Jetting through the Quark Soup

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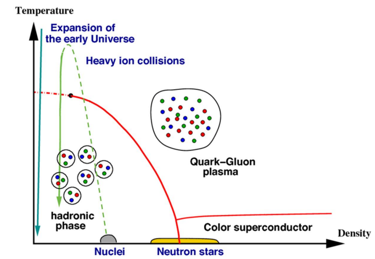
Outline

- Lecture 1
  Why do we study relativistic heavy ion collisions?
- Lecture 2
  How do we measure jets in heavy ion collisions?
- Lecture 3
  Parton energy loss and its parton flavor dependence
- Lecture 4
  Modification of jet substructure and medium response
- Lecture 5
  Open questions and future direction

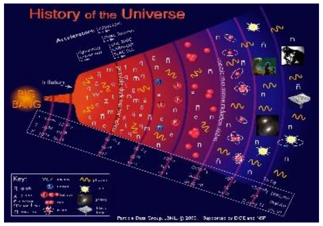
Why do we study relativistic heavy ion collisions?

WHY?

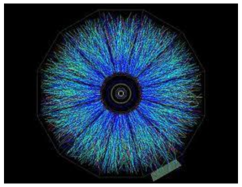
- Phase transition in QCD
  - "Melt the protons"



- Matter in the early universe: QCD in Cosmology
  - The super high temperature period which is not easily accessible by telescopes



- To study the properties of the quantum matter
  - The earliest complex condense matter to form which is hard to compute without experimental guidance

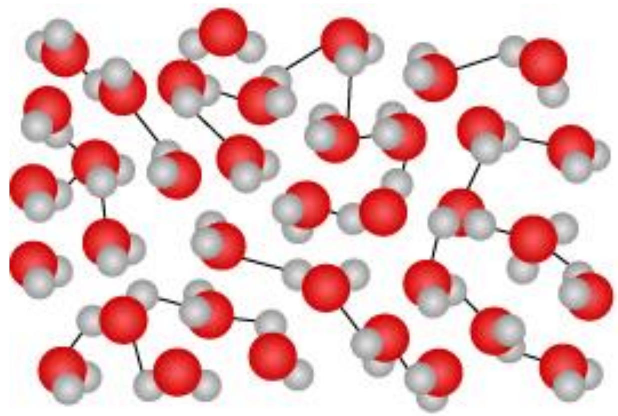


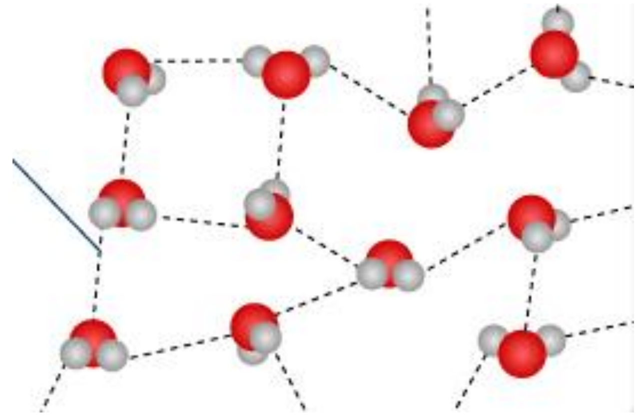
Phases of QED matter

Vapor

Water

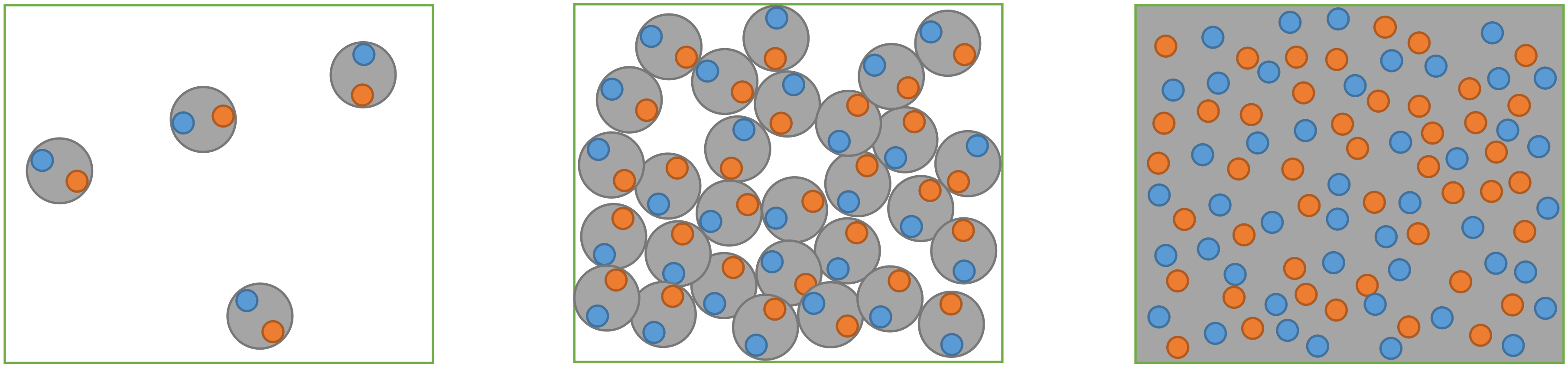
Ice





Ultra-dense QCD matter

Increase the Temperature (T)



$T<T_C$ $T \sim T_C$ $T>T_C$

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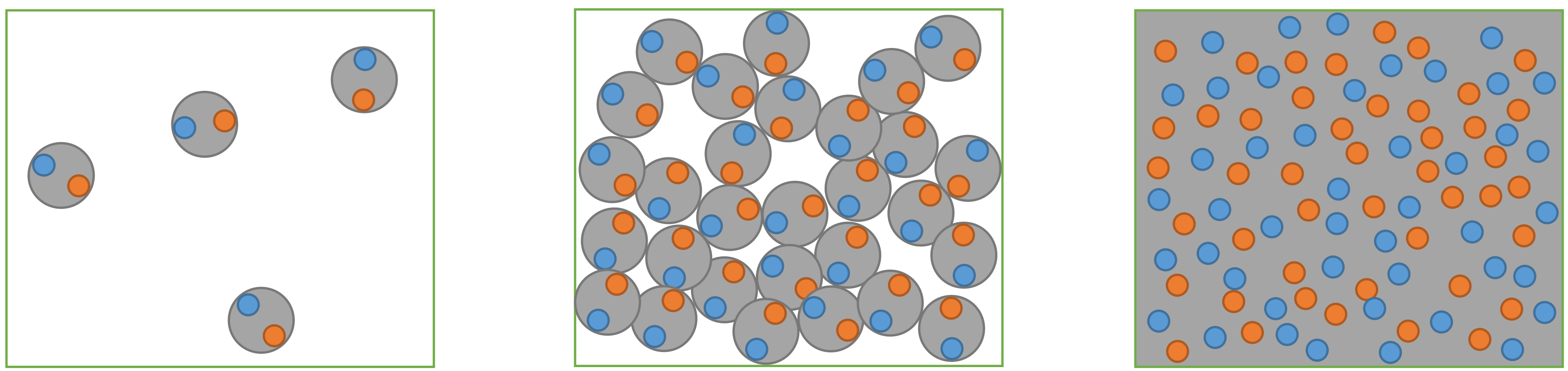
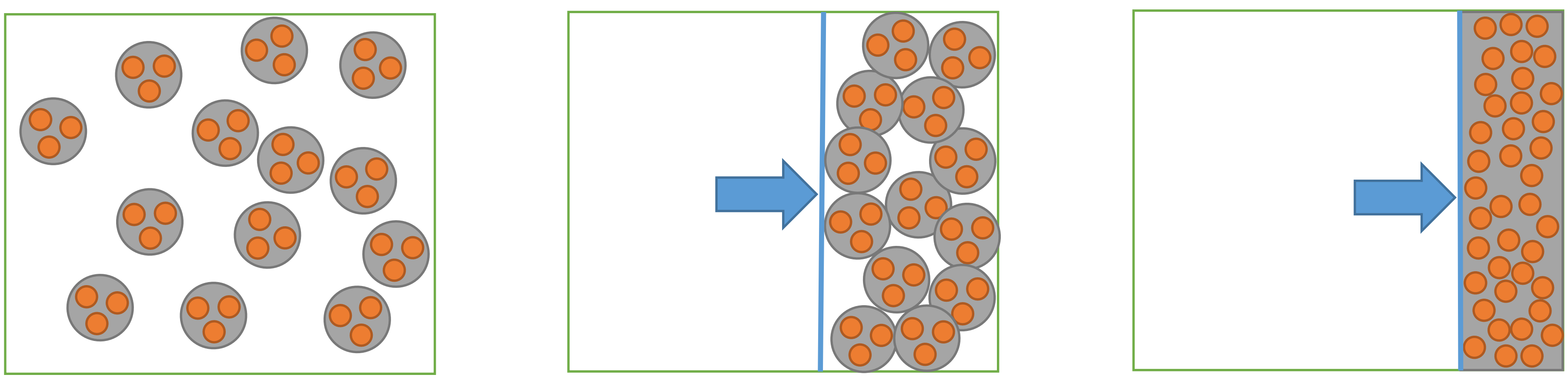


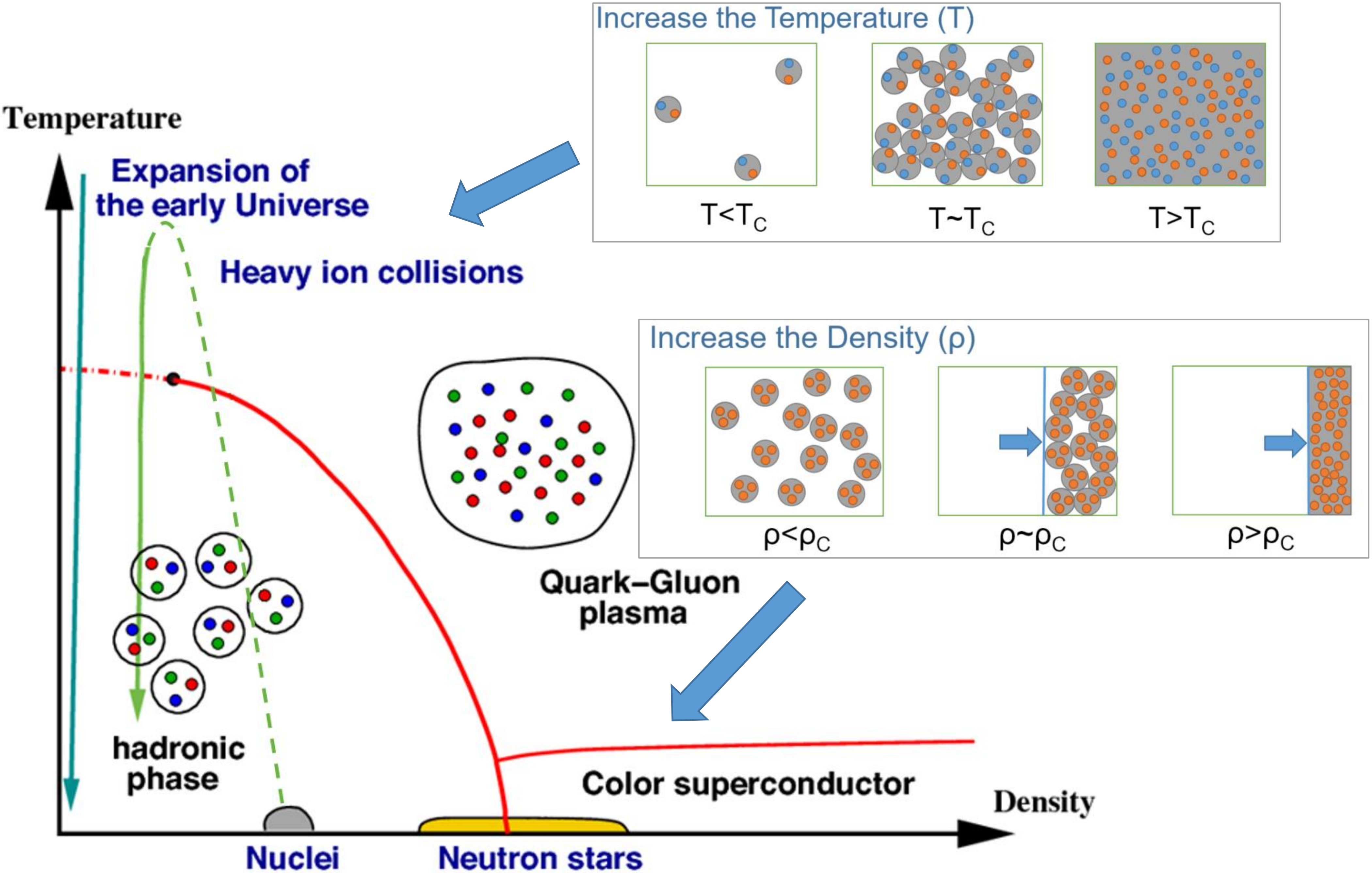
$T<T_C$ $\quad$ $T\sim T_C$ $\quad$ $T>T_C$

Increase the Density (ρ)

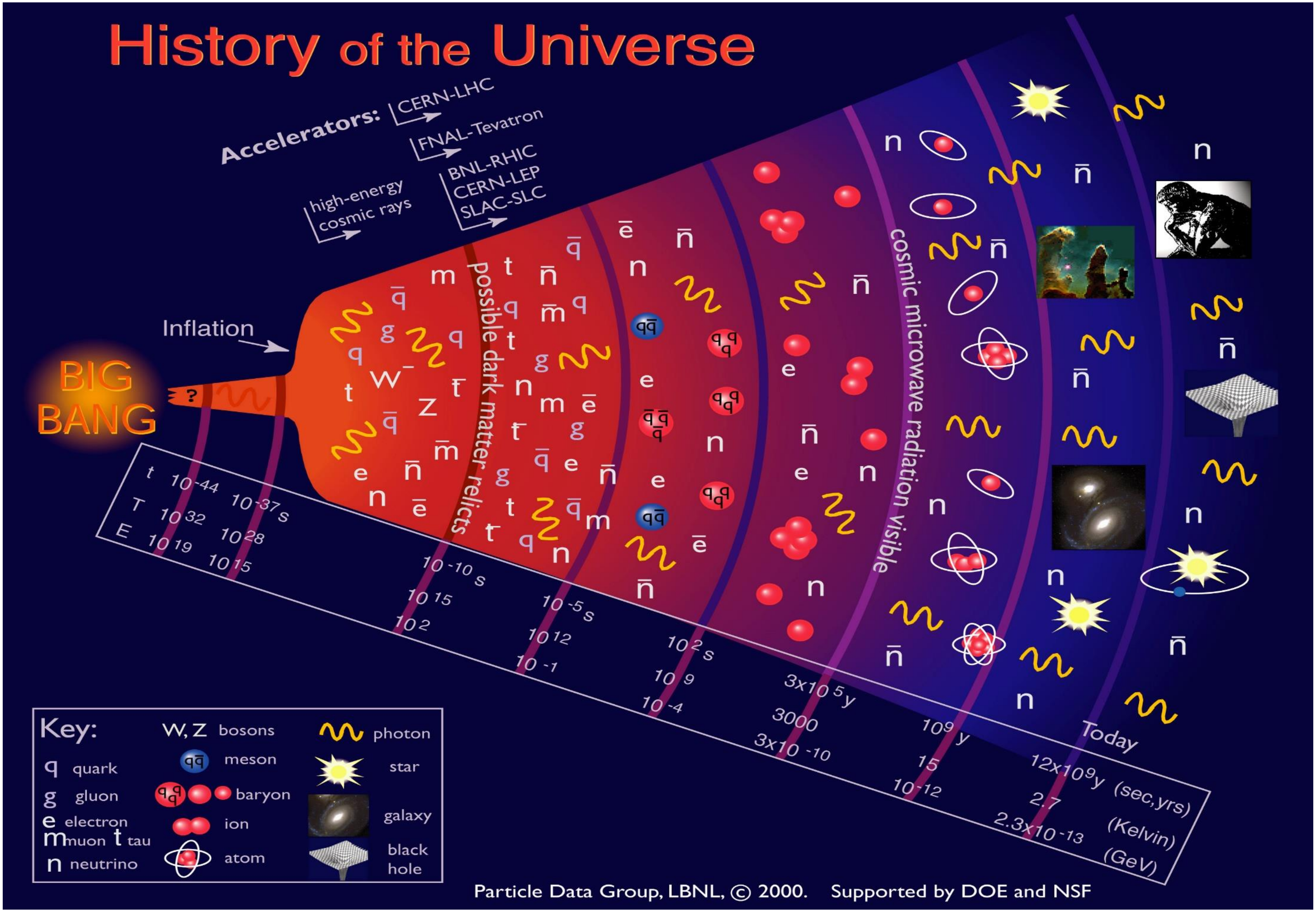


$\rho<\rho_C$ $\quad$ $\rho\sim\rho_C$ $\quad$ $\rho>\rho_C$

QCD Phase Diagram



History of the Universe



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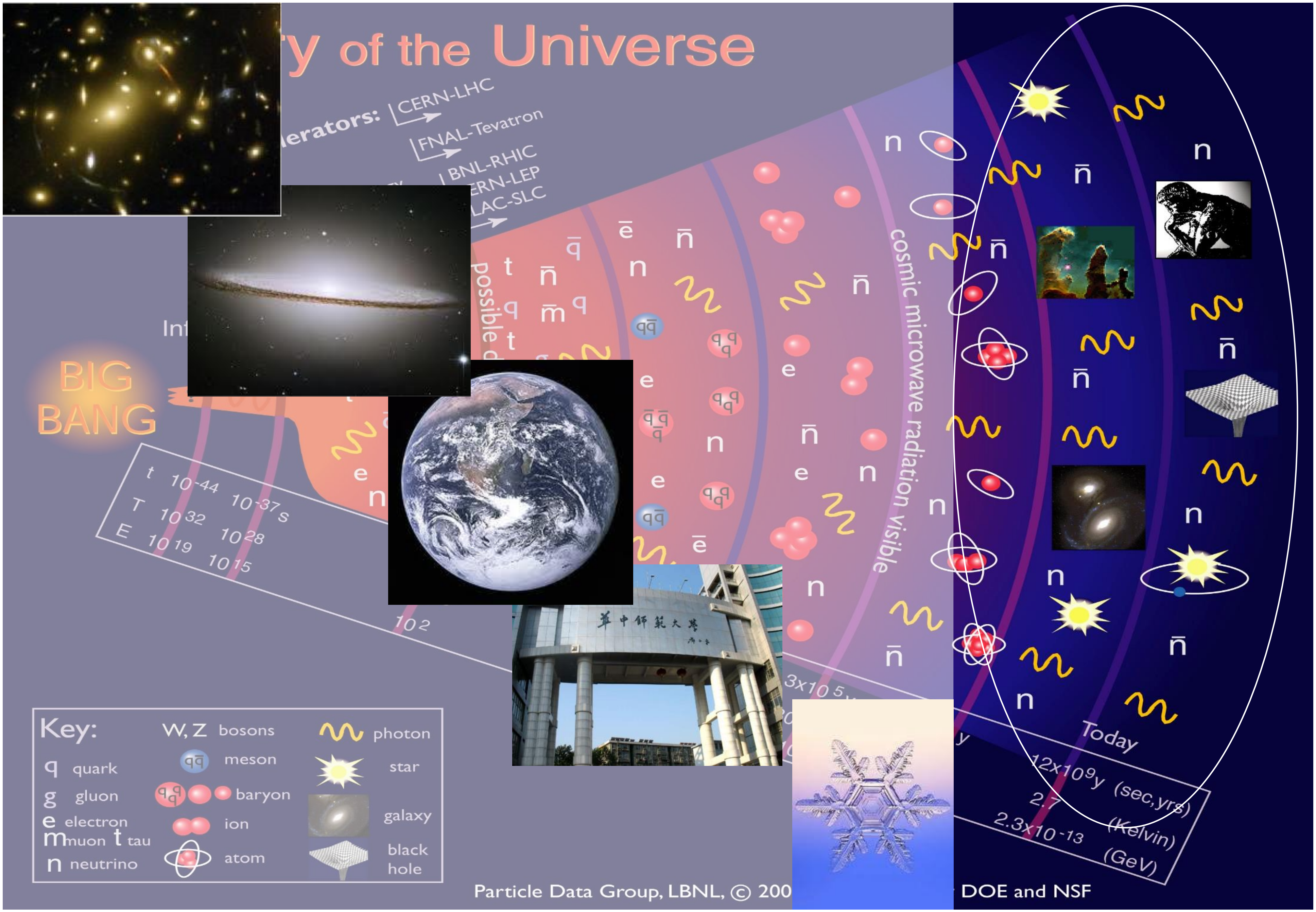

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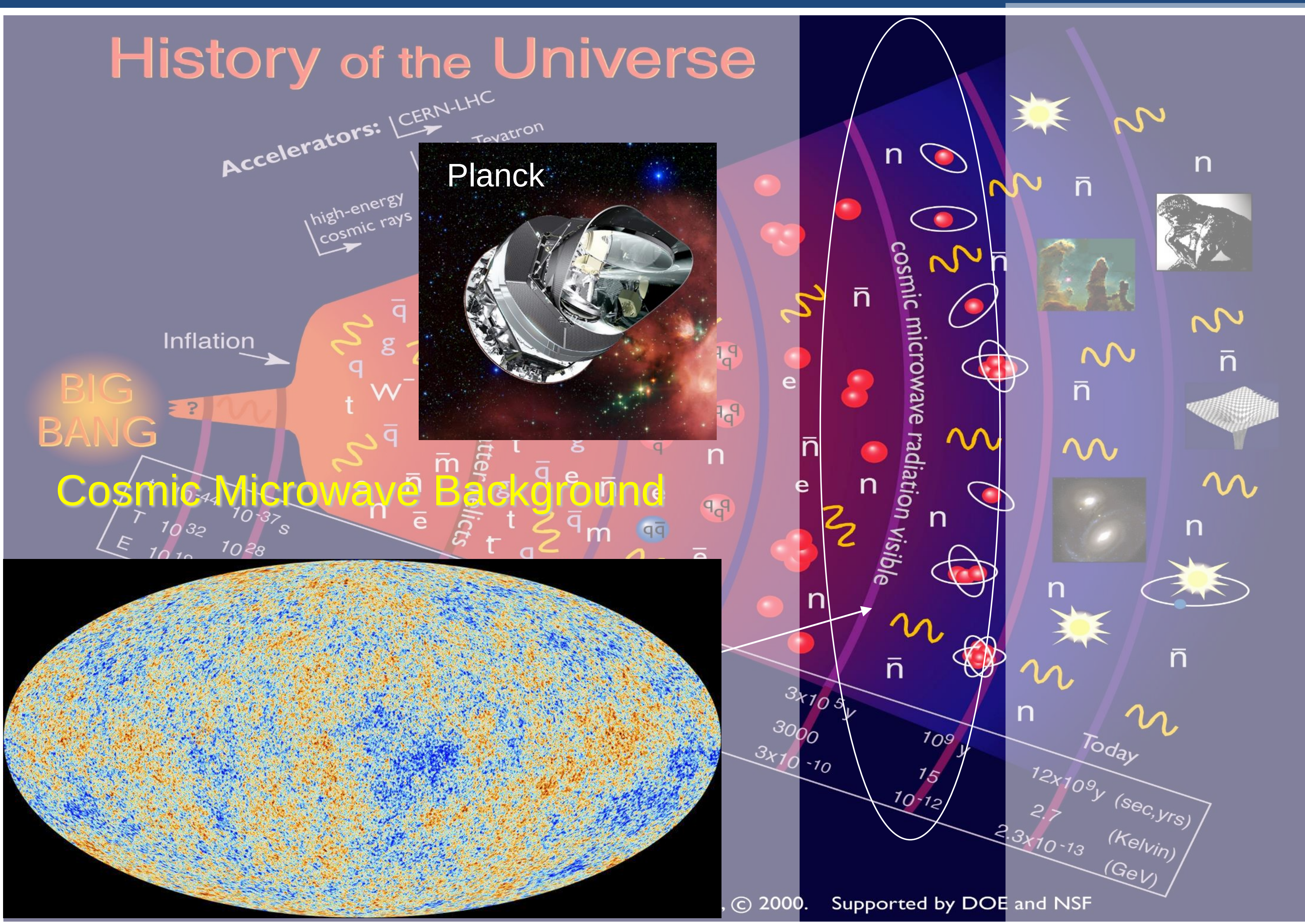

