

Heavy Ion Physics at the LHC



Anthony Timmins

What you learn in chemistry.....

The Periodic Table of the Elements

group 1																	18	
period 1	1.00794 1 H Hydrogen																	4.002602 2 He Helium
2	6.941 3 Li Lithium	9.012182 4 Be Beryllium											10.811 5 B Boron	12.0107 6 C Carbon	14.0067 7 N Nitrogen	15.9994 8 O Oxygen	18.998403 9 F Fluorine	20.1797 10 Ne Neon
3	22.98976 11 Na Sodium	24.3050 12 Mg Magnesium											26.98153 13 Al Aluminium	28.0855 14 Si Silicon	30.97696 15 P Phosphorus	32.065 16 S Sulfur	35.453 17 Cl Chlorine	39.948 18 Ar Argon
4	39.0983 19 K Potassium	40.078 20 Ca Calcium	44.95591 21 Sc Scandium	47.867 22 Ti Titanium	50.9415 23 V Vanadium	51.9962 24 Cr Chromium	54.93804 25 Mn Manganese	55.845 26 Fe Iron	58.93319 27 Co Cobalt	58.6934 28 Ni Nickel	63.546 29 Cu Copper	65.38 30 Zn Zinc	69.723 31 Ga Gallium	72.64 32 Ge Germanium	74.92160 33 As Arsenic	78.96 34 Se Selenium	79.904 35 Br Bromine	83.798 36 Kr Krypton
5	85.4678 37 Rb Rubidium	87.62 38 Sr Strontium	88.90585 39 Y Yttrium	91.224 40 Zr Zirconium	92.90638 41 Nb Niobium	95.96 42 Mo Molybdenum	(98) 43 Tc Technetium	101.07 44 Ru Ruthenium	102.9055 45 Rh Rhodium	106.42 46 Pd Palladium	107.8682 47 Ag Silver	112.441 48 Cd Cadmium	114.818 49 In Indium	118.710 50 Sn Tin	121.760 51 Sb Antimony	127.60 52 Te Tellurium	126.9044 53 I Iodine	131.293 54 Xe Xenon
6	132.9054 55 Cs Caesium	137.327 56 Ba Barium	174.9668 71 Lu Lutetium	178.49 72 Hf Hafnium	180.9478 73 Ta Tantalum	183.84 74 W Tungsten	186.207 75 Re Rhenium	190.23 76 Os Osmium	192.217 77 Ir Iridium	195.084 78 Pt Platinum	196.9665 79 Au Gold	200.59 80 Hg Mercury	204.3833 81 Tl Thallium	207.2 82 Pb Lead	208.9804 83 Bi Bismuth	(210) 84 Po Polonium	(210) 85 At Astatine	(220) 86 Rn Radon
7	(223) 87 Fr Francium	(226) 88 Ra Radium	(262) 103 Lr Lawrencium	(261) 104 Rf Rutherfordium	(262) 105 Db Dubnium	(266) 106 Sg Seaborgium	(264) 107 Bh Bohrium	(277) 108 Hs Hassium	(268) 109 Mt Meitnerium	(271) 110 Ds Darmstadtium	(272) 111 Rg Roentgenium	(285) 112 Cn Copernicium	(284) 113 Uut Ununtrium	(289) 114 Fl Flerovium	(288) 115 Uup Ununpentium	(292) 116 Lv Livermorium	117 Uus Ununseptium	(294) 118 Uuo Ununoctium

atomic mass or most stable mass number: 55.845

1st ionization energy in kJ/mol: 762.5

chemical symbol: Fe

name: Iron

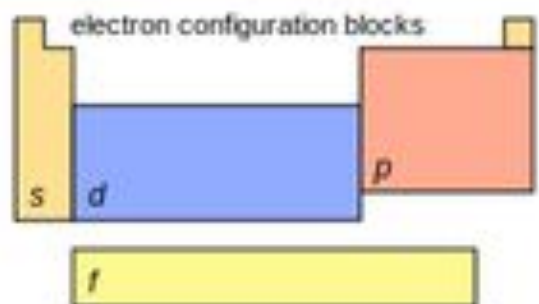
electron configuration: [Ar] 3d⁶ 4s²

atomic number: 26

electronegativity: 1.83

oxidation states: +6, +5, +4, +3, +2, +1, -1, -2

- alkali metals
- alkaline metals
- other metals
- transition metals
- lanthanoids
- actinoids
- metalloids
- nonmetals
- halogens
- noble gases
- unknown elements
- radioactive elements have masses in parentheses



notes

- as of yet, elements 113,115,117 and 118 have no official name designated by the IUPAC.
- 1 kJ/mol = 96.485 eV.
- all elements are implied to have an oxidation state of zero.

138.9054 57 La Lanthanum	140.116 58 Ce Cerium	140.9076 59 Pr Praseodymium	144.242 60 Nd Neodymium	(145) 61 Pm Promethium	150.36 62 Sm Samarium	151.964 63 Eu Europium	157.25 64 Gd Gadolinium	158.9253 65 Tb Terbium	162.500 66 Dy Dysprosium	164.9303 67 Ho Holmium	167.259 68 Er Erbium	168.9342 69 Tm Thulium	173.054 70 Yb Ytterbium
(227) 89 Ac Actinium	232.0380 90 Th Thorium	231.0358 91 Pa Protactinium	238.0289 92 U Uranium	(237) 93 Np Neptunium	(244) 94 Pu Plutonium	(243) 95 Am Americium	(247) 96 Cm Curium	(247) 97 Bk Berkelium	(251) 98 Cf Californium	(252) 99 Es Einsteinium	(257) 100 Fm Fermium	(258) 101 Md Mendelevium	(259) 102 No Nobelium

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		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	\bar{u} antiup	\bar{c} anticharm	\bar{t} antitop	g gluon	H higgs
		d down	s strange	b bottom	\bar{d} antidown	\bar{s} antistrange	\bar{b} antibottom		
LEPTONS	mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$		
	charge	-1	-1	-1	1	1	1		
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$		
		e electron	μ muon	τ tau	e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau		
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino			
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$			
	0	0	0	0	0	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$			
	W^+ W^+ boson				W^- W^- boson				
	$\approx 80.39 \text{ GeV}/c^2$				$\approx 80.39 \text{ GeV}/c^2$				
	1				-1				
	1				1				

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

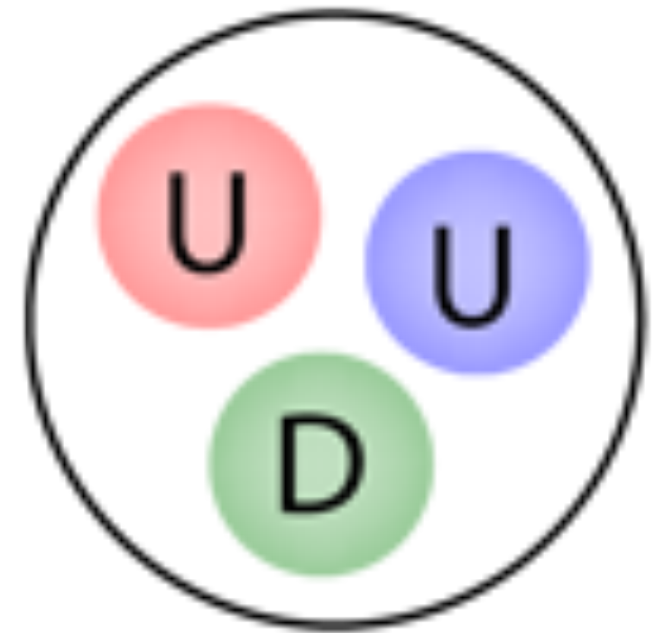
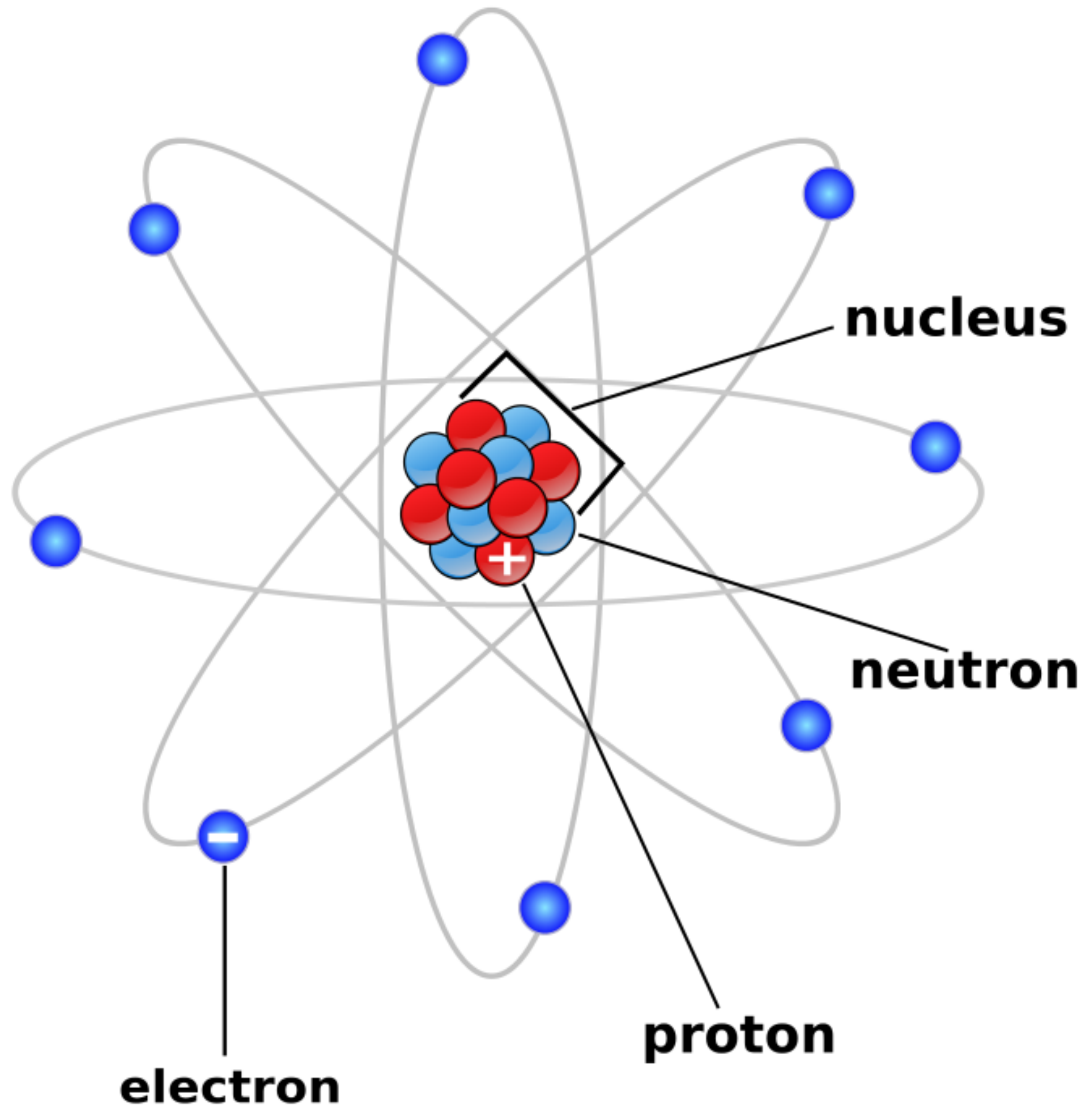
Standard Model of Elementary Particles

	three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)
	I	II	III	I	II	III	
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	u up	c charm	t top	\bar{u} antiup	\bar{c} anticharm	\bar{t} antitop	g gluon
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
	d down	s strange	b bottom	\bar{d} antidown	\bar{s} antistrange	\bar{b} antibottom	

QUARKS

GAUGE BOSONS
VECTOR BOSONS

Where do we find quarks?



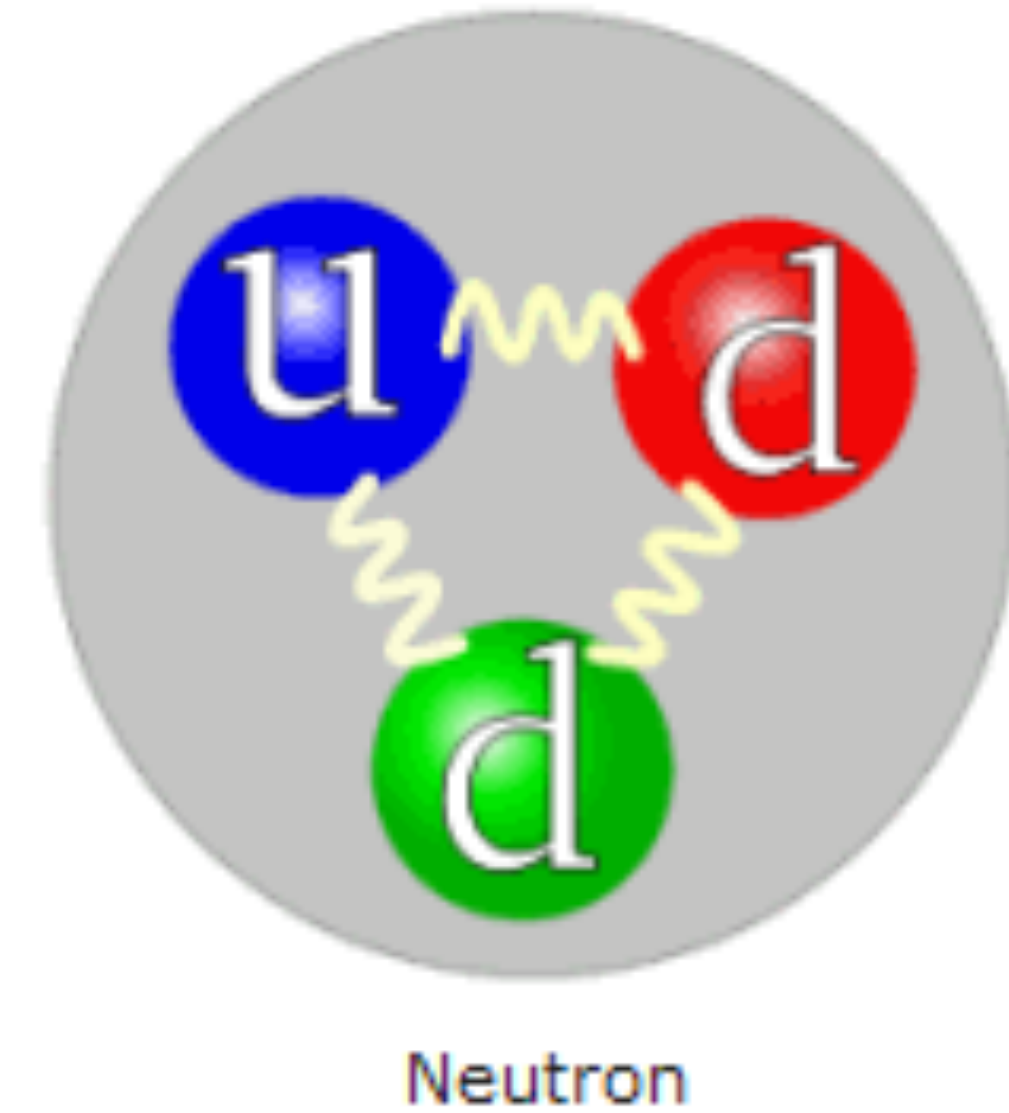
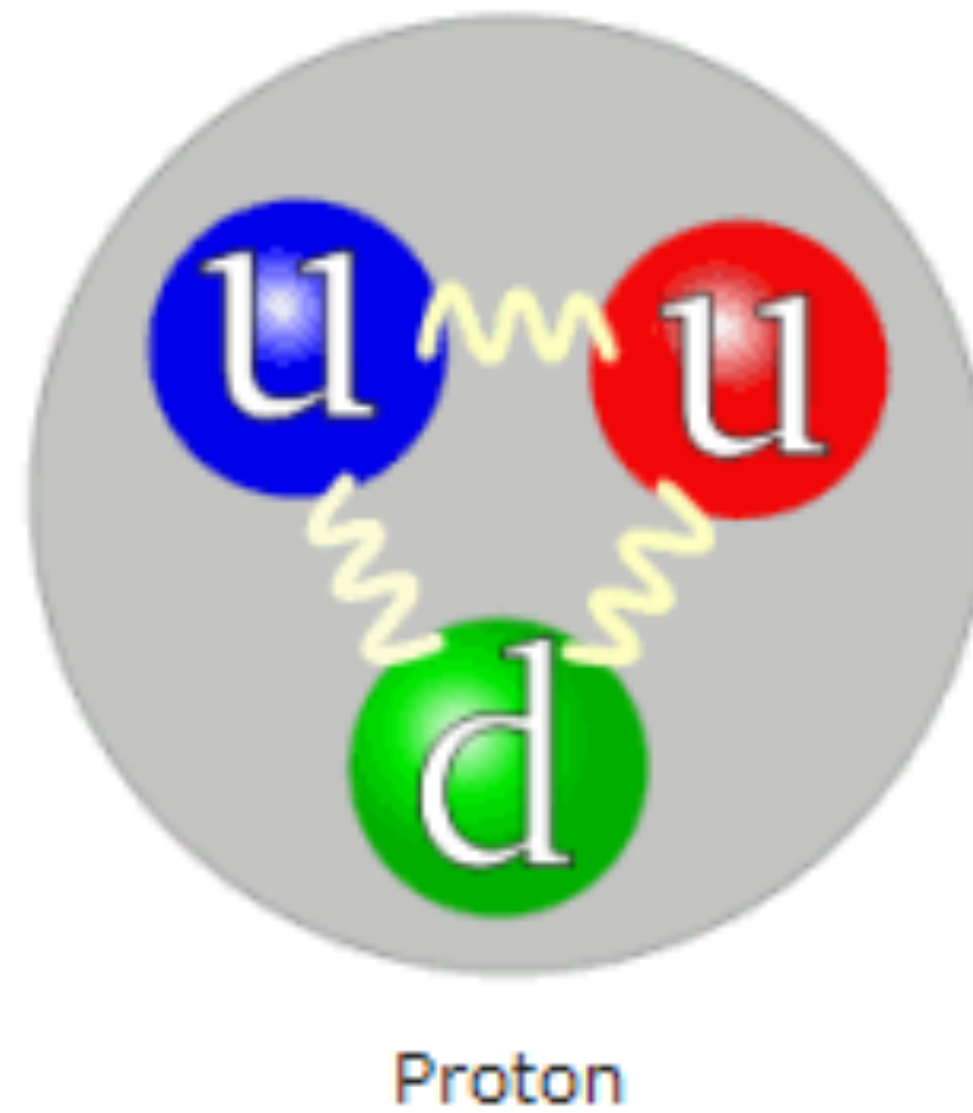
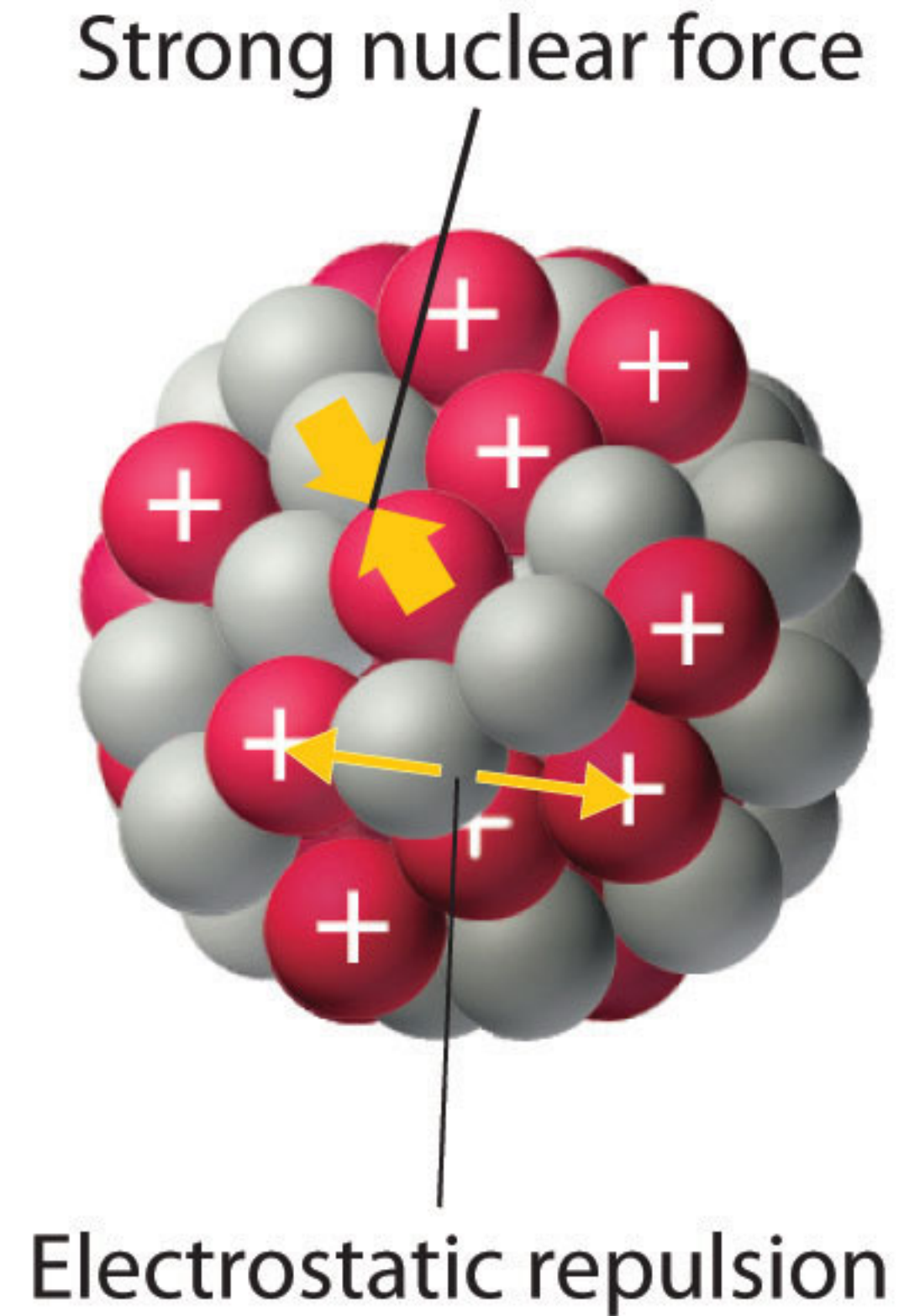
Proton



