High-Density QCD with Proton and Ion Beams

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Emmy Noether-Programm
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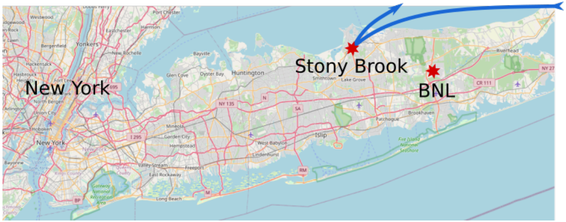


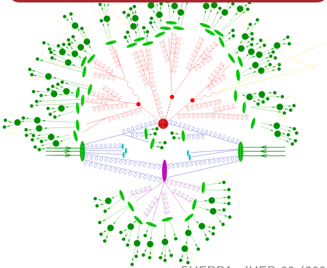
Motivation

Two strategies to study fundamental interactions

- HEP: concentrate higher energy in smaller and smaller volume.
- HIP: *distribute high energy or high nucleon density over a relatively large volume.* – T.D. Lee, 1974, Bear Mountain workshop

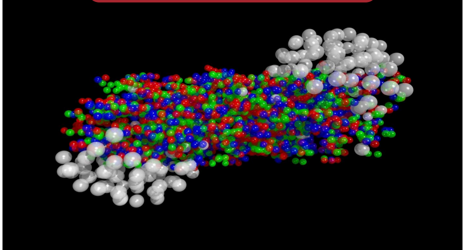
$$e \gg \rho_0 c^2 \approx 0.1\text{GeV/fm}^3 \quad \text{and} \quad V \gg 1\text{fm}^3.$$

High-energy physics (HEP)



SHERPA, JHEP 02 (2009)

Heavy-ion physics (HIP)

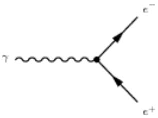


UrQMD, Marcus Bleicher

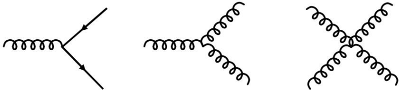
Condensed matter phenomena at extreme conditions

"More is different" – P.W. Anderson (1972)

QED - Abelian gauge theory

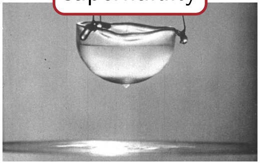


QCD - non-Abelian gauge theory

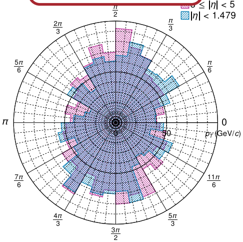


superconductivity

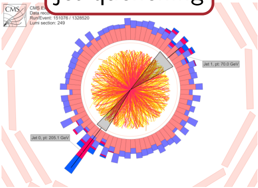
superfluidity



collective flow



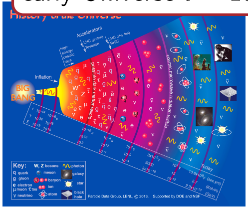
jet quenching



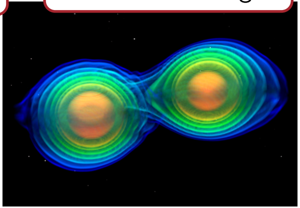
Unique chance to study the many-body dynamics of a strongly coupled non-Abelian gauge theory: new states of matter, thermalisation, material properties, phase transitions,. . .

Where can we find high-density QCD matter?

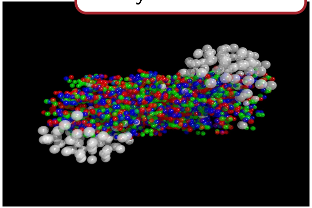
early Universe $t \sim 10^{-6}$s



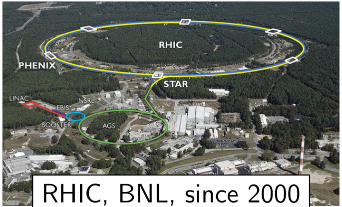
neutron star mergers



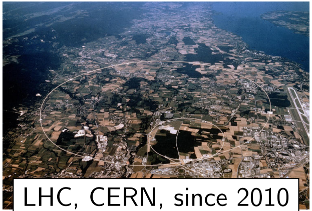
heavy-ion collisions



High-energy ion (Pb, Au) and proton colliders



RHIC, BNL, since 2000

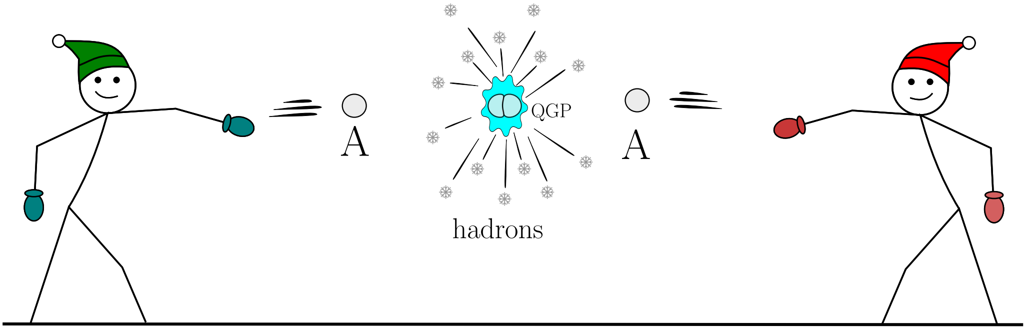


LHC, CERN, since 2010

Upcoming: electron-ion collider (BNL), antitproton-ion facility (GSL)

How to make Quark-Gluon Plasma at home?

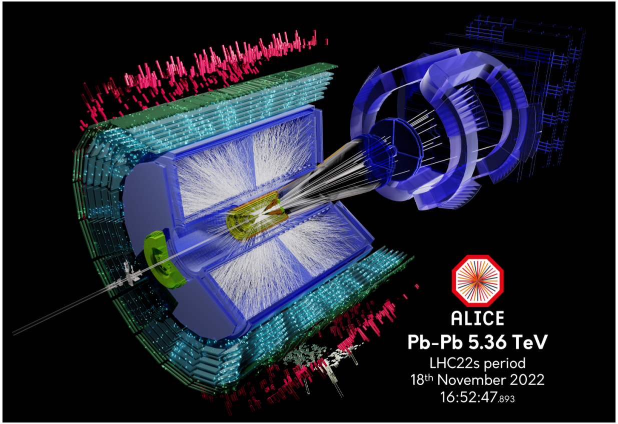
Collide clumps of nuclear mater to melt them into a Quark-Gluon Plasma (QGP).



Conditions for QGP exists for less than 10^{-22} s — need to reconstruct the collision history.

Real heavy-ion event display

ϕ – azimuthal angle, θ, η – longitudinal direction



- Charged hadrons per unit rapidity $dN_{\text{ch}}/d\eta \sim 2000$, c.f. pp $dN_{\text{ch}}/d\eta \sim 5$
- $N_{\text{ch}} \sim 25000$, mostly soft pions $p_T < 2$GeV, but also strange and charmed hadrons, light and exotic nuclei

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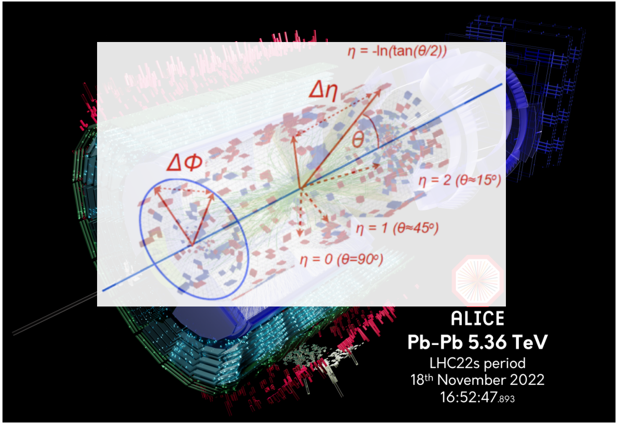

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Experimental LHC program with heavy (and light) ions

Last update: April 2023

- $\sim$ 1 month/year of heavy-ion datataking by ALICE, ATLAS, CMS and LHCb.
- Run 3+4: high-statistics p+Pb, Pb+Pb (special oxygen run in 2024).
- Surprising "heavy-ion" physics in pp collisions
- Proposal for next-generation heavy-ion detector ALICE 3 in Run 5.

