aspects théoriques de la matière déconfinée à haute température et de la matière riche en baryons

Marlene Nahrgang, Subatech Nantes

Thanks to M. Bluhm, J. Ghiglieri, PB. Gossiaux, H. Hansen, E. Kiritsis, S. Porteboeuf-Houssais, B. Ramstein, A. Uras, K. Werner

Content

- Theory of the QGP
- Dynamical modelling of Heavy-Ion Collisions (HIC)
- More challenges

Both at zero and finite net-baryon density!

Based on two contributions:

1) E. Kiritsis et al, “Neutron Stars, Gravitational Waves and the QCD equation of state”
2) M. Nahrgang et al, “Theory of hot and dense baryon-rich matter: heavy-ion collisions and compact stars”

Missing ingredients, weak points are marked in red!

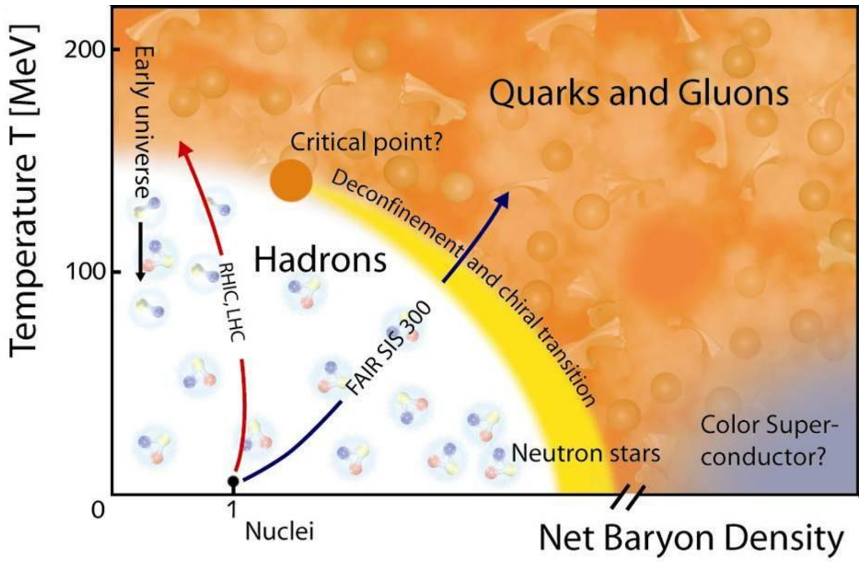
Perspectives, challenges and future developments are marked in green!

QCD under extreme conditions

Understanding the dynamics of the strong interaction in vacuum and under extreme conditions of temperature and density!

The QCD phase diagram connects to

- cosmology -> evolution of the early universe
- compact stars at high net-baryon density
- strongly coupled quantum fluids



GSI Helmholtzzentrum für Schwerionenforschung

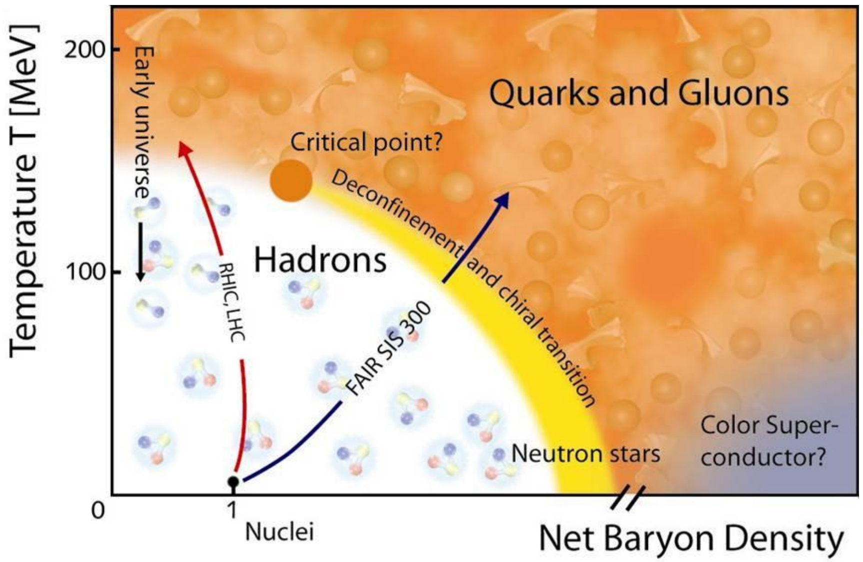
Connect first-principle QCD calculations with experimental observables via a realistic modeling of heavy-ion collisions and astrophysical events!

QCD under extreme conditions

Understanding the dynamics of the strong interaction in vacuum and under extreme conditions of temperature and density!

The QCD phase diagram features

- deconfinement
- chiral symmetry restoration
- a strongly coupled quantum fluid



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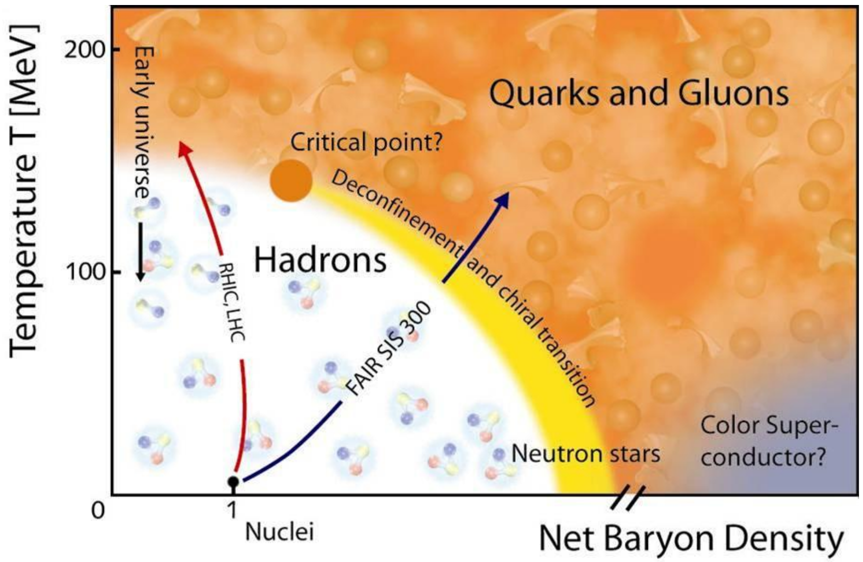
Connect first-principle QCD calculations with experimental observables via a realistic modeling of heavy-ion collisions and astrophysical events!

QCD under extreme conditions

Understanding the dynamics of the strong interaction in vacuum and under extreme conditions of temperature and density!

Important questions:

- onset of deconfinement and chiral symmetry restoration?
- properties of the strongly coupled QGP?
- existence of a phase transition with critical end point?
- dof in the core of compact stars?



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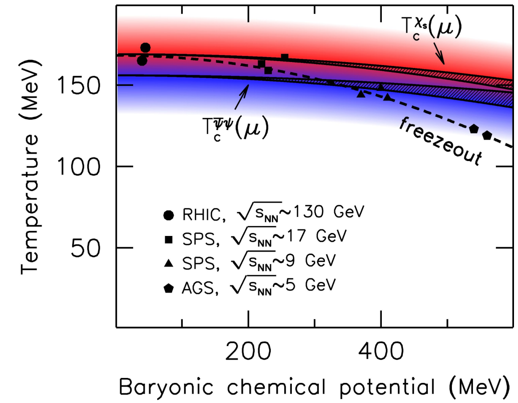
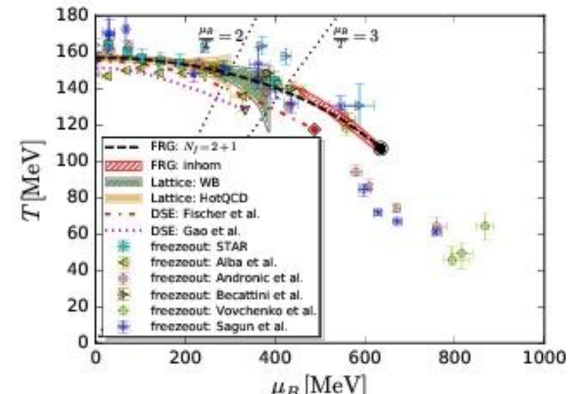
Connect first-principle QCD calculations with experimental observables via a realistic modeling of heavy-ion collisions and astrophysical events!

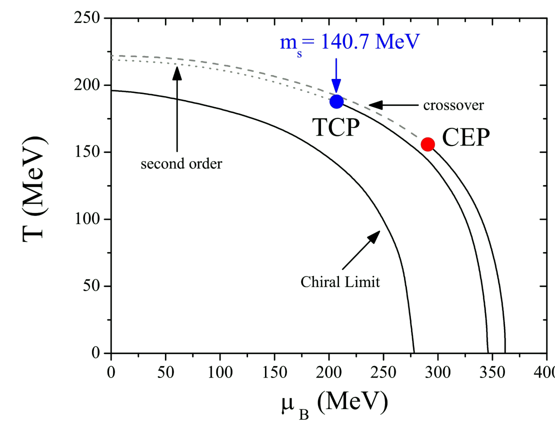
QCD at finite T and μ

- Lattice QCD:
  - Crossover at $\mu_B = 0$ and T = [145, 165] MeV
  WB JHEP1009 (2010), HotQCD PoS LATTICE2010 (2010)
  - Fermionic sign problem at $\mu_B \neq 0$
  - Methods to extend to finite μ_B , e.g. Taylor expansion, etc.
  $\Rightarrow$ no critical point for small μ_B /T < 1.
  - **Advance new lattice techniques, eg. Complex Langevin!**
- Functional Renormalization Group (FRG):
  - A critical point observed at larger densities
  - **Extend truncation schemes for larger densities!**
- Low-energy effective models of QCD:
  - e.g. PNJL, PQM models or quasi-particle models
  - **Constrain parameters by the lattice QCD for μ_B /T $\lesssim$ 1 and experimental data from HIC and astrophysical observations at larger μ_B!**
- Apply the AdS-CFT correspondence





WJ. Fu et al, arxiv:1909.02991

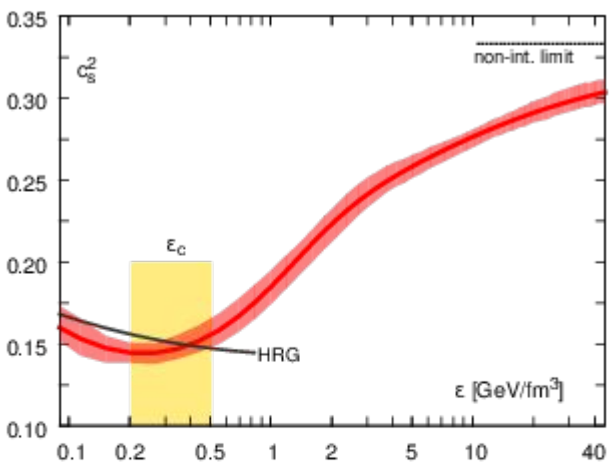


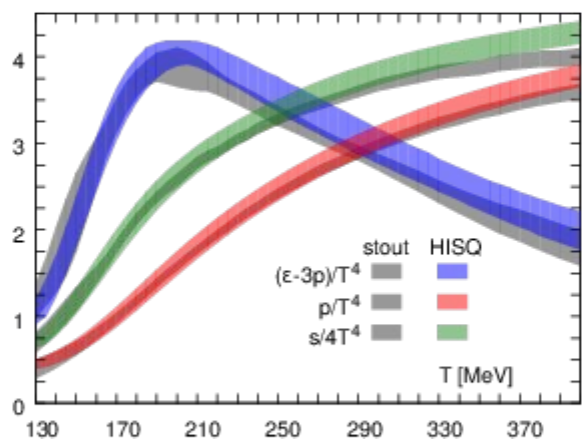
P. Costa et al, Symmetry 2 (2010)

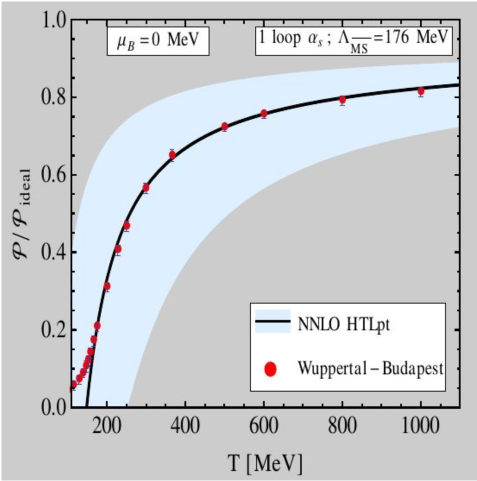
Equation of state (EoS)

Success story!
At μ_B = 0 the QCD EoS is known!

- Lattice QCD results on the EoS are far from the Stefan-Boltzmann-limit of a non-interacting gas => strongly coupled system
- Thermodynamic quantities change characteristically at the phase transition.
- Energy density, pressure and entropy increase at the crossover transition due to the liberation of color degrees of freedom -> quark-gluon plasma (QGP)
- Speed of sound has a minimum at the phase transition/ crossover
- **Naive pQCD poorly convergent** => **find more convergent gauge-invariant schemes (e.g. HTLpt, resummed DR)**







HotQCD Coll. PRD90 (2014); WB Coll. PLB730 (2014)

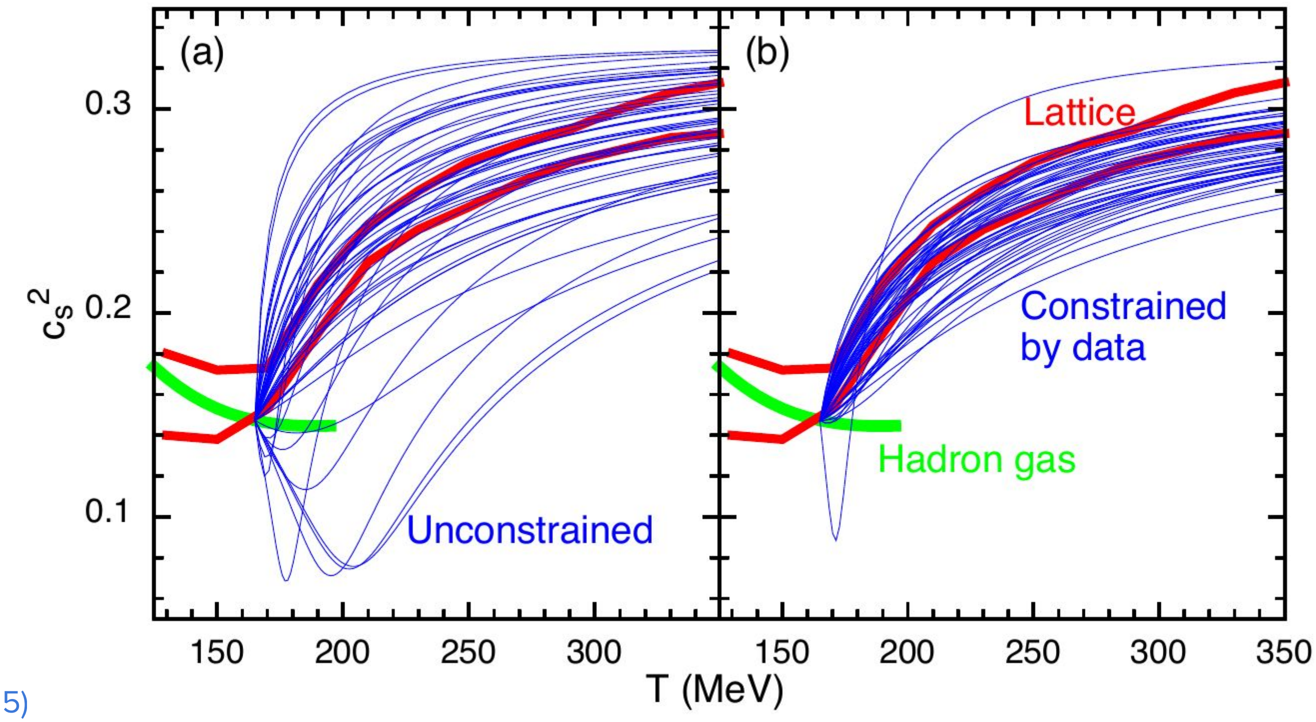
N. Haque et al, PRD89 (2014)

Equation of state (EoS)

Success story!
At $\mu_B = 0$ the QCD EoS is known!

- Not only is the EoS precisely known from lattice QCD calculations.
- It has also been validated in a model-to-data statistical analysis.
- This combined (Bayesian analysis) tunes model and physics parameters simultaneously!

An UNBIASED model-to-data comparison should be standard for all simulations of HIC!



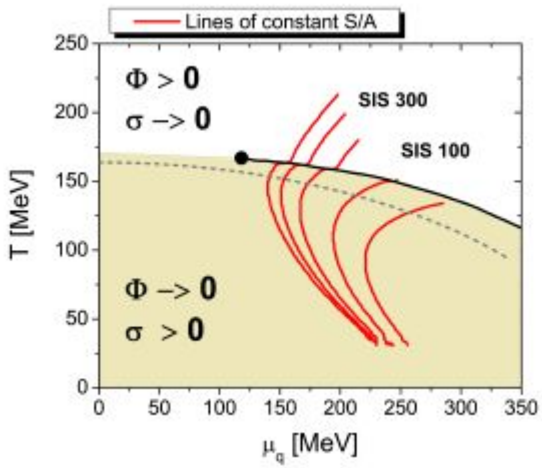
S. Pratt et al, PRL114 (2015)

EoS at finite density

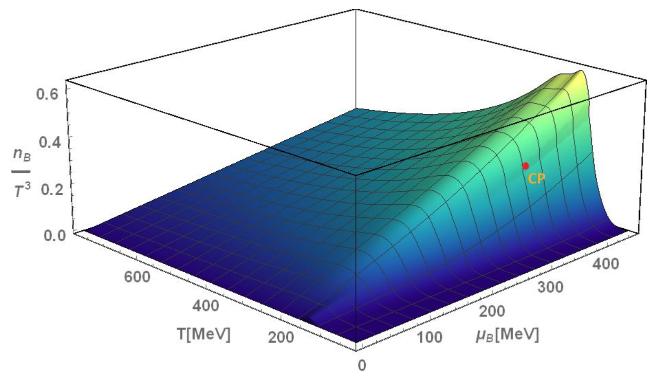
At $\mu_B \neq 0$ there are many unknowns in the QCD EoS...