Neutron

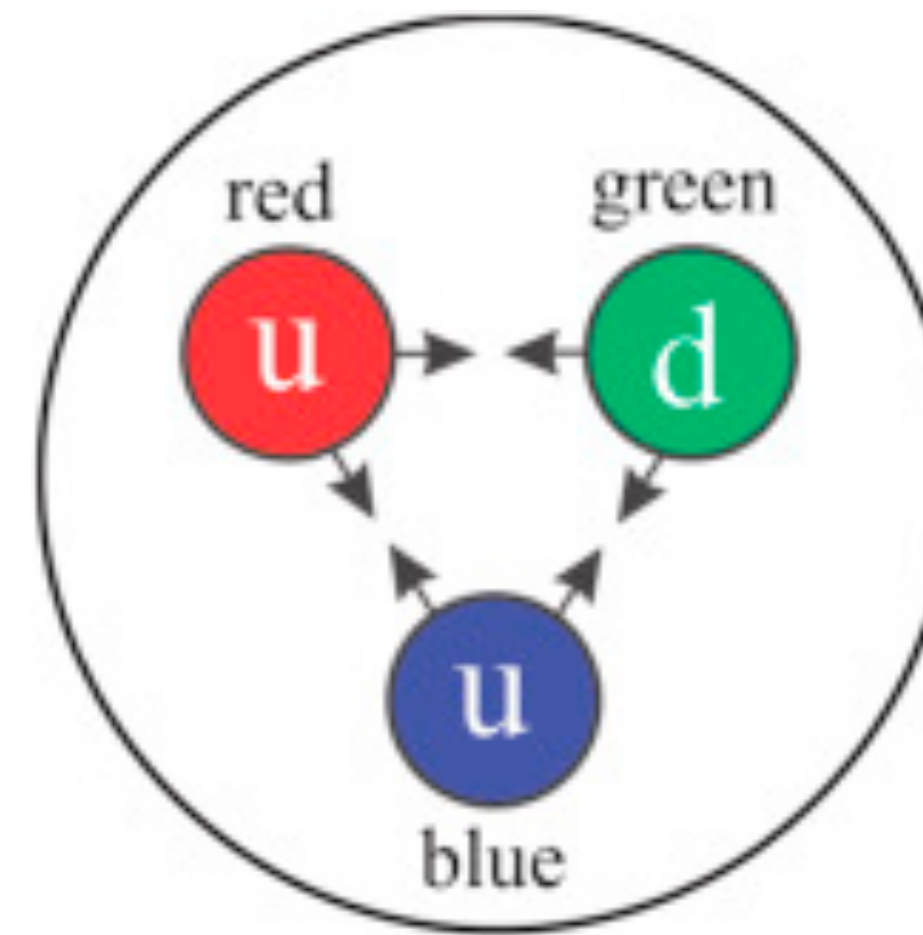
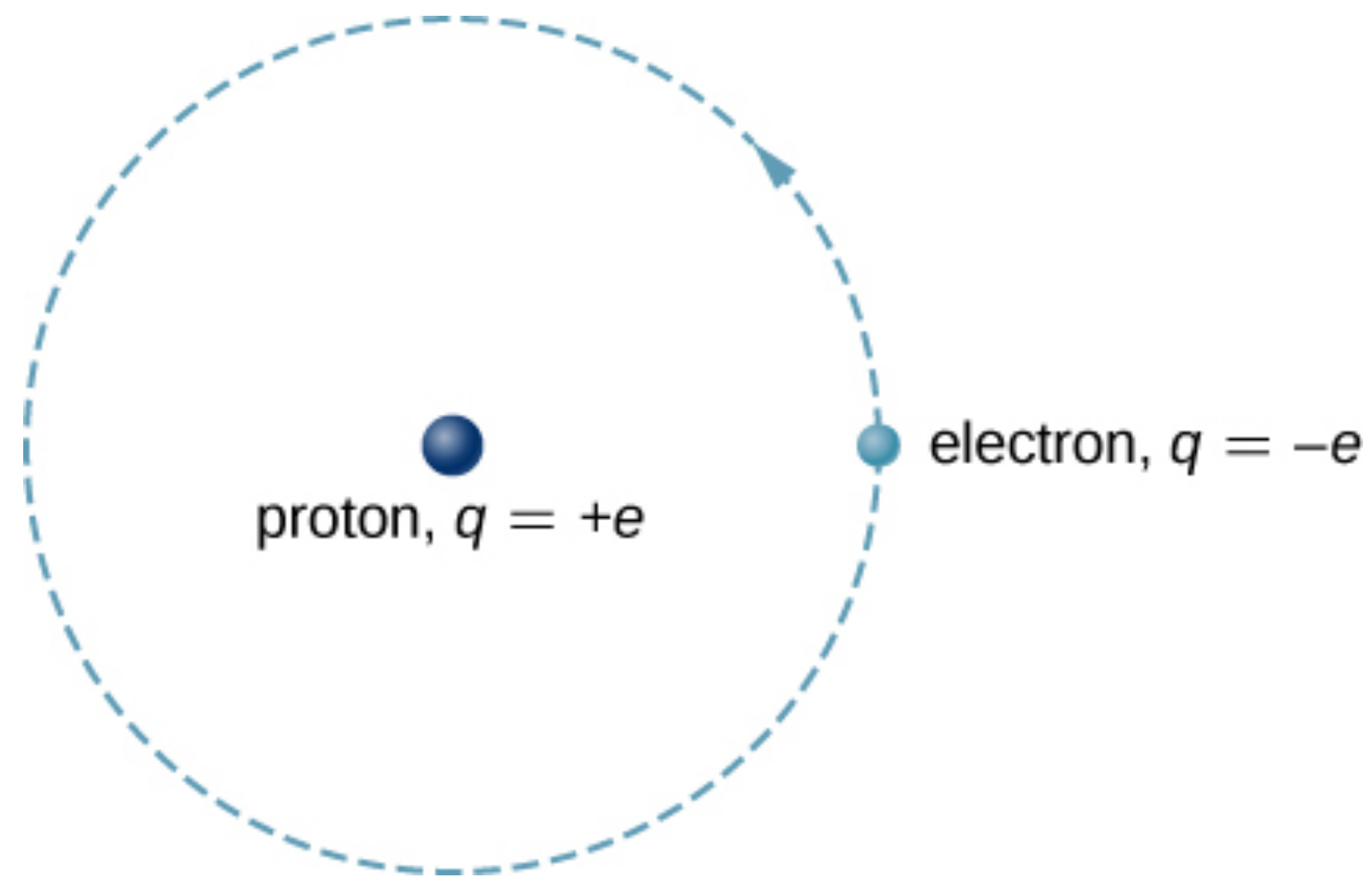
U = "up" quark $+\frac{2}{3} e$
D = "down" quark $-\frac{1}{3} e$

What keeps quarks confined in a proton or neutron?

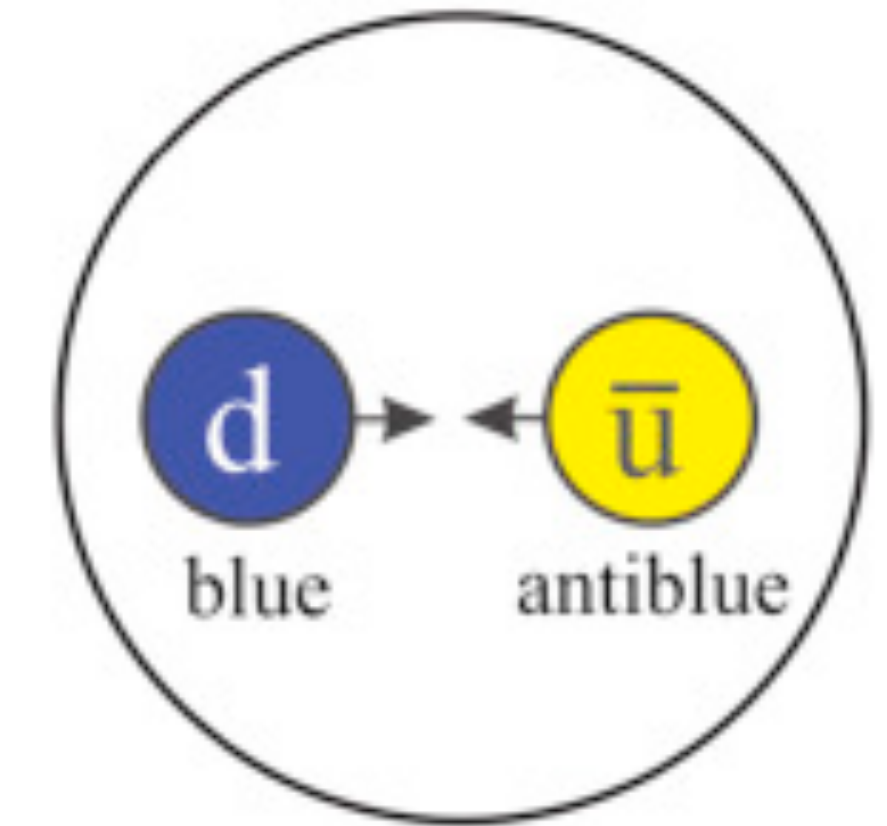


► **Color**: The “charge” associated with the strong force

How many color charges exist?



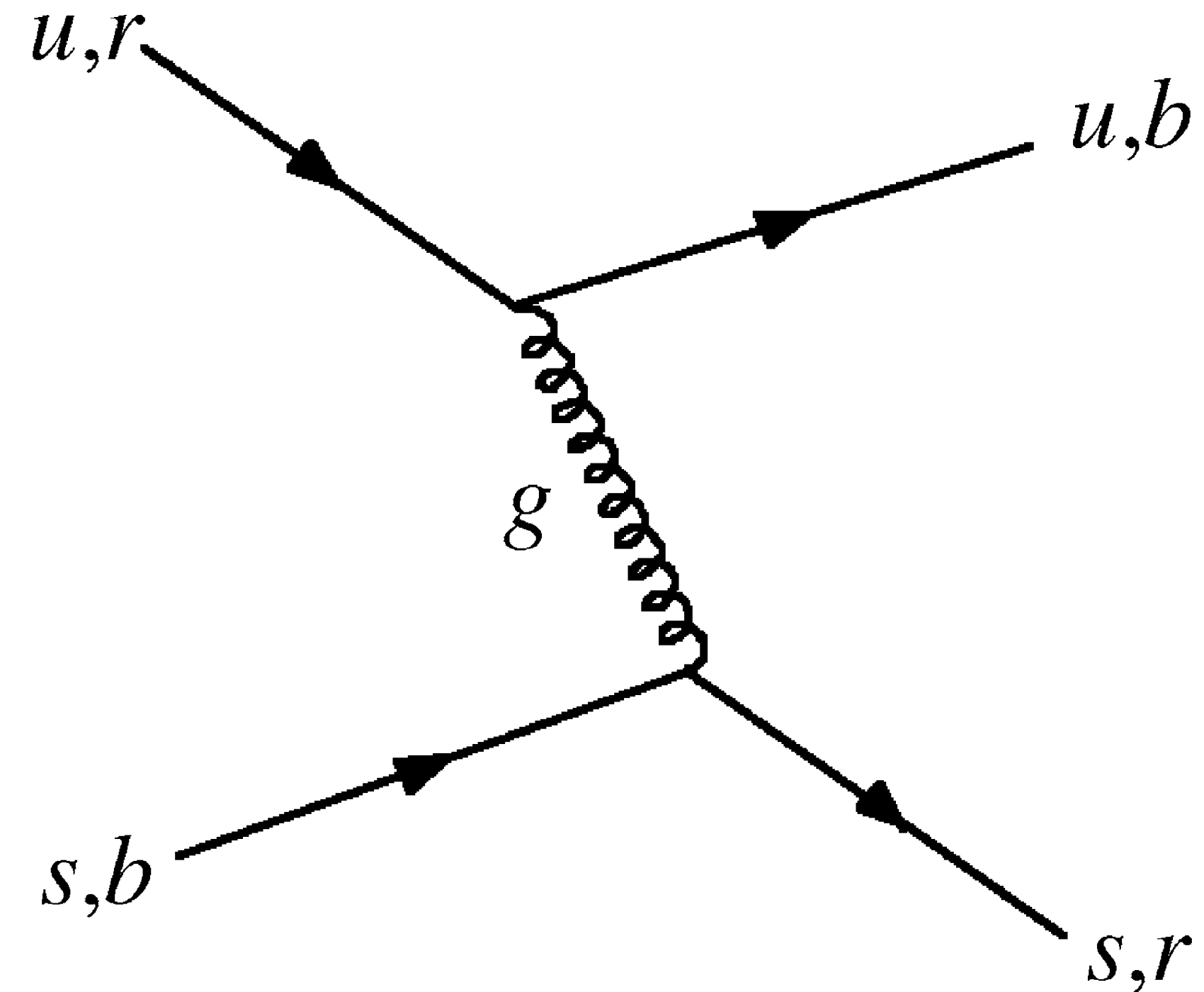
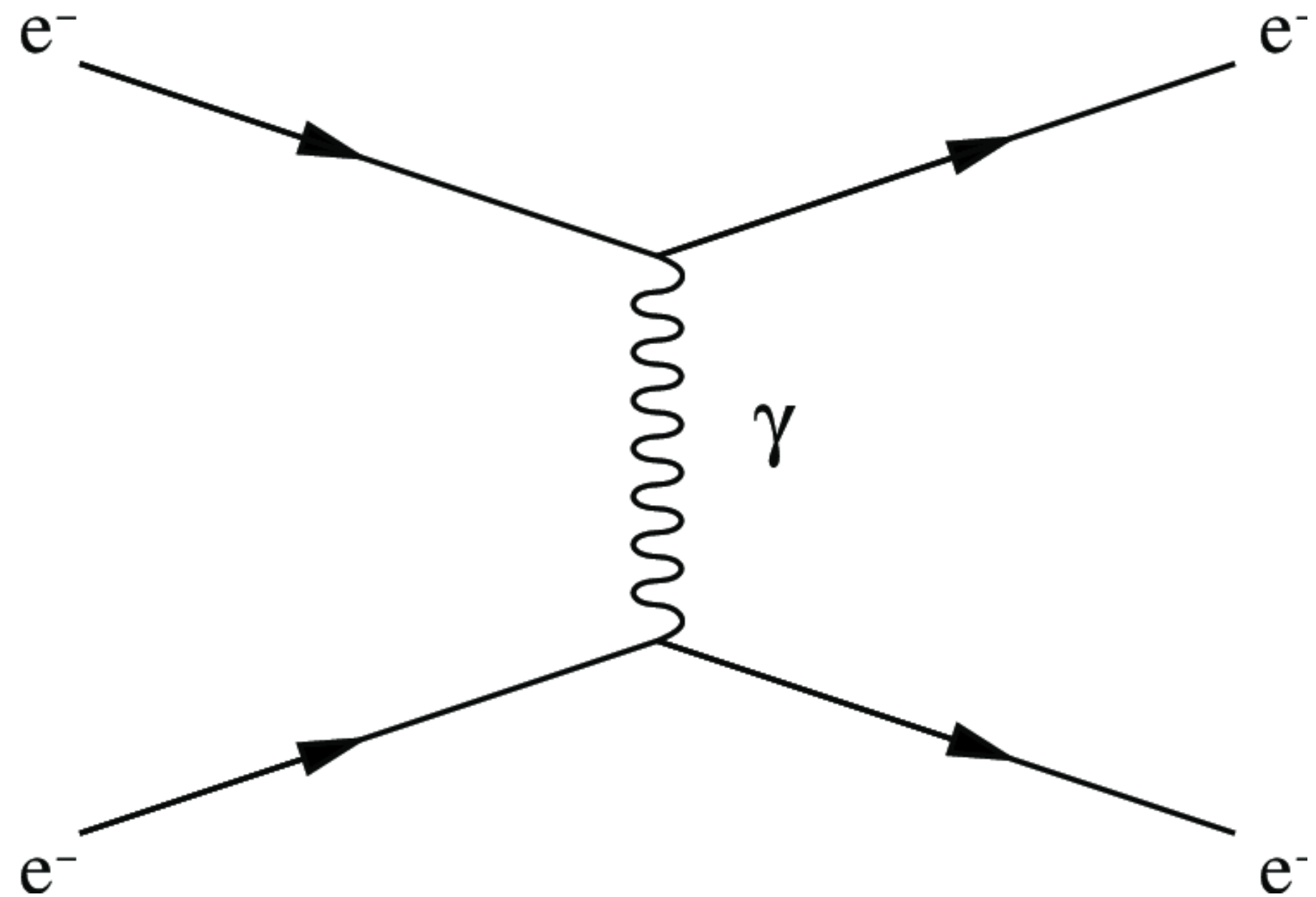
Baryon
(proton, p^+)



Meson
(negative pion, π^-)

