XIV International Workshop on Hadron Physics

High energy heavy-ion collisions - hot QCD in a lab

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Contents

- Focus on high-energy nuclear collisions
  - properties of matter at high densities/temperatures - accessible in a lab via heavy-ion collisions; control of high-energy strong interactions (colour glass condensate); study of structures of nucleons
  - Question for later: are smaller systems (pp, pPb) COLD QCD?
- HI collisions: experimental controls - calibration measurements
- How to measure the properties of a quark-gluon plasma
  - Collective effects: Particle correlations and flow
  - Probing the medium with quarks and jets

Thanks to all the authors/experiments for the graphics/slides shamelessly stolen for the purpose of this talk

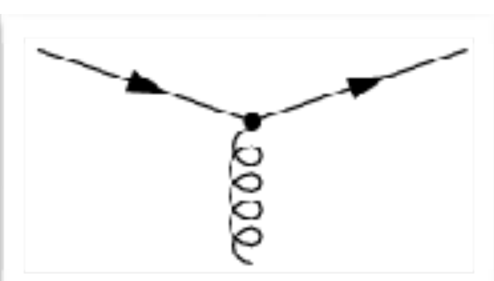
QCD (Quantum Chromo Dynamics)

$$\mathcal{L}_{QCD} = \bar{\psi}_i \left(i\gamma_\mu D^\mu_{ij} - m\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

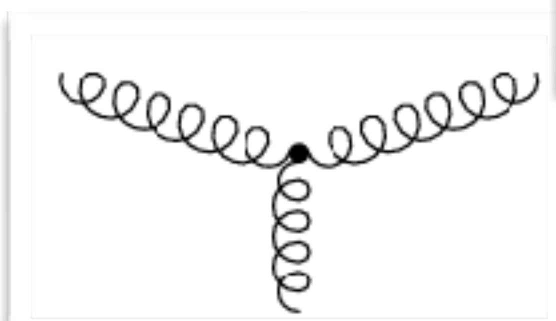
$$D^\mu_{ij} = \delta_{ij}\partial^\mu + i\, g\, A^\mu_a T^a_{ij}$$

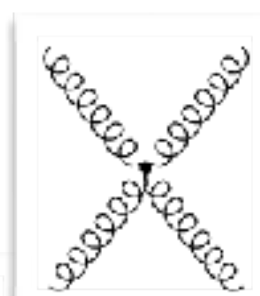
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\, f^{abc} A^b_\mu A^c_\nu$$

Quark-Gluon interaction



Gluon-Gluon interactions

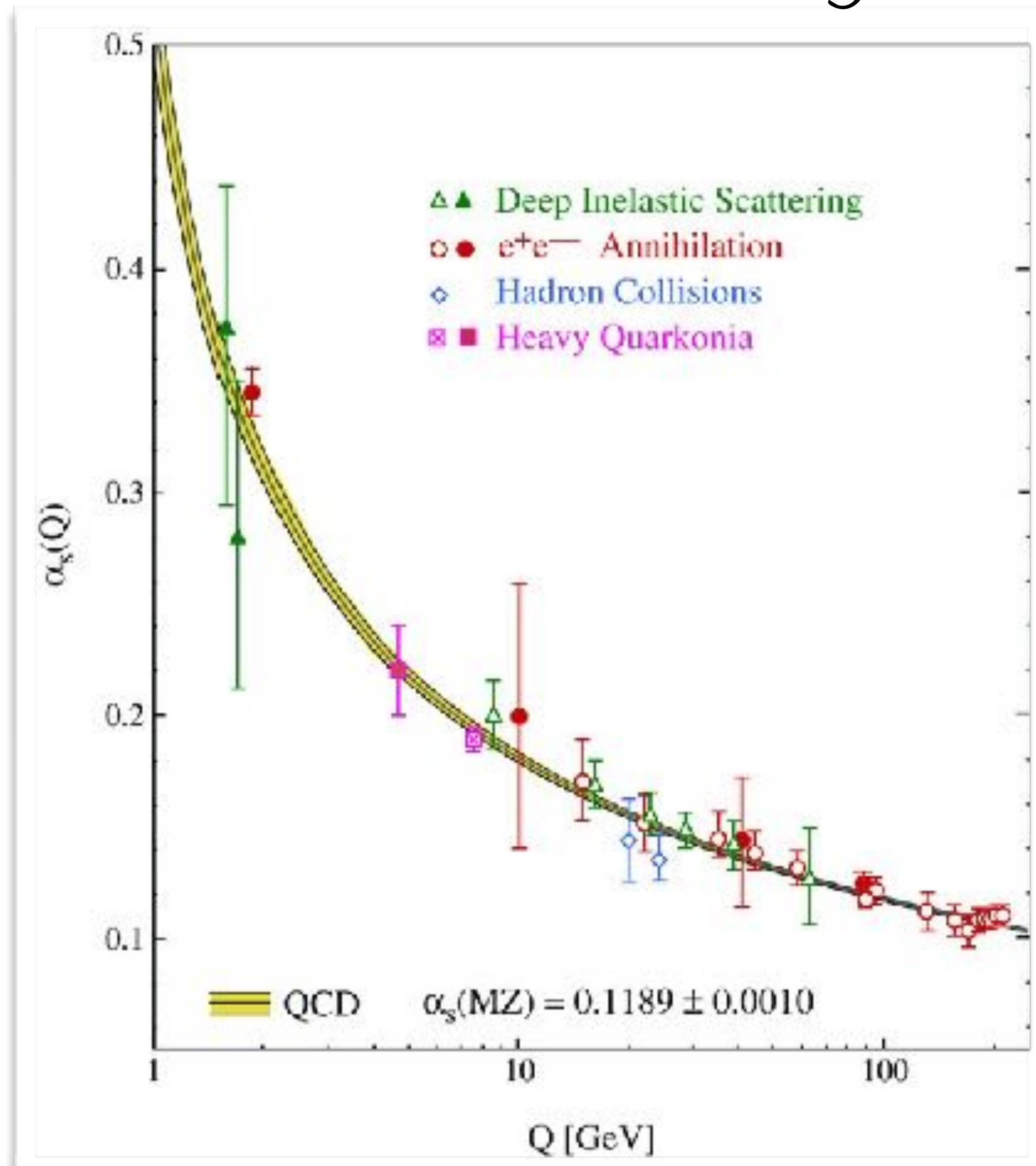




Short distance (high-Q^2) - good agreement theory-experiment; pQCD - more on that in the next lecures

Long distance (low-Q)

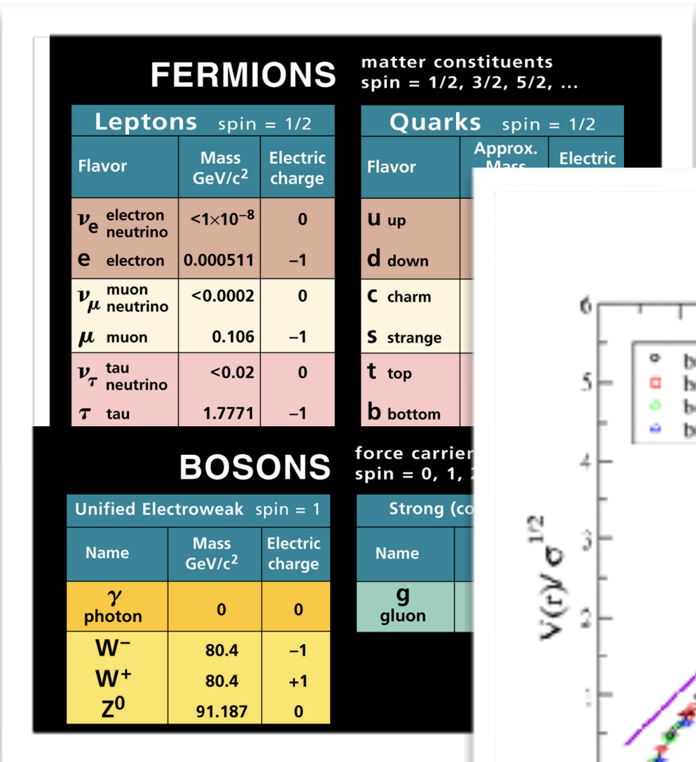
Short distance (large-Q)

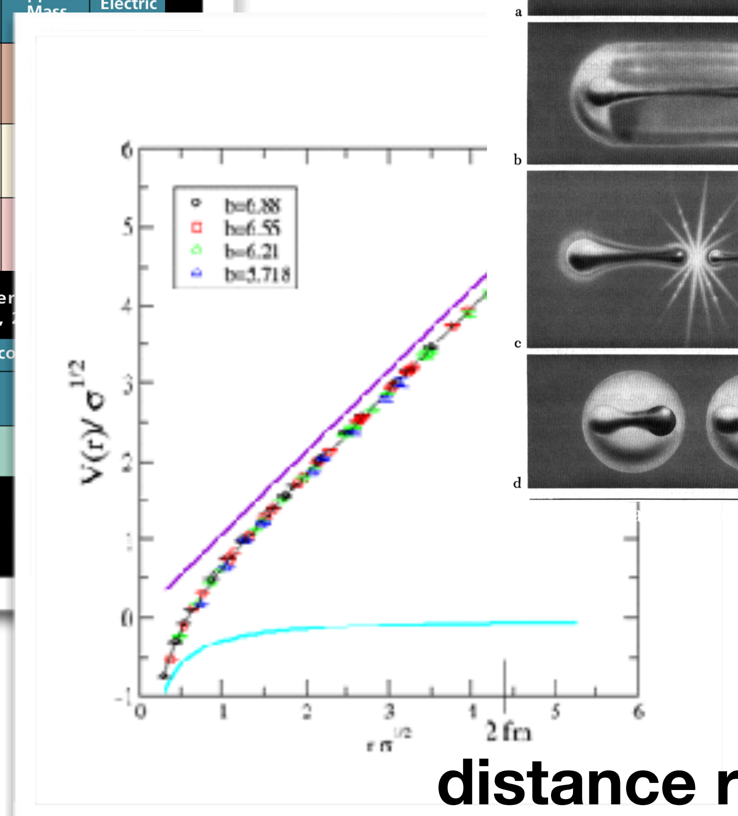


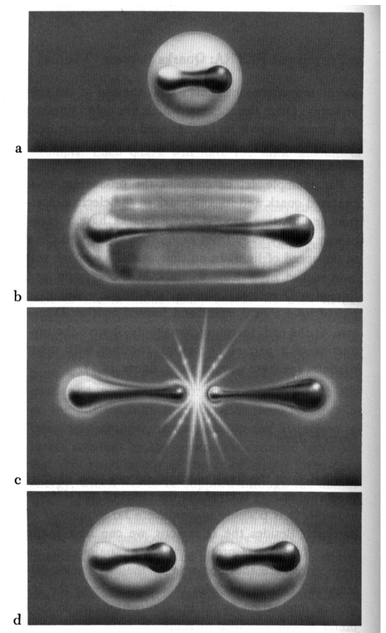
Asymptotic freedom

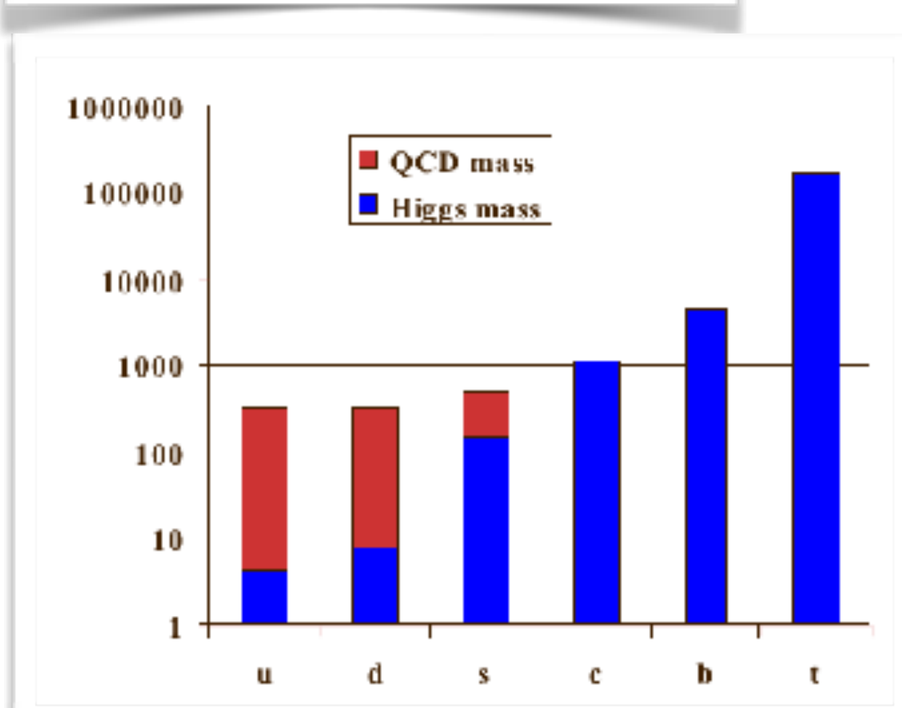
Gross, Politzer, and Wilczek (2004)

QCD... one minute summary









QCD describes interaction between colour charges mediated by strong force carriers (gluons)

Confinement: strong interaction binds quarks into hadrons and nucleons into nuclei – no free quarks/color – half of fundamental fermions!

Perturbative QCD successful in describing many short-distance phenomena – at long distances experimental input crucial

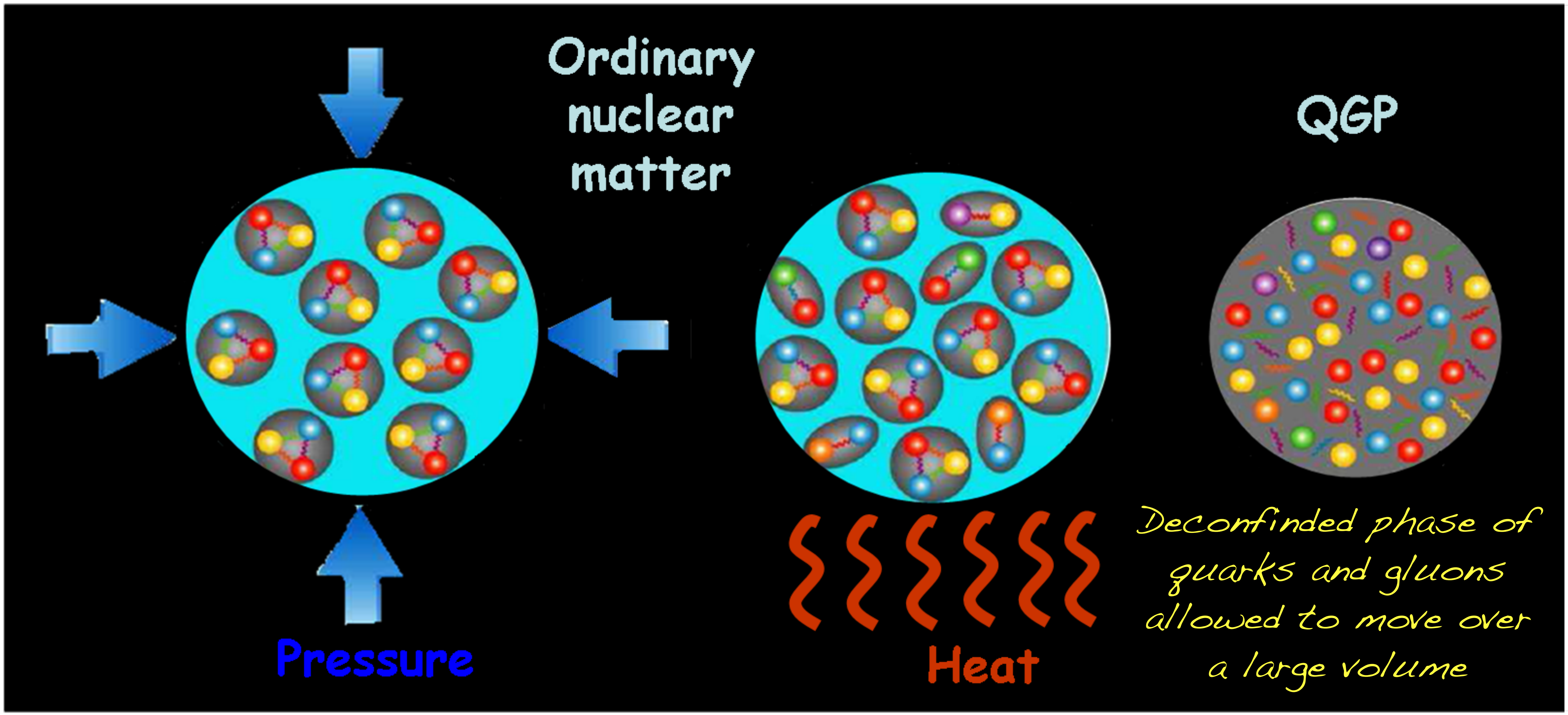
QCD vacuum – rich physics:

- sum of masses of the constituent quarks (12 MeV) in a proton is much less than the mass of a proton (~1000 MeV)
- wave functions of hadrons (only ~20% of nucleon-spin in quarks)

Create hot & colored medium

temperatures ~1.5 x 10^{12} K (~200 MeV)

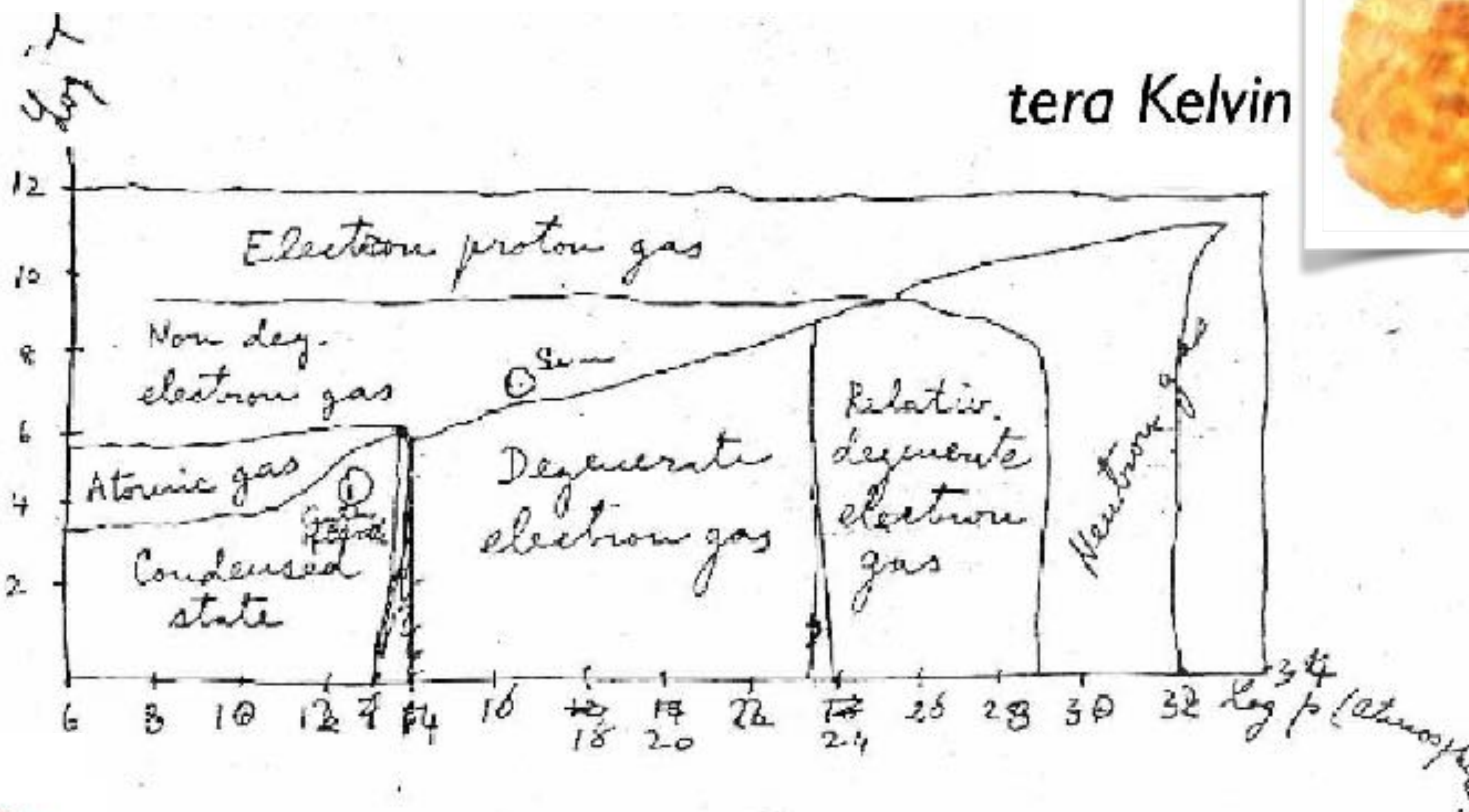
far hotter than center of the sun (~1.5 x 10^{7}K)



Heat and/or compress matter such that the individual nucleons start to "overlap"...

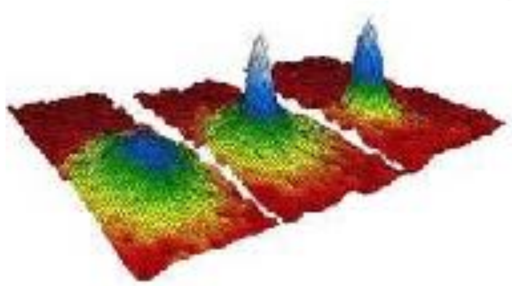
An old question: state of matter in "unusual conditions"

Fermi 1953

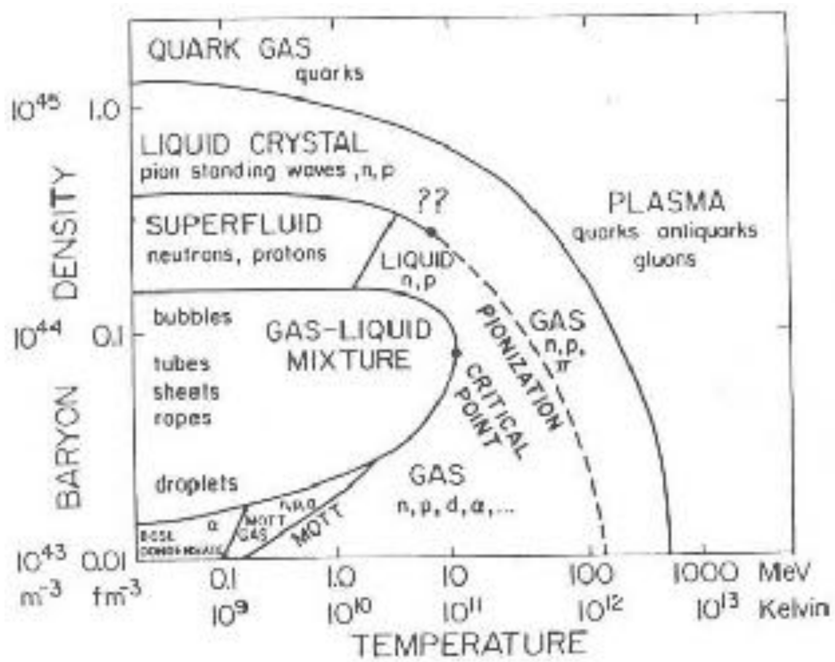


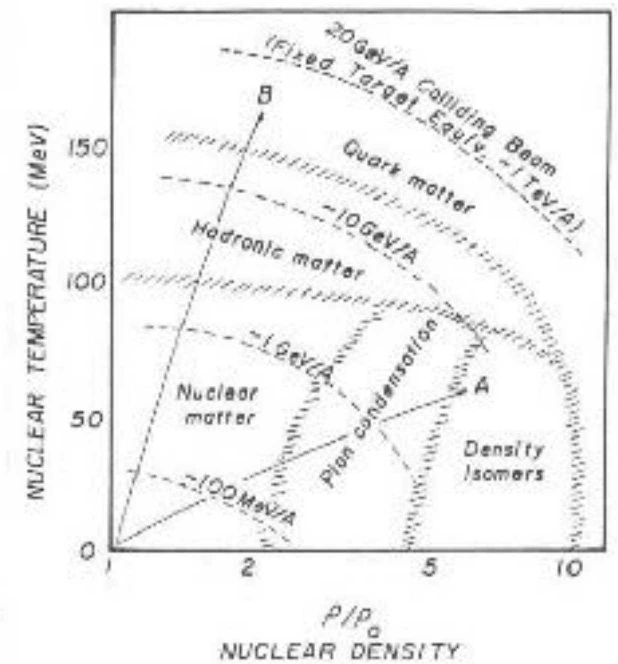
Matter in unusual conditions

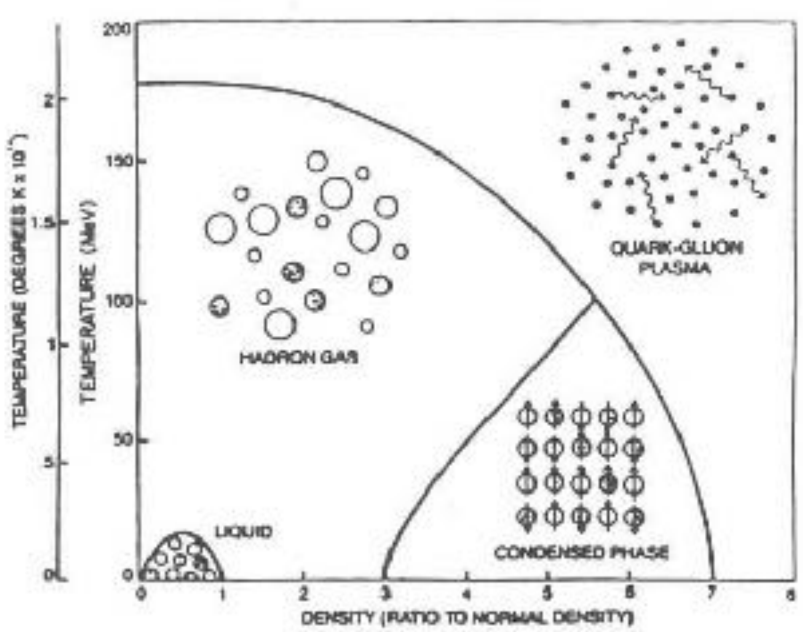
tera Kelvin

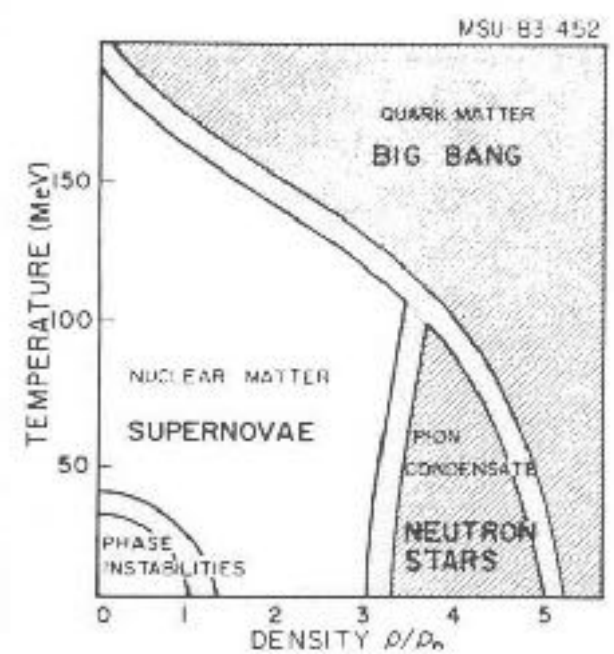


discussed for many years ....

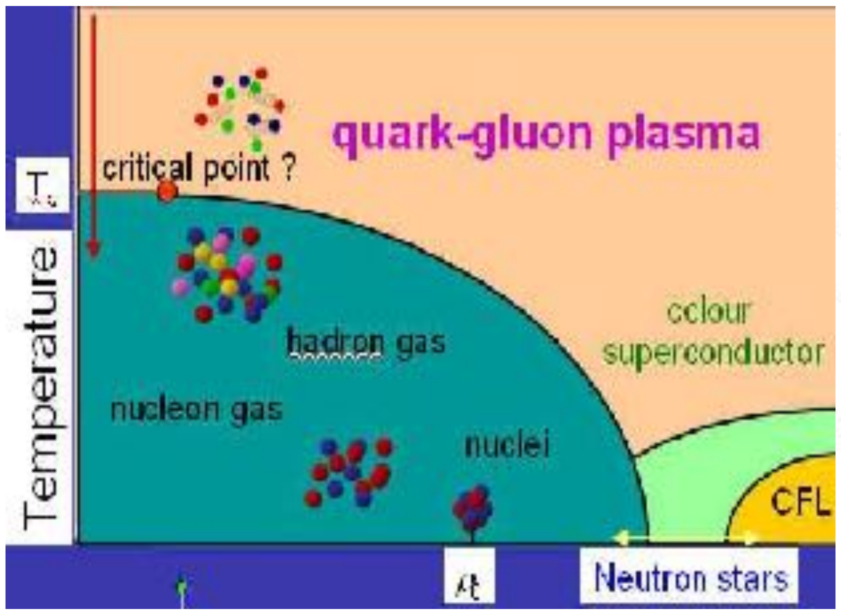


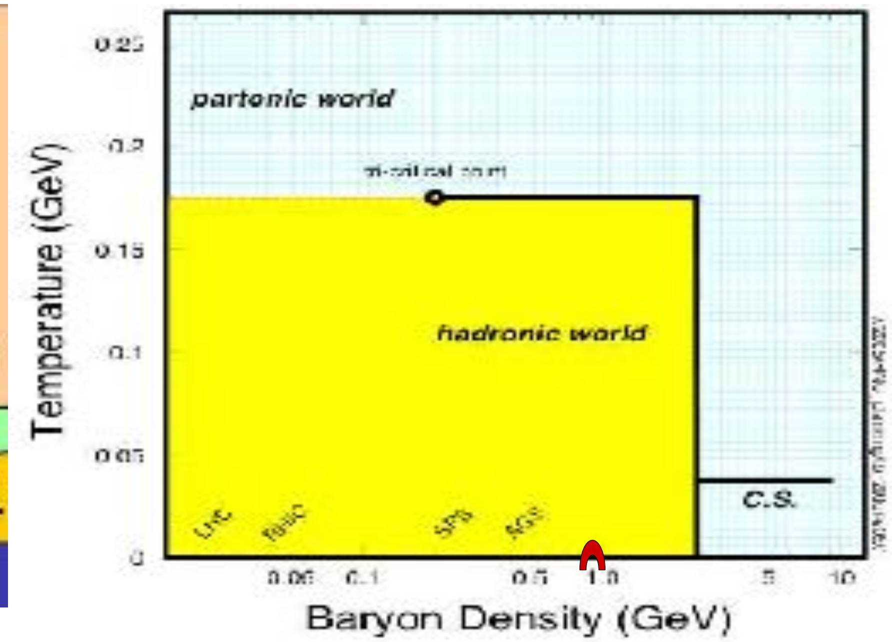


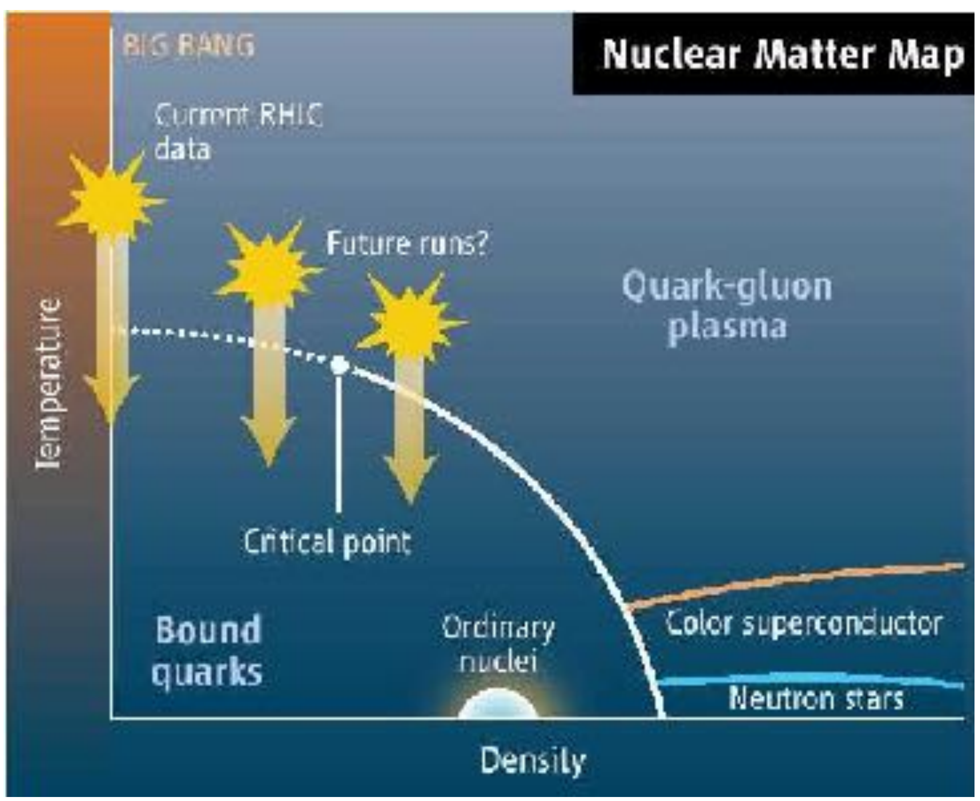


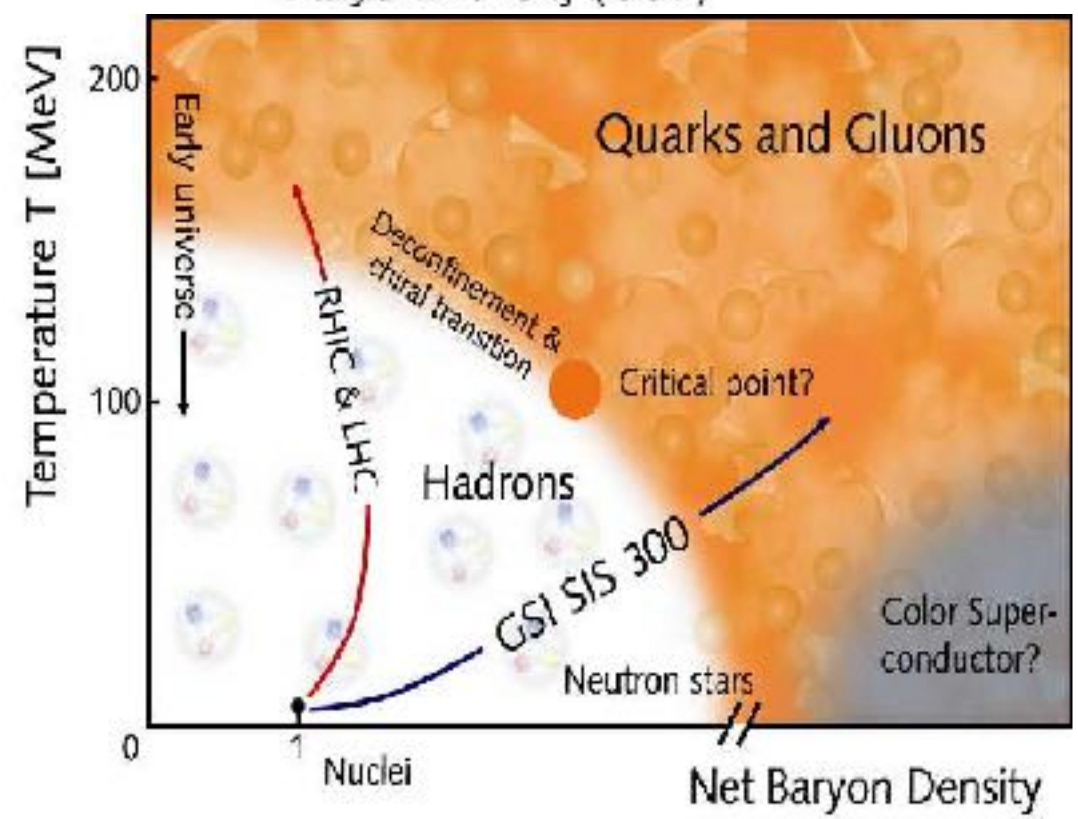


quite a bit discussed...



