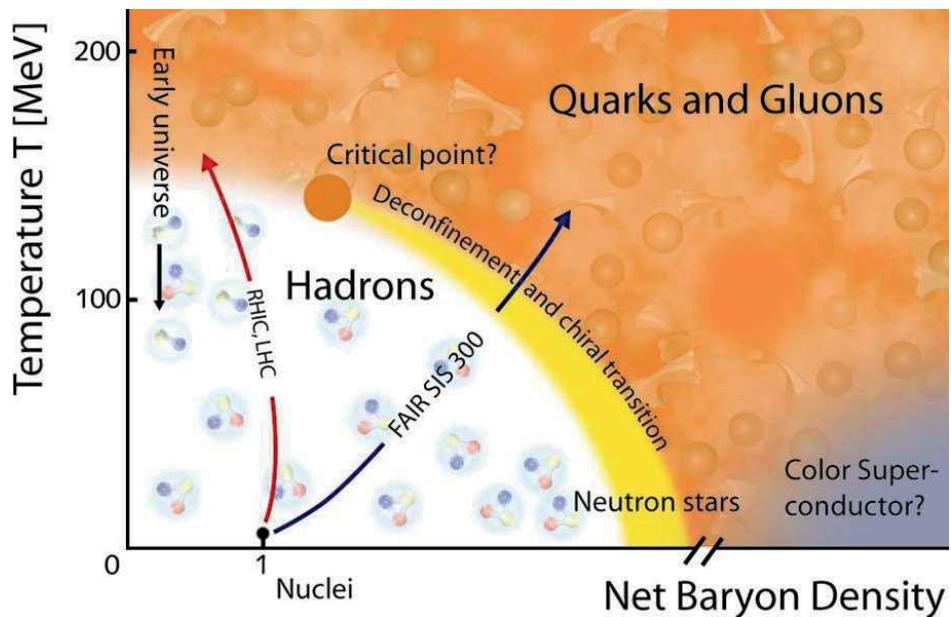


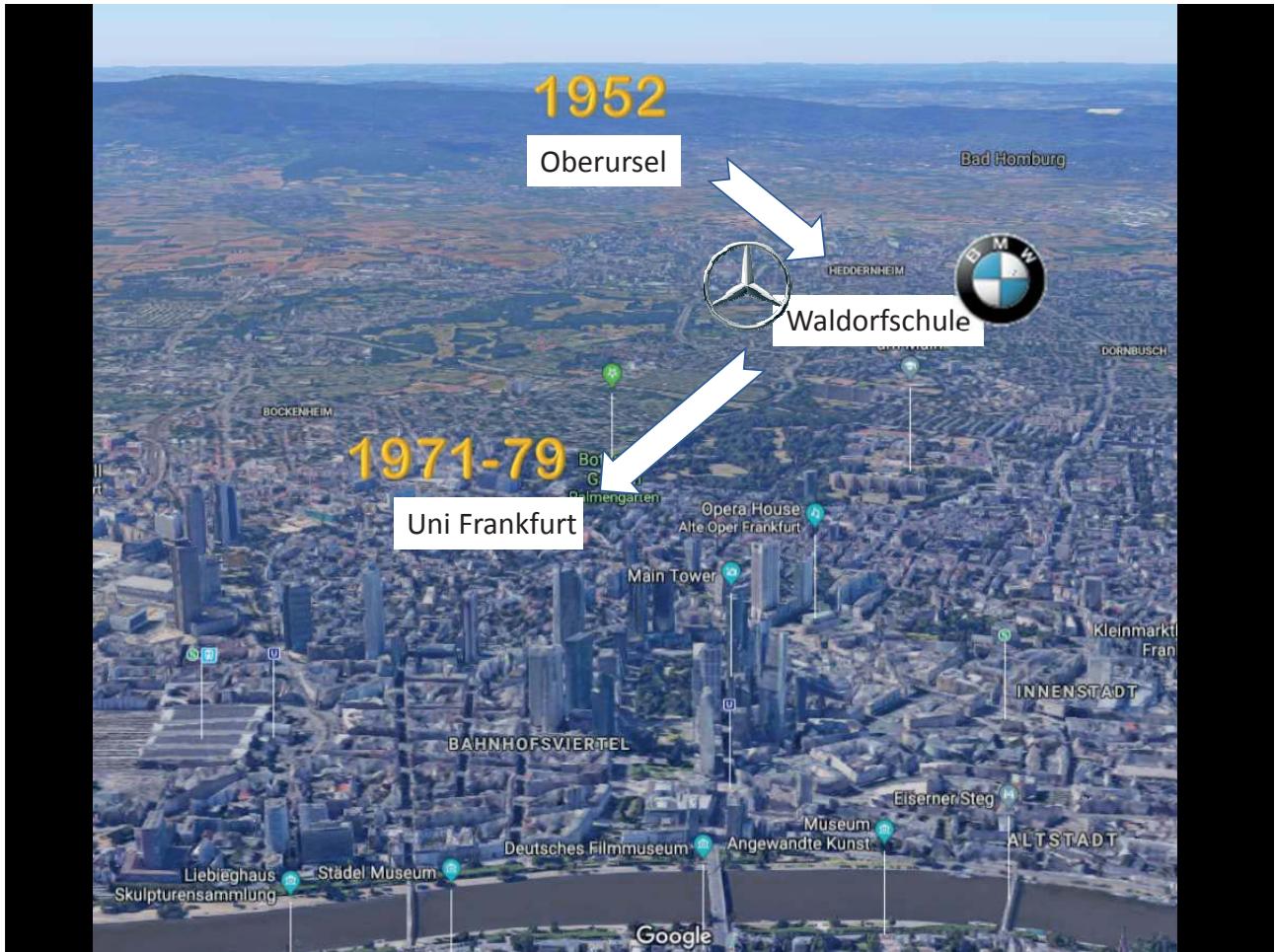
# The Nuclear Equation of Stateöcker

Emeritierungskolloquium



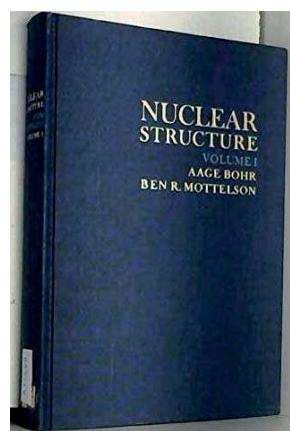
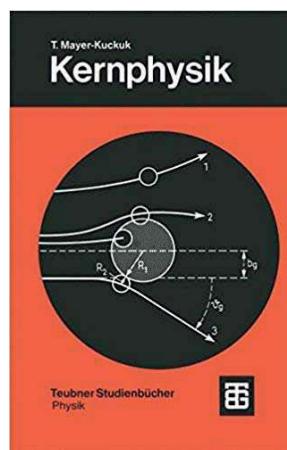
Prof. Dr. Dr. h.c. mult. Horst Stöcker





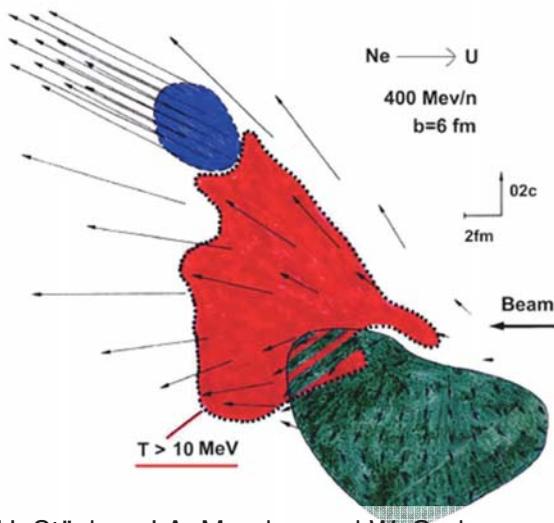
## Nuclear Physics B.S. (before Stöcker)

- Shell Model
  - 1p 1h, 2p 2h, ... excitations
- Collective rotations and vibrations
- Fission & Fusion, alpha, beta, gamma
- Compound nucleus
- Droplet Model
- Fermi-gas model
- Scattering
  - Partial waves
  - Optical potential
  - Deep-inelastic
  - DWBA



# Horst's Dissertation

- Hydrodynamics
- “Shock waves in nuclear matter – proof by circumstantial evidence”



H. Stöcker, J.A. Maruhn, and W. Greiner,  
PRL 44, 725 (1980)

218 citations (!) as of yesterday

Z. Physik A 286, 121–122 (1978)

Zeitschrift  
für Physik A  
© by Springer-Verlag 1978

## Short Note

### Dependence of Particle Production in High Energy Heavy Ion Collisions on the Nuclear Equation of State

Horst Stöcker and Walter Greiner  
Institut für Theoretische Physik der Johann Wolfgang Goethe Universität,  
Frankfurt am Main

Werner Scheid  
Institut für Theoretische Physik der Justus Liebig Universität, Gießen

135 citations (!) as of yesterday

### • Frankfurter Schule:

- A completely new way to look at nuclear physics and nuclear collisions



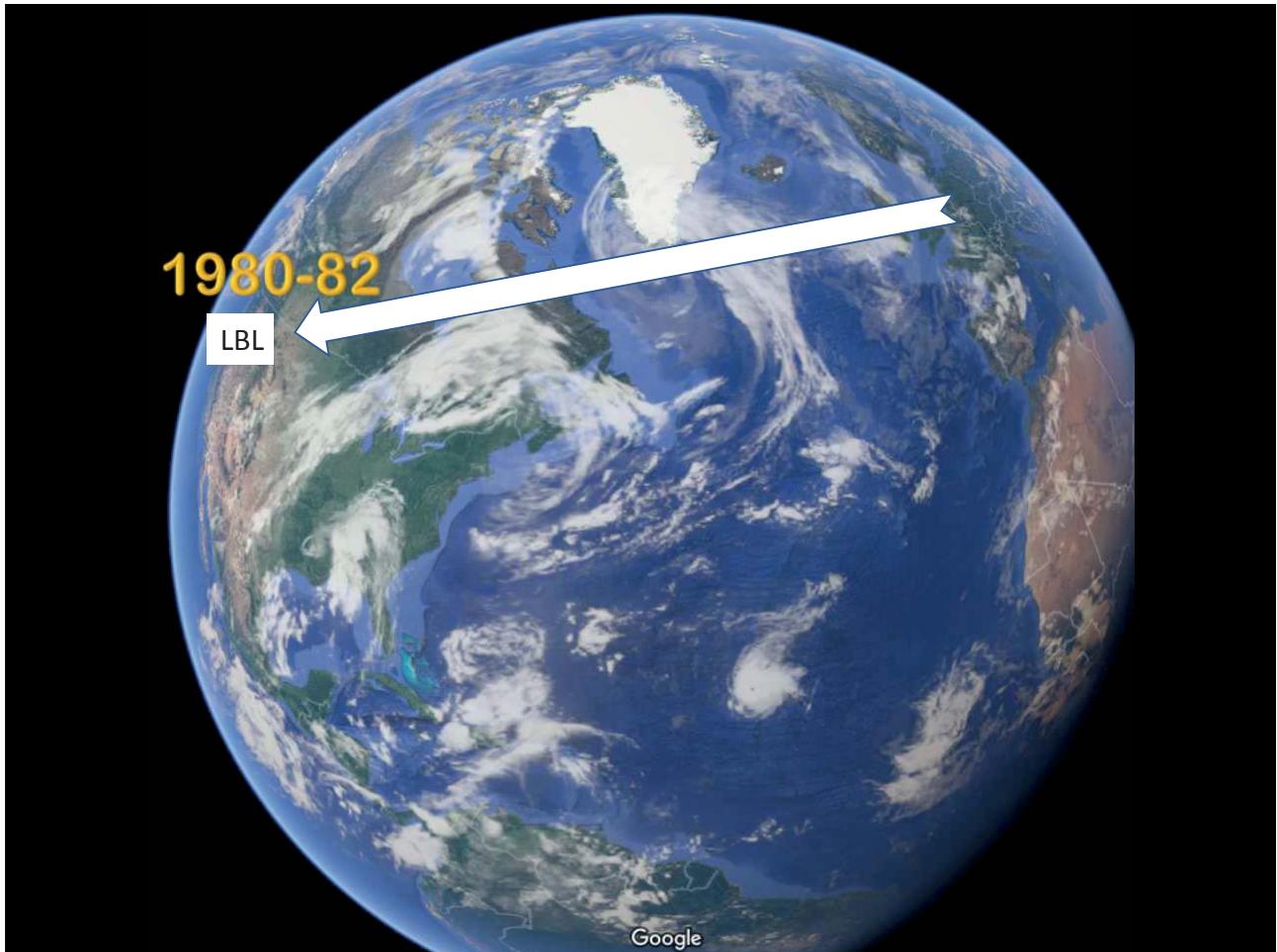
SciFri

9 October 2018

W.B. 4 H.S.

