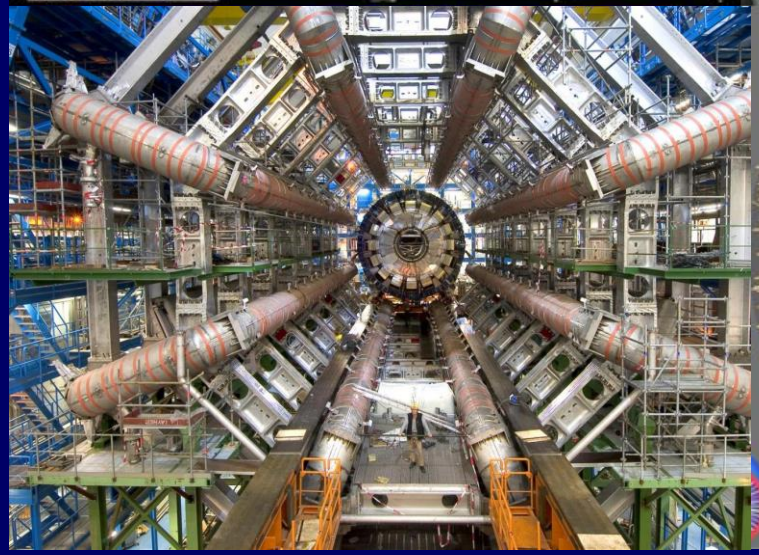
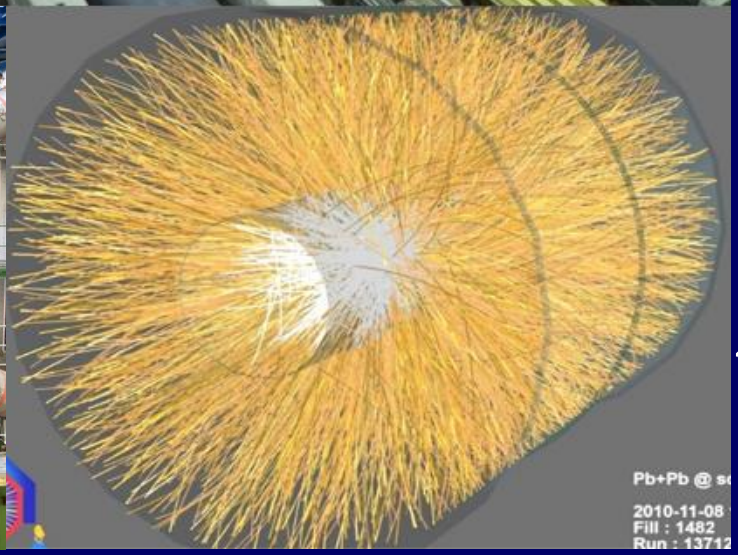
# “Highlights from 30 Years of Ultra-Relativistic Heavy Ion Physics”

1986




2016

Hea

PRESSE

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics
Europäisches Laboratorium für Teilchenphysik

PR 11 86
29.09.86

World Record in Energy … Break new ground

$^{208}Pb$

$^{16}O$

CERN'S SUBATOMIC PARTICLE ACCELERATORS

SET UP WORLD-RECORD IN ENERGY AND BREAK NEW GROUND FOR PHYSICS

Already acknowledged as the world's most versatile system of subatomic particle accelerators, CERN's complex of big machines put on a spectacular performance early in September, accelerating ions (=atomic nuclei) and taking them to the highest energy ever reached in a laboratory.

.. up to 400 particles/collision

- the detector technology used in those experiments was able to track the extraordinary amount of up to 400 particles created per collision.

..over 300 physicists

over 300 physicists from 62 institutions in 19 countries are

sicists all around the world are now analyzing the data collected to find out whether the famous quark-gluon plasma really has been achieved. A new experiment with continually improving conditions is

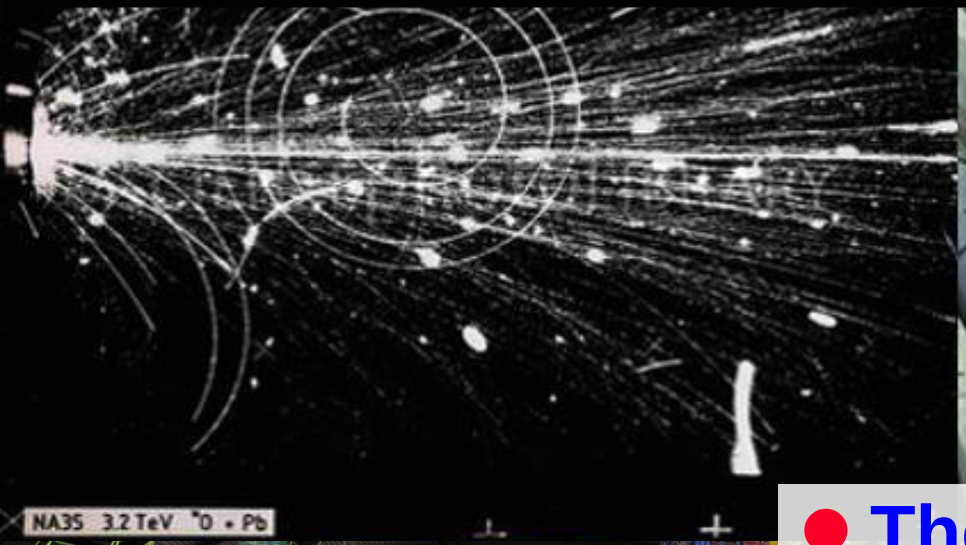
NA35 3.2 TeV $^{16}O$ + Pb

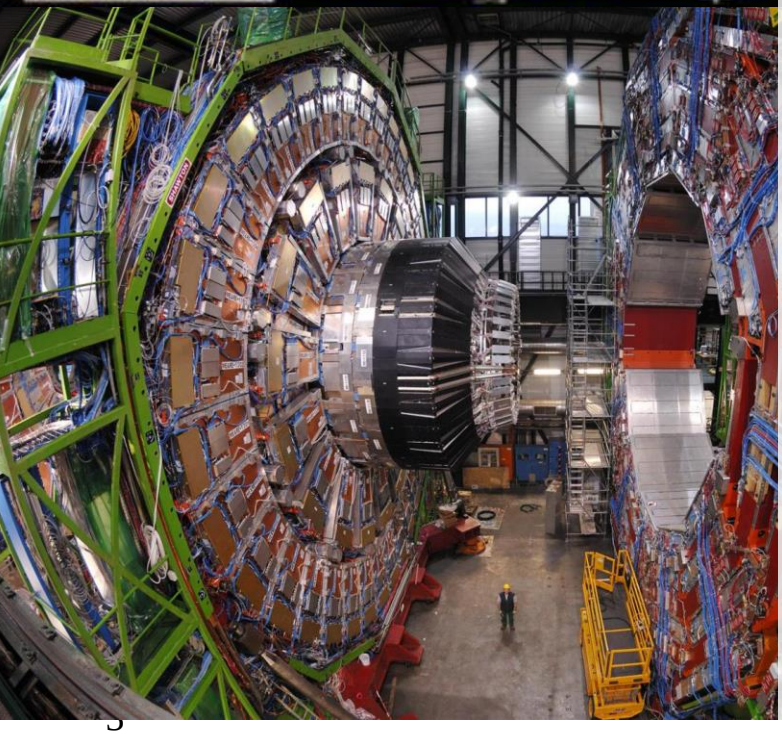
..weather the famous quark-gluon plasma really has been achieved

CERN SPS
$\sqrt{s}$ = 20 GeV/Nucleon

NA35 streamer chamber picture, ca 1986

# Highlights from 30 Years of URHI Physics

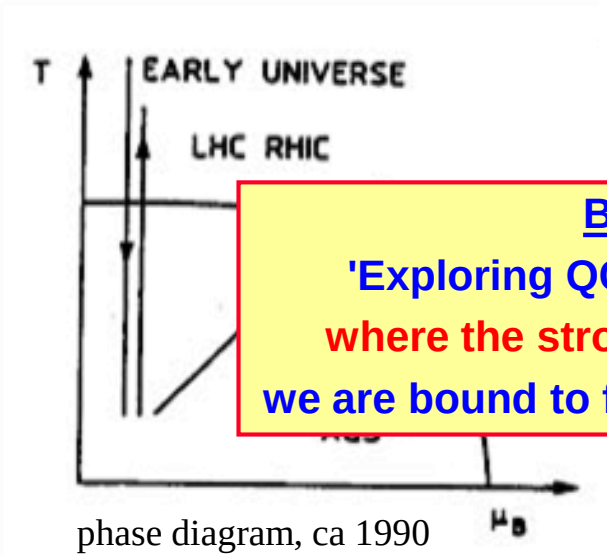


- **The Questions**
  - What do we want to learn from HIC
- **The Tools**
  - Accelerators, Experiments, Theory
- **Some Answers**
  - Highlights from (AGS)/SPS/RHIC/LHC
- **The Future**
  - Open Questions, New Facilities

# Matter under Extreme Conditions

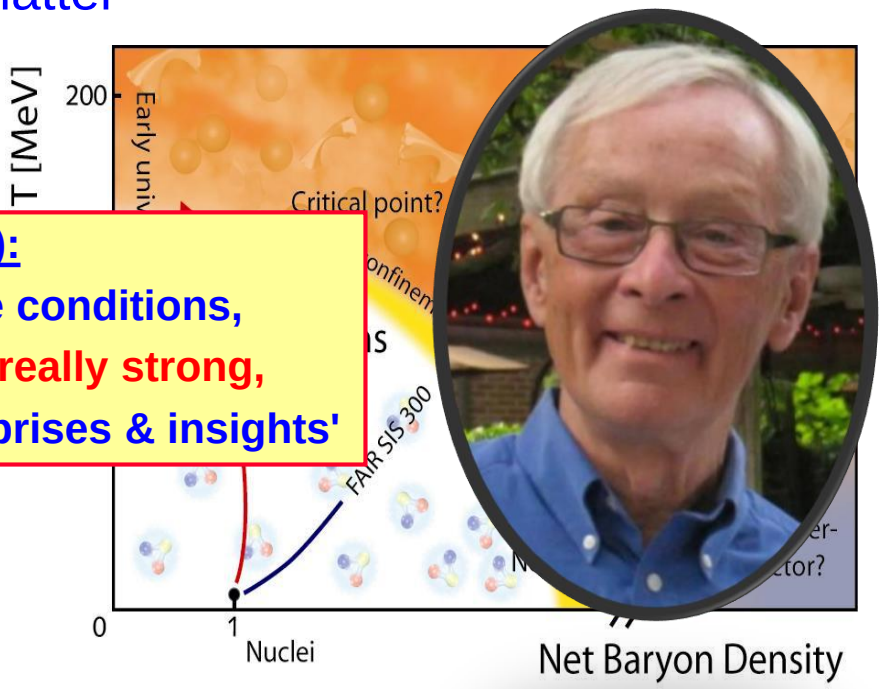
- Phase diagram of strongly interacting matter



phase diagram, ca 1990

**Bill Willis (ca 1984):**

**'Exploring QCD under extreme conditions,**
**where the strong interaction is really strong,**
**we are bound to find plenty of surprises & insights'**




- 'state of matter' at high temperature & energy density: '**The QGP**'
  - ⇨ **theoretical** expectations & predictions :
    - ✪ **weakly interacting plasma** / ideal gas of (quasi-free) quarks & gluons
    - ✪ partons are **deconfined** (not bound into composite color neutral hadrons)
    - ✪ **chiral symmetry** is restored (partons ≈ massless, vanishing gluon condensate)
  - ⇨ **experimental** definition

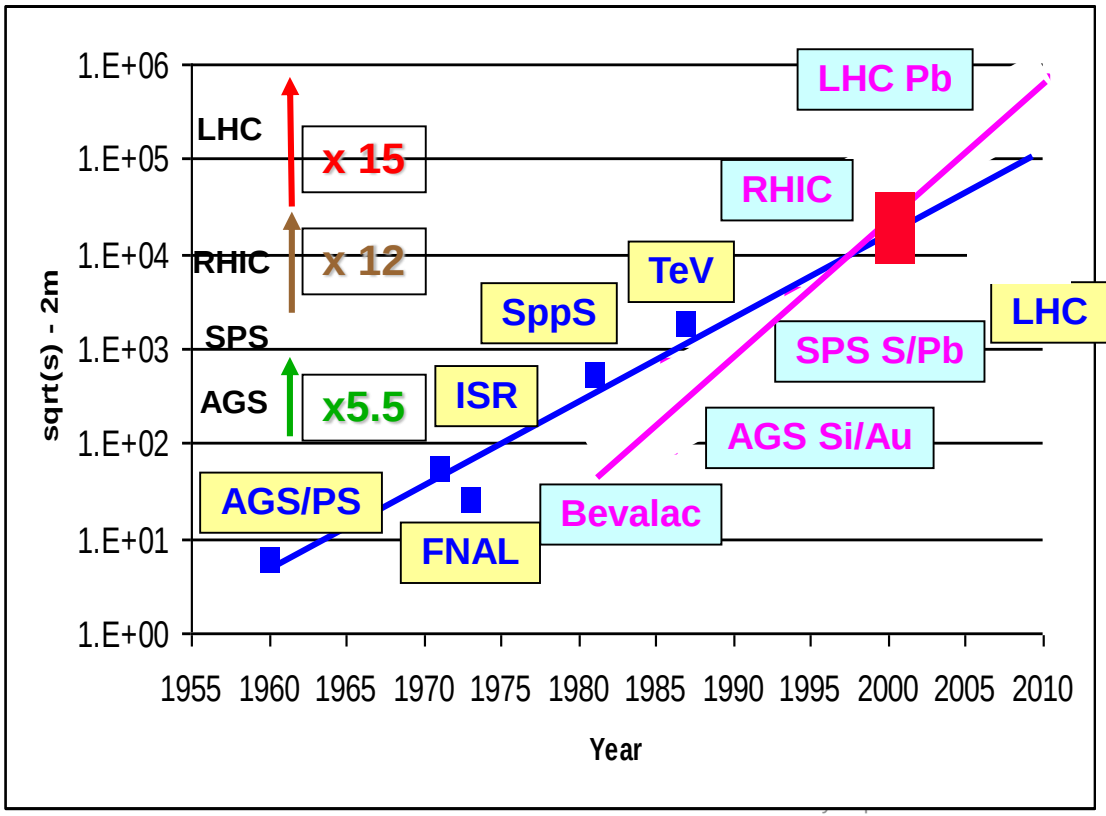
**'the stuff at high T where ordinary hadrons are no longer the relevant d.o.f'**

# Accelerators

- **Particle Physics: energy doubling time ~ 4 years**
- **Heavy Ion Physics: doubling time ~ 2 years**
  - ⇨ energy increase by factor $10^4$ in ~ 30 years
  - ⇨ starting 70'- to early 80's at **Bevalac**/Berkely & **Synchrophasotron**/Dubna
    - ✪ field started by a few dozen physicists from a handful of countries
    - ✪ > 2500 physicists active worldwide today

Field went from the periphery into a **central activity** of contemporary **Nuclear Physics**

Total center-of-mass energy versus time




Livingston plot

# First Generation SPS Exp ts

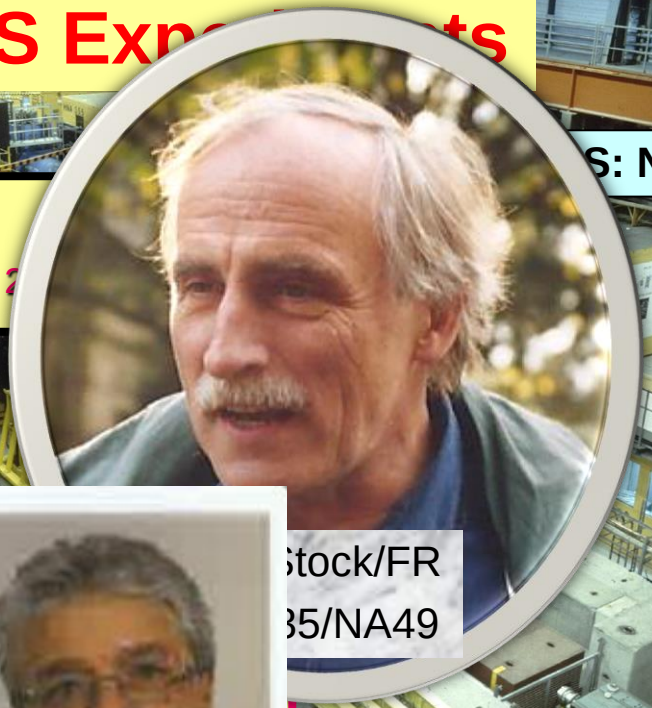
SPS:

S: NA35

1986 - 1992

light ions ($^{16}O$, $^{32}S$, ?