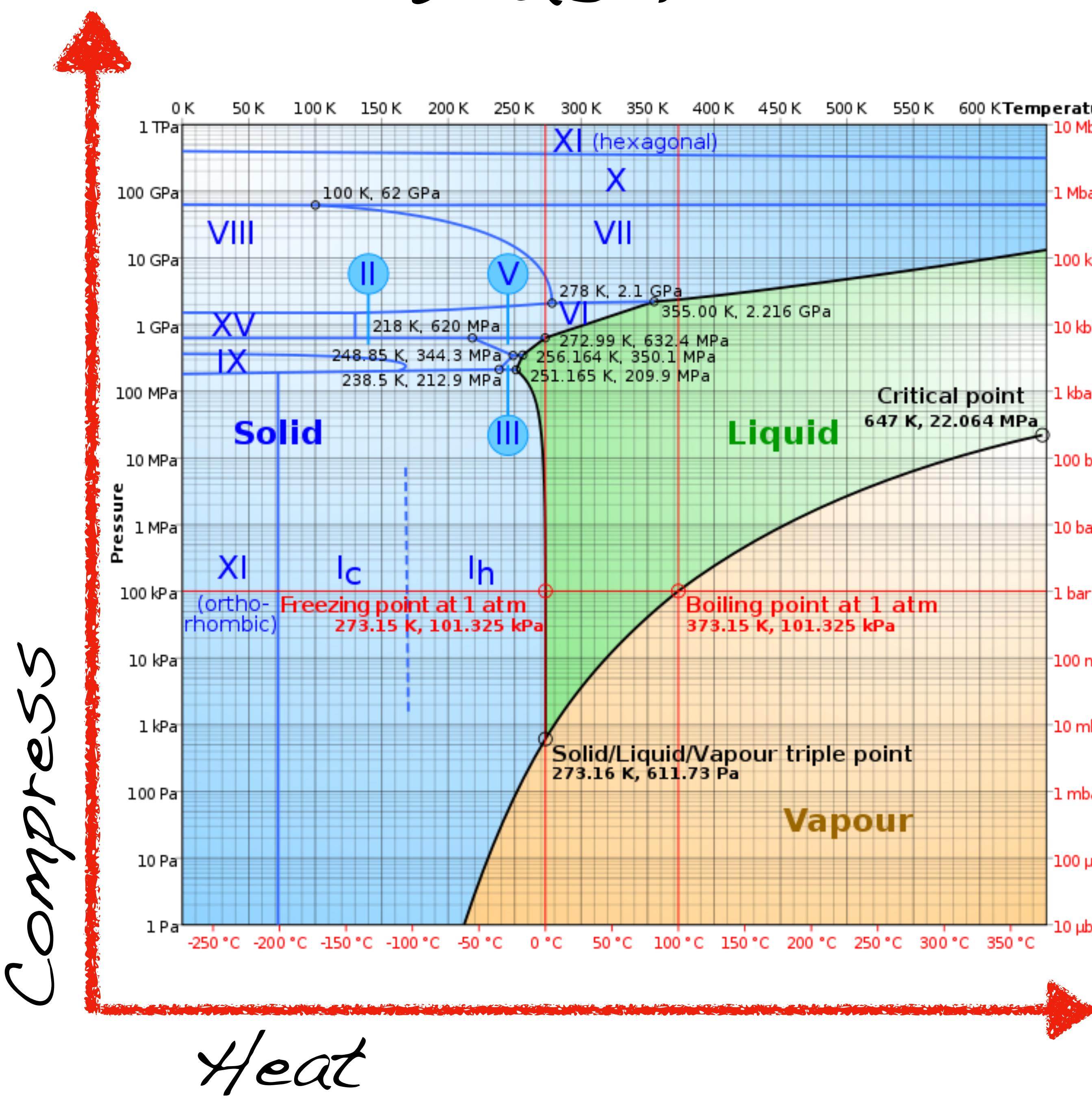




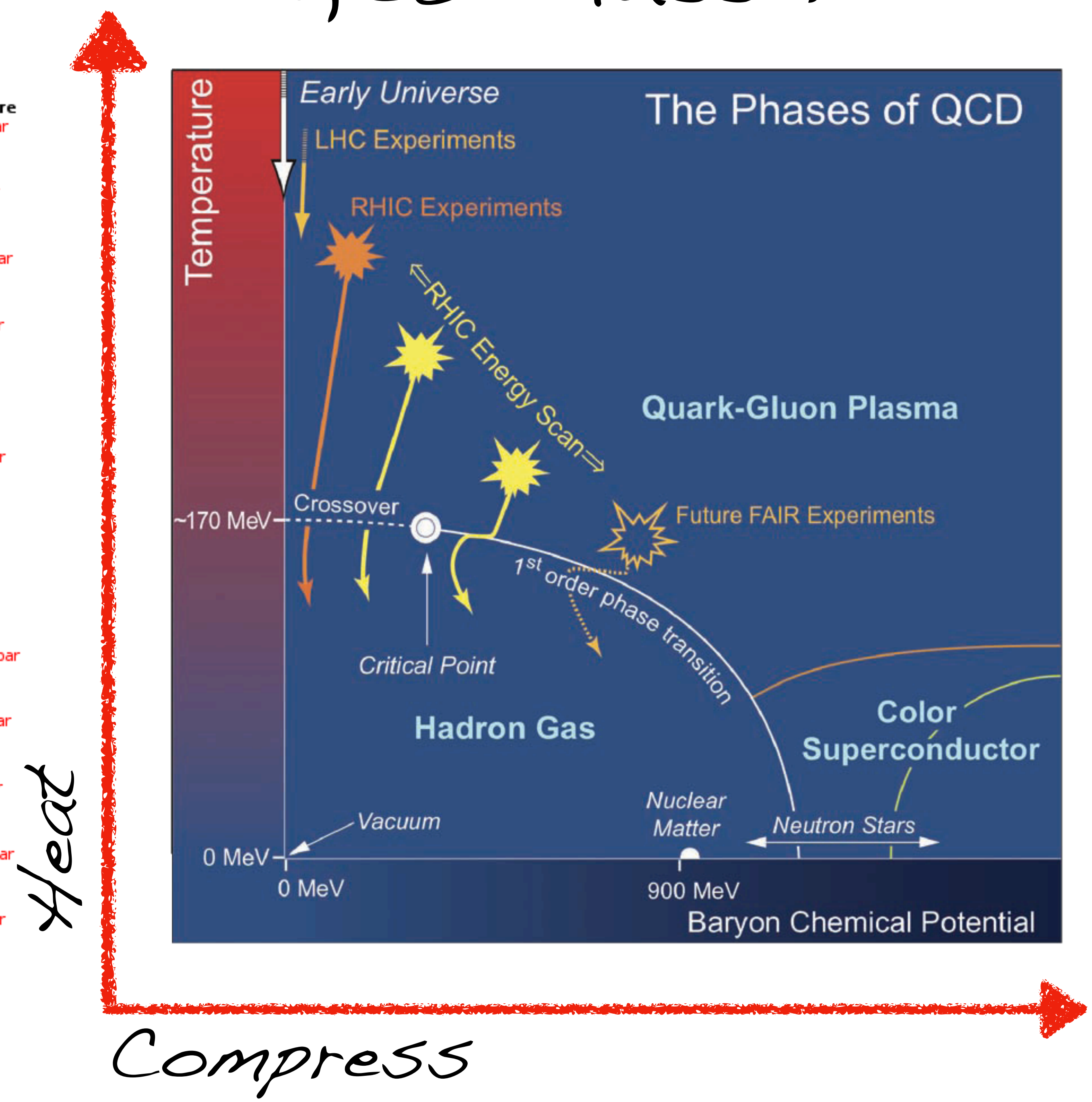


… this is about exploration of properties of matter…

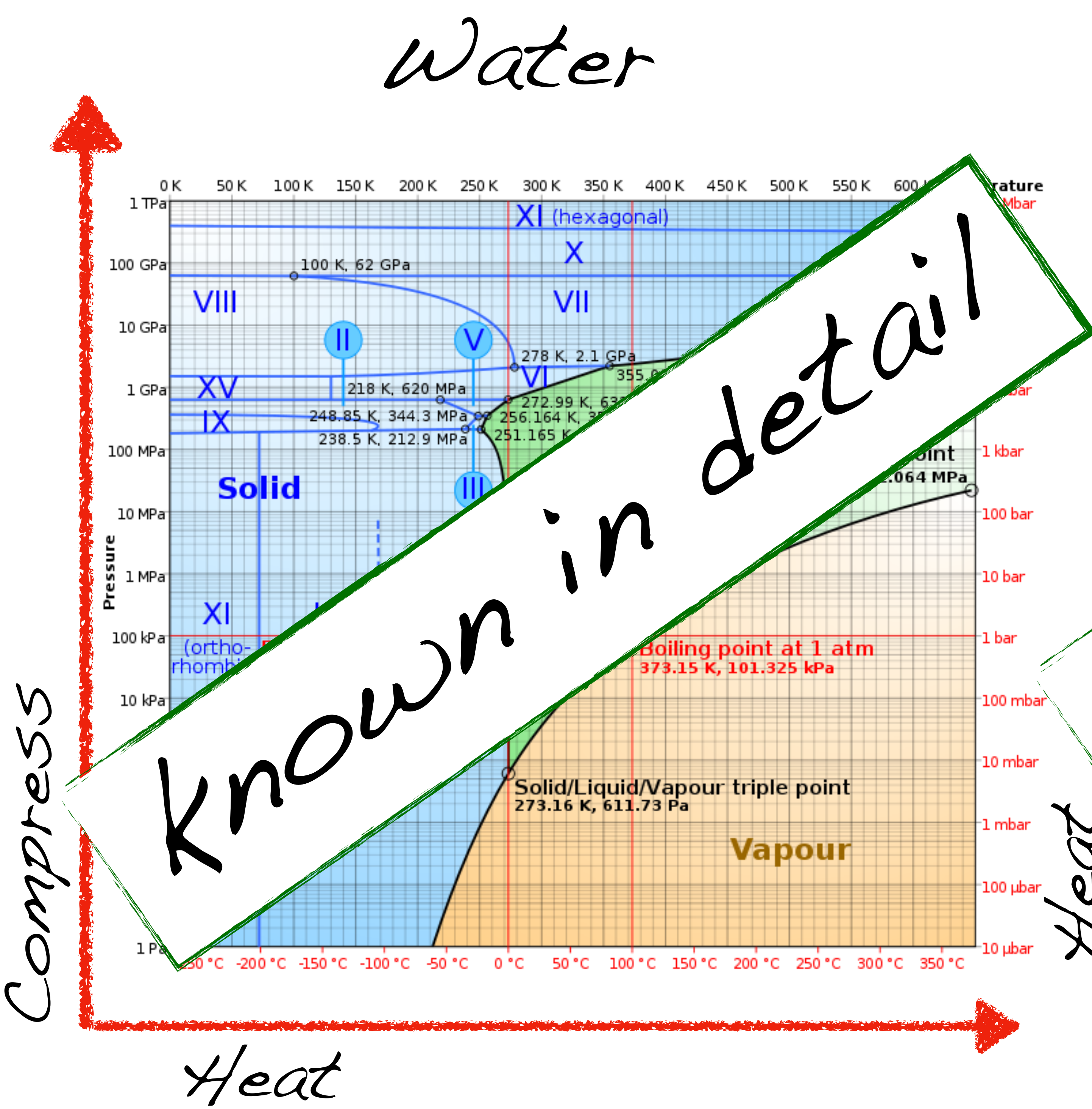
Water

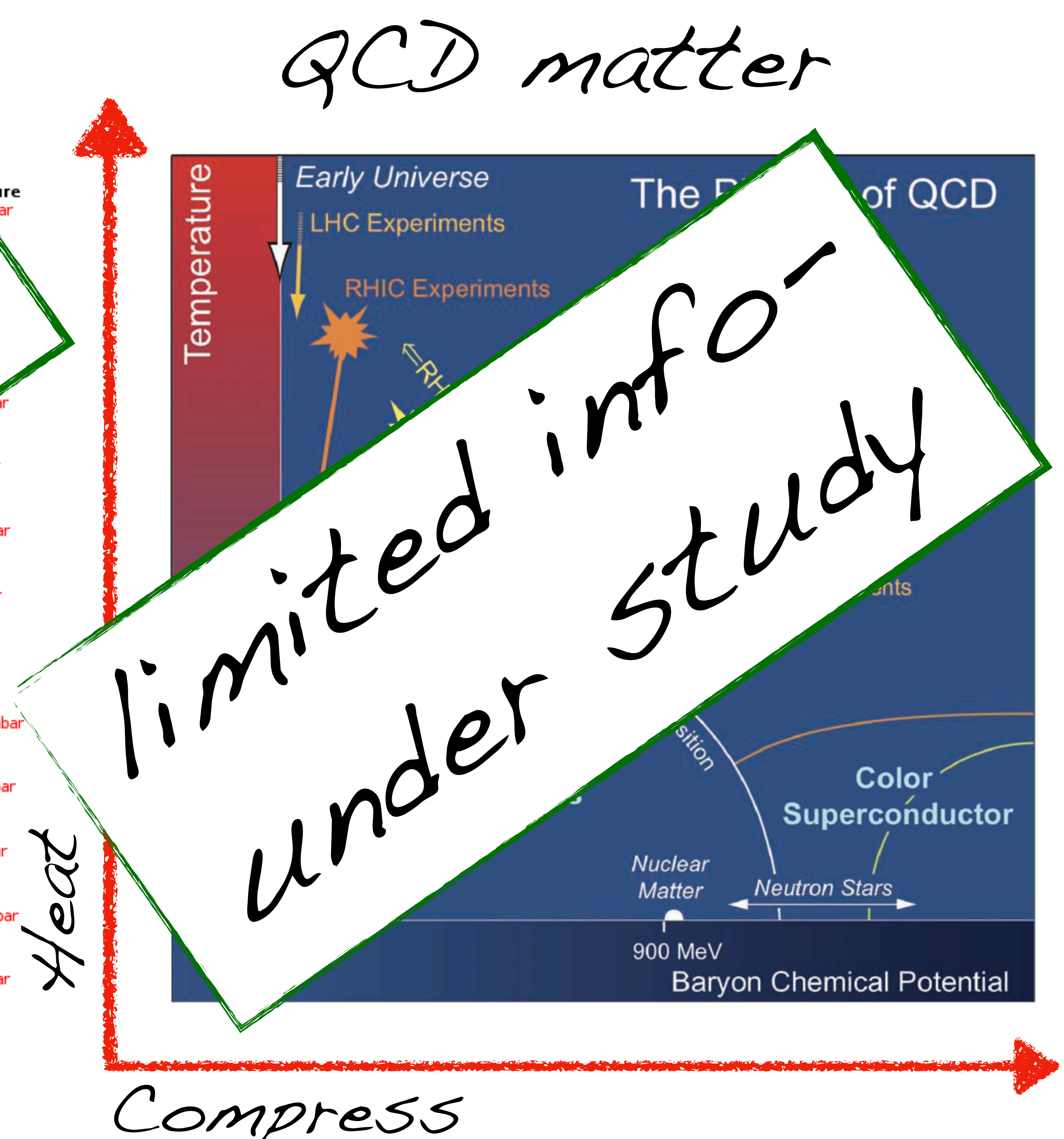


QCD matter

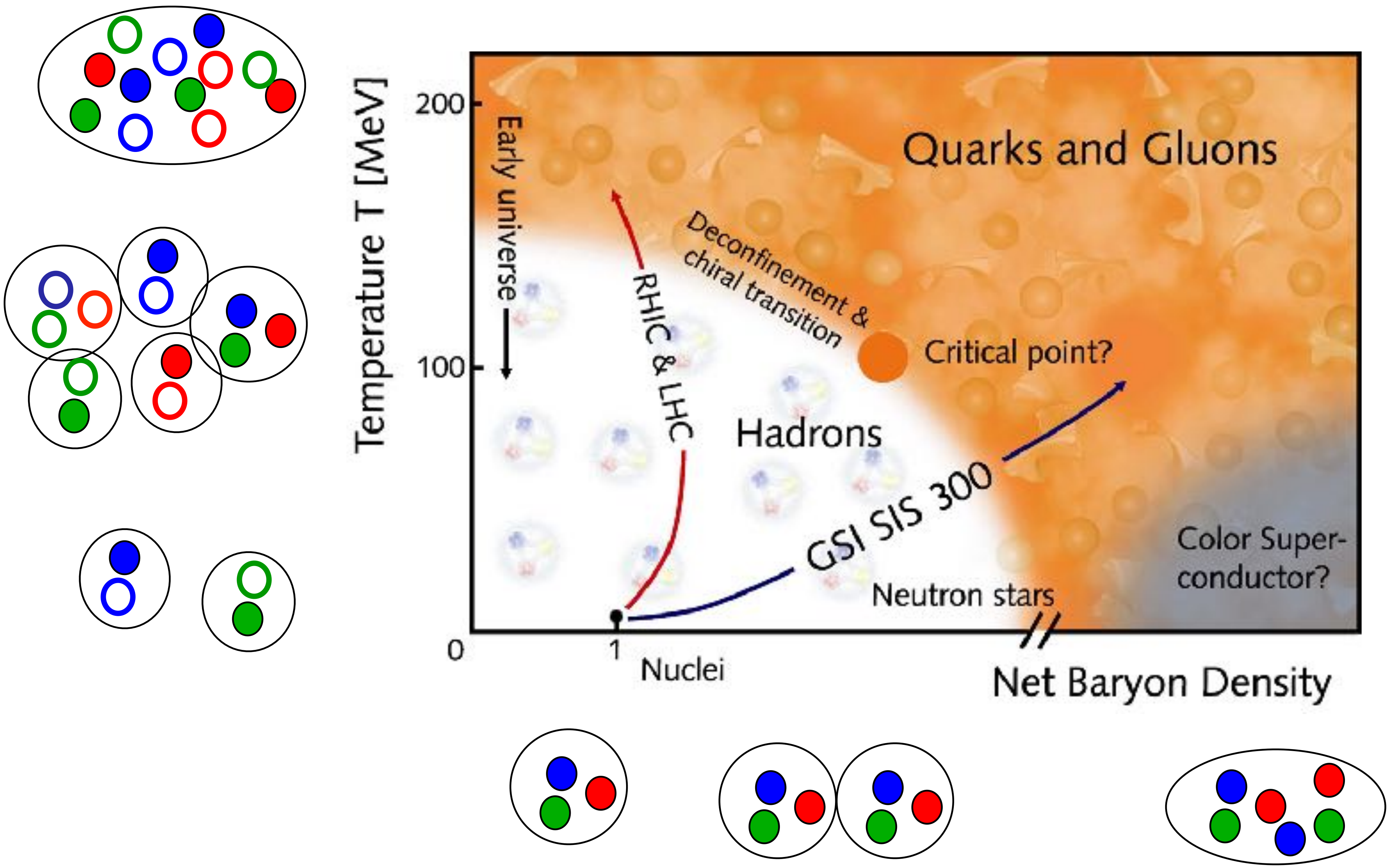


... this is about exploration of properties of matter...





Heating the QCD vacuum / compressing QCD matter



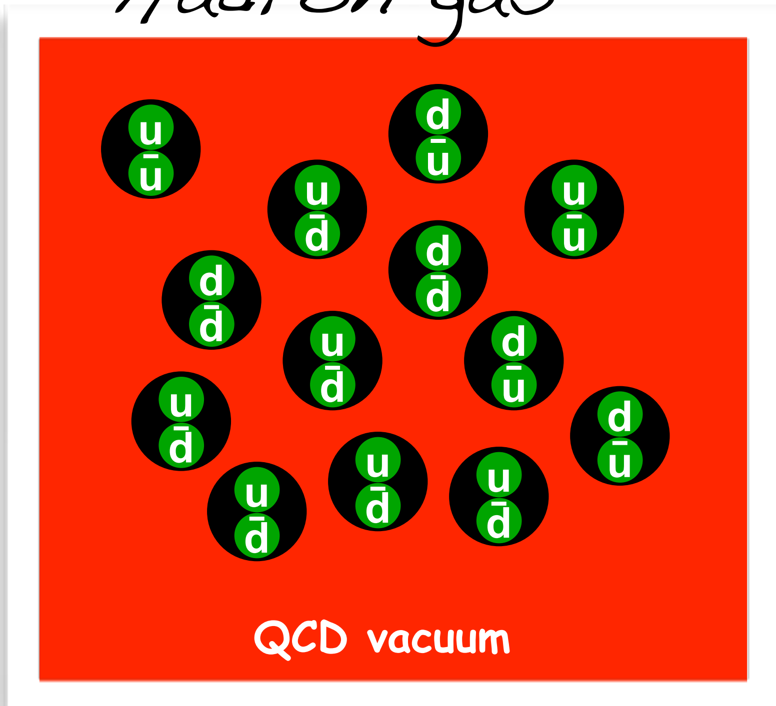
Pressure-temperature considerations

Gibbs' criterion: the stable phase is the one with the largest pressure

Statistical mechanics (ideal gas):

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90}$$

Hadron gas

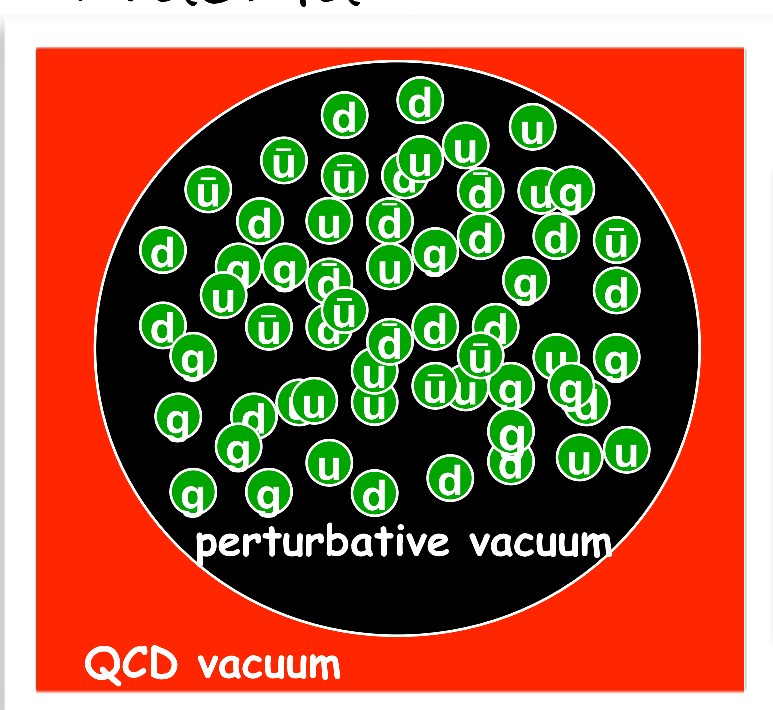


$g_B = 3 \quad g_F = 0$

$$p = \frac{3}{90}\pi^2 T^4 + B$$

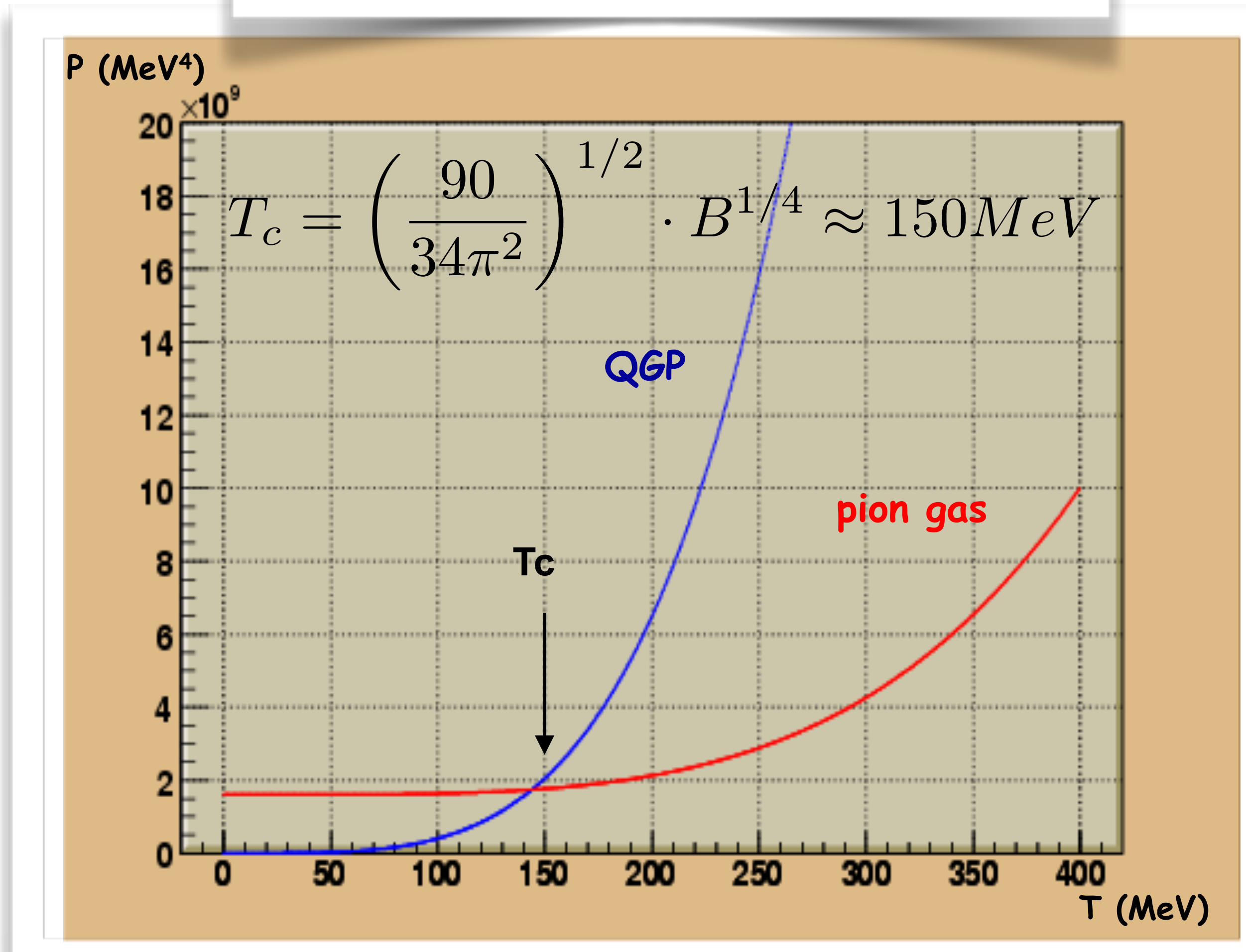
QCD vacuum pressure
B~(200MeV)^4

Plasma



$g_B = 16 \quad g_F = 24$

$$p = \frac{37}{90}\pi^2 T^4$$



At low-T: hadron gas is the stable phase

At high-T: above T_c QGP is the stable phase

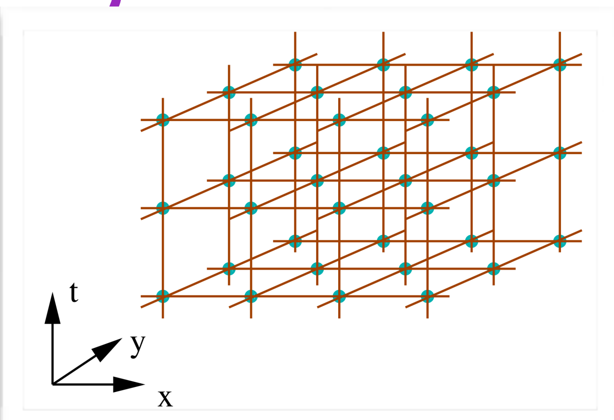
Refined calculations: Tc=155 MeV:

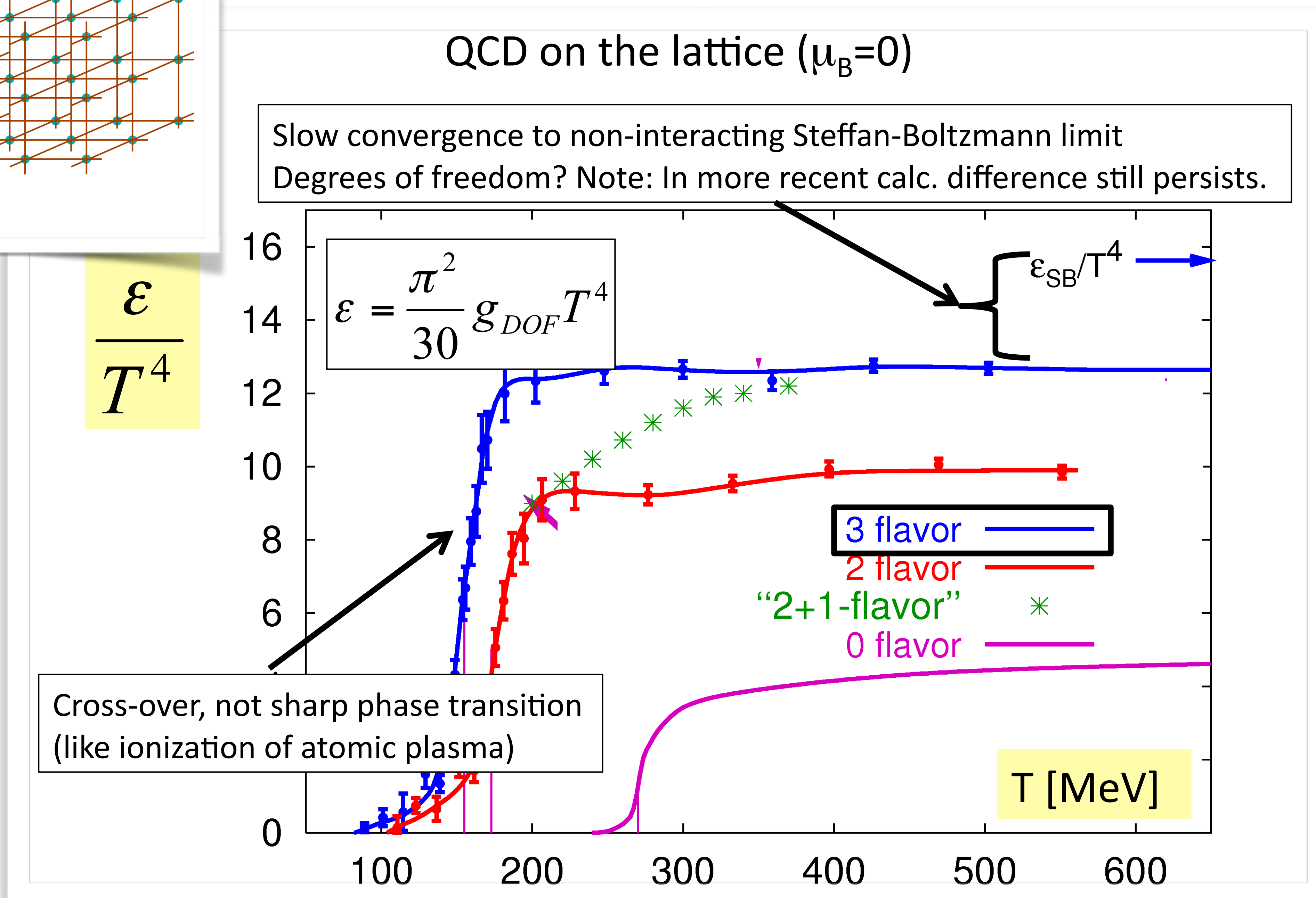
NOTE: T_{room} (300 K) ~ 25 meV (!lowercase m)

Tc ≈ 160 MeV ≈ 2 thousand billion K

(compare Sun core: 15 million K)

QCD Thermodynamics - calculation





"Lattice": rigorous calculations in non-perturbative regime of QCD - discretization on a space-time lattice - ultraviolet (large momentum scale) divergencies avoidable

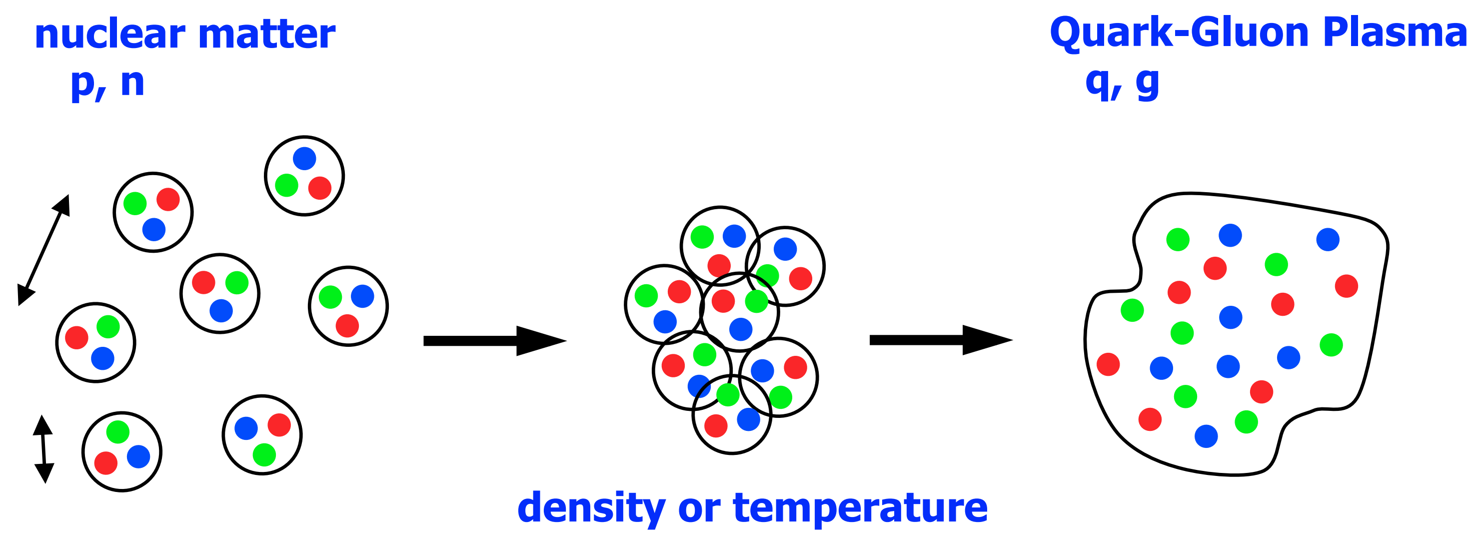
Zero baryon density, 3 flavours: ε changes rapidly around T_c = 170 MeV: ε_c = 0.6 GeV/fm³ (at $T \sim 1.2\, T_c$: ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of $q, \bar{q}, g$ (ε_{SB}))

What it the critical energy-density?

