Alles Gute zum 210. Geburtstag, Miklos,
45 Years with Miklos & Gyoerygi … Family & Kids & “La Famiglia”

Summer 1974: QCD - GSI Starts - TD Lee’s Bear Mountain BNL Workshop - LBL-GSI HEHI Summer Study
Sep. ’74 Horst joins Walter Greiner’s Institute as grad. stud. “High Density Nuclear Shock Waves & the EoS”
Oct. ’74-76 Miklos joins as Walter’s Postdoc “Pion Condensation in Dense Hot Matter”
Nov. ’74 First HEHI Kolloq. Marburg
Jan. ’75 Miklos & Horst Bormio Winter Workshop - and many more to come!

Sep. ’80-81 Oda & Horst DAAD-Fellow at LBL Theory Group with Miklos & Gyoerygi, ’82-85 Ass.Prof. MSU + LBL PAC
Sep. ’86-87 Miklos AvH Award at ITP at Uni Frankfurt with Walter, Berndt & Horst, Gyoerygi & Oda
Sep. ’93 Miklos moves to Columbia & RBRC BNL with TD Lee & Larry McLerran. Horst: RHIC PC & AGS PAC
Apr. ’06-07 *MikLaz Visiting Prof. at ITP with Walter & Horst, Gyoerygi & Oda - Horst to GSI
Sep. ’16 Miklos retires HOME to LBL Horst to FIAS

Mach Shock Cones

JETS

Lee Wick State of massless particles
Excited Vacuum
What is the EoS?

- The nuclear EoS offers endless research opportunities.
- Binding energy of nuclear matter as function of the density $E/A(n/n_0, T); p(n,T)$.
- $n_0 = 0.15$ particles per fm$^3$. (Ten to the power of $-45$ cubic meters).
- How to verify this new state of matter?
- Goal of Heavy Ion Physics!
Larry McLaren: La Famiglia at Walter’s 60th
Hydro splash
MAGIC
Matter, Astrophysics, Gravitational waves & Ion Collisions

E. Most, A. Motornenko, J. Papenfort, M. Hanauske, V. Dexheimer, L. Rezzolla,

Stefan Schramm (deceased), J. Steinheimer, H. Stoecker*

FIAS & Institut Theoretische Physik Goethe Universitaet Frankfurt
*GSI Darmstadt, CCNU, Wuhan; HU, Huzhou; USTC, Hefei
1679 I. Newton published his theory of gravitation. According to Newton, gravity manifests itself as an instantaneous force between masses proportional to their masses and inversely proportional distance squared. With this theory he could explain all of the astronomical observations of this time.

1915 A. Einstein, born in Ulm, published GR: Gravity governs the motion of masses and light by curving spacetime.

1915 Karl Schwarzschild, born 1873 in Frankfurt am Main, found the static solution of GR - died in WW I just after publishing his article.

Consequences of SchwarzSchild’s vision: black holes, neutron stars

Add Einstein’s Gravitational Waves - see a whole new Universe
Neutron Star, Quark Star, Black hole?

Neutron Stars  Hybrid Stars  Quark Stars  Black Holes

\[ \rho_c = \rho_0 \quad \approx 2\rho_0 \quad \approx 5\rho_0 \quad \cdots \quad \infty \]

Central density \( \rho_c \) in the star

\( \rho_0 := 0.15/\text{fm}^3 \)
Chiral Mean Field CMF - Model - Quarks, Gluons and Hadrons in Heavy Ion collisions

relativistic mean field model of quarks and hadrons
Interacting via mesonic fields / condensates

susceptibilities $\chi^B_i = \text{fluctuations of baryon number}$

$\propto <(N\!-\!N)^i> $

can be related / measured in heavy-ion experiments

structures in particle number fluctuations
Interference of liquid-gas and quark-hadron transitions

_analysis requires model with good description of hadronic matter!

