High-energy nuclear collisions

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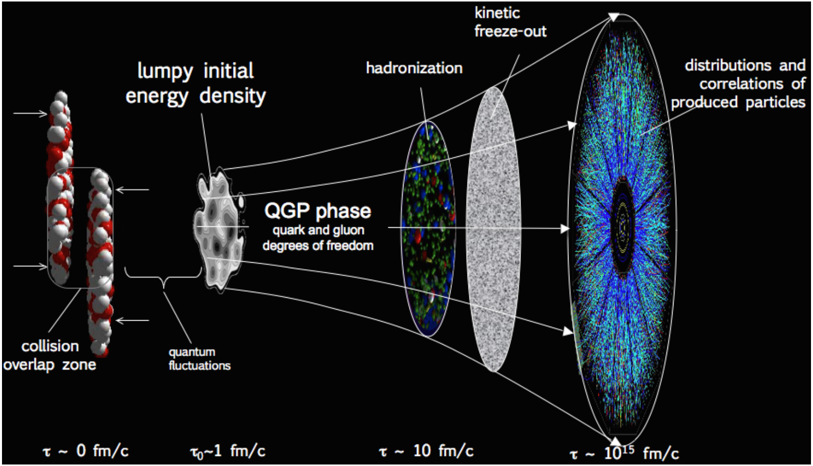
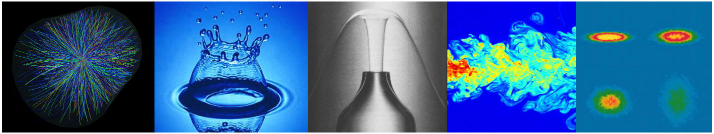
Little bangs in the laboratory



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

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

- 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

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

- equation for **fluid velocity** u^μ

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

- 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}

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

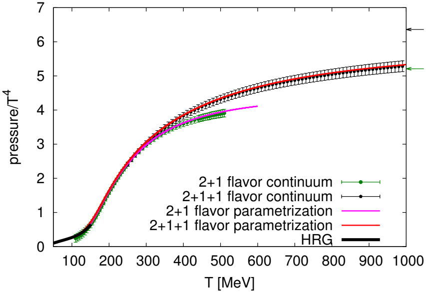
  with **bulk viscosity** $\zeta(T, \mu)$

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

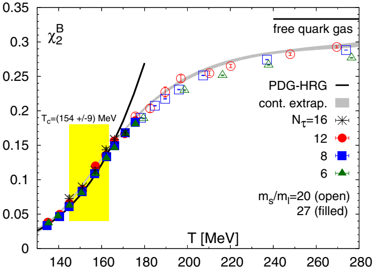
$$\tau_{\text{heat}}\, \Delta^\alpha{}_\beta\, u^\mu \nabla_\mu \nu^\beta + \nu^\alpha + \kappa \left[\frac{nT}{\epsilon + p}\right]^2 \Delta^{\alpha\beta} \partial_\beta \left(\frac{\mu}{T}\right) + \ldots = 0$$

  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

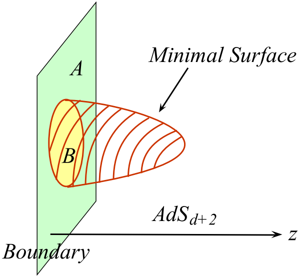
$$\chi_2^{\mathrm{B}} = \frac{\langle (N_{\mathrm{B}} - N_{\bar{\mathrm{B}}})^2 \rangle}{VT^3}$$

  and higher order understood
- progress in computing power

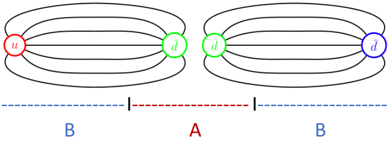
Quantum fields and information

- 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)]

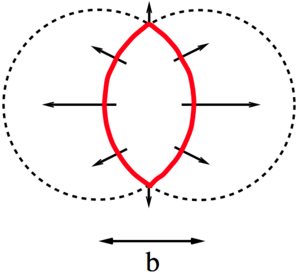


[Ryu, Takayanagi (2006)]



[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

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

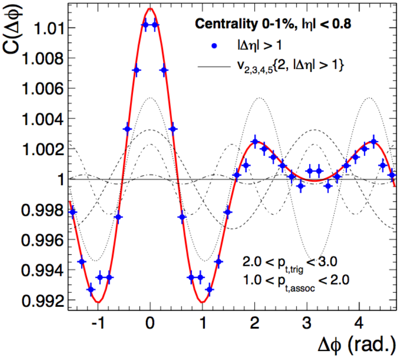
- symmetry $\phi \to \phi + \pi$ implies $v_1 = v_3 = v_5 = \ldots = 0$.

