Extremely hot matter and heavy-ion collisions

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&
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Atomic nucleus in extreme conditions

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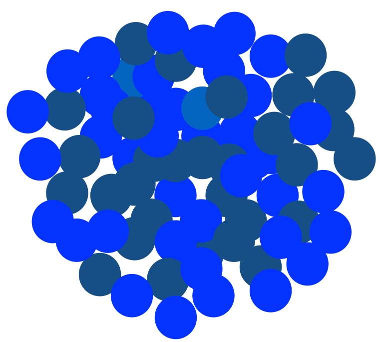

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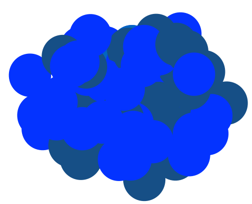

extremely high pressure
extremely high particle density
extremely high energy density

Compact (neutron) stars

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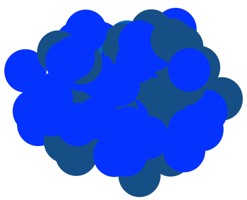

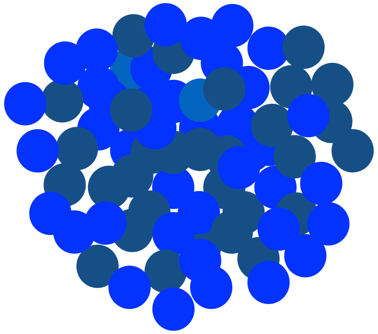

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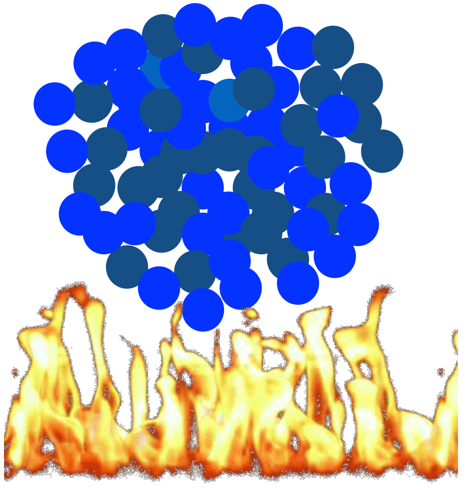

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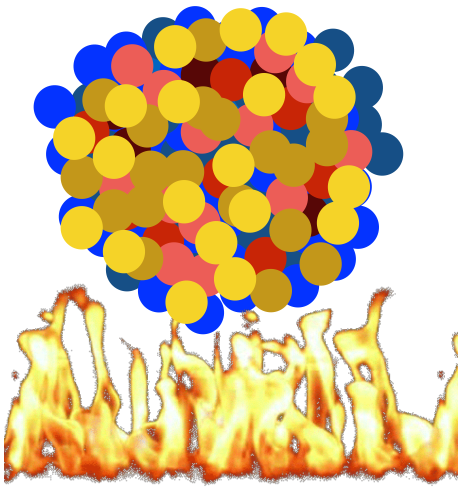

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Compact (neutron) stars

extremely high temperature
extremely high density of (new) particles
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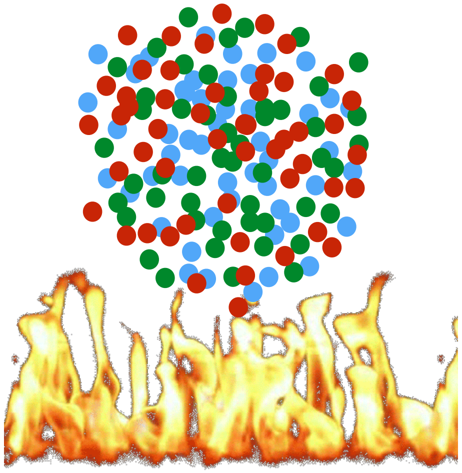
Early Universe

Atomic nucleus in extreme conditions



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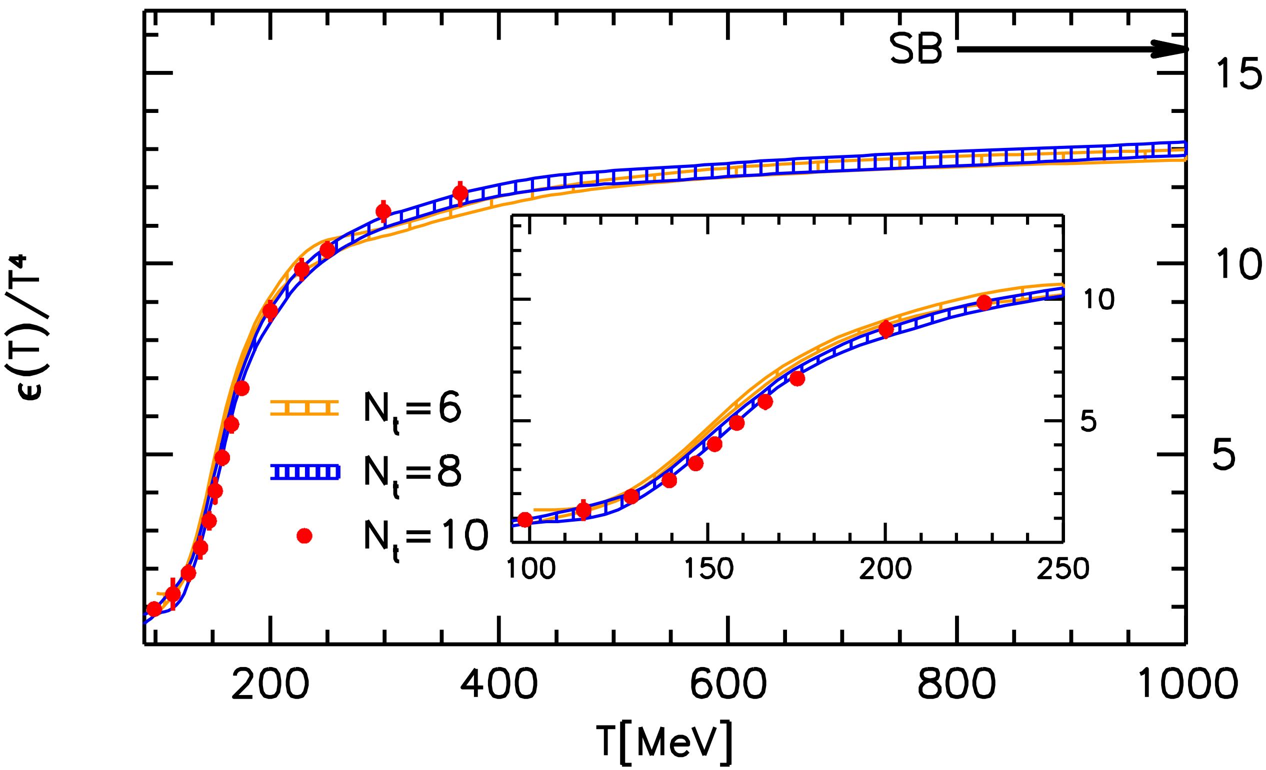
Early Universe
Quark-Gluon plasma

Transition to a new phase

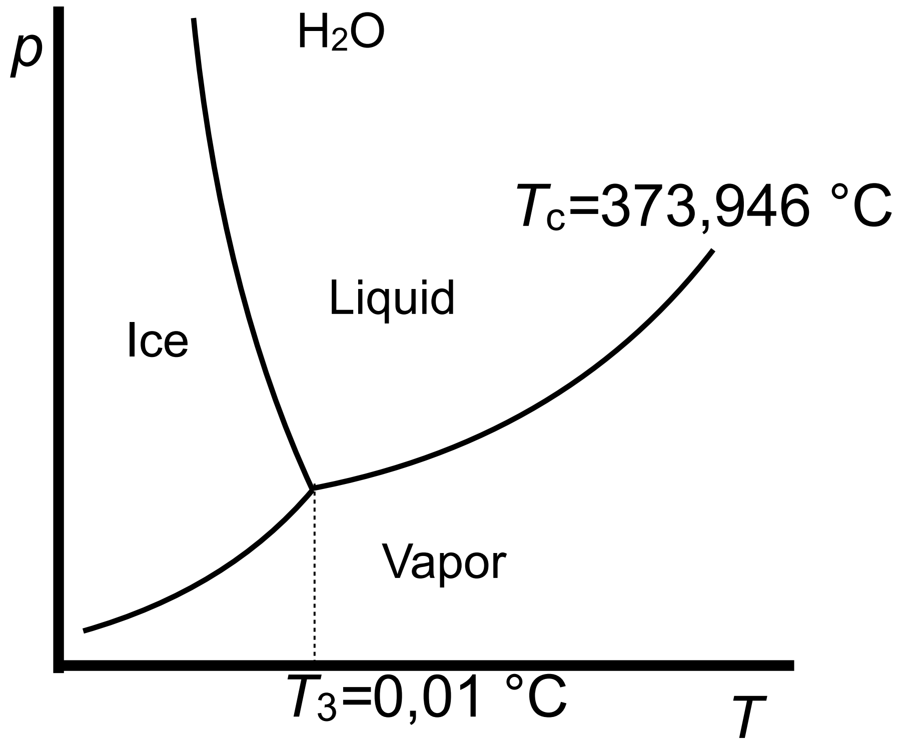
Lattice QCD: fast increase of $\varepsilon(T)$ at $T \approx 160$ MeV (2.10^{12} K)

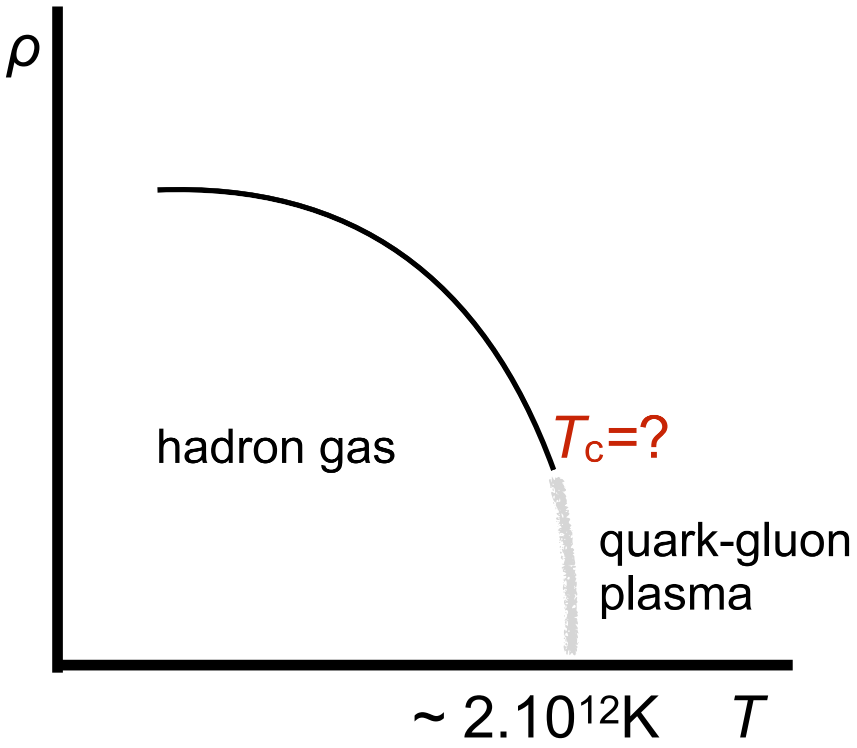


[S. Borsányi et al., JHEP 1011:077 (2010)]

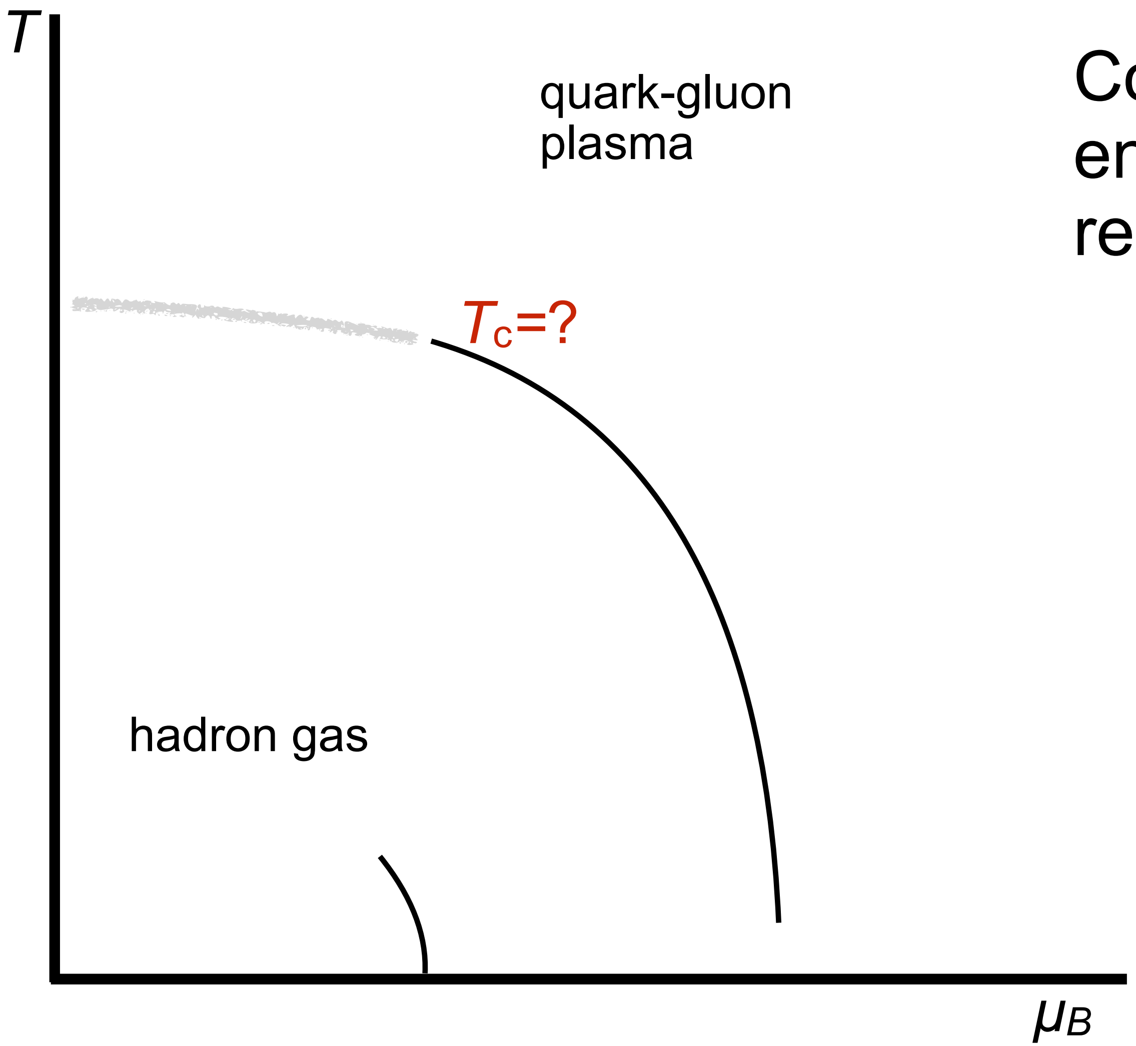
- confinement of quarks at low temperature
- deconfinement of quarks and gluons at high temperature
- quark-gluon plasma