5





## Relativistic Heavy Ion Physics in Berkeley

- 1954: Bevatron – built for the discovery of the antiproton
- 1957: HILAC – Heavy Ion Linear Accelerator
- 1971: SuperHILAC
- 1974: Bevalac
  - Use SuperHILAC as injector for Bevatron
  - Allowed heavy ions to be accelerated to relativistic energies ( $\sim 1 \text{ A}\cdot\text{GeV}$ )
  - Exploration of new states of matter
  - Mapping of the phase diagram, the Nuclear Equation of State
  - Important collaboration with GSI
- Terminated 1992/3
- Relativistic Heavy Ion Physics moved on to AGS-BNL, CERN-SPS, SIS-GSI, RHIC, LHC, ... (in a few years)  
**FAIR**



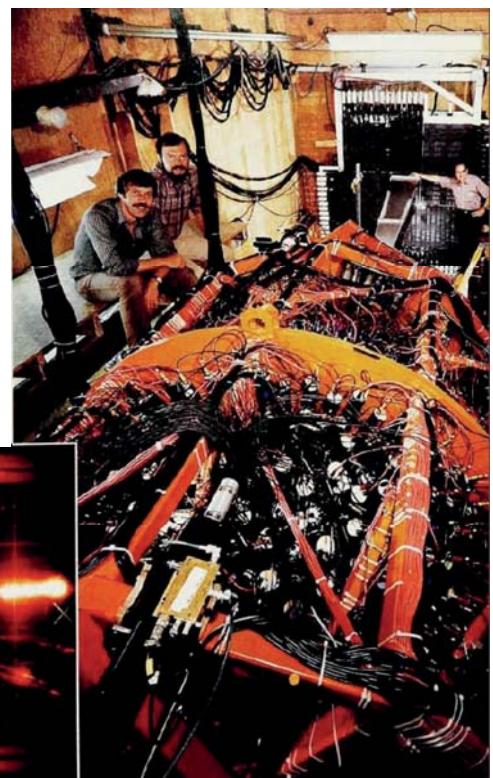


Photo credit: John Harris

## Experiments at the Bevalac

- Main Detectors
  - Plastic Ball (Shown here with Art Poskanzer, Hans-Georg Ritter, and Hans Gutbrod)
  - Streamer Chamber (Reinhard Stock, John Harris)
- Main Observables
  - Pion production
  - Multifragmentation
  - Collective flow
- Exploration of the **Nuclear Equation of State**

S. Das Gupta &  
G.D. Westfall  
Physics Today  
46(5), 34 (1993)



# What is an “Equation of State”?

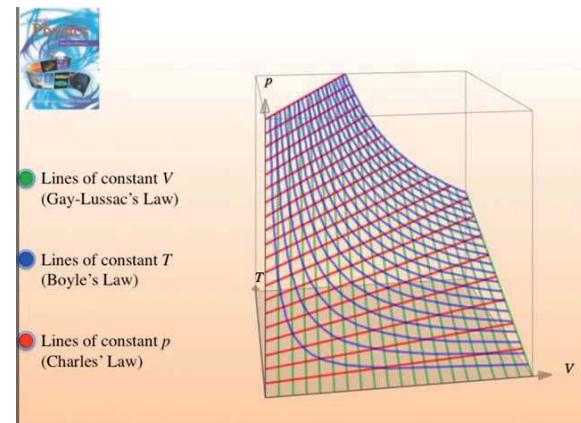
- **State Variables:** pressure  $p$ , temperature  $T$ , density  $\rho$  (internal energy, chemical potential, strangeness, ...)
- **Equation of State:** relationship between state variables,

$$f(p, T, \rho) = 0$$

- Thermodynamic equation describing state of matter under given physical conditions
- Example: Ideal gas:  

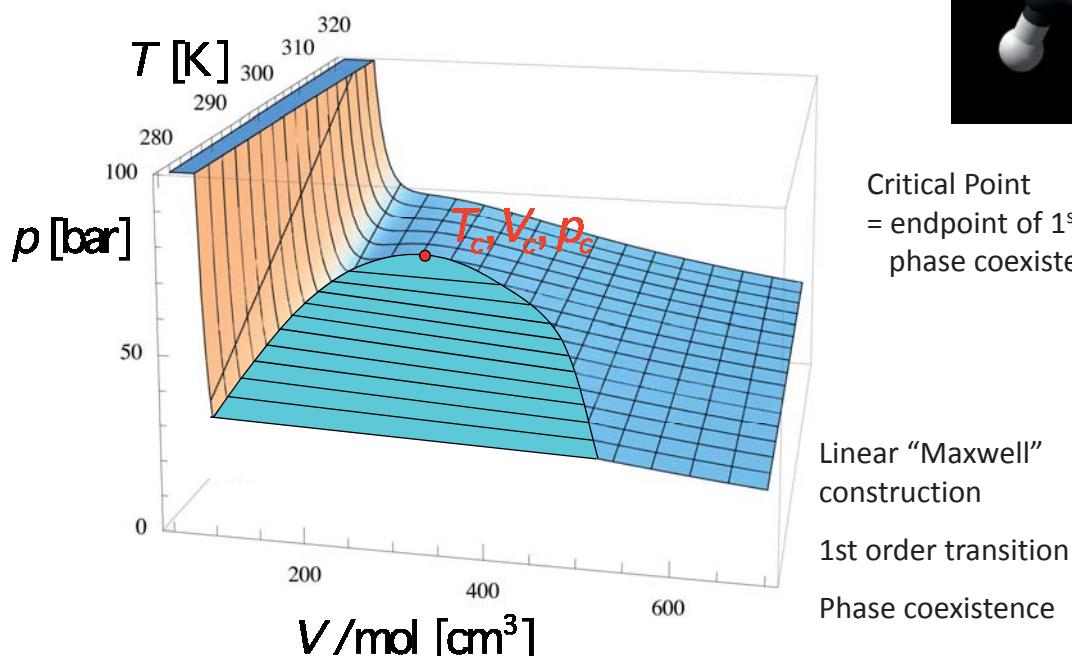
$$pV = nRT$$
- Example: Ultra-relativistic fluid:  

$$p = c_s^2 \epsilon$$
- More realistic equations of state need to contain phase transitions, coexistence regions, critical points, ...



## EoS for $C_2H_6$ (Ethane)

- Soave Redlich Kwong EoS,  $p(T, V)$



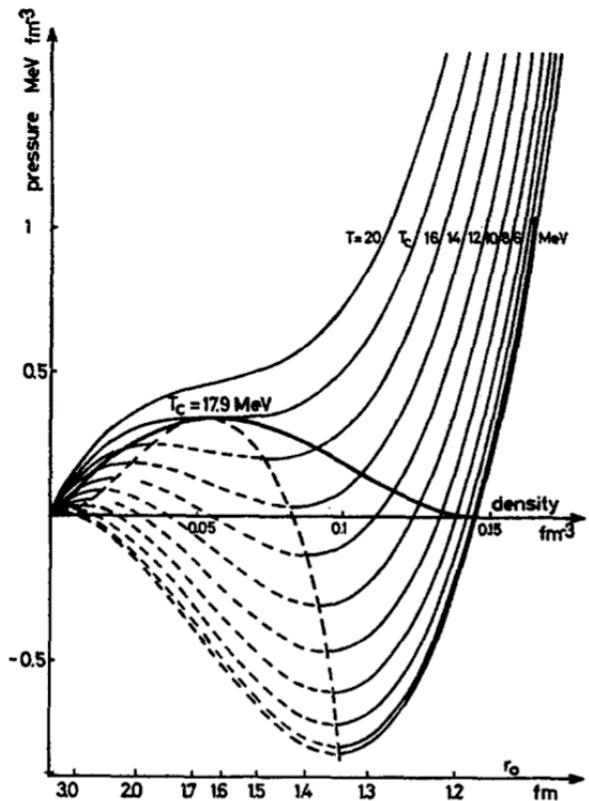
Critical Point  
= endpoint of 1<sup>st</sup> order  
phase coexistence

Linear “Maxwell”  
construction  
1<sup>st</sup> order transition  
Phase coexistence

## Nuclear EoS

- Can be computed, if you know nuclear force
- Here: Skyrme
  - Note:  
Coexistence region,  
critical point.

(Sauer, Chandra, Mosel,  
NPA 264 (1976) )

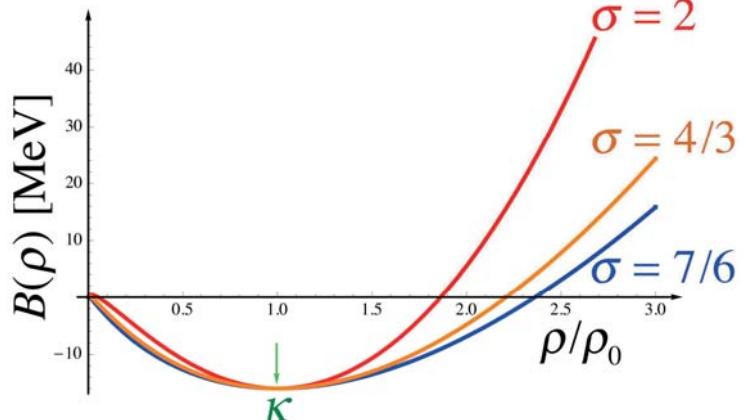


## Nuclear Matter Compressibility

- Curvature at minimum of binding energy (= at nuclear matter density, for temperature 0)

$$k_F^2 \frac{d^2 B(\rho)}{dk_F^2} \Big|_{\rho=\rho_0}$$

- Astrophysical relevance
- Isospin dependence



# Compressibility from Nuclear Collisions

- Not so easy!



- Final momenta determined by initial momenta and energy and momentum conservation
- Compressibility of spring between carts never entered!

# Compressibility from Pion Multiplicity

VOLUME 58, NUMBER 5

PHYSICAL REVIEW LETTERS

2 FEBRUARY 1987

## Pion Production in High-Energy Nucleus-Nucleus Collisions

J. W. Harris, G. Odyniec, H. G. Pugh, L. S. Schroeder, and M. L. Tincknell  
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

W. Rauch and R. Stock  
Fachbereich Physik, University of Frankfurt, Frankfurt, West Germany

R. Bock, R. Brockmann, A. Sandoval, and H. Ströbele  
Gesellschaft für Schwerionenforschung, Darmstadt, West Germany

R. E. Renfordt and D. Schall  
University of Heidelberg, Heidelberg, West Germany

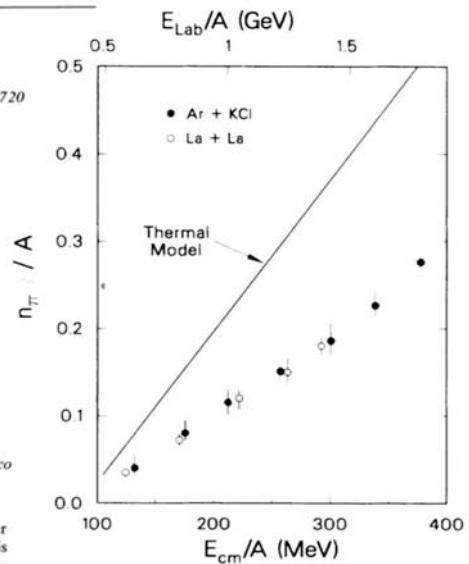
D. Bangert<sup>(a)</sup>  
University of Marburg, Marburg, West Germany

J. P. Sullivan and K. L. Wolf  
Texas A&M University, College Station, Texas 77843

and

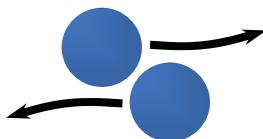
A. Dacal, C. Guerra,<sup>(b)</sup> and M. E. Ortiz  
Instituto de Fisica, Universidad Nacional Autónoma de México, Mexico City, 21 Distrito Federal, Mexico  
(Received 18 August 1986)

Negative-pion multiplicity  $\langle n_\pi \rangle$  was measured over the range of participant nucleon number  $80 \leq A \leq 270$  for incident energies from 530 to 1350 MeV/nucleon in the La+La system. The  $\langle n_\pi \rangle$  is proportional to  $A$  and increases linearly with the c.m. energy. Thermal and potential energies, and temperatures of the maximum-density phase of the collision are extracted from the data. The results require a stiff nuclear-matter equation of state.

