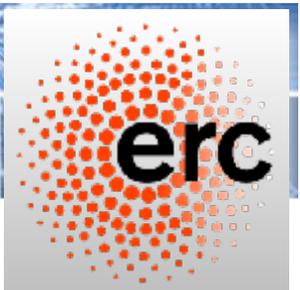




CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire



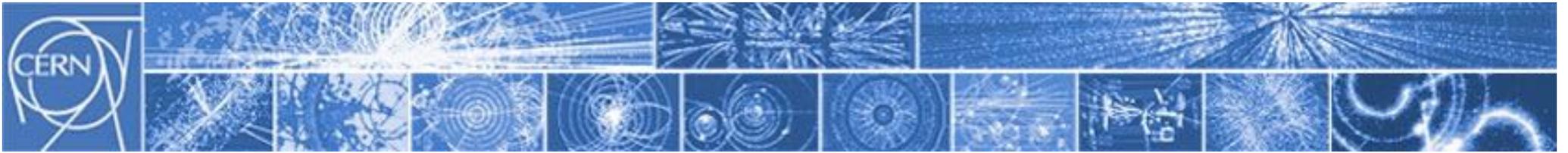
NewDark

Fisica delle Particelle, Astrofisica & Cosmologia

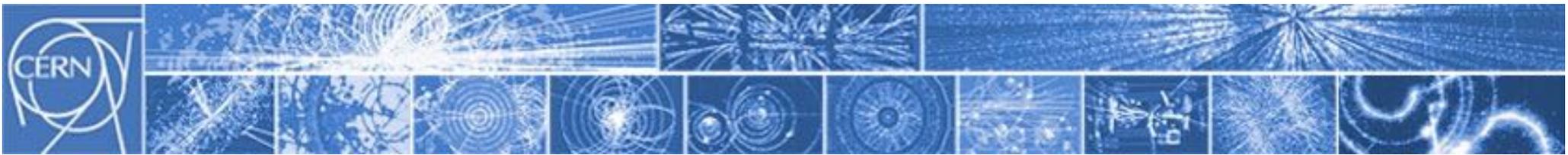
- Breve storia dell'Universo:
inflazione, BG, BBN, CMB, LSS
- Neutrini e oscillazioni
- Materia Oscura
- Energia Oscura
- Altri problemi aperti in fisica delle particelle

Marco CIRELLI [CNRS LPTHE Jussieu]

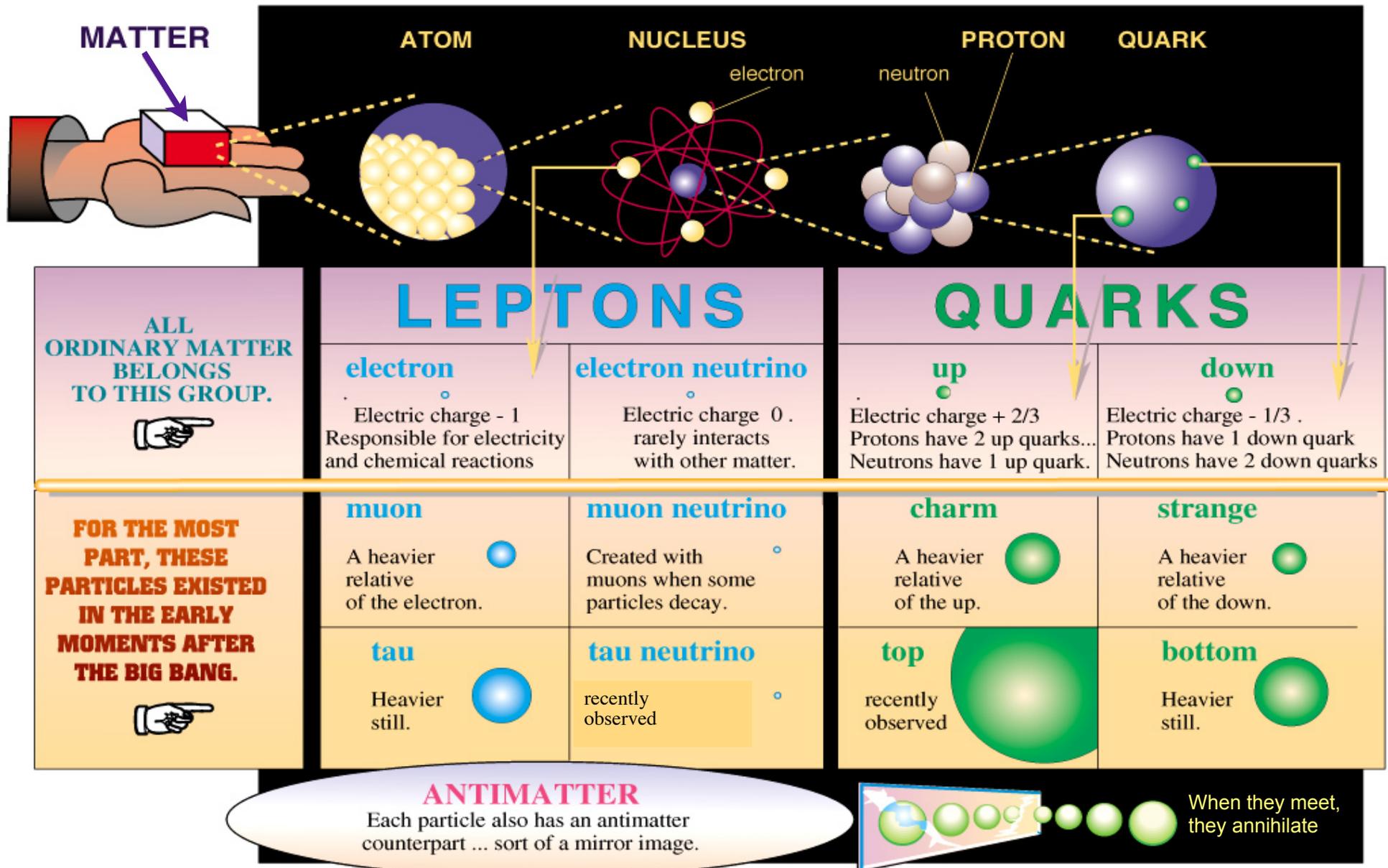
Mini-intro:
- livello variabile
- open questions
- about MC

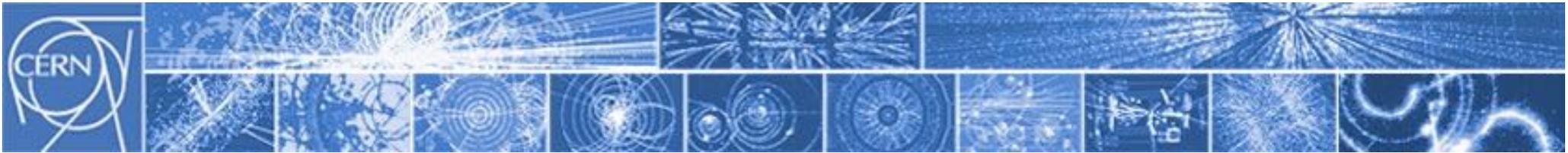


Richiami sul Modello Standard

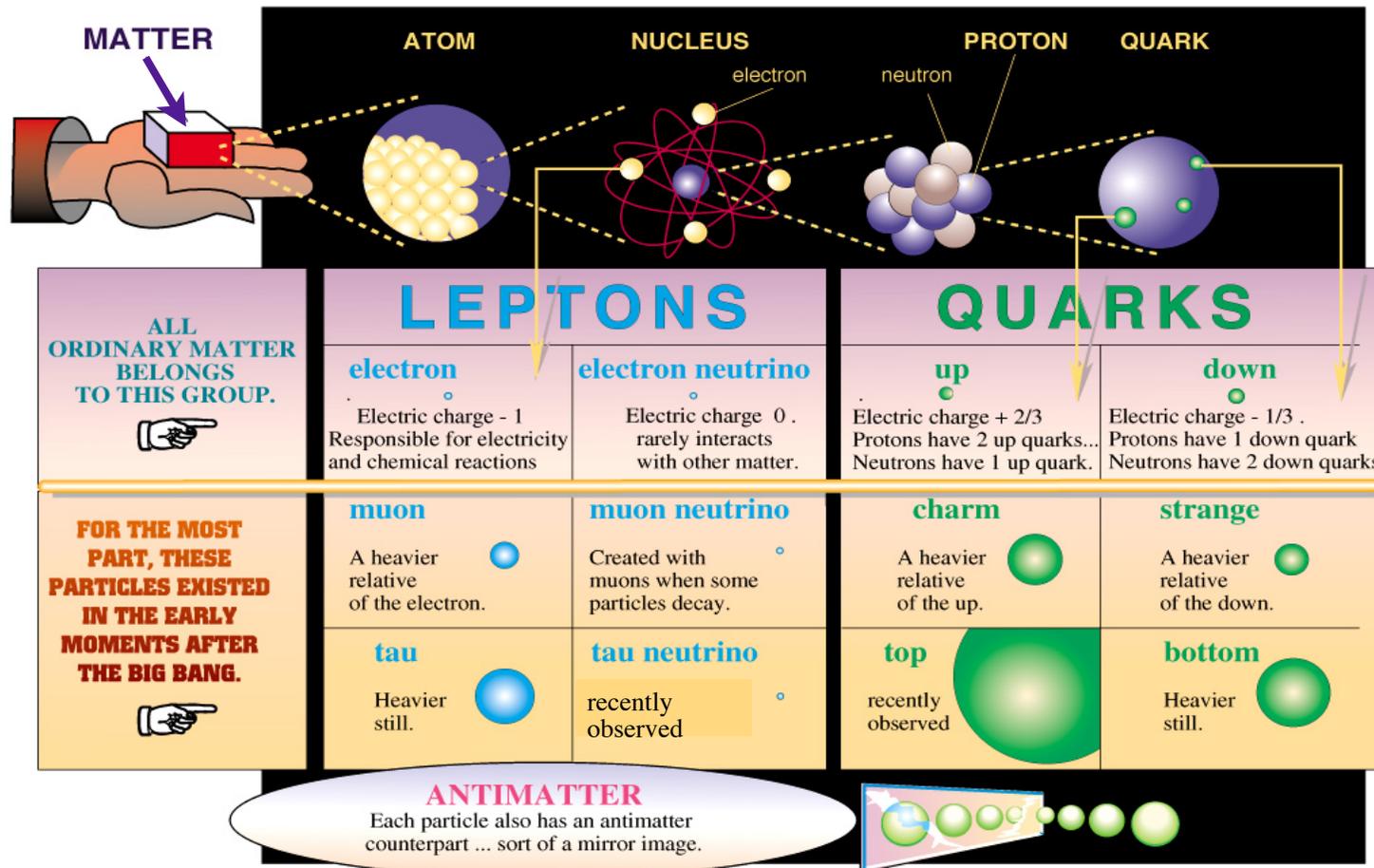


STANDARD MODEL





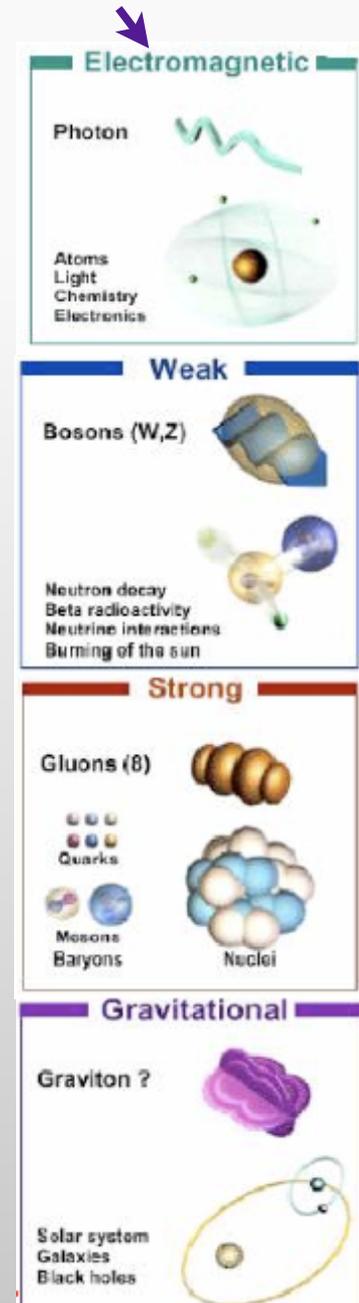
STANDARD MODEL

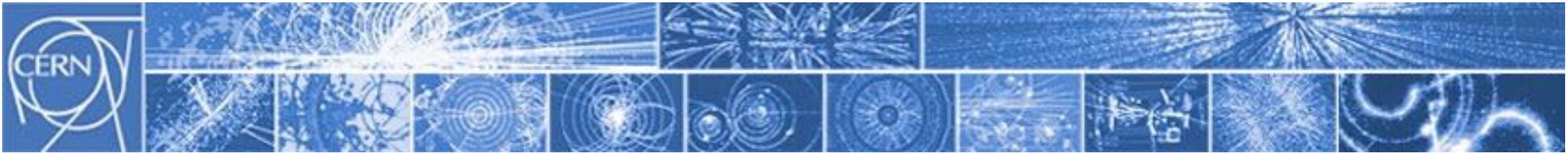


from Time magazine

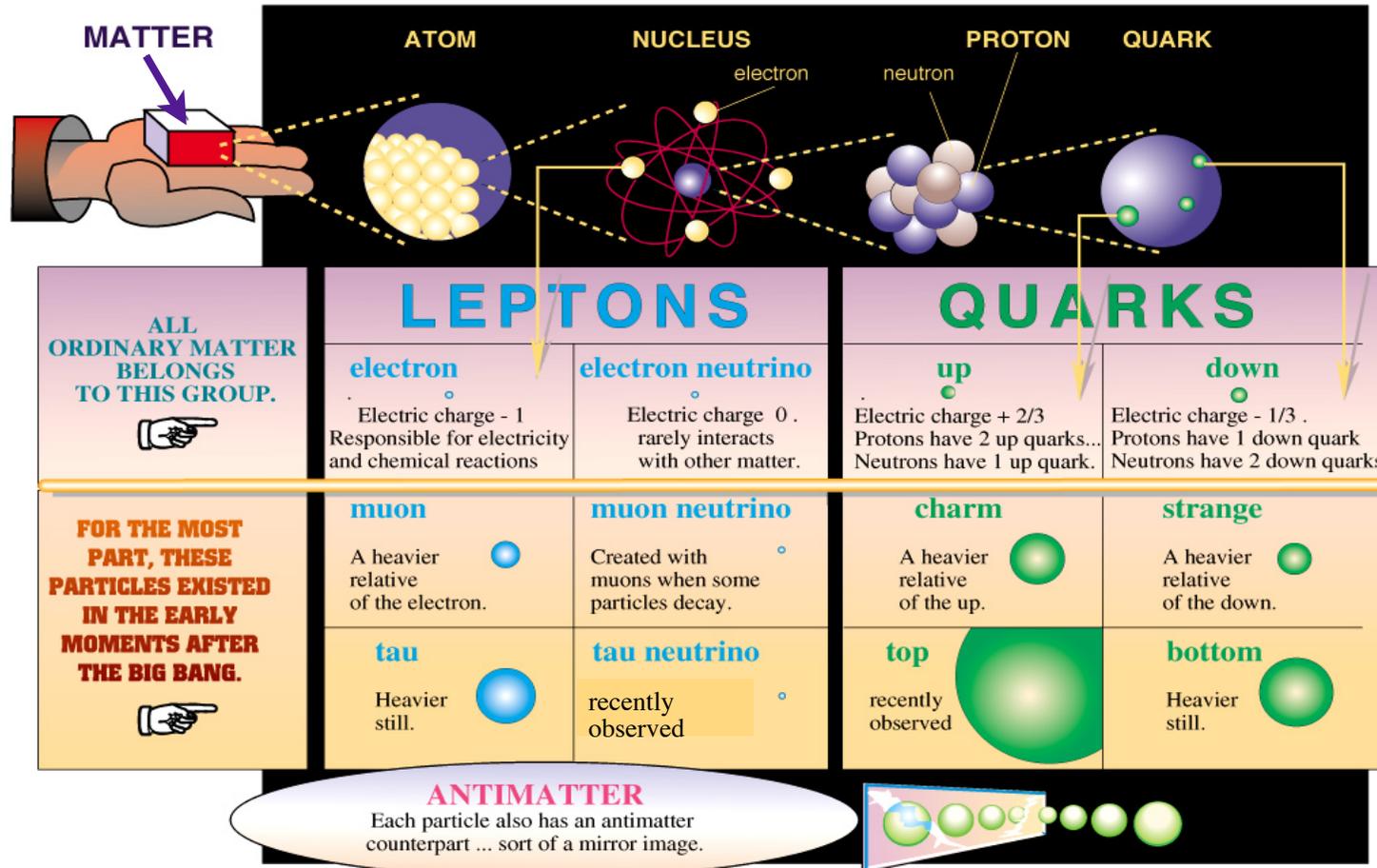
CERN AC _ E11-7

FORCES





STANDARD MODEL



from Time magazine

CERN AC _ E11-7

FORCES

Electromagnetic

Photon

Atoms
Light
Chemistry
Electronics

Weak

Bosons (W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

Strong

Gluons (8)

Quarks

Mesons

Baryons

Nuclei

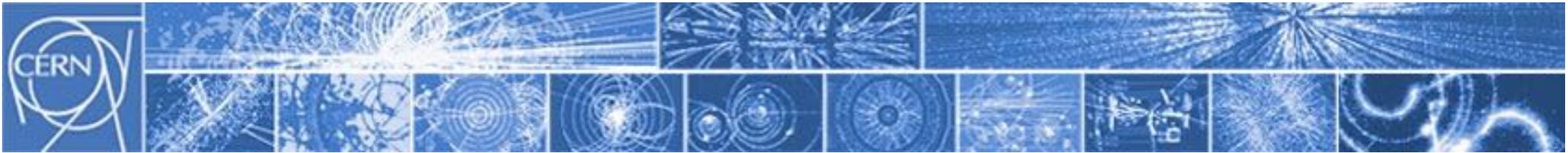
Gravitational

Graviton ?

Solar system
Galaxies
Black holes

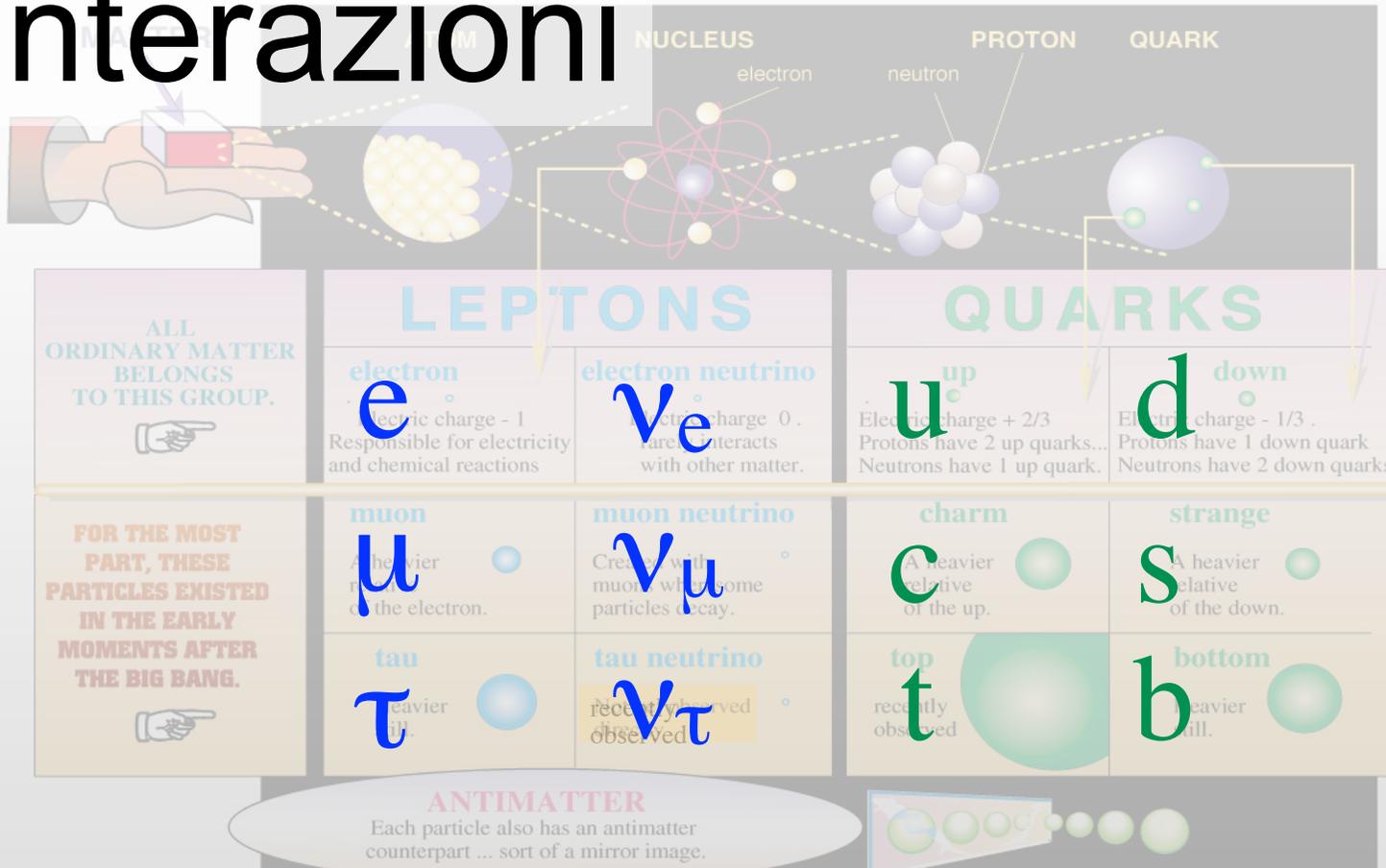
Higgs boson

h



STANDARD MODEL

Interazioni



from Time magazine

CERN AC_E11-7

FORCES

Electromagnetic

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Weak

Bosons (W,Z)

