Sergei A. Voloshin

WAYNE STATE UNIVERSITY

QCD in extreme: relativistic nuclear collisions
(Quest to understand multiparticle production)

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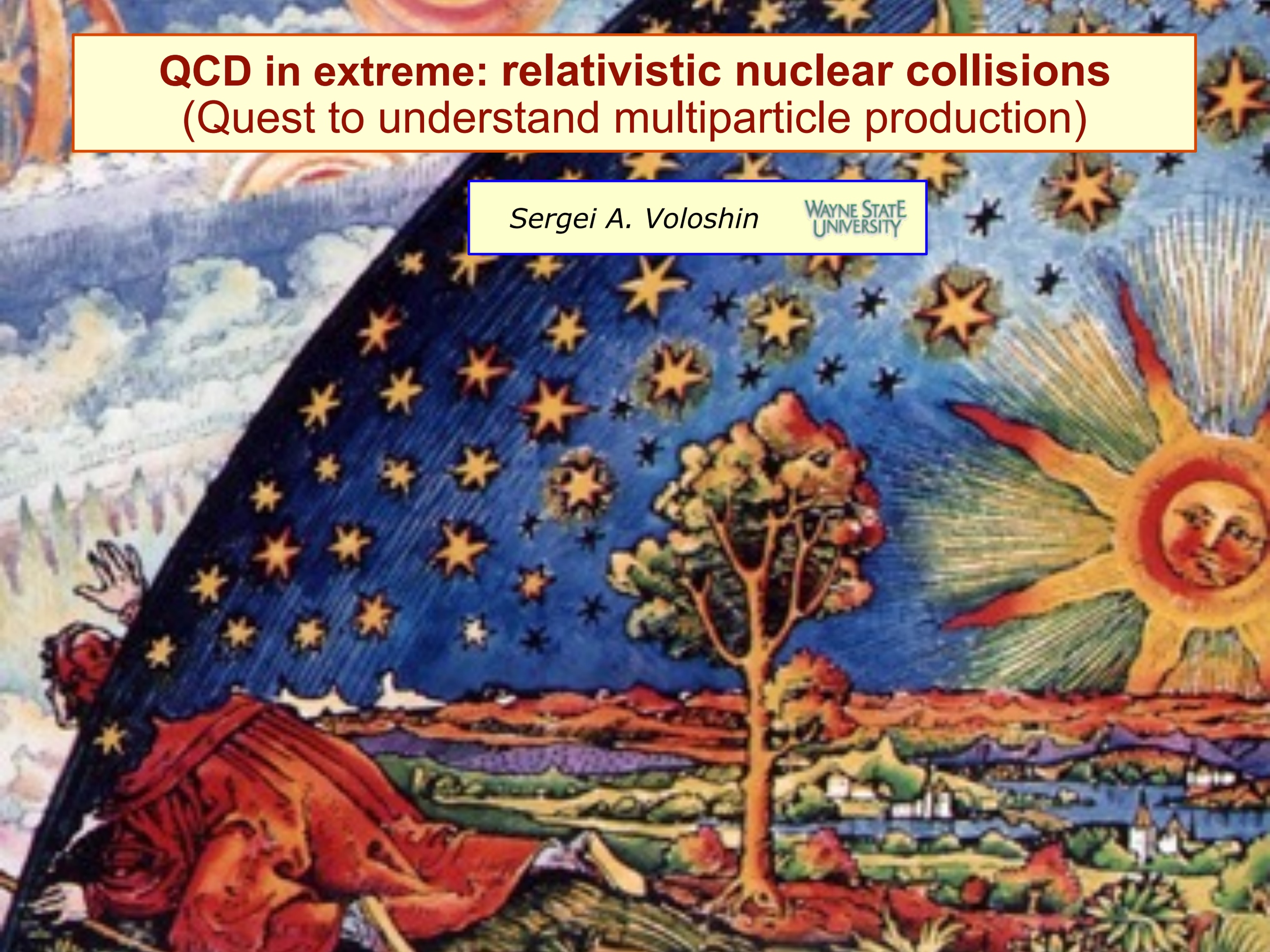

QCD in extreme: relativistic nuclear collisions
(Quest to understand multiparticle production)

Sergei A. Voloshin

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"cv":

Graduated from Moscow Engineering Physics Institute
specializing in theoretical physics

Worked at MEPhI,
TPI Minnesota,
Pittsburgh U.,
U. of Heidelberg,
Berkeley Lab

Experimental Collaborations:
E877 @ AGS.BNL
NA49, NA45(CERES) @ SPS.CERN
STAR @ RHIC.BNL
ALICE @ LHC.CERN

~300 papers
> 18 (5 – "few" authors) with citation index > 250
discovery of anisotropic flow at AGS, SPS,
RHIC (first STAR paper), LHC (first ALICE Pb+Pb paper)…

2008 APS Fellow

QCD in extreme: relativistic nuclear collisions
(Quest to understand multiparticle production)

Sergei A. Voloshin

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Outline:

- what questions we try to answer
- what experiments we perform
- 3 examples of my “contribution”

QCD in extreme: relativistic nuclear collisions
(Quest to understand multiparticle production)

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WAYNE STATE UNIVERSITY

Fundamental physics: questions to answer

What is dark matter?

What is dark energy?

How were the heavy elements from iron to uranium made?

Do neutrinos have mass?

Where do ultra-energy particles come from?

Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?

Are there new states of matter at ultrahigh temperatures and densities?

Are protons unstable?

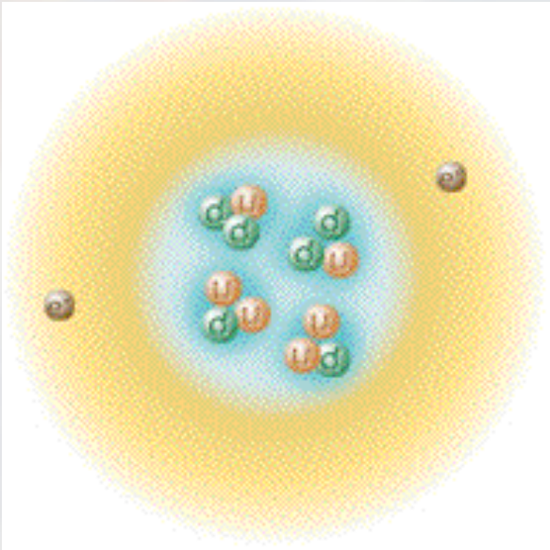
What is gravity?

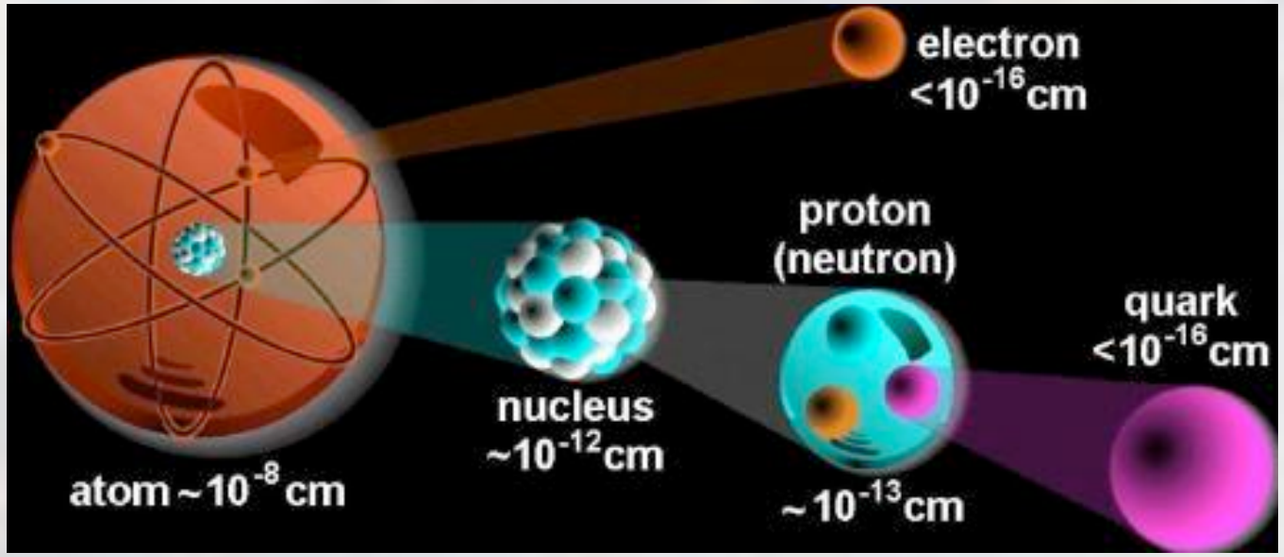
Are there additional dimensions?

How did the Universe begin?

The February 2002 issue of Discover magazine based its cover story on the recent 105-page public draft of the National Research Council Committee on Physics of the Universe report, *Connecting Quarks with the Cosmos*

The Structure of matter. Types of interactions





FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

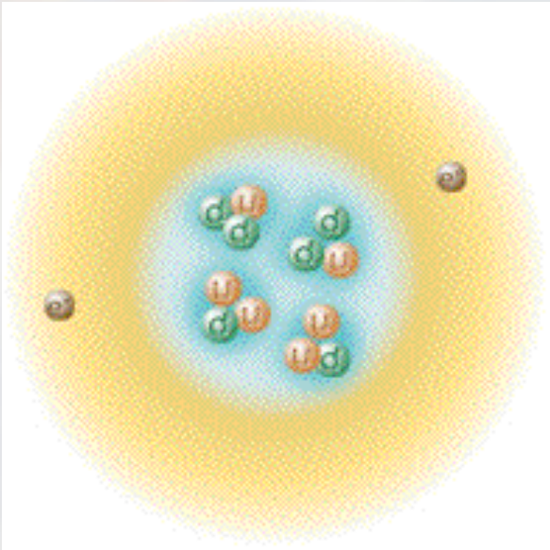
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

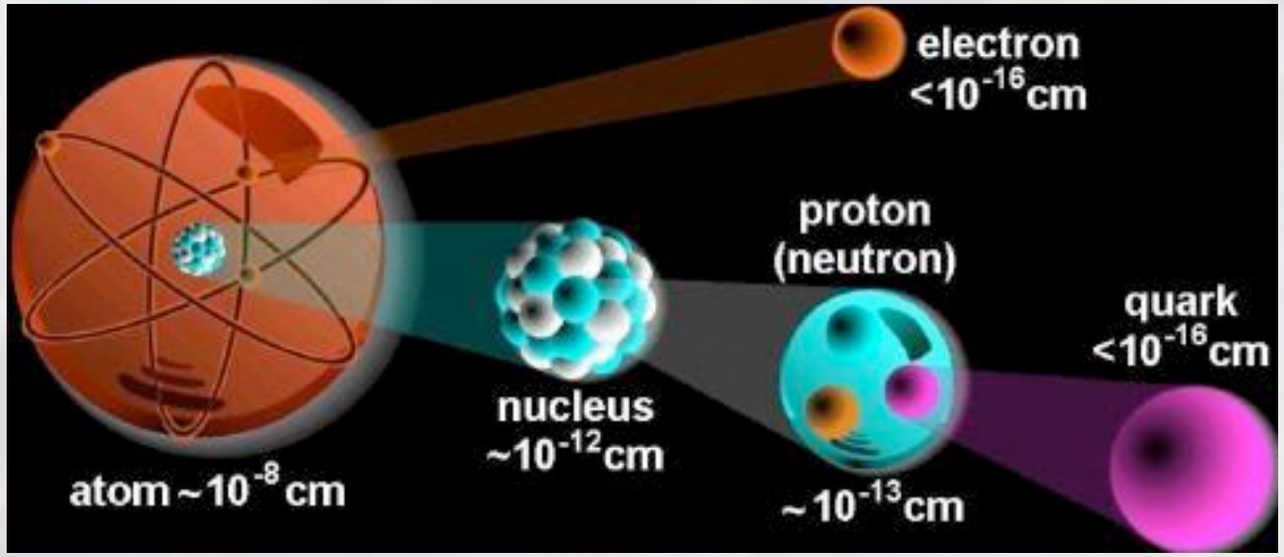
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

The Structure of matter. Types of interactions





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Hadrons are particles "participating" in the strong interactions

Quantum Chromo Dynamics (QCD)

Forces between *quarks*: exchange of colour *gluons*

Confinement: at larger distances interaction become stronger ➔ Free quarks are not observed in nature;

Non-trivial structure of the vacuum:

Spontaneous breaking of the chiral symmetry – generation of masses.

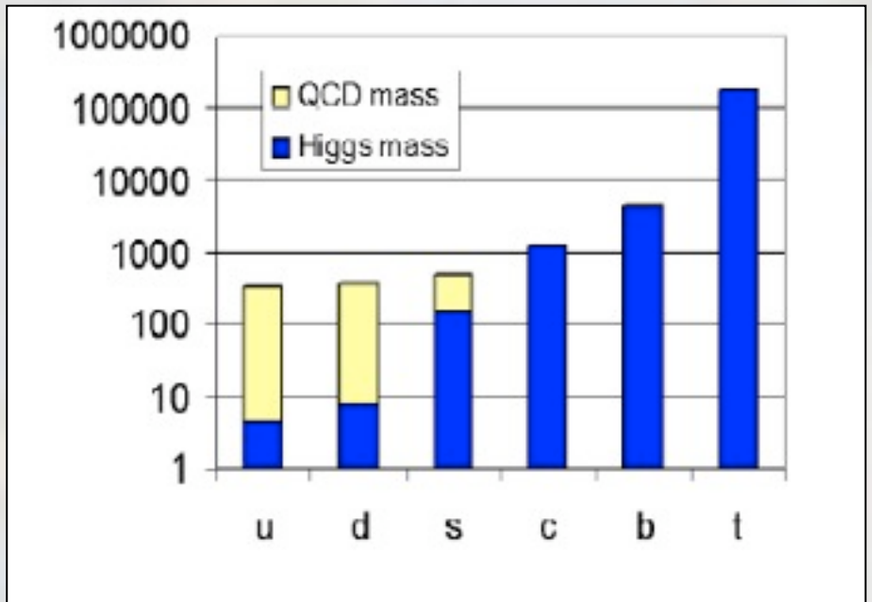
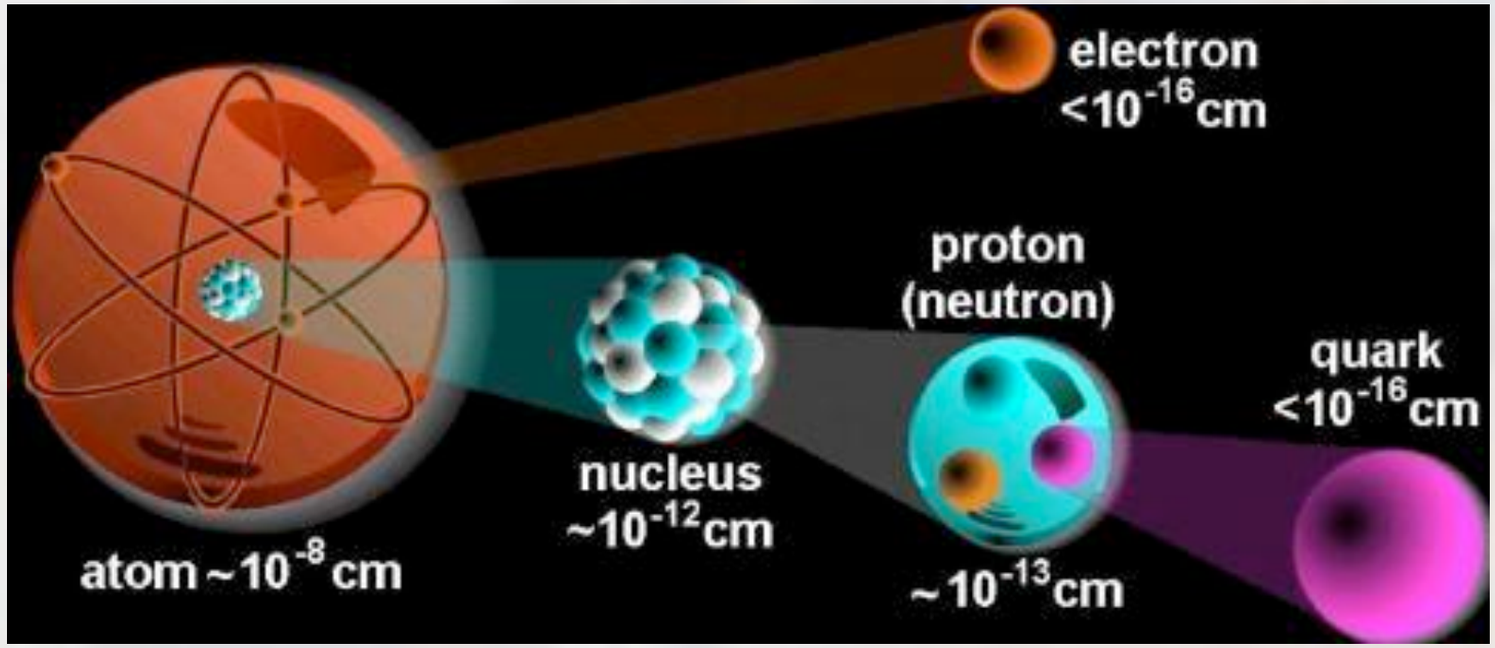