- Toward finite net-baryon density the phase transition is supposed to change from crossover to a first-order phase transition via a critical end point.
- Beyond the onset density the hadronic gas description is not valid anymore => nuclear liquid or a mixed phase.
- The correct inclusion of the hadronic degrees of freedom is crucial and constraints from the nuclear ground state need to be taken into account.
- Constrain parameters by experimental results from HIC and astrophysical observations.

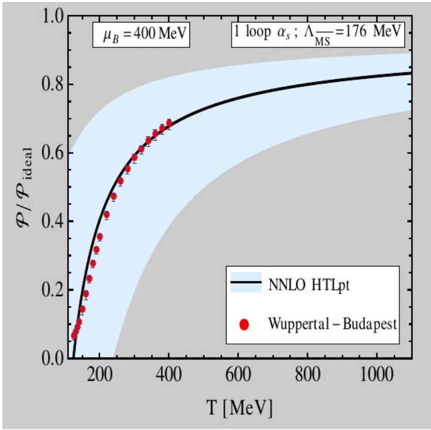
Need to extend the validity of the approaches to the QCD EoS to $\mu_B \neq 0$!



V. Dexheimer et al, PRC81 (2010)



P. Parotto, MN et al, accepted in PRC



N. Haque et al, PRD89 (2014)

EoS at high density & low temperature - astrophysics

Nuclear experiments ⟷ **Theory for dense matter** ⟷ **Global astrophysical modelling** ⟷ **Observational facilities**

Nuclear experiments

CERN (LHC, SPS)
BNL (RHIC, AGS)
GANIL
GSI/FAIR
JINR (NICA)
JPARC

Theory for dense matter

Equation of state (ComPOSE)
Neutrino diffusion
Transport Coefficients

Global astrophysical modelling

Neutron stars (Lorene library, meta-model)
BH & NS mergers (Einstein toolkit, WHISKY-THC)
Kilonova, Supernova (COCONUT),
Galactic chemical evolution

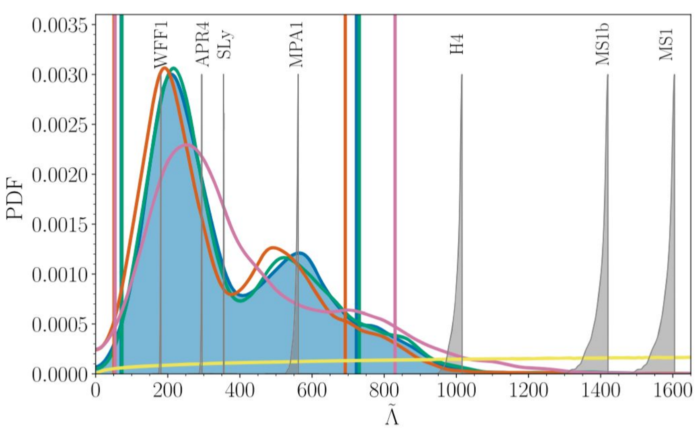
Observational facilities

GW (LIGO-Virgo)
GRB (FERMI-LAT, XMM Newton),
E-M (GRANDMA, ZTF,...)

Improved understanding of extreme matter physics

cross fertilisation

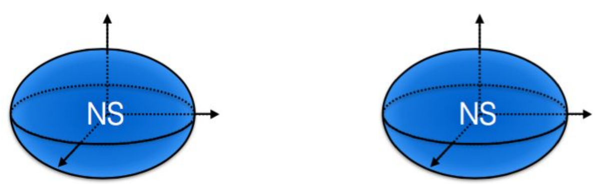
Improved understanding of astrophysical objects

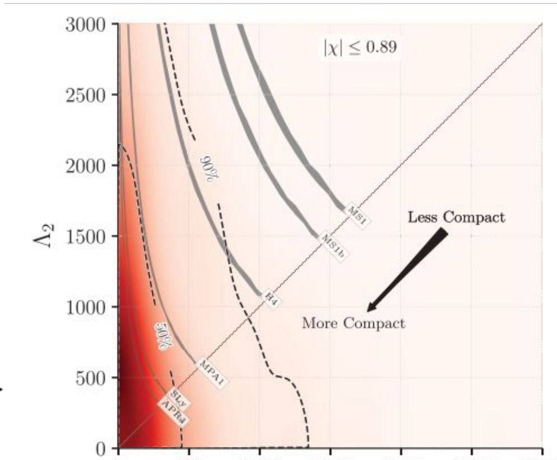


Tidal deformability measurement LVC, PRX9 (2019)

First constraints from GW put on EoS, excluding some models!

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$





LIGO-VIRGO Collab. PRL 119 (2017)

EoS at high density & low temperature - astrophysics

Nuclear experiments ⟷ **Theory for dense matter** ⟷ **Global astrophysical modelling** ⟷ **Observational facilities**

CERN (LHC, SPS)
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JPARC

Equation of
(Co

GW (LIGO-Virgo)
GRB (FERMI-LAT, XMM
on),
ANDMA, ZTF,...)

Improved unde
extreme matter

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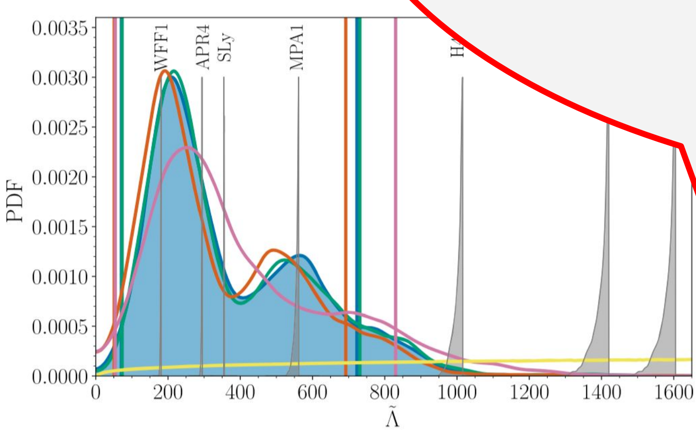
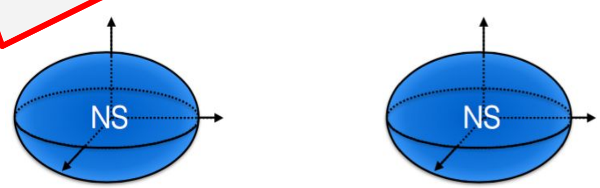
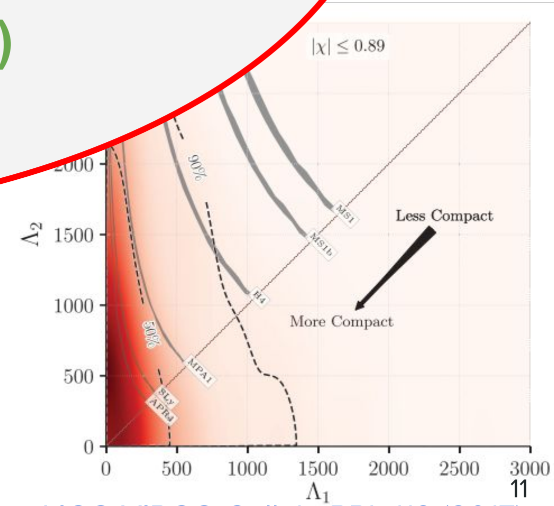
Connections to
GT02: Compact stars and matter at extreme conditions
(M. Urban (IJCLab) et al.)
GT04: Probing extreme matter physics with gravitational waves
(J. Margueron (IP2I) et al.)



Tidal deformability measurement LVC, PRX9 (2019)





LIGO-VIRGO Collab. PRL 119 (2017)

EoS at high density & low temperature - astrophysics

Approaches to the EoS at high density

Agnostic
(no Lagrangian, no matter composition)

Semi-agnostic
(no Lagrangian, matter composition)

Phenomenological
(pheno. Lagrangian, matter composition)

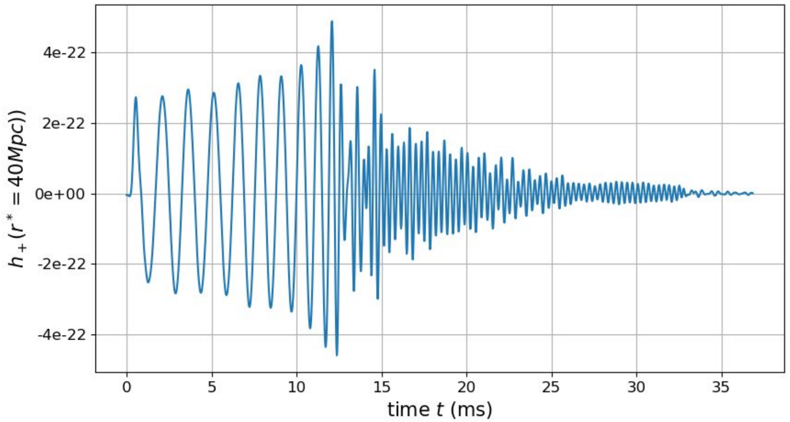
Microscopic
(reproduce NN XS, predict dense matter properties)

QCD based
(LQCD, chiral EFT, holography)

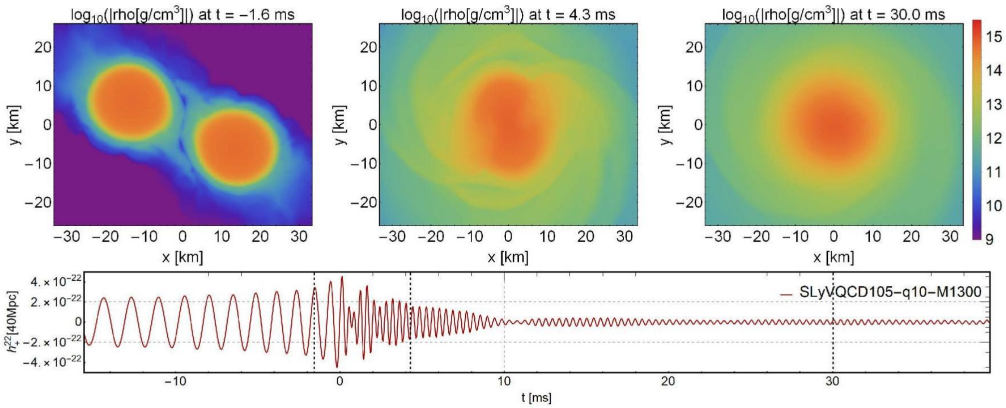
All nuclear models are based on the phenomenology at nuclear ground state density and extrapolated to higher densities!

Make use of meta-modelization (using Bayes' statistics) to connect lower density measurements to very-high density observables!

Gravitational wave signal, calculated with a nuclear EoS showing the presence of a transient supermassive neutron star:



First simulation by IP2I (theory group)



NS merger, simulated with a hybrid EoS containing a holographic QCD part

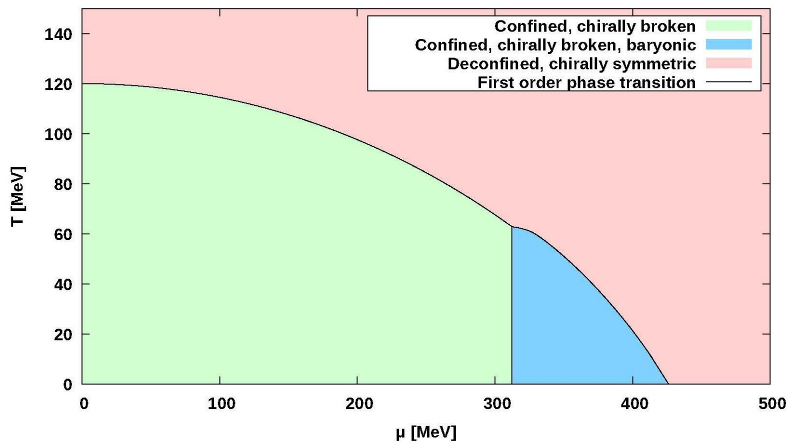
C. Ecker et al, arxiv:1908.03213

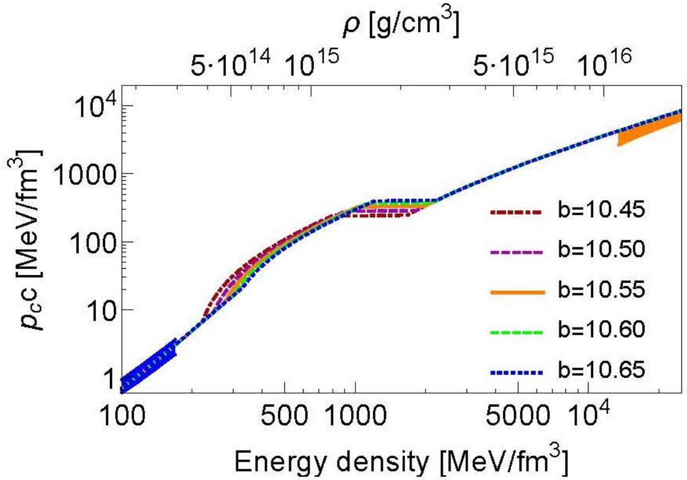
EoS from holography and the link to astrophysics

- The holographic correspondence is a duality between gauge theories and string theories, prototypical example of N=4 supersymmetric gauge theory in 4 space-time dimensions is equivalent to string theory in 10 dimensions on $AdS_5 x S^5$ J. M. Maldacena, IJTP 38 (1999)
- Apply holography to construct semi-phenomenological models for 4d Yang-Mills theory and QCD using the gravitational description
- Detailed map between observables in the QFT (correlation functions) and in gravity (S-matrix in asymptotical AdS spaces)
- Improved Holographic QCD: confinement and asymptotic freedom fix the asymptotics of the potential
- Full Holographic QCD: includes quark degrees of freedom

U. Gursoy et al, JHEP0802 (2008)

Matching parameters in hybrid EoS not well constraint and the treatment of baryons remains approximative!





T. Ishii et al, JHEP1907 (2019)

C. Ecker et al, arxiv:1908.03213

Probes of the QGP

Fluid dynamics requires (close-to) local thermal equilibrium => loss of memory of interactions with the bulk medium

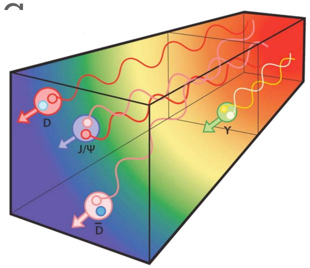
Look at probes which do not thermalize with the QGP and therefore carry information on the QCD interactions:

Open heavy flavor:

- Produced in initial hard processes => do not thermalize with the QGP at tau0
- Keep some memory of the interaction with QGP constituents
- Probes different physics at low and high pT

High-pT jets:

- Produced in initial hard processes
- Perturbative regime
- Probe opacity of the matter
- Collisional and (coherent) radiative energy loss => jet quenching parameter



Hidden heavy flavor:

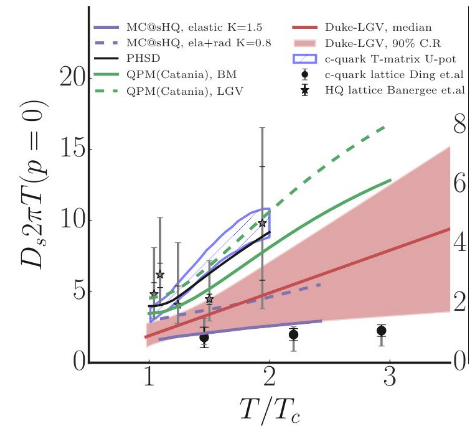
- Bound state with non-zero extension
- Can propagate as a color-neutral bound state
- Melting due to screening of QQbar potential in the medium
- Probe the in-medium force between 2 quarks
- Simplest confined state -> probe reconfinement at FO

Probes of the QGP - heavy quarks

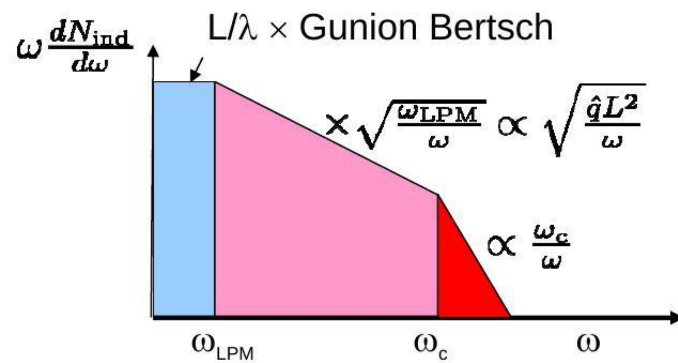
QCD interaction at finite temperature:

- (In)elastic scattering with the QGP partons
- At lower pT: elastic diffusion => diffusion coefficient
  How to include nonperturbative effects?
- At higher pT: importance of radiative corrections
- Coherent emission for $t_f > l_{mfp}$
- Path length effects for finite systems, where $\Delta E \propto L^2$
  Transition from incoherent - coherent - finite size radiation pattern!
- Mass dependence - generalized dead cone effect
- Strong-coupling approaches, holographic QCD
  U. Gürsoy et al, JHEP0912 (2009), JHEP1012 (2010); E. Kiritsis et al, JHEP02 (2014)
- Consistent picture of J/psi suppression and regeneration

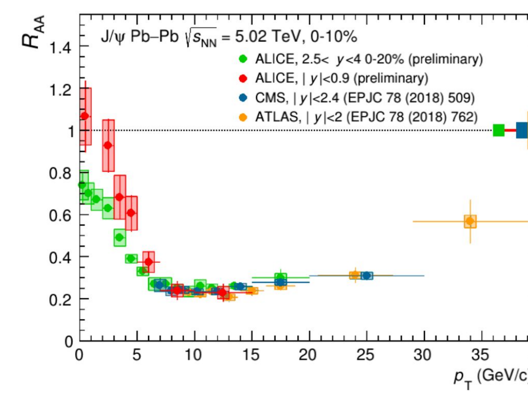
Many theory approaches are valid in certain kinematic regimes only. It will be crucially important to bridge the gap between these approaches!