HJ Specht/HD
NA34-2/NA45



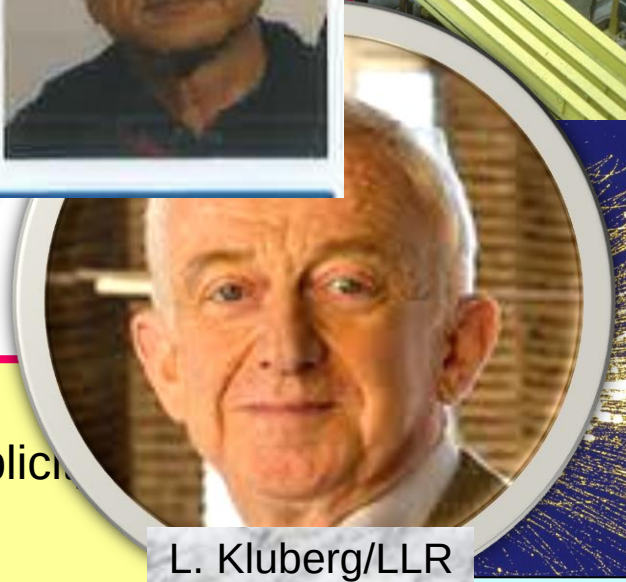
Stock/FR
35/NA49

<1990


2016


WA85/WA98

H. Gutbrod/GSI
WA80/WA93



L. Kluberg/LLR
NA38/NA50

**ory Program:**

**measure** these high multiplici

**we analyze** them ?

**Is it interesting ?**

Plastic Ball -> WA80

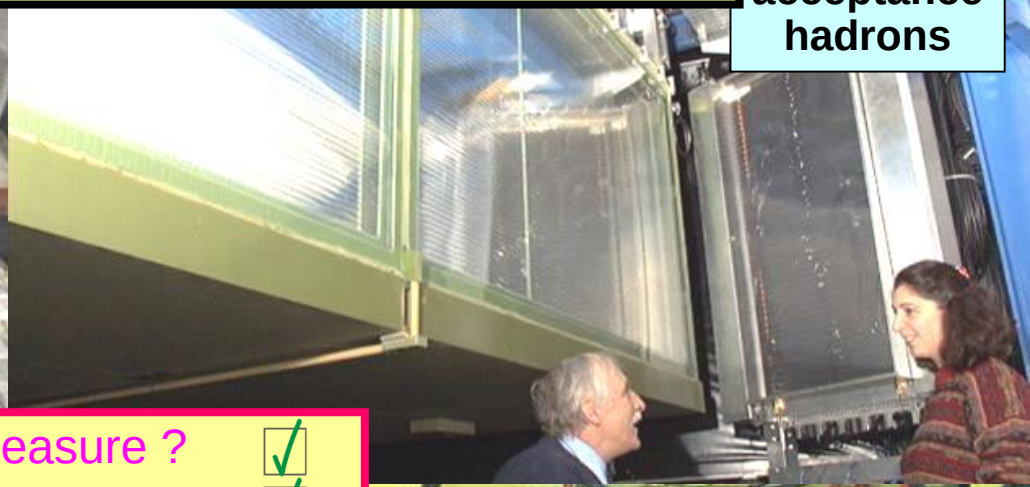
chamber -> NA35

NA35 64 TeV $^{32}S+Au$

# 2nd Generation SPS Experiments208
## $^{208}$Pb beams 1994 – 2002 (…NA60, NA61)

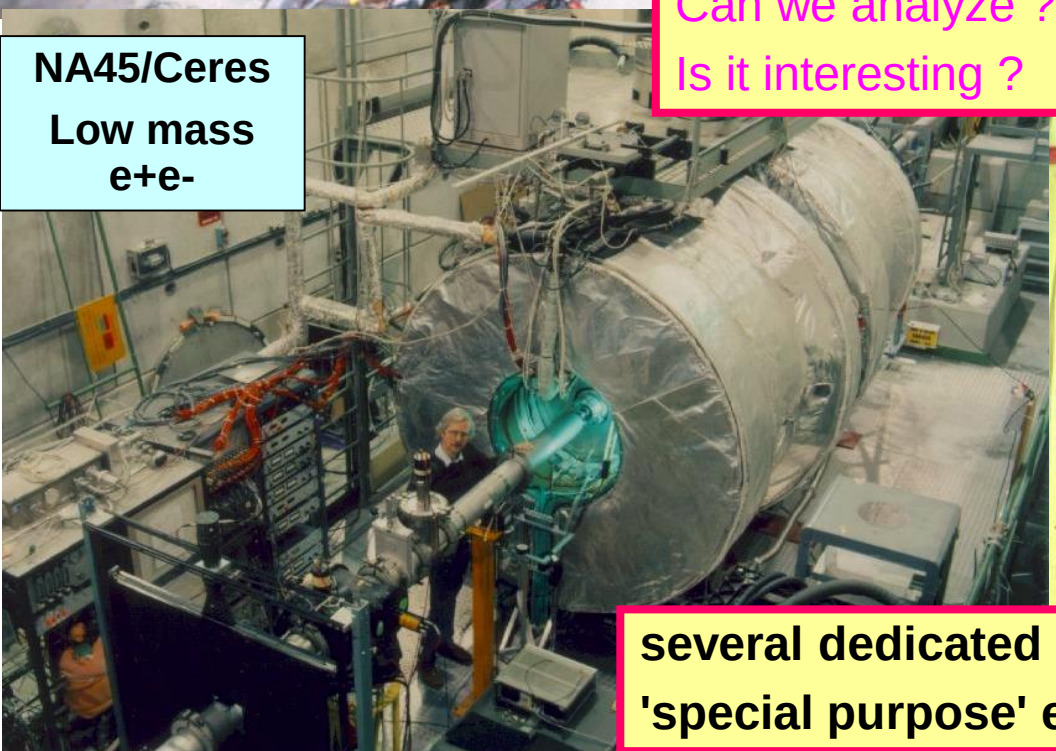
**NA44**
**Small angle hadrons**

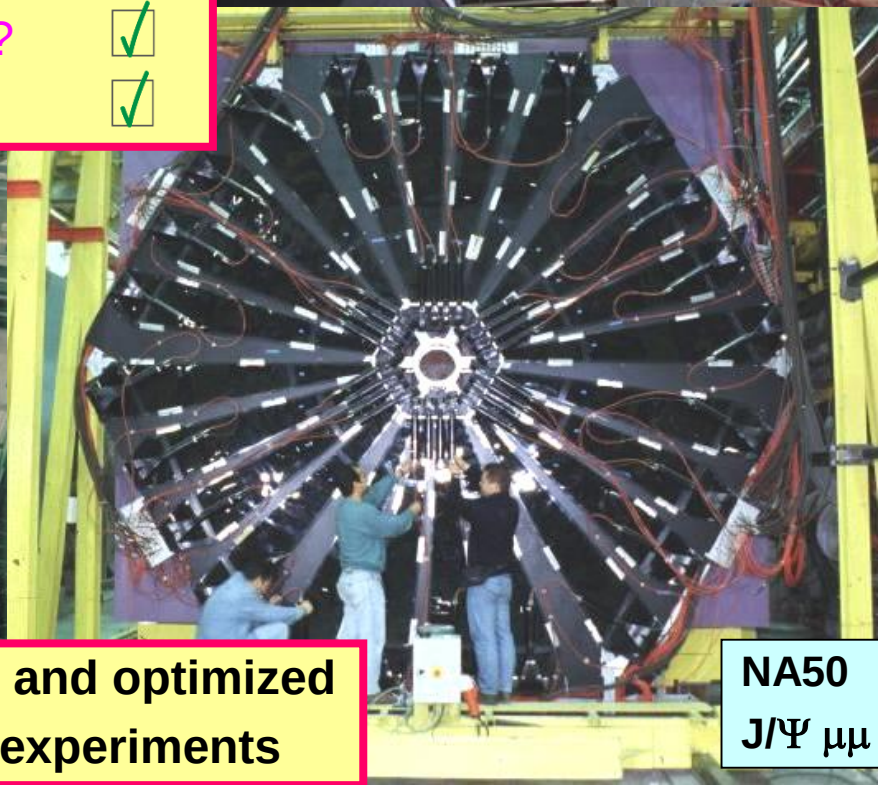
**NA49**
**Large acceptance hadrons**



Can we measure ? ☑
Can we analyze ? ☑
Is it interesting ? ☑

**NA45/Ceres**
**Low mass e+e-**





**NA50**
**J/Ψ μμ**

**several dedicated and optimized 'special purpose' experiments**

# 3rd Generation: RHIC Experiments > 2000

STAR

PHENIX

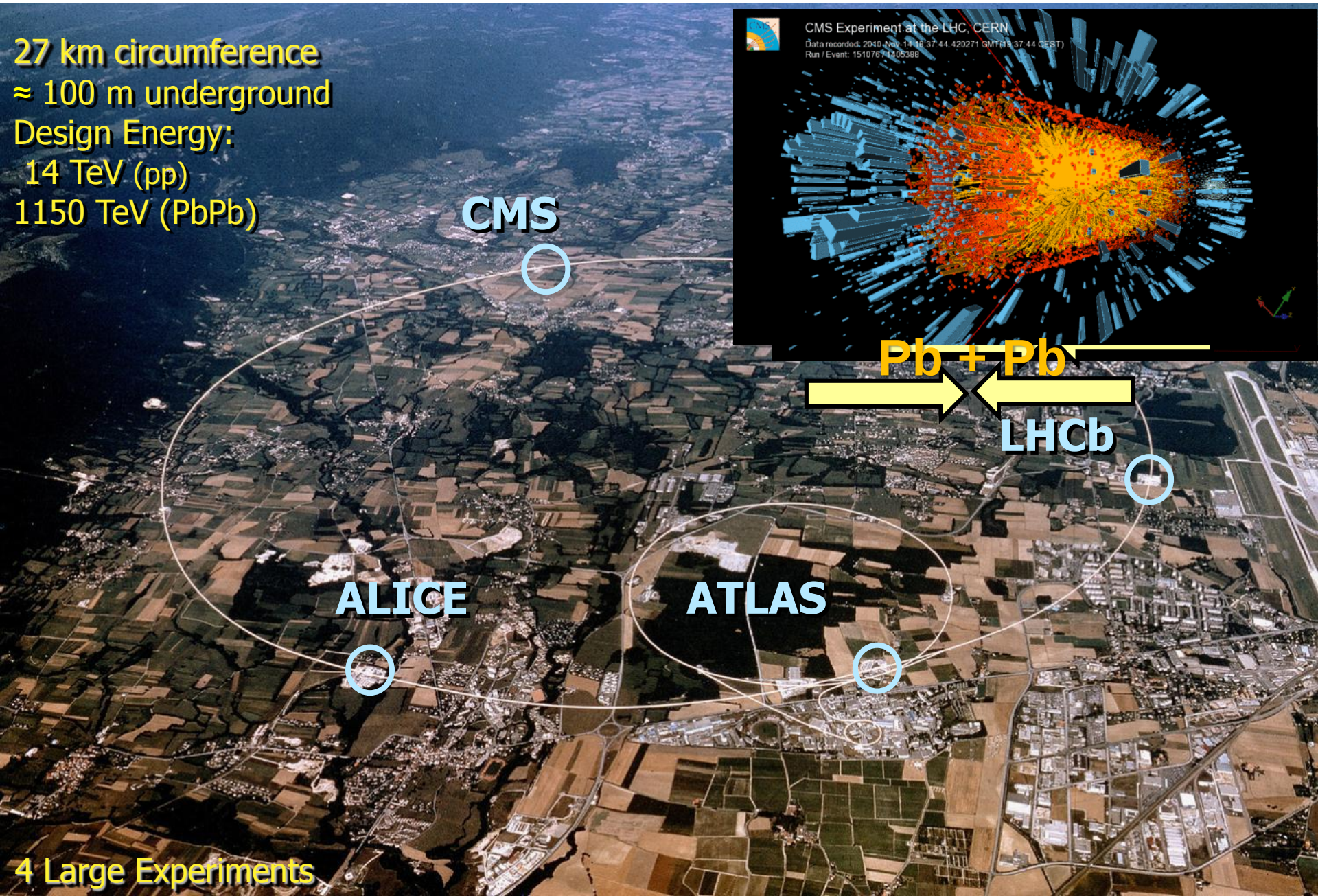
first 'general purpose' collider detectors

BRAHMS

PHOBOS

# Collider of 'Large Colliders'

Large Hadron Collider



# Large Hadron Collider LHC

27 km circumference
≈ 100 m underground
Design Energy 14 TeV (pp)