Vacuum (quarks and gluons in bags
(MIT bag model)) and nucleons

distance of two nucleons:
$2\,r_0 \sim 2.3$ fm

size of nucleon
$r_n \sim 0.8$ fm



- **normal nuclear matter ρ_0**

$$\rho_0 = \frac{A}{\frac{4\pi}{3} R^3} = \frac{3}{4\pi\, r_0^{\,3}} : \; 0.16\, fm^{-3}$$

$$\varepsilon_0 : \; 0.15\, GeV / fm^3$$

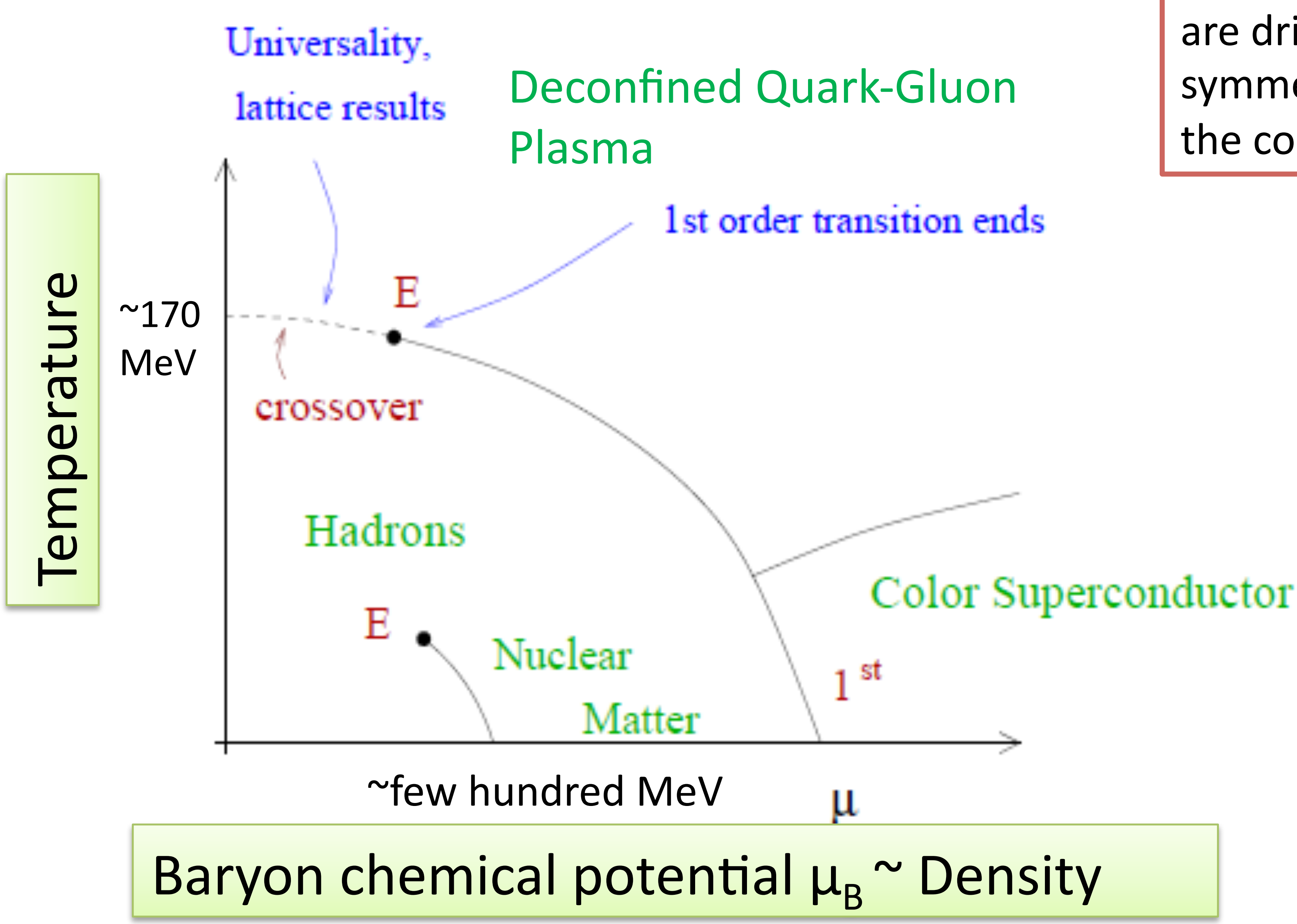
- **critical density:**
  naïve estimation
  nucleons overlap $R \sim r_n$

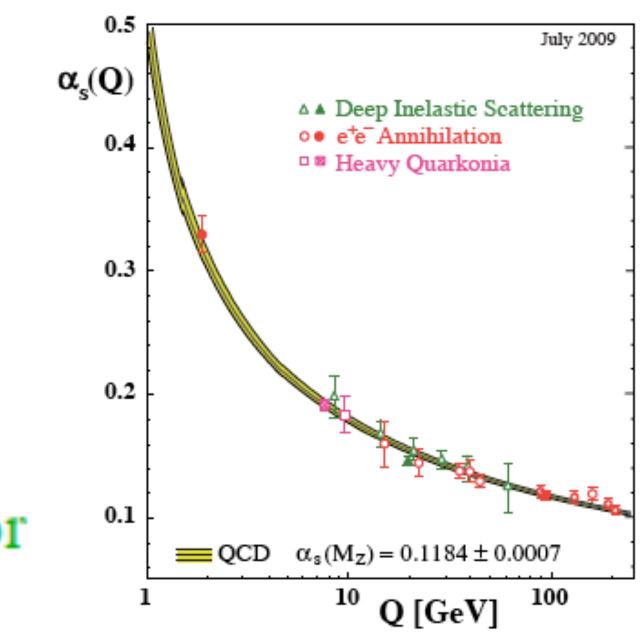
$$\rho_c = \frac{3}{4\pi\, r_n^{\,3}} : \; 0.5\, fm^{-3} \approx 3.1 \rho_0$$

$$\varepsilon_c : \; 0.5\, GeV / fm^3$$

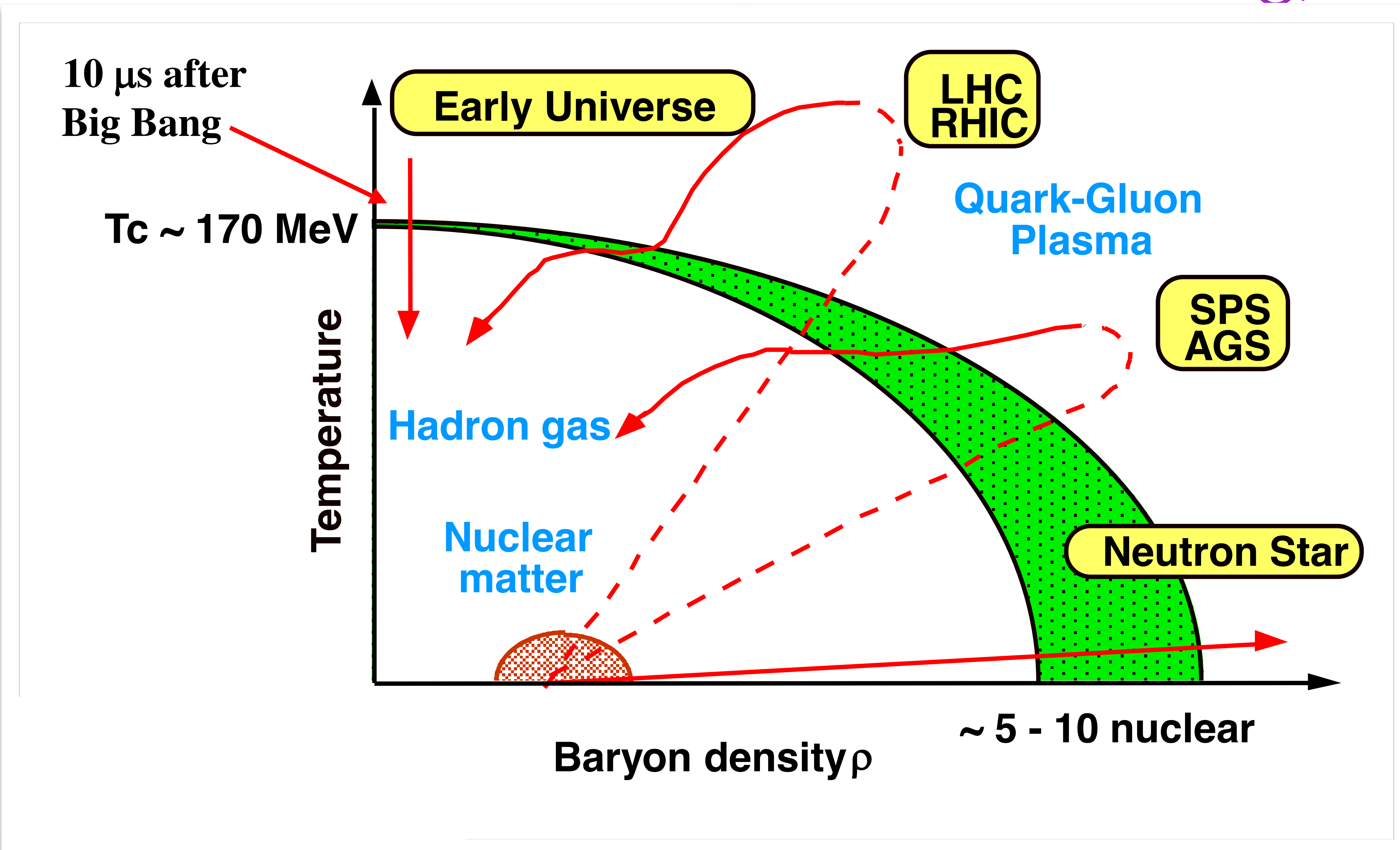
QCD phase diagram - theoretical landscape - more structures within the diagram

The features of this diagram are driven by QCD symmetries and running of the coupling constant





Another view - qualitative view of a HI collision evolution (collision energy)

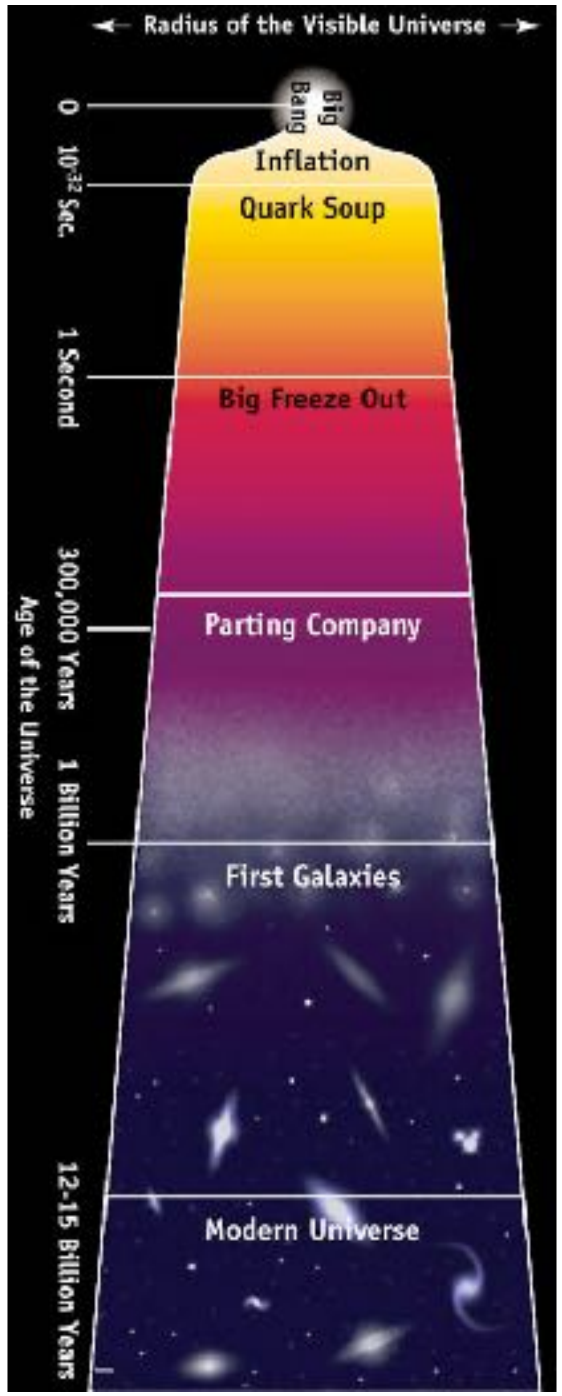


Note to myself: by now you have shown a phase diagram about dozen times! ... stop! - for the moment...

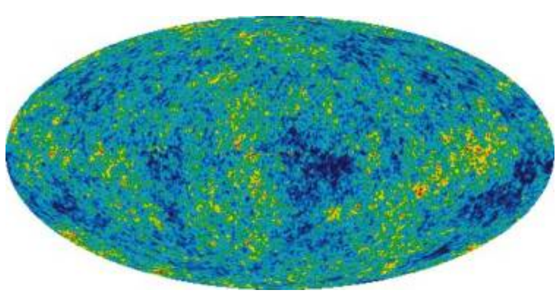
Some history...

(how much of this will need to be rewritten? - see Joge's lectures)

QCD Lab
"a few" years later?



10^{-44} sec	Quantum Gravity	Unification of all 4 forces	10^{32} K
10^{-35} sec	Grand Unification	E-M/Weak = Strong forces	10^{27} K
10^{-35} sec?	Inflation	universe exponentially expands by 10^{26}	10^{27} K
$2\ 10^{-10}$ sec	Electroweak unification	E-M = weak force	10^{15} K
$2 \cdot 10^{-6}$ sec	Proton-Antiproton pairs	creation of nucleons	10^{13} K
6 sec	Electron-Positron pairs	creation of electrons	$6 \cdot 10^{9}$ K
3 min	Nucleosynthesis	light elements formed	10^{9} K
10^{6} yrs	Microwave Background	recombination - transparent to photons	3000 K
10^{9} yrs ?	Galaxy formation	bulges and halos of normal galaxies form	20 K



Physical properties of QGP?

- What is the equation of state?
  - Flow measurements

$p\left(\epsilon, T, \mu_i\right), \ T_{\mu\nu}$

Lattice QCD

- What are the transport properties?
  - Flow measurements, jet spectra

$$\eta = \frac{V}{T}\int_0^\infty dt \langle T_{xy}(t)\, T_{xy}(0)\rangle$$

- What are the relevant degrees of freedom?
  - Multiplicities, Fluctuations, Correlations
    Photons, di-leptons

$$\chi_{ij} = \frac{V}{T}\frac{\partial^2}{\partial\mu_i\partial\mu_j}\log Z = \frac{1}{T}\int d^3x \langle \rho_i(x)\rho_j(0)\rangle$$

- What are the phases of QGP (QCD matter)?
  - Fluctuations, energy dependence
    of various observables

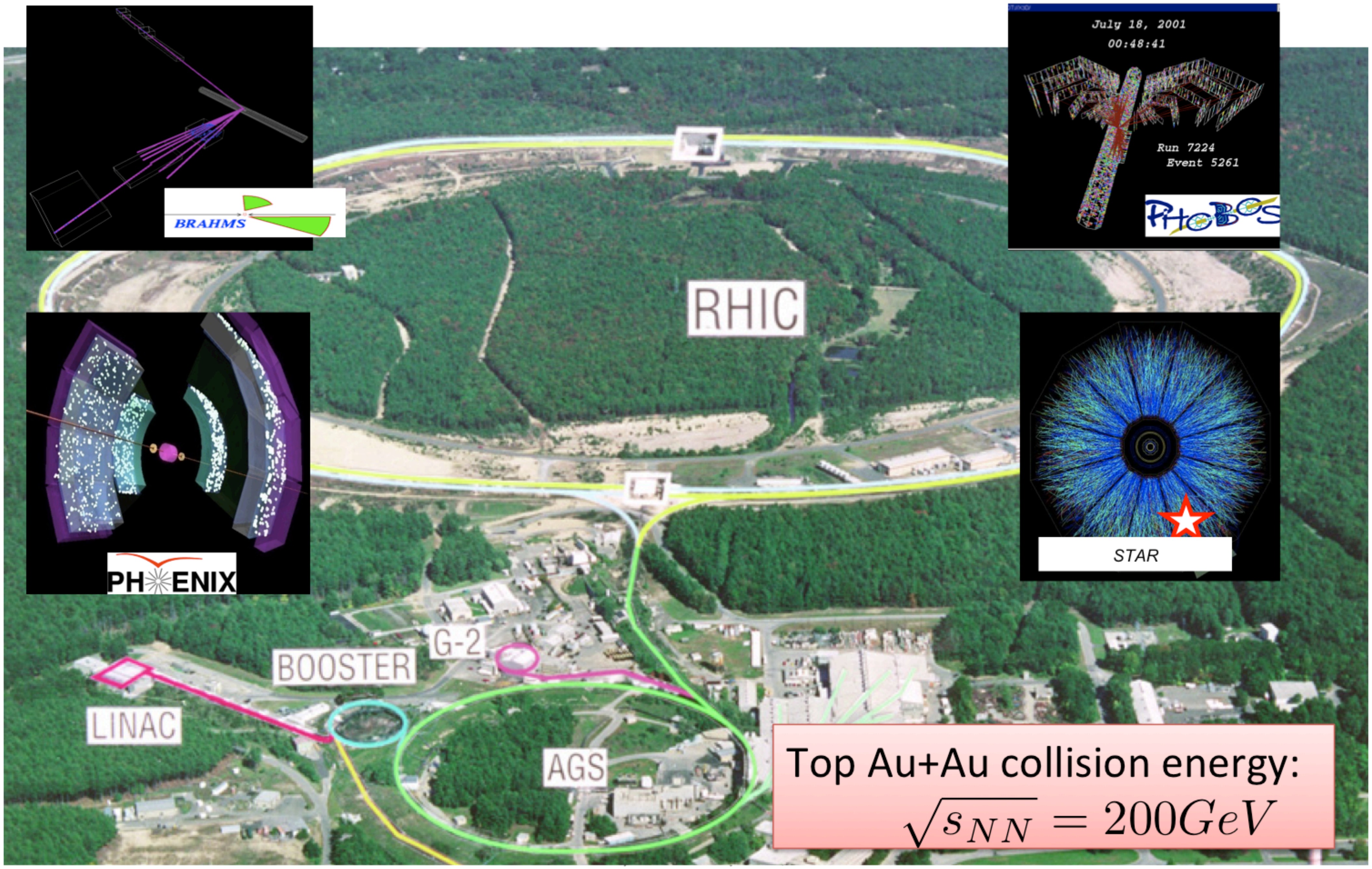
Lattice QCD

Strategy: how to study QCD matter experimentally?

- Need to find those observables that:
  - Are sensitive to crucial parameters of hot QCD matter
  - Can be modeled well – theoretical understanding
  - Can be measured well – experimental control
  - Can connect theory and data
- => Inclusive measurements; correlations; compare with more elementary collisions (p-p, p-A); compare different energy regimes

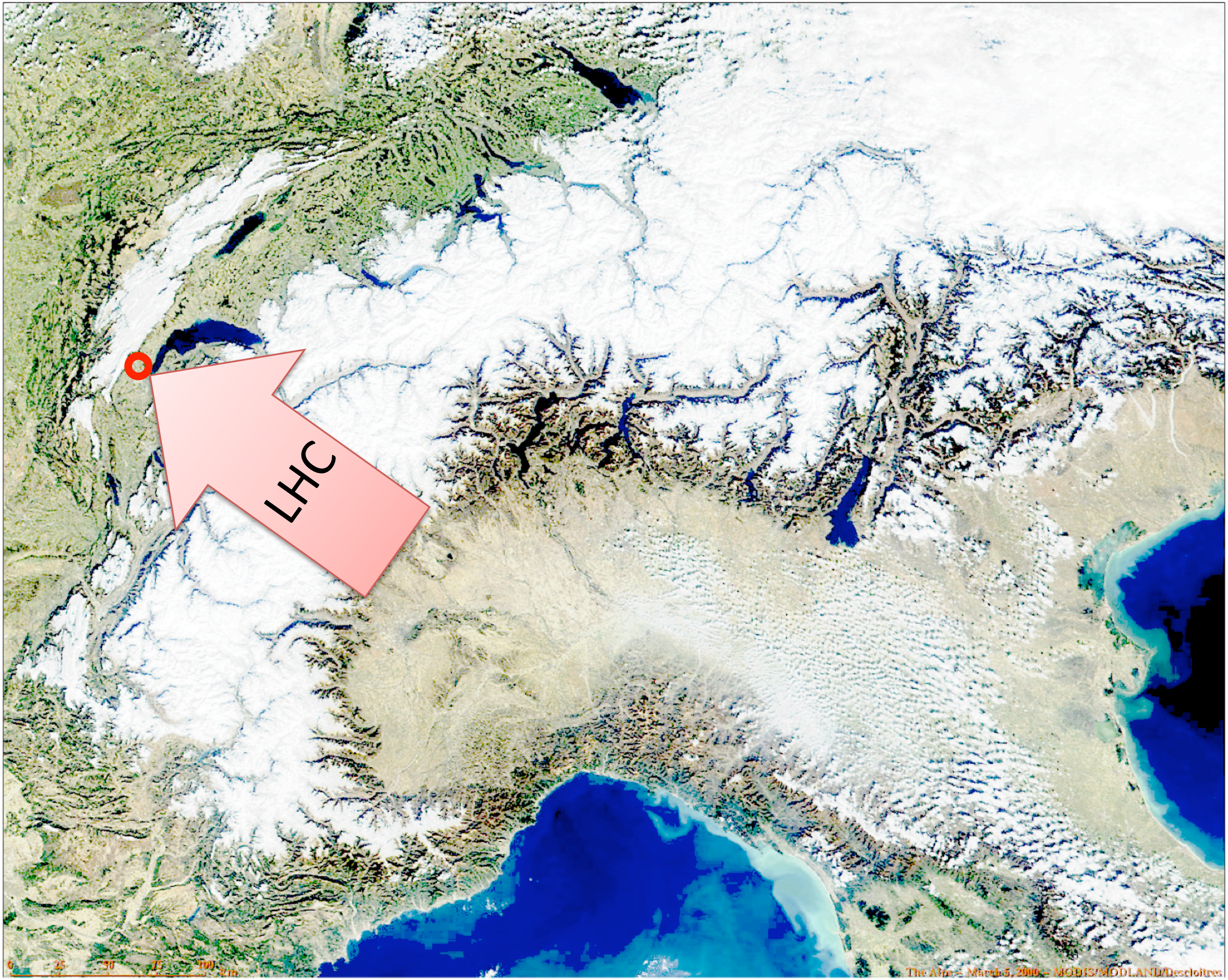
The hot-QCD laboratories - a.k.a. QCD vacuum ovens

The Relativistic Heavy Ion Collider (BNL)

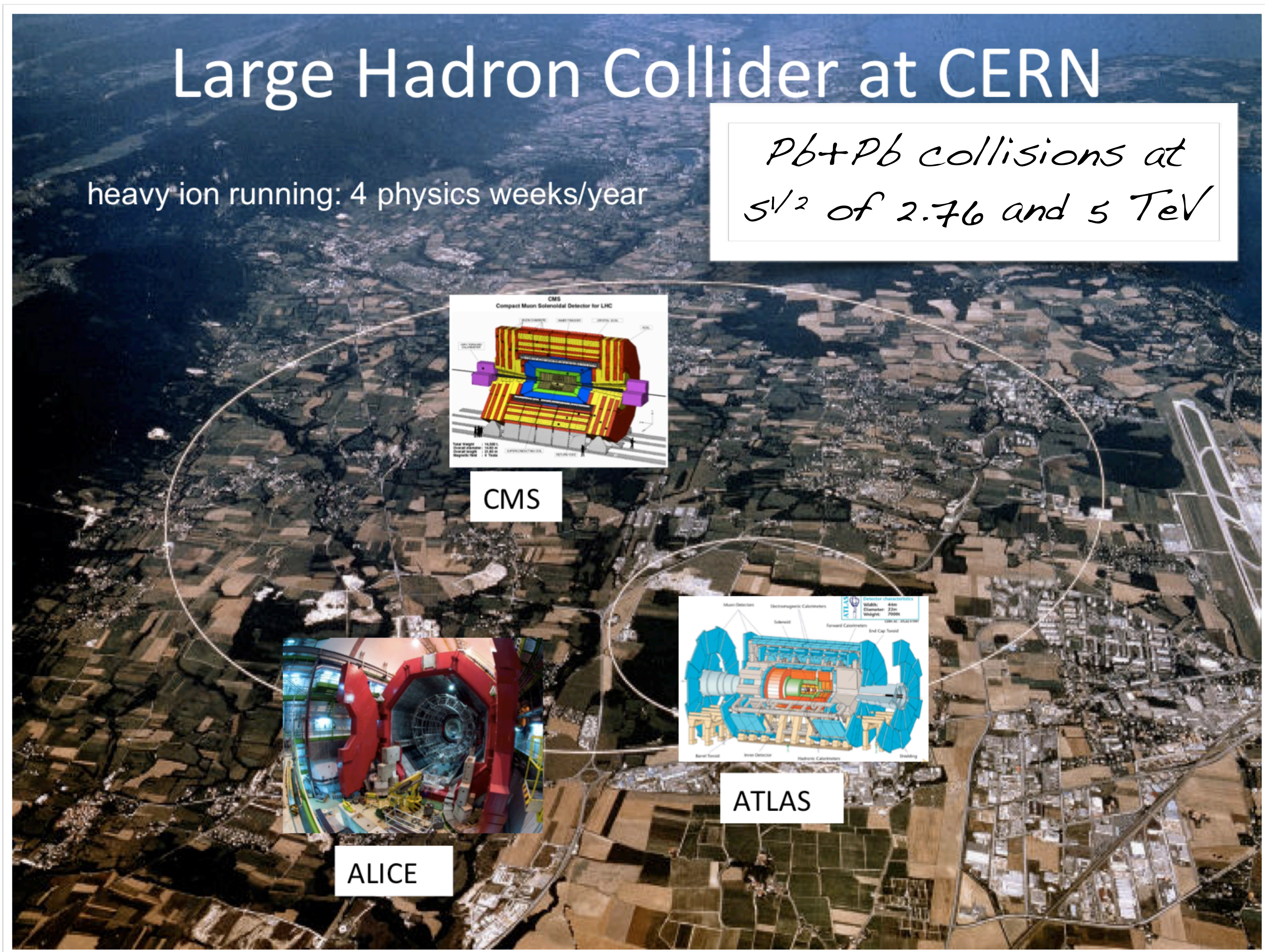


Top Au+Au collision energy:

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

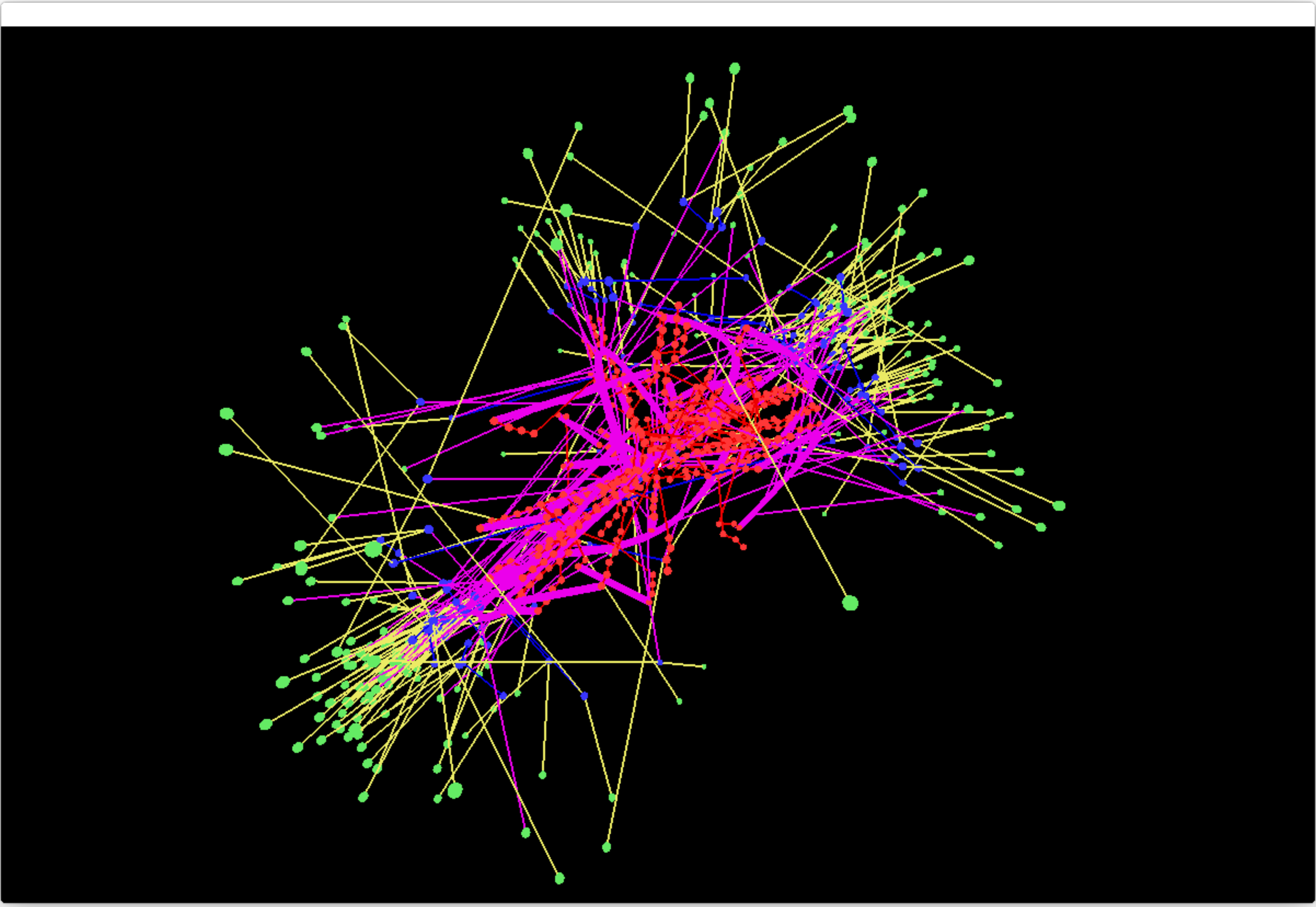

LHC
0 25 50 75 100 km
The Alps – March 5, 2000 – MODIS/MODLAND/Descloitres

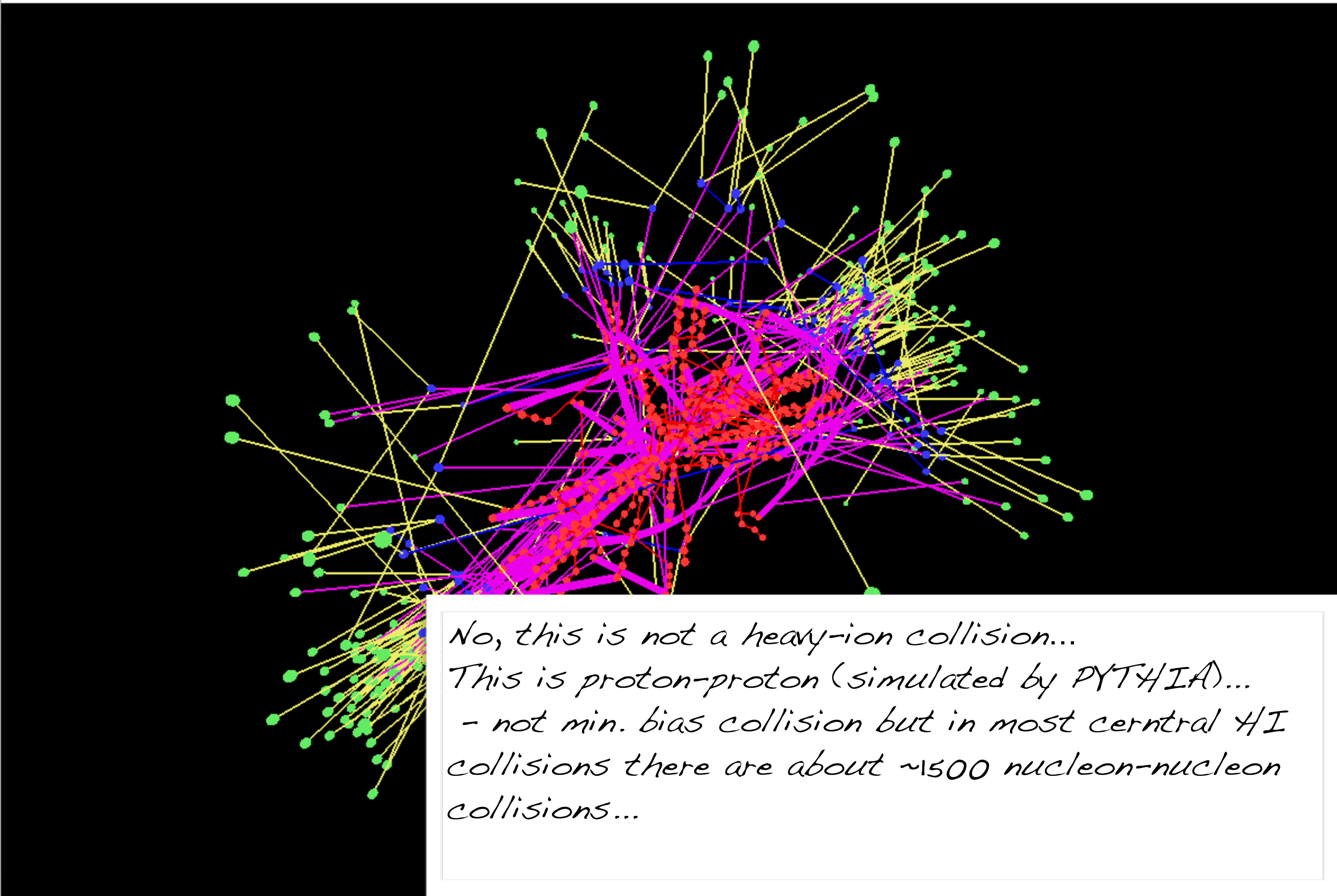
The hot-QCD laboratories



Pb+Pb collisions at $s^{1/2}$ of 2.76 and 5 TeV

Also: p-Pb and other ions planned.

