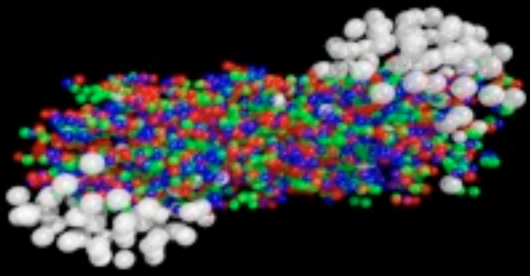


Heavy Ion Physics

Part 1

Raimond Snellings

NIKHEF

Content

QCD at high density and temperature

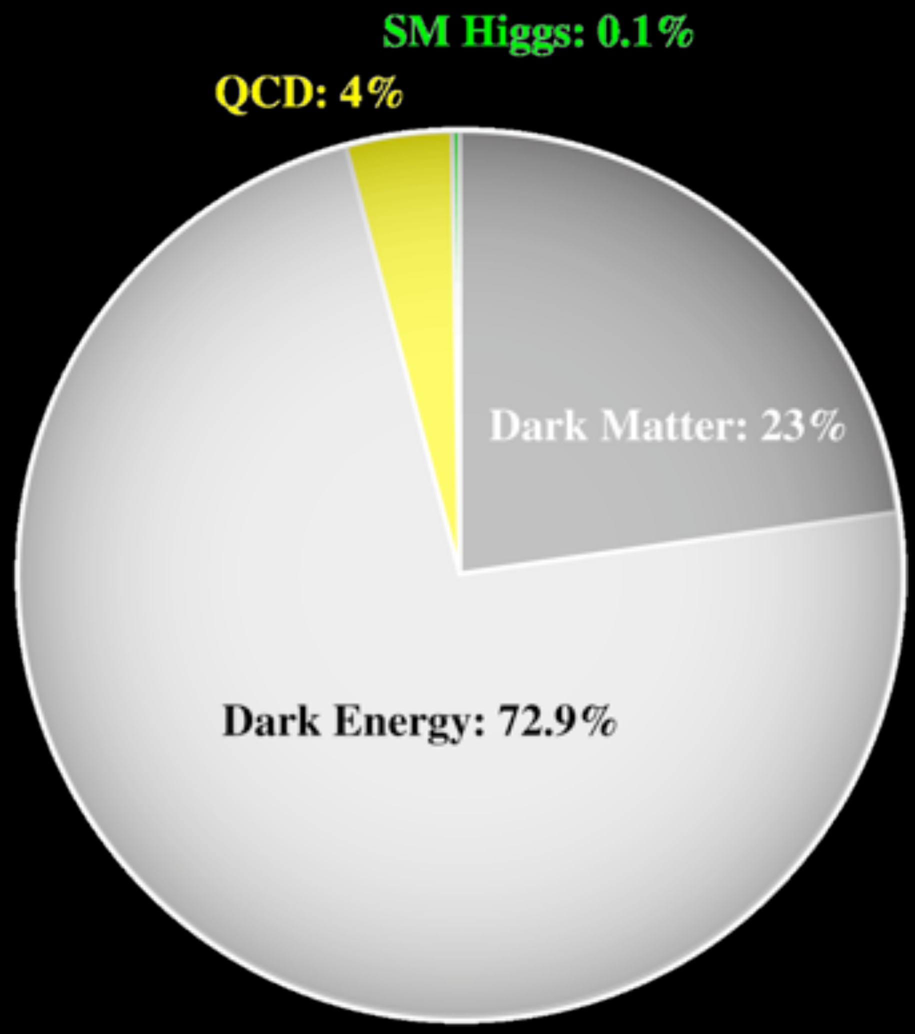
heavy-ion accelerators, experiments, global collision characterization

QGP observables and experimental probes

the LHC heavy-ion program and ALICE the dedicated heavy-ion detector

What is the universe made of?

- elementary particles make up 0.1% of the mass in the universe
  - ✓ SM Higgs mechanism
- composite particles (hadrons) can account for ~ 4%
  - ✓ QCD chiral symmetry breaking
- dark Matter 23%
- dark Energy 72.9%
- the 4% are still not understood very well and the other 96% are a complete mystery!



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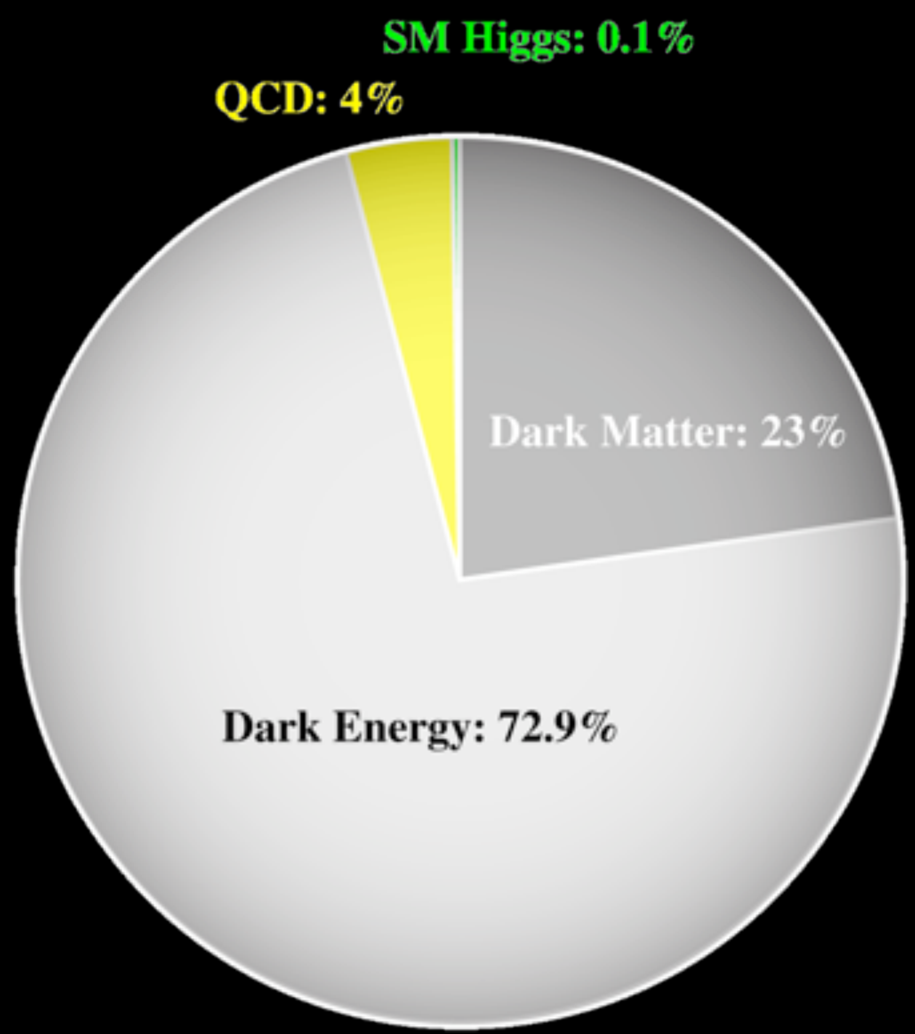


The Standard Model

(matter)

	1st generation	mass	2nd generation	mass	3rd generation	mass	charge
quarks	u u u	~3	c c c	1250	t t t	174300	2/3
	d d d	~6	s s s	120	b b b	4200	-1/3
leptons	ν_e	~0	ν_μ	~0	ν_τ	~0	0
	e	0.511	μ	106	τ	1770	-1

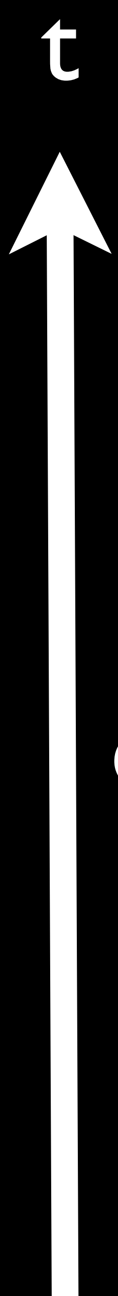
The Standard Model

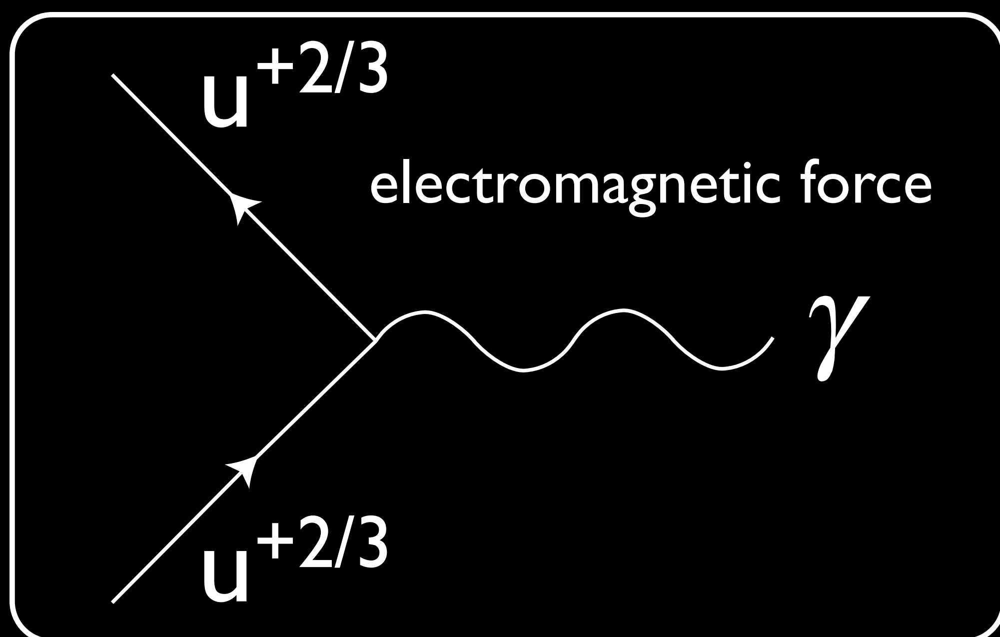
(anti-matter)

	1st generation	mass	2nd generation	mass	3rd generation	mass	charge
anti-quarks	$\overline{u}$ $\overline{u}$ $\overline{u}$	~3	$\overline{c}$ $\overline{c}$ $\overline{c}$	1250	$\overline{t}$ $\overline{t}$ $\overline{t}$	174300	-2/3
	$\overline{d}$ $\overline{d}$ $\overline{d}$	~6	$\overline{s}$ $\overline{s}$ $\overline{s}$	120	$\overline{b}$ $\overline{b}$ $\overline{b}$	4200	1/3
anti-leptons	$\overline{\nu_e}$	~0	$\overline{\nu_\mu}$	~0	$\overline{\nu_\tau}$	~0	0
	e	0.511	μ	106	τ	1770	+1

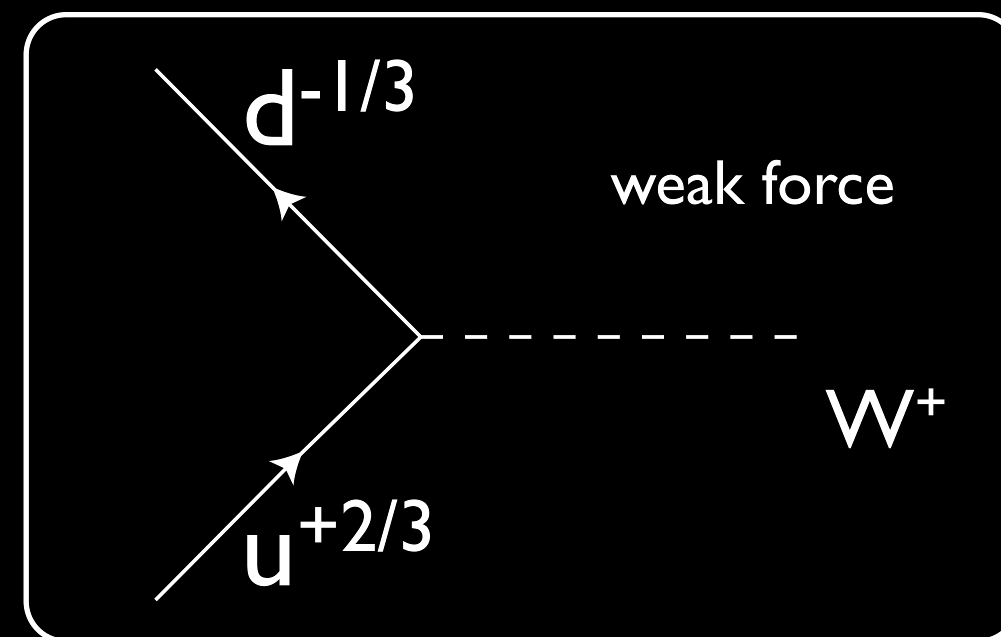
The Standard Model

(forces)

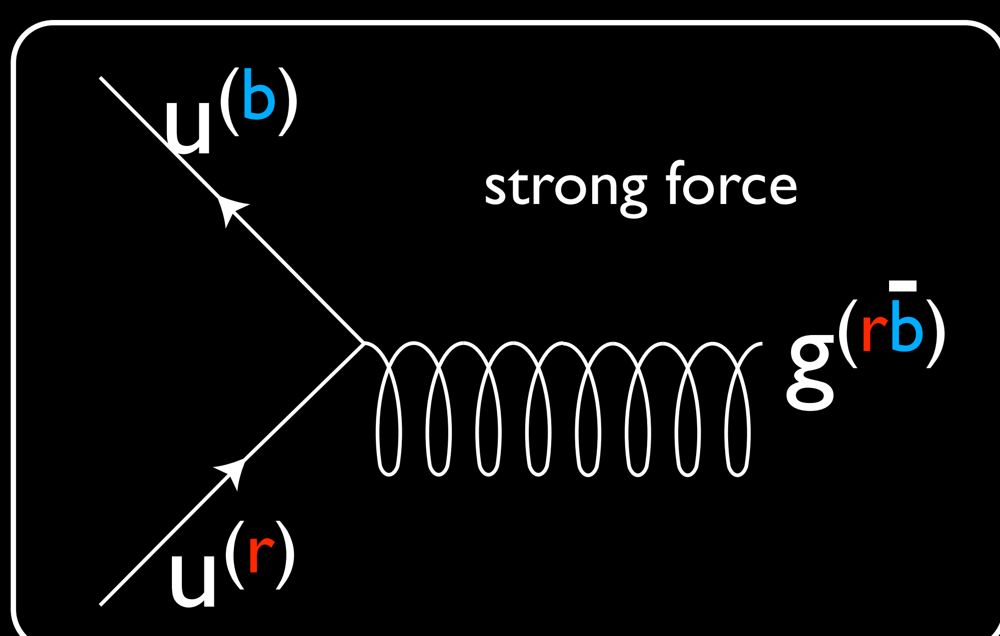




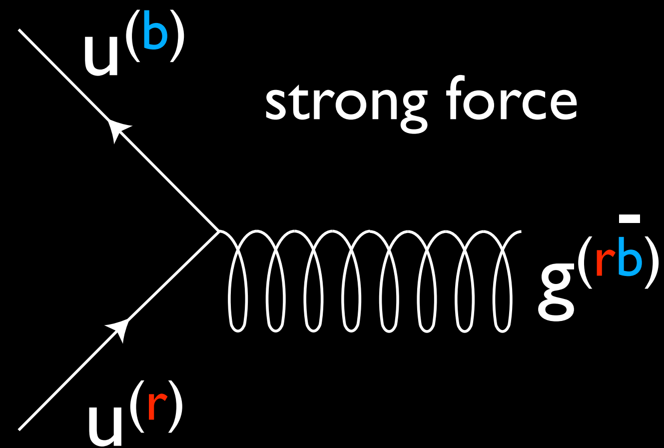
Quantum Electro Dynamics (QED)



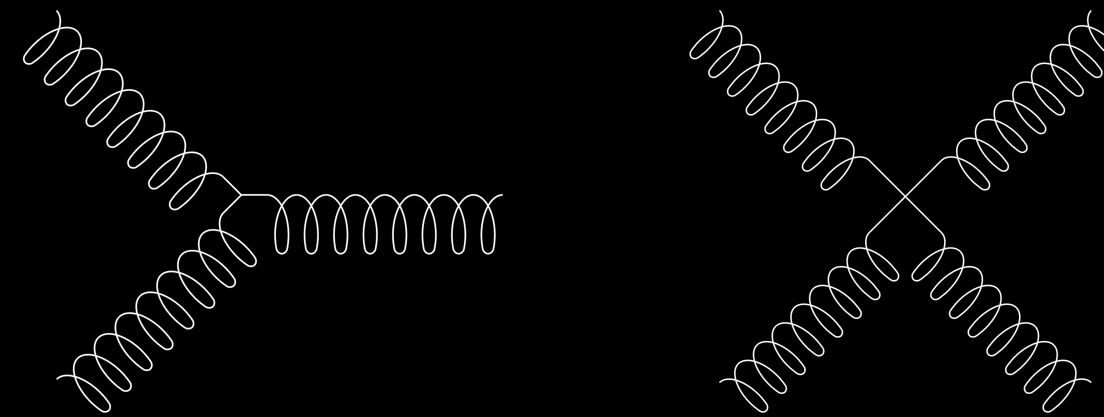
Quantum Flavor Dynamics (QFD)



Quantum Chromo Dynamics (QCD)



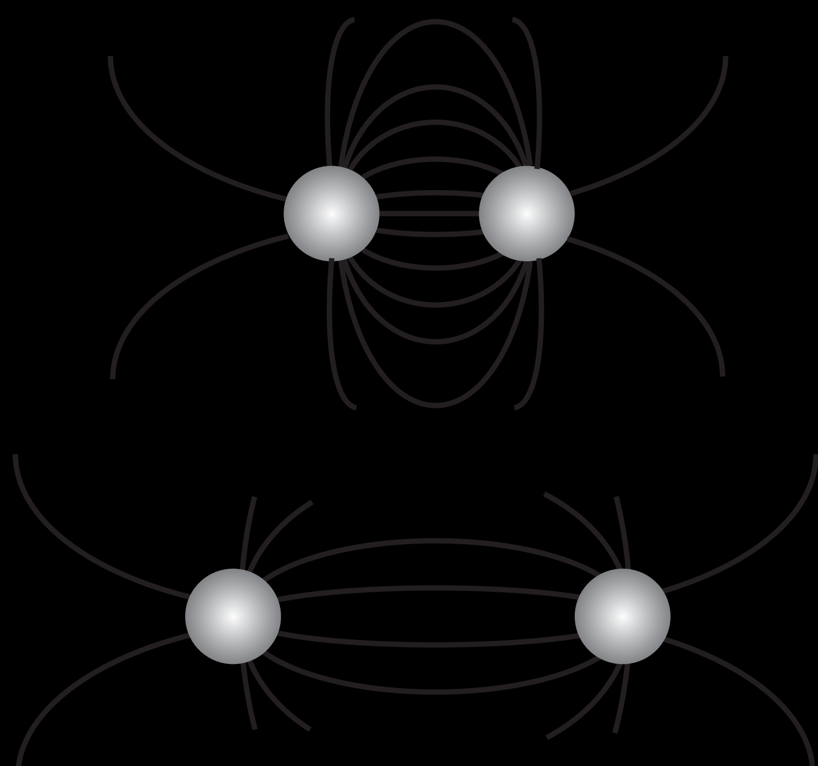
gluons carry color!

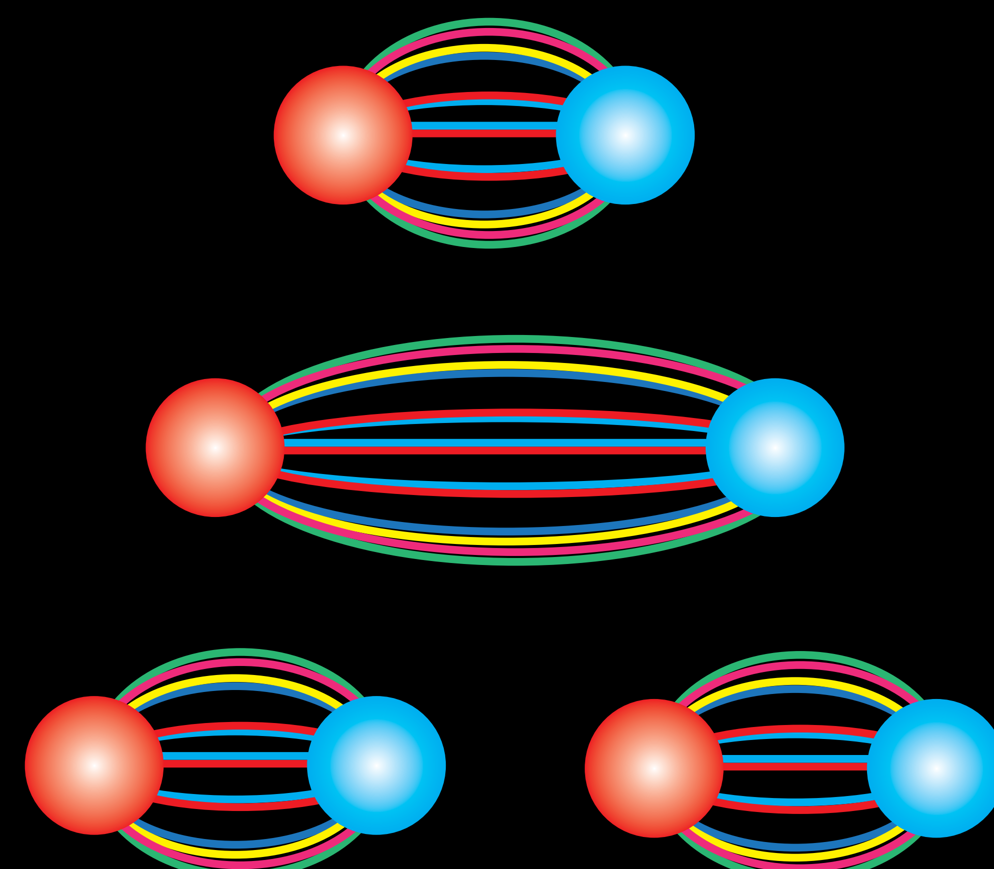


gluon self-coupling!

QCD mechanism of confinement

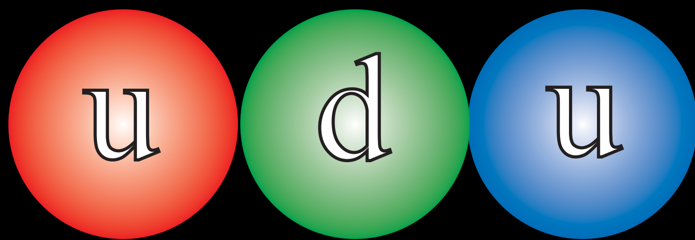
QED



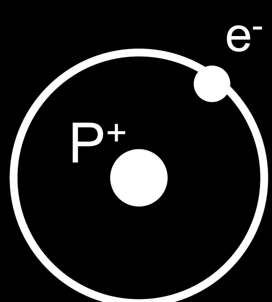


QCD

mass generation in the strong interaction



hydrogen atom

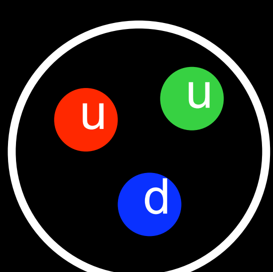


M_e = 0.5 MeV/c^2

M_P = 938 MeV/c^2

M_H = 932 MeV/c^2

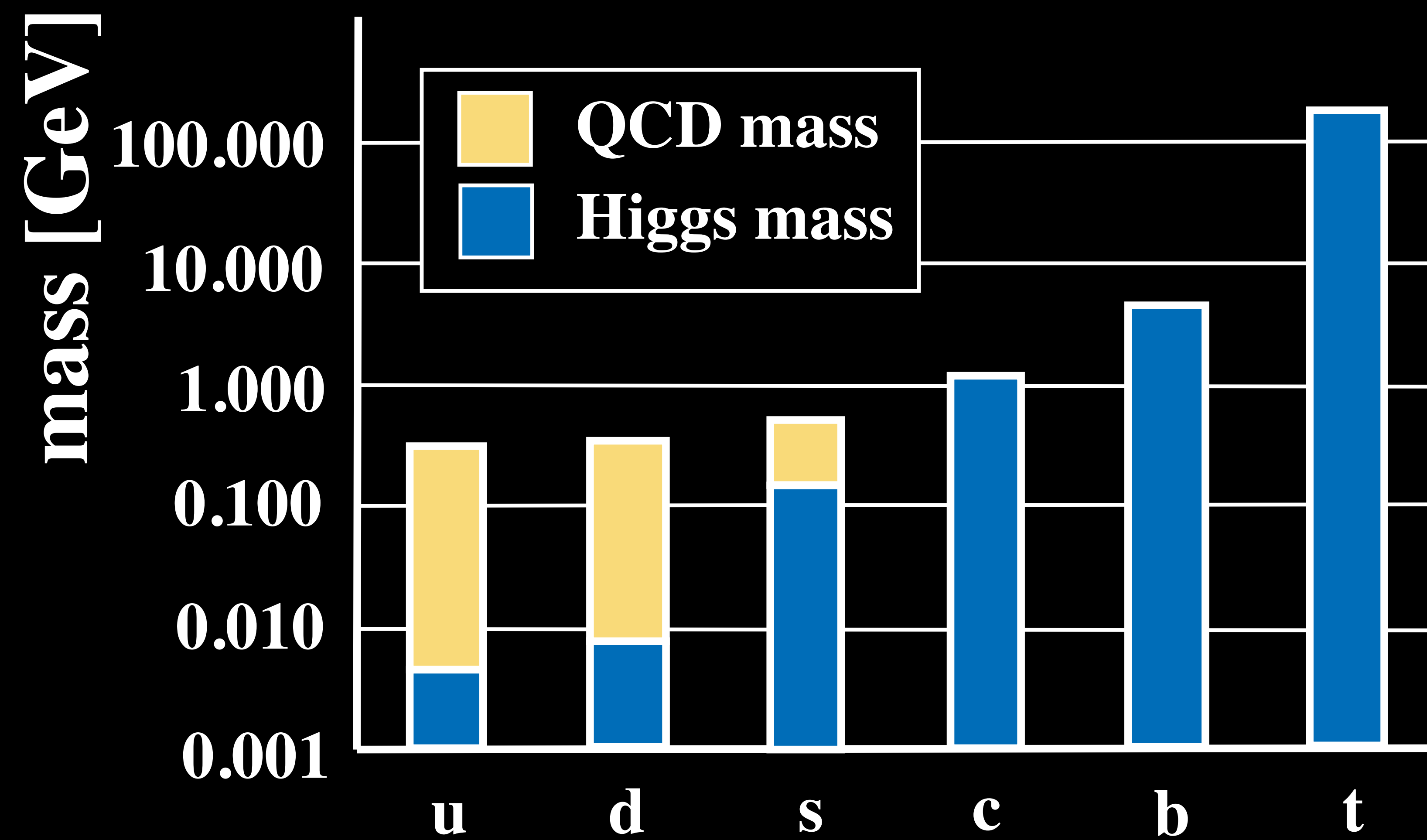
proton



M_u = 3 MeV/c^2

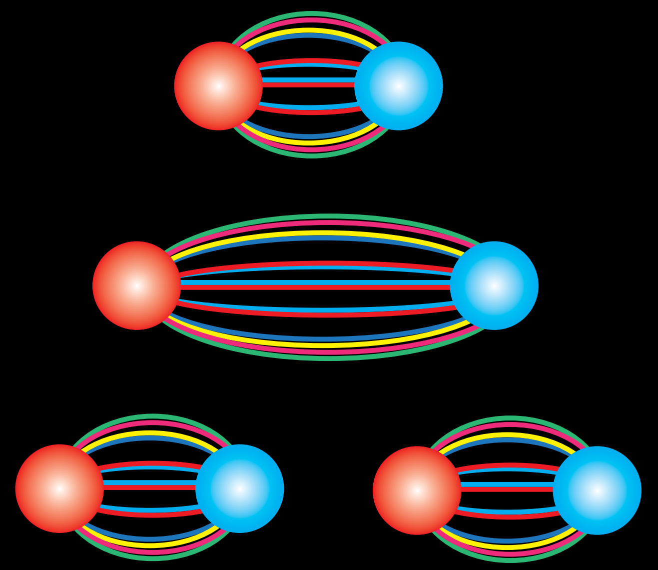
M_d = 6 MeV/c^2

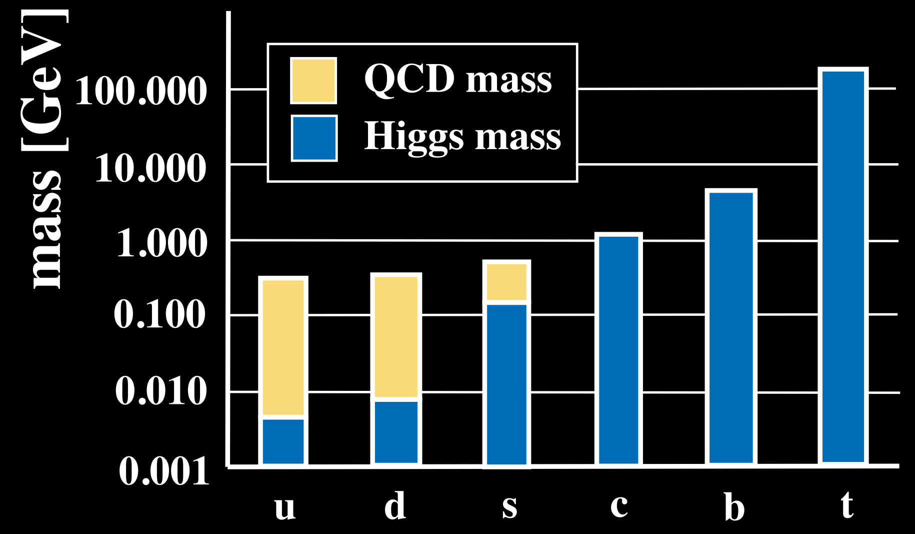
M_P = 938 MeV/c^2



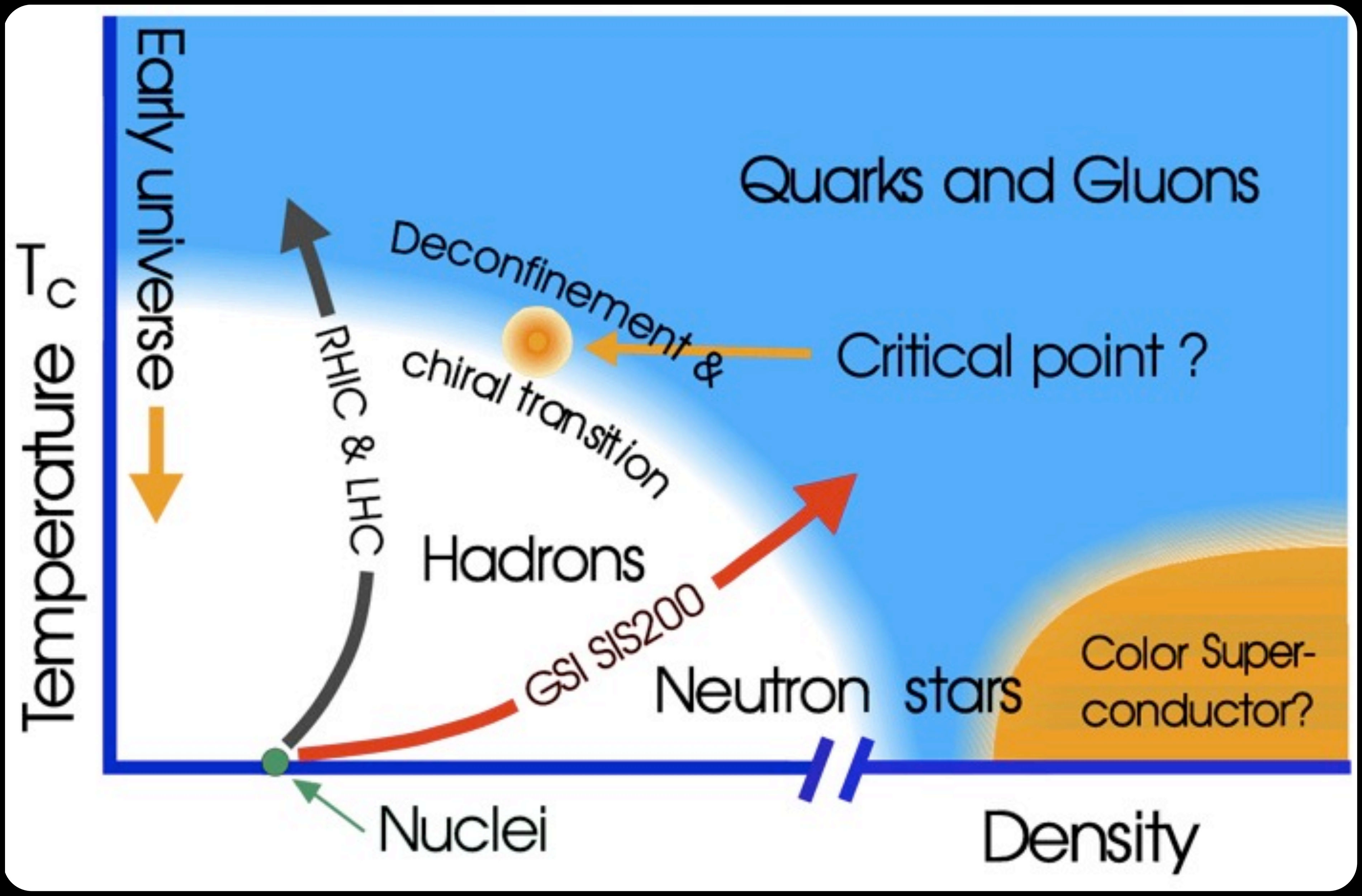
Quantum Chromo Dynamics

- theory of the strong interaction
- QCD is an asymptotic free theory
  - pertubation theory can be applied at short distances/high momentum transfer, source of much of our current knowledge of the theory
- non-perturbative features: confinement and chiral symmetry breaking still poorly understood from first principles

