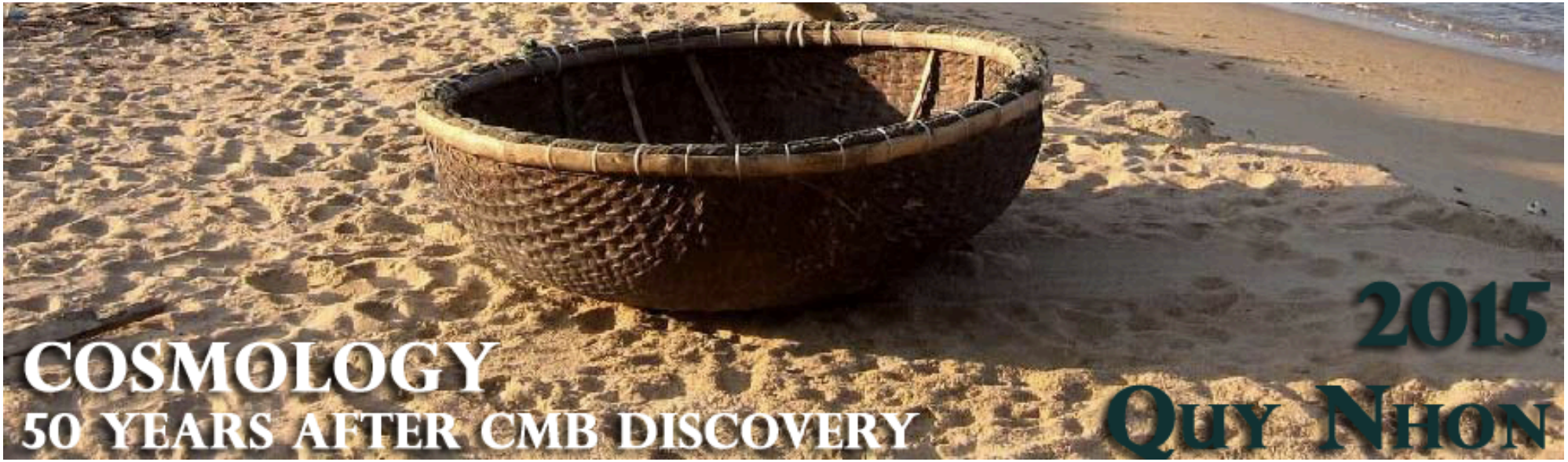


Quark-gluon plasma: from accelerator experiments to early Universe

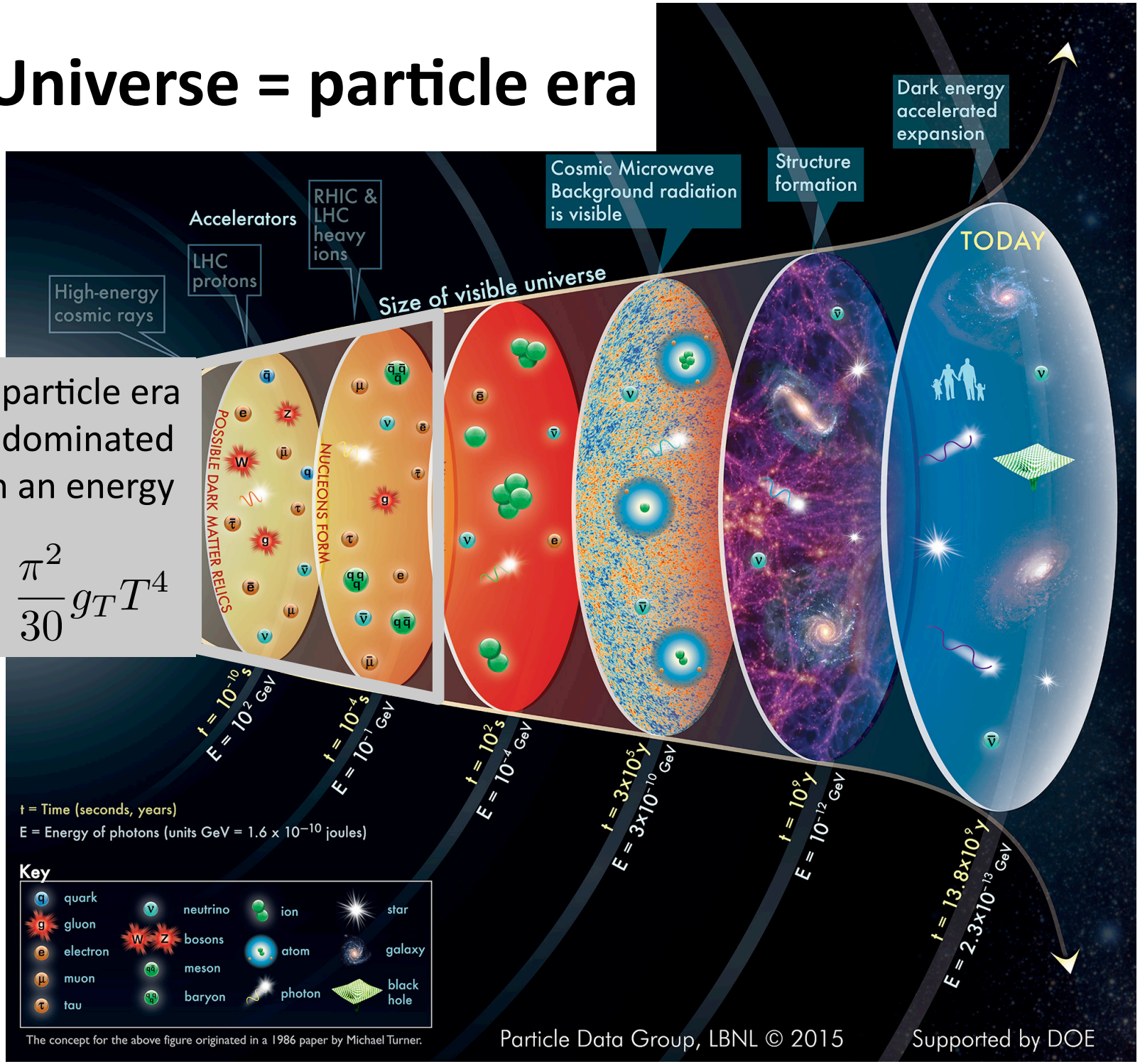
Philippe Rosnet
Laboratoire de Physique Corpusculaire
Université Blaise Pascal – CNRS/IN2P3

Member of the ALICE Collaboration

Early Universe = particle era

Ultra-relativistic particle era means Universe dominated by radiation with an energy density

$$\epsilon_{\rm rad} = \frac{\pi^2}{30} g_T T^4$$

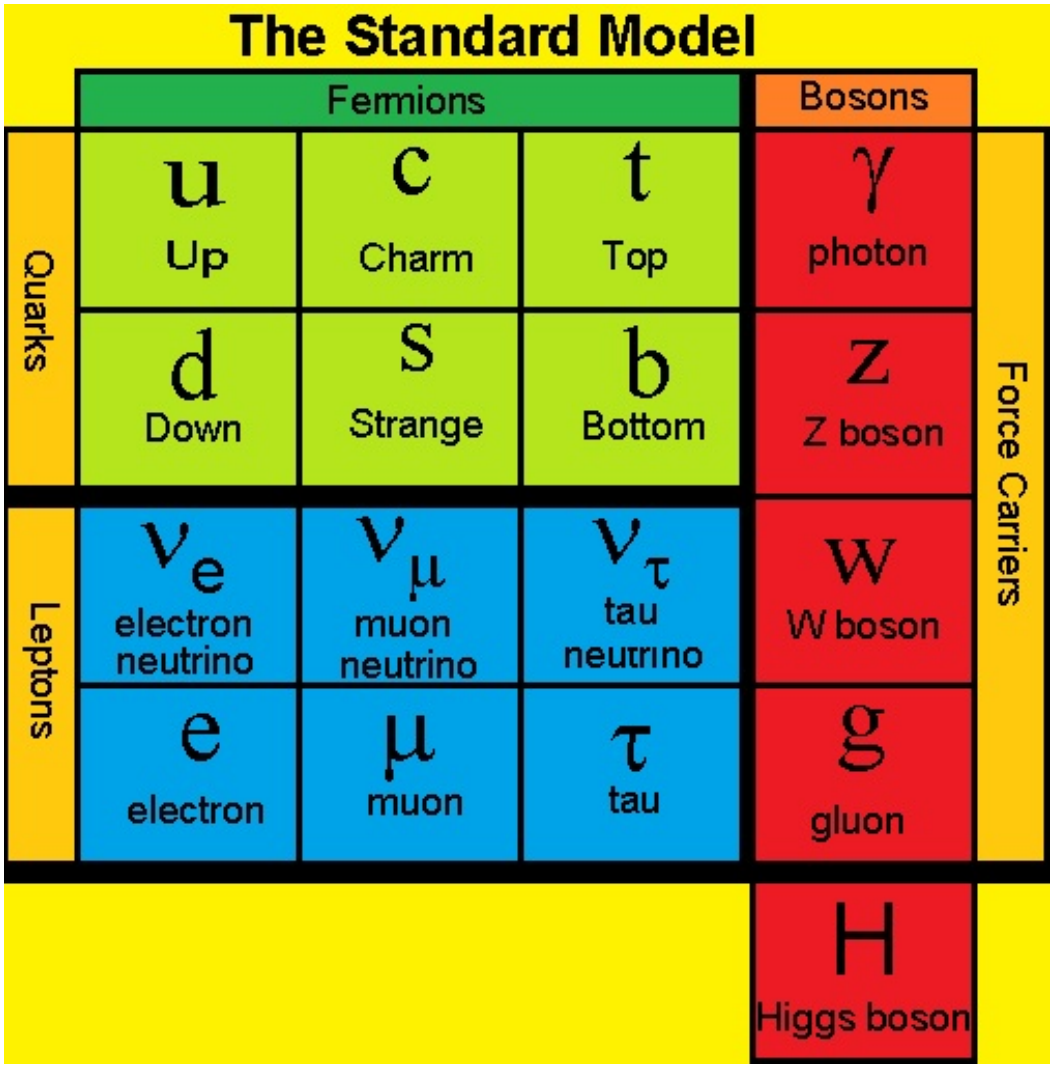


The Standard Model of particle physics

Fermions: spin ½

Quarks: 3 colours

Neutrinos: only left-handed state



Gauge bosons: spin 1

Gluons: 8 colour states

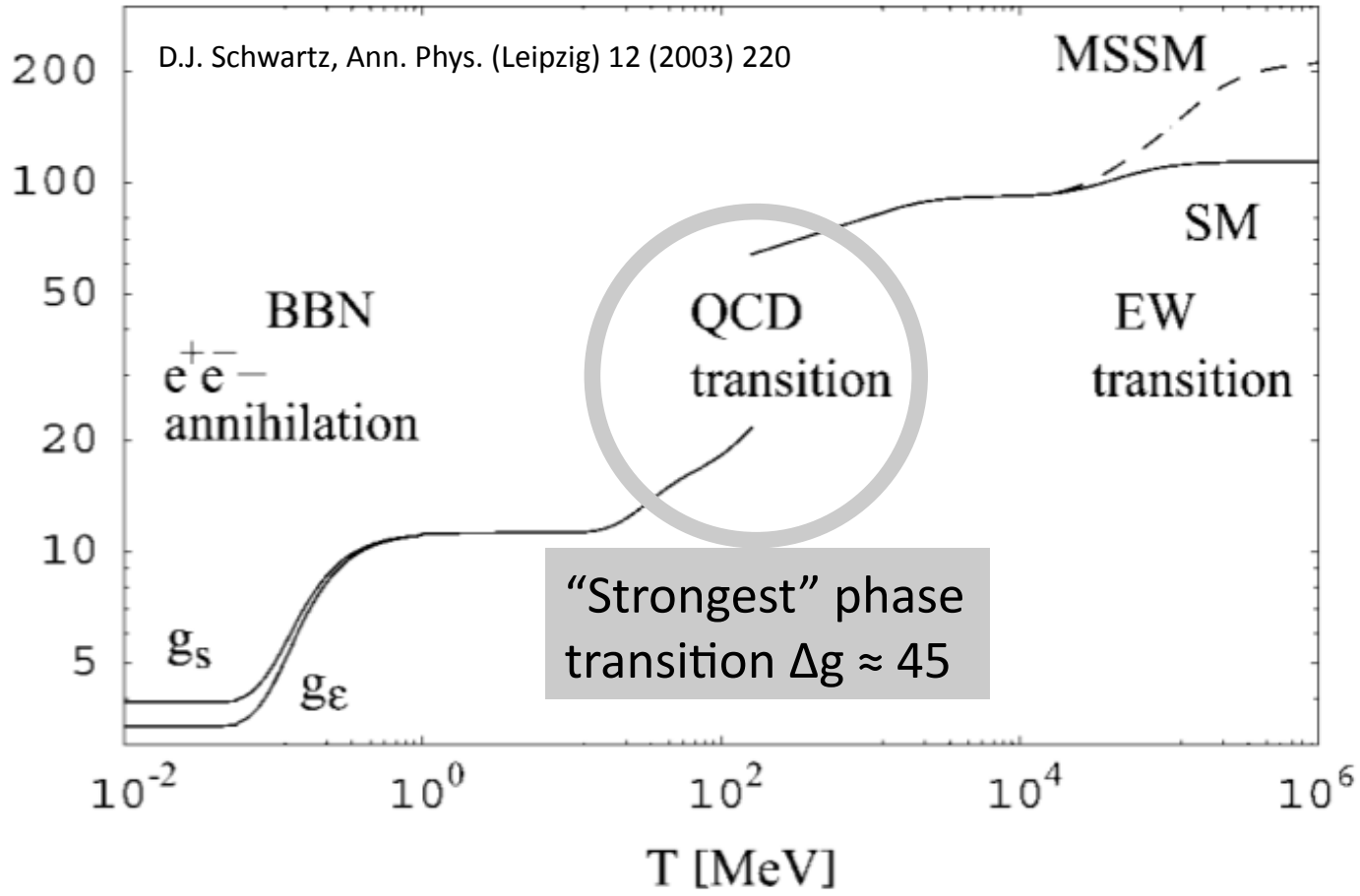
Higgs boson: spin 0

+ anti-fermions

Degrees of freedom in Standard Model era

Counting degrees of freedom in Standard Model ($T >> m_{top} = 173$ GeV)

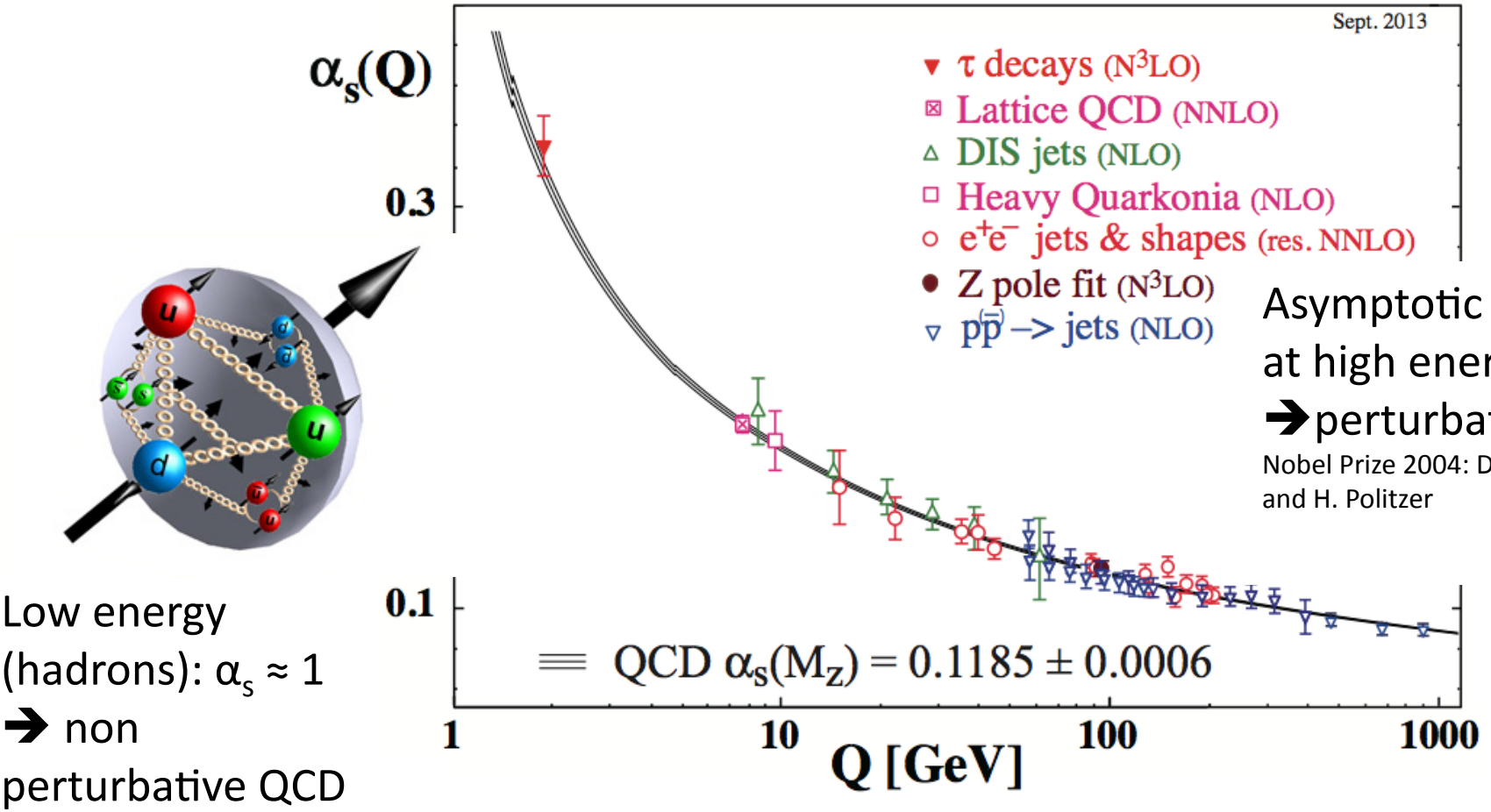
- $g_{boson} = 4_{Higgs} + 4_{EW\ boson} \times 2_{massless\ spin\ 1} + 8_{gluon} \times 2_{massless\ spin\ 1} = 28$
- $g_{fermion} = 2_{(anti\text{-})particle} \times 3_{family} \times (2_{quark} \times 3_{color} \times 2_{spin\ ½} + 1_{l\text{-}} \times 2_{spin\ ½} + 1_{\nu} \times 1_{Left}) = 90$
- $g_{SM} = g_{boson} + (7/8)_{massless} \times g_{fermion} \approx 107$



Quarks, gluons and asymptotic freedom

Quantum ChromoDynamics (QCD) = theory of quark-gluon and gluon-gluon interactions characterized by the strong coupling constant α_s

