# Heavy Ion Physics

## part I

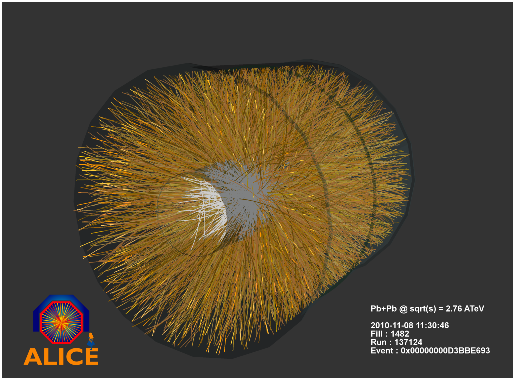
Korinna Zapp

Lund University

ESHEP 2023

European Research Council
Established by the European Commission

# A heavy ion collision



- $\sim$ 1600 primary charged hadrons per unit rapidity
- p+p at comparable $\sqrt{s}$: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \simeq 4-5$

## Heavy ion collisions: bird's eye view

- heavy ion collisions create strongly interacting system of high density
- Bjorken's energy density estimate:

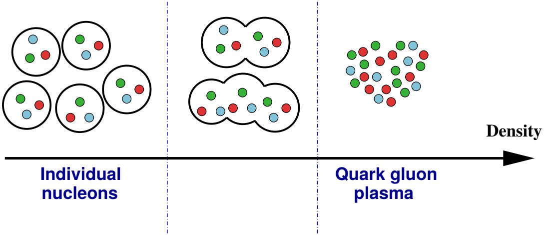
$$\epsilon_0 \simeq \frac{1}{\pi R^2 \tau_0} \left. \frac{\mathrm{d}E_\perp}{\mathrm{d}\eta} \right|_{\eta=0} \simeq 25\,\mathrm{GeV}/\mathrm{fm}^3$$

Bjorken, Phys. Rev. D **27** (1983) 140
ALICE, Phys. Rev. C **94** (2016) 034903

- there has to be re-scattering in the final state
- scattering drives a system towards thermal equilibrium
- How and to what extent does the final state in heavy ion collisions equilibrate?

# What is this stuff we're producing? – qualitative arguments

- QCD is asymptotically free → becomes weakly coupled at high temperature and/or density



S. Flörchinger, ESHEP 2015

- formation of a quark-gluon plasma (QGP)
  - (anti-)quarks and gluons become deconfined
  - chiral symmetry is restored
- in heavy ion collisions at collider energies: nuclei are largely transparent → central rapidity region essentially baryon-free

# What is this stuff we're producing? – QCD thermodynamics

- Stefan-Boltzmann law: pressure of non-interacting gas of $N_\mathrm{B}$ massless bosons and $N_\mathrm{F}$ massless fermions

$$p(T) = \frac{\pi^2}{90}\left(N_\mathrm{B} + \frac{7}{8}N_\mathrm{F}\right)T^4$$

- high temperature QGP:

$$N_\mathrm{B} = 2[\mathrm{spin}]\cdot(N_c^2-1)[\mathrm{colour}] = 16$$
$$N_\mathrm{F} = 2[\mathrm{anti\text{-}/particle}]\cdot 2[\mathrm{spin}]\cdot N_c[\mathrm{colour}]\cdot N_f[\mathrm{flavour}] = 36$$

- low temperatures $M_\pi < T < M_\rho$:

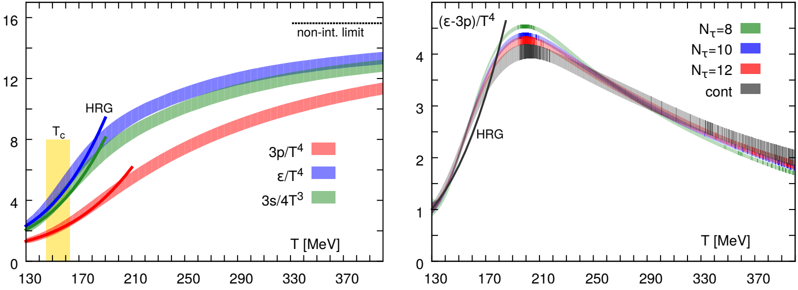
$$N_\mathrm{B} = 3 \qquad N_\mathrm{F} = 0$$

- expect strong increase of pressure at phase boundary

# What is this stuff we're producing? – Lattice QCD

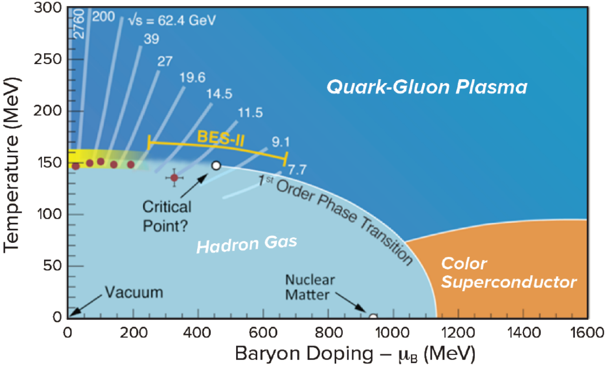
- solve QCD numerically on space-time lattice → Lattice QCD
- suitable for thermodynamic (static) properties of QCD matter
- works for $\mu_\mathrm{B} \simeq 0$
- finds crossover at $T_\mathrm{c} = (154 \pm 9)\,\mathrm{MeV} \approx 1.7 \cdot 10^{12}\,\mathrm{K} \approx 10^5\,T_\odot$
- QGP doesn't seem to be weakly coupled

