



CERN



SORBONNE
UNIVERSITÉ
CRÉATEURS DE FUTURS
DEPUIS 1257



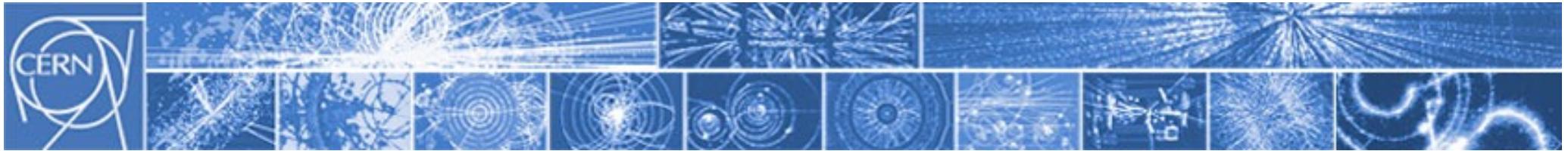
LPTHE
LABORATOIRE DE PHYSIQUE
TÉORIQUE ET HAUTES ÉNERGIES



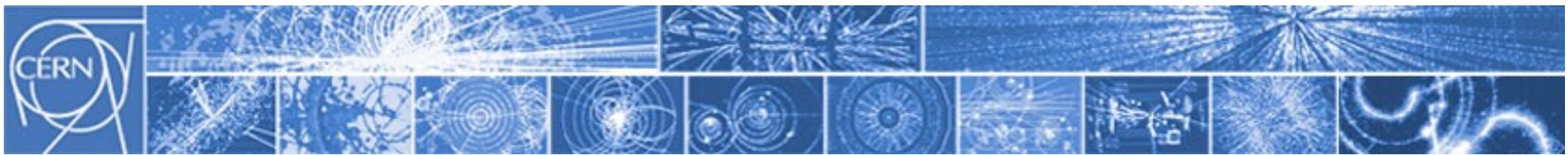
Fisica delle Particelle, Astrofisica & Cosmologia

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

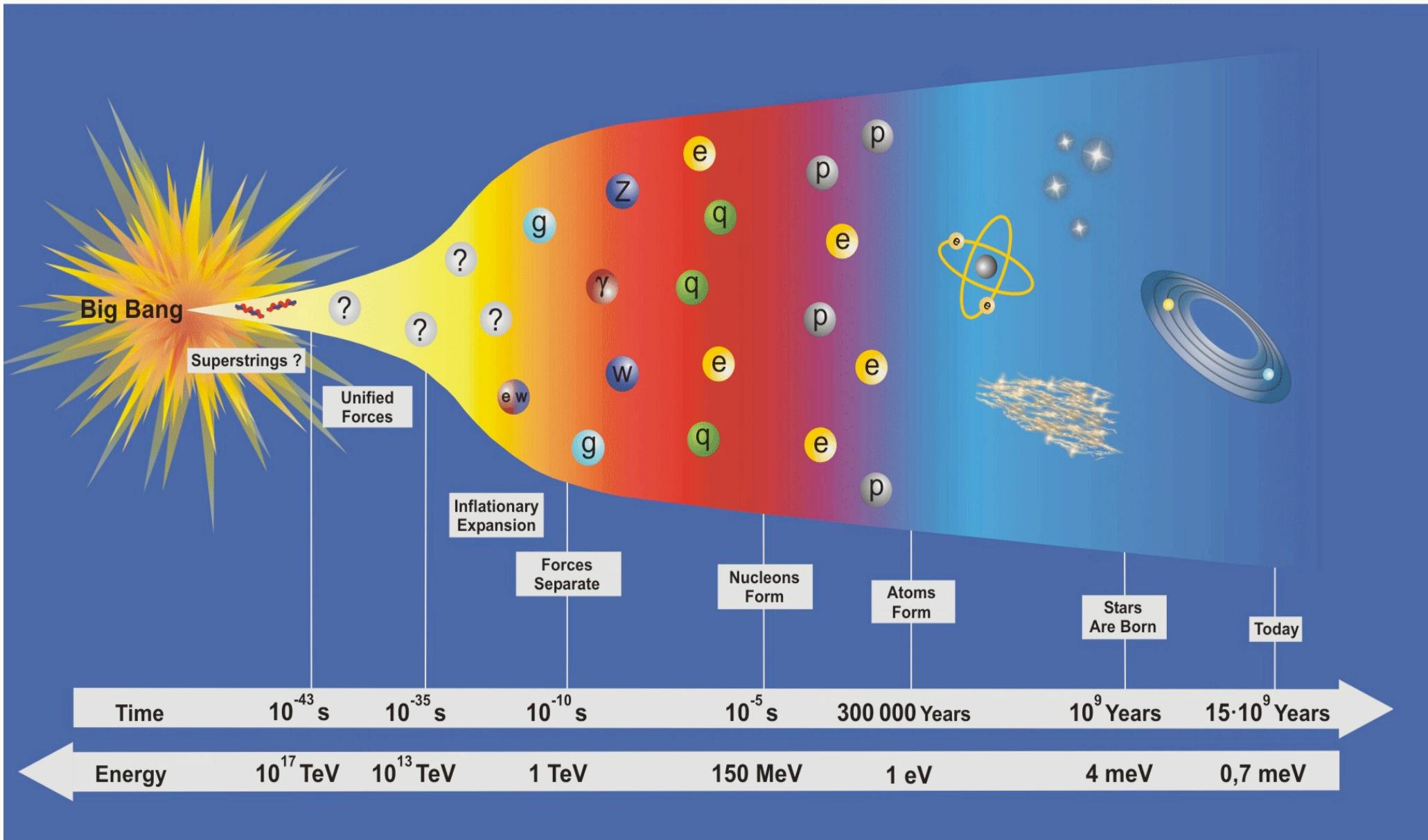
Marco CIRELLI [CNRS LPTHE Jussieu]

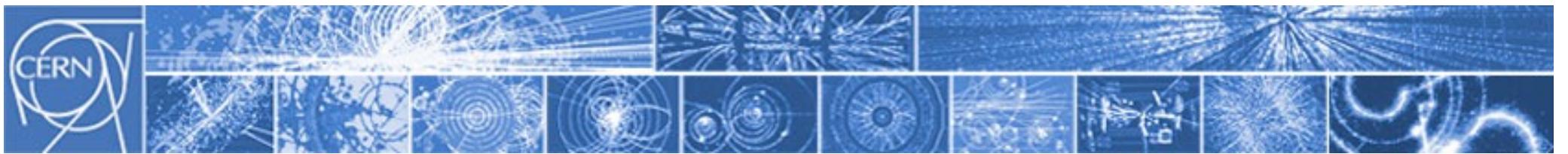


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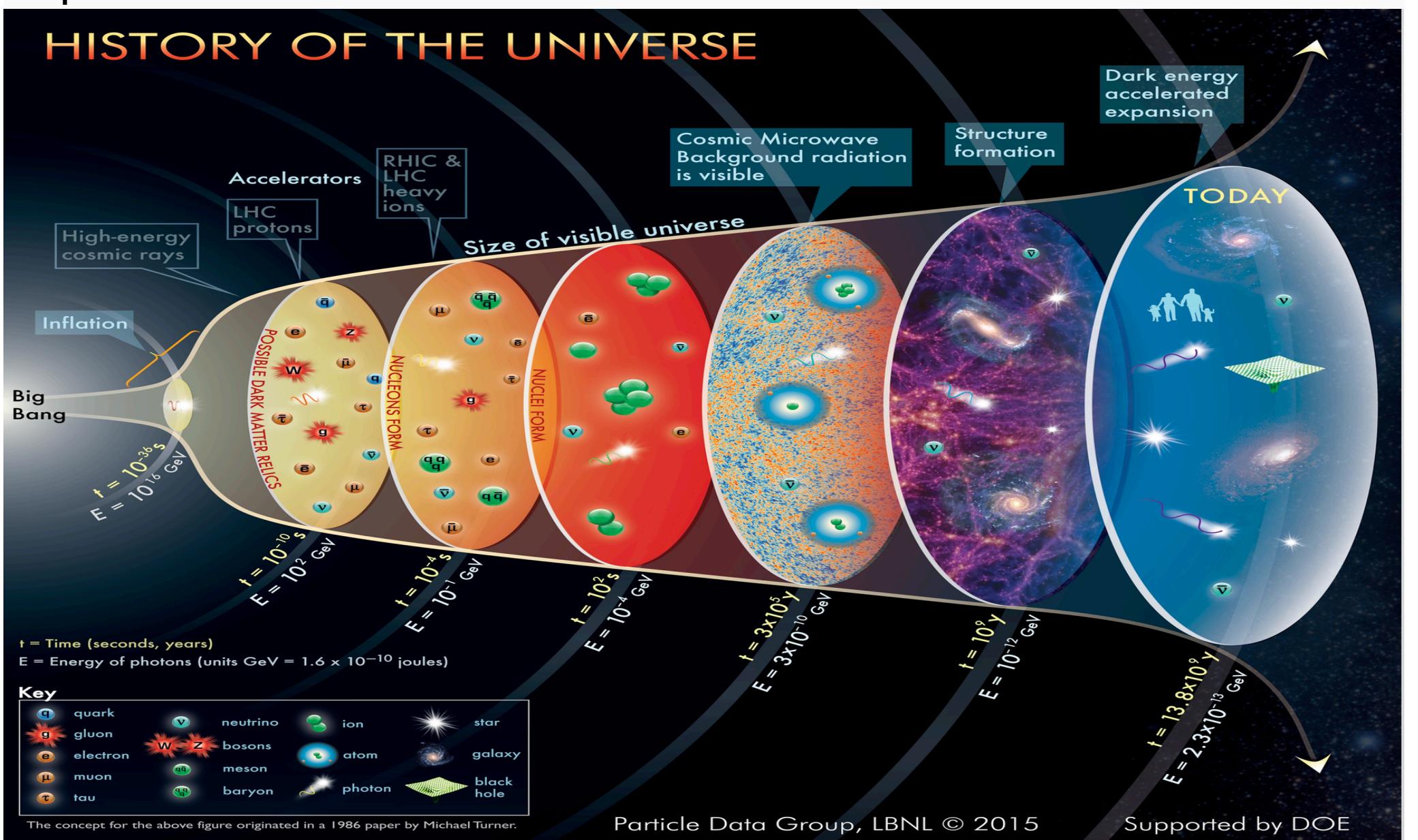


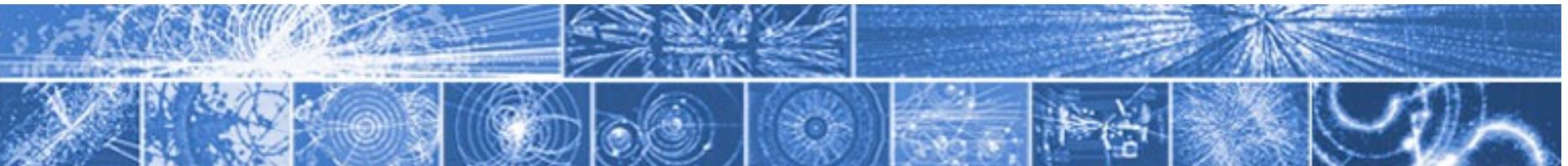
Ripercorrere all'indietro la storia dell'Universo





Ripercorrere all'indietro la storia dell'Universo





(non in scala!)

?

