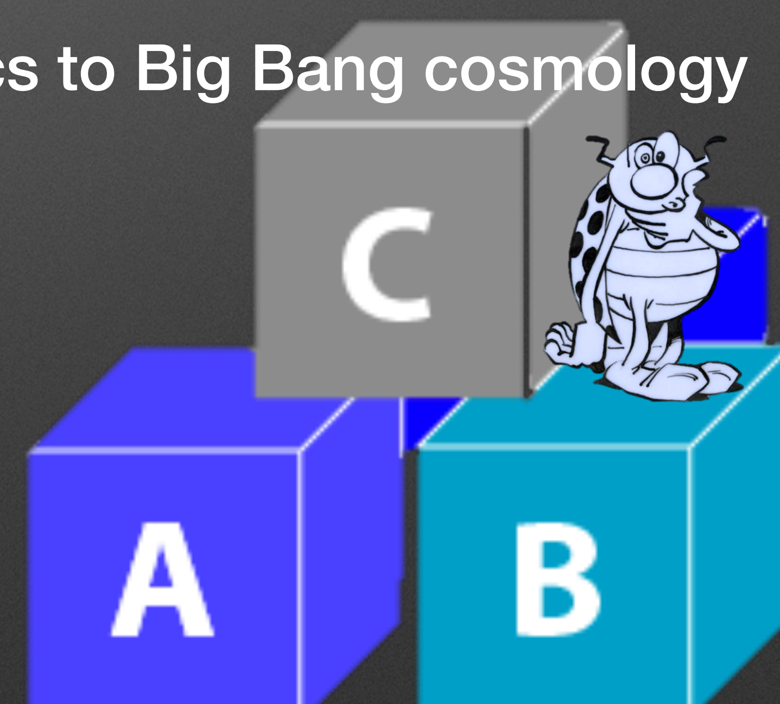
ALICE
A JOURNEY OF DISCOVERY

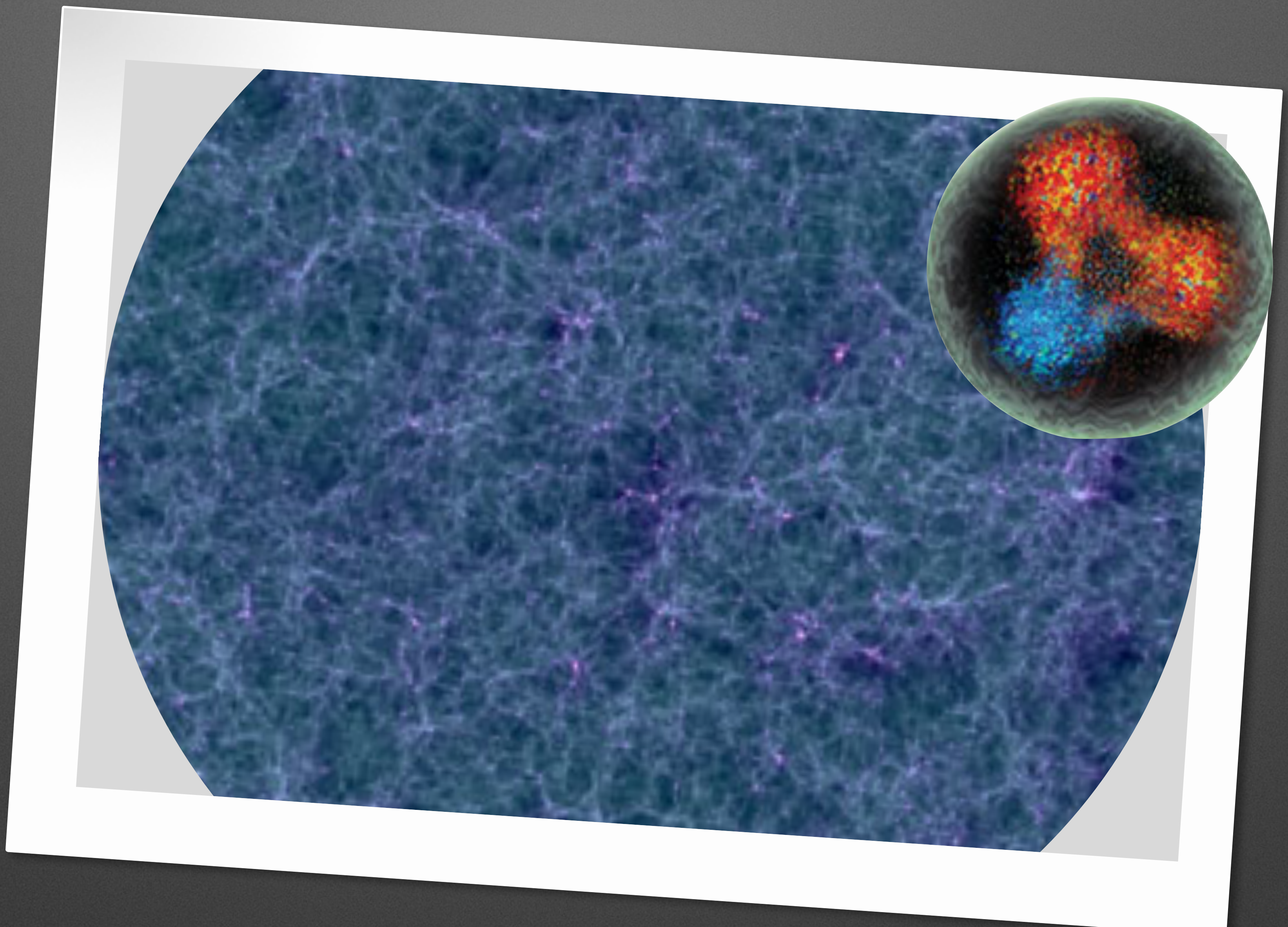
An introduction to heavy-ion physics

France-China Summer School 2017

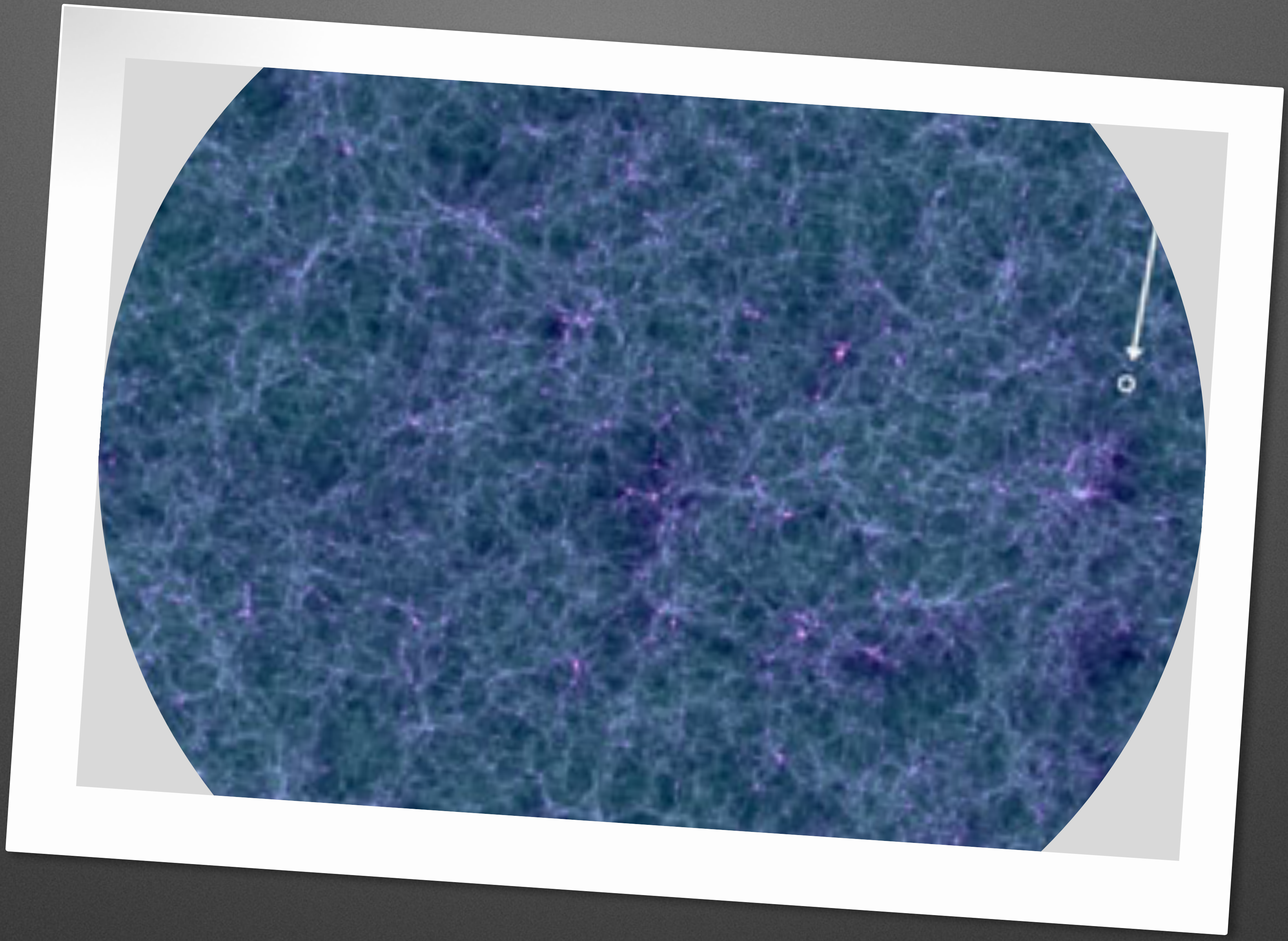
The basics …

From the Standard Model of Particle Physics to Big Bang cosmology



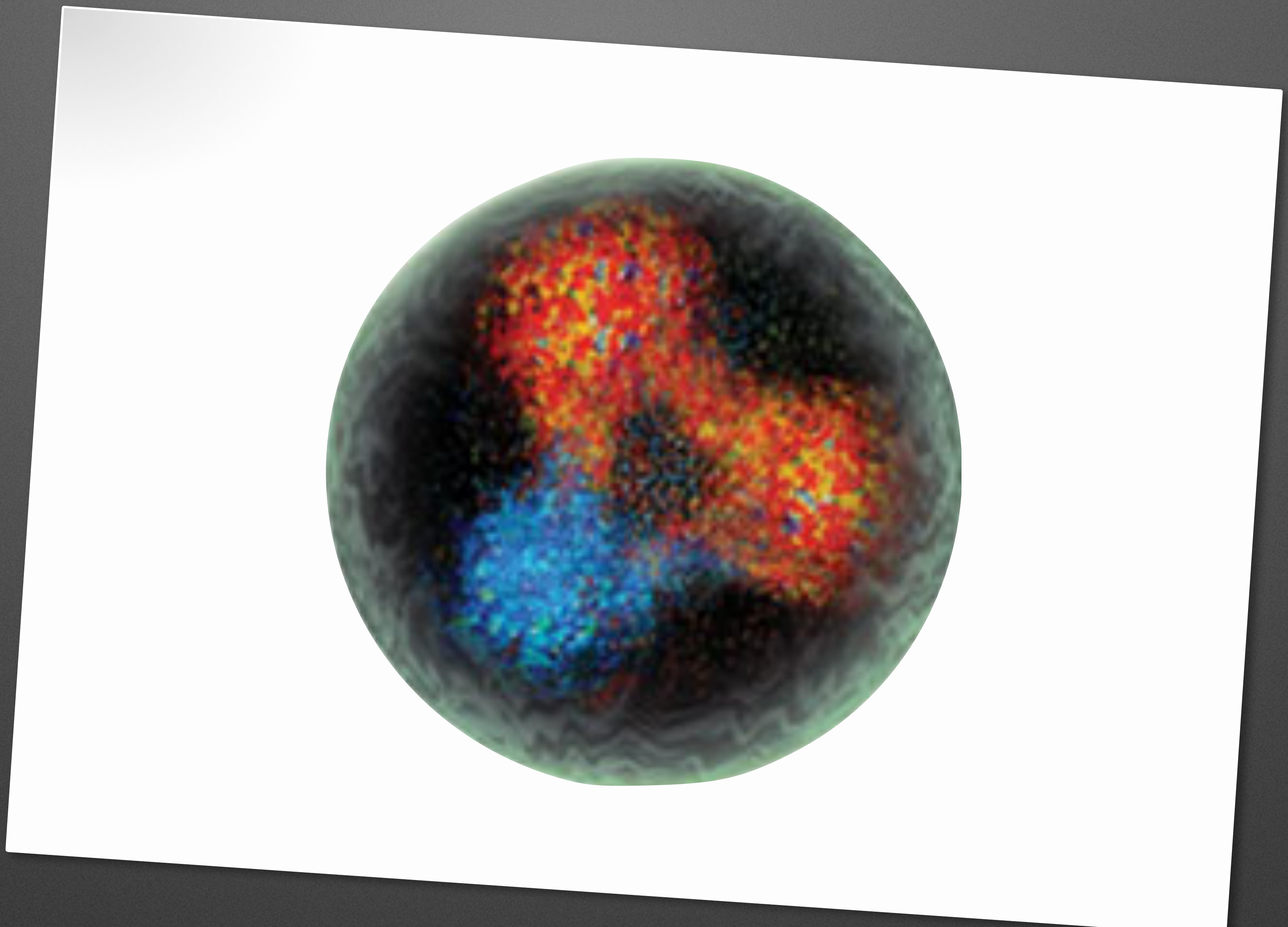


Modern physics describes the Universe at all scale



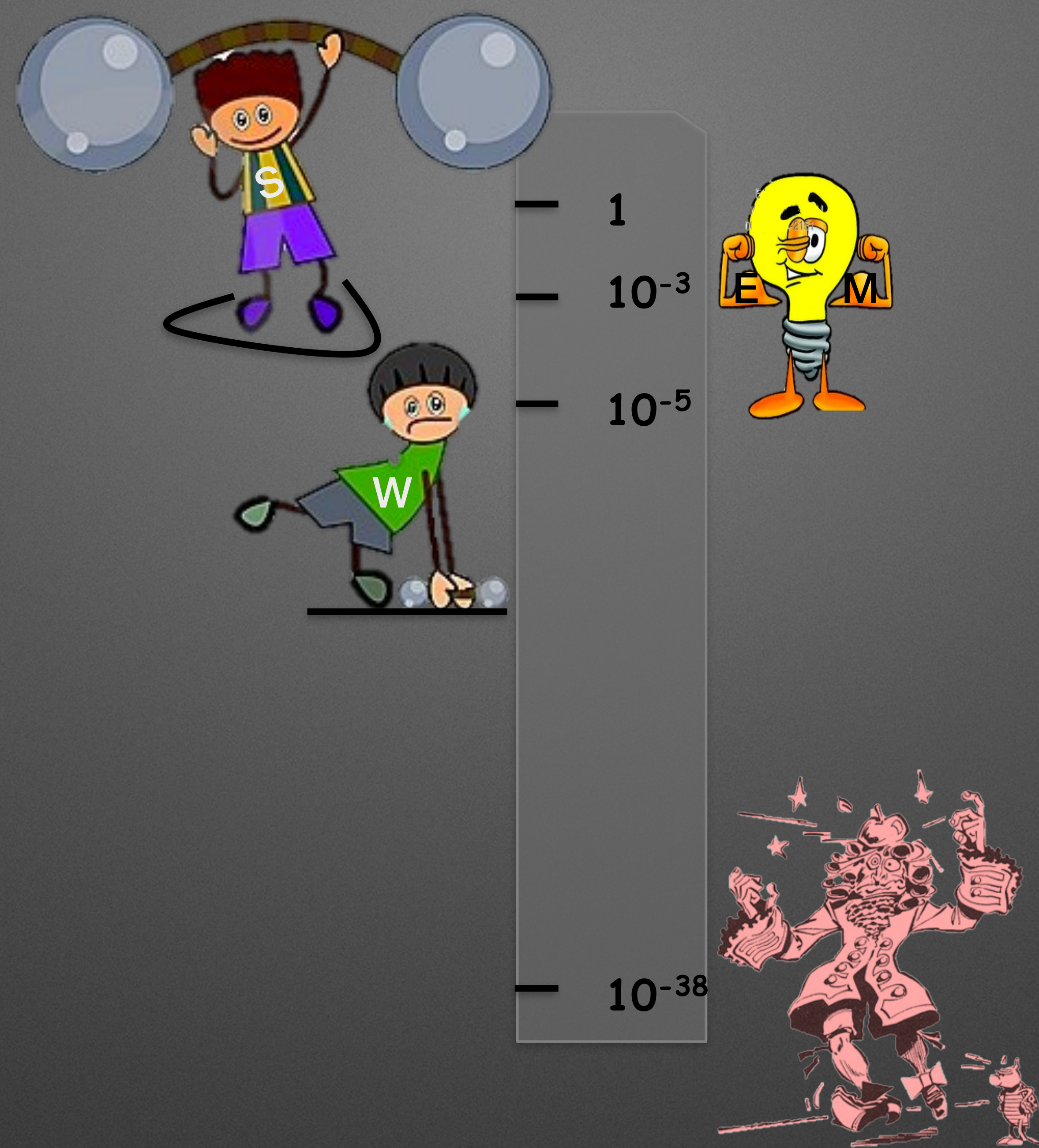
Modern physics describes the Universe at all scale

From 10^{28} cm …



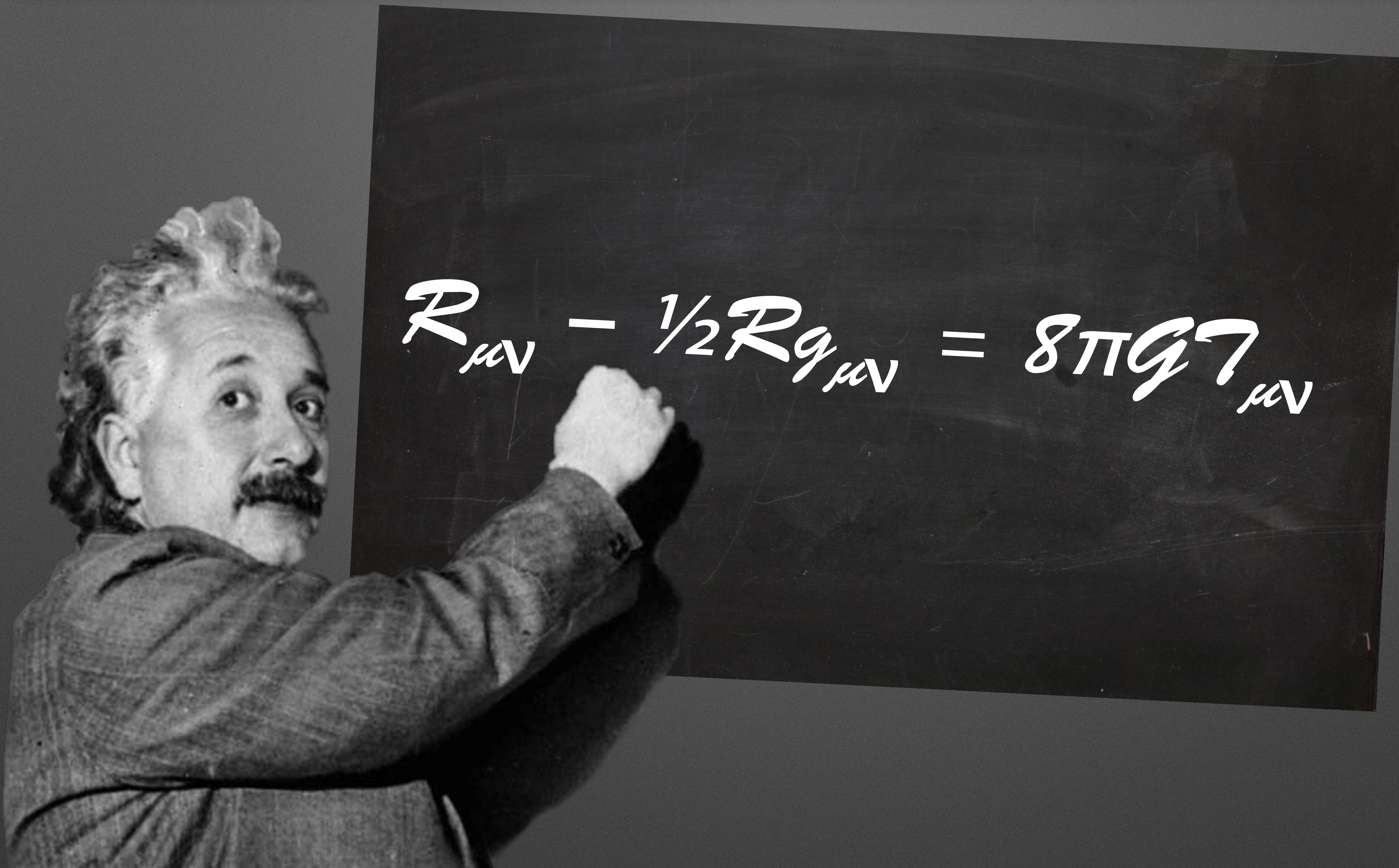
Modern physics describes the Universe at all scale

… down to 10^{-18} cm …



Modern physics describes the Universe at all scale

… using 4 fundamental interactions



Gravity

General relativity

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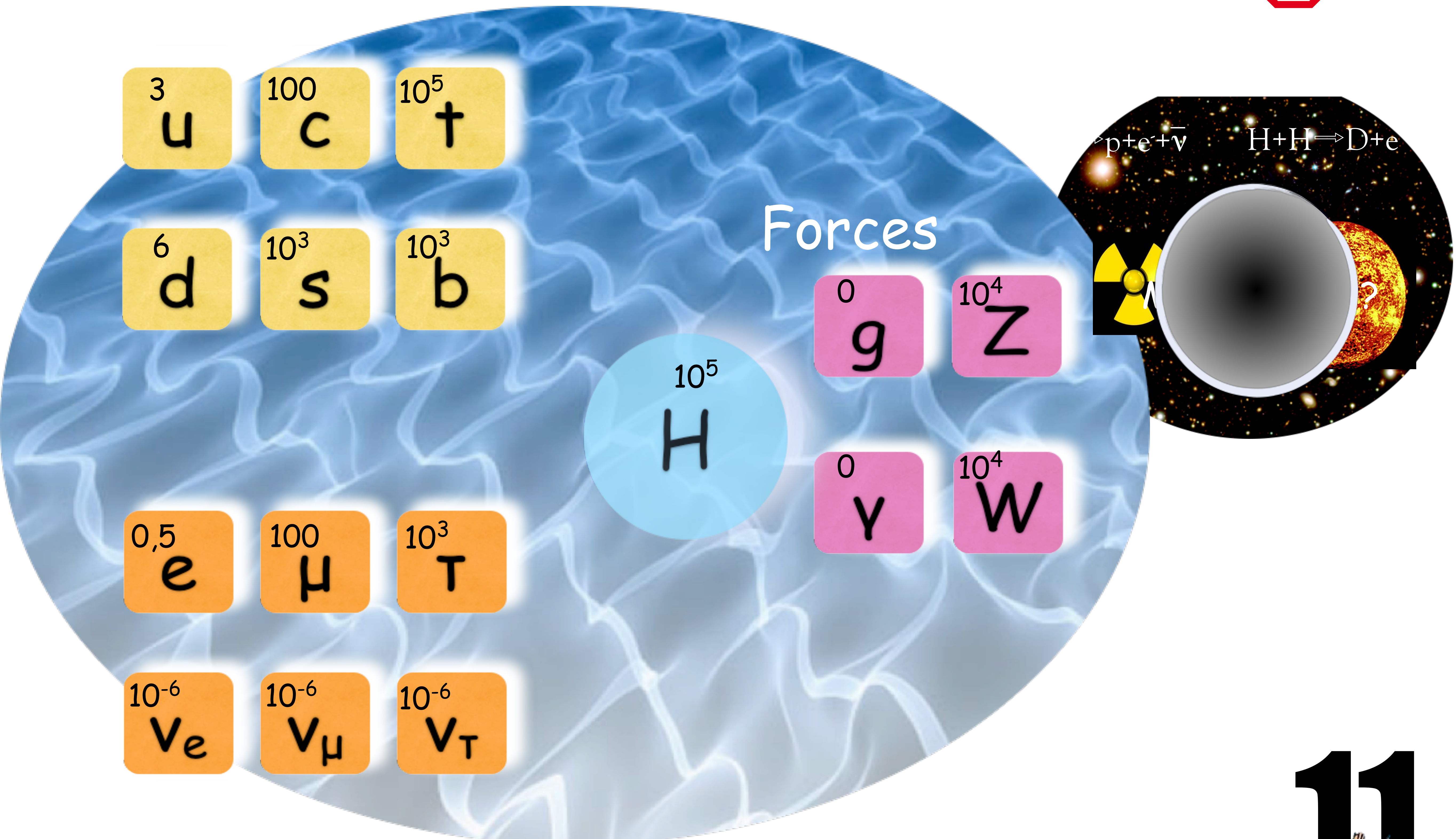
$$
\begin{aligned}
\mathcal{L}_{SM} = \; & \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\
& + \underbrace{\bar{L}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})L + \bar{R}\gamma^{\mu}(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu})R}_{\text{kinetic energies and electroweak interactions of fermions}} \\
& + \underbrace{\frac{1}{2}\left|(i\partial_{\mu} - \frac{1}{2}g\tau\cdot\mathbf{W}_{\mu} - \frac{1}{2}g'YB_{\mu})\,\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma,\text{ and Higgs masses and couplings}} \\
& + \underbrace{g''(\bar{q}\gamma^{\mu}T_{a}q)G^{a}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.)}_{\text{fermion masses and couplings to Higgs}}
\end{aligned}
$$

Strong, Electromagnetic, Weak

Relativistic quantum field theory: the Standard Model



3
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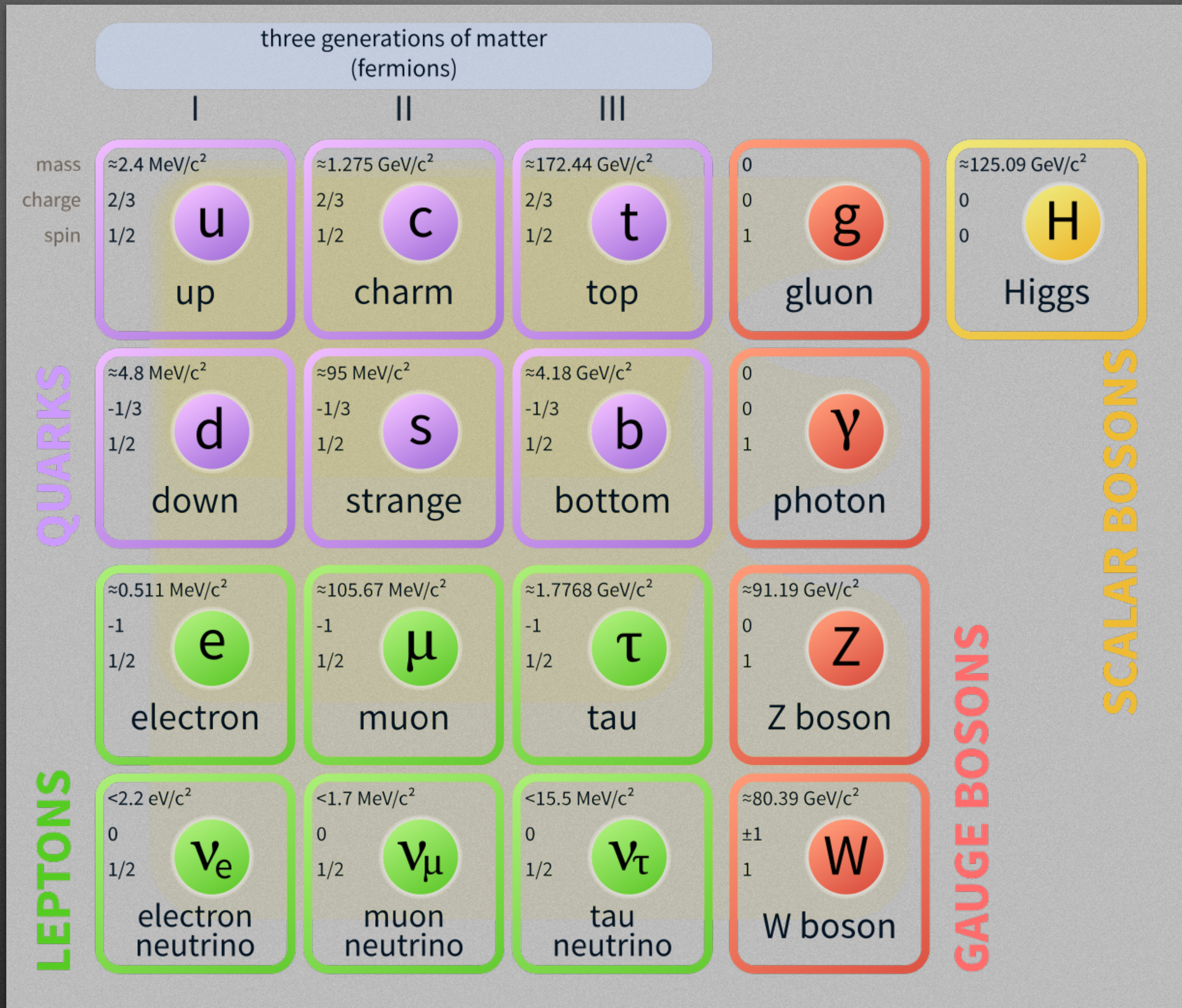
10^{-6}
ν_μ
10^{-6}
ν_τ
10^5
H
Forces
0
g
10^4
Z
0
γ
10^4
W
$p+e+\bar{\nu}$
H+H⇒D+e

11

Standard Model of Elementary Particles



The heavy-ion scientific program is about the Strong Interaction

- Quantum Chromodynamics (QCD) is the relevant theory
- Quarks and Gluons are the characters of the story

QCD primer

Quark mass

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Mass is generated through symmetry breaking phase transition

- Bare mass: electroweak phase transition, interaction with the Higgs field
- Composite mass: chiral symmetry spontaneously broken, non vanishing mass of the chiral condensate

Color charge

- Color charge (R, G, B) is the relevant charge for the strong interaction
  - Only color singlet (color neutral) states appear in nature
  - This is called confinement: there exists no ab initio rigorous mathematical proof