See LHC Yellow report (2018) [1] for detailed description of LHC HIP program.

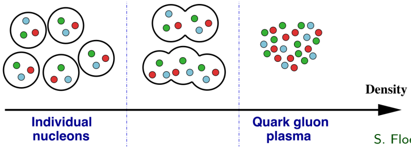
QCD thermodynamics in a box

Asymptotic freedom at high temperature and density QCD matter

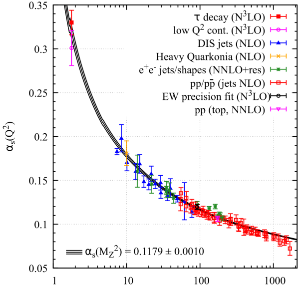
Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.



S. Floerchinger



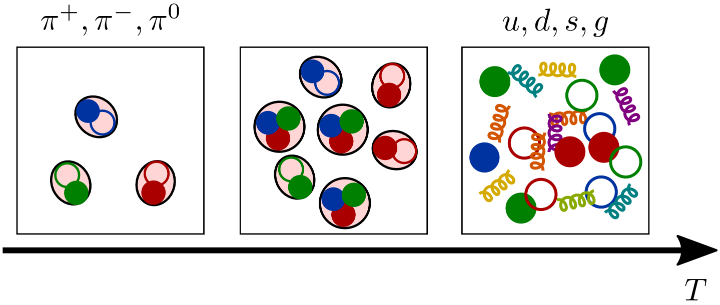
PDG review (2020) [2]

- In vaccum:
  - colour neutral hadrons (confinement)
  - mass from chiral symmetry breaking ($m_p = 938\,\text{MeV}$ vs $2m_u + m_d \sim 10\,\text{MeV}$)
- At high temperature or density $\alpha_s \to 0$
  - quarks and gluons become deconfined, no bound states
  - new state of matter — quark-gluon plasma (QGP)

What is the transition between hadronic matter and QGP? What are QGP properties?

Equation of state of QCD matter at low and high temperatures

Consider baryon symmetric matter (baryon chemical potential $\mu_B = 0$) at temperature T.
What is energy density e dependence on T?



- Low temperature: dominant degrees of freedom – 3 light pions

$$\text{energy density} \quad e = \nu_\pi \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{p/T} - 1} = \frac{\pi^2}{30}(3)T^4 \approx T^4.$$

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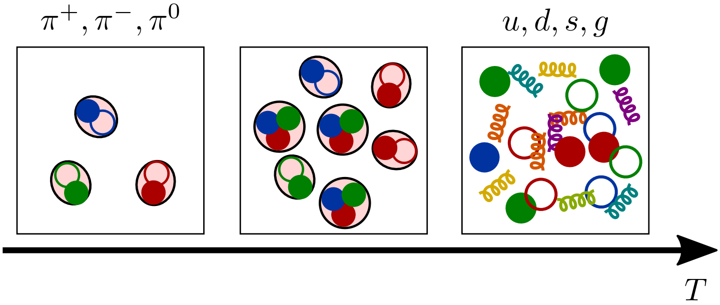

- Intermediate T: excite hundreds of hadron resonance states (see PDG tables).

fitted mass spectrum $\rho_{\text{HR}}(m) = \frac{c}{(m^2 + m_0^2)^{5/4}} \exp(\frac{m}{T_H}) \quad T_H \approx 160\,\text{MeV}.$

(pre-QCD prediction) breakdown of hadronic description at the Hagedron temperature.

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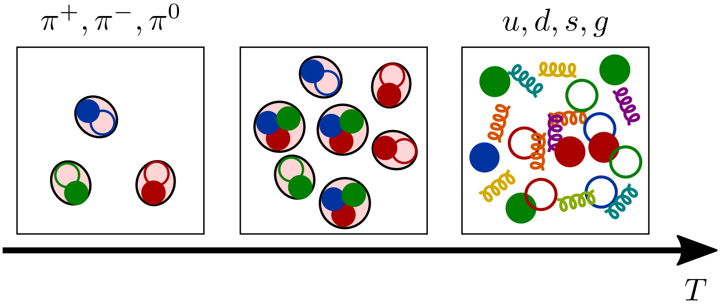

- High temperature: free gas of 3 massless quarks (up, down, strange) and gluons

$$e = \frac{\pi^2}{30}\Big(\underbrace{\nu_g}_{\text{bosons}} + \underbrace{\nu_q}_{\text{fermions}}\frac{7}{8}\Big)T^4.$$

Perturbative corrections converge slowly $\Longrightarrow$ need non-perturbative methods.

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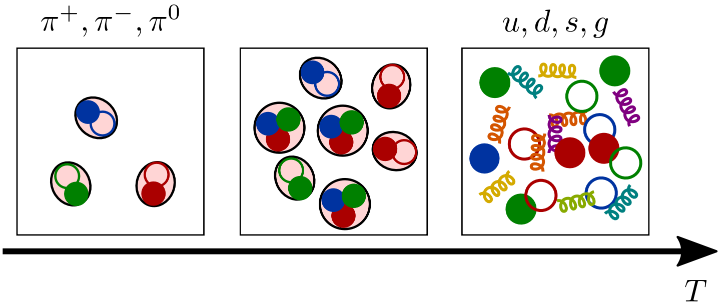


- High temperature: free gas of 3 massless quarks (up, down, strange) and gluons

$$e = \frac{\pi^2}{30}\Big(\underbrace{2}_{\text{polarization}} \times \underbrace{8}_{\text{colour}} + \underbrace{2}_{\text{anti-/particle}} \times \underbrace{2}_{\text{spin}} \times \underbrace{3}_{\text{colour}} \times \underbrace{3}_{\text{flavour}} \frac{7}{8}\Big)T^4 \approx 16T^4.$$

Perturbative corrections converge slowly $\Longrightarrow$ need non-perturbative methods.

Expect change of e/T^4 from ~ 1 to ~ 16 going from hadrons to QGP. Is there a jump?

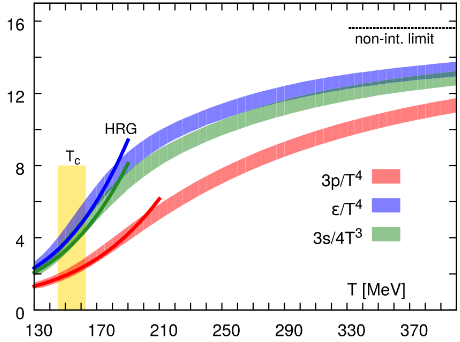
Lattice QCD at finite temperature

Non-perturbative finite temperature QCD computations on a lattice

$$U(0,t) = e^{-i\hat{H}t} \quad t \to -i\tau, 0 < \tau < 1/T \quad Z = \sum_{\psi} \langle\psi| e^{-\hat{H}/T} |\psi\rangle \,.$$

Applicable to static quantities (e.g. thermodynamics), only $\mu_B = 0$ (sign problem).

