An introduction to the Little Bang

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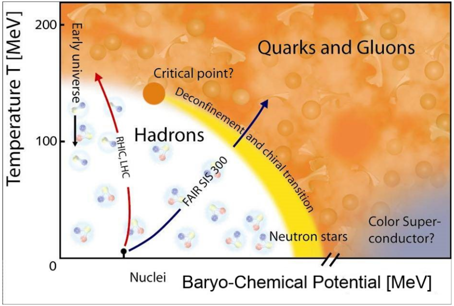
INFN - Sezione di Torino

"Advanced Nuclear Physics" PhD course

Heavy-ion collisions: exploring the QCD phase-diagram



QCD phases identified through the *order parameters*

- Polyakov loop $\langle L \rangle \sim e^{-\beta \Delta F_Q}$: energy cost to add an isolated color charge
- Chiral condensate $\langle \overline{q} q \rangle \sim$ effective mass of a "dressed" quark in a hadron

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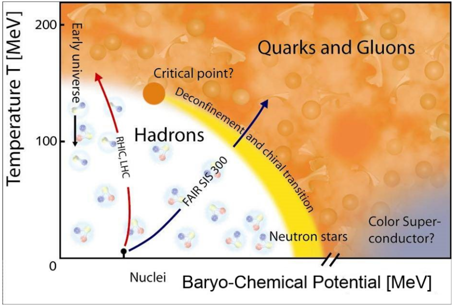

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Heavy-Ion Collision (HIC) experiments performed to study the transition

- From QGP (color deconfinement, chiral symmetry restored)
- to hadronic phase (confined, chiral symmetry broken)

NB $\langle \overline{q} q \rangle \neq 0$ responsible for most of the baryonic mass of the universe: *only ∼35 MeV of the proton mass from* $m_{u/d} \neq 0$

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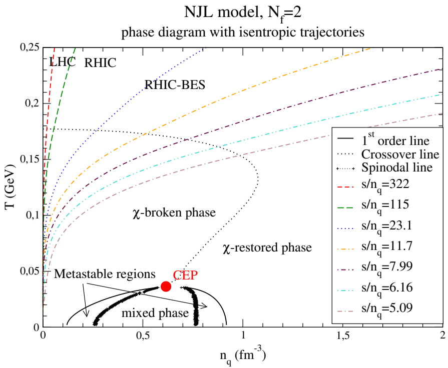

- Region explored at the LHC and highest RHIC energy: *high-T/low-density* (early universe, $n_B/n_\gamma \sim 10^{-9}$)
- Higher baryon-density region accessible at lower $\sqrt{s_{\rm NN}}$ (Beam-Energy Scan at RHIC)

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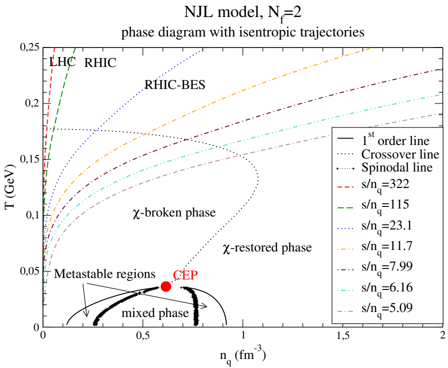

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Is there a Critical End-Point in the QCD phase diagram?

QCD at high temperature: expectations

Based on *asymptotic freedom*, for $T \gg \Lambda_{QCD}$ hot-QCD matter should behave like a non-interacting plasma of massless quarks (the ones for which $m_q \ll T$) and gluons. In such a regime T is the only scale μ at which evaluating the gauge coupling, for which one has

$$\lim_{T/\Lambda_{QCD}\to\infty} g(\mu\sim T) = 0$$

Hence one expects the asymptotic *Stefan-Boltzmann* behaviour

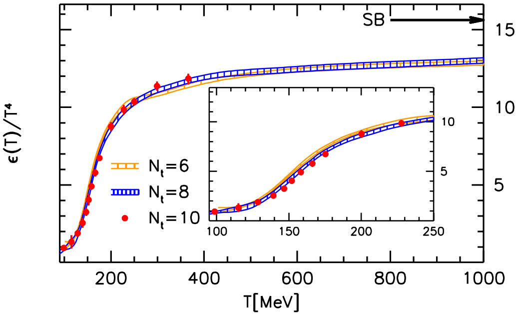
$$\epsilon = \frac{\pi^2}{30}\left[g_{\rm gluon} + \frac{7}{8} g_{\rm quark}\right] T^4,$$

where

$$g_{\rm gluon} = \underbrace{2\times(N_c^2-1)}_{\rm pol.\ \times\ col.} \quad \text{and} \quad g_{\rm quark} = \underbrace{2\times 2\times N_c\times N_f}_{q/\overline{q}\ \times\ \rm spin\ \times\ col.\ \times\ flav.}$$

