Quark Matter 2022
Kraków

The fascinating evolution of the questions of interest in relativistic heavy ion physics

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Note: Talk is mainly about questions , not about answers
References will be quoted in the written version
Names will be used only when absolutely necessary

Acknowledgements : A very large number of experimenters and theorists in the field of relativistic heavy ion physics
Also, I learnt much from the colloquium given in 2013 at MIT by Tetsuo Matsui
and discussions with Roman Hołyński about the Kraków group

At the beginning of a Quark Matter Conference
good to ponder on:

1. Where are we ?
2. Where are we going?
3. How will we know we got there?
4. How did we get here?

- Questions 1 &2 will be answered by this conference.
- 3 will have been answered if in Feynmann Vol IV there
  is a chapter on QCD, which includes answers to most
  of today's important questions.

That leaves the last question

How did we get here?

- it’s an interesting story
- It is fun
- Much insight can be obtained from the past re the present and future, in particular, what are the really big questions, and what is just a fad

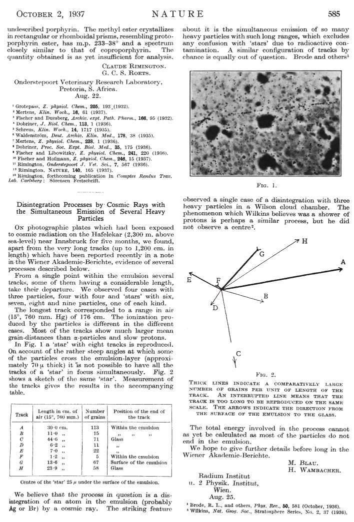
By the 1930's:

- There is the beginning of nuclear physics and discovery of strong interactions
- Visual tracking devices have been invented
- Cosmic rays are actively studied (note: by then Millikan's shackles had been removed from cosmic ray studies)

What happens when strongly interacting cosmic rays collide with nuclei?

1937 Marietta Blau places a nuclear emulsion on top of a mountain and observes a "STAR".
8 charged tracks are seen, including that of strongly interacting relativistic ones

It is the first observed AA collision (probably a pBr or pAg)



OCTOBER 2, 1937 NATURE 585

undescribed porphyrin. The methyl ester crystallizes in rectangular or rhomboidal prisms, resembling protoporphyrin ester, has m.p. 233–38° and a spectrum closely similar to that of coproporphyrin. The quantity obtained is as yet insufficient for analysis.

CLAUDE RIMINGTON.
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Pretoria, S. Africa.
Aug. 22.

[1] Grotepass, Z. physiol. Chem., 205, 193 (1932).
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[13] Rimington, forthcoming publication in Comptes Rendus Trav. Lab. Carlsberg: Sörensen Festschrift.

Disintegration Processes by Cosmic Rays with the Simultaneous Emission of Several Heavy Particles

ON photographic plates which had been exposed to cosmic radiation on the Hafelekar (2,300 m. above sea-level) near Innsbruck for five months, we found, apart from the very long tracks (up to 1,200 cm. in length) which have been reported recently in a note in the Wiener Akademie-Berichte, evidence of several processes described below.

From a single point within the emulsion several tracks, some of them having a considerable length, take their departure. We observed four cases with three particles, four with four and 'stars' with six, seven, eight and nine particles, one of each kind.

The longest track corresponded to a range in air (15°, 760 mm. Hg) of 176 cm. The ionization produced by the particles is different in the different cases. Most of the tracks show much larger mean grain-distances than α-particles and slow protons.

In Fig. 1 a 'star' with eight tracks is reproduced. On account of the rather steep angles at which some of the particles cross the emulsion-layer (approximately 70 μ thick) it is not possible to have all the tracks of a 'star' in focus simultaneously. Fig. 2 shows a sketch of the same 'star'. Measurement of the tracks gives the results in the accompanying table.

Track	Length in cm. of air (15°, 760 mm.)	Number of grains	Position of the end of the track
A	30·0 cm.	113	Within the emulsion
B	11·0 ,,	15	,, ,, ,,
C	44·6 ,,	71	Glass
D	6·2 ,,	11	,,
E	7·0 ,,	22	,,
F	1·2 ,,	5	Within the emulsion
G	13·6 ,,	67	Surface of the emulsion
H	23·9 ,,	58	Glass

Centre of the 'star' 25 μ under the surface of the emulsion.

