carl Sagan

Come sono prodotti tutti gli altri elementi?

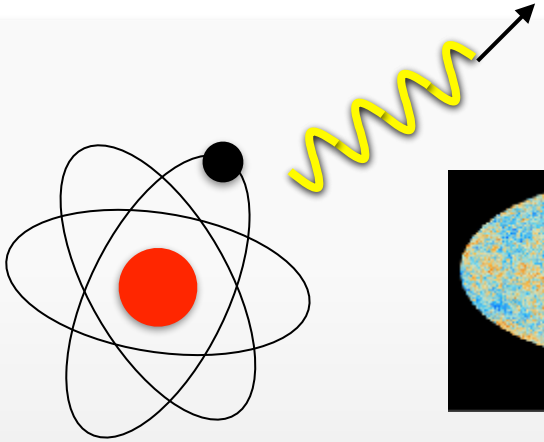


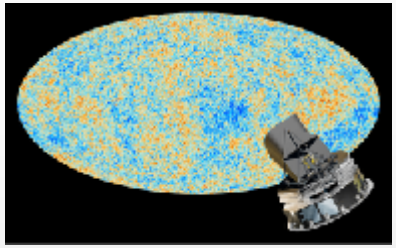
Radiazione Cosmica di fondo (Cosmic Microwave Background) *(CMB)*

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
≃ 3000 K

z = 1100

Temperatura oggi: 2.725 K

CMB

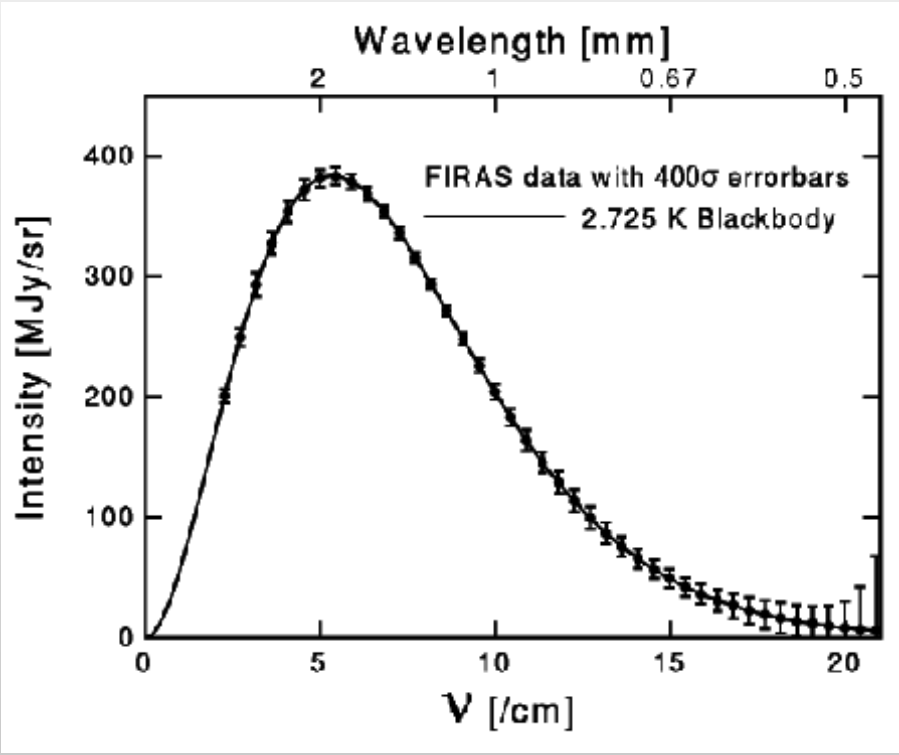
Energia ionizzazione H: 13.6 eV

↓

Temperatura ricombinazione H: 0.25 eV
≃ 3000 K

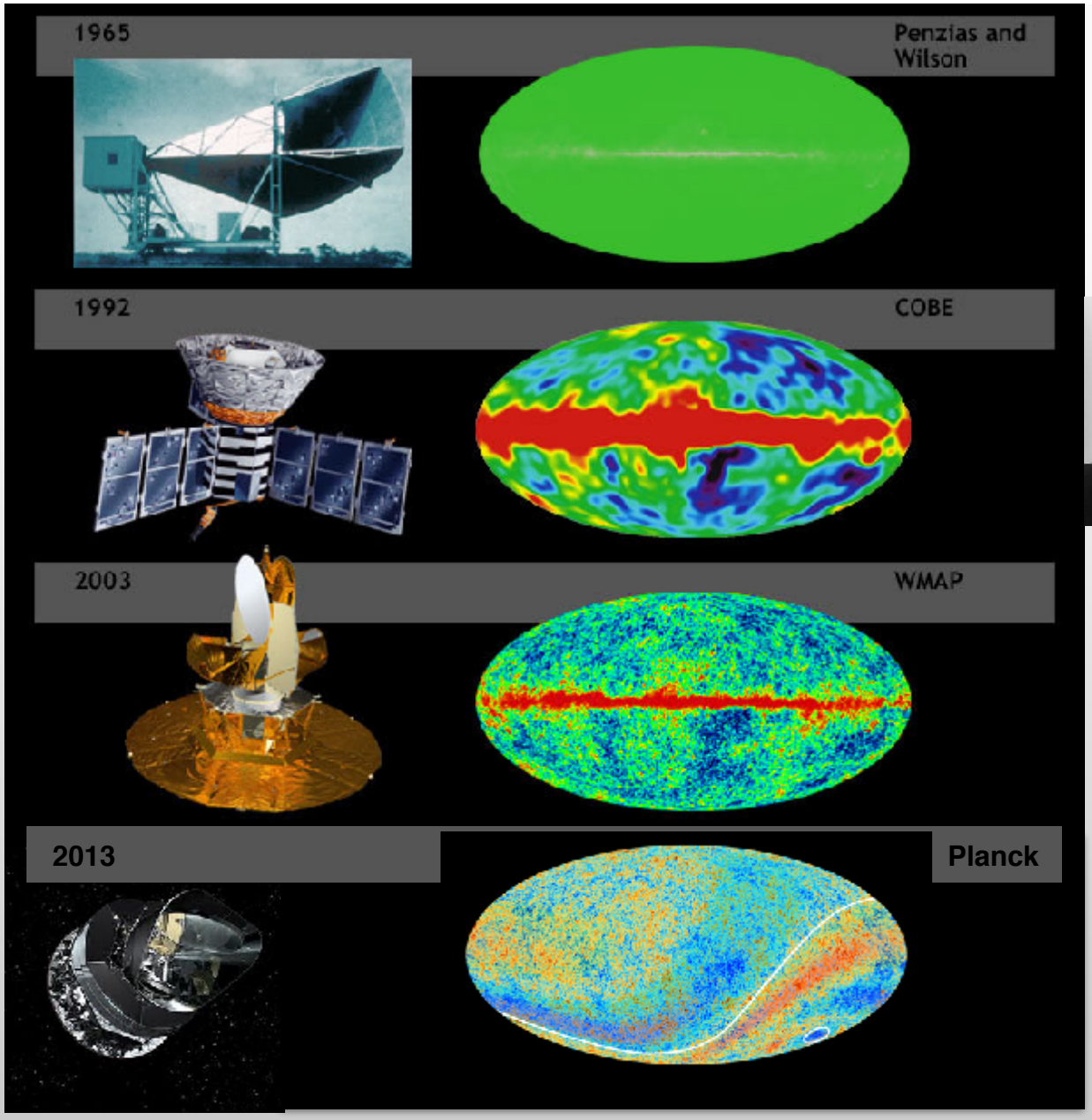
↓ z = 1100

Temperatura oggi: 2.725 K



NB: 'Microwave' perché λ ~ 1 mm, come il wifi, i GSM o il famoso forno
(niente a che vedere con il micron, anche se, alla ricombinazione, λ ~ 1 μm!)

CMB - storia

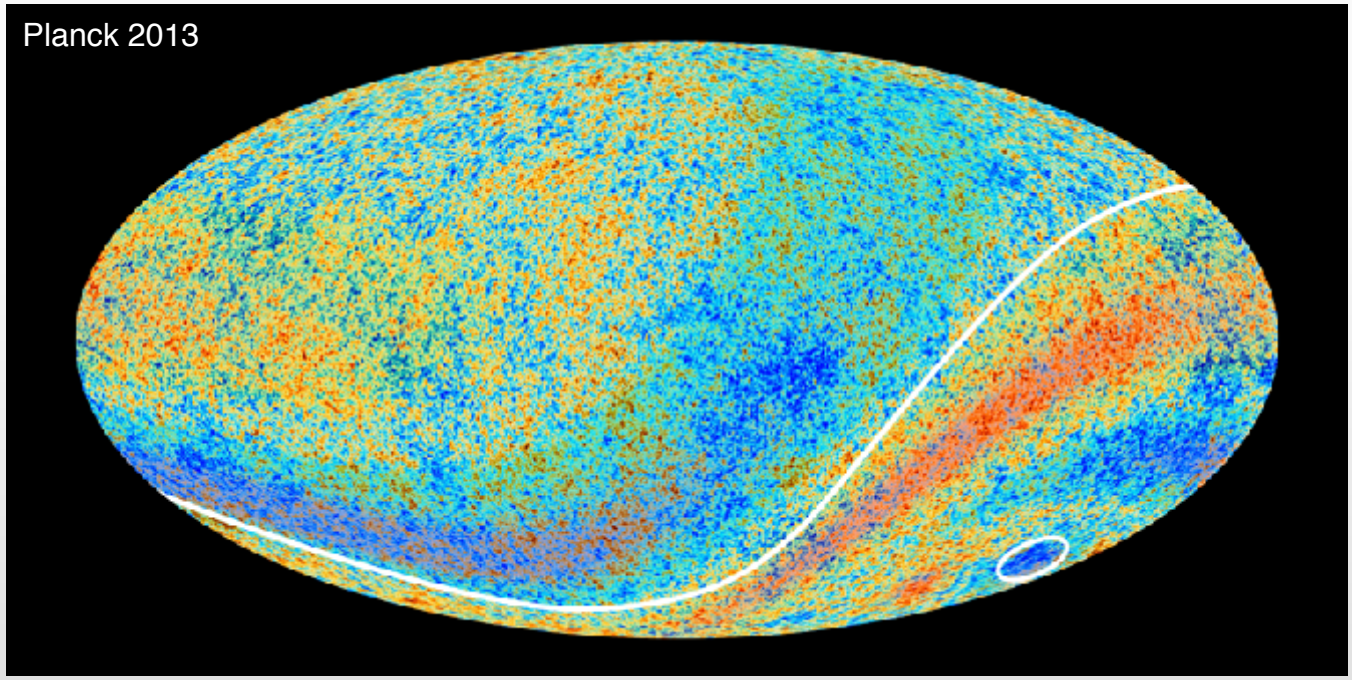


1978

2006

>200 scienziati
IT+F+…

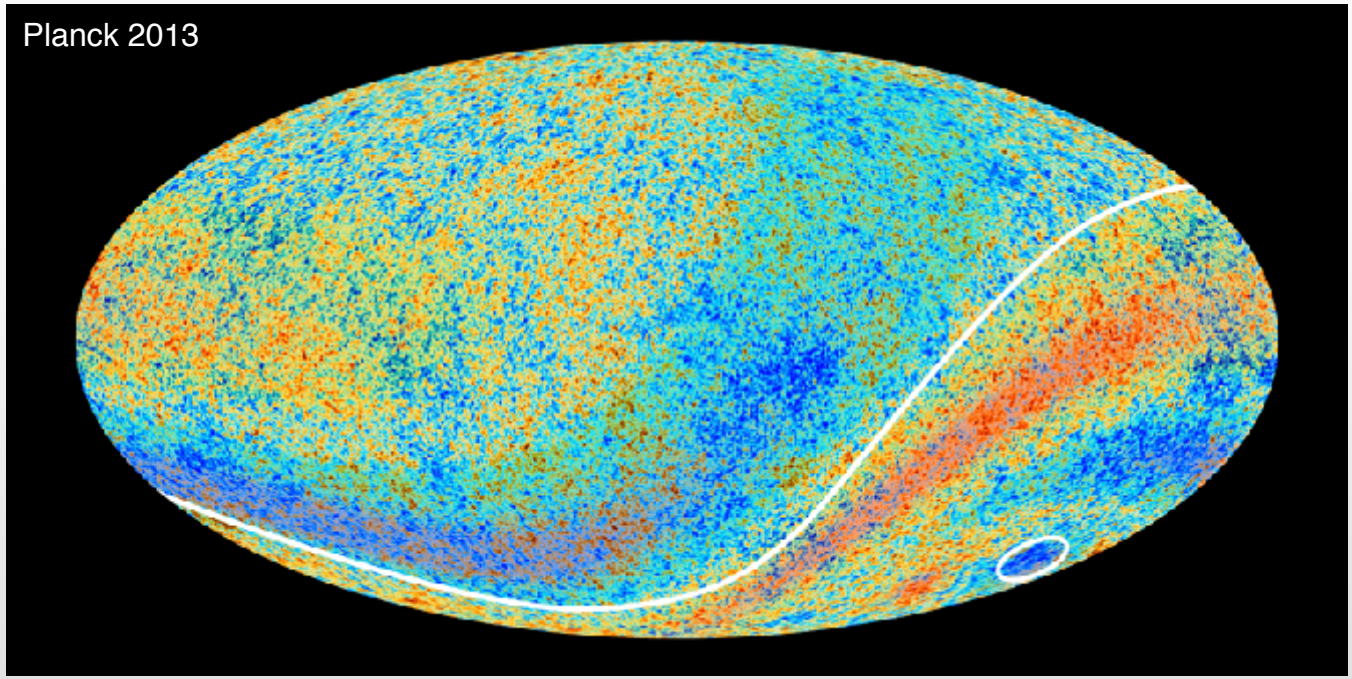
CMB - fluttuazioni



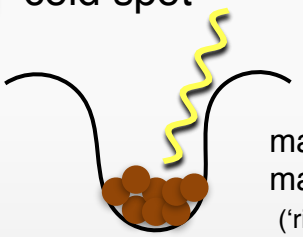
$$T = 2.725^\circ K$$

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

CMB - fluttuazioni

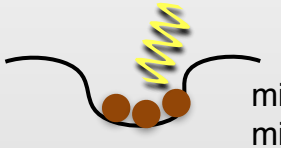


‘cold spot’



maggiore densità
maggiore perdita E
(‘risalire la china’)

‘hot spot’

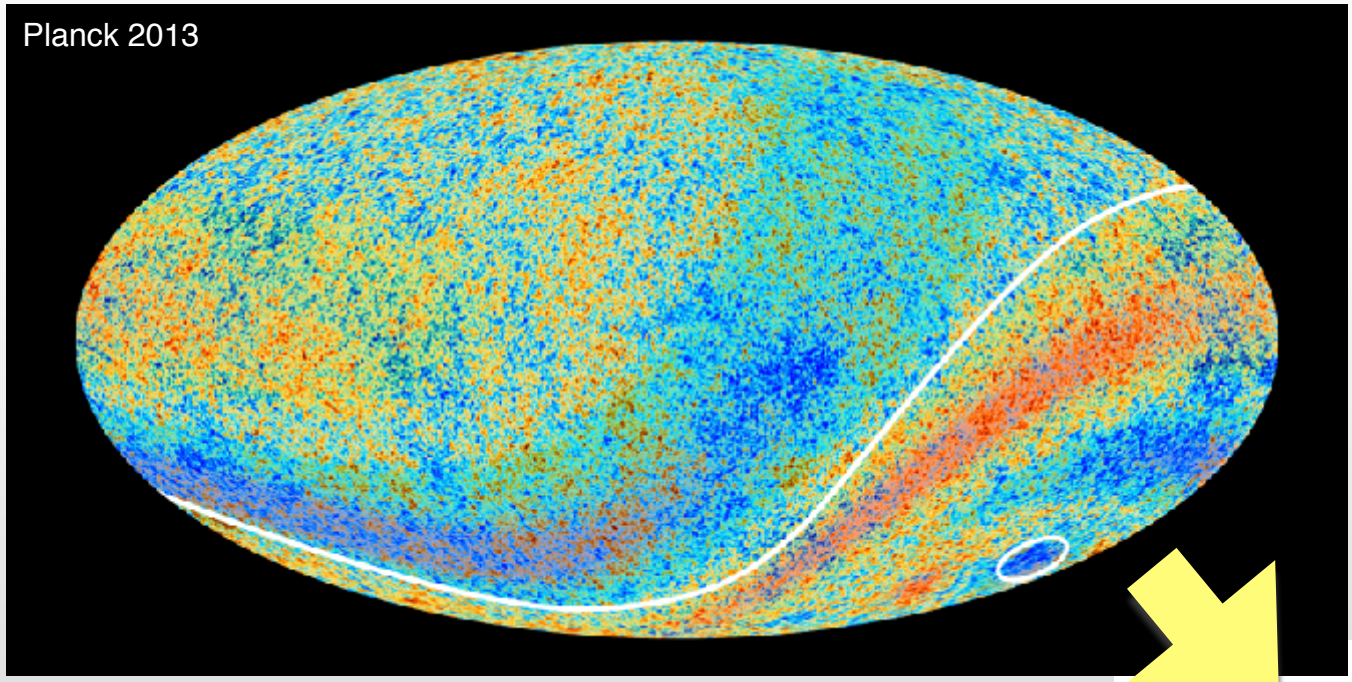


minore densità
minore perdita E

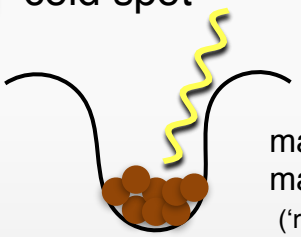
$$T = 2.725^\circ K$$

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

CMB - fluttuazioni

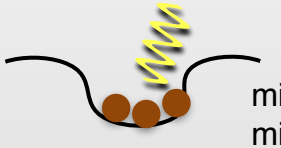


‘cold spot’



maggiore densità
maggiore perdita E
(‘risalire la china’)

