Physics perspectives with heavy ions at the High Luminosity - LHC and beyond

Stefan Floerchinger (Heidelberg U.)

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UNIVERSITÄT
HEIDELBERG
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SEIT 1386

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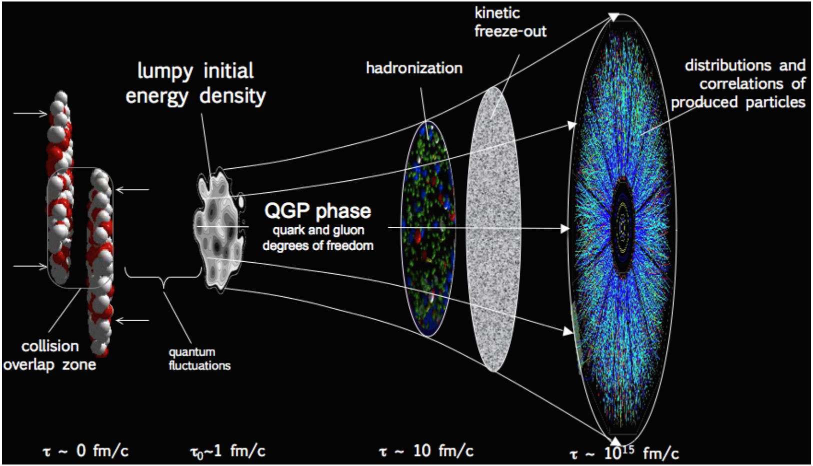
Heavy ions at the HL-LHC

Ongoing discussion, see for example:

- Jan-Fiete Grosse-Oetringhaus, talk at *Workshop on the physics of HL-LHC*, 30.10.2017: https://indico.cern.ch/event/647676/timetable/
- Andrea Dainese, talk at *ECFA High Luminosity LHC Experiments Workshop*, 04.10.2016: https://indico.cern.ch/event/524795/timetable/
- J. M. Jowett, M. Schaumann and R. Versteegen, *Heavy-Ion Operation of HL-LHC*: https://cds.cern.ch/record/1977371
- Antonio Uras, *Heavy-Ions at the High-Luminosity LHC*: http://inspirehep.net/record/1589642
- preparation of a CERN yellow report chapter on *Heavy ions at the HL-LHC*, working group meeting: https://indico.cern.ch/event/717641/
- existing CERN yellow report chapter on *Heavy Ions at the Future Circular Collider*: http://inspirehep.net/record/1455787?ln=de

I will not attempt to reflect the full ongoing discussion, but rather present my own point of view (as a theorist).

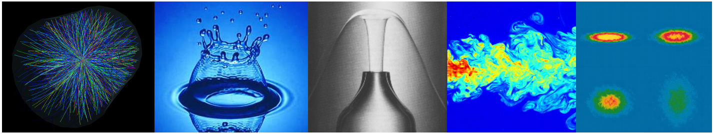
Little bangs in the laboratory



A great challenge

- quantum fields at finite energy density and temperature
- fundamental gauge theory: QCD
- strongly interacting
- non-equilibrium dynamics
- experimentally driven field of research
- big motivation for theory development

Fluid dynamics



- long distances, long times or strong enough interactions
- matter or quantum fields form a fluid!
- needs **macroscopic** fluid properties
  - thermodynamic equation of state $p(T, \mu)$
  - shear viscosity $\eta(T, \mu)$
  - bulk viscosity $\zeta(T, \mu)$
  - heat conductivity $\kappa(T, \mu)$
  - relaxation times, ...
- *ab initio* calculation of fluid properties difficult but fixed by **microscopic** properties in $\mathscr{L}_{\text{QCD}}$

Relativistic fluid dynamics

Energy-momentum tensor and conserved current

$$T^{\mu\nu} = \epsilon\, u^\mu u^\nu + (p + \pi_{\text{bulk}})\Delta^{\mu\nu} + \pi^{\mu\nu}$$
$$N^\mu = n\, u^\mu + \nu^\mu$$

- tensor decomposition using fluid velocity u^μ, $\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$
- thermodynamic equation of state $p = p(T, \mu)$

