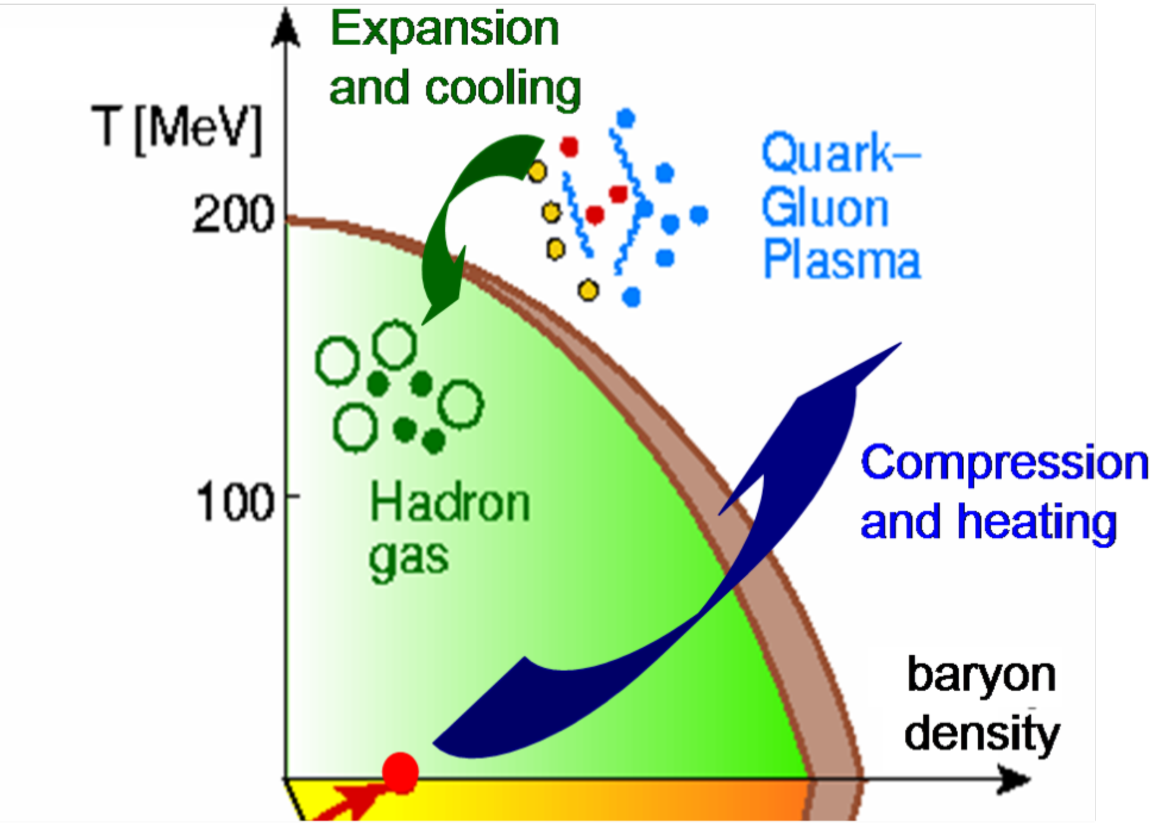
Beam Energy Scan: Observables and the Equation of State

Hannah Petersen

11.06.18, EMMI rapid reaction task force, GSI

The QCD Phase Diagram

- Main goals of the **heavy ion research**:



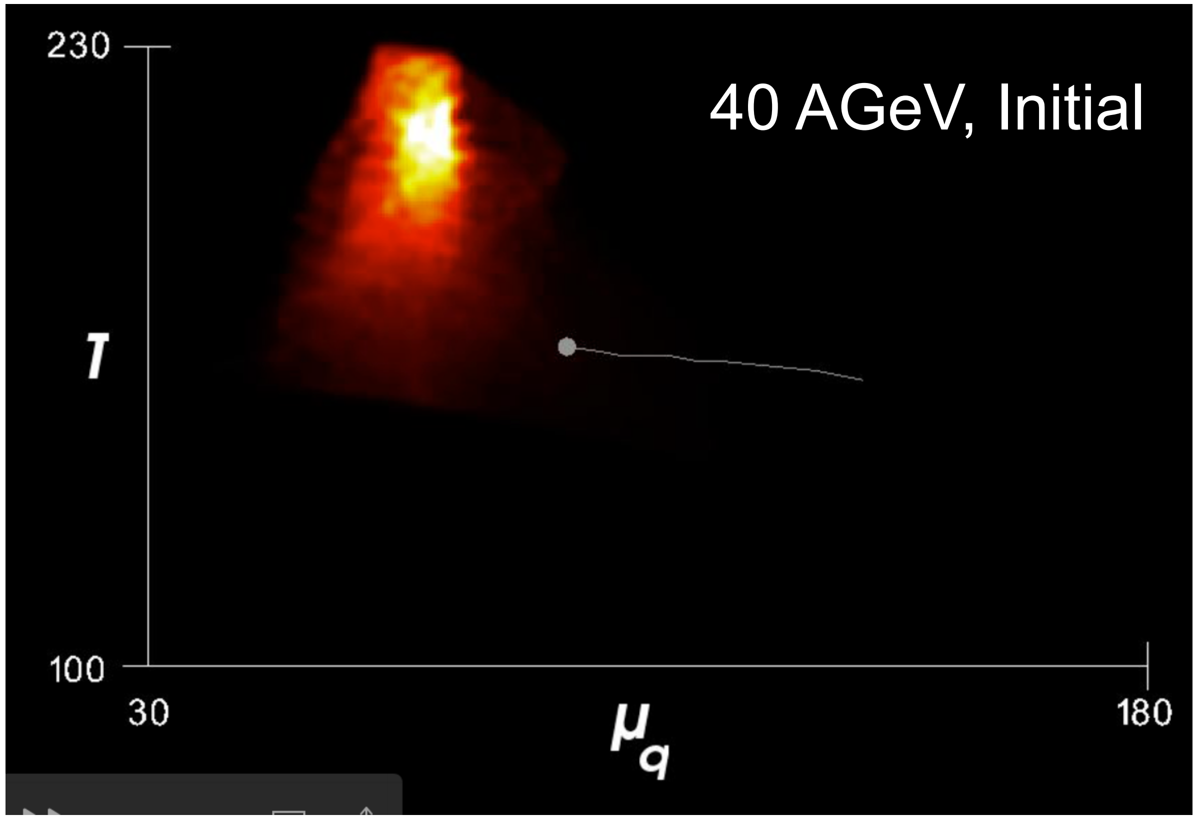
nuclei (n_B=0.14/fm³)

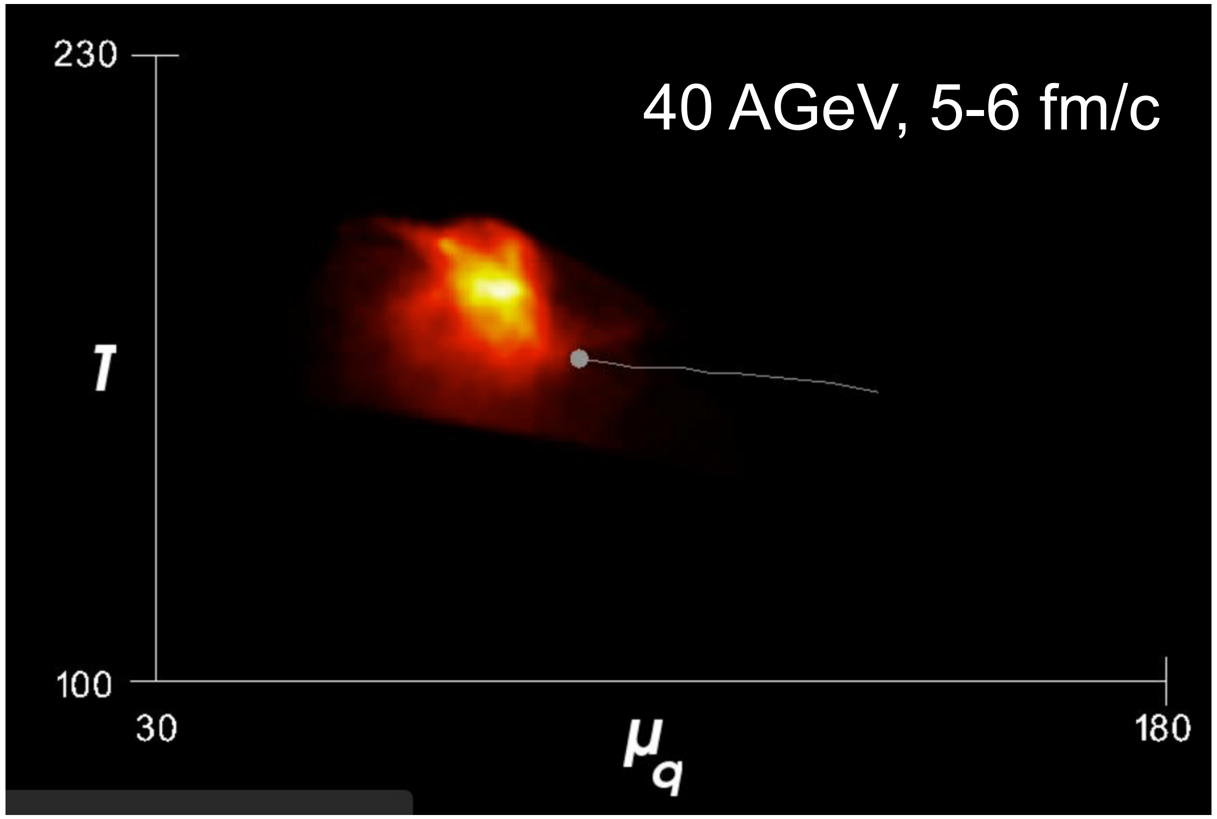
- **Questions** to be answered:
  - What is the temperature and the density? What are the relevant degrees of freedom?
  - Phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- **The** chance to learn about QCD thermodynamics that is not (yet) accessible by lattice techniques
- What is necessary to establish **definitive links** between observables and structures in the QCD phase diagram?

Finite System Size

- **Spread of the system** in temperature and baryo-chemical potential has consequences on observables

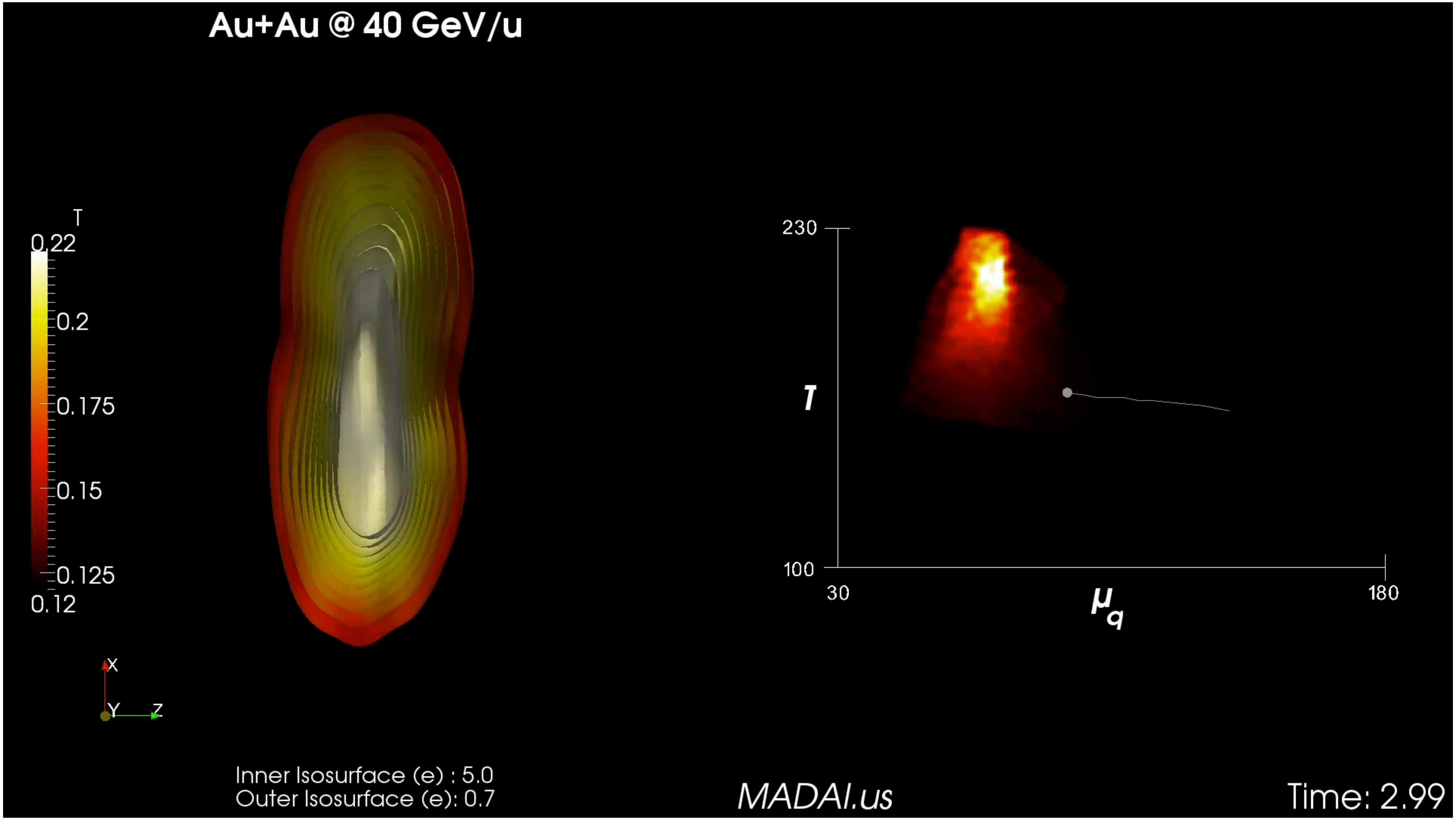




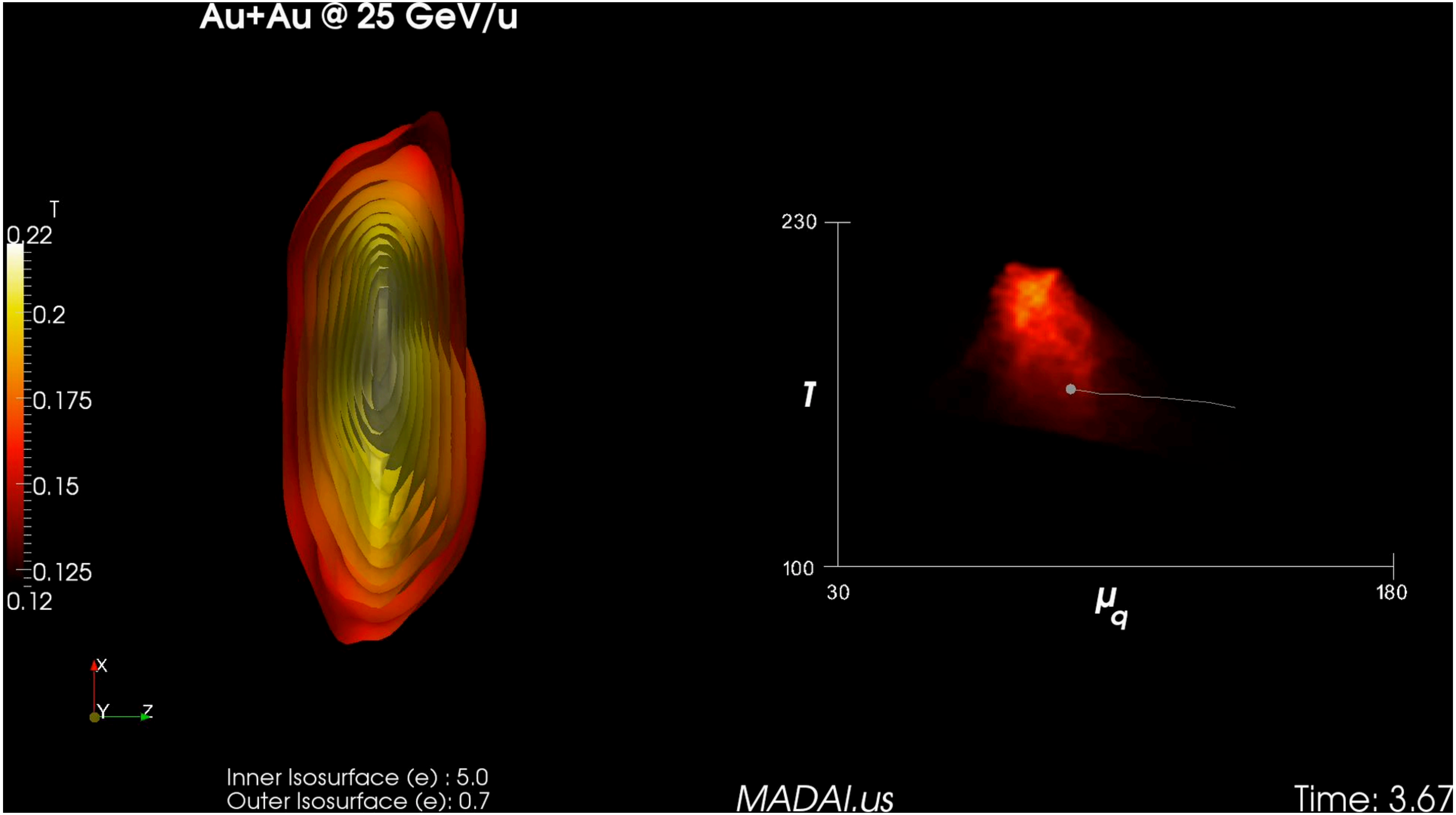
S. Bass et al, arXiv:1202.0076, CPOD 2011

- Detailed dynamical modeling is required:
  - EoS and transport coefficients in the whole phase diagram
  - Non-equilibrium dynamics at the phase transition