Phase diagram





Phase diagram and heavy-ion collisions



Collisions at different energies probe different regions of the phase diagram

net baryon density parametrised with chemical potential

$$\frac{\rho_B}{\rho_{\bar{B}}} \propto \exp\left(\frac{2\mu_B}{k_B T}\right)$$

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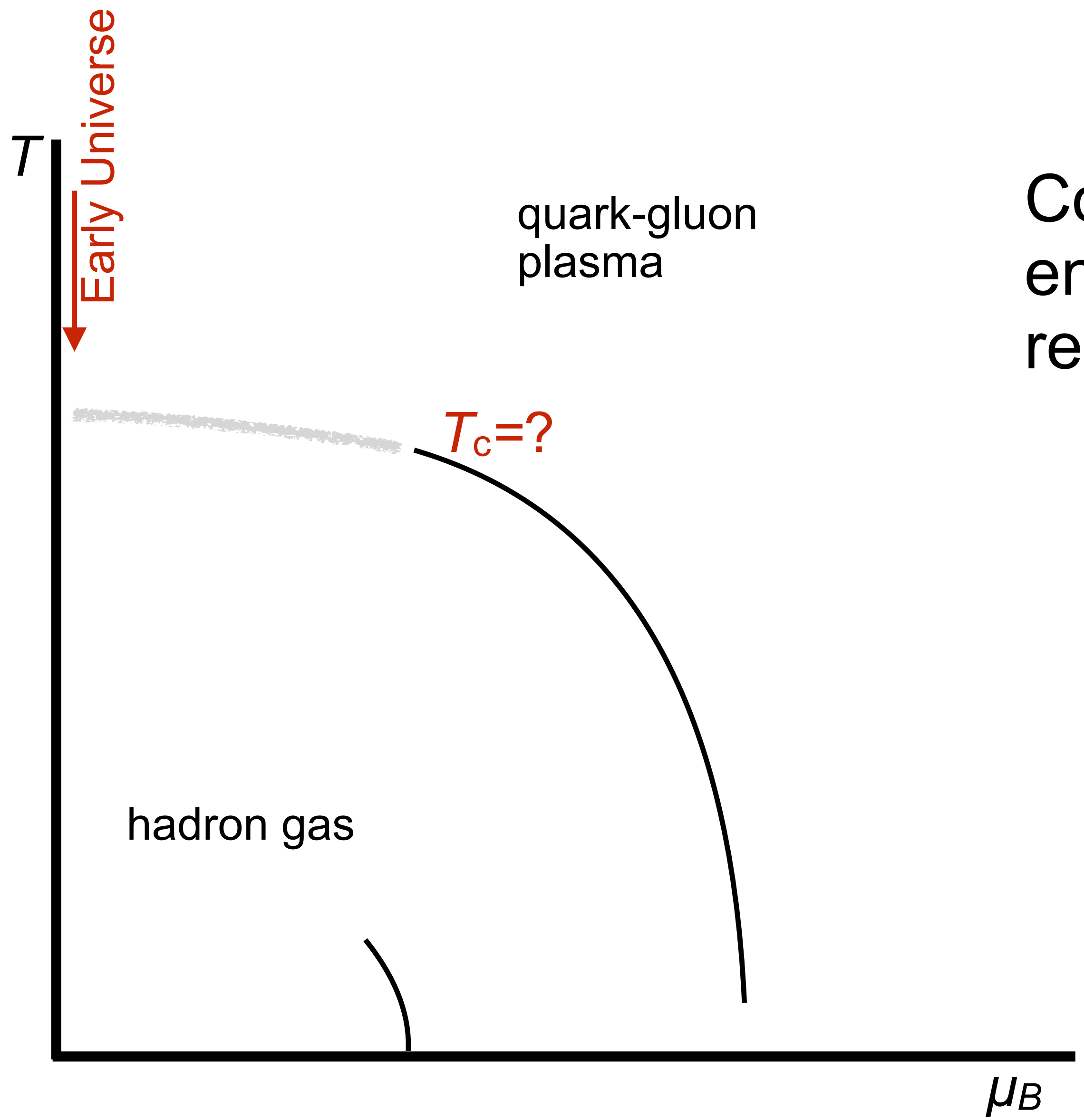

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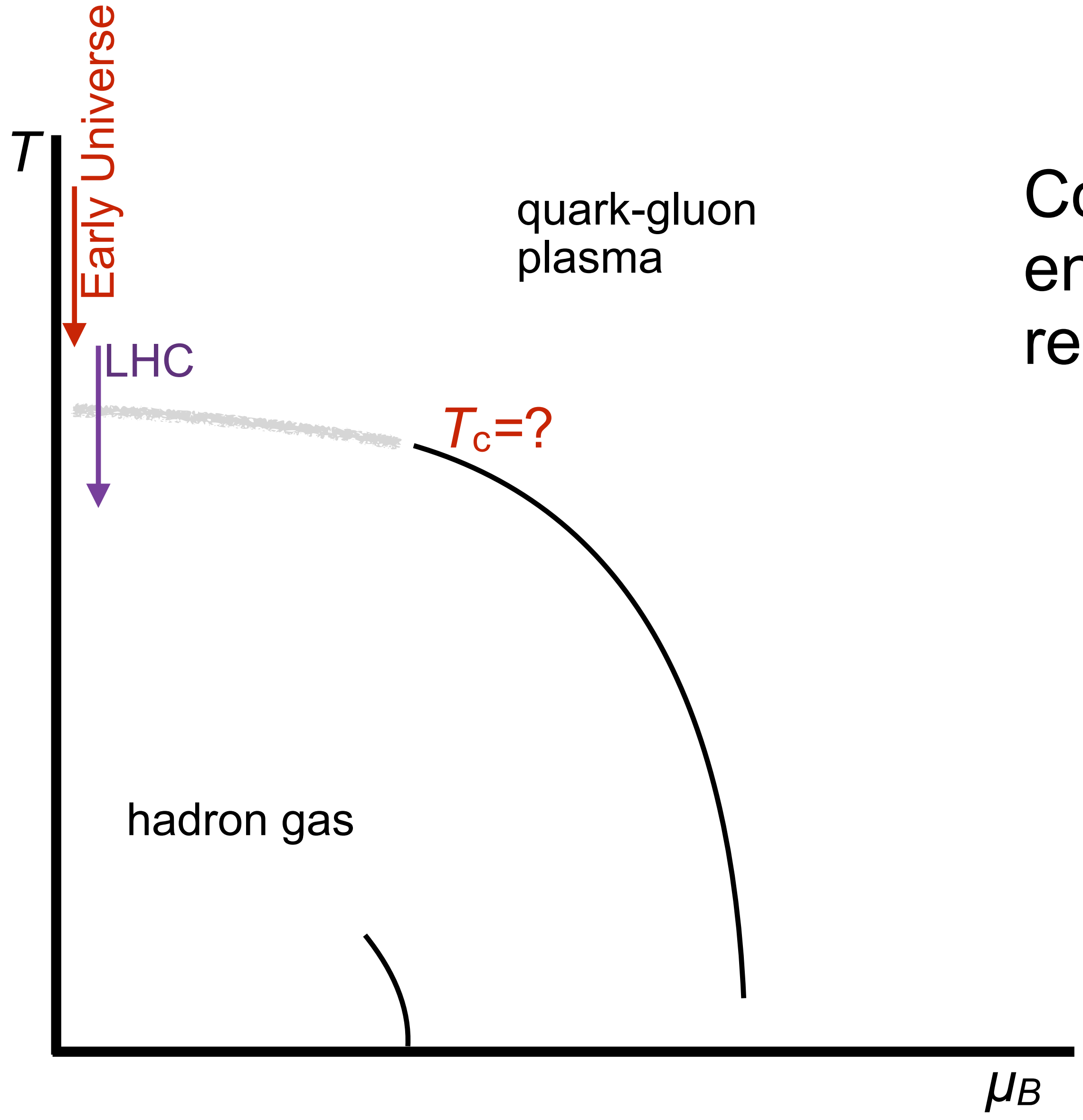

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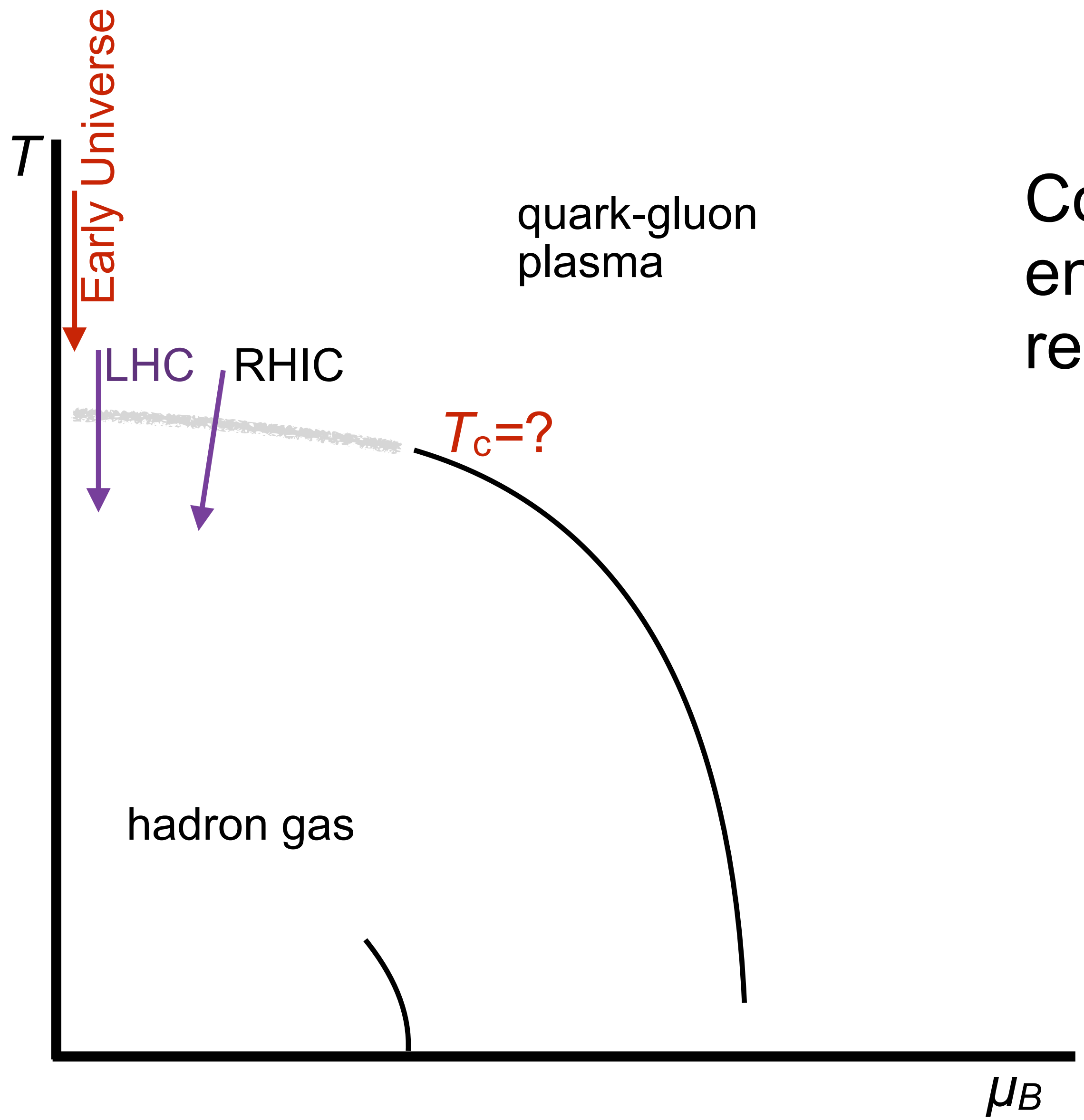

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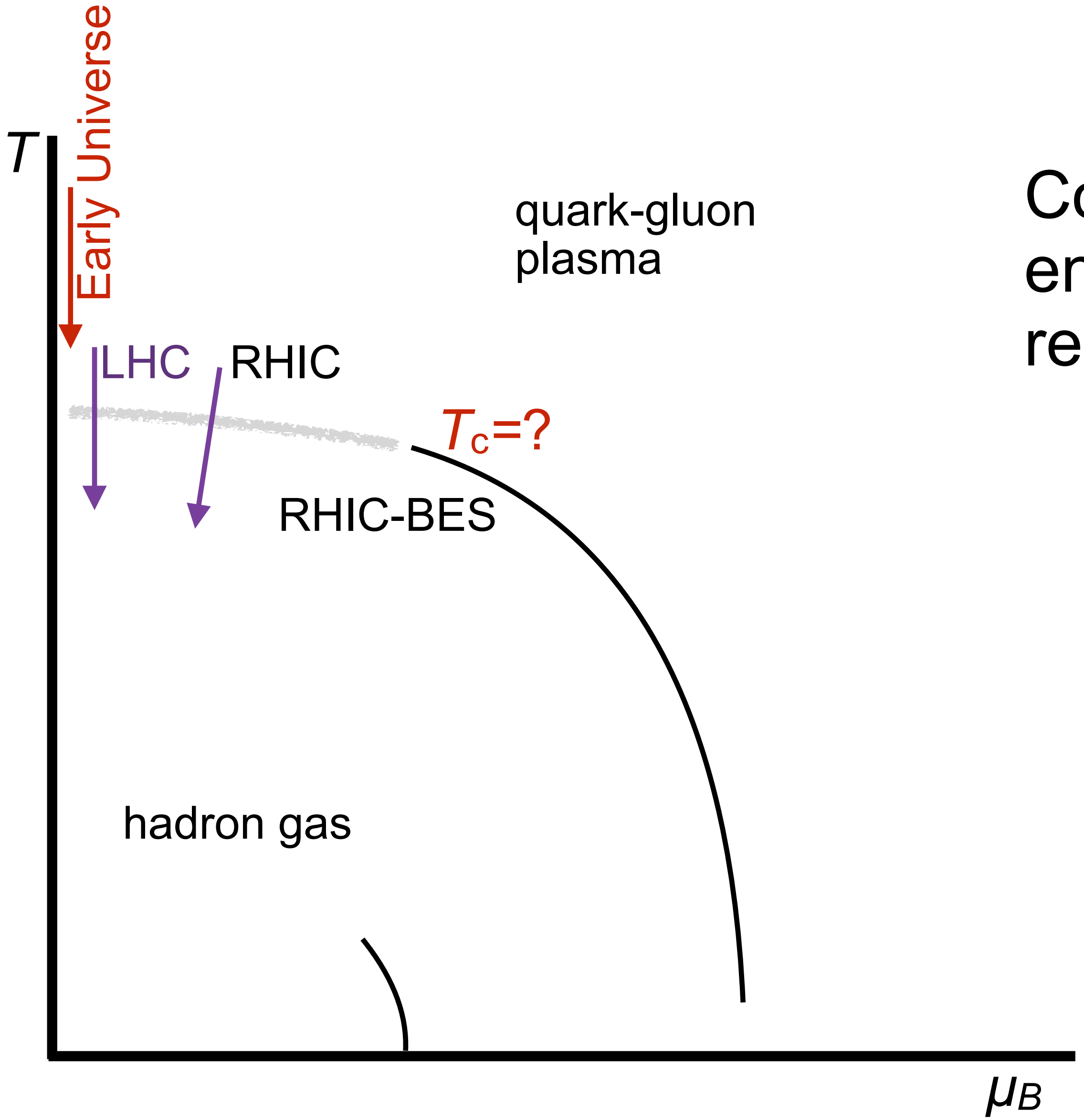