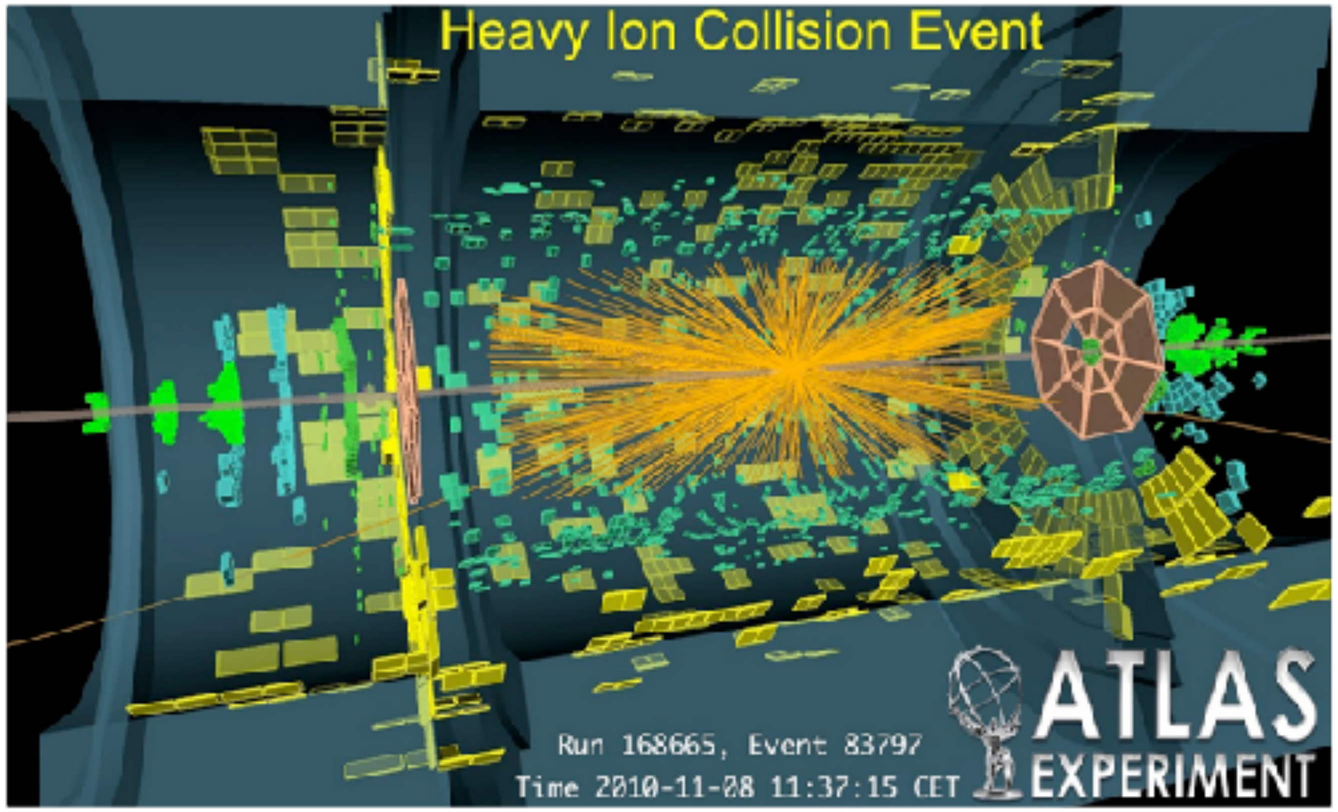


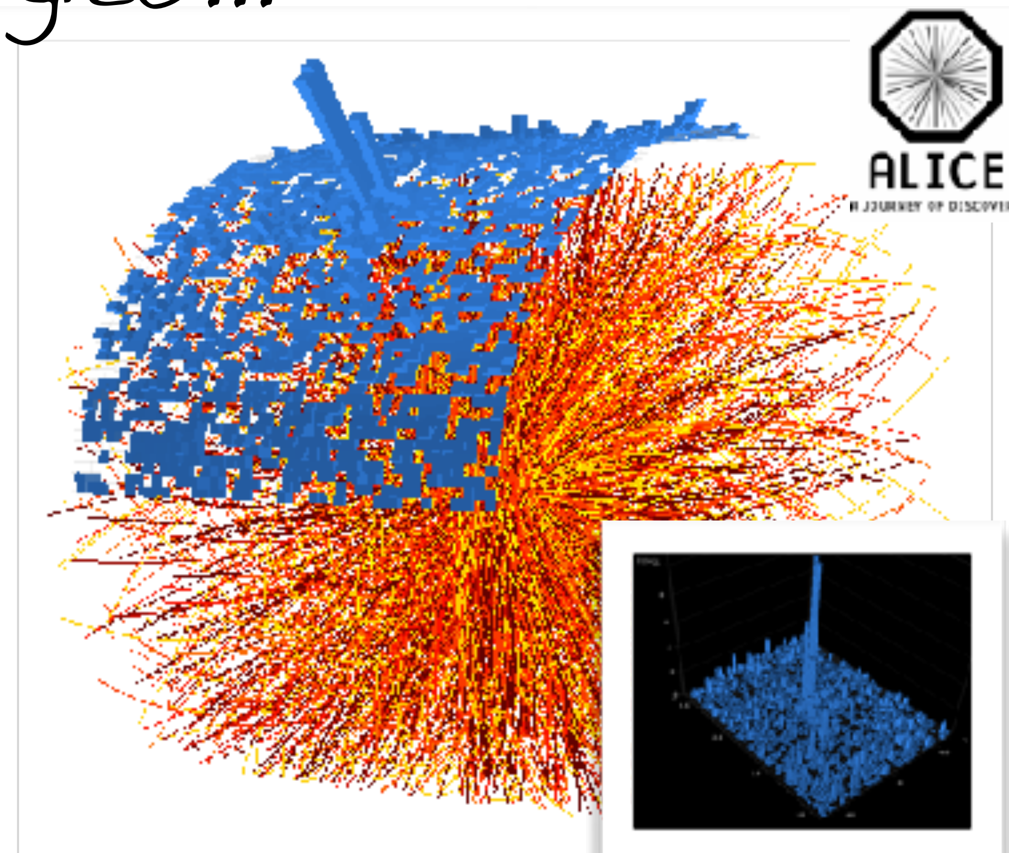


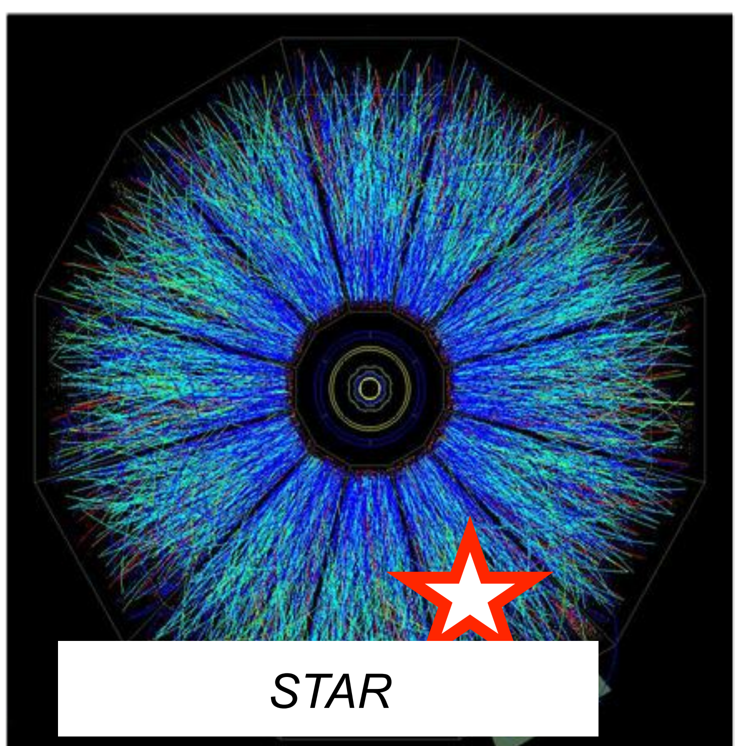
No, this is not a heavy-ion collision...
This is proton-proton (simulated by PYTHIA)...
 - not min. bias collision but in most cerntral HI collisions there are about ~1500 nucleon-nucleon collisions...

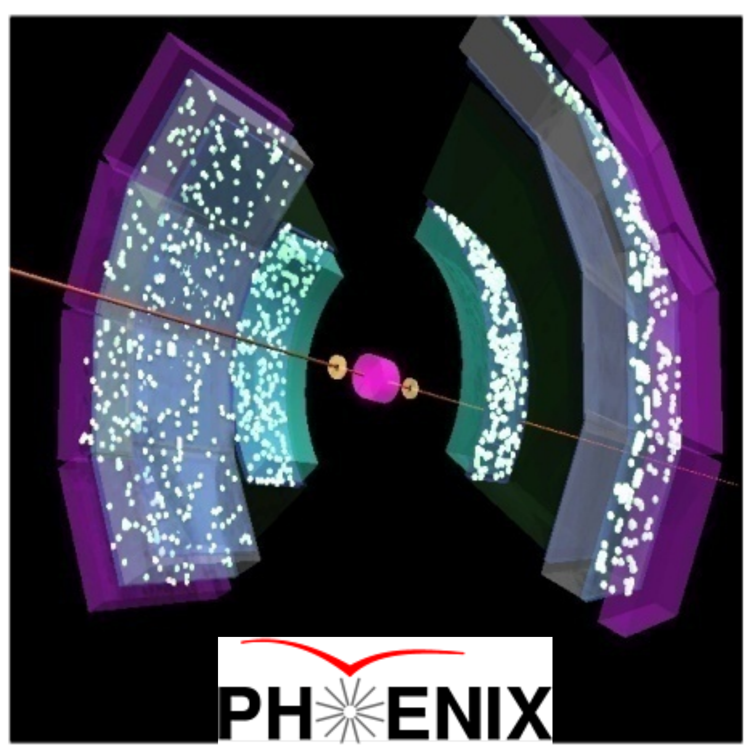
Heavy-ion collisions

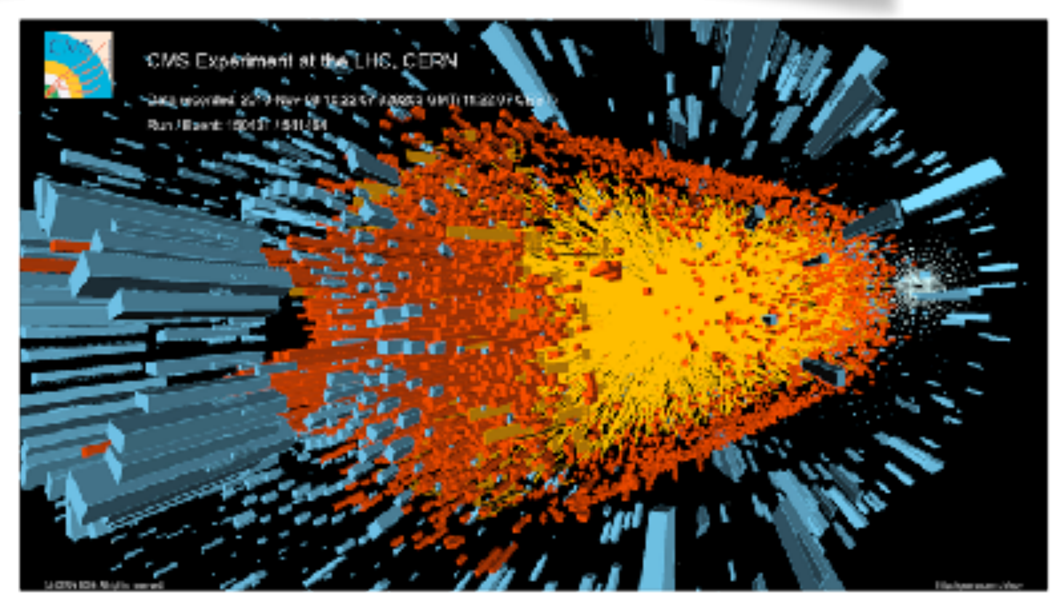
at high energies...







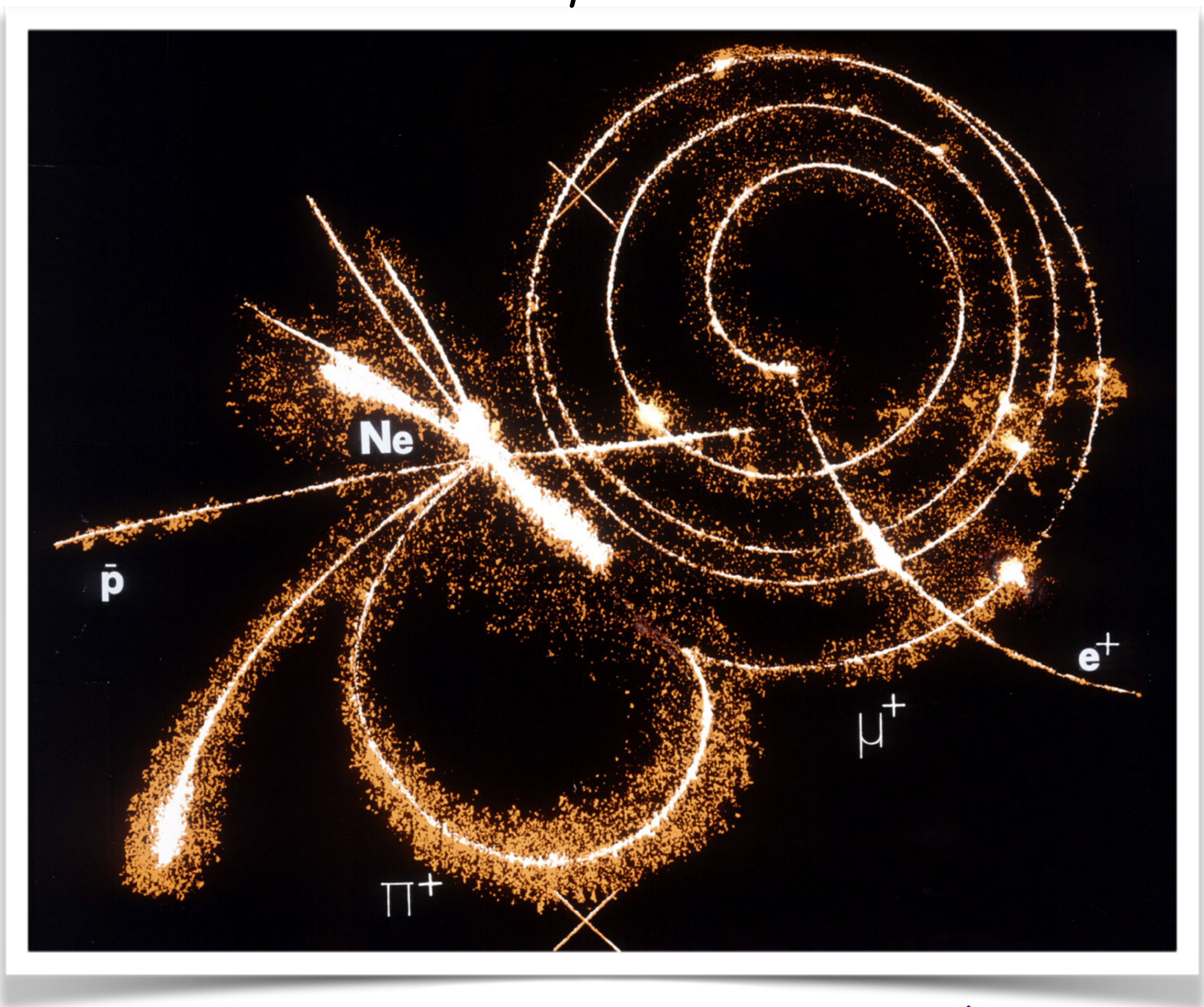




...RHIC to LHC

These are most advanced/complex cameras...

$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

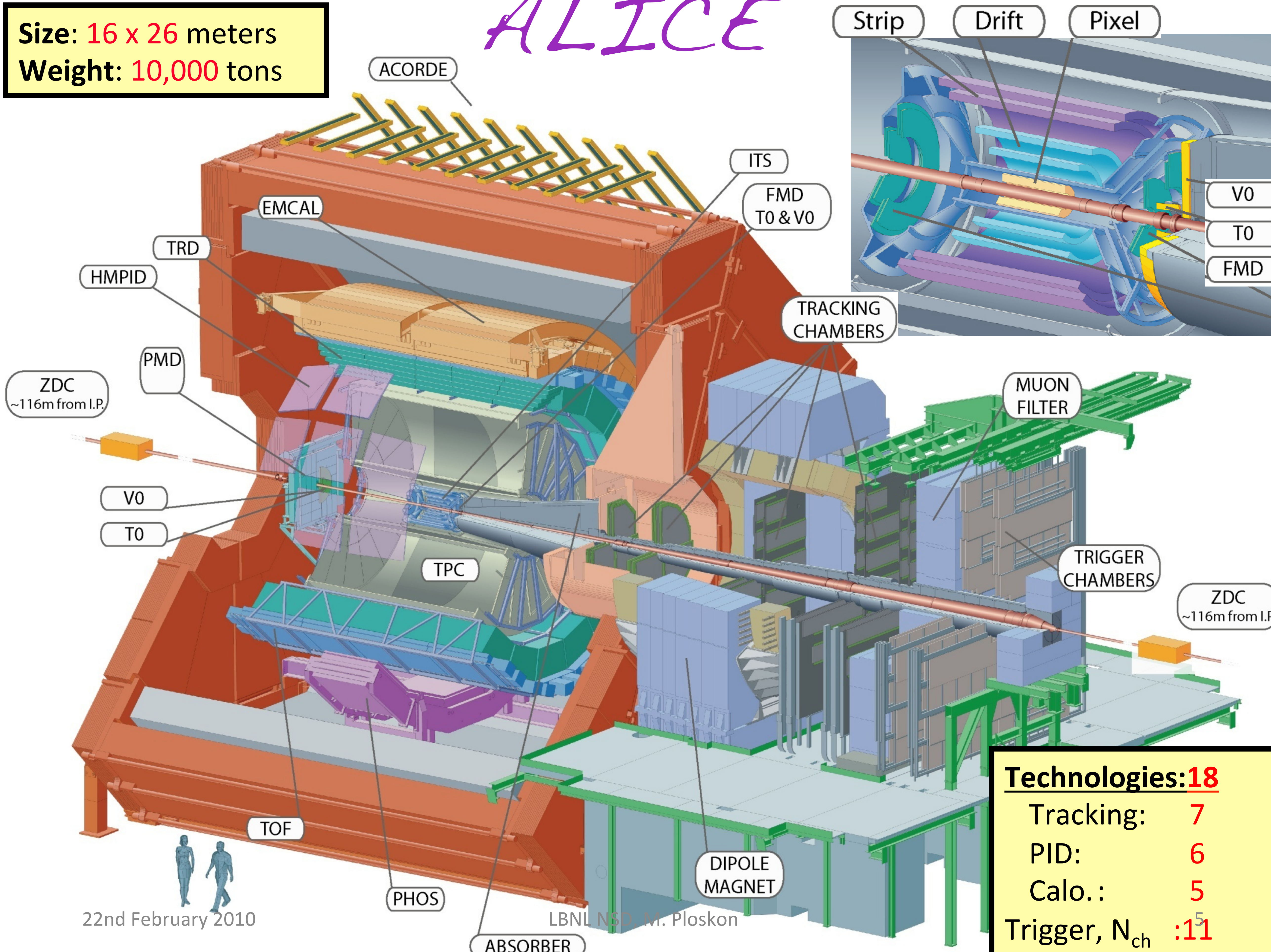


in streamer chamber (1984)

Dedicated HI experiment: ALICE

Size: 16 x 26 meters
Weight: 10,000 tons

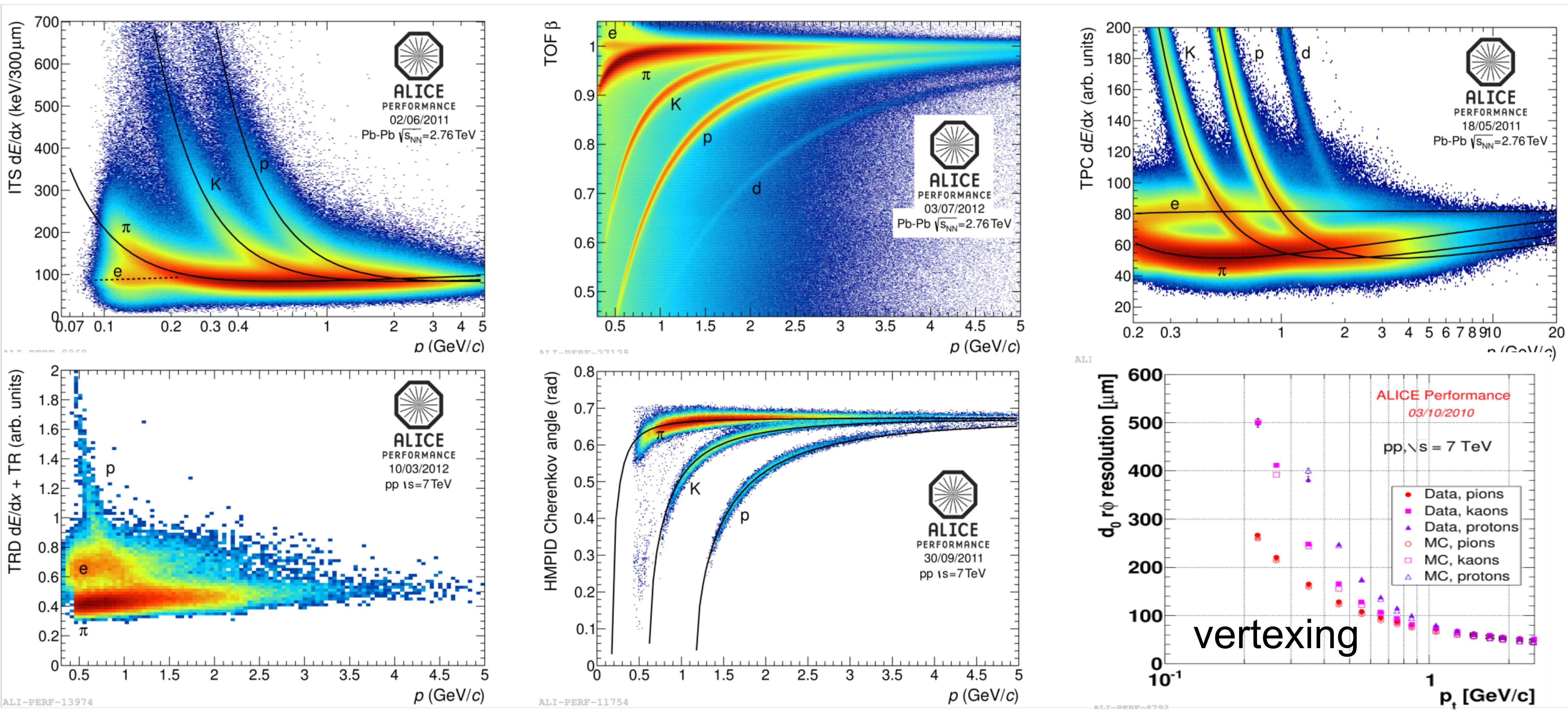
ALICE



Technologies:18

Tracking:	7
PID:	6
Calo.:	5
Trigger, N_{ch}	:11

ALICE - Particle identification



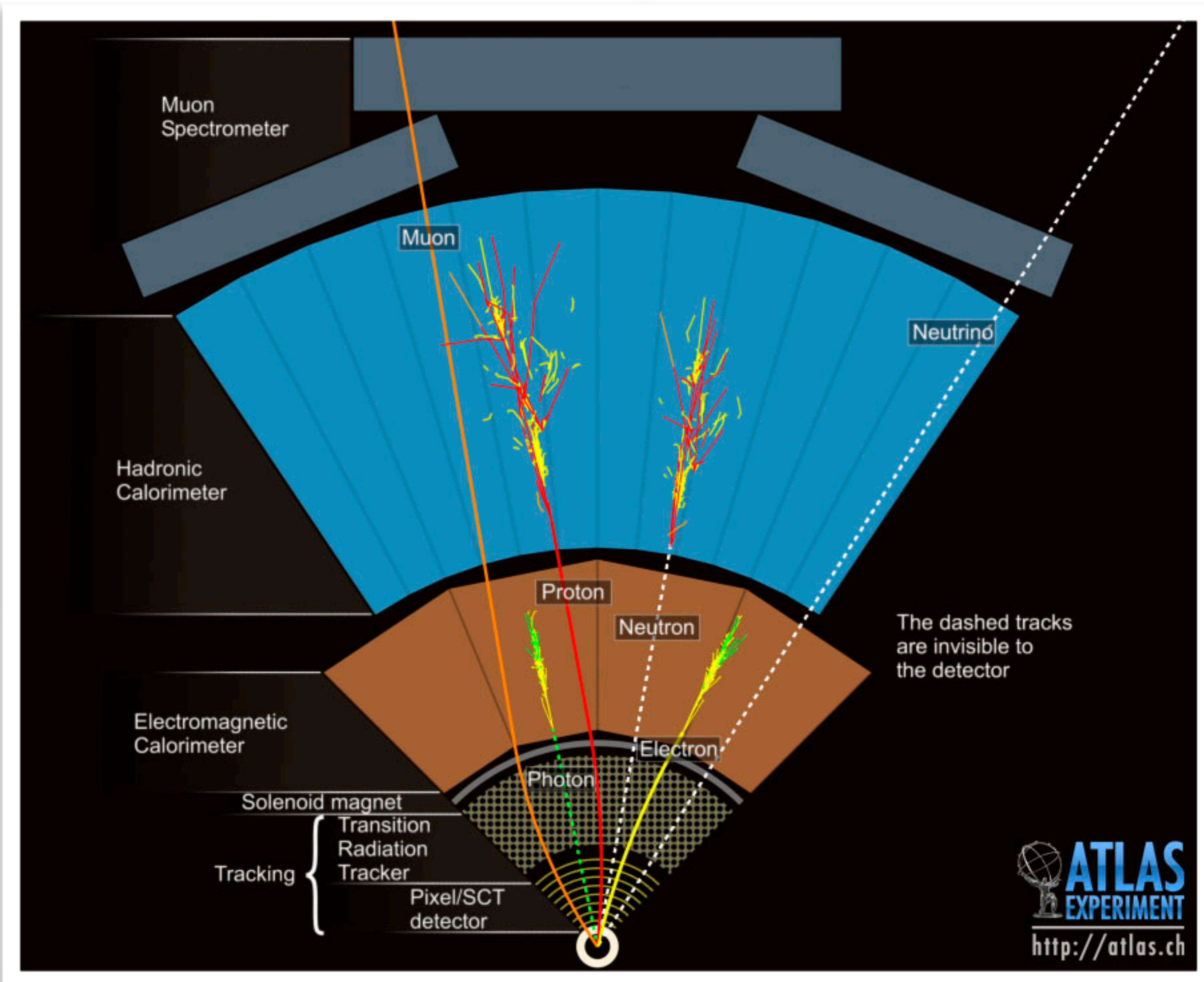
Particle identification (multiple techniques)

