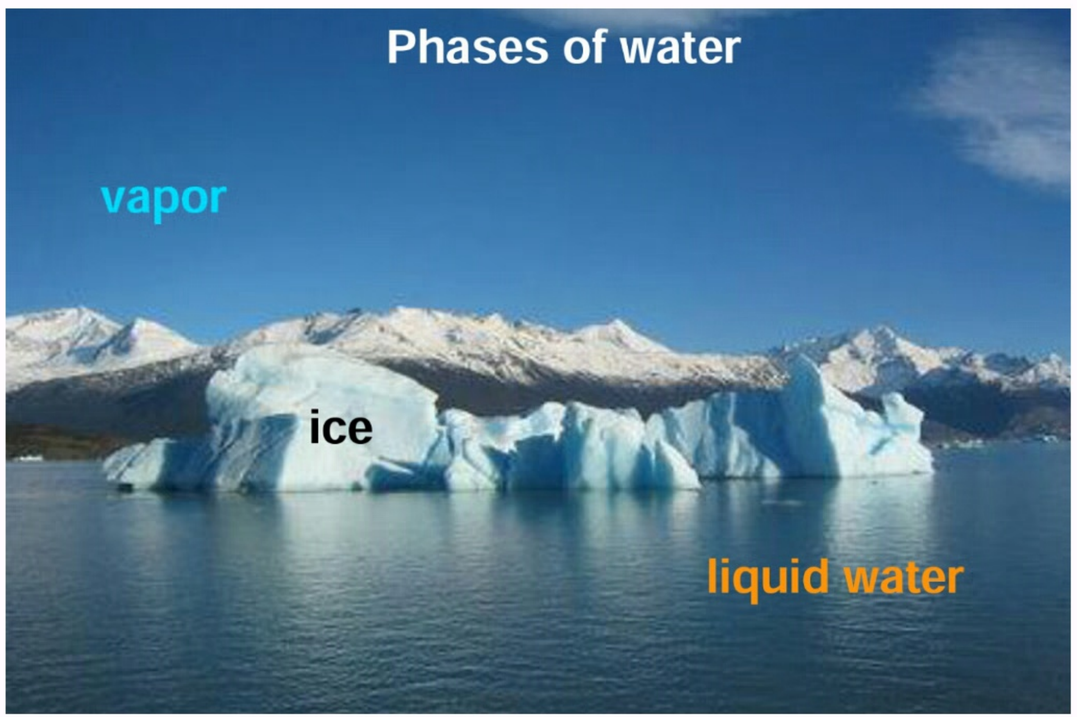
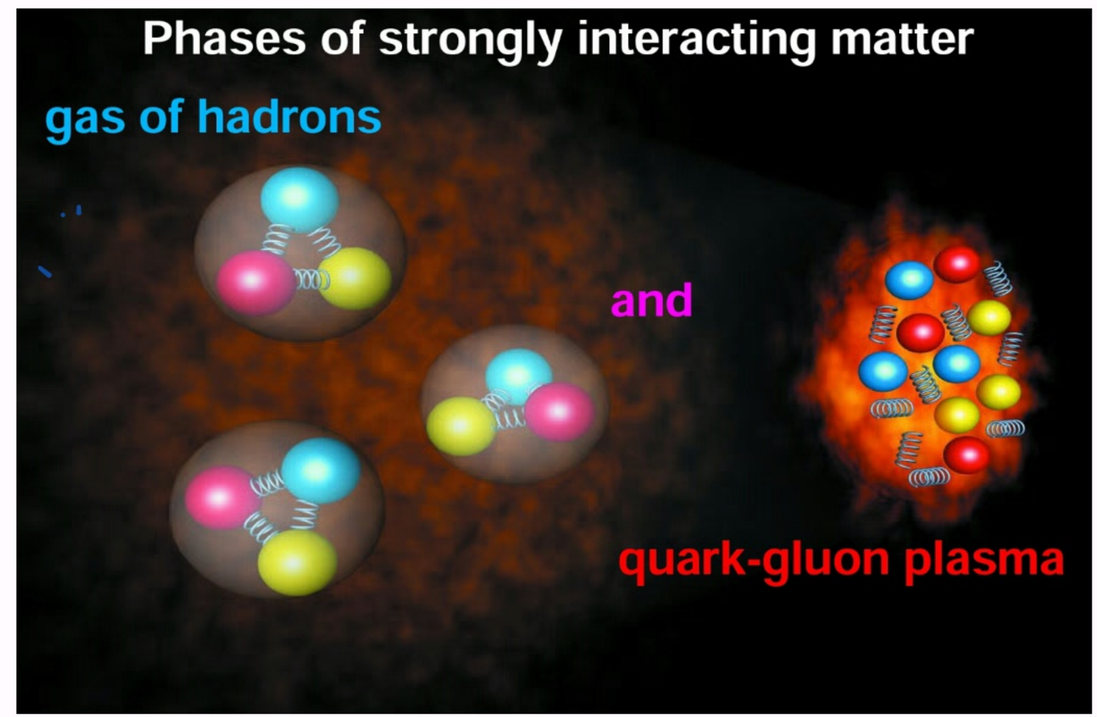
SHORT HISTORY OF A LONG-LASTING EFFORT
TO ANSWER THE SIMPLE QUESTION:

WHAT ARE PHASES AND TRANSITIONS ($\rightarrow$ CRITICAL STRUCTURES)
IN STRONGLY INTERACTING MATTER ?



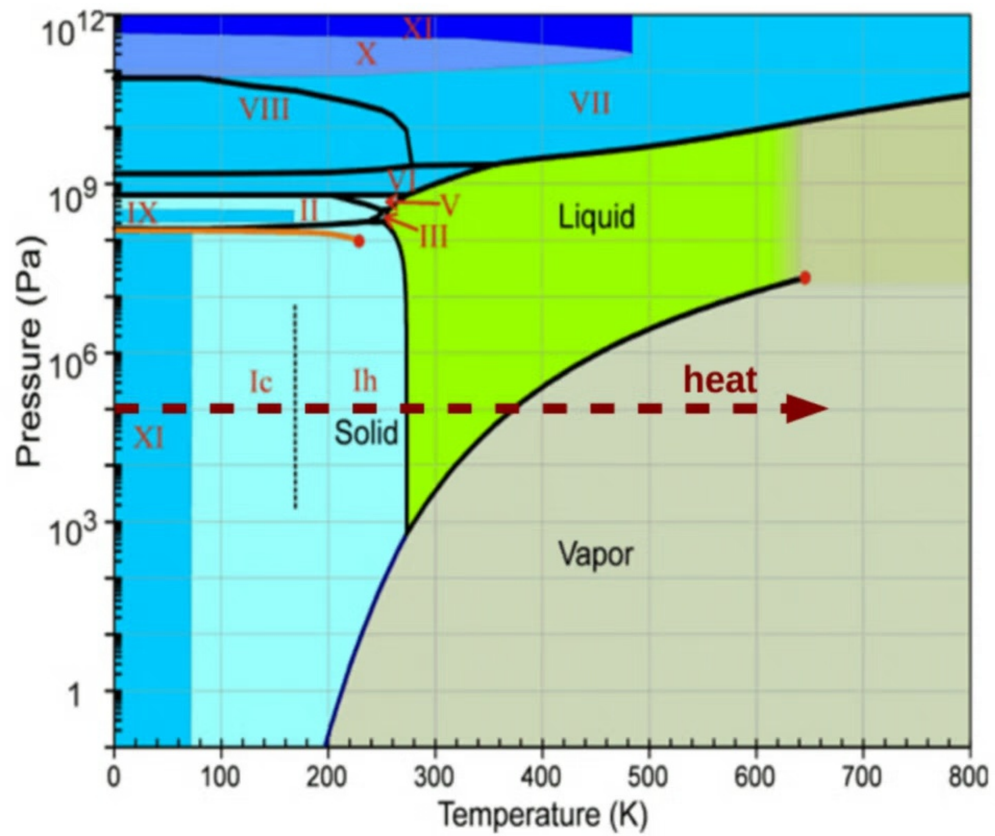
$T \approx 300\ K$



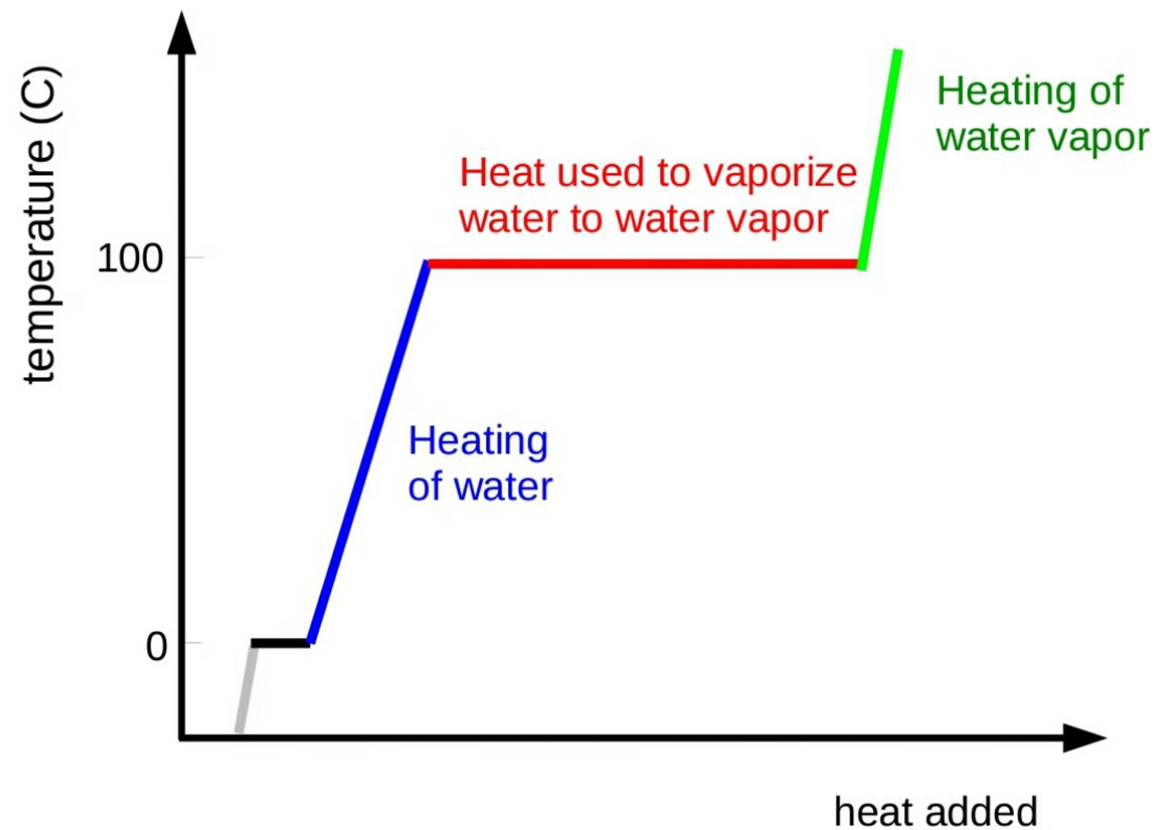
$T \approx 10^{12}\ K$

WATER: PHASES AND TRANSITIONS

PHASE DIAGRAM OF WATER



HEATING CURVE OF WATER



20 YEARS AFTER DISCOVERY OF A NEW STATE OF MATTER

STUDIES OF PHASE DIAGRAM OF STRONGLY INTERARCTING MATTER AT THE CERN SPS

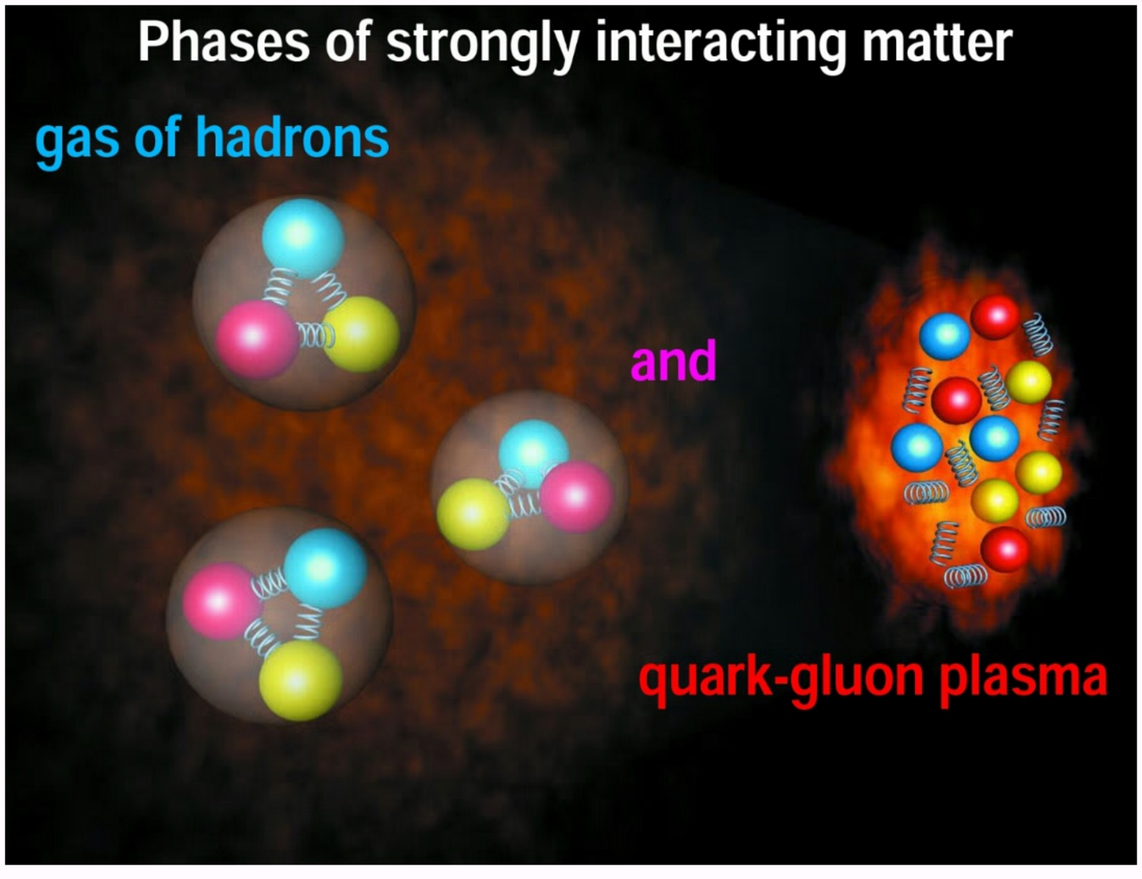
M. GAZDZICKI, KIELCE, FRANKFURT

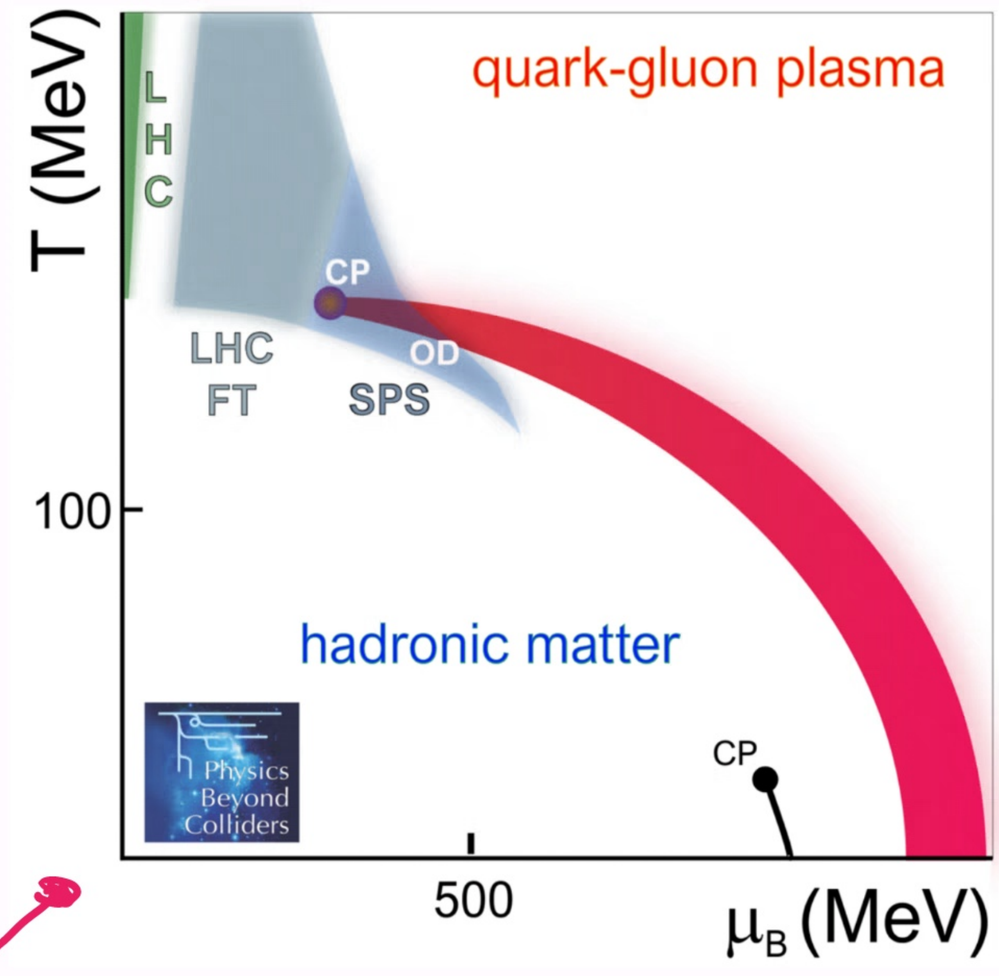
- VOCABULARY
- STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS (< 1986)
- QUARK-GLUON PLASMA (1986 – 2003)
- CRITICAL STRUCTURES (1997 - 2025 ?)
- INVENTING FUTURES