Y. Xu



PB. Gossiaux



R. Arnaldi

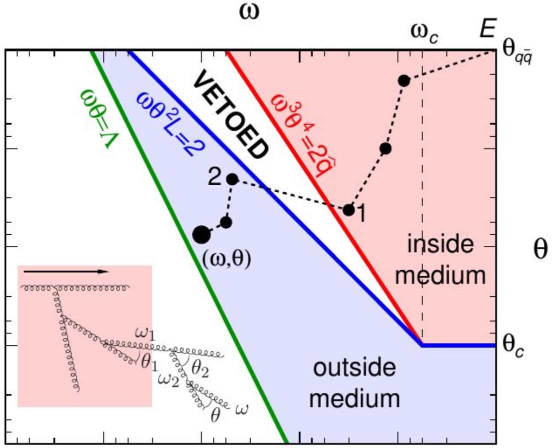
Transport coefficients - jet quenching

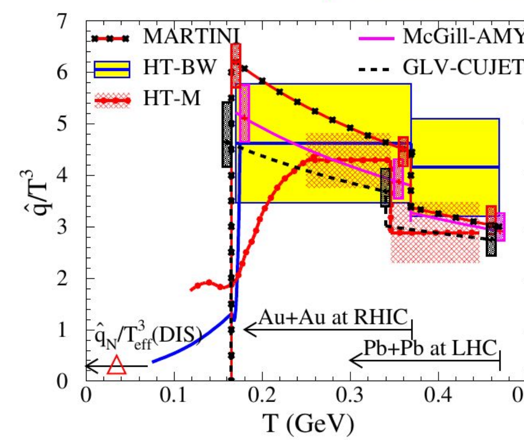
Study the modifications of an energetic jet to due its interaction with the QGP:

- Vacuum-like emission due to the jet virtuality
- Medium-induced radiation, like BDMPS-Z formalism

=> Complete picture of both radiation mechanisms is still missing!

- **Calculating medium effects of vacuum-like parton showers within controlled approximations of pQCD.**
- **Go beyond just calculating qhat (it is not the only parameter affecting in-medium modifications and not differential)**





P. Caucal et al, PRL120 (2018)

JET collab. PRC90 (2014)

Theory of QGP - future developments in France

- Extend effective models (PQM, PNJL) at $\mu_B = 0$ and $\mu_B \neq 0$:
  - Constrain parameters by lQCD, HIC and astrophysics.
  - Develop new truncation schemes beyond mean-field, FRG, DSE, etc.

Subatech, Univ Lyon

- QCD EoS at $\mu_B \neq 0$
  - Inclusion of correct degrees of freedom and interactions.
  - Constrain parameters with nuclear ground state and liquid properties, astrophysics.
  - Further develop effective models and the holographic correspondence.

APC, Subatech, IP2I

- Probes of the QGP - open and hidden heavy flavor:
  - Connect different kinematic regimes, transition from low to high to very high pT
  - Fundamental description of quarkonia as open quantum systems

IJClab, Subatech

- Probes of the QGP - jet quenching:
  - Combine vacuum-like emission with medium induced radiation
  - Go beyond qhat and identify quantities that relate the jet evolution to observables

IPhT Saclay, Subatech

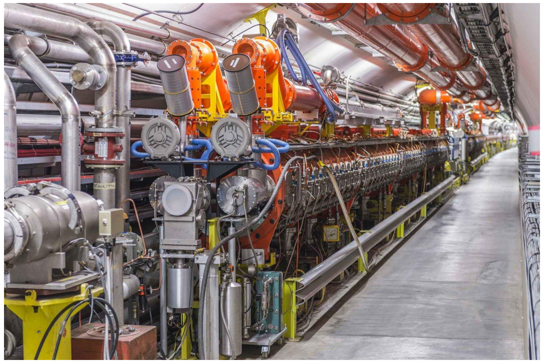
- Chiral symmetry and dilepton emission:
  - After G. Chanfray presented the original work leading to the rho spectral function by Rapp/Wambach, most of the development concerning linking chiral symmetry restoration to dilepton emission is done outside of French theory group

HIC and the QCD phase diagram

- elementary reactions e + e − , pp, pp- ⇒ (mostly) vacuum QCD
- p- A, pA ⇒ nuclear modifications
- heavy-ion collisions AA ⇒ medium formation and properties

- Highest energies at LHC/RHIC: PbPb/AuAu at $\sqrt{s_{NN}}$= 0.2 – 5 TeV
  ⇒ Energy deposition ➔ handle on the temperature.
- Lower energies at GSI/FAIR, SPS/CERN, JPARC: AuAu at $\sqrt{s_{NN}}$= 2 – 20 GeV
  ⇒ Baryon stopping ➔ handle on the baryon chemical potential.



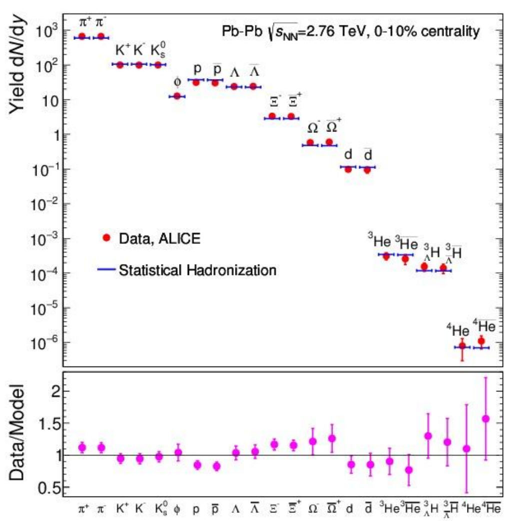


HIC and the QCD phase diagram

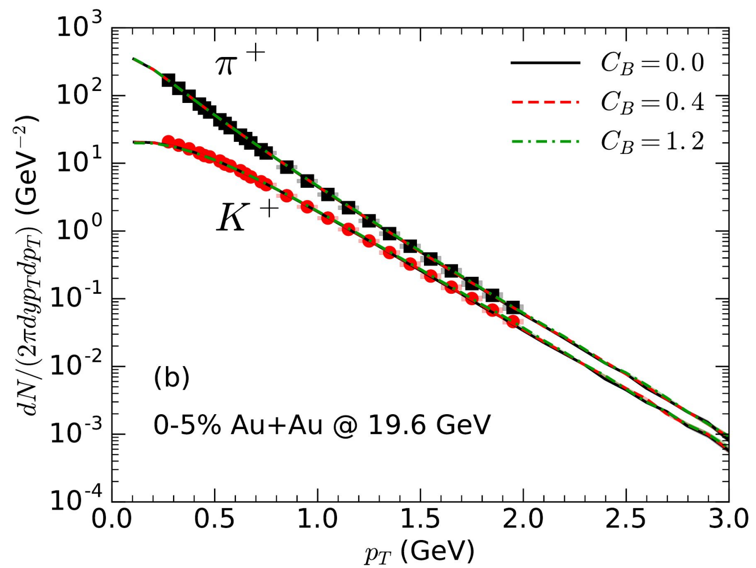
Do HIC have something to do with the QCD phase diagram?

- Particle yields at chemical freeze-out
- success of statistical hadronization
- chemical equilibration

- Particle spectra at kinetic freeze-out
- local thermal equilibration
- Success of fluid dynamics



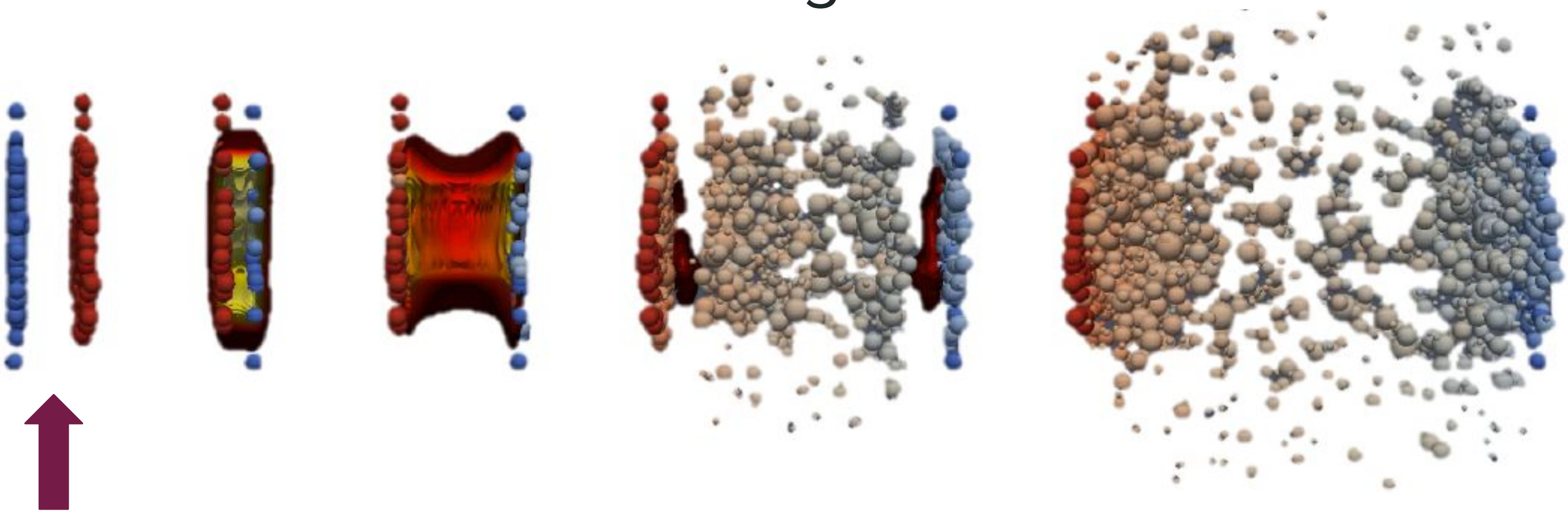
A.Andronic et al, Nature 561 (2018)



G. Denicol et al, PRC98 (2018)

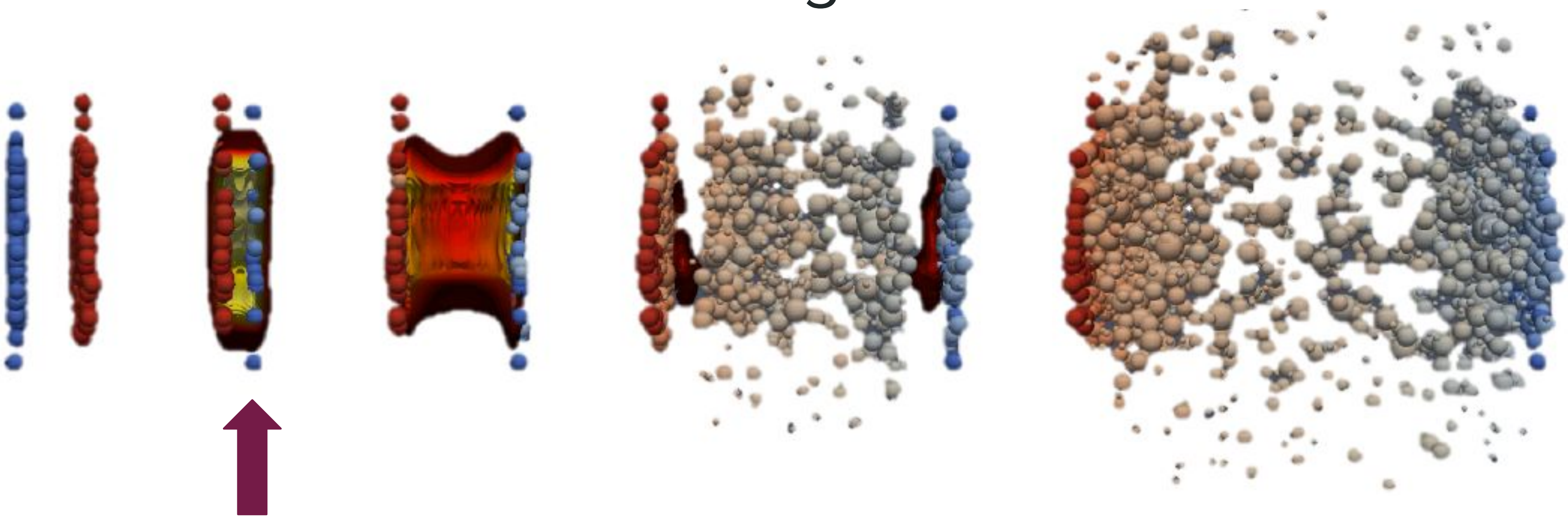
⇒ Heavy-ion collisions are connected to the QCD phase diagram!

Standard model of simulating HIC



- Initial state
  - Color Glass Condensate, EPOS, MC Glauber, ERKT, MC-KLN, etc…
  - Nuclear shadowing
- Pre-equilibrium phase -> rapid thermalization, fluidization, etc.
- Expansion of the QGP -> fluid dynamical description
- Hadronization and Particlization -> Cooper-Frye prescription
- Final hadronic interactions -> microscopic transport

Standard model of simulating HIC



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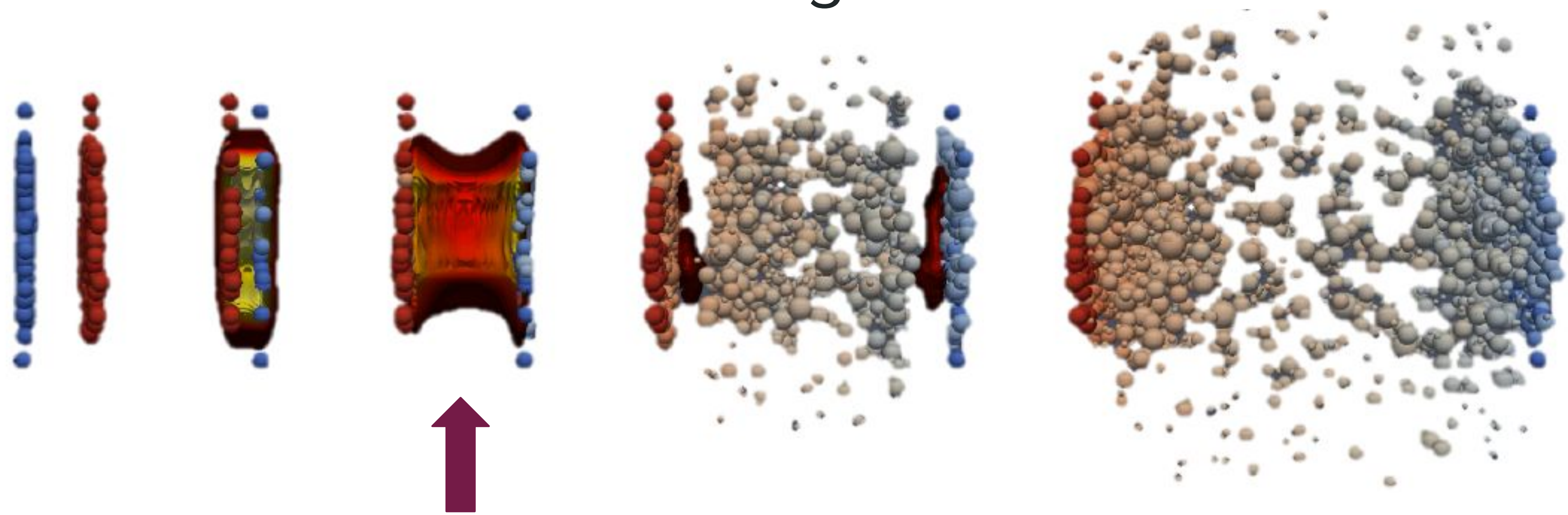

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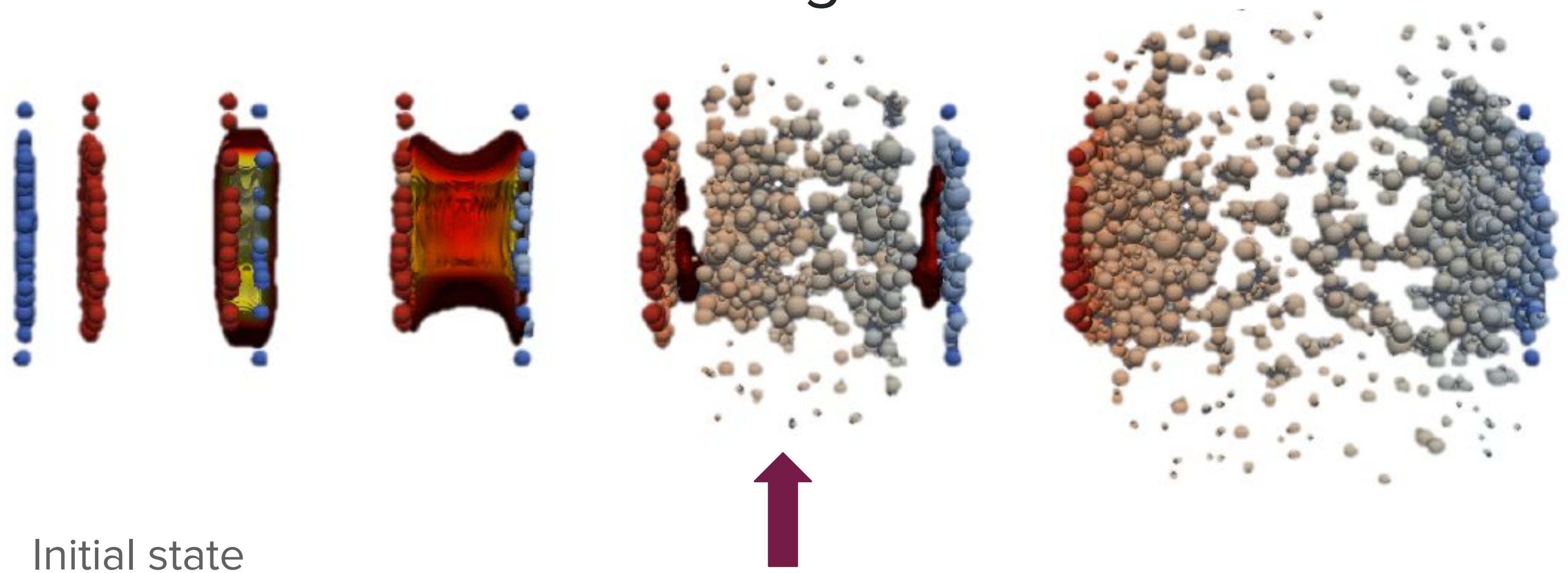