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

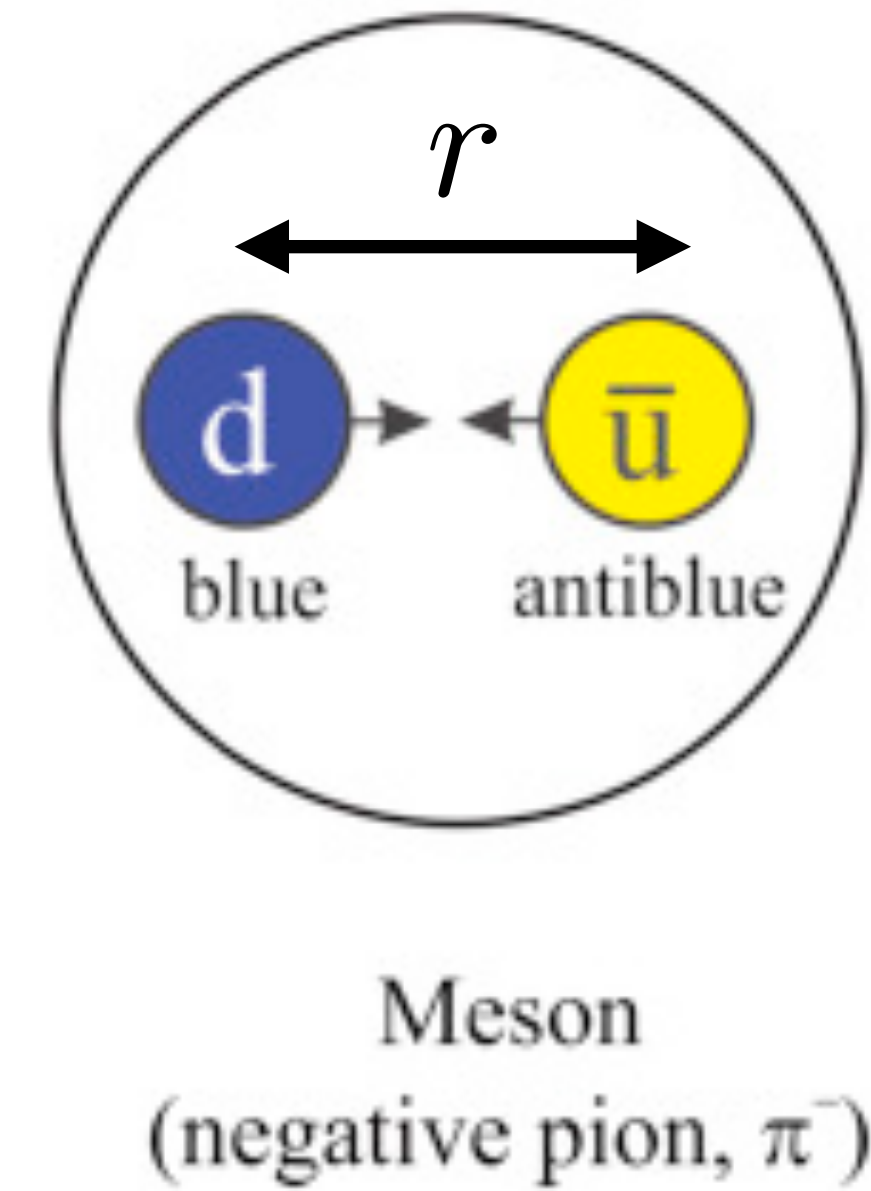
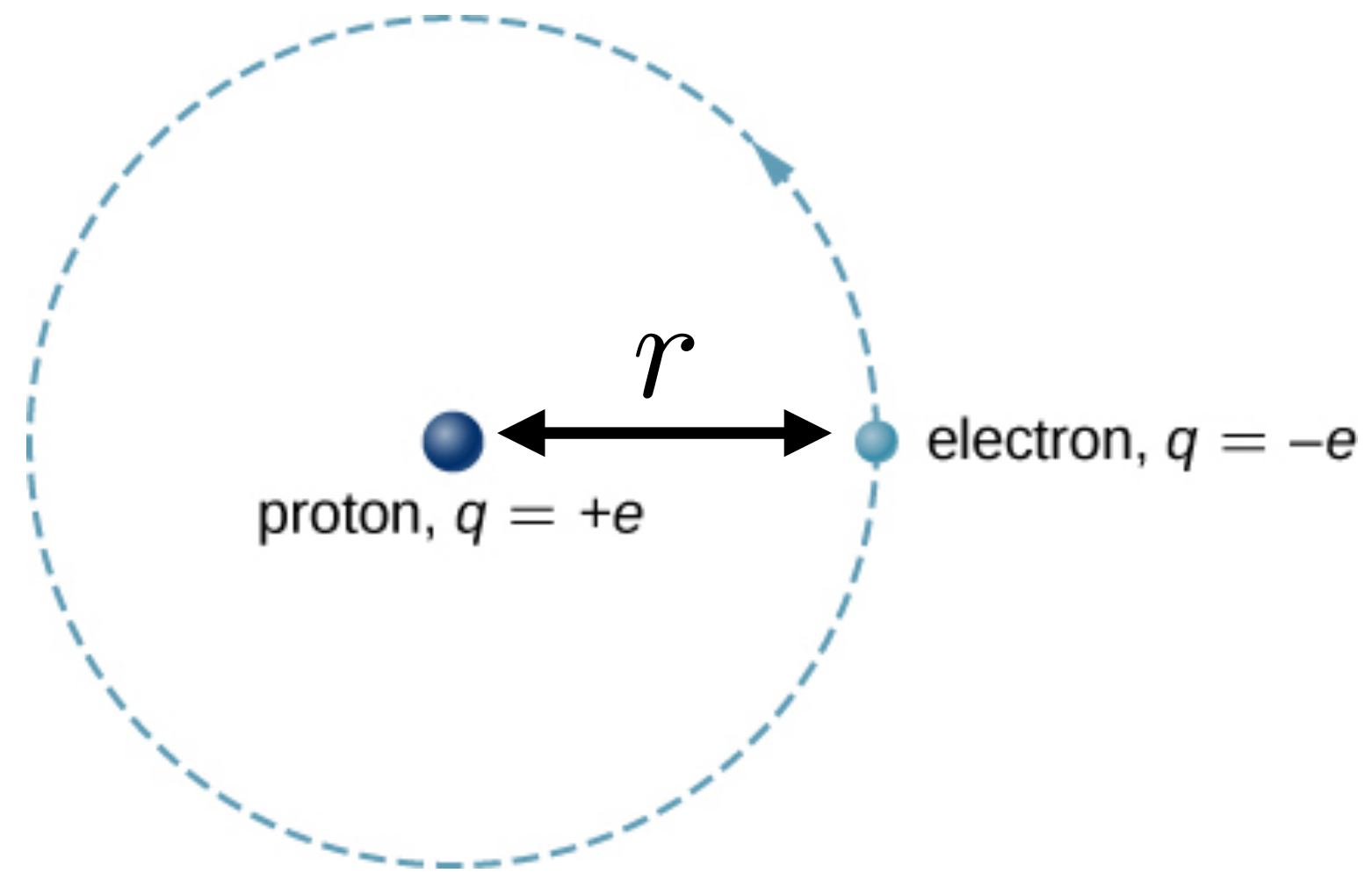
How do the electromagnetic and strong forces arise?



- ▶ **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?

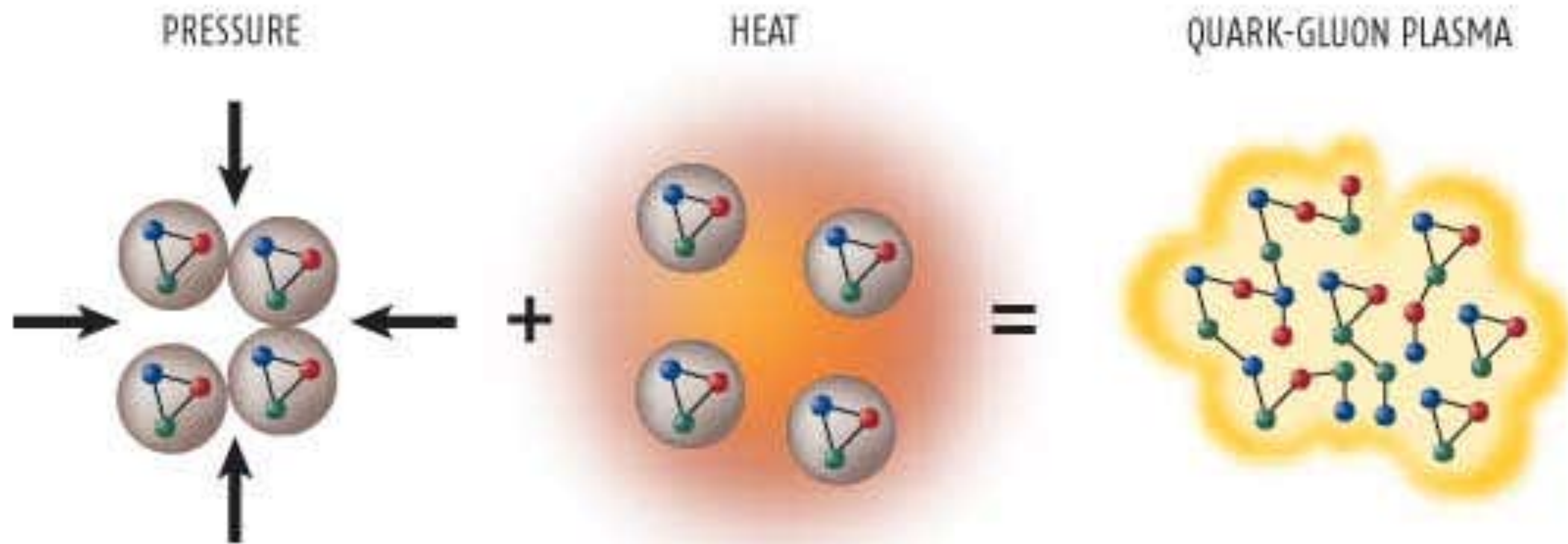


$$F_{em}(r) = \frac{a}{r^2}$$

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

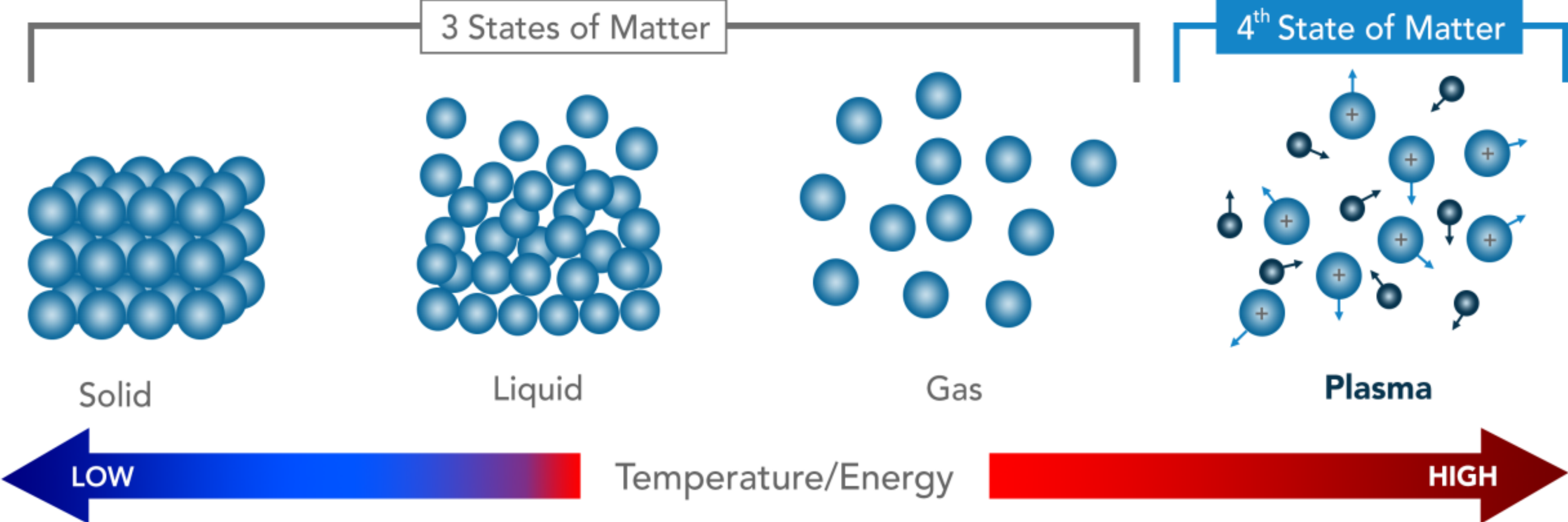
- ▶ An increasing strong force with distance leads to **confinement**
 - ✓ Infinite amount of energy needed to separate quarks
 - ✓ Reason why quarks only found in baryons (e.g. proton) or mesons (e.g. pion)

The Quark Gluon Plasma (QGP)



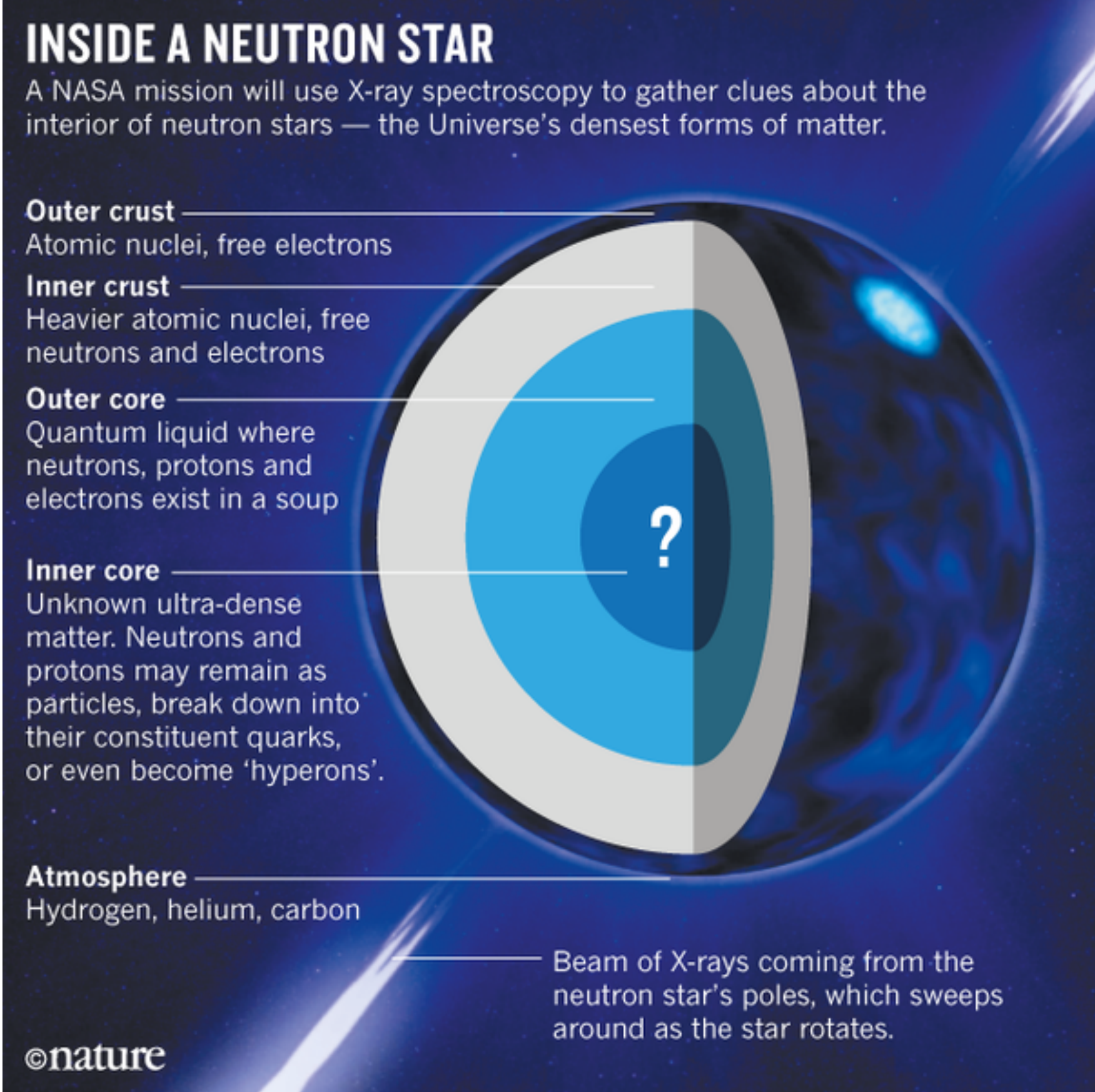
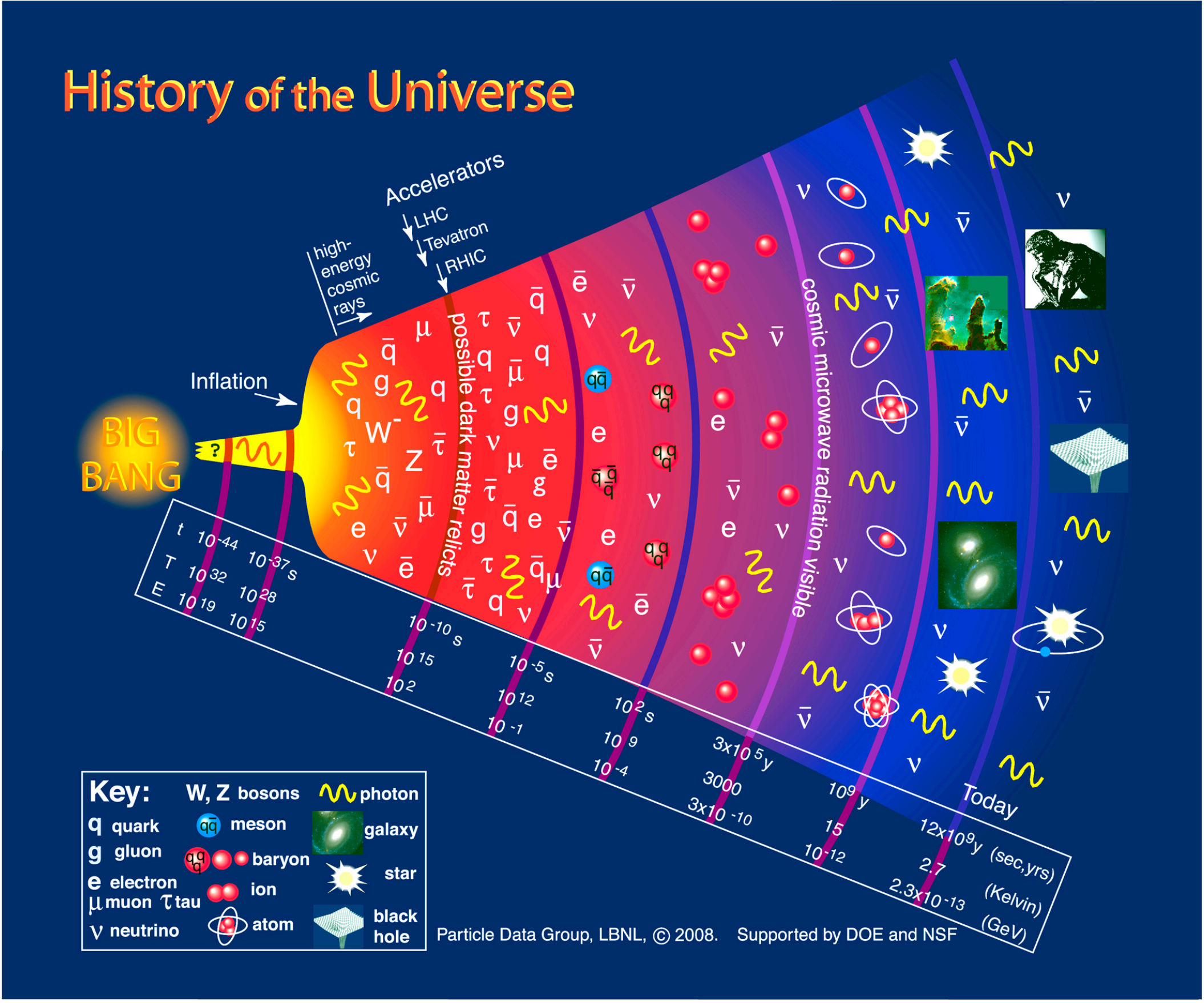
- ▶ When a nucleus is compressed and heated, a QGP forms
 - ✓ Quarks are no longer localized within protons and neutrons

Where does the word plasma come from?