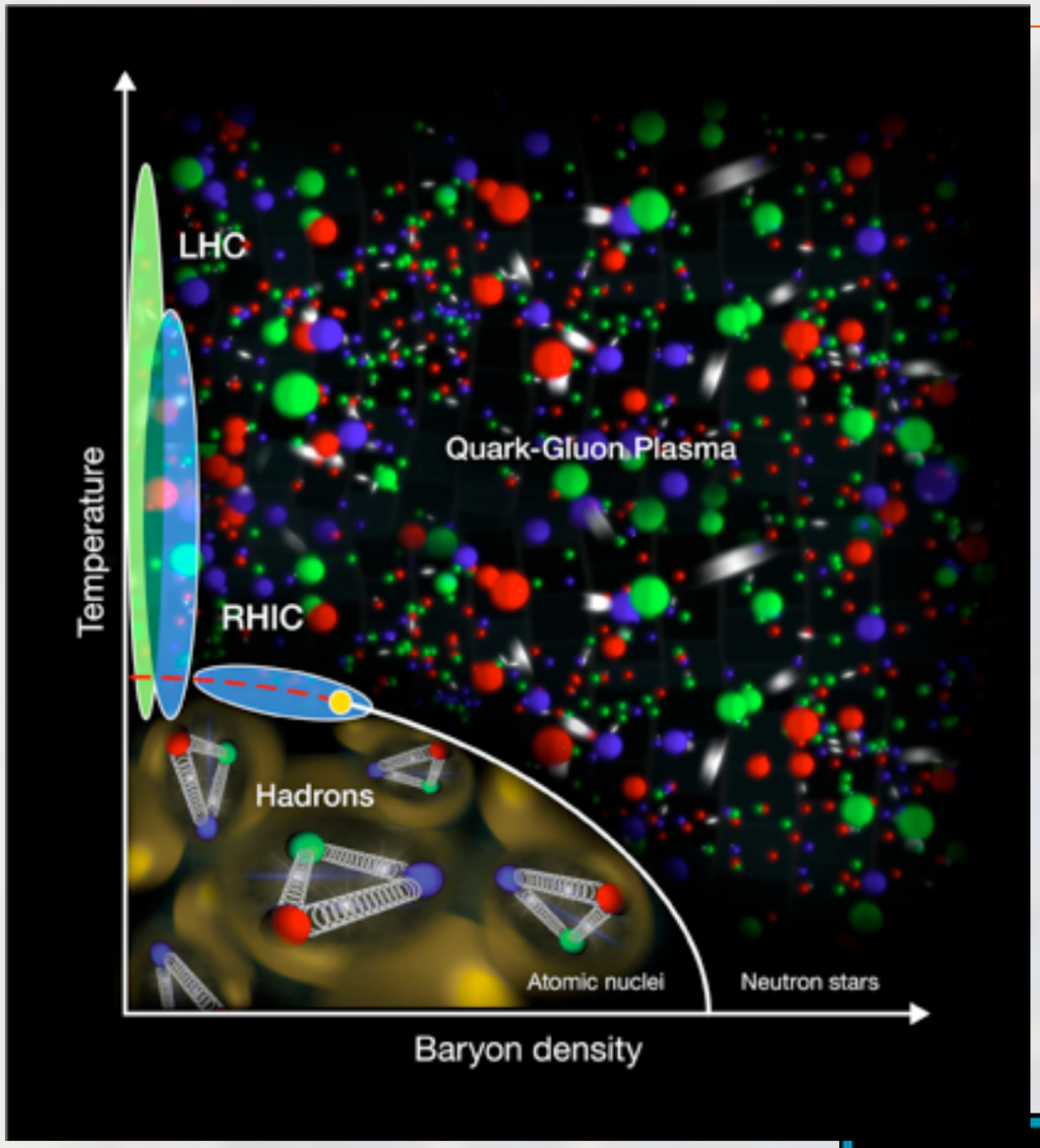
FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale. Berndt Müller

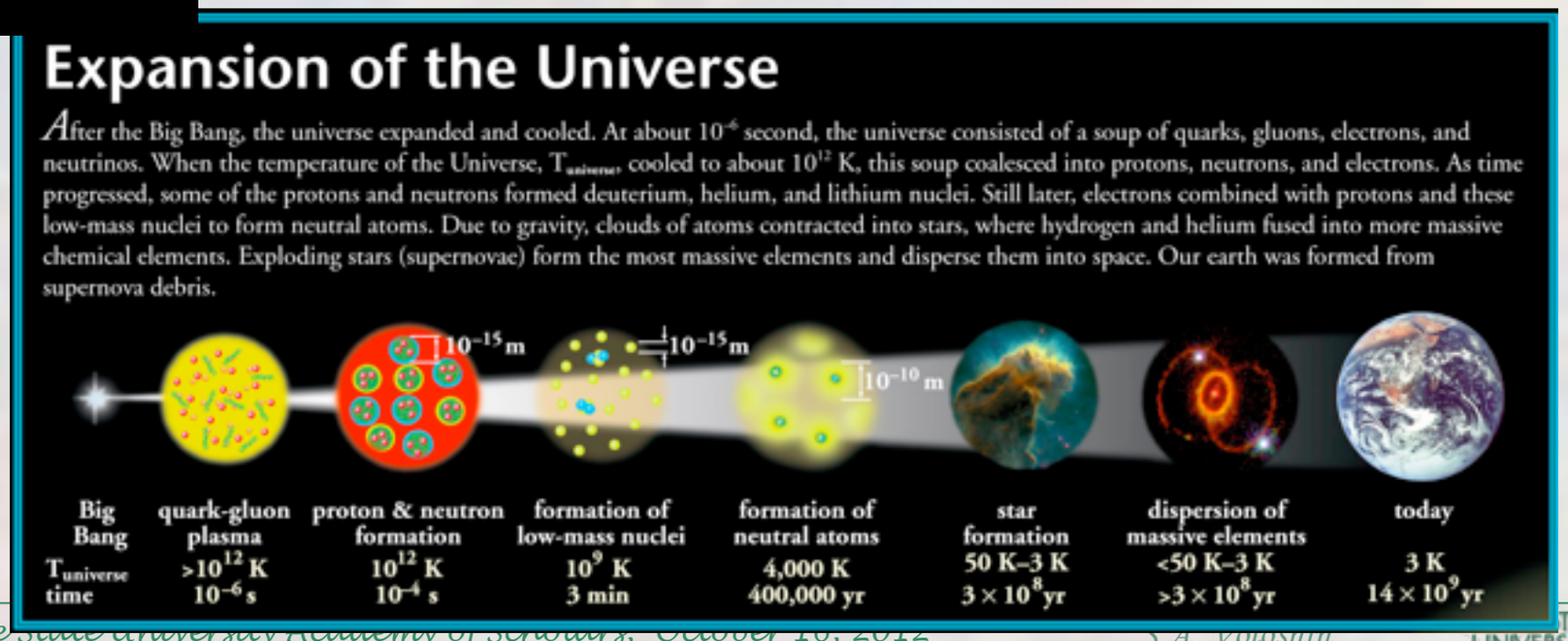


Questions we try to answer:

- Are there a new (deconfined) state of matter - **Quark Gluon Plasma**, where quarks and gluons can move "freely"?
- What are the properties of this matter (e.g. viscosity)?
- How it hadronizes (converts to regular matter)?

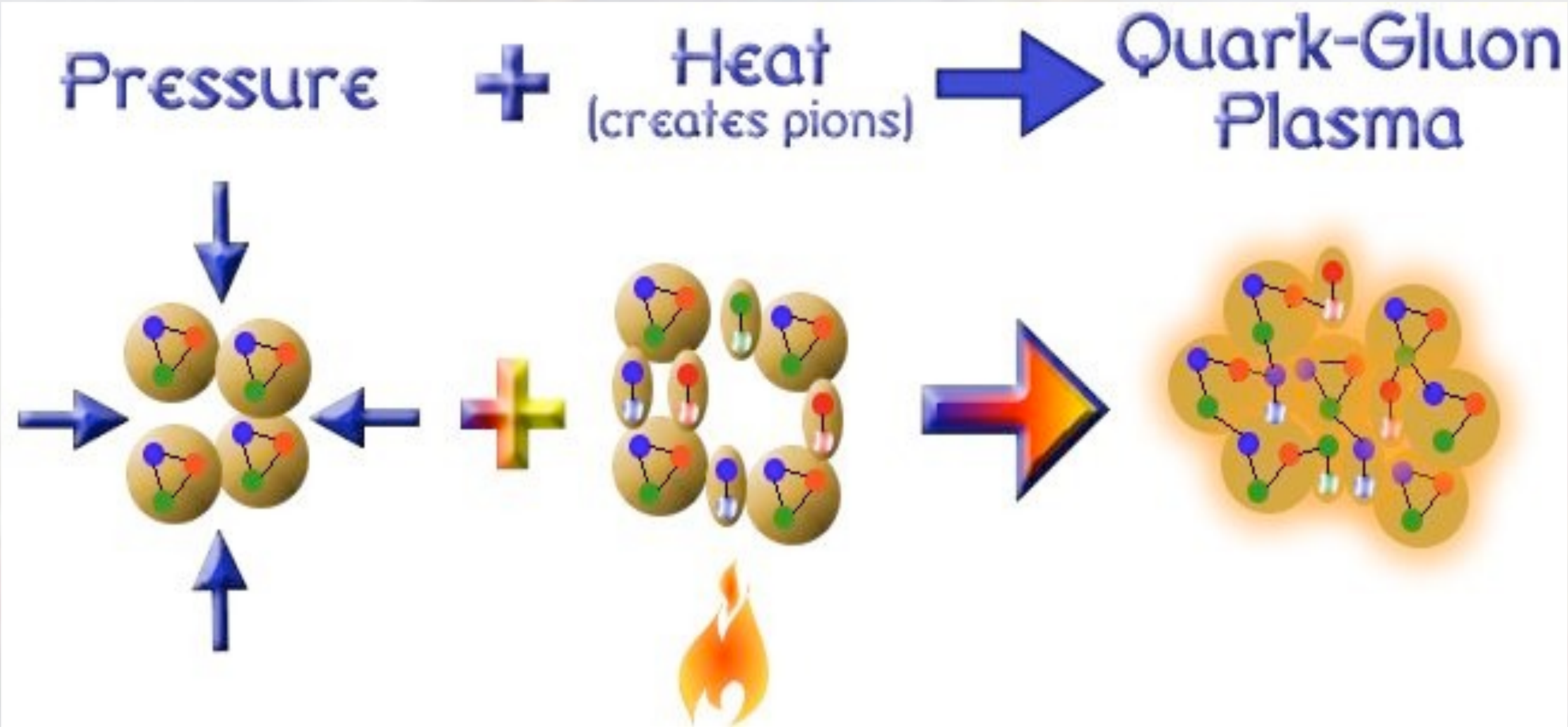
The Phase Diagram of QCD





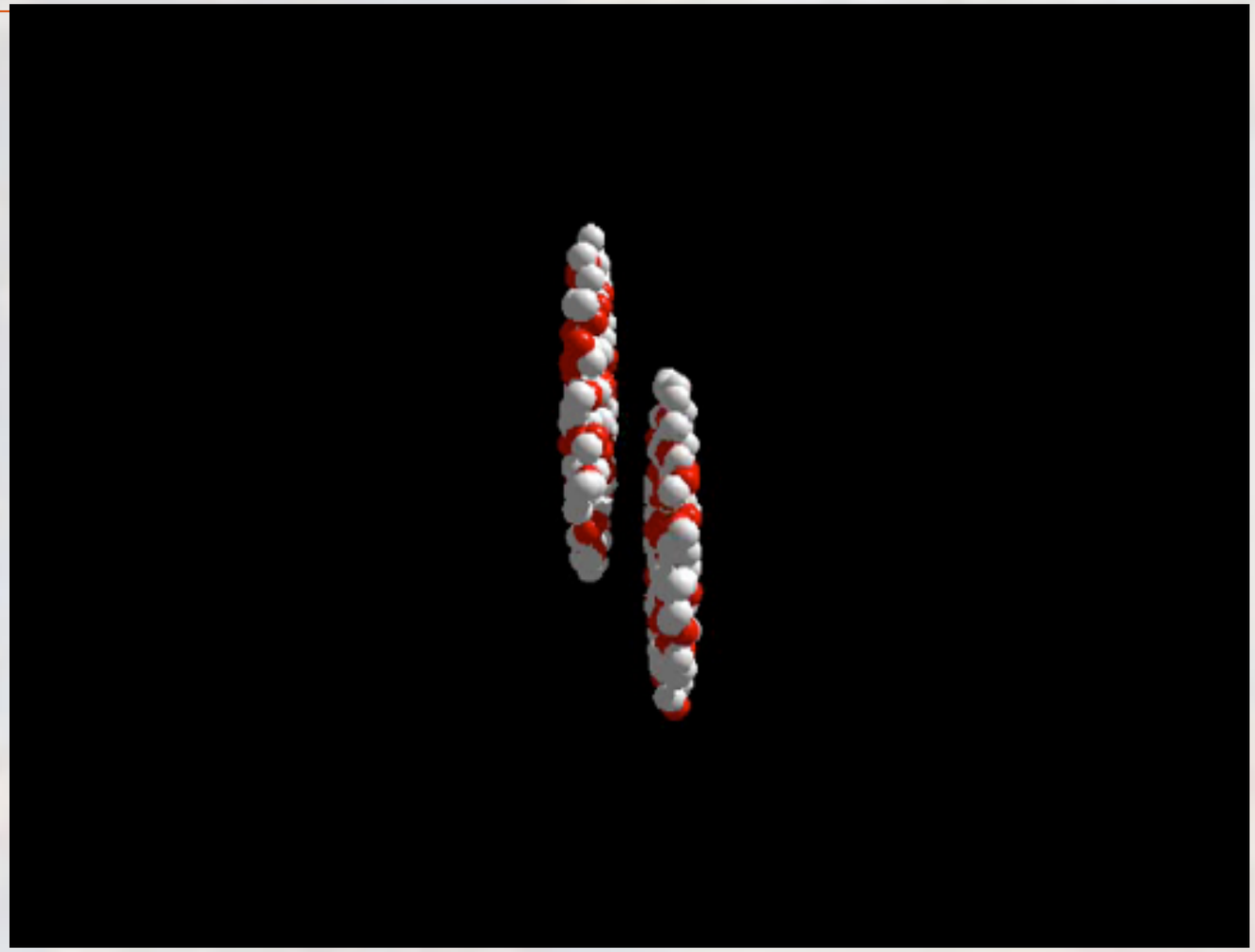
QGP

Quark-Gluon Plasma = color deconfinement
+ thermalization



Local color screening ➔ deconfinement
(“free” color propagation over large distances

Ultrarelativistic nuclear collisions



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CERN European Organization for Nuclear Research

Large Hadron Collider

RHIC relativistic heavy ion collider

Google

$m_N \approx 1$ GeV

BNL AGS	CERN SPS	**BNL RHIC**	**CERN LHC**
$\sqrt{s_{NN}}$ ~5 GeV	~ 17 GeV	up to **200 GeV**	**~5500 GeV**