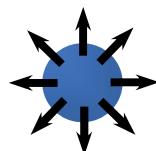


# Compressibility from Flow

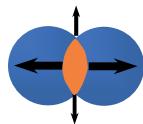
- Directed (sideways in reaction plane)



- Radial (like monopole)



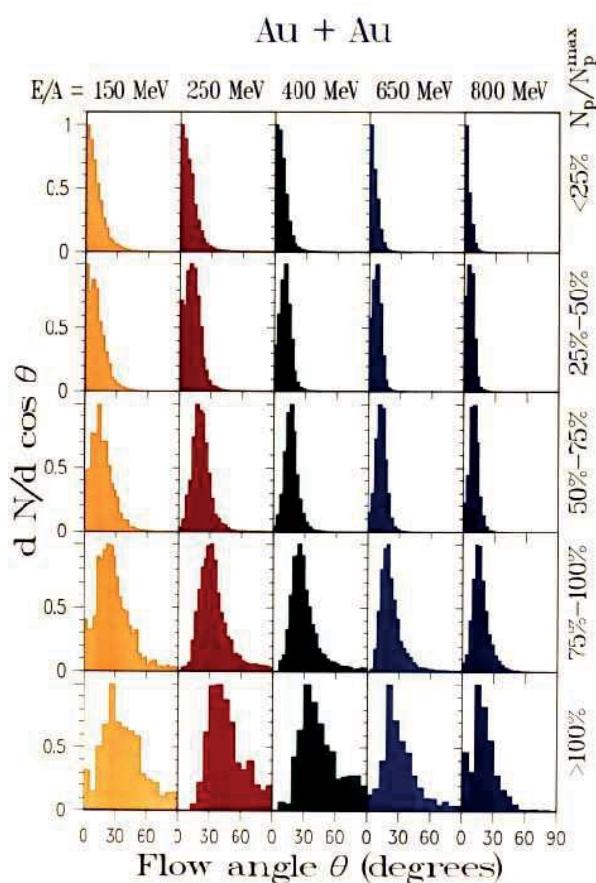
- Elliptic ( $v_2$ ), Squeezeout

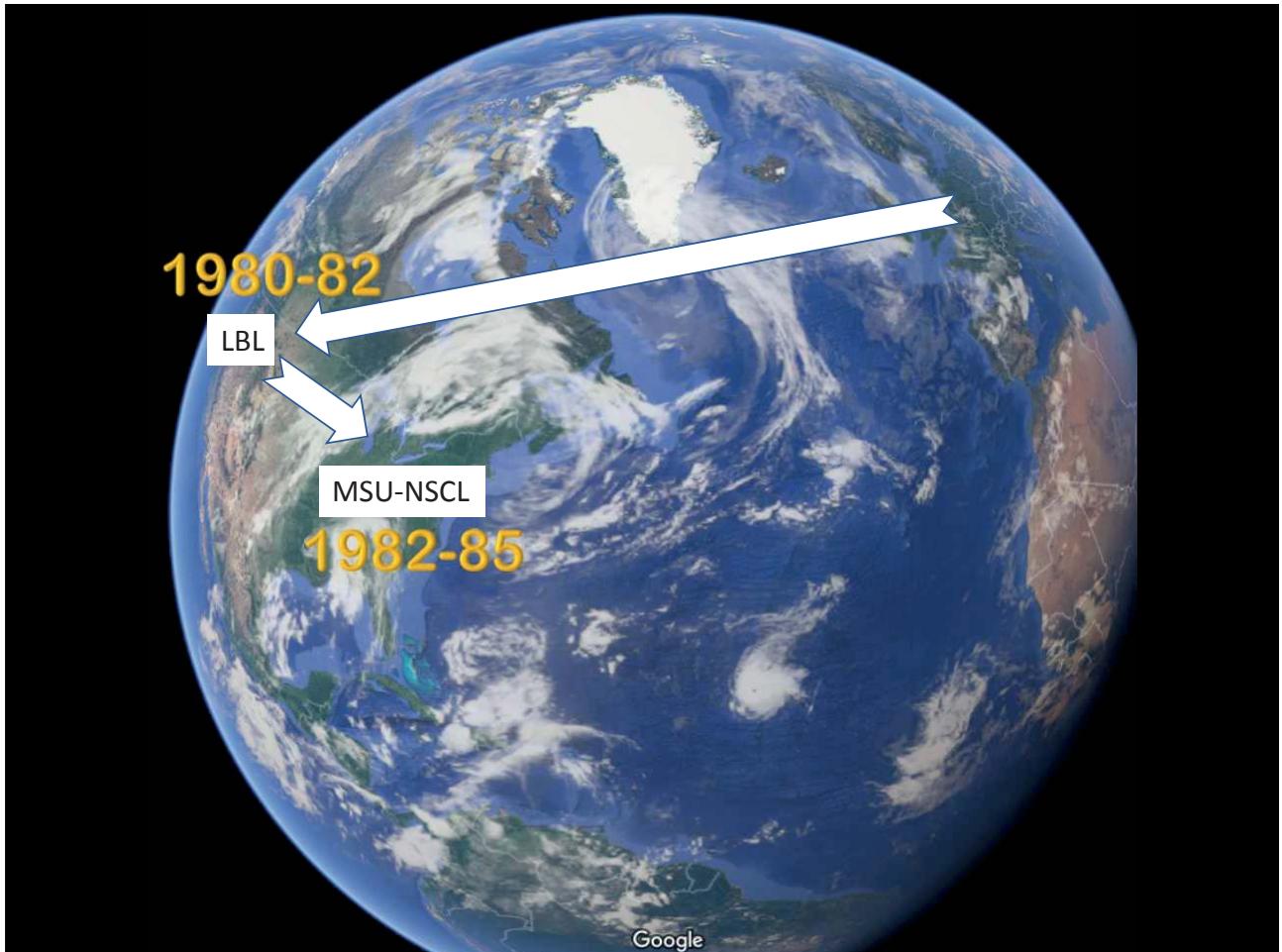


- **Main idea:** see differential changes in collective motion from different amounts of transient nuclear compression
  - Hydro / viscosity
  - EoS sensitivity
  - Momentum dependence

## Directed Flow: Plastic Ball Results

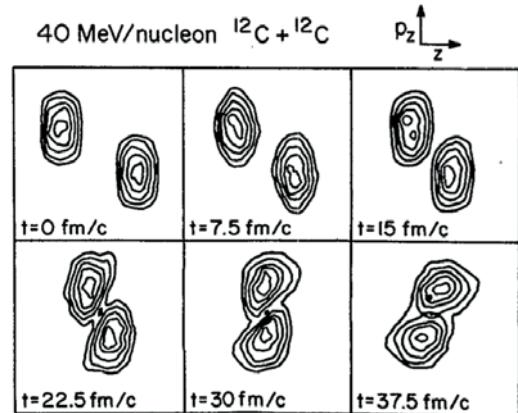
Plastic Ball, H.G. Ritter et al.,  
Nucl. Phys. **A447**, 3c (1985)





## Simulations of Nuclear Collisions

- Hydro, mean field, cascades
- Numerical solution of transport theories
  - Need to work in 6d phase space => prohibitively large grids ( $20^3 \times 40^2 \times 80 \sim 10^9$ )
  - Idea: Only follow initially occupied phase space cells in time and represent them by test particles
  - One-body mean-field potentials ( $\rho, p, \tau$ ) via local averaging procedures
  - Test particles scatter with realistic cross sections => (exact) solution of Boltzmann equation (+Pauli, Bose)
  - Very small cross sections via perturbative approach
  - Coupled equations for many species no problem
  - Typically 100-1000 test particles/nucleon



1<sup>st</sup> Developed  
@ MSU/FFM

Bertsch, Kruse and Das Gupta, PRC (1984)  
Kruse, Jacak and **Stöcker**, PRL (1985)  
Bauer, Bertsch, Cassing and Mosel, PRC (1986)  
**Stöcker** and Greiner, Phys Rep (1986)

# Transport Equations (from BBGKY Hierarchy)

$$\begin{aligned}
 \frac{\partial}{\partial t} f(\vec{r}, \vec{p}, t) + \frac{\vec{p}}{m} \vec{\nabla}_r f(\vec{r}, \vec{p}, t) - \vec{\nabla}_r U \vec{\nabla}_p f(\vec{r}, \vec{p}, t) & \\
 = \frac{g}{2\pi^3 m^2} \int d^3 q_{1'} d^3 q_2 d^3 q_{2'} & \xrightarrow{\text{Mean field EoS}} \\
 \delta \left( \frac{1}{2m} (p^2 + q_2^2 - q_{1'}^2 - q_{2'}^2) \right) \cdot \delta^3(\vec{p} + \vec{q}_2 - \vec{q}_{1'} - \vec{q}_{2'}) \cdot \frac{d\sigma}{d\Omega} & \\
 \cdot \left\{ f(\vec{r}, \vec{q}_{1'}, t) f(\vec{r}, \vec{q}_{2'}, t) (1 - f(\vec{r}, \vec{p}, t)) (1 - f(\vec{r}, \vec{q}_2, t)) \right. & \\
 \left. - f(\vec{r}, \vec{p}, t) f(\vec{r}, \vec{q}_2, t) (1 - f(\vec{r}, \vec{q}_{1'}, t)) (1 - f(\vec{r}, \vec{q}_{2'}, t)) \right\} &
 \end{aligned}$$

Energy &  
 Momentum  
 Conservation

2-body scattering

Final state interaction  
 Pauli Exclusion Principle

$f$  = one-body phase space density for baryons

## Test Particles

- Baryon phase space function,  $f$ , is Wigner transform of density matrix
- Approximate formally by sum of delta functions, test particles

$$f(\vec{r}, \vec{p}, t) = \int d^3 r_0 d^3 p_0 \delta^3(\vec{r} - \vec{R}(\vec{r}_0, \vec{p}_0, t_0)) \delta^3(\vec{p} - \vec{P}(\vec{r}_0, \vec{p}_0, t_0)) f(\vec{r}_0, \vec{p}_0, t_0)$$

- Insert back into integral equation to obtain equations of motion for 6 coordinates of each test particle

# Test Particle Equations of Motion

$$\begin{aligned}
 \frac{d}{dt} \vec{p}_i &= -\vec{\nabla} U(\vec{r}_i) + \sum_{j \neq i} \frac{q_i q_j}{(\vec{r}_i - \vec{r}_j)^2} + \mathcal{C}(\vec{p}_i), \\
 \frac{d}{dt} \vec{r}_i &= \frac{\vec{p}_i}{\sqrt{m_i^2 + p_i^2}}, \\
 i &= 1, \dots, (A_t + A_p)\mathcal{N}
 \end{aligned}$$

Nuclear EoS                          Two-body scattering

Just like an intra-nuclear cascade (Cugnon et al., Willets et al., Bodmer et al.), **BUT** with self-consistently generated one-body mean field potential (like TDHF)

## HI Collisions

- Point 1: Kinetic theory without collisions (= Vlasov) reproduces mean field theory (= TDHF)

JOSEPH J. MOLITORIS, DETLEV HAHN,  
HORST STÖCKER,  
Prog. Nuc. Part. Phys. 15, 239 (1985)



High energy heavy ion collisions—probing the equation of state of highly excited hadronic matter

Horst Stöcker <sup>a, b</sup>, Walter Greiner <sup>a, b</sup>

(1266 citations (!!) as of yesterday)