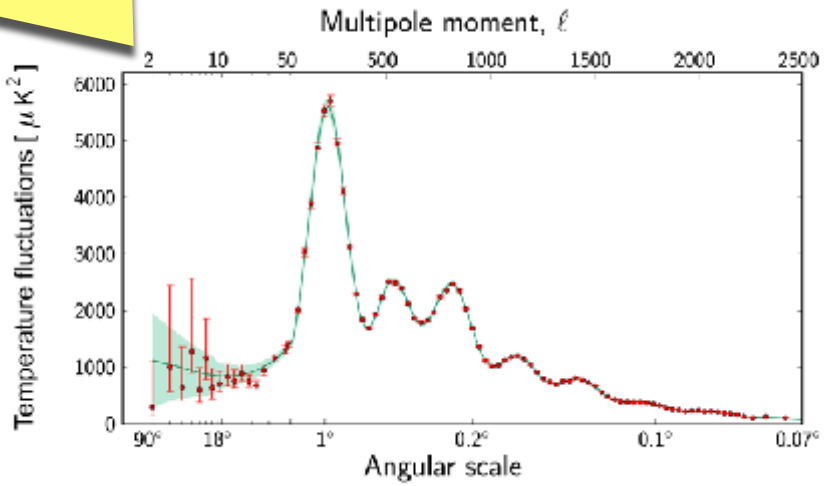
‘hot spot’



minore densità
minore perdita E

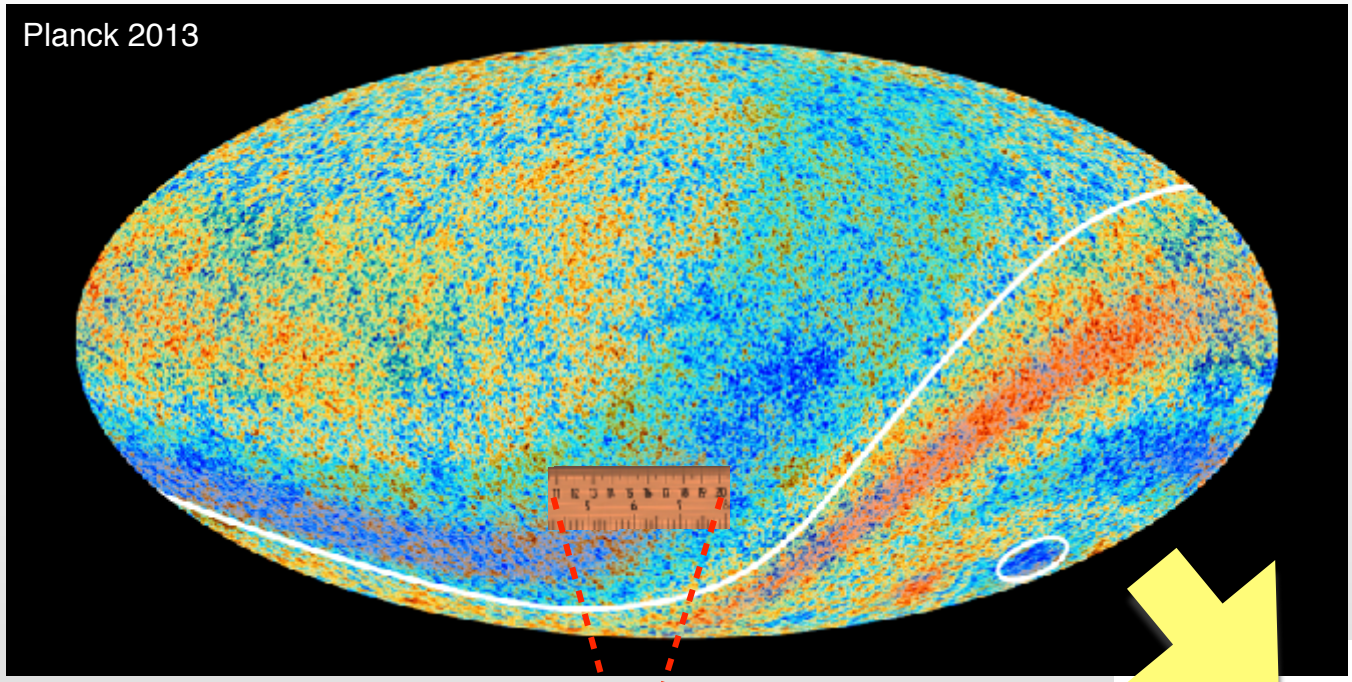
$$T = 2.725° K$$

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



Spettro di potenza della CMB
(CMB power spectrum)

CMB - fluttuazioni

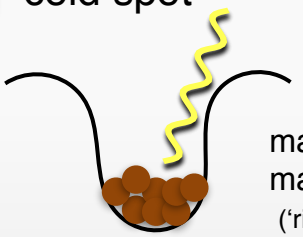


0.5°

$$T = 2.725° K$$

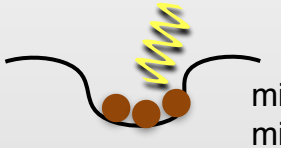
$$\frac{\delta T}{T} \sim 10^{-5}$$

'cold spot'

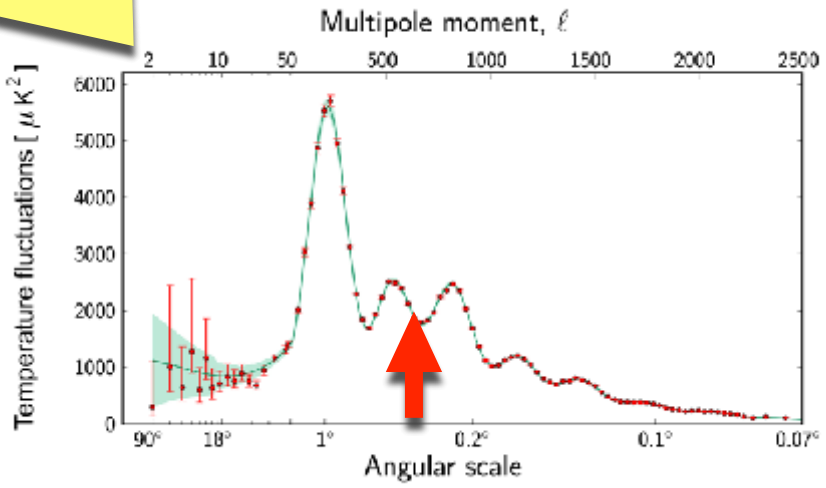


maggiore densità
maggiore perdita E
('risalire la china')

'hot spot'

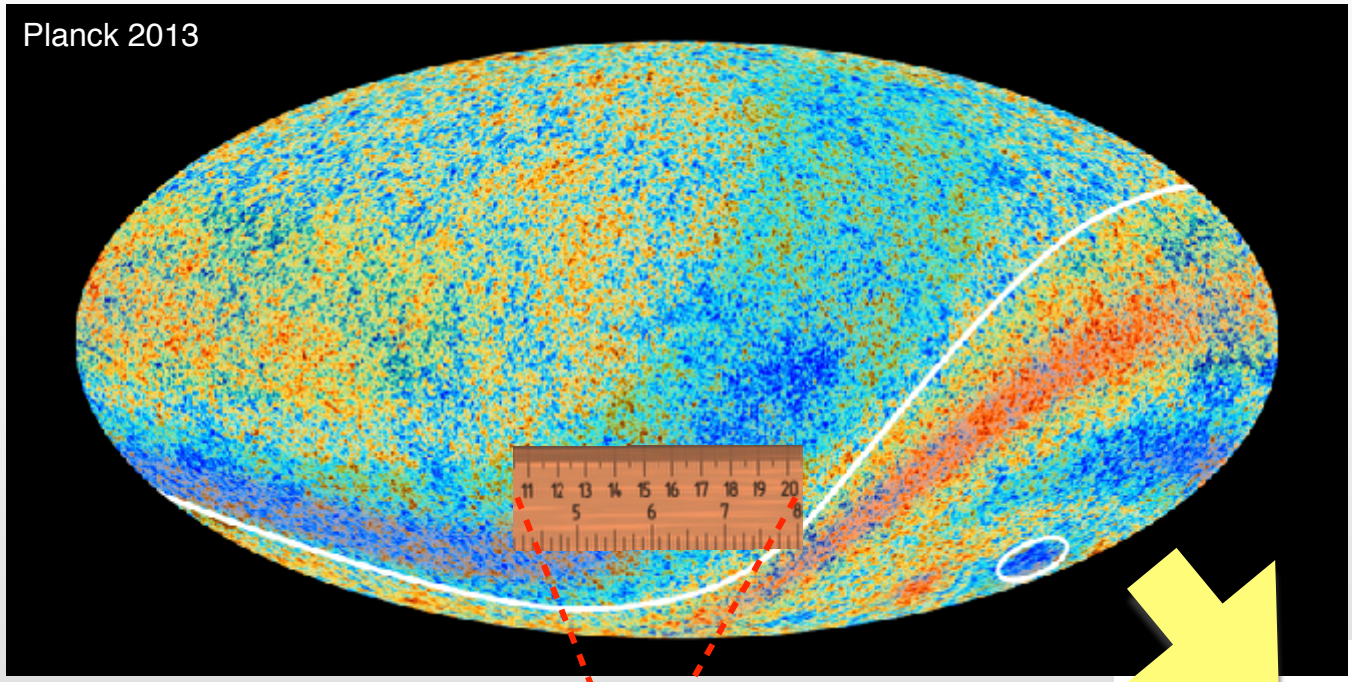


minore densità
minore perdita E



Spettro di potenza della CMB
(CMB power spectrum)

CMB - fluttuazioni

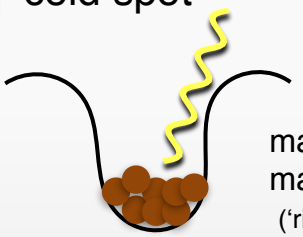


1°

$$T = 2.725° K$$

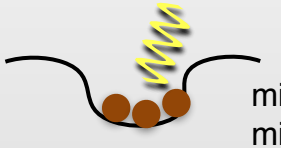
$$\frac{\delta T}{T} \sim 10^{-5}$$

'cold spot'

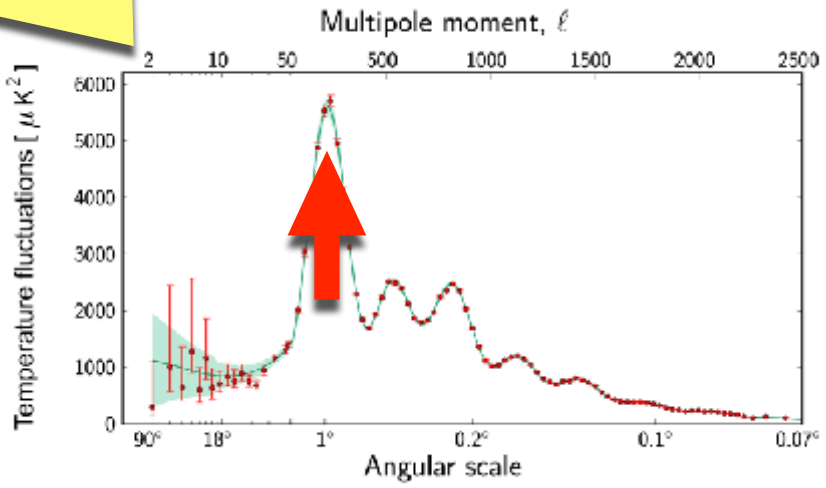


maggiore densità
maggiore perdita E
('risalire la china')

'hot spot'

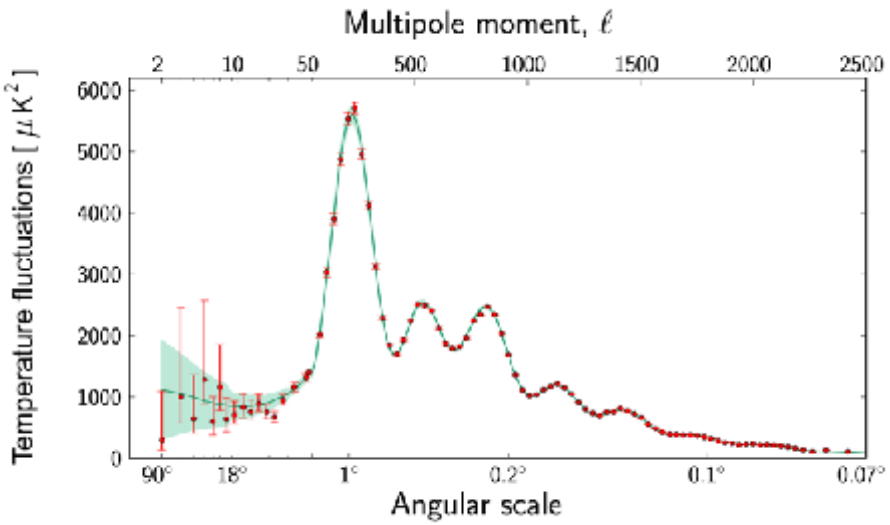


minore densità
minore perdita E



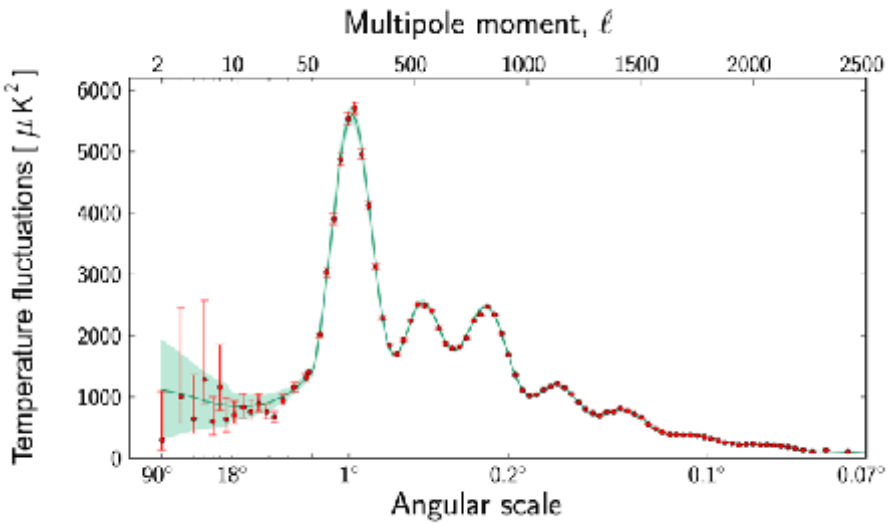
Spettro di potenza della CMB
(CMB power spectrum)