Ultrarelativistic nuclear collisions

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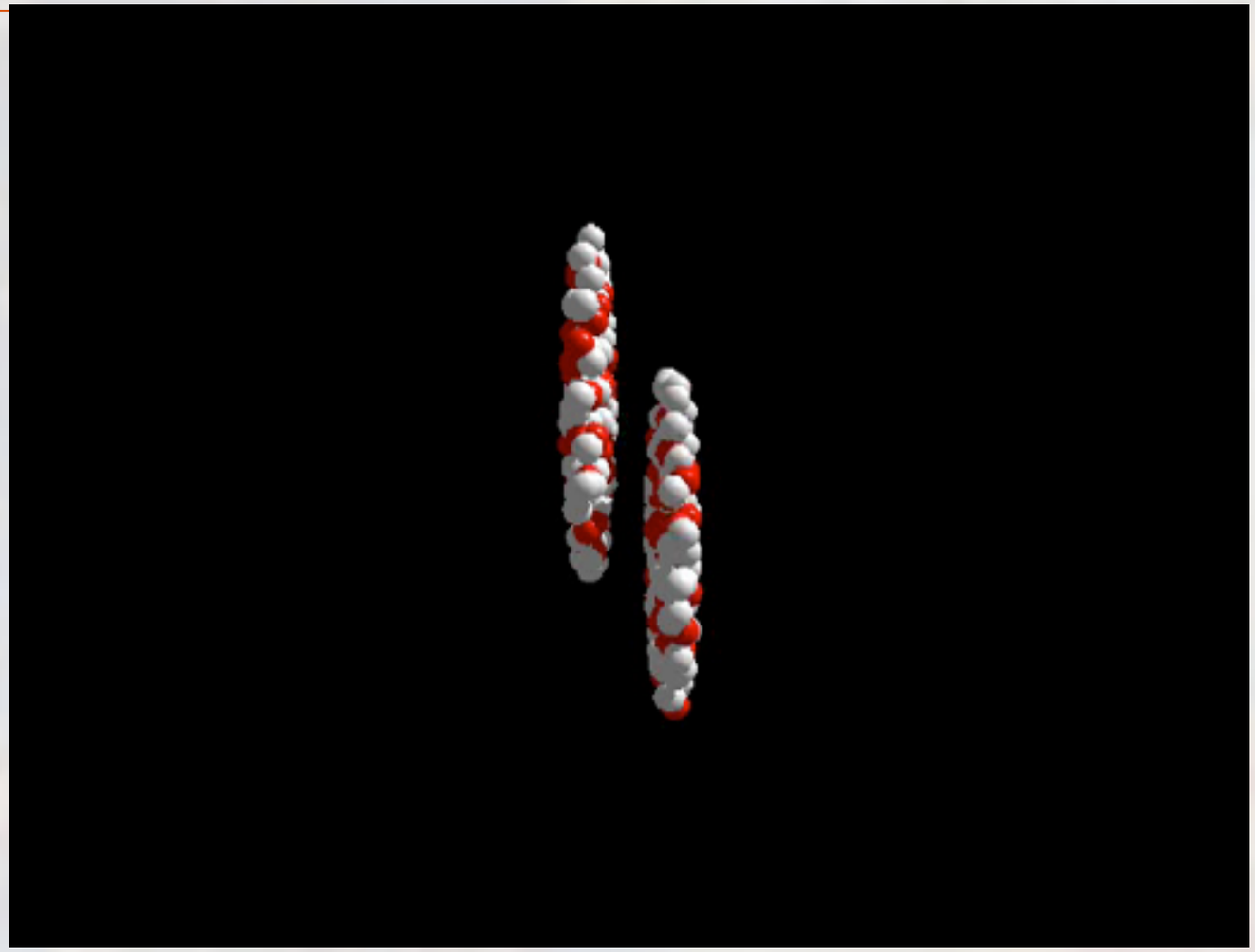

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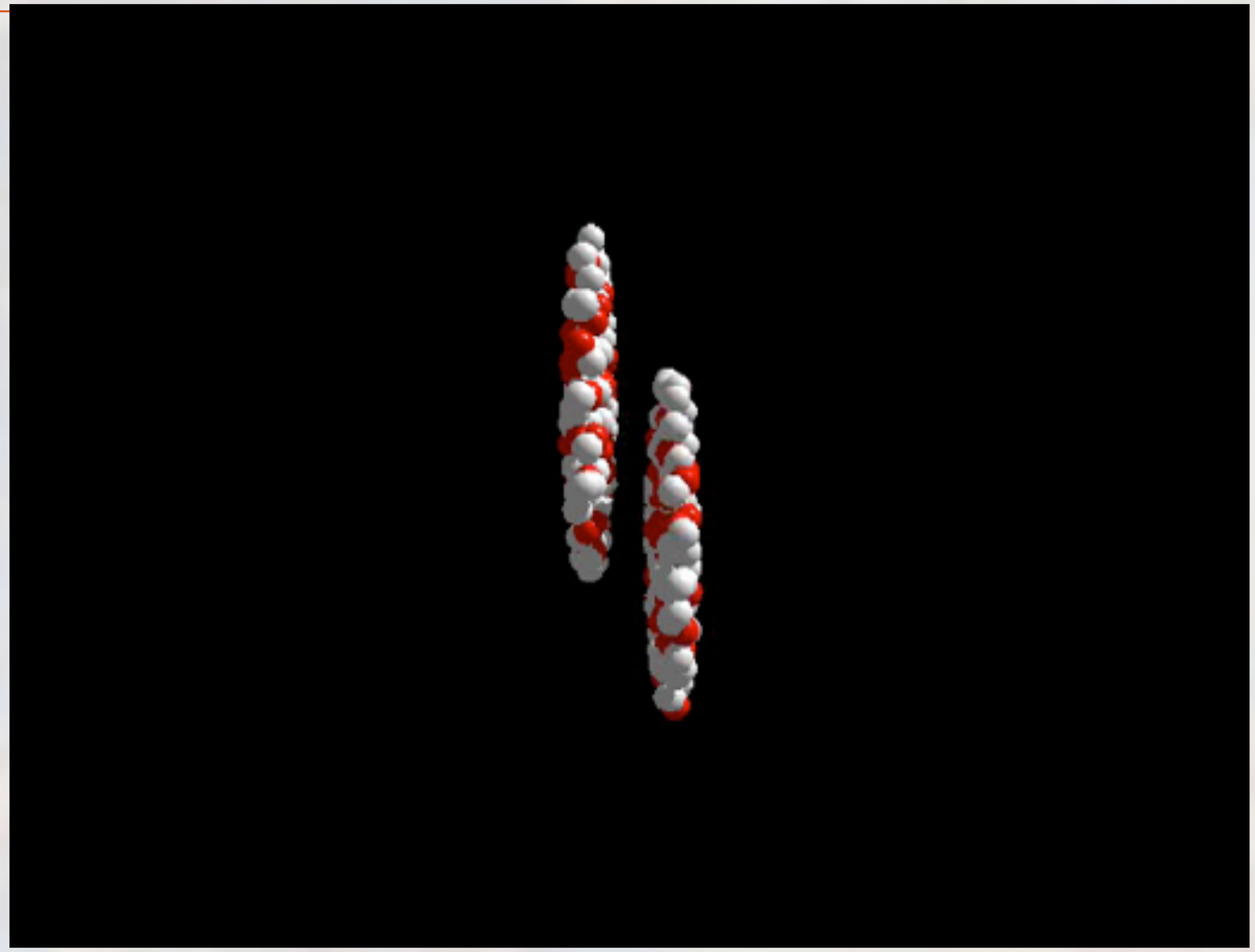
Energy of the Pb beam at LHC ~ 1 ton of TNT !

Ultrarelativistic nuclear collisions



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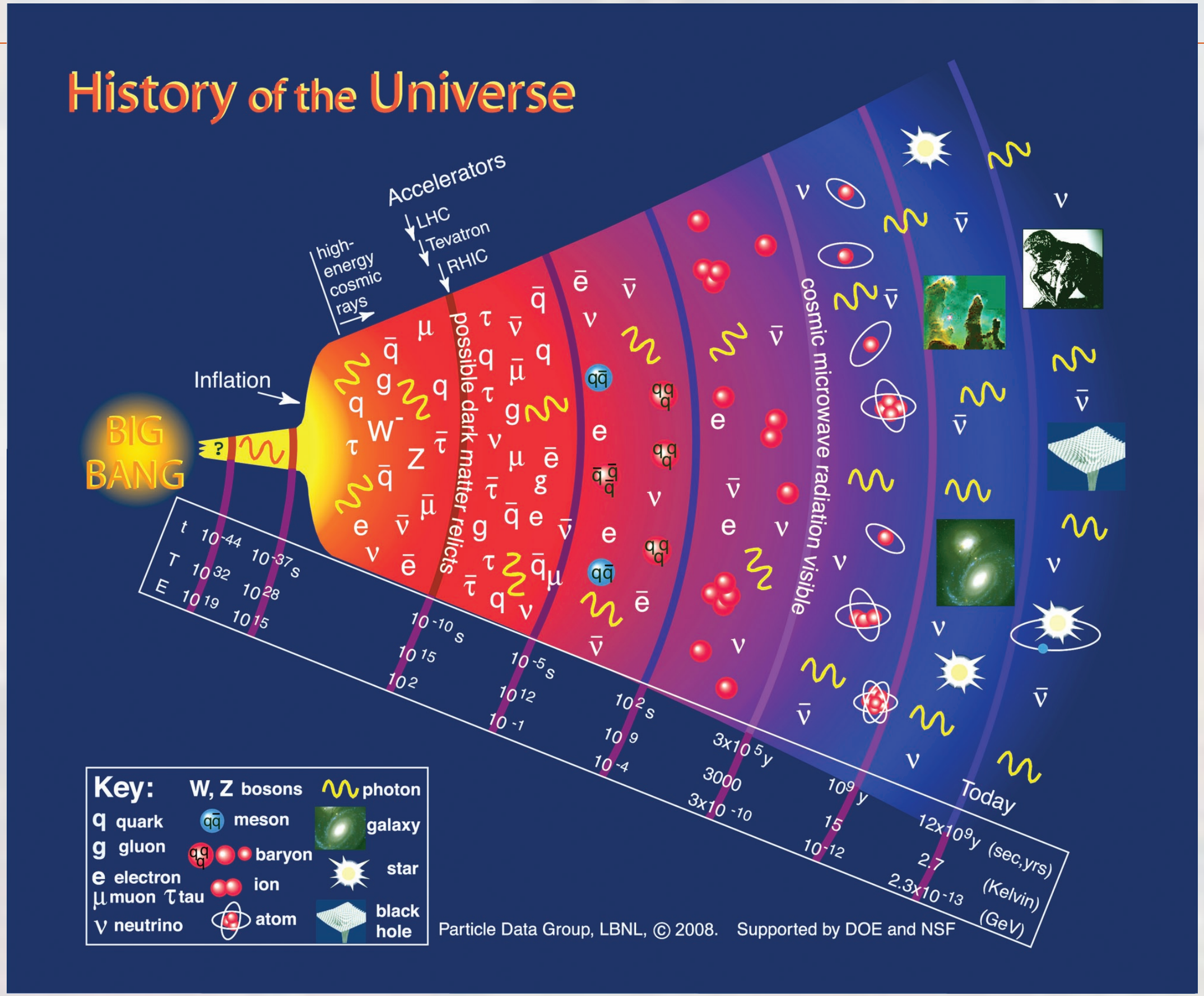
History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 102 1012 10-1 10 9 3000 15 2.7 (Kelvin)
E 1019 1015 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

STAR @ RHIC

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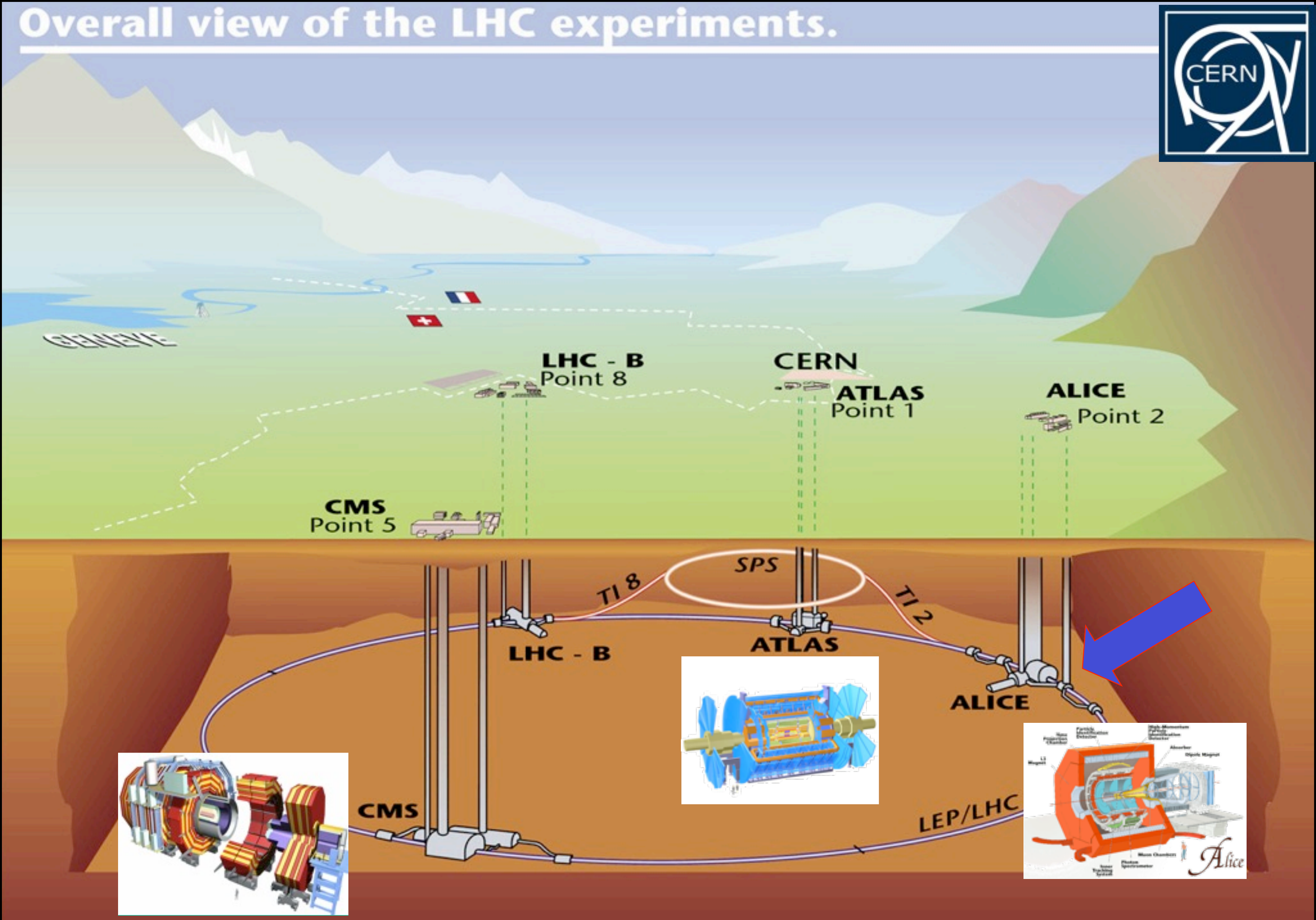
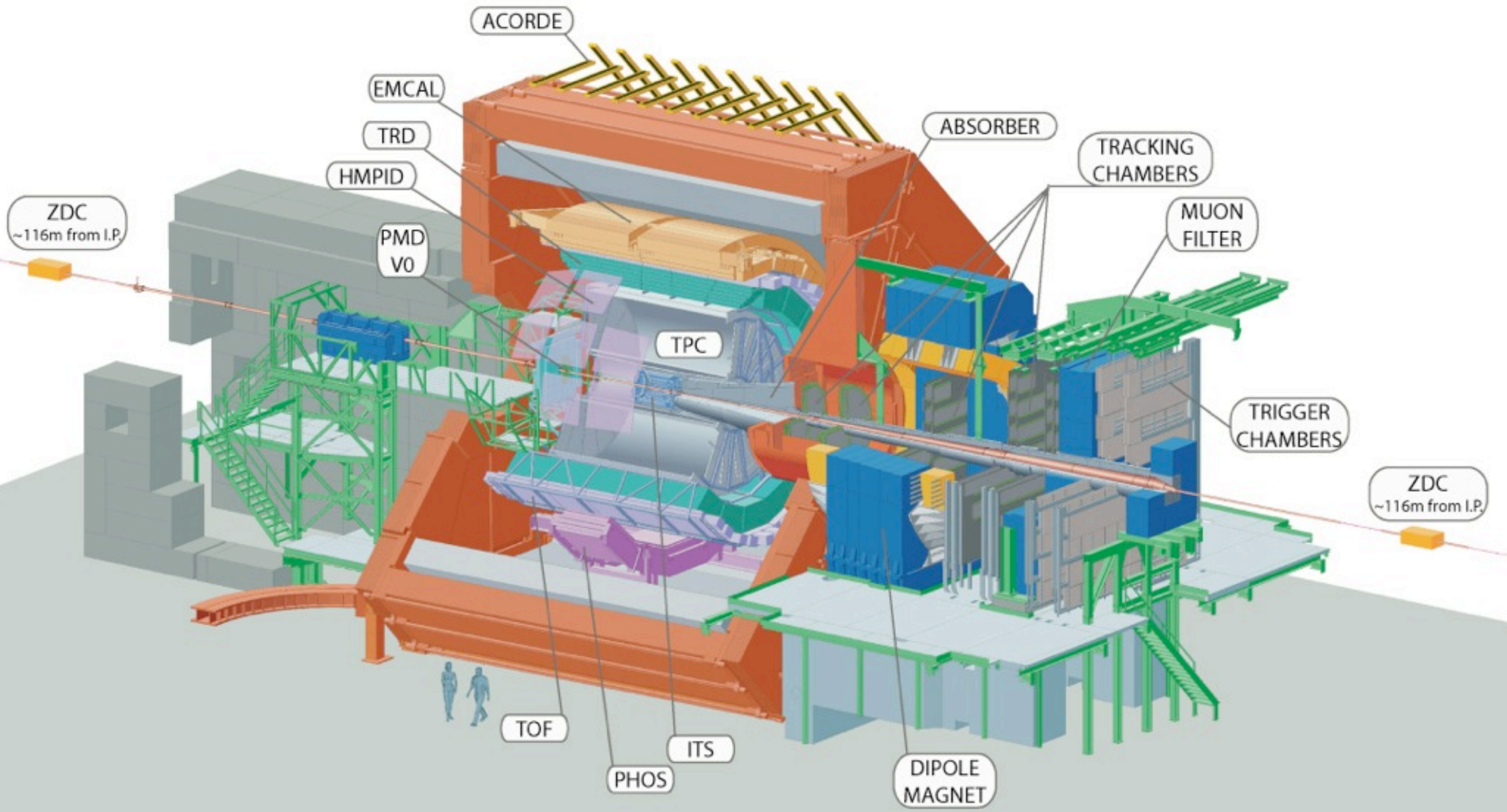
European Organization for Nuclear Research

Overall view of the LHC experiments.