Lake Geneva

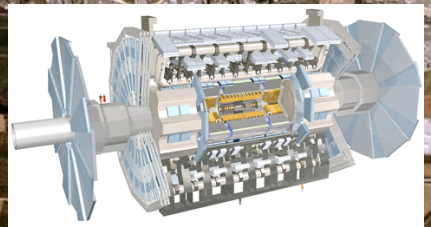
CMS

4 Experiments
**3 Physics Programs**

LHCb

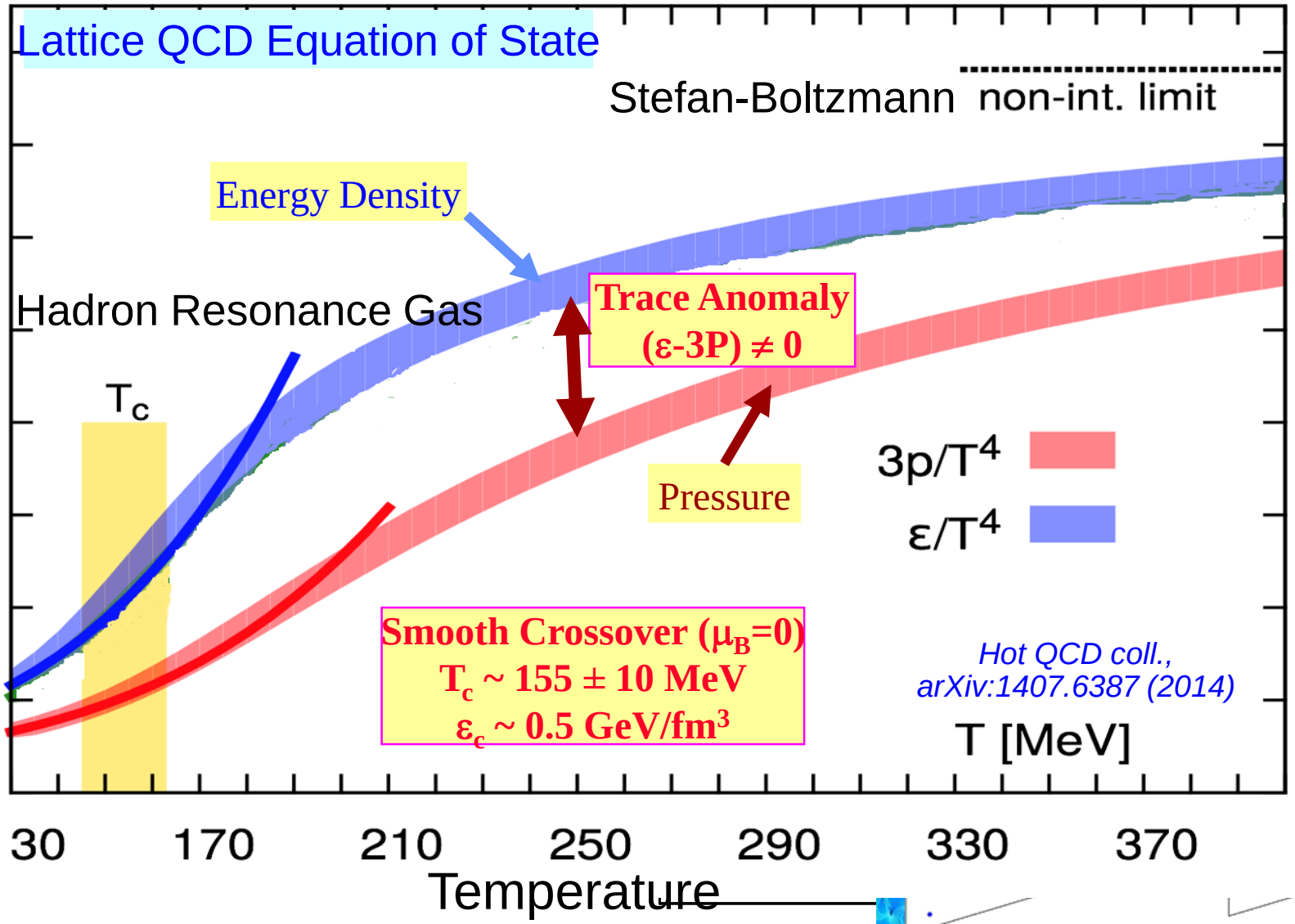
ALICE

ATLAS



# Theory Tools

- **Lattice QCD**
  - ⇨ ideal for thermodynamics(static), EoS, $T_c$




**SPS: 1986 - 2002(4);** NA61: >2009

O, S, Pb

$\sqrt{s_{NN}}$ = 6.5 - 20 GeV/A, 3.9 - 17 GeV/A

Users: ~ 600

**LHC: 2010 - 2029(?)**

Pb, $\sqrt{s_{NN}}$ = 2.76, 5.5 TeV/A

Users: ~ 1500

**AGS: 1986 - 1996(8)**

Si, Au

$\sqrt{s_{NN}}$ = 2.5 - 5.5 GeV/A

Users: ~ 400

**RHIC: 2000 – 2024(?)**

d, Cu, Au,

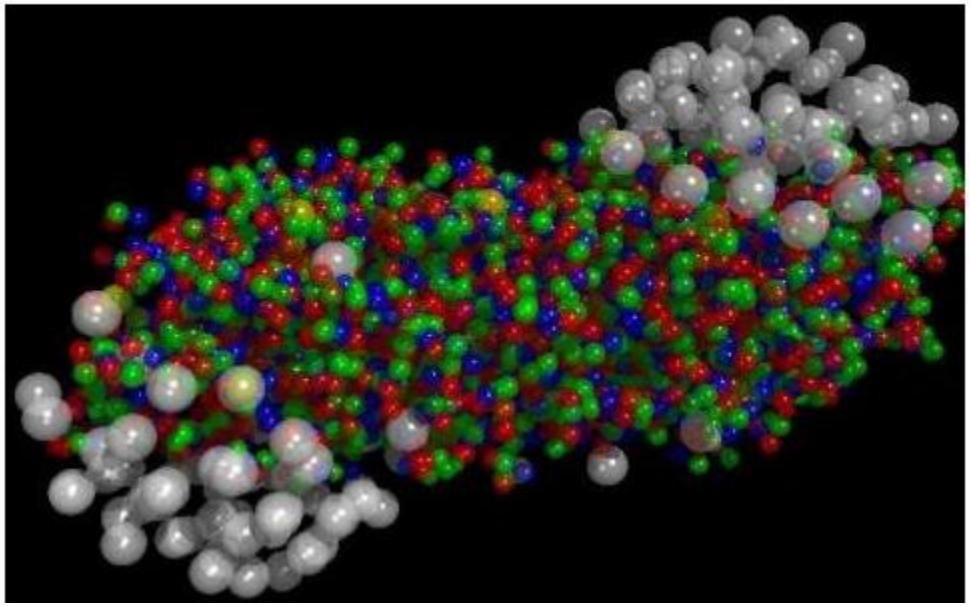
$\sqrt{s_{NN}}$ = 7.7-200 GeV/A

Users: ~ 1000

# New State of Matter created at CERN

10 Feb 2000

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern



Based on a (unpublished)

**'common assessment'** of

results from ~ half dozen experiments

collected & published over the course of the SPS Pb program (1994 - 2000)

http://arxiv.org/abs/nucl-th/0002042v1

**'.. a QGP-like state ..'**

The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma..

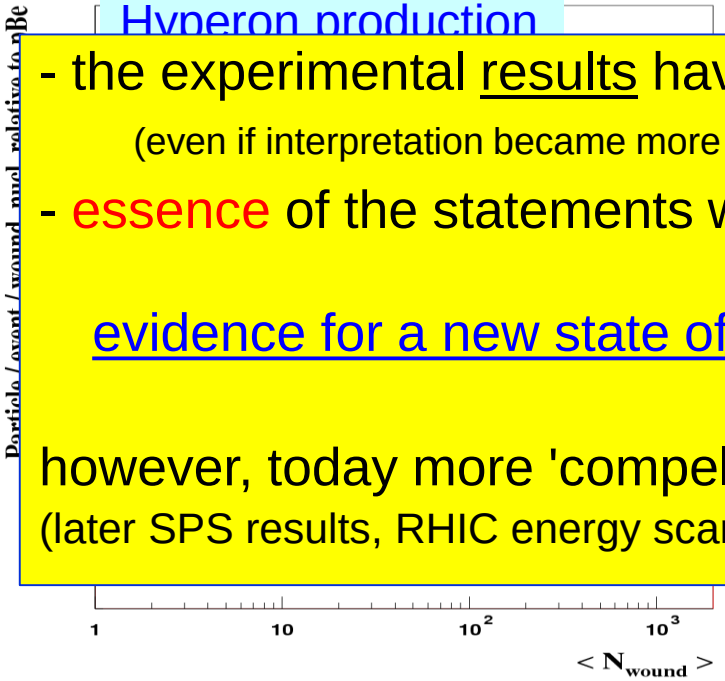
M. Jacob

U. Heinz

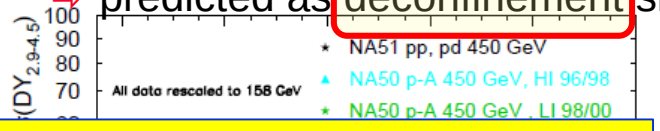
# Main Results from SPS

- strangeness enhancement
  - ⇨ in general: thermal particle production
  - ⇨ predicted for equilibrated matter/QGP

Hyperon production




- 'anomalous' J/Ψ suppression
  - ⇨ predicted as deconfinement signal



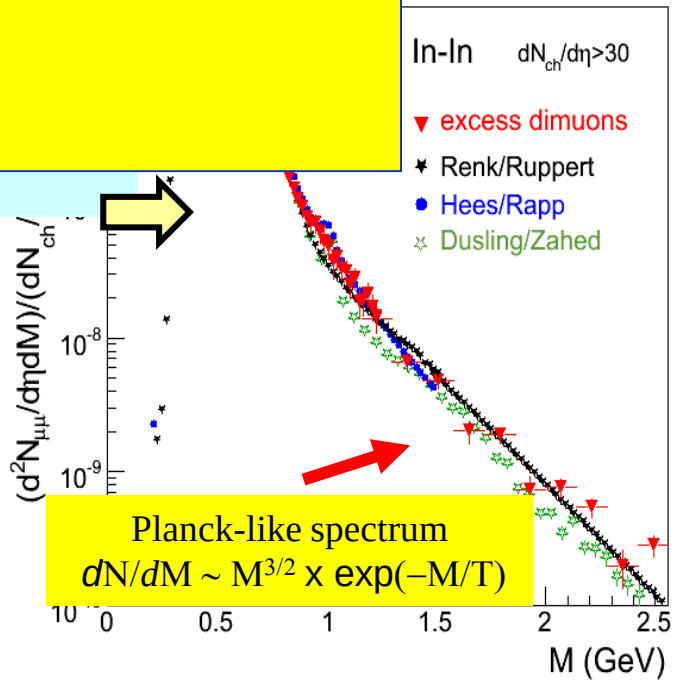

Drell-Yan

- the experimental results have stood the test of time
  (even if interpretation became more involved over time)
- essence of the statements was & is correct

evidence for a new state of matter at the SPS energy range

however, today more 'compelling' than in 2000 !
(later SPS results, RHIC energy scan, LHC)

(>> 2000 !)




Planck-like spectrum
$dN/dM \sim M^{3/2} \times \exp(-M/T)$

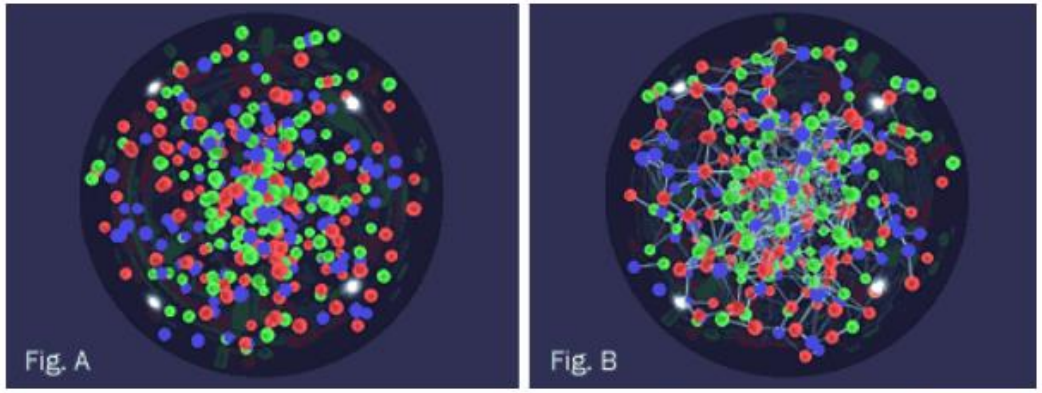
- Low mass lepton pair enhancement
  - ⇨ 'rho melting', sign of chiral symmetry restoration ?
  - ⇨ continuum -> thermal radiation **<T> = 230 ± 10 MeV**

http://www.bnl.gov/newsroom/news.php?a=1303

# RHIC Scientists Serve Up "Perfect" Liquid

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

April 18, 2005




These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective

+ ENLARGE

Based on a (published)
**comprehensive (re)analysis** of
the first years of RHIC (2000 - 2004)

Nucl.Phys.A757:1-284,2005

.. created a new state of hot, dense matter out of the quarks and gluons .., but it is a state quite different and even more remarkable than had been predicted.

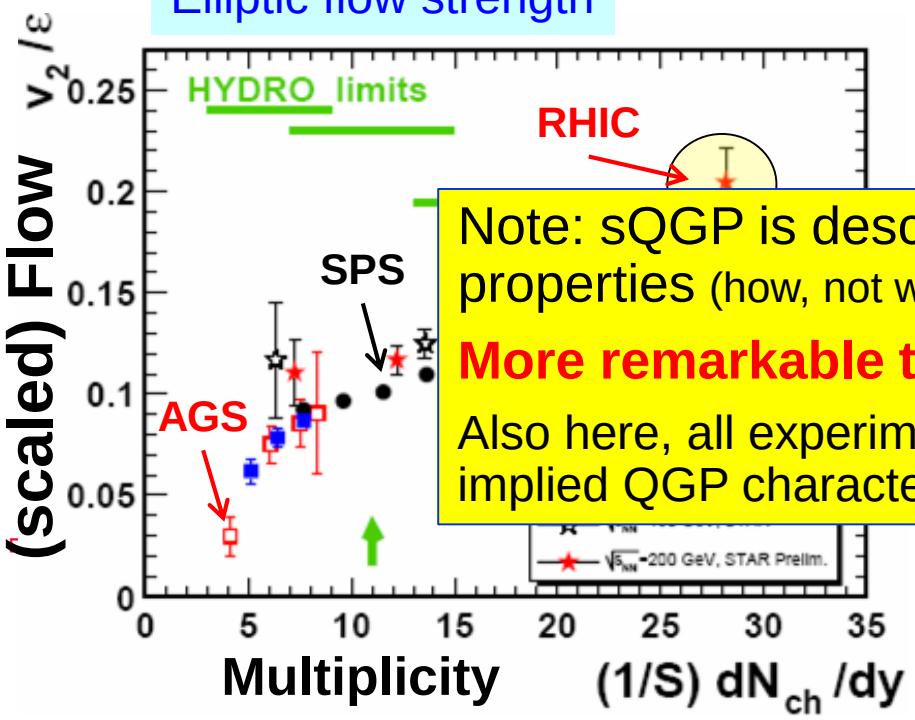
i' **..the QGP ..'**
**but**
**'.. a QGP ..': sQGP**

sQGP: strongly interacting QGP

# Main Results from RHIC

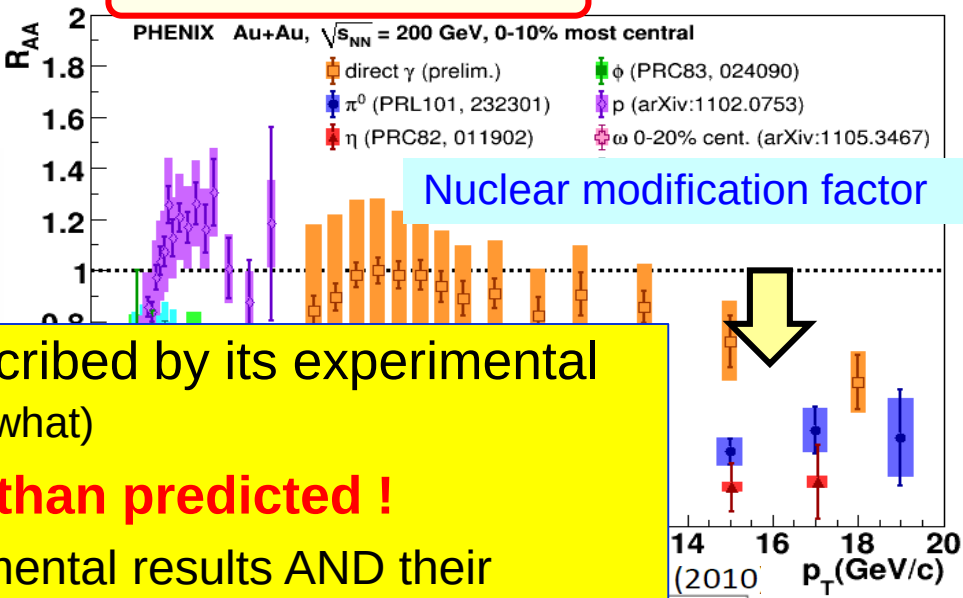
- strong elliptic flow
  - ⇨ ~ maximum possible i.e 'ideal liquid' ($\eta/s \approx 0$)
  - ⇨ mostly produced in the early phase (partonic?)