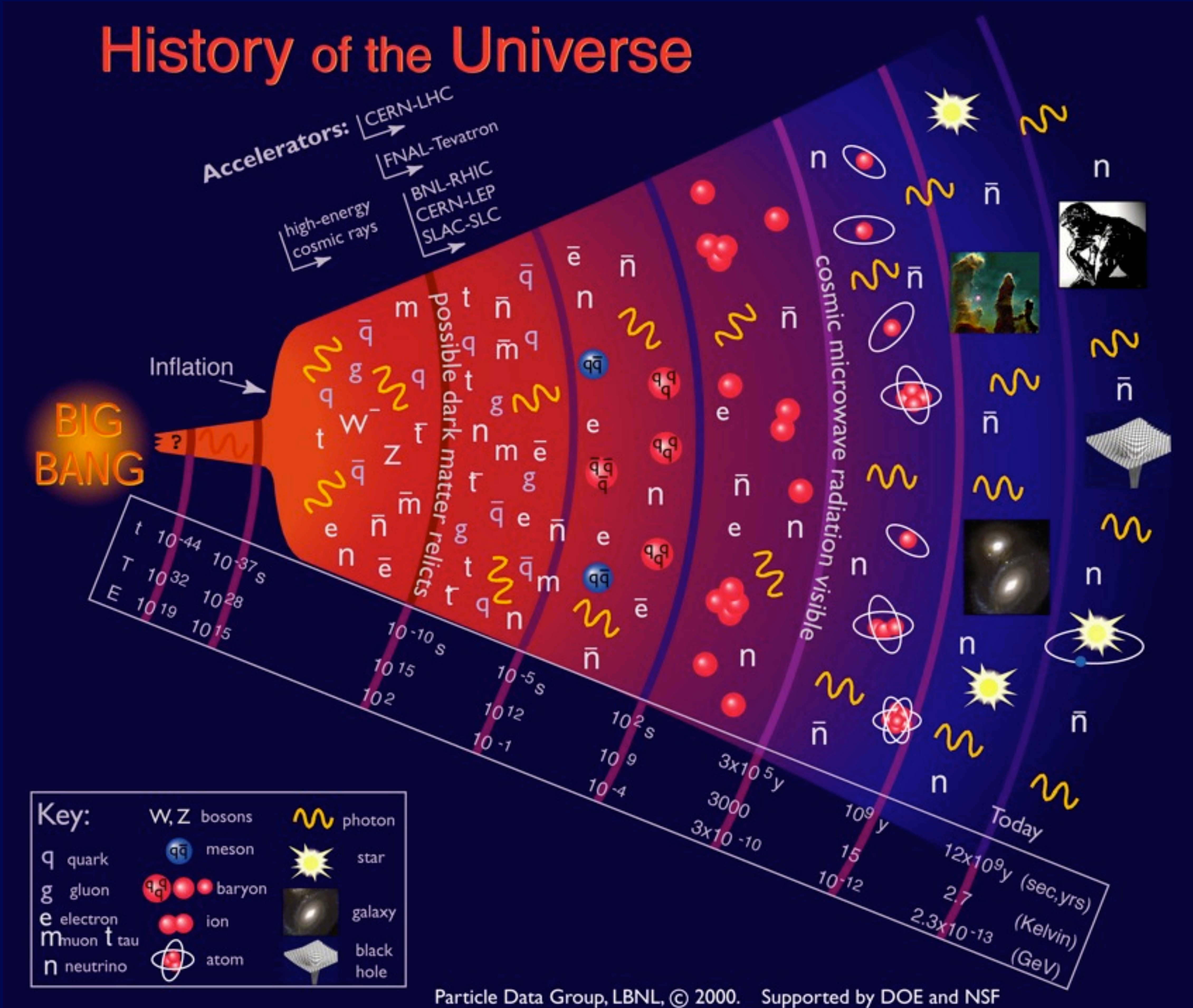


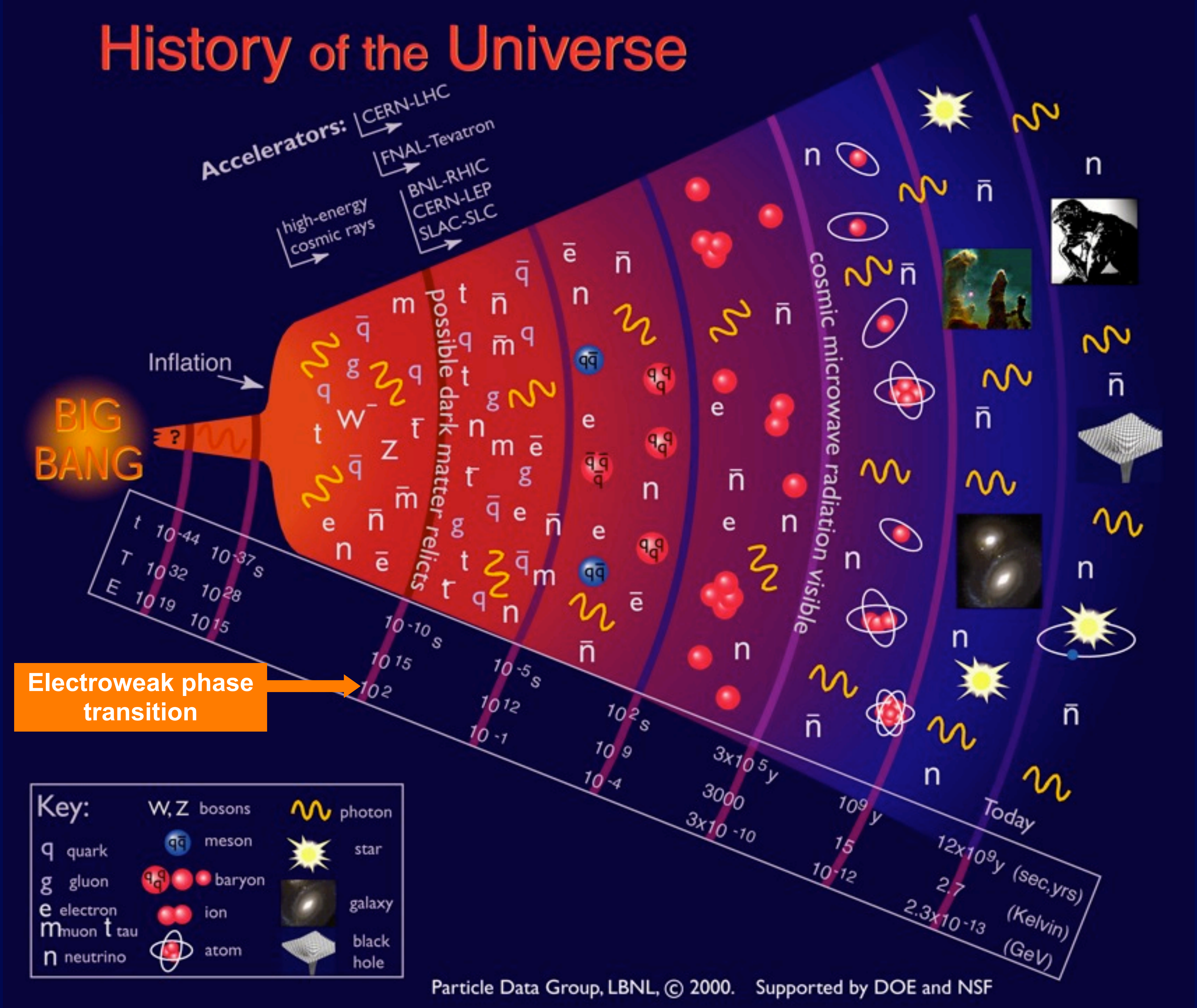


What happens when you heat and compress matter to very high temperatures and densities?

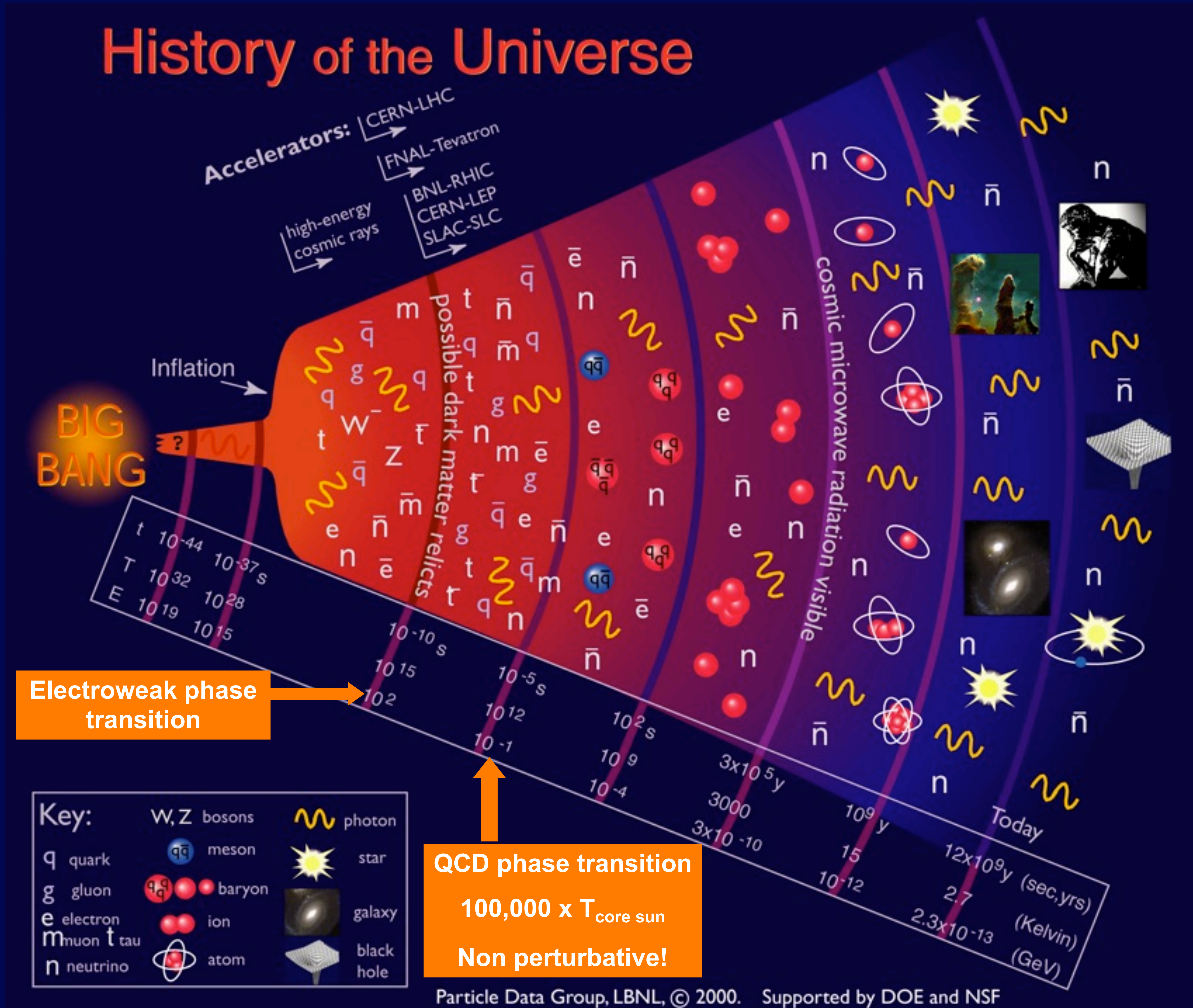


Based on Krishna Rajagopal and Frank Wilczek: Handbook of QCD


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec, yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



Electroweak phase transition



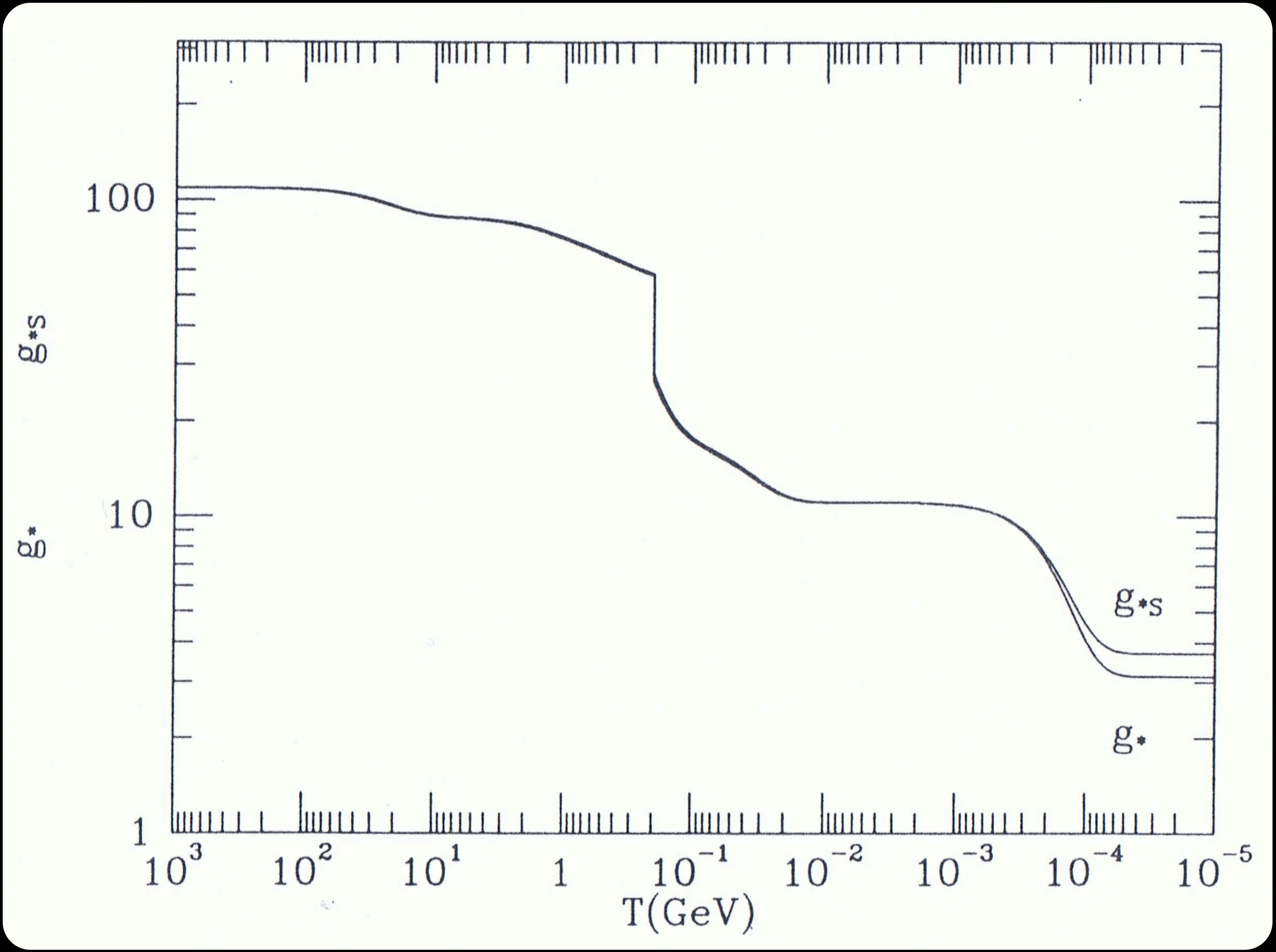
Electroweak phase transition

QCD phase transition

100,000 x $T_{core\ sun}$

Non perturbative!

Early Universe: degrees of freedom



Kolb and Turner: the early universe

rough estimate: EoS and degrees of freedom

ideal gas Equation of State: $p = \frac{1}{3}\varepsilon = g\frac{\pi^2}{90}T^4$

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

➡ energy density of g massless degrees of freedom

$$\frac{\varepsilon}{T^4} = 3\frac{\pi^2}{30}$$

➡ hadronic matter dominated by lightest mesons (π^+, π^-, and π^0)

➡ deconfined matter, quarks and gluons

$$g = 2_{\text{spin}} \times 8_{\text{gluons}} + \frac{7}{8} \times 2_{\text{flavors}} \times 2_{\text{quark/anti-quark}} \times 2_{\text{spin}} \times 3_{\text{color}}$$

$$\frac{\varepsilon}{T^4} = 37\frac{\pi^2}{30}$$

➡ during phase transition large increase in degrees of freedom !

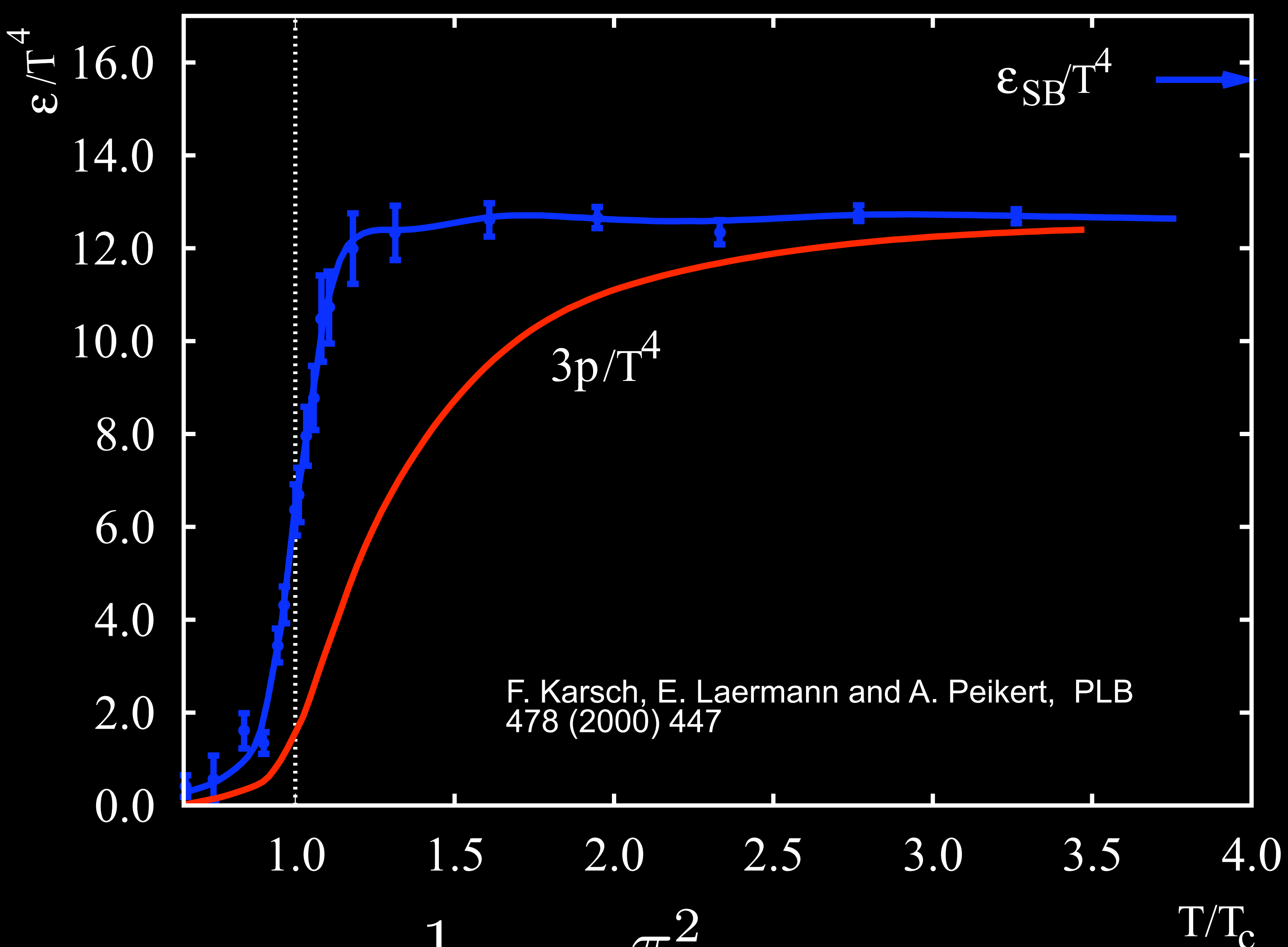
rough estimate: QCD phase transition temperature

- confinement due to bag pressure B (from the QCD vacuum)
  - $B^{1/4} \sim 200$ MeV
- deconfinement when thermal pressure is larger than bag pressure

$$
\begin{aligned}
p &= \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4 \\
T_c &= (\frac{90B}{37\pi^2})^{1/4} = 140 \text{ MeV}
\end{aligned}
$$

crude estimate!

QCD on the Latice



$T_C \sim 170$ MeV, $\varepsilon_C \sim 0.6$ GeV/fm^3

at the critical temperature a strong increase in the degrees of freedom

✓ gluons, quarks & color!

not an ideal gas!

✓ residual interactions

at the phase transition dp/dε decreases rapidly

$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

$$g_{\mathrm{H}} \approx 3 \quad g_{\mathrm{QGP}} \approx 37$$

$$g = 2_{\mathrm{spin}} \times 8_{\mathrm{gluons}} + \frac{7}{8} \times 2_{\mathrm{flavors}} \times 2_{q\bar{q}} \times 2_{\mathrm{spin}} \times 3_{\mathrm{color}}$$

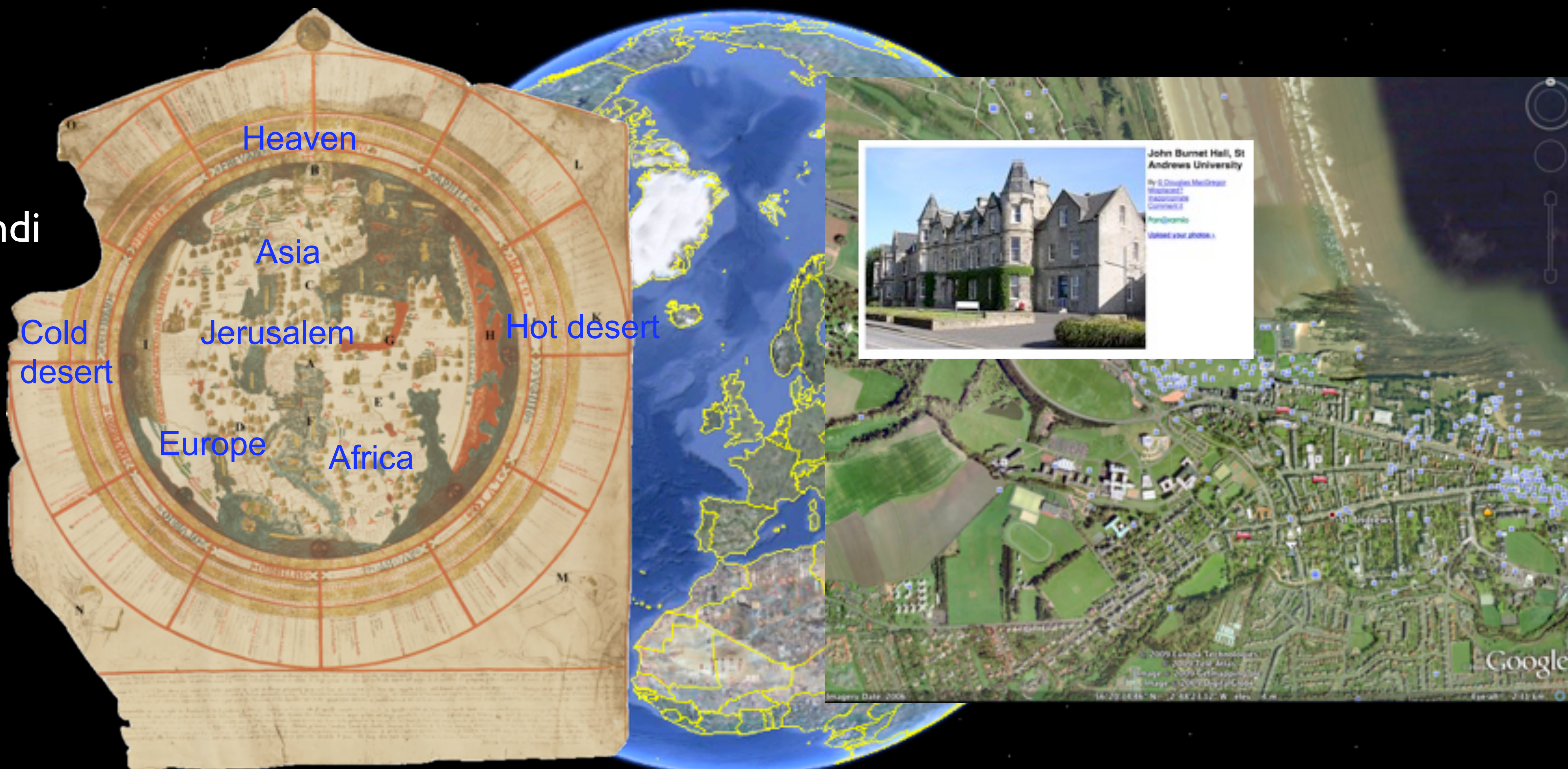
so far only a theory view of the world!

so far only a theory view of the world!

so far only a theory view of the world!

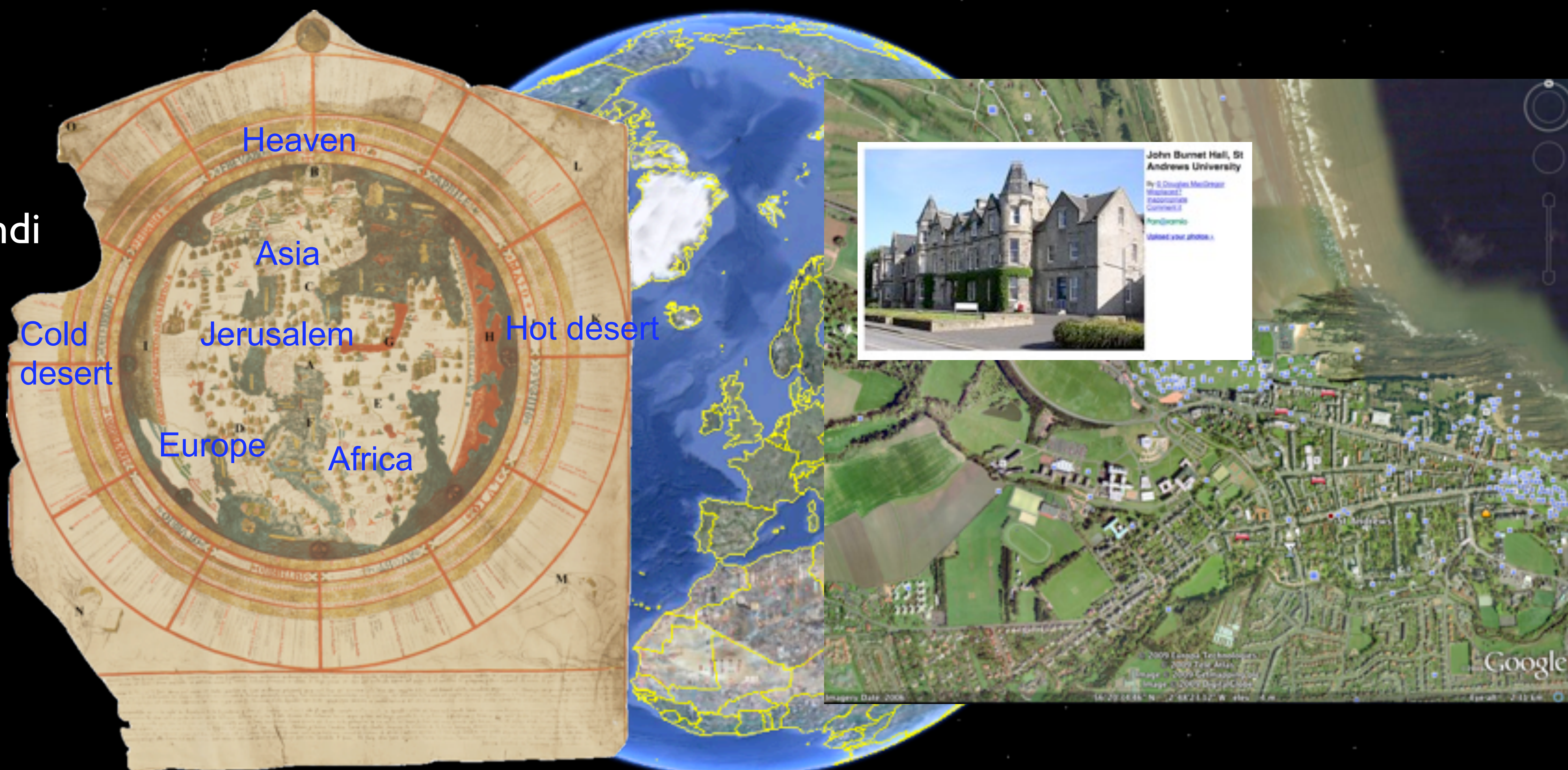
so far only a theory view of the world!

mappa mundi
1452



so far only a theory view of the world!

mappa mundi 1452



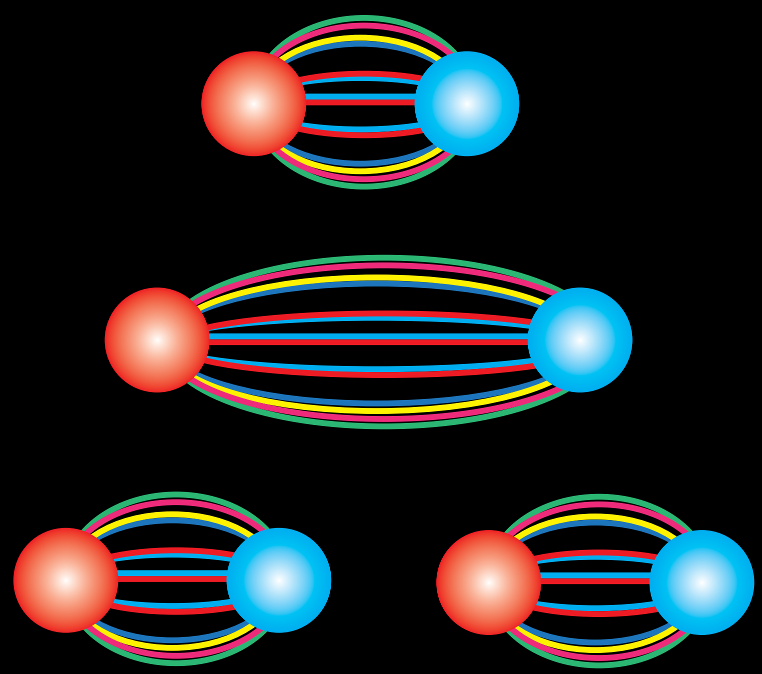
explore experimentally the properties of this Quark Gluon Plasma

understanding the phase transition

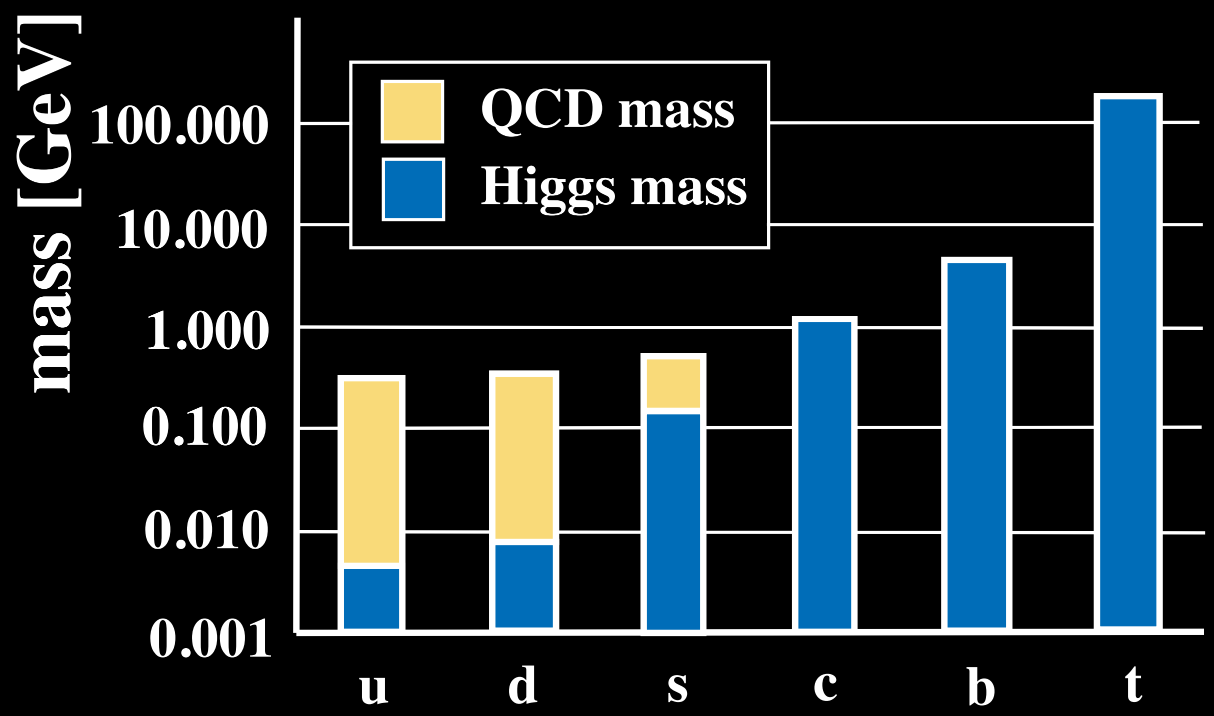
- experimentally we like to determine:
  - ✓ the effective number of hadronic degrees of freedom g_H at T_C
  - ✓ the change in number of active degrees of freedom $g_{QGP} - g_H$
  - ✓ the vacuum pressure B or latent heat
  - ✓ the (transport) properties of the QGP just above the phase transition temperature