$e/T^4 \sim 1$



HotQCD (2014) [3]

$e/T^4 \sim 16$

$e > 3p$ ($p = \frac{1}{3}e$ for ideal QGP)

Transition from hadrons to QGP is a crossover at $T_c \approx 155\,\mathrm{MeV}, e_c \approx 0.3\,\mathrm{GeV/fm}^3$.

Phase diagram of QCD matter

- Matter/anti-matter symmetry in high energy collisions $\Longrightarrow \mu_B = 0$
- At low energy collisions more baryon stoping $\Longrightarrow \mu_B > 0$.
- Neutron star mergers $\Longrightarrow$ large μ_B, low T.

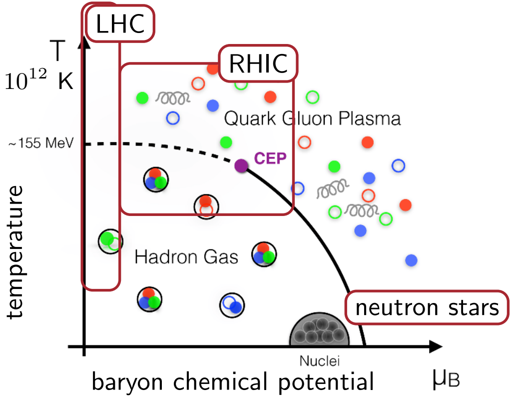
What are the properties of baryon-rich high-density QCD matter ($\mu_B > 0$)

First order transition line at $\mu_B > 0$?
Critical end point (CEP)?

- Beam Energy Scan at RHIC; SPS at CERN;
  FAIR at GSI
- Lattice extrapolations from $\mu_B = 0$.

Matter properties inside neutron stars/mergers.

- Constraints on equation of state from gravitation wave observations.
- Perturbation theory in cold quark matter.



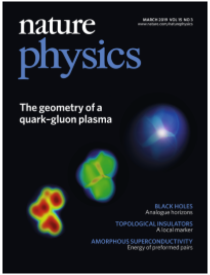
Ding, Karsch, Mukherjee (2015) [4]

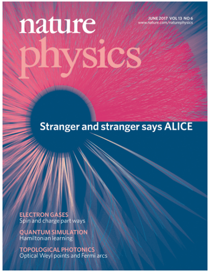
In this lecture we will focus on QGP properties at $\mu_B \approx 0$ studied at LHC.

Quark Gluon Plasma Hall of Fame

QGP in heavy-ion collisions is one of most extreme phases of matter:

- Hottest matter created $T \sim 10^{12}$ K
- Most perfect fluid $\eta/s \sim 0.08$
- Most vortical fluid $\omega \sim 10^{22}\,\mathrm{s}^{-1}$



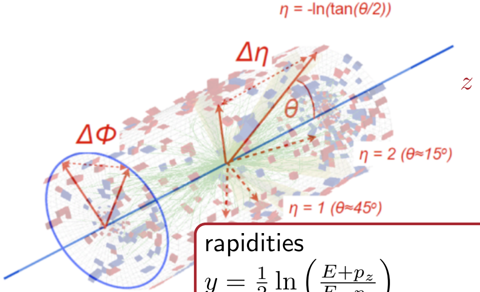


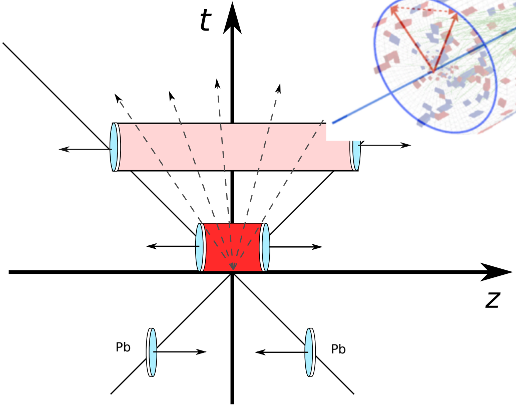
- How does the hot and dense QCD matter thermalise?
- How does collective behaviour emerge from interactions of a few particles?
- What are the material properties of Quark Gluon Plasma?

See reviews: Busza, Rajagopal, van der Schee (2018) [5], Nagle, Zajc (2018) [6], Berges, Heller, AM, Venugopalan (2020) [7]

Phases of heavy-ion collisions

Co-moving (Bjorken or Milne) coordinates





rapidities

$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

$\eta_{\text{pseudo}} = \frac{1}{2}\ln\left(\frac{|\mathbf{p}|+p_z}{|\mathbf{p}|-p_z}\right)$

$\eta_{\text{space-time}} = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right)$

$\tau - \eta$ co-moving coordinates

$\tau = \sqrt{t^2 - z^2}$

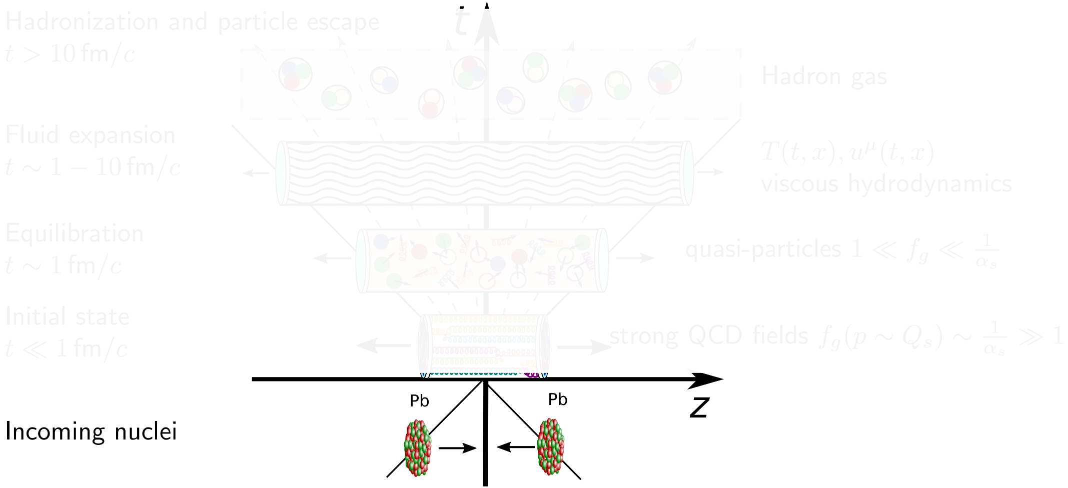
$v^z = \tanh\eta$

$ds^2 = -d\tau^2 + dx^2 + dy^2 + \tau^2 d\eta^2$

We will discuss mid-rapidity region $\eta \approx 0$ (take $\eta_{\text{space-time}} \approx \eta_{\text{pseudo}} \approx y$).