BMBF project (with Ivan Kisel)
to be integrated into UrQMD (Marcus Bleicher)

Mukherjee, Steinheimer, Stefan Schramm, arxiv:1611.10144
Maximum NS-mass observed = 2.0xMsolar & <2.1xMsolar - limit of GW170817
Radii ~ 12-13km observed

hybrid star’s rel.EoS at high $\mu_B$ must agree with lattice QCD data at low $\mu_B$

Anton Motornenko, Vovchenko, Steinheimer, Stefan Schramm, Stoecker 1809.02000, NPA (2019), QM’19 Wuhan
Phase diagram

Quark fraction:

Chiral condensate:

Pure quark matter

Chiral symmetry restoration (parity partners + quarks)

Hadronic liquid

Gas of interacting hadrons
Relating to heavy ion collisions: 1D hydro

We estimate trajectories along the phase diagram with a simple 1D hydro model:
- baryonic charge in heavy ion collisions is conserved \( B = \text{const} \)
- produced matter is a perfect fluid \( \rightarrow \) no dissipations \( \rightarrow \) total entropy is constant

This gives: constant entropy per baryon \( S/A = \text{const} \), the same as entropy density / baryon density \( s/n_B = \text{const} \)

Evolution occurs along lines of constant entropy per baryon:

How one can relate collision energy \( s_{NN} \) to produced entropy?

Relativistic Rankine–Hugoniot Equations

A. H. Taub

University of Illinois, Urbana, Illinois and Institute for Advanced Study, Princeton University, Princeton, New Jersey*  
(Received April 13, 1948)

The relativistic Rankine–Hugoniot equations can be derived from the continuity of the

- particle flux density \( [j^0] = [\rho u_x] = 0 \)
- energy flux density \( [T_{0x}] = [i u_0 u_x] = 0 \) \hspace{1cm} (II.88)
- and momentum flux density \( [T_{xx}] = [i u_x^2 + P] = 0 \)

Horst Stoecker and Walter Greiner, Phys.Rept. 137 (1986) 277-392

H. Stöcker, 2019
Isentropes (S/A = const) illustrate hydrodynamical evolution of the central region in heavy ion collision.

Initial entropy per baryon S/A, was estimated by Taub adiabat (shock wave solution):

\[
(P_0 + \varepsilon_0)(P + \varepsilon)n^2 \over (P_0 + \varepsilon)(P + \varepsilon_0)n_0^2 = 1,
\]

\[
\gamma = \frac{\varepsilon n_0}{\varepsilon_0 n},
\]

\[
\gamma = \sqrt{\frac{1}{2} \left( 1 + \frac{E_{\text{lab}}}{m_N} \right)}
\]

P_0, \varepsilon_0, and n_0 correspond to the initial pressure, energy density, and baryon density in the local rest frame of each slab.
Probing phase diagram by heavy ions collisions

speed of sound $c_s^2$ (left) and quark fraction (right) along the isentropes as functions of temperature $T$.
Colored lines = different collision energies (initial S/A), black solid line correspond to the initial state speed of sound and quark fraction respectively.

Scenario for higher energy $\sqrt{s_{NN}} \gtrsim 7$ GeV:
1. start at the quark phase
2. softest point of deconfinement
3. baryons rapidly appear providing repulsion and increase of $c_s^2$
4. transition to dilute hadronic phase and lowering of $c_s^2$
The model provides relativistic consistency $c_s < 1$;

Structures in $c_s$ coincide with the structures in the susceptibilities;

At critical regions local minima of $c_s$ are present;

Nuclear liquid provides large values $c_s \approx 0.8$, result of the strong baryon repulsion;
Equation of state at $T=0$: neutron stars