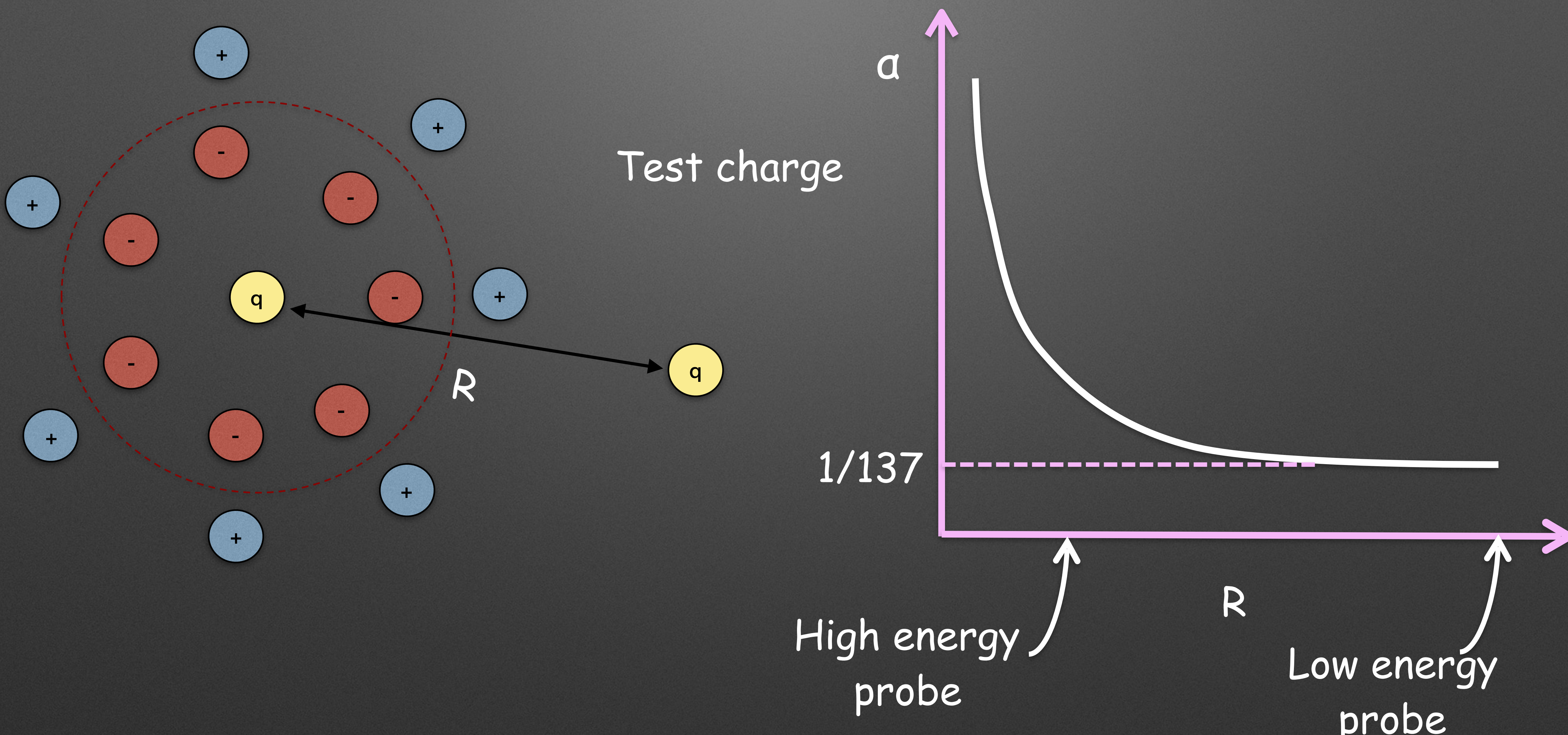
- Quarks (fermions) degrees of freedom
  - 6 flavors
  - 3 colors
  - 2 charge states
  - 2 spin states

Gluon

- The mediator of the strong interaction
  - gluon interact among themselves: asymptotic freedom, color confinement, chiral symmetry breaking
- Gluon (boson) degrees of freedom
  - 8 choices of colors
  - 2 helicity states

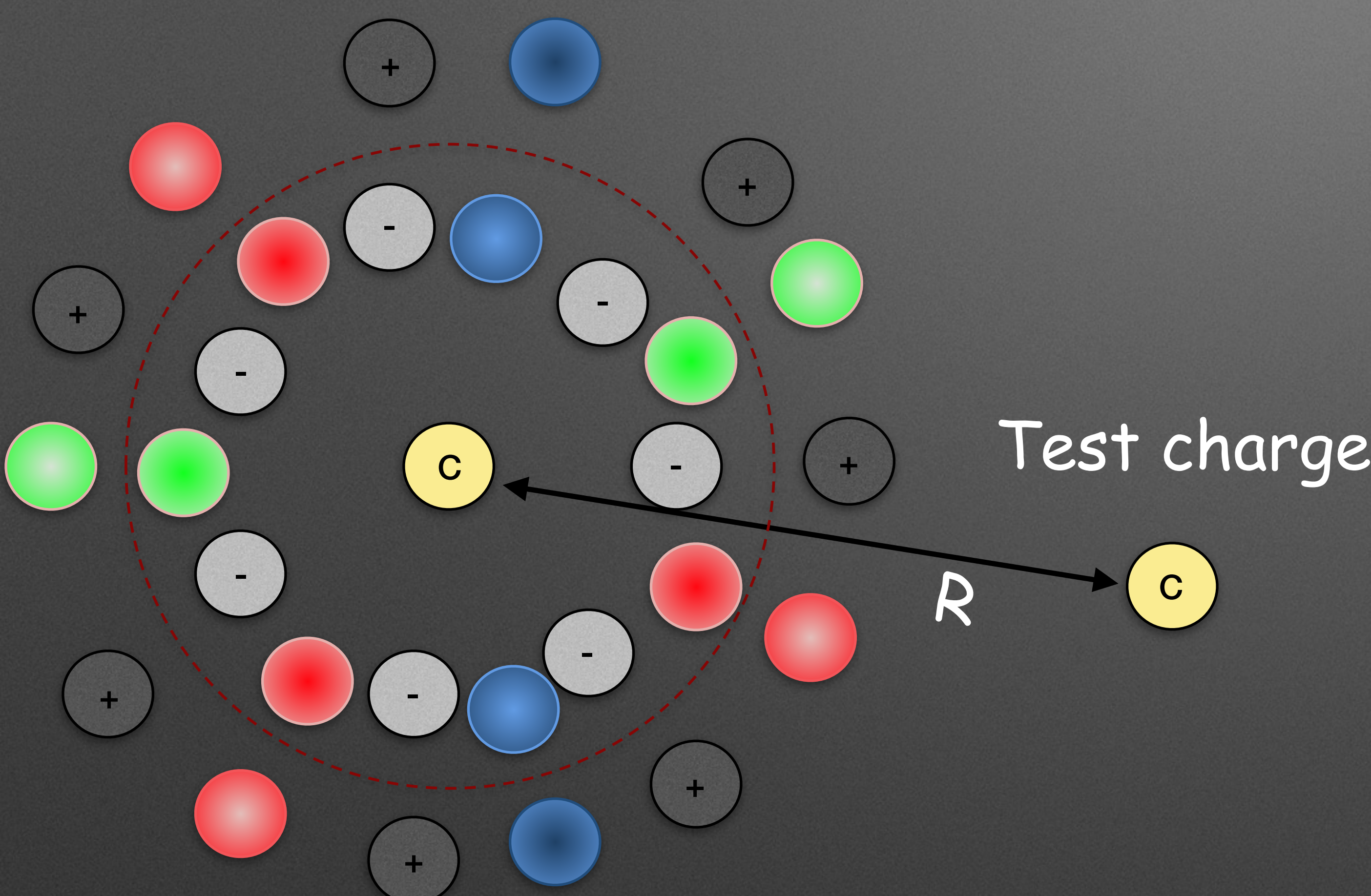
Vacuum polarisation

Remember QED

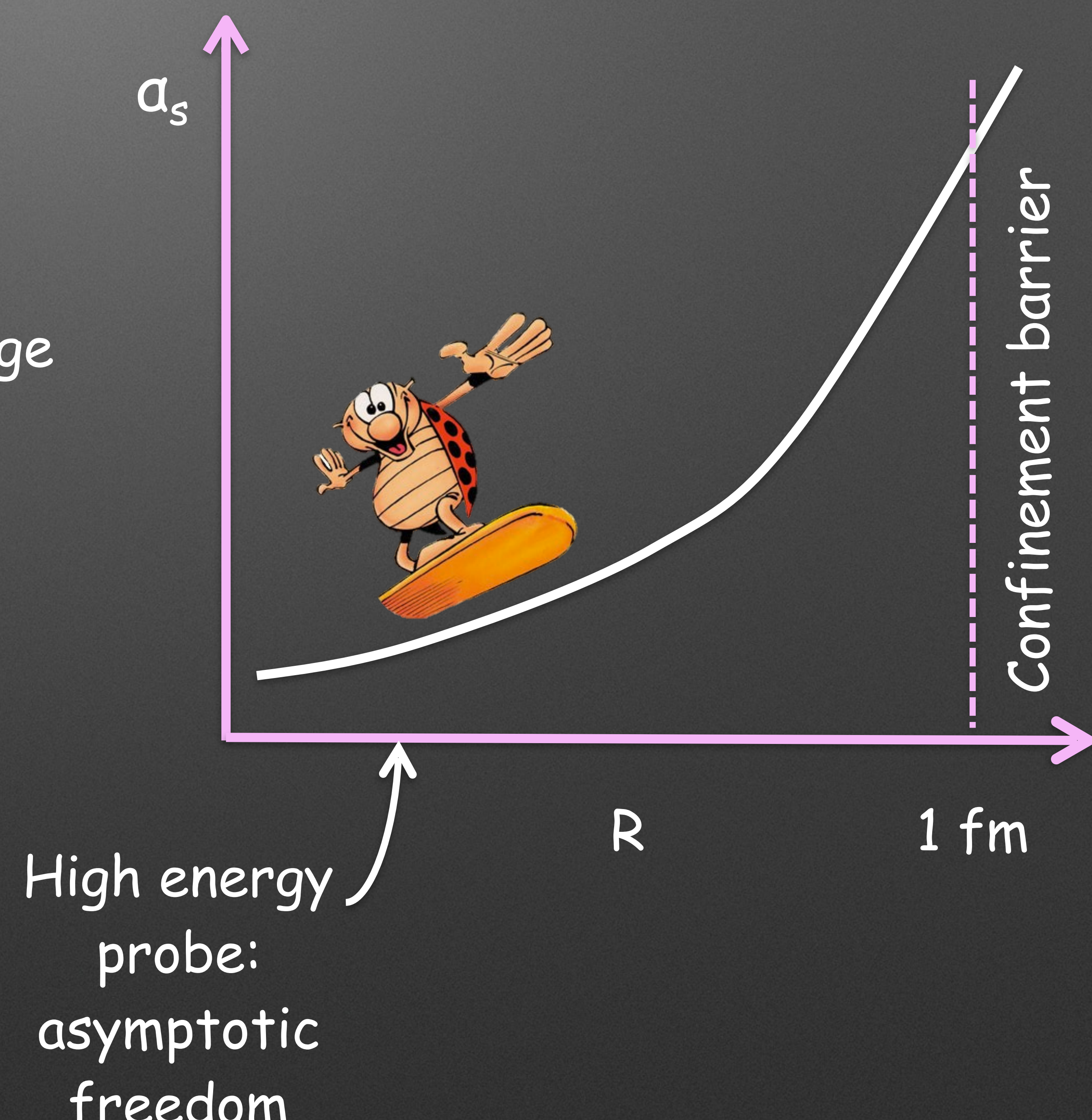


Vacuum polarisation

QCD is different



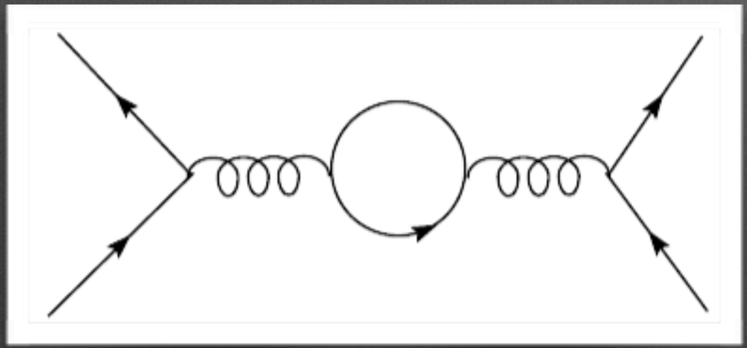
$q\bar{q}$ screening
+
$g\bar{g}$ anti-screening



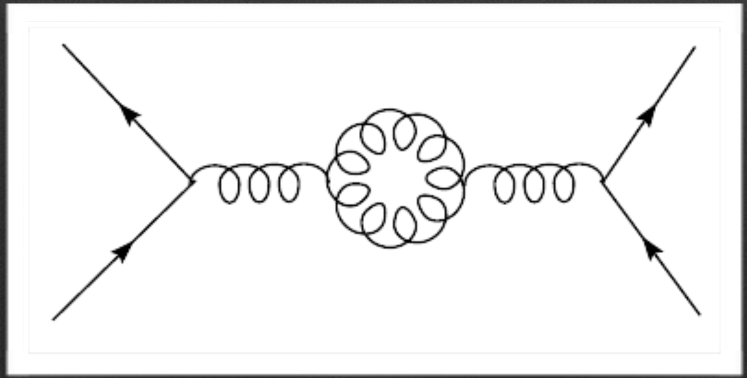
Asymptotic freedom

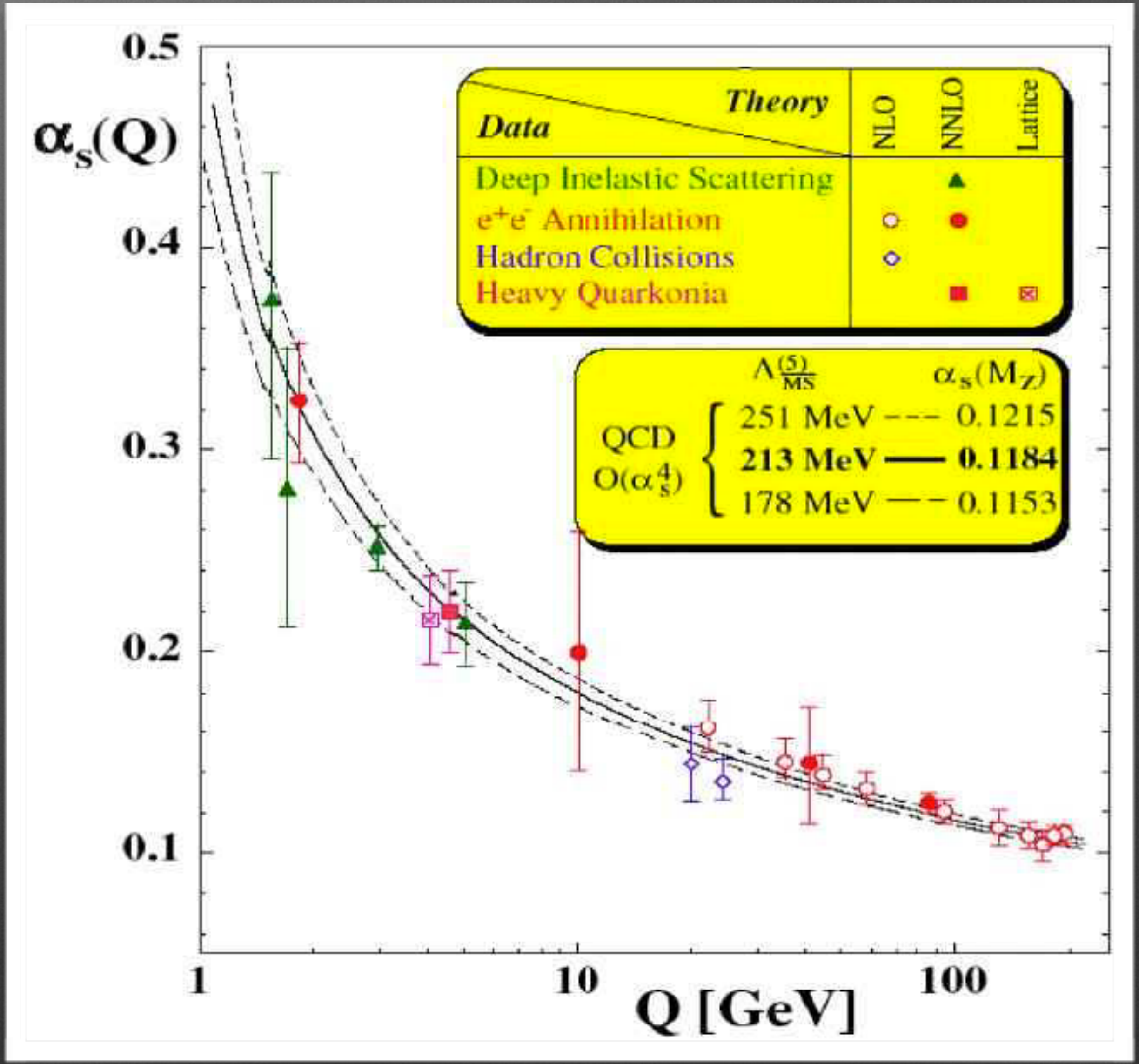
At short distance

- Vacuum polarization makes the interaction stronger ($q\bar{q}$ screening)



- Non linear gluon interaction makes the interaction weaker ($g\bar{g}$ anti screening)





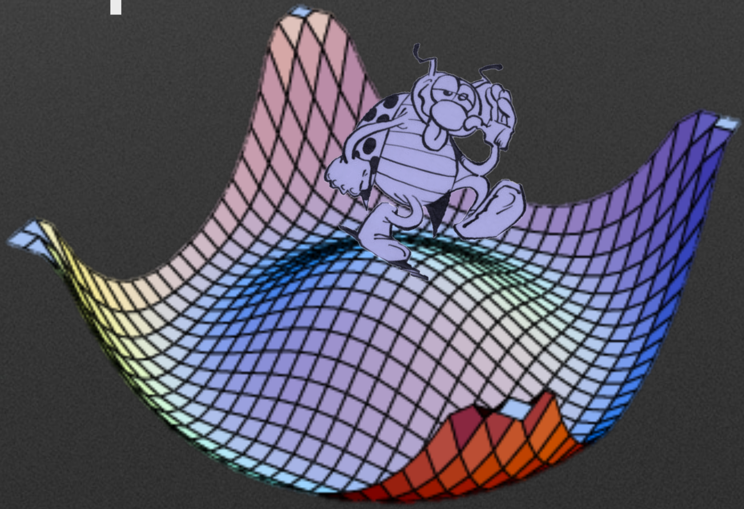
Chiral symmetry

- QCD vacuum

  An intrinsic symmetry of QCD for massless quarks: the strong interaction does not couple the left- and right-handed quarks

- True vacuum

  Quarks acquire mass through the spontaneous breaking of the symmetry



Explore the QCD vacuum

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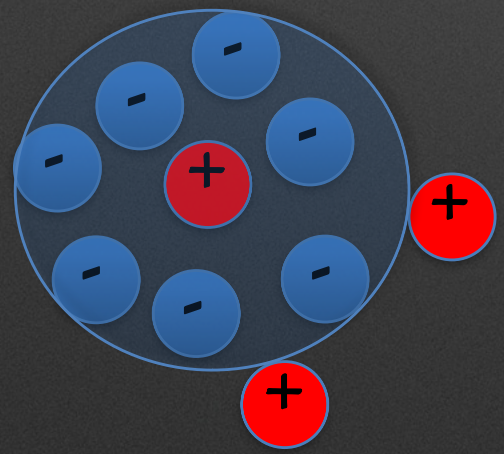
- If color charge density becomes sufficiently high, Debye screening (electric charge in a plasma) weakens the interaction also at large distance !

- The system becomes a color conductor with free color charges: we call such a system the Quark Gluon Plasma (QGP)



$$V(r) = \frac{e^{(-r/r_{Debye})}}{r}, \quad r_{Debye} = \frac{1}{gT}$$

Does such a system exist ?

- At very early times in the history of the Universe, temperature was high enough $T \approx 100$ GeV (electroweak phase transition)
  - All particles of the SM are relativistic
  - $N_{particles} = N_{\overline{particles}}$ (chemical potential $\mu = 0$)
  - Quarks interaction is weak
  - Chiral symmetry

} → Quarks with small bare mass are deconfined ≡ QGP

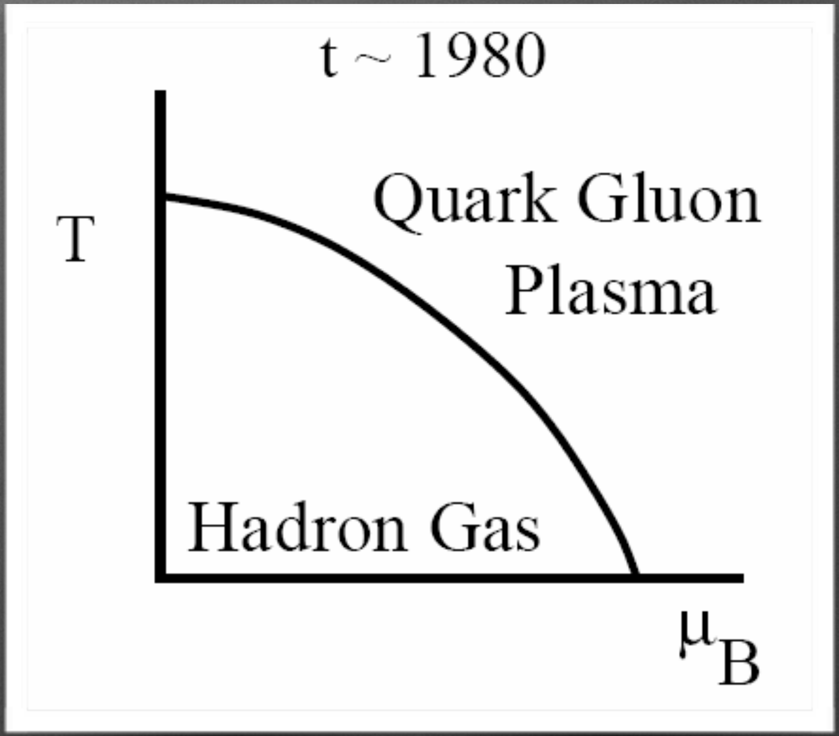
« In high-energy physics we have concentrated on experiments in which we distributed a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of 'vacuum' we must turn in a different direction; we should investigate some bulk phenomena by distributing high energy over a relatively large volume »

-T.D. Lee, Rev. Mod. Phys. 47 (1975)

QGP: a new state of matter

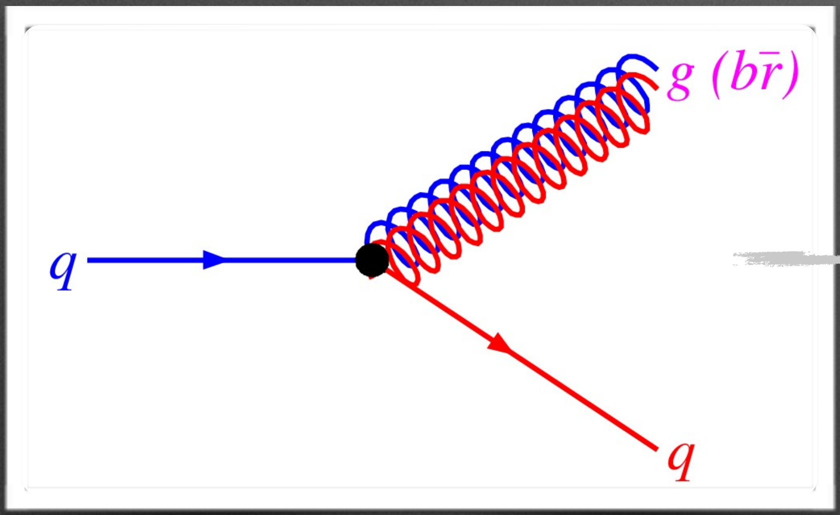
- Transformation of nuclear matter into deconfined phase at high T (*if temperature and/or nuclear densities are high enough quarks and gluons become free*)

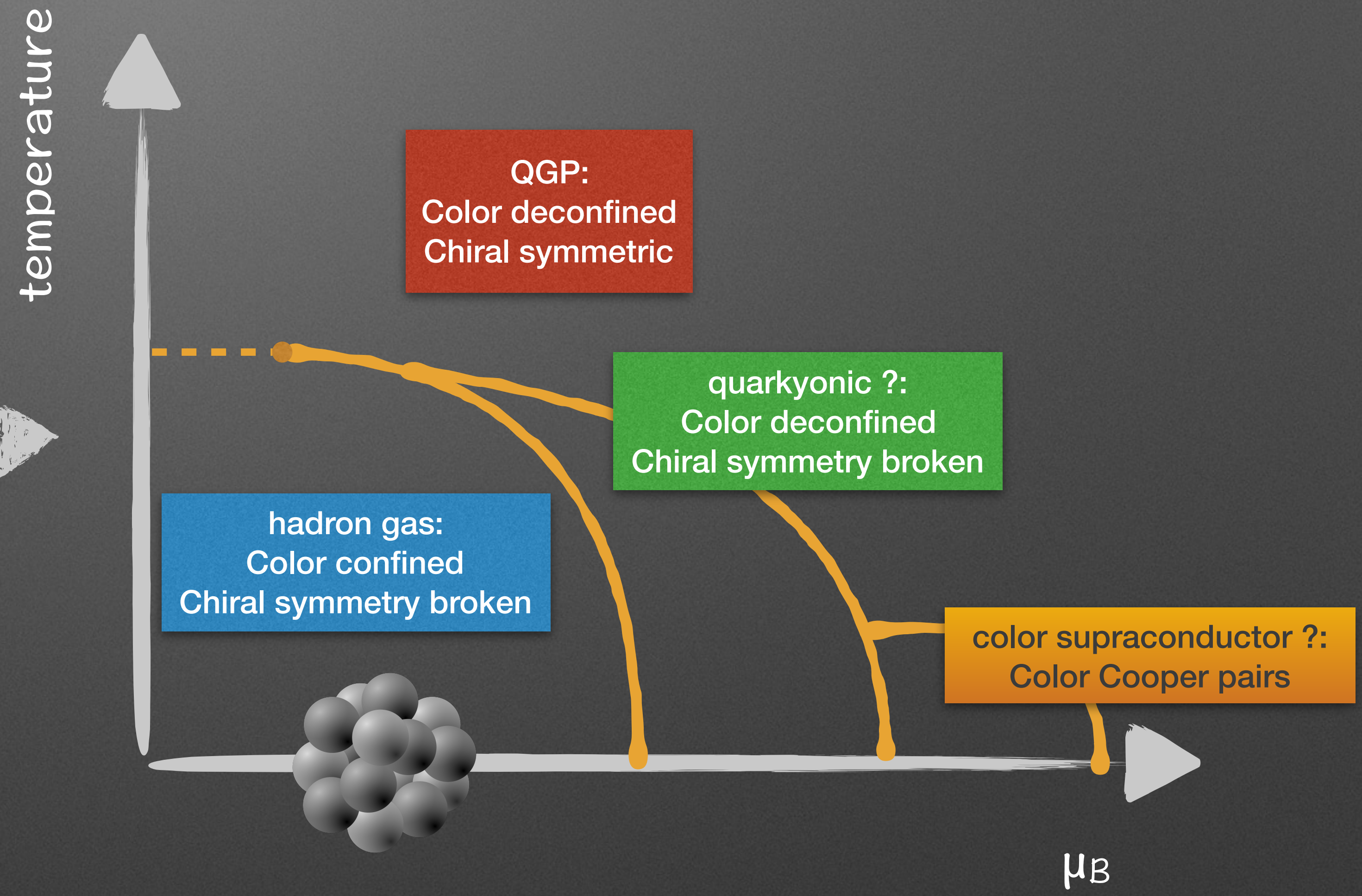
- Quark Gluon Plasma
  - Ideal gas: no interaction between quarks and gluons
  - Liquid: significant interactions between quarks and gluons



✓ μ_B = baryon chemical potential; measure of net baryon density
✓ T_c = critical temperature [150 - 200 MeV @ μ_B = 0]
✓ ρ_B = critical density [0.5 - 2 baryons/fm^3]

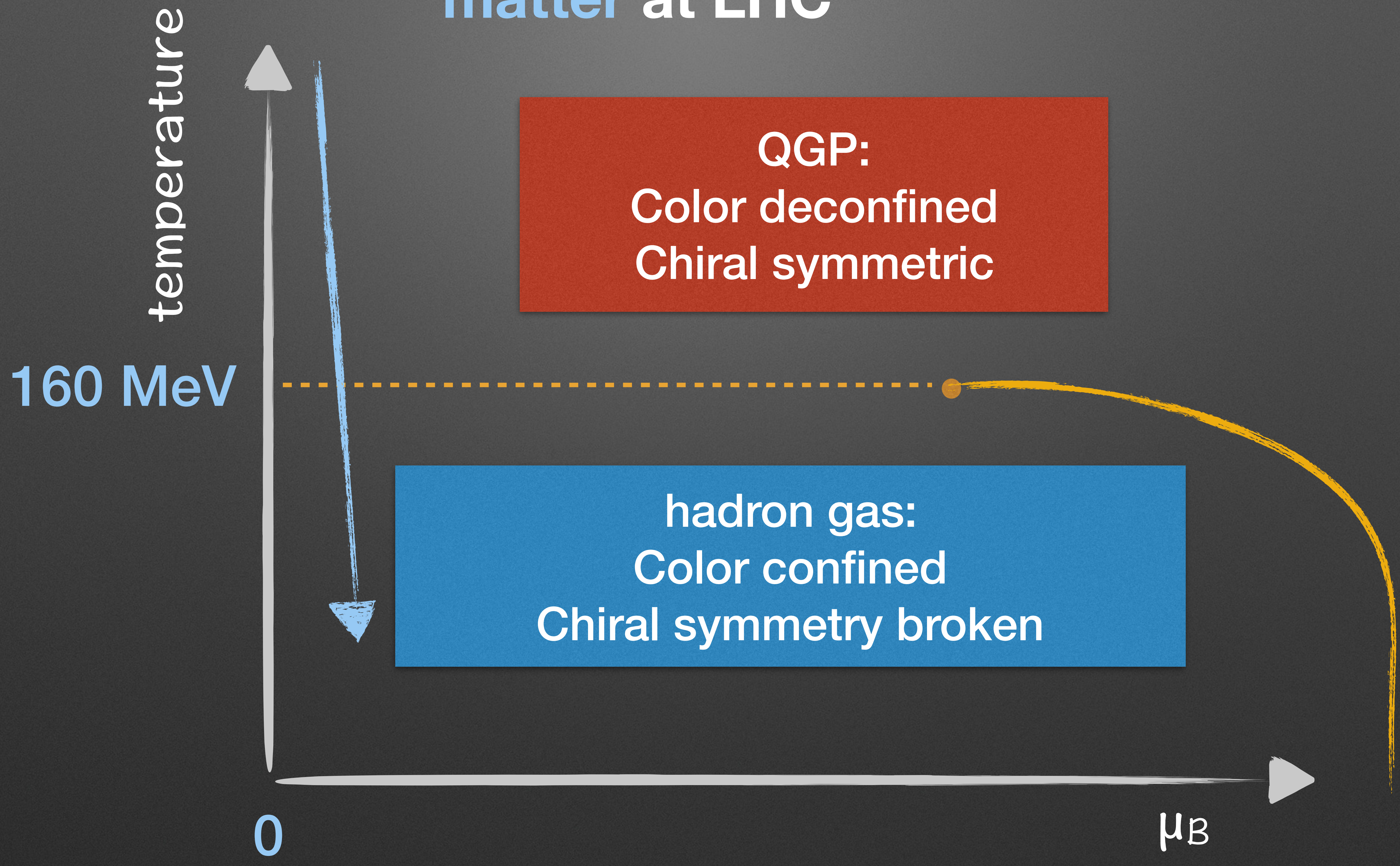
Thermodynamics of strongly interacting matter



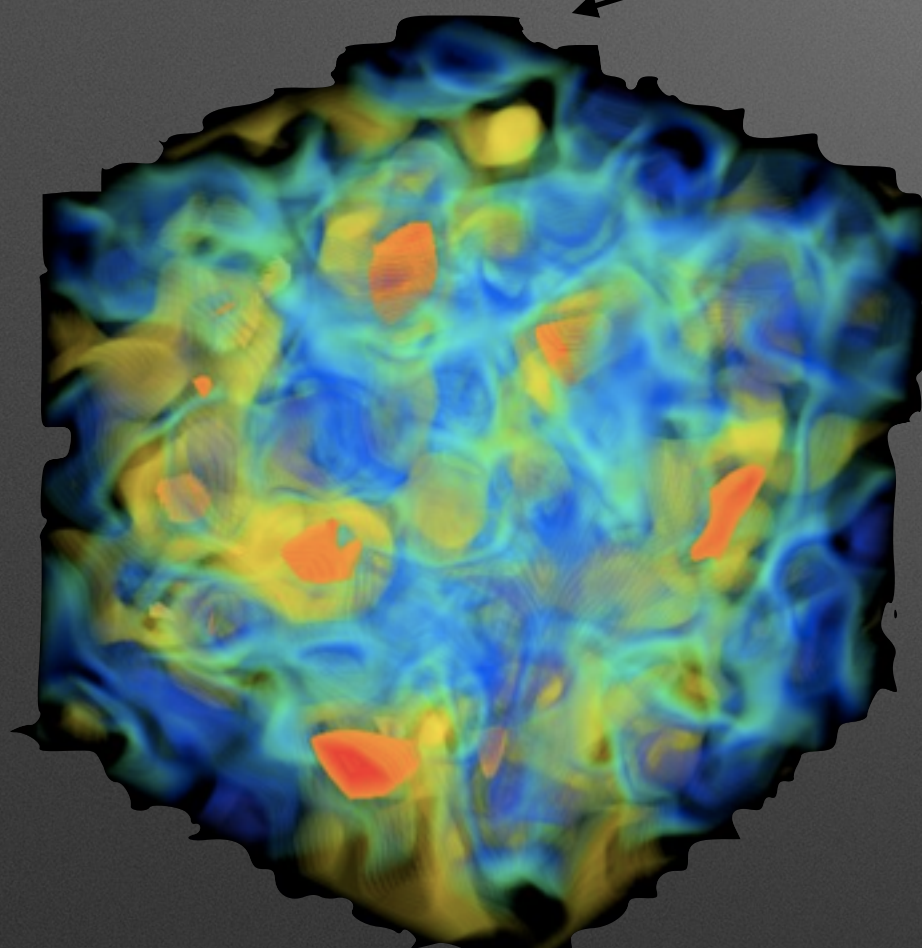


How does the complexity of the phase diagram of matter emerge from the dynamics of the strong interaction ?

