SQM 2013 Theory Summary Review

Subjective remarks

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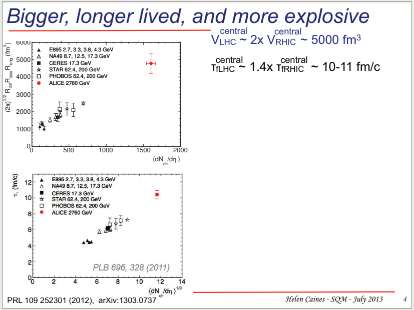
Fundamental Questions

- Gott würfelt nicht... (but oft enough it looks like that)
- Particles (mass points) or Fields (waves): both...
- Shall we ever know the Intitial State?

Outline

More... size, time, gradients Helen Caines

$$\frac{dN_{\mathrm{ch}}}{d\eta} \propto \ln \sqrt{s} \sim y_{\mathrm{beam}}$$



$$V \approx 730\mathrm{fm}^3 + 2.545\frac{dN_{\mathrm{ch}}}{d\eta}, \qquad \mathcal{T} \approx 0.875\left(\frac{dN_{\mathrm{ch}}}{d\eta}\right)^{1/3}$$

Versus

1. thermalization: exponential vs power-law
2. hydrodynamics: initial vs eos-driven
3. hadronization: phase space vs QCD
4. QM eos: lattice vs dual gravity
5. nuclear medium: cross sections vs mean fields
6. simulation: particle vs field

Outline

1. Versus
   - Thermalization
   - Hydrodynamics
   - Hadronization
   - Lattice

2. Highlights

Thermal and Hydro: why and how?

Florkowski: Thermalization of massive partons in anisotropic medium
Rafelski: First 3 seconds
Stachel: Thermal model
Kolomeitsev: Strangeness balance in HIC
Cleymans: Systematic Properties of the Tsallis Distribution
Beitel: Thermalization through Hagedorn States
Grossi: Relativistic distribution function...

Essence of Hydro: LCNC

Local Conservation of Noether Currents

$$\partial_\mu J^{\mu\, a} = 0. \qquad (1)$$

Essence of Hydro: dominant LCNC-s

$$\partial_\mu J^{\mu\,(B,S,Q)} = 0$$

$$\partial_\mu T^{\mu\,\nu} = 0$$

$$\partial_\mu M^{\mu\,\nu\rho} = 0 \qquad (2)$$

NC-s are connected

Essence of Hydro: Connections

chemistry (types of charges, single or multi-fluid)

$$J^{\mu\, a} = \sum_{i=+,-} q_i^a \, u_{(i)}^{\mu} \tag{3}$$

conductive (carried by the stream) + else

$$T^{\mu\nu} = P^{\mu} u^{\nu} + P^{\nu} u^{\mu} + \mathfrak{T}^{\mu\nu} \tag{4}$$

polarisation

$$M^{\mu\nu\rho} = x^{\mu} T^{\nu\rho} - x^{\nu} T^{\mu\rho} + S^{\mu\nu\rho} \tag{5}$$

Hydro Hopes

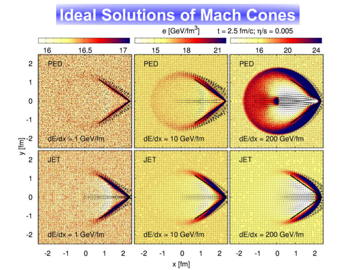
citing Takeshi Kodama

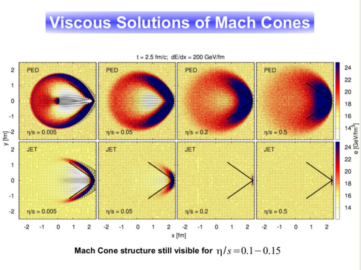
Expectations and hopes :

- Determination of Properties of Matter (EoS, Transport coefficieints)
- Comparison with Lattice QCD
- Determination of Initial State just after the Collision
- Key for the QCD dynamics···

