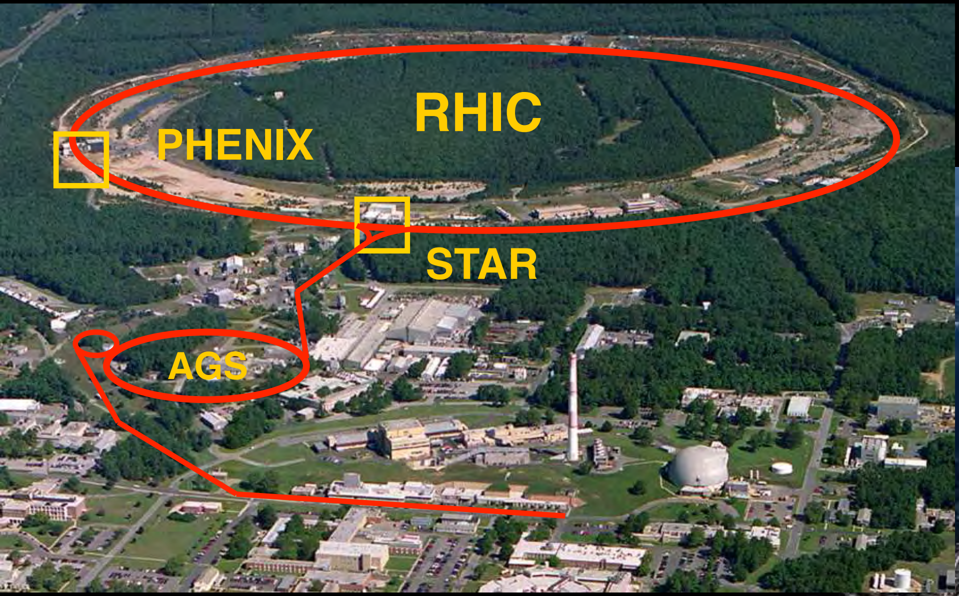
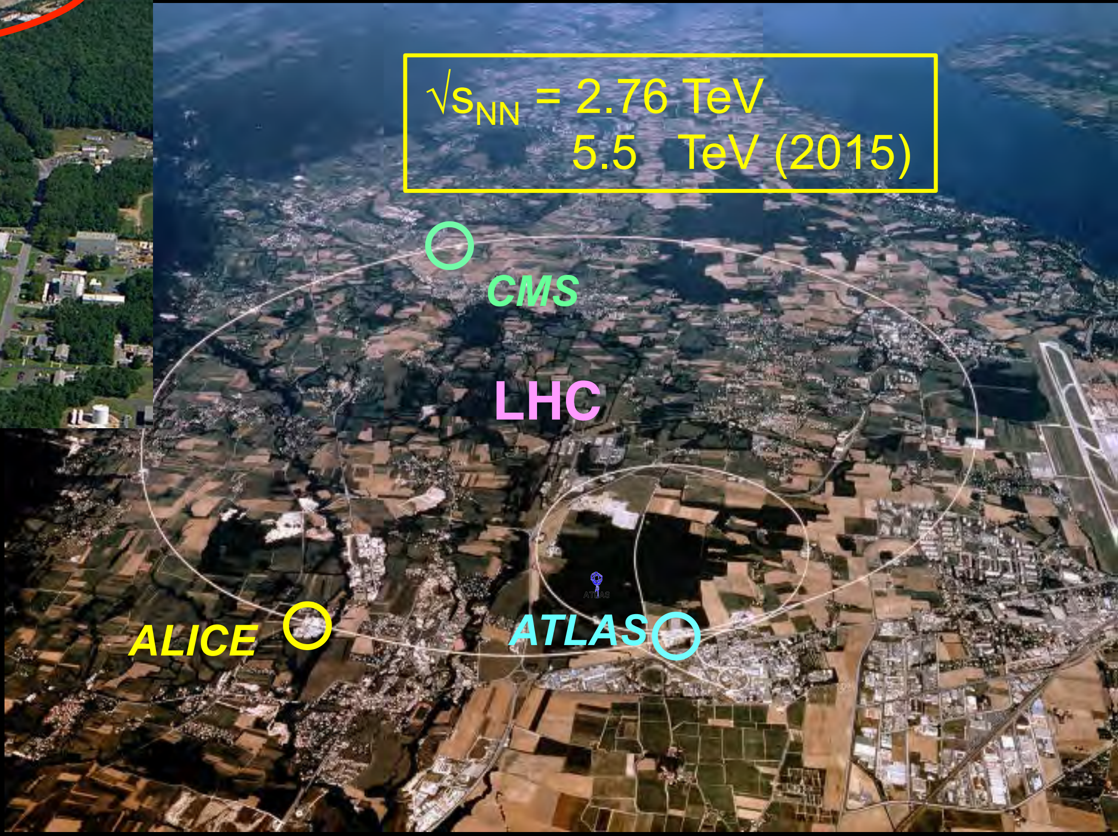
Creating the Primordial Quark-Gluon Plasma at RHIC and the LHC



$\sqrt{s_{NN}}$ = 5 - 200 GeV

Cover 3 decades of energy in center-of-mass



$\sqrt{s_{NN}}$ = 2.76 TeV
5.5 TeV (2015)

Investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

Top Ten Physics Newsmakers of 2000 – 2010

*http://**www.aps.org/publications/apsnews/201002/newsmakers.cfm***

"Stories with the most lasting physical significance & impact in physics"

*The **Large Hadron Collider (LHC)*** – modern marvel of science, last piece of standard model.

*The **Decade of Carbon*** – carbon nanotubes & graphene, will revolutionize electronics.

Negative Index of Refraction Materials – meta-materials make objects seem to disappear.

The Wilkinson Microwave Anisotropy Probe – leftover heat from Big Bang.

Quantum Teleportation – quantum information transport across macroscopic distances.

Quark-Gluon Plasma – first instances after Big Bang, all matter as hot quarks & gluons.

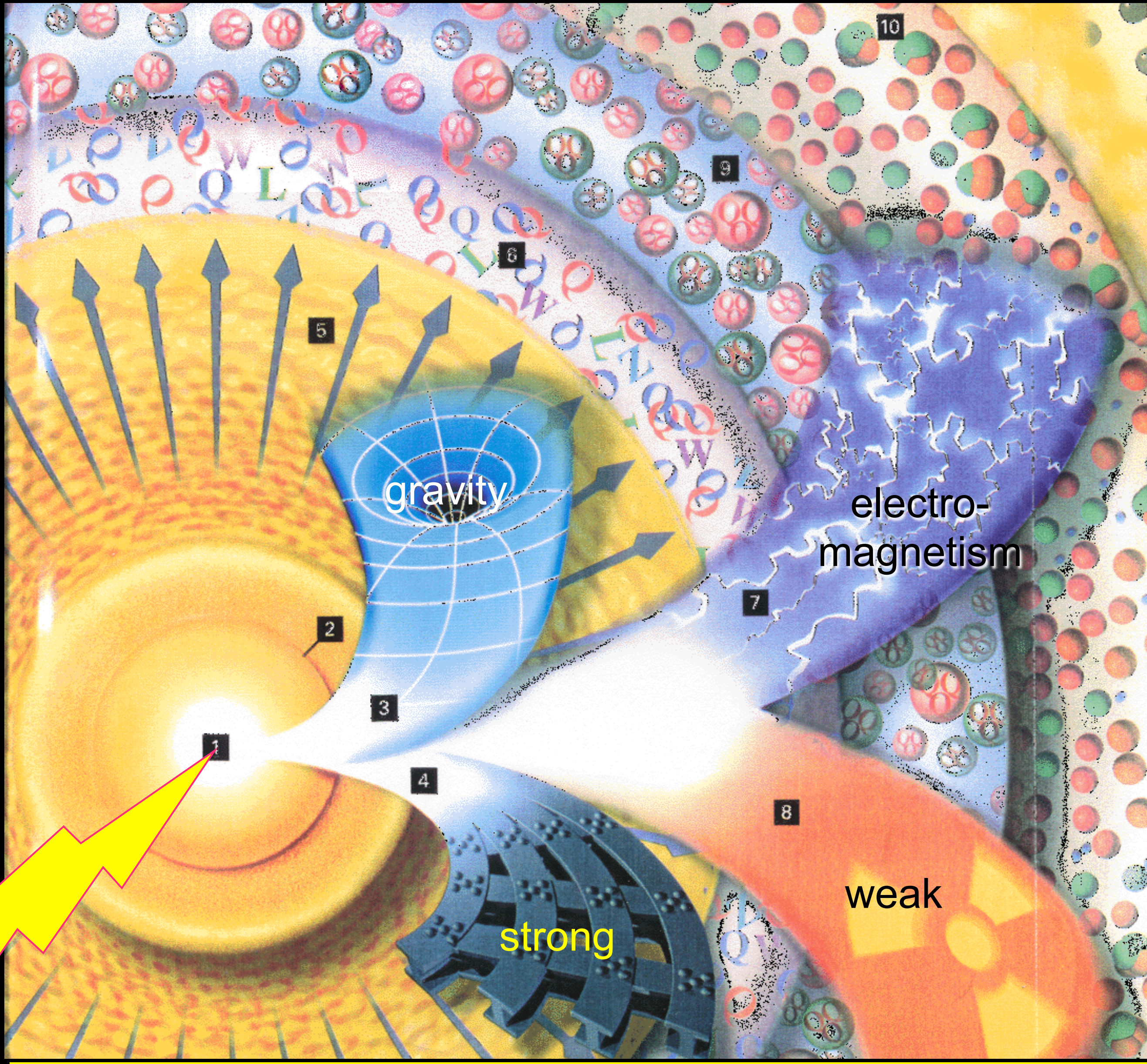
Gravity Probe B – observed the geodetic effect (to look for frame dragging in general relativity).

Light Stopped – actually stopped altogether and stored for up to 20 milliseconds.

Direct Evidence for Dark Matter – two colliding galaxies confirm presence of dark matter.

Advances in Computing – $> 10^{15}$ calculations / sec., map bio-structures, supercomputers.

On the "First Day"



There was light!

Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
Consultants – Michael S. Turner and Sandra M. Faber

On the "First Day"

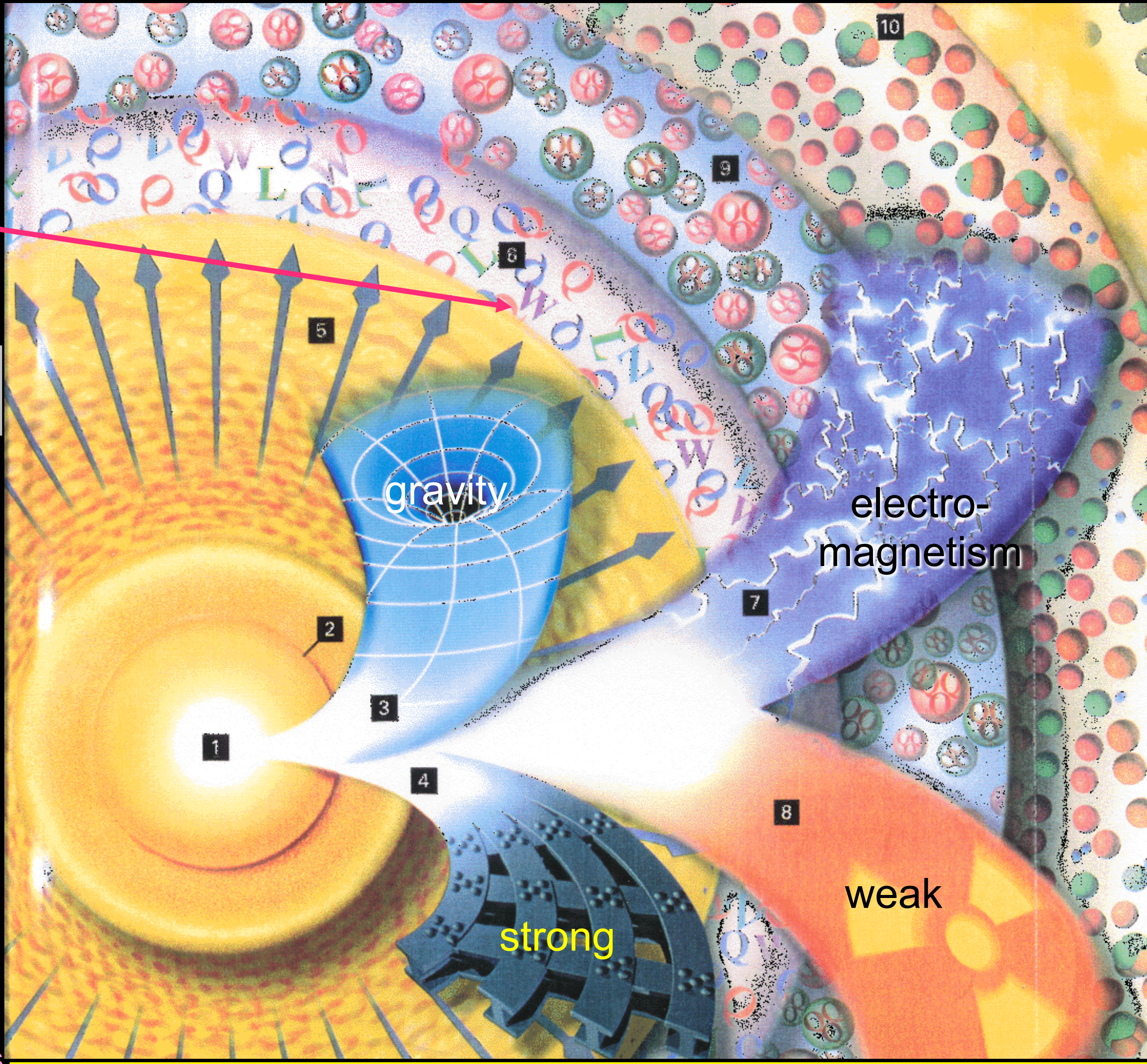
then at 10 μ-seconds
& 2 x 10^{12} Kelvin
Quark-to-hadron*
phase transition

Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W
forces separate

at 10^{-43} seconds



* hadrons = nuclear particles
= mesons, baryons

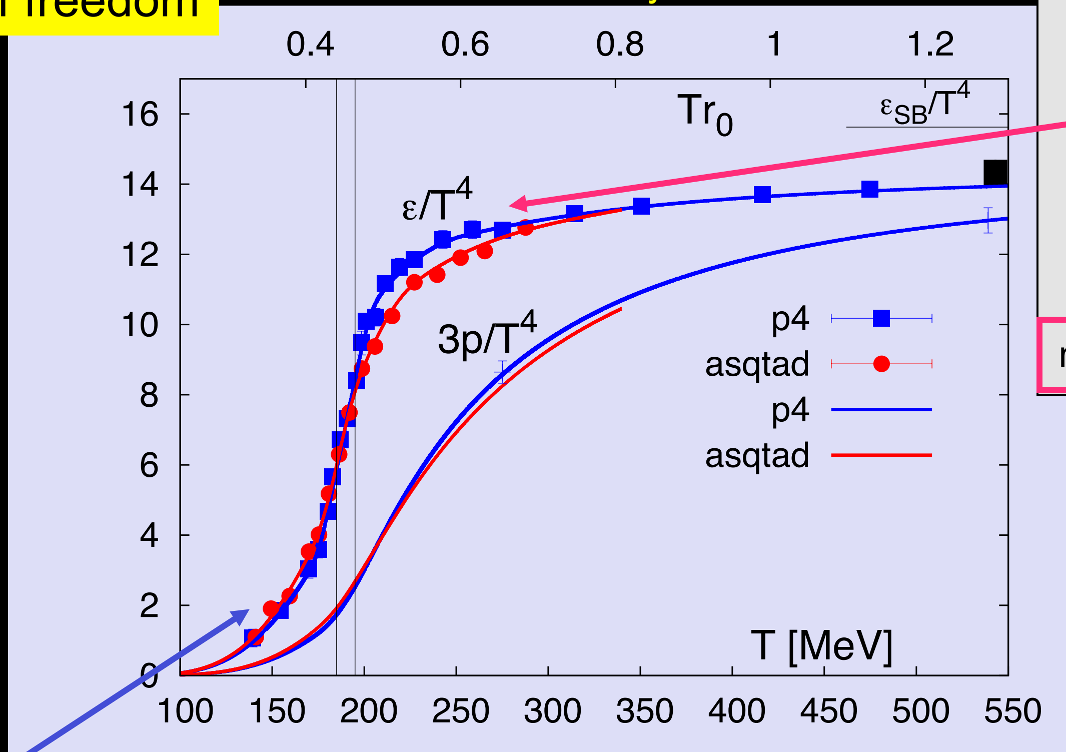
Courtesy Nat. Geographic, Vol. 185, No. 1, 1994 – Graphics by Chuck Carter
Consultants – Michael S. Turner and Sandra M. Faber

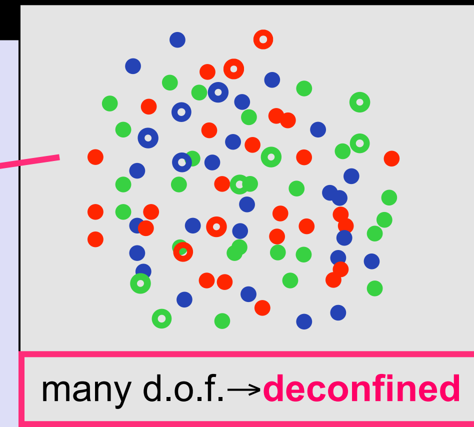
Behavior of QCD* at High Temperature

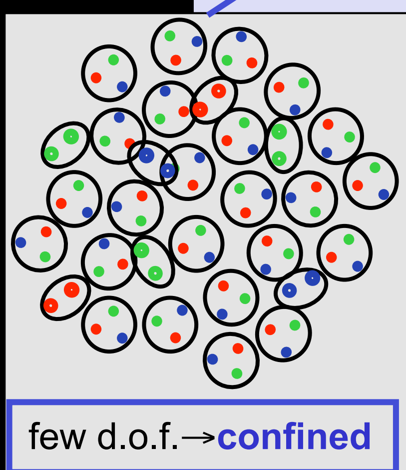
* Quantum Chomo-Dynamics

ε/T^4 ~ # degrees of freedom

$$\varepsilon = \frac{\nu\pi^2}{30}T^4$$



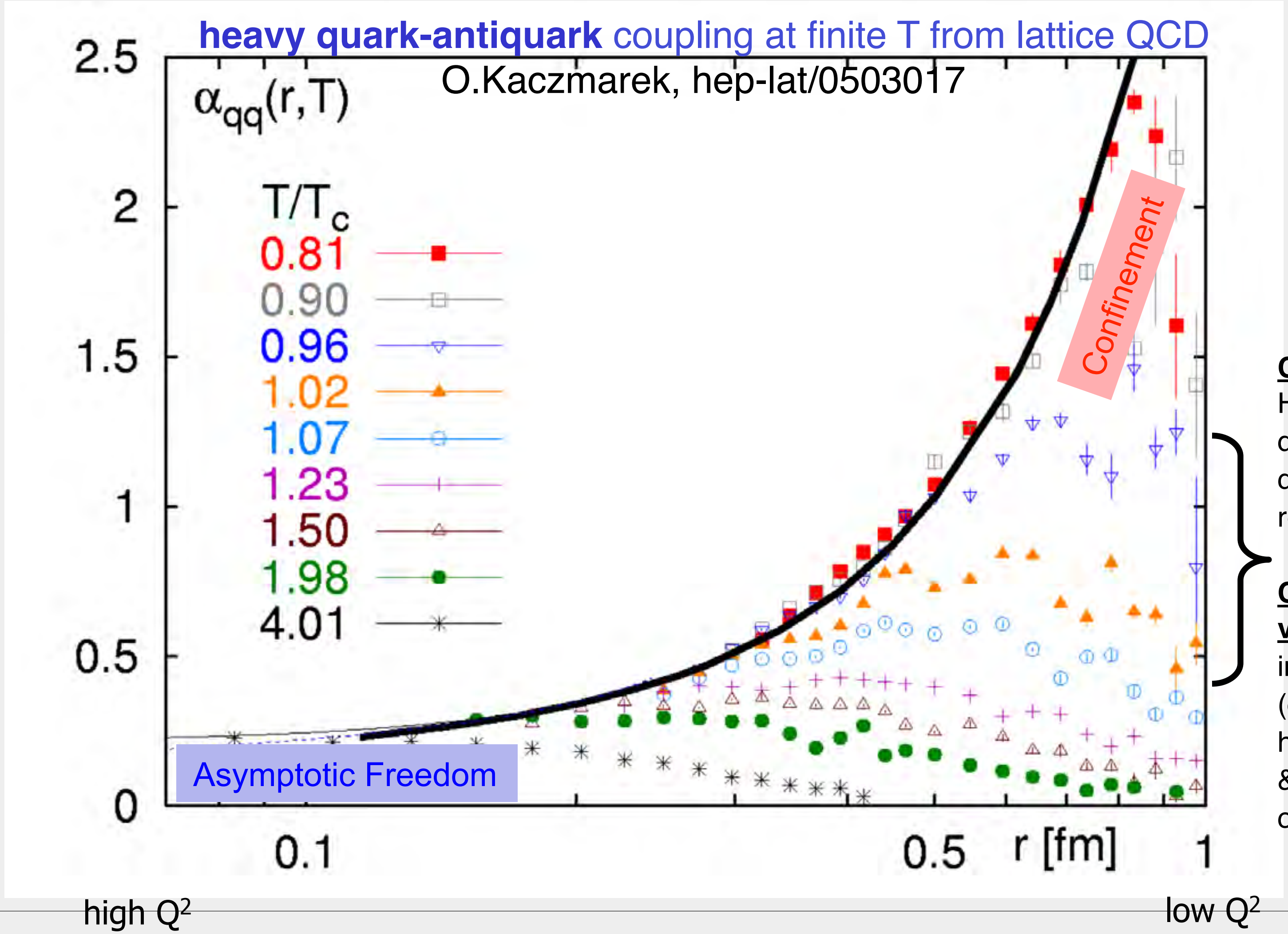




A. Bazavov et al, Phys. Rev. D80 (2009) 014504
P. Petreczky, Journal of Physics G39 (2012) 093002

T_C ~ 185 – 195 MeV → ε_C ~ 0.3 - 1 GeV/fm^3

Modifications to QCD Coupling Constant α_s



Constituents - Hadrons, dressed quarks, quasi-hadrons, resonances?

Coupling strength varies investigates (de-)confinement, hadronization, & intermediate objects.

Modifications to QCD Coupling Constant α_s

Nobel Prize 2004

D. Gross
H.D. Politzer
F. Wilczek

QCD Asymptotic Freedom (1973)

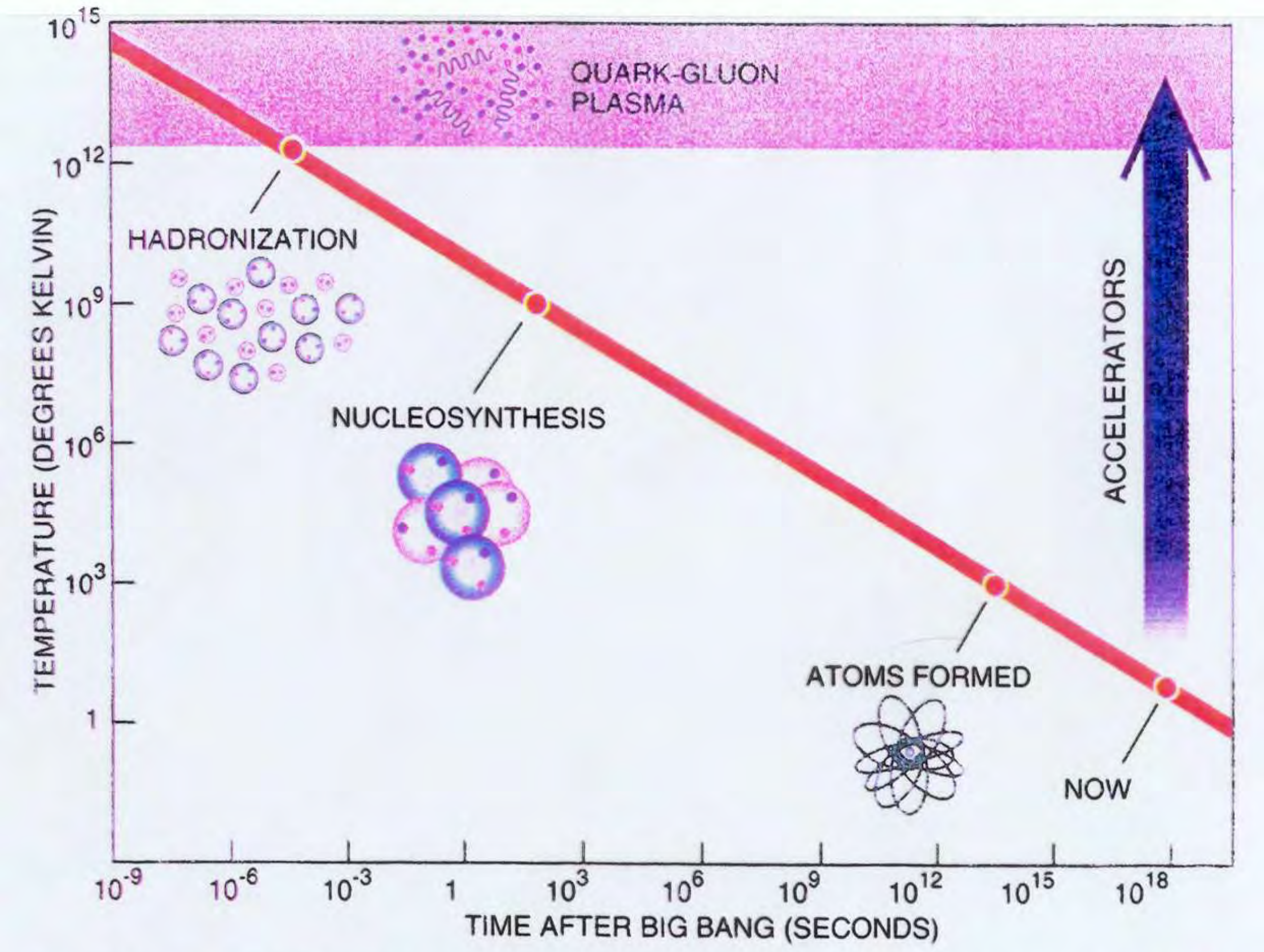
"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

Quark-Gluon Plasma (Soup)

- Standard Model → Lattice Gauge Calculations predict
  QCD Deconfinement phase transition at T = 175 MeV
- Cosmology → Quark-hadron phase transition in early Universe
- Astrophysics → Cores of dense stars (?)
- Can we make it in the lab?