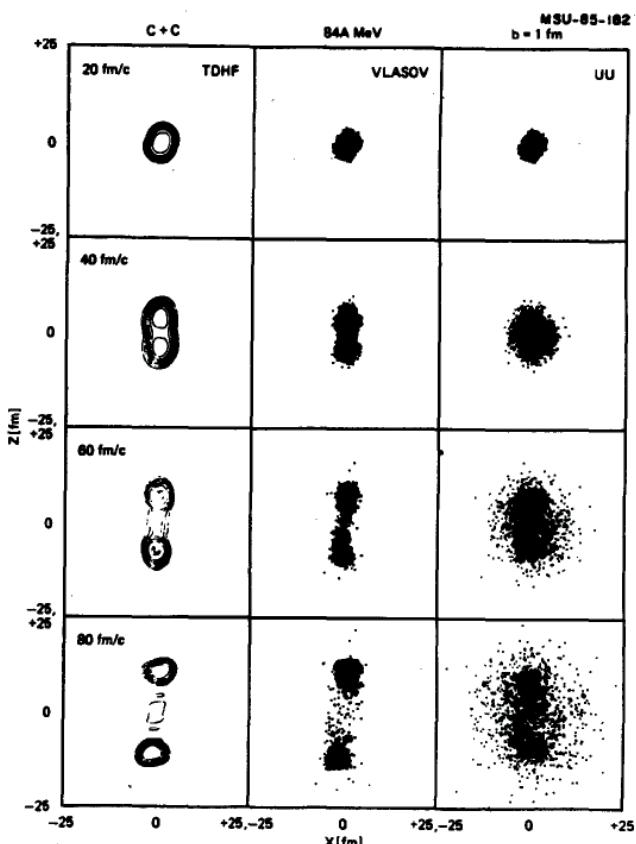
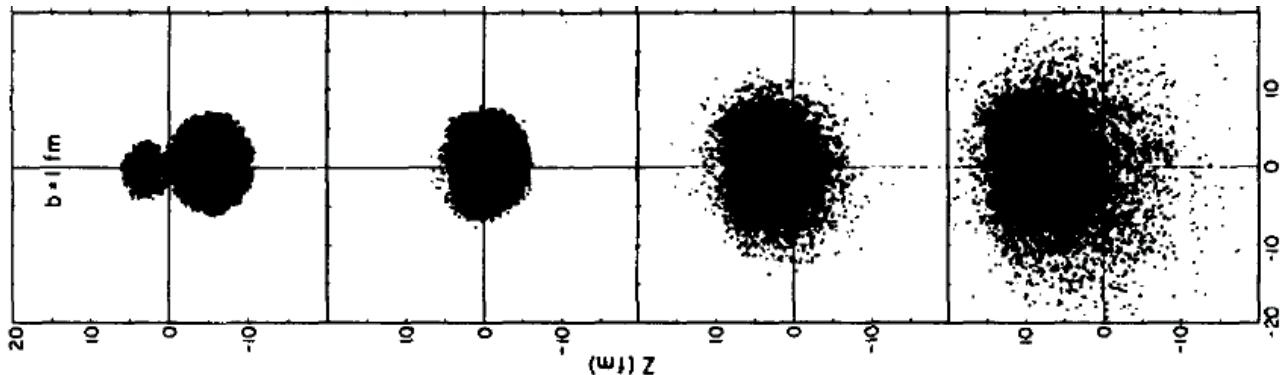


Fig. II.2 Time evolution in configuration and momentum space for C (85 MeV/nucleon) + C at  $b=1$  fm for TDHF, the Vlasov equation, and the Vlasov-Uehling-Uhlenbeck theory. Transparency occurs in both cases with a mean field only.

# HI Collisions

- Point 2: Kinetic theory with collisions (= VUU, BUU, ...) reproduces hydro!

JOSEPH J. MOLITORIS, DETLEV HAHN,  
HORST STÖCKER,  
Prog. Nuc. Part. Phys. 15, 239 (1985)



October 9, 2018

25

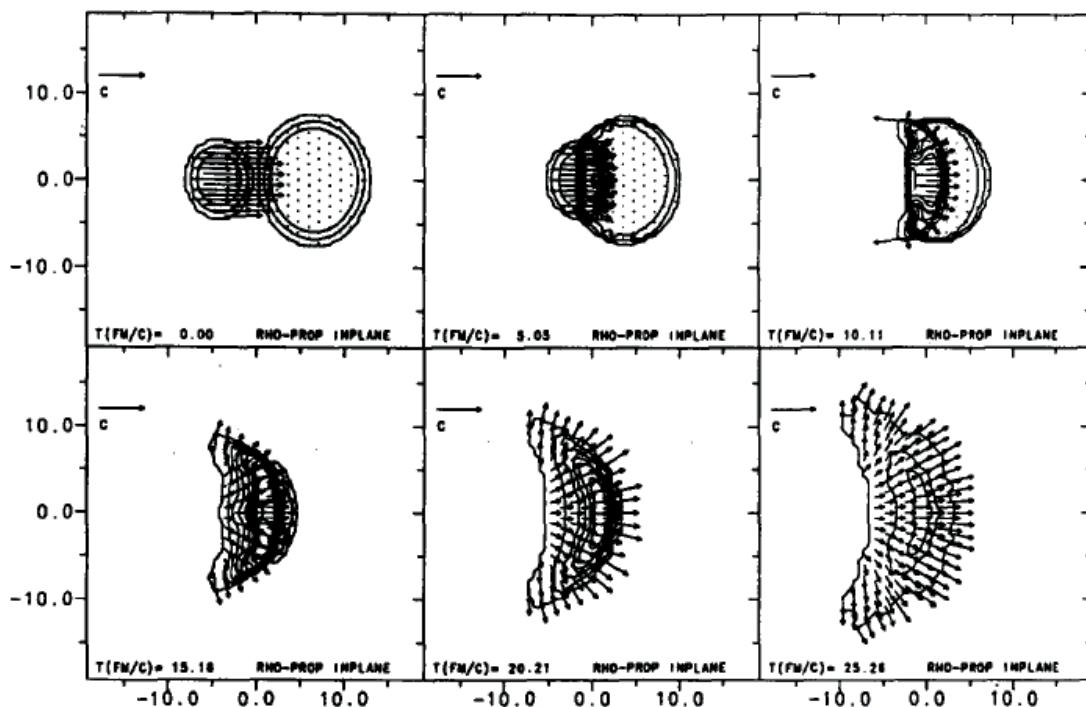


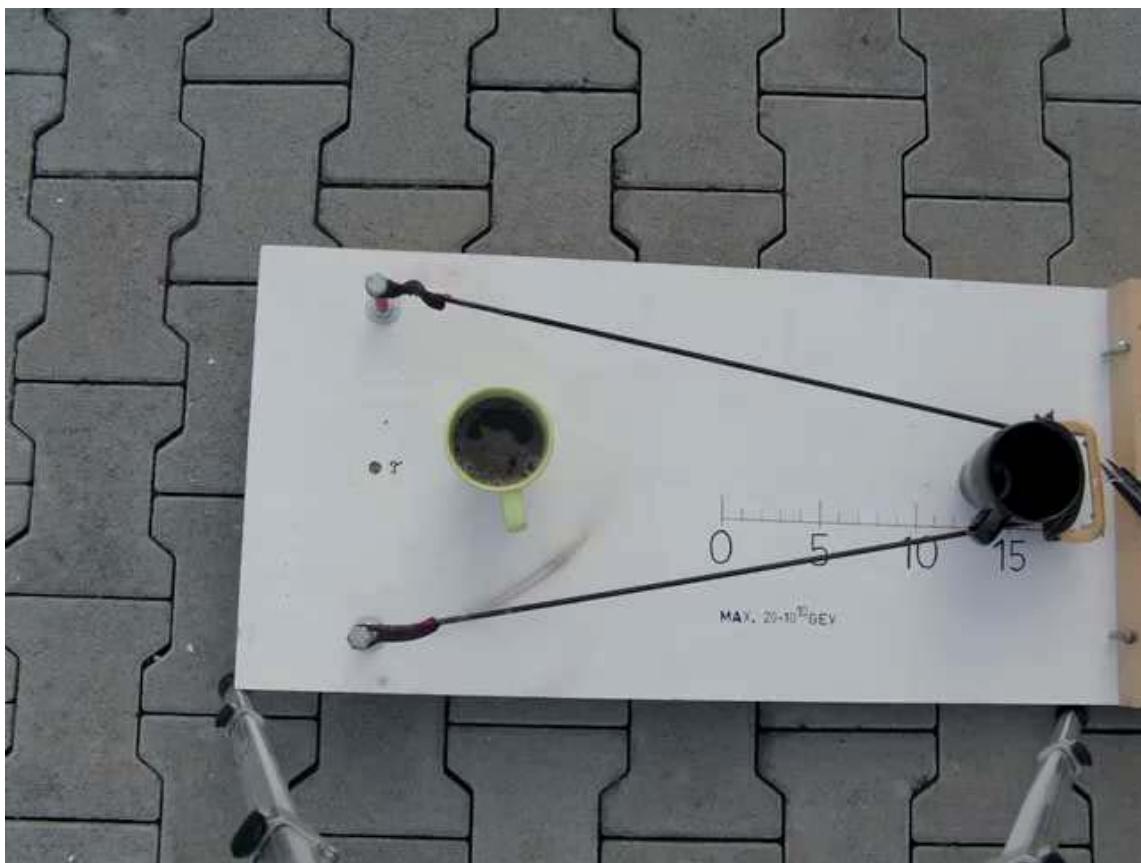
Fig. II.12 Collision of Ar (770 MeV/nucleon) + Pb at  $b = 0 \text{ fm}$  in the Nuclear Fluid Dynamic model. Note the remarkable similarity to the VUU theory.

JOSEPH J. MOLITORIS, DETLEV HAHN,  
HORST STÖCKER,  
Prog. Nuc. Part. Phys. 15, 239 (1985)

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26

# What About Shockwaves?

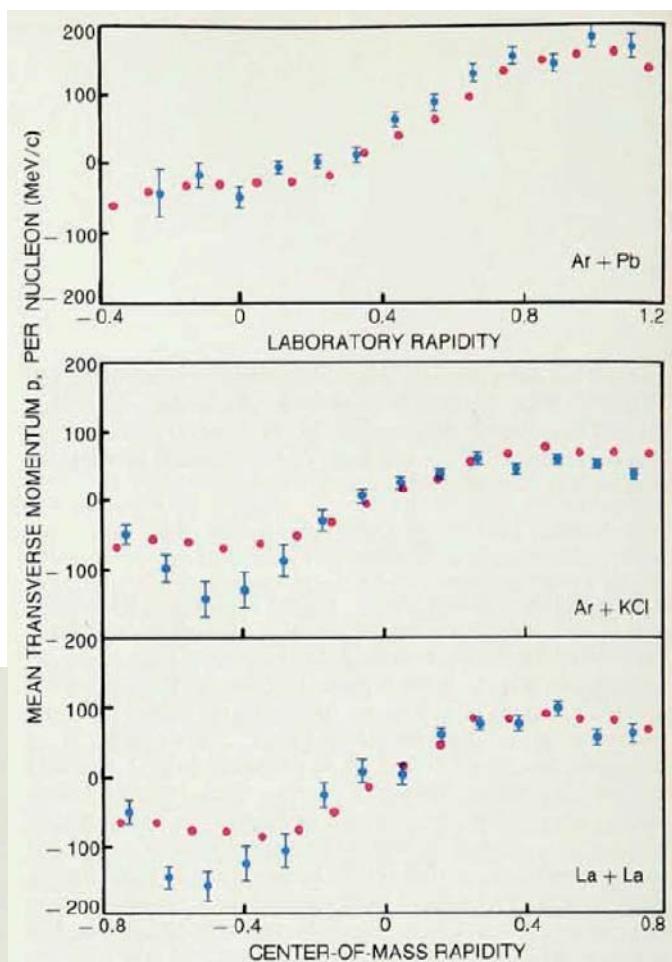


## Explains Data!

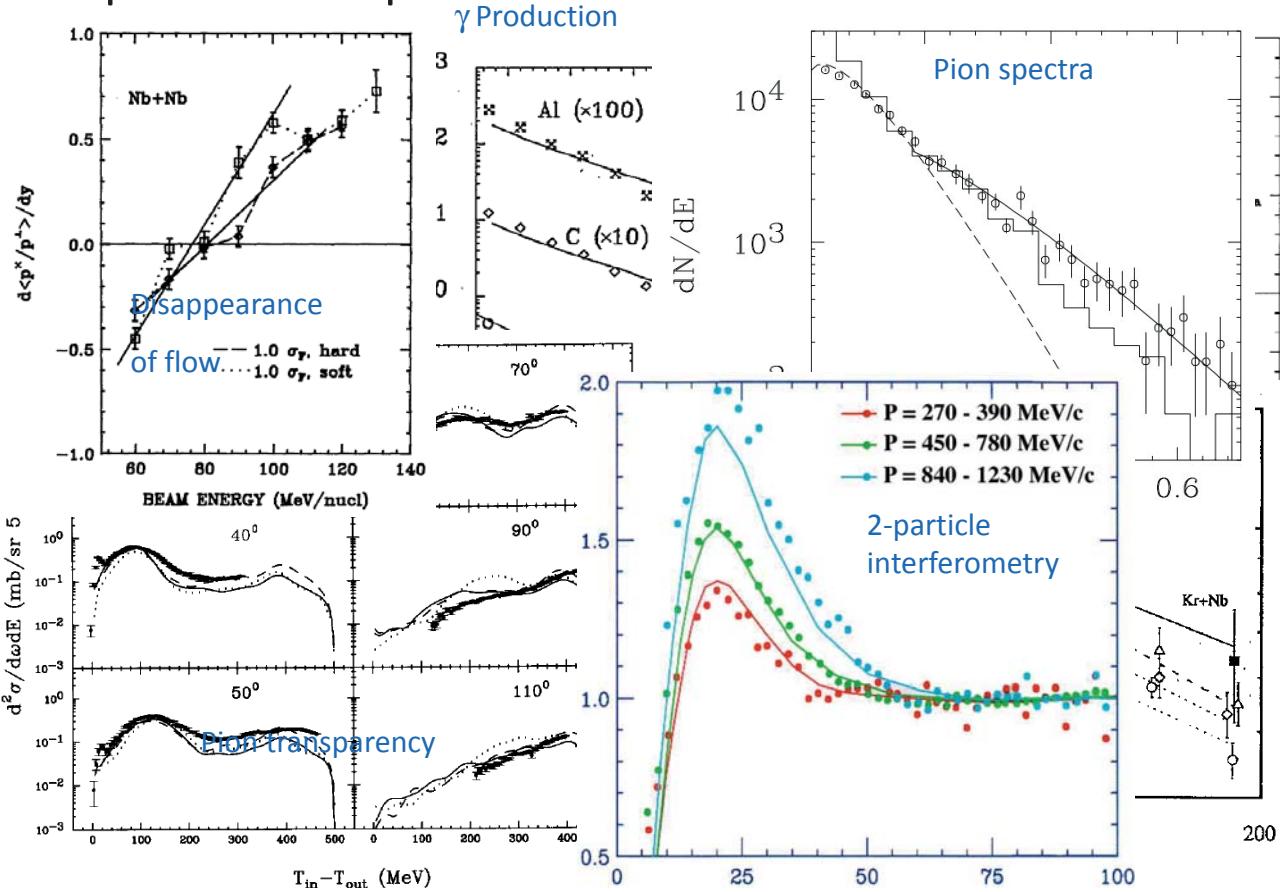
- One body (self-consistently generated nuclear mean field, EoS)
- Two body (NN scattering, final state interaction)
- In medium effects
  - $p$ -dependent interaction
  - Off-shell effects
  - Mass modification
  - Causality, Retardation
  - ...

