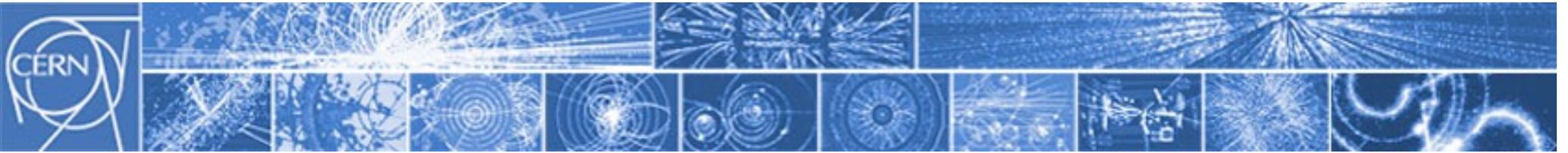




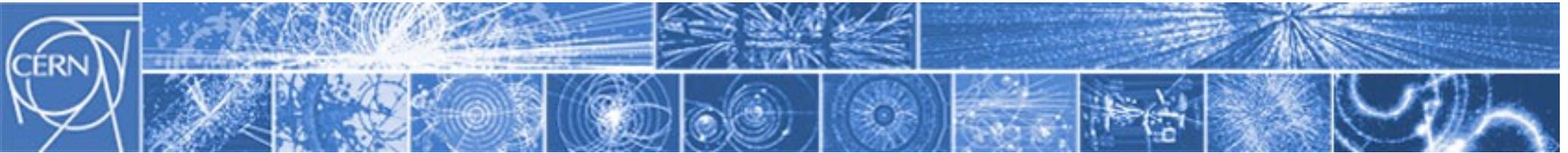
Fisica delle Particelle, Astrofisica & Cosmologia

- Breve storia dell'Universo:
inflazione, BG, BBN, CMB, LSS
- Neutrini (incl. oscillazioni)
- Materia Oscura
- Energia Oscura
- Beyond the Standard Model

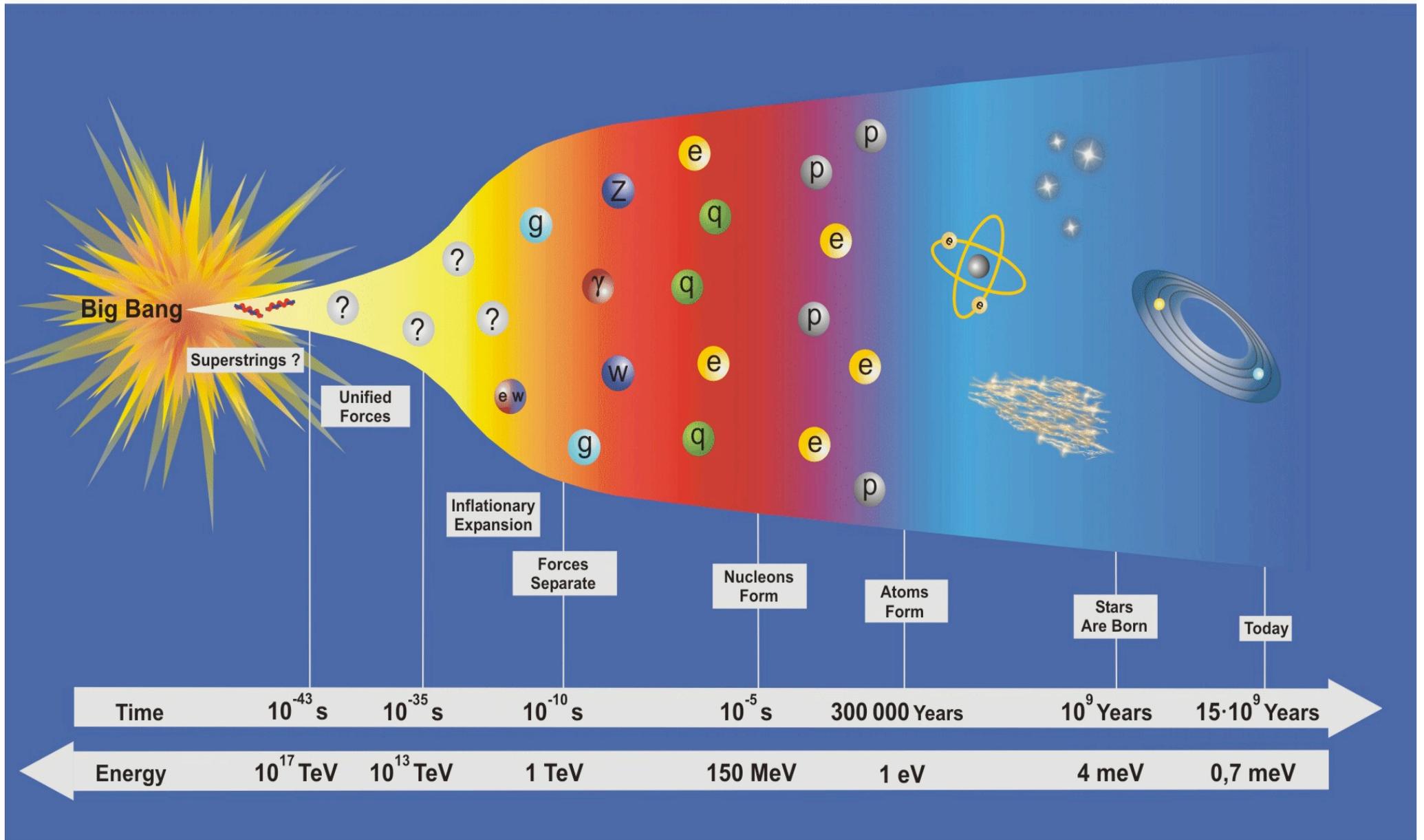
Marco CIRELLI [CNRS LPTHE Jussieu]

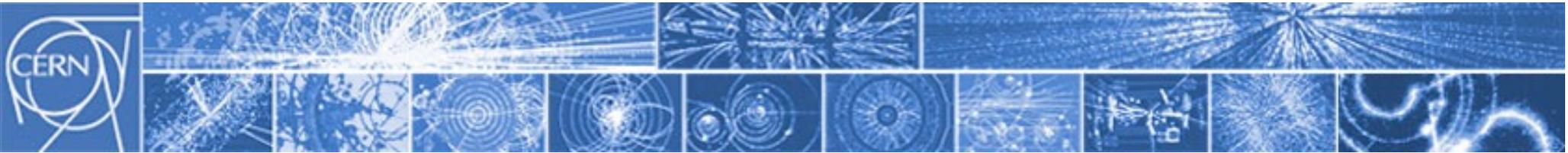


Breve storia dell'Universo



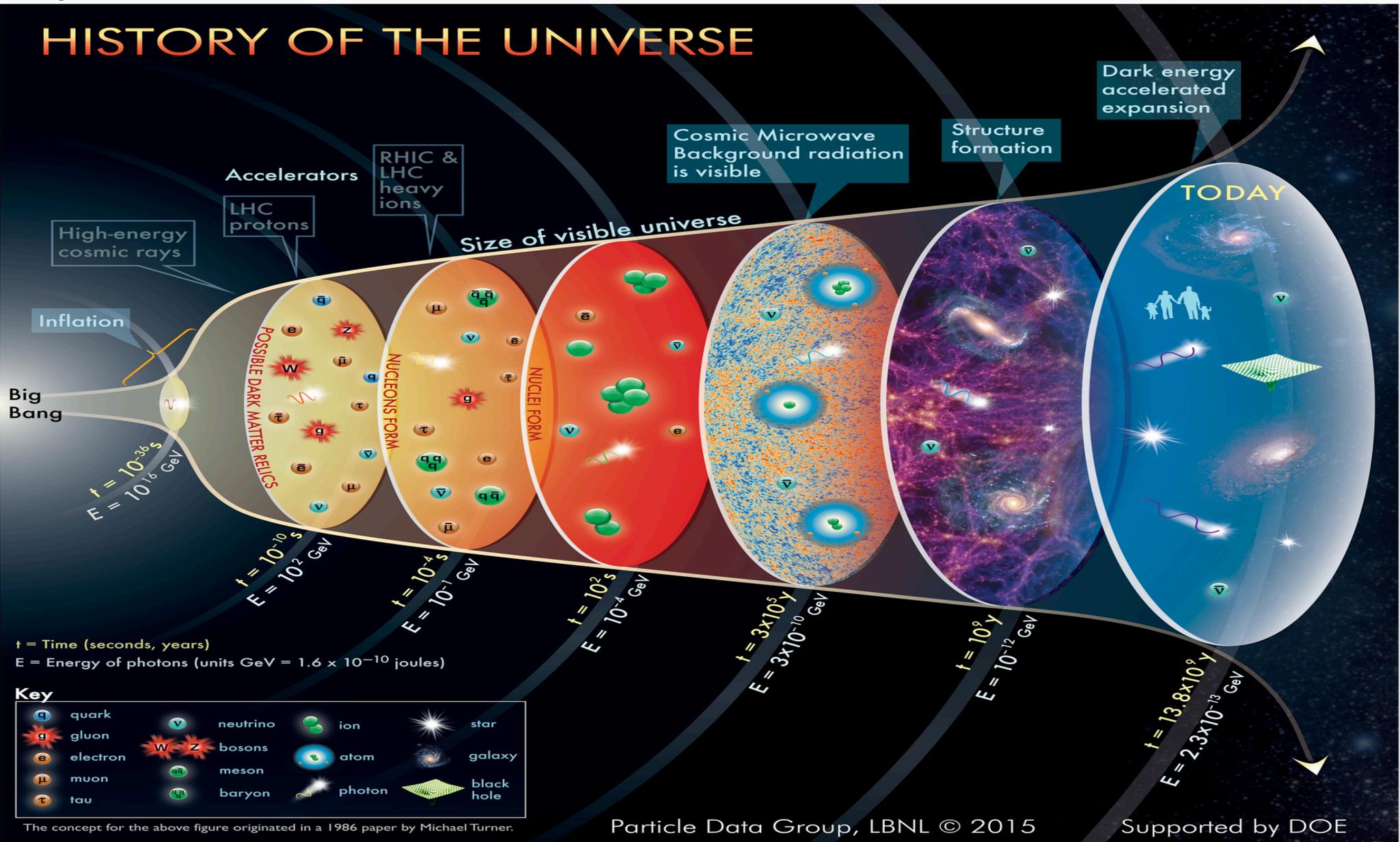
Ripercorrere all'indietro la storia dell'Universo

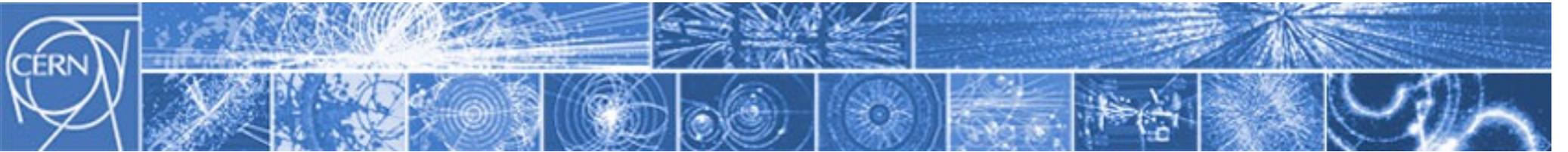




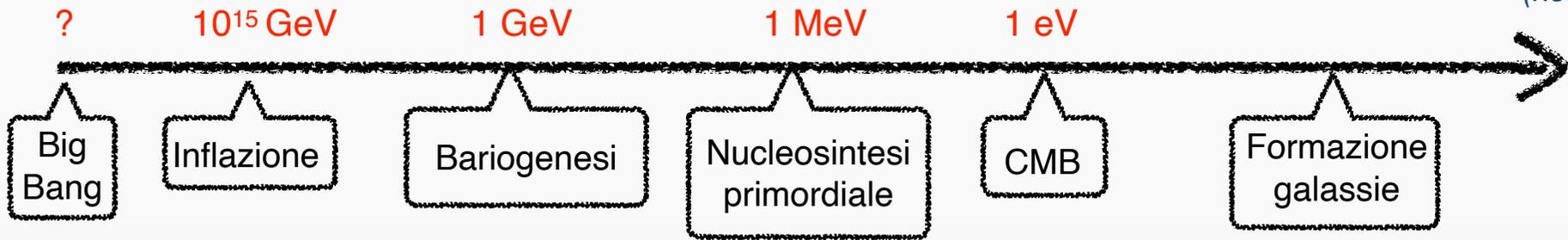
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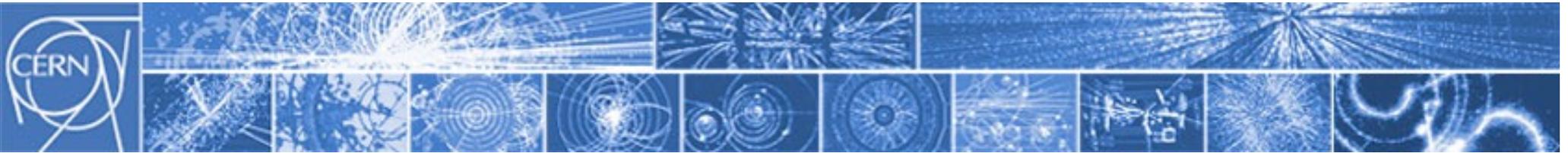
HISTORY OF THE UNIVERSE