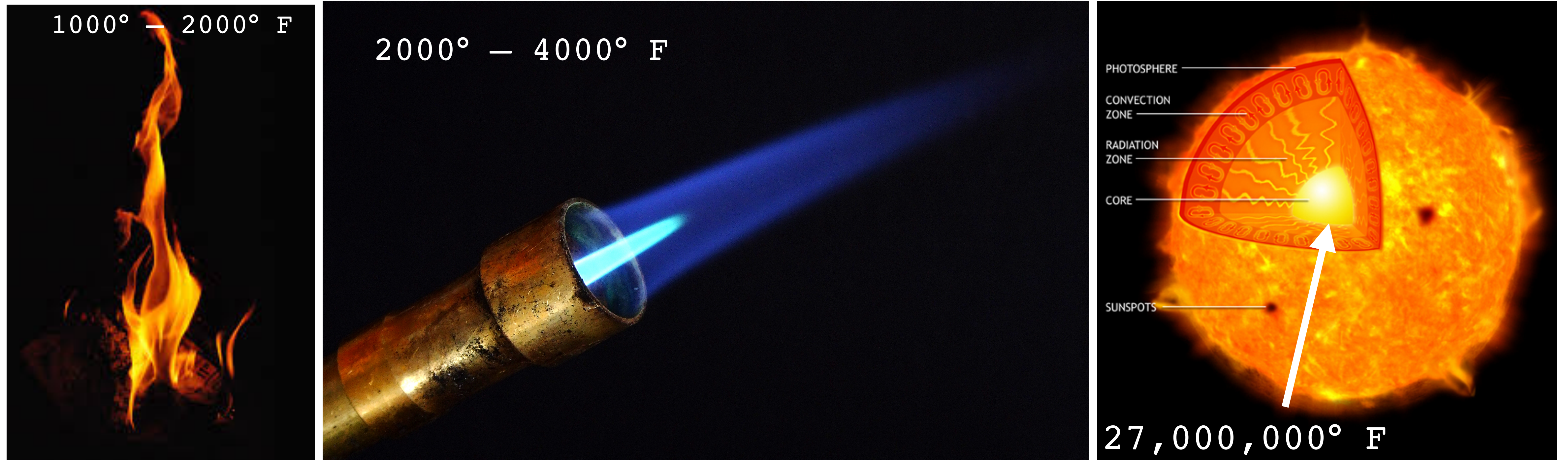
- ▶ Constituents of conventional plasma are electrically charged
 - ✓ Constituents of QGP are color charged!

Why is the Quark Gluon Plasma (QGP) interesting?



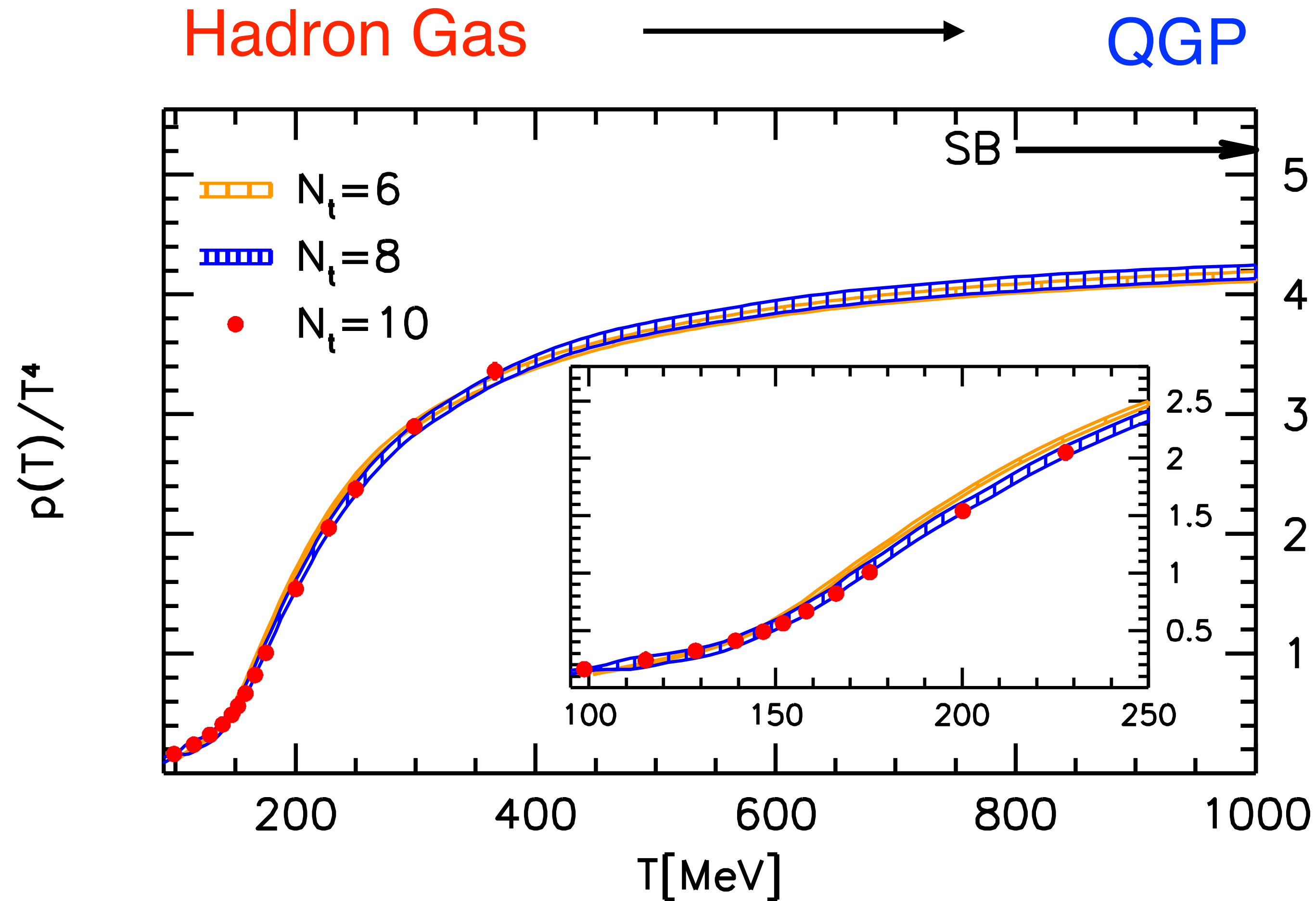
- ▶ Early universe would have been in the QGP state
- ▶ The core of neutron stars may contain a QGP

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

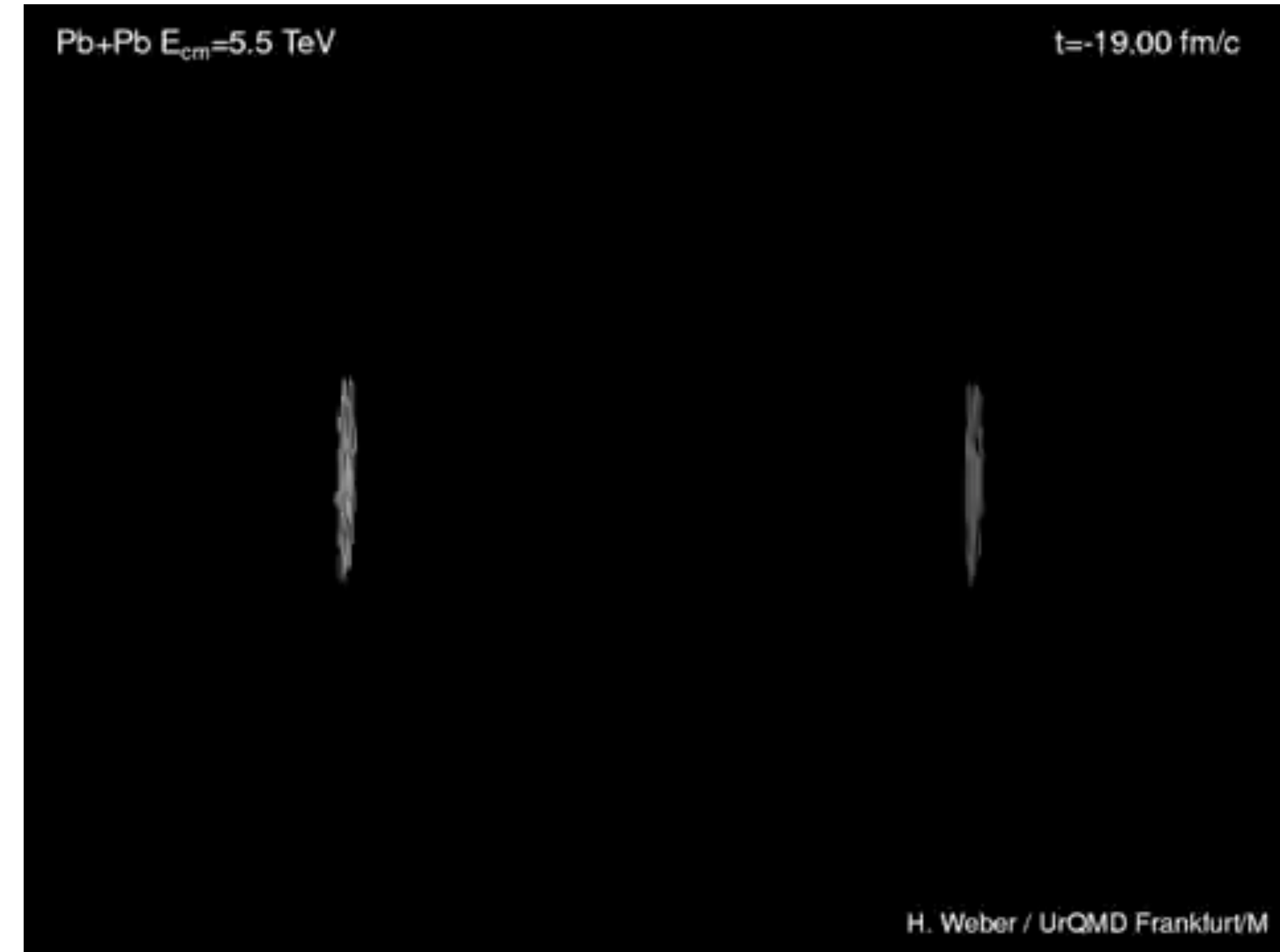
How can we achieve such temperatures?



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

► Crude but highly effective: collisions!

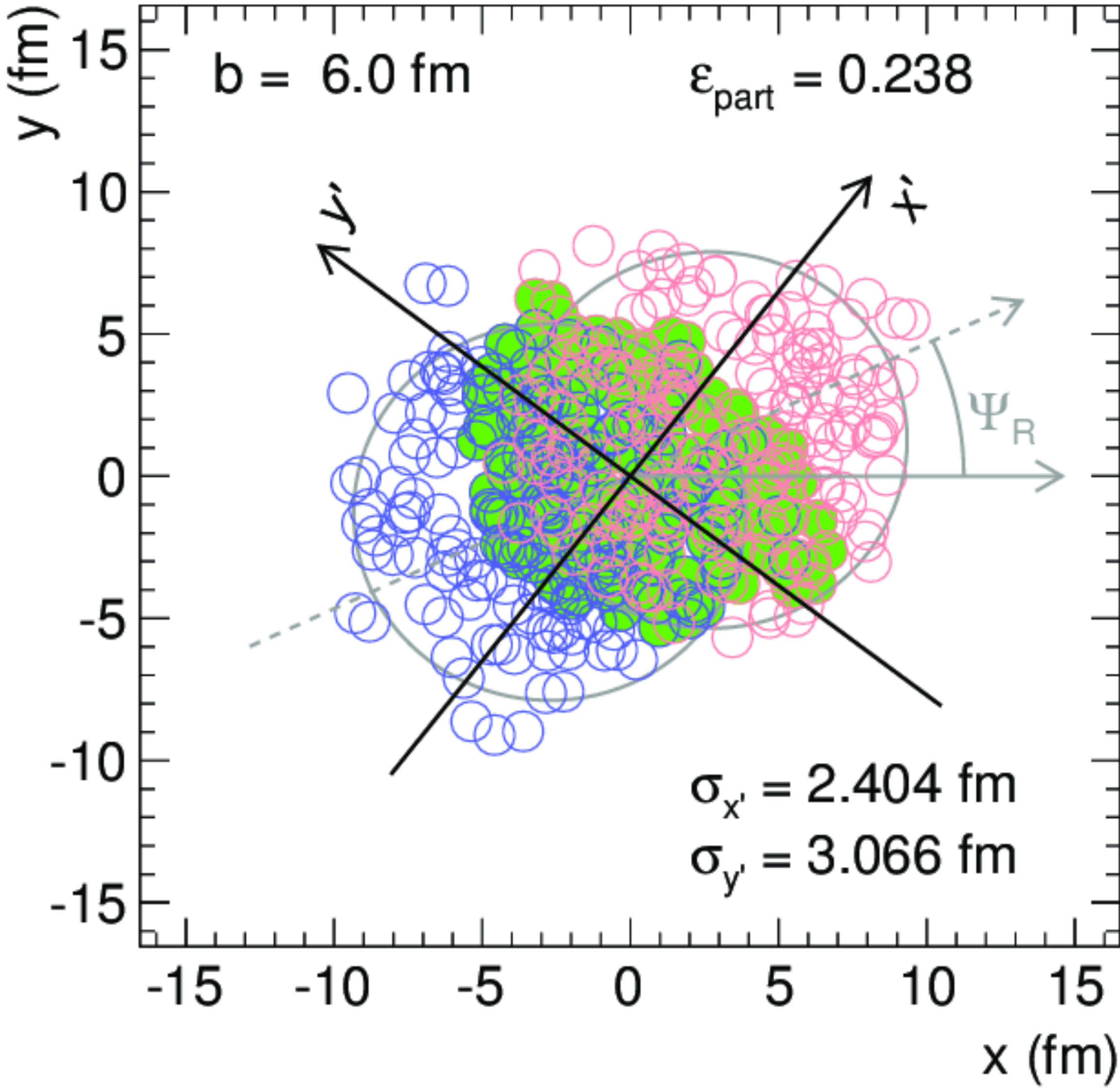
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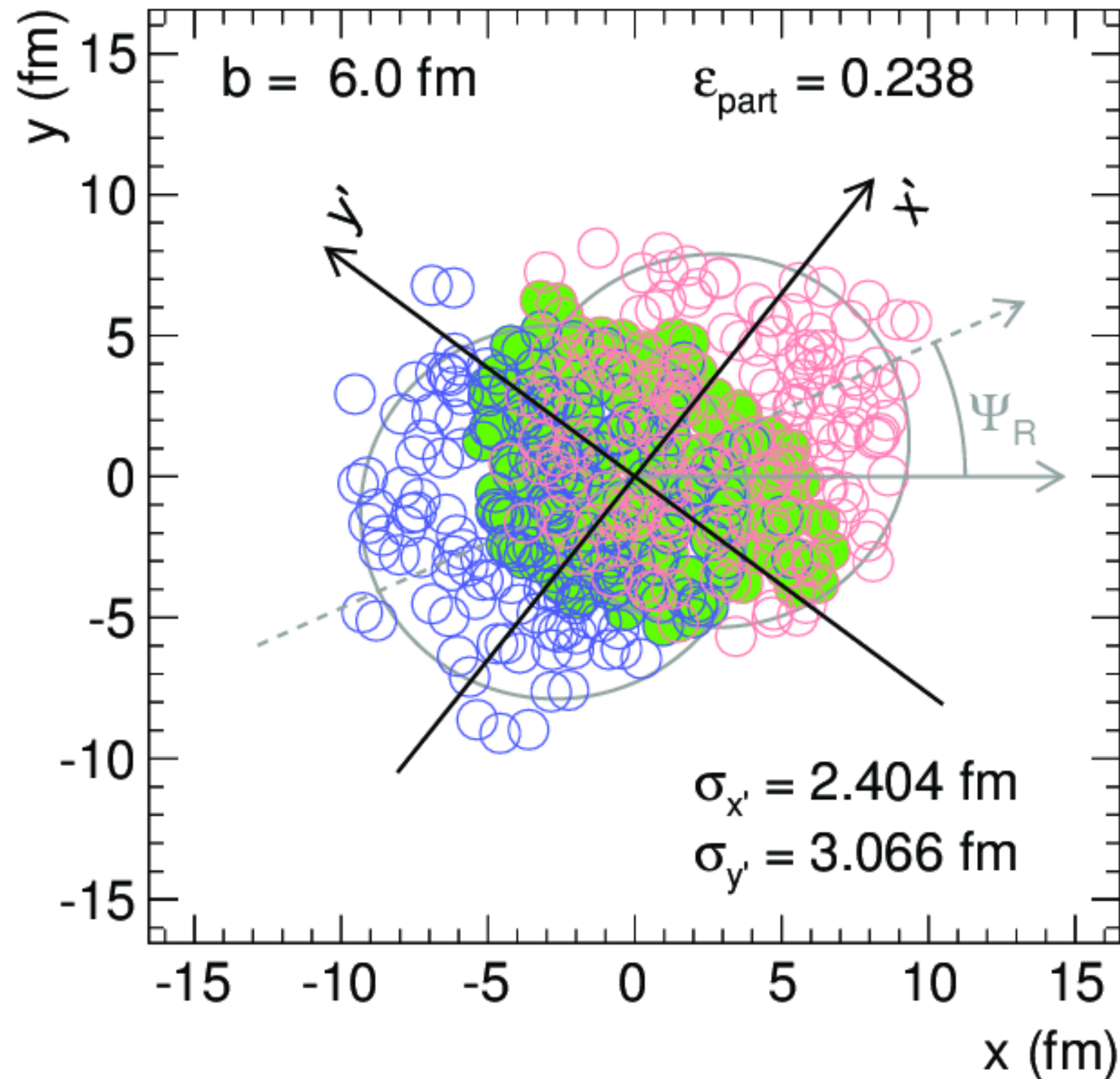
<https://videos.cern.ch/record/1304862>

