EPS-HEP2023 Conference, Hamburg
High Energy QCD Matter Theory

Pol Bernard Gossiaux, Subatech*

A tour in a colored field of research

Intended for a general HEP audience + quite large field => we will not visit everything

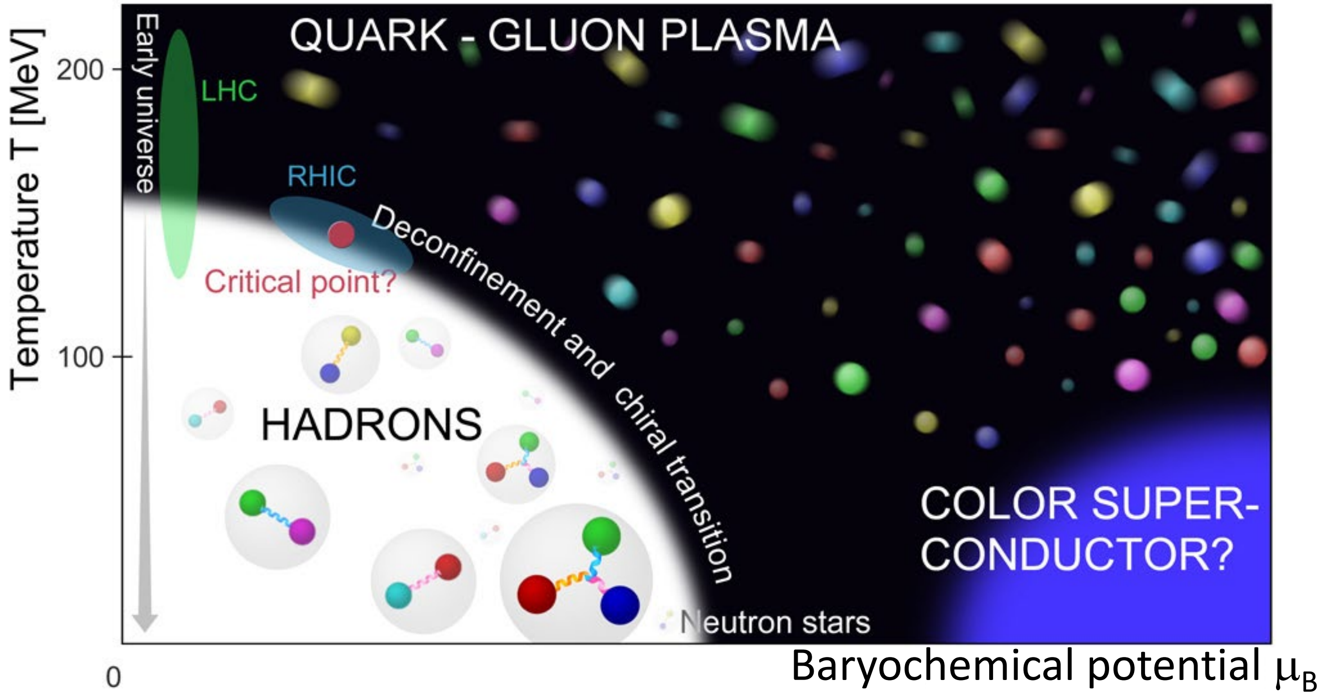
1. Introduction
2. The URHIC standard model
3. The quest of the viscosity coefficients
4. Back to the hadronic world
5. Hard probes
6. There is no point in being critical

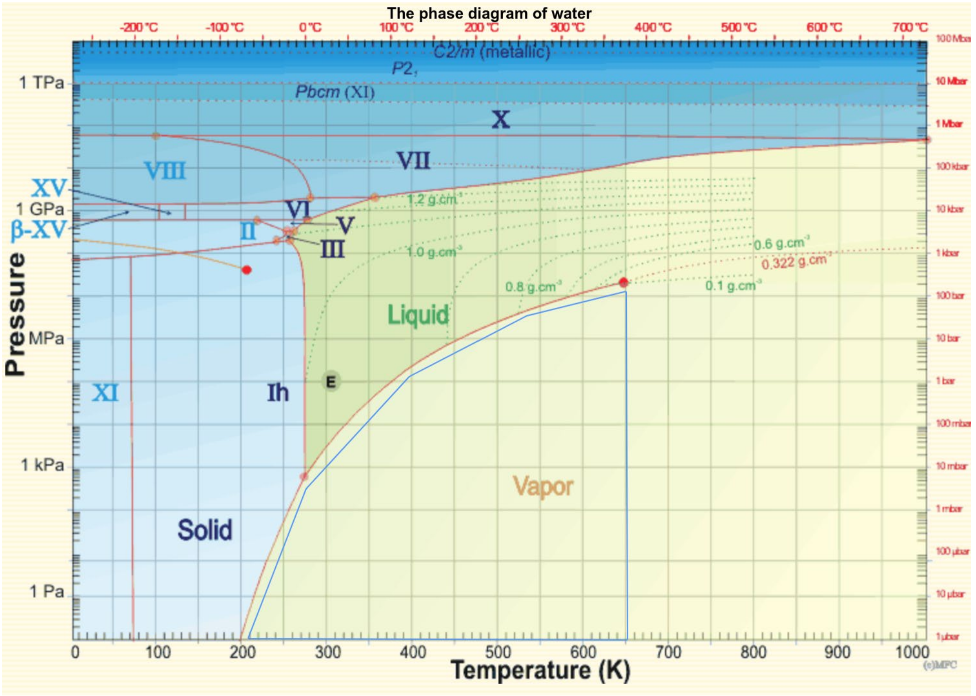
Exit

*IMT Atlantique, CNRS/IN2P3, Nantes Université

Motivation

Schematic phase diagram of hot (and dense) QCD matter (left) vs precise phase diagram of water (right)



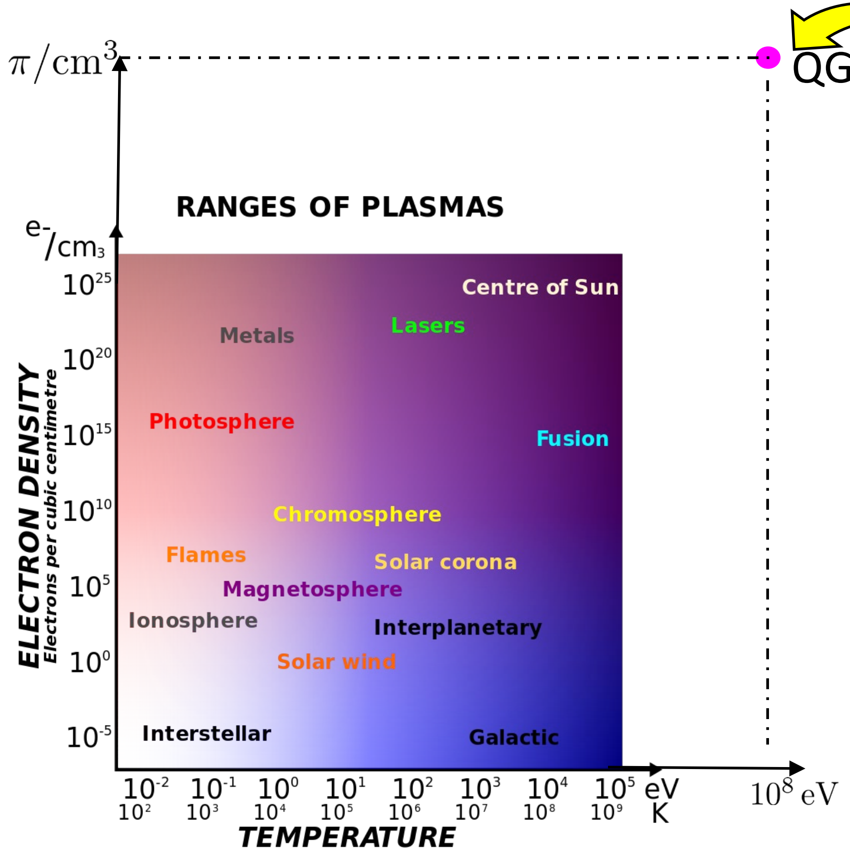


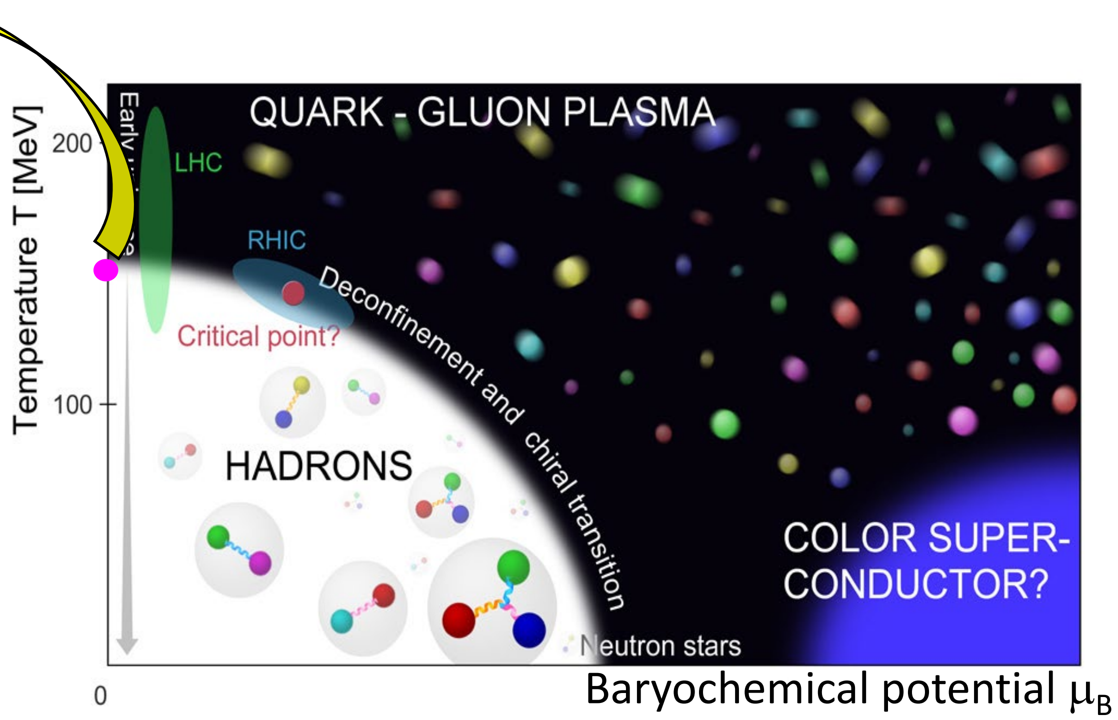
Still a lot of unknowns !… wish I could sneak a peak at EPS-HEP 2051

- Some similarities as for general features (gas, liquid, coexistence lines,…, possible critical point)
- From the simplicity of the elementary interaction to the complexity of the PS diagram. Emergent phenomena
- Beyond the structure, need to investigate associated properties (EOS, transport coefficients,…)
- **Best theoretical tool : QCD « on the lattice » (lQCD)**
- A stationary state, unreachable on Earth => Best experimental means : URHIC (see A.Kalweit)

The Quark Gluon Plasma

- The long standing Holy Grail of our field (late 70s), characterized by the spontaneous deconfinement of quarks and gluons





Despite being probably the hotest state of matter in the universe nowadays, **it is not a plasma !**

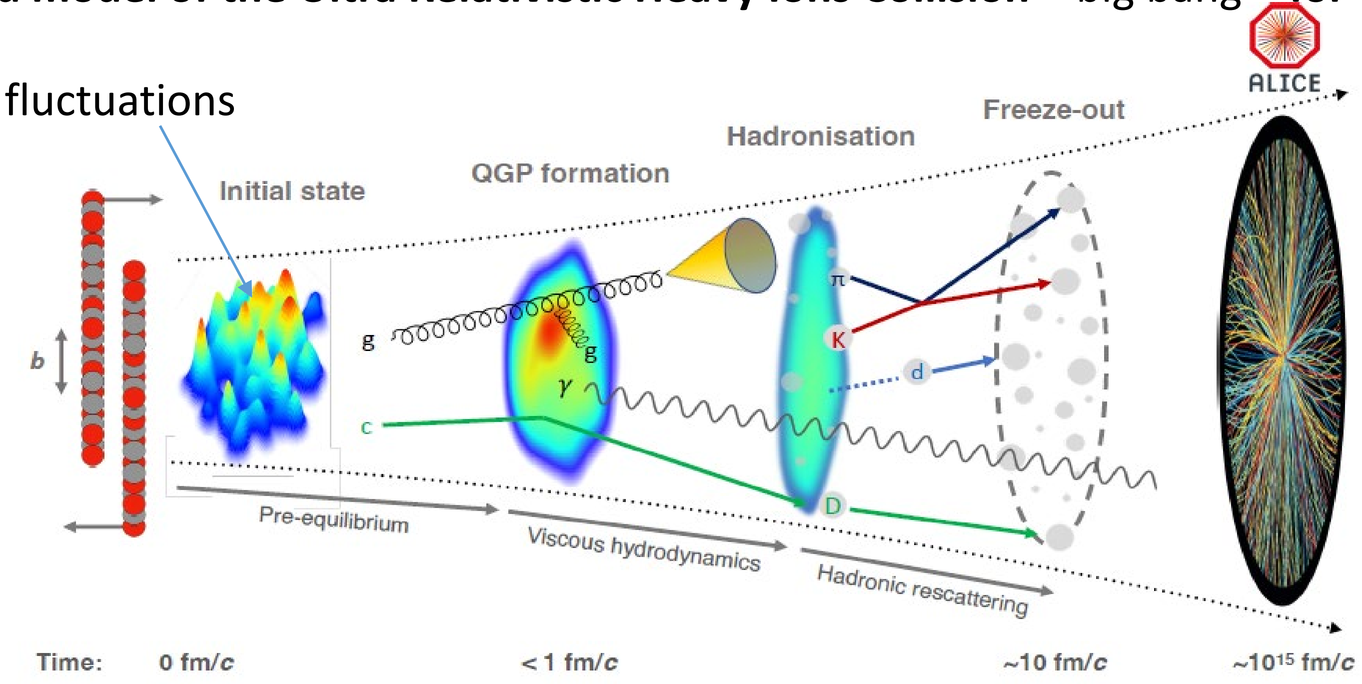
- Admittedly discovered early 2000s at RHIC (BNL USA)… some indications earlier at SPS (CERN, Ch)
- Warning : **QGP is NOT a plasma in the strict sense** :
  - Fundamental constituents are ionized : YES
  - **Interaction energy not small wrt Kinetic energy !!!**

⇒

- Not a gas of asymptotic partons with rare interactions
- *Strongly coupled fluid* (and in fact, a nearly perfect fluid)…
- Important consequences for the theoretical treatment

The smallest and the most ephemeral statistical system ?

- **Standard model of the Ultra Relativistic Heavy Ions Collision** « big bang » **for the soft QCD modes**

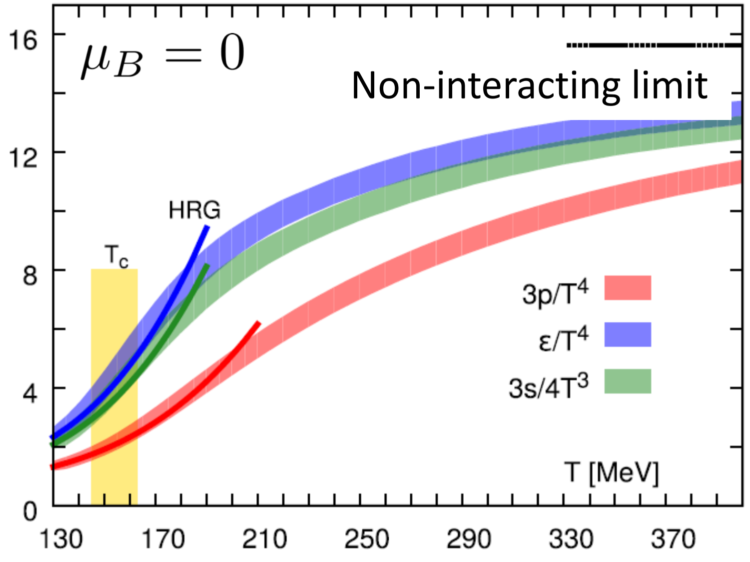


Not a stationary experiment with well-controllable conditions !