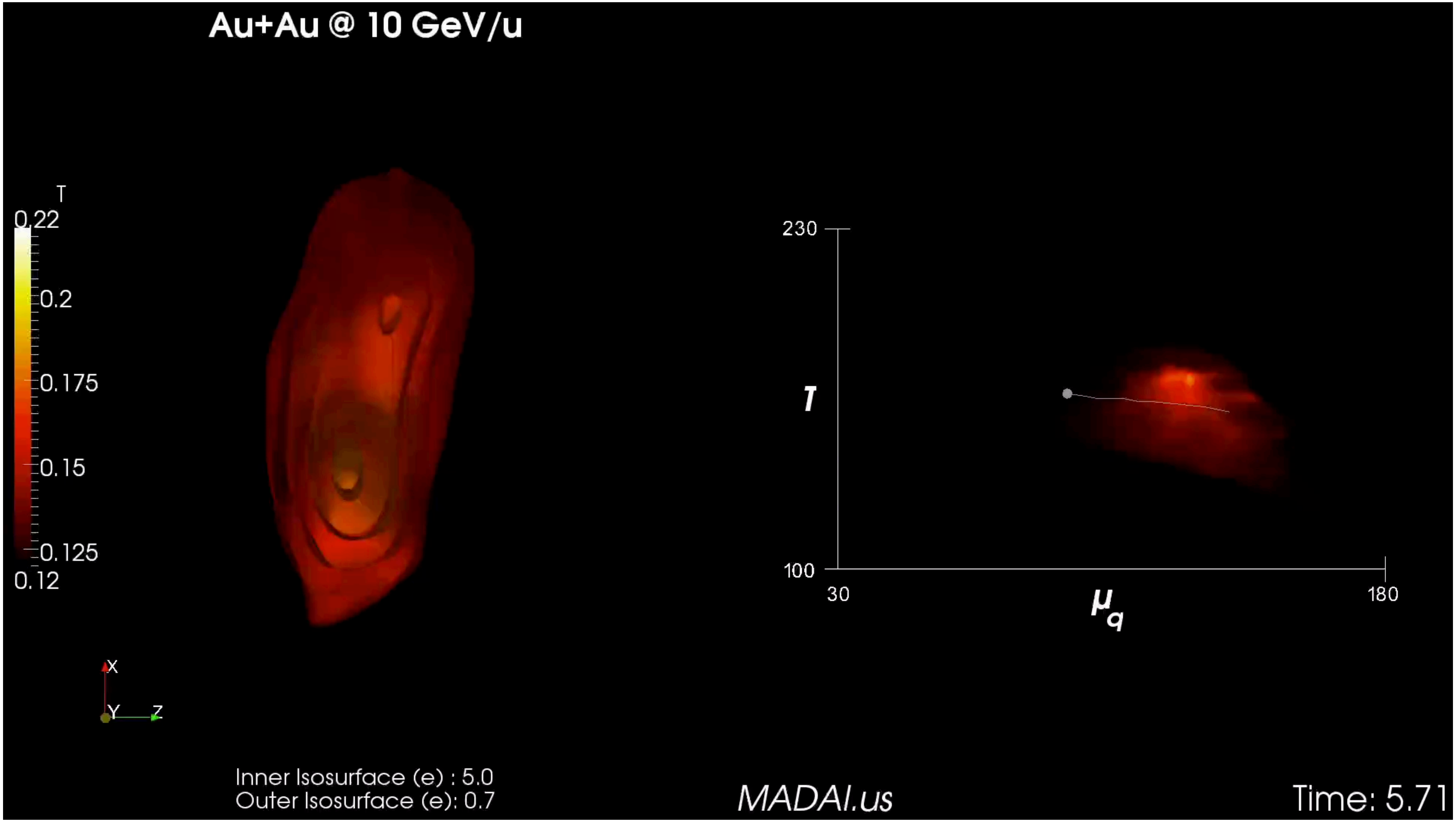
Time Evolution in Phase Diagram



FAIR Propaganda Plot :-)

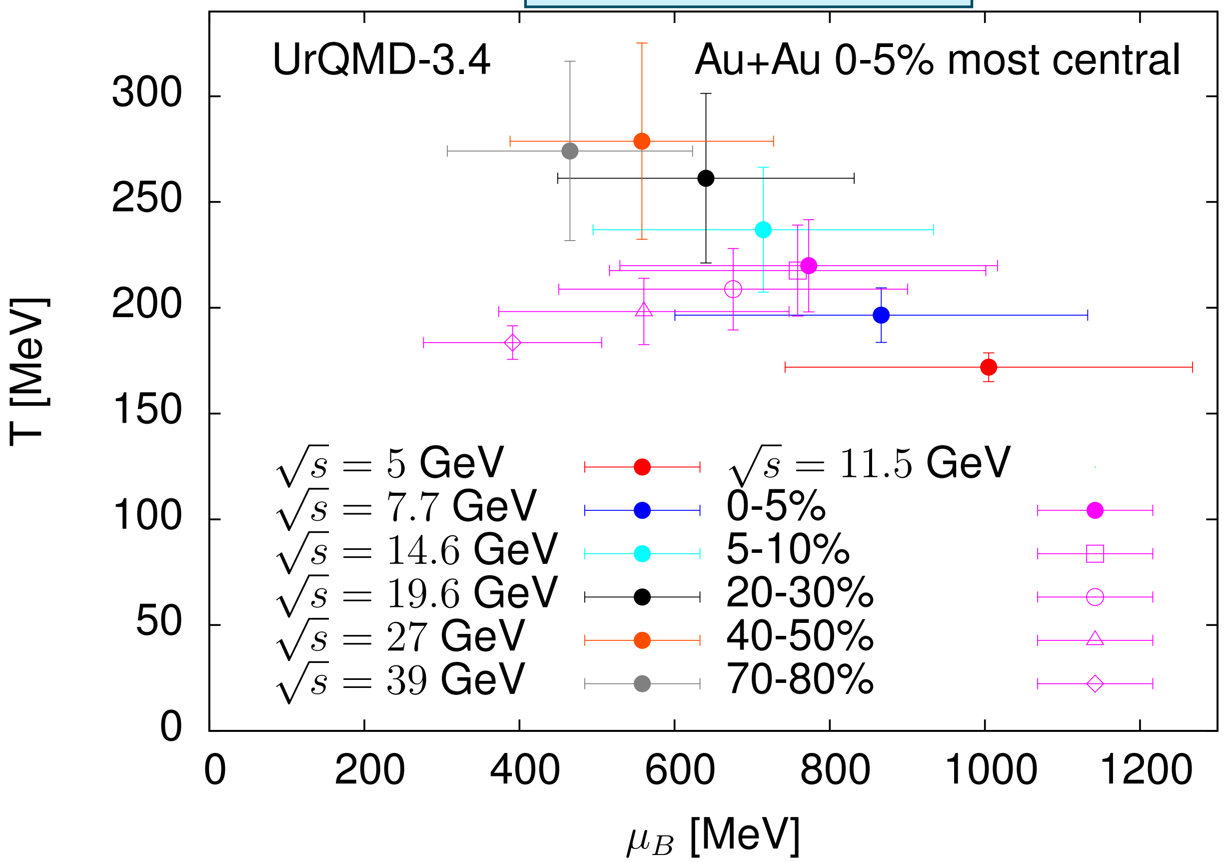


SIS-100 Energies

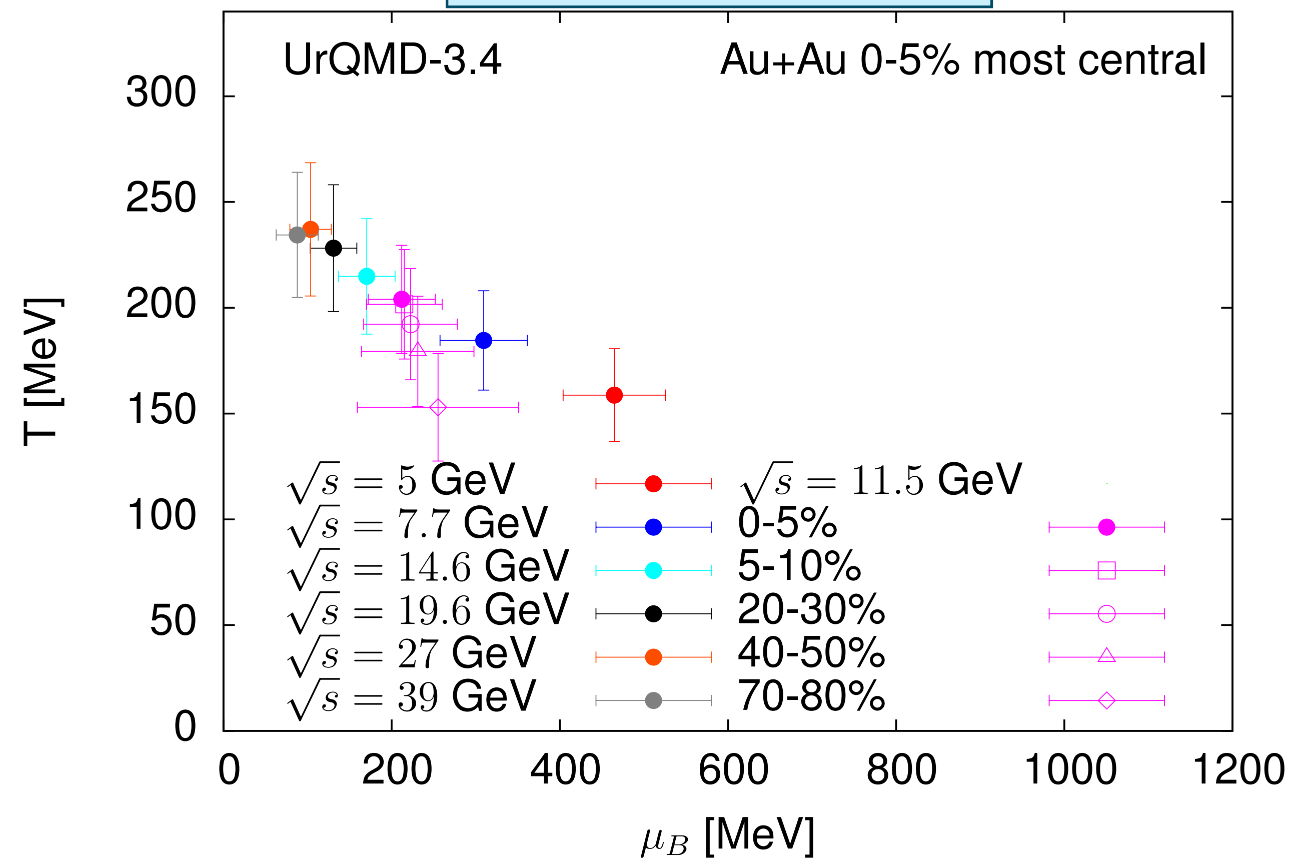


Experimental Access to Phase Diagram

Chiral EoS



Hadron Gas EoS



- Event-by-event fluctuations negligible, but sizable spread in **single** events → Different centralities increase spanned regions
- Absolute values are highly dependent on the Equation of State/ degrees of freedom
- Scan in rapidity windows might allow to divide spacing even more

G. Gräf, J. Steinheimer, UrQMD-3.4 on urqmd.org

Rapidity Scan

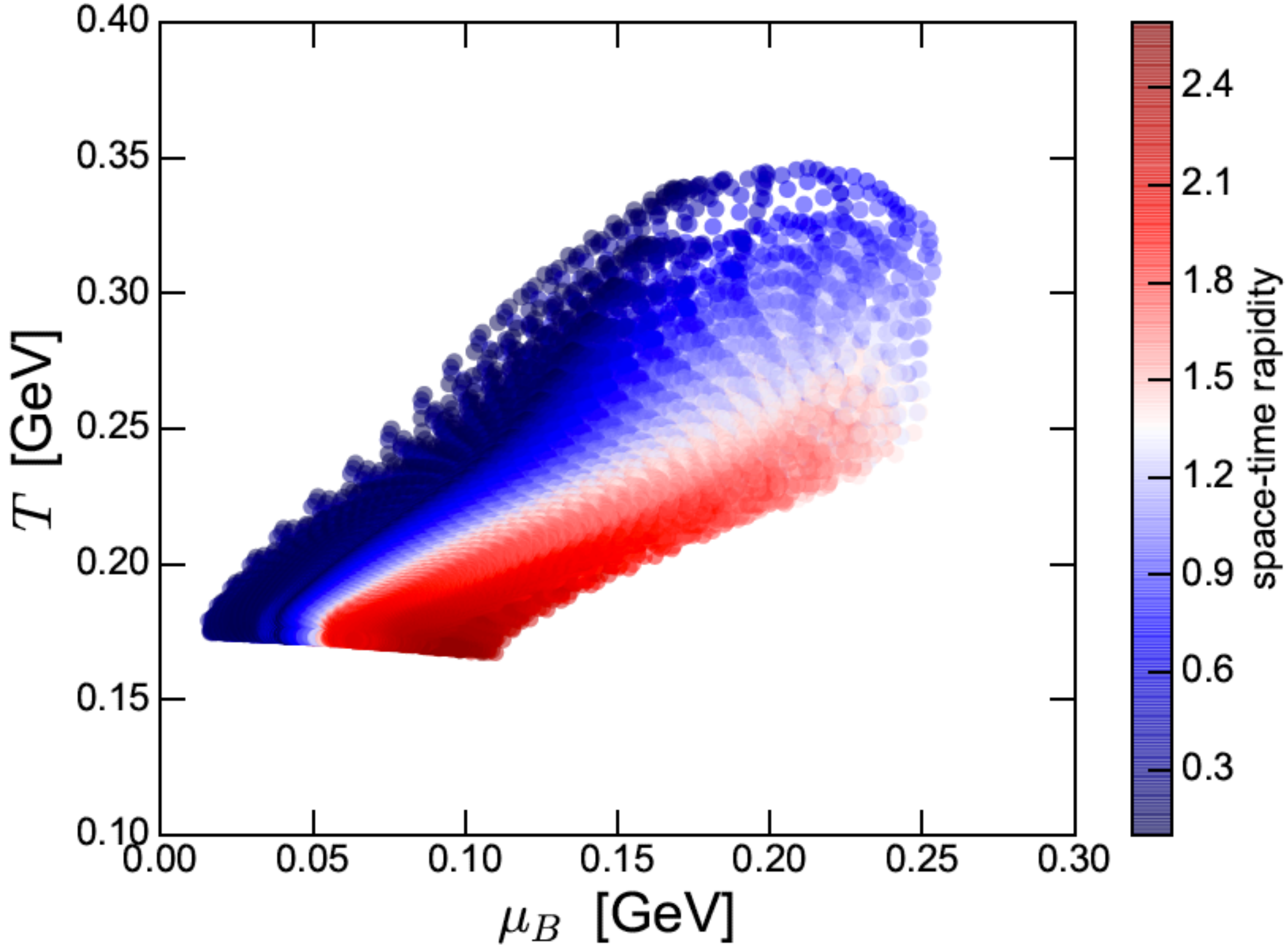
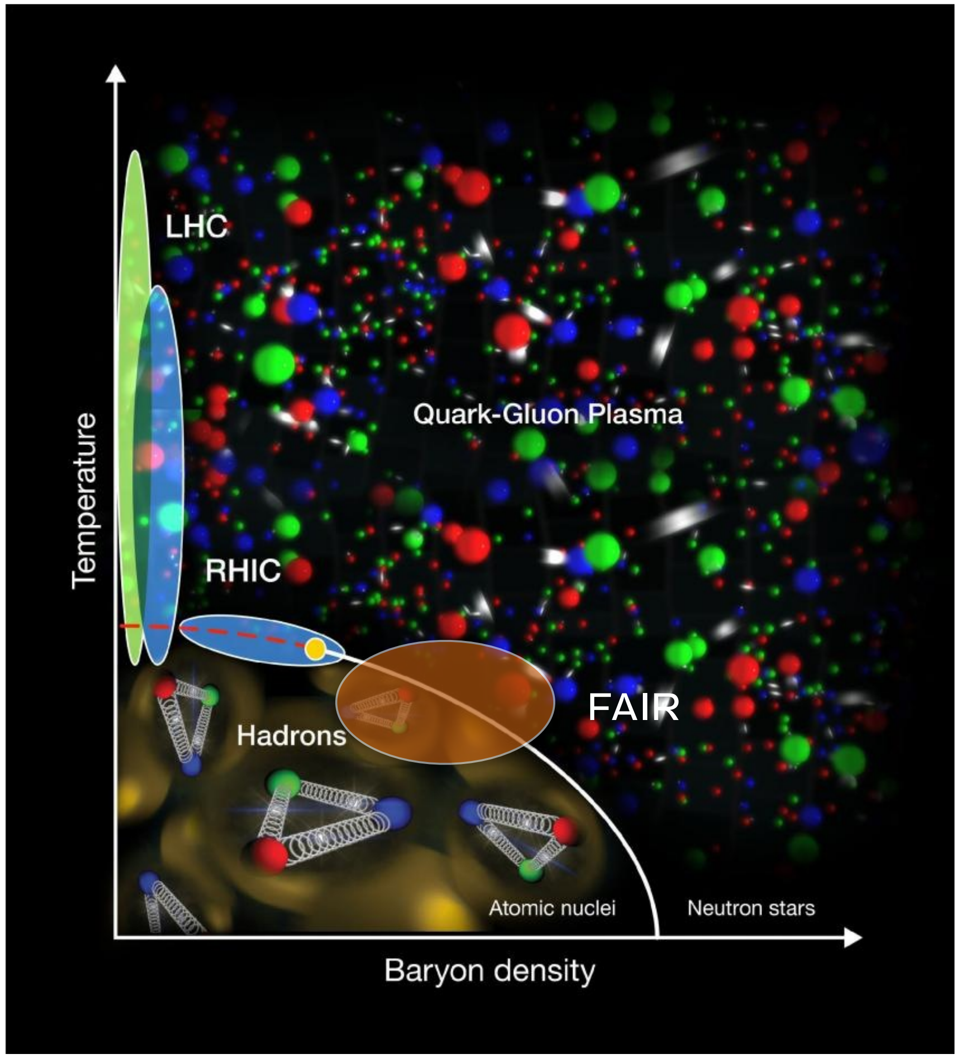


Fig. 3. Trajectories (represented by points) on the $T - \mu_{\mathrm{B}}$ plane, covered by the slices of the fluid corresponding to different rapidities. Color encode the rapidity of the slice. The simulation is performed for averaged initial state corresponding to 20-30% central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 72$ GeV.

- UrQMD+vHLLE hybrid by Y. Karpenko, see arXiv: 1805.11998

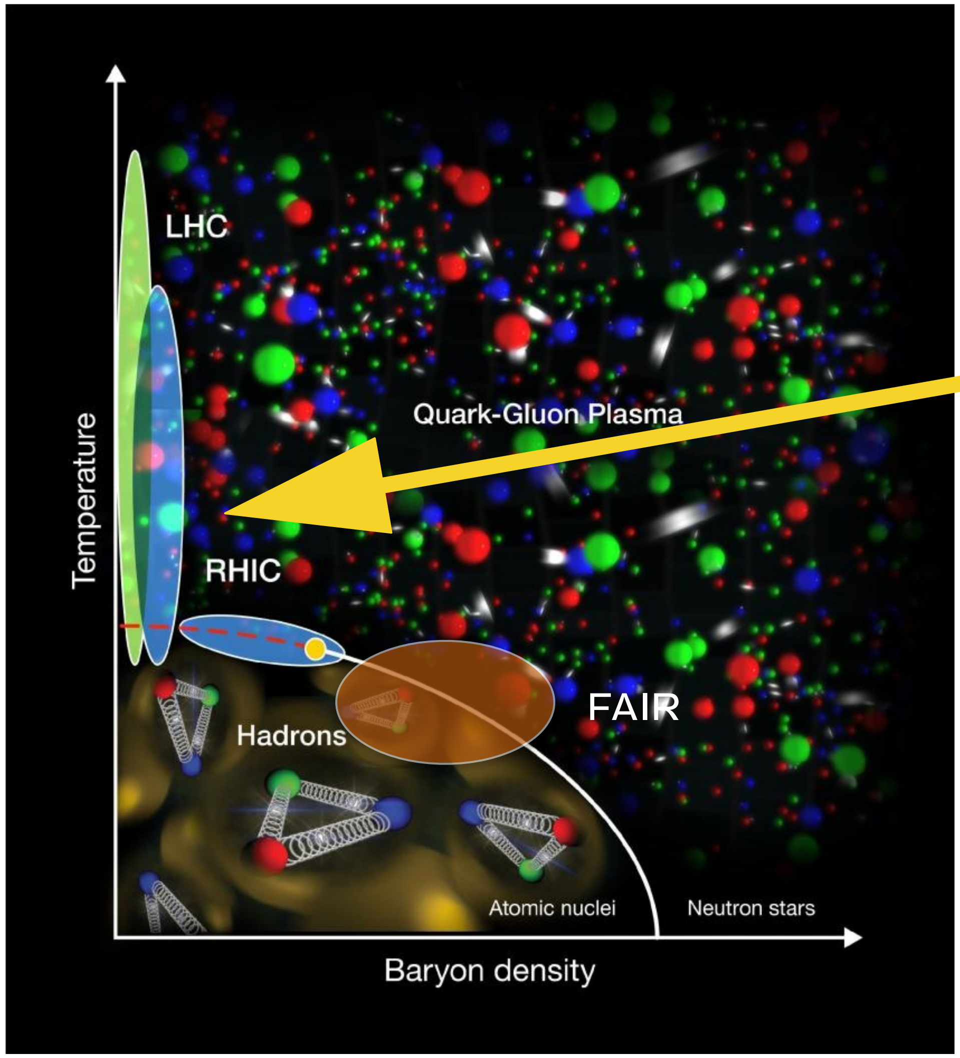
Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