Kruse, Jacak and **Stöcker**, PRL (1985)

**Results of BUU simulations** (magenta) incorporating momentum-dependent interactions as compared with experimental data (blue). Transverse momentum per nucleon is plotted as a function of rapidity in 800-MeV/nucleon central and semicentral collisions of different nuclei. The fits yield an incompressibility  $K$  of approximately 215 MeV. (Adapted from ref. 9.) **Figure 4**



# Reproduces Experiments



## OK, but what about Multifragmentation?

- Stöcker's Answer:  
**QMD (= 1 test particle per nucleon, Pauli potential)**

PHYSICAL REVIEW C

VOLUME 37, NUMBER 6

JUNE 1988

### Quantum molecular dynamics approach to heavy ion collisions: Description of the model, comparison with fragmentation data, and the mechanism of fragment formation

J. Aichelin,<sup>(a)</sup> G. Peilert,<sup>(b)</sup> A. Bohnet,<sup>(a)</sup> A. Rosenhauer,<sup>(c)</sup> H. Stöcker,<sup>(b)</sup> and W. Greiner<sup>(b)</sup>

<sup>(a)</sup>Institut für Theoretische Physik der Universität Heidelberg, Heidelberg, Federal Republic of Germany  
and Max-Planck-Institut für Kernphysik, D-6900 Heidelberg, Federal Republic of Germany

<sup>(b)</sup>Institut für Theoretische Physik, J. W. Goethe-Universität, D-6000 Frankfurt am Main, Federal Republic of Germany  
<sup>(c)</sup>Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

(Received 21 December 1987)

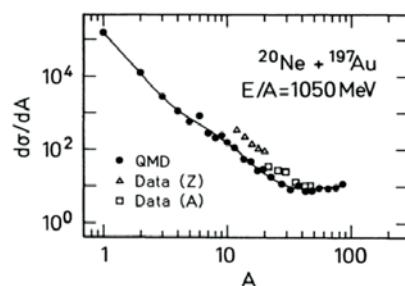


FIG. 5. The inclusive mass yield as compared with experimental data (Ref. 28).

489 citations (!!!) as of yesterday

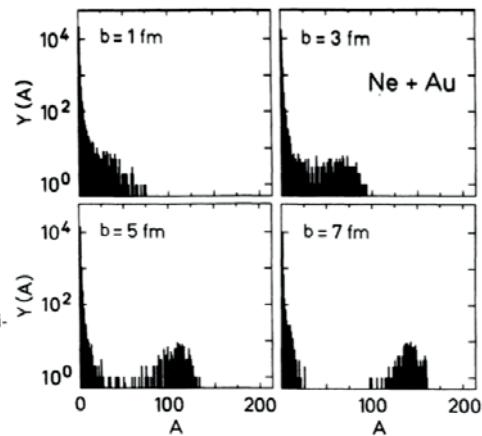
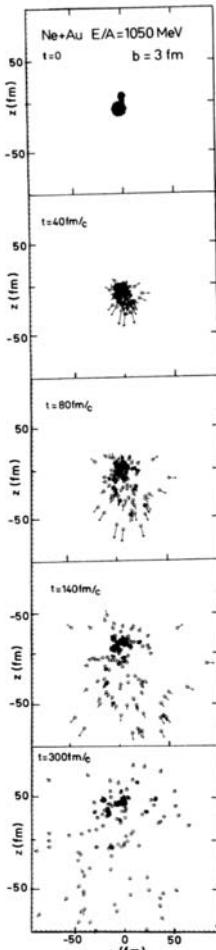
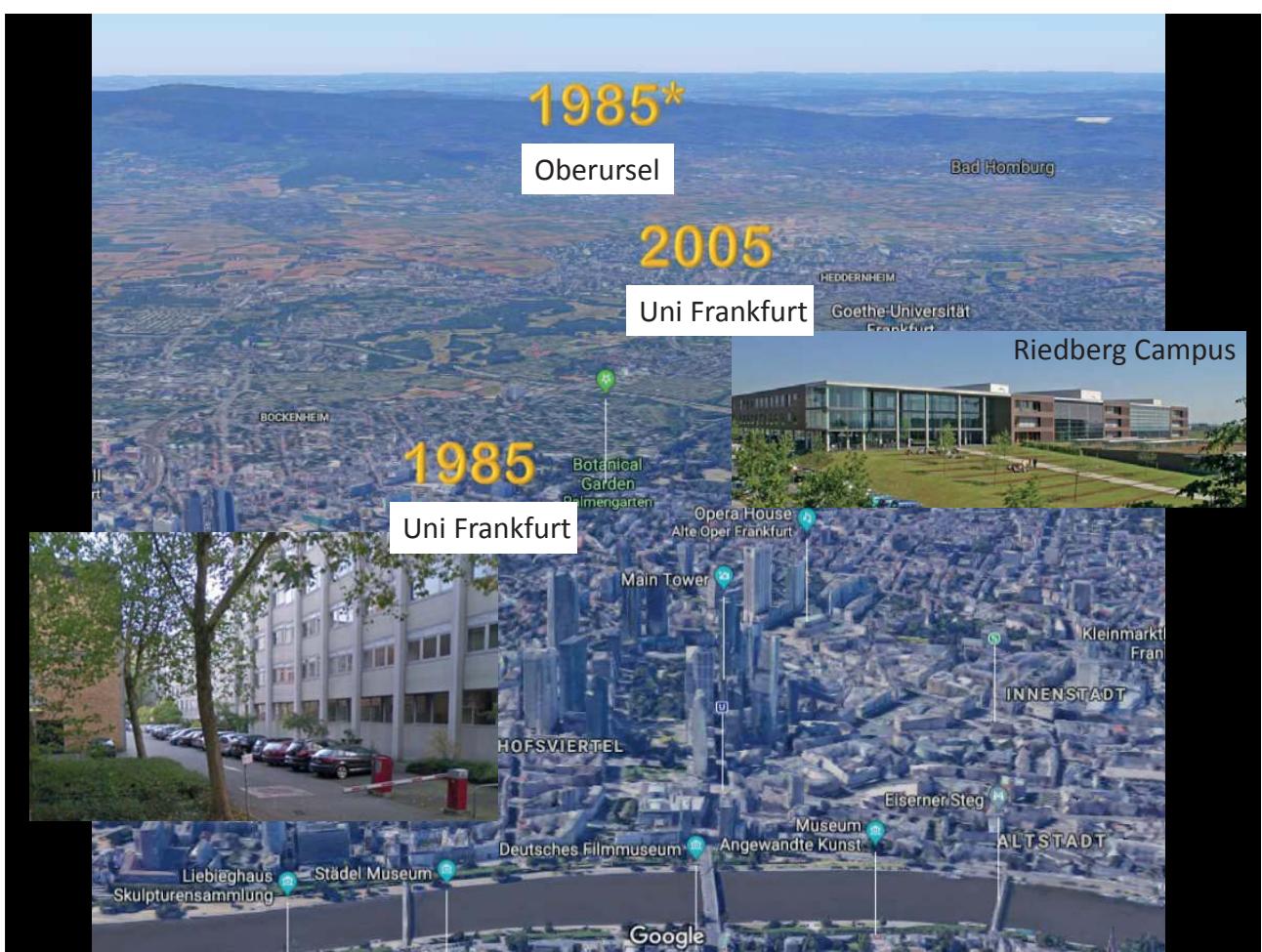
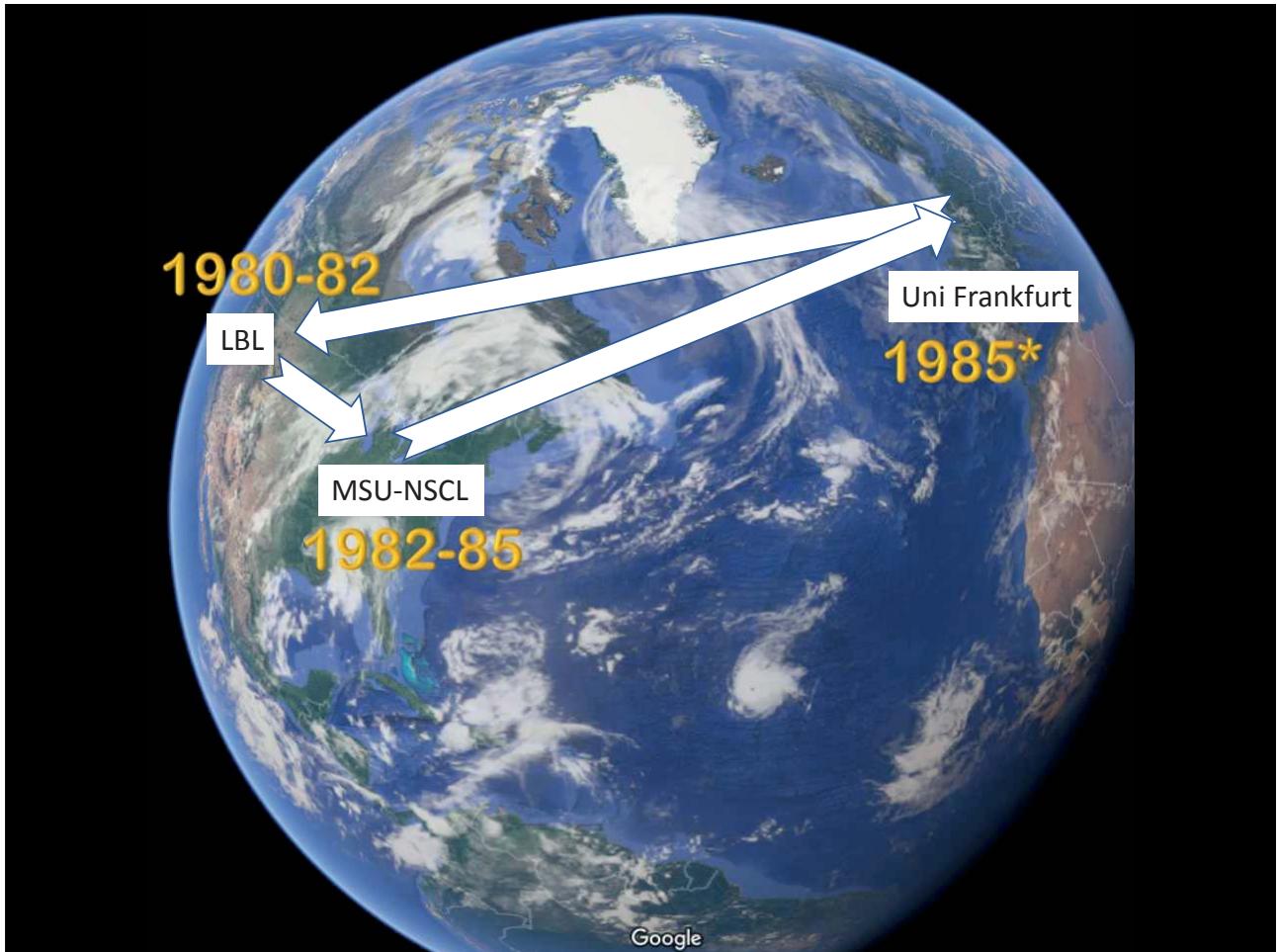
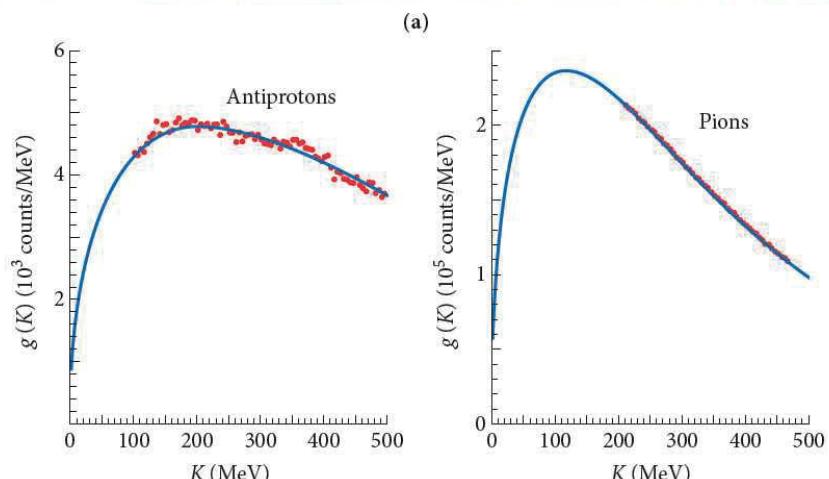


FIG. 9. The mass yield for four different impact parameters  $b = 1, 3, 5$ , and  $7 \text{ fm}$  for the reaction 1050 MeV/nucleon Ne + Au.