- ▶ 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

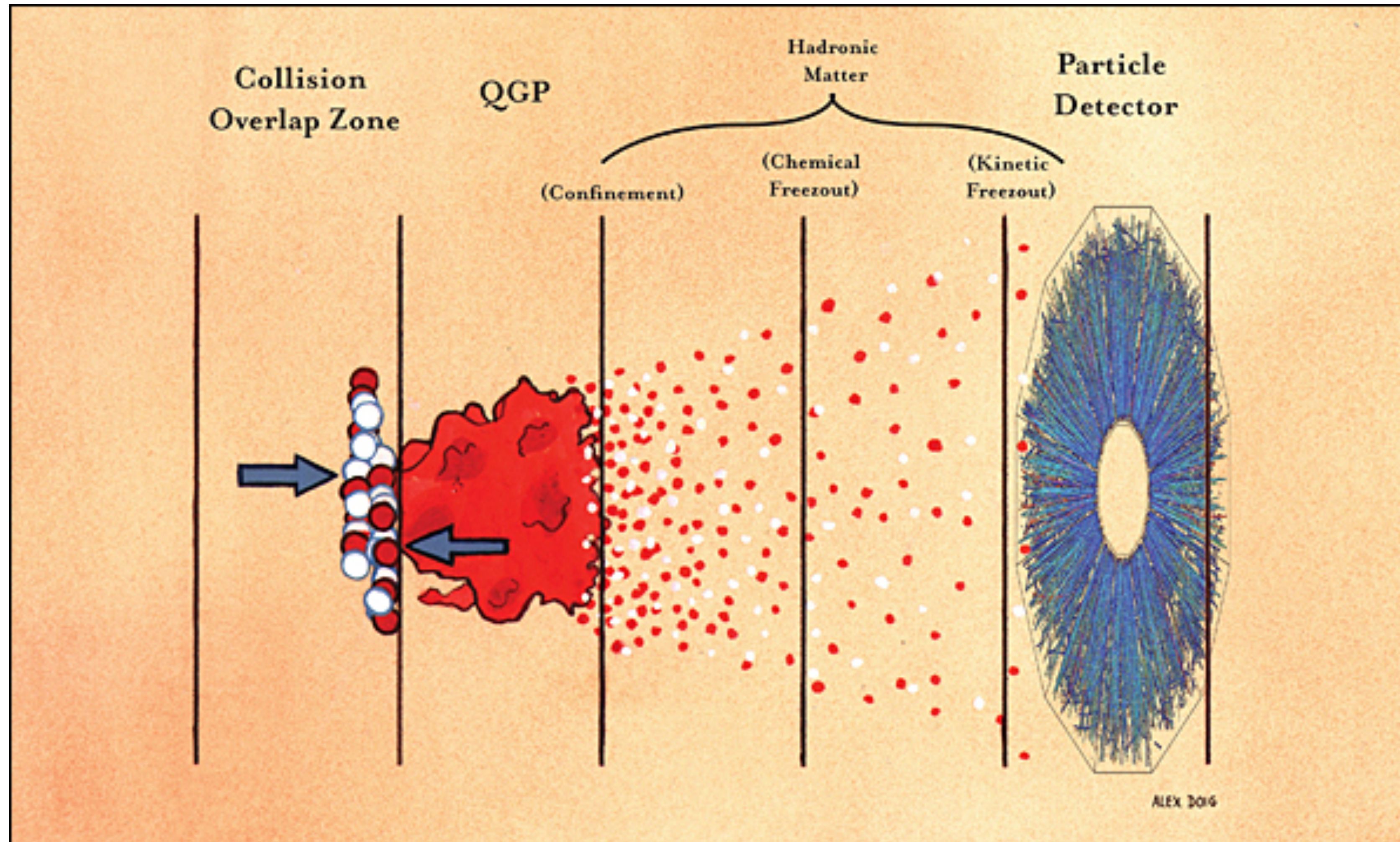


Head on view of Pb-Pb collisions



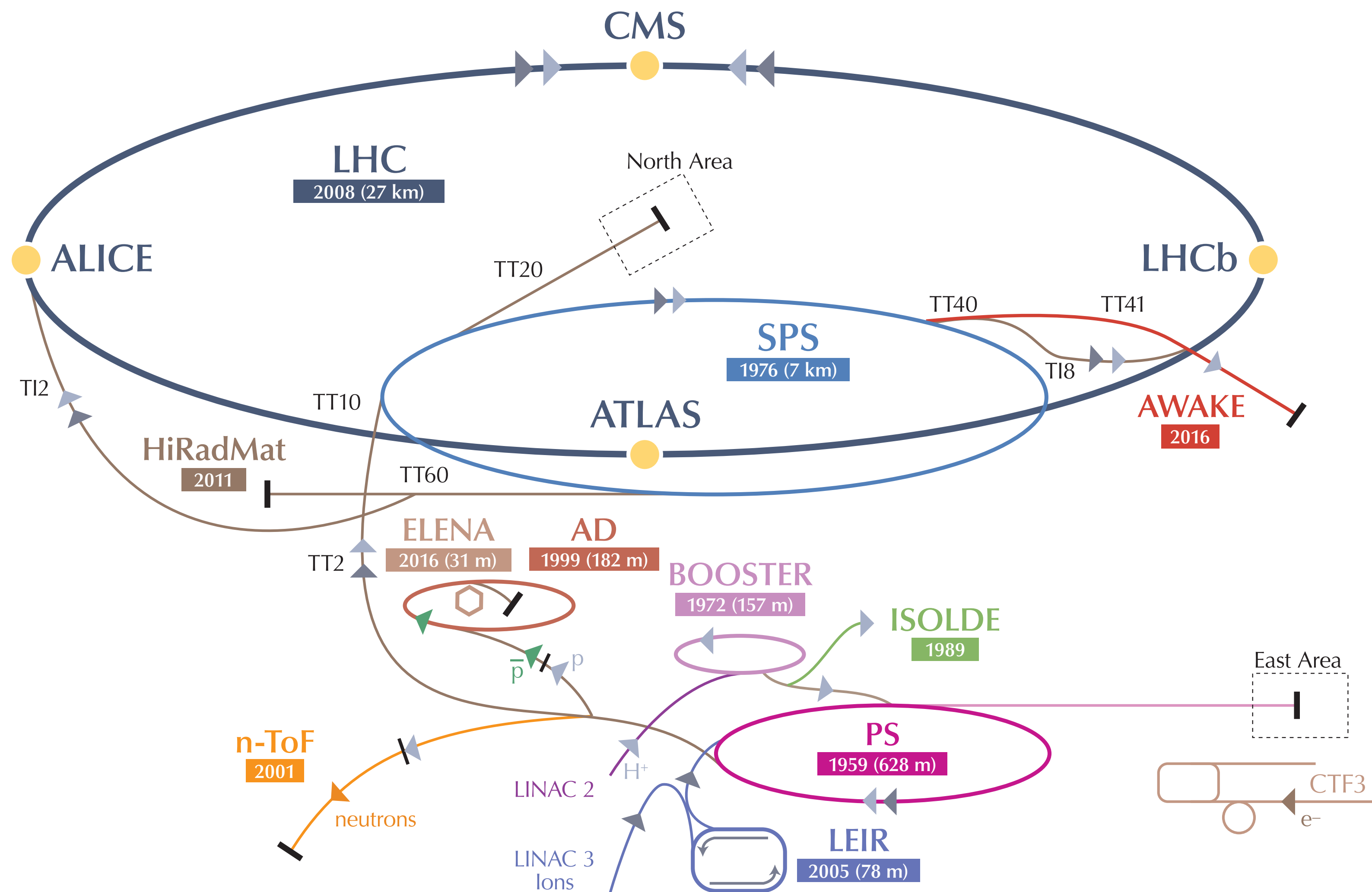
- ▶ Isotope used: $^{208}_{92}\text{Pb}$
- ▶ 92 protons and 116 neutrons
- ▶ $^{208}_{92}\text{Pb}$ extremely spherical nucleus
 - ✓ Double magic

What happens during a Pb-Pb collision?



Time →

The Large Hadron Collider (LHC)

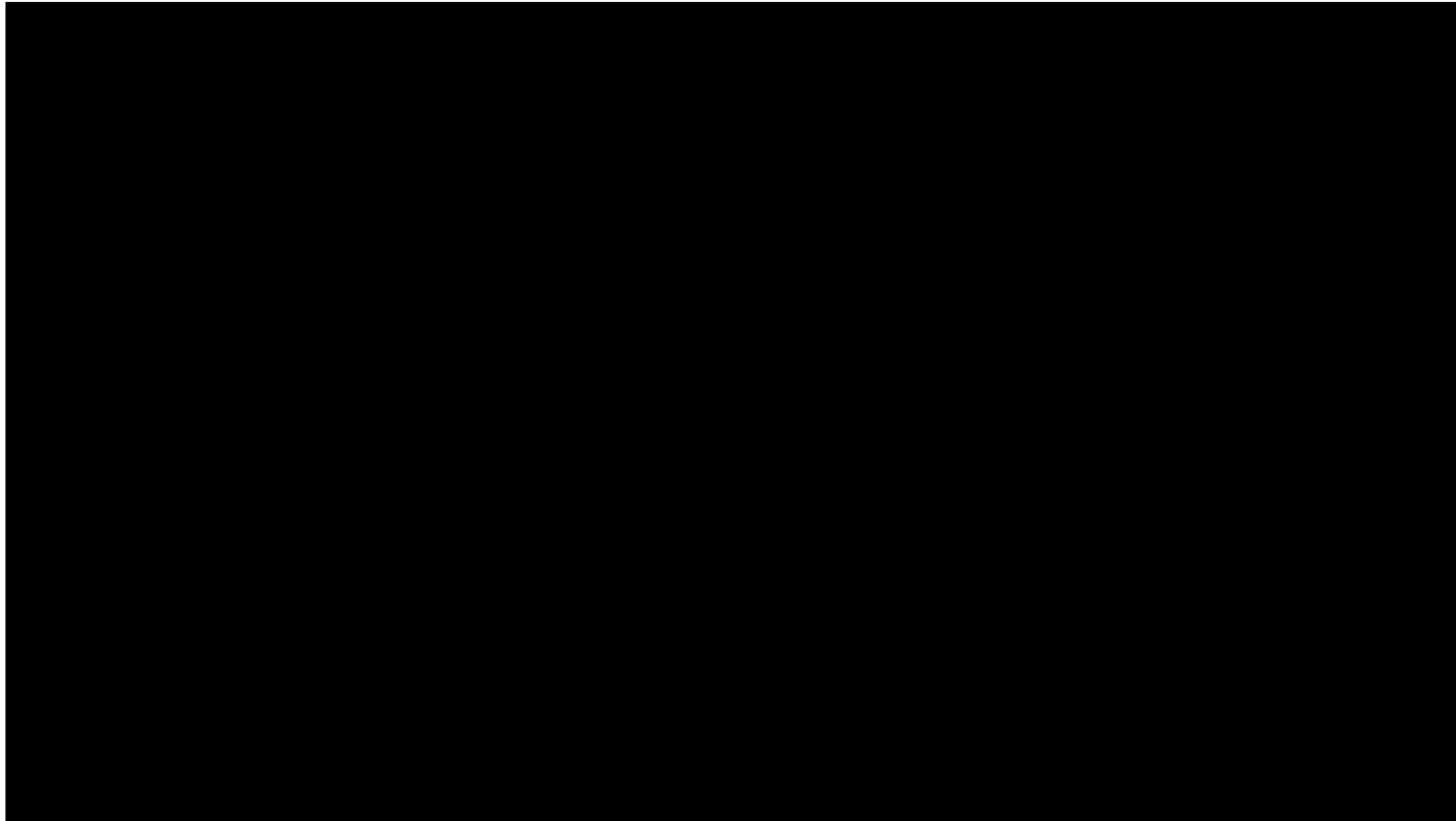


- ▶ Run 1 (2010-2013)
 - √Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
 - √p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

- ▶ 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

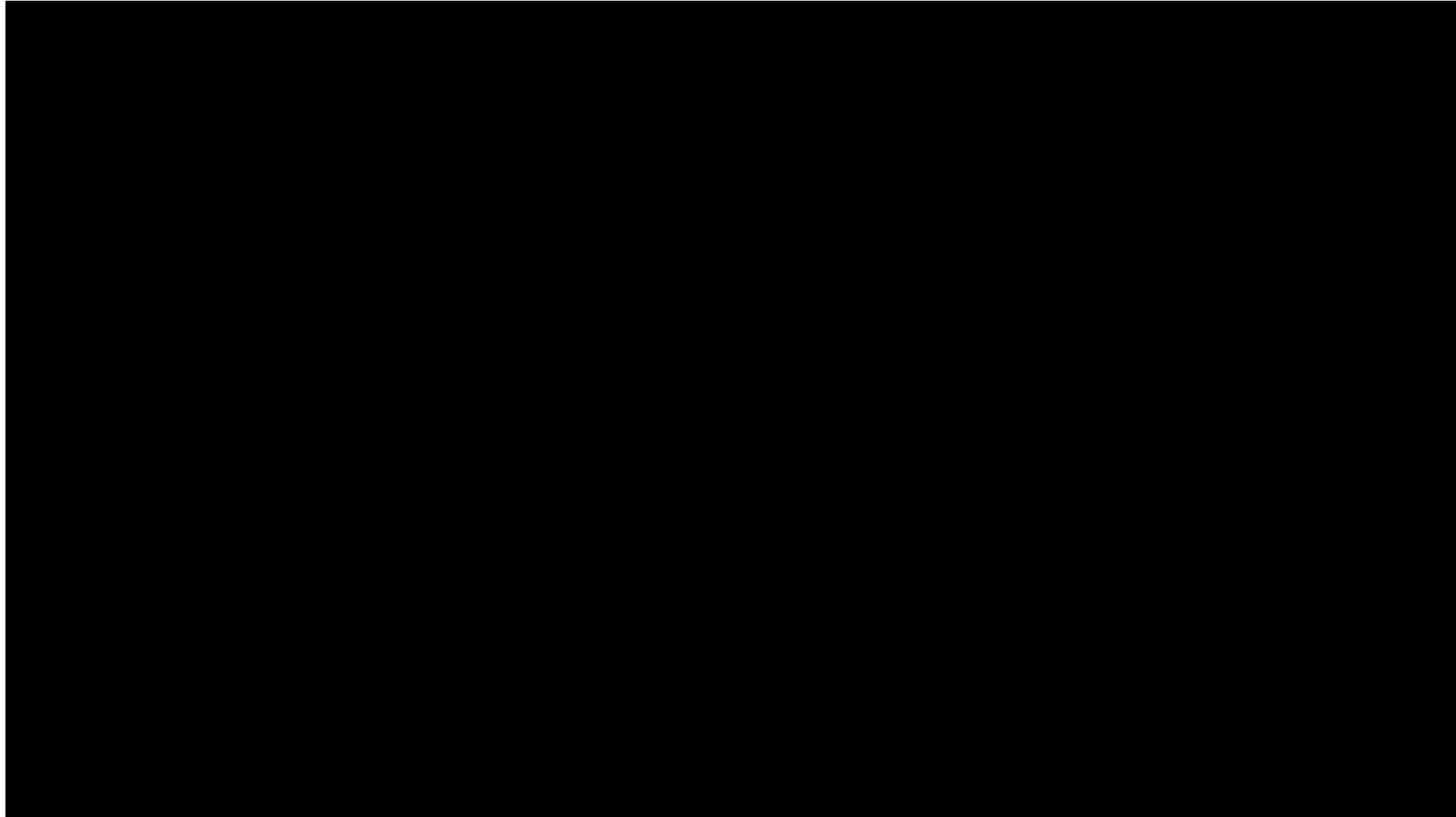
A Large Ion Collider Experiment (ALICE)



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

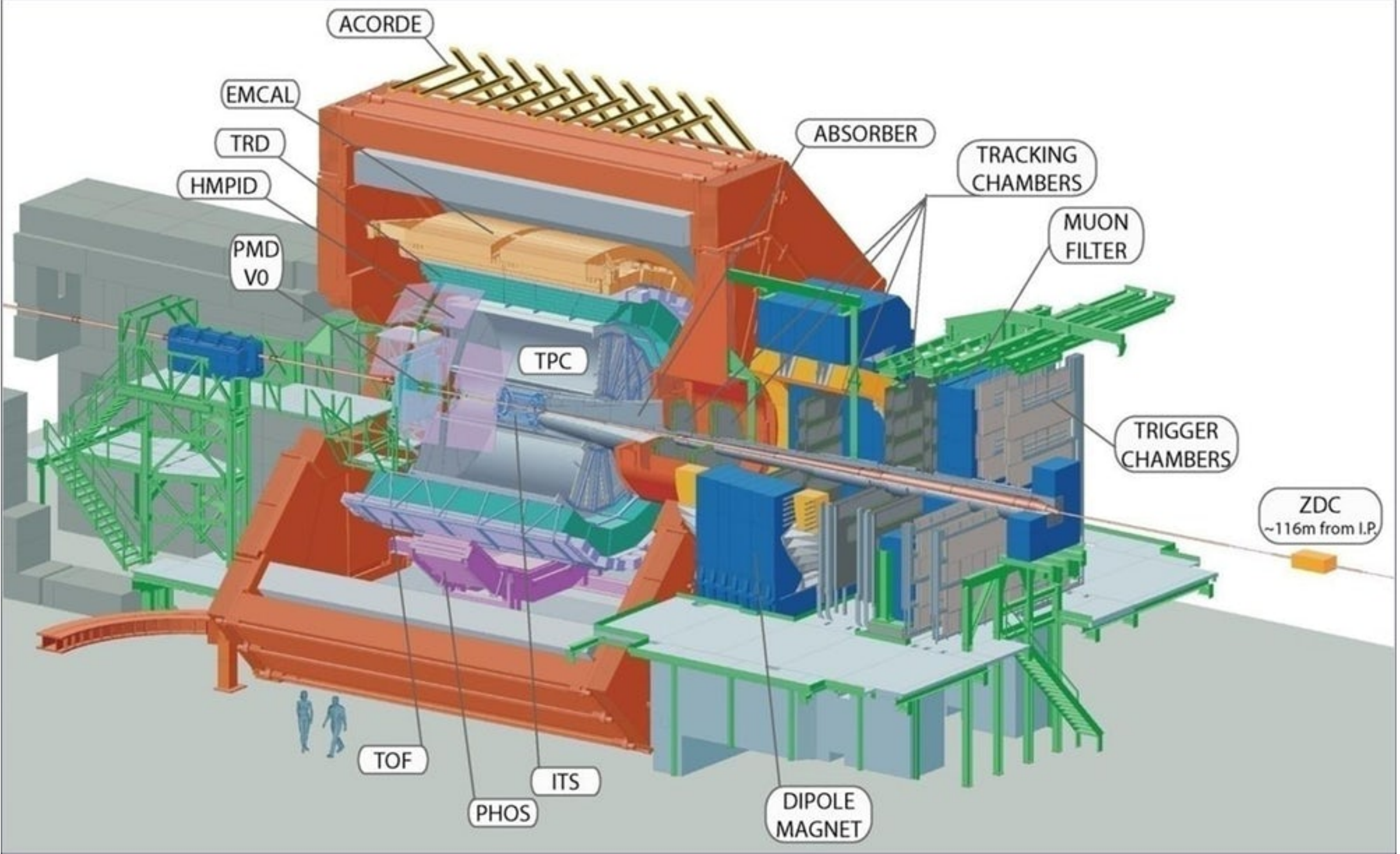


A Large Ion Collider Experiment (ALICE)