Different stages of heavy-ion collisions (high-energy/weak-coupling picture)

Transverse system size $2R_{\mathrm{Pb}} \sim 10\,\mathrm{fm}$



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Hadronization and particle escape
$t > 10\,\text{fm}/c$

Hadron gas

Fluid expansion
$t \sim 1 - 10\,\text{fm}/c$

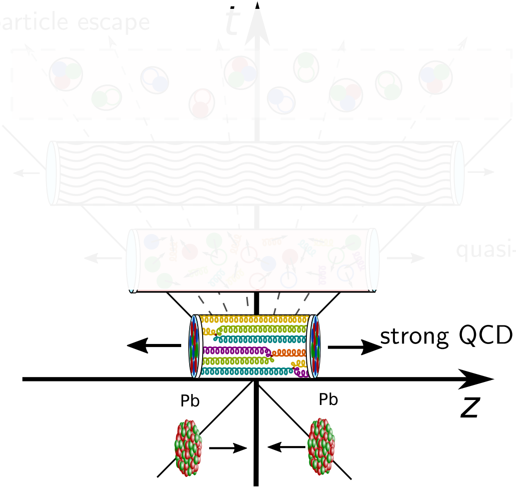
$T(t,x), u^{\mu}(t,x)$
viscous hydrodynamics

Equilibration
$t \sim 1\,\text{fm}/c$

quasi-particles $1 \ll f_g \ll \frac{1}{\alpha_s}$

Initial state
$t \ll 1\,\text{fm}/c$

strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$



Incoming nuclei

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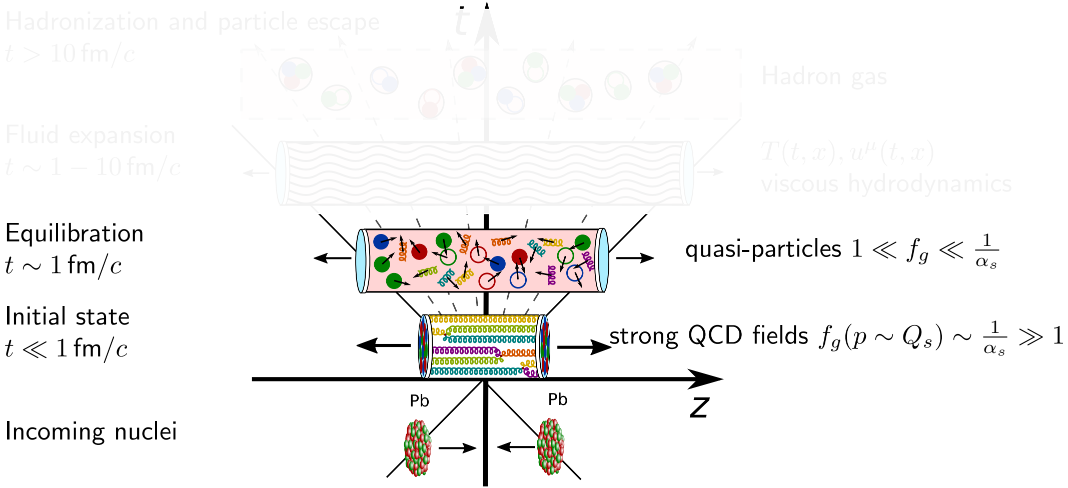

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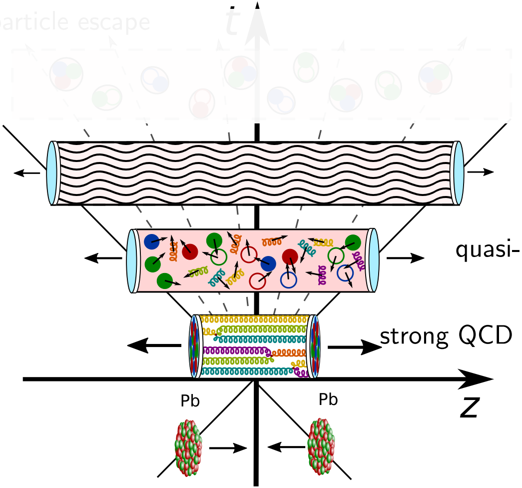

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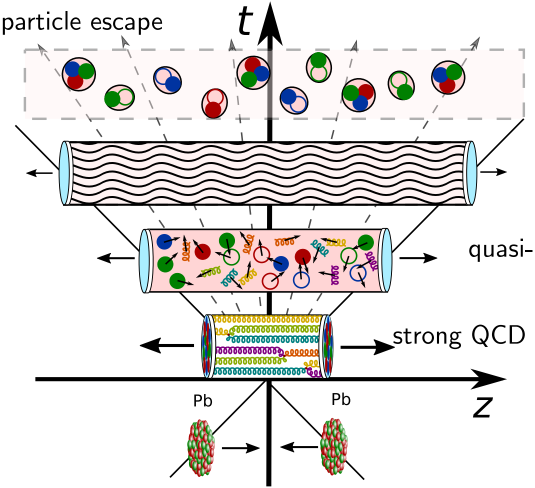

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Incoming nuclei

Relativistic viscous hydrodynamics

Ideal hydrodynamics

- Energy-momentum tensor for ideal fluid at rest:

$$T^{\mu\nu}_{\text{rest}} = \begin{pmatrix} e & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \implies \Lambda^{\mu}_{\rho}(u)\Lambda^{\nu}_{\sigma}(u)T^{\rho\sigma}_{\text{rest}} = eu^\mu u^\nu + p(g^{\mu\nu} + u^\mu u^\nu)$$

- e is relativistic energy density, equation of state $p(e)$, u^μ fluid 4-velocity, $u^\mu u_\mu = -1$.
- The energy-momentum conservation is written

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

- Ideal equations of motion in a fluid rest-frame

$$\partial_t e = -(e+p)\vec{\nabla}\vec{v}$$

$$\partial_t \vec{v} = -\frac{\vec{\nabla}p}{e+p}$$

- *Change in energy is driven by expansion $\theta = \partial_\mu u^\mu = \vec{\nabla}\vec{v}$!*
- *Change in velocity driven by gradients in pressure $\vec{\nabla}p$!*

Bjorken solution

- Let's find a hydro solution in Bjorken coordinates
- Fluid velocity $u^\mu = (1, 0, 0, 0)$, $\theta = \partial_\mu u^\mu = \frac{1}{\tau}$
- Energy density evolution

$$\frac{\partial e}{\partial \tau} = -\frac{e+p}{\tau}.$$

- For pressureless (free-streaming) expansion $p = 0$

$$e = e_0 \left(\frac{\tau_0}{\tau}\right).$$

- For ideal (conformal) QGP $p = \frac{1}{3}e$

$$e = e_0 \left(\frac{\tau_0}{\tau}\right)^{4/3}.$$

Faster decrease due to longitudinal work

$$ds^2 = -d\tau^2 + dx^2 + dy^2 + \tau^2 d\eta^2.$$

$$v^z = \frac{z}{t} = \tanh \eta.$$

$$\tau = t \quad \text{at} \quad \eta = 0.$$

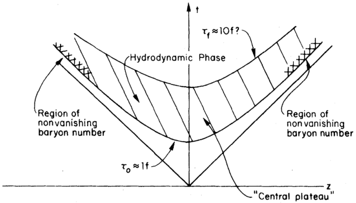


FIG. 3. Space-time diagram of longitudinal evolution of the quark-gluon plasma.