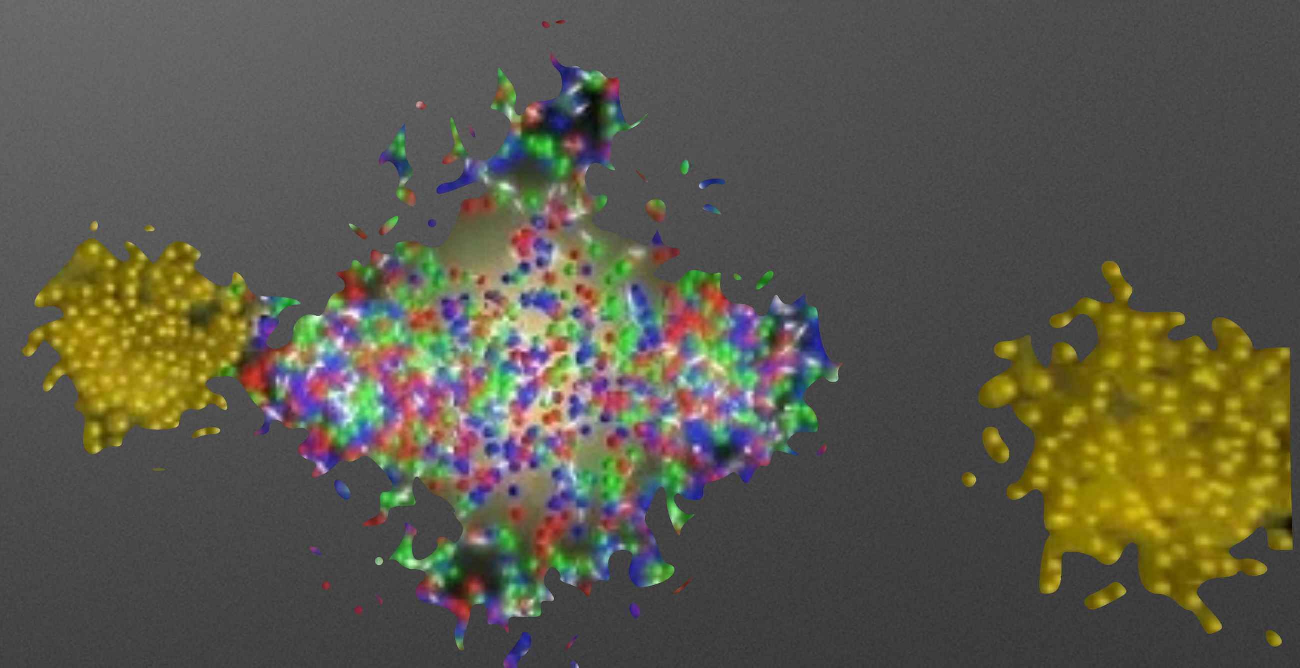
Thermodynamics of strongly interacting matter at LHC



Thermodynamics of strongly interacting matter



Statistical QCD



Heavy-ion collisions

Thermodynamics primer

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- Energy density (*free hot gas, μ neglected*)

$$\epsilon_i = \int \frac{d^3 p_i}{(2\pi)^3} \frac{E_i}{e^{\beta E_i} \pm 1}$$

fermions or bosons

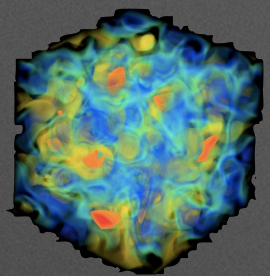
- At high T (*ignoring masses*)

$$\epsilon = \sum_i g_i \epsilon_i = \frac{\pi^2}{30} N \left(k_B T\right)^4$$

degrees of freedom

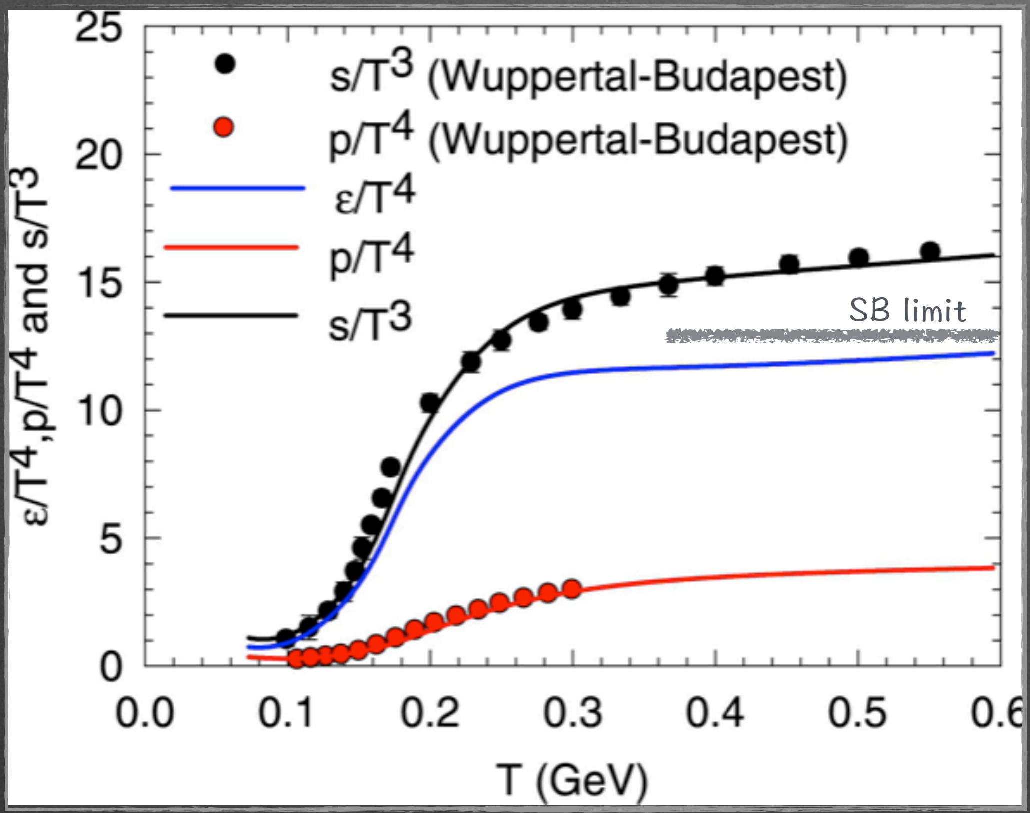
- QGP: $N = 2 \times 8 + 4 \times 3 \times n_F$ (gluons: 2×8; quarks: $4 \times 3 \times n_F$)

- Hadrons: $N = 3$ (pions only)



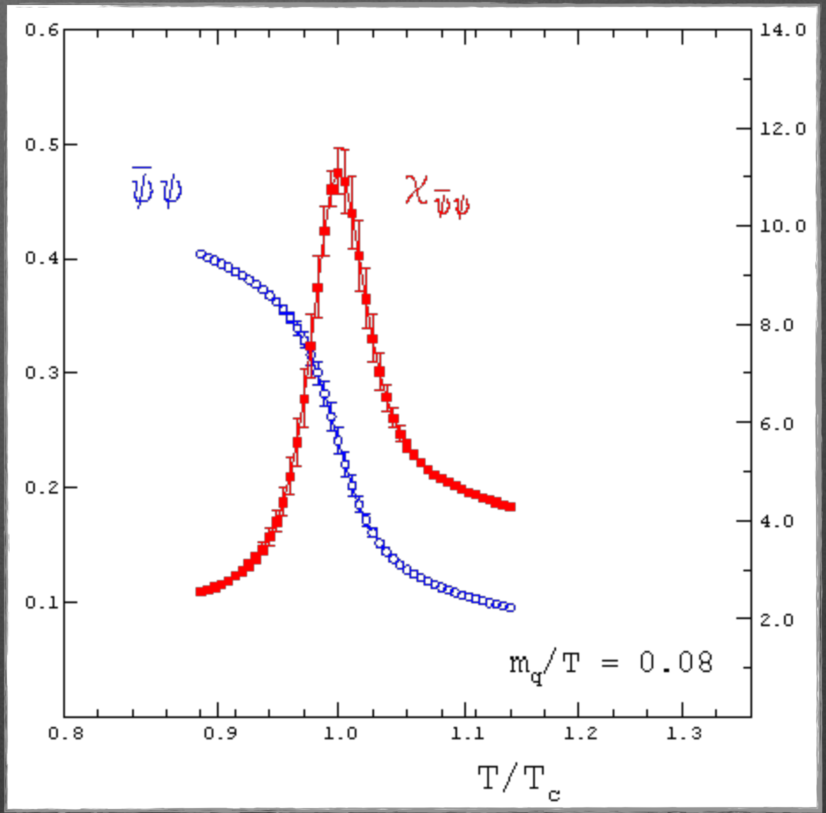
Established facts: theory

Z_3 symmetry restored



smooth transition from HG to QGP

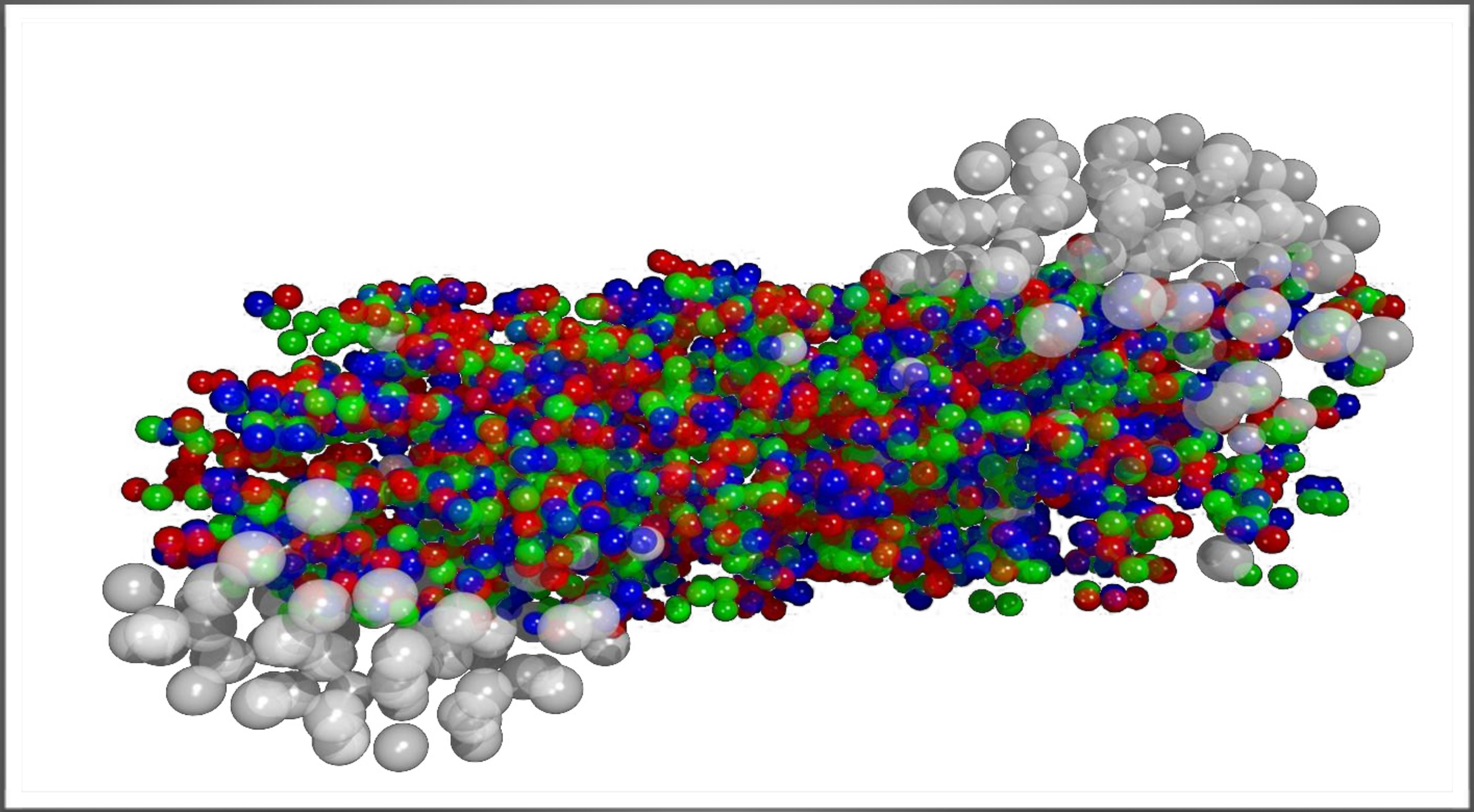
Chiral symmetry restored

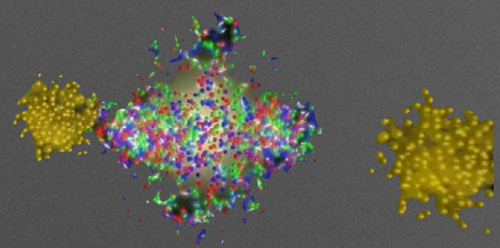


quarks mass reverts to Higgs mass

T = 154 ± 9 MeV

Established facts: experiment





Established facts: experiment

Matter created at LHC :

- hottest matter created in laboratory ($T > 300$ MeV)
- has the properties of a liquid (strongly coupled)
- the most perfect perfect liquid (non dissipative)

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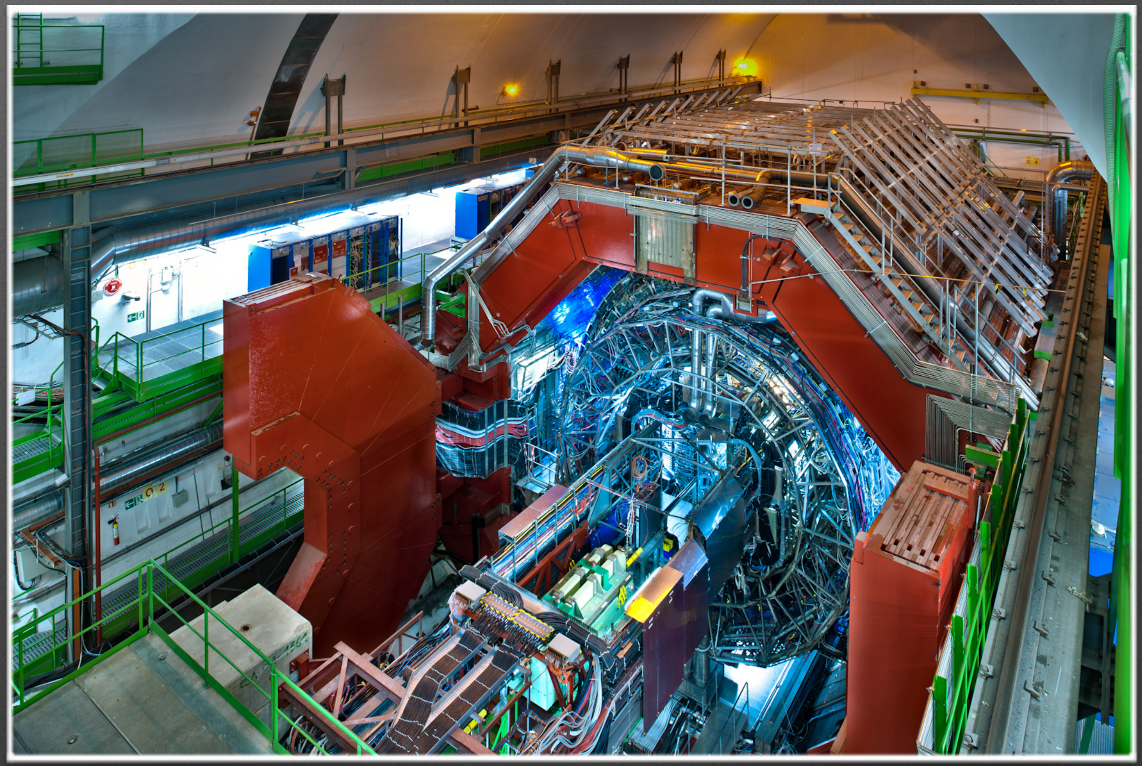
The ALICE core mandate

Establish the fundamental properties of strongly interacting matter through measurements

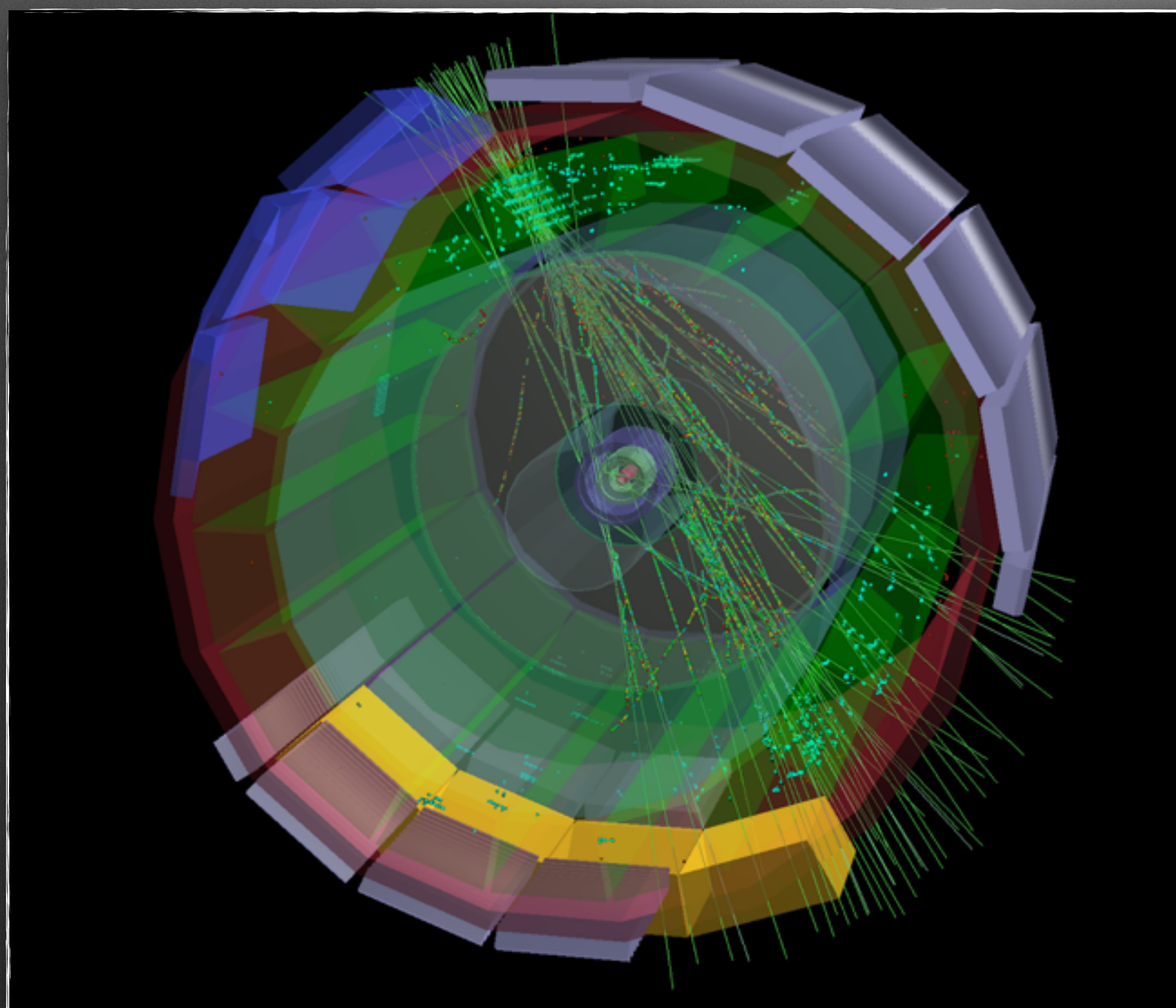
- complete ($p_t \sim T \oplus PID \oplus p_t \gg \Lambda_{QCD}$)
- precision

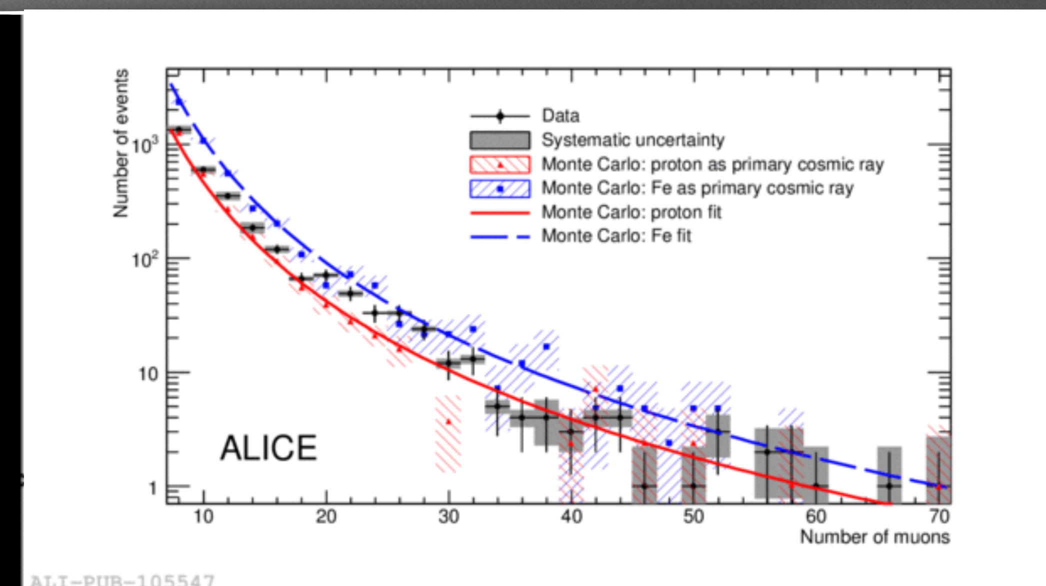


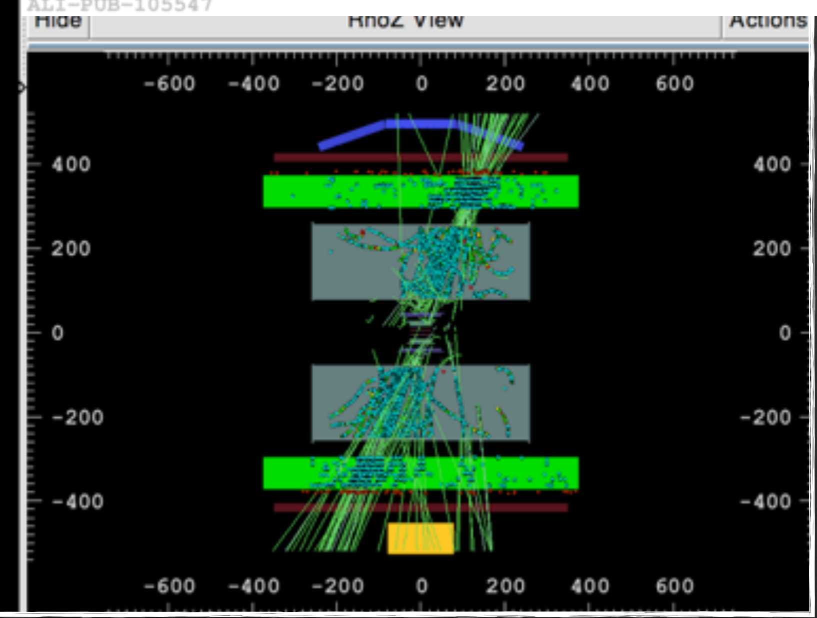
Standard strategy

- Large and dense: heavy-ion physics
  - AA ➜ pQCD + Npdf + FF + collectivity
- Small and dilute: comparison measurement
  - pp ➜ pQCD + pdf + FF
  - pA ➜ pQCD + Npdf + FF

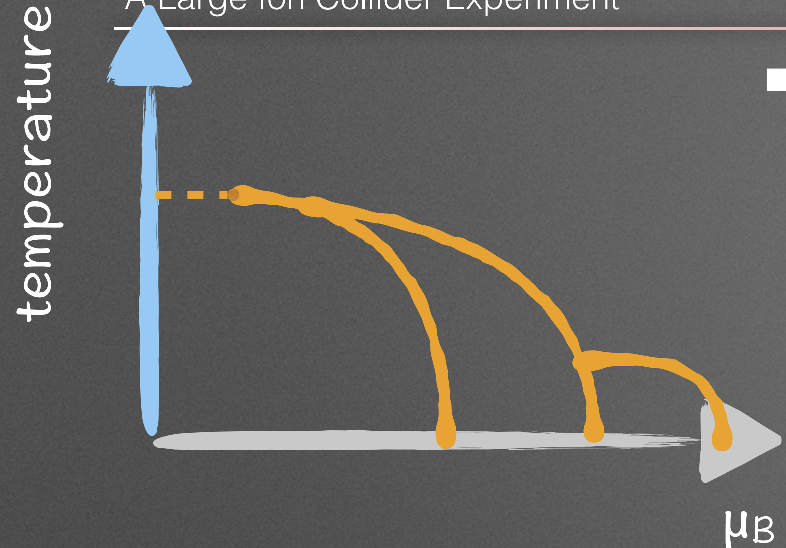
Cosmics




Number of events
Data
Systematic uncertainty
Monte Carlo: proton as primary cosmic ray
Monte Carlo: Fe as primary cosmic ray
Monte Carlo: proton fit
Monte Carlo: Fe fit
ALICE
Number of muons
ALI-PUB-105547

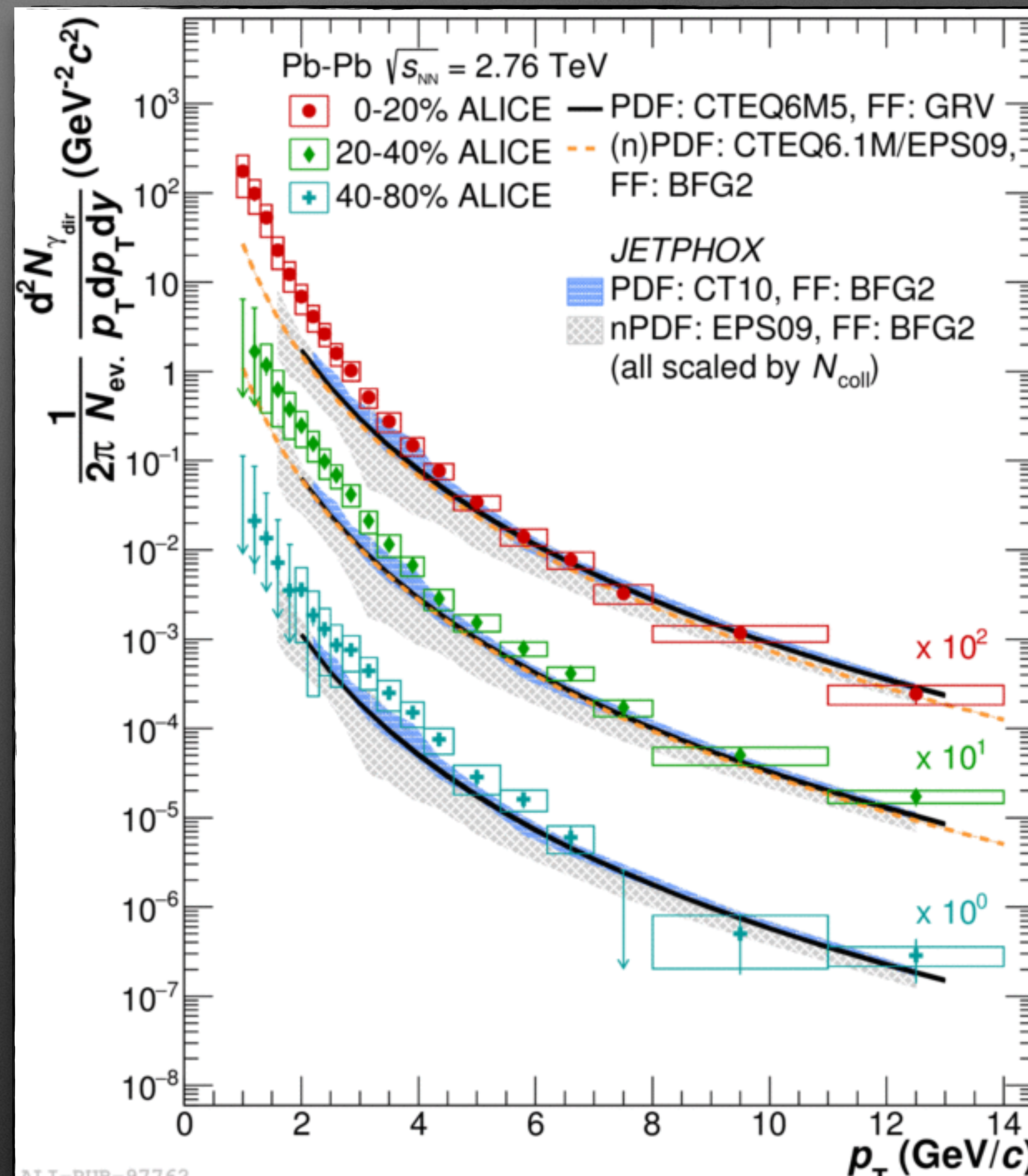

Hide
RhoZ View
Actions

Temperature

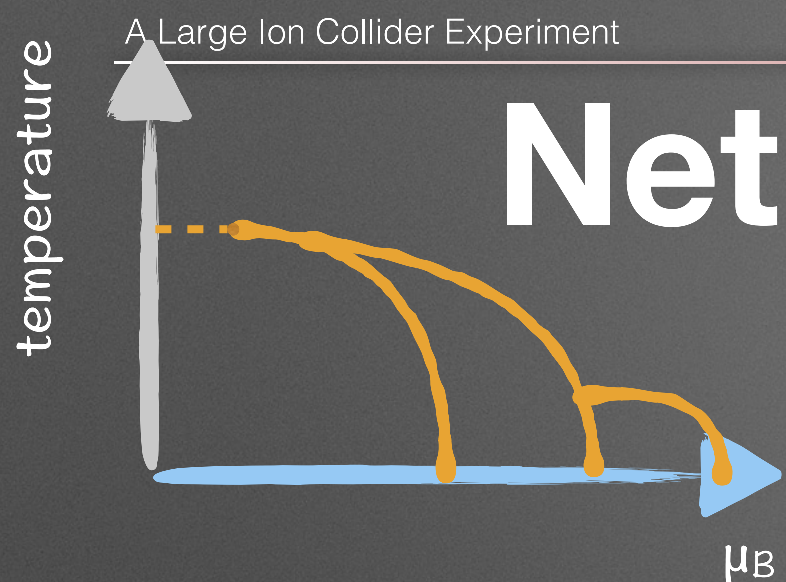


- Direct photons: pQCD + thermal
- $T_{eff} = 297 \pm 12^{stat} \pm 42^{syst}$ MeV