Review of particle physics Chin. Phys. C 38, (2014) 090001



Low energy (hadrons): $\alpha_s \approx 1$
➔ non perturbative QCD

Asymptotic freedom at high energy: $\alpha_s << 1$
➔perturbative QCD

Nobel Prize 2004: D. Gross, F. Wilczek and H. Politzer

QCD phase diagram

- Prediction of unconfined state

[N. Cabibbo and G. Parisi, Phys. Lett. B 59 (1975) 67]

- Superdense matter in neutron core

[J.C. Collins and M.J. Perry, Phys. Rev. Lett. 34 (1975) 1353]

- State called Quark-Gluon Plasma (QGP)

[E. Shuryak, Phys. Lett. B 78 (1978) 150]

N. Cabibbo and G. Parisi, Phys. Lett. B 59 (1975) 67

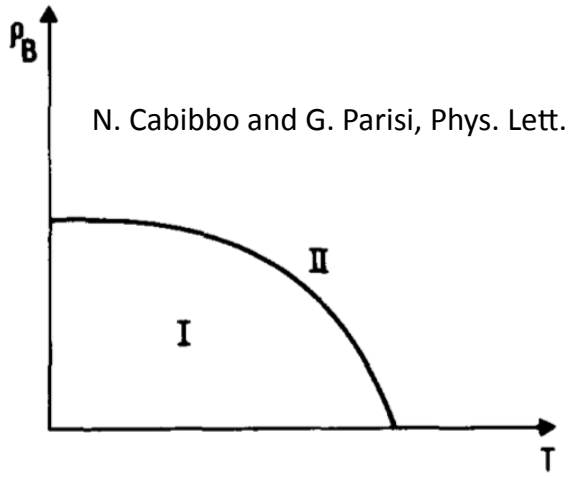
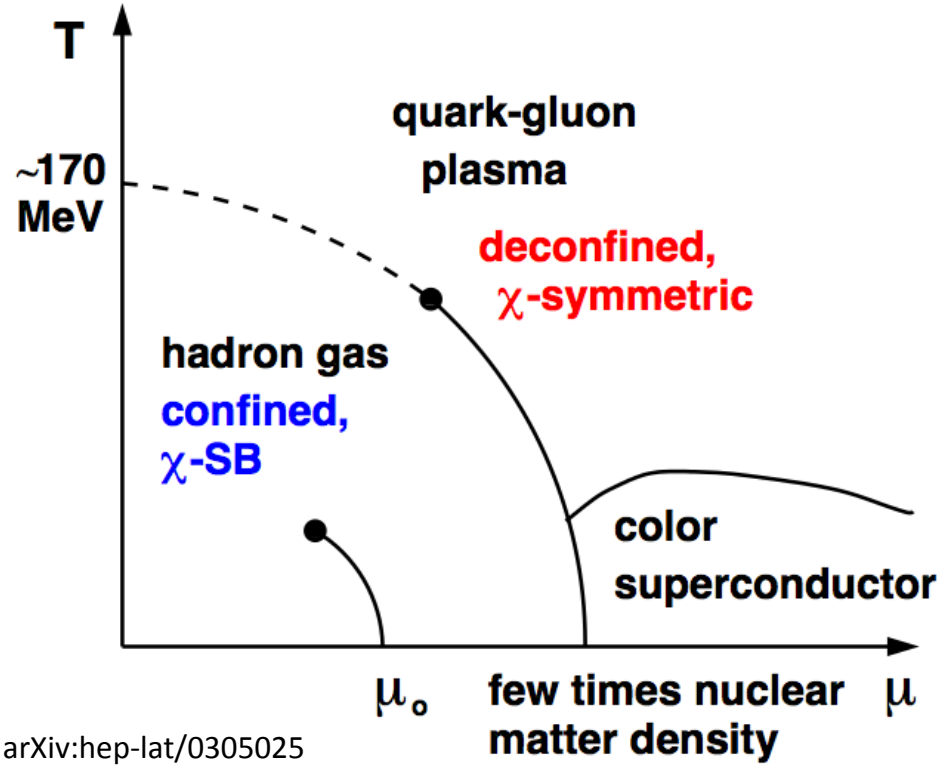


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Modern view of QCD phase diagram by lattice QCD (lQCD):

- first order transition at high net baryon density ρ_B (or high baryon chemical potential μ_B)
- critical point
- cross-over transition at zero net baryon density



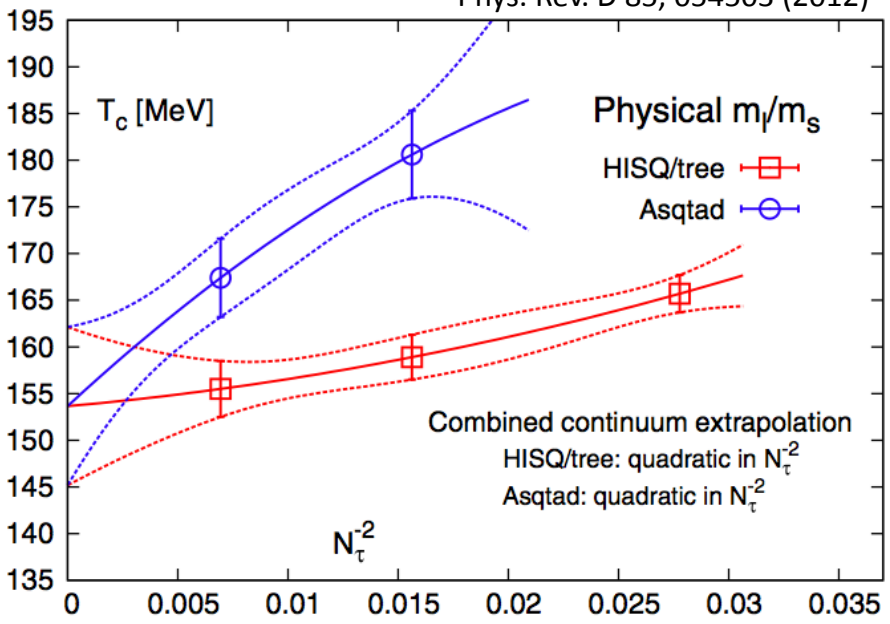
F. Karsch and E. Laermann, arXiv:hep-lat/0305025

Thermodynamics of lattice QCD

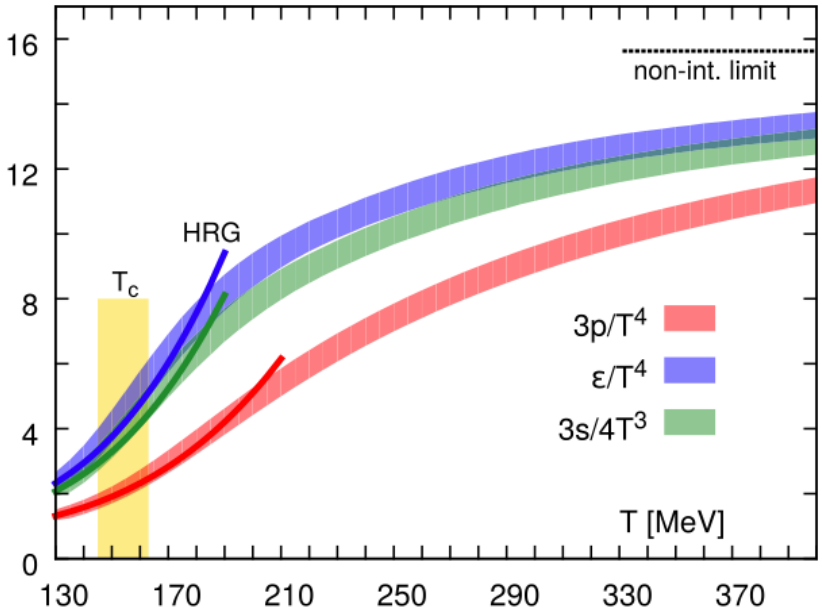
Transition temperature at zero net baryon density with lattice QCD calculation extrapolated to continuum limit

$$T_{QCD} = 154 \pm 9 \text{ MeV}$$
$$\approx 1.8 \times 10^{12} \text{ K}$$

Phys. Rev. D 85, 054503 (2012)



Phys. Rev. D 90, 094503 (2014)



Corresponding energy density at transition

$\varepsilon_c = (0.18–0.5)$ GeV/fm^3

$$\frac{3P}{T^4} \neq \frac{\epsilon}{T^4}$$

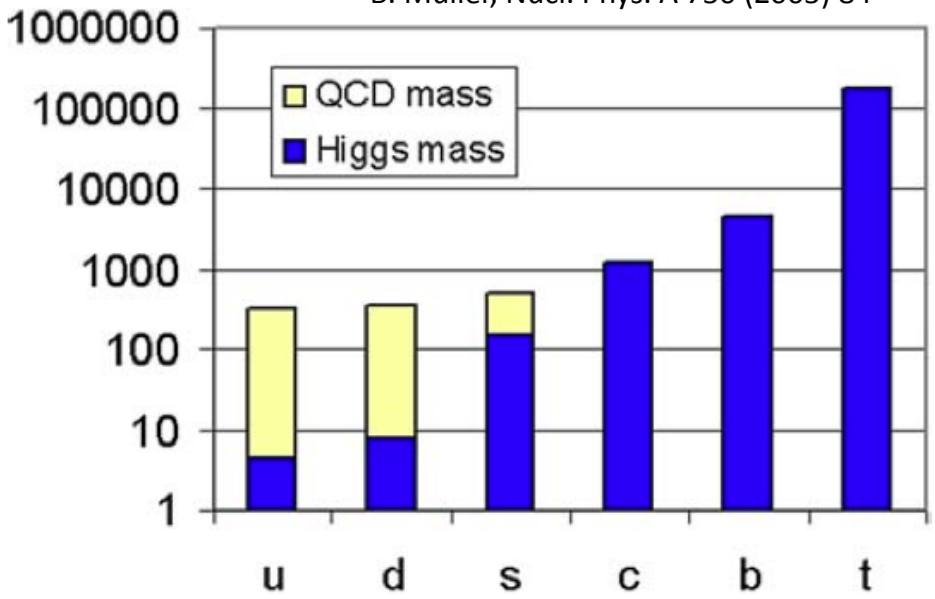
QCD equation of state (EoS) ≠ Radiation EoS

Result of QCD phase transition

What happen to quark and gluon degrees of freedom?

- QCD quark mass generation for hadron production due to spontaneous chiral symmetry breaking (quark and gluon condensates): proton, neutron, pions…

B. Müller, Nucl. Phys. A 750 (2005) 84



- "Radiation" hadronic degrees of freedom: mainly pions decaying in a short time scale
  - $\pi^0 \rightarrow 2\gamma$ with $\tau_{\pi 0} \approx 10^{-16}$ s
  - $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ with $\tau_{\pi\pm} \approx 10^{-8}$ s

Friedman equation radiation-dominant

Link to dynamical Friedmann equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\mathcal{G}}{3}\rho_{\mathrm{rad}} \quad \text{with} \quad \rho_{\mathrm{rad}} = \frac{\epsilon_{\mathrm{rad}}}{c^2}$$

giving $$t_{[\mathrm{s}]} = \frac{1}{2H} = \frac{2.42}{\sqrt{g_T}(T_{[\mathrm{MeV}]})^2}$$

QCD phase transition timing assuming a temperature transition T_{QCD} = 154 MeV

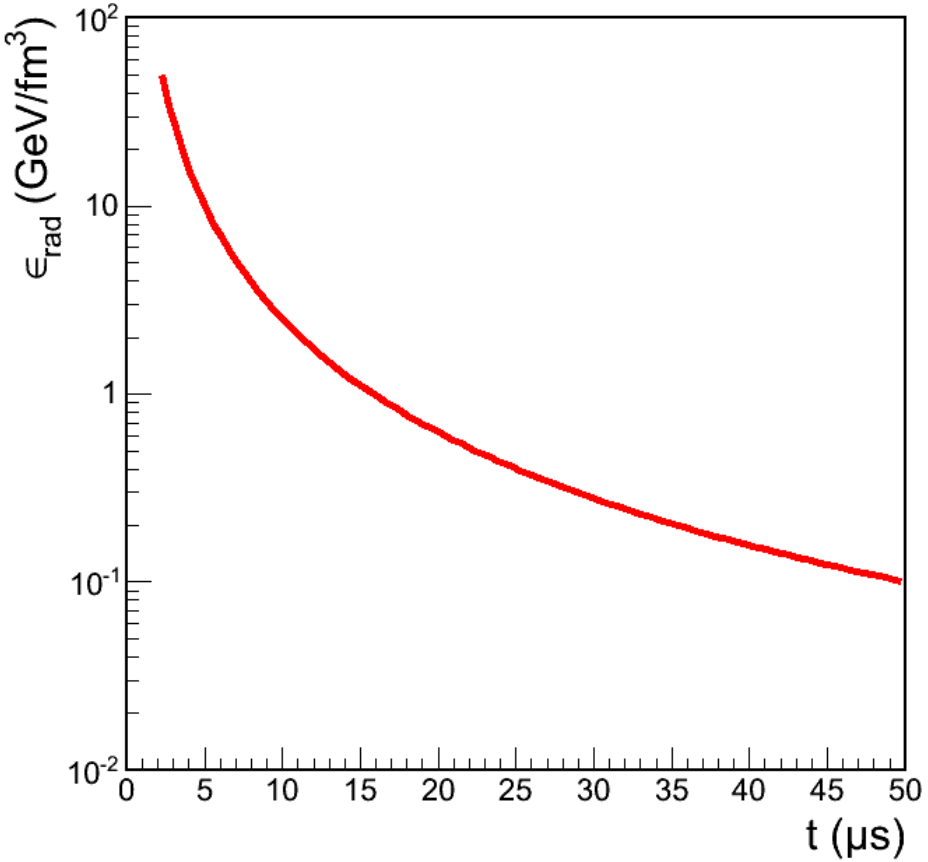
	$g_{photon\ (+\ qluons\ or\ pions)}$	$g_{leptons\ (+\ 3\ quarks)}$	g_{tot}	t
Transition starting point	18	50	≈ 62	13 µs
Transition end point	5	14	≈ 17	25 µs

$\Delta t_{QCD} \approx 12$ µs

QCD 1st order phase transition in expanding Universe

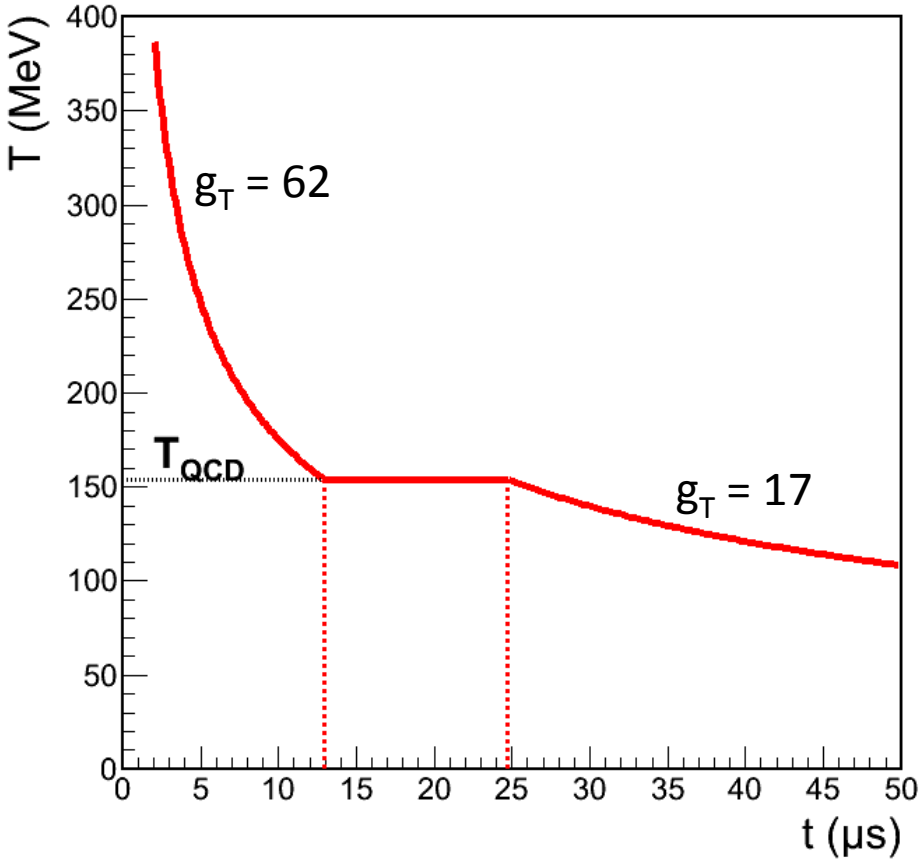
Evolution of radiation energy density at QCD phase transition

$$\epsilon_{\mathrm{rad}\ [\mathrm{MeV/fm^3}]} = \frac{\pi^2}{90}\frac{1}{(\hbar c)^3}\left(\frac{2.42}{t}\right)^2$$



Evolution of temperature at QCD phase transition

$$T_{[\mathrm{MeV}]} = \left(\frac{2.42}{\sqrt{g_T}\,t}\right)^{1/2}$$



QCD bag model phase transition

The bag model considers free massless quarks and gluons bound by a negative pressure called the bag constant *B* ➔ Bag EoS