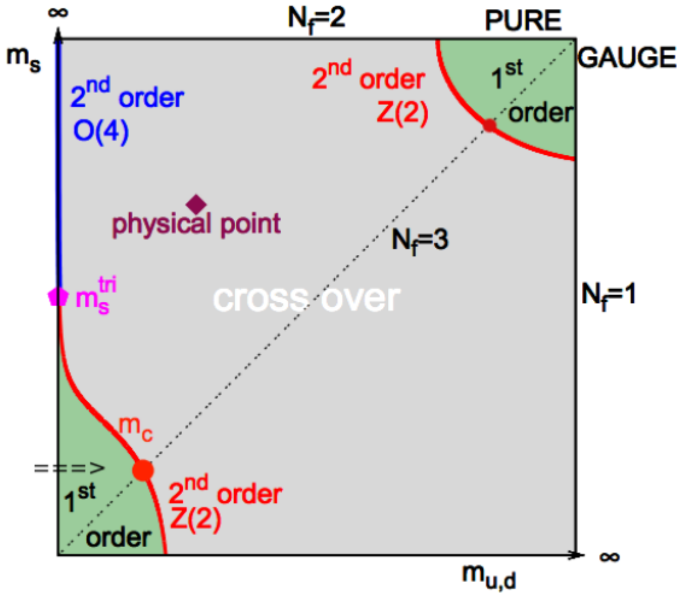
- QGP only lasts for small survival times ≈ 10 fm/c !!!
- Long wrt elementary collisions in usual particle physics… => space-time picture (complementary to energy-momentum)
- But still too short to reach some global equilibration (no confining wall)
- => **Theory should address non-equilibrium features of the evolution** => harder but provides more insights

- **lQCD not directly applicable for dynamical regimes** (real time)
- => Need to **resort to effective theories & models**, still hoping to learn something on the theory itself
- Models calibrated on lQCD, AND on data. **A field with large cross talk between theory and experiment**

Prediction from lattice QCD at μ_B=0



HotQCD Collaboration; PHYSICAL REVIEW D 90, 094503 (2014)



Ph. de Forcrand & M D'Elia, PoS LATTICE2016 (2017) 081

$$\mathcal{L}_{QCD} = \frac{1}{2g^2}\mathrm{Tr}F_{\mu\nu}F_{\mu\nu} + \boxed{\sum_f \bar{\psi}_f(\not{D} + m_f)\psi_f} \qquad D_\mu = \partial_\mu + iA_\mu$$

Partition function

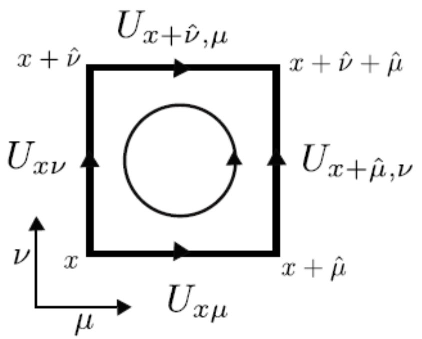
$$Z(T) = \mathrm{tr}\left(e^{-\frac{\hat{H}}{k_B T}}\right) = \mathrm{tr}\left(e^{-\beta\hat{H}}\right) \qquad Z = \int \mathcal{D}[U]\det[M]e^{-S}$$

Gauge links

Action on the lattice :

$$S[U] = \frac{\beta}{3}\sum_x \sum_{\mu<\nu} \Re\,\mathrm{tr}\left(1 - U_{x,\mu\nu}\right)$$

plaquette

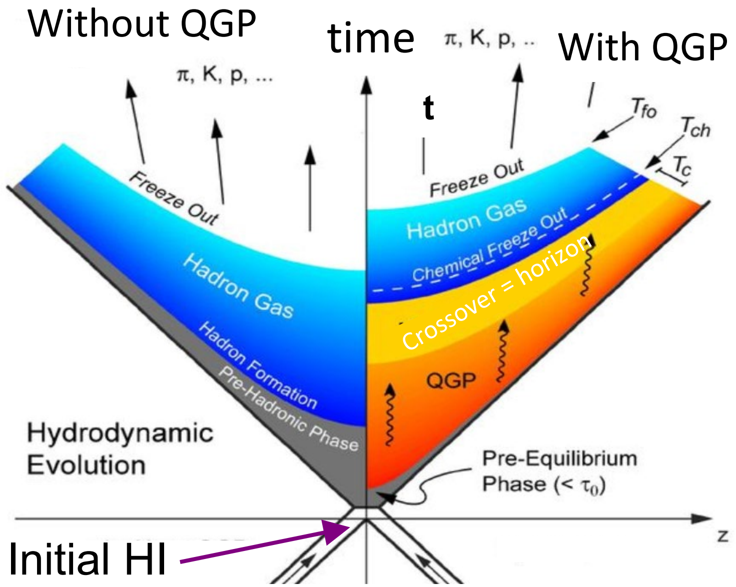


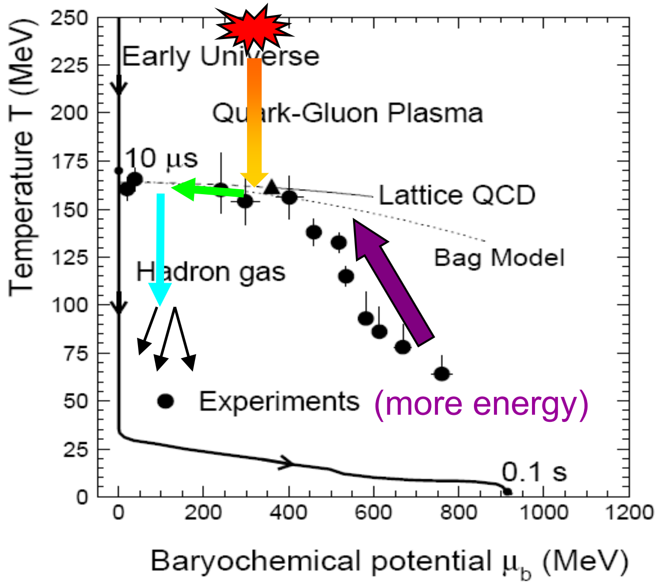
$$U_{x,\mu\nu} = U_{x\mu}U_{x+\hat{\mu},\nu}U^\dagger_{x+\hat{\nu},\mu}U^\dagger_{x\nu}$$

- **Cross over** around Tc ≈ 156 MeV
- CO close to the chemical freeze out temperature « measured » experimentally => hadrons abundances are fixed pretty fast after the reconfinement / chiral symmetry.
- **Low convergence -> the asymptotic limit of a non interacting quark-gluon plasma**

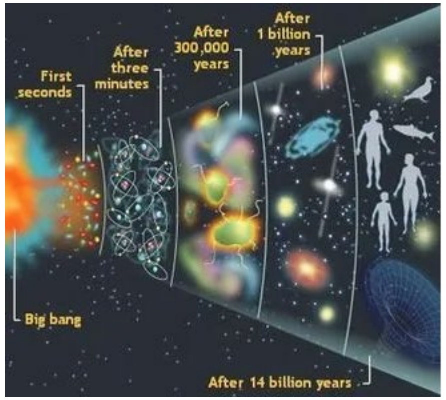
$T_c \approx \Lambda_{QCD}$… Probably not a pure coincidence

Beyond the QGP horizon





- **Experiments have revealed the freeze-out « horizon »**, the frontier between a gas of color-neutral hadrons and a thermalized state « beyond » …
- Challenge : As thermalization implies memory loss, how can we investigate the state « beyond the horizon », that is before the FO ?



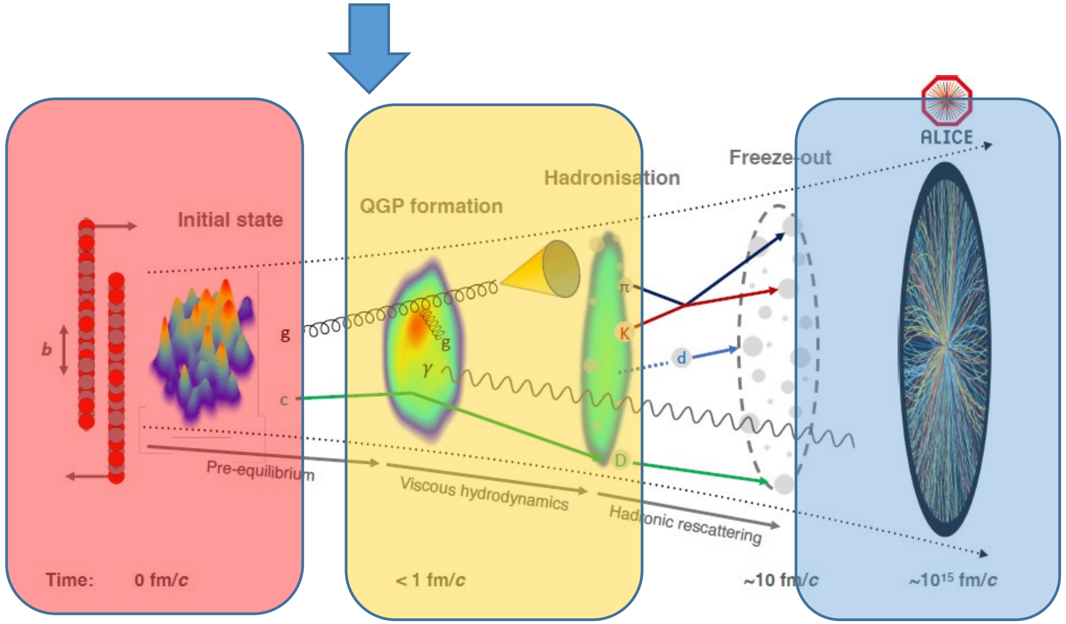
- **Three generic methods** (multi-messengers from the QGP):

- Measurement of particle directly produced in the hot phase and not much influenced by later stages: **weak probes** (photons, dileptons)
- The evolution of the « bulk QGP» itself has some slow modes which depend on the transports coefficient of the QGP (like shear and bulk viscosity). Can help in diagnosing QGP properties : **soft probes**
- Measurement of energetic and/or massive particles produced in the early stage of the evolution (hard momentum exchange) and *moderately* influenced by the ensuing QGP, (getting its footprints but not relaxing to thermalization): **hard probes** (jets, open HF, quarkonia,…)

Beyond the QGP horizon

Important Consequences :

➢ The standard URHIC model can generally be understood, for some of the soft and hard probes, as:



Response principle :

Observable / Output = **QGP** / Kernel ⊗ **Initial state** / Input

(Well-known math problem)

Need better control on the initial state to better understand/measure QGP

➢ Understanding each of these « observables » (how it couples to an evolving QGP) often requires extra theoretical developments that are not *per se* « hot QCD matter theory » but considered as such in a broad acceptance.

Science drivers of the field

1. What are the thermodynamic and global properties of the high energy QCD matter produced at RHIC and LHC ?
2. What are **the hydrodynamic** and transport properties of the QGP ?
3. Can some of these properties be described by suitable **effective theories** with appropriate degrees of freedom ?
   (depends on the scale at which QGP is probed)
4. How does the QGP affect the formation of hadrons ? (may help to understand confinement)
5. How does the QGP affect the propagation of energetic partons ?
6. How does deconfinement in the QGP affect the QCD force between 2 partons ?
7. what is the nature of the initial state in URHIC ? (initial state plays a key role in the QGP response)
8. What is the nature of hadron–hadron interactions in the final state ? (unique opportunity to test QCD)
9. Can the QGP lead to discovery of novel QCD effects? Emergent phenomena ?

… and should also improve our knowledge of the early universe:

A Short Survey of Matter-Antimatter Evolution in the Primordial Universe

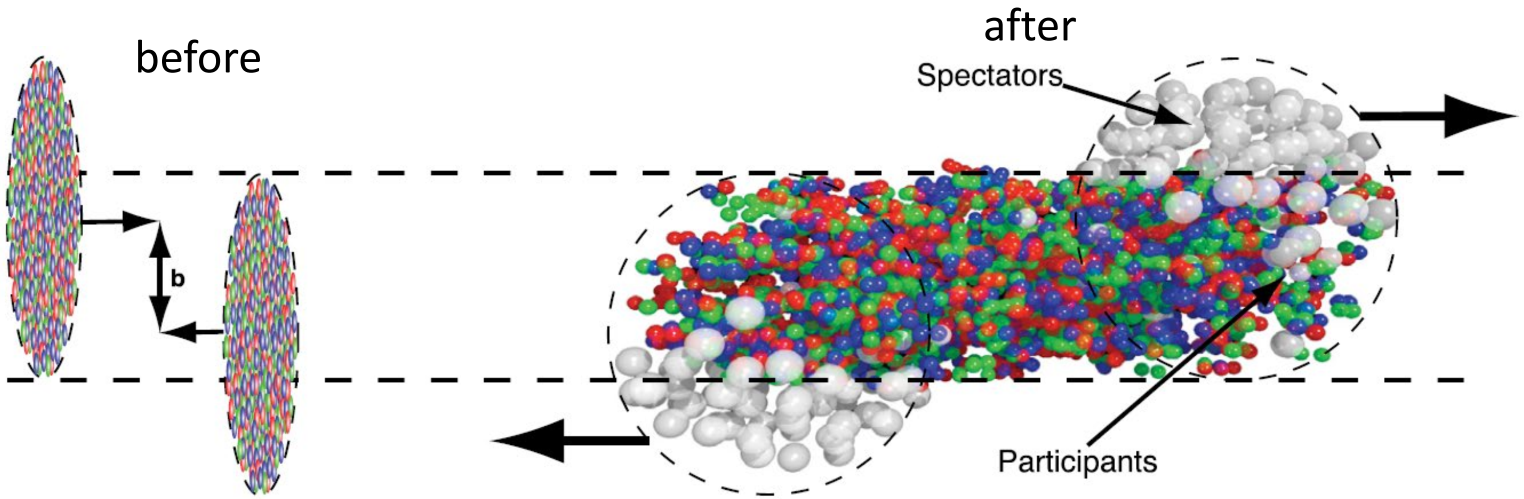
by Johann Rafelski *, Jeremiah Birrell, Andrew Steinmetz and Cheng Tao Yang

Department of Physics, The University of Arizona, Tucson, AZ 85721, USA

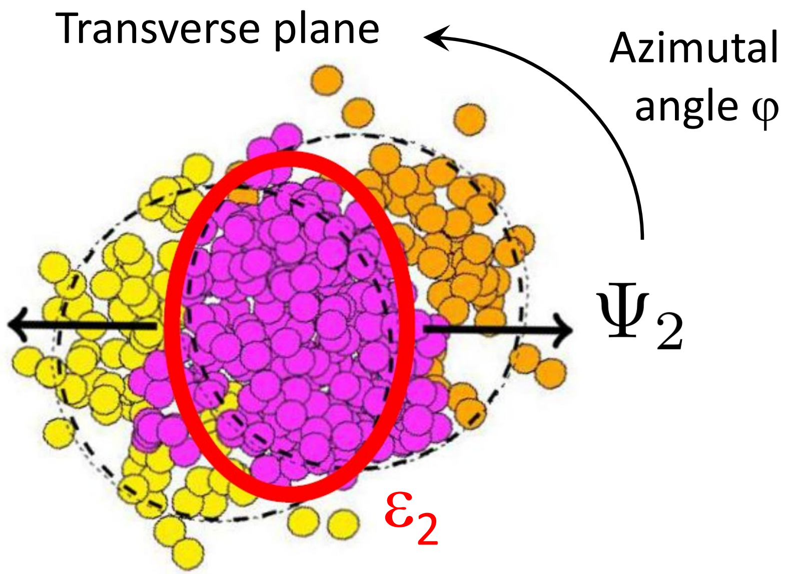
* Author to whom correspondence should be addressed.

Universe **2023**, *9*(7), 309; https://doi.org/10.3390/universe9070309

Azimuthal flows as a marker of the collective response



Raimond Snellings 2011 *New J. Phys.* 13 055008



- **Initial** eccentricity ε_2 in physical space => **final** anisotropy v_2 in momentum space :

$$\frac{dN}{d\varphi} = \frac{N}{2\pi} \times (1 + 2v_2 \cos(2(\varphi - \Psi_2))) \qquad v_2 : \text{elliptic flow}$$

- Several possible mechanisms; most efficient : strong *pressure* gradient along Ψ_2 => collective response and fast expansion along this direction … signature of a (hot) *collective* state of matter

Response principle : $\underbrace{\text{Observable / Output}}_{v_2} = \text{QGP / Kernel} \otimes \underbrace{\text{Initial state / Input}}_{\varepsilon_2}$

Fluid dynamics

- Low momentum (soft mode) effective theory based on local statistical equilibration

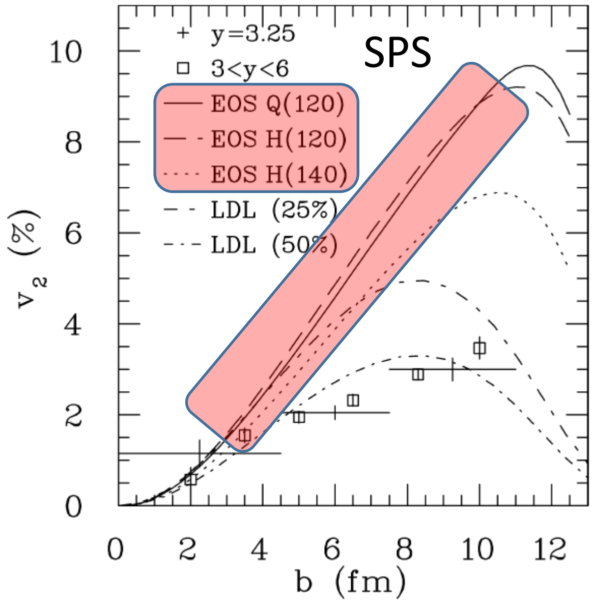
$$\boxed{\partial_\mu T^{\mu\nu} = 0}$$ (no conserved charge => μ_B=0)

where $$T^{\mu\nu} = eu^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}, \quad \text{with} \quad \Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

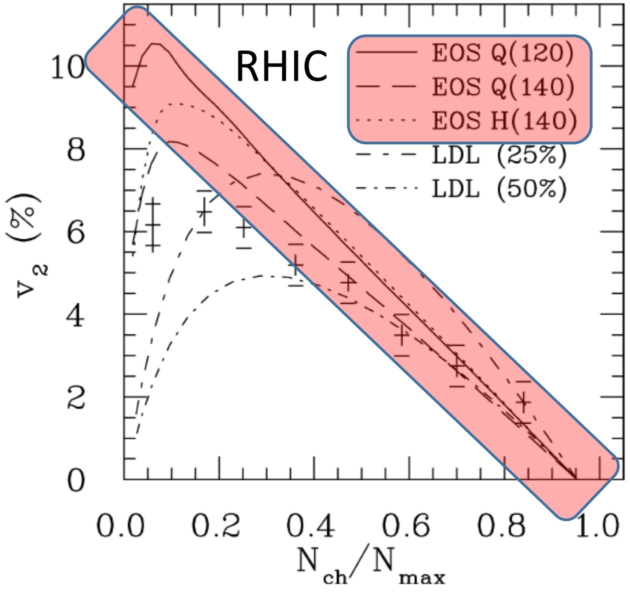
- Ideal hydro : $\Pi = \pi^{\mu\nu} = 0$ « Just » need the EOS to connect energy density *e* and pressure *P* (best : from lQCD)

- Kolb et al. **(Physics Letters B 500 (2001) 232–240):**
« **(Ideal) hydrodynamics is found to agree well with the RHIC data for semicentral collisions** …, but it considerably overestimates the measured elliptic flow at SPS energies. The low density limit LDL is inconsistent with the measured magnitude of *v*2 at RHIC energies. »

- Just the beginning of the story…



Elliptic flow for pions at midrapidity vs. centrality, for 158*A* GeV Pb + Pb collisions. Hydrodynamic calculations & results from the LDL are compared to NA49 data [3,4].



Centrality dependence of the elliptic flow coefficient *v*2 for charged particles from Au+Au collisions at √*s* = 130*A* GeV.