$T_{initial} \gg T_{critical}$

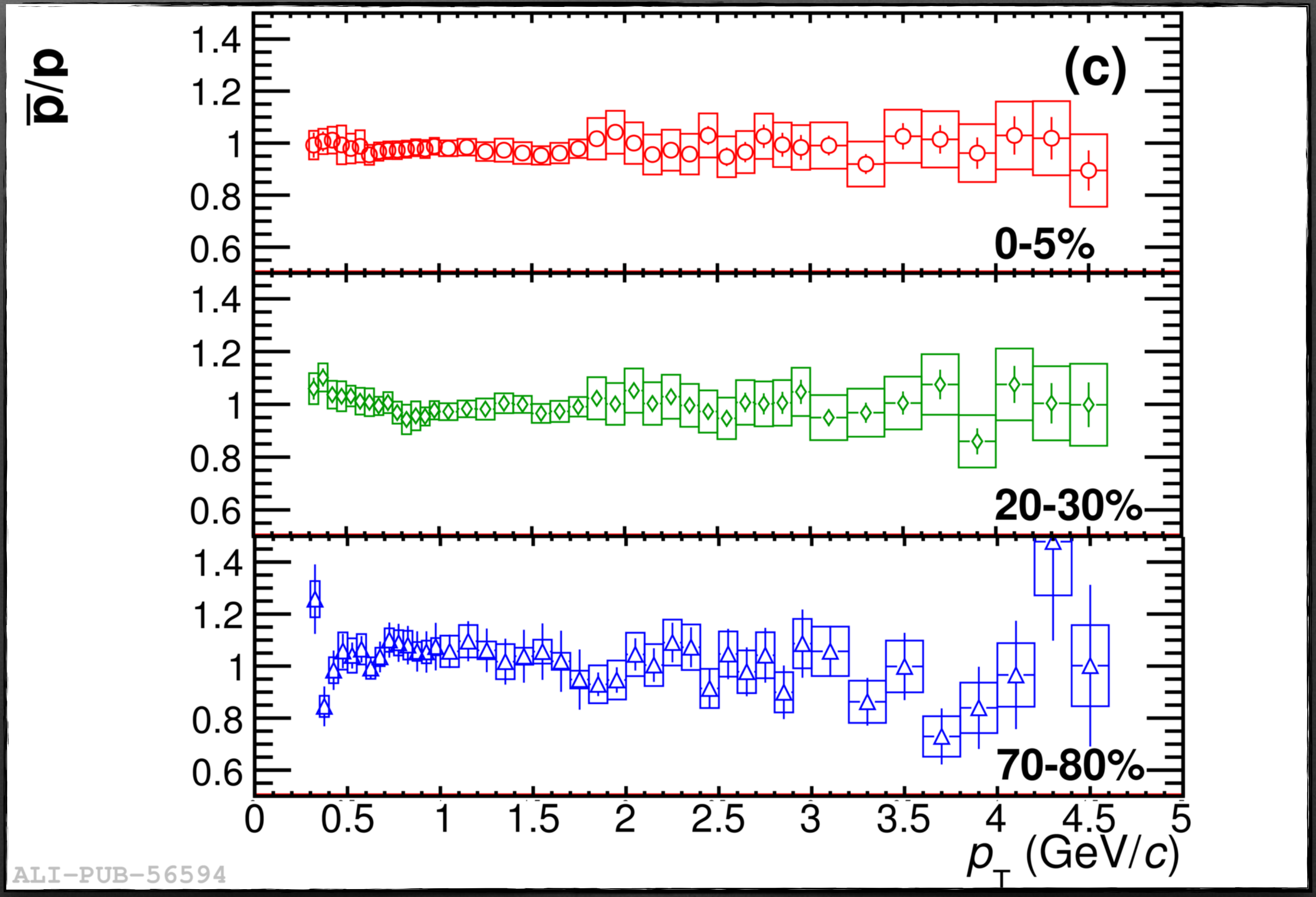


Net baryon number



- Particle to anti-particle ratio = 1

$\mu \sim 0$



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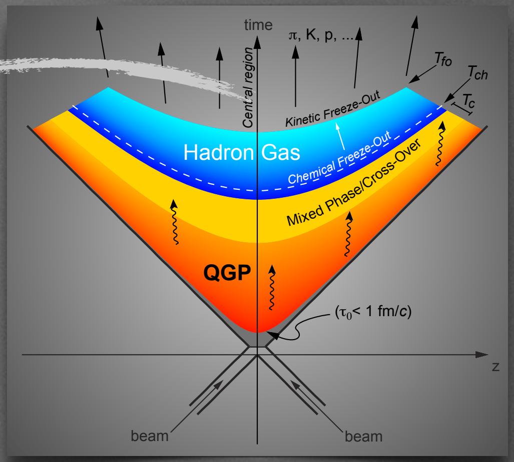
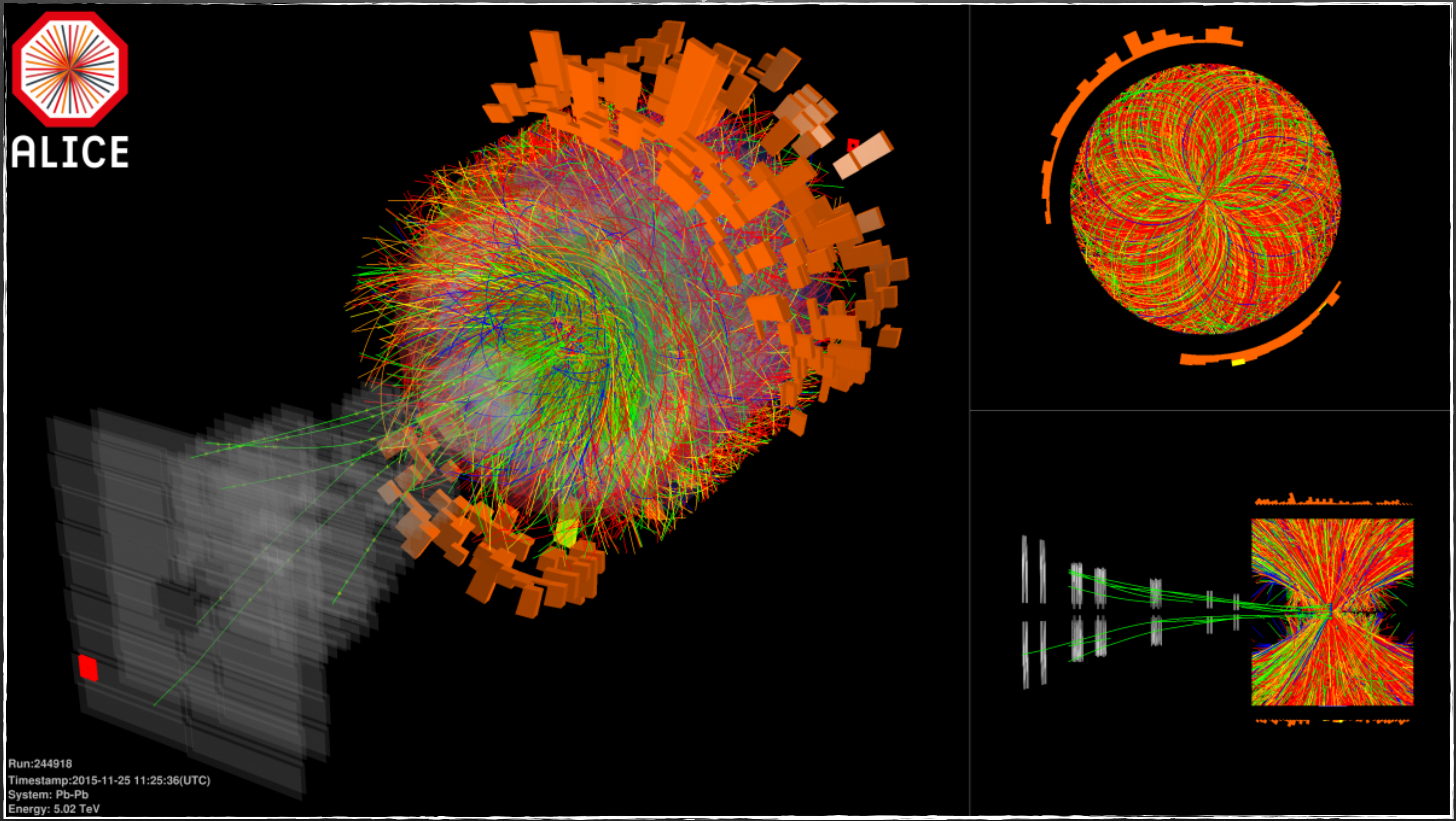
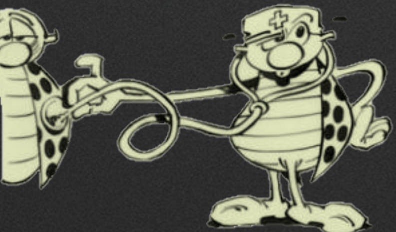
Final state





How to decipher ?

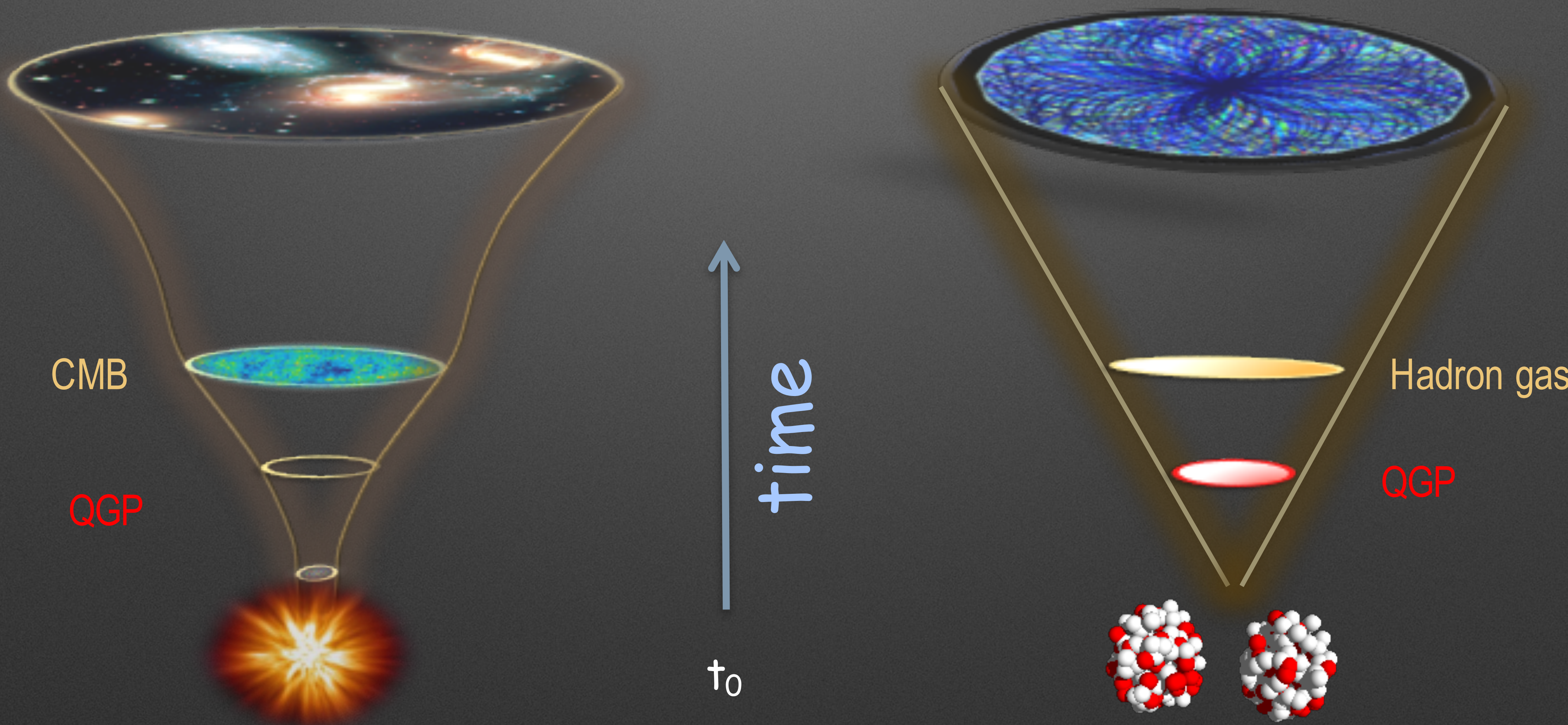


Big Bang

Present t_0+13.7×10^9 years

Little Bang

Present t_0+3×10^{-23} seconds

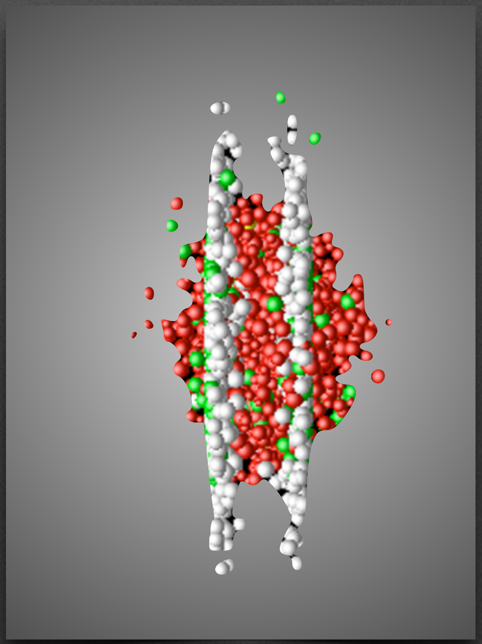


Big Bang

- Global characteristics
  - mass density Ω, age

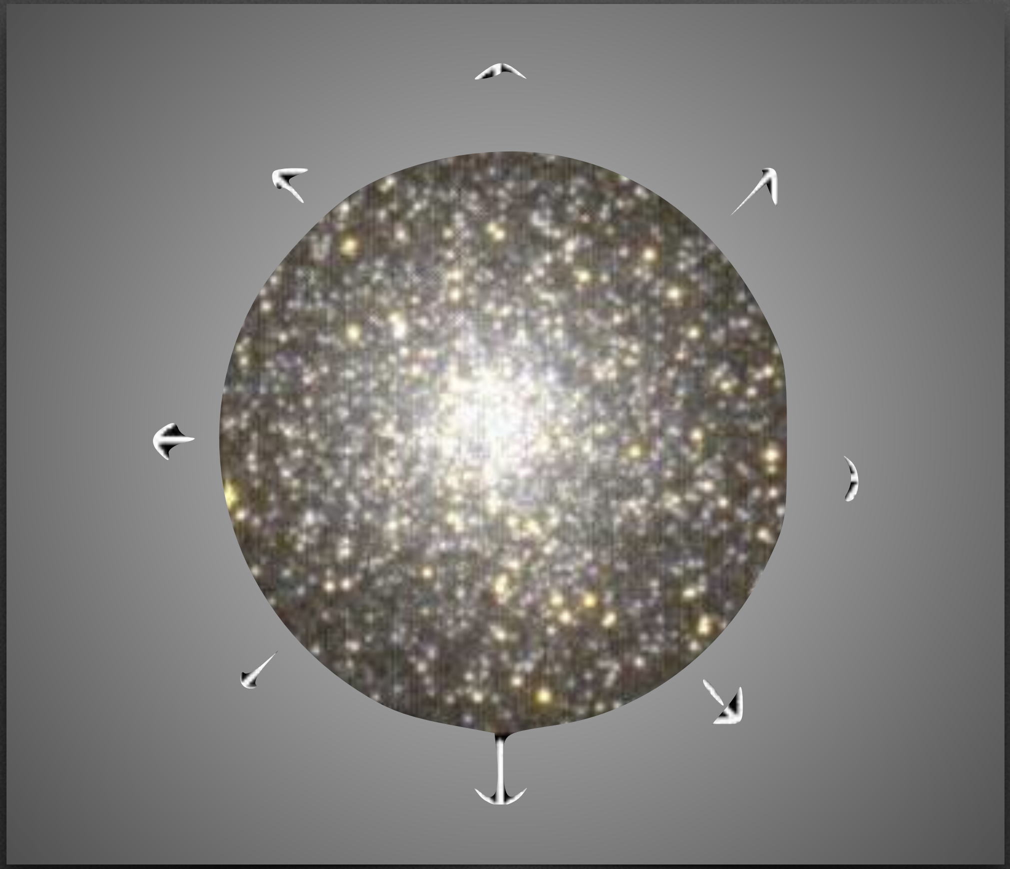
Little Bang

- Global characteristics
  - Energy density, size, lifetime



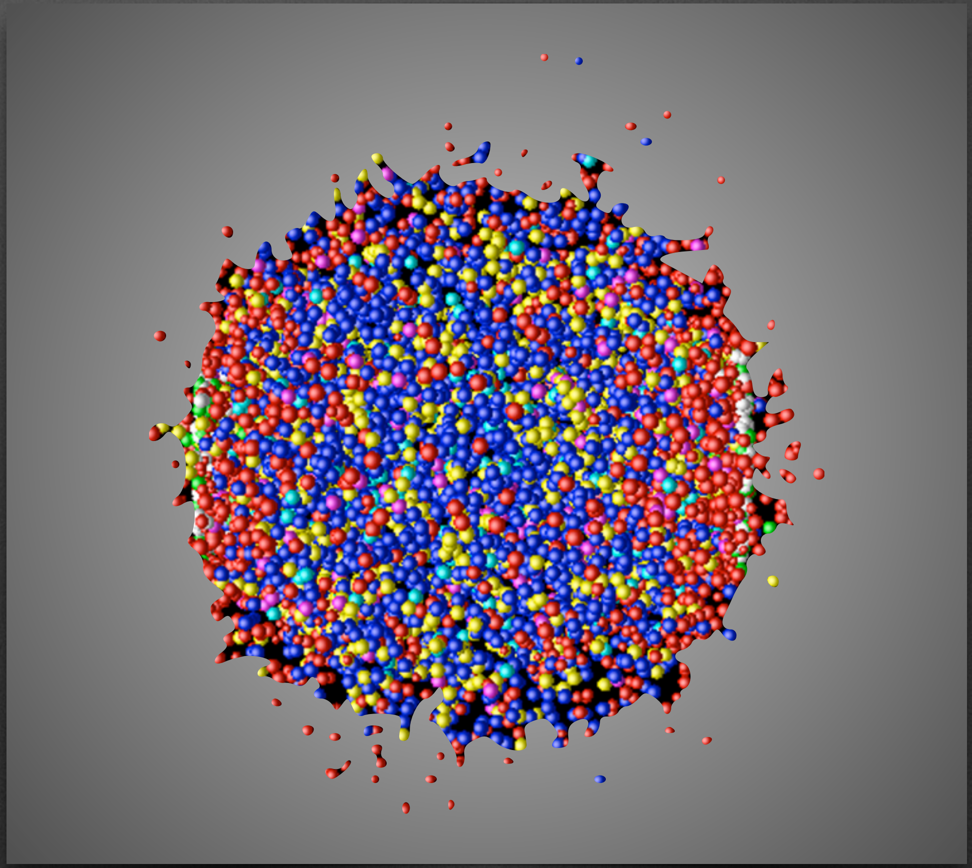
Big Bang

- Global characteristics
  - mass density Ω, age
- Expansion (galaxies)
  - Huble flow



Little Bang

- Global characteristics
  - Energy density, size, lifetime
- Expansion (hadrons)
  - Particles flow, π interferometry



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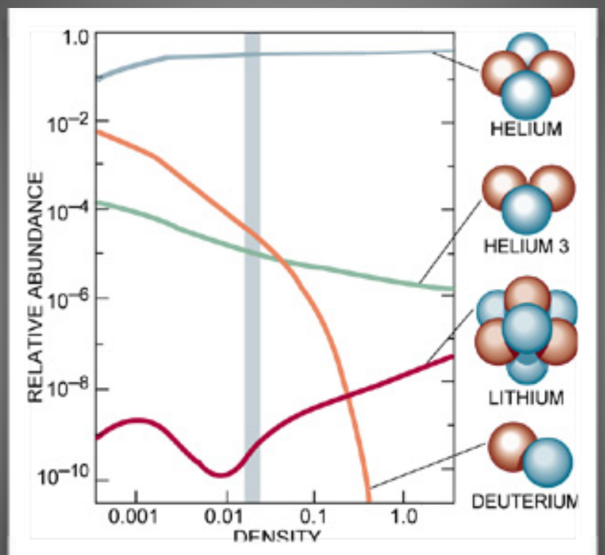
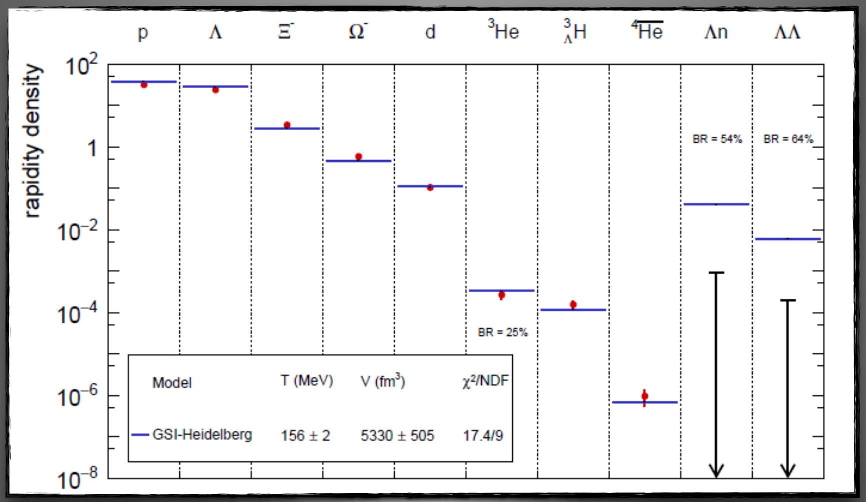
Big Bang

- Expansion (galaxies)
  - Huble flow
- Primordial nucleosynthesis (H, He, Li)
  - Thermodynamics at τ ~ 100 s

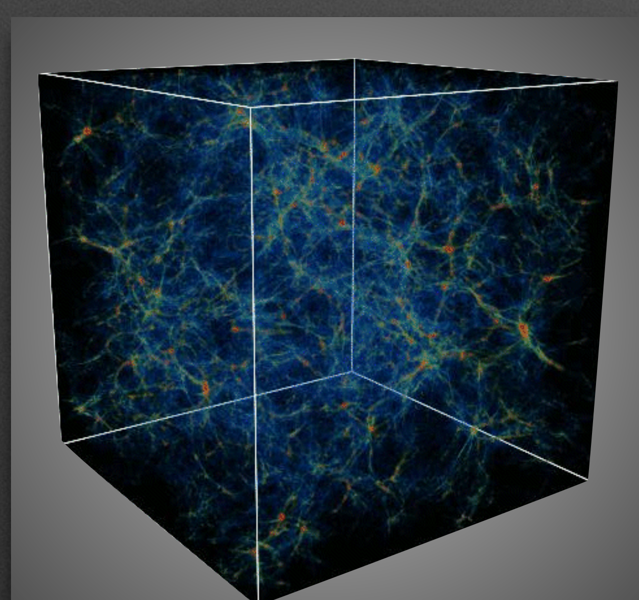


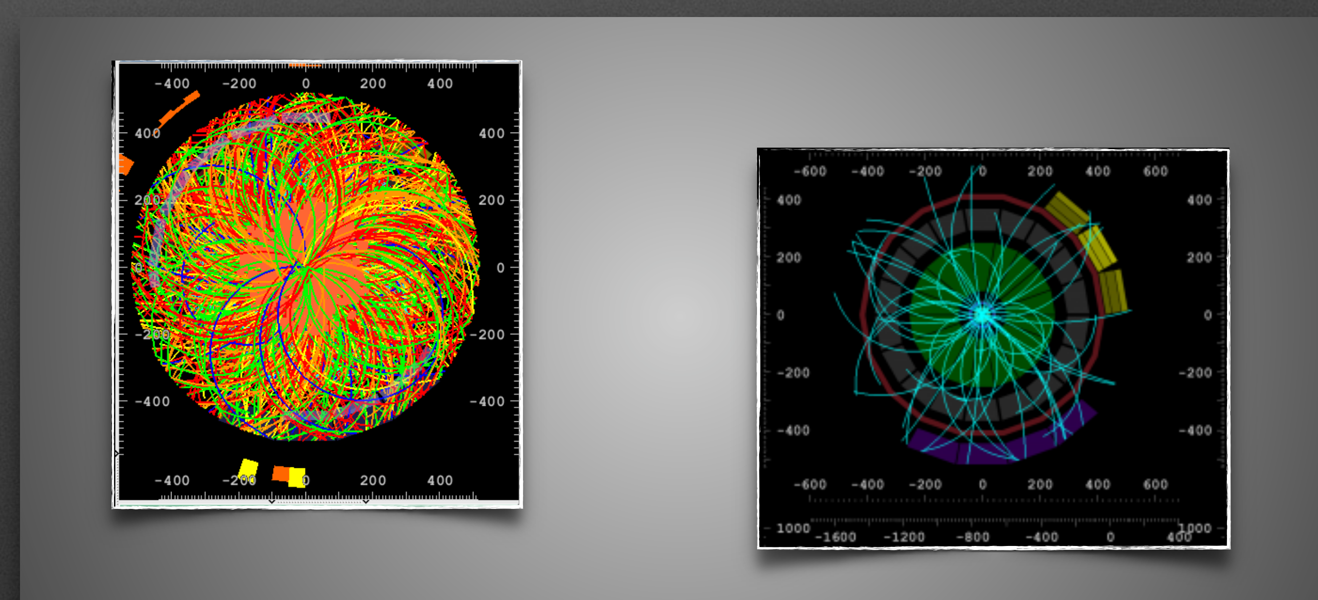
Little Bang

- Expansion (hadrons)
  - Particles flow, π interferometry
- Hadrochemistry (π, K, p ratios)
  - Thermodynamics at τ ~ 10^{-21} s



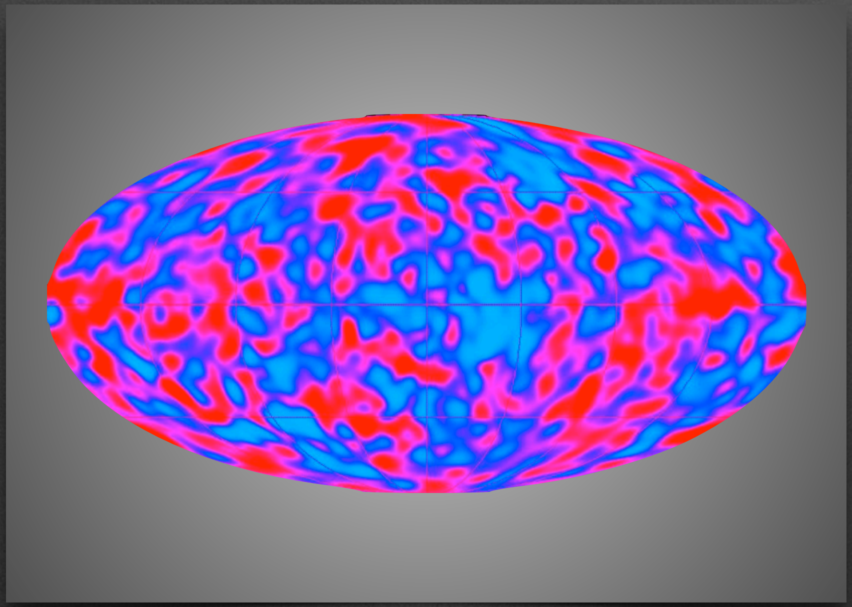
Big Bang	Little Bang
• Primordial nucleosynthesis (H, He, Li)	• Hadrochemistry (π, K, p ratios)
• Thermodynamics at τ ~ 100 s	• Thermodynamics at τ ~ 10^{-21} s
• Large scale structures	• Event structures
• Density fluctuations	• Fluctuations at phase transition





Big Bang

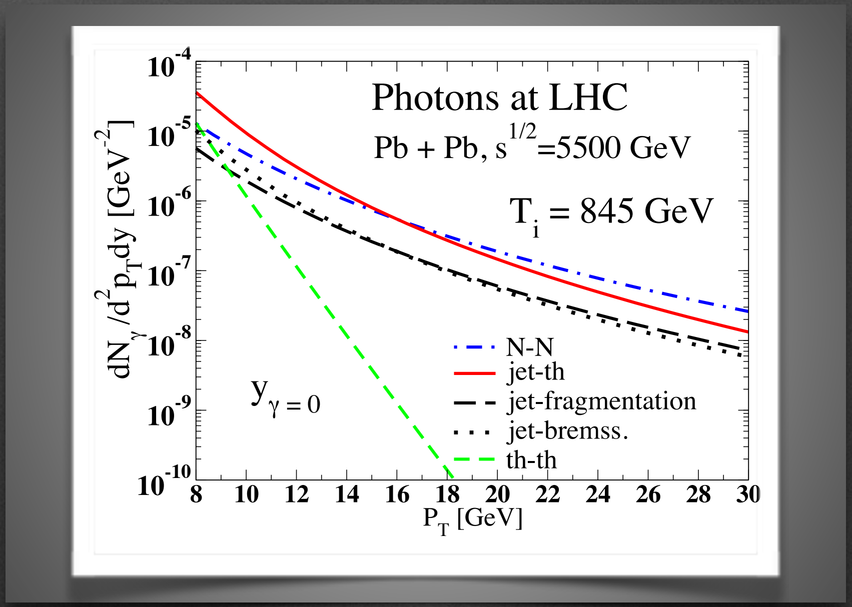
- Large scale structures
  - Density fluctuations
- Cosmic microwave background
  - Temperature at decoupling



COBE (*Cosmic Background Explorer*)

Little Bang

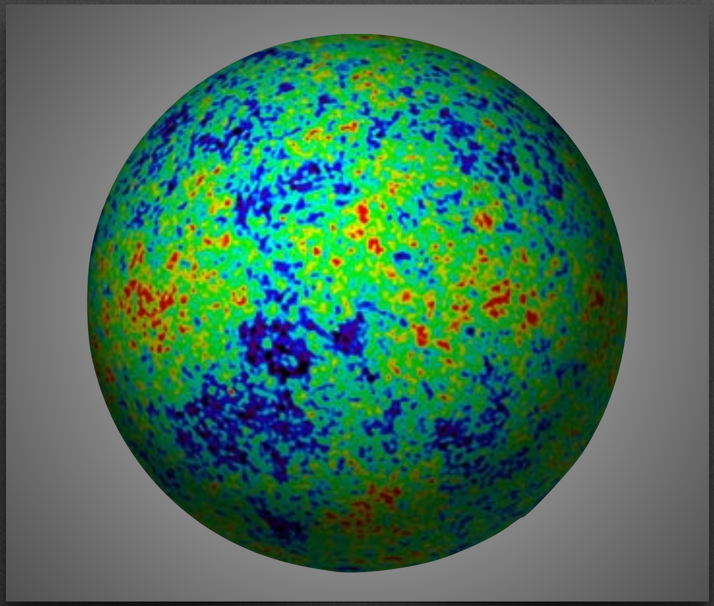
- Event structures
  - Fluctuations at phase transition
- Thermal radiation (γ, l^+l^-)
  - Time evolution of temperature