CMB - fluttuazioni



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

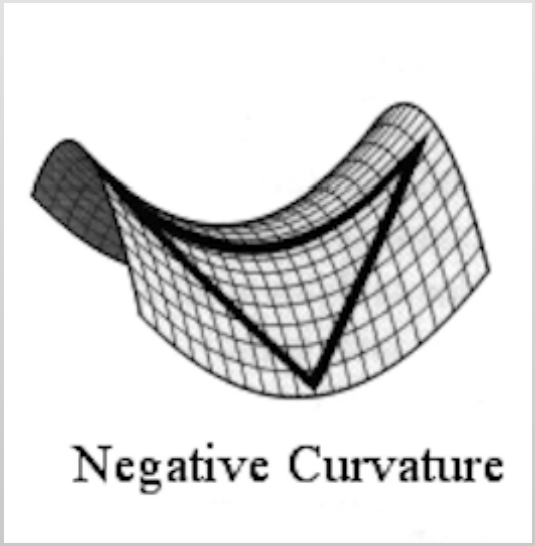
CMB - fluttuazioni

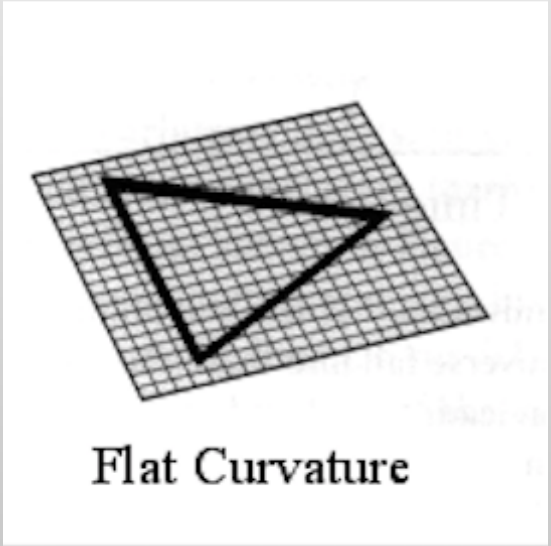


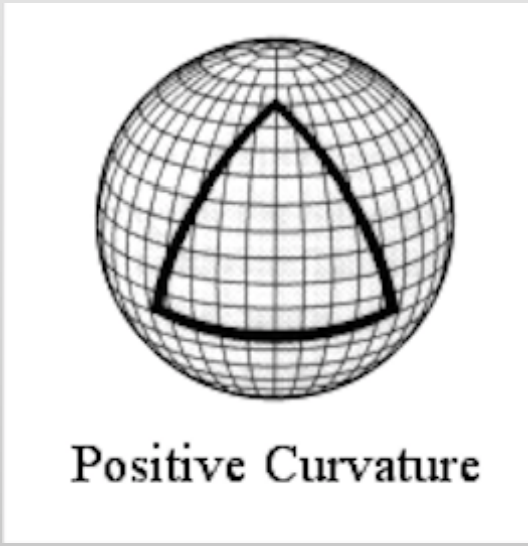
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

E.g.: curvatura dell'Universo

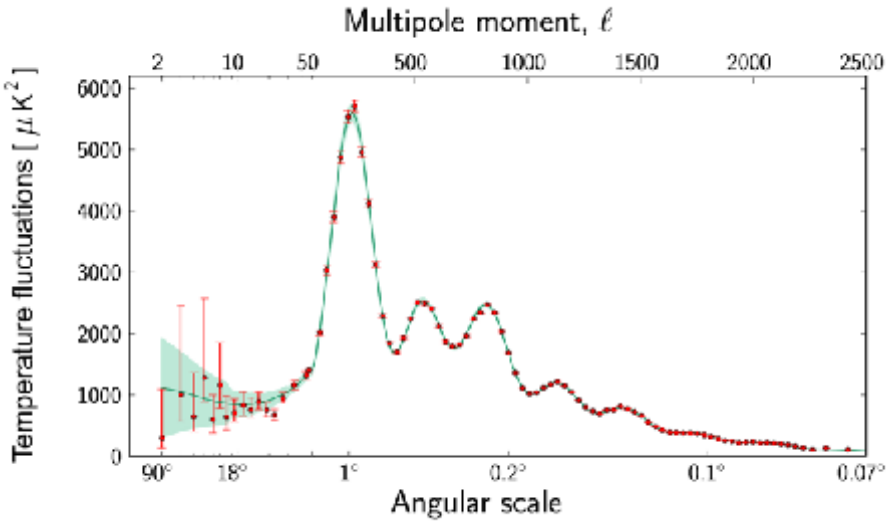
(somewhat oversimplified, but ok)