10^{15} GeV

1 GeV

1 MeV

1 eV

Big Bang

Inflazione

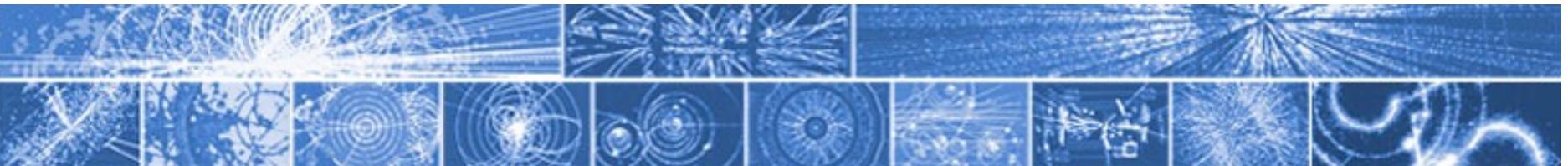
Bariogenesi

Nucleosintesi primordiale

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Formazione galassie





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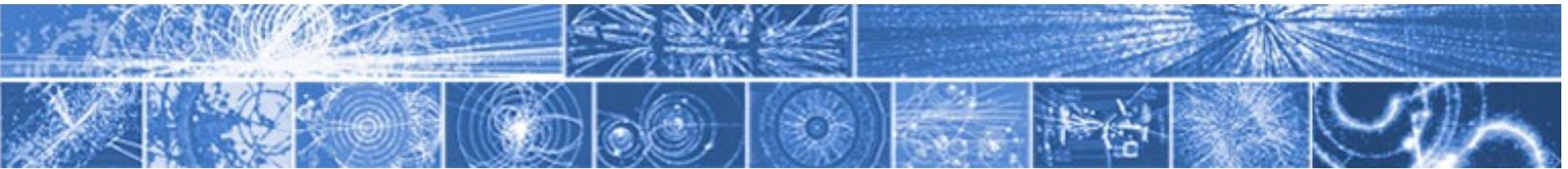
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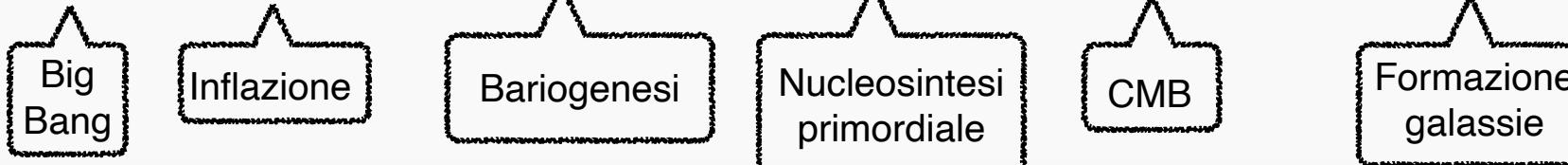
Concetto base:

I'Universo **si espande e si raffredda**



(non in scala!)

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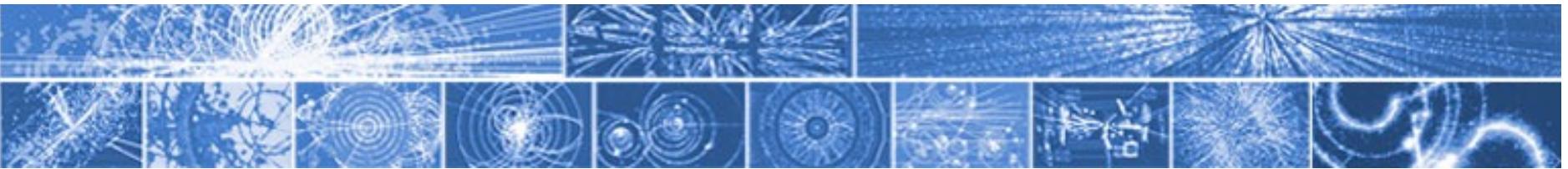


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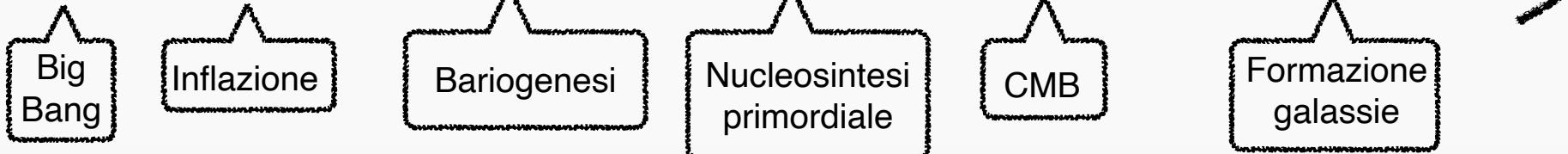
aumenta di volume
come un panettone che lievita

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



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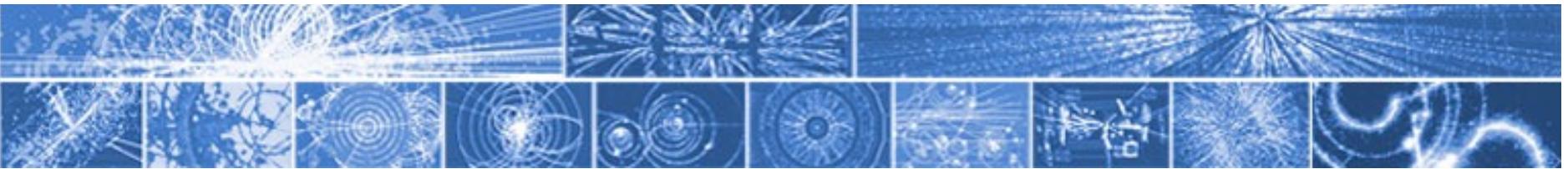
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a **alte T**, la materia si **dissocia**
nei costituenti fondamentali

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



(non in scala!)

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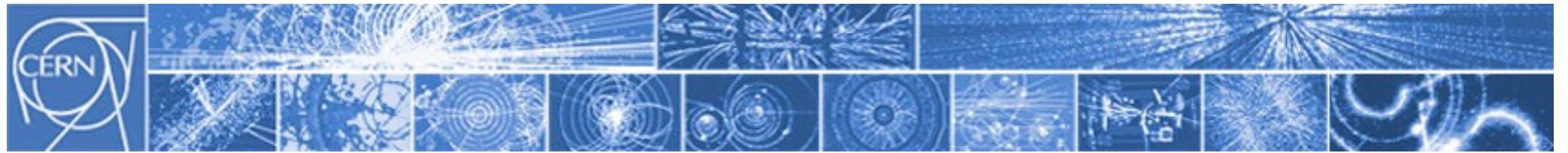
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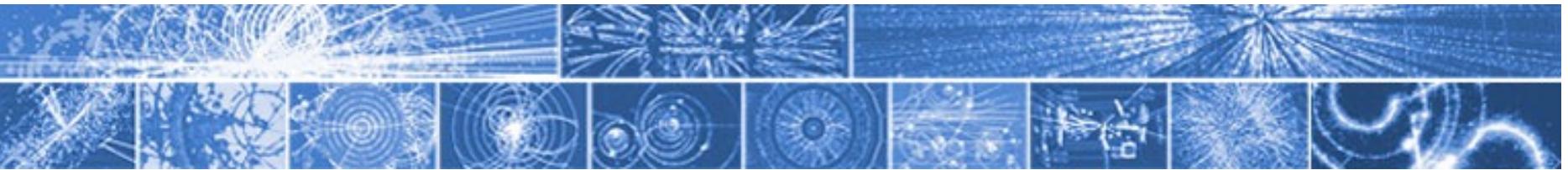
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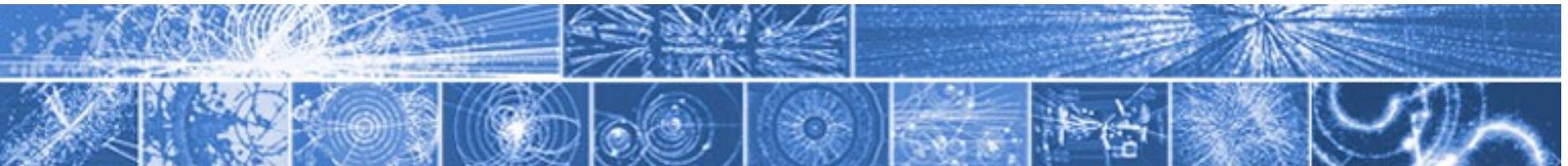
Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)



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

Equazioni di Einstein

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

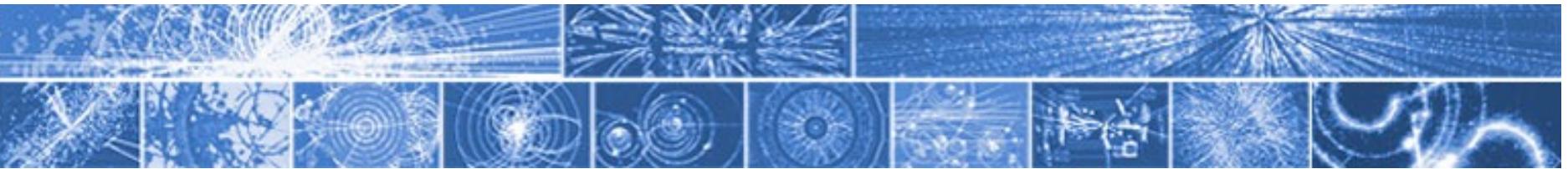


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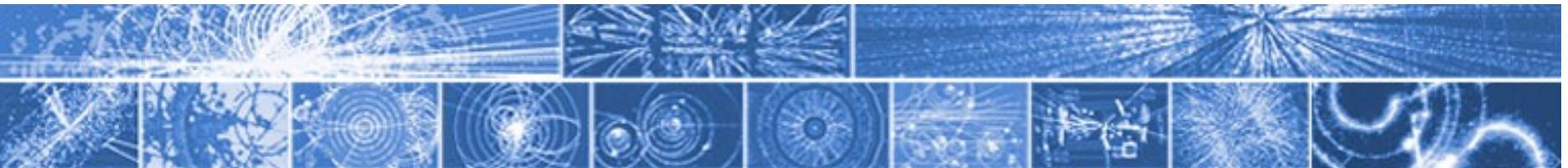
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*geometria dello
spazio-tempo*

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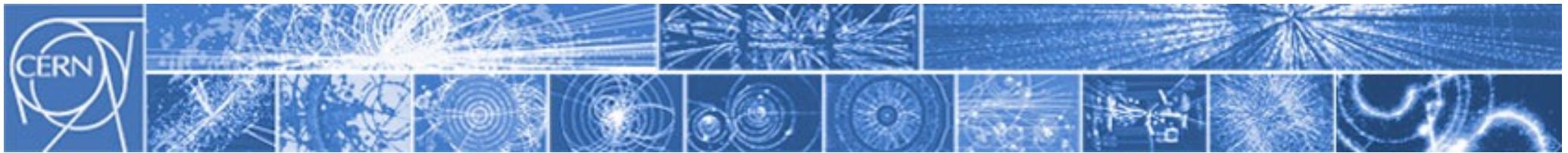
$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu}$$

*geometria dello
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materia e energia*

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

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



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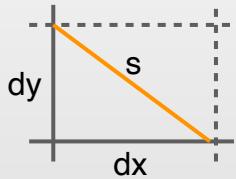
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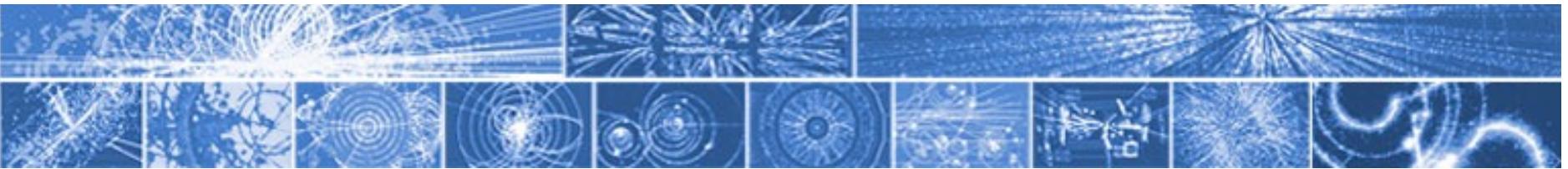
$g_{\mu\nu}$: la metrica