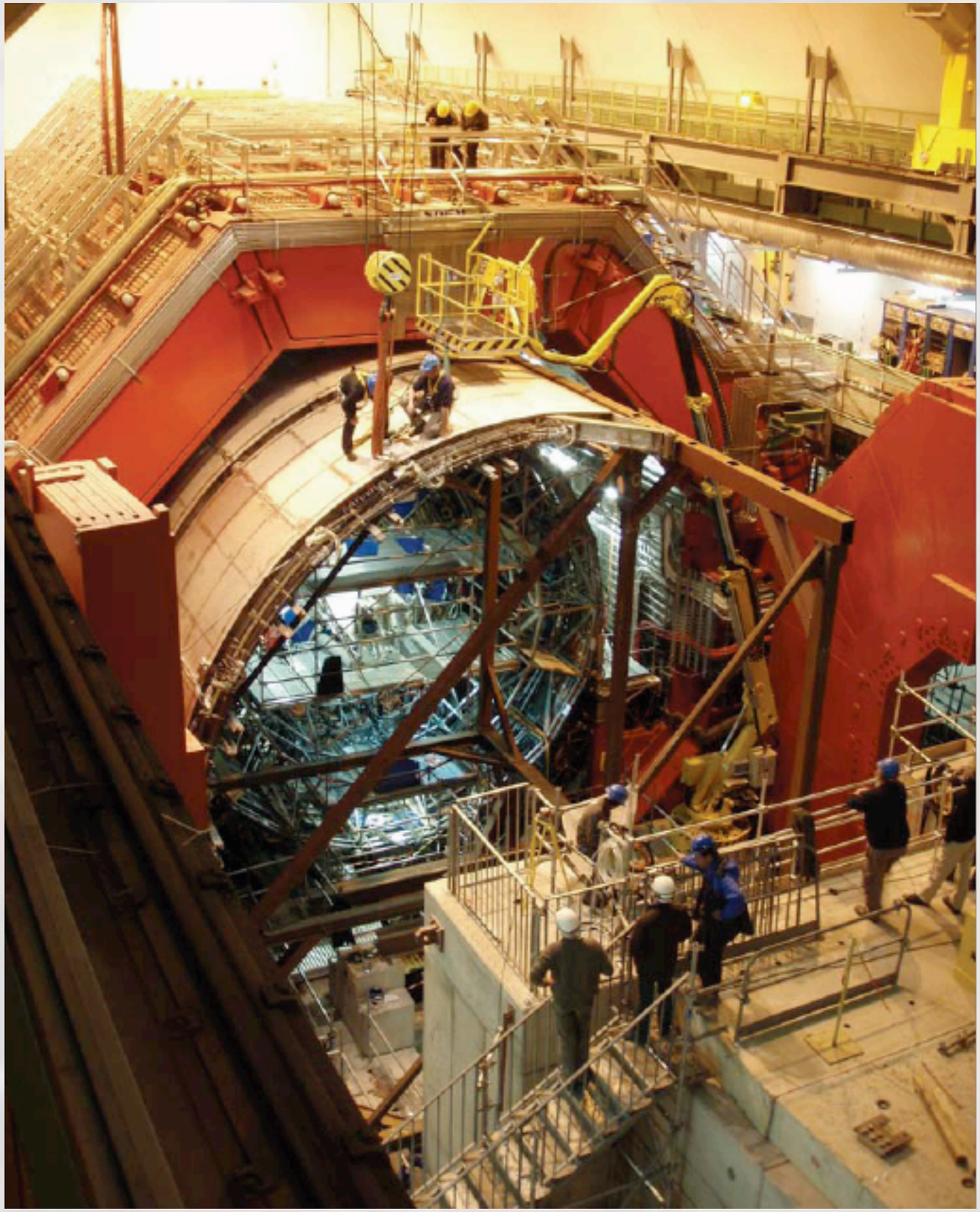
ALICE Detector



Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

Collaboration:
> 1000 Members
> 100 Institutes
> 30 countries

ALICE Detector construction



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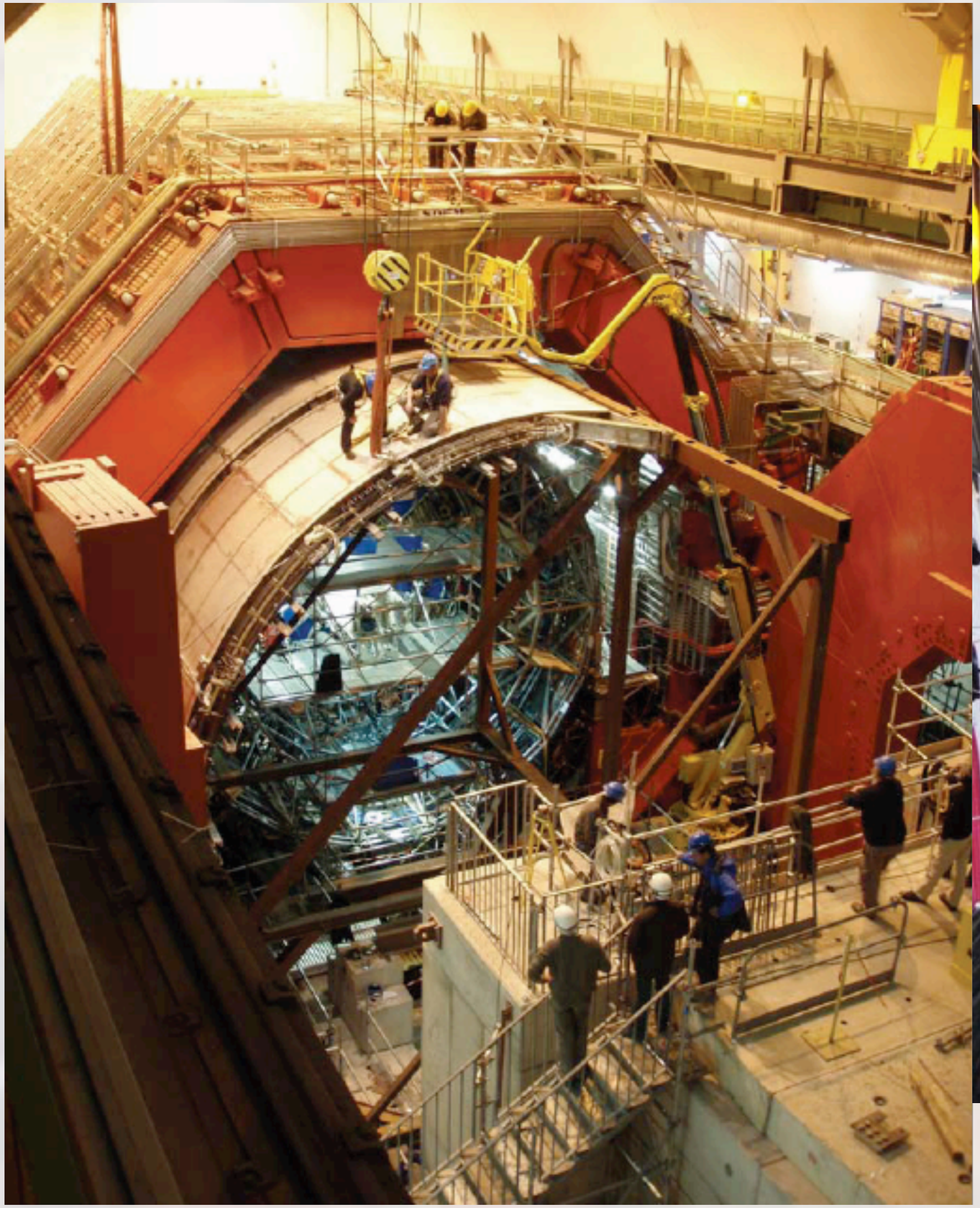
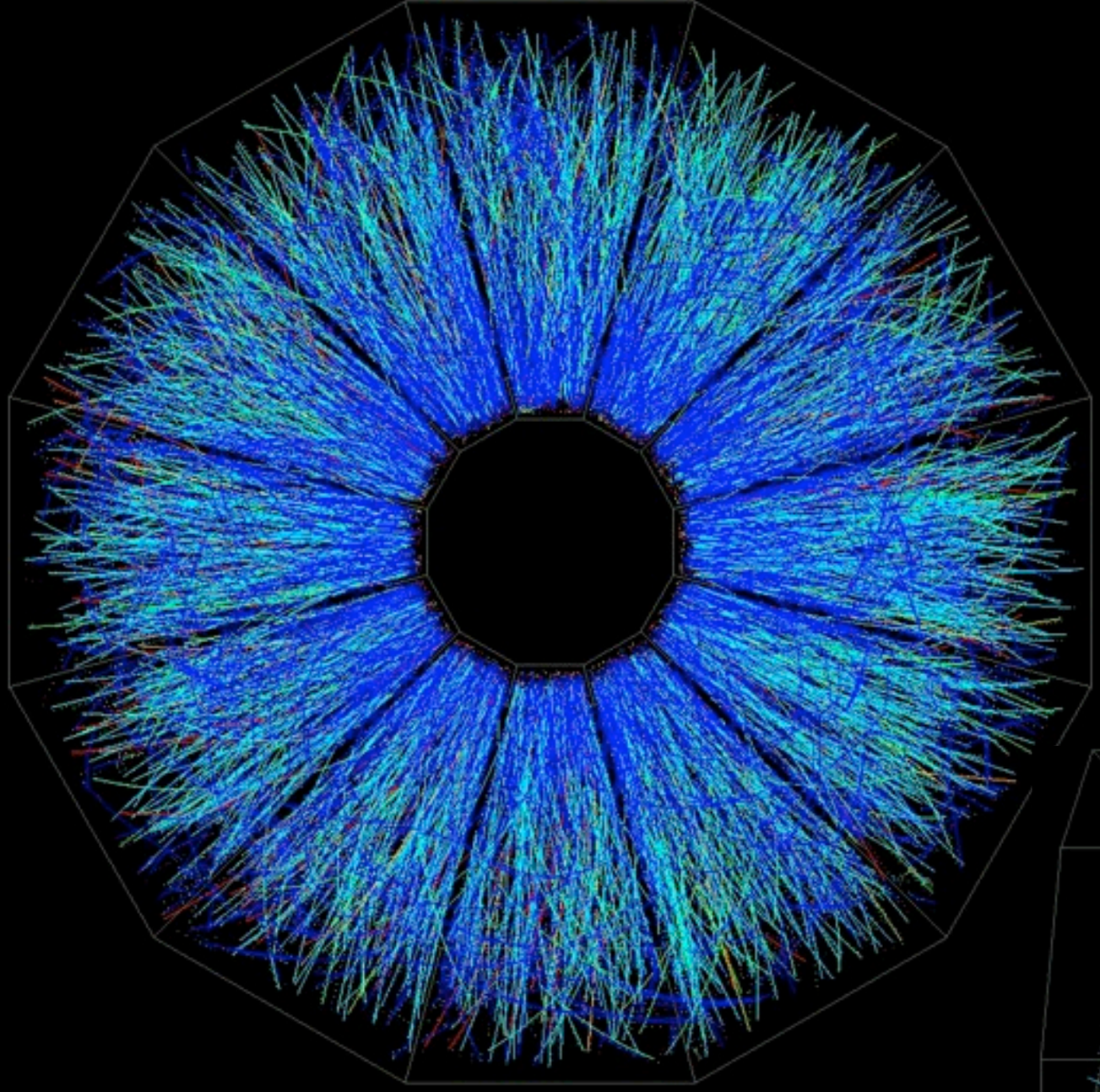
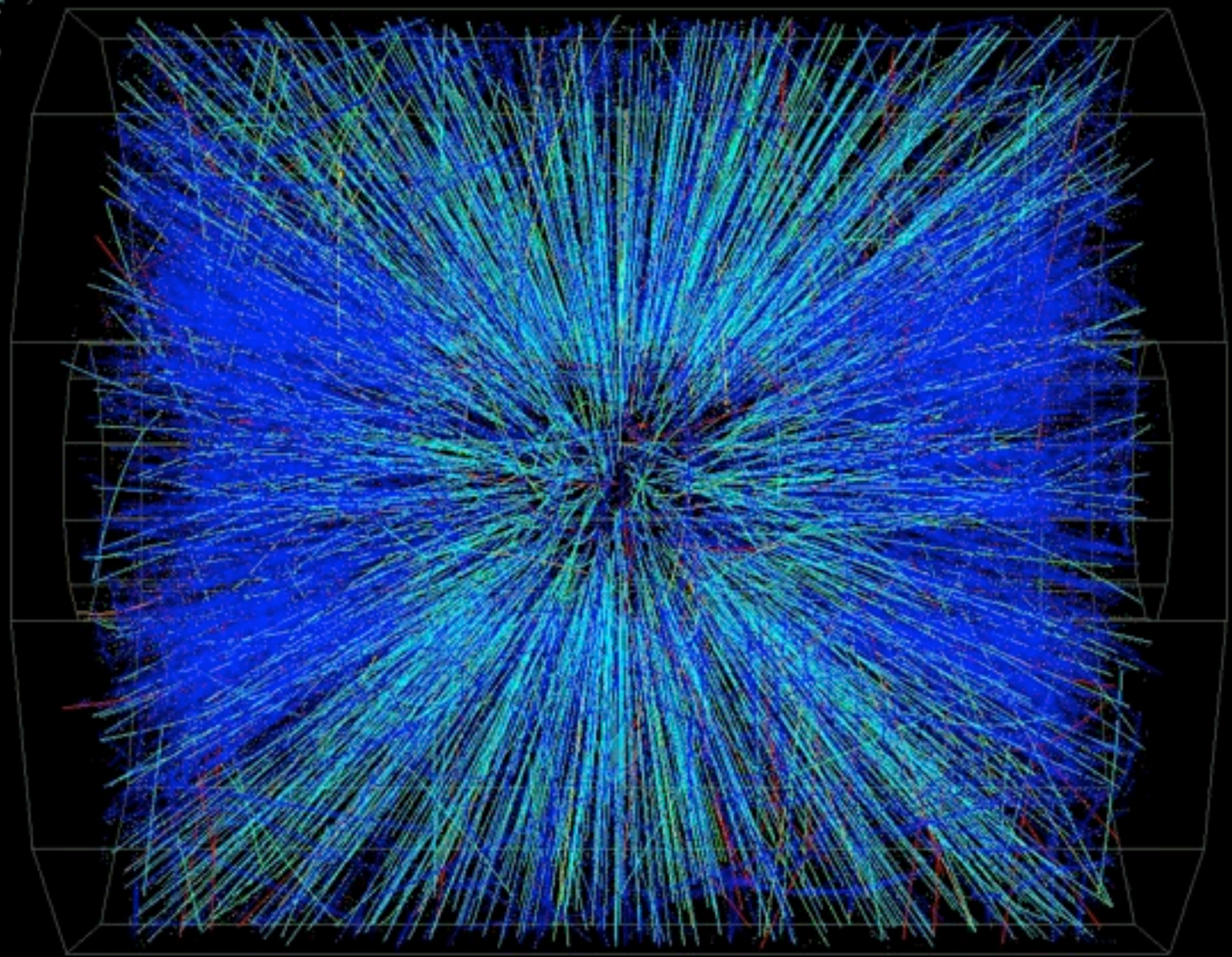


