Heavy Ion Physics at the LHC

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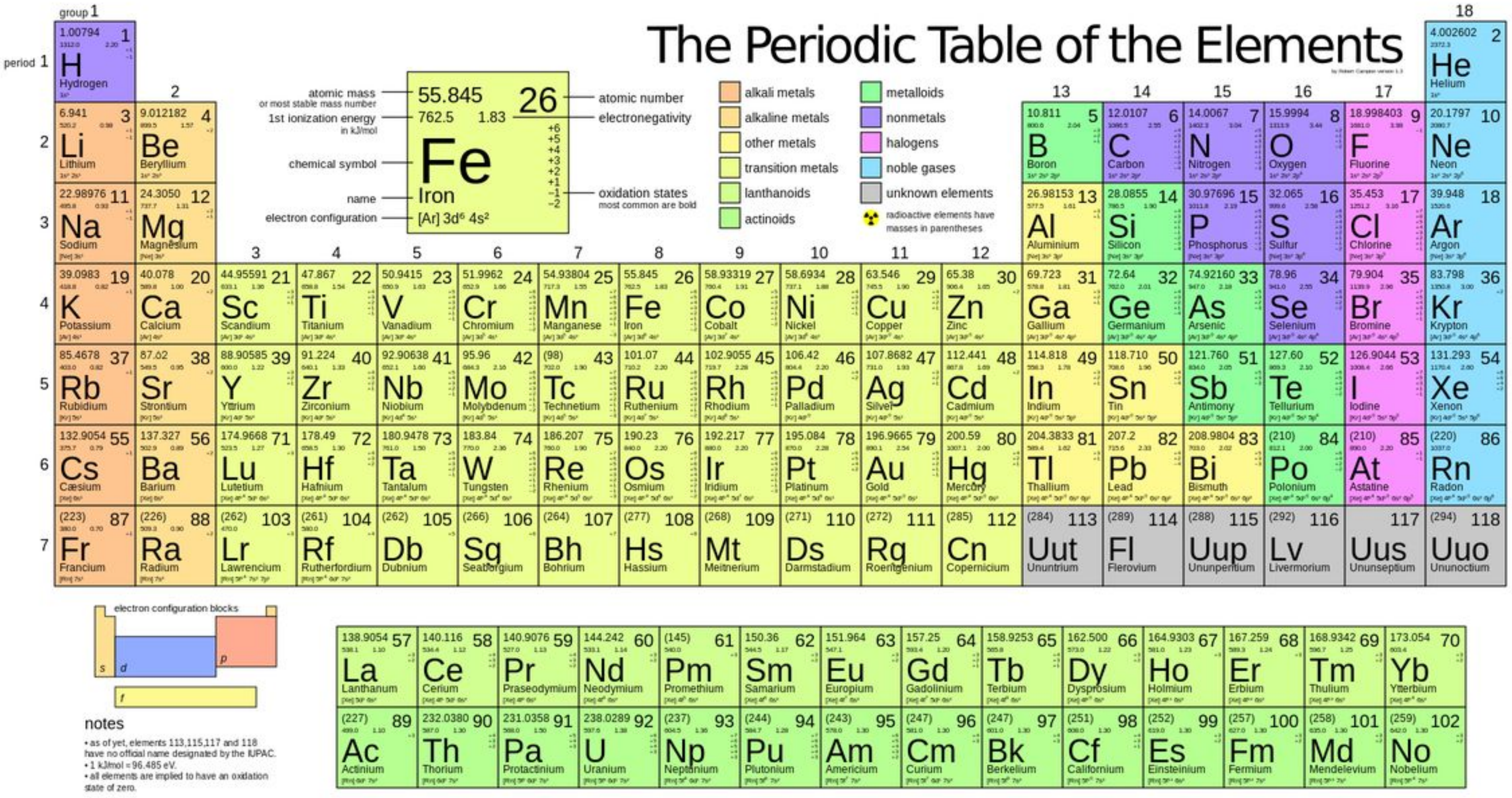
What you learn in chemistry….



Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
	I	II	III	I	II	III		
mass charge spin	≃2.2 MeV/c^2 2/3 1/2 u **up**	≃1.28 GeV/c^2 2/3 1/2 c **charm**	≃173.1 GeV/c^2 2/3 1/2 t **top**	≃2.2 MeV/c^2 −2/3 1/2 $\bar{u}$ **antiup**	≃1.28 GeV/c^2 −2/3 1/2 $\bar{c}$ **anticharm**	≃173.1 GeV/c^2 −2/3 1/2 $\bar{t}$ **antitop**	0 0 1 g **gluon**	≃124.97 GeV/c^2 0 0 H **higgs**
QUARKS	≃4.7 MeV/c^2 −1/3 1/2 d **down**	≃96 MeV/c^2 −1/3 1/2 s **strange**	≃4.18 GeV/c^2 −1/3 1/2 b **bottom**	≃4.7 MeV/c^2 1/3 1/2 $\bar{d}$ **antidown**	≃96 MeV/c^2 1/3 1/2 $\bar{s}$ **antistrange**	≃4.18 GeV/c^2 1/3 1/2 $\bar{b}$ **antibottom**	GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS
	≃0.511 MeV/c^2 −1 1/2 e **electron**	≃105.66 MeV/c^2 −1 1/2 μ **muon**	≃1.7768 GeV/c^2 −1 1/2 τ **tau**	≃0.511 MeV/c^2 1 1/2 e^+ **positron**	≃105.66 MeV/c^2 1 1/2 $\bar{\mu}$ **antimuon**	≃1.7768 GeV/c^2 1 1/2 $\bar{\tau}$ **antitau**		
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e **electron neutrino**	<0.17 MeV/c^2 0 1/2 ν_μ **muon neutrino**	<18.2 MeV/c^2 0 1/2 ν_τ **tau neutrino**	<2.2 eV/c^2 0 1/2 $\bar{\nu}_e$ **electron antineutrino**	<0.17 MeV/c^2 0 1/2 $\bar{\nu}_\mu$ **muon antineutrino**	<18.2 MeV/c^2 0 1/2 $\bar{\nu}_\tau$ **tau antineutrino**	≃80.39 GeV/c^2 1 1 W^+ **W^+ boson**	≃80.39 GeV/c^2 −1 1 W^- **W^- boson**

Standard Model of Elementary Particles

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	I	II	III	I	II	III	
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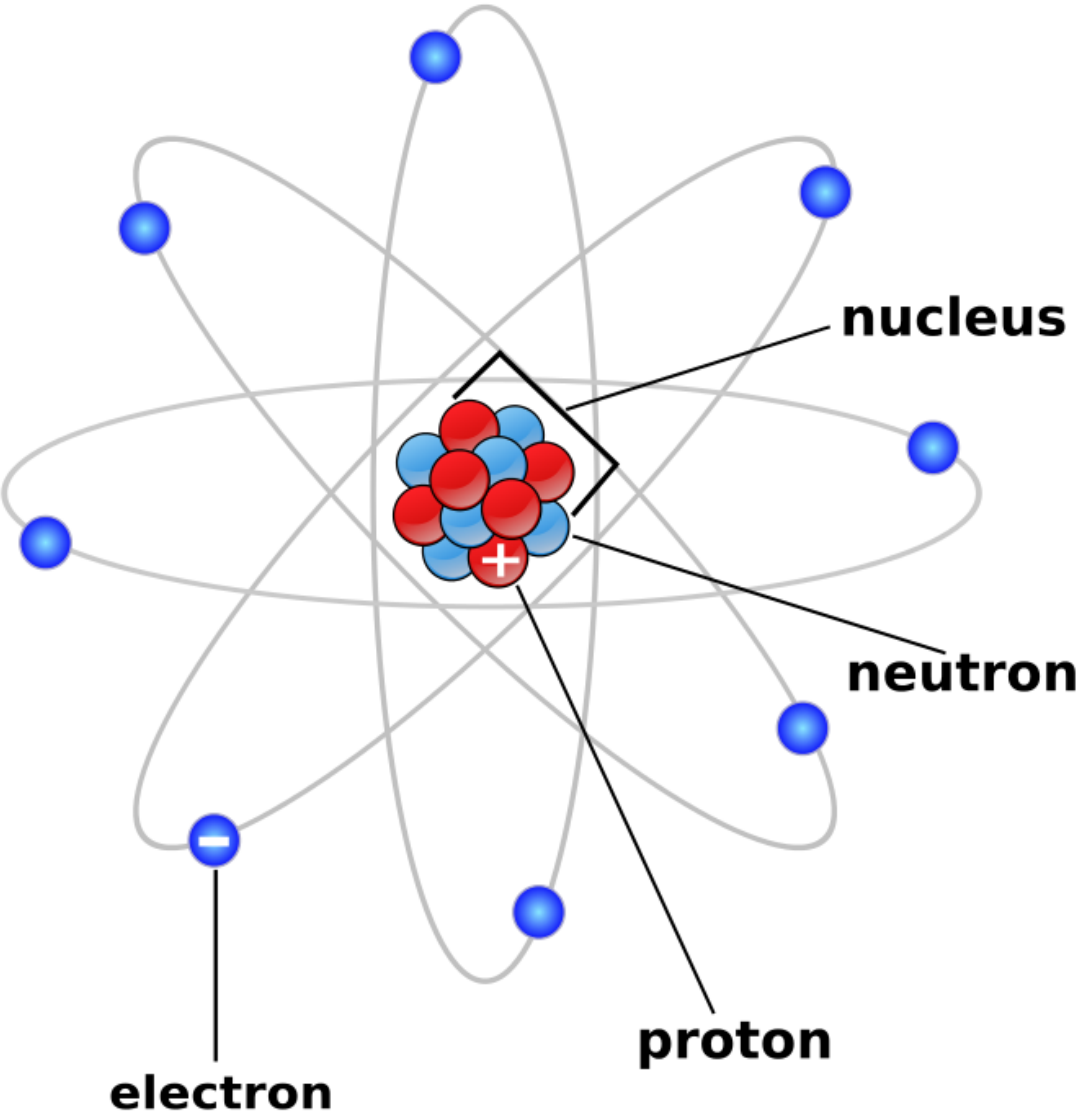
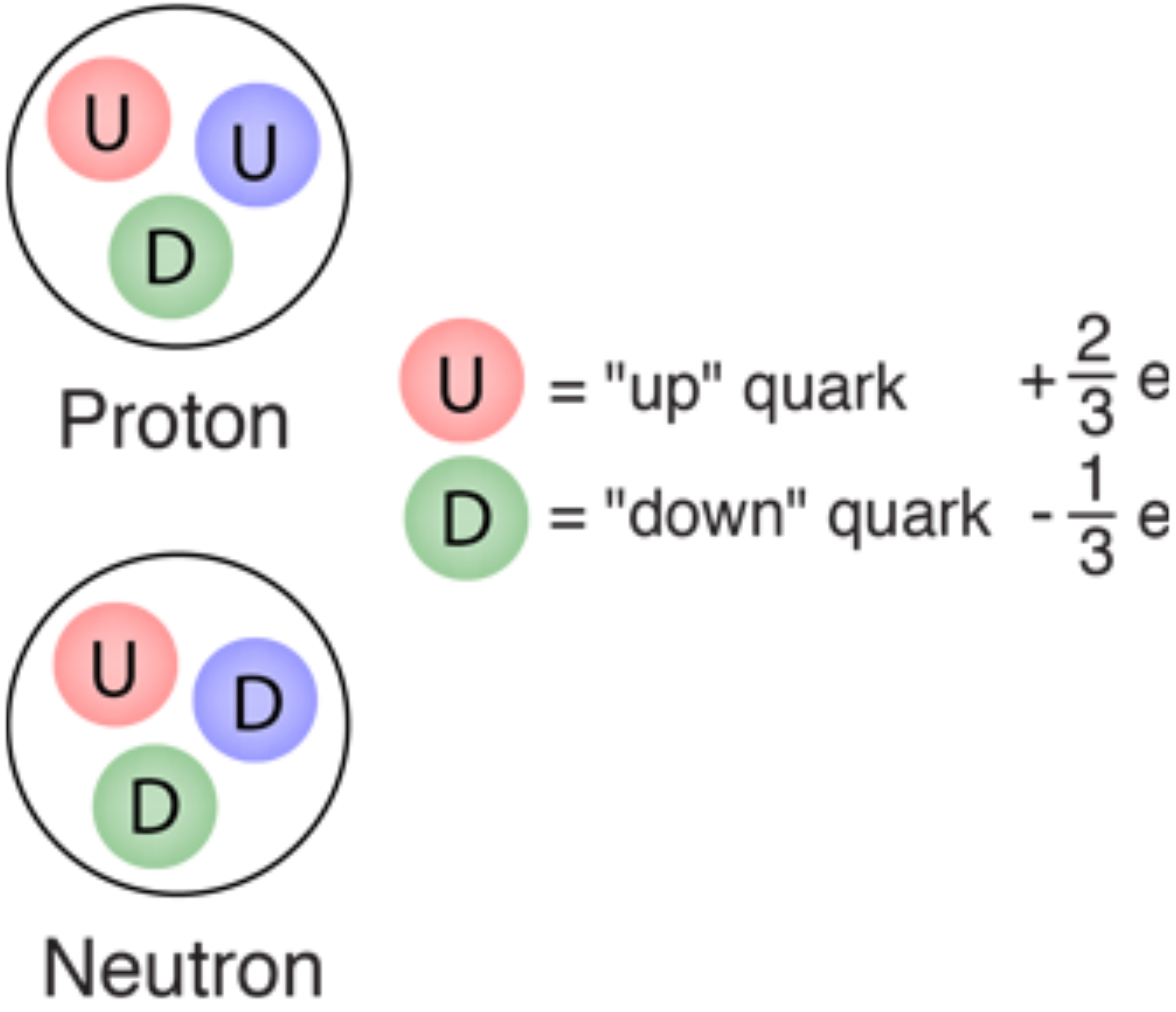
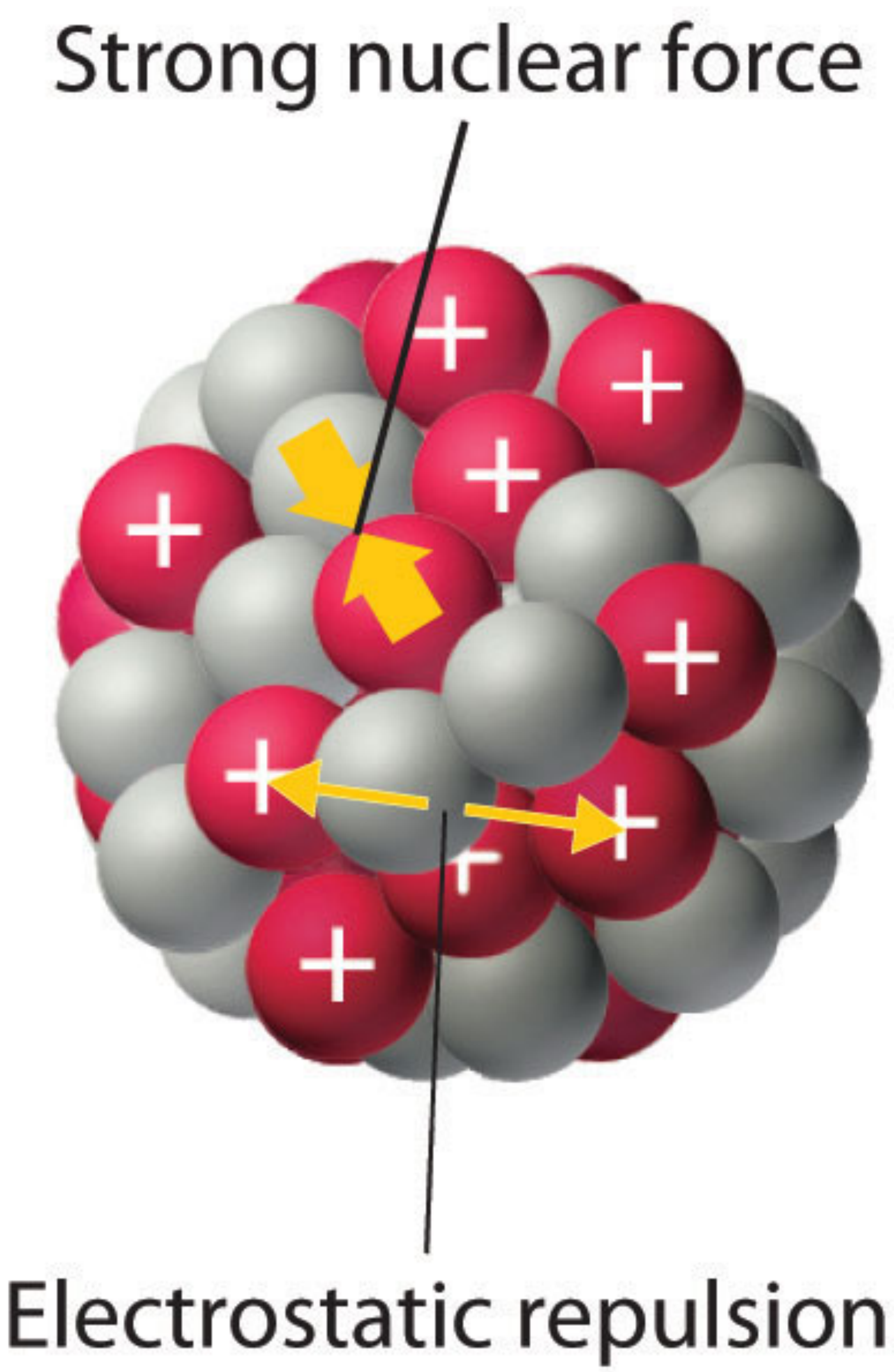
GAUGE BOSONS
VECTOR BOSONS

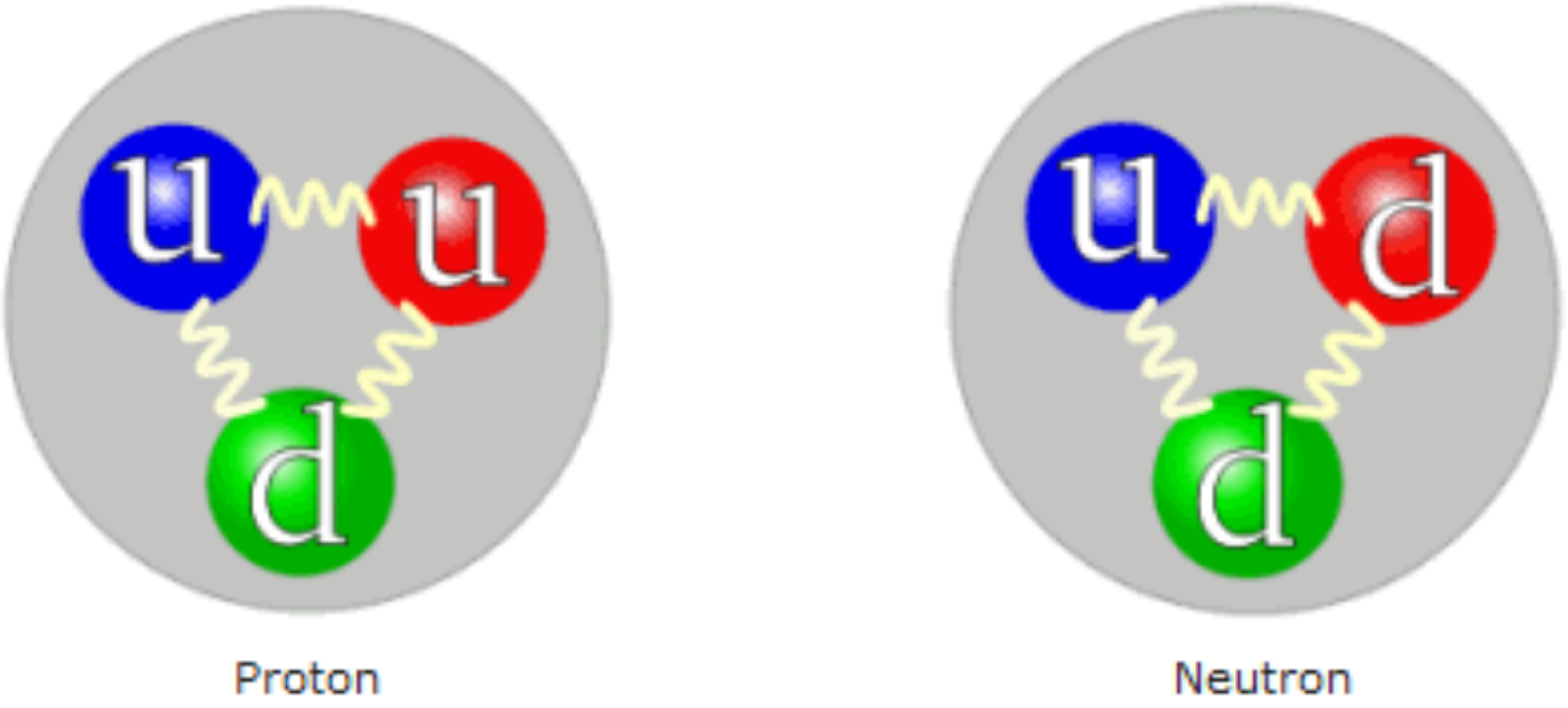
Where do we find quarks?