We believe that the process in question is a disintegration of an atom in the emulsion (probably Ag or Br) by a cosmic ray. The striking feature about it is the simultaneous emission of so many heavy particles with such long ranges, which excludes any confusion with 'stars' due to radioactive contamination. A similar configuration of tracks by chance is equally out of question. Brode and others[1] observed a single case of a disintegration with three heavy particles in a Wilson cloud chamber. The phenomenon which Wilkins believes was a shower of protons is perhaps a similar process, but he did not observe a centre[2].

FIG. 1.

FIG. 2.

THICK LINES INDICATE A COMPARATIVELY LARGE NUMBER OF GRAINS PER UNIT OF LENGTH OF THE TRACK. AN INTERRUPTED LINE MEANS THAT THE TRACK IS TOO LONG TO BE REPRODUCED ON THE SAME SCALE. THE ARROWS INDICATE THE DIRECTION FROM THE SURFACE OF THE EMULSION TO THE GLASS.

The total energy involved in the process cannot as yet be calculated as most of the particles do not end in the emulsion.

We hope to give further details before long in the Wiener Akademie-Berichte.

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Aug. 25.

[1] Brode, R. L., and others, Phys. Rev., 50, 581 (October, 1936).
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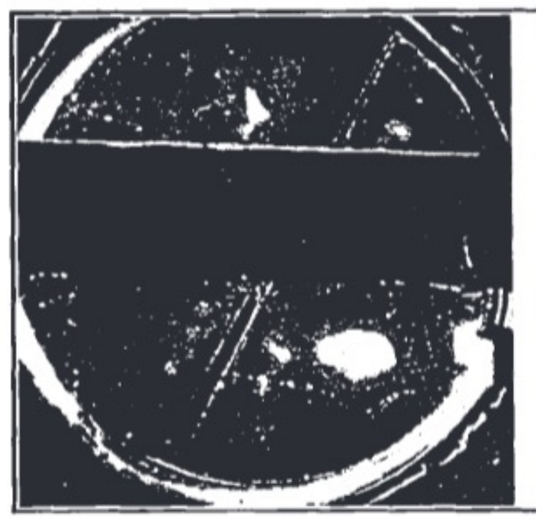
≳ 1938, in a Wilson cloud chamber, example of the production of ≥ 2 strongly interacting and penetrating particles (hadrons) produced together at a point



1938 – 1947:

Fascinating exchange between non-other than Heisenberg, Heitler and Janossy

What is the mechanism of particle production?

- Multiparticle production does occur in pp collisions
- pA collisions are interesting in themselves. The (very strong) interactions lead to sequential collisions inside nuclei

- Many of the (physics) “gods” of the day are interested in this question; Fermi, Heisenberg, Landau, Oppenheimer, to name few

1940's & 1950's:

The discussions and questions asked are not that different from those to-day

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Is particle production a fast process? Is it a slow process?
Since the interactions are so strong do particles stop each other?
If so, what is the initially created system?

- In early 1940's : Heisenberg and Oppenheimer view particle production a consequence of colliding fields. Production times are ≫ collision times, with low momentum particles produced isotropically and fast particles produced more forward and backward.

- In late 1940's and early 1950's: Fermi visualizes complete stopping and production of a boson gas which is in thermal equilibrium. During expansion, energy and number of particles remain constant. Landau visualizes the same beginning but system continuous to interact during a relativistic hydrodynamical expansion

- By late 1950's: Hagedorn considers the increase in the number of possible produced states, as one increases the energy of colliding particles, and concludes that the temperature of the produced hadronic system must reach a limiting value

1960’s and early 1970:

- We are in Kraków, so what were the questions asked here at that time?
- There was a very dynamic group led by Marian Mięsowicz
- Studied pA interactions using “discarded by HEP “ nuclear emulsions.

Why pp and pA are so similar?
What is the time of formation of particles?
How do newly produced particles interact? Transparent yet strongly interacting!
Do pA studies teach us something about pp physics or vice versa?
How to analyze AA data in terms of pp?