QCD at high temperature: lattice results

Continuum-extrapolated ($a \to 0$) lattice-QCD simulations with realistic quark masses now available (W.B. Collab. [JHEP 1011 (2010) 077])



Rapid rise in the energy density suggesting a change in the *number of active degrees of freedom* (hadrons $\to$ partons):

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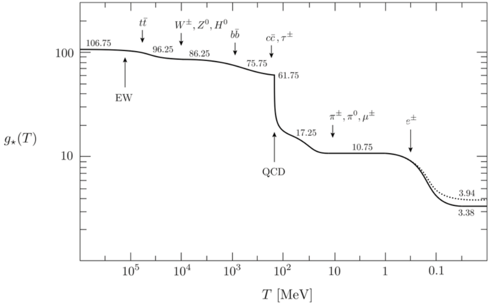
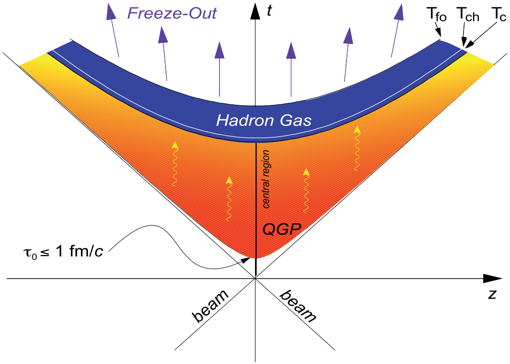


Rapid rise in the energy density suggesting a change in the *number of active degrees of freedom* (hadrons $\to$ partons):
the most dramatic drop experienced by the early universe in which

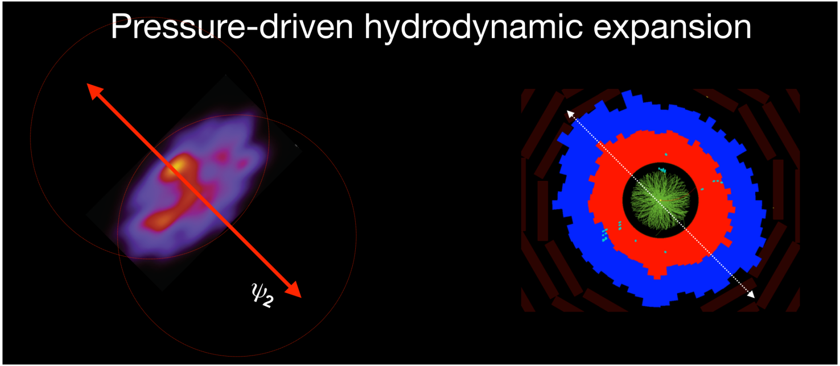
$$H^2 = \frac{8\pi G}{3}\epsilon_{\rm rel} = \frac{8\pi G}{3}\left(\frac{\pi^2}{30}g_* T^4\right)$$

Heavy-ion collisions: a cartoon of space-time evolution



- Soft probes (low-p_T hadrons): collective behavior of the *medium*;
- Hard probes (high-p_T particles, heavy quarks, quarkonia): produced in *hard pQCD processes* in the initial stage, allow to perform a tomography of the medium

A medium displaying a collective behavior



$$(\epsilon + P)\frac{dv^i}{dt} \underset{v \ll c}{=} -\frac{\partial P}{\partial x^i}$$

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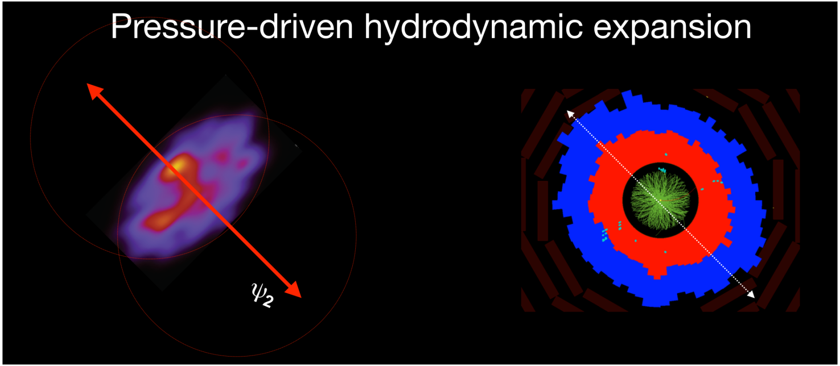