$T > T_{\mathrm{QCD}}$: QGP state

$$\epsilon_{\mathrm{QGP}} = g_T \frac{\pi^2}{30} T^4 + B$$

$$P_{\mathrm{QGP}} = g_T \frac{\pi^2}{90} T^4 - B$$

$T = T_{\mathrm{QCD}}$: Mixed state

$$\epsilon(t) = f(t)\epsilon_{HG} + [1 - f(t)]\epsilon_{QGP}$$

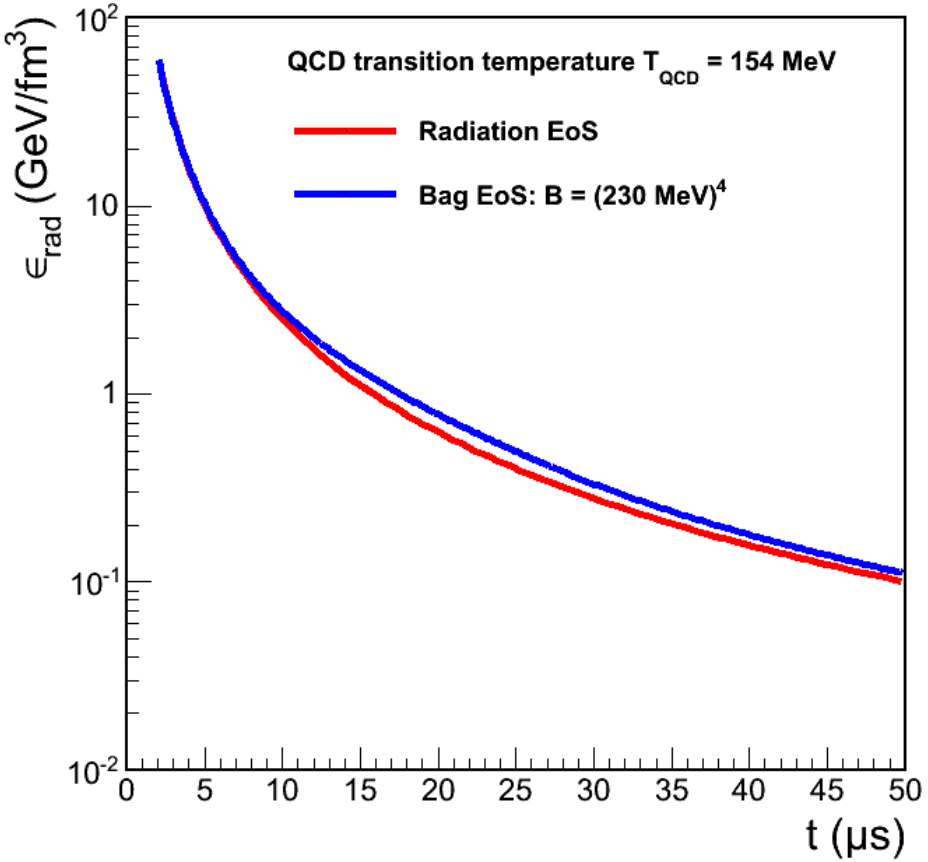
with $0 \leq f(t) \leq 1$

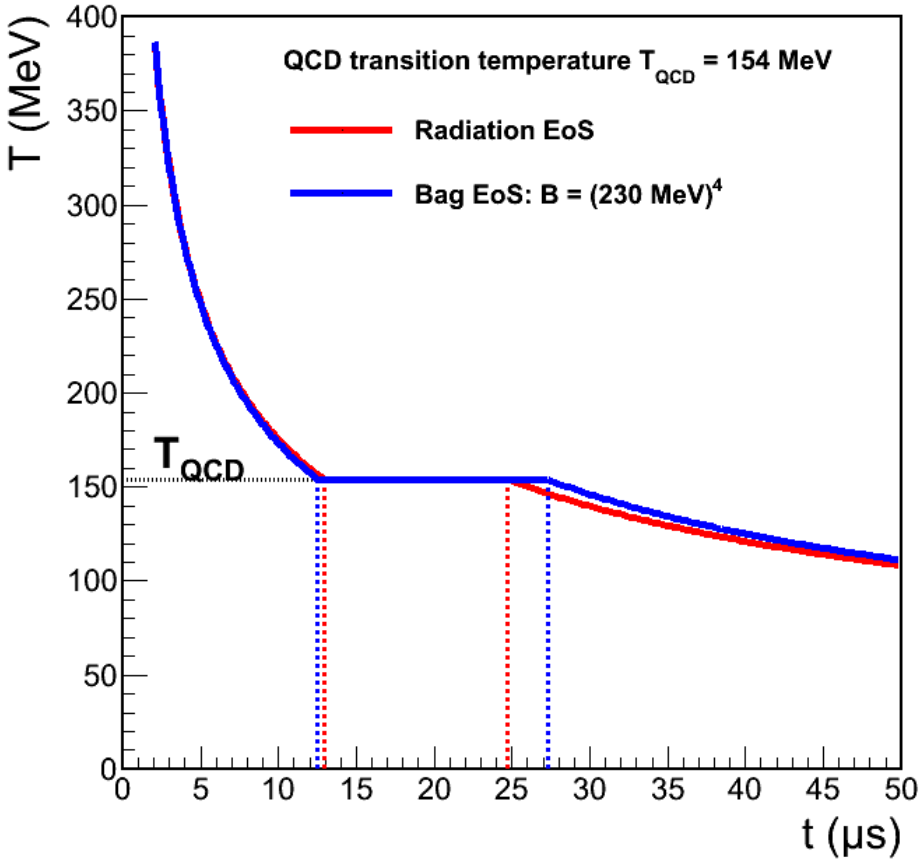
$T < T_{\mathrm{QCD}}$: Hadron Gas

$$\epsilon_{\mathrm{HG}} = g_T \frac{\pi^2}{30} T^4$$

$$P_{\mathrm{HG}} = g_T \frac{\pi^2}{90} T^4$$

K. Yagi, T. Hatsuda and Y. Miake, Camb. Monogr. Part. Phys. Nucl. Phys. 23 (2005)

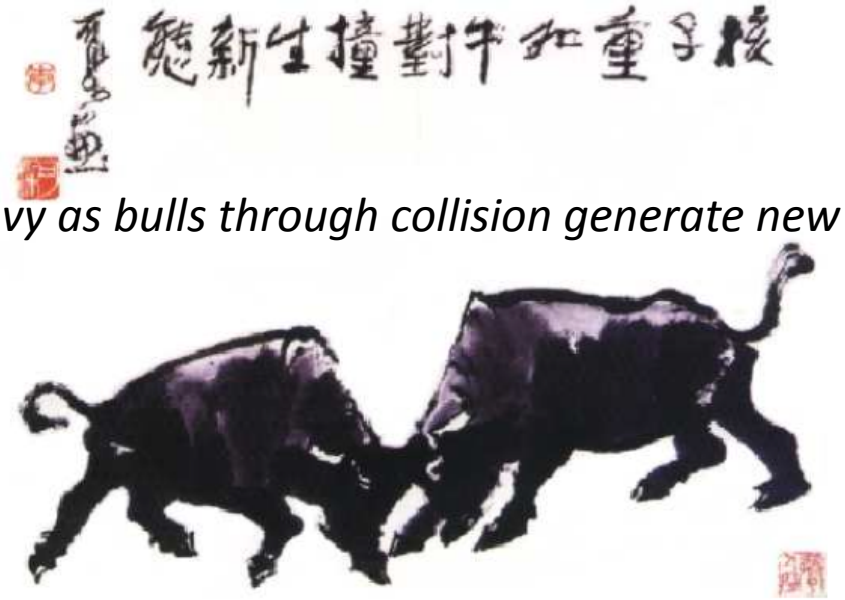




Open question

QCD phase transition can play an important role in the Universe evolution leading to open questions

J. Ellis, astro-ph/0504501

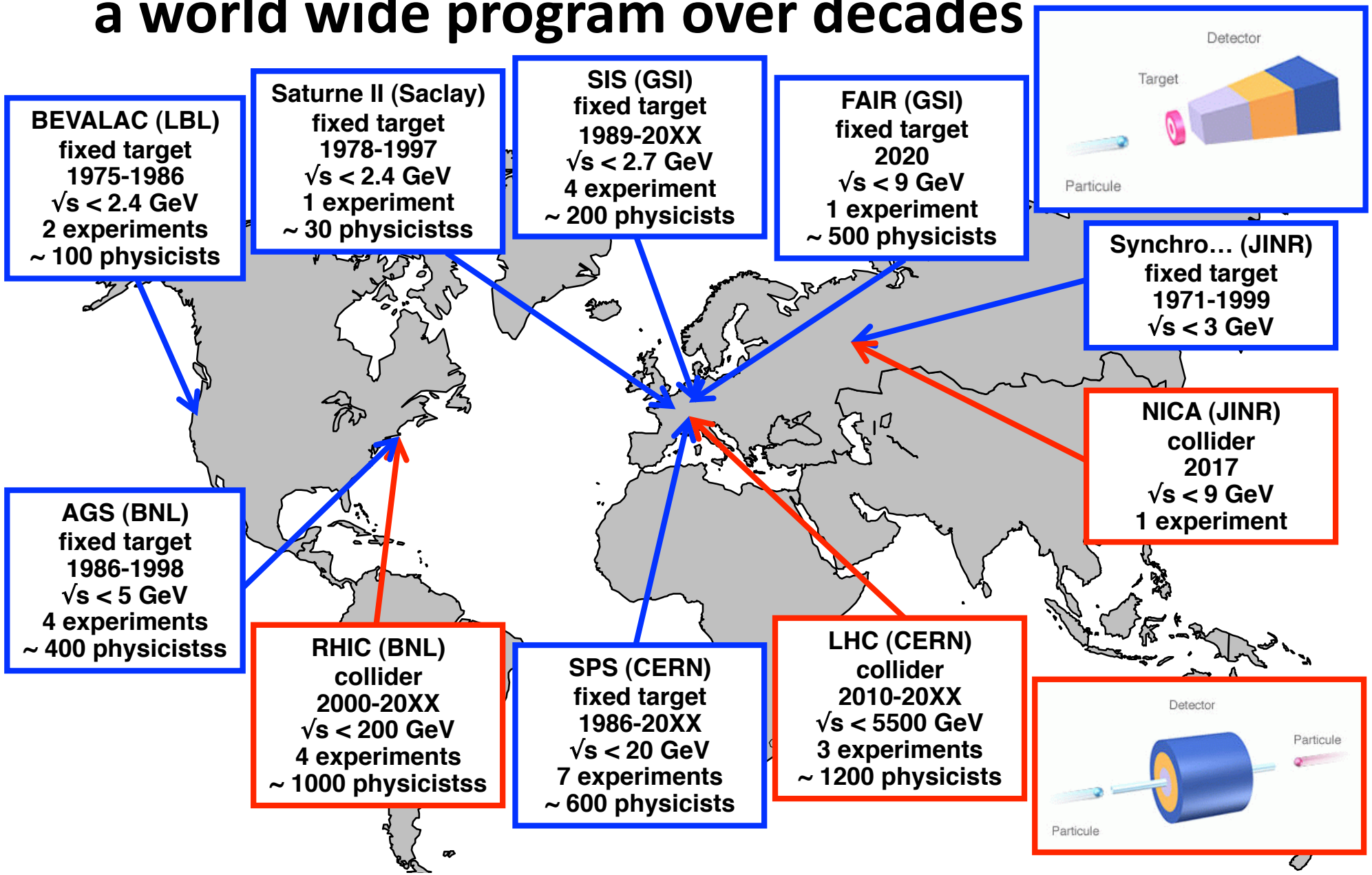


Nuclei as heavy as bulls through collision generate new states of matter.

Li Keran (Chinese painter, 1989)
in H. Satz, arXiv:1207.0341

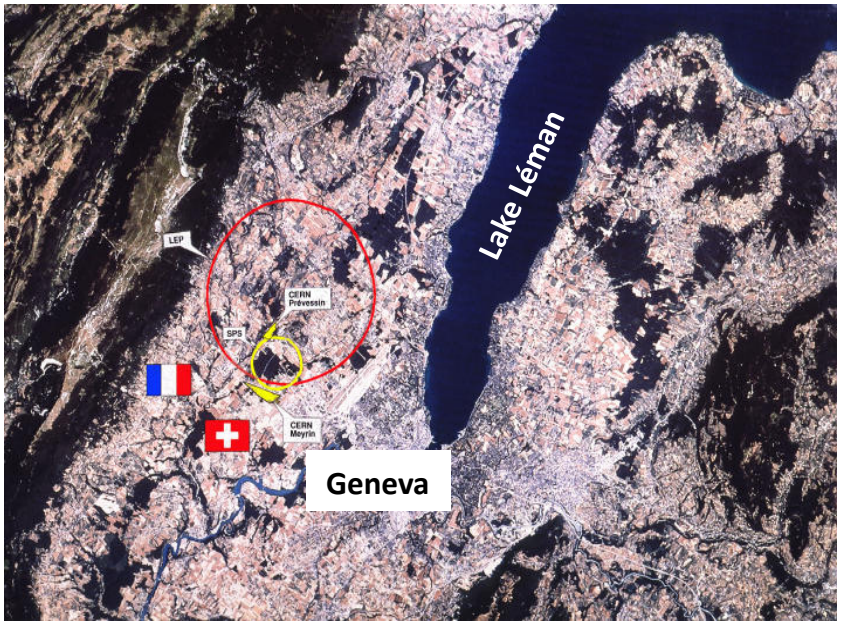
Experimental study of QCD phase transition is achieved by reaching high energy concentration in a tiny volume via **ultra-relativistic heavy-ion collisions**

Quark-Gluon Plasma search and study: a world wide program over decades

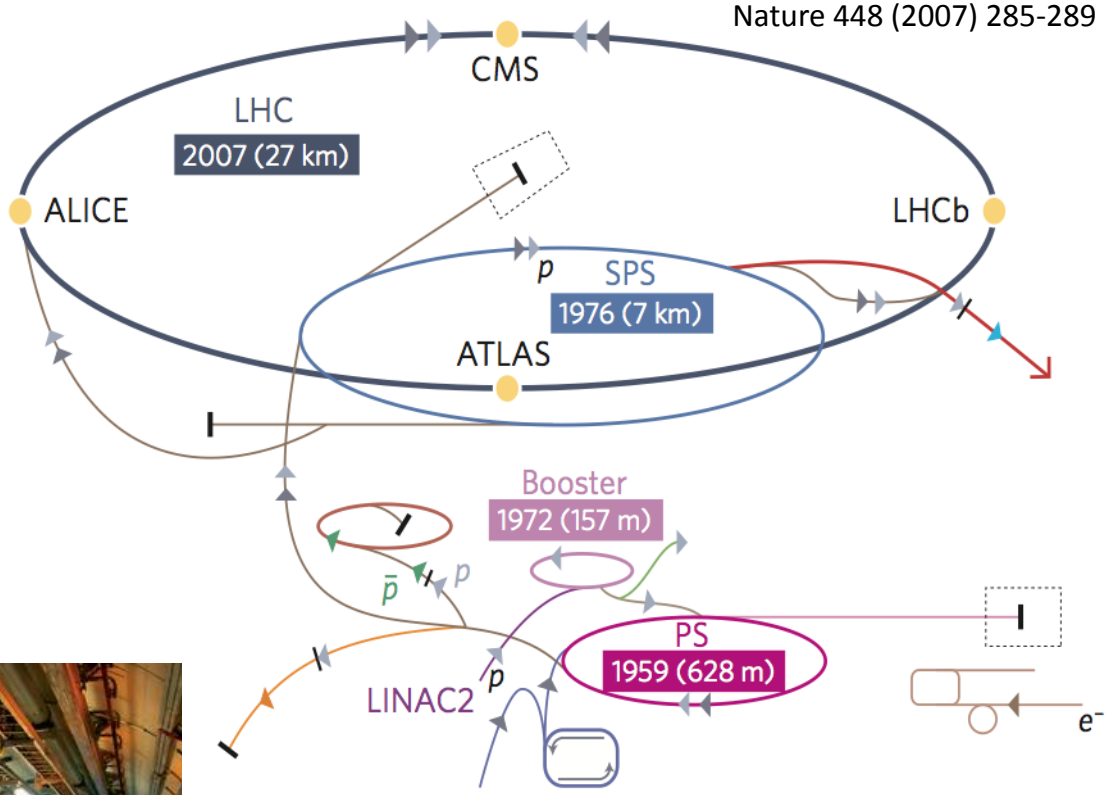


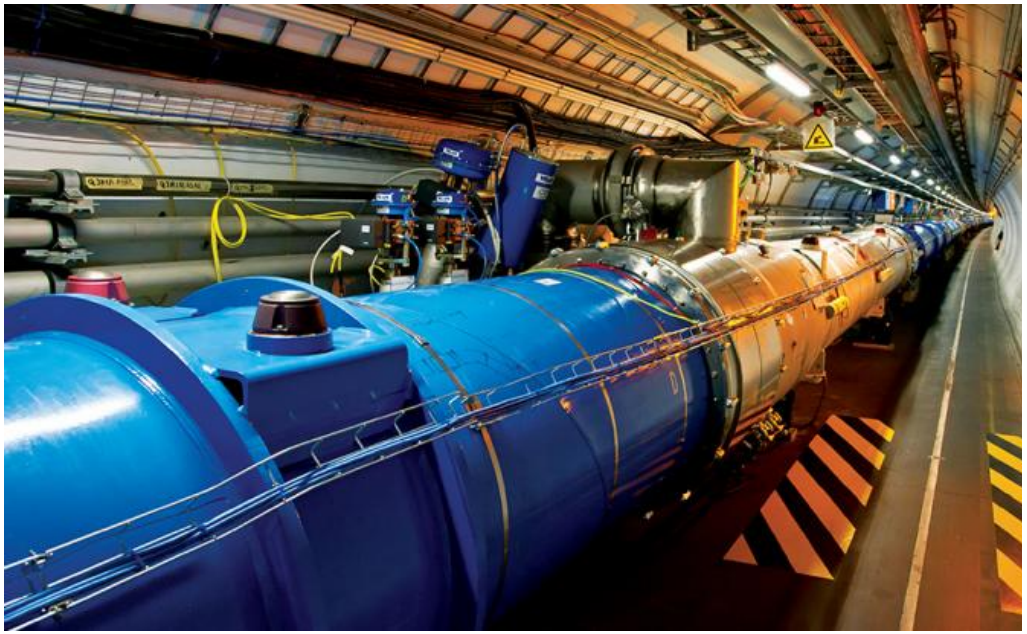
Centre-of-mass nucleon-nucleon energy ($\sqrt{s_{NN}}$) from 3 GeV in 1971 up to 2760 GeV in 2010