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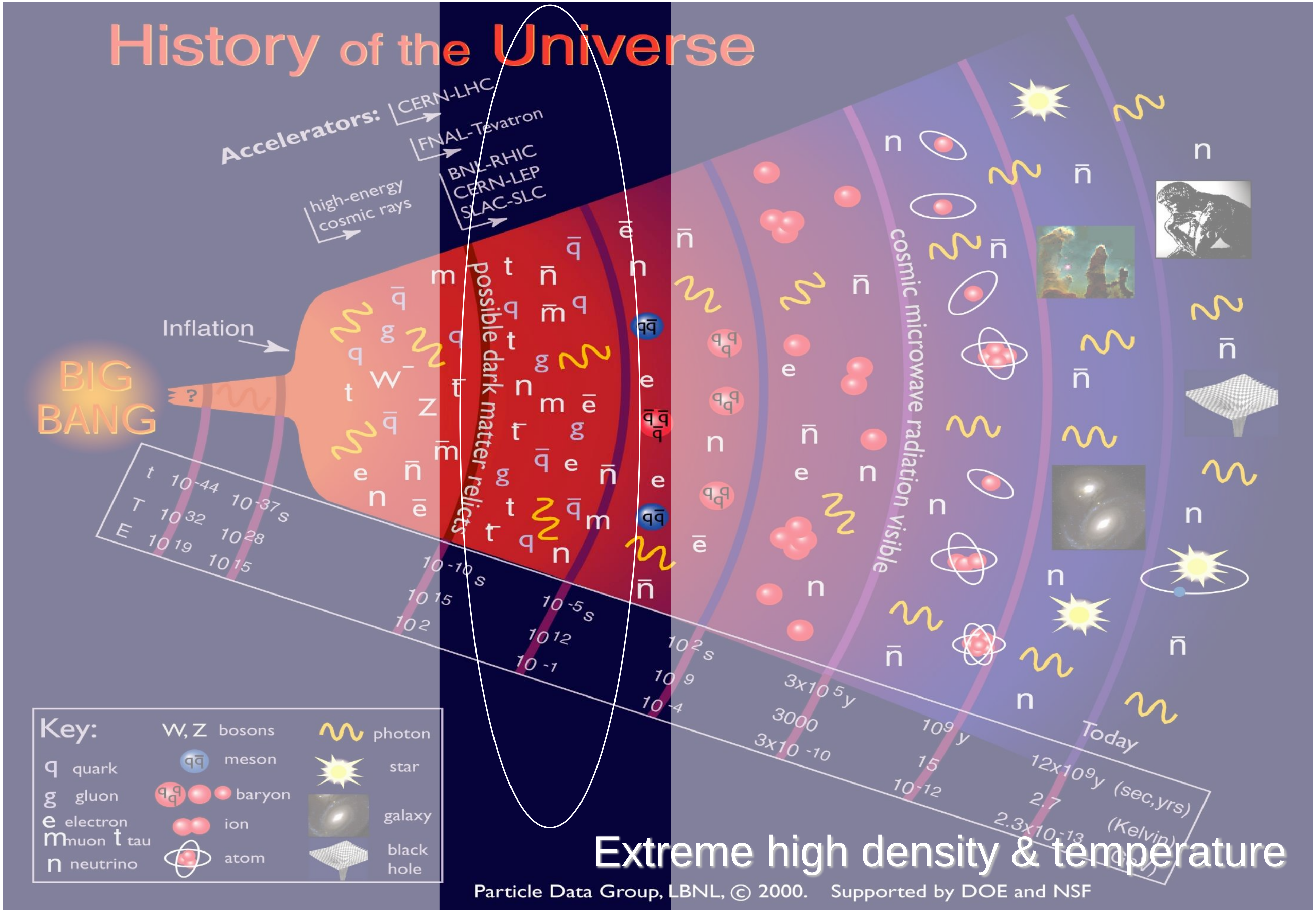
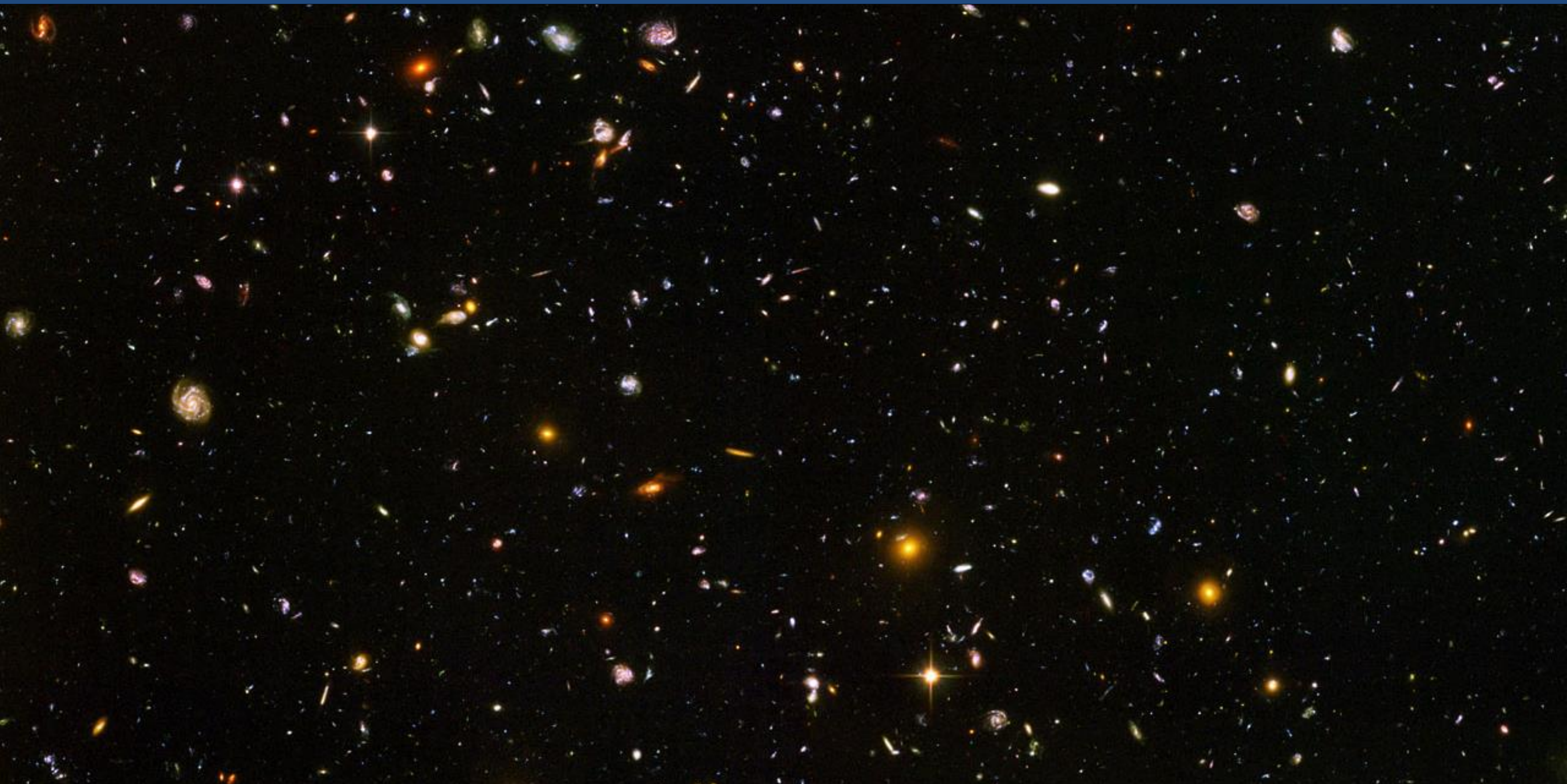


Extreme high density & temperature

First order transition between water and ice

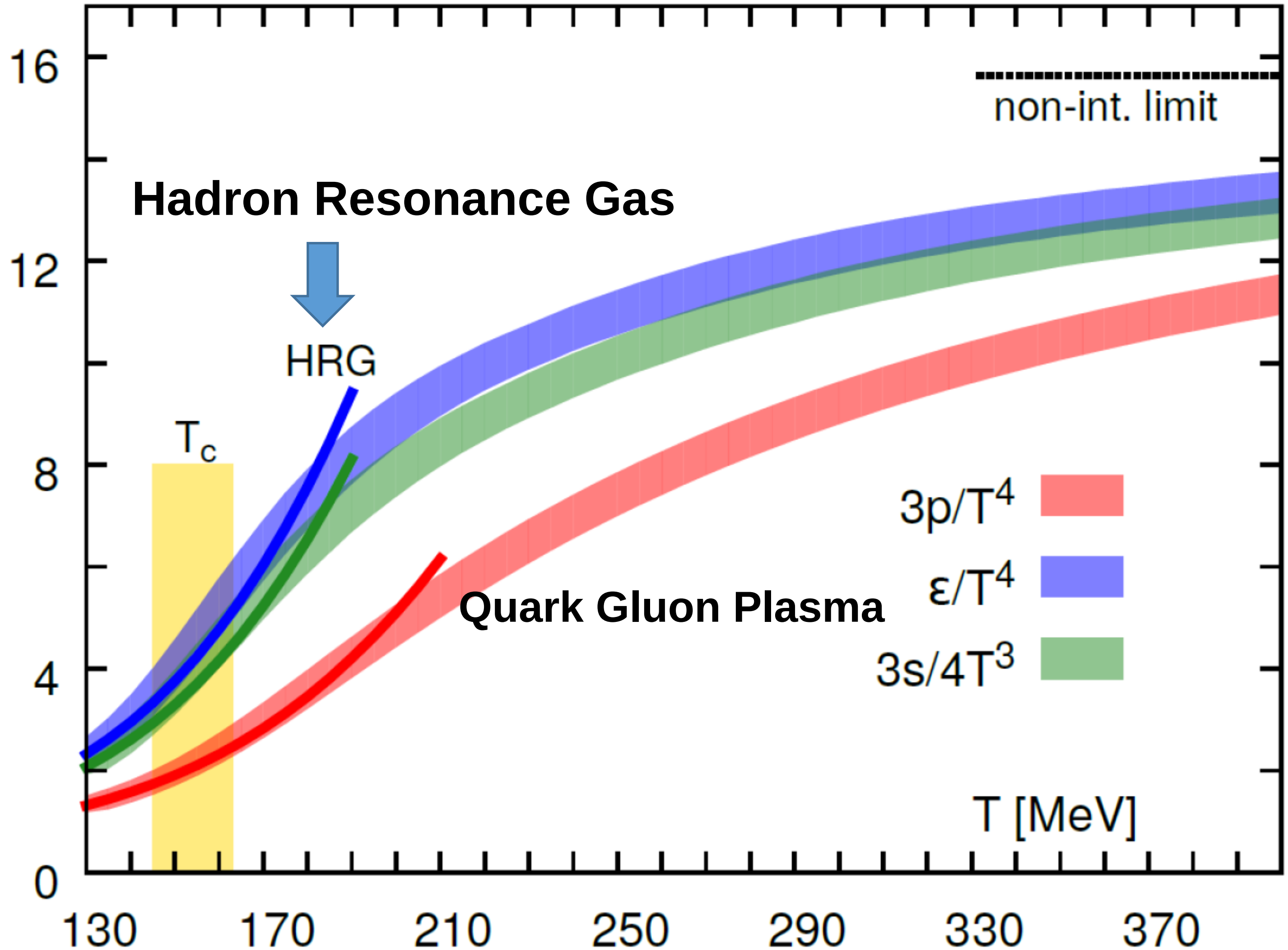
https://i7wen.com/zh-tw/articles/5041

QCD in Cosmology



Abundance of light elements, such as Li, Be, B … could modified if there is a first order QCD phase transition which created an inhomogeneous distribution of baryons

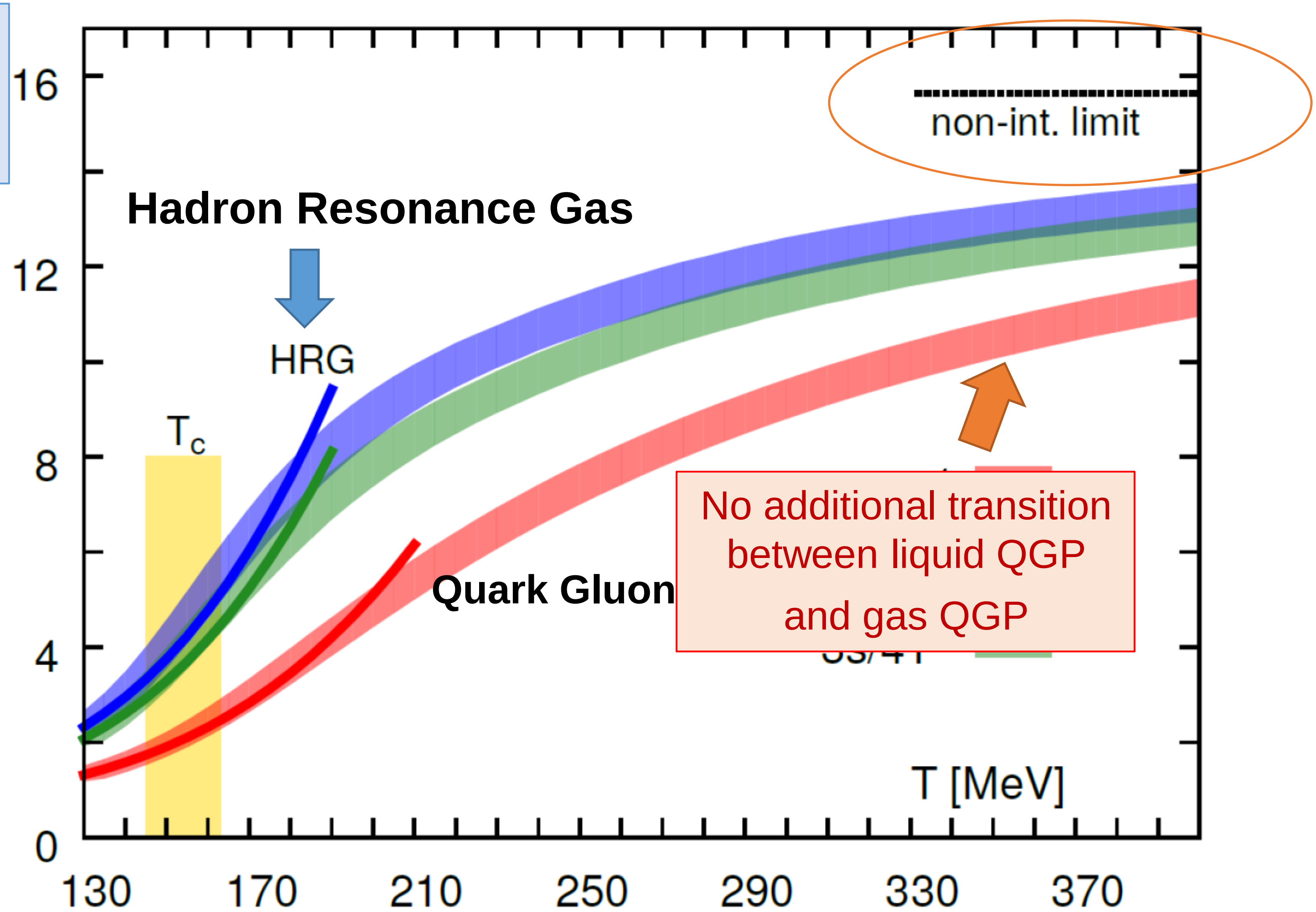
QCD Equation of State at μ_B=0



Lattice QCD predicts a **continuous cross-over** between hadron gas and quark gluon plasma

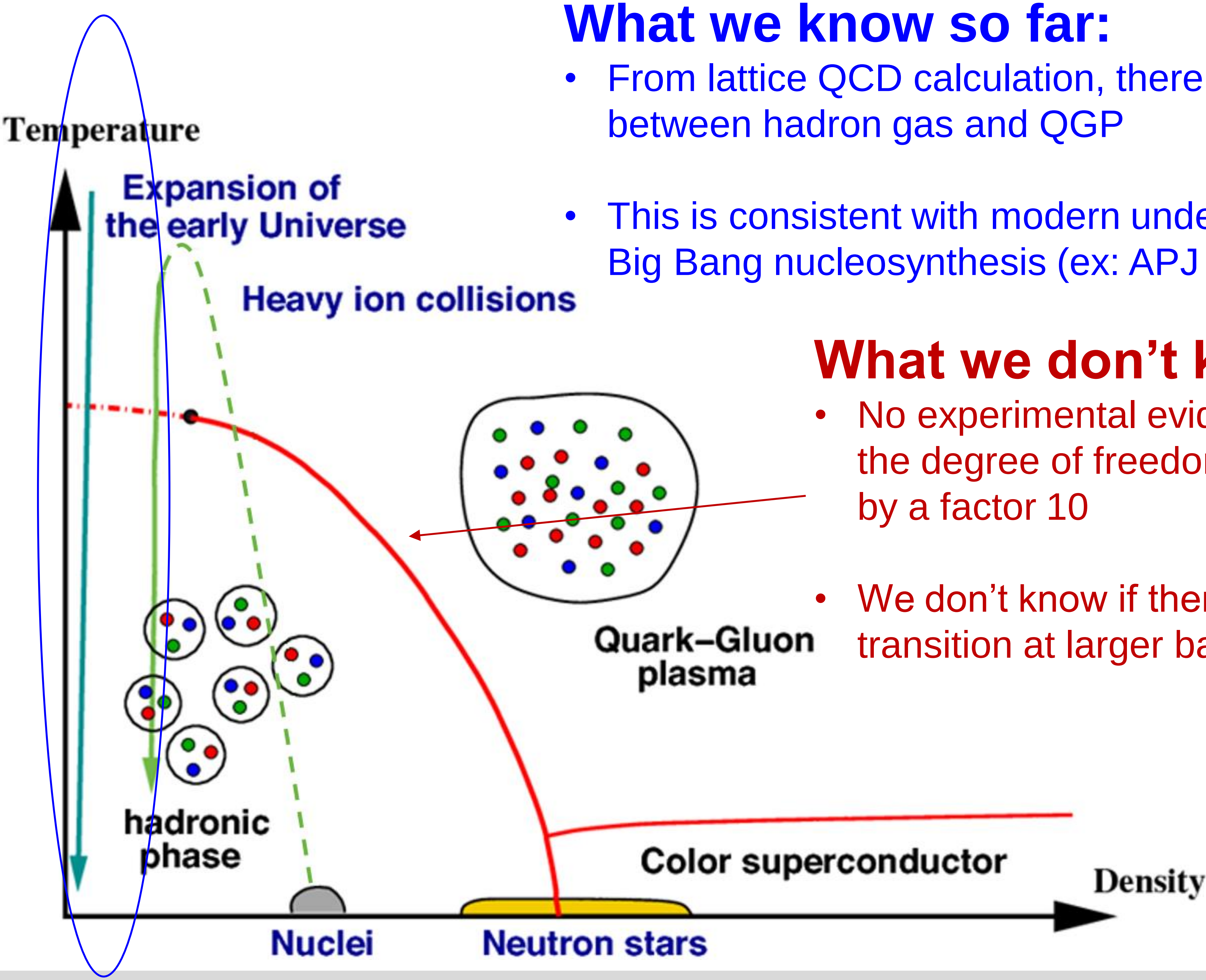
QCD Equation of State at μ_B=0

Degrees of freedom increased by a factor of **10**



Lattice QCD predicts a **continuous cross-over** between hadron gas and quark gluon plasma

QCD Phase Diagram



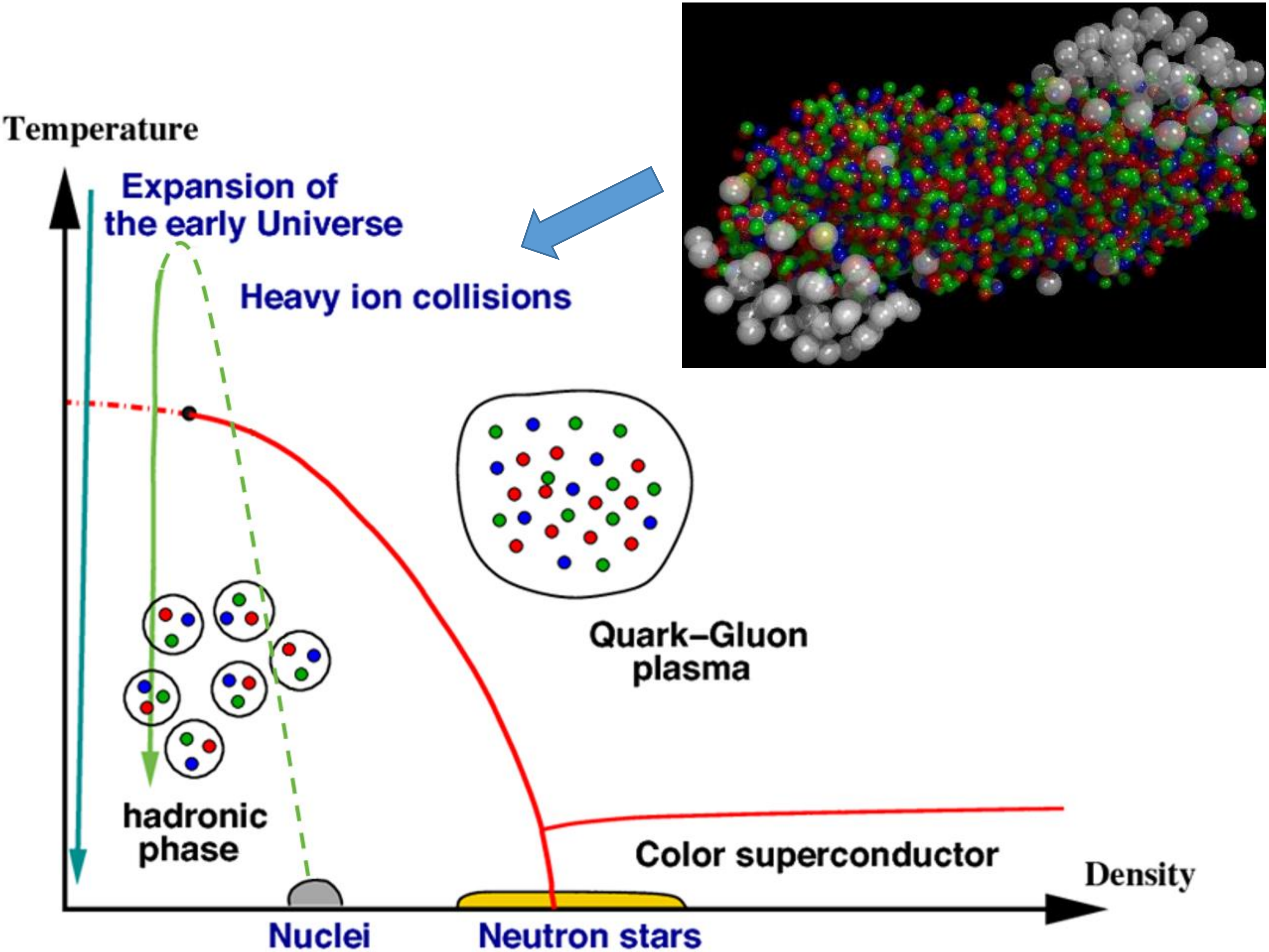
What we know so far:

- From lattice QCD calculation, there is a cross-over between hadron gas and QGP
- This is consistent with modern understanding of Big Bang nucleosynthesis (ex: APJ 430, 291 (1994))

What we don’t know yet:

- No experimental evidence yet that the degree of freedom has increased by a factor 10
- We don’t know if there is a first order transition at larger baryon density