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NB picture relying on the condition $\lambda_{\mathrm{mfp}} \ll L$

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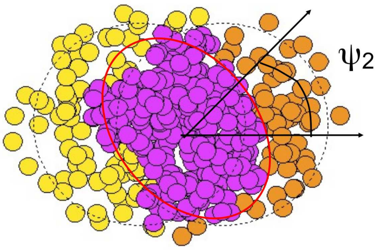
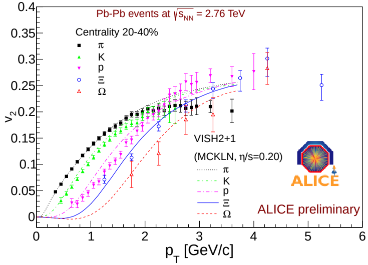


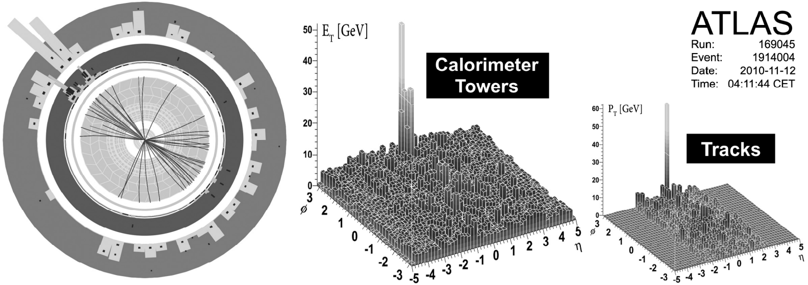


Anisotropic azimuthal distribution of hadrons as a response to pressure gradients quantified by the *Fourier coefficients* v_n

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_n)] + \dots\right)$$

$$v_n \equiv \langle \cos[n(\phi - \psi_n)] \rangle$$

A medium inducing energy-loss to colored probes



Strong unbalance of di-jet events, visible at the level of the event-display itself, without any analysis: jet-quenching

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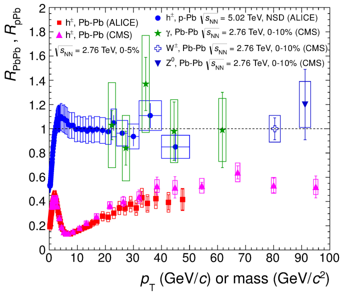

Medium-induced suppression of high-momentum hadrons and jets quantified through the *nuclear modification factor*

$$R_{AA} \equiv \frac{\left(dN^h/dp_T\right)^{AA}}{\langle N_{\rm coll}\rangle \left(dN^h/dp_T\right)^{pp}}$$

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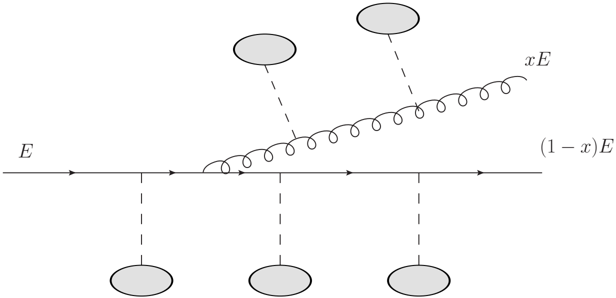

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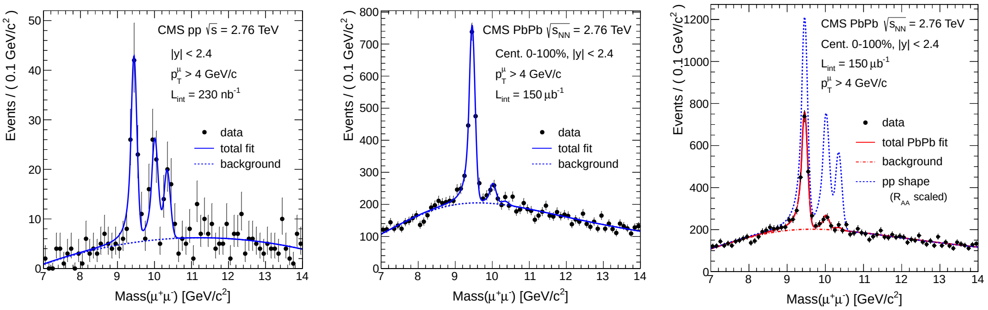
interpreted as energy carried away by radiated gluons

A medium screening the $Q\overline{Q}$ interaction



Suppression of Υ production in Pb-Pb collisions at the LHC, in particular its excited (weaker binding, larger radius!) states.