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- Viscous : Simple relativistic generalization of Navier-Stokes:

H. Song & U. W. Heinz, Phys. Rev. C77, 064901 (2008).

$$\Pi = -\underset{\text{Bulk viscosity}}{\zeta}\underbrace{\nabla \cdot u}_{\theta} \quad \text{and} \quad \pi^{\mu\nu} = \underset{\text{Shear viscosity}}{\eta} \underbrace{\left[\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}(\nabla \cdot u)\Delta^{\mu\nu}\right]}_{\sigma^{\mu\nu}}$$

But (non physical) acausal propagation of some solutions

- Usual solution (Israel-Stewart) : go up to the 2nd order in gradient expansion => causal equations for Π and $\pi^{\mu\nu}$:

$$\left.\begin{aligned} \tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} &= \eta\sigma^{\mu\nu} + \cdots \\ \tau_\Pi \dot{\Pi} + \Pi &= -\zeta\theta + \cdots \end{aligned}\right\}$$

Viscosities as input of these equations : $\eta(T)$ & $\zeta(T)$

The viscosity quest

- Most « early » calculations performed using some kind of Boltzmann equation / kinetic theory for the distribution of quarks and gluons => assumption on the microscopic degrees of freedom

$$[\partial_t + v_p \cdot \nabla_x + F_{\text{ext}} \cdot \nabla_p] f(x,p) = \mathcal{C}[f]$$ Collision integral

- Viscous contributions (Π and $\pi^{\mu\nu}$) to $T^{\mu\nu}$ ⇔ $f = f_{\text{eq}} + \delta f(x,p)$ with $\mathcal{C}[f_{\text{eq}}] = 0$
- **Linearize Boltzmann equation** : $[\partial_t + v_p \cdot \nabla_x + F_{\text{ext}} \cdot \nabla_p] f_{\text{eq}}(x,p) = \mathcal{C}[\delta f]$
- Solve for δf (not trivial !!!), reinject in $T^{\mu\nu}$ and « read » the transport coefficient.

- **Simplest approximation : « collision time approximation »** :$\mathcal{C}[\delta f] = -\frac{\delta f}{\tau_{\text{coll}}}$

$\eta(m=0) = \frac{4\tau_{\text{coll}}}{15} \times e(T)$ with $\tau_{\text{coll}} \propto \frac{T^{-1}}{\alpha_s^2 \ln(1/\alpha_s)}$ ⇒ $\eta(m=0) \propto \frac{1}{\alpha_s^2 \ln(1/\alpha_s)} \times \underbrace{\frac{e(T)}{T}}_{s(T)}$

S. Gavin, Nucl Phys A435, 826 (1985) **Hosoya and Kajantje; Nucl Phys B250(1985) 666-668**

η measured in units of $s = \frac{e}{T}$ (entropy density)
Large coupling ⇔ small mean free path ⇔ small viscosity ⇔ ≈ perfect fluid

Early RHIC data explained by ideal hydro, hence the conclusion of « strongly coupled fluid »

The viscosity quest

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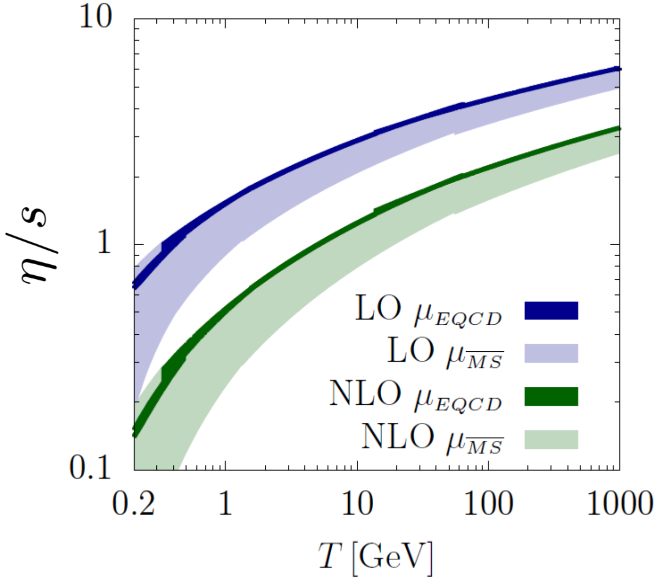
- Arnold Moore Yaffe : **systematic solution thanks to kinetic theory & variational metho**

Peter Arnold et al JHEP11(2000)001, Peter Arnold et al JHEP05(2003)051, Jacopo Ghiglieri, Guy D. Moore and Derek Teaney, "QCD shear viscosity at (almost) NLO", JHEP03(2018)179



- 2018: Large NLO corrections lowering η/s close to the 1/4π lower bound in the strong coupling limit

P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. 94 (2005) 111601

The viscosity quest

- Exact calculations for the transport coefficients are performed using the Kubo fluctuation dissipation theorem

$$\eta = \lim_{\omega\to 0} \frac{\rho_{\text{shear}}(\omega)}{\omega} \quad \text{with} \quad \rho_{\text{shear}}(\omega) = \frac{1}{10}\int d^3x \int_{-\infty}^{+\infty} dt e^{i\omega t}\langle[\pi^{lm}(x,t),\pi^{lm}(0,0)]\rangle_T$$

Spectral density at k=0.

Autocorrelation of energy-momentum tensor

where

$$\langle\mathcal{O}\rangle_T = \frac{1}{Z}\int \mathcal{D}[U]\mathcal{O}\det[M]e^{-S_G}$$

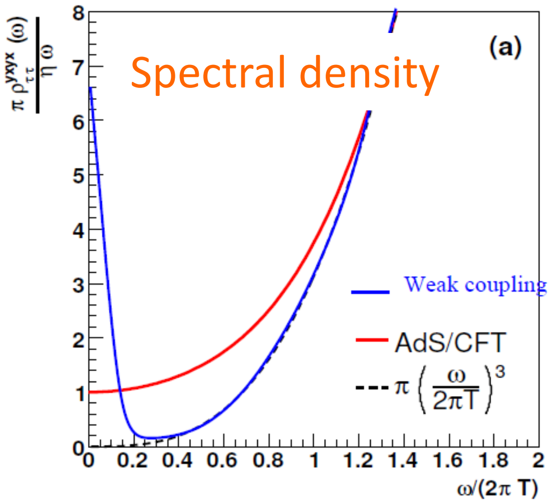
Statistical average

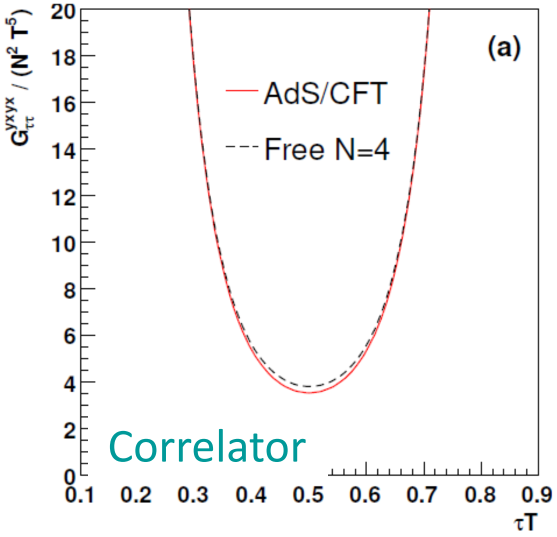
- In lQCD, spectra densities can only be extracted after Wick rotation -> **imaginary time (τ) correlator**

$$\mathbf{G}(\tau) = \int \frac{d\omega}{2\phi}\frac{\rho_{\text{shear}}(\omega)}{\omega}K(\omega,\tau) \quad \text{with} \quad K(\omega,\tau) = \frac{\omega\ \cosh(\omega(\tau-1/2T))}{\sinh(\omega/2T)}$$

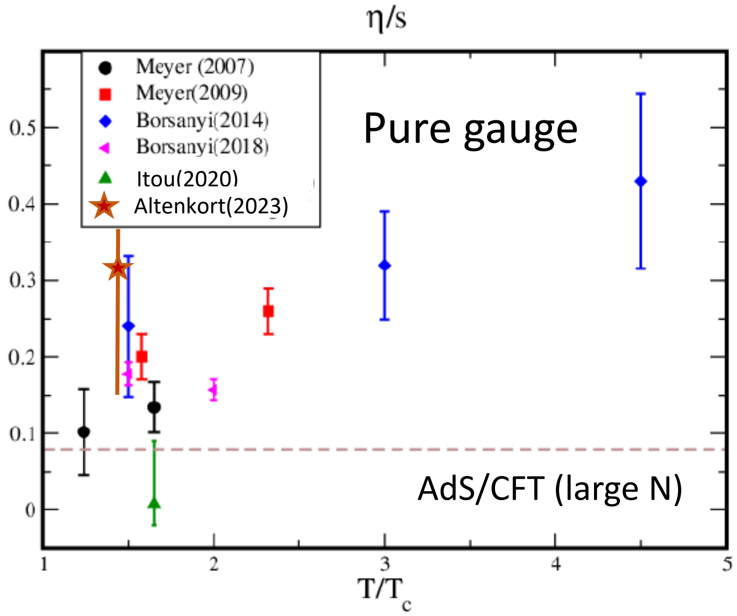
Karsch & Wyld, PRD, vol 35 (1987), 2518

- Kernel K => very little sensitivity of $G(\tau)$ to low ω => required all the expertise from the lQCD community since 1987





G. Moore, arxiv: 2010.15704



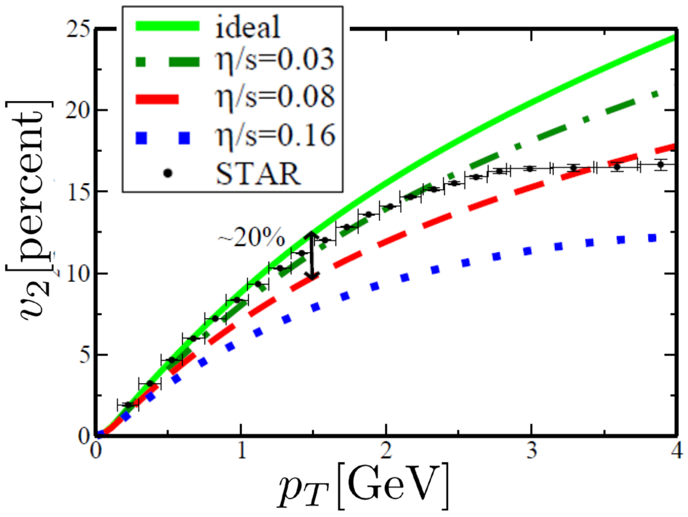
L. Altenkort et al, Phys. Rev. D 108, 014503 (2023)

- Great achievement but precision still need to be improved !

Azimuthal flows… one step beyond

- Ideally, one obtains the viscosity from the theory and better constrains the other features of the evolution
- **Finite and increasing shear viscosity => reduction of the elliptic flow** (momentum transfer btwn the various fluid layers reduce the anisotropic expansion from the initial ε_2).

Possibility to *extract* from experiment + fluid dynamics



P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99 (2007) 172301

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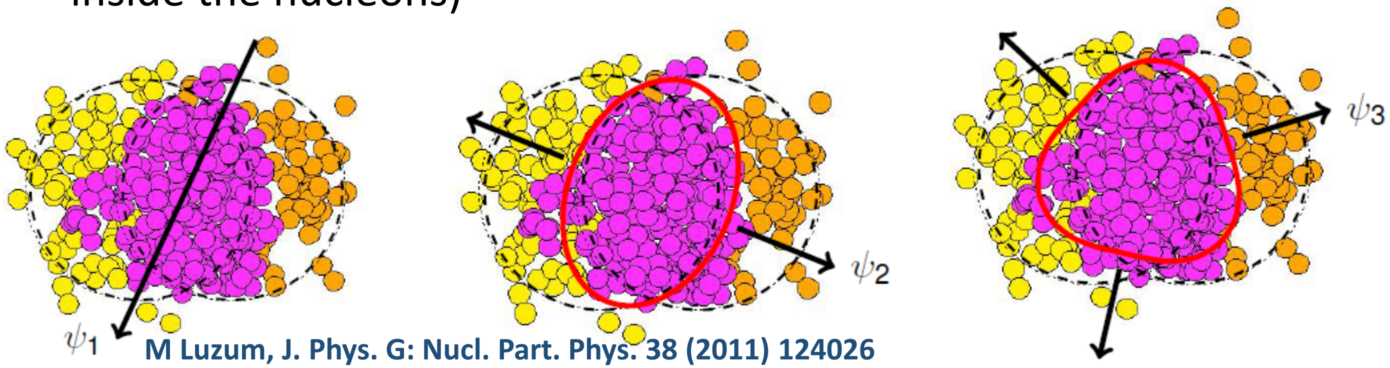
  Possibility to *extract* from experiment + fluid dynamics
- **Fluctuations** in the initial distribution of nucleon (and partons inside the nucleons)



M Luzum, J. Phys. G: Nucl. Part. Phys. 38 (2011) 124026

- => decomposition of the initial (transverse) profile in several eccentricities : ε_2, ε_3, ε_4 … => **response from the QGP to build final v_2, v_3, v_4,…** Good correlation for the first 2 harmonics

$$\frac{dN}{d\varphi} = \frac{N}{2\pi} \times \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos(n(\varphi - \Psi_n))\right)$$

- => event by event simulations

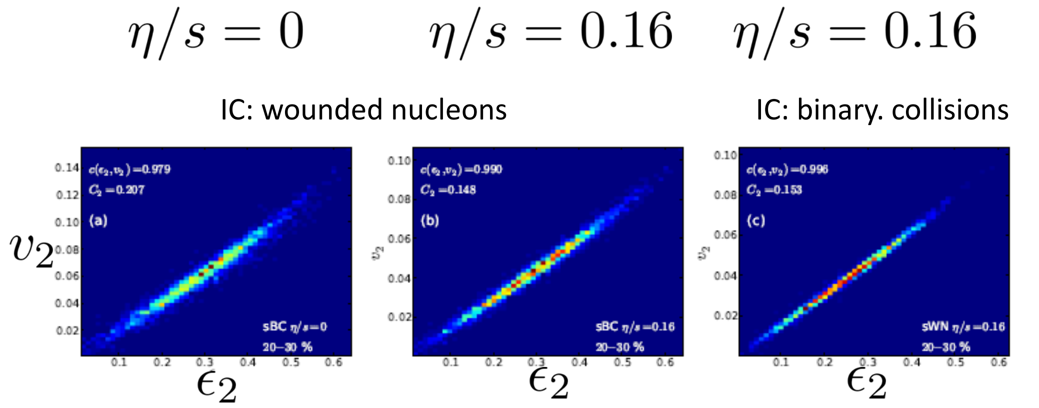


FIG. 1. ϵ_2 and v_2 of pions in the 20 − 30 % centrality class using different initializations and viscosities. a) sBC and $\eta/s = 0$, b) sBC and $\eta/s = 0.16$ and c) sWN and $\eta/s = 0.16$.

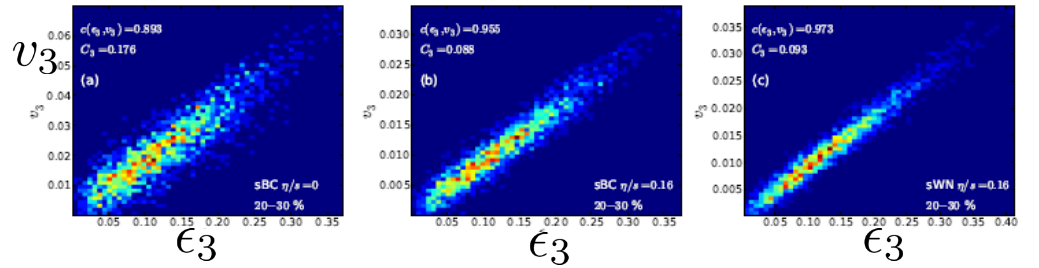


FIG. 2. ϵ_3 and v_3 of pions in the 20 − 30 % centrality class using different initializations and viscosities. a) sBC and $\eta/s = 0$, b) sBC and $\eta/s = 0.16$ and c) sWN and $\eta/s = 0.16$.

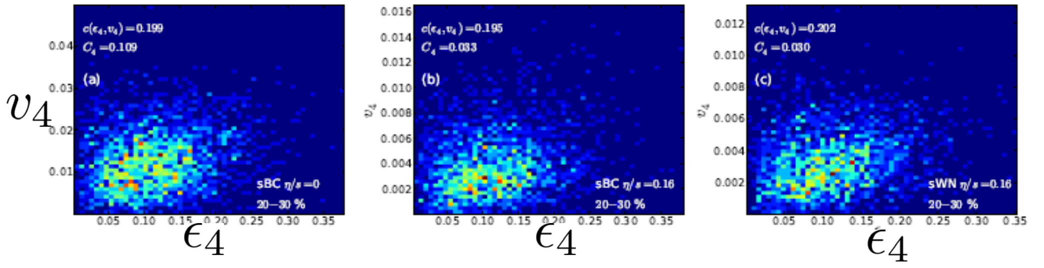
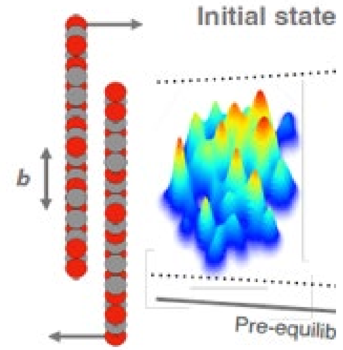
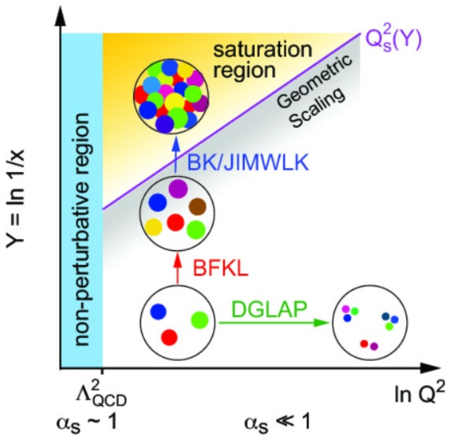


FIG. 3. ϵ_4 and v_4 of pions in the 20 − 30 % centrality class using different initializations and viscosities. a) sBC and $\eta/s = 0$, b) sBC and $\eta/s = 0.16$ and c) sWN and $\eta/s = 0.16$.

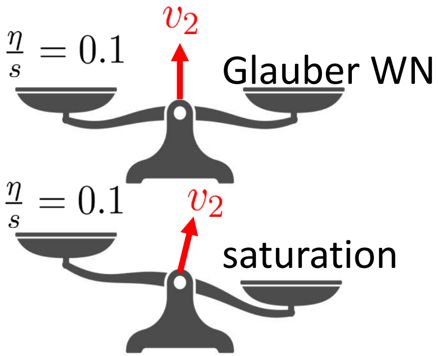
H. Niemi et al, Phys. Rev. C 87 (2013) 054901, arXiv:1212.1008.