Black body radiation

Big Bang

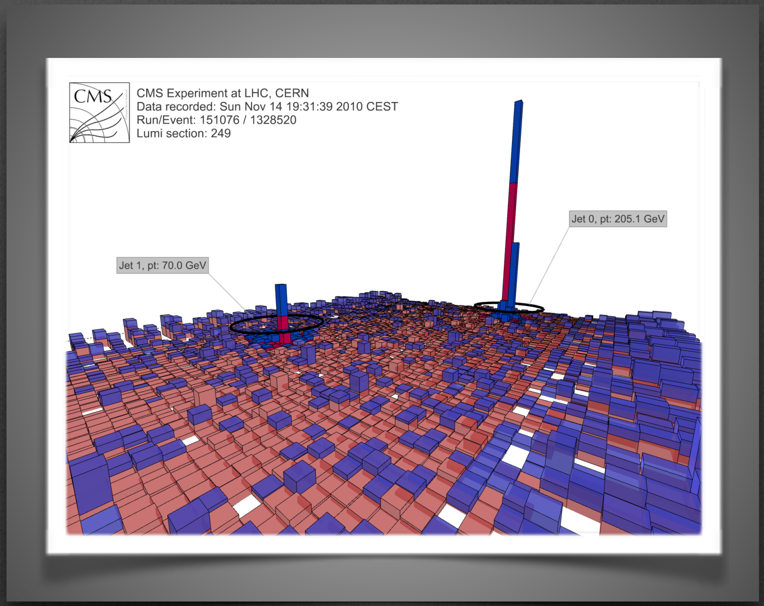
- Cosmic microwave background
  - Temperature at decoupling
- Temperatures fluctuations
  - Origin of big structures



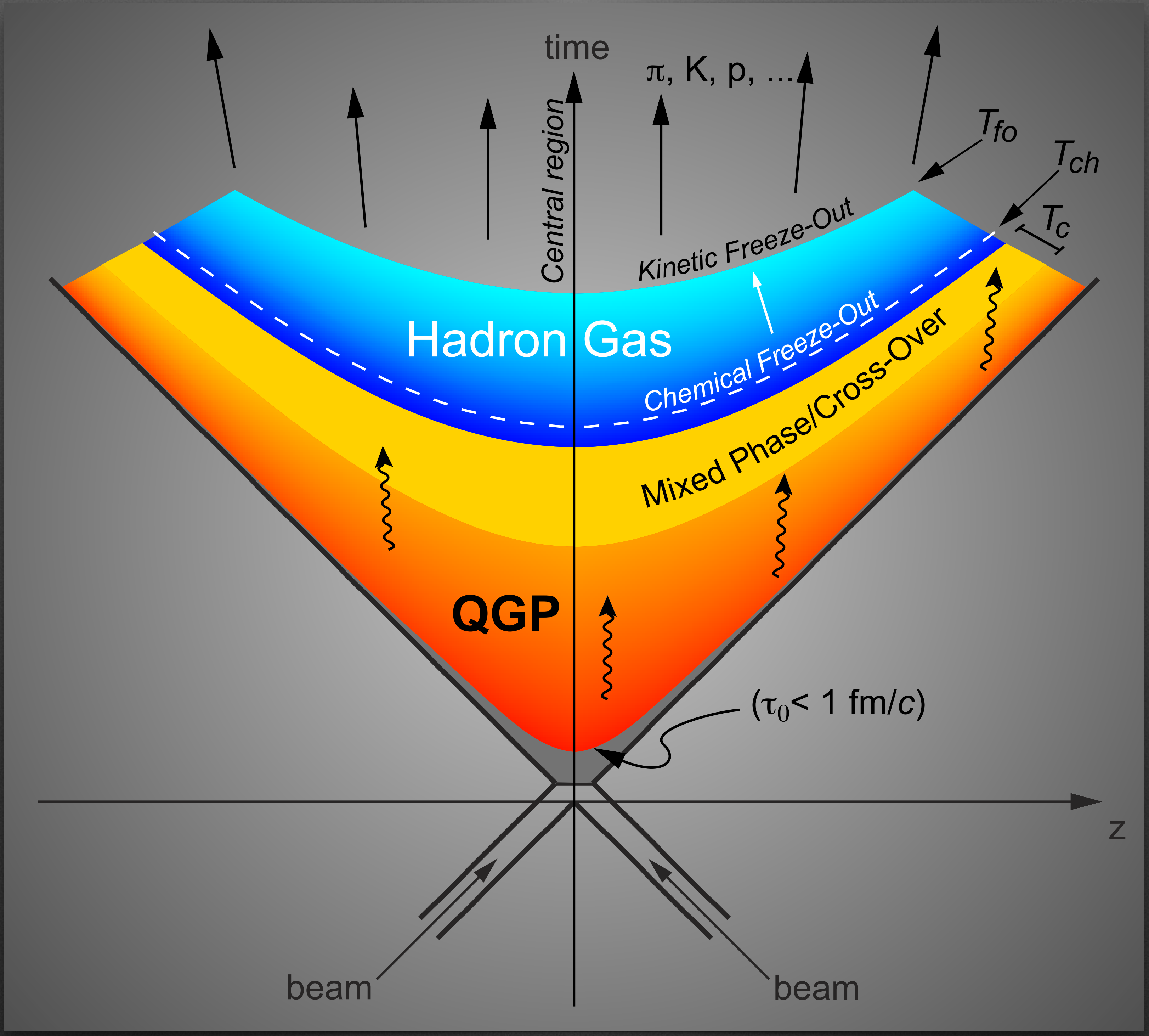
WMAP (Wilkinson Microwave Anisotropy Probe)

Little Bang

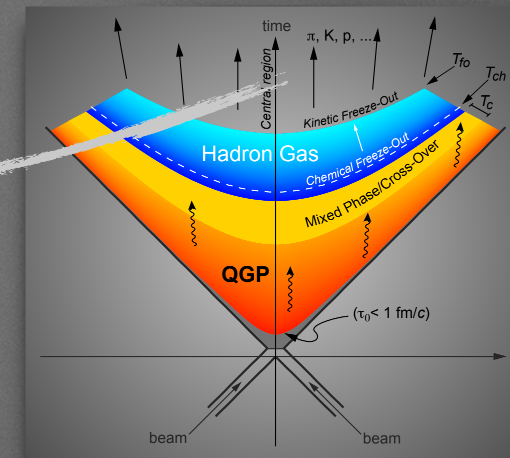
- Thermal radiation
  - Time evolution of temperature
- Tomography of QGP
  - Jet quenching, color screening