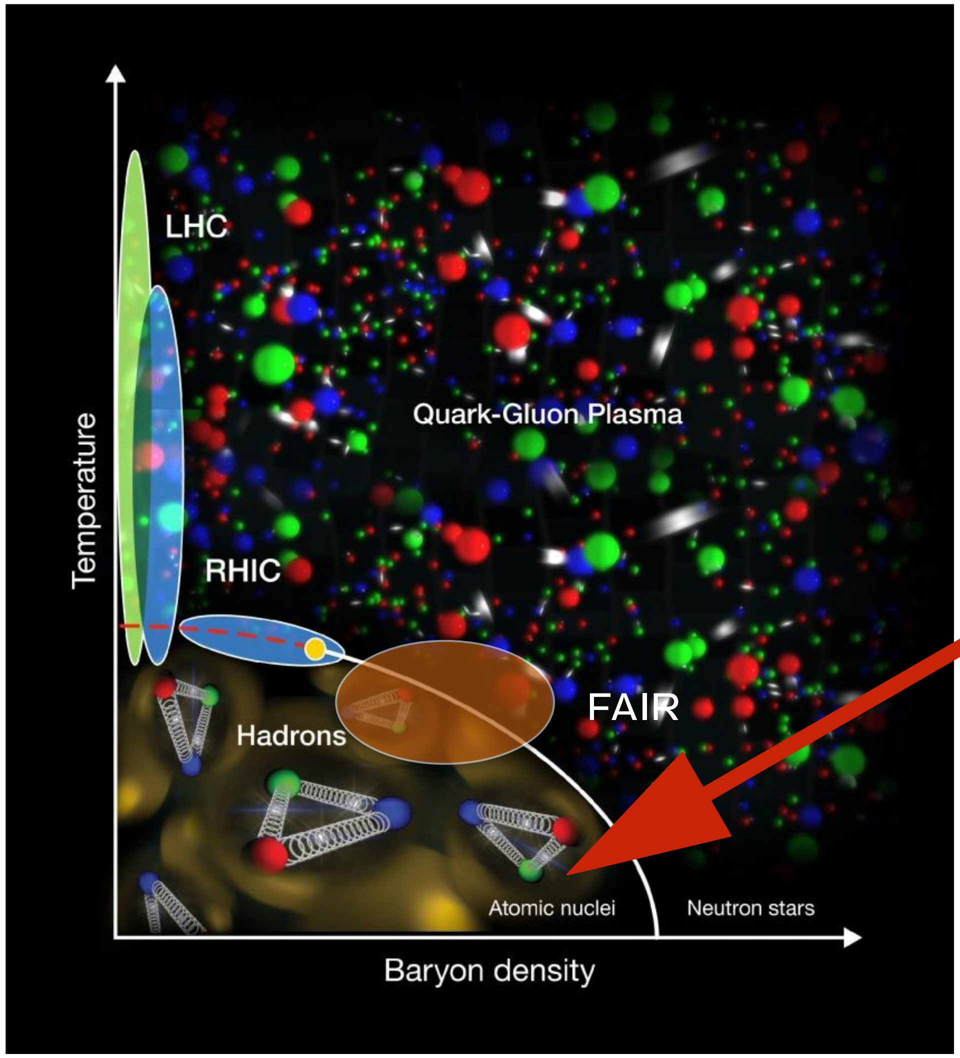
‚Standard model‘ at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+):

- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic transport

—> Refinement and
Bayesian multi-parameter analysis

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



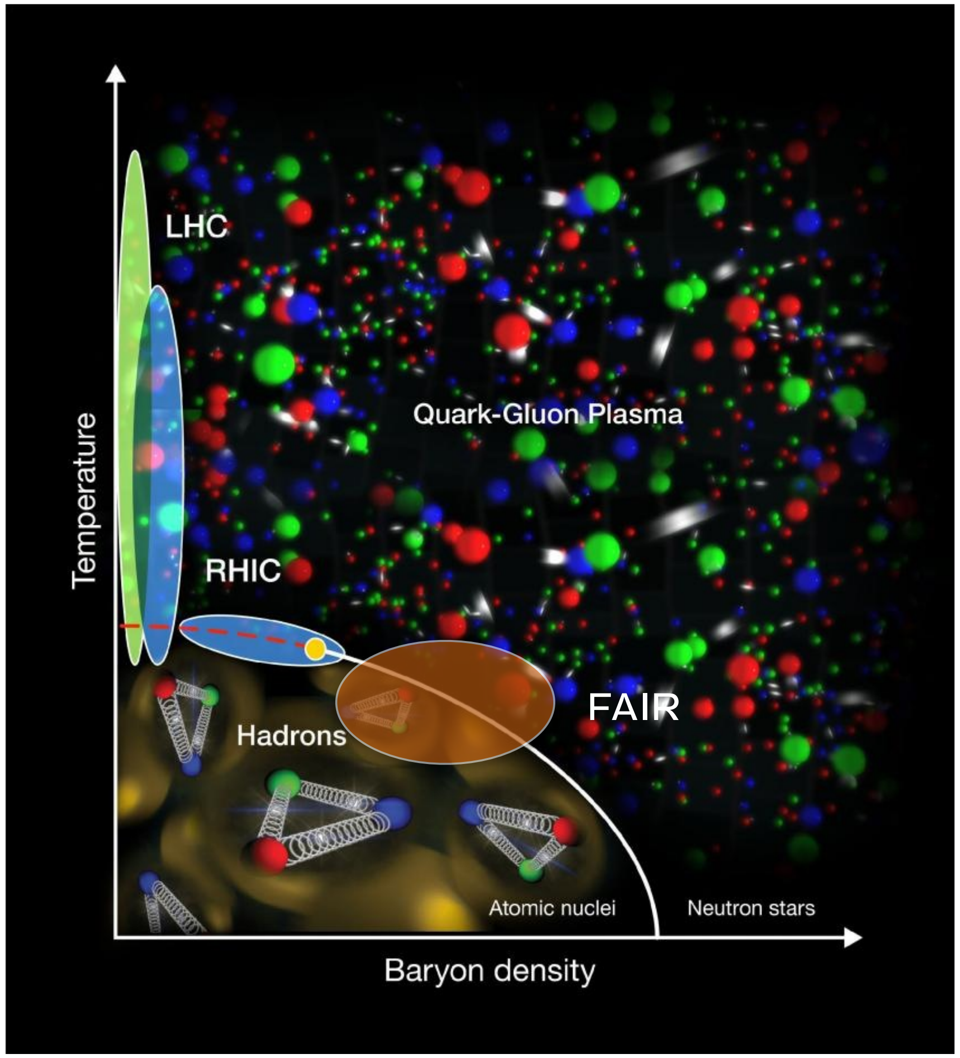
At very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV):

- **Hadronic** transport approaches
- Resonance dynamics
- Nuclear potentials

—> High density phase?
Multi-particle interactions?

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches

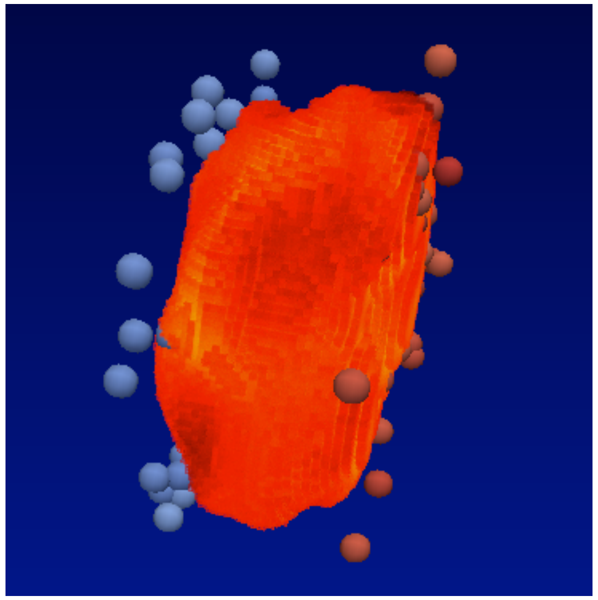


‚Standard model‘ at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+)

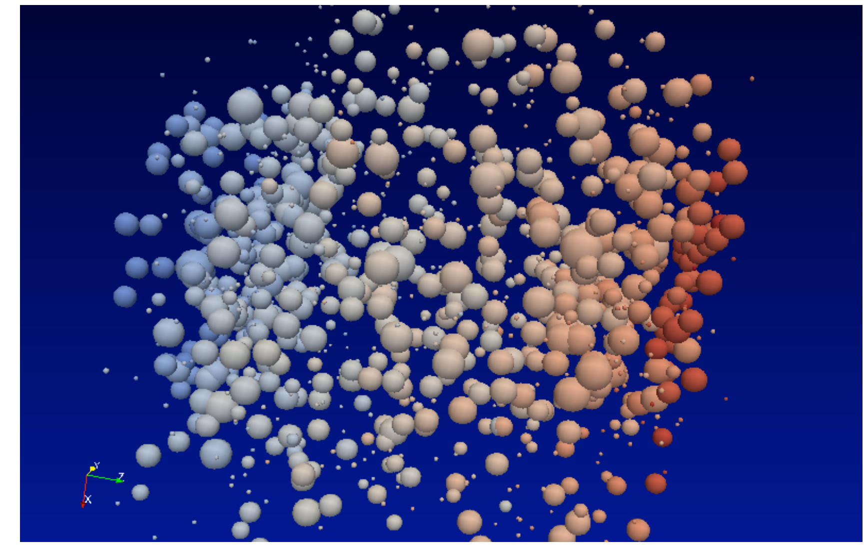
Hadron transport at very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV)

- How to **interpolate** between the two? Transport with hydro bubbles? Hydro with transport corona?
- How to model the phase transition/critical point?

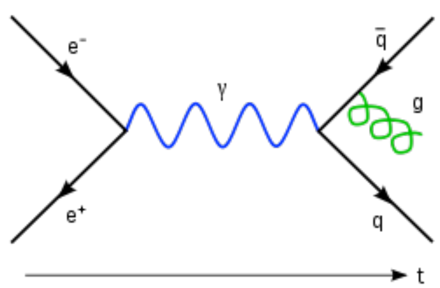
Theoretical Description



Dynamical description of heavy ion reactions

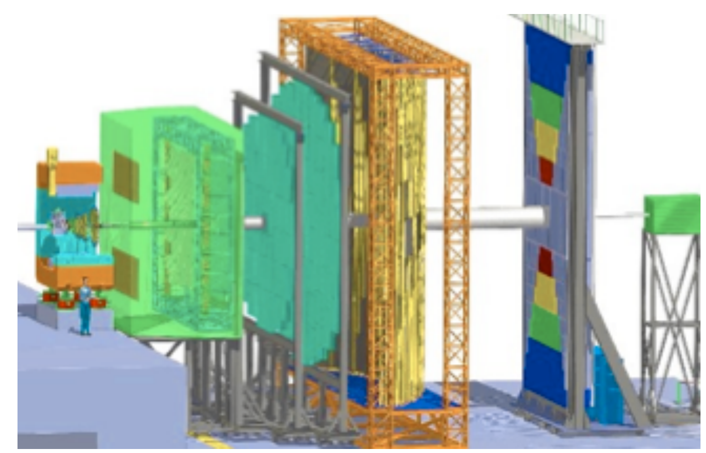


Fundamental field theory of strong interactions (QCD)



$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Measurements in the detector (CBM@FAIR)



- **Theoretical models** are essential to gain insights about the properties of the quark gluon plasma, since the short timescale and small volume do not allow for a direct observation

Hybrid approaches

Transport

Microscopic description of the whole phase-space distribution

Non-equilibrium evolution based on the Boltzmann equation

$$\left(p^{\mu}\partial_{\mu}\right)f = I_{coll}$$

Partonic or hadronic degrees of freedom

Cross-sections are calculable using different techniques

Phase transition?

Hydrodynamics

Macroscopic description

Local equilibrium is assumed

$$\partial_{\mu} T^{\mu\nu} = 0 \quad \partial_{\mu}\left(nu^{\mu}\right) = 0$$

Propagation according to conservation laws

Equation of state is an explicit input

Boundary conditions: Breakdown of equilibrium assumptions?

- Combine the advantages of both approaches
- Successful description from initial to final state

Checking Hydrodynamics

- Verification of codes against analytic solutions is crucial
- Standard tests for relativistic fluid dynamics:
  - Riemann problem (shock propagation)
  - Bjorken solution
  - Gubser solution for viscous hydrodynamics

see for example:
L.-G. Pang, HP, X.-N. Wang, arXiv:1802.04449

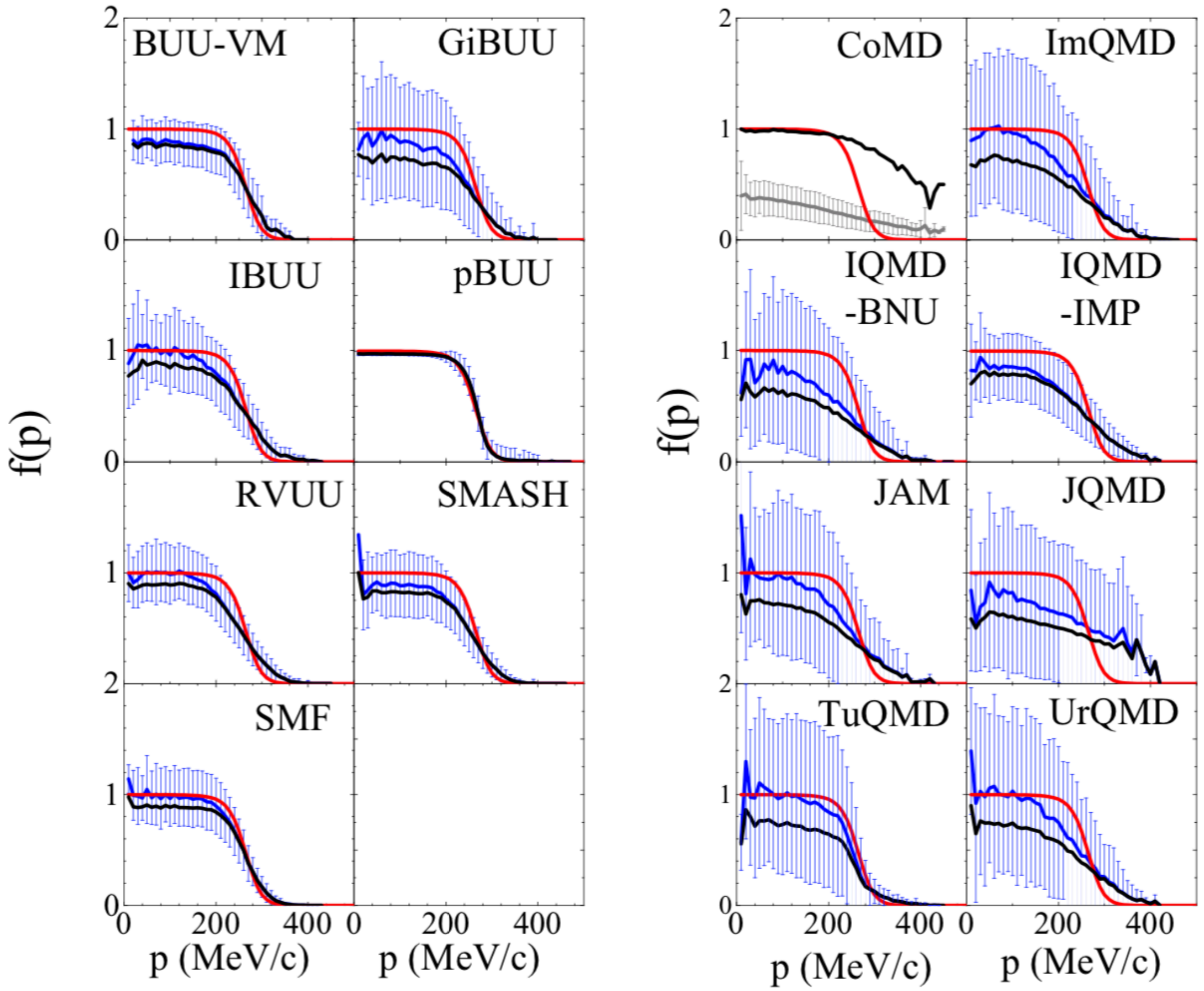
- Under realistic conditions: TECHQM (~2008)
  - Define common initial conditions and common formats (useful for the future as well)
  - Calculation of a few main observables
  - Careful determination of common parameter sets

https://wiki.bnl.gov/TECHQM/index.php/TECHQM_Main_Page

Transport Code Comparison

Comparison of heavy-ion transport simulations: Collision integral in a box

Ying-Xun Zhang,[1,2,*] Yong-Jia Wang,[3,†] Maria Colonna,[4,‡] Pawel Danielewicz,[5,§] Akira Ono,[6,¶] Manyee Betty Tsang,[5,**] Hermann Wolter,[7,††] Jun Xu,[8,‡‡] Lie-Wen Chen,[9] Dan Cozma,[10] Zhao-Qing Feng,[11] Subal Das Gupta,[12] Natsumi Ikeno,[13] Che-Ming Ko,[14] Bao-An Li,[15] Qing-Feng Li,[3,11] Zhu-Xia Li,[1] Swagata Mallik,[16] Yasushi Nara,[17] Tatsuhiko Ogawa,[18] Akira Ohnishi,[19] Dmytro Oliinychenko,[20] Massimo Papa,[4] Hannah Petersen,[20,21,22] Jun Su,[23] Taesoo Song,[20,24] Janus Weil,[20] Ning Wang,[25] Feng-Shou Zhang,[26,27] and Zhen Zhang[14]



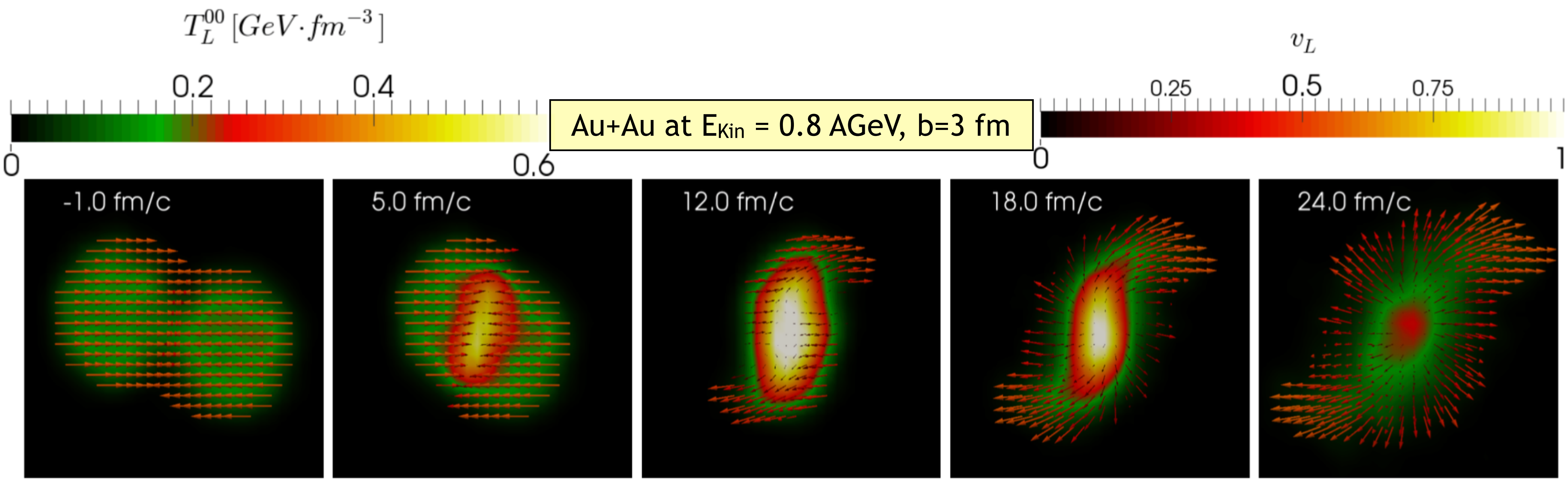
- Occupation probabilities in momentum space
- blue: mean and variance)
- red: initial
- black: Pauli blocking