QCD Phase Diagram



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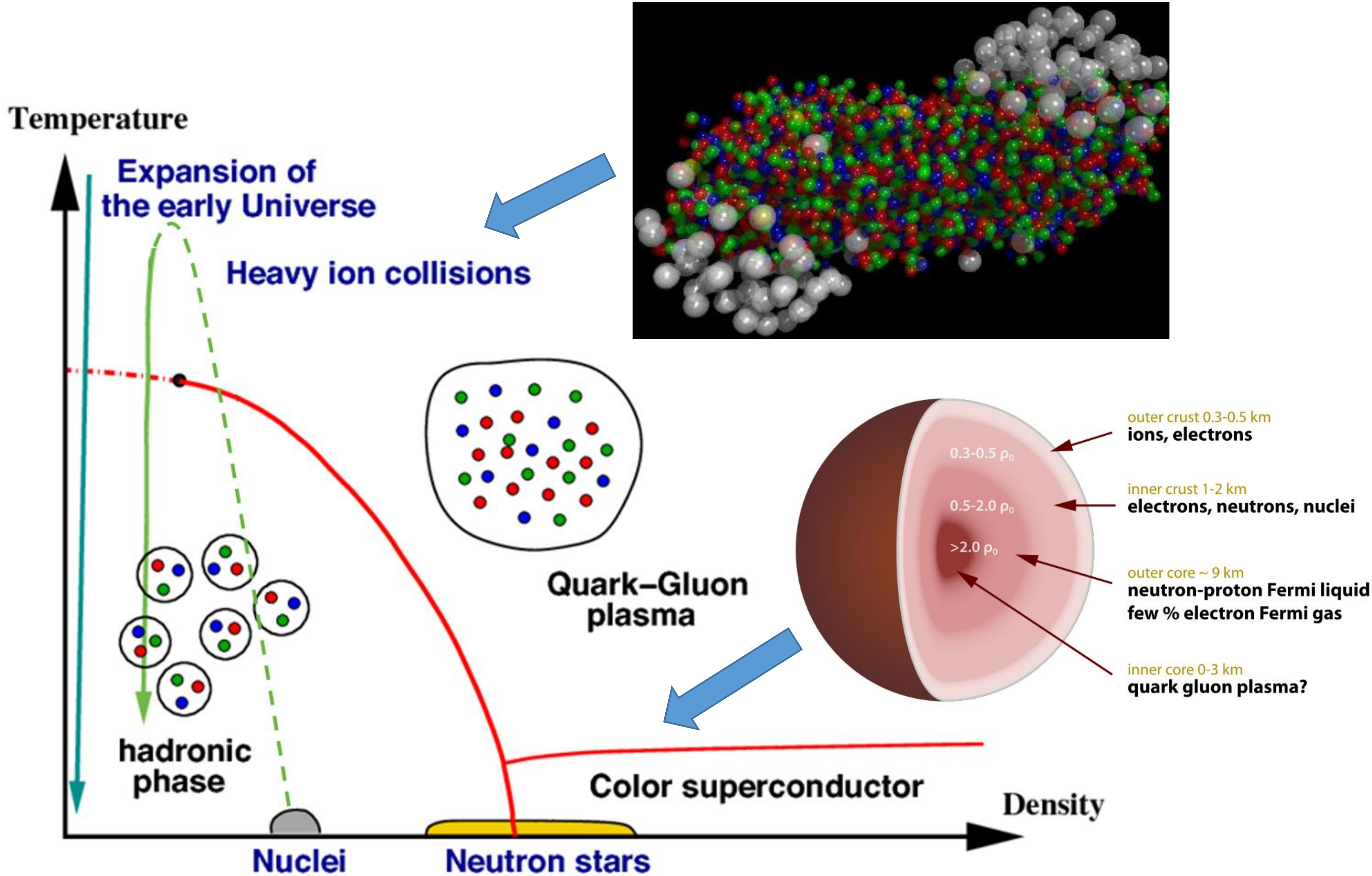
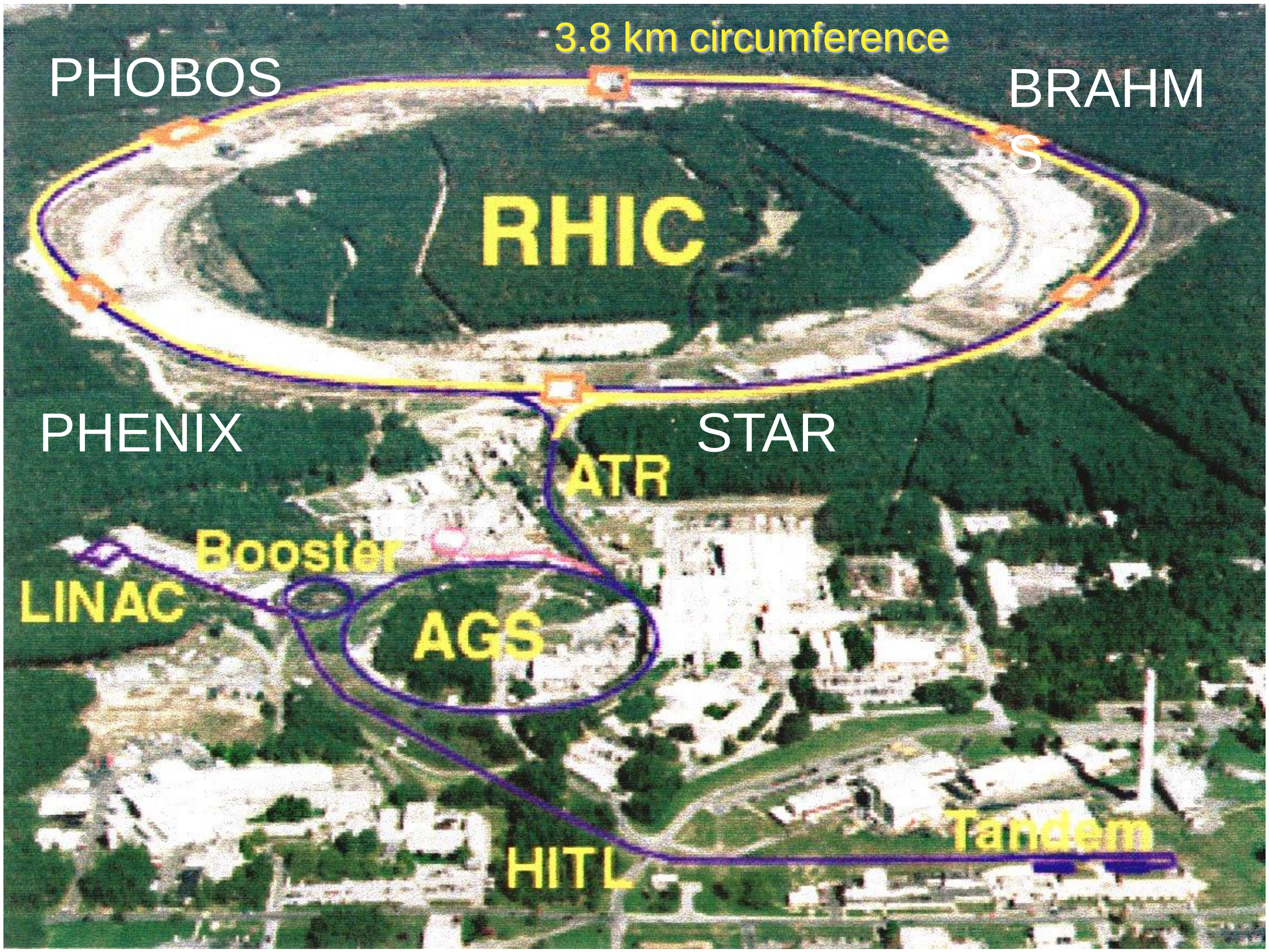


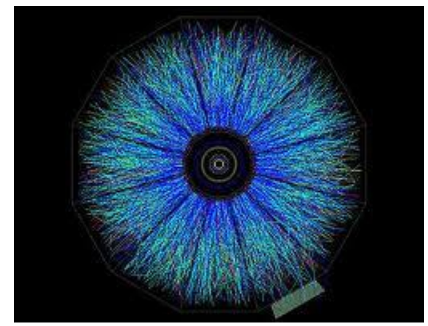
The First Dedicated Heavy Ion Collider

Relativistic Heavy Ion Collider



Gold+Gold

7.7 - 200 GeV

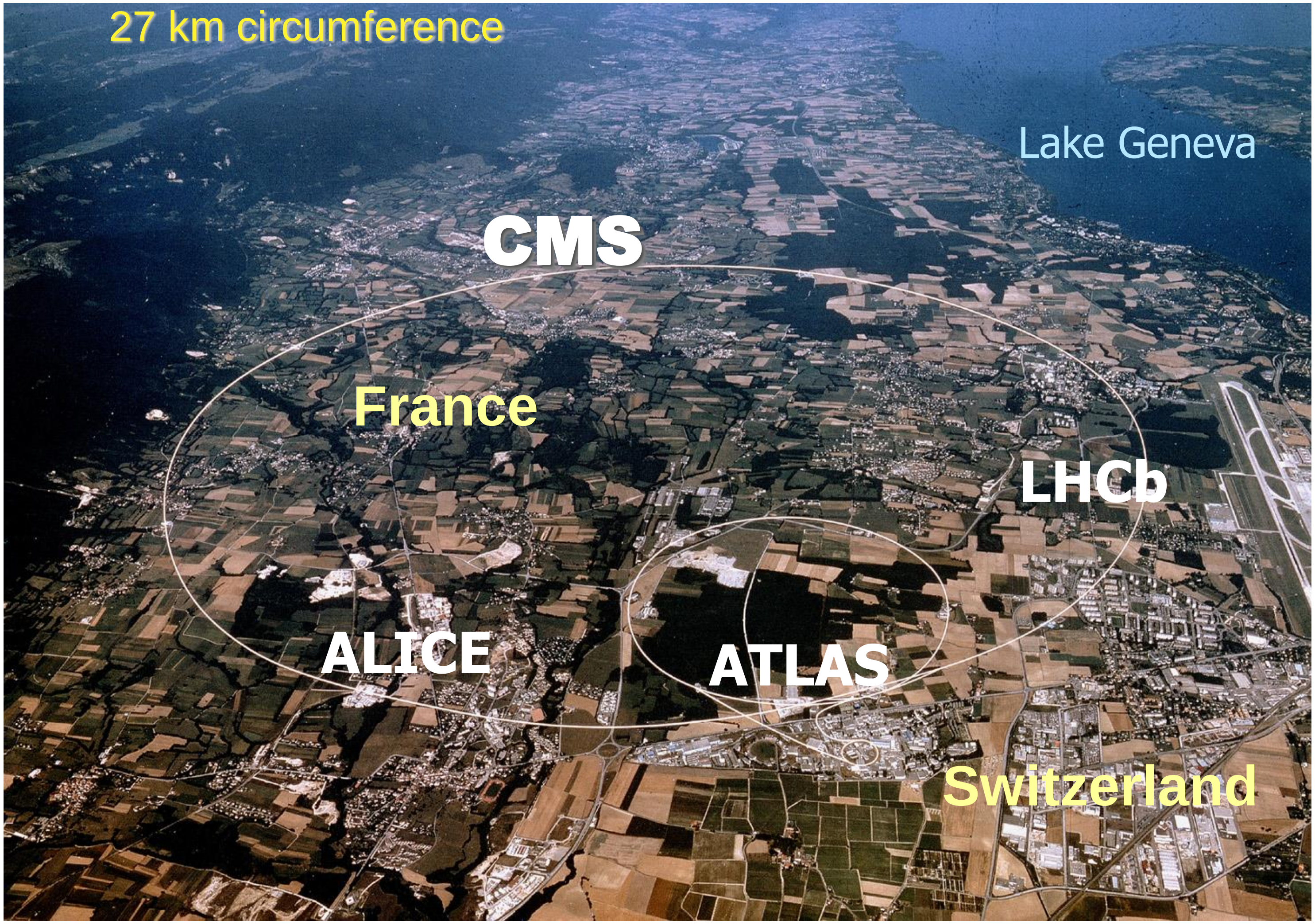


Since 2000~

The High Energy Frontier

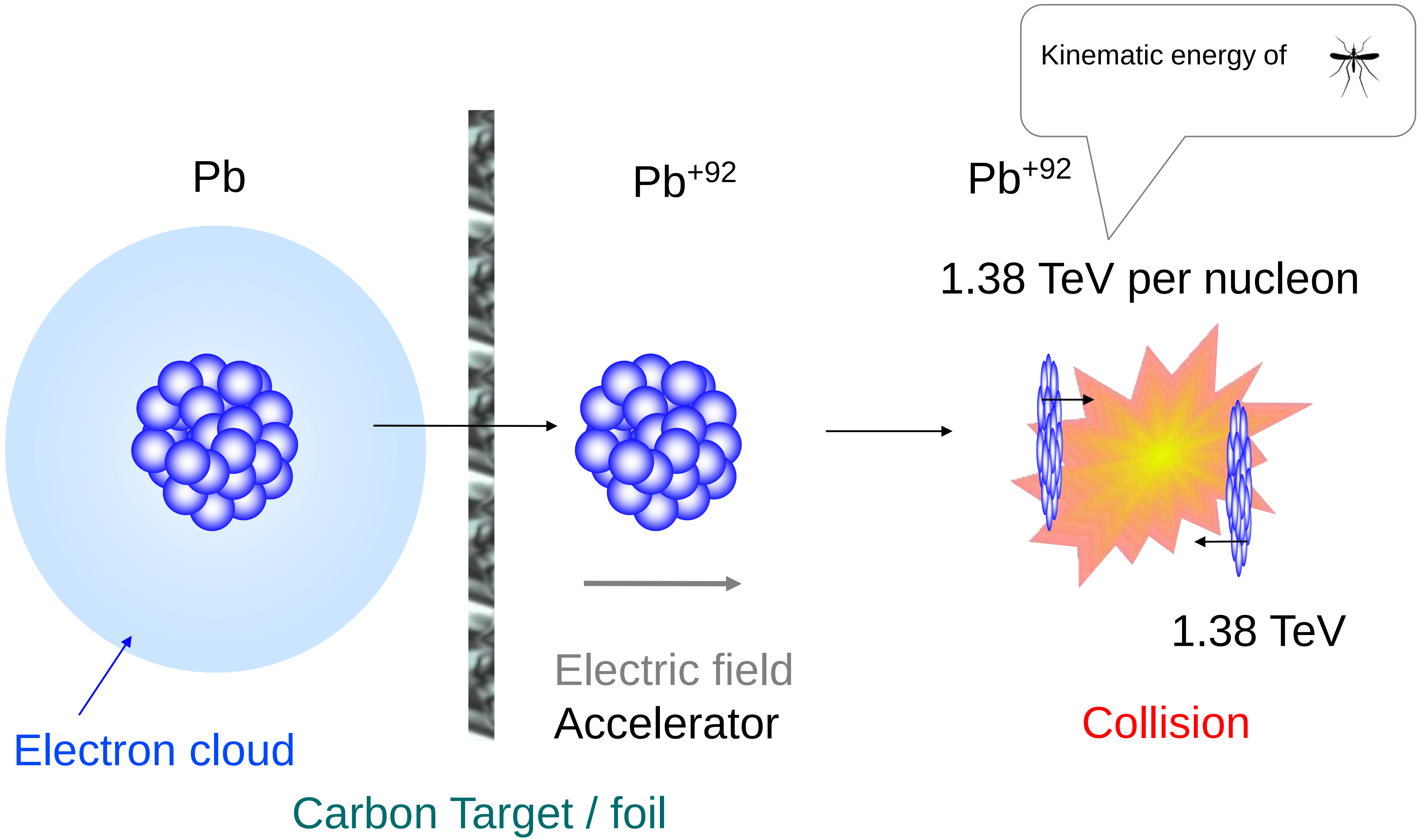
Large Hadron Collider

Lead+Lead collisions
2010-11: 2.76 TeV
2015: 5.02 TeV
25x jump with respect to RHIC!



RHIC

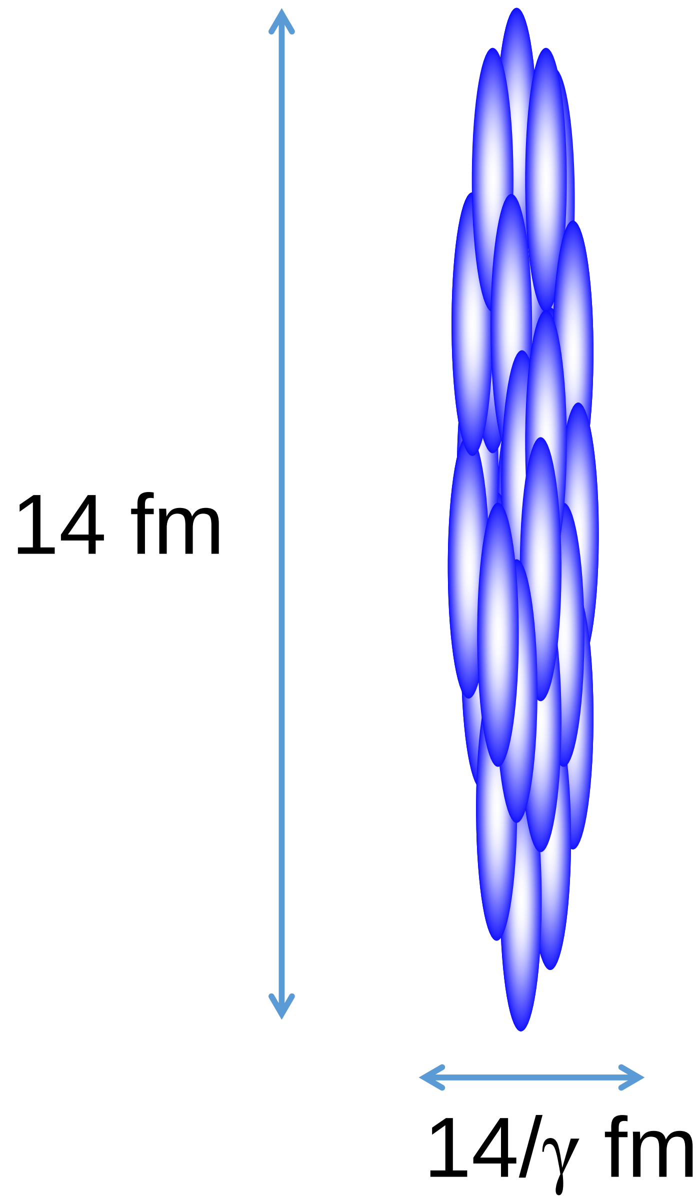
How do we collide ions?



Each ion carry 1.38 TeV x 208 ~ 50 μJ

Lorentz Contracted Discs

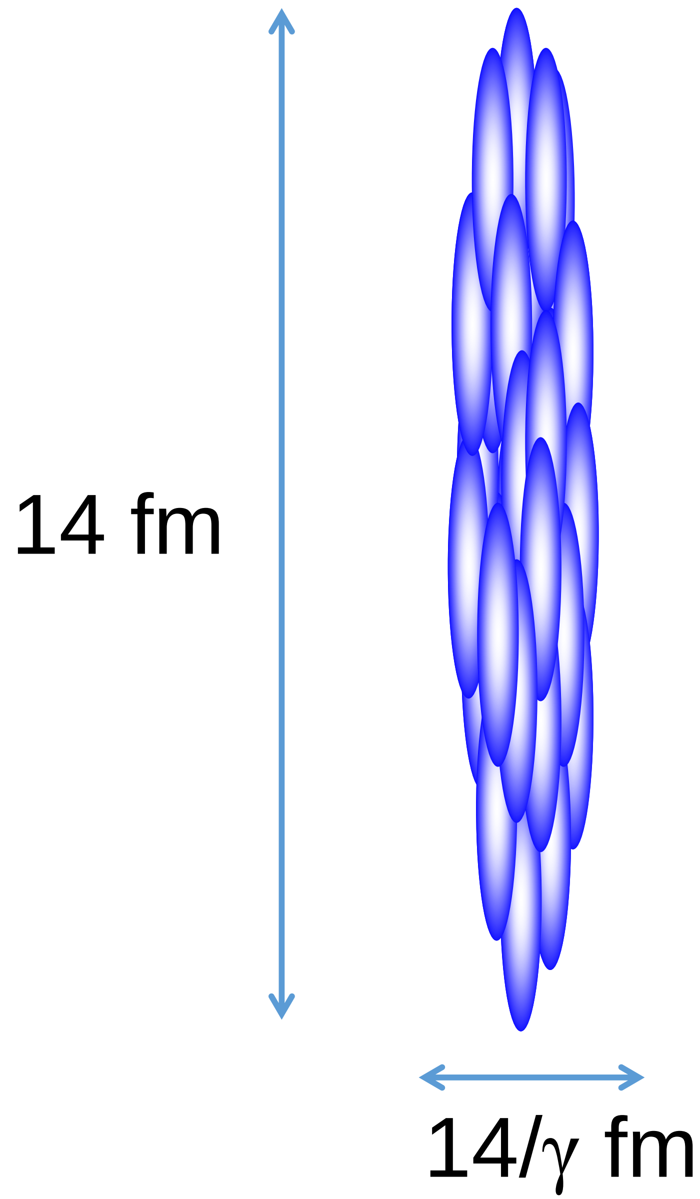
For large nuclei such as Gold (Au) and Lead (Pb):

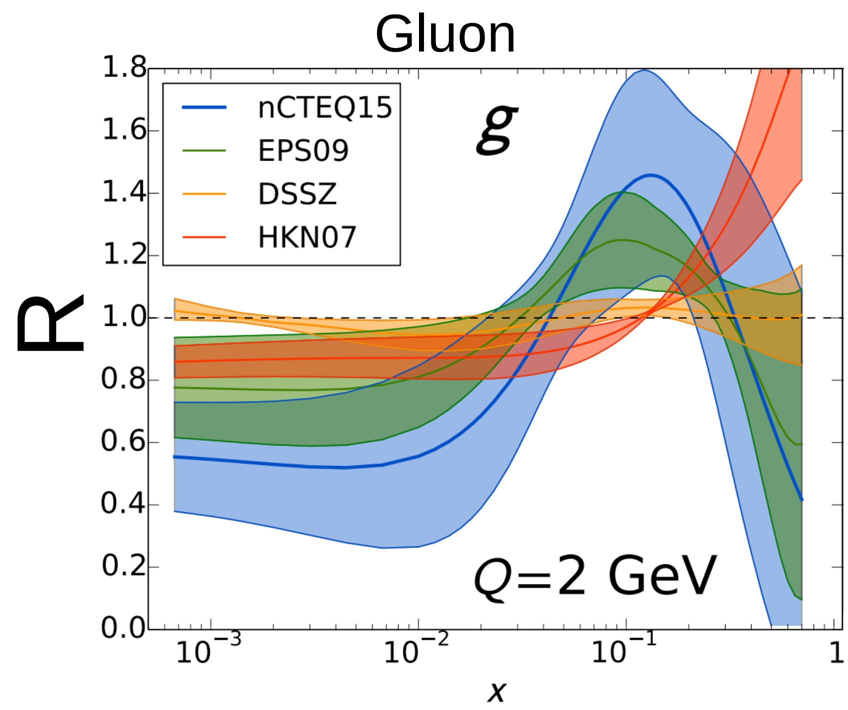


γ = 100 at RHIC
2500 at LHC

Parton Distribution Function (PDF)

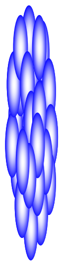
For large nuclei such as Gold (Au) and Lead (Pb):



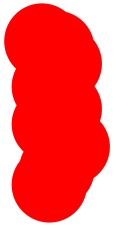


$$R = \frac{nPDF}{PDF}$$

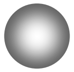
Relativistic Heavy Ion Collisions



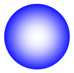
Heavy Ion



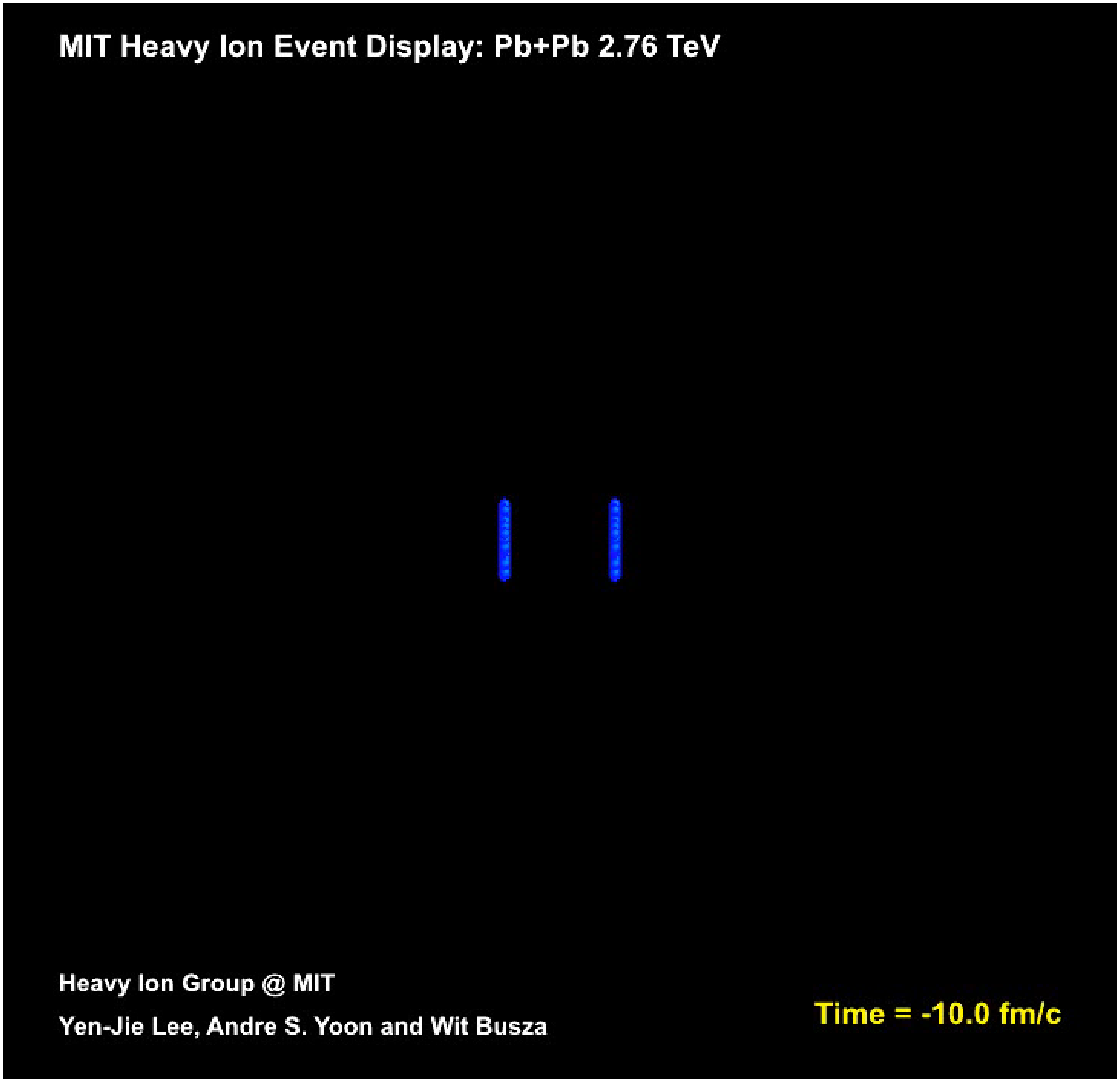
Particles before hadronization
(Quark Gluon Plasma)



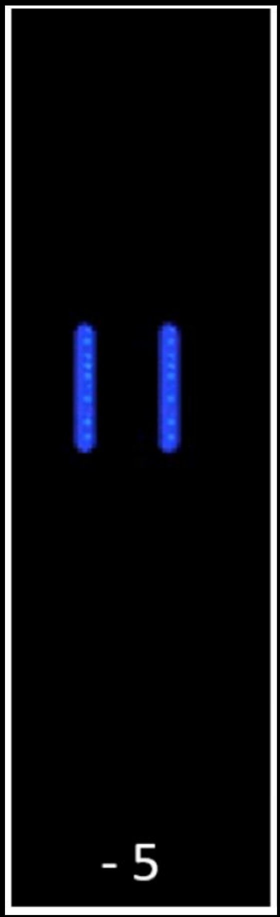
Meson



Baryon



Relativistic Heavy Ion Collisions

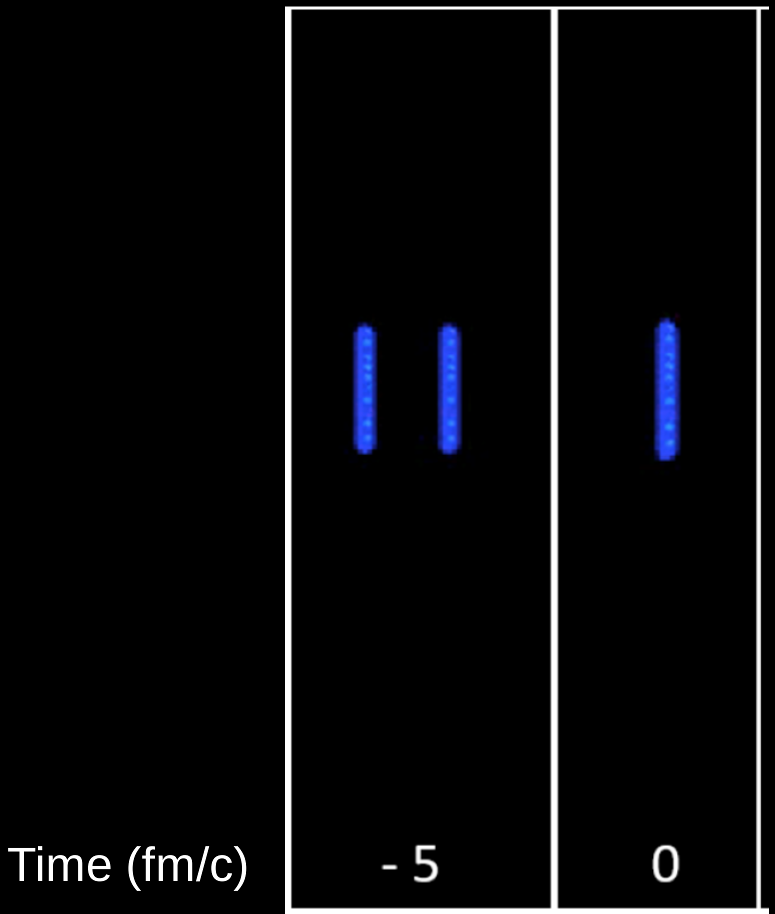


Time (fm/c)

Two discs of almost real quarks and gluons

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.