Numerical Hydro

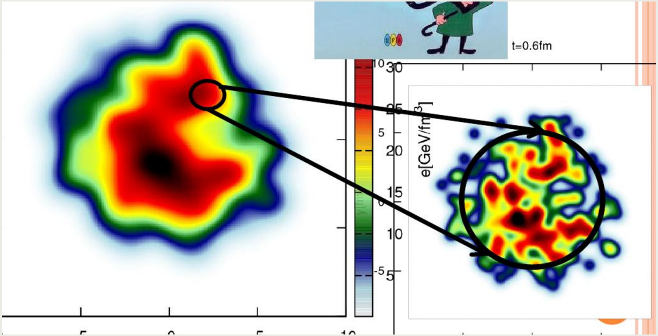
Joanis Bouras: BAMP Mach Cones





Improving Hydro?

Kodama, Wilk, Biro+Molnar, Denicol



Coarse Graining = UV open (anti/dissipative?) system

Finite Reservoir (fluctuating intensives) = IR open system

Hydro $\rightarrow$ Thermo

Equilibrium after dissipation:

$$\partial_\mu S^\mu + \lambda_a \partial_\mu J^{\mu,a} \geq 0. \tag{6}$$

Gibbs potential

$$S^\mu + \lambda_a J^{\mu\,a} = \Phi^\mu \tag{7}$$

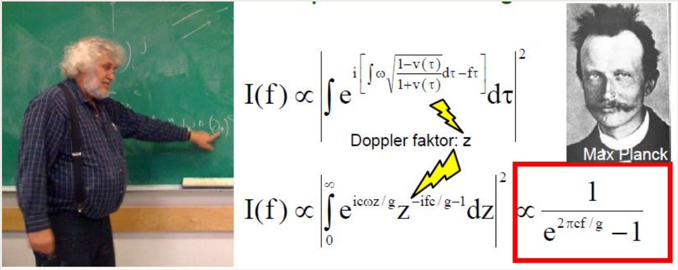
Gibbs-Duhem relation (in/out local equilibrium)

$$\partial_\mu \Phi^\mu \geq J^{\mu\,a} \partial_\mu \lambda_a \tag{8}$$

Linear transport (η_{ab} positive semi-definite)

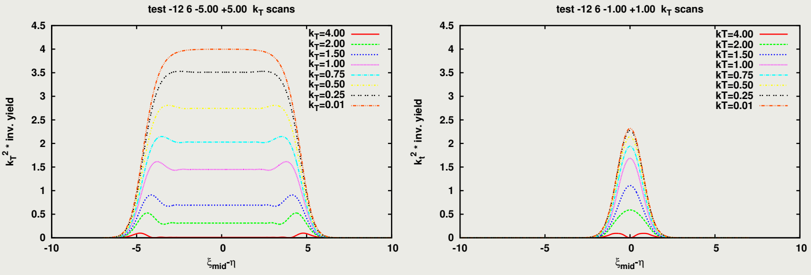
$$\partial^\mu \lambda_a = -\eta_{ab} J^{\mu\,b}. \tag{9}$$

Pseudo-thermalization? Pseudo-Hydro?



(Semi)classical Photon Spectra

T. S. Biro, Z. Schram, Z. Szendi: *work in progress...*



Hydro: initial state or eos?

Takahashi: Effects of Jets in the Flow Observables
Kodama: Thermal Equilibrium and ... Initial Condition
Tamosiunas: Landau hydrodynamics...
Wiranata: Shear viscosity of hadrons...
Csernai: Turbulence, Vorticity and Lambda Polarization
Bozek: Hydrodynamic models of particle production
Song: QGP viscosity and the flow ...
Molnar: Event-by-event correlation...
Scradina: Elliptic Flow from CGC
Huovinen: Dynamical freeze-out in event-by-event hydro...

Hadronization: Phase Space or QCD dynamics?