Two-particle correlation function

- normalized two-particle correlation function

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

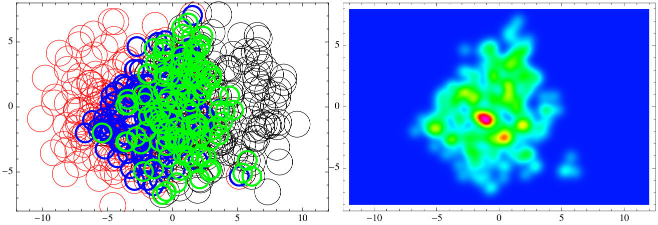
- surprisingly v_2, v_3, v_4, v_5 and v_6 are all non-zero!



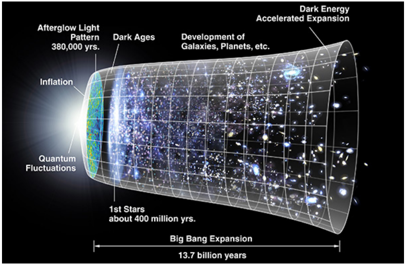
[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

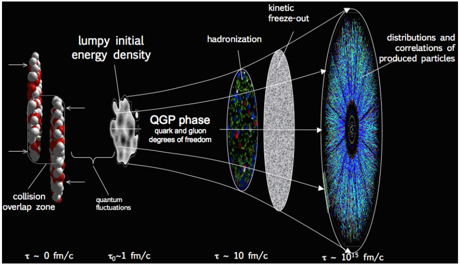
Event-by-event fluctuations

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



Big bang – little bang analogy



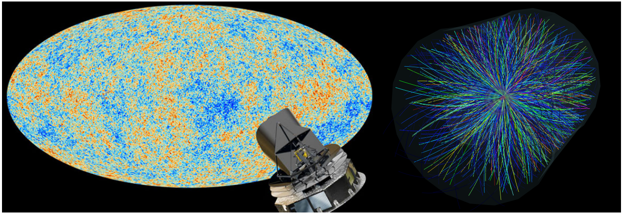


- cosmol. scale: MPc$= 3.1 \times 10^{22}$ m
- Gravity + QED + Dark sector
- one big event

- 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

The dark matter fluid

- **high energy nuclear collisions**

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

- **late time cosmology**

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

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

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

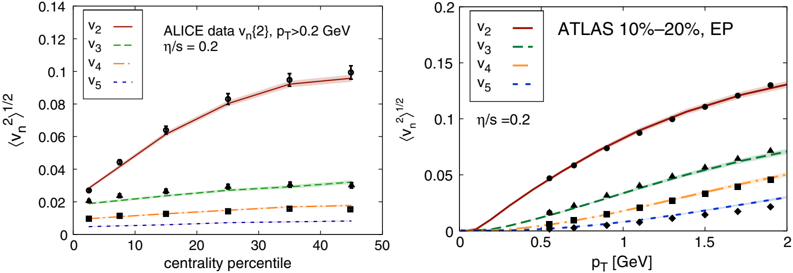
  so all we can access is

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

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

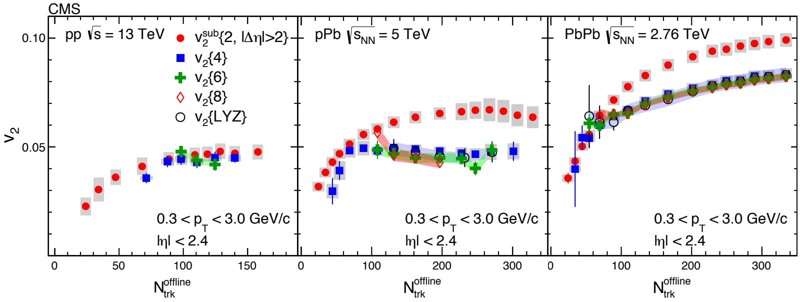
Fluid dynamic simulations

- second order relativistic fluid dynamics solved numerically
- fluctuating initial conditions
- η/s is varied to find experimentally favored value
- differential information in centrality and p_T