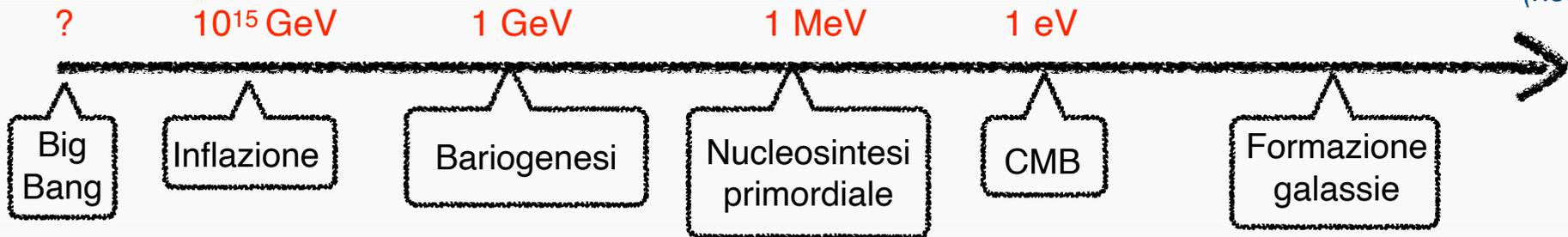


(non in scala!)



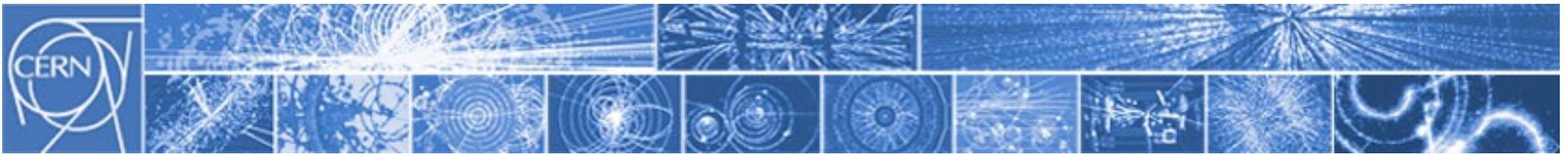


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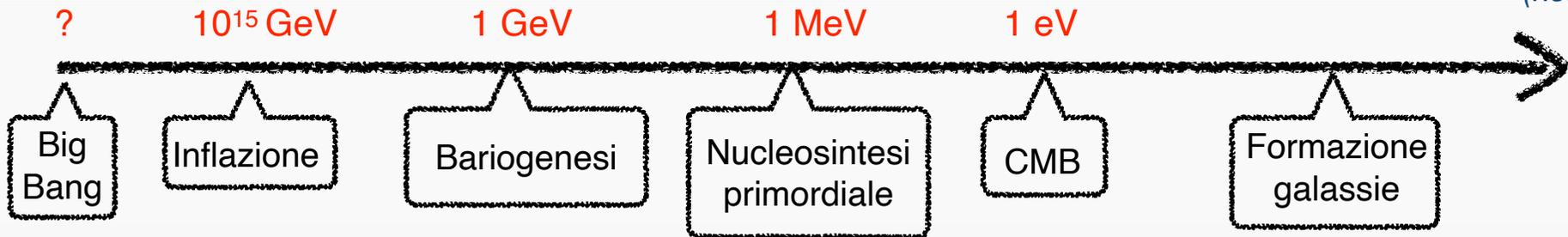


Concetto base:

l'Universo si espande e si raffredda



(non in scala!)

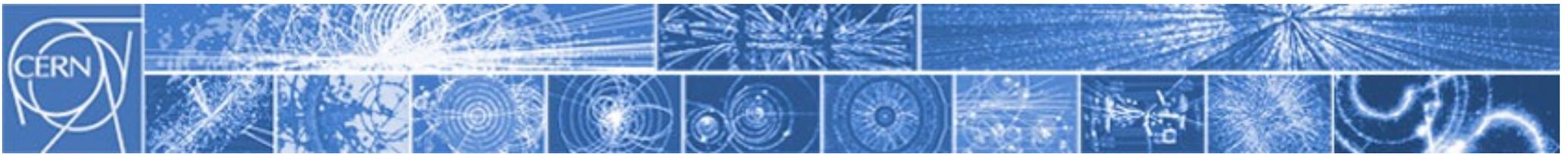


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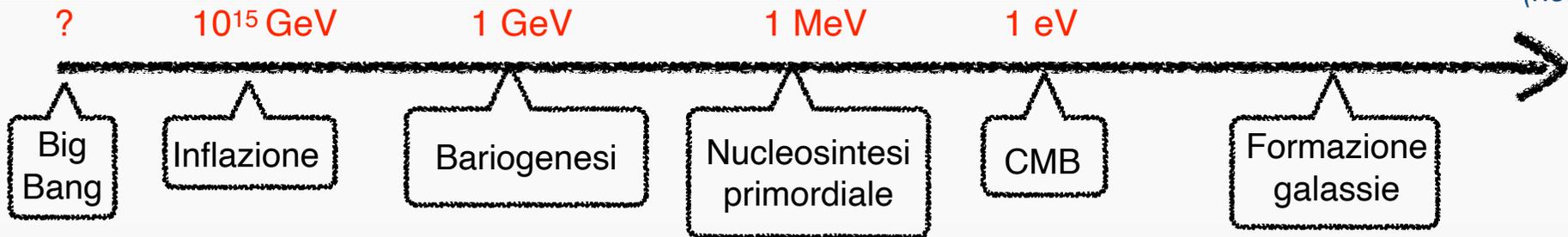
l'Universo si espande e si raffredda

aumenta di volume
come un panettone che lievita

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



(non in scala!)



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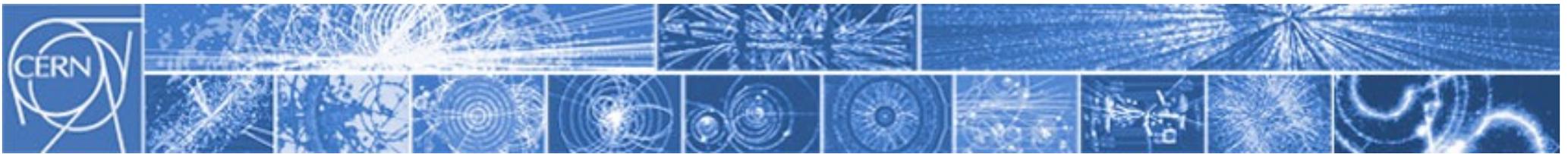
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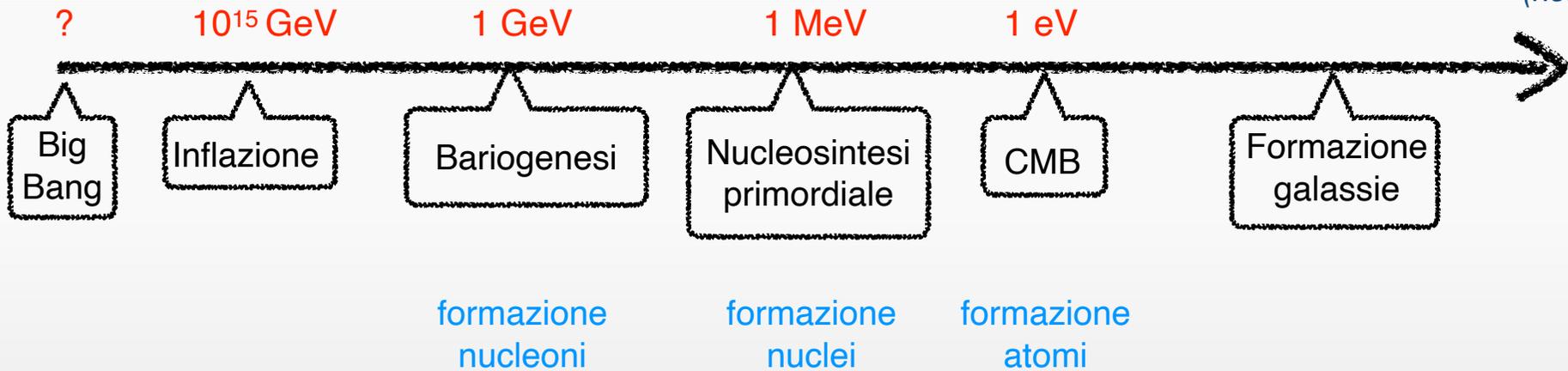
(FAQ: *in* che cosa si espande?)

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:

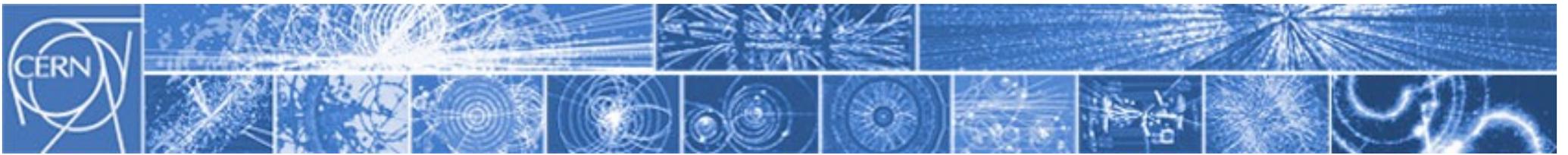
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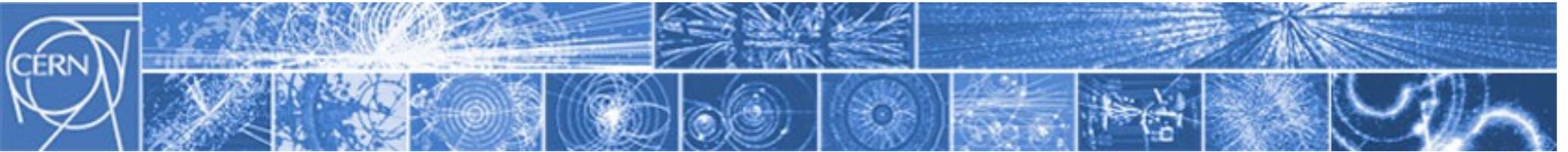
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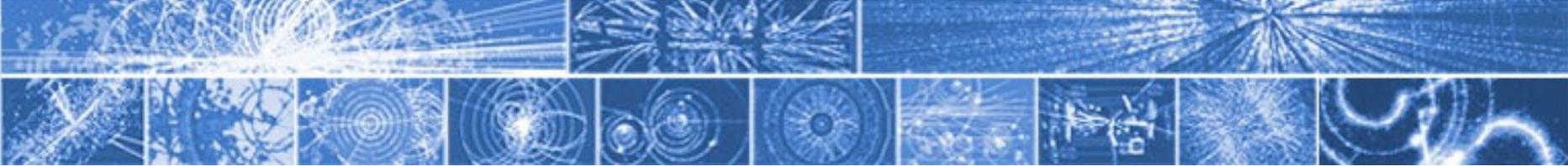
Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)