DETAILS, REFERENCES: MG, GORENSTEIN, SEYBOTH, 2004.02255

VOCABULARY

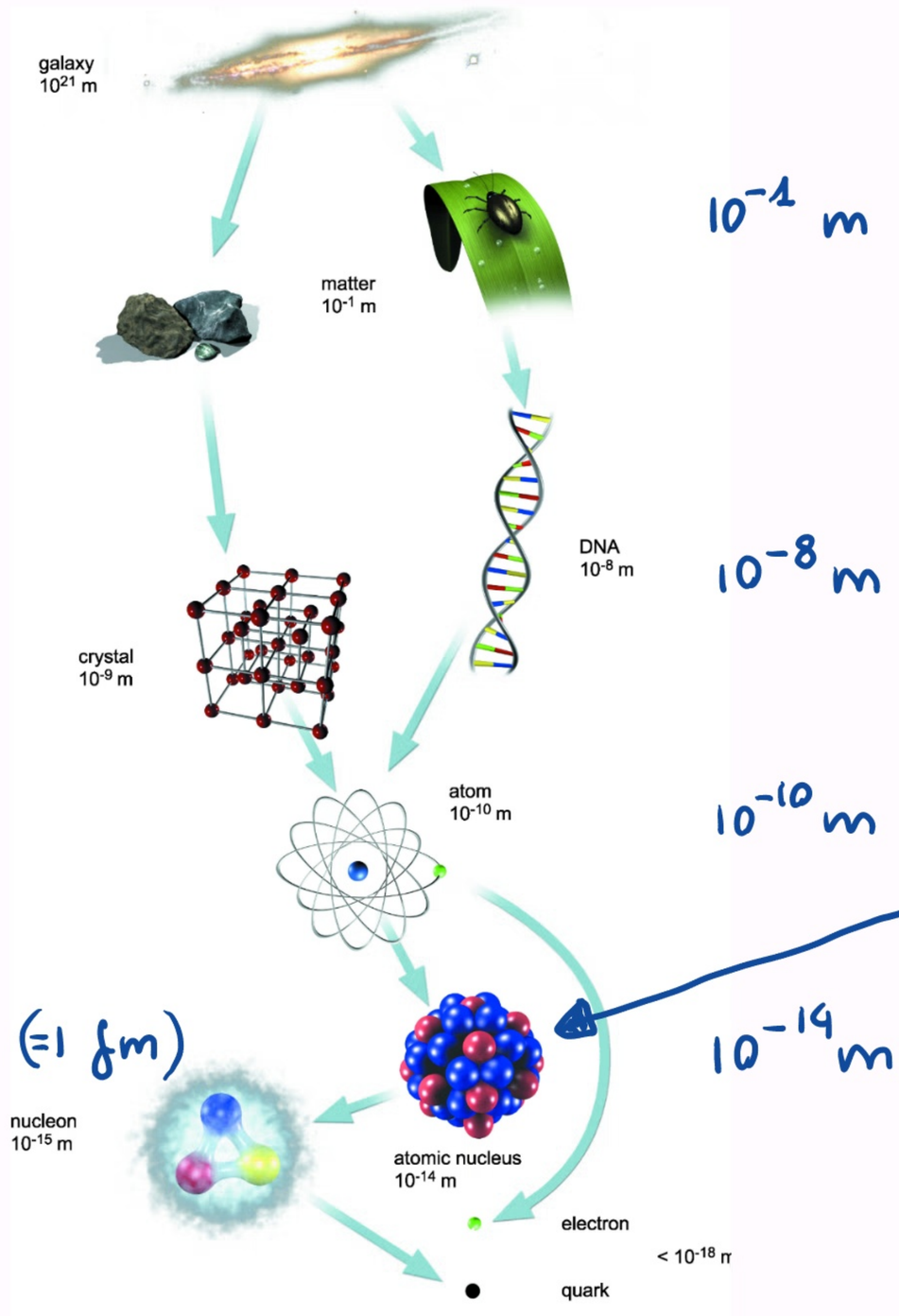
THE QUARK-GLUON PLASMA HYPOTHESIS
(1965 - 1975)





EARLY UNIVERSE
NEUTRON STARS
HEAVY ION COLLISIONS

VOCABULARY



10^{-1} m

10^{-8} m

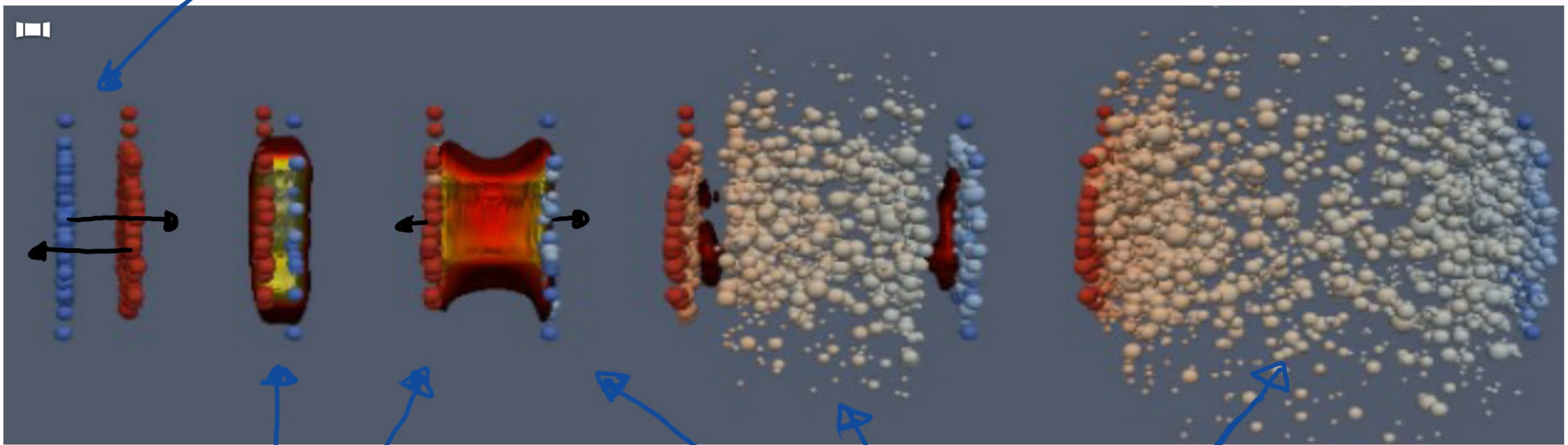
10^{-10} m

10^{-14} m

10^{-15} m (=1 fm)

ATOMIC NUCLEI – THE LARGEST DROPLETS OF STRONGLY INTERACTING MATTER IN LABORATORY

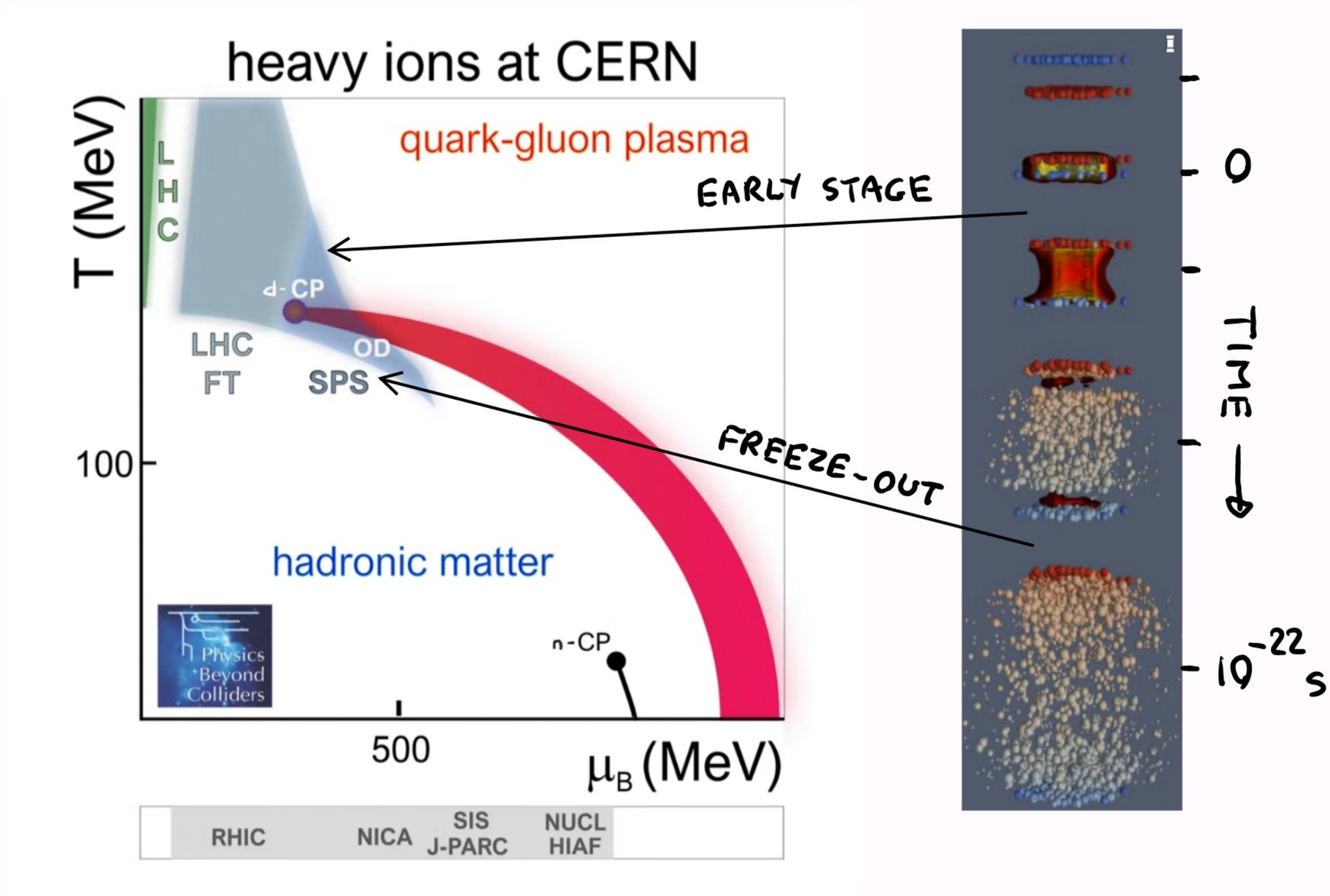
ATOMIC NUCLEI, DROPLETS OF STRONGLY INTERACTING MATTER, ARE ACCELERATED ALMOST TO LIGHT VELOCITY AND COLLIDED



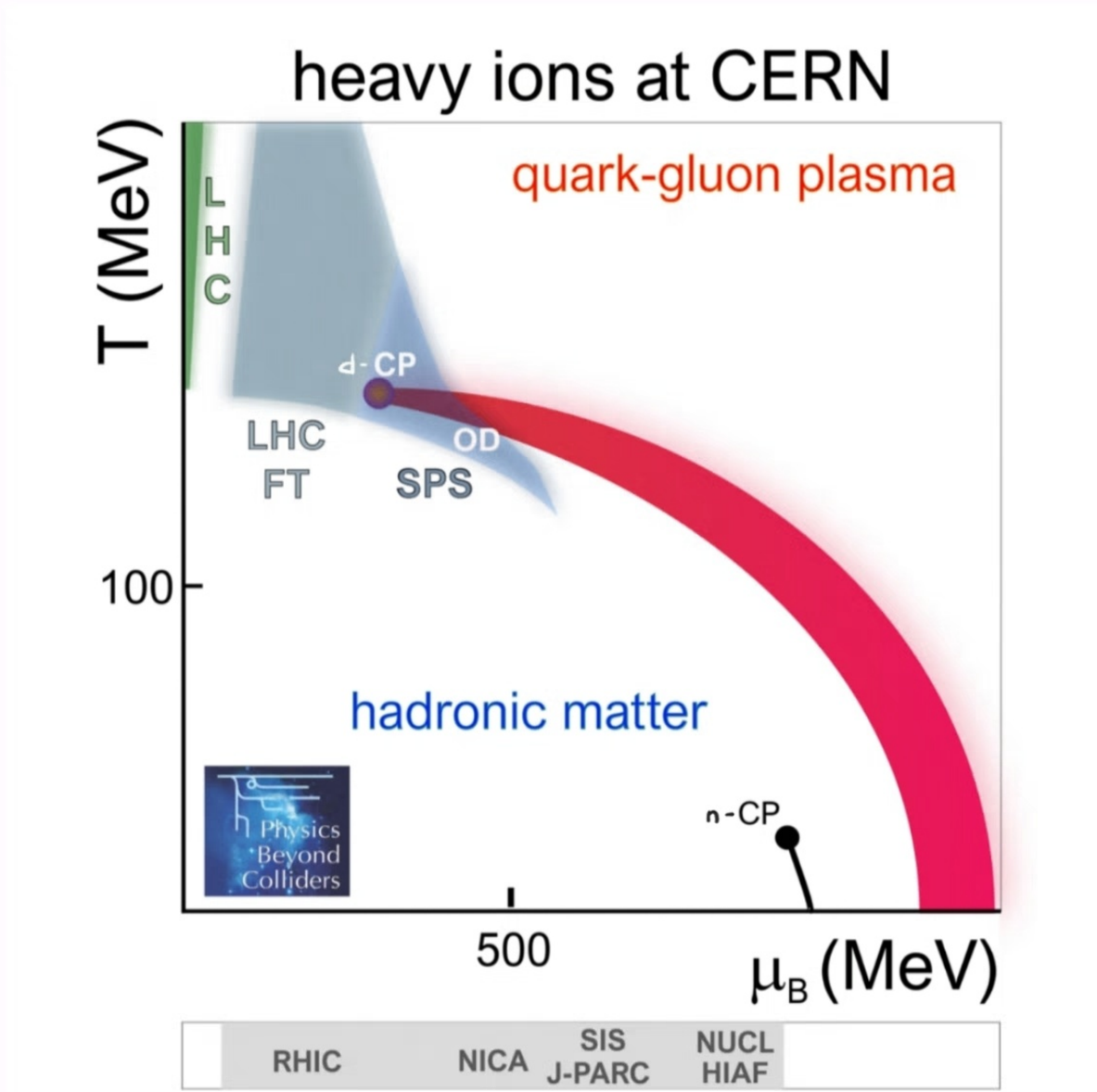
HIGH ENERGY DENSITY STRONGLY INTERACTING MATTER IS CREATED