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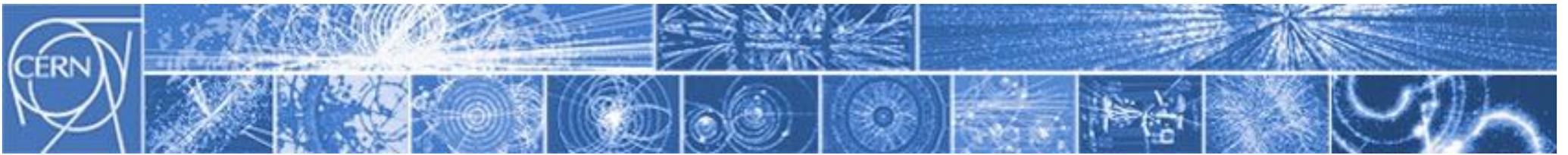
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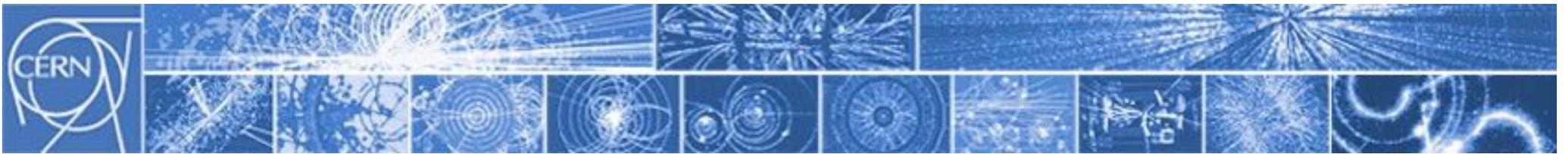
Solar system
Galaxies
Black holes

Higgs boson

h



Masse



Masse

KeV

MeV

GeV

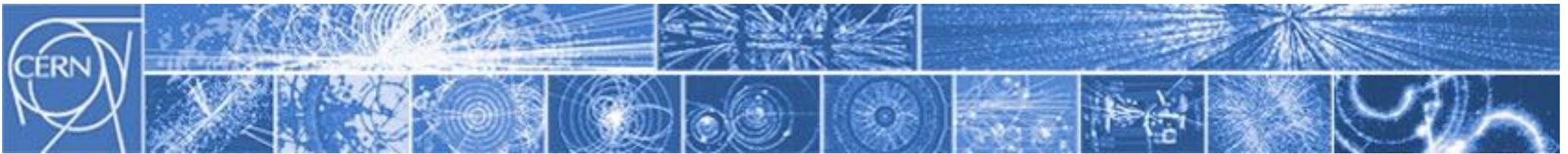
TeV

		e			μ	τ		
--	--	---	--	--	-------	--------	--	--

e 511 KeV

μ 105.7 MeV

τ 1.777 GeV



Masse

KeV		MeV			GeV		TeV
		e			μ	τ	
			u d		s	c b	t

e 511 KeV

μ 105.7 MeV

τ 1.777 GeV

u ~2.3 MeV

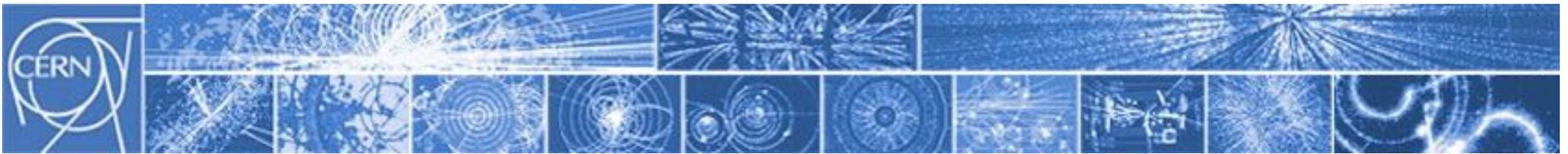
d ~5 MeV

s ~95 MeV

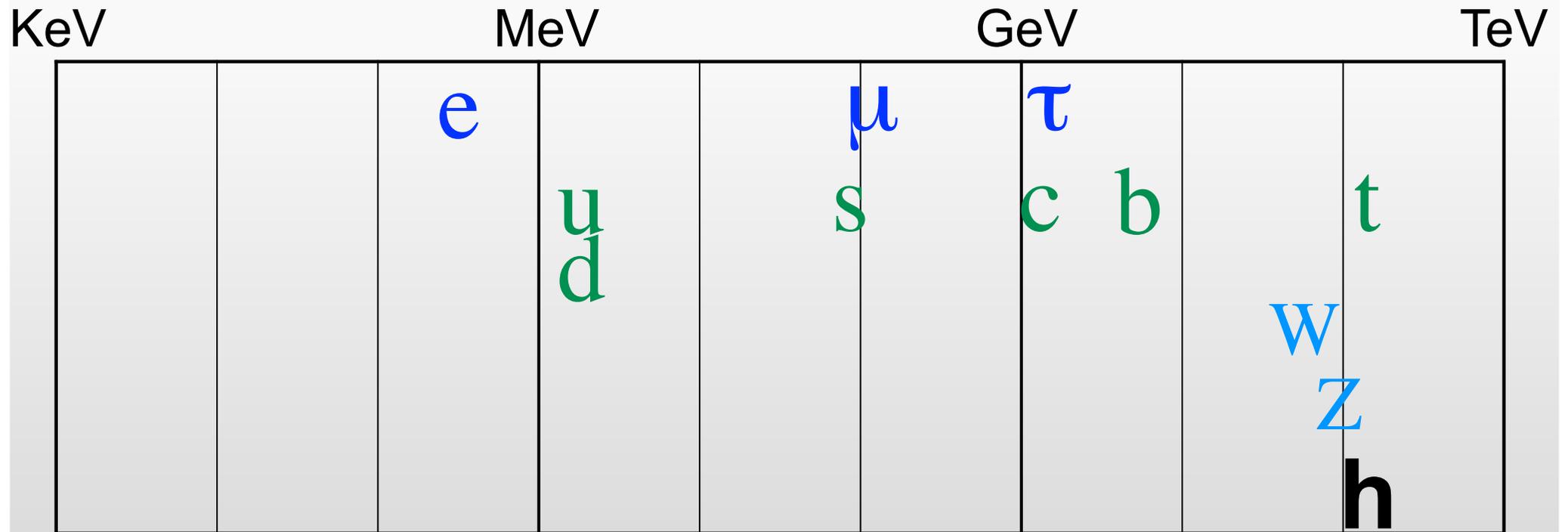
c 1.27 GeV

b 4.2 GeV

t 173.2 GeV



Masse



e 511 KeV

μ 105.7 MeV

τ 1.777 GeV

u ~2.3 MeV

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s ~95 MeV

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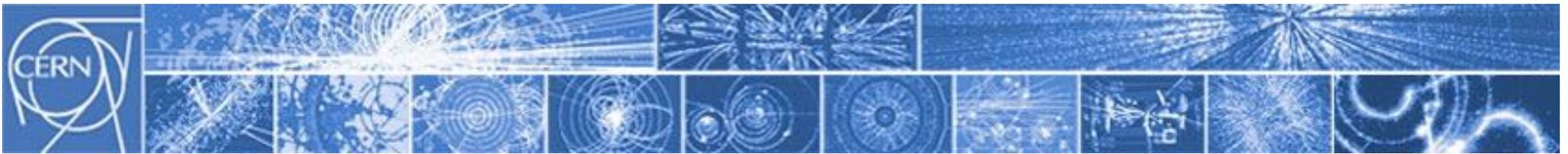
b 4.2 GeV

t 173.2 GeV

W[±] 80.385 GeV

Z 91.1876 GeV

h 125.7 GeV

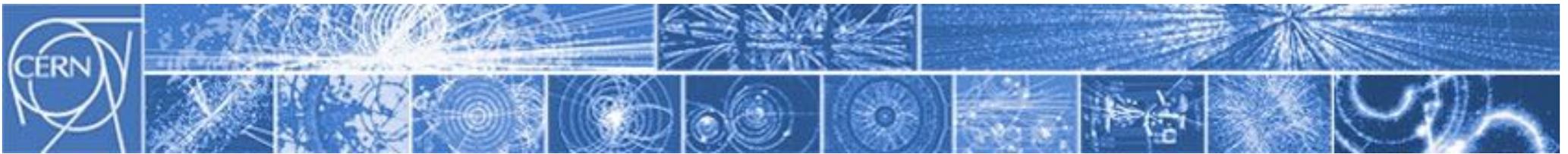


Masse

meV		eV		KeV		MeV		GeV		TeV	
ν_e	ν_μ						e		μ	τ	
	ν_τ						u		s	c	b
							d				t
											W
											Z
											h

e 511 KeV	u ~2.3 MeV	c 1.27 GeV	W^\pm 80.385 GeV
μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
τ 1.777 GeV	s ~95 MeV	t 173.2 GeV	h 125.7 GeV

$9 \cdot 10^{-3} \text{ eV} \approx \nu_i \approx 0.2 \text{ eV}$



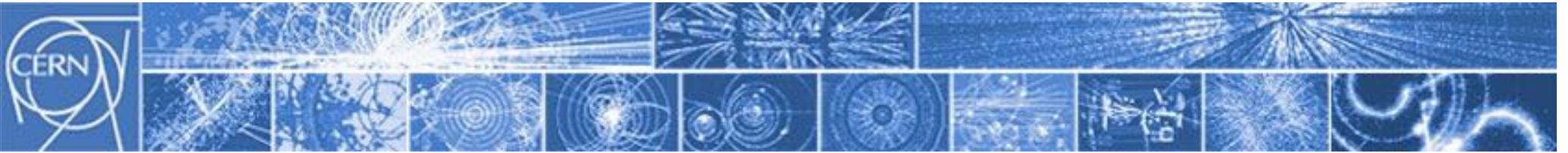
Masse

massa zero: γ g G

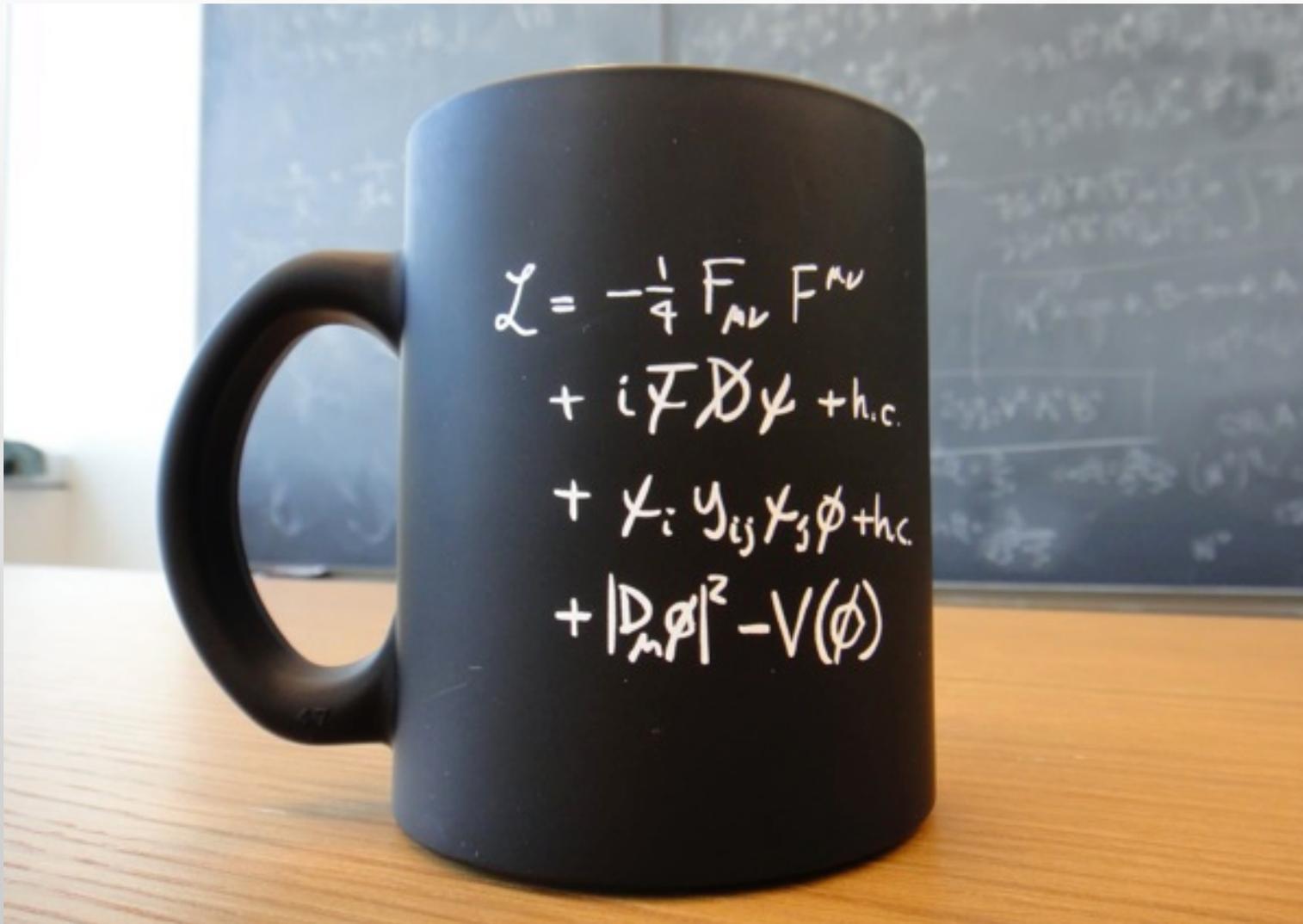
meV		eV		KeV		MeV		GeV		TeV	
ν	ν						e		μ	τ	
	ν						u		s	c	b
							d				
											t
											W
											Z
											h

e 511 KeV	u ~2.3 MeV	c 1.27 GeV	W^\pm 80.385 GeV
μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
τ 1.777 GeV	s ~95 MeV	t 173.2 GeV	h 125.7 GeV

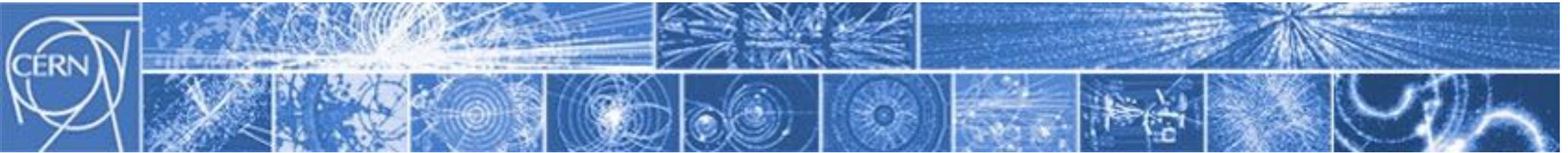
$$9 \cdot 10^{-3} \text{ eV} \approx \nu_i \approx 0.2 \text{ eV}$$



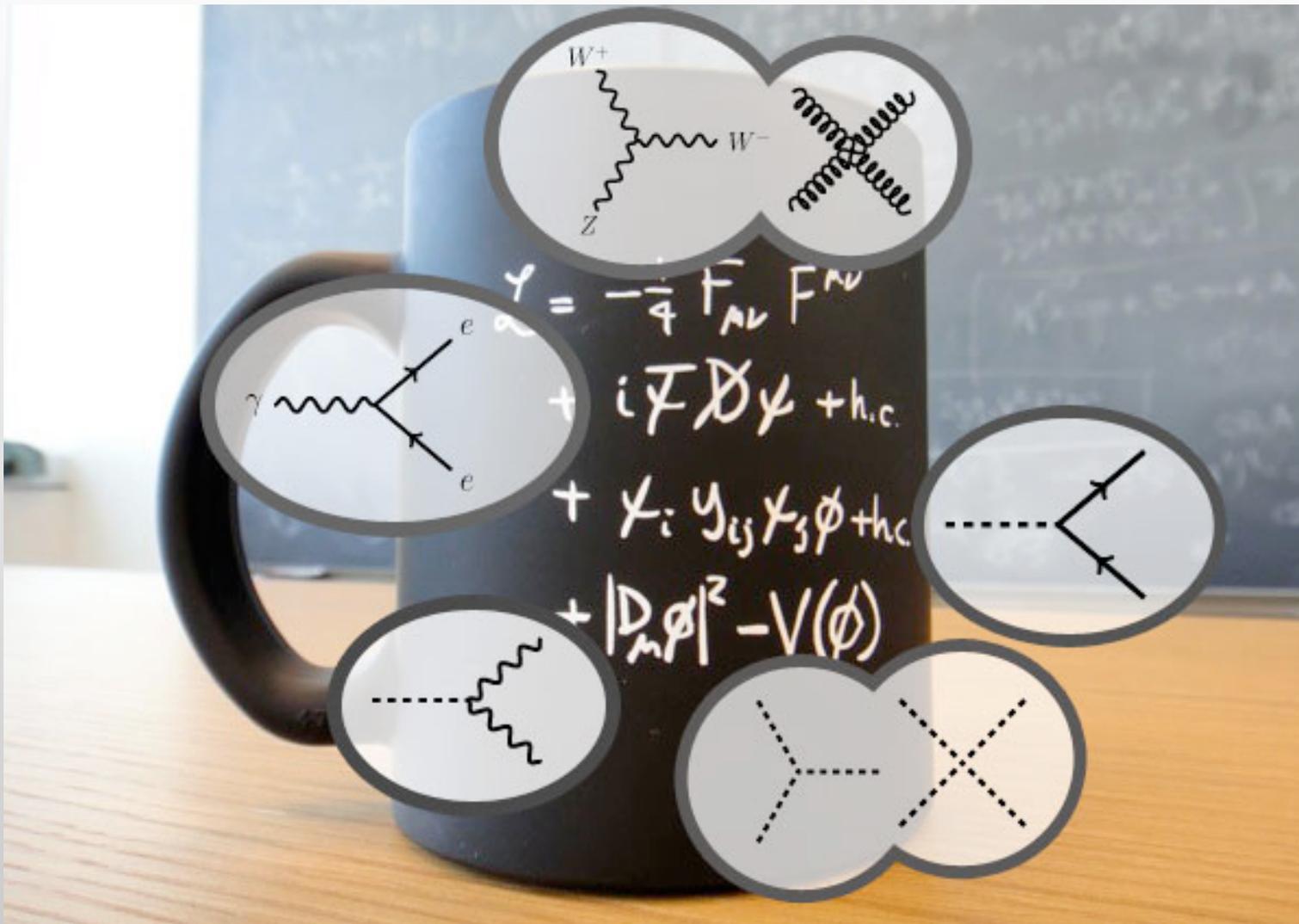
Lagrangiana del Modello Standard



Credit: Flip Tanedo, QuantumDiaries.org



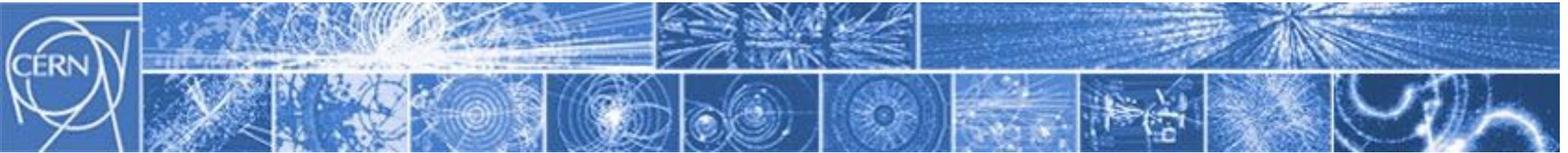
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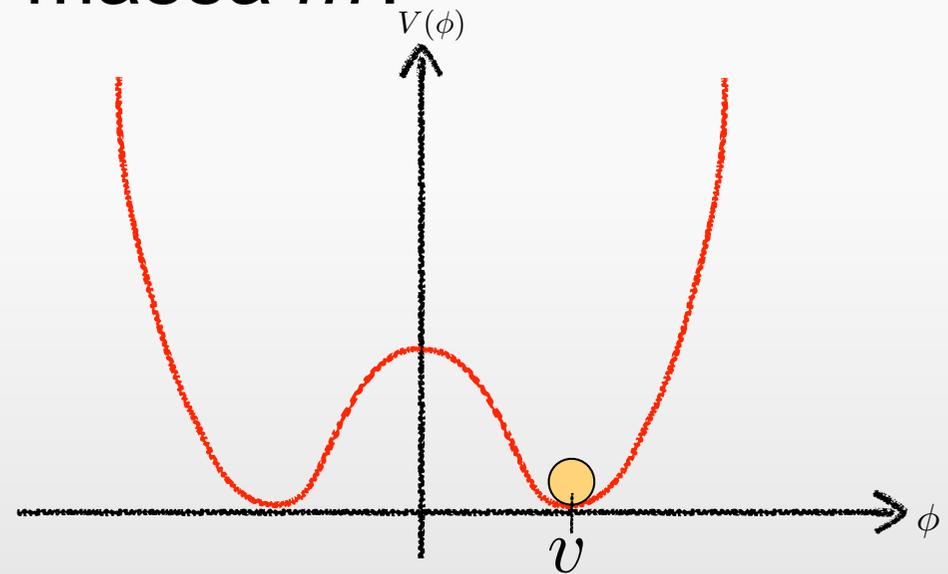
presentazione
per insegnanti:

J. Woithe, J. Wiener, F. Van der Veken, *Let's have a coffee with the Standard Model of particle physics!*, Phys. Educ. 52 (2017) 034001



Q. Perché una particella ha massa m ?

$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D}\Psi + y_{ij} \Psi_i \Psi_j \phi + |D_\mu \phi|^2 - V(\phi)$$

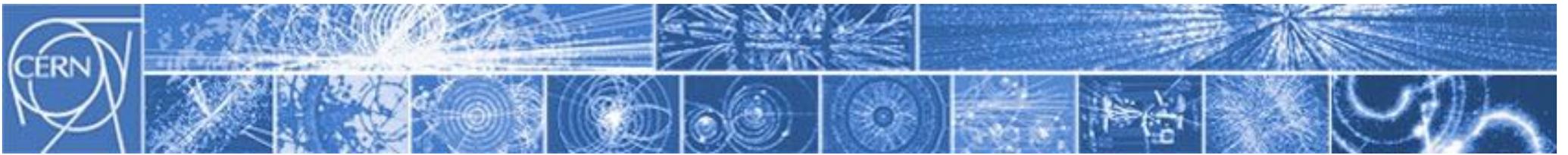


$$y_{ij} \Psi_i \Psi_j \frac{1}{\sqrt{2}}(v + h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}} \mu\mu + \frac{y_\mu}{\sqrt{2}} \mu\mu h = \mu + h$$

$\phi = \frac{1}{\sqrt{2}}(v + h)$

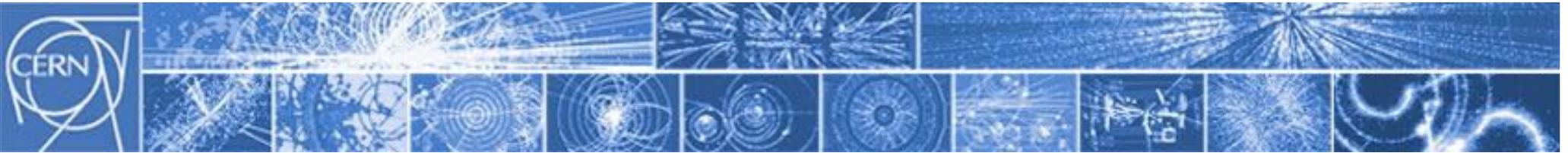
$$|D_\mu \phi|^2 \rightsquigarrow \frac{g v}{2} W^+ W^- \quad V(\phi) \rightsquigarrow \frac{1}{2} (2\lambda v^2) h h$$

A. Perché interagisce con l'higgs con intensità $y = \sqrt{2}m/v$!



Q. Perché una particella ha massa m ?

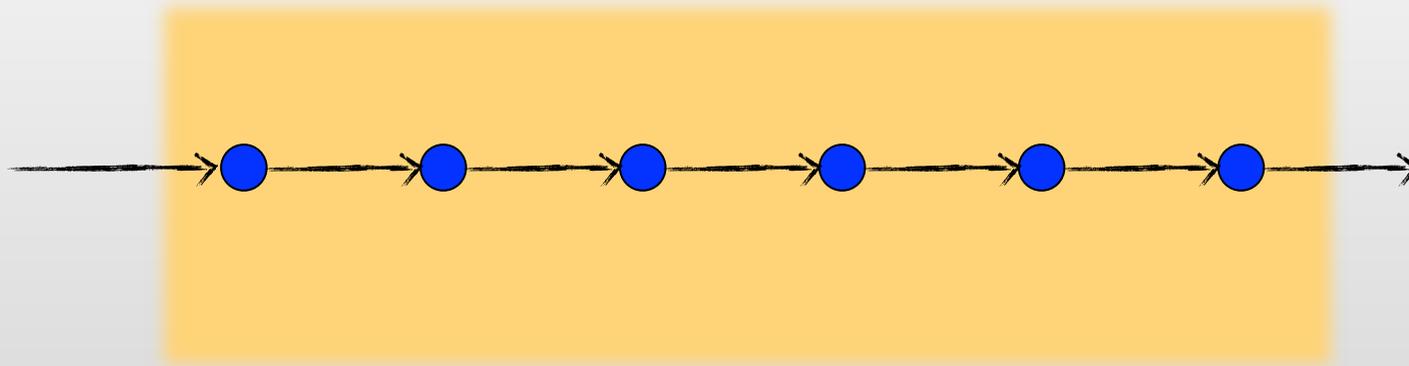
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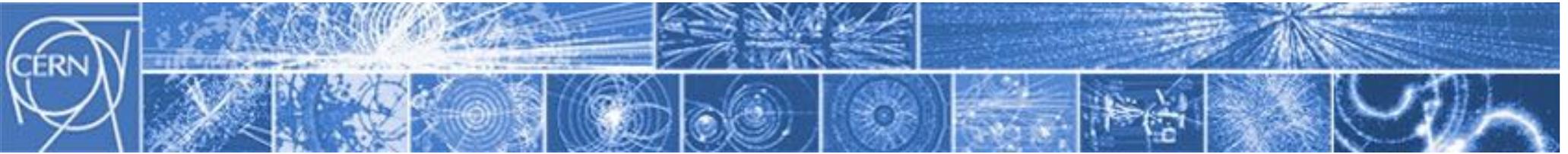


Q. Perché una particella ha massa m ?

A. Perché interagisce con l'higgs con intensità $y=\sqrt{2}m/v$!

Il *campo di higgs* è un mezzo continuo che permea l'universo.
Le particelle, interagendo col campo, acquistano un'inerzia/massa.

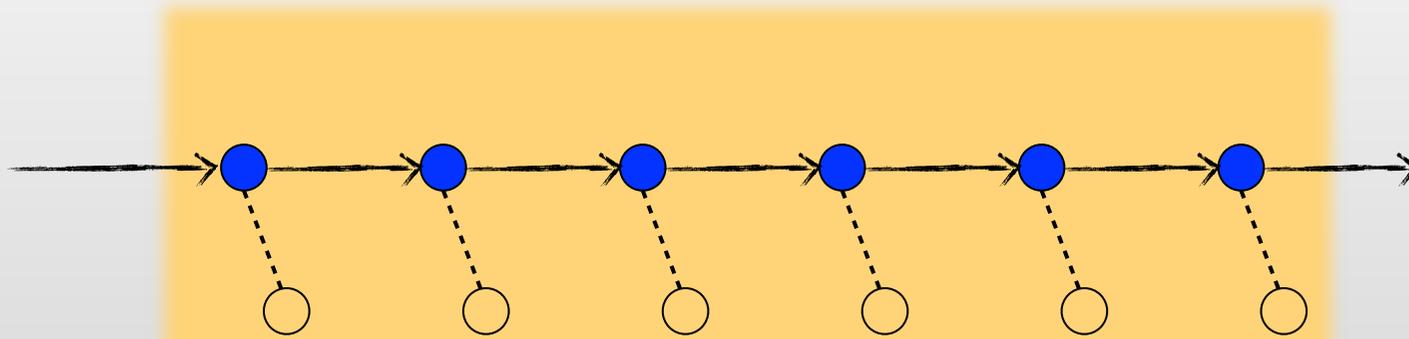


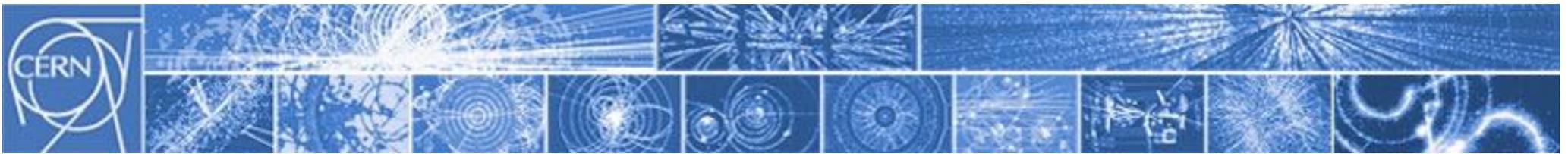


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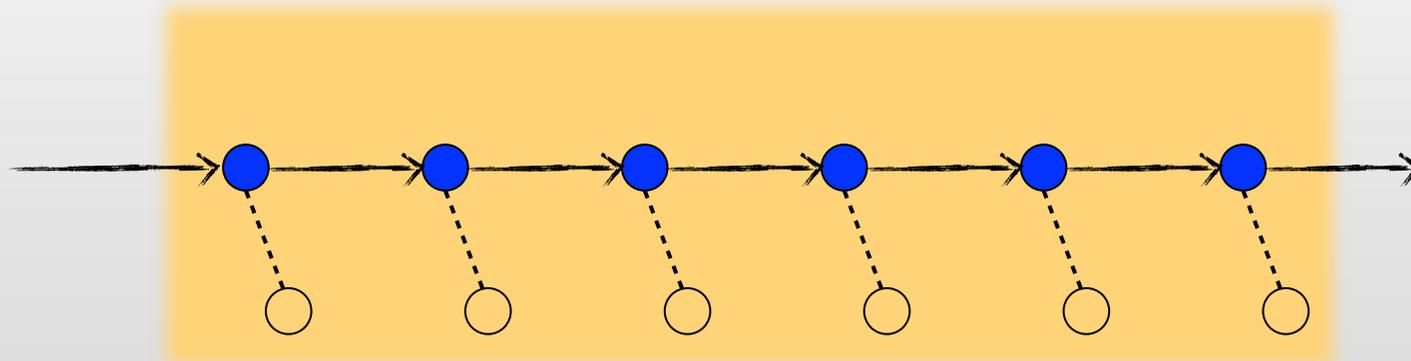




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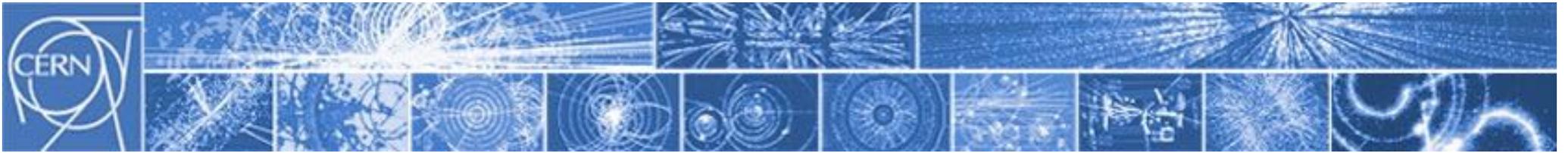
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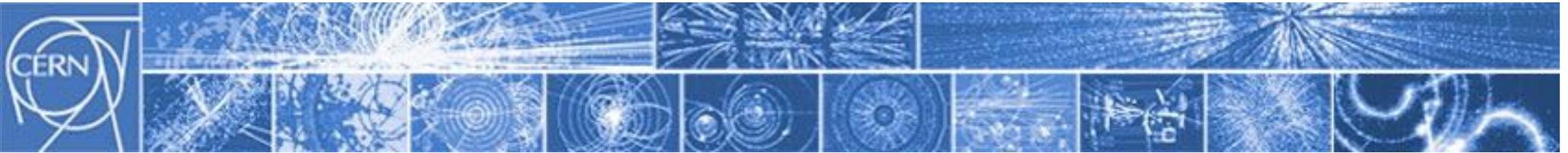


Le 'onde' del *campo* di Higgs sono una *particella*: la particella di Higgs (bosone).

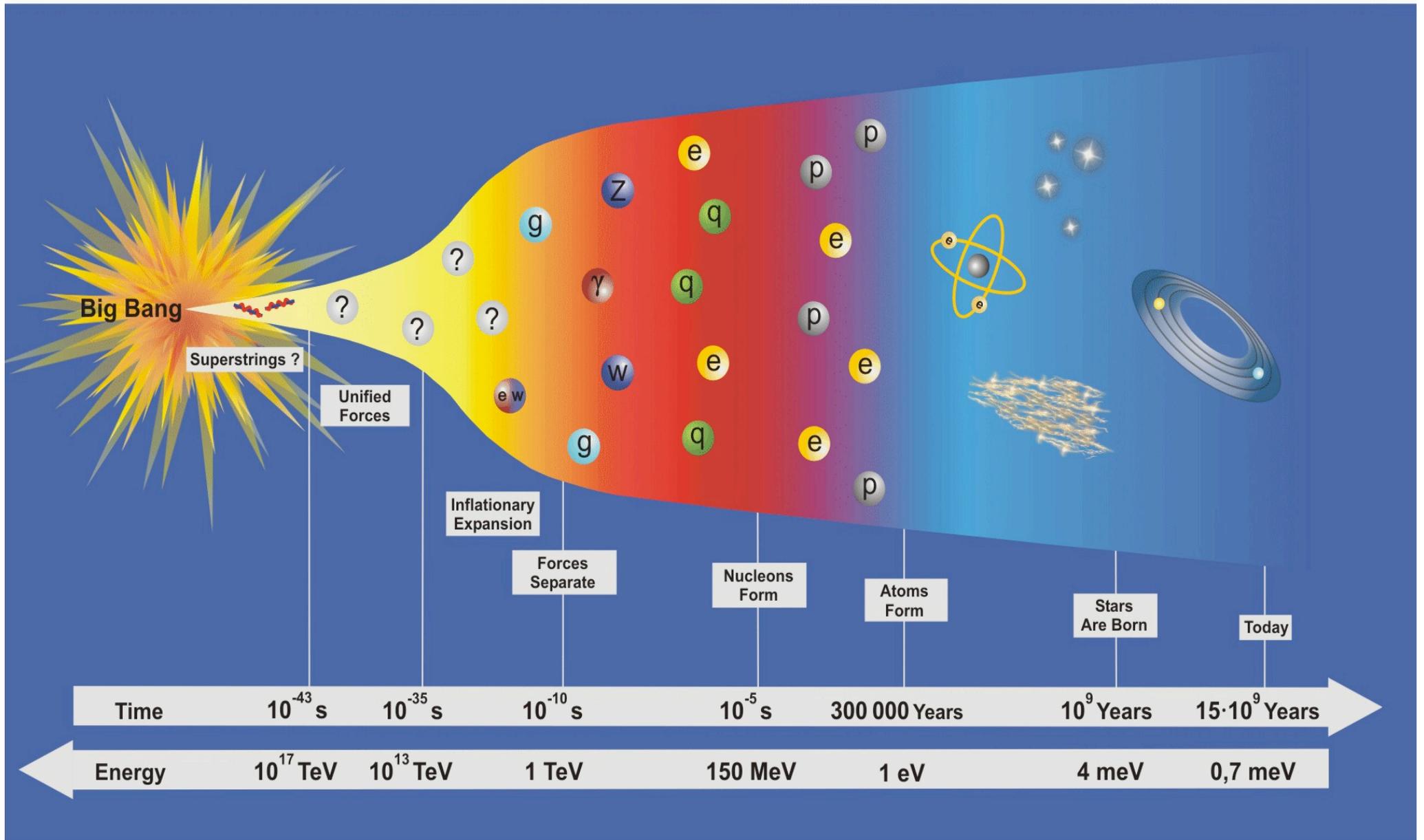
Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$

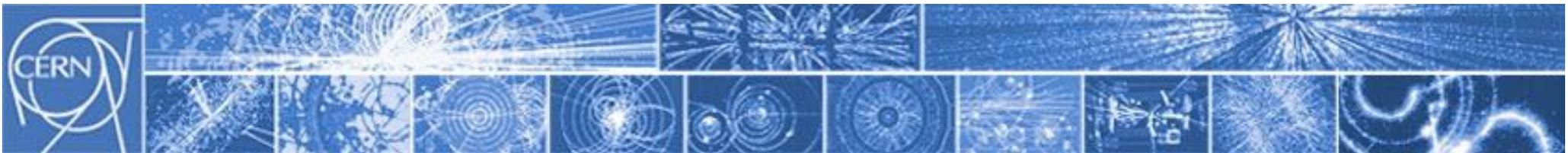


Breve storia dell'Universo

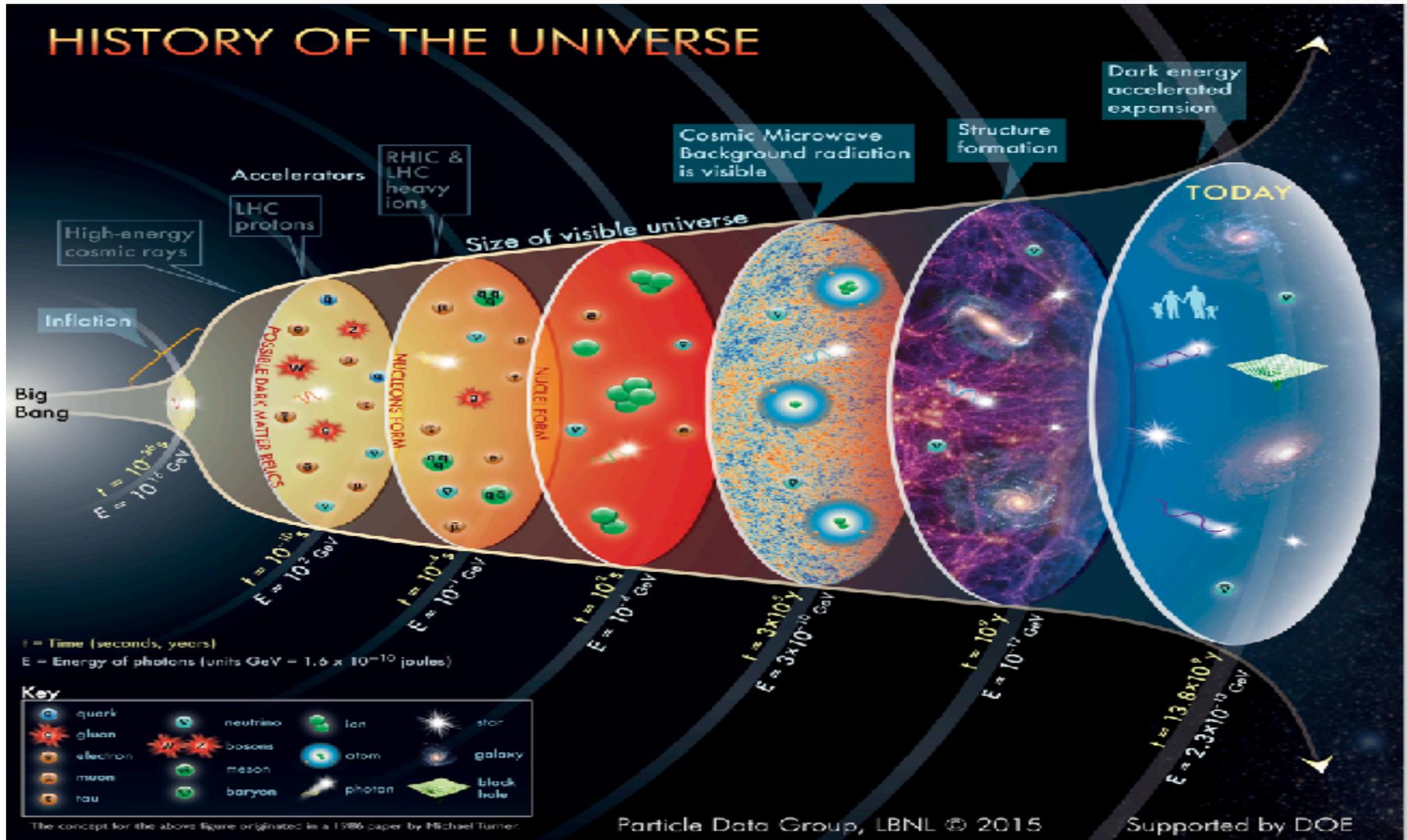


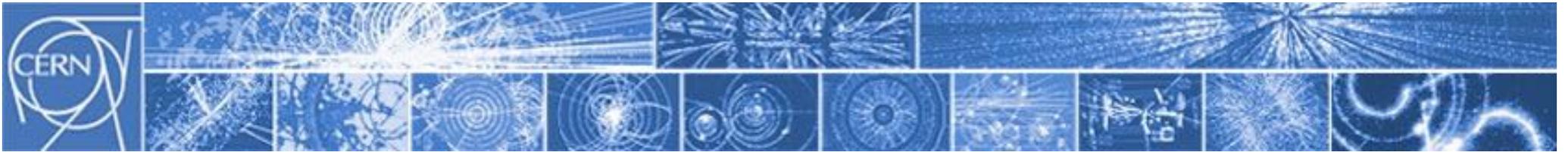
Ripercorrere all'indietro la storia dell'Universo



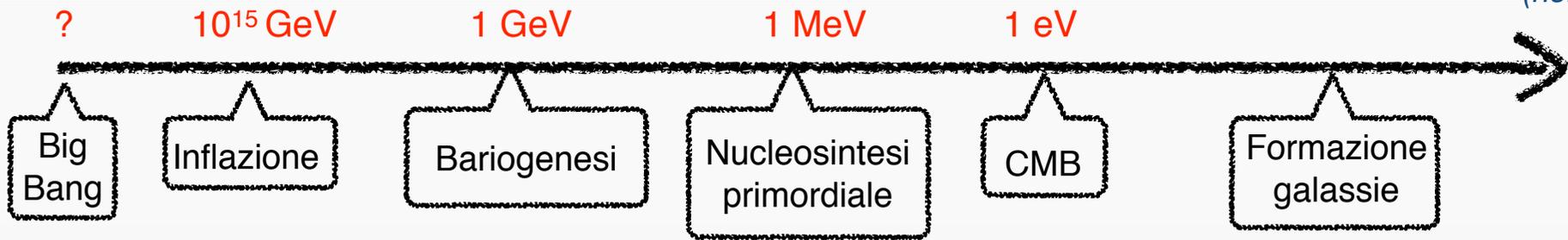


Ripercorrere all'indietro la storia dell'Universo





(non in scala!)