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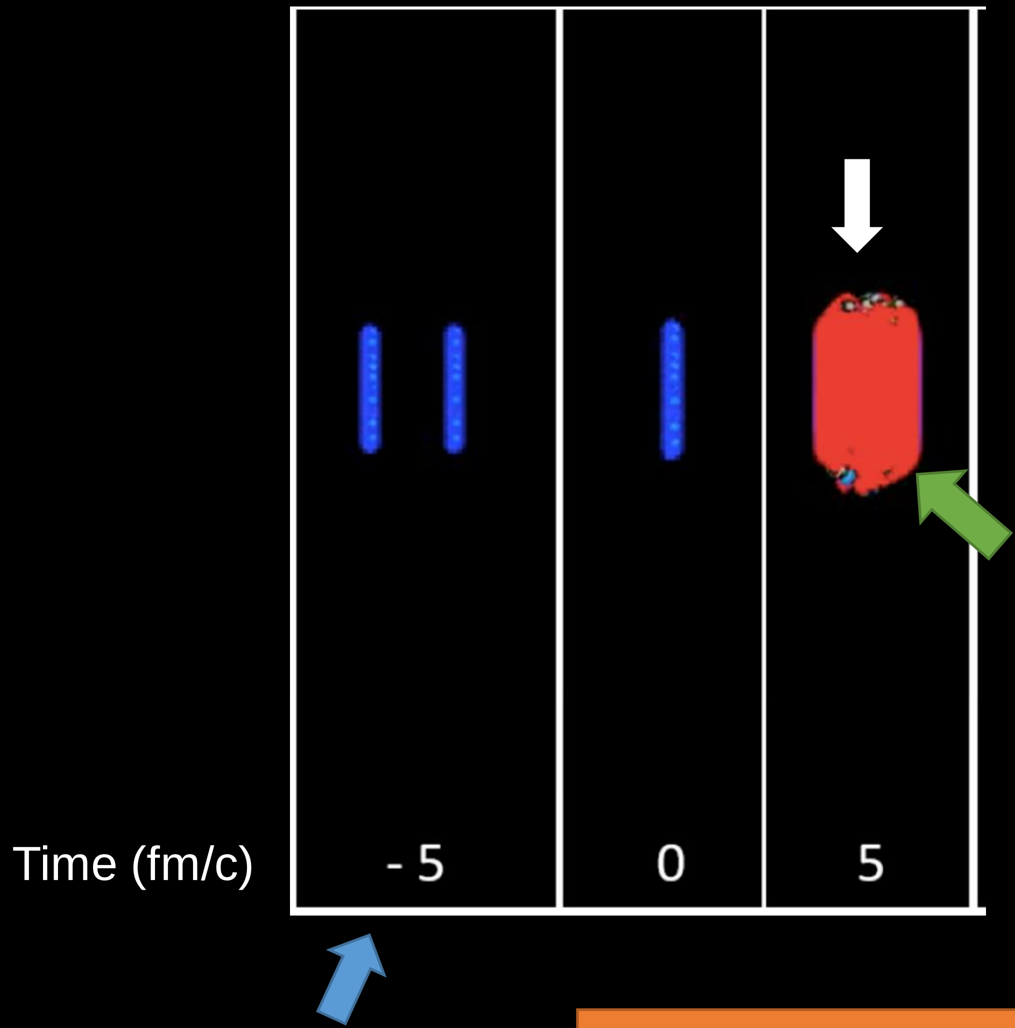


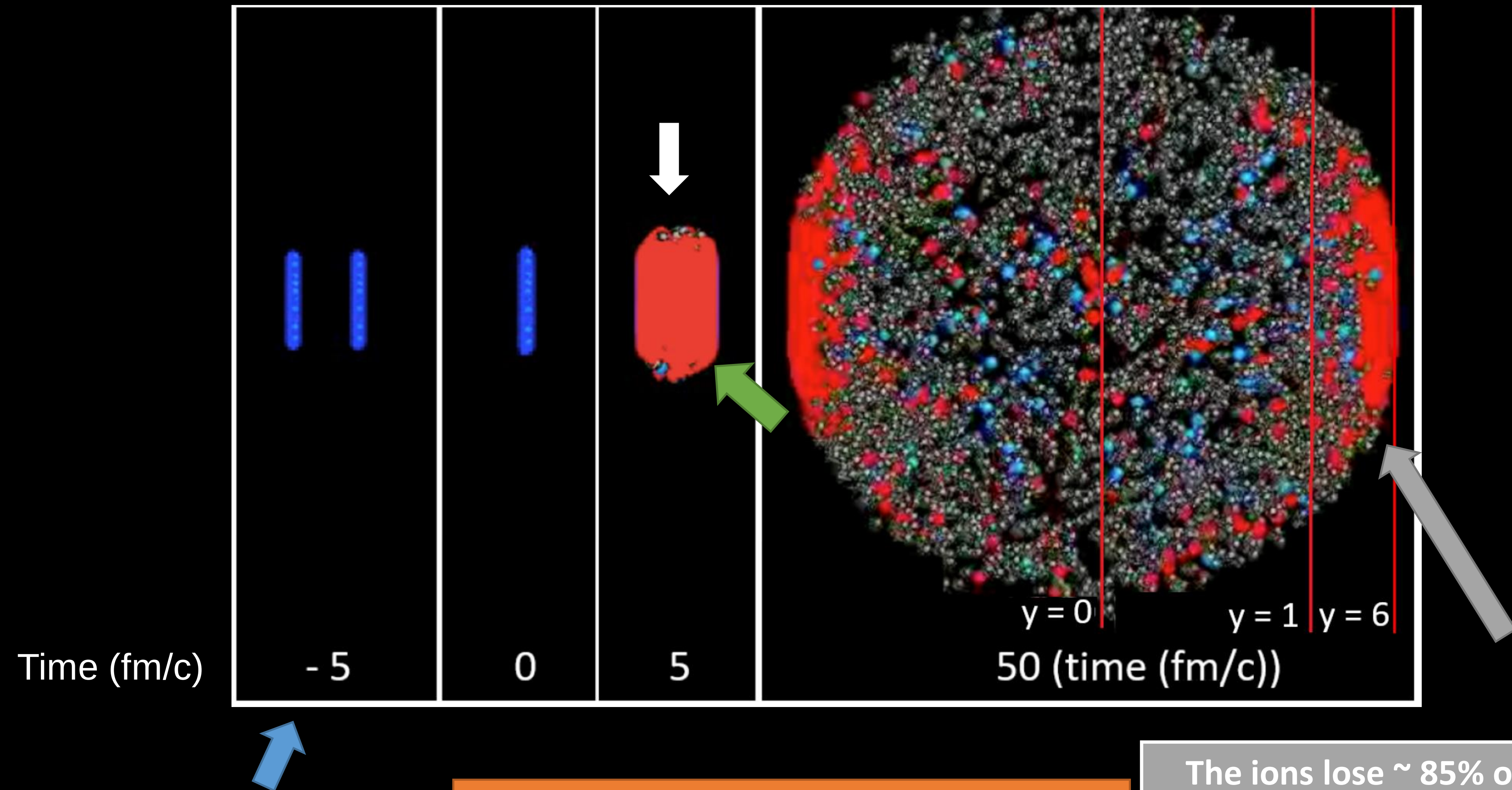
Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

Relativistic Heavy Ion Collisions

Collision! Highest energy density state. Huge amount of soft (low momentum transfer) scatterings.

Hadronization of QGP, different from elementary collisions like e^+e^- or pp collisions

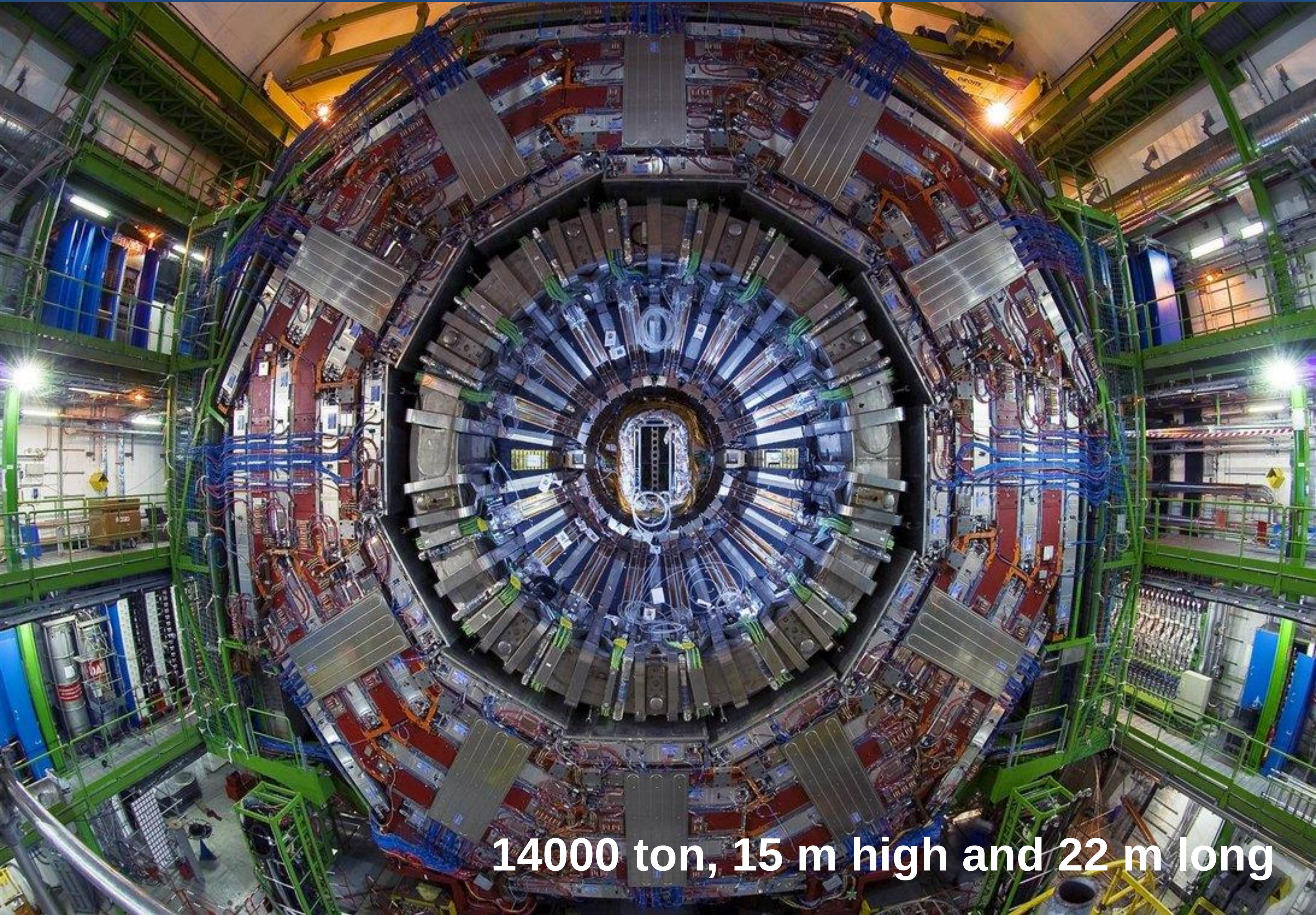


Two discs of almost real quarks and gluons

Midrapidity: thermalized QGP with very small baryon doping (μ_B)
Forward: QGP just created

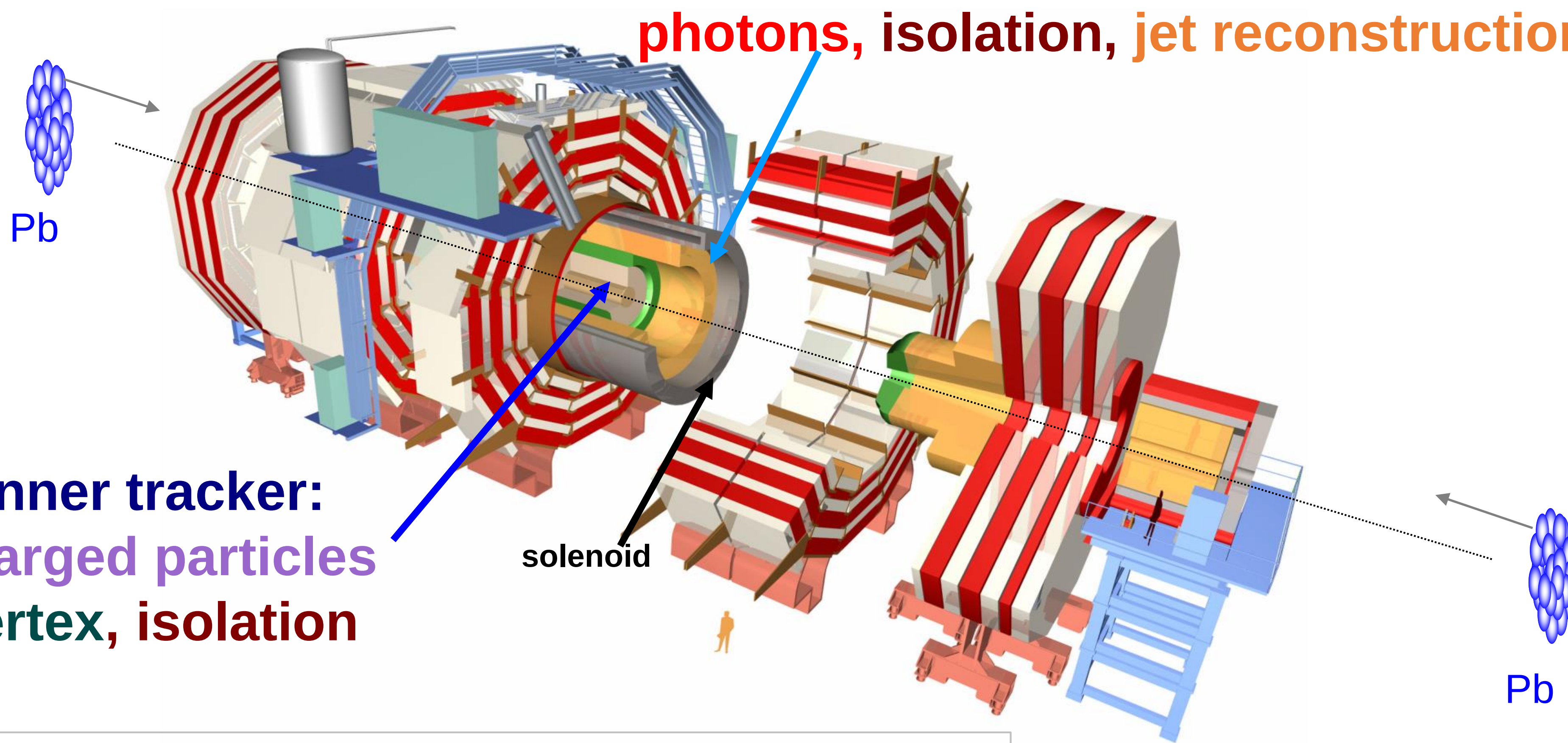
The ions lose ~ 85% of the momentum and form a compressed baryon-rich QGP (high μ_B) at large rapidity

A QGP detector: CMS (2008)