[Gale, Jeon, Schenke, Tribedy, Venugopalan (2013)]

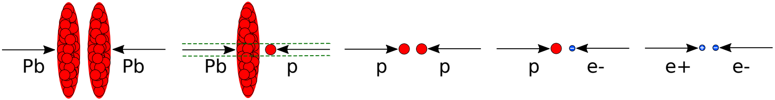
Collective behavior in large and small systems



- 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

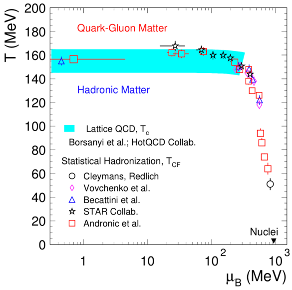
- how universal are collective flow and fluid dynamics?
  - as a limit of kinetic theory / perturbation theory / multi-parton interactions
  - non-perturbative understanding / entanglement
- what determines density distribution of a proton?
  - constituent quarks or interacting gluon cloud?
  - generalized parton distribution functions
- what about more elementary collision systems?

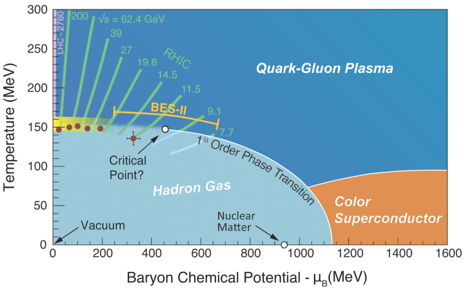


- role of electromagnetic fields and vorticity for fluid dynamics
- role of quantum anomalies (e. g. Chiral Magnetic Effect)

Chemical freeze-out

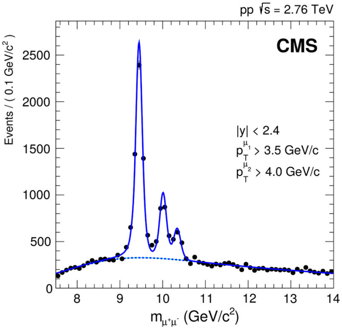
[Andronic, Braun-Munzinger, Redlich, Stachel (2017)]

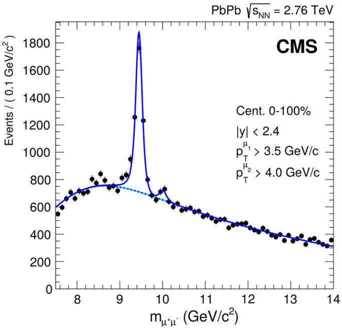




- chemical freeze-out close to chiral crossover transition for large $\sqrt{s}$
- chiral transition should be visible in higher moments $\langle (N_B - N_{\bar{B}})^n \rangle$
- traces of the evolving chiral condensate / pion condensate ?
- more insights at large μ_B expected from FAIR

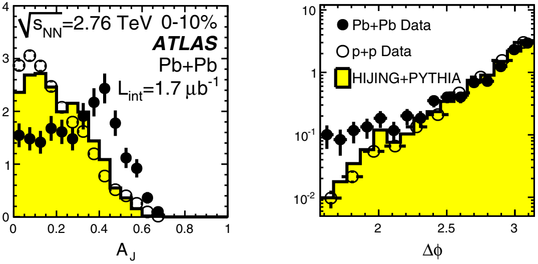
Quarkonium and how it gets modified

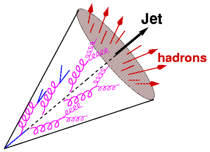




- $\mu^+\mu^-$ mass spectrum in the range of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$
- all Υ states are suppressed by medium effects, excited states even more
- more detailed understanding of heavy quark bound states in a medium
- also at LHC: regeneration and flow of charmed mesons

Jet quenching





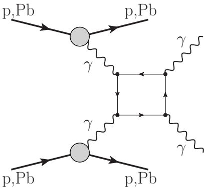
- asymmetry between reconstructed jet energies

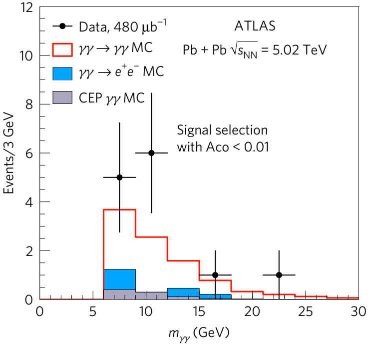
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \qquad \Delta\phi > \pi/2$$