- Establish properties of QCD at high T

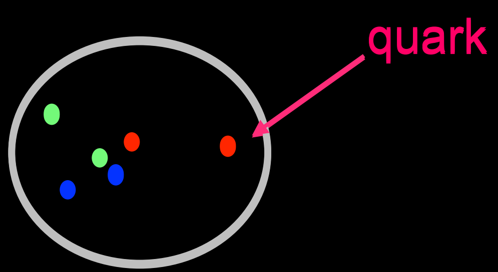
"How Can We Make a Quark Soup?"



TEMPERATURE OF THE UNIVERSE has been falling since the big bang. During the first microsecond, all matter is thought to have existed as quark-gluon plasma. As the universe expanded and cooled, more complex matter condensed out of the plasma, eventually forming the atoms observable today.

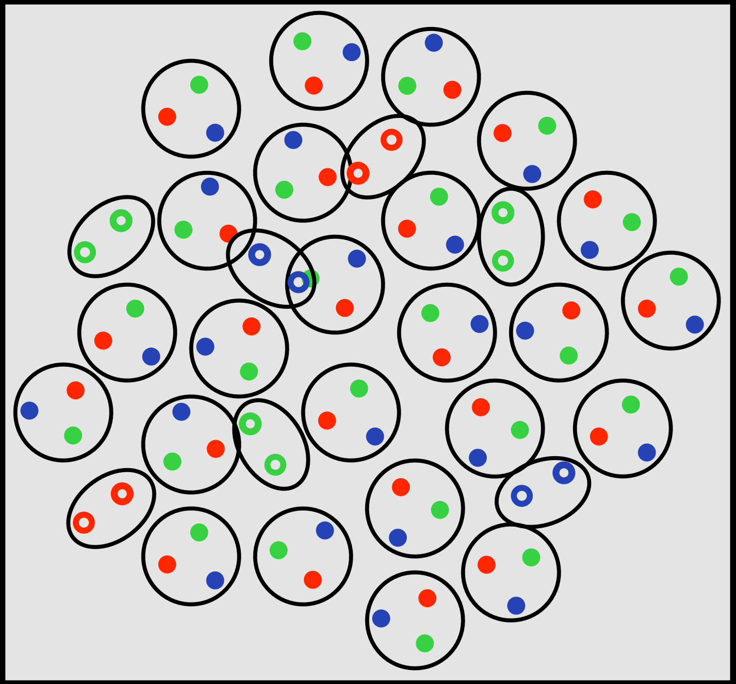
How to Make Quark Soup!

Strong – Nuclear Force
"confines" quarks and gluons to be in particles



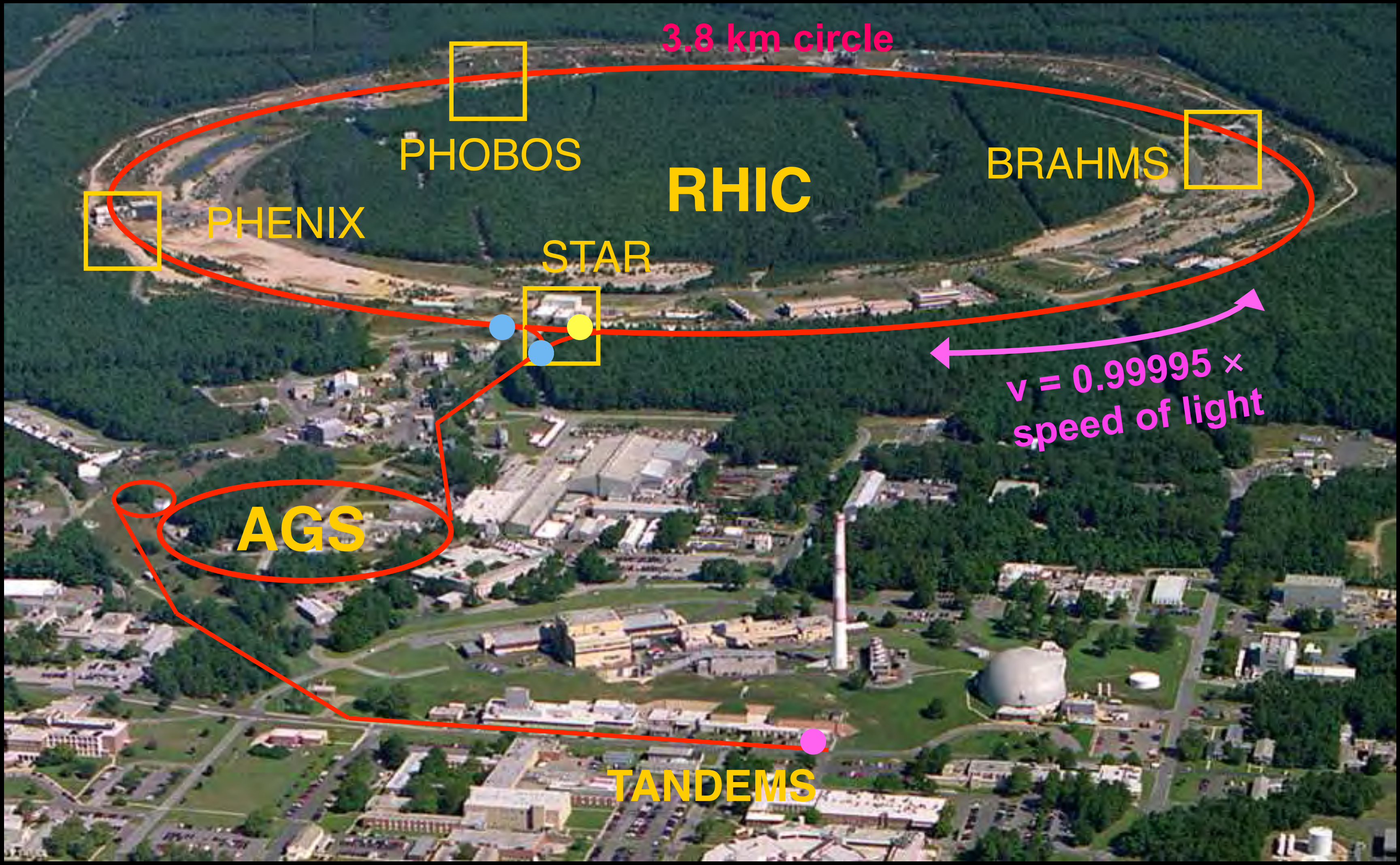
- Compress or Heat Nuclei
- To melt the vacuum!

→ *Quark-Gluon Soup !*



Quark Gluon Soup!
(quarks are confined)

With the Relativistic Heavy Ion Collider (since 2000)

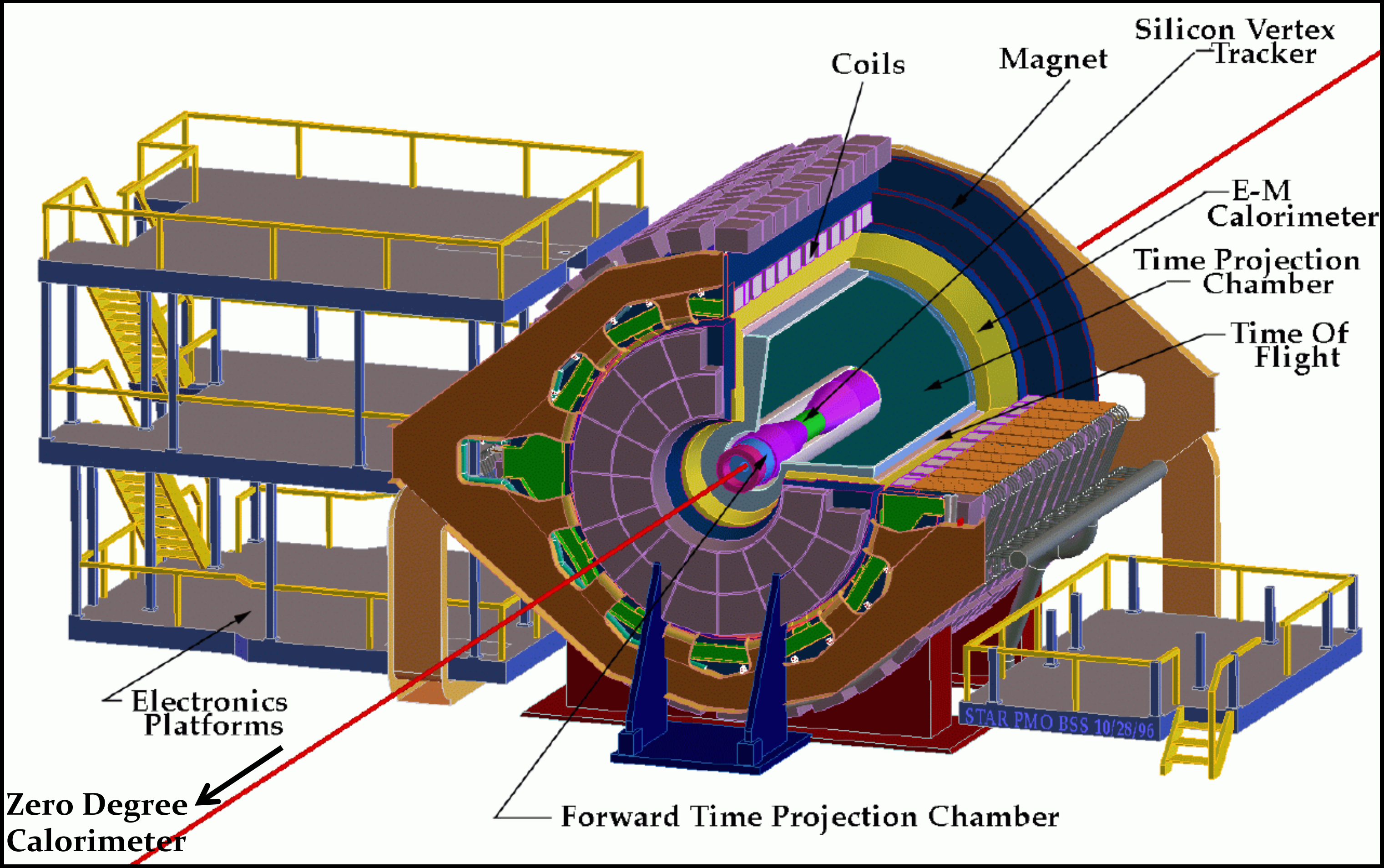


Gold nuclei each with 197 protons + neutrons are accelerated

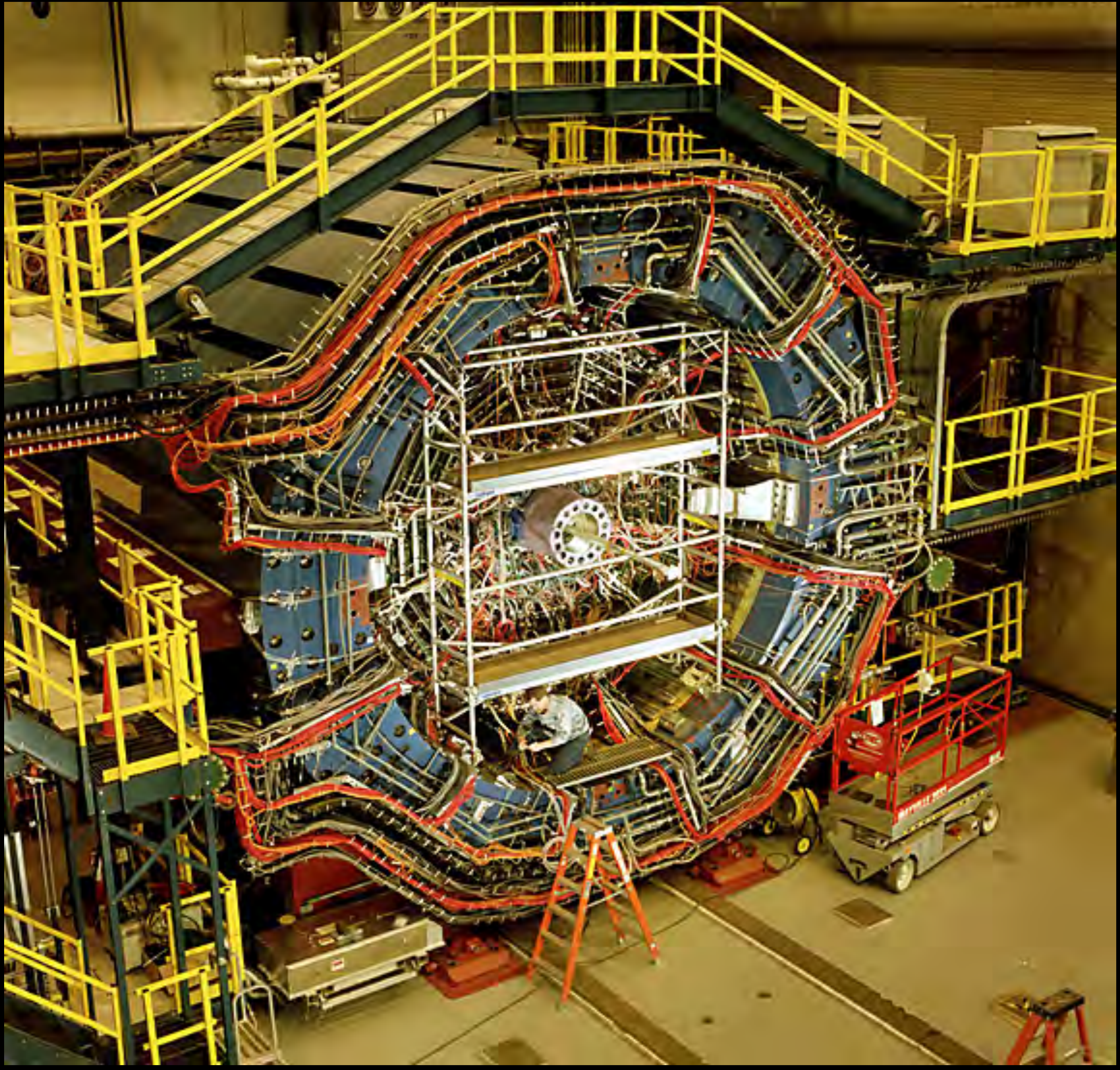
With the Relativistic Heavy Ion Collider (since 2000)

Gold nuclei each with 197 protons + neutrons are accelerated

STAR (Solenoidal Tracker At RHIC) Detector



$0 < \varphi < 2\pi$
$|\eta| < 1$



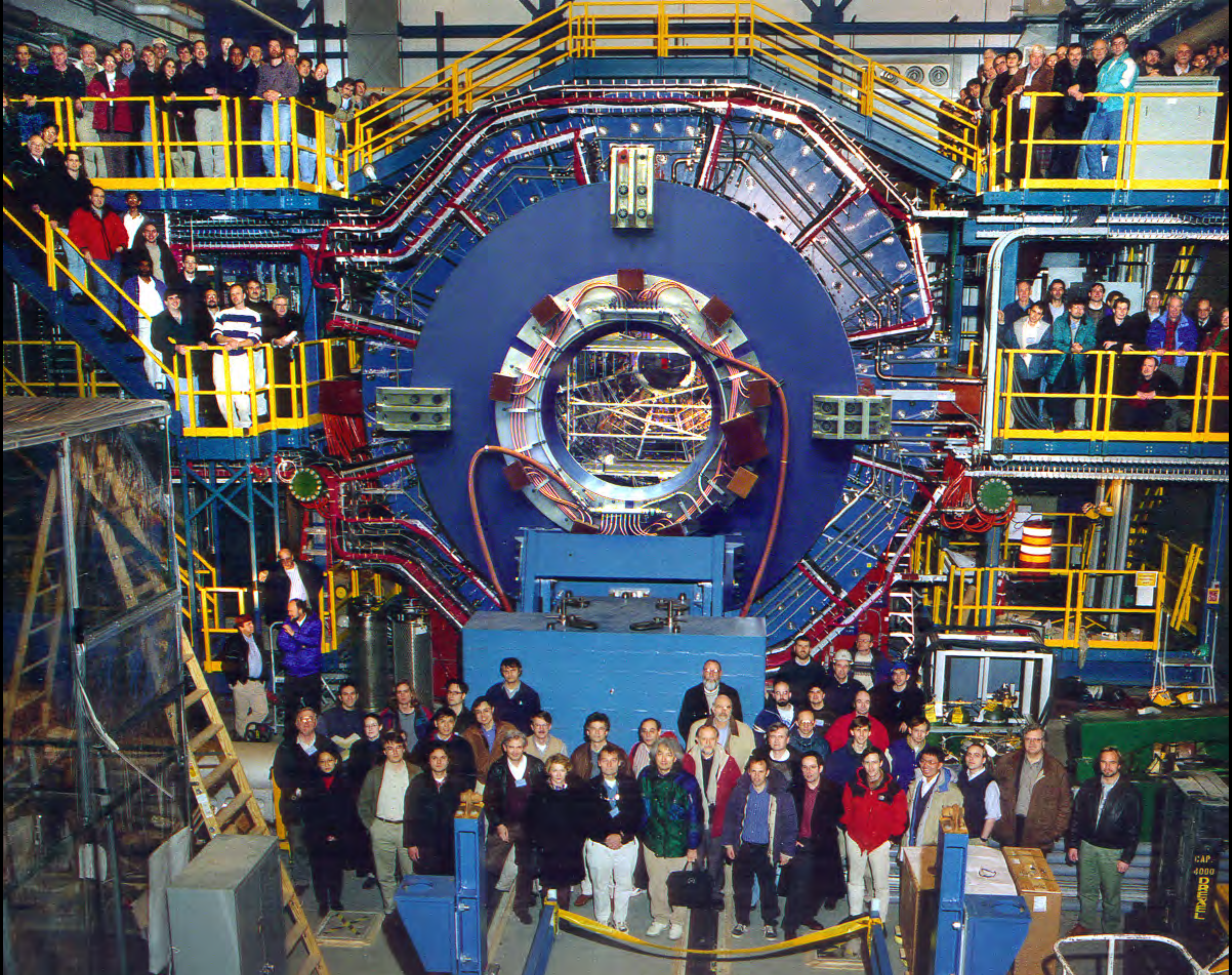
The STAR Experiment

at

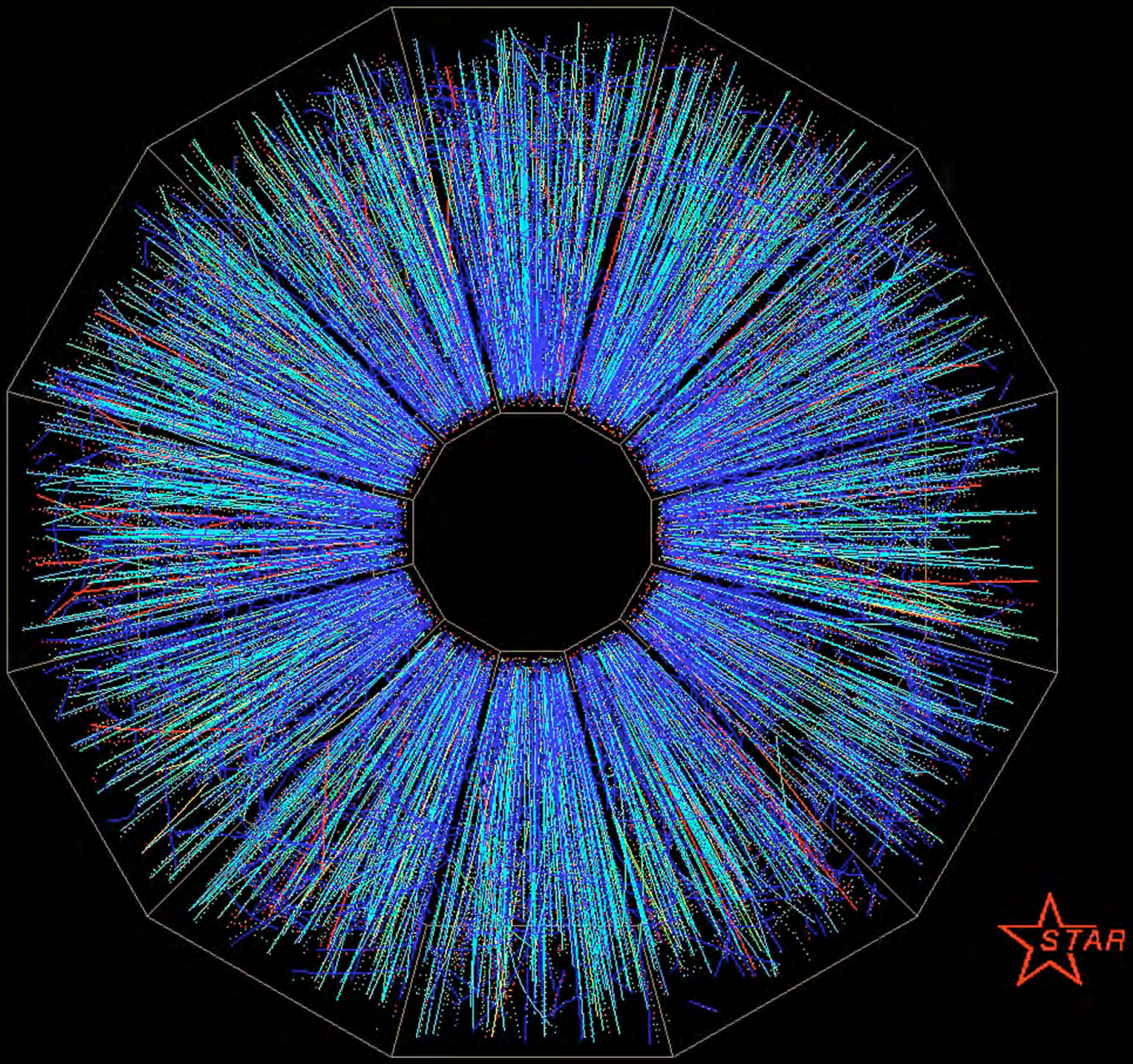
Brookhaven

Lab

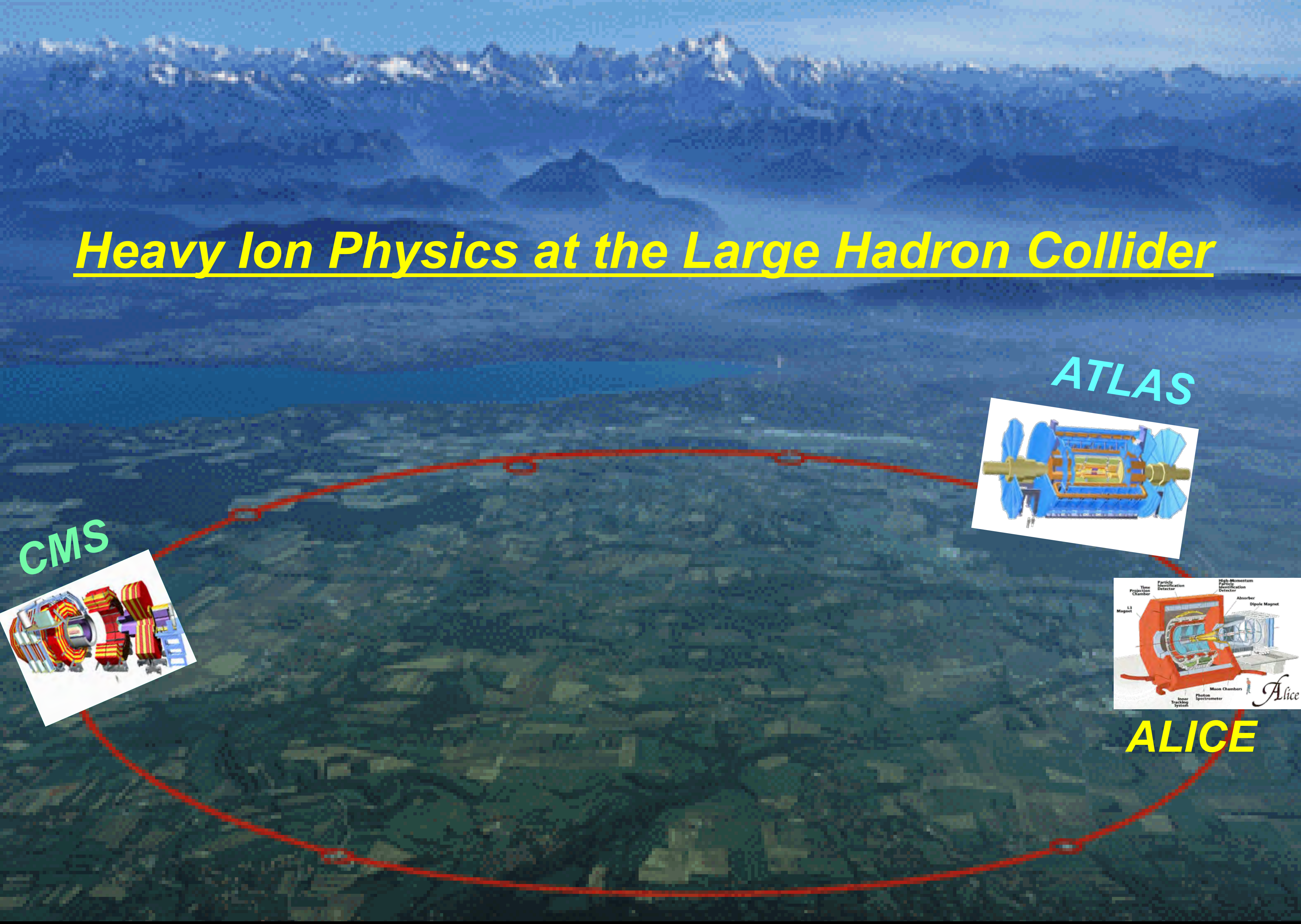
in N.Y.