Azimuthal flows… and the initial state

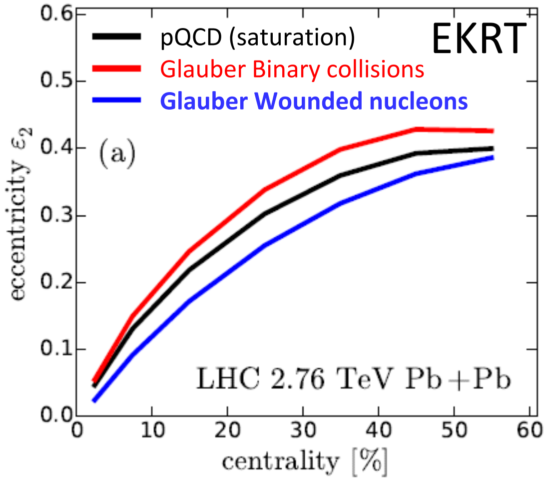


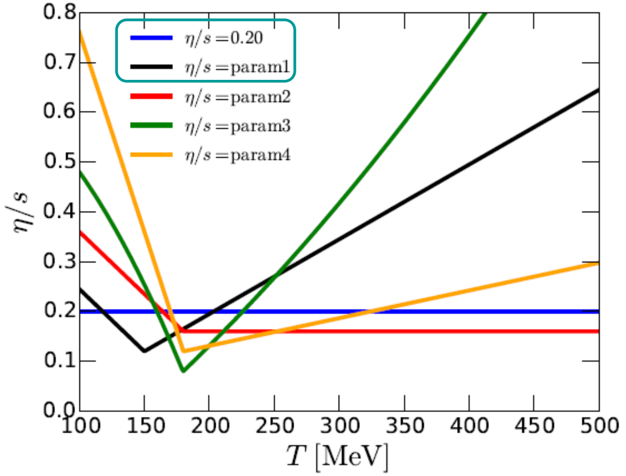


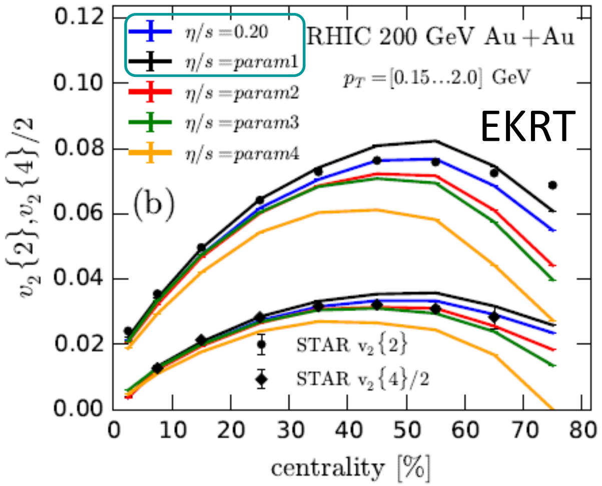
- **Initial state** of the URHIC results from the interaction of **low x gluons** of both nuclei…
- … which are thought to be **saturated** for transverse momentum $\lesssim Q_s$ (saturation scale)
  - Less gluons than in the usual BFKL evolution
  - Harder transverse momentum distribution
  - Depends on: position in transverse plane, impact parameter *b*.
  - => larger eccentricity as compared to usual Glauber model



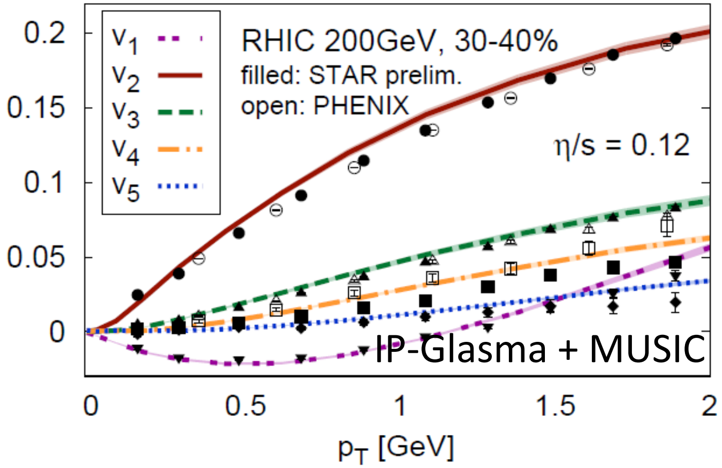
- Compensation between saturation and (shear) viscosity
- Competing models for initial condition of the hydro evolution (KLN, IP-Glasma,EKRT, Trento,…), some including the early evolution of gluonic fields (IP-Glasma)







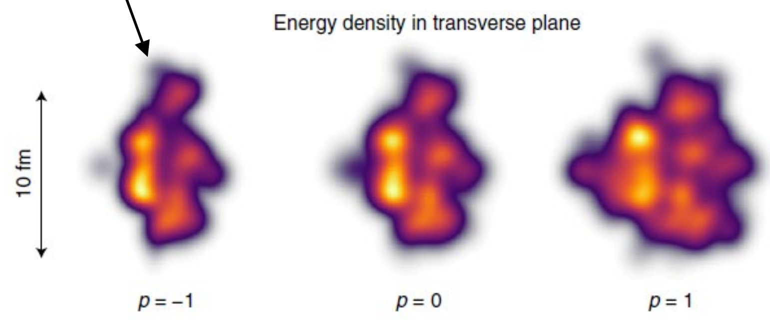
Niemi et al., Phys. Rev. C 93, 024907 (2016)



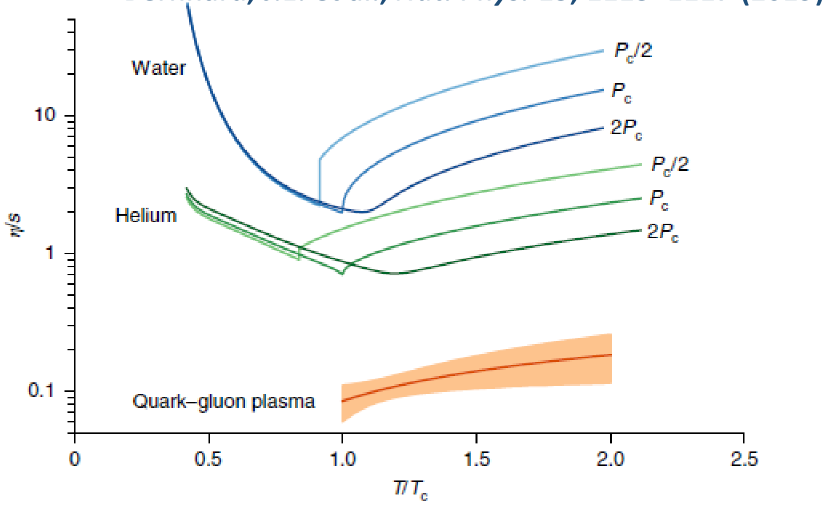
C. Gale et al., Phys. Rev. Lett. 110 (2013), 012302

Towards a global extraction: Bayesian analysis

- **Global extraction of several key components of the standard URHIC model** :
  - Energy deposition in the initial condition (saturation according to Trento)
  - Thermalization time
  - Shear and bulk viscosities of T
  - Kinetic freeze out temperature
  - Parameterless hadronic phase

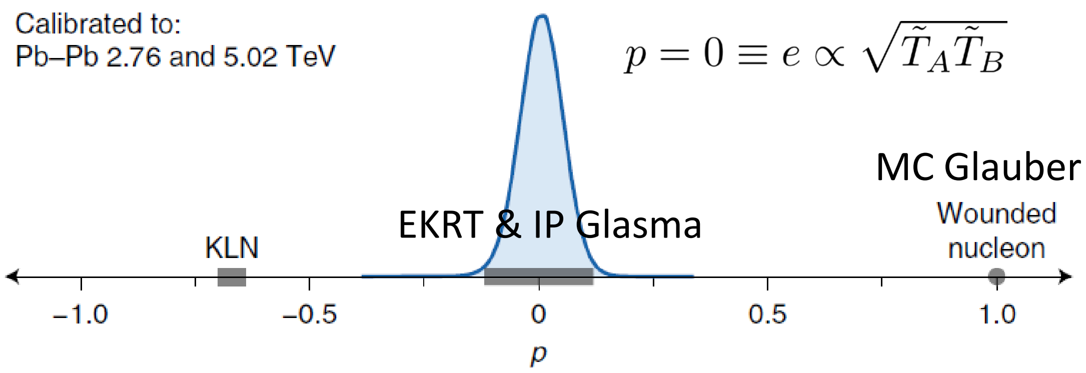


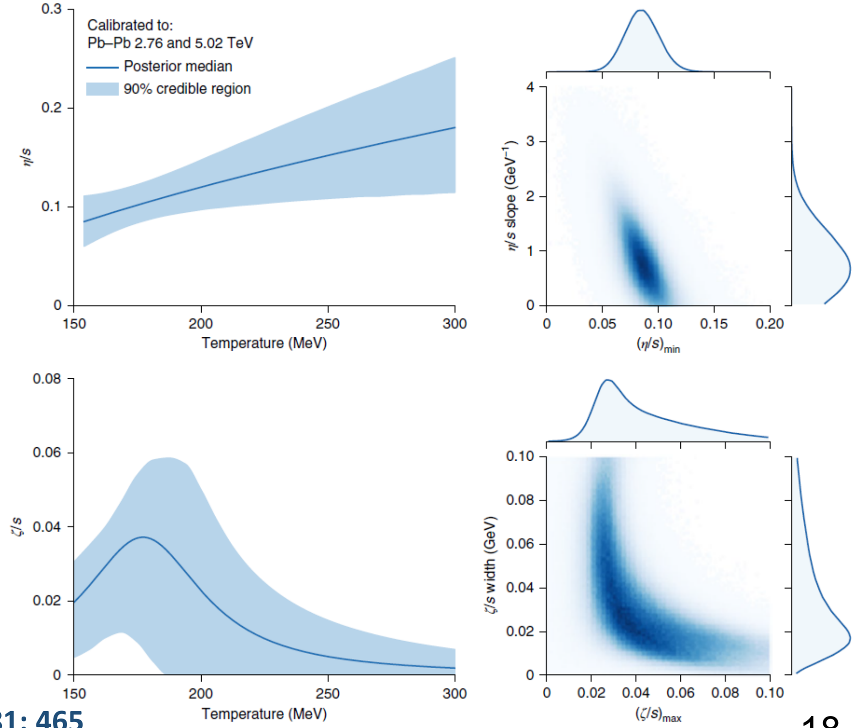
Bernhard, J.E. et al., *Nat. Phys.* 15, 1113–1117 (2019)



- State of the art treatment of the combined errors

$$p = 0 \equiv e \propto \sqrt{\tilde{T}_A \tilde{T}_B}$$





- Due to the wealth of RHIC and LHC data, Bayesian analysis is able to see « through the horizon » and even favor some scenario for initial energy deposition.
- Good illustration of the new methodology : start from a realistic effective theory and rely on state of the art methods in data analysis + wealth of data.

See as well : D. Everett et al. (JETSCAPE Collaboration) Phys. Rev. C 103, 054904 (2021), V Gonzales et al., Eur. Phys. J. C (2021) 81: 465

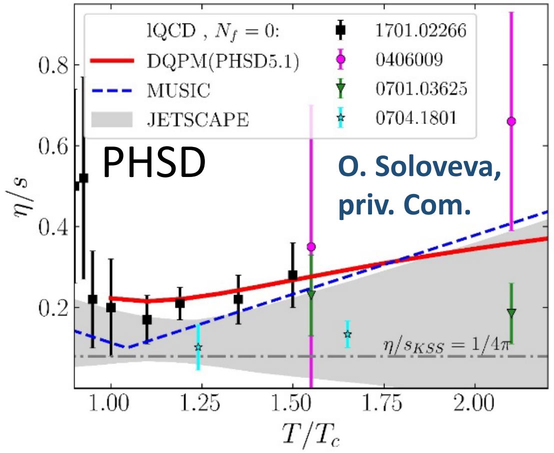
Quasi particle-like kinetic approaches

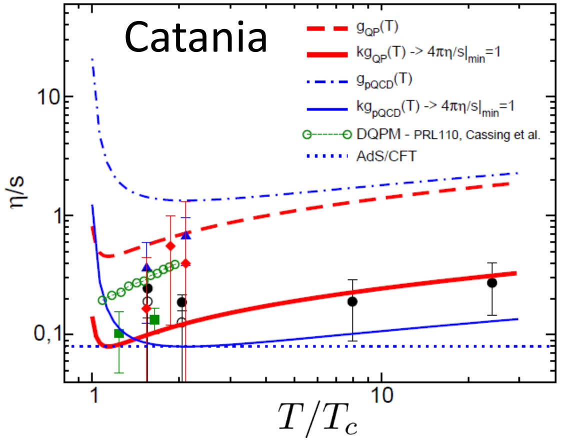
- QDPM: Quarks and gluons considered as QP, with masses and $\alpha_s(T)$ tuned on lQCD EOS

BSM approaches: PHSD, Catania, BAMPS,…

Typical parametrization: $g^2_{QP}(T) = 48\pi^2/(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2$

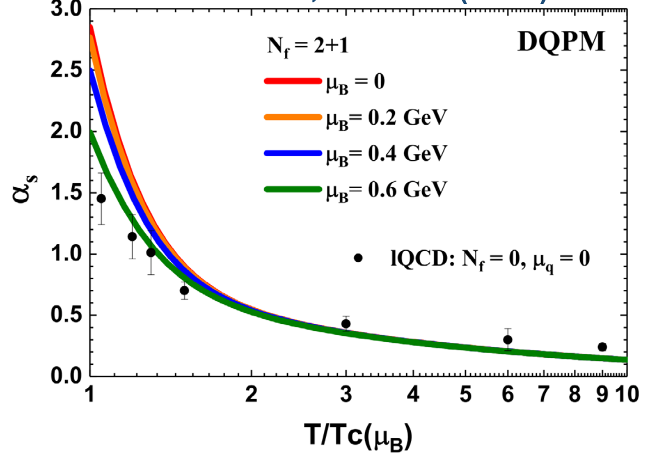
- Transport coefficients evaluated with collision-time method



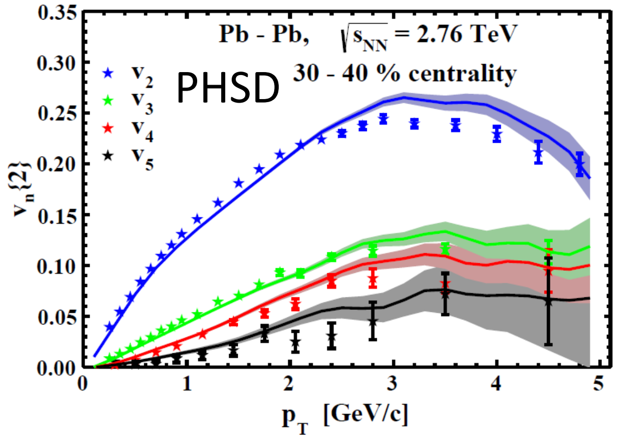


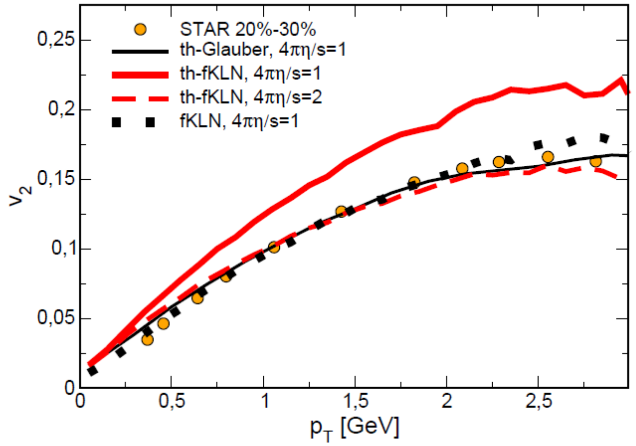
Armando Puglisi, *Phys.Lett.B* 751 (2015) 326-330

P. Moreau et al., PRC100 (2019) 014911



- Evolution performed according to Boltzmann or Kadanoff-Baym eqs





- Equally good agreement found with PHSD and CATANIA for the azimuthal flows
- **Naturally extends to smaller or more dilute systems where fluid dynamics is not justified (Knudsen number not << 1)**

V P Konchakovski et al 2015 J. Phys. G: Nucl. Part. Phys. 42 055106

M. Ruggieri et al., Phys. Rev. C 89, 054914

Science drivers of the field

Nice review talk by Giuliano Giacalone at this conference for latest updates on the « standard model » and its applications **to small systems**

1. What are the thermodynamic and global properties of the high energy QCD matter
2. What are the hydrodynamic and transport properties of the QGP ?
3. Can some of these properties be described by suitable effective theories with appropriate degrees of freedom ? (depends on the scale at which QGP is probed)
4. How does the QGP affect the formation of hadrons ? (may help to understand confinement)
5. How does the QGP affect the propagation of energetic partons ?
6. How does deconfinement in the QGP affect the QCD force between 2 partons ?
7. what is the nature of the initial state in URHIC ? (initial state plays a key role in the QGP response)
8. What is the nature of hadron–hadron interactions in the final state ? (unique opportunity to test QCD)
9. Can the QGP lead to discovery of novel QCD effects? Emergent phenomena ?

… and should also improve our knowledge of the early universe:

A Short Survey of Matter-Antimatter Evolution in the Primordial Universe

by Johann Rafelski *, Jeremiah Birrell, Andrew Steinmetz and Cheng Tao Yang

Department of Physics, The University of Arizona, Tucson, AZ 85721, USA

* Author to whom correspondence should be addressed.