SMASH*

- Hadronic transport approach:

J. Weil et al, PRC 94 (2016)

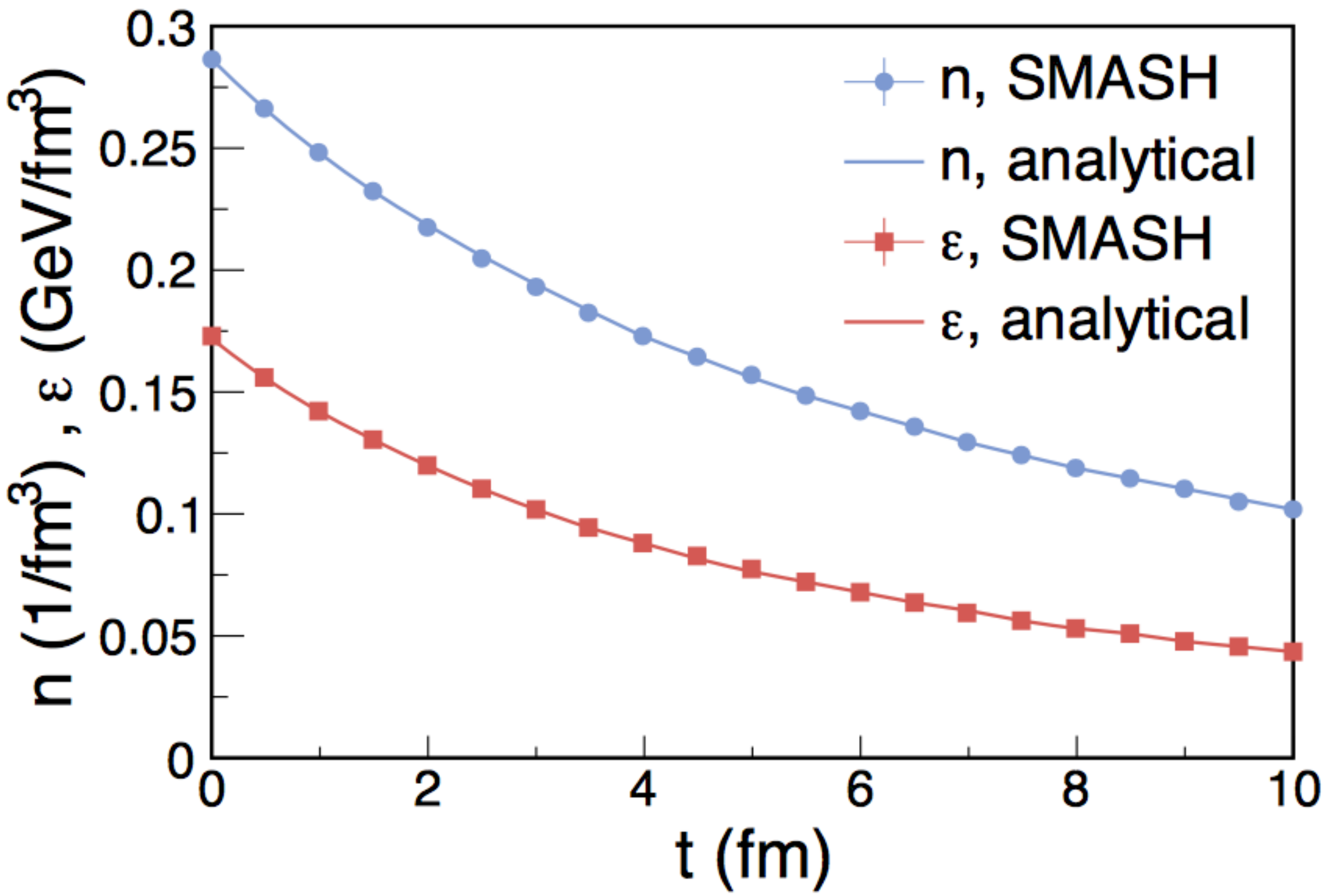
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Redmine, Doxygen, (ROOT)

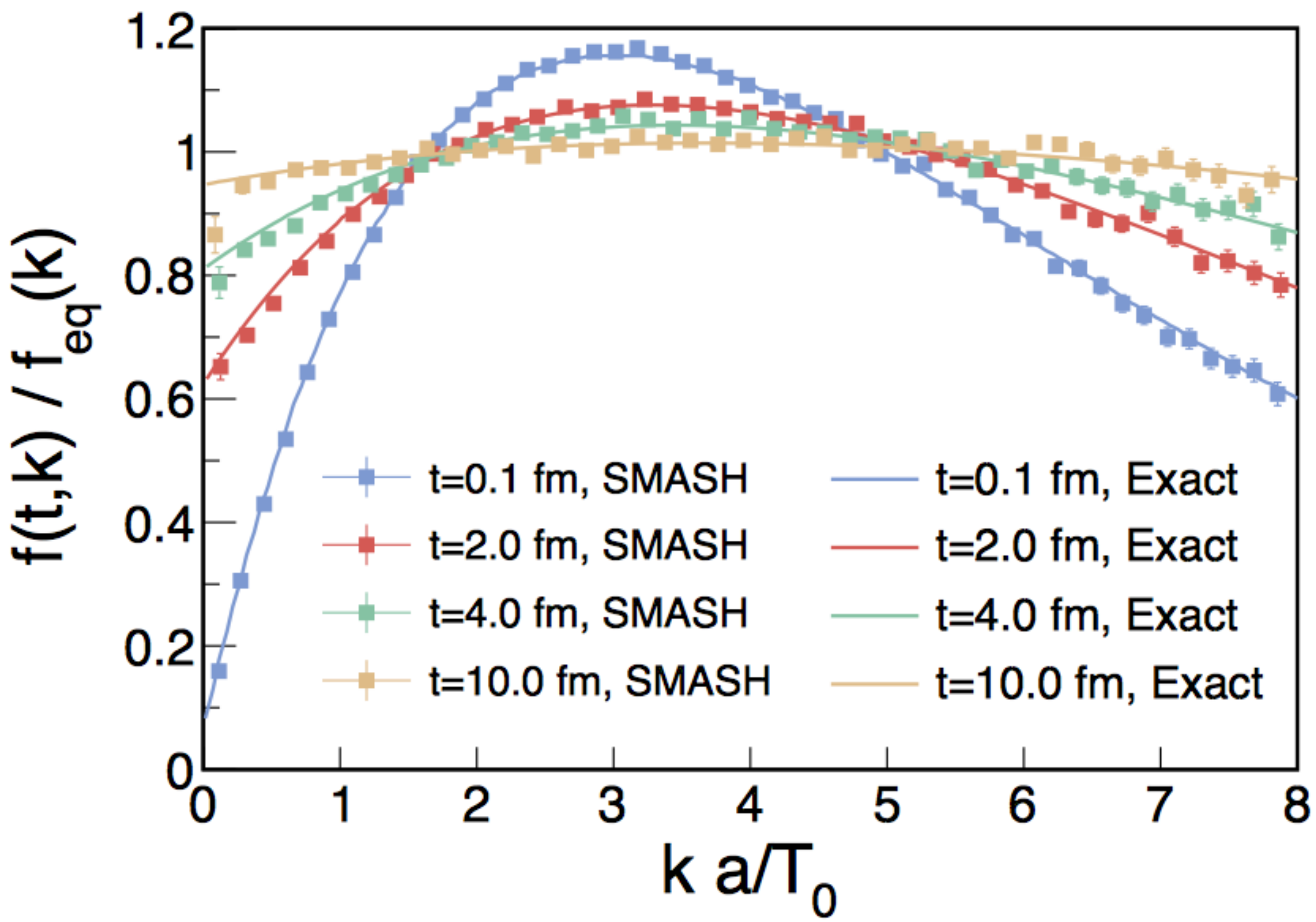


* Simulating Many Accelerated Strongly-Interacting Hadrons

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





- Perfect agreement proves correct numerical implementation of collision algorithm

D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

J. Tindall et al., PLB 770 (2017)

Collective Behaviour

- Potentials in SMASH
  - Basic Skyrme and symmetry potential

$$U_{\text{Skyrme}} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\tau \qquad U_{\text{Symmetry}} = \pm 2 S_{\text{Pot}} \frac{\rho_{I_3}}{\rho_0}$$

  - Describes interactions between nucleons, repulsive at high densities

	soft EoS	default EoS	hard EoS
α	-356.0 MeV	-209.2 MeV	-124.0 MeV
β	303.0 MeV	156.4 MeV	71.0 MeV
τ	1.17	1.35	2.00
κ	200 MeV	240 MeV	380 MeV

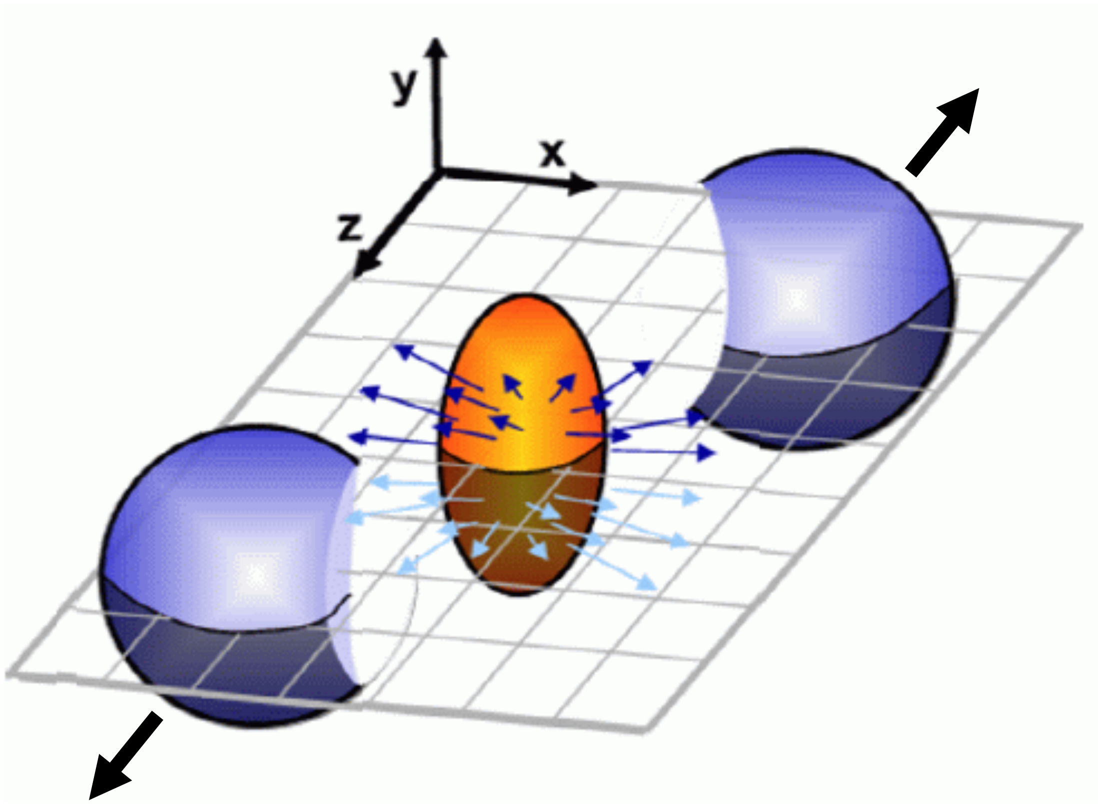
  - Default values according to recent transport code comparison

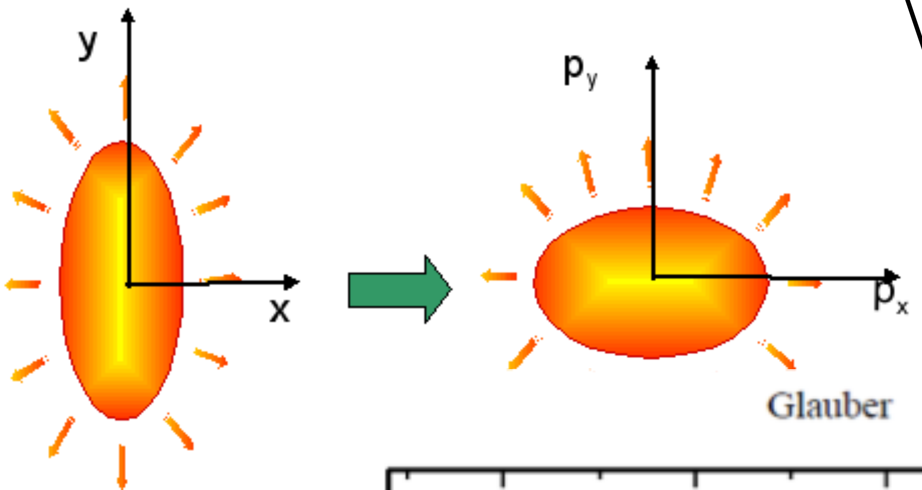
J. Xu et al., PRC 93 (2016)

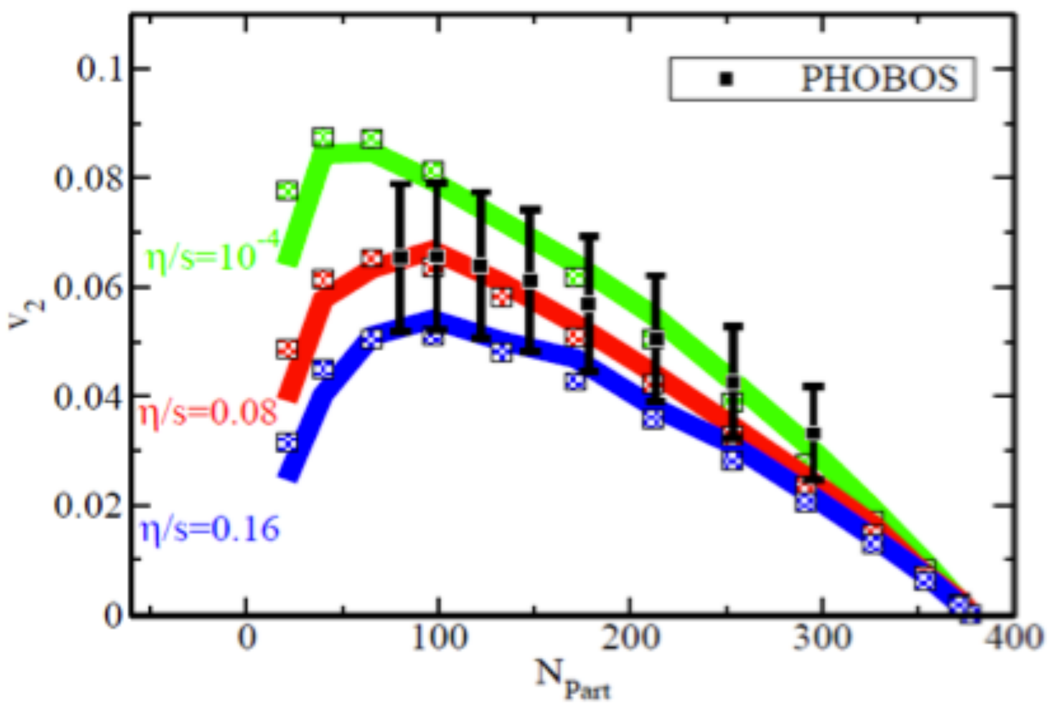
Elliptic Flow

Second coefficient of the Fourier expansion of the azimuthal particle distribution:

$$v_2 = \left\langle \left(\frac{p_x^2 - p_y^2}{p_T^2} \right) \right\rangle$$







Coordinate space asymmetry
→ momentum space **anisotropy**

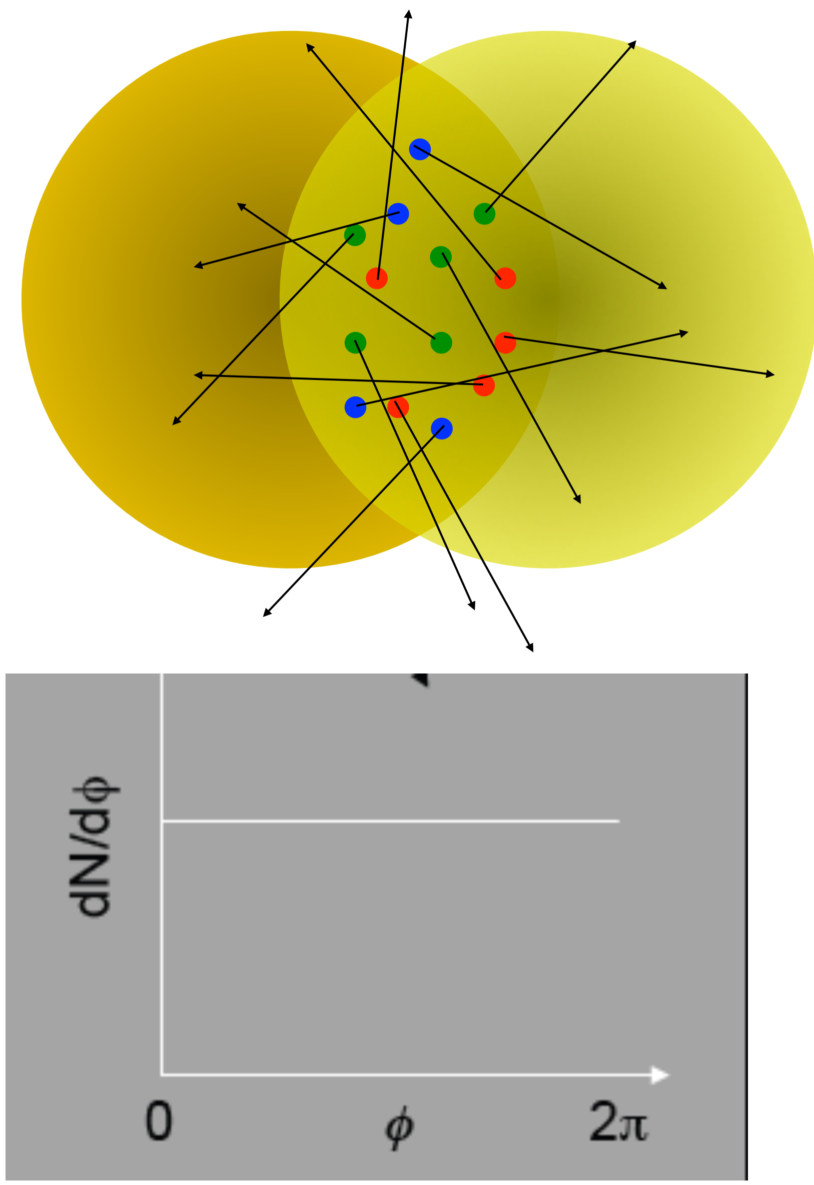
Relativistic fluid dynamics with very **low viscosity** describes elliptic flow at RHIC (and LHC)