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

Equazioni di Einstein

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

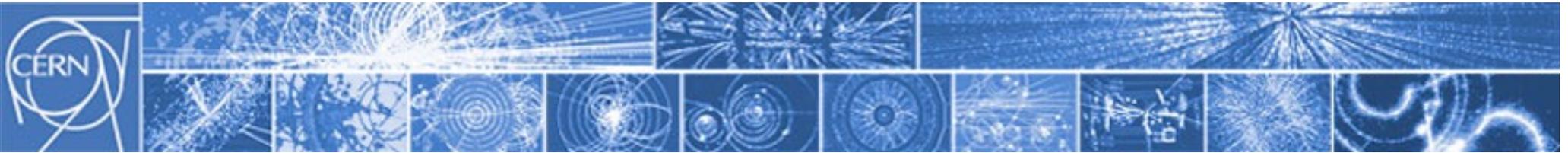


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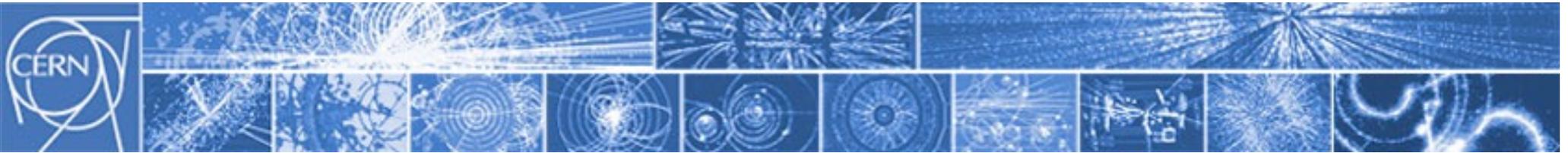
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*geometria dello
spazio-tempo*

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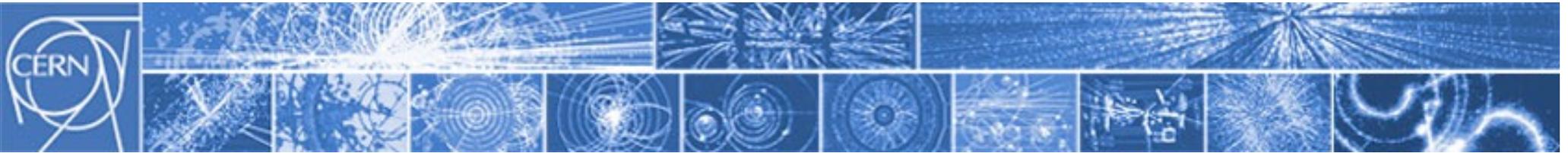
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$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

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

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

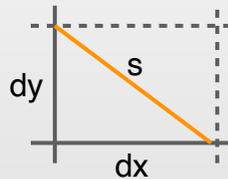
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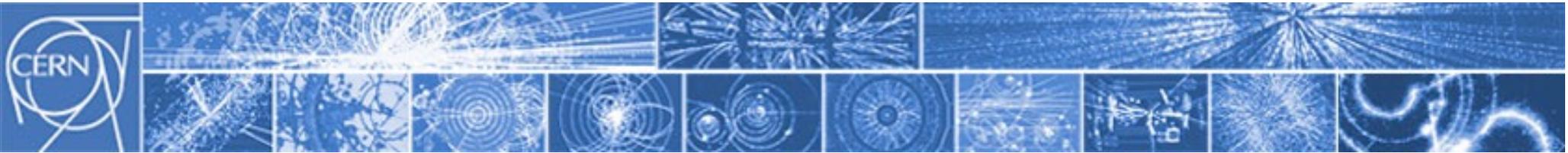
$$s^2 = dx^2 + dy^2$$

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

'Teorema di Pitagora'

geometria dello spazio-tempo

contenuto di materia e energia



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

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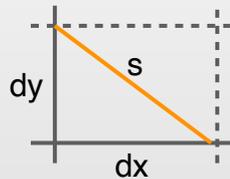
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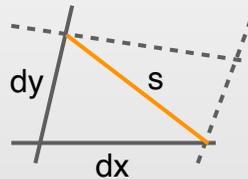
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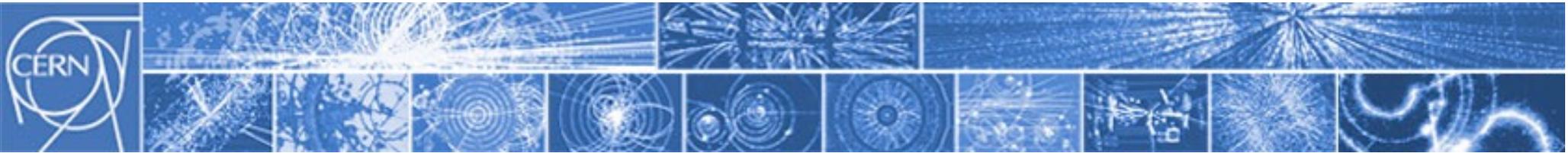
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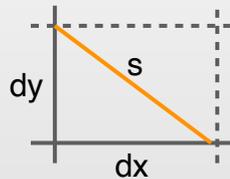
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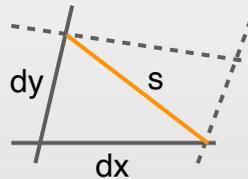
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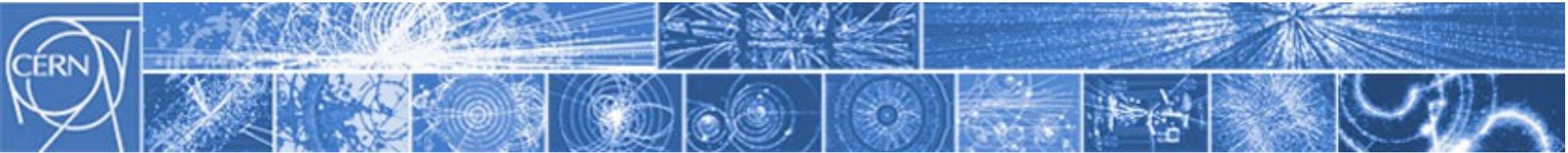
Esempio: metrica di Schwarzschild attorno a un buco nero di massa M:

$$s^2 = \frac{\left(1 - \frac{M}{2R}\right)^2}{\left(1 + \frac{M}{2R}\right)^2} dt^2 - \left(1 + \frac{M}{2R}\right)^4 (dx^2 + dy^2 + dz^2)$$

$$R = \sqrt{x^2 + y^2 + z^2} \quad (\text{in coordinate "isotropiche"})$$

per 'M grande' o 'R piccolo', deviazioni da spazio-tempo piatto

(NB nel seguito guarderemo allo spazio-tempo dell'intero universo, non a effetti locali)



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

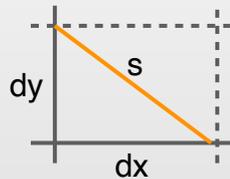
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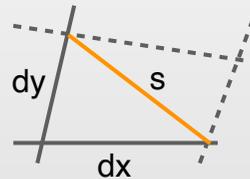
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contenuto di materia e energia

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

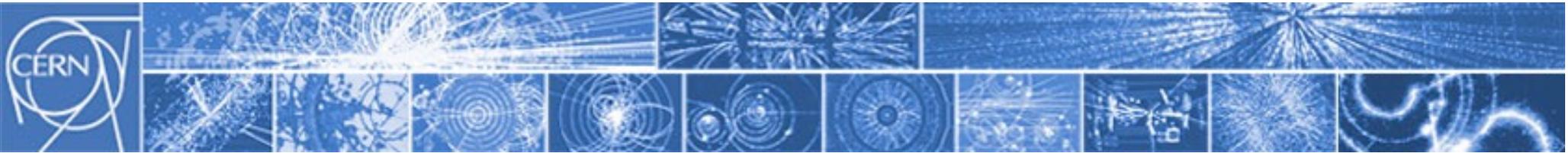
Parametro di Hubble

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

Redshift

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

(a è da intendersi come rapporto, non ha un significato fisico intrinseco)



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

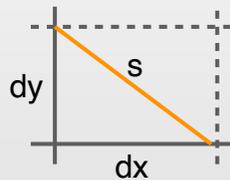
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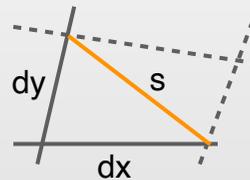
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$$g_{\mu\nu} = \dots$$

contenuto di materia e energia

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

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

(assumendo fluido perfetto)

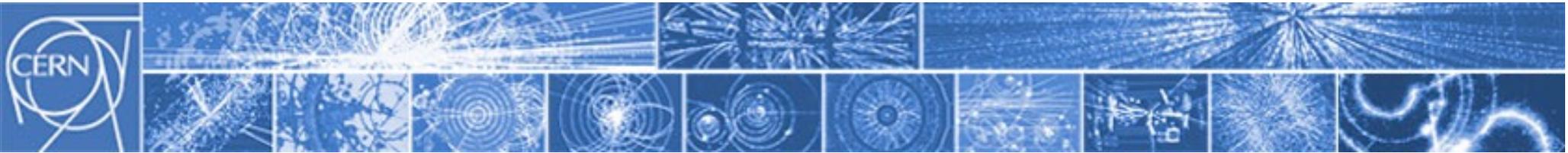
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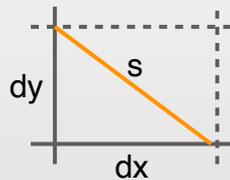
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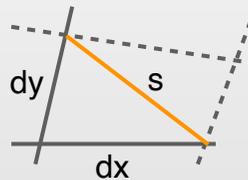
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Equazione di stato $P = w\rho$

'matter'	$P = 0$	$\rho \propto 1/a^3$
'radiation'	$P = \frac{1}{3}\rho$	$\rho \propto 1/a^4$
'vacuum'	$P = -\rho$	$\rho \propto \text{cost}$