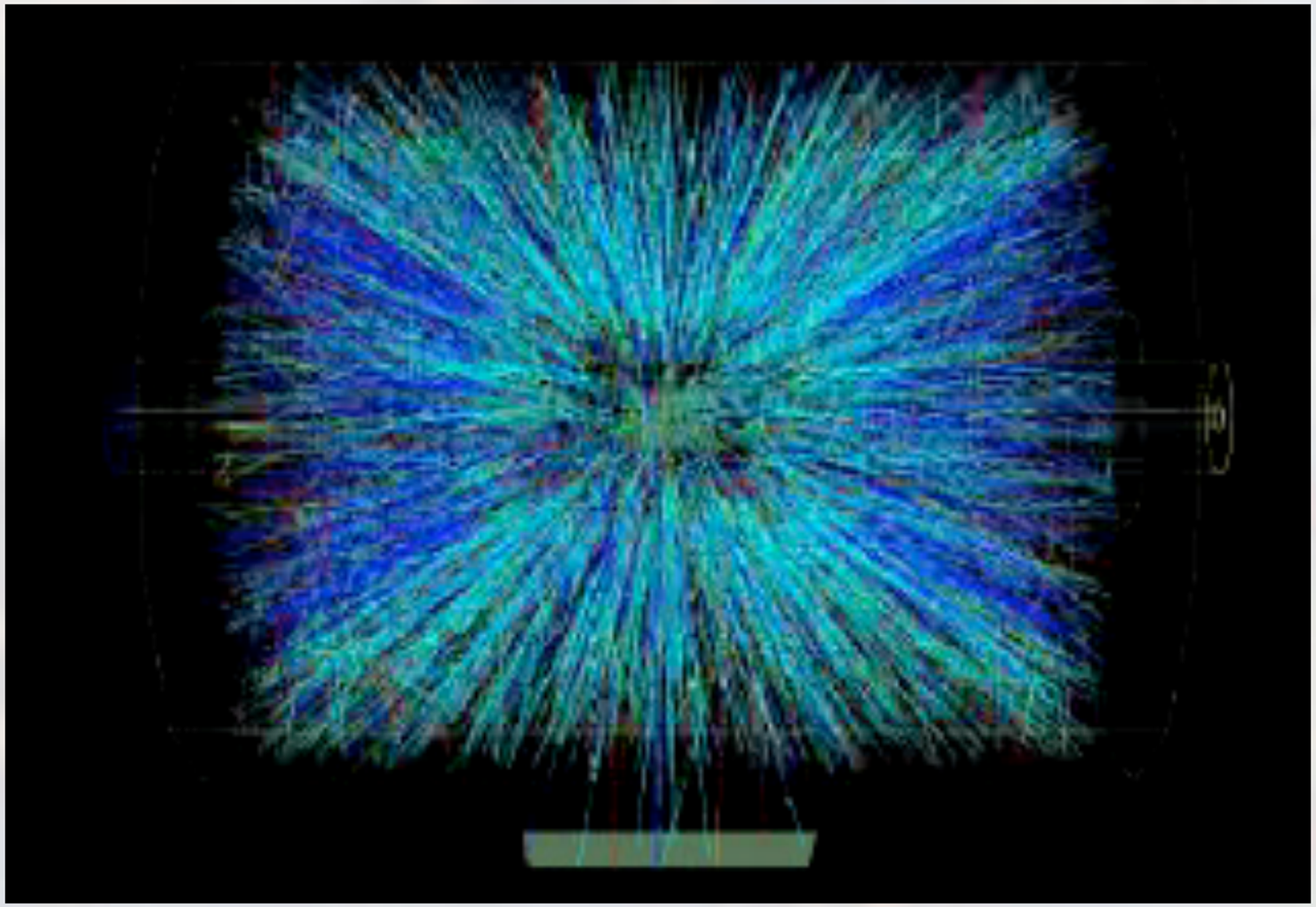


Central Event

From real-time Level 3 display.

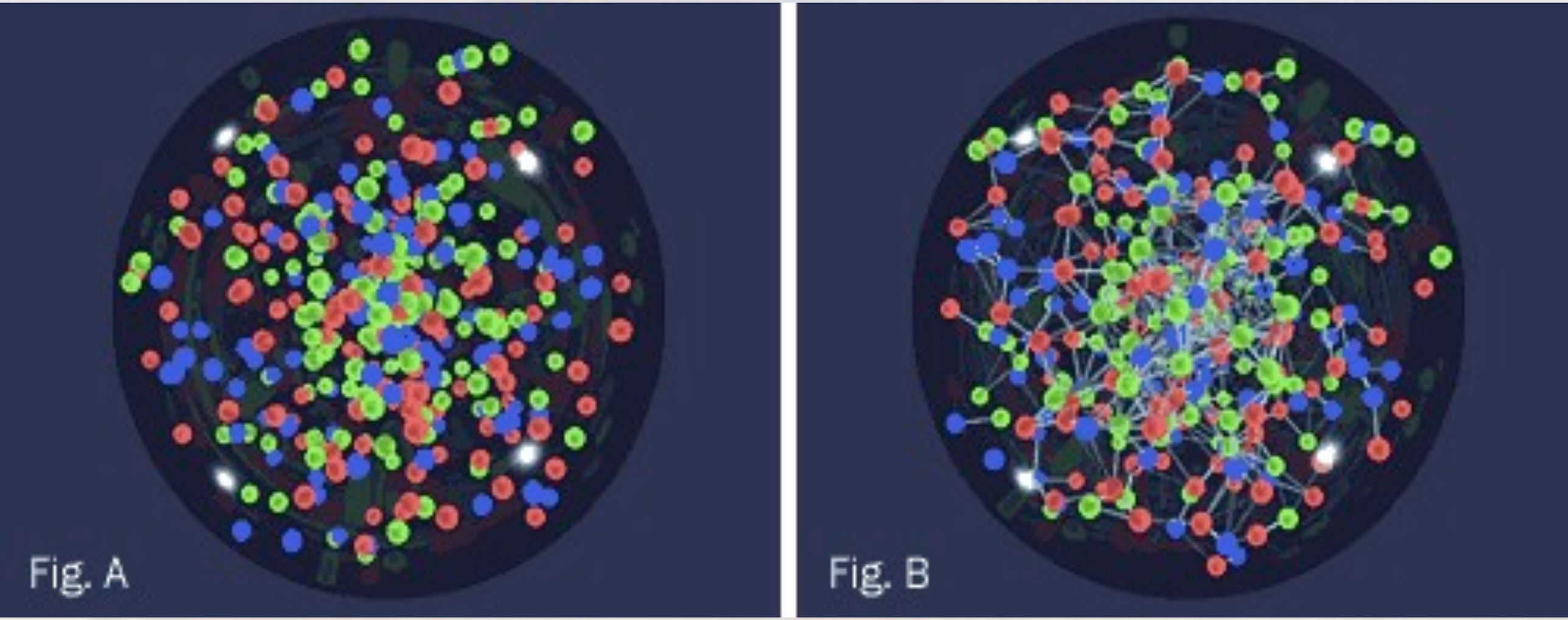


STAR event



QGP@RHIC: Gas or Liquid?

Quark-Gluon Plasma = color deconfinement
+ thermalization + ?



Local color screening ➔ deconfinement = "free" color propagation over large (>> 1 fm) distances

RHIC answer in the news

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have perv

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first m
results from an atom-smashing experiment.

New State of Matter Is 'Nearly Perfect' Liquid

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

SCIENTIFIC AMERICAN

Image: BNL

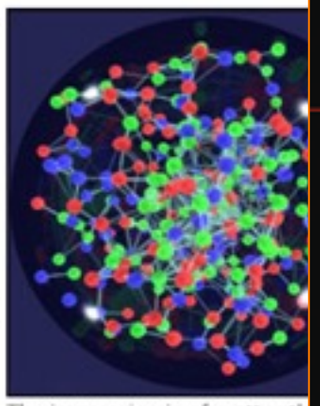
There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the

found that the particles produ

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

BBC NEWS



The impression is of matter th
more strongly interacting than
pred

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost p

社会 asahi.comトップ > 社会 > その他・話題

宇宙の始まりはしずく？ 「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは１８日、物質を形づく
が、気体のよ
態にあったと
宇宙や物質の
ある。

Science

Iran Daily April 20, 2005 4

niverse Liquid-Lik

gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that

happens in a black hole and what goes on when two gold nuclei collide at RHIC.

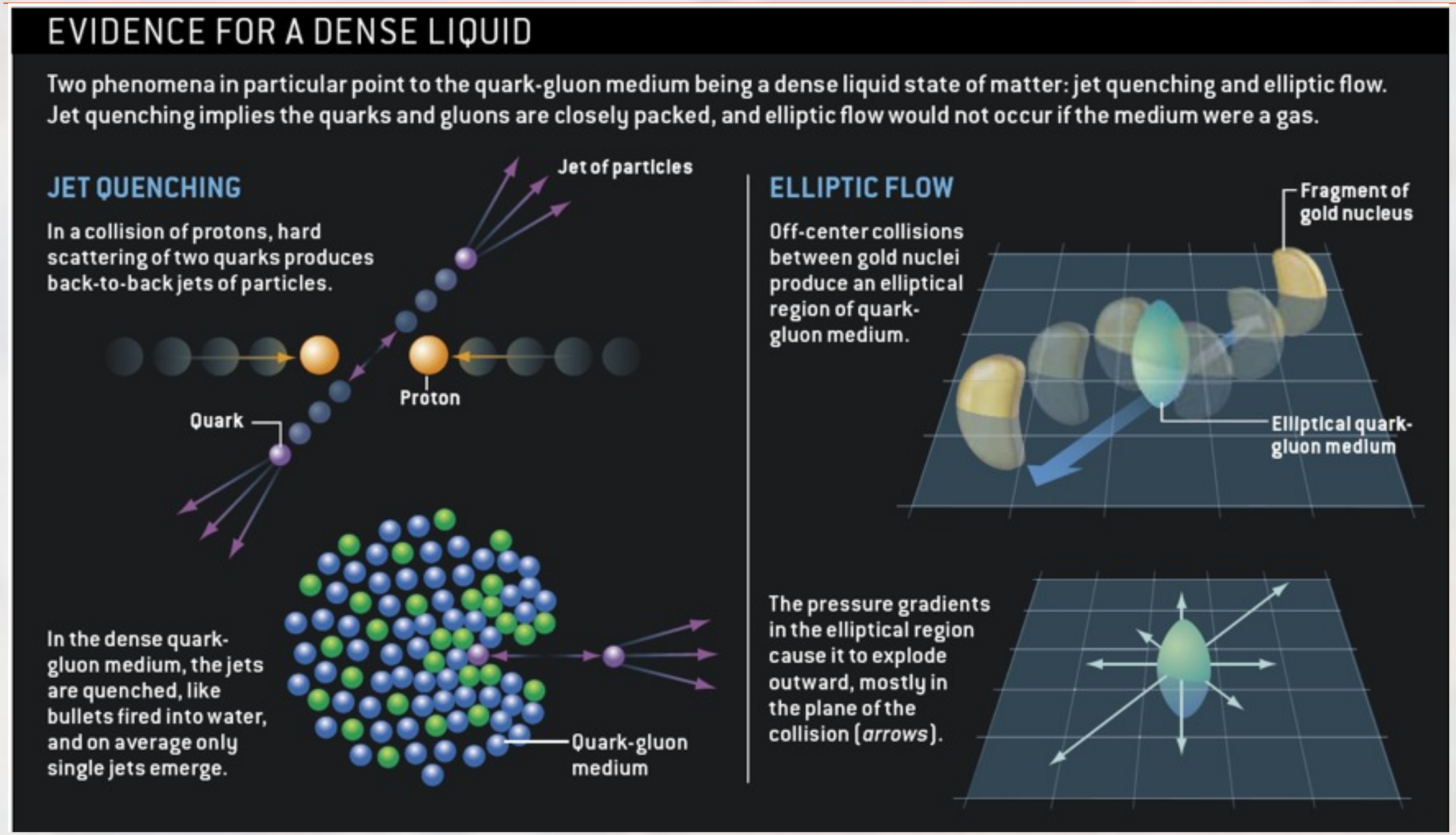
offers opportunities to exciting questions," said smashed the nuclei of

Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

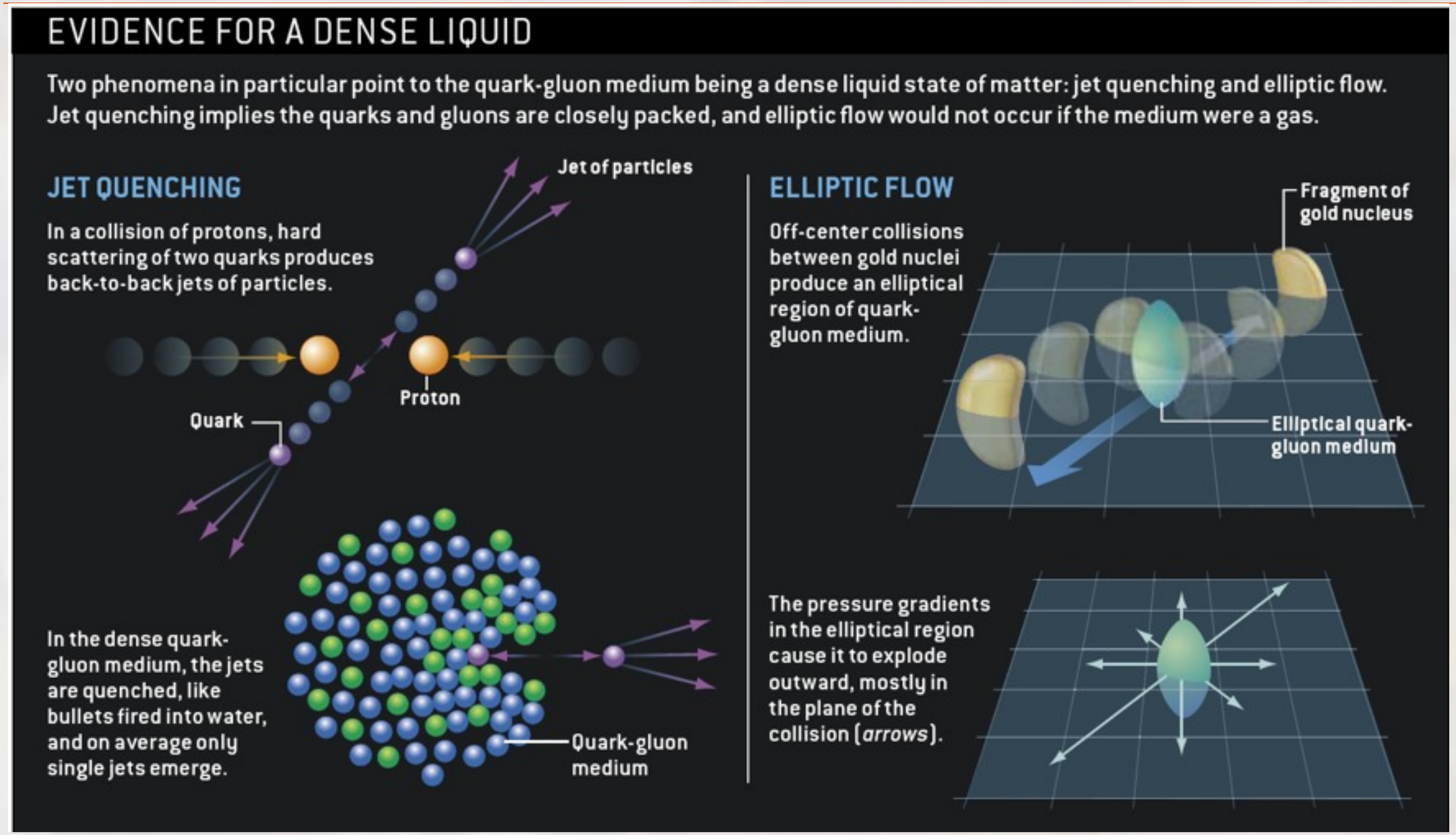
Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Major RHIC discoveries



"The physical picture emerging from the four (RHIC) experiments is consistent and surprising. The quarks and gluons indeed break out of confinement and behave collectively, if only fleetingly. But this hot mélange acts like a liquid, not the ideal gas theorists had anticipated."
M. Riordan, W. Zajc, Sci. Am., May 2006, 34-41.

Major RHIC discoveries



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M. Riordan, W. Zajc, Sci. Am., May 2006, 34-41.