# Relativistic Heavy Ion Physics moved to RHIC and LHC

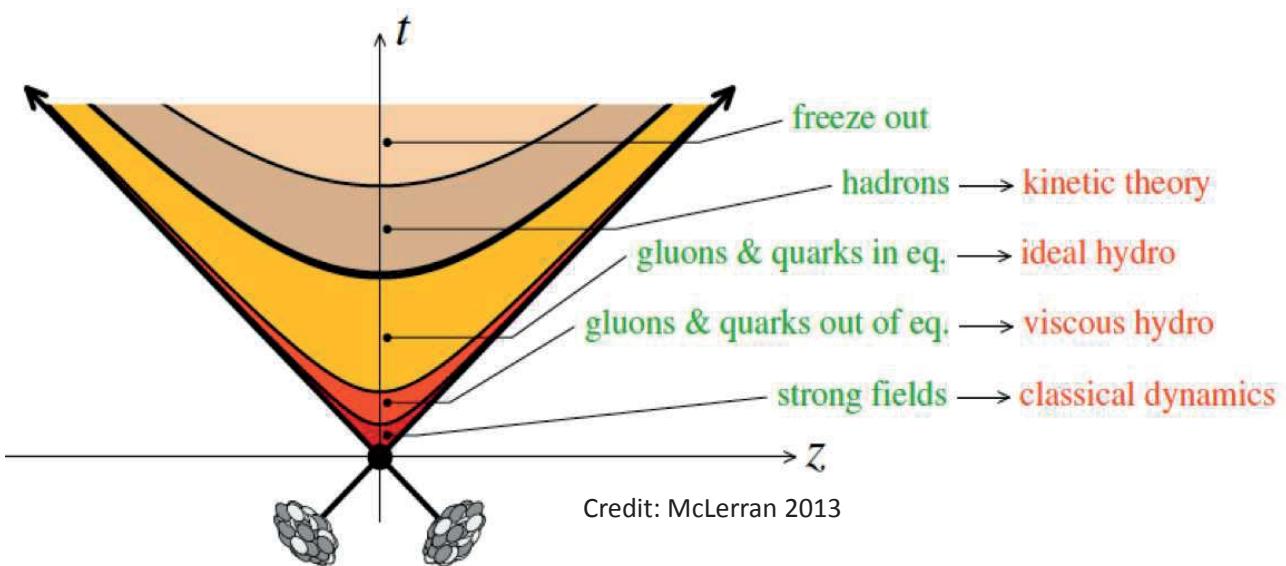


Relativistic Heavy Ion Collider (RHIC).

Data: STAR Collaboration

9 October 2018

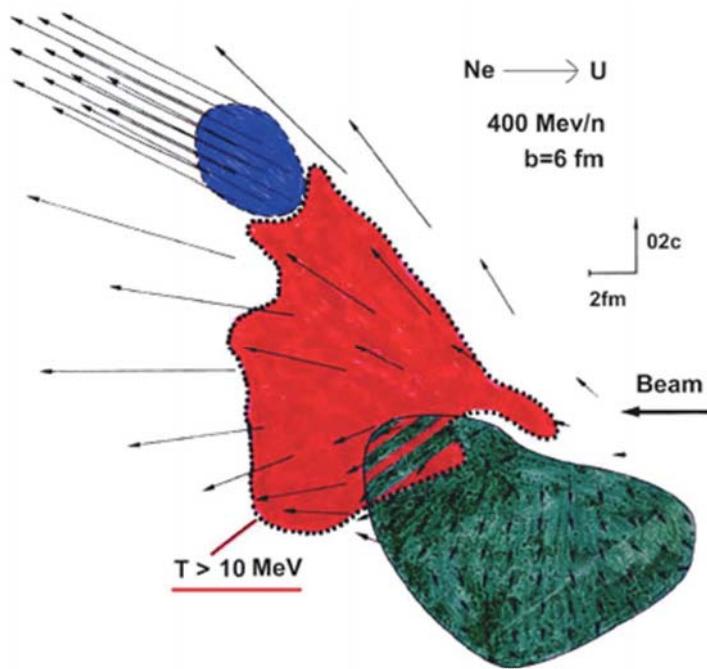
33



Cartoon of the time evolution of an ultra-relativistic heavy ion collision

# Hydro @ RHIC

- Relativistic heavy ion collisions
- Scale  $10^{-15}$  m
- Shock wave (?)
- Successful @RHIC
  - $v_2$  ✓
  - $\eta/s$  small ✓



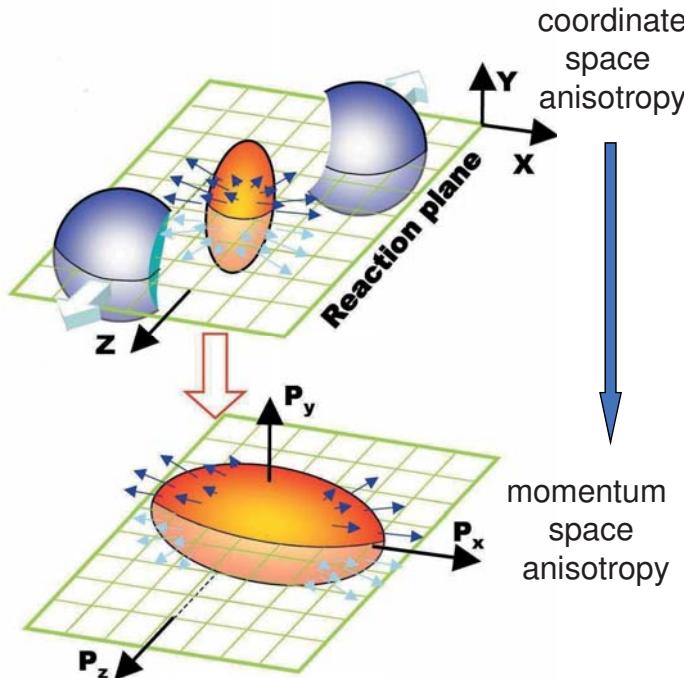
H. Stöcker, J.A. Maruhn, and W. Greiner, PRL 44, 725 (1980)

October 9, 2018

35

# Hydro @ RHIC

Collective Flow Signals the Quark-Gluon Plasma  
H. Stöcker, NPA 750(1), 121 (2005)  
510 citations (!! ) as of yesterday



$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y) \cos(n(\phi - \Psi_r)) \right)$$

$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$

➤ Azimuthal correlation with the reaction plane.

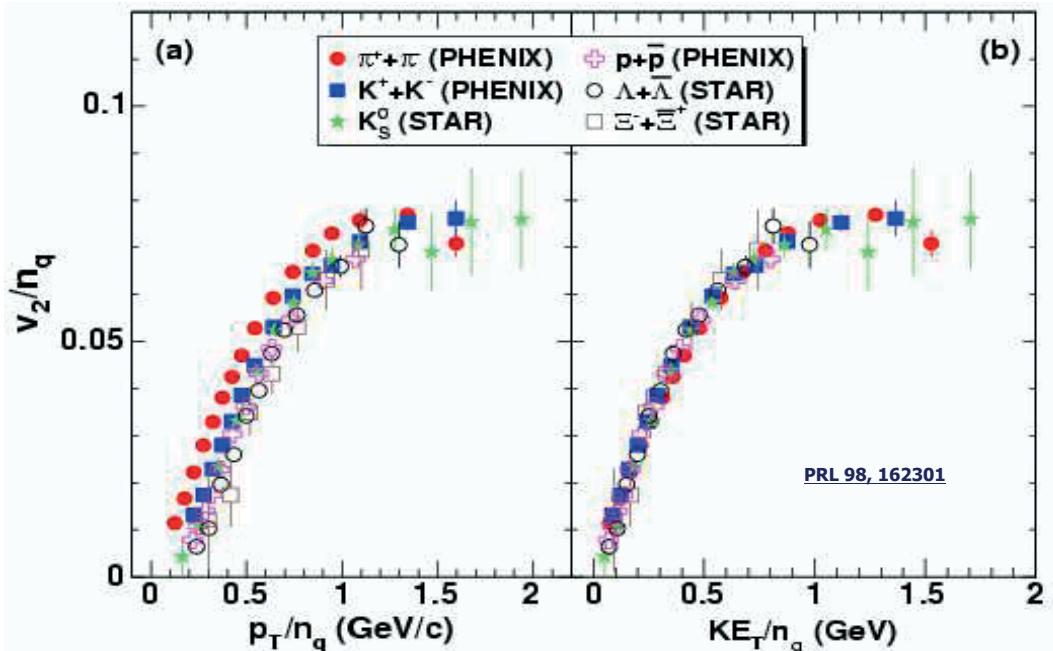
➤ Built up in the early stage, therefore supplies the early information of matter generated in the collision.

Credit: Na Li, 25<sup>th</sup> WWND, 2009

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36

# Hydro @ RHIC



Quark-# scaling: Strong indication for hydrodynamic flow!

October 9, 2018

37

## Ultra-Relativistic Heavy Ion Collisions Beyond Hydro

- Extension of VUU/BUU & QMD into ultra-relativistic domain
- RQMD
- Nucleon dynamics, coupled with string dynamics, decay matrix elements, ...
- First expedition of the Stöcker/Greiner group into sub-nucleon degrees of freedom

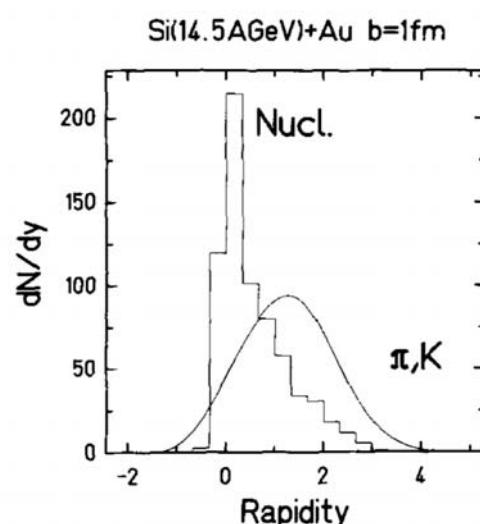
ANNALS OF PHYSICS 192, 266–306 (1989)

Poincaré Invariant Hamiltonian Dynamics:  
Modelling Multi-hadronic Interactions in a Phase  
Space Approach

HEINZ SORGE, HORST STÖCKER, AND WALTER GREINER

Institut für Theoretische Physik,  
Johann Wolfgang Goethe-Universität  
Frankfurt/Main, Germany

645 citations (!!) as of yesterday



# UrQMD

M. Bleicher et al., J. Physics G 25(9), 1859, 1999  
 (1445 citations (!!!) as of yesterday)

- Better treatment of resonance excitation, string excitation and fragmentation, color degrees of freedom
- Gets phase space right: stopping, transverse momenta, particle production, ...