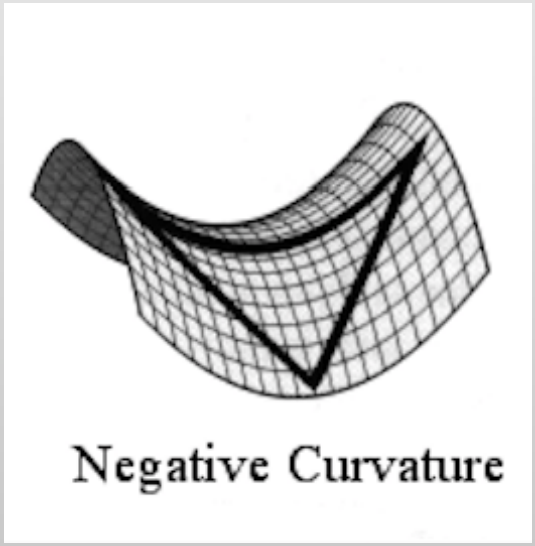


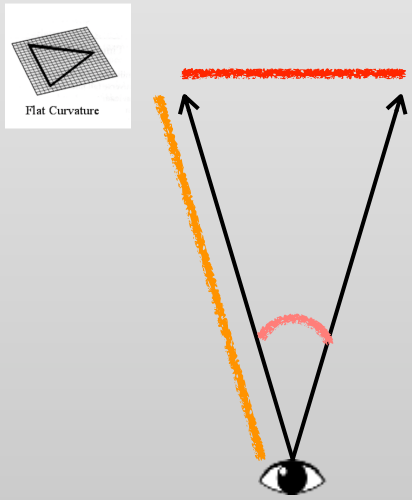
CMB - fluttuazioni

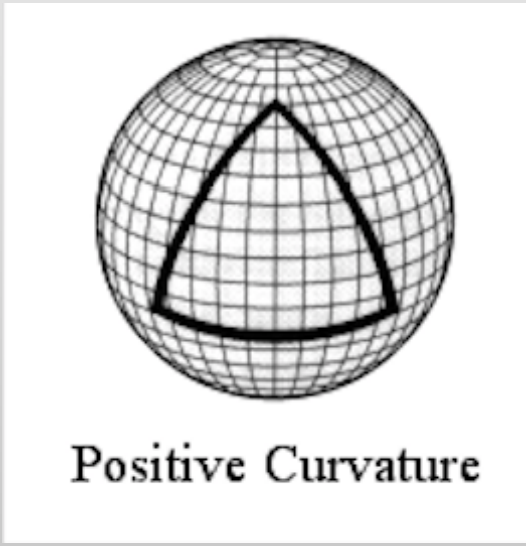


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

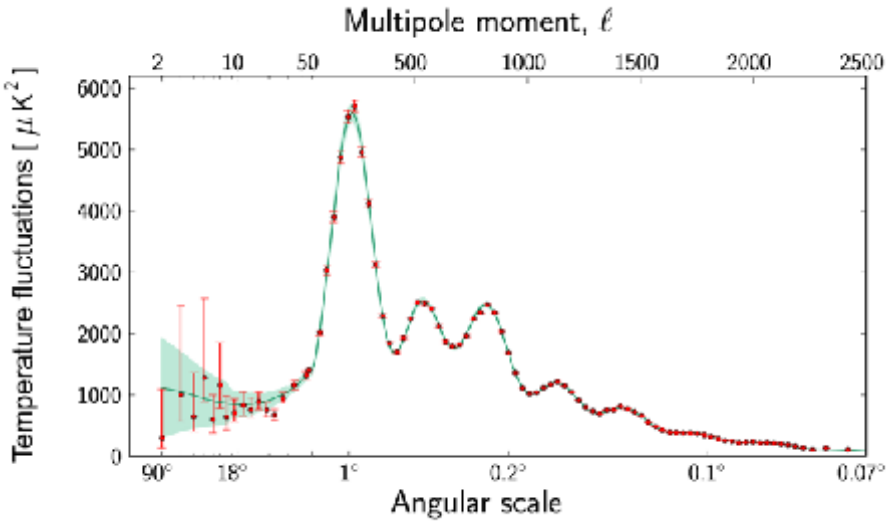
E.g.: curvatura dell'Universo





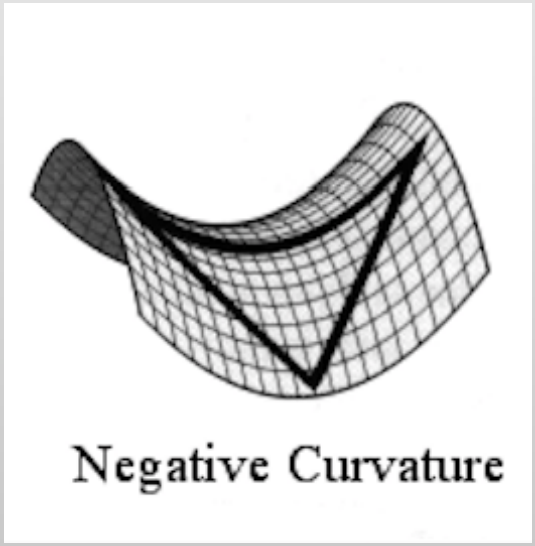


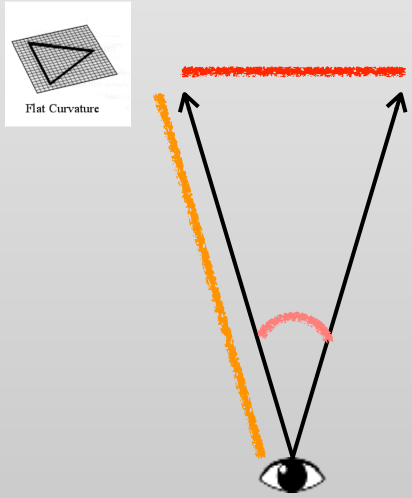
CMB - fluttuazioni

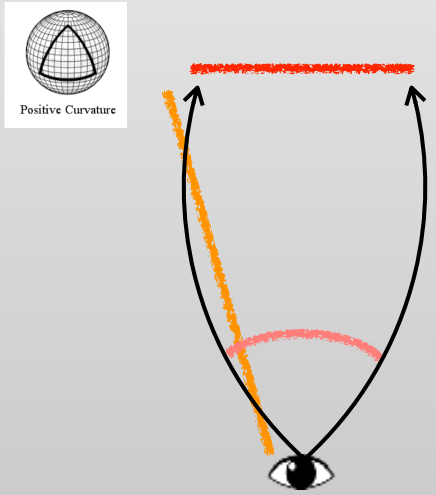


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

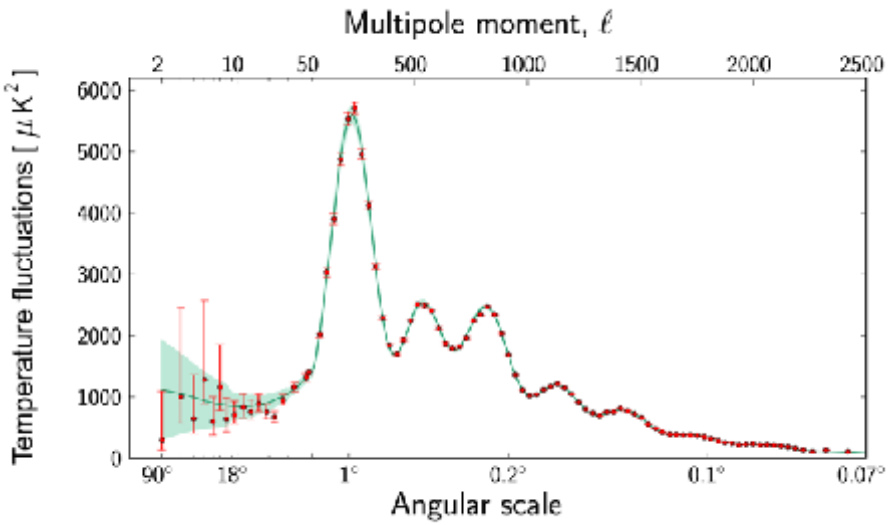
E.g.: curvatura dell'Universo





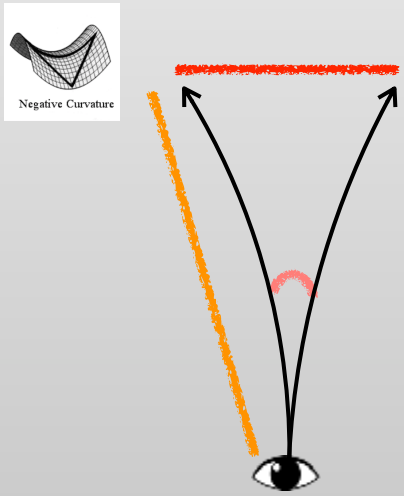


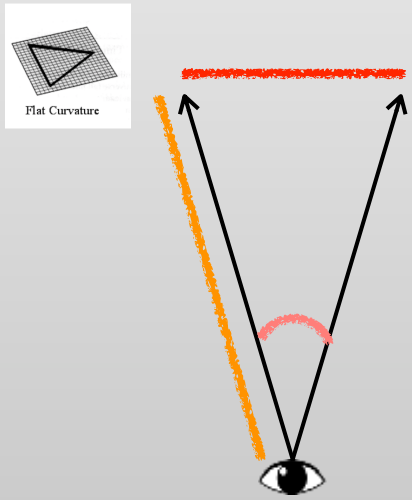
CMB - fluttuazioni

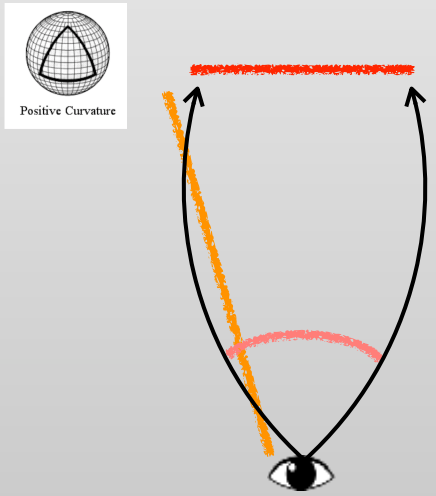


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

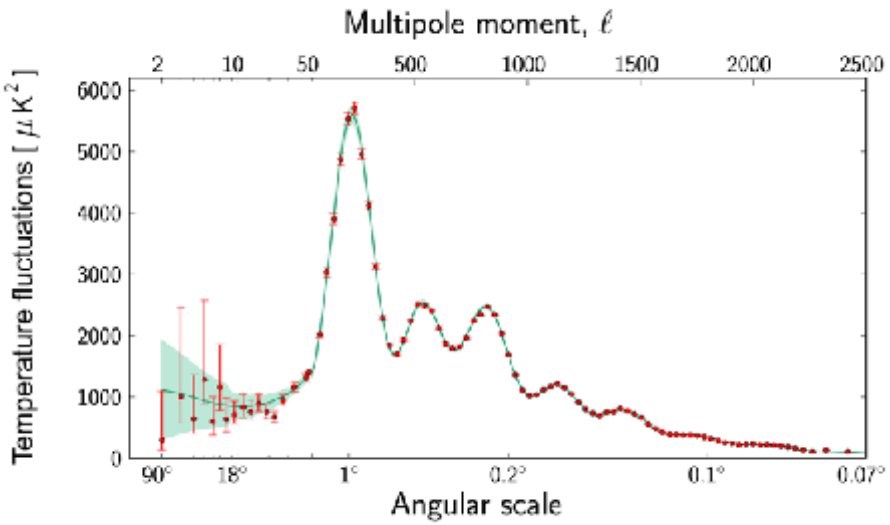
E.g.: curvatura dell'Universo







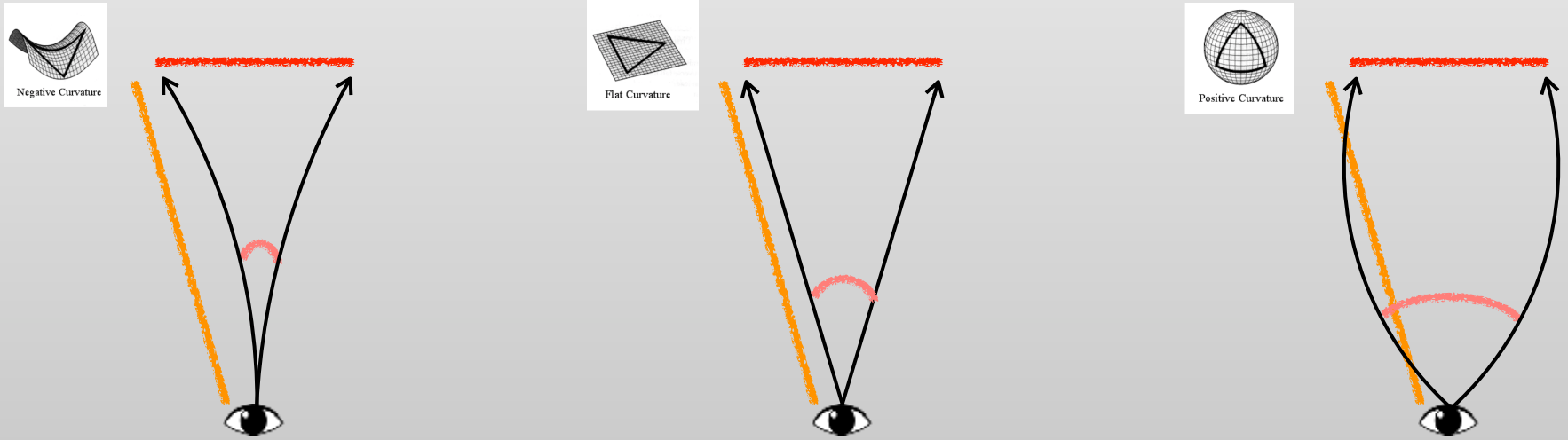
CMB - fluttuazioni



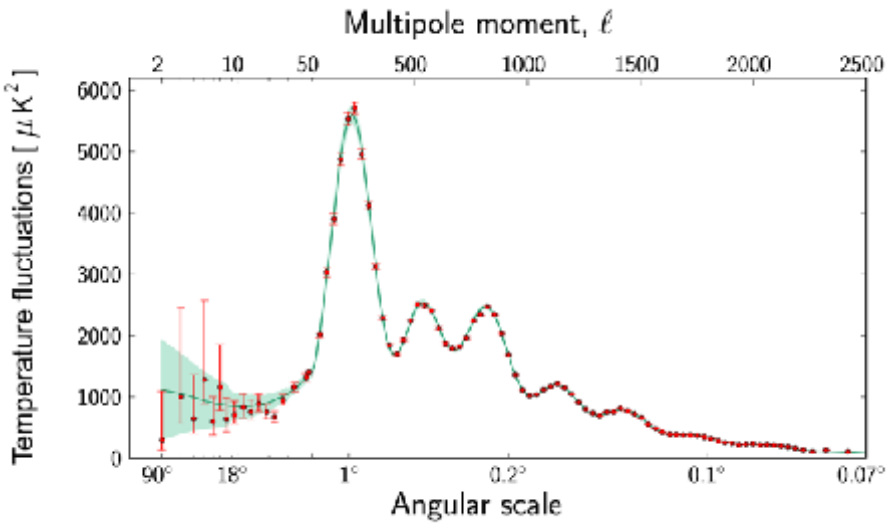
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

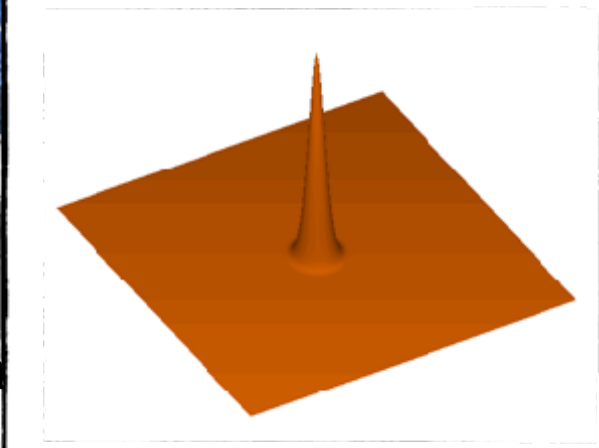
E.g.: curvatura dell'Universo

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



CMB - fluttuazioni

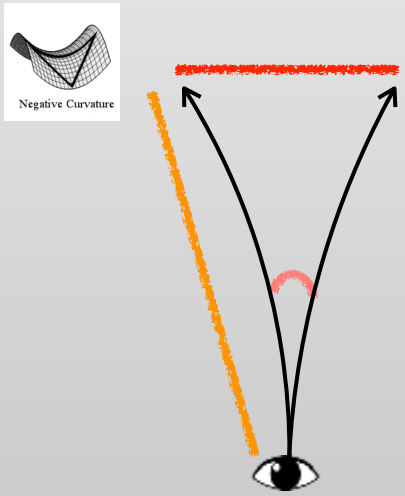


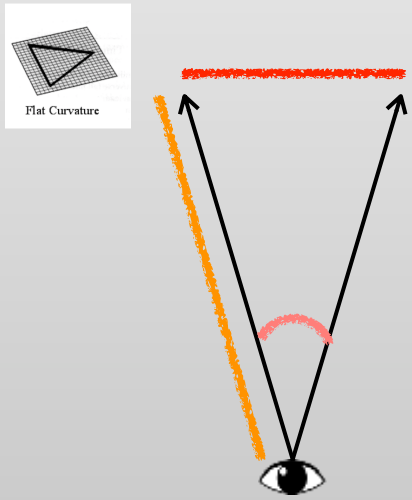


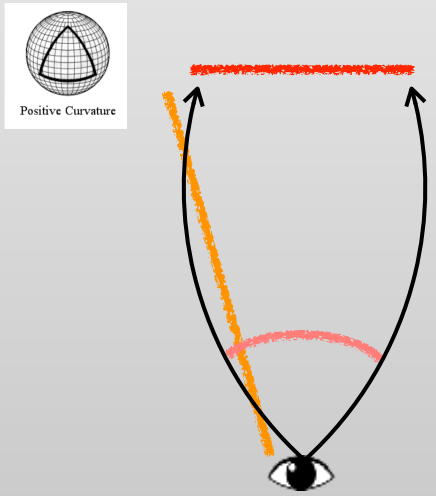
Lo spettro di
un'eccezionale
sulle propriet

E.g.: curvatura dell'Universo

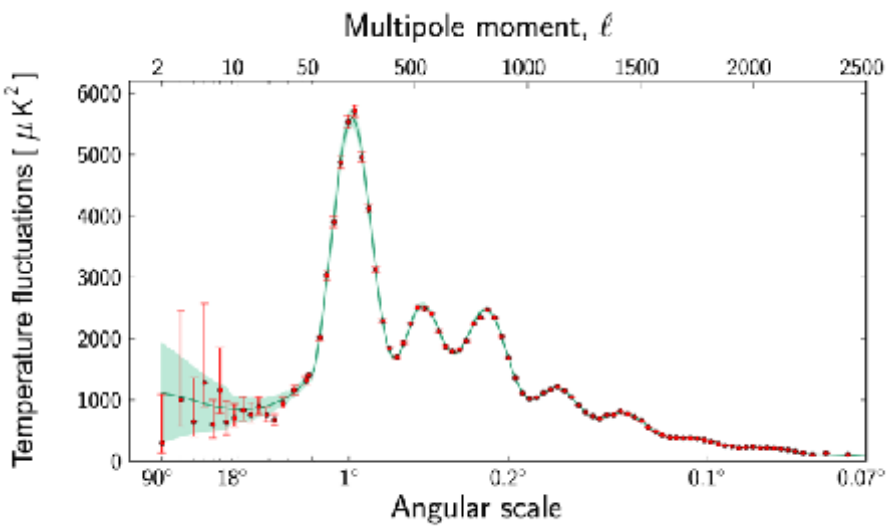
lunghezza nota: la distanza percorsa da un'onda di materia dal Big Bang alla ricombinazione







CMB - fluttuazioni

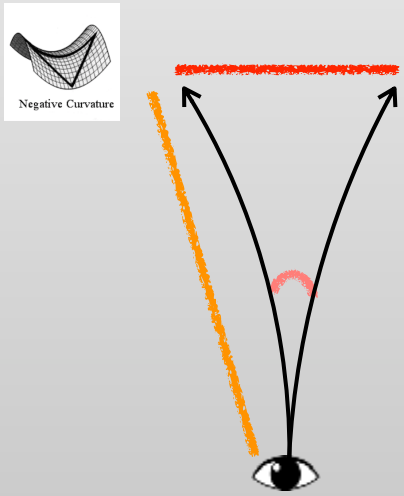


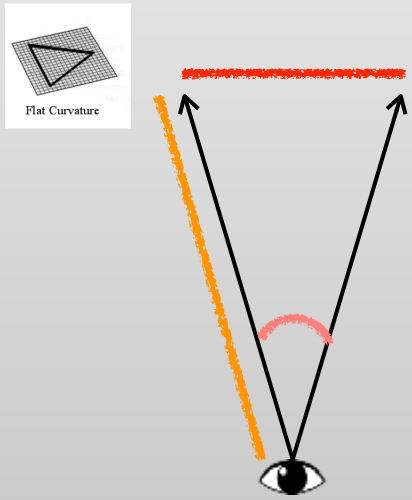
Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

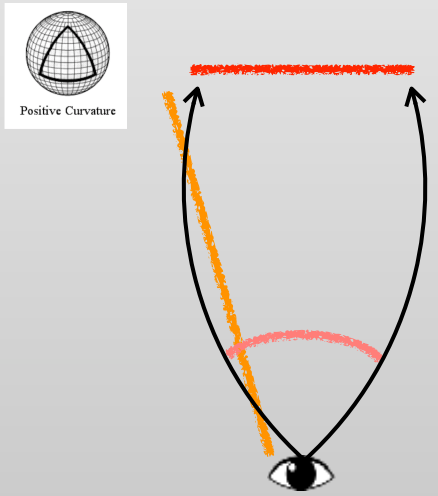
E.g.: curvatura dell'Universo

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

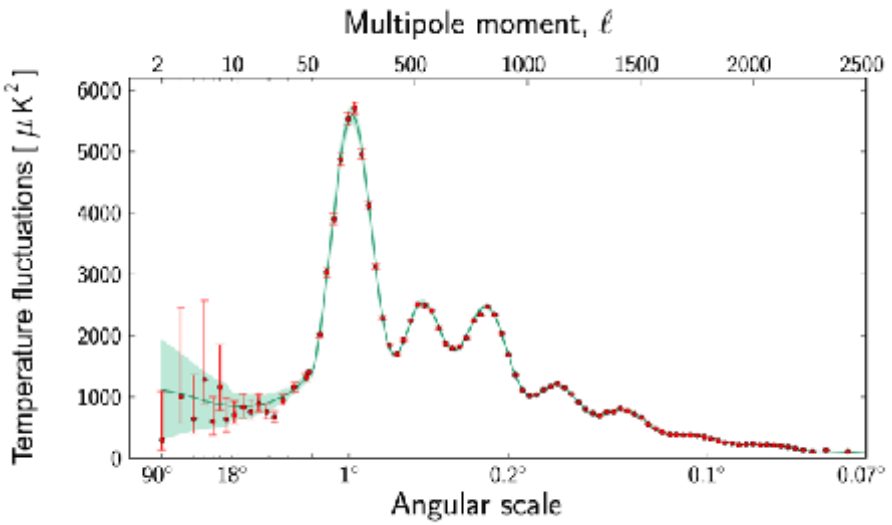
distanza nota: la distanza percorsa dai fotoni CMB fino ad oggi







CMB - fluttuazioni

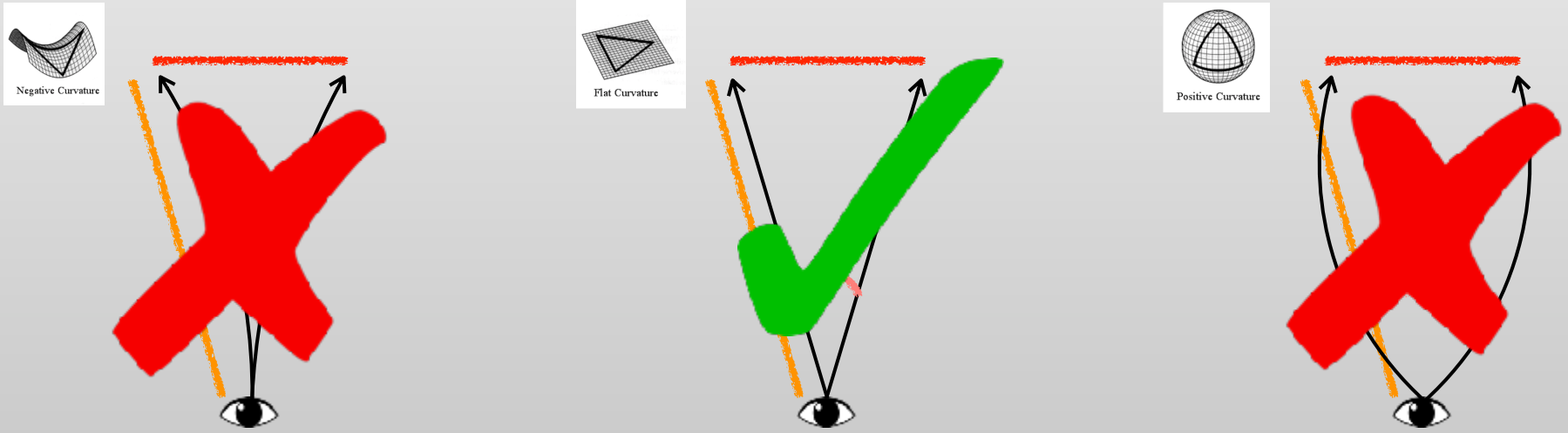


Lo spettro di potenza della CMB è un'eccezionale miniera di informazioni sulle proprietà dell'Universo