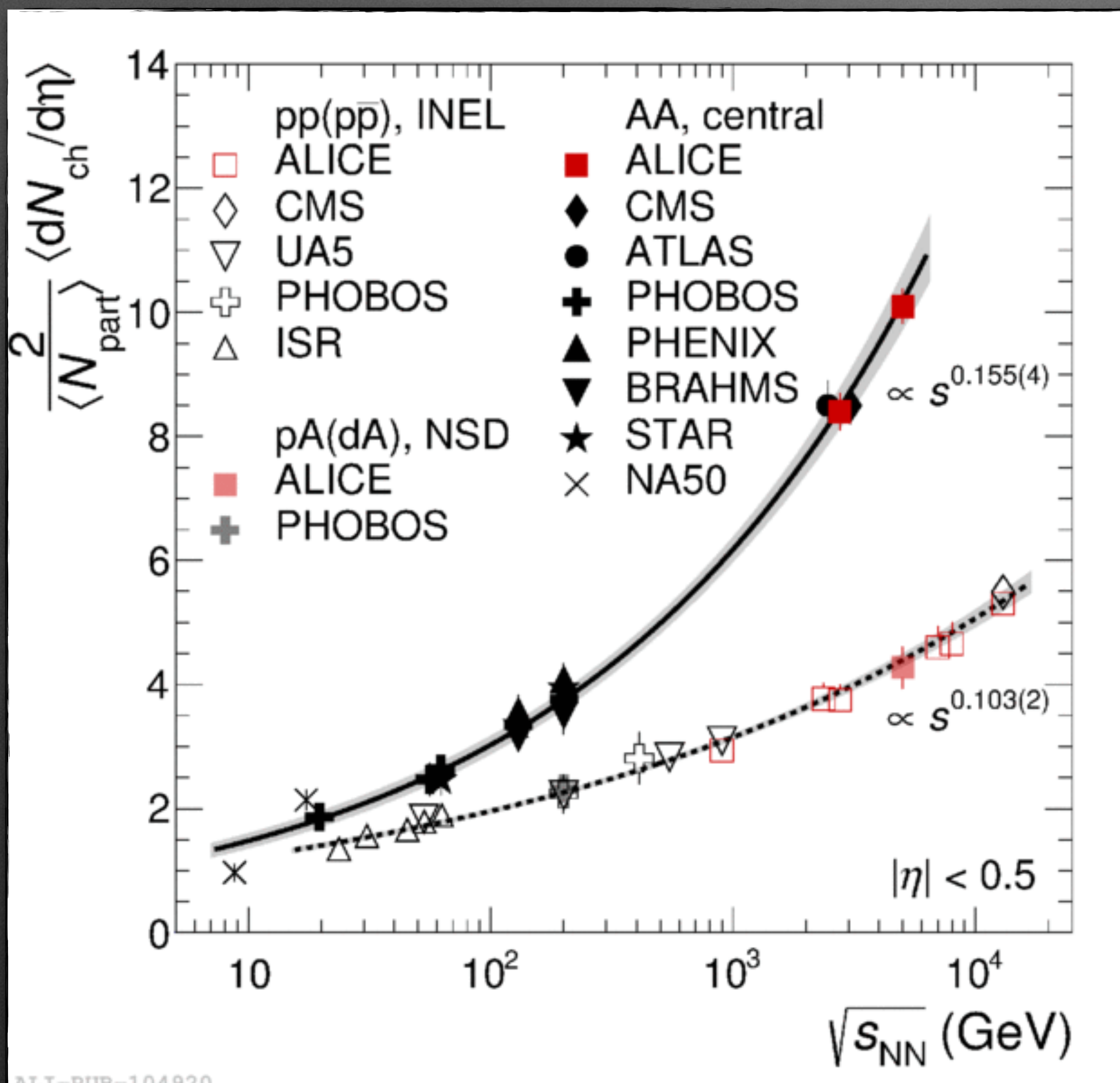


HIC dynamics

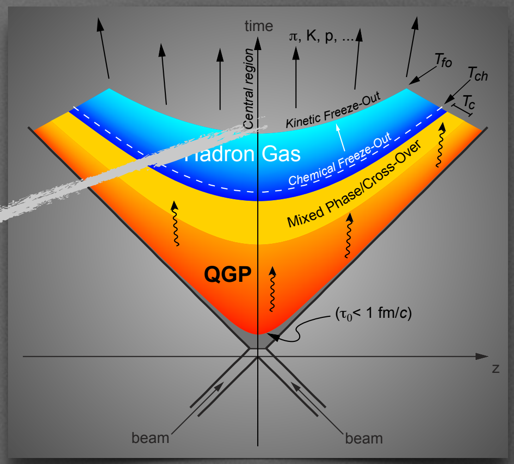


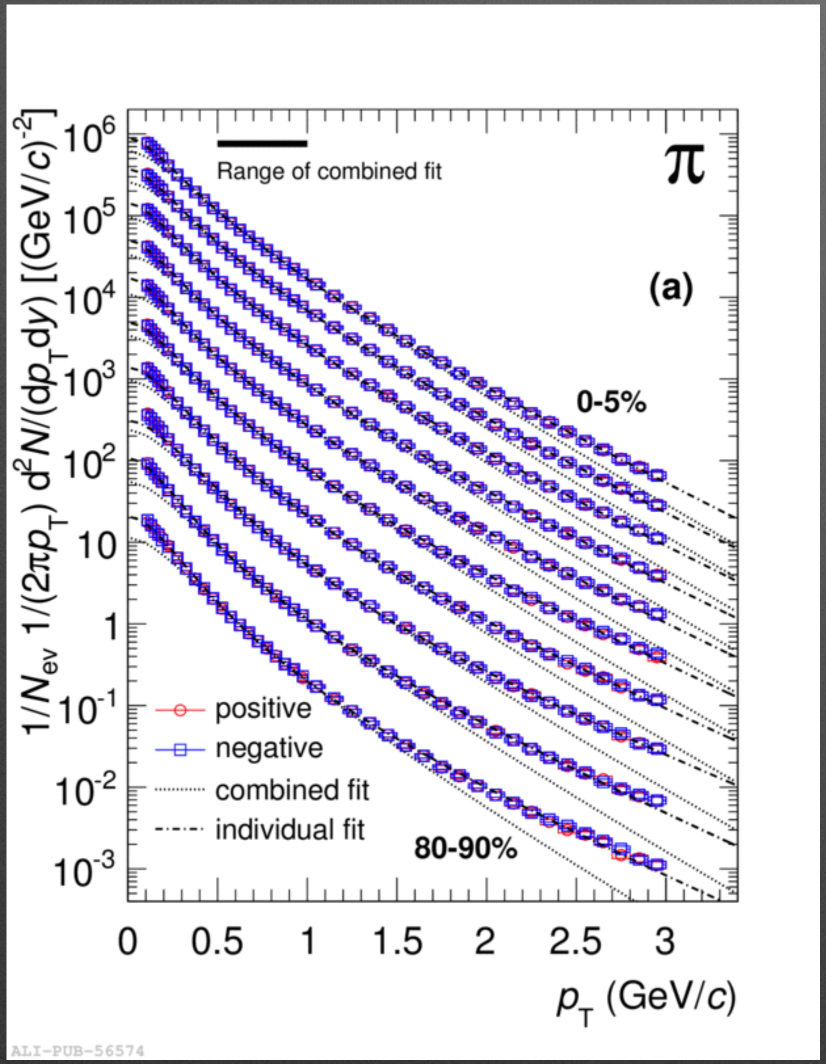
Multiplicity



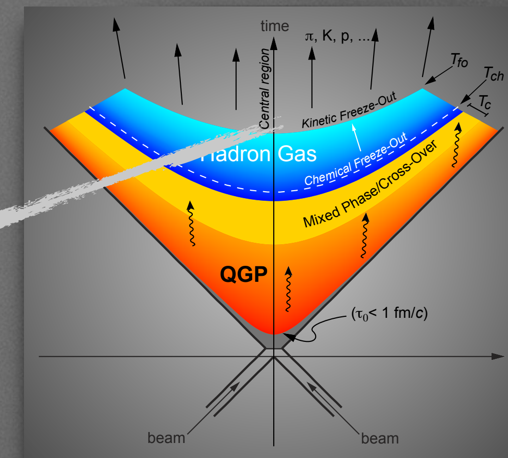


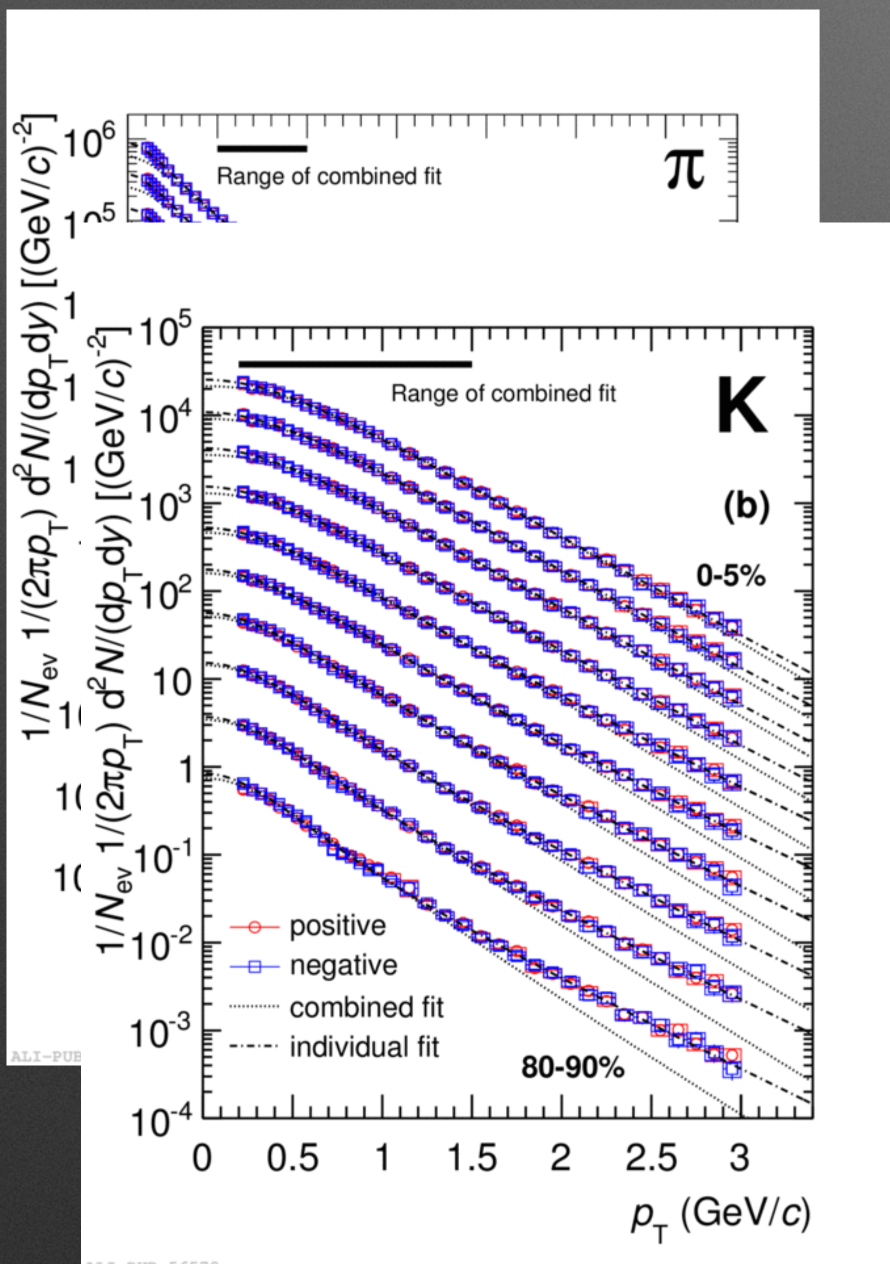
Kinetic freeze out



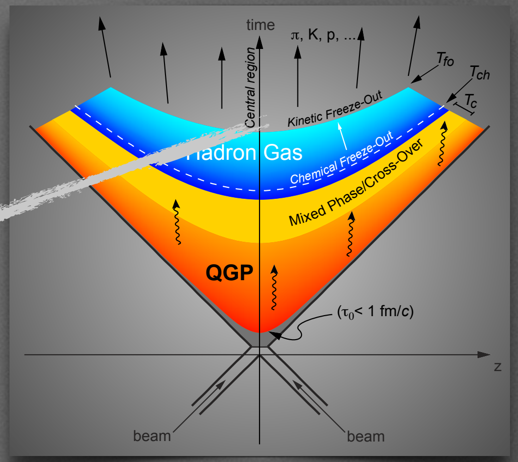


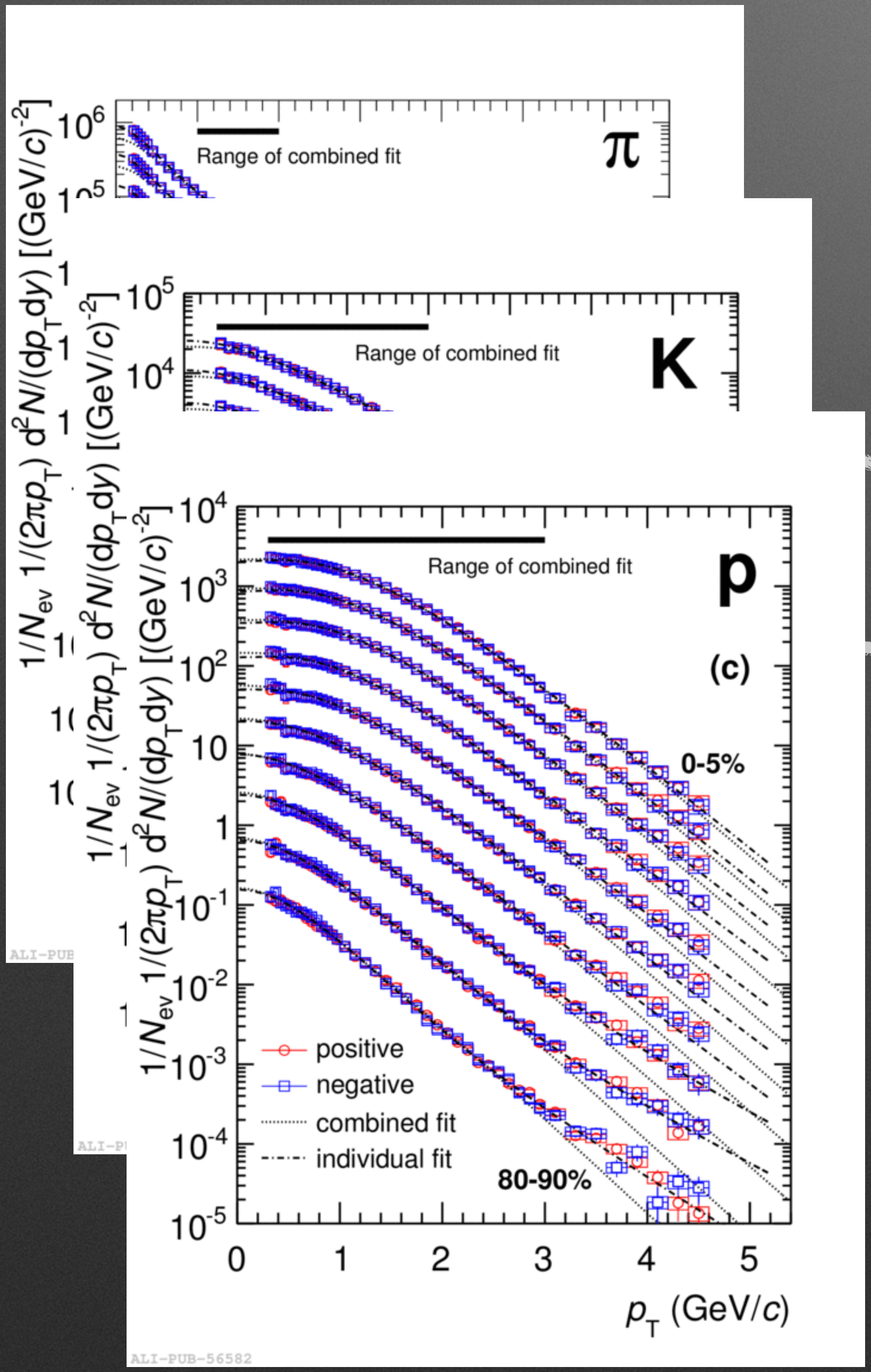
Kinetic freeze out

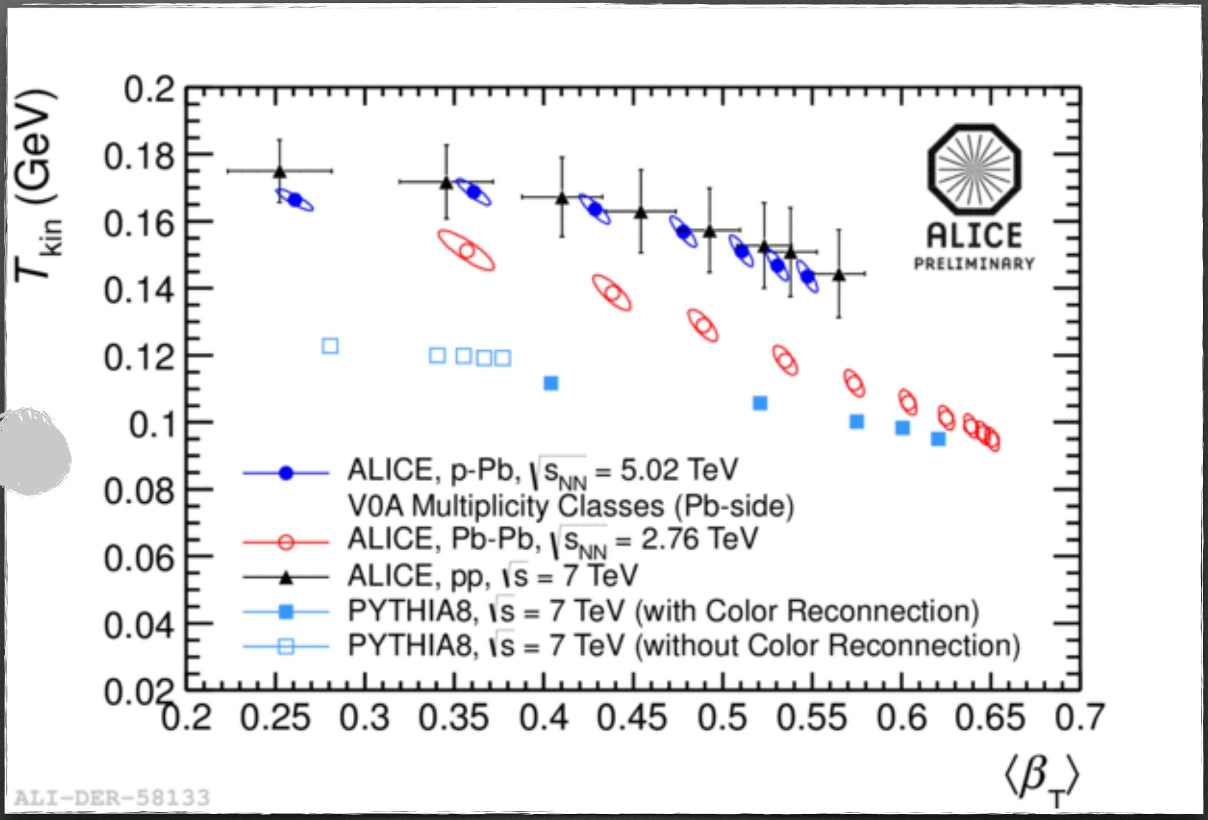




Kinetic freeze out



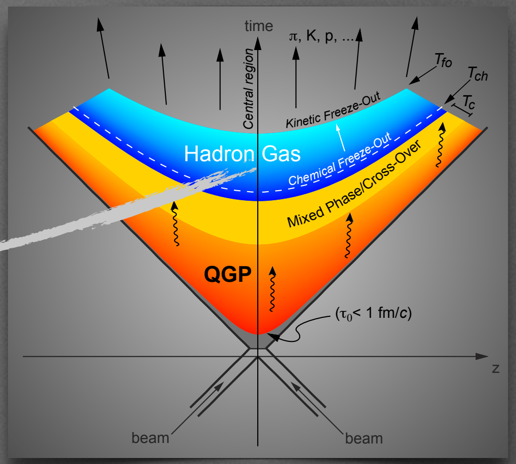


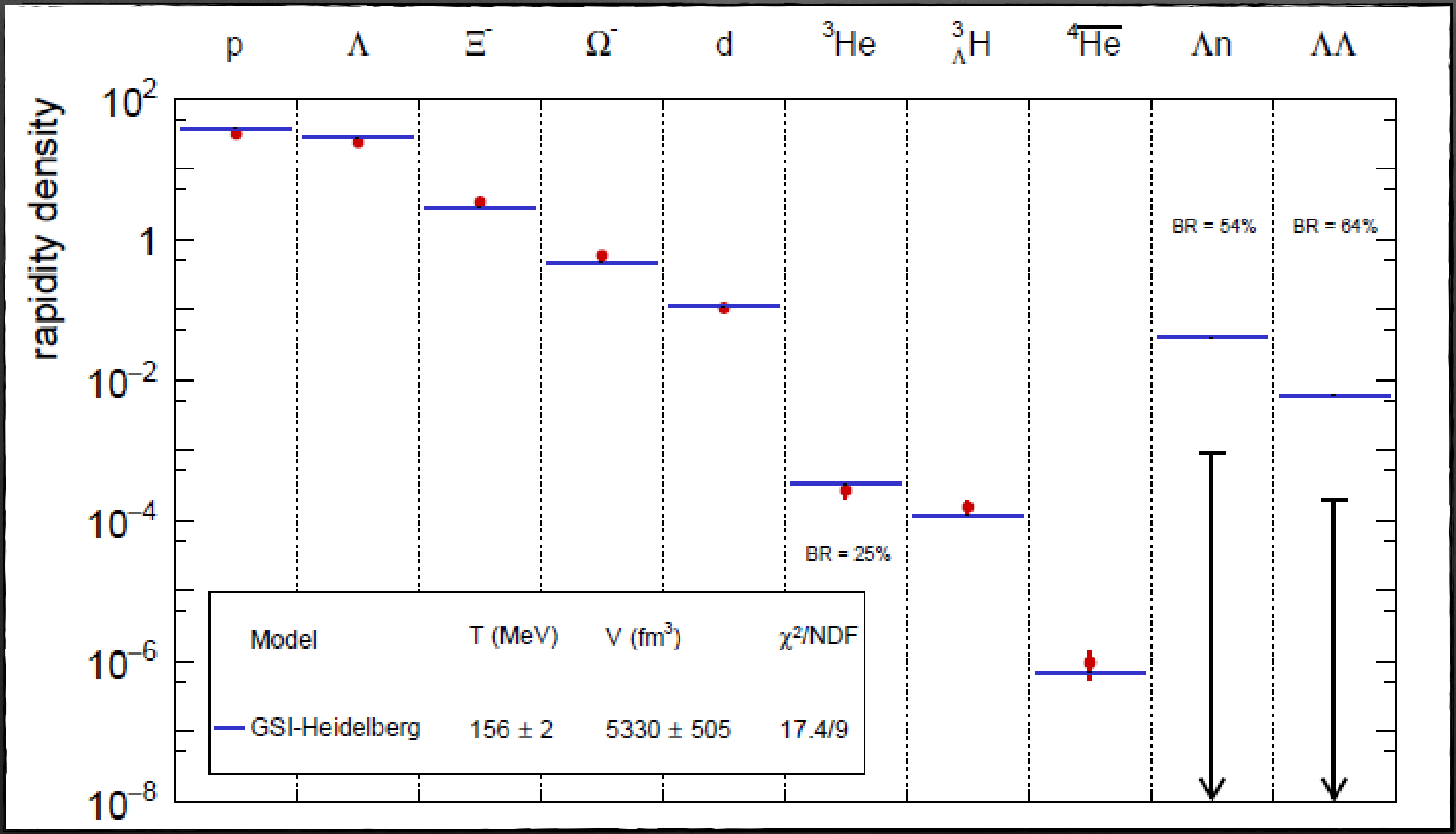


T_{kfo} ~ 100 MeV

β_T ~ 0,65c

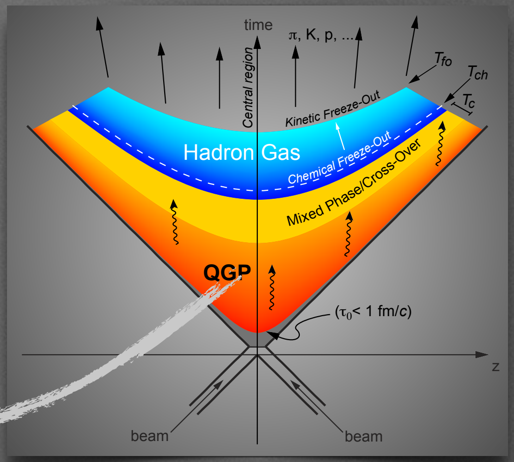
Hadron gas





T_{cfo} ~ 155 MeV

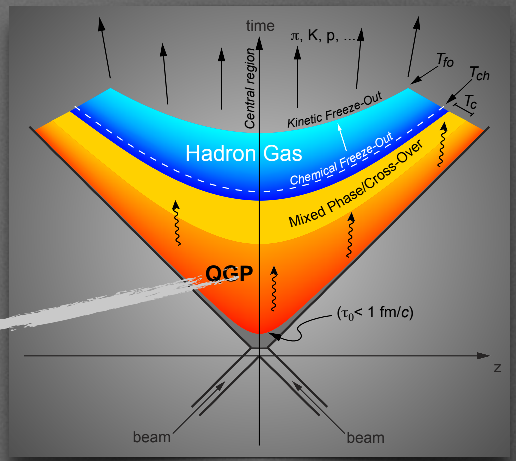
QGP

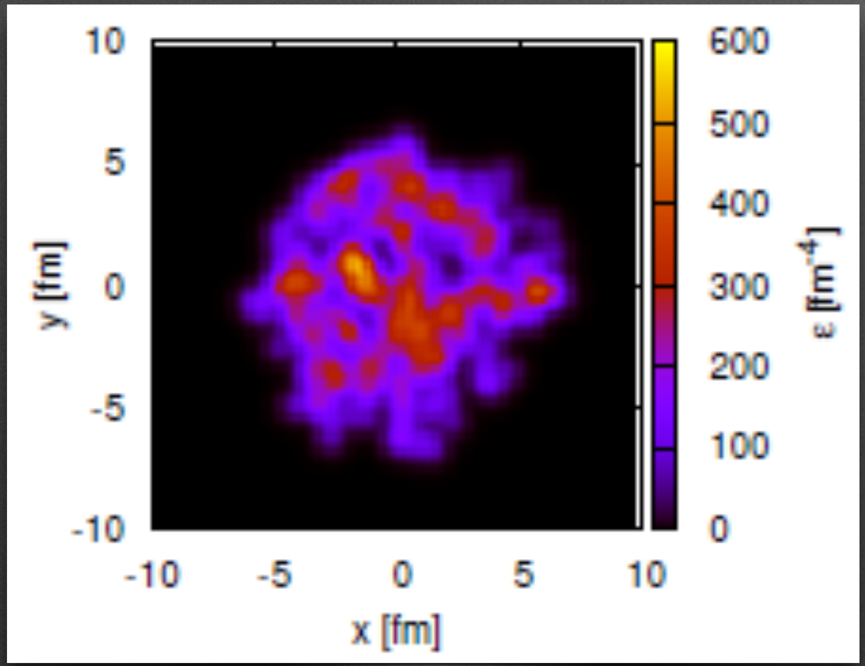


soft: $p_T \sim T, \Lambda_{QCD}$

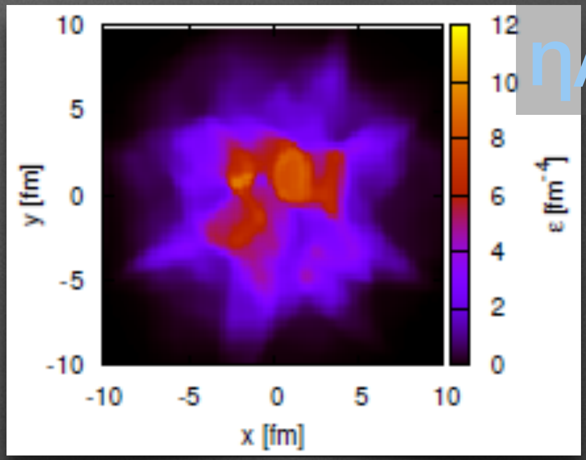
probe the collective properties of QGP

QGP

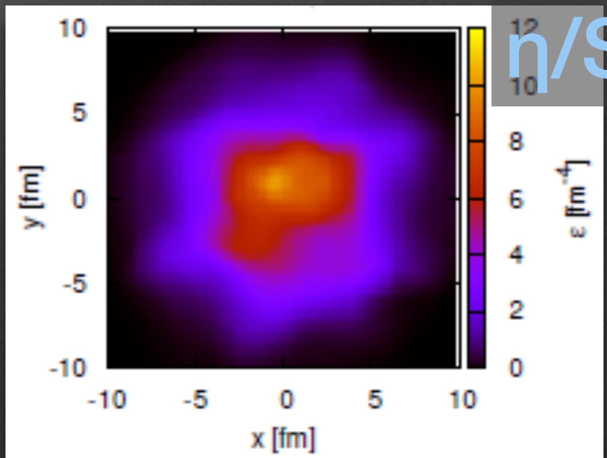




classical field dynamics
+
non dissipative
hydrodynamics



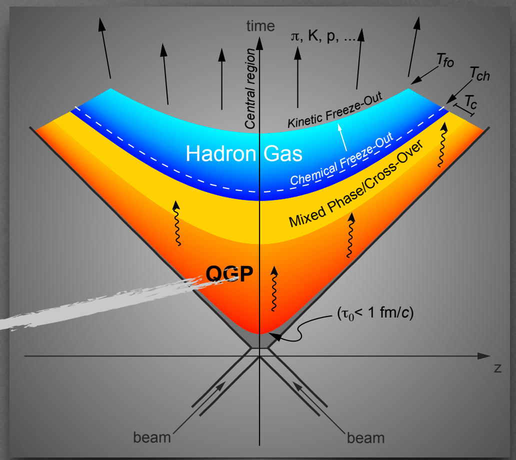
η/S = 0



η/S = 1/4π

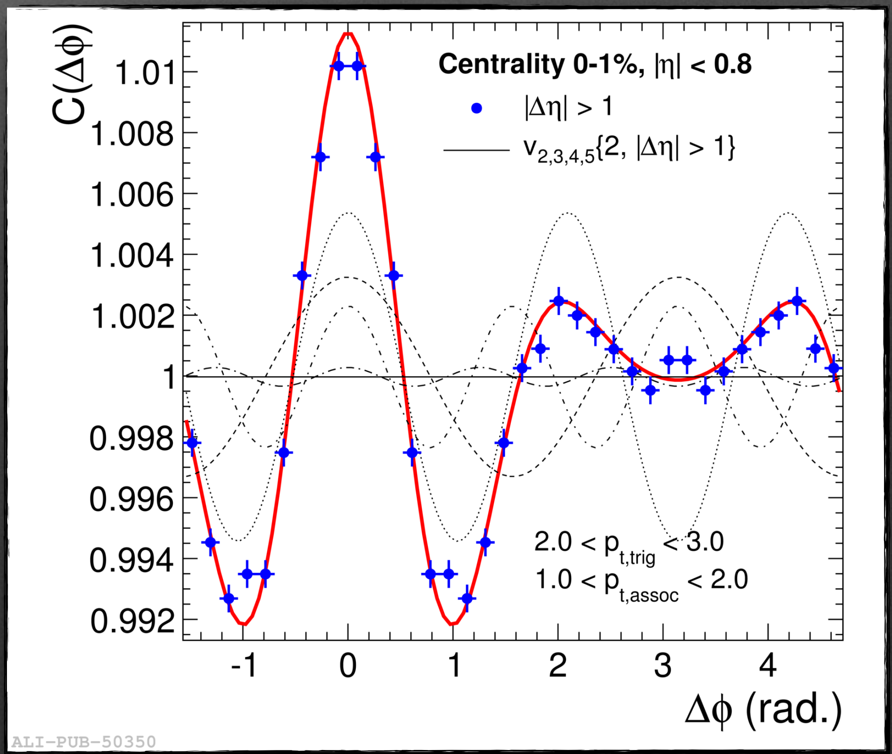
Dissipation in a perfect fluid is minimal:
QGP is transparent to IS quantum fluctuations

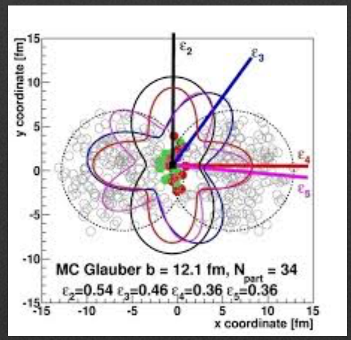
QGP



IS: weakly coupled pure gauge field
+
quantum fluctuations

classical field dynamics
+
non dissipative hydrodynamics

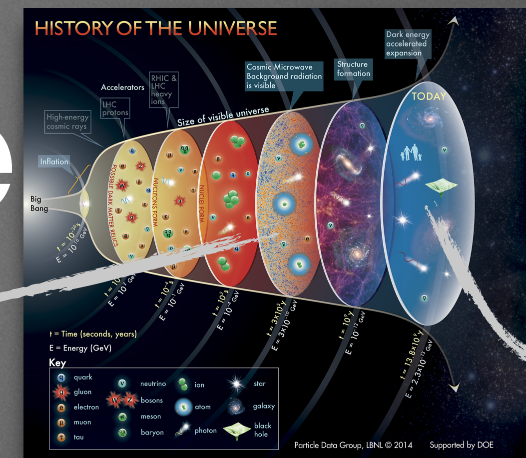


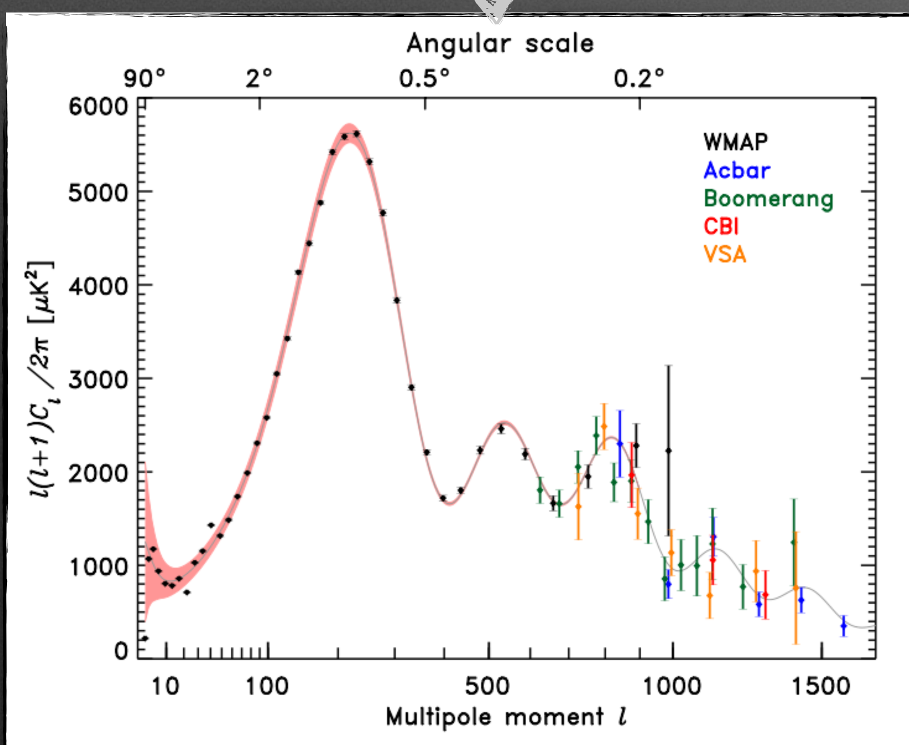


Dissipation in a perfect fluid is minimal:
QGP is transparent to IS quantum fluctuations

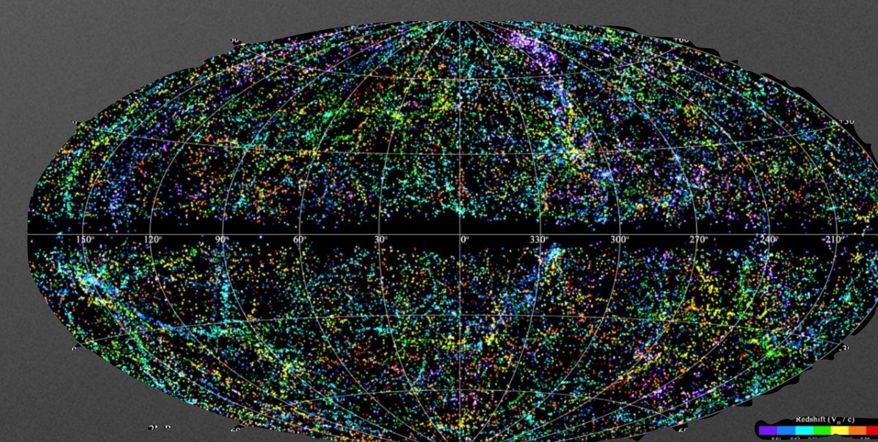
ALICE
A JOURNEY OF DISCOVERY

Matter in Universe



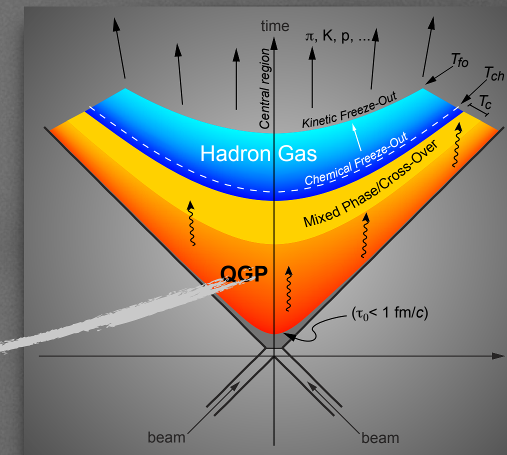


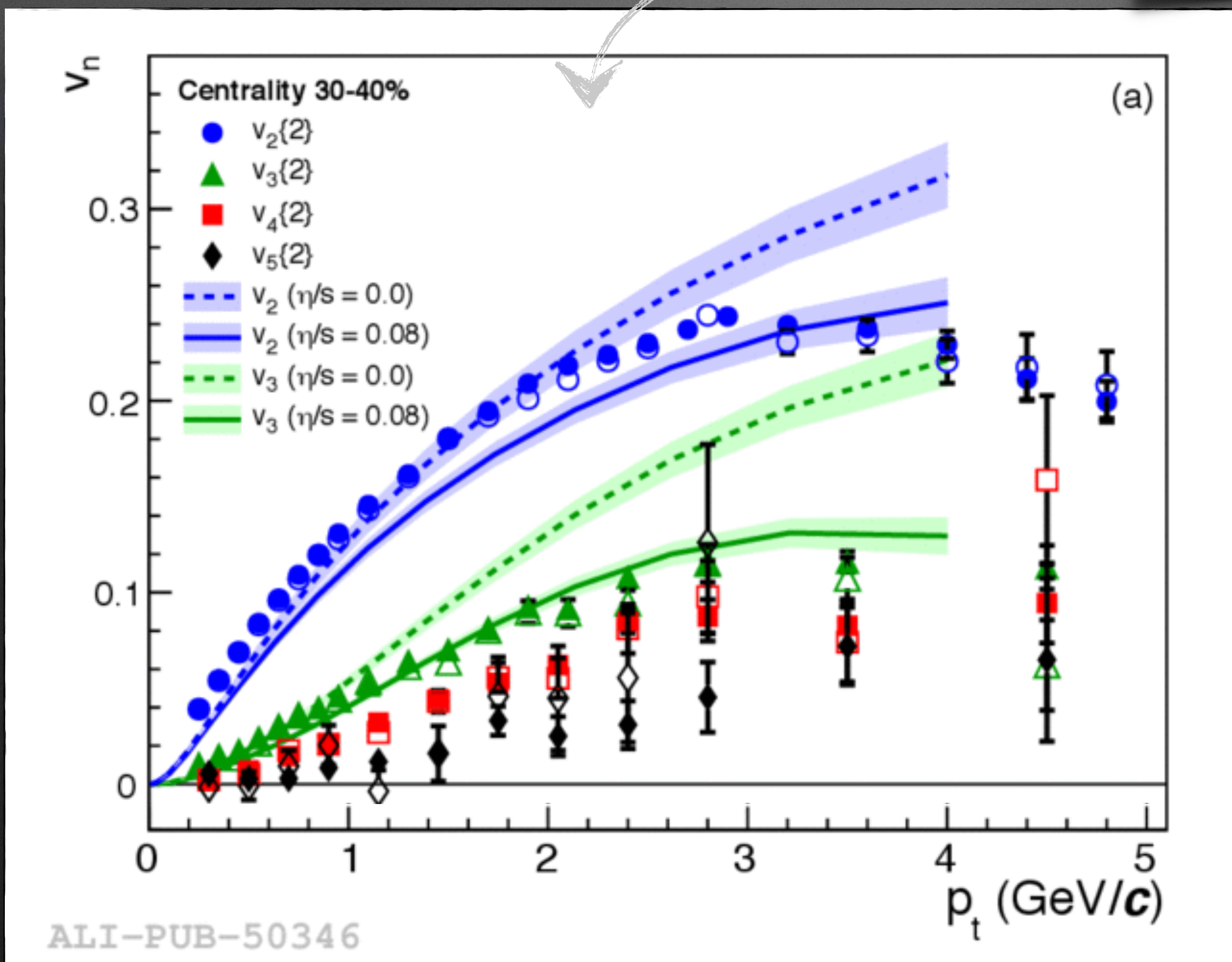
BB model
+
parameters



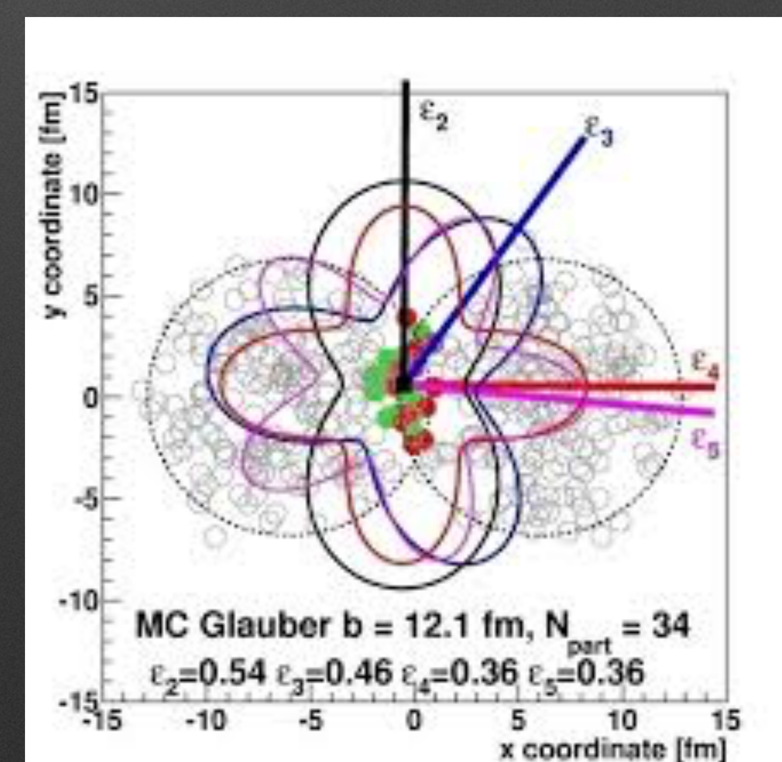
Dissipation in a perfect fluid is minimal:
from CMB T fluctuations to matter distribution

QGP

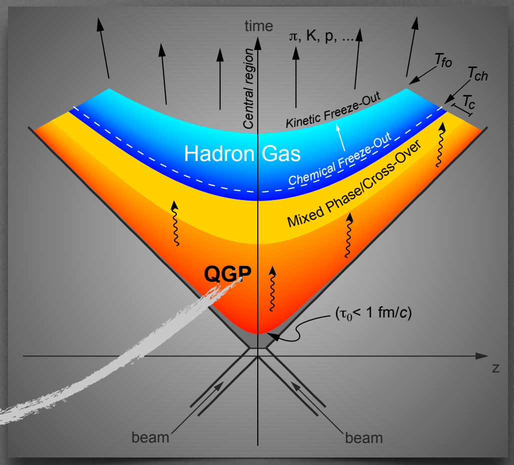




Pb+Pb @ 2.76 TeV



QGP

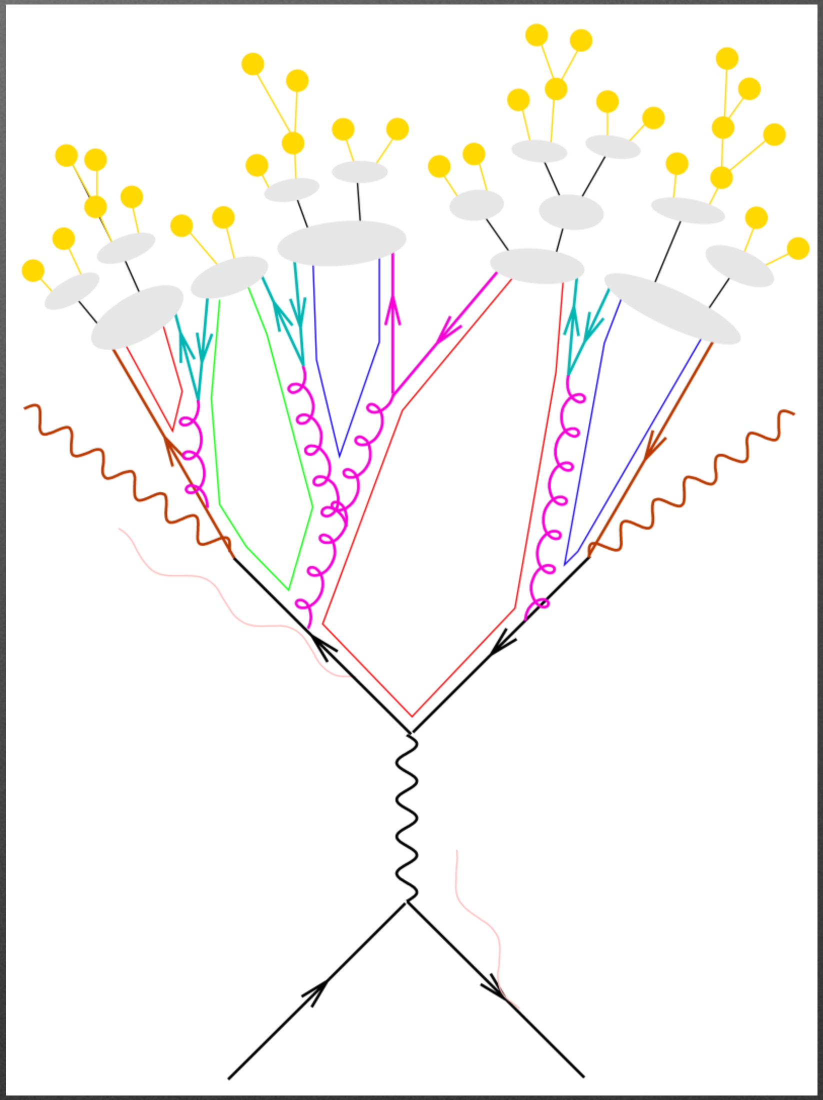


hard: p_T, $m_T \gg T$, Λ_{QCD}

probe QGP at high resolution scale

Parton shower

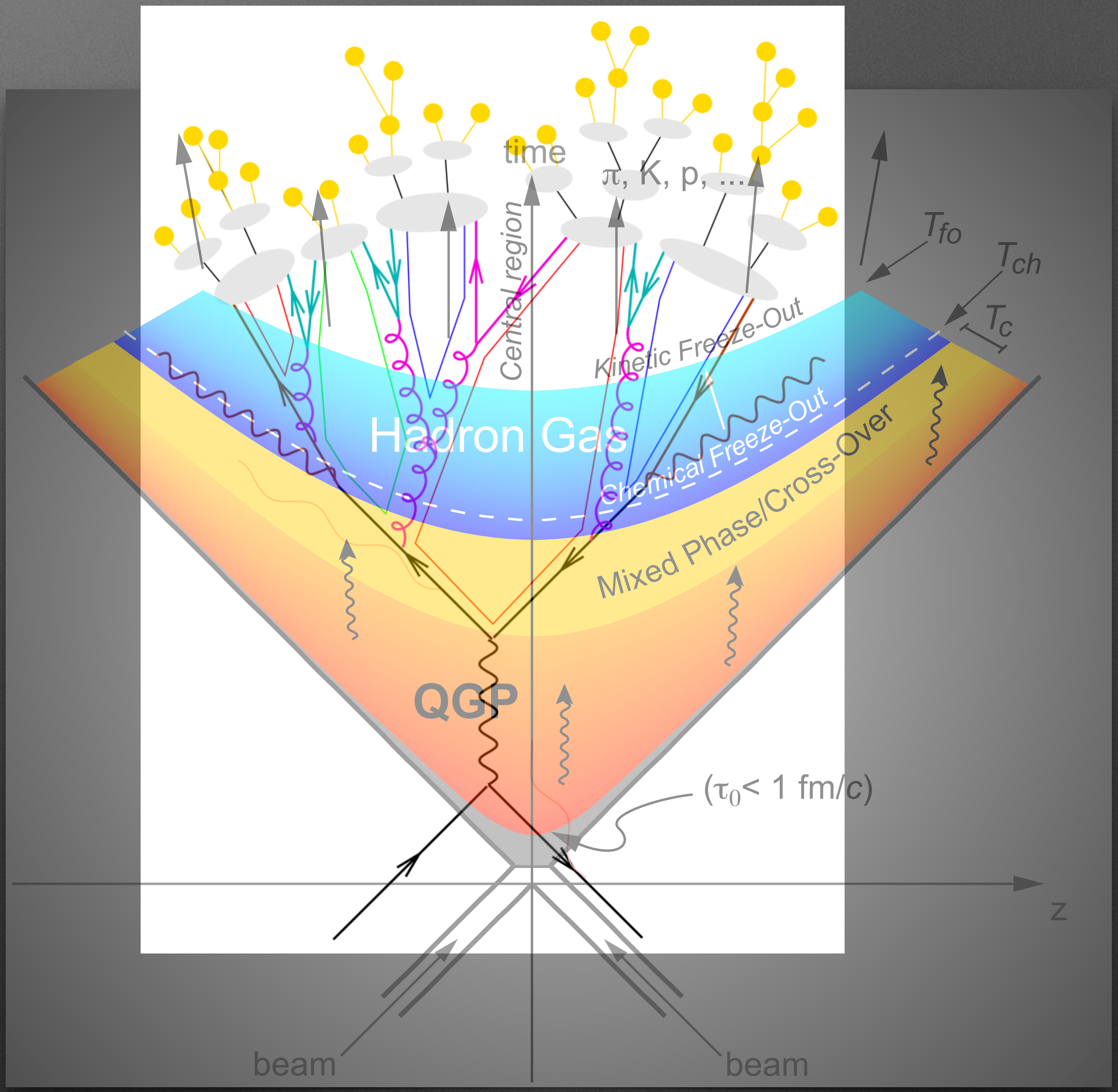
- high p_T, m_T created in initial hard scattering
- develop a partonic shower and hadronize at Λ_{QCD} scale



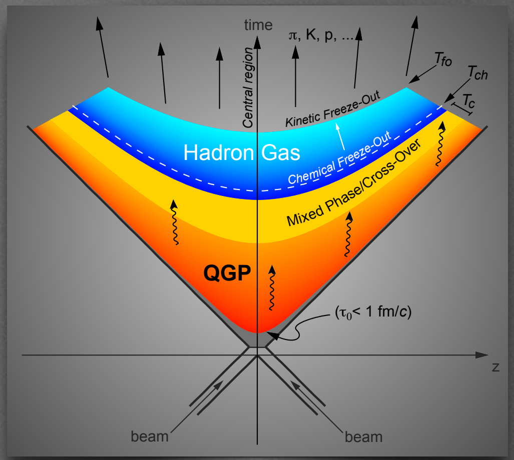
QGP

- high p_T, m_T created in initial hard scattering
- develop a partonic shower and hadronize at Λ_{QCD} scale
- probe QGP at small scale

color density, transport properties, degrees of freedom



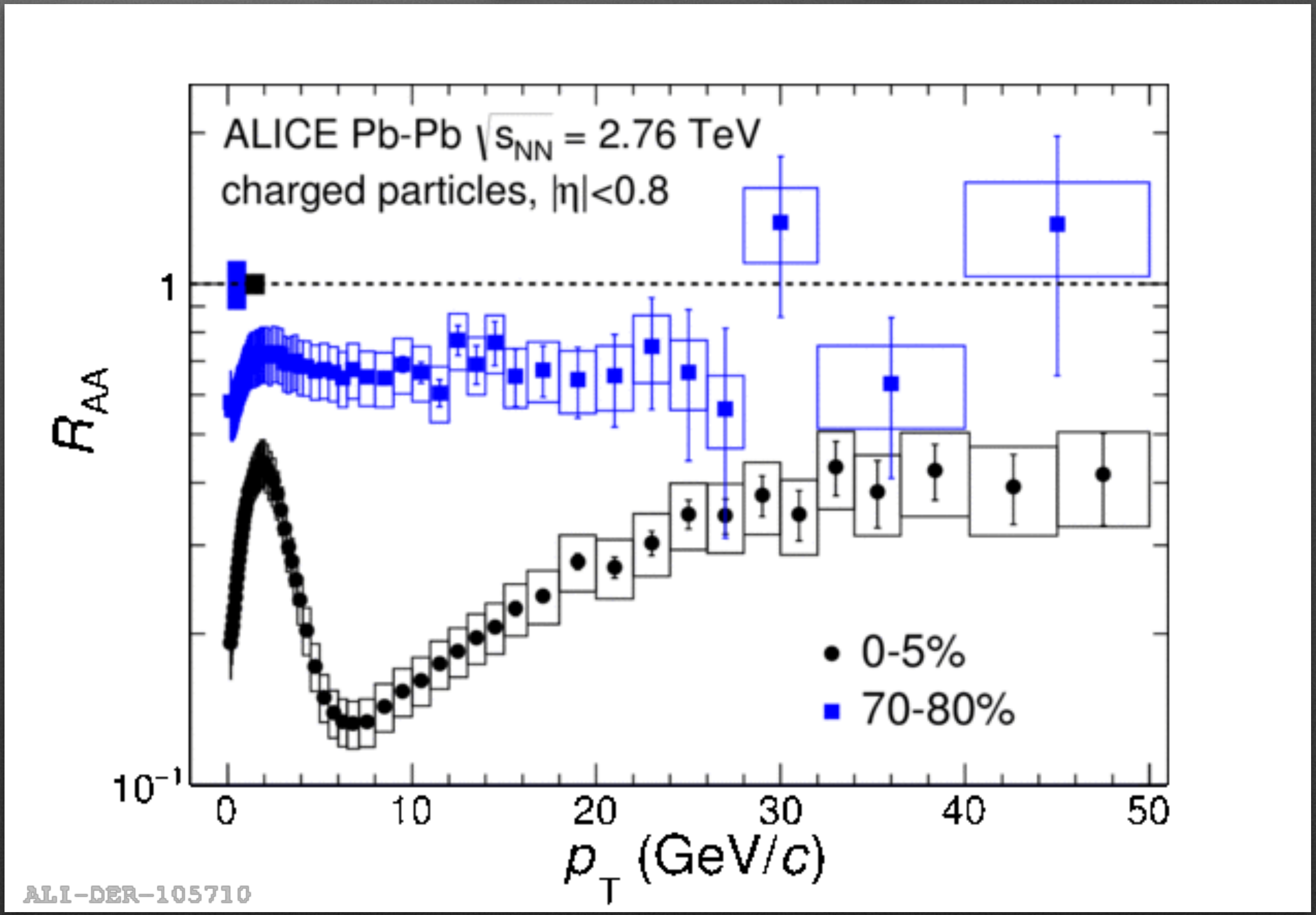
QGP: R_{AA}



$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2Nch/d\eta dp_T}{d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