$\epsilon = 3p$ for ideal quark-gluon gas



Bazavov *et al.* [HotQCD Collaboration], Phys. Rev. D **90** (2014) 094503 [arXiv:1407.6387]

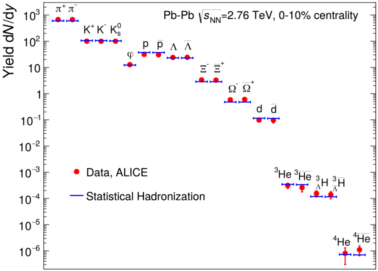
# The QCD phase diagram

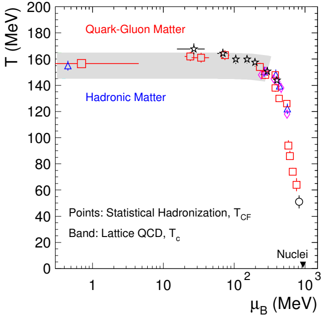


A. Aprahamian *et al.*, *Reaching for the horizon: The 2015 long range plan for nuclear science*

# Putting experimental points on QCD phase diagram

- assume hadron gas in thermal & chemical equilibrium
  - number changing processes require high density → stop soon after hadronisation
  - elastic scattering continues, but change affect hadron species
- fit identified hadron yields with fit parameters temperature, volume and chemical potentials





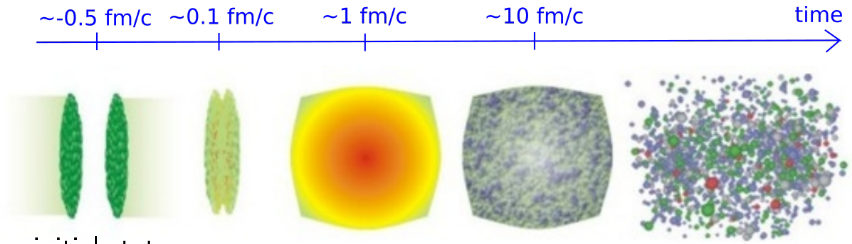
Andronic, Braun-Munzinger, Redlich, Stachel, Nature **561** (2018) no.7723, 321 [arXiv:1710.09425]

# Why is this interesting?

- QGP: only strongly coupled system of Standard Model microscopic degrees of freedom
  - understand strongly interacting matter at temperatures $\sim 10^5$ times higher than the core of the sun
  - How do heavy ion collisions equilibrate?
  - How does collectivity arise in asymptotically free theory?
- QGP: "simplest form of complex quantum matter"
  - understand QGP properties and QCD phase diagram theoretically and experimentally
  - How does multitude of complex materials arise from simple underlying theory?
- early universe went through QGP phase ($\mathcal{O}(10^{-6}\,\mathrm{s})$)

possibly no phenomenological consequences at later times

# Timeline of heavy ion collisions



initial state

pre-equilibrium dynamics

hydrodynamic expansion

hadronisation

hadronic re-scattering

picture from `https://phy.duke.edu/modeling-relativistic-heavy-ion-collisions`

# Outline for rest of lectures

## Part I – today

- go through different stages of heavy ion collisions
- focus on soft particle production

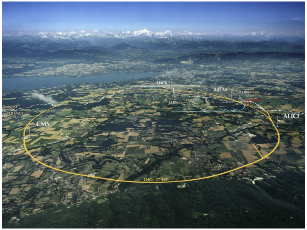
## Part II – tomorrow

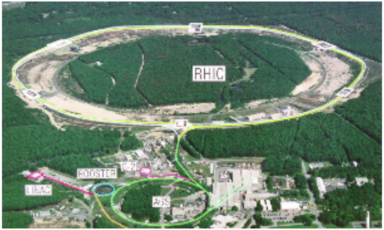
- hard processes
    - quarkonia
    - electroweak bosons
    - jets
- small collision systems
- other fun stuff with heavy ions