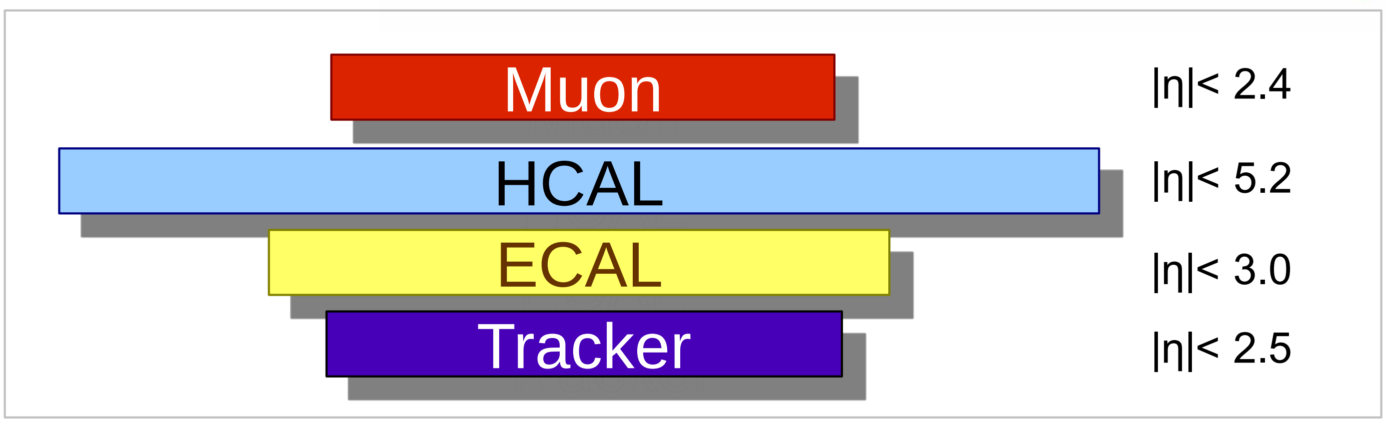


A QGP detector: CMS

EM and Hadron calorimeters
photons, isolation, jet reconstruction

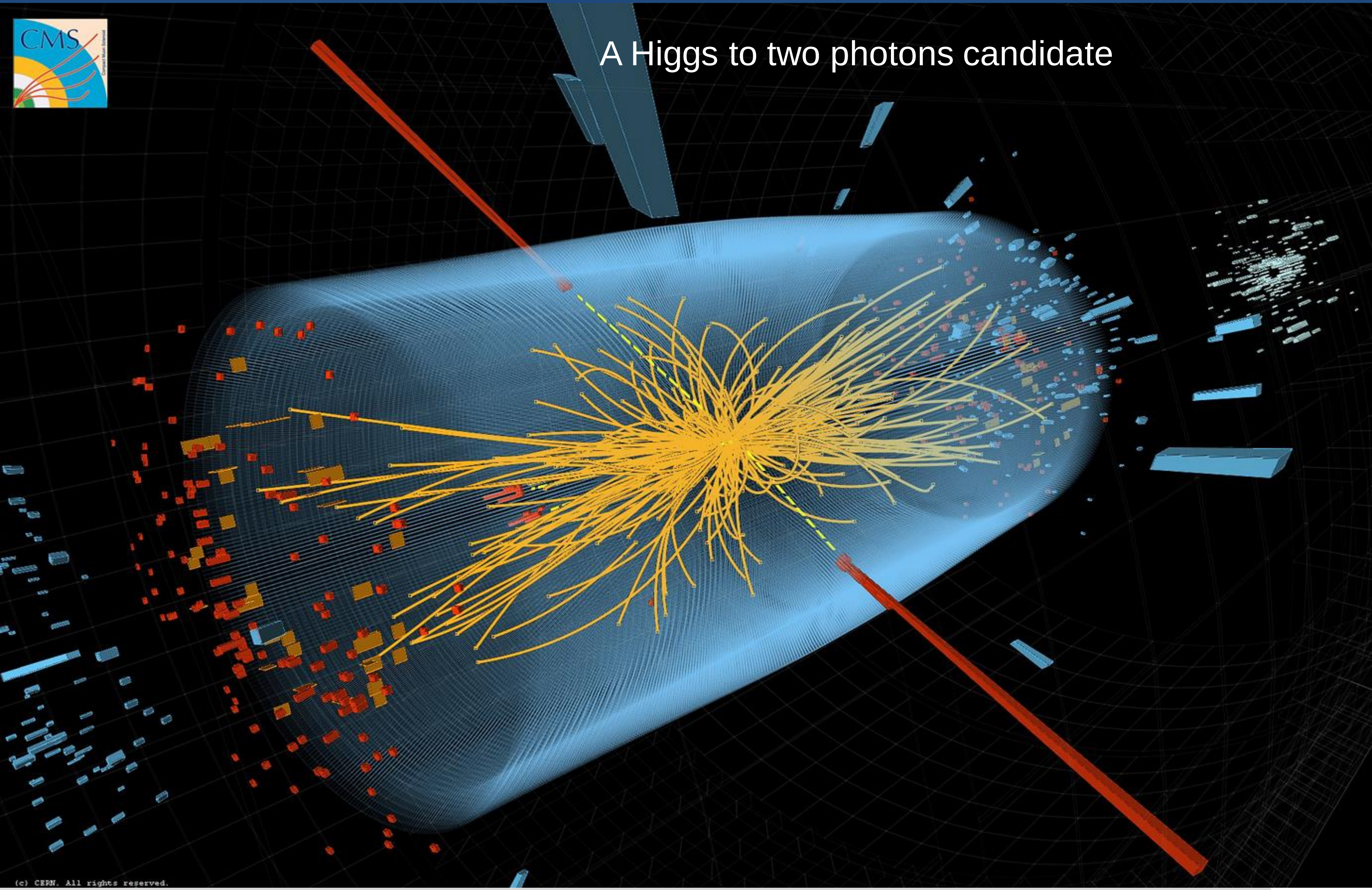


Inner tracker:
charged particles
vertex, isolation

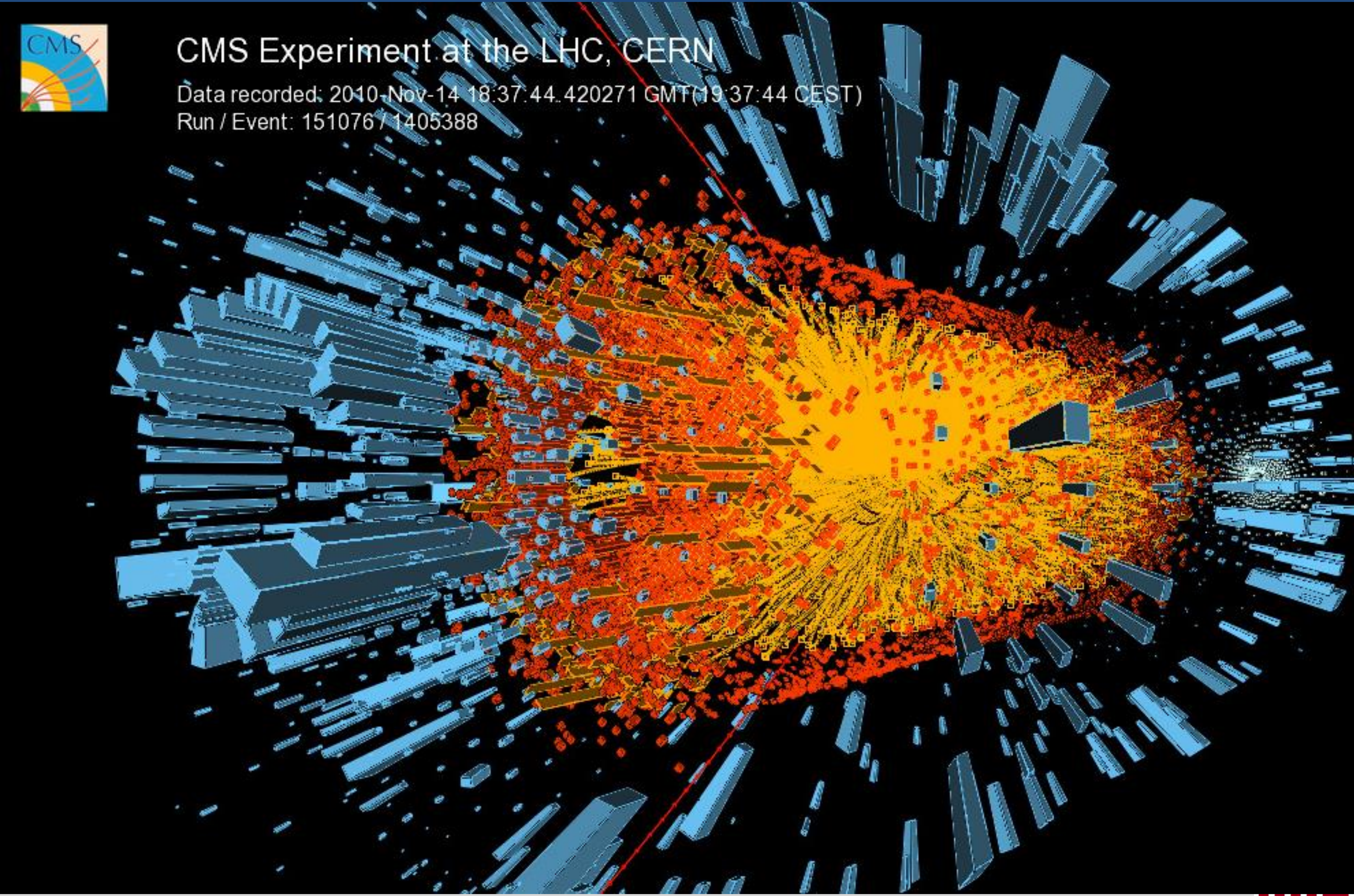


Optimized for high p_T physics: a perfect jet detector for the studies of QGP

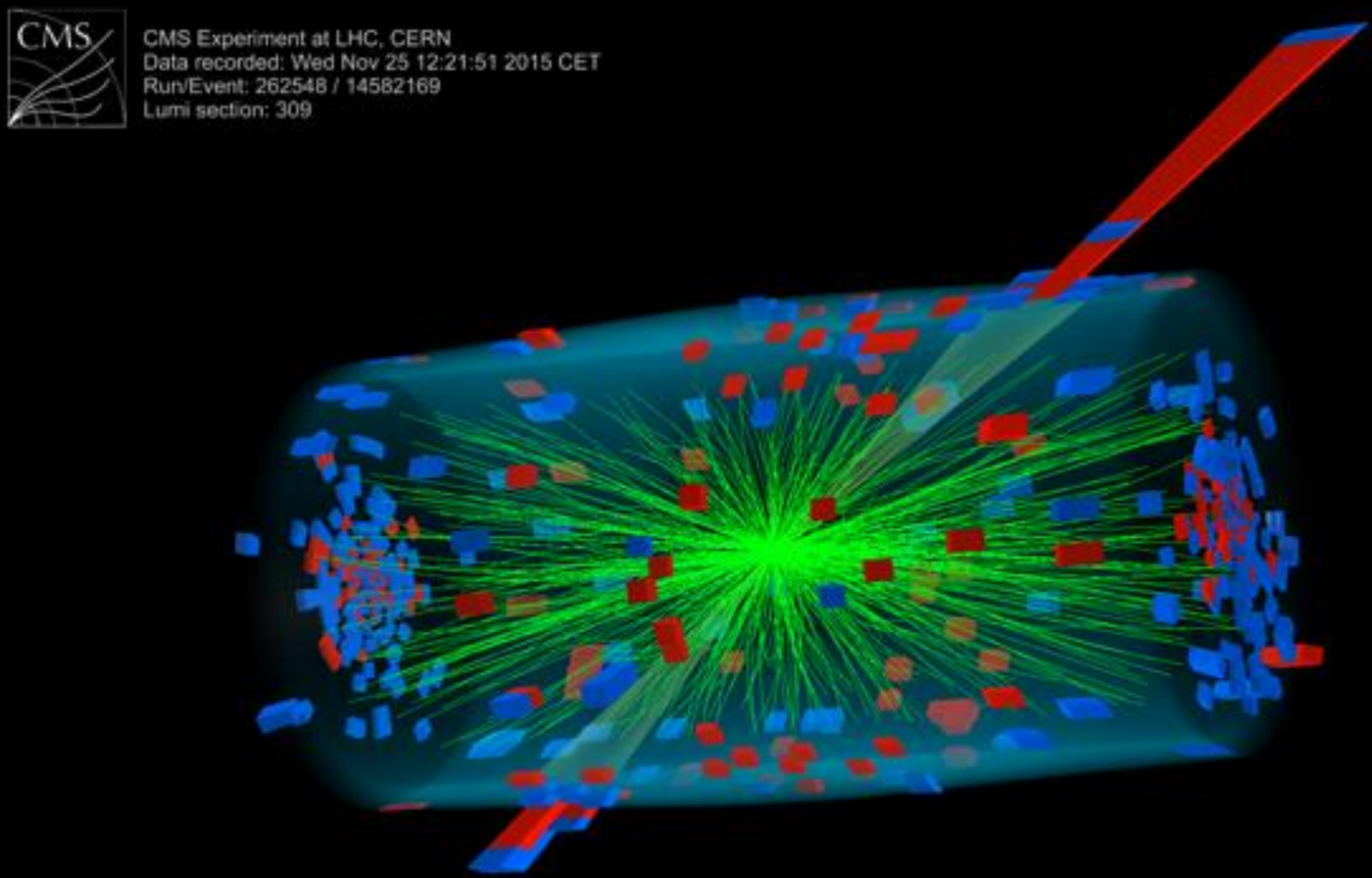
Proton-Proton Collision Recorded by the CMS detector



Lead-Lead Collision Recorded by the CMS Detector (2010)

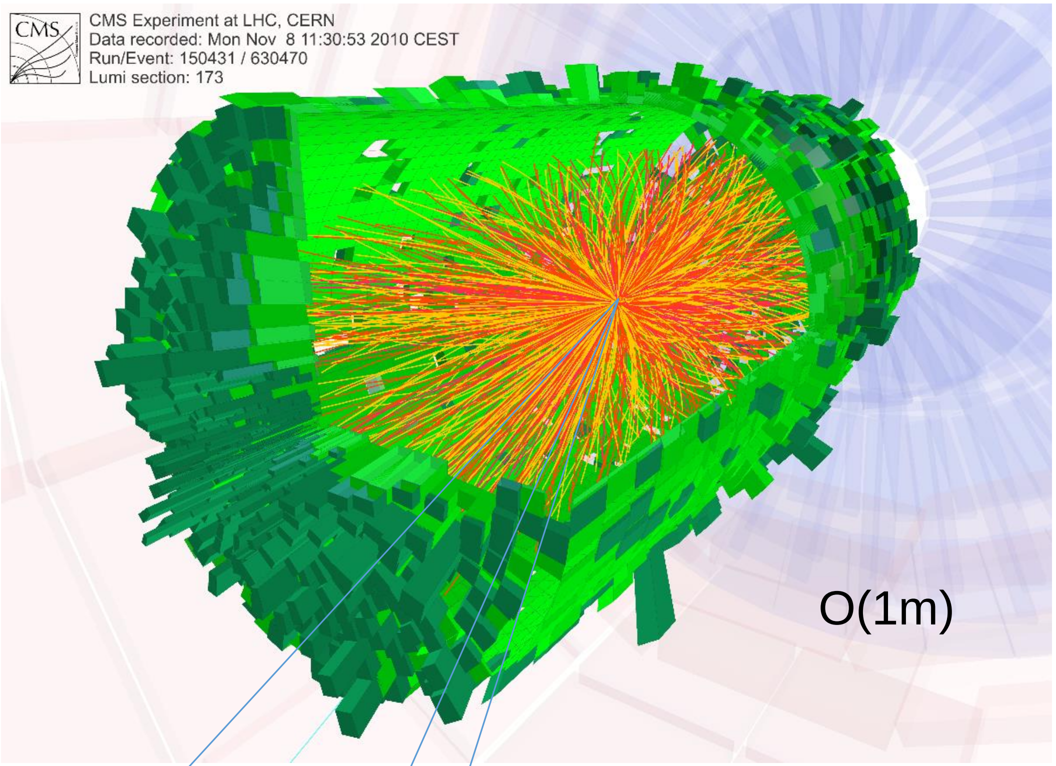


A beautiful dijet event in PbPb collisions

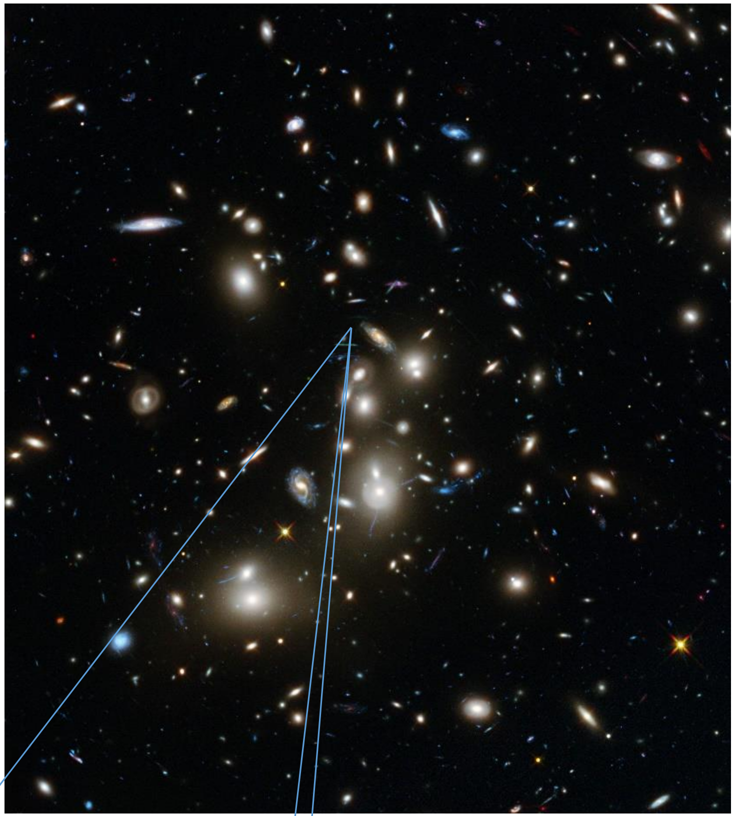


PbPb @ 5 TeV (2015)

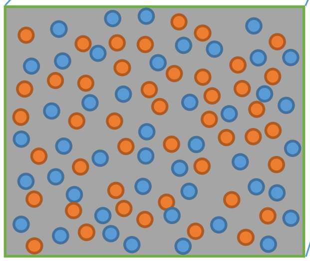
"Reconstruct the QGP" with CMS detector



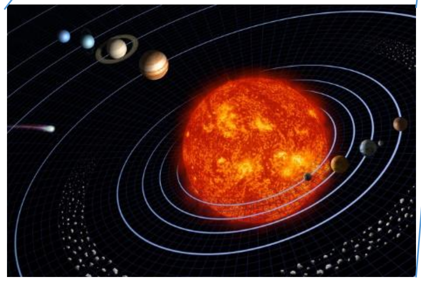
O(1m)



O(10^{27} m)



O(10^{-15} m)

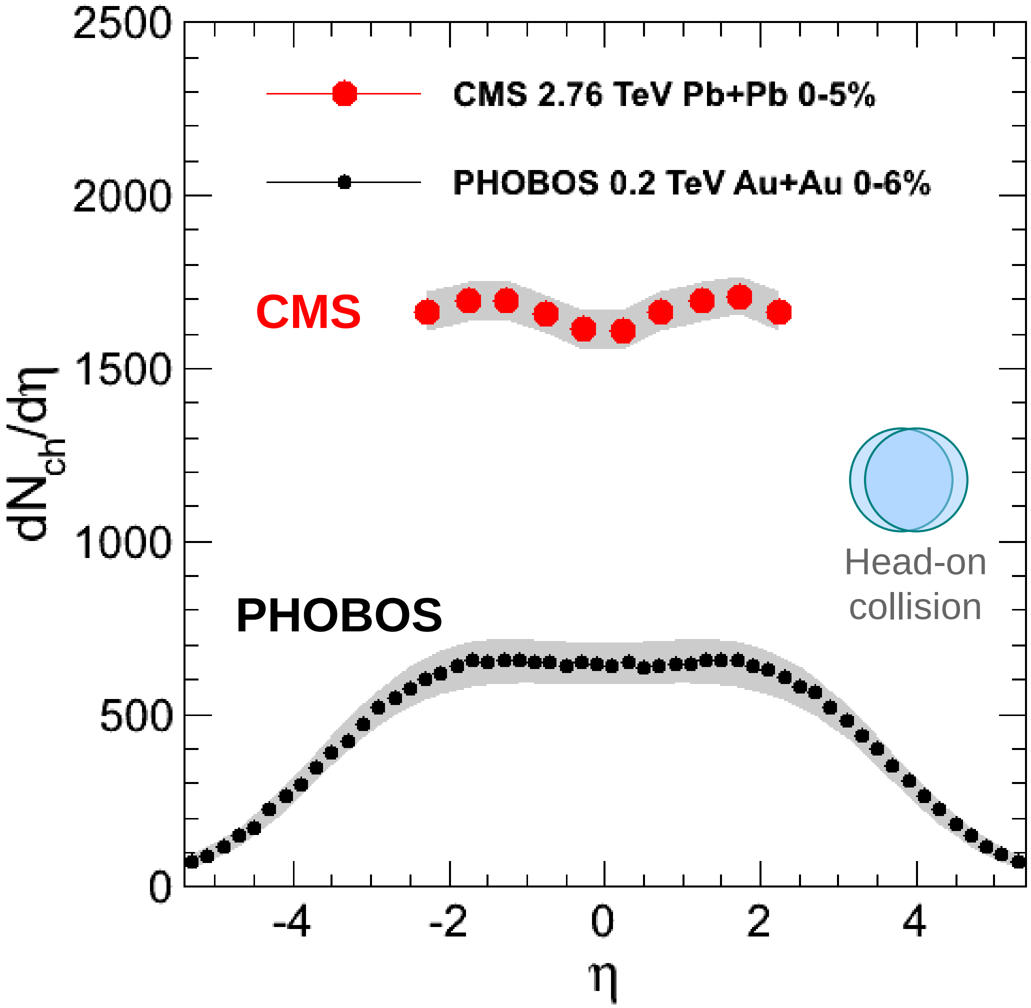


O(10^{13} m)

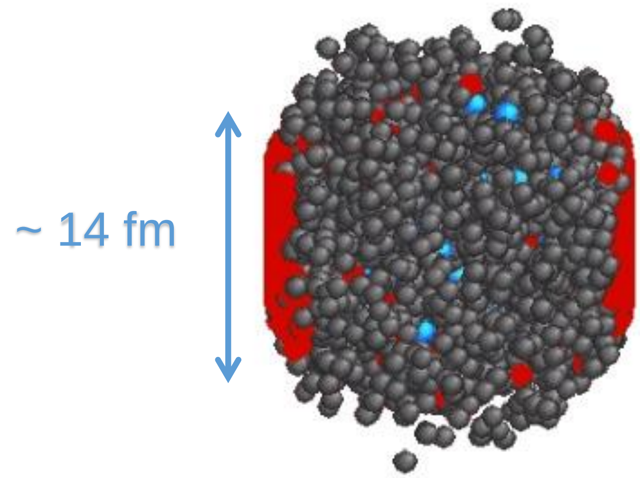
Charged Particle Counting

Number of particles produced in the collisions.

Particle density in Lead+Lead ~ **400x** of that in proton+proton



Consider the situation at t=1 fm/c:



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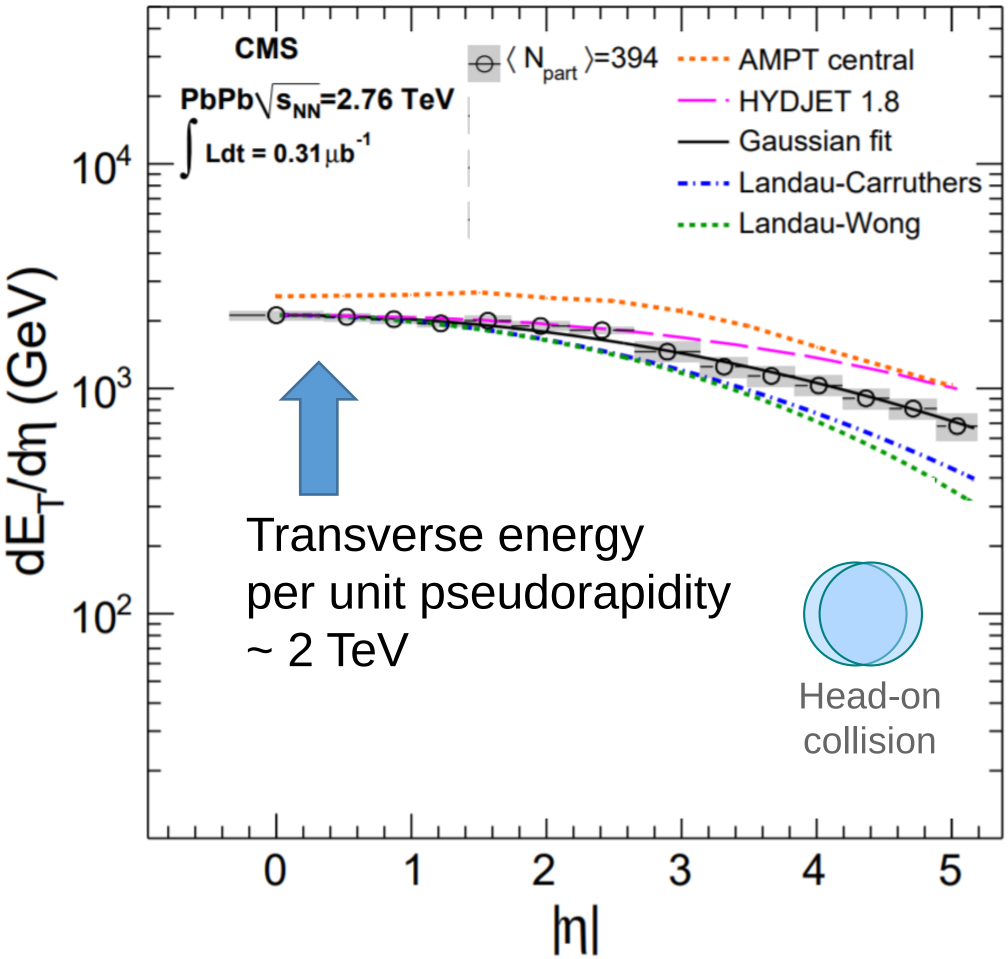

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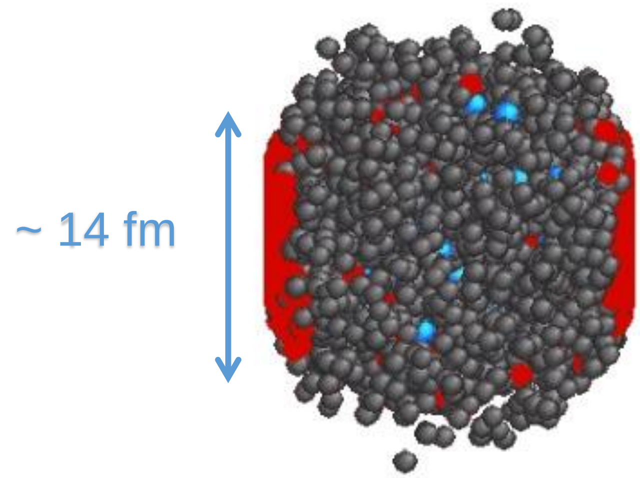

Energy density of this medium at this time:

2 TeV / [π (7 fm)^2 (1 fm)] = 13 GeV / fm^3

Hadron: ~0.5 GeV / fm^3

>10x denser than the proton!

At **early time** of the collision, the system can not be described by hadrons

PRL 109 (2012) 152303

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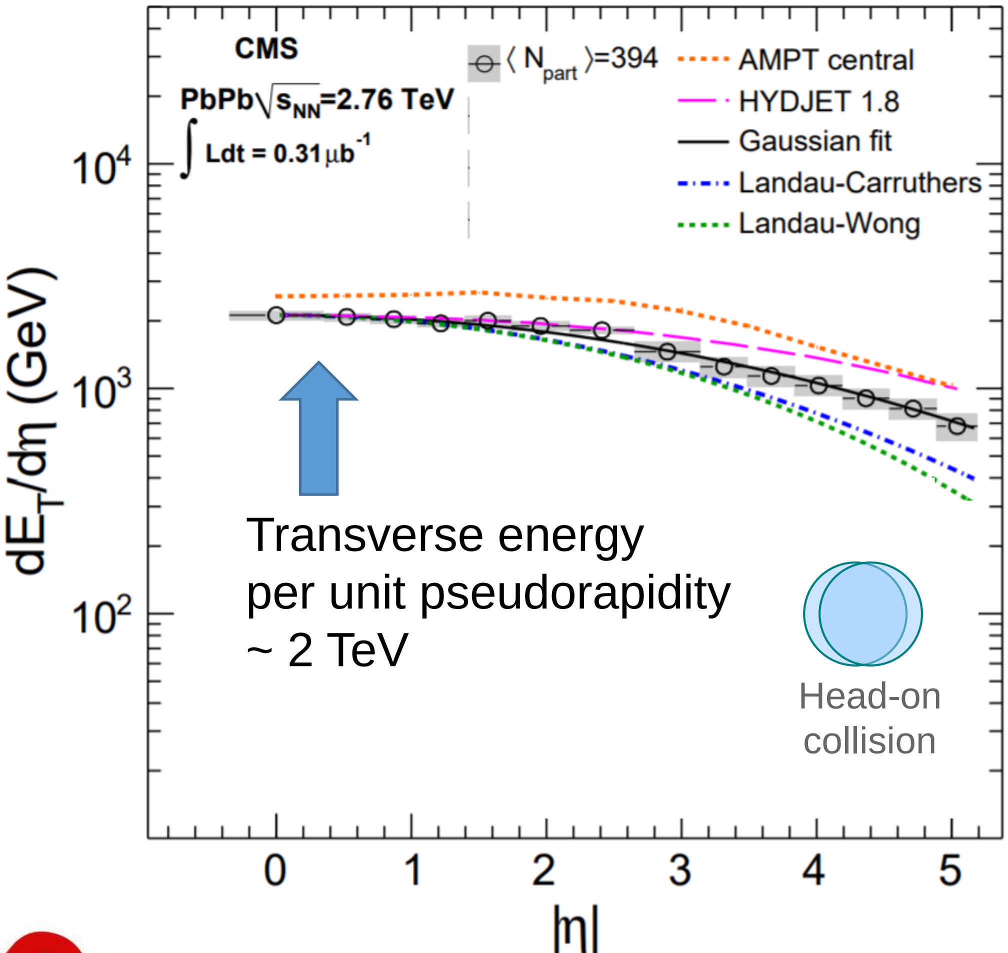

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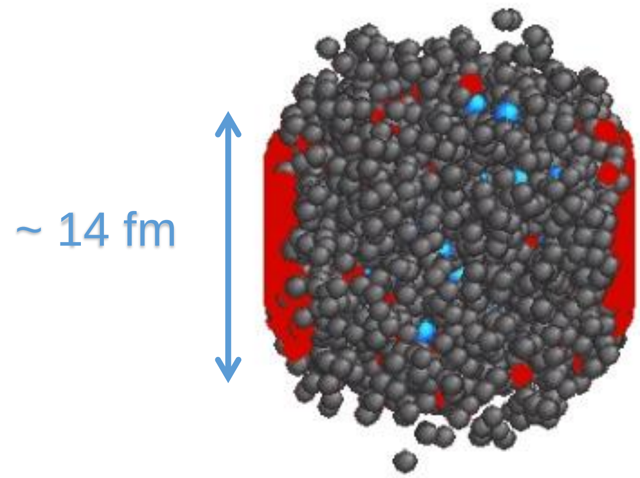

Energy density of this medium at this time:

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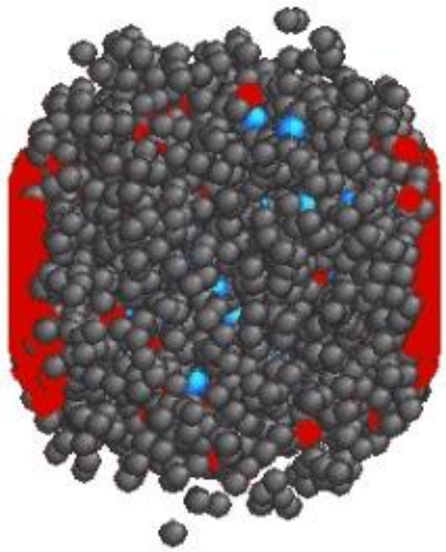
Wait! How do we know this system is not just a lot of incoherent NN collisions overlapping each other?

PRL 109 (2012) 152303

Hydrodynamization and Isotropization

Can the debris be described by hydrodynamics?