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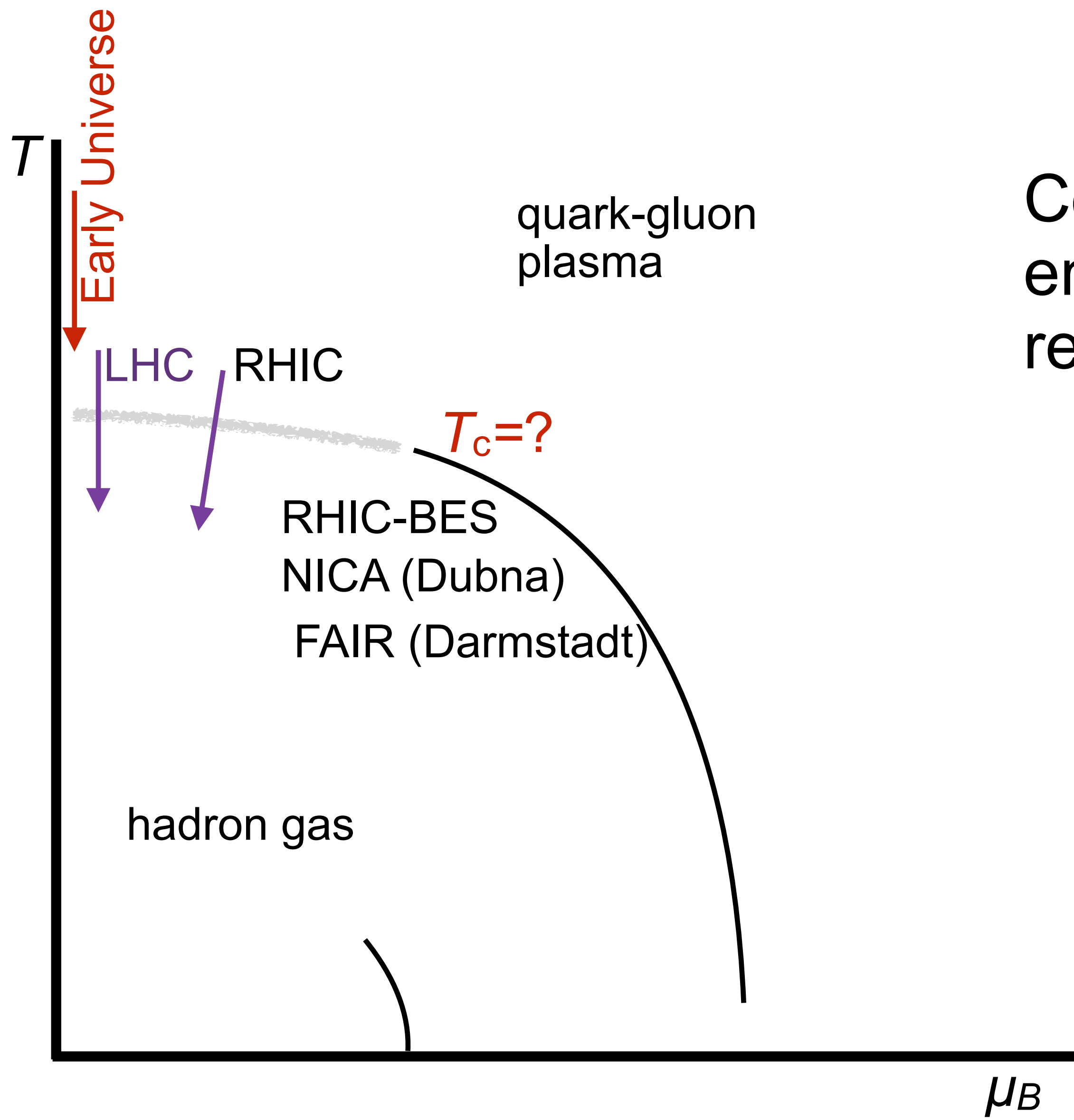

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CERN: colliding heavy ions

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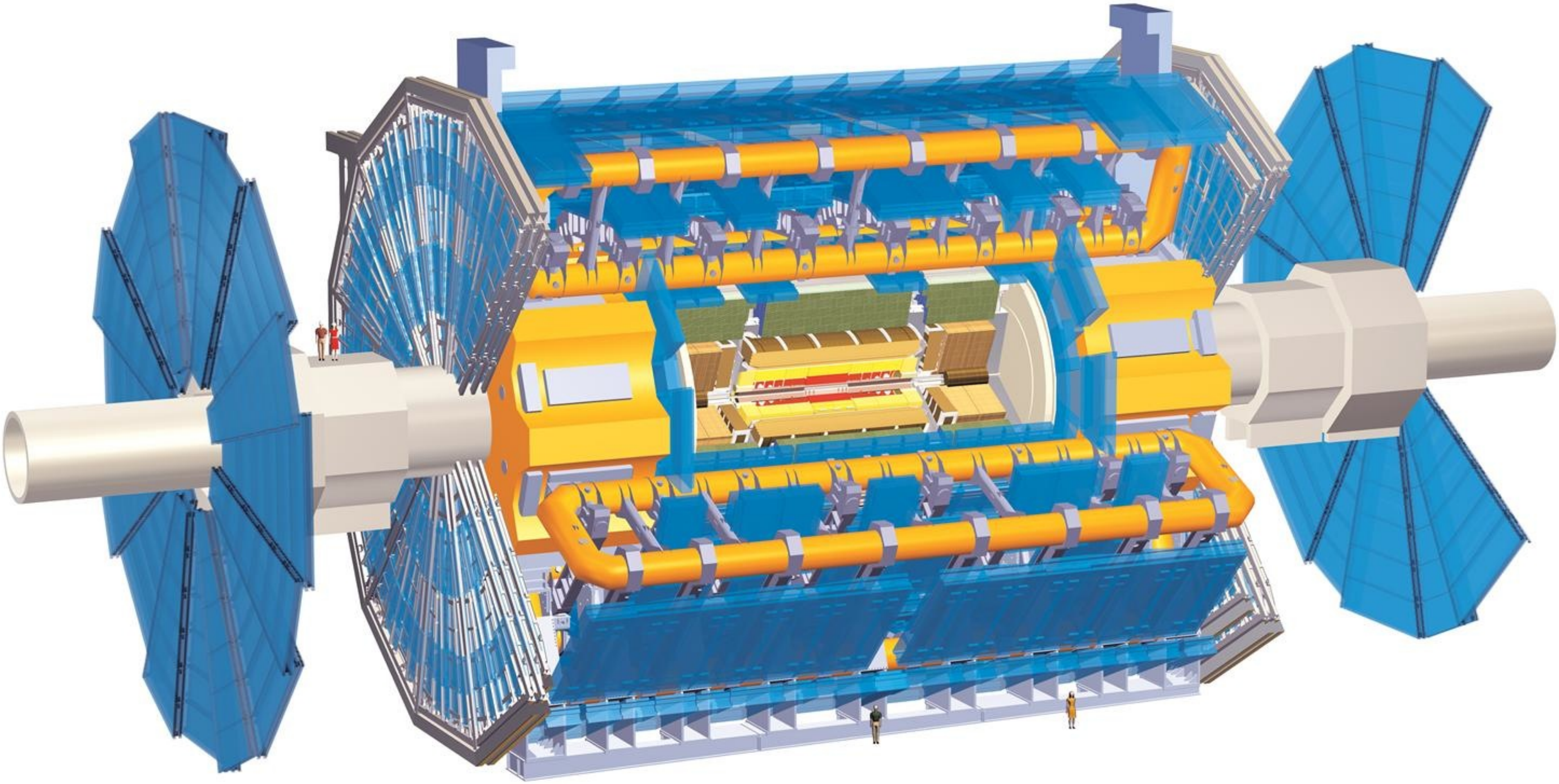
ATLAS experiment



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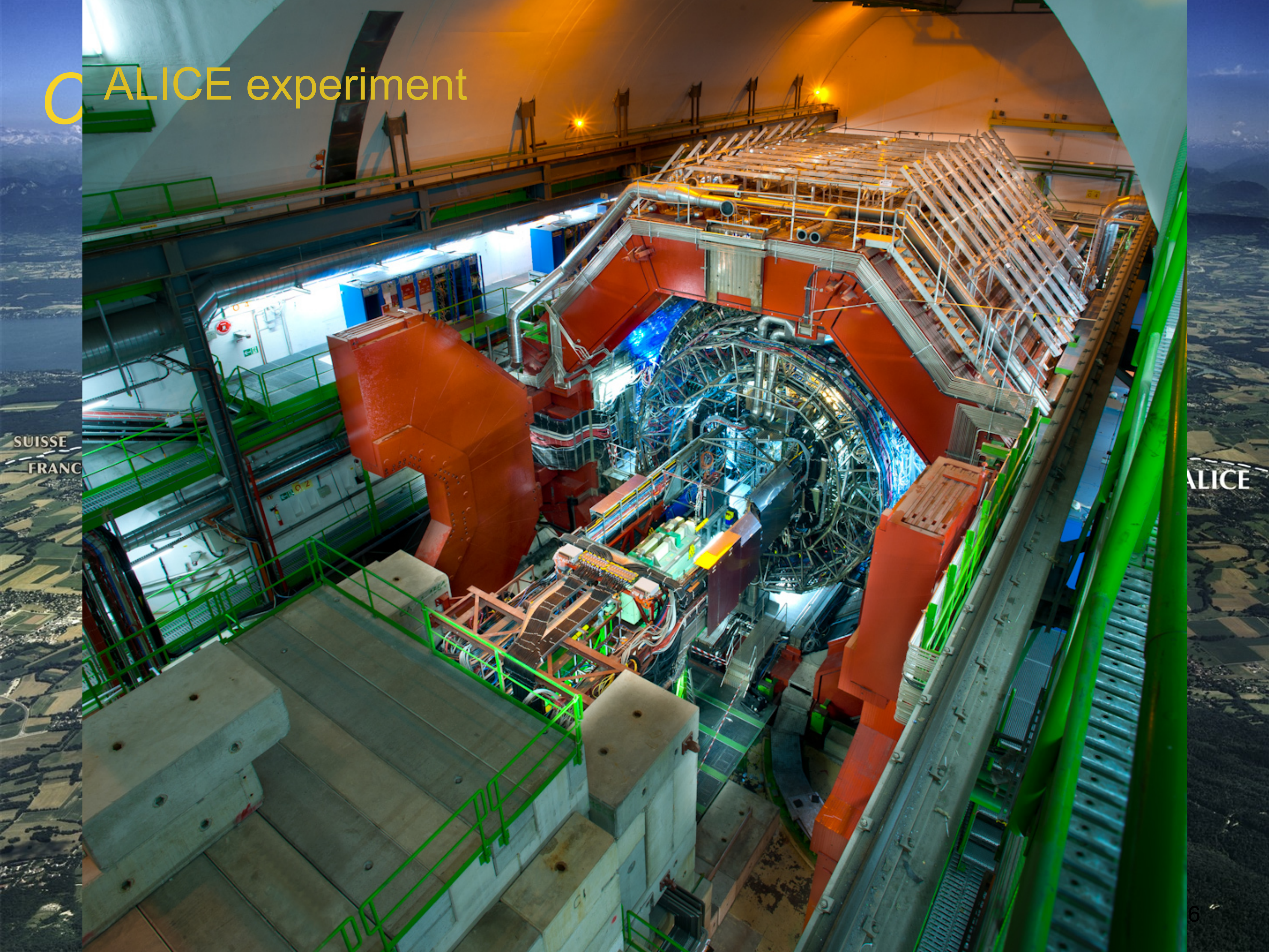

CERN: colliding heavy ions

QGP in lab: nuclear collisions

Simlation of Au+Au collision at 200 GeV per nucleon (RHIC accelerator at BNL)

kinetic calculation: transport simulation UrQMD (only hadronic phase)
animation: Jeffery Mitchell (Brookhaven National Laboratory)

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Collision energy

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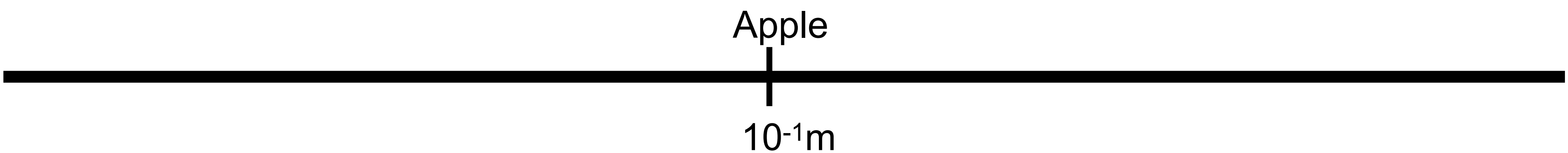

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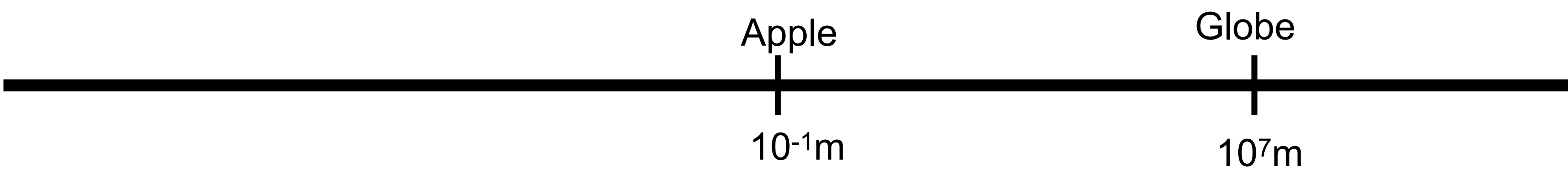

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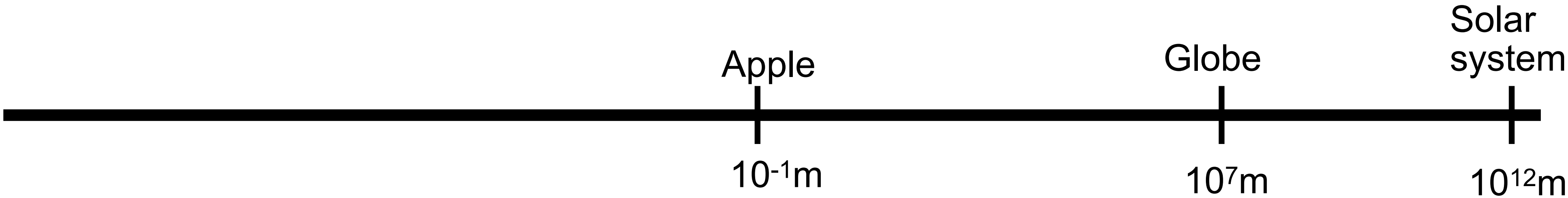