CAP.
4000
DREXEL

Head-on Collision

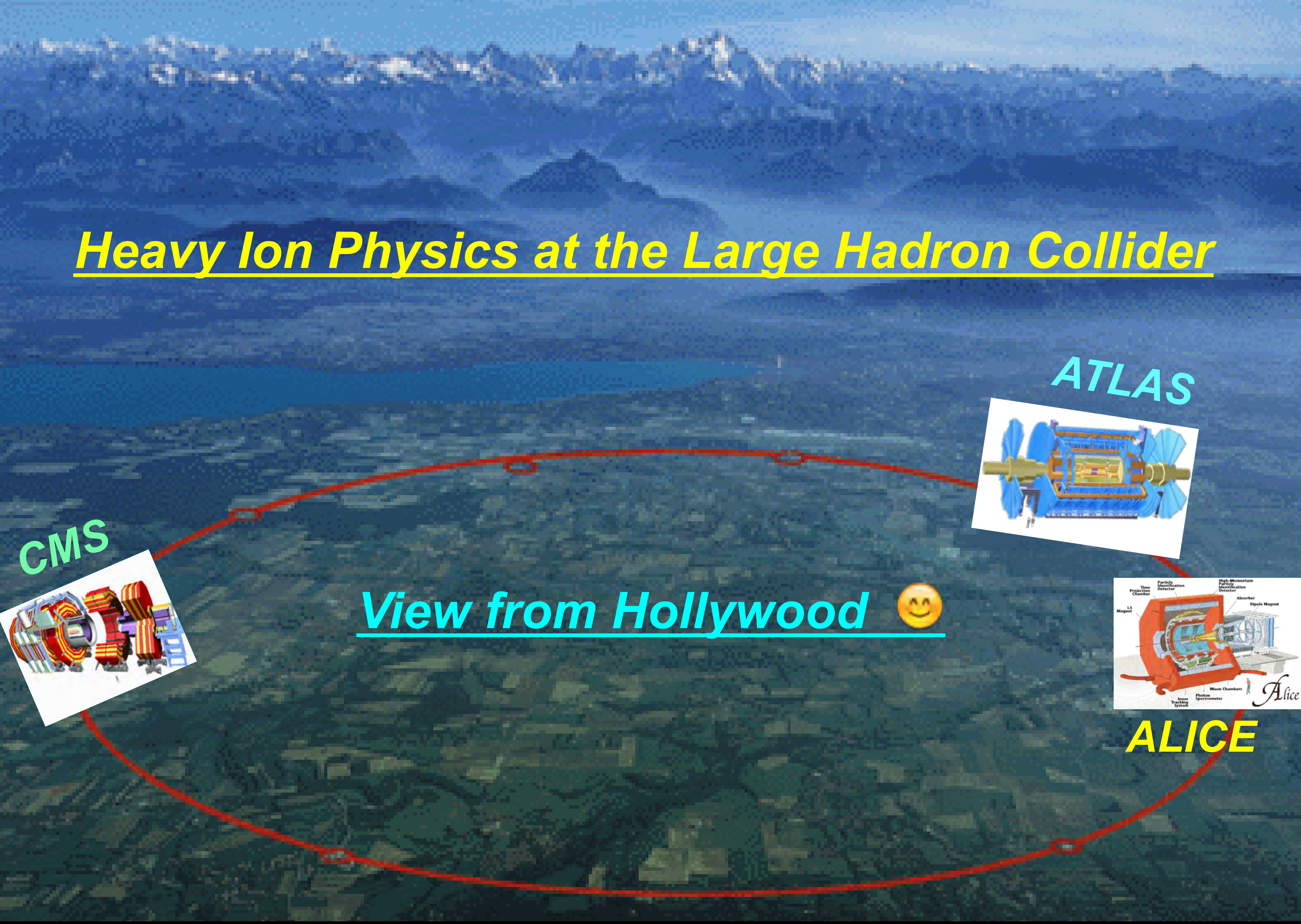


Heavy Ion Physics at the Large Hadron Collider

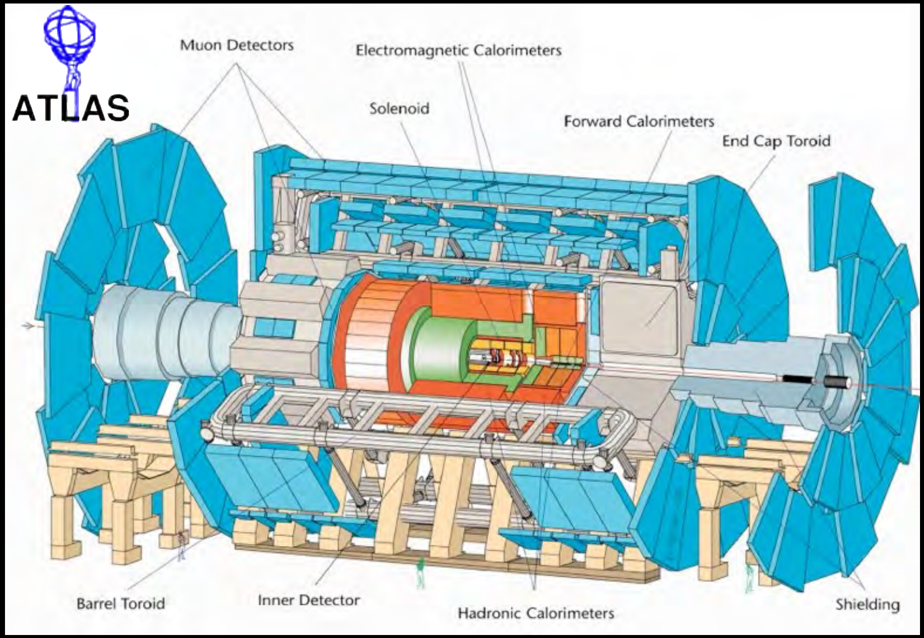


Heavy Ion Physics at the Large Hadron Collider

View from Hollywood 😊



LHC Heavy Ion Program



LHC Heavy Ion Data-taking

Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

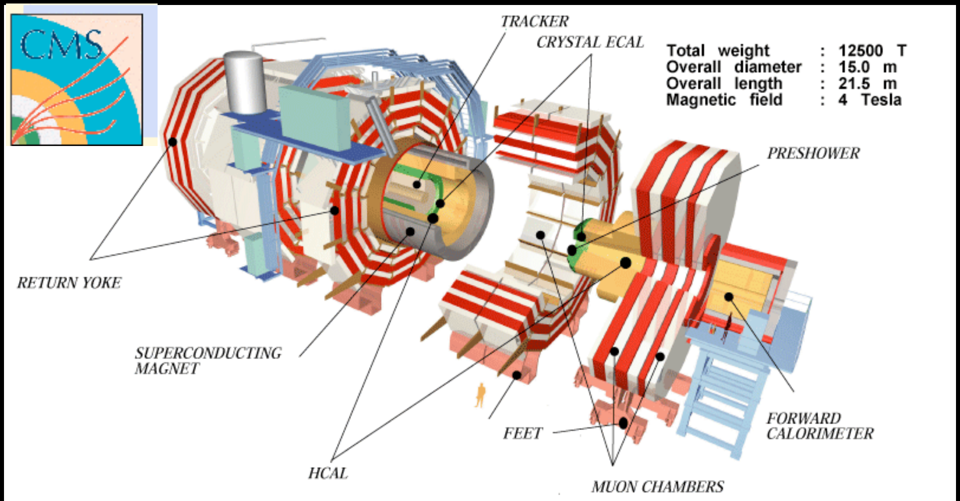
(1 month per year)

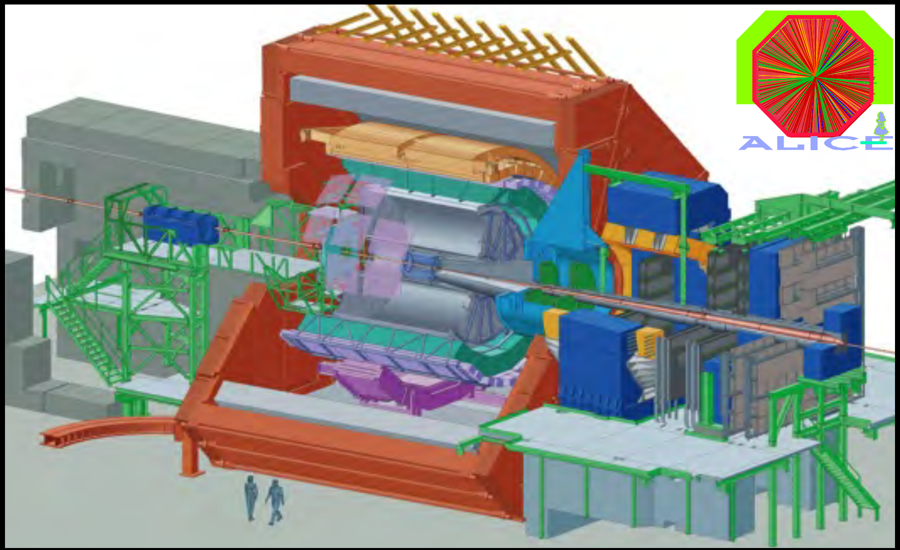
2010-11: Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

2013 : p + Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

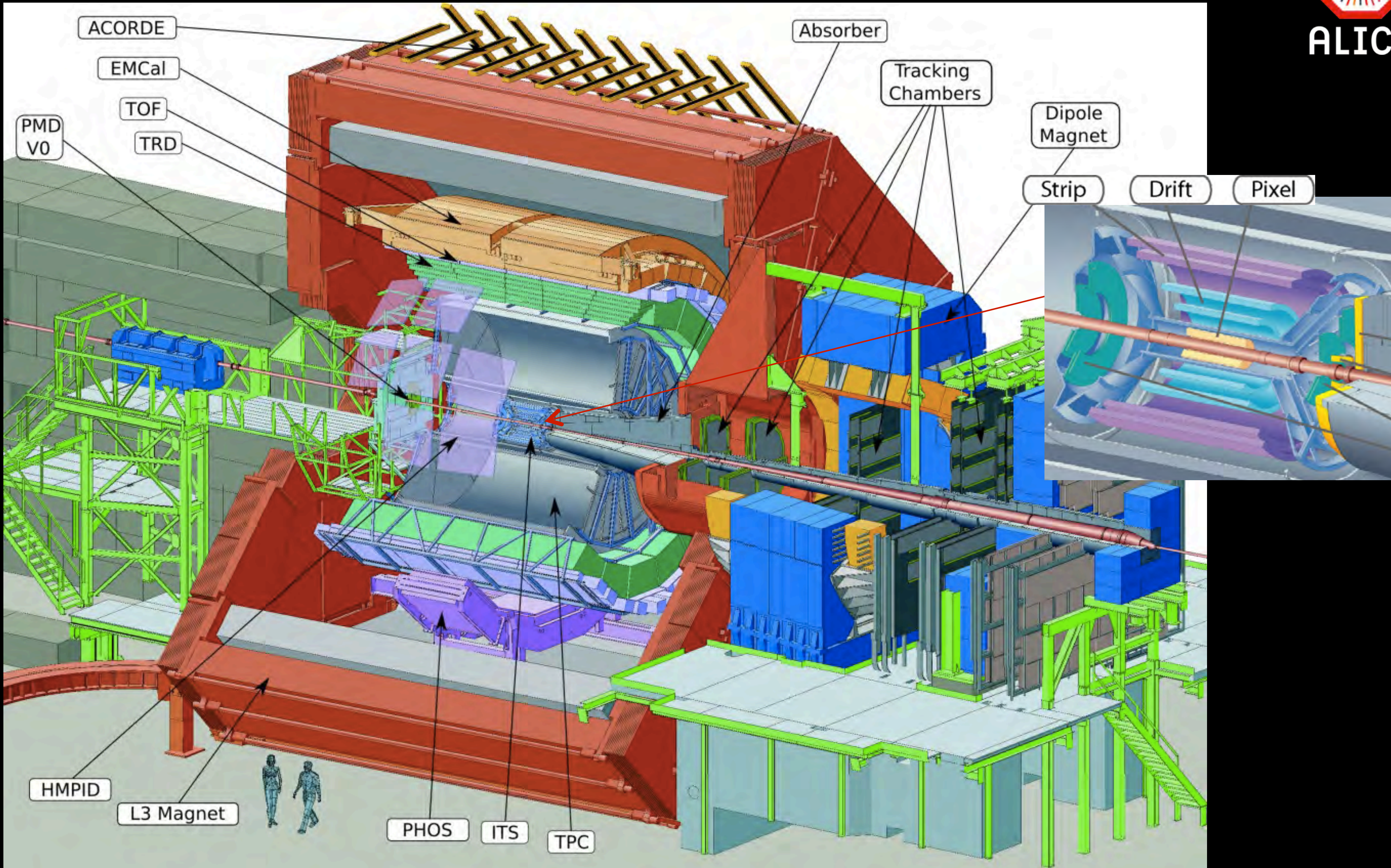
LHC Collider Detectors

ATLAS CMS ALICE

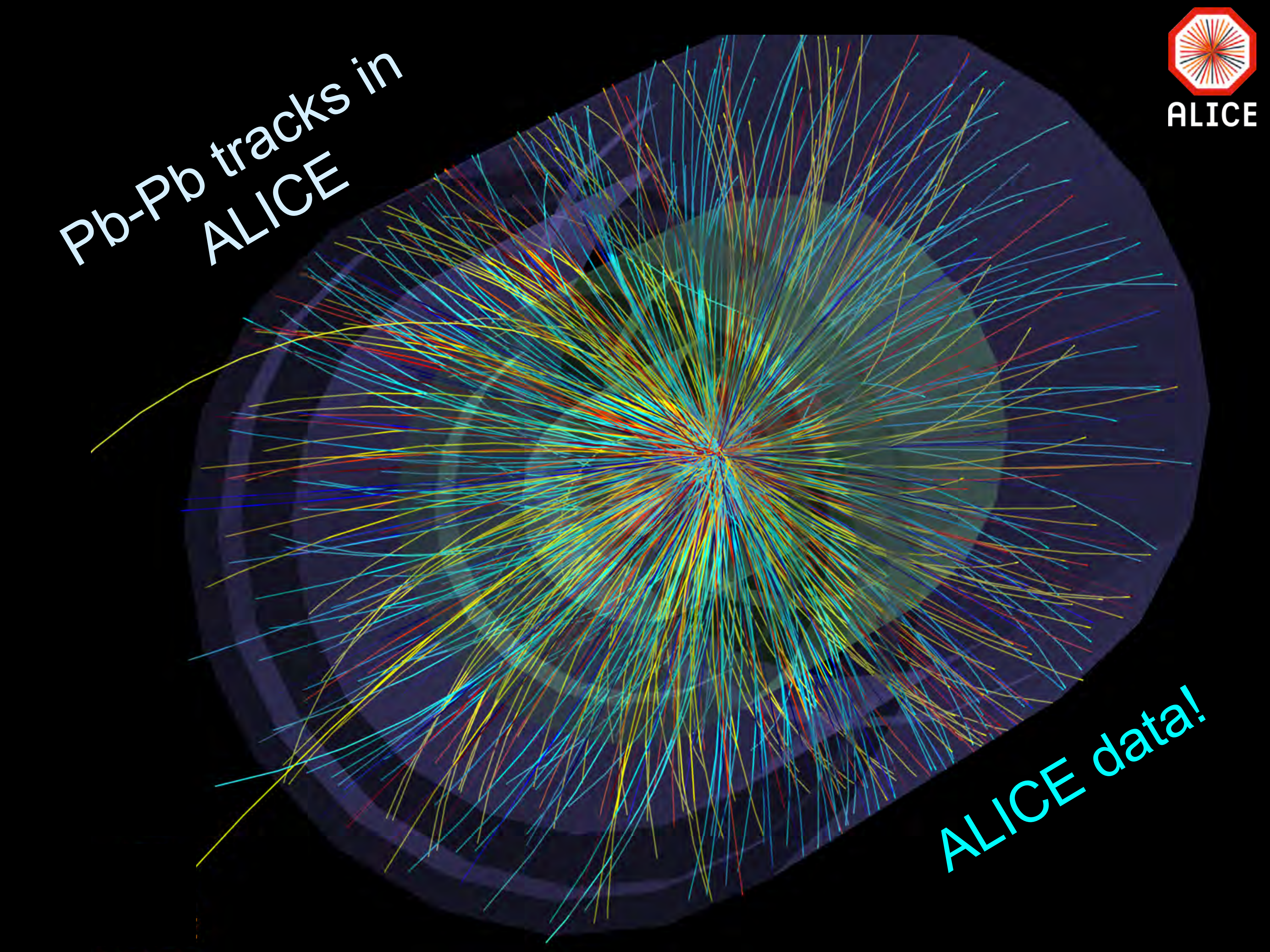




The ALICE Experiment

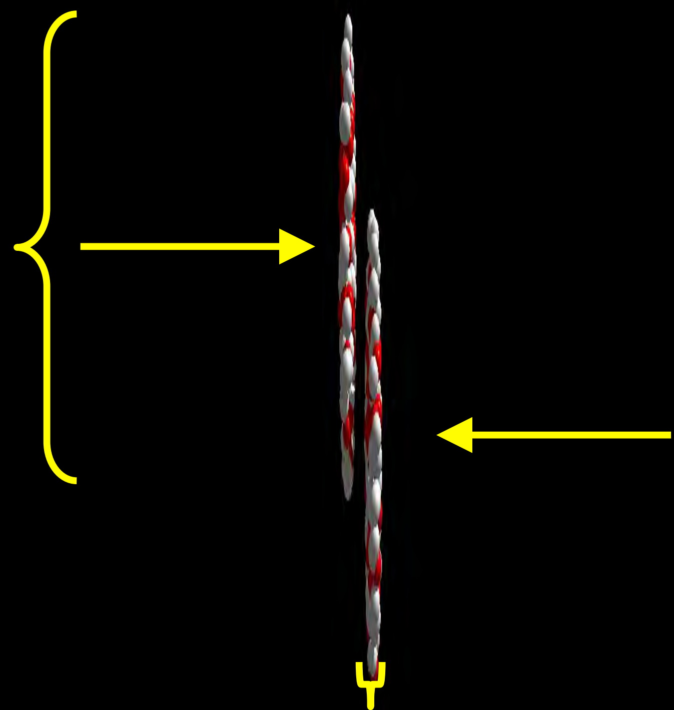


The LHC Experiment designed for heavy ions


Pb-Pb tracks in ALICE
ALICE data!

Heavy Ion Collisions at RHIC & LHC

Lead nucleus
diameter ~ 14 fm



γ = 100 → 1,350
(Lorenz contracted)

$\tau \sim (14\ \text{fm}/c) / \gamma < 0.1 \rightarrow \sim 0.01\ \text{fm}/c$

General Orientation

Hadron masses ~ 1 GeV

Hadron sizes ~ fm

Heavy Ion Collisions

RHIC: E_{cm} = 0.2 TeV per nn-pair

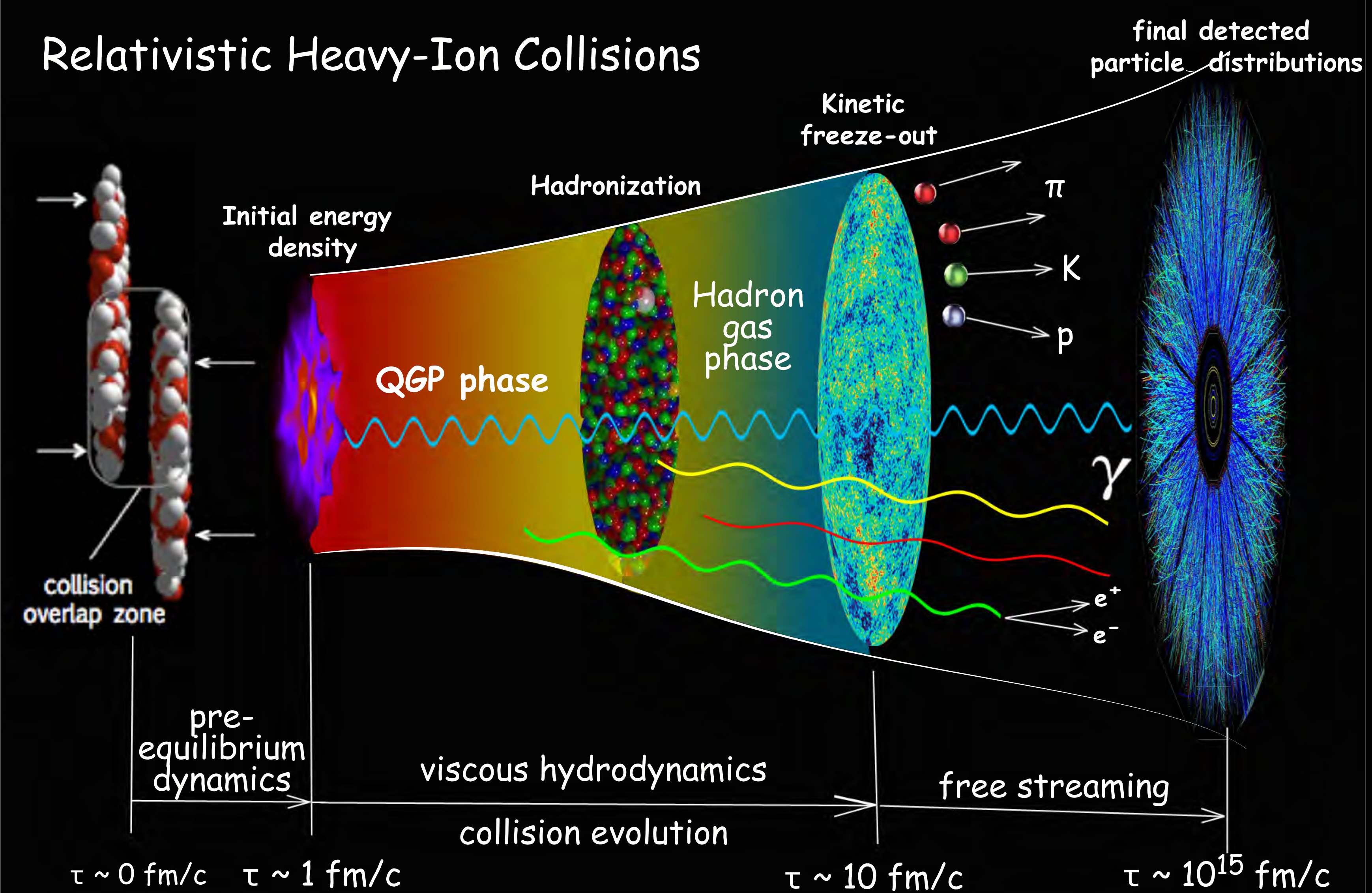
LHC: E_{cm} = 2.76 TeV per nn-pair

Evolution of a Heavy Ion Collision at RHIC & LHC

(Computer Simulation for RHIC)

red → protons white → neutrons participants → interacting p's & n's

The Little Bang



Ref: U. Heinz, Hard Probes Conference 2013

Original Conception – Paul Sorensen

BIG PICTURE Questions

What are the states of matter that exist at high temperature and density?