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

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

'Teorema
di Pitagora'



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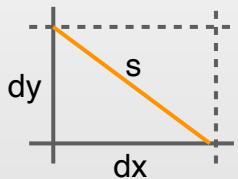
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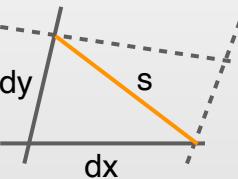
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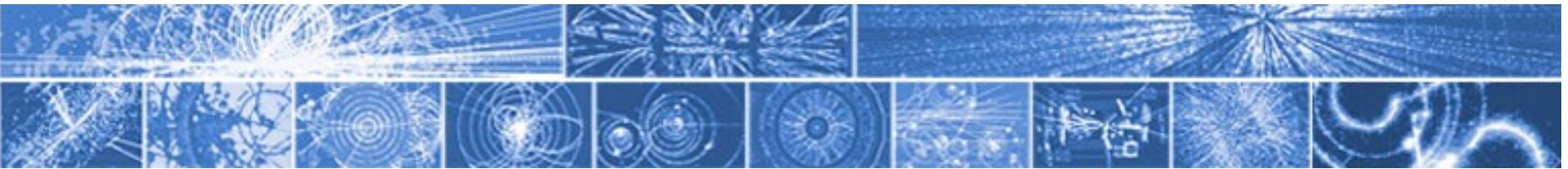
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$$g_{\mu\nu} = \dots$$

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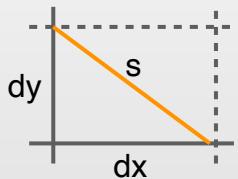
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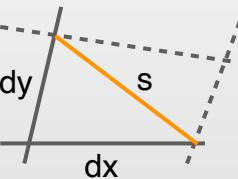
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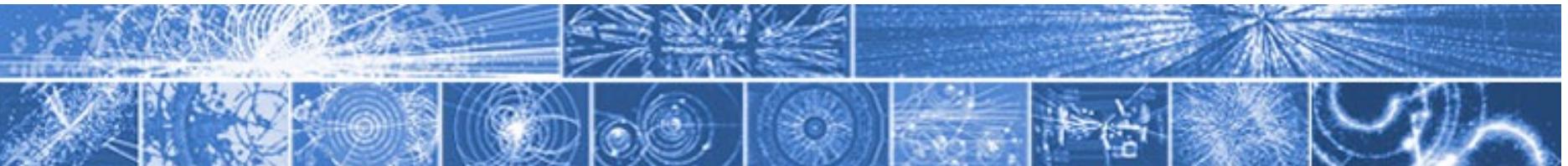
Esempio: metrica di Schwarzschild attorno a un buco nero di massa M:

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

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

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)



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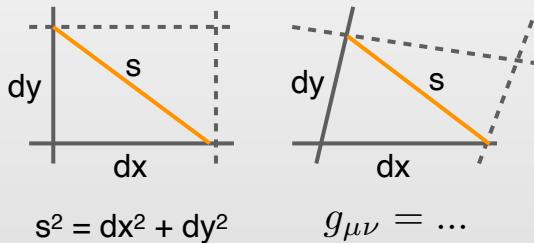
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$a(t)$: il fattore di scala
(la grandezza)
dell'Universo

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

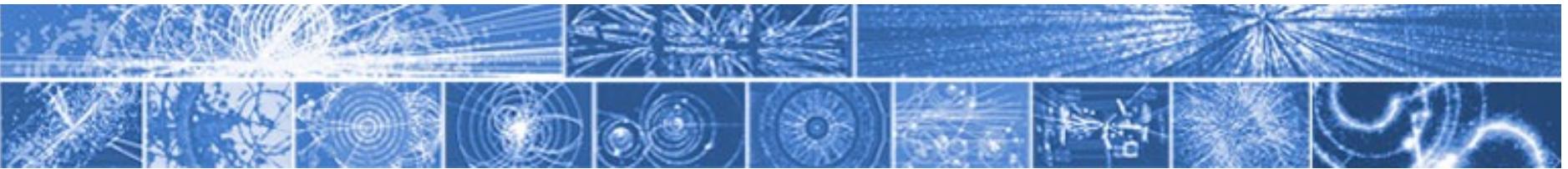
(a è da intendersi come rapporto,
non ha un significato fisico intrinseco)

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)

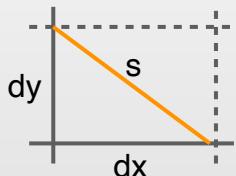
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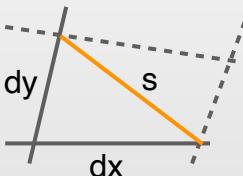
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geometria dello spazio-tempo



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

contenuto di materia e energia

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

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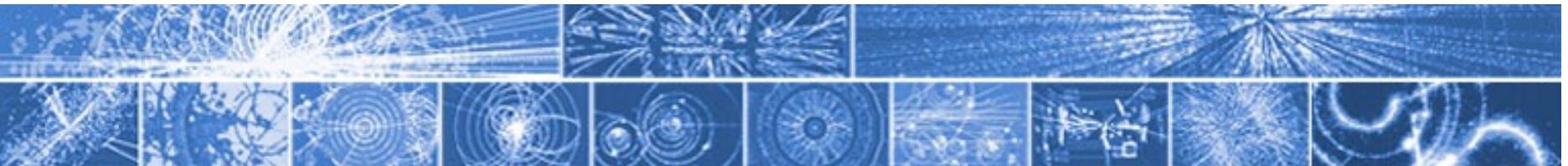
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$$G = \frac{1}{M_{Pl}^2}$$

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

(assumendo fluido perfetto)



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

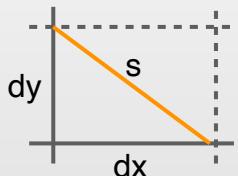
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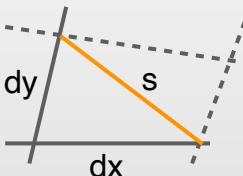
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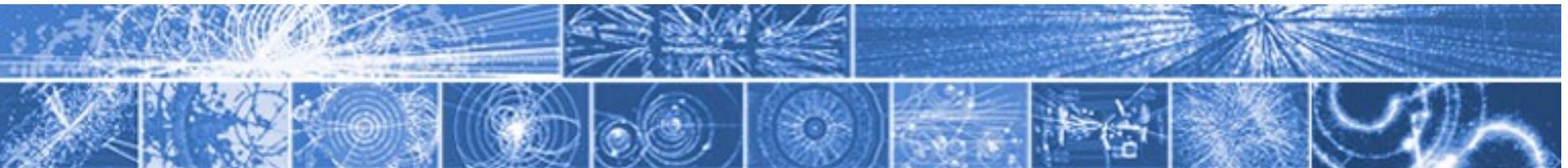
$$T_{\mu\nu} = \begin{pmatrix} \rho & -P & & \\ -P & -P & & \\ & & -P & \\ & & & -P \end{pmatrix}$$

Equazione di stato $P = w\rho$

'matter' $P = 0$ $\rho \propto 1/a^3$

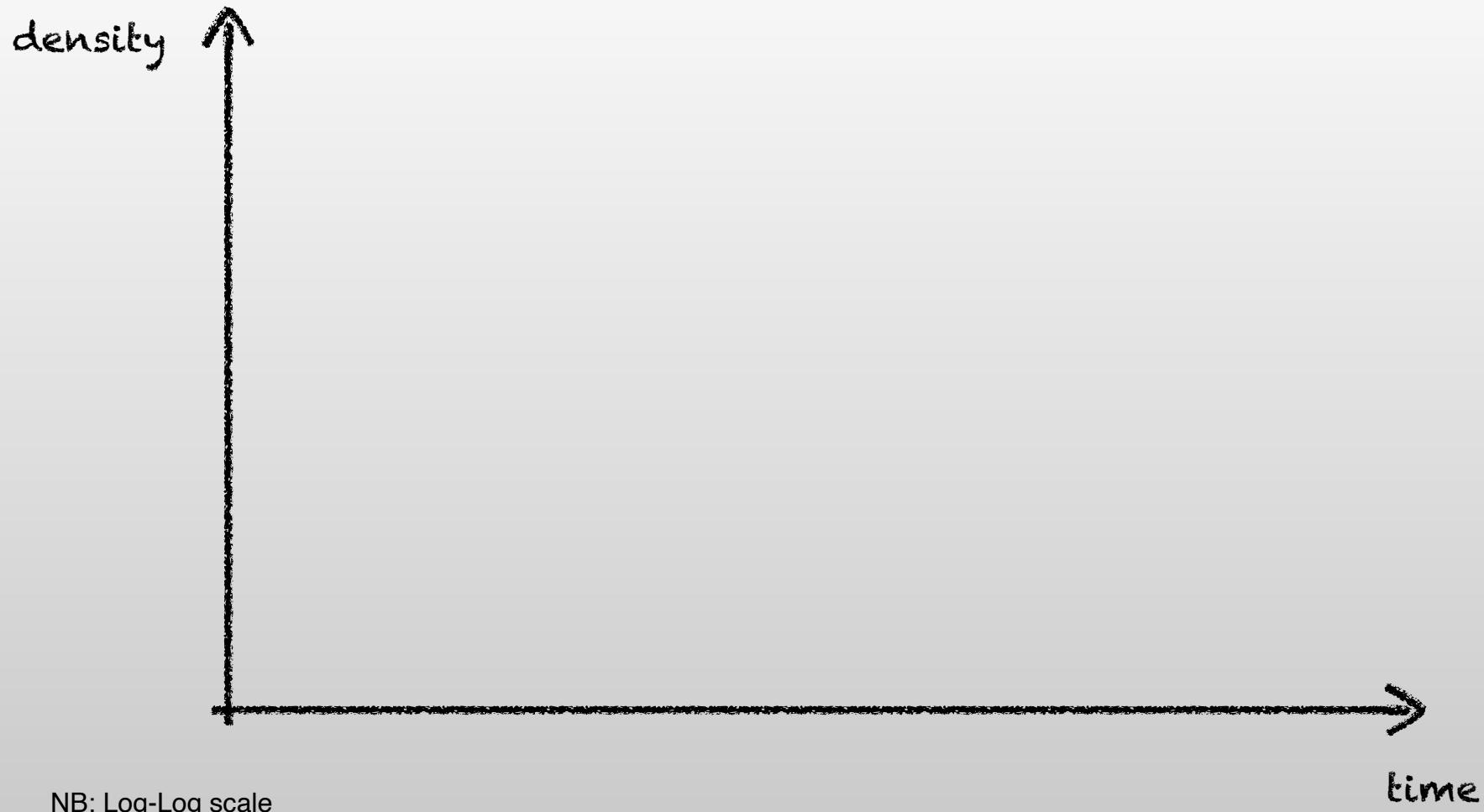
'radiation' $P = \frac{1}{3}\rho$ $\rho \propto 1/a^4$

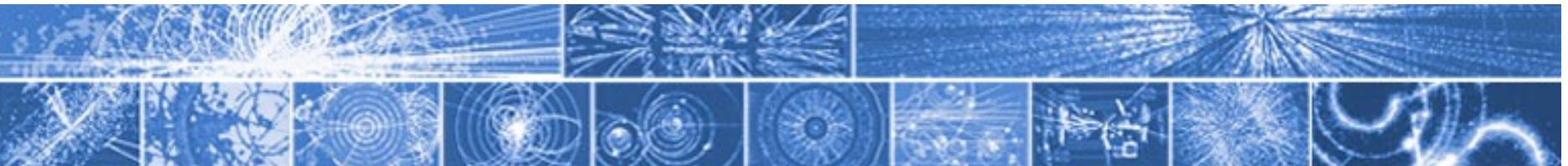
'vacuum' $P = -\rho$ $\rho \propto \text{cost}$