Big Bang

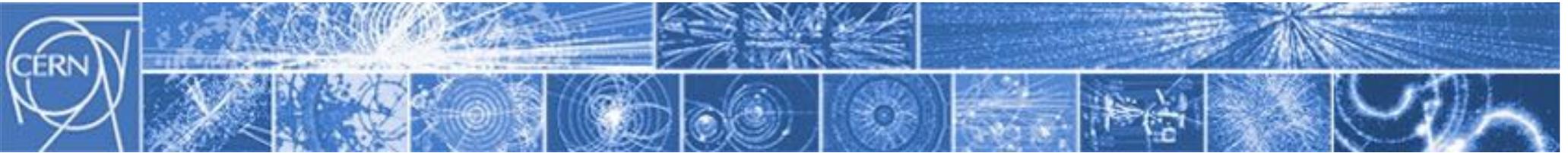
Inflazione

Bariogenesi

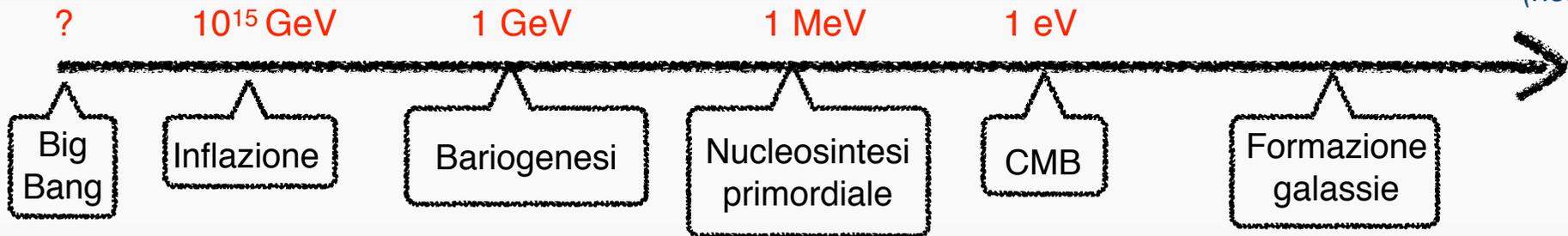
Nucleosintesi primordiale

CMB

Formazione galassie

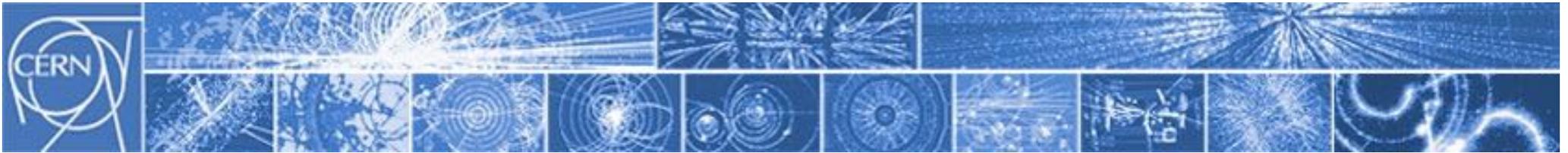


(non in scala!)

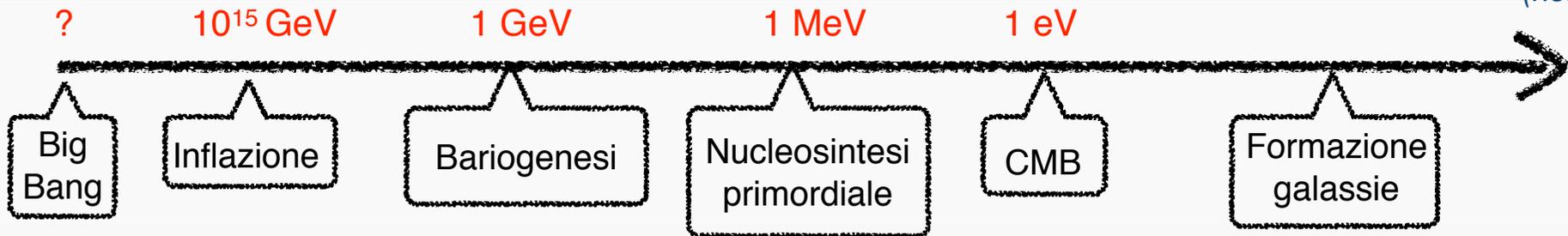


Concetto base:

l'Universo **si espande** e **si raffredda**



(non in scala!)

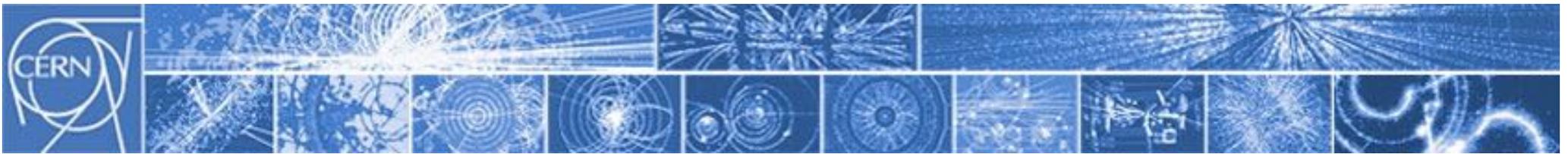


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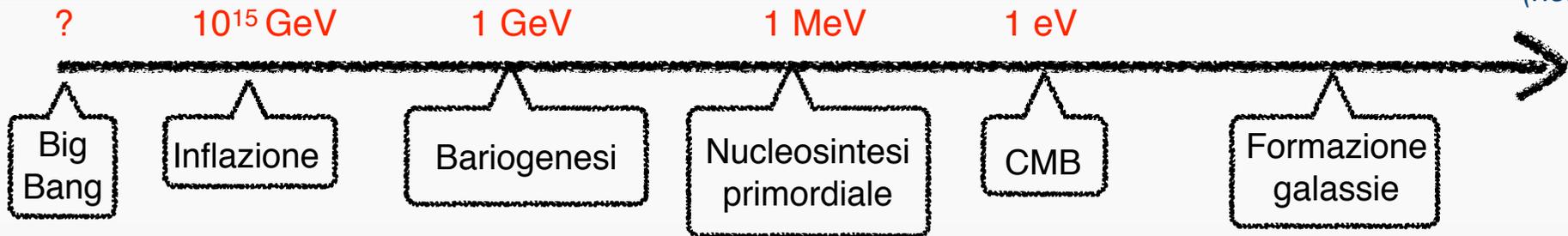
l'Universo si espande e si raffredda

aumenta di volume
come un panettone che lievita

(FAQ: *in* che cosa si espande?)



(non in scala!)



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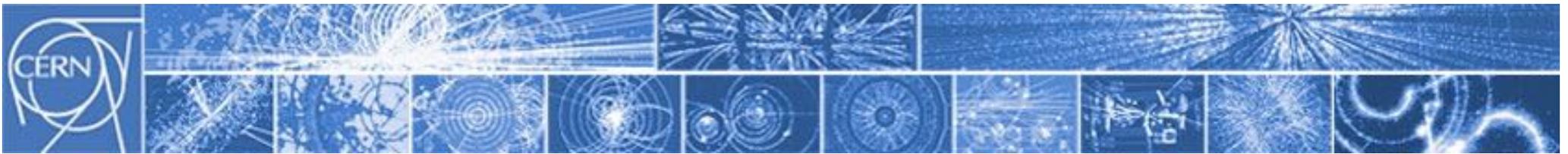
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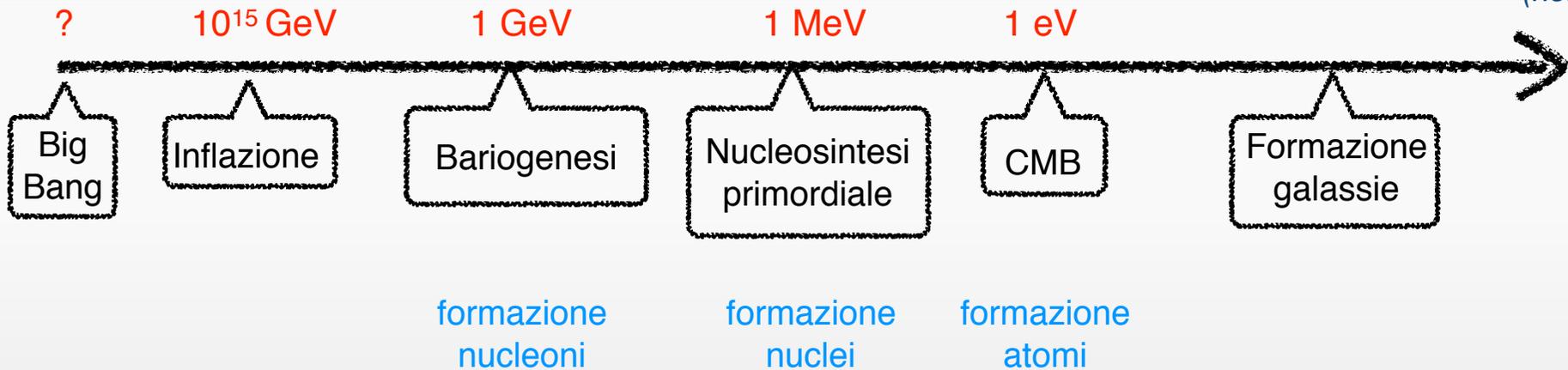
(FAQ: *in* che cosa si espande?)

a **alte T**, la materia si **dissocia**
nei costituenti fondamentali

a **basse T**, la materia si **agglomera**
in strutture sempre più complesse



(non in scala!)



Concetto base:

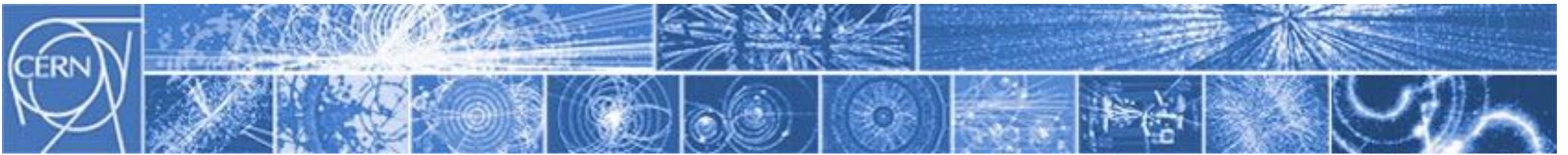
l'Universo **si espande** e **si raffredda**

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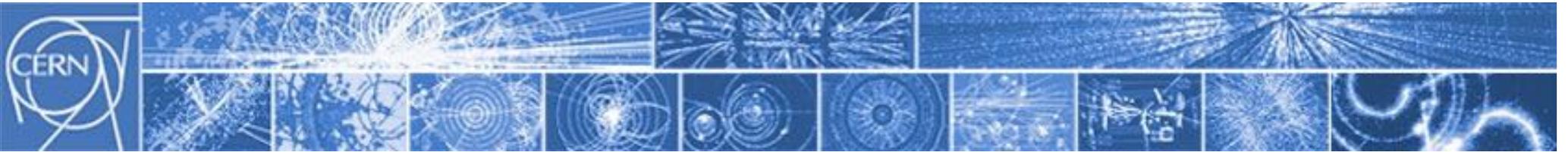
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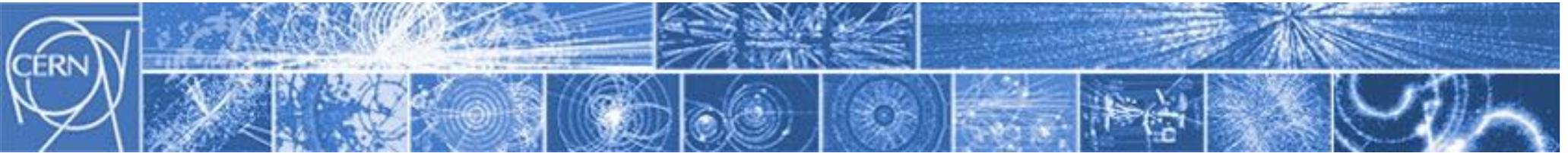
Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)



Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

Equazioni di Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



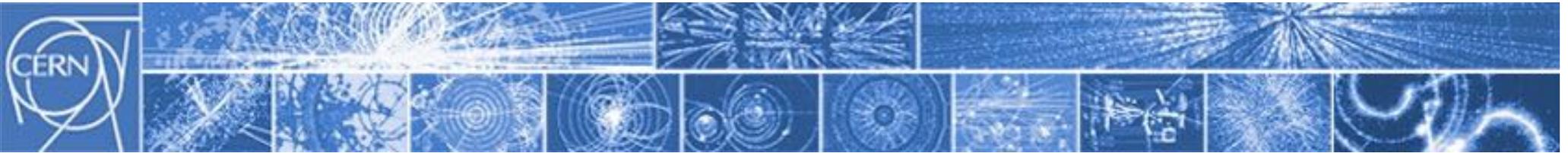
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*geometria dello
spazio-tempo*

*contenuto di
materia e energia*



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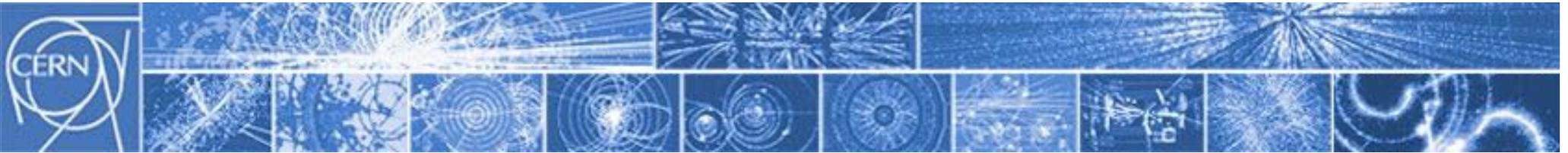
$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} \mathcal{R} g_{\mu\nu}$$

$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

$g_{\mu\nu}$: la metrica

*geometria dello
spazio-tempo*

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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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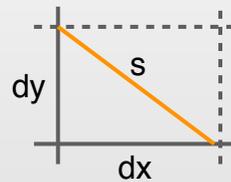
*geometria dello
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*contenuto di
materia e energia*

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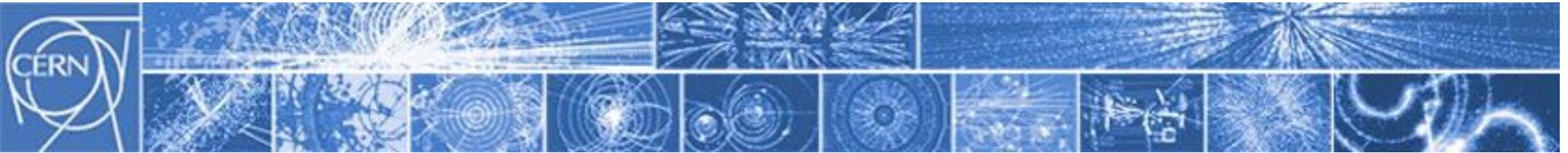
$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

$g_{\mu\nu}$: la metrica



$$s^2 = dx^2 + dy^2$$

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$



Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

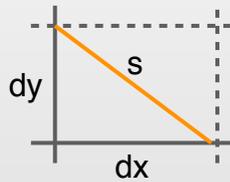
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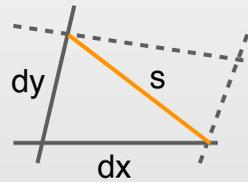
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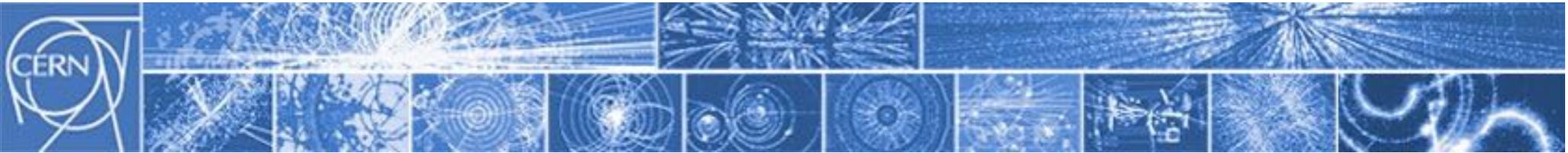
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geometria dello spazio-tempo



$$g_{\mu\nu} = \dots$$

contenuto di materia e energia



Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

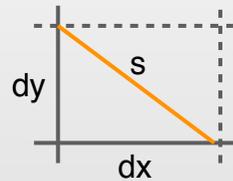
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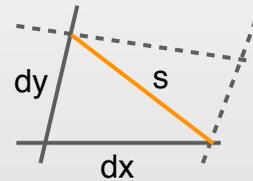
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geometria dello spazio-tempo



$$g_{\mu\nu} = \dots$$

contenuto di materia e energia

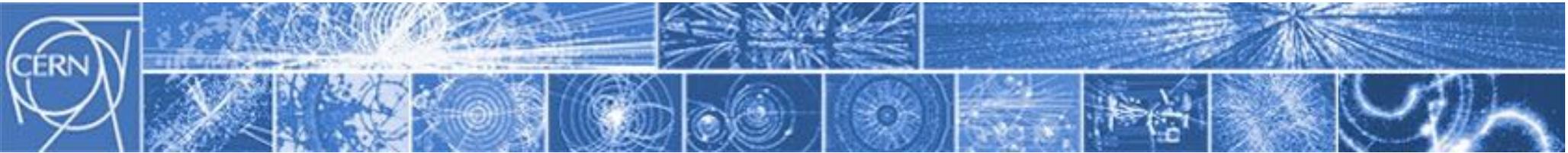
$a(t)$: il fattore di scala (la grandezza) dell'Universo

Parametro di Hubble

$$H = \frac{\dot{a}}{a}$$

Redshift

$$z = \frac{\lambda_0}{\lambda_1} \propto \frac{T_1}{T_0}$$



Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

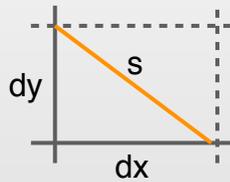
Equazioni di Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} \mathcal{R} g_{\mu\nu}$$

$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

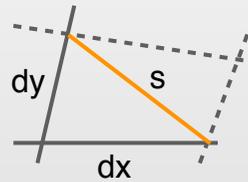
$g_{\mu\nu}$: la metrica



$$s^2 = dx^2 + dy^2$$

$$g_{\mu\nu} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

geometria dello spazio-tempo



$$g_{\mu\nu} = \dots$$

contenuto di materia e energia

$$G = \frac{1}{M_{Pl}^2}$$

$$T_{\mu\nu} = \begin{pmatrix} \rho & & & \\ & -P & & \\ & & -P & \\ & & & -P \end{pmatrix}$$

(assumendo fluido perfetto)

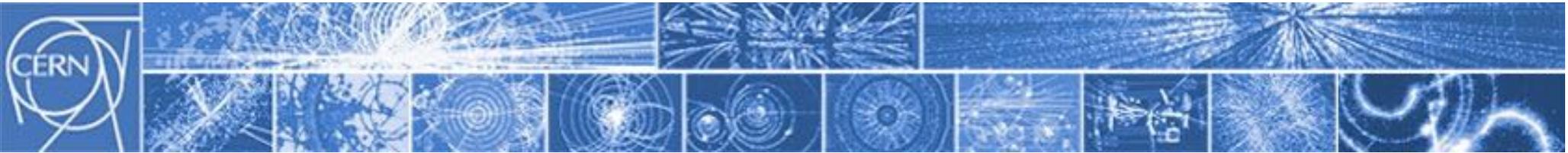
$a(t)$: il fattore di scala (la grandezza) dell'Universo

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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

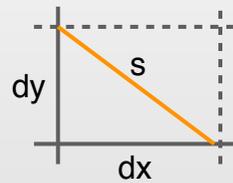
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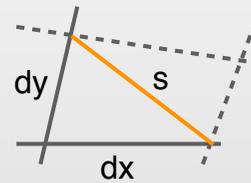
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Equazione di stato $P = w\rho$