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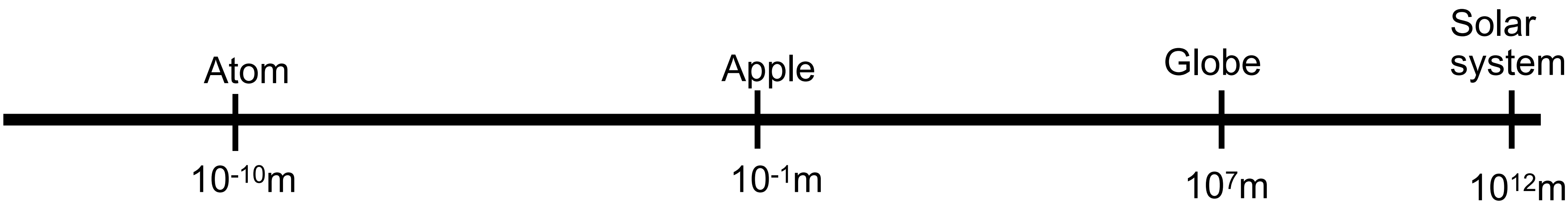

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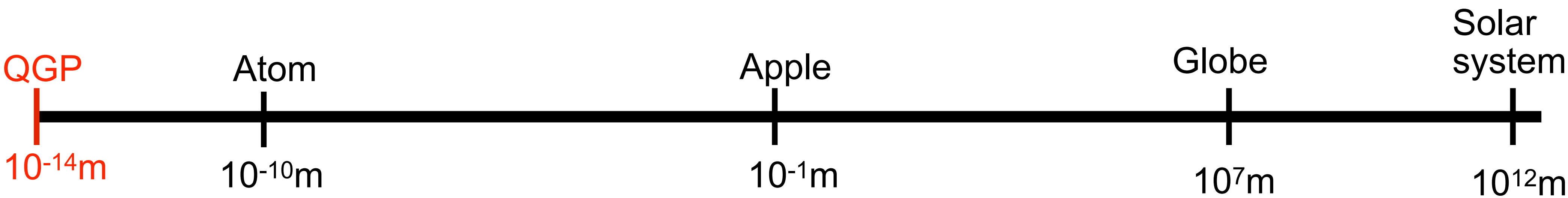

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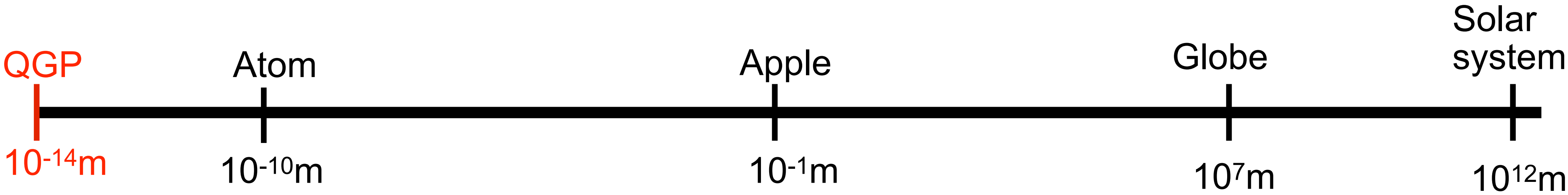
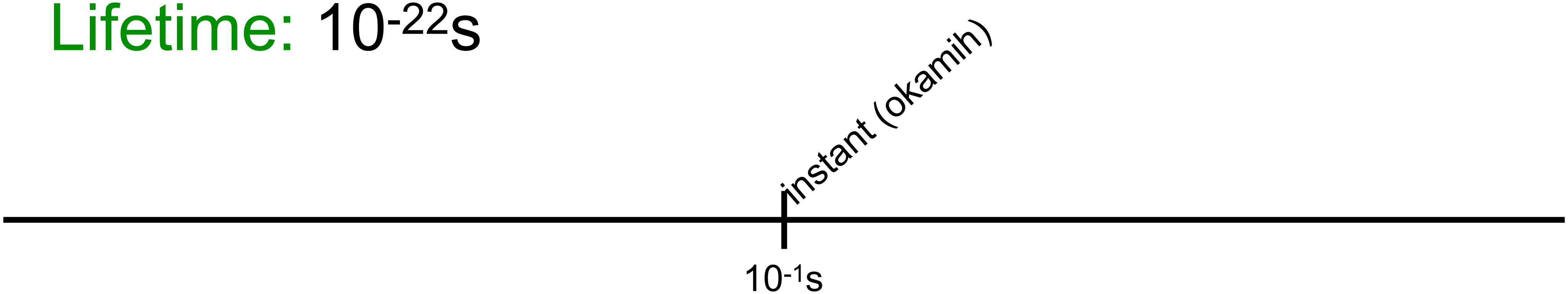


Lifetime: 10^{-22}s



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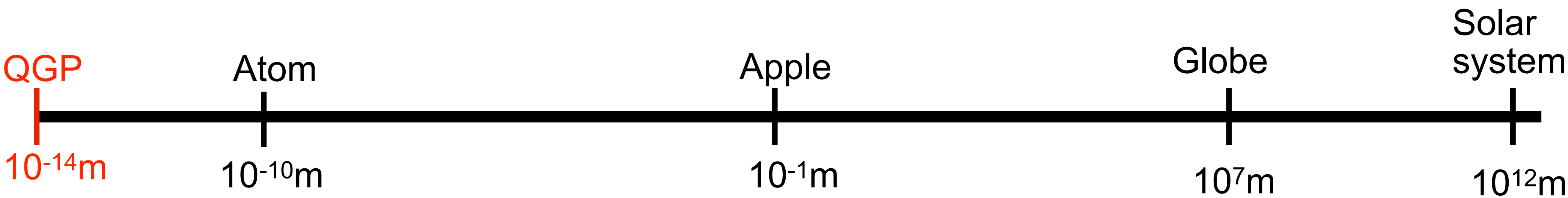

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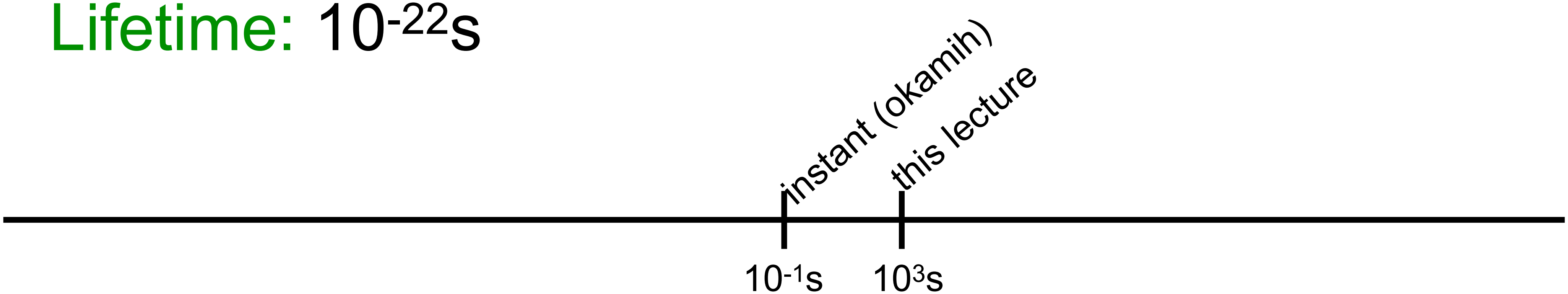

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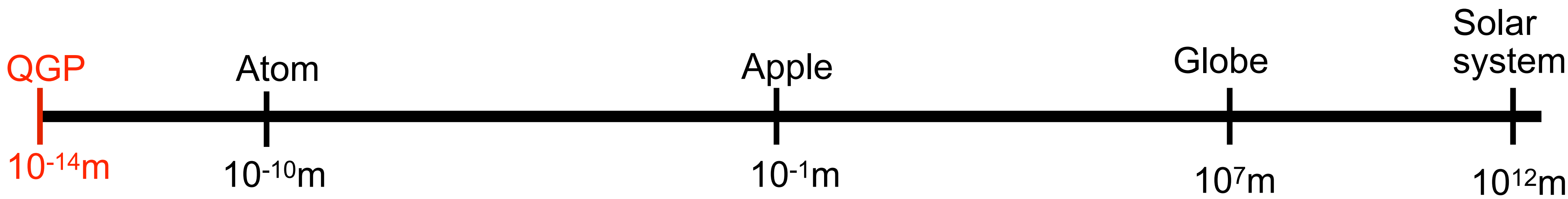

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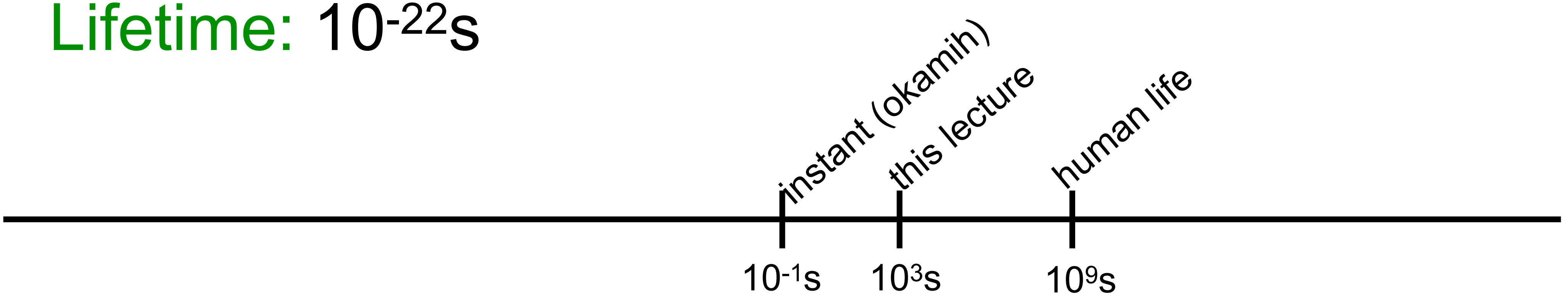

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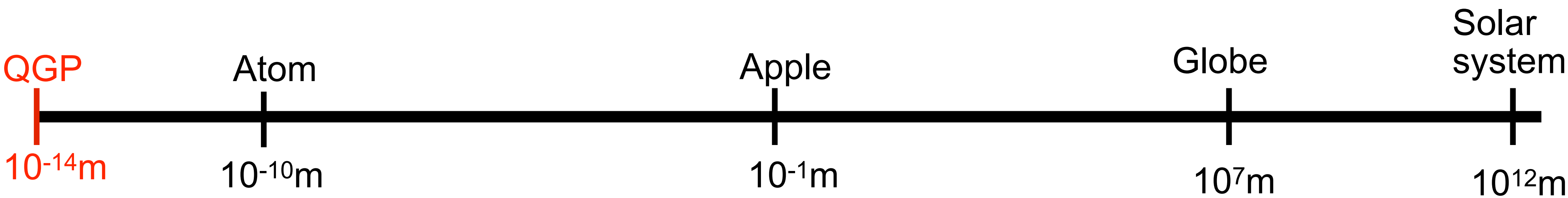

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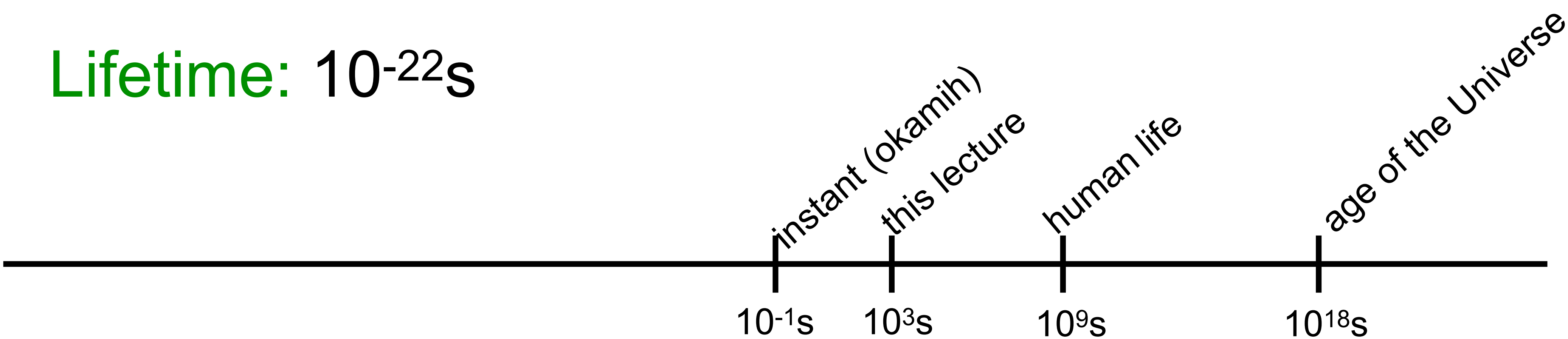

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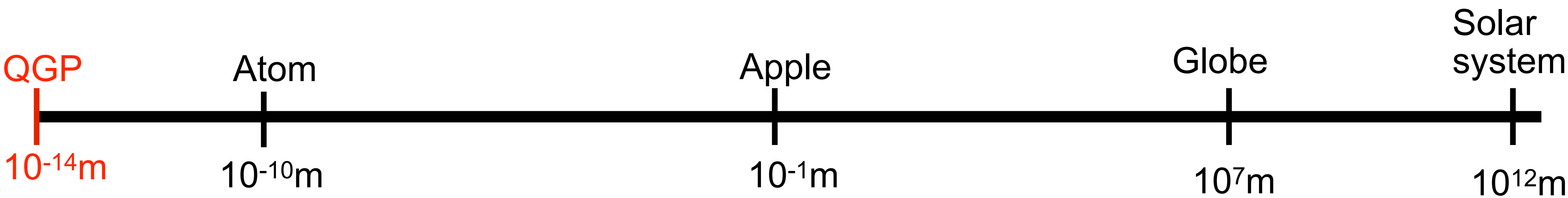

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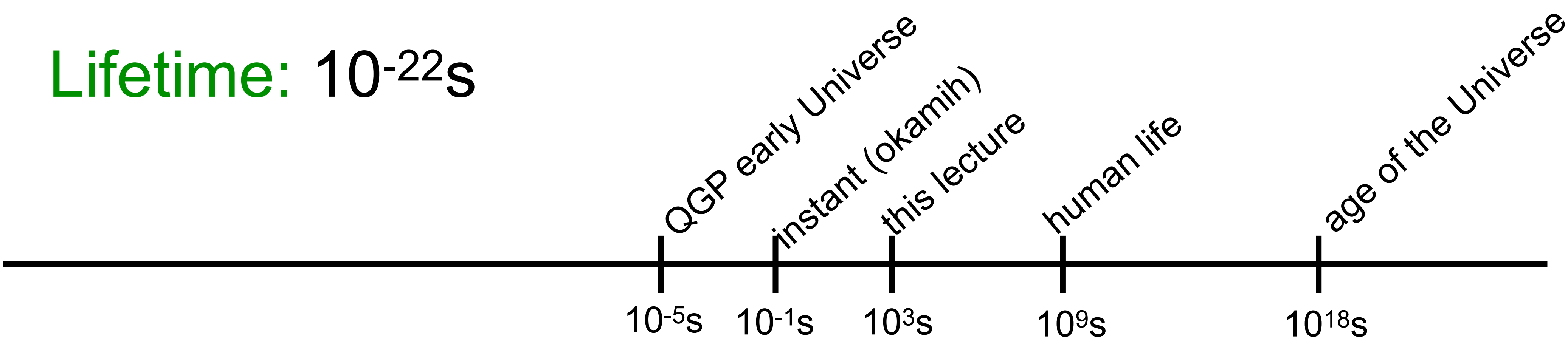