The Large Hadron Collider (LHC) at CERN



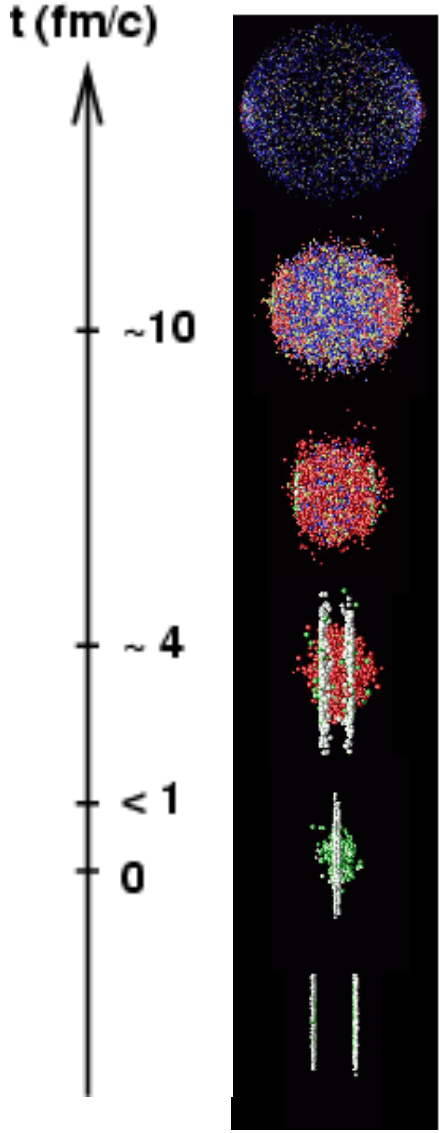
Nature 448 (2007) 285-289



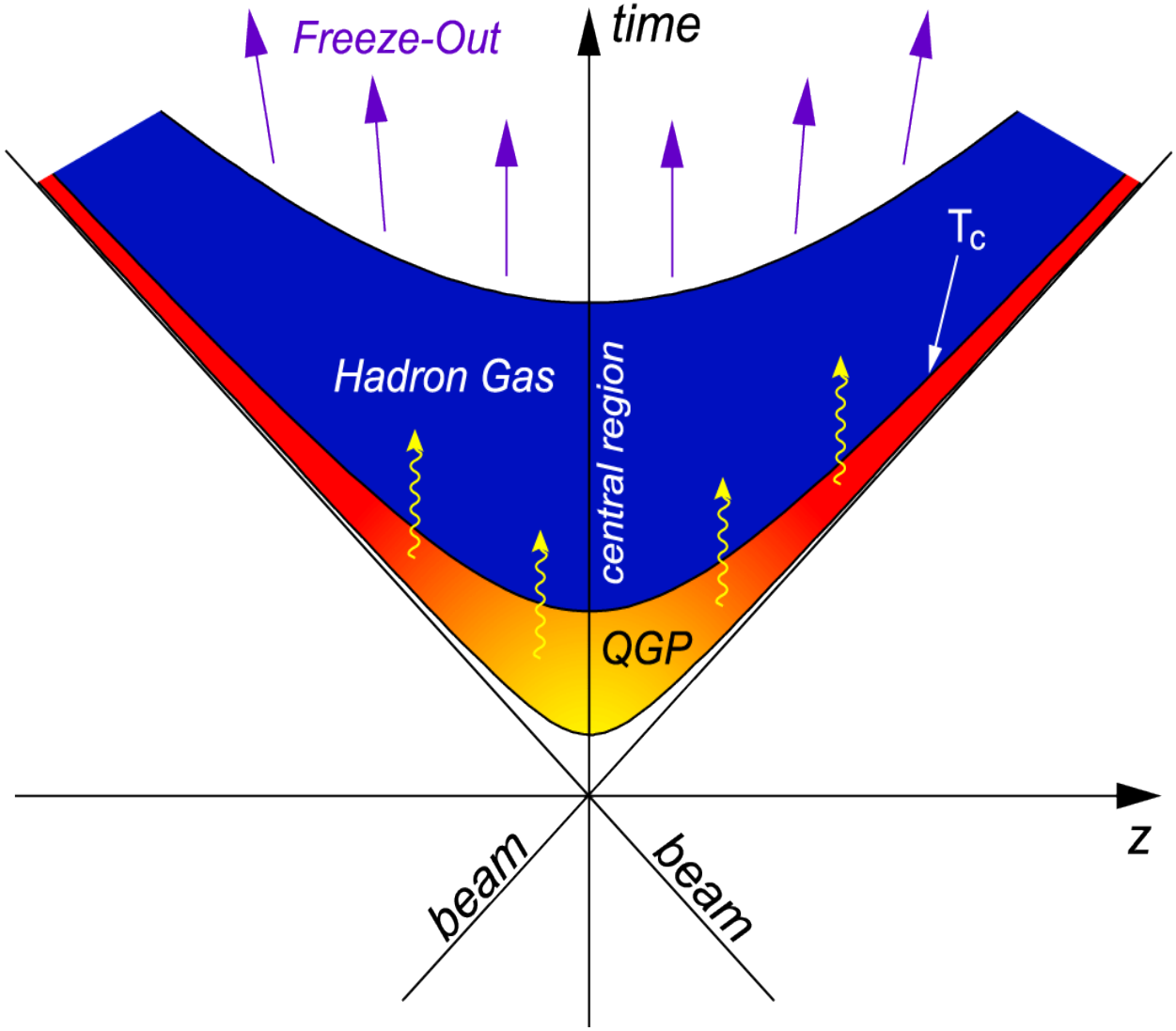


- 27 km superconductor collider
- proton-proton (p-p) collisions at √s = 0.9 to 13 TeV
- proton-lead (p-Pb) and lead-lead (Pb-Pb) collisions with $E_{Pb} = (Z/A)\ E_p$
- 4 multi-detector experiments

What happens in a heavy-ion collision?



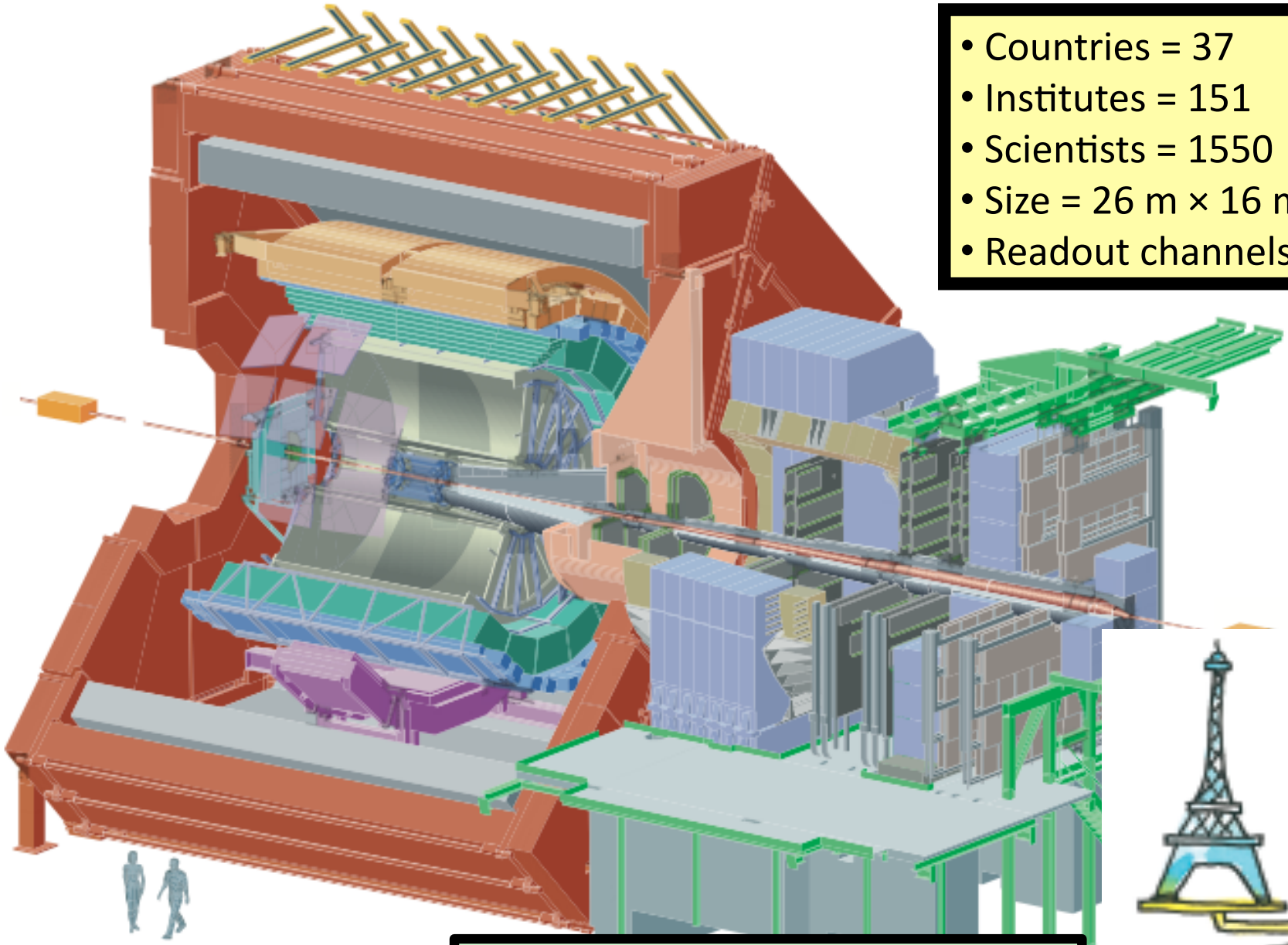
1 fm/c ≈ 3×10^{-24} s



Two nuclei are sent in (frontal) collision at high energy (Lorentz contraction): $d = d_0/\gamma$ with $\gamma = 1468$ at LHC (run 1)

ALICE: A Large Ion Collider Experiment

- Countries = 37
- Institutes = 151
- Scientists = 1550
- Size = 26 m × 16 m
- Readout channels = 16×10^6

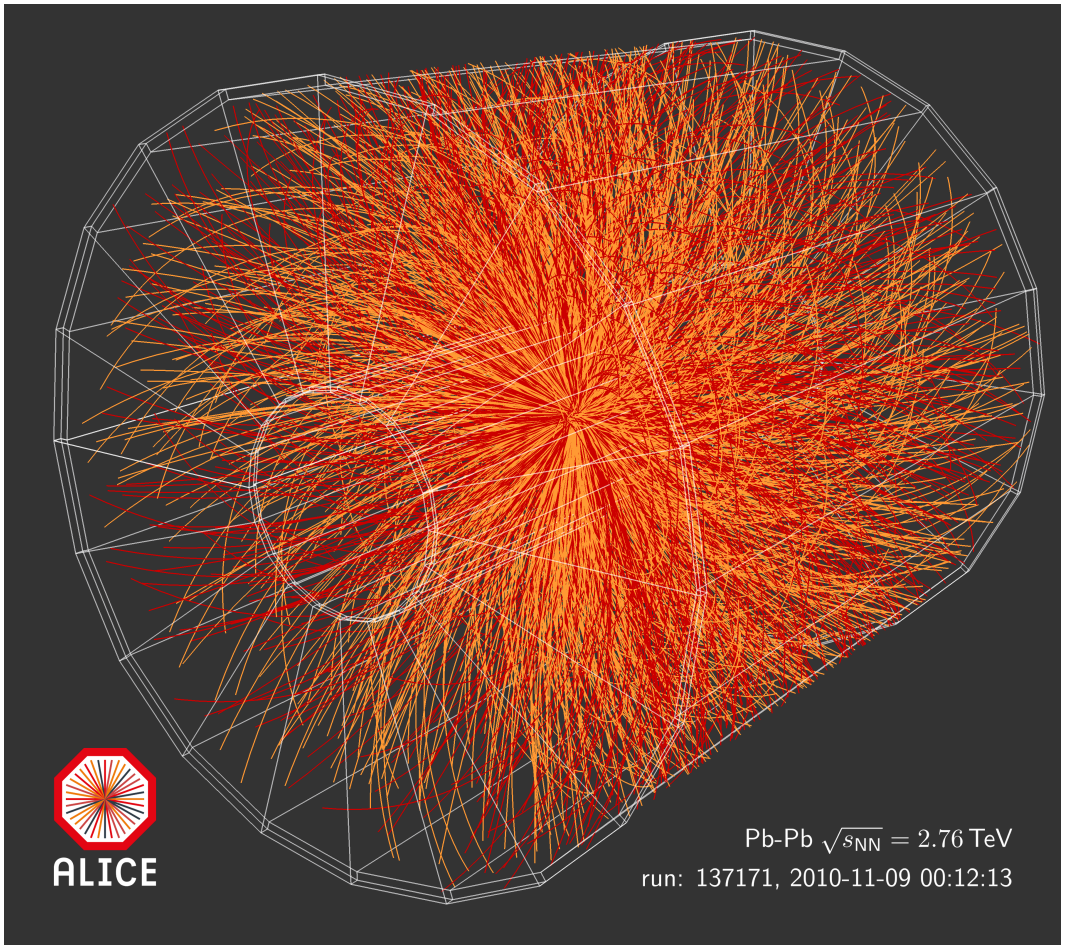


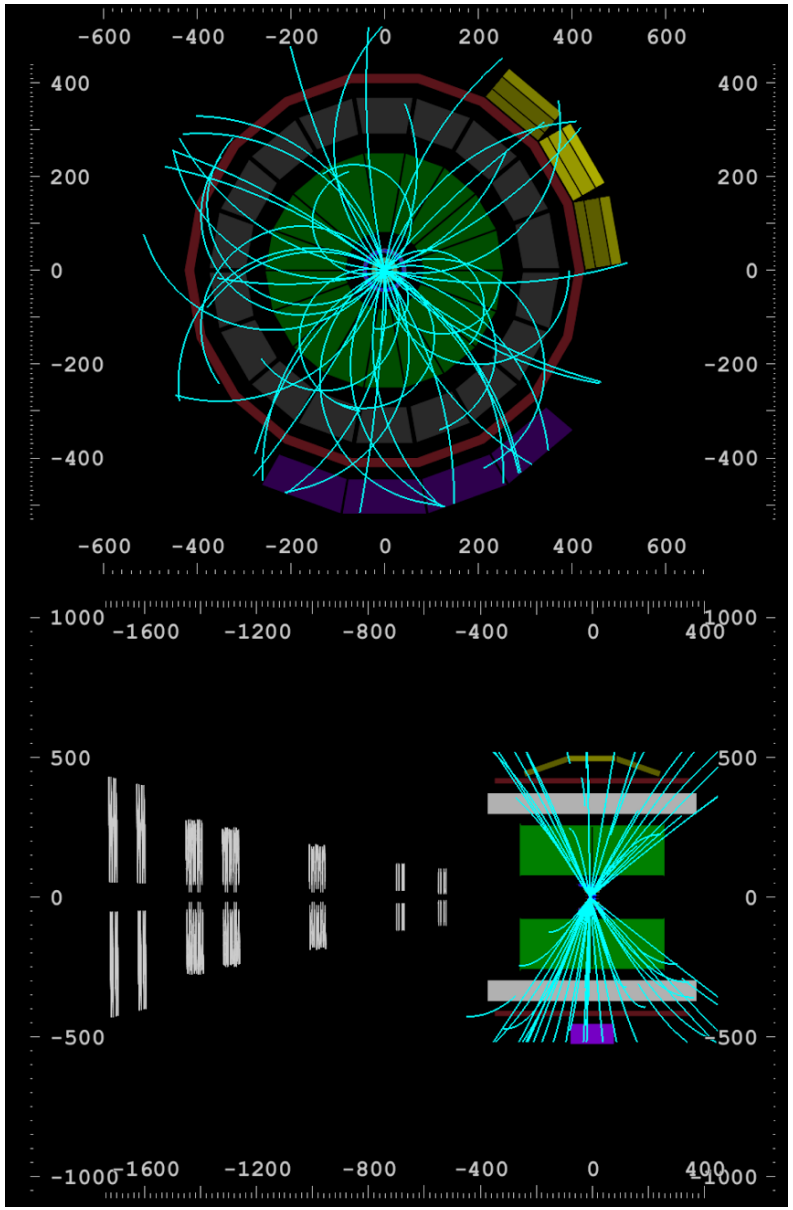
ALICE Collaboration, 2008 JINST 3 S08002

August 2015: 110 physics publications

A collision in ALICE

- Lead-lead collision at a nucleon-nucleon centre-of-mass energy $\sqrt{s_{NN}}$ = 2.76 TeV
- Up to 30,000 particles produced per collision in most central collisions



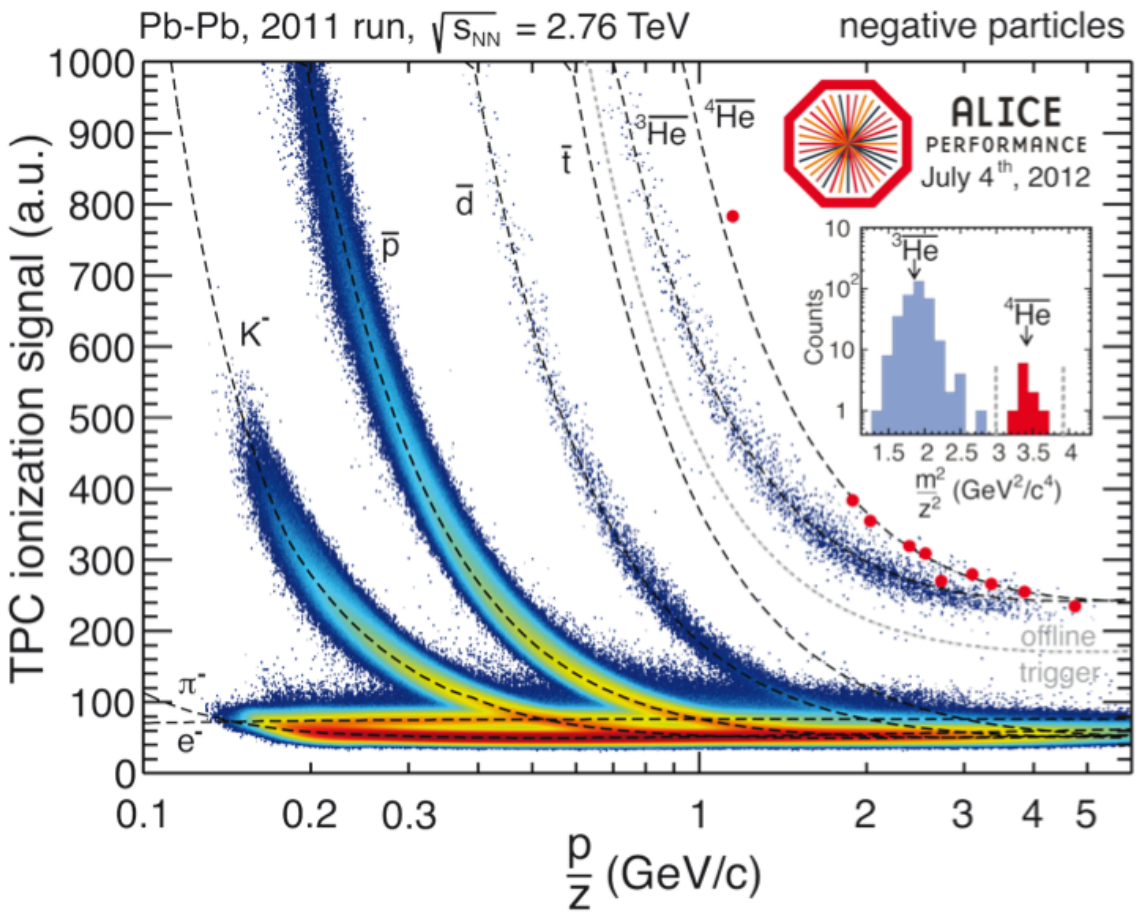


Proton-proton collision at a centre-of-mass energy $\sqrt{s}$ = 13 TeV

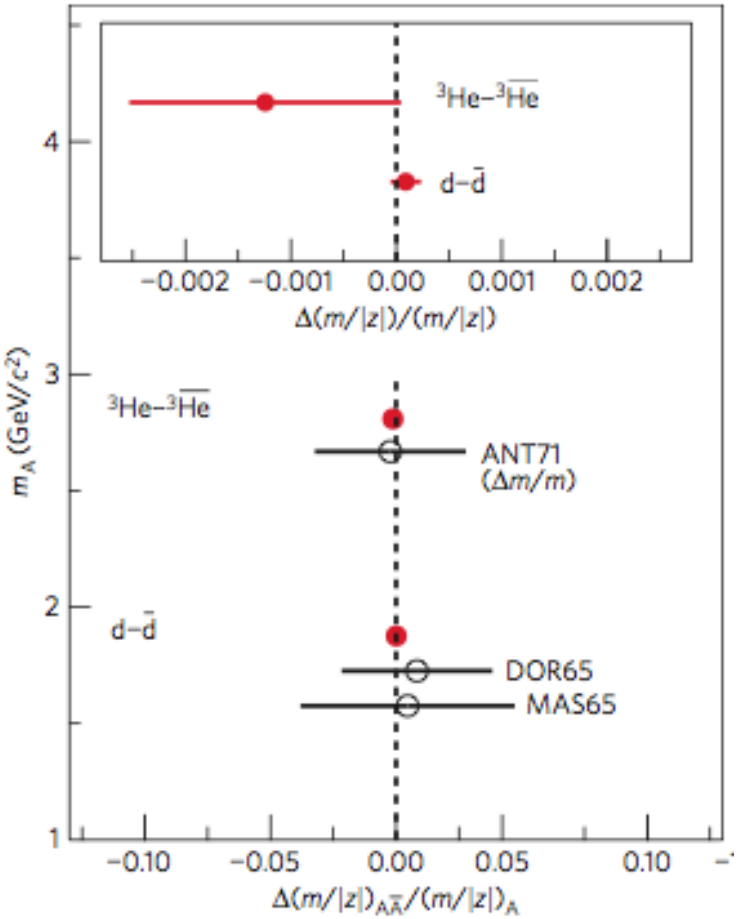
ALICE performance

Unique LHC apparatus for particle identification:

- anti-^{4}He detection
- test of CPT invariance via difference between light nucleus and anti-nucleus



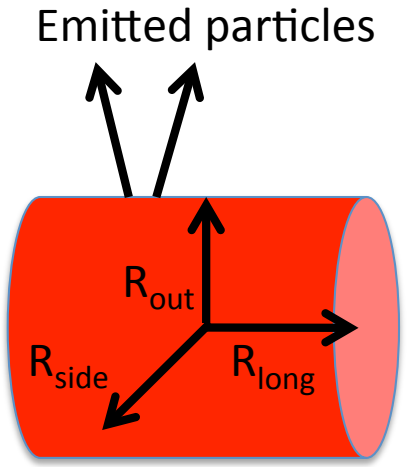
ALICE Collaboration
J. Phys. G: Nucl. Part. Phys. 41 (2014) 087001



ALICE Collaboration
Nature Physics, 17 August 2015

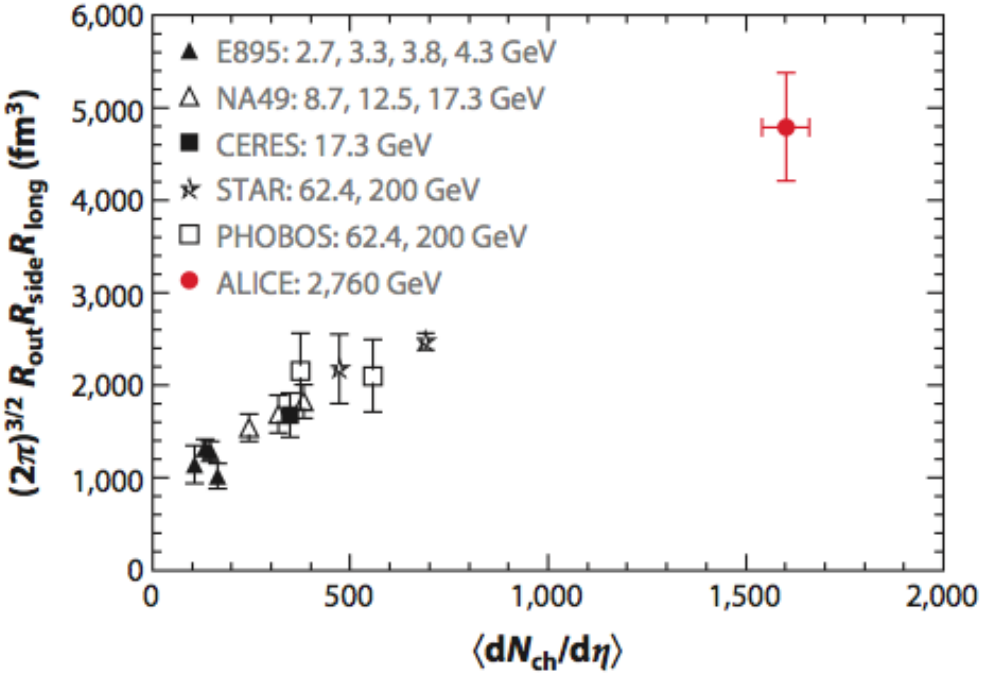
Measuring the bulk size and lifetime

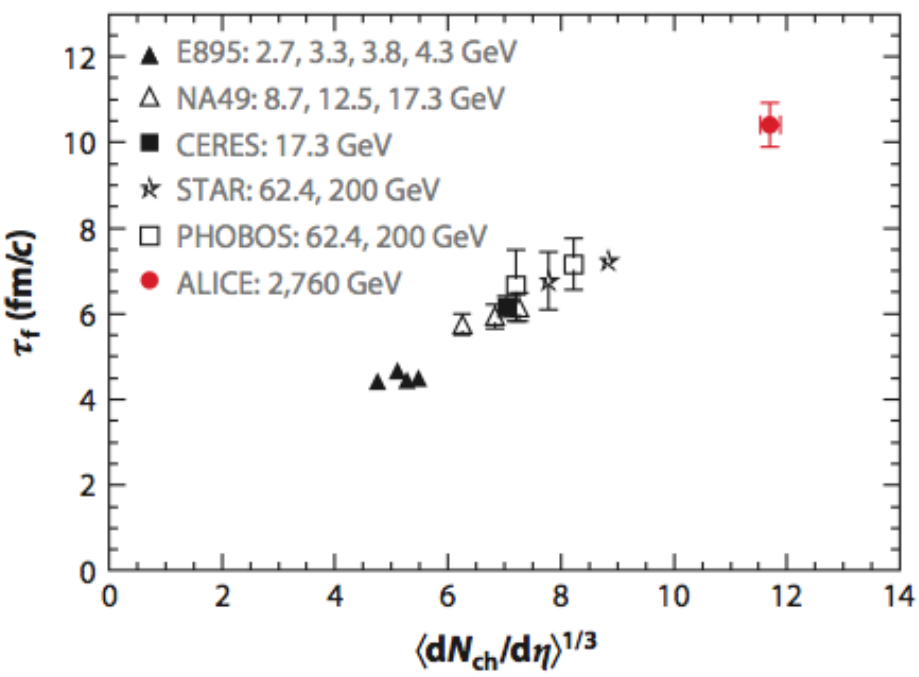
Measurements of the system size just after QCD transition and the lifetime since the collision are achieved by identical particles (HBT) interferometry: modulation of two-particle correlation function in momentum and energy variables are related by Fourier transform to space and time distribution of emitting system at freeze-out



- Volume ≈ 5,000 fm^3
- Lifetime ≈ 10 fm/c ≈ 3 × 10^{-23} s

- B. Müller, J. Schukraft and B. Wyslouch, Annu. Rev. Nucl. Part. Sci. 2012.62:361-386
- ALICE Collaboration, Phys. Lett. B 696 (2011) 328

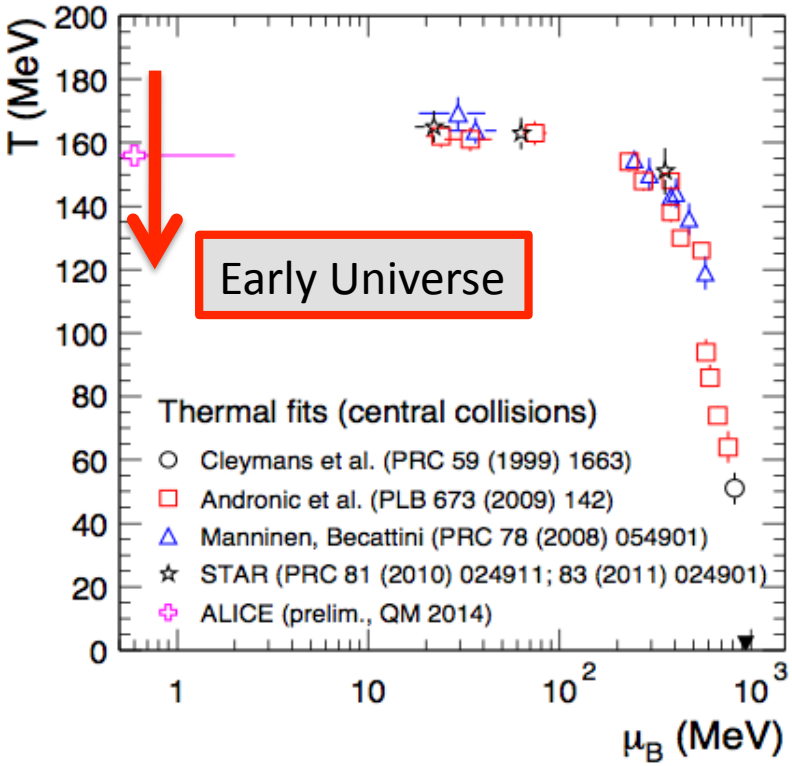




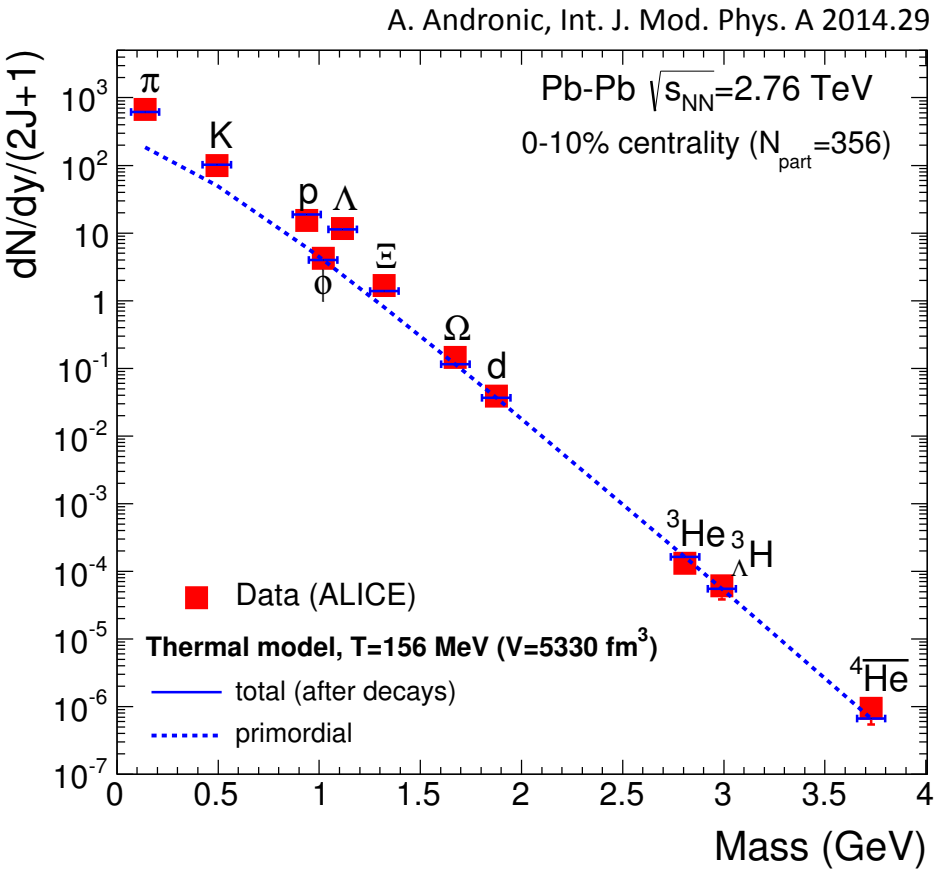
Measuring the transition temperature

Statistical hadronization of quarks and gluons in hadrons

- Freeze-out temperature (≈ transition temperature): T_{fo} = 156 MeV
- Baryon chemical potential at freeze-out: μ_B = 0



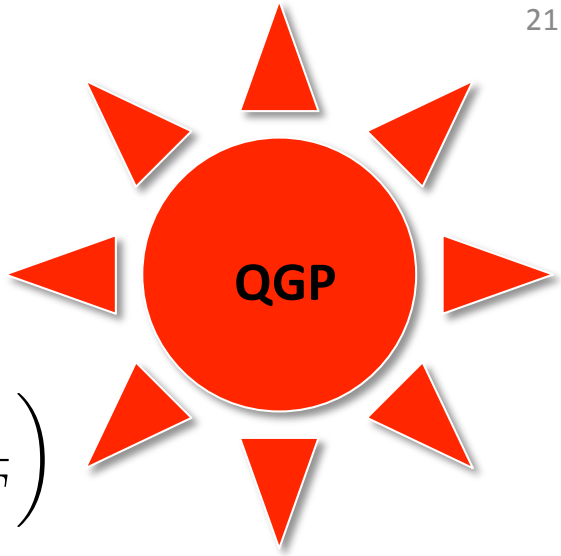
A. Andronic, Int. J. Mod. Phys. A 2014.29



QCD transition explored at LHC is very closed to early Universe one

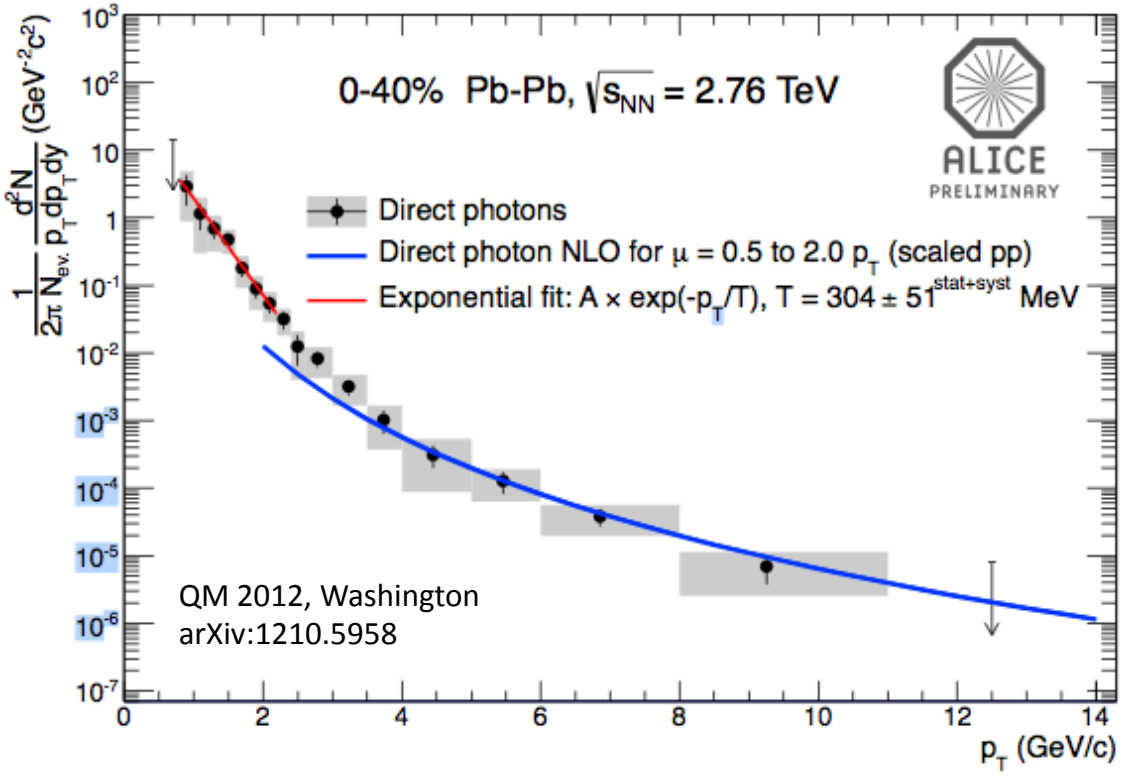
A. Andronic, Int. J. Mod. Phys. A 2014.29

Measuring the QGP temperature and its energy density



The QGP is a blackbody emitting photons

$$u_T(\nu) = \frac{8\pi h}{c^3}\frac{\nu^3}{\exp(\frac{h\nu}{kT})-1} \overset{E \gg kT}{\longrightarrow} E\frac{d^3N}{d^3p} = A\exp\left(-\frac{E}{kT}\right)$$



- At mid-rapidity (y ≈ 0): E ≈ p_T (transverse momentum w.r.t beam axis)
- **At high p_T:** QCD process
- **At low p_T:** direct photons from the source with a black-body like temperature

T_γ = 304 ± 51 MeV

≈ 2 T_{QCD}

QGP energy density at a time of 1 fm/c after the collision

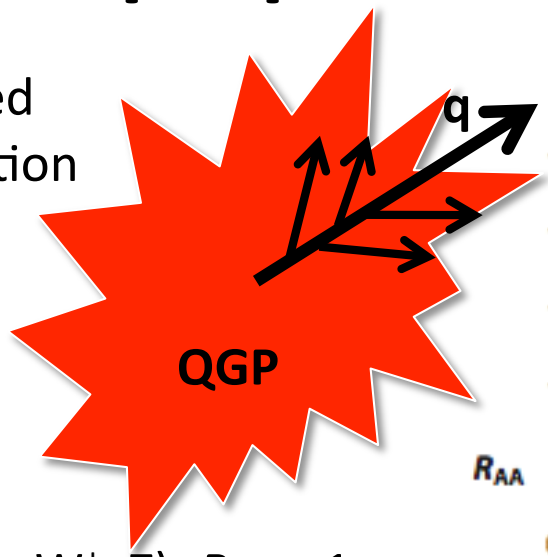
ε ≈ 14 GeV/fm³

CMS Collaboration, Phys. Rev. Lett. 109, 152303 (2012)