M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path λ→∞



Spatial anisotropy

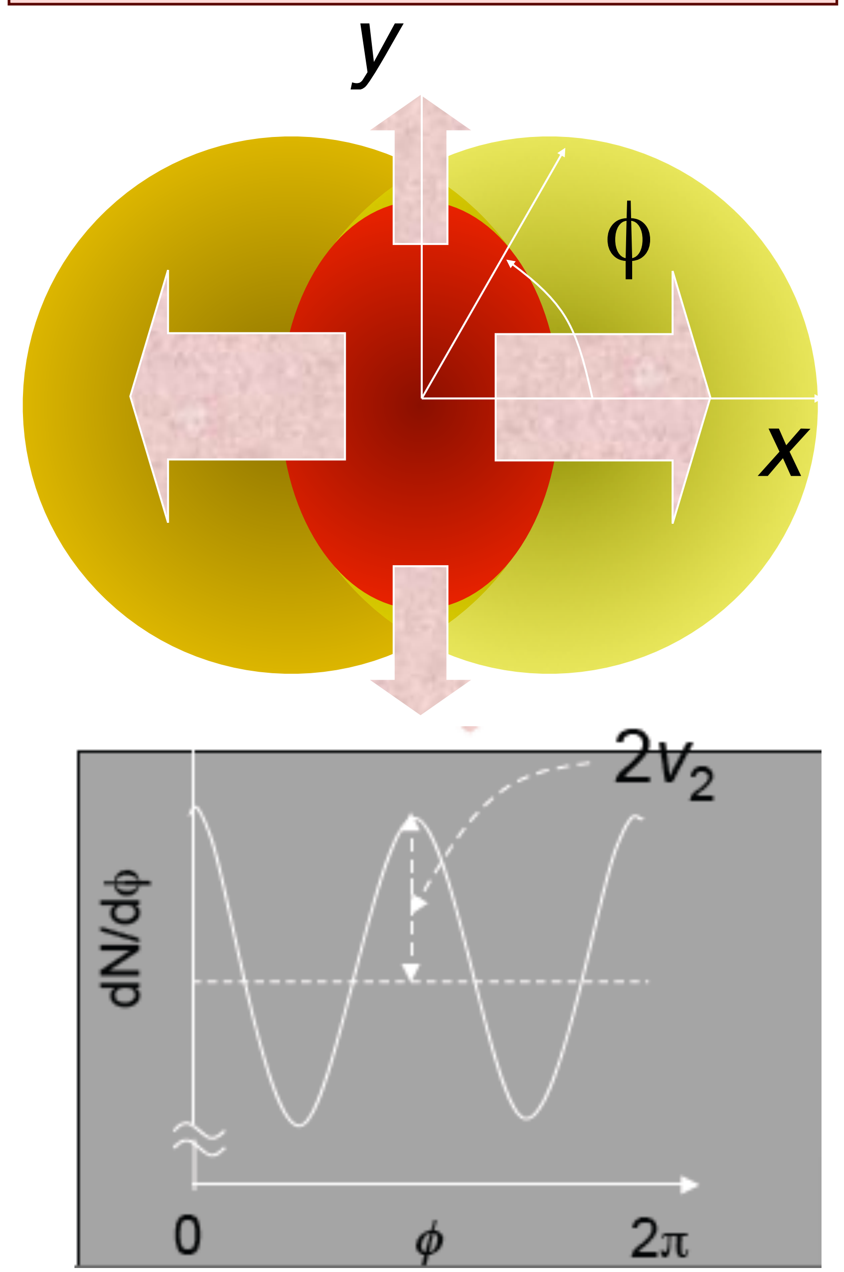
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Interactions between particles

Momentum anisotropy

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

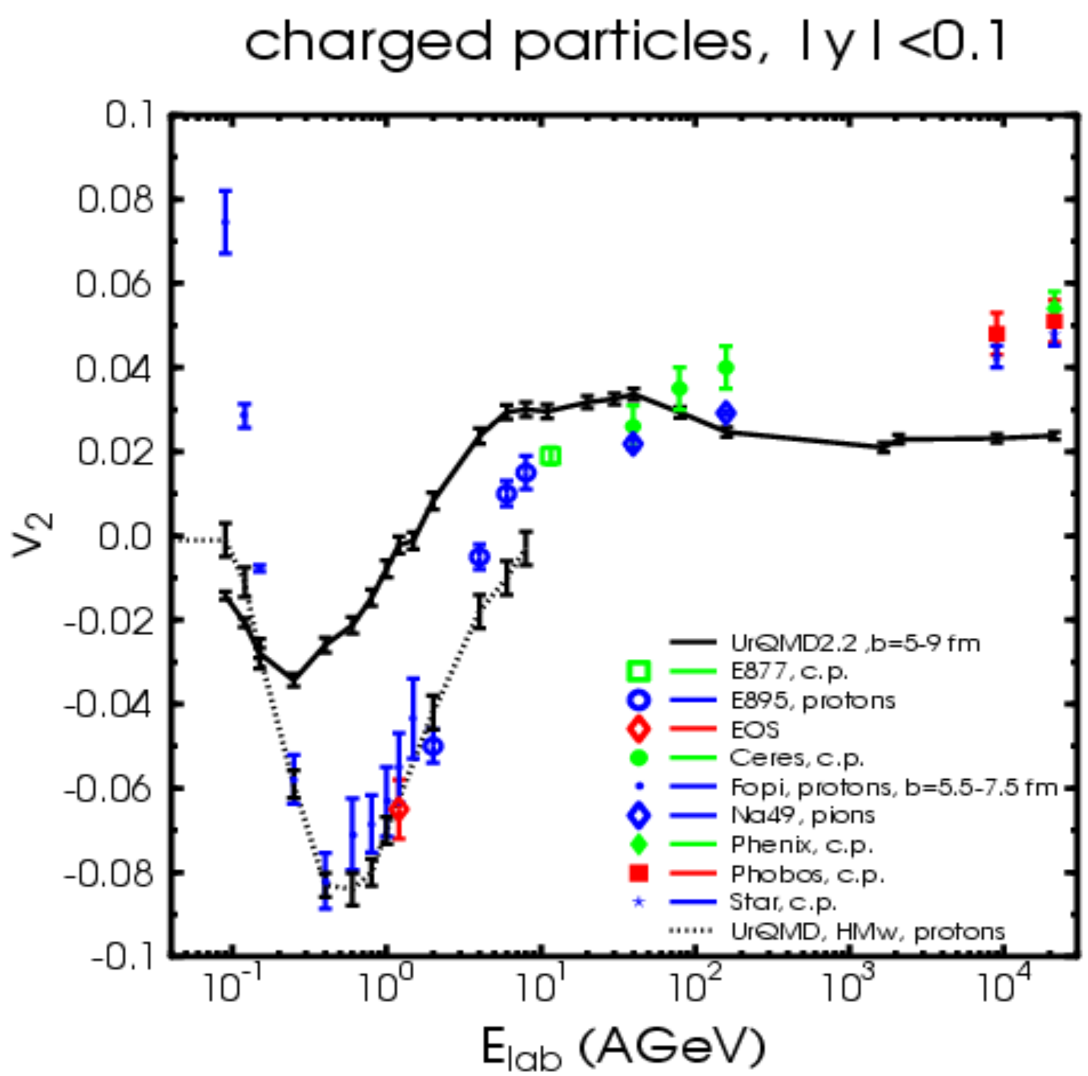
Hydrodynamic behaviour
mean free path λ→0



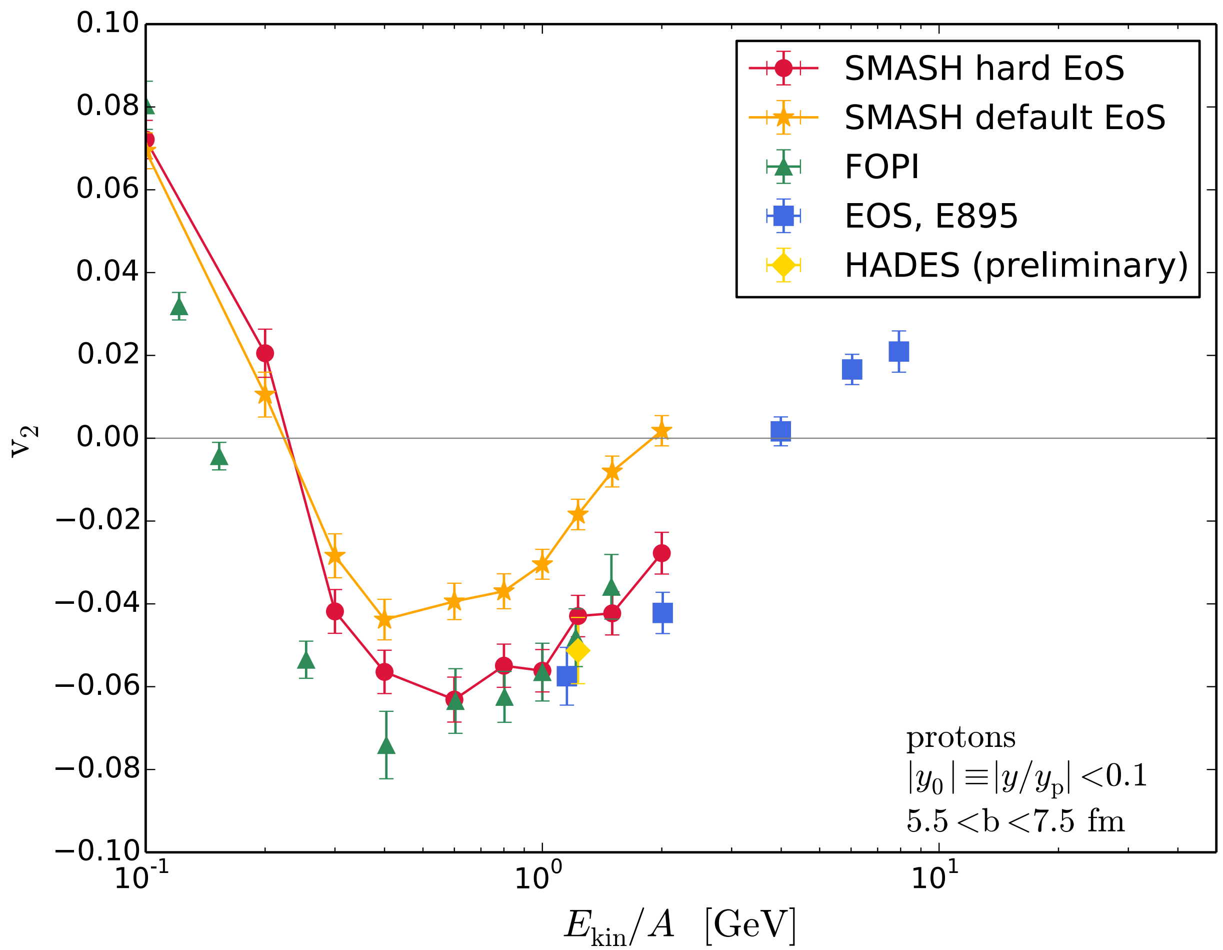
v_2 Excitation Function

- Transition from squeeze-out at low energies to in-plane flow at high energies-> hadron transport underestimates flow

HP et al, Phys.Rev. C74 (2006) 064908



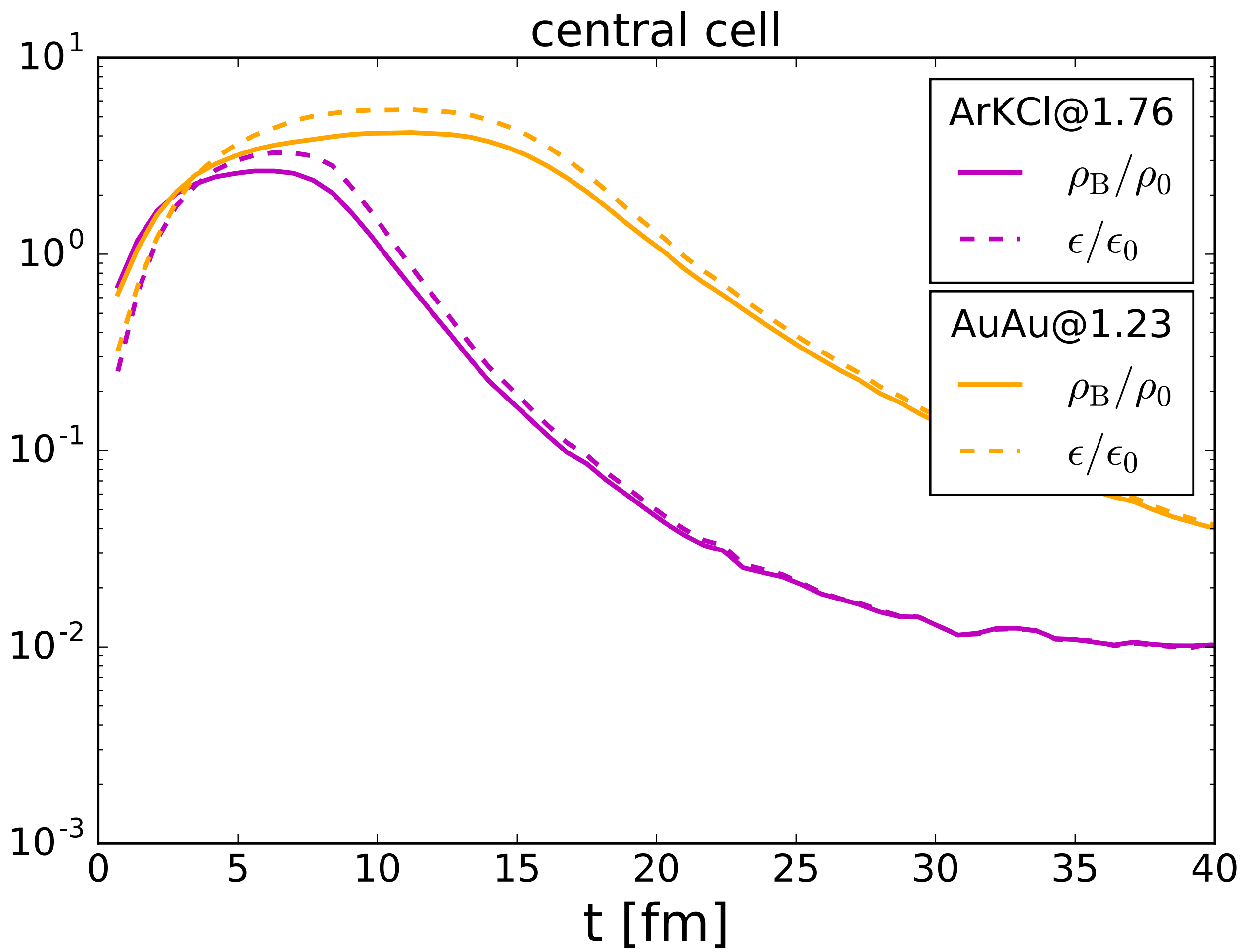
by Markus Mayer

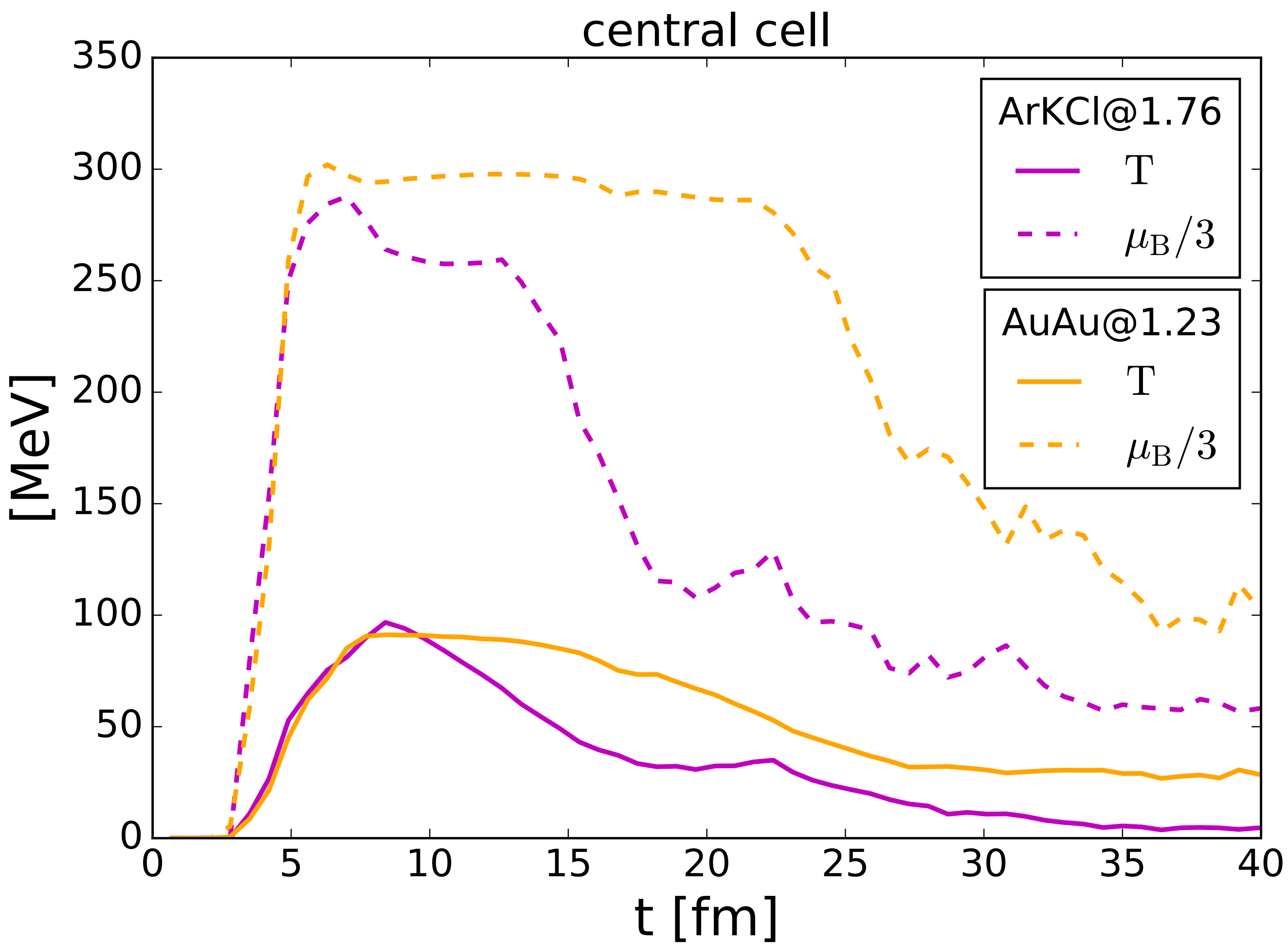


- Sensitive to equation of state of nuclear matter, here in terms of a mean field between nucleons

Coarse-Graining Transport

- Density and temperature in a central cell for heavy ion collisions at SIS-18 energies