Universe **2023**, *9*(7), 309; https://doi.org/10.3390/universe9070309

The Statistical Hadronisation Model

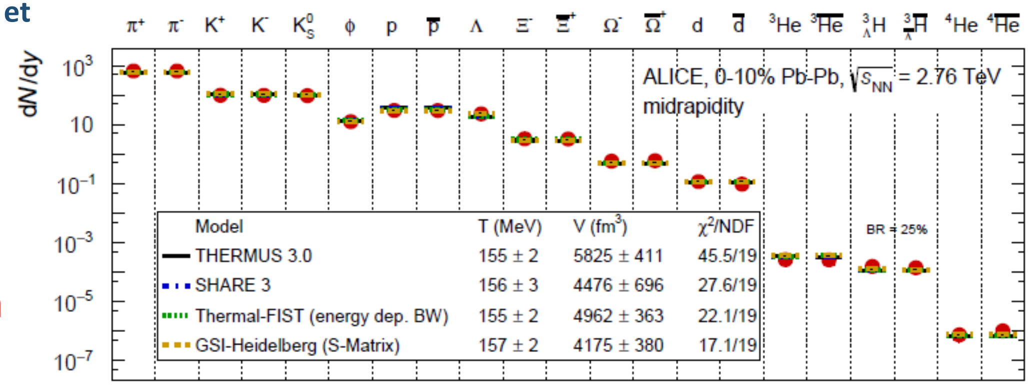
J. Cleymans et al., Phys. Rev. C 74 (2006) 034903, A. Andronic et al. Phys. Lett. B 792 (2019) 304–309, M. Petran et al. Phys. Rev. C 88 (2013) 034907, V. Vovchenko and H. Stoecker Comput. Phys. Commun. 244 (2019) 295–310,

- ➢ Quarks & gluons « reconfined » into hadrons at the end of the QGP

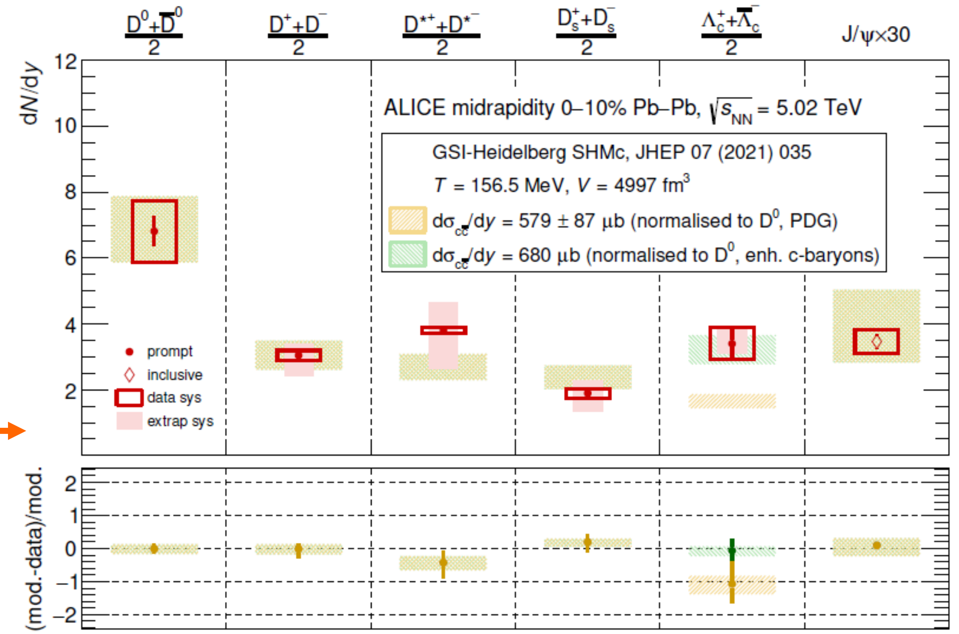
- ➢ Hadronization schemes at low p_T:
- ○ **Surroundings quarks abundantly available =>**
- ○ Mechanisms different from the standard fragmentation function known in elementary collisions at high p_T (factorisation theorem)

- ➢ Statistical Hadronisation Model :
- ○ Assumes all hadronic species are produced in each « cluster » according to their canonical / grand canonical weight.
- ○ **Very few parameters : T, μ_B and fugacities,**
- ○ Extremely good agreement with the data for the absolute yields
- ○ Indicates that all light hadrons are produced at ≈ the same T, irrespective of their mass … ⇔ light quarks have small relaxation time
- ○ But also in c-quark sector ! Indications that Open HF and close charmed are born « in equilibrium »
- ○ Recently, **some hint of tension for the ψ' yield** (talk Himanshu Sharma): challenges the SHM and may be the sign of dynamical production.

SHM doesn't rely on any microscopic dof and is agnostic of the detailed dynamical process of hadronisation **=> difficult extract any information on the hadronization mechanism**



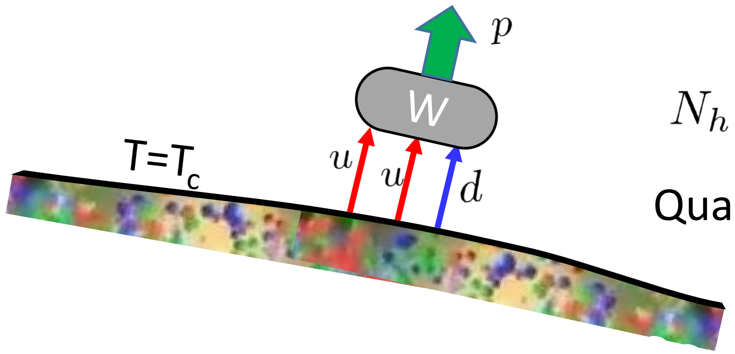
Measured multiplicity per unit of rapidity of different light hadron species and light nuclei (ALICE) compared to SHM. CERN-EP-2022-227



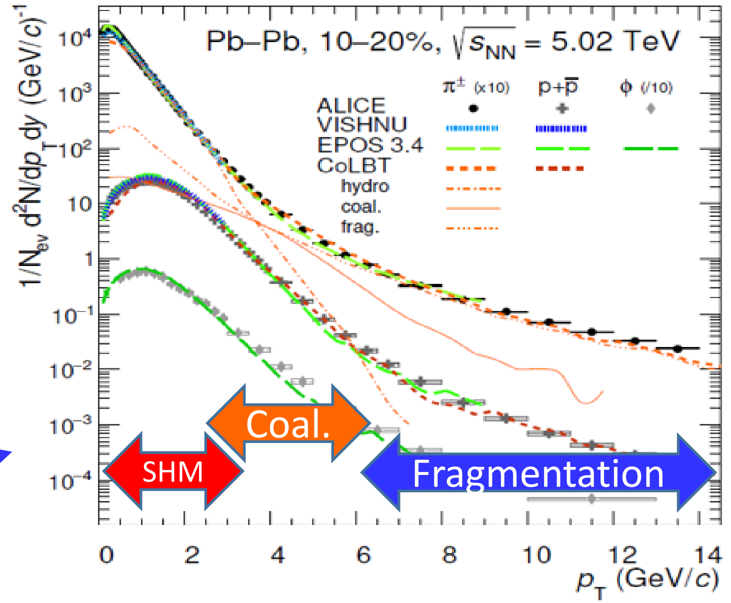
pT-integrated yields per unit of rapidity measured at midrapidity for different charm-hadron species in central Pb–Pb collisions at compared to SHM predictions. CERN-EP-2022-227

The coalescence mechanism

- Microscopic mechanism suggested to dominate at intermediate p_T ($\lesssim 5\,\mathrm{GeV}/c$): **instantaneous coalescence** (also compatible with the SHM at low p_T)

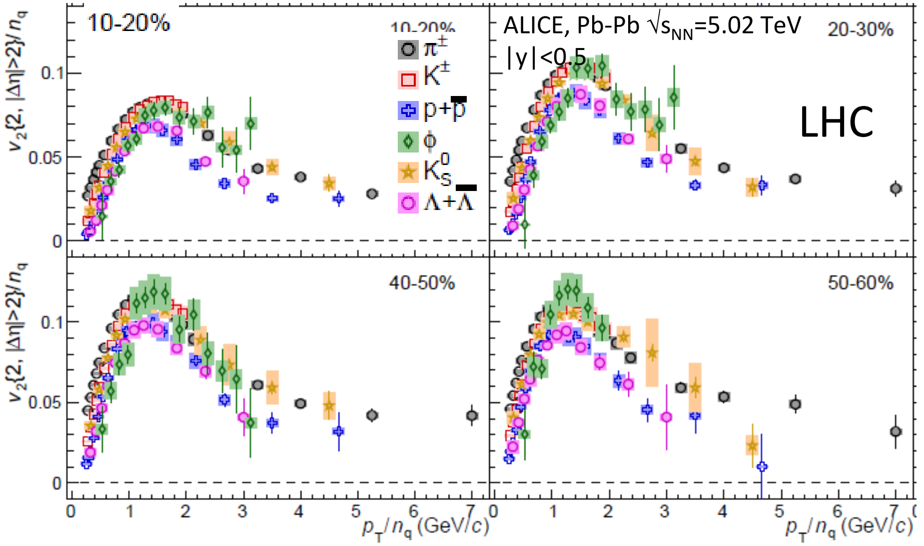


$$N_h = \underbrace{f(p_1, x_1; p_2, x_2; p_3, x_3)}_{\text{Quarks (fluid + minijets)}} \otimes \underbrace{W_h}_{\text{Wigner distribution <-> hadron wave function}}$$



- Leads to extra yield at intermediate p_T ,combining partons from the bulk hydro and partons from the (mini) jets
- **Best signature of the coalescence mechanism: scaling of the v_n flows with the quark number** at intermediate p_T, seen both at RHIC and at LHC ⇔ each quarks brings an equal contribution to the hadron azimutal flow.
- well reproduced by models like EPOS, Catania, ColBT including coalescence.

- Goog news: Confirms that **quarks are in a deconfined phase prior to T_c.**
- This scaling was used recently to address the quark content of f_0
- A bit deceiving (to my own taste): The mechanism simply rely on the hadronic wave functions; no spectacular footprint of the reconfinement.



The p_T/n_q dependence of v_2/n_q for several hadrons and for various centrality classes; **ALICE Collab, JHEP09 (2018)006**

Hadronization of heavy quarks

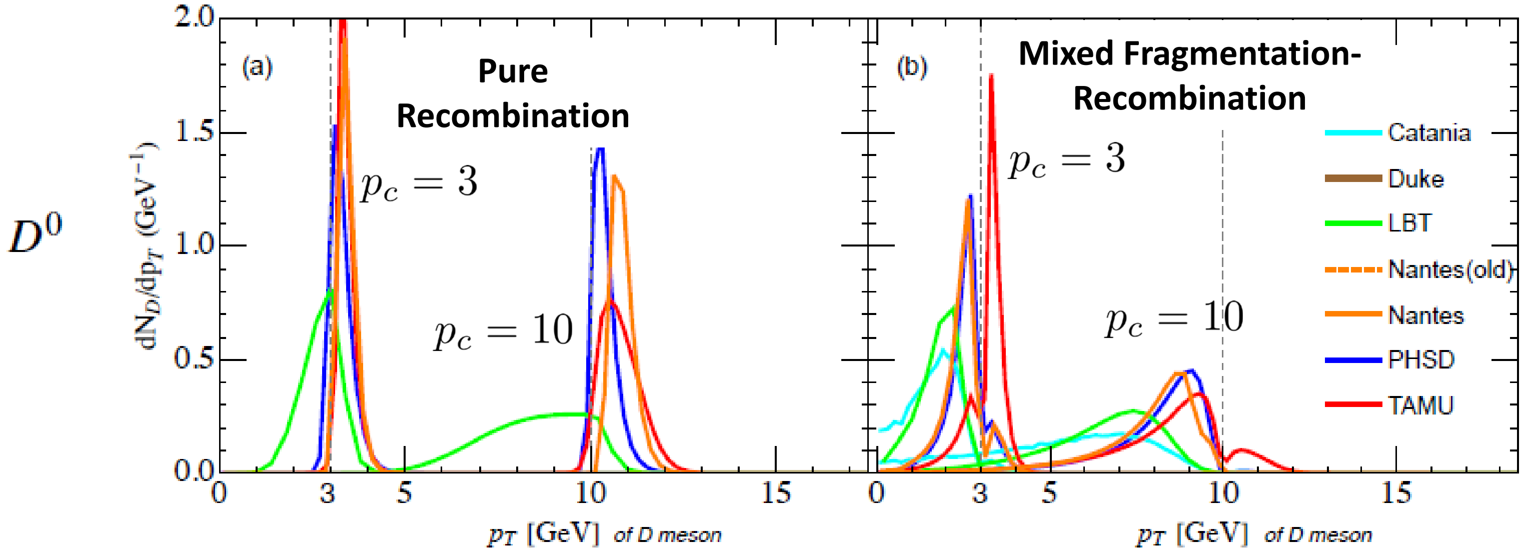
- The hadronization of heavy quarks in AA collisions has received a lot of interest recently…

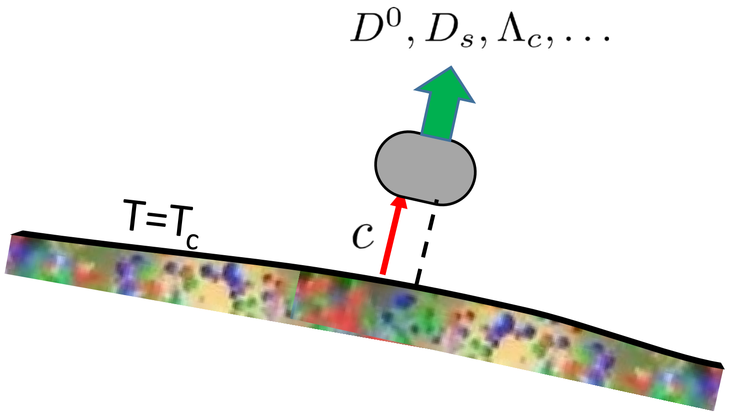
- … but also in pp collisions, as the Λ^+_c/D yield ratio is larger then in e^+ - e^- collisions (see ALICE talk) which is an argument in favor of the coalescence mechanism

- **Recent effort of theorists to compare their hadronization schemes at the end of the QGP**

dN_D/dpT of the direct D^0 meson produced by a c-quark with p_T = 3 GeV *and* 10 GeV

Jiaxing Zhao, Hard Probes 2023





- Diversity => things to learn !
- Will be a major subject of investigation for ALICE3

Science drivers of the field

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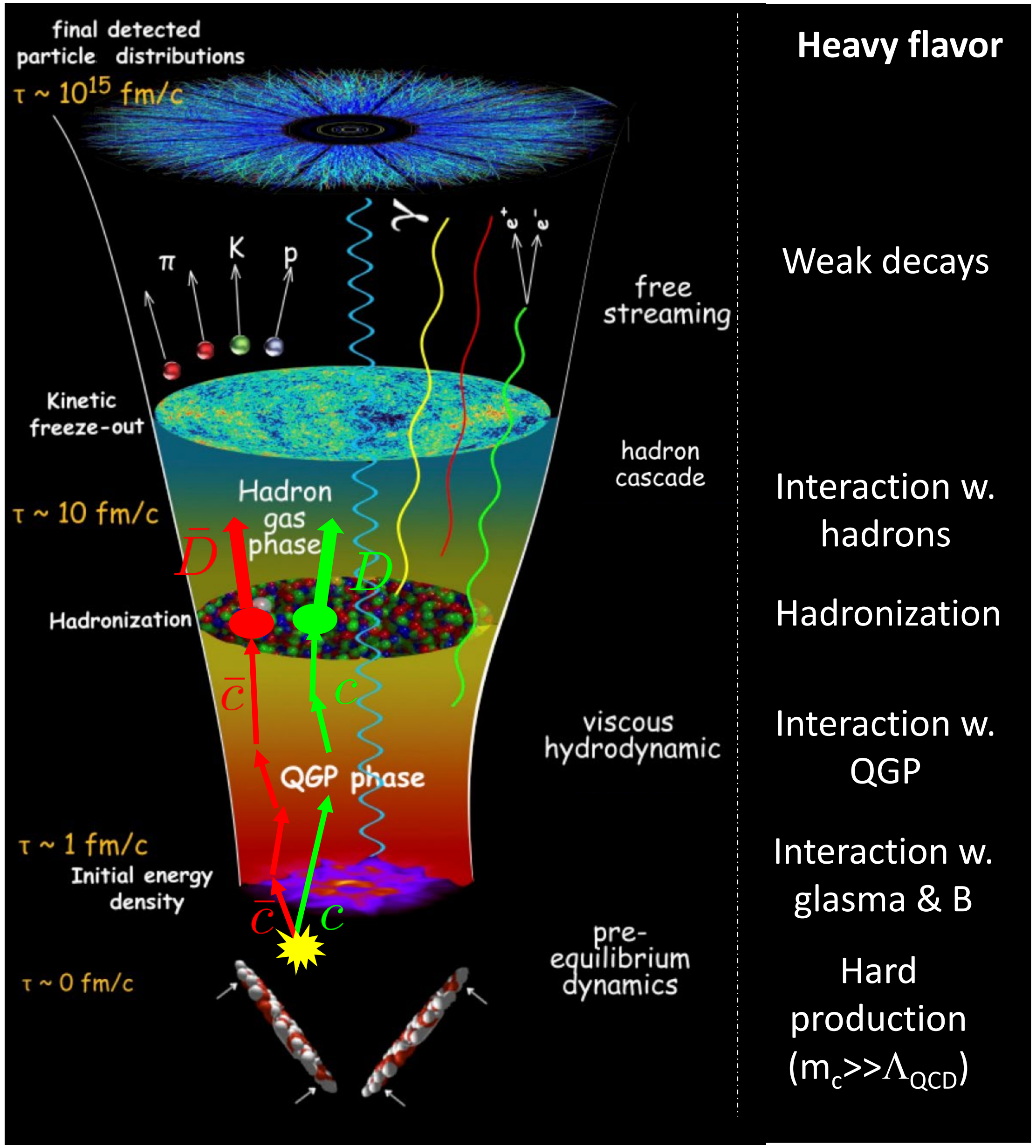
Universe **2023**, *9*(7), 309; https://doi.org/10.3390/universe9070309

Hard probes: Heavy quarks



- Produced early ($t \approx 1/m_c$)
  - => No further c-cbar generation in ensuing QGP
  - Initial production well controlled (advantage of $m_Q >> \Lambda_{QCD}$)
  - But early phase might not be so innocent (magnetic field, CGC-glasma,…)

- **Experience the full deconfined phase + hadronic phase**
  - probes the QGP on harder scales than the other hadronic observables *while not fully thermalized* ($t_{relax} \propto m_Q/T^2$)
  - accumulates several effects => need to compare different systems to better differentiate them

- Produced over a wide range of rapidities and p_T
  - increased richness in scrutinizing the interaction of HQ with medium…
  - but also sets more challenges (interactions for $p_T << m_Q$, $p_T \approx m_Q$, $p_T >> m_Q$, appropriate transport theory ?).