Probing QGP properties

Medium effect quantified by the nuclear modification factor

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \, \sigma_{\mathrm{pp}}}$$

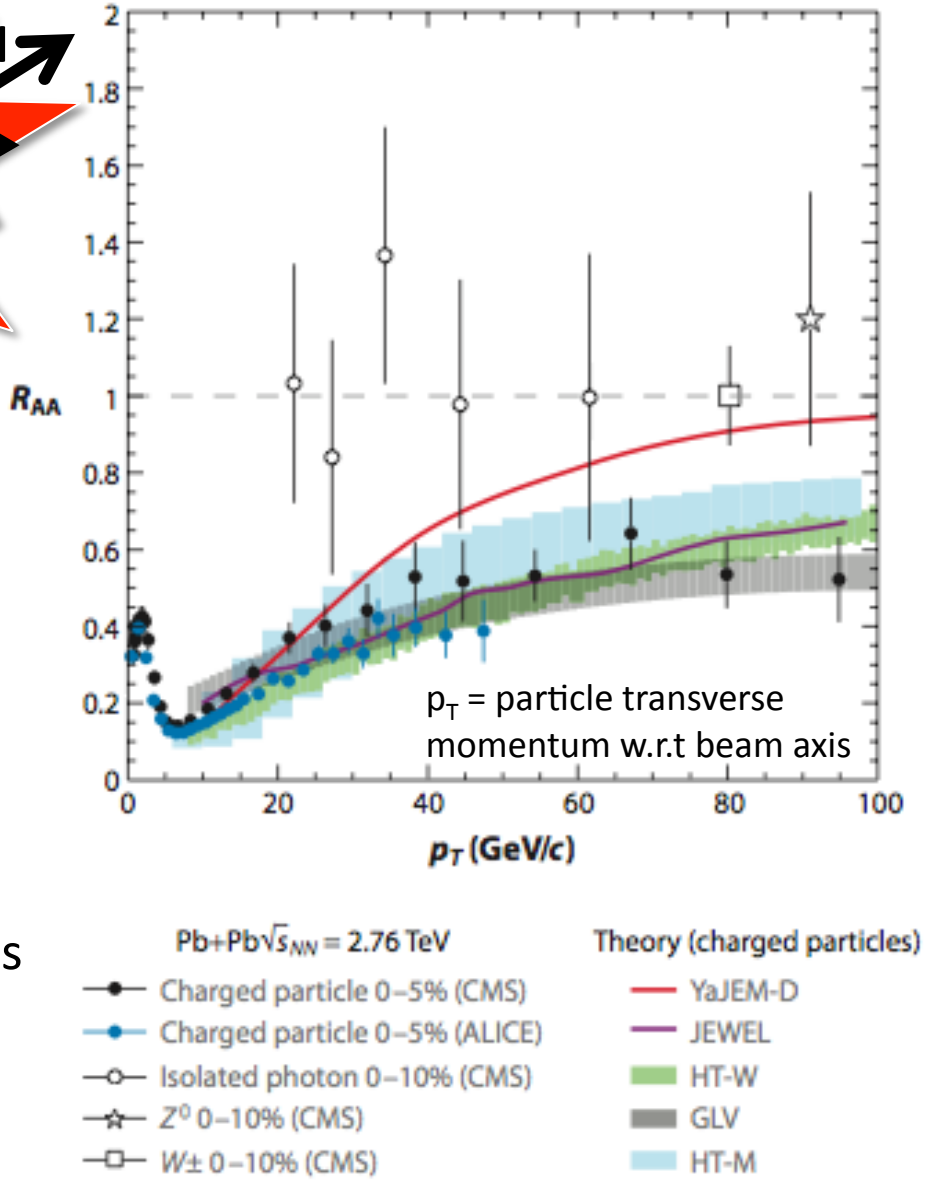


- Electroweak bosons (γ, $W^{\pm}$, Z): $R_{AA} \approx 1$, i.e. not suppressed ➔ insensitive to QGP
- Charged particles (hadrons): $R_{AA} < 1$, i.e. suppressed ➔ quarks and gluons experience energy loss in QGP by strong interaction (gluonstrahlung)
- Comparison to theoretical predictions leads to an estimation of coloured charge (gluon) density (per rapidity y unit):

$$dN_g/dy \approx 2{,}800$$

or transport coefficient measurement

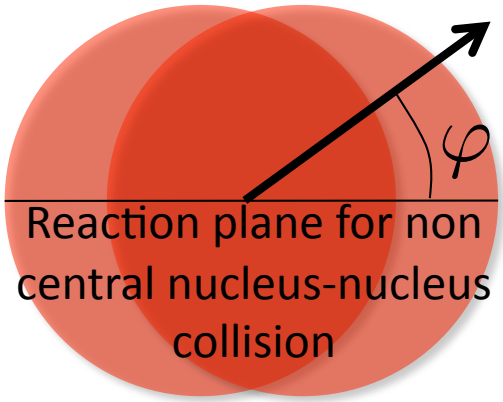
B. Müller, J. Schukraft and B. Wyslouch
Annu. Rev. Nucl. Part. Sci. 2012.62:361-386



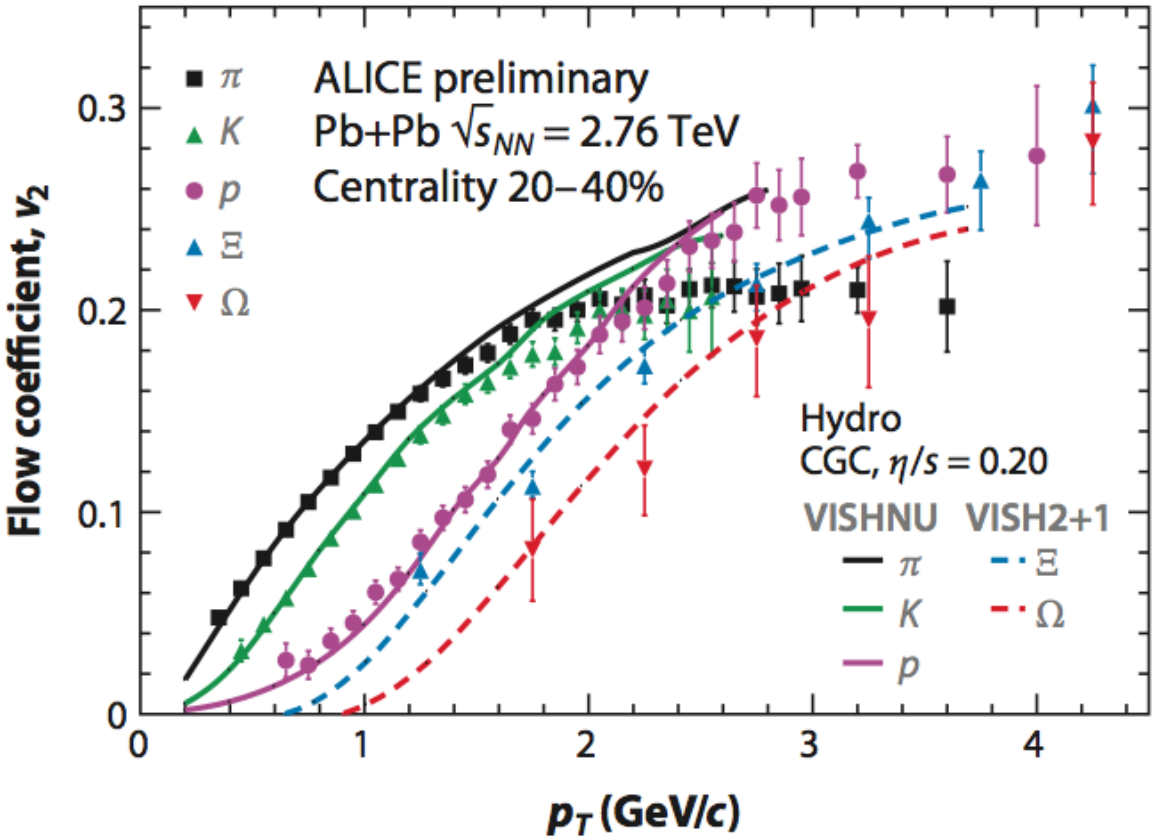
A strongly interacting QGP

Spatial asymmetry in non central collisions results in anisotropic particle distribution in momentum space (flow)

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(n\varphi)\right)$$



- B. Müller, J. Schukraft and B. Wyslouch, Annu. Rev. Nucl. Part. Sci. 2012.62:361-386
- ALICE Collaboration, JHEP 06 (2015) 190



Good description of particle flow by hydrodynamics models

- constraint on QGP EoS
- QGP behaviour in agreement with a nearly perfect fluid (shear viscosity η over entropy density s)

$4\pi\eta/s \leq 2.5$

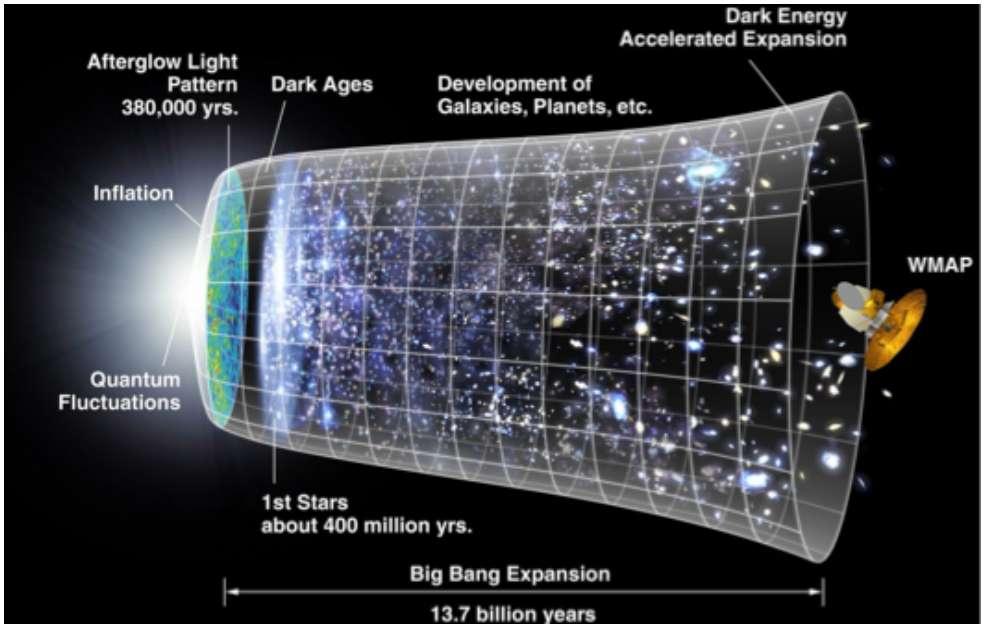
to be compared to the conjectured AdS/CFT limit

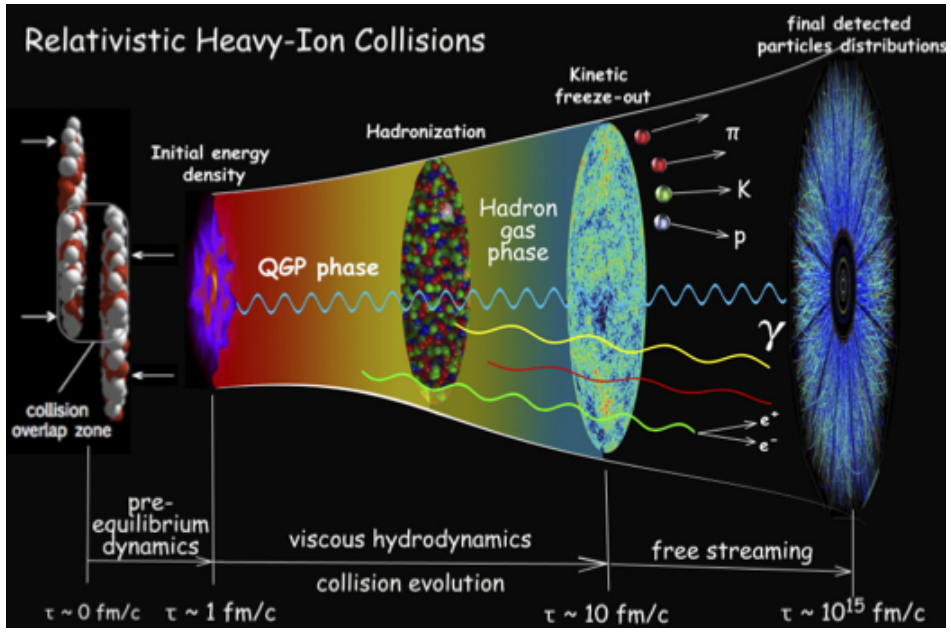
$4\pi\eta/s \geq 1$

P. Kovtun, D. Son and A. Starinets, Phys. Rev. Lett. 94, 111601 (2005)

Towards a Little Bang Standard Model

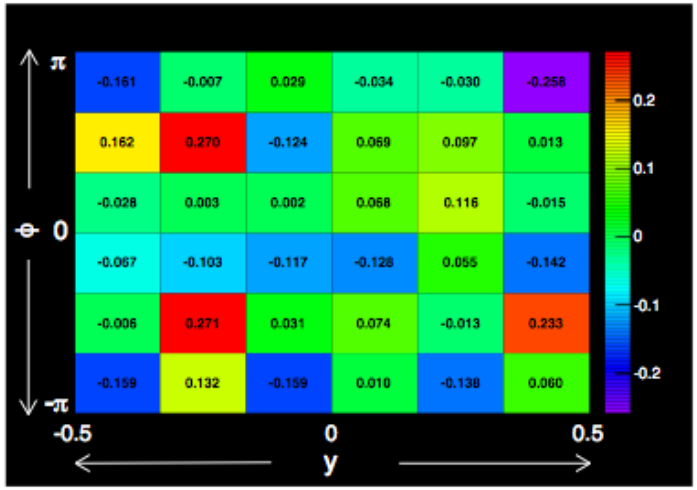
U. Heinz, arXiv:1304.3634



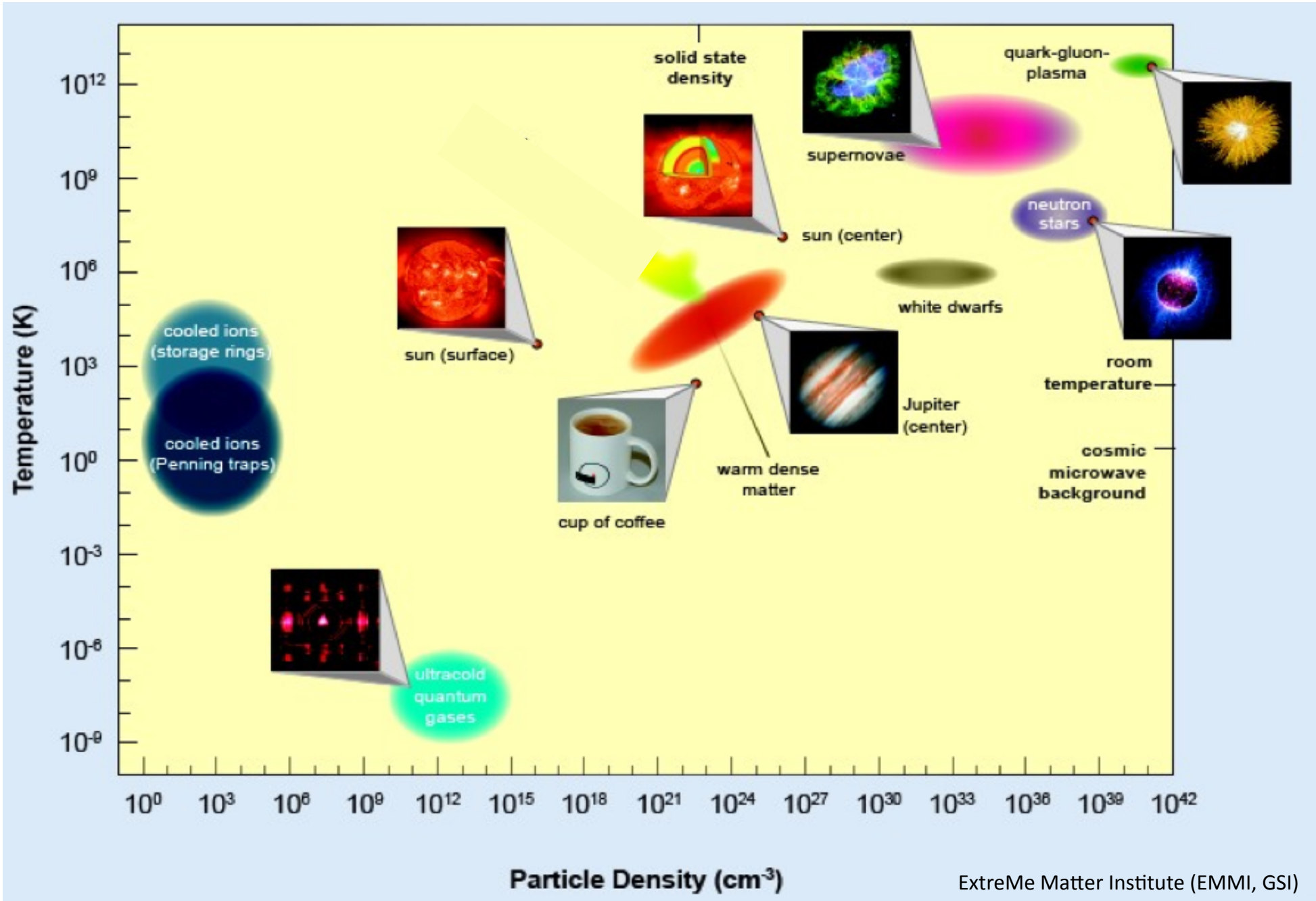


New ideas to map QCD phase transition and QGP EoS

- Event shape engineering [Phys. Lett. B 719 (2013) 394]
- CMB-like harmonic analysis in (y,ϕ) plane of high-multiplicity events in heavy-ion collisions at LHC [Phys. Rev. C 86, 024916 (2012)]
- Study of temperature fluctuations: map of heavy-ion hydrodynamics calculation [arXiv:1504.04502]
- …



QGP: a hot and dense medium



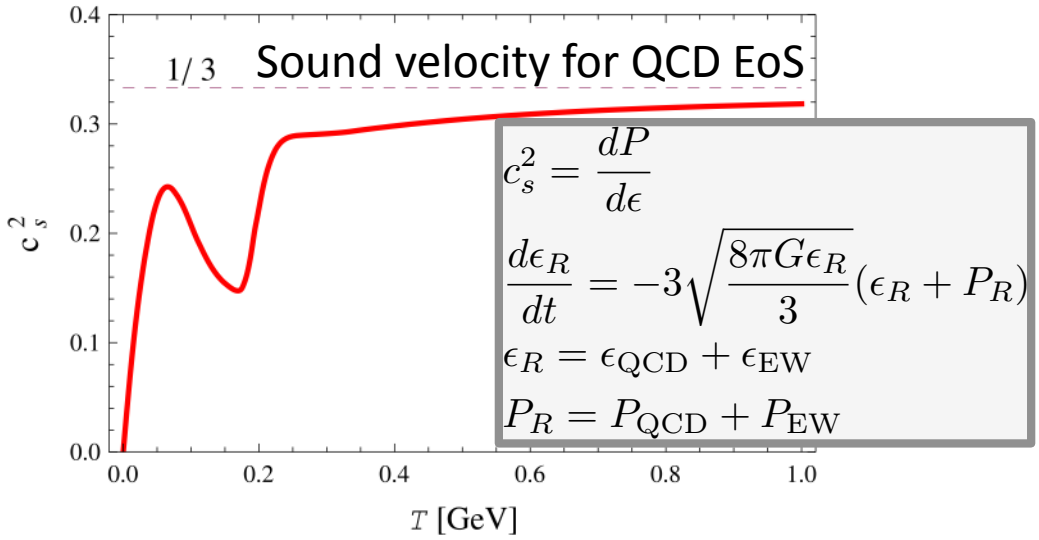
ExtreMe Matter Institute (EMMI, GSI)