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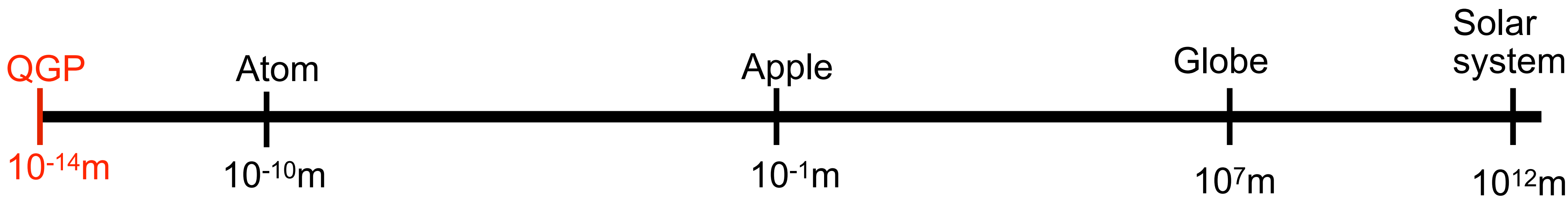

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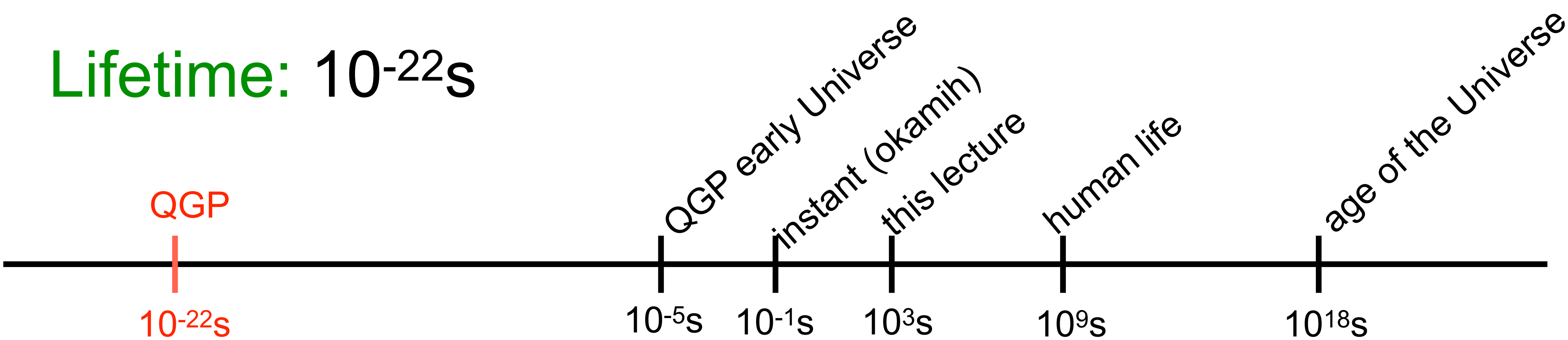

Take-home messages

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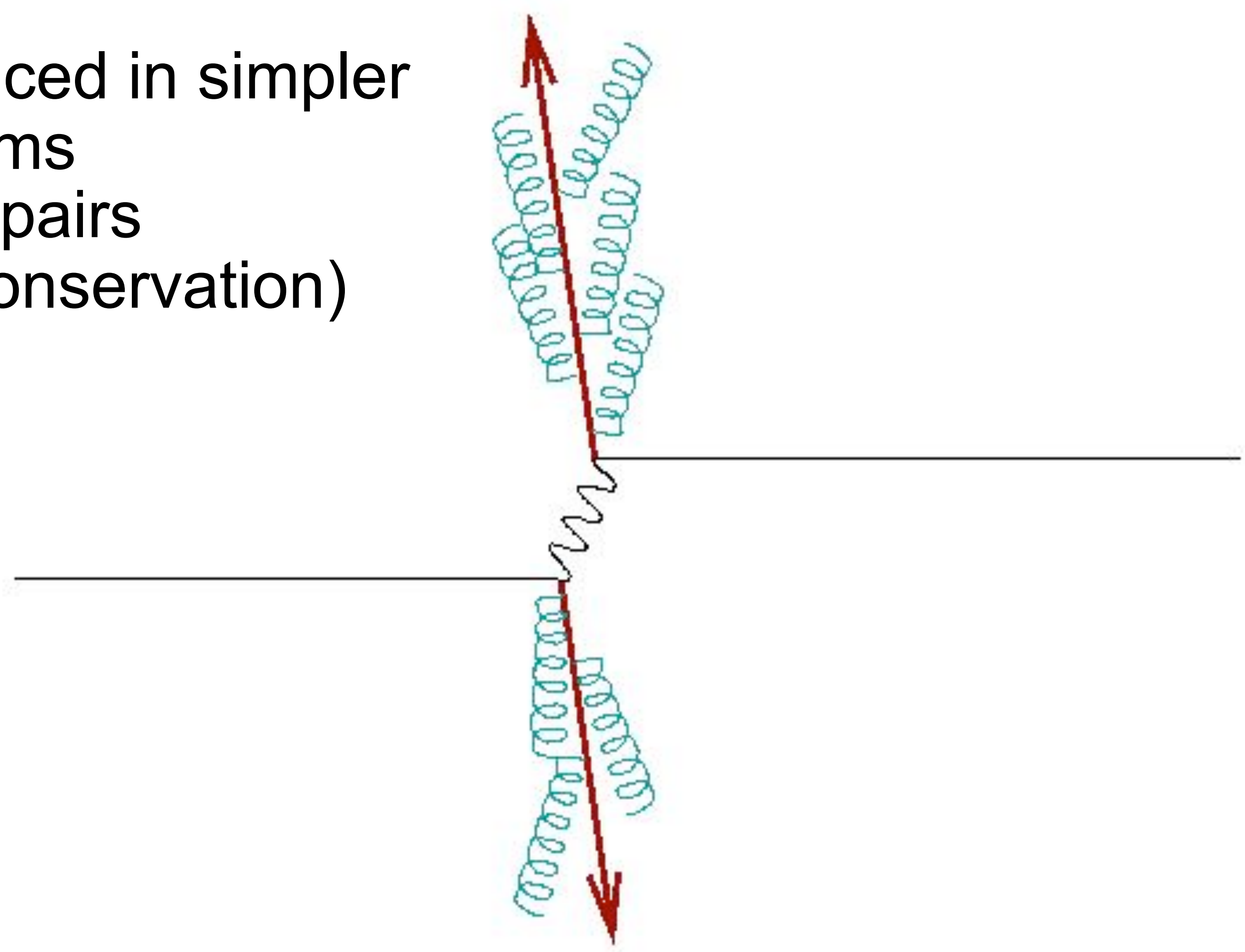
- Quark-gluon plasma filled the early Universe just a few microseconds after the Big Bang

- We want to measure the properties of QGP (Equation of State, viscosities, …)

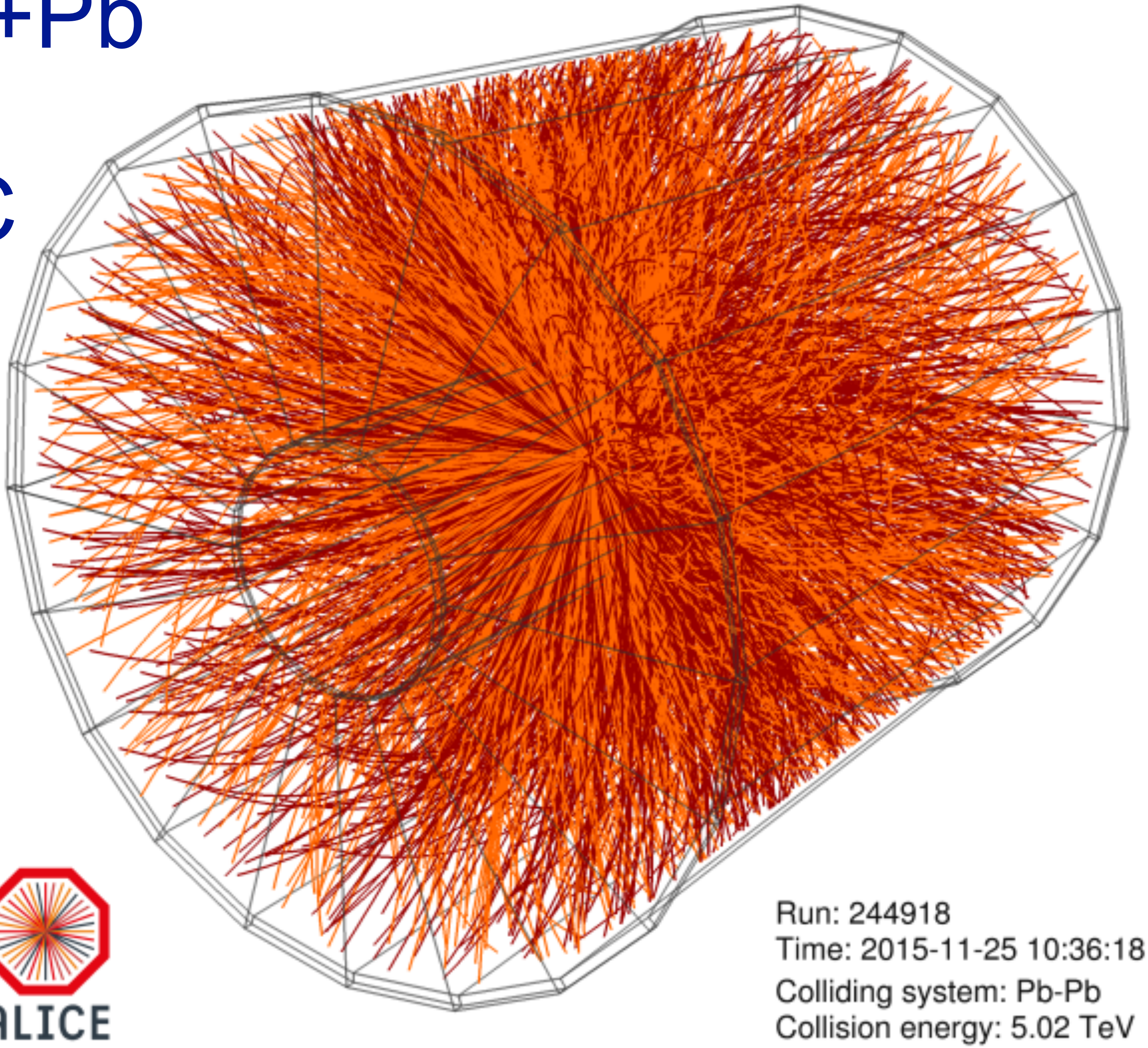
Jet suppression

Jets are produced in simpler collision systems
and always in pairs
(momentum conservation)



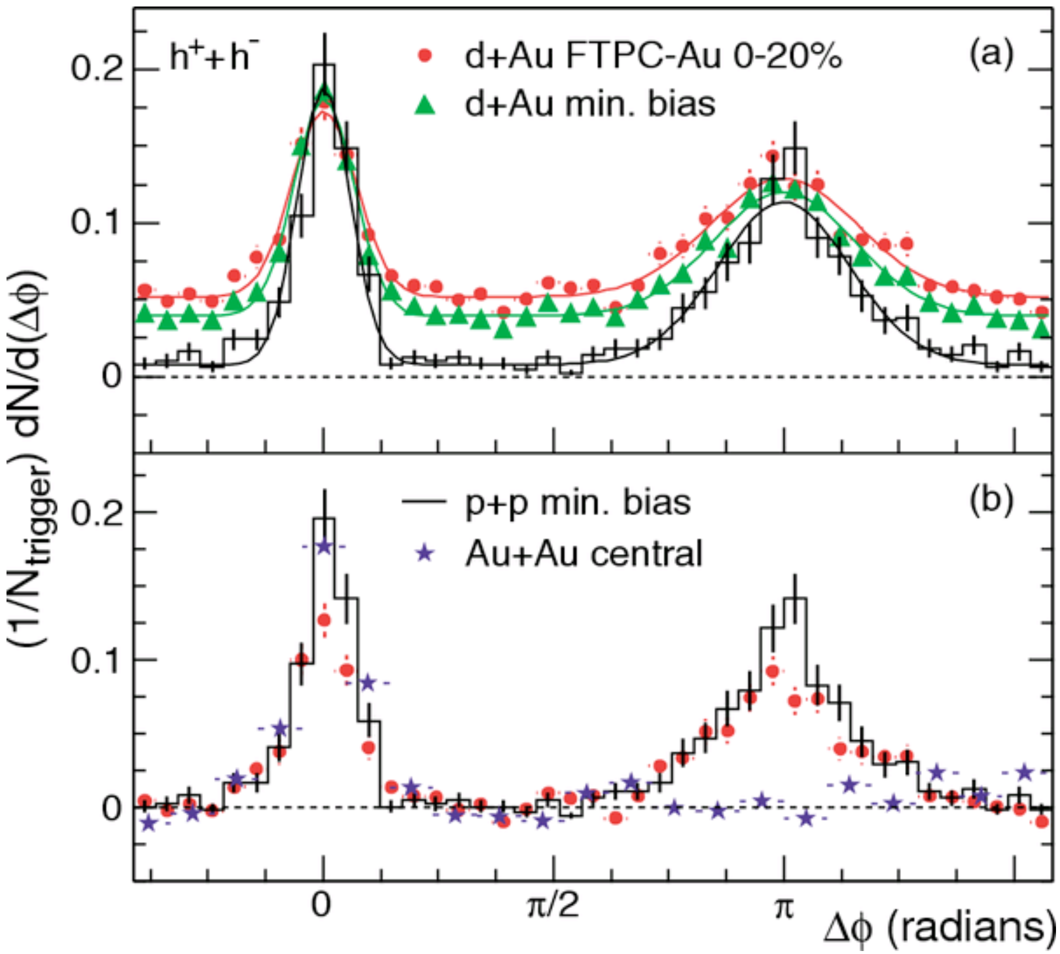
Jets in e^+e^- collision

Jets in Pb+Pb collision at the LHC



ALICE

Jet quenching on the opposite side



[STAR Collaboration, PRL **91** (2003) 072304]