Covariant **conservation laws** $\nabla_\mu T^{\mu\nu} = 0$ and $\nabla_\mu N^\mu = 0$ imply

- equation for **energy density** ϵ

$$u^\mu \partial_\mu \epsilon + (\epsilon + p + \pi_{\text{bulk}})\nabla_\mu u^\mu + \pi^{\mu\nu}\nabla_\mu u_\nu = 0$$

- equation for **fluid velocity** u^μ

$$(\epsilon + p + \pi_{\text{bulk}})u^\mu \nabla_\mu u^\nu + \Delta^{\nu\mu}\partial_\mu(p + \pi_{\text{bulk}}) + \Delta^\nu{}_\alpha \nabla_\mu \pi^{\mu\alpha} = 0$$

- equation for **particle number density** n

$$u^\mu \partial_\mu n + n\nabla_\mu u^\mu + \nabla_\mu \nu^\mu = 0$$

Constitutive relations

Second order relativistic fluid dynamics:

- equation for **shear stress** $\pi^{\mu\nu}$

$$\tau_{\text{shear}} \, P^{\rho\sigma}{}_{\alpha\beta} \, u^\mu \nabla_\mu \pi^{\alpha\beta} + \pi^{\rho\sigma} + 2\eta \, P^{\rho\sigma\alpha}{}_{\beta} \, \nabla_\alpha u^\beta + \ldots = 0$$

  with **shear viscosity** $\eta(T, \mu)$

- equation for **bulk viscous pressure** π_{bulk}

$$\tau_{\text{bulk}} \, u^\mu \partial_\mu \pi_{\text{bulk}} + \pi_{\text{bulk}} + \zeta \, \nabla_\mu u^\mu + \ldots = 0$$

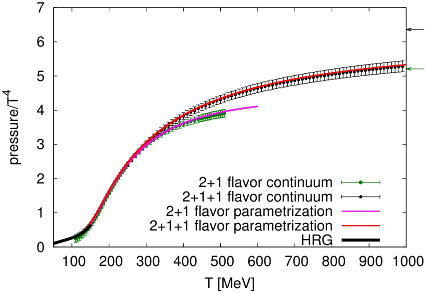
  with **bulk viscosity** $\zeta(T, \mu)$

- equation for **baryon diffusion current** ν^μ

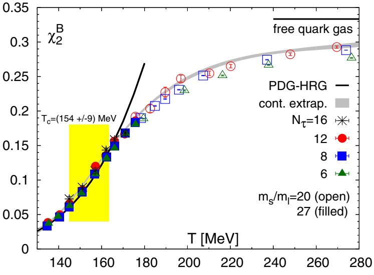
$$\tau_{\text{heat}} \, \Delta^{\alpha}{}_{\beta} \, u^\mu \nabla_\mu \nu^\beta + \nu^\alpha + \kappa \left[\frac{nT}{\epsilon + p} \right]^2 \Delta^{\alpha\beta} \partial_\beta \left(\frac{\mu}{T} \right) + \ldots = 0$$

  with **heat conductivity** $\kappa(T, \mu)$

Thermodynamics of QCD



[Borsányi *et al.* (2016)], similar Bazavov *et al.* (2014)



[Bazavov *et al.* (2017), similar Bellwied *et al.* (2015)]

- thermodynamic equation of state $p(T)$ rather well understood now
- also moments of conserved charges like

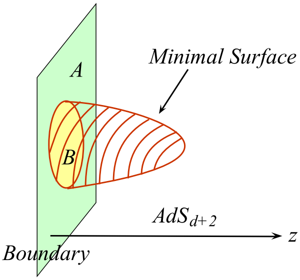
$$\chi_2^{\mathrm{B}} = \frac{\langle (N_{\mathrm{B}} - N_{\bar{\mathrm{B}}})^2 \rangle}{VT^3}$$

  and higher order understood
- progress in computing power

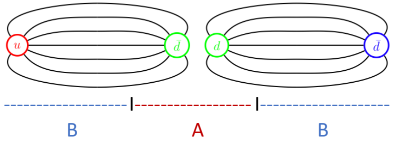
Quantum fields and information

- surprising relations between quantum field theory and information theory
- well understood in thermal equilibrium
- currently investigated out-of-equilibrium
- fluid dynamics / entanglement entropy / black hole physics (AdS/CFT)
- shear viscosity to entropy density ratio $\eta/s \geq \hbar/(4\pi k_B)$