[1] T. Matsui and H. Satz, Phys.Lett. B178 (1986) 416-422

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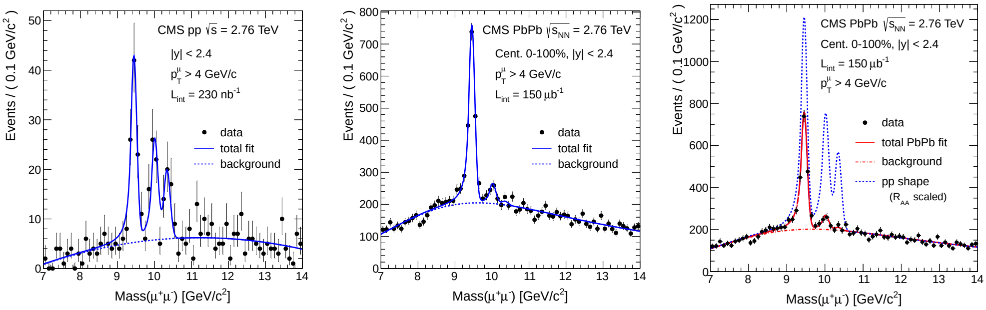

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In first approximation, Debye screening of the $Q\overline{Q}$ interaction[1]:

$$V_{Q\overline{Q}}(r) = -C_F \frac{\alpha_s}{r} \quad \longrightarrow \quad -C_F \frac{\alpha_s}{r} e^{-m_D r}$$

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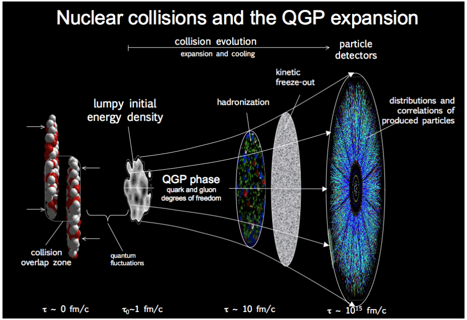
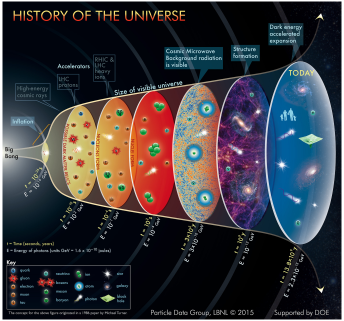
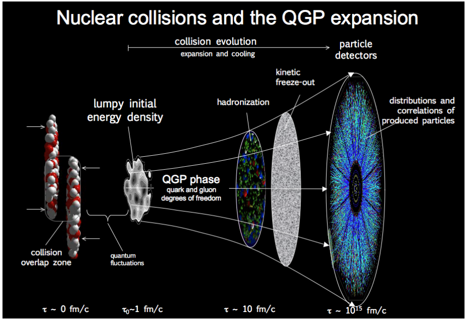
Little Bang vs Big Bang

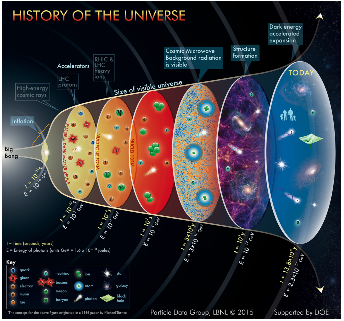




Which differences between the Little-Bang created in the lab and the Big-Bang from which our universe was born?