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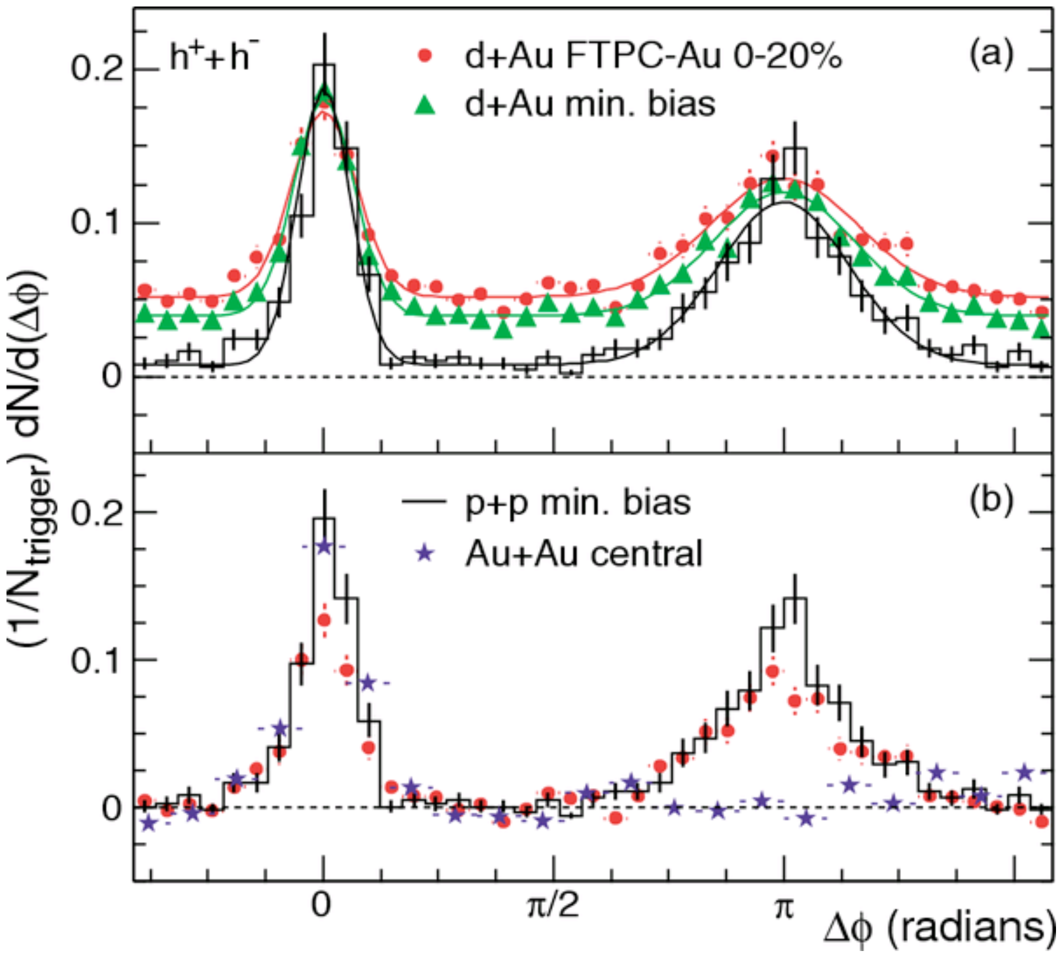

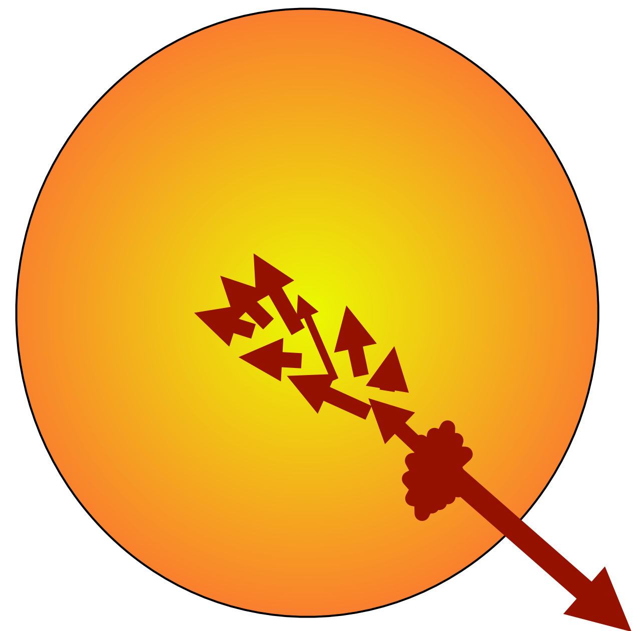

Accompanying jet suppressed

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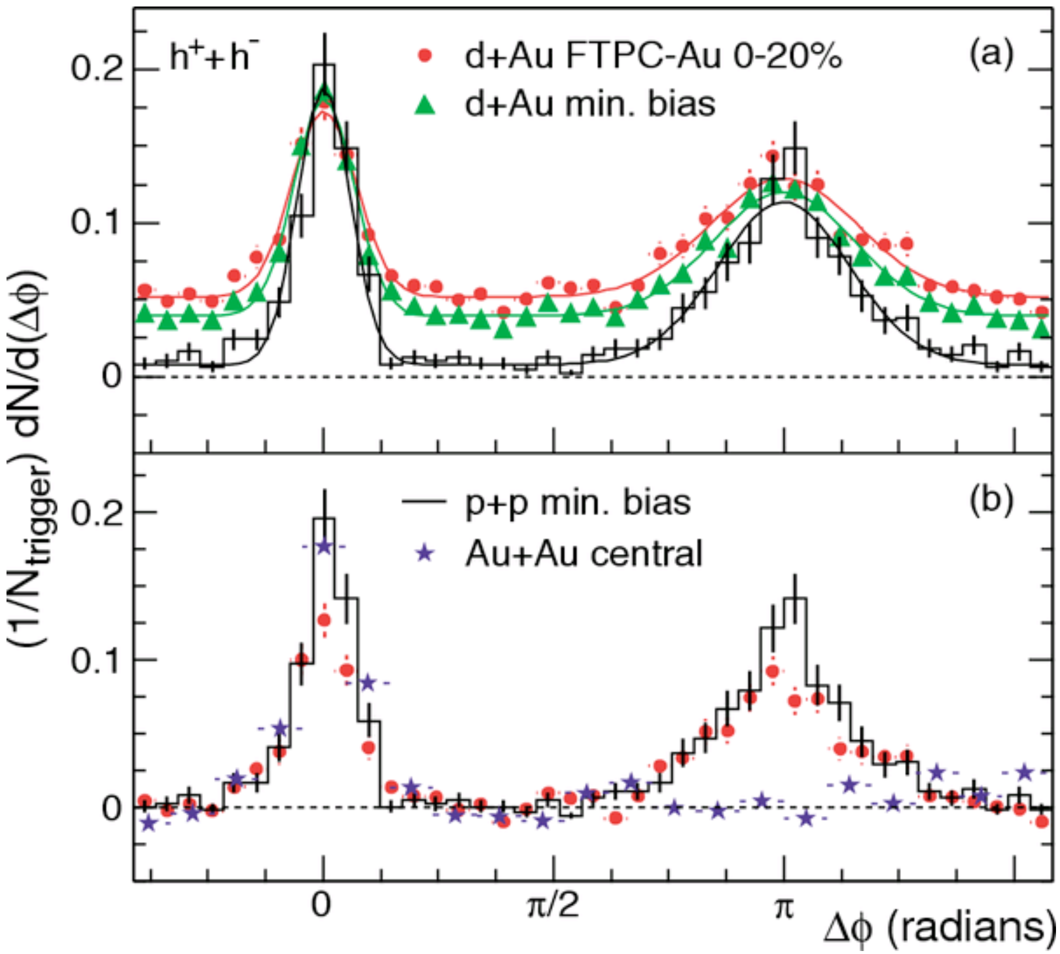

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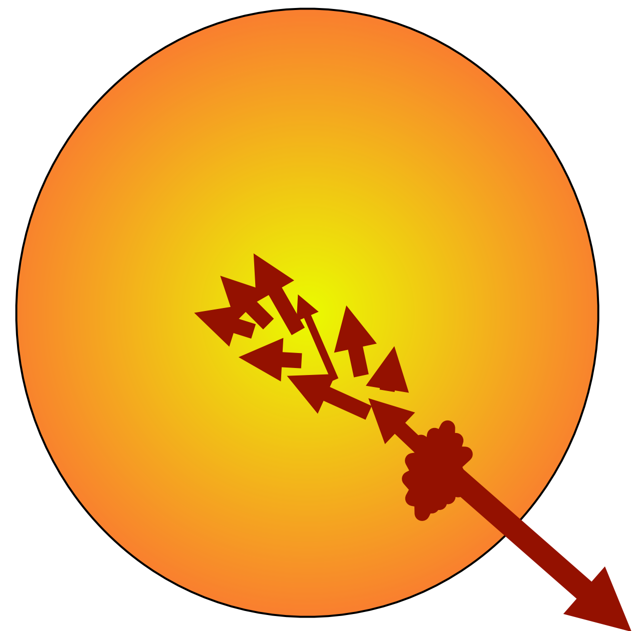
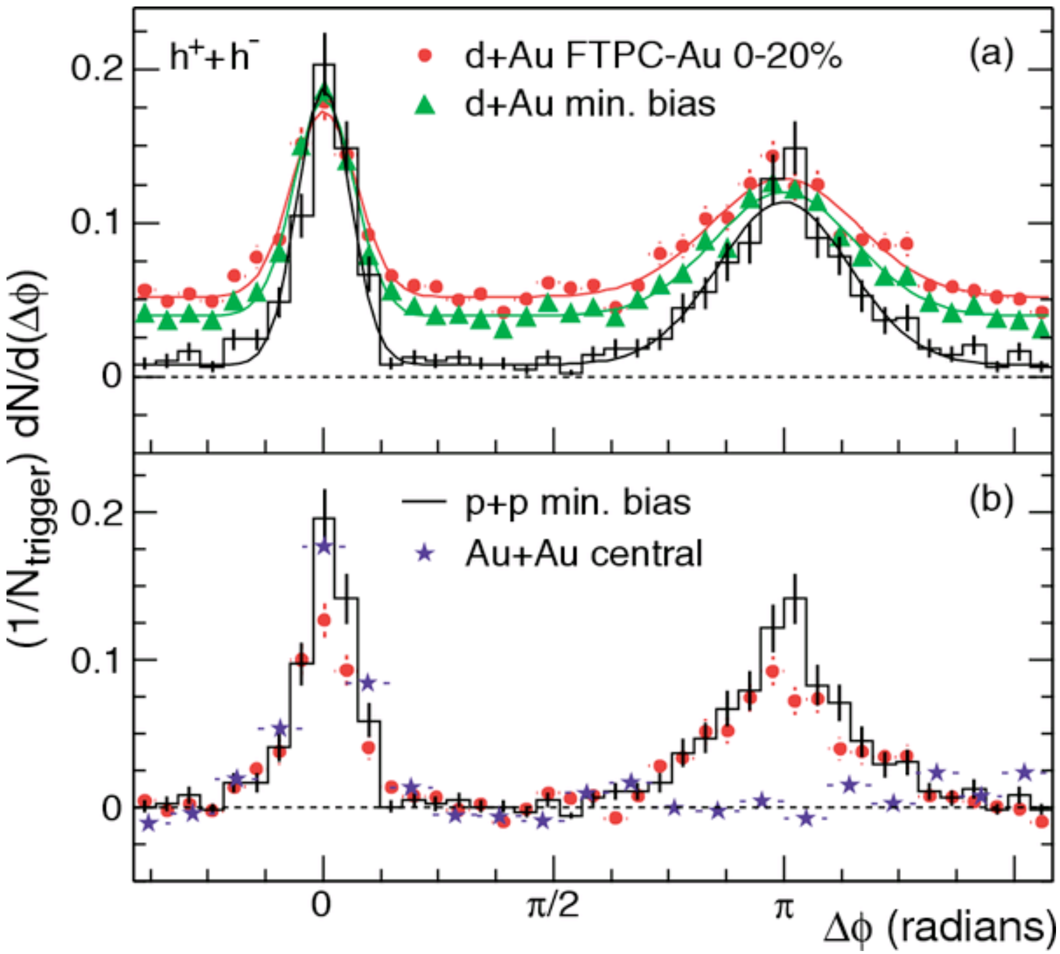


Accompanying jet suppressed

A medium is produced which eats up jets.

Jet quenching on the opposite side



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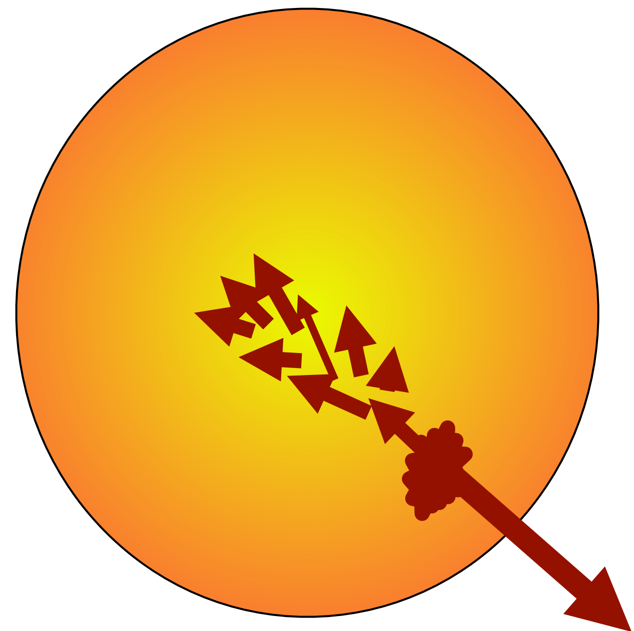

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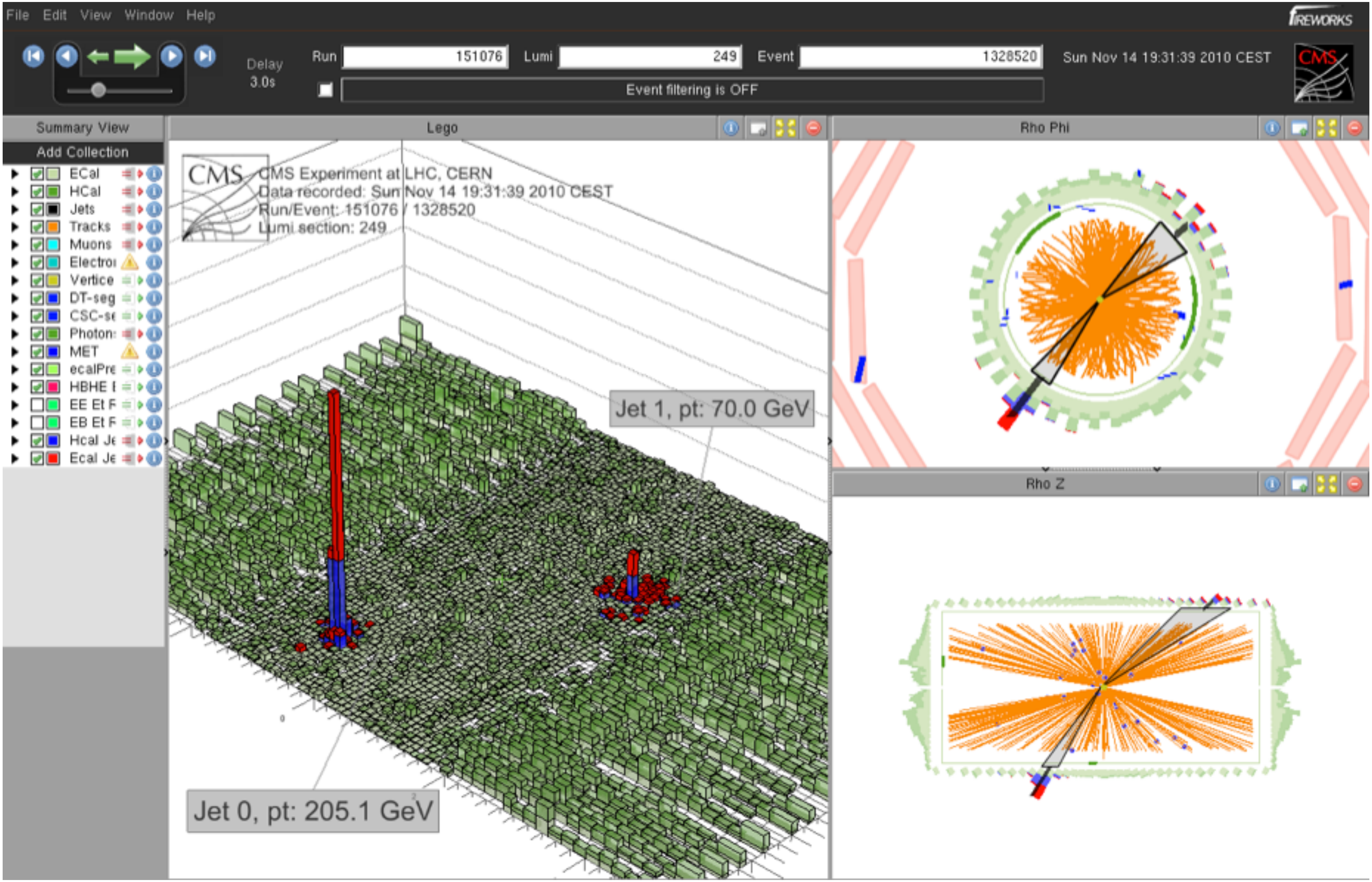
A medium is produced which eats up jets.