Hydrodynamization



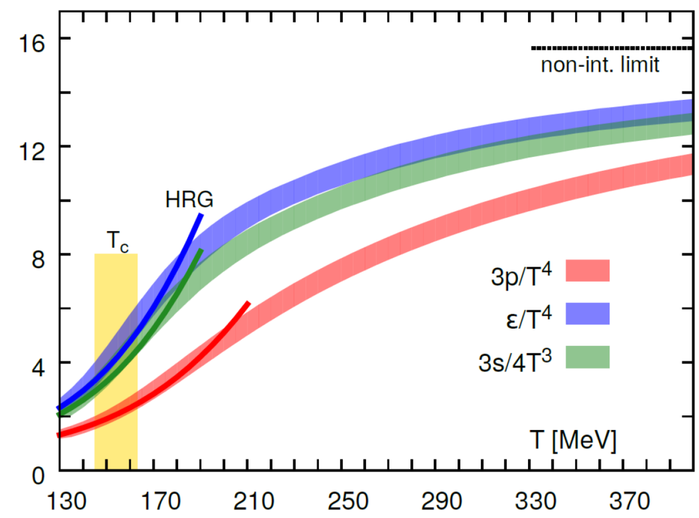
$$T_{\mu\nu} = \varepsilon\, u_\mu u_\nu + p[\varepsilon]\Delta_{\mu\nu} - \eta[\varepsilon]\,\sigma_{\mu\nu} - \zeta[\varepsilon]\Delta_{\mu\nu}\nabla_\mu u^\mu + \mathcal{O}(\partial^2), \text{ where}$$

$$\sigma_{\mu\nu} = \Delta_{\mu\alpha}\Delta_{\nu\beta}(\nabla^\alpha u^\beta + \nabla^\beta u^\alpha) - \frac{2}{3}\Delta_{\mu\nu}\Delta_{\alpha\beta}\nabla^\alpha u^\beta,$$

$$\Delta_{\mu\nu} = g_{\mu\nu} + u_\mu u_\nu,$$

QCD come in here

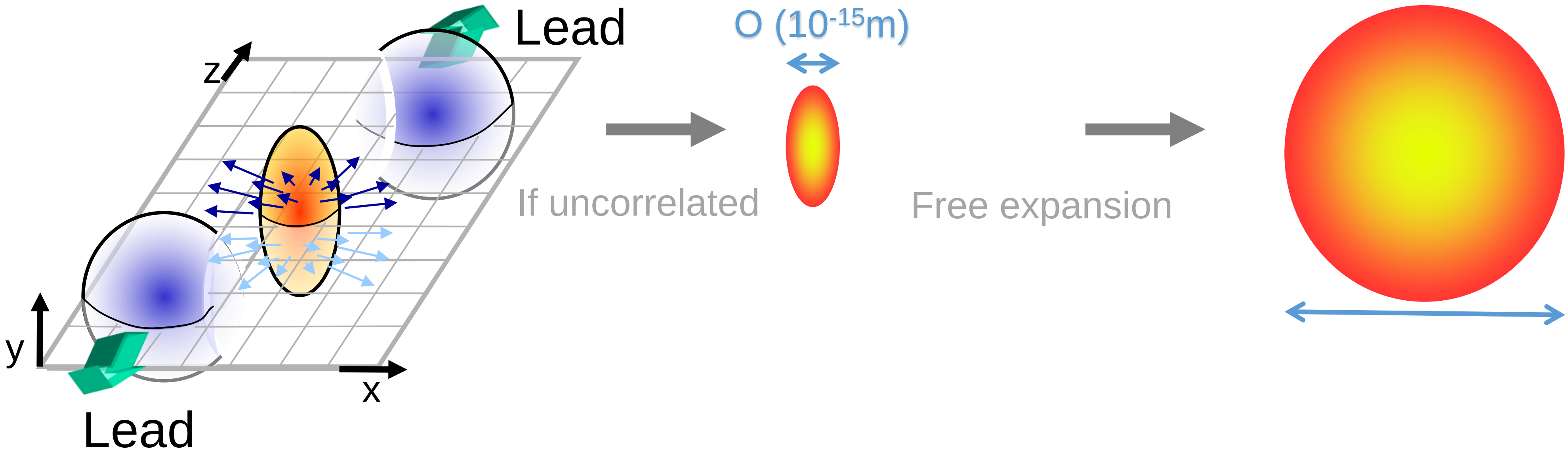
hydrodynamic evolution equations, $\nabla_\mu T^{\mu\nu} = 0$



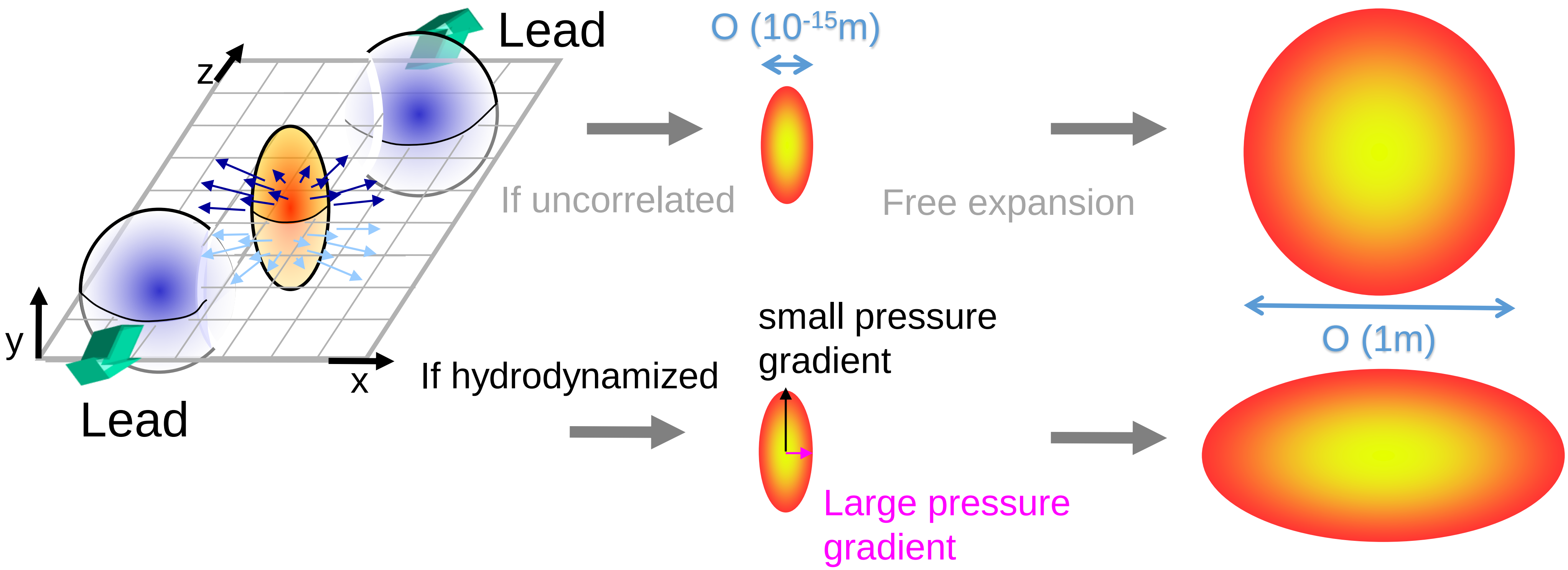
Can the debris isotropize (i.e., isotropic in the local QGP rest frame) and thermalize?

Isotropization

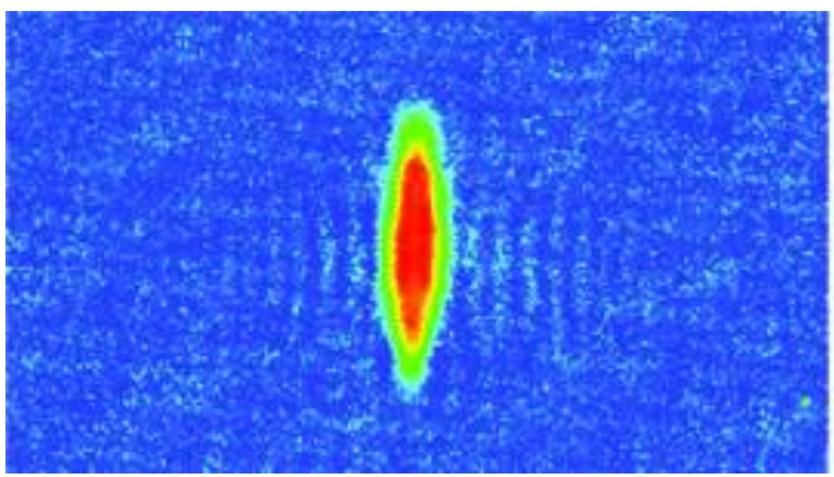
Free streaming vs. strong interacting



Free Streaming vs. Strongly Interacting

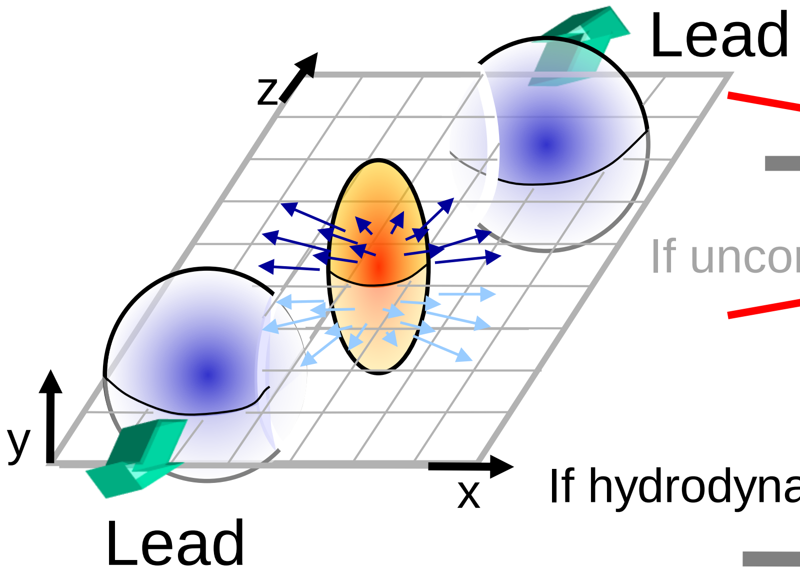


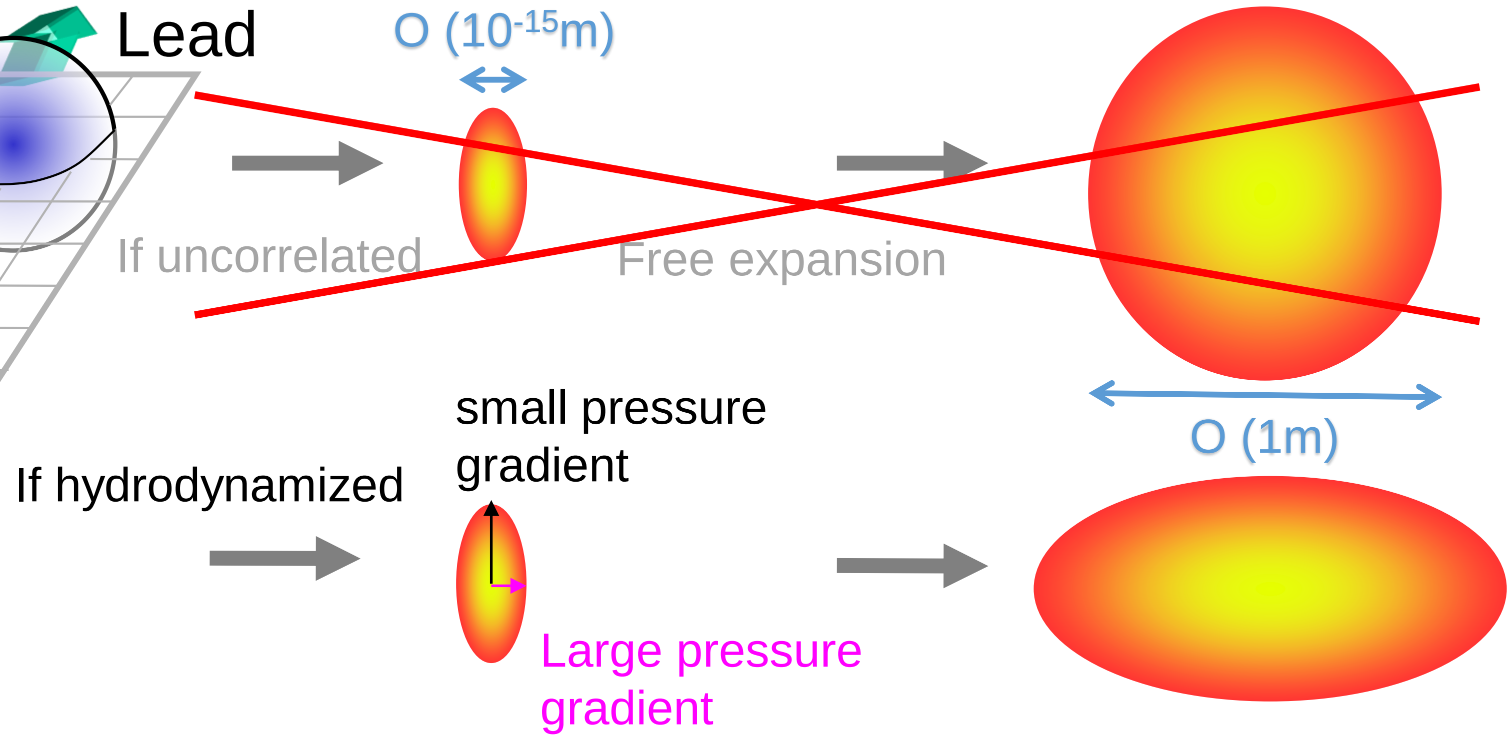
Expansion of Ultra-cold atoms released from trap



100 μs

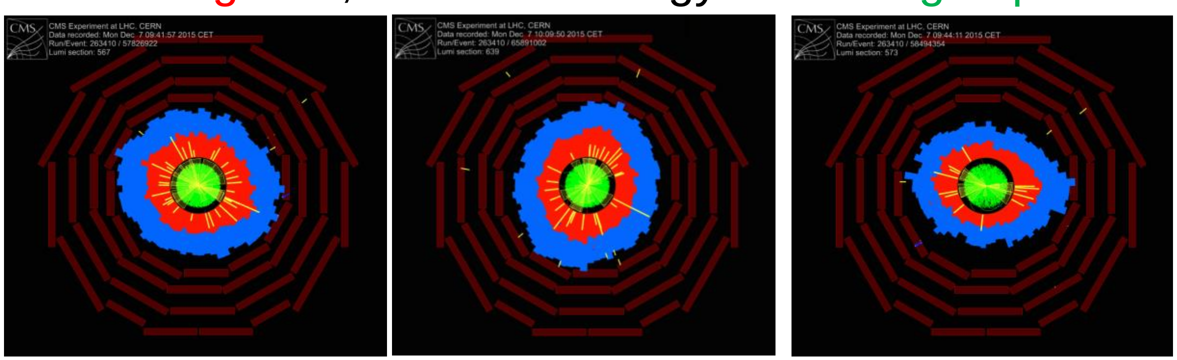
Free Streaming vs. Strongly Interacting



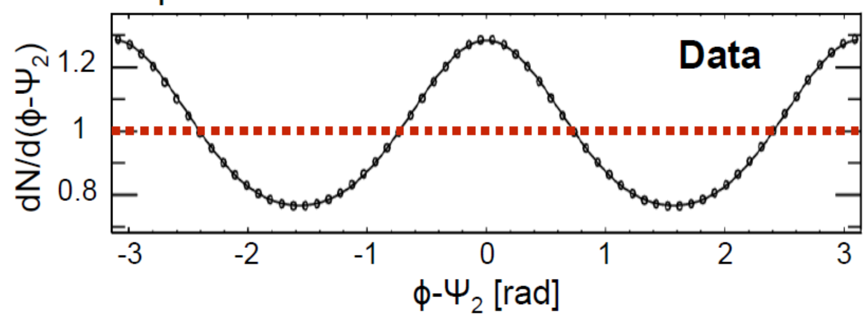


CMS detector:

Electromagnetic, Hadronic energy and charged particles



Anisotropic azimuthal distribution:

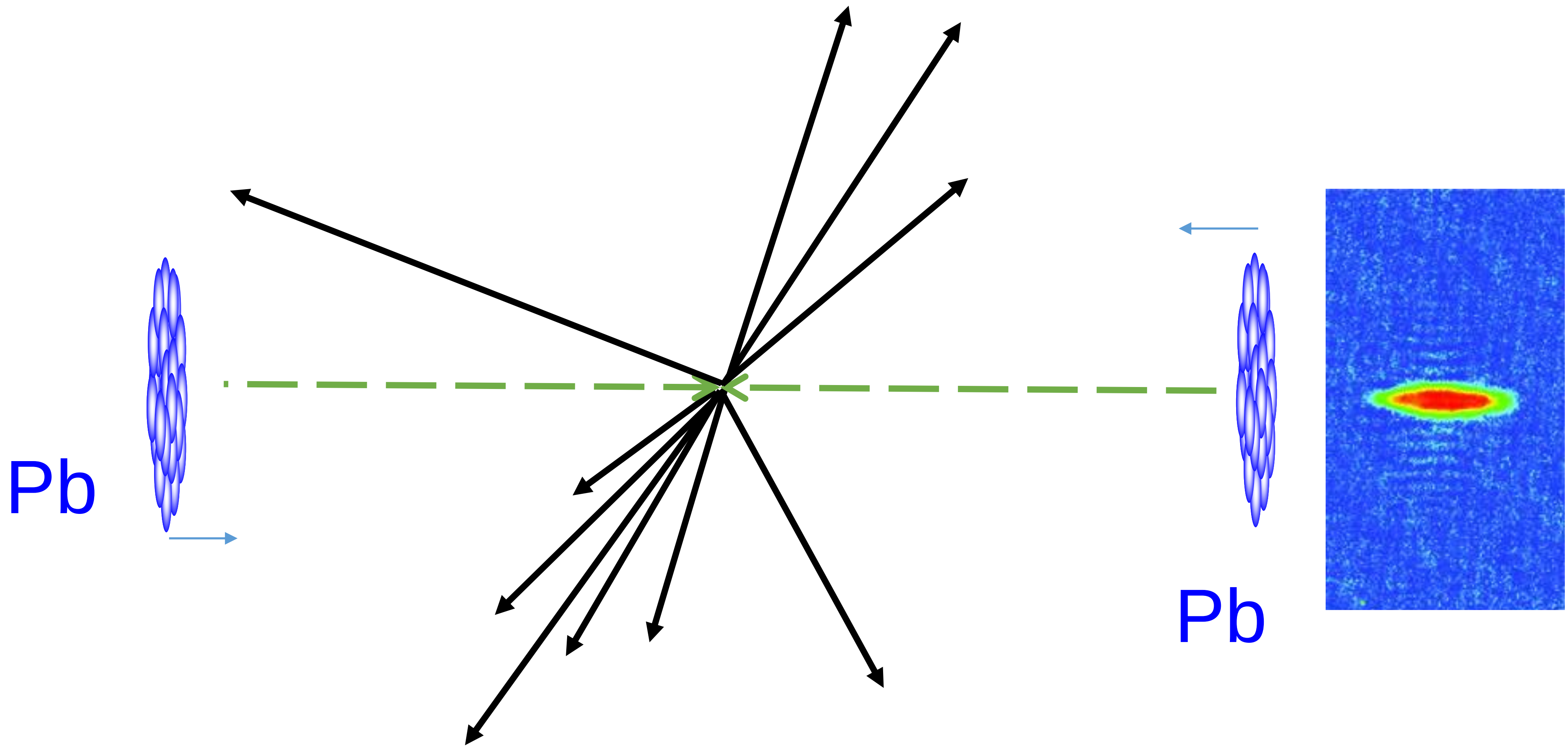


$dN/d(\phi-\Psi_2) \sim 1+2v_2\cos[2(\phi-\Psi_2)]$ v_2: elliptic flow

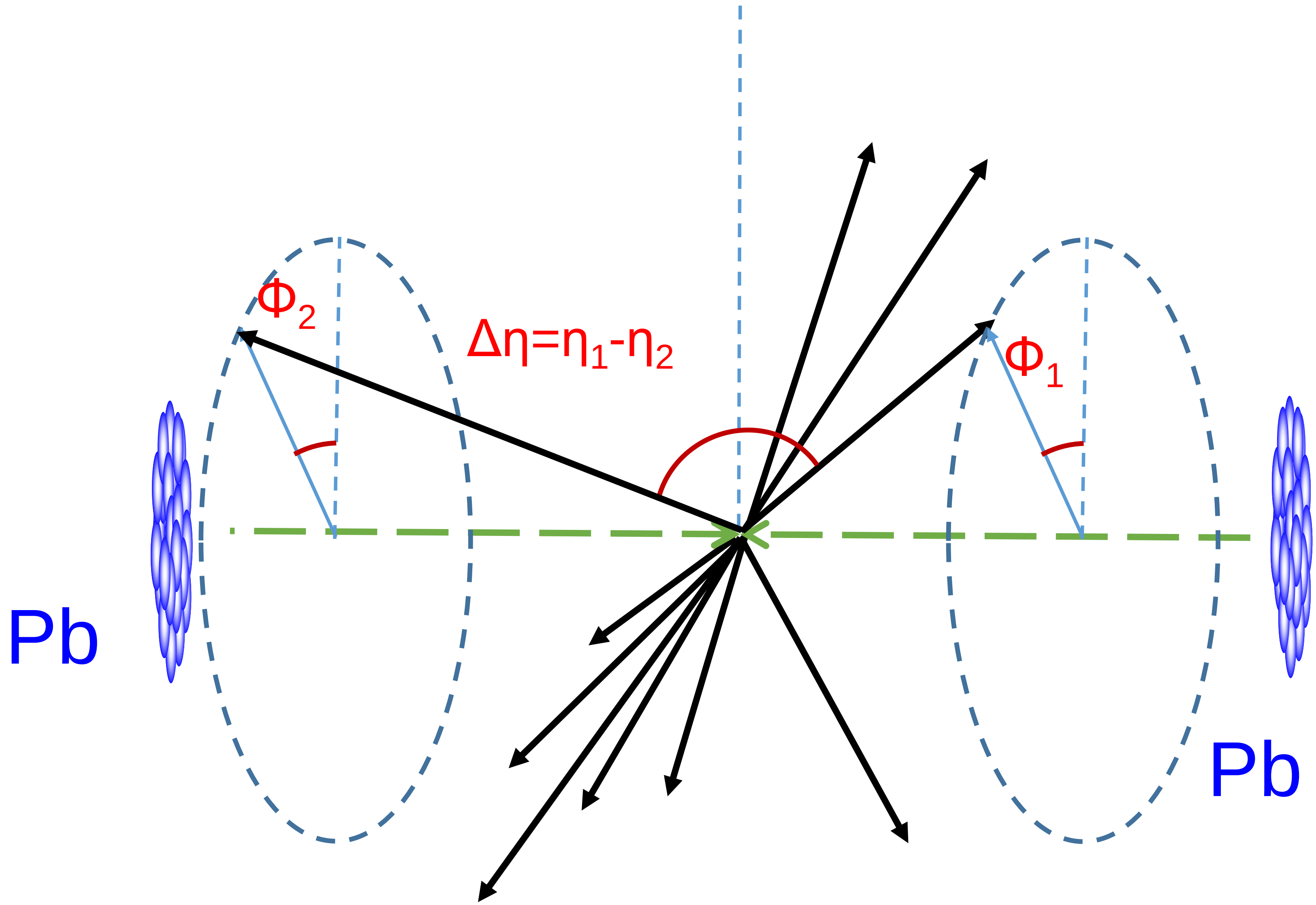
Particle azimuthal distributions

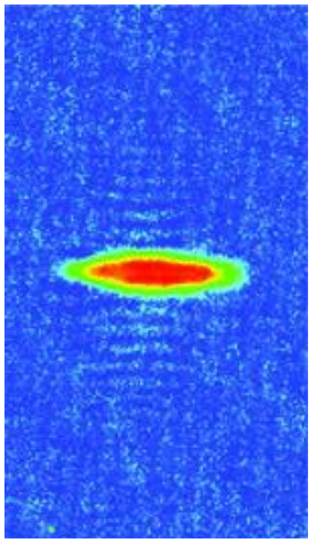
Collective motion is observed in the particle azimuthal distributions!! → **Early hydrodynamization**

Particle Angular Distribution

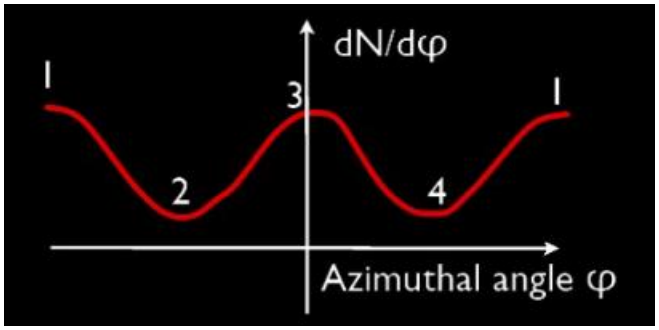


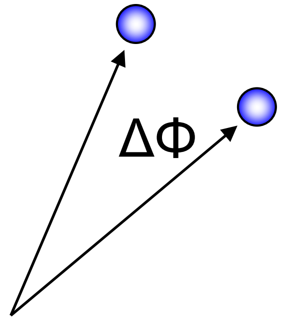
Particle Angular Distribution



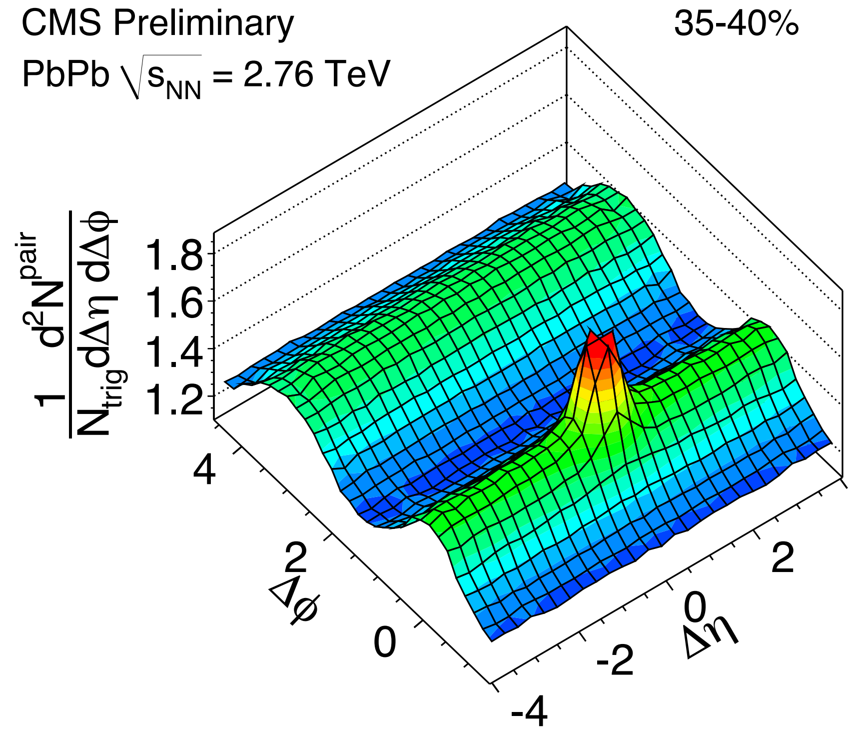


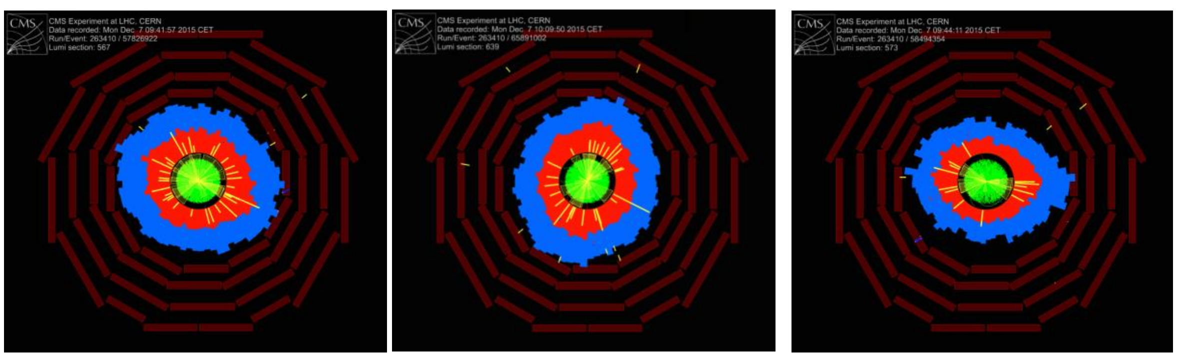
Have we created the Quark-Gluon Plasma?