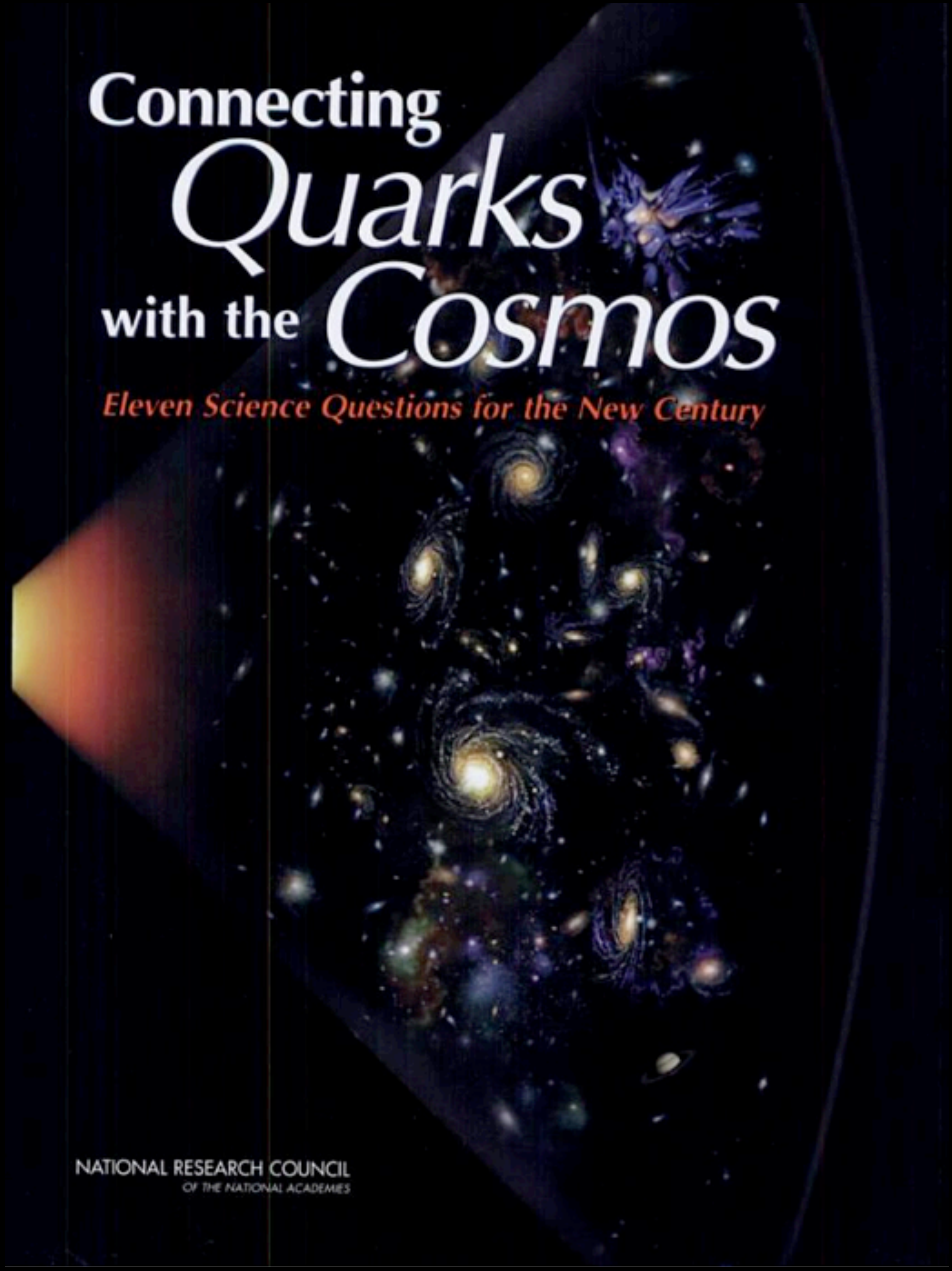
The macroscopic quantities of the QGP will give us better understanding of the underlying microscopic theory (QCD) in the non-perturbative regime

mechanism of confinement



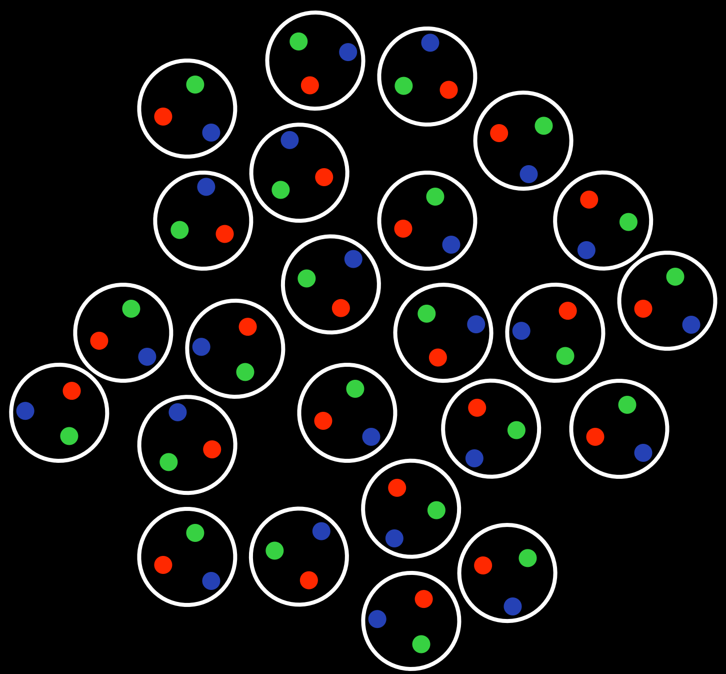
mass generation in the strong interaction





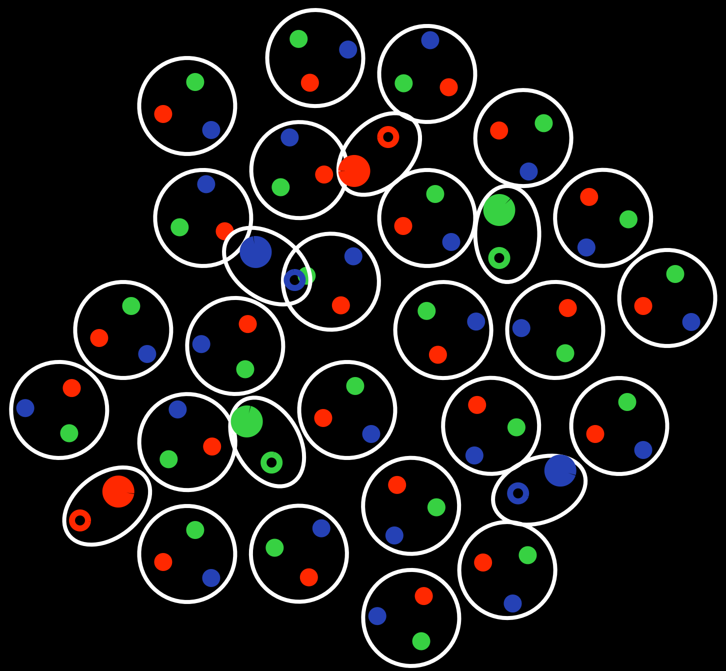
what are the new states of matter at exceedingly high temperature and density?

How?

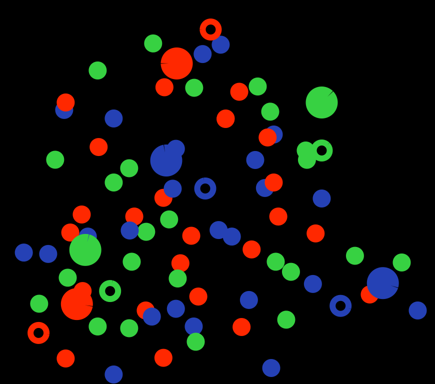


Nuclear Matter
(confined)

How?

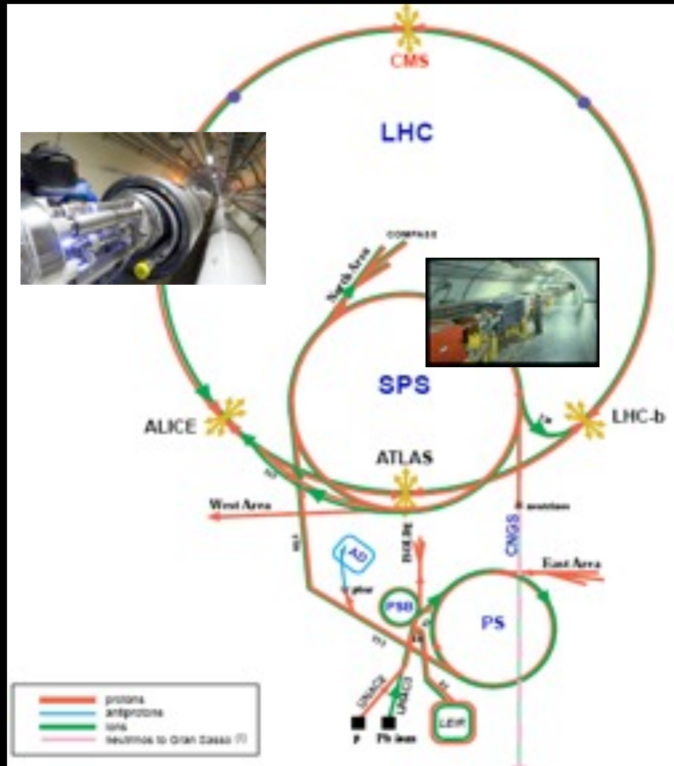


How?

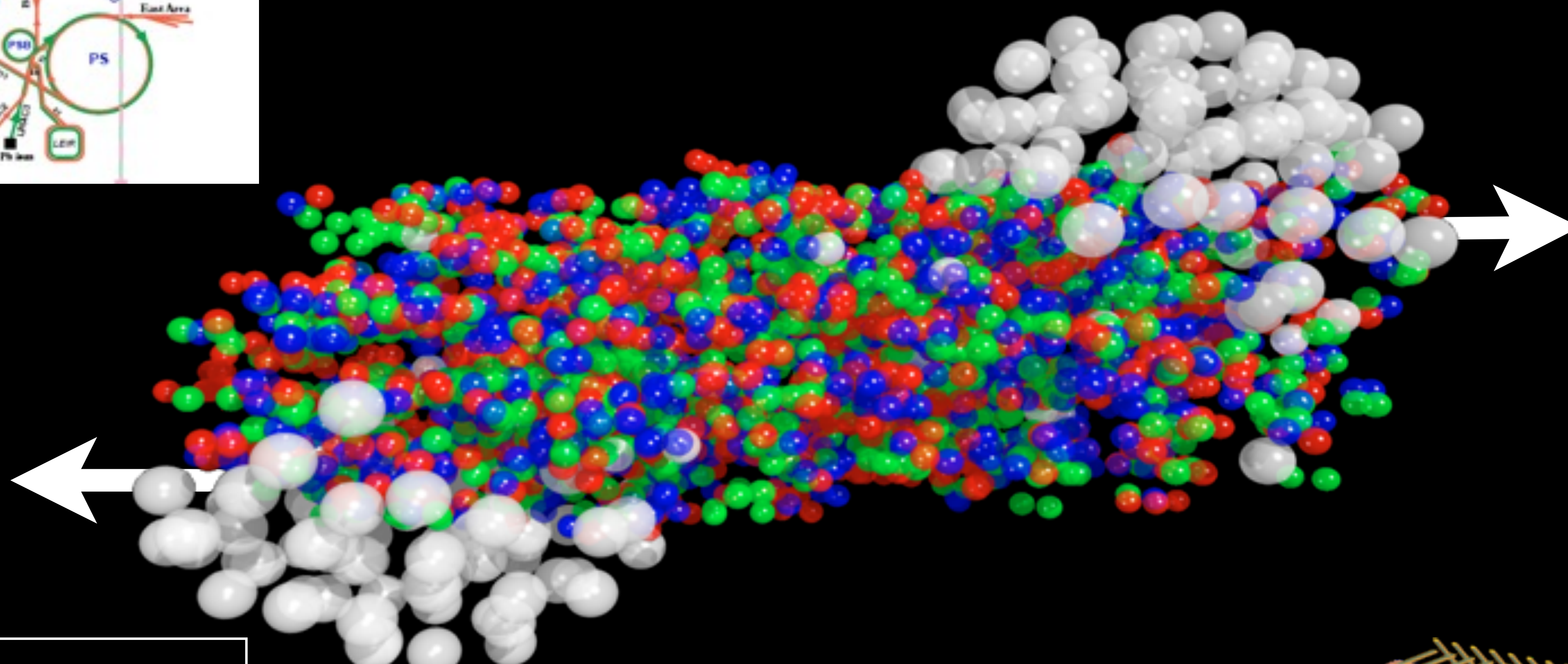


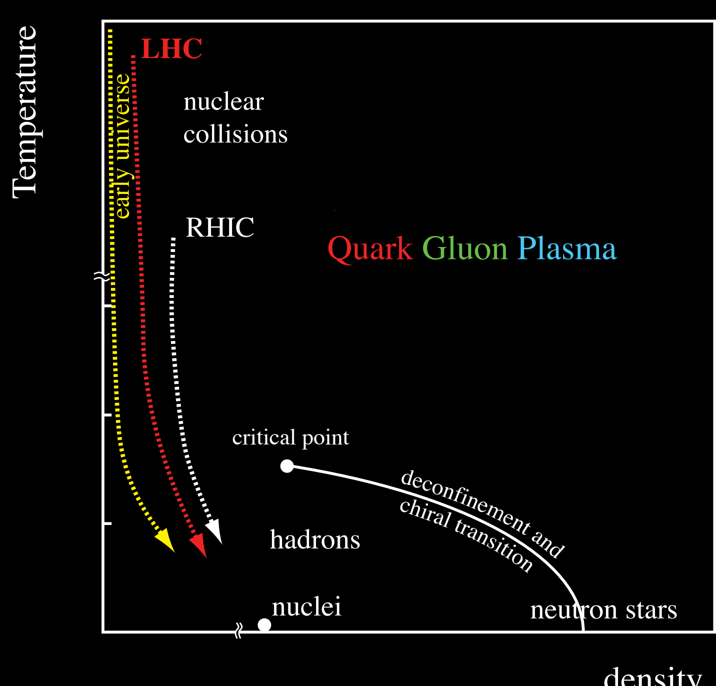
Quark Gluon Plasma
deconfined !

transition expected to occur around 1 GeV/fm^3

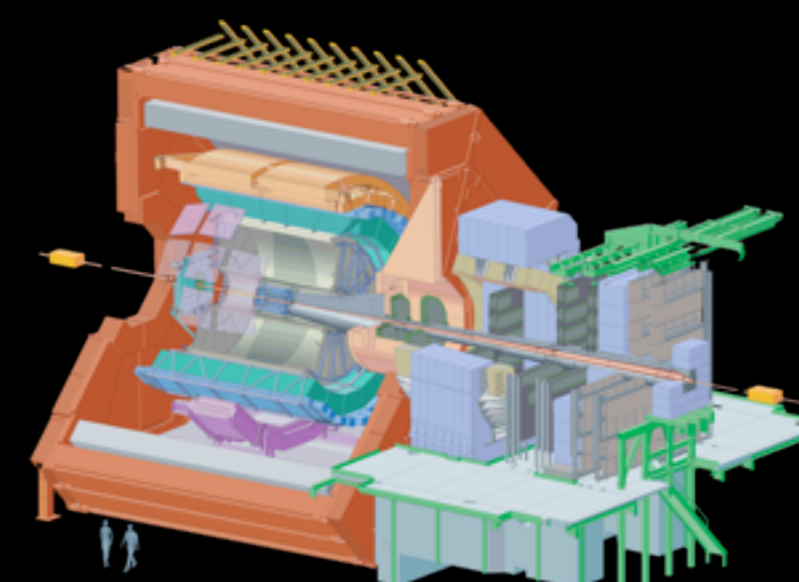


How?

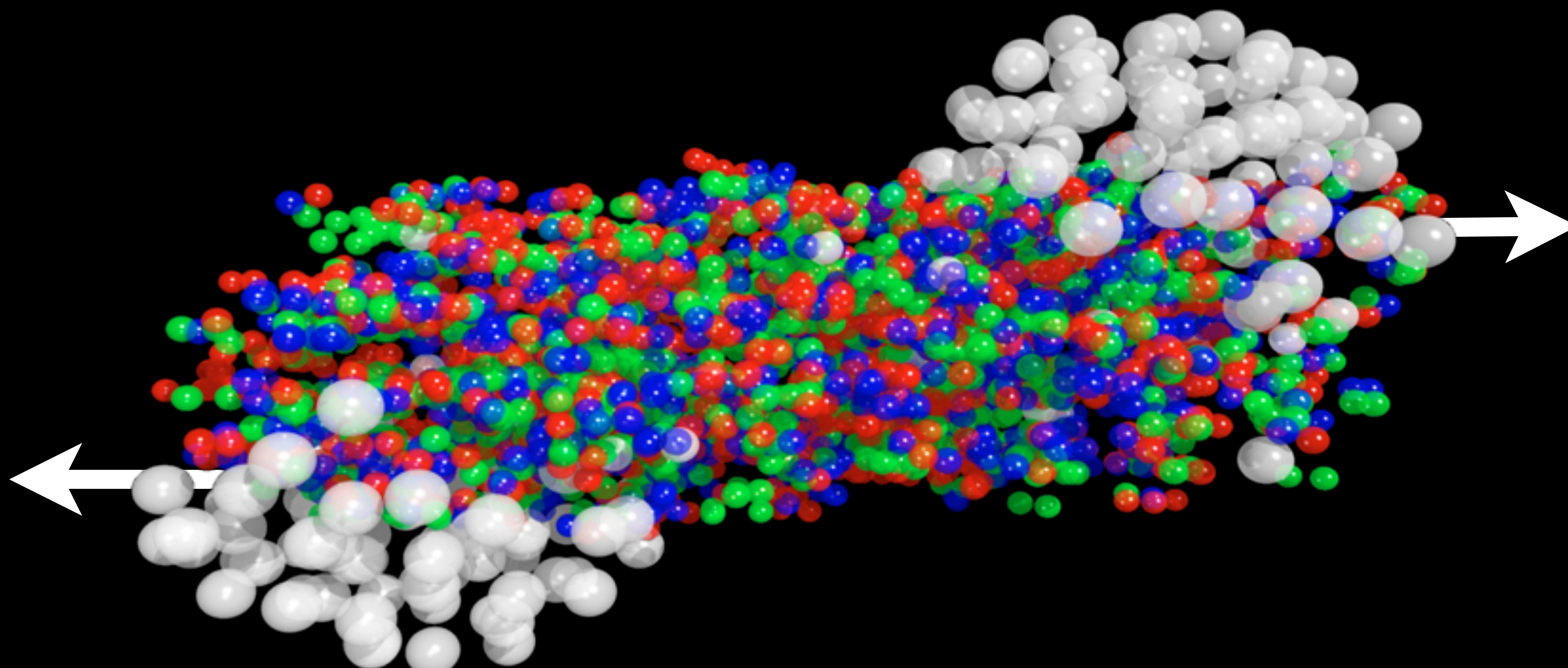




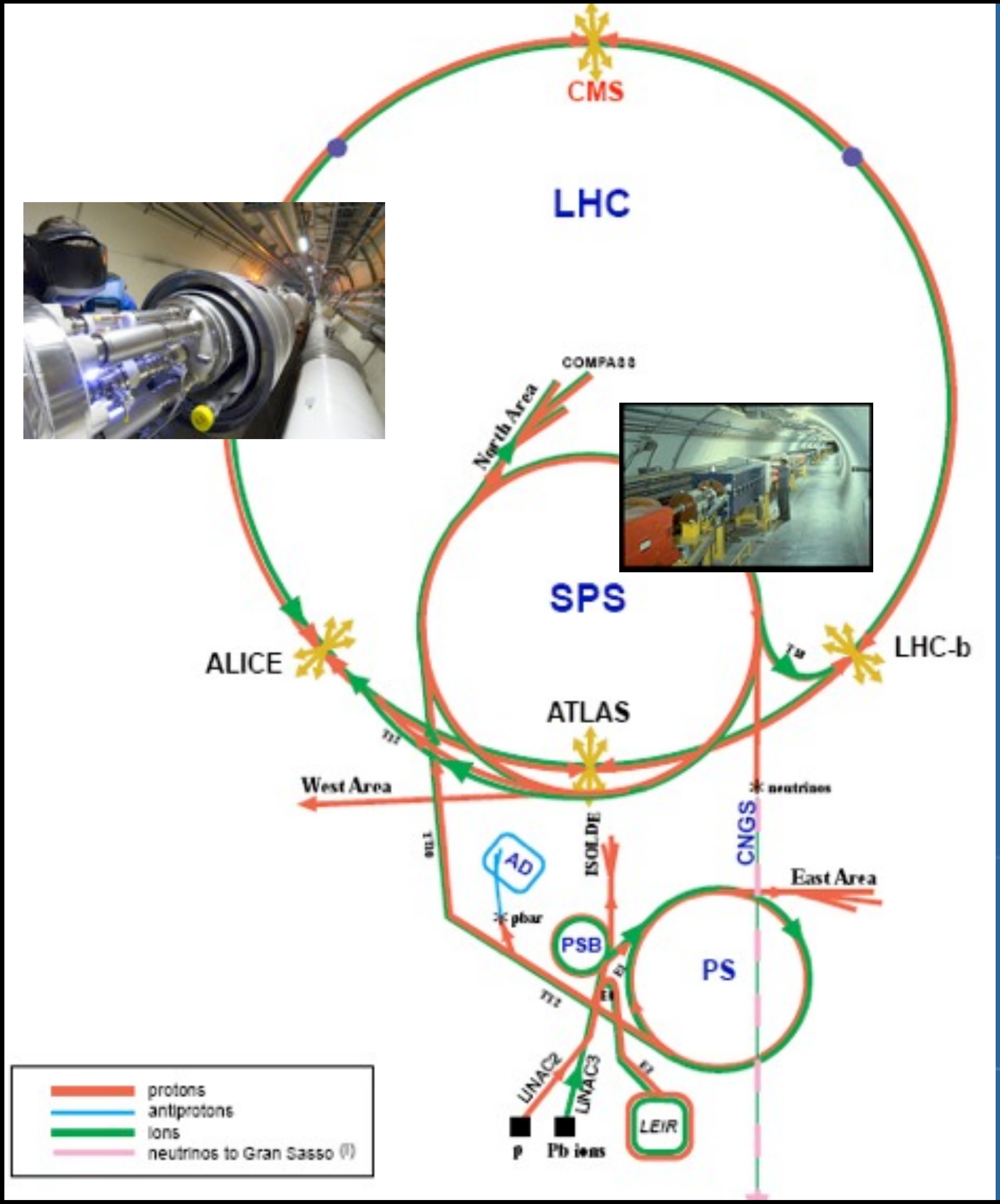
study phase transition in controlled lab conditions by colliding heavy-ions

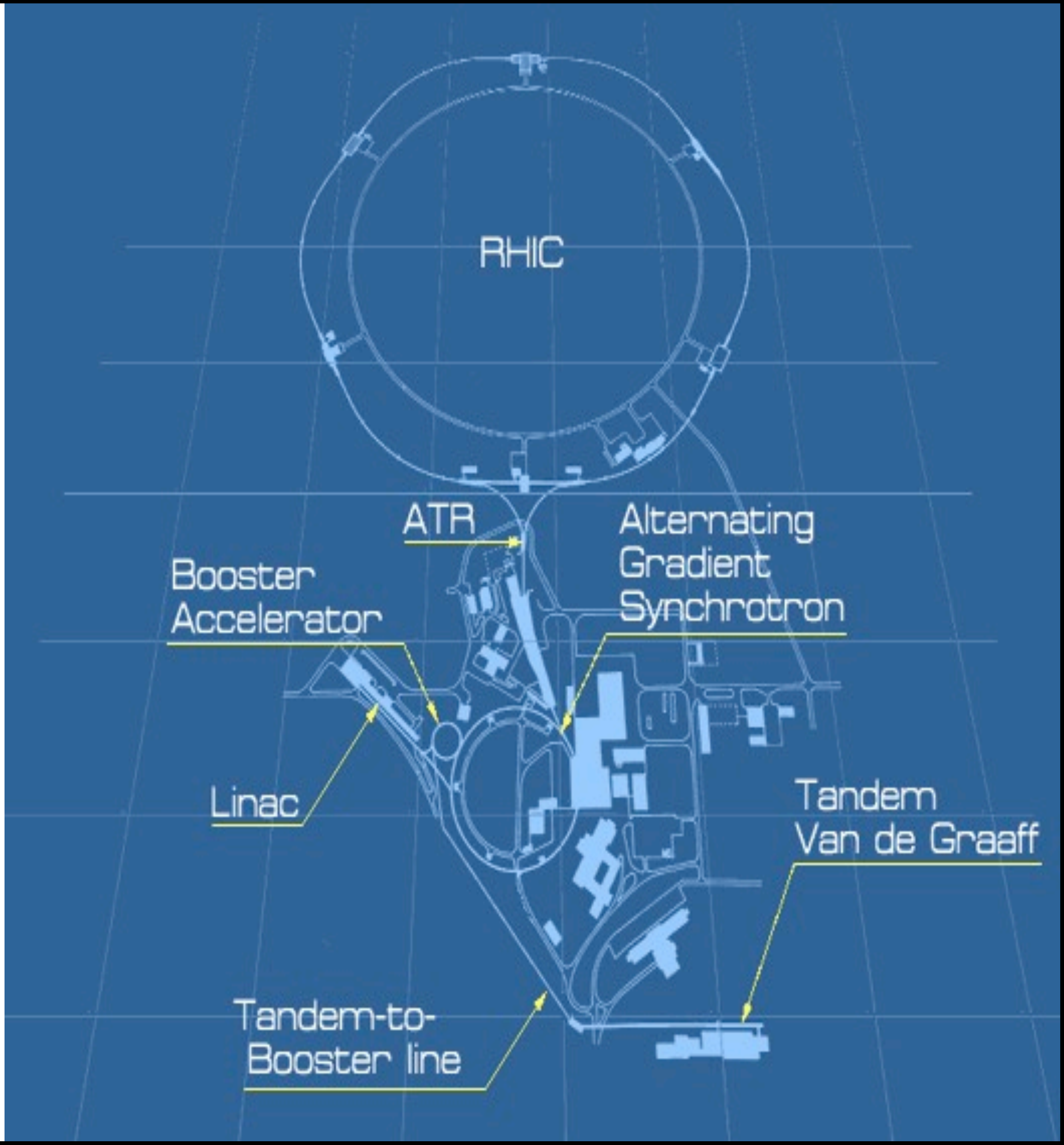


Accelerators and Experiments

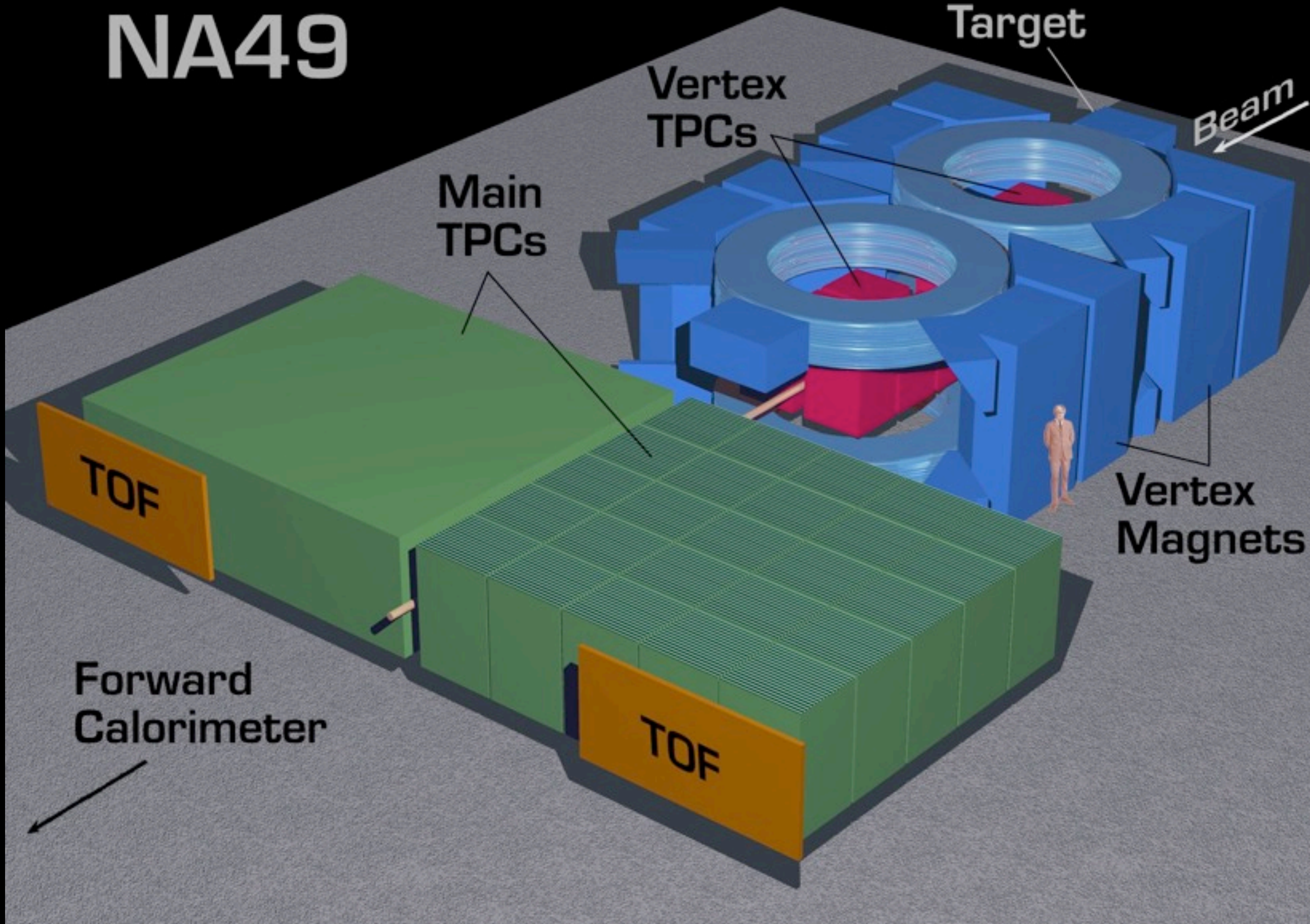


CERN and BNL

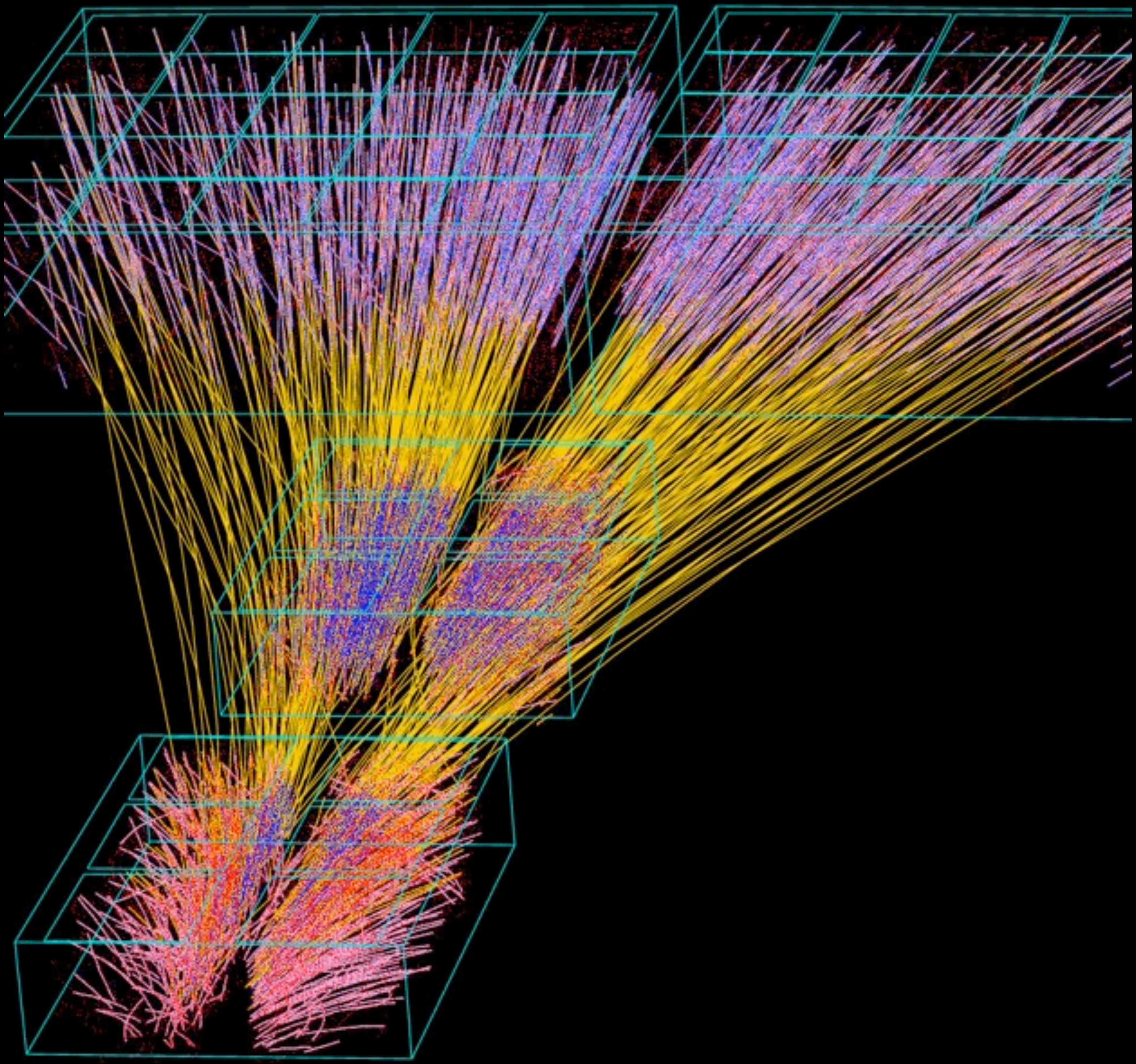

CMS
LHC
COMPASS
North Area
SPS
ALICE
LHC-b
ATLAS
West Area
neutrinos
CNGS
ISOLDE
AD
pbar
East Area
PSB
PS
LINAC2
LINAC3
LEIR
p
Pb ions
protons
antiprotons
ions
neutrinos to Gran Sasso