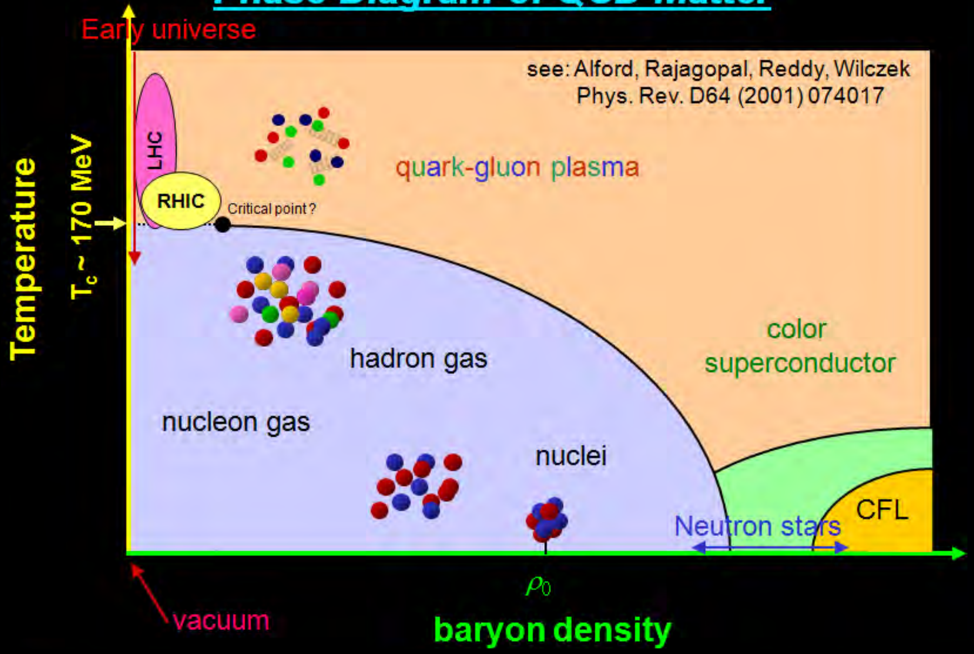
- Can we explore the phase structure of a fundamental gauge (QCD) theory?
  - → Can we use this to understand other gauge theories (like gravity!)?
- Is the Phase Diagram of QCD featureless above Tc?
  - → What are the constituents (are there quasi-particles, exotic states, others)?
  - → Is there a critical point (can it be found in a RHIC Beam Energy Scan)?

What are the properties of the QGP?

transport properties, α_s (T),
sound attenuation length,
sheer viscosity/entropy density,
formation time (τ_f),
excited modes, ….EOS?

Are there new phenomena,
new states of matter?

Phase Diagram of QCD Matter



Definitions

- **Relativistic treatment**

Energy

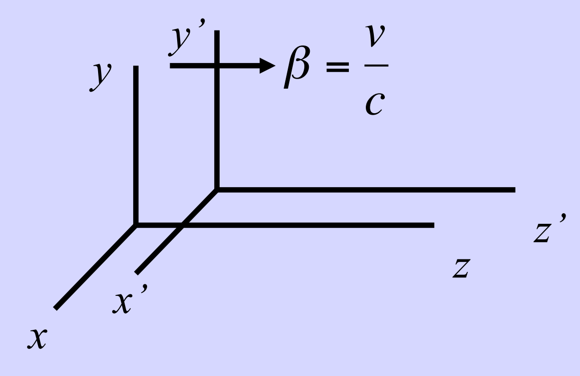
$$E^2 = p^2 + m^2$$ or $$E = T + m$$ or $$E = \gamma m$$

where,

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$ and $$\beta = \frac{v}{c} = \frac{p}{E}$$

- **Lorentz transforms**

$$E' = \gamma(E + \beta p_z)$$
$$p'_z = \gamma(p_z + \beta E)$$



- **Longitudinal and transverse kinematics**

$$p_L = p_z$$
$$p_T = \sqrt{p_x^2 + p_y^2}, \quad m_T = \sqrt{p_T^2 + m^2}$$ **Transverse mass**
$$y = \frac{1}{2}\ln\left[\frac{E + p_L}{E - p_L}\right]$$ **Rapidity**
$$y' = y + \tanh^{-1}\beta$$

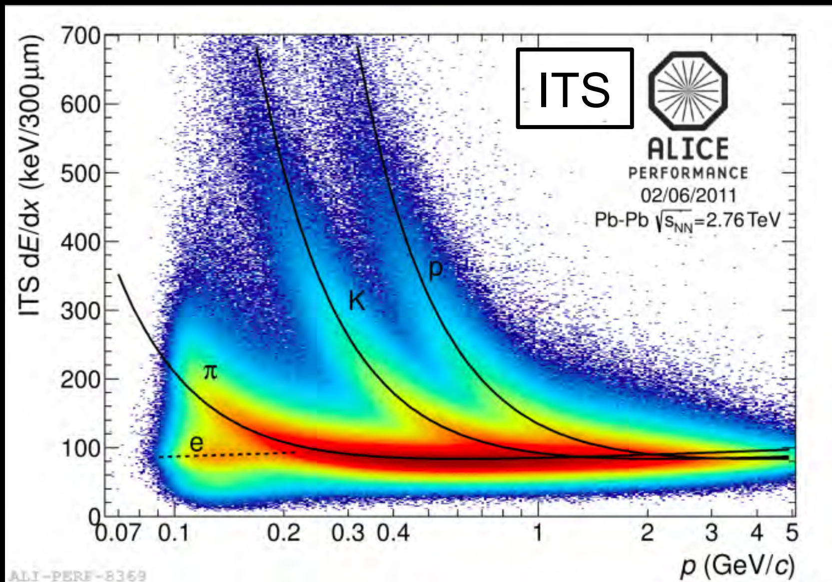
$\eta = -\ln(\tan\theta/2)$ **Pseudo-rapidity**

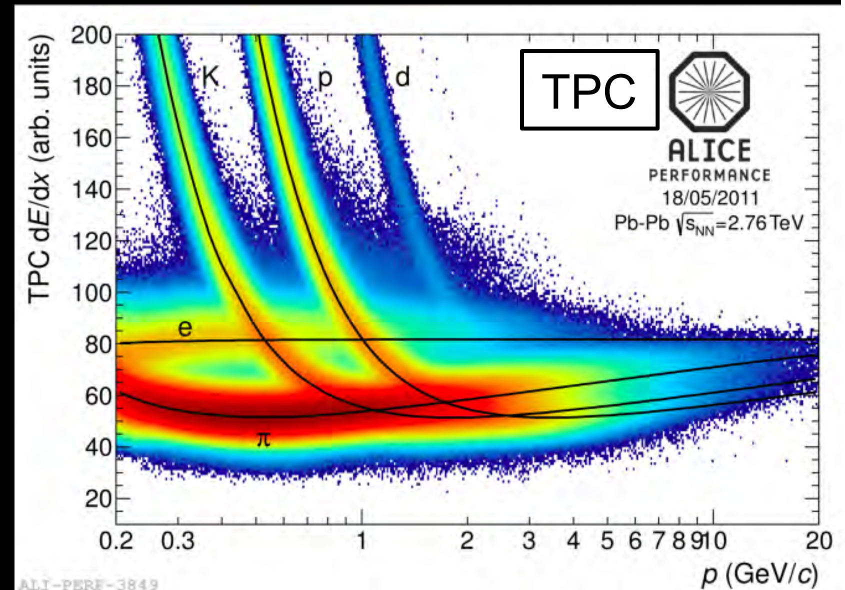
Useful relations

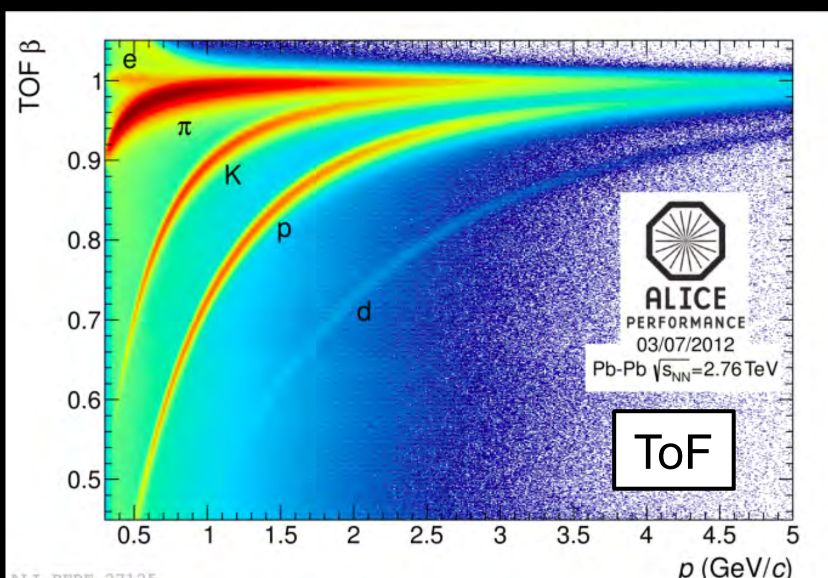
$$\gamma = \cosh y$$
$$\beta = \tanh y$$
$$E = m_T \cosh y$$
$$p_L = m_T \sinh y$$

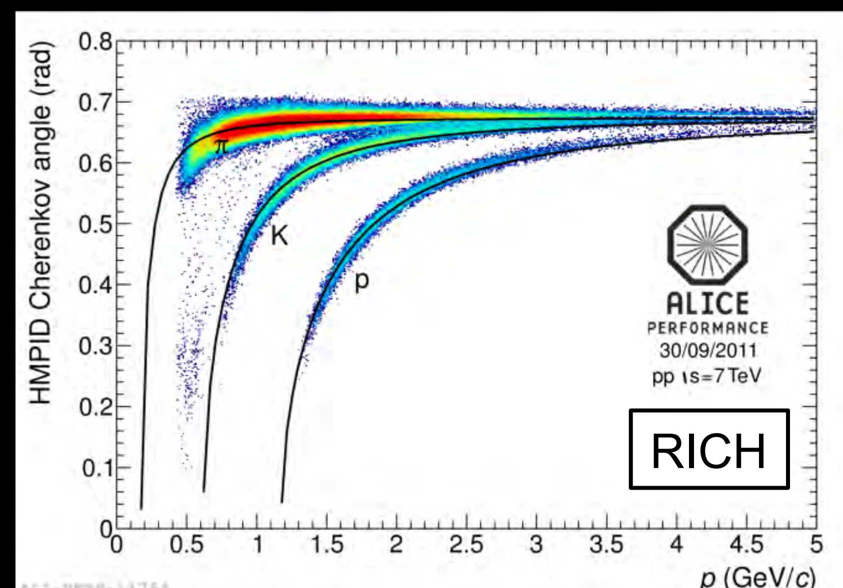
Particle Identification in ALICE Detectors

ALICE

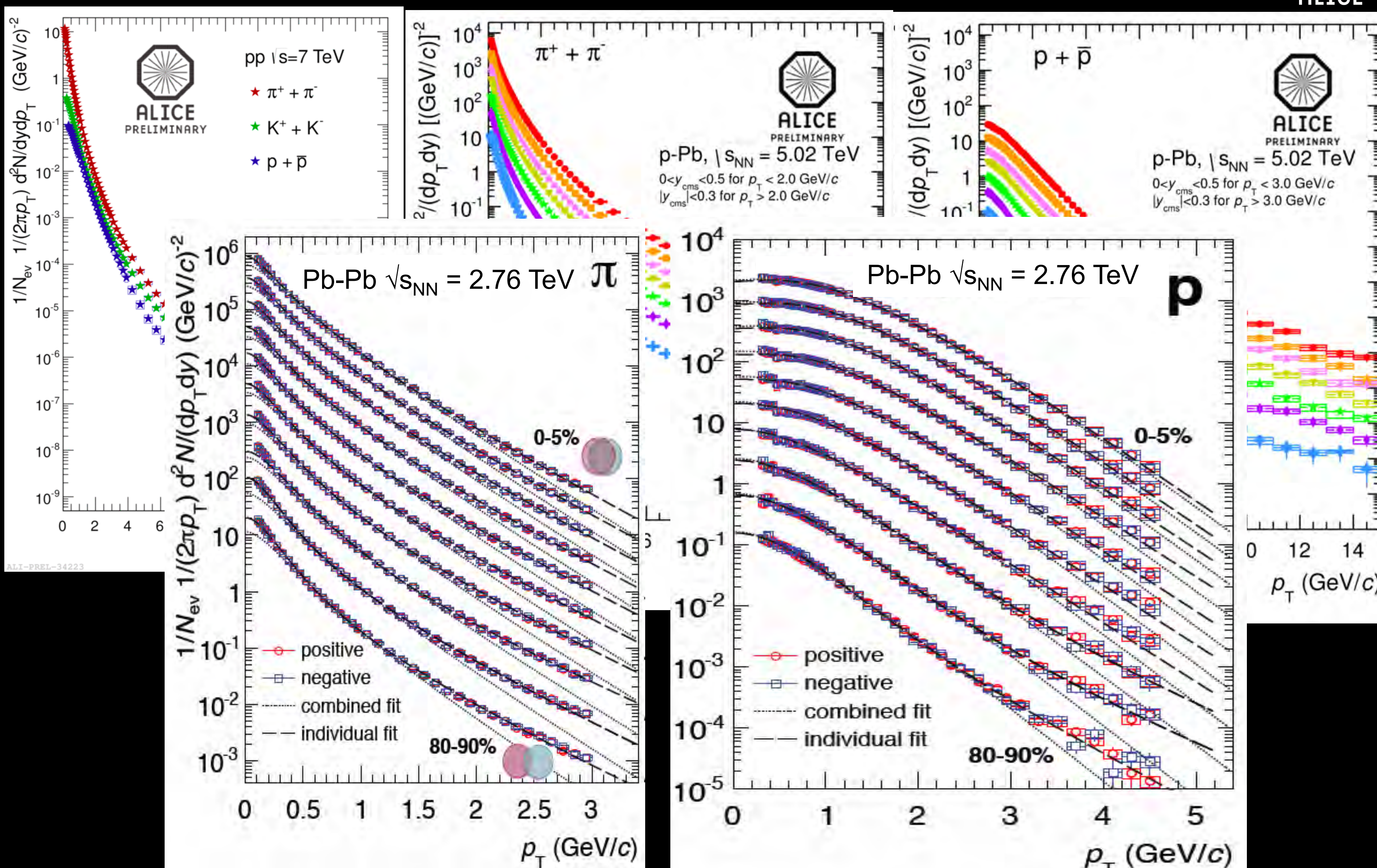




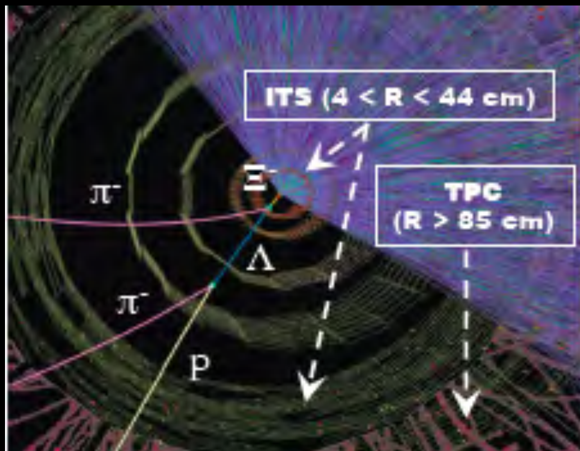




Particle Identification in ALICE Detectors



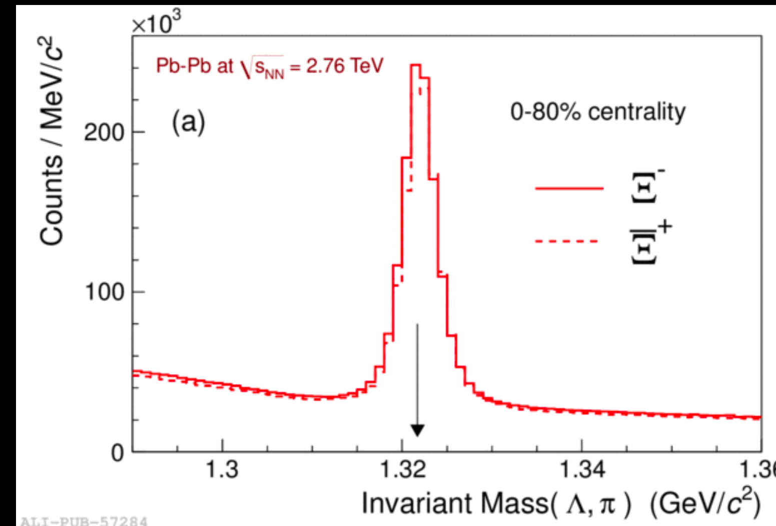
Vertex Identification in ALICE Detectors



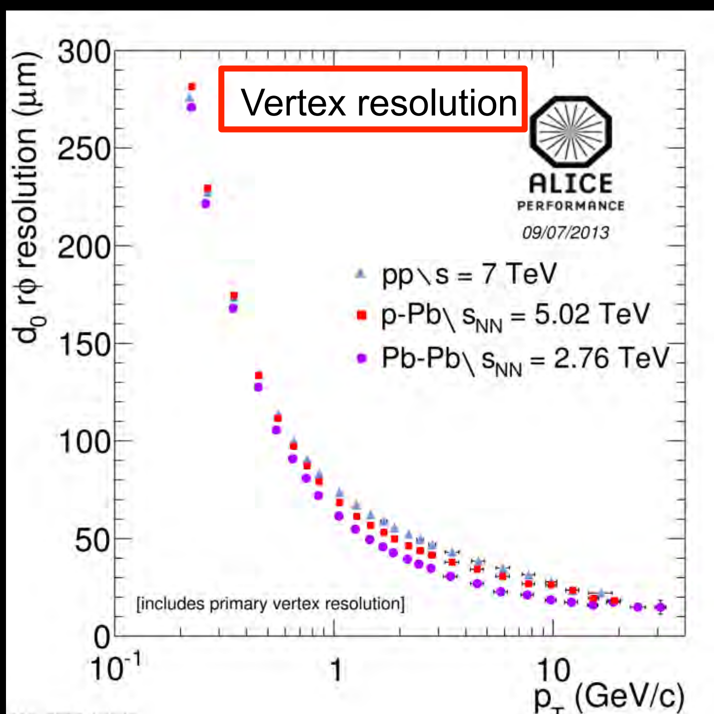
$K^0_s \rightarrow \pi\pi$

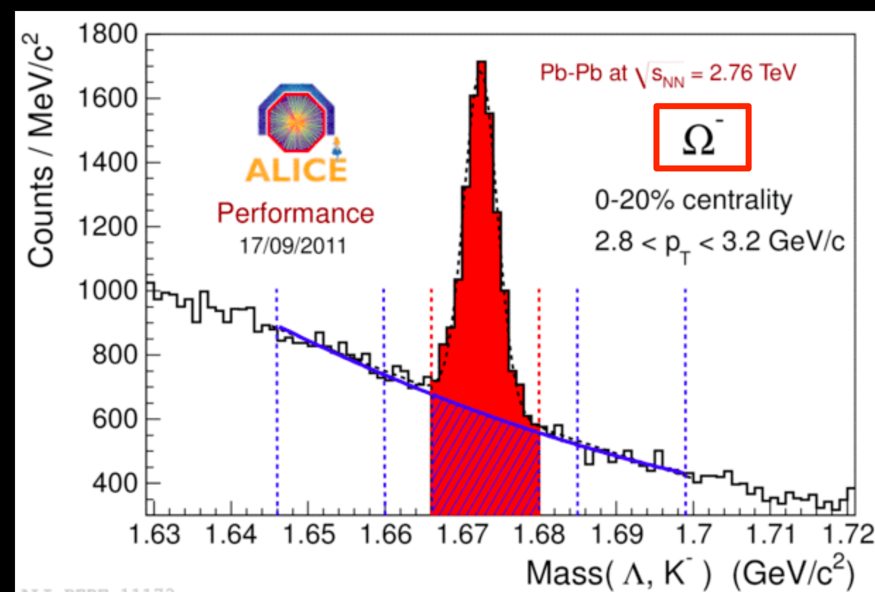
$\Lambda \rightarrow p\pi$

$\Xi \rightarrow \Lambda\pi$



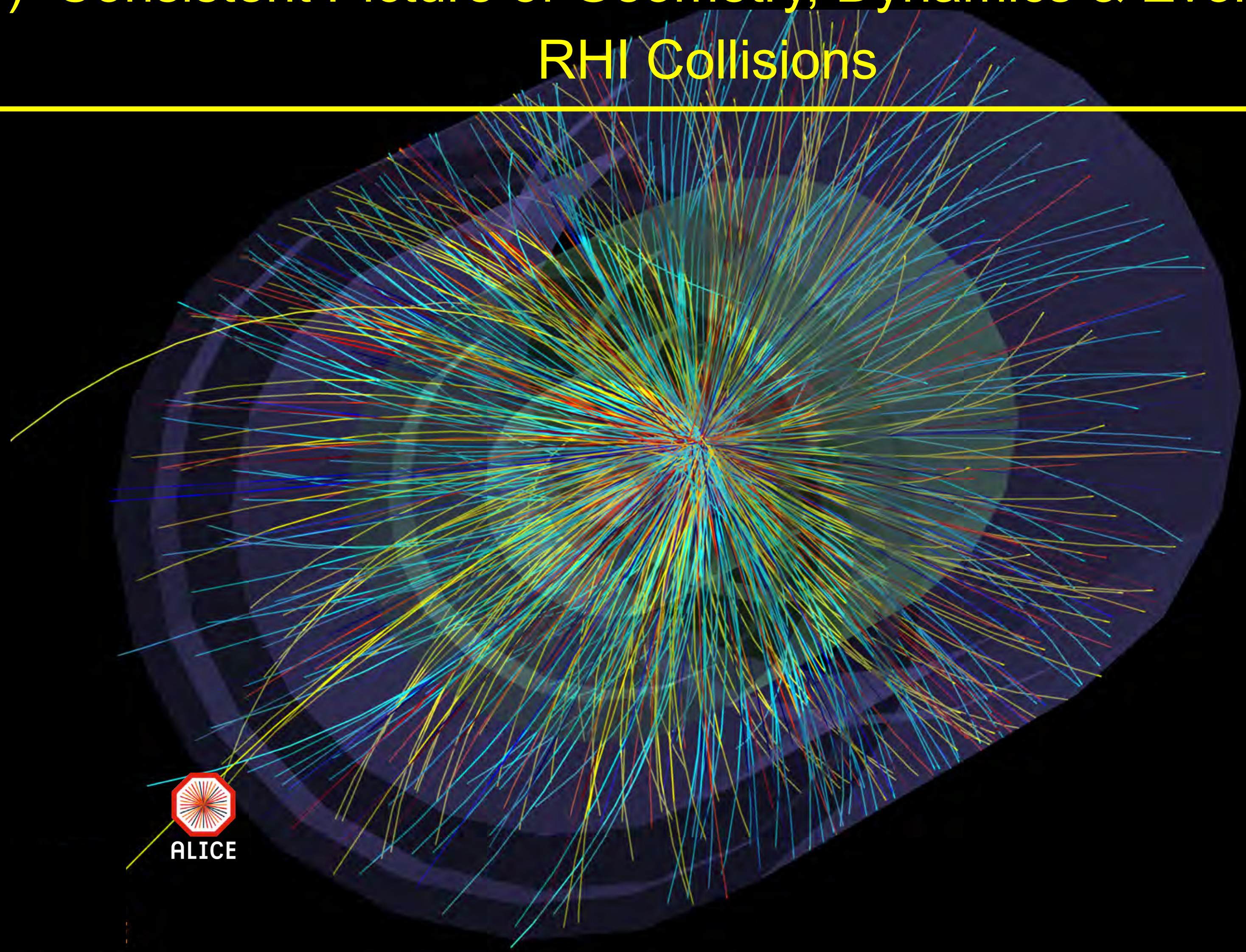
ALICE, arXiv:1307.5543





“What Have We Learned” from RHIC & LHC

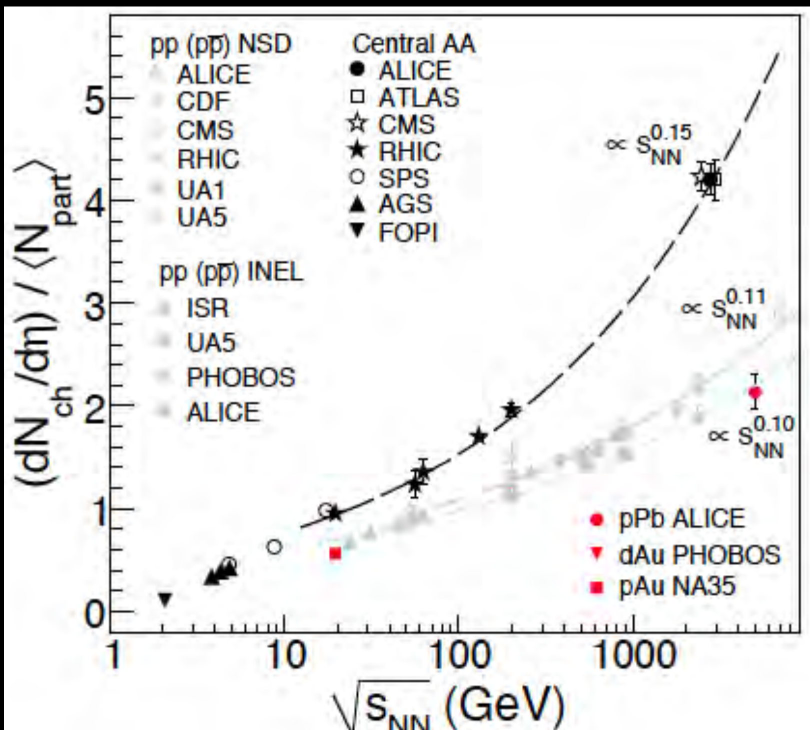
1) Consistent Picture of Geometry, Dynamics & Evolution of RHI Collisions