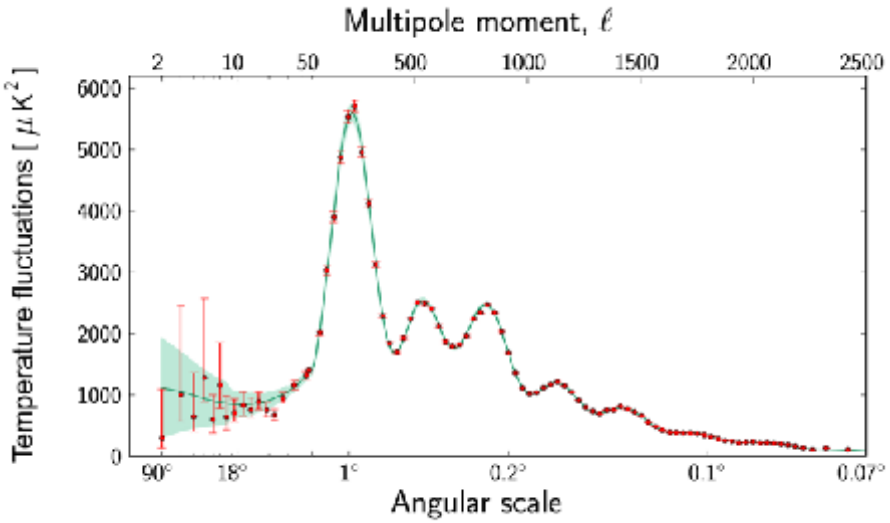
E.g.: curvatura dell'Universo

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



CMB - fluttuazioni



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

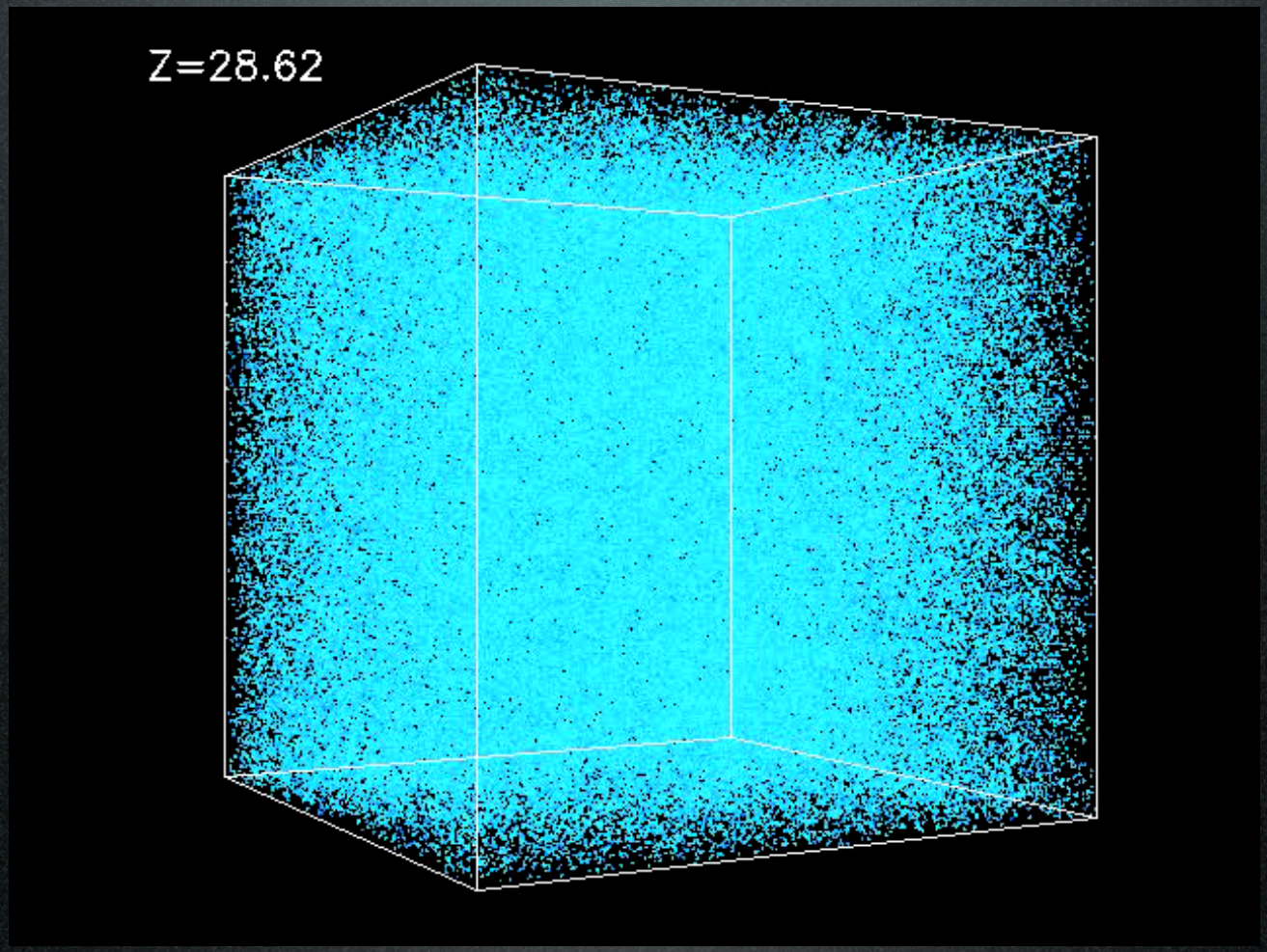
Parameter	TT+lowP 68% limits
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_Λ	0.685 ± 0.013
Ω_m	0.315 ± 0.013
$\Omega_m h^2$	0.1426 ± 0.0020
$\Omega_m h^3$	0.09597 ± 0.00045
σ_8	0.829 ± 0.014
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013
z_{re}	$9.9^{+1.8}_{-1.6}$
$10^9 A_s$	$2.198^{+0.075}_{-0.085}$
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014
Age/Gyr	13.813 ± 0.038
z_*	1090.09 ± 0.42
r_*	144.61 ± 0.49
$100\theta_*$	1.04105 ± 0.00046
z_{drag}	1059.57 ± 0.46
r_{drag}	147.33 ± 0.49
k_D	0.14050 ± 0.00052
z_{eq}	3393 ± 49

Formazione Galassie, Ammassi

(LSS formation)

DM N-body simulations

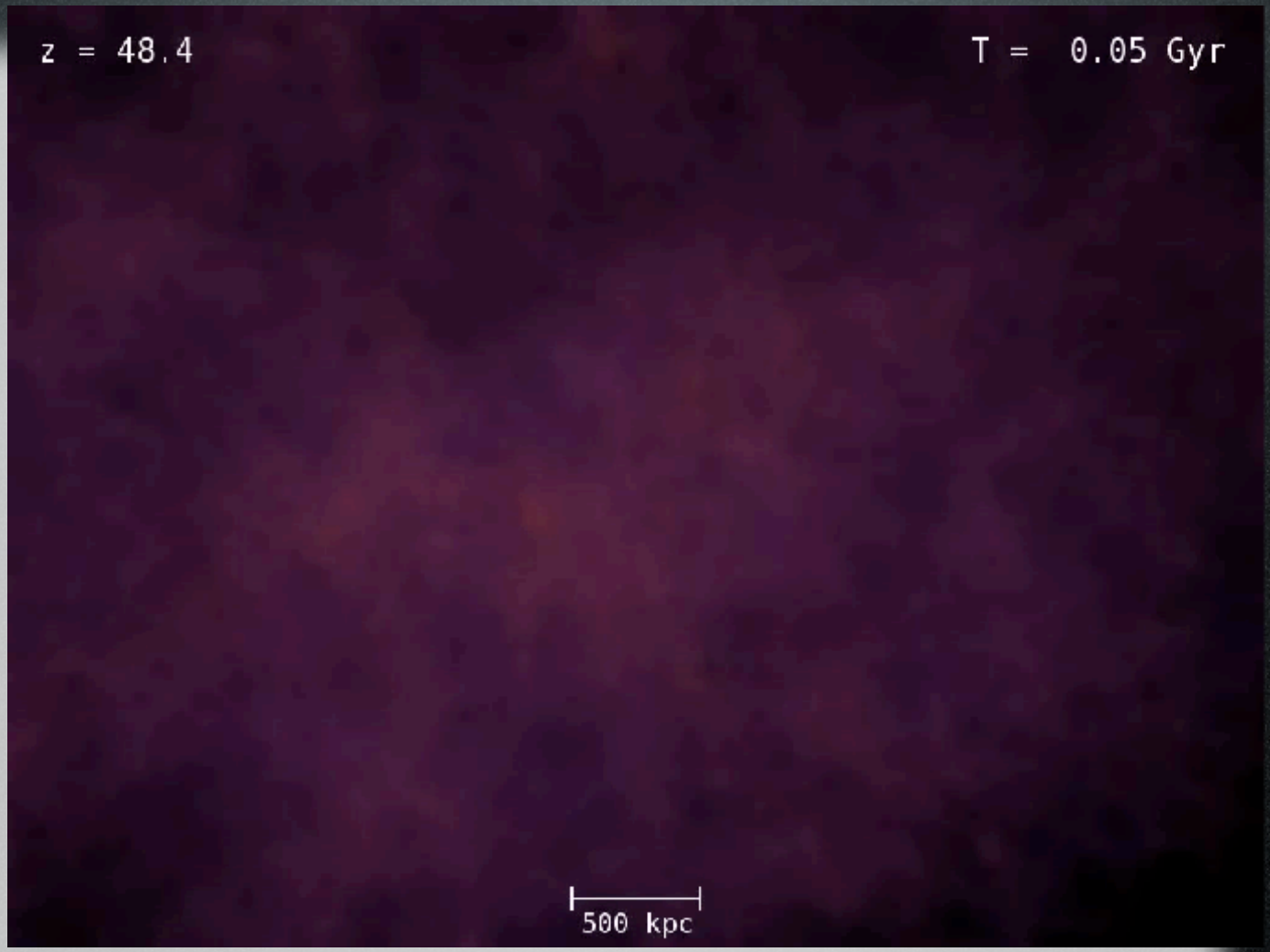
2 10^6 CDM particles, 43 Mpc cubic box



Andrey Kravtsov, cosmicweb.uchicago.edu

DM N-body simulations

Aquarius project of the VIRGO coll.:
$1.5\ 10^9$ CDM particles, single galactic halo

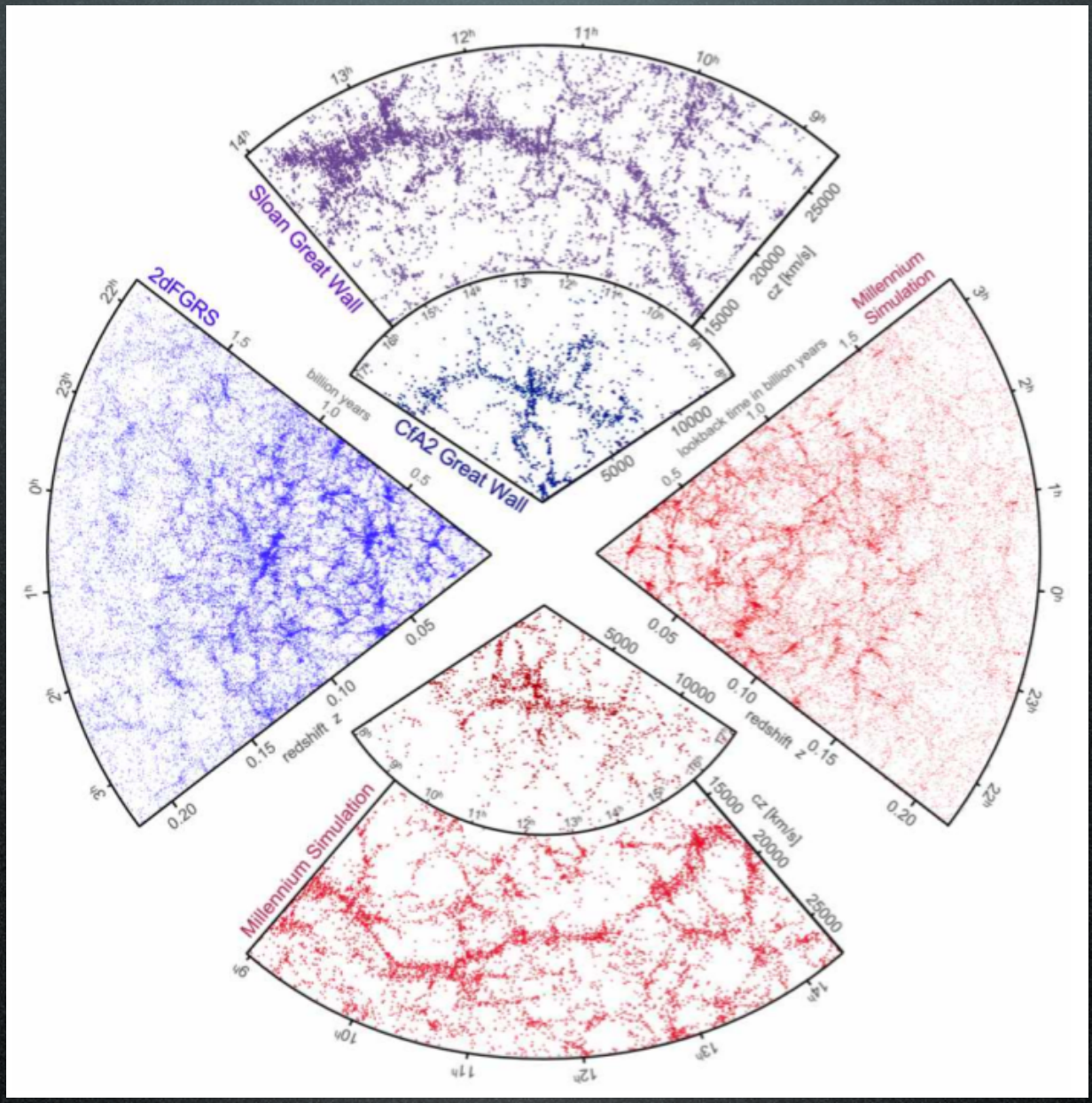


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies, 2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

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

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

(non in scala!)