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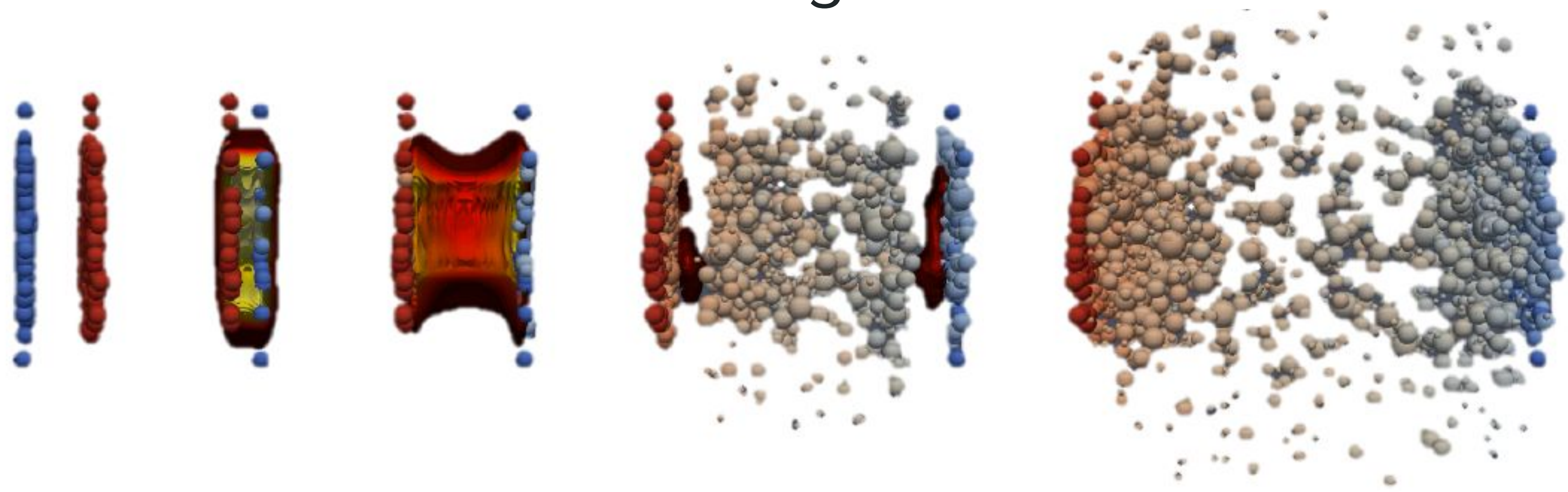

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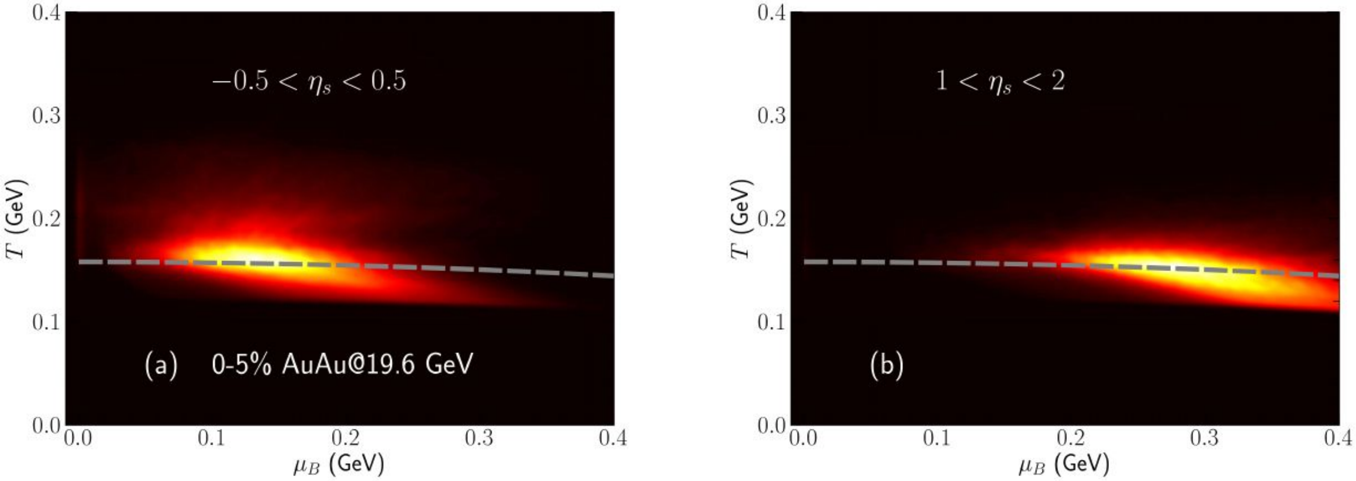
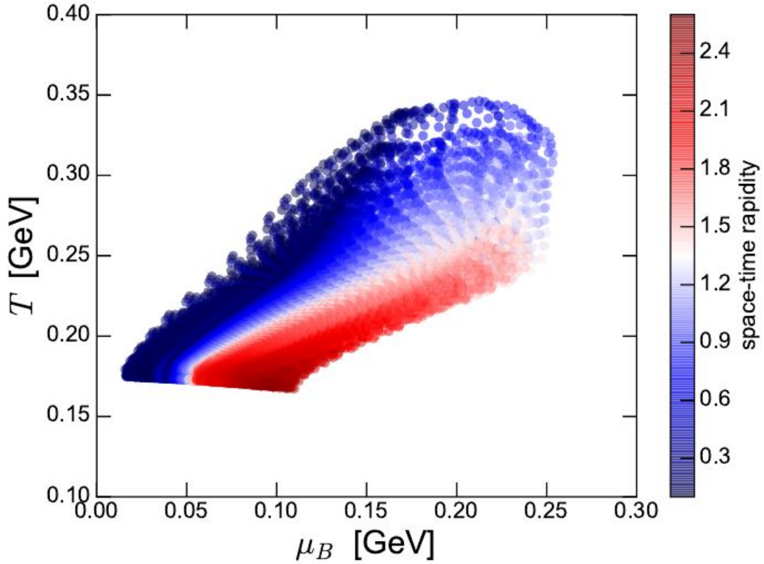
Heavy-ion collisions at finite density



plots by Chun Shen

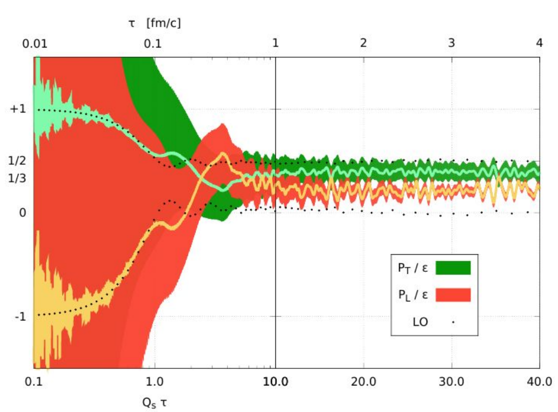


plot by Iurii Karpenko

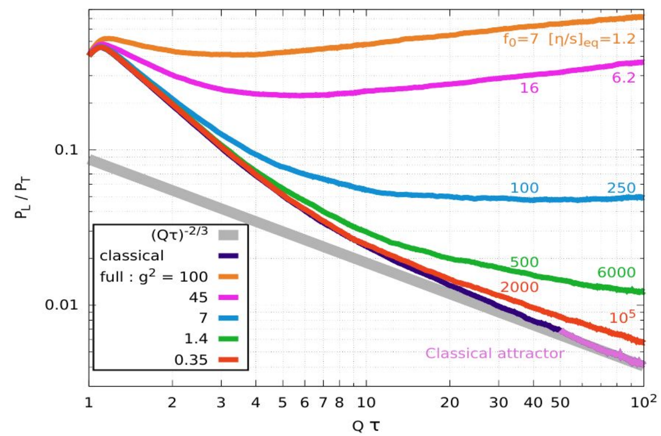
- Especially at low densities HIC span over large regions in the phase diagram.
- Already in $\sqrt{s_{NN}}$=72GeV rather large μ_B/ T > 1 are probed.

Pre-equilibrium, thermalization, fluidization

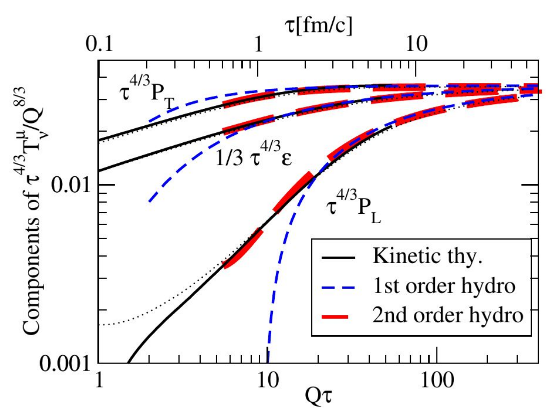
- ... remains the least well understood phase of a heavy-ion collision...
- At high energies (LHC, top-RHIC) nuclei are probed at high gluon density
  => standard formalism of (single) parton distributions becomes difficult
  => non-linear gluon interactions limit the growth of the density, gluon saturation
  => how do these gluonic fields thermalize?
- Two possible routes studied so far, solve classical Yang-Mills equations or the Boltzmann equation within kinetic theory.
- Apply the 2PI formalism (renormalizable scheme) to expanding systems, resumming the relevant contributions to thermalization!



T. Epelbaum et al, PRL111 (2013)



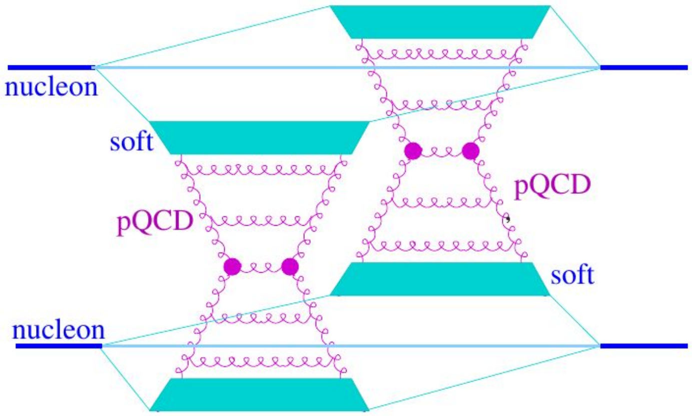
T. Epelbaum et al, JHEP1509 (2015)

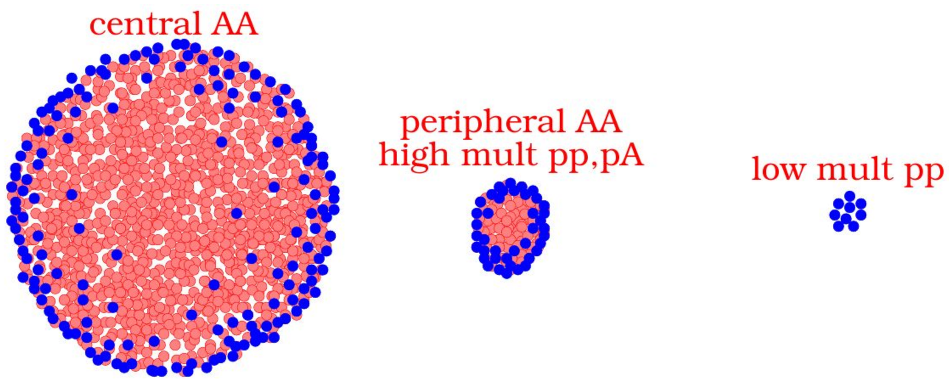


A.Kurkela et al, PRL115 (2015)

EPOS initial state

- Gribov-Regge approach to multiple scattering for each NN collision
- Each elementary process is represented by a parton ladder, which are represented by flux tubes.
- High-density/low-pT flux tubes constitute the bulk (core), while low-density/high-pT form the corona or jet-particles.

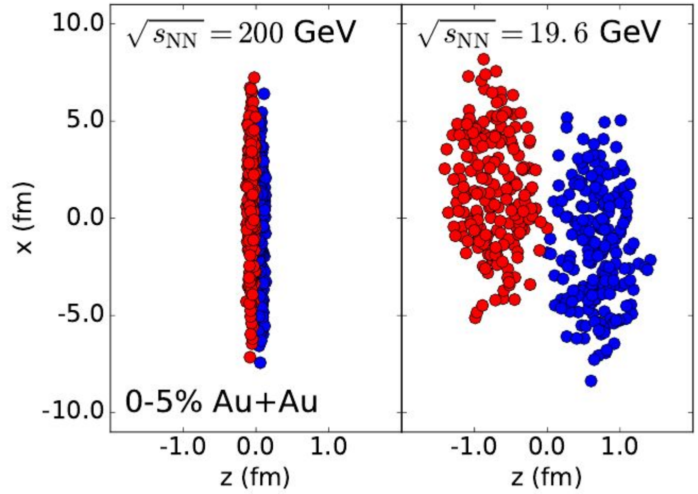


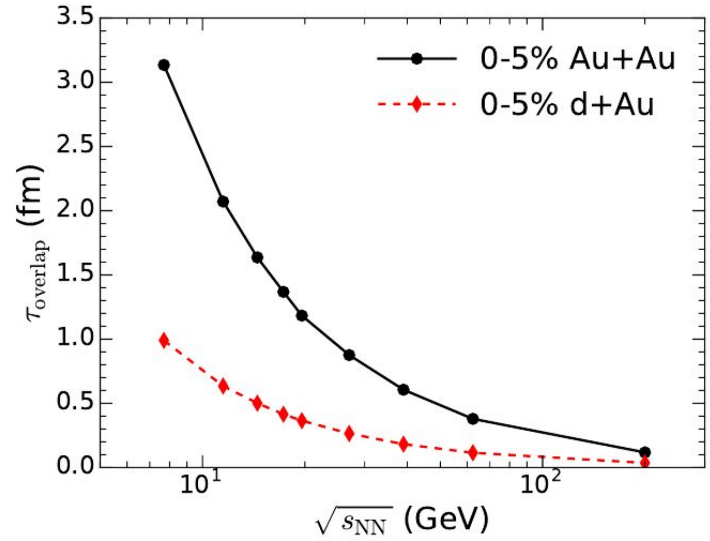


K. Werner et al, Phys. Rept. 350 (2001), PRC85 (2012), PRL112 (2014), PRC89 (2014), PRC92 (2015)

The initial state of HIC at finite density

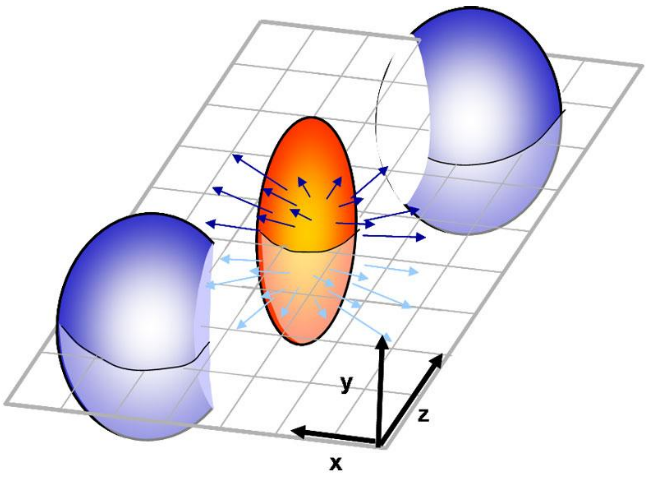
- Boost invariance is not a good approximation anymore -> thick pancakes!
- Increasing penetration time for colliding nuclei. J. Auvinen and H. Petersen, PRC88 (2013)
- CGC picture does not work anymore.
- Dynamical fluidization: Y. Akamatsu et al, PRC98 (2018)
  Need to evolve pre-fluid and fluid in parallel!
- Multi-fluid approach: fluid dynamical description from the initial state on.
  P. Batyuk, MN et al, PRC94 (2016)
  Need to couple the fluid description dynamically to the corona formation!
- **EPOS: currently all collisions happen in parallel, for application at finite density a cascade with sequential collisions needs to be implemented!**

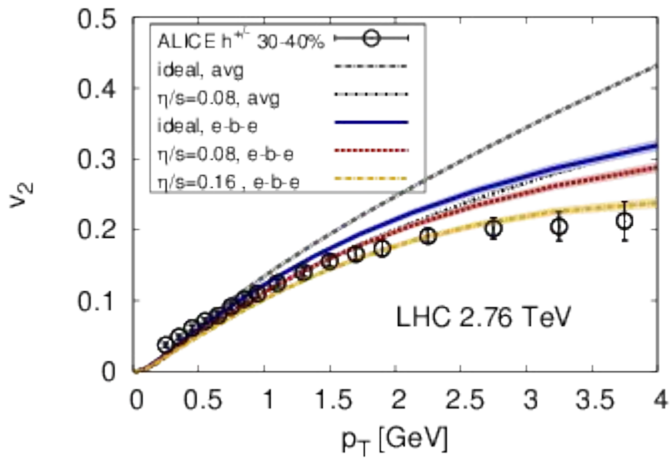




C. Shen and B. Schenke, PRC97 (2018)

Fluid dynamical simulations of HIC





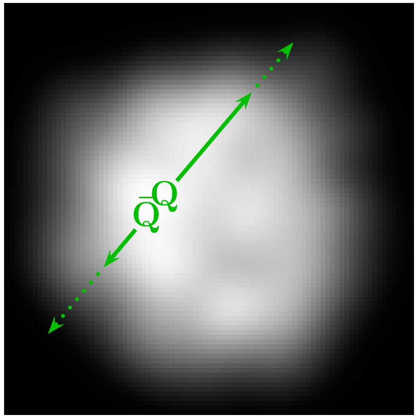
- Fluid dynamical simulations of heavy-ion collisions describe successfully, particle spectra and anisotropic flow coefficients v_n
- Many improvements in recent years have started:
  - viscosities and coupling terms between viscosities - done
  - initial state fluctuations - done
  - anisotropic fluid dynamics - preliminary
  - external fields (magnetic field, order parameters, etc) - preliminary

No code has it all (yet)!