RHIC
ATR
Alternating Gradient Synchrotron
Booster Accelerator
Linac
Tandem Van de Graaff
Tandem-to-Booster line

Fixed Target Detector



Event Display



STAR Detector at Collider

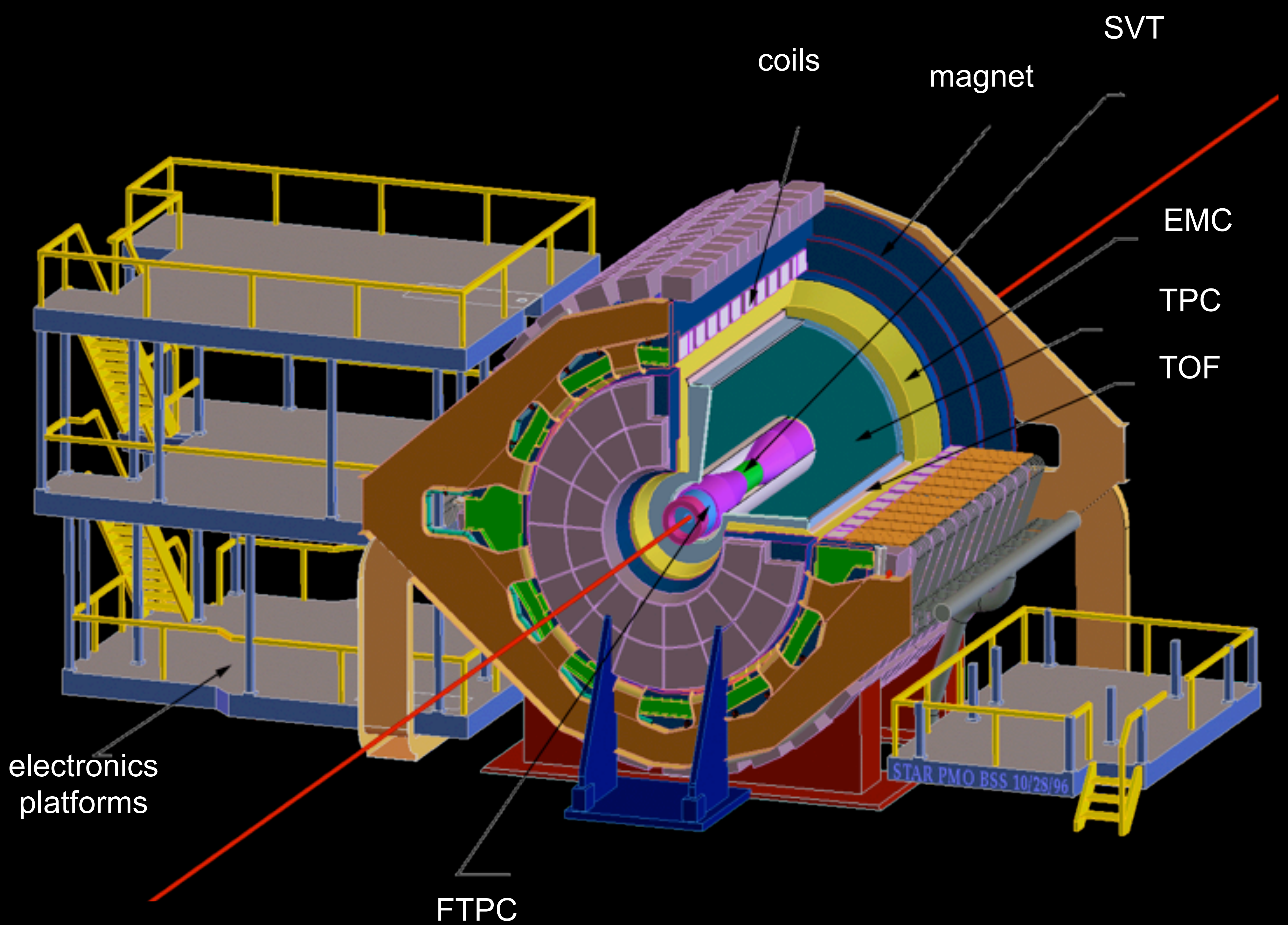
large acceptance

- ✓ event-by-event capabilities

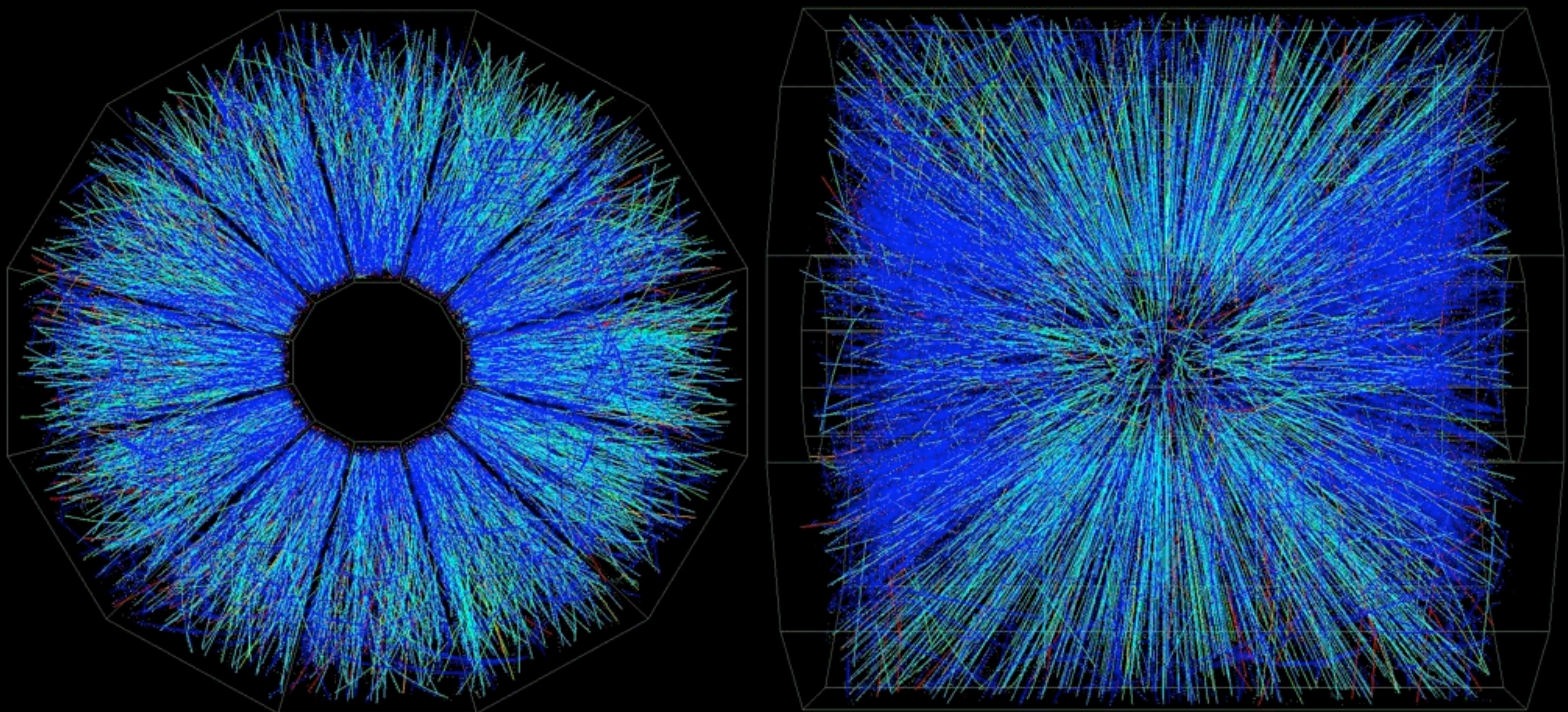
large Time Projection Chamber in solenoidal magnetic field

silicon tracking, electromagnetic calorimeter, time of flight detector

~ 500 collaborators

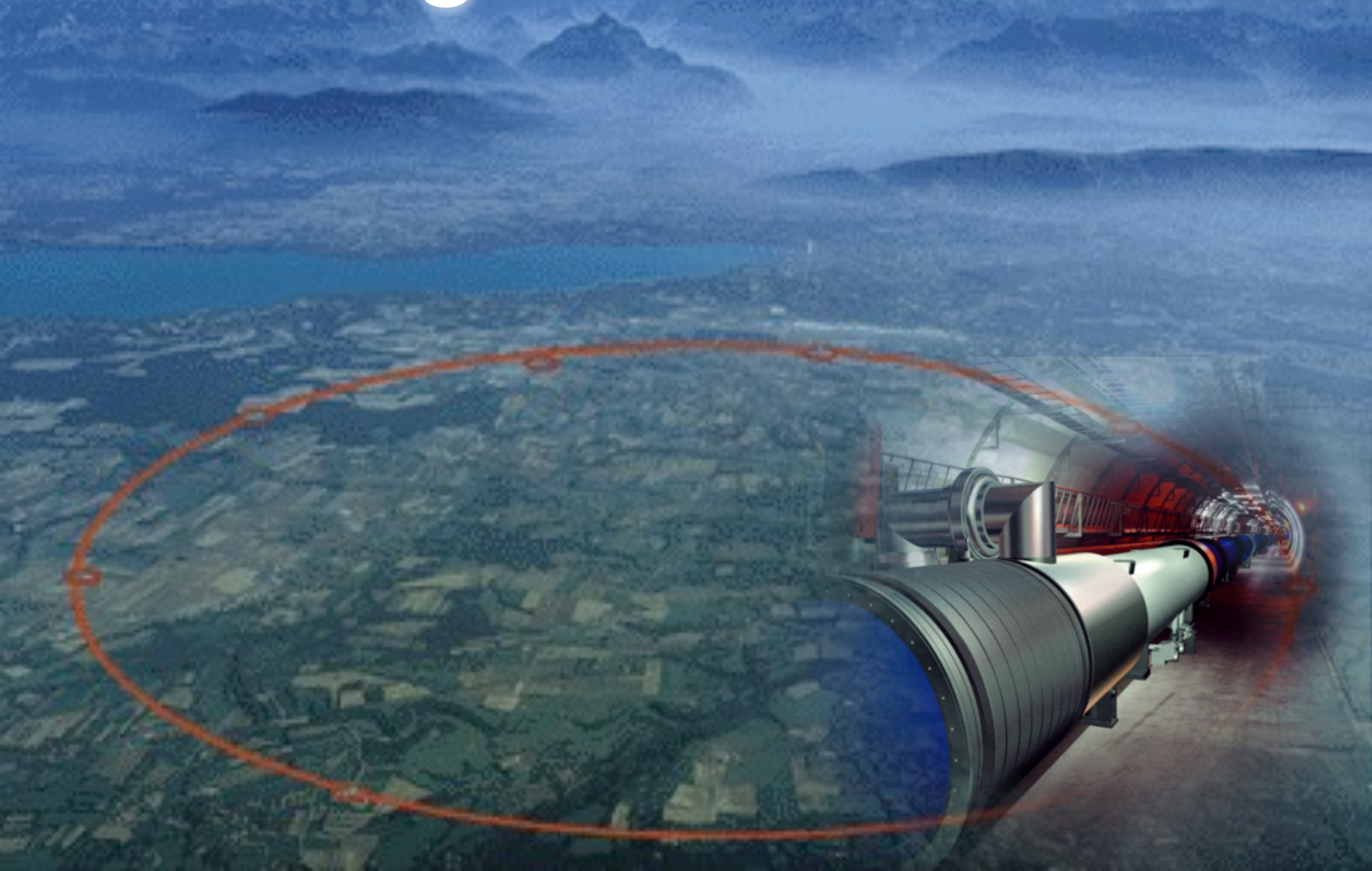


STAR at RHIC



Online Level 3 Trigger Display

The Large Hadron Collider

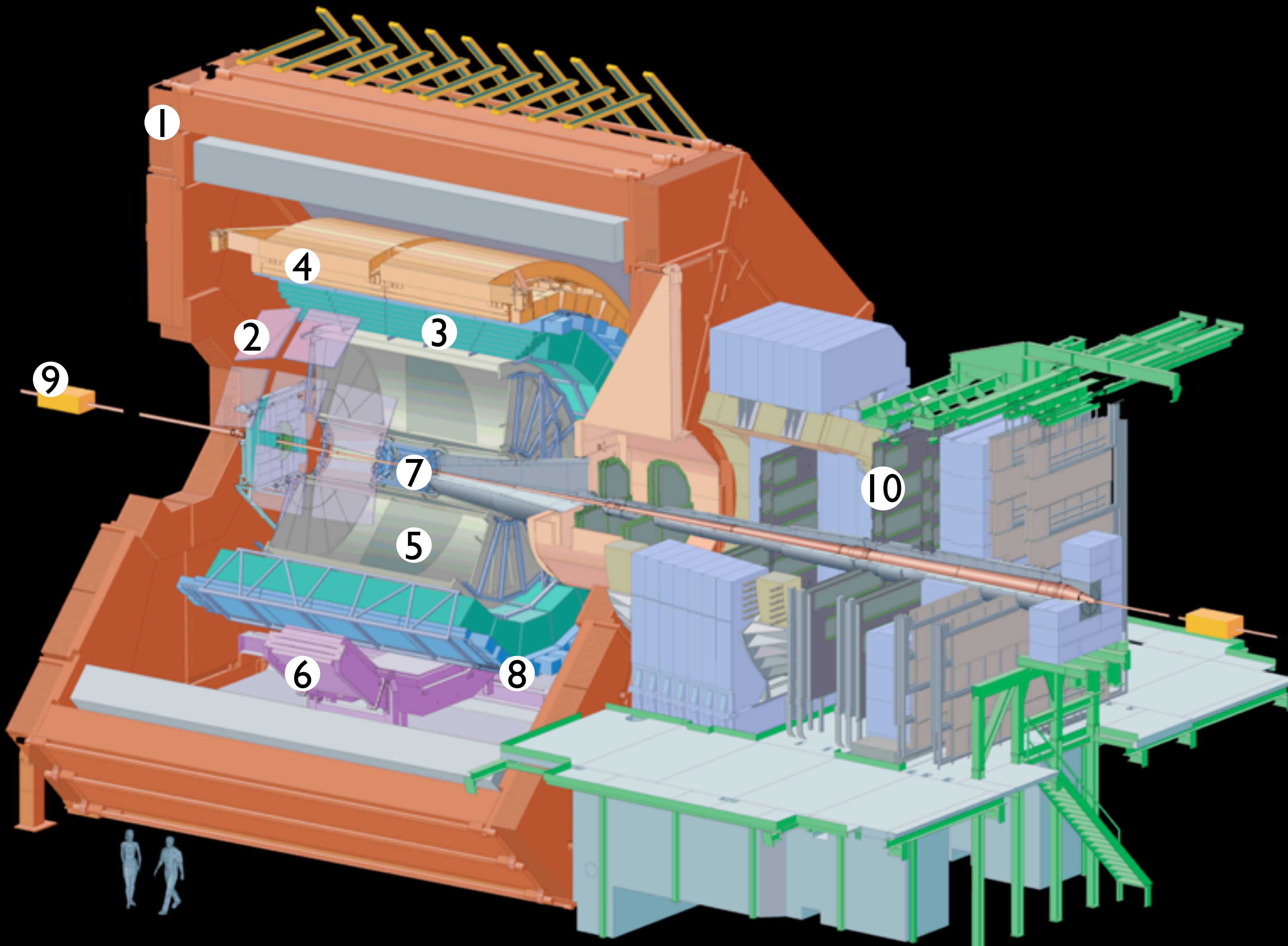


The Large Hadron Collider

(The Large Heavy ion Collider)

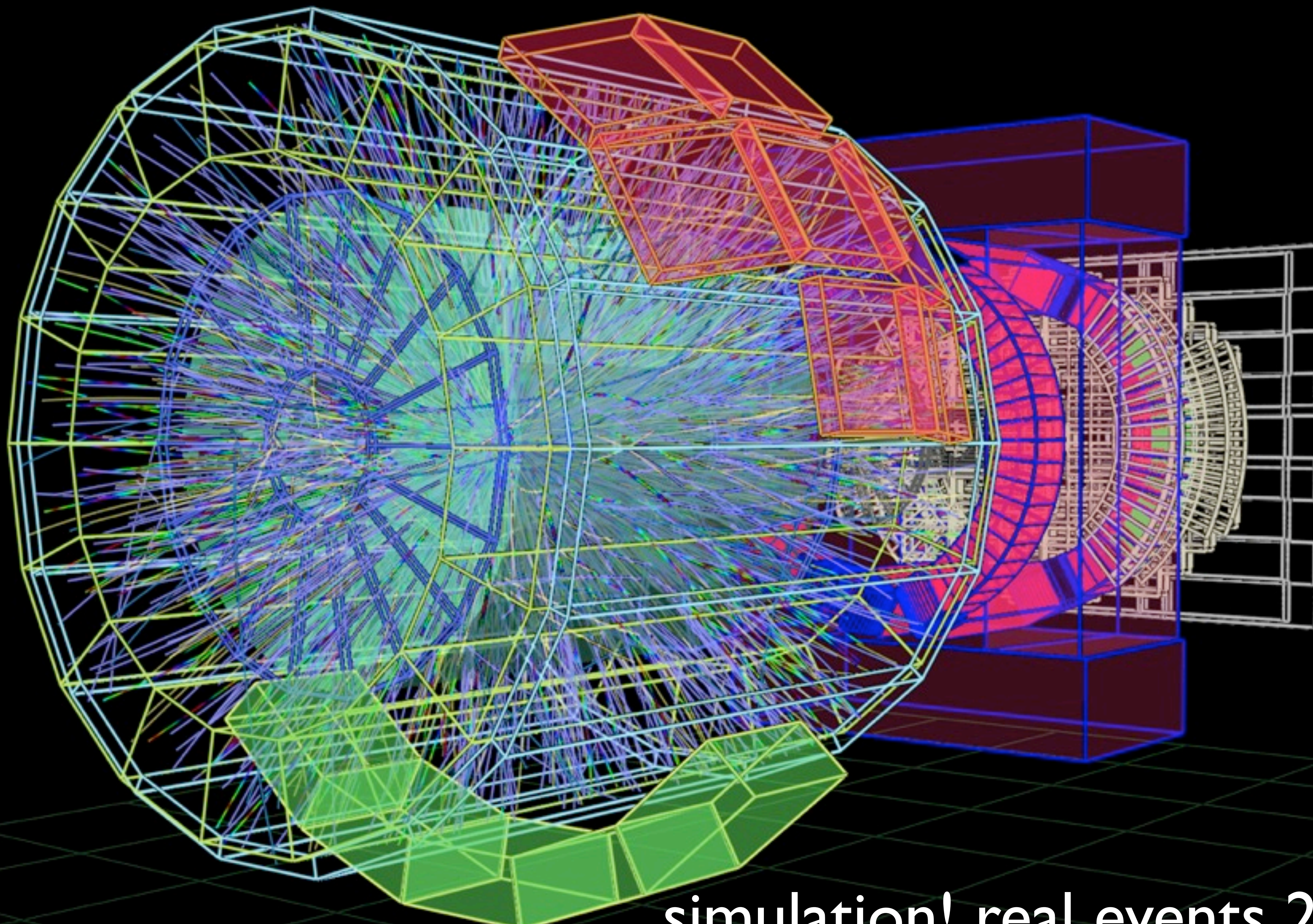
ALICE at the LHC

1. L3 magnet
2. HMPID
3. TRD
4. EMCAL
5. TPC
6. PHOS
7. ITS
8. TOF
9. ZDC
10. Muon system



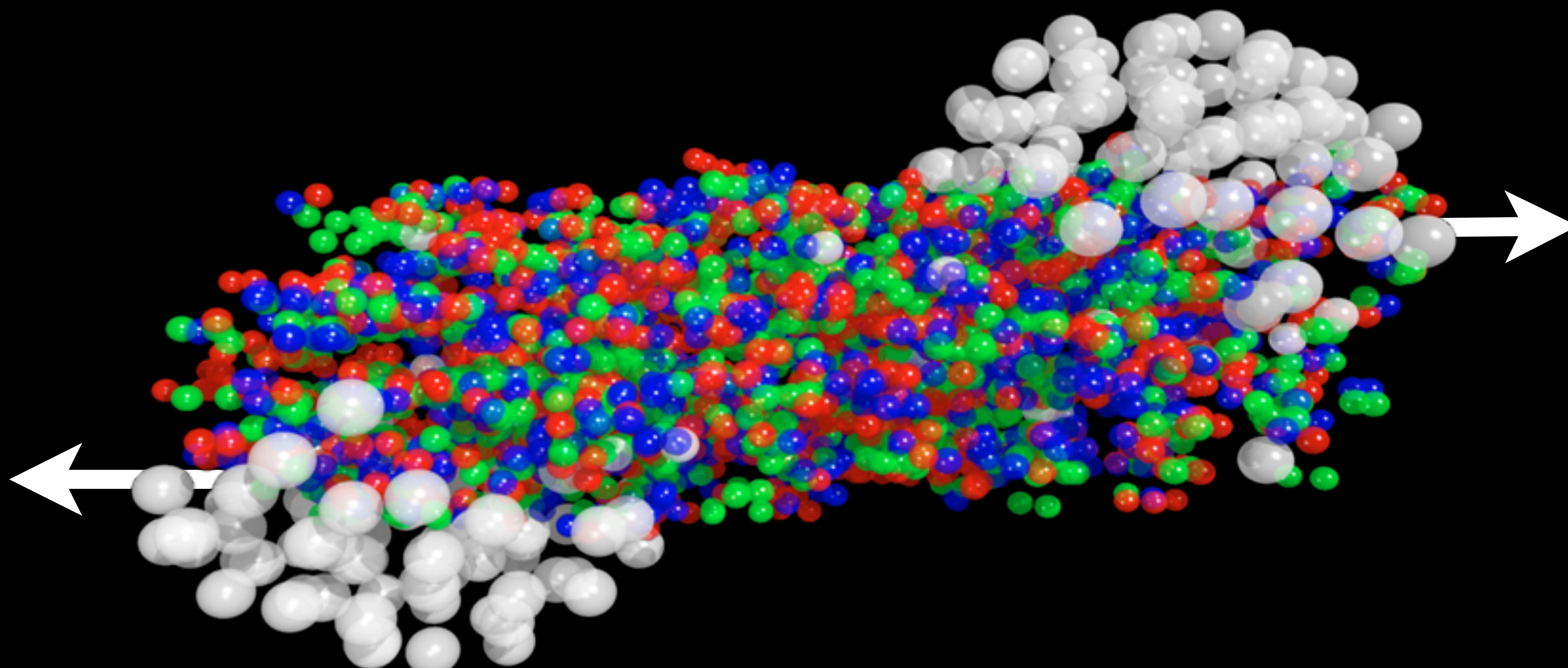
~1000 collaborators from 109 institutes in 31 countries

ALICE at the LHC

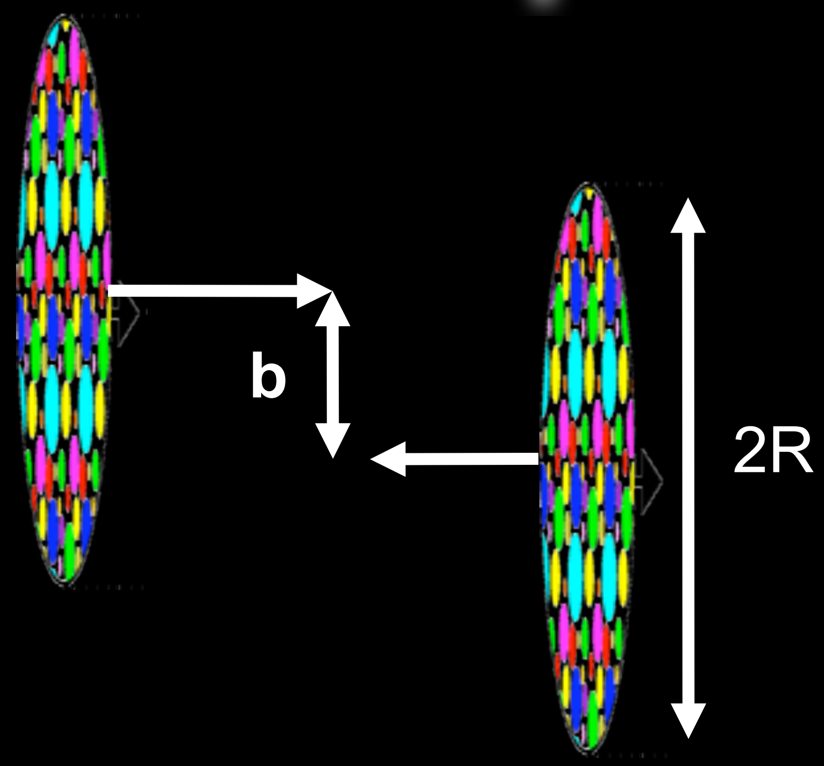


simulation! real events 2010

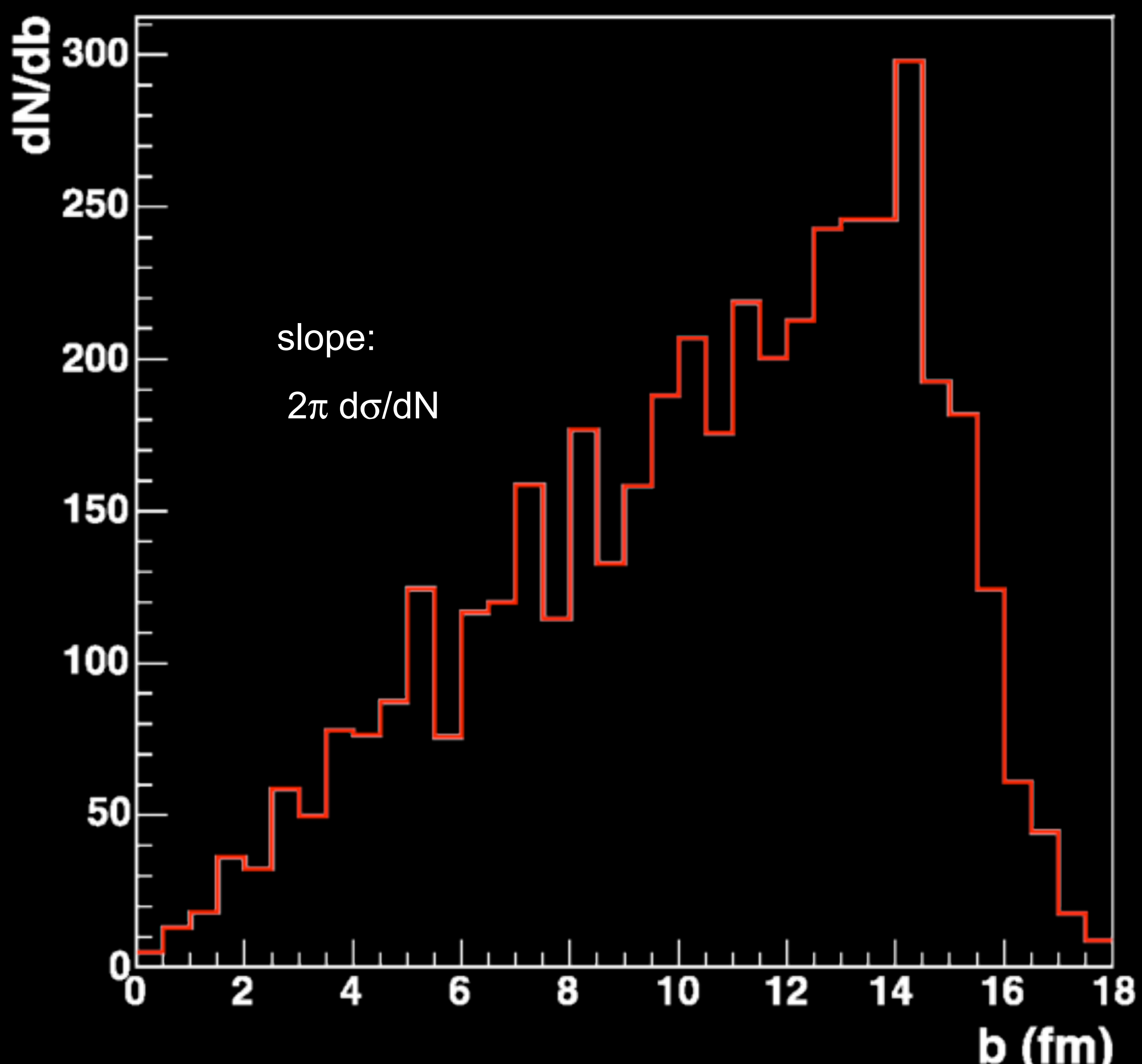
Event Characterization



Impact Parameter

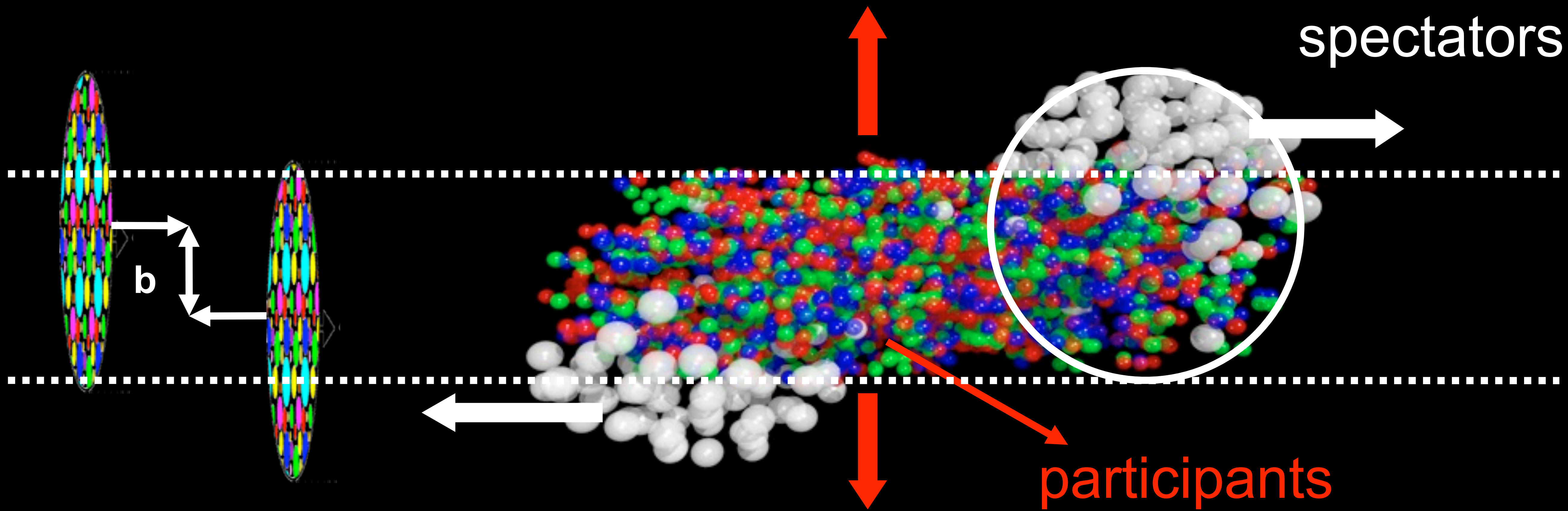


- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions



$$d\sigma = 2\pi b\,db$$

Centrality Determination (I)



centrality characterized by:

1. N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
2. N_{coll}, N_{bin}: number of inelastic nucleon-nucleon collisions

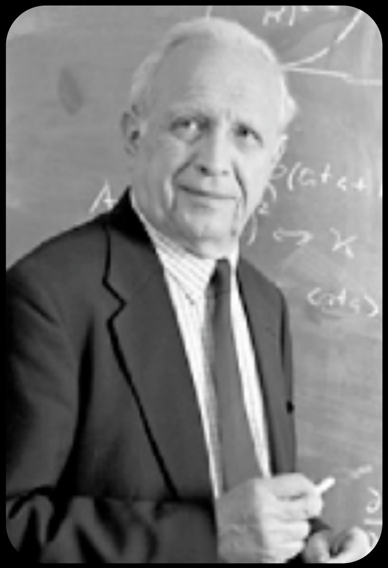
Glauber Model Calculations

- ✓ nuclear density from Wood-Saxon distribution

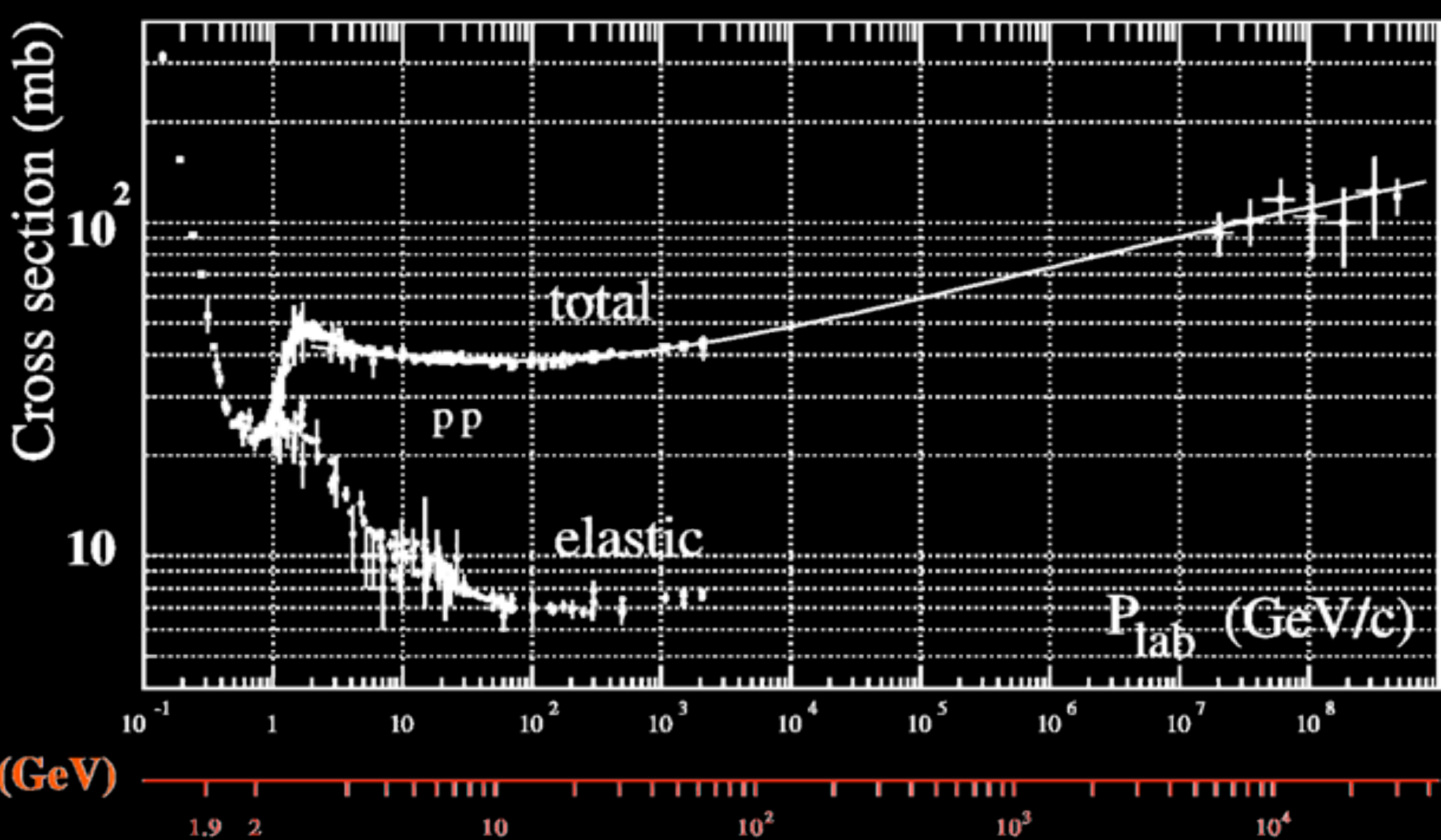
$$\rho(r) = \frac{\rho_0 \left(1 + wr^2 / R^2\right)}{1 + e^{(r-R)/a}}$$

Nucleus	A	R	a
Au	197	6.38	0.535
Pb	208	6.68	0.546

$\sqrt{S}$ (GeV)	$\sigma_{in,pp}$ (mb)
20	32
200	42
5500	~70

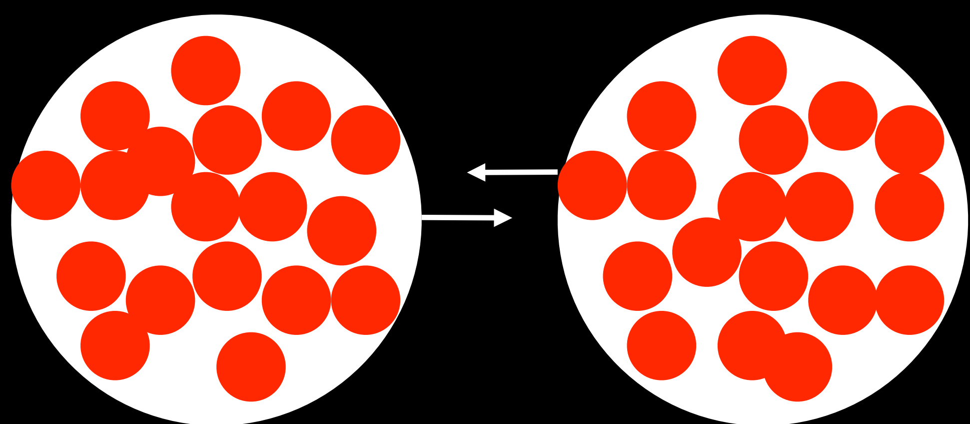


- ✓ nucleons travel on straight lines, no deflection after NN collision
- ✓ NN collision cross section from measured inelastic cross section in p+p
- ✓ NN cross section remains constant independent of how many collisions a nucleon suffered



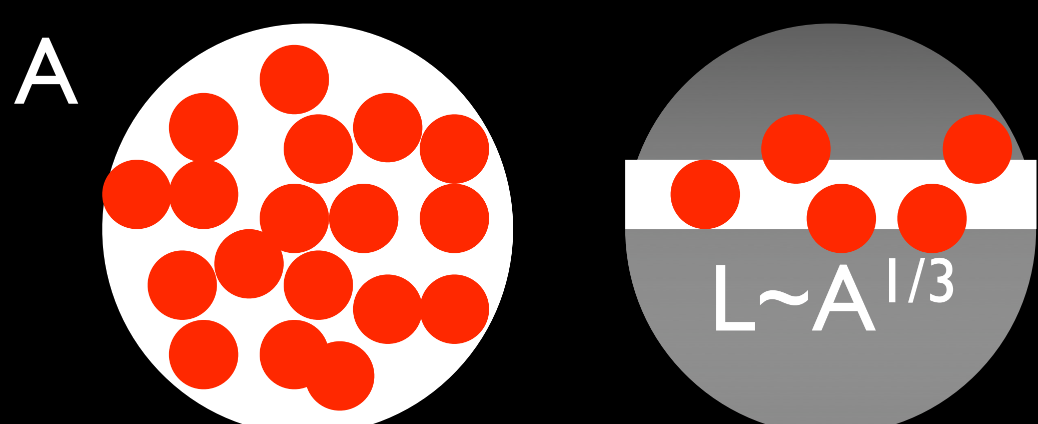
Wounded nucleons and binary collisions

wounded nucleon scaling

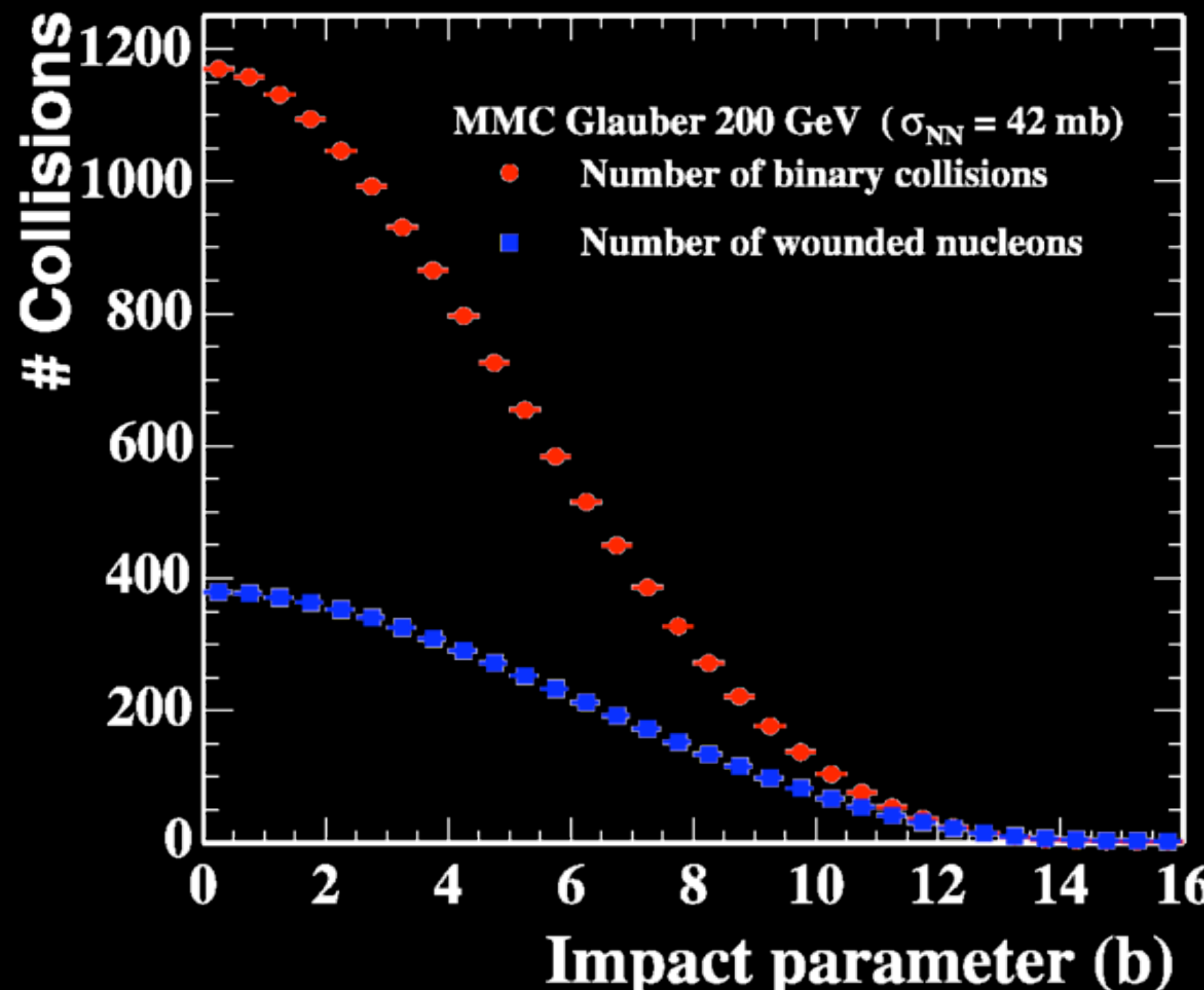


number of participating nucleons scales with volume ~ 2A

binary scaling

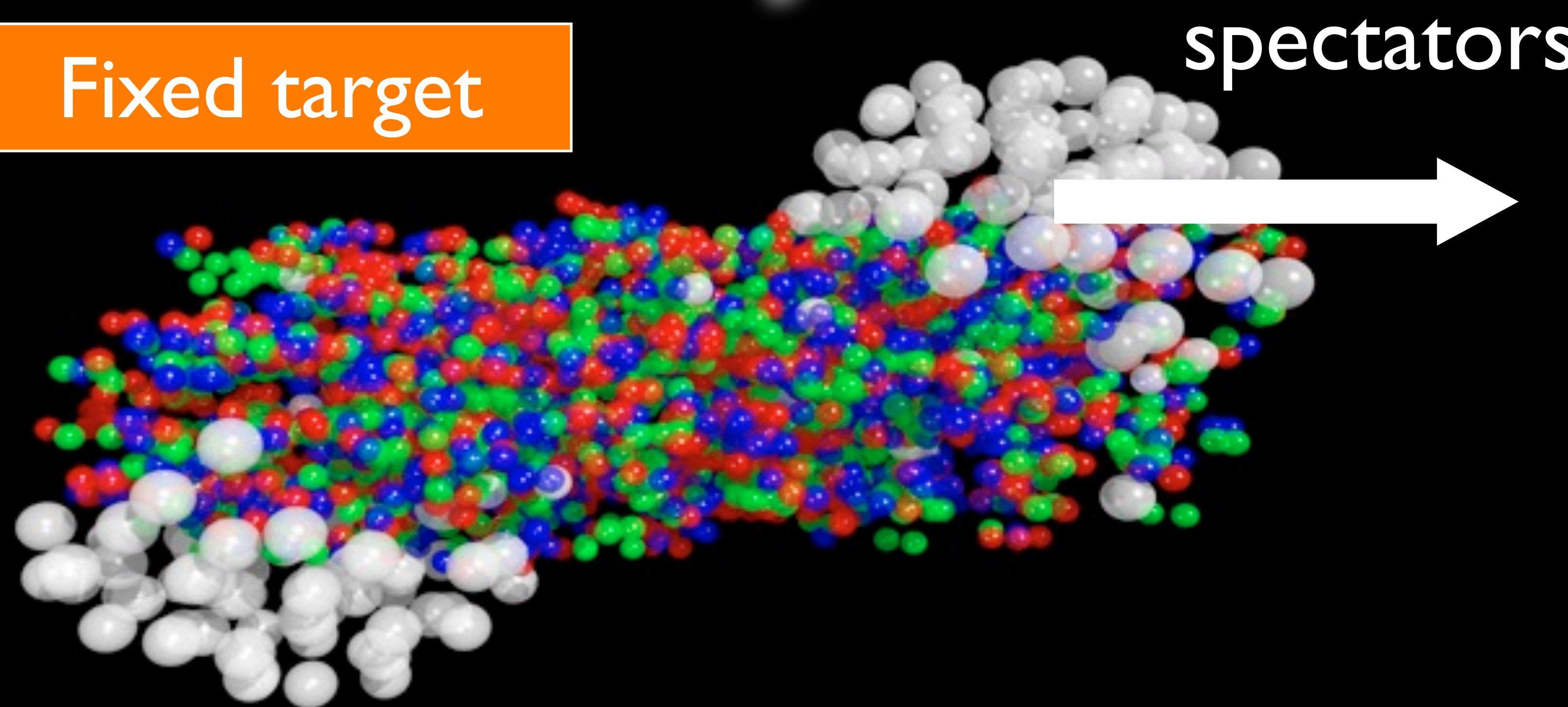


number of NN collisions, point like, scales with ~ $A^{4/3}$



Centrality determination (II)

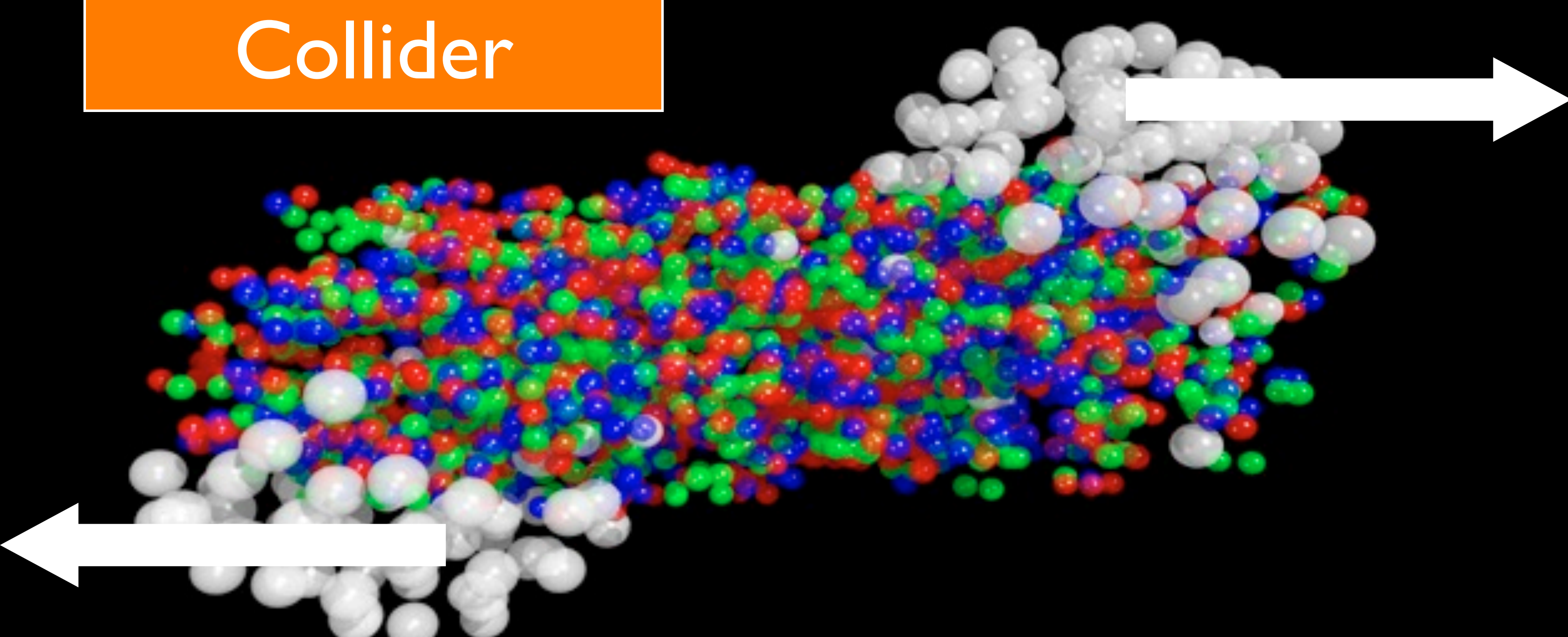
Fixed target



Zero-Degree-Calorimeter (ZDC) measures energy of all spectator nucleons

$$N_{\text{spec}} \approx E_{\text{ZDC}} / \left(E_{\text{beam}} / A\right),$$
$$N_{part} \approx 2 \cdot \left(A - N_{\text{spec}}\right)$$

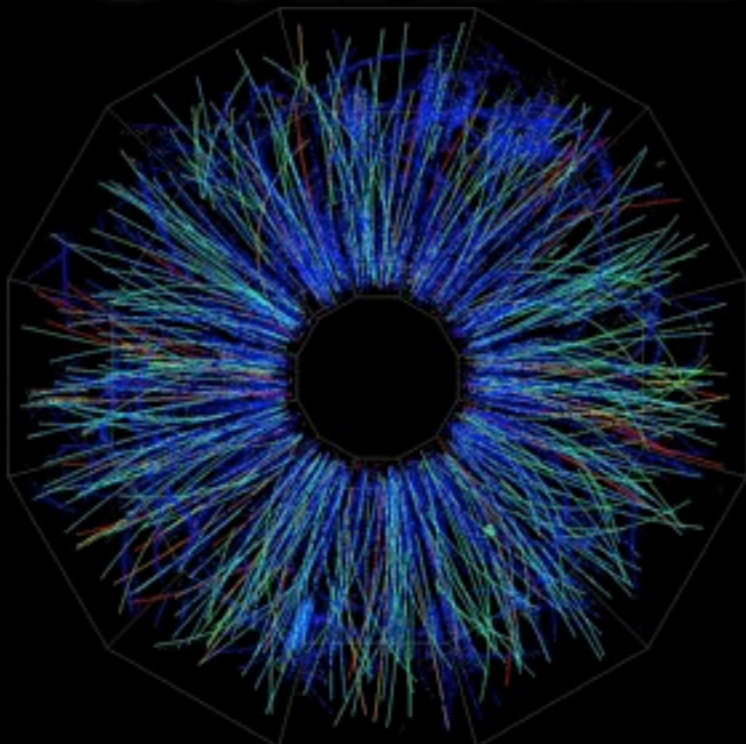
Collider



Zero-Degree-Calorimeter (ZDC) measures energy of all <u>unbound</u> spectator nucleons

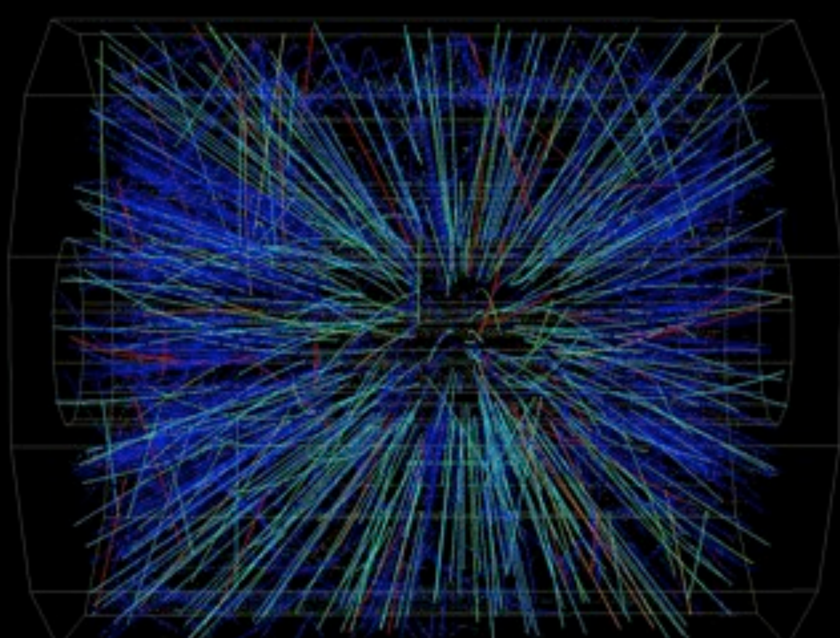
- ➡ charged fragments (p, d, and heavier) are deflected by accelerator magnets
- ➡ E_{ZDC} small for very central and very peripheral collisions, ambiguous

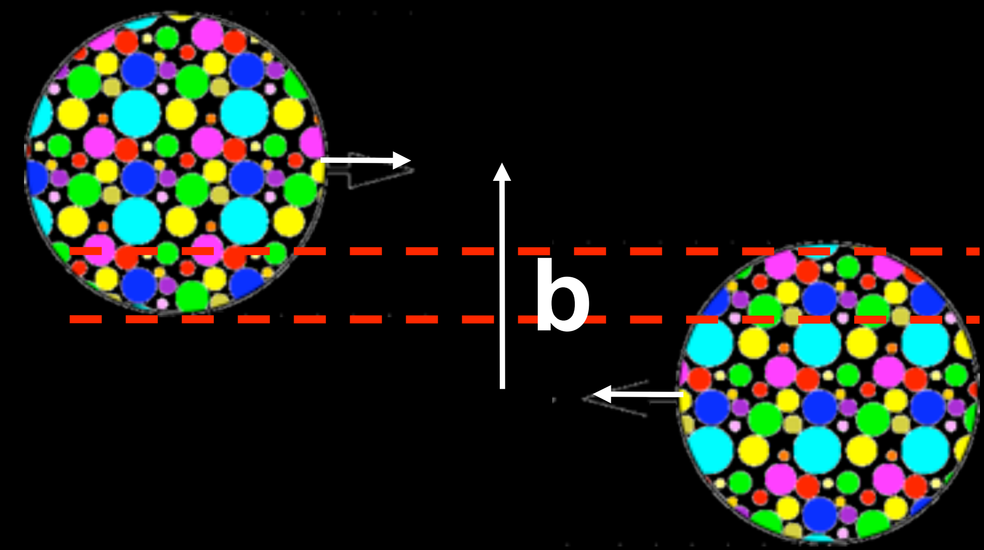
Centrality determination (III)



Peripheral Event

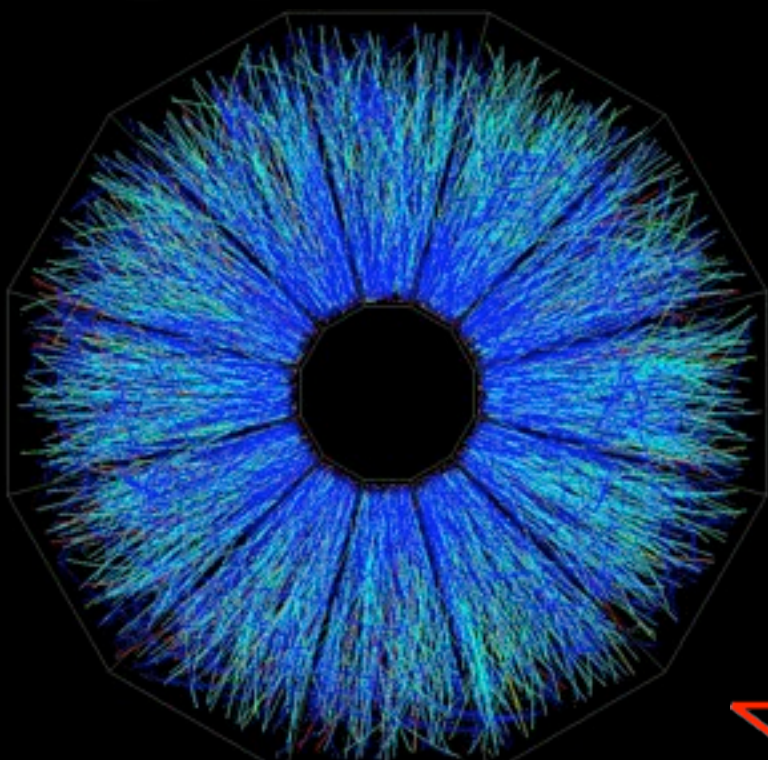
From real-time Level 3 display





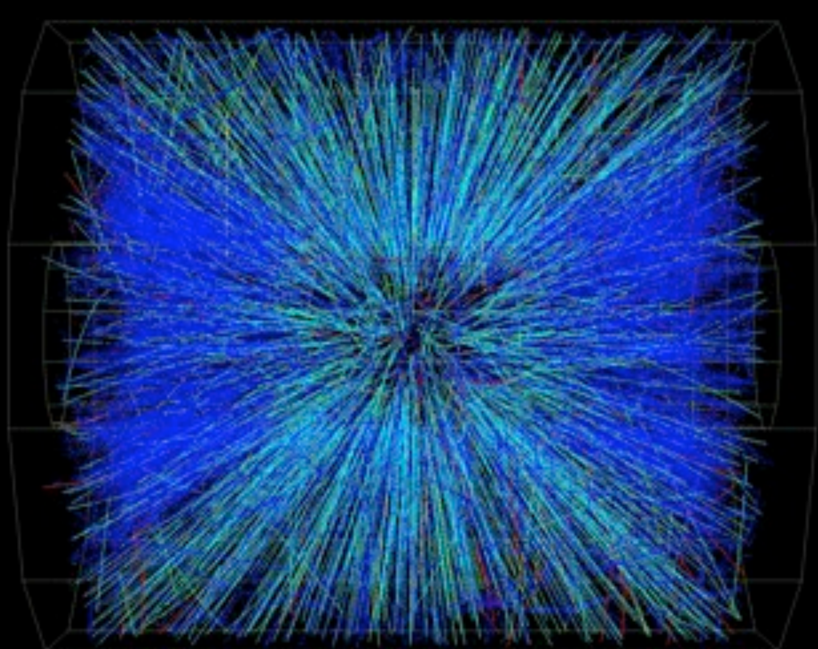
- ✓ peripheral collisions, largest fraction cross section
- ✓ many spectators
- ✓ “few” particles produced

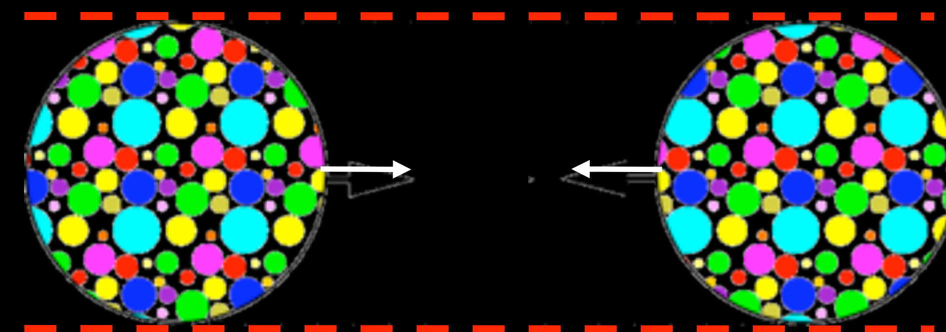
Centrality determination (IV)