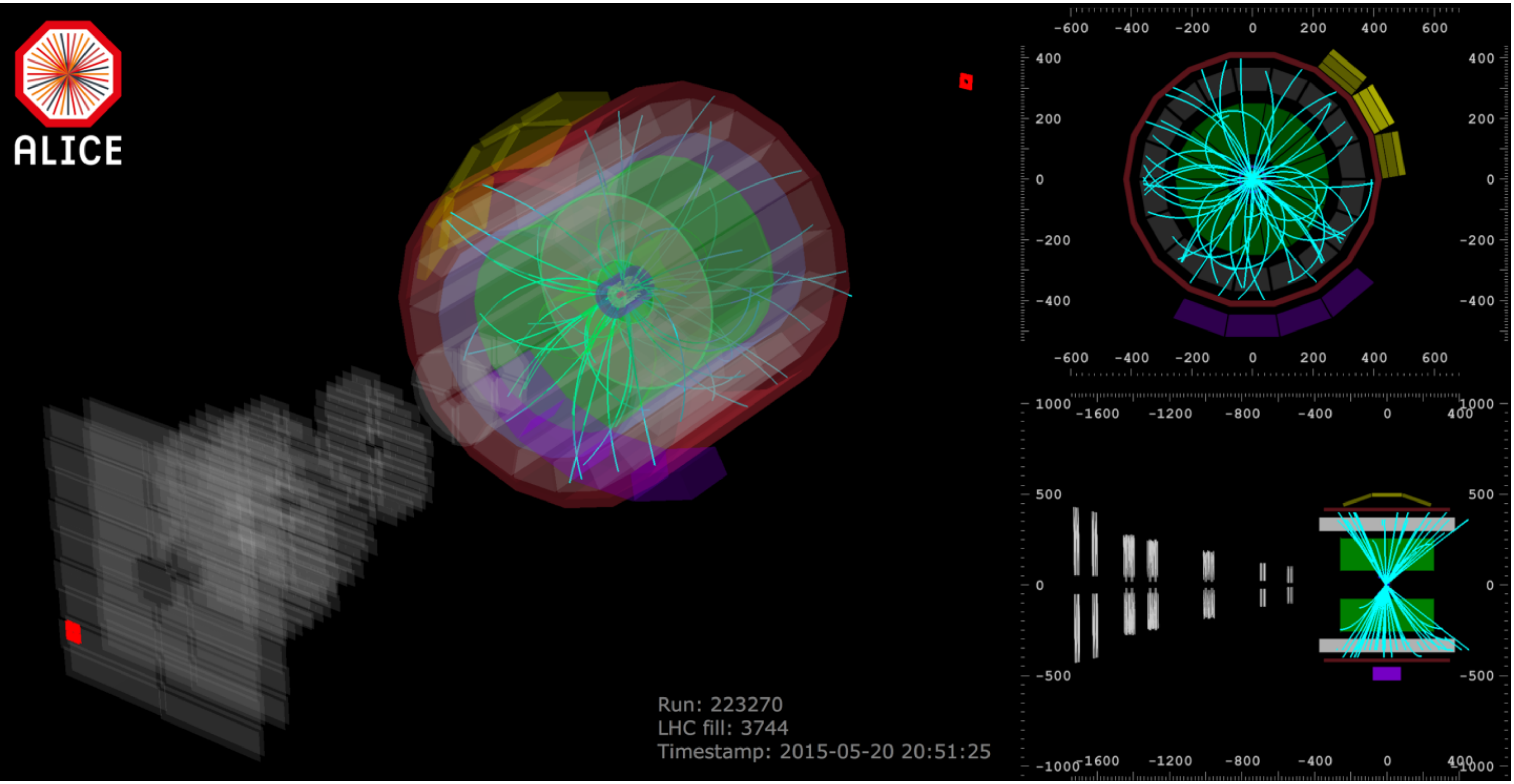


<https://www.youtube.com/watch?v=yWBWzIUCNpw>

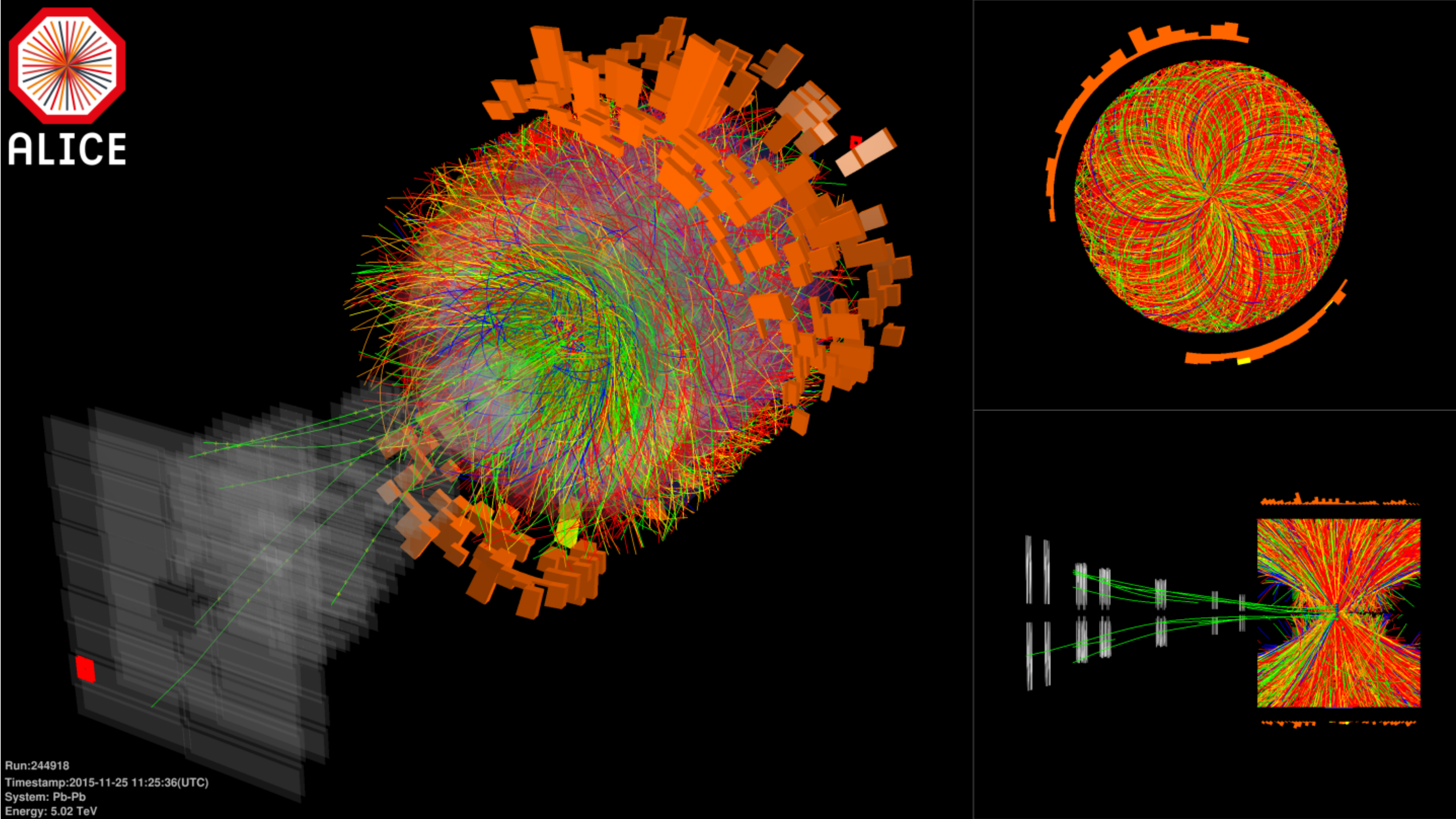
A Large Ion Collider Experiment (ALICE)



A proton-proton collision in ALICE



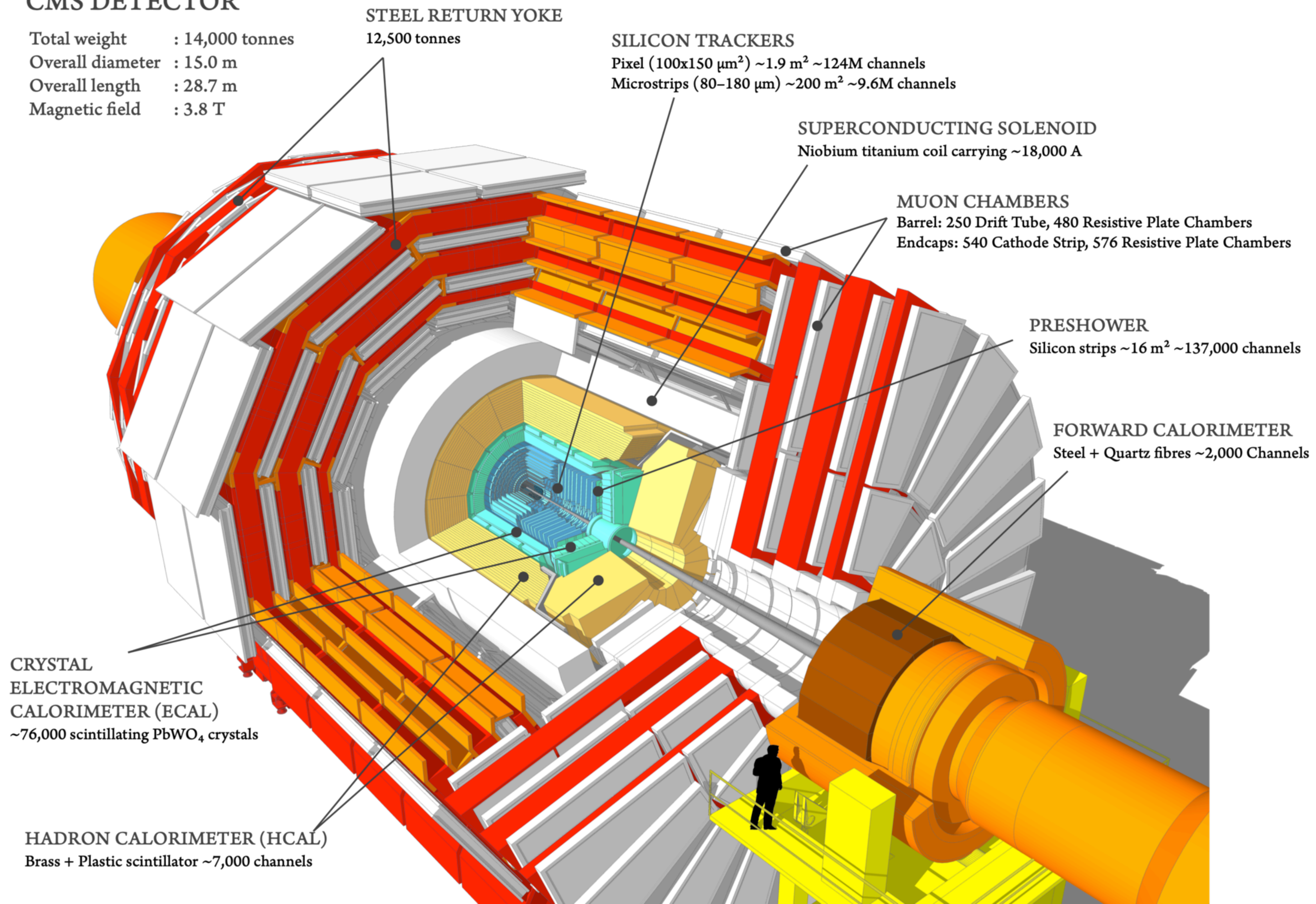
A Pb-Pb collision in ALICE



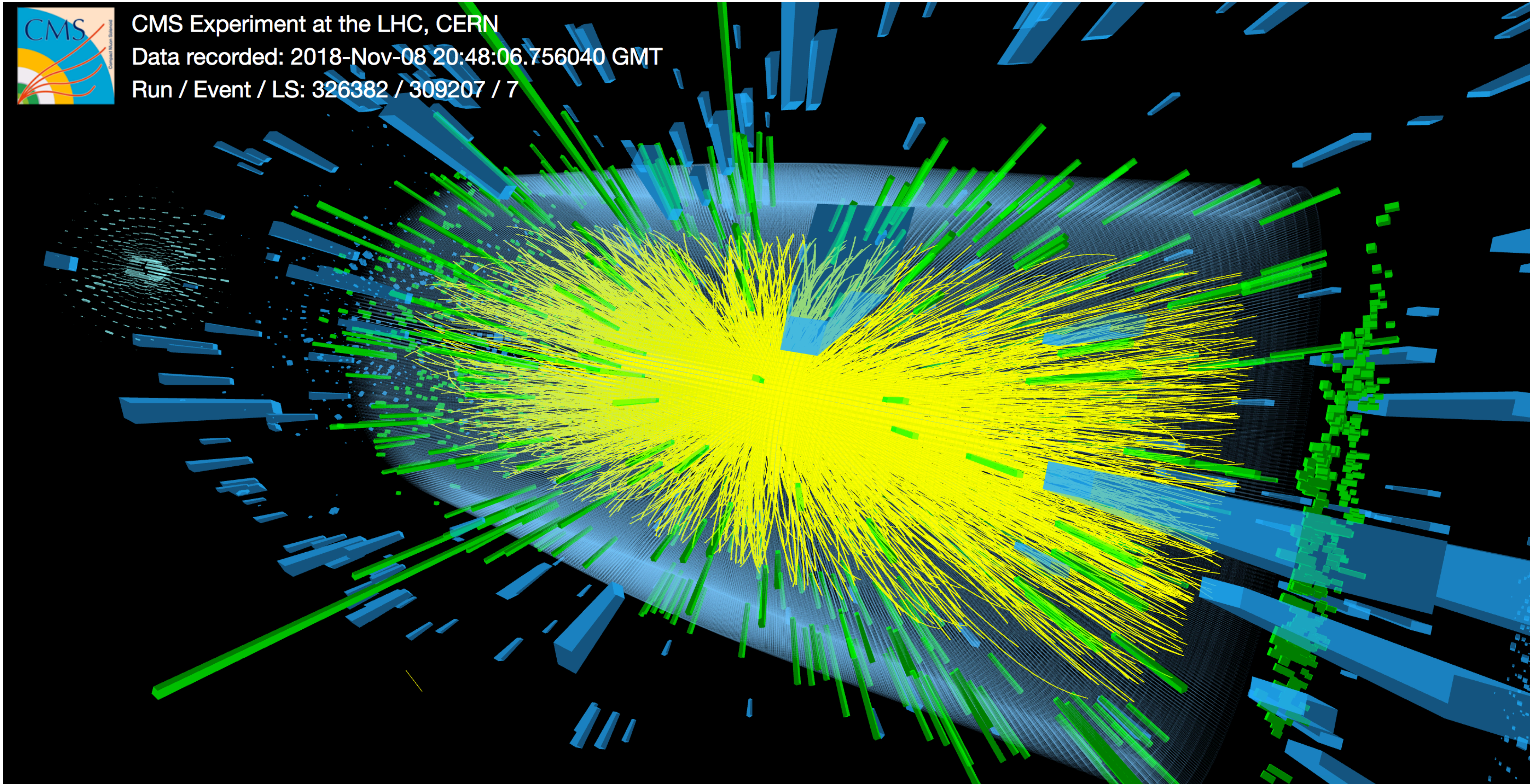
The Compact Muon Solenoid (CMS)

CMS DETECTOR

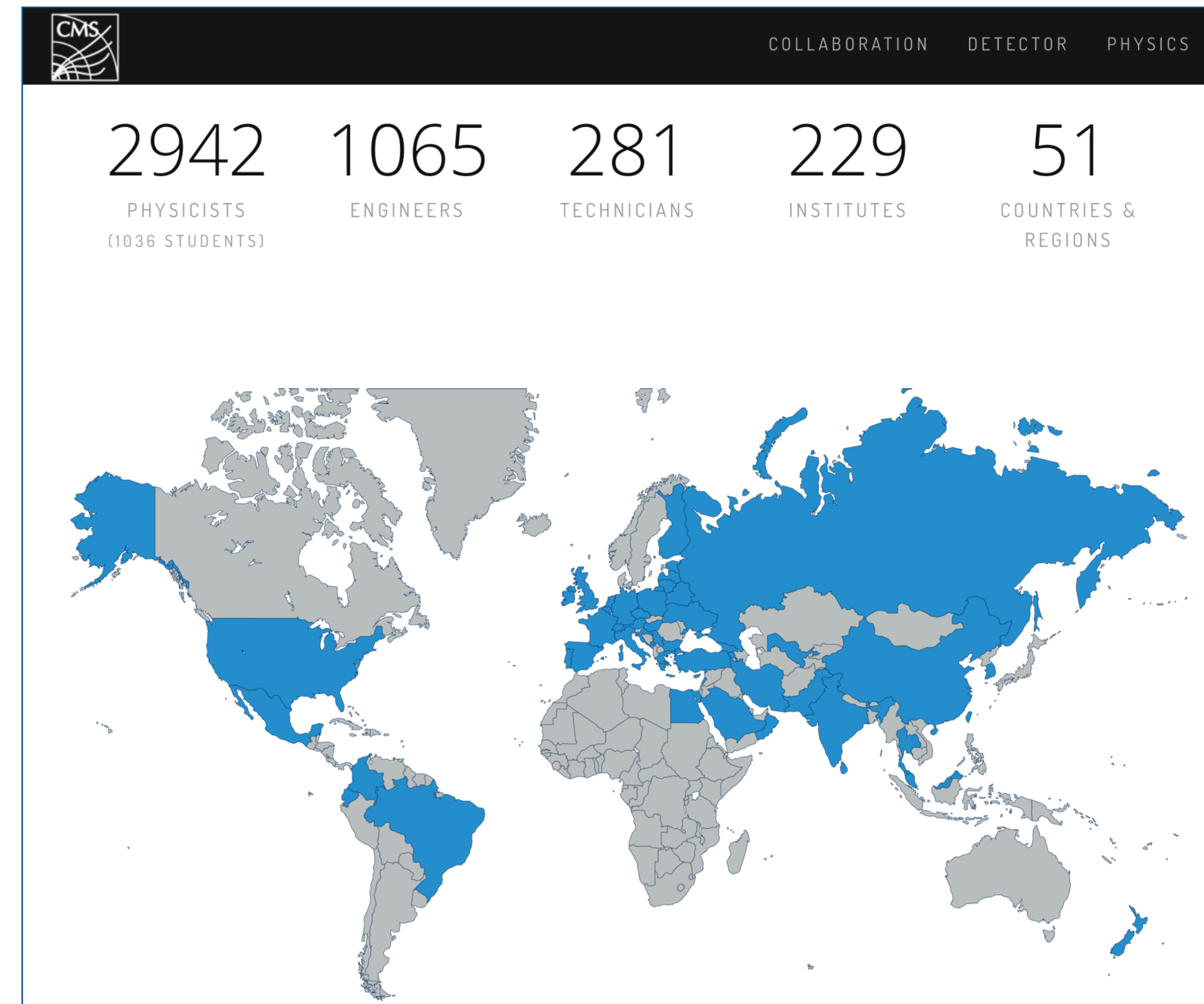
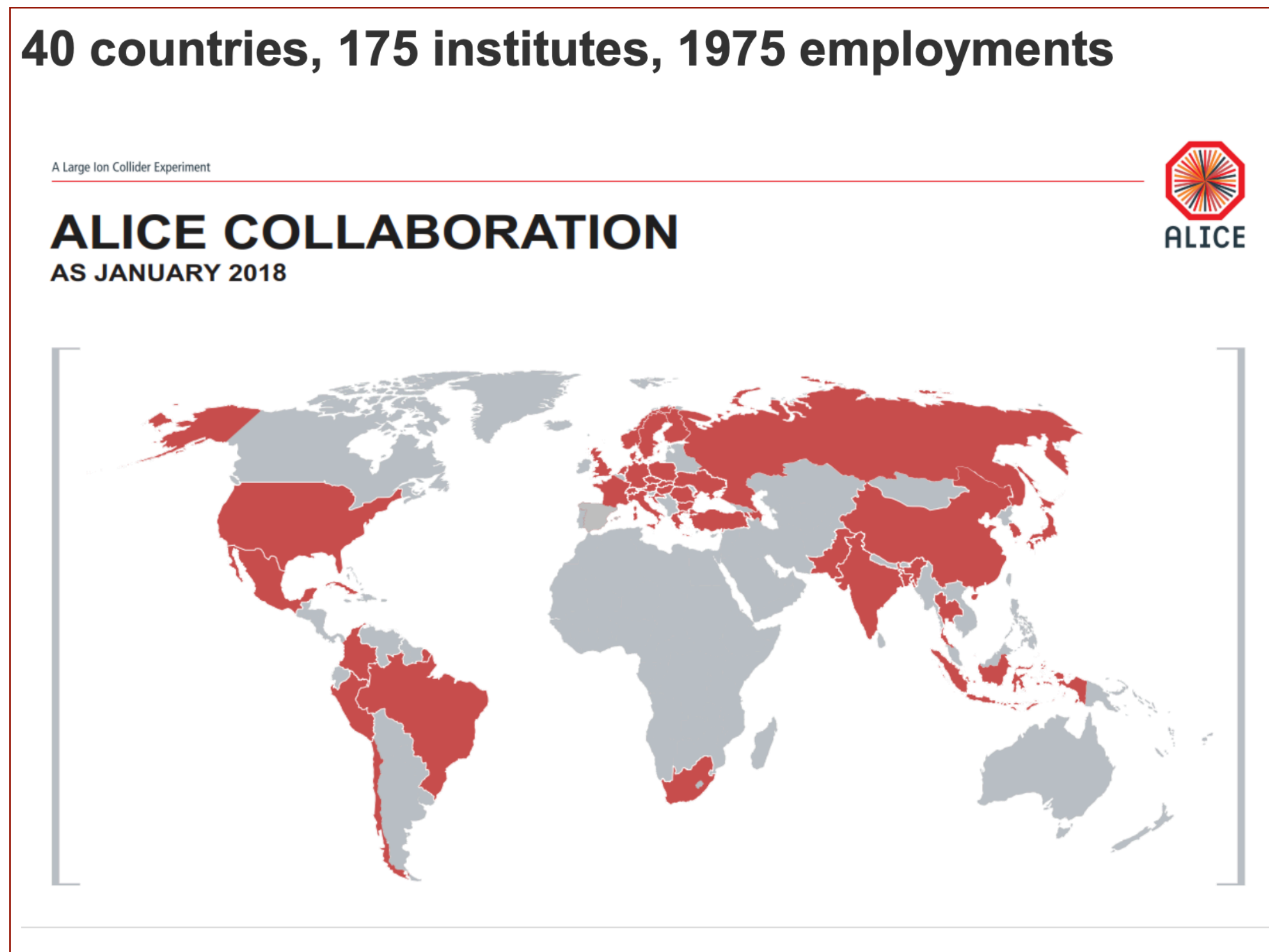
Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T