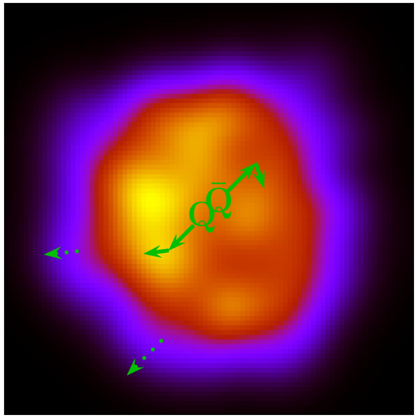
- **NOT included so far: thermal fluctuations!**

Dynamics of heavy quarks in the QGP

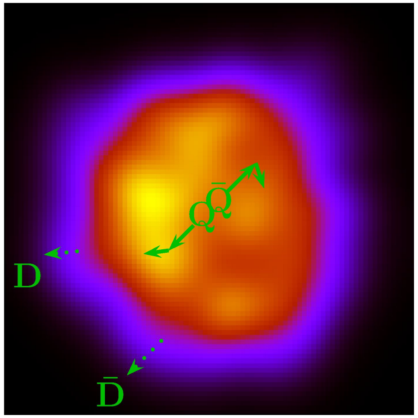
Initialization



In-medium interaction



Hadronization



Consistent coupling to the evolution of the QGP:

- Results depend on QGP modeling

- Strong uncertainties from nuclear shadowing!

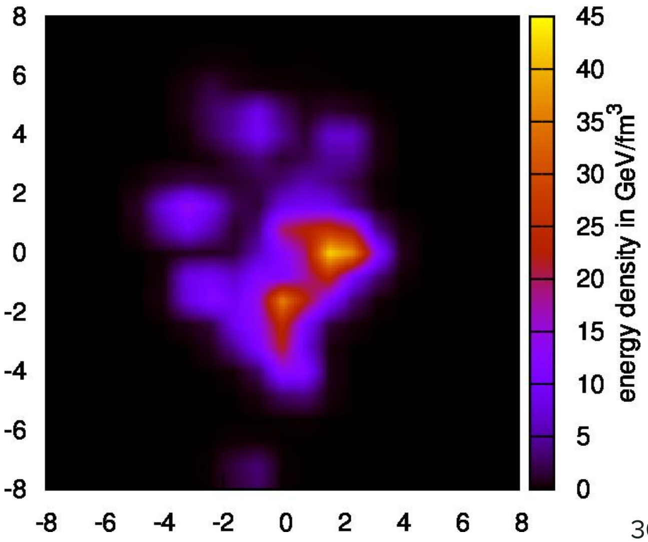
- Constrain shadowing by HF data from p-Pb

- Scattering processes and hadronization must be consistent with the EoS and the fluid dynamics!

- Include the interaction jets -- medium!

- Dynamical realization of coherent emission!

- Dynamical realization of (sequential) hadronization!

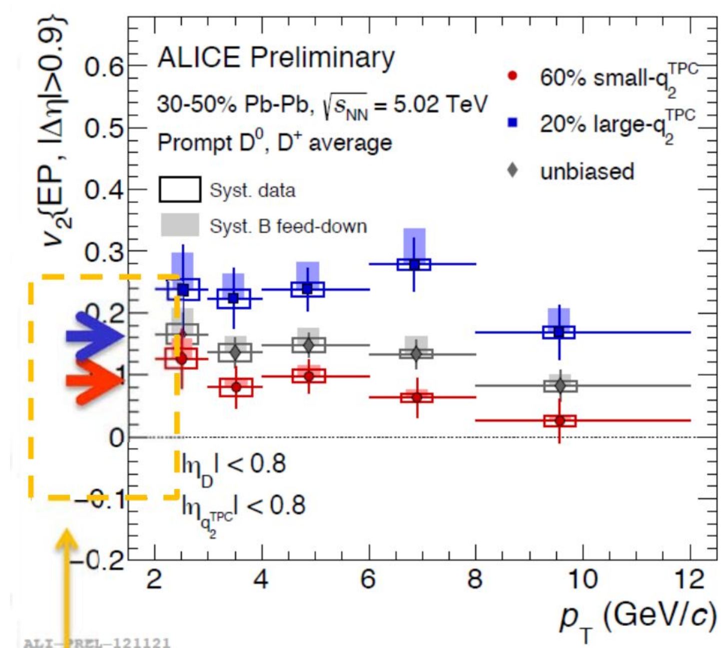


EPOS 3 + heavy quarks and jets

Progress: consistent production of heavy quarks and jets within the EPOS IC.

Goal: study correlations between the probes and the bulk

- Include the interaction between probe and medium, i.e. energy and momentum repartition in the QGP   See also: E. Iancu et al, arxiv:1506.07871
- Study hybrid approaches between jet shower evolutions and leading parton energy loss
- Follow the full chemistry of coalescence/ fragmentation
- Relevant observables require a true event-by-event treatment and an analysis that is as close to experiment as possible
- Combine open and hidden HF in a consistent dynamical framework
- Determine key observables to pin down the correct physics!



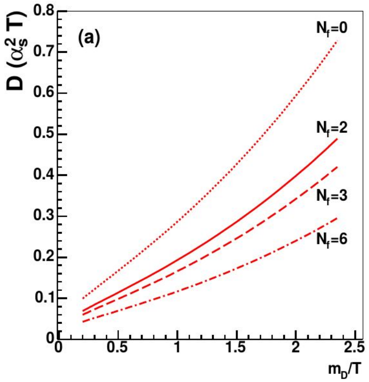
PB Gossiaux et al, QM 2017, NPA967 (2017)

Own predictions (@2.76 TeV)

Modelling of HIC - future developments in France

- Pre-equilibrium phase **IPhT Saclay**
  - How does the QGP thermalize, fluidize? How to map to fluid dynamics?
- The initial state at $\mu_B \neq 0$ **Subatech**
  - dynamical fluidization, multi-fluid descriptions
  - cascading of multi scatterings in EPOS
- Probes of the QGP - open and hidden heavy flavor: **IPhT Saclay, Subatech**
  - Hadronization of HF mesons, baryons and charmonium, bottomonium states
  - Dynamical realization of coherent emission, an open quantum system in the QGP, etc.
  - Consistent coupling between the QGP and the probe particles, nuclear shadowing, correlations between bulk and probe
- Probes of the QGP - jet quenching: **IPhT Saclay, Subatech, ...**
  - Jet energy deposition in the medium, embedding of energy loss into fluid dynamics
  - Identify jet measurements (RAA, shape, substructure, etc) which are related to properties of the QGP

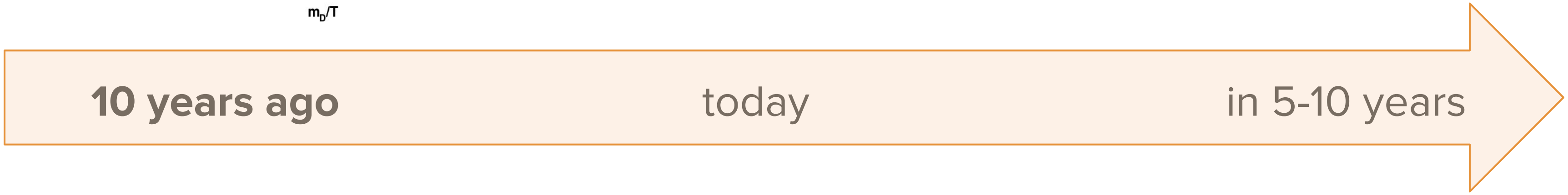
Main axes - heavy quarks and jets

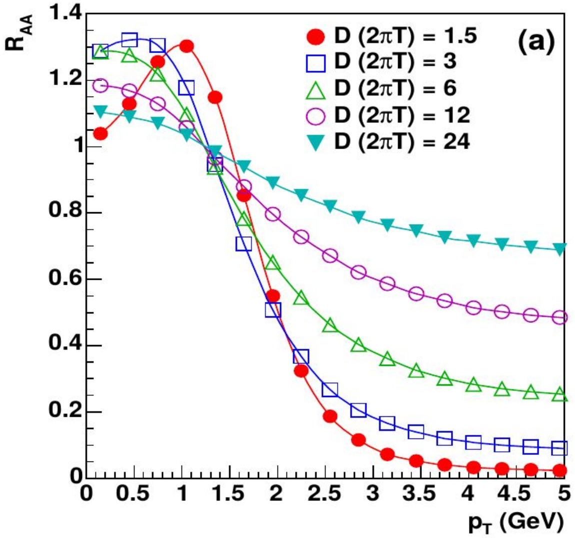


Pioneering work by G. Moore and D. Teaney!

- Elastic energy loss with simple ingredients
- Simplistic medium evolution (with p = 1/3e)
- No hadronization

G. Moore, D. Teaney, PRC71 (2005)

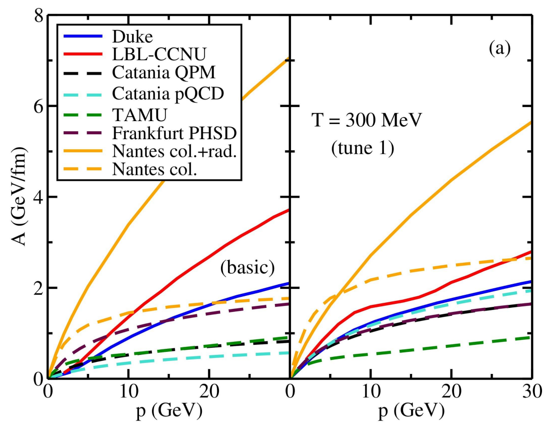




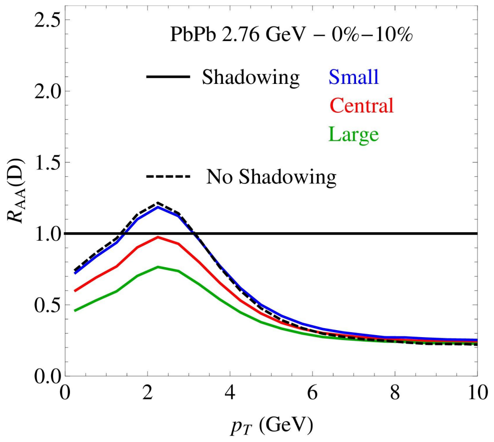
Main axes - heavy quarks and jets

- Many models describe the existing experimental data qualitatively/semi-quantitatively.
- These models have very different ingredients!
- Ongoing community effort to pin down the differences and develop strategies to identify the correct physics.
- Large uncertainties from nuclear shadowing and hadronization!
- Some inconsistency between QGP modeling and in-medium interaction!

10 years ago → **today** → in 5-10 years



S. Cao et al, PRC99 (2019)



R. Rapp et al, NPA979 (2018)

Main axes - heavy quarks and jets

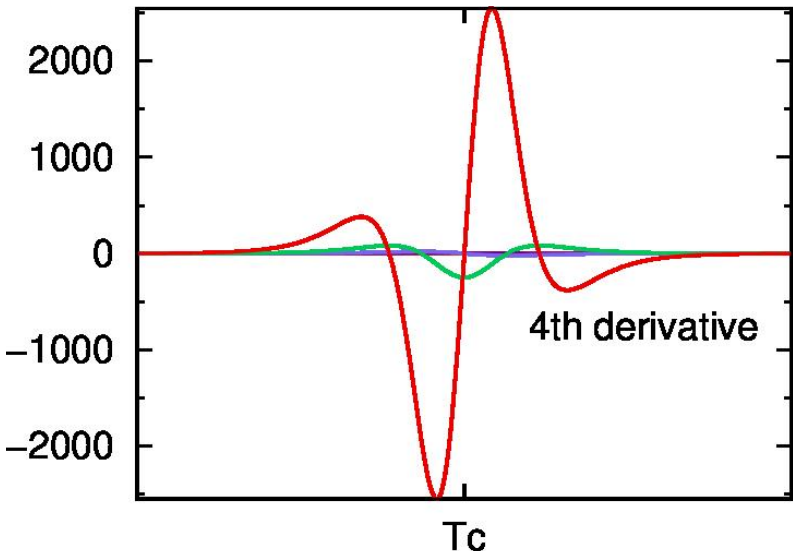
Coherence between
- **the in-medium interaction,**
- **the degrees of freedom describing the QGP,**
- **the energy loss description,**
- **and the hadronization process!**

10 years ago — today — **in 5-10 years**

Bridging between
- **perturbative and nonperturbative physics,**
- **elastic and inelastic energy loss,**
- **weak and strong coupling scenarios,**
- **quasi-particles and holographic QCD**
- **vacuum-like and medium-induced radiation**
- **small and large systems…**

…in well defined / constraint approximations / phenomenological models!

Role of fluctuations



- Derivatives reveal more details about the phase transition.
- Derivatives of thermodynamic quantities are related to fluctuations.

=> Obtain more information about the phase transition from fluctuation observables!

Susceptibilities relate to fluctuations in multiplicities

$$\chi_1 = \frac{1}{VT^3}\langle N\rangle\,, \quad \chi_2 = \frac{1}{VT^3}\langle(\Delta N)^2\rangle\,, \quad \chi_3 = \frac{1}{VT^3}\langle(\Delta N)^3\rangle\,,$$

$$\chi_4 = \frac{1}{VT^3}\langle(\Delta N)^4\rangle_c \equiv \frac{1}{VT^3}\left(\langle(\Delta N)^4\rangle - 3\langle(\Delta N)^2\rangle^2\right)\,.$$

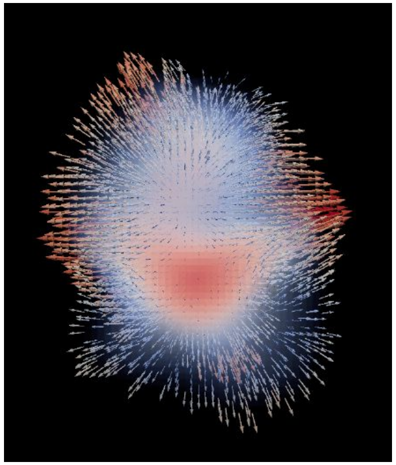
To zeroth order in volume fluctuations:

$\frac{\chi_2}{\chi_1} = \frac{\sigma^2}{M}$	$\frac{\chi_3}{\chi_2} = S\sigma$	$\frac{\chi_4}{\chi_2} = \kappa\sigma^2$
variance	Skewness	Kurtosis

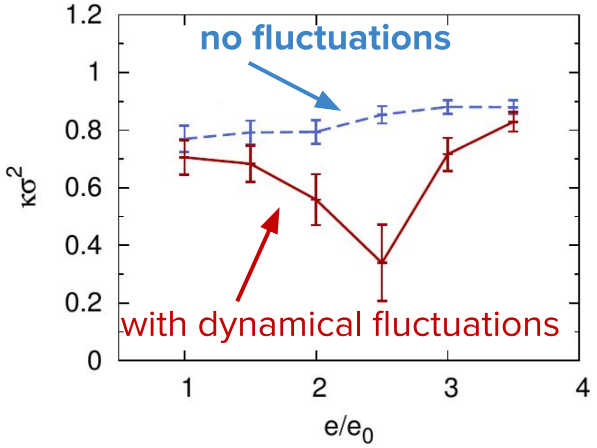
Can be applied to freeze-out conditions, the critical point search and fluid dynamics!

Role of fluctuations & the phase transition

- Fluctuation observables, in particular higher-order cumulants of net-baryon number, are sensitive to critical phenomena at the phase transition.
- So far predictions are based on grand-canonical thermodynamics, but HIC are highly dynamical!



=> Need to include the fluctuation dynamics into descriptions of HIC!



C. Herold, MN, et al, PRC93 (2016)

- **Propagate fluctuations of the chiral order parameter and fluid dynamical fields coupled to the regular evolution**
- **Highly non-trivial due to conceptual challenges, e.g. renormalization of the EoS and the transport coefficients.**
- **Numerical implementation requires new algorithms!**

So far, largely unexplored territory!

Role of fluctuations and the transport coefficients

The viscosity is related to the two-point correlator of the energy-momentum tensor via the Green-Kubo formula according to the fluctuation-dissipation theorem. **In standard fluid dynamical simulations of HIC only the dissipative part is included so far...**

Include fluctuations consistently!

- symmetrized correlator:

$$G_S^{xyxy}(\omega, \mathbf{0}) = \int \mathrm{d}^3x\mathrm{d}t\, e^{i(\omega t - \mathbf{k}\cdot\mathbf{x})} \left\langle \frac{1}{2}\{T^{xy}(t,\mathbf{x}), T^{xy}(0,\mathbf{0})\} \right\rangle$$

- for the shear-shear contribution $\Rightarrow$

$$G_{R,\mathrm{shear-shear}}^{xyxy}(\omega, \mathbf{0}) = -\frac{7T}{90\pi^2}\Lambda^3 - i\omega\frac{7T}{60\pi^2}\frac{\Lambda}{\gamma_\eta} + (i+1)\omega^{3/2}\frac{7T}{90\pi^2}\frac{1}{\gamma_\eta^{3/2}}$$

cutoff-dependent fluctuation contribution to the pressure

cutoff-dependent correction to η

frequency-dependent contribution to η and τ_π

P. Kovtun et al, PRD84 (2011); C.Chafin, T. Schäfer, PRA87 (2013); P. Romatschke et al, PRA87 (2013)

The role of numerics and computational resources

Time for two heavy nuclei to collide and produce particles:

~ 10^{-23} seconds

Time for a simulation of two colliding heavy nuclei and particle production:

~ 1 hour

Example: even with a Gaussian Process Emulator the Bayesian analysis of the temperature dependence of bulk and shear viscosity costs 100 Mio CPU hours.

This assumes $O(10^4)$ events per point, fluctuation studies easily require $O(10^8)$ events per point…

The role of numerics and computational resources

Time for two heavy nucl... produce particles:

Time for ... ion:

Need people with the expertise of writing, maintaining, running and analysing high-performance computing codes.
Connections to GT09 (calcul)

Example:
Emulator th...
temperature de...
shear viscosity costs 100...