Bjorken (1982) [8]

Relativistic viscous hydrodynamics

- Gradient corrections to the energy momentum tensor

$$T^{\mu\nu}_{1st} = T^{\mu\nu}_{\text{ideal}} + \Pi(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

- Viscous corrections: allowed gradients in fluid field

$$\text{shear tensor} \quad \pi^{\mu\nu} = -\eta\partial^{(\mu}u^{\nu)}$$

$$\text{bulk pressure} \quad \Pi = -\zeta\partial_\mu u^\mu$$

- *η – shear viscosity, ζ bulk viscosity*, positive quantities, properties of the medium.
- Effect of viscous corrections for 1D boost-invariant expansion ($e + p = sT$)

$$\frac{\partial e}{\partial \tau} = -\frac{e + p - \frac{4}{3}\frac{\eta}{\tau} - \frac{\zeta}{\tau}}{\tau} = -\frac{e+p}{\tau}\left(1 - \frac{4}{3}\frac{\eta/s}{T\tau} - \frac{\zeta/s}{T\tau}\right).$$

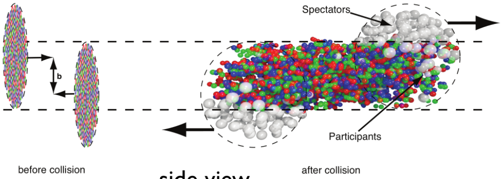
  Energy drops slower in viscous fluid (entropy production).
- At high temperature QCD ($g \ll 1$): $\eta/s \approx 5.11/(g^4 \log\frac{2.4}{g})$
- For infinitely strongly coupled supersymmetric theories: $\eta/s = \frac{1}{4\pi} \approx 0.08$

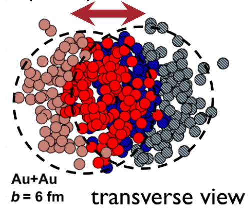
Viscosity per entropy $\eta/s, \zeta/s$ are key transport properties of QGP.

Experimental signals of QGP formation: Collective flow

Transverse geometry and centrality

see Miller, Reygers, Sanders and Steinberg (2007) [9]

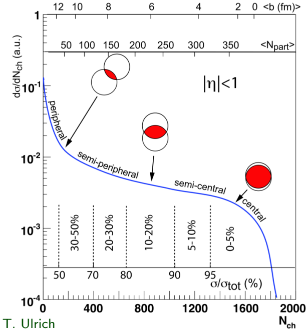




Not all nucleons participate in a collision.

- Monte-Carlo Glauber model of nucleons inside nuclei
- More colliding nucleons N_{part} if b is small.
- Larger $N_{\text{part}} \Longrightarrow$ more produced particles.
- Order events in multiplicity (centrality) classes
- 0-5% centrality $\Longrightarrow$ most head on collisions.

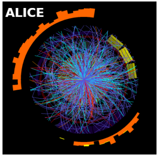
Strong correlation between initial geometry and particle multiplicity $\Longrightarrow$ select events with different geometry/size.



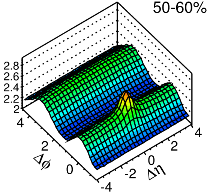
T. Ulrich

Multiparticle collective flows

Produced particles show significant angular modulations v_n in the azimuthal angle ϕ



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2v_2\cos(2\phi) + 2v_3\cos(3\phi)\ldots\right)$$



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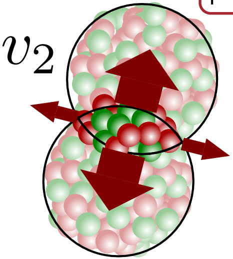
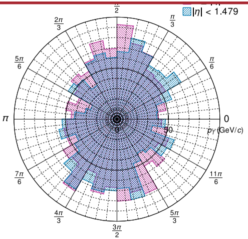
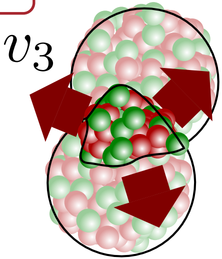
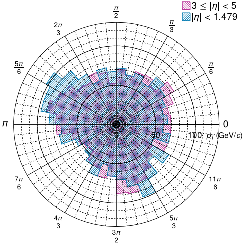
particle momentum deposition









CMS Detector Performance Plots [10]

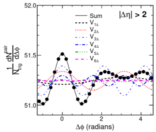
Collective particle flow is explained by pressure gradient driven transverse QGP expansion.

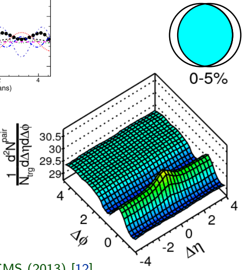
Two-particle correlations — near-side and away-side ridges

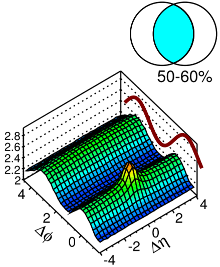
Practical way of quantifying collective flows – two-particle correlation function

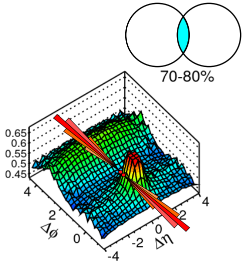
$$\left\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2} \right\rangle \propto 1 + 2\sum_n v_n^2 \cos(n\Delta\phi).$$

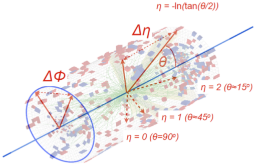
Also generalizes to multi-particle correlations (8-particle v_n's measured).











CMS (2012) [11], CMS (2013) [12]

elliptic+triangular flow

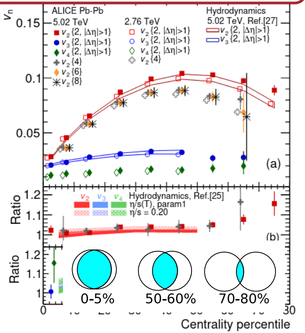
strong elliptic flow

dominance of jet fragmentation

Collective flow correlations are long-ranged $|\Delta\eta| > 1$ – must be sourced by initial state.

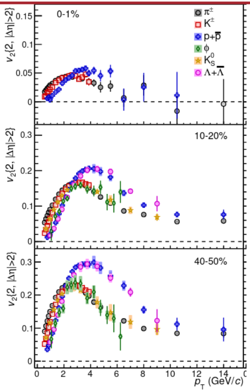
Centrality and momentum dependence of flow coefficients

centrality dependence of v_n

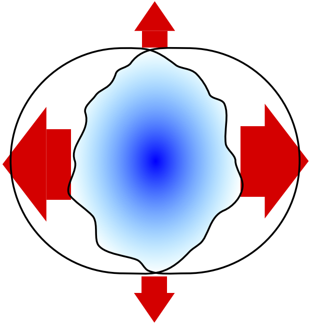


ALICE (2016) [13]

p_T and particle species dependence



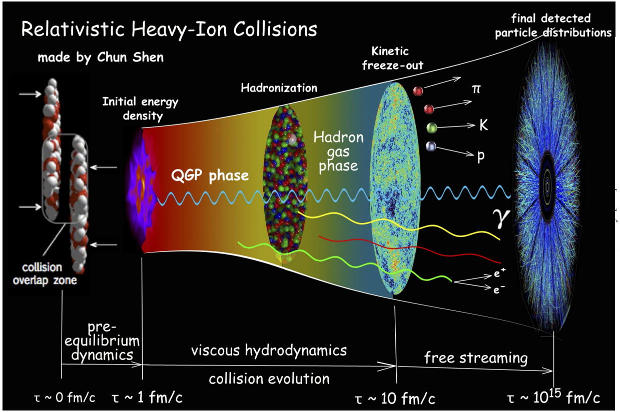
ALICE (2018) [14]

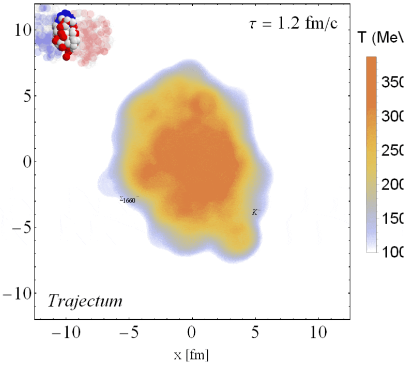


- Strong elliptic flow in mid-central events $\Longrightarrow$ overlap geometry
- v_3, v_4 with weak centrality dependence $\Longrightarrow$ fluctuations in geometry
- Mass ordering of $v_n(p_T)$ $\Longrightarrow$ radial flow velocity $p_T \sim m v_T$

Standard hydrodynamic model of little Big Bang

- Multi-stage 2D/3D viscous hydrodynamic codes are widely available.
- Initial conditions and transport properties have to be constrained by data.