IT EXPANDS AND DECAYS INTO HADRONS WHICH ARE MEASURED IN PARTICLE DETECTORS

VOCABULARY


heavy ions at CERN
T (MeV)
100
500
μ_B (MeV)
quark-gluon plasma
hadronic matter
LHC
p-CP
LHC
FT
OD
SPS
n-CP
Physics Beyond Colliders
RHIC
NICA
SIS
J-PARC
NUCL
HIAF
EARLY STAGE
FREEZE-OUT
0
TIME
10^{-22} s

VOCABULARY



CRITICAL STRUCTURES:

- ONSET OF DECONFINEMENT (OD) – BEGINING OF QGP CREATION WITH INCREASING COLLISION ENERGY

- CRITICAL POINT (CP) – END POINT OF FIRST ORDER TRANSITION LINE THAT HAS PROPERTIES OF SECOND ORDER PHASE TRANSITION

- ONSET OF FIREBALL – BEGINING OF CREATION OF STRONGLY INTERACTING MATTER WITH INCREASING NUCLEAR MASS NUMBER.
  TRANSITION FROM NON-EQULIBRIUM STRINGS AND RESONACES TO EQULIBRIUM HADRON GAS OR QGP

STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

QUARK-GLUON PLASMA HYPOTHESIS

DISCOVERIES OF HADRONS (CR, BNL, LBL, CERN PS)

1964: QUARK MODEL OF HADRON CLASSIFICATION
GELL-MANN, ZWEIG

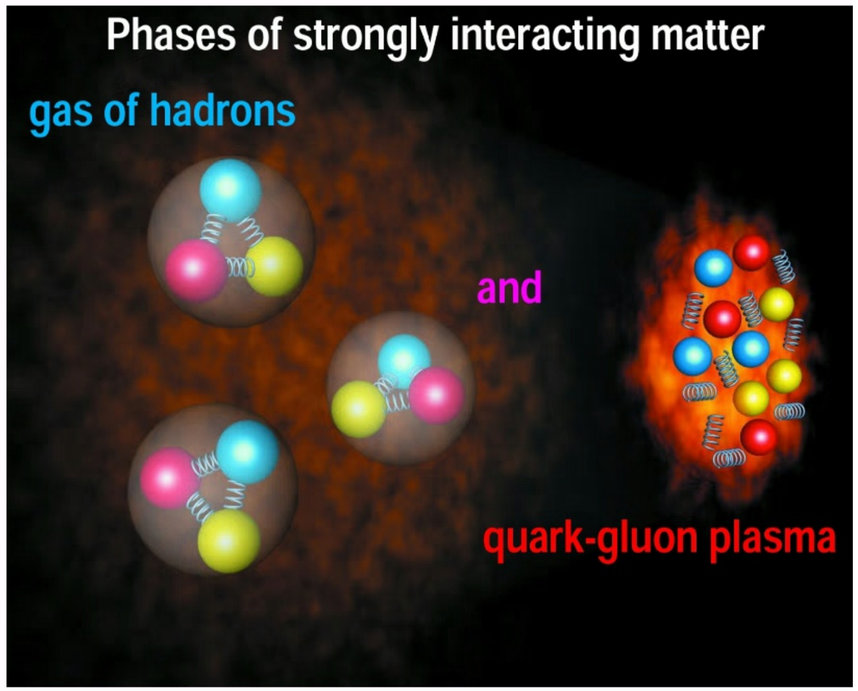
1965-1975: QUARK MATTER IN SUPERDENSE STAR CORES
IVANENKO, KURDGELAIDZE, ITOH, COLLINS, PERRY

1968: DISCOVERY OF PARTONS (SLAC)

1972: QCD AS THEORY OF STRONG INTERACTIONS
GELL-MANN, FRITZSCH, GROSS, WILCZEK, POLITZER

1975: QCD QUARK-GLUON PLASMA
SHURYAK

1979: DISCOVERY OF GLUONS (DESY)



STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

FIRST RELATIVISTIC HEAVY ION EXPERIMENTS:

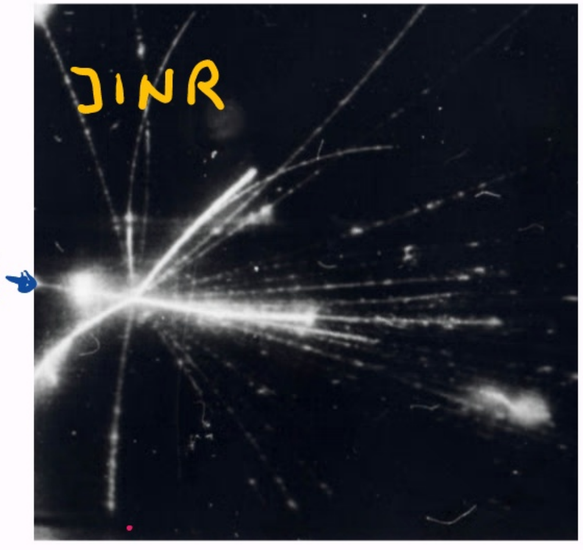
- SINCE 1970: AT SYNCHROPHASOTRON IN DUBNA (UP TO ≈5A GEV)
- SINCE 1975: AT BEVELAC IN BERKELEY (UP TO ≈2A GEV)

$\Downarrow$

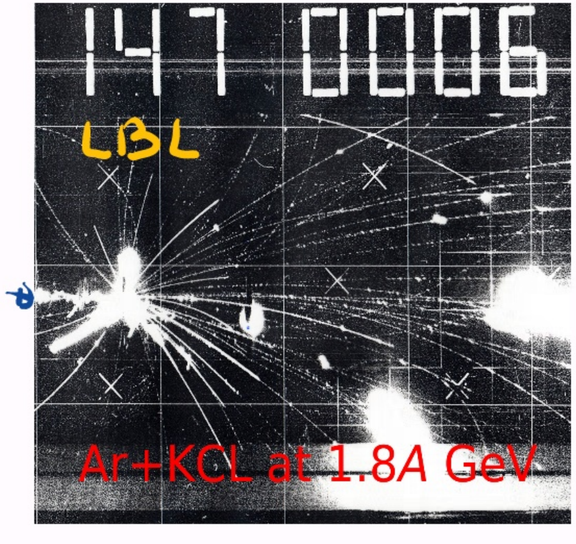
OBSERVATION OF COLLECTIVE EFFECTS (FLOW, STRANGENESS ENHANCEMENT, ...)

$\Downarrow$

STRONGLY INTERACTING MATTER (SIM) IS PRODUCED IN HEAVY ION COLLISIONS



$^{12}C \rightarrow$



$^{40}Ar \rightarrow$

STRONGLY INTERACTING MATTER IN HEAVY ION COLLISIONS

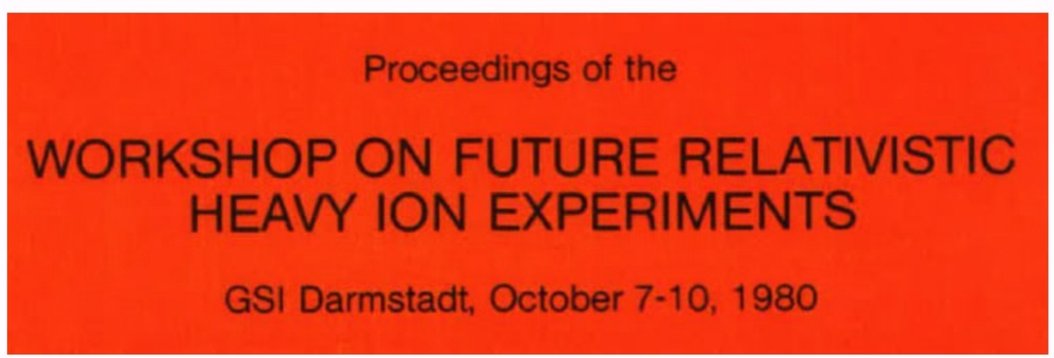
TOWARDS QUARK-GLUON PLASMA

THEORY:
SIM AT HIGH ENERGY DENSITY IS IN A STATE OF QUARK-GLUON PLASMA

EXPERIMENT:
SIM IS PRODUCED IN RELATIVISTIC HEAVY ION COLLISIONS

↓

COLLIDE HEAVY IONS AT THE MAXIMUM POSSIBLE ENERGY AND DISCOVER QGP



BEGINING OF QUARK MATTER CONFERENCE

→ HIC AT THE CERN SPS

EDITORS: BOCK AND STOCK
OPENING TALK: WILLIS
SUMMARY: SPECHT

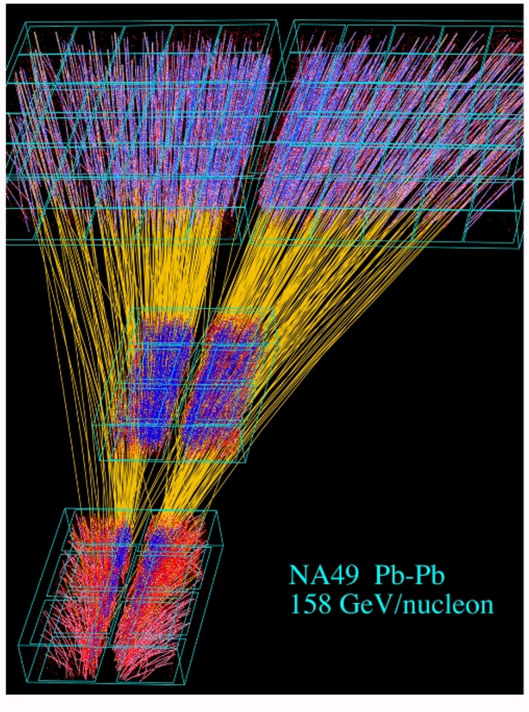
QUARK-GLUON PLASMA

PREDICTED QGP SIGNALS:

- DILEPTON/PHOTON QGP RADIATION (SHURYAK, 1980)
- STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT (RAFELSKI, MULLER, 1982)
- J/ψ SUPPRESSION (MATSUI, SATZ, 1986)

MEASURMENTS:

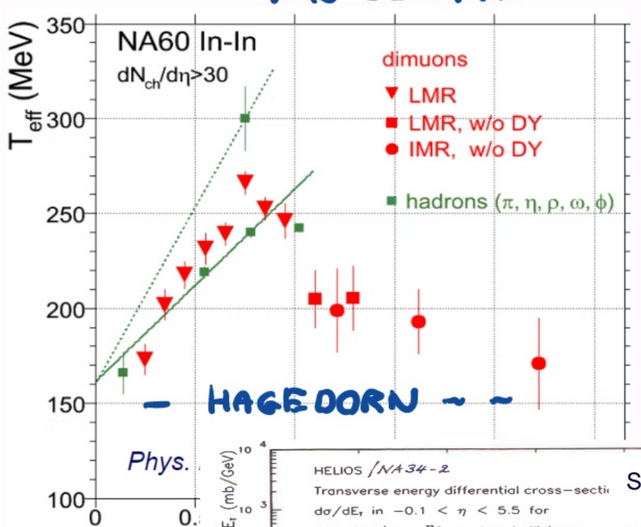
- 1986-1987: OXYGEN AND SULPHUR AT 200A GEV (NA34-2, 35, 36, 38, WA80, 85, 94)
- 1996-2003: LEAD AND INDIUM AT 158A GEV (NA44, 45, 49, 50, 52, 57, 60, WA97, 98)



QUARK-GLUON PLASMA

RESULTS ARE CONSISTENT WITH A QGP BEING CREATED ...

QGP TEMPERATURE $T \approx 200$ MEV



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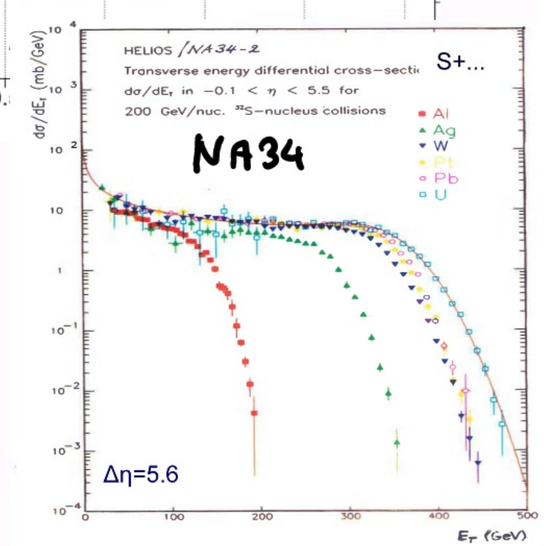
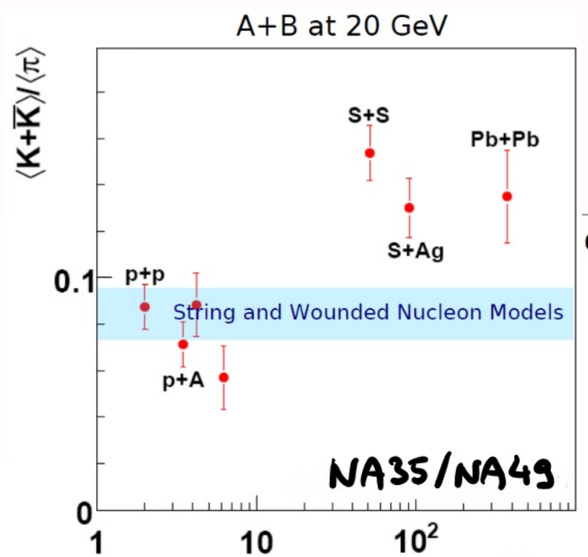
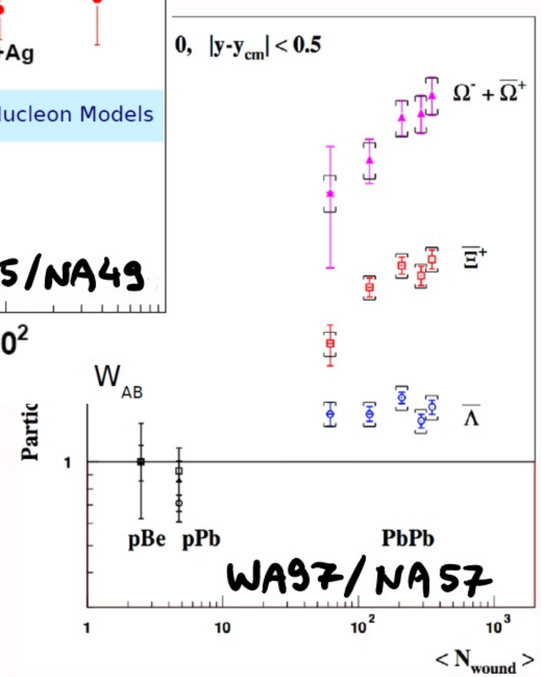


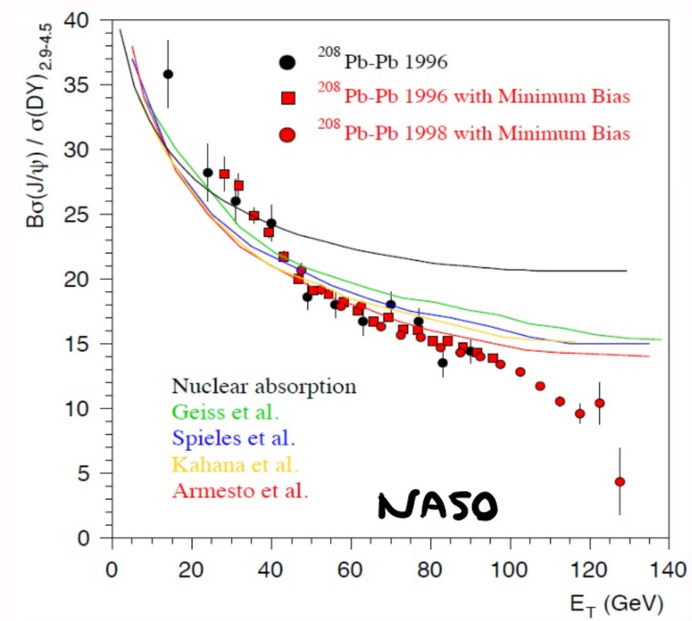
STRANGENESS AND MULTI-STRANGE HYPERON ENHANCEMENT IN QGP