# Heavy ion colliders; RHIC & LHC

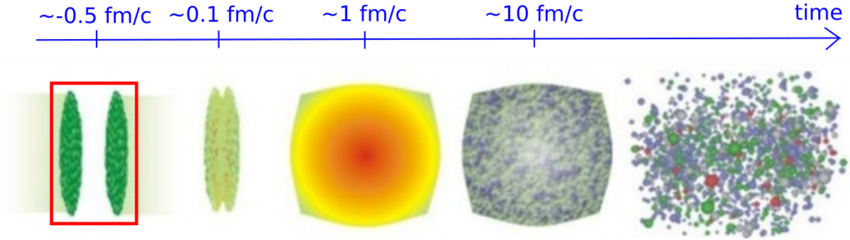
- RHIC: Relativistic Heavy Ion Collider in Brookhaven
    - Au+Au $\sqrt{s_{\rm NN}} = 200\,\mathrm{GeV}$

      centre-of-mass energy per nucleon pair
    - p+p, p+Au and d+Au
    - U, Cu, O, Ru, Zr, . . .
- LHC: Large Hadron Collider at CERN
    - Pb+Pb $\sqrt{s_{\rm NN}} = 2.76\,\mathrm{GeV}$ and $5.02\,\mathrm{GeV}$
    - p+p and p+Pb
    - Xe+Xe, O+O (coming soon)





# Timeline of heavy ion collisions



initial state

pre-equilibrium
dynamics

hydrodynamic
expansion

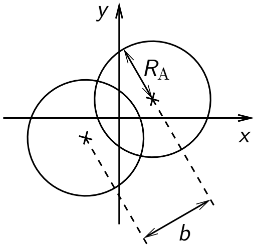
hadronisation

hadronic
re-scattering

# Centrality

impact parameter $b$: transverse distance between centres of colliding nuclei

centrality: fraction of geometric cross section



- if nuclei were billiard balls:

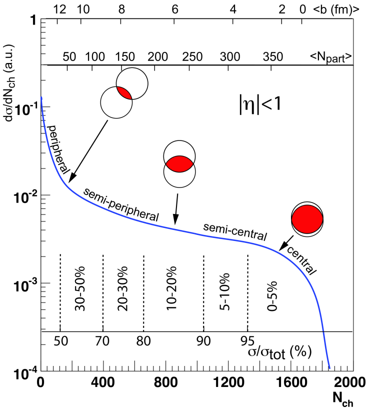
$$\sigma_\mathrm{geo} = \pi (R_A + R_B)^2$$

$$\sigma(b) = \int_0^b \int_0^{2\pi} b' \, \mathrm{d}b' \, \mathrm{d}\phi = \pi b^2$$

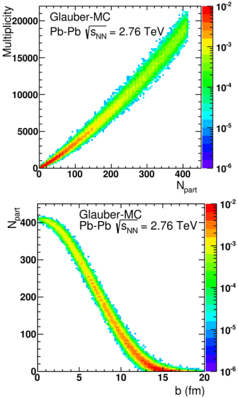
$$\mathrm{centrality}(b) = b^2 / (R_A + R_B)^2$$

# Measuring centrality

- one option: forward multiplicity
- relation to $b$ or $N_{\mathrm{part}}$ relies on models



Sarkar, Satz, Sinha,"The physics of the quark-gluon plasma",Lect. Notes Phys. 785 (2010) pp.1



ALICE, Phys. Rev. C 91 (2015) no.6, 064905 [arXiv:1412.6828]

# Dealing with geometry: Glauber model

- nuclei are not billiard balls:
  - nuclear potential, e.g. Woods-Saxon potential

$$n_A(r) = \frac{n_0}{1 + \exp\left(\frac{r-R}{d}\right)}$$

  - (inelastic) nucleon-nucleon cross section $\sigma_{\text{inel}}^{\text{NN}}$

elastic scattering has no effect near mid-rapidity

- integrate over beam direction

$$T_A(s) = \int_{-\infty}^{\infty} \mathrm{d}z\, n_A(\sqrt{s^2 + z^2})$$

- overlap of two colliding nuclei

$$T_{AB}(b) = \int \mathrm{d}^2 s T_A(\mathrm{s})\, T_B(\mathrm{s} - \mathrm{b})$$

# Dealing with geometry: Glauber model

- number of binary nucleon-nucleon collisions

$$N_{\mathrm{coll}} = T_{AB}(b)\,\sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

- number of participant nucleons

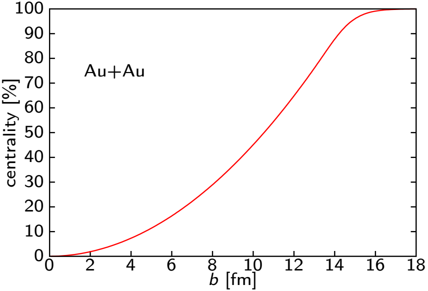
$$N_{\mathrm{part}}(b) = \int \mathrm{d}^2 s\, T_A(\mathrm{s}) \left\{ 1 - \left[ 1 - \frac{\sigma_{\mathrm{inel}}^{\mathrm{NN}}\, T_B(\mathrm{s}-\mathrm{b})}{B} \right]^B \right\} + \int \mathrm{d}^2 s\, T_B(\mathrm{s}) \left\{ 1 - \left[ 1 - \frac{\sigma_{\mathrm{inel}}^{\mathrm{NN}}\, T_A(\mathrm{s}+\mathrm{b})}{A} \right]^A \right\}$$