Fantastic atmosphere attracted theorists such as Białas and Czyż, who became instrumental in converting a quantum mechanical analysis of elastic pA collisions into a useful technique, the so-called “Glauber Method”

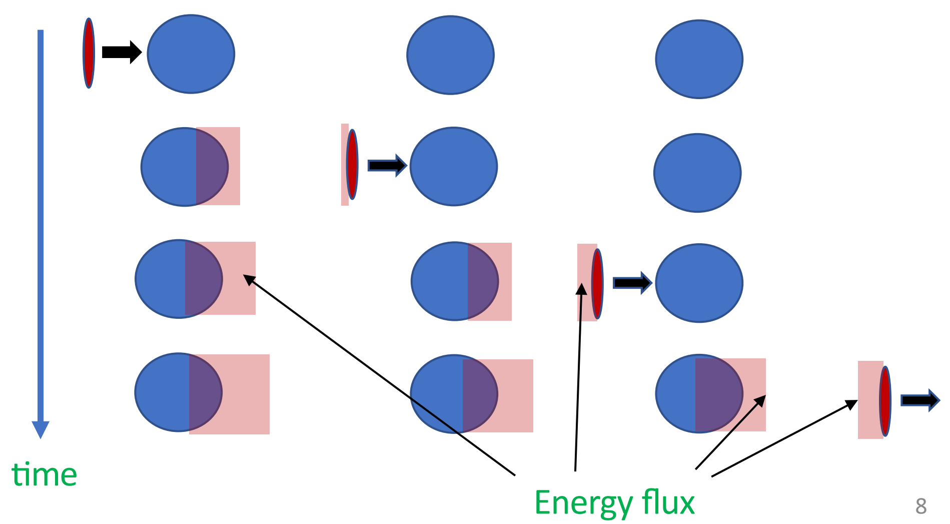
Early 1970's:

- accelerators, particularly Fermilab, replace cosmic rays
- have well defined beams and targets
- Lead to quantitative studies of pA collisions

What is the space-time picture of particle production, from instant of impact to final free streaming particles?
What are the properties of the intermediate state?

- "participant" is a useful concept
- participant scaling
- extended longitudinal scaling
- realization of the importance of relativity (that the collision looks very different in different reference frames)

Eg Gottfried's energy flux cascade model for **pA** in **A's** frame



1960's (in parallel with the HEP nuclear studies):

- Discovery of neutron star (1967)
- GeV/u accelerators study motion and breakup of nuclear matter inside nuclei & EoS
- Lee & Wick postulate new kind of abnormal vacuum and nuclear matter

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What happens if you compress, distort or breakup nuclear matter?
Does superdense nuclear matter exist?
Are there different kinds of vacua?

In 1974 these questions lead to a very influential meeting - the so-called "Bear Mountain Meeting"

Mid 1970's:

There are two communities that almost do not talk to each other, yet are asking highly related questions

---

What is the system produced immediately after a collision of hadrons?
What is the system produced when nuclei are highly compressed?

T.D.Lee, 1974:

"So far almost all our nuclear physics experiments have been restricted to nuclei at a constant density. We have never ventured out to study nuclear physics at any densities other than the normal one.