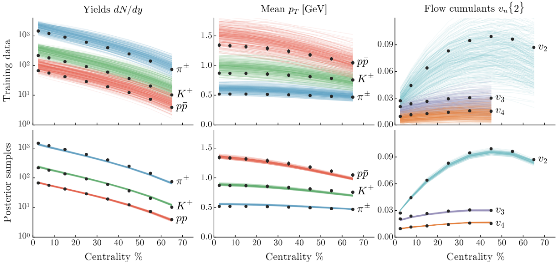


QGP properties from Bayesian parameter estimation

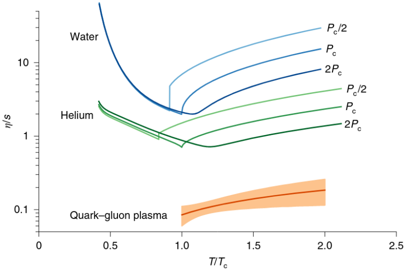
- Thousands of sample points in parameter space × thousands of events
- Construct the posterior distributions for model parameters

$$\underbrace{P(\text{parm}_i|\text{data})}_{\text{posterior}} \sim \underbrace{P(\text{data}|\text{parm}_i)}_{\text{likelihood}}\underbrace{P(\text{parm}_i)}_{\text{prior}}.$$

$$P(\text{data}|\text{parm}_i) \sim \exp\left[-\Delta_i(\Sigma^{-1})_{ij}\Delta_j\right],\ \Delta = \text{data} - \text{model}$$



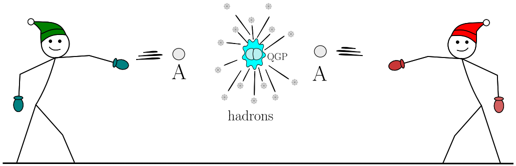
Bernhard et al. (2016) [15]



Bernhard, Moreland, Bass (2019) [16]

Extracted physical parameters of QGP, e.g. $\eta/s \sim 0.08 - 0.2$ – smallest of all fluids.

Summary of the first lecture



High-density QCD with ion and proton beams – an alternative way to study strong force.

- Emergent many-body QCD phenomena in heavy-ion collisions
  - De-confined state of quarks and gluons at $T > 155\,\mathrm{MeV}$.
  - Fast QCD thermalization and applicability of hydrodynamics.
  - Hydrodynamic flow of QGP (small $\eta/s \implies$ strongly interacting fluid)
- Collective multi-particle flows — key signature of medium formation.
- Heavy-ion collision is a multi-stage process:
  - Initial state (nuclear geometry, nucleonic fluctuations, strong QCD fields (CGC))
  - Equilibration (kinetic theory, fast emergence of hydrodynamics)
  - Hydrodynamic expansion (viscous fluid with small $\eta/s, \zeta/s$)
  - Freeze-out and hadronic cascade (rescatterings and decays)
- Advanced hydrodynamic models predict a large range of soft hadronic observables.

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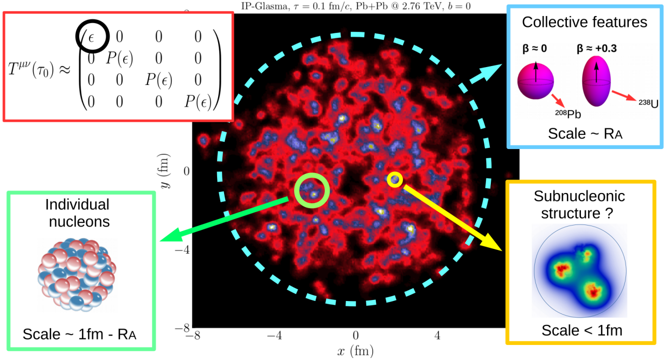
Backup

Sources of transverse energy density fluctuations

Initial geometry is characterized by eccentricities $\varepsilon_n \implies$ strong correlation with $v_n \approx k_n \varepsilon_n$

$$\varepsilon_n e^{in\Phi} = -\frac{\int d^2\mathbf{x}\, r^n e^{in\phi} e(\mathbf{x}_\perp)}{\int d^2\mathbf{x}_\perp\, r^n e(\mathbf{x}_\perp)}.$$

Structure of nuclei across length scales → primordial anisotropy → observed anisotropy



from Giacalone, SEWM 2021 [indico]

The goal of hydrodynamic models is to predict v_n response to initial geometry fluctuations.

Multi-stage hydrodynamic models of nuclear collisions

initial conditions → viscous hydrodynamics → hadron cascade

- Initial transverse geometry: collisions of Monte-Carlo sampled nucleons
- Energy deposition: saturation-based (IP-Glasma, EKRT) or parametrized (Trento)
- With/without pre-equilibrium evolution, hydro starting time τ_0
- 2D/3D numerical viscous hydrodynamic evolution
  - Equation of state: input from lattice QCD
  - $\eta/s, \zeta/s$ – model parameters, can be T dependent.
  - Higher order transport coefficients.
- Freeze-out temperature, hadron transport codes (URQMD or SMASH)

Compute and compare to a large set of observables

- Particle yields, mean p_T, spectra for pions, kaons, protons
- Flow harmonics v_2, v_3, v_4: integrated and p_T differential

Many comprehensive analyses: Novak, Novak, Pratt, Vredevoogd, Coleman-Smith, Wolpert (2013) [17], Niemi, Eskola, Paatelainen (2015) [18] Bernhard, Moreland, Bass, Liu, Heinz (2016) [15],Devetak, Dubla, Floerchinger, Grossi, Massiocchi, AM, Selyuzhenkov (2019) [19], Nijs, van der Schee, Gürsoy, Snellings (2020) [20]...

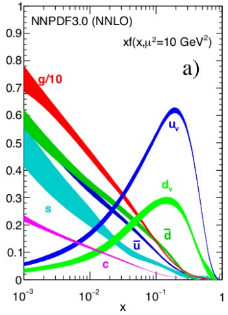
Theoretical descriptions

High-occupancy initial state and gluon condensation

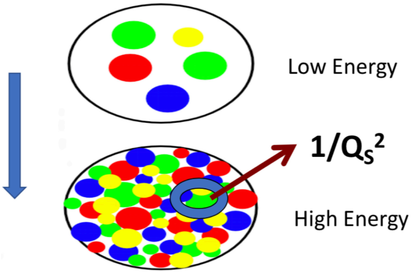
- Soft particle production at mid-rapidity is dominated by small Bjorken-x gluons.
- In high energy limit, the proliferation of gluons is capped by self-interactions

$$\frac{1}{\alpha_S\left(Q_S\right)} = \frac{xG_A\left(x, Q_s^2\right)}{2\left(N_c^2-1\right)\pi R_A^2 Q_S^2} \sim f_g(p \sim Q_S).$$

- Q_S – saturation scale. Dense gluon packing (Colour Glass Condensate (CGC)).



PDG review (2020) [2]



Iancu, Venugoapalan (2003) [21]

Strong colour field evolution described by classical field approximation.

At later times fields dilute and decohere $\Longrightarrow$ switch to partonic description.