QCD cross-over phase transition

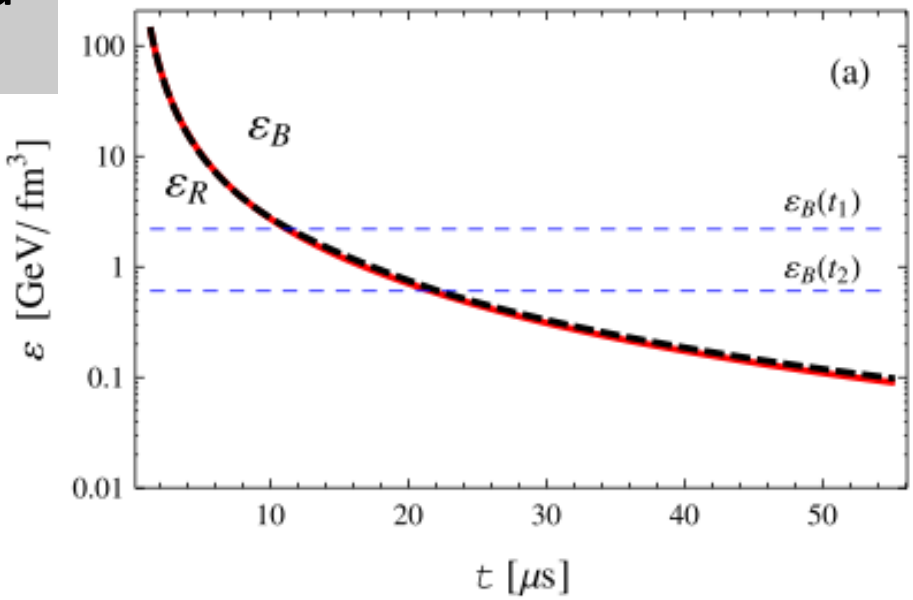
Accelerator experiment outputs can be used as inputs for early Universe understanding

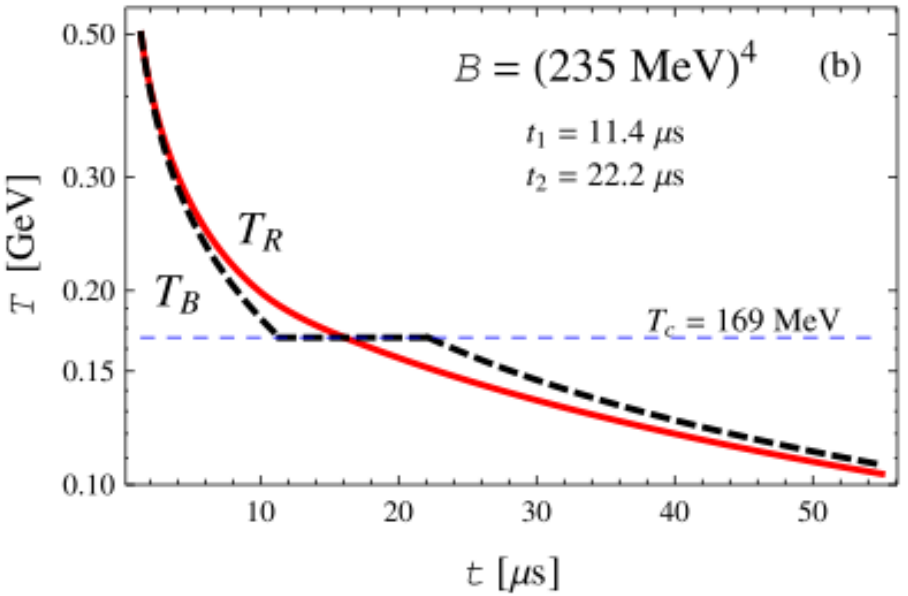
Equation of state with T_{QCD} = 169 MeV

- **B** = Bag EoS (see slide 11) with g_{QGP+EW} = 51.25 and g_{HG+EW} = 17.25
- **R** = Realistic or cross-over transition with lQCD EoS describing RHIC data + electroweak radiation (g_{EW} = 14.25) in isentropic expanding Universe



W. Florkowski, Nucl. Phys. A 853 (2011) 173-188

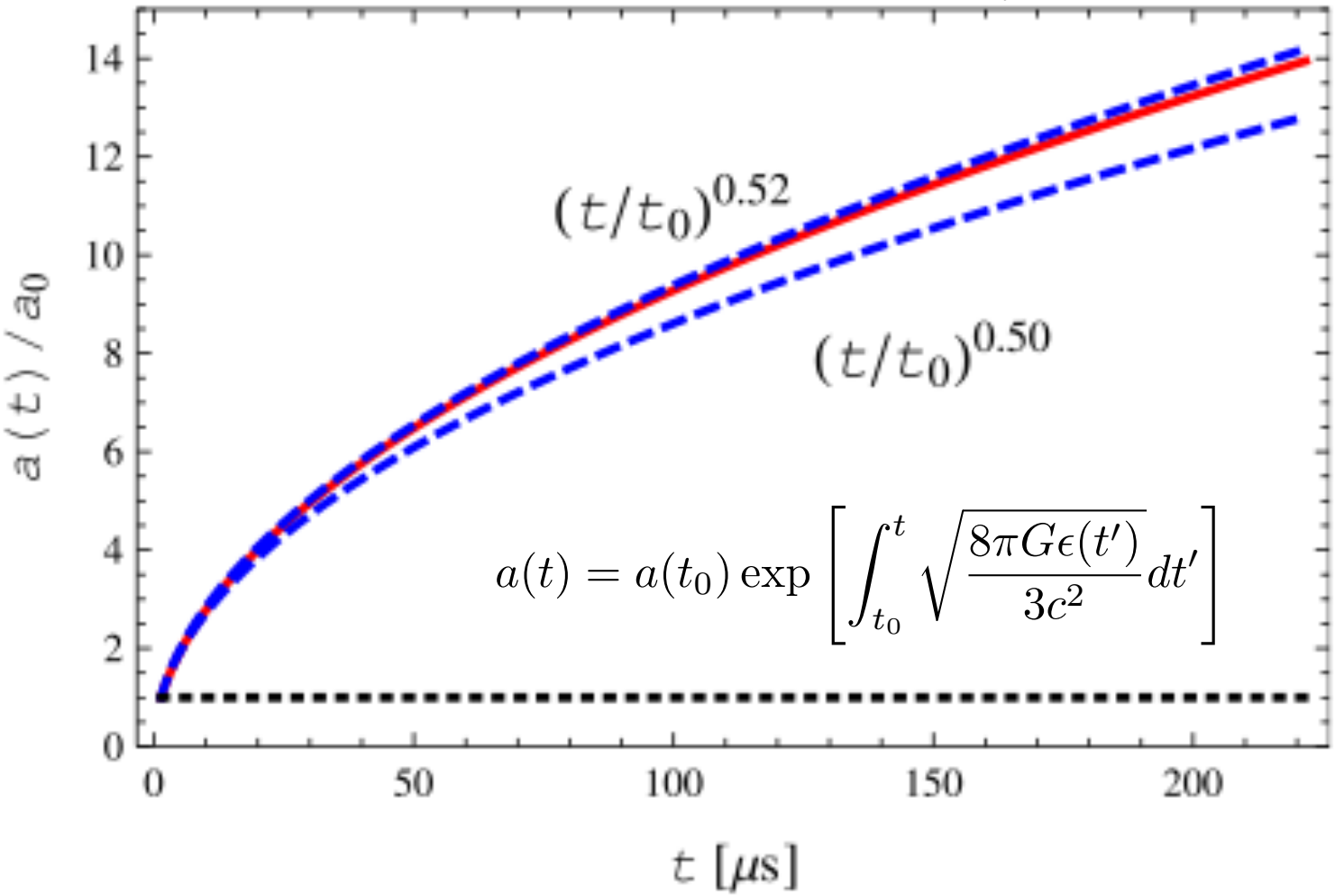




Impact on cosmology : scale factor

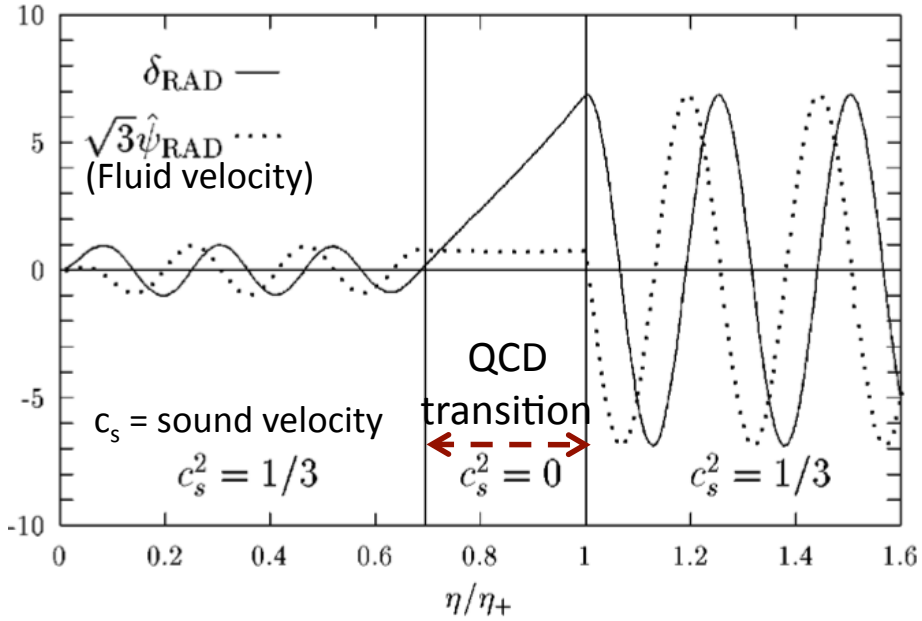
Deviation from radiation behaviour $a(t) \propto \sqrt{t}$
after QCD phase t > t_{QCD} ≈ 10 – 20 µs

W. Florkowski, Nucl. Phys. A 853 (2011) 173-188



Impact on cosmology: inhomogeneities

C. Schmid, D.J. Schwarz and P. Widerin, Phys. Rev. D 59 (1999) 043517



- Bag EoS (1st order phase transition)
➔ amplification of cosmological inhomogeneities

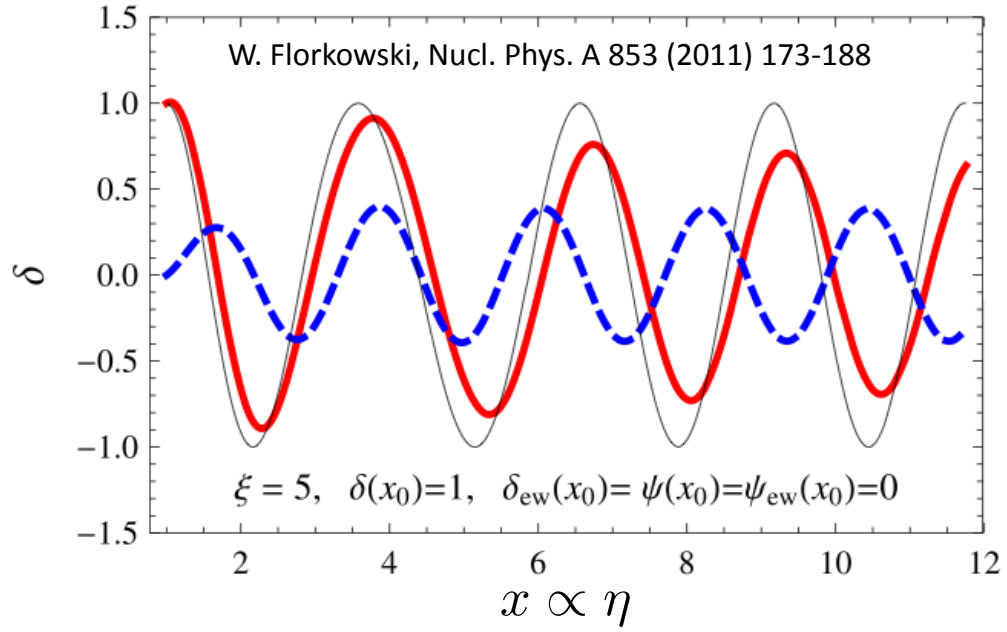
$$\text{Density contrast} \qquad \delta = \frac{\delta\epsilon}{\epsilon}$$

$$\text{Conformal time} \qquad \eta = \int \frac{dt}{a(t)}$$

- Cross-over EoS

  — QCD attenuation (-30%)
  ➔ opposite trend w.r.t. 1st order QCD transition

  - - - EW oscillations triggered by QCD phase transition



In conclusion

- **Impact of QCD phase transition on cosmology is an open question**
- **Study of QCD phase transition through hot and dense medium created in heavy-ion collision can produce valuable inputs for Cosmology**
- **New experimental results from LHC (closer to early Universe conditions) need to be taken into account for updated Cosmological implications**
- **More experimental data (LHC and RHIC) to come in the next decade with new challenging ideas**

Keeping in mind that in accelerator experiments:

i. Initial state comes from two heavy nuclei: different w.r.t. particle era in early Universe

ii. QGP expansion occurs in Euclidean 3D space: compared to 4D space-time of General Relativity

iii. Short time scale $\approx 10^{-23}$ s of QCD phase transition: w.r.t. QCD phase transition $\approx 10^{-5}$ s in early Universe

The End

Cosmological relations

Energy density $$\epsilon_{\rm rad} = \frac{E}{V} = \frac{Nhc}{\lambda V} \propto \frac{1}{[a(t)/a_0]^4} = (1+z)^4$$

- $a(t) \propto \sqrt{t}$ = scale factor at time t
- a_0 = scale factor today
- z = redshift corresponding to time t

Temperature

$$T(z) = T_0(1+z)$$

with T_0 today temperature (CMB)

Scale factor $$a(t) \propto \frac{1}{T(t)}$$

Cosmological inhomogeneities

W. Florkowski, Nucl. Phys. A 853 (2011) 173-188

Below we study the system of equations introduced by Schmid, Schwarz, and Widerin [17, 18]. They read

$$\frac{1}{\mathcal{H}}\delta' + 3\left(c_s^2 - w\right)\delta = \frac{k}{\mathcal{H}}\psi - 3(1+w)\alpha, \tag{26}$$

$$\frac{1}{\mathcal{H}}\delta'_{\rm ew} = \frac{k}{\mathcal{H}}\psi_{\rm ew} - 4\alpha, \tag{27}$$

$$\frac{1}{\mathcal{H}}\psi' + (1-3w)\psi = -c_s^2\frac{k}{\mathcal{H}}\delta - (1+w)\frac{k}{\mathcal{H}}\alpha, \tag{28}$$

$$\frac{1}{\mathcal{H}}\psi'_{\rm ew} = -\frac{k}{3\mathcal{H}}\delta_{\rm ew} - \frac{4k}{3\mathcal{H}}\alpha, \tag{29}$$

$$\left[\left(\frac{k}{\mathcal{H}}\right)^2 + \frac{9}{2}(1+w_R)\right]\alpha = -\frac{3}{2}\left(1+3c_{sR}^2\right)\delta_R. \tag{30}$$

Eqs. (26) and (27) follow from the energy–momentum conservation, Eqs. (28) and (29) from the 3-divergence of the Euler equation of general relativity, and Eq. (30) from the Einstein R_0^0-equation. The prime denotes the derivative with respect to the conformal time η defined by Eq. (22). The quantities $\delta = \delta\varepsilon/\varepsilon$ and $\delta_{\rm ew} = \delta\varepsilon_{\rm ew}/\varepsilon_{\rm ew}$ describe the energy density fluctuations (*density contrasts* for strongly-interacting and electro-weak matter, respectively), ψ and $\psi_{\rm ew}$ are related to the fluid velocities (*peculiar velocities*, again for strongly-interacting and electro-weak matter, respectively), and α defines the correction to the temporal part of the metric tensor (*lapse function*).

Realistic QCD EoS

W. Florkowski, Nucl. Phys. A 853 (2011) 173-188

Thermodynamics quantities

$$\epsilon + P = T\,s$$
$$d\epsilon = T\,ds$$
$$dP = s\,dT$$
$$c_s^2 = \frac{dP}{d\epsilon} = \frac{s\,dT}{T\,ds}$$

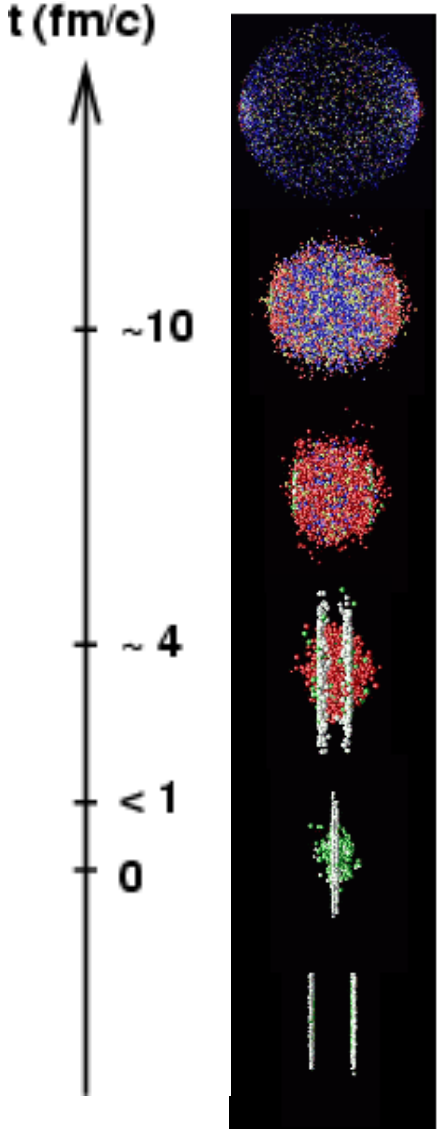
with

$s = \text{entropy density}$
$\epsilon = \text{energy density}$
$T = \text{temperature}$
$P = \text{pressure}$
$c_s = \text{sound velocity}$

Time evolution of the scale factor

$$a(t) = a(t_0)\exp\left(\int_{t_0}^{t}\sqrt{\frac{8\pi\mathcal{G}\epsilon_R(t')}{3}}dt'\right) \quad \text{with} \quad T_R(t_0) = 500\ \text{MeV} \Rightarrow t_0 = 1.35\ \mu\text{s}$$

What happens in a heavy-ion collision?