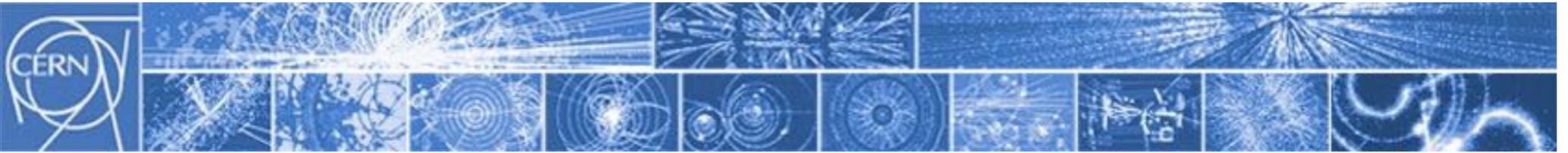
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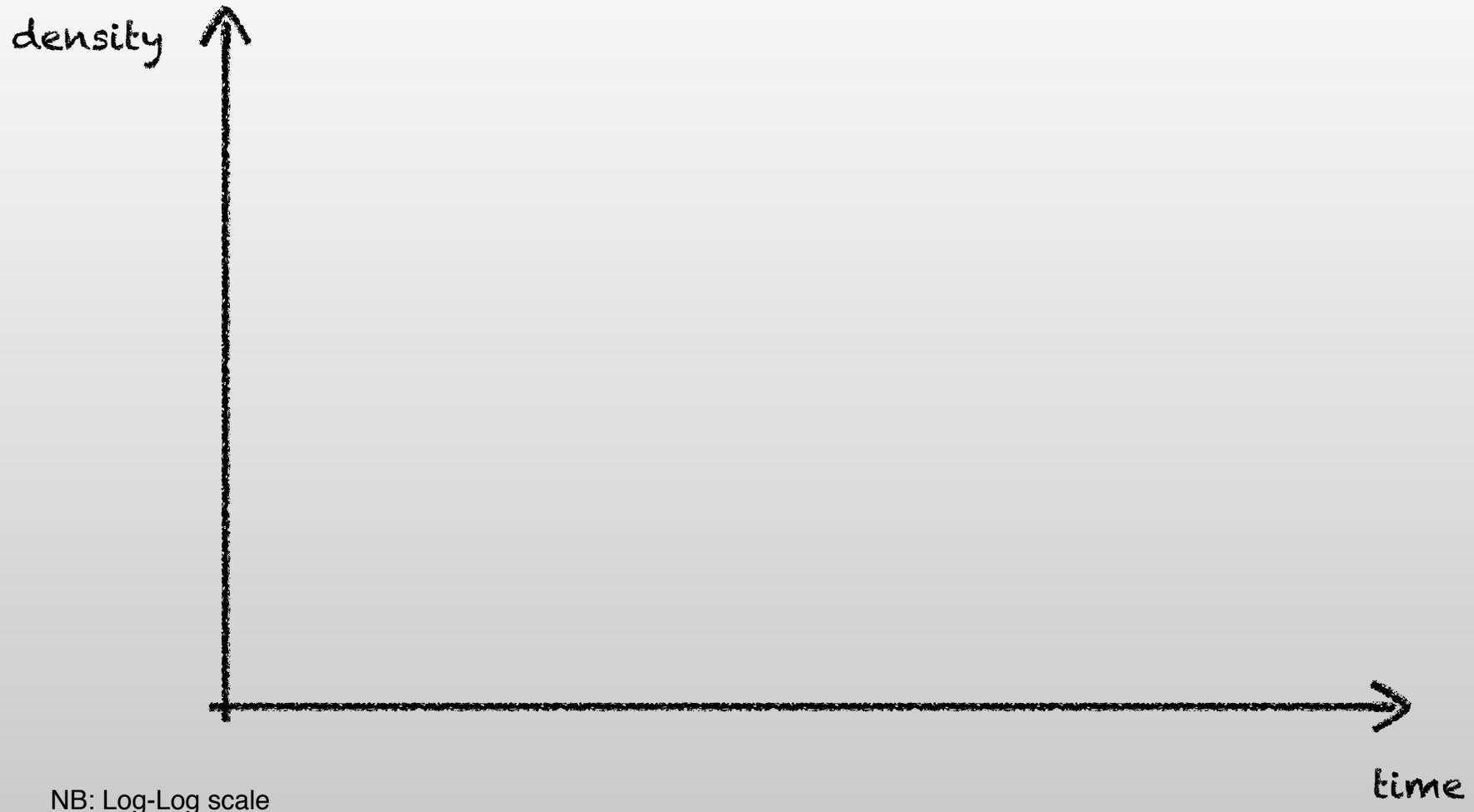
Redshift

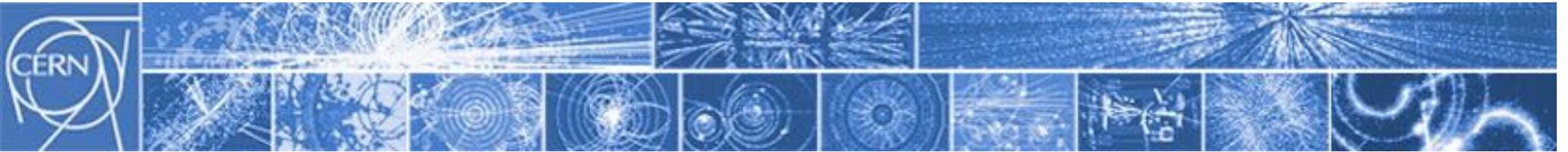
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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

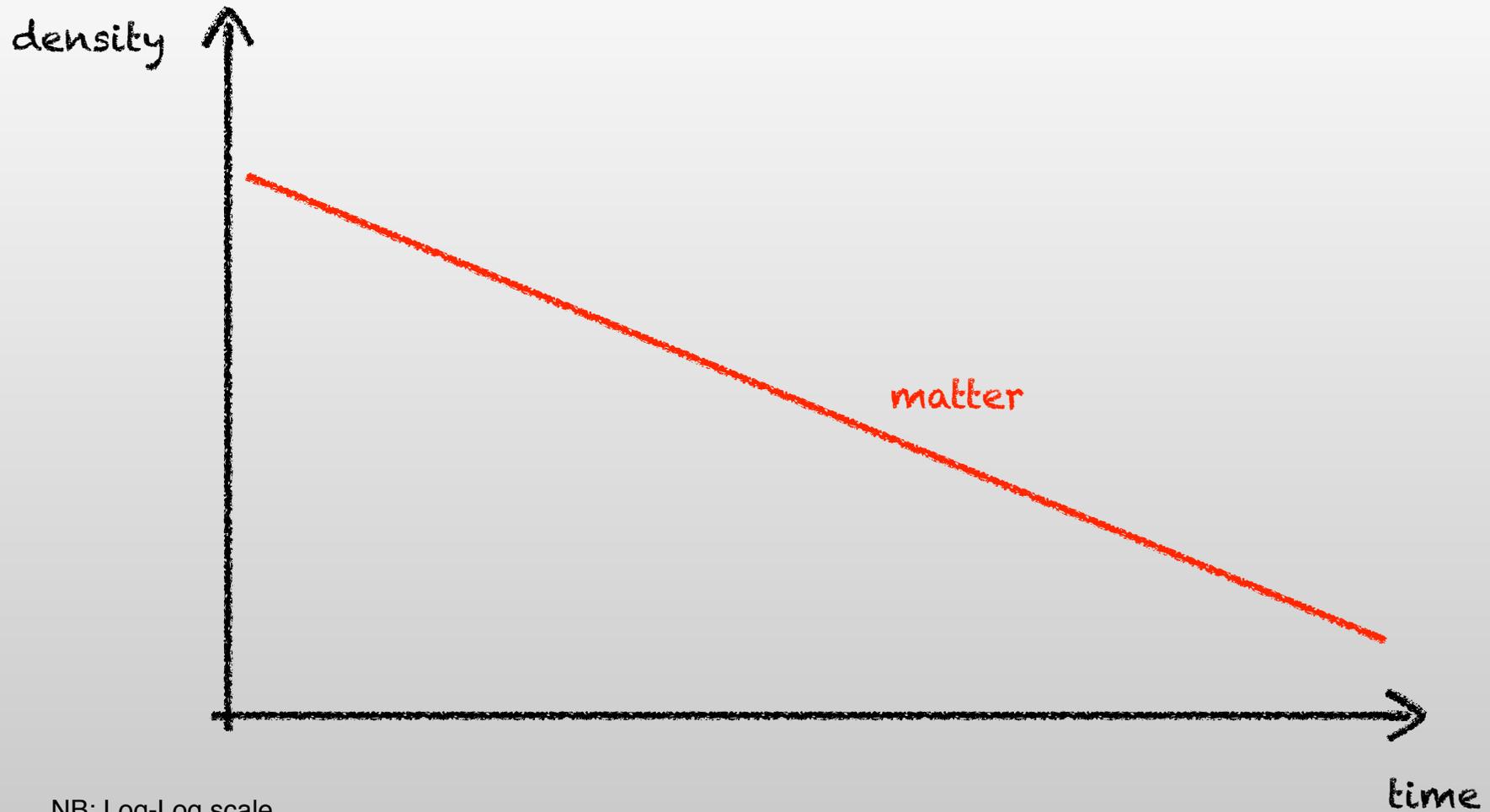
Evoluzione delle componenti dell'Universo

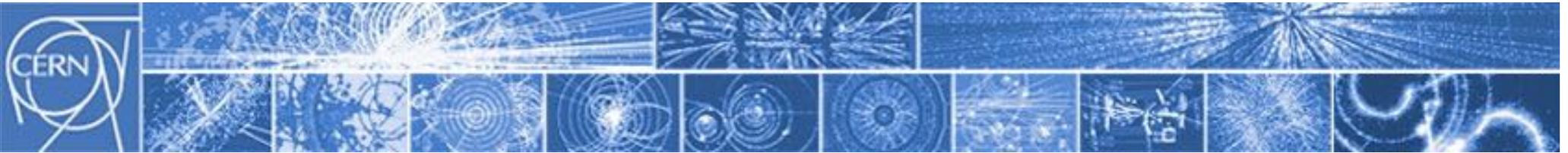




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

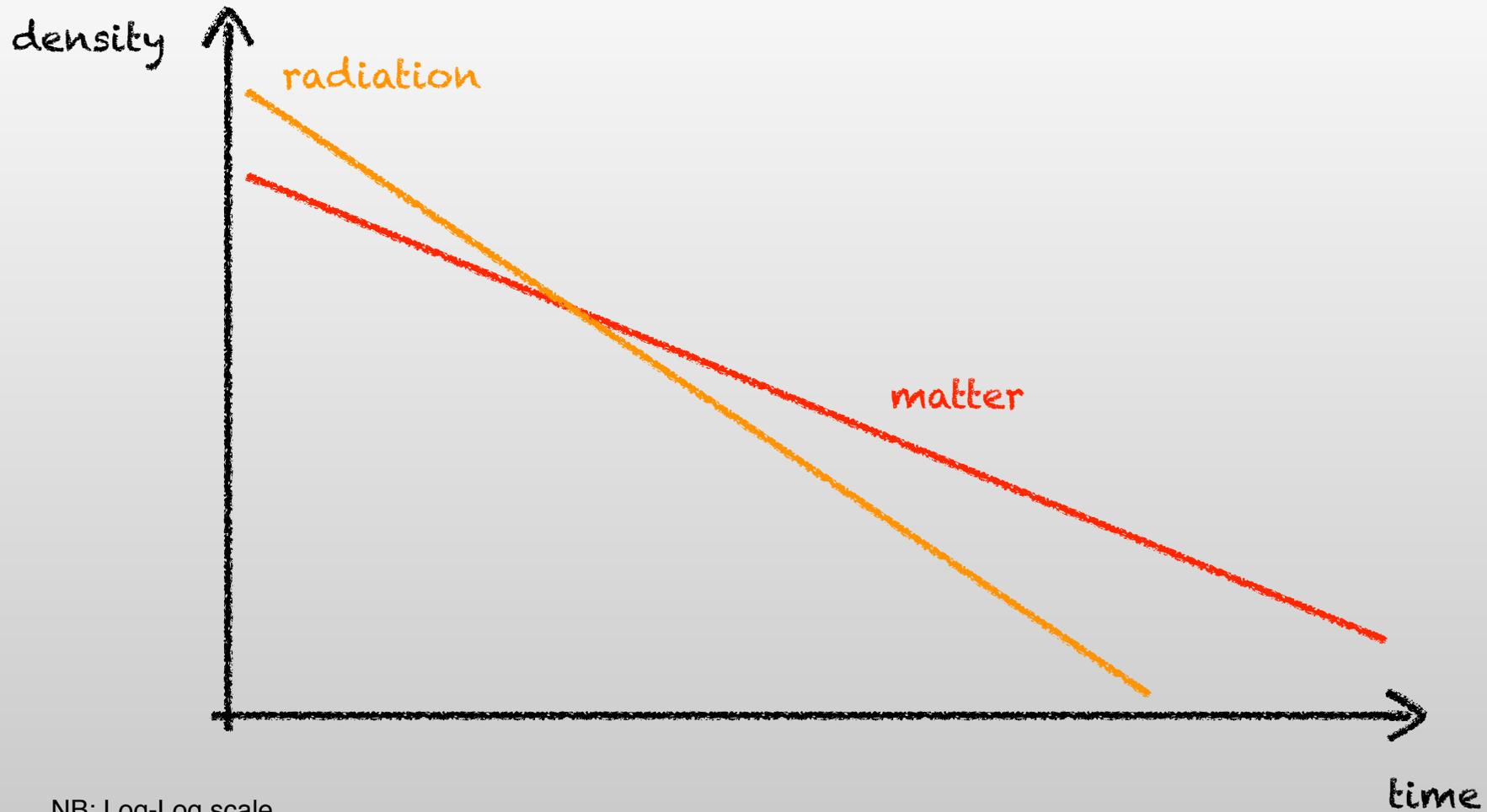
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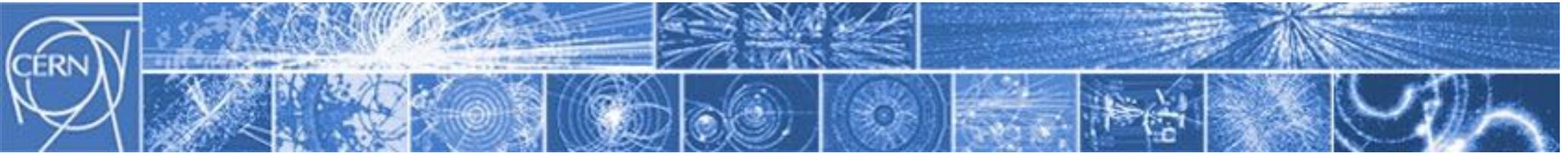


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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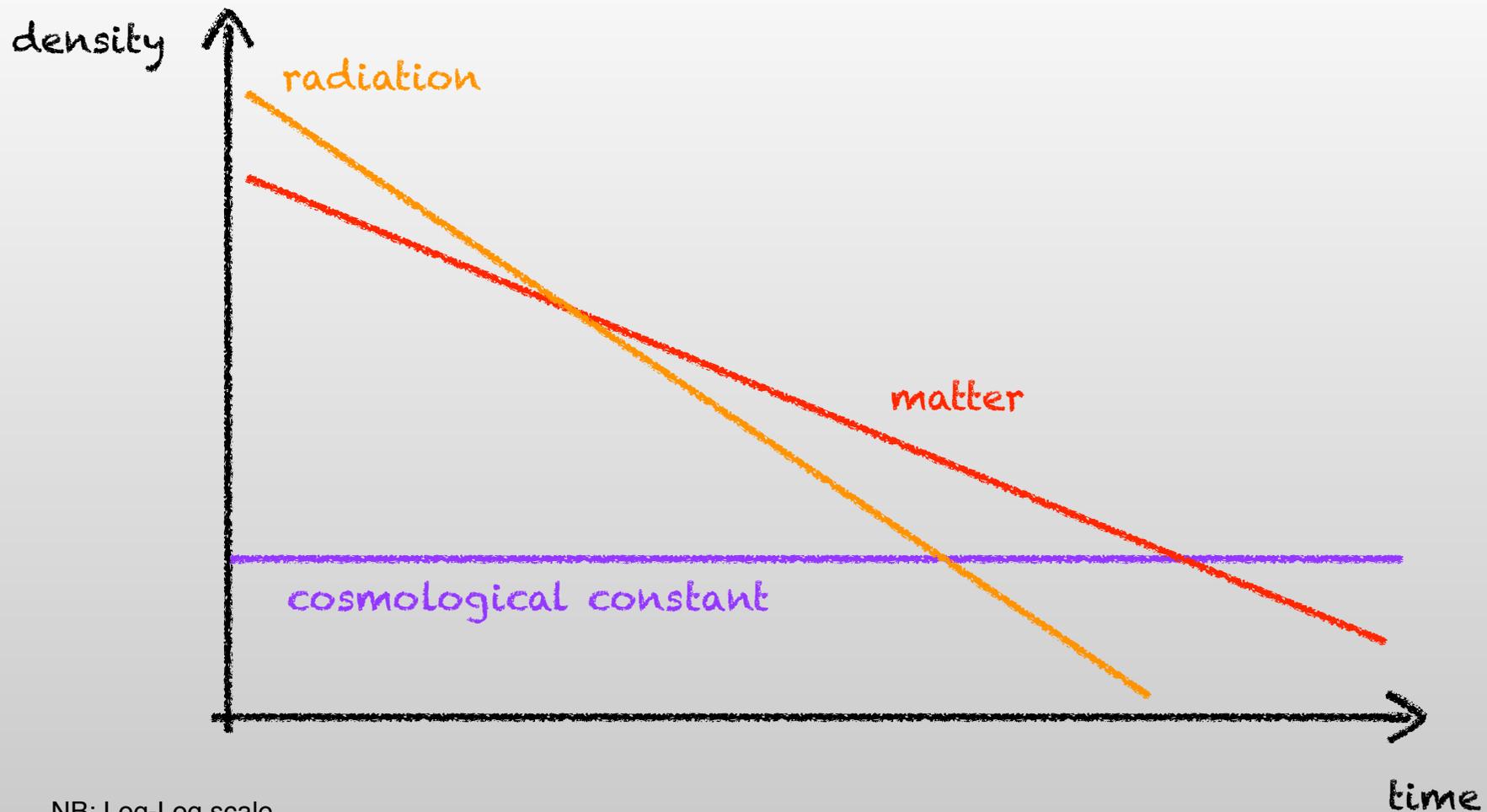


NB: Log-Log scale

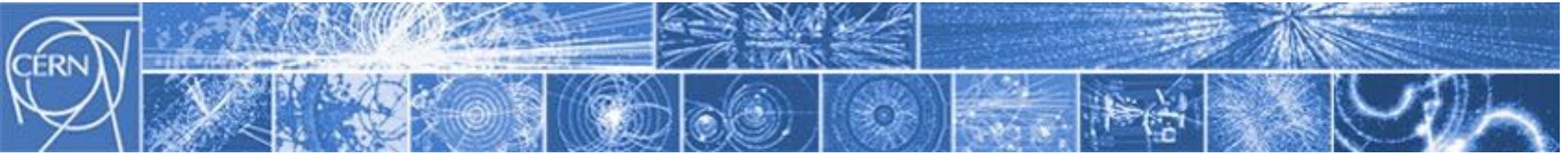


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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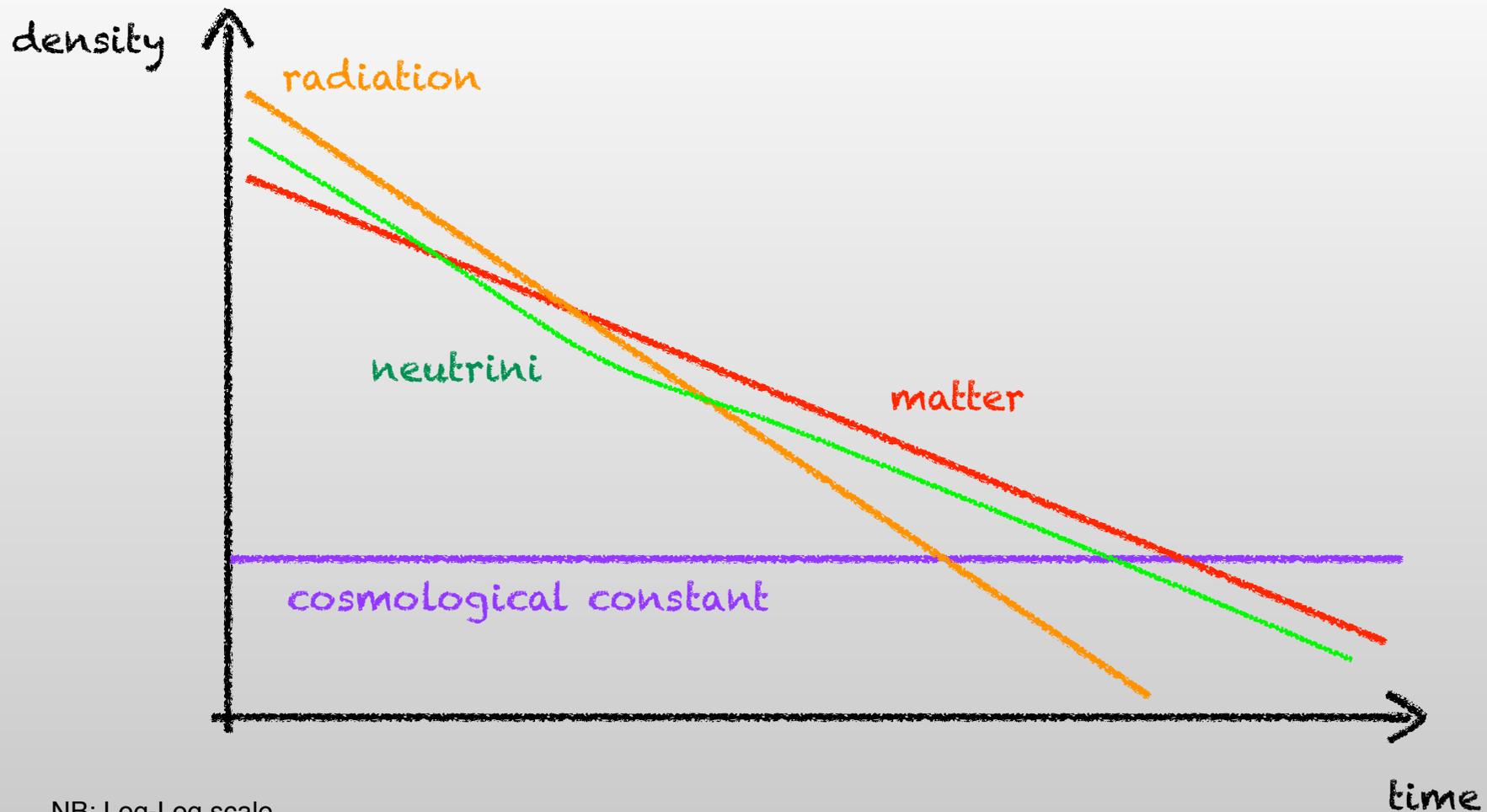