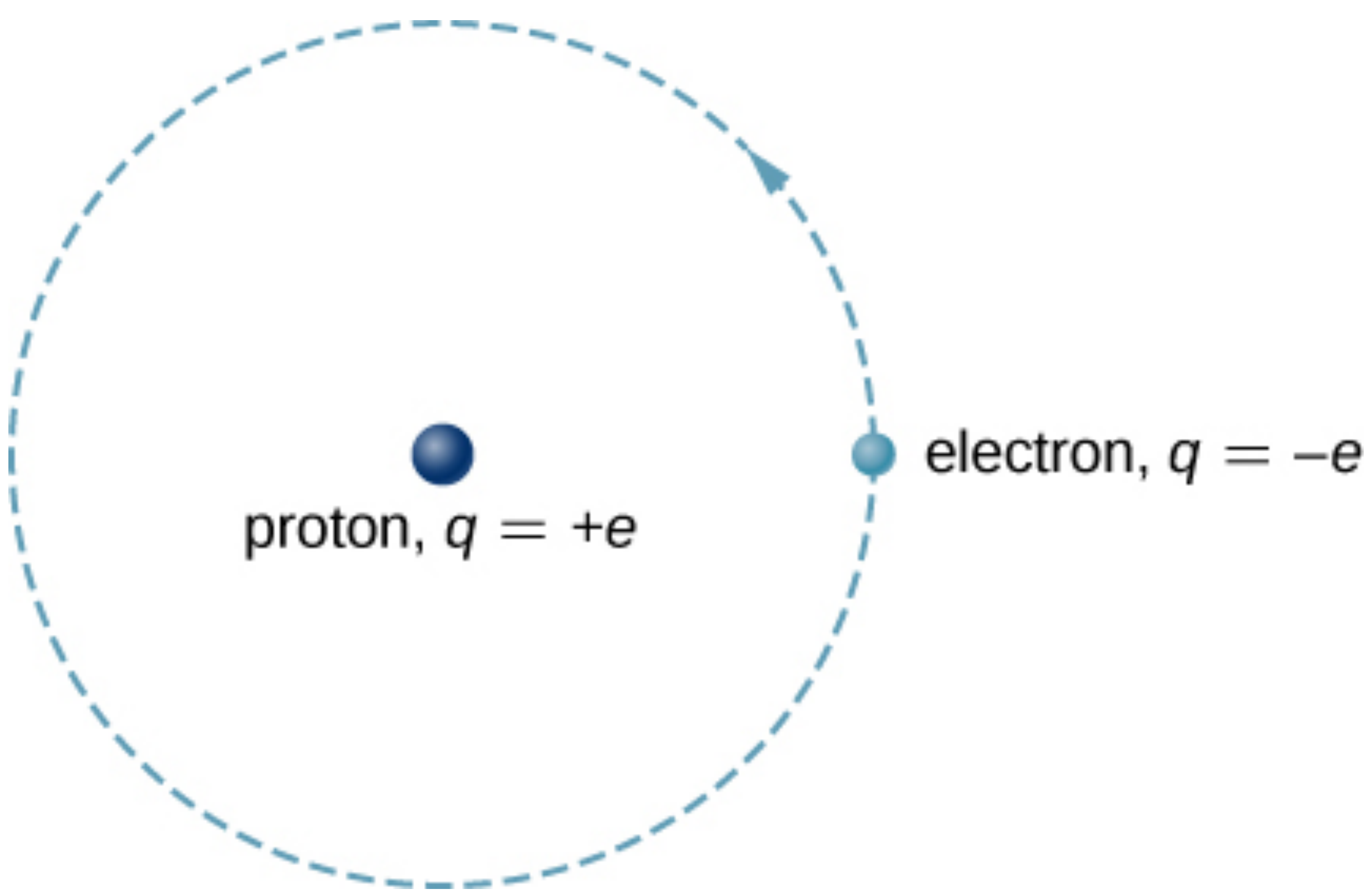
What keeps quarks confined in a proton or neutron?

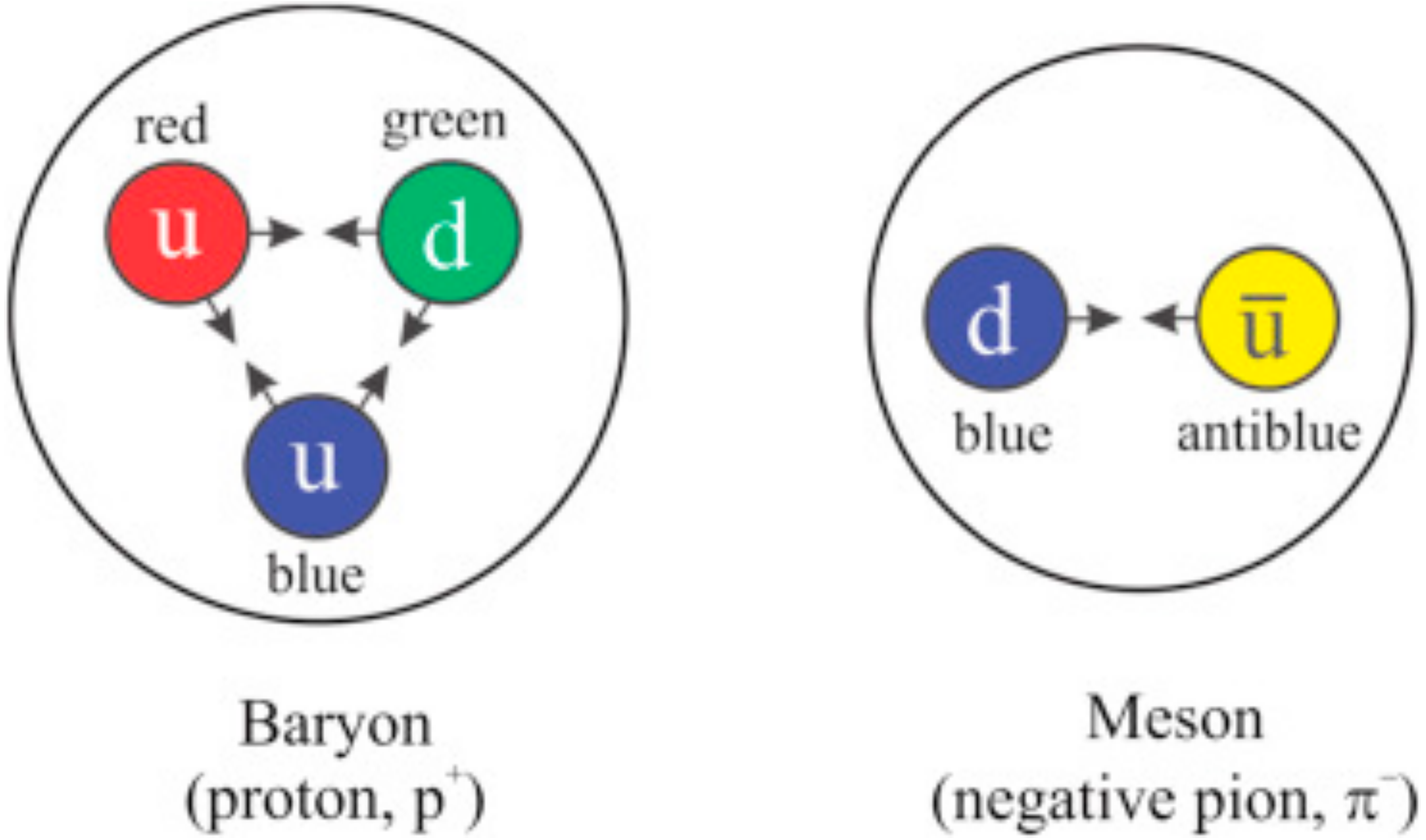




- **Color**: The "charge" associated with the strong force

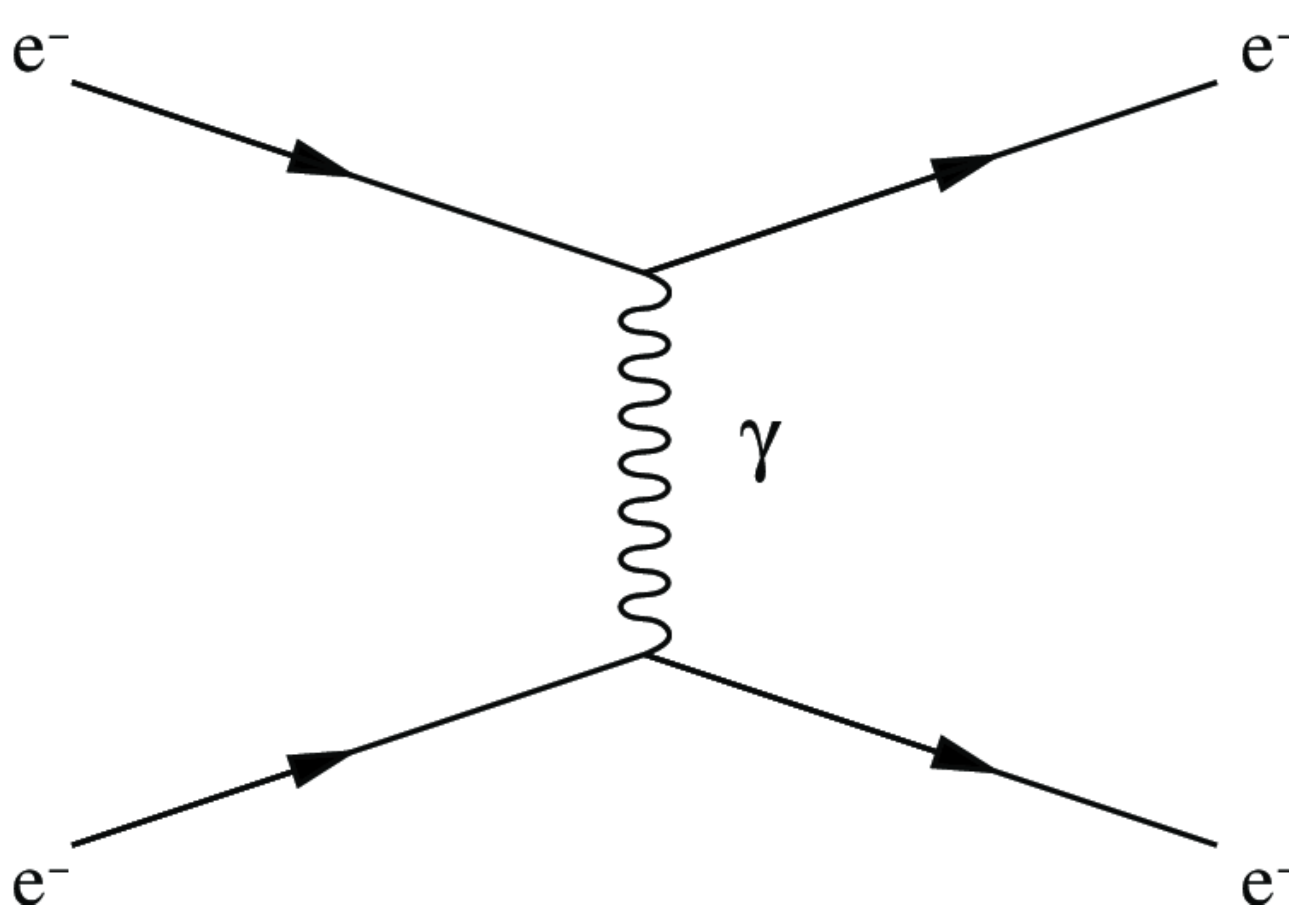
How many color charges exist?

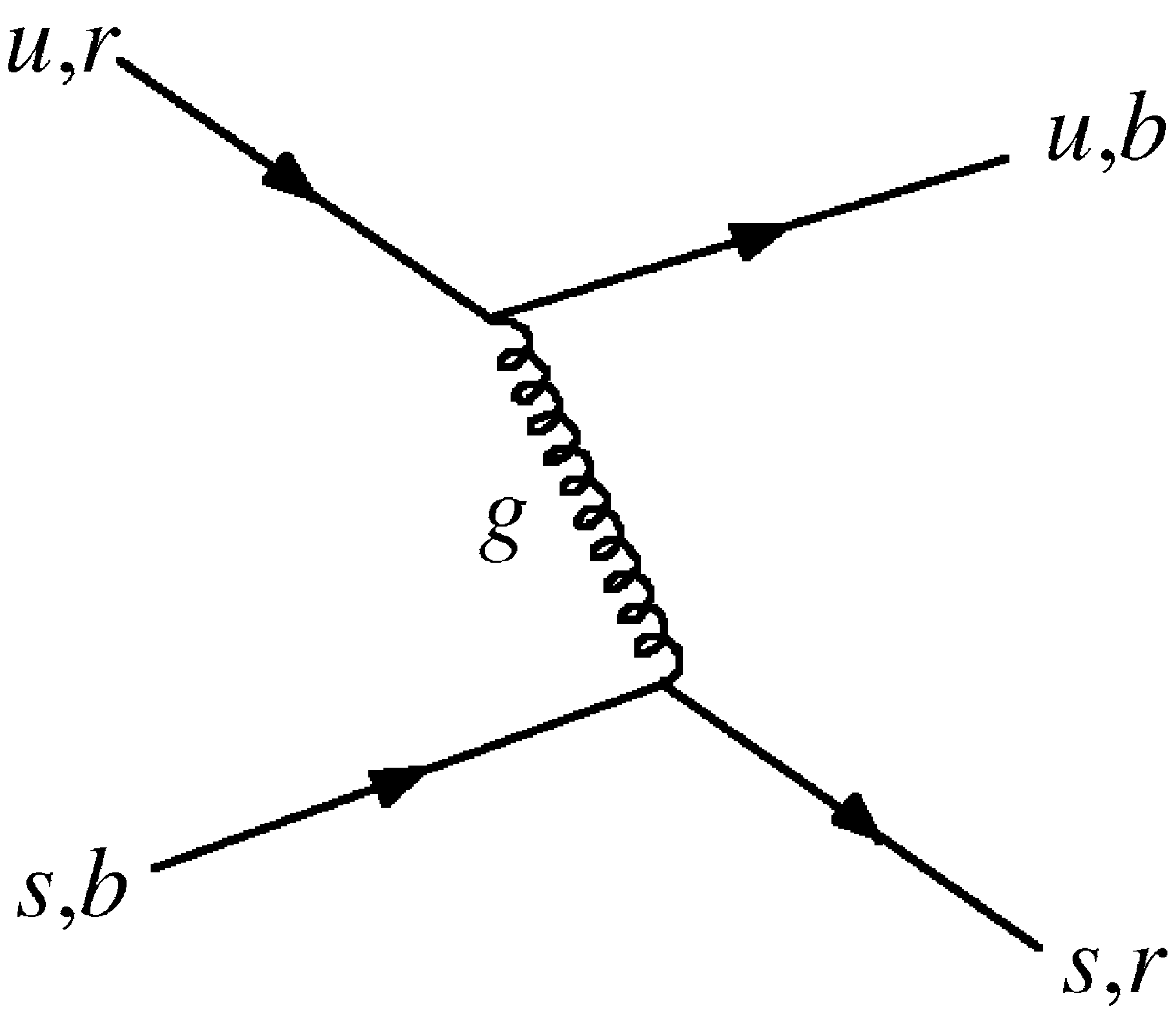




- Electromagnetic force: 2 + and -
- Strong force: 6 **red**, **blue**, **green**, **anti-red**, **anti-blue**, and **anti-green**

How do the electromagnetic and strong forces arise?