Extremely low-mass tracker ~ 10% of X_0

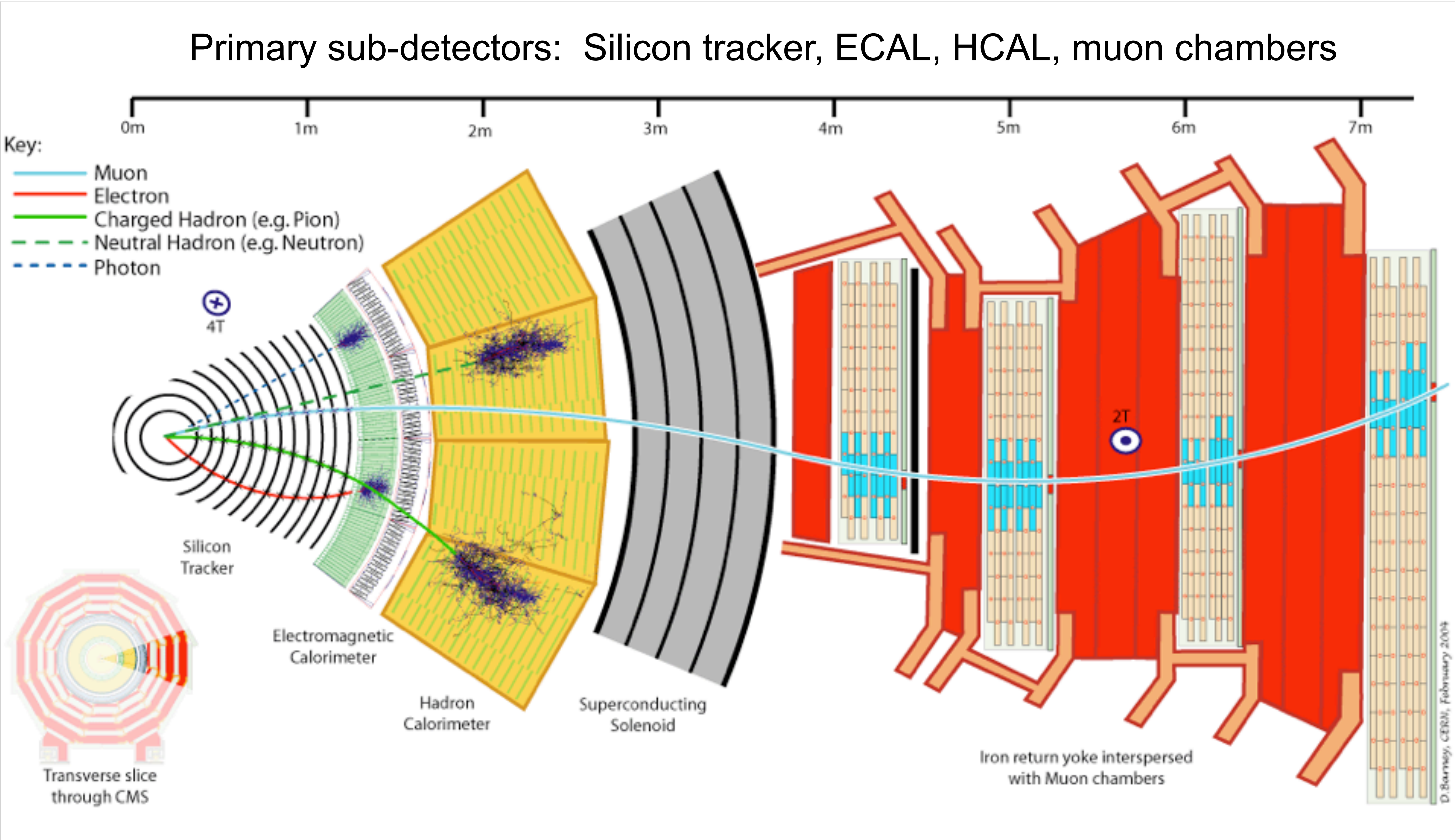
Excellent vertexing capability

Efficient low-momentum tracking - down to ~ 100 MeV/c

High energy particle detection - ATLAS



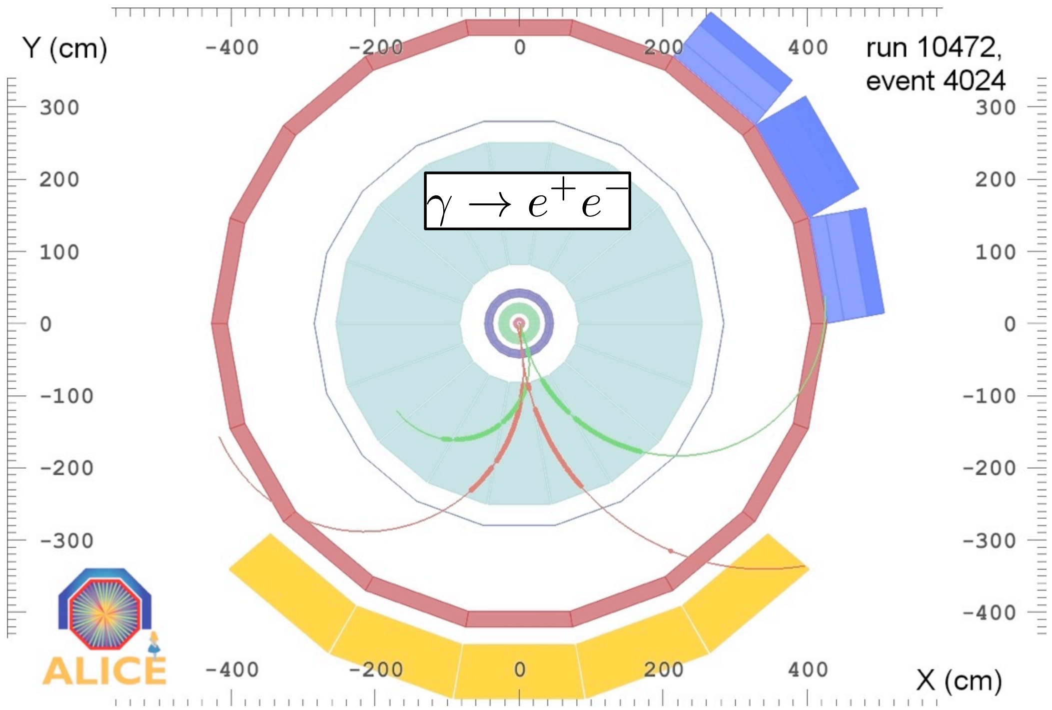
Compact Muon Spectrometer

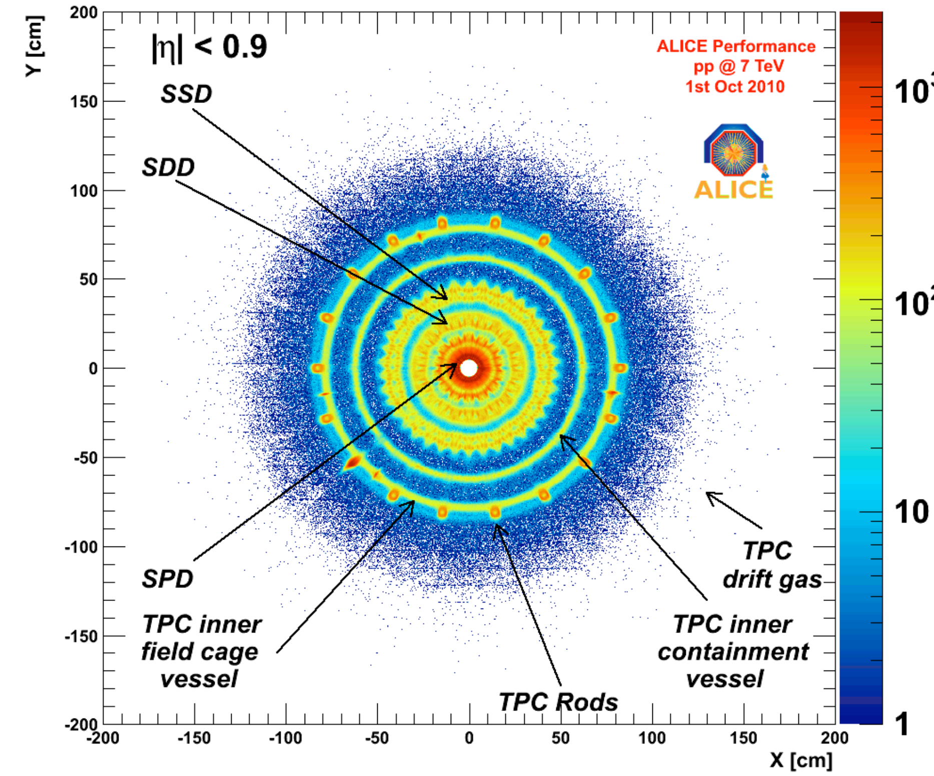


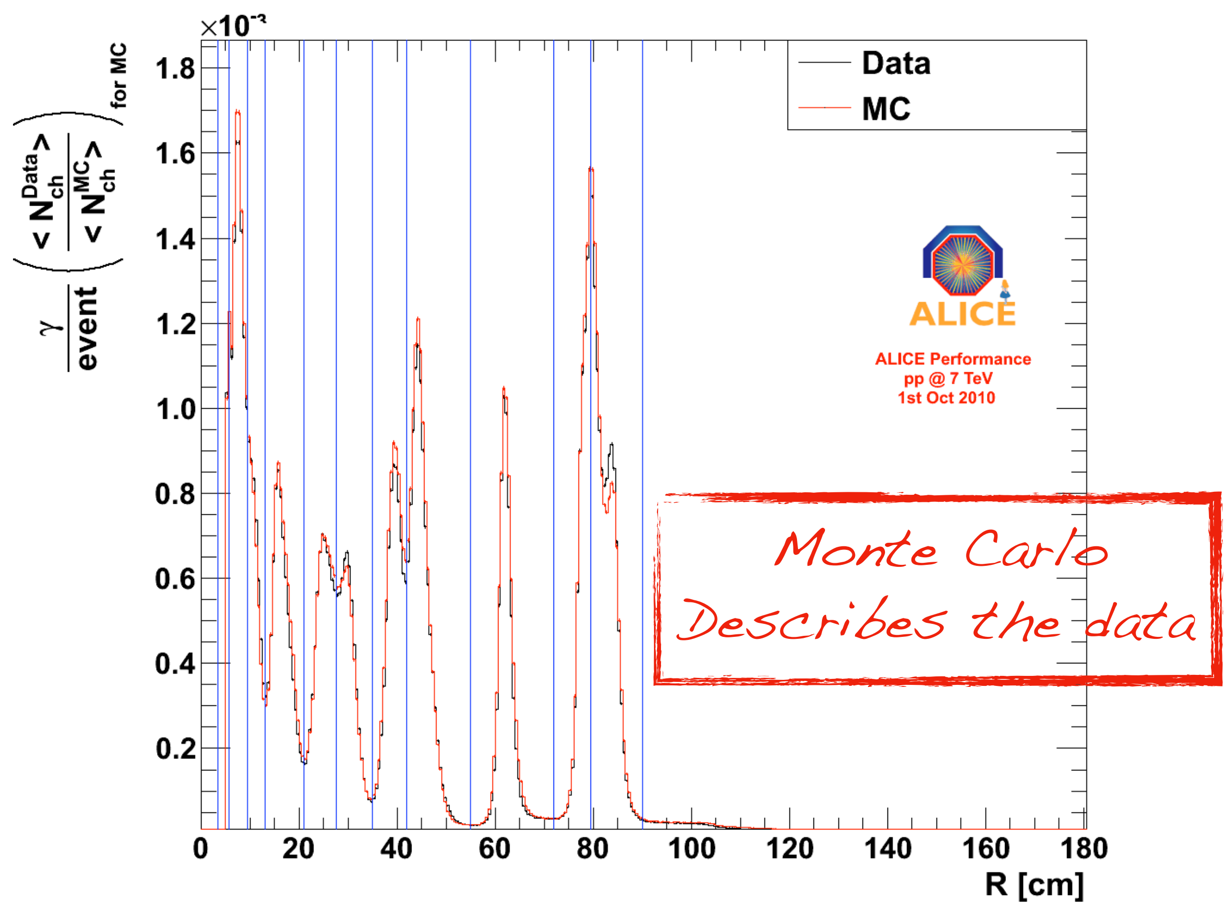
Extremely important for theorists

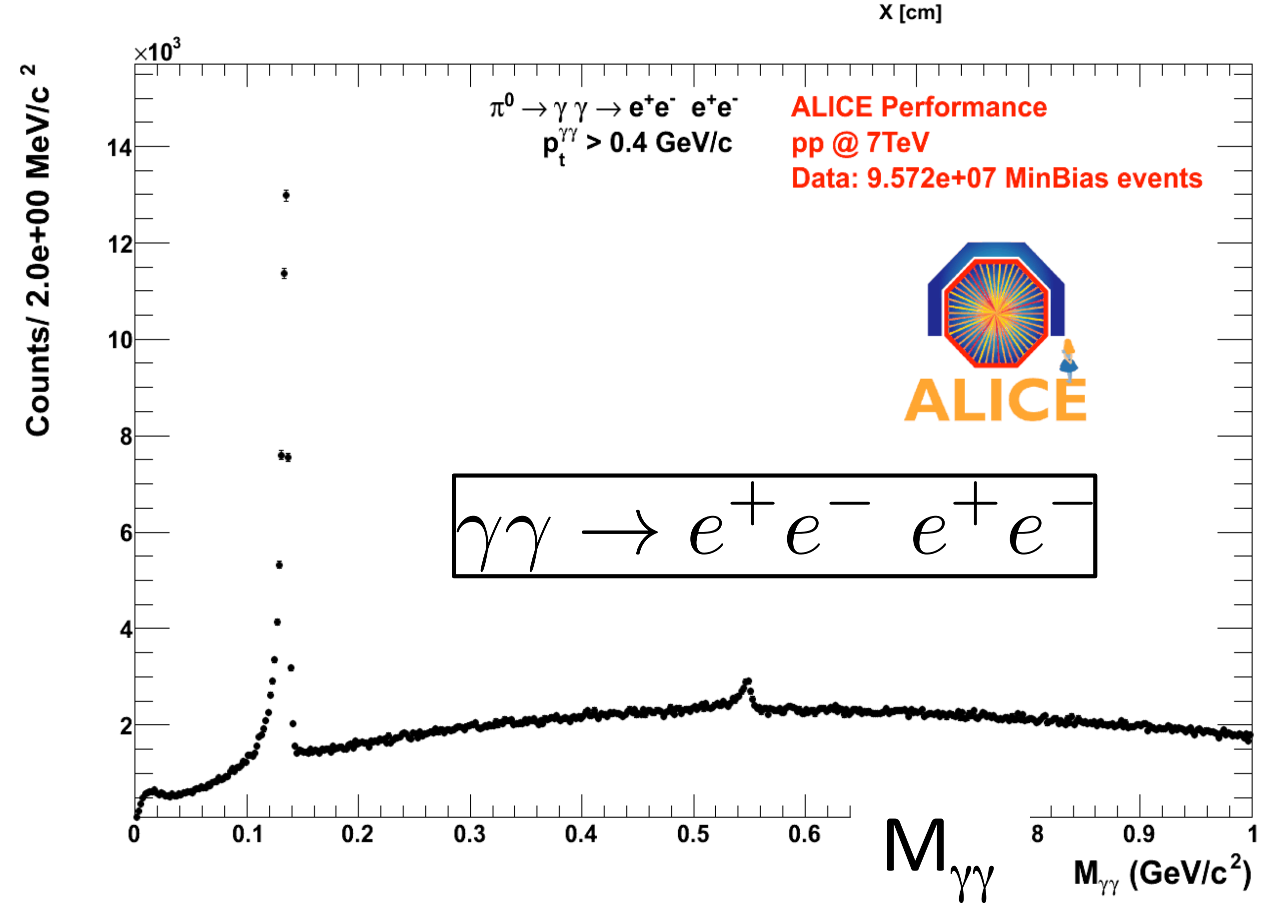
(experimentalists know that)

KNOW YOUR DETECTOR!







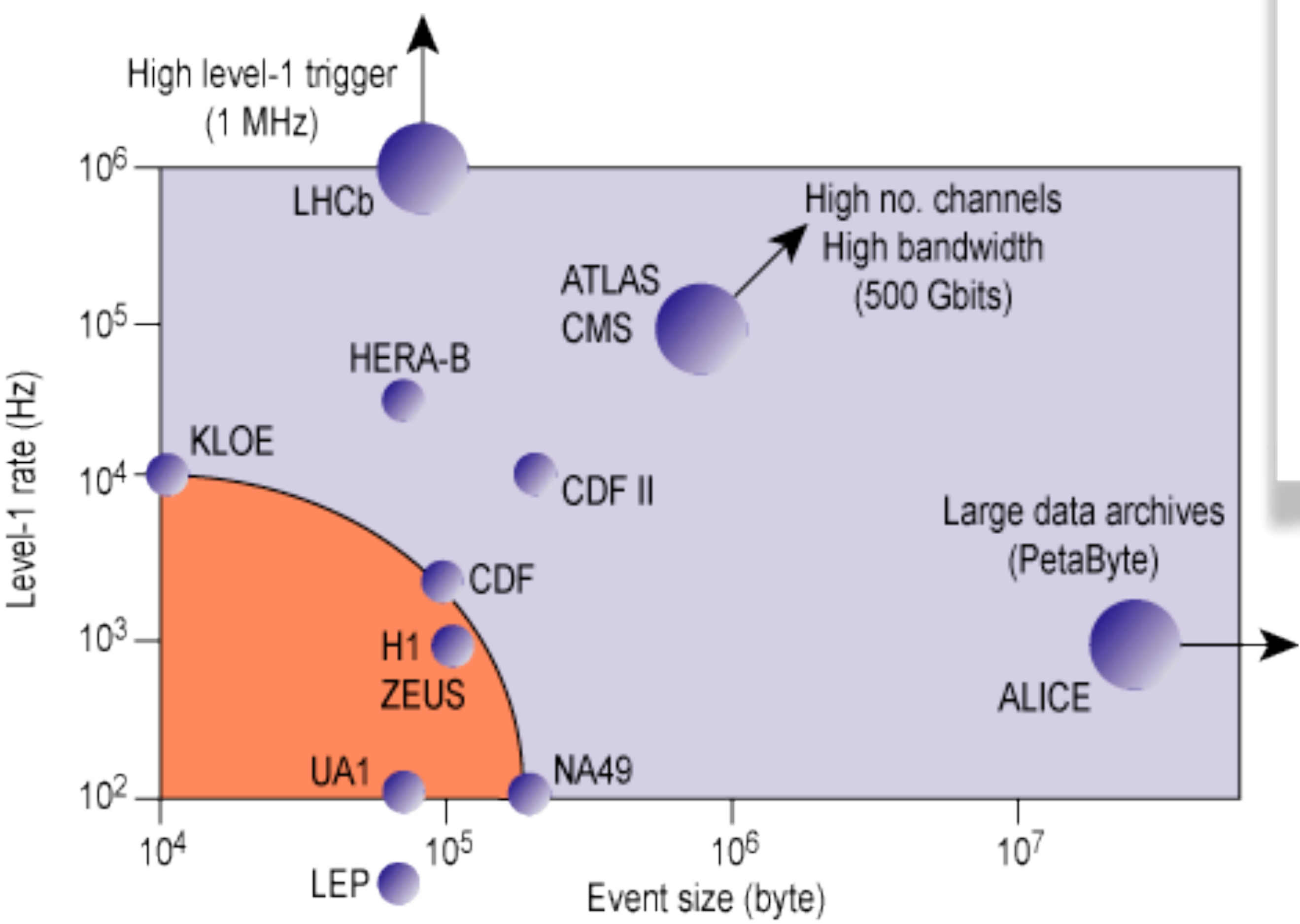


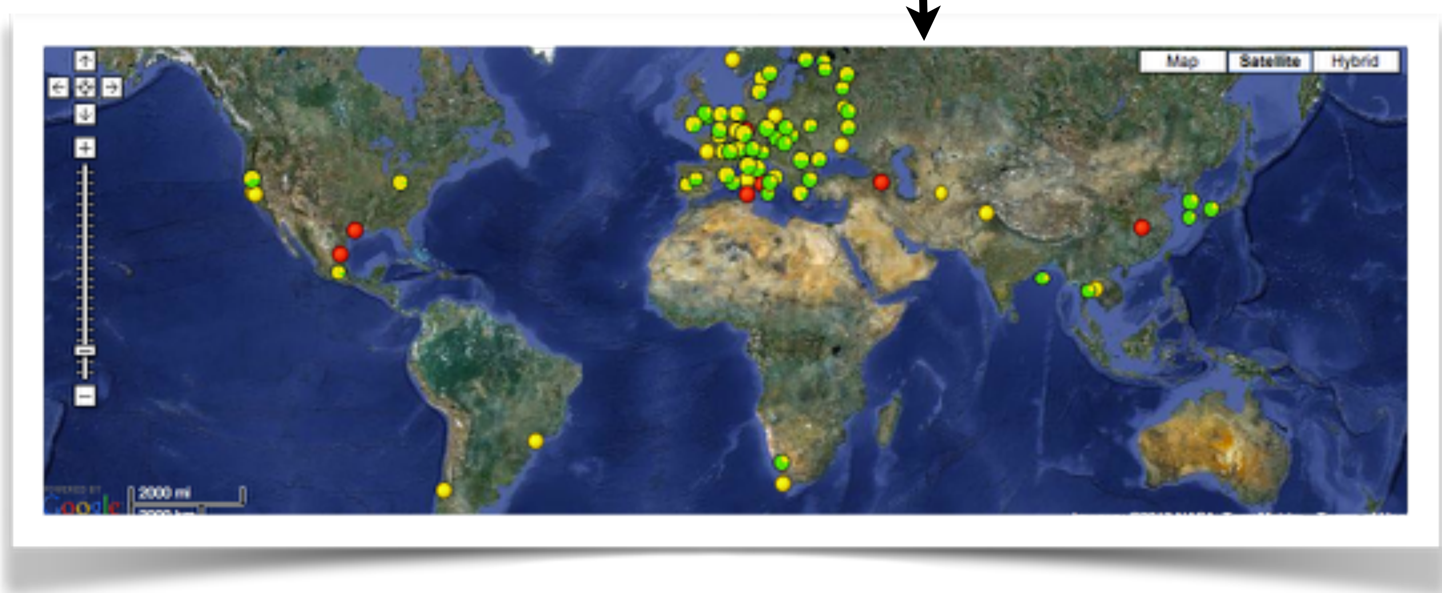
From trigger to data analysis...

Detector (front-end-electronics, digitalized information)

→ **Online systems** (Trigger: event rejection; online algorithms)

→ **Offline computing** (high capacity; offline reconstruction analysis; distributed computing - GRID)



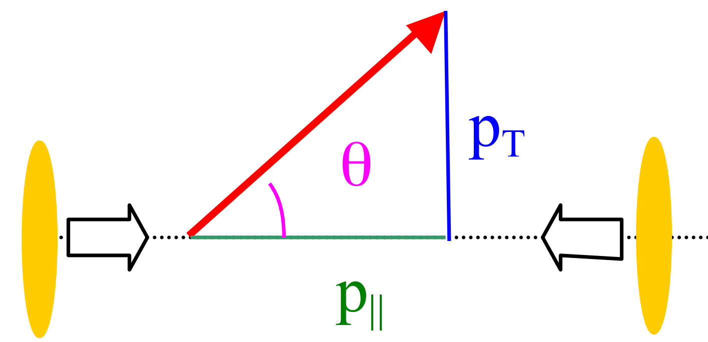


Onto heavy-ion collisions...

Some kinematic variables

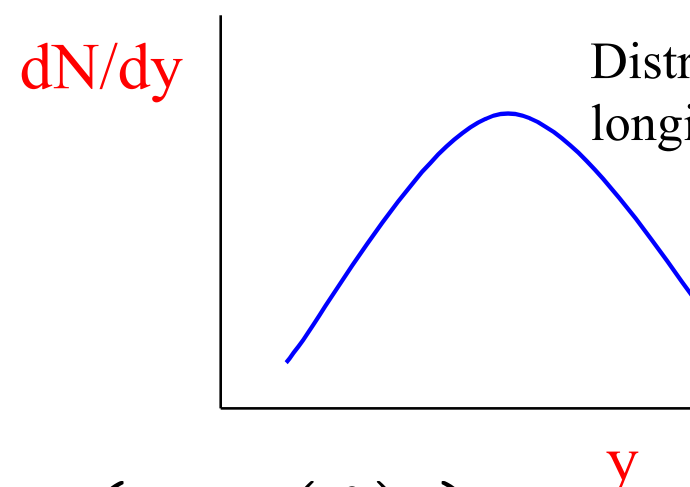
Rapidity

$$y = \frac{1}{2}\ln\left(\frac{E+p_{\parallel}}{E-p_{\parallel}}\right)$$



... boost invariant

$$\delta y \sim \frac{\delta p_{\parallel}}{E}$$



Distribution invariant with longitudinal boost

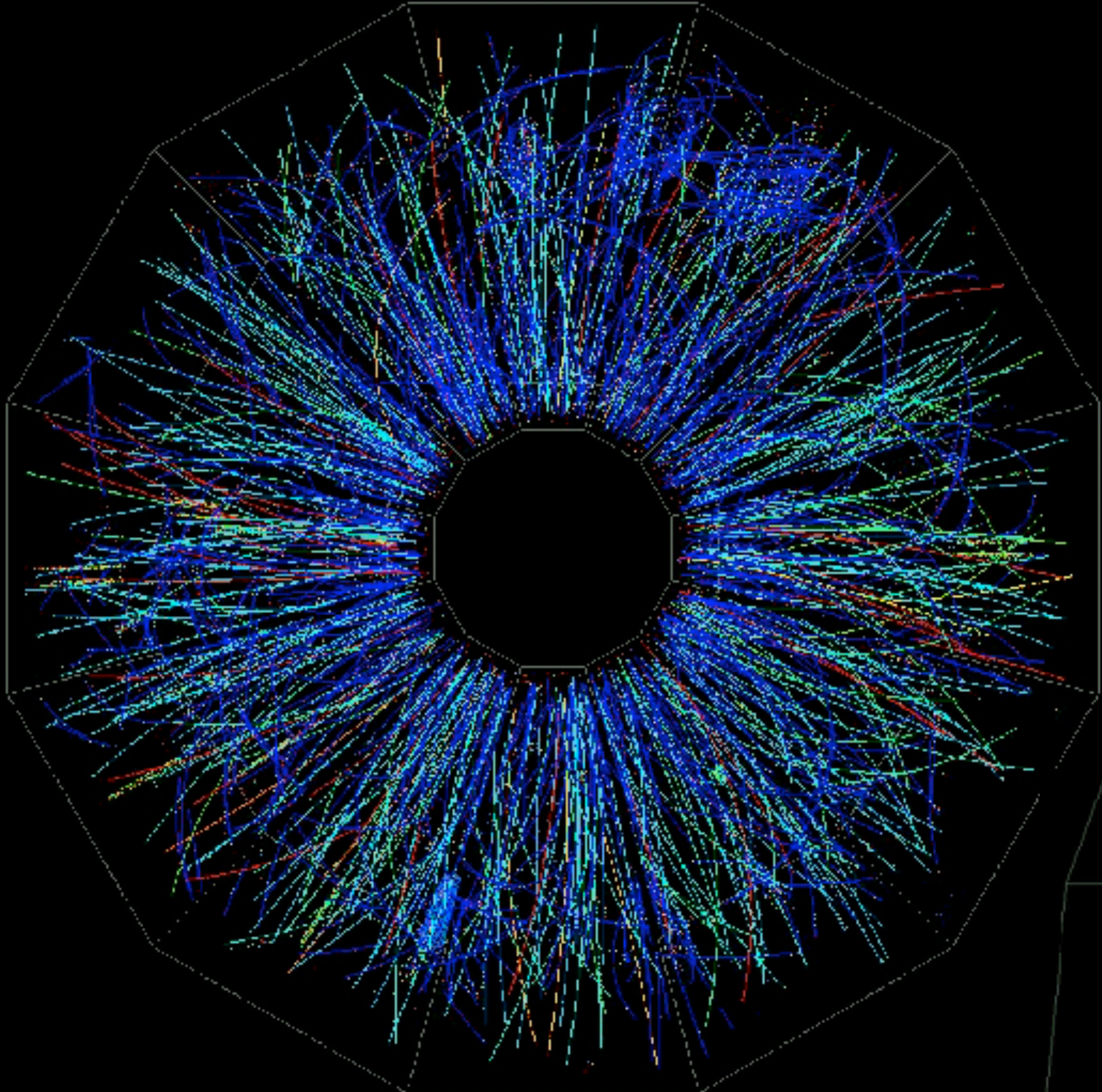
Pseudo-rapidity

$$y \to \eta = -\ln\left\{\tan\left(\frac{\theta}{2}\right)\right\}$$

$m/p << 1$

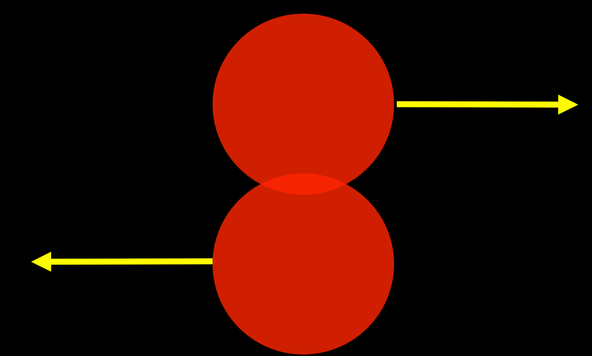
Invariant cross-section

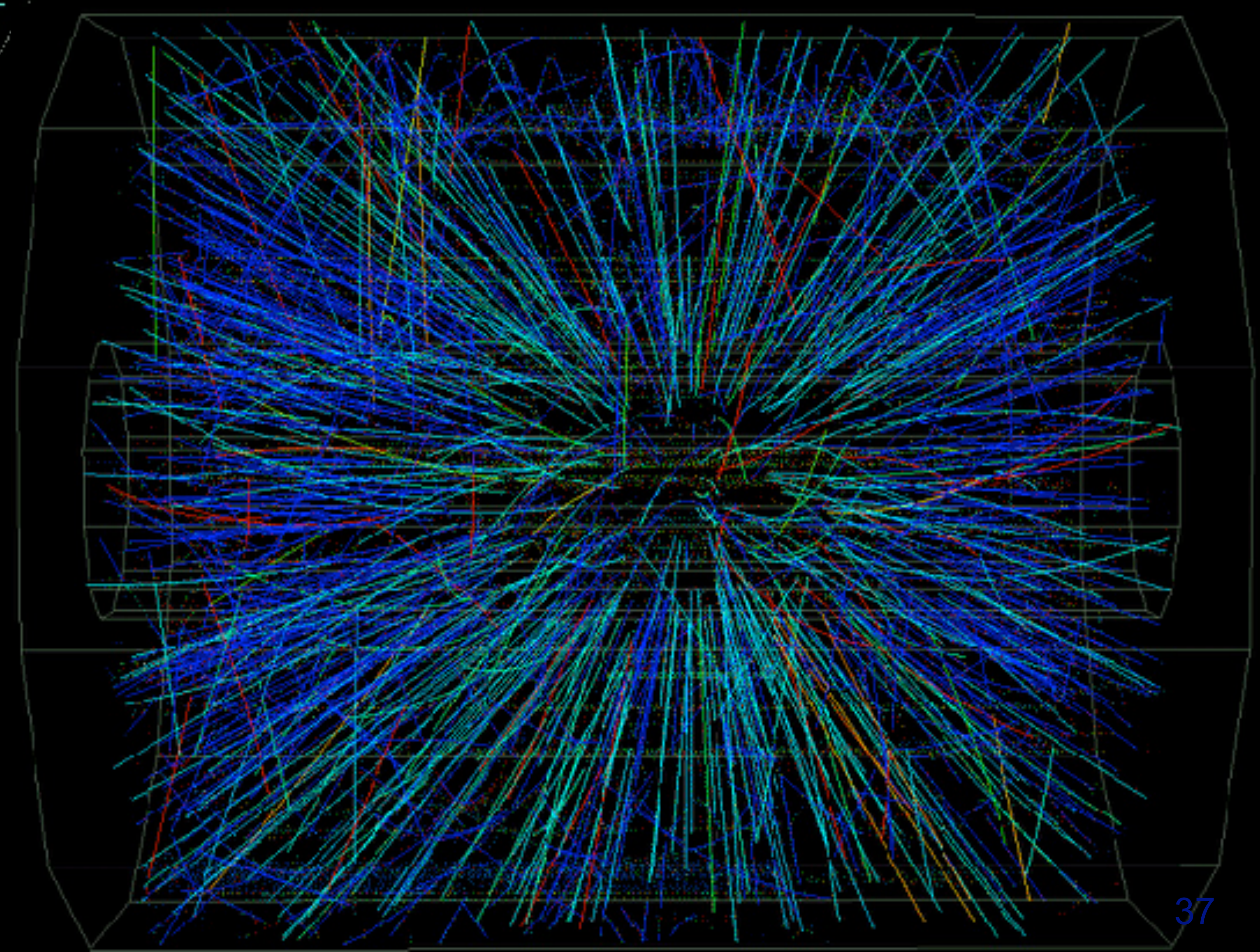
$$E\frac{d^3\sigma}{dp^3} = \frac{d^2\sigma}{2\pi p_T dp_T dy}$$



only charged particles visible

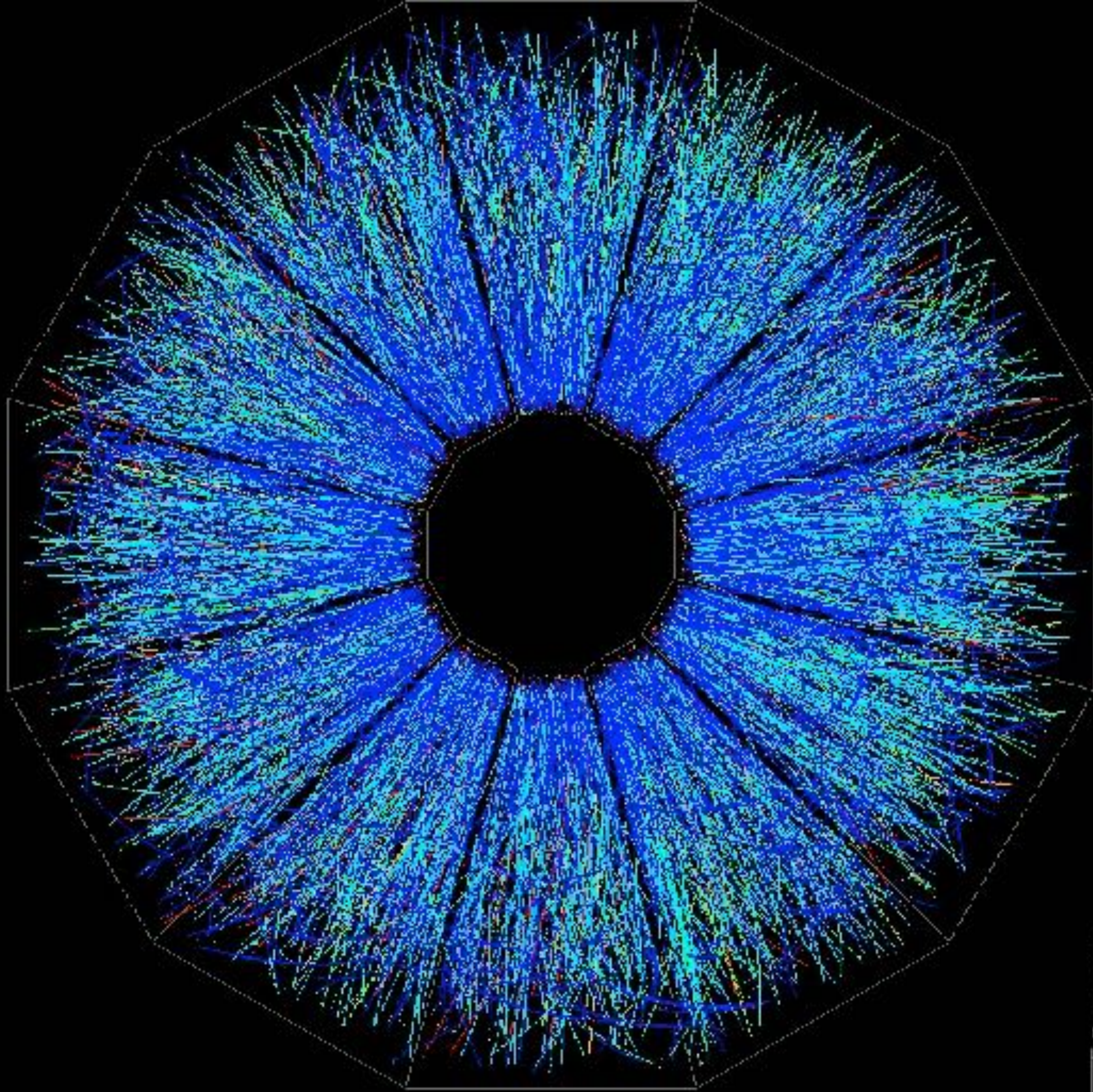
Peripheral Collision





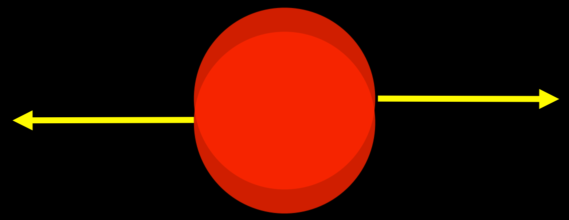
Color $\Rightarrow$ Energy loss in TPC gas

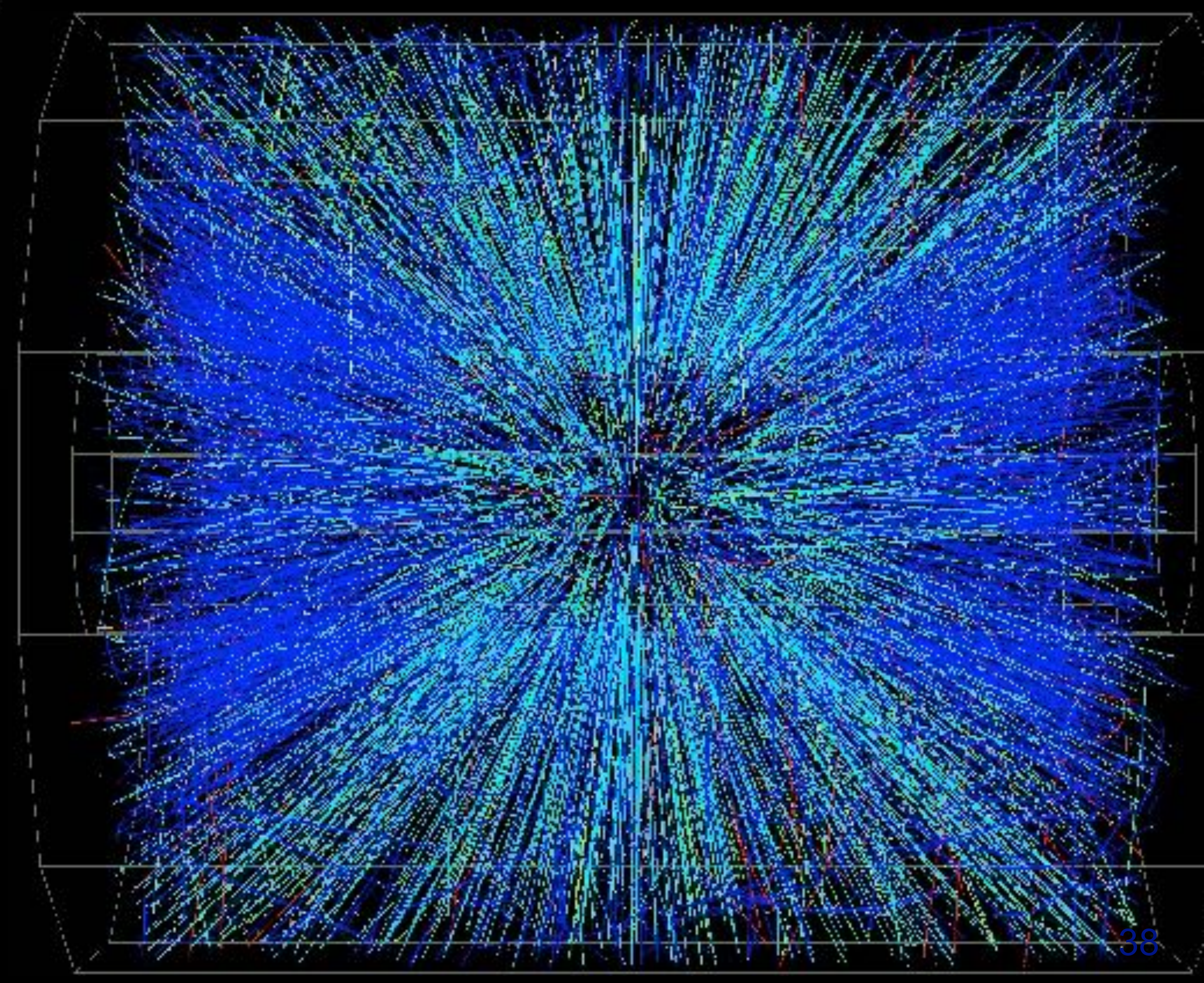
STAR



only charged particles visible

Central Collision

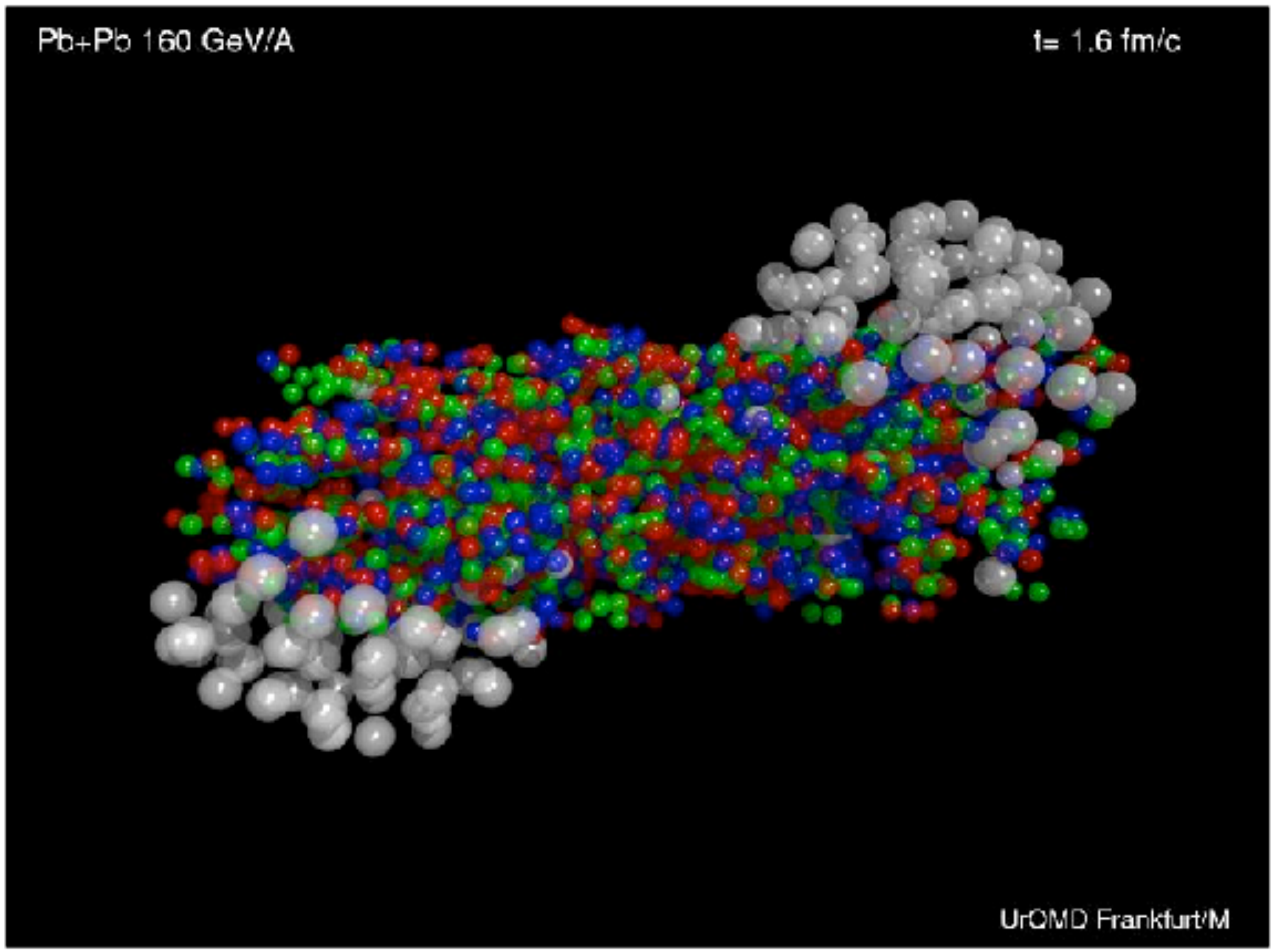




200 GeV Au+Au: **N_{ch}~4800**

STAR

Glauber model - a description of heavy-ion collisions



central collisions:

small impact parameter b
- high number of participants
- high energy density
- large volume