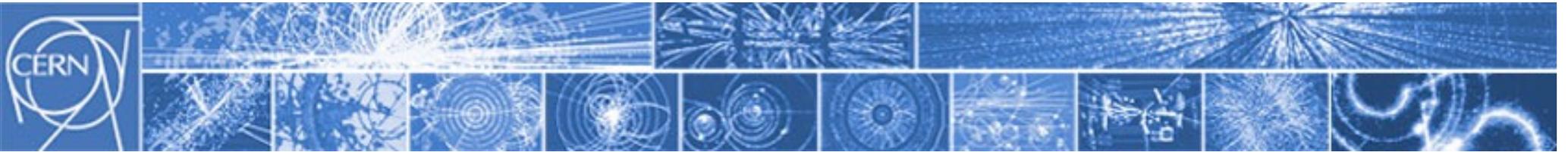
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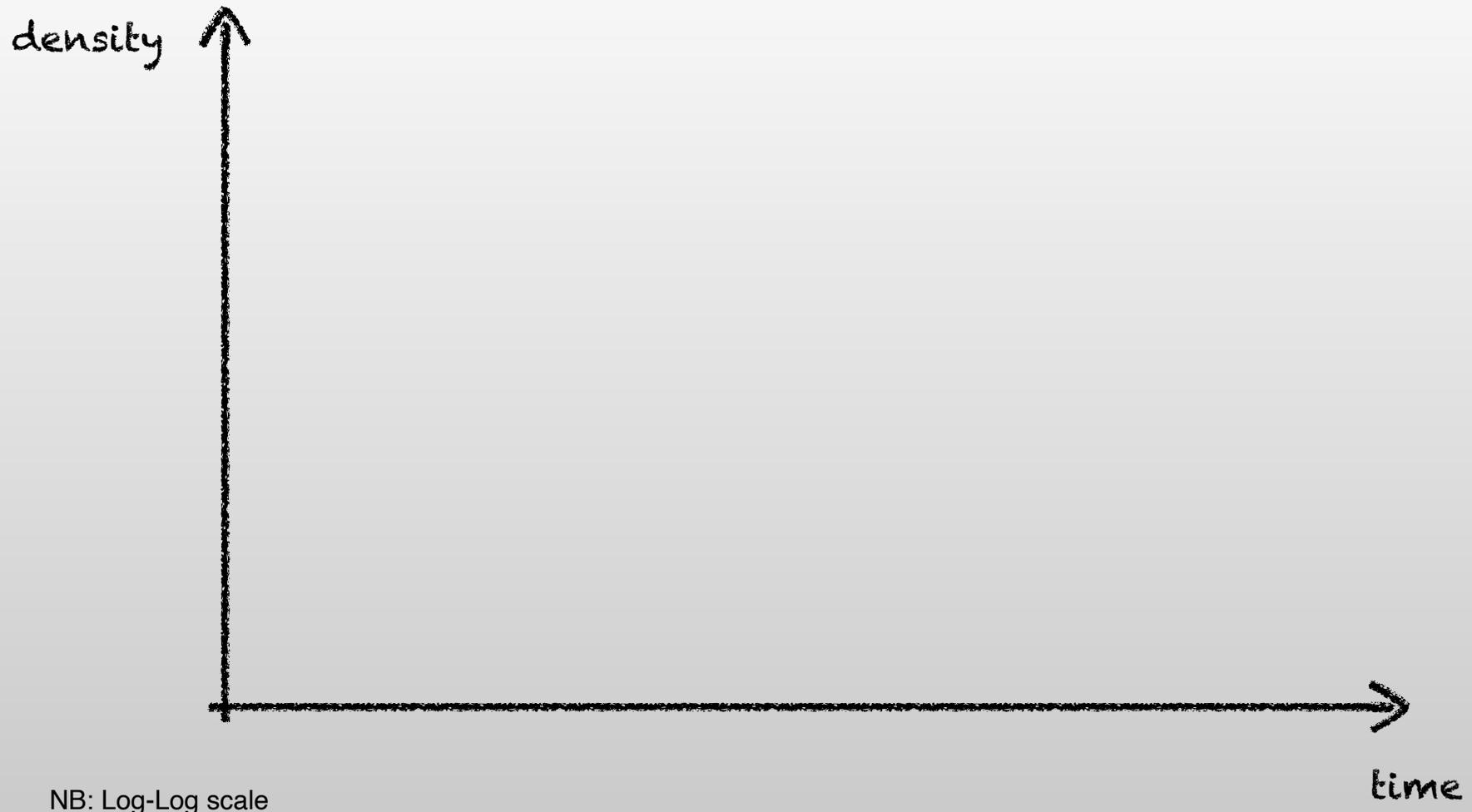
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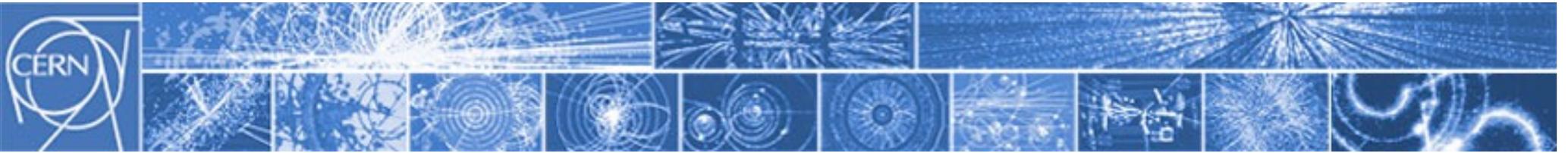
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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

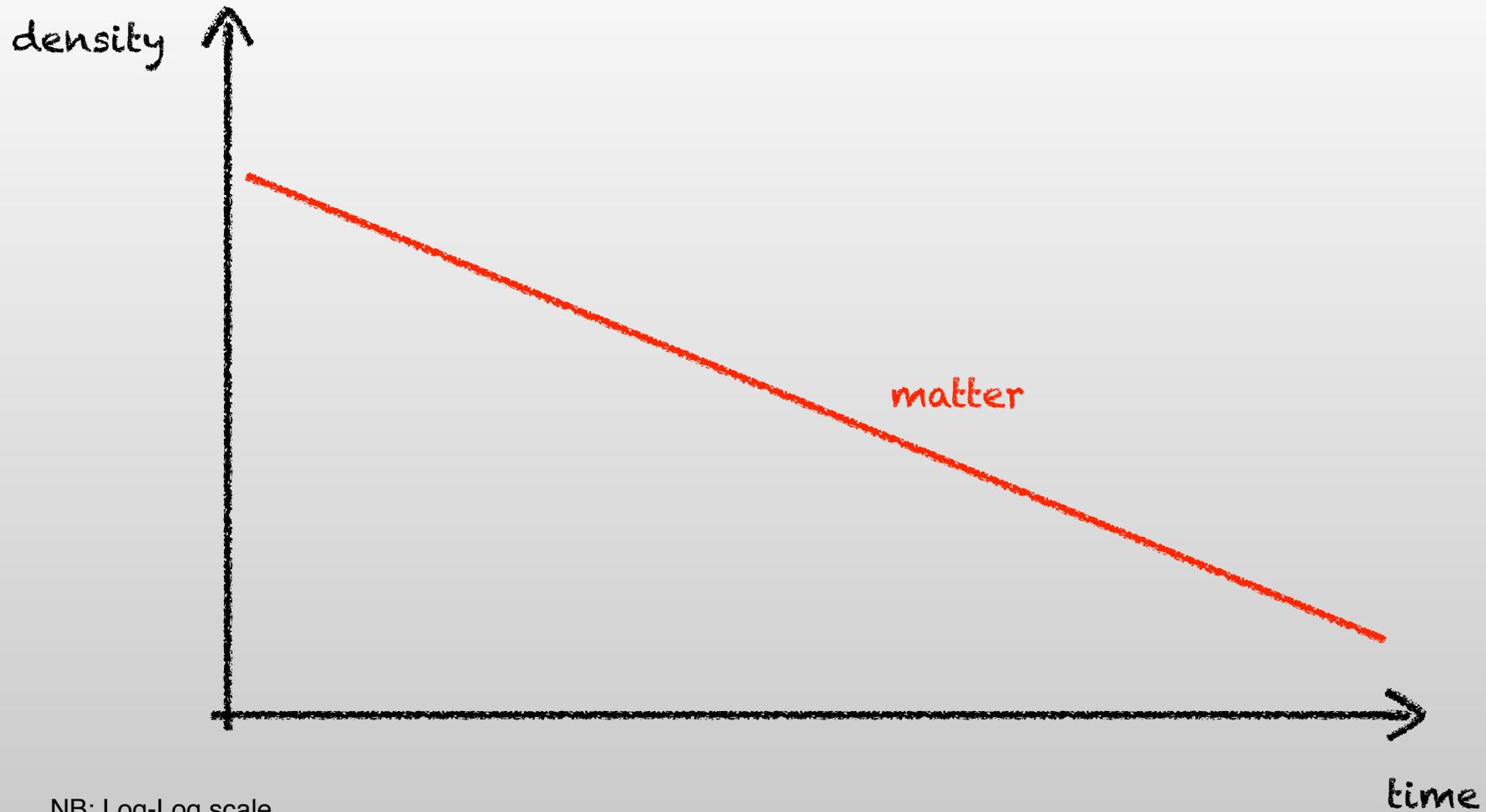
Evoluzione delle componenti dell'Universo

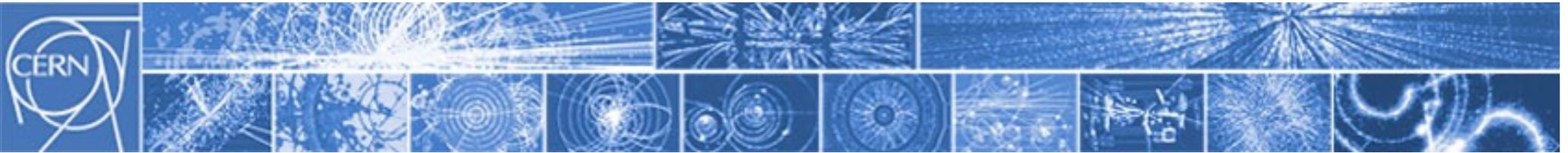




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

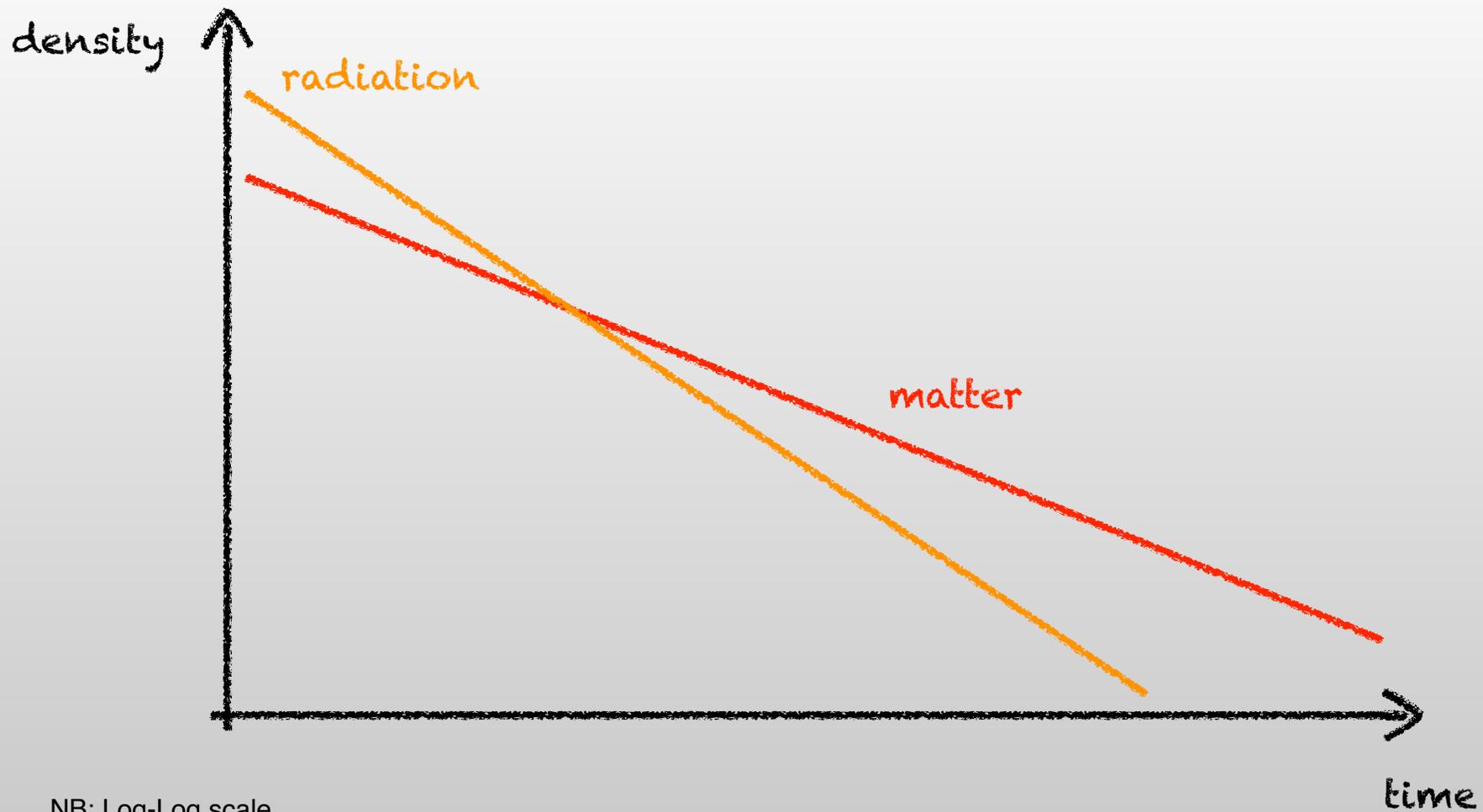
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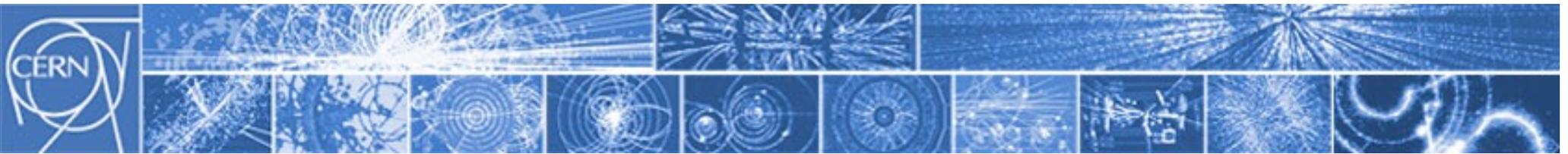




Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

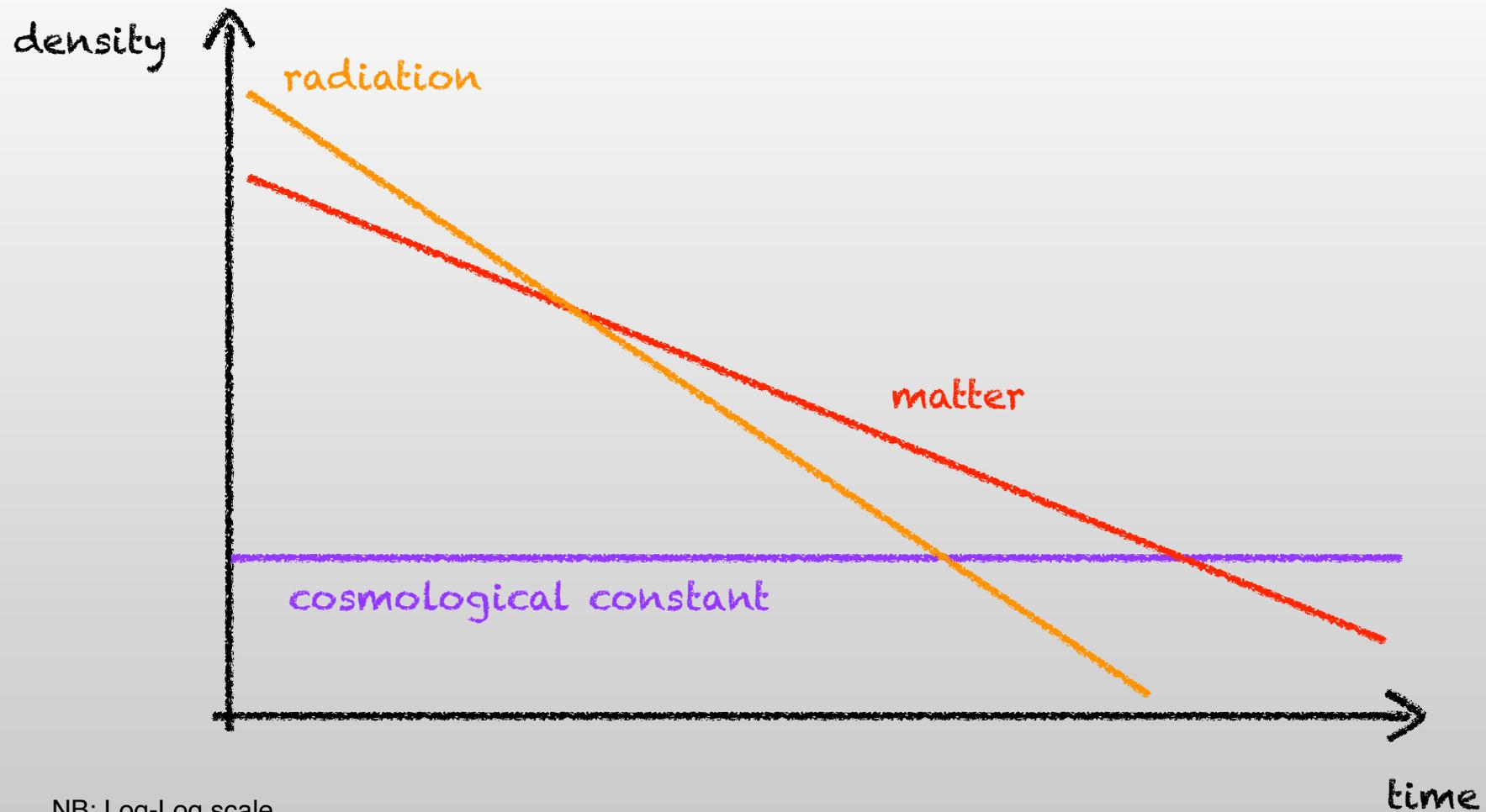
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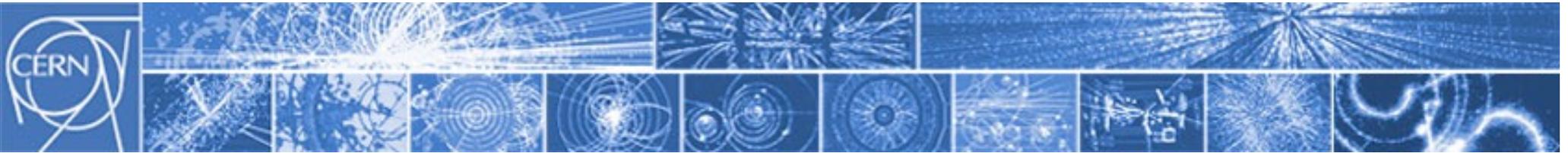


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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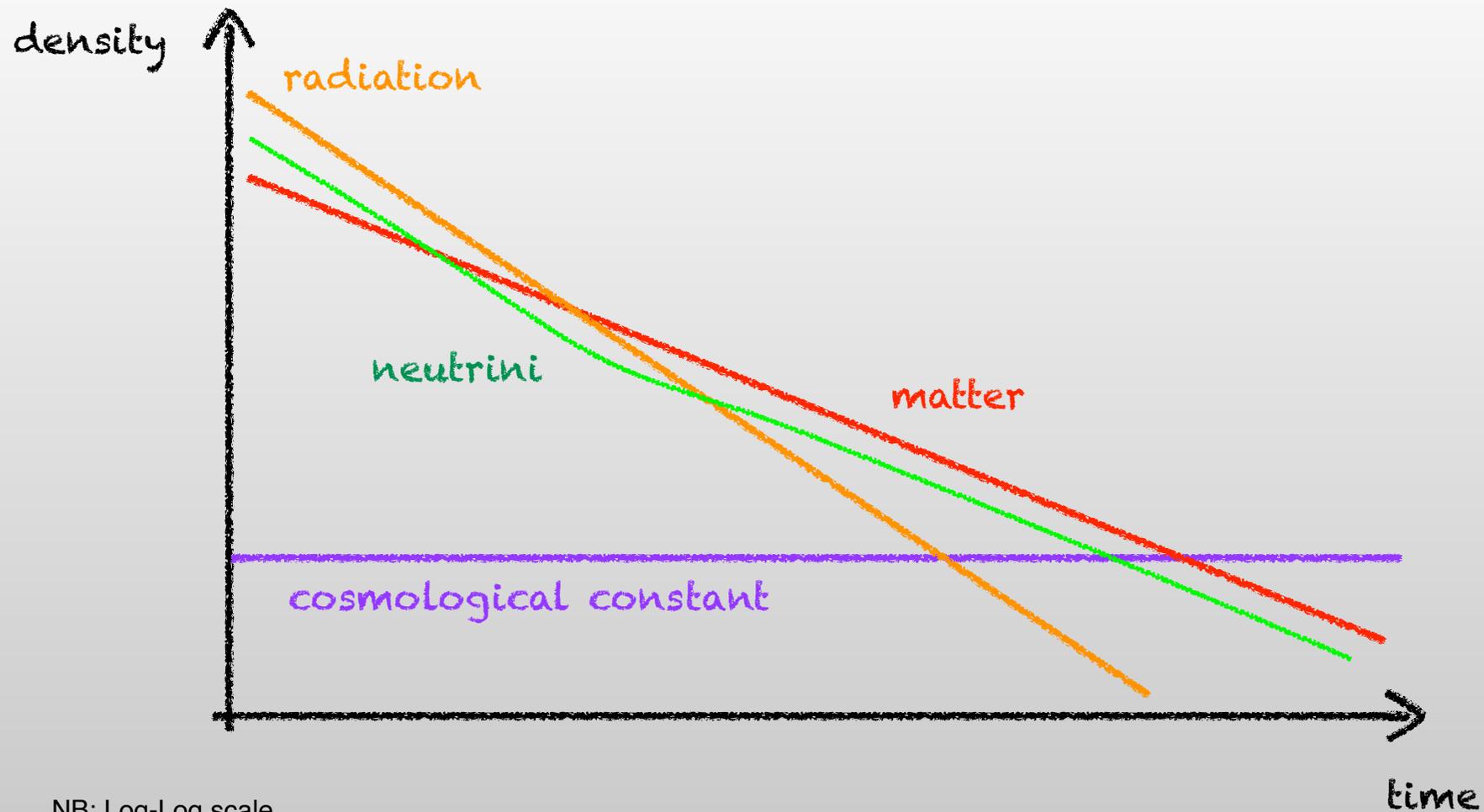


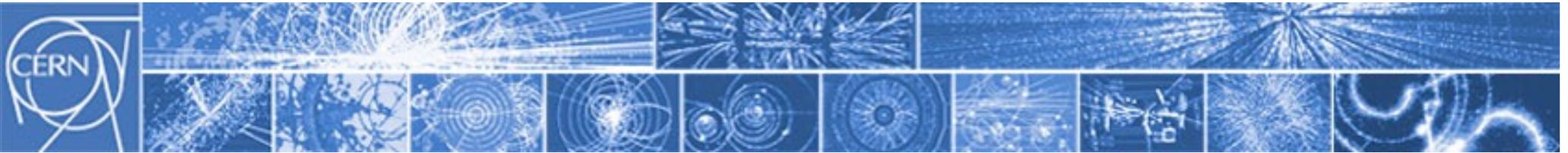
NB: Log-Log scale



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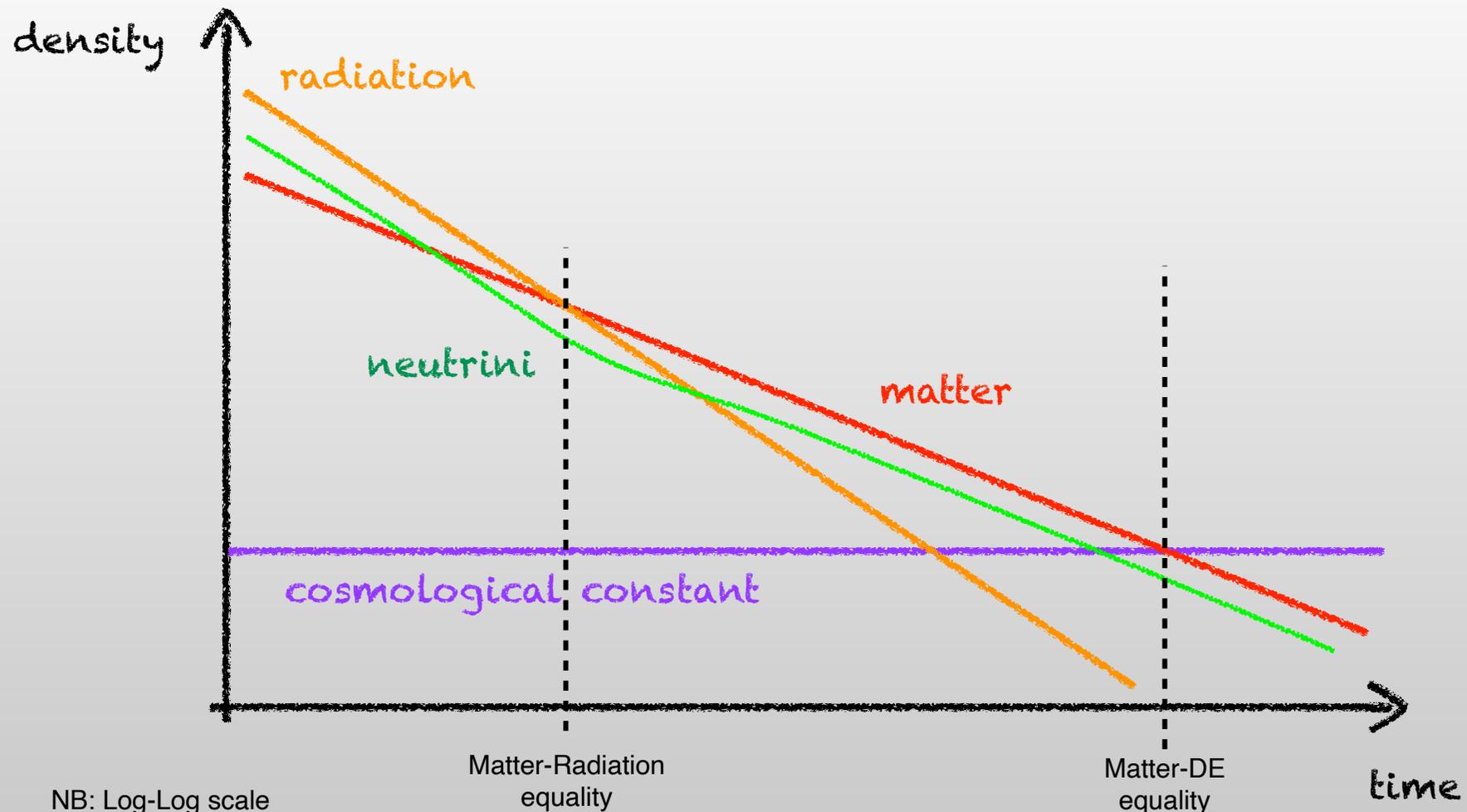
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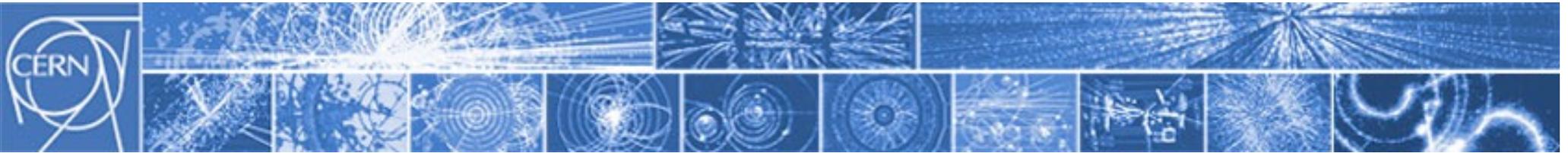