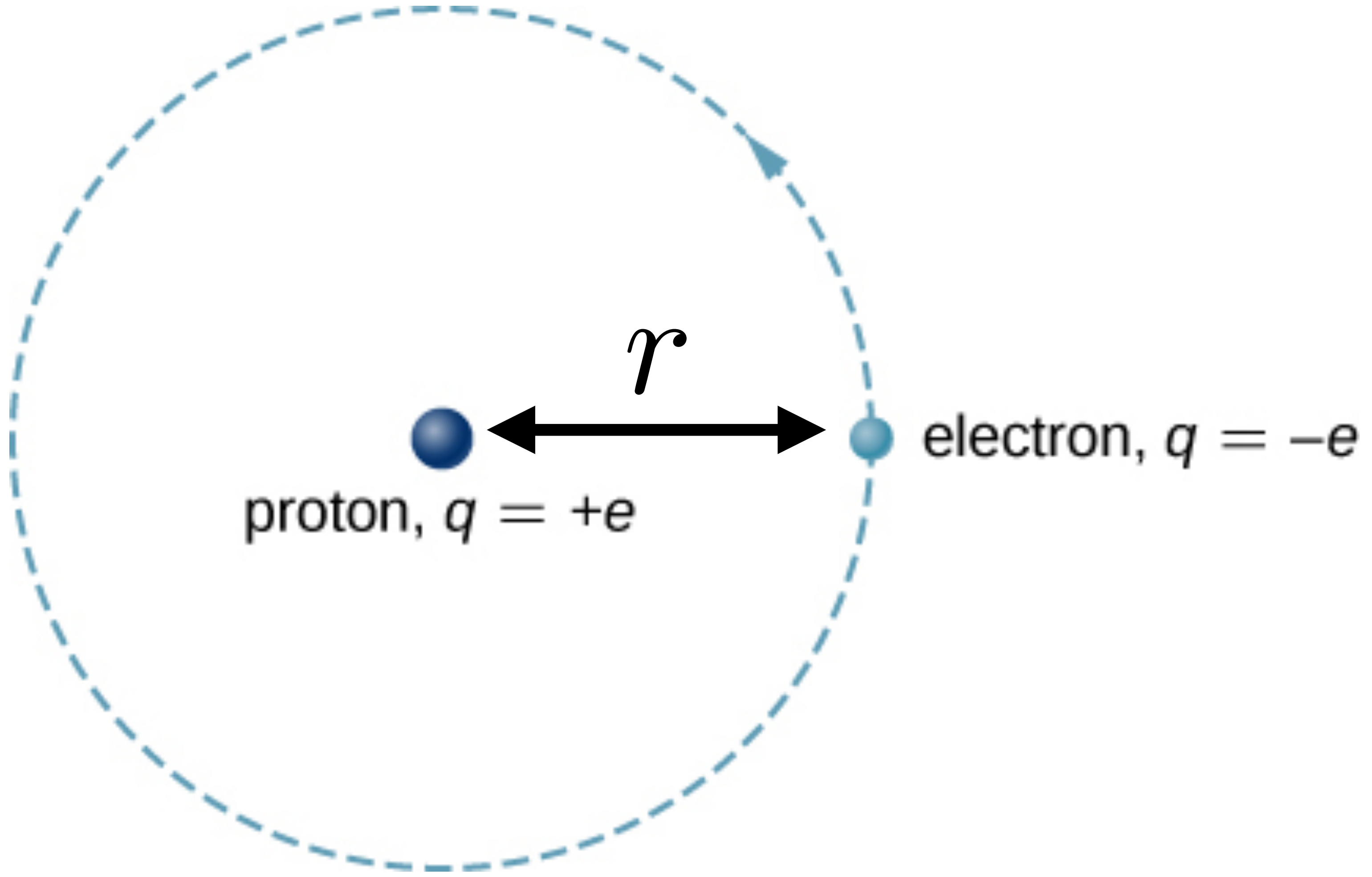


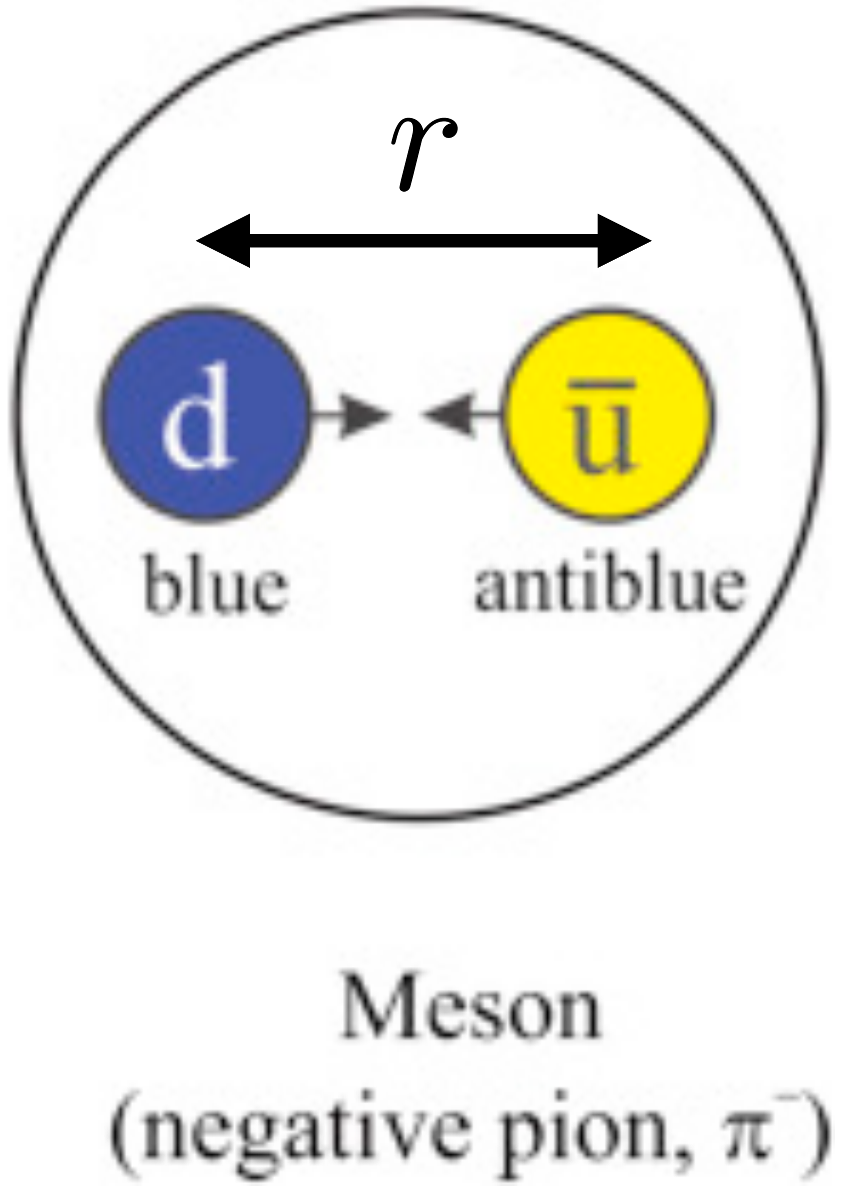


- **Modern view:** via the exchange of force carriers
  - ✓Photons are exchanged in the electromagnetic force
  - ✓**Gluons** are exchanged in the strong force

$$\Delta E \Delta t \geq \frac{h}{2\pi}$$

How does the strong force behave?



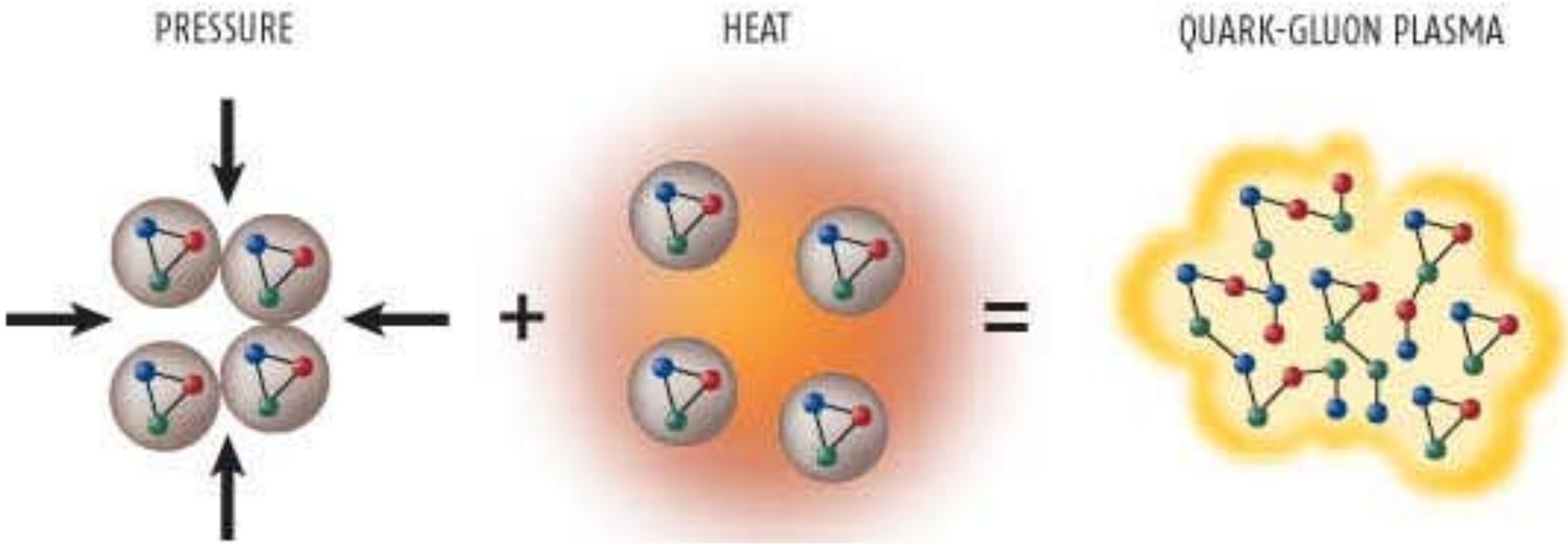


$$F_{em}(r) = \frac{a}{r^2}$$

$$F_{strong}(r) = \frac{b}{r^2} + cr^2$$

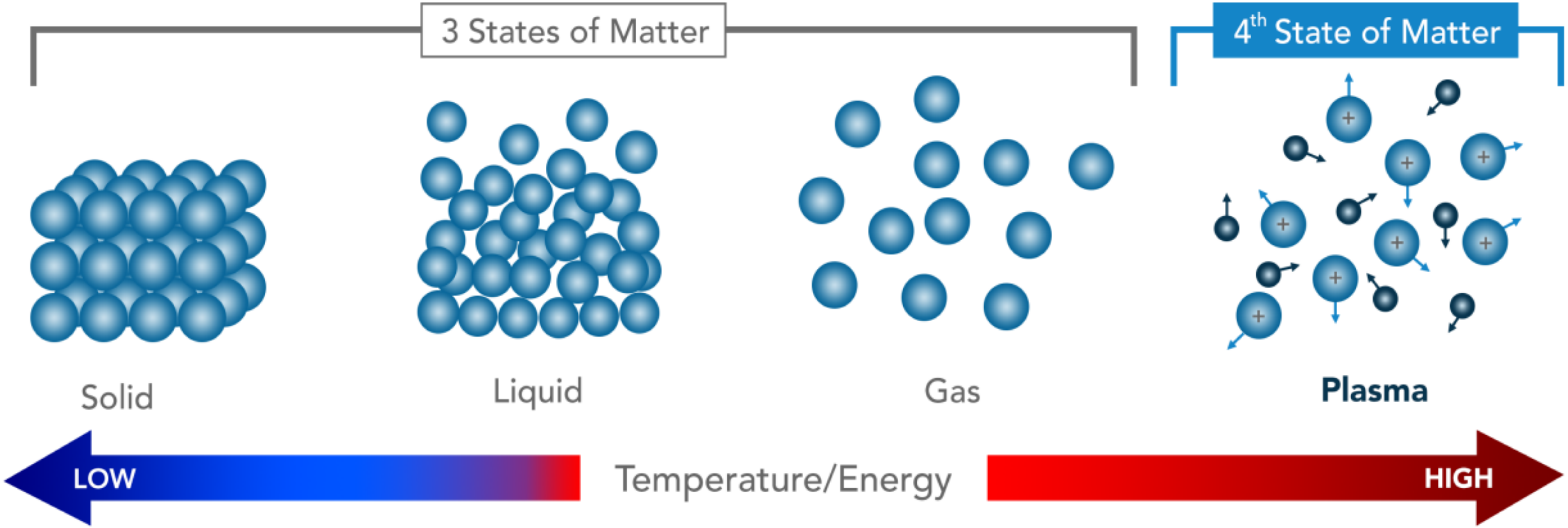
- An increasing strong force with distance leads to **confinement**
  - ✓Infinite amount of energy needed to separate quarks
  - ✓Reason why quarks only found in baryons (e.g. proton) or mesons (e.g. pion)

The Quark Gluon Plasma (QGP)



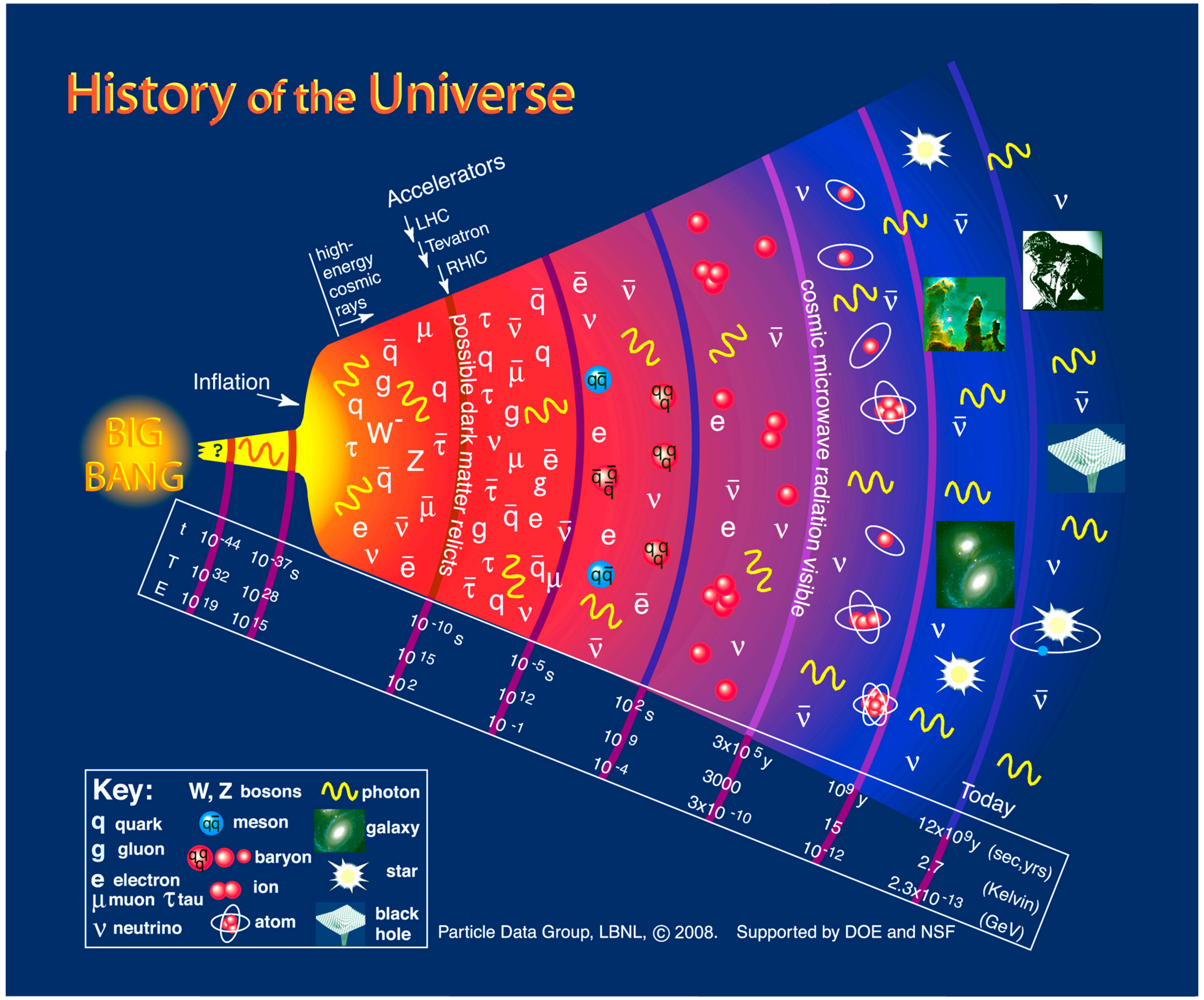
- When a nucleus is compressed and heated, a QGP forms
  - ✓Quarks are no longer localized within protons and neutrons

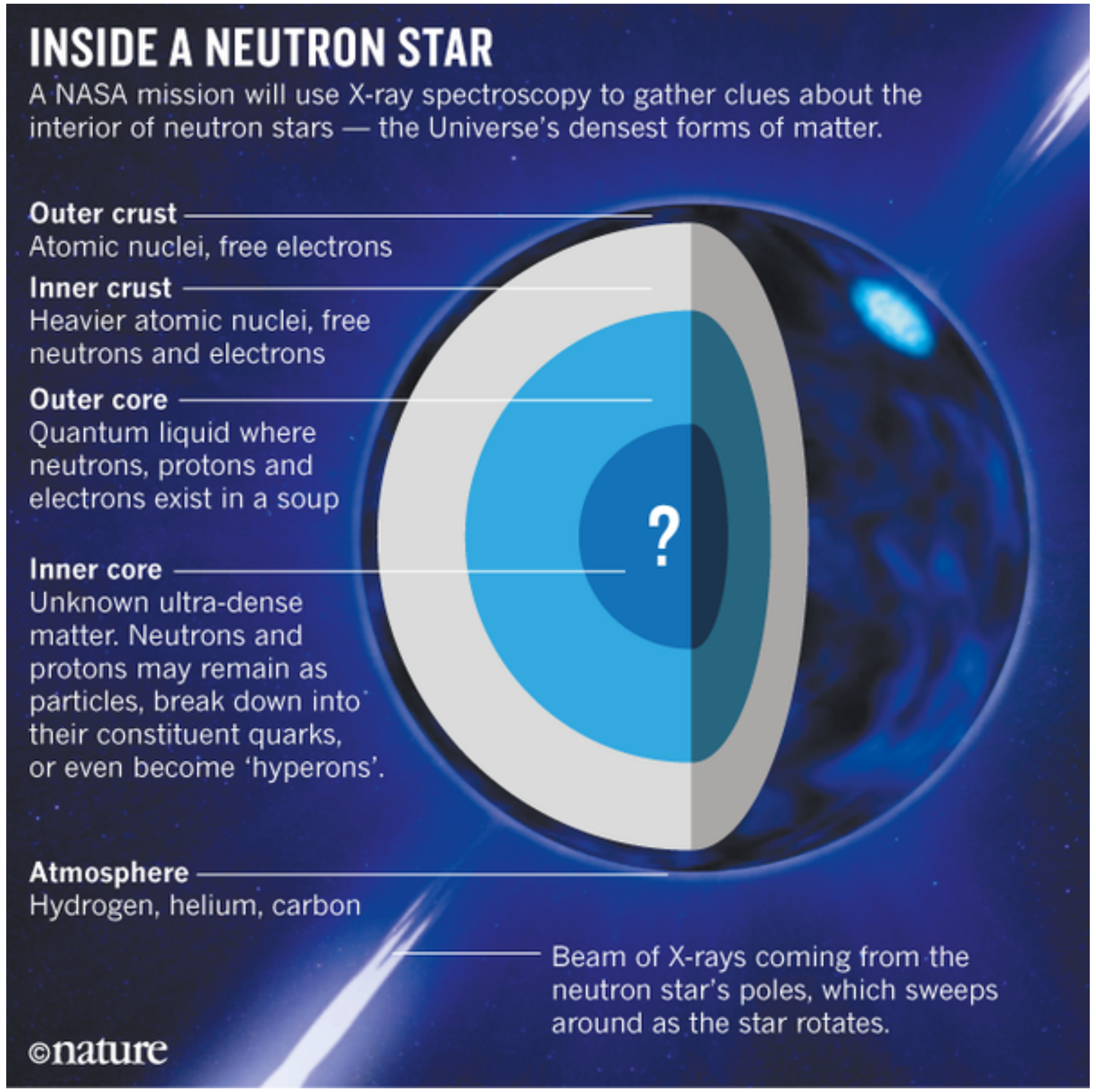
Where does the word plasma come from?



- Constituents of conventional plasma are electrically charged
  - ✓Constituents of QGP are color charged!

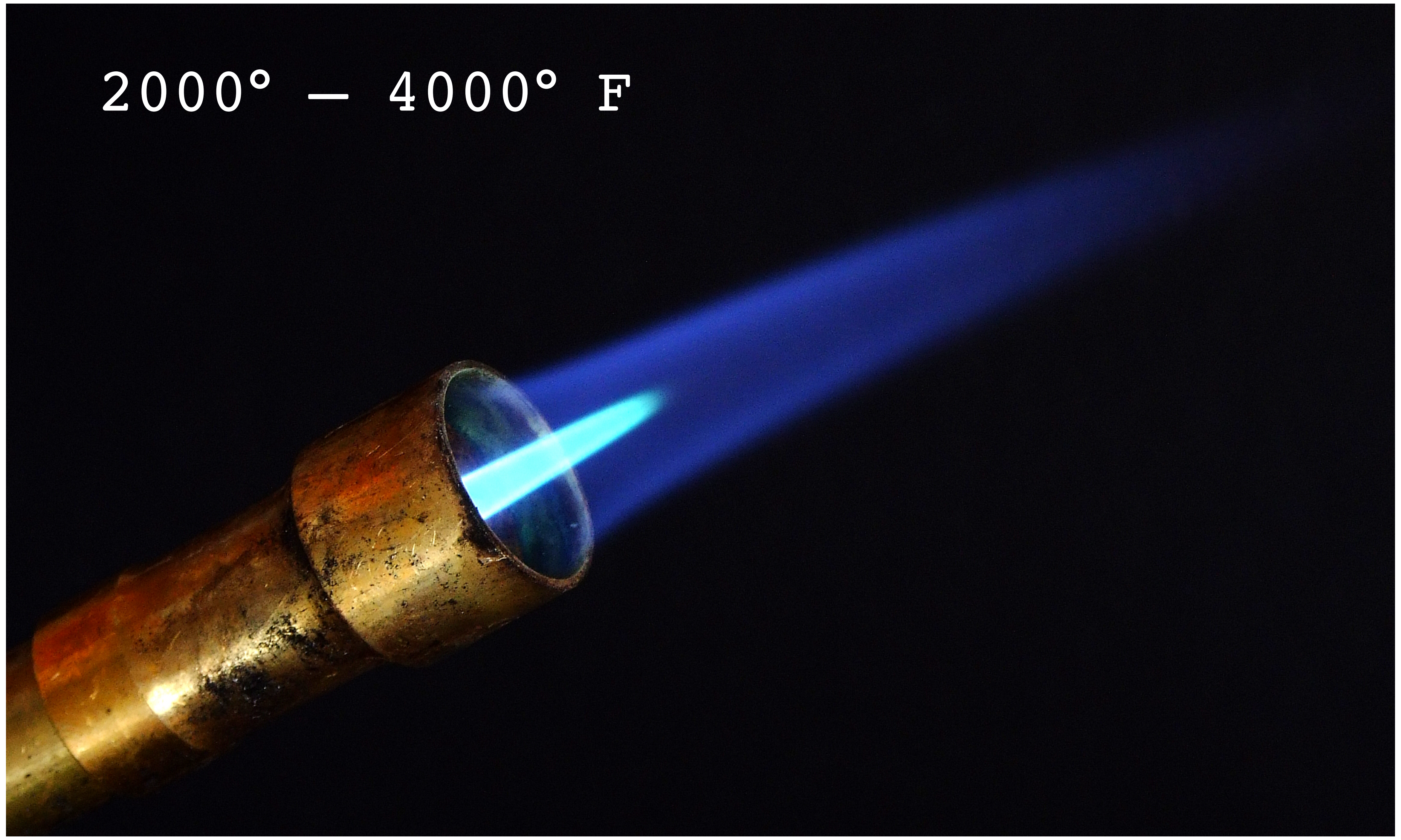
Why is the Quark Gluon Plasma (QGP) interesting?