- $T=0$
- Electric charge is zero
- Leptons are included
- No nuclear ground state
- Chiral transition is at $n \approx 4n_0$
- Quark matter is at $n \approx 23n_0$
- Hyperons at $T=0$ are suppressed by hard-core repulsion (nevertheless are present at $T \neq 0$)
- Strange quarks are included
The model can be easily employed for the description of neutron star matter at $T=0$ in beta-equilibrium without any changes to the parameters. The EoS then can be used as an input to model neutron stars by solving Tolman–Oppenheimer–Volkoff equation:

$$\frac{dP}{dr} = -\frac{Gm}{r^2} \rho \left(1 + \frac{P}{\rho c^2}\right) \left(1 + \frac{4\pi r^3 P}{mc^2}\right) \left(1 - \frac{2Gm}{rc^2}\right)^{-1}$$

Additional input is needed to model star’s crust — Nuclear Statistical Equilibrium (Baym, Pethick, Sutherland, 1971, Astrophys. J., 170, 299.)

- The model approaches Stefan-Boltzmann limit at high energy densities.
Mass-radius relations

Maximal mass is in agreement with recent constraints on maximal mass of neutron star from GW170817:

\[ 2.01^{+0.04}_{-0.04} \leq \frac{M_{\text{TOV}}}{M_{\odot}} \lesssim 2.16^{+0.17}_{-0.15} \]

- EoS is stiff enough to provide $2M_{\odot}$ neutron stars
- No second family of NS
- Quark fraction < 30% for stable stars
- Agreement with observations
Quarks appear smoothly — no separation between phases.

Strange quark fraction is <13%, produced by weak decays.

Quarks give significant contribution to stars with central density $n_c > 6n_0$, where pQCD calculations for EoS are available:

**Local quark fraction (dashed — unstable stars):**

A. Kurkela, P. Romatschke, A. Vuorinen, 0912.1856
Tidal deformability — measures stars’ induced quadruple moment $Q_{ij}$ as a response to the external tidal field $\mathcal{E}_{ij}$:

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

important EoS-dependent quantity for inspiral phase of binary neutron star system. Related to second Love number $k_2$:

$$\lambda = \frac{2}{3} k_2 R^5$$

One presents the dimensionless tidal deformability $\Lambda$ (mostly dependent on compactness $M/R$):

$$\Lambda = \frac{\lambda}{M^5} = \frac{2}{3} k_2 \left( \frac{R}{M} \right)^5$$

Bands — recent constraints for radius and tidal deformability of $1.4M_{\odot}$ star.

*Most, Weih, Rezzolla, Schaffner-Bielich., 1803.00549*

Line — results on $\Lambda$ using EoS obtained from the model.
Summary

- **Chiral SU(3) parity-doublet quark-hadron mean-field model** — unified phenomenological approach to model QCD thermodynamics at wide range of scales;
- $\mu_B=0$ lattice QCD data is used to constrain parameters of model’s quark sector;
- **Nuclear liquid-vapor** phase transition gives strong signals in fluctuations even at $\mu_B=0$;
- Chiral symmetry restoration and transition to quark-dominated phase are at very high $\mu_B$ and/or $T$;
- Model produces neutron stars in agreement with modern constraints;
- Model’s EoS can be used as an input for both finite $T$ and $T=0$ neutron star physics
- … as well as for hydro simulations of heavy ions collisions.

Thanks for your attention!
Neutron Star merger vs. heavy ion collisions: Baryon *Densities and Temperatures*

+ initialize by Relativistic Rankine Hugoniot Taub Adiabat with Relativistic CMF- EoS

**Graph:**
- **Temperature:**
  - HIC matter (dotted red line)
  - Star matter (dashed black line)
- **Density:**
  - HIC matter (solid red line)
  - Star matter (solid black line)

**Equation:**
$$E^2 - E_0^2 = (p - p_0)(E/n - E_0/n_0)$$

Compare central heavy ion collisions with head-on neutron star collisions:
Rankine Hugoniot Taub Adiabate
conserves baryon number and energy momentum current densities across shock front yields stationon.1+1D, hydrodynamical equation for $n, p$ vs $E$:
Dense Matter, Strange Matter, Quark Matter, Quark Stars?
FAIR: Relativistic collisions of NS-NS vs. Heavy Ions