- **Turning into precision physics thanks to abundance of LHC results !!!**

Modeling heavy quark transport in QGP

Two methods
(low and intermediate p_T)

Langevin Dynamics

- Key ingredients : transport coefficients

$$-\frac{d}{dt}\langle\vec{p}\rangle = \vec{A}(\vec{p},T) = \underbrace{\eta_D(\vec{p},T)}_{\text{Relaxation rate}} \times \vec{p}$$

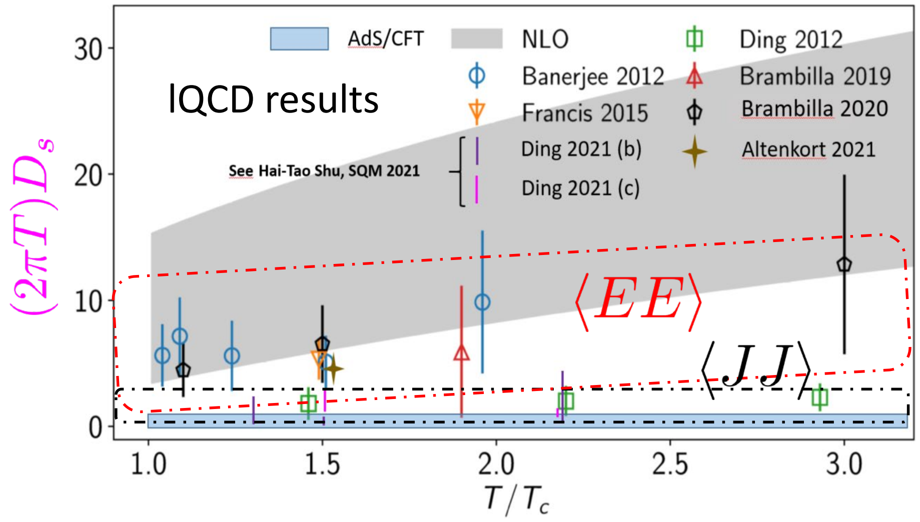
$$\frac{d}{dt}\langle\vec{p}_i\vec{p}_j\rangle = \underbrace{\kappa_{T/L}(\vec{p},T)}_{\text{Transverse/long. diffusion coefficient (p space)}}\delta_{i,j}$$

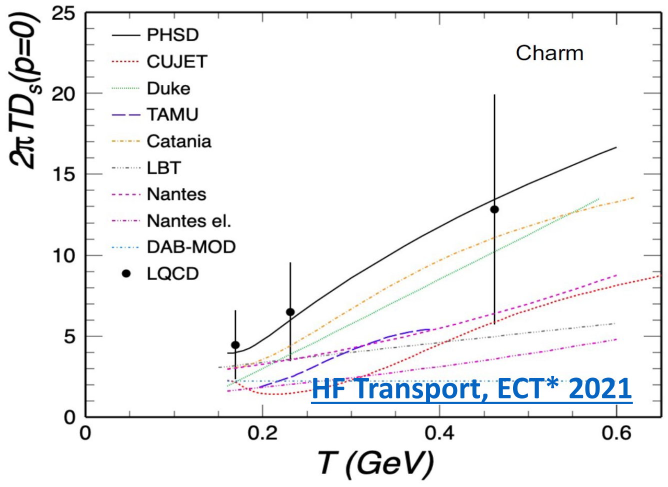
- Would be the simplest method if η and κ were known

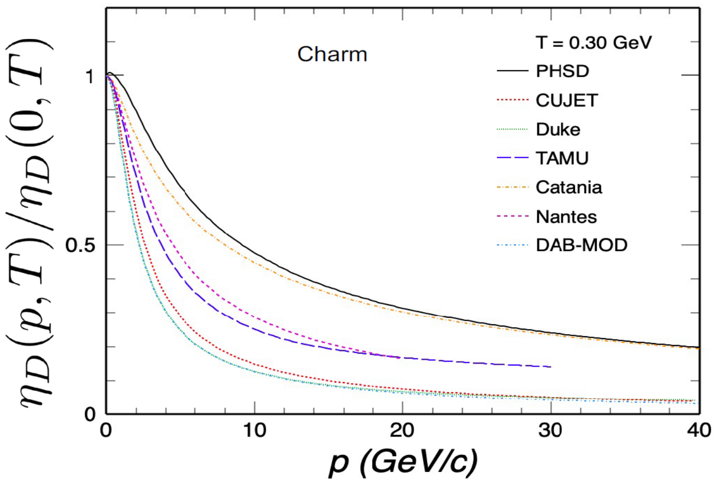
Boltzmann Equation

- Key ingredients : $d\sigma^{\mathrm{el}}_{Q+x}, d\sigma^{\mathrm{inel}}_{Q+x}$
- Requires to set up a model for the (off-shell) propagation of light partons
- … can of course produce the transport coefficients

Gauge for the coupling strength: $(2\pi T)D_s = \frac{4\pi T^3}{\kappa(p=0)} = \frac{2\pi T^2}{E_Q\eta_D(p=0)} \Rightarrow \tau_{\mathrm{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$





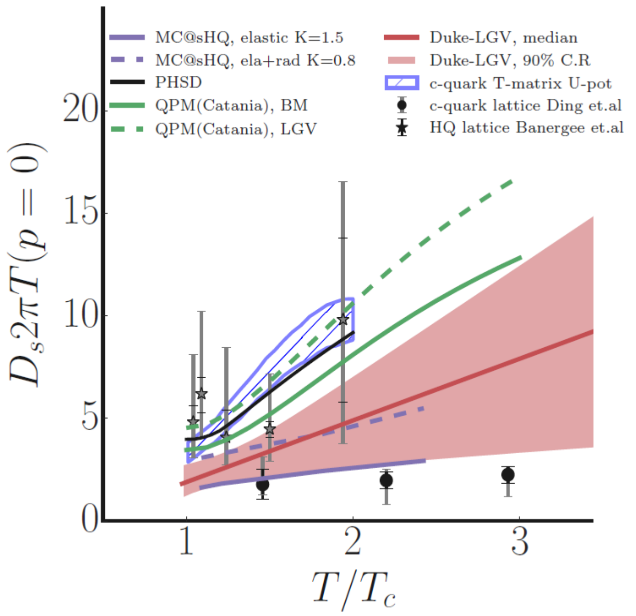


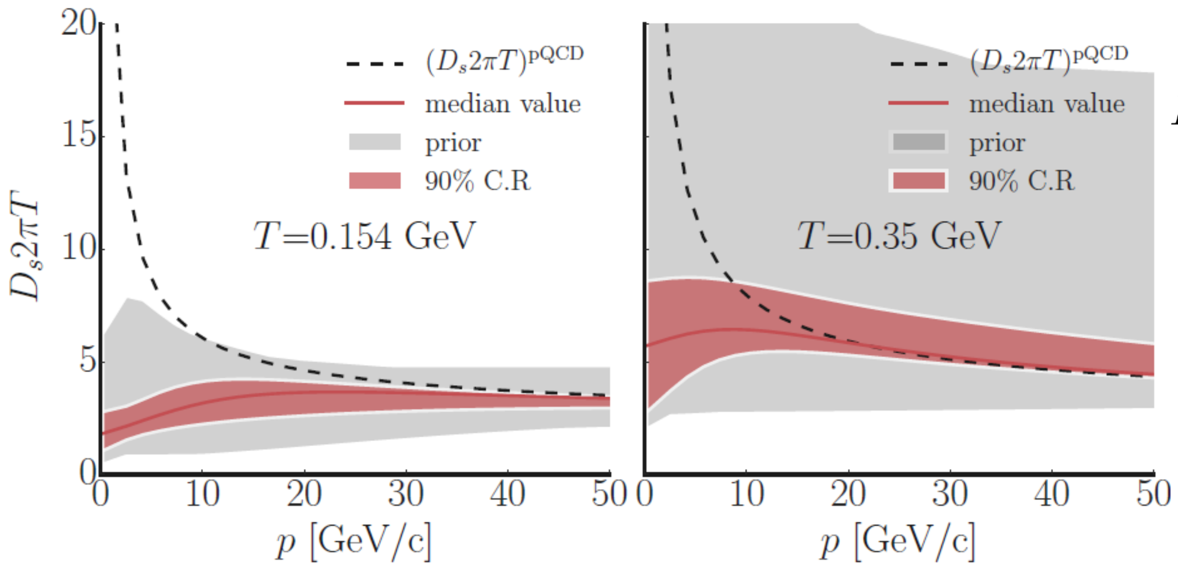
R. Rapp et al, Nucl. Phys. A, Vol 979 (2018), 21-86

- Large diversity in the models and not enough constrains at finite p.

Some directions for heavy quarks in QGP

- Efforts should be maintained from lQCD community to evaluate quantities as close possible to the **Fokker-Planck coefficients at finite momentum** (easier contact with phenomenology)
- **Calibration of the transport models** to the QGP EOS is a good starting point but **other quantities more directly connected to HQ physics should be considered as well** (space correlators, imaginary potential,…)
- Precision data and new HF observables (like correlations) measured in the last years of RHIC and at LHC run3 & 4 will put drastic constrains on models when combined with modern data analysis (Bayesian, ML,…)





Y. Xu et al. , Phys. Rev. C 97, 014907 (2018)

$$D_s(T,p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{lin}} + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{pQCD}}$$

$$(D_s 2\pi T)^{\mathrm{pQCD}} = 4\pi/(\kappa_T/T^3)$$

$$(D_s 2\pi T)^{\mathrm{lin}} = \alpha\left(1+\beta\left(\frac{T}{T_c}-1\right)\right)$$

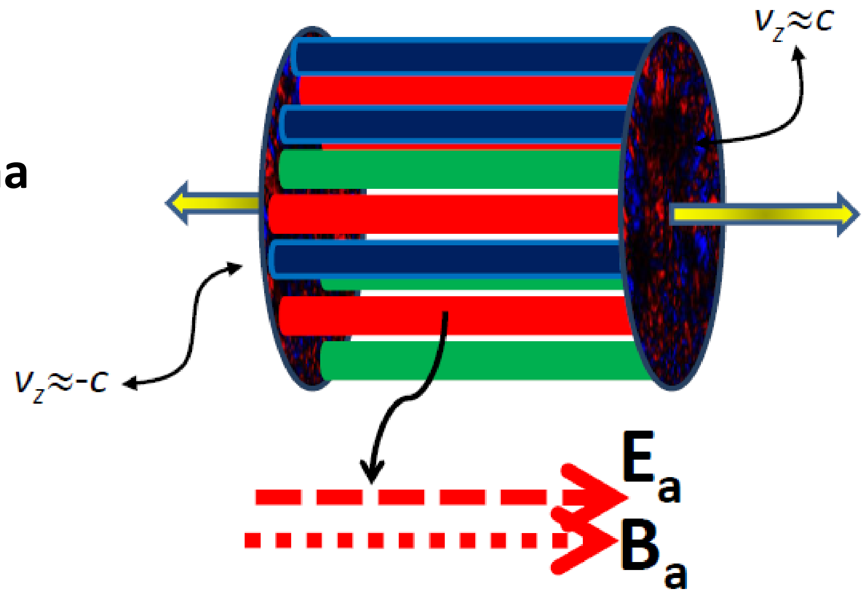
Non-pert. physics

- **All together, a comprehensive understanding of the microscopic properties will only stem from collaborative actions btwn lQCD, models and precise measurements.**

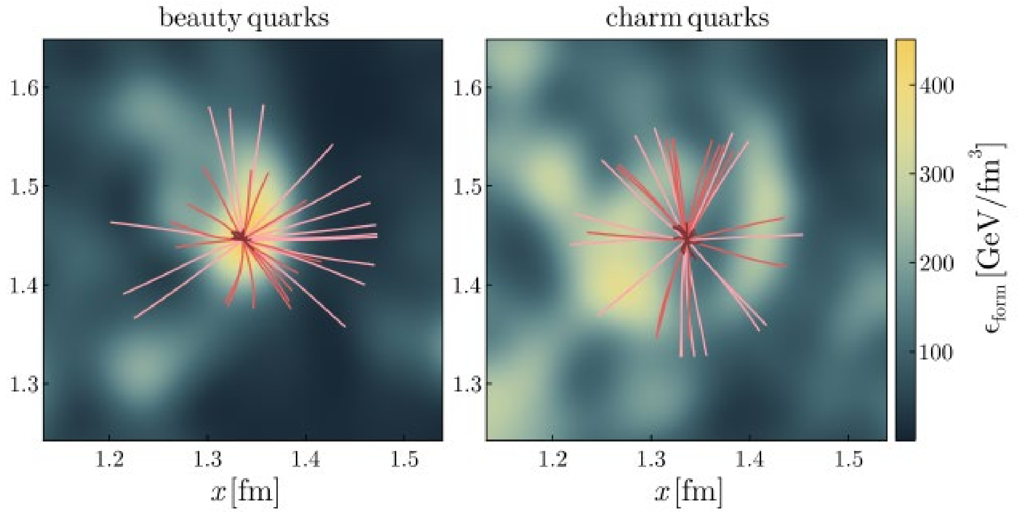
Some directions for heavy quarks in QGP

➢ Diffusion of heavy quarks in the early stages of high energy nuclear collisions

Early stage : **Glasma**



D. Avramescu et al, Phys. Rev. D 107 (2023), 114021



trajectories of heavy quarks propagating in a single Glasma flux tube

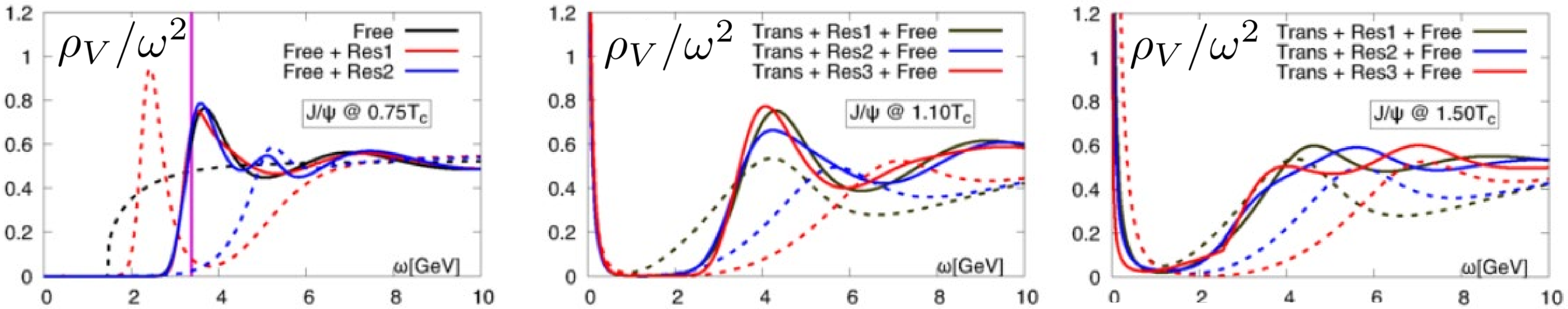
○ Diffusion of HQs in the early stage of high energy collisions is affected by the strong fields: coherence memory effects are substantial

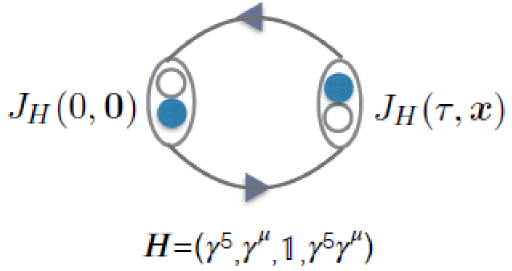
Quarkonia at low transverse momentum

- One of the historical candle of QGP formation : sequential suppression of bound $Q\bar{Q}$ due to Debye screening
- Theoretical tool : spectral quarkonium functions in lattice (NR)QCD : ill-defined inversion problem

$$\int \frac{d\omega}{2\pi} K(\omega,\tau,T)\rho_H(\omega,\vec{p},T) = G_H(\tau,\vec{p}) \quad \text{with} \quad G_H(\tau,\vec{p}) = \sum_{x,y,z} \exp(-i\vec{p}\cdot\vec{x})\langle J_H(0,\vec{0})J_H^\dagger(\tau,\vec{x})\rangle$$

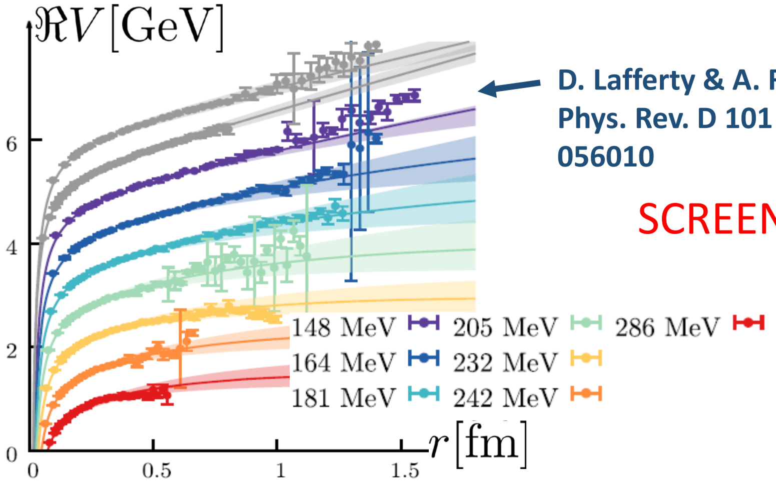
- o Consensus: spectral functions are loosing their structure with increasing T





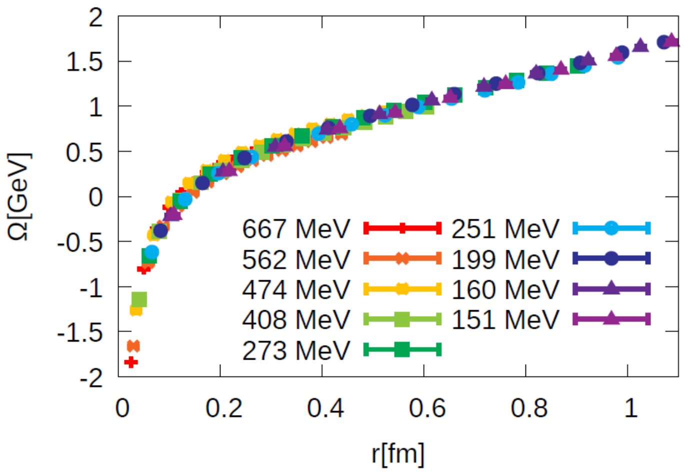
H.-T. Ding et al., Nucl. Phys. A 982 (2019) 715–718

- Other theoretical tool (pNRQCD): **complex** potential: $V(r) = \lim_{t\to\infty} \frac{i\partial_t W_\square(r,t)}{W_\square(r,t)}$ real-time evolution of the QCD Wilson loop
- o **No consensus on the real potential at finite T :**