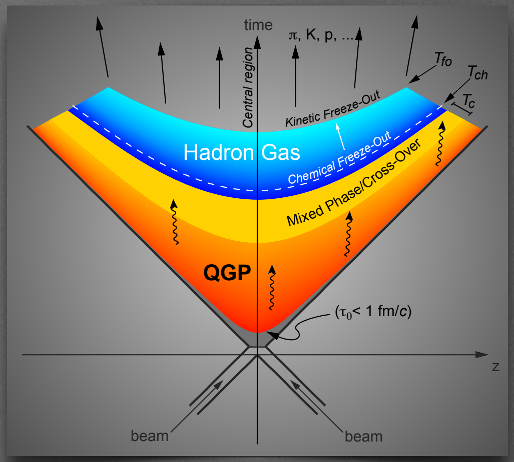
how different is AA from Σ_{A}pp

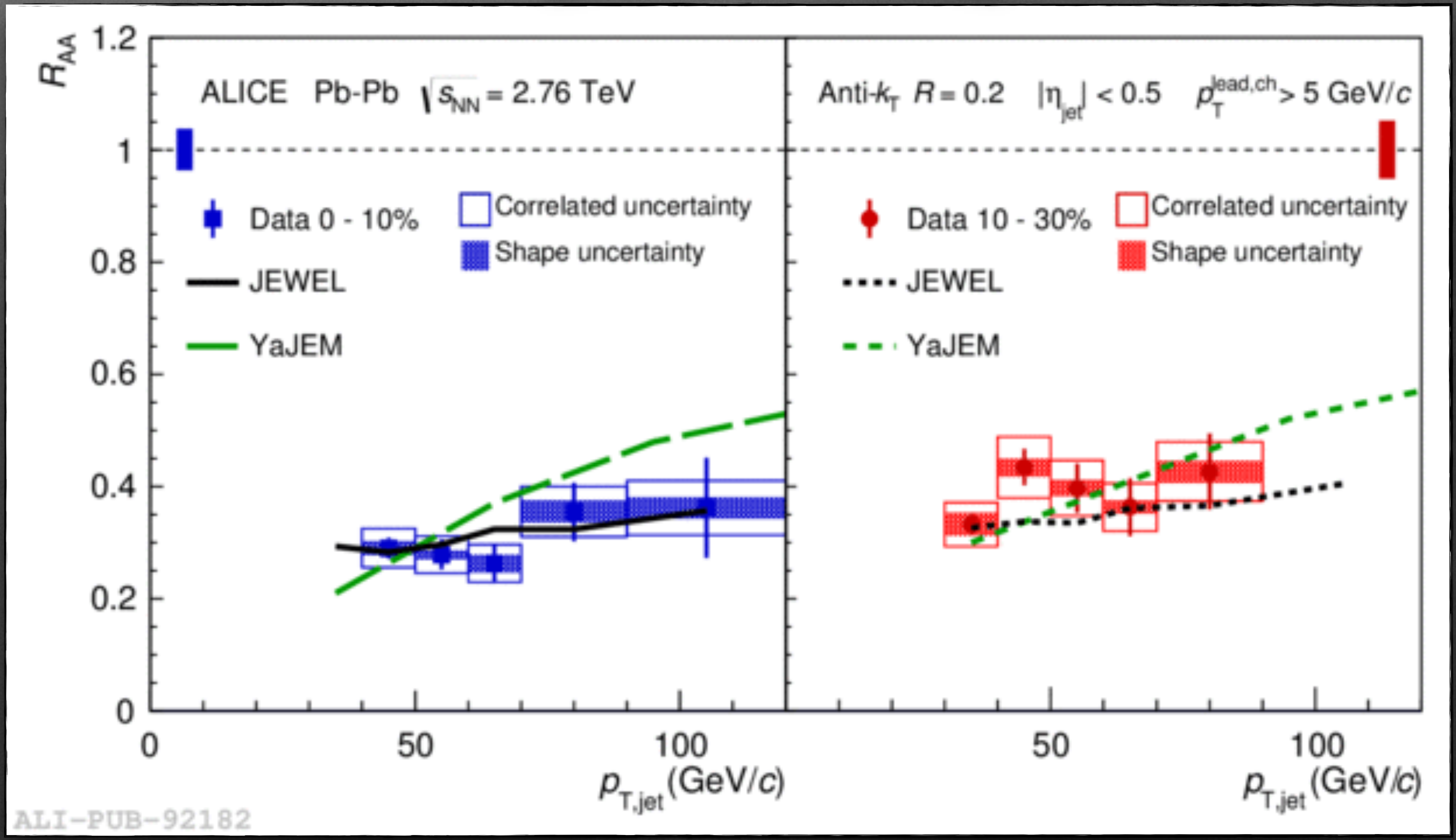
- single hadron



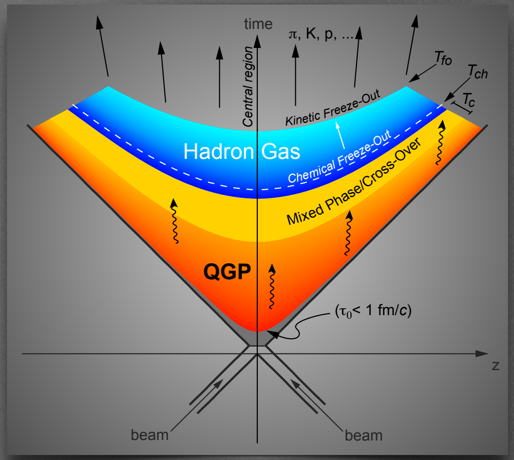
QGP: R_{AA}

- single hadron → full jet

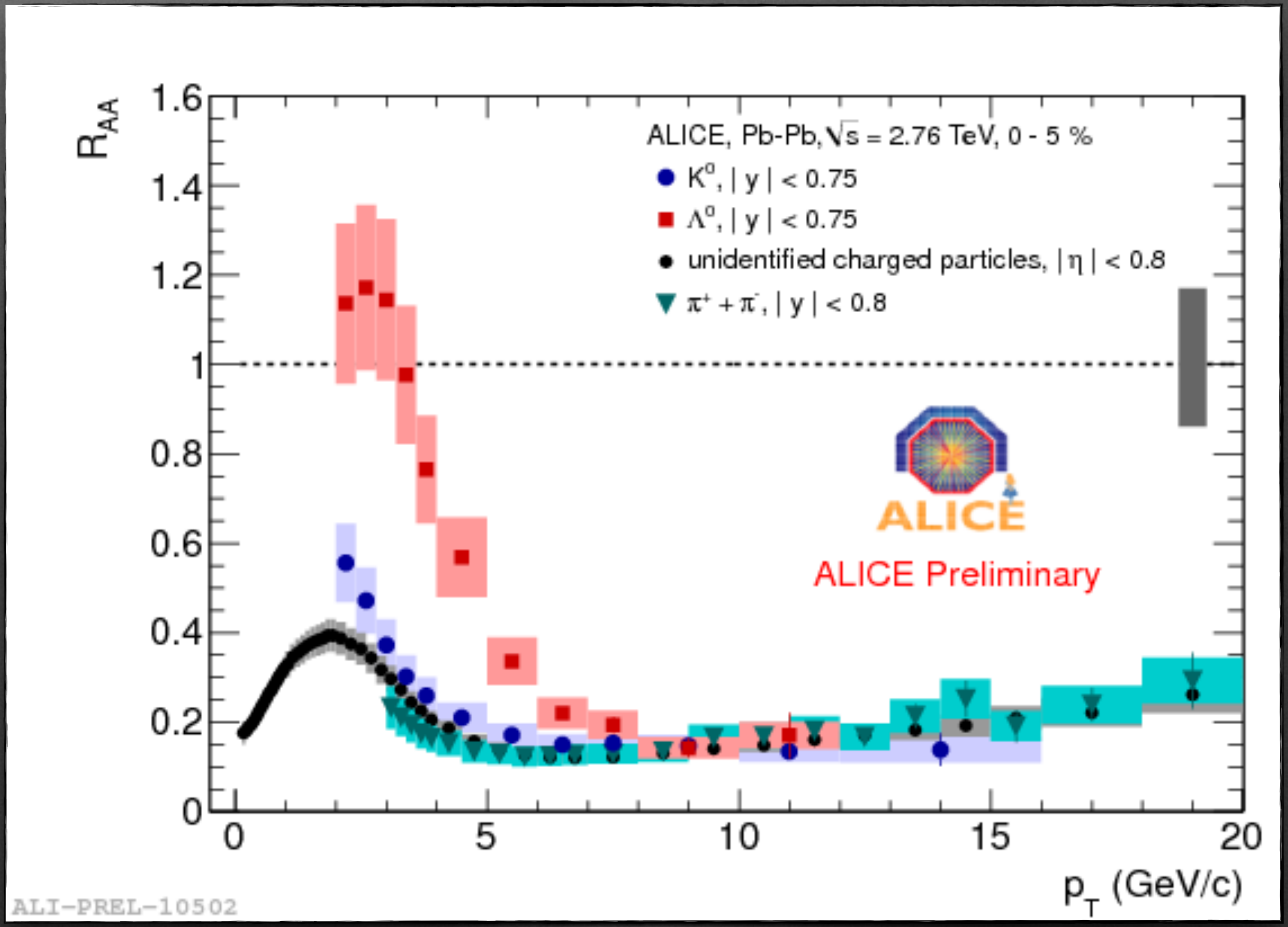




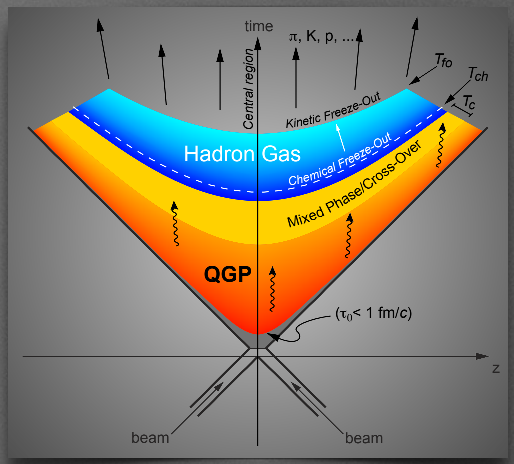
QGP: R_{AA}



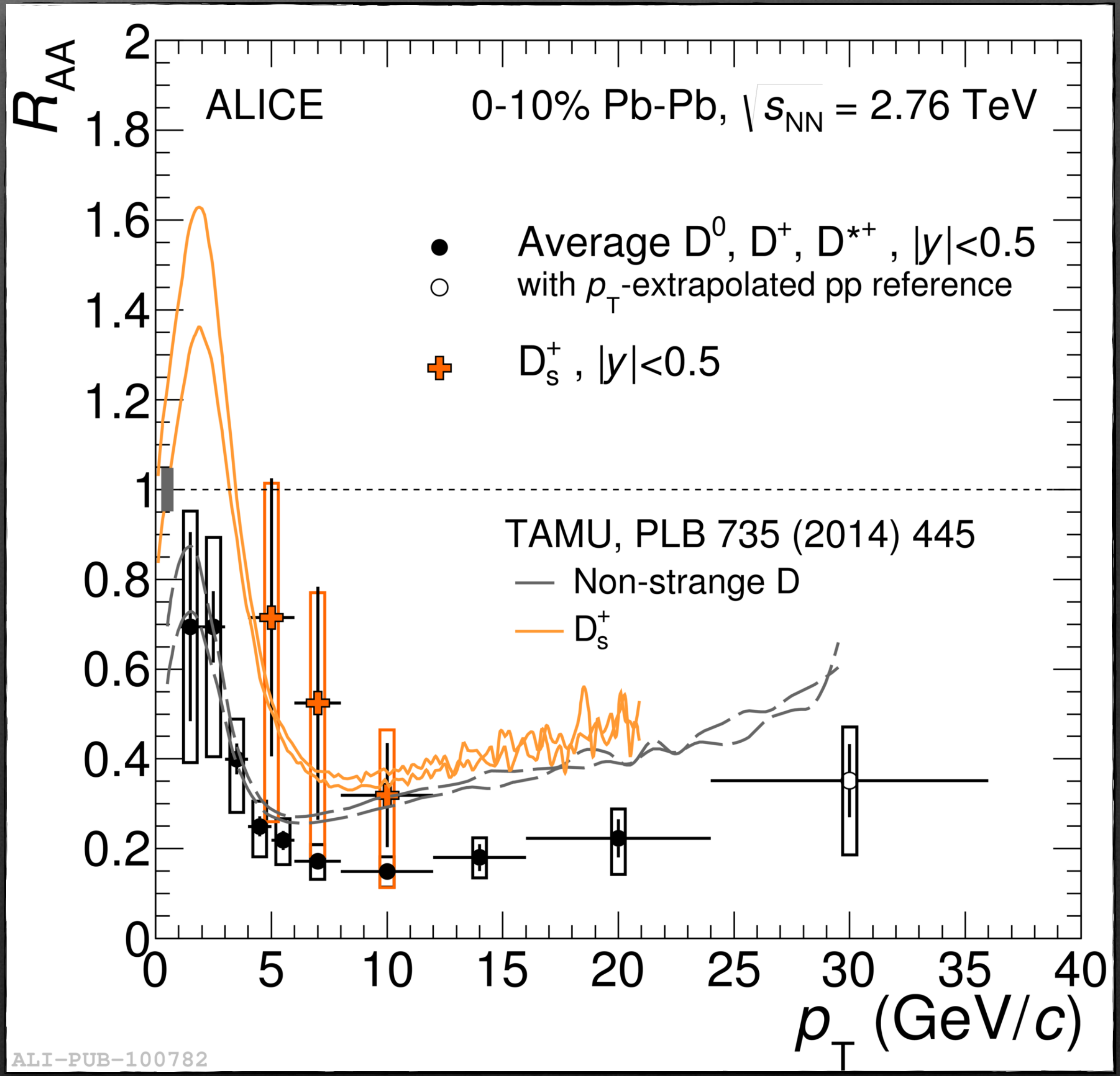
- single hadron → full jet
- Identified hadrons



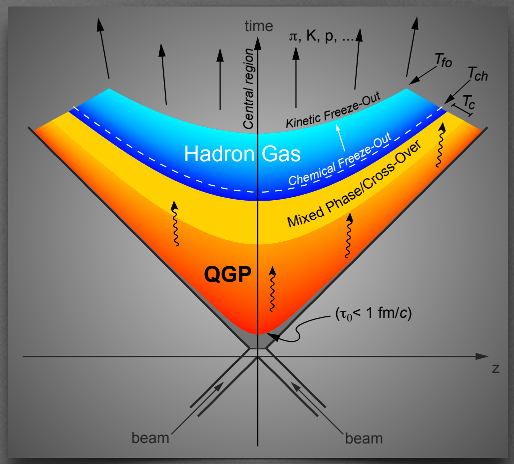
QGP: R_{AA}



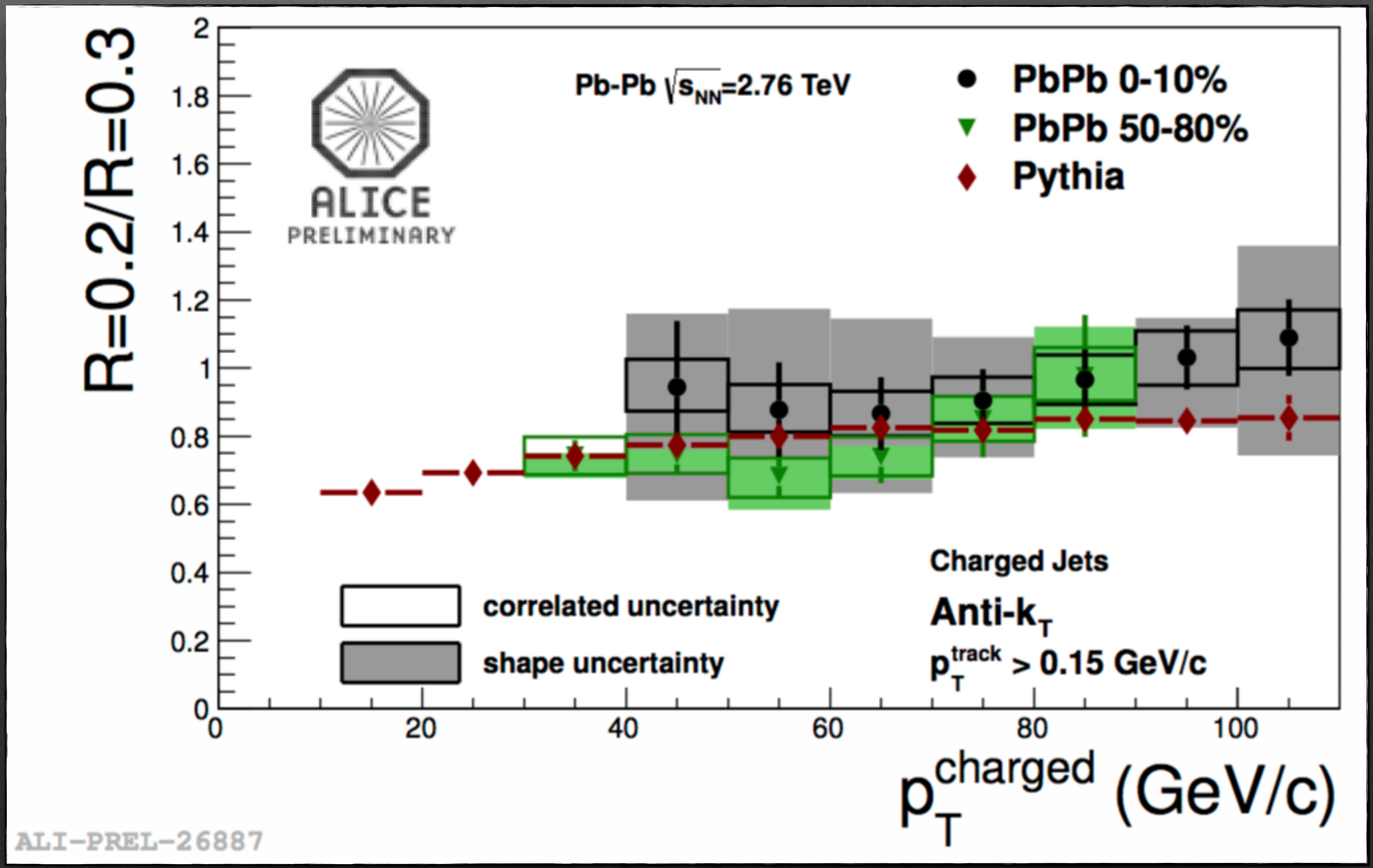
- single hadron → full jet
- Identified hadrons
- g, q (u, d, s, c, b)



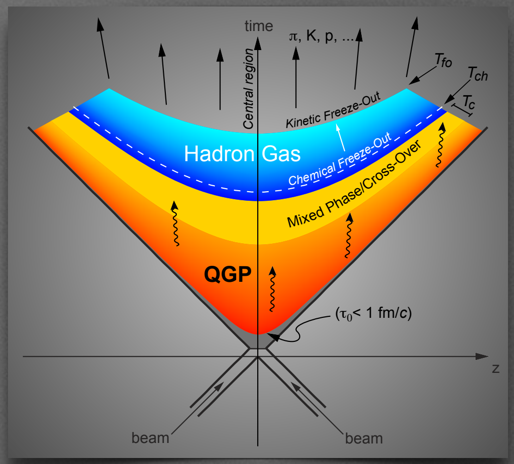
QGP: R_{AA}

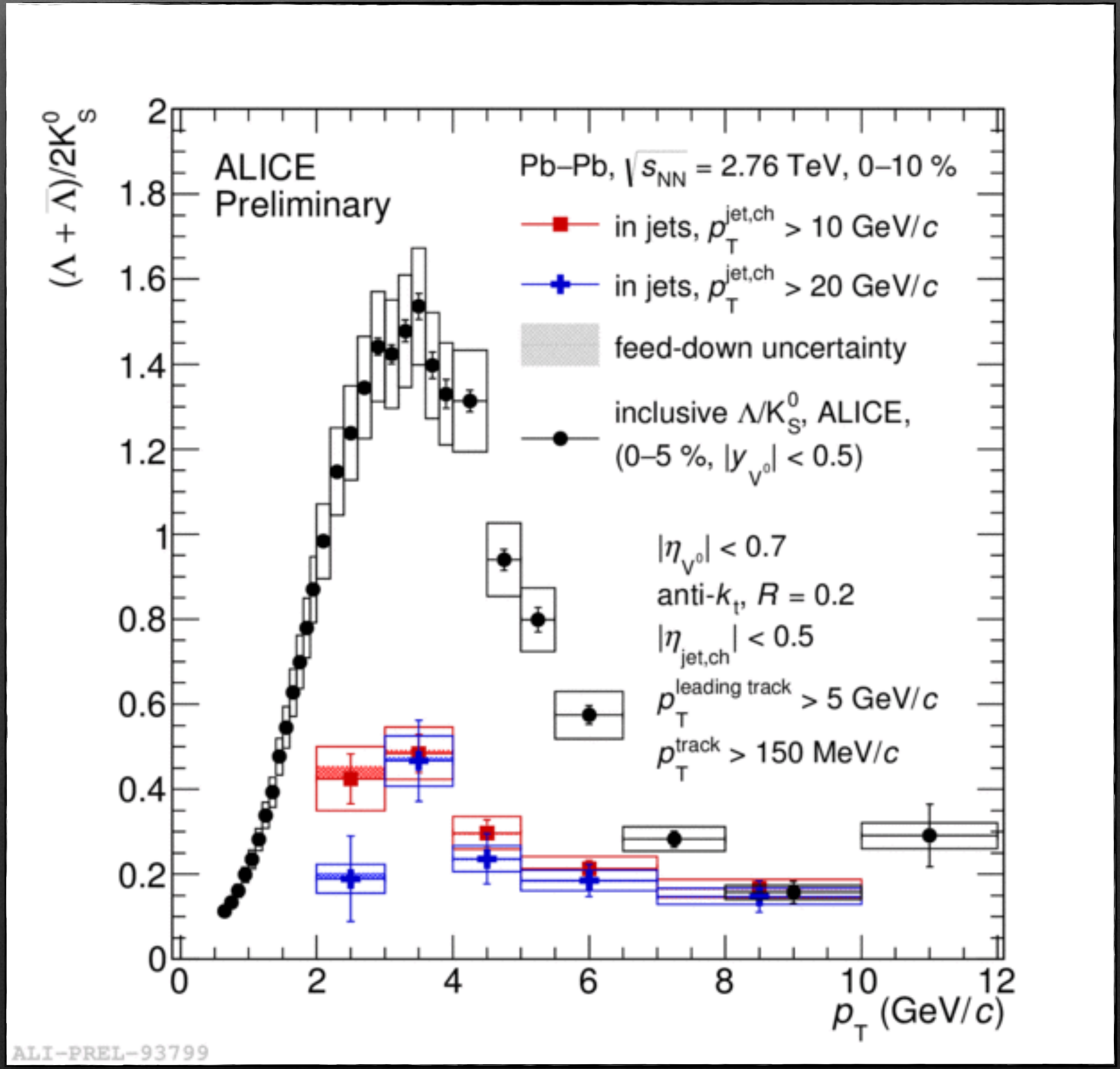


- single hadron → full jet
- Identified hadrons
- g, q (u, d, s, c, b)
- jet shape



QGP: R_{AA}

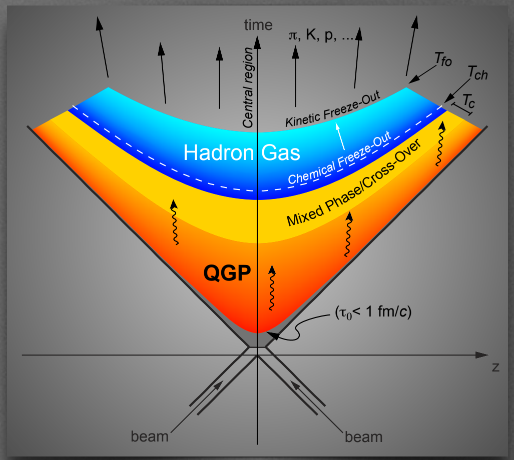


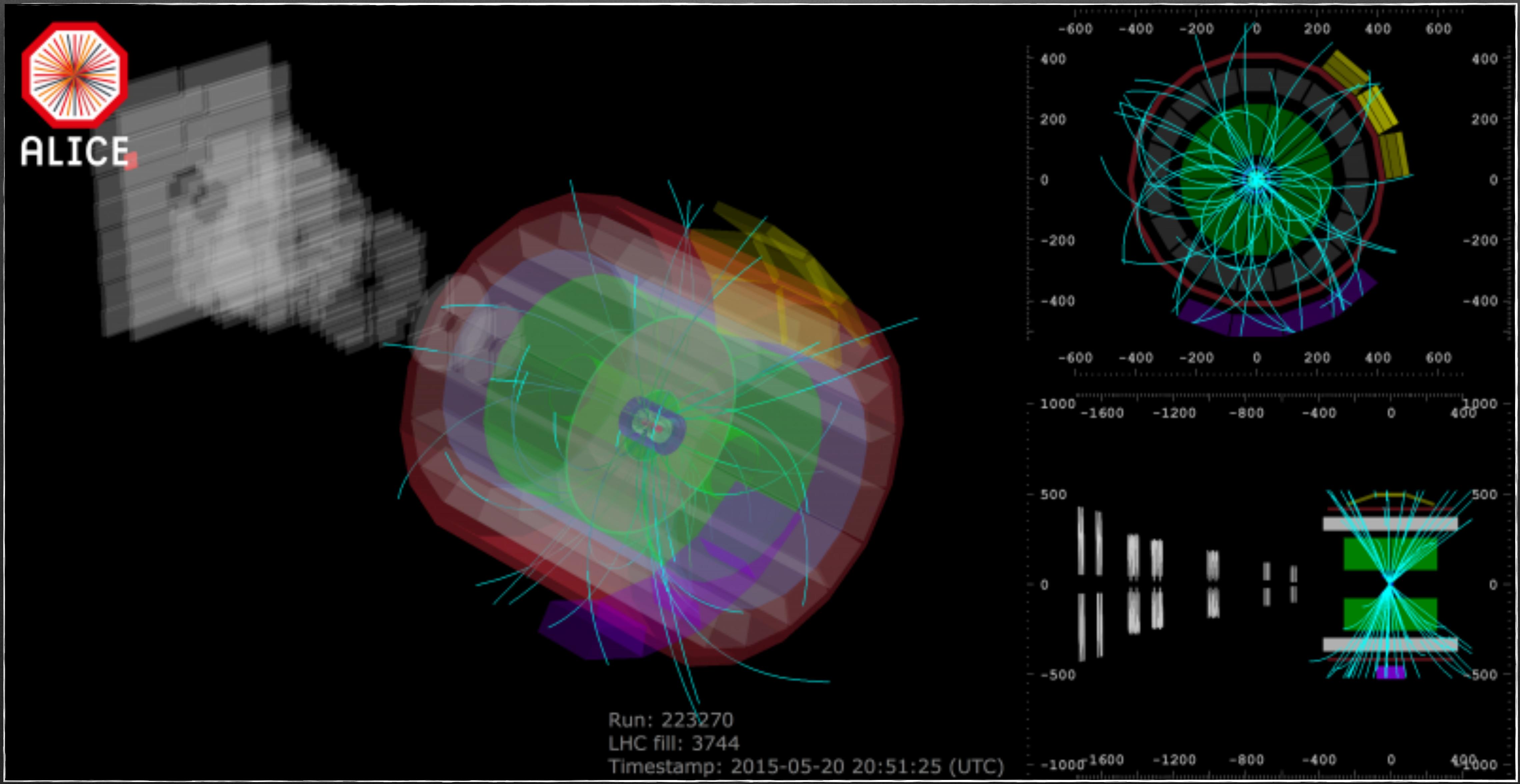


- single hadron → full jet
- Identified hadrons
- g, q (u, d, s, c, b)
- jet shape
- correlations

LHC discovery

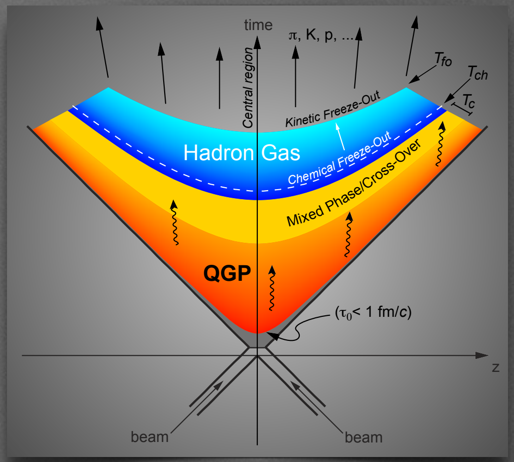
QGP in small systems ?

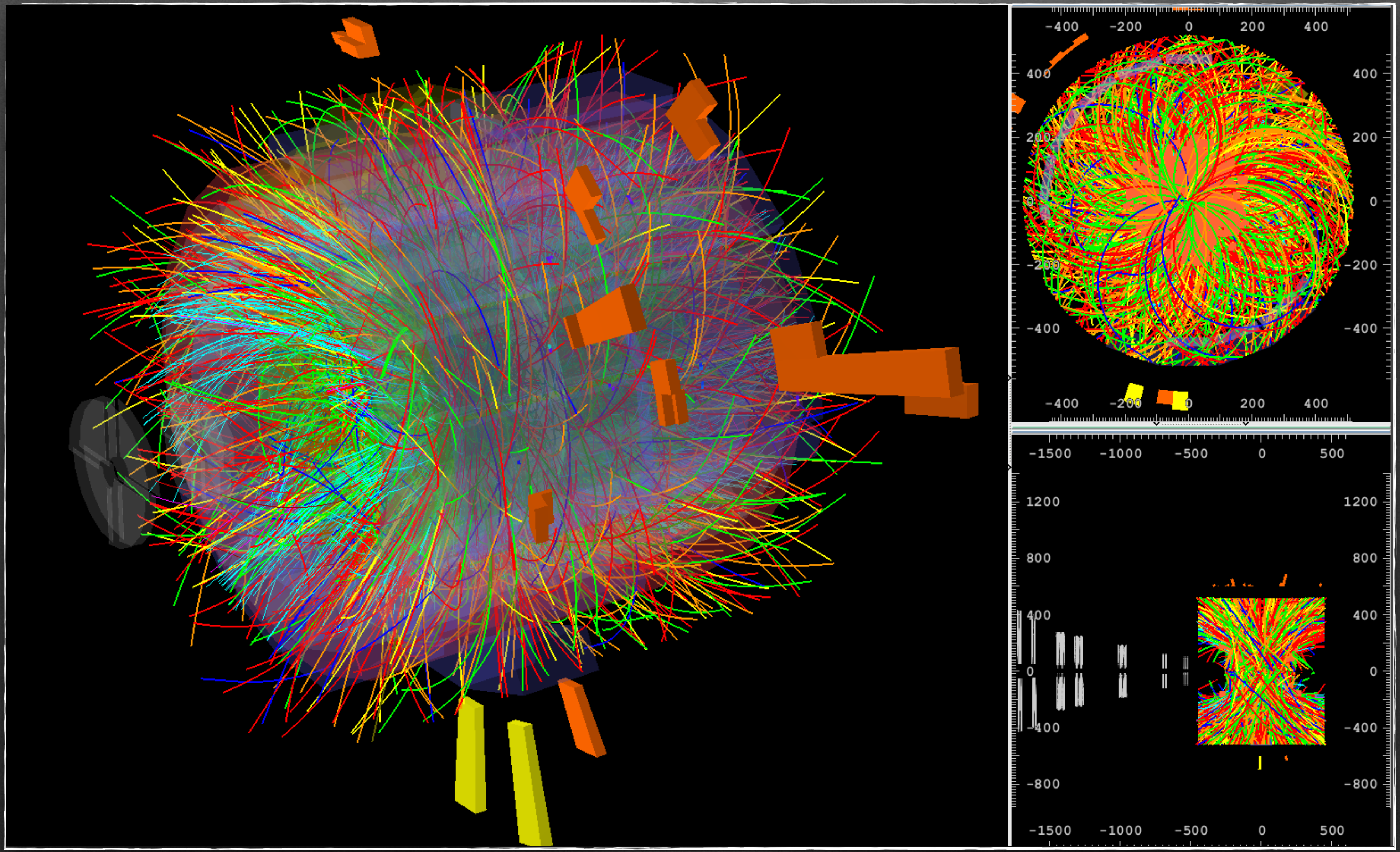




LHC discovery

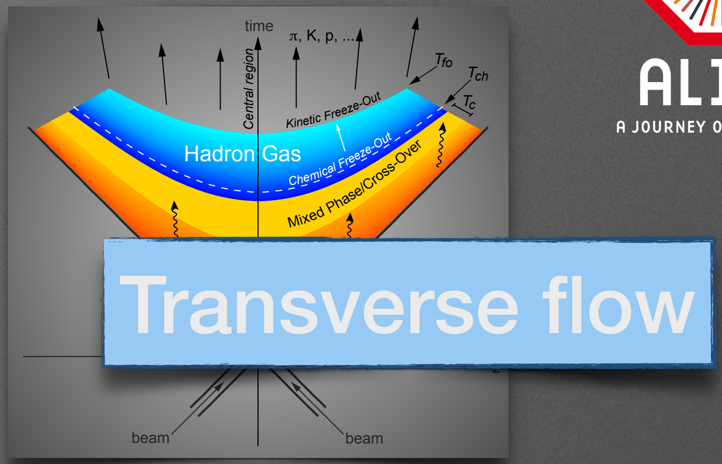
QGP in small systems ?