Azimuthal angle difference between two charged particles



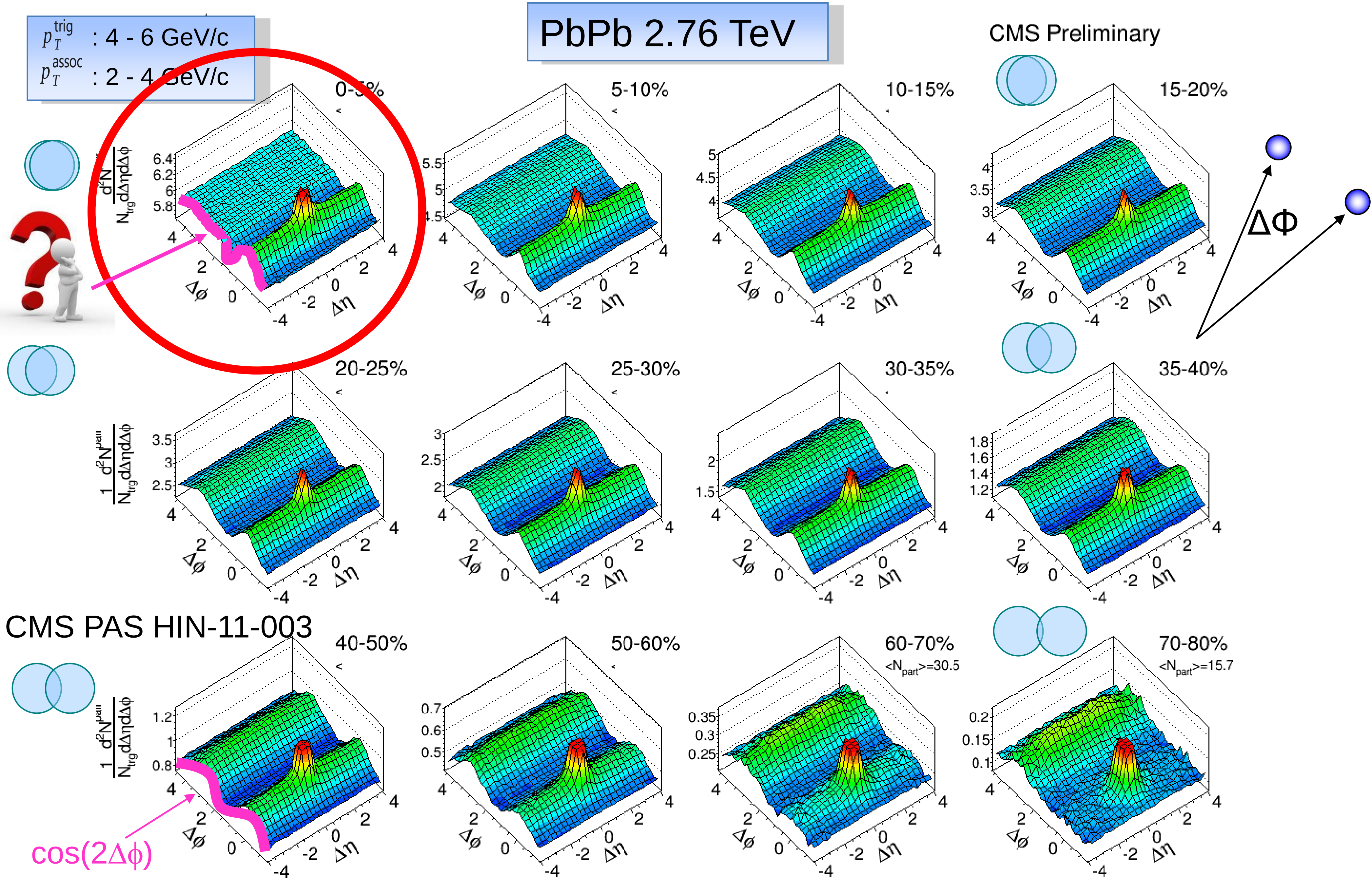


Particle azimuthal distributions:

$dN/d\phi \propto 1 + 2\, V_2 \cos(2\phi - \phi_0)$

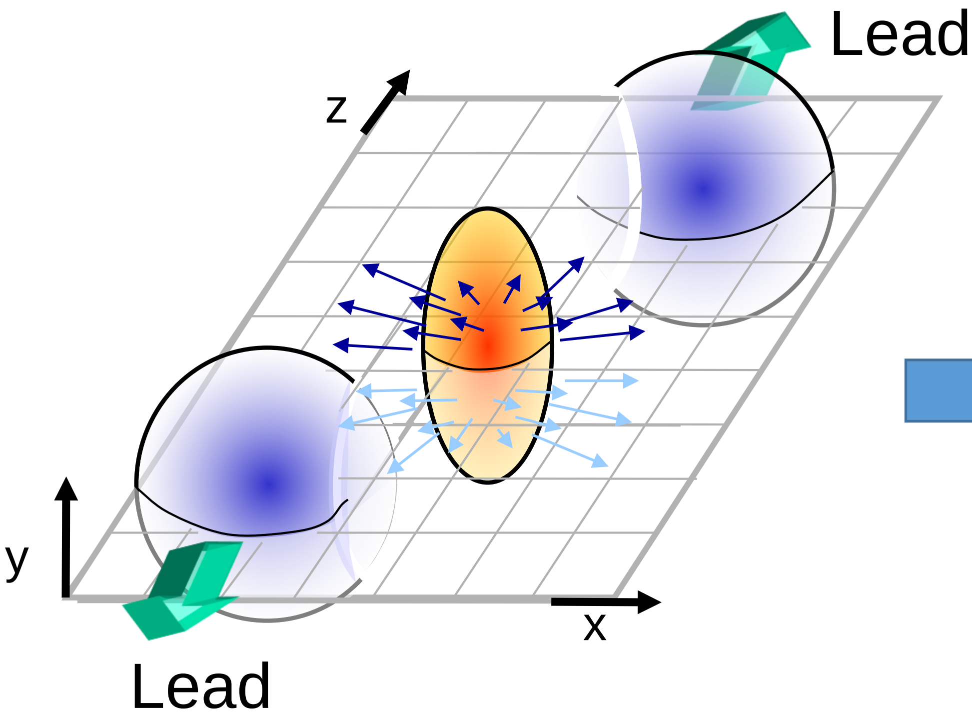
Collective motion is seen in the particle azimuthal distributions → Early hadrodynamization

Two-particle correlation: Centrality dependence in PbPb

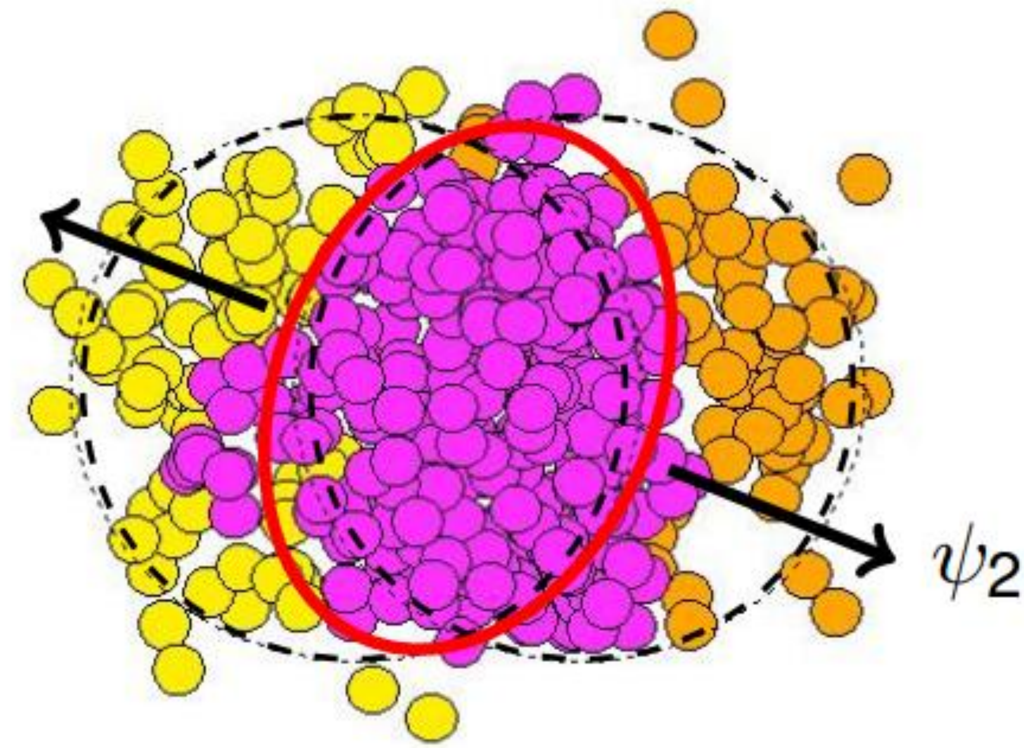


Initial Condition

"Classic view"



"Modern view"

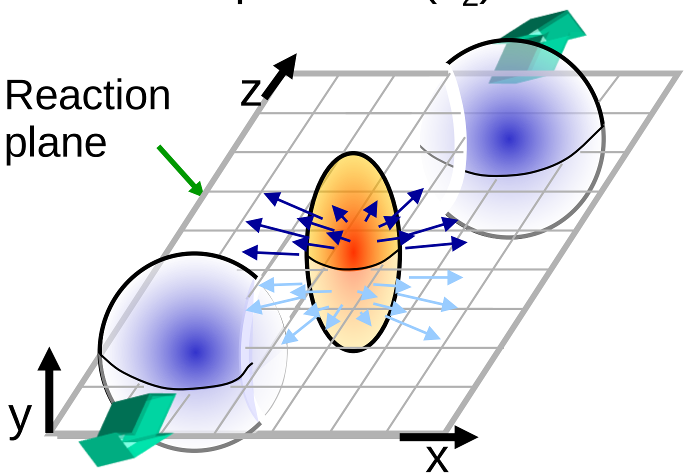


B. Alver & G. Roland *Phys. Rev. C81:054905, 2010*

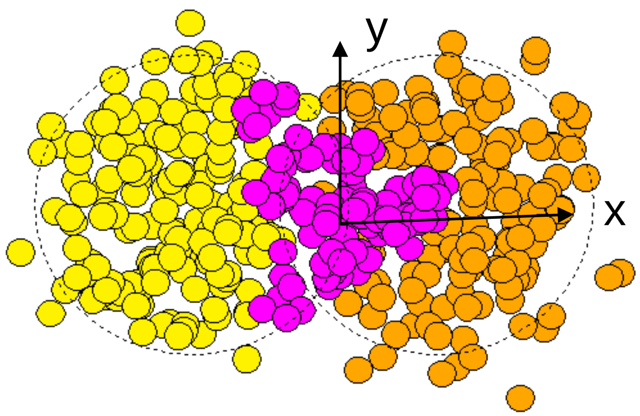
Fourier Decomposition

It was recently realized that the ridge may be induced just by higher order flow terms (v_2, v_3, v_4, v_5, …)

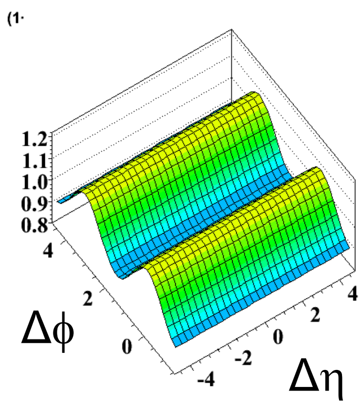
Elliptic flow (v_2)



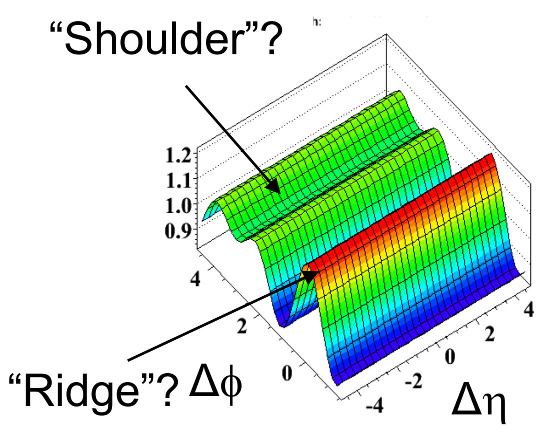
Triangular flow (v_3) from event-by-event fluctuation

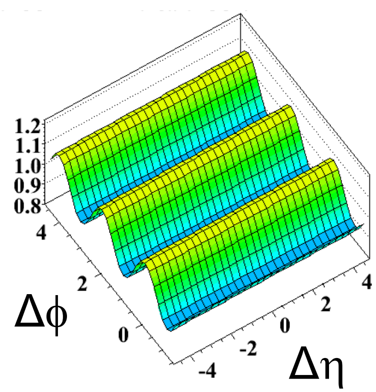


Add V_2 and V_3 together



~ $V_2 \cos(2\Delta\phi)$

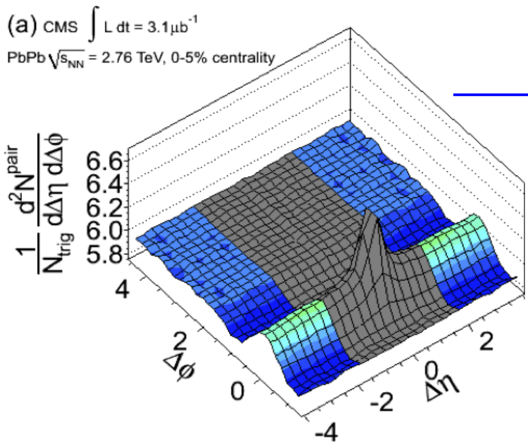


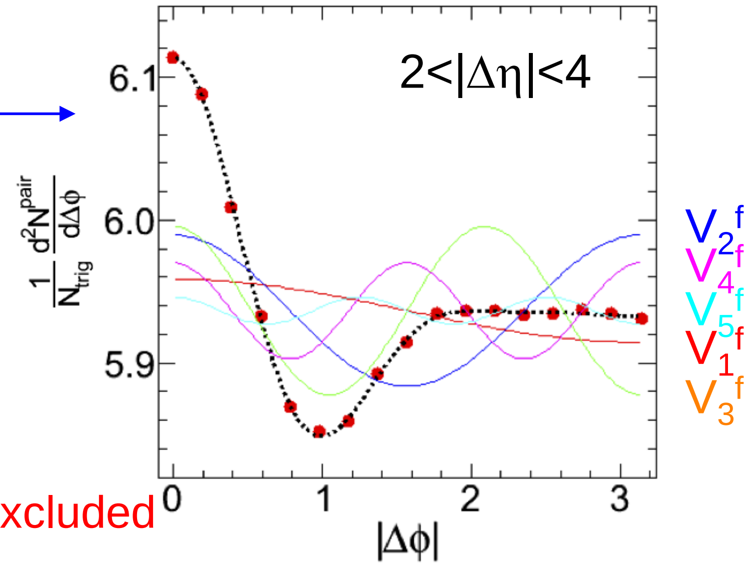


~ $V_3 \cos(3\Delta\phi)$

Fourier Decomposition of $\Delta\phi$ correlations

Fourier decomposition $$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left\{1 + \sum_{n=1}^{\infty} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$





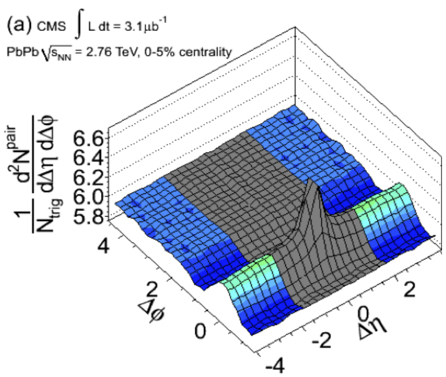
Short-range non-flow effects excluded

Flow driven correlations:

$$V_{n\Delta} \sim v_n^{\mathrm{trig}} \times v_n^{\mathrm{assoc}}$$

(f: Fourier analysis of long-range dihadron correlations)

ArXiv:1105.2438
JHEP 1107:076,2011



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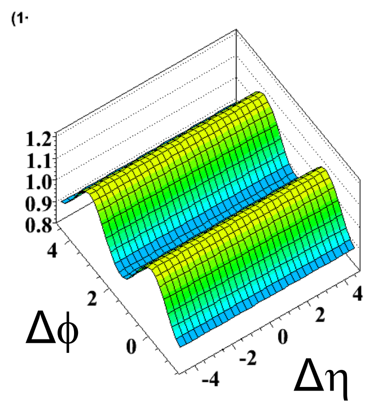
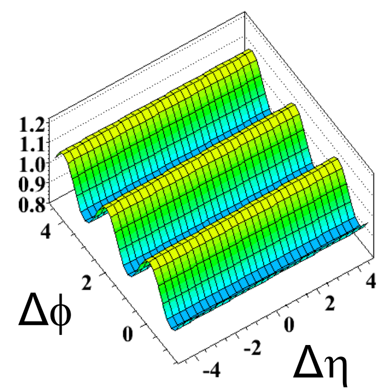