  - probability for nucleon not to interact: $\left[ 1 - \frac{\sigma_{\mathrm{inel}}^{\mathrm{NN}}\, T_A(\mathrm{b})}{A} \right]^A$
  - soft particle production scales like $N_{\mathrm{part}}$
  - hard processes scale like $N_{\mathrm{coll}}$

# Dealing with geometry: Glauber model

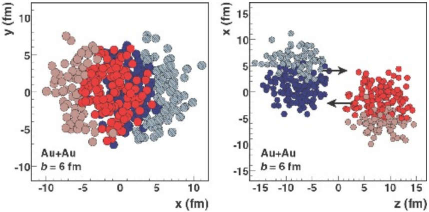
- geometric cross section: cross section for $N_{\text{coll}} \geq 1$

$$\sigma_{\text{geo}} = \int \mathrm{d}^2 b \left[1 - e^{-T_{AB}(b)\,\sigma_{\text{inel}}^{\text{NN}}}\right]$$



# Monte Carlo Glauber model

- simple way of dealing with event-by-event fluctuations
- distribute nucleons in nucleus according to nuclear potential
- for each nucleon in one nucleus calculate number of nucleons in other nucleus with transverse distance $< \sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}$
- from this compute $N_{\text{part}}$ and $N_{\text{coll}}$



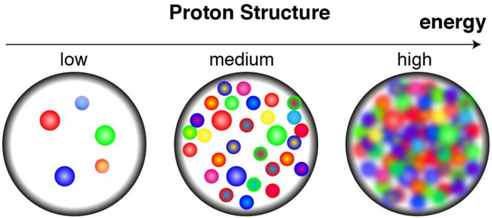
Miller, Reygers, Sanders, Steinberg, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205 [nucl-ex/0701025]

# Gluon saturation

- soft particle production probes low-$x$ gluons
- rapid rise of gluon density due to scale evolution
- at high gluon densities recombination becomes important

slows down evolution and leads to gluon saturation

- saturation scale $Q_s$: typical $p_\perp$ of saturated gluons
- or: saturated gluons have size $1/Q_s$
- for RHIC and LHC energies $Q_s$ is of order a few GeV



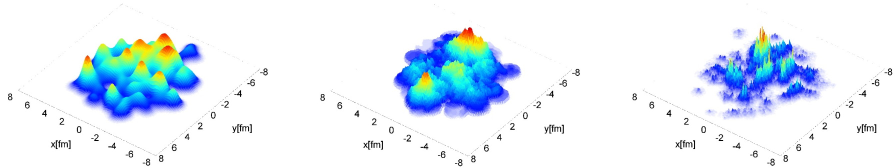
https://www.uu.nl/en/research/institute-for-subatomic-physics/research/color-glass-condensate

# The Colour Glass Condensate (CGC)

- hard valence partons: “frozen” by time dilation, act as colour sources for
- saturated gluons with typical momenta $Q_s$
- saturated gluons have occupation number $1/\alpha_s \rightarrow$ over-occupied
- strong fields but weakly coupled ($\alpha_s(Q_s) \ll 1$)
- can be described using classical field theory
- obey RG evolution equation (JIMWLK equation)
- interactions between nuclei lead to strong colour fields decaying to partons

# Comparing different models

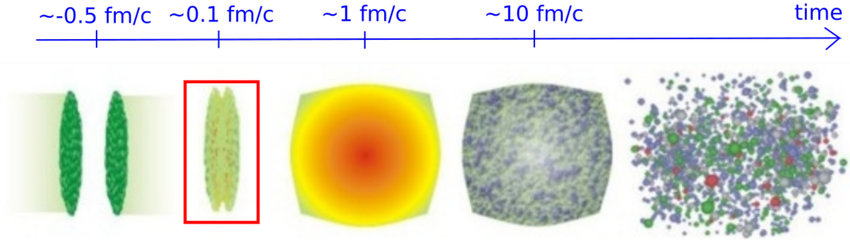
- compute distribution of energy density $\epsilon$ in different models
- Glauber model doesn't predict $\epsilon$
  $\rightarrow$ have to make assumptions & tune to data
- here: for each participant add Gaussian with width 0.4 fm
- in contrast: length scale for fluctuations in IP-Glasma is $1/Q_s$



Glauber-MC MC-KLN IP-Glasma

Schenke, Tribedy, Venugopalan, Phys. Rev. Lett. **108** (2012) 252301 [arXiv:1202.6646]

# Timeline of heavy ion collisions



initial state

pre-equilibrium dynamics

hydrodynamic expansion

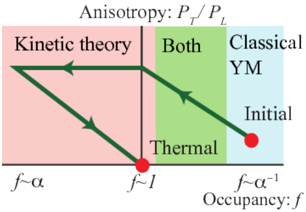
hadronisation

hadronic re-scattering

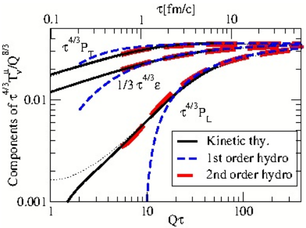
# Approach to equilibrium

- early stages of HIC are far-from-equilibrium systems
- system expands rapidly
- hydrodynamic description becomes applicable at 1 fm/c
- at 1 fm/c the system is still very an-isotropic
- “hydrodynamisation”