Central Event

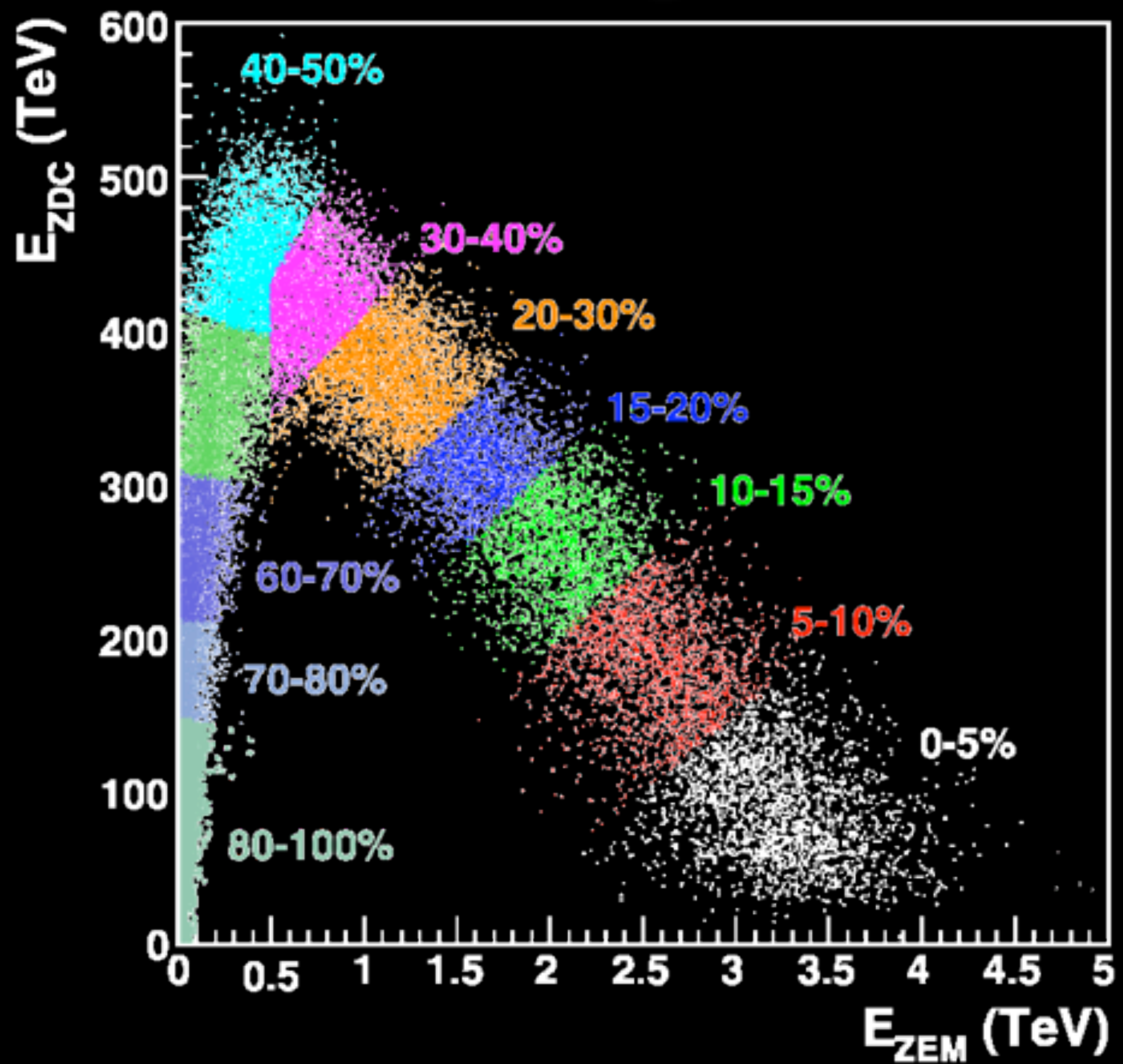
From real-time Level 3 display

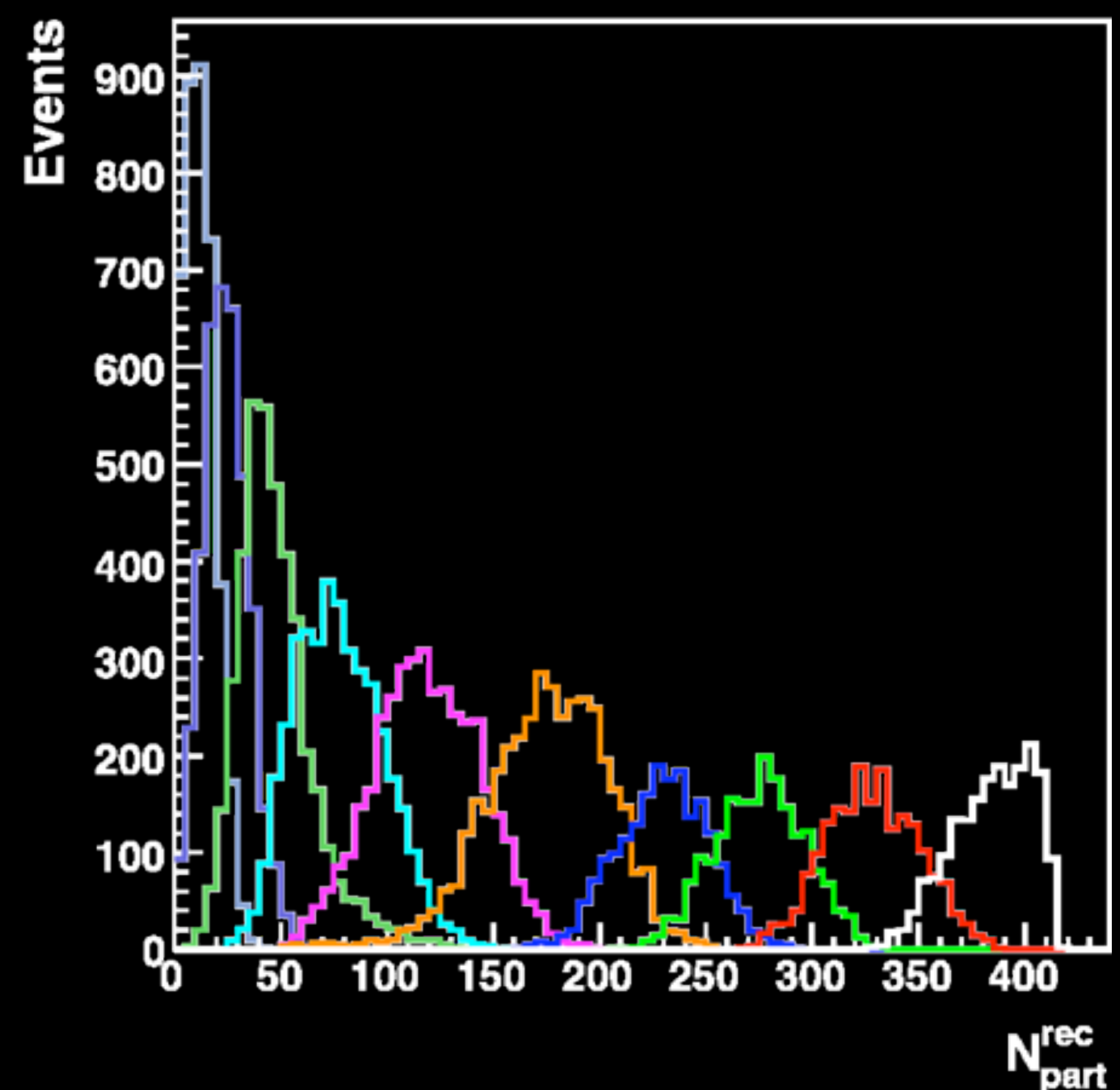




- ✓ impact parameter **b** = 0
- ✓ central collisions, small cross section
- ✓ no spectators
- ✓ many particles produced

Centrality determination (ALICE)

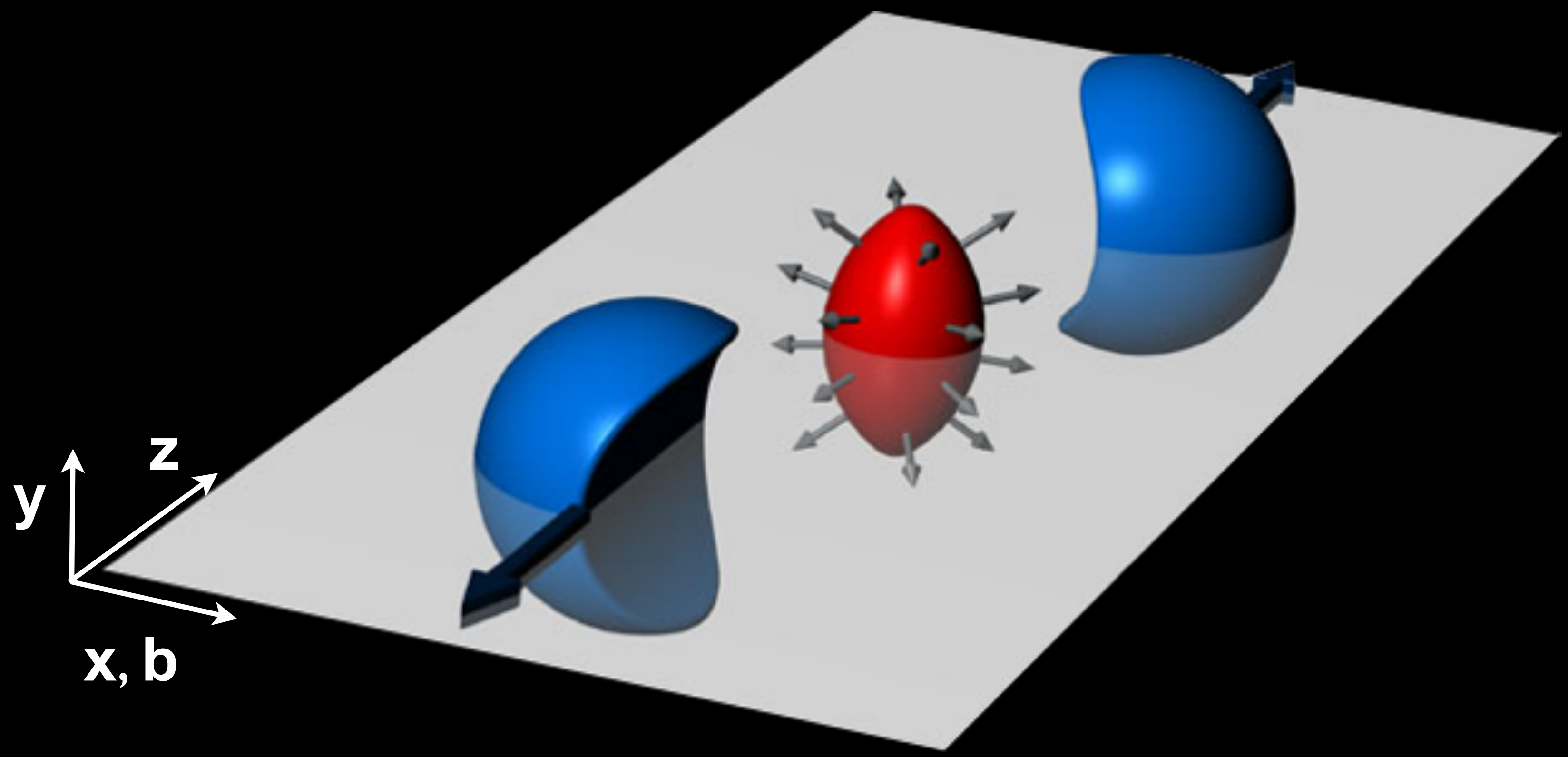


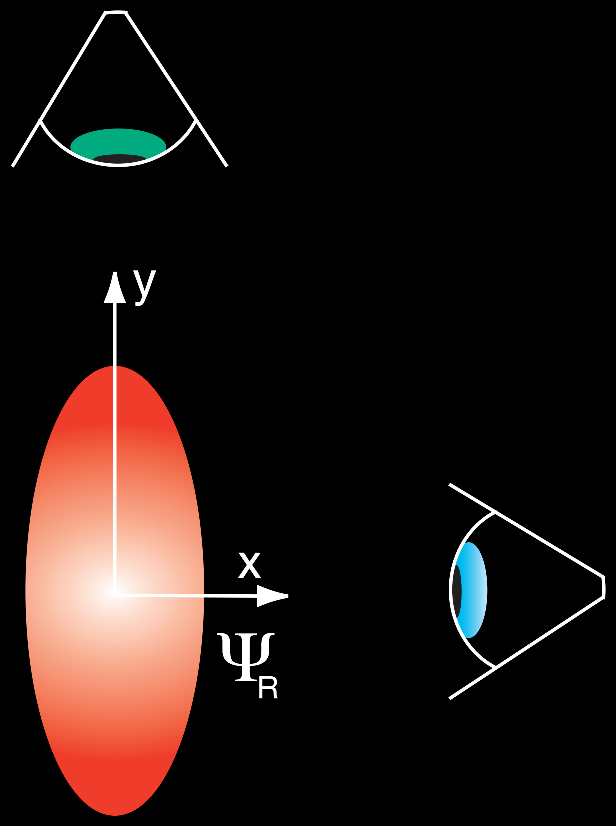


✓ Determines the magnitude of the impact parameter

$\%\sigma_{tot}$	$<N_{part}>$	$<b>$
0-5	386	2.48
20-30	177	7.85
60-70	25	12.66

The Reaction Plane

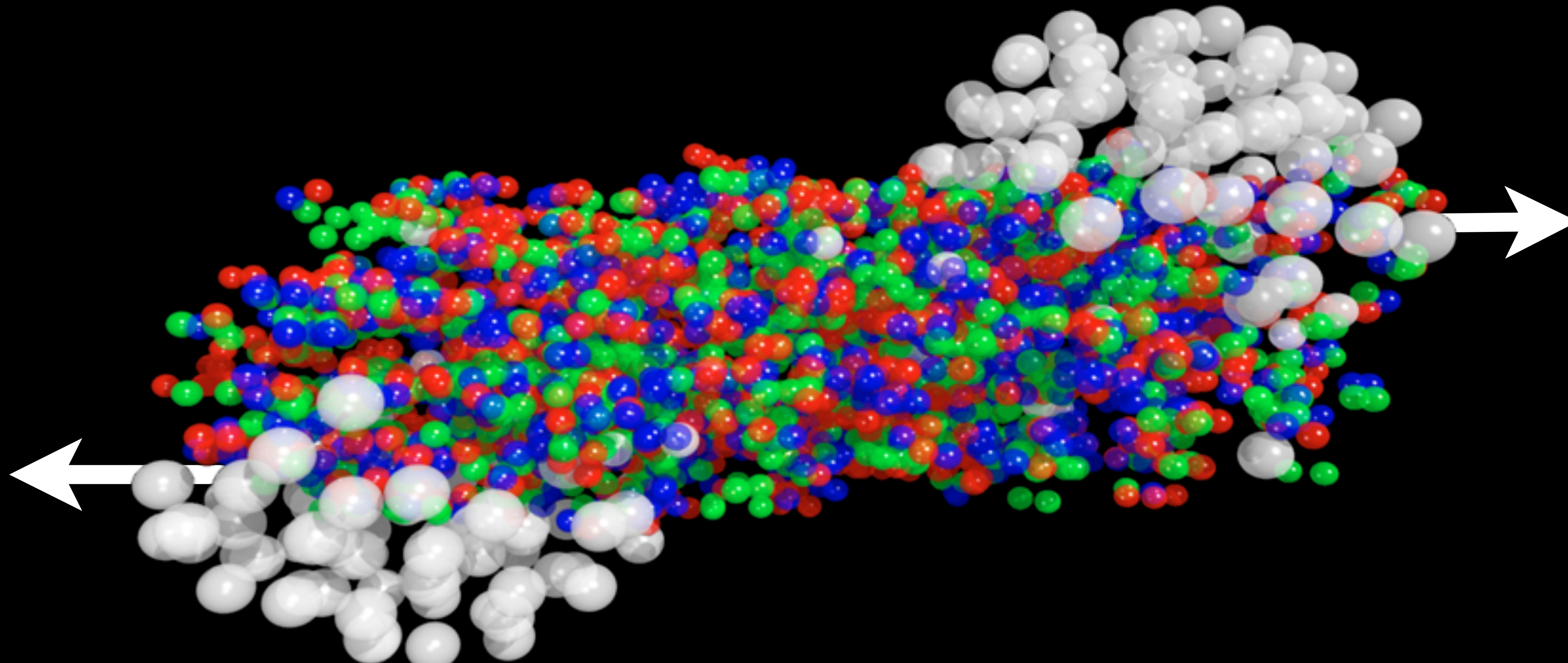




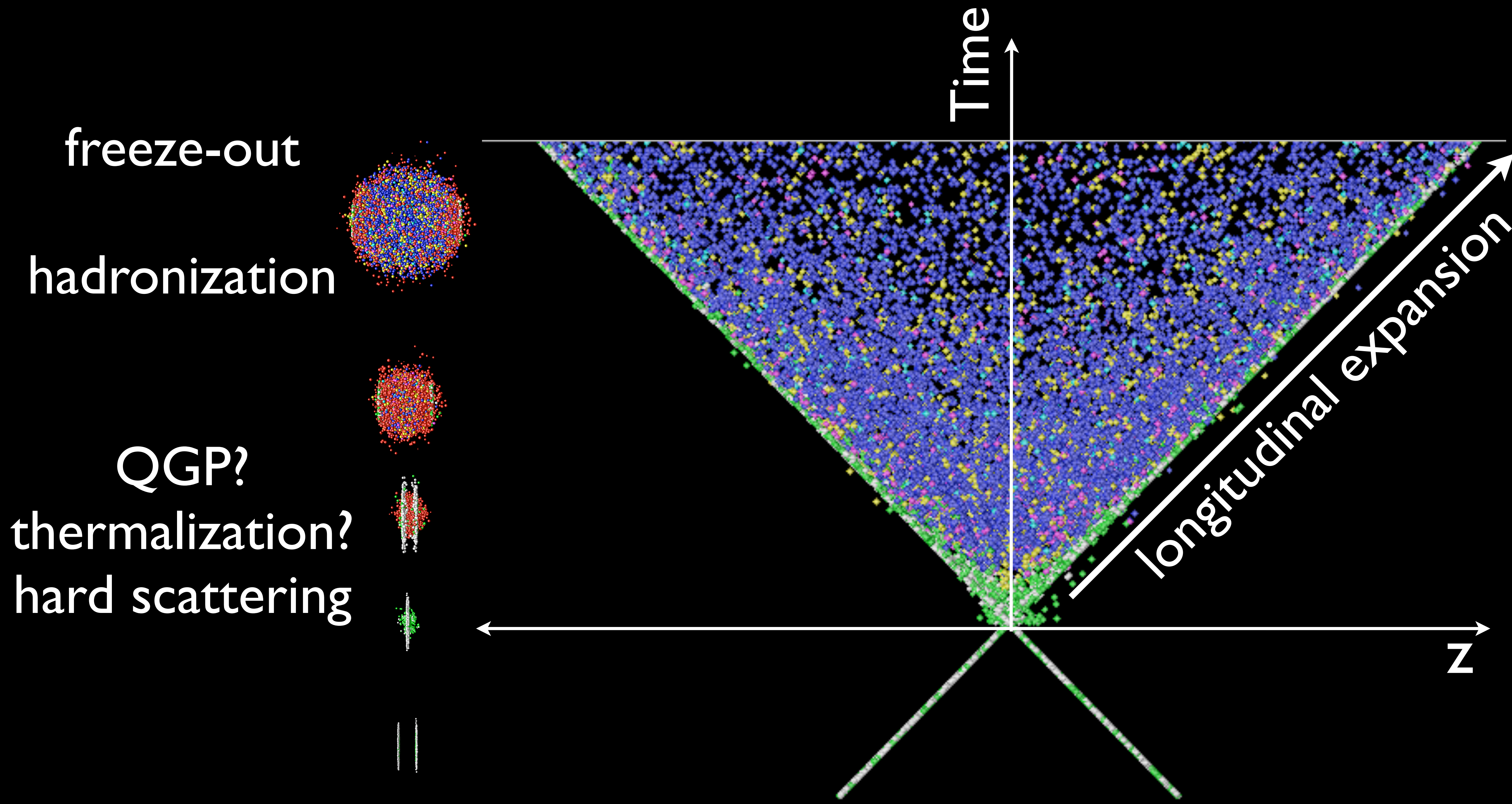
$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{\mathrm{d}^3N}{p_t\mathrm{d}p_t\mathrm{d}y\mathrm{d}(\phi - \Psi_R)}$$

determine the angle of the reaction plane ψ_R

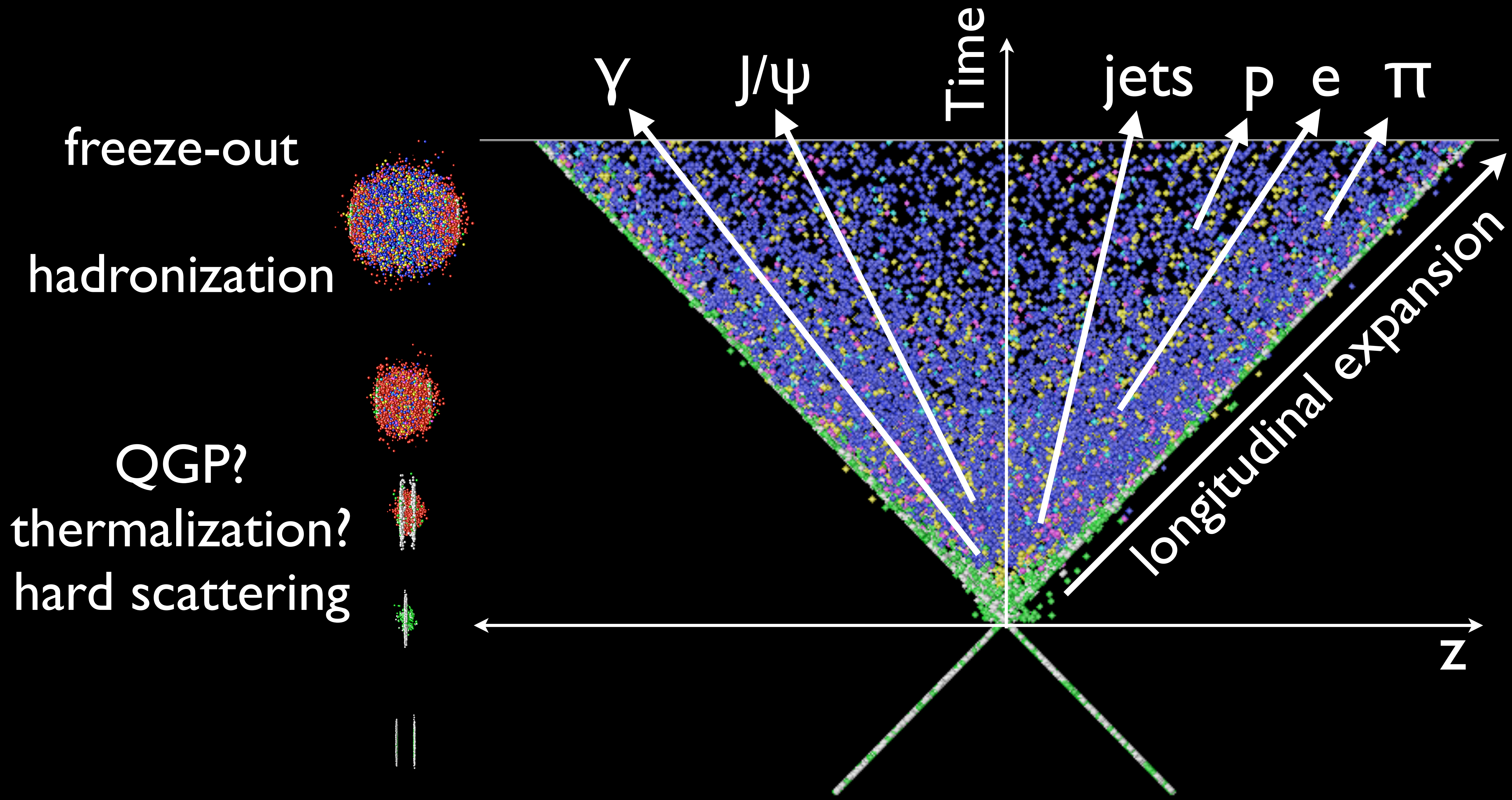
Observables/Probes

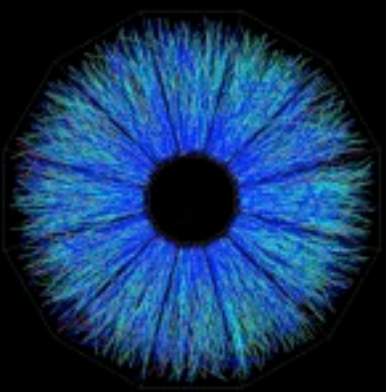


Time Evolution



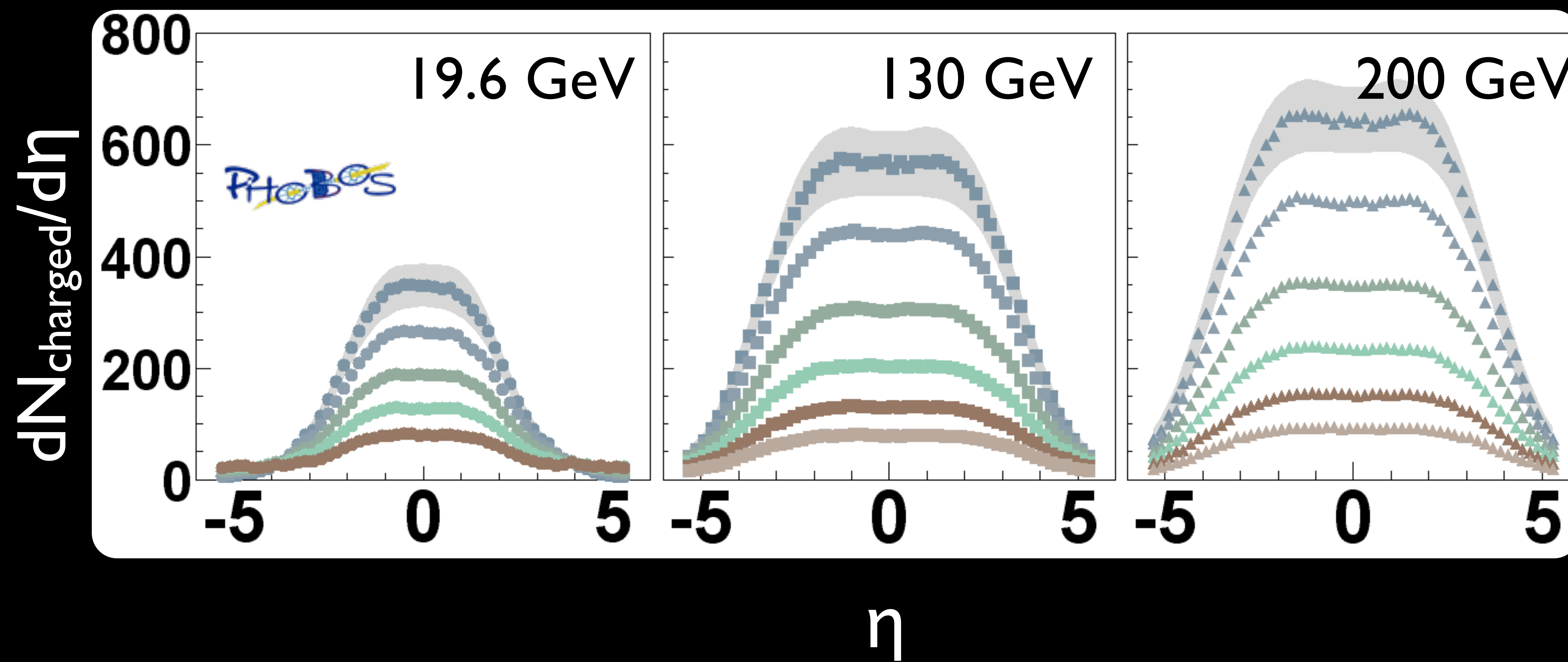
different observables





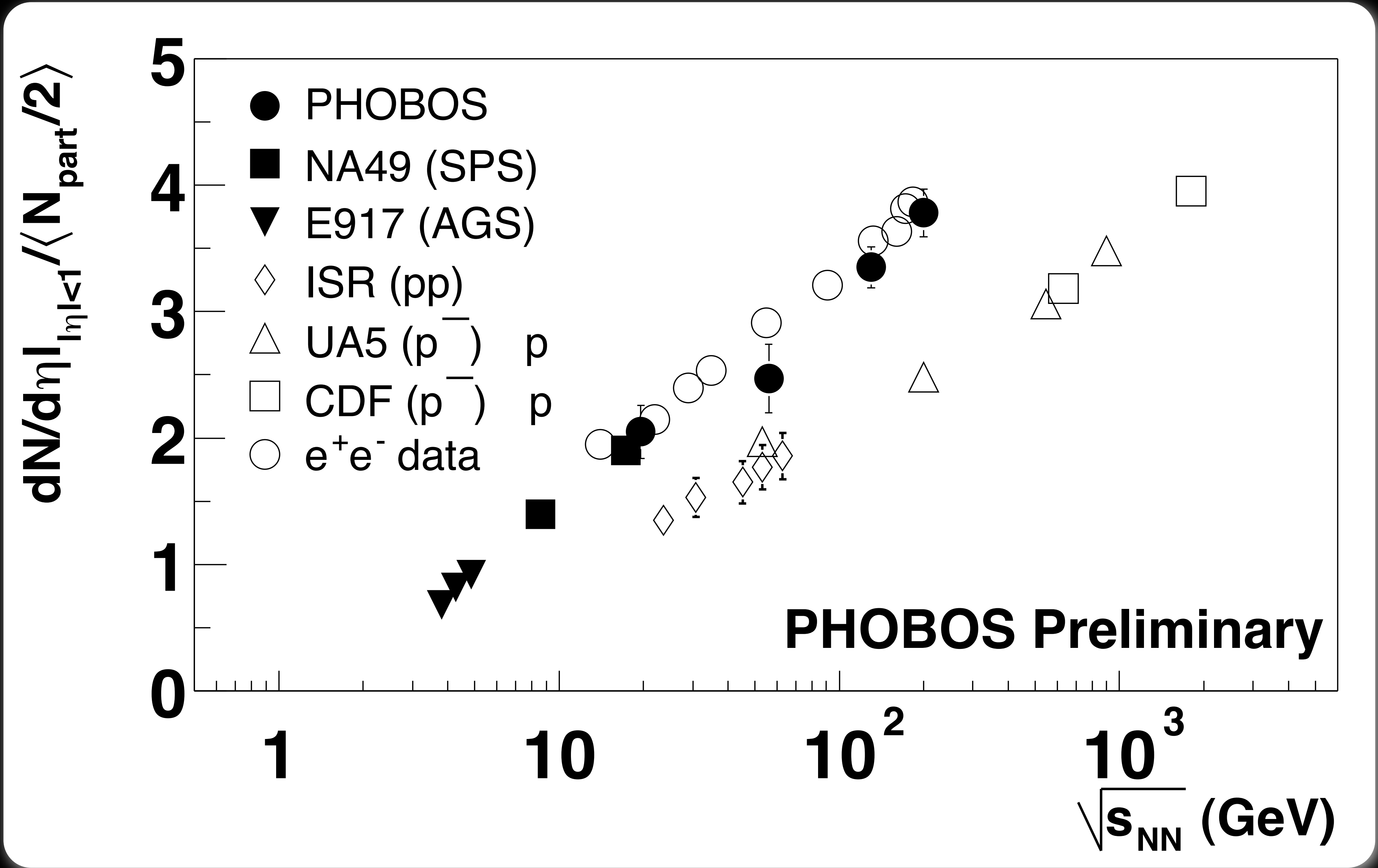
Particle Production

$$y = \frac{1}{2}\ln\left(\frac{p_0 + p_z}{p_0 - p_z}\right) \qquad \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



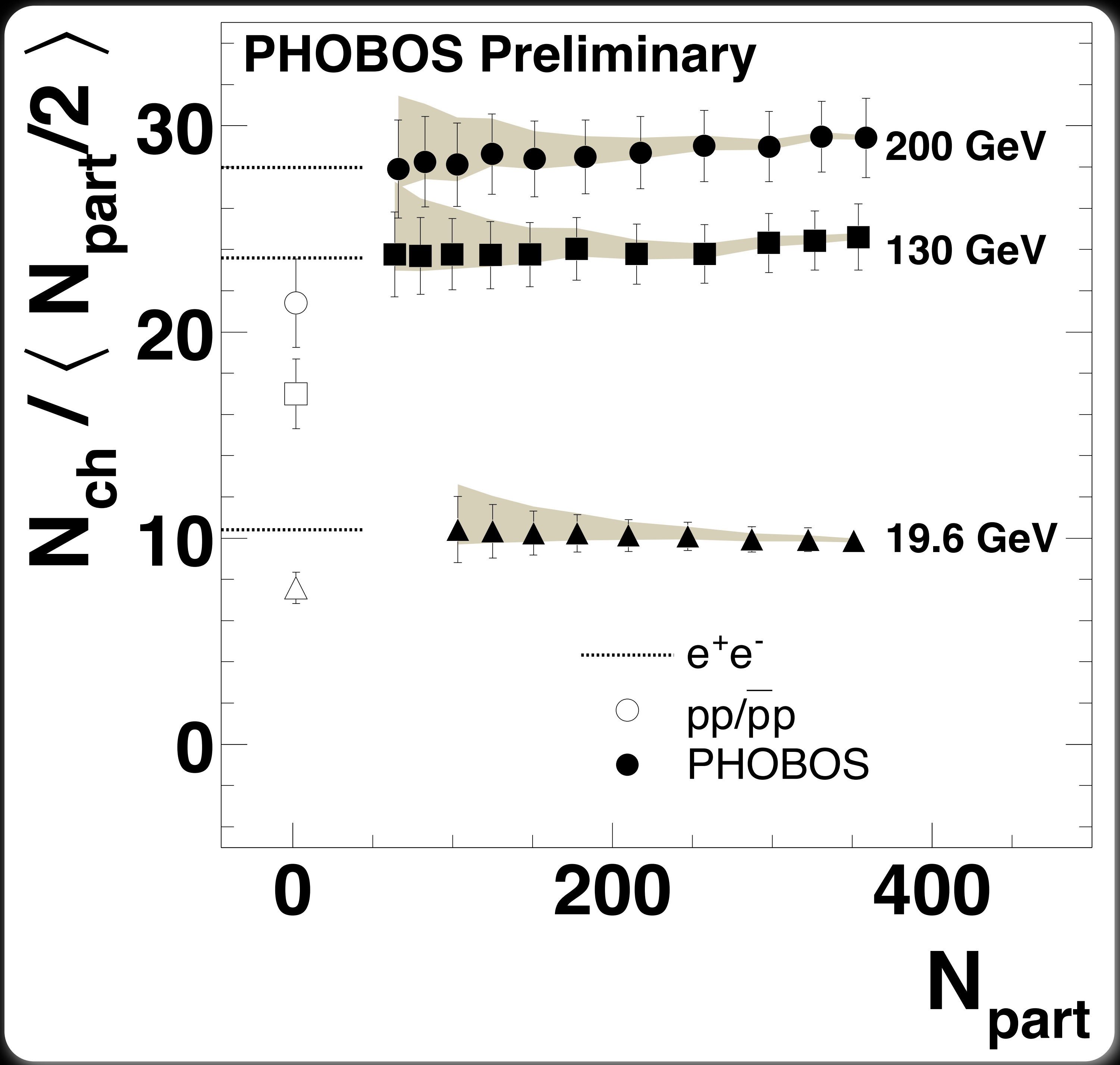
more than 4000 charged particles produced at 130 GeV!