1 fm/c ≈ 3×10^{-24} s

End of hadron interactions: particles can fly freely (decay) and reach the detectors

Phase transition: hadronization of quarks and gluons to form a hadron gas

QGP: unconfined phase of quarks and gluons expanding and then cooling down

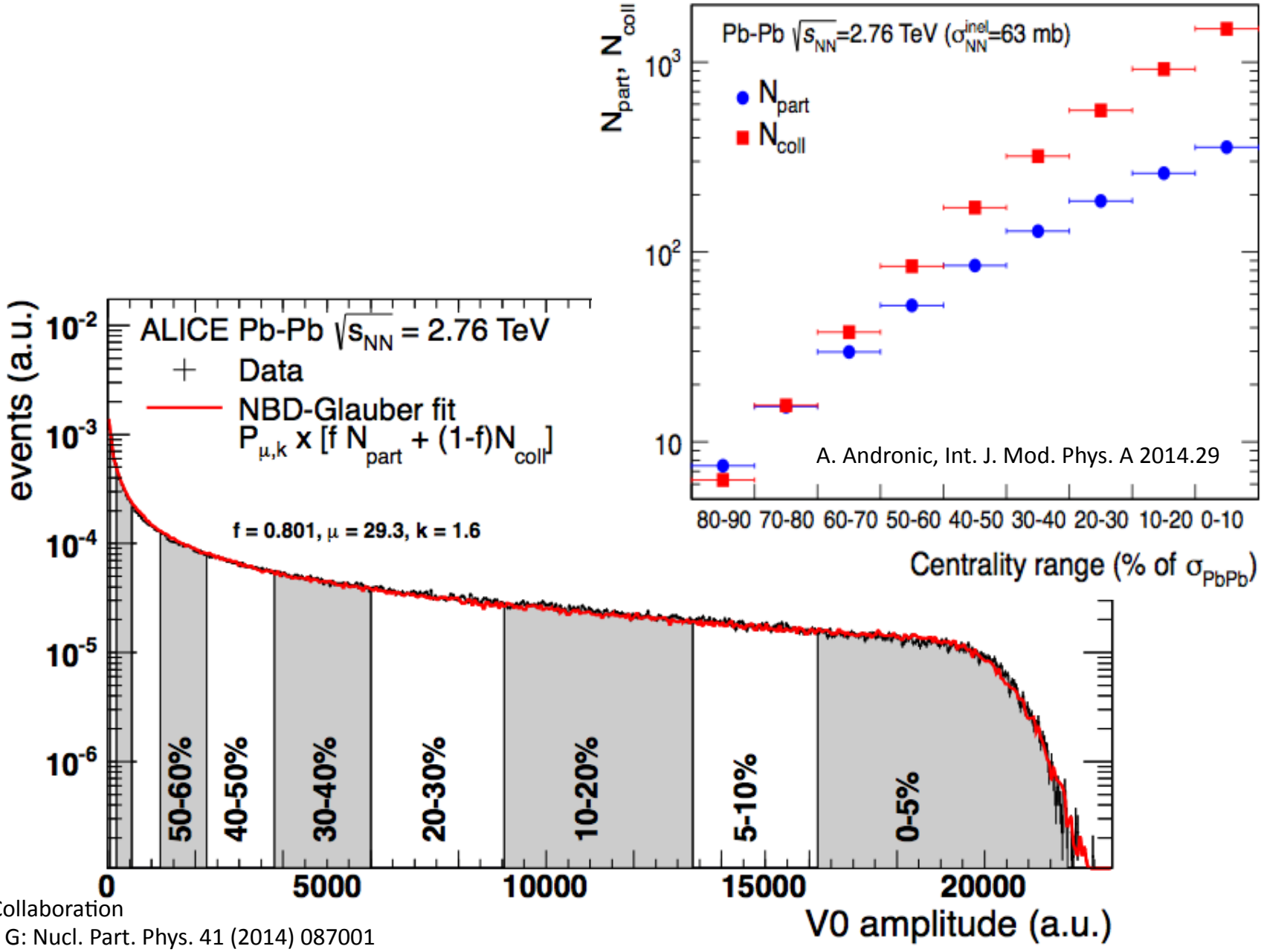
Thermalization of the system

Hard interactions between quarks and gluons of 208 × 208 nucleons for Pb-Pb

Two nuclei are sent in (frontal) collision at high energy (Lorentz contraction):

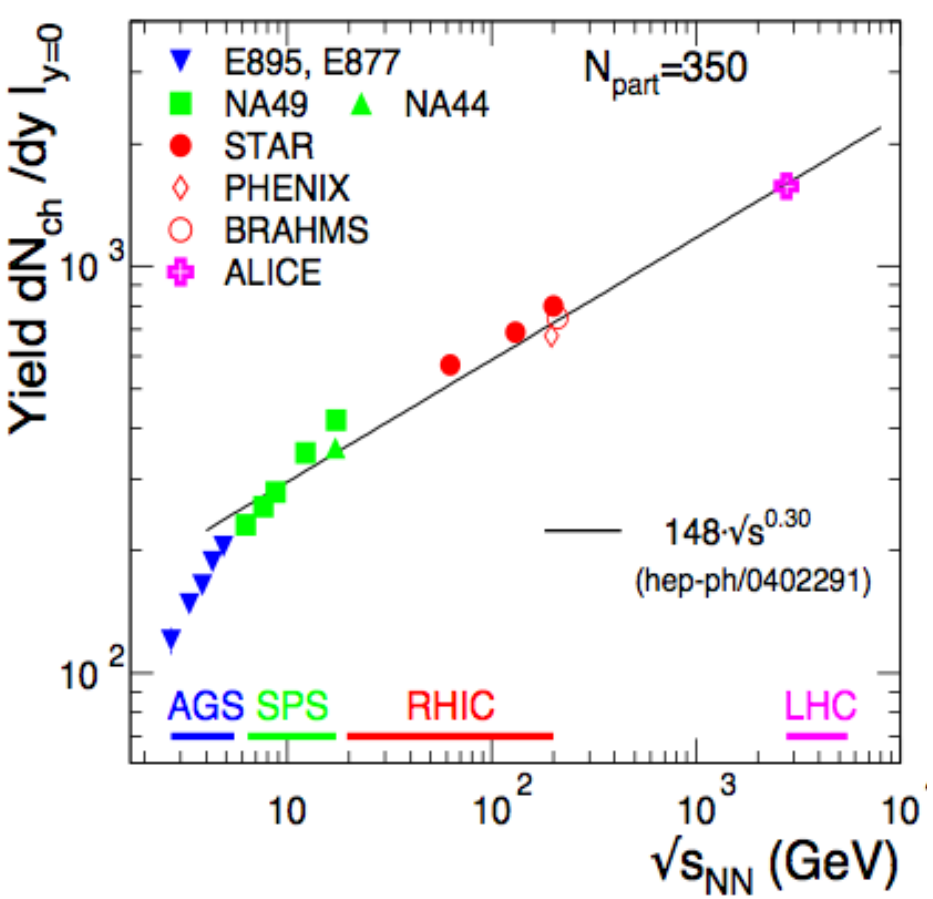
$d = d_0/\gamma$ with $\gamma = 1468$ at LHC (run 1)

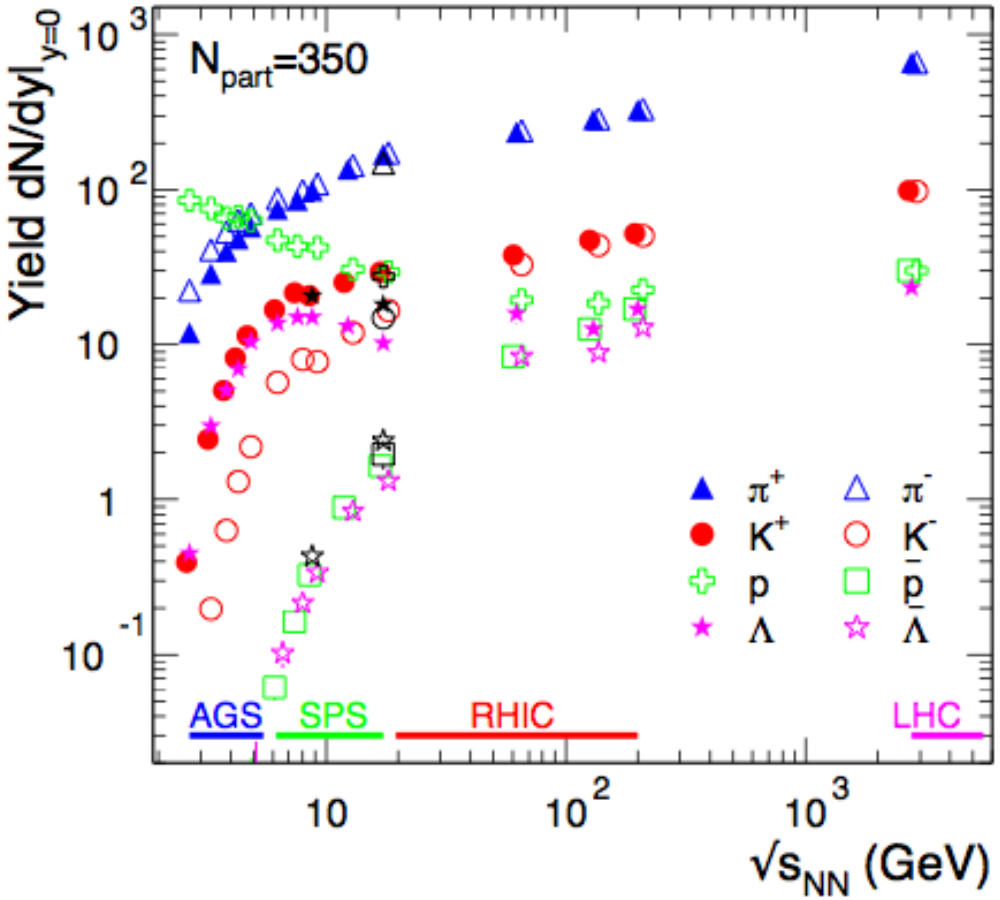
Centrality in Pb-Pb collisions



ALICE Collaboration
J. Phys. G: Nucl. Part. Phys. 41 (2014) 087001

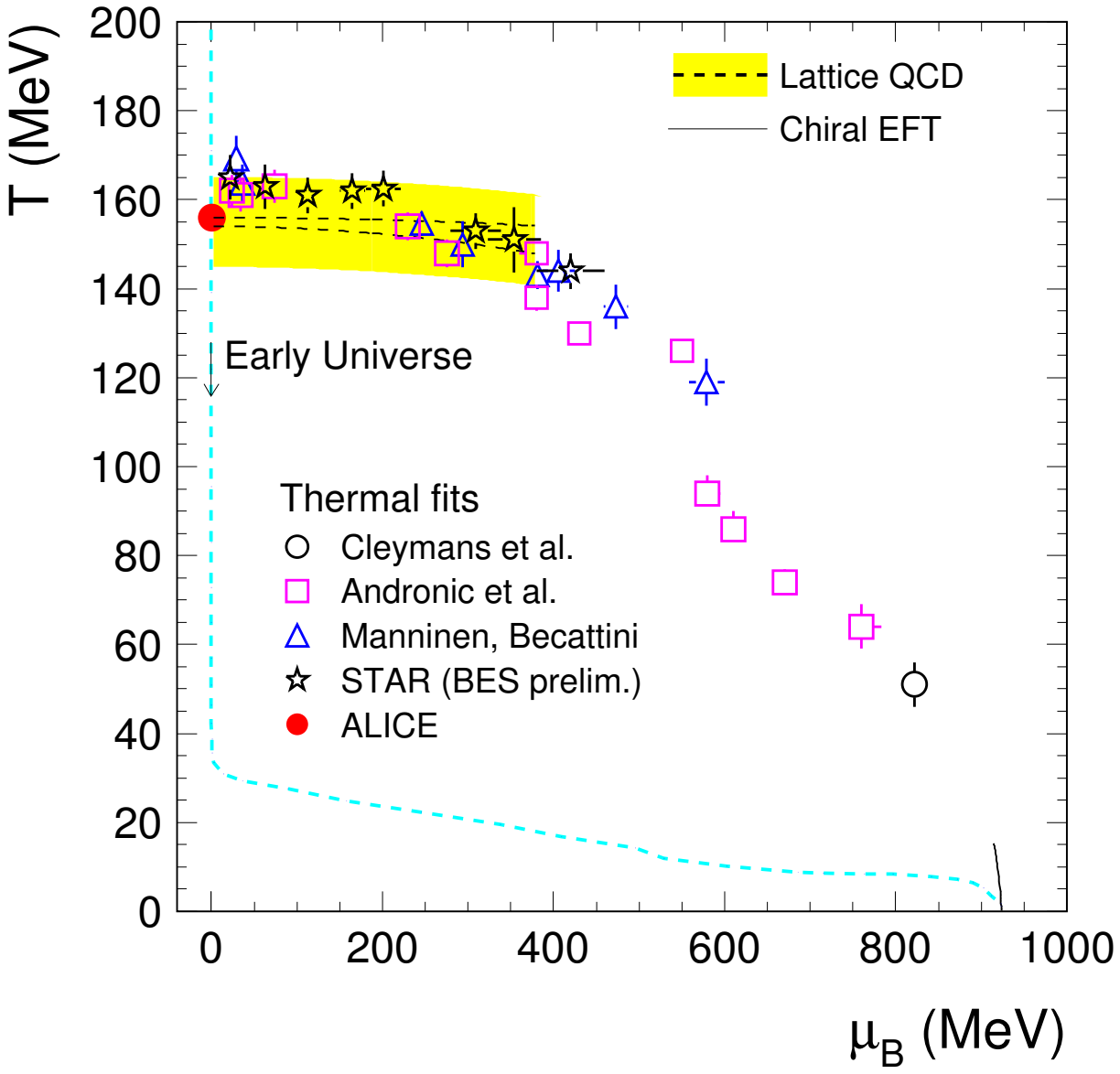
Statistical hadronization





A. Andronic, Int. J. Mod. Phys. A 2014.29

QCD phase diagram



A. Andronic, EMMI workshop: Imprints the QGP, 16-17 April 2015

Hydrodynamics description of QGP

① Energy-momentum conservation (here for a perfect fluid)

$$\partial_\mu T^{\mu\nu} = 0$$

with $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$

$\epsilon =$ energy density

$P =$ pressure

$u^\mu(x) = \gamma(x)(1, \mathbf{v}(x))$

$g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$

② Baryon number conservation

$$\partial_\mu \mathrm{J}^\mu_\mathrm{B} = 0$$

with $\mathrm{J}^\mu_\mathrm{B}(x) = n_\mathrm{B}(x) u^\mu(x)$

$n_\mathrm{B}(x) =$ baryon number density

③ Entropy conservation

$$\partial_\mu (s u^\mu) = 0$$

with $s(x) =$ entropy density

④ Equation of state (lattice QCD)

$$p = p(\epsilon)$$

QCD EoS

arXiv:1501.06477

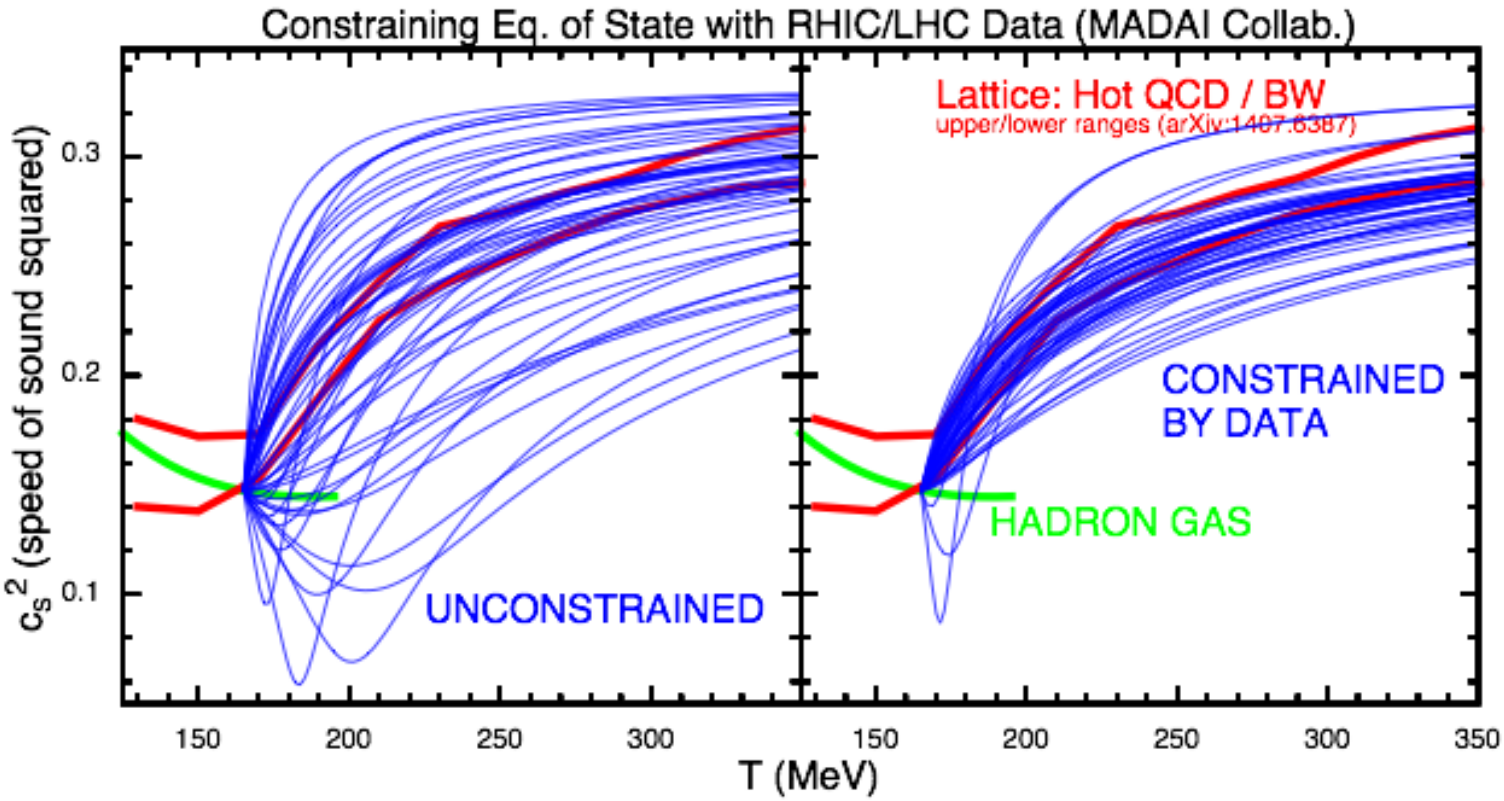


Figure 2: The QCD Equation of State (more precisely: the squared speed of sound, c_s^2, as a function of temperature) from lattice QCD calculations and from models constrained by data from RHIC and the LHC. The red lines delimit the present uncertainty range of c_s^2 from lattice QCD. The blue lines show a number of parametrizations of $c_s^2(T)$; in the left panel, they are constrained only by their asymptotic values at $T = 165\,\mathrm{MeV} \simeq T_c$ and $T = \infty$, in the right panel they are additionally required to provide an acceptable fit to experimental data as described in [48, 49]. The right panel shows that experimental data give preference to an Equation of State consistent with lattice QCD. This demonstrates that our model of the collision dynamics is good enough to allow us to study emergent properties in QCD matter.

Accelerator experiment outputs

① **Observation of multiple signals of QGP formation in heavy-ion collisions since more than a decade**

② **QGP corresponds to a hot and dense medium coloured state**

③ **Confrontation of data to theoretical modelling of heavy-ion collisions allows to constrain the QGP EoS**