# Equilibration in kinetic theory



Kurkela, Nucl. Phys. A **956** (2016) 136



Kurkela, Zhu, Phys. Rev. Lett. **115** (2015) no.18, 182301

- region $f \ll 1/\alpha_s$ described by effective kinetic theory
- solve Boltzmann transport equation

$$-(\partial_t + \mathrm{v} \cdot \nabla_x) f(\mathrm{x}, \mathrm{p}, t) = \mathcal{C}_{\text{“}1\leftrightarrow 2\text{”}}[f] + \mathcal{C}_{2\leftrightarrow 2}[f]$$

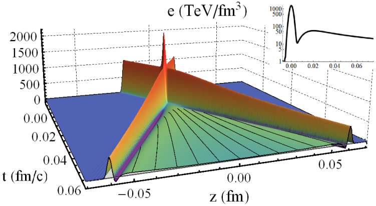
  - $\mathcal{C}_{\text{“}1\leftrightarrow 2\text{”}}$: splitting/merging rate in presence of multiple scattering
  - $\mathcal{C}_{2\leftrightarrow 2}$: elastic scattering rate
- hydrodynamisation on timescales $\lesssim 1\,\mathrm{fm/c}$

# Equilibration at strong coupling

- AdS/CFT correspondence: relates strongly coupled conformal field theory to a weakly coupled type IIB string theory
- can be used to study strongly coupled field theories

here: $\mathcal{N} = 4$ Super-Yang-Mills theory

- model heavy ion collision as collision of shock waves
- thermalisation related to black hole formation in 5th dimension
- hydrodynamic behaviour reached quickly (timescale $\sim 1/T$)

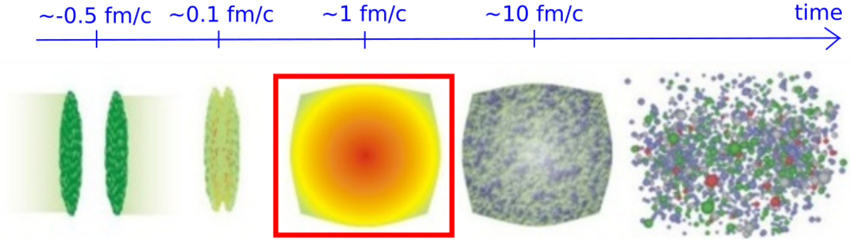


- unfortunately $\mathcal{N} = 4$ SYM is not QCD

QCD nearly conformal at high $T$

Chesler, van der Schee, Int. J. Mod. Phys. E 24 (2015) no.10, 1530011 [arXiv:1501.04952]

# Timeline of heavy ion collisions



initial state

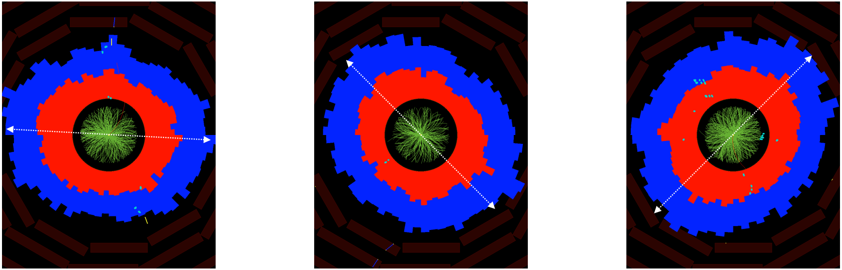
pre-equilibrium dynamics

hydrodynamic expansion

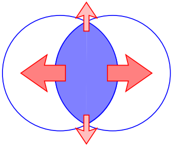
hadronisation

hadronic re-scattering

# First main discovery of heavy ion physics



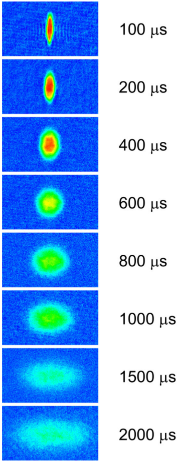
event displays from G. Roland, CMS



- anisotropy due to different pressure gradients

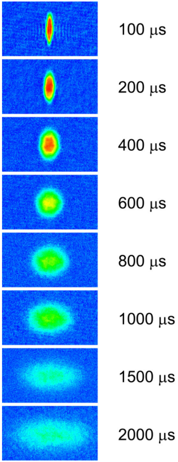
→ collective flow

# Collective flow

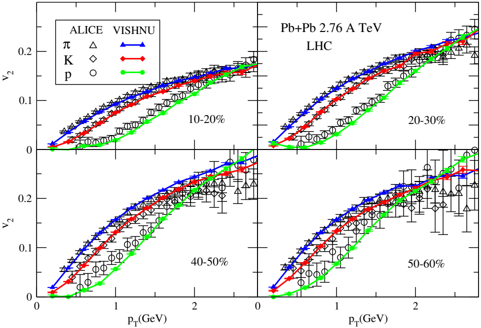


O'Hara et al., Science **298** (2002) 2179

# Collective flow



O'Hara et al., Science **298** (2002) 2179



$$\frac{\mathrm{d}\,N}{\mathrm{d}\,\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos(n(\phi - \Psi_n))\right]$$