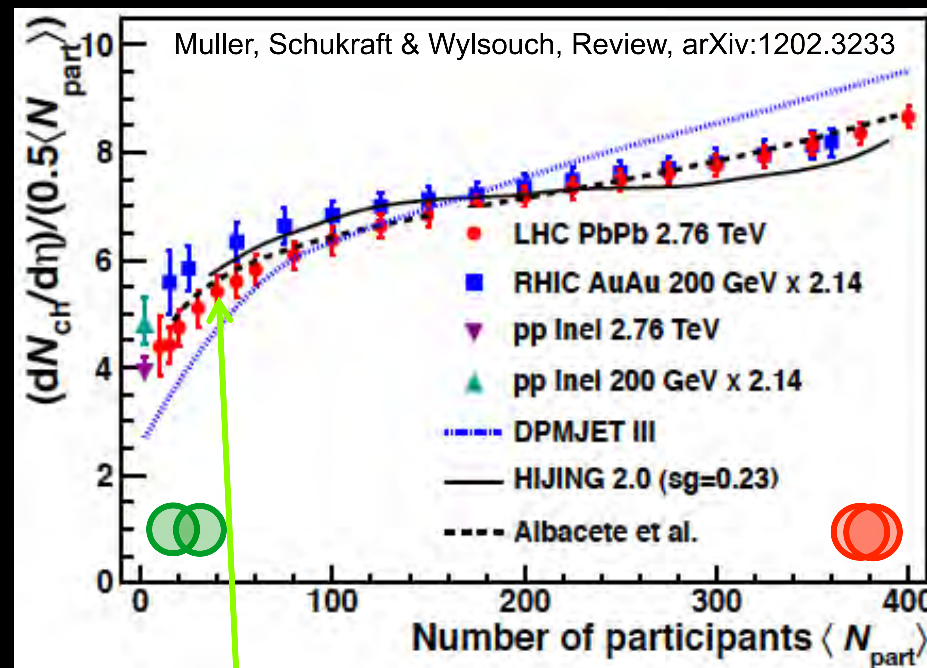


Dynamics & Evolution of RHI Collisions

Multiplicities (per participant nucleon) from RHIC to LHC

vs. C.M. energy | vs. # of participants





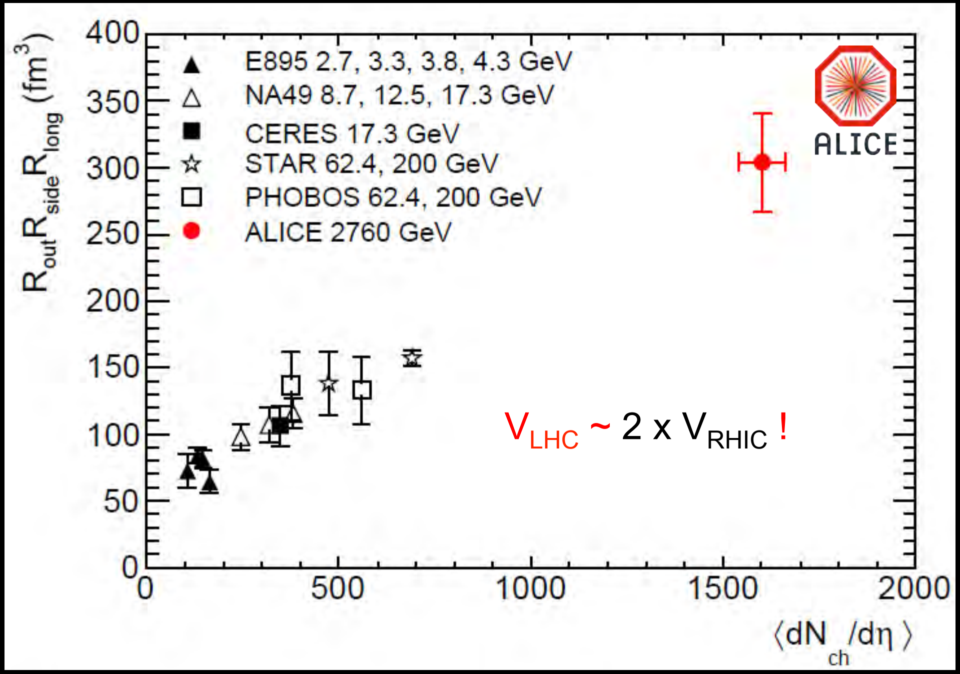
Initial state fluctuations?
Degree of shadowing?
See → data from 2013 p-Pb run!

Small differences due to initial conditions?
Gluon shadowing vs geometry,
Hard scattering ~ # binary collisions
Are there differences at LHC & RHIC?

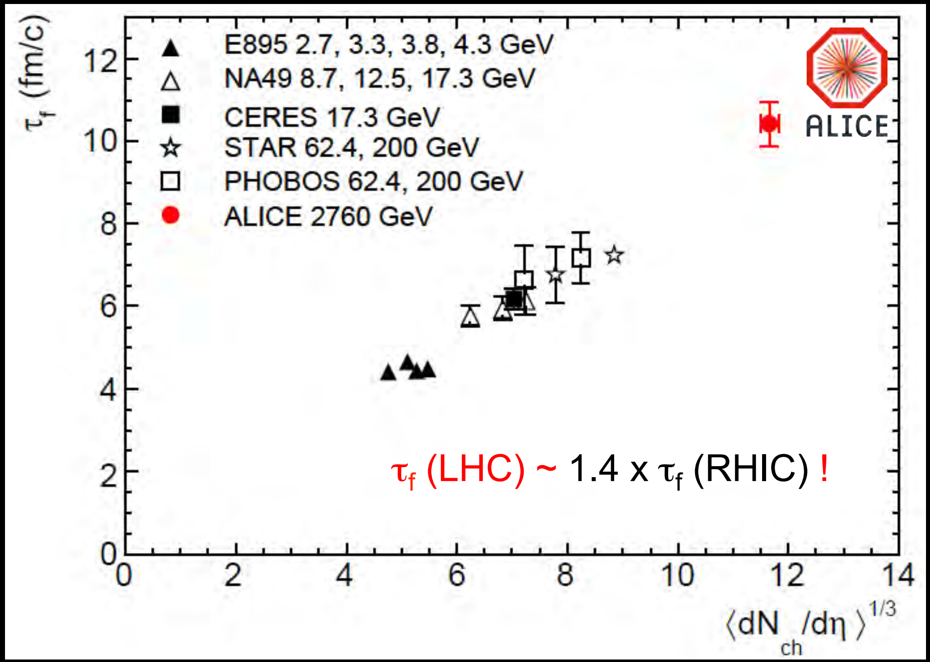
System Size & Lifetimes

ALICE, Phys.Lett. B696 (2011) 328

System size



Lifetimes



Size → Volume ~ dN/dη

i.e.~ multiplicity density

Lifetime $\tau_f \sim \langle dN_{ch}/d\eta \rangle^{1/3}$

τ_f (central PbPb) ~ 10 – 11 fm/c

Lifetime → hydrodynamic expansion

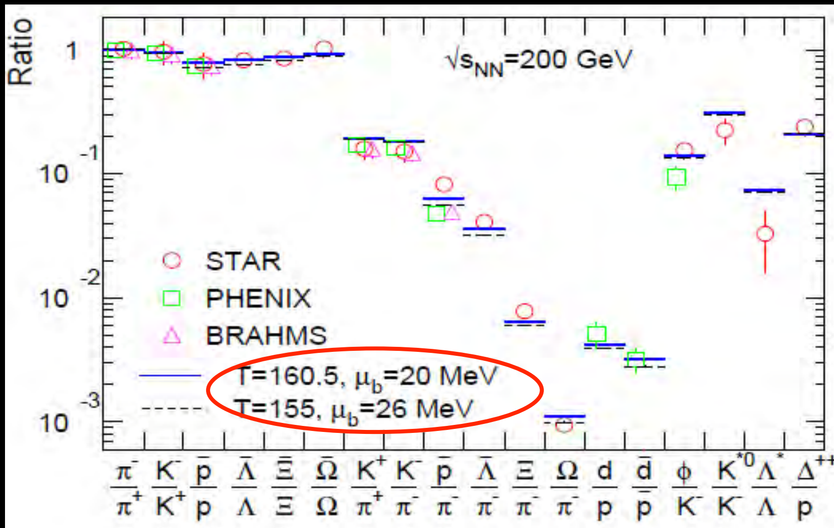
“What Have We Learned” from RHIC & LHC

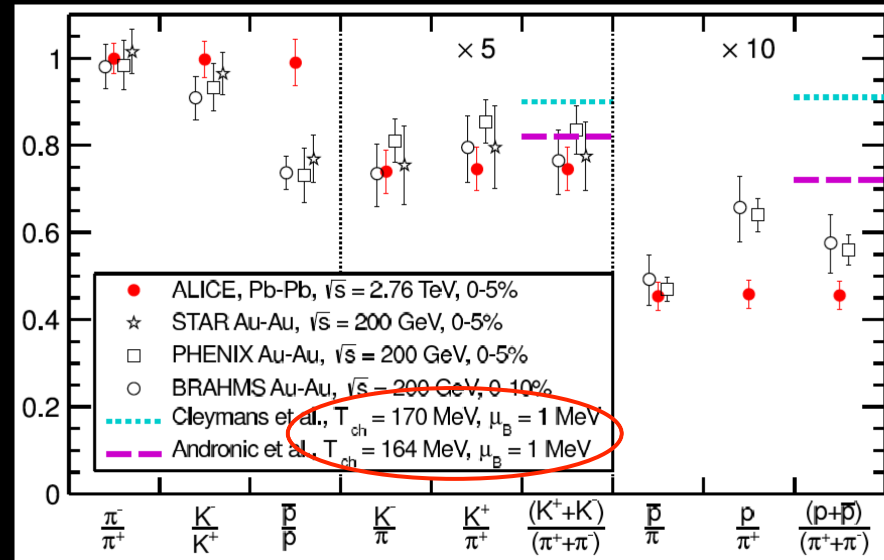
2) Particle ratios reflect equilibrium abundances

→ universal hadronization $T_{critical}$

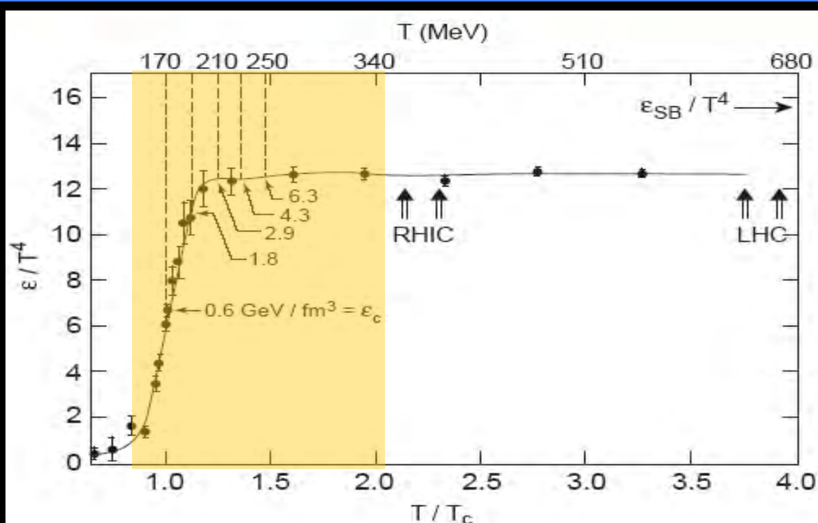
→ Confirm lattice predictions for $T_{critical}$, μ_B

Particles Formed at Universal Hadronization T



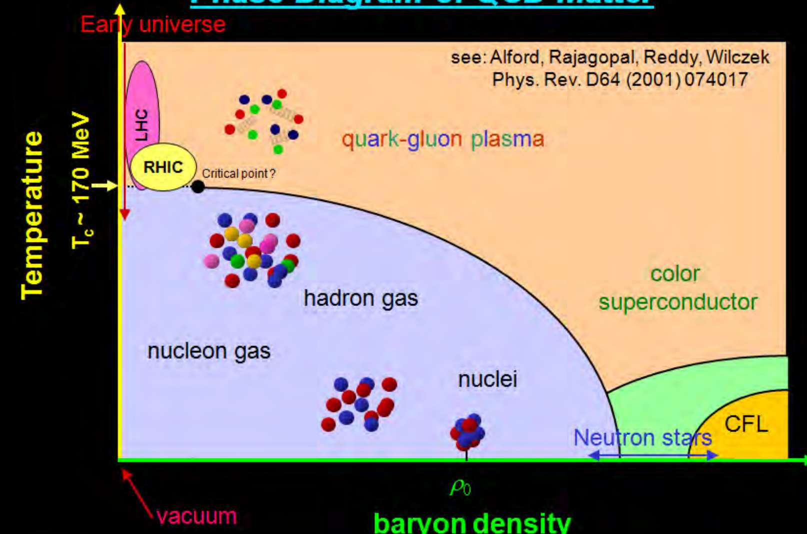


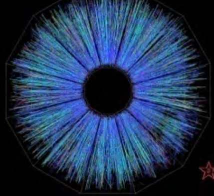
Particles yields → equilibrium abundances → universal hadronization $T_{critical}$



Confirm lattice predictions for $T_{critical}$, μ_B

Phase Diagram of QCD Matter





"What Have We Learned" from RHIC & LHC

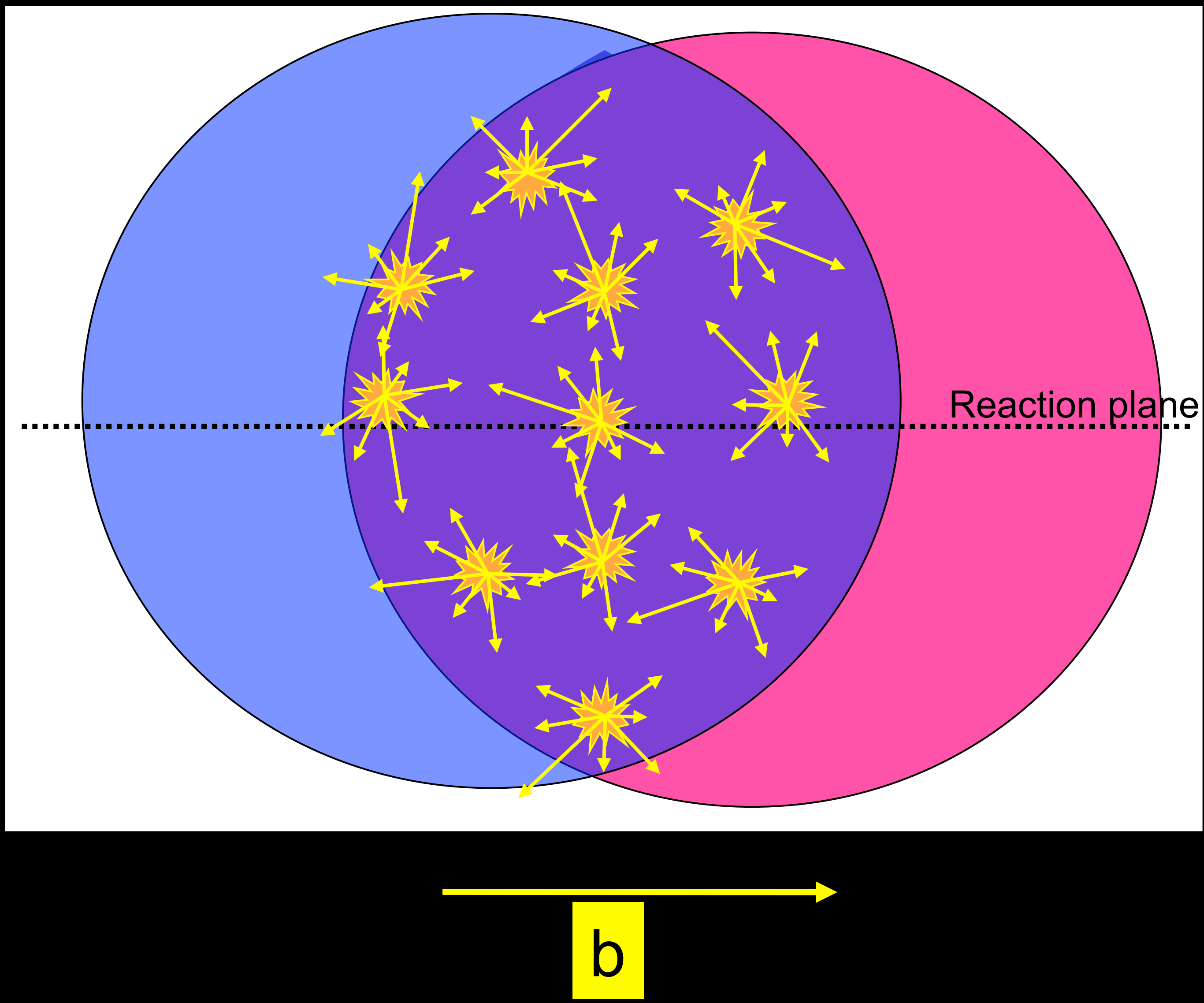
3) Strong flow observed → ultra-low shear viscosity

Strongly-coupled liquid → quark-gluon plasma

How do Heavy Ion Collisions Evolve? – Beam View

1) Superposition of independent p+p:

momenta random
relative to reaction plane



How do Heavy Ion Collisions Evolve?

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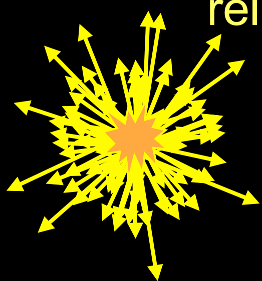
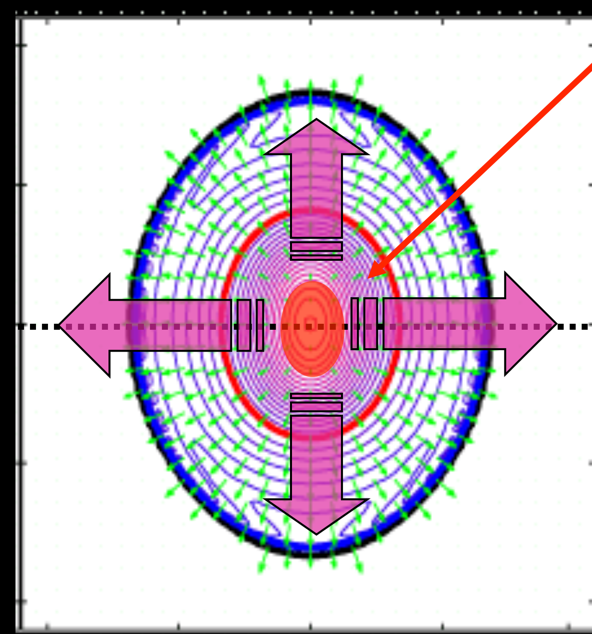
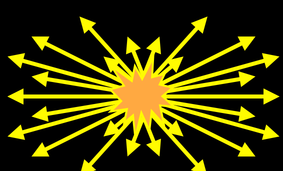


High density
pressure
at center



2) Evolution as a **bulk system**

Pressure gradients (larger in-plane)
push bulk "out" → flow"



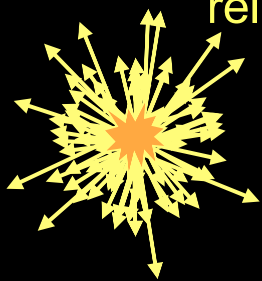
more, faster particles
seen in-plane

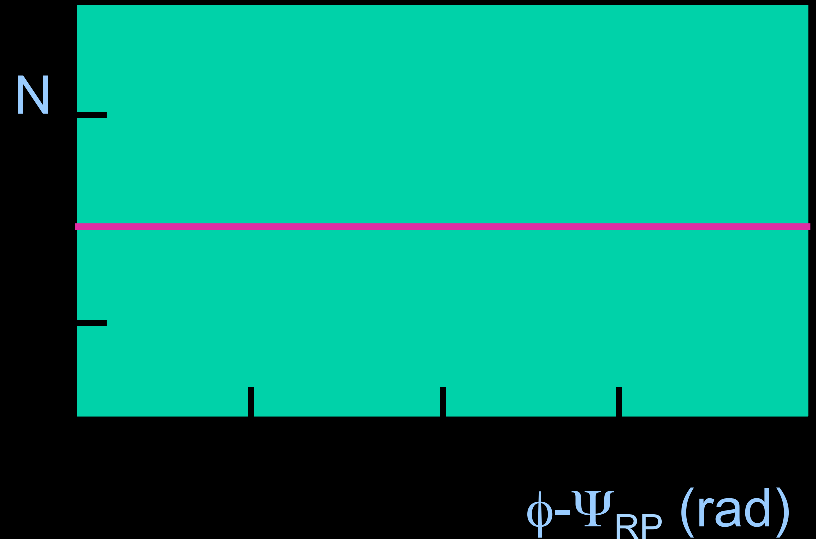
"zero" pressure
in surrounding vacuum

Azimuthal Angular Distributions

1) Superposition of independent p+p:

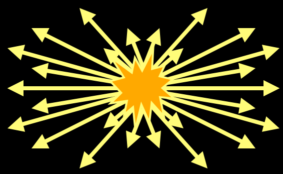
momenta random
relative to reaction plane