A Pb-Pb collision in CMS

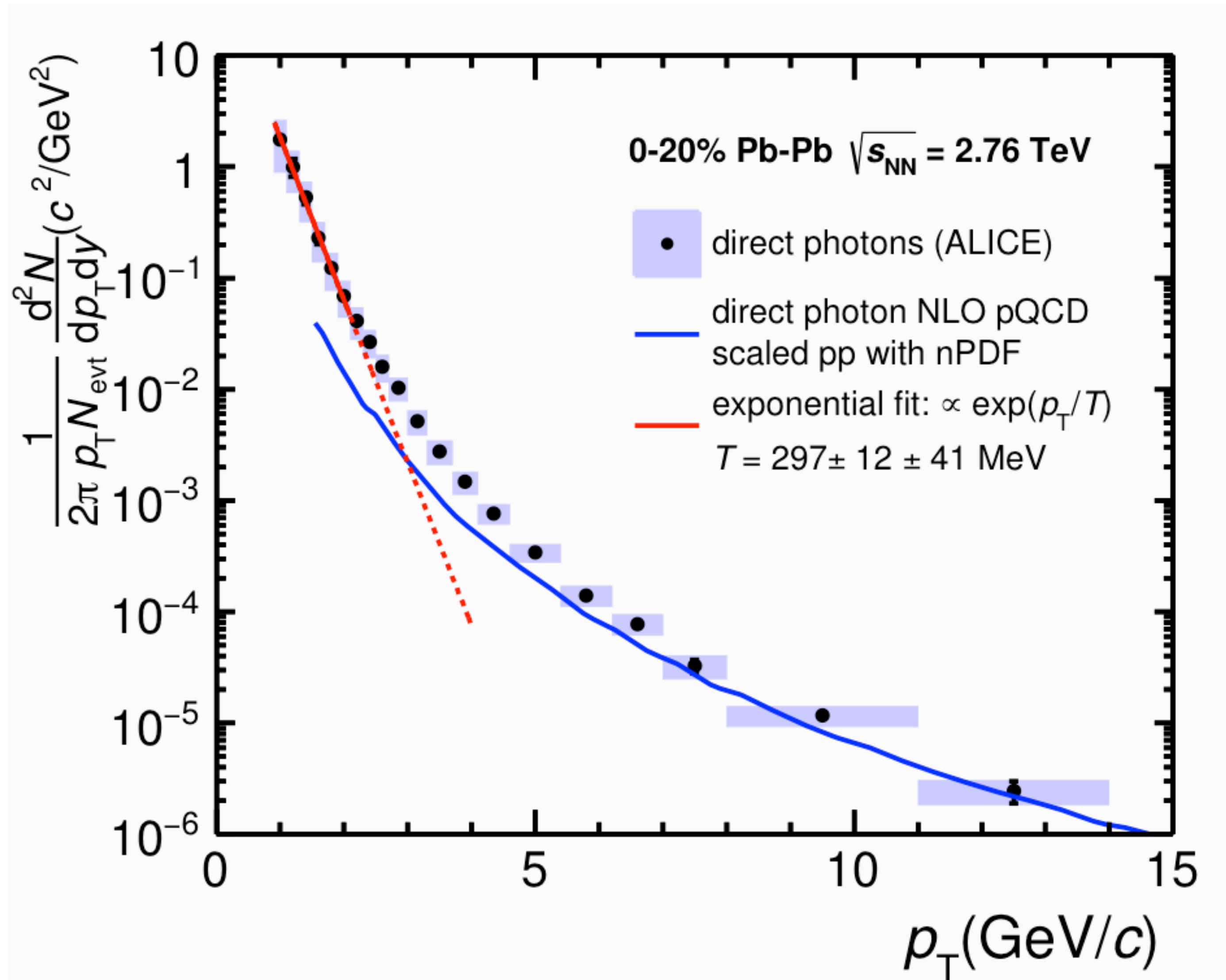


These are big global collaborations!



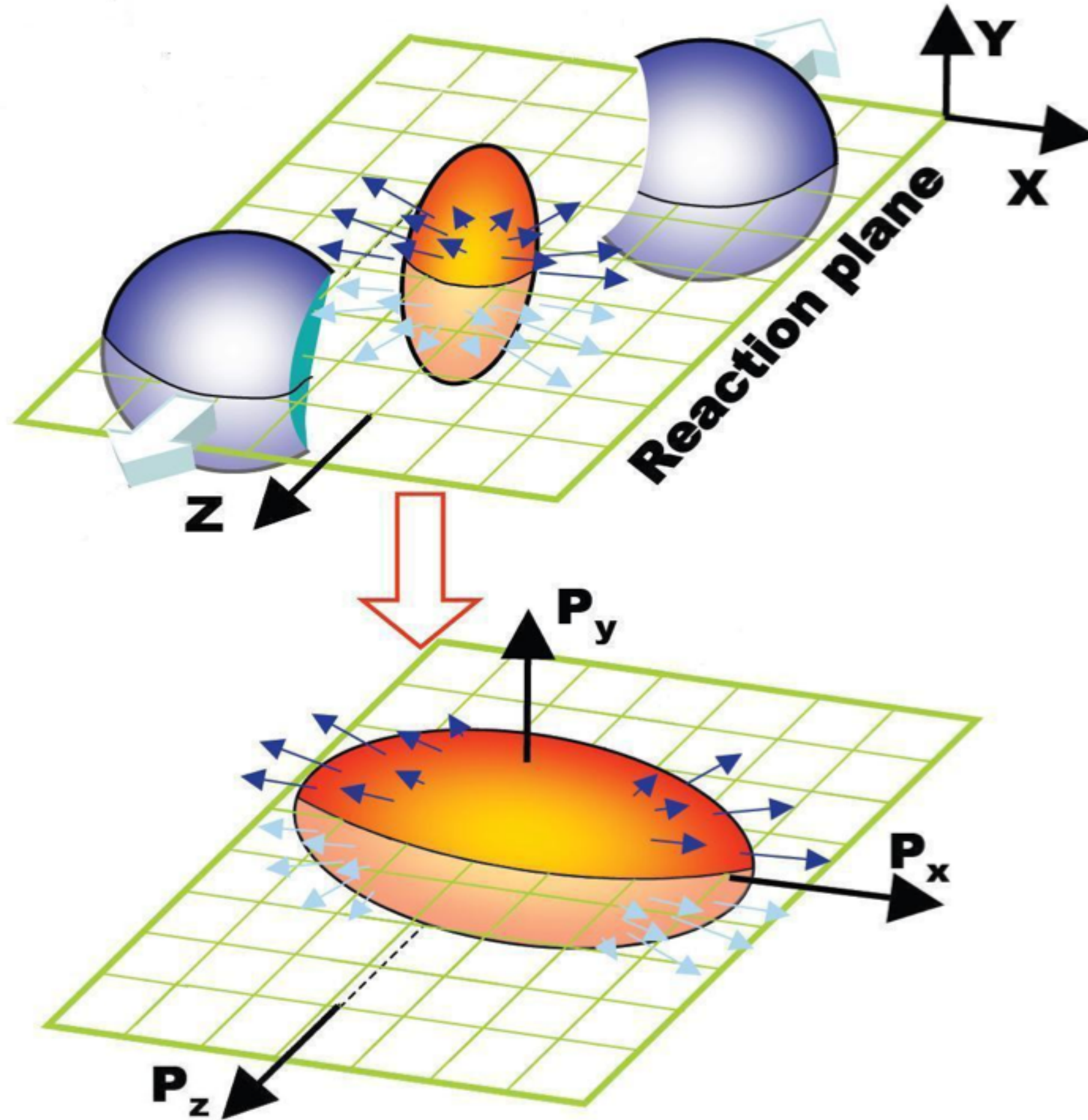
- ▶ A dedicated heavy-ion physics program occurs at Brookhaven National Lab
 - ✓ Relativistic Heavy Ion Collider - Main experiments STAR and PHENIX

Heavy-ion Physics achievements at the LHC

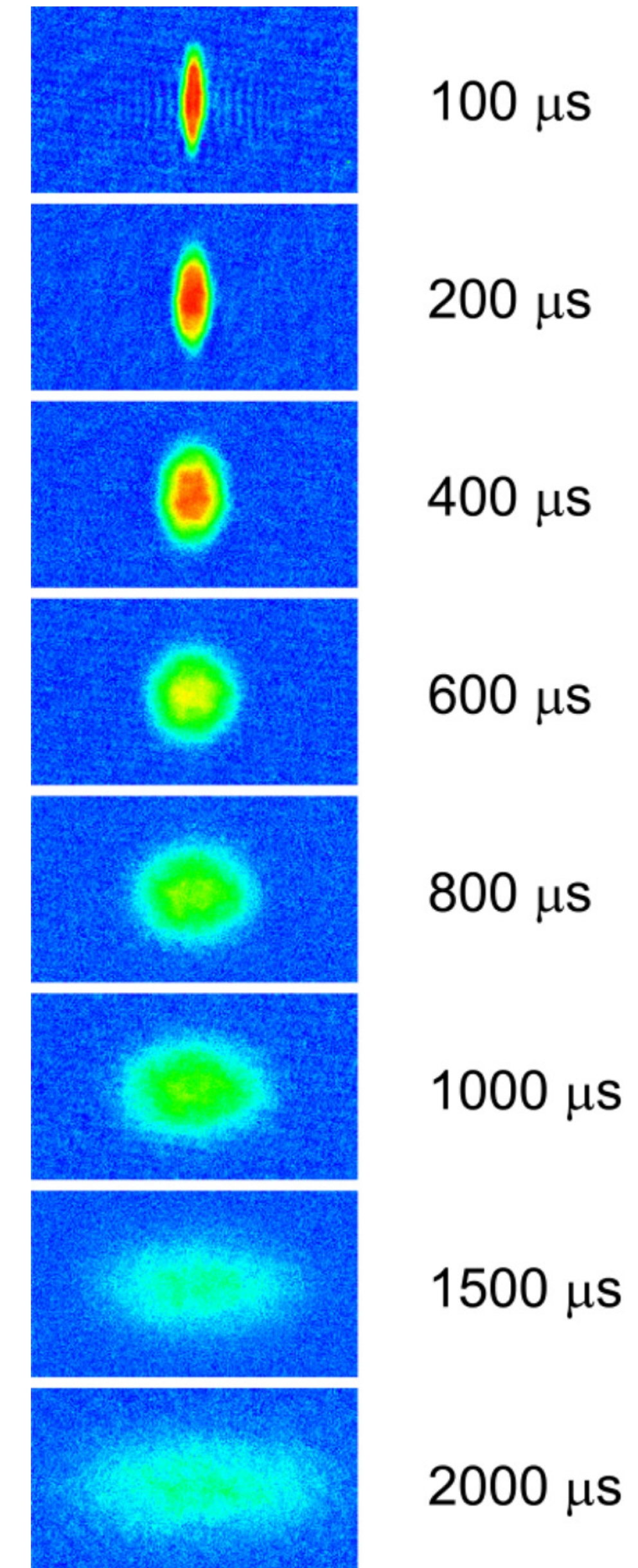


- ▶ Created hottest every matter on earth!
- ▶ Average energy of photons emitted can be used to infer QGP temperature
- ▶ Measured temperature **twice temperature** needed for **QGP formation**