  [Kovtun, Son, Starinets (2003)]

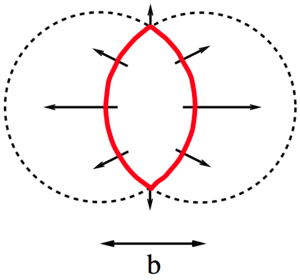


[Ryu, Takayanagi (2006)]



[Berges, Floerchinger, Venugopalan (2017)]

Non-central collisions



- pressure gradients larger in reaction plane
- leads to larger fluid velocity in this direction
- more particles fly in this direction
- can be quantified in terms of elliptic flow v_2
- particle distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_m v_m \cos\left(m\left(\phi - \psi_R\right)\right)\right]$$

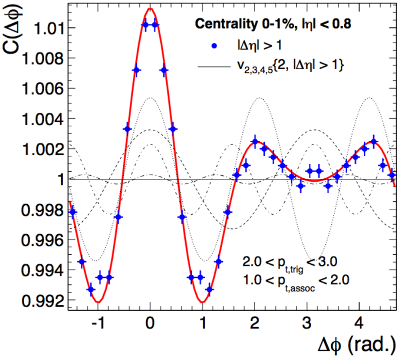
- symmetry $\phi \to \phi + \pi$ implies $v_1 = v_3 = v_5 = \ldots = 0$.

Two-particle correlation function

- normalized two-particle correlation function

$$C(\phi_1, \phi_2) = \frac{\left\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \right\rangle_{\text{events}}}{\left\langle \frac{dN}{d\phi_1} \right\rangle_{\text{events}} \left\langle \frac{dN}{d\phi_2} \right\rangle_{\text{events}}} = 1 + 2 \sum_m v_m^2 \cos(m(\phi_1 - \phi_2))$$

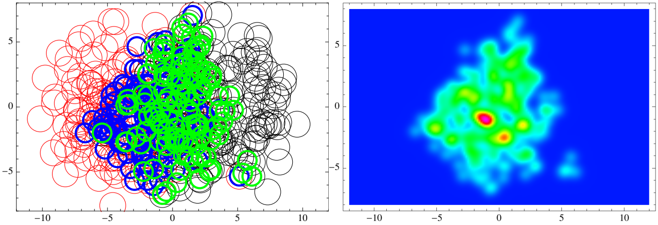
- surprisingly v_2, v_3, v_4, v_5 and v_6 are all non-zero!



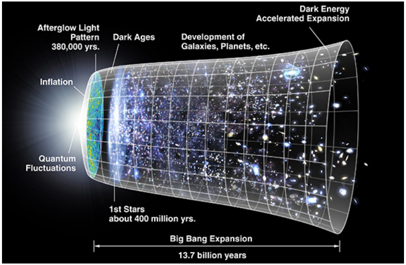
[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

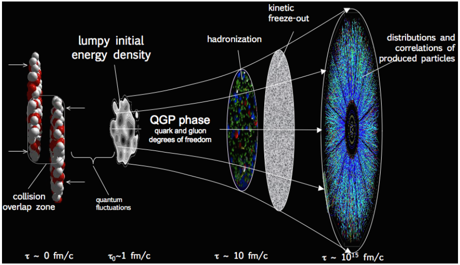
Event-by-event fluctuations

- deviations from symmetric initial energy density distribution from event-by-event fluctuations
- one example is Glauber model



Big bang – little bang analogy



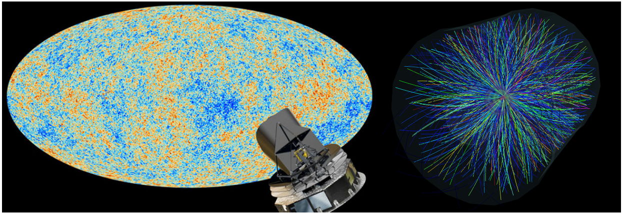


- cosmol. scale: MPc$= 3.1 \times 10^{22}$ m
- Gravity + QED + Dark sector
- one big event