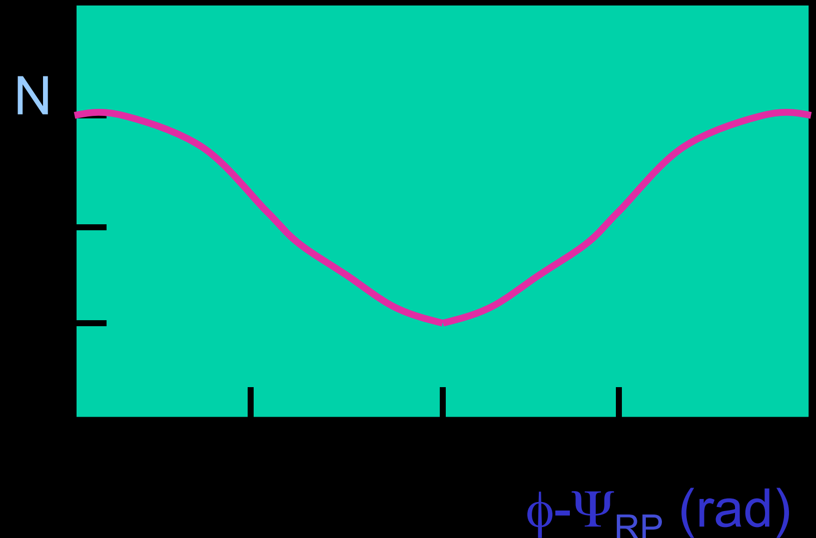


2) Evolution as a **bulk system**

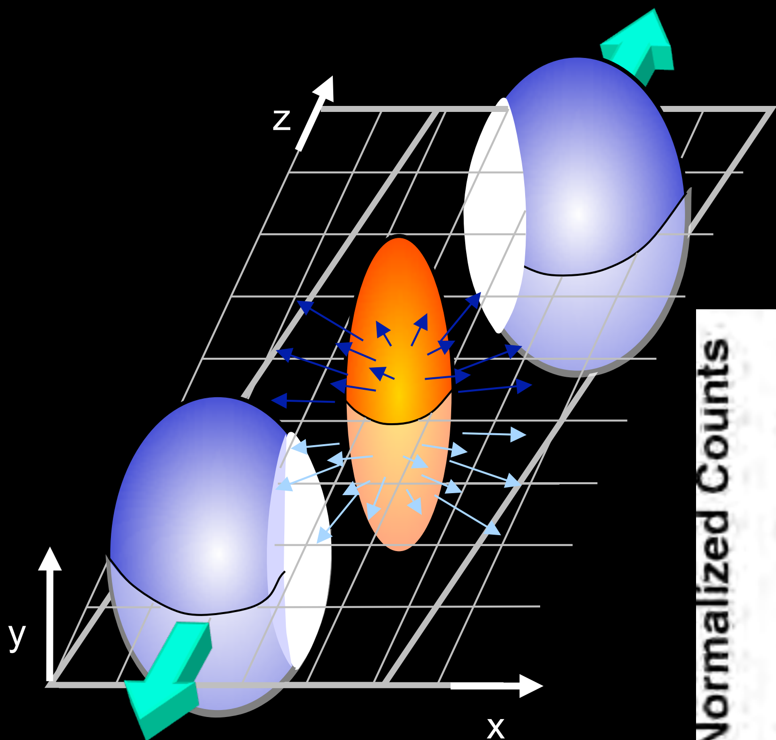
Pressure gradients (larger in-plane)
push bulk "out" → flow



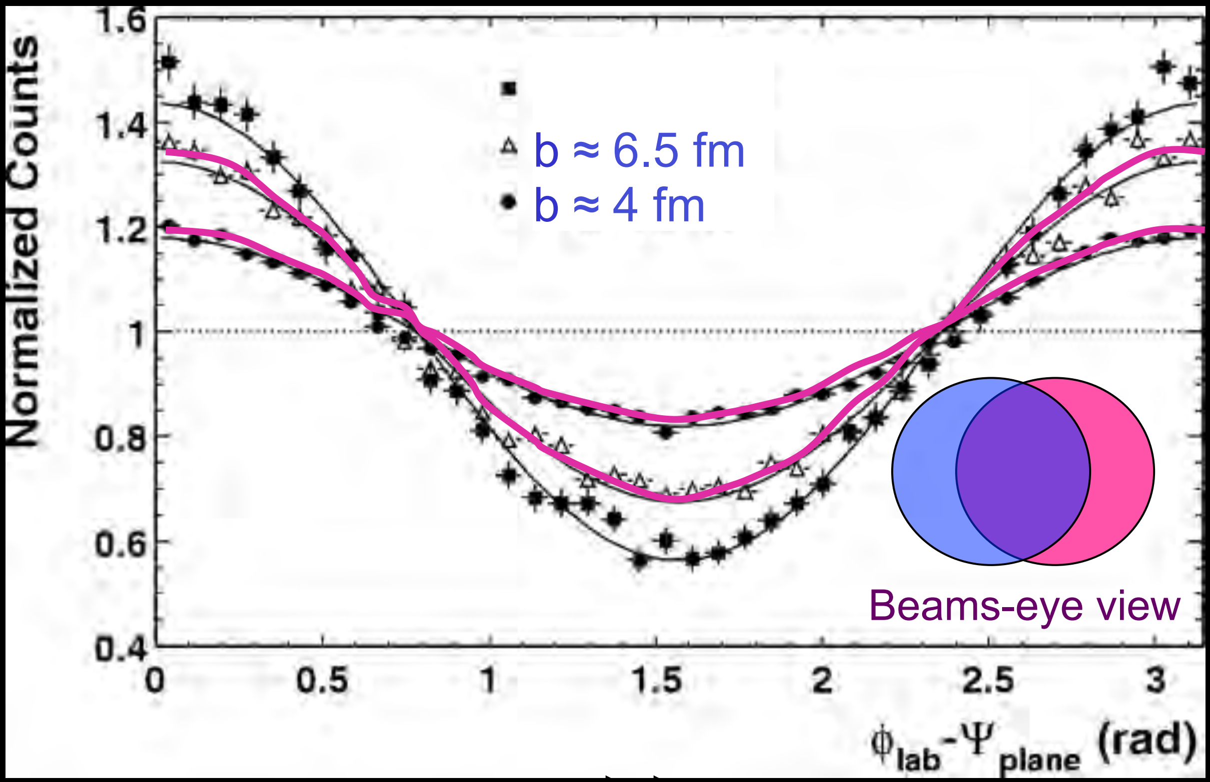
more, faster particles
seen in-plane



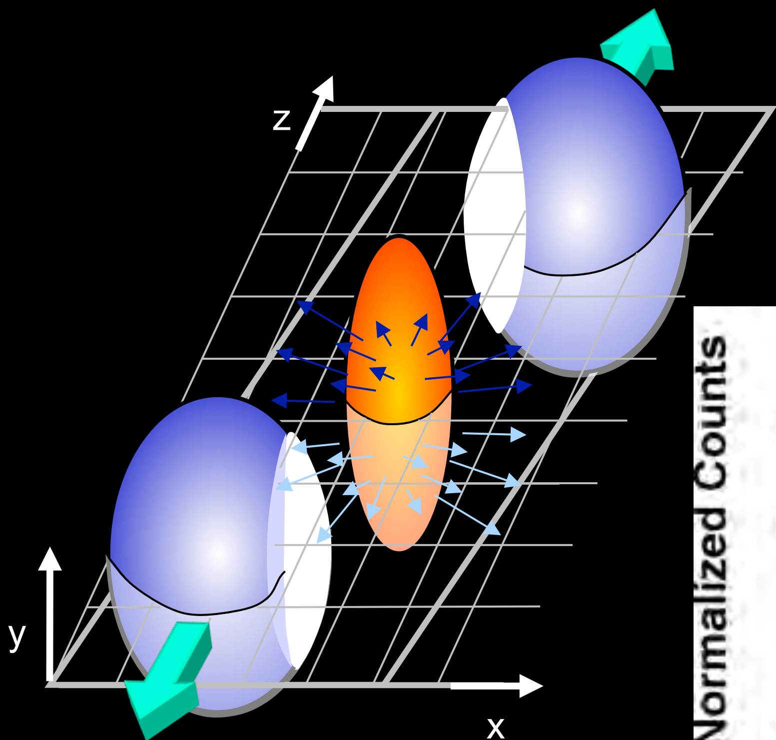
Large Elliptic Flow Observed at RHIC and LHC!



Azimuthal asymmetry of particles:
$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



Large Elliptic Flow Observed at RHIC and LHC!



Azimuthal asymmetry of particles:
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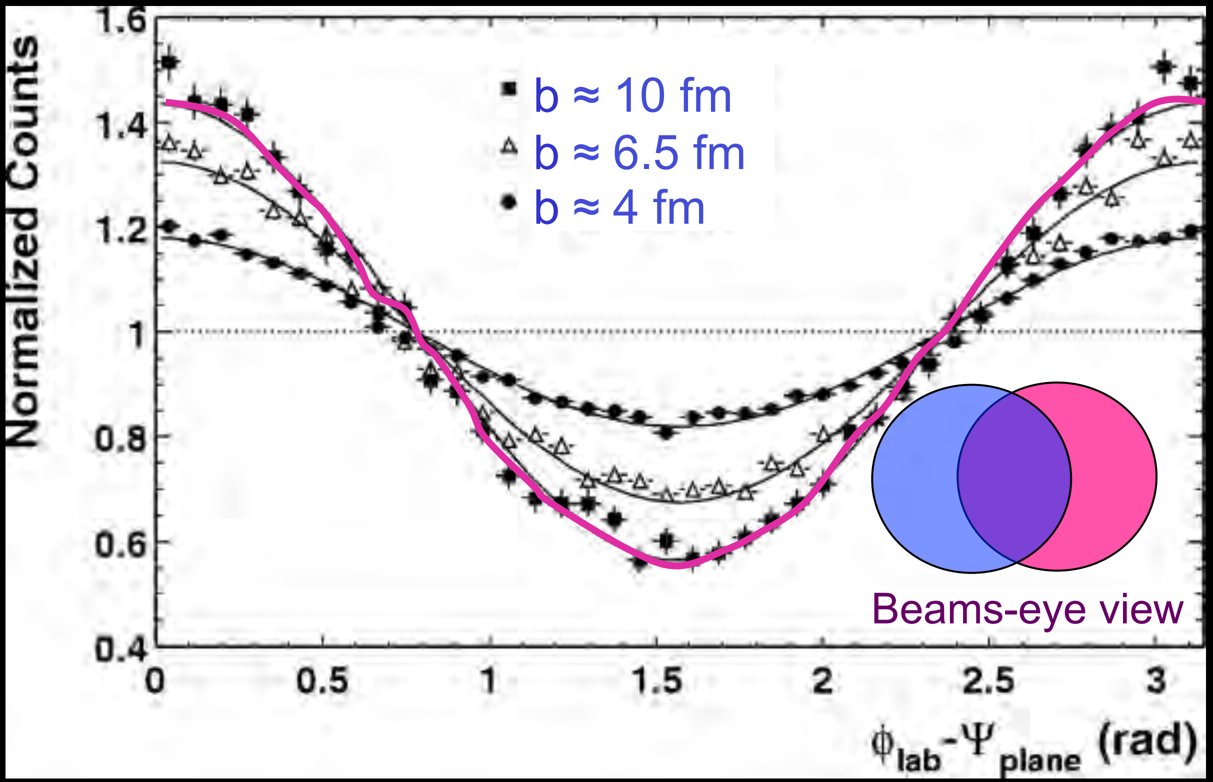
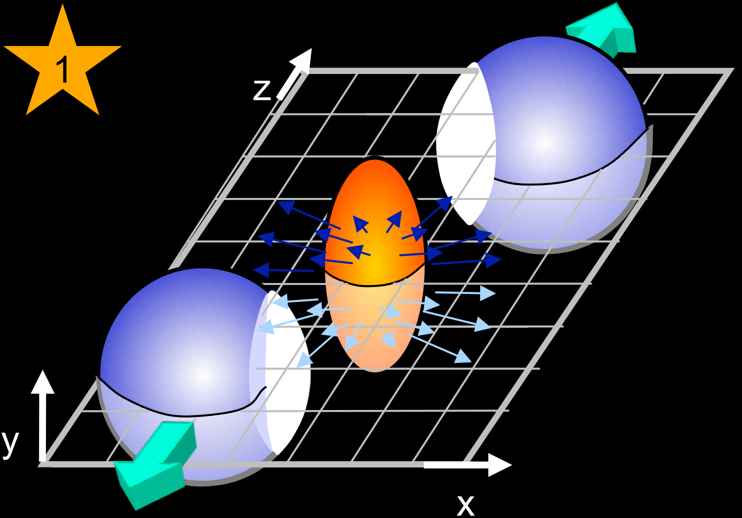
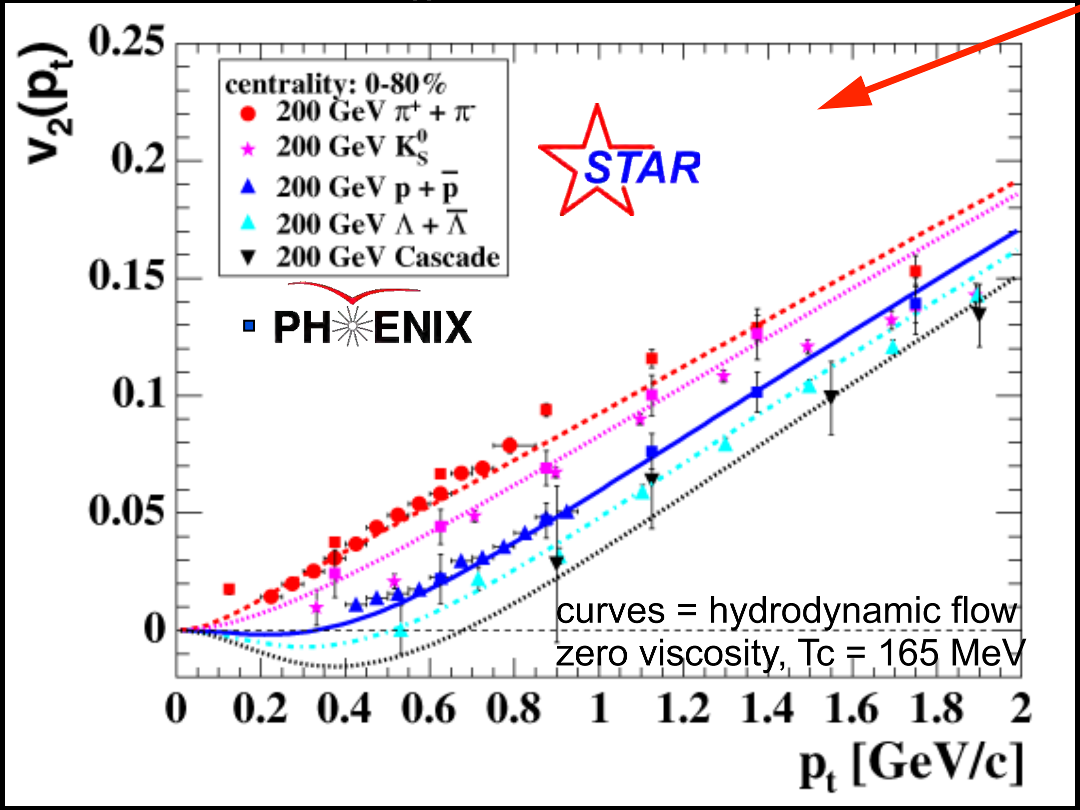




Elliptic Flow Saturates Hydrodynamic Limit

- Azimuthal asymmetry of charged particles:

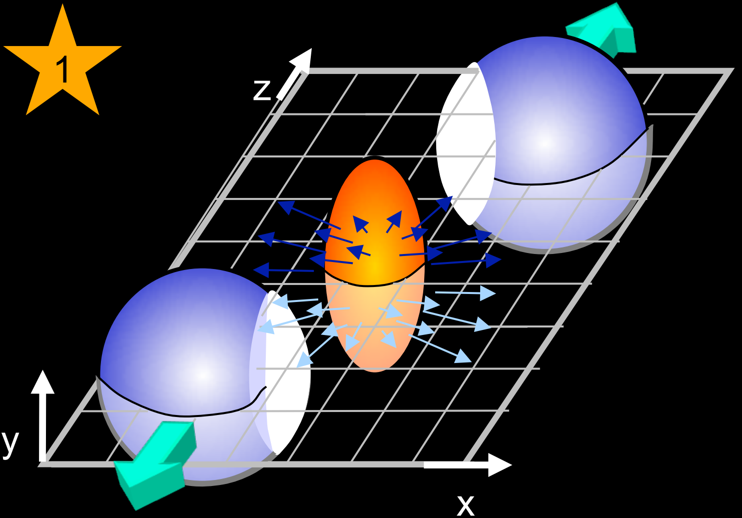
$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$



Mass dependence of v_2

Initial studies require -

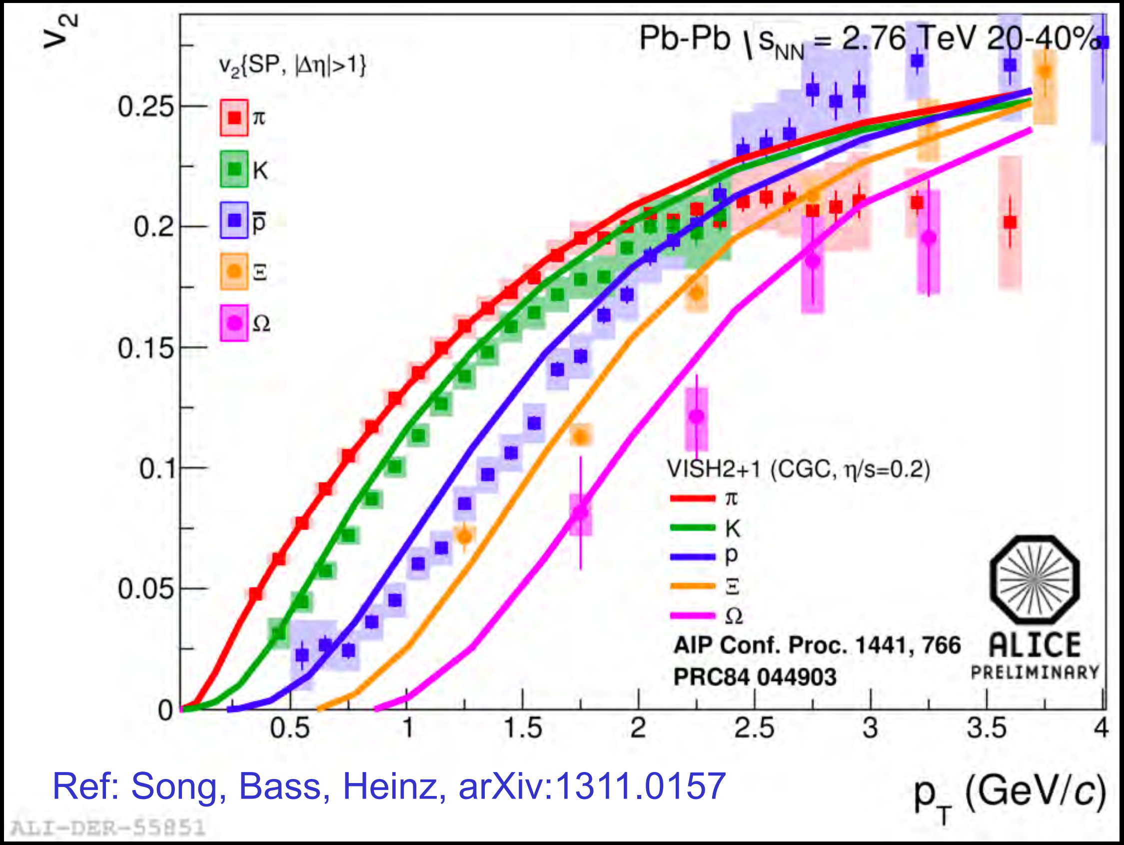
- Early thermalization (0.6 fm/c)
- Ideal hydrodynamics (zero viscosity) → "nearly perfect fluid"
- $\varepsilon \sim 25\ GeV/fm^3$ (>> $\varepsilon_{critical}$)
- Quark-Gluon Equ. of State



Elliptic Flow in Viscous Hydrodynamics

- Azimuthal asymmetry of charged particles:

  $dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$



Ref: Song, Bass, Heinz, arXiv:1311.0157

Mass dependence of v_2

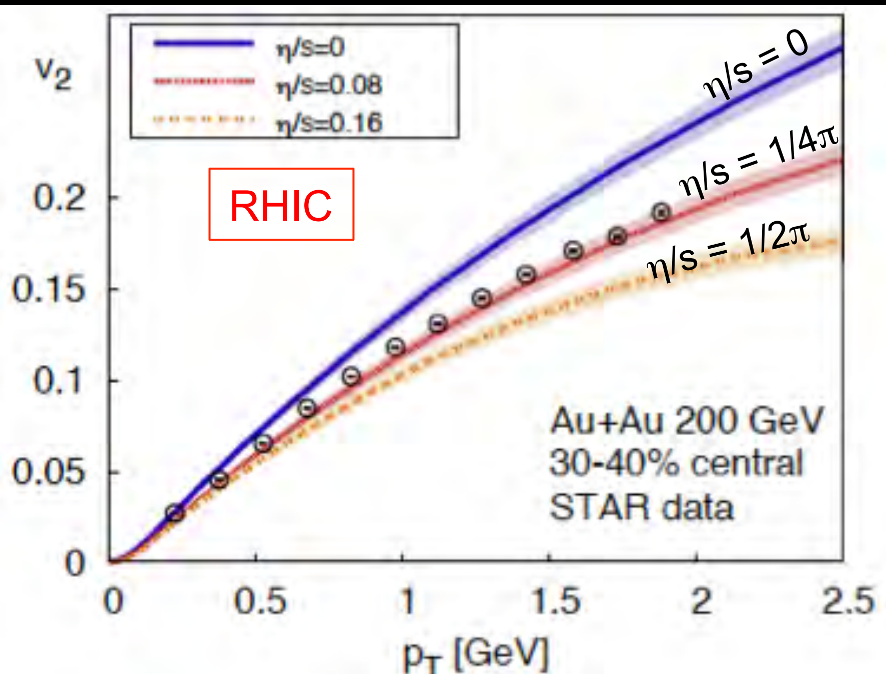
Viscous hydrodynamics -

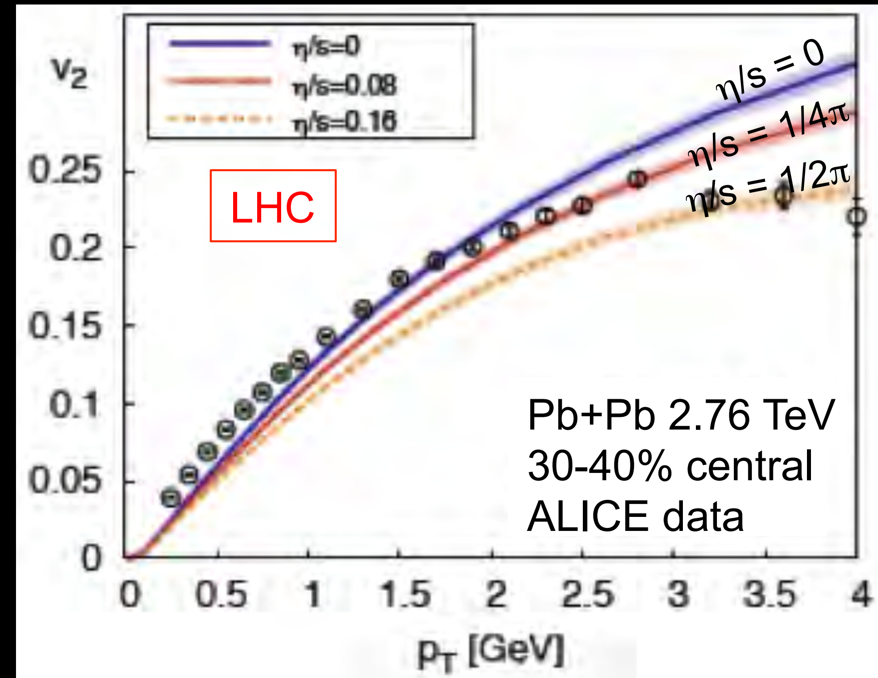
- CGC Initial State
- Early thermalization (0.5 fm/c)
- Shear viscosity / entropy ($\eta/s \sim 0.2$)

→ still "nearly perfect fluid"

- $\varepsilon \gg \varepsilon_{critical}$

It's a Strongly-Coupled Medium with Ultra-Low Shear Viscosity





Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301

$\rightarrow 1/4\pi < \eta/s < 1/2\pi$

Universal lower bound on shear viscosity / entropy ratio (η/s)

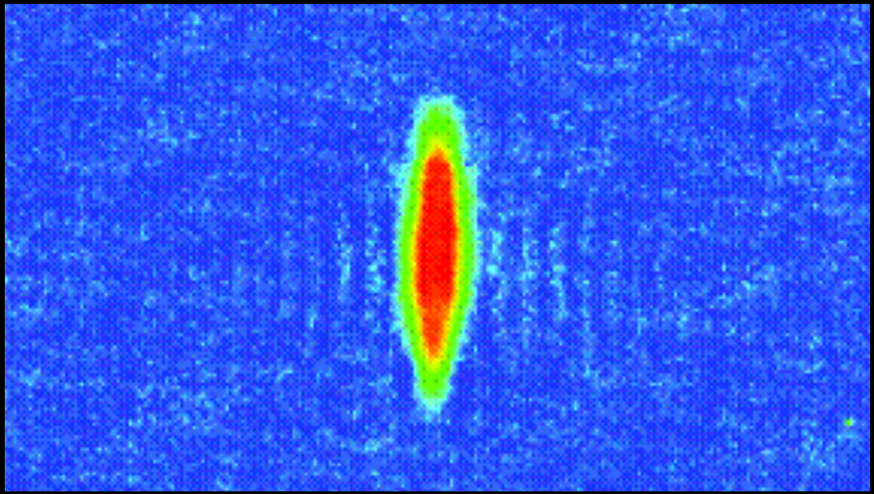
$\rightarrow \eta/s = 1/4\pi$ for the "perfect liquid"

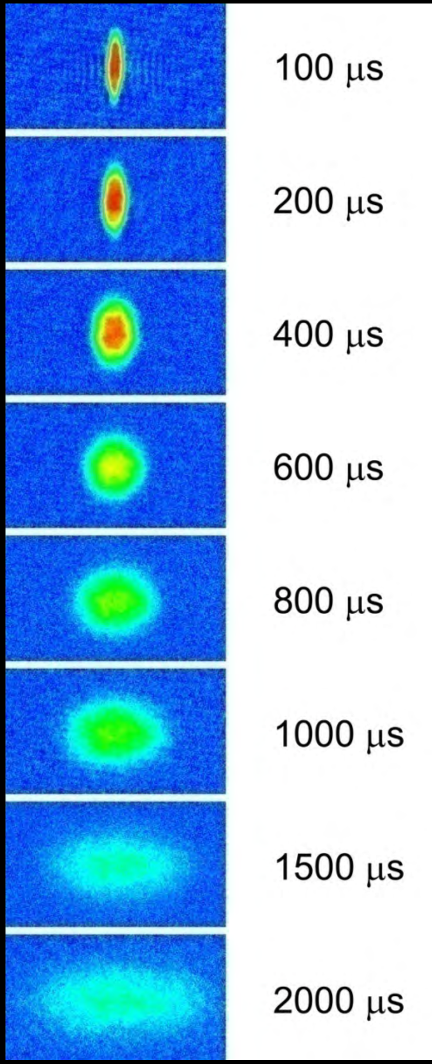
The strong-coupling limit of non-Abelian gauge theories with a gravity dual

(ref: Kovtun, Son, Starinets, PRL 94, 111601 (2005))

Universality of Classical Strongly-Coupled Systems?