Elliptic flow strength




- high $p_T$ suppression 'jet-quenching'
  - ⇨ very strongly interacting (large energy loss)

Nuclear modification factor

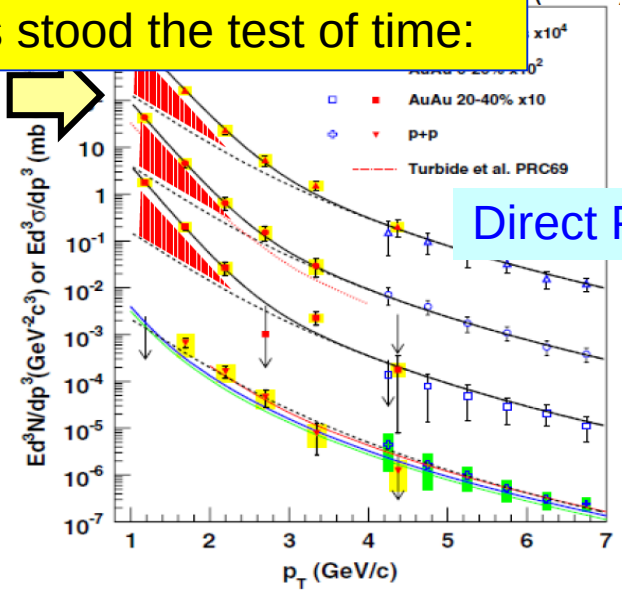



Note: sQGP is described by its experimental properties (how, not what)

**More remarkable than predicted !**

Also here, all experimental results AND their implied QGP characteristics stood the test of time:

Direct Photons

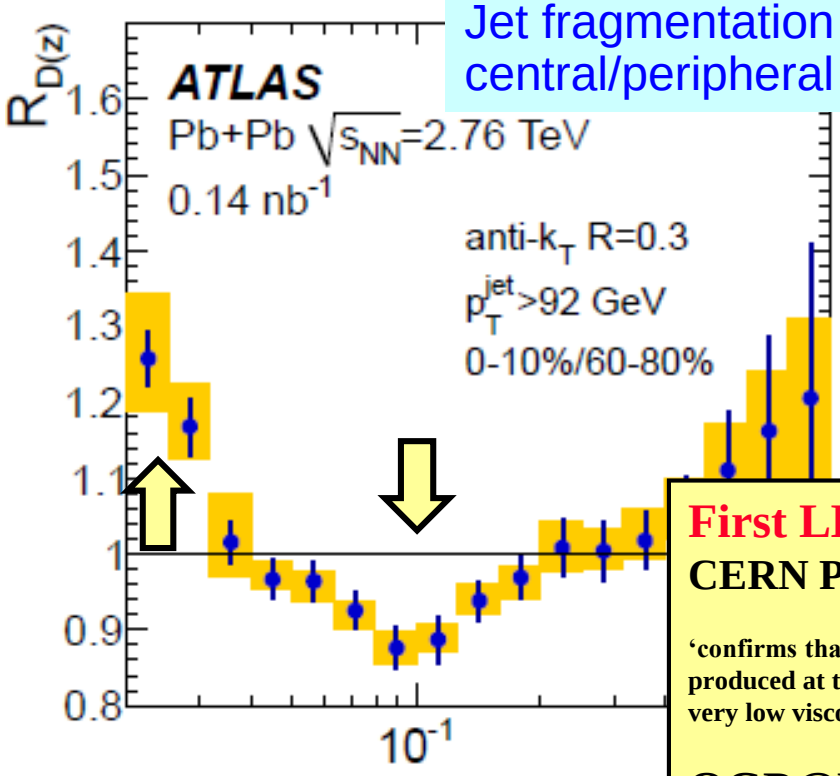



- direct 'thermal' photons => 'hot matter'
  - ⇨ data: inverse slope T ~ 220 ± 20 MeV
    model dependent $T_0$: 300 - 600 MeV

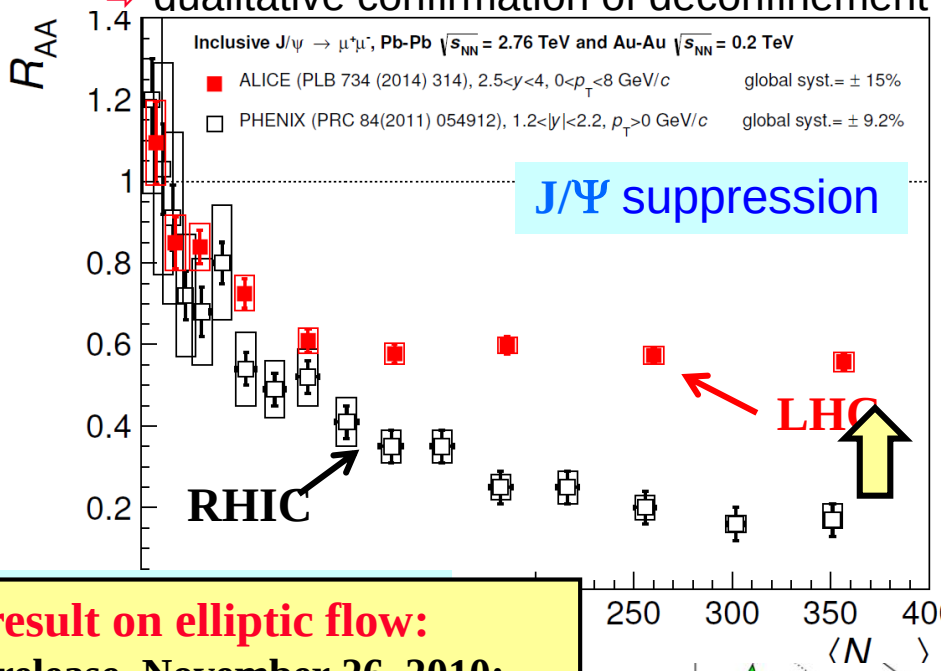
# Main Results from LHC

- in-medium jet fragmentation
  - ⇨ insight into dynamics of jet quenching
    - ✪ multiple soft gluon radiation at large angles (inverted angular and time ordering !!)

Jet fragmentation D(z) central/peripheral




- J/Ψ coalescence & seq. Υ melting
  - ⇨ SPS/RHIC J/Ψ puzzle solved
  - ⇨ qualitative confirmation of deconfinement

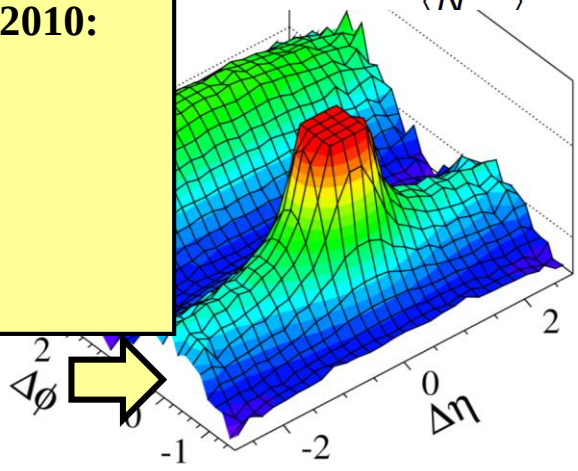



**First LHC result on elliptic flow:**

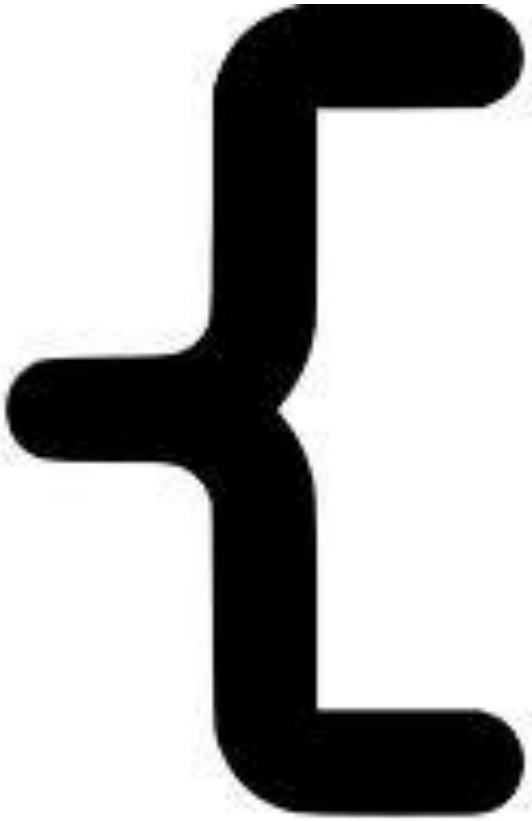
**CERN Press release, November 26, 2010:**

**'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'**

**QGP@LHC :**
**still a (almost) perfect liquid**

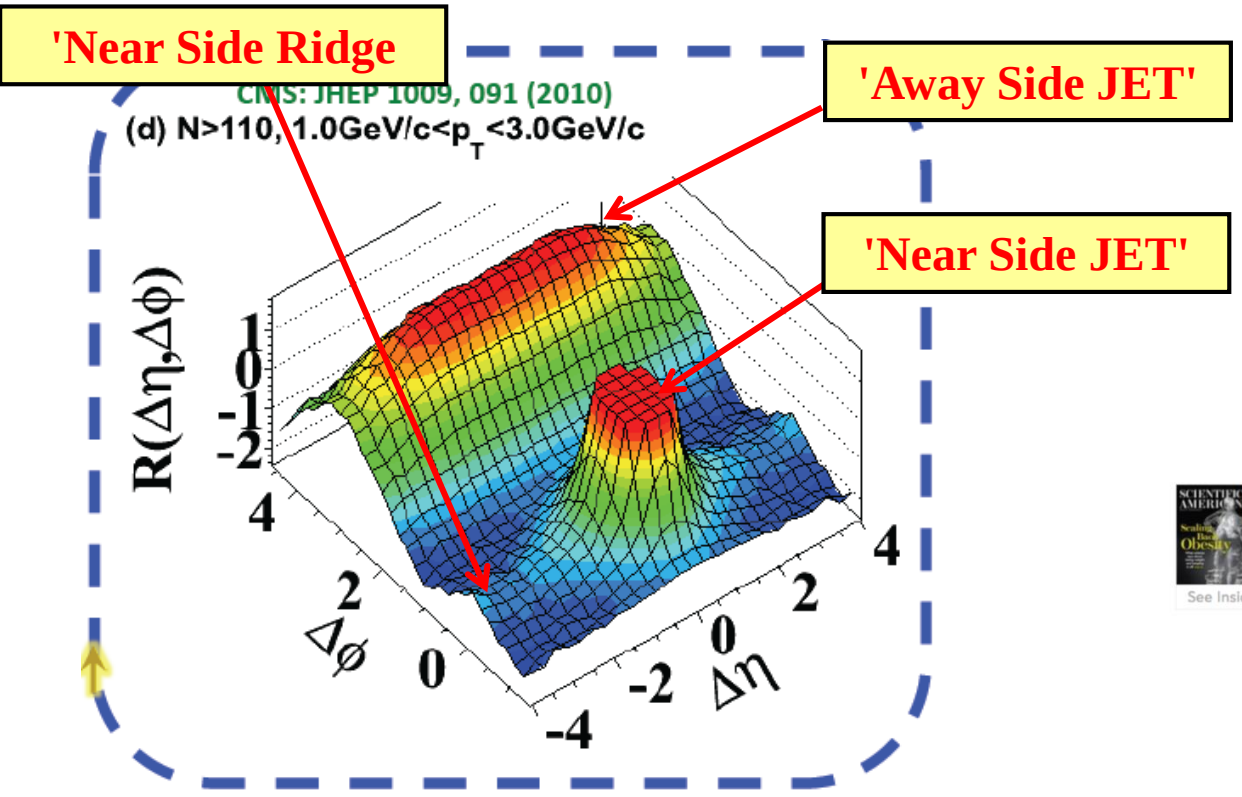



- the ever surprising ideal
  - ⇨ collectivity in small systems (pp, pA)



# Discovery

- The first LHC Discovery (pp, Sept 2010)
  - ⇨ long range rapidity 'ridge' in 2-particle correlations
    - ✪ visible in the highest multiplicity pp collisions
    - ✪ arguably still the most unexpected LHC discovery






**Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider**

Scientific American, February (2011)

Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

The 'Opera' defense !

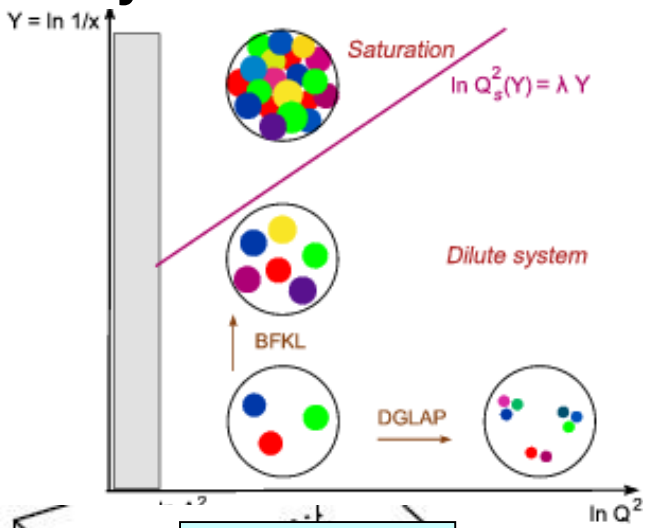
If we are here today it is because we didn't succeed to kill it.

We have therefore submitted the paper to expose our findings to the scrutiny of the scientific community at large.