? 10^{15} GeV 1 GeV 1 MeV 1 eV

Big Bang

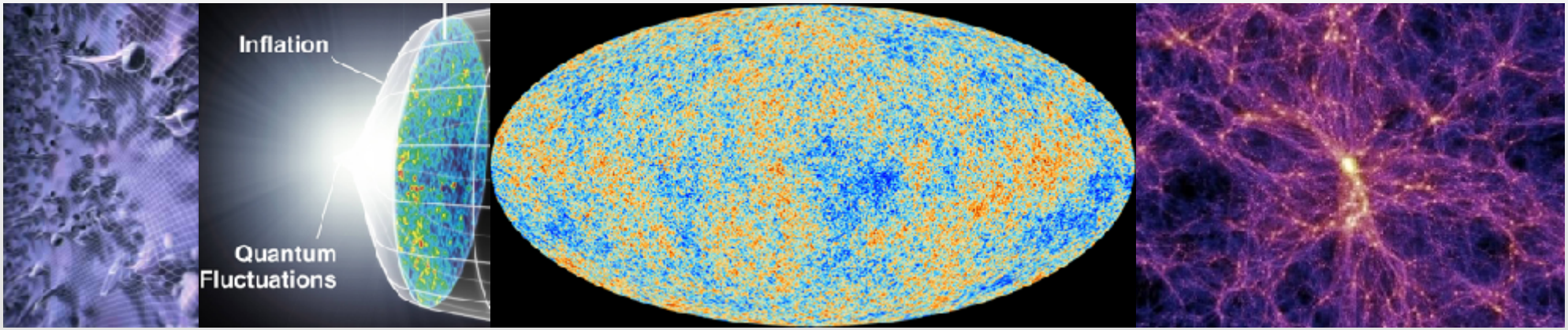
Inflazione

Bariogenesi

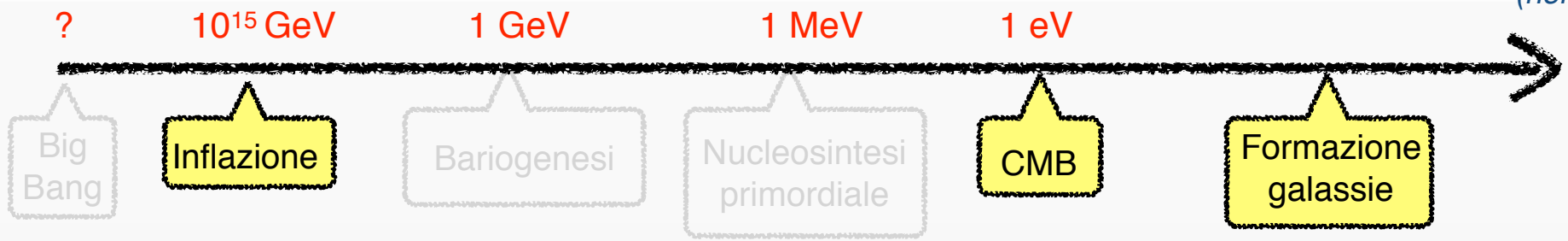
Nucleosintesi primordiale

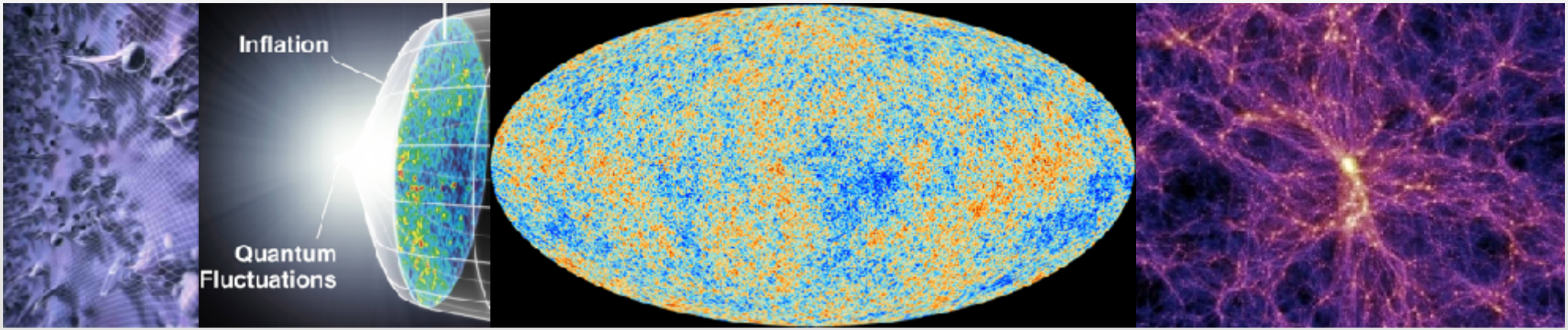
CMB

Formazione galassie



(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

Neutrini e oscillazioni

Neutrini e oscillazioni dei neutrini

Neutrini e oscillazioni dei neutrini

1930 proposto da Pauli

N -> N' e^-

N -> N' e^- ν

per spiegare lo spettro continuo del decadimento beta

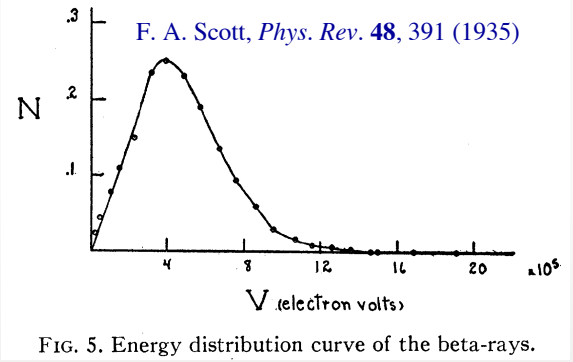
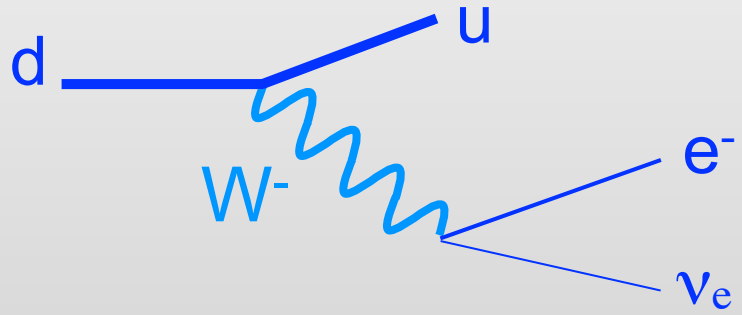
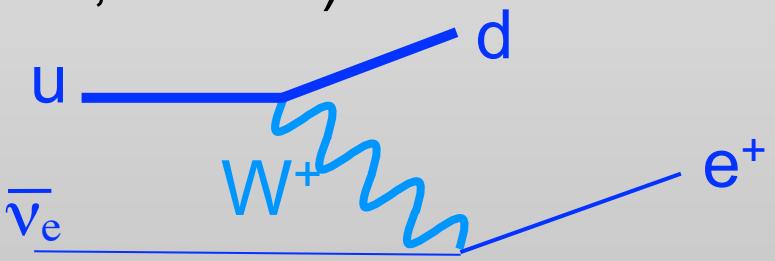


FIG. 5. Energy distribution curve of the beta-rays.

1932 teoria di Fermi del decadimento beta- interazioni deboli



1956 rivelazione diretta (Cowan, Reines)



Neutrini e oscillazioni dei neutrini

1930 proposto da Pauli

N -> N' e^-

N -> N' e^- ν

per spiegare lo spettro continuo del decadimento beta

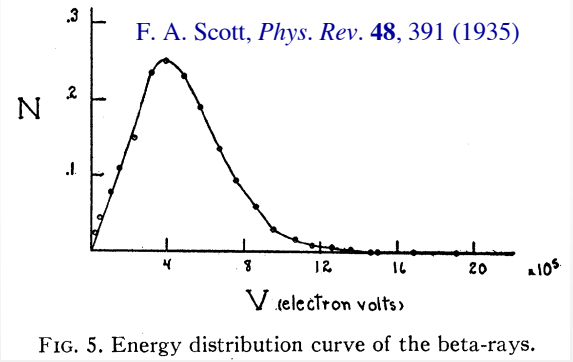
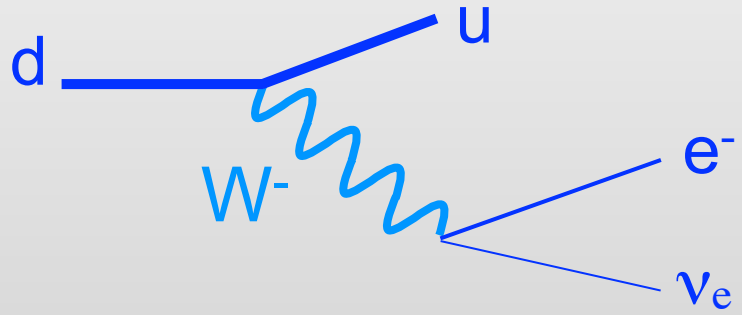
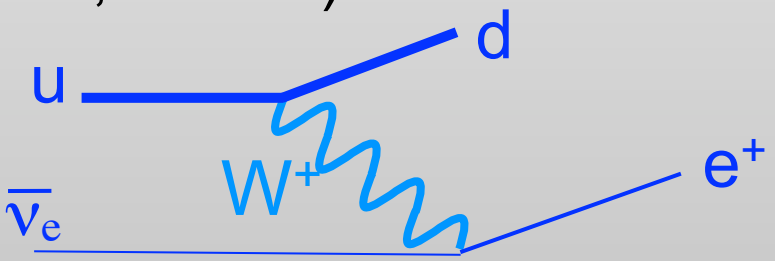


FIG. 5. Energy distribution curve of the beta-rays.

1932 teoria di Fermi del decadimento beta- interazioni deboli



1956 rivelazione diretta (Cowan, Reines)



1962 neutrino mu

2000 neutrino tau

Neutrini e oscillazioni dei neutrini

I neutrini interagiscono (molto) debolmente!

E.g., per una particella da ~1 MeV

protone	1mm carta
elettrone	<1cm alluminio
neutrone	2-3 cm plastica
gamma	10 cm H_2O
neutrino	

Neutrini e oscillazioni dei neutrini

I neutrini interagiscono (molto) debolmente!

E.g., per una particella da ~1 MeV

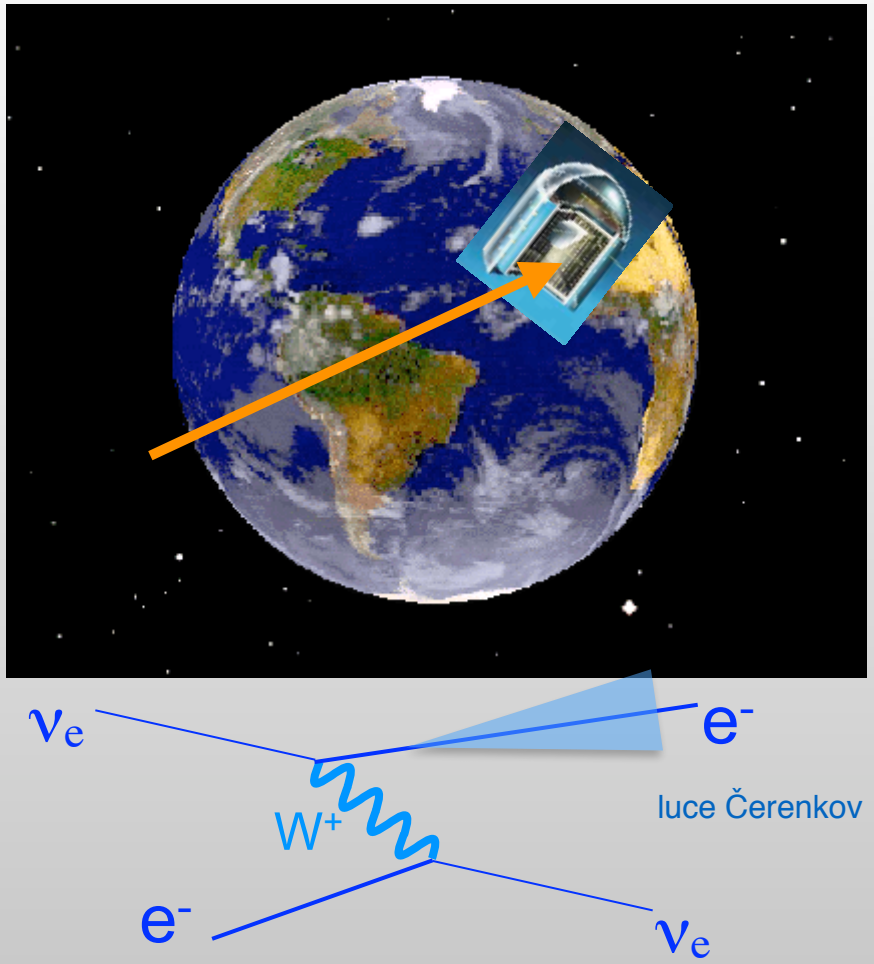
protone	1mm carta
elettrone	<1cm alluminio
neutrone	2-3 cm plastica
gamma	10 cm H_2O
neutrino	*1 anno luce di Piombo*

Neutrini e oscillazioni dei neutrini

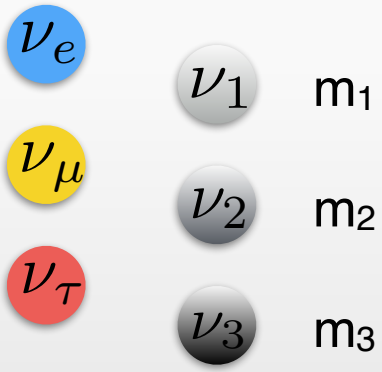
I neutrini interagiscono (molto) debolmente!

E.g., per una particella da ~1 MeV

protone	1mm carta
elettrone	<1cm alluminio
neutrone	2-3 cm plastica
gamma	10 cm H_2O
neutrino	*1 anno luce di Piombo*



Neutrini e oscillazioni dei neutrini

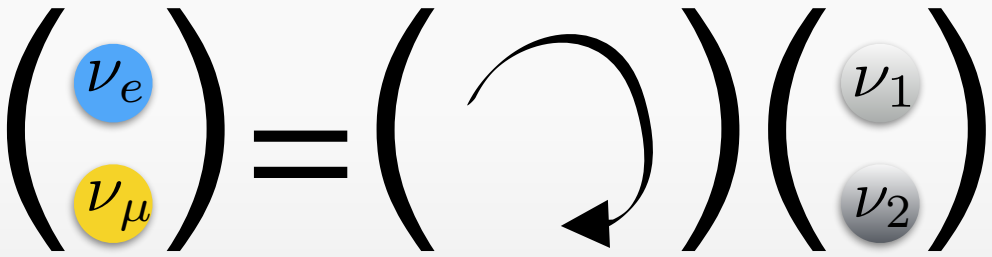


m_1

m_2

m_3

Neutrini e oscillazioni dei neutrini



Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Un'analogia (abbastanza deludente): la carrozza di Cenerentola

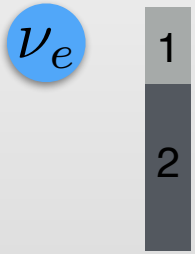
Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

produzione



Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

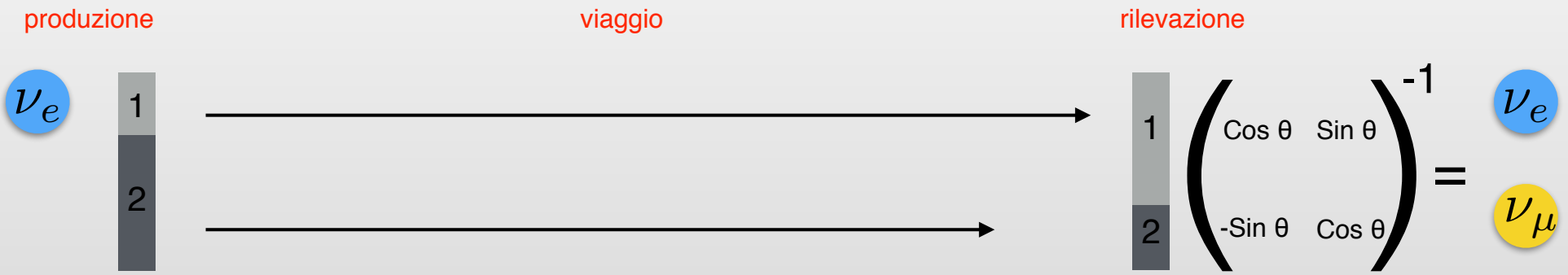
$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$



Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Un'altra analogia:

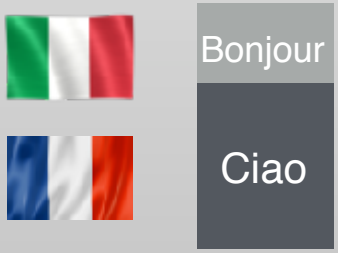
Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Un'altra analogia:



Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Un’altra analogia:

Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

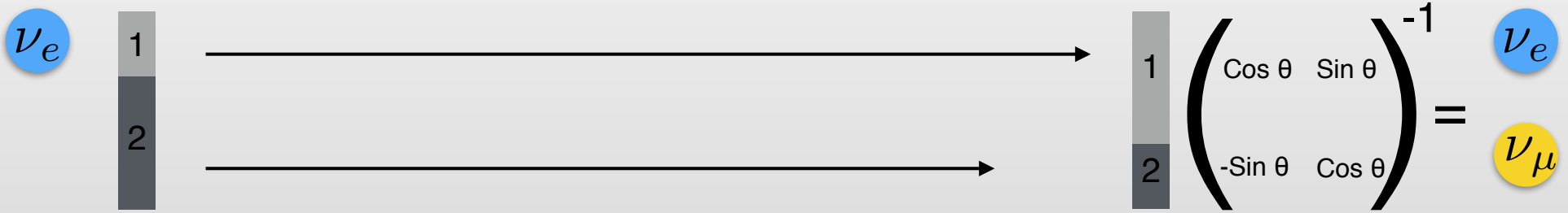
Un'altra analogia:

Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$



Un'altra analogia:

Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Un'altra analogia:

Neutrini e oscillazioni dei neutrini

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

Neutrini e oscillazioni dei neutrini

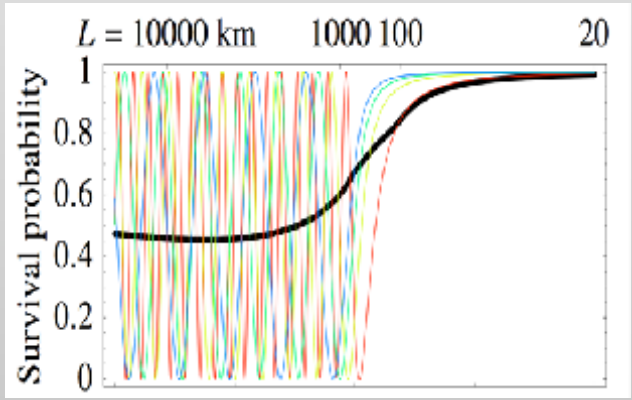
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \text{Cos } \theta & \text{Sin } \theta \\ \text{-Sin } \theta & \text{Cos } \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\nu_e = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\nu_\mu = \cos\theta\ \nu_2 - \sin\theta\ \nu_1$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta\ \sin^2 \frac{\Delta m^2 L}{4E}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

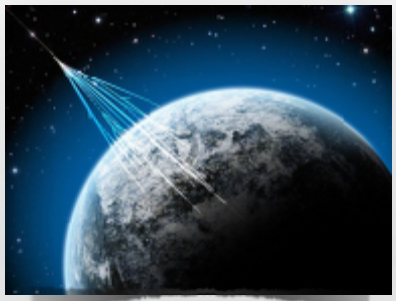


Neutrini e oscillazioni dei neutrini

Sorgenti di neutrini:

Naturali

raggi cosmici sull'atmosfera



$\nu_{e,\mu}$, $\bar{\nu}_{e,\mu}$ GeV-TeV

radioattività rocce ('geoneutrini')

$\bar{\nu}_e$ MeV

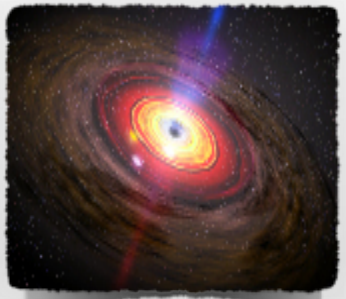
Sole (fusione)

ν_e MeV

supernovae

$\nu_{e,\mu,\tau}$, $\bar{\nu}_{e,\mu,\tau}$ 50 MeV

Active Galactic Nuclei



$\nu_{e,\mu,\tau}$, $\bar{\nu}_{e,\mu,\tau}$ TeV, more?