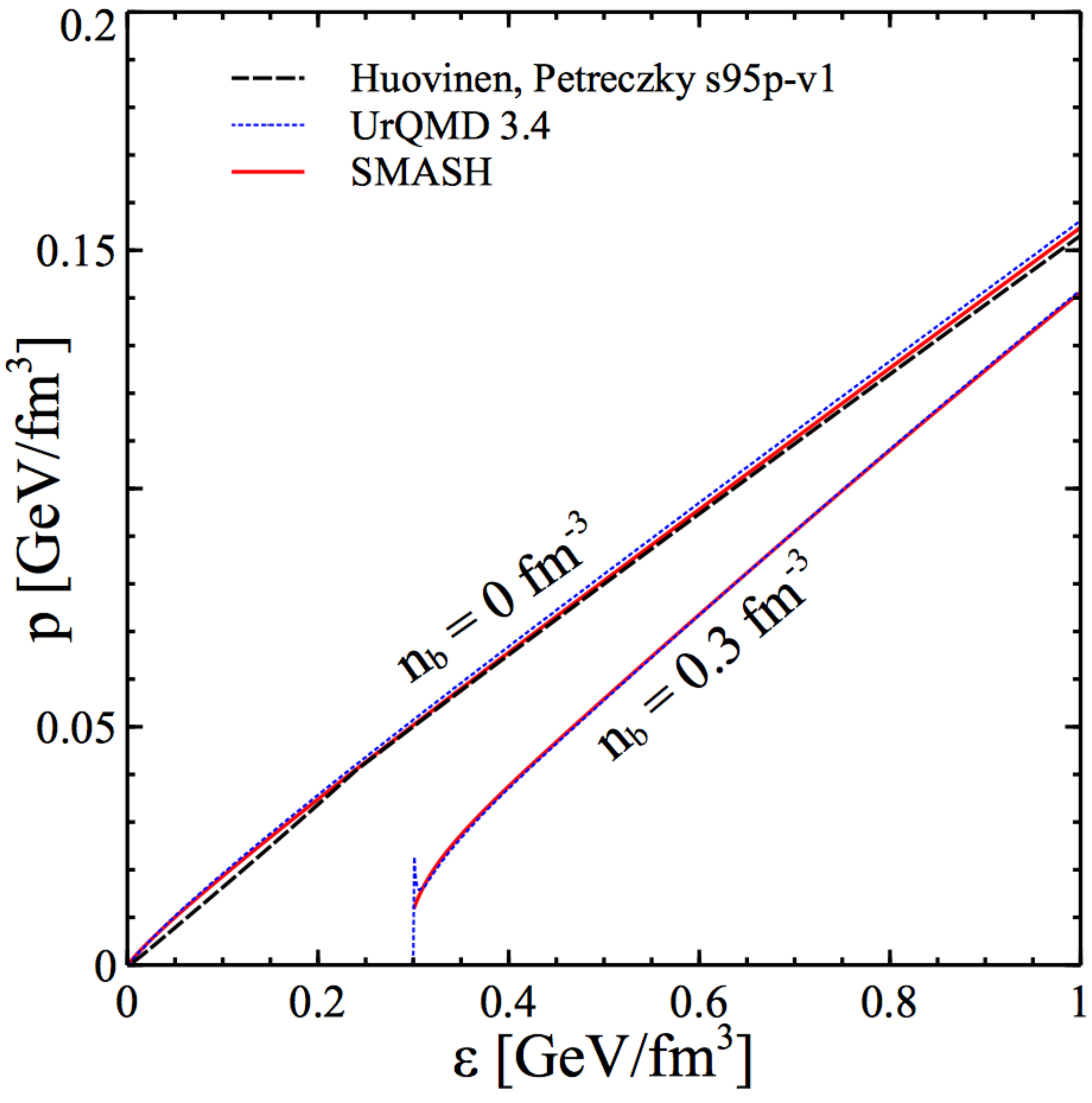
J. Staudenmaier et al, arXiv:1711.10297

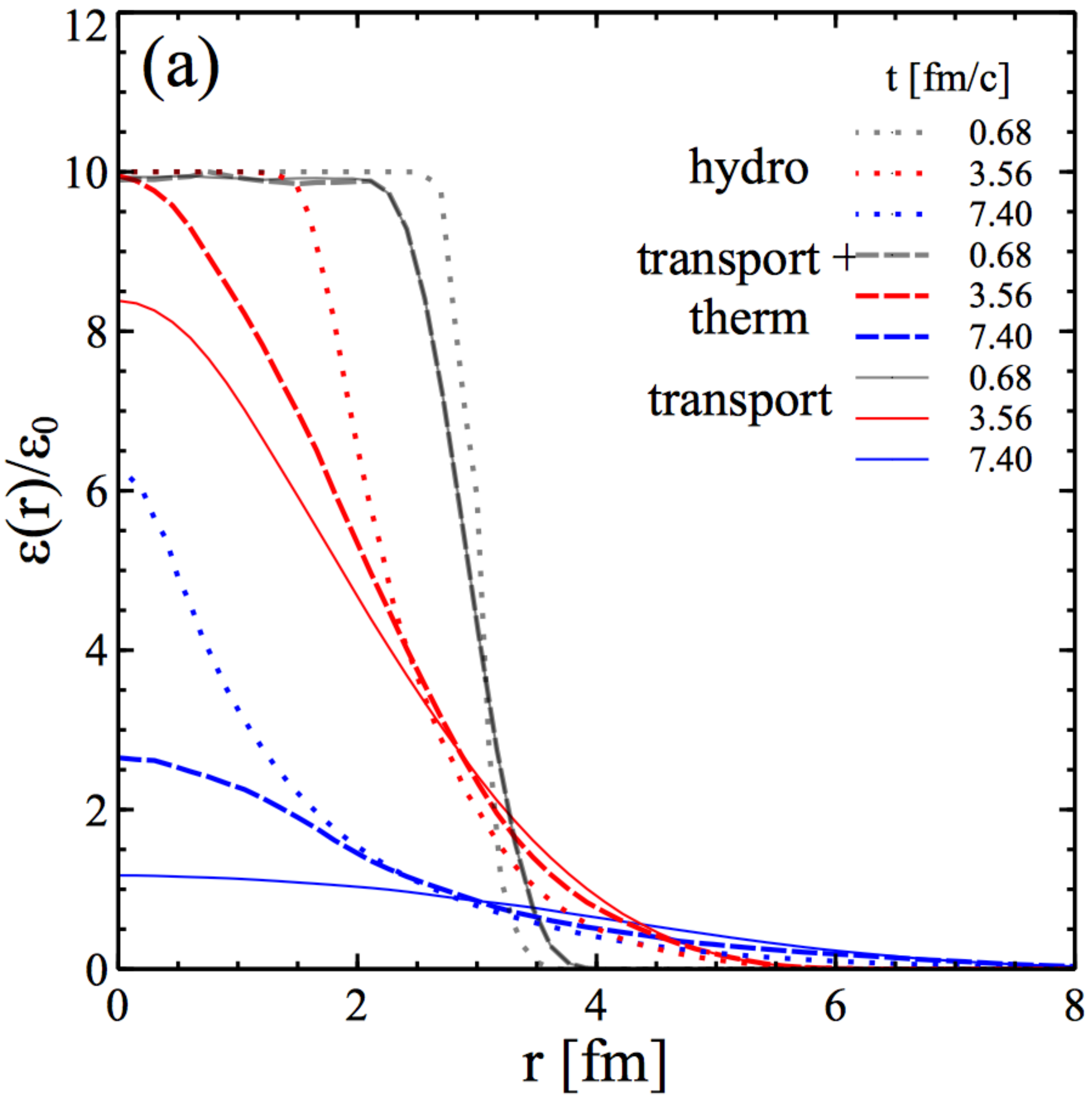
- 3-5 times nuclear ground state density reached

see also, T. Galatyuk et al. and S. Endres et al

EoS and Hydro Comparison

- Equation of state fits lattice hadron gas



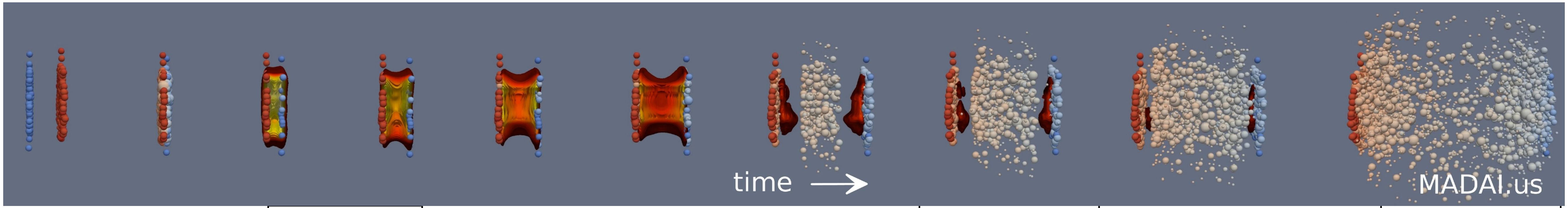


- Interpolation between transport and hydrodynamics

Dmytro Oliinychenko, HP, JPG 44, 2017

‚Standard Model' at High Energies

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport



1x 10^{-23} s

10 x 10^{-23} s

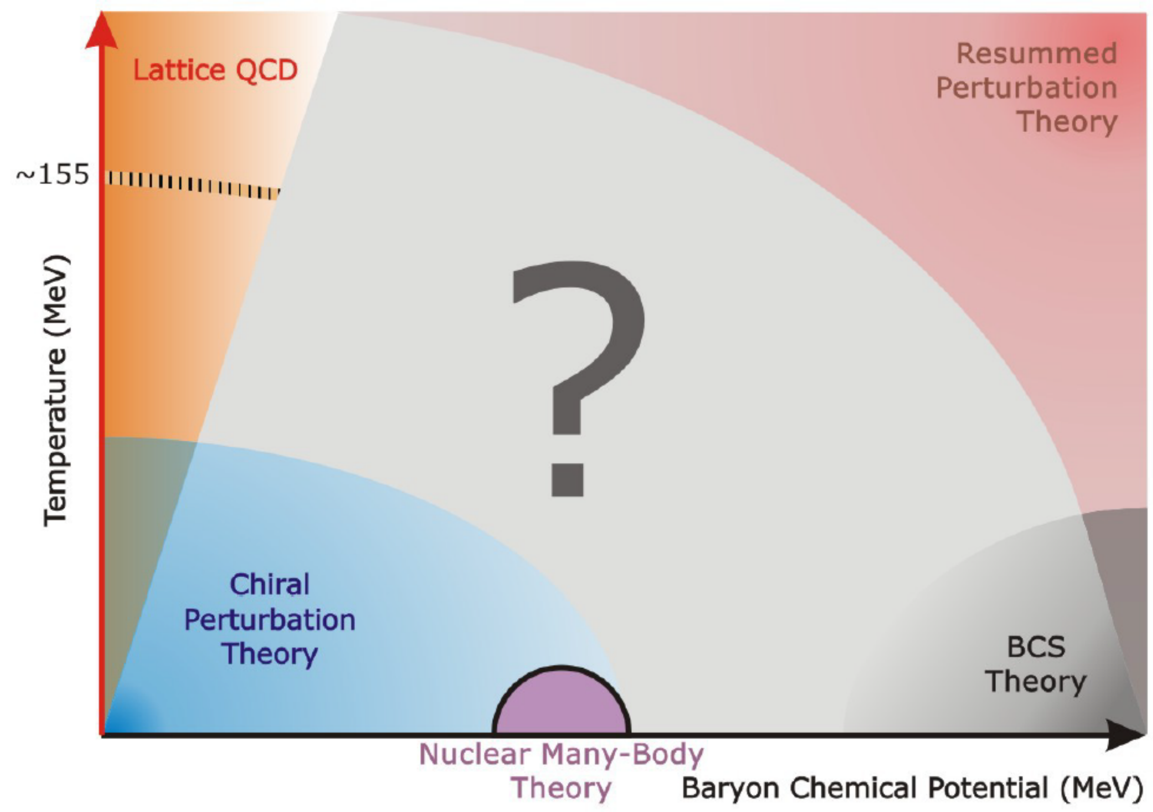
30 x 10^{-23} s

- Challenges at lower beam energies:
  - Finite **net-baryon density** (as conserved current and in EoS)
  - Dissipative effects/hadronic interactions gain importance
  - Non-equilibrium dynamics with a probably **first order** phase transition

Equation of State

- Known **Constraints:**
  - Lattice QCD: $\mu_B/T < 2.2$
    e.g. Bazavov et al, arXiv:1701.04325
  - Nuclear ground state
    A. Mukherjee et al, arXiv: 1611.10144
  - Hadron gas properties
  - Neutron stars: Mass-radius
  - Neutron star mergers (up to T~100 MeV)

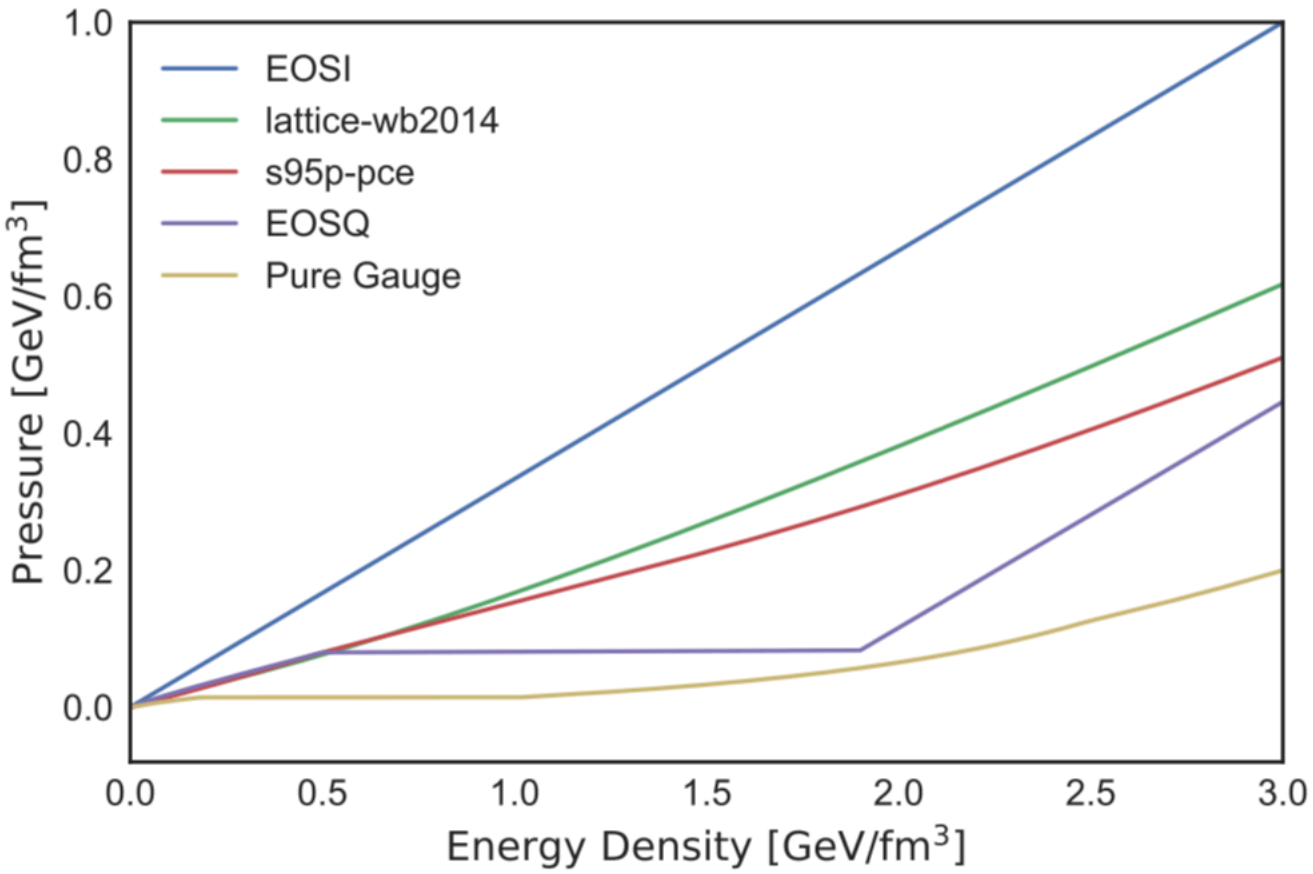
Source: Uni Frankfurt (A. Steidl)



- Extrapolate the EoS into the whole phase diagram and assess the **uncertainties**
- Use input from **functional** methods: FRG collaboration and Dyson-Schwinger with baryons e.g. G. Eichmann et al, arXiv:1509.02082
- What about **strangeness** and **isospin**?
- **Consistency** between equation of state and transport coefficients?

EoS in Hydrodynamics

- Typical choices for equations of state in hydrodynamic calculations



EOSI: The simplest EoS – ideal gas EoS where pressure is 1/3 of energy density.

lattice-wb2014: The recent lattice QCD calculations from Wuppertal-Budapest group, whose trace anomaly differ from s95p lattice results by a large margin for the temperature range 180 – 320 MeV [81].

s95p-pce: The default s95p partial chemical equilibrium EoS [82] used in this paper is given by lattice QCD EoS at high energy density and hadronic resonance gas (HRG) EoS at low energy density with a smooth crossover in between using interpolation.

EOSQ: Employs a first order phase transition between QGP and HRG [83].

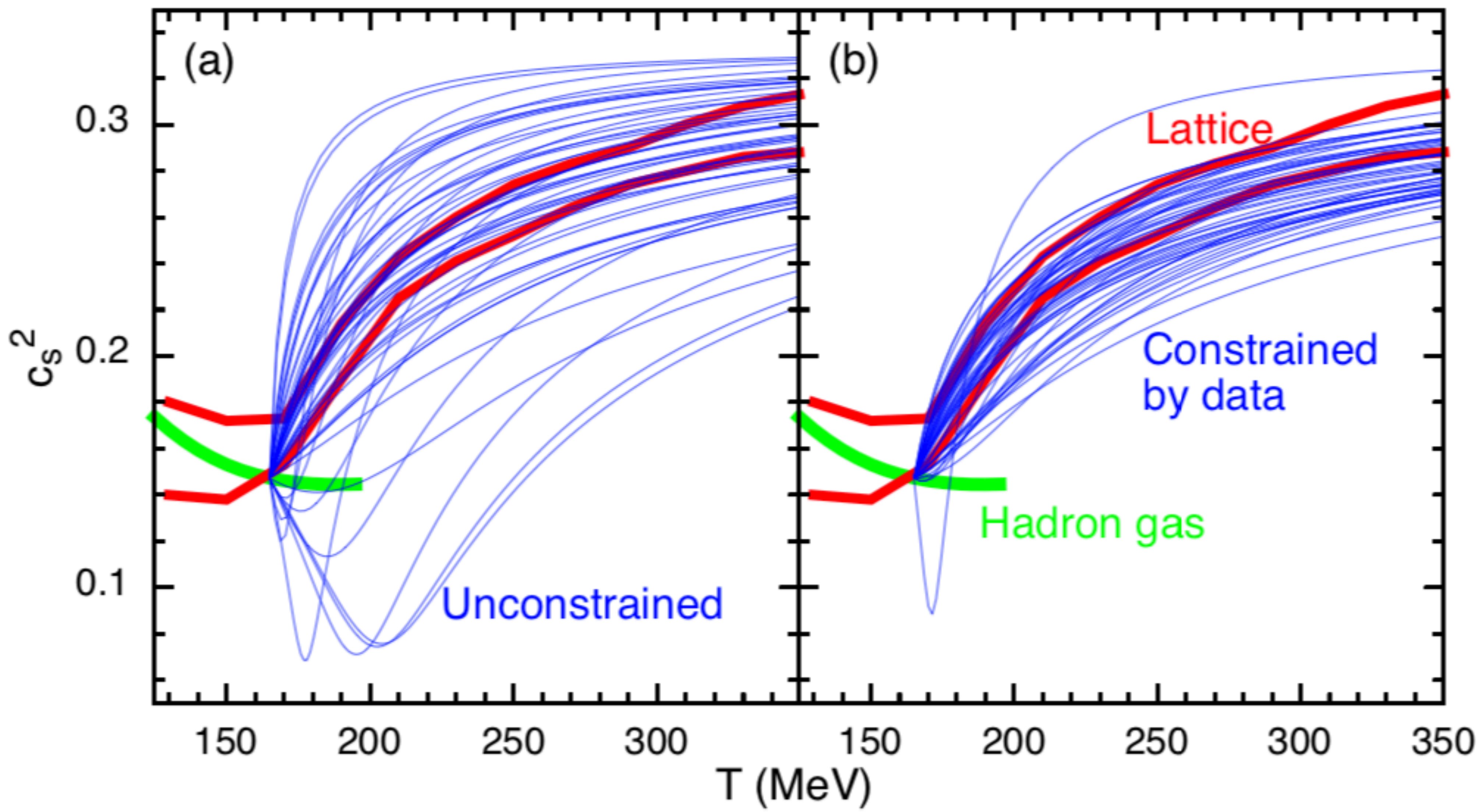
pure gauge: Pure gauge EoS with a first order phase transition given by gluodynamics without (anti)quarks [84–86].