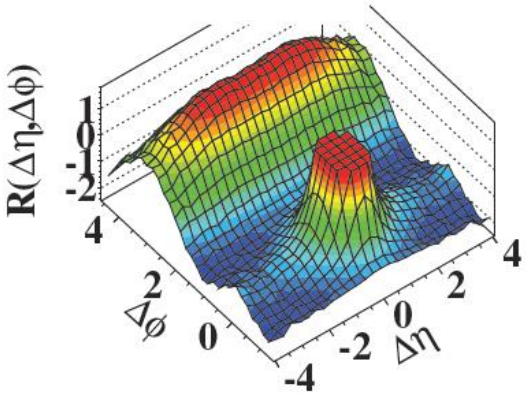
# Origin of the pp 'Ridge'

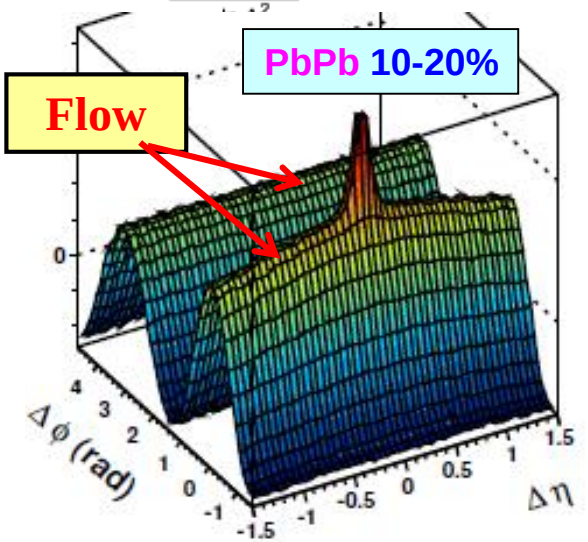
- Spawned a large number of different explanations
  - ⇨ mostly rather ad hoc, very speculative, or outright weird

- Color Glass Condensate CGC: **'first principles' theory**
  - ⇨ classsical FT in high density limit (small x, small $Q^2$)
  - ⇨ 'new state of cold & dense parton matter'
  - ⇨ some success describing aspects of ep, pp, eA:
    geometric scaling, low-x, particle production, ..
    - ✪ however, no 'smoking gun' so far…

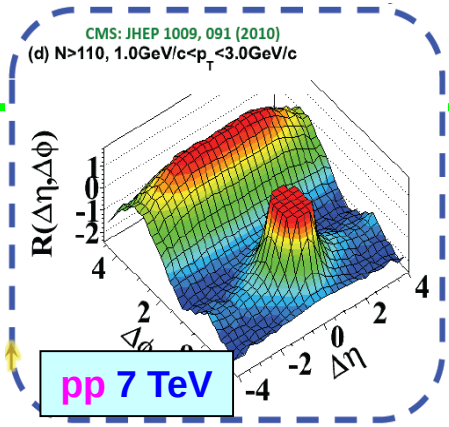



- Collective flow (Hydro) ?
  - ⇨ vaguely similar correlations in nucleus-nucleus



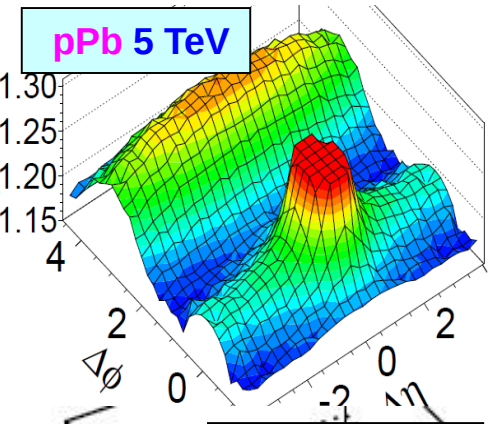



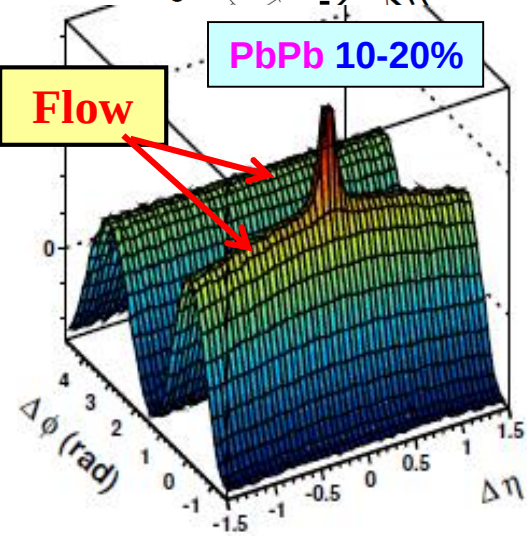
# it looks like a rose, it smells like a rose

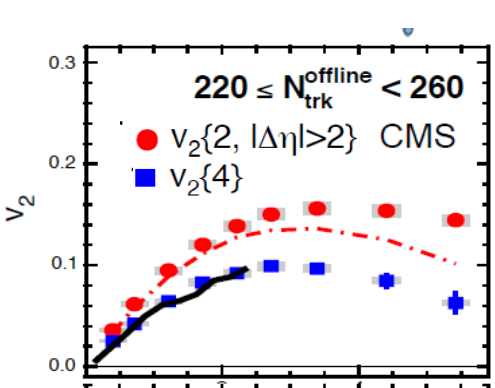


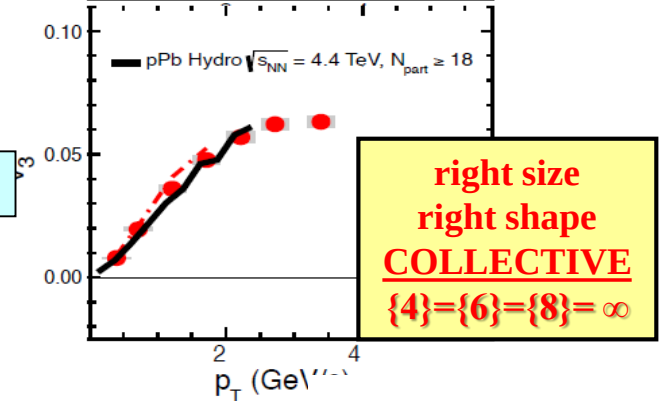

.. With ALL the bells & whistles

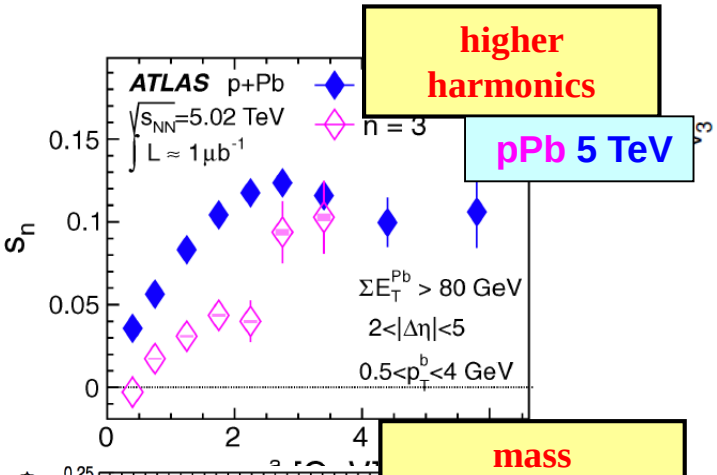
measured to be fully collective

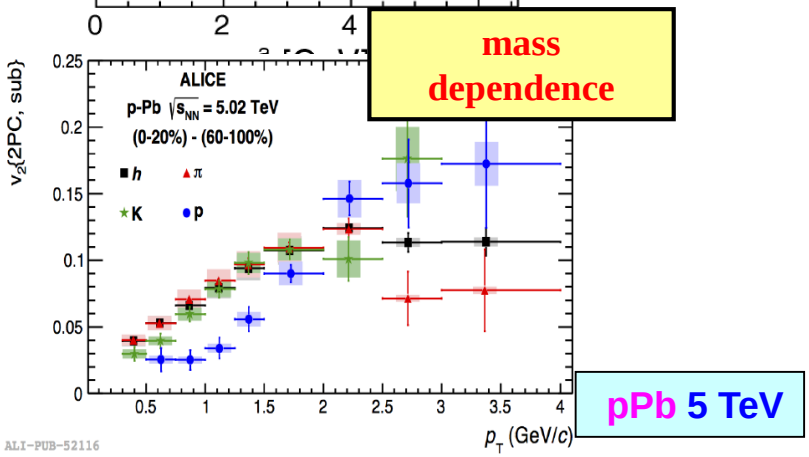


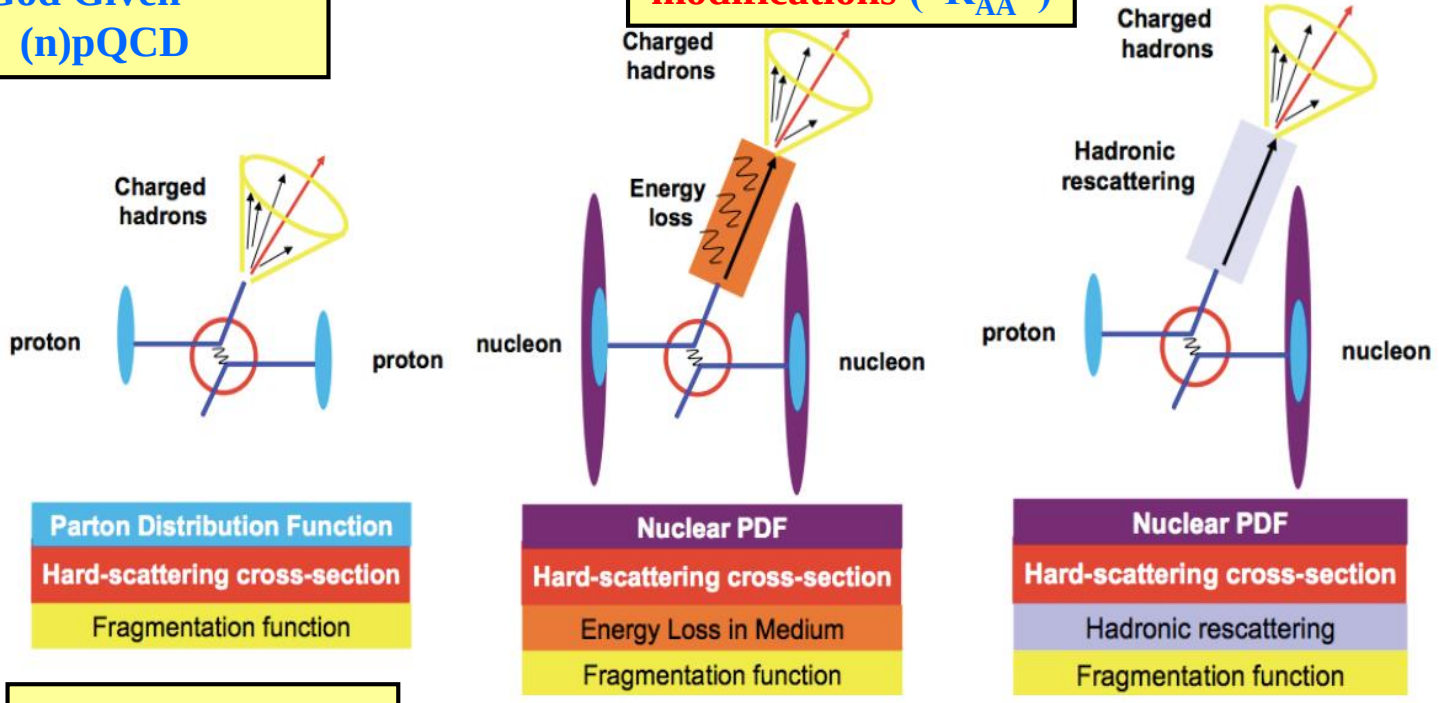

# URHI Paradigm (Modus Operandi)

- large & dense systems = QGP physics
- small & dilute systems = comparison data

**pp:**
**God Given = (n)pQCD**

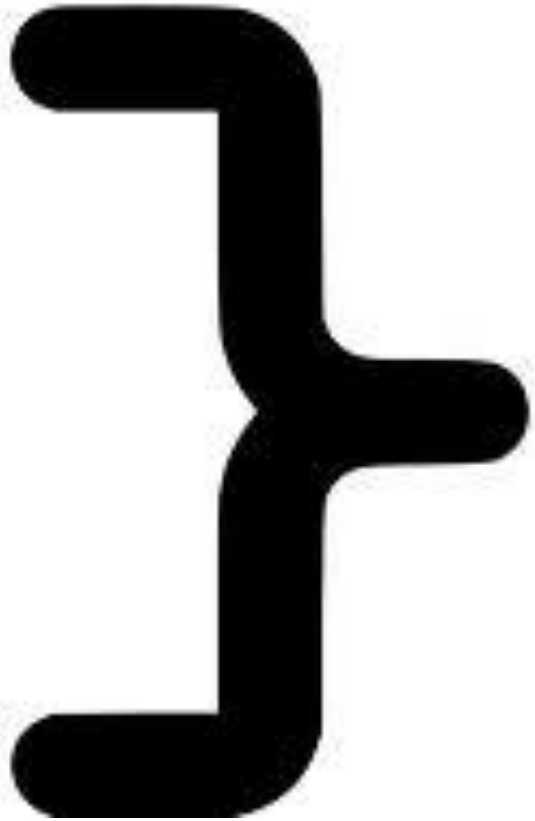
**AA:**
**'Hot Matter' modifications ("$R_{AA}$")**