Artificiali

reattori nucleari (fissione)

$\bar{\nu}_e$ MeV

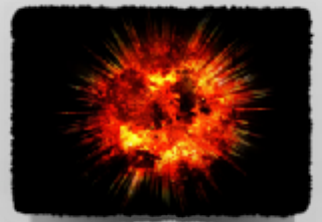
acceleratori

$\nu_{e,\mu}$, $\bar{\nu}_{e,\mu}$ ~GeV

bomba atomica

$\bar{\nu}_e$ MeV

Big Bang



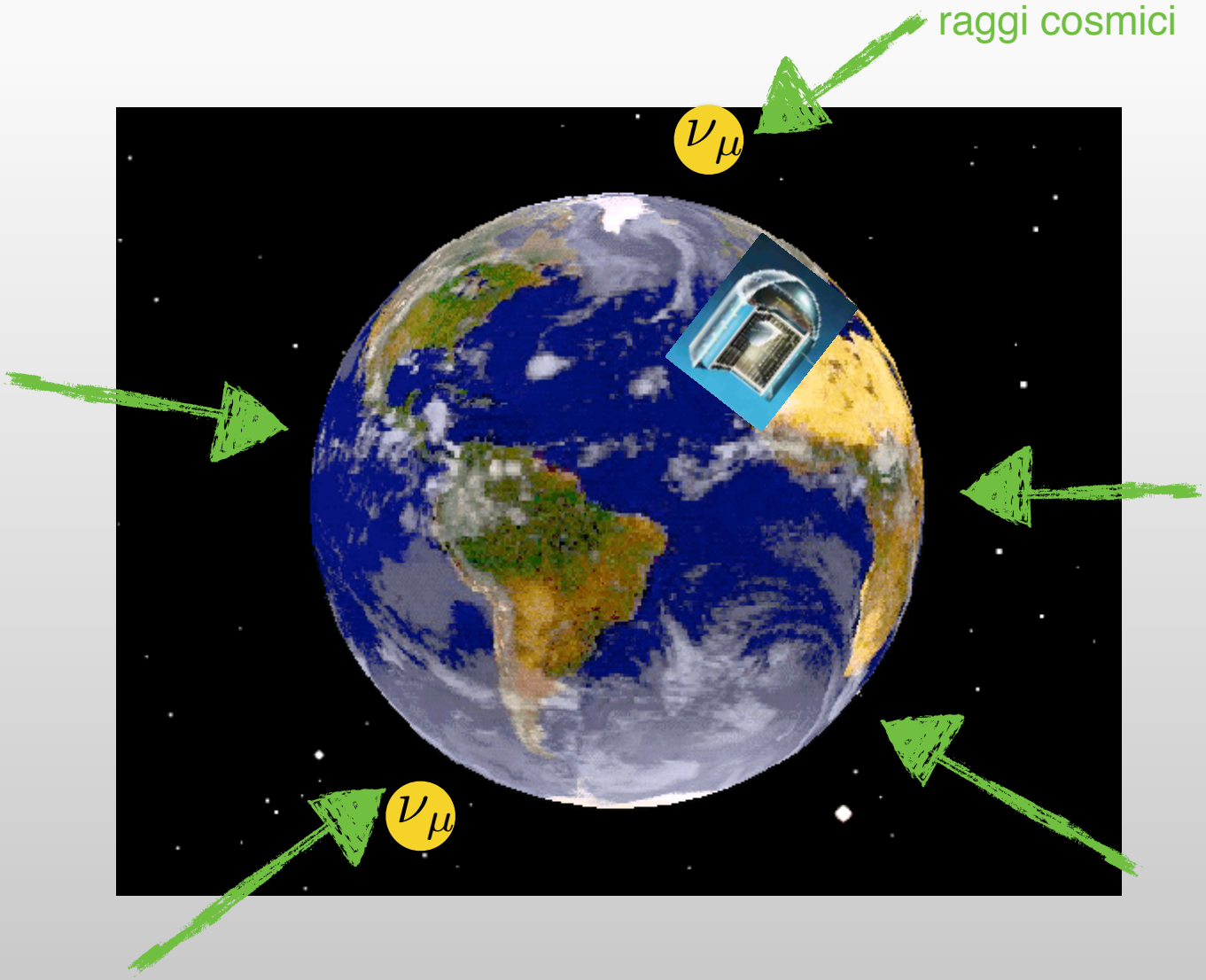
$\nu_{e,\mu,\tau}$, $\bar{\nu}_{e,\mu,\tau}$ meV

Dark Matter?