Werner: Monte Carlo
Bratkovskaya: Strongly interacting parton-hadron matter...
Gousset: Gluon radiation by heavy quarks
Kitazawa: Diffusion of Non-Gaussianity ...
Flores: Strangeness baryon to meson ratio
Tiwari: ... Excluded-Volume Model
Petran: Interpretation of strange hadron production at LHC
Chatterjee: Chemical freezeout via HRG

Defactorizing the ”Thermo” Part

1. Find Scaling Variable(s) which unifies different mass hadron $p_\perp$-spectra
2. Try Coalescence Hypothesis, if Baryon and Meson branches differ
3. Find out the Functional Form on the quark (parton) level
4. Test trends (with binary scaling, participant number, rapidity window)
5. Interpret Parameters (vs on/off-equilibrium, finite/infinite size, . . .)

Defactorizing the "Thermo" Part

1. Is it $f(p_T, m) = f(E_v(p_t, m) - \mu(m)) = f(X)$?
2. Coalescence scaling? $f_h(X) = f_q^n(X/n)$ for $n = 2, 3$
3. (X-)Energy distribution? $f(X) \sim (1 + a\beta X)^{-1/a} \longrightarrow e^{-\beta X}$
4. Test trends $(N_{part}, N_{bin}, P(N), \sqrt{s}, \Delta\eta$ ...)
5. Interpret Parameters: $\beta, v, a, \ldots$

Thermal Cosmology

Johann Rafelski

When old people make a new theory, they know all about assumptions, approximations, implied or explicit. But young people, who learn it from a textbook, believe that this were TRUTH.

Jan Rafelski, Arizona *The first three seconds* *SQM2013,* page 2

WHY? – Four Pillars of QGP/RHI Collisions Research Program

RECREATE THE EARLY UNIVERSE IN LABORATORY:
Recreate and understand the high energy density conditions prevailing in the Universe when matter formed from elementary degrees of freedom (quarks, gluons) at about 30 μs after big bang.

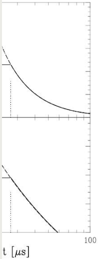
QGP-Universe hadronization led to nearly matter-antimatter symmetric state, the later ensuing matter-antimatter annihilation leaves behind as our world the tiny 10^{-10} matter asymmetry.

STRUCTURED VACUUM-AETHER (Einsteins 1920+ Aether/Field/Universe)
The vacuum state determines prevailing fundamental laws of nature. Demonstrate by changing the vacuum from hadronic matter ground state to the deconfined quark matter ground state.

ORIGIN OF MASS OF MATTER –(DE)CONFINEMENT
The confining quark vacuum state is the origin of 99.9% of mass, the Higgs mechanism applies to the remaining 0.1%. We want to confirm the quantum zero-point energy of confined quarks as the mass of matter. When we 'melt' the vacuum structure setting quarks free the energy locked in mass of nucleons is transformed into thermal QGP energy.

ORIGIN OF FLAVOR
Normal matter made of first flavor family (u, d, e, ν_e). Strangeness rich quark-gluon plasma the sole laboratory environment filled with 2nd family matter (s, c, μ, ν_μ) – arguable the only experimental environment where we could unravel the secret of flavor.

Hadronization is when? – Time scales



Combine both dynamical equations

$$\dot{\epsilon}^2 = \frac{128\pi G}{3}\epsilon\,(\epsilon - \mathcal{B})^2,$$

for $\mathcal{B} \to 0$ and massless particles:

$$\epsilon = \frac{3}{32\pi G}\frac{1}{(t_0+t)^2} \Rightarrow \frac{T}{T_0} = \sqrt{\frac{t_0}{t_0+t}}$$

Analytic solution also with $\mathcal{B}$:

$$\epsilon_{\rm QGP} = \mathcal{B}\coth^2 x, \quad x = \frac{\tau_0}{\tau_{\rm U}}\left(\frac{t_0+t}{\tau_0}\right),$$

With time constant:

$$\tau_{\rm U} = \sqrt{\frac{3c^2}{32\pi G\mathcal{B}}} = 25\sqrt{\frac{\mathcal{B}_0}{\mathcal{B}}}\,\mu{\rm s}, \quad \mathcal{B}_0 = 0.4\,\frac{\rm GeV}{\rm fm^3}$$

τ_0: time of prior latent heat jump at electro-weak transition 1000 times greater T as compared to QGP: $\tau_0 \simeq 30$ ps

Transition time at $\Delta t \simeq \tau_{\rm U}/3 \simeq 10\mu$s, $\Delta R = 3$km.