- partons/jets loose energy to the quark gluon plasma
- jet structure investigated in details
- 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)]





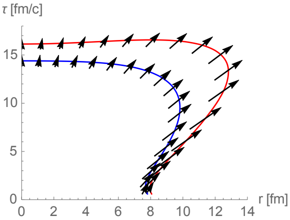
- ultra-peripheral ion collisions produce strong electromagnetic fields
- beam of quasi-real photons (equivalent photon approximation)
- Halpern scattering $\gamma\gamma \to \gamma\gamma$ observed
- also ultra-peripheral: nuclear PDFs

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 !

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 GeV/fm^3	16–17 GeV/fm^3	35–40 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)
  $\rightarrow$ soft photon theorems
- 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
  $\rightarrow$ spectral distortions ? (cf. current discussion in cosmology)

The high energy nuclear collision experiments landscape

present

- LHC (ALICE / ATLAS / CMS / LHCb)
- RHIC (Star / Phenix)
- SPS (NA61/SHINE)
- SIS (HADES)

future (approved)

- GSI/FAIR (CBM)
- JINR/NICA (MPD, BM@N)

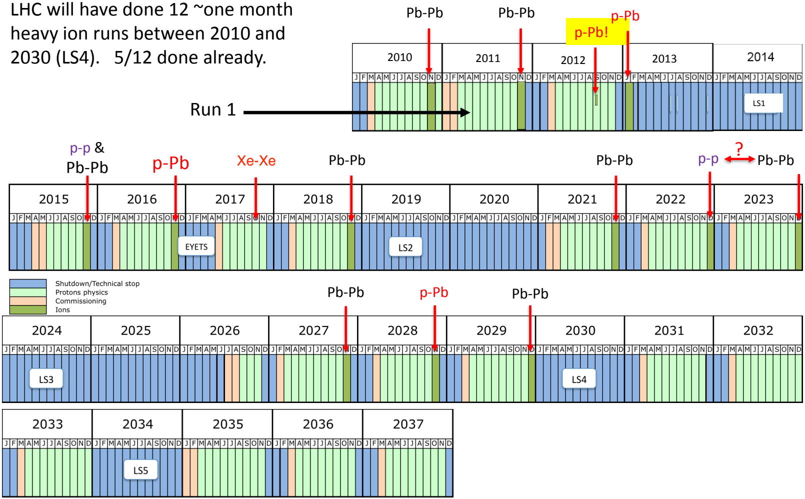
future (proposed)

- sPhenix (RHIC)
- Electron-Ion collider in the USA (eRHIC / JLEIC)

CERN schedule

[J. M. Jowett, 10/2017]

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 5/12 done already.

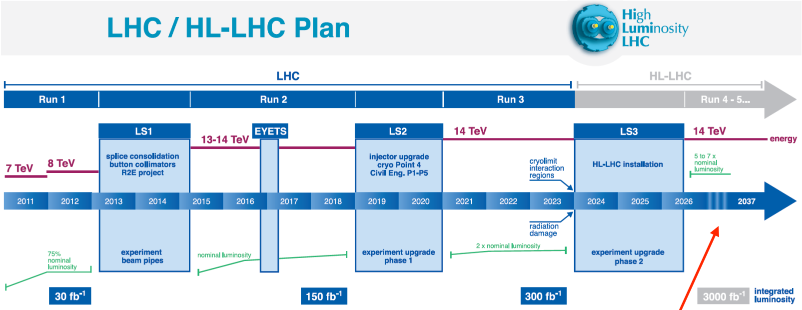


Conclusions

- high energy nuclear collisions produce a relativistic QCD fluid!
- interesting parallels between cosmology and heavy ion collisions
- chance to understand a relativistic fluid from first principles
- experimental hints for collective flow also in pPb and pp collisions
- interesting to study also smaller energy / higher baryon density regime
- QCD fluid can be understood in much more detail with combined effort of theory and experiment!

Backup slides

High-Luminosity LHC schedule



ALICE physics programme approved until Run 4 (~2030)

High-Energy LHC and FCC

[M. Benedikt, FCC Week, 04/2018]