? $< M_{DM}$

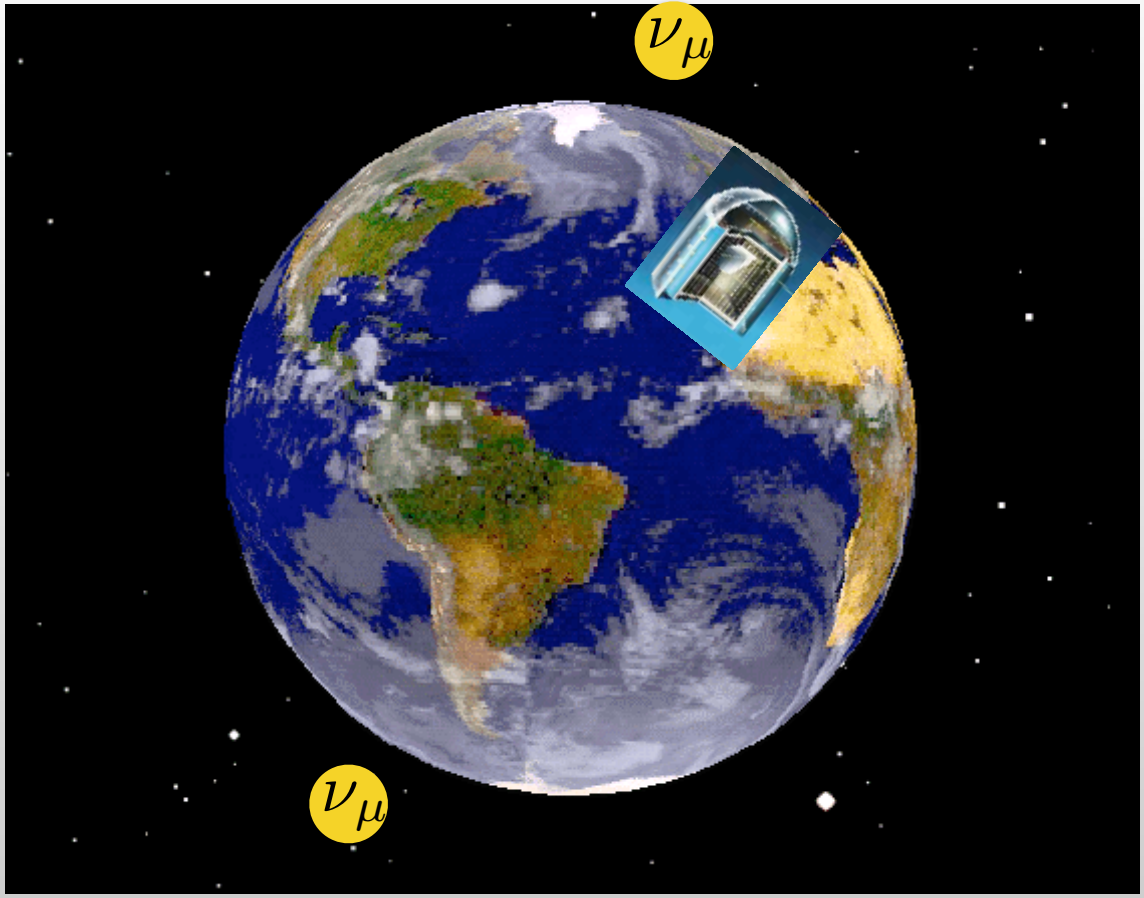
Neutrini e oscillazioni dei neutrini

Il problema dei neutrini atmosferici



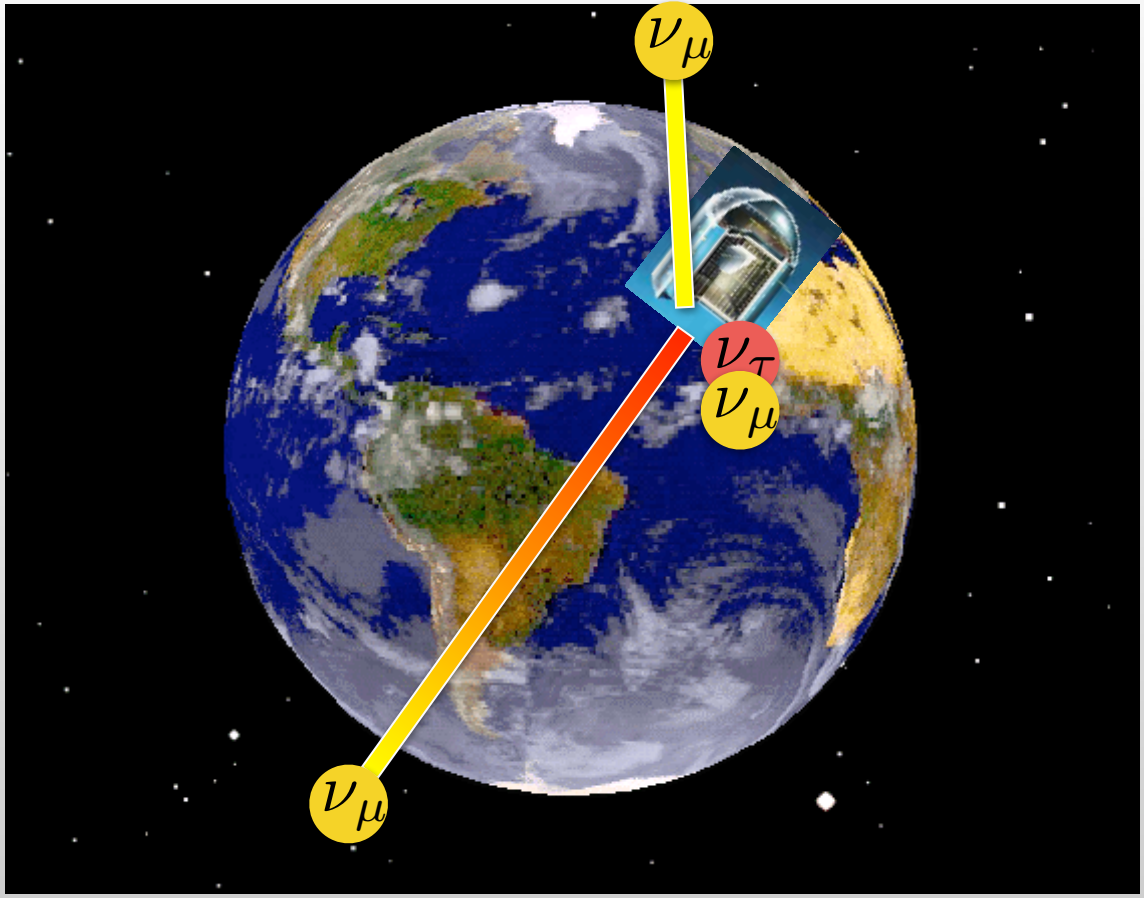
Neutrini e oscillazioni dei neutrini

Il problema dei neutrini atmosferici



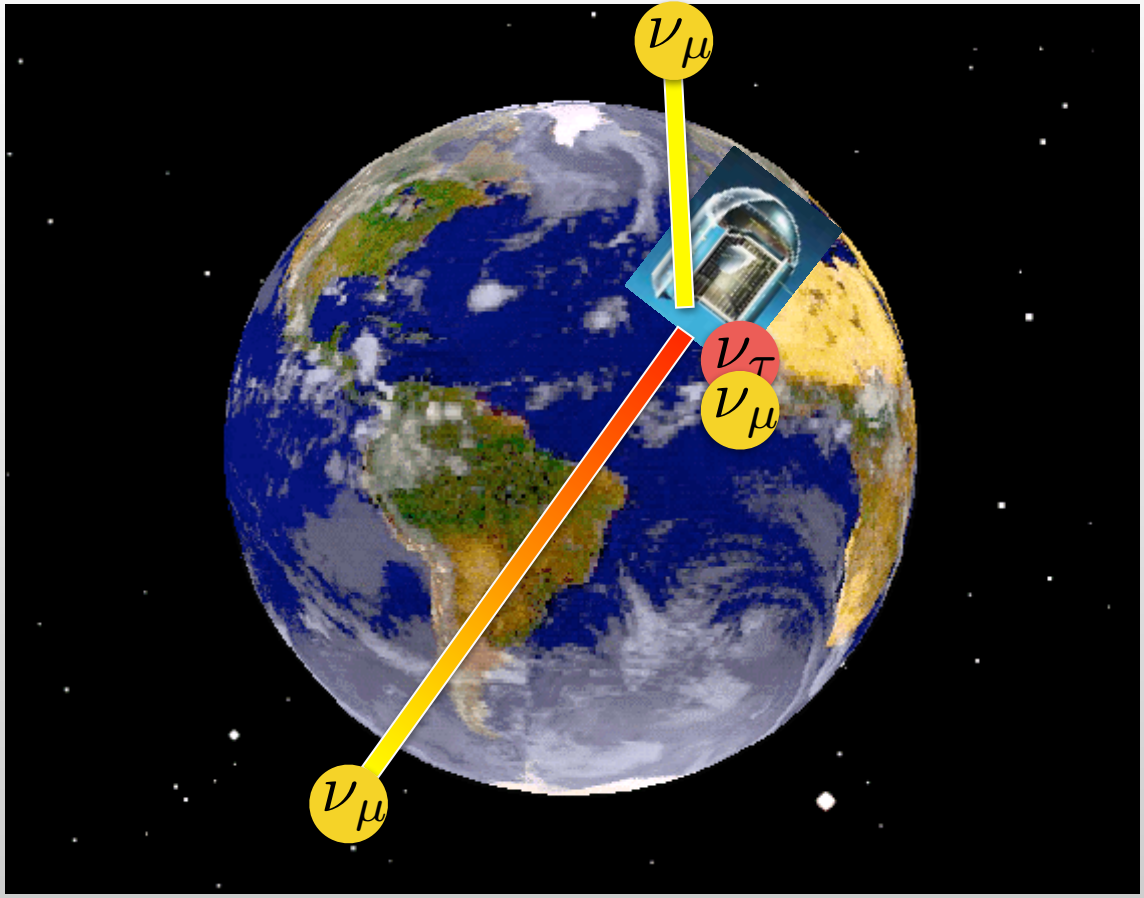
Neutrini e oscillazioni dei neutrini

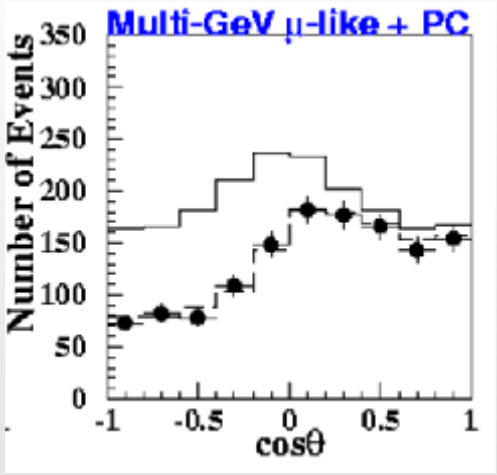
Il problema dei neutrini atmosferici



Neutrini e oscillazioni dei neutrini

Il problema dei neutrini atmosferici





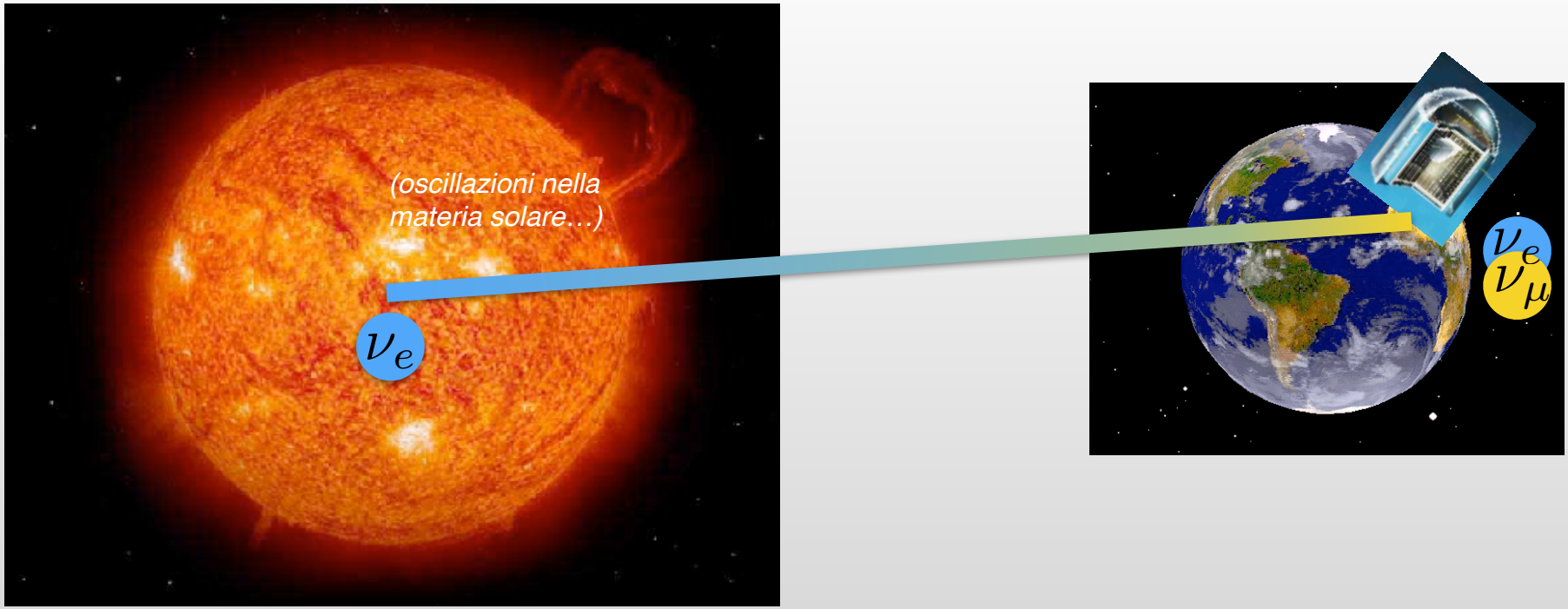
Super-Kamiokande

2015

Takaaki Kajita

Neutrini e oscillazioni dei neutrini

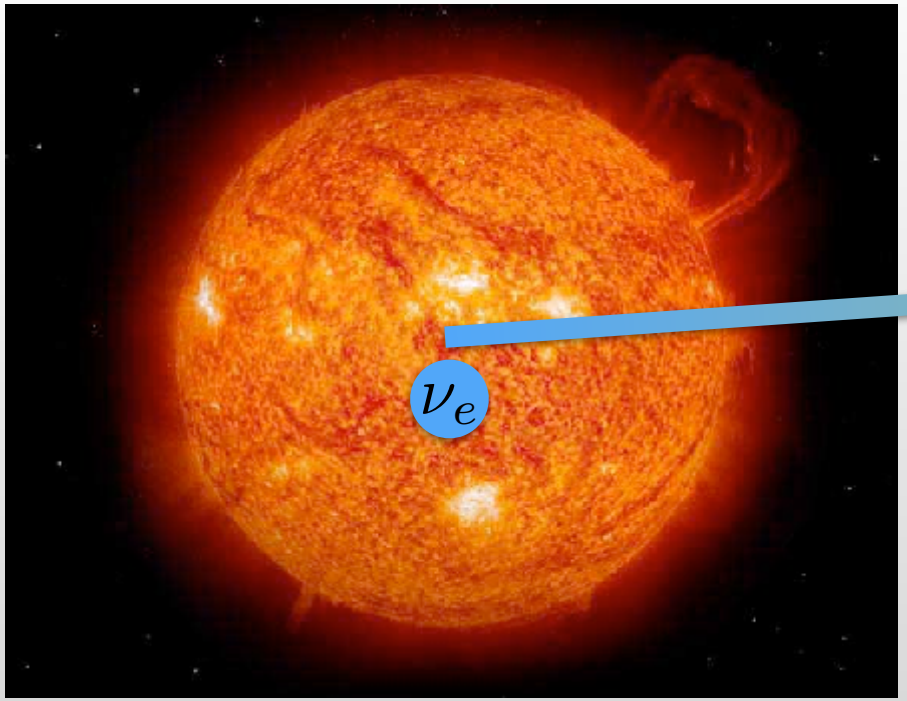
Il problema dei neutrini solari

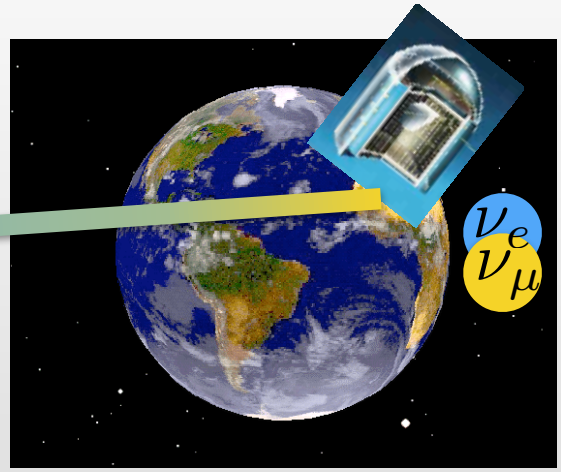


$$4p + 2e^- \rightarrow \mathrm{He} + 2\nu_e$$

Neutrini e oscillazioni dei neutrini

Il problema dei neutrini solari





$$4p + 2e^- \rightarrow \mathrm{He} + 2\nu_e$$

Homestake

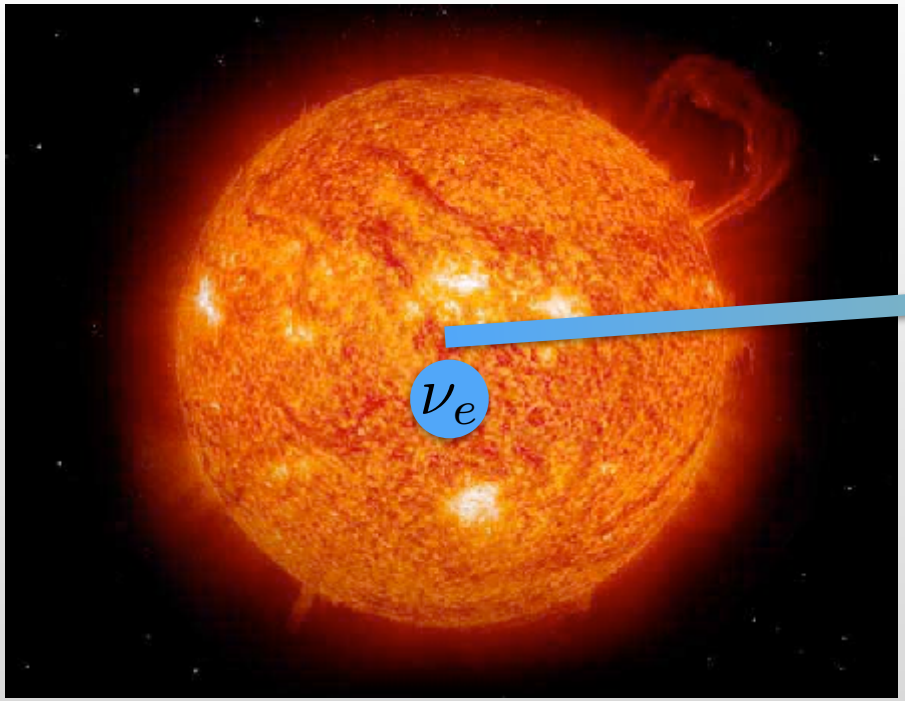
~30% dei ν_e attesi (?!?)

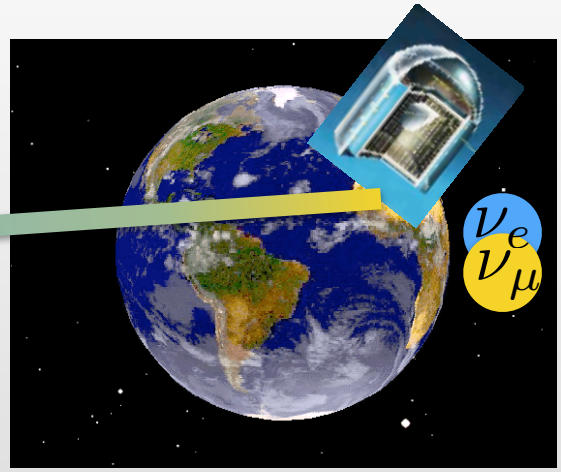
2002

Ray Davis

Neutrini e oscillazioni dei neutrini

Il problema dei neutrini solari





$$4p + 2e^- \rightarrow \mathrm{He} + 2\nu_e$$

Homestake

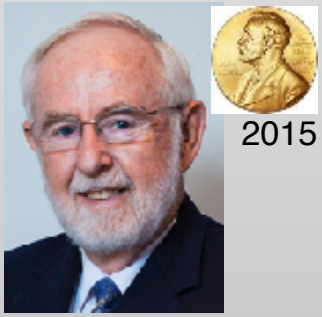
~30% dei ν_e attesi (?!?)

2002

Ray Davis

SNO

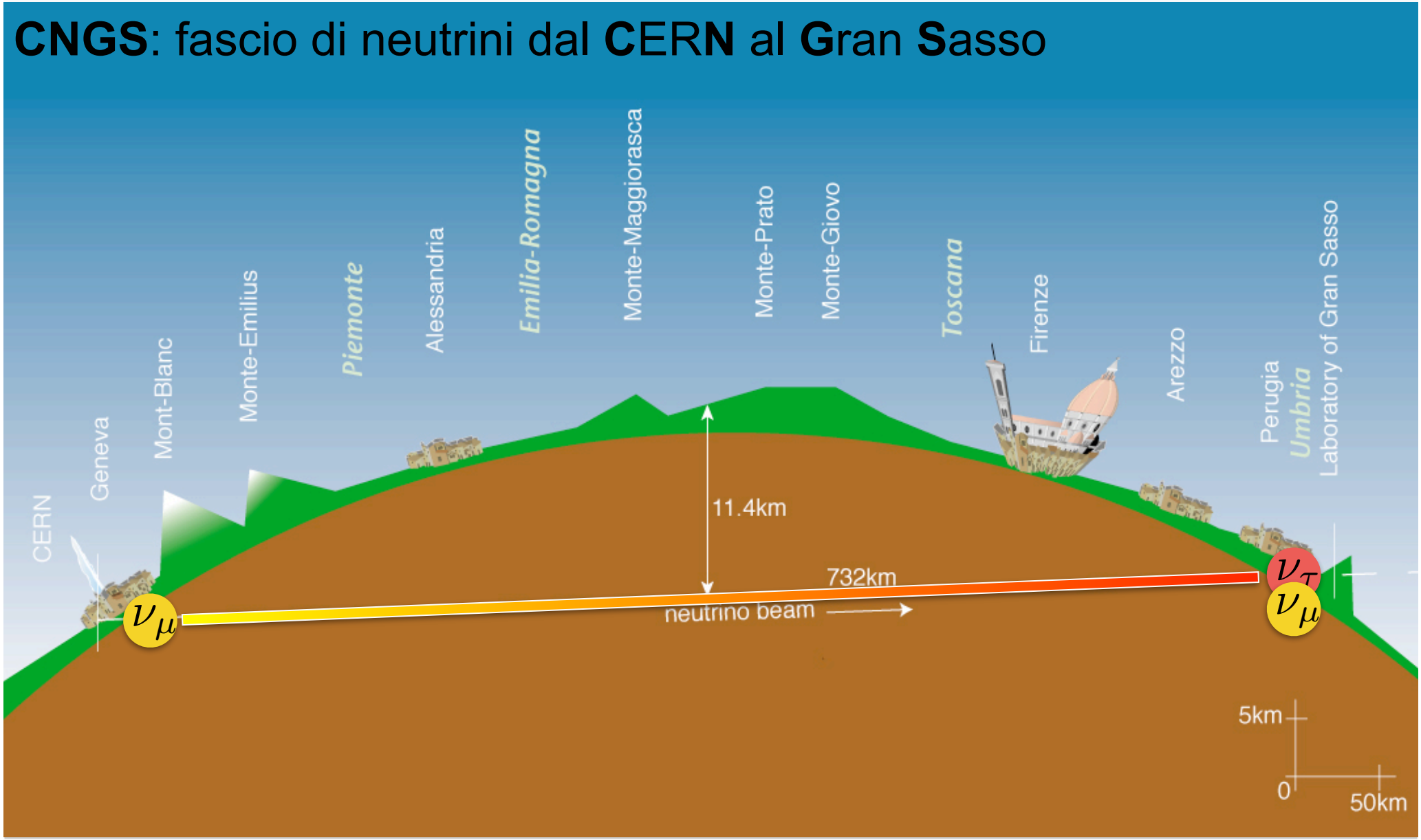
$\nu_e + \nu_\mu + \nu_\tau = 100\%$!



2015

Art McDonald

Neutrini e oscillazioni dei neutrini



Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*

Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*

(conseguenza del fatto che le interazioni deboli sono *left-handed*…)

$$y_{ij}\Psi_i\Psi_j\,\frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\,\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h + \nu\nu$$

Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*

(conseguenza del fatto che le interazioni deboli sono *left-handed*…)

$$y_{ij}\Psi_i\Psi_j\,\frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\,\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h + \cancel{\nu\nu}$$

Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*
  (conseguenza del fatto che le interazioni deboli sono *left-handed*…)

$$y_{ij}\Psi_i\Psi_j\,\frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\,\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h + \cancel{\nu\nu}$$

- *New Physics*: e.g. introduciamo ‘neutrini’ RH pesanti *N* (~10^{15} GeV)

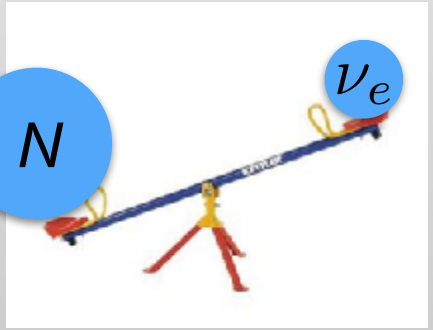
Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*
  (conseguenza del fatto che le interazioni deboli sono *left-handed*…)

$$y_{ij}\Psi_i\Psi_j\,\frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\,\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h + \cancel{\nu\nu}$$

- *New Physics*: e.g. introduciamo ‘neutrini’ RH pesanti *N* (~10^{15} GeV)
  spiegherebbe anche perché la massa dei neutrini ‘normali’ è così piccola: meccanismo del *see-saw*



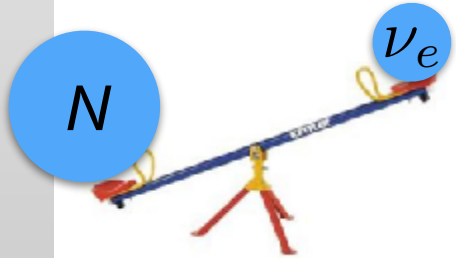
Neutrini e oscillazioni dei neutrini

La massa dei neutrini e la fisica Oltre il Modello Standard:

- nel MS, i neutrini hanno strettamente massa = *zero!*
  (conseguenza del fatto che le interazioni deboli sono *left-handed*…)

$$y_{ij}\Psi_i\Psi_j\,\frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\,\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h + \cancel{\nu\nu}$$

- *New Physics*: e.g. introduciamo 'neutrini' RH pesanti *N* (~10^{15} GeV)
  spiegherebbe anche perché la massa dei neutrini 'normali' è così piccola: meccanismo del *see-saw*



Neutrini *N* ⟶ possono decadere asimmetricamente

⟶ *leptogenesi* ⟶ *baryogenesi* ⟶

asimmetria materia-antimateria ⟶ the reason why we exist