Particle Production



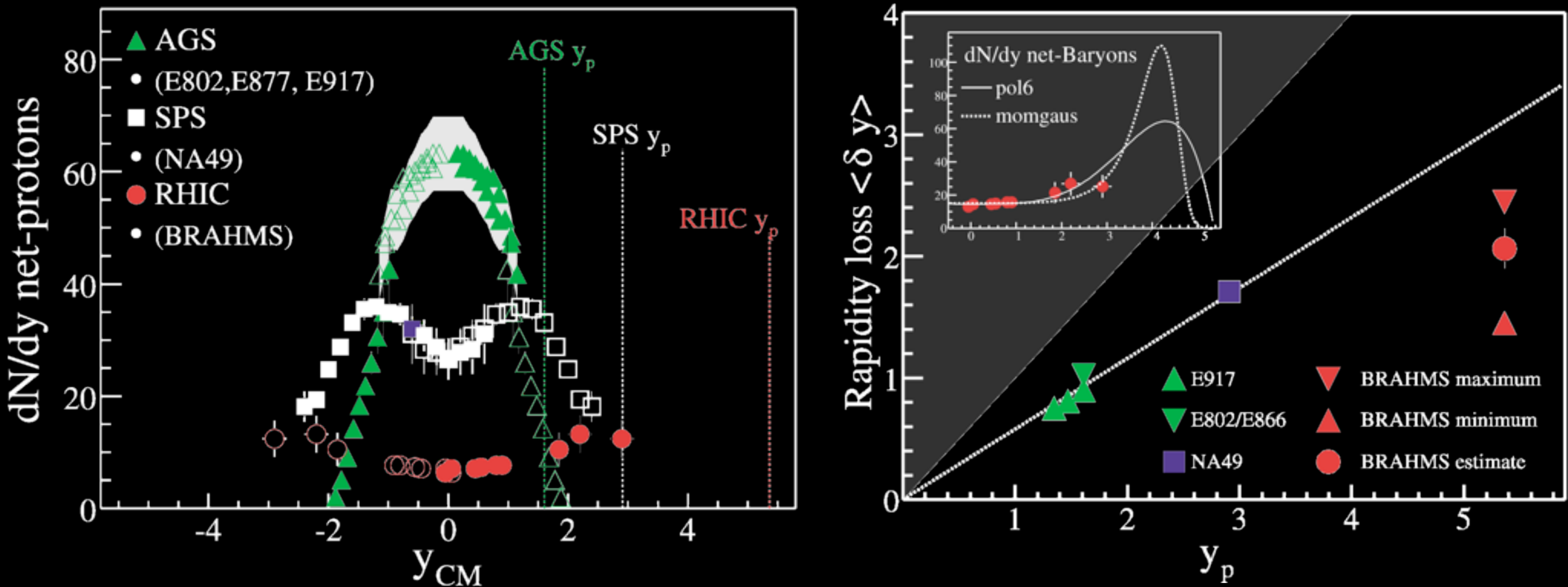
- particle production in AA and e^+e^- collisions follows the same scaling as function of beam energy, and is larger than in pp collisions
  - leading particle effect

Particle Production



- particle production per participant pair is approximately constant as function of centrality in AA
- yield per participant in AA similar as in e^+e^- annihilation

Available Energy: baryon-stopping

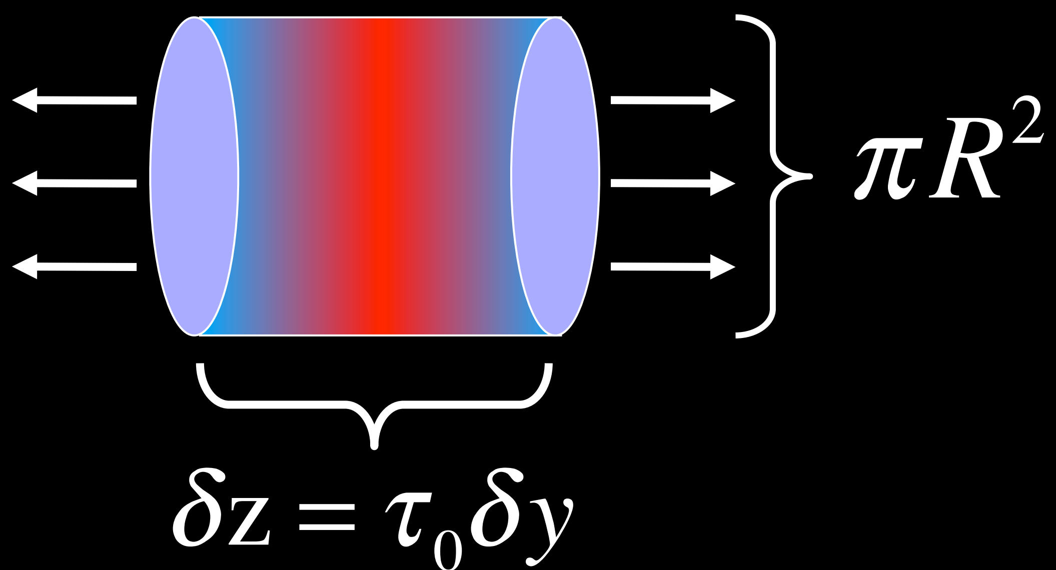


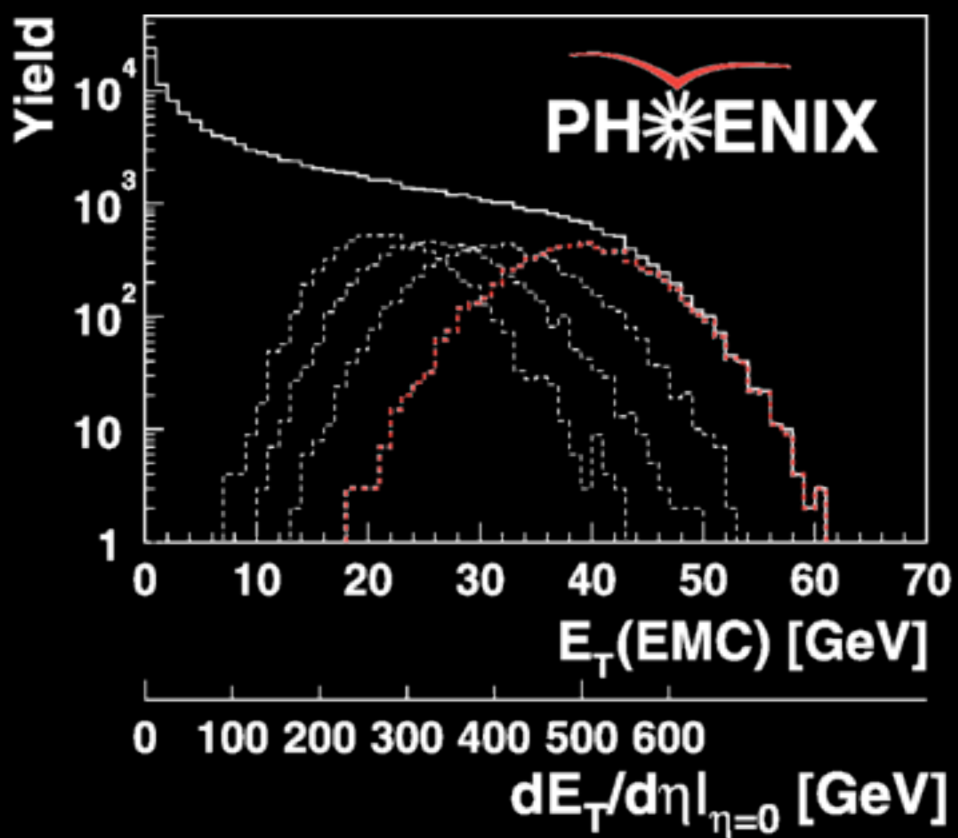
- in pp collisions 50% of beam energy available for particle production
- in AA collisions 70-80% of incoming energy available for particle production (in accordance with expectations from pA)

Transverse Energy and Energy Density

Björken energy density estimate

$$\varepsilon_{\mathrm{Bj}} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{\mathrm{d}E_T}{\mathrm{d}y}$$





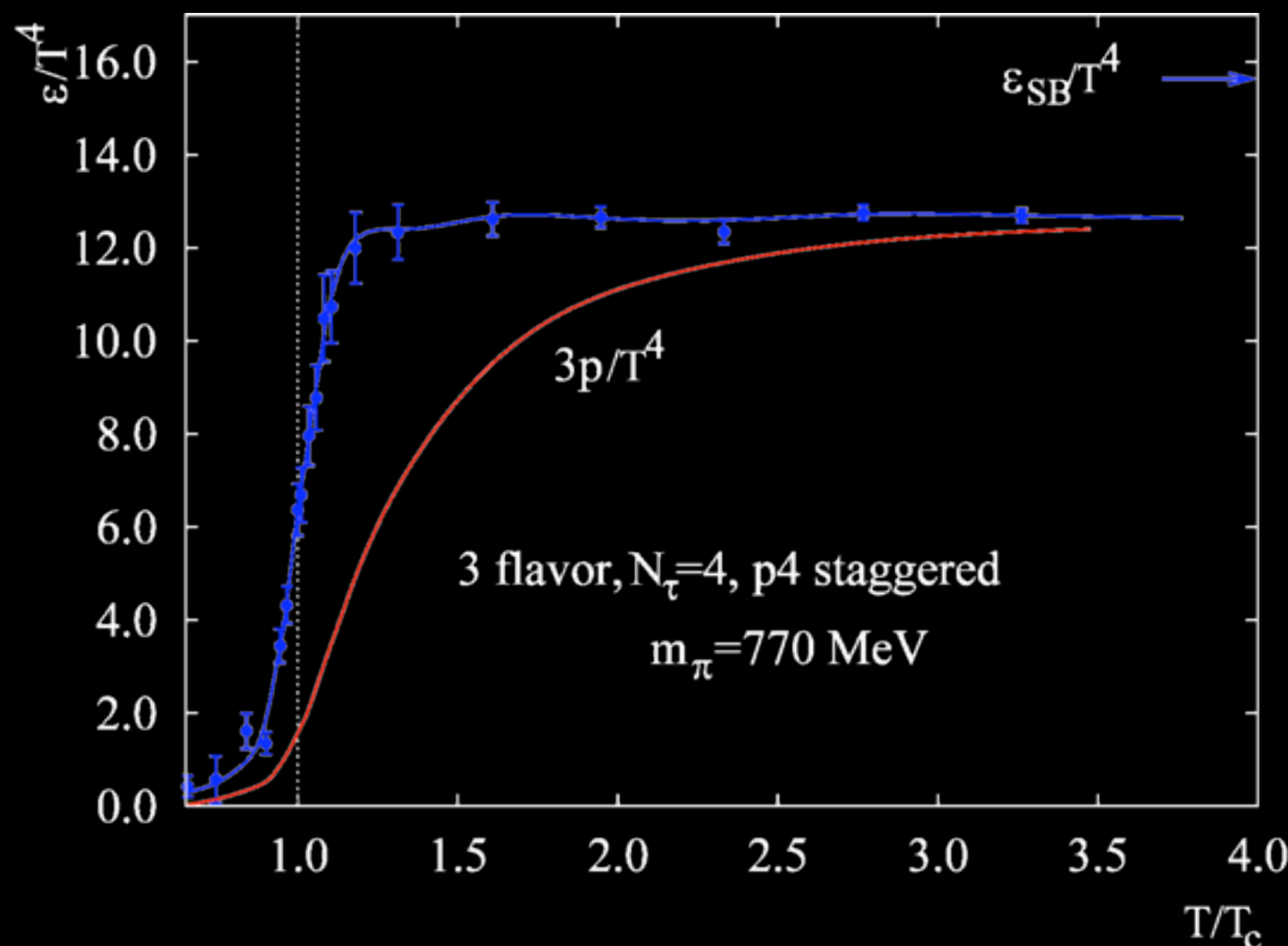
$$\left\langle \frac{\mathrm{d}E_T}{\mathrm{d}\eta} \right\rangle_{\eta=0} = 503 \pm 2 \text{ GeV}$$

$$\varepsilon_{\mathrm{Bj}} = 4.6 \ \mathrm{GeV/fm^3}$$

much larger than the critical energy density!!

QGP probes and observables

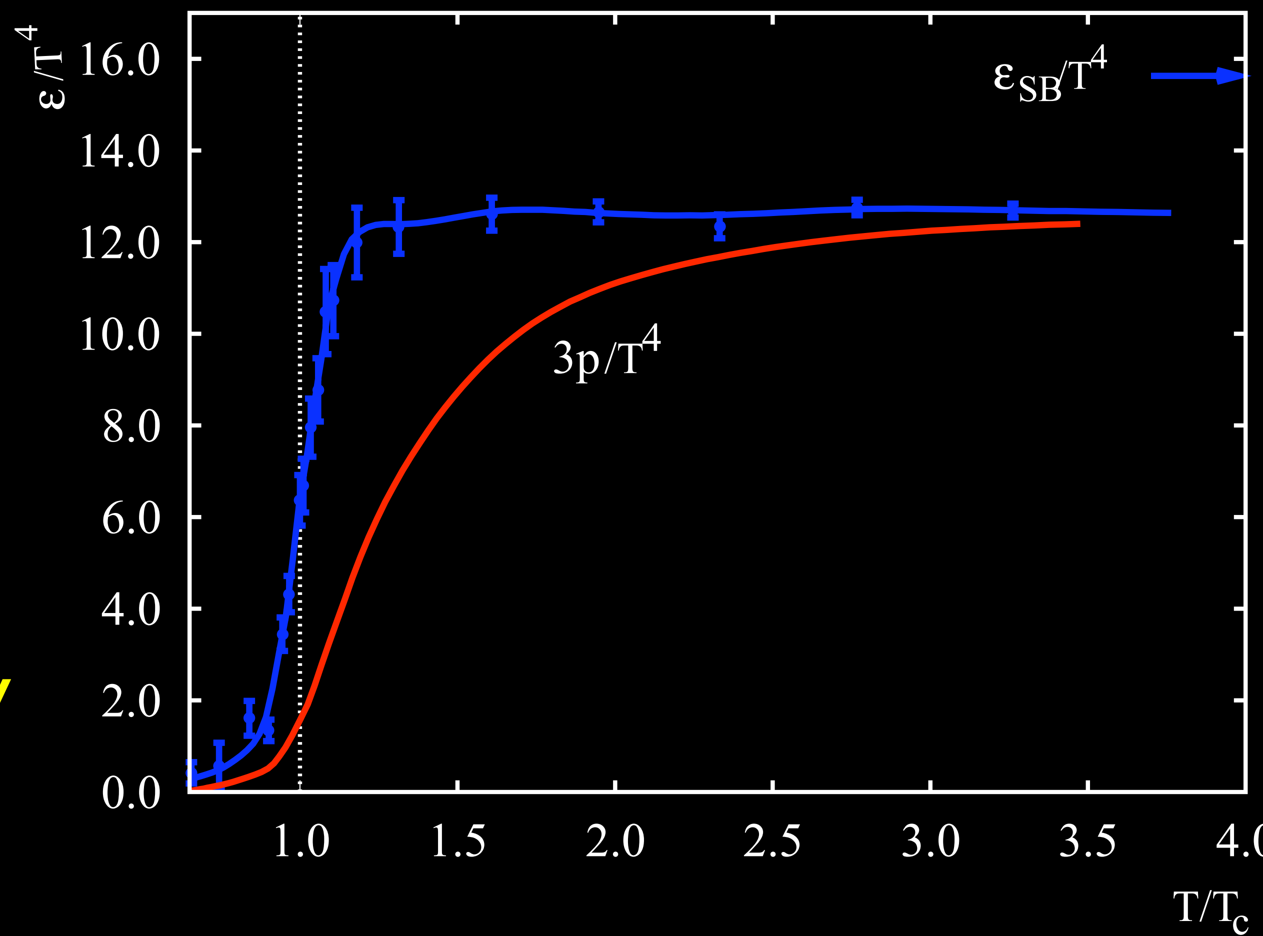
- at the SPS and at RHIC the initial conditions are already favorable for QGP formation!
- what are the QGP signatures?



- what have we learned about the nature of the phase transition?
- what have we learned about the properties of the QGP medium?

Some Key Observables

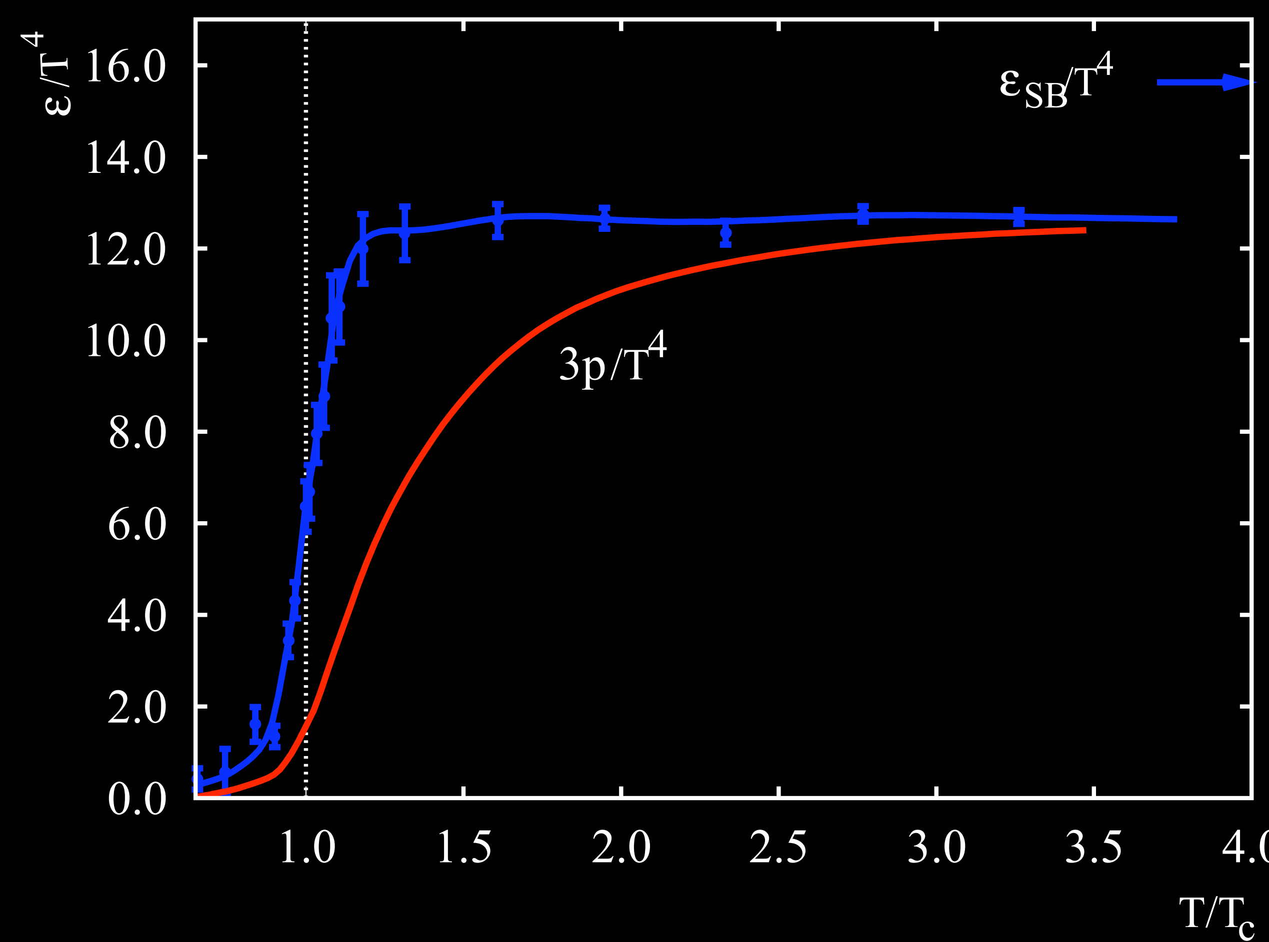
- temperature
  - direct photons, ...
- (energy) density
  - transverse energy, parton energy loss, heavy-quark energy loss, ...
- pressure gradient
  - collective motion, collective motion of heavy-quarks, ...



$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

Some Key Observables

- chiral symmetry restoration
  - strangeness enhancement
- deconfinement
  - J/ψ suppression



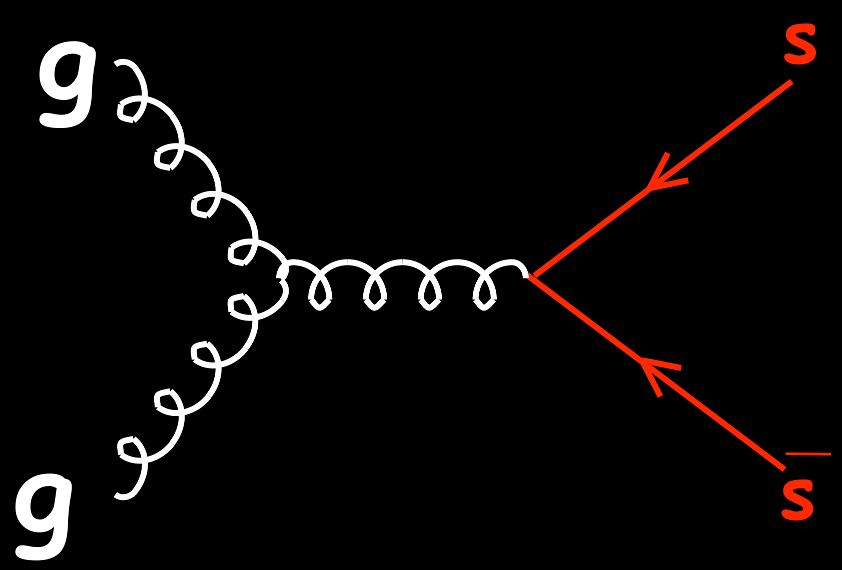
$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

Strangeness enhancement

- QGP signature proposed by Rafelski and Muller, 1982
- the masses of deconfined quarks are expected to be about 350 MeV lower compared to confined
- m_s(constituent) ~ 500 MeV → m_s(current) ~ 150 MeV
- T_c ~ 170 MeV strange quark should be a sensitive probe

Strangeness production in a QGP

- copious strangeness production by gluon fusion:



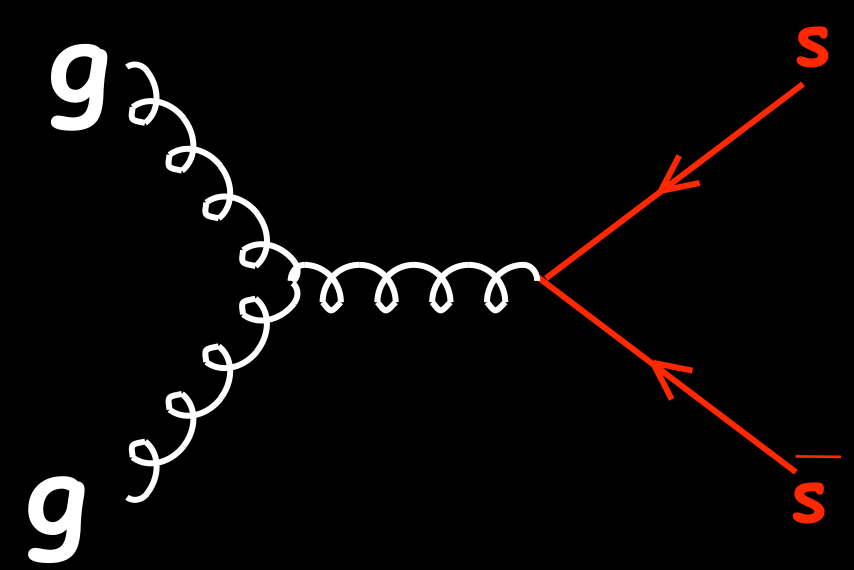
$$T \approx m_s = 150 \text{ MeV}$$

$$N(s) \propto \exp\left(-\frac{m_s}{T}\right)$$

- in a system which is baryon rich (i.e. an access of quarks over anti-quarks), the enhancement can be further enhanced due to Pauli blocking of light quark production

Strangeness abundances in a QGP

- the QGP strangeness abundance is enhanced
- the strange quarks recombine into hadrons (when the QGP cools down and hadronizes)
- the abundance of strange hadrons should also be enhanced
- this enhancement should be larger for particles of higher strangeness content



$E(\Omega^-)$ >	$E(\Xi^-)$ >	$E(\Lambda)$
(sss)	(ssd)	(sud)

Strangeness abundances in a hadron gas

- in a relatively long lived strongly interacting hadronic system strangeness can also be enhanced
- these hadronic processes are relatively fast and easy for kaons and Λ, but progressively harder for particles of higher strangeness
- the production of multi-strange baryons is expected to be sensitive to deconfinement

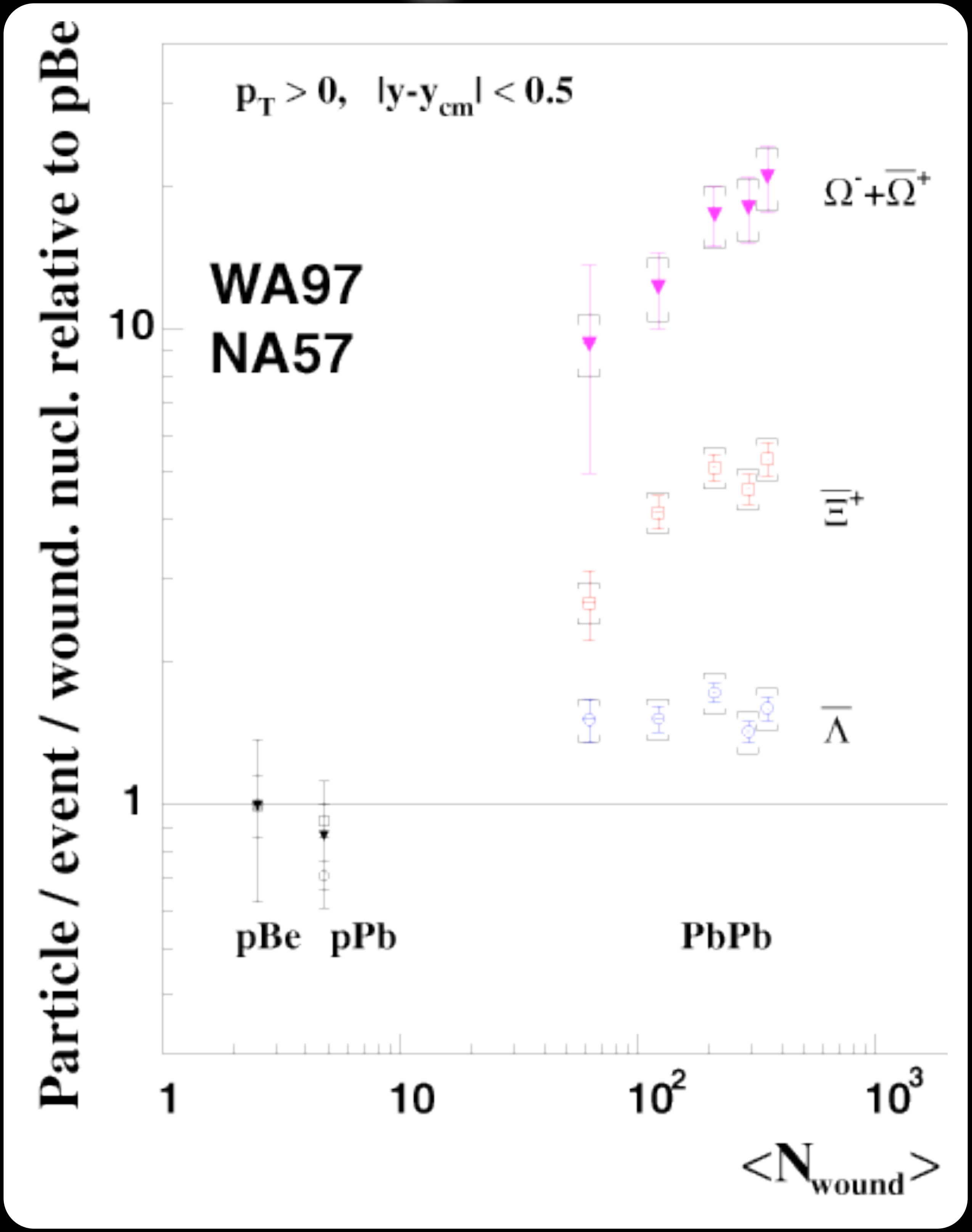
$$\pi + \pi \to K + \bar{K}$$

$$\pi + N \to \Lambda + K$$

E(Ω^-) <	E(Ξ^-) <	E(Λ)
(sss)	(ssd)	(sud)

only 2→2 processes considered!!