~ $V_2 \cos(2\Delta\phi)$

+



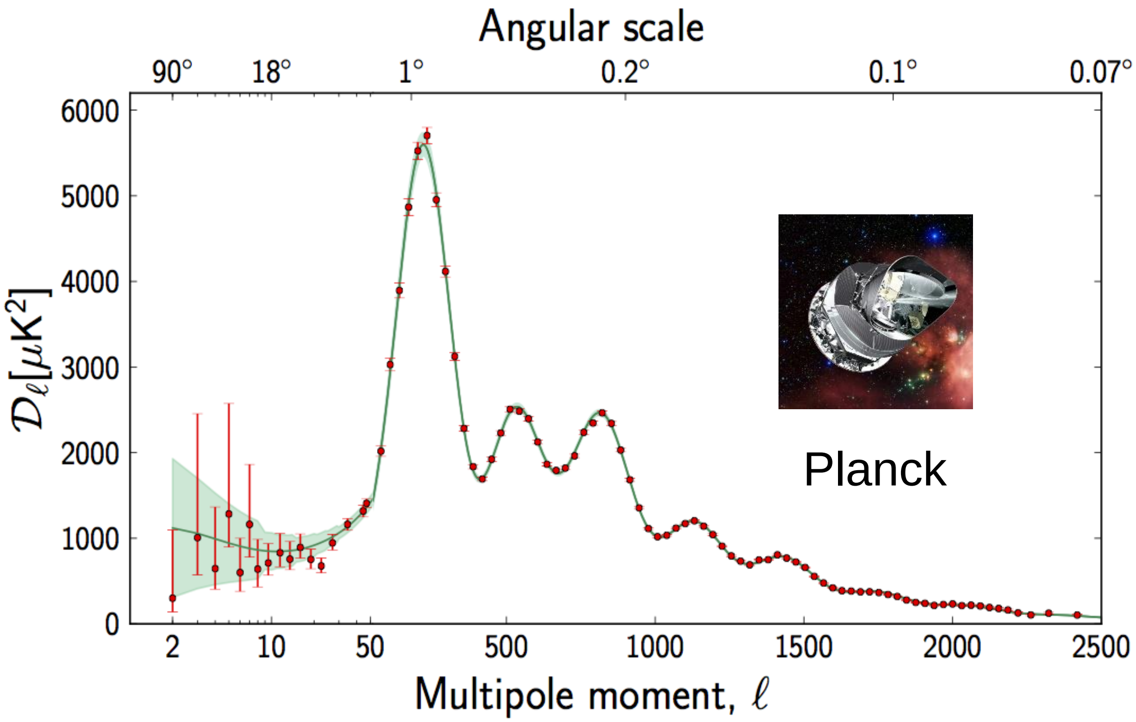
~ $V_3 \cos(3\Delta\phi)$

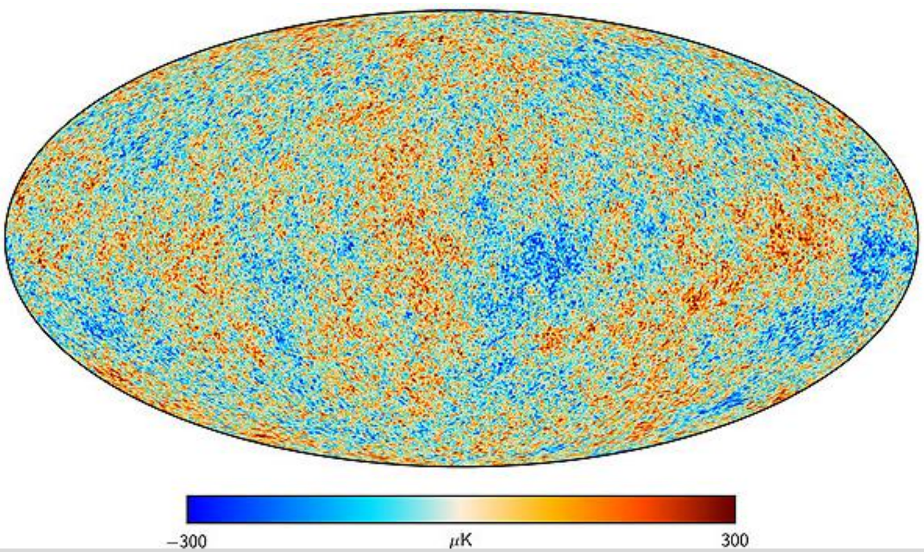
+ … …

Higher order terms

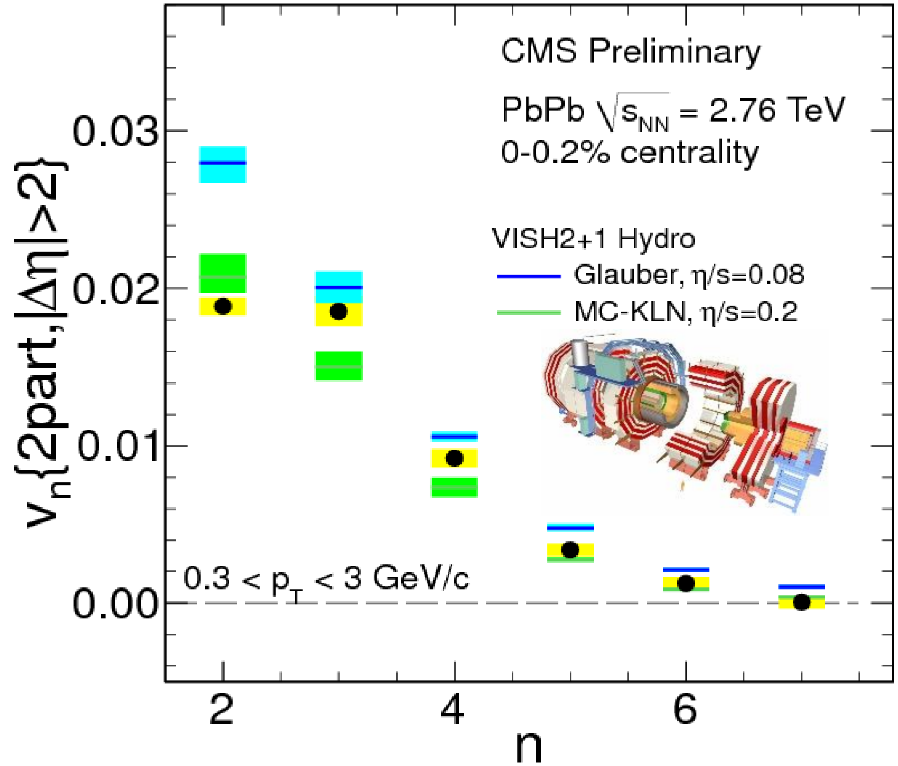
Density Fluctuation

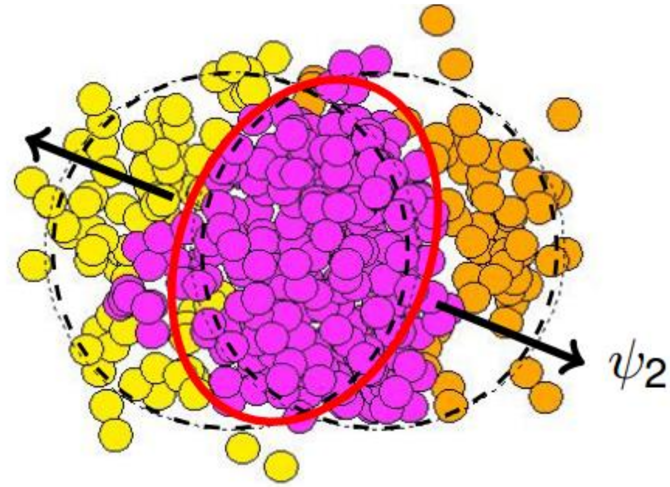
Power spectrum of the Big Bang





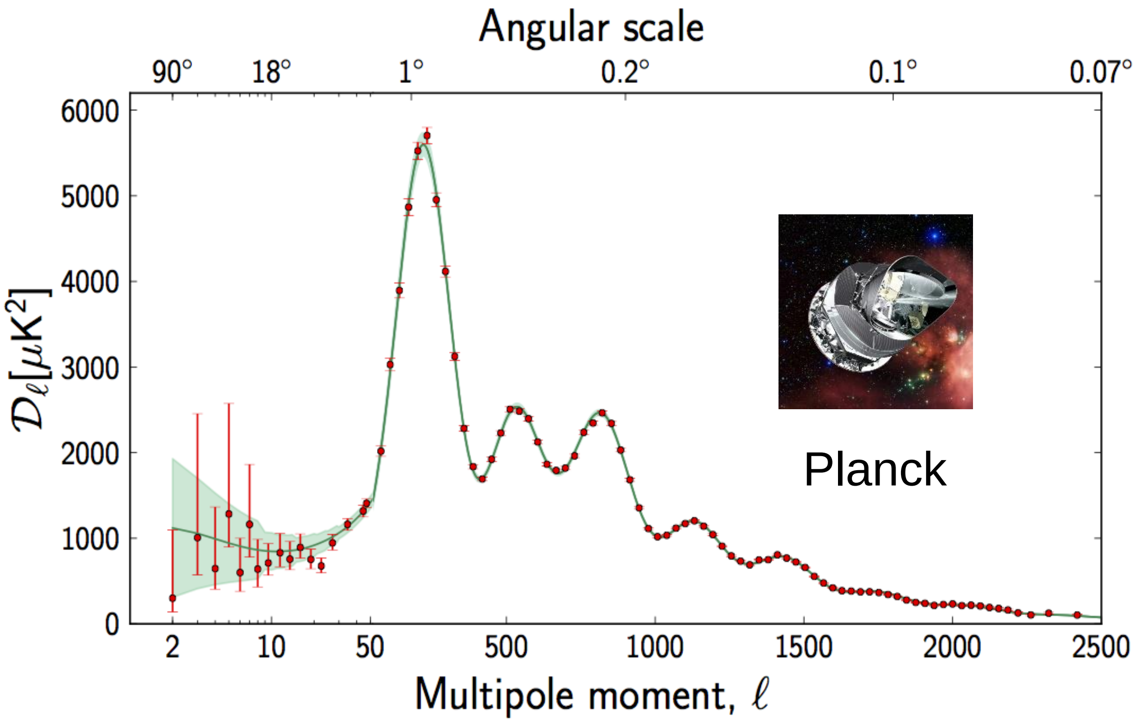
Fourier analysis of many little bangs

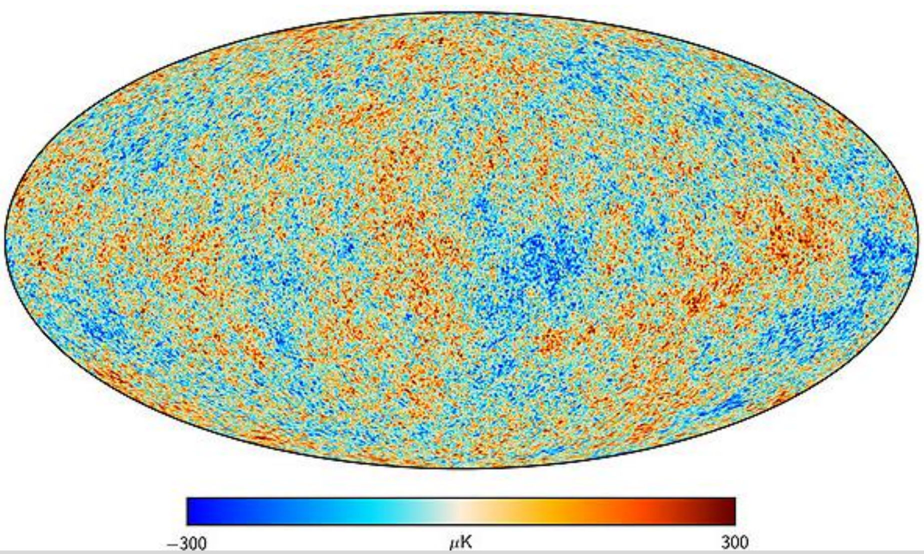




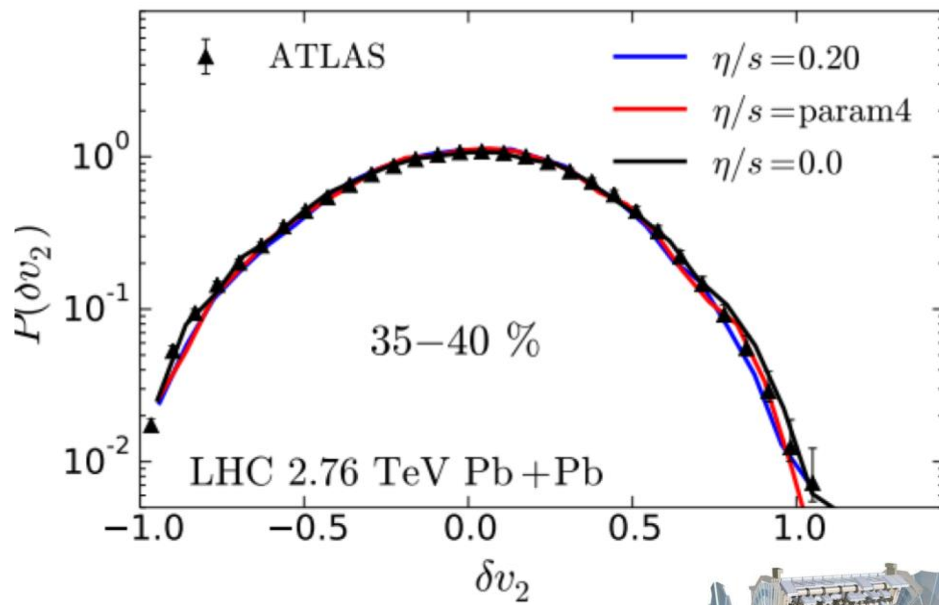
Density Fluctuation

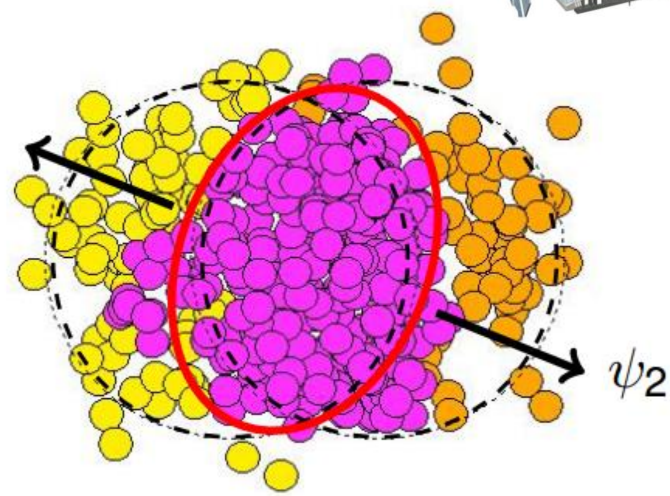
Power spectrum of the Big Bang





Fourier analysis of many little bangs
Event by event!!!



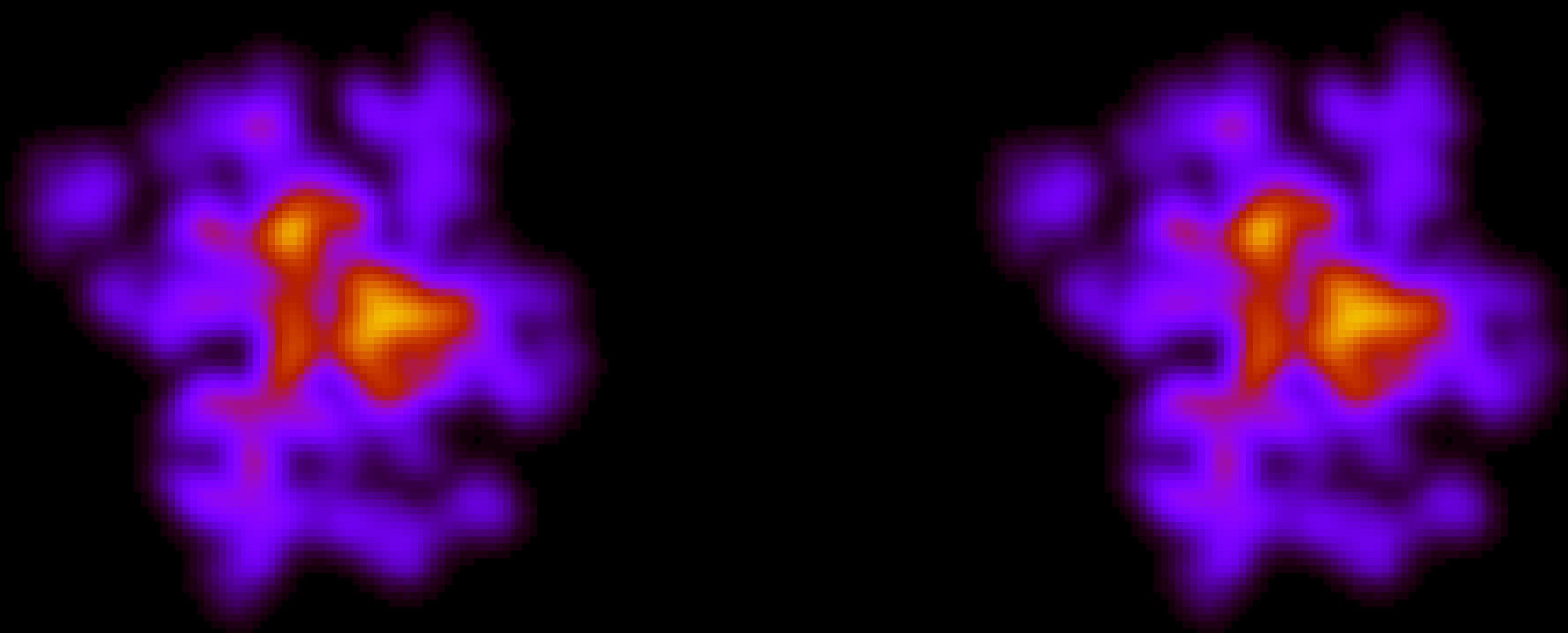


Effect of Shear Viscosity

Animation made by Bjorn Schenke
https://quark.phy.bnl.gov/~bschenke/

Ideal hydrodynamics

Viscous hydrodynamics



t = 0.5 fm/c

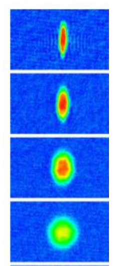
Alver and Roland (MITHIG)
“Collision geometry fluctuation”
PRC82 (2010) 039903

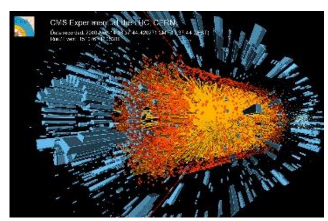
Flow coefficients (v^f_n) vs centrality and viscosity

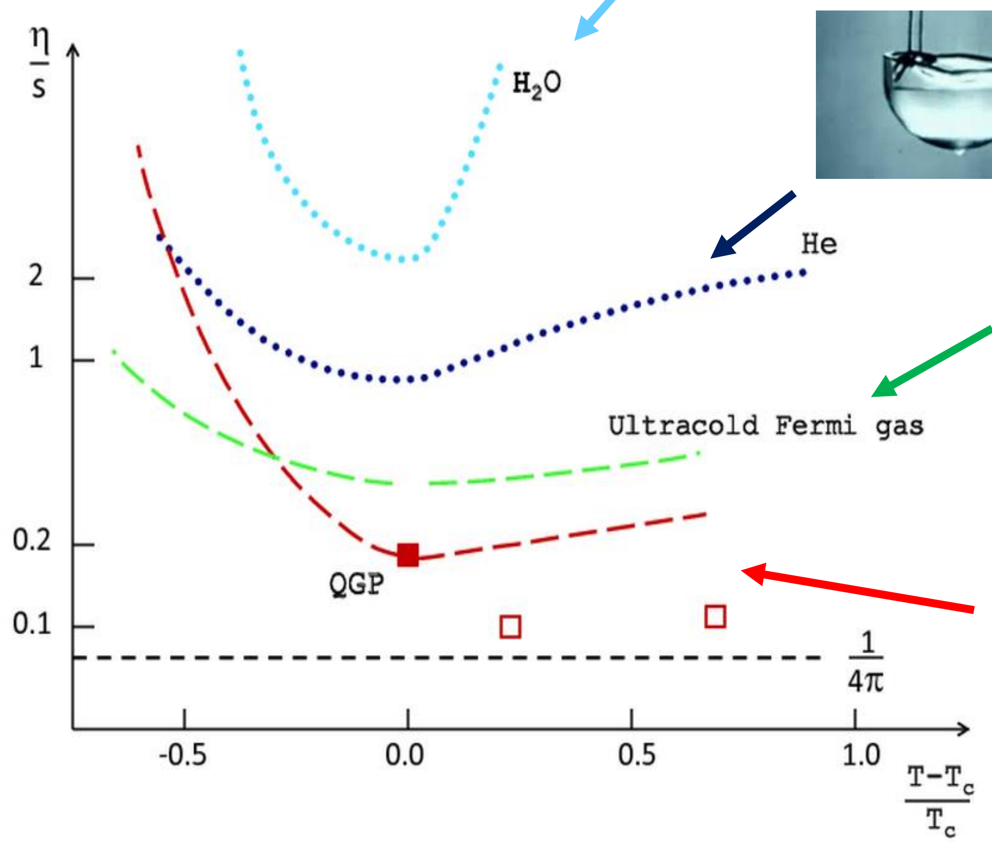
$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{N_{\rm assoc}}{2\pi}\left\{1+\sum_{n=1}^{\infty}2V_{n\Delta}\cos(n\Delta\phi)\right\}$$

Can be explained by hydrodynamics calculation + Initial state fluctuation

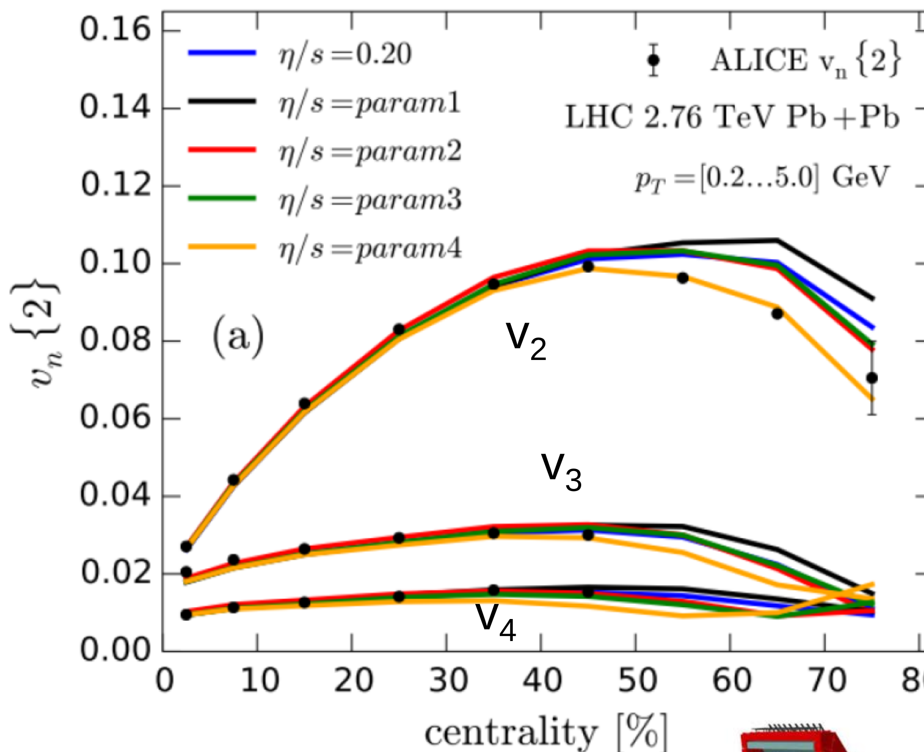
Shear viscosity to entropy ratio

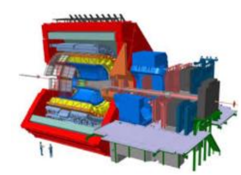






Temperature





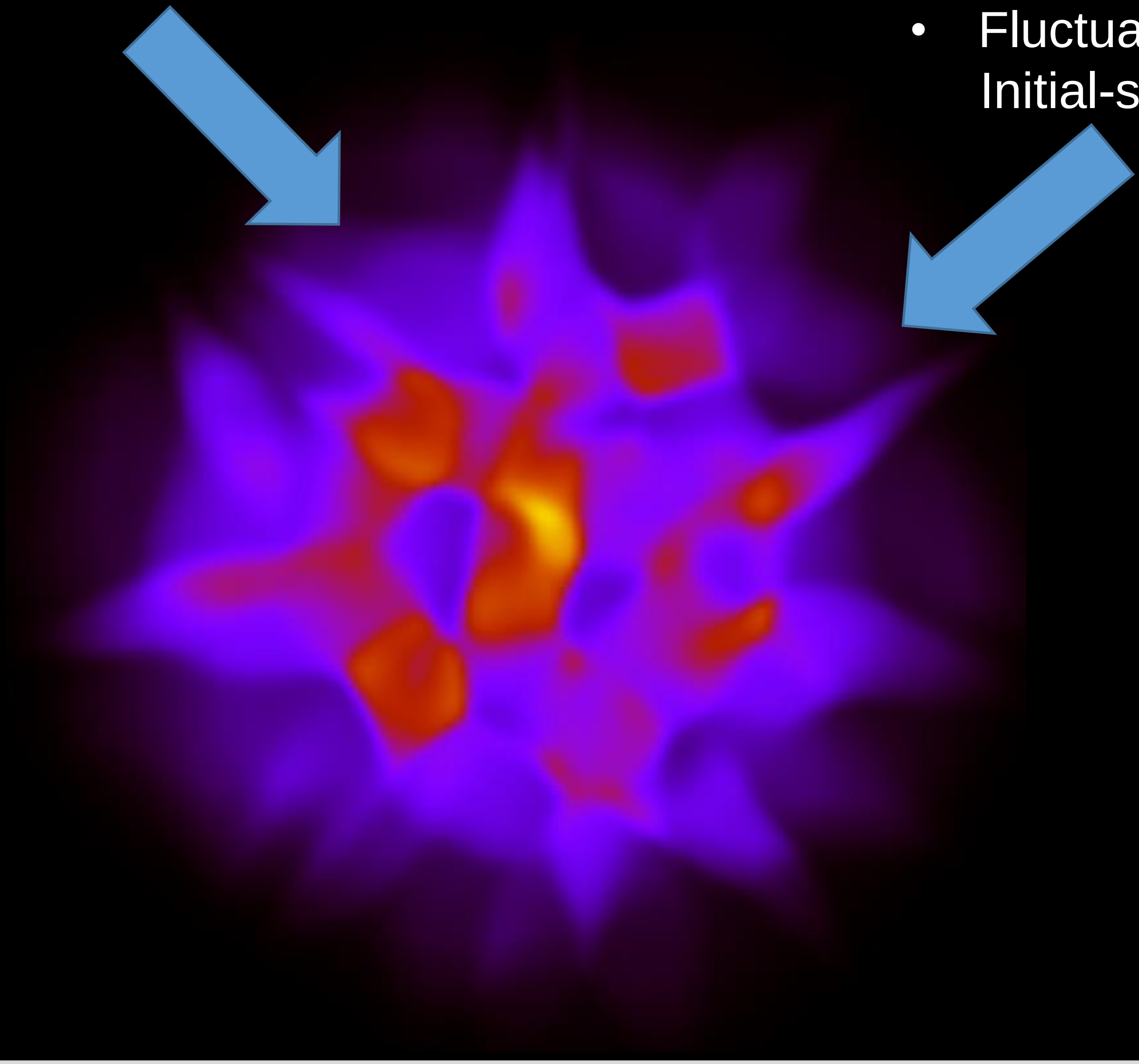
Prepare the Quark Soup

Particle Multiplicity

- Collision impact parameter
- Energy density

Azimuthal anisotropy

- Early thermalization <1 fm/c
- Shear viscosity
- Fluctuation of v_N coefficients: Initial-state geometry fluctuation



What have we learned so far?

- The produced medium is strongly interacting
- Based on hydrodynamics models with the equation of state from lattice QCD calculation:
  - Initial state fluctuations (leads to elliptic flow (v_2) triangular flow (v_3) …)
  - The system has to hydrodynamize extremely fast start from around **0.2 – 1 fm/c** to produce the observed azimuthal anisotropy
  - Isotropization / complete thermalization could take as long as **a few fm/c**
  - Both shear viscosity (η) and the entropy (s) of the produced medium are **HUGE**
  - The extracted η/s ratio is **extremely small** (smaller than any known materials), close to ideal fluid

What we still don't know very well

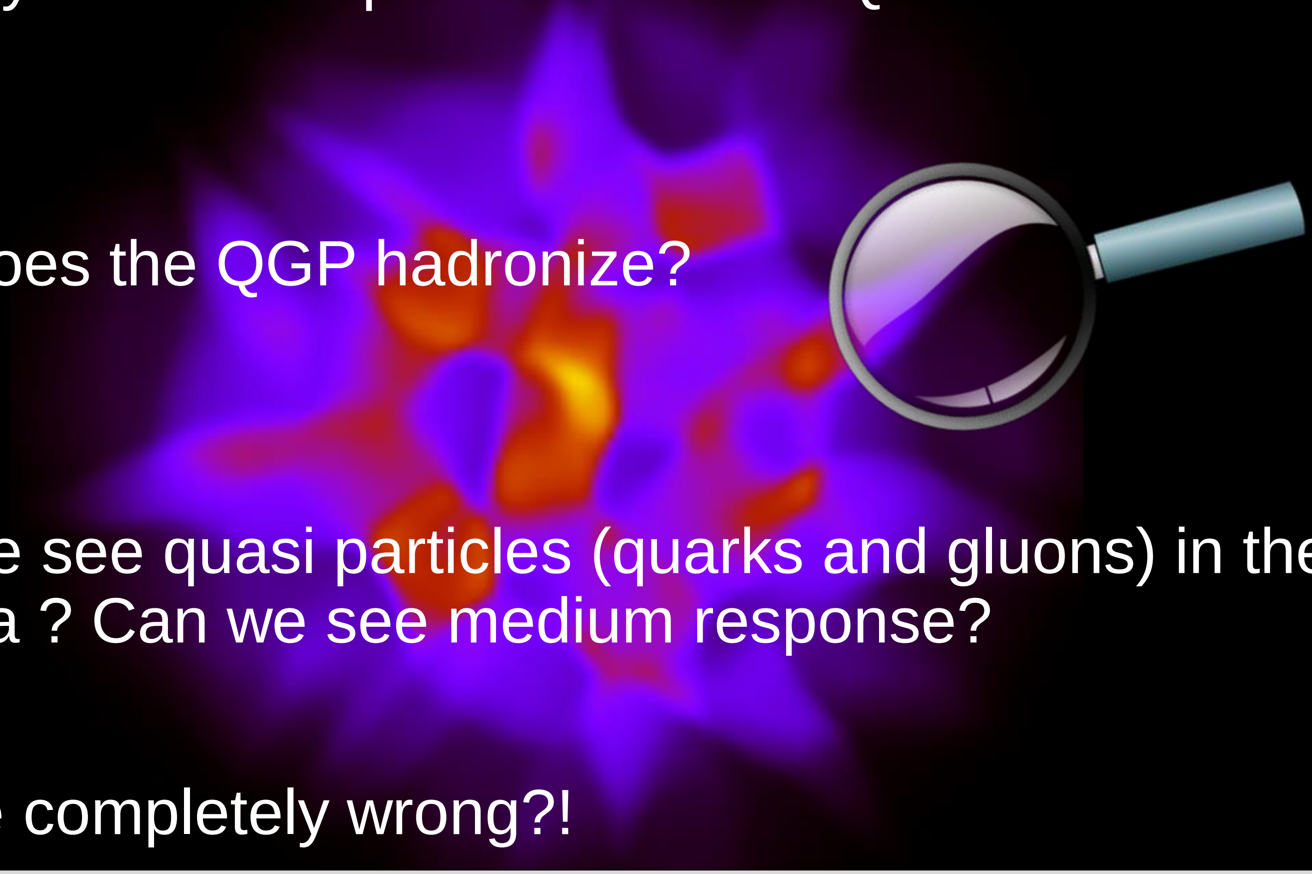
- Why is the system hydrodynamize so fast? How does the strongly interacting medium emerge from an asymptotic free theory?
- What is the initial transverse fluid velocity and the role of the pre-hydrodynamization phase? When is QGP formed?
- How does the QGP hadronize?
- Can we see quasi particles (quarks and gluons) in the Quark Gluon Plasma ? Can we see medium response?
- Are we completely wrong?!

What we still don’t know very well

- Why is the system hydrodynamize so fast? How does the strongly interacting medium emerge from an asymptotic free theory?

Start from “un-thermalized” objects and see how they are hydrodynamized / thermalized in the Quark Soup

- What is the initial transverse fluid velocity and the role of the pre-hydrodynamization phase? When is QGP formed?



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Study hard probes with different formation time
Final a way to "turn off" temporarily the interaction with QGP

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Study the hadronization of a hard scattered partons and heavy quarks

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  Shoot colored objects through the QGP

- Are we completely wrong?!

What we still don’t know very well

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Shoot colored objects through the QGP

- Are we completely wrong?! **Extract medium properties with probes**