- described by hydrodynamics
- mass ordering due to common velocity

Song, Bass & Heinz, Phys. Rev. C **89** (2014) no.3, 034919

# Hydrodynamics: what it is

Romatschke, Int. J. Mod. Phys. E **19** (2010), 1-53

- low energy effective theory describing long distance, late time behaviour of averaged macroscopic features of the system
- applicable to very generic set of theories
- assumes that matter is close to local thermal equilibrium
- microscopic details of theory enter in inputs of hydrodynamics
  - equation of state
  - transport coefficients
  - relaxation times
- valid for
  - distances large compared to mean free path
  - times long compared to inverse scattering rate
  - systems with sufficiently smooth variation

# Ideal hydrodynamics

- fluid in global thermal equilibrium described by energy-momentum tensor

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + p(g^{\mu\nu} + u^\mu u^\nu)$$

with metric $g^{\mu\nu}$ and fluid velocity $u^\mu$

- energy density and pressure related through equation of state
- allow small deviation from equilibrium such that

$$\epsilon = \epsilon(x) \qquad u^\mu = u^\mu(x)$$

- for small gradients systems stays in local thermal equilibrium
- energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$ leads to

$$\begin{aligned} u^\mu \partial_\mu \epsilon + (\epsilon + p)\partial_\mu u^\mu &= 0 \\ (\epsilon + p) u^\mu \partial_\mu u^\nu + (g^{\nu\mu} + u^\nu u^\mu)\partial_\mu p &= 0 \end{aligned}$$

independent of micro-physics

# Viscous corrections

- allow for perturbations with larger gradients → need more general form of $T^{\mu\nu}$:

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + p\Delta^{\mu\nu} + \Pi^{\mu\nu}$$

with $\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$

viscous stress tensor

- decompose $\Pi^{\mu\nu}$ into traceless part and remainder

$$\Pi^{\mu\nu} = \pi^{\mu\nu} + \pi_{\text{bulk}} \Delta^{\mu\nu}$$

shear stress

bulk viscous pressure

- parametrise deviations from ideal fluid dynamics

# Viscous corrections

- viscous fluid dynamics can be organised as gradient expansion

$$\pi_{\mathrm{bulk}} = -\zeta\partial_\mu u^\mu + \dots$$

$$\pi^{\mu\nu} = -2\eta\left(\frac{1}{2}\Delta^{\mu\alpha}\Delta^{\nu\beta} + \frac{1}{2}\Delta^{\mu\beta}\Delta^{\nu\alpha} + \frac{1}{3}\Delta^{\mu\nu}\Delta^{\alpha\beta}\right)\partial_\alpha u_\beta + \dots$$

- at first order: bulk viscosity $\zeta = \zeta(\epsilon)$ & shear viscosity $\eta = \eta(\epsilon)$
- at second order: many more parameters

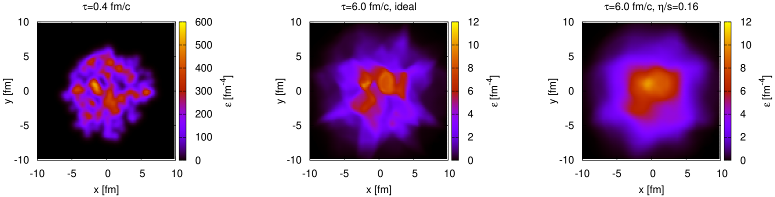
relaxation times, more transport coefficients, . . .

- increasingly complicated evolution equations

have to be solved numerically

# Shear viscosity

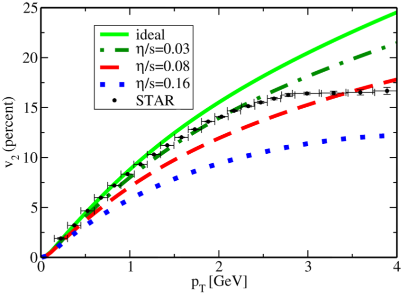
- shear viscosity related to momentum transport
  - large $\eta/s \rightarrow$ momentum transport over large distances by quasi-particles
  - small $\eta/s \rightarrow$ no well-defined quasi-particles
- $\eta/s$ calculable at weak coupling (kinetic theory) and at strong coupling (AdS/CFT)



Schenke, Jeon, Gale, Phys. Rev. Lett. **106** (2011) 042301 [arXiv:1009.3244]

# Shear viscosity

- efficiency of $v_2$ generation sensitive to shear viscosity $\eta$
- heavy ion collisions least dissipative system known



Romatschke & Romatschke, Phys. Rev. Lett. **99** (2007) 172301

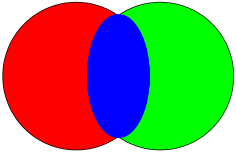
- conjectured lower bound form obtained from AdS/CFT