- nuclear scale: fm$= 10^{-15}$ m
- QCD
- very many events

- initial conditions not directly accessible
- all information must be reconstructed from final state
- dynamical description as a fluid
- fluctuating initial state

Similarities to cosmological fluctuation analysis



- fluctuation spectrum contains info from early times
- detailed correlation functions are compared to theory
- can lead to detailed understanding of evolution
- Mode-by-mode fluid dynamics for heavy ion collisions
  [Floerchinger, Wiedemann (2014)]

The dark matter fluid

- **high energy nuclear collisions**

$$\mathscr{L}_{\text{QCD}} \quad \to \quad \text{fluid properties}$$

- **late time cosmology**

$$\text{fluid properties} \quad \to \quad \mathscr{L}_{\text{dark matter}}$$

- until direct detection of dark matter it can only be observed via gravity

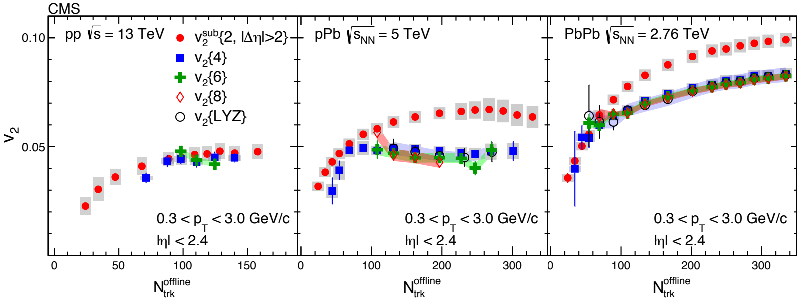
$$G^{\mu\nu} = 8\pi G_{\text{N}}\, T^{\mu\nu}$$

  so all we can access is

$$T^{\mu\nu}_{\text{dark matter}}$$

- strong motivation to study heavy ion collisions and cosmology together!

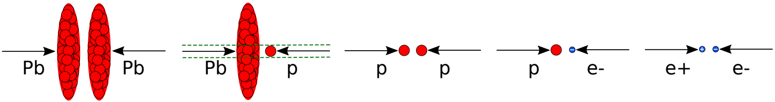
Collective behavior in large and small systems



- flow coefficients from higher order cumulants $v_2\{n\}$ agree:
  $\rightarrow$ collective behavior
- elliptic flow signals also in **pPb** and **pp** !
- can fluid approximation work for pp collisions?

Questions and puzzles

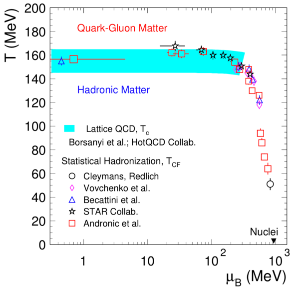
- how universal are collective flow and fluid dynamics?
  - as a limit of kinetic theory / perturbation theory / multi-parton interactions
  - non-perturbative understanding / entanglement
- what determines density distribution of a proton?
  - constituent quarks or interacting gluon cloud?
  - generalized PDFs
- more elementary collision systems? [News at Quark Matter 2018!]

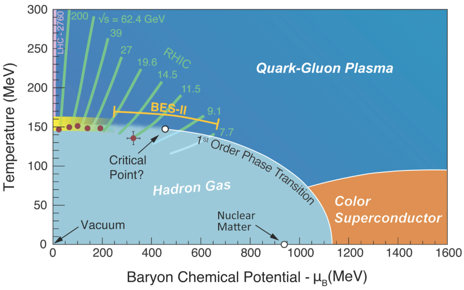


- role of electromagnetic fields and vorticity for fluid dynamics
- role of quantum anomalies (e. g. chiral magnetic effect)