Different stages of heavy-ion collisions (high-energy/weak-coupling picture)

Hadronization and particle escape
$t > 10\,\mathrm{fm}/c$

Hadron gas

Fluid expansion
$t \sim 1 - 10\,\mathrm{fm}/c$

$T(t,x), u^\mu(t,x)$
viscous hydrodynamics

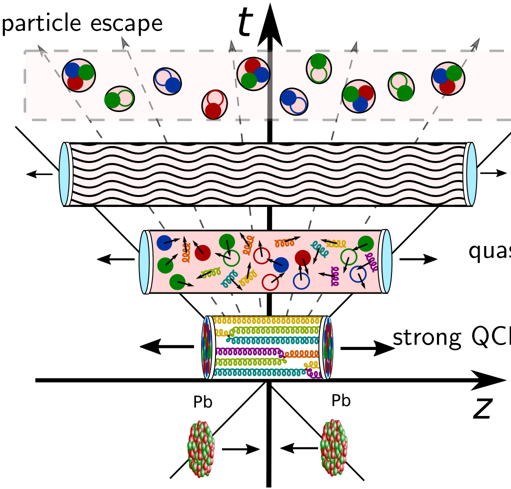
Equilibration
$t \sim 1\,\mathrm{fm}/c$

quasi-particles $1 \ll f_g \ll \frac{1}{\alpha_s}$

Initial state
$t \ll 1\,\mathrm{fm}/c$

strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$

Incoming nuclei



High temperature QCD kinetic theory

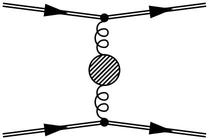
Arnold, Moore, Yaffe (2003)[22]

Weakly coupled $g \ll 1$ gas of quark and gluon quasi-particles $f(p_x, p_y, p_z)$

$$\text{Boltzmann eq.:} \quad \partial_t f + \underbrace{\frac{\mathbf{p}}{|p|} \cdot \nabla f}_{\text{expansion}} = - \underbrace{\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]}_{\text{in-medium QCD collisions}}$$

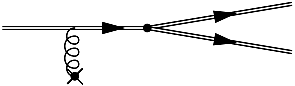
Leading order processes:

1. $2 \leftrightarrow 2$ elastic scatterings: $gg \leftrightarrow gg$, $qq \leftrightarrow qq$, $qg \leftrightarrow gq$, $gg \leftrightarrow q\bar{q}$



with screening mass $m_D \sim gT$

2. $1 \leftrightarrow 2$ medium induced collinear radiation: $g \leftrightarrow gg$, $q \leftrightarrow qg$, $g \leftrightarrow q\bar{q}$



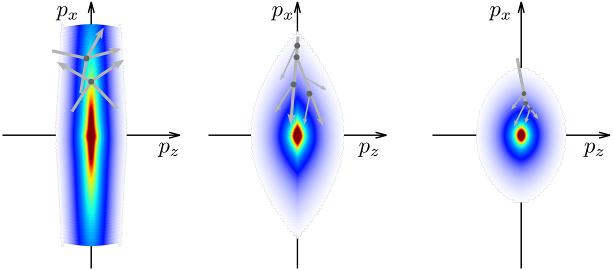
including interference effects

Contains the necessary physics for QCD thermalisation.

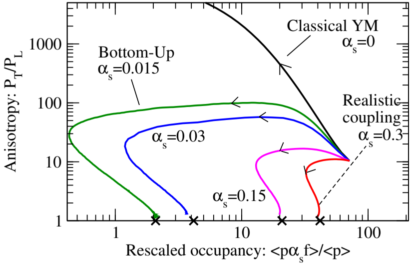
Equilibration à la "bottom-up" thermalisation scenario

Baier, Mueller, Schiff, and Son (2001)[27]

- Start with over-occupied and anisotropic hard gluons $p \sim Q_s$ from CGC.
- Do numerical simulations of QCD kinetic theory at different couplings.



$2 \leftrightarrow 2$ broadening　collinear cascade　mini-jet quench



Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018) [23, 24, 25, 26]

Extrapolated to "realistic" couplings leads to short equilibration time $\tau_{eq} \approx 1\,\mathrm{fm}$

At realistic energy scales QCD is not that weakly coupled $g \sim 1 \ldots$

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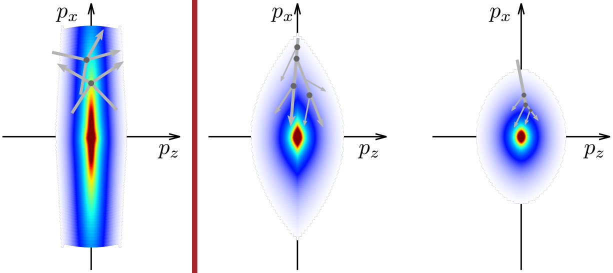

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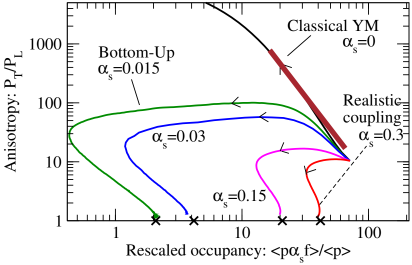

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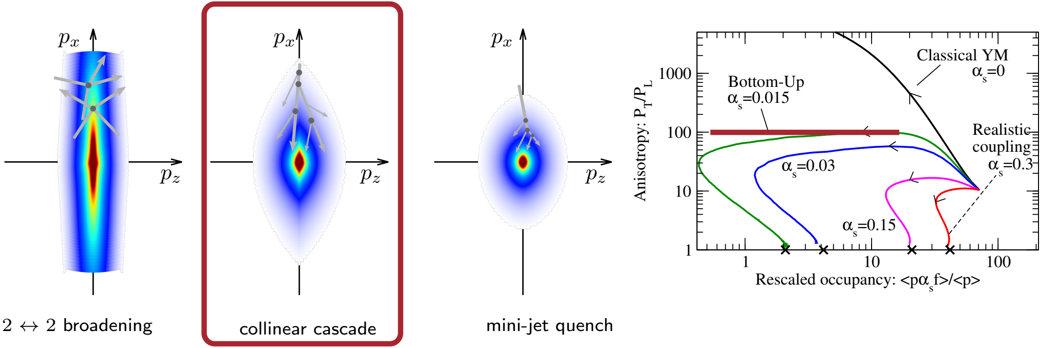

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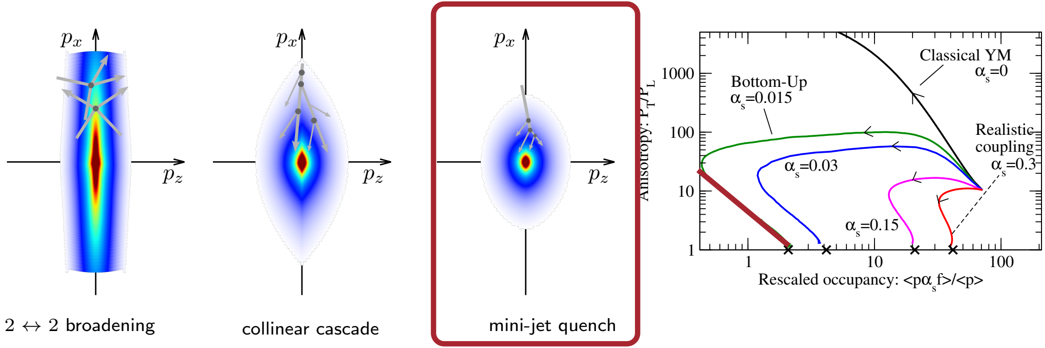

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Equilibration at strong couplings

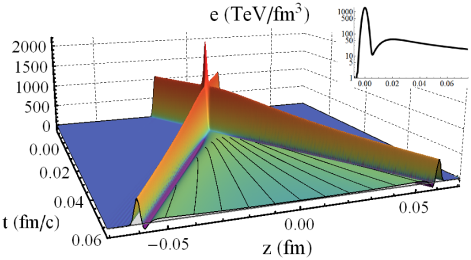
see Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann (2014) [28]

- $N=4$ Super Yang-Mills theory (not QCD)
  - Different particle content
  - Conformal theory: no confinement, no running coupling
- Can be solved in the strong coupling limit using holography (AdS/CFT)

$$N_c \to \infty \quad \lambda = 4\pi\alpha_s N_c \to \infty.$$

$\Longrightarrow$ involves solving general relativity in 5D

- Heavy-ion collisions: planar shock wave collisions of energy.