Three major RHIC discoveries (my view):

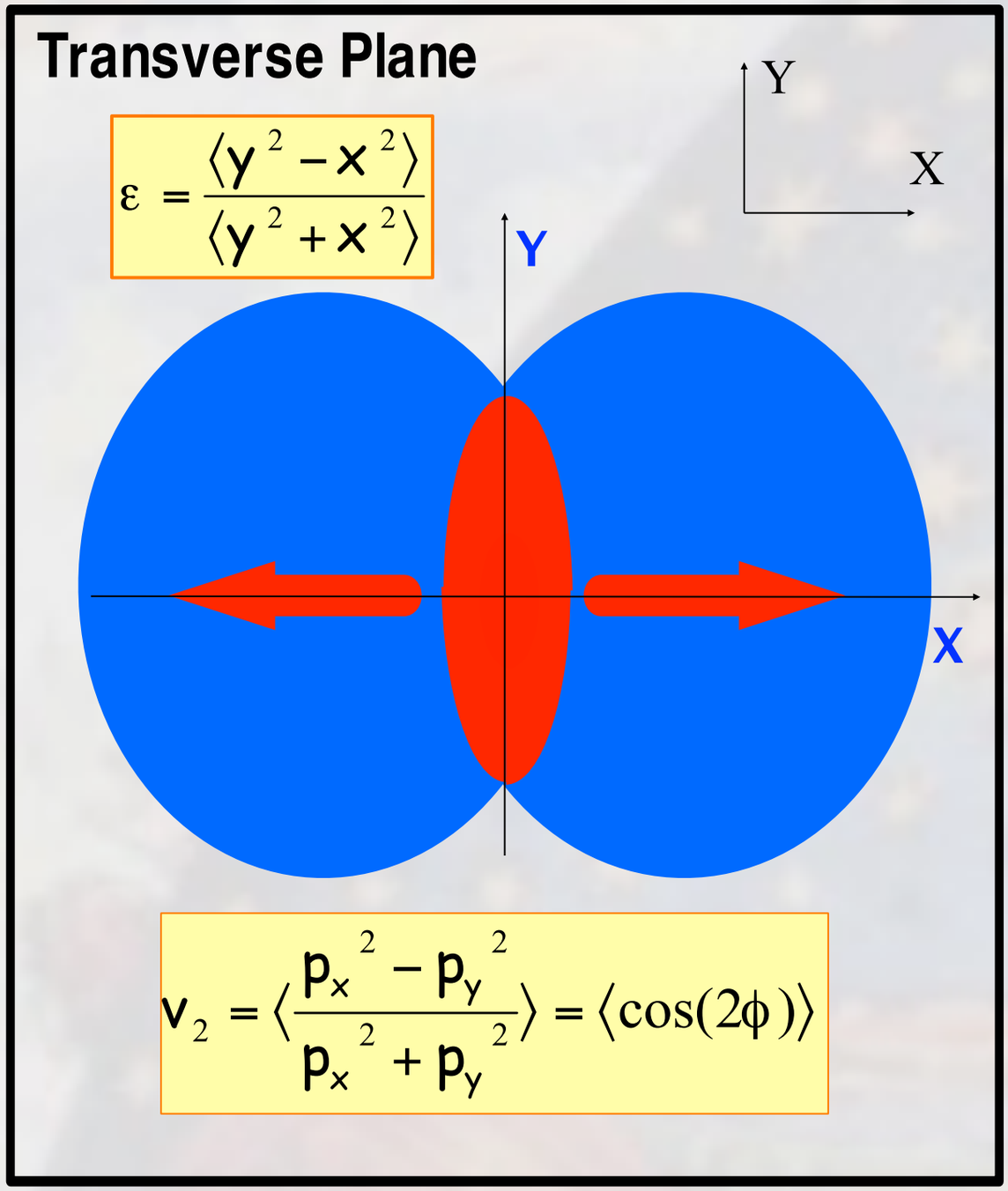
1. Large elliptic flow SV, Poskanzer, Snellings (STAR)
2. Jet quenching
3. Constituent quark scalingSV, QM2002

Note the importance of item #3, "partonic flow" -> deconfinement !).

At present, we are in the second phase of RHIC – quantitative understanding of sQGP

Elliptic Flow

XZ-plane - the reaction plane

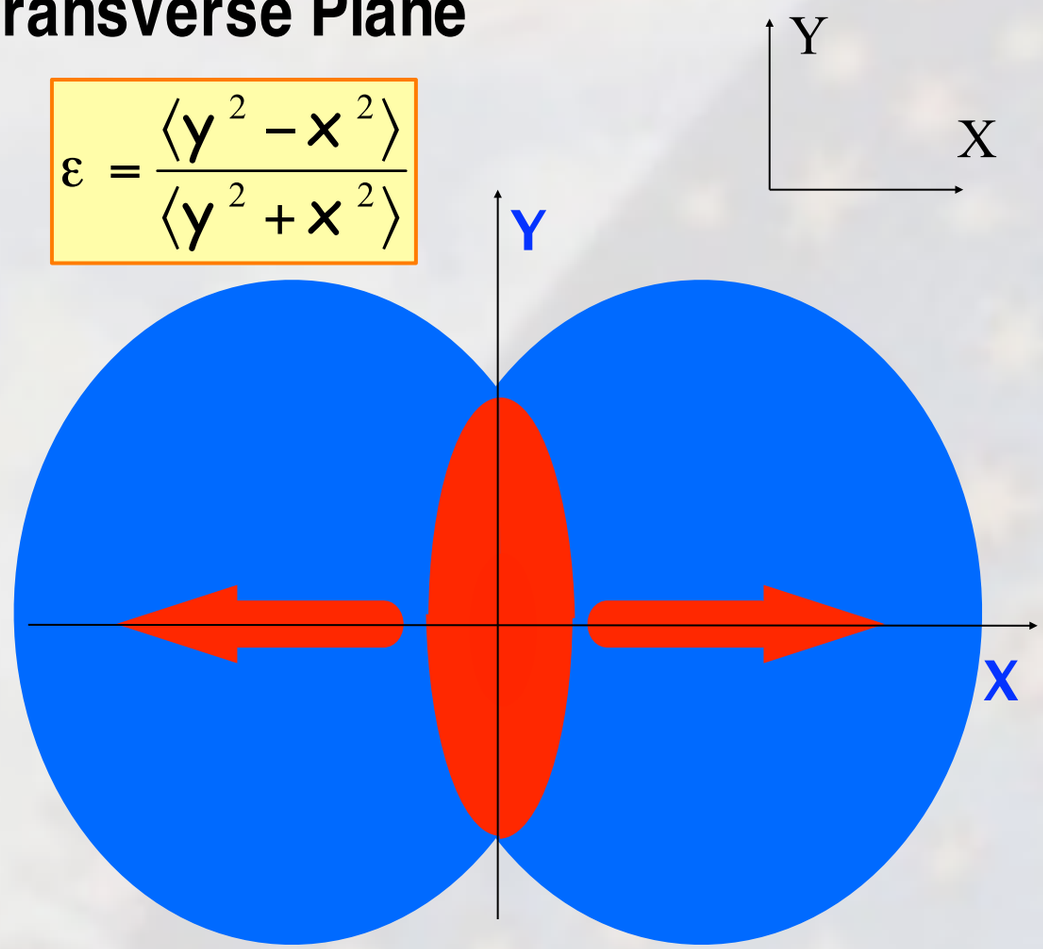


Elliptic Flow

XZ-plane - the reaction plane

Transverse Plane

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

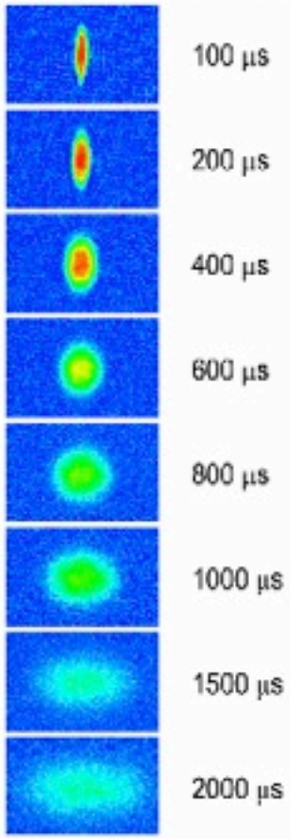


$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos(2\phi) \rangle$$

Elliptic flow with trapped Li^6 atoms:

K.M.O'Hara et al, Science 298,2179, 2002

T.Bourdel et al, PRL 91 020402 , July 11 2003



Magnetic field $B \sim 800G$ shifts (via the Feschbach resonance $|f = 1/2, m_f = 1/2 > <=> |f = 1/2, m_f = -1/2 >$) and makes the 38-th vibrational Li_2 state to exactly zero energy => infinite scattering length a, very large size and lifetime ~ 1 sec.

Normally gas is transparent, $l \ll L$, and expands without collisions isotropically

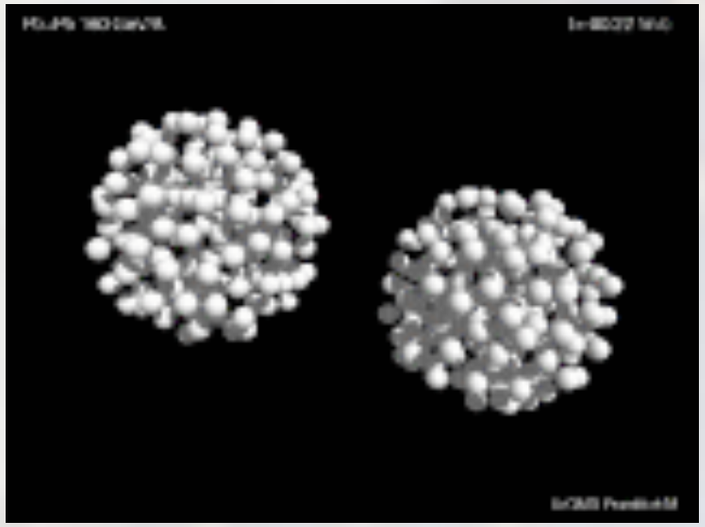
But in the strong coupling regime $l \ll L$ it explodes hydrodynamically !, see the figure

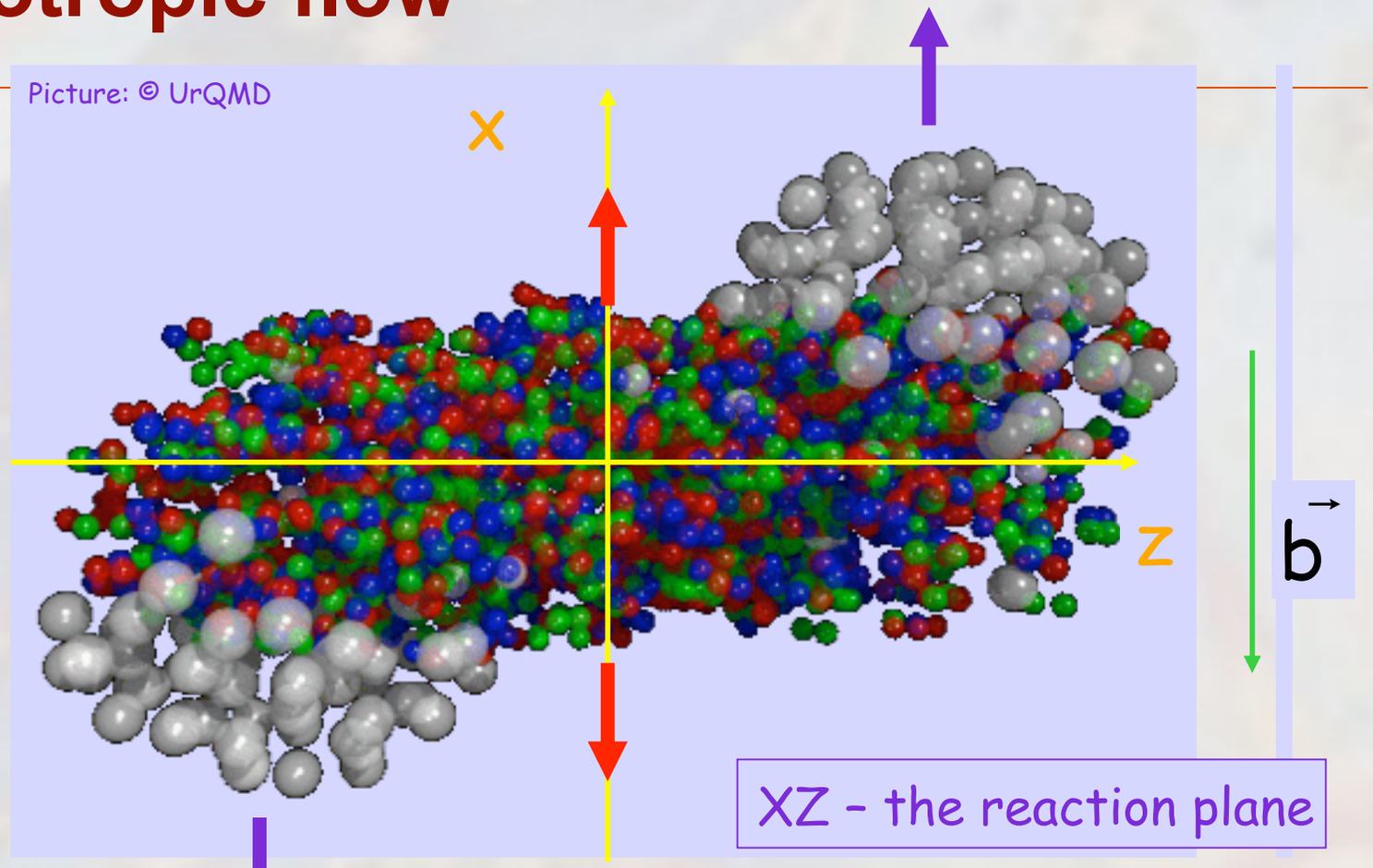
Cross section can be changed by many orders of magnitude, but the EoS changes by $\sim 20\%$ only ! (like in QGP and CFT... why?)

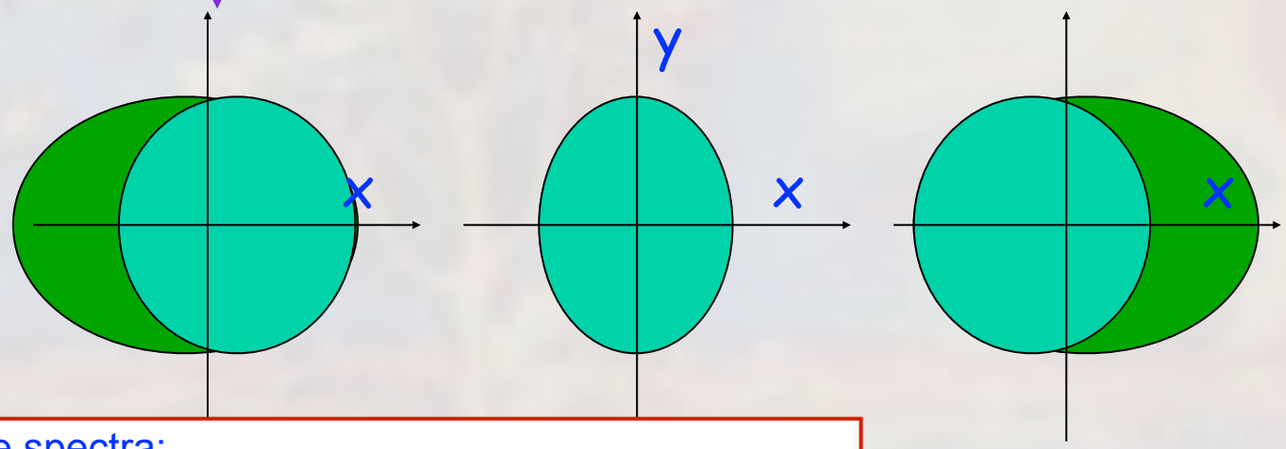
Anisotropic flow

Anisotropic flow ≡correlations with respect to the reaction plane

Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior ←→ multiparticle azimuthal correlation.