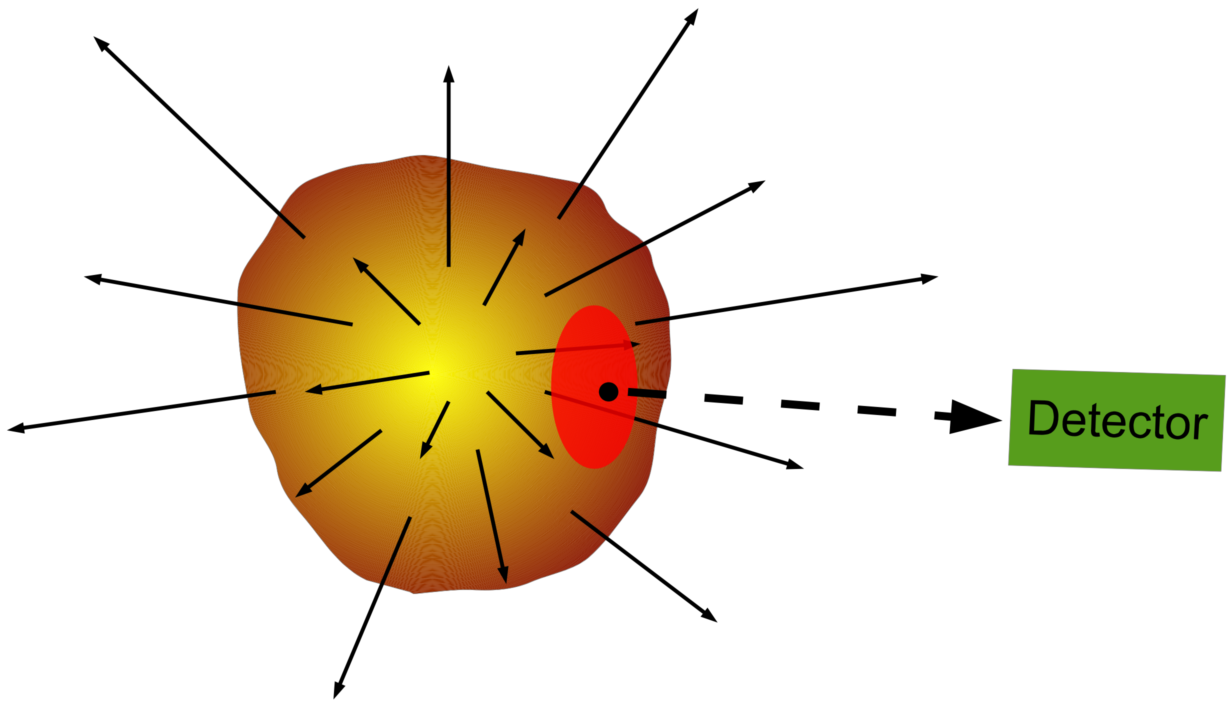
The only medium capable of that is **quark-gluon plasma**.

Strong jet quenching at the LHC (CMS)



Expansion of hot matter

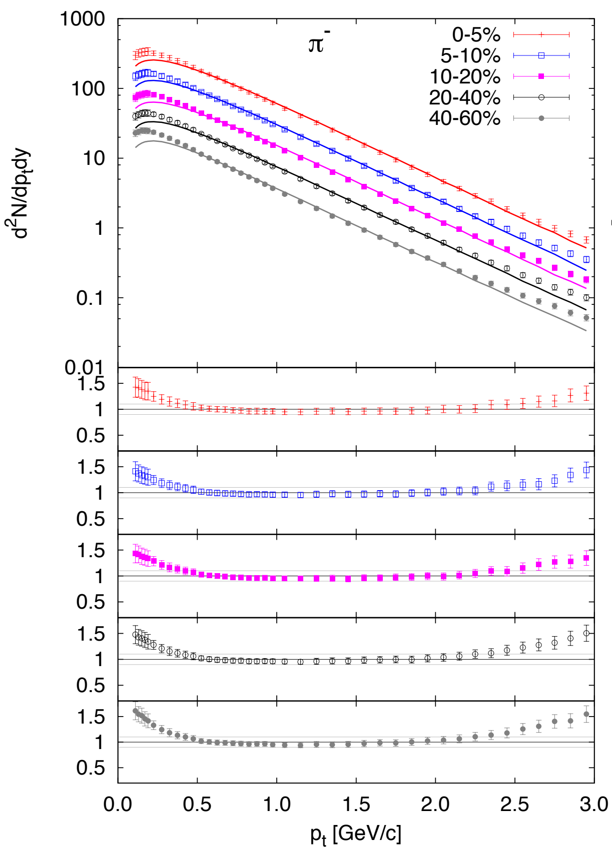
Expansion influences the distribution of produced particles via Doppler blue shift.

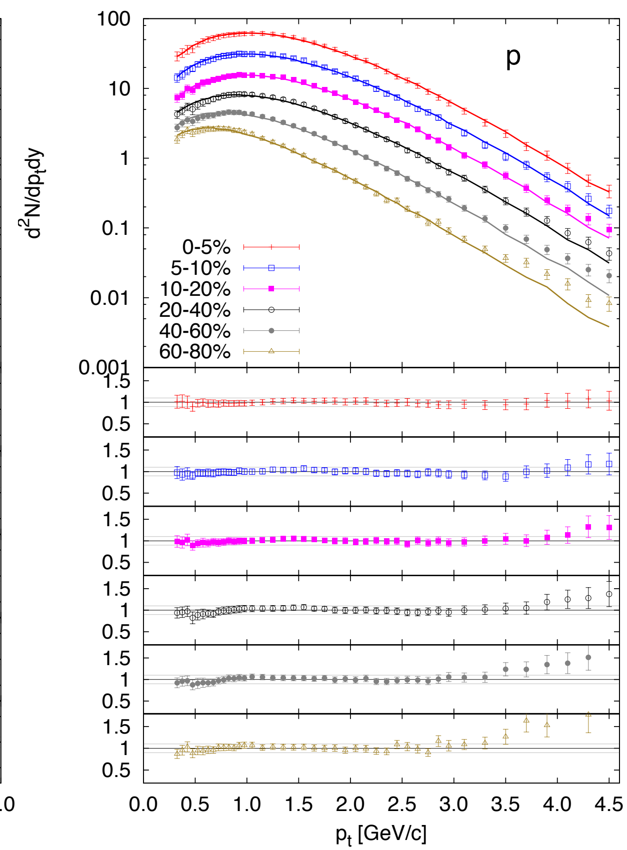


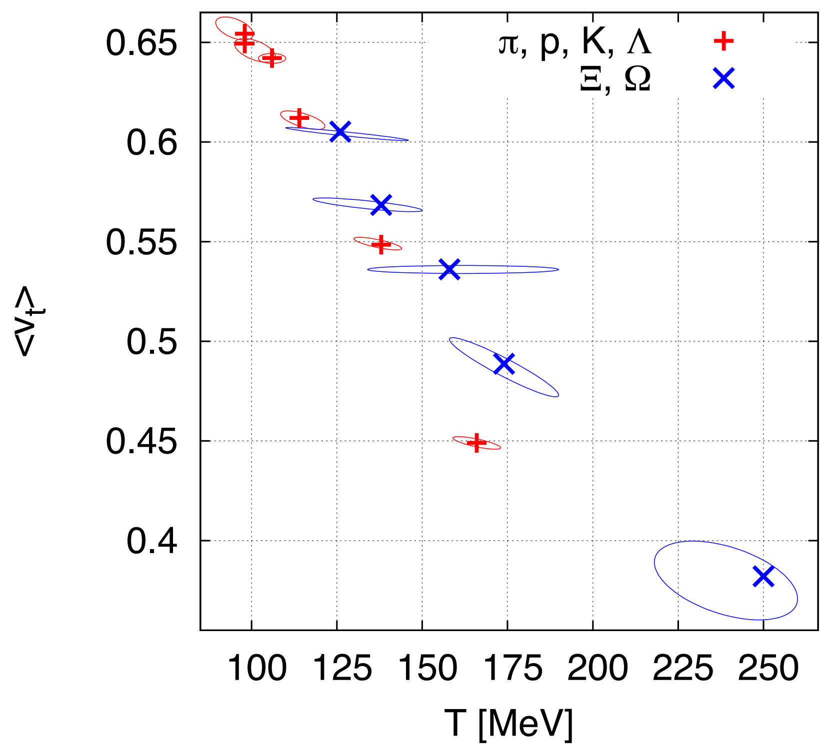
Particles with given momentum are produced only from the corresponding region of homogeneity.

Spectra in transverse momentum

Fit to data from Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the Blast Wave model: locally thermalised fireball and transverse expansion



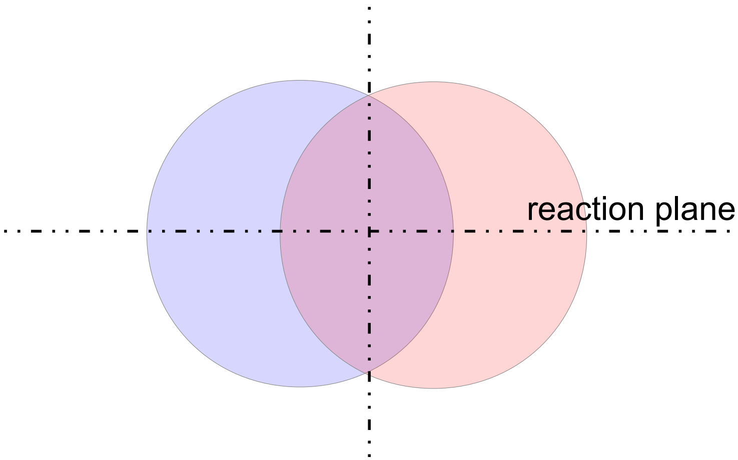




Data: ALICE Collaboration
Fit: I. Melo, B. Tomášik, J. Phys. G. **43** (2016) 015102

Elliptic flow

Observation: in non-central collisions
an elliptic anisotropy of hadron distribution



Parametrisation of the distribution of hadrons
in azimuthal angle

$$\frac{d^2N}{p_t dp_t d\phi} = \frac{1}{2\pi} \frac{dN}{p_t dp_t} \left(1 + \sum_{n=1}^{\infty} 2v_n(p_t) \cos(n(\phi - \phi_n))\right)$$

Symmetry constraints for averaging over a large number of events:

- all $\phi_n = 0$
- only even terms are non-vanishing

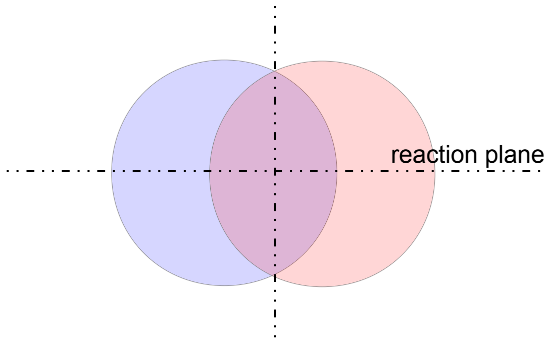
Hydrodynamic model

Assumption: the fireball consists of compressible fluid, its microscopic structure shows up in the Equation of State and transport coefficients

Higher pressure gradient in the reaction plane:

⇒ faster expansion in the reaction plane

⇒ enhanced production in the reaction plane



Energy and momentum conservation

$$\partial_\mu T^\mu = 0$$

Perfect fluid: $T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu / c^2 + p g^{\mu\nu}$

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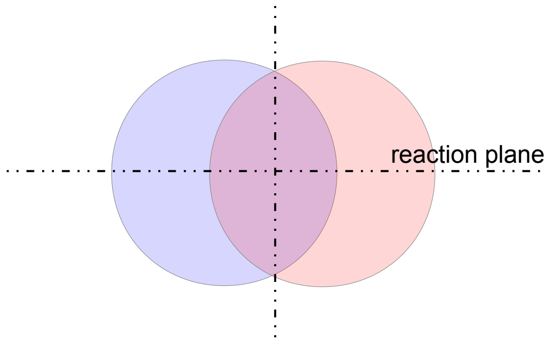

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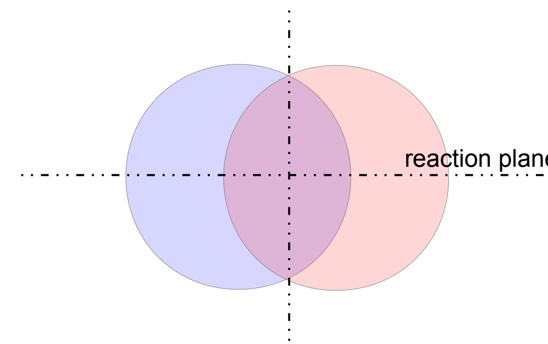

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Five unknowns, ϵ, p, $\vec{v}$, but only four equations!