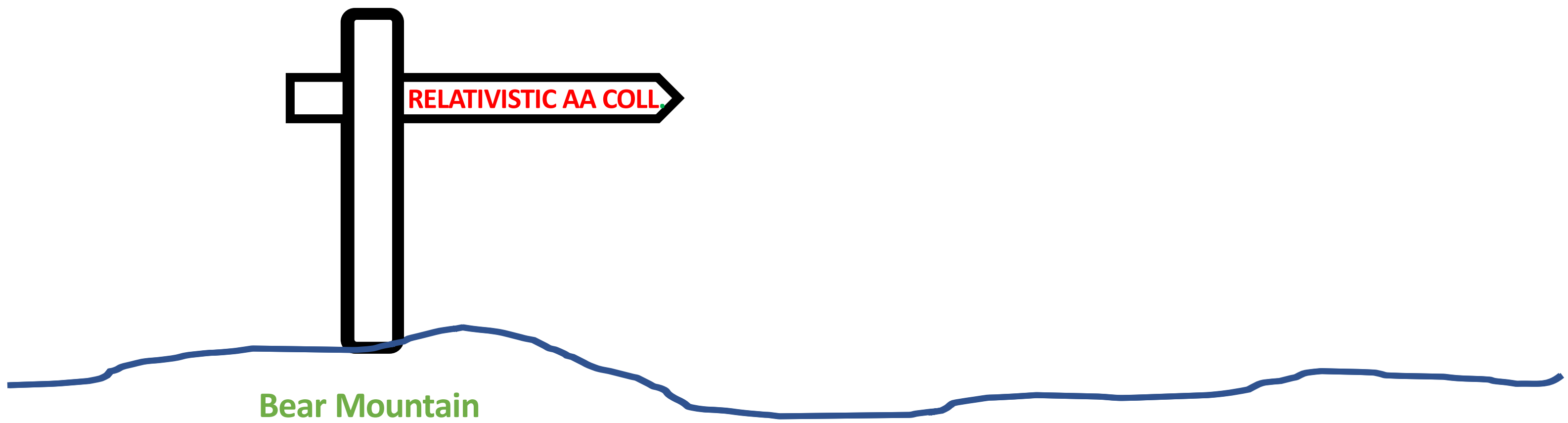
Likewise

in particle physics … hitherto, we have concentrated only on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions …

We should investigate some "bulk" phenomena by distributing high energy or high nucleon density of a relatively large volume.

The fact that such directions have never been explored should, by itself, serve as an incentive for doing such experiments".

1974: Guidance where to go



Timing was perfect!

In theory, there was the parton/QCD revolution – a paradigm shift
In experiment, unexpected results – EMC and Cronin Effects & transparency of coherently produced states

All of which led to some very sexy questions, such as:

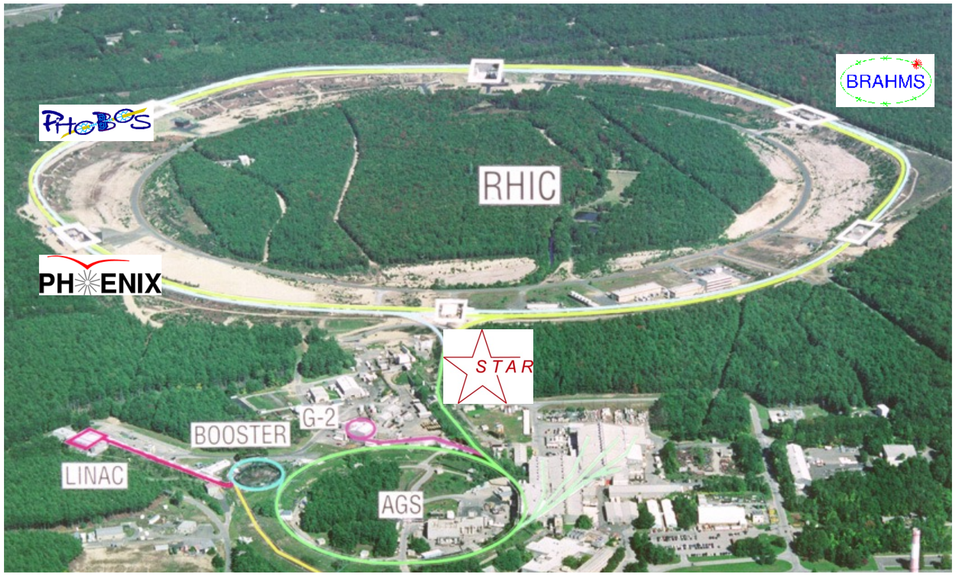
Can confined quarks be liberated?
Can we recreate on earth the conditions that existed in the early universe?
Can we produce some new kinds of matter and abnormal vacua?
Are free nucleons different from those in nuclei?

- Lab directors saw the possibilities of extra funding for their labs!
- Ambitious physicists smelled gold!
- Meetings sprung up as mushrooms!
- There was no shortage of speculations re the QCD phase diagram and the space-time picture of hadronic collisions
- Terms like Quark Soup, QGP etc. were coined up
- There was a colossal expansion of the field

- In short it was the beginning of a renaissance period for our field.

The best example

CBA (ISABELLE) tunnel 1983
Empty and unfunded



RHIC Complex 2000

Late 1970's and early 1980's:

Focus shifts to practical questions

What are the needed energy densities?

What are the needed baryon (or nuclear matter) densities?

For how long must they last to be interesting, achievable and detectable?