- No chemical potential…

L.-G. Pang, HP, X.-N. Wang, arXiv:1802.04449

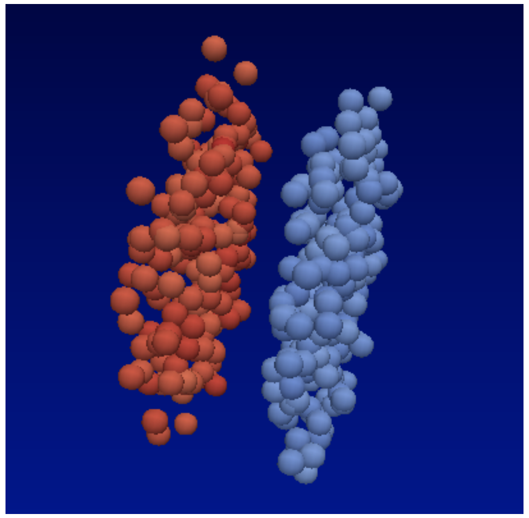
High Temperature EoS

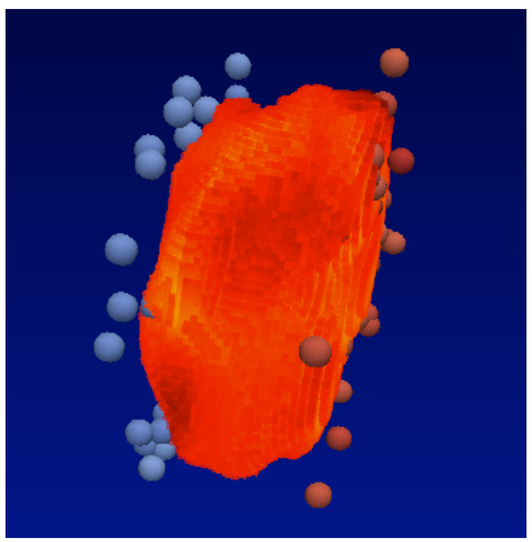
- Within a hybrid approach the equation of state has been constrained with a Bayesian multi-parameter analysis with RHIC/LHC data

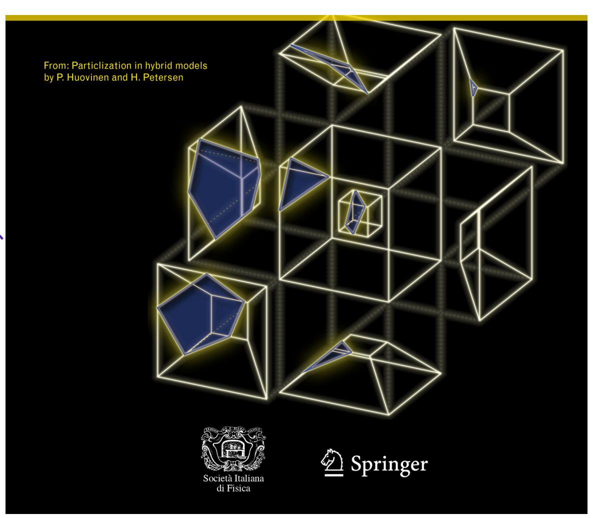


S. Pratt et al, PRL 114, 2015

Hybrid Approach







P. Huovinen, HP EPJ A48 (2012) 171

HP, arXiv:1404.1763 (special issue)
J. Phys. G: Nucl. Part. Phys. 41 (2014) 124005

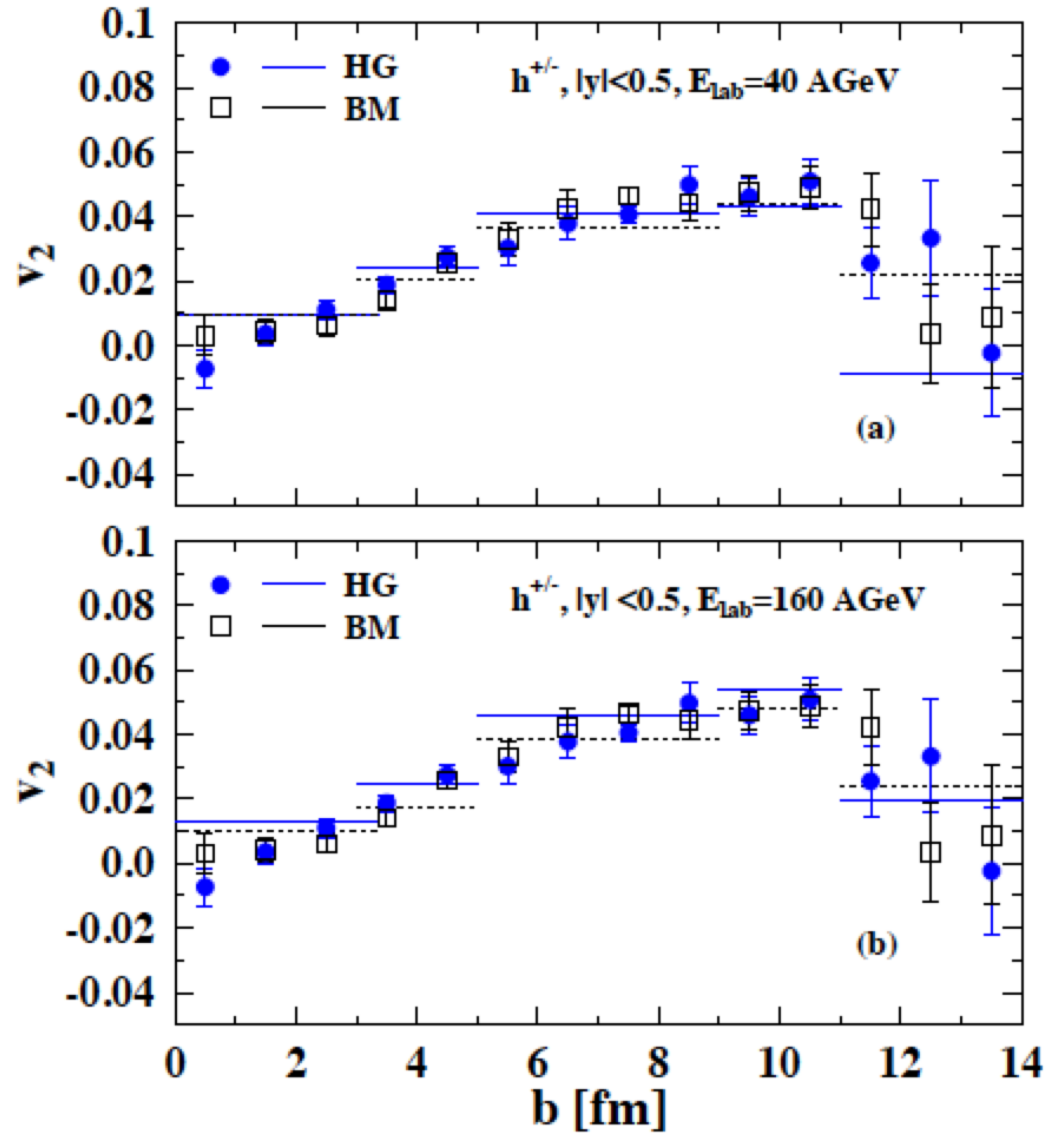
- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally
- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finite μ_B
  - Karpenko et al: 3+1d viscous hydrodynamics
- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within hadron transport

HP et al, PRC78 (2008) 044901, G. Gräf, J. Steinheimer and M. Bleicher, UrQMD-3.4 (urqmd.org)

Equation of State and IC Fluctuations

- Symbols: Event-by-event calculations
- Horizontal lines: Averaged results
- Blue: Hadron Gas EoS
- Black: Bag Model EoS with first order phase transition

- **NO** difference visible in the centrality dependence of elliptic flow

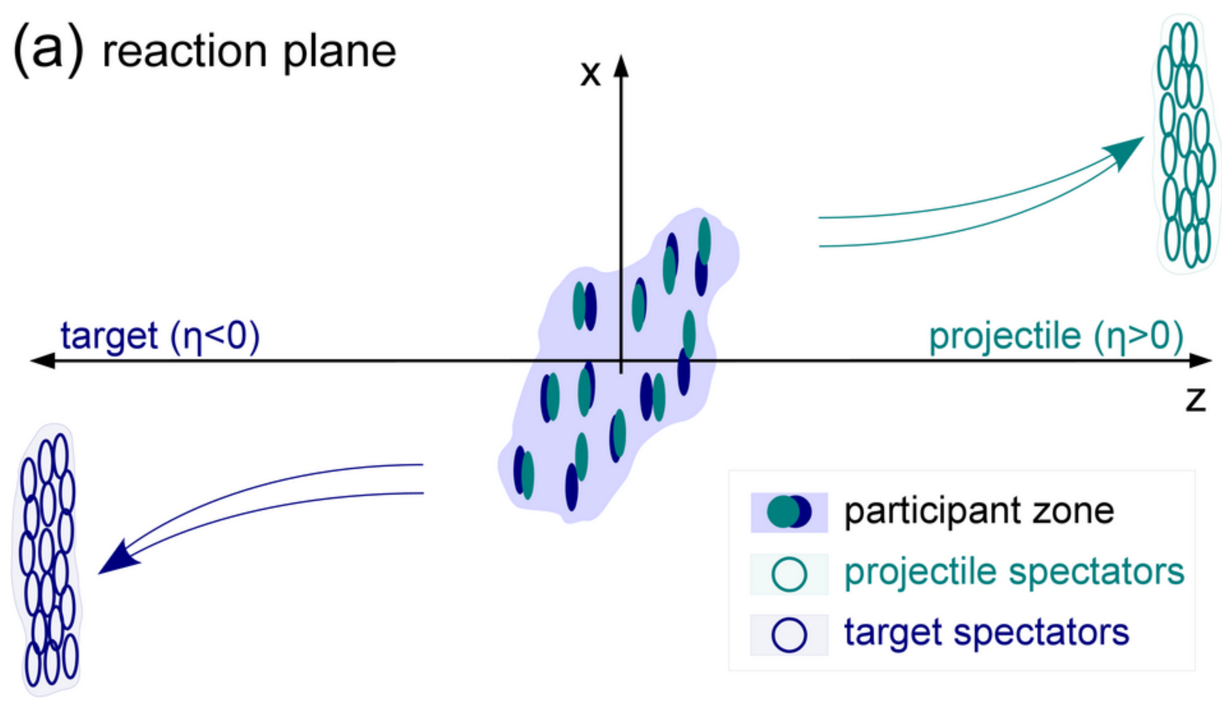


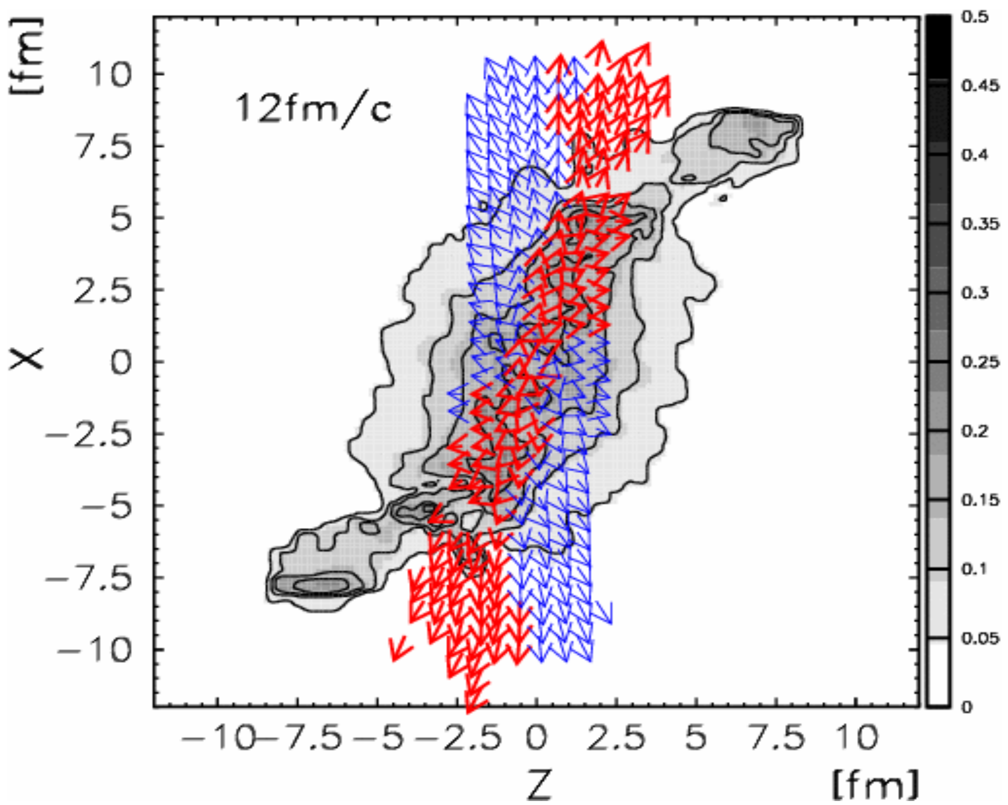
HP et al, Phys.Rev. C81 (2010) 044906

Directed Flow

- Collective deflection of particles in reaction plane

sketch from ALICE, Phys. Rev. Lett. 111





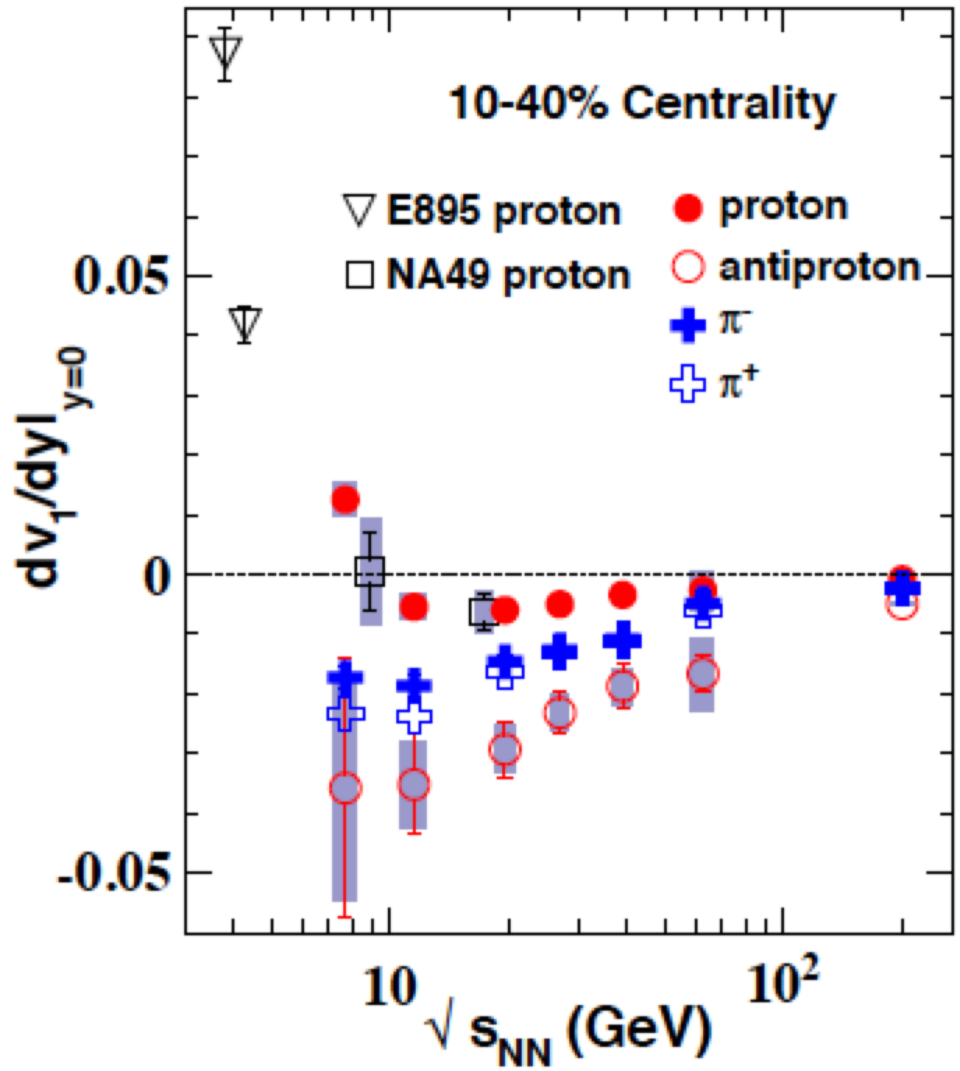
J.Brachmann et al., Phys.Rev. C, 61, 2000

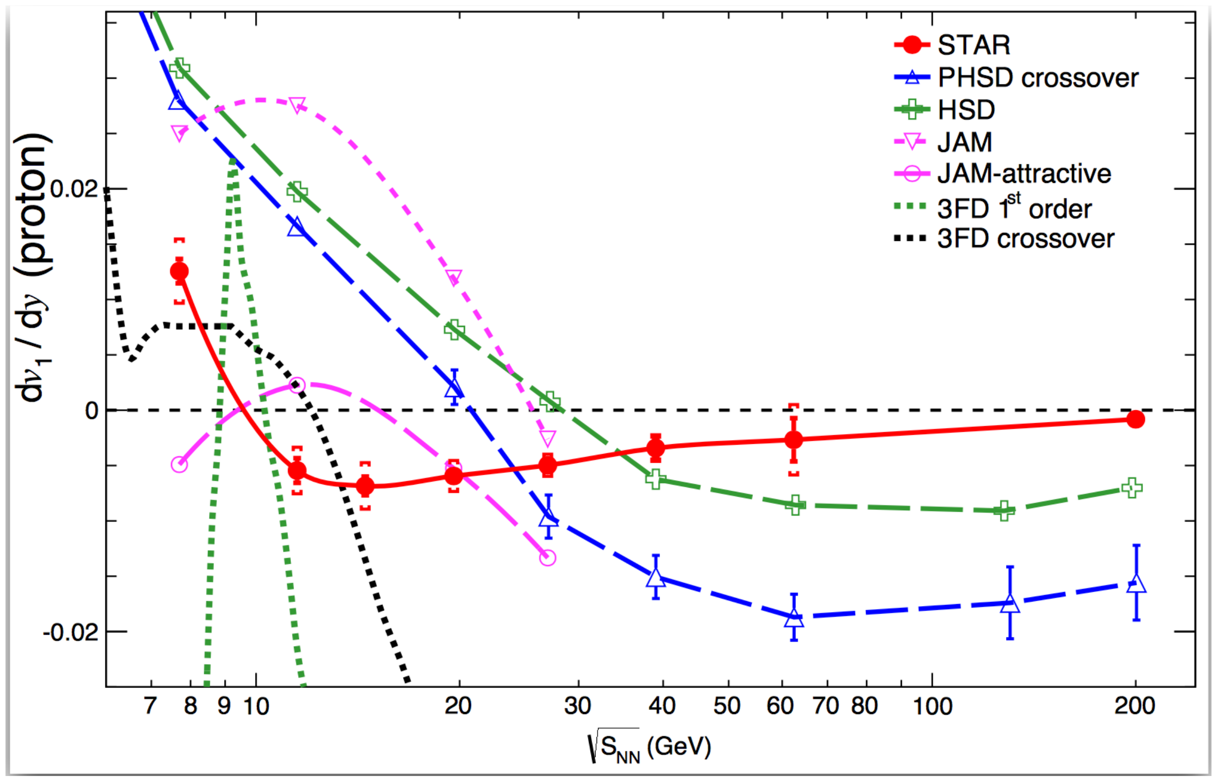
- Non-monotonic energy dependence of v1 slope
  - First order phase transition?