**pA:**
**CNM modifications**




**MB pp/$e^+e^-$**
**The modifications start here !**

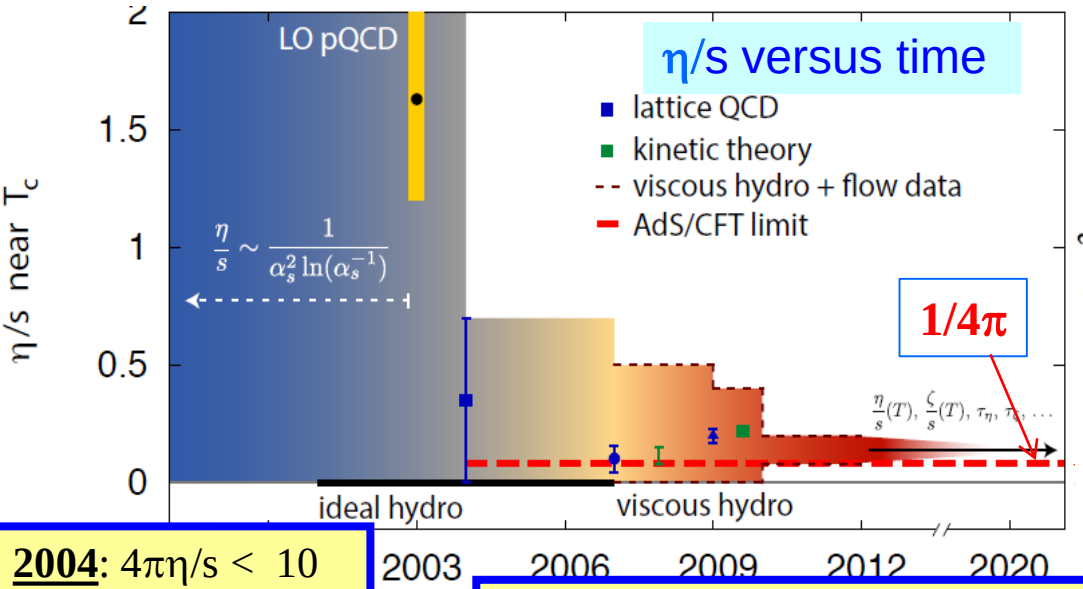
**'central' pp/pA:**
**Hot Matter ?**

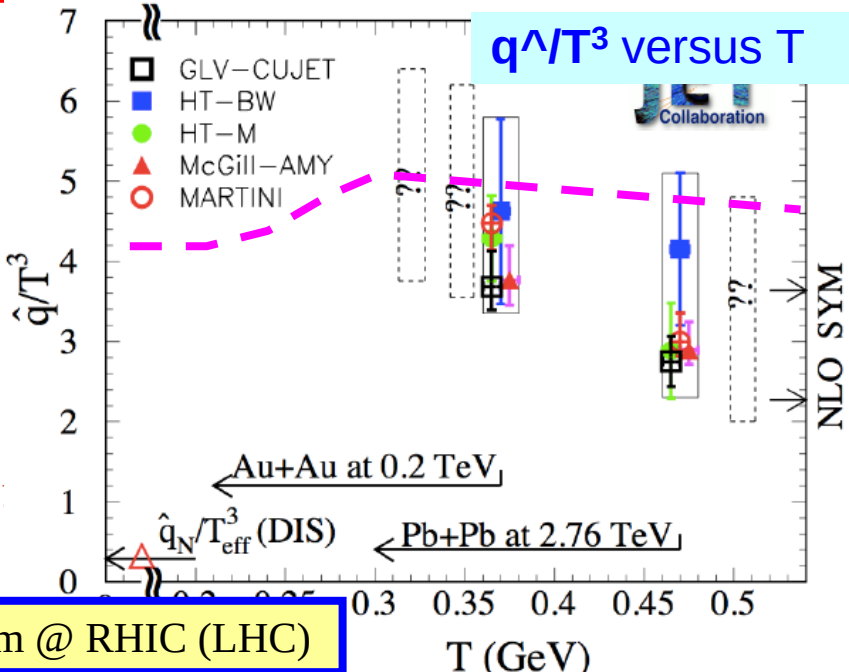


# sQGP: The stuff at high T..

We set out to find a weakly interacting gas of quarks & gluons

- **'Very strongly interacting, almost perfect liquid' :** sQGP
  - ⇨ **'Macroscopic' piece of matter with amazing properties**
    - ✪ reaches thermo/hydro equilibrium incredibly fast & in small volumes (< 1 fm)
    - ✪ tiny viscosity reveals density fluctuations in the initial state, event-by-event !
    - ✪ dynamically evolves, expands and cools
    - ✪ transforms into a hadron resonance gas which stays at or close to equilibrium
  - ⇨ **we can experimentally measure its properties and follow its evolution !**
    - ✪ transport coefficients: **η/s** (viscosity/Entropy), **q^** (radiation), **D ≈ 4/2πT** (HQ diffusion),



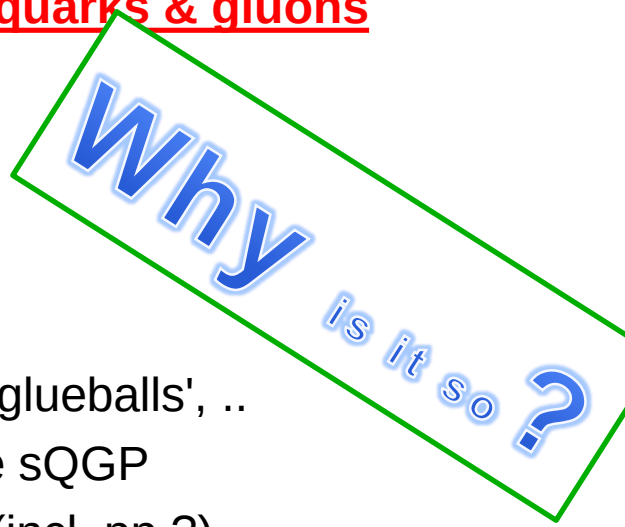




**2004**: 4πη/s < 10
**2014**: 4πη/s ≈ 1 - 2

**q^** ≈ 1.2 ± 0.3 (1.9 ± 0.7) GeV²/fm @ RHIC (LHC)

# Answers … and new Questions

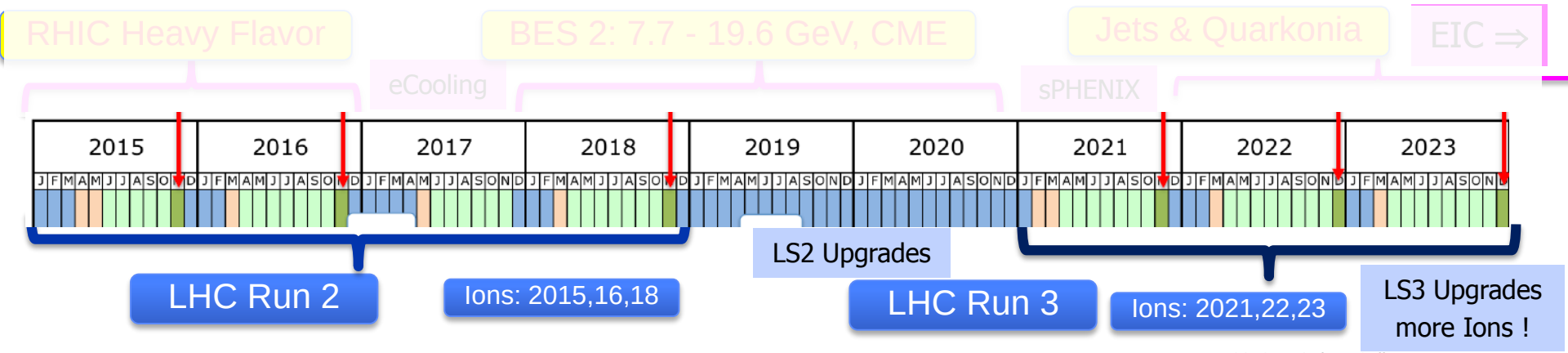

- What we know:
  - ⇨ increasingly precise measurements of **macroscopic properti**
    - ✪ η/S, ξ, q^, e^, $D_{(iffusion)}$, EoS, $c_s$, …
  - ⇨ good evidence for **deconfinement** (J/Ψ, Υ)
    - ✪ J/Ψ coalescence = **color conductivity**, Υ suppression = **resonance melting**
  - ⇨ some evidence for **chiral symmetry restoration,** but indirect
    - ✪ strangeness ???, low mass $l^+l^-$ (connection between rho melting and chiral sym ?)
  - ⇨ the relevant dof (particles, excitations, ..) are **NOT free quarks & gluons**
    - ✪ the interaction is much too strong !




- What we don't know
  - ⇨ **what ARE the relevant dof** in the QGP ?
    - ✪ pseudoparticles, collective excitations (plasmons, ..), 'glueballs', ..
  - ⇨ **What is the dynamics ?** 'looking under the hood' of the sQGP
    - ✪ how can it happen so fast, and in very small systems (incl. pp ?)
  - ⇨ **Where is the onset ?**
    - ✪ how does collectivity & statistical behavior emerge with size & energy density ?

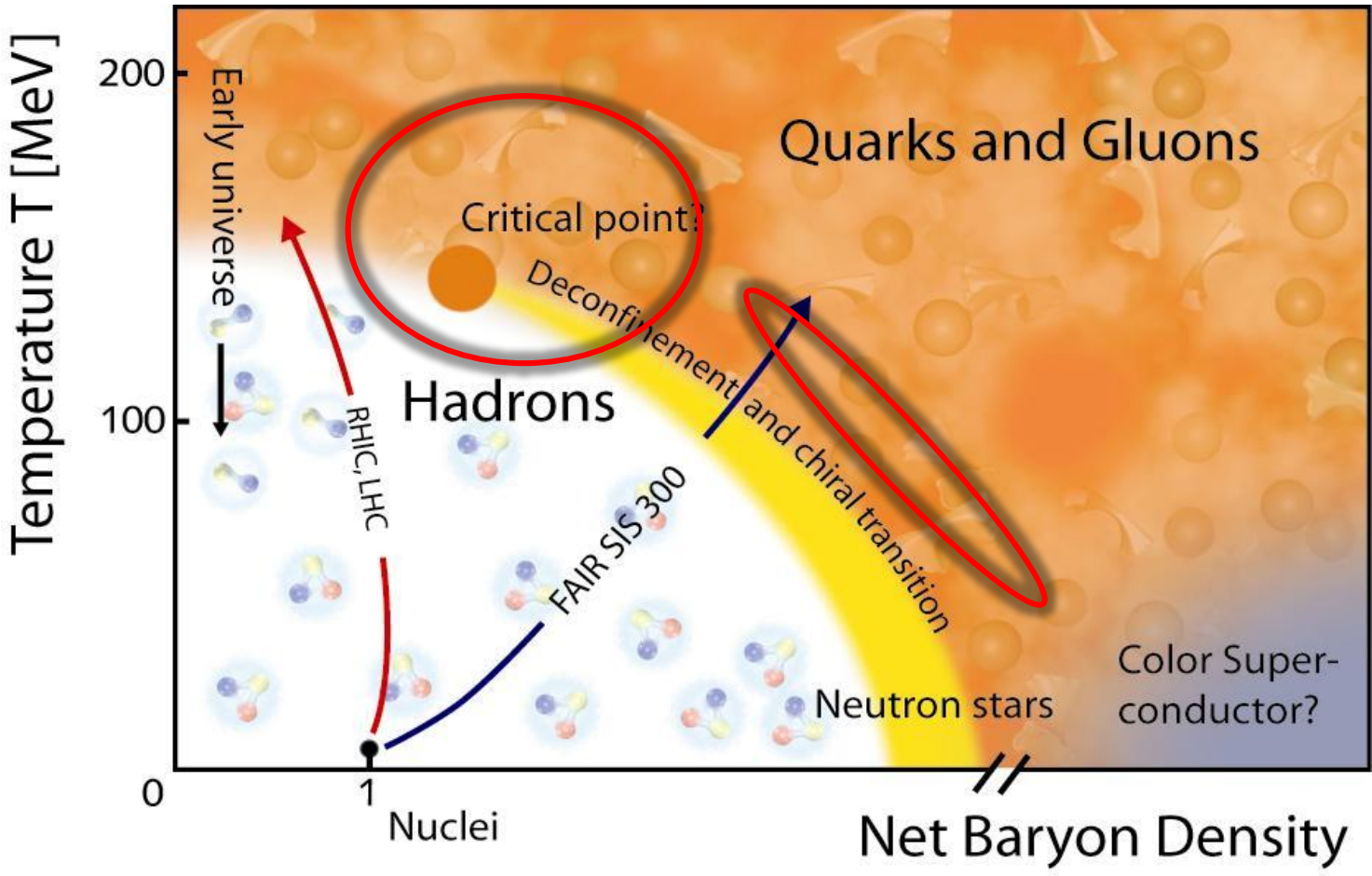
# Future directions I

- High Energy Frontier: 2015 – 2029(?) — How ?
  - ⇨ **increased precision** — Heavy Quarks, Quarkonia, Jets, γ, W/Z, …
    - ✪ transport coefficients, screening length, EoS, T dependence RHIC/LHC, …
  - ⇨ unravel **dynamics & sQGP structure**: looking for non-equilibrium effects — Why ?
    - ✪ jet-quenching (parton-plasma scattering 'Rutherford experiment')
    - ✪ sQGP **onset in small systems** (pp, pA): finite size/lifetime effects
- Upgrades (completed & ongoing)
  - ⇨ **LHC**: **Energy**(x2)/**Luminosity**(x2-5) : Run2: $\mathcal{L} \approx$ 2x10$^{27}$,1nb$^{-1}$, R3: 5x10$^{27}$, R3+4: >10nb$^{-1}$
    - ✪ **LS2: Alice/Atlas/CMS**: faster DAQ, better Trigger, improved Si-vertex, …
  - ⇨ **RHIC**: **e-cooling** for BES 2 — $\mathcal{L}$ x 3-10, $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV/A
    - ✪ **Star**: improved TOF & tracking, **sPhenix**: new large acceptance detector

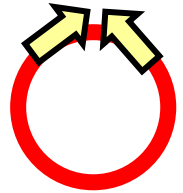


# Future Directions II

- High Baryon Density Frontier
  - ⇨ search for the **QCD Critical Point**
  - ⇨ **QGP onset** at low energy
  - ⇨ QGP properties at **high baryon density** (eg Chiral symmetry, in medium masses)

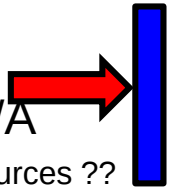


# Low Energy Facilities & Experiments



- RHIC BES-2: 2018-2020
  - ⇨ **e-cooling** for BES 2 $\mathcal{L}$ x 3-10, $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV/A

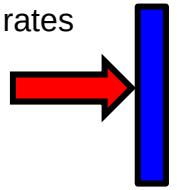
Fixed Target option (Target wire inside BP): Tested, but not analysed. $E_{lab}$ > 4 GeV/A



- SPS FT: **NA61**: 2009-2018 (> 2020 ?)
  - ⇨ systematic energy and volume scan (fragmented beams) $\sqrt{s_{NN}}$ = 5 - 17 GeV/A

**NA61:** Hadronic signals (fluctuations). **NA60'** (HF, $\mu^+\mu^-$ LMR): Resources ??

- GSI/FAIR: SIS-100 ≥ 2019 (SIS-300 tbc)
  - ⇨ **$E_{lab}$ = 10** (35) GeV/A ($\sqrt{s_{NN}}$ < 4.5 (8.4) GeV for Au/U), very high $\mathcal{L}$/event rates

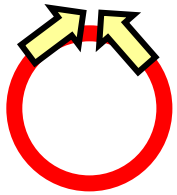


  - ⇨ **Hades** upgrade (Ag+Ag), **CBM** experiment
    - ✪ Hadrons, Heavy Flavors, J/Ψ, continuum lepton pairs