D. Lafferty & A. Rothkopf Phys. Rev. D 101 (2020), 056010

SCREENING



Hot QCD collaboration: Phys Rev. D 105, 054513 (2022)

NO SCREENING

=> interpretation: The melting of the spectral function originates from the imaginary part of V (inelastic interactions with QGP)

Bottomonia production in AA collisions

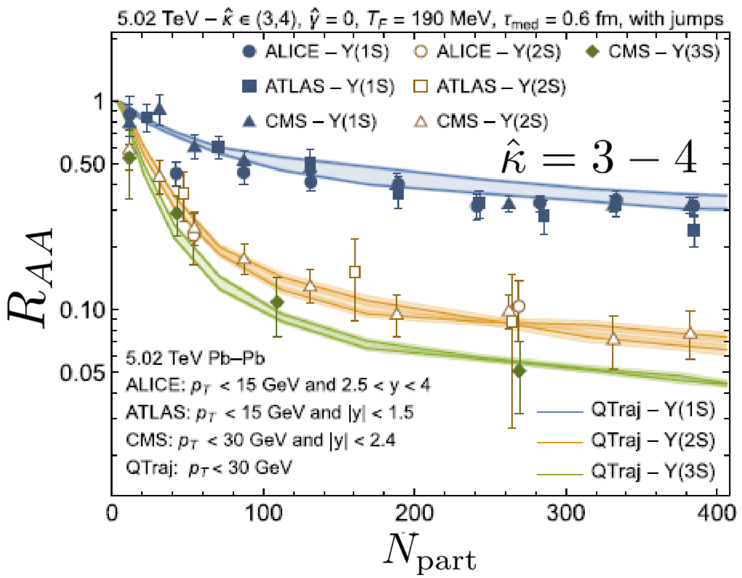
- **Emerging precision tool : Open Quantum System + Effective (p)NRQCD theory** (=> limited set of operators)
- Allows to deal with the quantum evolution of the $b\bar{b}$ pair in the presence of a heat bath => **preserves essential quantum properties**
- The most used **Quantum Master Equation** in our field : **Linblad Equation** :

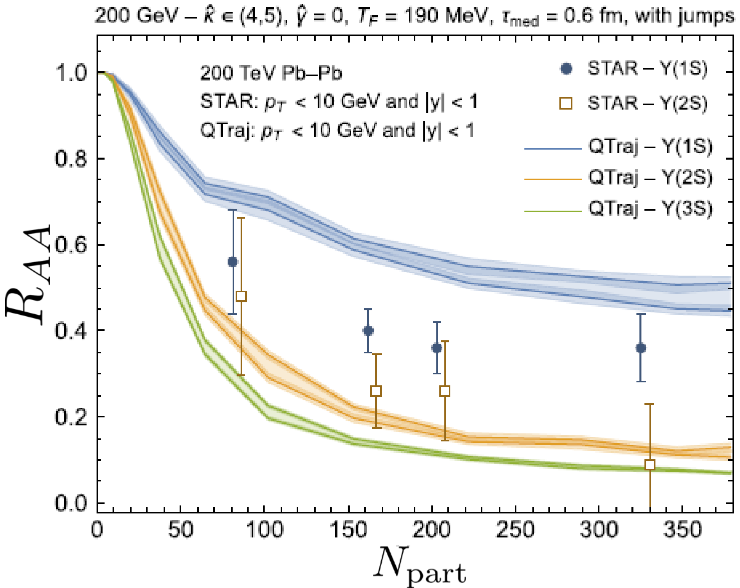
$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{Q\bar{Q}}(t) = -i\left[H_{Q\bar{Q}}, \rho_{Q\bar{Q}}(t)\right] + \underbrace{\sum_i \gamma_i \left[L_i \rho_{Q\bar{Q}}(t) L_i^\dagger - \frac{1}{2}\left\{L_i L_i^\dagger, \rho_{Q\bar{Q}}(t)\right\}\right]}_{\text{Non Unitary Evolution}}$$

$H_{Q\bar{Q}}$: $\{Q, \bar{Q}\}$ kinetics + Vacuum potential V + Lamb shift / screening

L_i : Collapse operators, depend on the properties of the medium

- Recent « QTRAJ » implementation by Kent-State University (& TUM)





M. Strickland & S. Thapa, Phys. Rev. D 108, 014031 (2023)

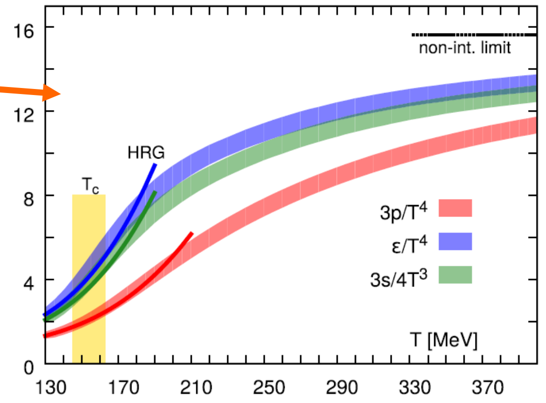
Good agreement with suppression at LHC but not at RHIC

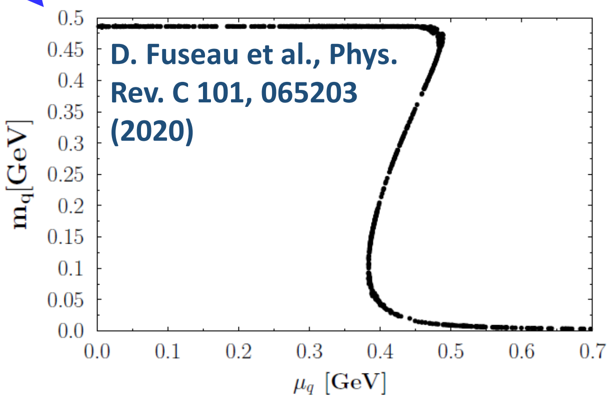
Other implementations : Osaka, Saclay, Nantes, Duke,…

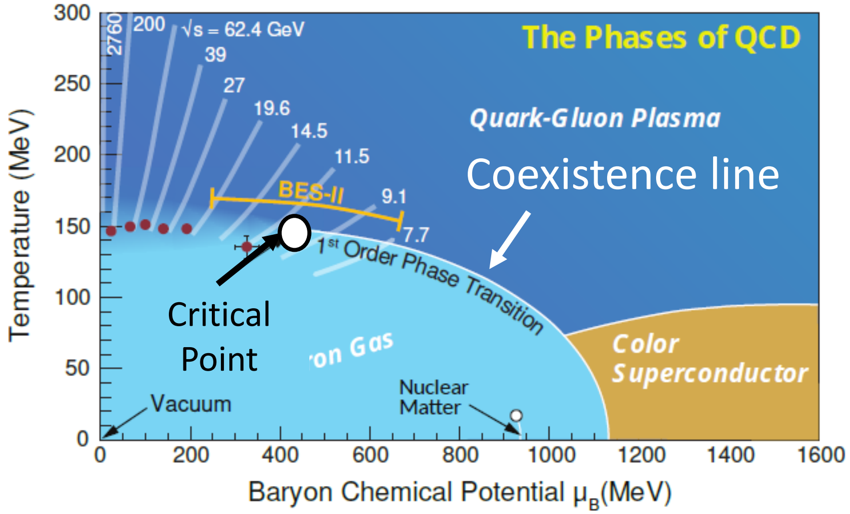
The search for a critical point

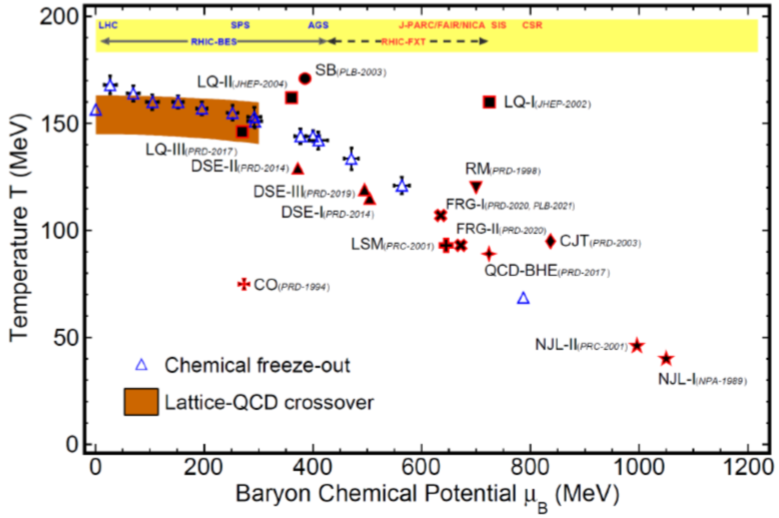
- The **fast cross-over** at T≈150 MeV **for $\mu_B \approx 0$** is the first **pivotal quantitative information** one could extract from both lQCD and experimental analysis.
- For large μ_B, and T ≈ 0, many models predict a 1rst order transition (gap equation for the light quark masses)
- As a consequence, a Critical End Point (2nd order phase transition) should be located at the end of the coexistence line. Major driver of our field !!!

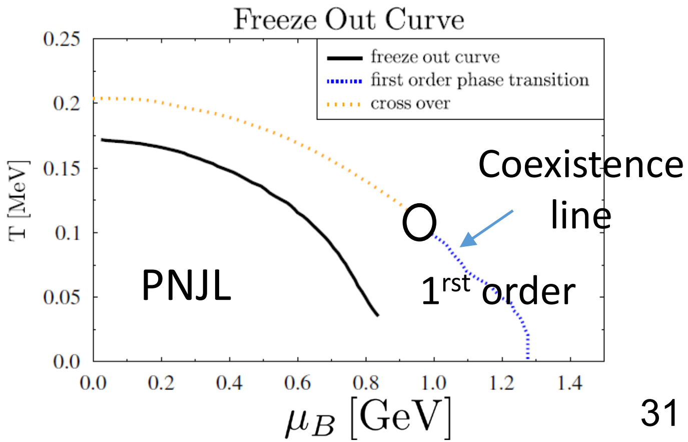
  - lQCD does not apply at finite μ_B (Taylor expansion in μ_B /T) => only partial guidance
  - Different predictions from different approaches (pNJL, FRG,…) => **Beam Energy Scan**
  - => locating the CEP will allow to better constrain these approaches and **gain theoretical understanding of dense nuclear matter**, with many consequences











The search for a critical point

- ➢ 2^{nd} order transitions lead to **critical fluctuations of the order parameters : χ condensate, charge density**,…
  - Flattening of the thermodynamical potential (Landau-Ginsburg theory)
  - In infinite medium : diverging correlation length ξ

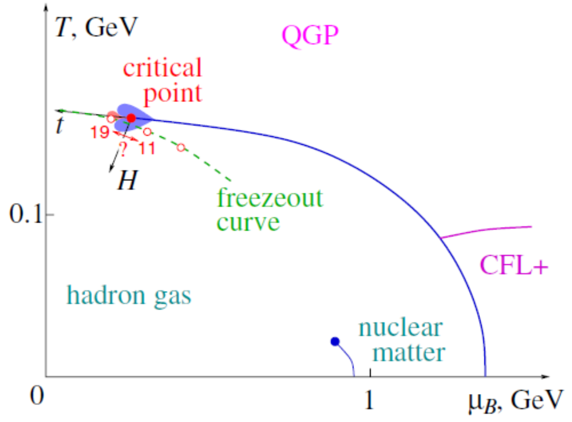
- ➢ In well-controlled experiments (precise fixing of (μ_B,T)):
  - Fluctuations or the O parameters imply **large fluctuations of the number of particles**, like for instance the net Baryon density
  - General arguments pertaining to the **universality class of the 2^{nd} order transition**
    - ✓ => **non-monotonic behavior of the kurtosis in**
    - ✓ => fluctuations growing with the rapidity acceptance Δy

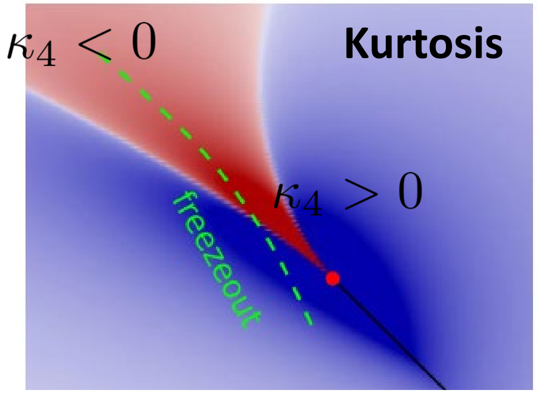
- ➢ However, in real URHIC life, the **correlation length ξ cannot grow above the system size** (10 fm) and is even limited by the **critical slowing down** (the growth rate vanishes when one approaches the critical point).

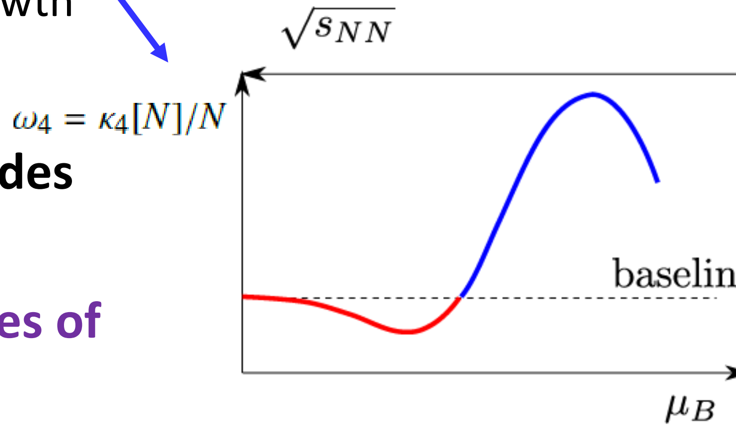
Boris Berdnikov & Krishna Rajagopal, Phys.Rev. D61 (2000) 105017

- ➢ => **Need for dynamical modelling**, especially to **couple the slow critical modes with fluid dynamics**

In the absence of reliable lQCD prediction, one resorts to universal properties of phase transitions







Coupling the slow critical modes with fluid dynamics

Two typical ways

Stochastic (chiral) fluid dynamics

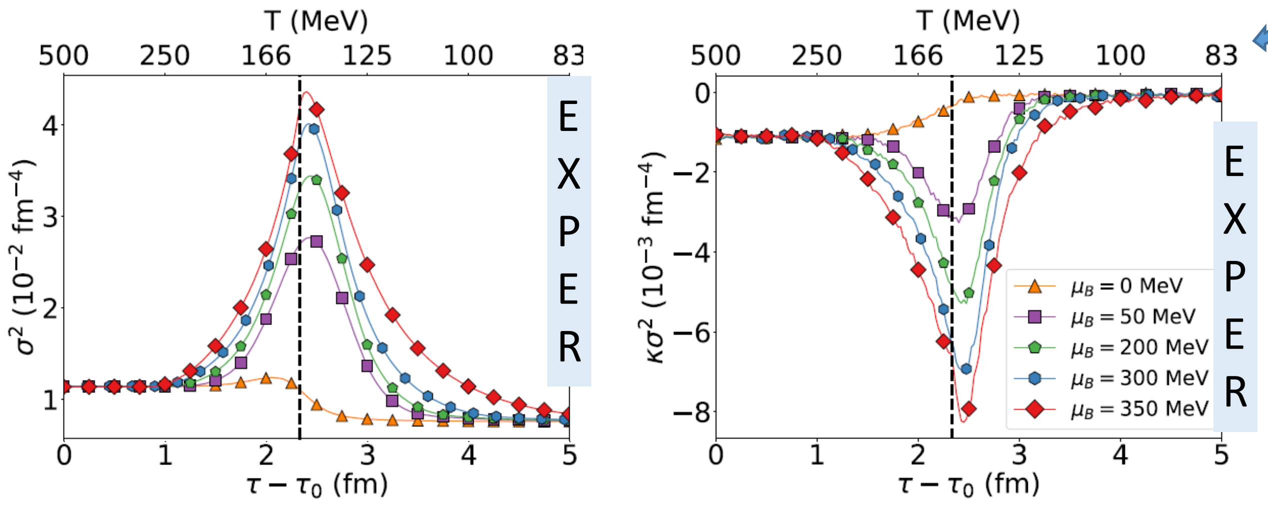
- Stochastic equations for the chiral σ field :

$$\underbrace{\boxed{\partial_\mu \partial^\mu \sigma + \frac{\delta U}{\delta \sigma} + g\rho_s}}_{\text{Mean-field evolution}} + \underbrace{\boxed{\eta \partial_t \tilde{\sigma}(x)}}_{\text{Dissipation}} = \underbrace{\boxed{\xi(x)}}_{\text{Noise}}$$

- Back reaction on the Fluid dyn. from the ξ noise
- Observables calculated from EbE averages

M Nahrgang et al., Physics Letters B 711 (2012) 109–116, M. Sakaida et al, Phys. Rev. C 95, 064905, Ch. Herold et al., Phys. Rev. C 106, 024901 (2022),…, G. Pihan, Phys. Rev. C 107, 014908 (2023)

Rise and fall of the cumulants…

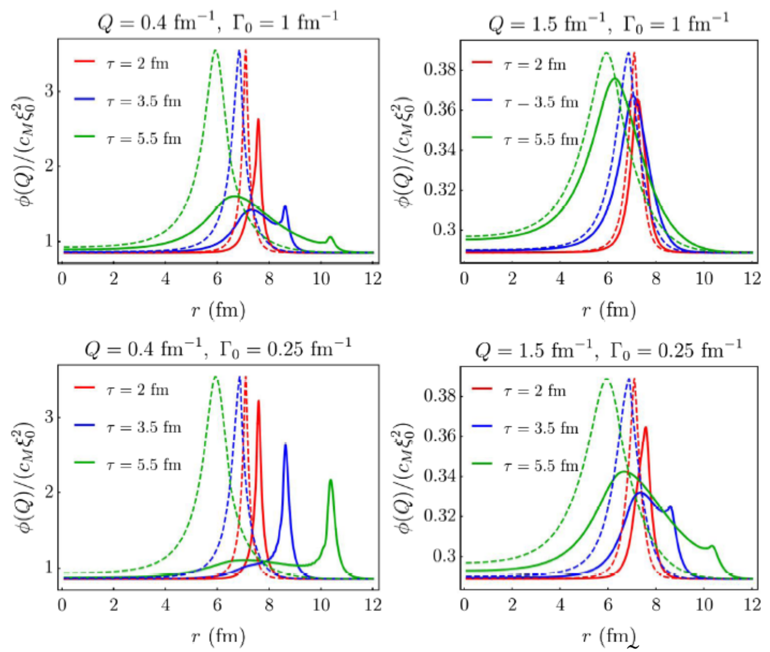


The 2nd (left) and 4th (right) order cumulants of n_B within a space-time rapidity window of y = 1 as a function of proper-time for different constant μ_B