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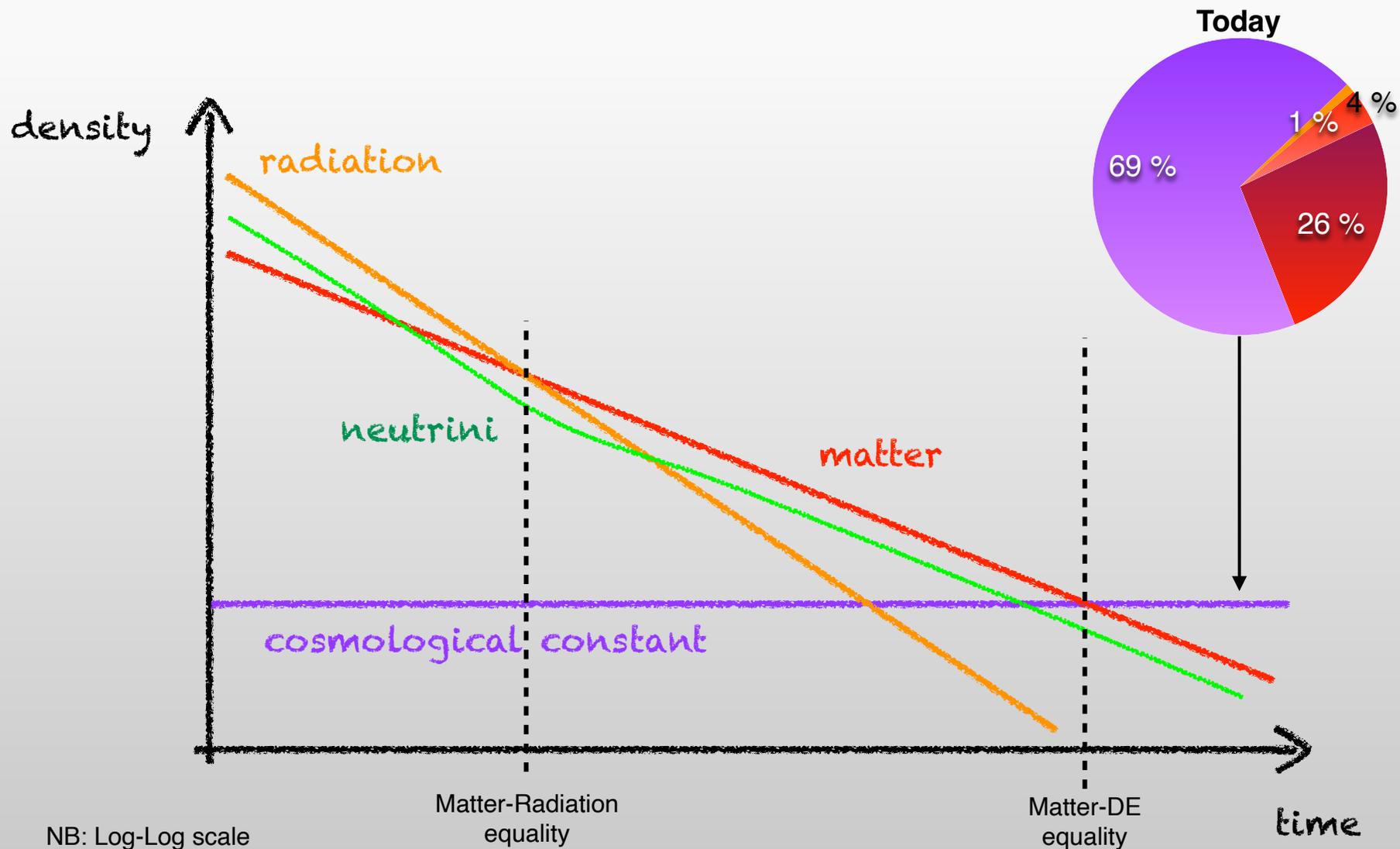
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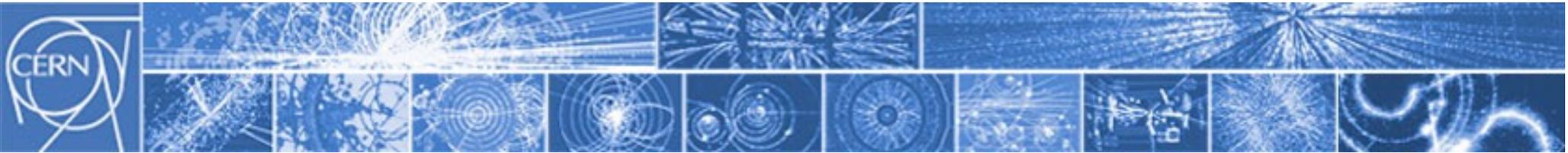




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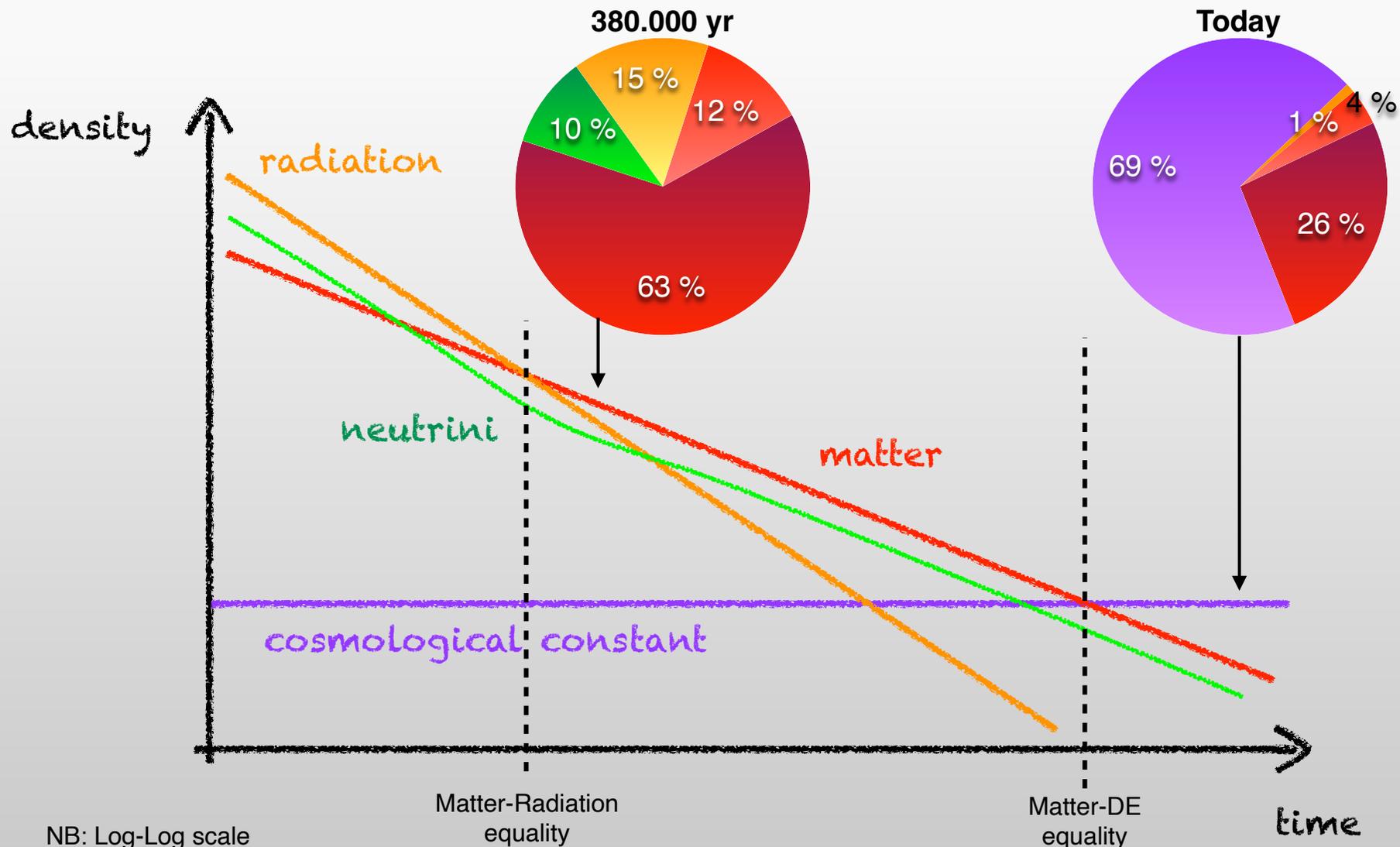
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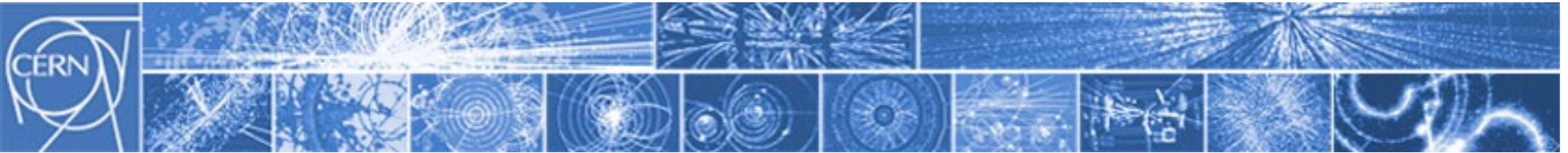