Strangeness measurement at the SPS

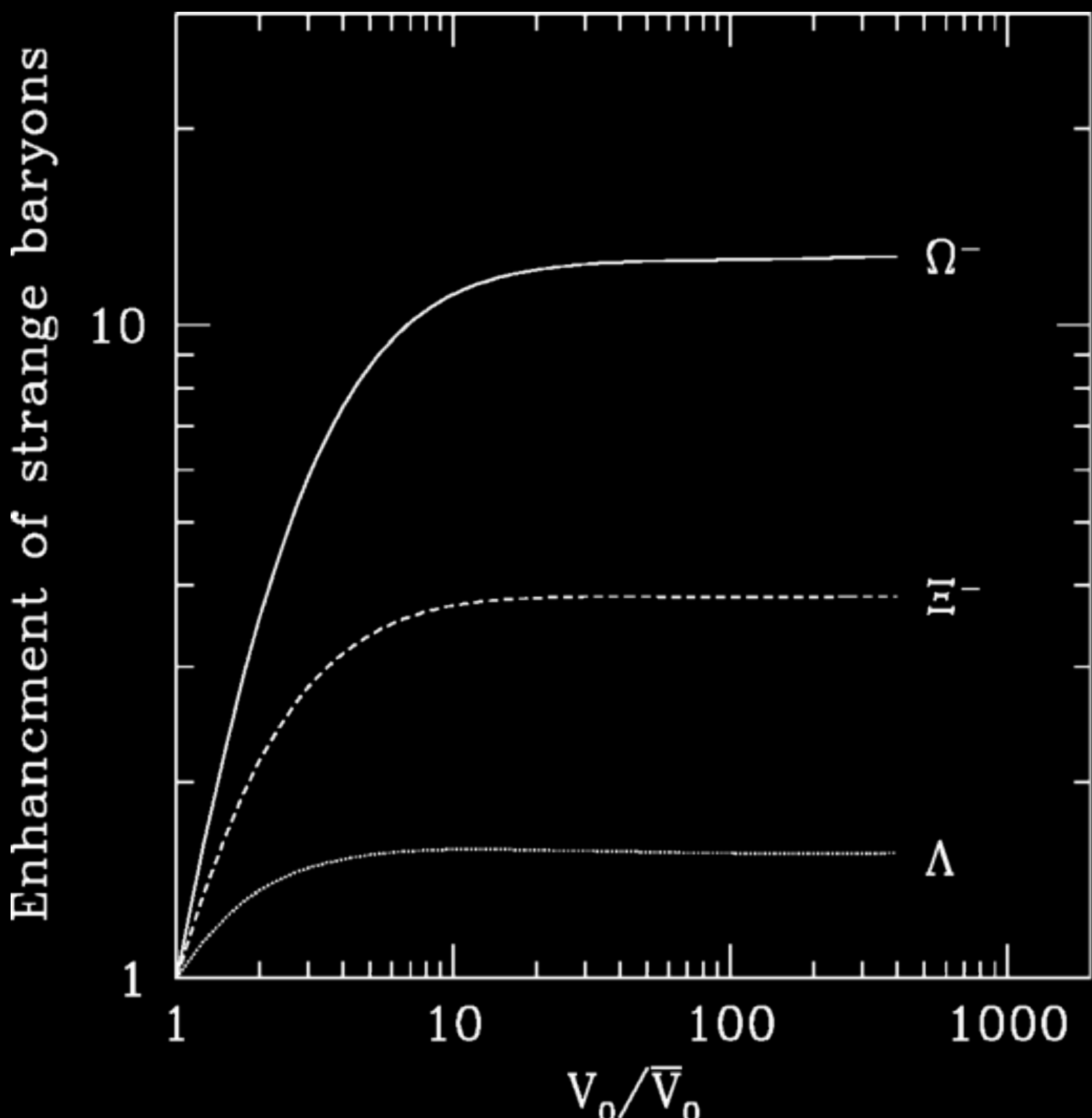


- enhancement: yield per participant relative to yield per participant in p-Be

$$E_{\Omega^-} = \frac{\left(N_{\Omega^-} / \left\langle N_{\mathrm{wounded}} \right\rangle\right)_{Pb+Pb}}{\left(N_{\Omega^-} / \left\langle N_{\mathrm{wounded}} \right\rangle\right)_{p+Be}}$$

- Ω more than a factor 20 enhanced
- relative order follows QGP prediction

Canonical suppression of strangeness



S. Hamieh, K. Redlich A. Tounsi, PL B486 (2000) 61

- successful description of strangeness production in heavy ion collisions with a thermal model using a grand canonical ensemble
- for small systems exact strangeness conservation becomes important, canonical ensemble, reduces available phase space

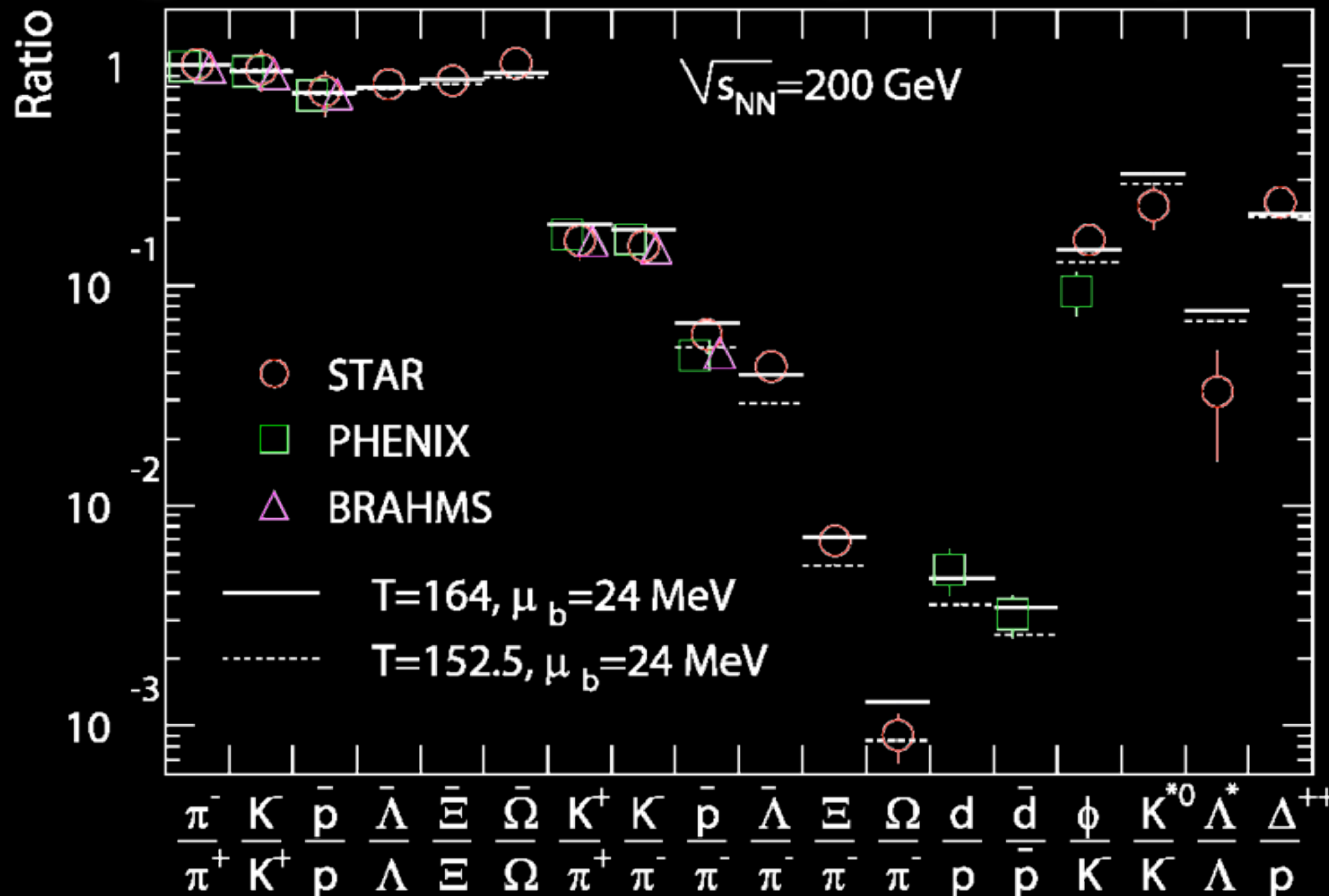
Thermal Model

- assume chemically equilibrated system at freeze-out (constant T_{ch} and μ)
- composed of non-interacting hadrons and resonances
- given T_{ch} and μ 's, particle abundances (n_i's) can be calculated in a <u>grand canonical ensemble</u>

$$n_i = \frac{g}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- obey conservation laws: Baryon Number, Strangeness, Isospin
- short-lived particles and resonances need to be taken into account

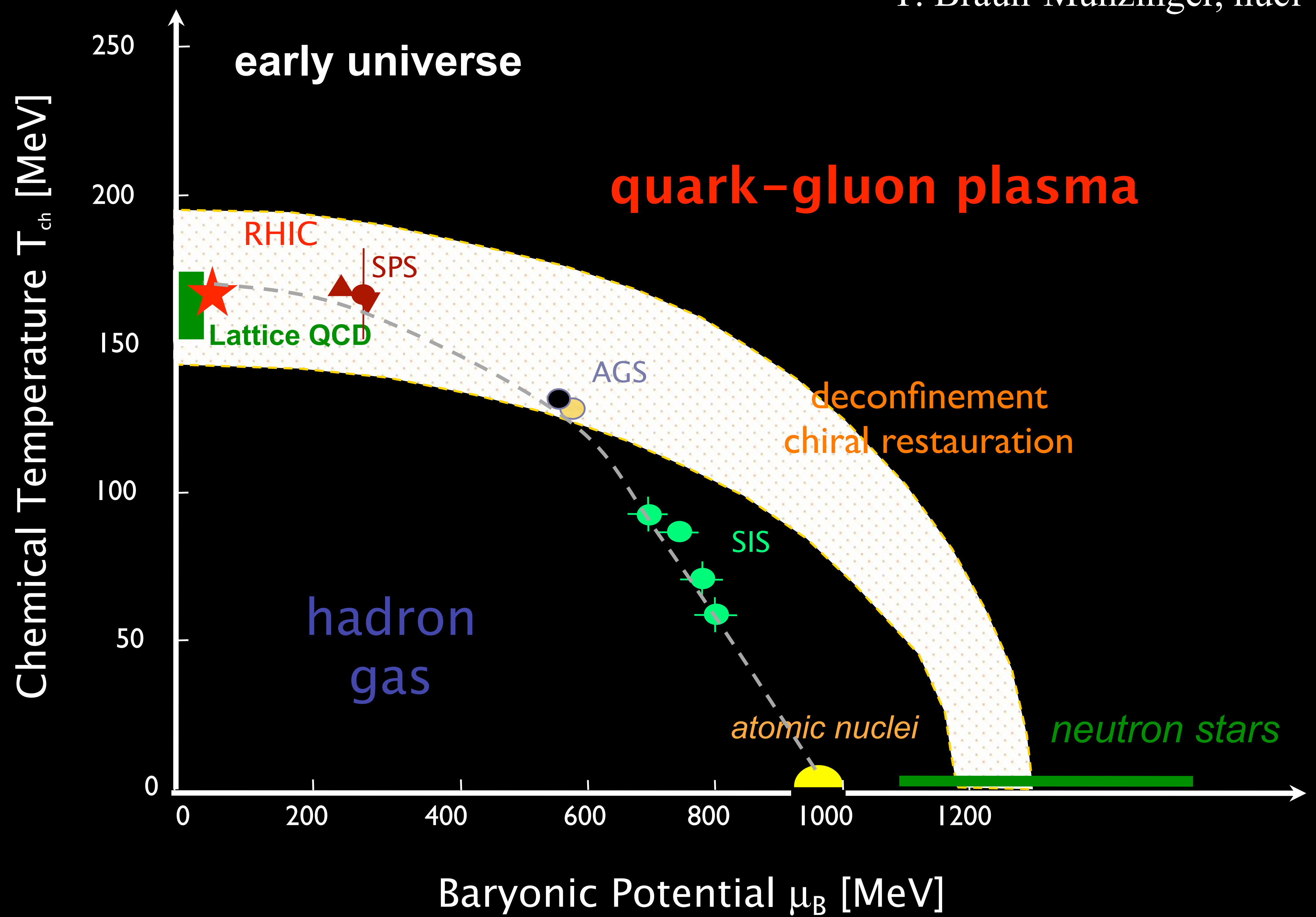
Integrated identified particle yields



- thermal model fits rather well
- works rather well in $e^+ e^-$ and proton-proton collisions as well, except for strange particles

The phase diagram revisited

P. Braun-Munzinger, nucl-ex/0007021



Charmonium suppression (I)

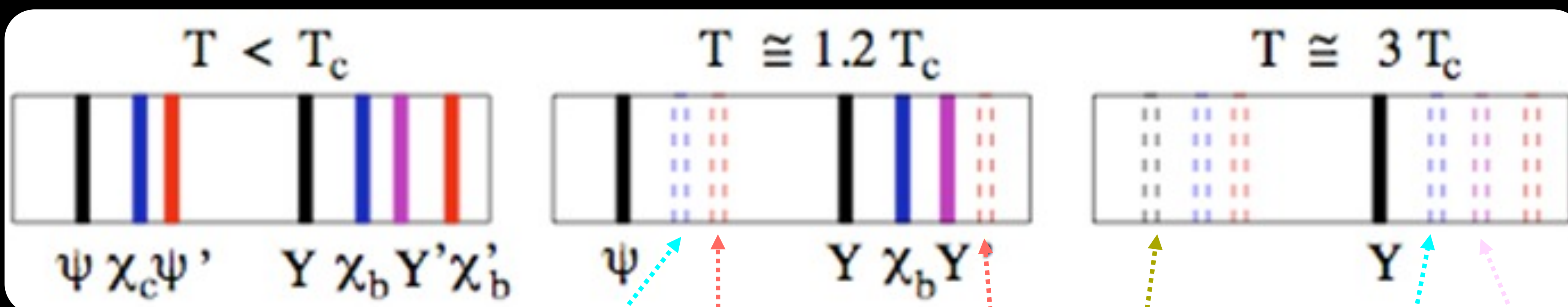
- QGP signature predicted by Matsui and Satz, 1986
- in the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening)
- charmonium (cc_{bar}) and bottonium (bb_{bar}) states with $r > \lambda_D$ will not bind; their production will be suppressed

Charmonium suppression (II)

- λ_D depends on temperature, thus which states are suppressed depends on temperature
- charmonium suppression key signature of deconfinement!!!
- cc_{bar} and bb_{bar} bound states are particularly sensitive probes because the probability of combining an uncorrelated pair at the hadronization stage is small
- in fact, at the SPS the only chance of producing a cc_{bar} bound state is shortly after the pair is produced. Debye screening destroys this correlations

Quarkonium: thermometer dense QCD

Quarkonium Physics



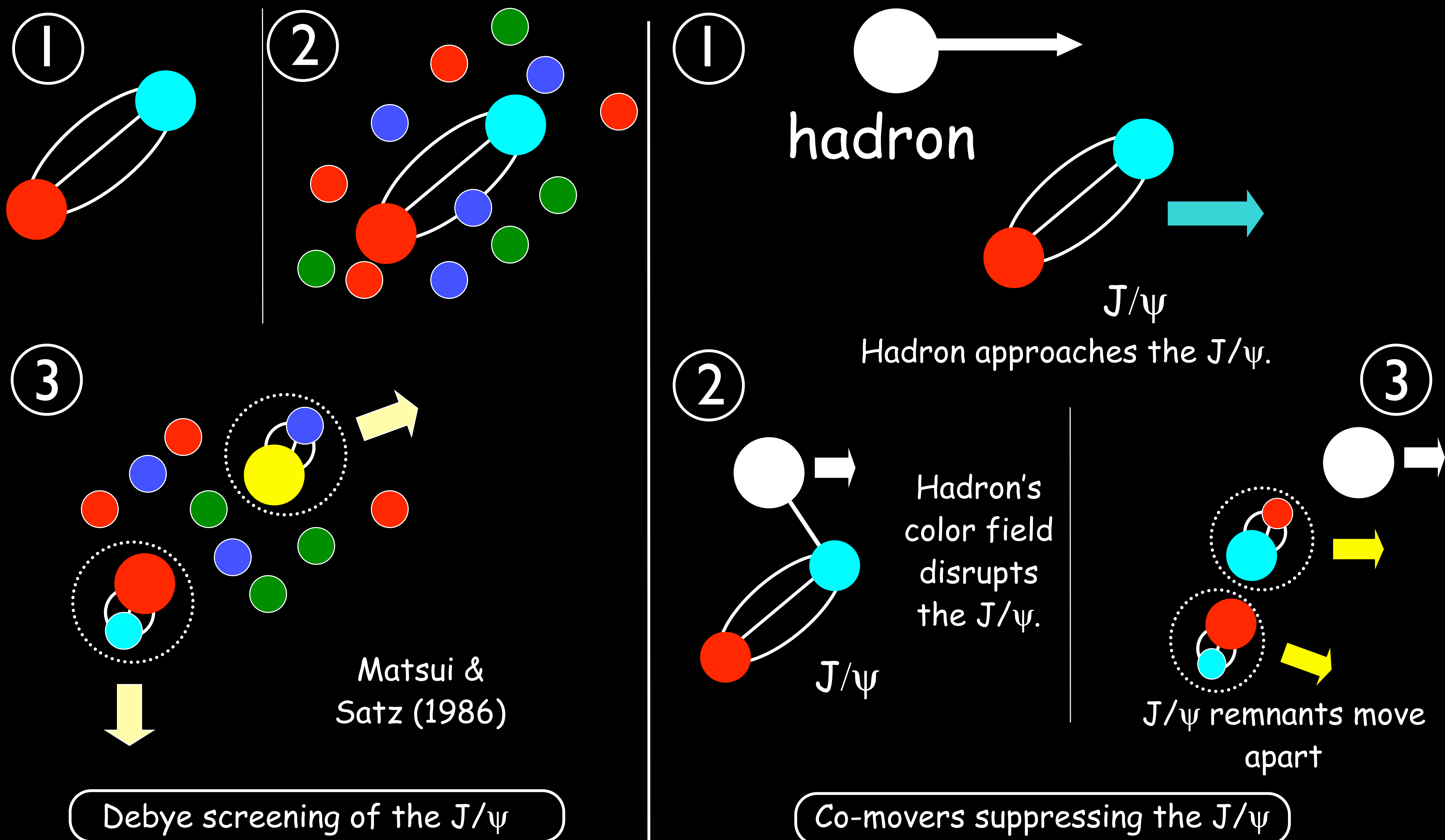
Satz, HP2006

$T_{RHIC} > T_{melt}(\chi_c)\,,\ T_{melt}(\Psi')\ ,\ T_{melt}(\Upsilon(3S))$

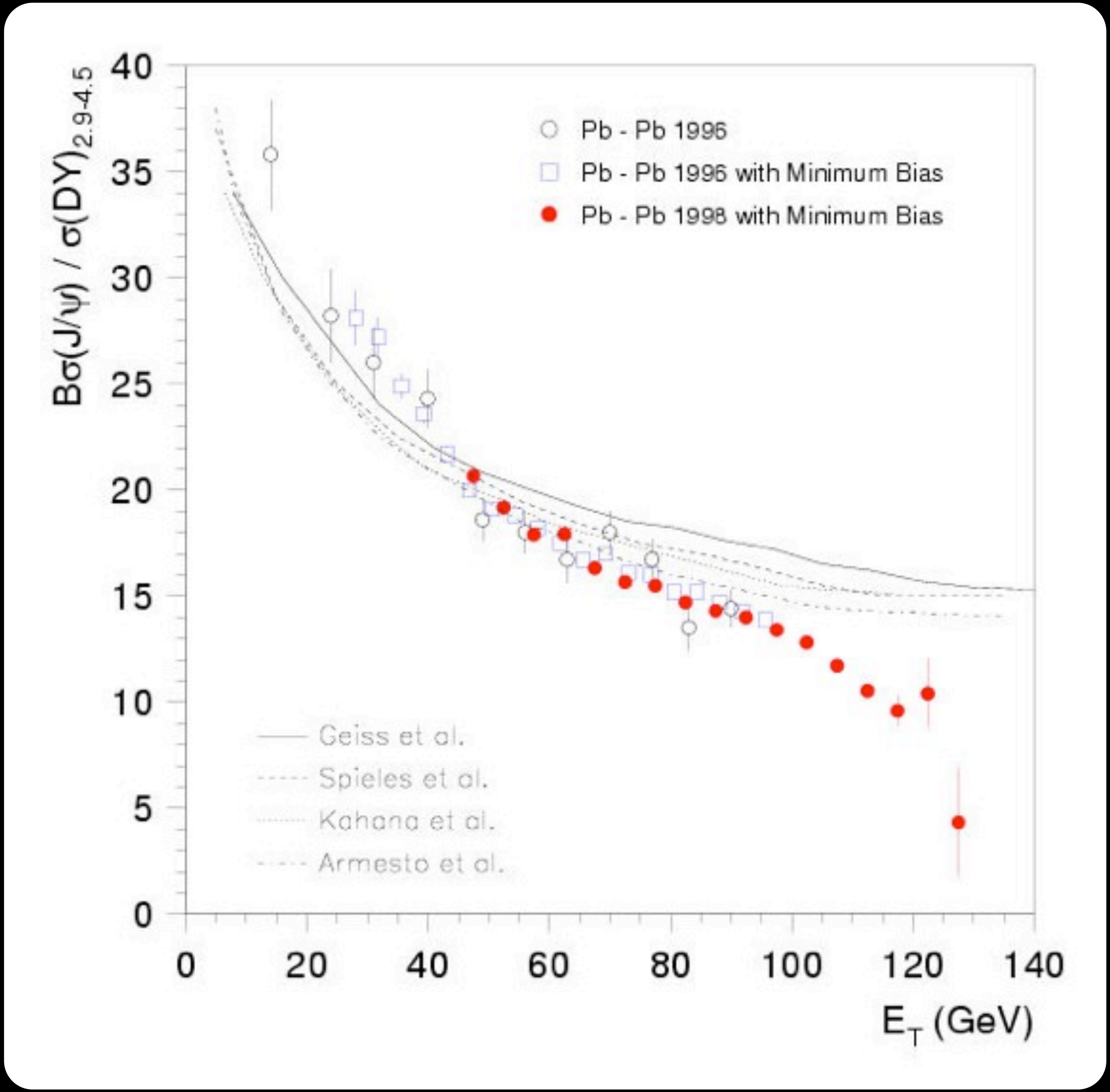
$T_{LHC} > T_{melt}(J/\Psi)\ ,\ T_{melt}(\chi_b)\ ,\ T_{melt}(\Upsilon(2S))$

$T_{melt}(\Psi') < T_{melt}(\Upsilon(3S)) < T_{melt}(J/\Psi) \approx T_{melt}(\Upsilon(2S)) < T_{RHIC} < T_{melt}(\Upsilon(1S))$?

Sources of J/Ψ suppression

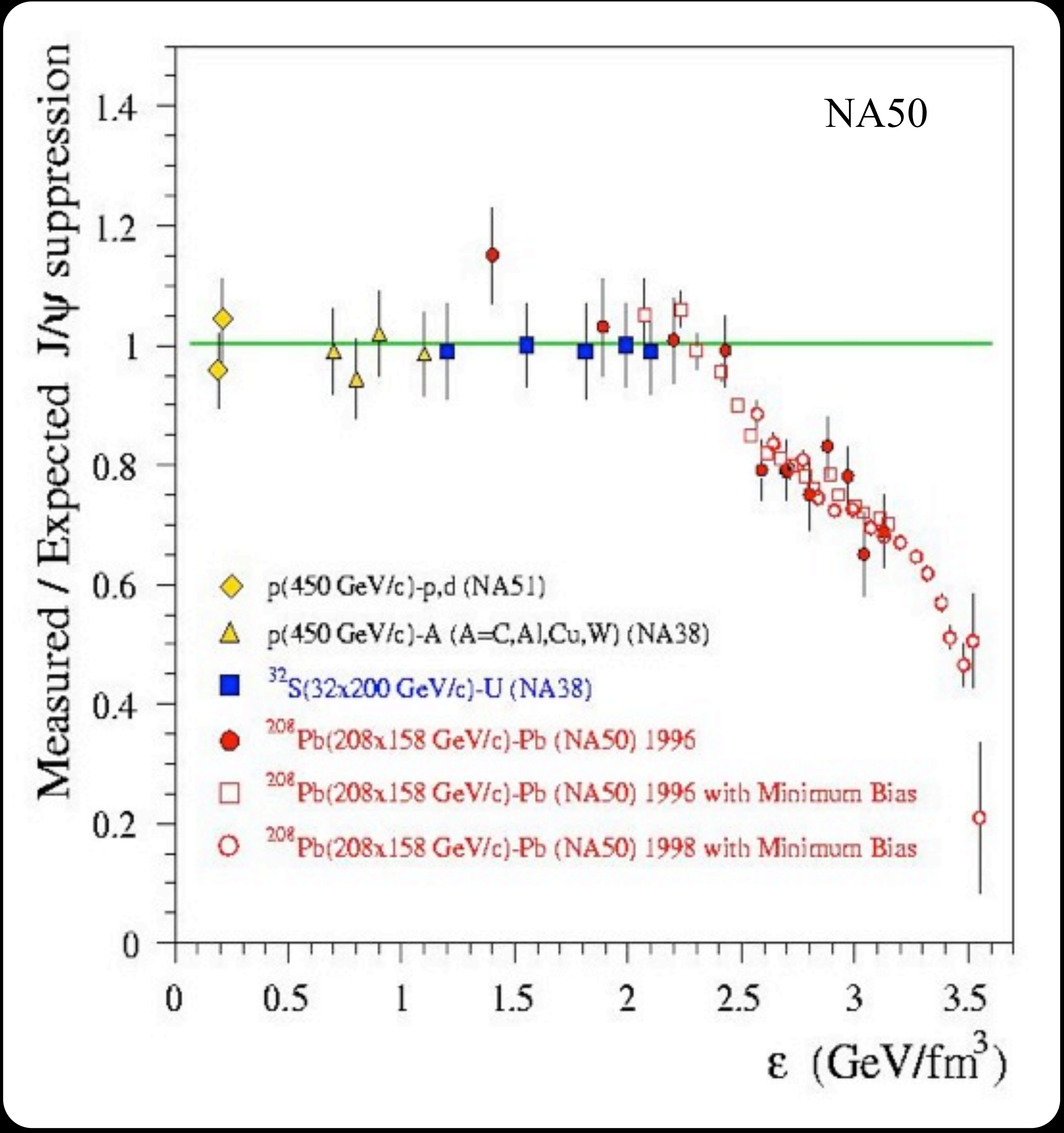


Hadronic J/Ψ dissociation



- before
  - before the J/ψ formation
  - color-octet precursor interacts strongly, even with cold nuclear matter
  - gives rise to the observed A-dependence: $\sigma \sim A^{0.92}$
- during
  - while the J/ψ is in the nuclear medium
  - this is the Debye screening signature of Matusi and Satz
- after
  - as the hadrons escape the collision zone
  - co-movers can disrupt or destroy J/ψ's after they have exited the nuclear medium

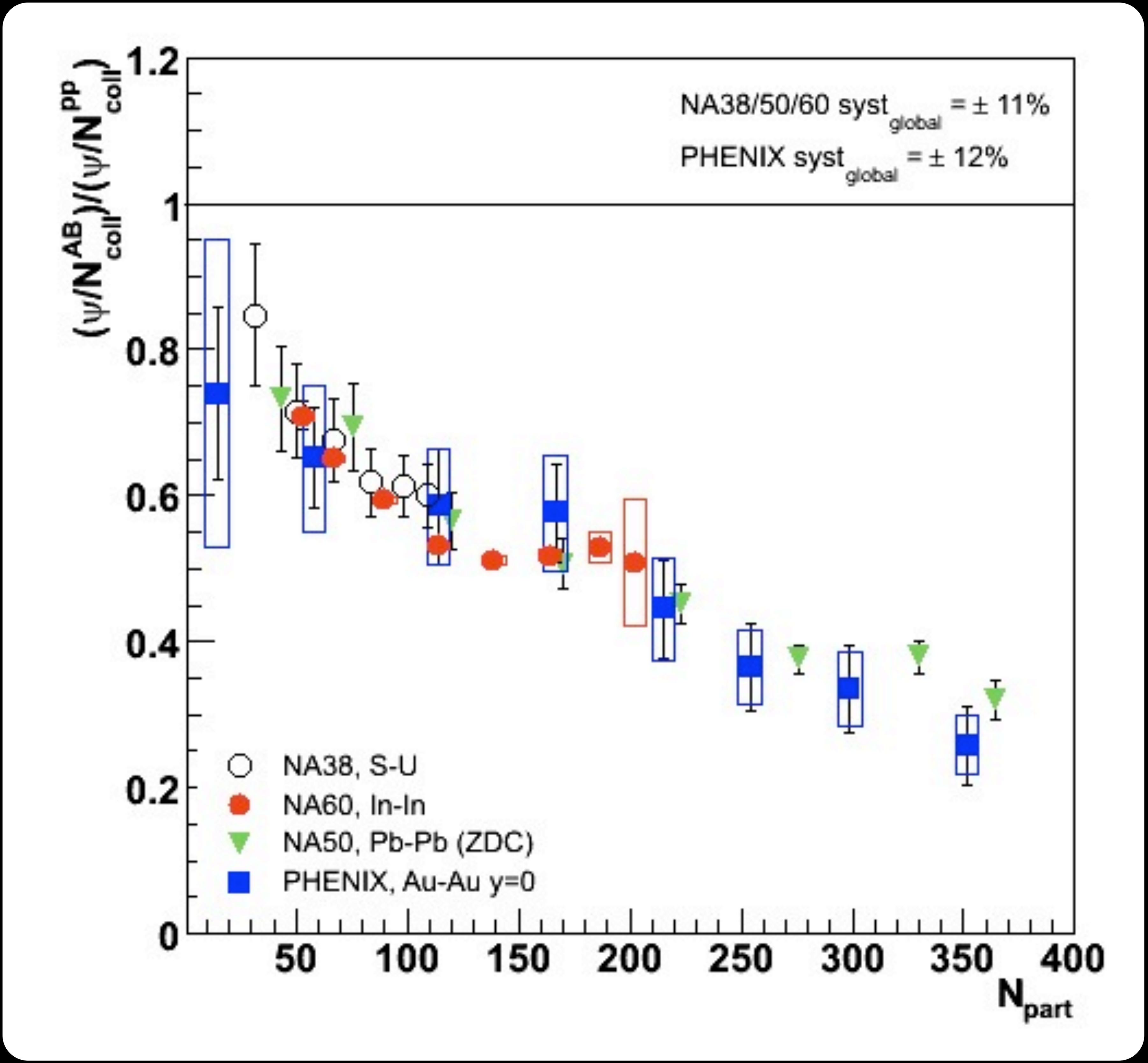
The J/Ψ measurement at the SPS



- measured/expected J/Ψ suppression versus estimated energy density
  - anomalous suppression sets in at ε~ 2.3 GeV/fm^3
  - double step was initially interpreted as successive melting of the χ_C and of the J/Ψ

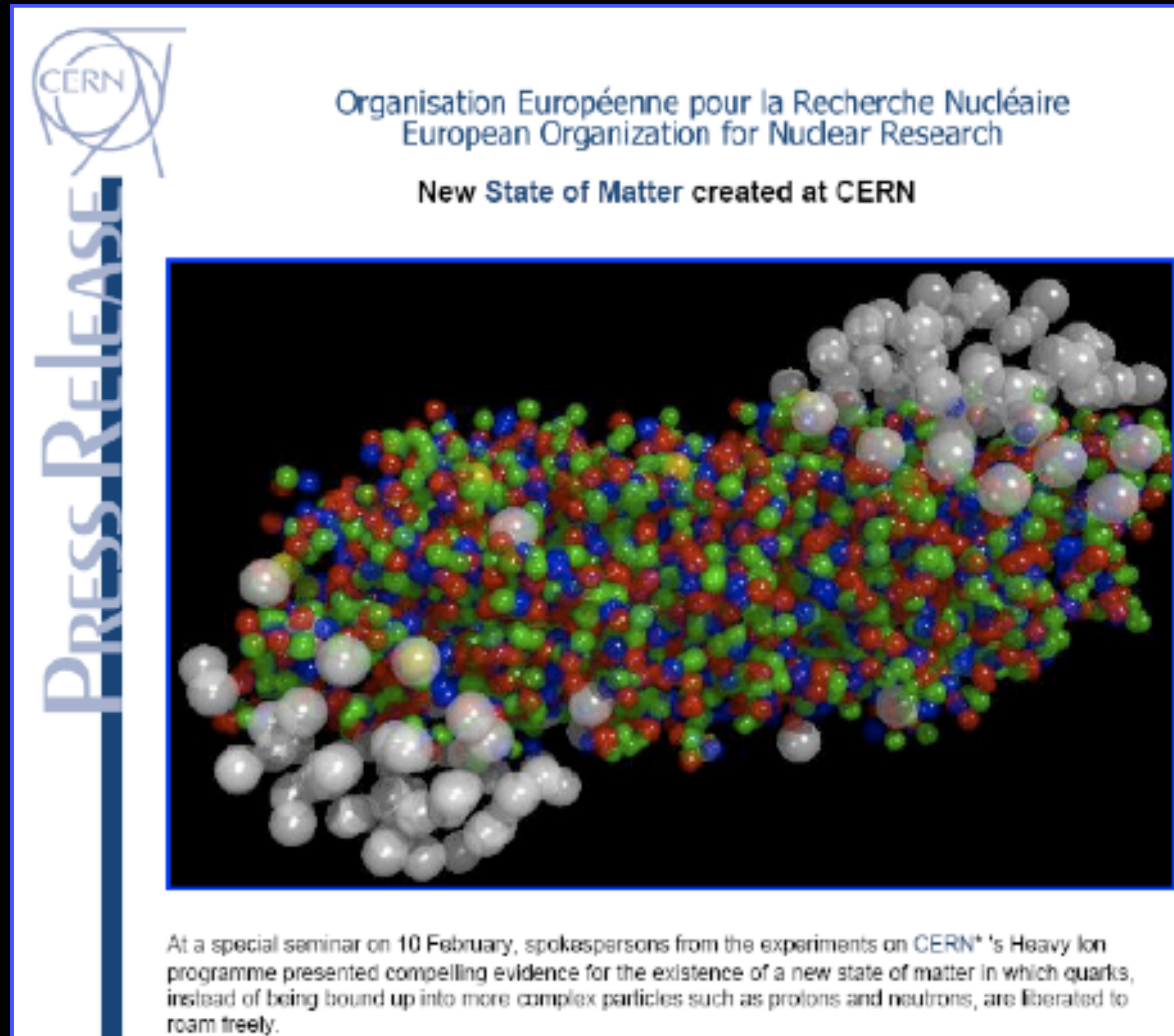
The J/Ψ measurement at RHIC

- suppression pattern almost the same as at the SPS???
- J/Ψ production at RHIC is more complicated due to possible contributions from coalescence
- matching energy dependence is a challenge to theory!



From SPS, RHIC to the LHC

- SPS
  - observed many of the signatures predicted for QGP formation
  - CERN announced a new state of matter



CERN

Press Release

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

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.

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 pervaded the first microseconds of existence.

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 moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

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

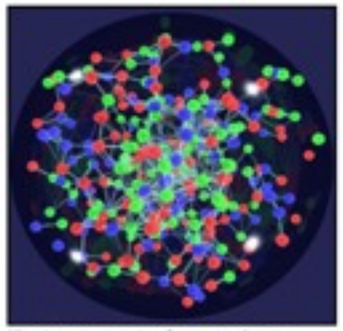
Image: BNL

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 patterns of the atoms' trajectories after these collisions, they found that the particles produced in the collisions tended to move collectively, much like a school of fish does. Brookhaven's associate laboratory director for high energy and nuclear physics, Sam Aronson, remarks that "the degree of collective interaction, rapid thermalization and extremely low viscosity of the matter being formed at RHIC make this the most nearly perfect liquid ever observed."

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 that is more strongly interacting than predicted

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 perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Thanks