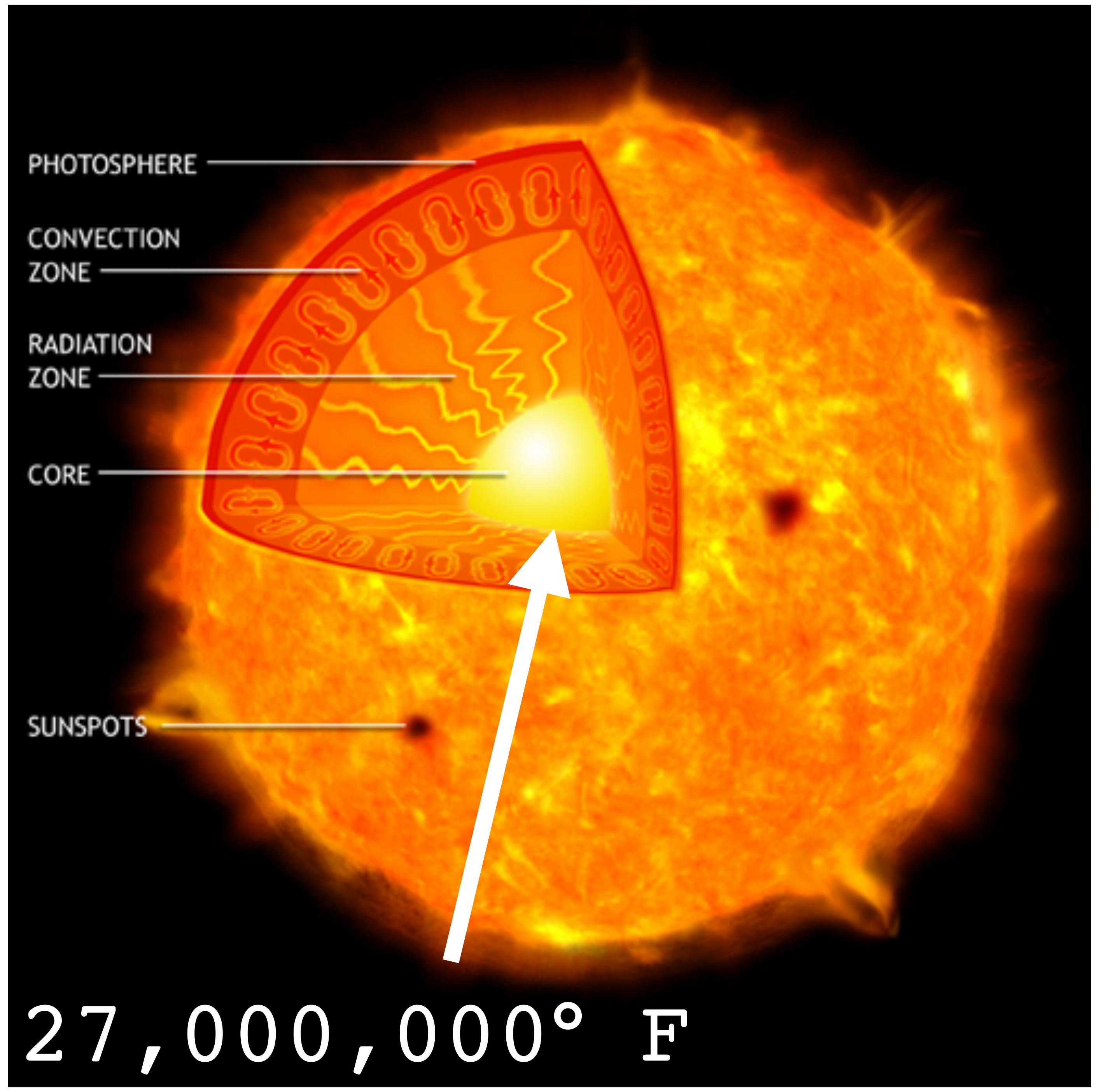




- Early universe would have been in the QGP state
- The core of neutron stars may contain a QGP

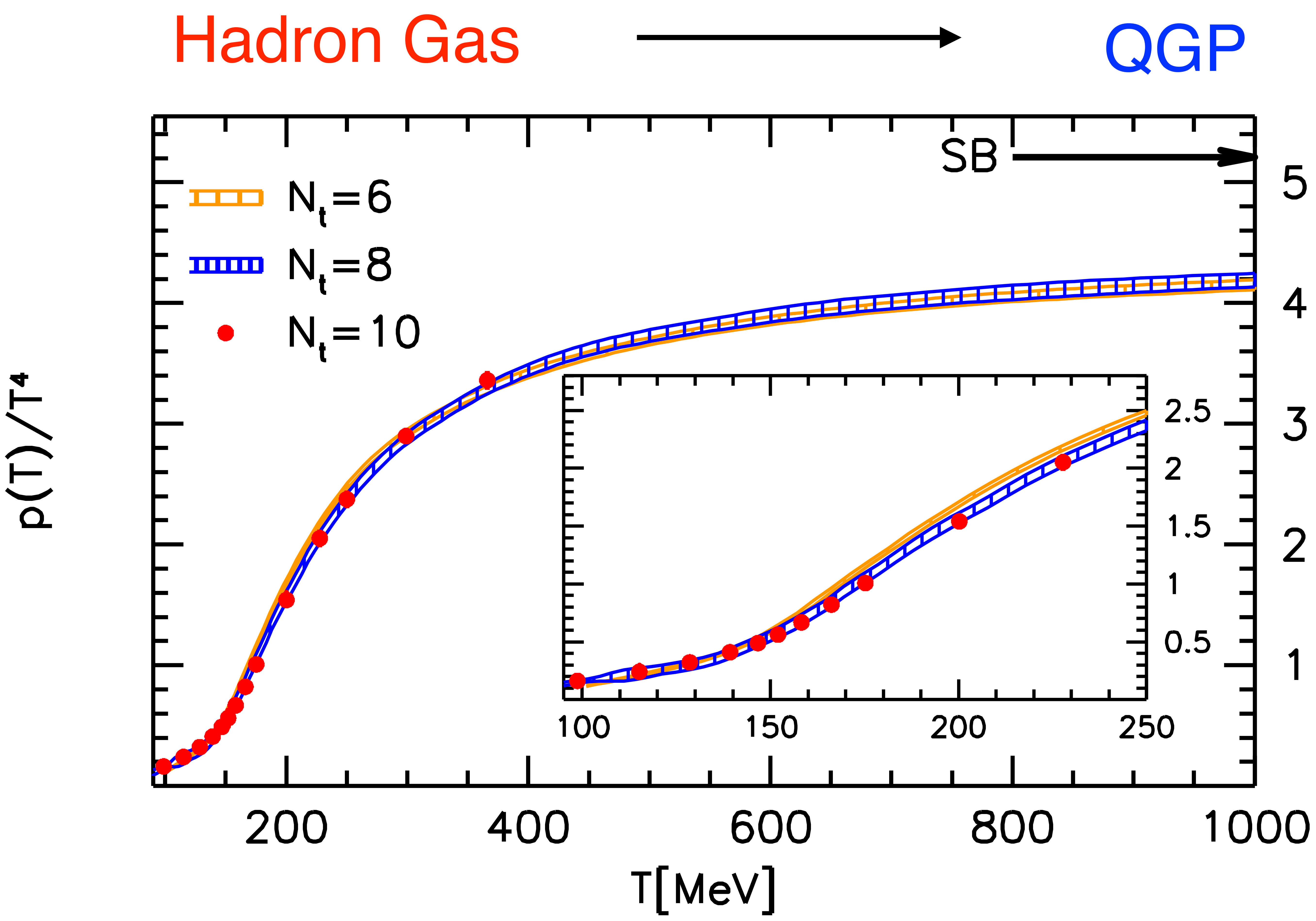
How much heat do we need to create a QGP?





- **5,000,000,000,000° F!!!**
  - Roughly a million times higher temperature than center of sun

How much heat do we need to create a QGP?



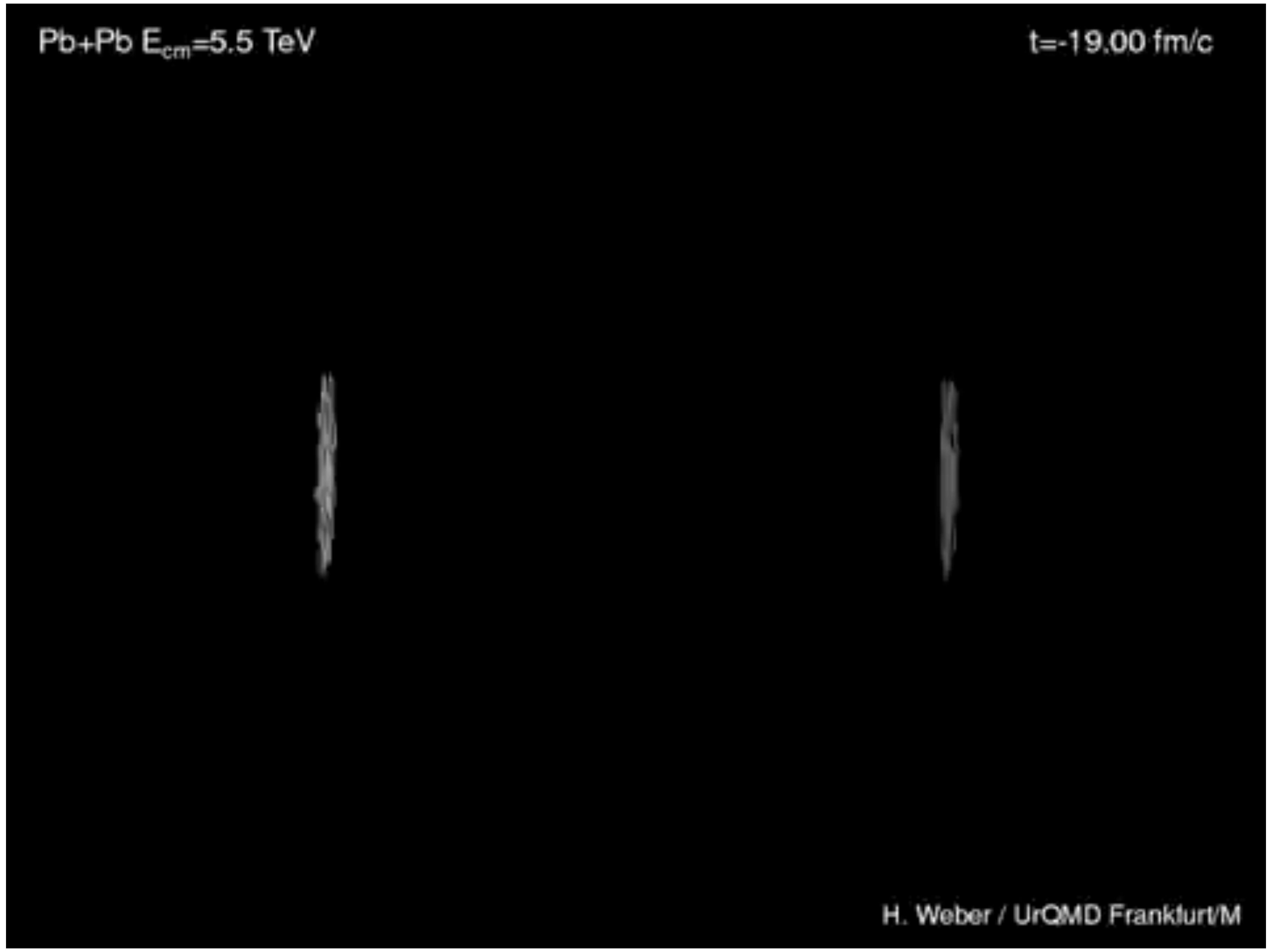
- Work by Professor Claudia Ratti at the University of Houston

How can we achieve such temperatures?

https://videos.cern.ch/record/1304862

- Crude but highly effective: collisions!

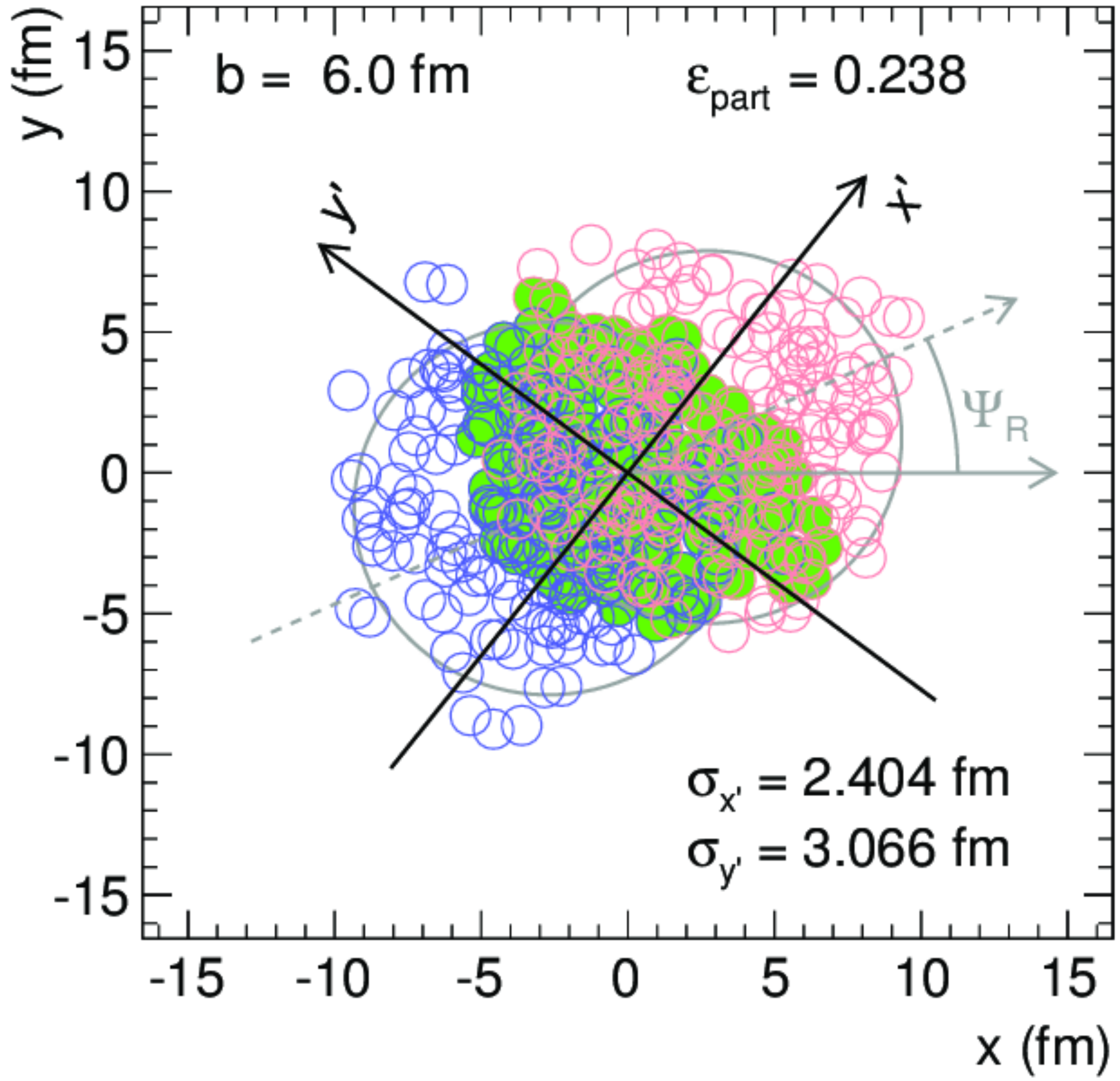
How can we achieve such temperatures?