The QGP Universe expands,

Quarkonia and Energy Loss

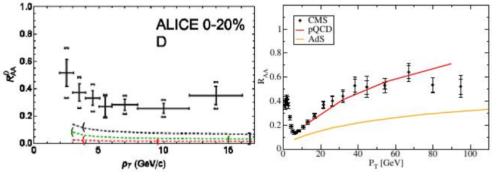
Horowitz: Heavy Quark Energy Loss
Das: ... Boltzmann vs Langevin
Berrehrah: Towards... (QGP)
Uphoff: Heavy vs light flavor energy loss...
Renk: Jet quenching and Heavy Quarks
Lee: Free energy vs internal energy potential...
Katz: Quantum and semiclassical...
Djordjevic: ... finite magnetic mass...

Does AdS/CFT well?

From Thorsten Trenk's review

AdS, light and heavy quarks

- Does AdS get the scaling from RHIC to LHC?



⇒ Clear **no** for both heavy and light quarks! AdS techniques predict too much suppression at LHC when tuned to RHIC and extrapolated.

- No viable AdS/CFT model candidate for the more involved light quark observables ⇒ revise or abandon!

W. Horowitz, Nucl. Phys. A904-905 **2013** (2013) 186c,T. R., Phys. Rev. C **85** (2012) 044903

Lattice or other Models?

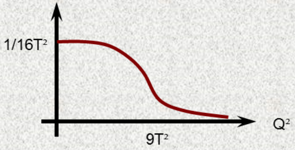
Torrieri: ... high-density quark matter
Chao: ... Sphalerons
Bluhm: Flavor Hierarchy...
Yamazaki: ... PNJL model
Marty: ...Nambu-Jona-Lasinio model for SU(3)f
Allton: First Principles Calculation...
Redlich: Role of fluctuations in detecting the QCD phase transition
Kumar: Holographic descriptions of dense quark matter
Herold: "chiral fluid dynamics"
Schmidt: "ab initio Lattice QCD calculations"

High-T = pQCD ???

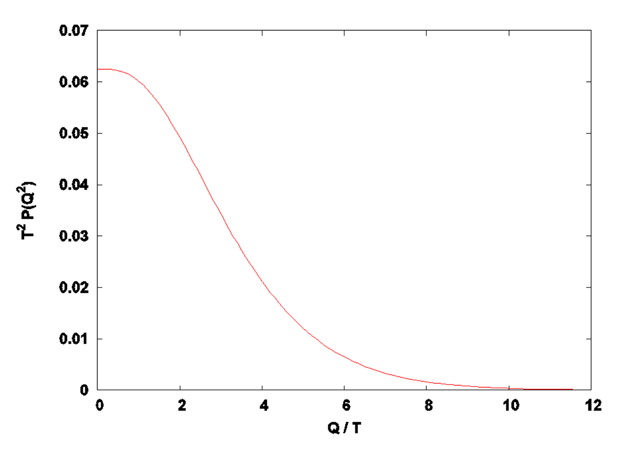
Thermal distribution of Q^2

$$P(Q^2) = \frac{\iint dE_1 dE_2 d\theta \; E_1^2 E_2^2 \; e^{-\beta(E_1+E_2)} \; \delta\left(Q^2 - 2E_1E_2(1-\cos\theta)\right)}{\iint dE_1 dE_2 d\theta \; E_1^2 E_2^2 \; e^{-\beta(E_1+E_2)}}$$

$$P(Q^2) = \frac{1}{64T^2}\left(\frac{Q^3}{T^3}K_1\left(\frac{Q}{T}\right) + 2\frac{Q^2}{T^2}K_2\left(\frac{Q}{T}\right)\right)$$