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

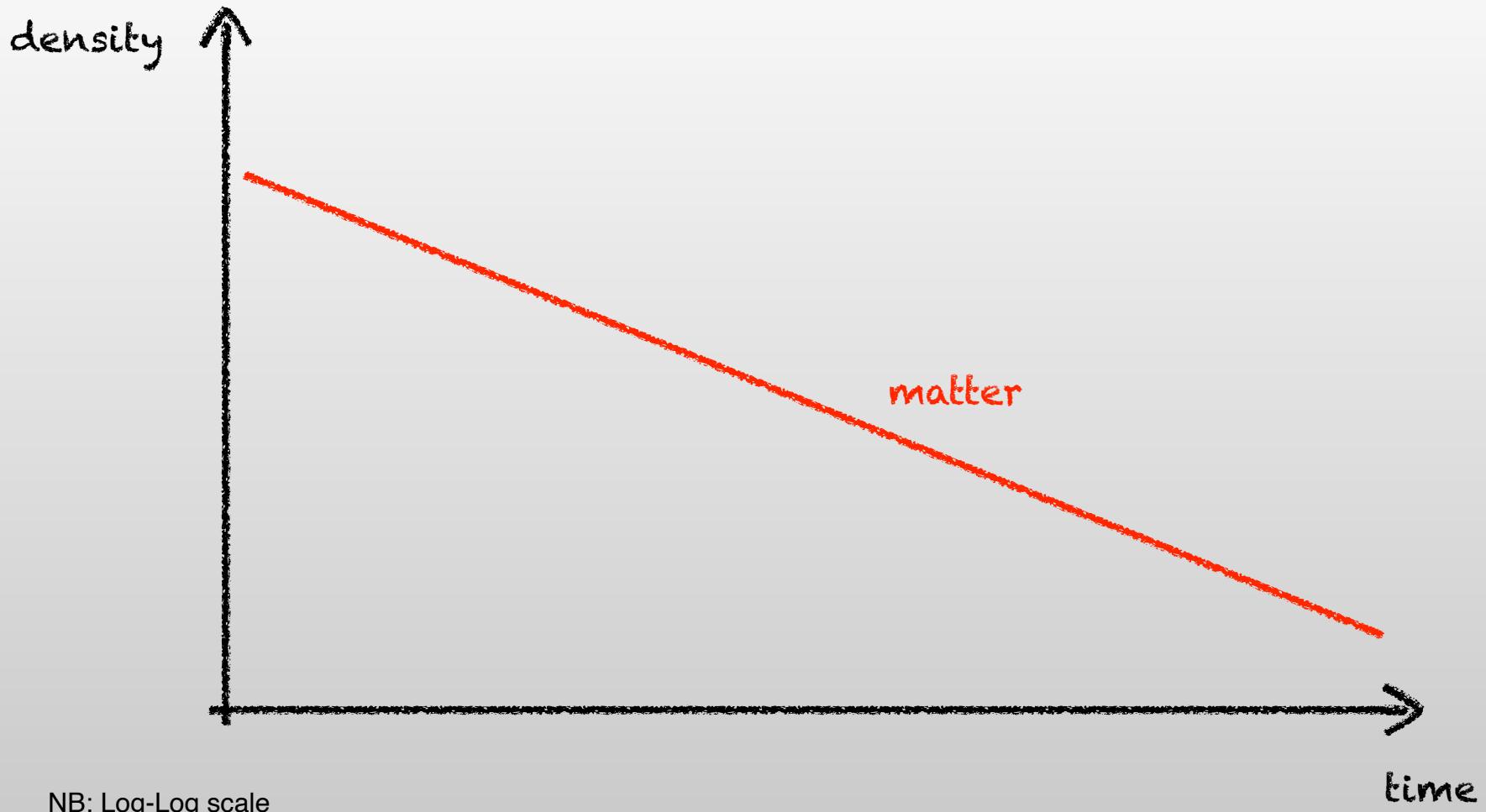
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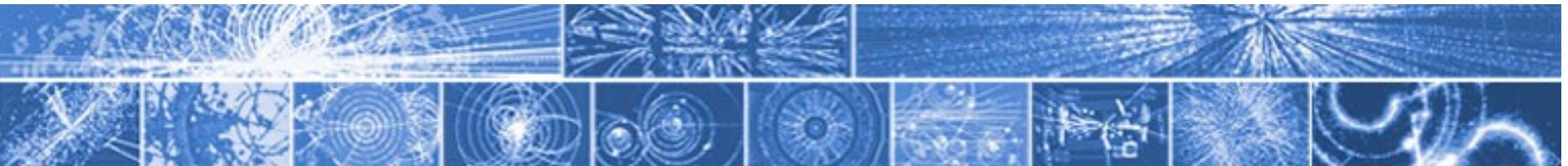




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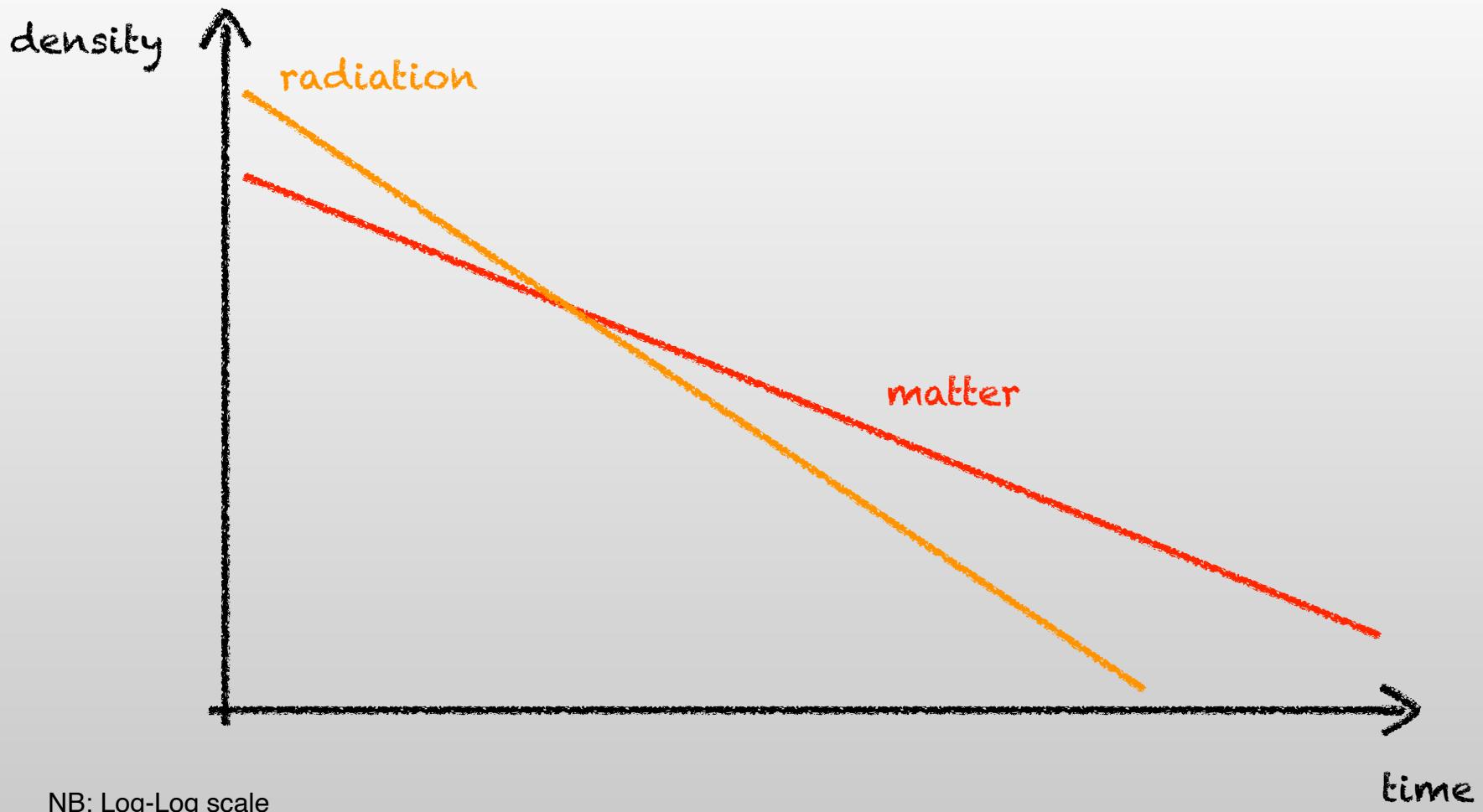
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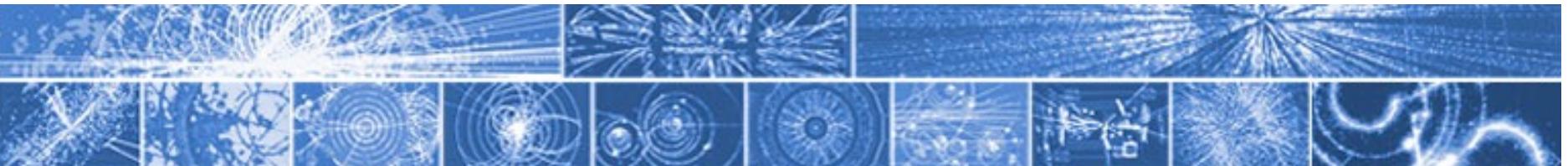