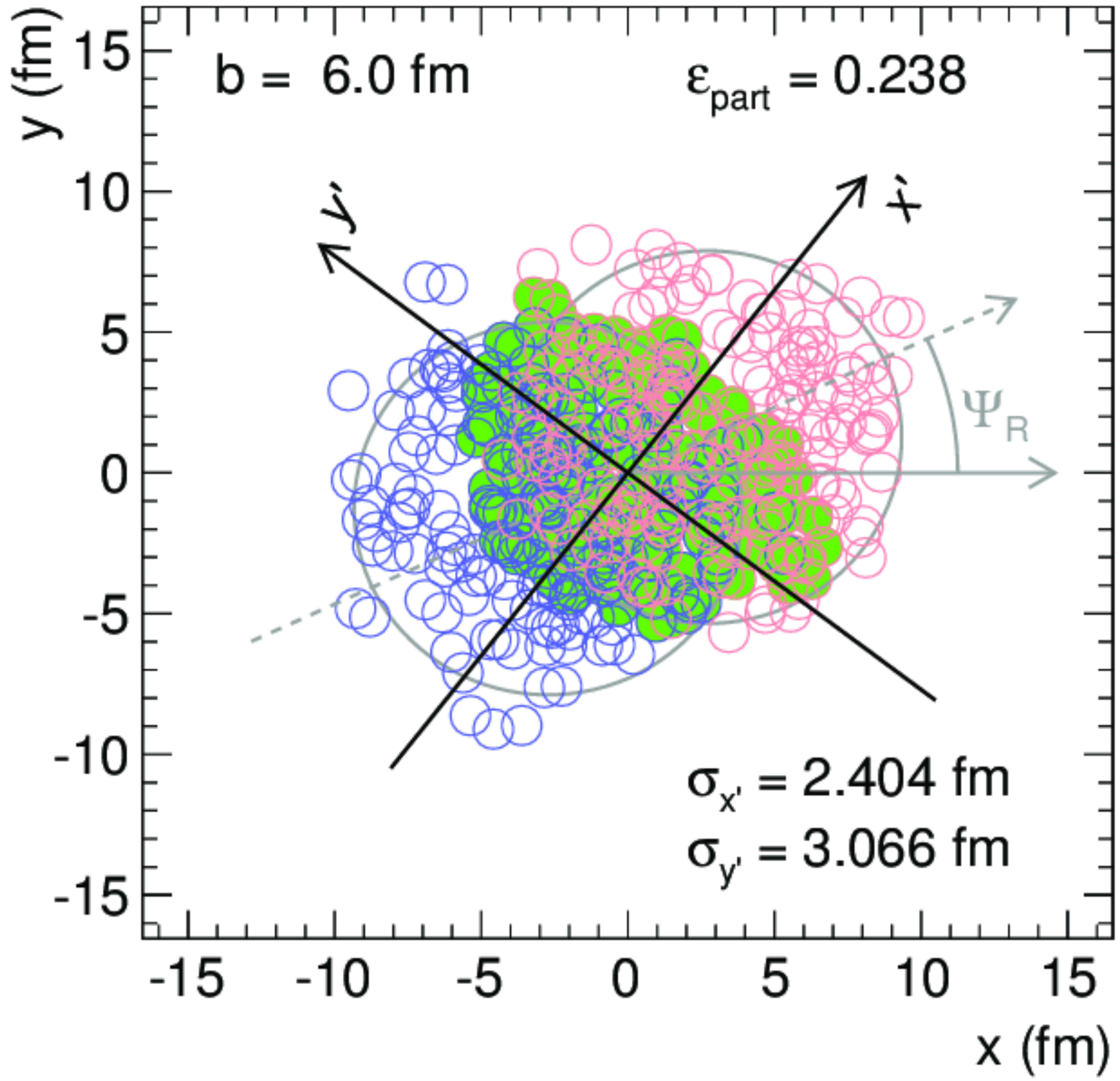
https://videos.cern.ch/record/1304862

- Crude but highly effective: collisions!
- To make the QGP, we collide Pb-Pb heavy ions (nuclei) at the LHC

Head on view of Pb-Pb collisions

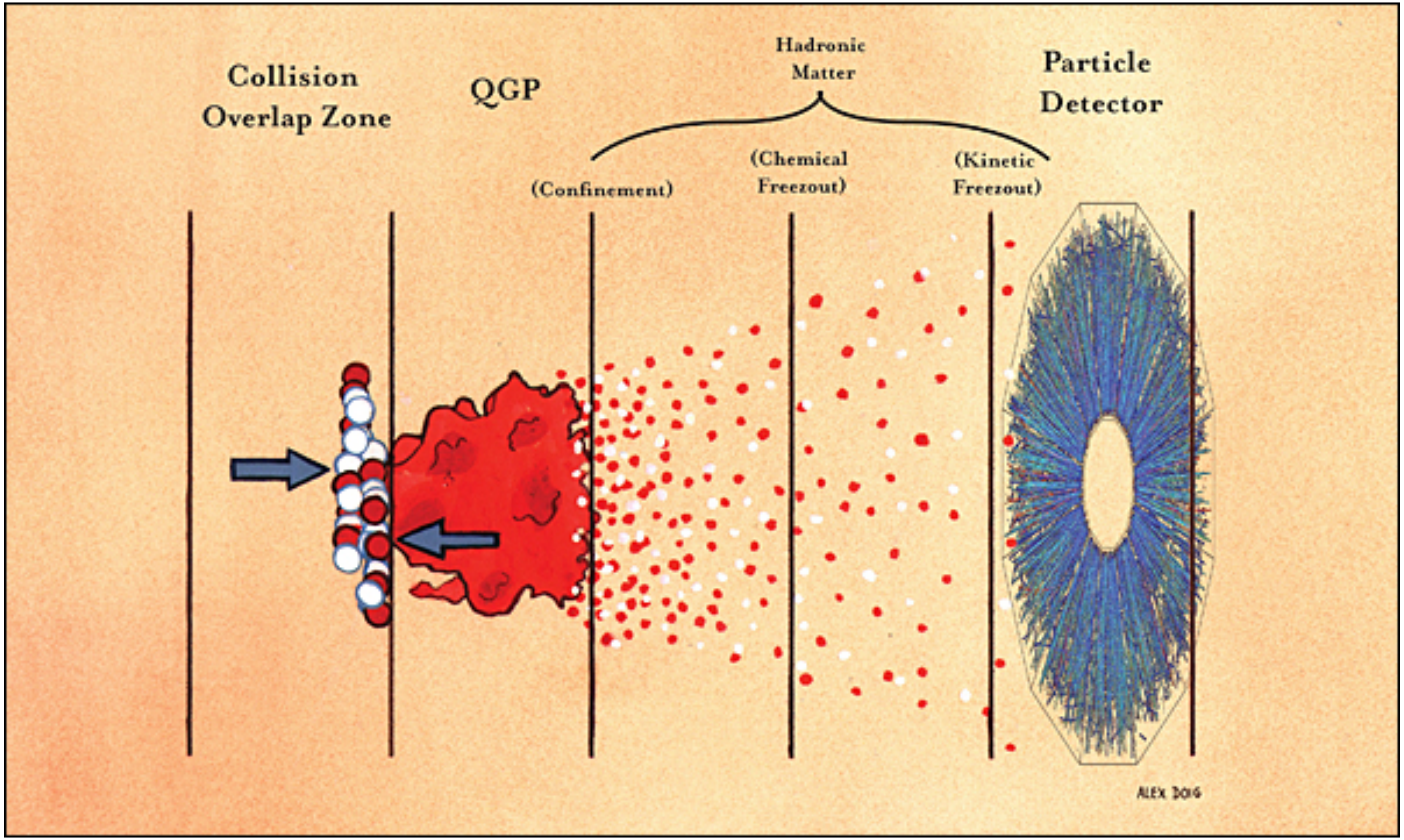


Head on view of Pb-Pb collisions



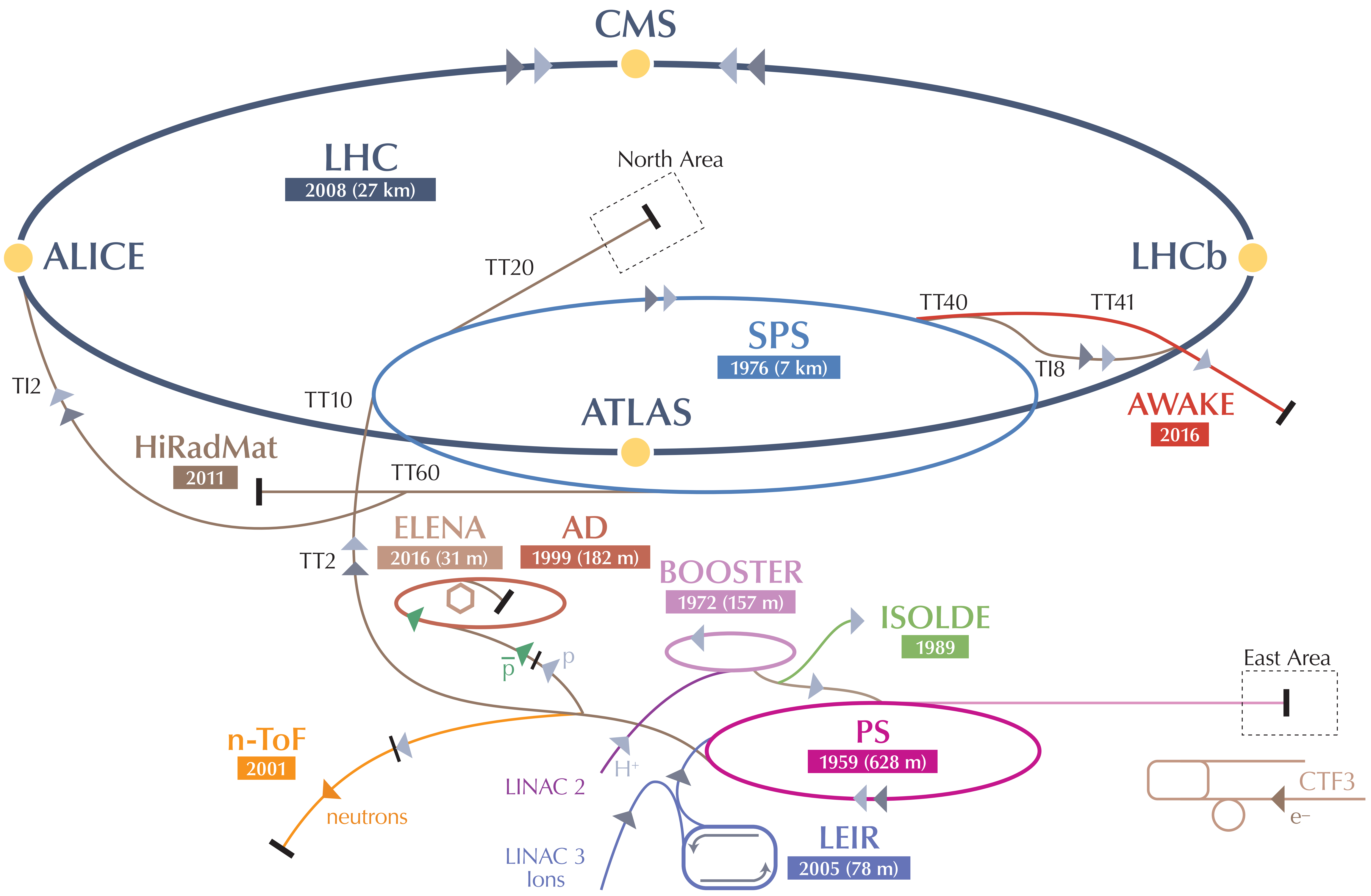
- Isotope used: $^{208}_{92}Pb$
- 92 protons and 116 neutrons
- $^{208}_{92}Pb$ extremely spherical nucleus
  - ✓Double magic

What happens during a Pb-Pb collision?



- Time →

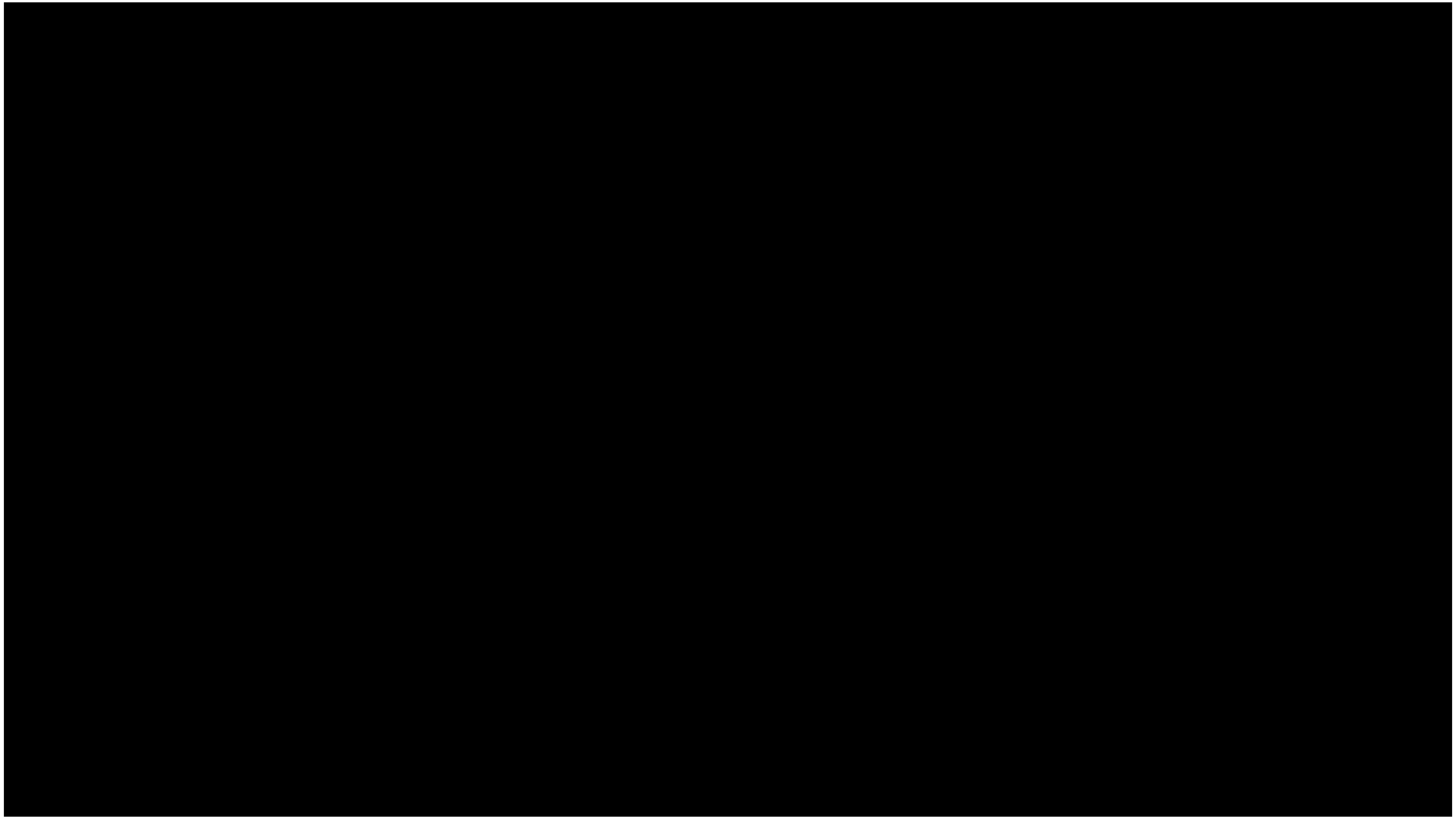
The Large Hadron Collider (LHC)



- Run 1 (2010-2013)
  - ✓Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
  - ✓p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
- Run 2 (2015-2018)
  - ✓Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓Xe-Xe $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓p-Pb $\sqrt{s_{NN}}$ = 8 TeV

1 TeV = 1.6×10^{-7}J

A Large Ion Collider Experiment (ALICE)



https://www.youtube.com/watch?v=yWBWzIUCNpw

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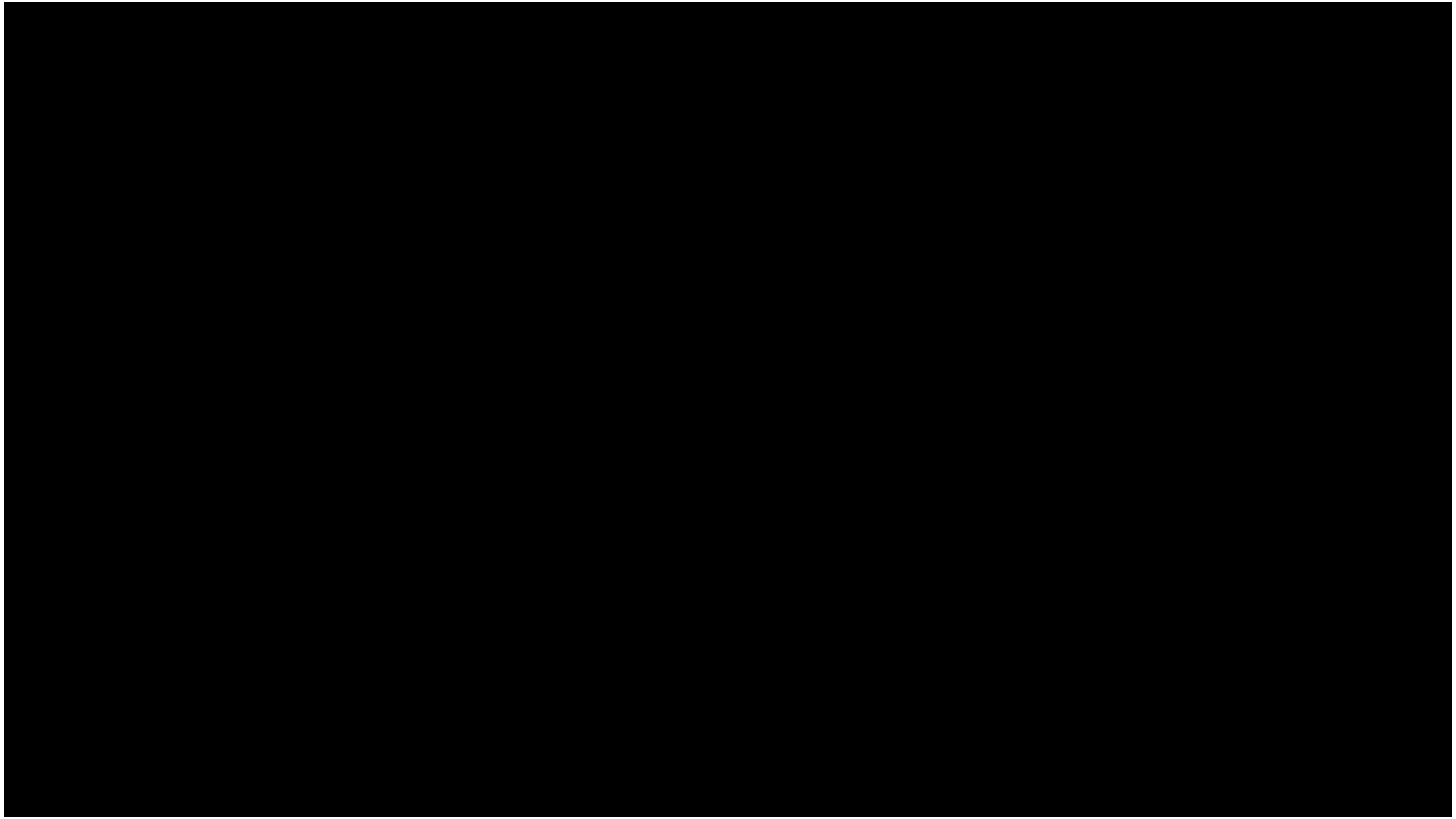