AND ENERGY DENSITY $\varepsilon \gtrsim 1$ GeV/fm^3

J/ψ MELTING IN QGP

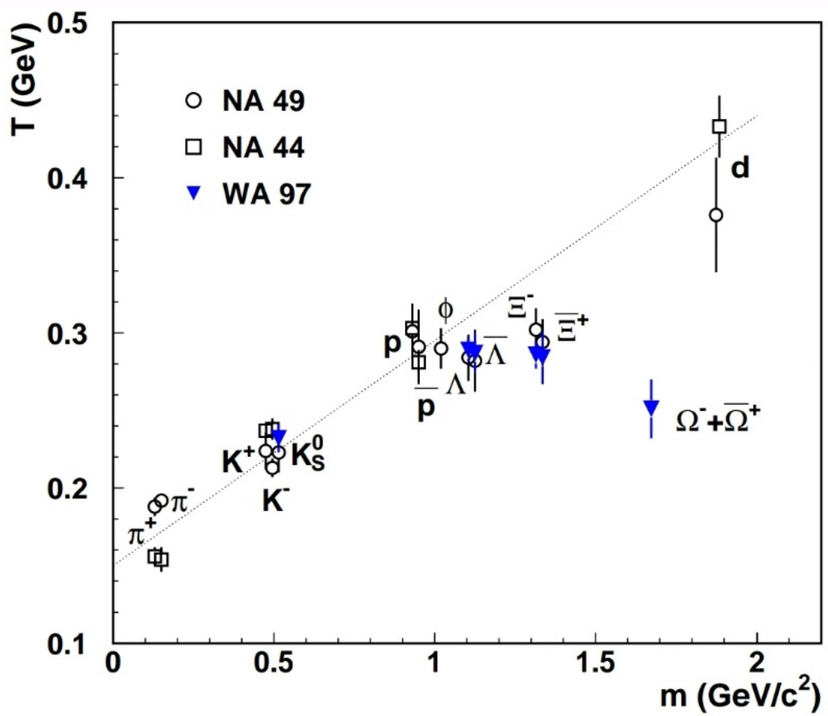


QUARK-GLUON PLASMA

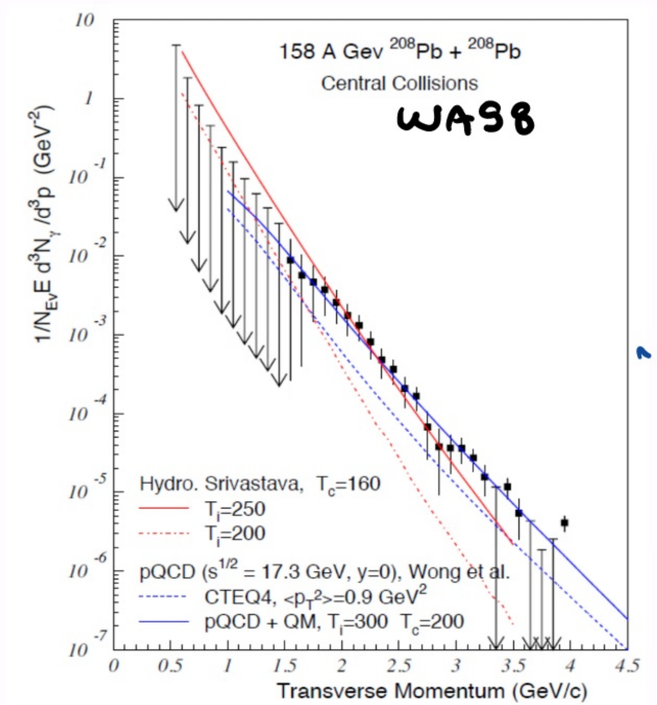
STANDARD MODEL OF HEAVY ION COLLISIONS:

... MATTER EXPANDS, RADIATES PHOTONS AND DILEPTONS ...

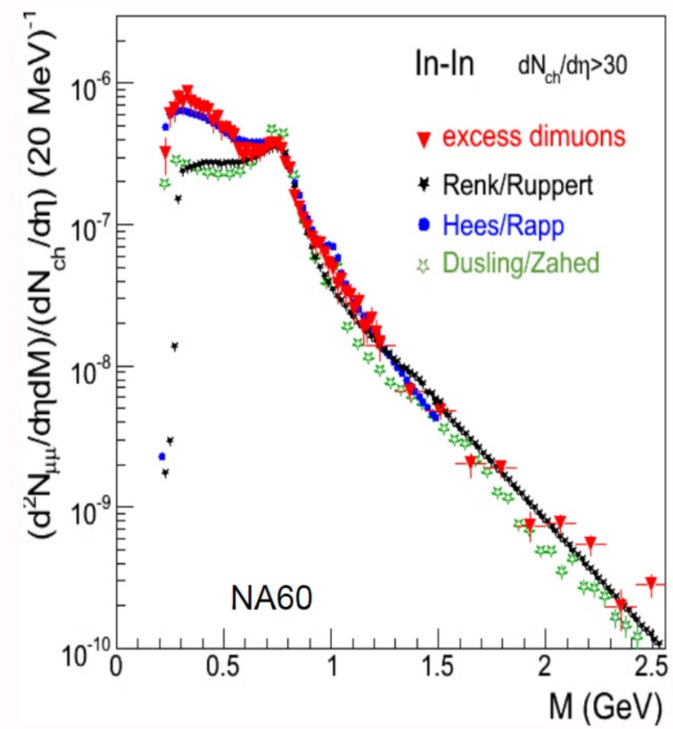
TRANSVERSE EXPANSION



PHOTON RADIATION



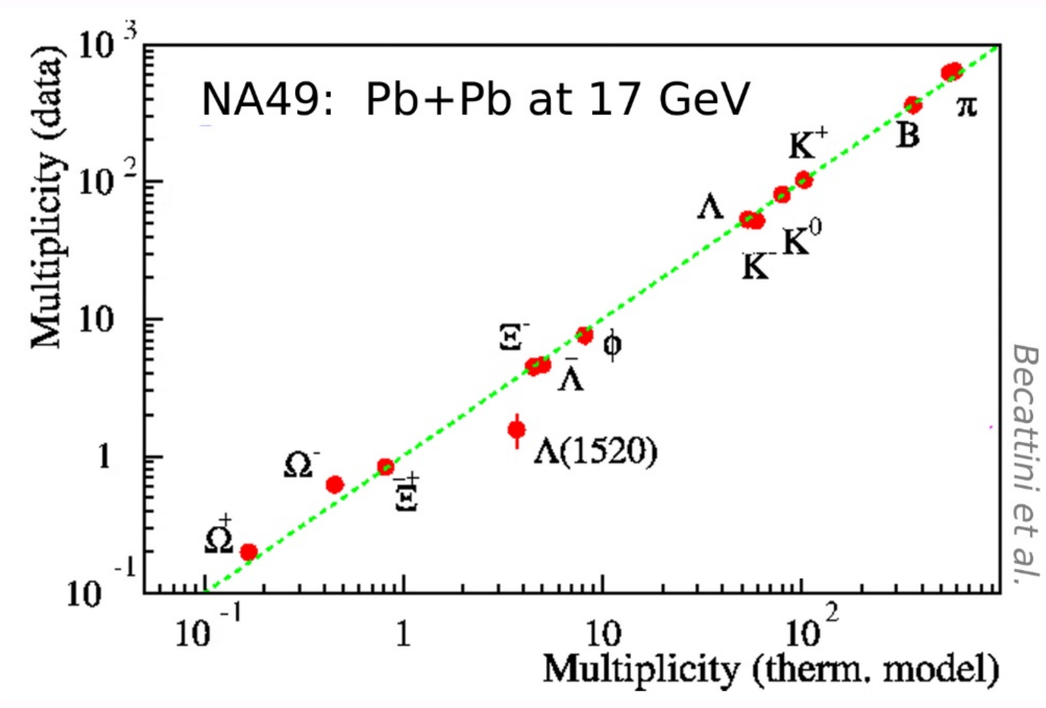
DIMUON RADIATION



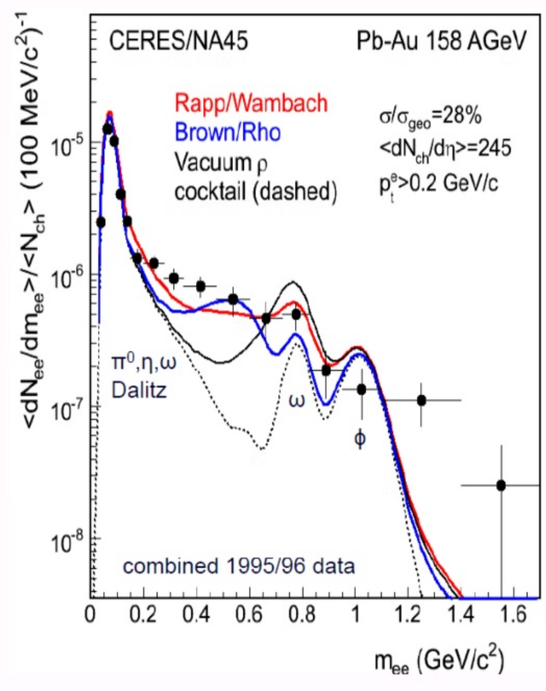
QUARK-GLUON PLASMA

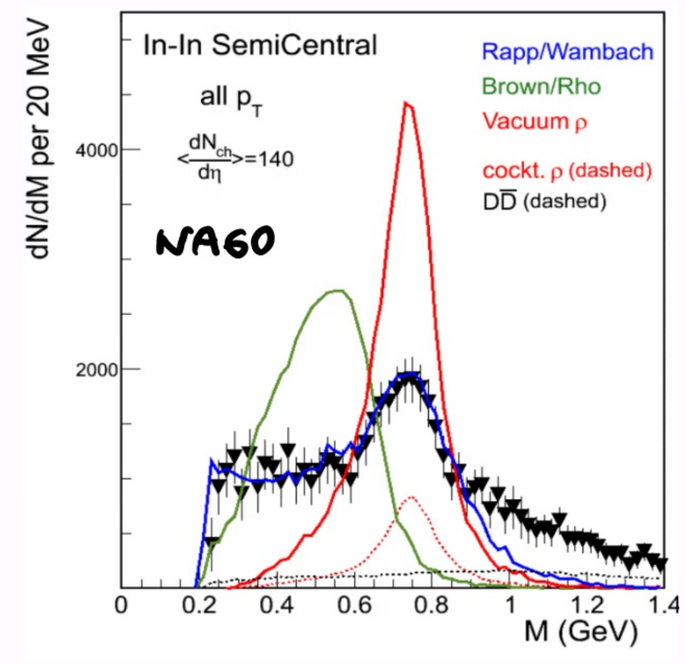
... AND AFTER STATISTICAL HADRONIZATION, THE MATTER IS STILL DENSE ENOUGH TO MODIFY HADRON PROPERTIES

STATISTICAL HADRONIZATION



MODIFICATION OF VECTOR MESON PROPERTIES





QUARK-GLUON PLASMA

CERN PRESS RELEASE (FEB 2000)

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

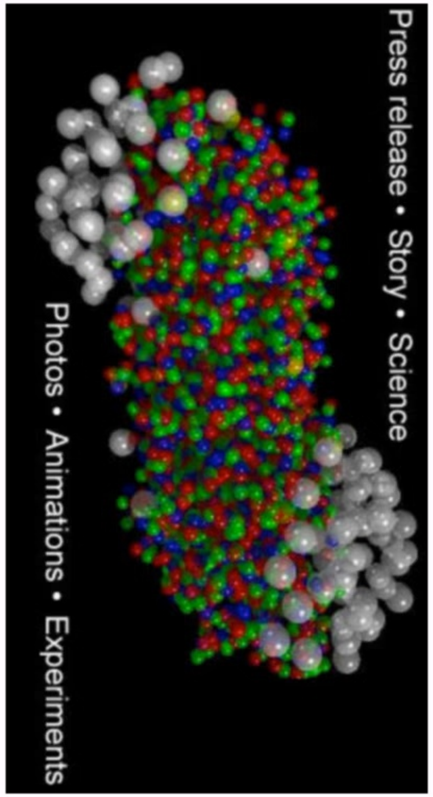
PR01.00
10.02.00

New State of Matter created at CERN

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

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN[1] Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*



HEAVY ION COMMUNITY SPLITS:

→ PROPERTIES OF HIGH TEMPERATURE QGP → VERY HIGH ENERGIES AT RHIC, LHC

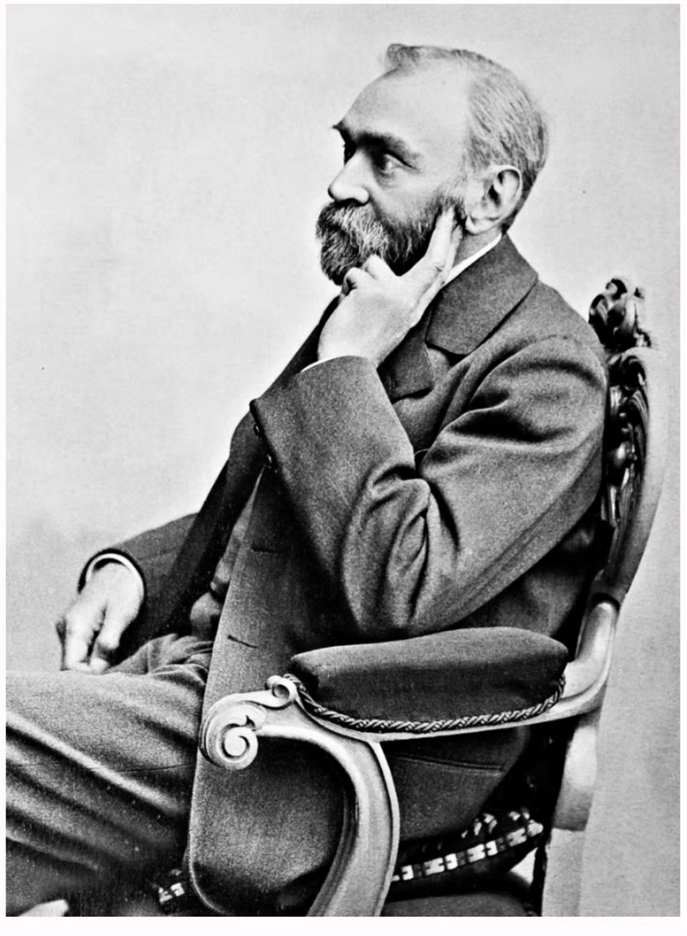
→ SEARCH FOR THE ONSET OF QGP CREATION → COLLISION ENERGY SCAN AT SPS