Fourier decomposition of single particle (semi) inclusive spectra:

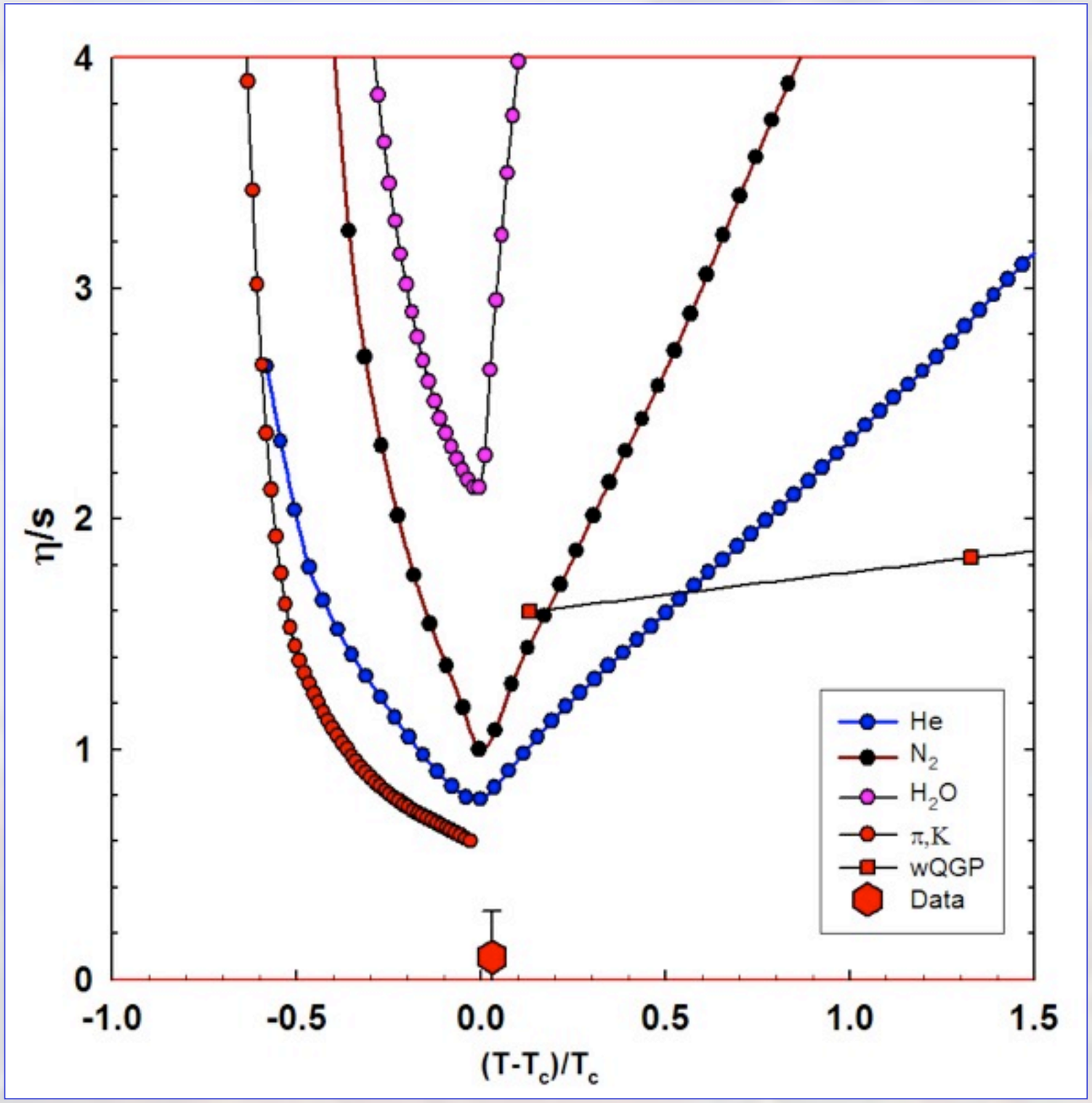
$$\frac{d^3N}{dp_t\,dy\,d\Delta\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + \ldots\right)$$

Directed flow

Elliptic flow

S.V., Y. Zhang
hep-ph/9407282
Z.Phys. C70 (1996) 665

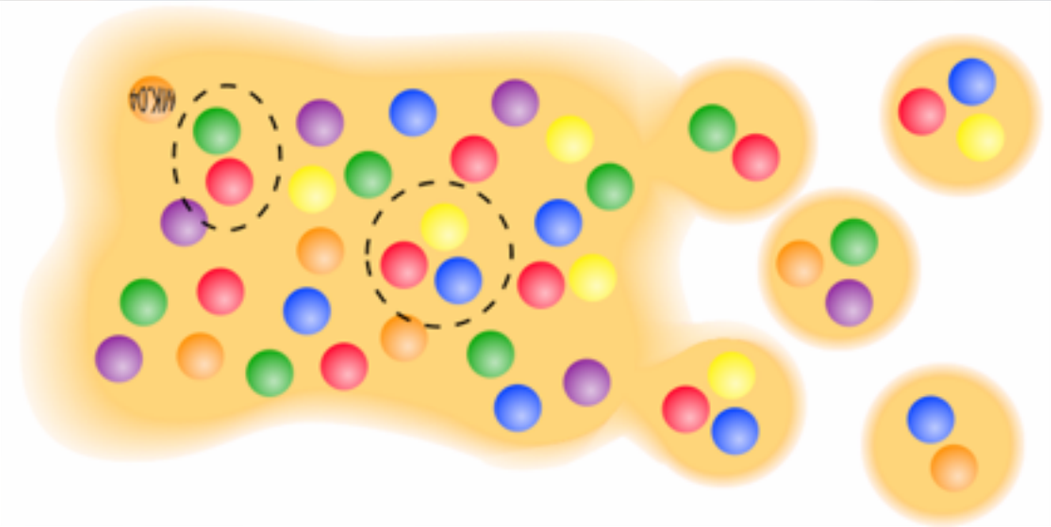
Shear viscosity / entropy density



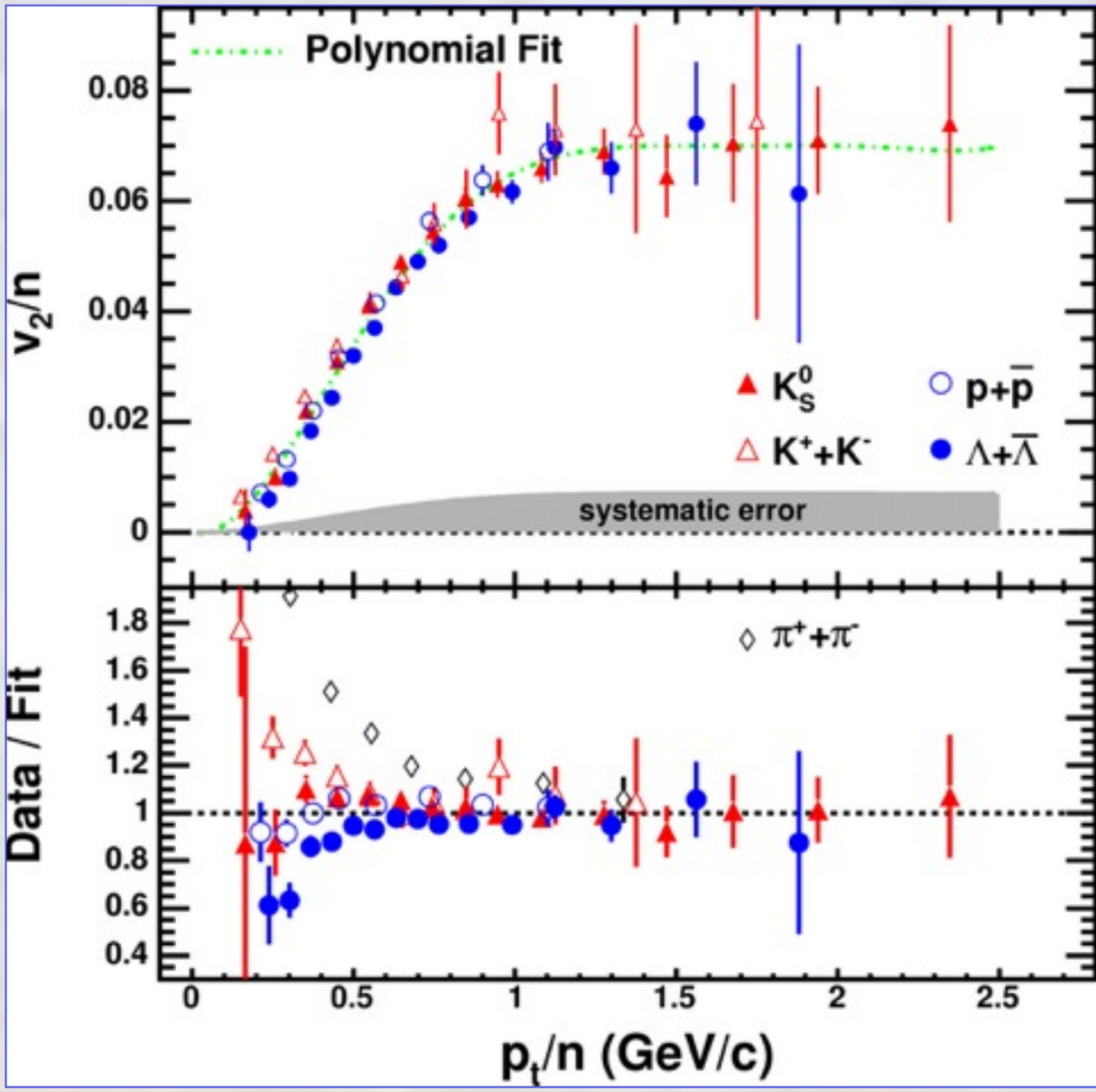
Shear viscosity to the entropy density ratio close to the low quantum limit --> “perfect liquid”

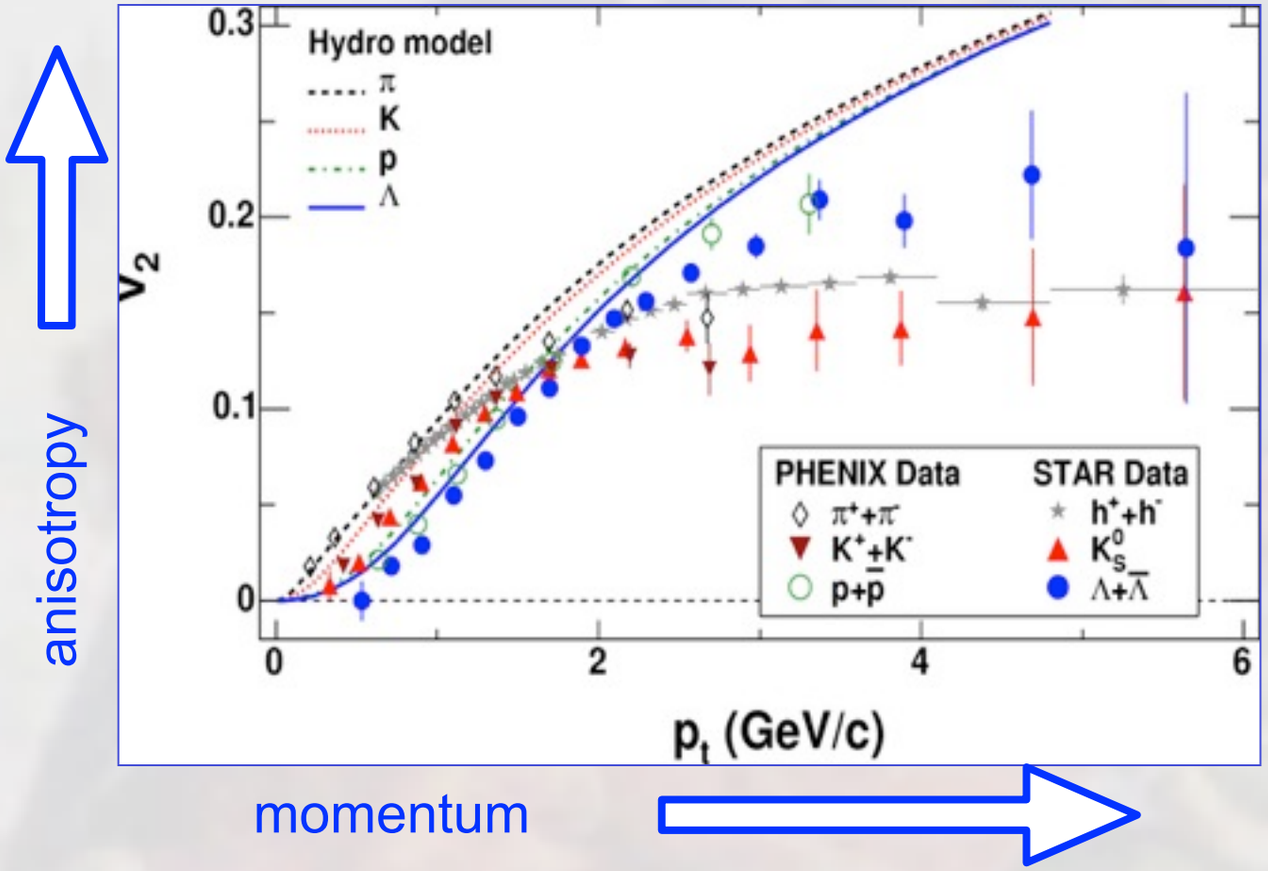
Elliptic flow: number of quarks scaling

S.V., QM2002
D. Molnar, S.V., PRL 2003



STAR PRL 92(2004)052302



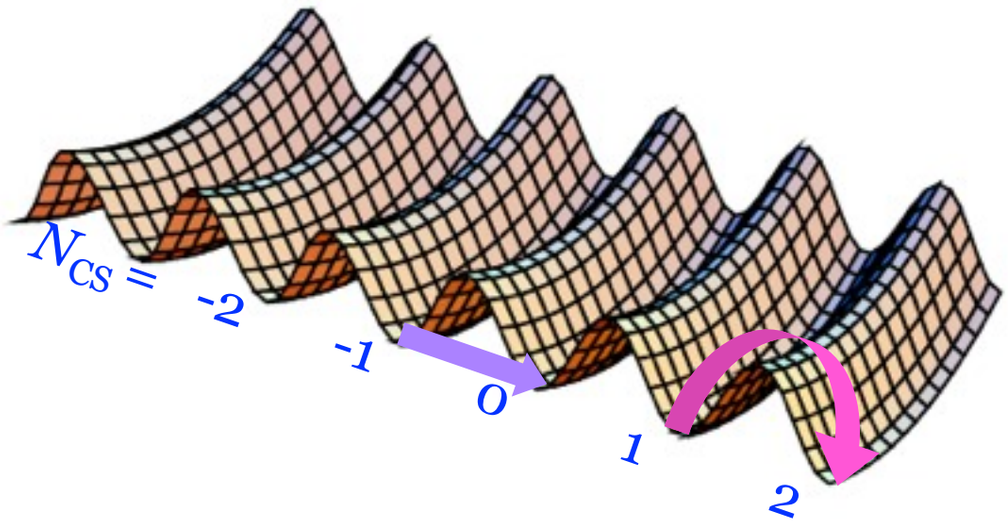


Constituent quark scaling holds very well.
Deviations are where expected.