Casalderrey-Solana et al. (2013) [29]

- Thermalisation at timescales $\tau \sim 1/T \sim 1\text{fm}$ (formation of a black hole)

Different stages of heavy-ion collisions (high-energy/weak-coupling picture)

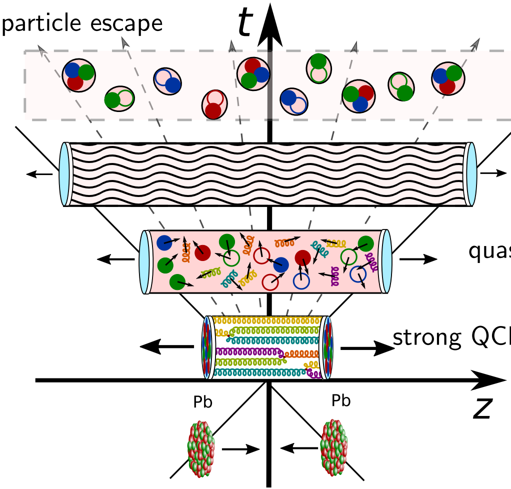
Hadronization and particle escape
$t > 10\,\mathrm{fm}/c$

Fluid expansion
$t \sim 1 - 10\,\mathrm{fm}/c$

Equilibration
$t \sim 1\,\mathrm{fm}/c$

Initial state
$t \ll 1\,\mathrm{fm}/c$

Incoming nuclei



Hadron gas

$T(t,x), u^\mu(t,x)$
viscous hydrodynamics

quasi-particles $1 \ll f_g \ll \frac{1}{\alpha_s}$

strong QCD fields $f_g(p \sim Q_s) \sim \frac{1}{\alpha_s} \gg 1$

Theoretical approaches of calculating η/s

- Weakly coupled QCD kinetic theory with quark and gluon quasiparticles Arnold, Moore, Yaffe (2003) [30]

$$\lambda \to 0 \quad \frac{\eta}{s} = \frac{34.784}{\lambda^2 \ln\left(4.879/\sqrt{\lambda}\right)} \gg 1.$$

  Recent NLO computations (large NLO corrections).

- Strongly interacting theories with gravity duals, e.g. $N = 4$ Super-Yang Mills Policastro, Son, Starinets (2001) [31]

$$\lambda = \infty \quad \frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08.$$

  Corrections to infinity coupling limit.

- Lattice QCD: only discrete Euclidean time separations. No reliable extractions.

$$\eta = -\lim_{\omega \to 0} \frac{1}{\omega} \mathrm{Im} G^R_{xy,xy}(\omega, 0).$$

- Phenomenological η/s extraction from data to model comparisons.

One of HIP goals is to experimentally determine η/s and other transport properties of QGP.

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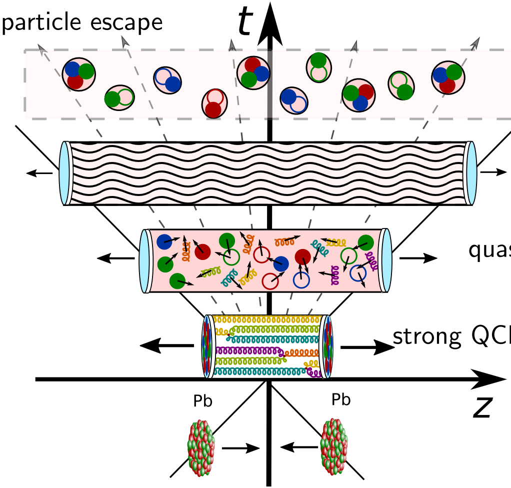

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Hadronization and freeze-out

Eventually expanding system falls out of equilibrium $\Longrightarrow$ hydrodynamics not applicable.

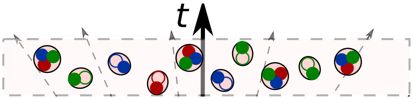
- QGP hadronise at $T_c \sim 155\,\text{MeV} \Longrightarrow$ change in microscopic degrees of freedom.
- Convert fluid-fields to hadrons while conserving momentum on freeze-out surface σ (Cooper-Frye)

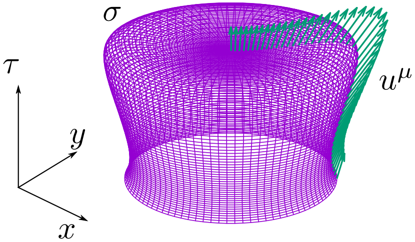
$$\underbrace{E\frac{dN}{d^3p}}_{\text{initial hadrons}} = \frac{\nu}{(2\pi)^3}\int_\sigma f(p^\mu, T, u^\mu, \ldots)p^\mu d\sigma_\mu.$$

- Evolve resonance gas (Boltzmann equation + PDG hadron properties)

$$\underbrace{E\frac{dN}{d^3p}}_{\text{initial hadrons}} \underbrace{\Longrightarrow}_{\text{decays and rescatterings}} \underbrace{E\frac{dN}{d^3p}}_{\text{long lived hadrons}}.$$

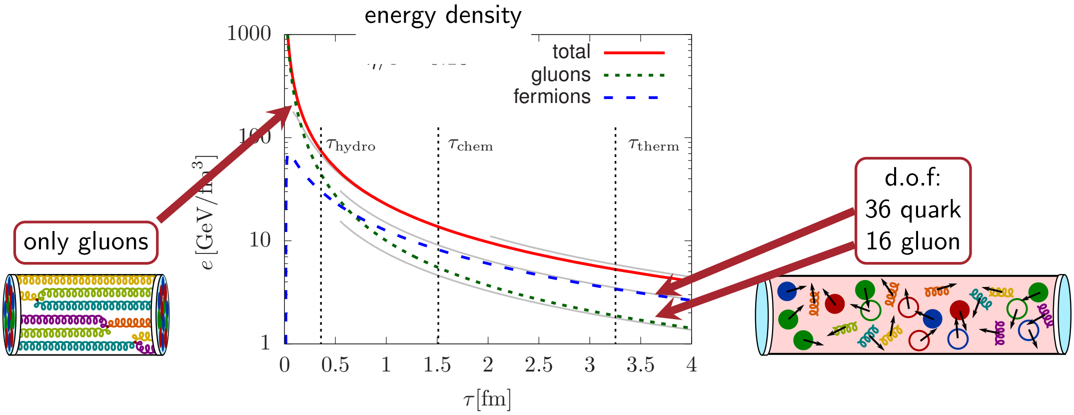
- *Finally can construct soft/bulk experimental observables from long lived hadrons.*





Fermion production in QCD kinetic theory

Fermions are produced through fusion $gg \to q\bar{q}$ and splitting $g \to q\bar{q}$.



Kurkela, AM (2018) [32, 33]

We found the timescale of chemical equilibration in the Quark Gluon Plasma.