What is the stopping power of nuclei?

Which existing accelerators can produce interesting AA results?

What new accelerators need to be built?

How do we detect new physics?

What detectors need to be built and what measurements made?

It leads to vigorous AA research programs at:

- AGS 1986-97
- SPS 1986-99
- RHIC ≥ 2000

to crucial progress in "QCD on the lattice" calculations

and exciting ideas and speculations such as: existence of DCC's, of color superconductor states, of chiral magnetic effects, analogies with cold atoms phenomenology and string theory.

1990's and early 2000's:

A flood of interesting AA data

Lattice calculations and data suggest that sufficient energy and temperature are achieved to produce a QGP

Has a QGP been produced?
If so, which Laboratory saw it first?
Who can claim discovery?

An ideal gas of weakly interacting quarks and gluons has not been produced
- For that we will have to go to asymptotically high energy densities or temperatures, comparable to those in the early universe

The second two questions are therefore mute!

2000’s:
As you all know, something much more interesting is found to exist at high energy densities and temperatures
- an extremely strongly interacting system which flows remarkably well
- which has no end of interesting properties that need studying

How do we explain to our colleagues and funding agencies that we have not produced the weakly interacting QGP, a QCD phase we said must exist and we know how to produce?

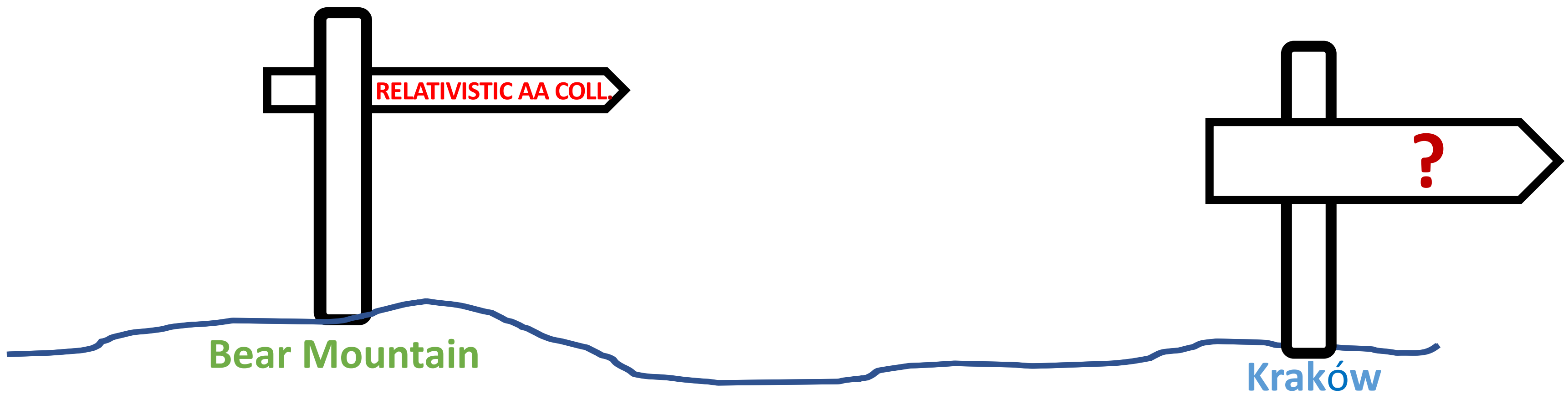
No Problem!
- We simply redefined the QGP; as the fascinating QCD system which we produced

2022:

I find it so fascinating that many of the questions we are asking today are not that different from those asked in the past

Past & Present questions	What is the mechanism of particle production, from the instant of impact to the free streaming of hadrons? What is the space time evolution of particle production? What is the complete phase diagram of the condensed matter of QCD? What are the properties of all the phases? . .
Present questions	Questions that you know better than I . .
My question	At a little later than a microsecond after the big bang the hadronic part of the universe consisted of an ideal gas of non interacting quarks and gluons. How did structure begin to evolve from such a structureless system? Is it vacuum fluctuations magnified by gravity, analogous to the creation of galaxies?

2022: We need guidance, in simple & exciting language, of where to go



To the organizers:

Thank you for giving me the opportunity to share with you this exciting story

& for organizing this conference, in such difficult circumstances