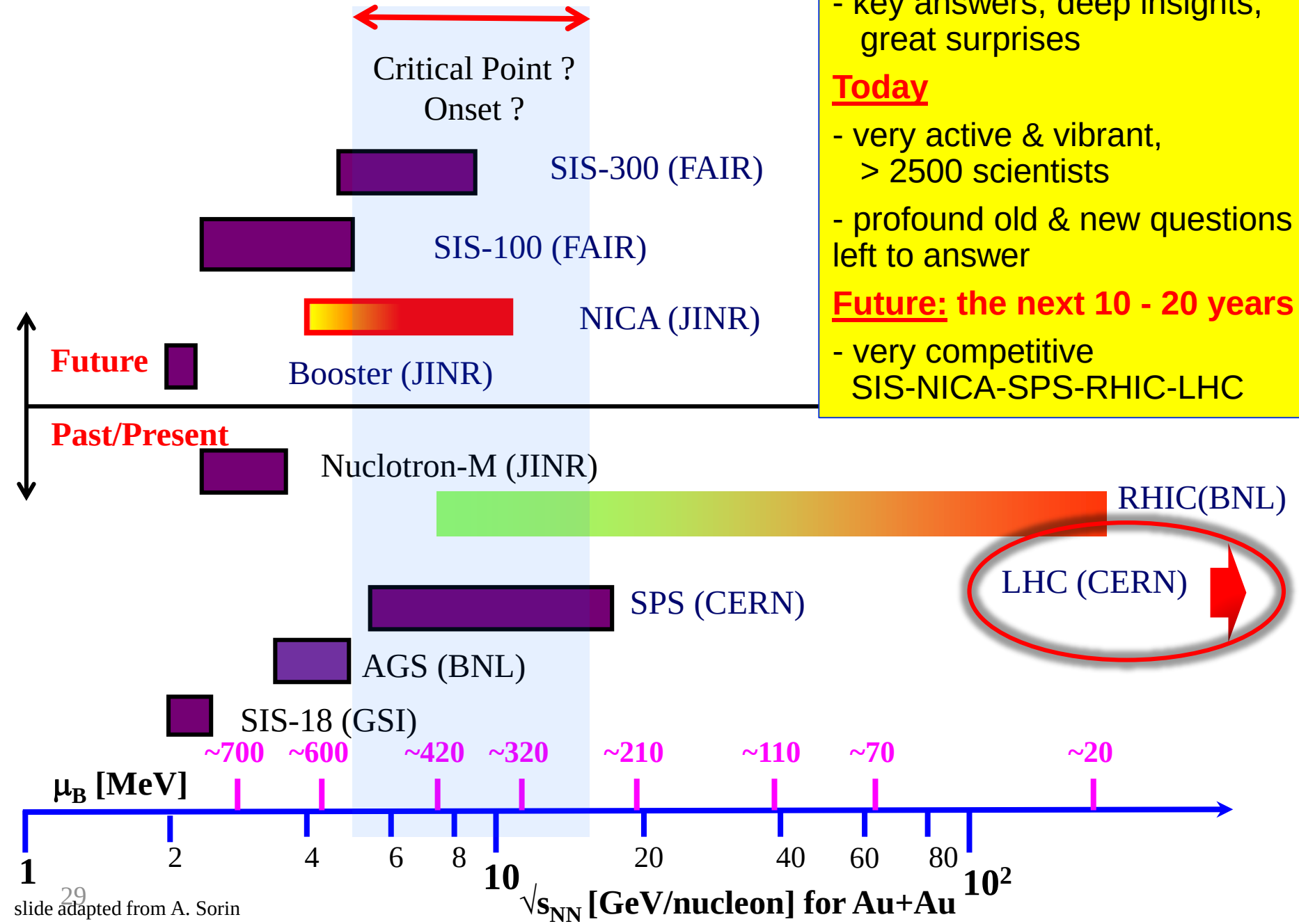
- JINR/NICA: ≥ 2019 **$\sqrt{s_{NN}}$ = 4 - 11 GeV** (Au beams),

fairly high $\mathcal{L}$ (Au ~$10^{27}$), flexible collider (A+B, pA), extracted beams (BM@N)

  - ⇨ **MPD** experiment
    - ✪ large acceptance collided detector; Hadrons + calorimeter



# Past-Present-Future




**URHI, the first 30 years**

- key answers, deep insights, great surprises

**Today**

- very active & vibrant, > 2500 scientists
- profound old & new questions left to answer

**Future: the next 10 - 20 years**

- very competitive SIS-NICA-SPS-RHIC-LHC



slide adapted from A. Sorin

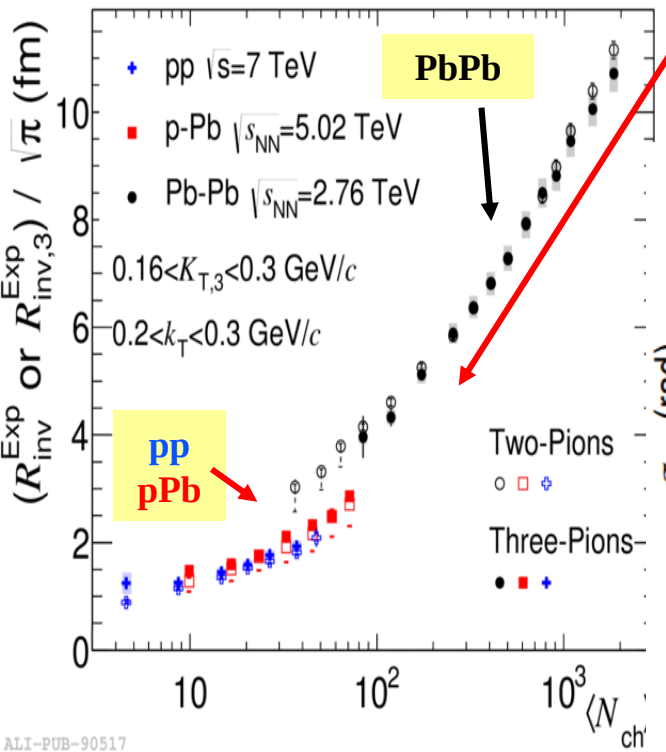
# Spares/Backup

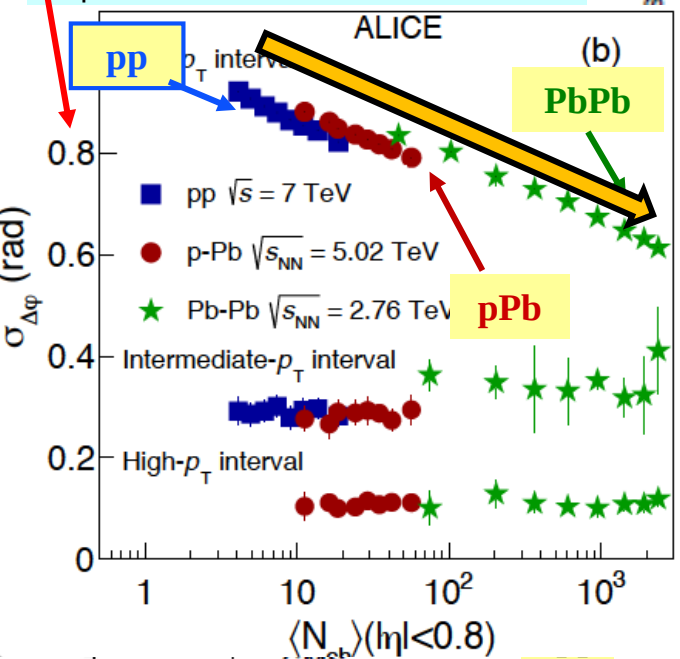
# Continuous & smooth down to dN/dy ~ 0 !

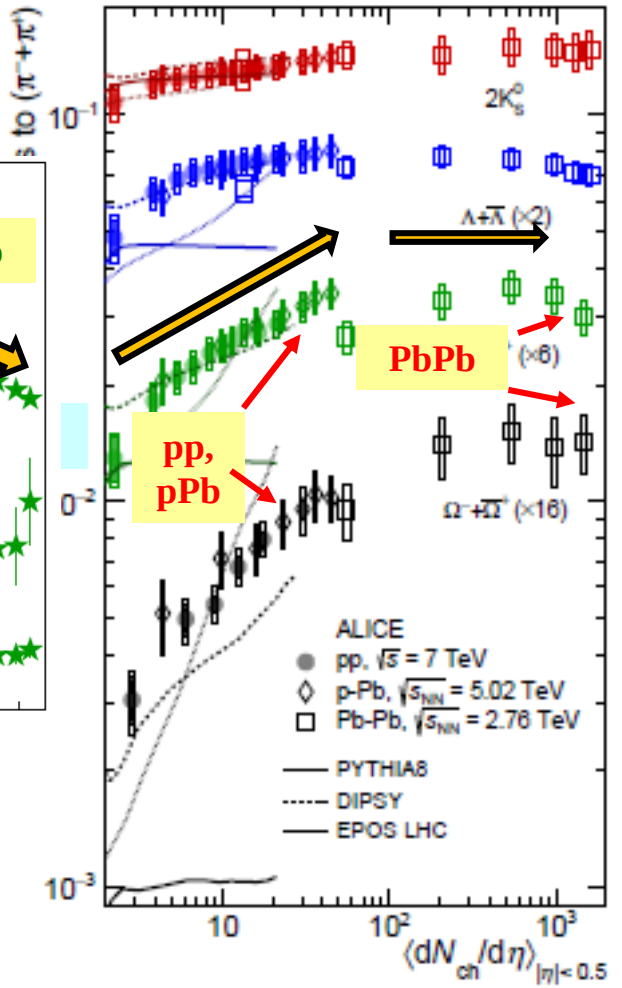
**HBT** $k_T$ dependence

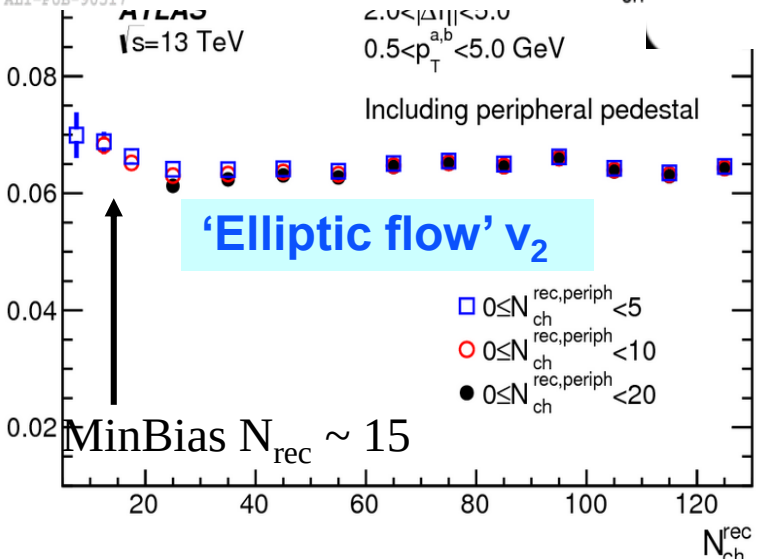
**Charge Balance Function**

space-time-momentum correlation!



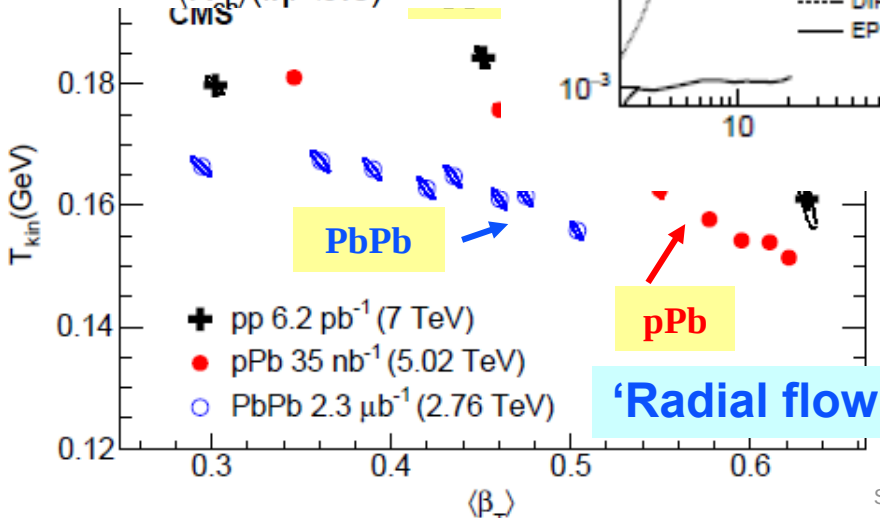




**'Elliptic flow' $v_2$**

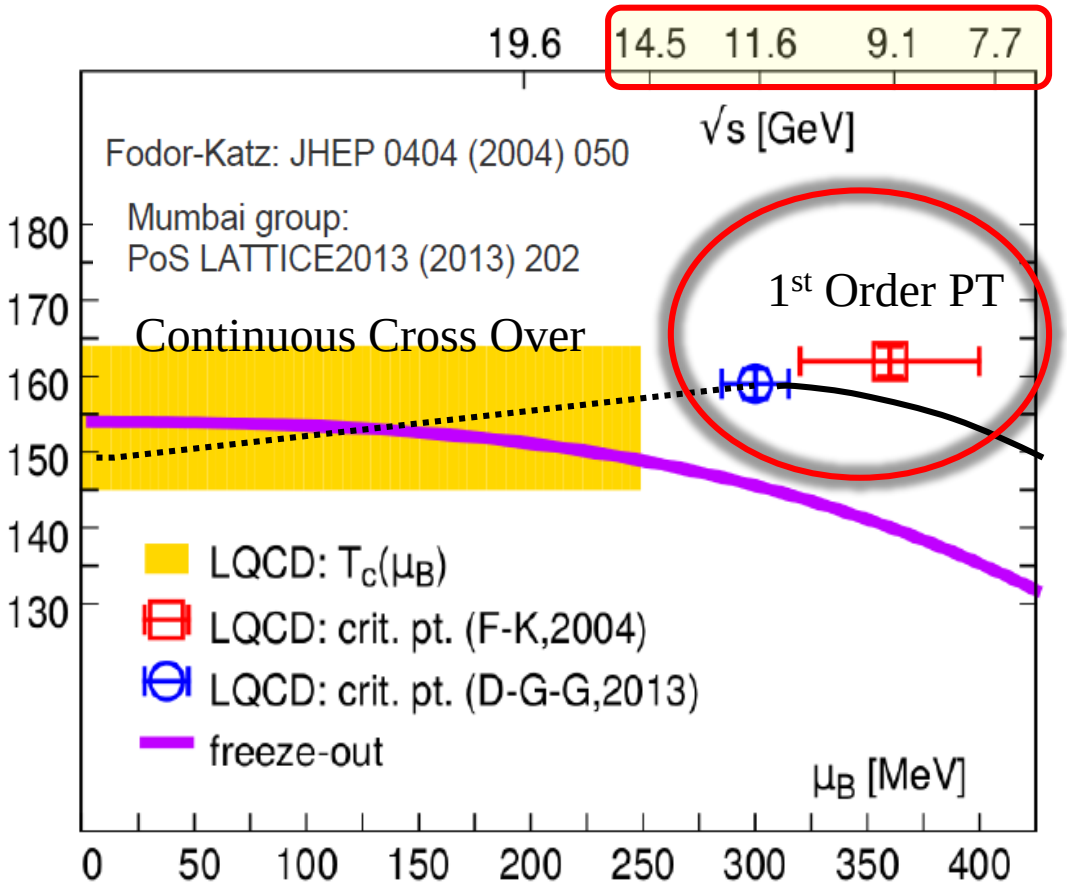
MinBias $N_{rec}$ ~ 15




**'Radial flow'**

# QCD Critical Endpoint

- An important landmark in the phase diagram of matter (1st order ⇔ cross over)
  - ⇨ LQCD hints, but no consensus **where** it is located
    - ✪ nor, in fact, **if** it does exist..
  - ⇨ will CP(T, $\mu_B$) be **reachable** with heavy ions ?
  - ⇨ will fluctuation **signals** survive hadronic FSI ?