Anisotropic flow

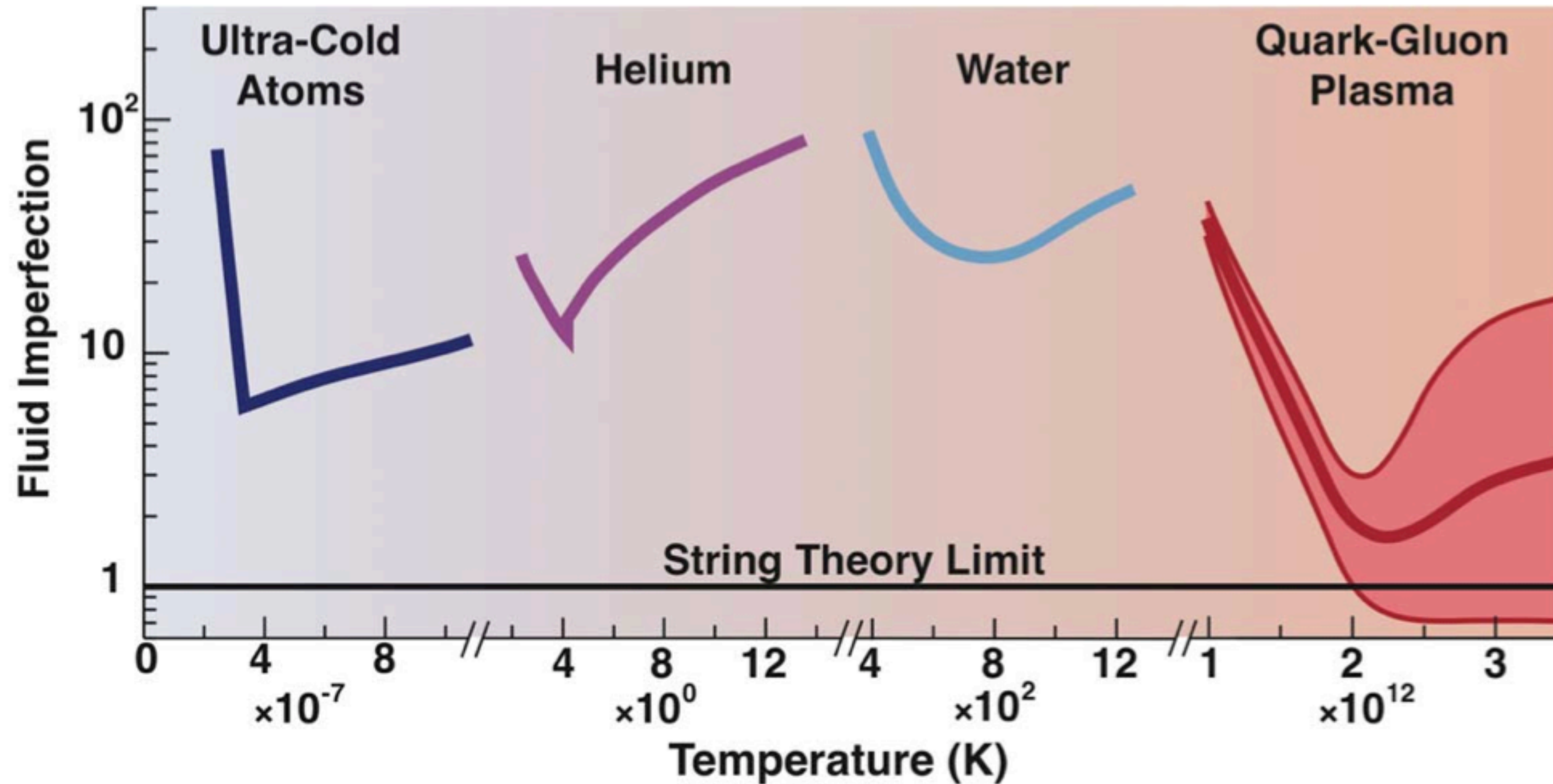


Science Dec 13 2002 2179-2182



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

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>

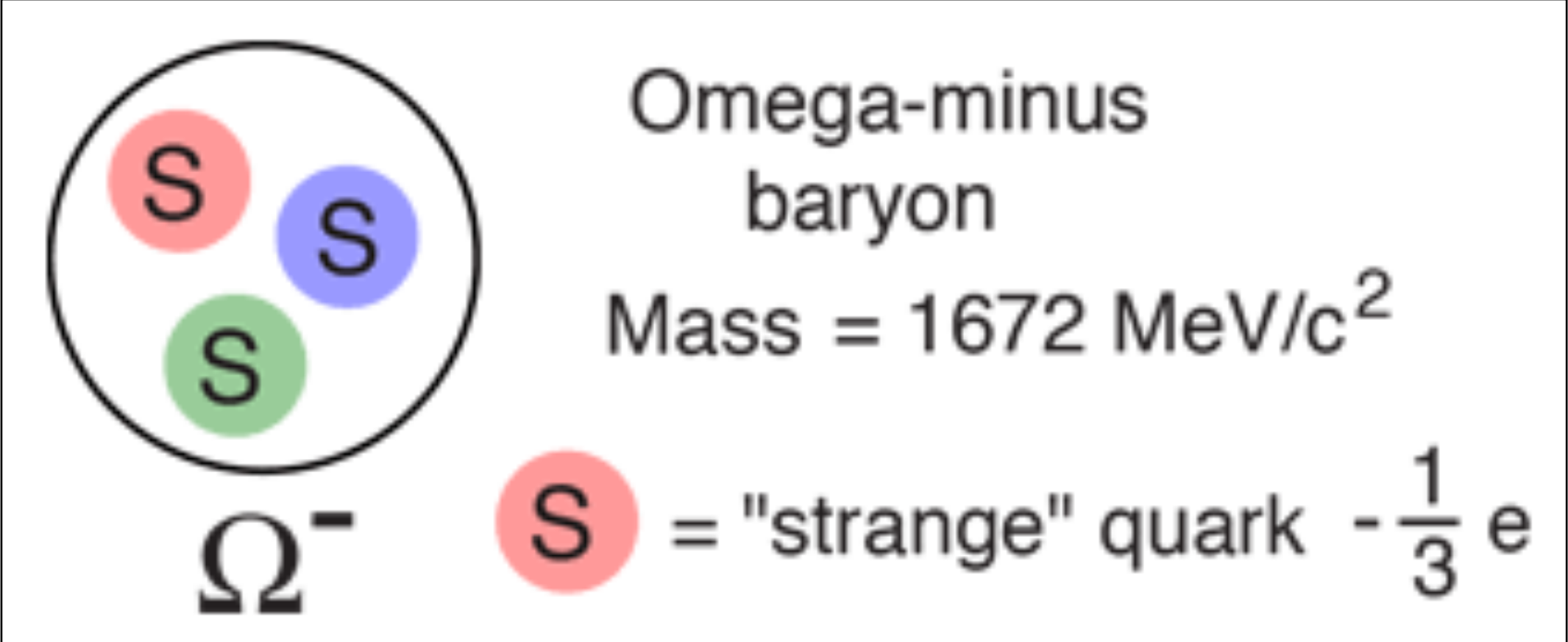
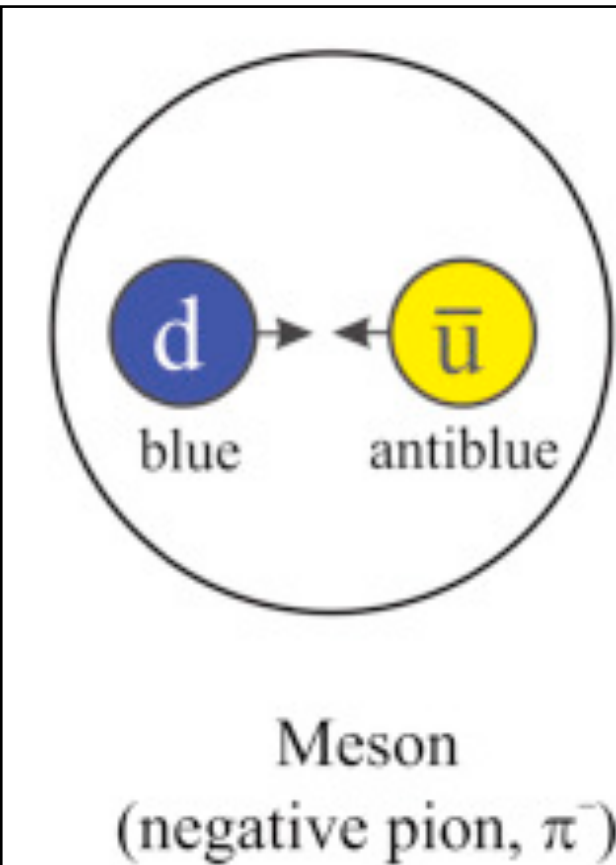
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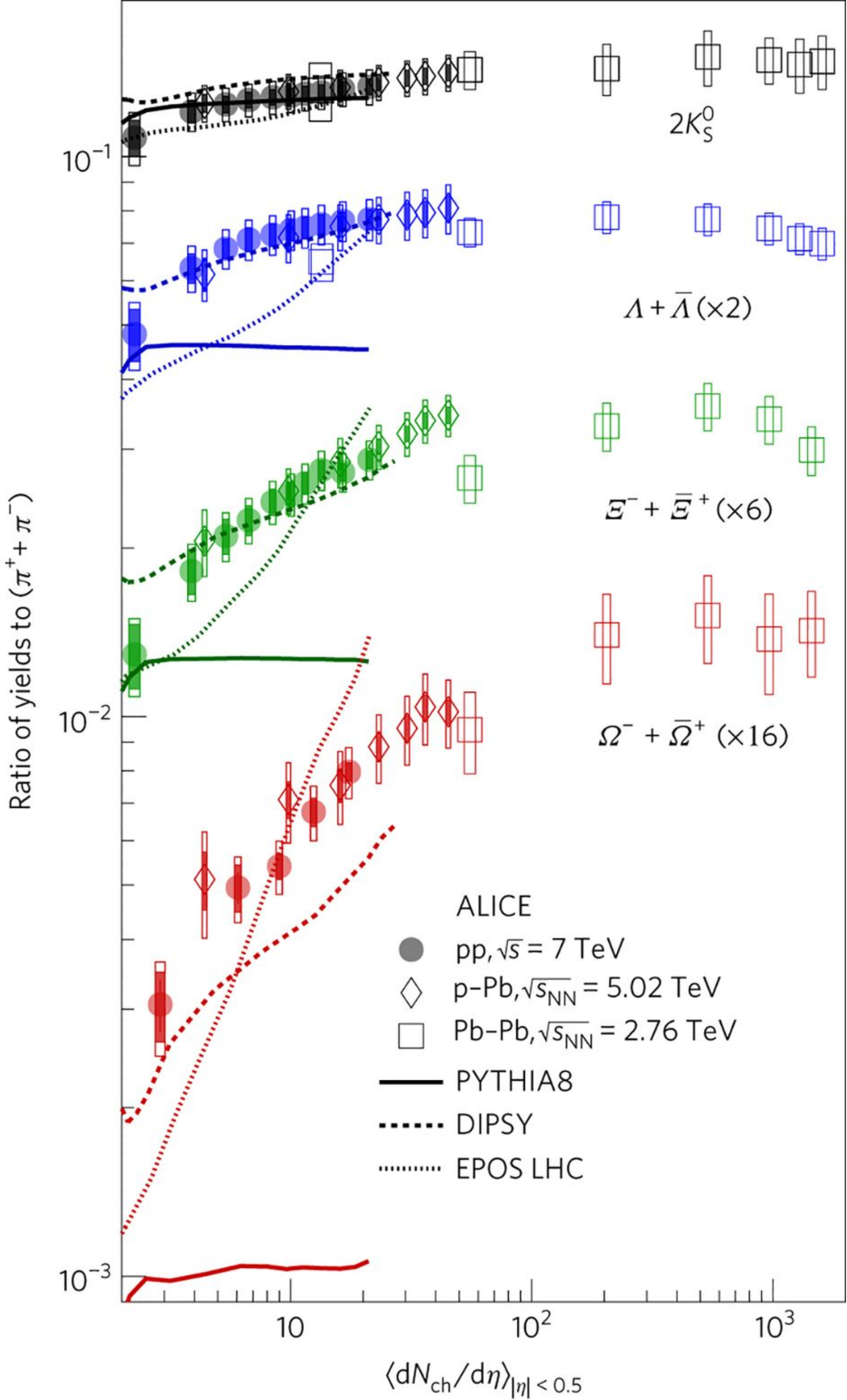
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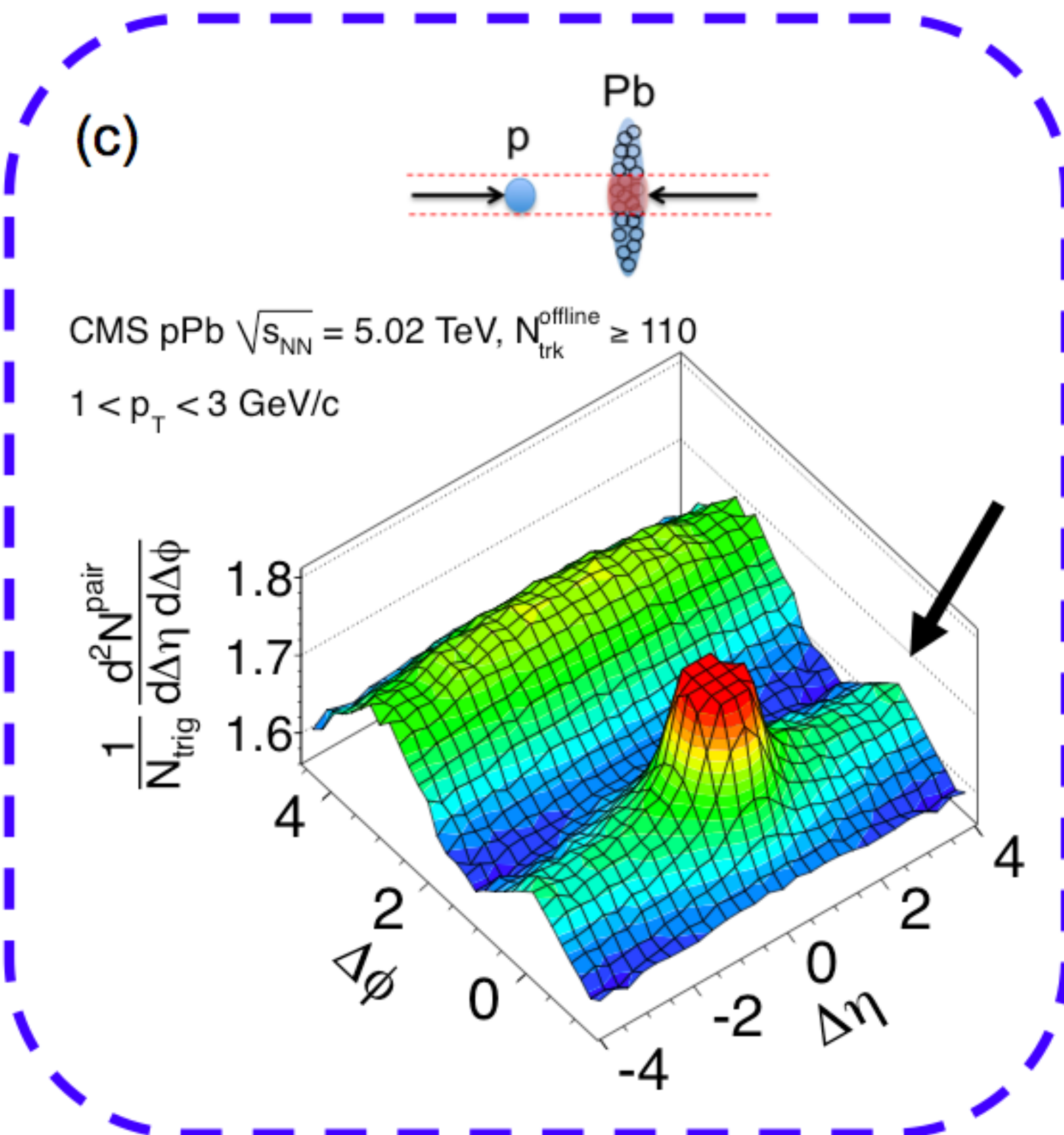
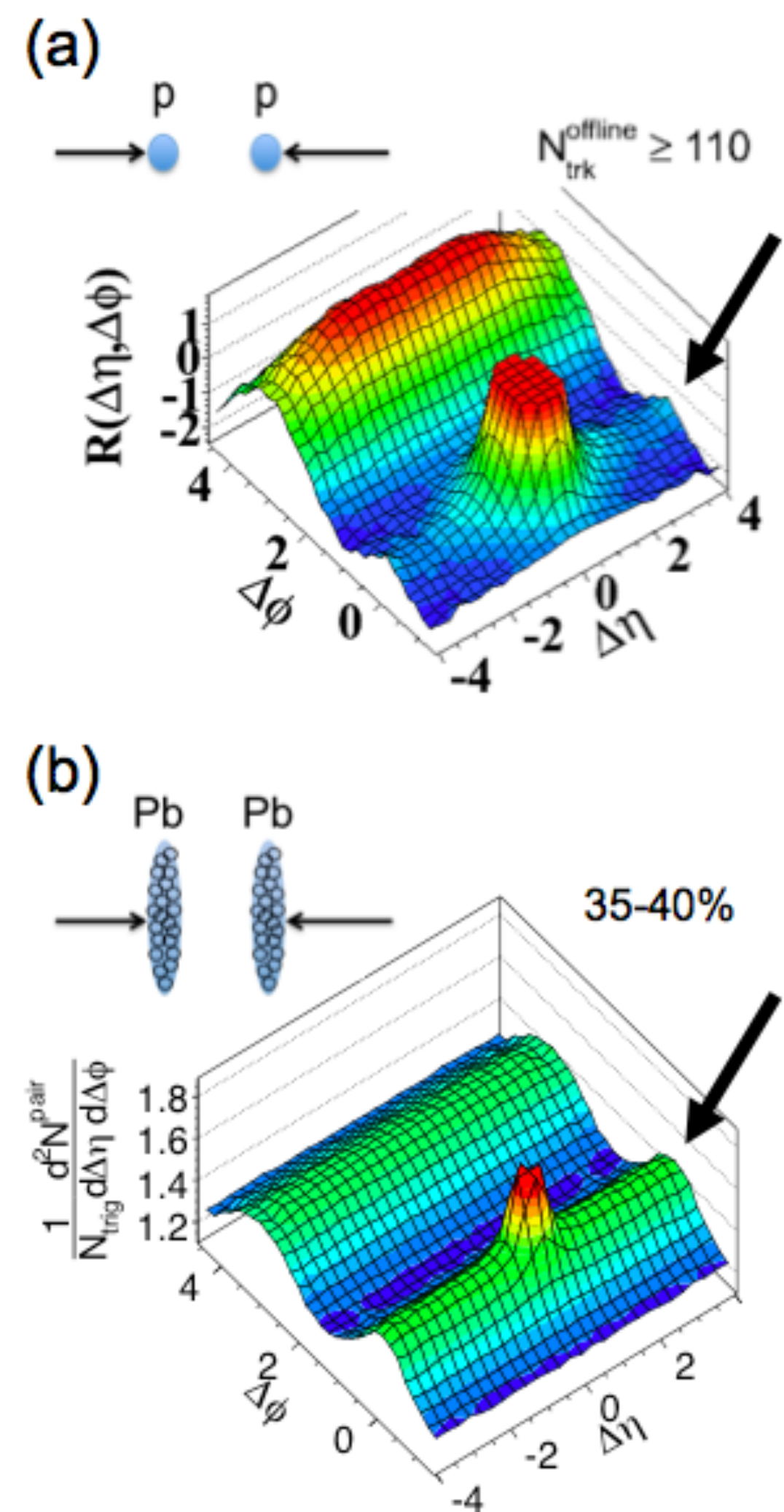
The early universe was strange



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

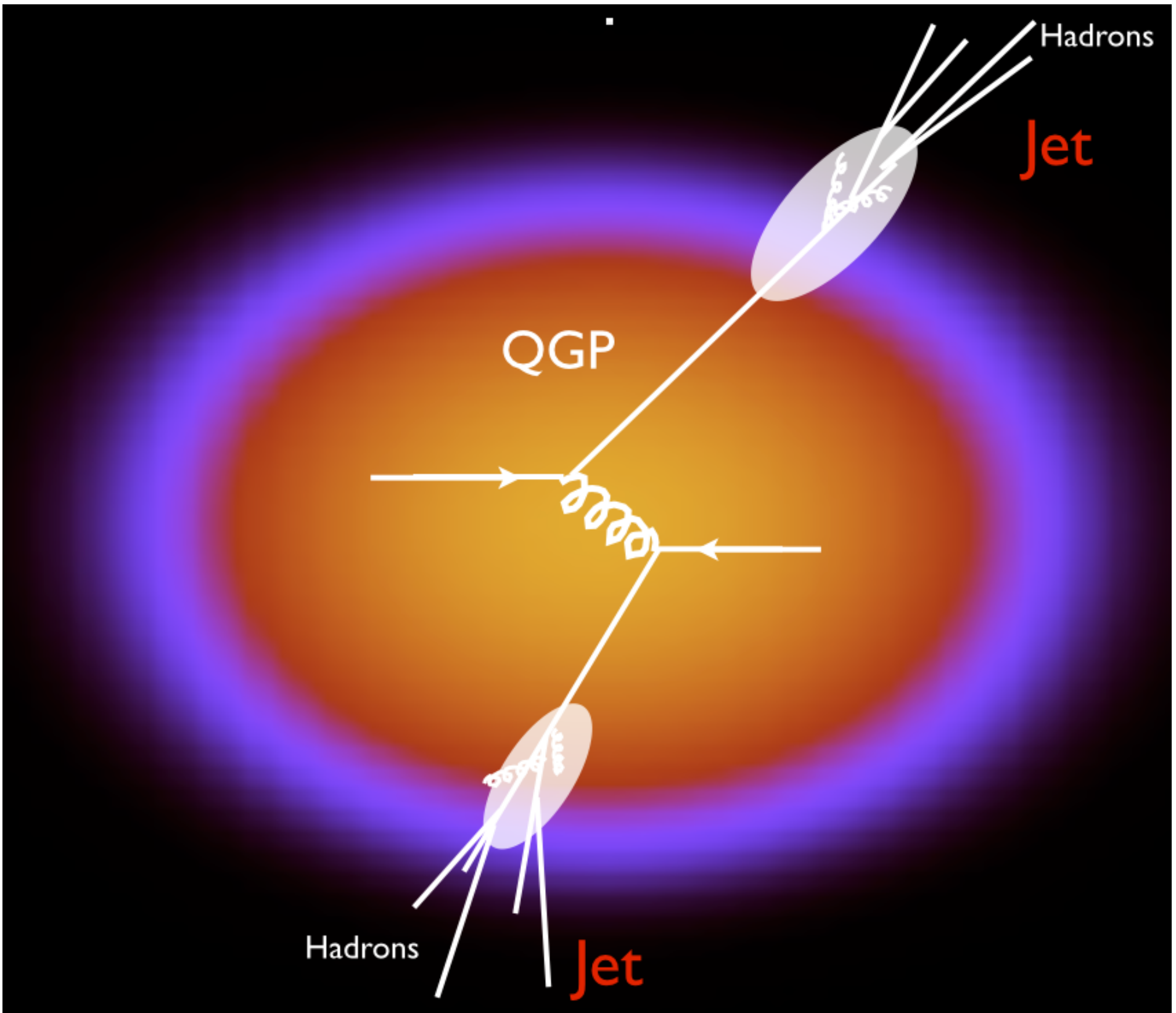
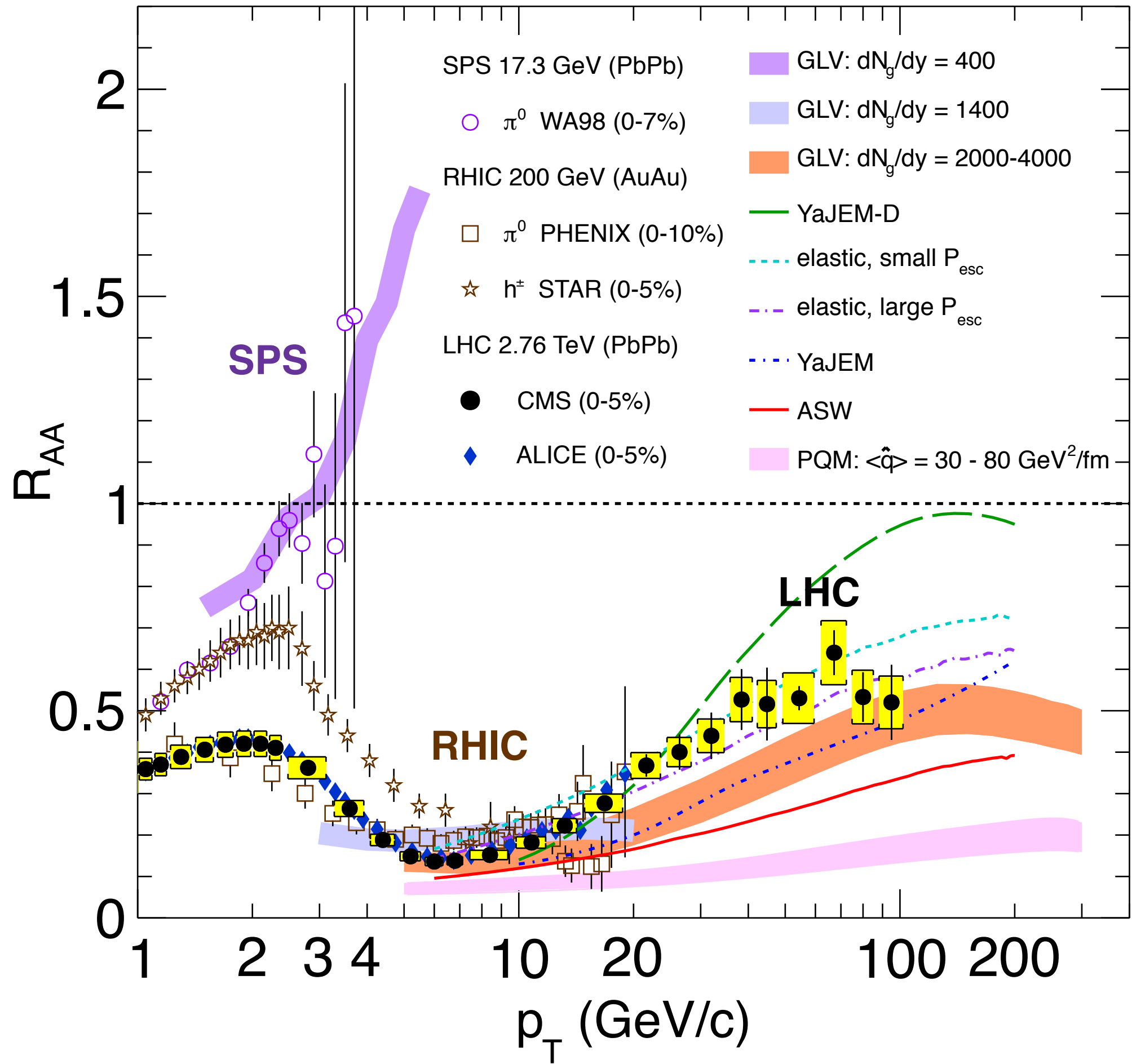


A QGP might be produced in proton-proton collisions



- ▶ 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!