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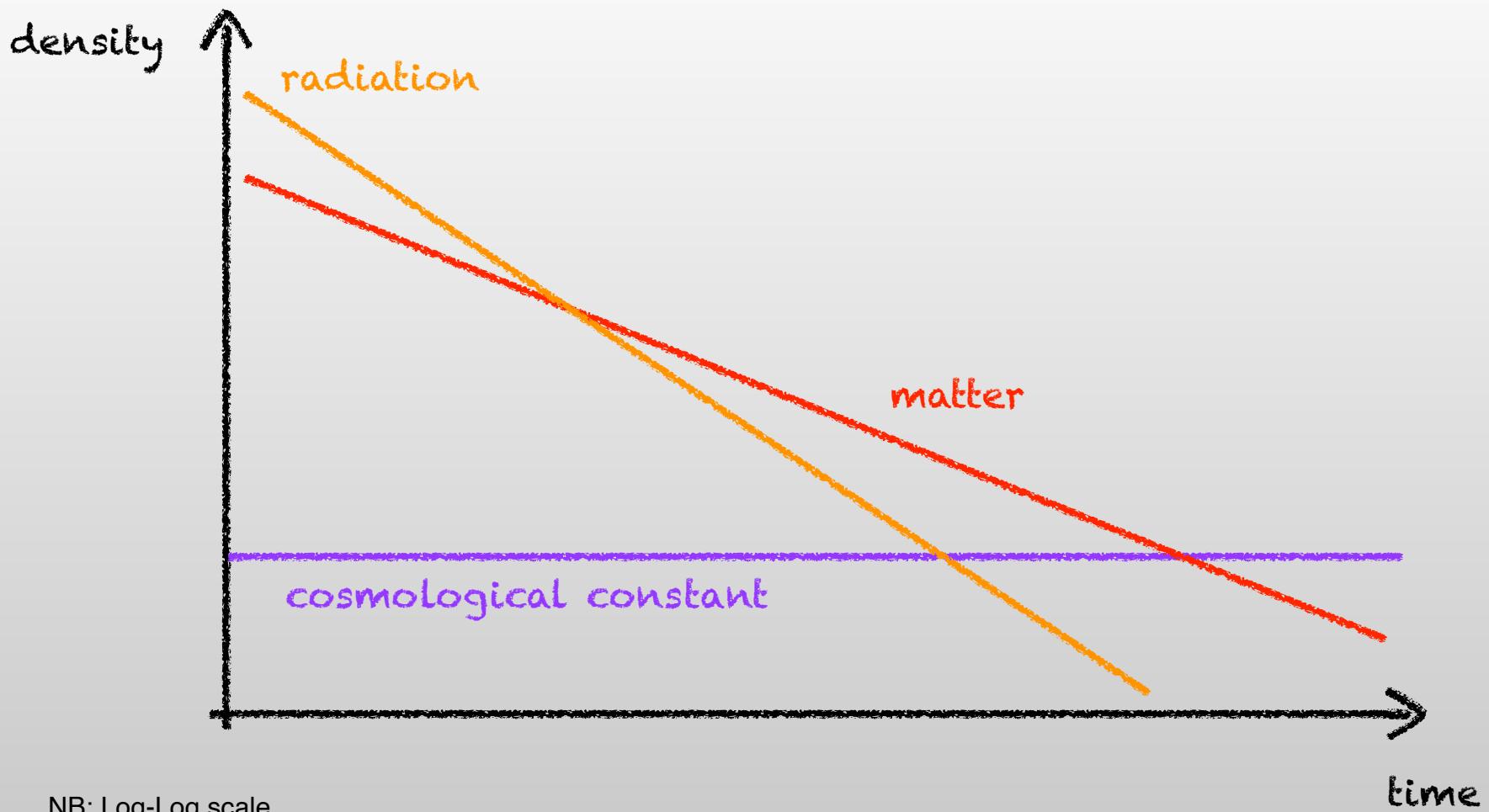
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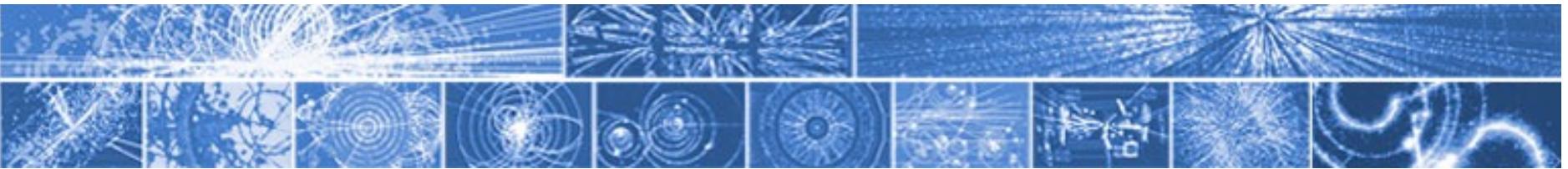




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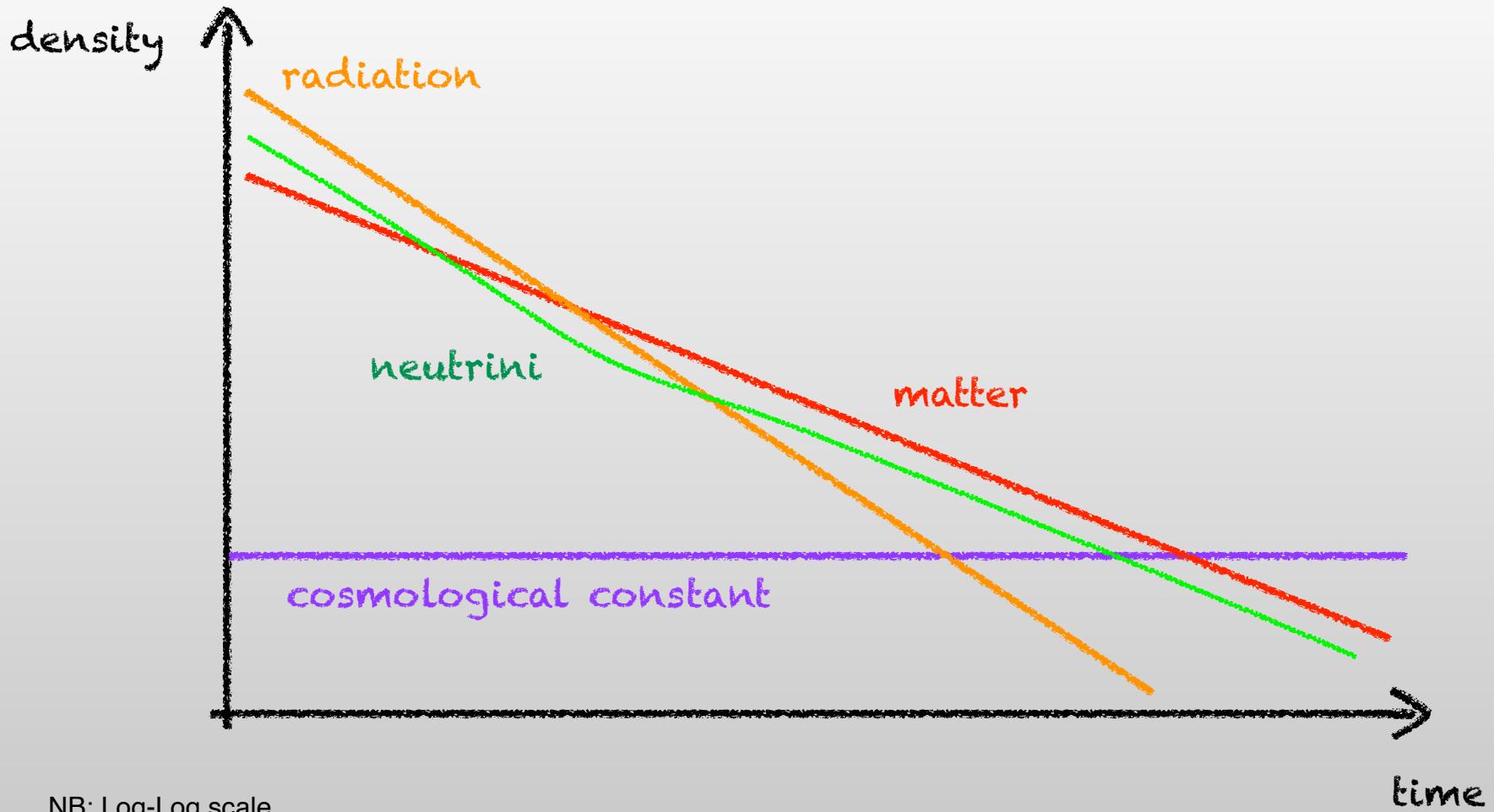
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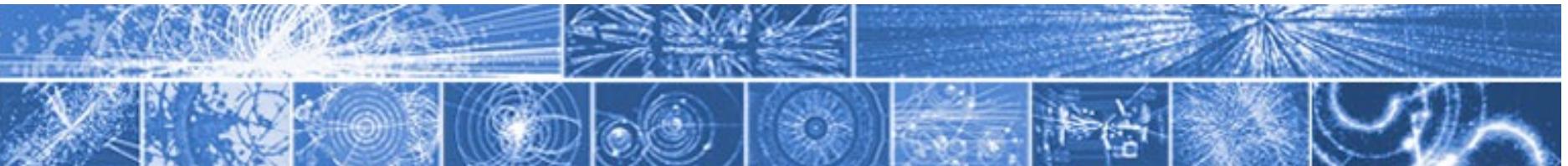




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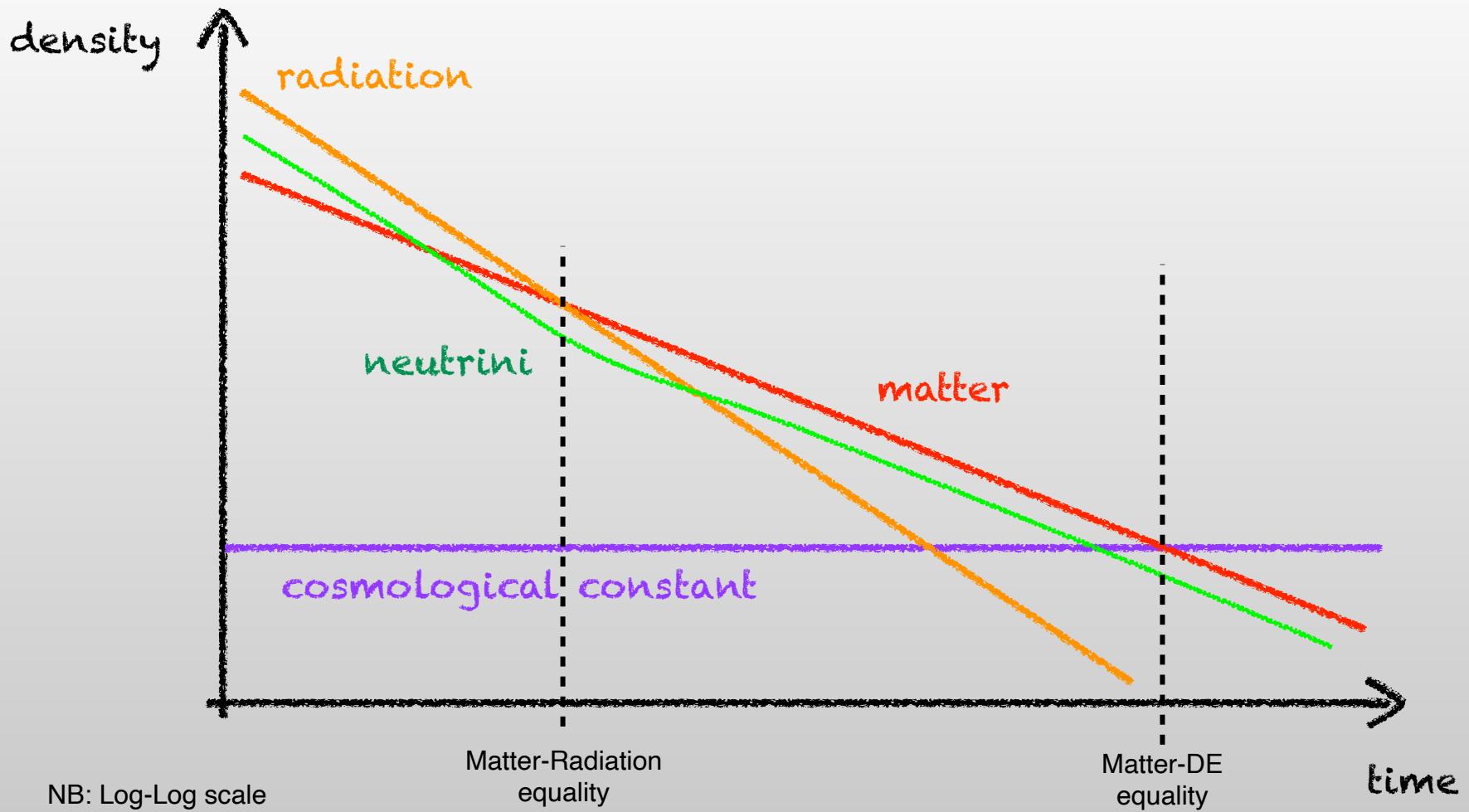
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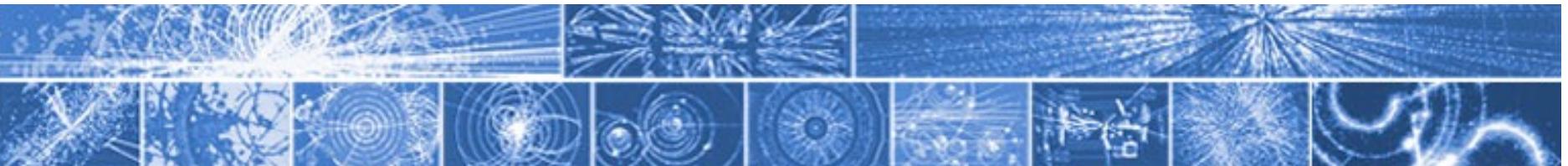