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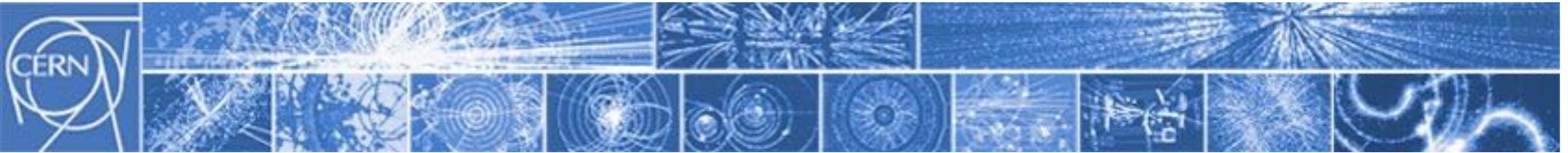


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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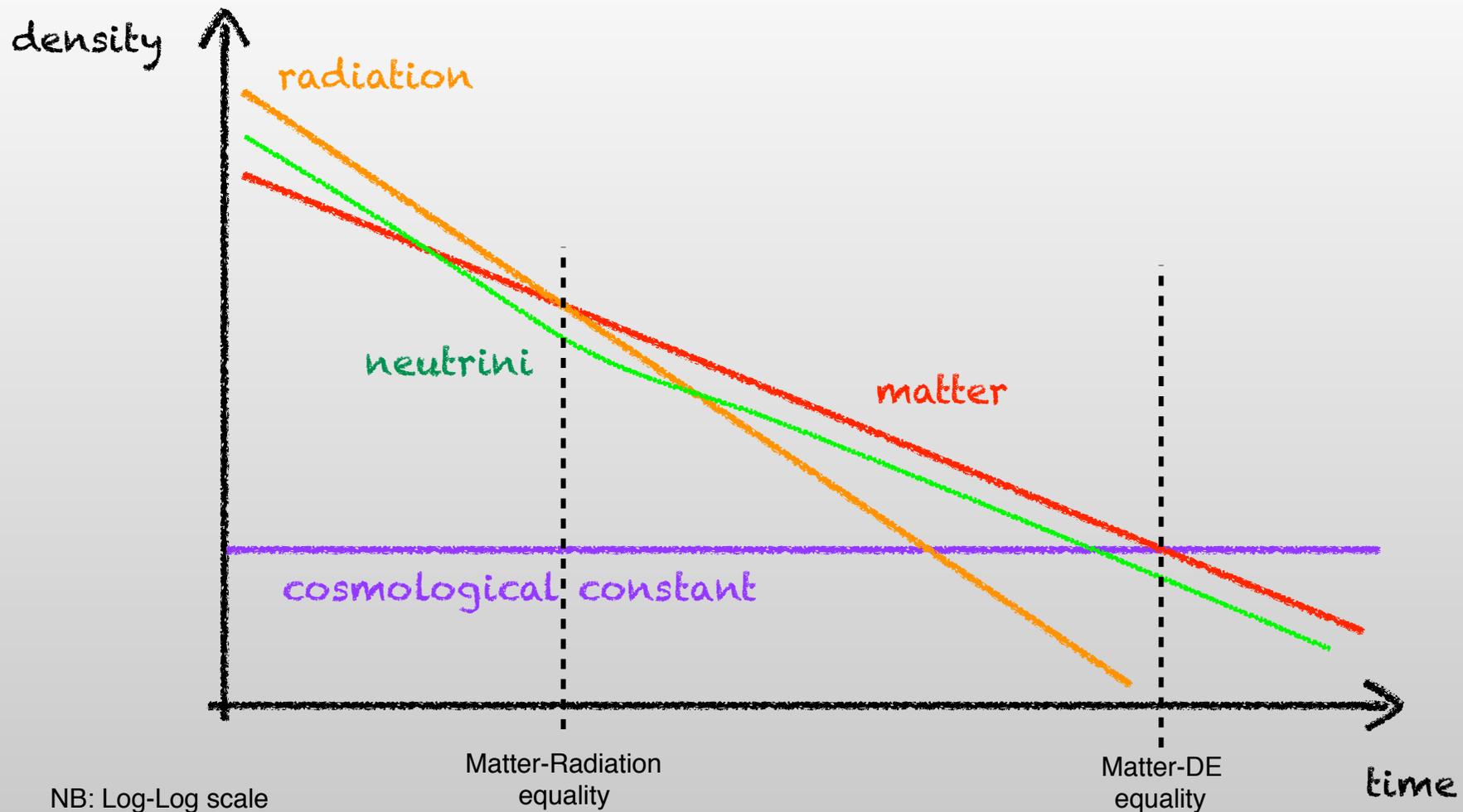


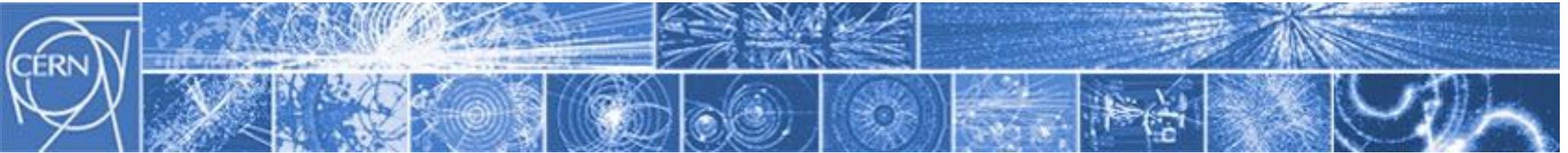
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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

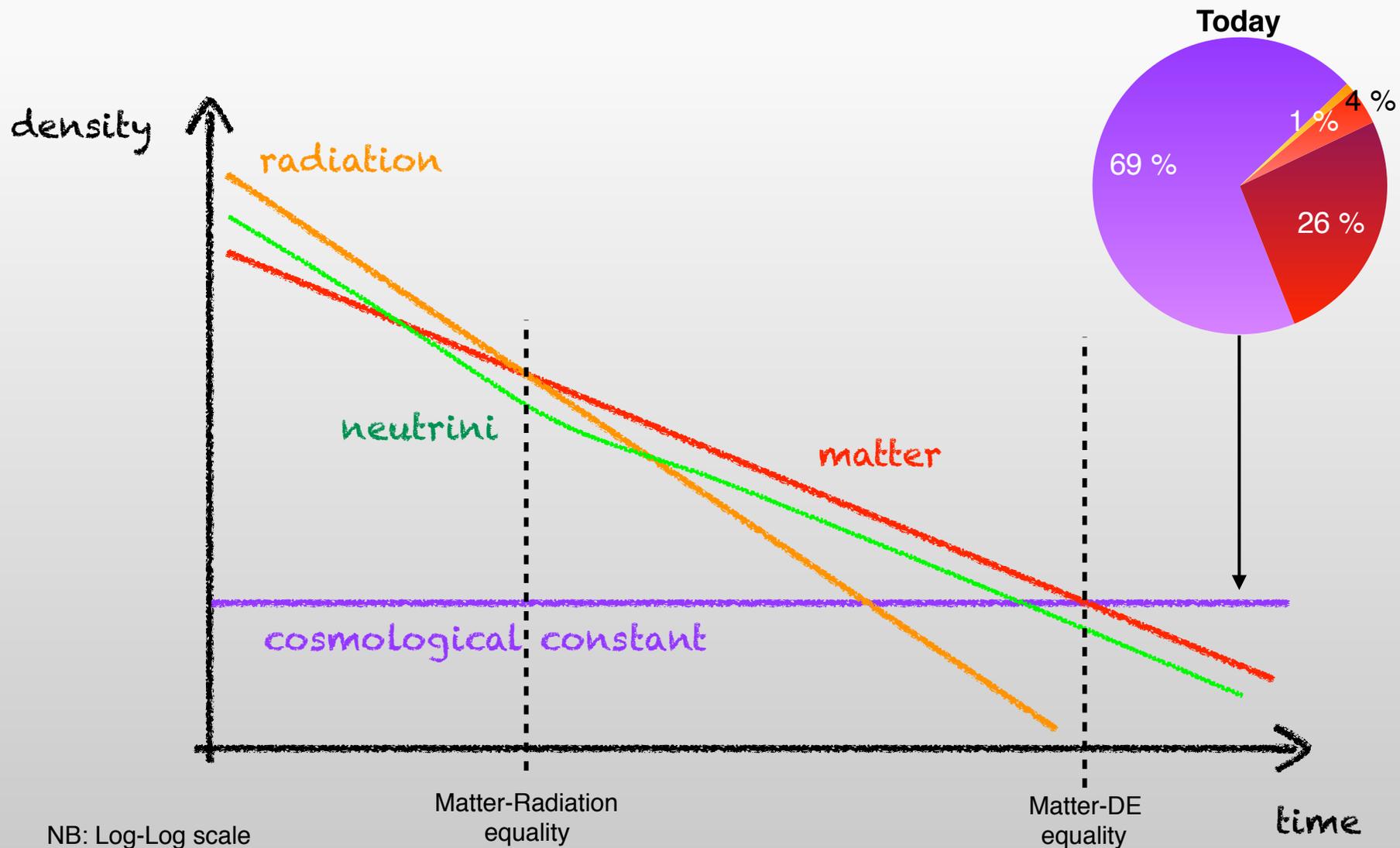
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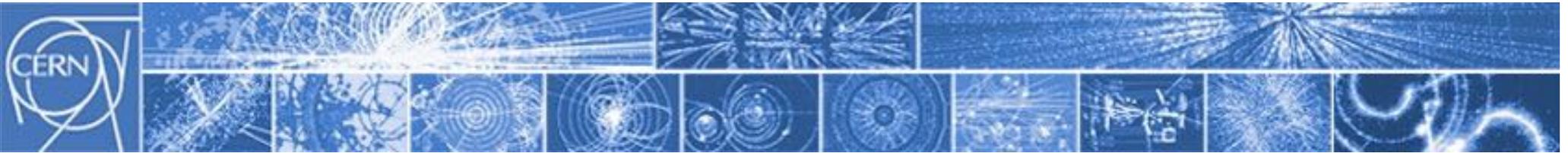




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

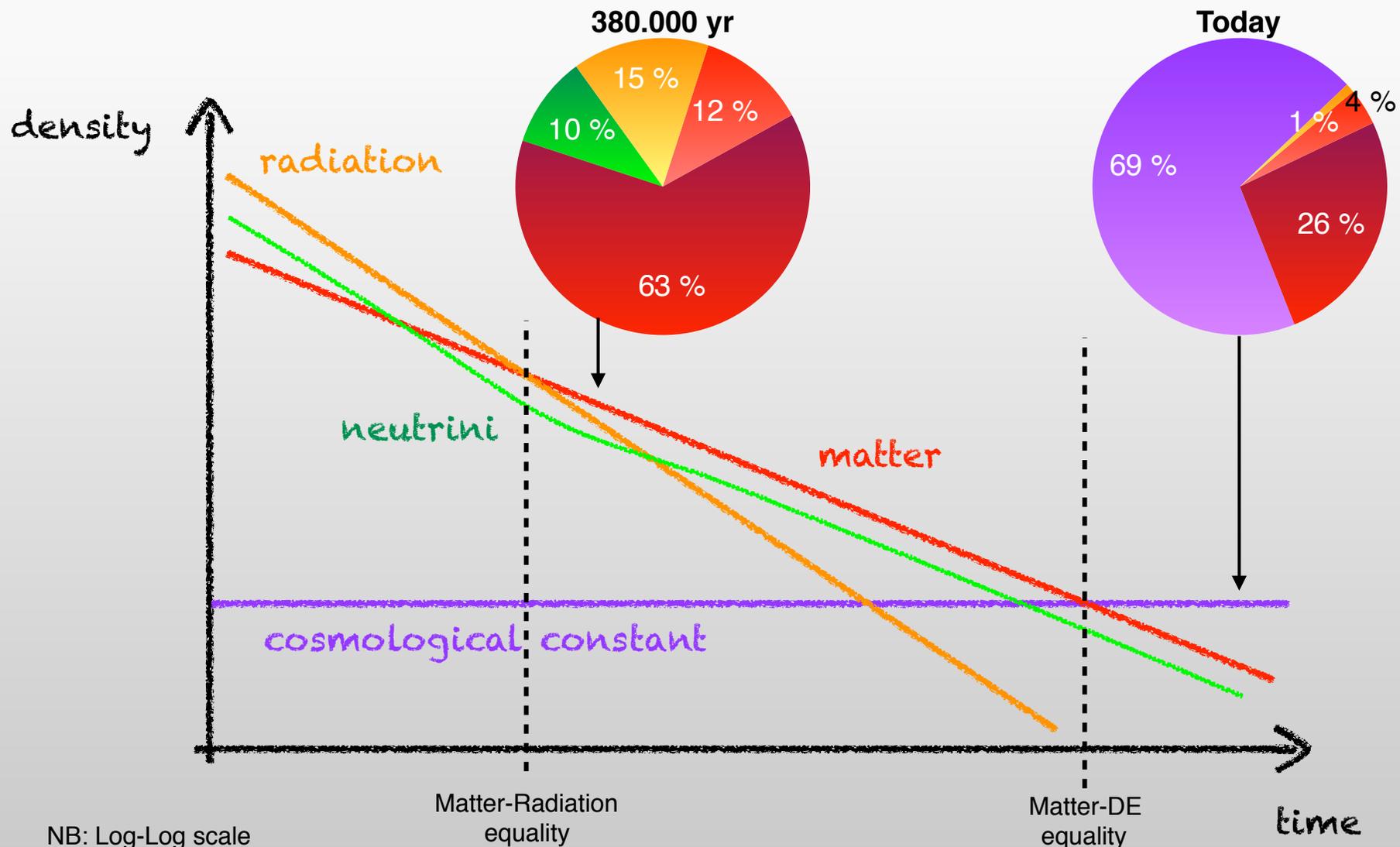
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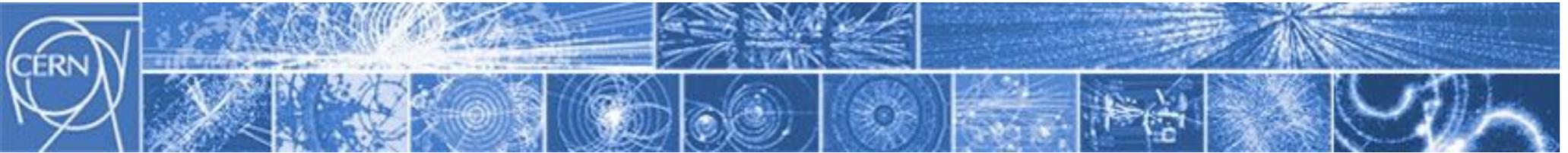




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

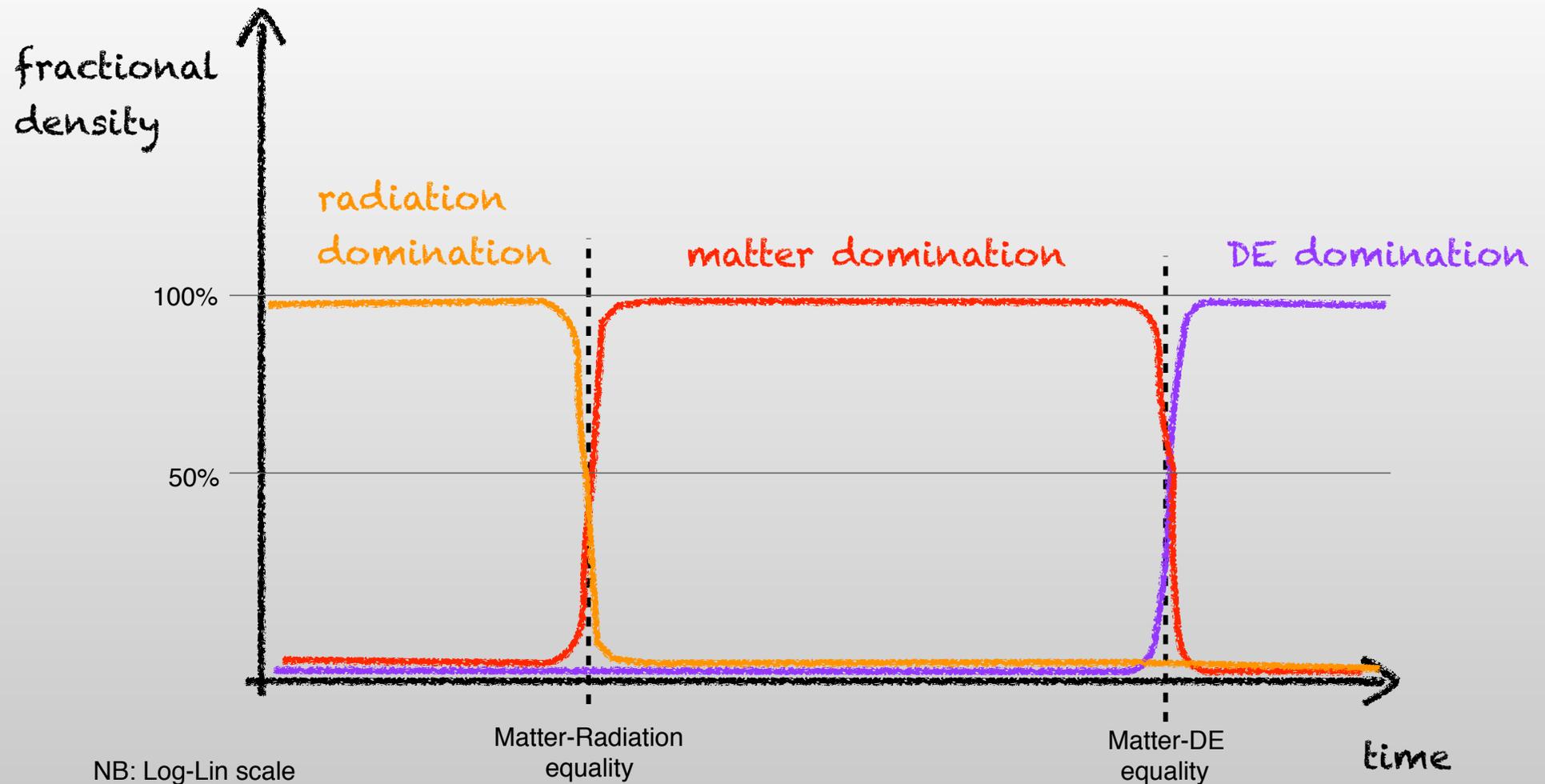
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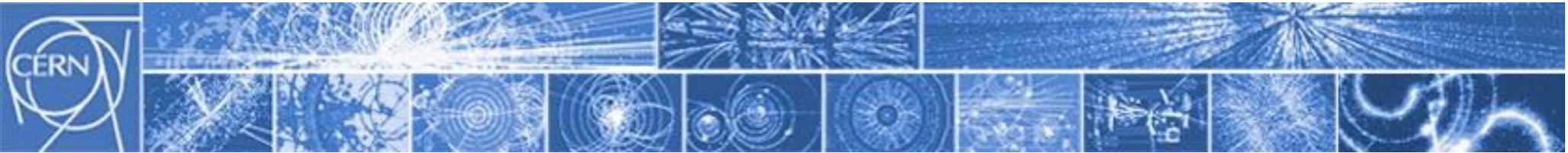




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

Evoluzione delle componenti dell'Universo





Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

Equazioni di Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

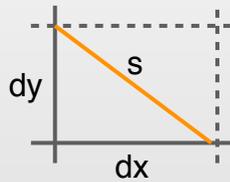
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contenuto di materia e energia

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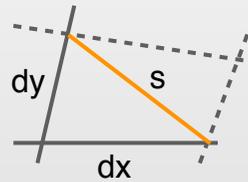
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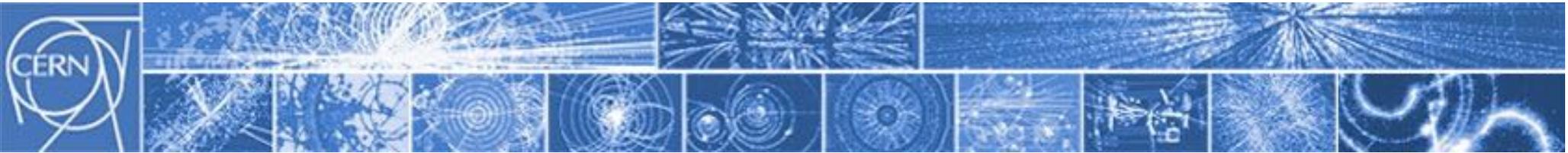
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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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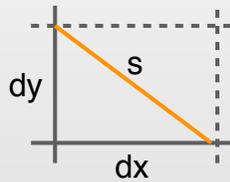
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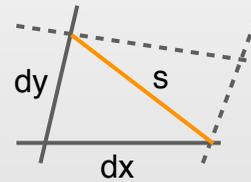
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omogeneità isotropia