Chemical freeze-out

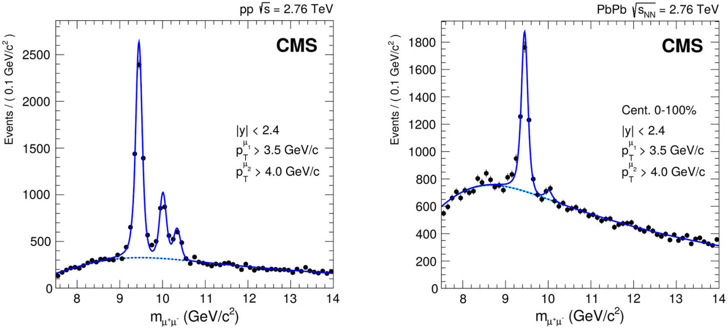
[Andronic, Braun-Munzinger, Redlich, Stachel (2017)]





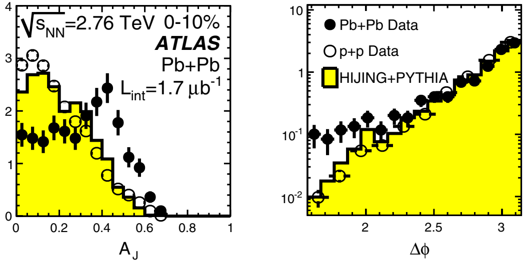
- chemical freeze-out close to chiral crossover transition for large $\sqrt{s}$
- chiral transition should be visible in higher moments $\langle (N_B - N_{\bar{B}})^n \rangle$
- traces of the evolving chiral condensate / pion condensate ?
- more insights at large μ_B expected from FAIR

Quarkonium and how it gets modified



- all Υ states are suppressed by medium effects, excited states even more
- more detailed understanding of heavy quark bound states in a medium
- also at LHC: regeneration and flow of charmed mesons
- future: also bottom

Jet quenching



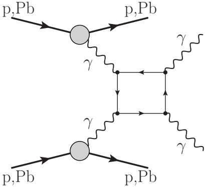
- asymmetry between reconstructed jet energies

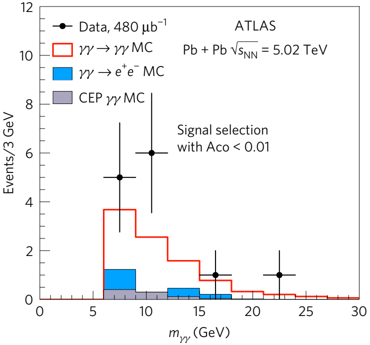
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \qquad \Delta\phi > \pi/2$$

- partons/jets loose energy to the quark gluon plasma
- jet structure can be investigated in detail
- more possible: b-jets, t-jets
- interplay of microscopic partons / jets and macroscopic QCD fluid

Light-by-light scattering

[ATLAS, Nature Phys. 13, 852 (2017)]





- ultra-peripheral ion collisions produce strong electromagnetic fields
- beam of quasi-real photons (equivalent photon approximation)
- Halpern scattering $\gamma\gamma \to \gamma\gamma$ observed, more detailed studies possible
- also ultra-peripheral: nuclear PDFs

Theory development

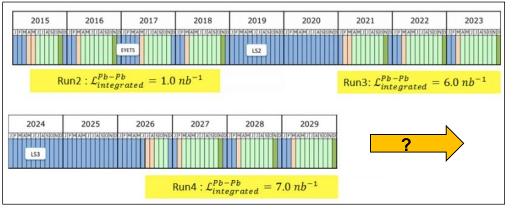
- many interesting experimental results available or in reach
- precise studies need interplay of theory and experiment
- **more dedicated theory development needed**
- **we need to develop and maintain a standard model**
- heavy ion collisions and QCD dynamics can be understood much better !

Plans for heavy ions at runs 2-4 at the LHC

[J.-F. Grosse-Oetringhaus, CERN, 30.10.2017]

$\sigma_{hadr,PbPb}$ **= 8 barn !**

- Run 2:
  - Pb-Pb: few nb^{-1} (0.7 nb^{-1} in 2015, ~1 nb^{-1} in 2018) at $\sqrt{s_{NN}}$ = 5 TeV
  - p-Pb at 5 and 8 TeV (185 nb^{-1} in 2016)
  - pp reference at Pb-Pb energy (5 TeV, Nov 2017)
- LS2:
  - LHC injector upgrades; bunch spacing reduced to 50 ns
  - Pb-Pb interaction rate up to 50 kHz (now <10 kHz)
  - Experiments' upgrades (also LS3)
- Runs 3+4:
  - Request for **Pb-Pb: >10 nb^{-1}**
    (ALICE: 10 nb^{-1} at 0.5T + 3 nb^{-1} at 0.2T)
  - In line with projections by machine:
    3.1 nb^{-1}/month (Chamonix 2017)



HL-LHC for heavy ions begins in Run 3 !