System complemented by the Equation of State (EoS)

$$p = p(\epsilon)$$

By comparing results to data one obtains information on the EoS

State of the art hydrodynamics

The hydrodynamic model should:

- include viscosity (shear and bulk)
- start with inhomogeneous initial conditions (different from event to event)

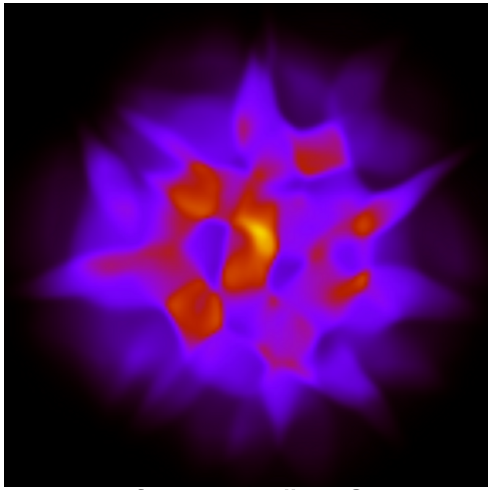


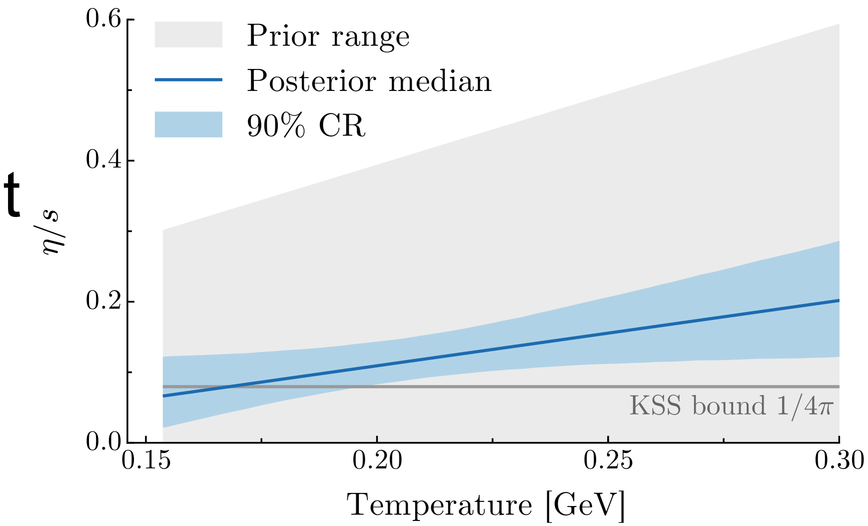
figure: Björn Schenke

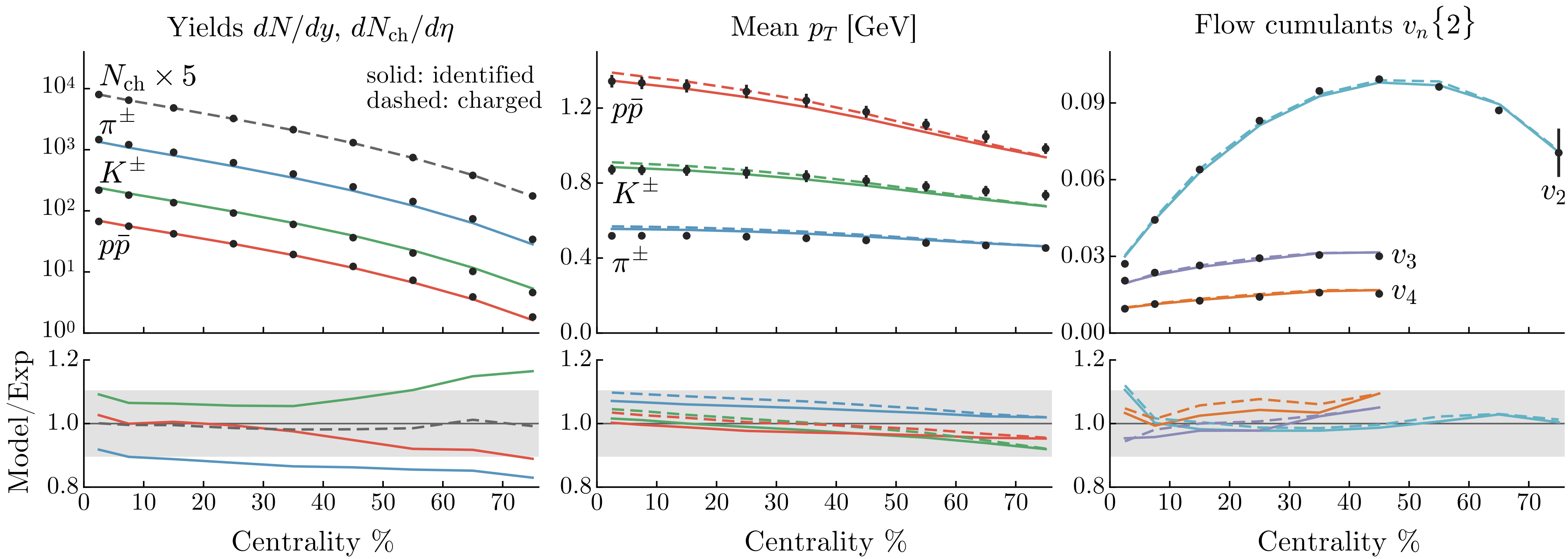
- be 3-dimensional
- Simulation must be performed many times in order to provide good statistics for data analysis
- The production of particles is treated with transport model (which takes into account the possibility that hadrons can scatter)

Comparison theory vs. data

[J.E. Bernhard at al., Phys. Rev. C 94 (2016) 024907]

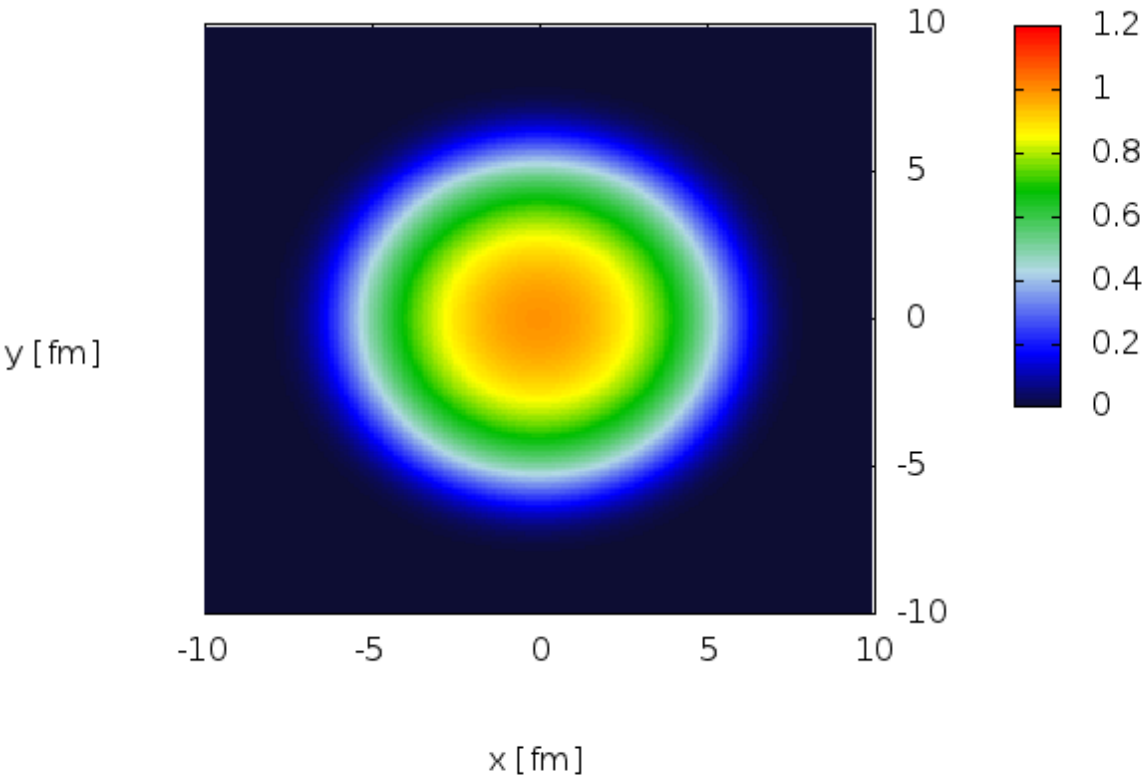
Hybrid model (IC+hydro+transport) generation of 300 events with different parameters & procedure to find best parameters by comparison to data:
Results on IC, viscosities, $T_{hadronisation}$

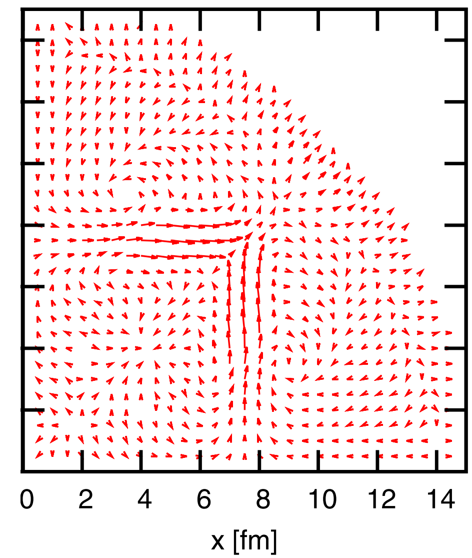


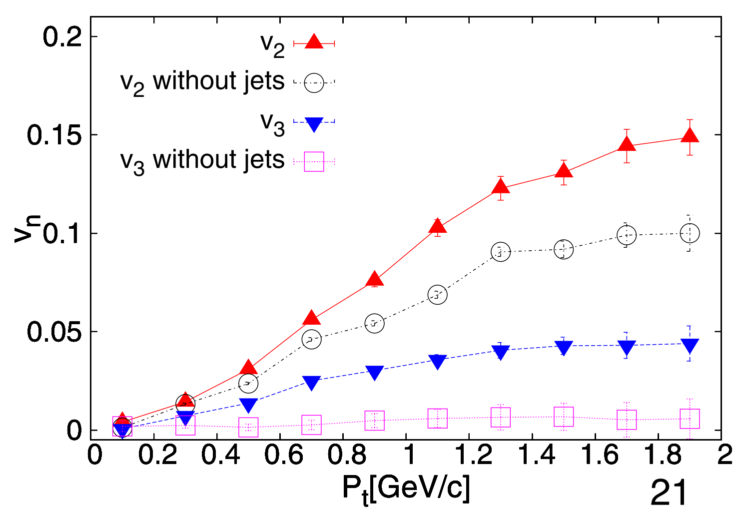


Jets + fluid = anisotropies

At the LHC energies, many partons with high p_t fly through QGP.
They deposit their momentum and energy into plasma and make it flow.







The produced anisotropies are important for quantitative analyses!

M. Schulc, B. Tomášik: J. Phys. G **40** (2013) 125104,
Phys. Rev. C **90** (2014) 064910

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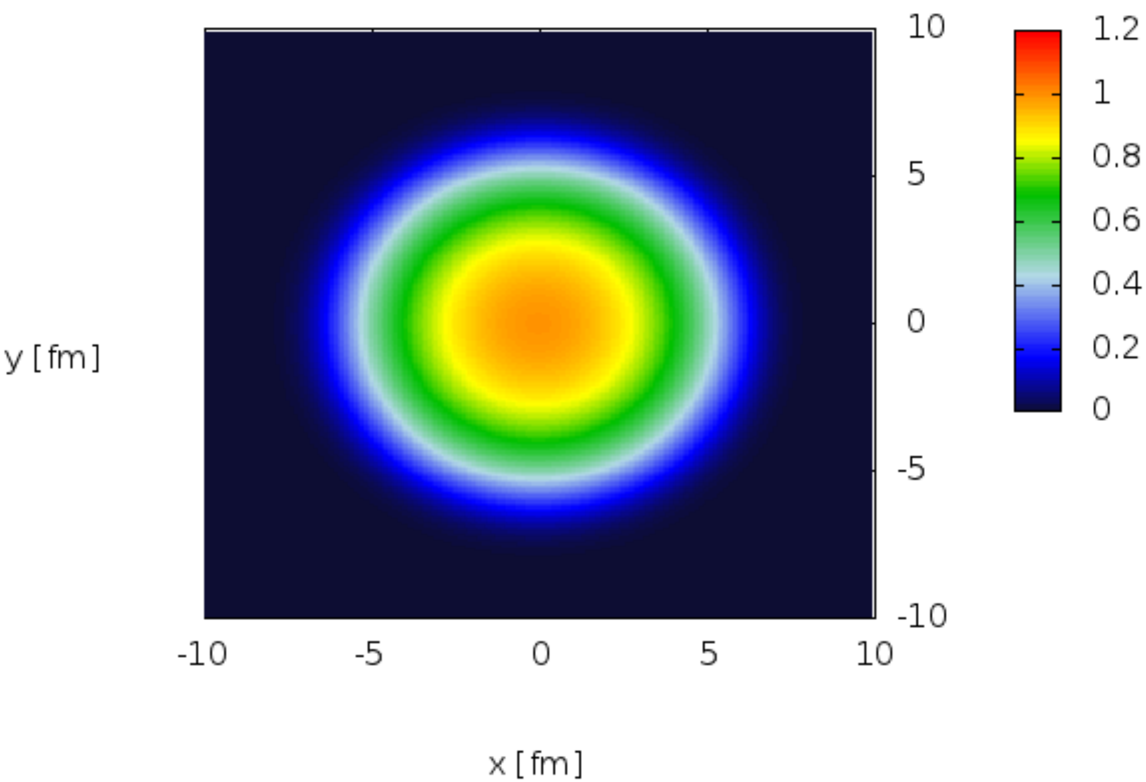

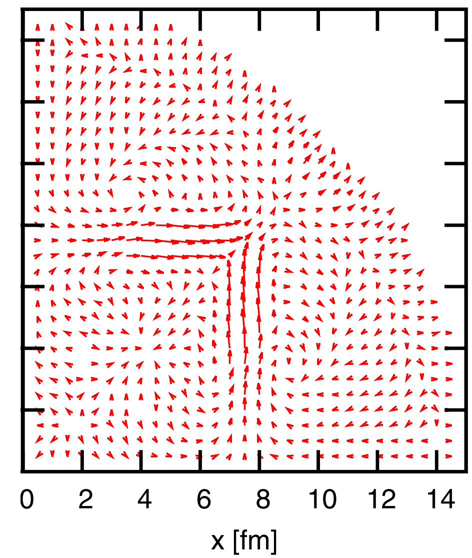

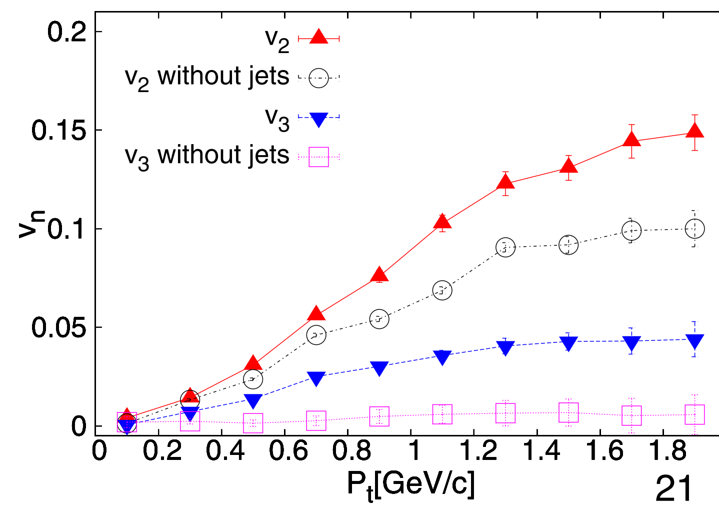

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Conclusions

We study the properties of quark-gluon plasma:

- its Equation of State at μ_B=0 shows smooth crossover
- its shear viscosity is low - somewhere above $1/4\pi$
- It can stop very energetic partons, but the corresponding transport coefficient is still unknown

QGP is created in heavy-ion collisions at the LHC and RHIC

- strong pressure causes very strong transverse expansion in spite of lifetime about 10 fm/*c*
- inhomogeneities of the initial state show up in the large anisotropies of the observed hadron distributions

Questions:

- Where is the critical point of the phase diagram?
- What are the values of transport coefficients?
- What are the initial conditions of the fireball evolution?

This is very rich field where many different aspects of the observables and underlying theory can be studied.