COMMENT ON NOBEL PRIZE

DIFFICULTIES IN OBTAINING UNIQUE AND QUANTITATIVE PREDICTIONS OF QGP SIGNALS FROM QCD

$\Downarrow$

THE NOBEL PRIZE FOR THE QGP DISCOVERY WAS NOT YET AWARDED



INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

DYNAMICAL MODEL

HADRON GAS:

$$N + N \to N + Y + K$$

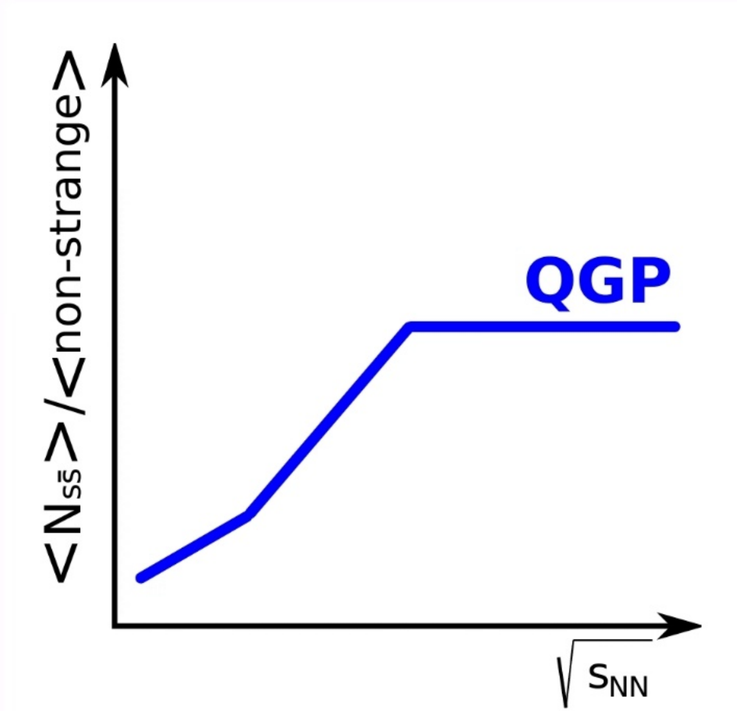
$$\pi + N \to K + Y \qquad \pi + \overline{N} \to \overline{K} + \overline{Y}$$

$$\pi + Y \to \Xi + K \qquad \pi + \overline{Y} \to \overline{\Xi} + \overline{K}$$

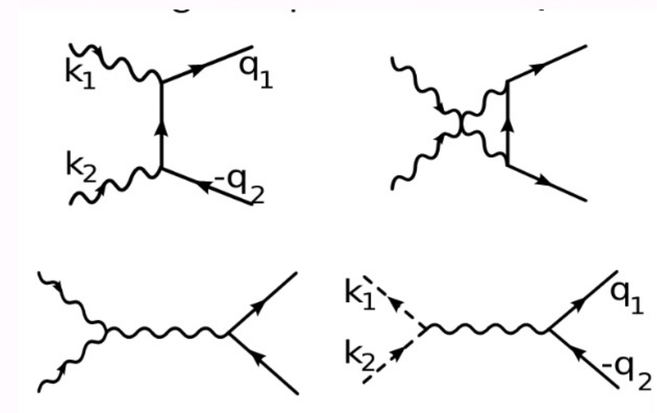
$$\pi + \Xi \to \Omega + K \qquad \pi + \overline{\Xi} \to \overline{\Omega} + \overline{K}$$

$m_K \gg T_c \approx 150$ MeV

$\tau_{EQUIL} \approx 100$ fm/c



QUARK-GLUON PLASMA



$m_s < T_c \approx 150$ MeV

$\tau_{EQUIL} \approx 1\text{-}10$ fm/c

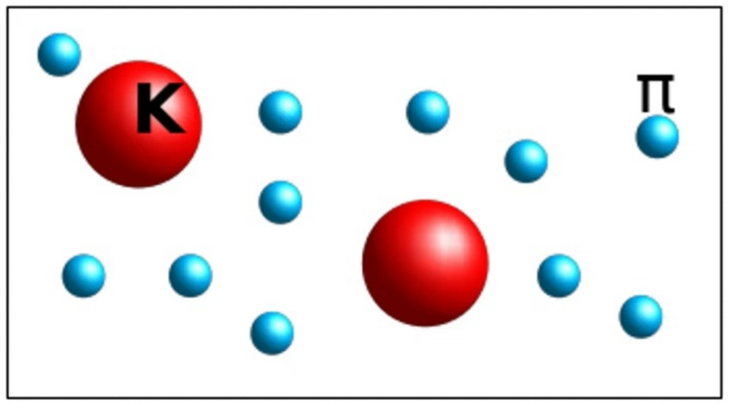
CROSSING THRESHOLD FOR QGP CREATION →
→ STRANGENESS ENHACEMENT

RAFELSKI, MULLER, GLENDENNING 1982+...

INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

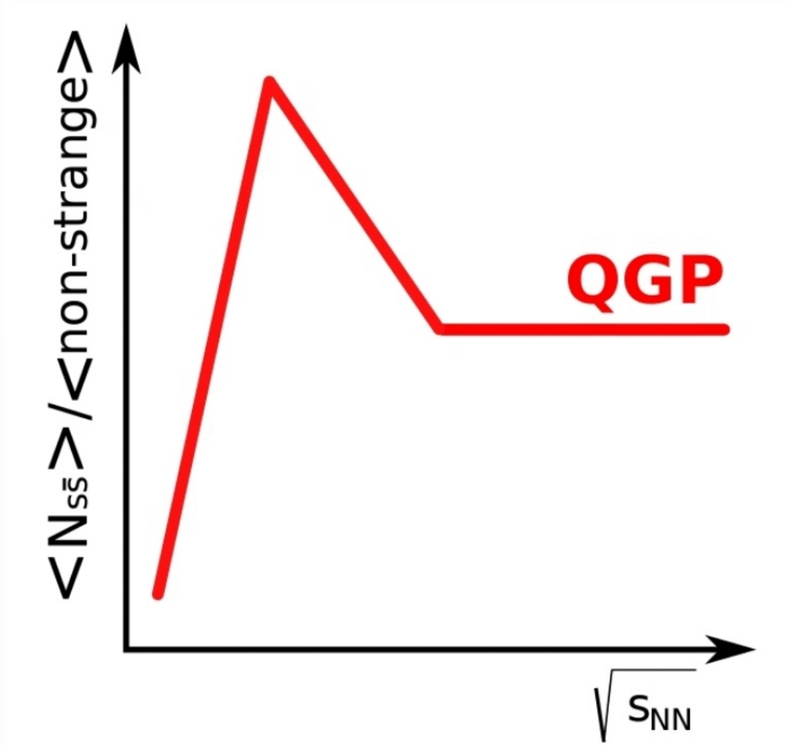
STATISTICAL MODEL OF THE EARLY STAGE

HADRON GAS

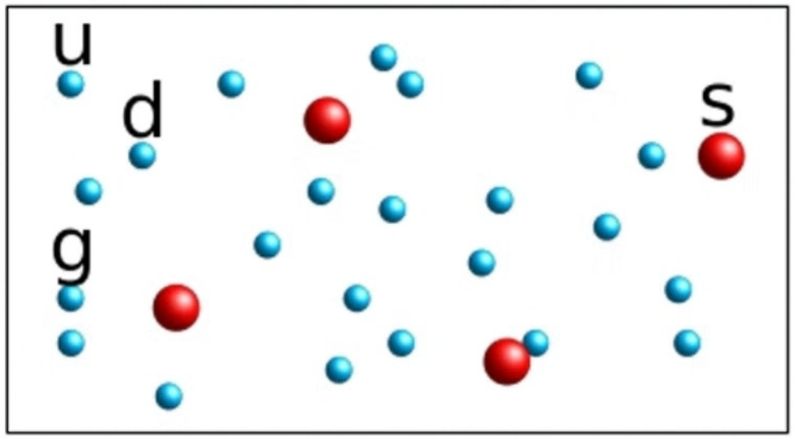


$m_K \gg T_c \approx 150$ MeV

$\langle \bar{K} \rangle \sim e^{-m_K/T}$



QUARK-GLUON PLASMA



$m_s < T_c \approx 150$ MeV

$\langle \bar{s} \rangle \sim T^3$

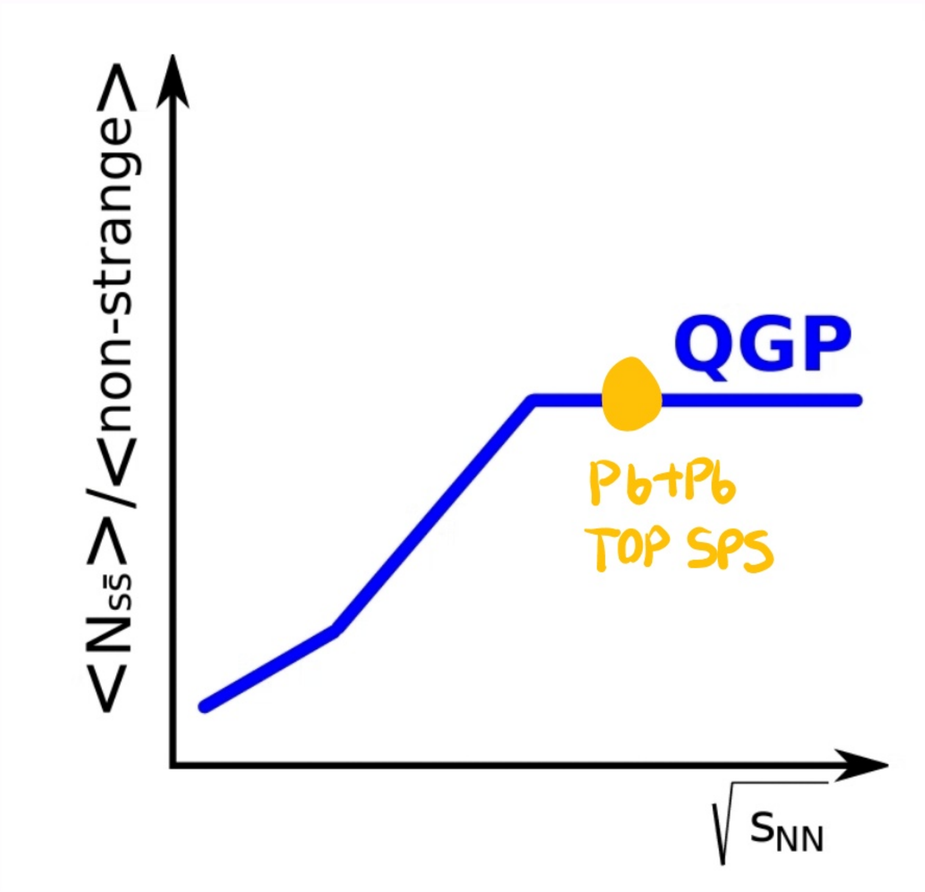
CROSSING THRESHOLD FOR QGP CREATION →

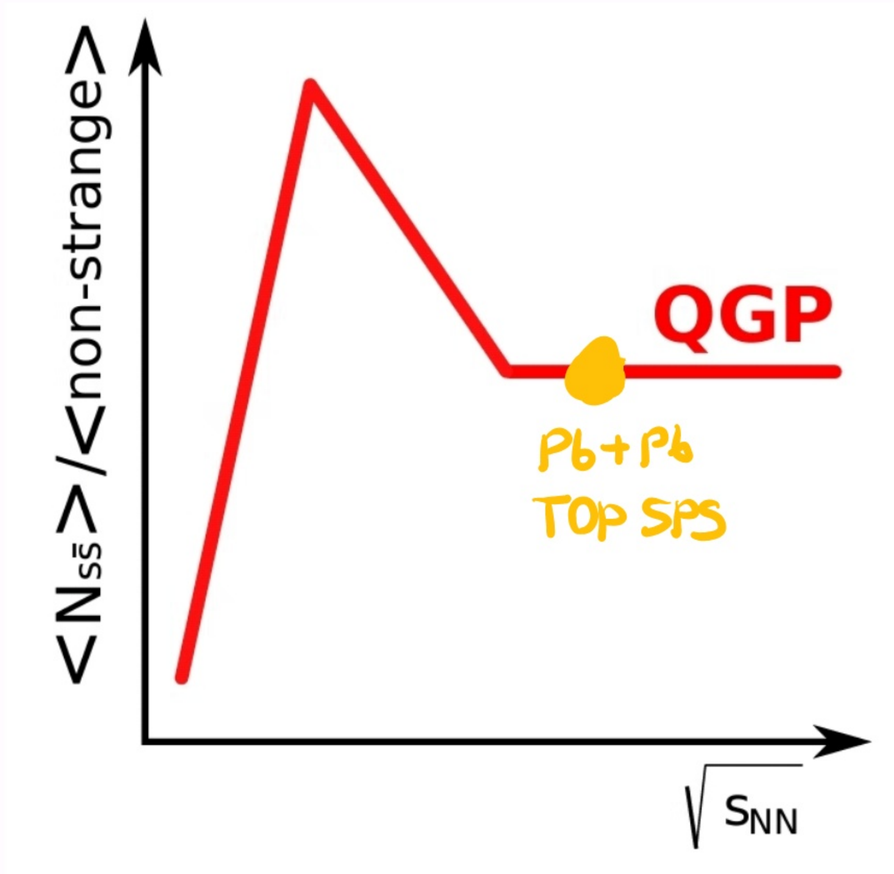
→ HORN-LIKE STRUCTURE

MG, GORENSTEIN, 1996 +

INTERMEZZO I: STRANGENESS PRODUCTION AND QGP

DYNAMICAL VERSUS STATISTICAL MODELS





≈ 2000: COLLISION ENERGY SCAN IS NEEDED

- SEARCH FOR THE ONSET OF QGP CREATION
- DISTINGUISH BETWEEN DYNAMICAL AND STATISTICAL MODELS

CRITICAL STRUCTURES

PHASE I: SEARCHING FOR ONSET OF QGP CREATION

PREDICTED SIGNALS:

- PION YIELD ENHANCEMENT AND STRANGENESS TO PION YIELD SUPPRESSION (MG, GORENSTEIN 1998)

- SOFTENING OF COLLECTIVE FLOW (GORENSTEIN, MG, BUGAEV 2003, STOECKER 2004, BLEICHER 2005)

MEASUREMENTS:

- 1999 – 2002: Pb BEAMS AT 20A, 30A, 40A, 80A, 158A GEV ← CERN SPS (NA49, NA45, NA57, NA60) →

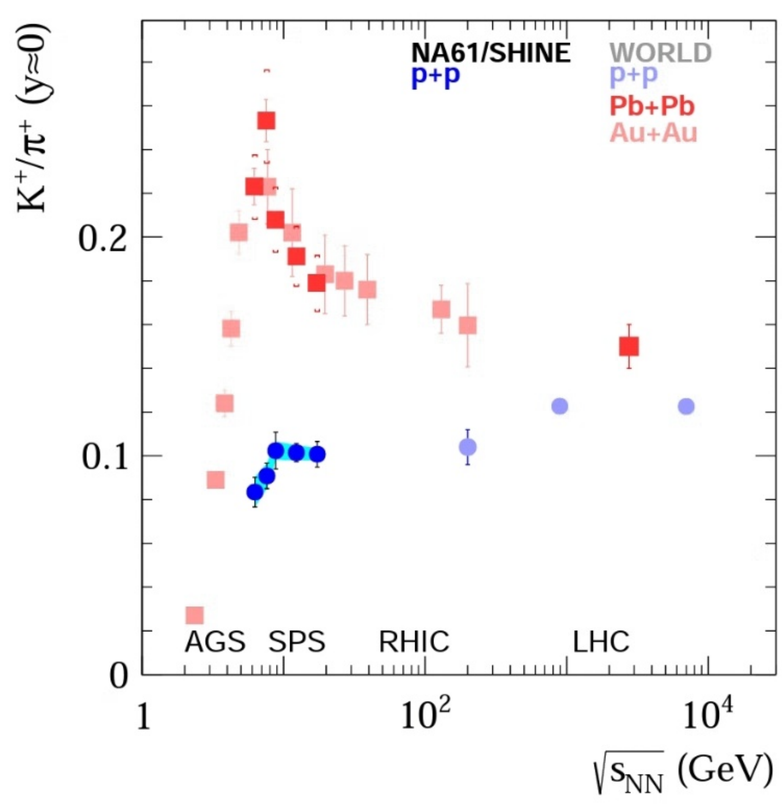
  → 2010 – 2014: Au BEAMS AT EQUIV. 30A – 200A GEV ← BNL RHIC (STAR, PHENIX : BEST)