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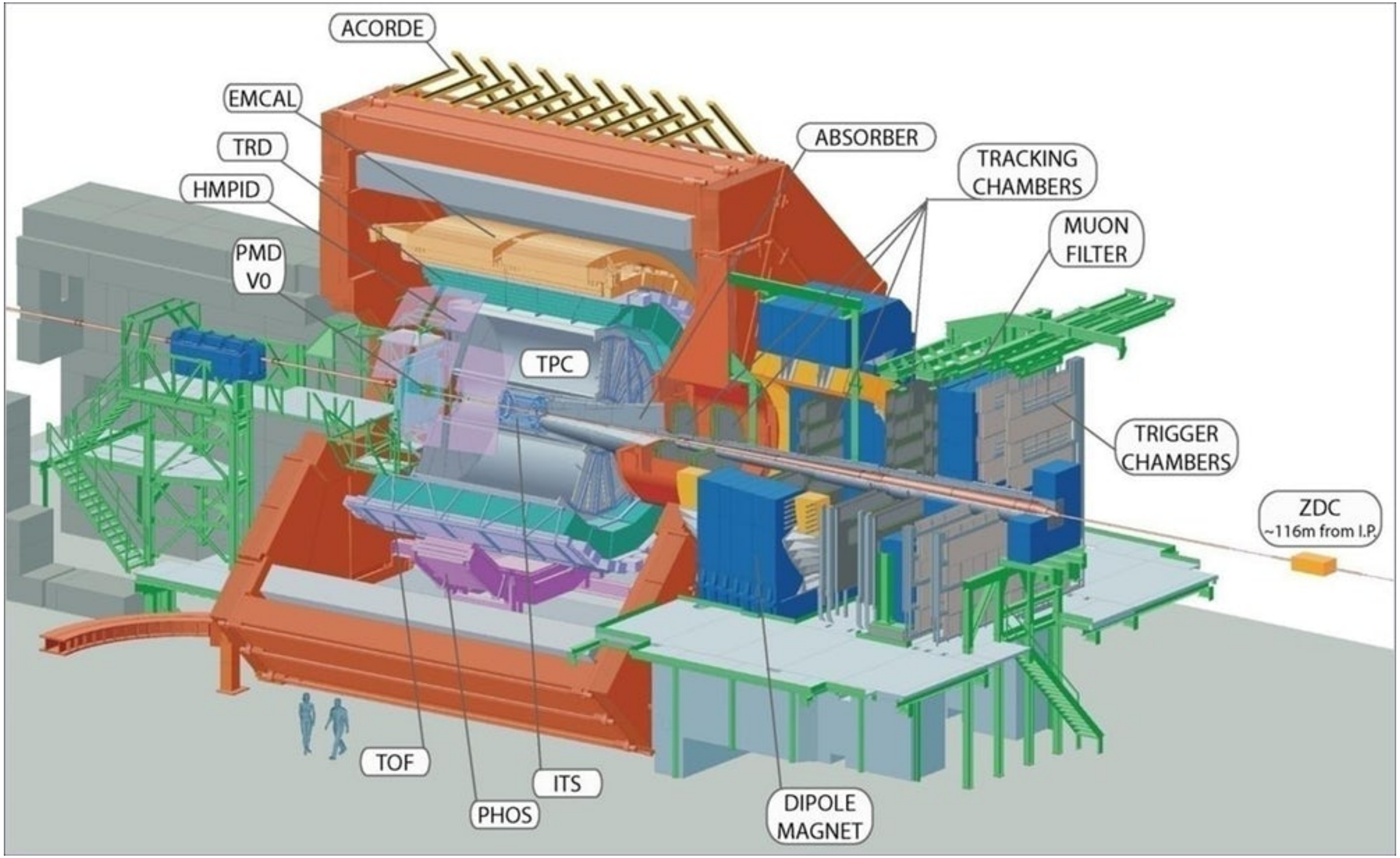
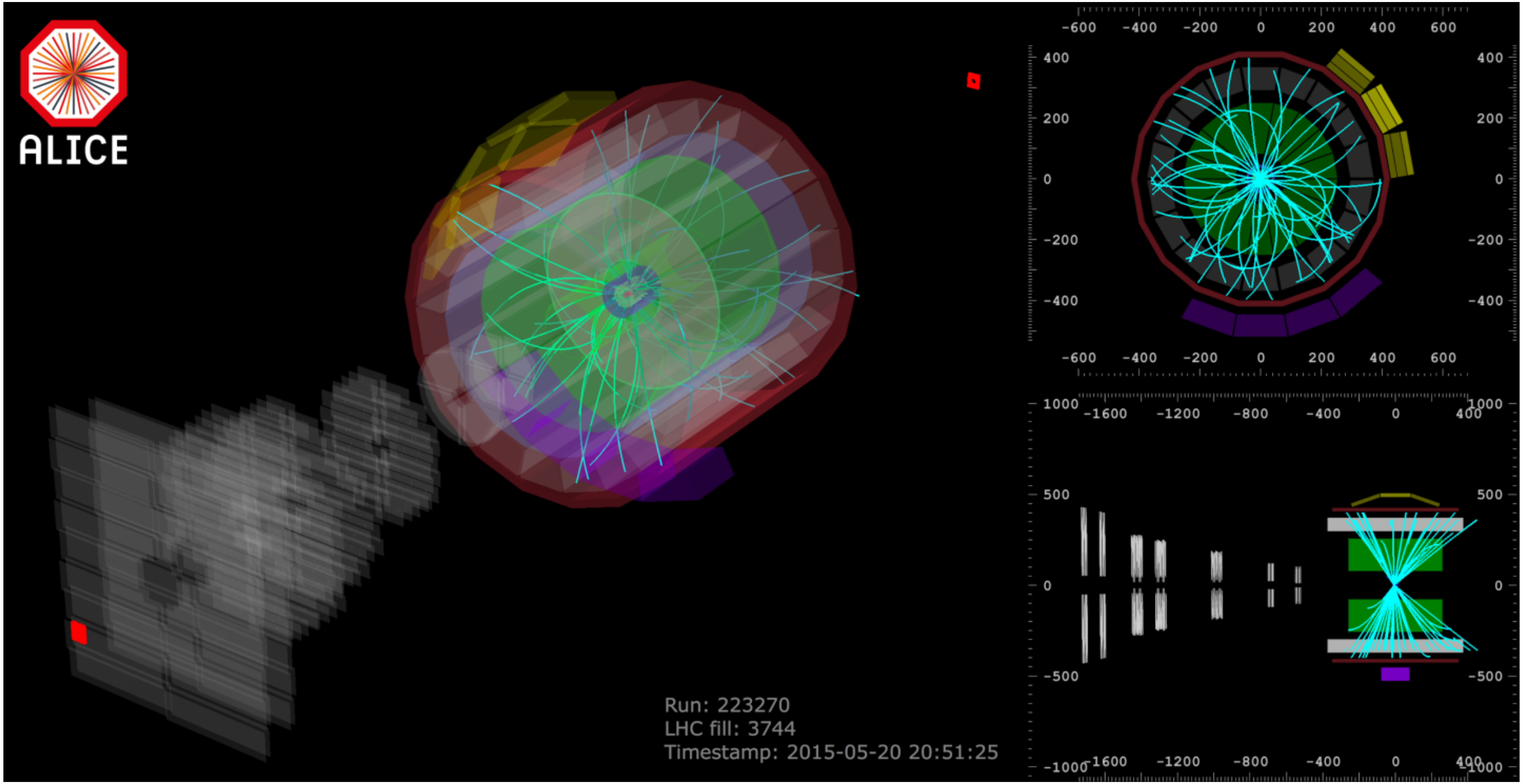
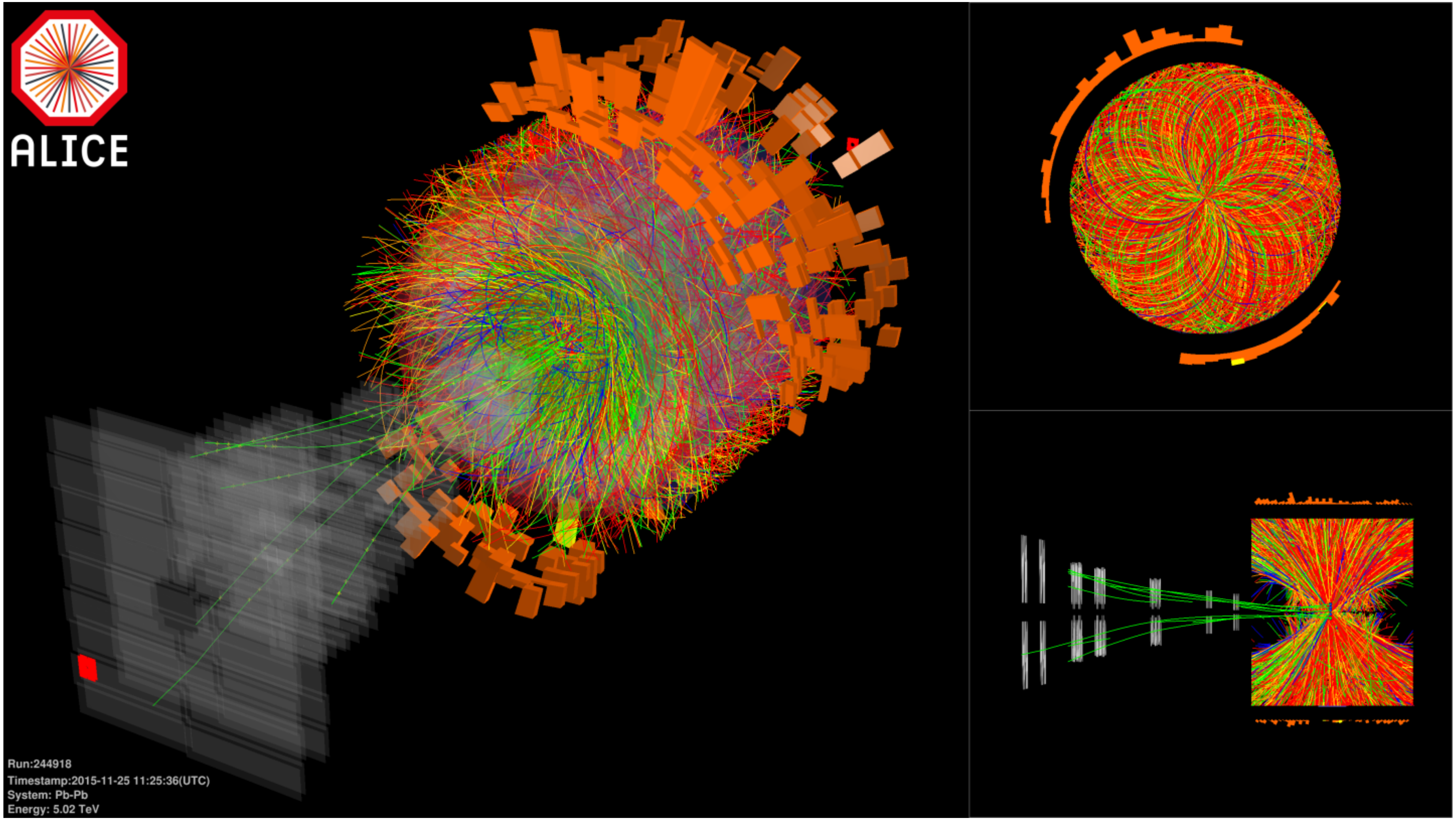


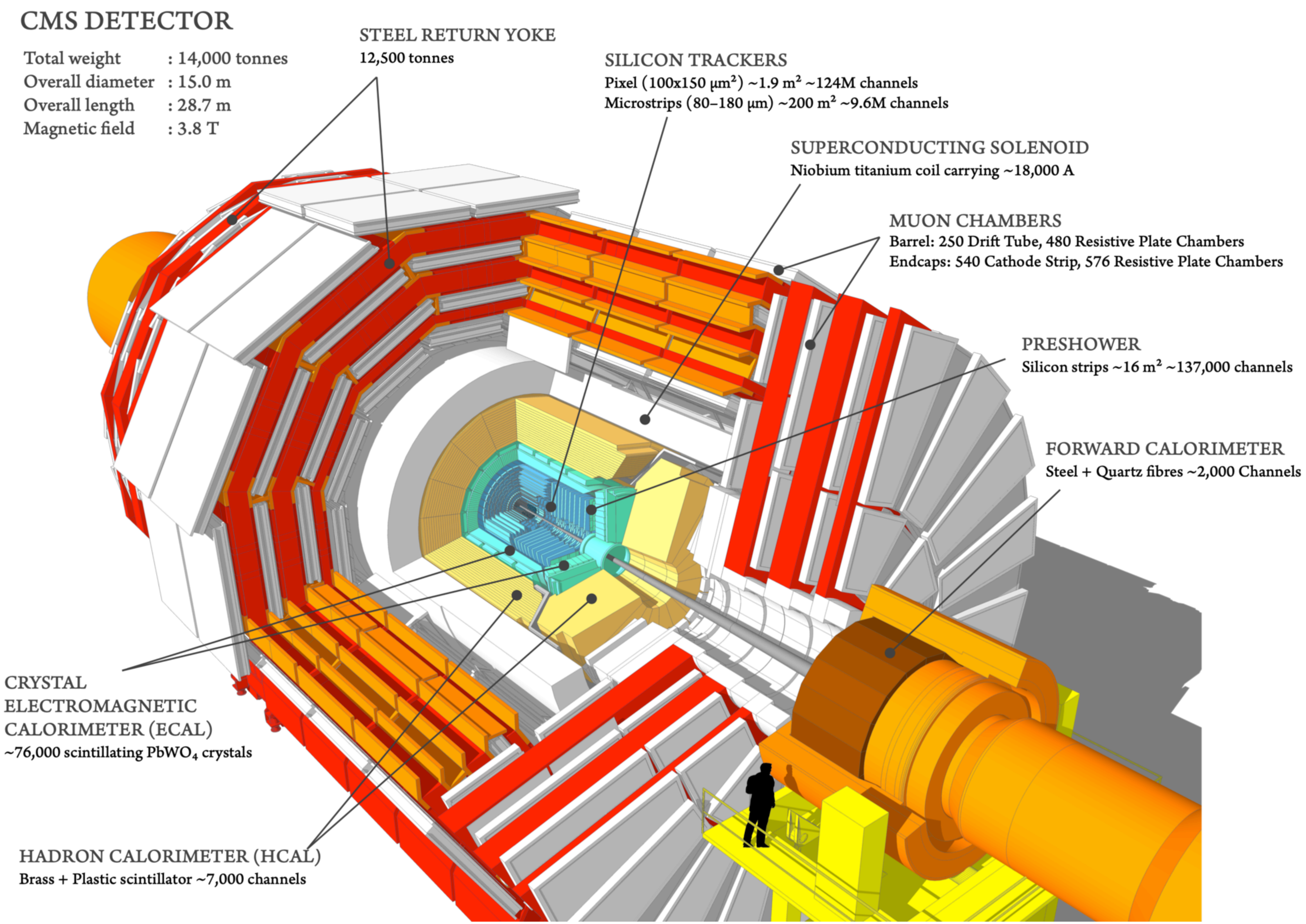
A proton-proton collision in ALICE



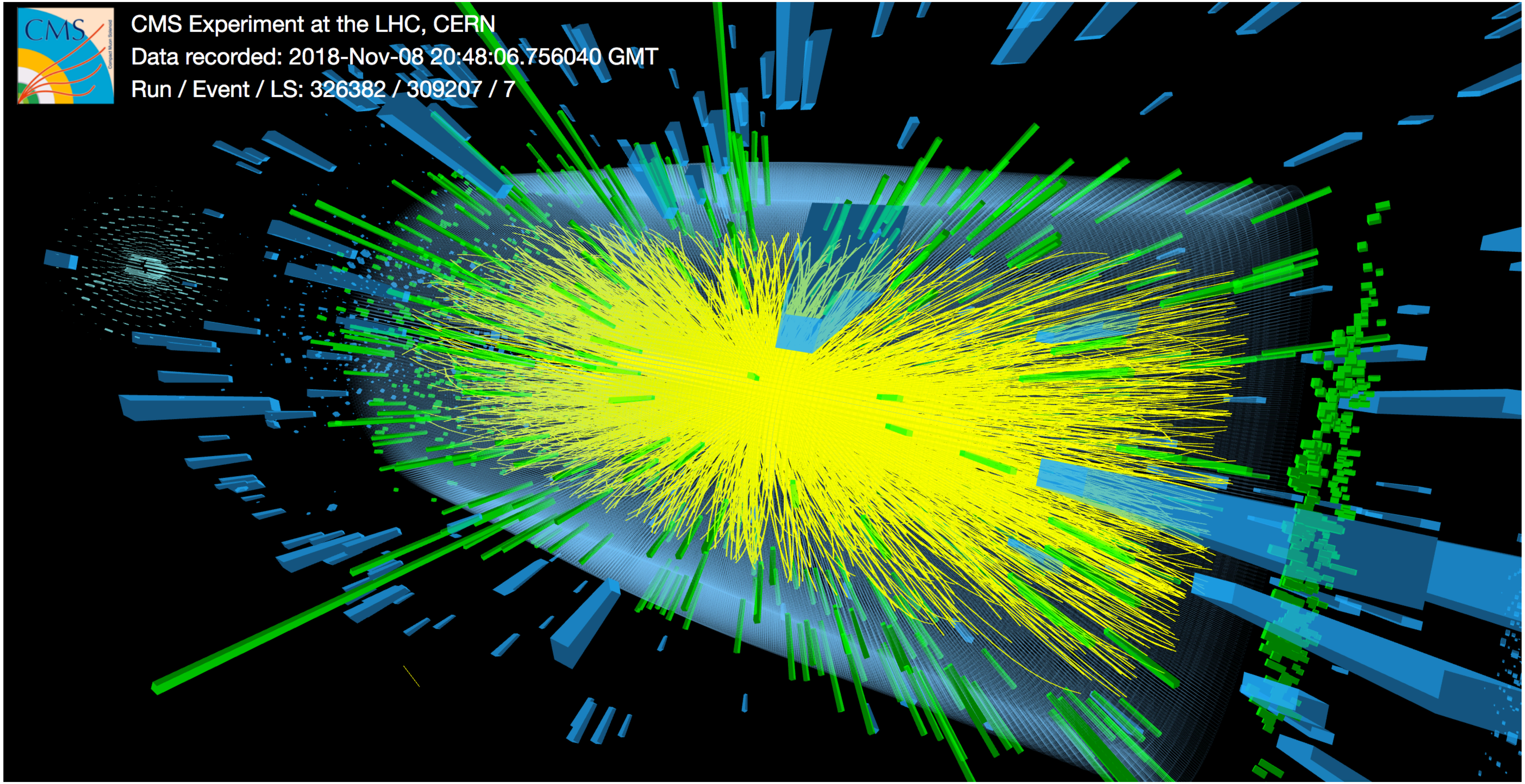
A Pb-Pb collision in ALICE



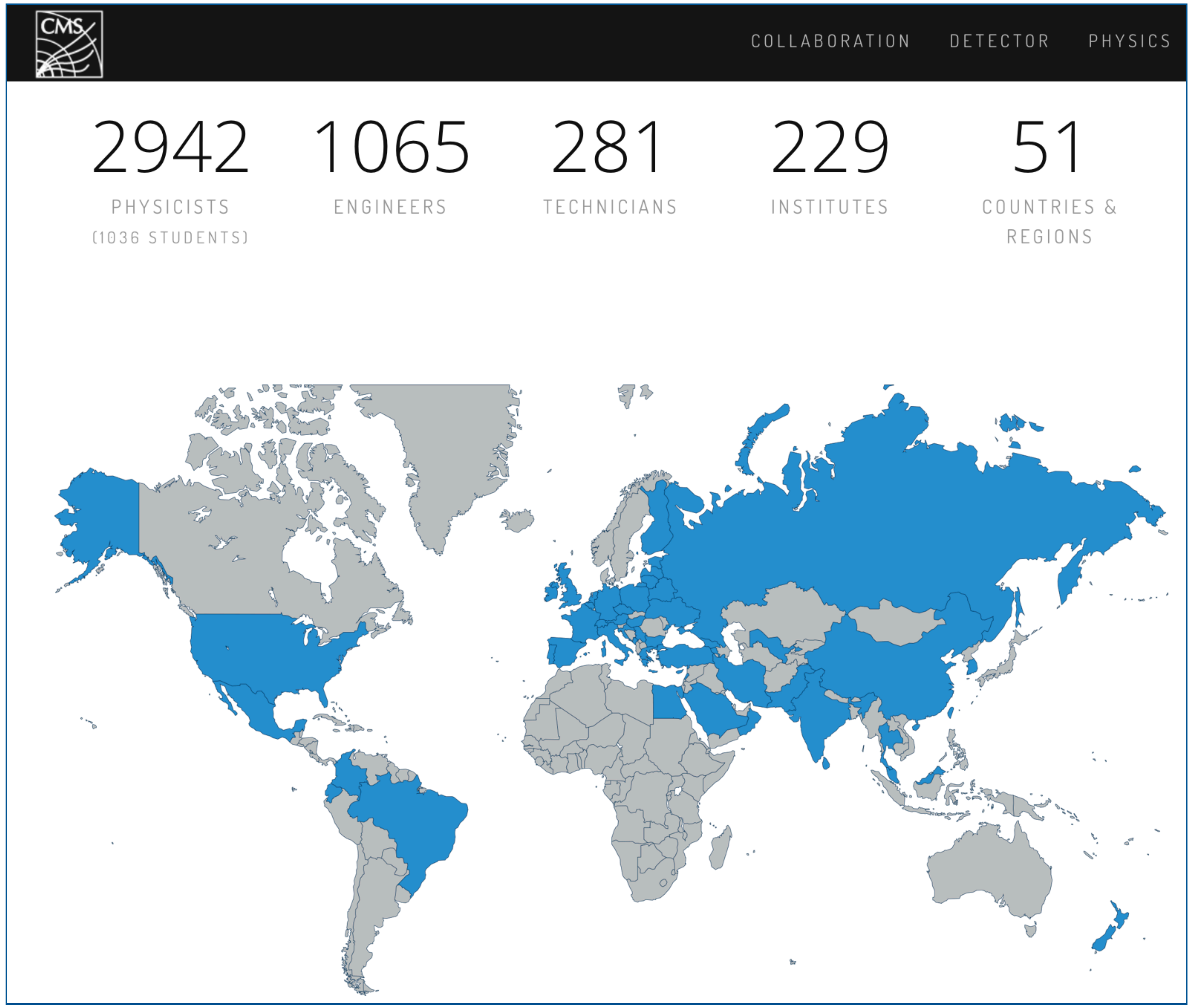
The Compact Muon Solenoid (CMS)