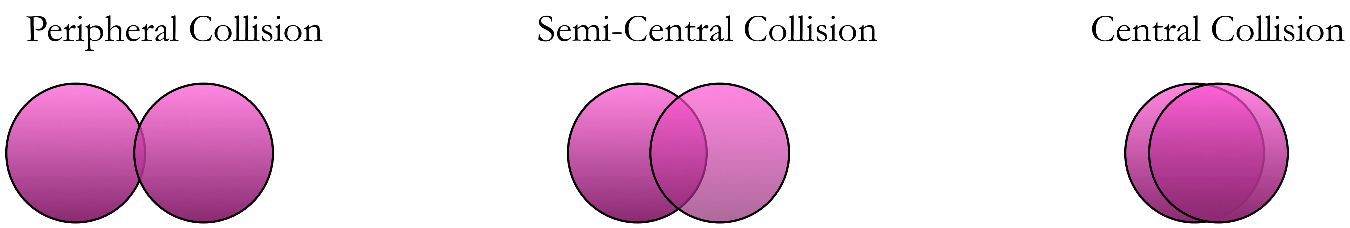
-> large number of produced particles

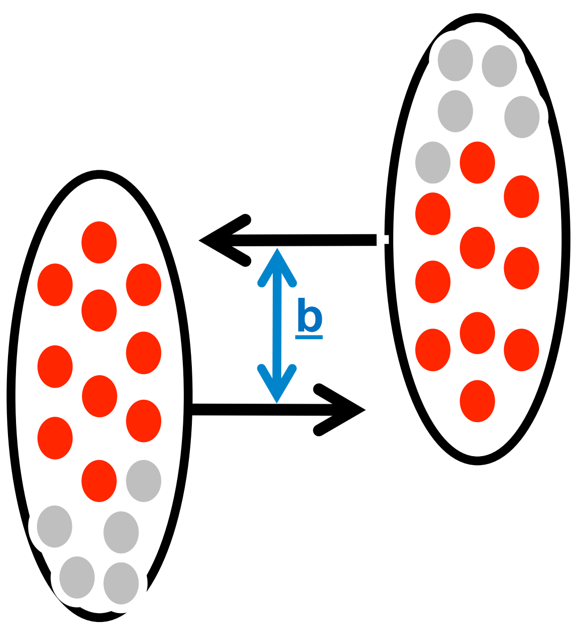
peripheral collisions:

large impact parameter b
- low number of participants

-> low multiplicity

Glauber model - a description of heavy-ion collisions





Spectators

Participants
aka wounded nucleons

Impact parameter b is measured as:
- Fraction of cross section "centrality"
- Number of participants
- Number of nucleon-nucleon collisions

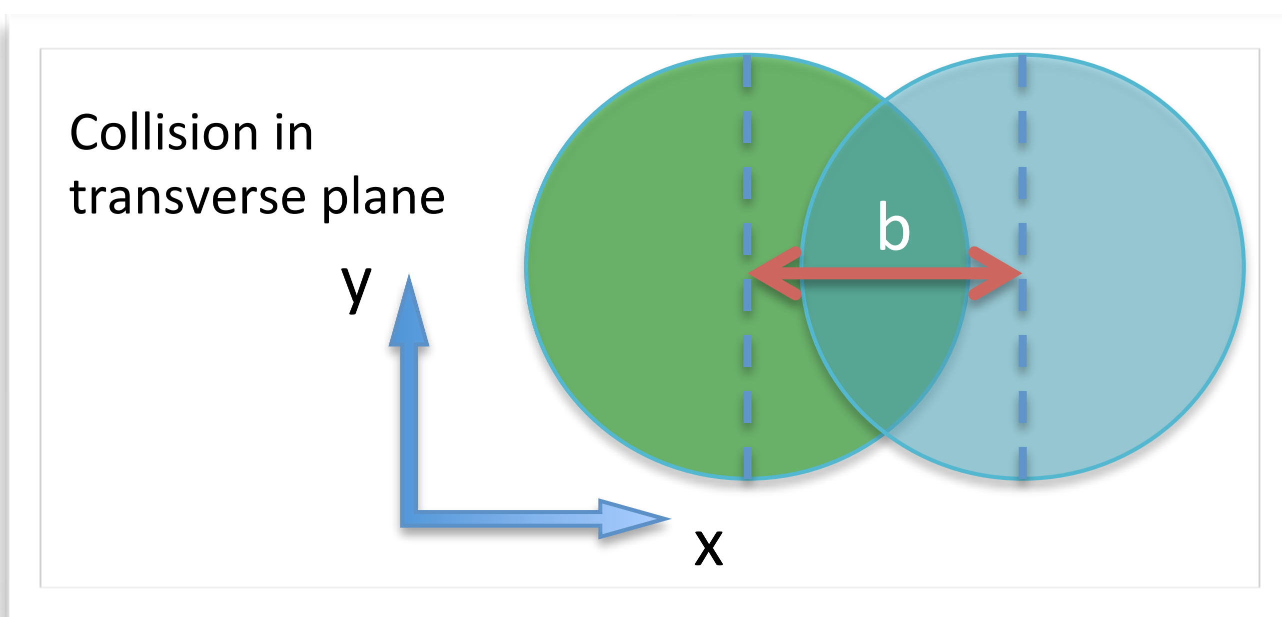
central collisions:
small impact parameter b
- high number of participants
- high energy density
- large volume
-> large number of produced particles

peripheral collisions:
large impact parameter b
- low number of participants
-> low multiplicity

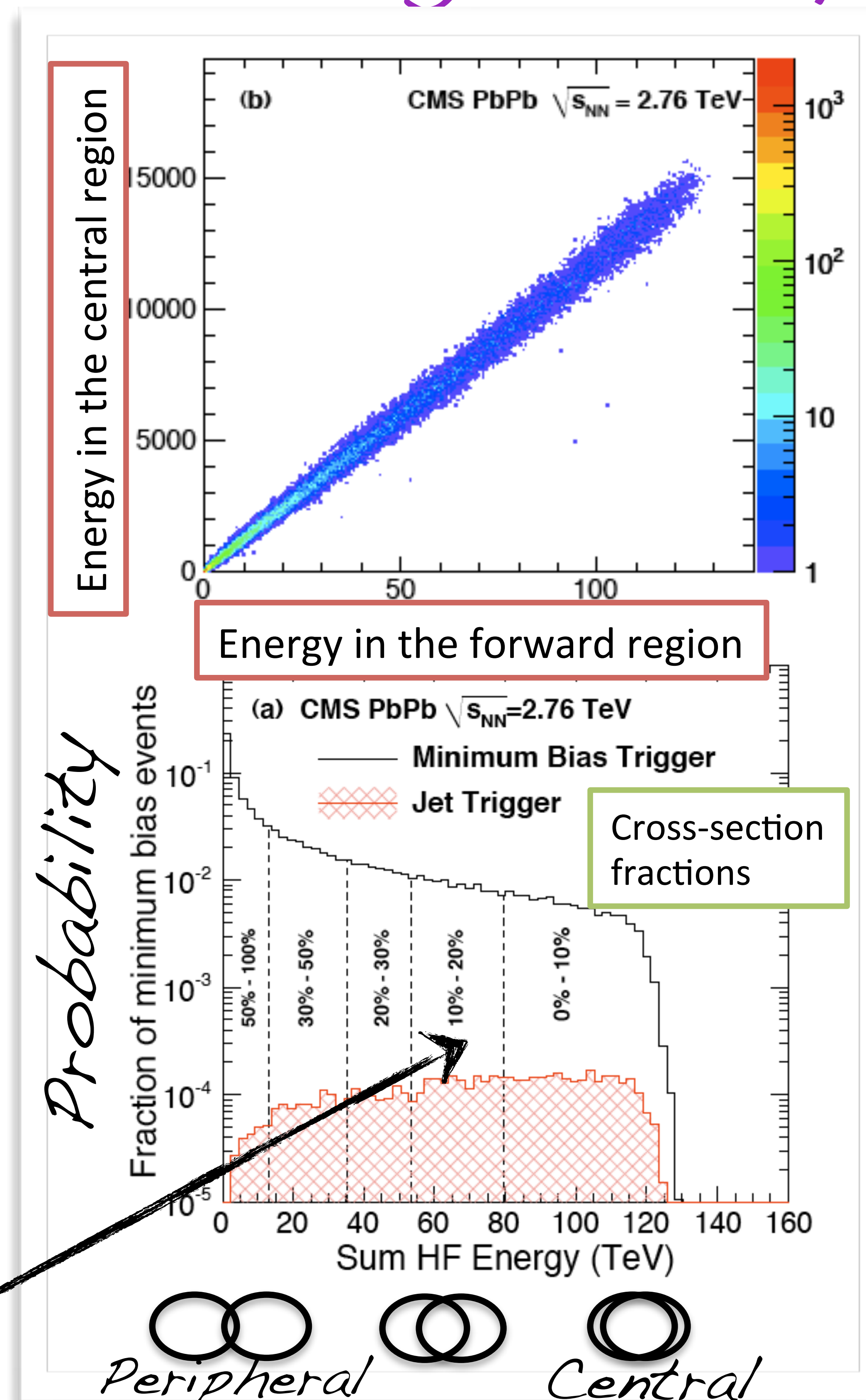
Experimental control of collision geometry

How can we measure impact parameter in heavy-ion collisions?

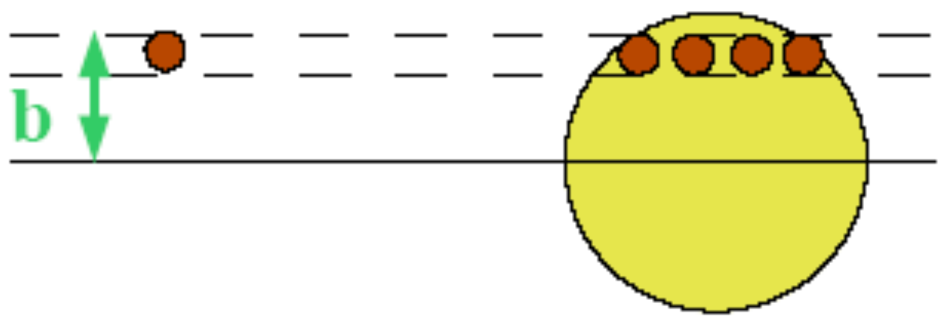
=> Correlate observables connected only by geometry



Characterize events via percentile (fraction) of inelastic cross section (jargon: "N% most central")



Nuclear geometry - Glauber model and hard (high-Q^2) processes



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A:

$$\sigma_{pA}^{inel} = \int d\vec{b}\left(1 - \left[1 - T_A(b)\sigma_{NN}^{inel}\right]^A\right)$$

Glauber scaling: hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions

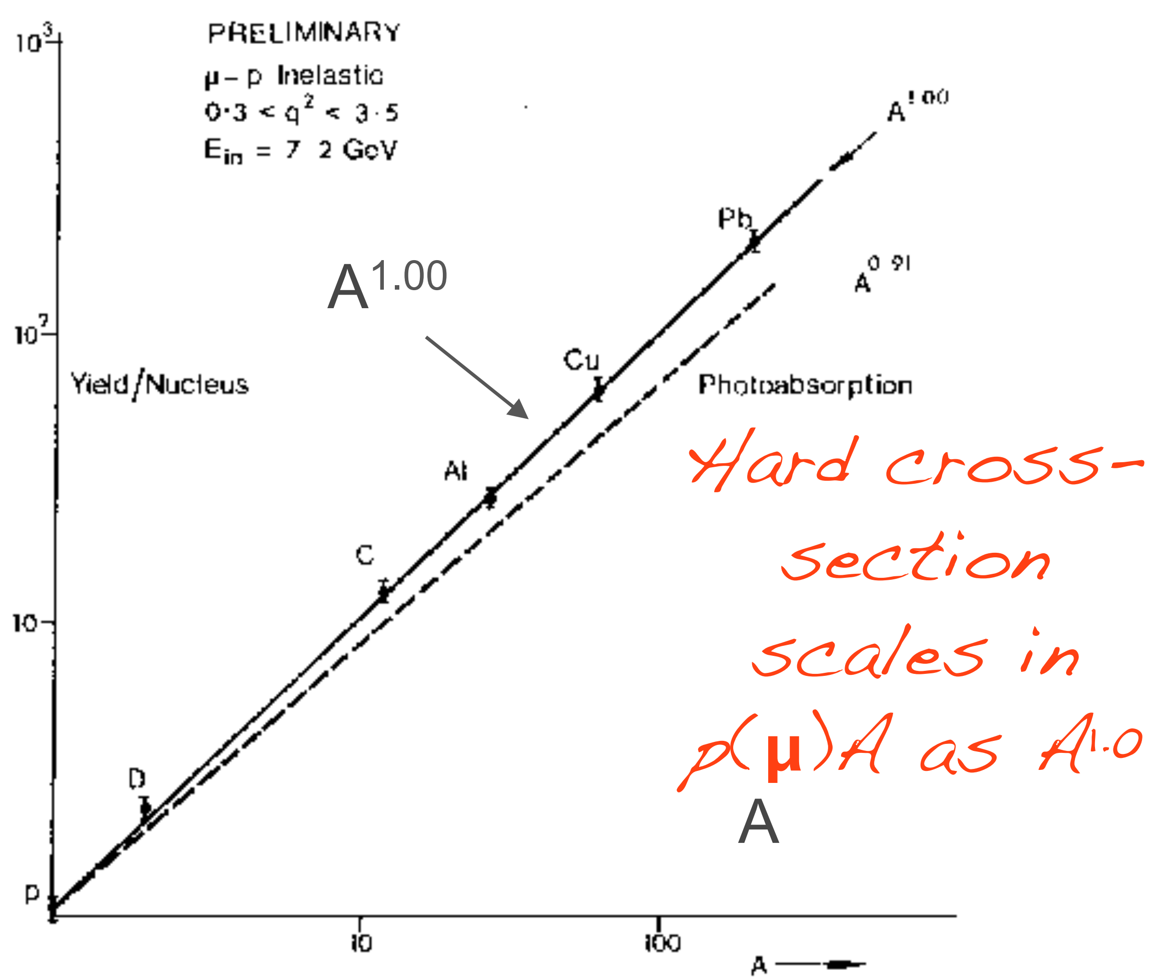
$$\sigma_{pA}^{hard} \approx A\sigma_{NN}^{hard} \int d\vec{b}\, T_A(\vec{b}) = A\sigma_{NN}^{hard}$$

Glauber scaling of hard processes

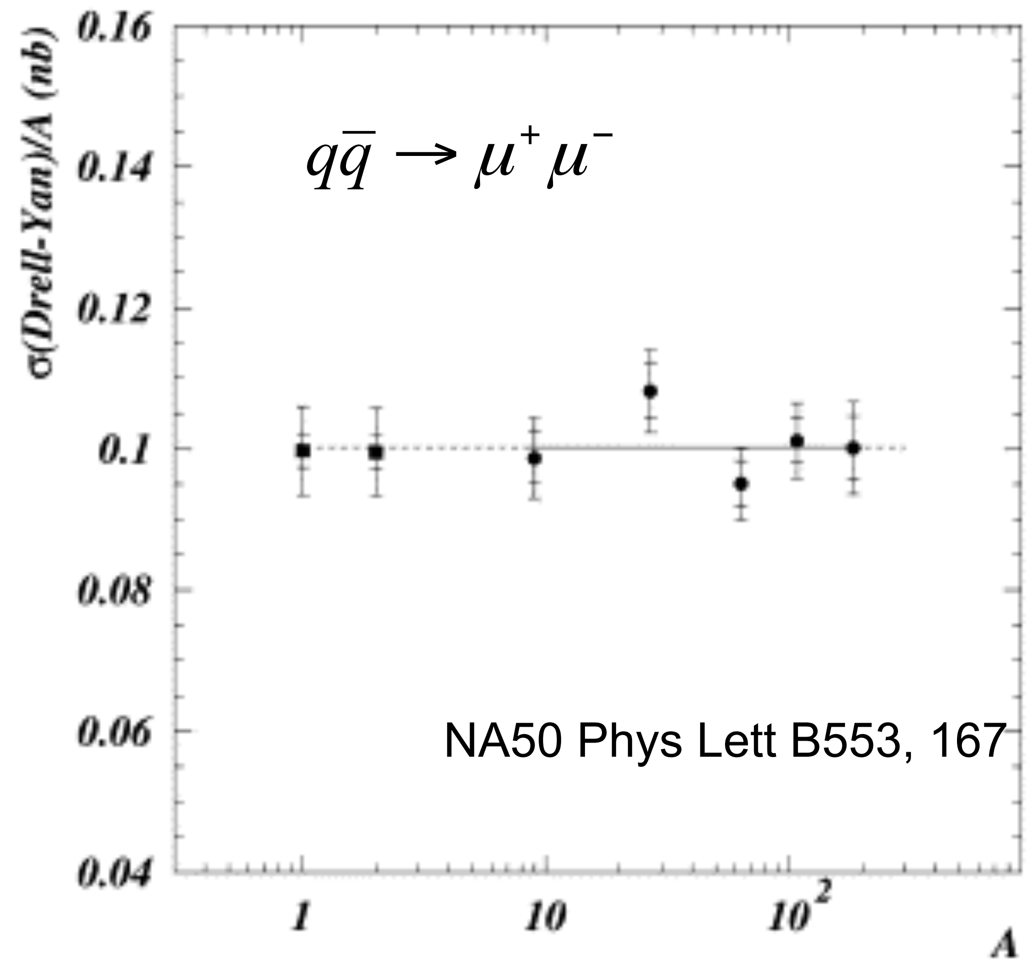
Glauber scaling: $\boxed{\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}}$

σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS



Experimental control in heavy-ion collisions?

=> direct photons, Z's, measure pA collisions (discussed later...)

Centrality measurement: use of the Glauber model in an experiment

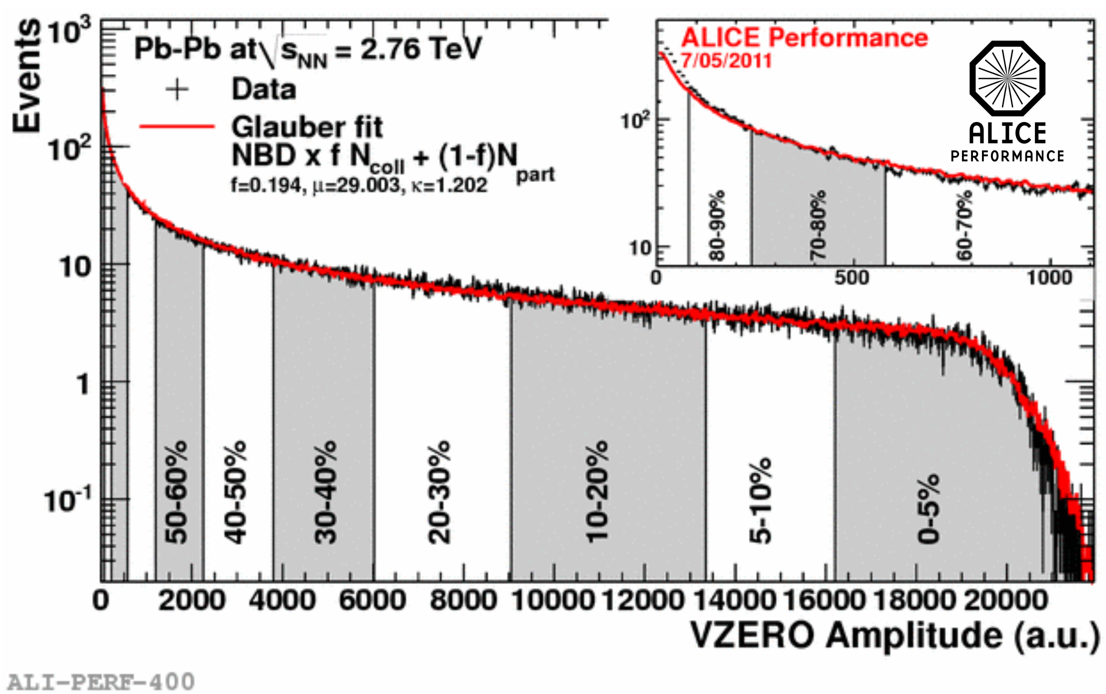
- Fraction of cross section, 2 approaches:
  - Fit with Glauber Monte Carlo
  - Correct: subtract BG, efficiency and integrate multiplicity distributions
- N_{part}, N_{coll}, N_{spect}: require Glauber fit (computed using cuts on impact parameter)
- Estimators:

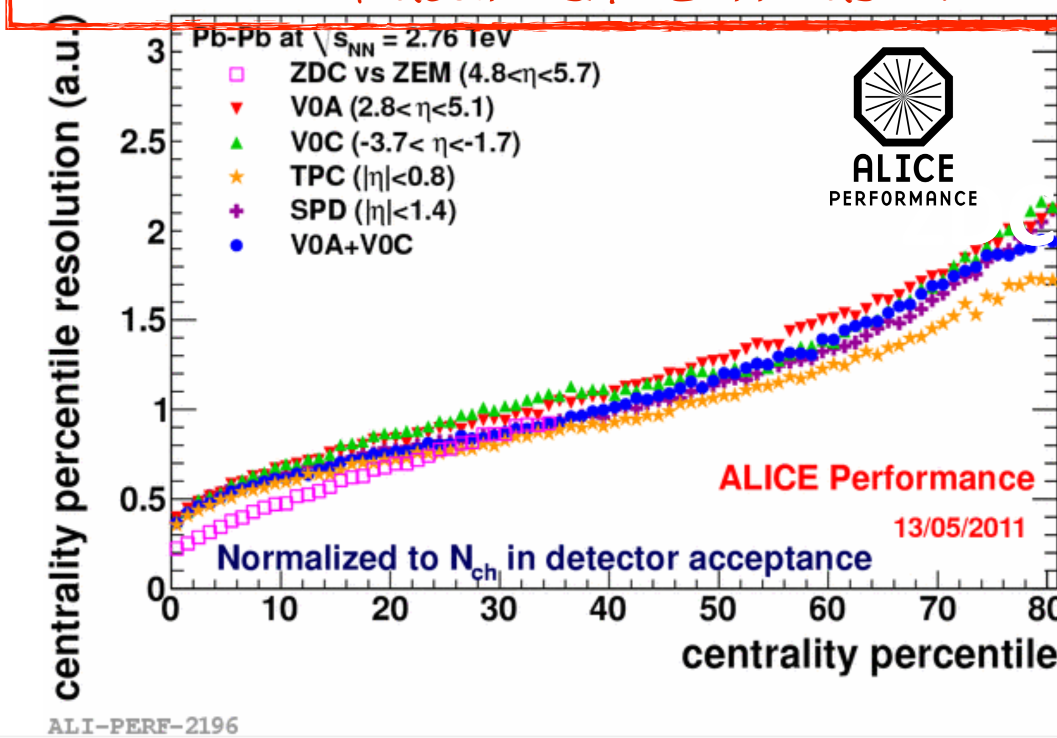
  V0, SPD clusters, TPC tracks, ZDCs, …
- ZDC measures N_{spect}: test of Glauber picture

- Glauber fit ingredients
  - Woods-Saxon (constrained by low energy electron-nucleus scattering)
  - Inelastic pp cross section (measured by ALICE)
  - Nucleons follow straight line trajectories, interact based on their distance
  - Compute (fit) observables assuming:
    $$N_{ancestors} = \alpha \cdot N_{part} + (1-\alpha) \cdot N_{coll}$$

Several detectors

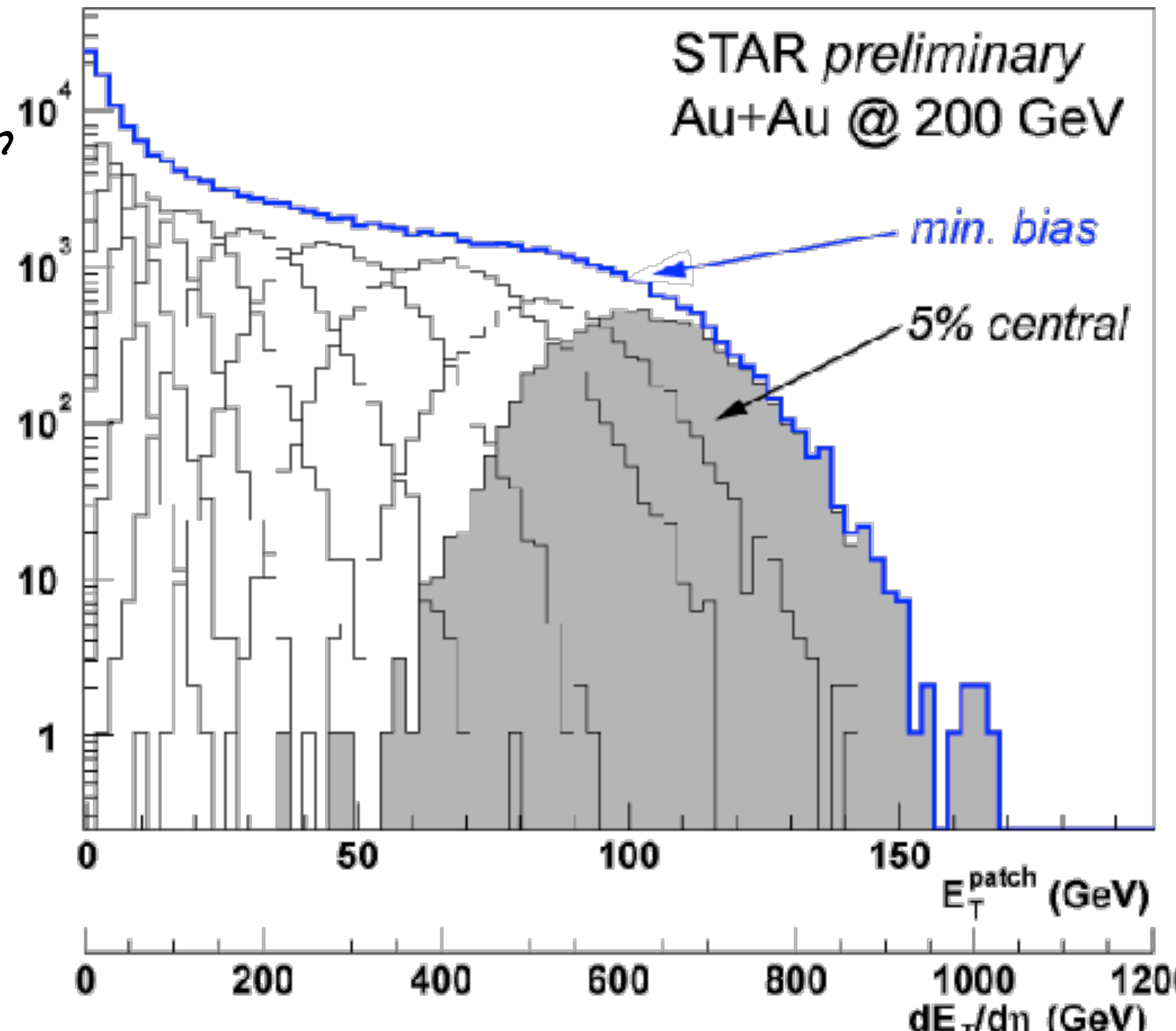
– measure the correlation





Energy density in AA collisions - RHIC example

- (calorimeters) measure energy
- estimate volume of collision

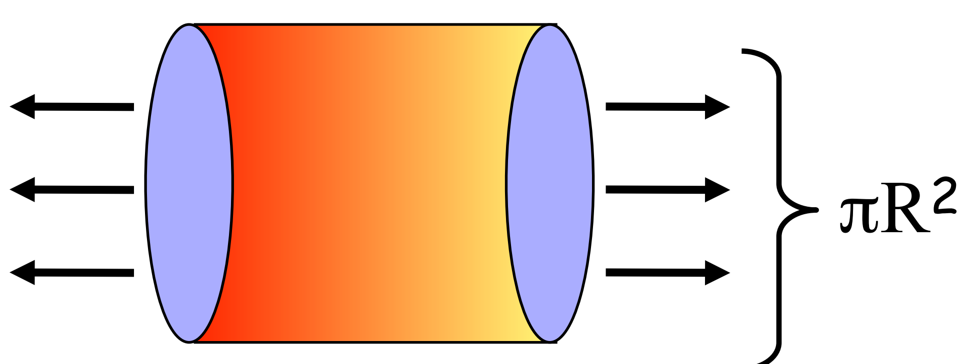


Bjorken energy density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system ($t_0 \sim$ 1 fm/c)



$$dz = \tau_0 dy$$

$\varepsilon_{BJ} \approx 5.0\ \mathrm{GeV/fm^3}$ RHIC:

~30 times normal nuclear density

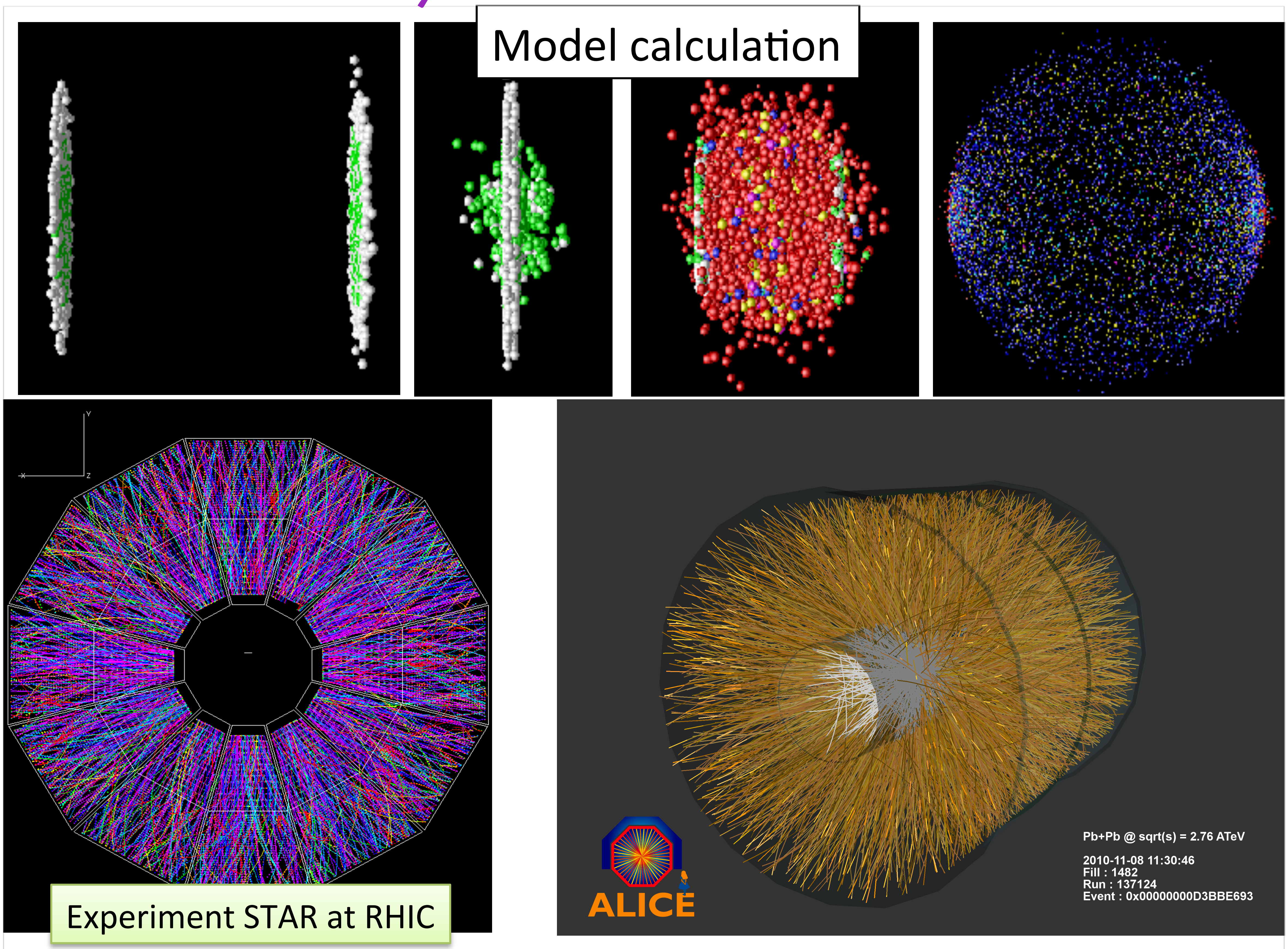
~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

Will see later: LHC ~ 3 x RHIC

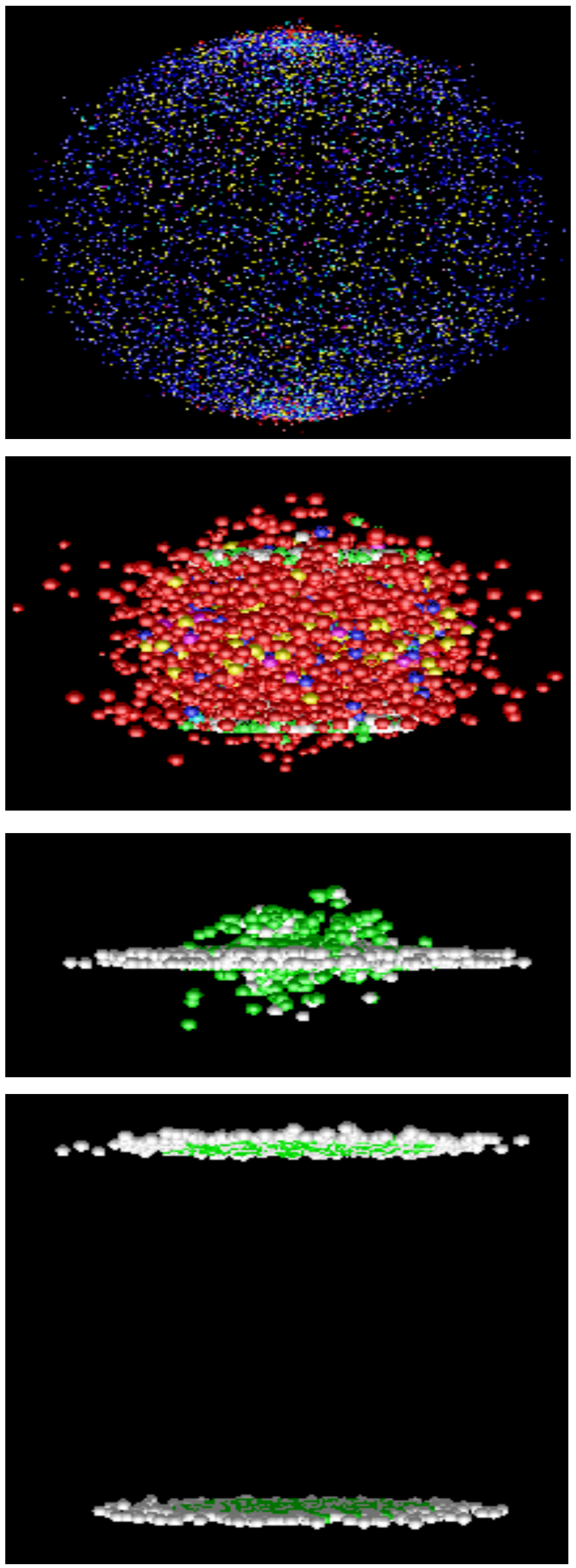
First: "control" understanding - before further insight to QGP properties...