Temperature

$10^{12} K$

Magnetic field

$10^{15} g/cm^3$

Baryon density

Neutron Star - Neutron Star Collisions

critical endpoint?

early Universe

heavy-ion collision

neutron stars
Death-Star- Machines - FAIR HIAF NICA STAR
NeutronStar matter in the Lab - Heavy Ion Collisions
Charm and Beauty of International Collaboration
Neutron Star matter in CBM @FAiR-GSI Helmholtzcentre

FAIR Experiments

CBM

APPA

NuSTAR

Super-FRS

PANDA
The CBM experiment

HADES
p+p, p+A
A+A (low mult.)

Dipol Magnet
Silicon Tracking System
Micro Vertex Detector

Ring Imaging Cherenkov
Muon Detector

DAQ/FLES HPC cluster

Transition Radiation Detector
Time of Flight Detector
Projectile Spectator Detector
CBM: How DL may help when it works

Challenges:
- $10^5$-$10^7$ collisions per second, high data flux
- High radiation load, aging
- Many particles/tracks per collision

Solutions:
- AI allows online decoding of underlying physics for the event selection, with controlled accuracy
- AI-algorithms for frequent recalibration and quality control of detector sub-systems
- Great speed-up of tracking and realignment algorithms by AI-optimization

BMBF FSP ErUM-CBM Computing@FIAS
Hiring New Doctoral Students & Postdocs

'Oce' Visiting Student from SUT Thailand

Paper selected the #26 most important paper in physics 2018. Nature Communications.
The ideal fluid equations - but should include bulk- & shear viscosity & thermoconductivity - cf. A. Muronga & J. Noronha

\[ R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi T_{\mu\nu}, \]  
(field equations)

\[ \nabla_\mu T^{\mu\nu} = 0, \]  
(cons. energy/momentum)

\[ \nabla_\mu (\rho u^\mu) = 0, \]  
(cons. rest mass)

\[ \nabla_\nu F^{\mu\nu} = I^\mu, \quad \nabla^* F^{\mu\nu} = 0, \]  
(Maxwell equations)

\[ T_{\mu\nu} = T_{\mu\nu}^{\text{fluid}} + T_{\mu\nu}^{\text{EM}} + \ldots \]  
(energy – momentum tensor)

\[ p = p(\rho, \epsilon, Y_e, \ldots) , \]  
(equation of state)

These equations do not possess analytic solutions in strong-field regimes: numerical approaches inevitable
Gold+Gold collisions at GSI: Helmholtz Zentrum für Schwerionenforschung.
At the FAIR facility: with high intensity beam

Density in units of nuclear ground state density

\[
\text{Temperature in MeV}
\]

\[
time = 0.08 \text{ fm/c}
\]

**Jan Steinheimer**, FIAS Frankfurt

Special Relativistic 3+1Dim Hydrodynamics for HIC '80-90-ies:
G. Graebner, D. Rischke, et al., ITP, Goethe University
Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.
Gravitational Waves discovered

Collision of 2 Neutron Stars

GW170817

Masses of BHs: 1.4 & 1.4 Solar Masses

Distance to Earth \( \text{Gpc} \)

Length Difference \( 10^{-21} \text{ m} \)

Credit: Les Wade from Kenyon College.
Nuclear Matter EoS in Binary NS Mergers & Quark Matter Phase Transition Signatures in Gravitational Waves

Most, Papenfort, Dexheimer, Hanuske, Schramm, Stoecker, Rezzolla (PRL 2019)

see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel (PRL 2019)
# Deep NN hydrodynamic simulations