A Pb-Pb collision in CMS

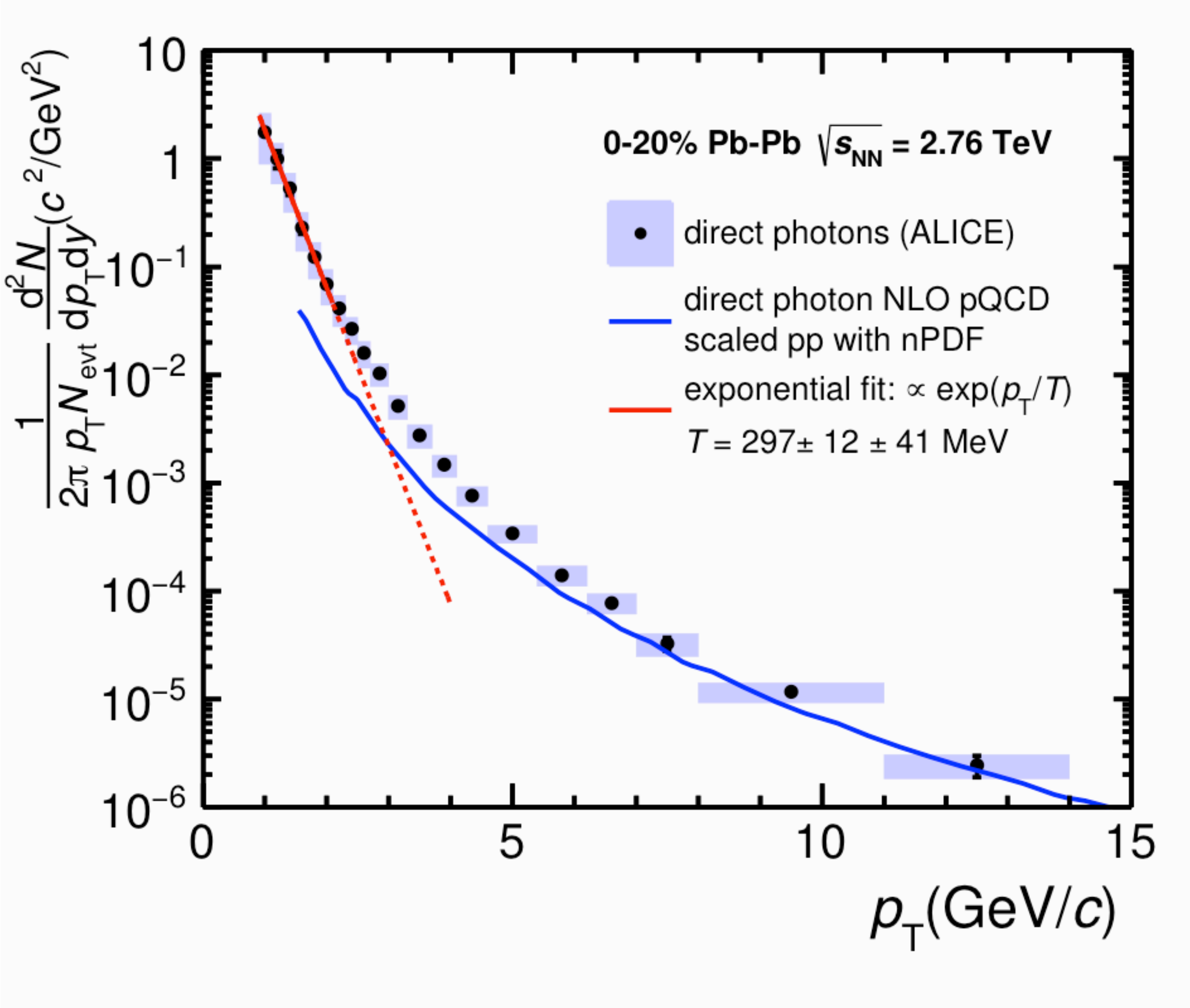


These are big global collaborations!



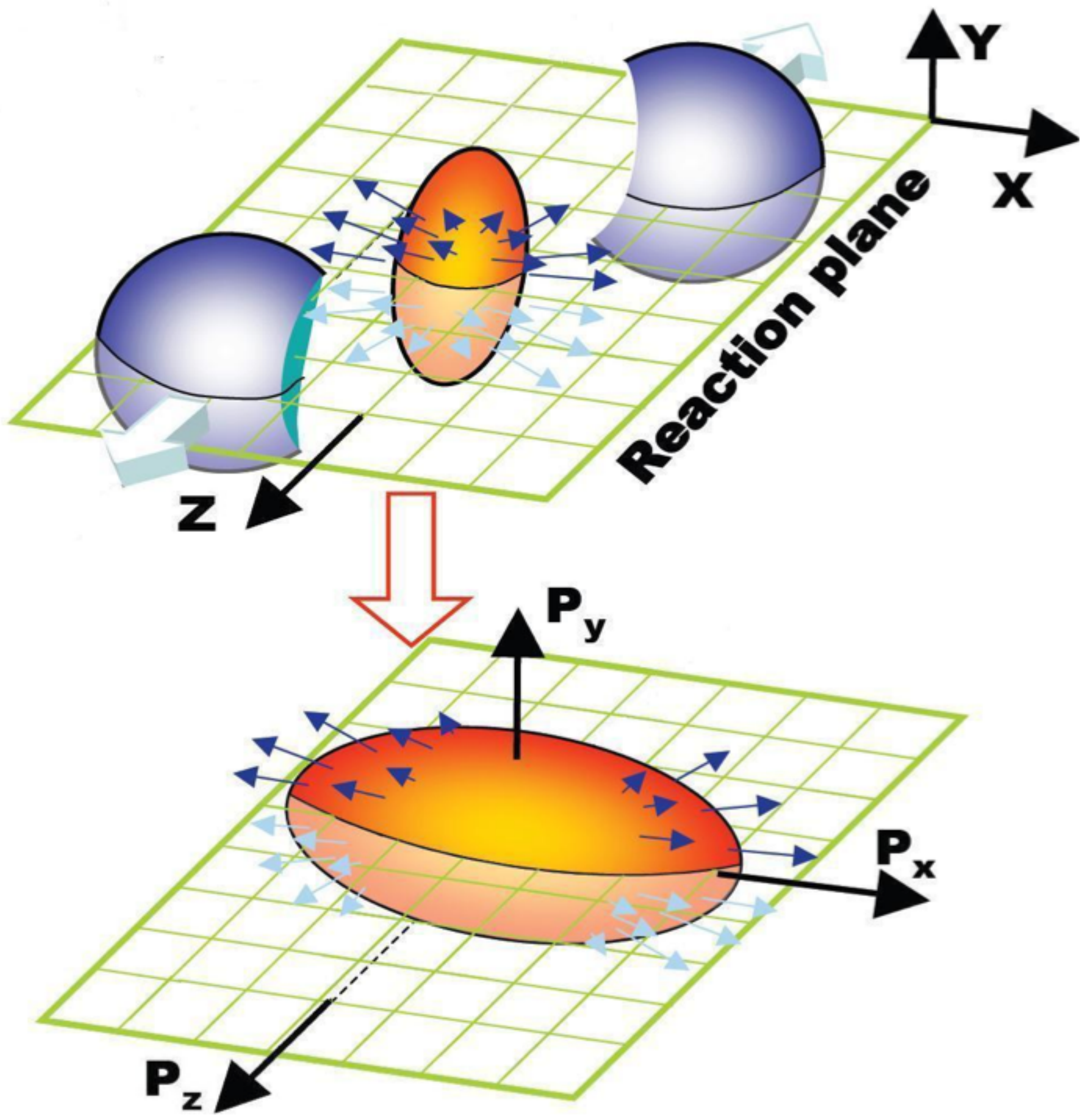
- A dedicated heavy-ion physics program occurs at Brookhaven National Lab
  - ✓Relativistic Heavy Ion Collider - Main experiments STAR and PHENX

Heavy-ion Physics achievements at the LHC

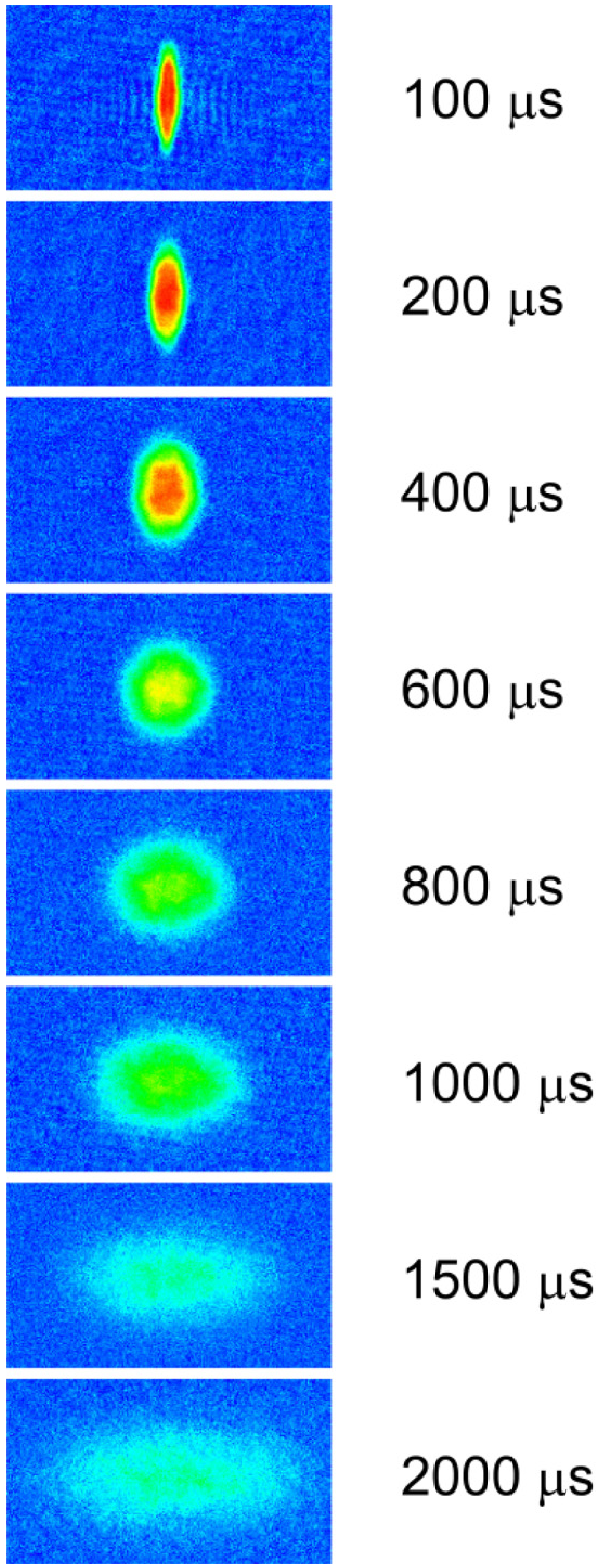


- Created hottest every matter on earth!
- Average energy of photons emitted can used to infer QGP temperature
- Measured temperature **twice temperature** needed for **QGP formation**

Anisotropic flow

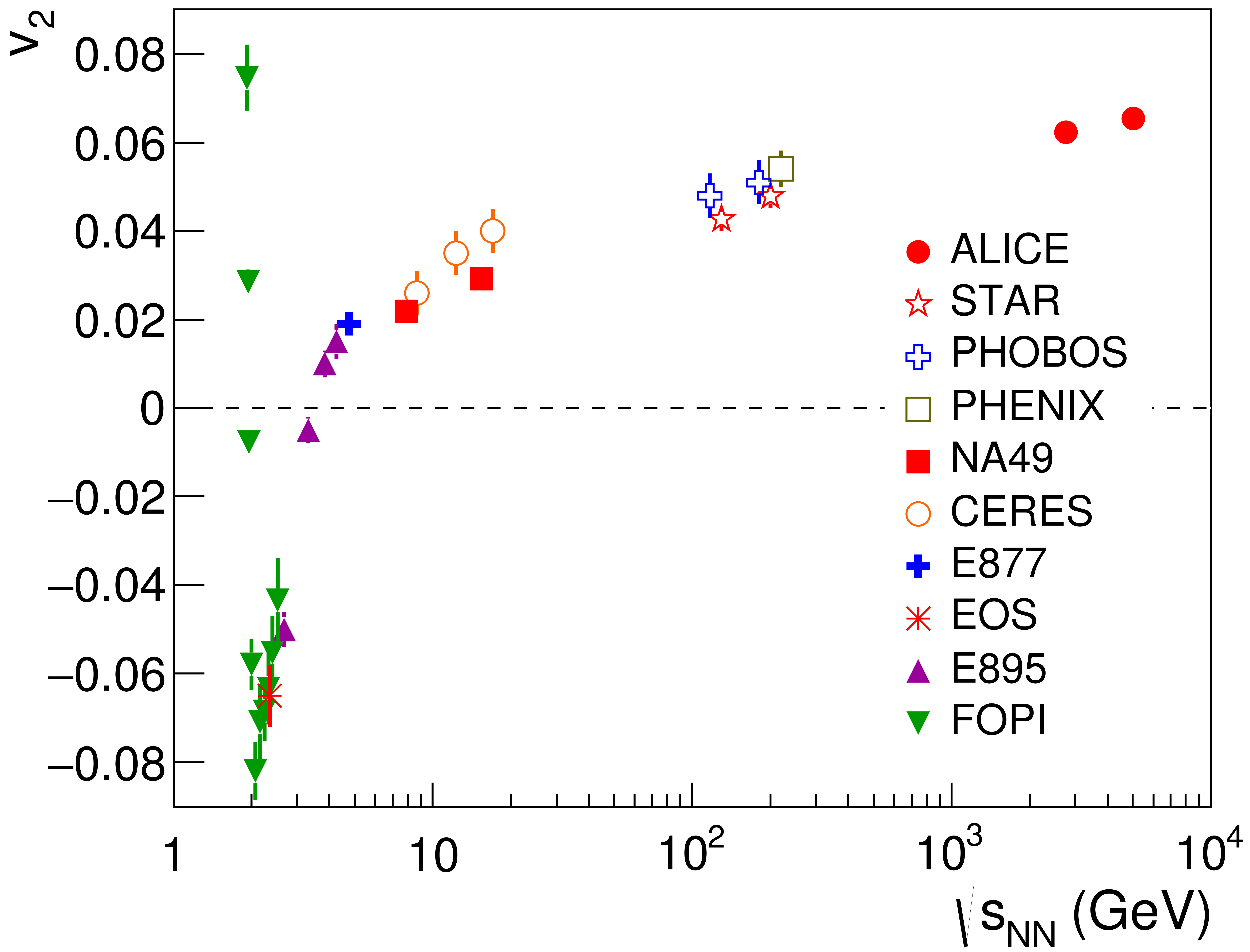


Science Dec 13 2002 2179-2182



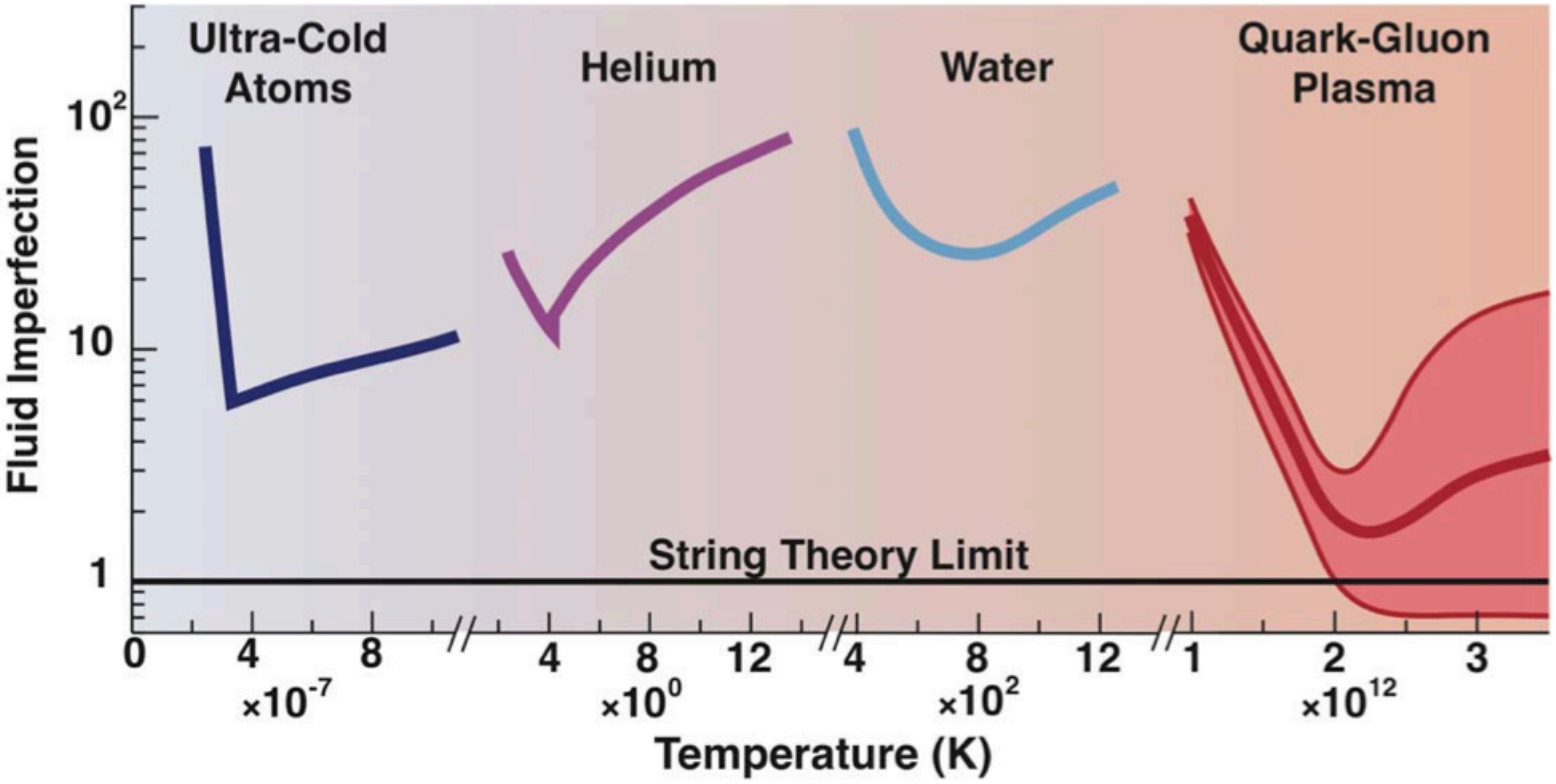
- Spatial anisotropies in the initial QGP state converted to momentum anisotropies

Anisotropic flow in Pb-Pb collisions



- v_2 characterizes strength of anisotropic flow
- Highest ever values observed at the LHC
- What does that mean?

The most perfect fluid ever



- Viscosity limits development of anisotropic flow
- Extracted viscosities from collisions creating the QGP at the LHC are the smallest observed in nature!

Other systems with small viscosities….