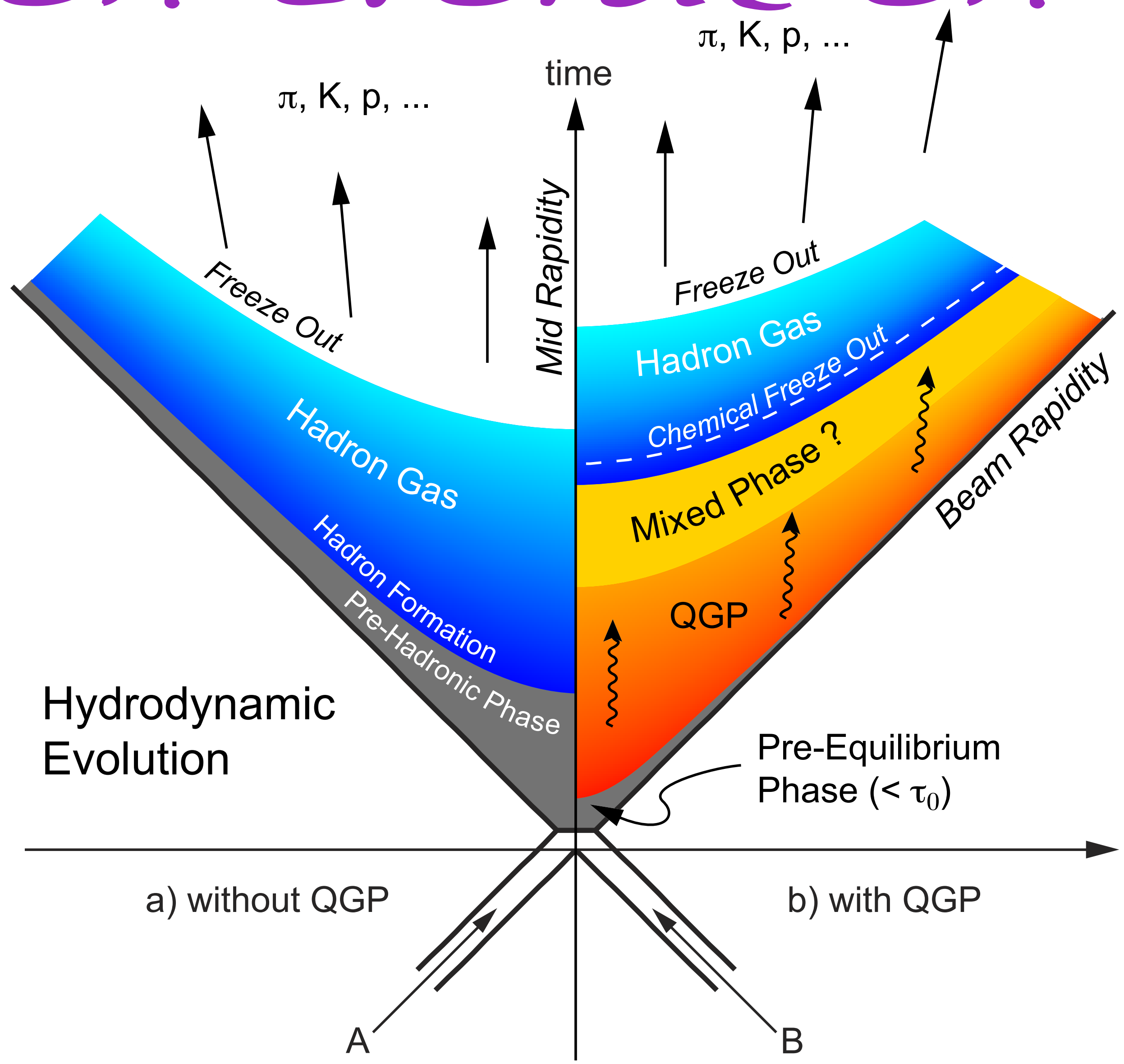
Warning: need to know what observations are "trivial" (we are colliding heavy-ions at hight energies) vs. what observations are sensitive to QGP properties (a thought experiment: what to expect when QGP is NOT formed - what is the baseline - when you know you created QGP - answer is suprisingly complex... more on that later...)

Heavy-ion collisions



Collision evolution





Note: hard scatterings occur early (at t~0)!

Flow & correlations - in #2

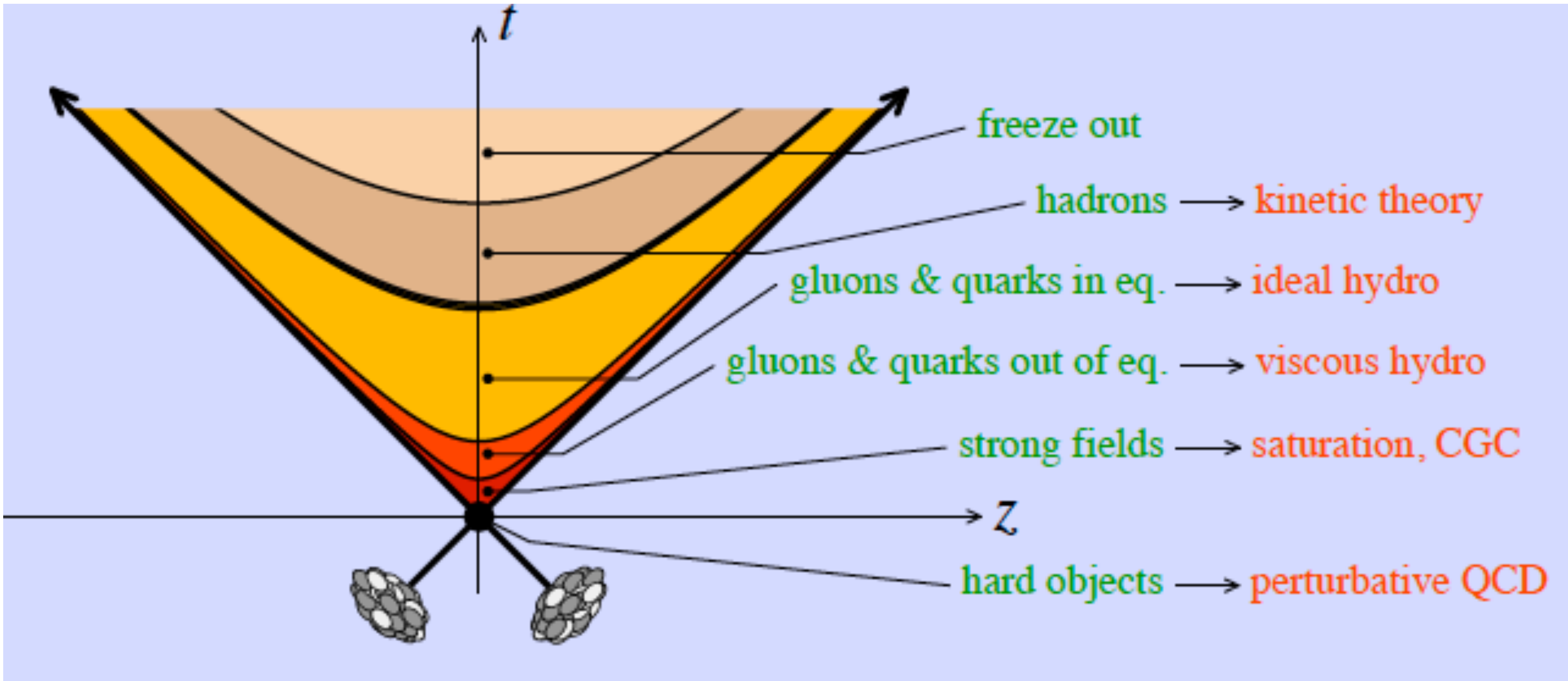
High energy partons "witness" the evolution

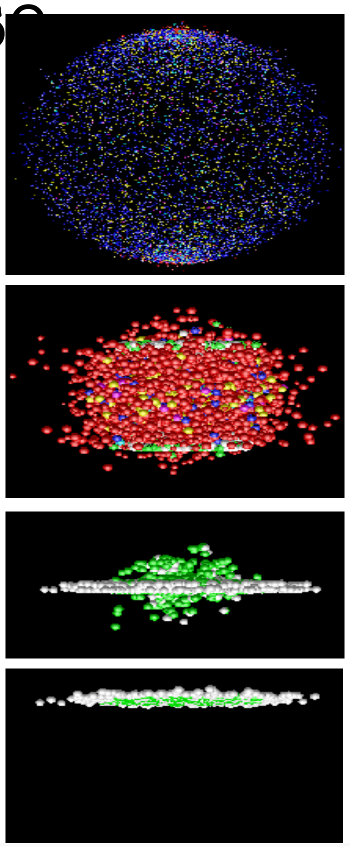
- more on that in #2 & #3

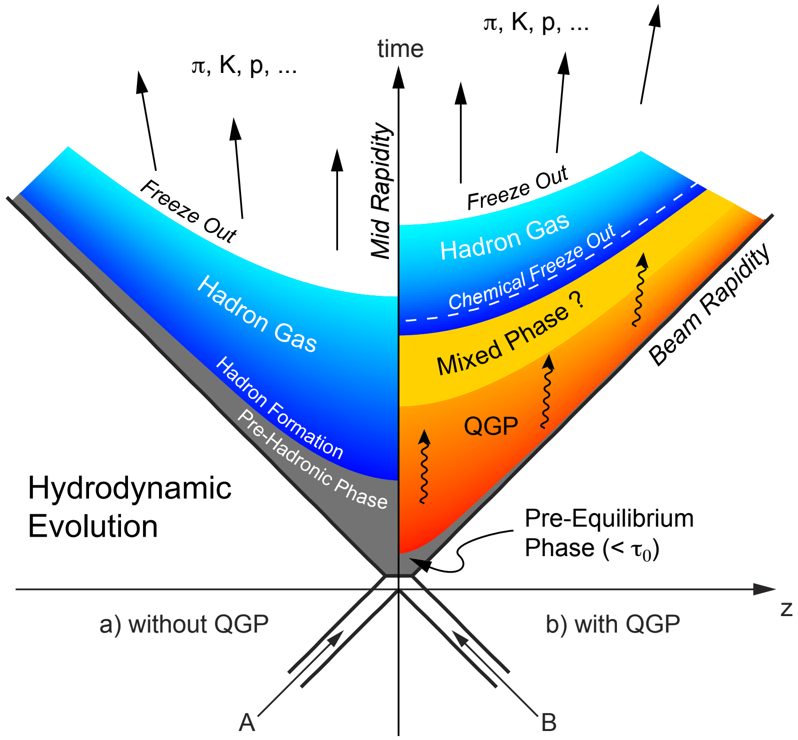
Two key things to follow-up: Chemical freeze-out

Kinetic freeze-out

Collision stages & theoretical description







Collision evolution

Few notes:

We are interested in properties of QGP (lifetimes ~ few fm/c !)

Need to disentangle effects from different phases

- not a simple problem by principle: detectors do NOT measure these time-periods/phases separately (detector: particles after hadronization!)

=> need for detail understanding of the physics processes, particle production, dynamics of the system in each phase(!)

=> modeling, various assumptions may play an important role in physics interpretation

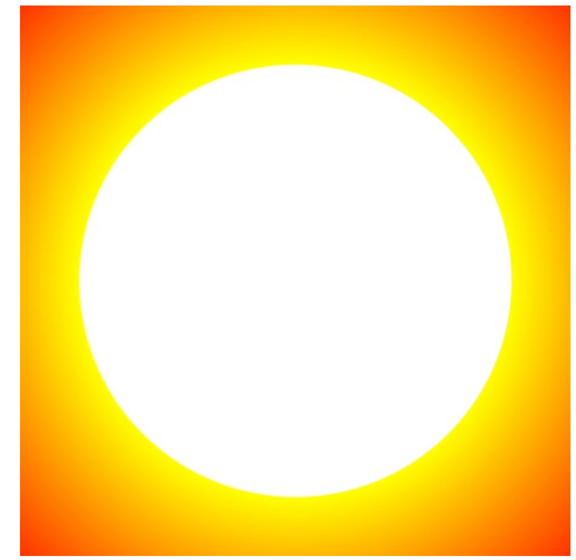
Need for control of the initial conditions, geometry of the collision, the incoming parton distributions (nuclear-PDF vs nucleon-PDF) ...

Measurements...
estimating T

What is hot and what is not: Thermal radiation from a source

Remote Temperature Sensing

Red Hot



White Hot

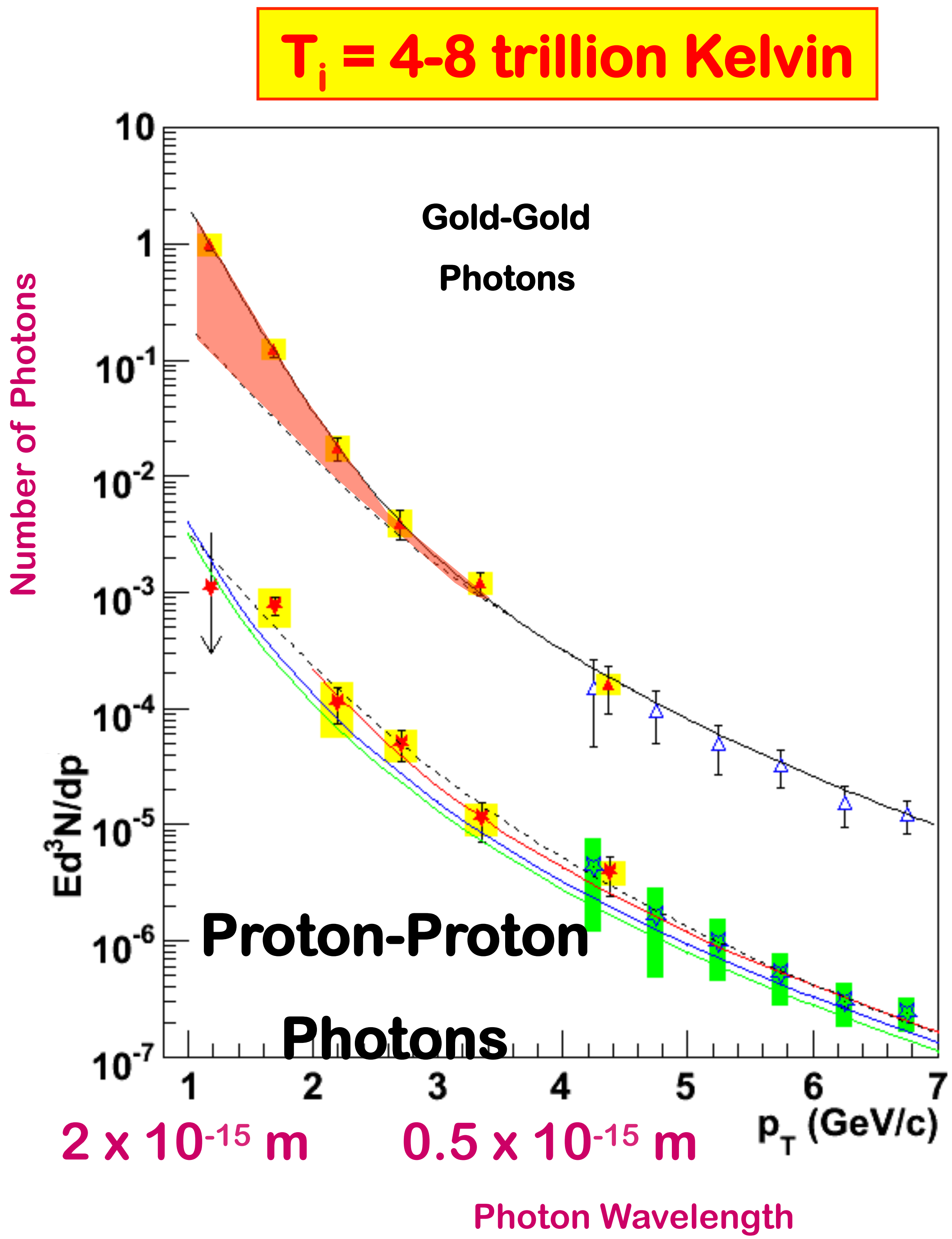
- **Hot Objects produce thermal spectrum of EM radiation.**
- **Red clothes are NOT red hot, reflected light is not thermal.**

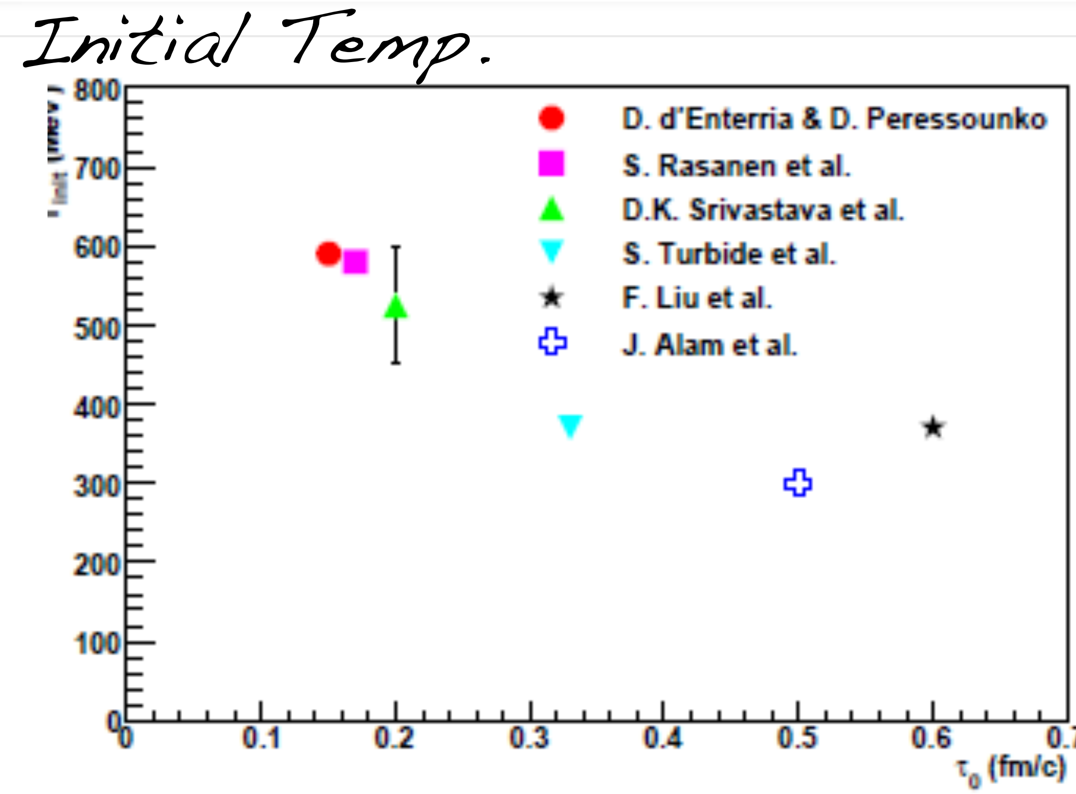
Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Not Red Hot!

Thomas K Hemmick

Photons - RHIC



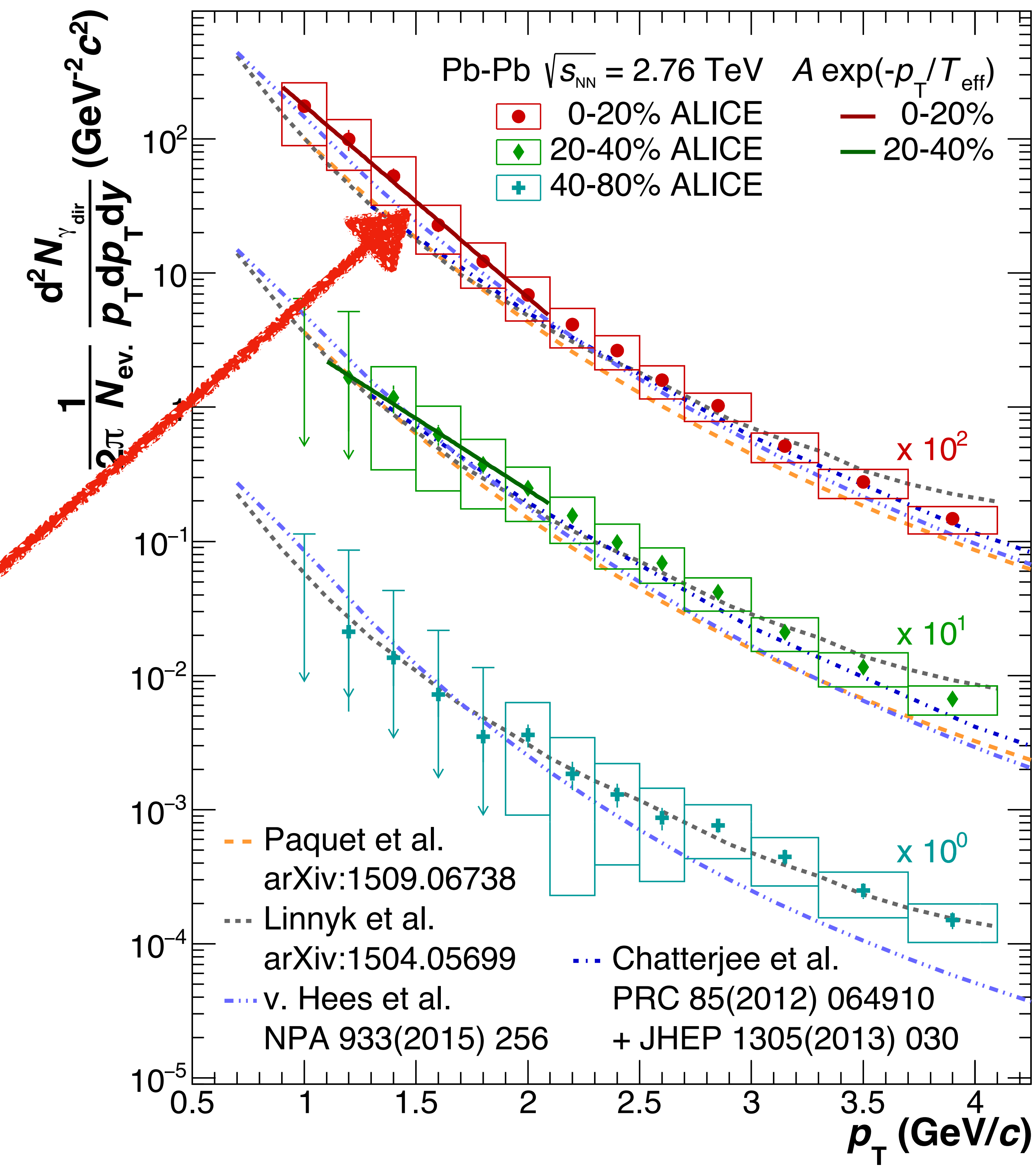


Emission rate and distribution consistent with equilibrated matter

T~300-600 MeV

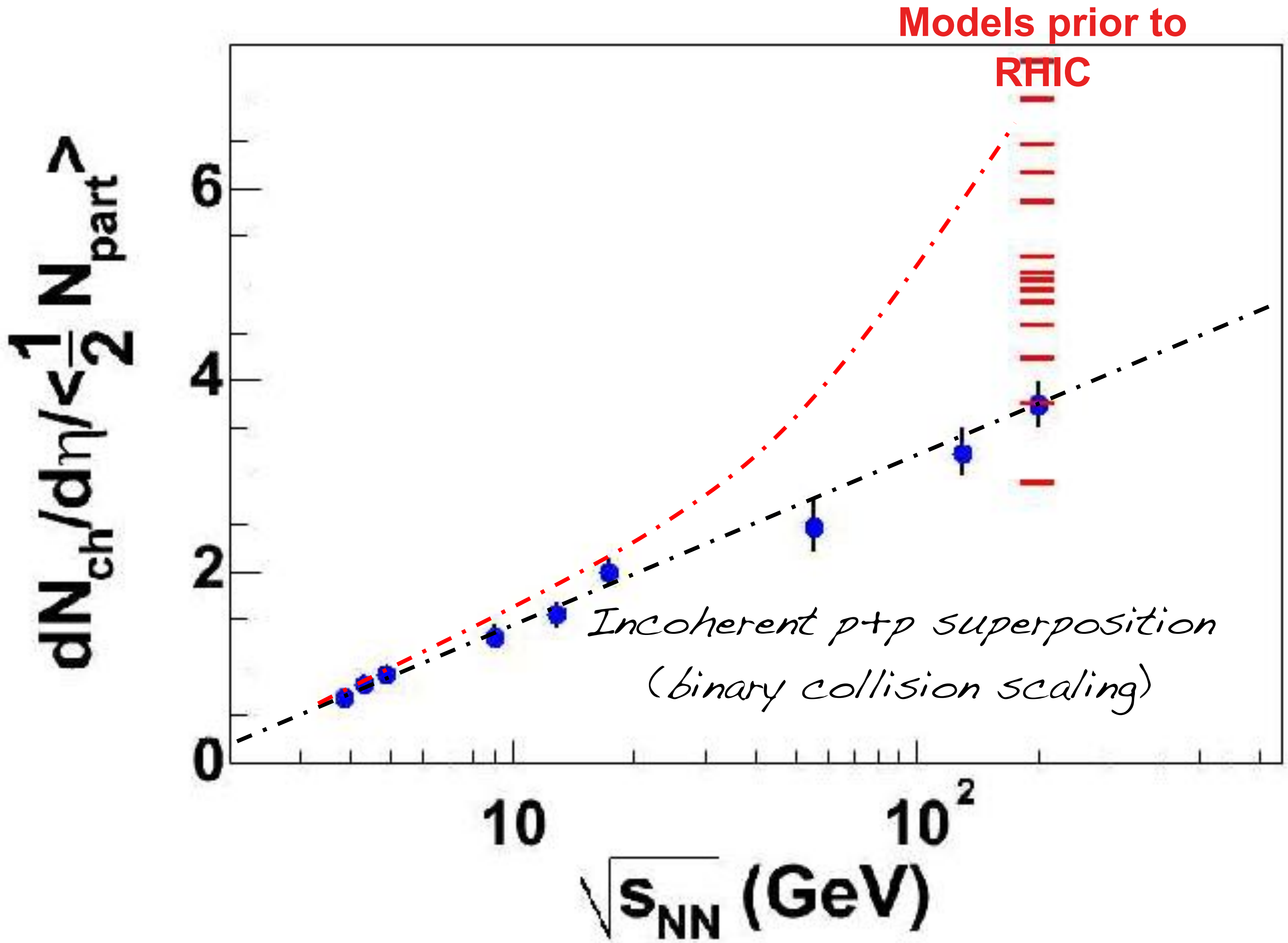
LHC-QGP Shines bright - thermal photons

- Production of photons in Pb-Pb collisions
- Thermal emission - photons shine from the plasma
  - Most central collisions: Inverse slope fits for low-p_T: T~300 MeV
- LHC QGP - hottest man-made matter



Calibration measurements...

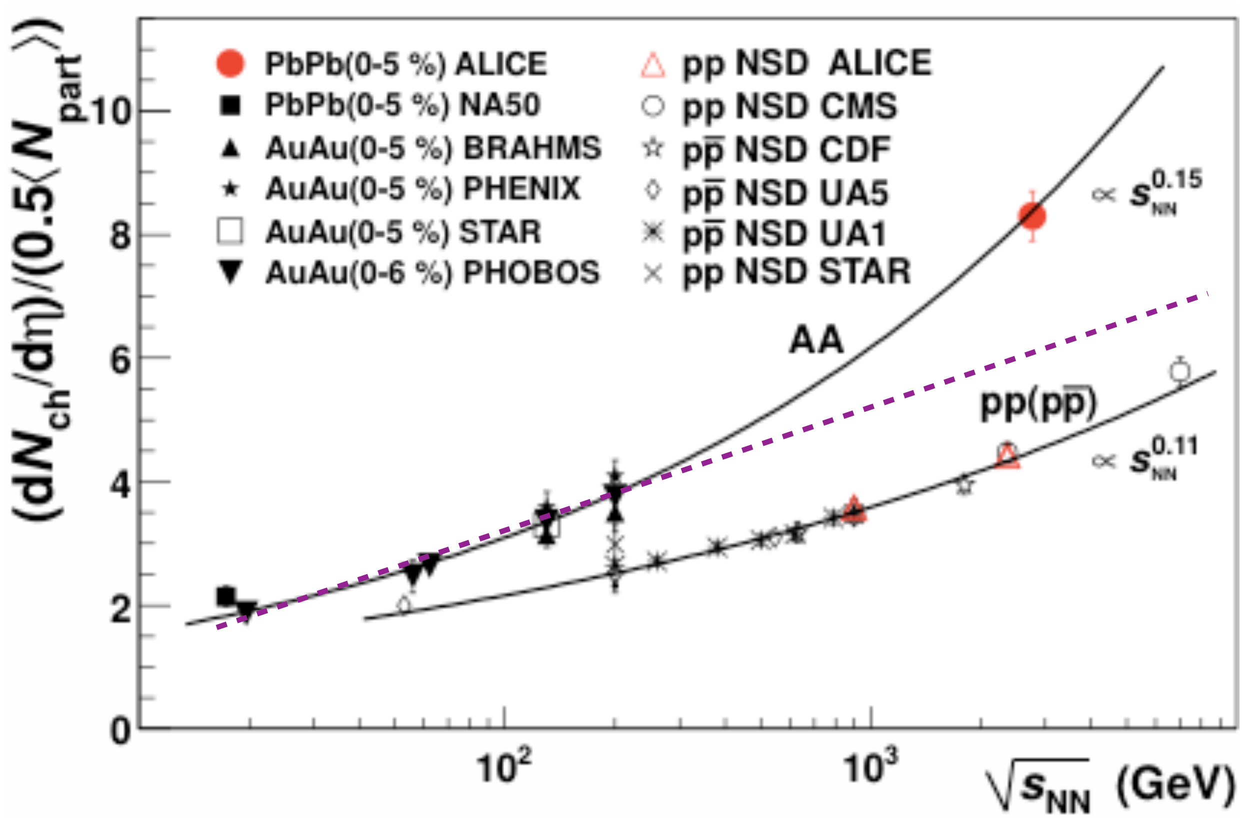
Multiplicity – energy dependence



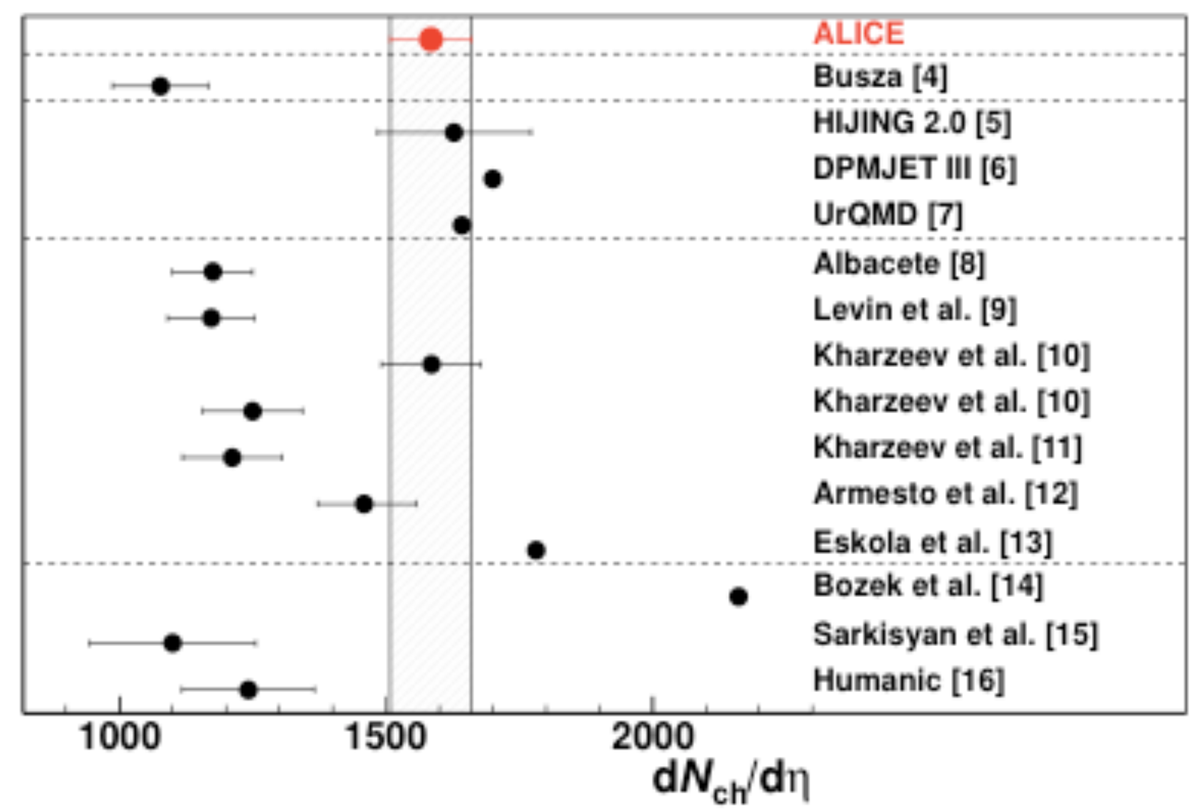
Scales just like pp; No evidence for (incoherent) multi-parton interactions at RHIC.