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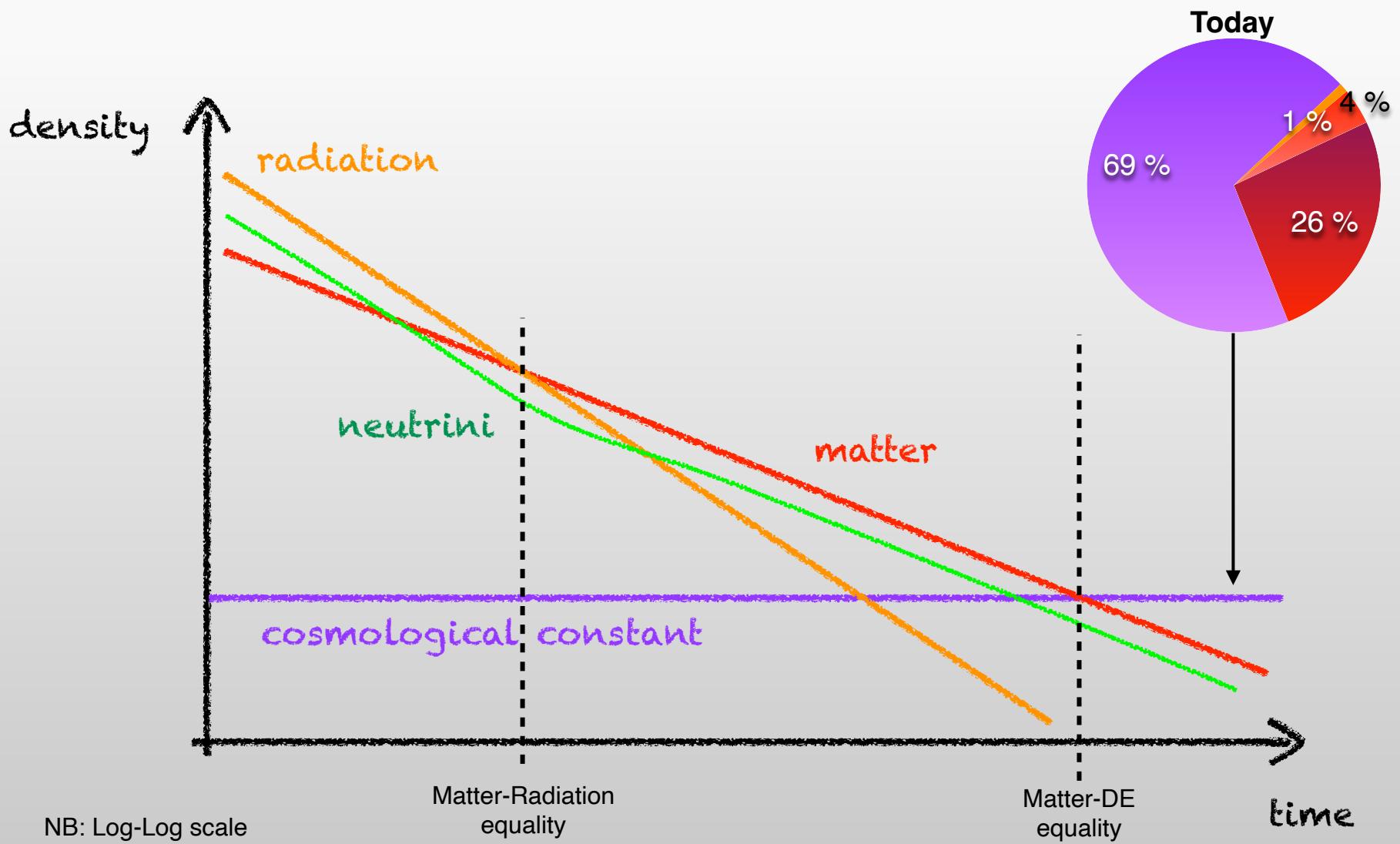
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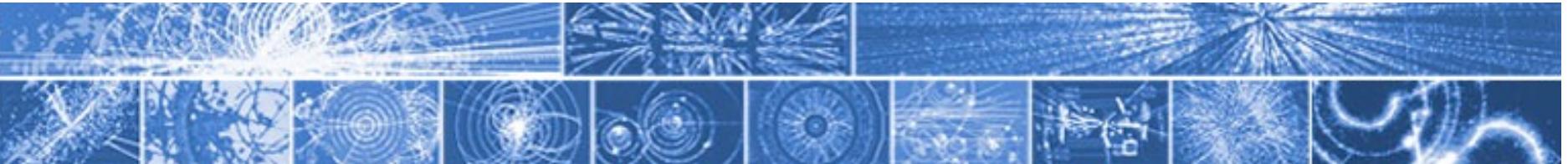




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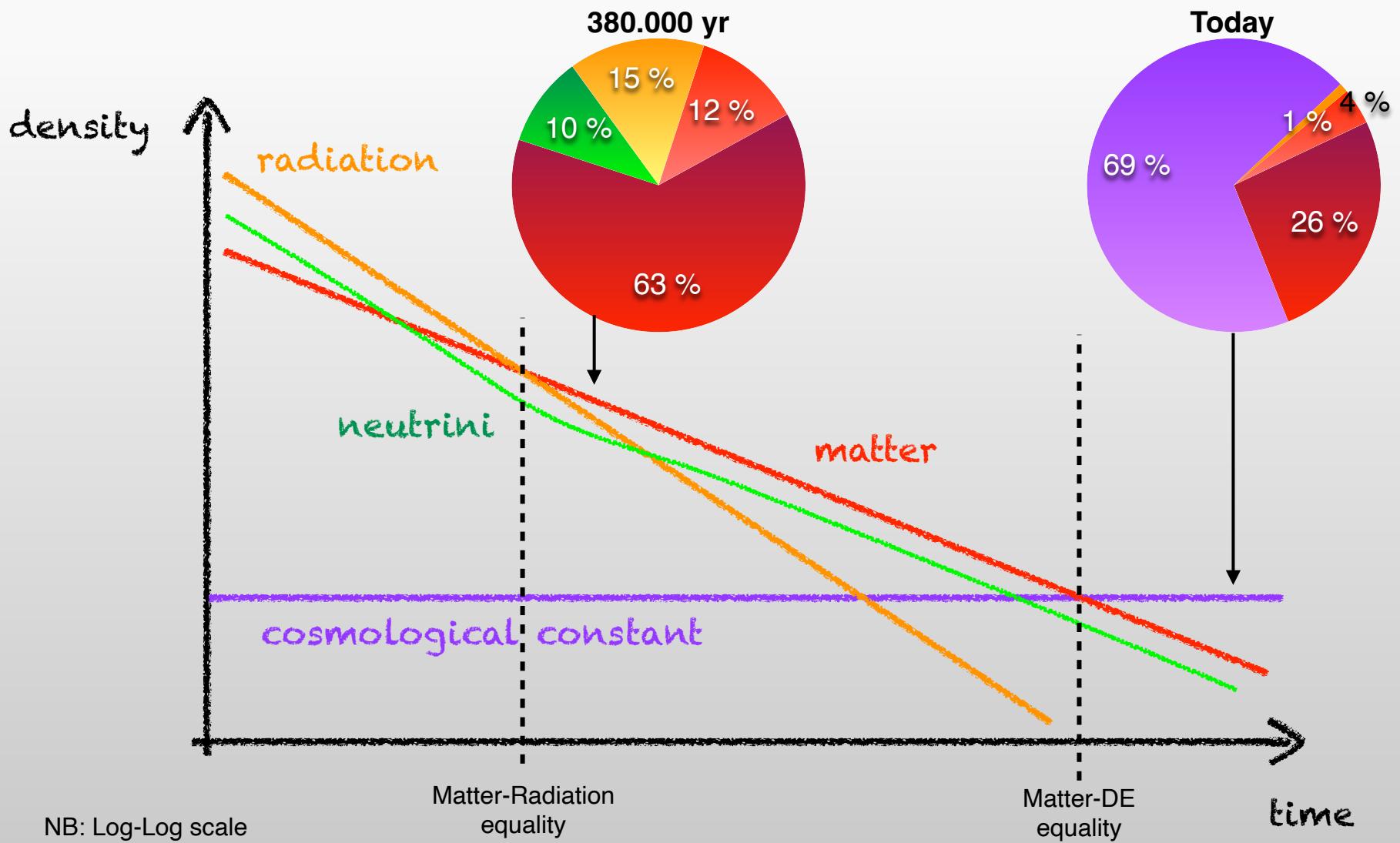
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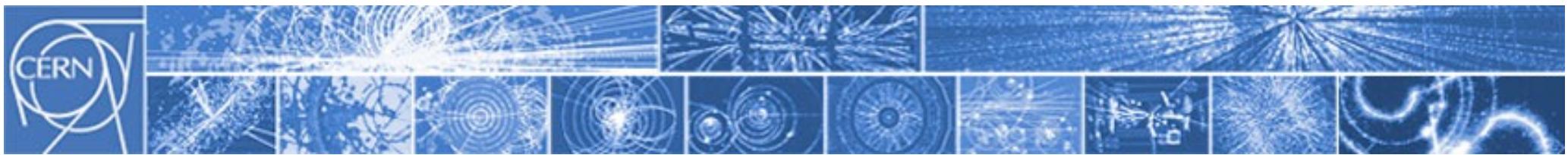