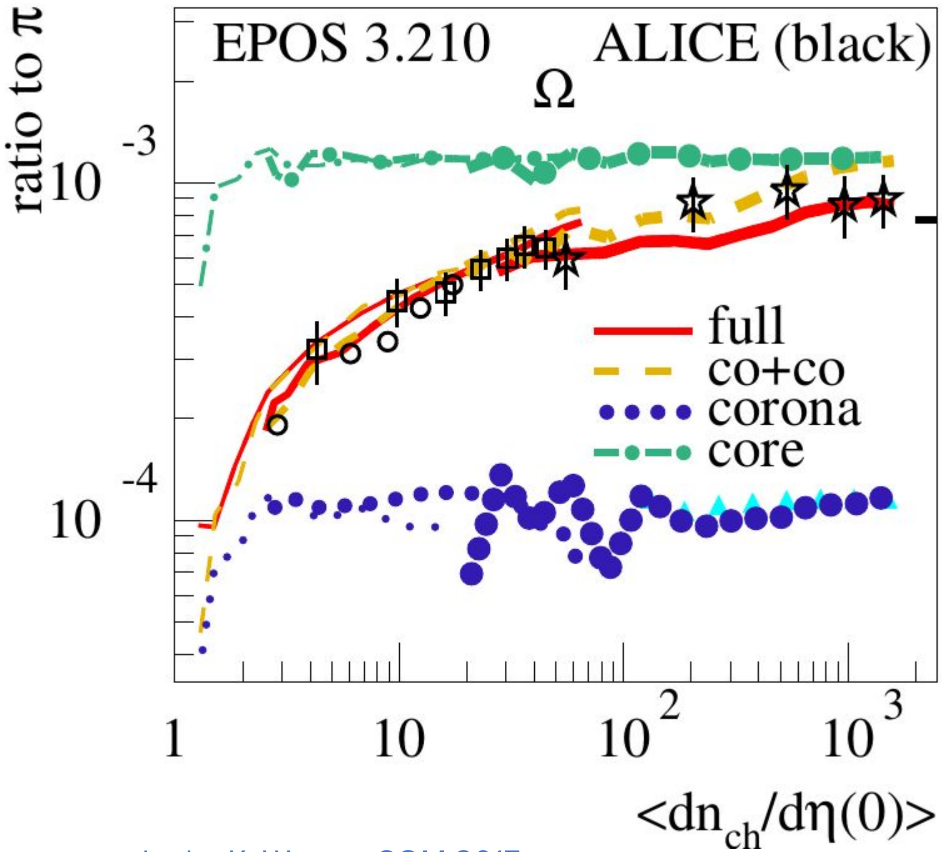
This assumes O(10^4) even... per point, fluctuation studies easily require O(10^8) events per point...

What about proton-proton and proton-nucleus?

- From low-multiplicity pp to pA to central AA - all is QCD!

In EPOS:
=> increasing multiplicity
=> increasing number of pomerons
=> increasing Qs (individual saturation scale for each pomeron)
=> harder pomerons
=> harder strings
=> more high pT particles
=> strong increase of <pT>
=> strong nonlinear increase of D meson or J/psi multiplicity

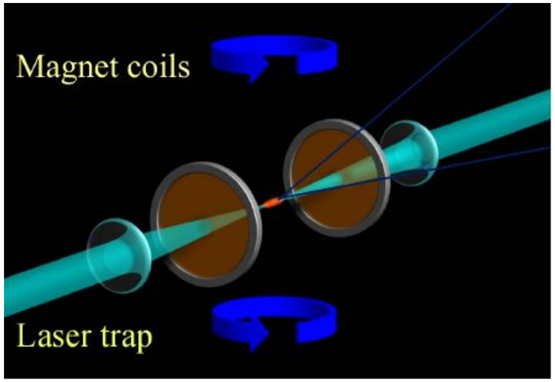
- Can also be tested with resonance production



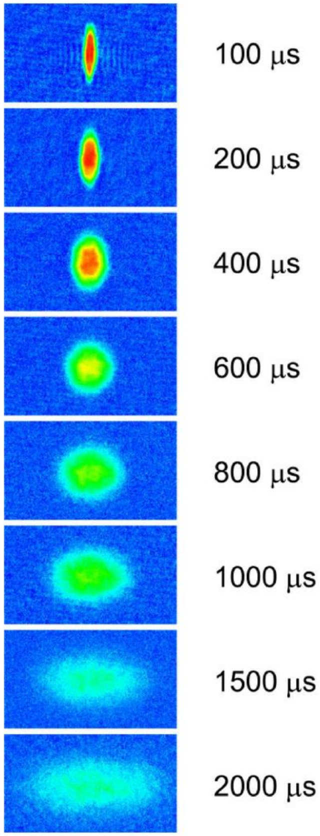
plot by K. Werner, SQM 2017

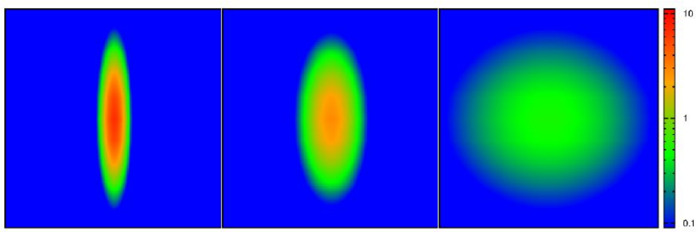
Connections to related systems

- The QGP shares features with other strongly coupled quantum systems, like **ultracold atomic gases**.
- UAG: unique experimental playground to study fermionic many-body problems: variable density, temperature and interatomic interaction strength
- Elliptic flow measurements: release the UAG from the trapping potential and take pictures of the expansion.
- Can theoretically be well described by anisotropic fluid dynamics:

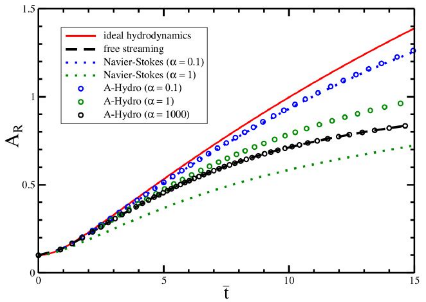


K.M. O'Hara et al. Science 298 (2002)

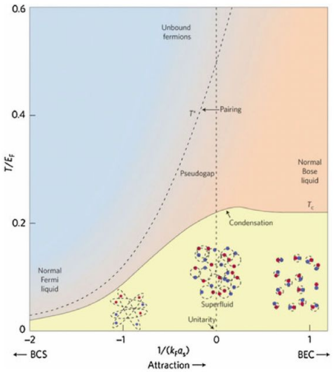




M. Bluhm et al, PRA92 (2015)



- **Include fluctuations in anisotropic fluid dynamics and study the BCS-BEC crossover and the second-order superfluid phase transition - in equilibrium and dynamically!**
- **Connect to further research groups in France: e.g. IPN Orsay (superfluidity in UAG and neutron stars) or IP2I Lyon!**



More challenges - future developments in France

- Fluctuations
  - Include dynamical fluctuations in fluid dynamics and the simulation of HIC
  - Propagate fluctuations of the chiral order parameter explicitly.
  - Renormalization of FD in theory and practice
  - New numerical approaches needed

Subatech !

- Anisotropic fluid dynamics -> extends the validity of fluid dynamics
- External fields

Subatech ?

- Small systems
  - Fluid dynamics vs in-medium modification of probes
  - Consistent description of minimum-bias pp

IPhT Saclay, LLR, Subatech

- Bayesian statistical analysis for unbiased determination of all parameters
  - promote it to a **standard** procedure for tuning any HIC (pp, pA) simulation tool
  - set up the numerical environment with a sufficient background in statistical analysis
  - requires large computational power
- Interdisciplinarity with cold atomic gases
  - fluctuating anisotropic fluid dynamics at the phase transition

IPN Orsay, IP2I, Subatech ?

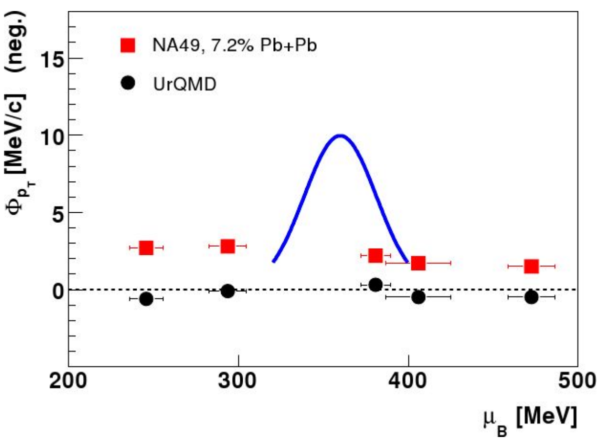
Main axes - dynamics of fluctuations

Predictions for the critical point only based on thermodynamics !

- Very rough estimates for finite time effects
- No coupling of critical fluctuations to the evolution
- Typical time evolution for the background temperature : a sudden quench

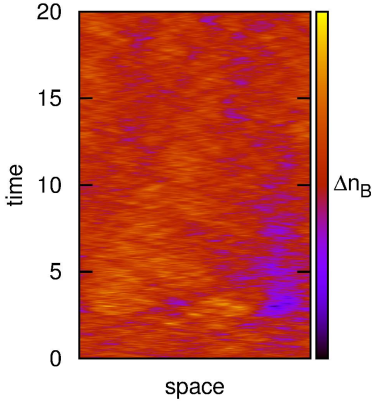
M. Stephanov et al, PRL81 (1998), PRD60 (1999)

10 years ago | today | in 5-10 years



NA49 Collab. JPG 35 (2008)

Main axes - dynamics of fluctuations



First dynamical models

- propagate fluctuations of the chiral order parameter
- evolve fluctuations in net-baryon density in 1+1d
- include some version of fluid dynamical fluctuations
- or try to avoid stochastics by truncation on the dynamics of n-point correlation functions

10 years ago **today** in 5-10 years

- **No renormalization of the lattice spacing dependence in 3d performed!**
- **No systematic numerical implementation applied!**
- **Typically no coupling to all sources of fluctuations…!**

Main axes - dynamics of fluctuations

Fluctuating dissipative fluid dynamics with

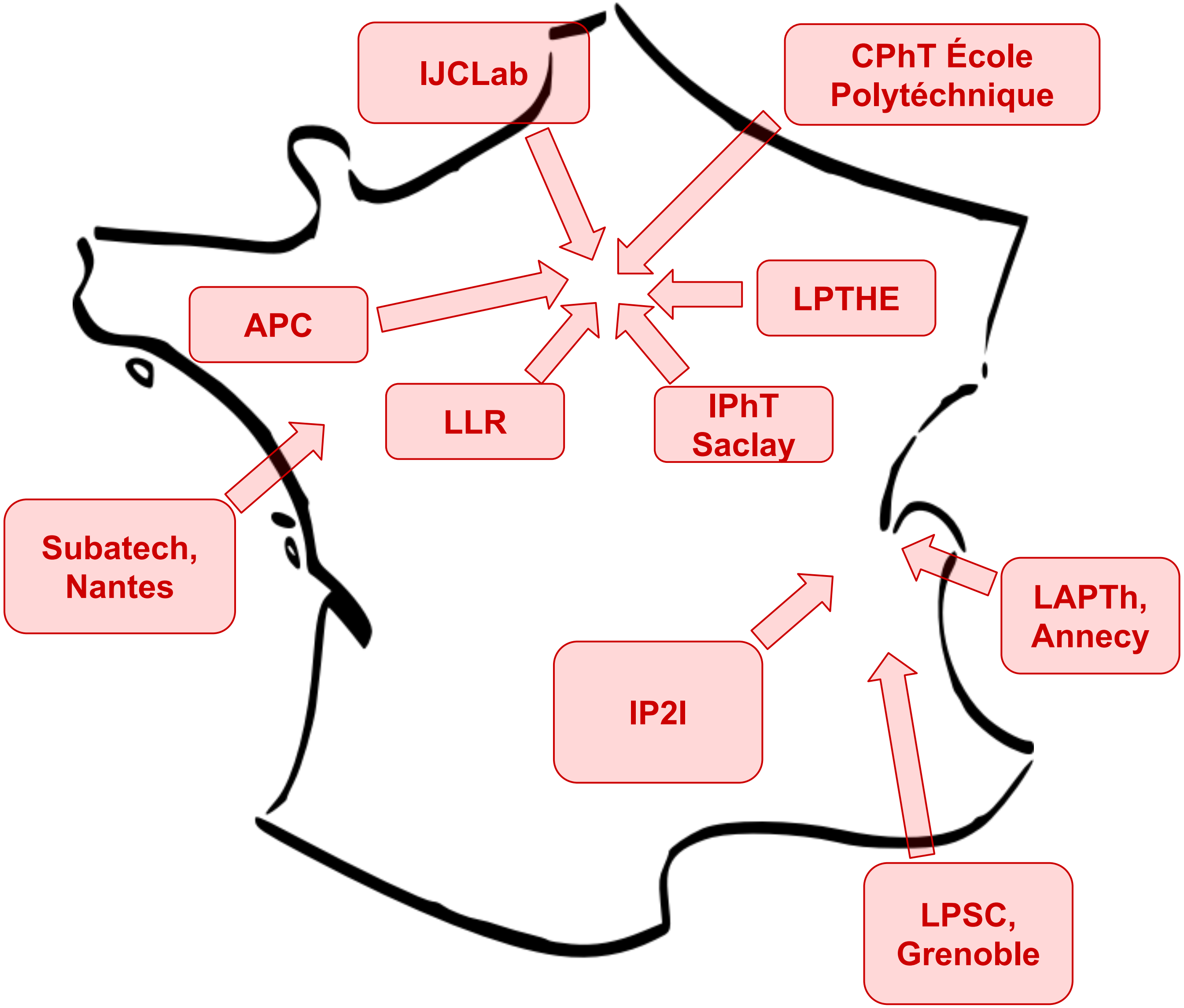
- **renormalized equation of state and transport coefficients,**
- **thoroughly tested numerical algorithms,**
- **coupling to initial state fluctuations and final state hadrons**

10 years ago — today — **in 5-10 years**

Event-by-event applications to

- **HIC (pp, pA) to constrain parameters by Bayesian analysis,**
- **HIC at highest energy in order to extract transport coefficients,**
- **HIC at lower energies in order to study critical point observables,**
- **smaller systems in order to capture deviations from (conventional) fluid dynamics,**
- **Other strongly coupled quantum fluids, like cold atomic gases!**

Panorama of the QGP theory community



Summary

QCD under extreme conditions ranges ...

- from high-energy collisions to compact stars and astrophysics
  (with connections to ultracold atomic gases)
- from top-LHC to GSI/HADES energies
- from pp to pA to heavy-ion collisions
- from collective phenomena to rare probes
- from strong to weak coupling

→ it all needs to be described coherently!

APPENDIX

Transport coefficients - shear viscosity

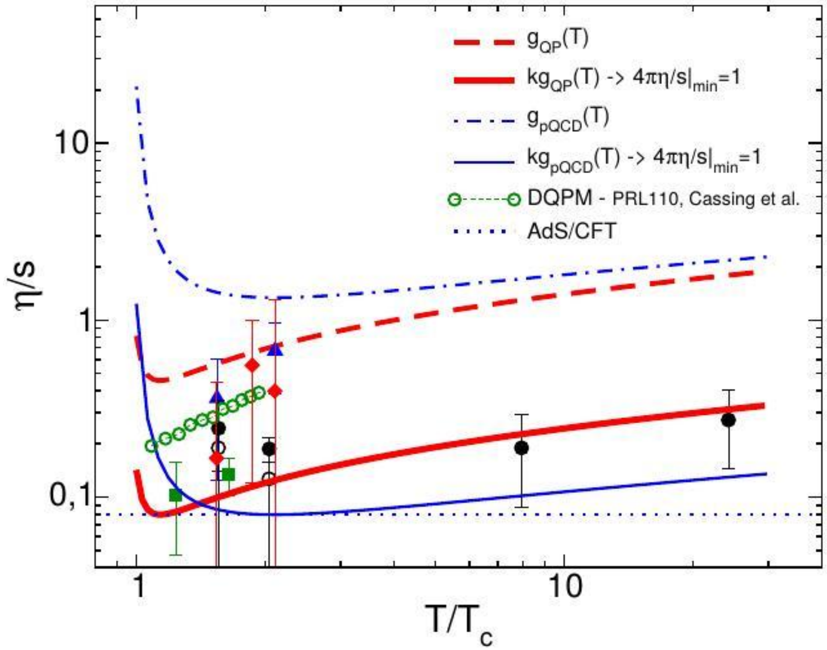
- Close to equilibrium the QGP can be characterized by transport coefficients, such as the shear and bulk viscosities, charge conductivities and diffusion or energy loss coefficients for probe particles.
- Real-time dynamics needed => **difficult for lattice QCD (Euclidean space)**
- E.g. the shear viscosity probes how easily fluctuations in momentum density propagate in the medium, can be calculated from:

Green-Kubo formula:

$$\eta = \frac{1}{T}\int_0^\infty \mathrm{d}t \int_V \mathrm{d}x^3 \langle \pi^{xy}(\mathbf{x},t)\pi^{xy}(\mathbf{0},0)\rangle$$

Large spread in theory calculations of η/s!