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

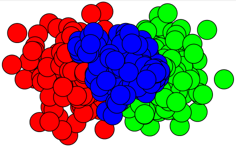
$\eta/s = 1/4\pi$ realised in field theories with gravity duals

Kovtun, Son, Starinets, Phys. Rev. Lett. **94** (2005) 111601

# Higher harmonics

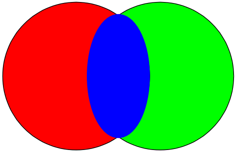


no odd harmonics

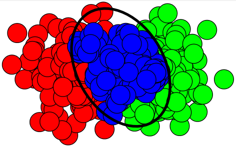


fluctuations generate odd harmonics

# Higher harmonics

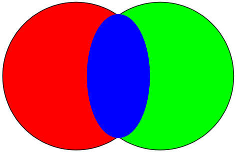


no odd harmonics

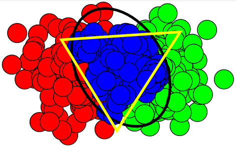


fluctuations generate odd harmonics

# Higher harmonics

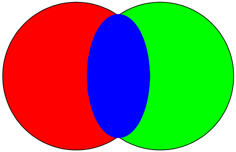


no odd harmonics

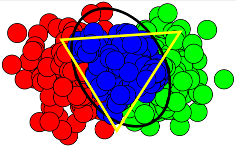


fluctuations generate odd harmonics

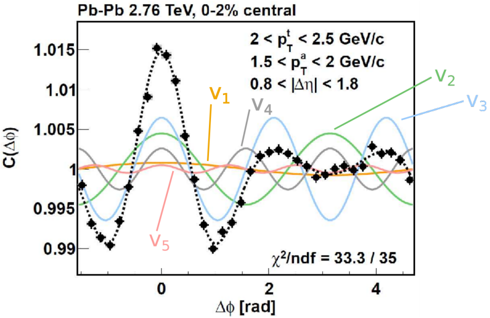
# Higher harmonics



no odd harmonics



fluctuations generate odd harmonics



- very central collisions
- $v_2$ small
- mid-central collisions

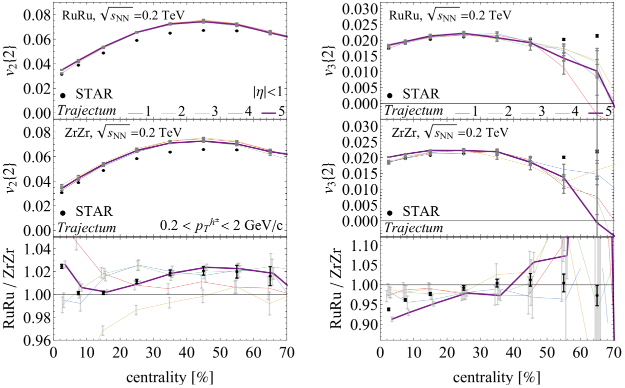
  $v_2 \gg v_3 > v_4 \ldots$

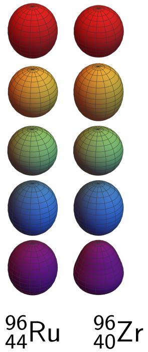
ALICE, Phys. Lett. B **708** (2012) 249

# Anisotropic flow and nuclear structure

- anisotropic flow sensitive to geometry of collision

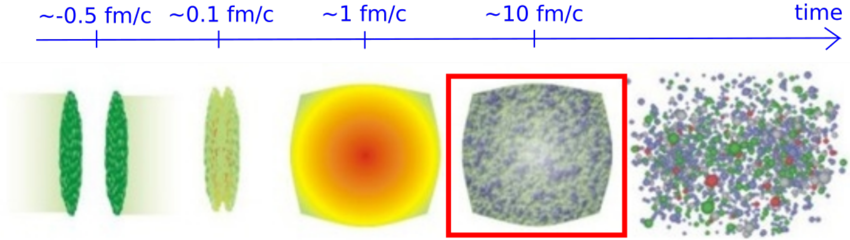
→ sensitive to nuclear structure





Nijs, van der Schee, SciPost Phys. 15 (2023), 041

# Timeline of heavy ion collisions



initial state

pre-equilibrium dynamics

hydrodynamic expansion

hadronisation

hadronic re-scattering

# From fluid to particles

- run hydrodynamics until interactions cease → kinetic freeze-out

happens in hadronic phase

- neglecting viscous corrections: occupation numbers for each fluid element

$$\frac{\mathrm{d}N_i}{\mathrm{d}^3x\,\mathrm{d}^3p} = f_i(p^\mu; T(x), u^\mu(x)) \propto \left[e^{\frac{u_\mu(x)p^\mu}{T(x)}} \pm 1\right]^{-1}$$

- Cooper-Frye prescription: integral over surface of last scattering (freeze-out surface) $\Sigma_f$ gives particle spectra

$$E\frac{\mathrm{d}N_i}{\mathrm{d}^3p} = \frac{1}{(2\pi)^3}\int_{\Sigma_f} p_\mu \mathrm{d}\sigma^\mu\, f_i$$