Hydro-kinetics (hydro+)

- **Deterministic kinetic eqns for n-point functions** of slow critical modes, f.i. $\phi(x-y) = \langle \delta\sigma(x)\delta\sigma(y)\rangle$, with local temperature-dependent kinetic rates
- Statistical average performed in the derivation of deterministic equations

M. Stephanov and Y. Yin, Phys. Rev. D 98, 036006 (2018), K Rajagopal et al., Phys. Rev. D 102, 094025 (2020),…



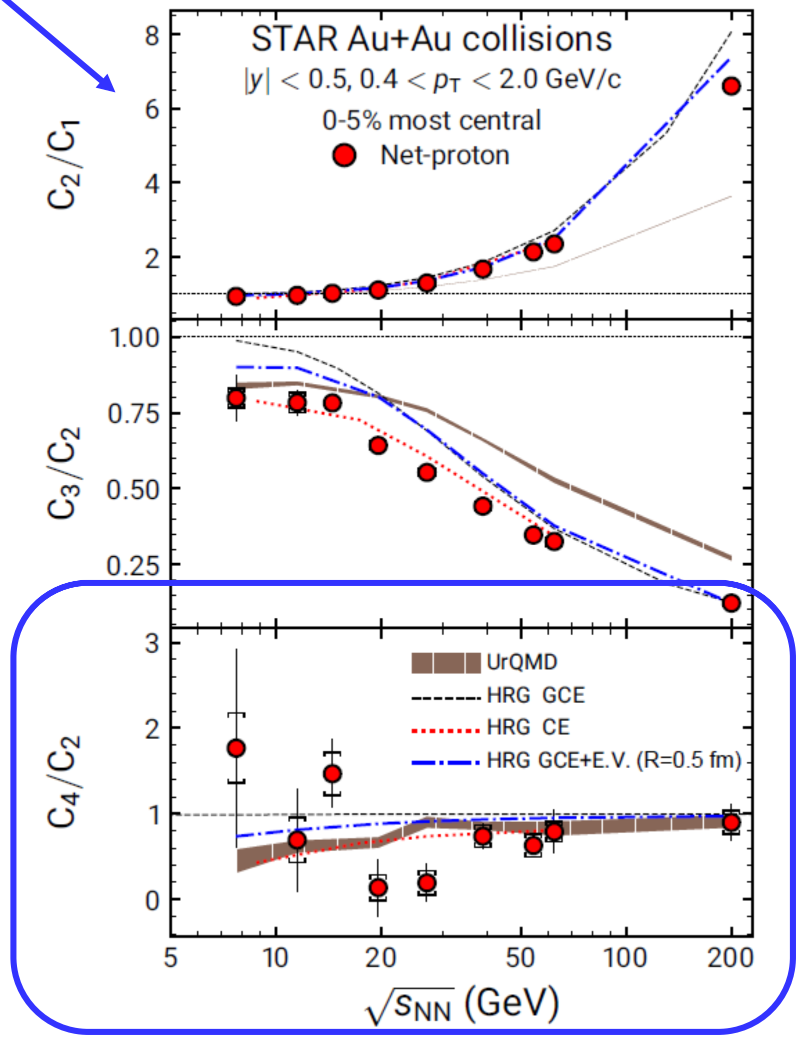
Advection of the critical modes with radial flow

The magnitude of the critical fluctuations $\tilde{\phi}(Q) = \mathcal{F}(\phi)$ plotted as a function of radius r at two values of the wave vector, Q

The search for a critical point: status

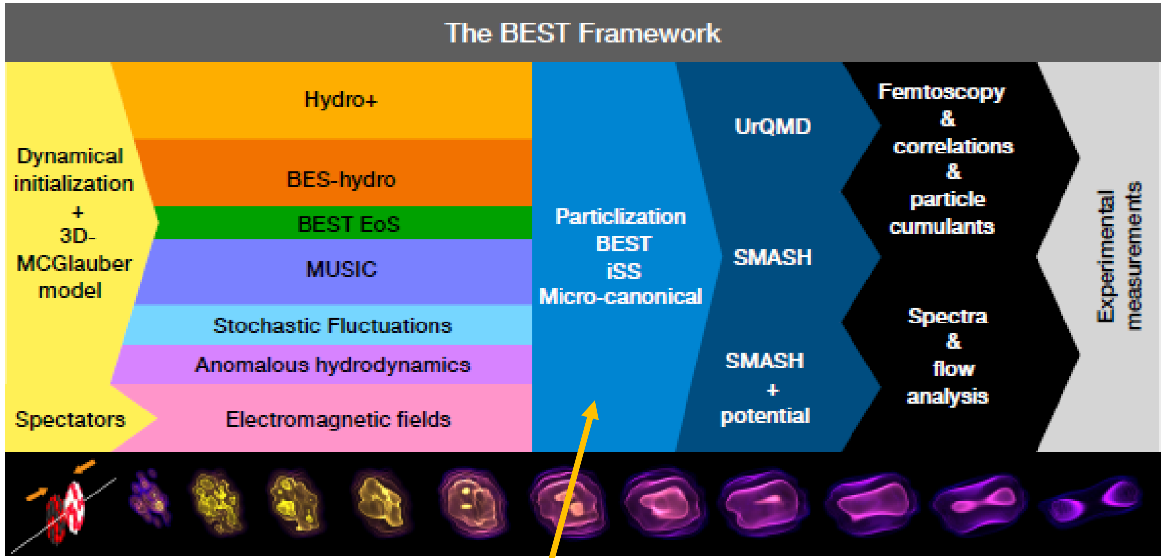
- BES-I STAR: « First indications of a **non-monotonic energy dependence of the net-proton C4/C2**… » that goes beyond simple hadronic physics
- Some models are able to reproduce this trend, others not
- Many theorists have gathered into the BEST collaboration
  - Some from Europe
  - Versatile framework with all parts of the standard URHIC model
  - Will have a major impact on the interpretation of BES 2nd round of measurements

STAR Collab, Phys. Rev. C 104, 024902 (2021)



Collision energy dependence of C2/C1, C3/C2, & C4/C2 for net-proton multiplicity distributions in 0-5% central Au+Au collisions, compared to UrQMD and HRG models

BeamEnergyScanTheory
Nuclear Physics A, Vol. 1017 (2022), 122343

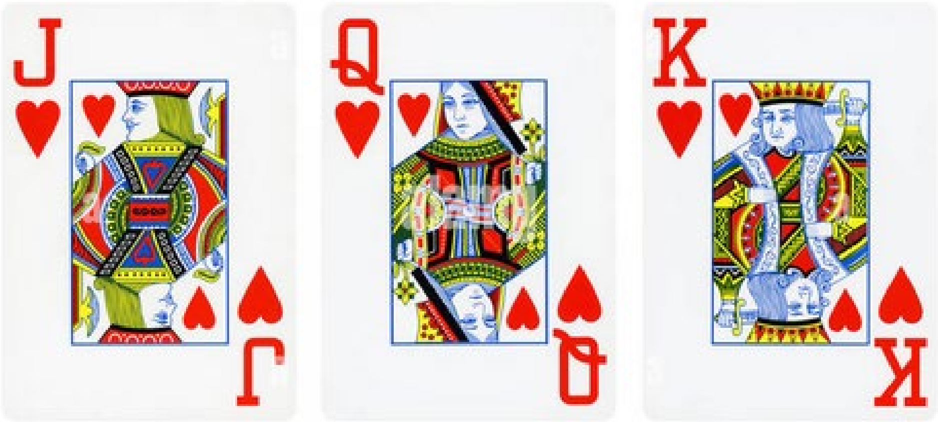


Key issue : « particlization» should be done faithfully to all fluctuations conveyed by the QGP

L. Jiang, Nucl. Phys. A ,Vol 956 (2016), 360, D. Oliinychenko & V. Koch, Phys. Rev. Lett. 123, 182302 (2019), D. Oliinychenko et al., Phys. Rev. C 102, 034904 (2020), M. Pradeep, Phys. Rev. D 106, 036017 (2022)

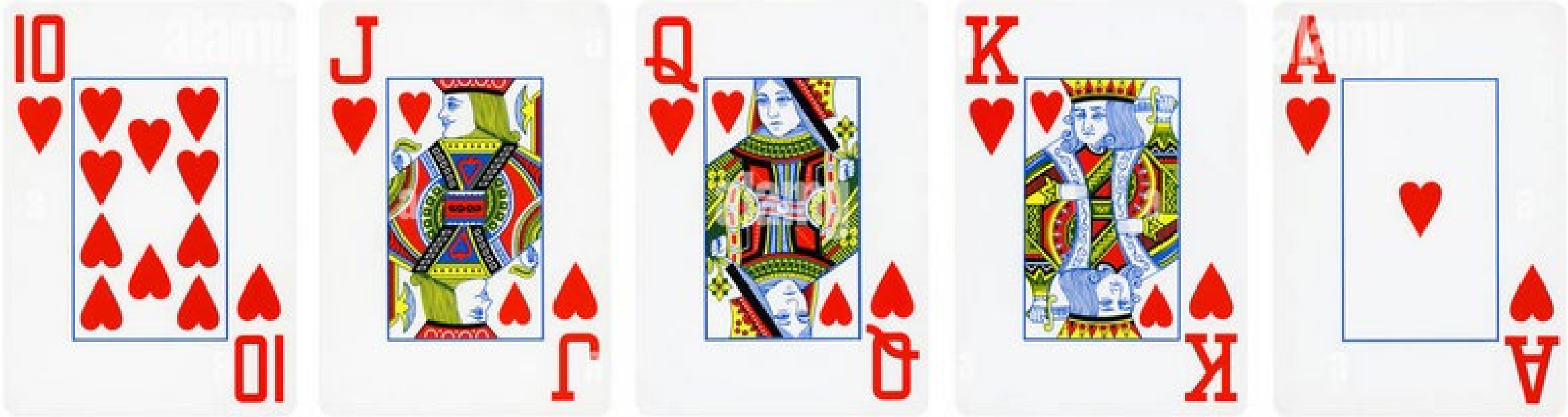
Conclusions

- We have entered the era where we need to diagnose and quantify QGP properties based on the URHIC « standard model »
- Theory developments are vivid , **combining** advances both in the fields of lattice QCD, effective theories and models…



Conclusions

- We have entered the era where we need to diagnose and quantify QGP properties based on the URHIC « standard model »
- Theory developments are vivid , **combining** advances both in the fields of lattice QCD, effective theories and models…
- …But one gets a real winner by adding experimental data and modern analysis methods



- A lot of progresses in the field are achieved due to exchanges, collaborations and discussions between *QGPists** which need to be maintained and even reinforced (Thanks STRONG !).

* Physicist studying the hot QCD matter, aka the QGP

Other fascinating topics I could not cover

Extending and challenging the standard model of URHIC

Stochastic Fluid Dynamics
(mandatory to propagate initial and internal fluctuations)

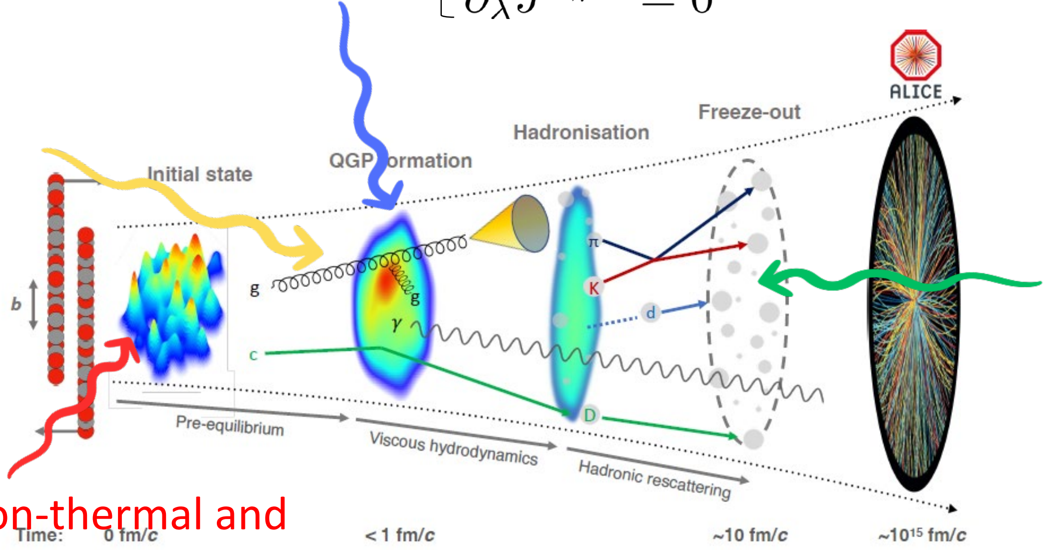
f.i. : [« New developments in relativistic hydrodynamics »; Nora Weickgenannt, Quark Matter 22, Krakow, Poland]

Spin Fluid Dynamics
(Promote spin tensor to additional dynamical quantity)

$$\begin{cases} J^{\lambda,\mu\nu} = x^\mu T^{\lambda\nu} - x^\nu T^{\lambda\mu} + \hbar S^{\lambda,\mu\nu} \\ \partial_\lambda J^{\lambda,\mu\nu} = 0 \end{cases}$$

Jets
The multi-scale hard probe

[“What we can learn about the QGP dynamics from jets”; Yacine Mehtar-Tani, Exploring QGP, 2023, Belgrade, Serbia]

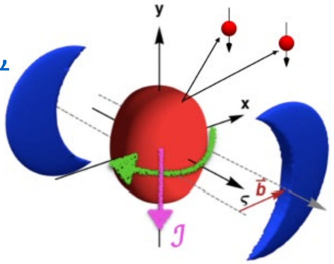


More constraining observables : symmetric cumulants, direct flow, correlations, event shape analysis,...

Glasma, Early thermalisation, non-thermal and hydrodynamic attractors
(how to converge so fast to thermal fluid though weak coupling)

[f.i. : « Early time dynamics and constraints on medium evolution», Kirill Boguslavski, Hard Probes 23, Aschaffenburg, Germany]

Early Electromagnetic field and high vorticity
(and interesting phenomena like the Chiral Magnetic Effect)



$$\omega \approx 10^{22}\,\mathrm{s}^{-1}$$

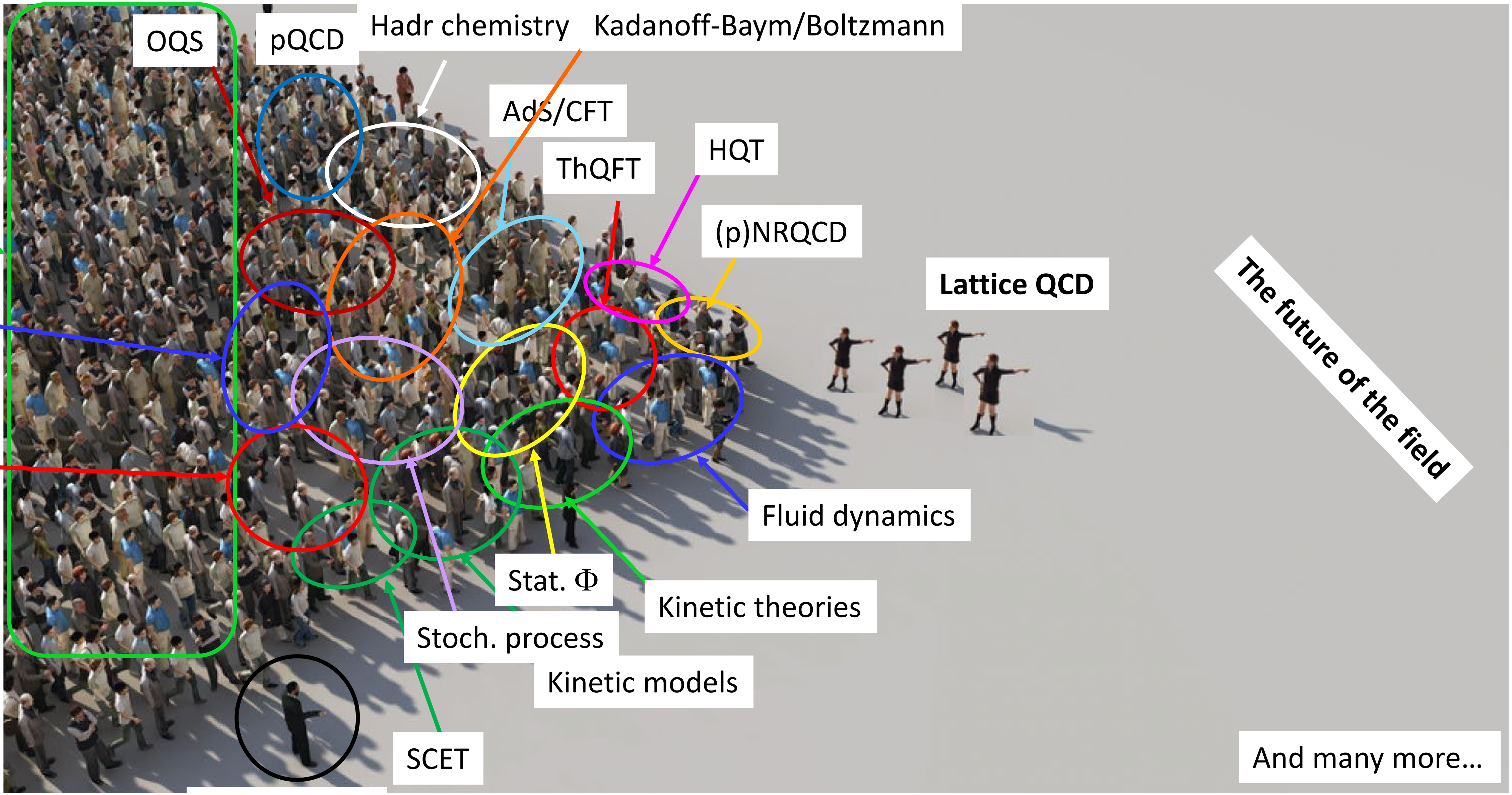
[“Polarization in heavy ion collisions: a theoretical review”; Matteo Buzzegoli, SQM 2022, Busan, Korea]

The structure of Hot QCD matter theory (in a broad acceptance)

“Trying to catch up” models

Renorm. group

Little room for your own model (hurry up)



proud outlier