CRITICAL STRUCTURES

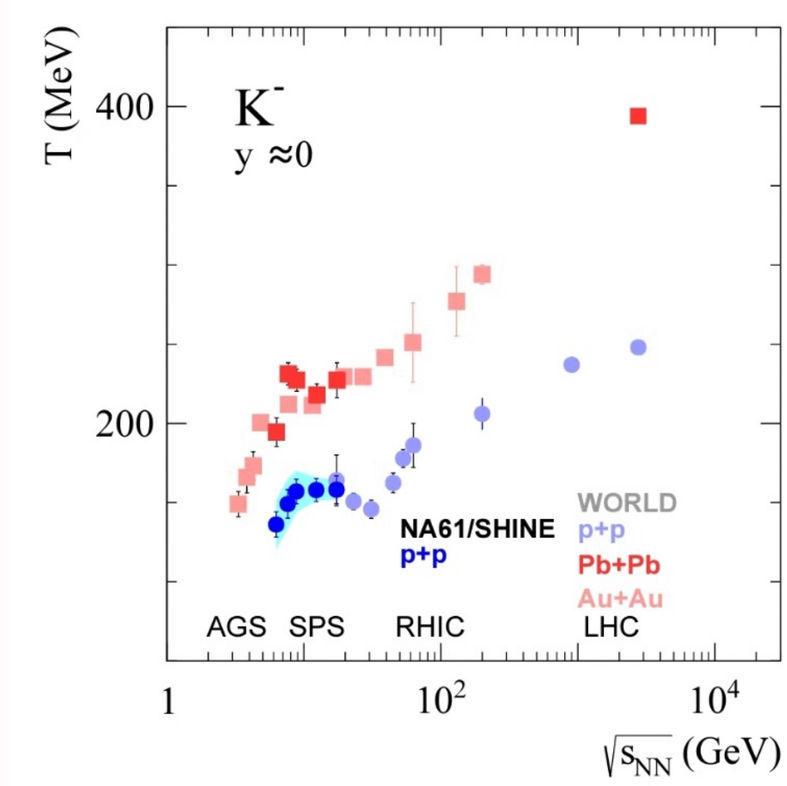
PHASE I: SEARCHING FOR ONSET OF QGP CREATION

OBSERVED ANOMALIES IN COLLISION ENERGY DEPENDENCE ARE CONSISTENT WITH THE QGP ONSET AT LOW SPS ENERGIES

STRNGENESS/PION SUPPRESSION



SOFTENING OF COLLECTIVE FLOW



CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

APRIL 2004: WORKSHOP IN ECT TRENTO:

→ RESULTS ARE CONSISTENT WITH QGP ONSET IN Pb+Pb AT LOW SPS ENERGIES →

→ SEARCH FOR CRITICAL POINT

→ SCAN IN ENERGY AND NUCLEAR MASS NUMBER

CERN COURIER SEPT. 2004

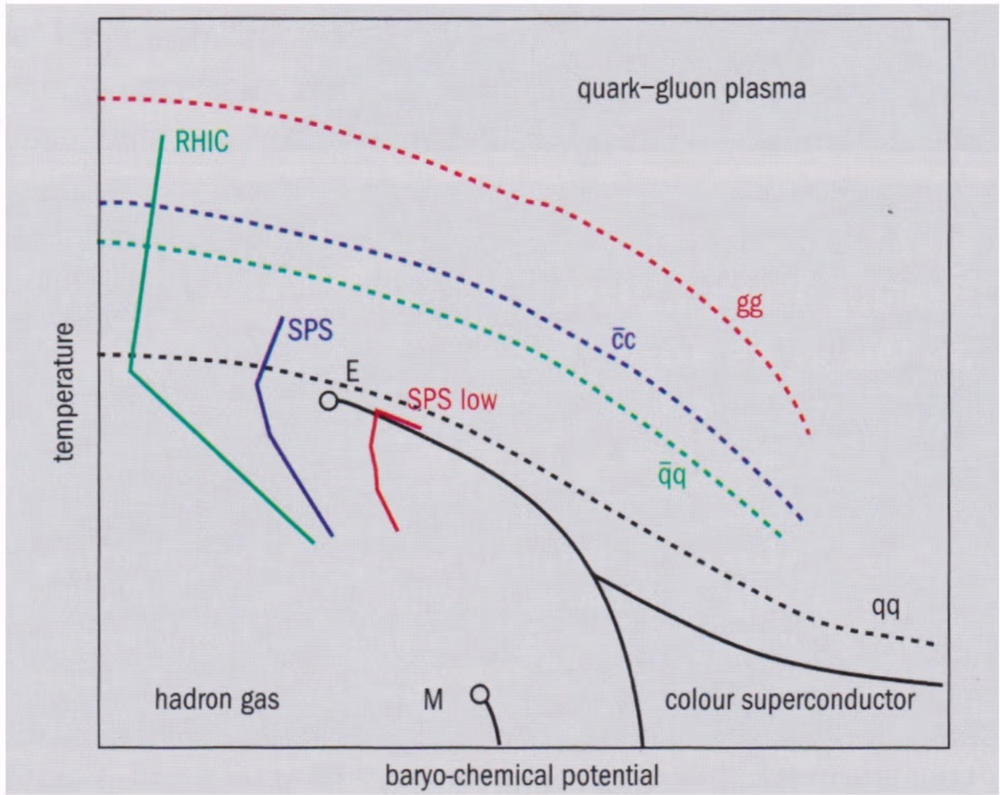
HEAVY IONS

When quarks and gluons become free

Recent results and future experiments were the topics in a workshop to look into exactly what happens as strongly interacting matter becomes deconfined.

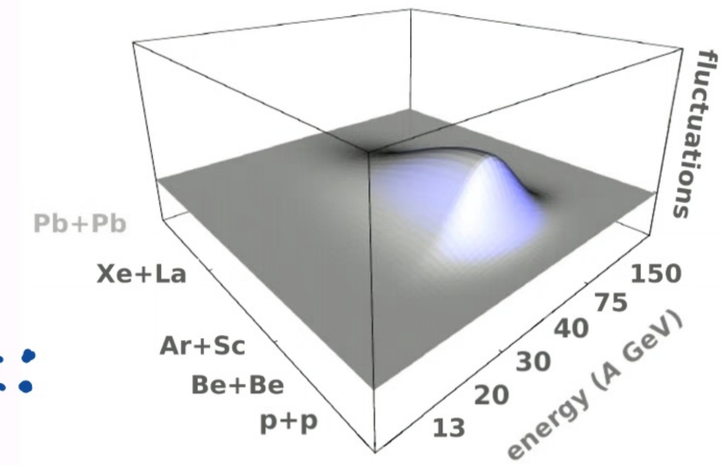
MG
SEYBOTH
SHURYAK

BEGINING OF CRITICAL POINT AND ONSET OF DECONFINEMENT WORKSHOPS



CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

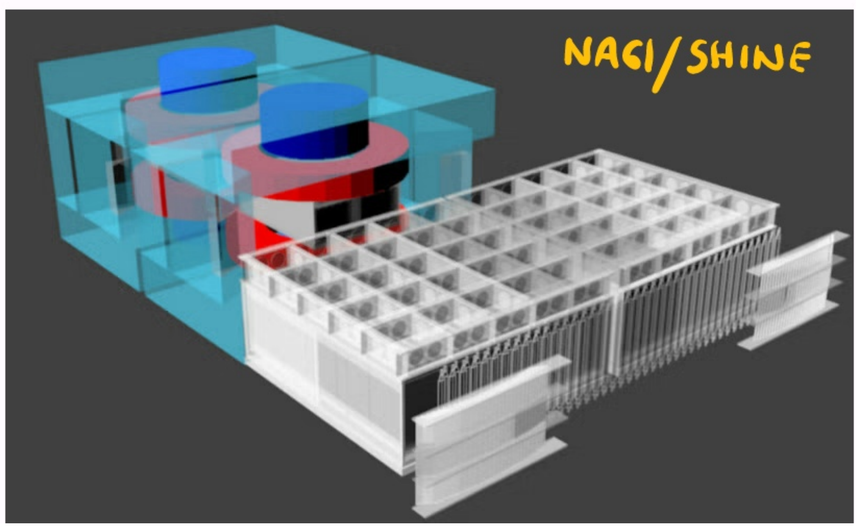


PREDICTED SIGNALS:

- MAXIMUM OF FLUCTUATIONS IN (COLLISION ENERGY) - (NUCLEAR MASS NUMBER) PLANE:
  - INTERMITTENCY AND PROTON FLUCTUATIONS (BIALAS, HWA 1991, ANTONIOU, DIAKONOS, KAPOYANIS 2006, STEPHANOV 2011)
  - PION P_T-N FLUCTUATIONS (STEPHANOV, RAJAGOPAL, SHURYAK 1998)

MEASUREMENTS:

- 2009 - 2018: SCAN IN $\sqrt{s_{NN}}$ - A (NA61/SHINE AT CERN SPS)
- 2019 - 2020: SCAN IN $\sqrt{s_{NN}}$ WITH Au (STAR, PHENIX AT BNL RHIC; BES I/II)

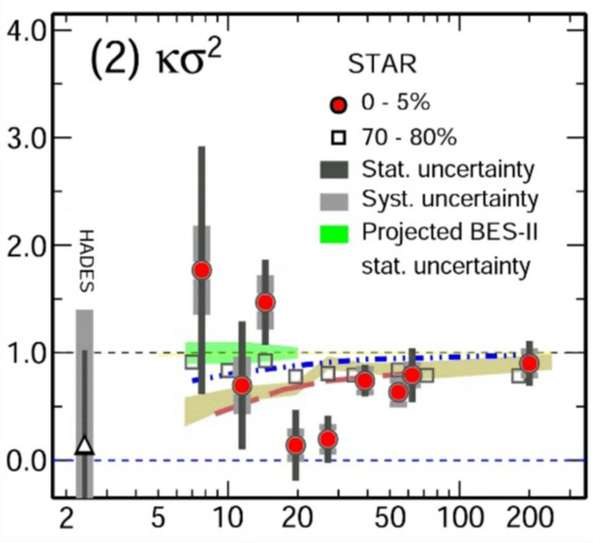


CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

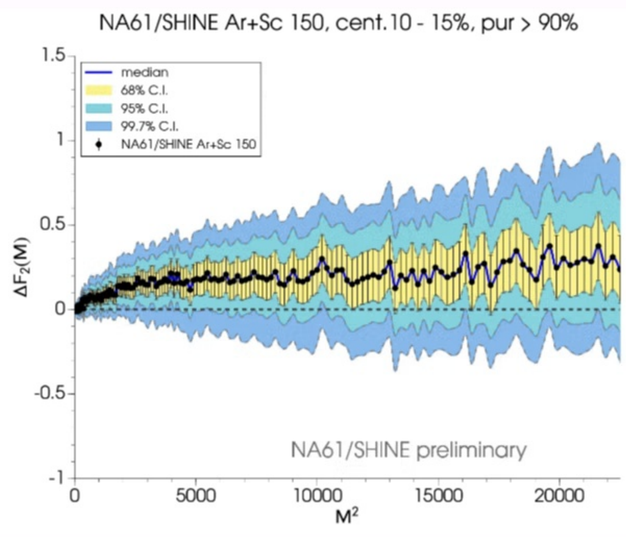
CP INDICATIONS → DIFFERENT ENERGIES/REACTIONS

HIGHER ORDER MOMENTS



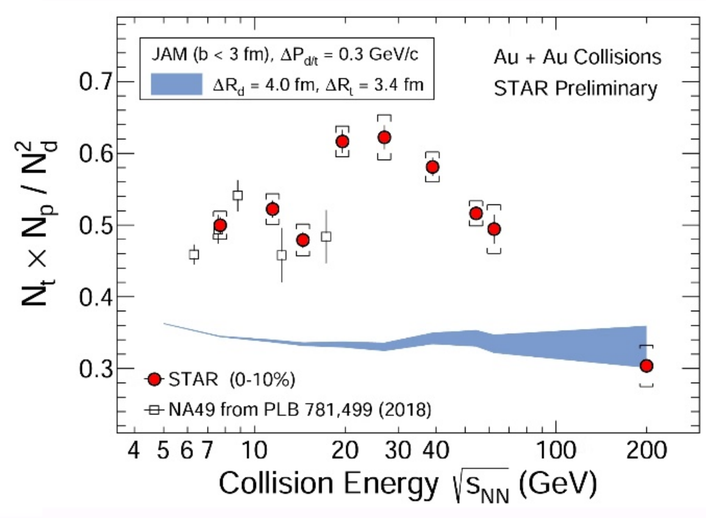
≈ 7 GeV

PROTON INTERMITTENCY



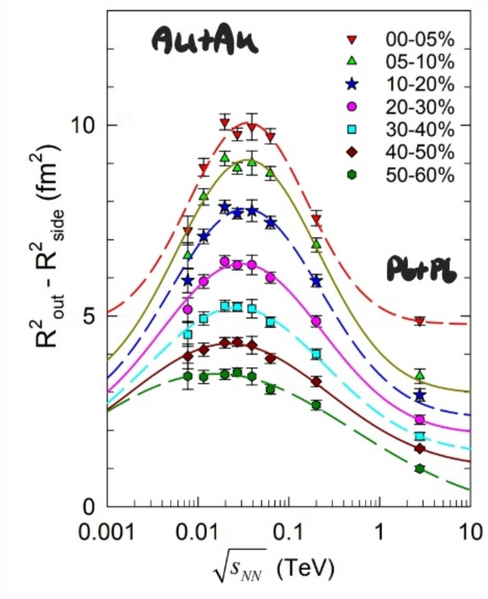
≈ 17 GeV

LIGHT IONS



≈ 20 GeV

SHORT-RANGE CORRELATIONS



≈ 50 GeV

CRITICAL STRUCTURES

PHASE II: SEARCHING FOR CRITICAL POINT

AS FOR NOW EXPERIMENTAL AND THEORETICAL RESULTS ARE INCONCLUSIVE / CONFUSING

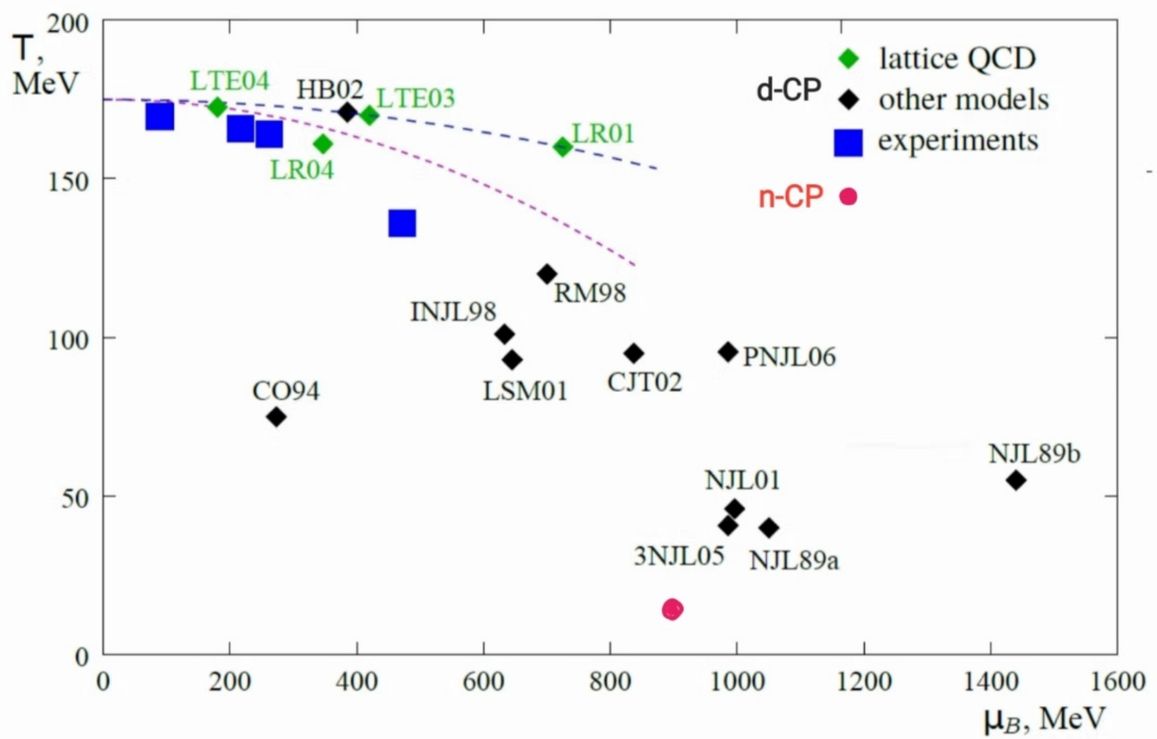
CZAPLAWICZ SQM 2019

4th moment of net-proton dist.: ≈ 7 GeV (Au+Au)