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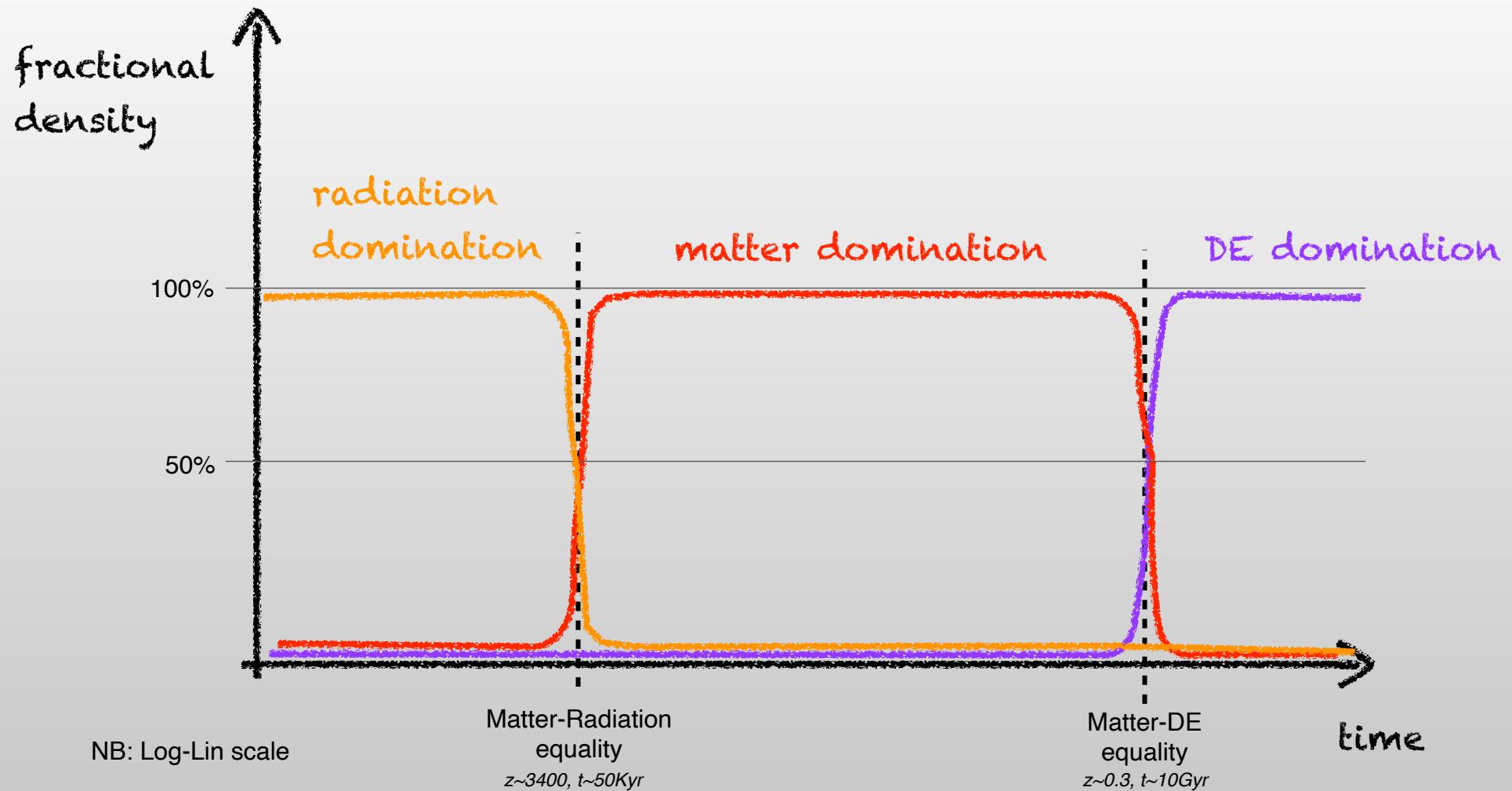
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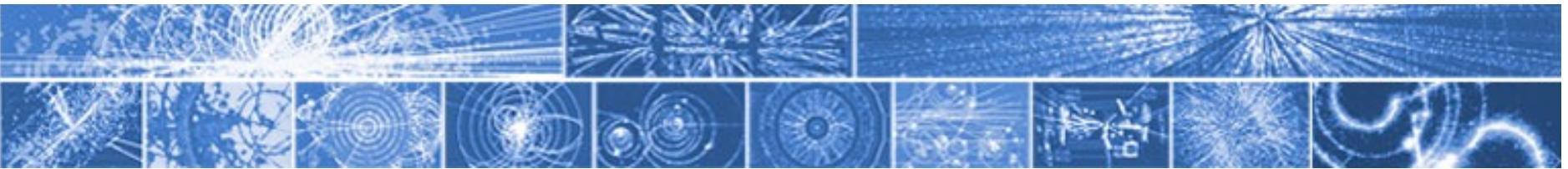




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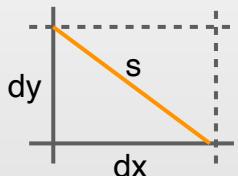
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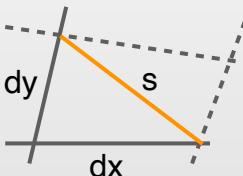
$R_{\mu\nu}$ funzione di $g_{\mu\nu}$

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



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

geometria dello spazio-tempo



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

omogeneità isotropia

contenuto di materia e energia

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

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

Parametro di Hubble

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

Redshift

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

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

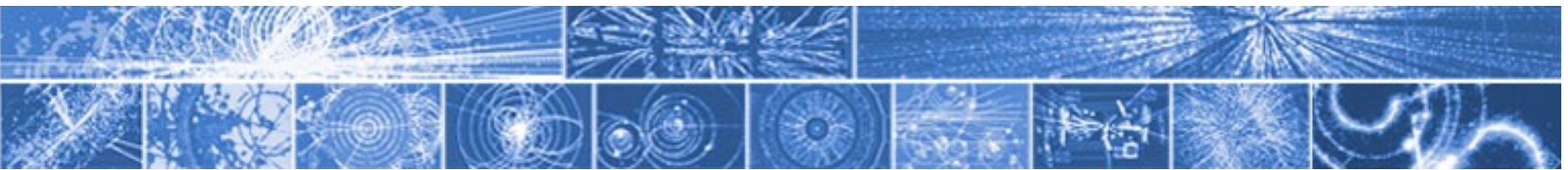
$$T_{\mu\nu} = \begin{pmatrix} \rho & -P & & \\ -P & -P & & \\ & & -P & \\ & & & -P \end{pmatrix}$$

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' $P = -\rho$ $\rho \propto \text{cost}$



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

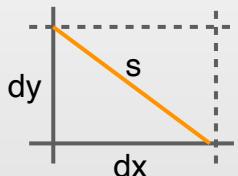
Equazioni di Einstein

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

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

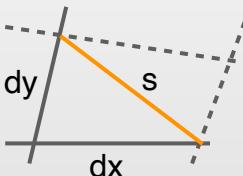
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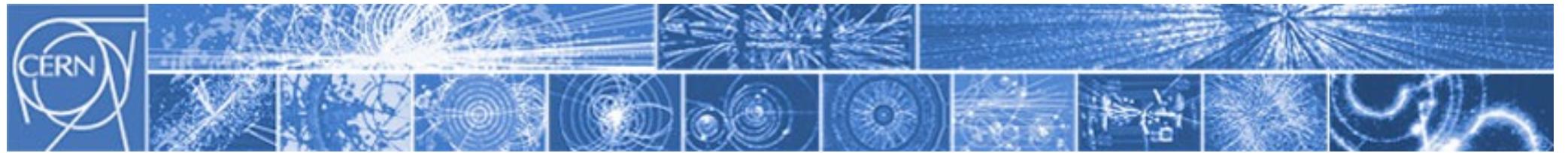
Equazioni di Friedmann-Robertson-Walker

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

FRW I

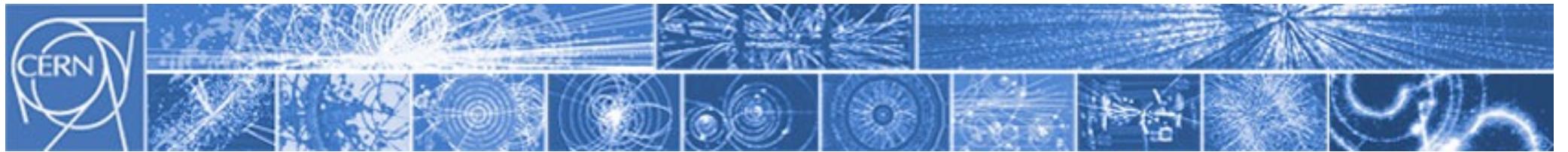
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

FRW II



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

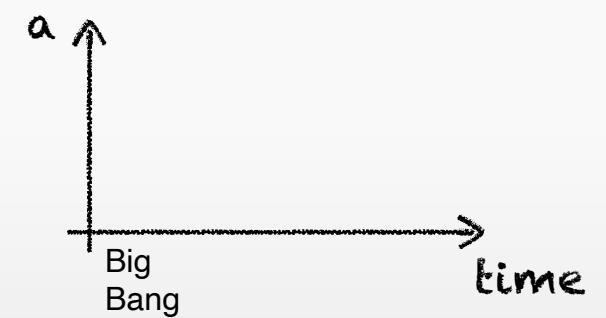
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$

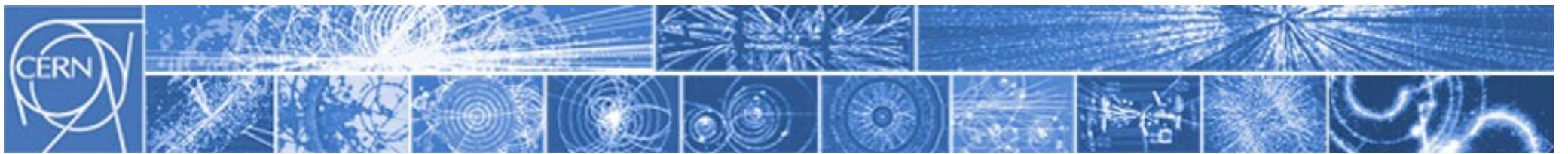


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

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

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



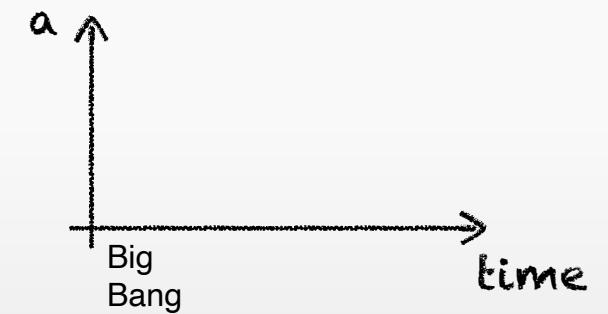


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

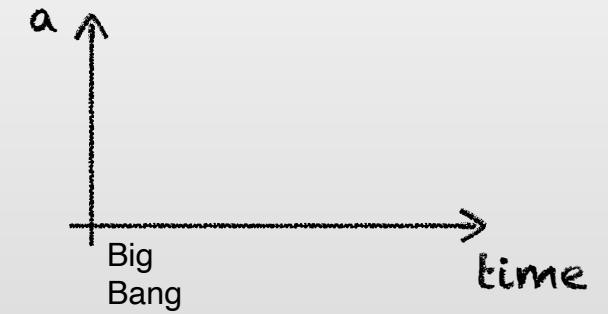
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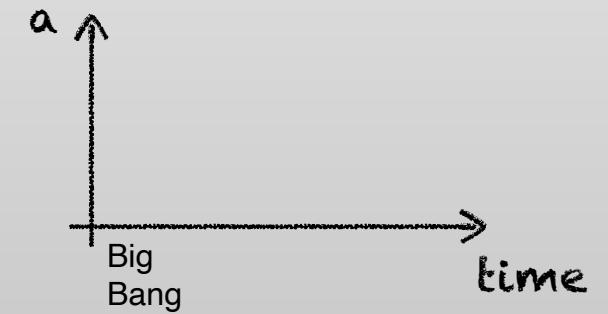
$$k < 0$$

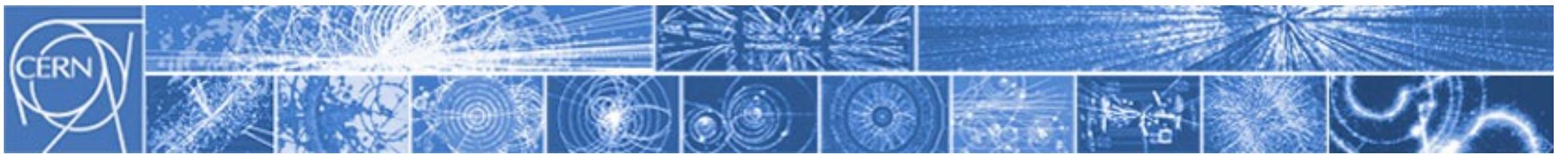


$$k = 0$$



$$k > 0$$



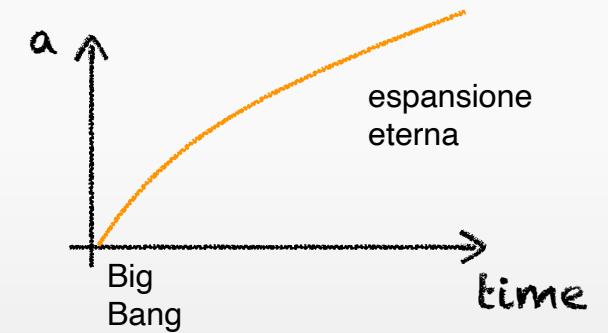


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

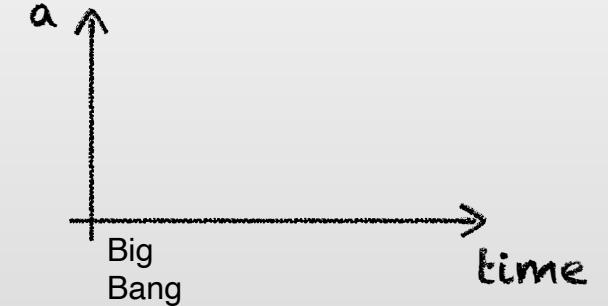
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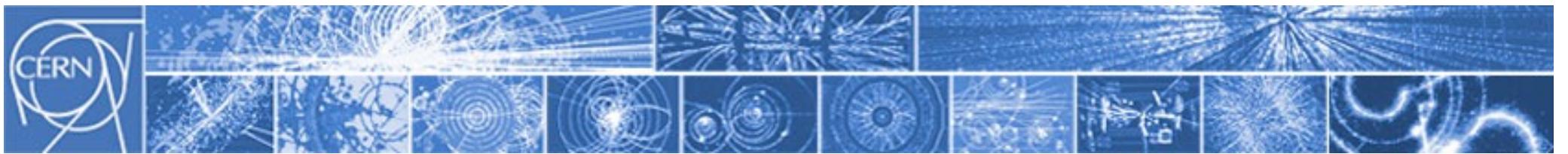