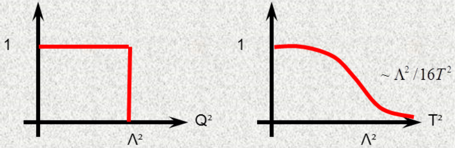
Boltzmann-Gibbs Q^2 distribution



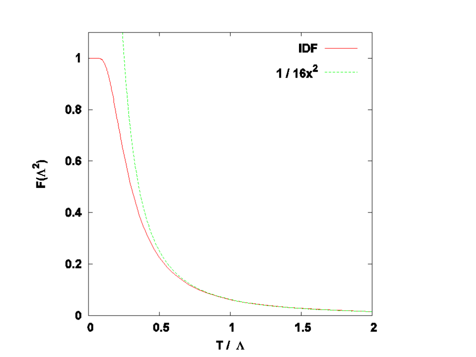
Order parameter of Non-Perturbativity

Thermal expectation of NP order parameter

$$\left\langle \Theta\left(\Lambda^2 - Q^2\right) \right\rangle = \int_0^{\Lambda^2} P(Q^2)\, dQ^2$$



Hadrons Survive until $T \approx 1$ GeV



Between $T_1 \approx 1/6$ GeV and $T_2 \approx 1$ GeV: **both worlds!**

Outline

1. Versus
2. Highlights
   - Other topics

Highlights

- New Theories
- New Aspects
- New Proposals
- New Calculations
- New Insights

(Towards) New Theory

EoS, transport, capacities (q=1-1/C), fluctuations, ...

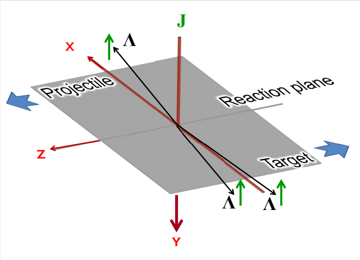
Expectations and hopes :

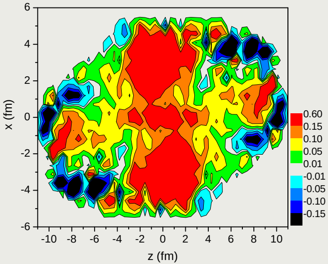
- Determination of Properties of Matter (EoS, Transport coefficieints)
- Comparison with Lattice QCD
- Determination of Initial State just after the Collision
- Key for the QCD dynamics···

What about the Birth of Hadrons?

New Aspect + Proposal

Becattini, Csernai, Wang: Lambda Polarization .... (1304.4427)



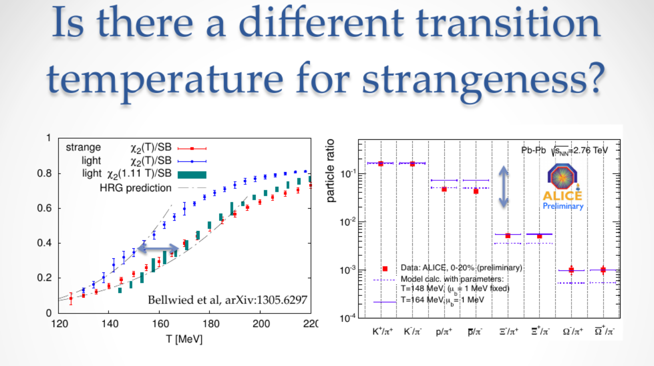


$$\Pi_\mu \sim \langle \varepsilon_{\mu\rho\sigma\tau} p^\tau \partial^\rho (\beta u^\sigma) \rangle_{Cooper-Fry} \tag{10}$$

analogy: Pauli-Lubanski vector

New Calculations: Strange Temperatures?

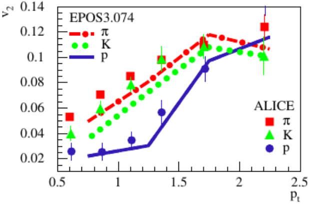
Markus Bleicher's opening talk:



New Insight: Flow Everywhere... Klaus Werner: EPOS

Summary

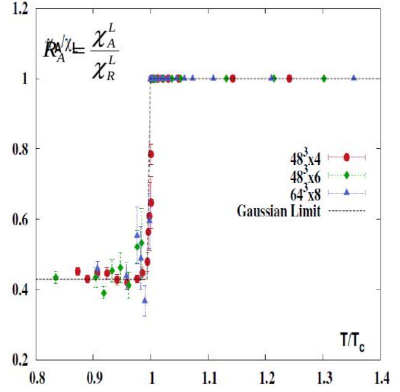
- ☐ **Traditional Monte Carlos have difficulties to describe strange particle production in pp.**
  Hydrodynamical picture helps.
- ☐ **pPb looks very much like**
  a hydrodynamically expanding system
  (more clean than PbPb, where hydro and minijets heavily interact, as well as the final hadrons among themselves)



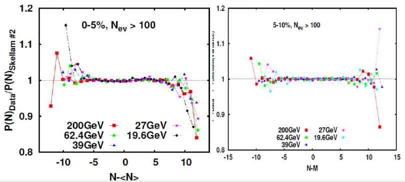
Proposal: Message via Fluctuations

Krzysztof Redlich

Pok Man Lo, B. Friman, O. Kaczmarek, C. Sasaki & K.R. , PRD (2013)

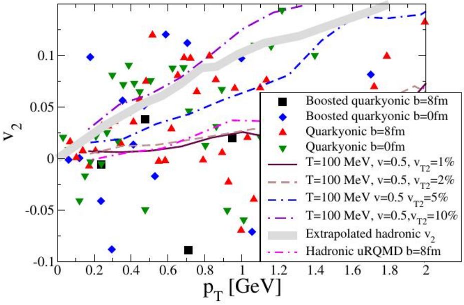


Energy dependence for different centralities



Proposal:

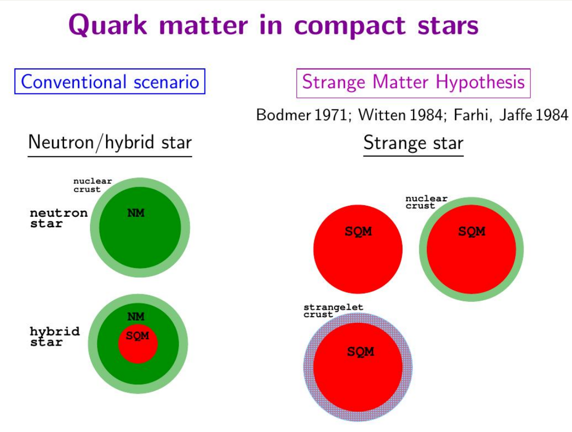
Giorgio Torrieri



"pure" quarkyonic effect, it is due to sensitivity of quark wavefunctions to baryon location. signature?

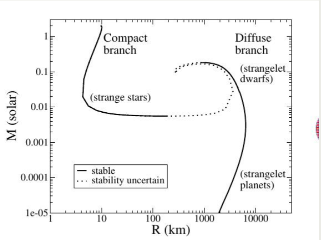
Astro, Nuclear, ... new insight?

Alford's review

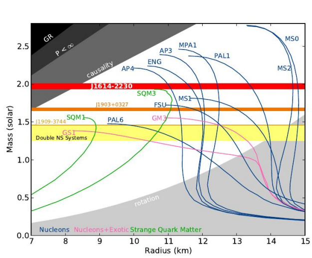


Astro, Nuclear, ... new insight?

Alford's review



Alford, Han arXiv:1111.3937



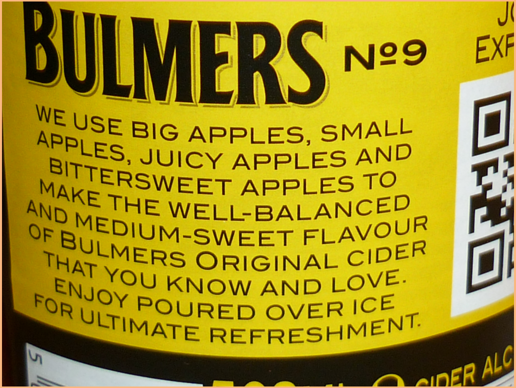
Recent measurement:

$M = 1.97 \pm 0.04\, M_{\odot}$

Demorest et al, Nature 467, 1081 (2010).

Not all theories survive observation...

Summary



Apple = Theory

Ice = Experiment