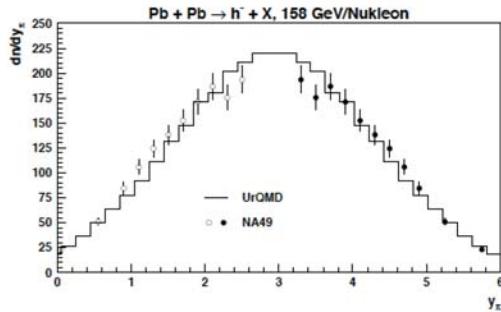


Figure 4.2: Rapidity distributions of negatively charged hadrons (i.e.  $\pi^-$ ,  $K^-$  and  $\bar{p}$ ) for Pb+Pb collisions at the SPS (160 AGeV) in comparison to preliminary NA49 data [157].

SA Bass et al., Progress in Particle and Nuclear Physics 41, 255-369, 1998

(1962 citations (!!!) as of yesterday)

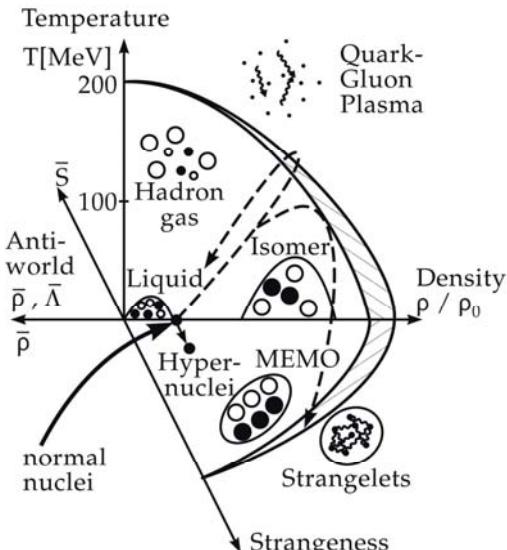
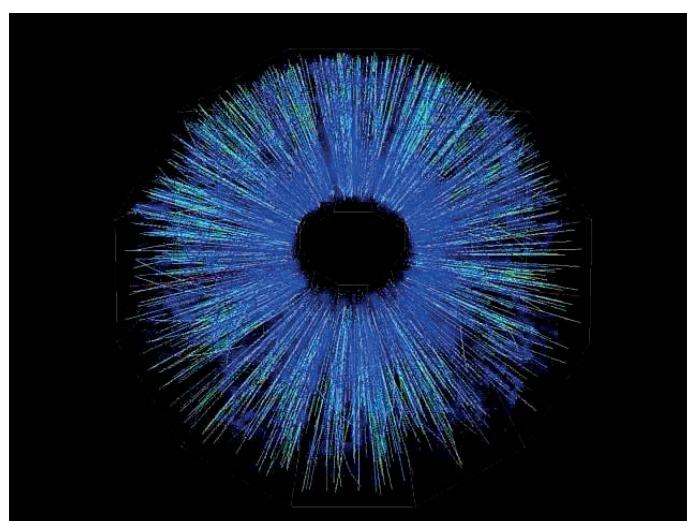


Figure 1.1: Phase diagram of hadronic matter: Only the point at ground state density is well known; the dashed lines show areas probed in the course of heavy ion reactions.

## Why Do All This?

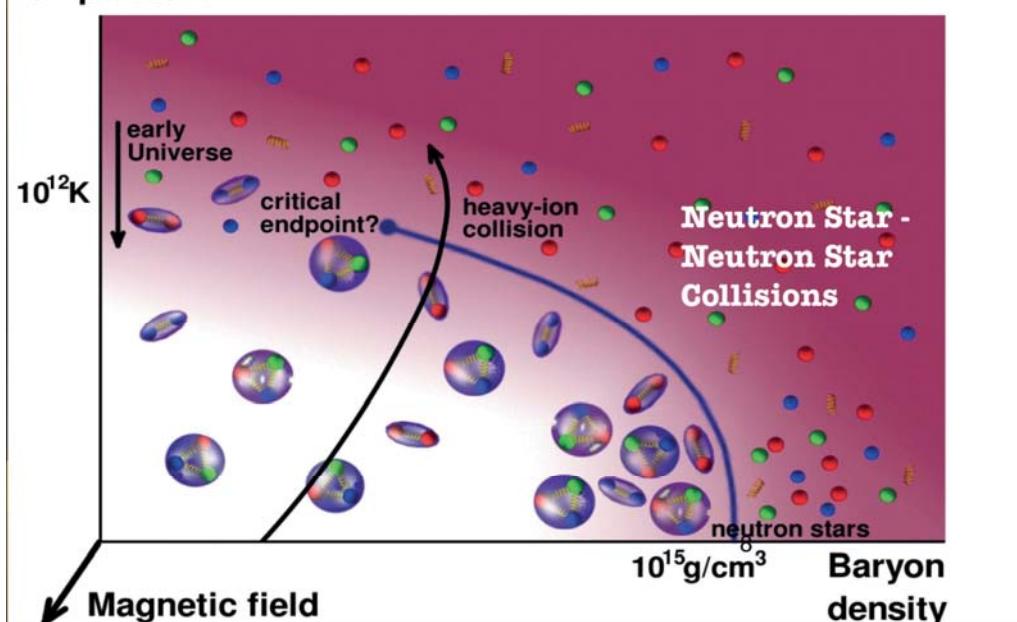
- Explore early phase of Big Bang
- Connection with Astrophysics
  - Neutron star stability limits
  - Black hole formation
- New phases of matter



Why Do All This? Horst's Answer: Kern->Kern = Stern->Stern

## FAIR: Dense Matter, Strange Matter, Quark Matter, Quark Stars? Relativistic collisions of NS-NS vs. Heavy Ions

### Temperature

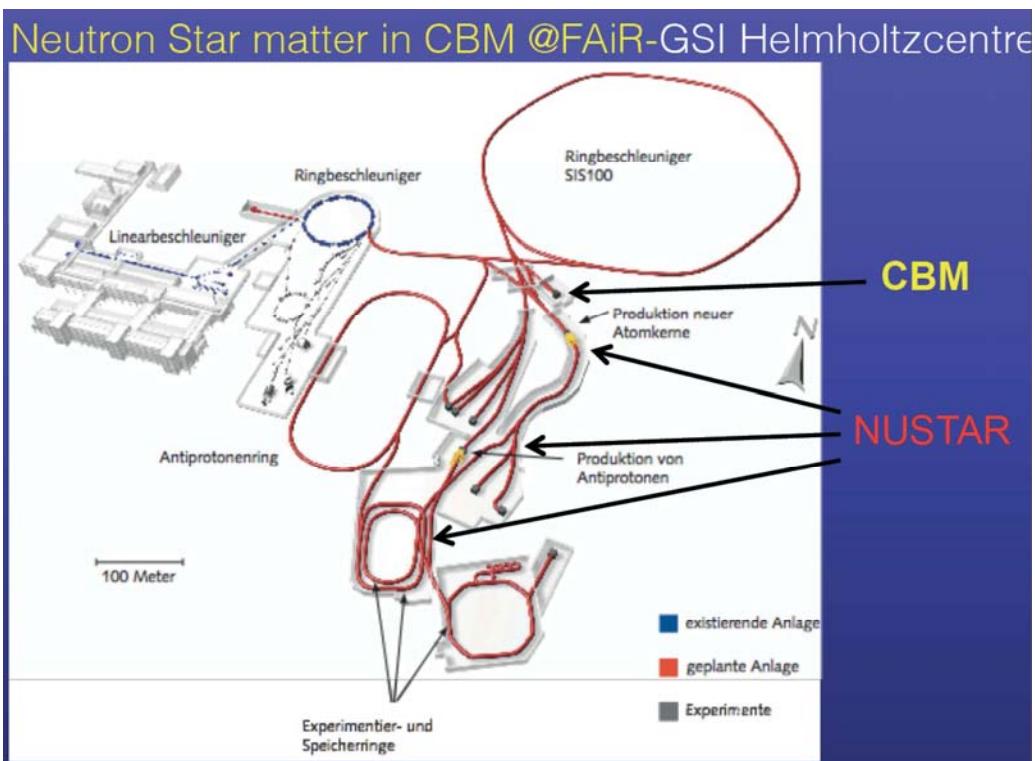


9 October 2018

W.B. 4 H.S.

41

Why Do All This? Horst's Answer: Kern->Kern = Stern->Stern

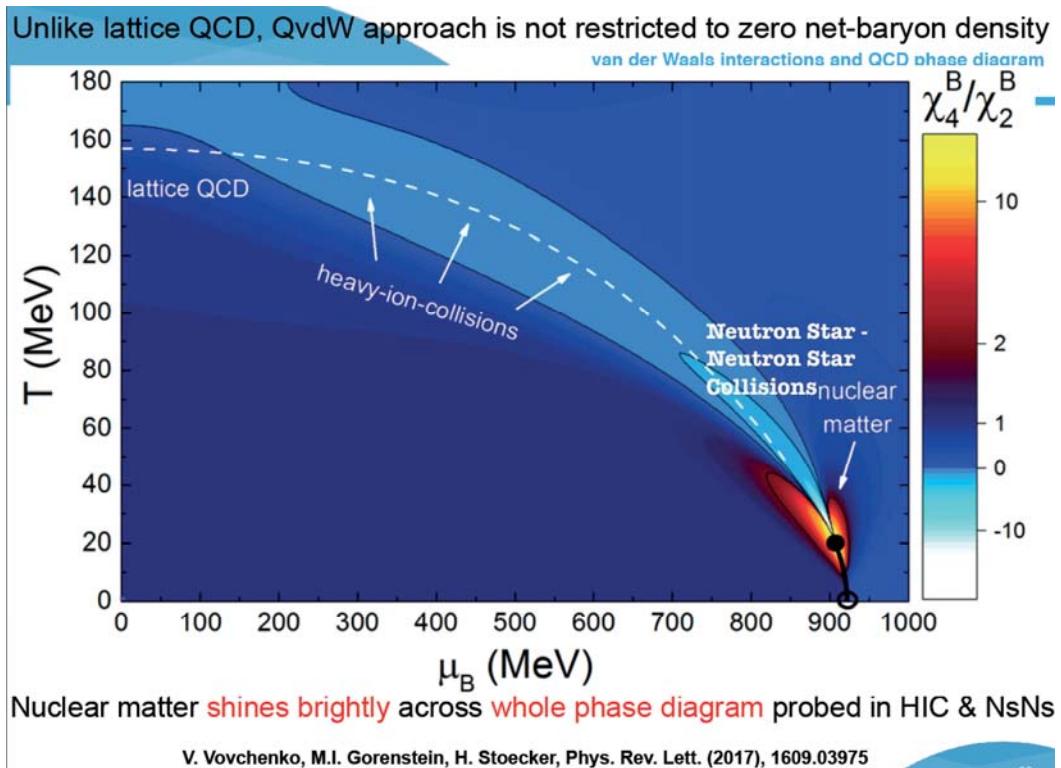


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42

## Why Do All This? Horst's Answer: Kern-> Kern = Stern-> Stern

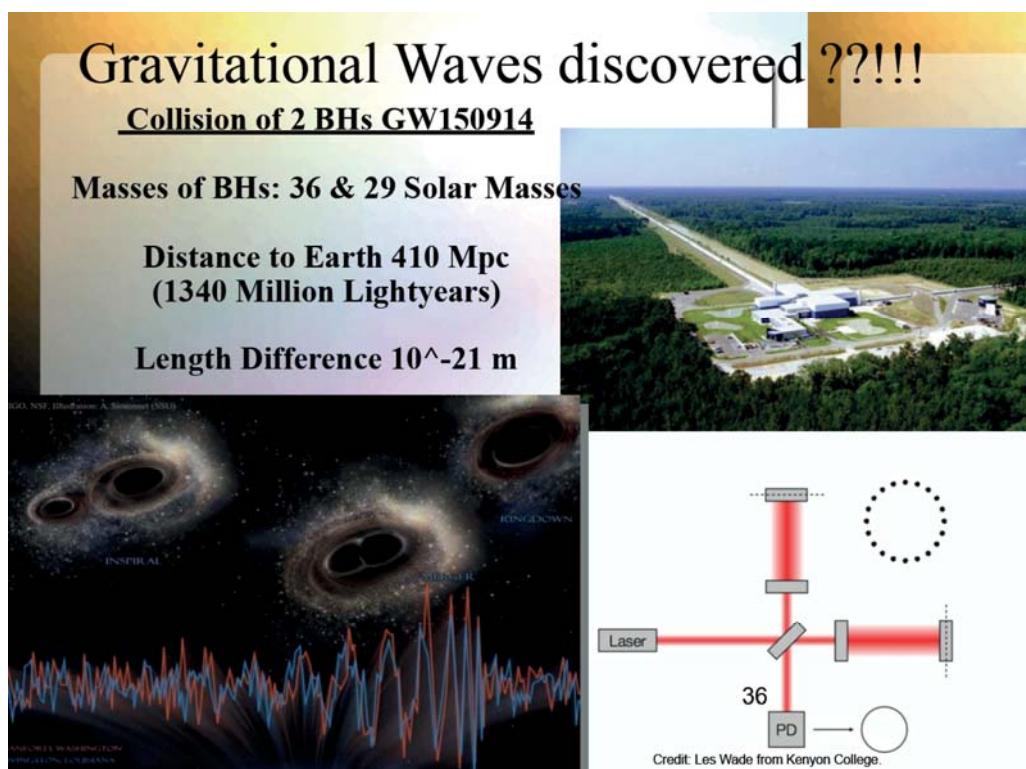


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43

## Why Do All This? Horst's Answer: Kern-> Kern = Stern-> Stern



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44

# Thinking **OUTSIDE** the Box

- Where others see annihilation,  
Horst sees opportunity!
  - Lee-Wick matter
  - Strangelets
  - Mini Black Holes