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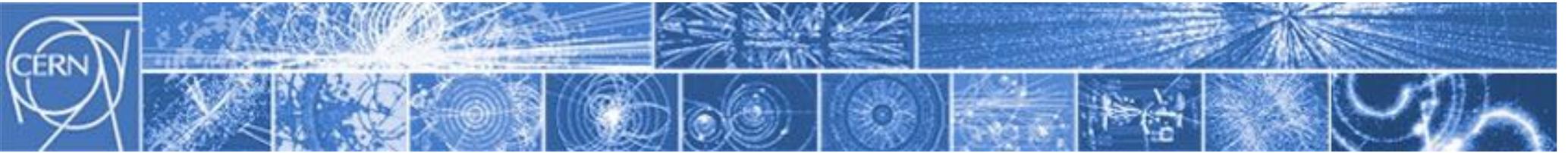
Redshift

$$z = \frac{\lambda_0}{\lambda_1} \propto \frac{T_1}{T_0}$$

Equazioni di Friedmann-Robertson-Walker

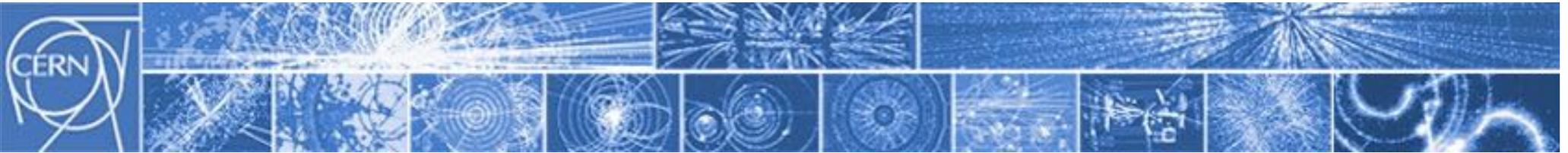
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3} \rho \quad \text{FRW I}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3P) \quad \text{FRW II}$$



Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

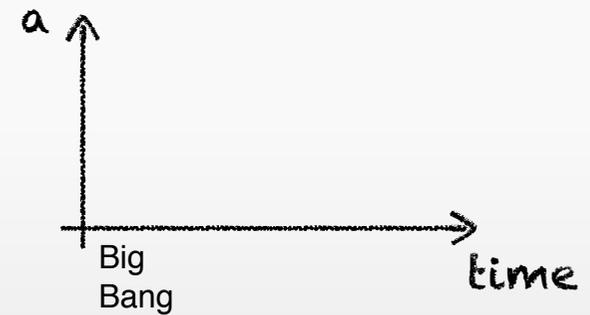
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

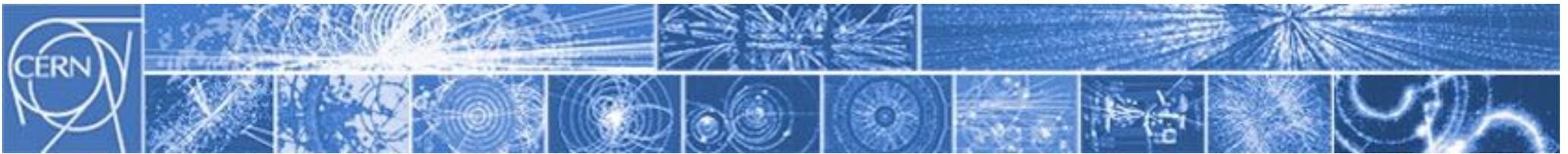


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

con alcuni (non semplici) passaggi
posso risolvere per $a(t)$:



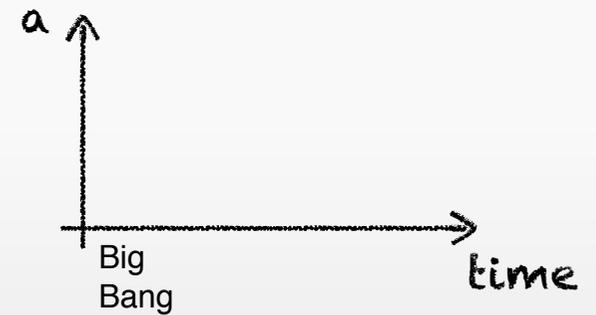


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

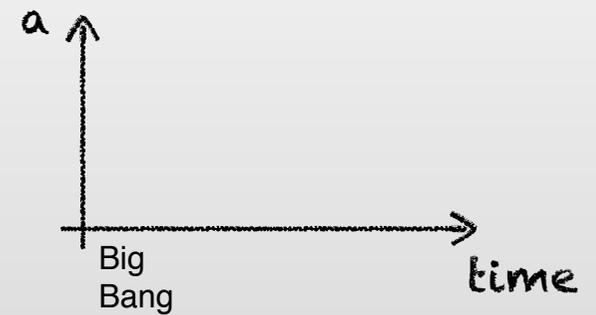
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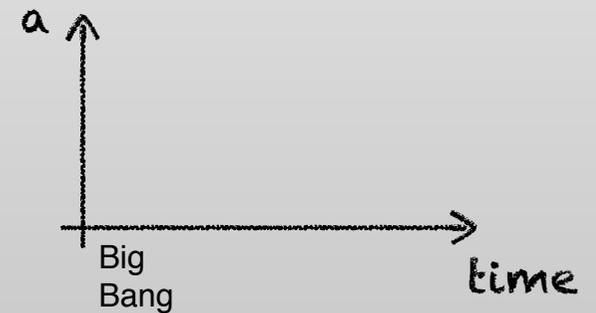
$$k < 0$$

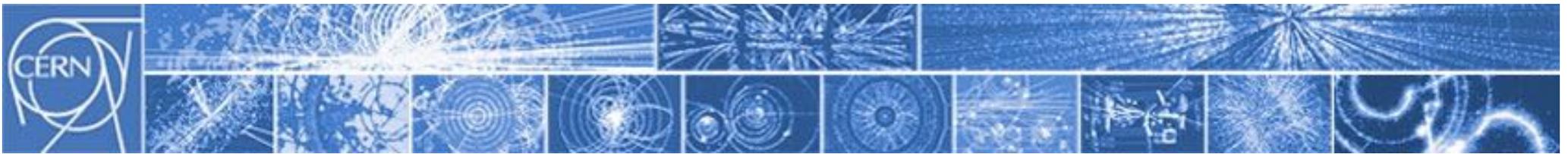


$$k = 0$$



$$k > 0$$



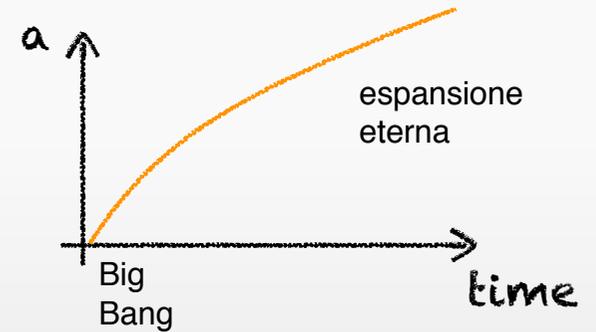


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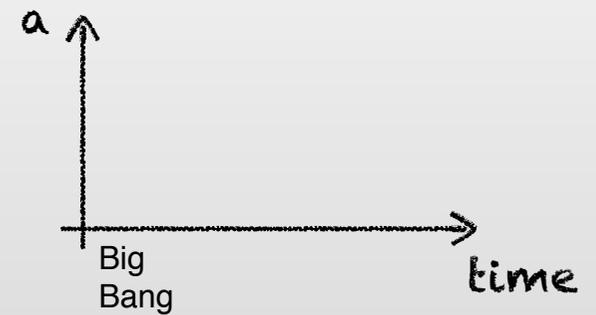
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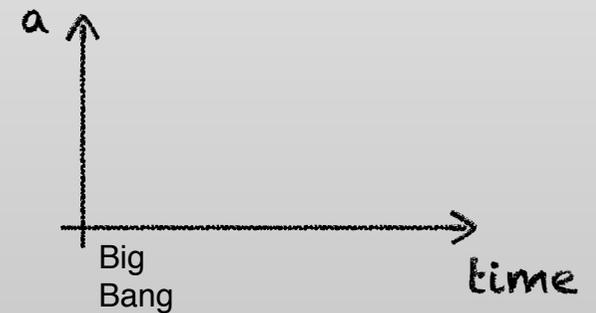
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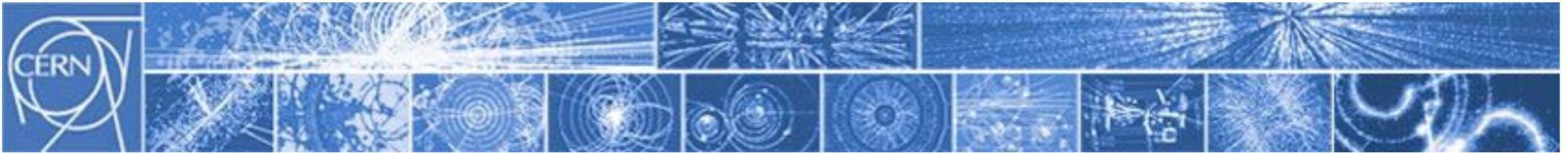


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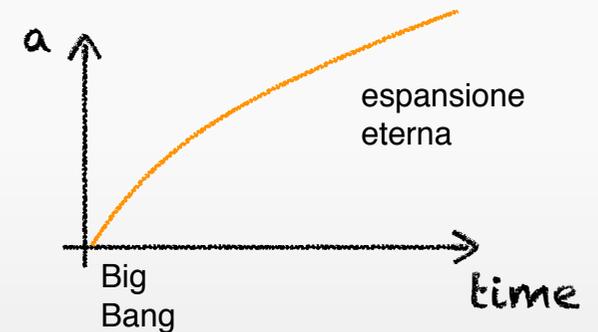


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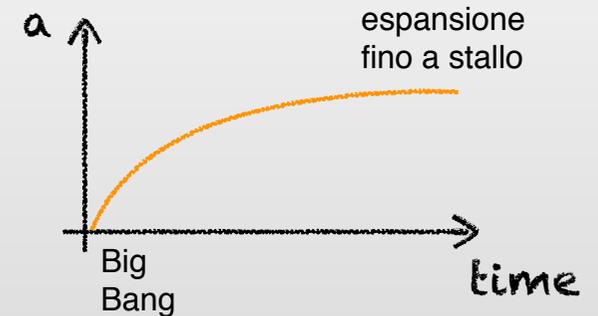
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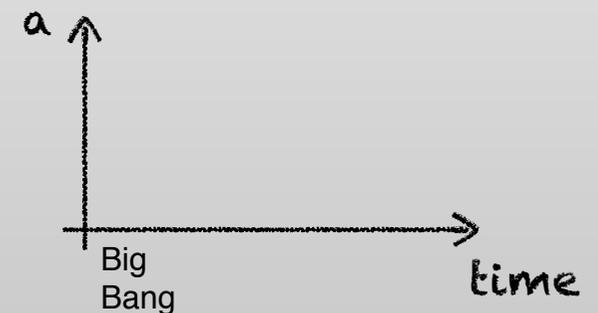
$$k < 0$$

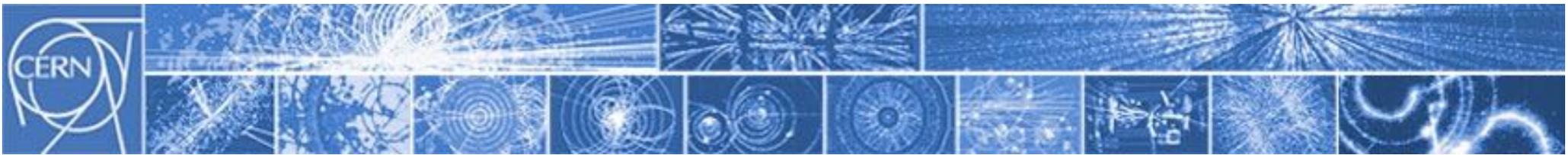


$$k = 0$$



$$k > 0$$



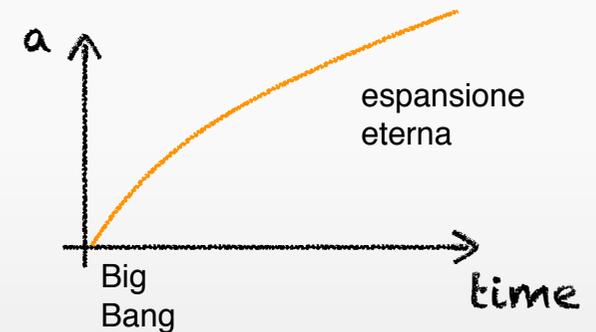


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

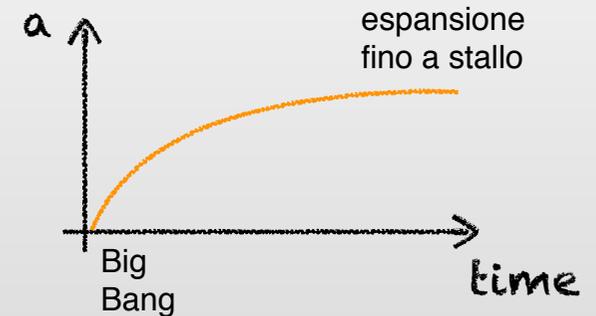
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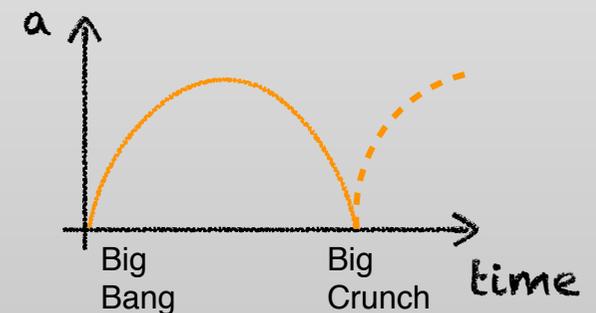
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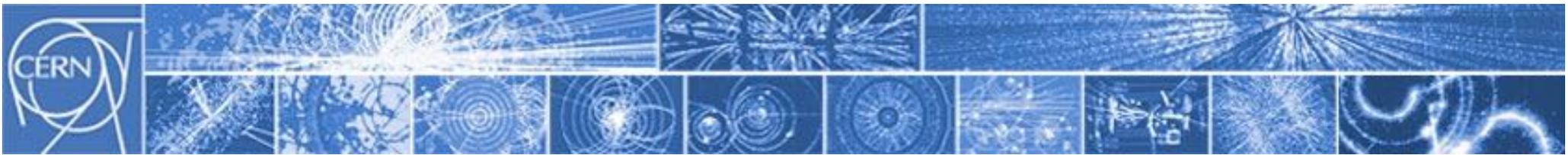


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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

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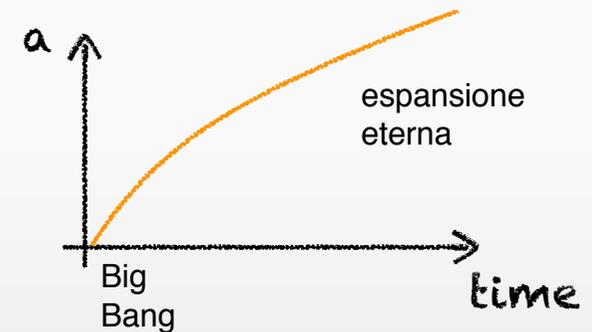
$$\frac{k}{H^2 a^2} = \Omega - 1$$

dove $\Omega = \frac{\rho}{\rho_{\text{crit}}}$

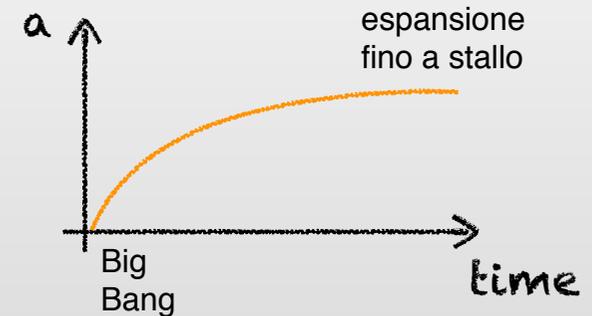
$$\rho_{\text{crit}} = \frac{3H^2}{8\pi G}$$

un valore ben preciso,
e.g. $0.96 \cdot 10^{-29} \text{ gr/cm}^3$ today

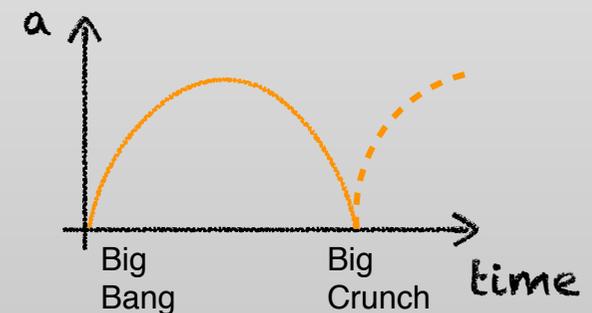
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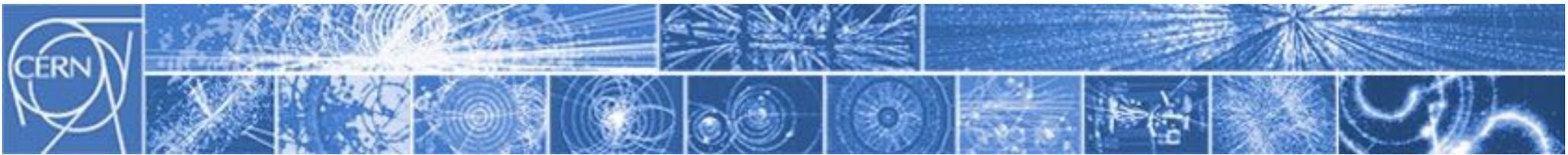


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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

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e.g. $0.96 \cdot 10^{-29} \text{ gr/cm}^3$ today

quindi

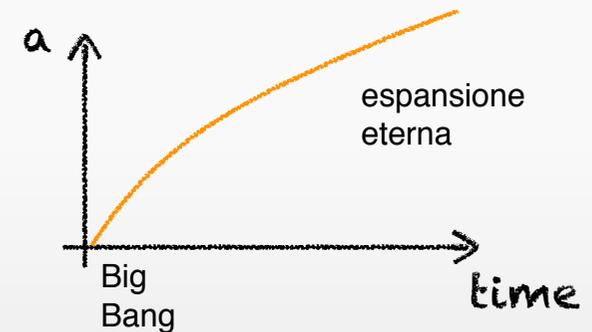
$$\rho < \rho_{\text{crit}} \Rightarrow \Omega < 1 \Rightarrow k < 0$$

$$\rho = \rho_{\text{crit}} \Rightarrow \Omega = 1 \Rightarrow k = 0$$

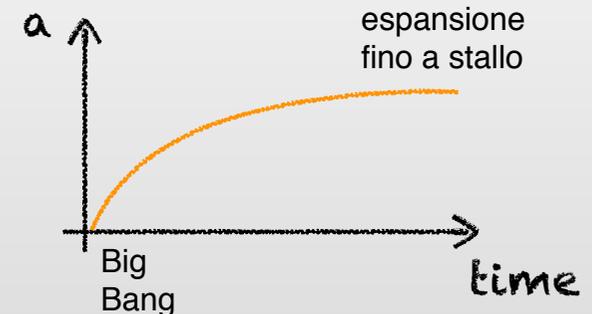
$$\rho > \rho_{\text{crit}} \Rightarrow \Omega > 1 \Rightarrow k > 0$$

pesare l'Universo per determinarne il fato!