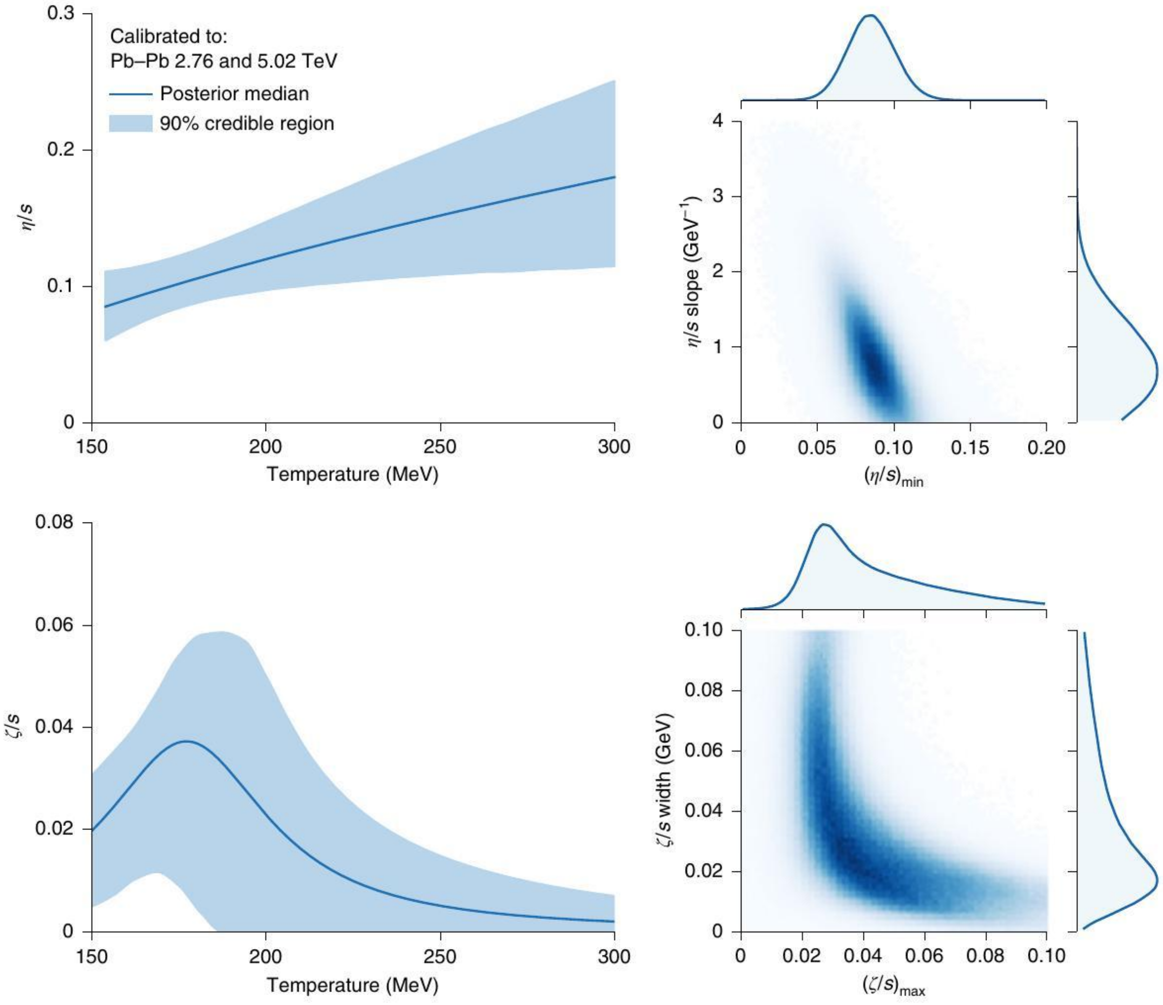
Something that needs to be done!



A.Puglisi et al, PLB751 (2015)

Bayesian analysis of shear & bulk viscosity at $\mu_B = 0$

- Parametric temperature dependence of shear and bulk viscosity.
- Model parameters tuned simultaneously.
- Likelihood distributions

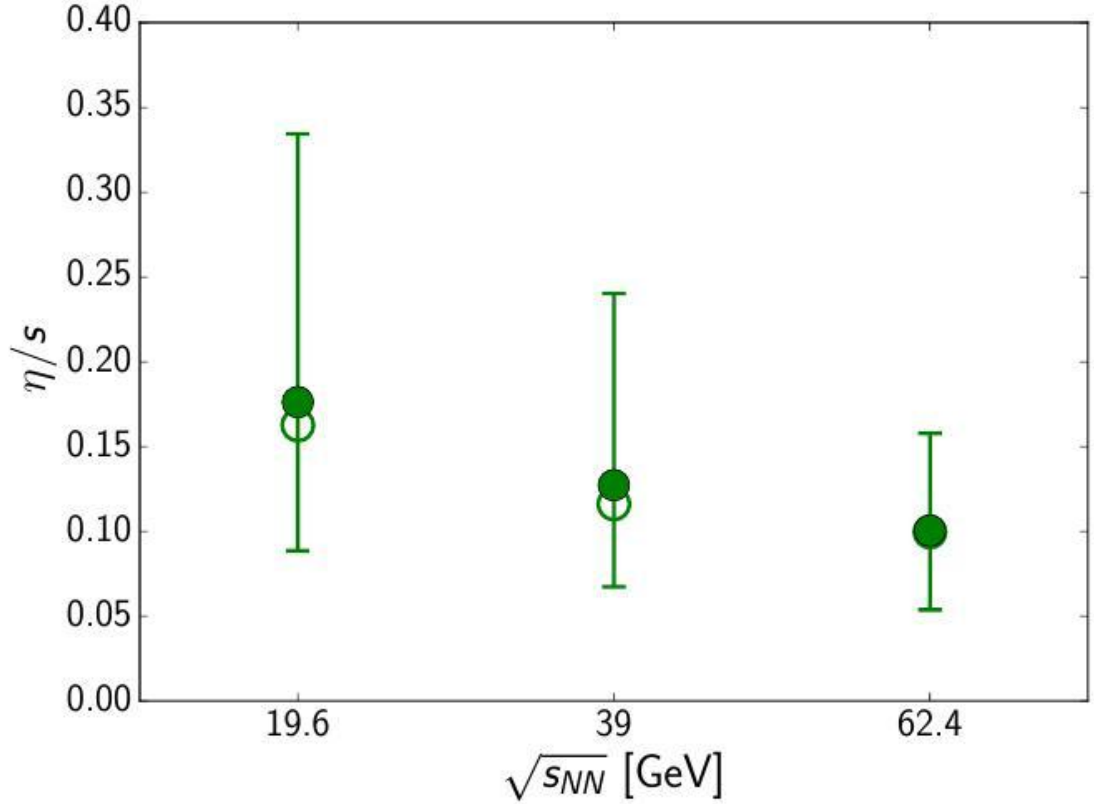


An UNBIASED model-to-data comparison should be standard for all simulations of HIC!

J. Bernhard et al, Nature Phys. 15 (2019)

Bayesian analysis of shear & bulk viscosity at $\mu_B \neq 0$

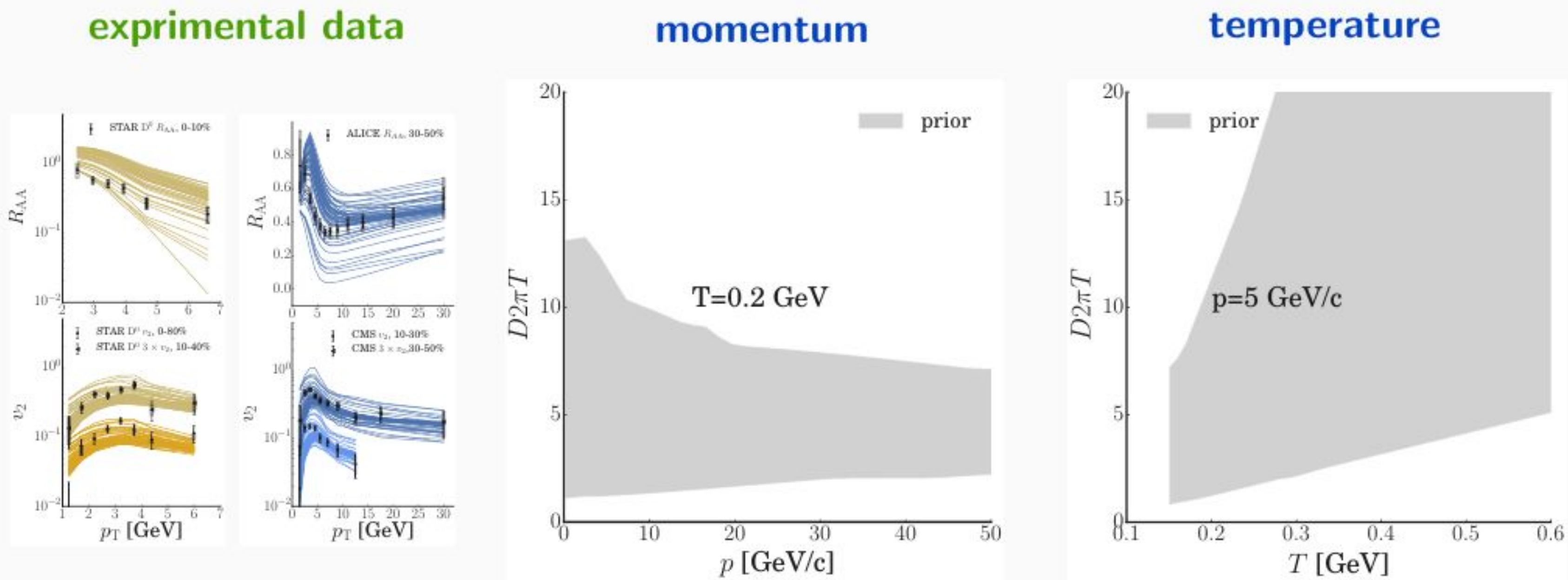
- Collision energy dependence of the shear viscosity.
- Model parameters tuned simultaneously.
- Likelihood distributions



An UNBIASED model-to-data comparison should be standard for all simulations of HIC!

J. Auvinen et al, PRC97 (2018)

Bayesian determination of HQ diffusion coefficient



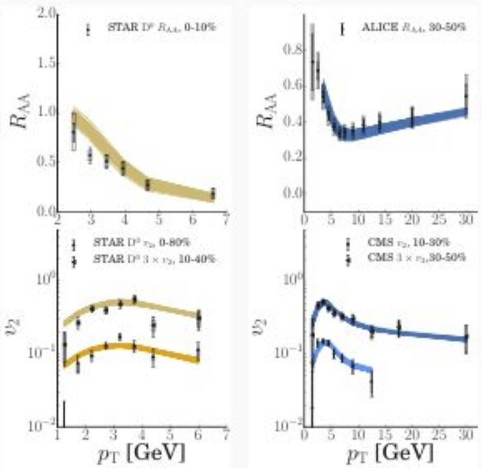
$$D_s(T,p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\rm np}(T;\alpha,\beta) + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\rm pQCD}(T,p)$$

+ distribution of all parameters and their correlations

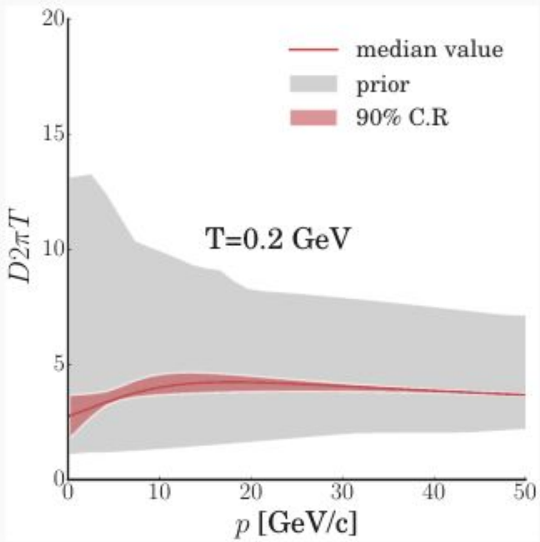
Y. Xu, MN et al, PRC97 (2018)

Bayesian determination of HQ diffusion coefficient

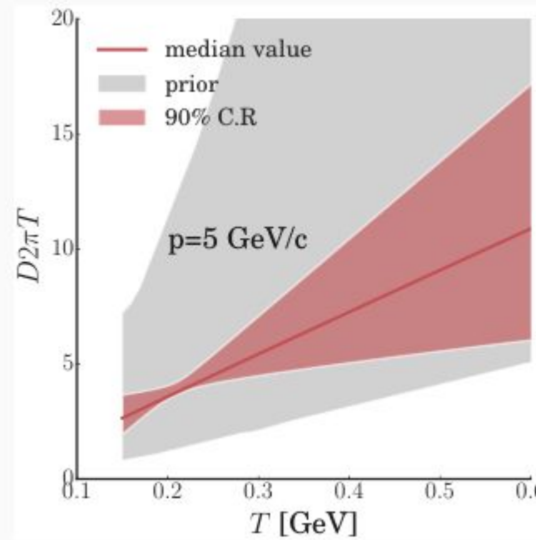
exprimental data



momentum



temperature

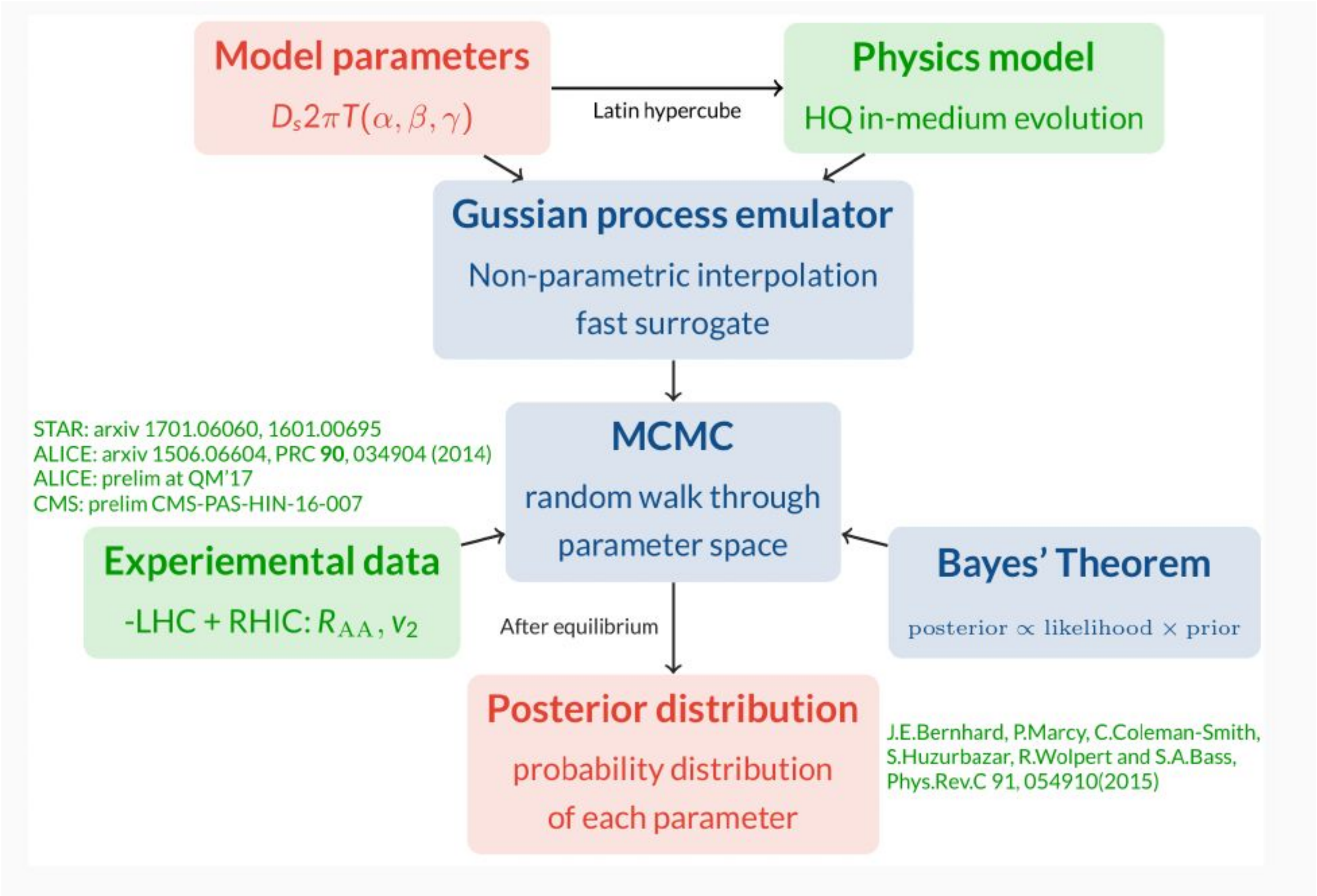


$$D_s(T,p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{np}}(T;\alpha,\beta) + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{pQCD}}(T,p)$$

+ distribution of all parameters and their correlations

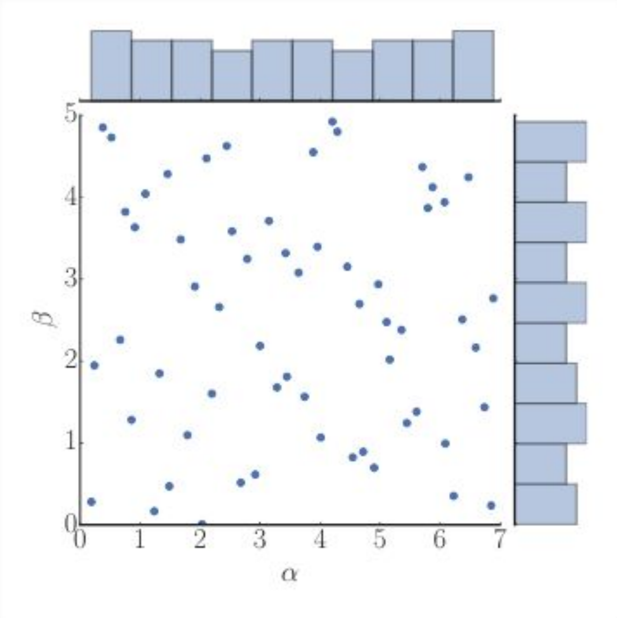
Y. Xu, MN et al, PRC97 (2018)

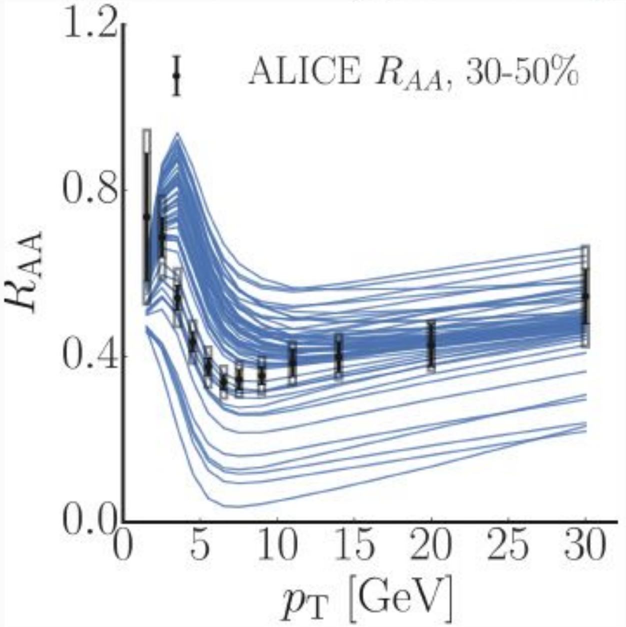
Bayesian analysis in a nutshell



Bayesian analysis in a nutshell

- Set of parameter values chosen according to a Latin hypercube algorithm.