Little Bang vs Big Bang





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- Expansion of the universe governed by the equations of the gravitational field. In nuclear collisions gravity does not play any role, expansion of the fireball driven by pressure gradients;

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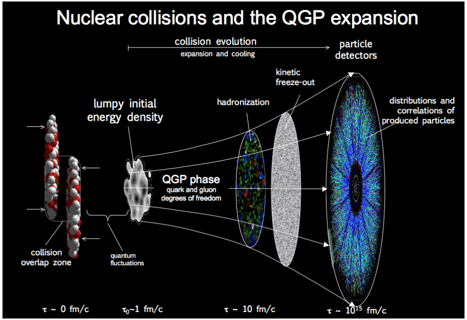

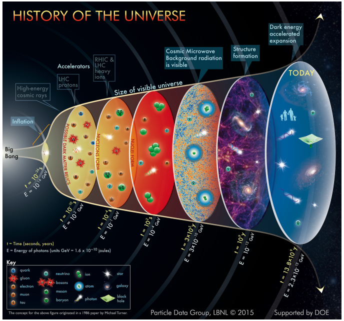

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- Expansion of the universe governed by the equations of the gravitational field. In nuclear collisions gravity does not play any role, expansion of the fireball driven by pressure gradients;
- QGP produced in nuclear collisions has a much shorter lifetime (10^{-22}s vs 10^{-6}s) and a much more violent expansion (with deep consequences!).

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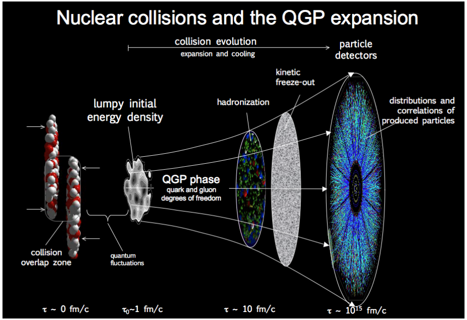
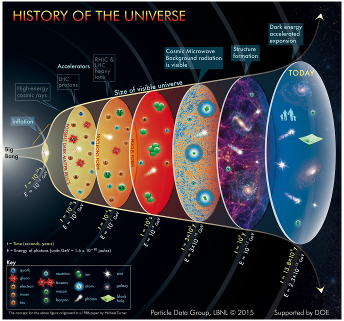




To be more precise, compare the expansion rates:

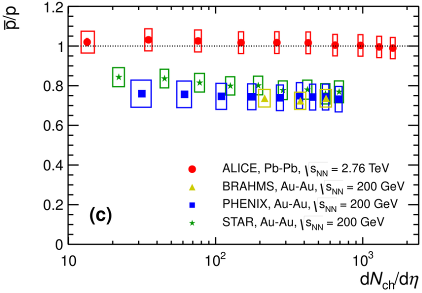
- Radiation-dominated universe

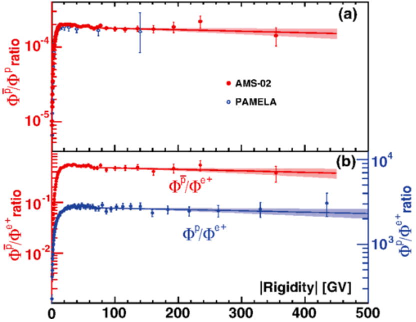
$$a \sim t^{1/2} \quad \longrightarrow \quad \dot{a} \sim \frac{1}{2} a^{-1/2} \quad H \equiv \frac{\dot{a}}{a} = \frac{1}{2t} \sim 10^6\,\mathrm{s}^{-1}$$

- QGP in HIC's undergoing longitudinal expansion $v^z = z/t$

$$\theta \equiv \partial_\mu u^\mu \underset{z \to 0}{\sim} \frac{1}{t} \sim 10^{22}\,\mathrm{s}^{-1}$$

Matter vs Antimatter in Little and Big Bang





In high-energy HIC's equal amount of particles and antiparticles produced, in our universe no track of primordial antimatter.

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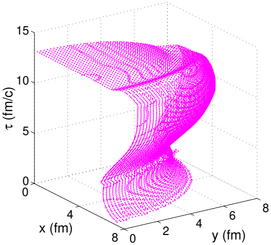

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Remember the very different expansion rates! Inelastic reactions like

$$p + \overline{p} \leftrightarrow \#\text{pions},$$

with $\sigma^{\text{in}}_{p\overline{p}} \approx \pi r_p \approx 30$ mb, do not have time to occur in HIC's.