Transport in gases of strongly-coupled atoms





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

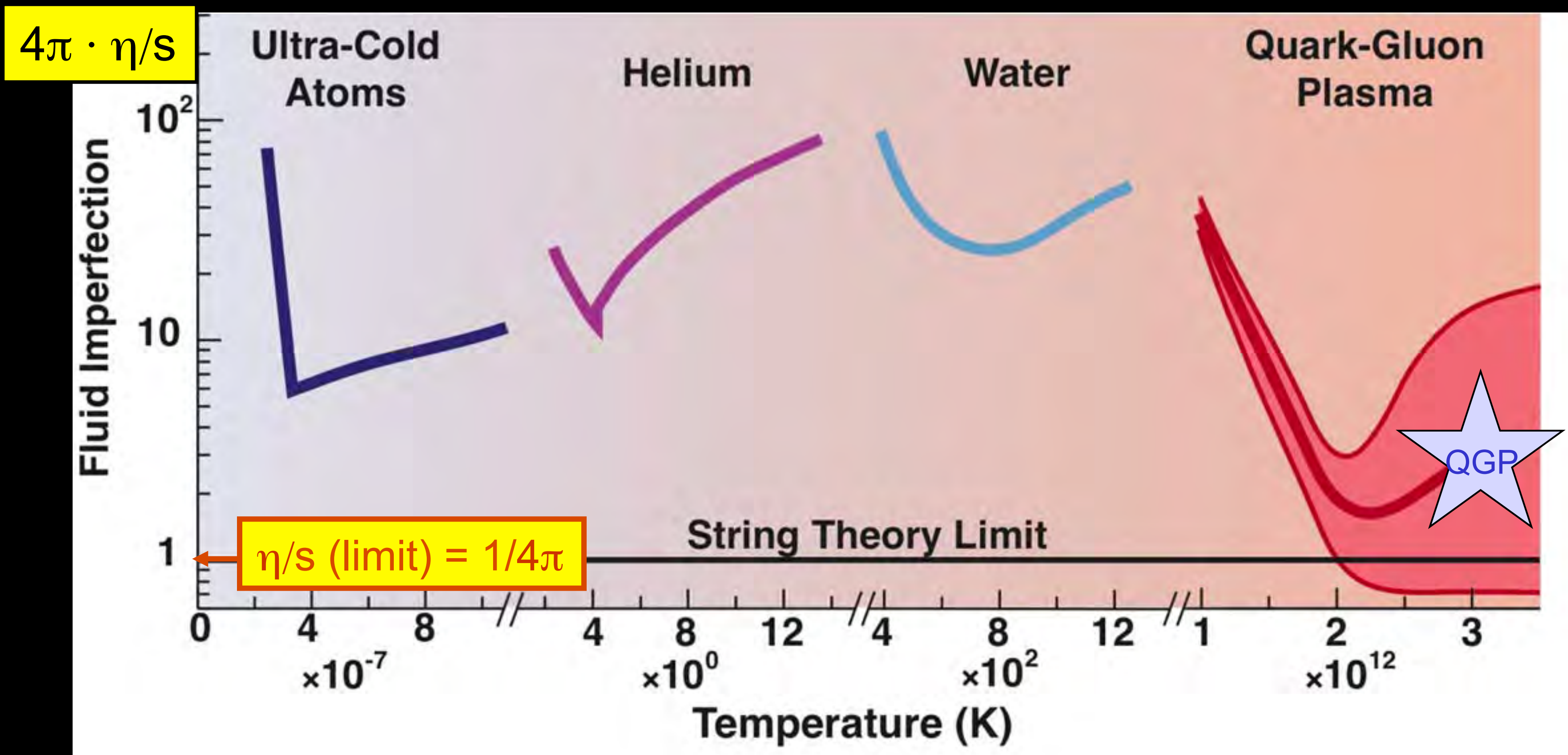
RHIC fluid behaves like this –

a strongly coupled fluid.

Universality of classical strongly-coupled systems?

→ Atoms, sQGP, … AdS/CFT (String Theory)

Ultra-low (Shear)Viscosity Fluids



T = 2 x 10^{12} K

Quantum lower viscosity bound: $\eta/s > 1/4\pi$ (Kovtun, Son, Starinets)

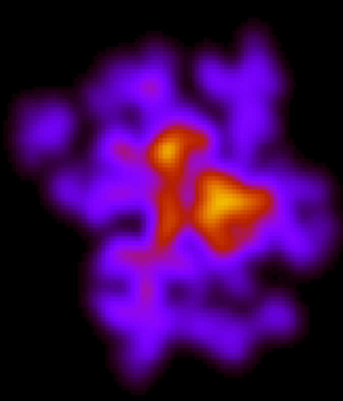
from strongly coupled *N* = 4 SUSY YM theory.

3-d Rel. Hydro describes RHIC/LHC v_2 data with $\eta/s \sim 1/2\pi$ near lower bound!

Event-by-Event Initial Conditions Vary!

Initial conditions vary event-to-event.

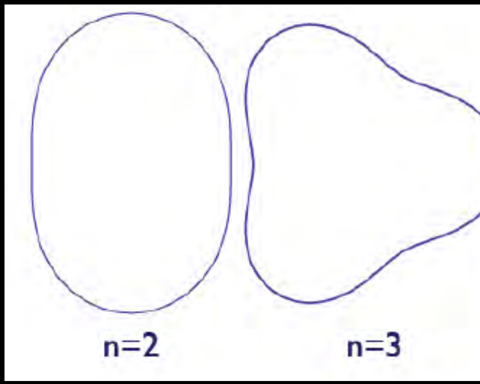
Overlap region (1 event): Kowalski, Lappi, Venugopalan, PRL 100:022303



Hydro evolution of overlap region: Schenke, et al. PRL 106:042301

Final observation

Final observation

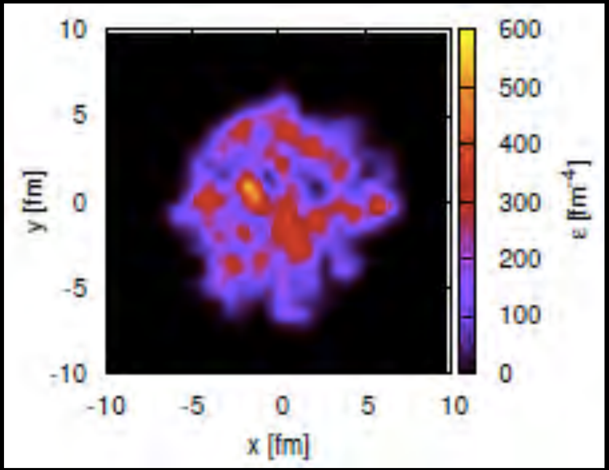


Azimuthal RHI harmonics provide information on viscous damping & spatial correlations:

$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Higher Order Harmonics → Probe Properties of the QGP

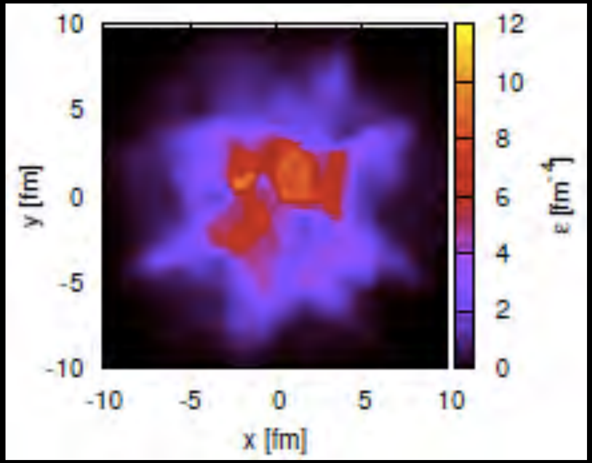
Initial State



Ideal $\eta/s = 0$

$\eta/s = 1/4\pi$

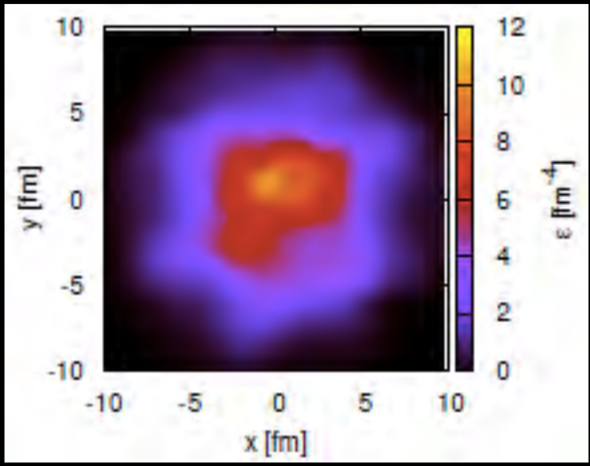
Final observation



Sound attenuation length:
$\Gamma_s = \eta/s * 1/T$
governs linear fluctuations.

Reynolds # ~ $1/\Gamma_s$
governs non-linear fluctuations.

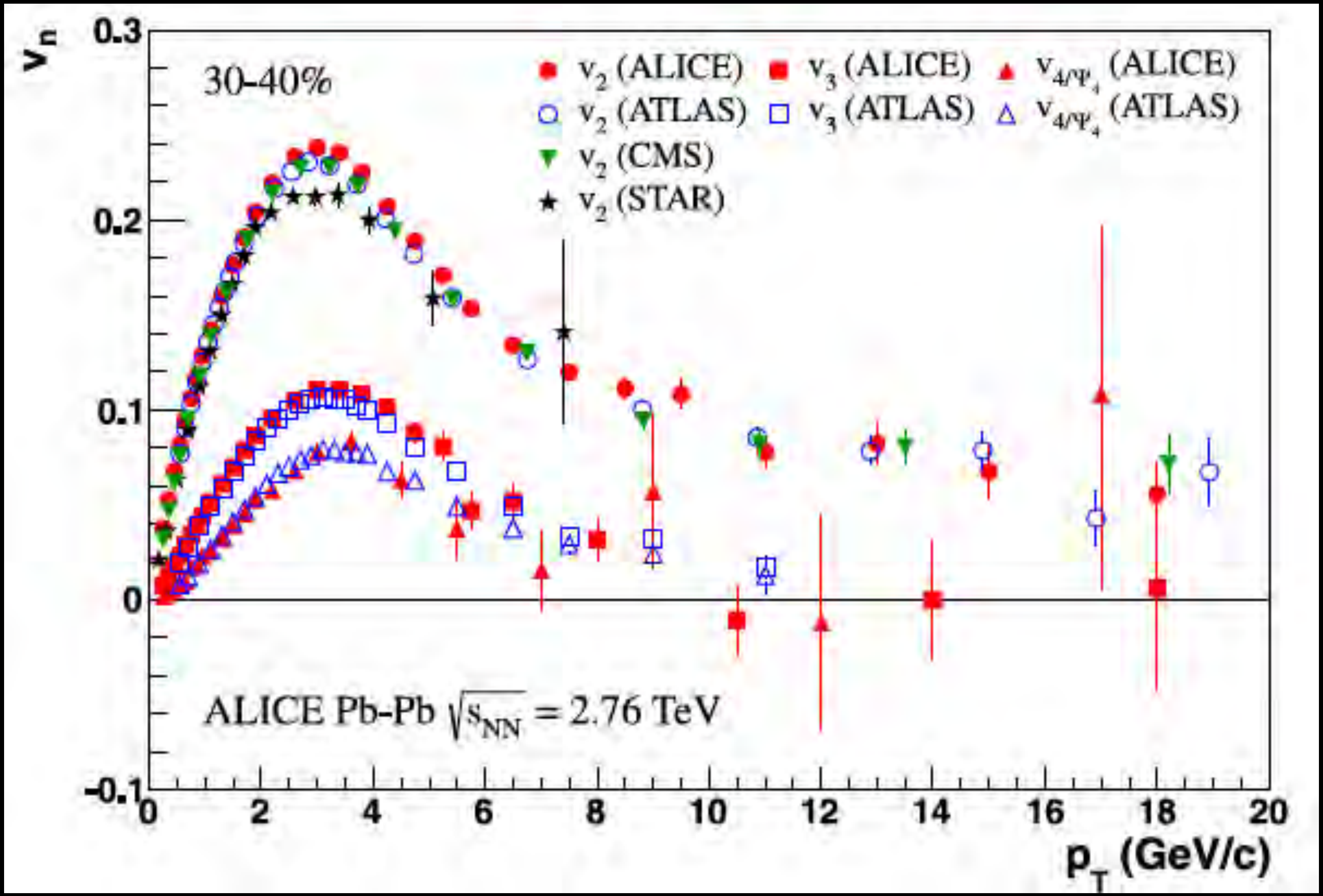
Final observation



Higher order harmonics provide extent to which initial inhomogeneity propagates thru the QGP:

$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

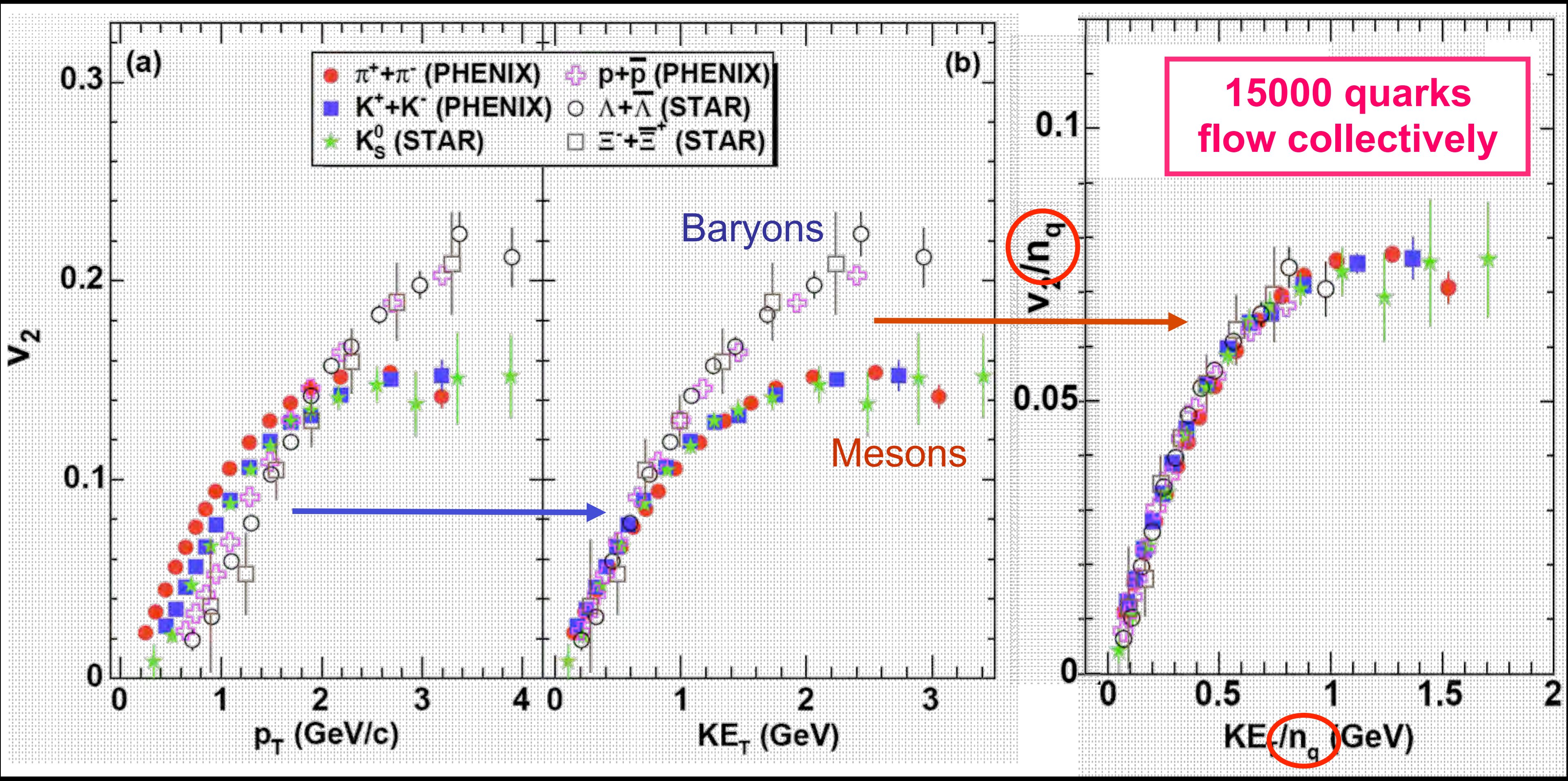
Higher Order Components at LHC and RHIC



Identified Hadron Elliptic Flow Complicated

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons →

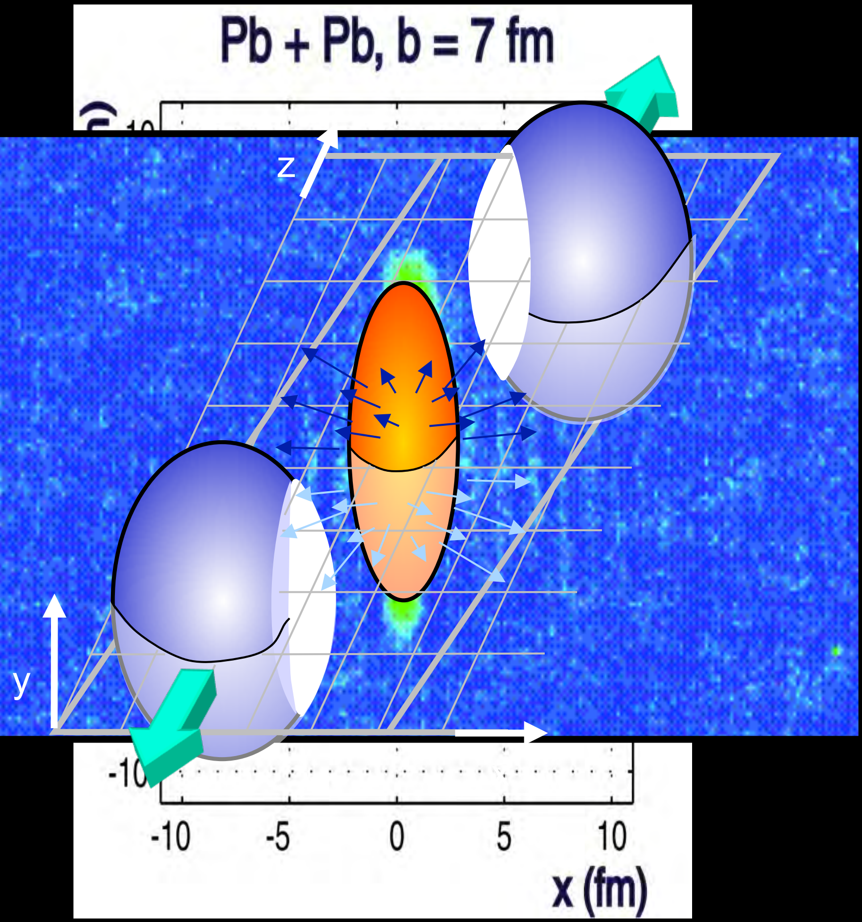
$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi)$



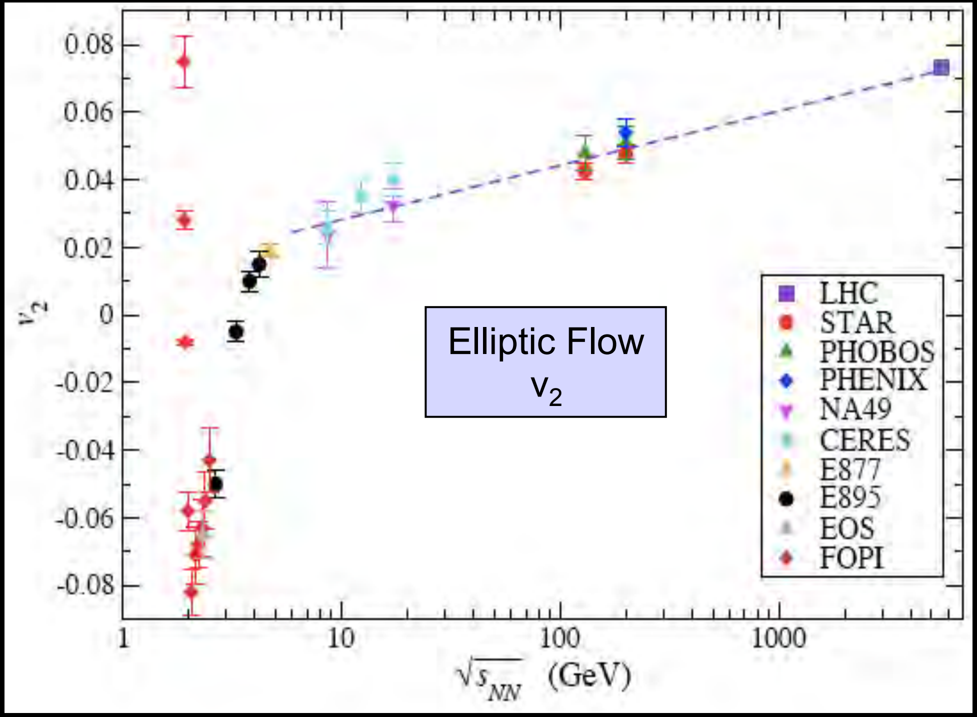
If flow established at quark level, it is predicted to be *simple* →

$KE_T \rightarrow KE_T / n_q$, $v_2 \rightarrow v_2 / n_q$, n_q = (2, 3 quarks) for (meson, baryon)

Large Elliptic Flow Observed at RHIC and LHC!



Azimuthal asymmetry of particles:
$dn/d\phi \sim 1 + 2\ v_2(p_T) \cos(2\ \phi) + \ldots$



Predicted by hydrodynamics with very low shear viscosity

Increase in v_2 from RHIC to LHC

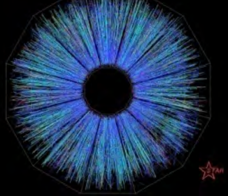
If baryons and mesons form

from independently flowing quarks

then

quarks are deconfined

for a brief moment (~ 10^{-23} s), then hadronization!



"What Have We Learned" from RHIC & LHC

4) QGP radiation (thermal photons)

→ exhibit time-integrated temperatures >> $T_{critical}$

Low mass di-leptons (virtual photons)

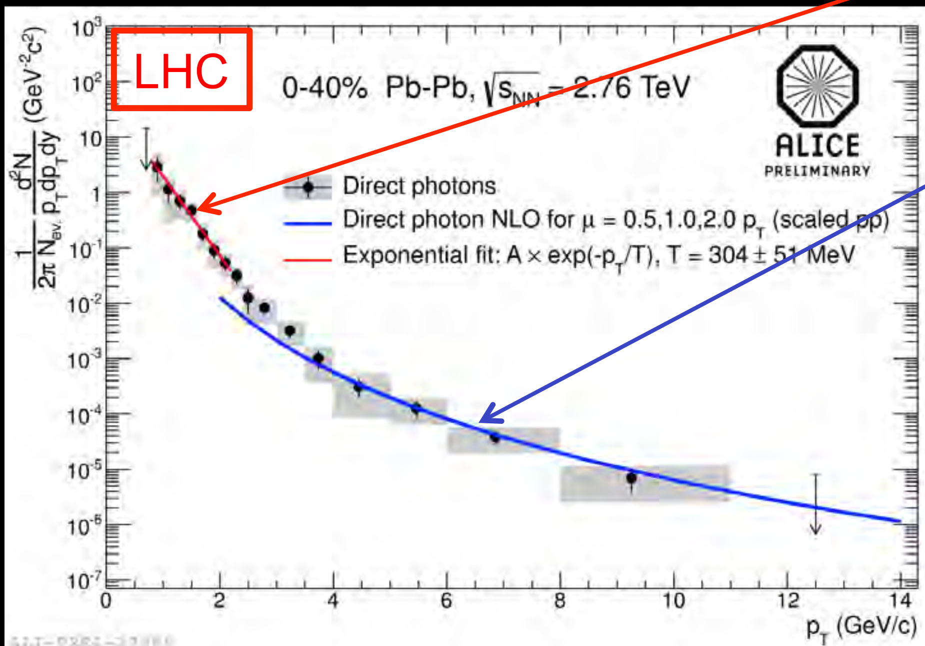
→ broadening of mass spectrum → medium modifications?