Gas of constituent quarks – **deconfinement !**

QCD vacuum

Energy of gluonic field is periodic in N_{CS} direction (~ a generalized coordinate) and oscillatory in other directions



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vaccua via tunneling or go-over-barrier

Chern-Simons number

$$N_{CS} = \frac{1}{16\pi^2}\int d^3\mathbf{x}\,\epsilon_{ijk}\left(A_i^a\partial_j A_k^a + \frac{1}{3}\epsilon^{abc}A_i^a A_j^b A_k^c\right)$$

winding number

$$A_i \to U^\dagger A_i U + iU^\dagger\partial_i U, \quad A_i \equiv A_i^a\frac{\tau^a}{2},$$

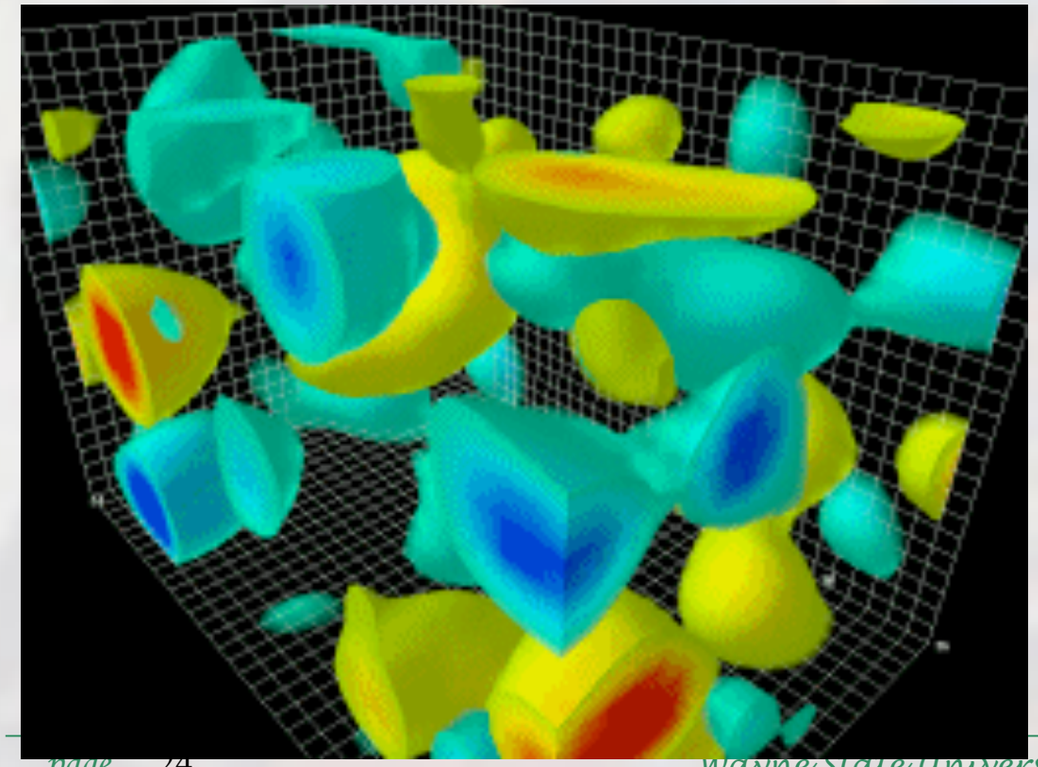
$$N_W = \frac{1}{24\pi^2}\int d^3\mathbf{x}\,\epsilon_{ijk}\left[(U^\dagger\partial_i U)(U^\dagger\partial_j U)(U^\dagger\partial_k U)\right].$$

$$N_{CS} \to N_{CS} + N_W$$

topological charge

$$Q_T = \frac{1}{32\pi^2}\int d^4x\, F_{\mu\nu}^a\tilde{F}_{\mu\nu}^a, \quad \tilde{F}_{\mu\nu}^a \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F_{\alpha\beta}^a.$$

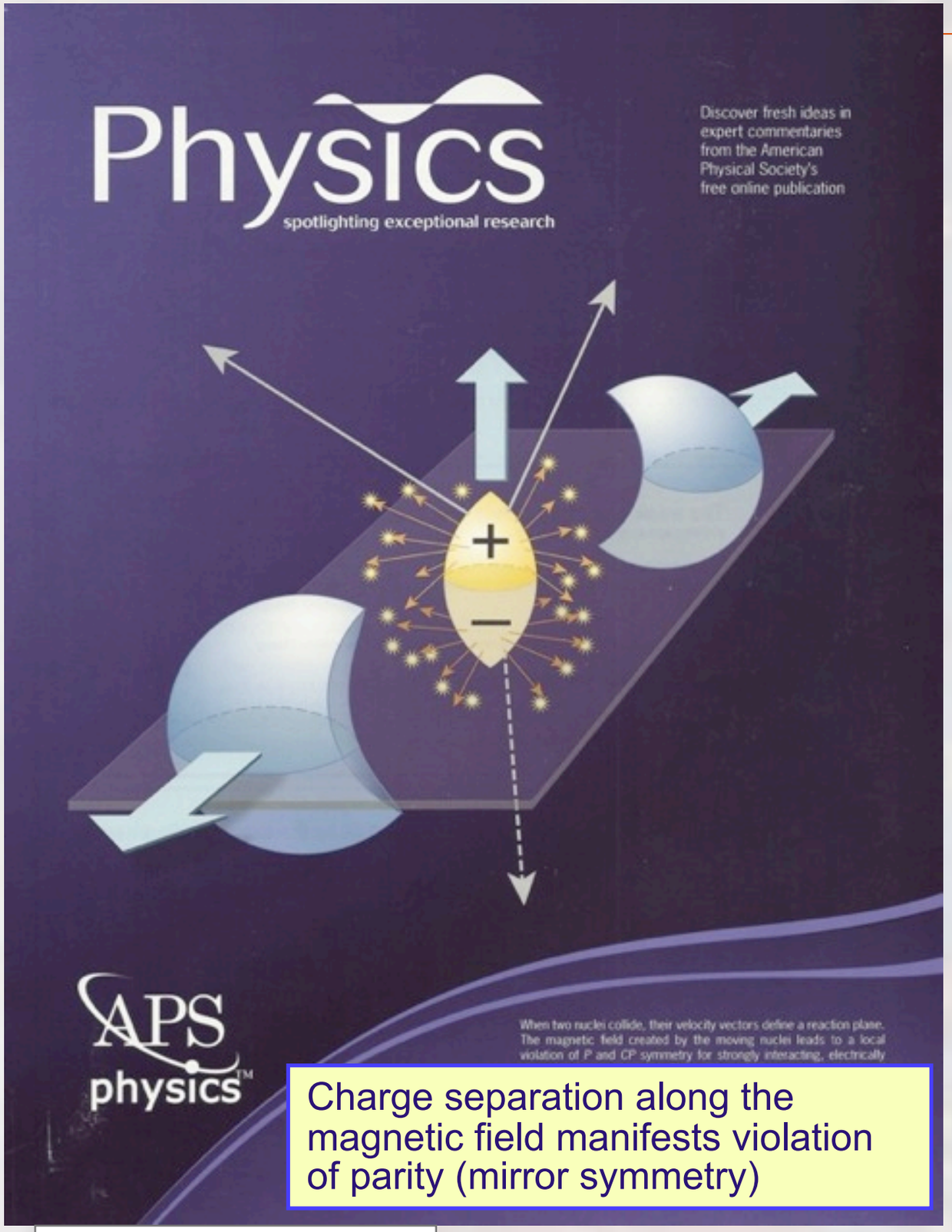
$$Q_T = N_{CS}(+\infty) - N_{CS}(-\infty).$$



The volume of the box is 2.4 by 2.4 by 3.6 fm.
The topological charge density
Animation be *Derek Leinweber*

Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS).
An observation of the *local strong* parity violation would be a clear proof for the existence of such physics.

Search for the Chiral Magnetic Effect

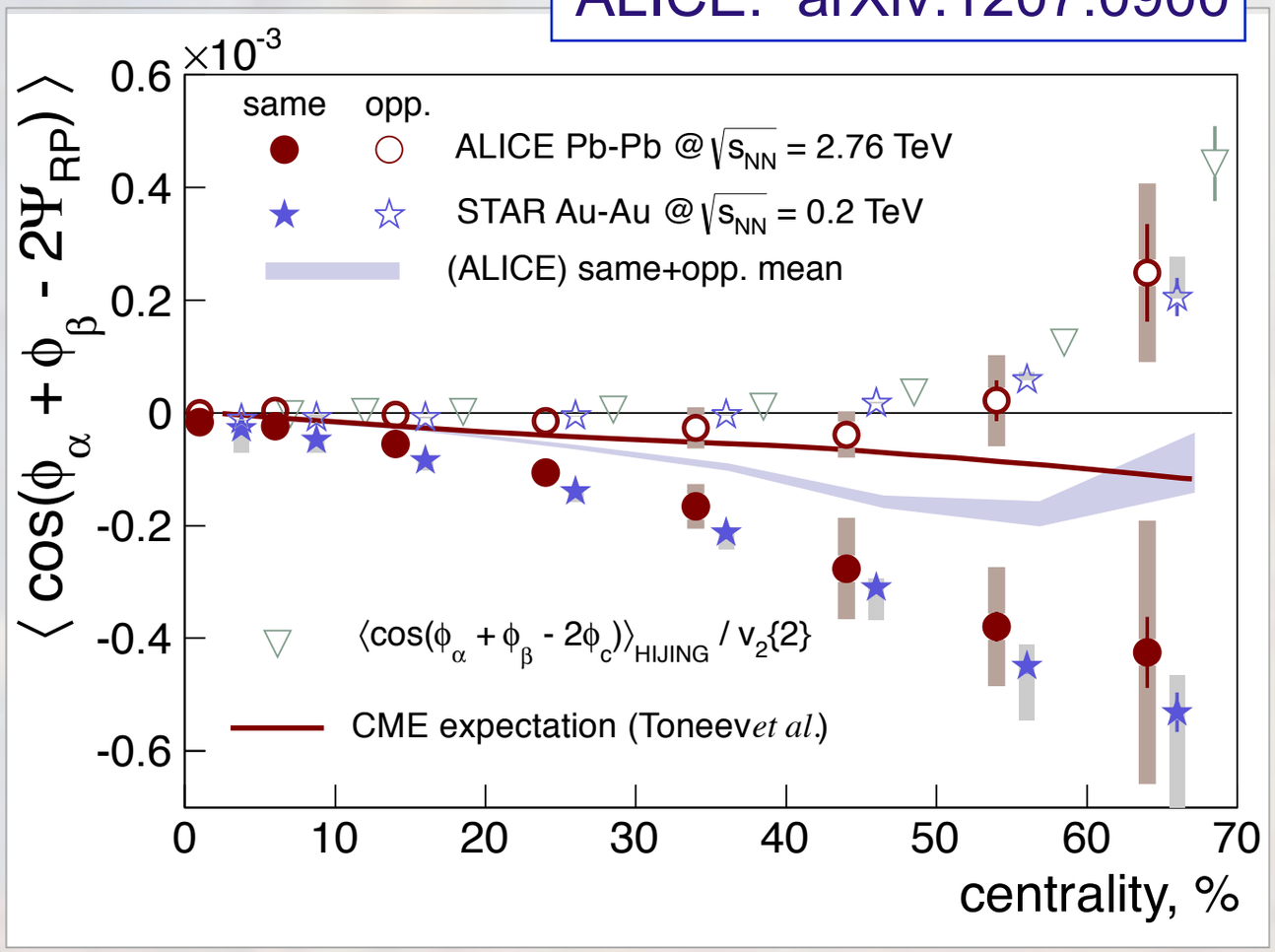


Charge separation along the magnetic field manifests violation of parity (mirror symmetry)

Kharzeev, PLB633 260 (2006))

Voloshin, PRC70 057901 (2004)

ALICE: arXiv:1207:0900



ALICE: charge dependent correlations qualitatively consistent with CME, and similar in strength to those observed by STAR.

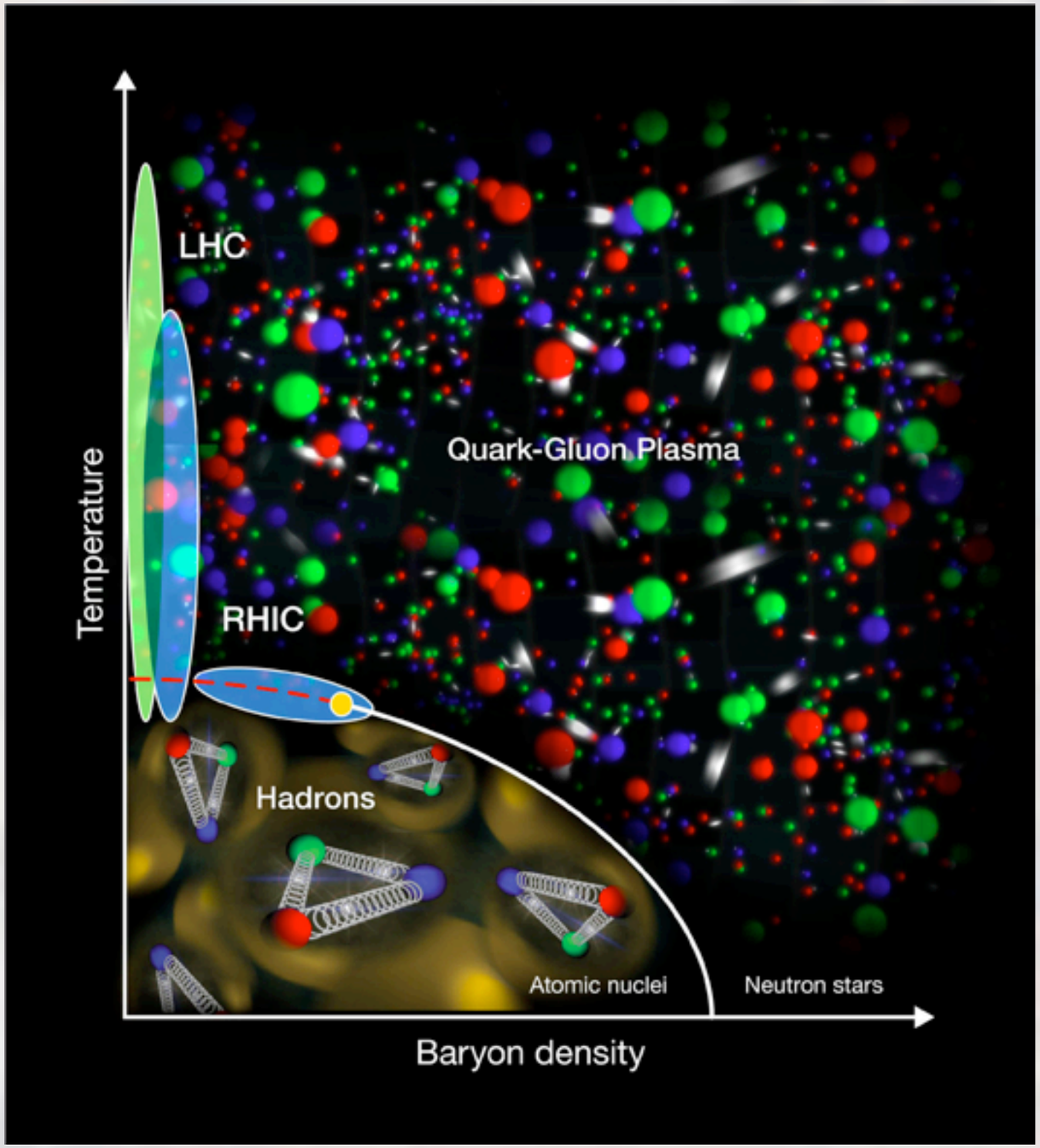
No model can reproduce the signal.

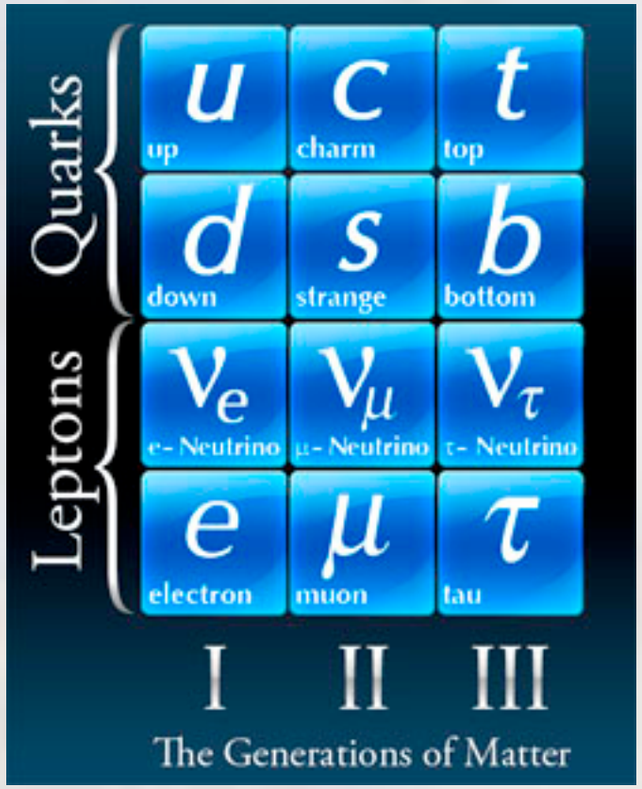
Thank you !

Acknowledgement:
Data Particle Group (LBNL)
CERN
BNL


WHERE THE
WEB
WAS BORN
In the offices of this corridor, all the fundamental technologies of the World Wide Web were developed.
Started in 1990 from a proposal made by Tim Berners-Lee in 1989, the effort was first divided between an office in building 31 of the Computing and Networking Division (CN) and one in building 2 of the Electronics and Computing for Physics Division (ECP).
In 1991 the team came together in these offices, then belonging to ECP. It was composed of two CERN staff members, Tim Berners-Lee (GR) and Robert Cailliau (BE), aided by a number of Fellows, Technical Students, a Coopérant and Summer Students.
At the end of 1994 Tim Berners-Lee left CERN to direct the WWW Consortium (W3C), a world-wide organization devoted to leading the Web to its full potential. The W3C was founded with the help of CERN, the European Commission, the Massachusetts Institute of Technology (MIT), the Institut National pour la Recherche en Informatique et en Automatique (INRIA), and the Advanced Research Projects Agency (ARPA).
In 1995 Tim Berners-Lee and Robert Cailliau received the ACM Software System Award for the World Wide Web. In 2004, Tim Berners-Lee was awarded the first Millenium Technology Prize by the Finnish Technology Award Foundation.
The CERN Library
June 2004

END


LHC
RHIC
Quark-Gluon Plasma
Temperature
Hadrons
Atomic nuclei
Neutron stars
Baryon density


Quarks
Leptons
u
up
c
charm
t
top
d
down
s
strange
b
bottom
νe
e- Neutrino
νμ
μ- Neutrino
ντ
τ- Neutrino
e
electron
μ
muon
τ
tau
I
II
III
The Generations of Matter