Multiplicity - at high energies...

Energy dependence



Comparison to predictions



PRL 105, 252301 (2010)

Energy dependence

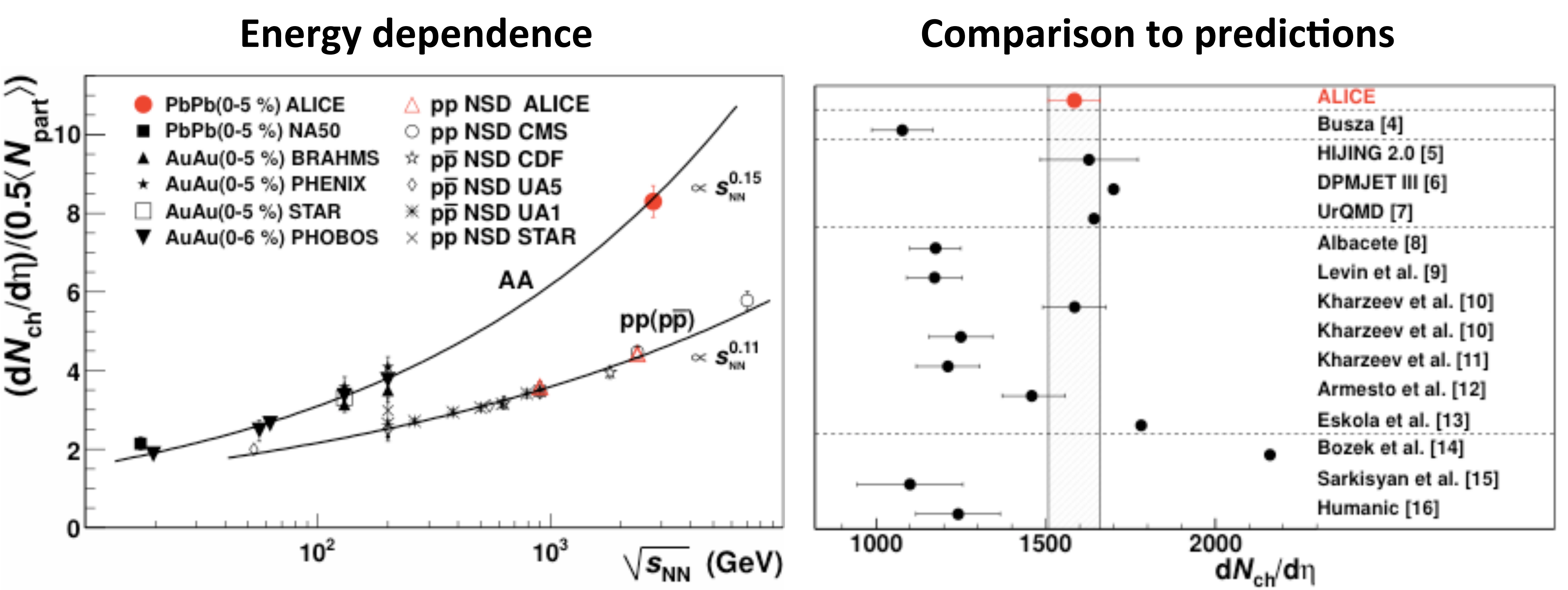
p-p ~ $s_{NN}^{0.11}$

A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)

– stronger rise than log extrapolation

Higher energy
<->
Stronger growth
<->
more partons interacting...

HI collisions: Particle production



PRL 105, 252301 (2010)

Feedback within the heavy-ion community:

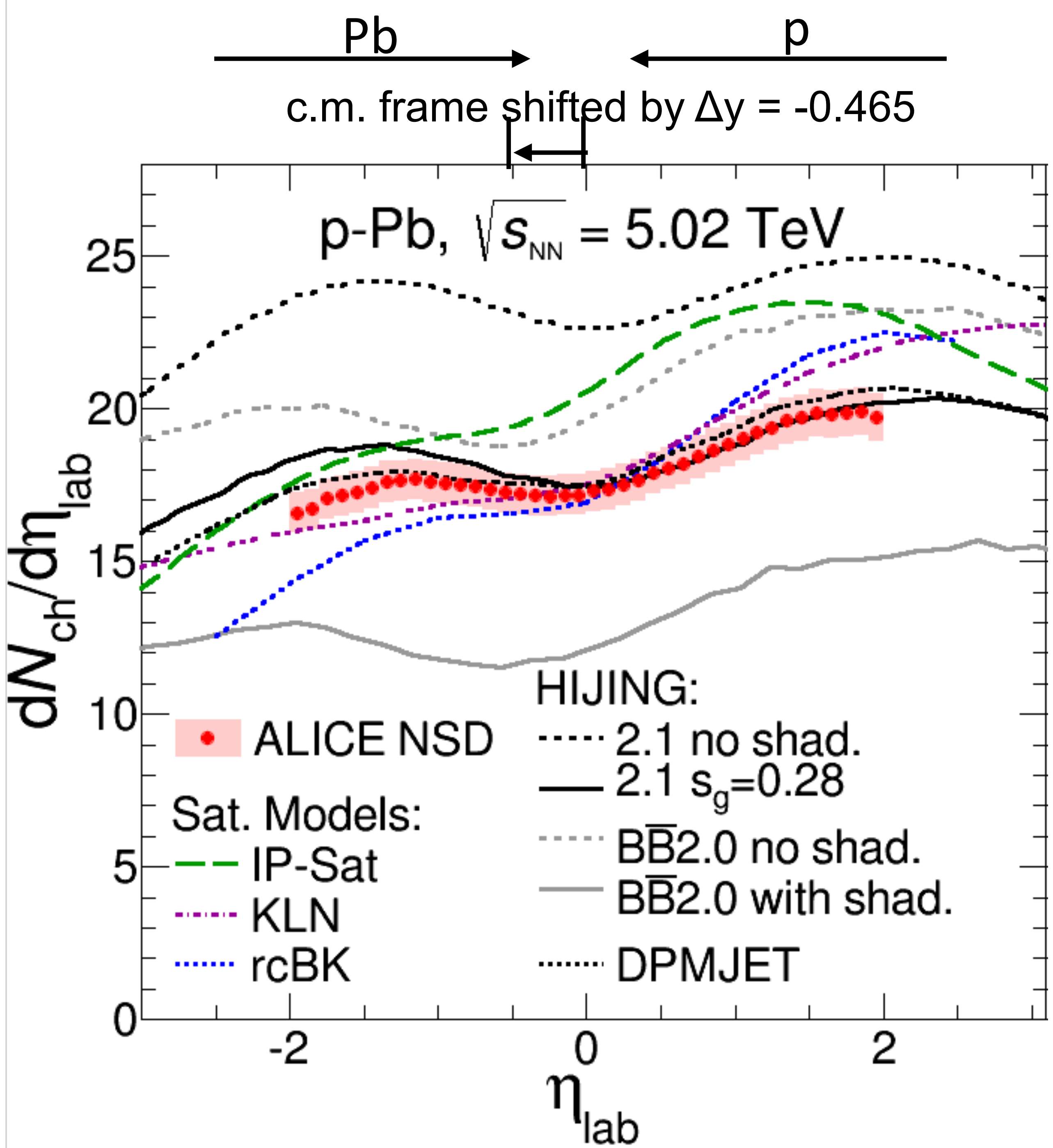
1. **Multiplicity is crucial [input] for modeling**
2. **Saturation models tend to predict lower multiplicity**
3. **Data driven extrapolations did not seem to anticipate the results**

Calibration: proton-A collisions

p-Pb - crucial tests at LHC & new phenomena

More during the next lectures...

ALICE: arXiv: 1210.3615



Basic measurement allows to discriminate between models

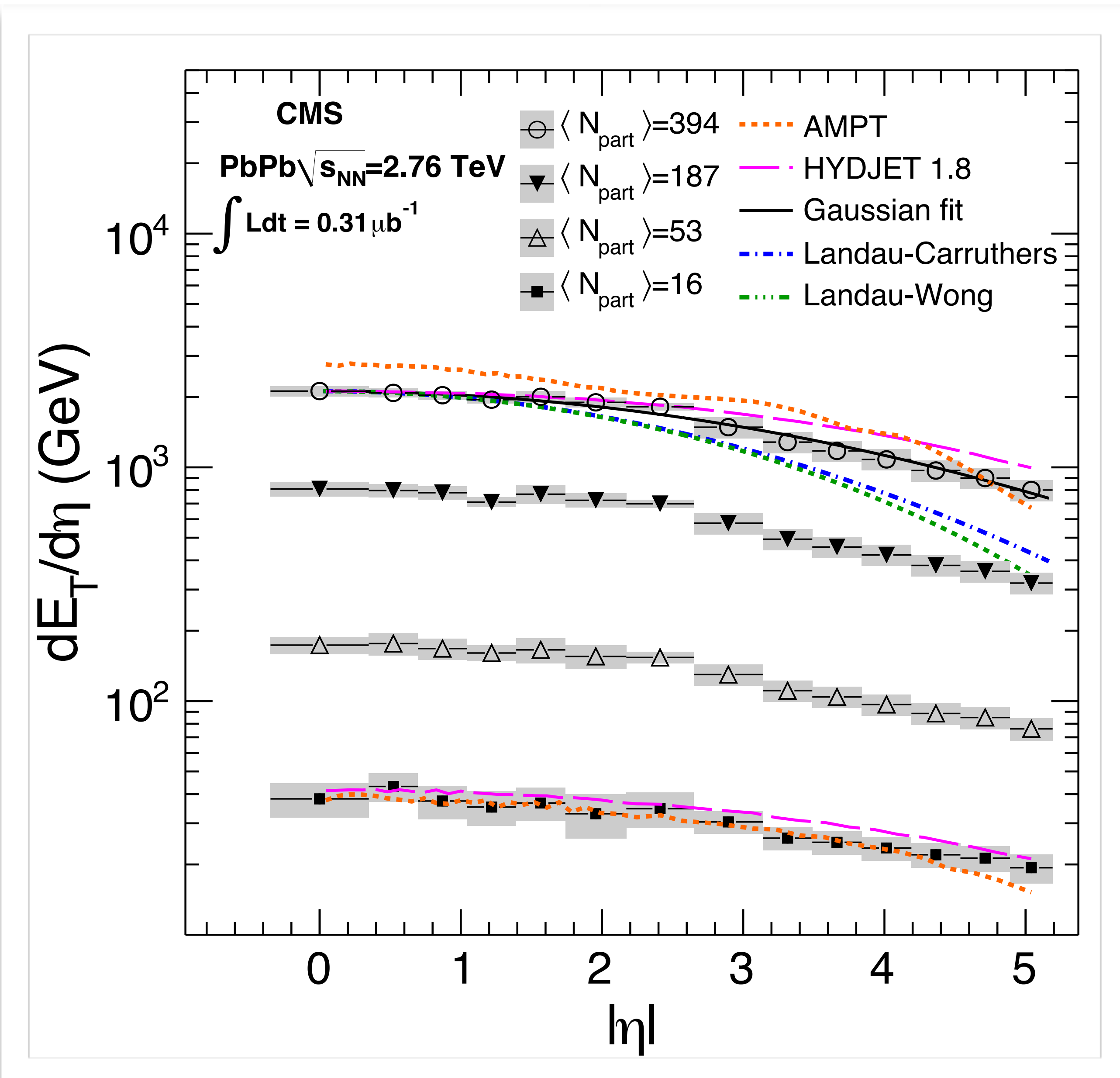
Data favors models that incorporate shadowing

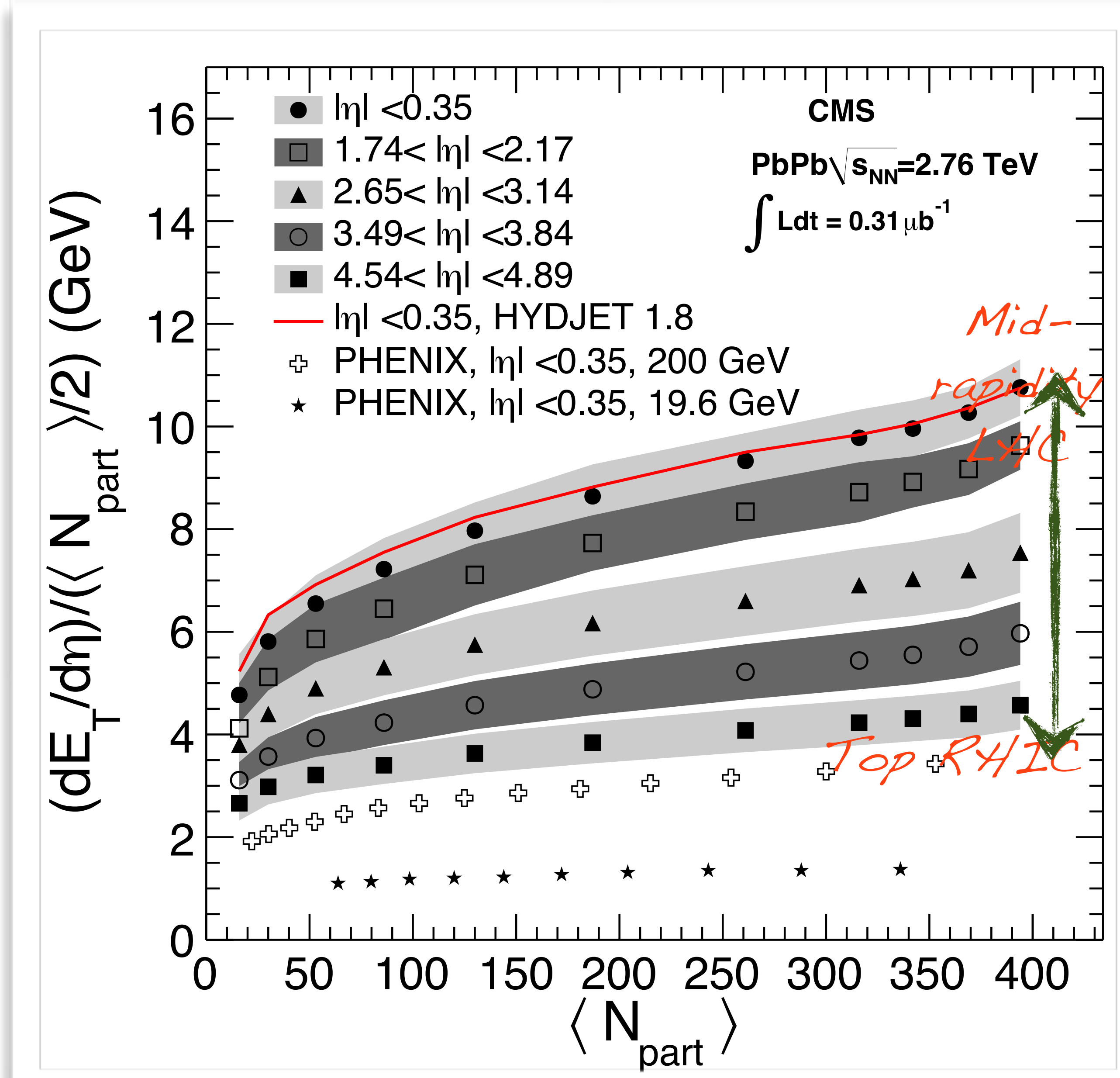
Saturation models predict much steeper η-dependence not seen in the data

Energy density: RHIC to LHC

LHC > 2.5 x RHIC

... within a volume (per nucleon)





Very hot, super dense? -> what are its "transport" properties... fundamental QCD questions

Calibration measurements: what do we know about the source emitting particles?

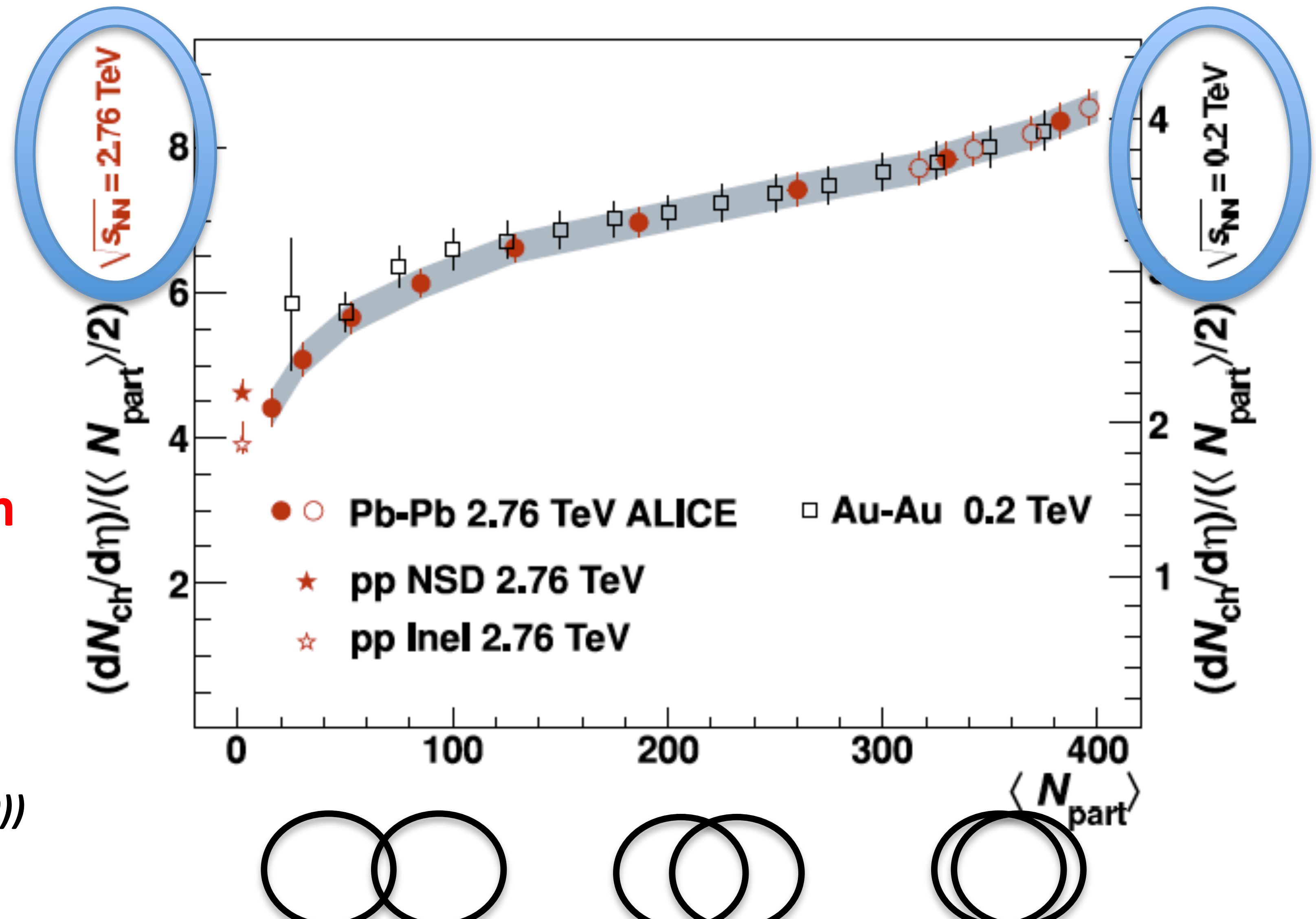
Systematic control: RHIC vs LHC

Centrality dependence of particle production

The same experiment under vastly different conditions!

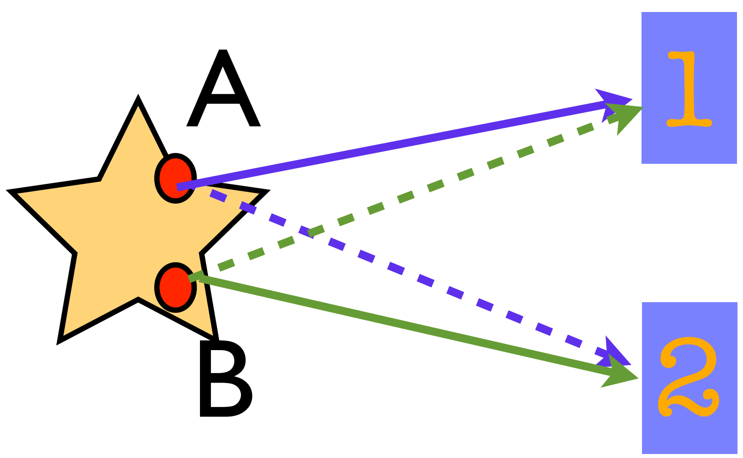
• **Identical variation of particle production with centrality (volume) at RHIC and LHC!**
⇒ Global features of the system independent on energy
⇒ Initial conditions!

More on RHIC:
*Phobos (**Phys. Rev. Lett. 102, 142301 (2009)**)*



Centrality of the collisions: peripheral semi-central central

How to measure the dimensions of a source... - interferometry



quantum phenomenon: enhancement of correlation function for identical bosons from Heisenberg's uncertainty principle

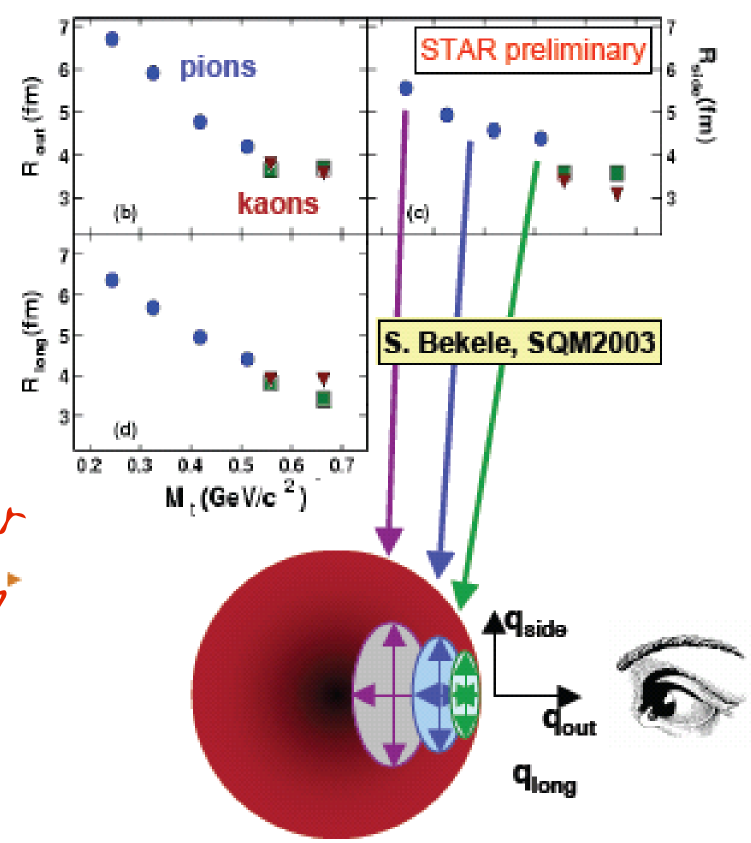
Two particles emitted from two locations (A,B) within a single source.
These two are detected by detector elements (1,2).

$$A = \frac{1}{\sqrt{2}}\left(e^{ik_1^\mu (r_1-r_a)^\mu} e^{ik_2^\mu (r_2-r_b)^\mu} + e^{ik_1^\mu (r_1-r_b)^\mu} e^{ik_2^\mu (r_2-r_a)^\mu}\right)$$

$$I = |A|^2 = 1 + \left\{e^{i(k_2-k_1)^\mu (r_a-r_b)^\mu} + c.c.\right\}$$

The intensity interference between the two point sources is an oscillator depending upon the relative momentum q=k$_2$-k$_1$, and the relative emission position!

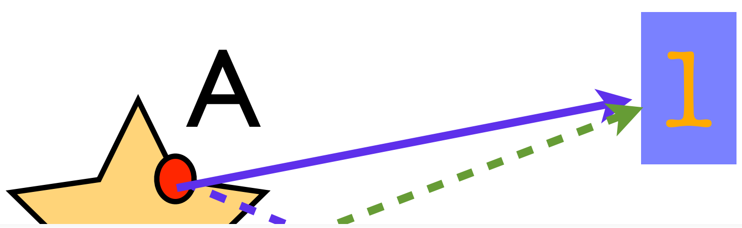
$$C(\mathbf{p}_1,\mathbf{p}_2) = \frac{E_1E_2dN/(d^3p_1d^3p_2)}{(E_1dN/d^3p_1)(E_2dN/d^3p_2)} . \quad E_p\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$



Correlation function summed incoherently (integration over all pairs of source points) in a function of 4-momentum sums and differences (q,K) - extract source dimensions:

$$C(q,K) = 1 \pm \lambda(K)\exp\left(-R_s^2(K)q_s^2 - R_o^2(K)q_o^2 - R_l^2(K)q_l^2\right)$$

How to measure the dimensions of a source... - interferometry



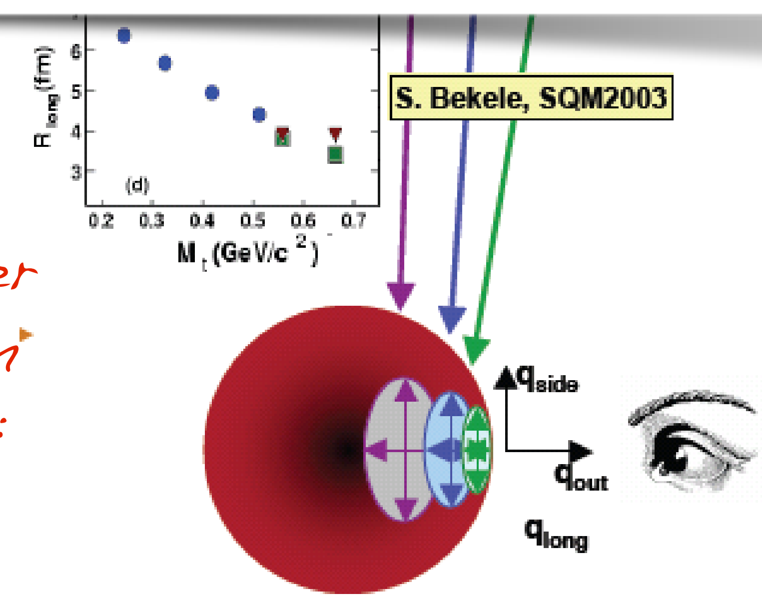
Two particles emitted from two locations (A,B) within a single source.

These two are detected by detector elements (1,2).

First used with photons in the 1950s by astronomers Hanbury Brown and Twiss - hence HBT measurements in heavy-ion collisions...
=> measured size of star Sirius by aiming at it two photomultipliers separated by a few meters

Th

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)} . \qquad E_p \frac{dN}{d^3p} = \int d^4x \, S(x,p)$$



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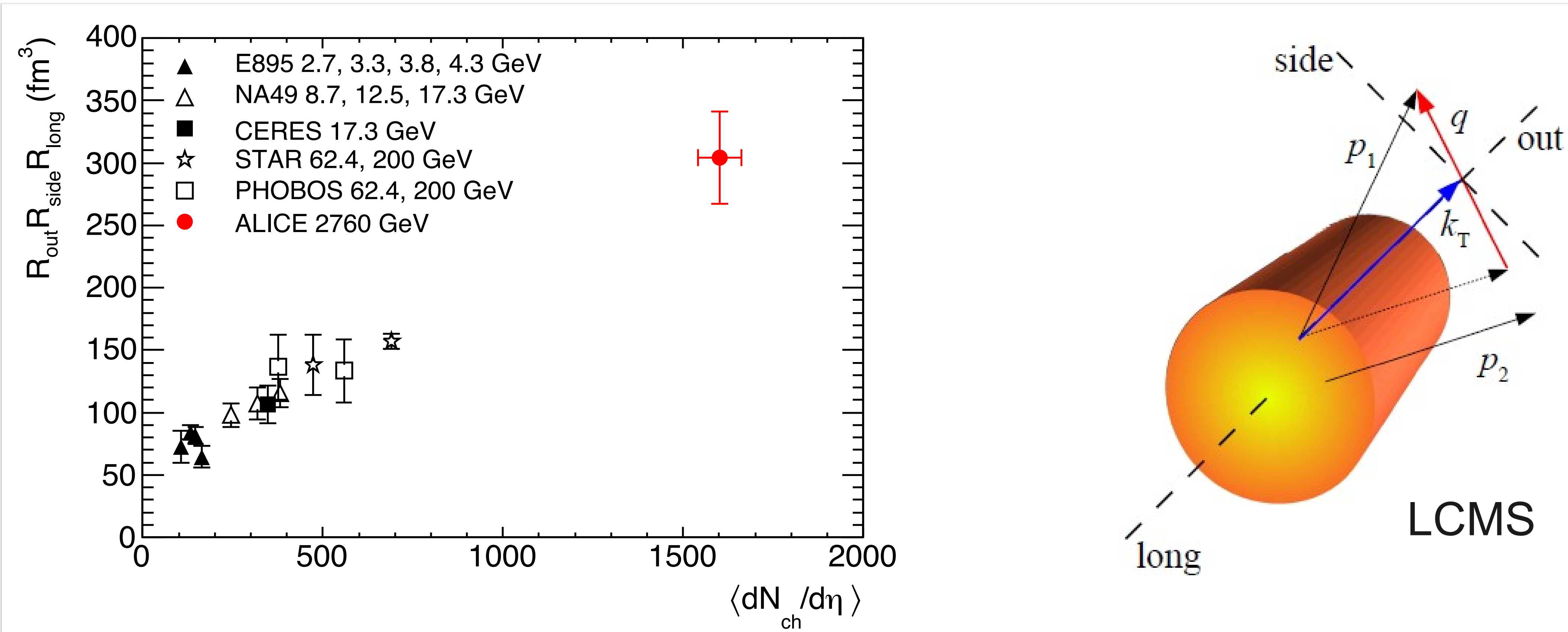
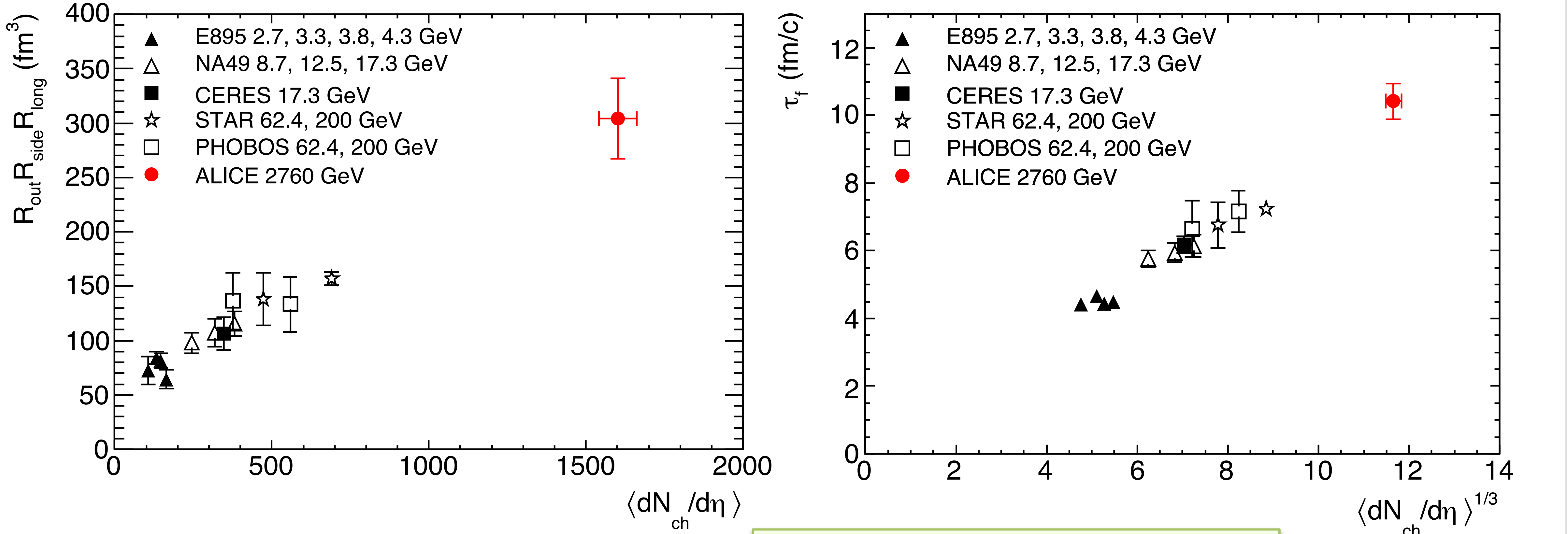
Particle production: source dimensions



Phys.Lett.B 696:328-337,2011

1. **Energy dependence:**
   - **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**
2. **Pair momentum dependence:**
   - **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**
3. **Important constrains to [hydrodynamical] modelling**

Particle production: source dimensions



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- **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**

3. Important constrains to [hydrodynamical] modelling

until now (1/3) ...

- QCD and the/a phase diagram
- Phases of HI collision
- Heavy-ion colliders and detectors
- How to measure centrality of a collision
- Energy density
- Temperature
- Freeze-out volume (and time)