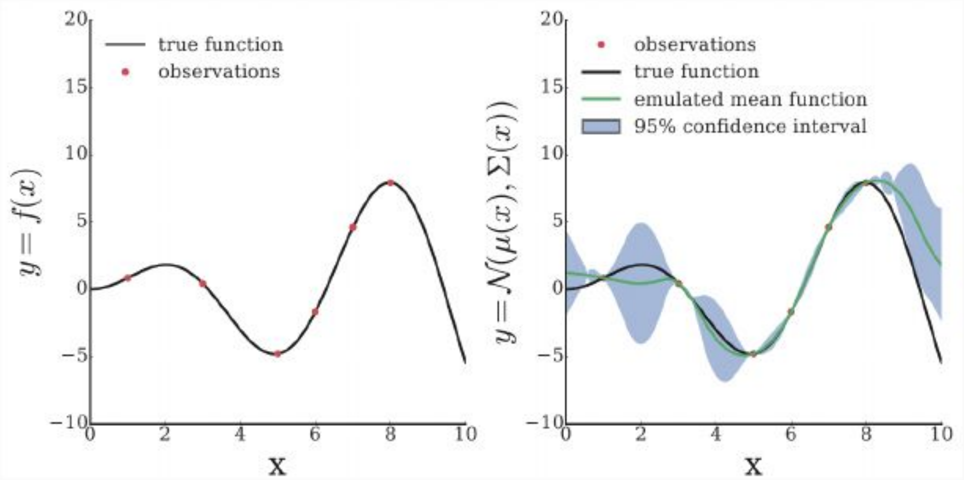




- Design points **X** are evenly spread across the *n*-dimensional parameter space.
- "Prior" parameter distribution is uniform.
- **Y** = Physics Model(**X**) gives the "prior".

Bayesian analysis in a nutshell

- Gaussian process emulator used as a fast surrogate for physics model.



Y. Xu, MN et al., PRC97 (2018)

- Calculation of exp. observables needs approx. 5000 runs of the Physics Model.
- $\mathcal{O}(1000)$ steps in the random walk are to be performed for calibration.
- Use a GP emulator for the top 8 principal components.
- Mapping from a *n*-dimensional input space to a normal distributed output.
- Interpolates and predicts the model output, provides the uncertainties of its prediction.

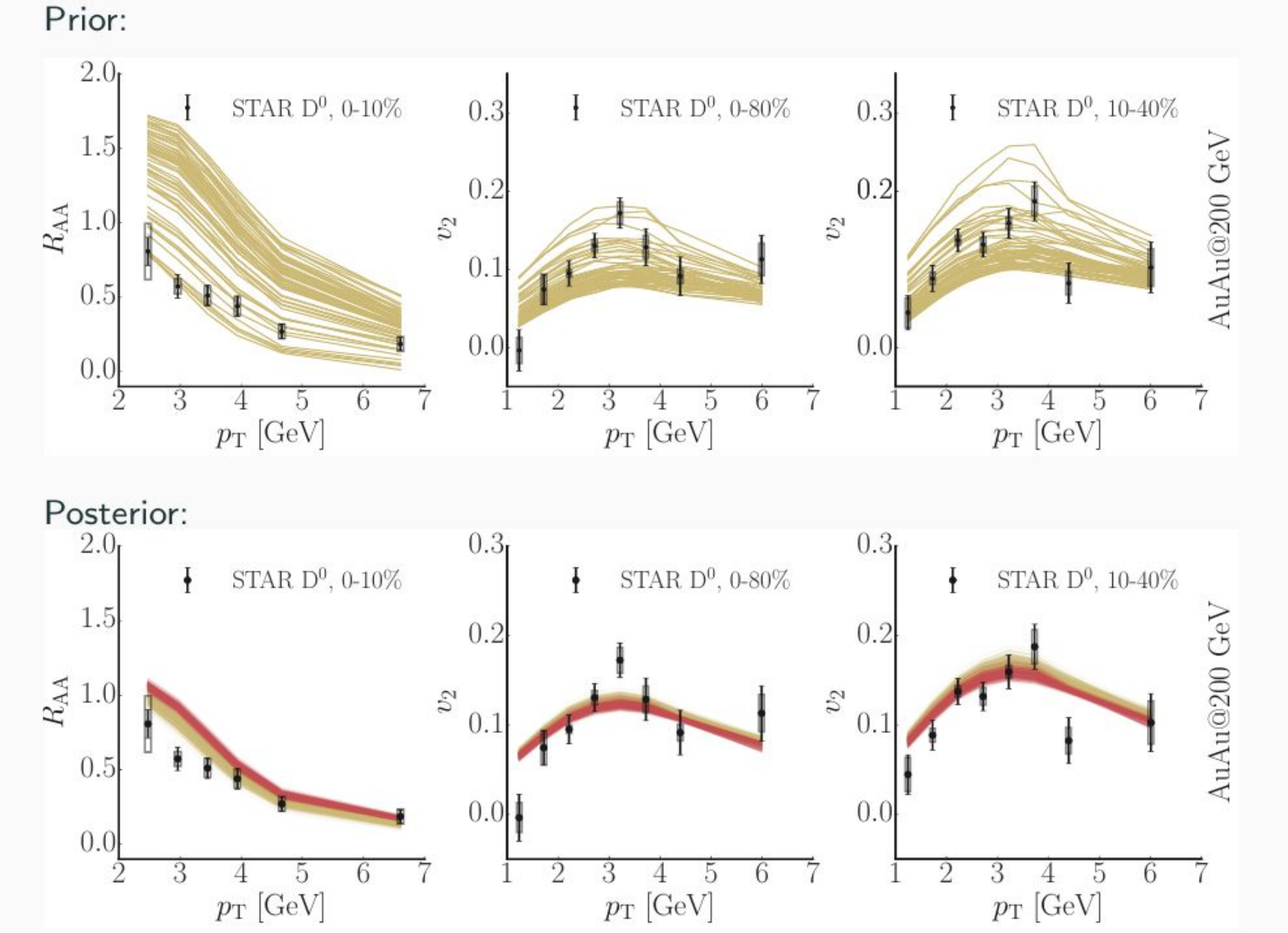
Bayesian analysis in a nutshell

- Bayes' theorem: posterior $\propto$ likelihood $\times$ prior

$$P(\mathbf{x}|\mathbf{X}, \mathbf{Y}, \mathbf{y}_{\mathrm{exp}}) = P(\mathbf{X}, \mathbf{Y}, \mathbf{y}_{\mathrm{exp}}|\mathbf{x})\, P(\mathbf{x})$$

- Likelihood $\propto \exp\left((\mathbf{y} - \mathbf{y}_{\mathrm{exp}})\, \Sigma^{-1} (\mathbf{y} - \mathbf{y}_{\mathrm{exp}})^{\mathsf{T}}\right)$
- Covariance matrix: $\Sigma^{-1} = \mathrm{diag}(\sigma^2_{\mathrm{stat}}) + \mathrm{diag}(\sigma^2_{\mathrm{sys}}) + \mathrm{diag}(\sigma^2_{\mathrm{GP}})$
- Uncorrelated experimental systematic errors assumed so far.
- Markov Chain Monte Carlo random walk is performed.
- Each step of the MCMC is accepted or rejected according to the likelihood.
- After equilibration $\rightarrow$ posterior distribution.

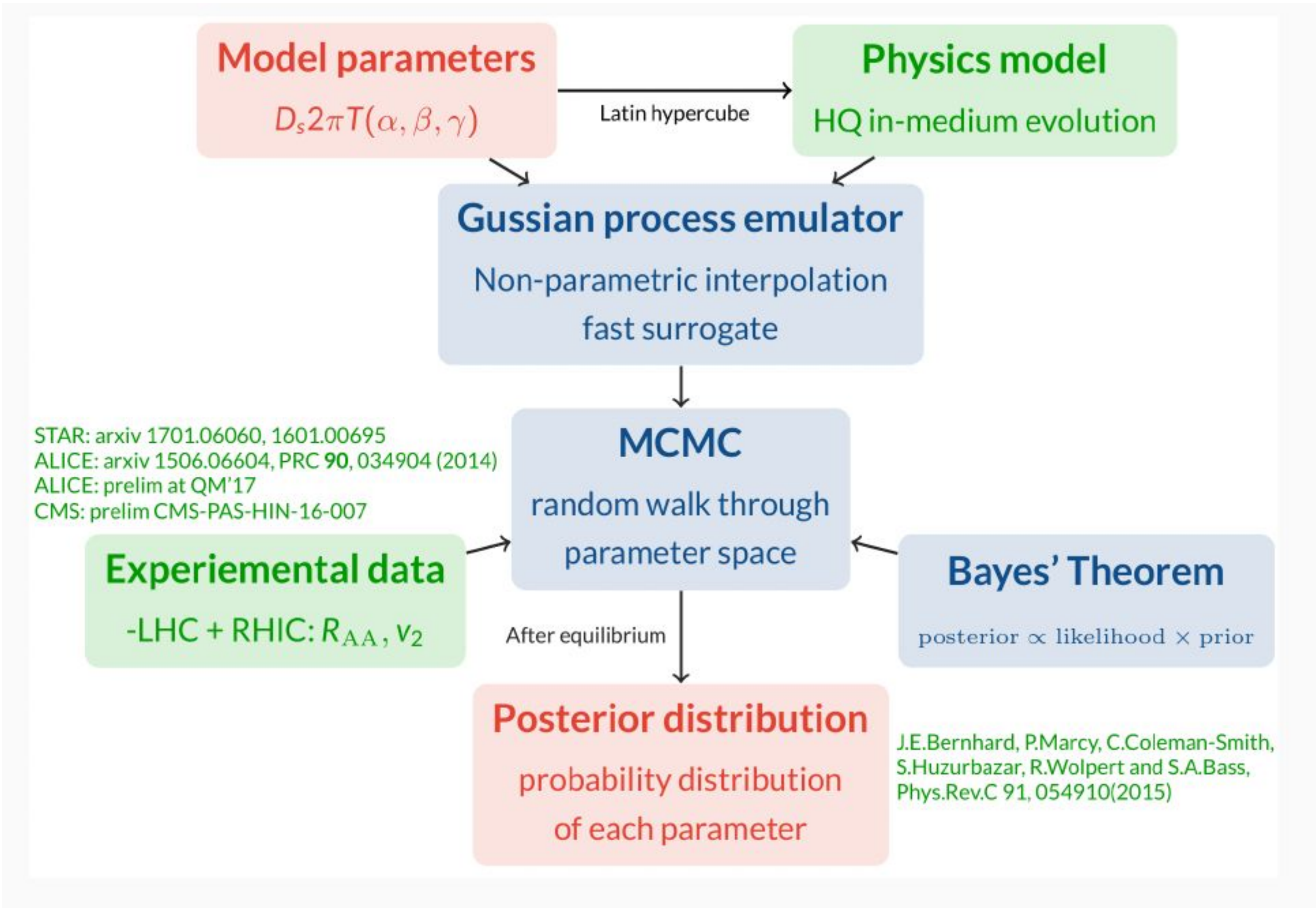
Bayesian analysis in a nutshell



red: calibrated on all energies

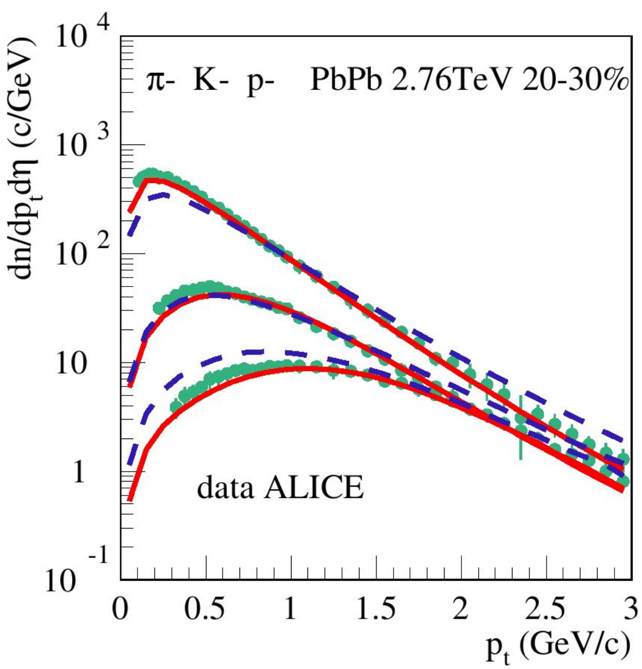
Y. Xu, MN et al., PRC97 (2018)

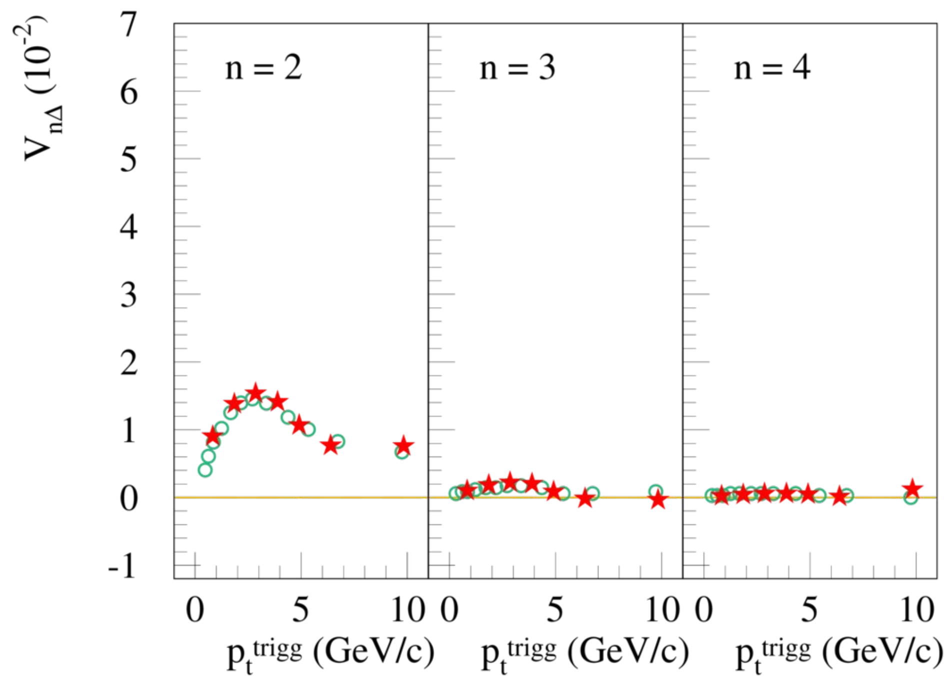
Bayesian analysis in a nutshell



Full results from EPOS

- Mapping to a viscous fluid dynamical evolution Tmunu
  - Parameter eta/s = ...
  - EoS from lattice QCD
- Cooper Frye Freeze-out **(works well for averages, not obvious for fluctuations!)**
- Hadronic final state interactions from UrQMD.



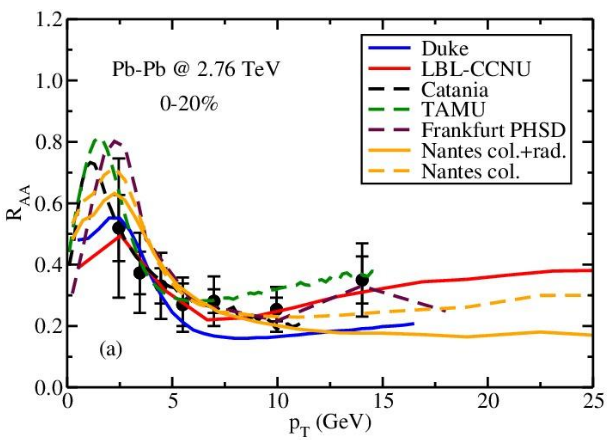


K. Werner et al, Phys. Rept. 350 (2001), PRC85 (2012), PRL112 (2014), PRC89 (2014), PRC92 (2015)

Probes of the QGP

D meson RAA

Good qualitative/ semi-quantitative description of various models

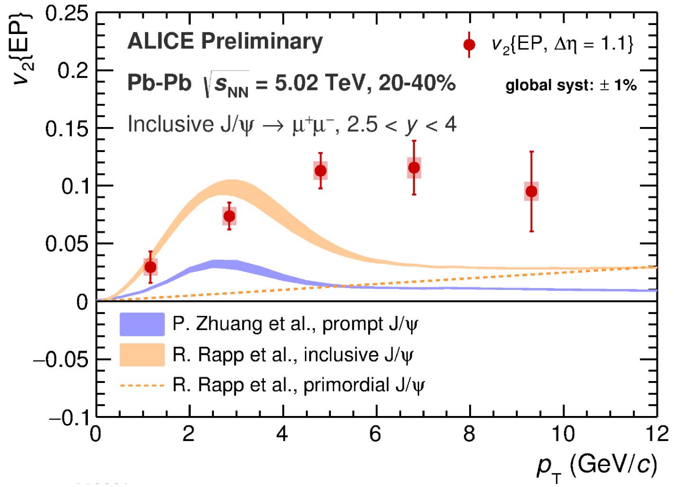


S. Cao et al, PRC99 (2019)

Large community effort to compare the different ingredients of the models!

Finite v2 of Jpsi

Some description at low pT

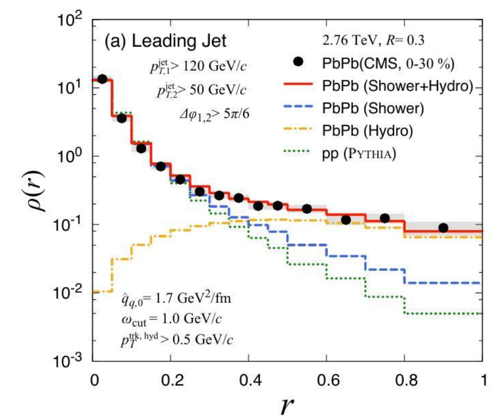


ALICE Coll., Quark Matter 2017

New theoretical ideas needed! Proper implementation into dynamical models challenging!

Jet shape function

Including medium response



Y. Tachibana, PRC95 (2017)

How can we connect jet observables to properties of QCD?