$$k = 0$$



$$k > 0$$



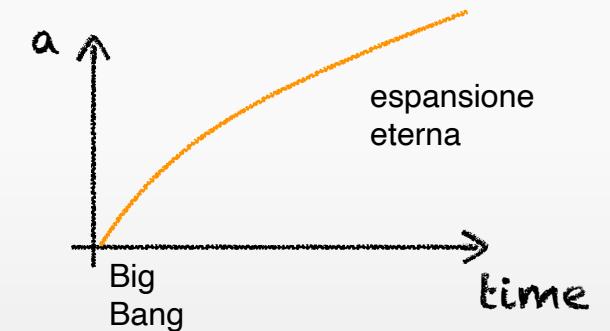


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

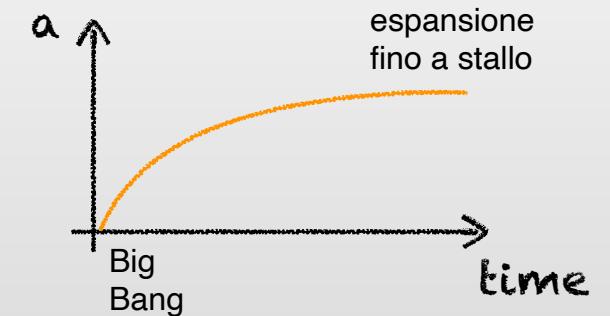
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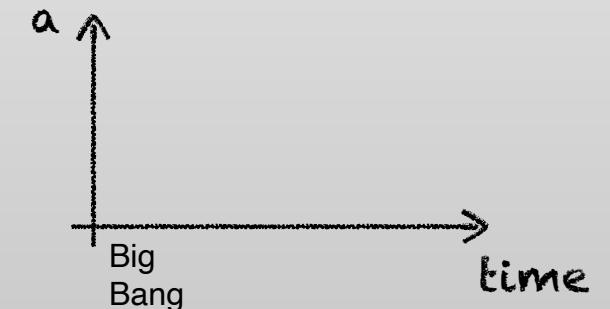
$$k < 0$$

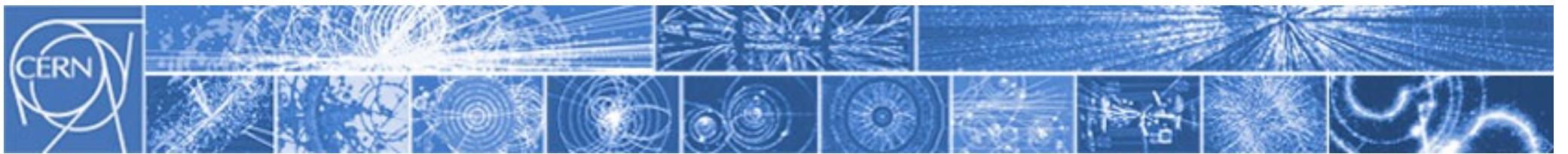


$$k = 0$$



$$k > 0$$



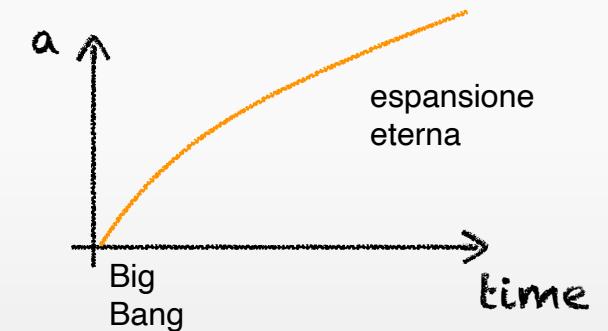


Relatività generale e basi di cosmologia (in 2 slides / 2 minuti)

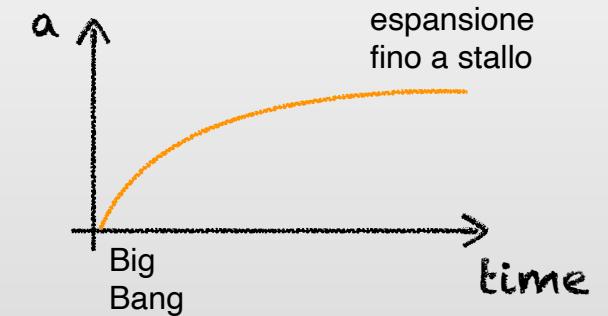
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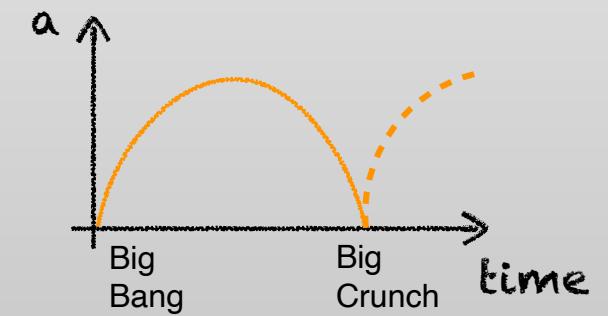
$$k < 0$$

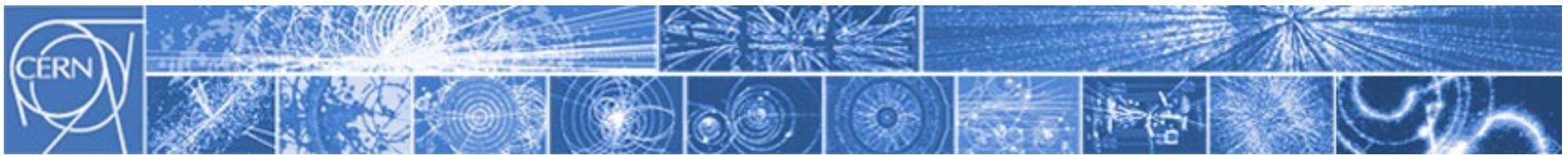


$$k = 0$$



$$k > 0$$





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

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

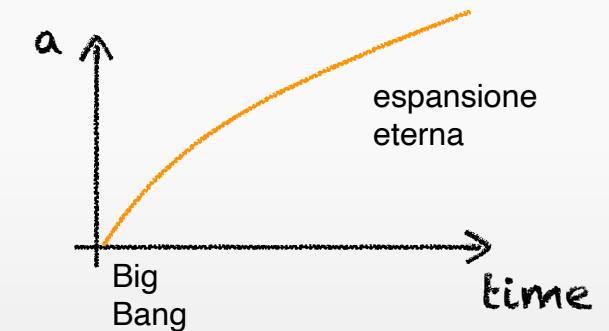
con alcuni (non semplici) passaggi
posso risolvere per $a(t)$:

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

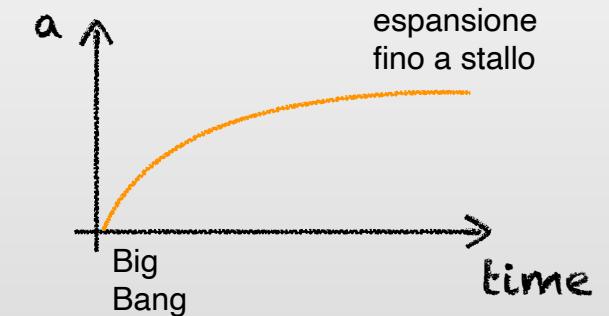
dove $\Omega = \frac{\rho}{\rho_{\text{crit}}}$ $\rho_{\text{crit}} = \frac{3H^2}{8\pi G}$

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

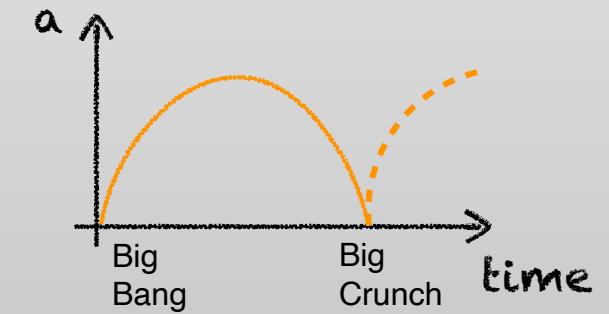
$$k < 0$$

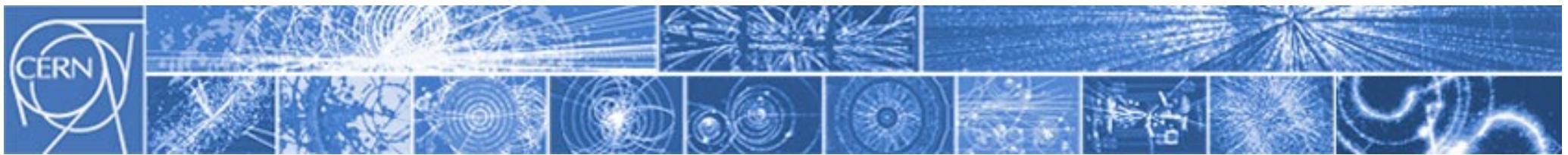


$$k = 0$$



$$k > 0$$





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 $a(t)$:

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

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

quindi

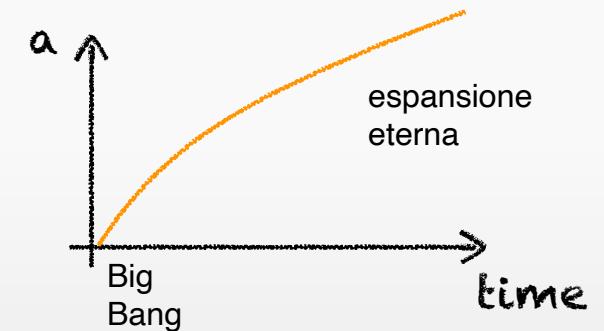
$$\rho < \rho_{\text{crit}} \Rightarrow \Omega < 1 \Rightarrow k < 0$$

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

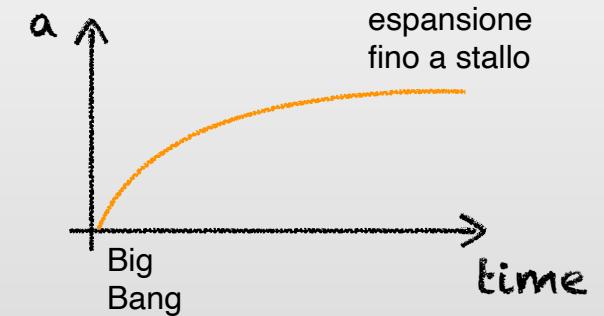
$$\rho > \rho_{\text{crit}} \Rightarrow \Omega > 1 \Rightarrow k > 0$$

pesare l'Universo per determinarne il fatto!

$$k < 0$$



$$k = 0$$



$$k > 0$$