Proton intermittency: ≈ 17 GeV (Si+Si and Ar+Sc)

Light ion production: ≈ 20 GeV (Au+Au)

Pion interferometry: ≈ 47 GeV (Au+Au)

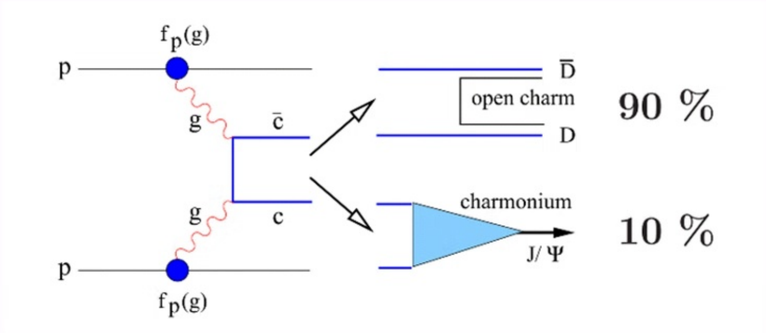


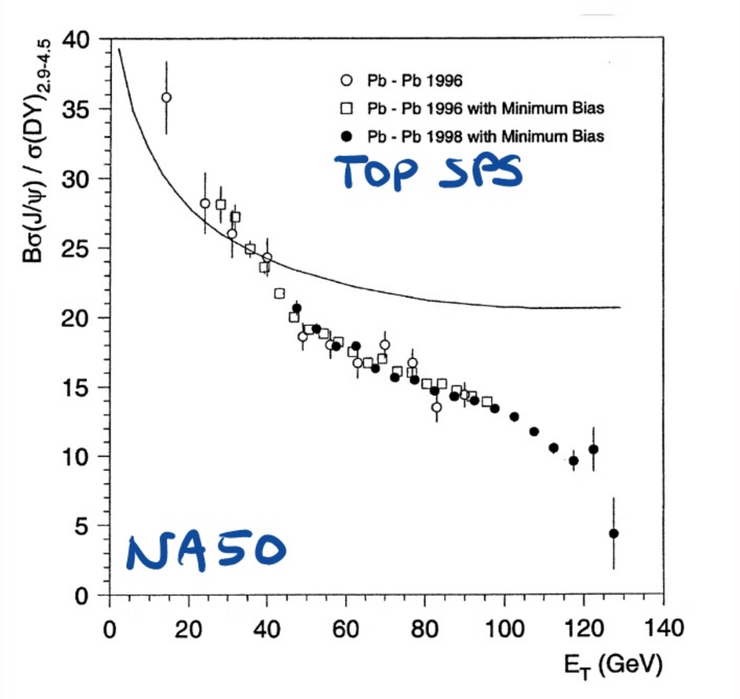
NEW RESULTS EXPECTED SOON FROM NA61/SHINE AND STAR BES II

INTERMEZZO II: CHARM PRODUCTION AND QGP

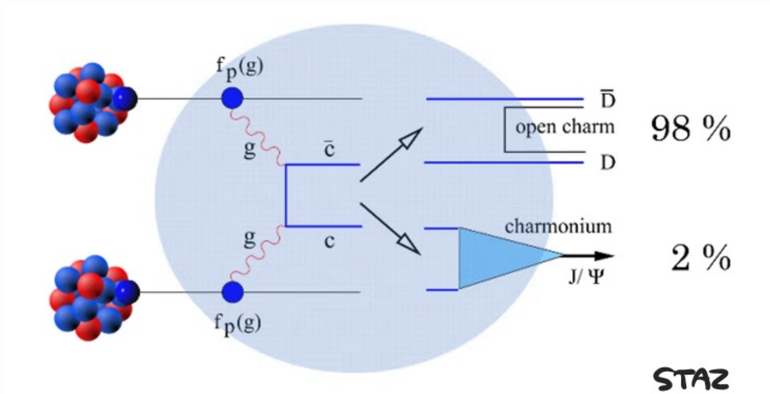
DYNAMICAL MODEL

ELEMENTARY p+p





Pb+Pb WITH QGP



BUT THERE ARE NO DATA ON D, $\bar{D}$ PRODUCTION

→ ASSUMPTION: $\langle D\bar{D} \rangle \sim \langle DY \rangle$

CROSSING THRESHOLD FOR QGP CREATION →

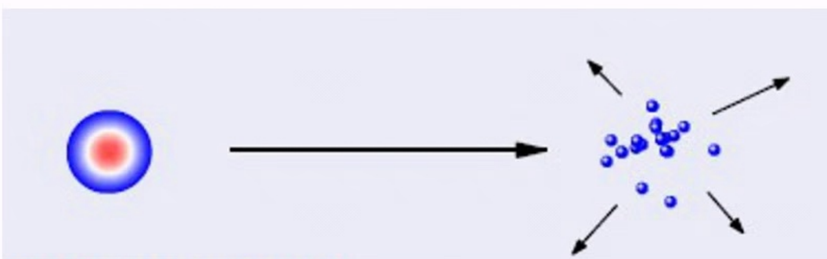
→ ANOMALOUS SUPPRESSION OF $\langle J/\psi \rangle / \langle c\bar{c} \rangle$ RATIO

MATSUI, SATZ, 1986+

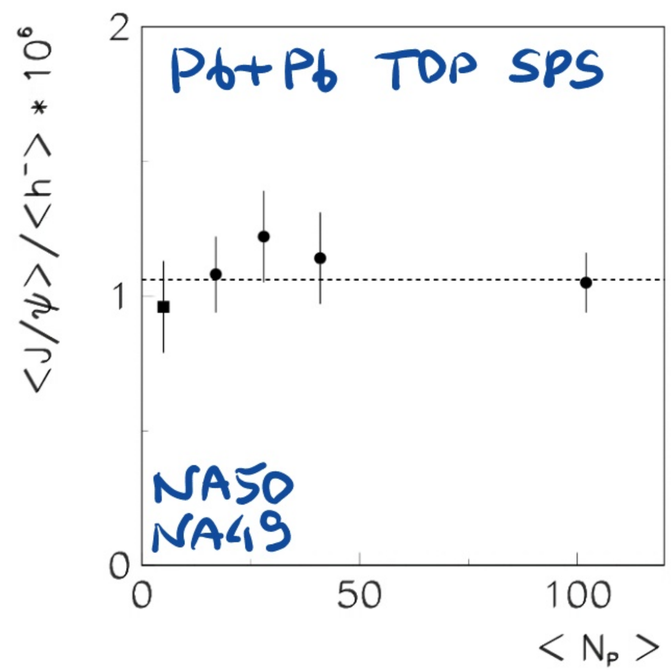
INTERMEZZO II: CHARM PRODUCTION AND QGP

STATISTICAL HADRONIZATION MODEL

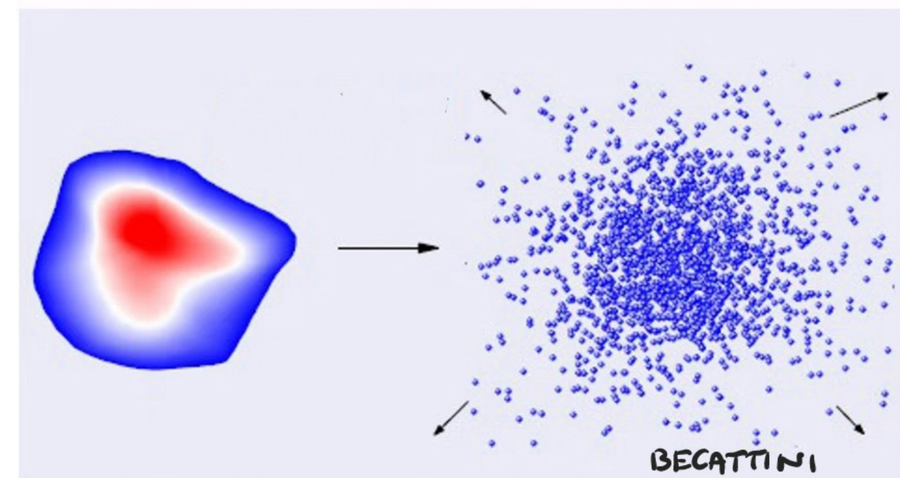
ELEMENTARY p+p



J/ψ BORN IN EQUILIBRIUM
AT $\varepsilon \approx 0.5$ GeV/fm^3



Pb+Pb WITH QGP



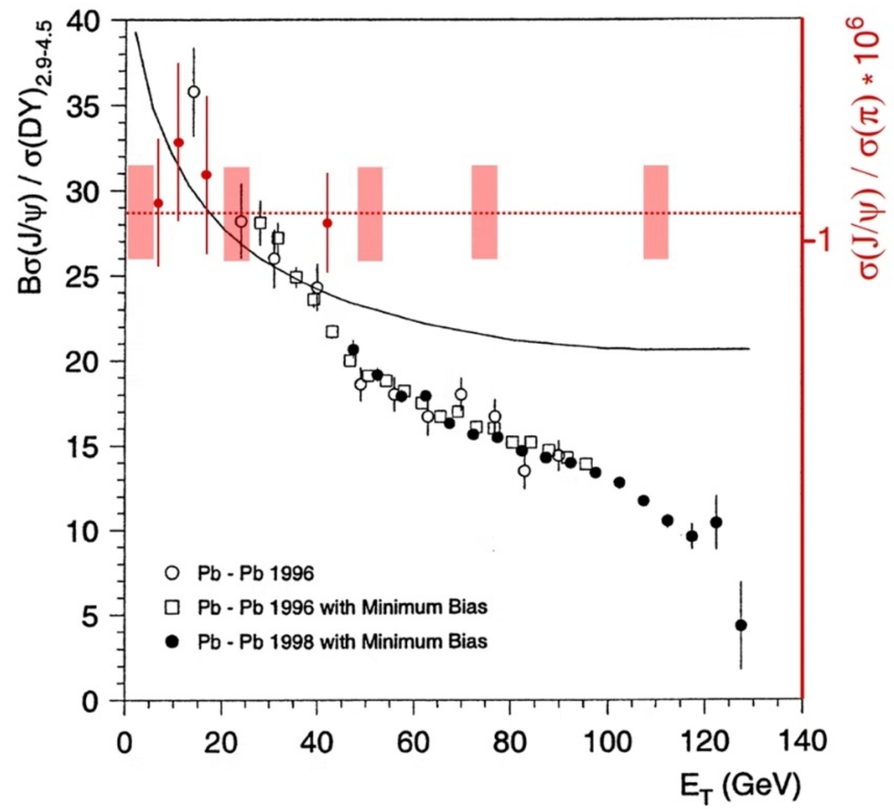
J/ψ BORN IN EQUILIBRIUM
AT $\varepsilon \approx 0.5$ GeV/fm^3

CROSSING THRESHOLD FOR QGP CREATION →
→ NO CHANGE IN $\langle J/\psi \rangle / \langle \pi \rangle$ RATIO

MG, GORENSTEIN, 1998 +

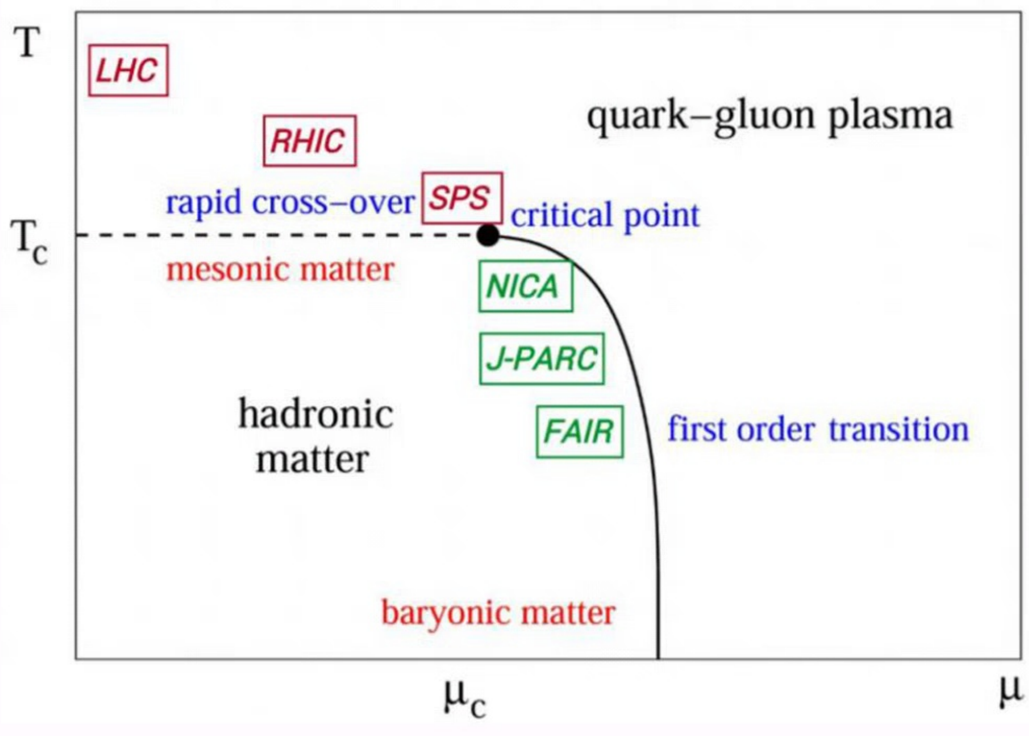
INTERMEZZO II: CHARM PRODUCTION AND QGP

DYNAMICAL VERSUS STATISTICAL HADRONIZATION MODELS



2020: DATA ON $\langle D\bar{D} \rangle$ AND $\langle J/\psi \rangle$ VERSUS COLLISION ENERGY AND NUCLEAR MASS NUMBER IS NEEDED

LANDSCAPE OF PRESENT AND FUTURE HEAVY ION EXPERIMENTS



POTENTIAL FOR DATA ON CHARM

LHC and RHIC at high energies ($\sqrt{s_{NN}} \geq 200$ GeV):
measurements in limited phase space due to collider geometry and kinematics