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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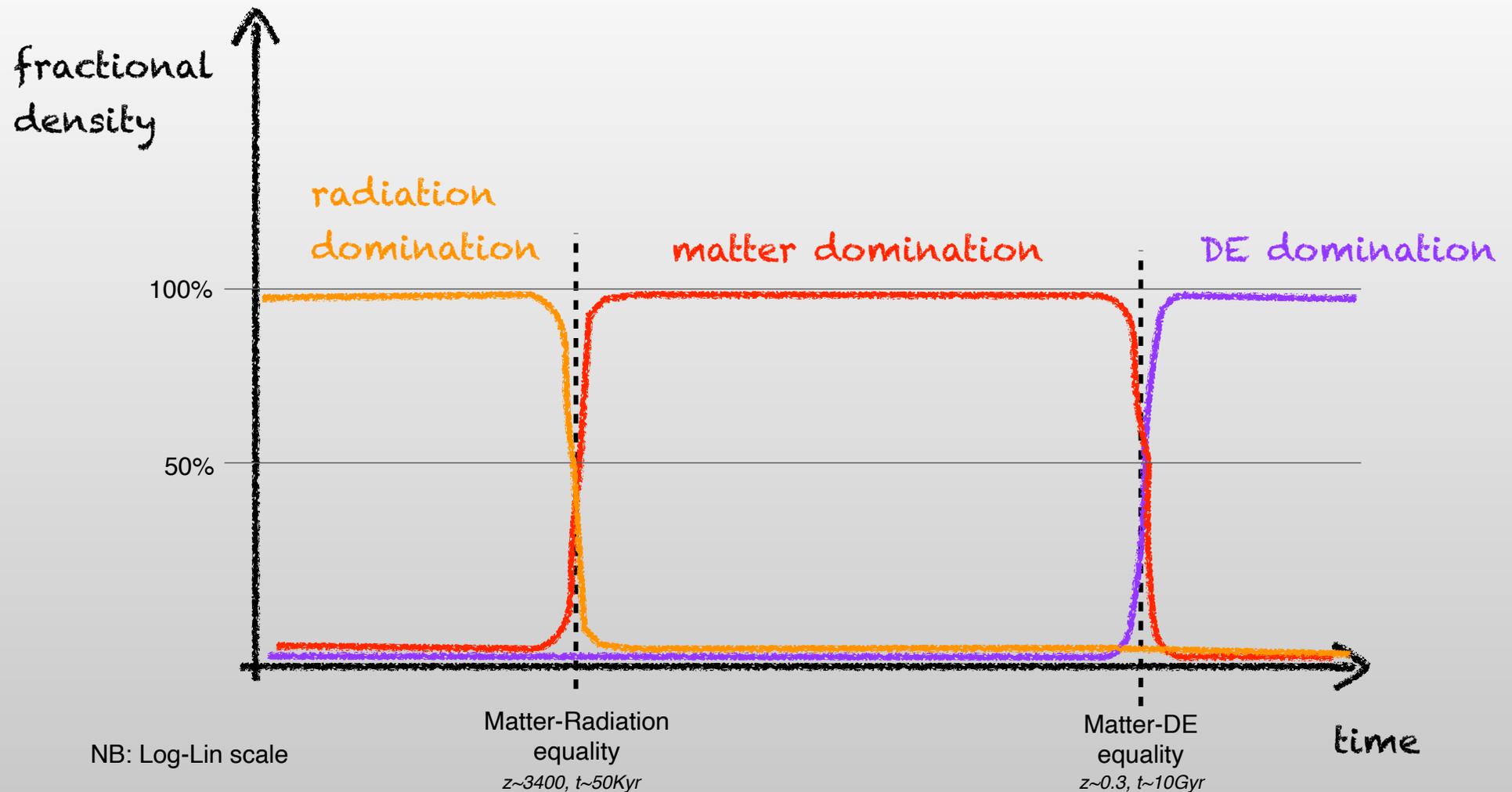


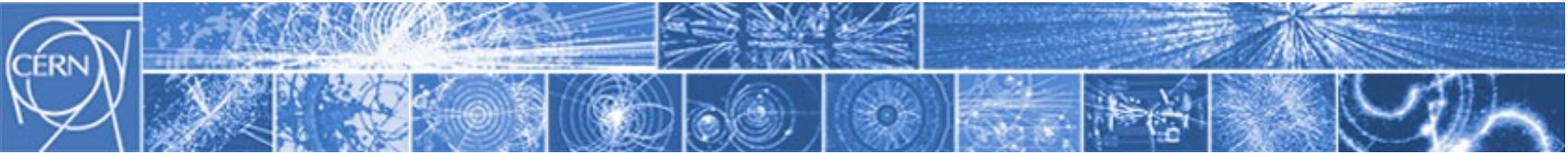
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Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

Evoluzione delle componenti dell'Universo





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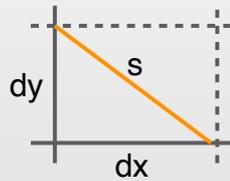
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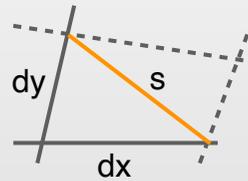
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**omogeneità
isotropia**

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

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

Equazione di stato $P = w\rho$

- 'matter' $P = 0$ $\rho \propto 1/a^3$
- 'radiation' $P = \frac{1}{3}\rho$ $\rho \propto 1/a^4$
- 'vacuum' $P = -\rho$ $\rho \propto \text{cost}$

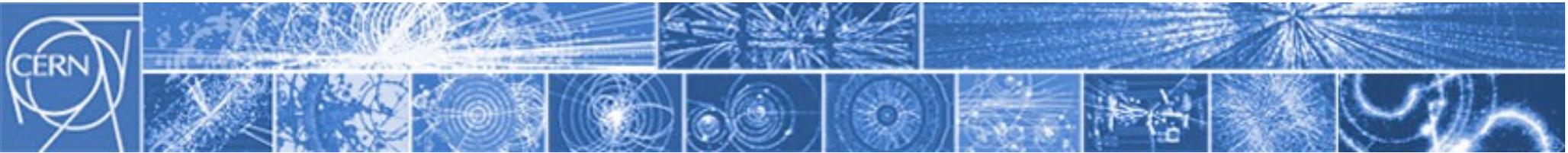
$a(t)$: il fattore di scala (la grandezza) dell'Universo

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

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

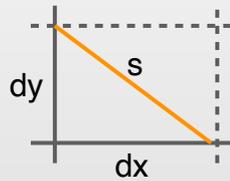
geometria dello spazio-tempo

contenuto di materia e energia

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

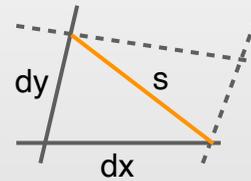
$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

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



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

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



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

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

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

Equazione di stato $P = w\rho$

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

omogeneità isotropia

Parametro di Hubble

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

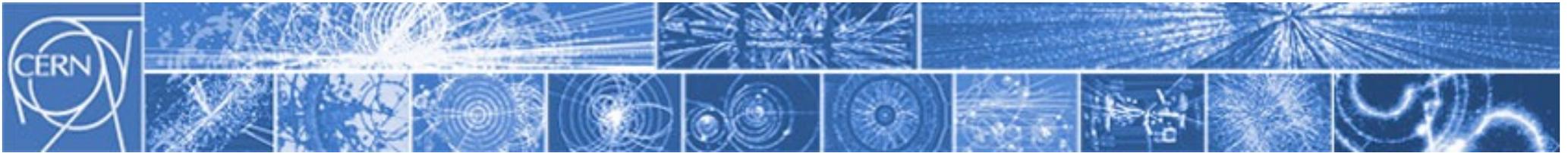
Redshift

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

Equazioni di Friedmann-Robertson-Walker

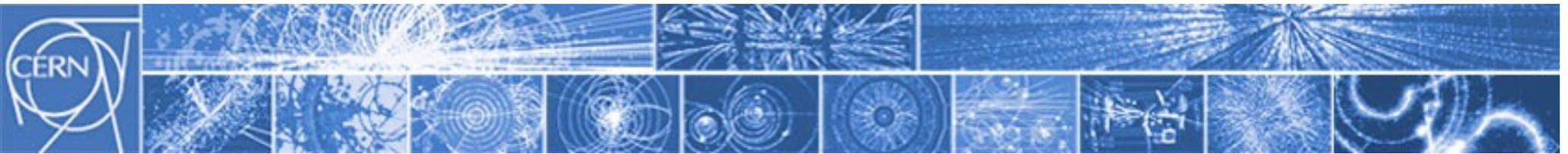
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3} \rho \quad \text{FRW I}$$

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



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

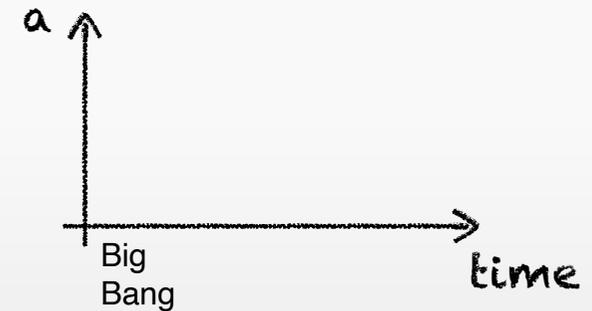
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

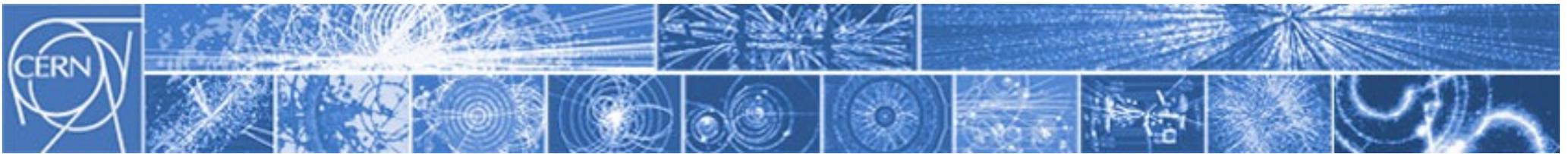


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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

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





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

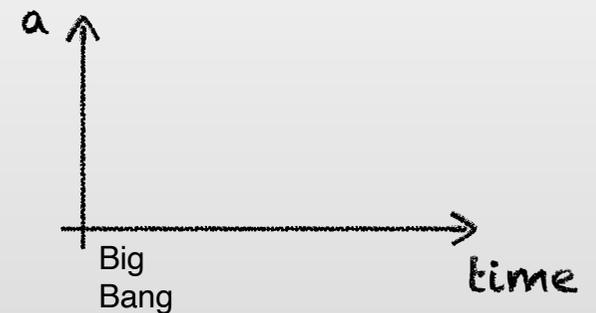
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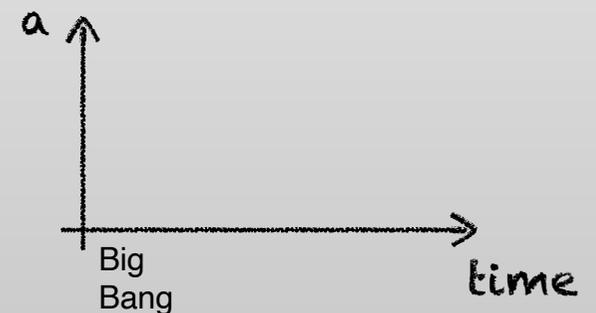
$k < 0$

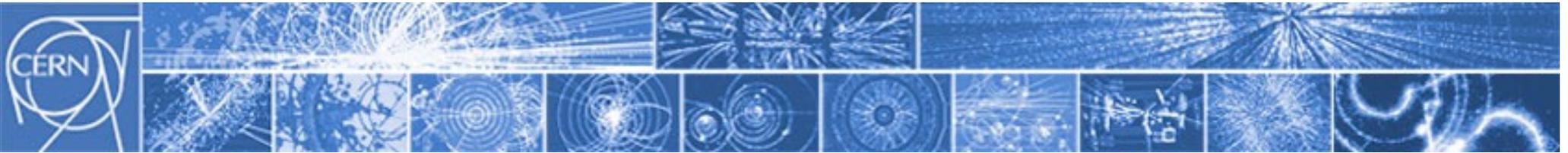


$k = 0$



$k > 0$



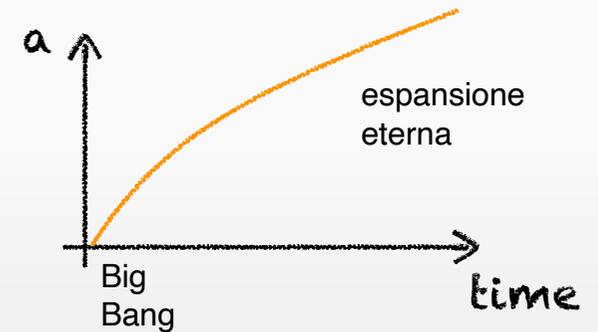


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

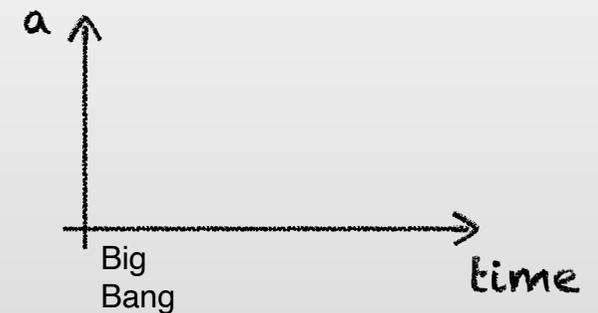
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