Searching for the CP is very important:

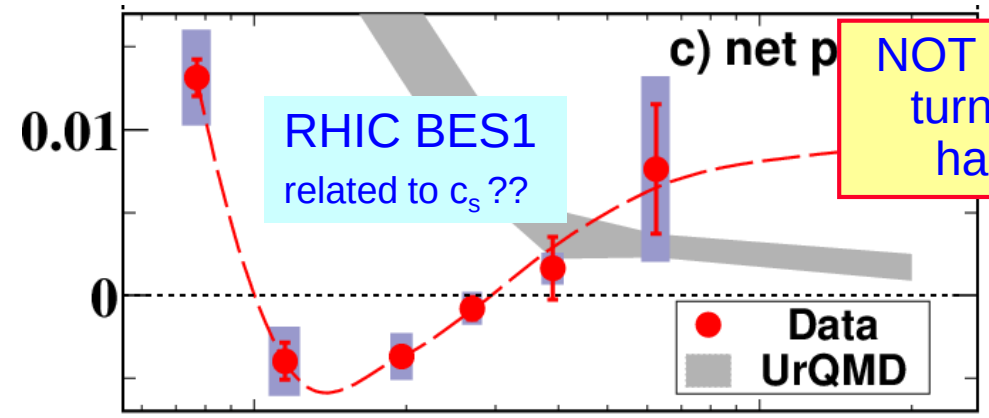
**High Risk,**

but potentially also

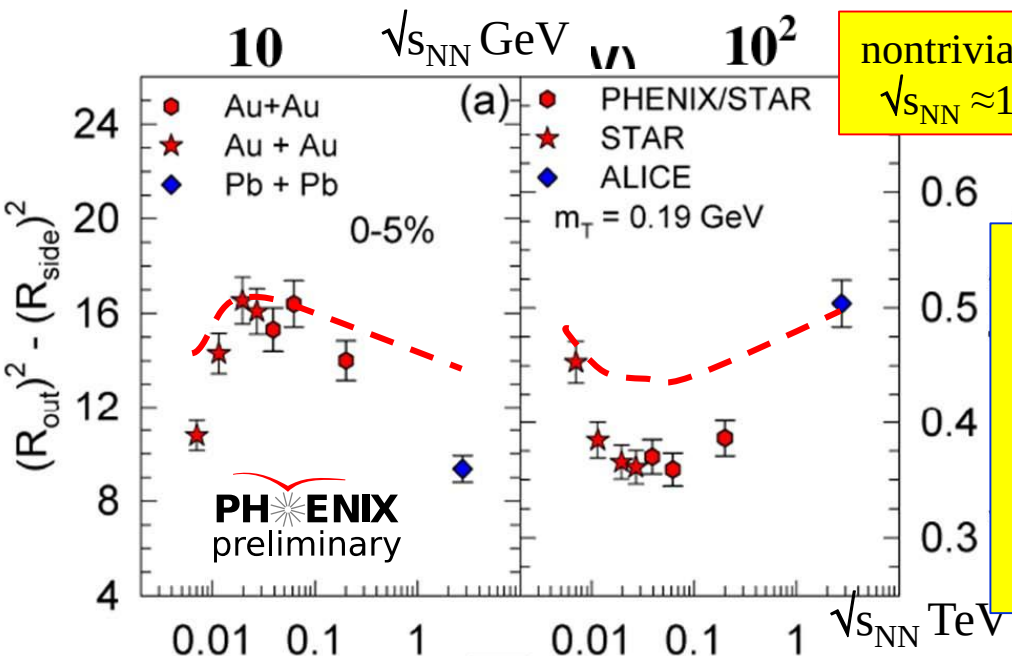
**High Return !**

# The Low Energy Frontier

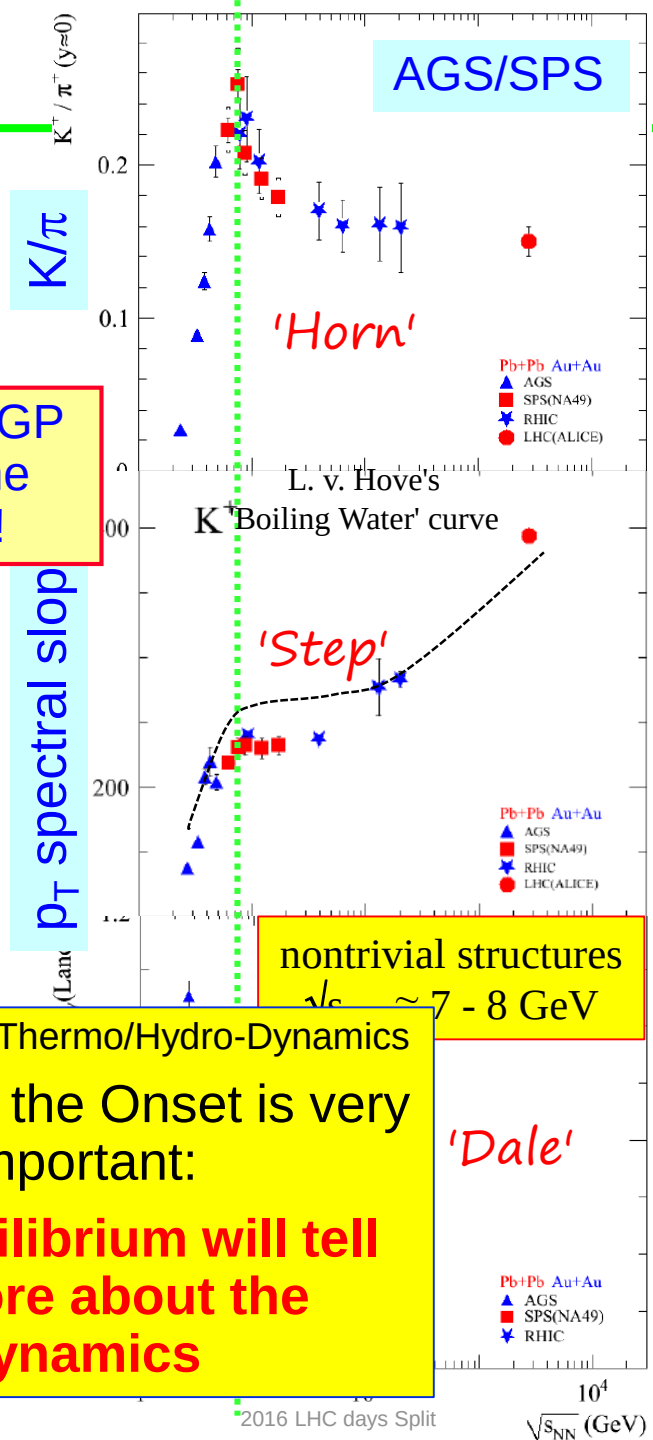
- The 'Onset' of the QGP f(T, $\rho_B$, r) = f($\sqrt{s}$, A+B, b)
  - ⇨ many hints, no coherent picture
    - ✪ onset may be very gradual, even signal specific




NOT finding the QGP turns out to be the harder problem!




nontrivial structures
$\sqrt{s_{NN}}$ ≈10-20 GeV




nontrivial structures
$\sqrt{s_{NN}}$ ≈ 7 - 8 GeV

Equilibrium => Thermo/Hydro-Dynamics

Measuring the Onset is very important:

**Non-equilibrium will tell us more about the dynamics**

# Questions from small & dilute systems

- Confront and 'explain' the size/density systematics
  - ⇨ **Factorize & separate** into different pp (CR, CGC) and AA (QGP, hydro) physics ?
    - ✪ naturally & economically, without epicycles..
    - ✪ where to put pA ?
  - ⇨ **Incorporate** into the current thermo & hydro sQGP 'ideal liquid' picture ?
    - ✪ **extend** the 'dense matter' framework **down** to zero density ?
    - ✪ **extend** the 'dilute transport' framework up to central AA ? (AMPT like ?)
    - ✪ 'probabilistic' hydro (#coll/particle << 1) ? Ok for thermo (< 1 Omega/evt even in 4π at SPS)
  - ⇨ Require **paradigm shift** ?
    - ✪ different but unified view(model/interpretation, ..) of soft multi-particle QCD

(personal) **Hypothesis: The physics underlying soft 'collectivity' signals is the same in AA, pA, and pp (e+e- ?):**
**It is a <u>generic</u> property of all strongly interacting many-body (≥2?) systems.**

# New Facilities & Experiments

- GSI/FAIR: SIS-100 ≥ 2019 (SIS-300 tbc)
  - ⇨ **$E_{lab}$ = 10** (35) GeV/A ($\sqrt{s_{NN}}$ < 4.5 (8.4) GeV for Au/U), very high $\mathcal{L}$/event rates
  - ⇨ **Hades** upgrade (Ag+Ag), **CBM** experiment
    - ✪ Hadrons, Heavy Flavors, J/$\Psi$, continuum lepton pairs

* **Hopefully the two will meet sooner rather than later..**

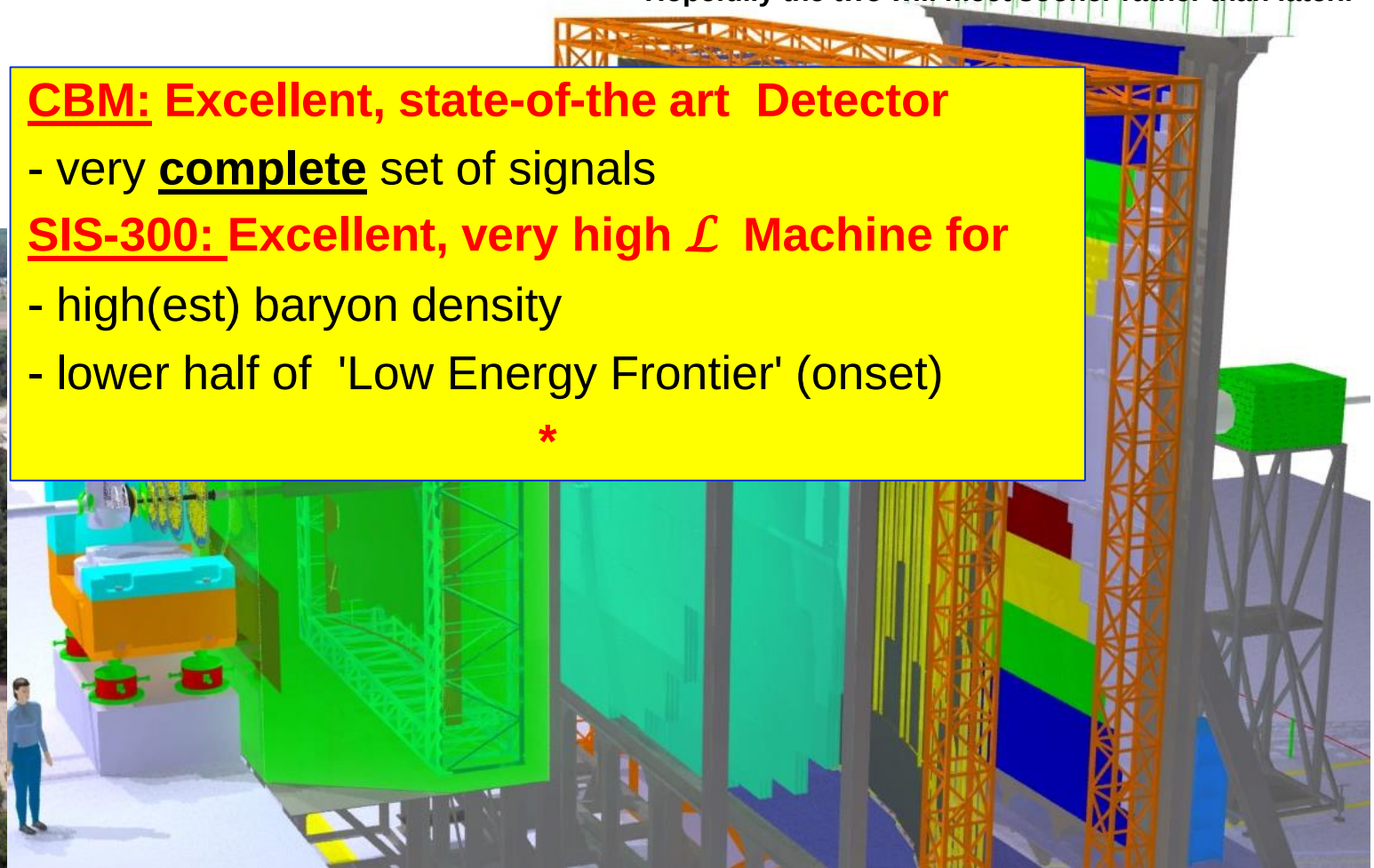
**CBM: Excellent, state-of-the art Detector**

- very **complete** set of signals

**SIS-300: Excellent, very high $\mathcal{L}$ Machine for**

- high(est) baryon density
- lower half of 'Low Energy Frontier' (onset)

*



# New Facilities & Experiments

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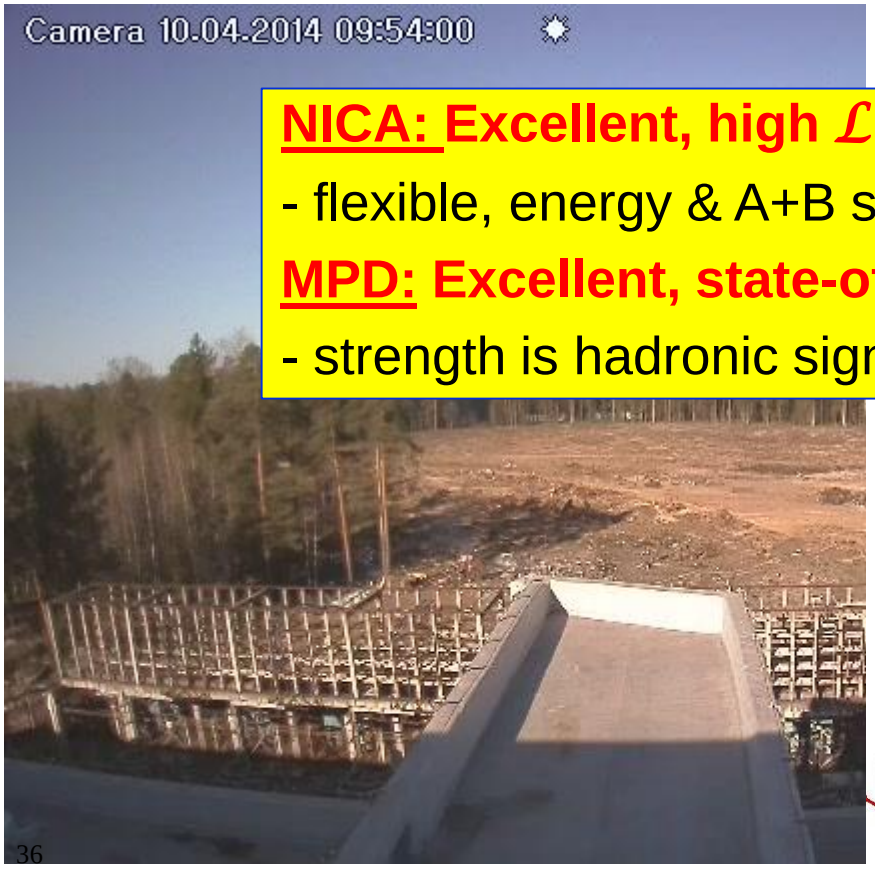
  - ⇨ fairly high $\mathcal{L}$ (Au ~$10^{27}$), flexible collider (A+B, pA), extracted beams (BM@N)
  - ⇨ **MPD** experiment
    - ✪ large acceptance (stage 3); Hadrons + calorimeter




**NICA: Excellent, high $\mathcal{L}$ Machine for**

- flexible, energy & A+B scans (collider!)

**MPD: Excellent, state-of-the art Detector**

- strength is hadronic signals