- The early universe was good at flowing!

https://www.youtube.com/watch?v=2Z6UJbwxBZI

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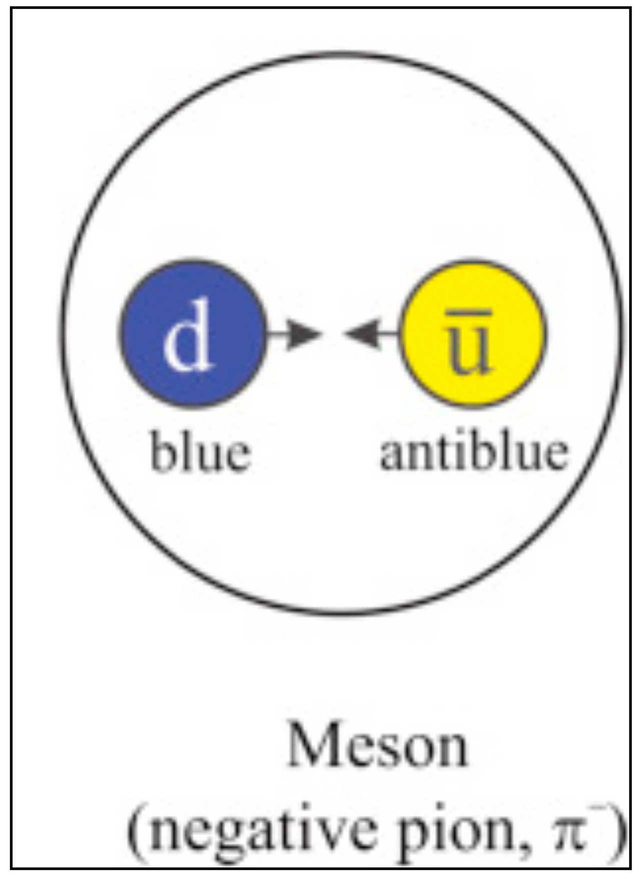
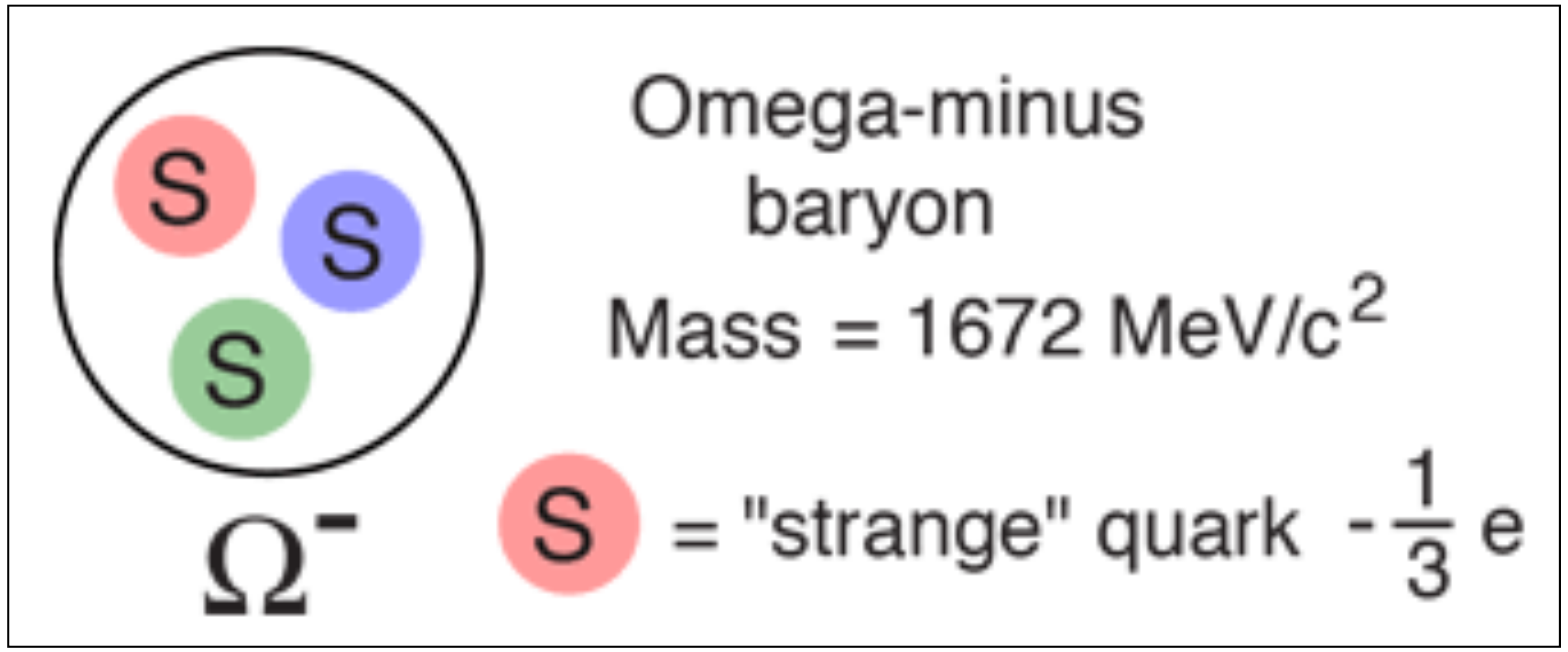
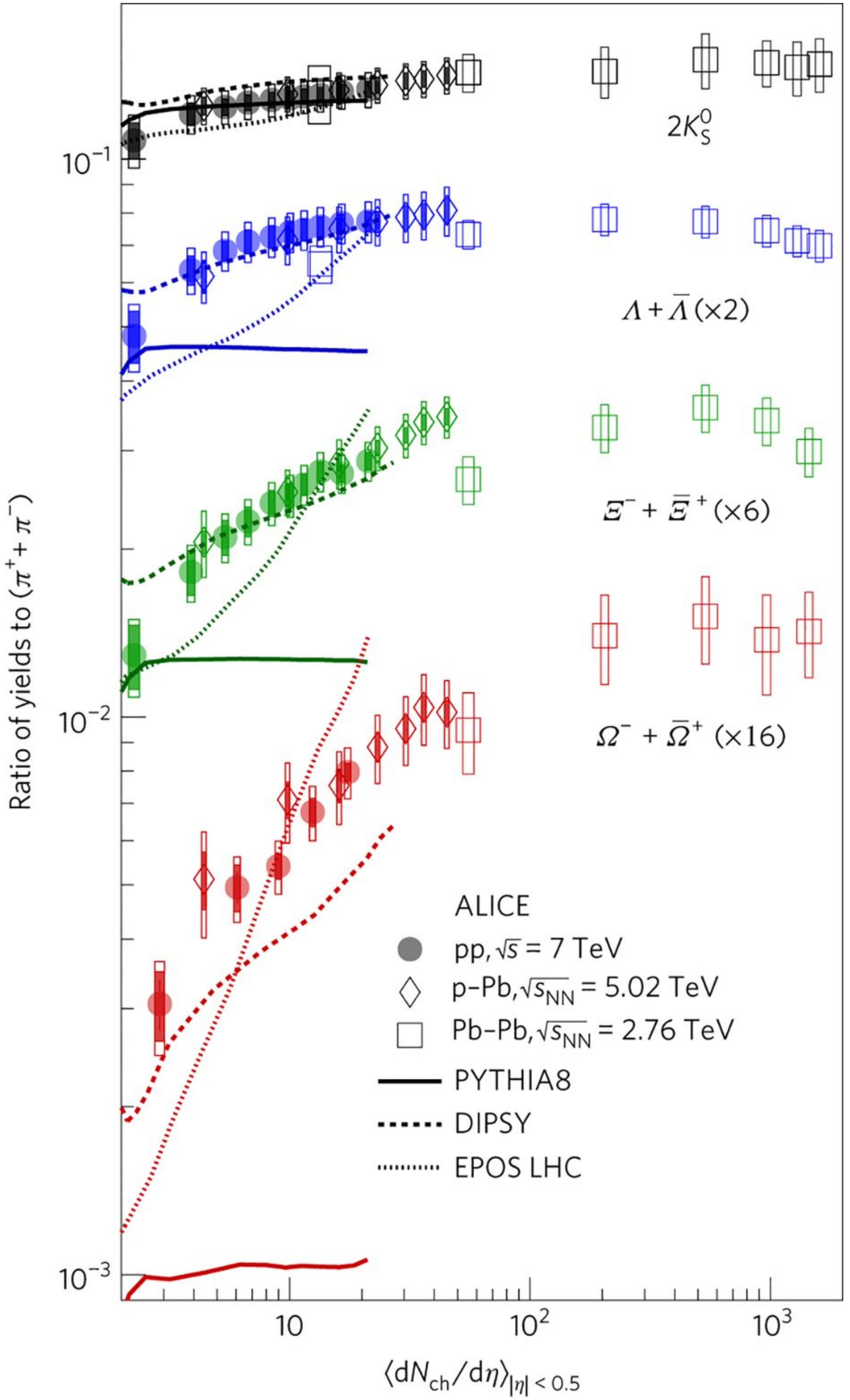
The early universe was strange

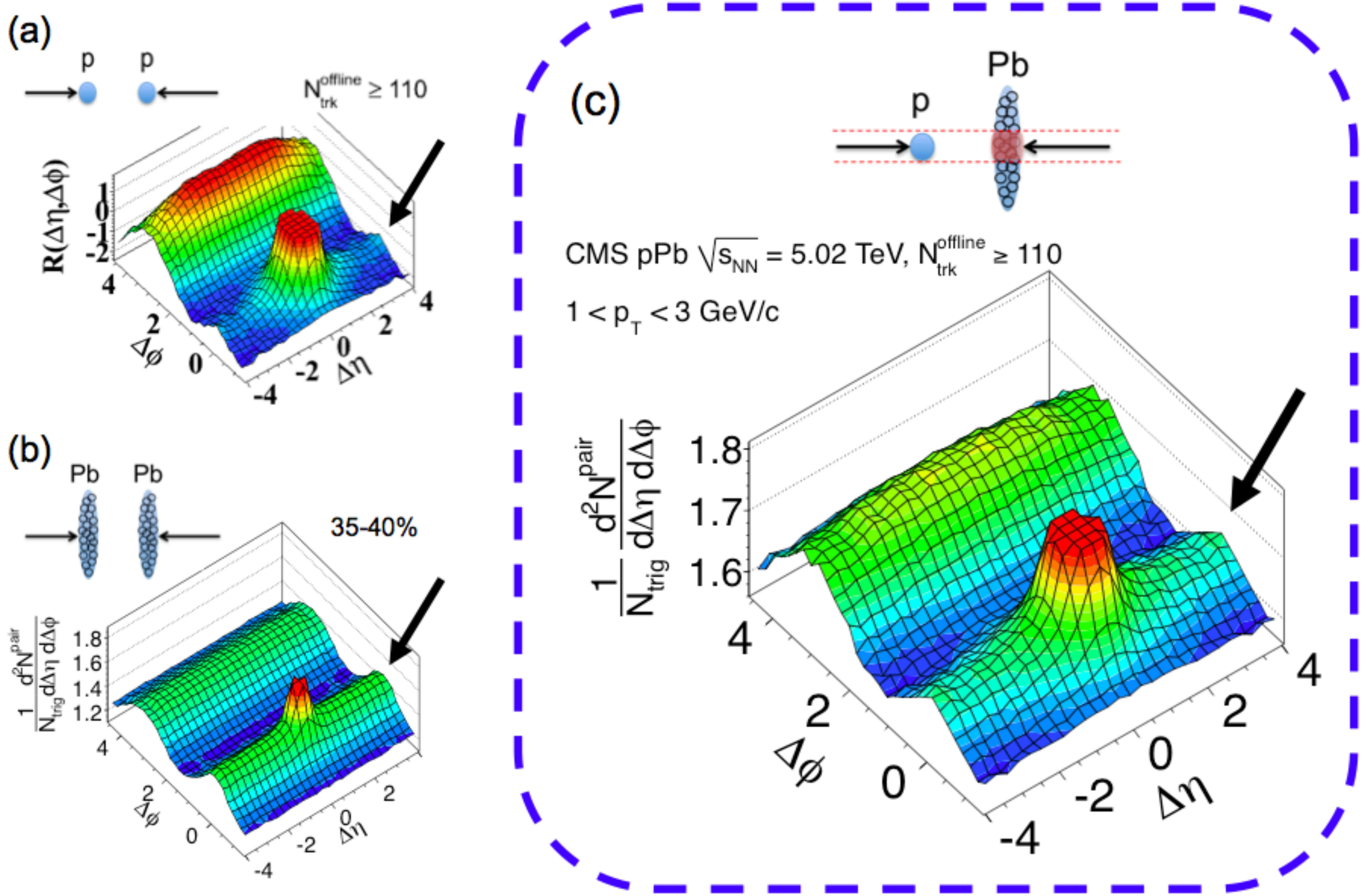






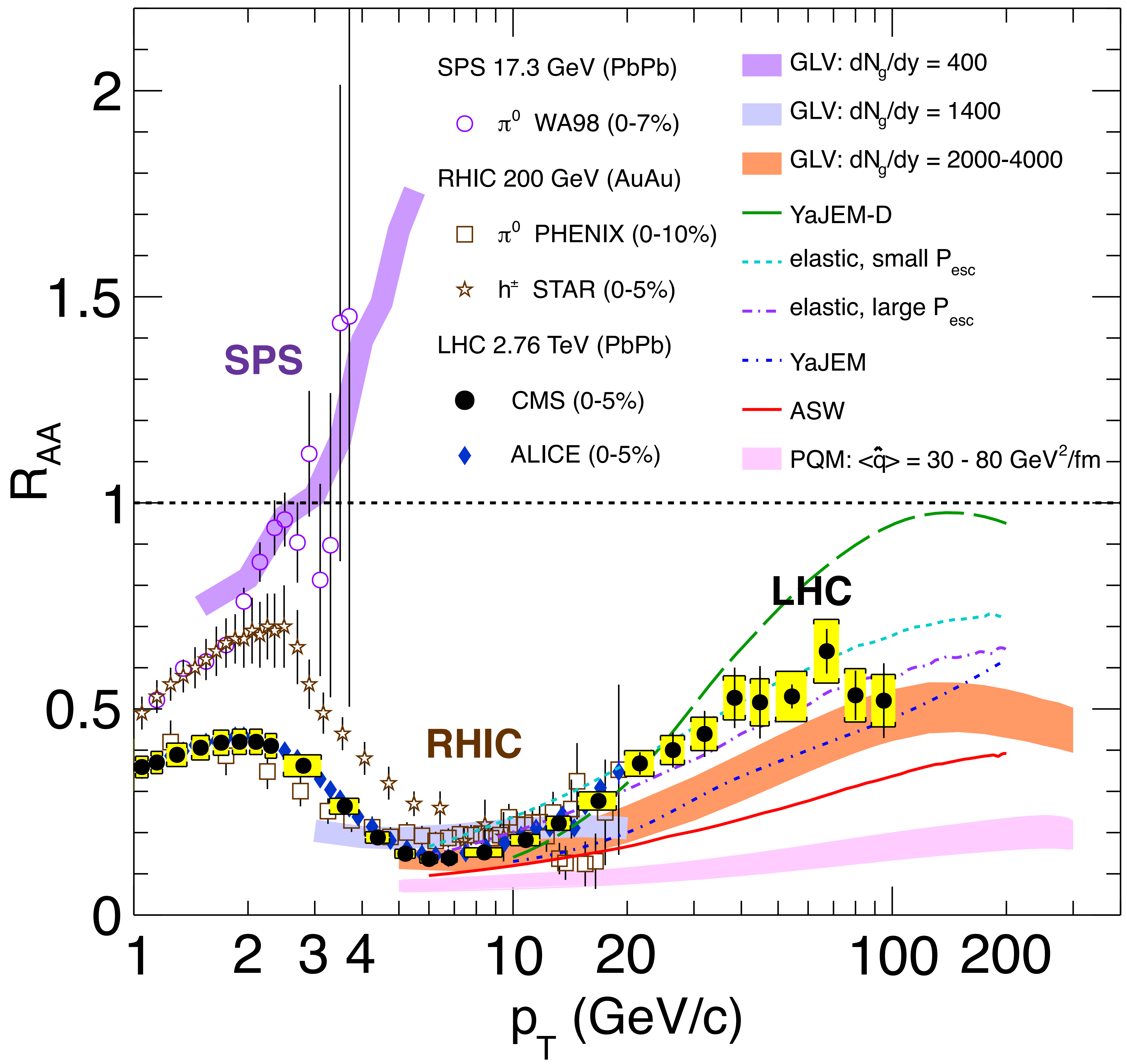
- The universe now is primarily composed of up and down quarks
- Strange quarks more copiously produced in the QGP

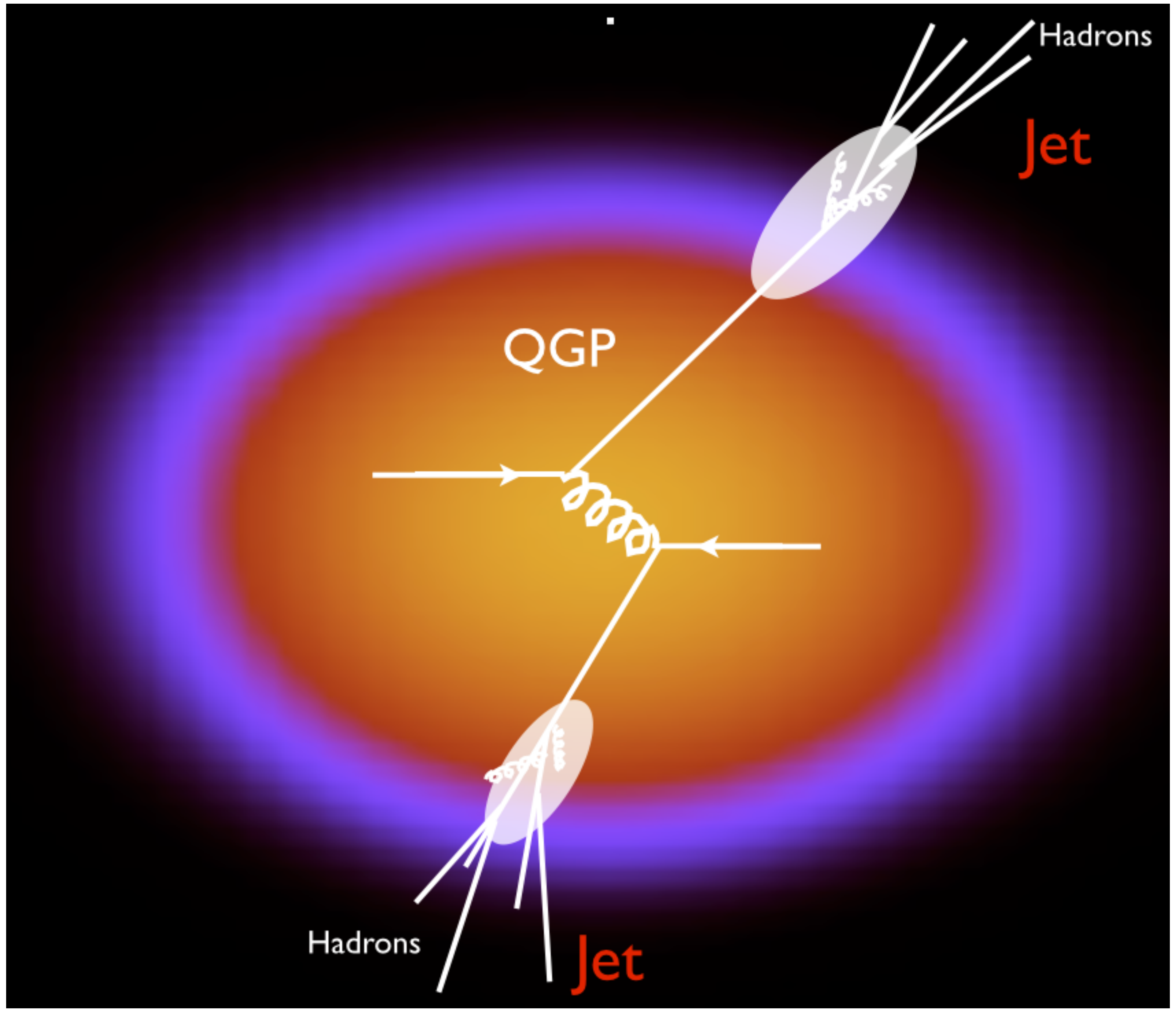
A QGP might be produced in proton-proton collisions



- Arrows correspond to evidence of v_2
- v_2 observed in p-p and p-Pb collisions
- Is there a QGP in these smaller systems with lower densities??

The Quark Gluon Plasma is rather opaque





- Production of particles with large energies is suppressed

Thanks for your attention!