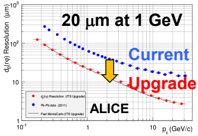
Foreseen detector upgrades

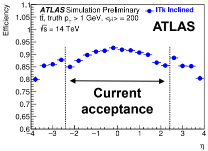
[J.-F. Grosse-Oetringhaus, CERN, 30.10.2017]

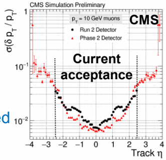
Detector Upgrades

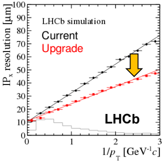
most relevant to heavy-ion physics

- **ALICE** (LS2)
  - New inner tracker: precision and efficiency at low p_T
  - New pixel forward muon tracker: precise tracking and vertexing for μ
  - TPC upgrade + readout + online data reduction x100 faster readout (continuous)
- **ATLAS** (LS2/LS3)
  - Fast tracking trigger (LS2): high-multiplicity tracking
  - Calorimeter and muon upgrades (LS2): electron, γ, muon triggers
  - ZDC replacement planned (LS2): radiation hardness, granularity
  - Completely new tracker (LS3): tracking and b-tag up to η=4
- **CMS** (mainly LS3)
  - Extension of forward muon system (LS2): muon acceptance
  - Completely new tracker (LS3): tracking and b-tag up to η=4
  - Upgrade forward calorimeter (LS3): forward jets in HI
- **LHCb** (LS2)
  - Triggerless readout, full software trigger, higher granularity detectors: impact on tracking performance in Pb-Pb being studied
  - Fixed-target programme with SMOG + possible extensions



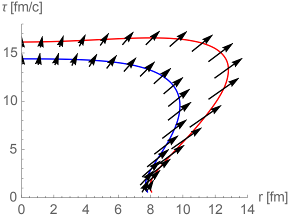






Higher energies

[Dainese, Wiedemann (ed.) *et al.* (2017)]



Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ at $\eta = 0$	1.8–2.0 TeV	2.3–2.6 TeV	5.2–5.8 TeV
Homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
Decoupling time	10 fm/c	11 fm/c	13 fm/c
ε at $\tau = 1$ fm/c	12–13 $\mathrm{GeV/fm}^3$	16–17 $\mathrm{GeV/fm}^3$	35–40 $\mathrm{GeV/fm}^3$

Larger collision energy

- higher initial energy density and temperature
- higher multiplicity N_{ch}
- larger lifetime and volume of fireball
- better probes of collective physics
- thermal charm quarks
- more hard probes

A dedicated detector for low p_T ?

- advances in detector technology might allow to construct dedicated detector for low p_T spectrum
- down to $p_T \approx 10$ MeV $\approx \frac{1}{20\text{ fm}}$?
- low momentum di-leptons
  $\rightarrow$ excellent understanding of charmonia and bottomonia (P-wave)
- probe macroscopic properties of QCD fluid: very soft pions, kaons, protons, di-leptons
  $\rightarrow$ dynamics of chiral symmetry restoration
  $\rightarrow$ pion condensates / disoriented chiral condensates ?
- understand thermalization and dissipation in detail
  $\rightarrow$ spectrum also at $p_T \ll T_{\text{kinetic freeze-out}} \approx 120$ MeV

Conclusions

- high energy nuclear collisions produce a relativistic QCD fluid!
- interesting parallels between cosmology and heavy ion collisions
- heavy ion collisions provide chance to understand a relativistic fluid from first principles
- experimental hints for collective flow also in pPb and pp collisions
- QCD fluid can be understood in much more detail with combined effort of theory and experiment!
- *I had to skip many interesting topics, please see also other presentations mentioned on the first slide.*