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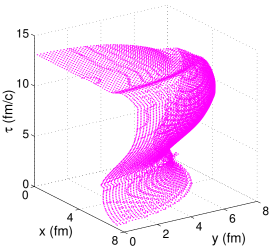

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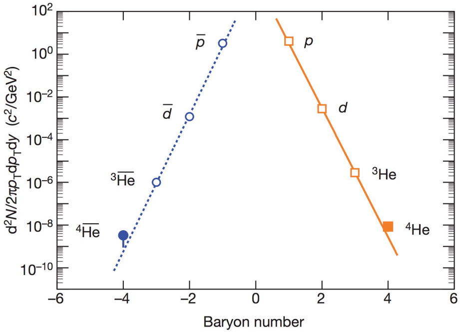
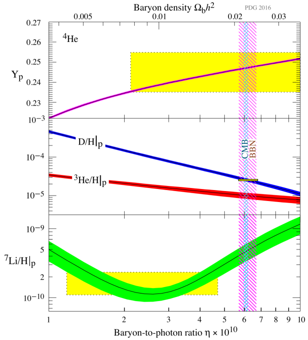
$$\lambda^{\text{ann}}_{\text{mfp}} = \frac{1}{n_p \sigma^{\text{in}}_{p\overline{p}}} \quad \text{with} \quad n \approx 10^{-2}\text{fm}^{-3} \quad \longrightarrow \quad \lambda^{\text{ann}}_{\text{mfp}} \approx 30\text{fm} \gg L$$

Protons and antiprotons decouple immediately after the QCD transition

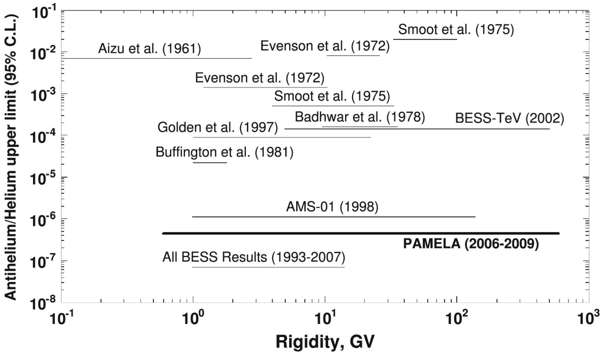
Little-Bang vs Big-Bang nucleosynthesis





- LBN: yields of light nuclei (and antinuclei!) decreaseas as A increases (fig. from STAR Coll., Nature 473, 353–356(2011));
- BBN: ^{4}He is by far the most abundant nucleus,

Little-Bang vs Big-Bang nucleosynthesis



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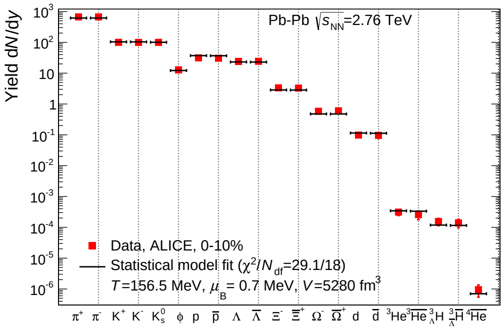

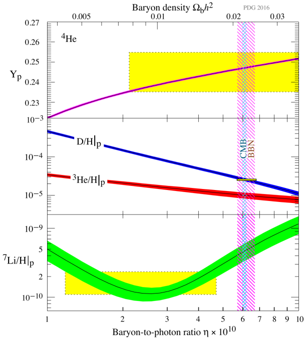

Expansion rate plays again the major role!

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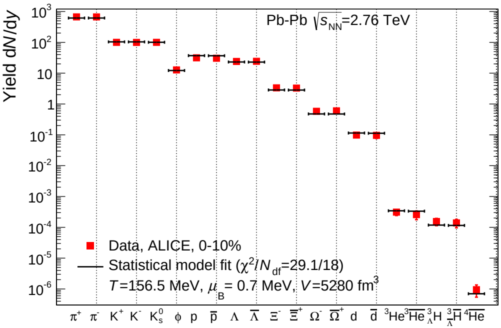

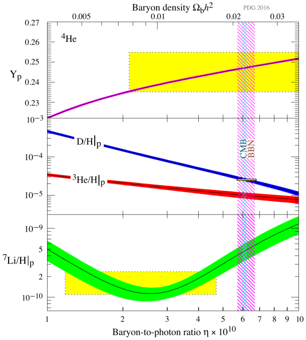

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- BBN: photons remain in thermal equilibrium with the plasma and continuously destroy deuteron as soos as it is formed (deuteron bottleneck)