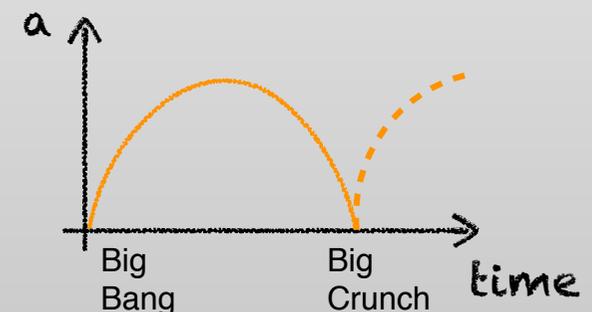
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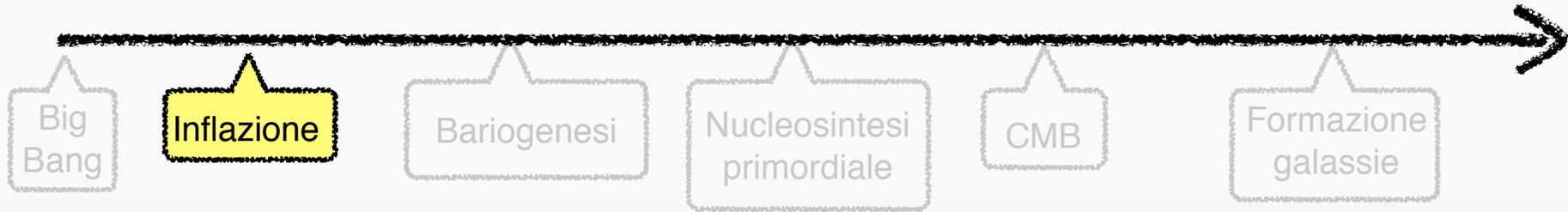
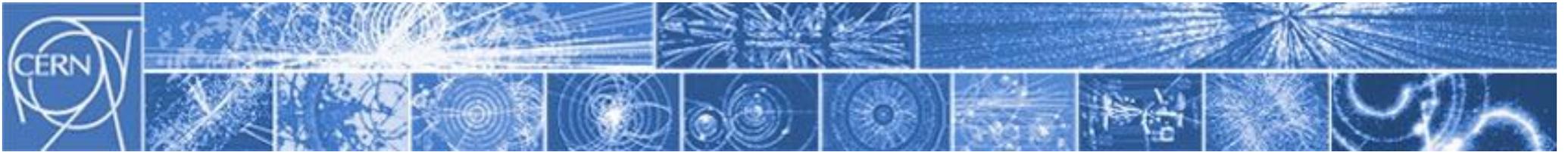


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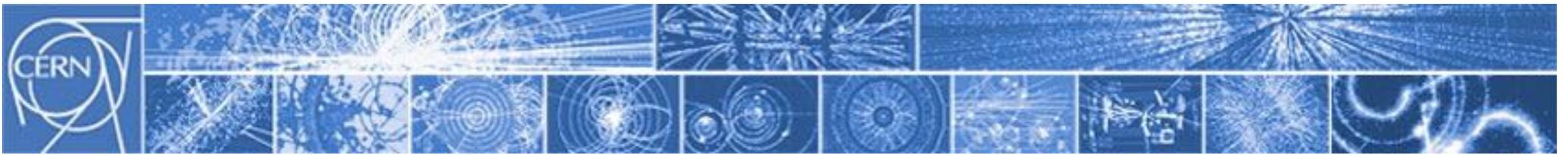


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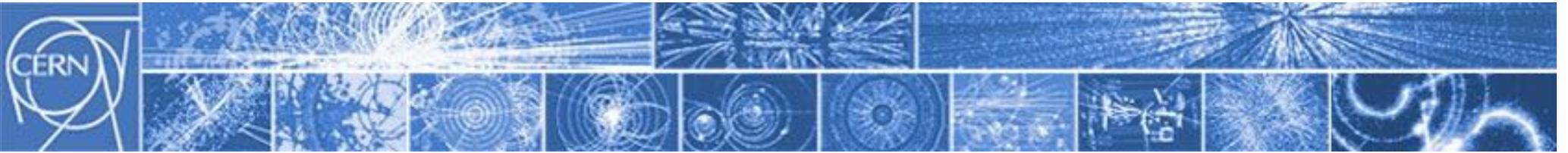




Inflazione



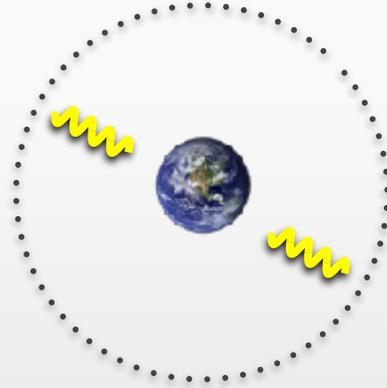
Inflazione

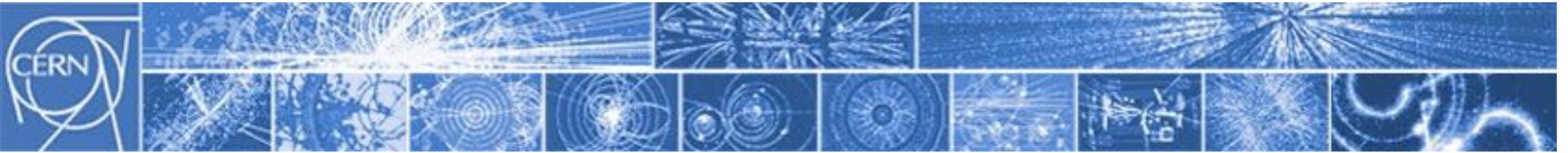


Inflazione

Problema:

come mai l'Universo
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regioni causalmente
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non hanno motivo
di essere simili

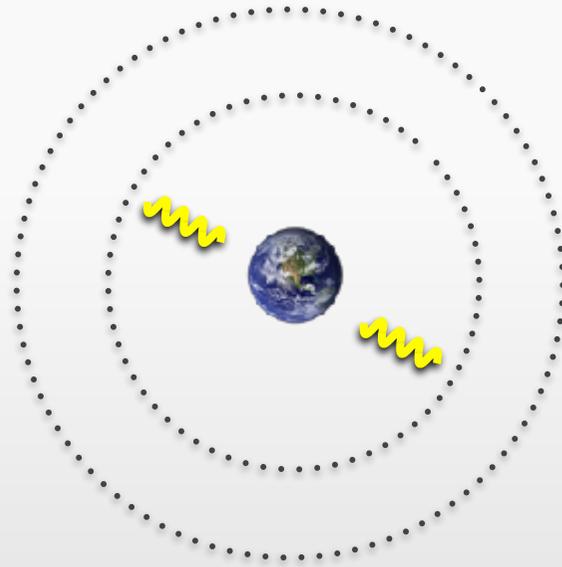


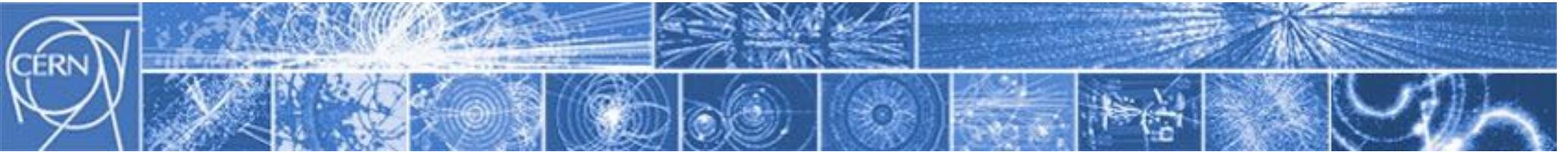


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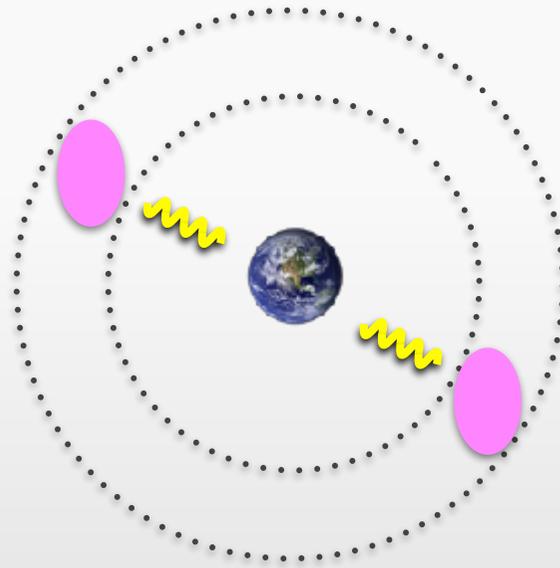


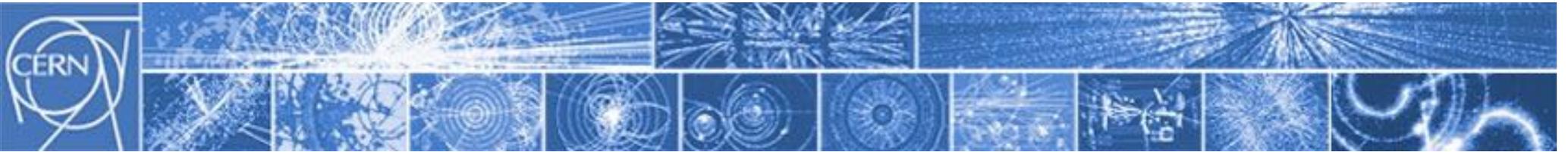


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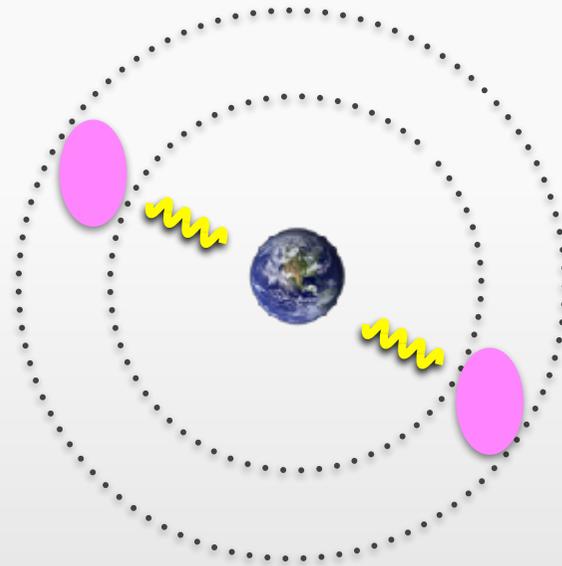




Inflazione

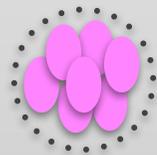
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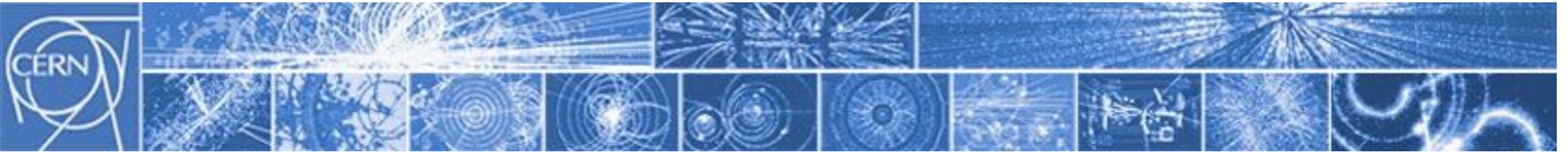
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Soluzione:

erano causalmente
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espansione 'esplosiva'

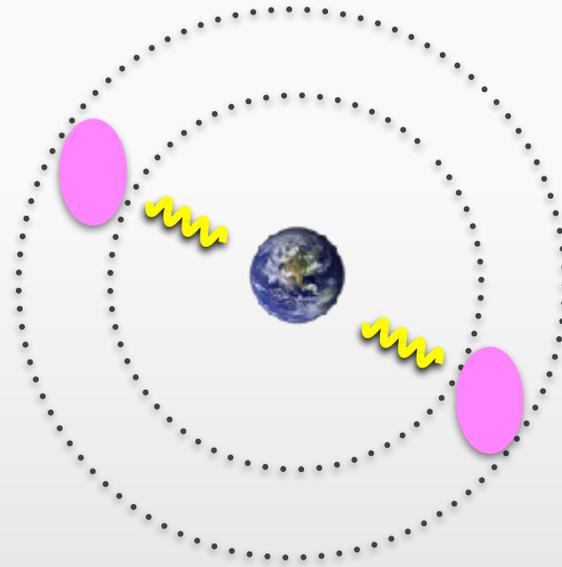




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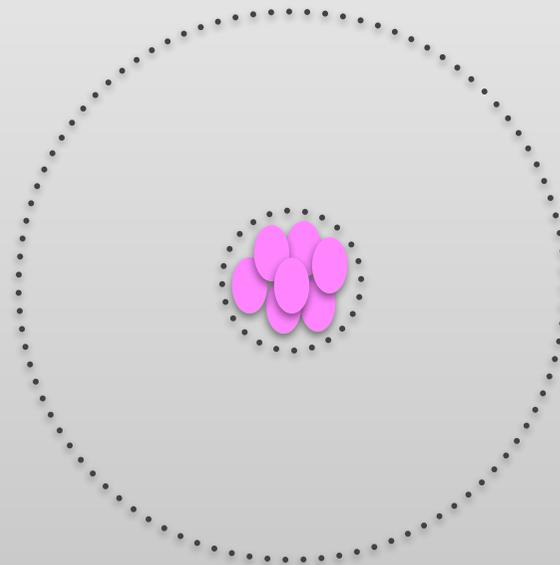
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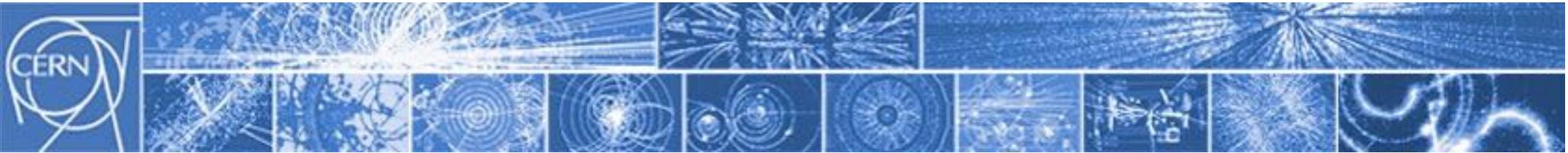
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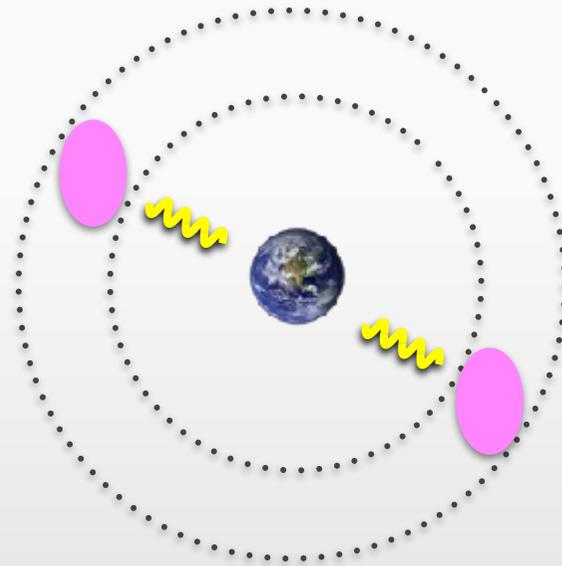




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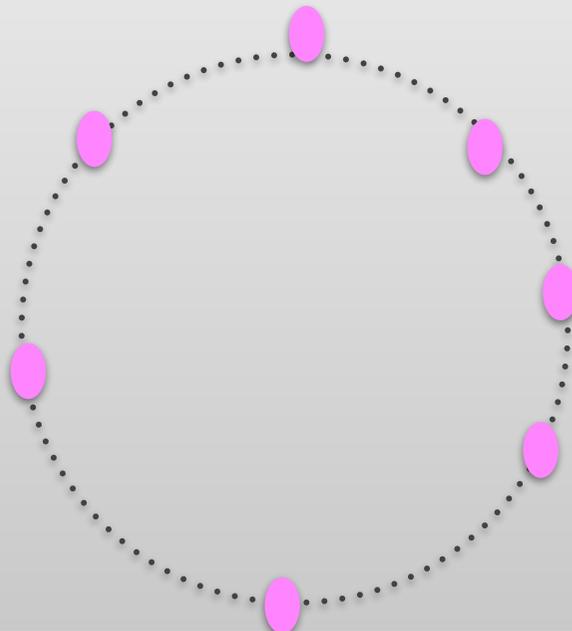
Problema:

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Soluzione:

erano causalmente connesse, poi separate da una espansione 'esplosiva'



$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

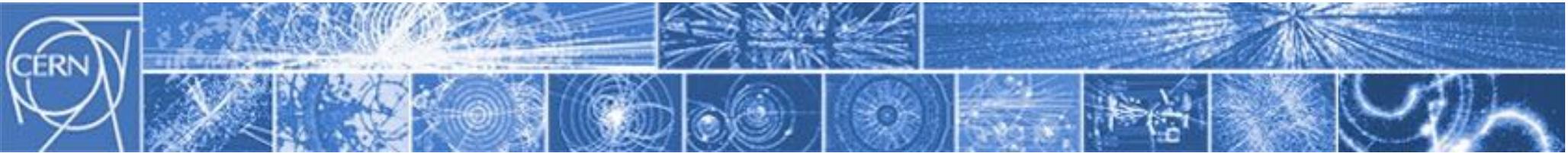
se ho una sostanza tale che $\rho = \text{cost}$

allora soluzione:

$$\dot{a} = \text{cost } a$$



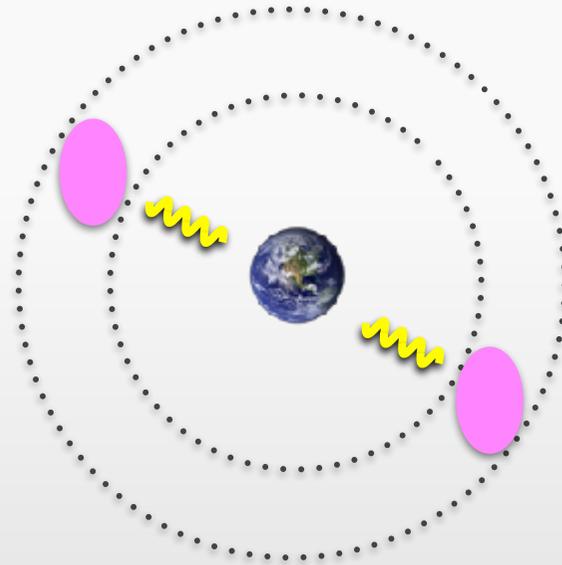
$$a \propto e^t$$



Inflazione

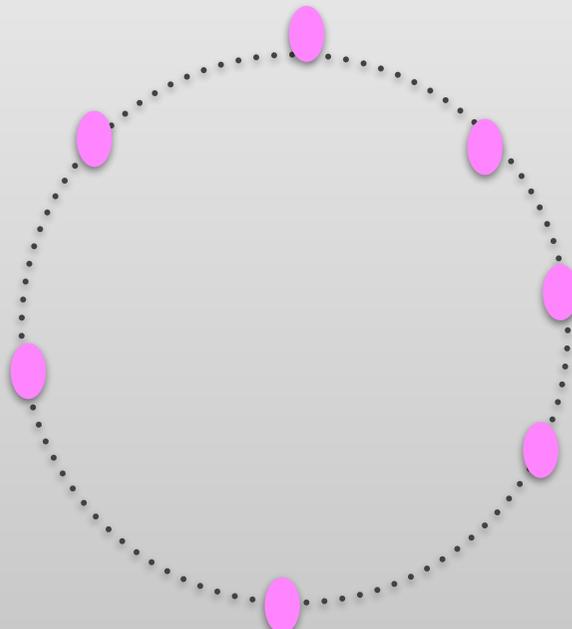
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Soluzione:

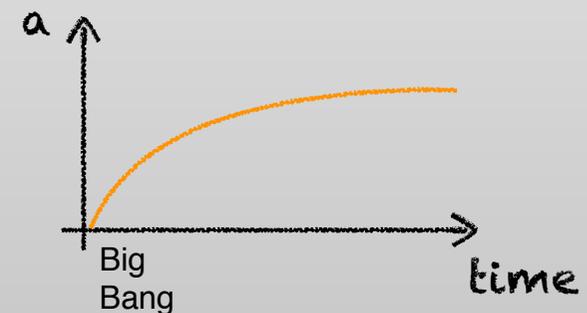
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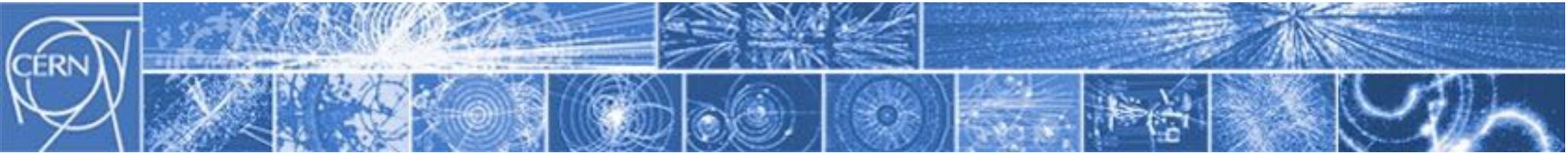


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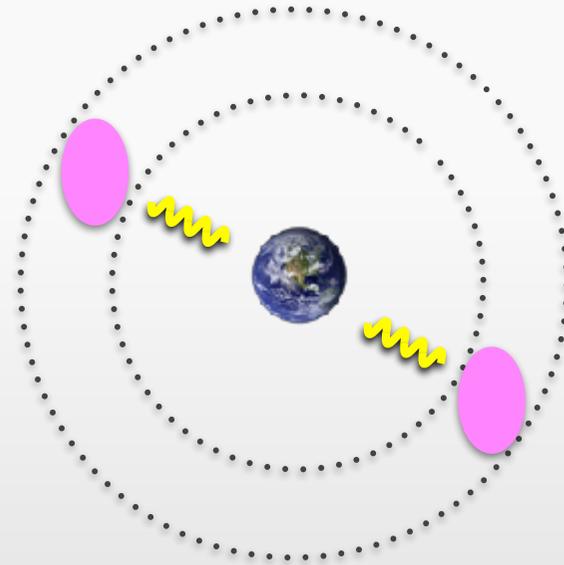




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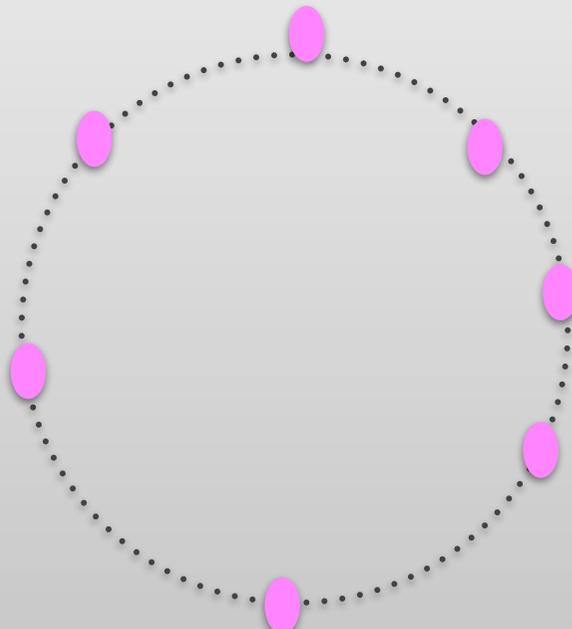
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