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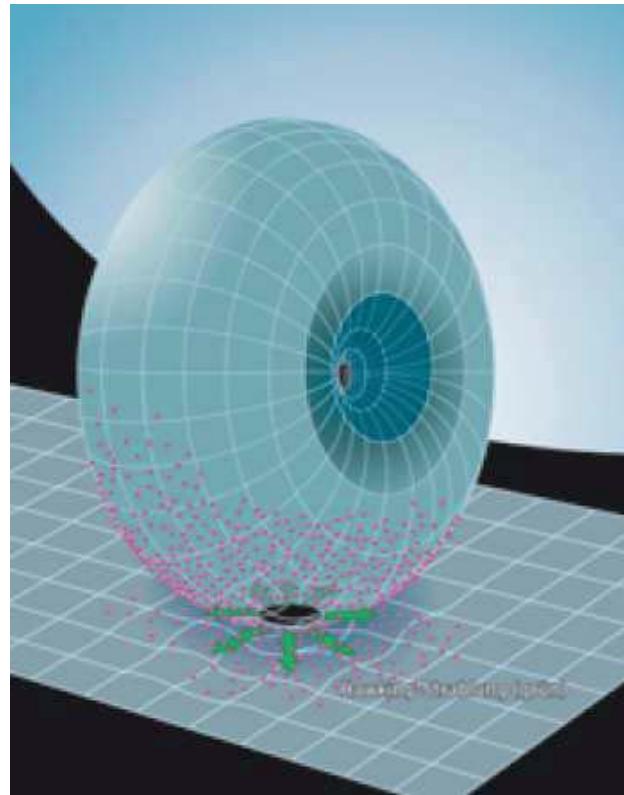
45

Forschung intensiv

Auf der Suche nach  
einer experimentellen  
Bestätigung  
der Stringtheorie

Schwarze Löcher  
im Labor?

von Marcus Bleicher und Horst Stöcker



What happens if you were to make a black hole at CERN?

Formel  $E=mc^2$ . Denkbar wäre ein »Relikt-Konverter«, bestehend aus einem Relikt, das einen Strahl von niedrigergetischen Teilchen, zum Beispiel Protonen, Neutronen oder ganze Kerne in Hawking-Strahlung umwandeln könnte. Dieser Prozess würde mit einer Umwandlungseffizienz von etwa 90 Prozent ablaufen, da nur die produzierten Gravitonen und Neutrinos nicht in nutzbare Energie überführt werden könnten. Das heißt, falls die Erzeugung von stabilen Relikten am LHC gelingt, könnte der gesamte Weltjahresenergieverbrauch von zirka  $10^{21}$  Joule in den Konvertern mit nur zehn Tonnen normaler Materie angefüttert, erzeugt werden!

Das hört sich beinahe wie Sciencefiction an, ist aber eine ernst zu nehmende Möglichkeit, die einer der Autoren (H. S.) hat patentieren lassen.

■ Simulation ei-

– Die emittierten Standardmodellteilchen (das heißt die

H. Stöcker,

Deutsches Patent- und Markenamt München,  
10 2006 007 824.1-54

die dabei erzeugt werden, hinterlas-

Detektor sichtbar werden. Im Gegensatz zu Schauern von bekannten Prozessen werden diese Tatsachen

einziges Signal bliebe dann die Suche »relics« in einer »time projection« speziellen Art von Detektor ■.

verter« als Energiequelle  
?

idige Theorie der Quanten-Gravitation, die Endphase eines Schwarzen Lösen. Viele theoretische Probleme lassen, wenn man einen stabilen Endzustand postuliert. Falls »mini black hole«-Reisen, erlaubten sie nicht nur das Studium der Gravitation in verschiedenen Zuständen, sondern eröffneten auch erstaunliche Möglichkeiten der Energiegewinnung über die Wandlung von Energie nach Einsteins berühmter Formel  $E=mc^2$ . Denkbar wäre ein »Relikt-Konverter«, das einen Strahl von niedrigergetischen Teilchen, zum Beispiel Protonen, Neutronen oder ganze Kerne in Hawking-Strahlung umwandelt. Dieser Prozess würde mit einer Umwandlungseffizienz von etwa 90 Prozent ablaufen, da

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Das Potenzial der Untersuchung von Schwarzen Lösen

## GSI Director

Cusco, Peru, June 2007





# Progress

SIS100 tunnel  
as of Sept. 30, 2018



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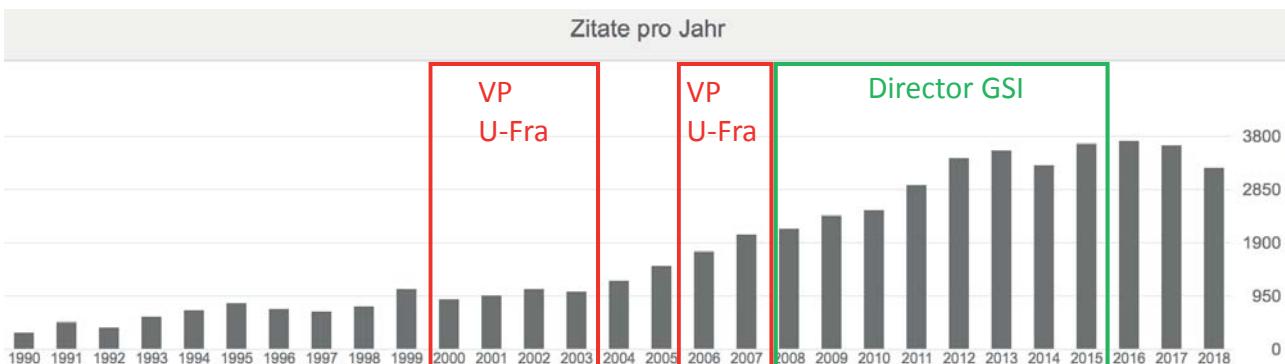
W.B. 4 H.S.

53

## One of the top-200 cited scientists of *ALL TIME*

Google Scholar (as of yesterday 3 am):

- > 600 scientific papers and books
- 53830 citations
- H-index: 80 (80 papers with >80 citations)
- i10-index: 352
- **A research career still *strongly* on the rise!**



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54

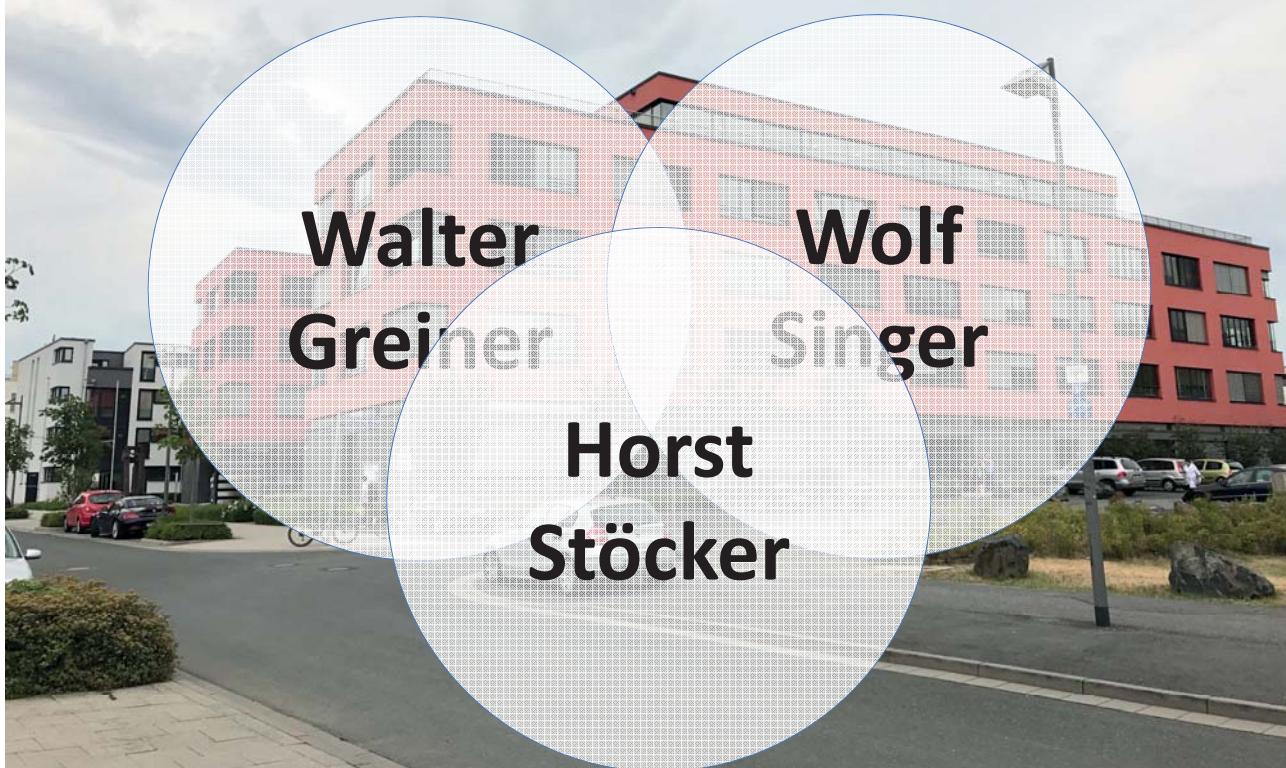
# Top Papers

TITEL	ZITIERT VON	JAHR
<b>GEANT4—a simulation toolkit</b> S Agostinelli, J Allison, K Amako, J Apostolakis, H Araujo, P Arce, M Asai, ... Nuclear instruments and methods in physics research section A: Accelerators ...	22670	2003
<b>Microscopic models for ultrarelativistic heavy ion collisions</b> SA Bass, M Belkacem, M Bleicher, M Brandstetter, L Bravina, C Ernst, ... Progress in Particle and Nuclear Physics 41, 255-369	1962	1998
<b>Relativistic hadron-hadron collisions in the ultra-relativistic quantum molecular dynamics model</b> M Bleicher, E Zabrodin, C Spieles, SA Bass, C Ernst, S Soff, L Bravina, ... Journal of Physics G: Nuclear and Particle Physics 25 (9), 1859	1445	1999
<b>High energy heavy ion collisions—probing the equation of state of highly excited hardronic matter</b> H Stöcker, W Greiner Physics Reports 137 (5-6), 277-392	1266	1986
<b>Thermodynamics and statistical mechanics</b> W Greiner, L Neise, H Stöcker Springer Science & Business Media	741	2012
<b>Handbook of mathematics and computational science</b> JW Harris, H Stöcker Springer Science & Business Media	711	1998
<b>Poincaré invariant hamiltonian dynamics: modelling multi-hadronic interactions in a phase space approach</b> H Sorge, H Stöcker, W Greiner Annals of Physics 192 (2), 266-306	645	1989
<b>Modelling the many-body dynamics of heavy ion collisions: Present status and future perspective</b> C Hartnack, RK Puri, J Aichelin, J Konopka, SA Bass, H Stoecker, ... The European Physical Journal A-Hadrons and Nuclei 1 (2), 151-169	629	1998
<b>Collective flow signals the quark-gluon plasma</b> H Stoecker Nuclear Physics A 750 (1), 121-147	510	2005

9 October 2018

55

FIAS - Frankfurt Institute for Advanced Studies  
est. 2004



Frankfurt will miss a Fantastic Teacher



## Frankfurter Schule

- Walter Greiner: ~110 Ph.D. students, 1/3 of whom stayed in academia
- Horst Stöcker: ~60 Ph.D. students, ¼ of whom stayed in academia
- Most prolific nuclear/particle/astro theory effort in the world

Making it all possible ...



Happy Emeritierung, Horst!