RHIC BES ($3 - 39$ GeV):
measurement not under consideration

NICA (< 11 GeV):
under consideration during stage 2

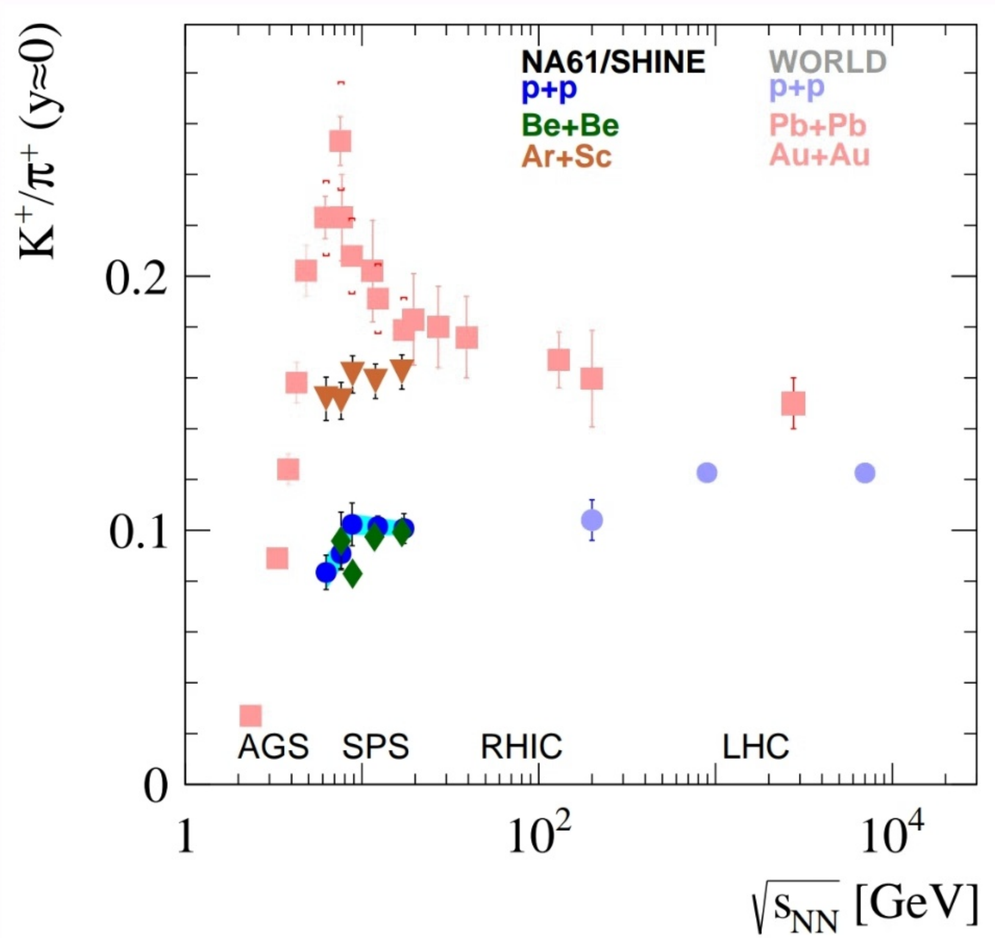
J-PARC (< 6 GeV) :
maybe possible after 2025

FAIR SIS-100 (< 5 GeV):
not possible at SIS-100,

NA61/SHINE (8, 17 GeV):
$\langle c\bar{c} \rangle$ IN 2021-2024

NA60+ (6-17 GeV):
J/ψ, $\langle c\bar{c} \rangle$ AFTER 2026

ONSET OF FIREBALL – RECENT NA61/SHINE DISCOVERY



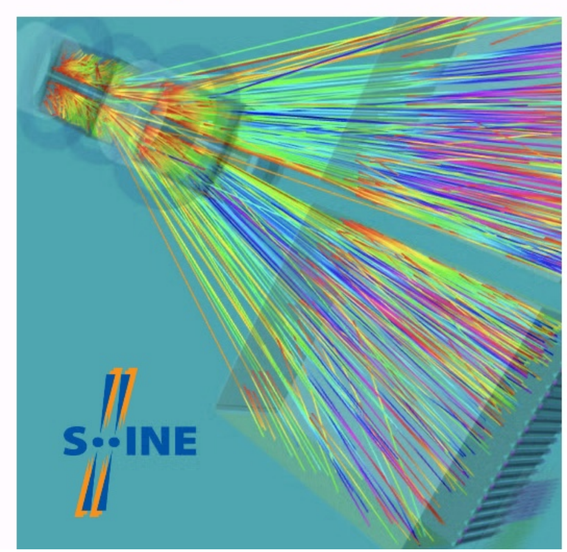
Ar+Sc ≲ ≲ Pb+Pb

Be+Be ≈ ≈ p+p

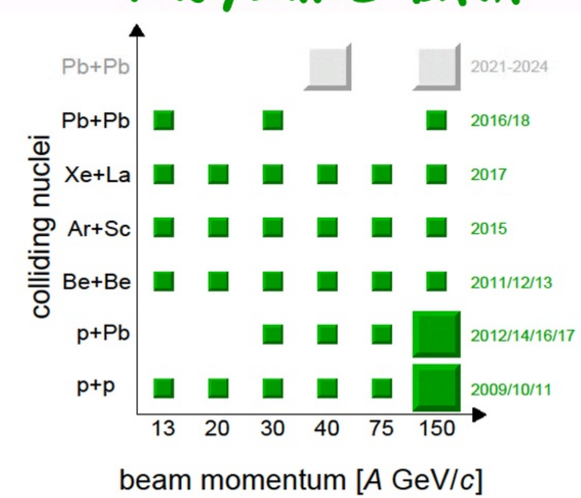
STATISTICAL MODELS

A ↑ ONSET OF FIREBALL

STRING-RESONANCE MODELS

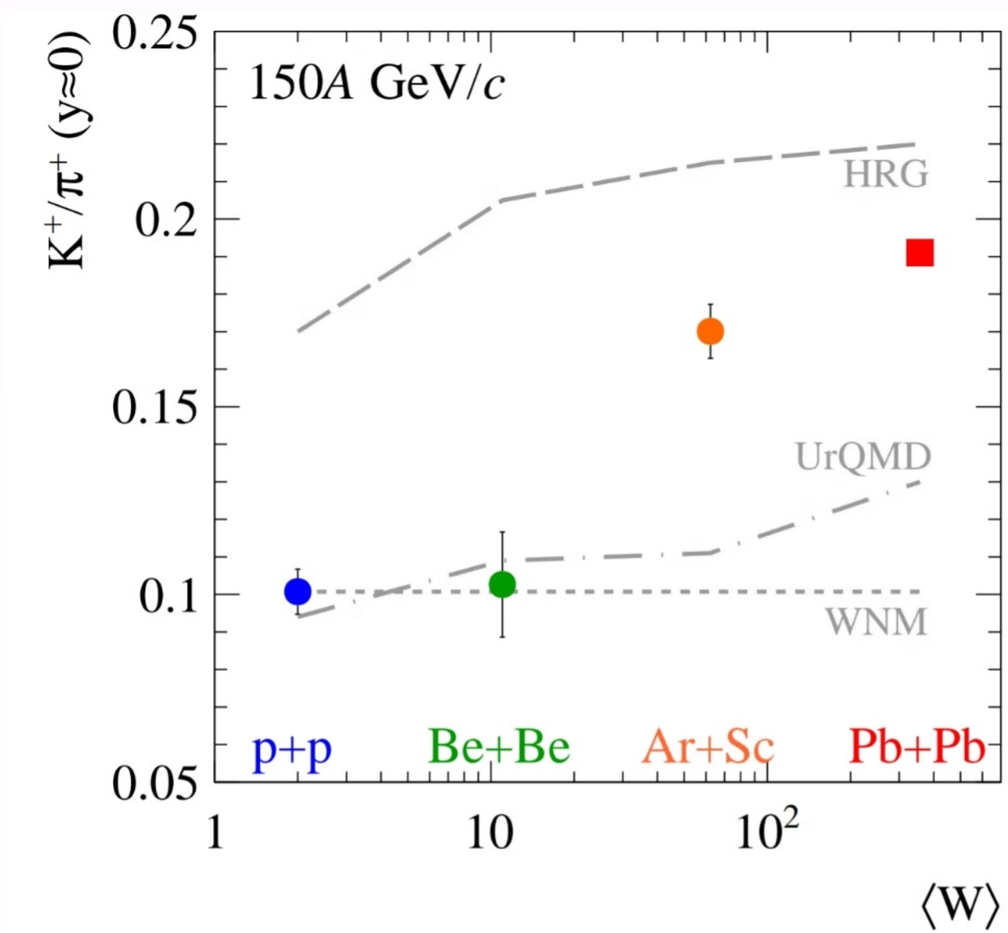


NA61/SHINE DATA



INVENTING FUTURES

ONSET OF FIREBALL – RECENT NA61/SHINE DISCOVERY



Ar+Sc ≲ ≲ Pb+Pb

Be+Be ≈ ≈ p+p

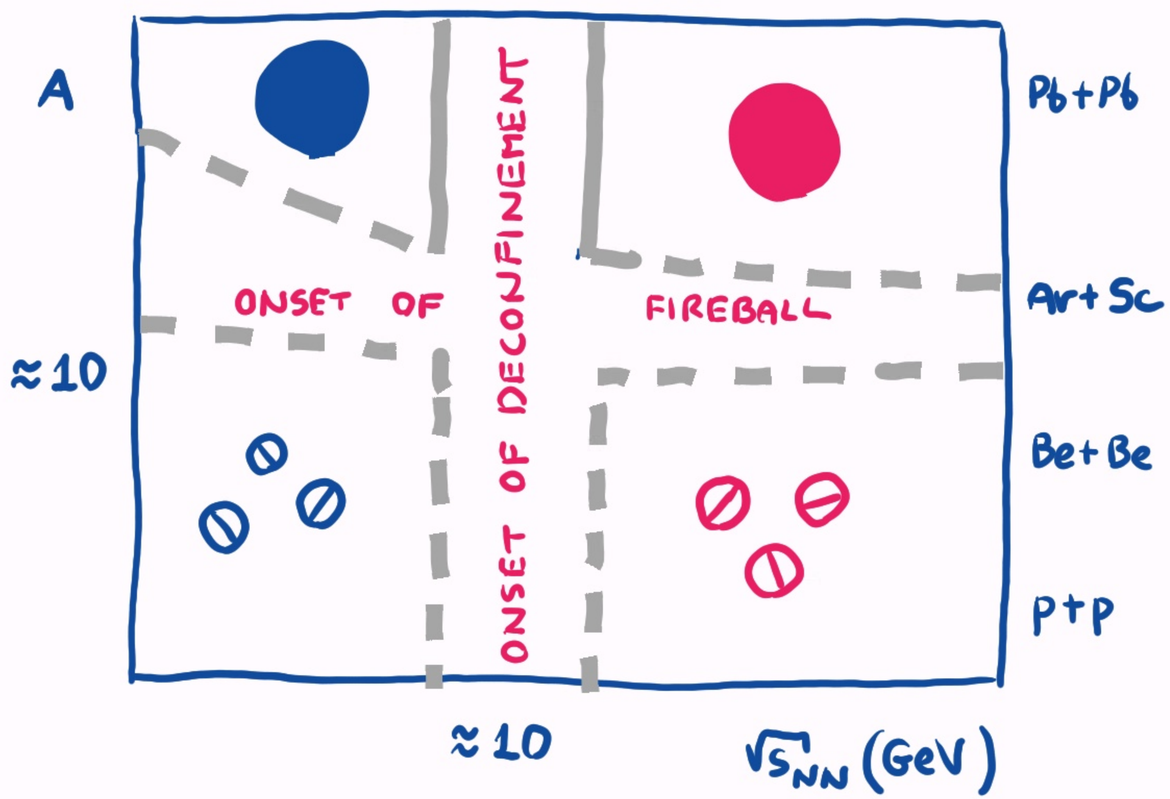
STATISTICAL MODELS

A ↑ ONSET OF FIREBAL

STRING-RESONANCE MODELS

INVENTING FUTURES

ONSET OF FIREBALL → DETAILED SCAN IN (NUCLEAR MASS NUMBER)–(COLLISION ENERGY) SHOULD BE POSSIBLE AT:



NICA (< 11 GeV); 2022+

FAIR (< 5 GeV): 2025+

SPS (5–17 GeV); 2025+

J-PARC (< 6 GeV); ?

SUMMARY

ONSET OF QGP (DECONFINEMENT):

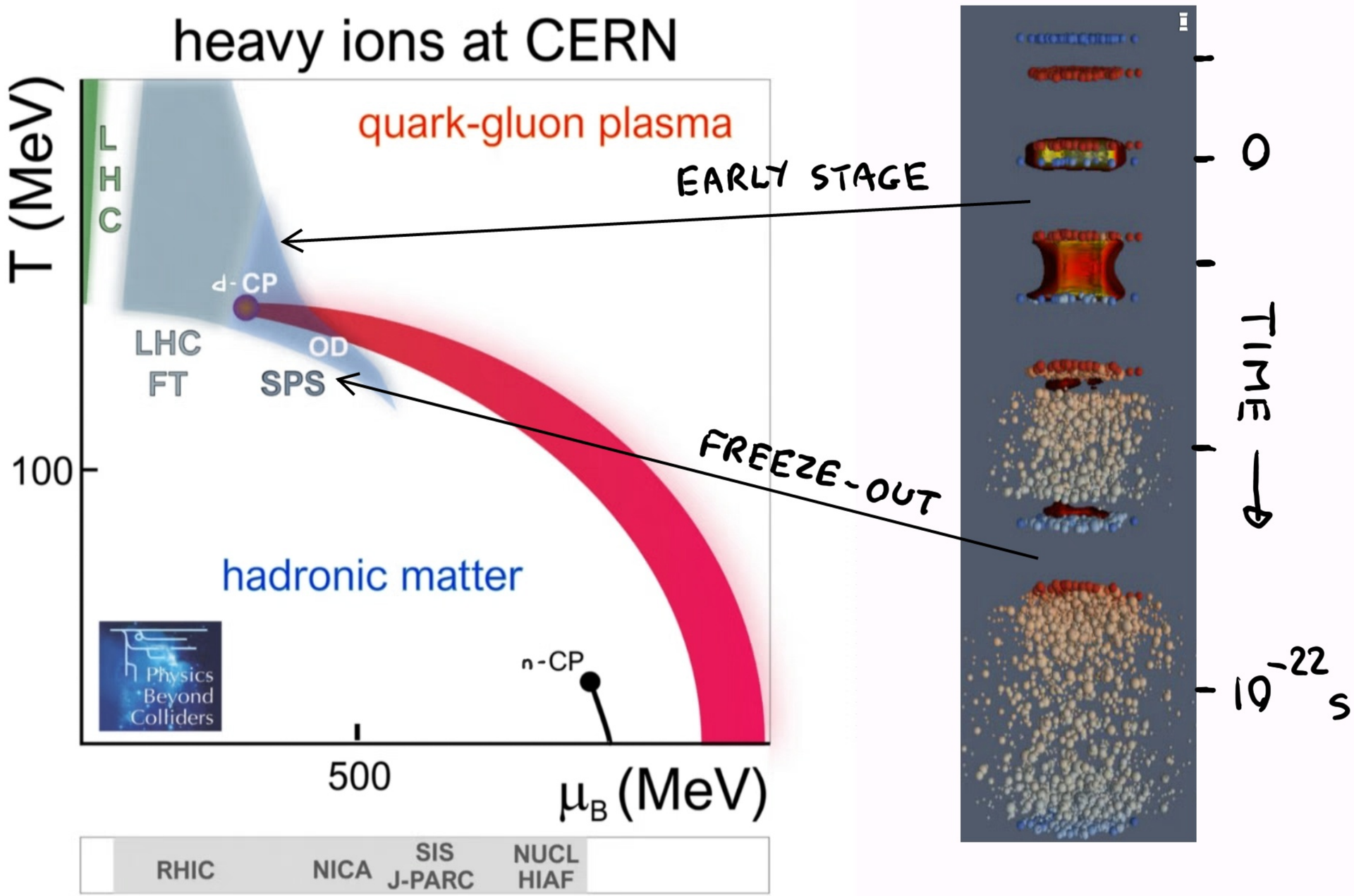
- OBSERVED IN Pb+Pb/Au+Au AT $\approx$ 8 GEV (SPS, RHIC BES)
- RESULTS TO BE COMPLETED BY CHARM ($\langle c\bar{c} \rangle$, J/ψ) MEASUREMENTS (SPS, NICA, J-PARC ?)

CRITICAL POINT:

- INCONCLUSIVE INDICATIONS FROM SPS AND RHIC
- COMING RESULTS FROM NA61/SHINE AND STAR BES II SHOULD (AT LEAST PARTLY) REMOVE THE TENSION AND ALLOW TO DEFINE NEXT STEPS

ONSET OF FIREBALL:

- INDICATIONS FROM 2D SCAN AT SPS (NA61/SHINE)
- DETAILED SCAN ($\sqrt{s_{NN}} \lesssim 20$ GEV, $A \lesssim 100$) IS NEEDED (NICA, SPS, SIS100, J-PARC ?)


heavy ions at CERN
T (MeV)
100
500
μ_B (MeV)
quark-gluon plasma
hadronic matter
LHC
LHC
FT
OD
SPS
p-CP
n-CP
Physics Beyond Colliders
RHIC
NICA
SIS
J-PARC
NUCL
HIAF
EARLY STAGE
FREEZE-OUT
0
TIME
10^{-22} s