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

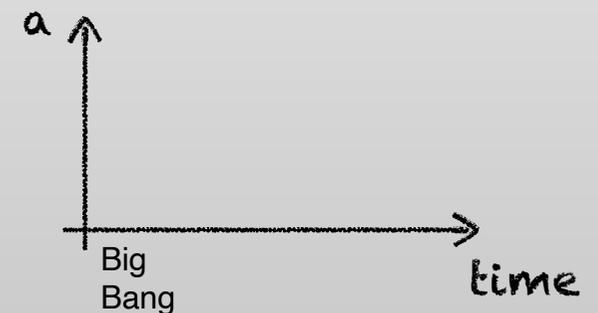
$k < 0$

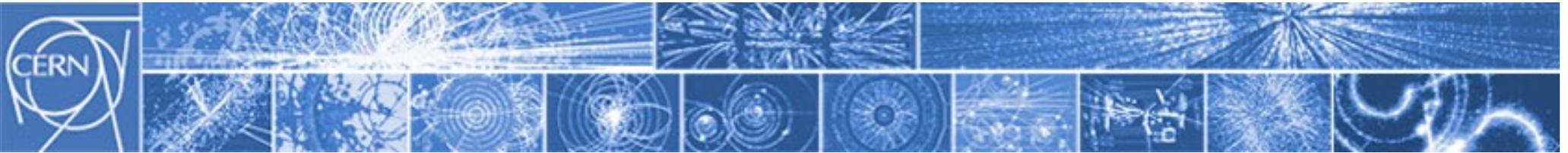


$k = 0$



$k > 0$



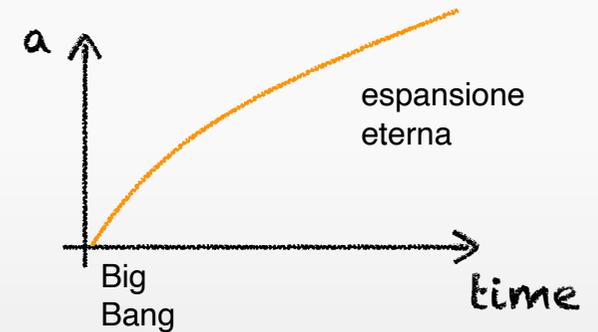


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

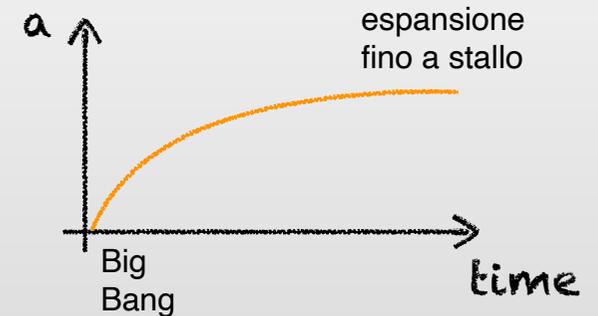
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

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

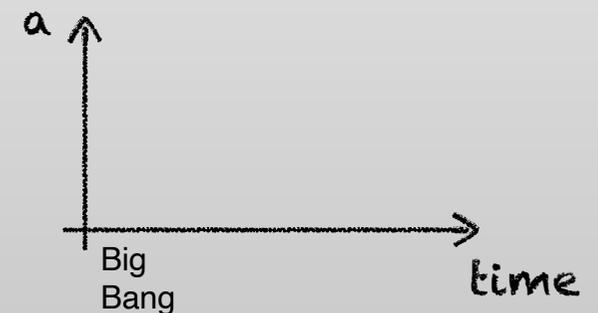
$$k < 0$$

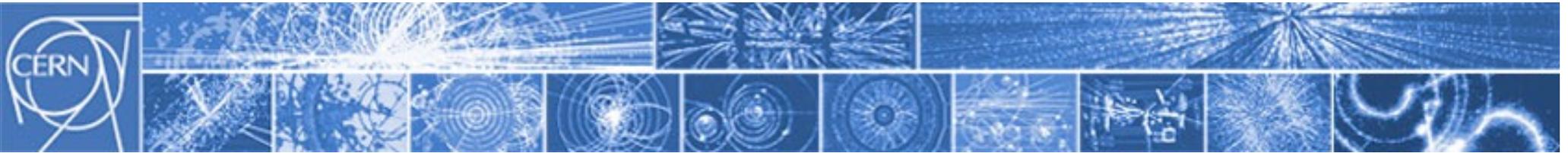


$$k = 0$$



$$k > 0$$



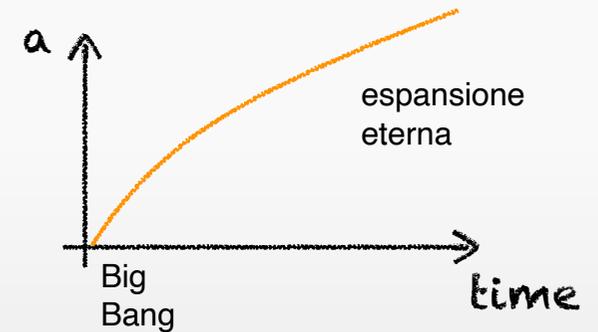


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

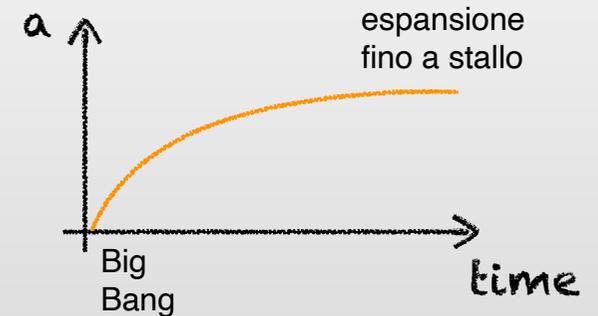
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

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

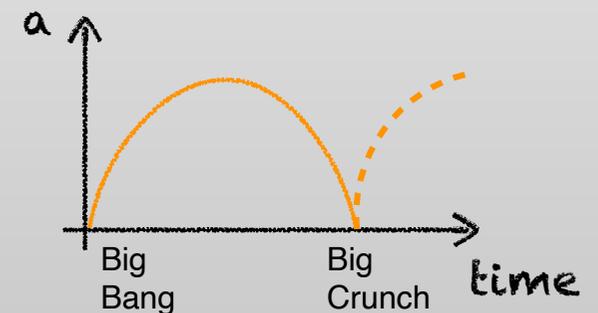
$k < 0$

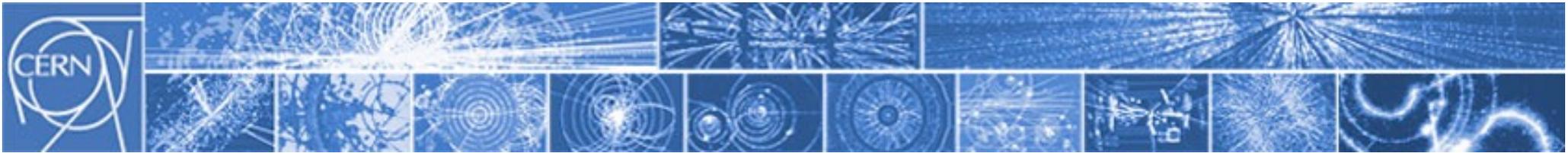


$k = 0$



$k > 0$





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 $a(t)$:

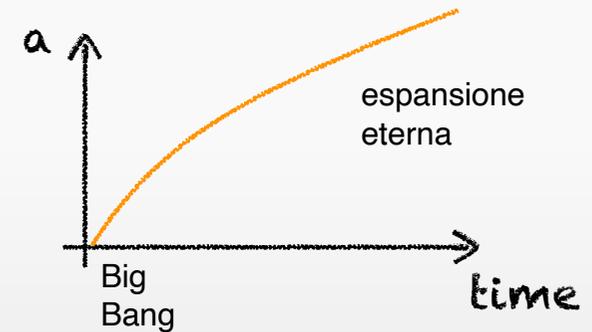
$$\frac{k}{H^2 a^2} = \Omega - 1$$

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

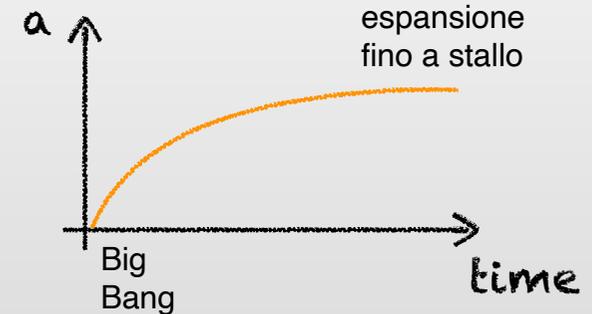
$$\rho_{\text{crit}} = \frac{3H^2}{8\pi G}$$

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

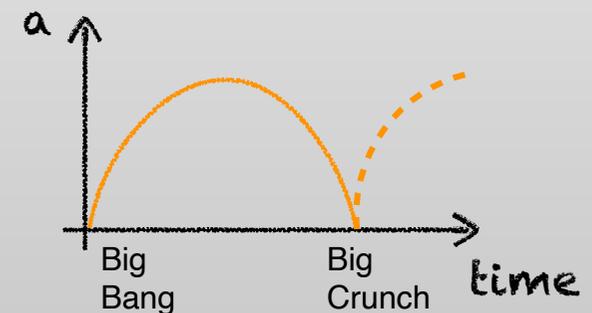
$k < 0$

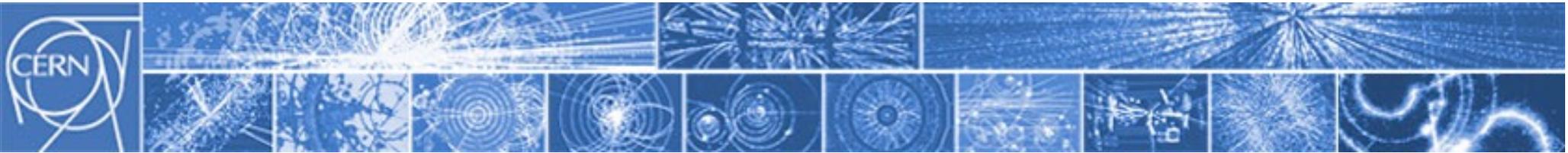


$k = 0$



$k > 0$





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):

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

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

quindi

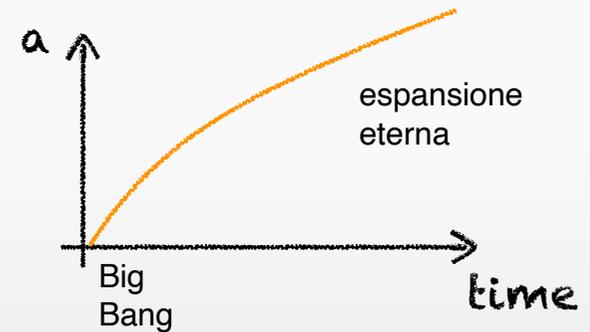
$$\rho < \rho_{\text{crit}} \Rightarrow \Omega < 1 \Rightarrow k < 0$$

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

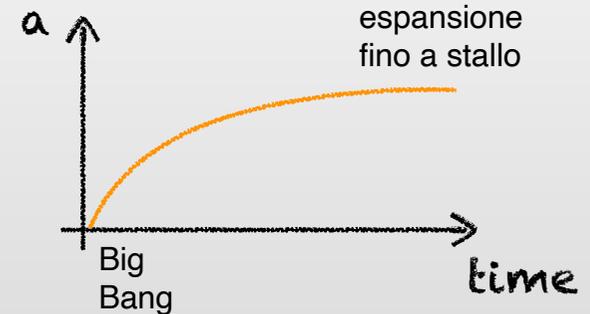
$$\rho > \rho_{\text{crit}} \Rightarrow \Omega > 1 \Rightarrow k > 0$$

pesare l'Universo per determinarne il fato!

$k < 0$



$k = 0$



$k > 0$