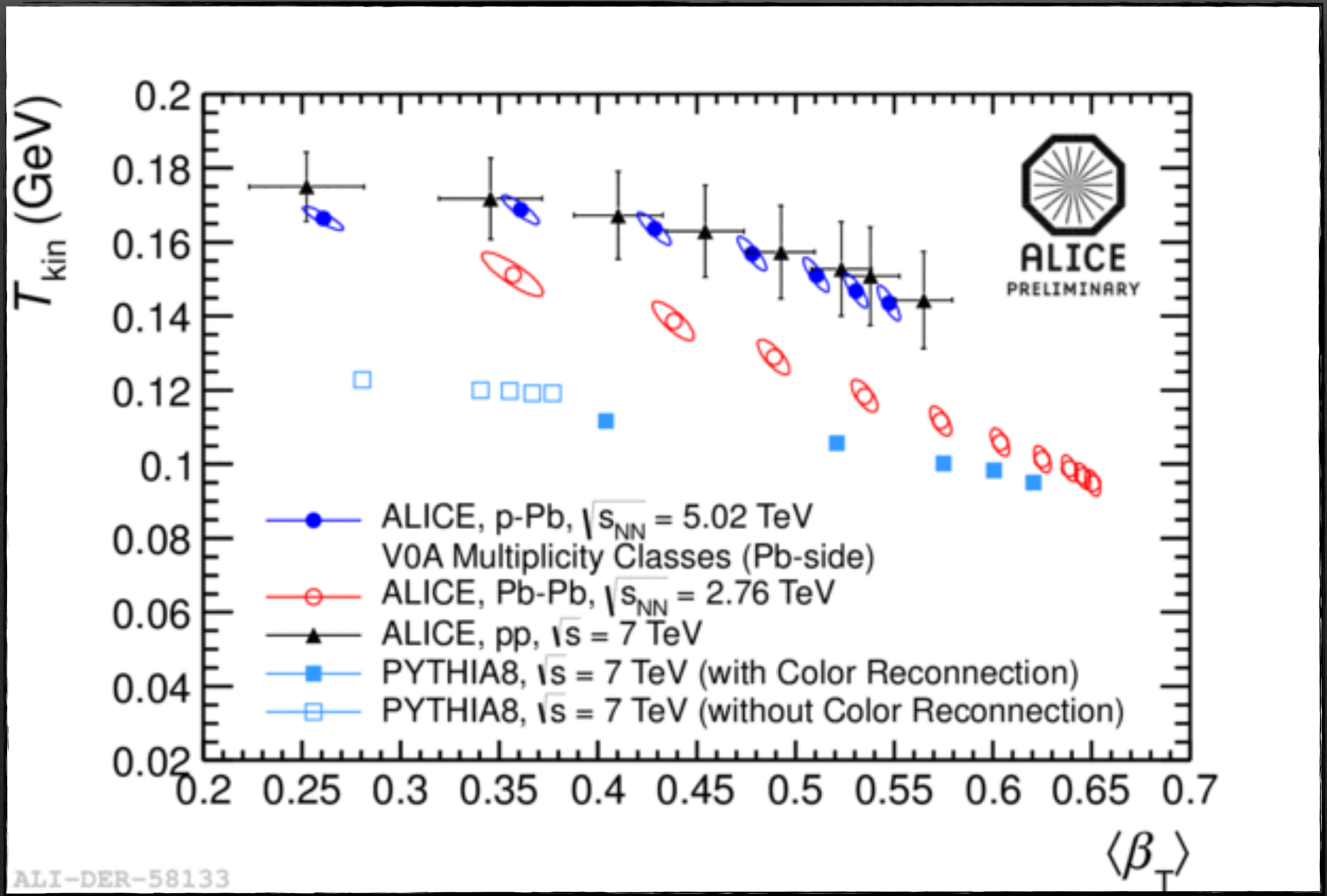


LHC discovery

QGP in small systems ?

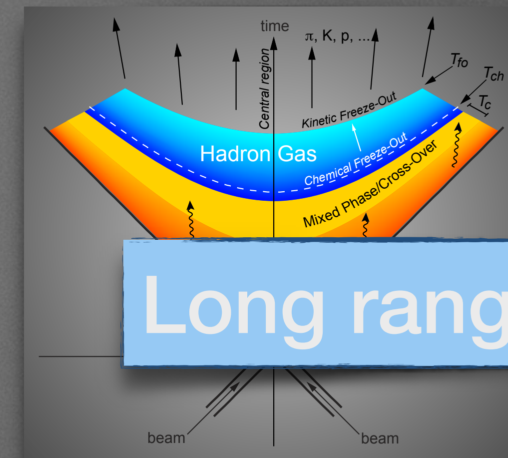


Most of features observed in AA and attributed to collective effects ... also observed in high M pA and pp



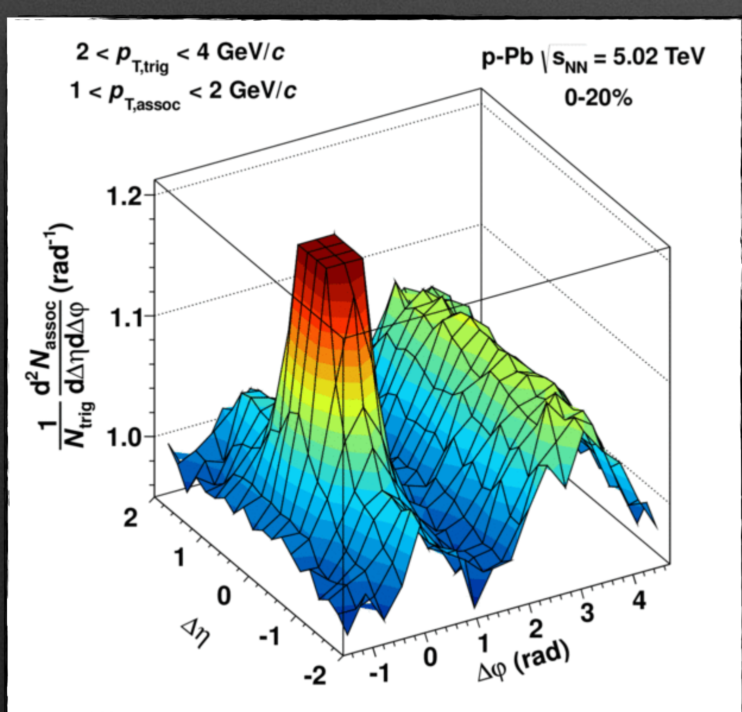
LHC discovery

QGP in small systems ?



Long range correlations

Most of features observed in AA and attributed to collective effects … also observed in **high M pA** and **pp**



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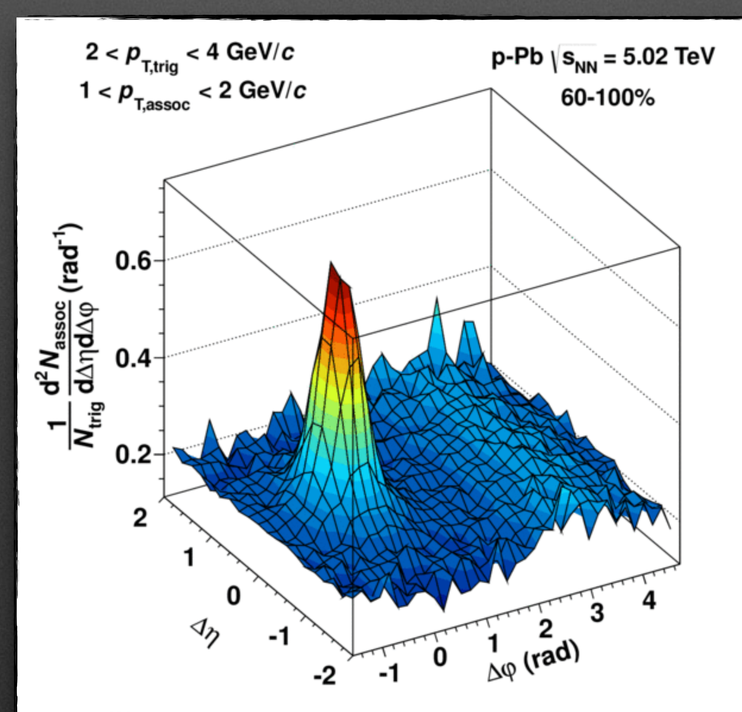

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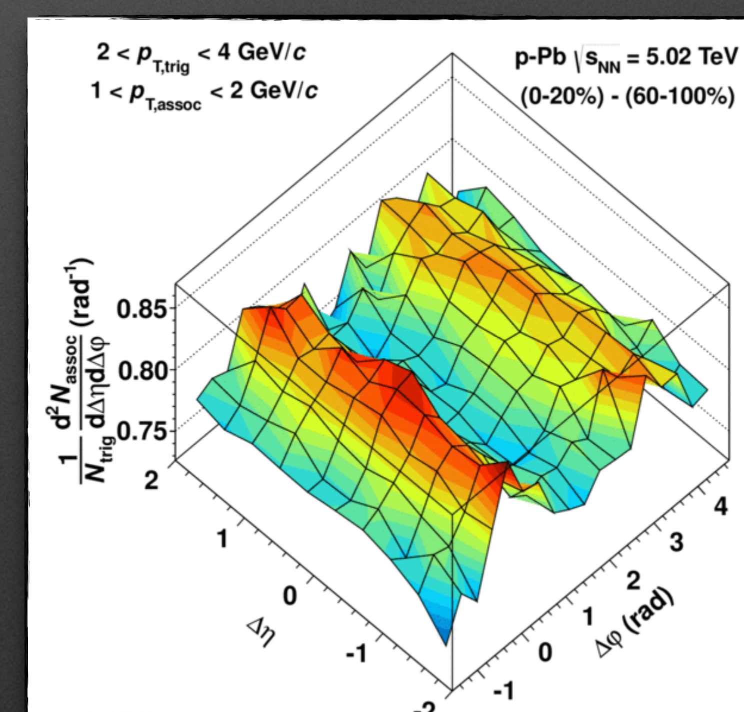
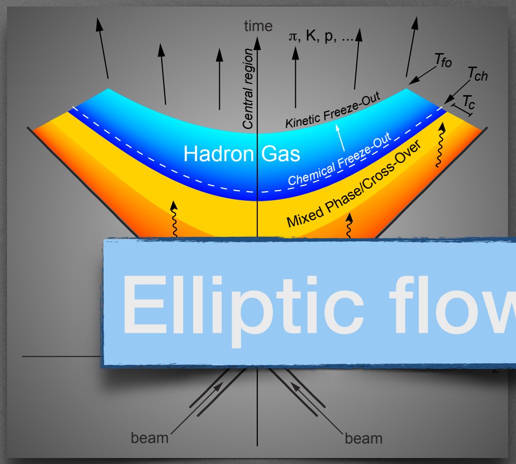
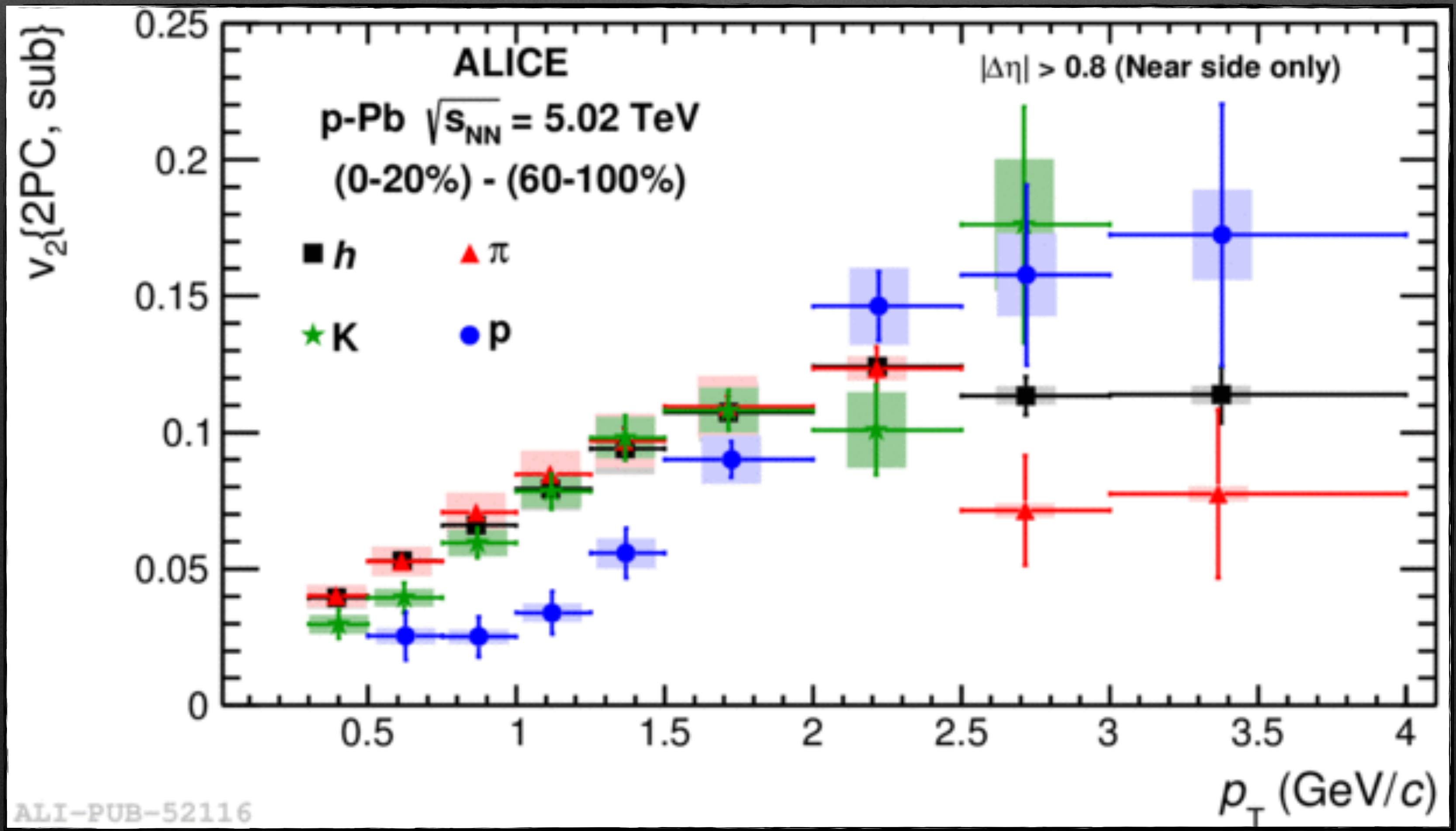


LHC discovery

QGP in small systems ?

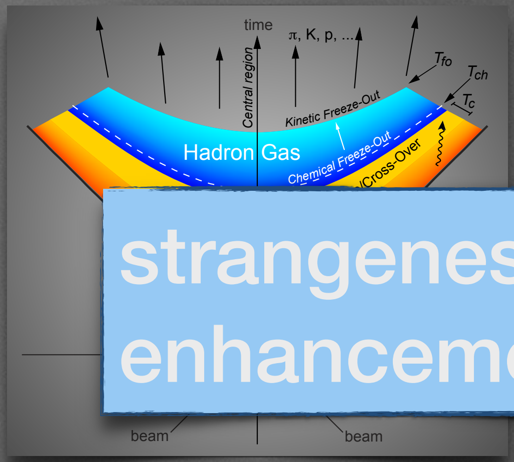


Most of features observed in AA and attributed to collective effects … also observed in high M pA and pp



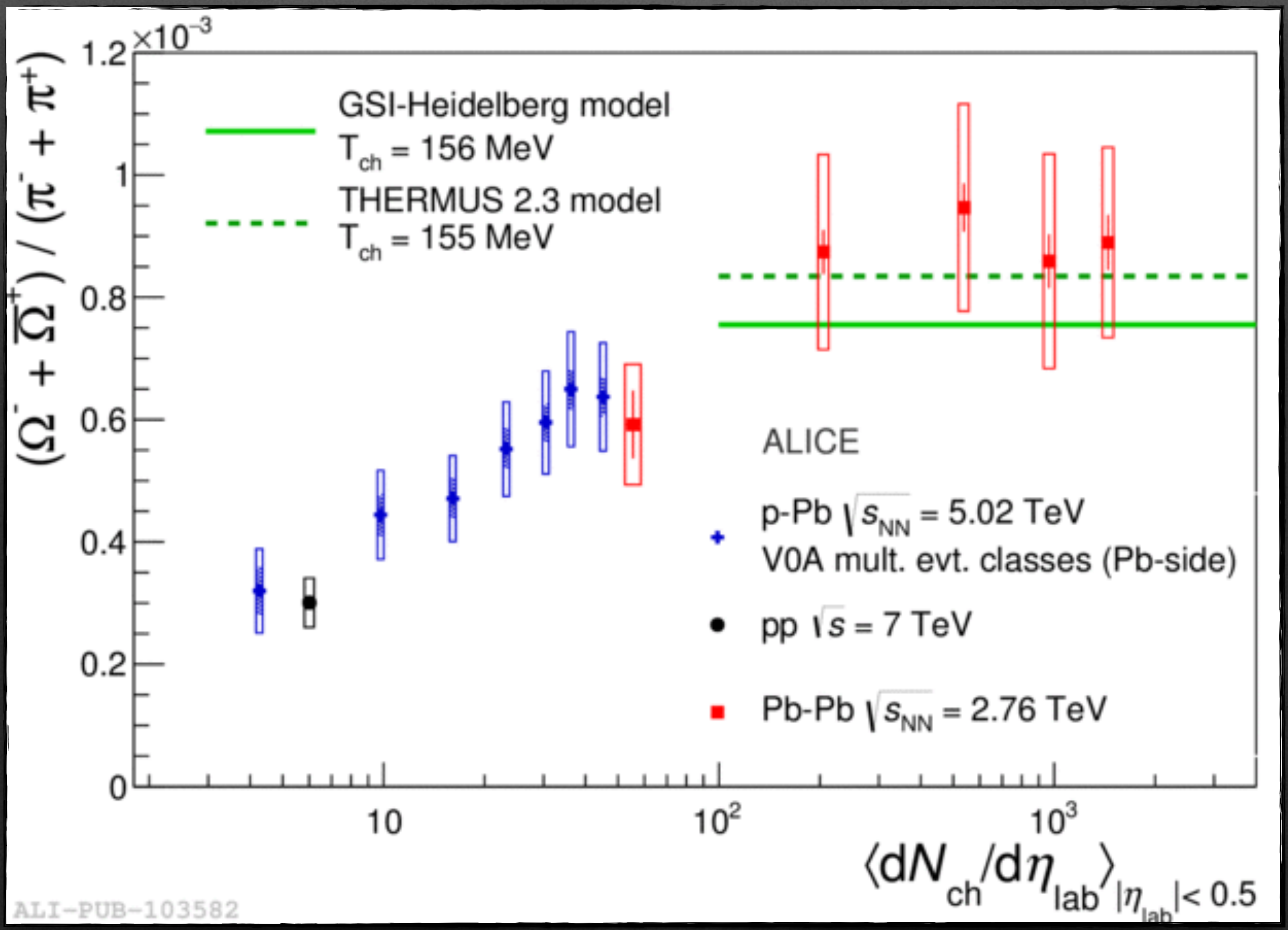
LHC discovery

QGP in small systems ?



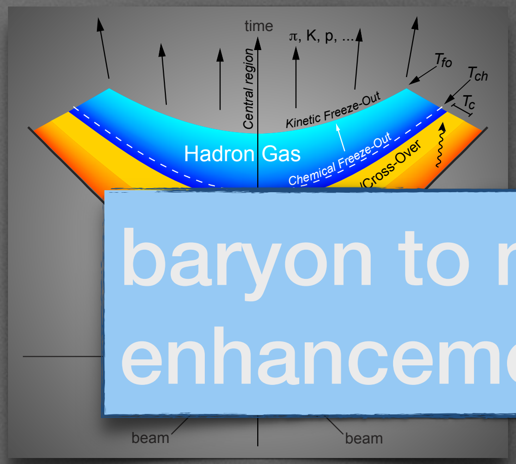
strangeness enhancement

Most of features observed in AA and attributed to collective effects … also observed in high M pA and pp



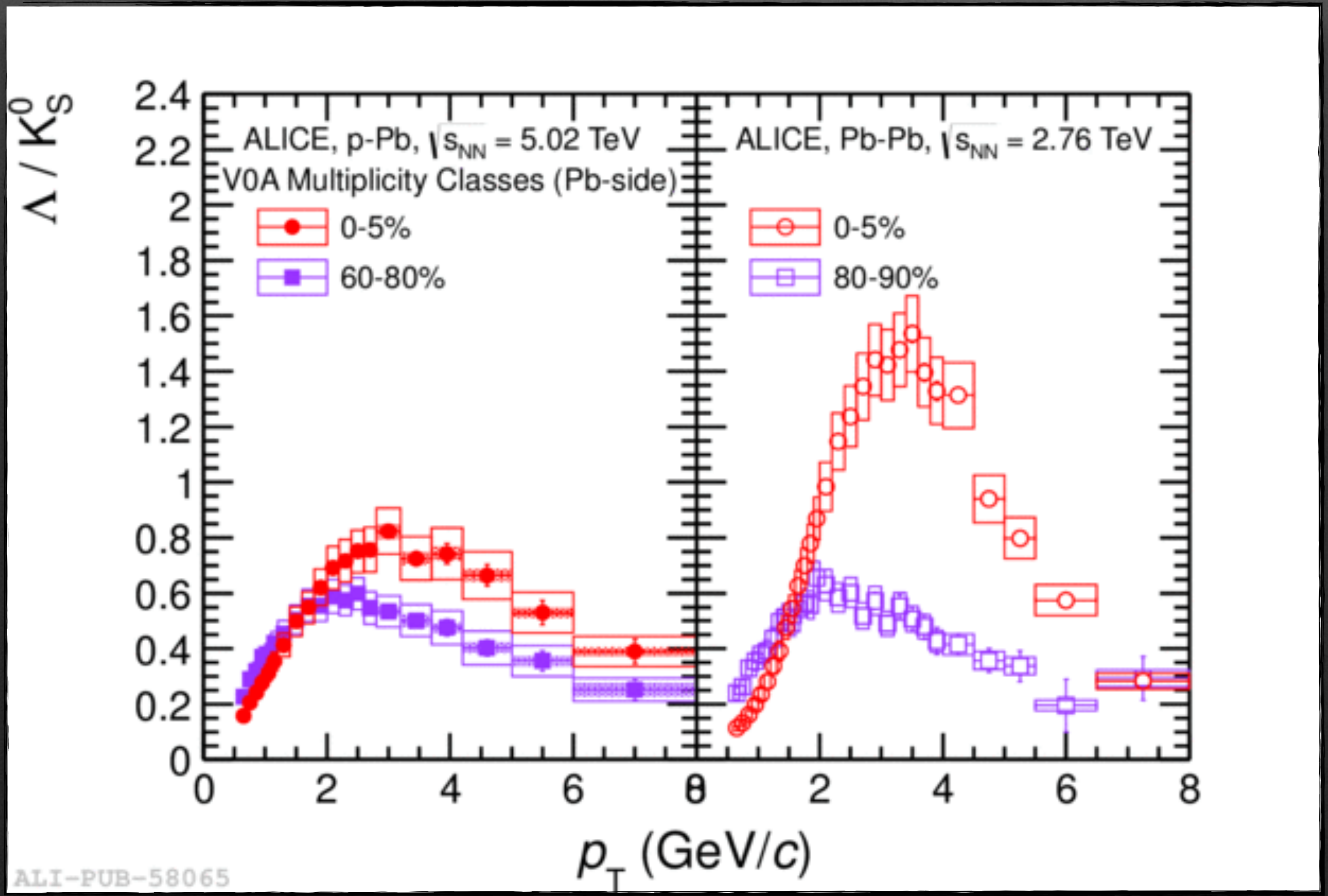
LHC discovery

QGP in small systems ?



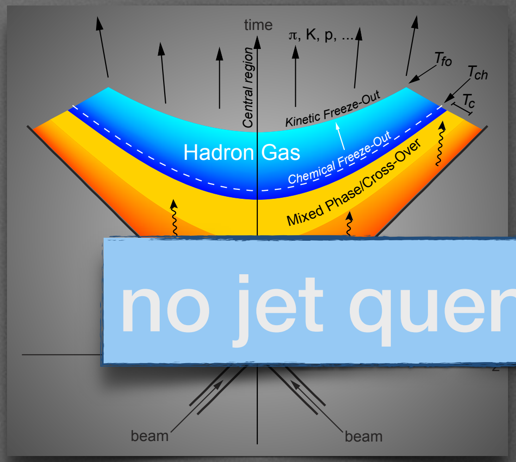
baryon to meson enhancement

Most of features observed in AA and attributed to collective effects … also observed in high M pA and pp



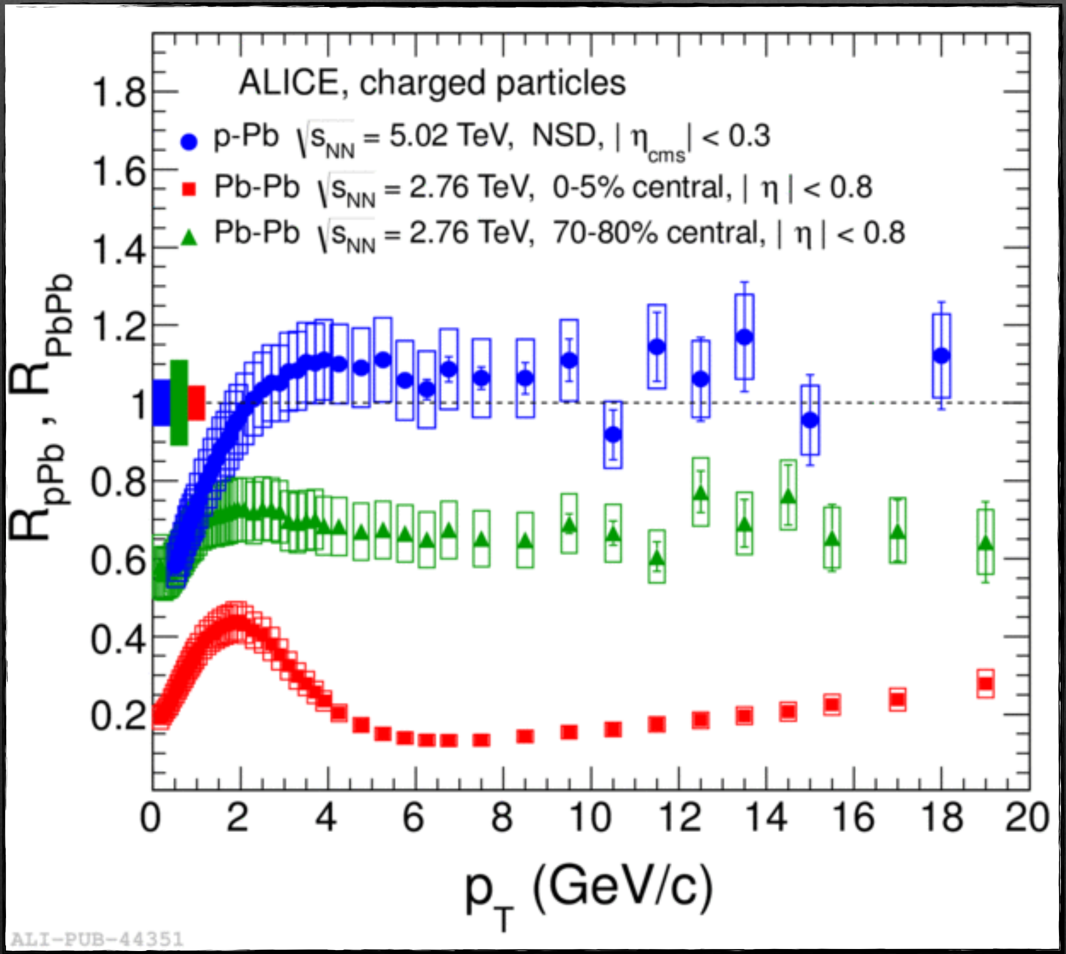
LHC discovery

QGP in small systems ?



no jet quenching

Most of features observed in AA and attributed to collective effects … also observed in high M pA and pp



ALICE
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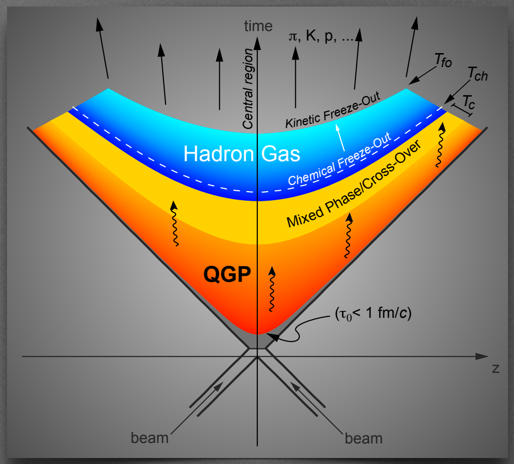
LHC discovery

Towards a new paradigm?



Most of features observed in AA and attributed to collective effects … also observed in **high M pA** and **pp**

T_H

mini droplet of QGP	small amount of QGP	infinite amount of QGP

e^+e^- → high M pp → high M pA → central AA

complexity