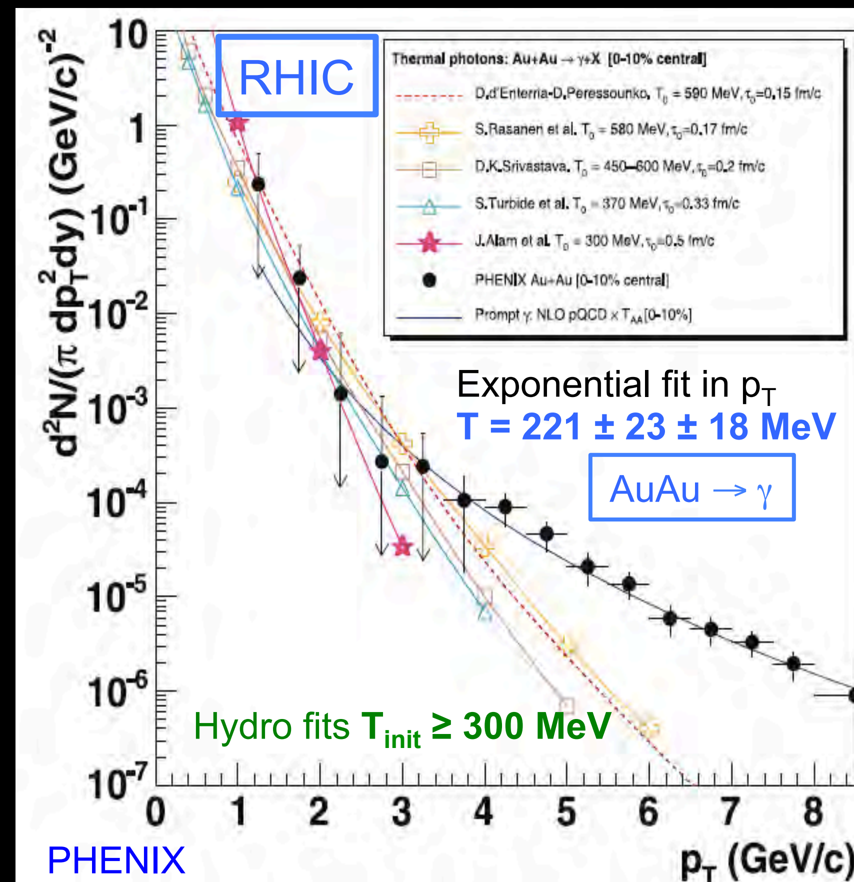
Thermal Photons – Shining of the QGP

A thermal component of direct photons:

Exponential fit for $p_T < 2.2$ GeV/c
inv. slope $T = 304 \pm 51$ MeV

N_{coll}-scaled NLO pQCD





LHC (ALICE): $T = 304 \pm 51$ MeV
for $\sqrt{s_{NN}} = 2.76$ TeV Pb-Pb

RHIC(PHENIX): $T = 221 \pm 19 \pm 19$ MeV
for $\sqrt{s_{NN}} = 0.2$ TeV Au–Au

Note: T is integral over entire evolution!

Properties of Medium – Virtual Photons

Virtual photons – Di-leptons

Medium modification of resonance & hadron masses

Initial studies at SPS → Chiral symmetry restoration?

Centrality dependence:
PHENIX, PRC81, 034911(2010), arXiv:0912.0244

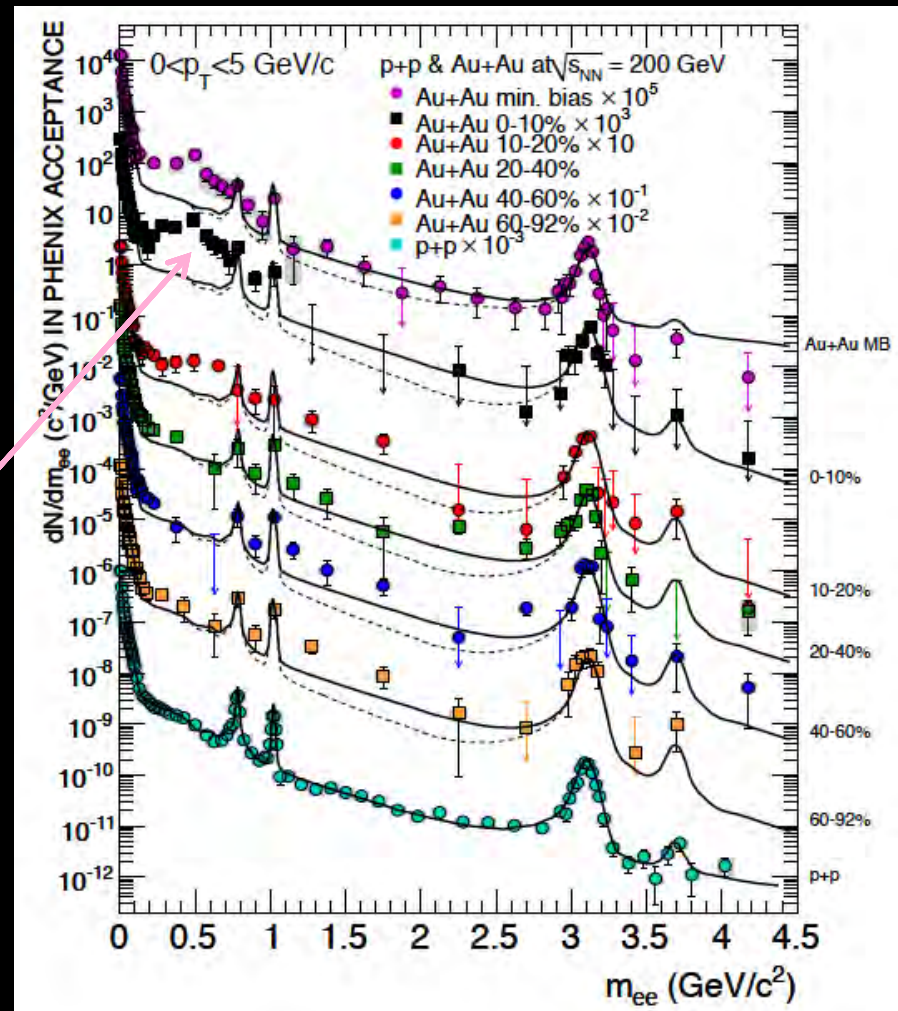
Virtual photons from decays in QGP

Must subtract all hadronic decays outside medium (scale pp data)

Low mass di-lepton enhancement!

The original case for medium effects!

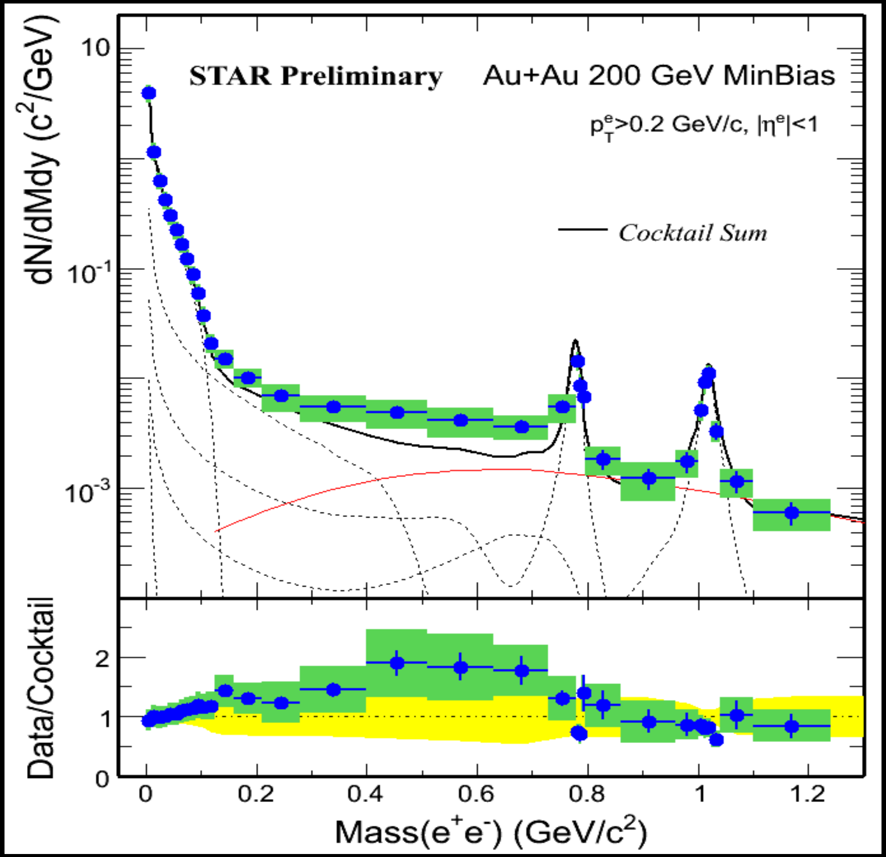
Increases with centrality.

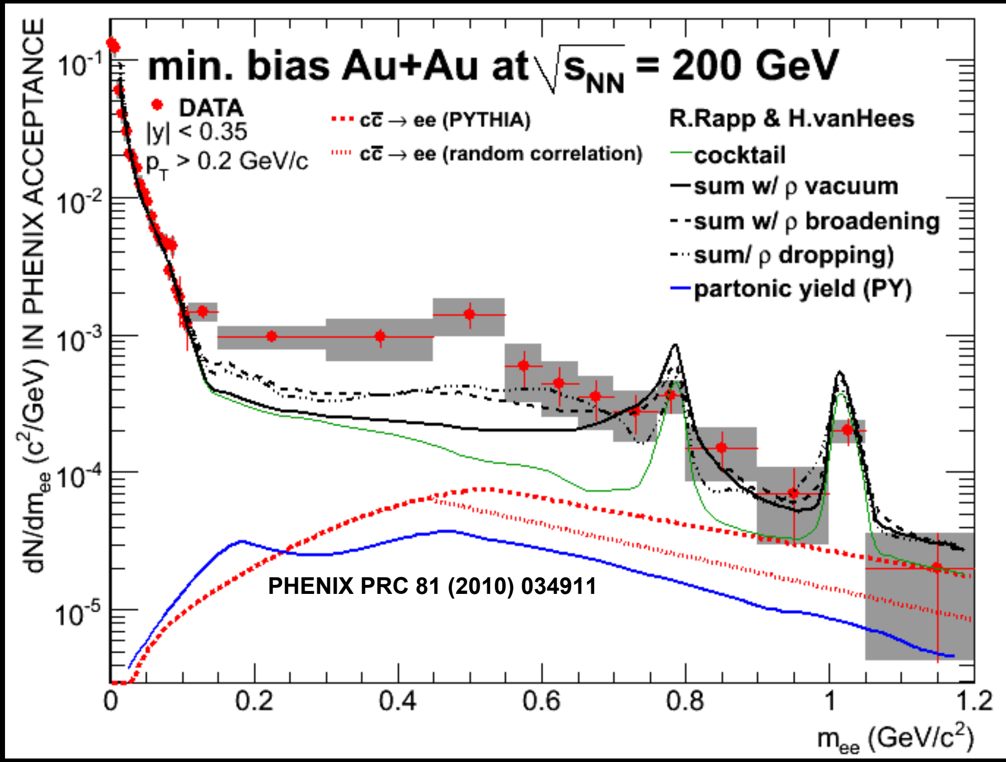


Space-time evolution?

Shuryak, arXiv:1203.1012v1

Low Mass Di-Leptons at RHIC LHC…?





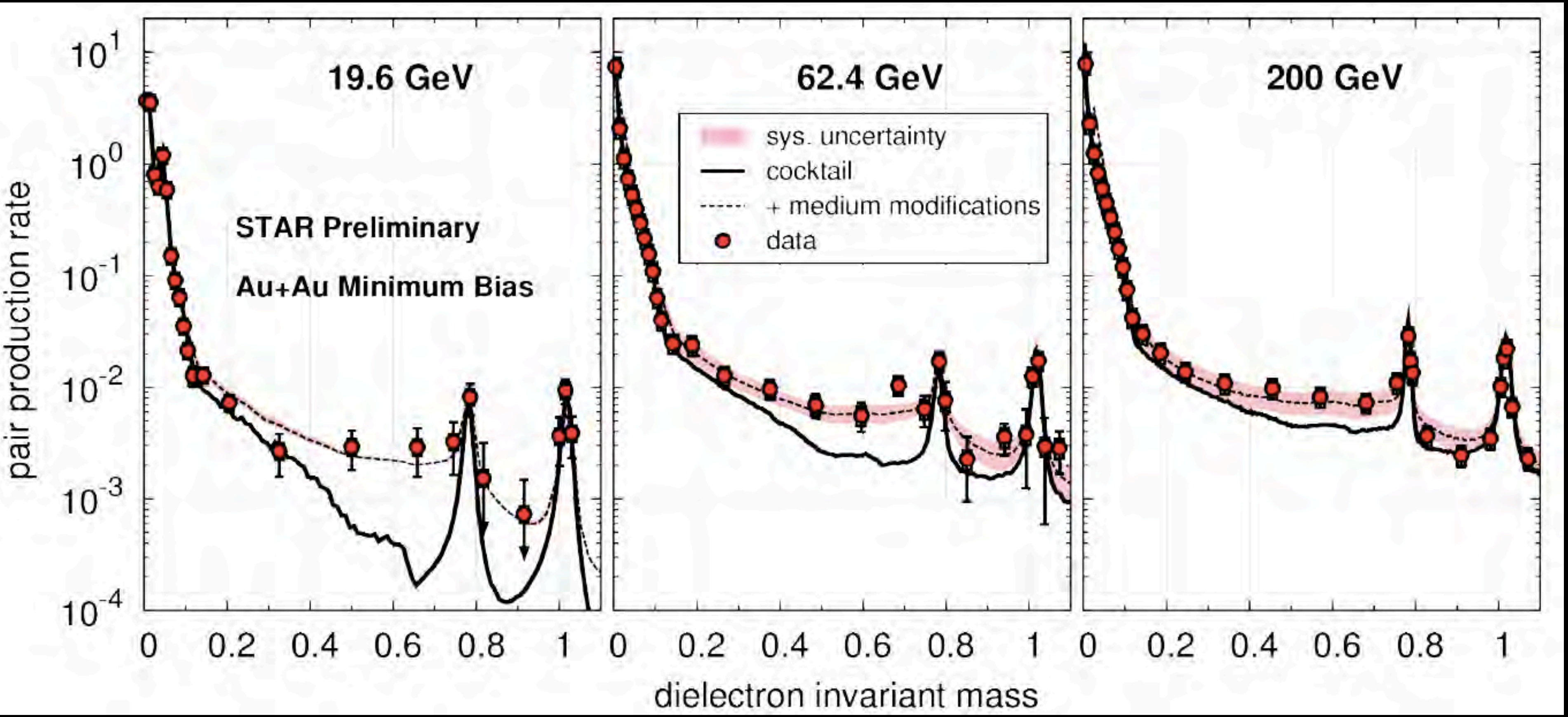
Enhancement factor in $0.15<M_{ee}<0.75$ Gev/c2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Disagreement & very difficult “task”!

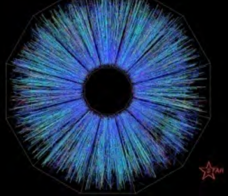
Note: Acceptance differences etc.

Low Mass Di-Leptons at RHIC – Lower Energies



Beam Energy Scan shows low mass enhancement at all $\sqrt{s_{NN}}$

- ρ melting sensitive to total baryon density not net baryon density
- model describing data include chirally symmetric phase



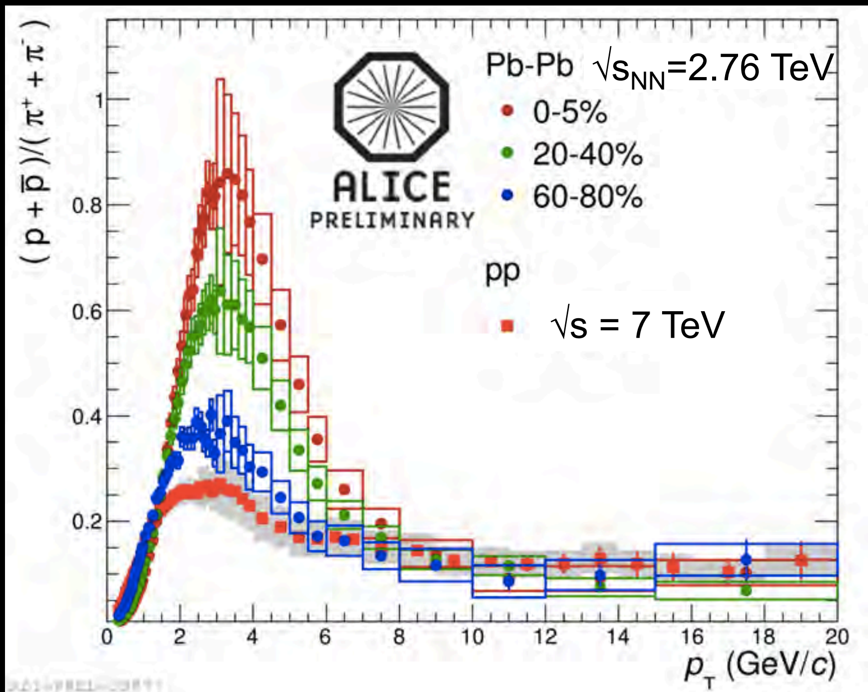
“What Have We Learned” from RHIC & LHC

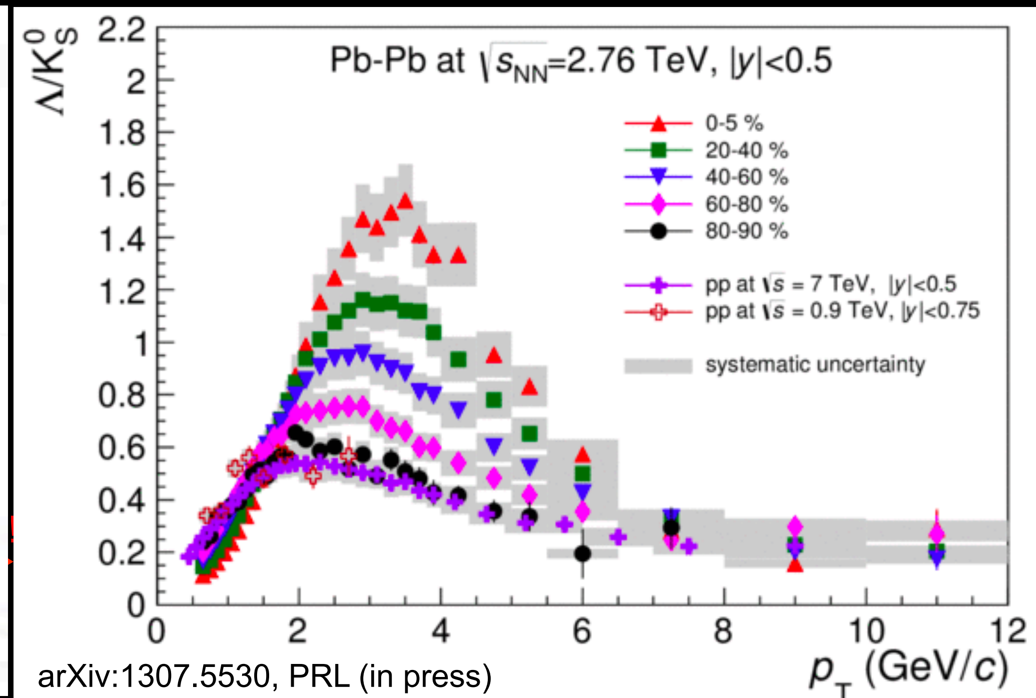
5) Baryon-Meson Anomaly?

→ Another mechanism producing hadrons at $p_T < 7$ GeV/c

(i.e. not parton fragmentation!)

π, K, p: Baryon-Meson Anomaly & Suppression





Baryon / meson ratio (p/π and Λ/K^0_s)

1.5 < p_T < 8 GeV/c

Increases for more central collisions

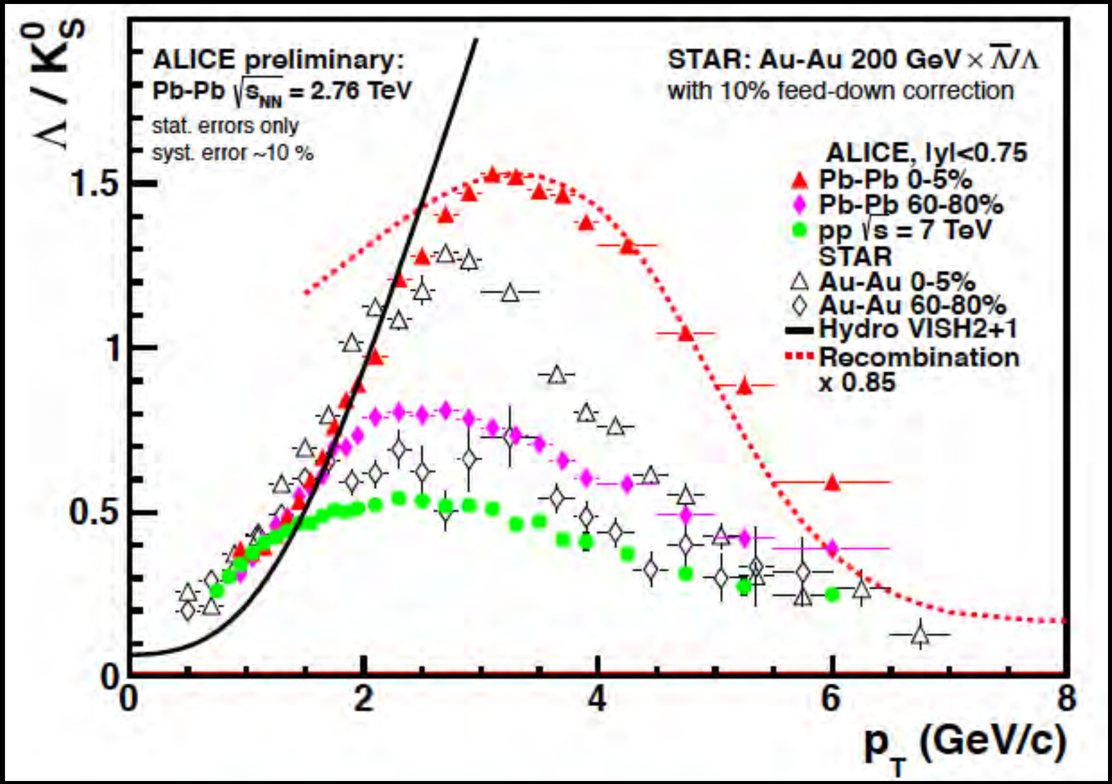
Peripheral Pb-Pb similar to pp

→ Effects of medium? Quark recombination? Radial flow? Stan's?

p_T > 8 GeV/c

No dependence on centrality / system → Parton fragmentation (unmodified)

Baryon-Meson Anomaly – ALICE & STAR



Baryon / meson ratio (p/π and Λ/K^0_s)

$1.5 < p_T < 8$ GeV/c

Increases for more central collisions

Peripheral Pb-Pb similar to pp

→ Effects of medium? Quark recombination? Radial flow? Stan's?

“What Have We Learned” from RHIC & LHC

1) Consistent Picture of Geometry, Dynamics and Evolution of RHI Collisions

2) Particle ratios → equilibrium abundances → universal hadronization $T_{critical}$

Confirm lattice predictions for $T_{critical}$, μ_B

3) It has characteristics of a quark-gluon plasma

Flows with ultra-low shear viscosity

Strongly-coupled liquid

4) QGP radiation (thermal photons) → time-integrated temperatures >> Tcritical

Low mass di-leptons (virtual photons) → in-medium modification?

5) Baryon-meson anomaly →

Hadron production not fragmentation for $p_T < 7$ GeV/c

Next Monday: Using Hard Probes to Investigate the QGP

The Real Impact of the LHC!