- in practice often assumed that $T = \text{const}$ on $\Sigma_f$
- corrections due to viscosity

Cooper, Frye, Phys. Rev. D **10** (1974), 186

# Quark Coalescence

- suitable if partonic distribution functions known
- idea: quarks and anti-quarks combine to form hadrons
- number of mesons

$$N_M = g_M \int_{\Sigma_f} (p_{1\mu} d\sigma_1^\mu)\,(p_{2\mu} d\sigma_2^\mu)\,\frac{d^3 p_1}{(2\pi)^3 E_1}\,\frac{d^3 p_2}{(2\pi)^3 E_2} \times f_q(x_1, p_1) f_{\bar{q}}(x_2, p_2) f_M(x_1, x_2, p_1, p_2)$$

- $f_a(x, p)$: (anti)quark distribution functions
- $f_M(x_1, x_2, p_1, p_2)$: probability for $q$ and $\bar{q}$ to form meson, e.g.

$$f_M(x_1, x_2, p_1, p_2) \propto \exp\left(\frac{(x_1 - x_2)^2}{2\Delta_x}\right) \cdot \exp\left(\frac{(p_1 - p_2)^2}{2\Delta_p}\right)$$

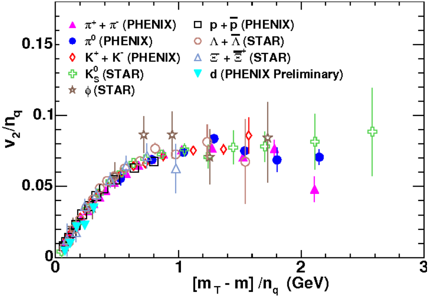
- corresponding expressions for baryons

Greco, Ko, Levai, Phys. Rev. C **68** (2003), 034904

# Quark number scaling

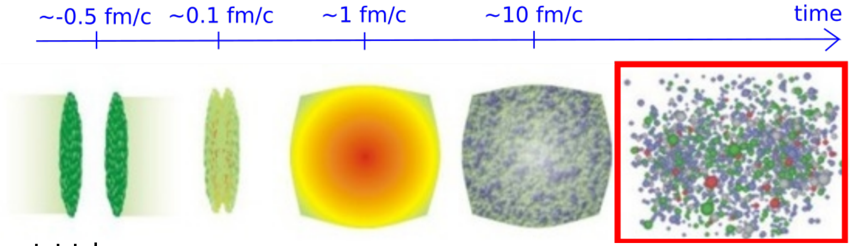
- coalescence picture predicts scaling of $v_2$ with number of constituent quarks
- observed in RHIC data

and to a lesser degree in LHC data



Granier de Cassagnac, Int. J. Mod. Phys. A 22 (2007) 6043 [arXiv:0707.0328]

# Timeline of heavy ion collisions



initial state

pre-equilibrium dynamics

hydrodynamic expansion

hadronisation

hadronic re-scattering

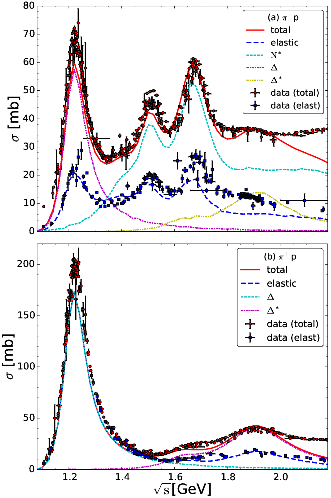
# Re-scattering in hadronic phase

## Option 1

- run hydrodynamics until kinetic freeze-out
- needs suitable input to deal with hadronic phase

## Option 2

- explicit simulation with transport codes
- based on Boltzmann equation
- need to include large number of resonances & cross sections



Weil *et al.*, Phys. Rev. C **94** (2016) no.5, 054905 [arXiv:1606.06642]

# Summary

- heavy ion collisions: unique opportunity to study matter at extreme conditions (temperature and pressure)
- formation of new phase of QCD matter: quark-gluon plasma

  → deconfinement, chiral symmetry restoration
- QGP: only strongly coupled system of Standard Model microscopic degrees of freedom
- what we have learned so far
  - QGP created in heavy ion collisions at RHIC and LHC
  - "rapid hydrodynamisation"
  - QGP is a strongly coupled liquid

## Summary: stages of a heavy ion collision

- initial state:
  - geometry ($\rightarrow$ Glauber model)
  - gluon saturation ($\rightarrow$ colour glass condensate)
- pre-equilibirium dynamics:
  - successful descriptions at weak (kinetic theory) and strong coupling (AdS/CFT)
  - leads to hydrodynamic regime on timescales $\mathcal{O}(1\,\mathrm{fm/c})$
- hydrodynamic expansion:
  - the QGP flows $\rightarrow$ collective behaviour
  - least dissipative system known ($\eta/s \gtrsim 1/4\pi$)
- hadronisation: phenomenological modeling
- hadronic re-scattering: hydrodynamics or transport theory

more important at lower beam energies