Kirill Taradiy, Kai Zhou, Jan Steinheimer, Longgang Pang, H.St.*

<table>
<thead>
<tr>
<th></th>
<th>NVIDIA GTX 1080 Ti</th>
<th>NVIDIA Titan V</th>
<th>NVIDIA RTX 2080 Ti</th>
<th>AMD Radeon VII</th>
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<td>TFLOPs(FMA)</td>
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<td>Memory Clock</td>
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<td>651Gbps HBM2</td>
<td>616Gbps GDDR6</td>
<td>1024Gbps HBM2</td>
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<td>Memory Bus Width</td>
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<td>3072</td>
<td>352</td>
<td>4096</td>
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<td>Cores</td>
<td>3584</td>
<td>5120 + 640 tensorcores</td>
<td>4352 + 576 tensorcores</td>
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<td>Price</td>
<td>650</td>
<td>2999</td>
<td>1100</td>
<td>800</td>
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</table>

- 5 Petaflops
- 8 M$ Goethe U. CSC
- 3000 GPUs AMD Radeon VII

Volker Lindenstruth
FIAS Frankfurt Institute for Advanced Studies
Real time 2D fluid simulation comparison
GPU vs CPU

Jesus Martin Berlanga, Real-Time GPU fluid dynamics
Neural Networks for Time evolution tasks

- A feed-forward network with a single hidden layer containing a finite number of neurons can approximate continuous functions on compact subsets.

\[ X \xrightarrow{f} Y \]


Riemann Problem

- 1 dimensional task
- Hydro equations are simplified to Euler form
- Piecewise – constant discontinuous initial conditions

\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau} + \rho \mathbf{g} \]

**Cauchy momentum equation**

\[ \sigma = \zeta (\nabla \cdot \mathbf{u}) I + \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} (\nabla \cdot \mathbf{u}) I \right) \]

**Linear stress constitutive equation**

**Navier–Stokes momentum equation (convective form)**

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla \mathbf{p} + \mu \nabla^2 \mathbf{u} + \frac{1}{3} \mu \nabla (\nabla \cdot \mathbf{u}) + \rho \mathbf{g}. \]

Sod Shock Tube

1) \( u_l = u_r, \quad p_l = 3 p_r \)

2) \( u_l = u_r, \quad p_l = p_r \)

Collision or Expansion
Sod Shock Tube

The purpose is to learn the dependence rather than the data itself.

Expansion and Collision

S. Tokareva, A. Skurikhin, Machine learning approach for the solution of the Riemann problem in fluid dynamics

DNN predicts correctly the time dependence of hydrodynamic evolution!


Adam

<table>
<thead>
<tr>
<th>Epochs</th>
<th>In range</th>
<th>Out of range</th>
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</thead>
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<td>30</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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</tbody>
</table>

Custom sgd (stoch. grad. descent) with momentum:

- bad network predictability
- Outside of the training interval signal of overfitting
- network may perform worse
- On the test set, but better
- Predictability outside of training interval - result of particular local minimum found

- optimizer type + the initial definition of weights and biases
- greatly Influenceds the network’s predictability outside training set.
Disco-Fox, Merengue and Tango-Phase
Where it’s hot and dense in neutron star mergers

- Separation of **hot hadronic corona** and **dense, cold quark matter core**
Evolution in the phase diagram

- Evolution of the max. temperature and density.
- Quarks appear early on in Torus: $T \sim 50$ MeV
- Once core reaches density $n/n_0 \sim 3.5$, transition into SQM occurs
Modelling a CMF - EOS with Quarks: by Dexheimer & Schramm

- EOS based on Chiral Mean Field (CMF) and nonlinear SU(3) sigma model
- Includes hyperons and quarks that can be turned on / off
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures
- In **low-mass binary**, after \(~\sim 5\) ms, quark fraction is large enough to change quadrupole moment and yield differences in the waveforms.
- In **high-mass binary**, phase transition takes place rapidly after \(~\sim 5\) ms. We see a clear mismatch between hadronic inspiral and post-merger phase.

Signature of Quark Matter - crossing or 1.OPT?
Thank You, and all the Best, dear Goergyi and Miklos