Directed Flow

- Collective deflection of particles in reaction plane

STAR, PRL 112, (2014) 162301

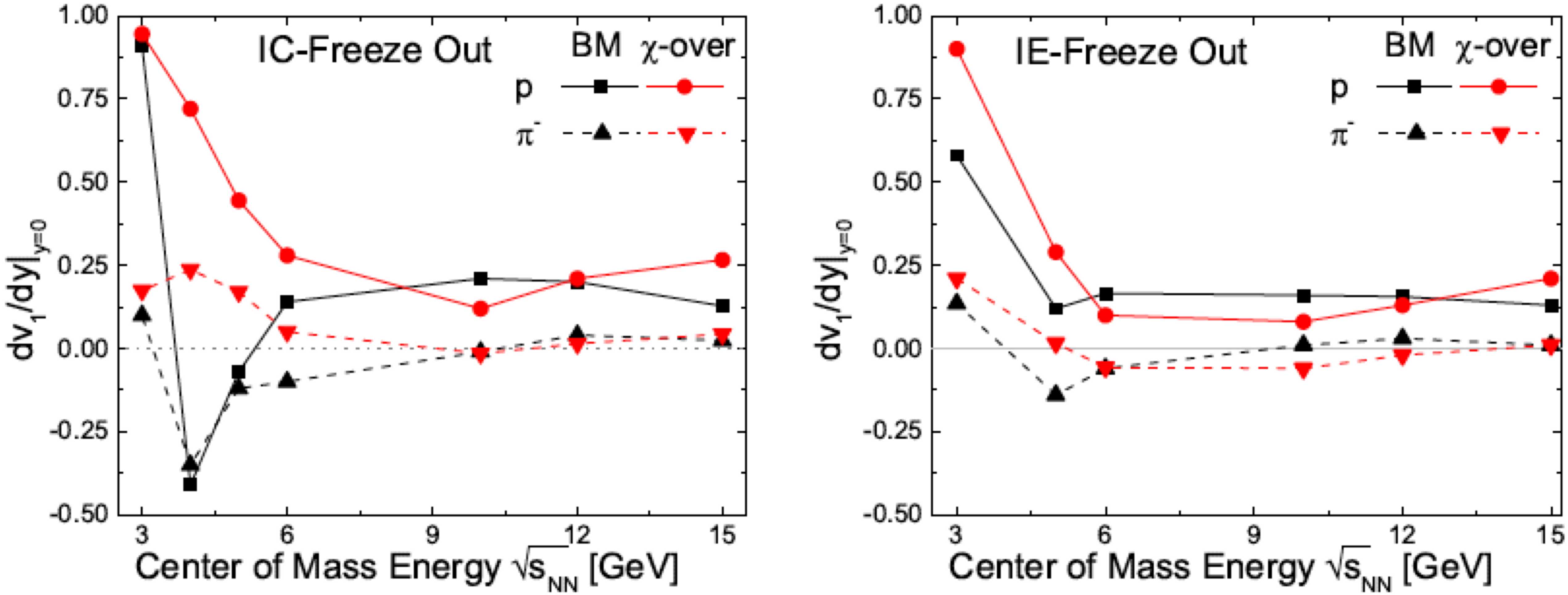




S. Singha, talk at INT-16-3

- Non-monotonic energy dependence of v1 slope
  - First order phase transition?
  - No quantitative theory description so far

v_1 Slope for Pions and Protons



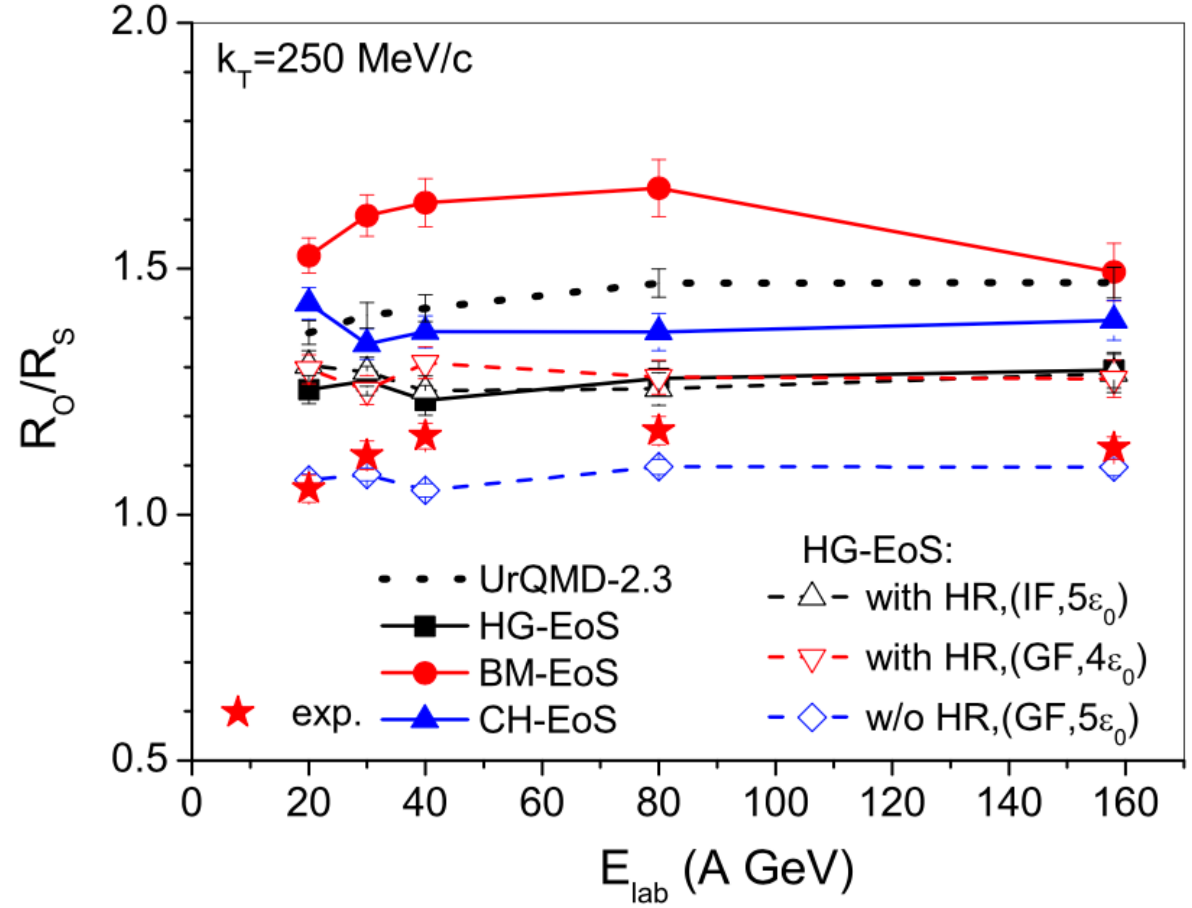
- Particlization added including hadronic rescattering
- Isochronous versus iso-energy density transition criterion
  - Drastic effect on dip structure

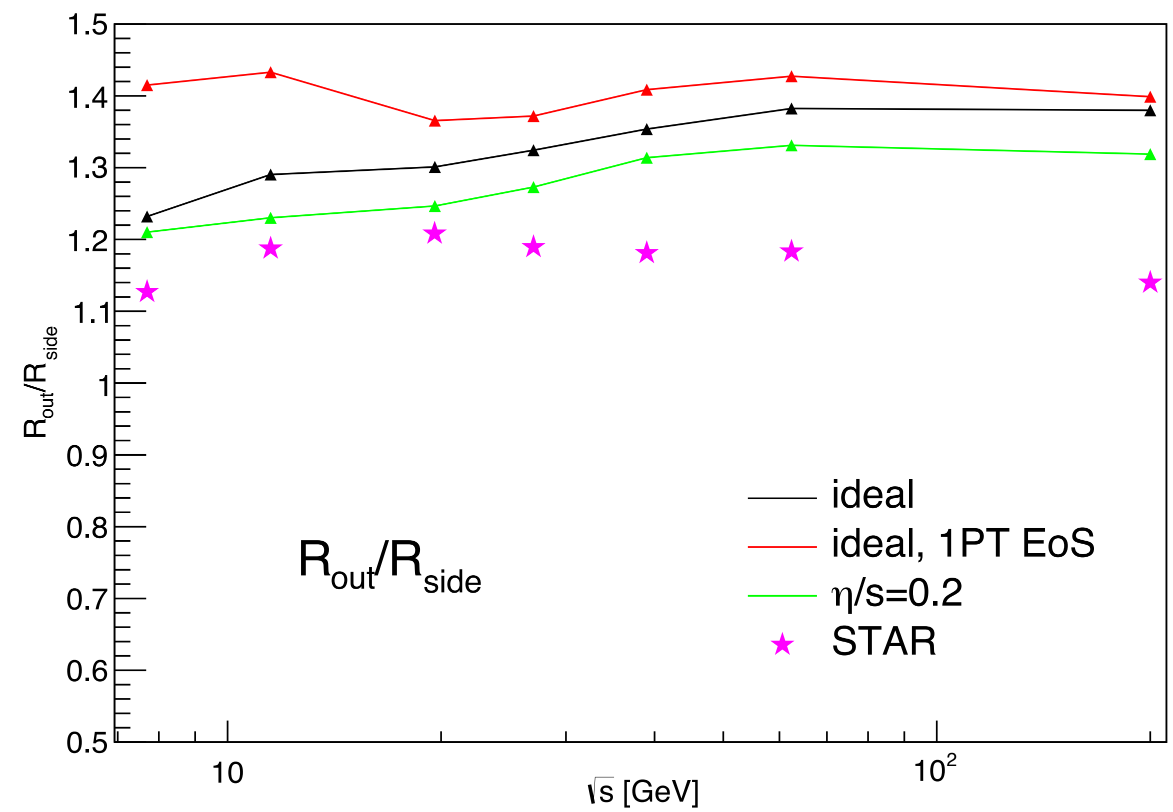
J. Steinheimer, J. Auvinen, HP, M. Bleicher and H. Stöcker, Phys.Rev. C89 (2014) 054913

Observable: Ro/Rs Ratio

- Idea: Softest point increases the lifetime of the system

Q. Li et al, Phys.Lett. B674 (2009)



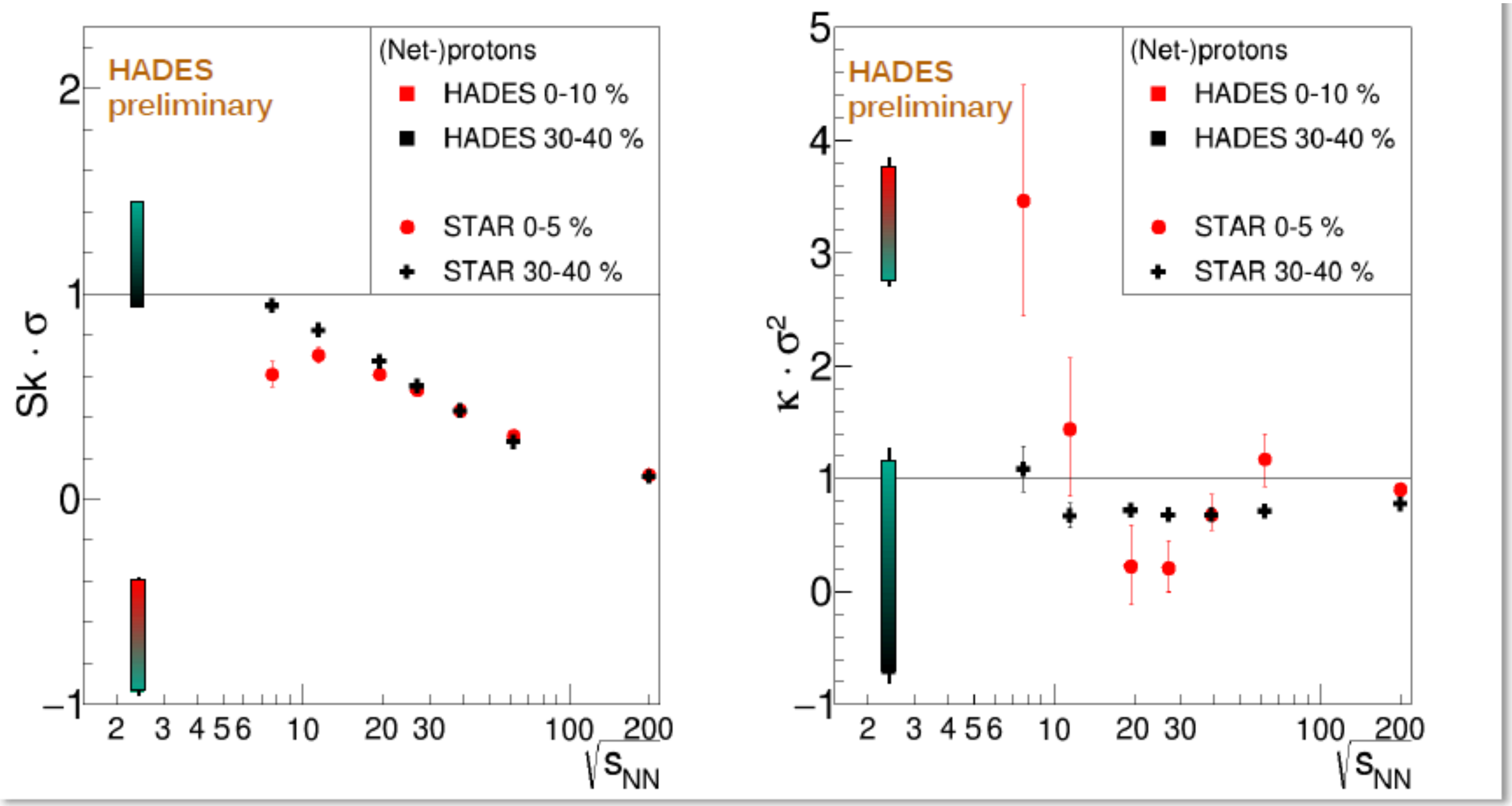


Y. Karpenko, WPCF 2014

- NA49 and STAR data show a **slight** peak
- Hybrid approach confirms larger ratio for **first order** transition
- Open question: **Cluster** formation from phase separation?

Observable: Higher Moments

- Including new result from HADES Au+Au collisions: Skewness and kurtosis show **non-trivial** energy dependence



M. Lorenz, QM 17,
STAR: X. Luo, PoS (CPOD 2014) 019

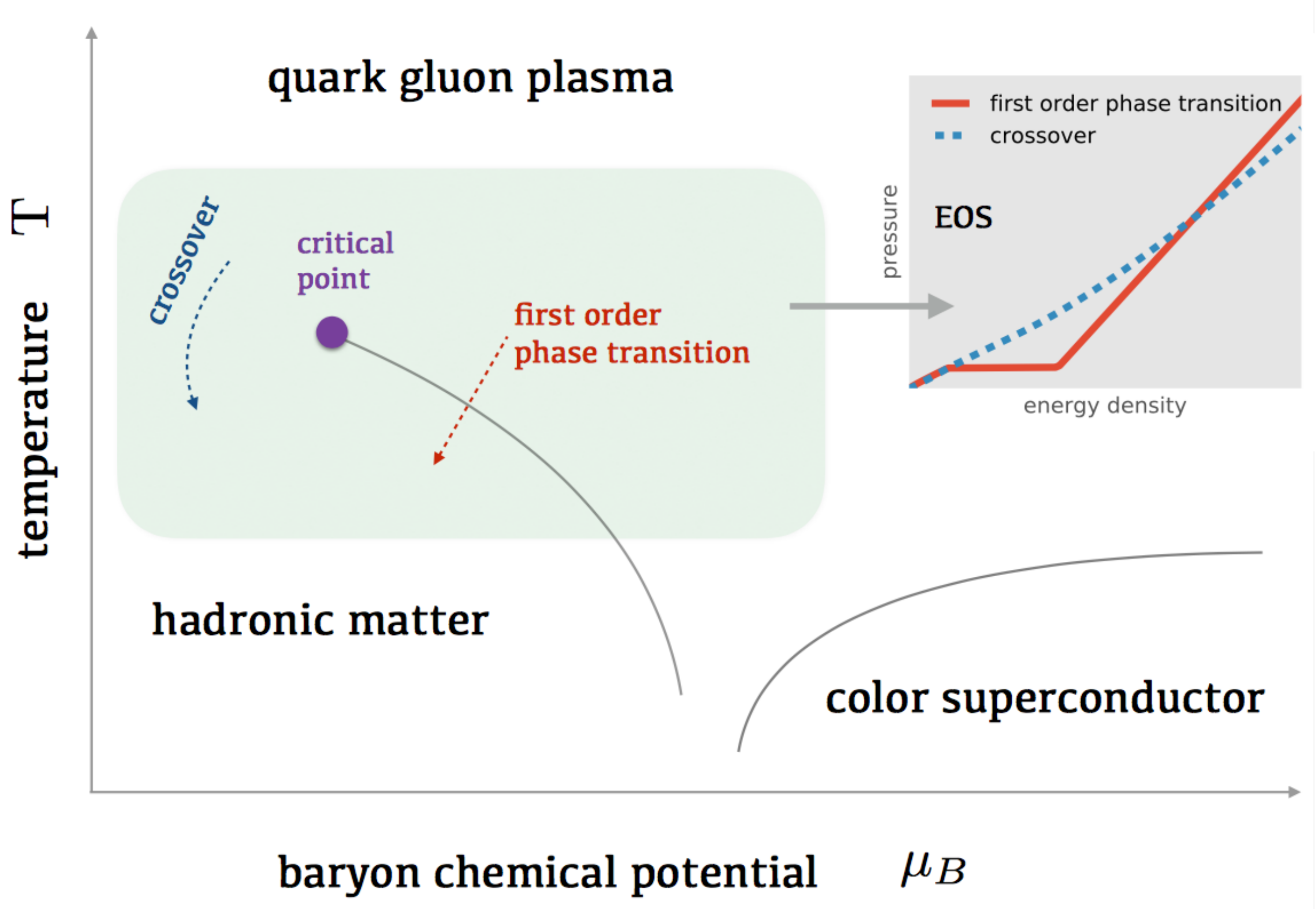
P 8.1 R. Holzmann

- Experimental results are **scrutinised**
- Can we draw **exclusion plots** on the phase diagram by extracting 2-, 3- and 4-particle correlations?

A. Bzdak, V. Koch and N. Strodthoff, arxiv:1607.07375

Deep Learning Techniques

- First proof-of-principle application of deep learning to heavy ion physics



TRAINING DATASET	$\eta/s = 0$		$\eta/s = 0.08$	
	EOSL	EOSQ	EOSL	EOSQ
Au-Au $\sqrt{s_{NN}} = 200\,\text{GeV}$	7435	5328	500	500
Pb-Pb $\sqrt{s_{NN}} = 2.76\,\text{TeV}$	4967	2828	500	500

TESTING ACCURACIES	GROUP 1		GROUP 2	
	EOSL	EOSQ	EOSL	EOSQ
Number of events	3349	3994	4164	4752
Accuracy	98.5%	91.6%	99.2%	99.2%

- Extraction of QCD equation of state seems possible
- Plans: Device new observables and apply to real data

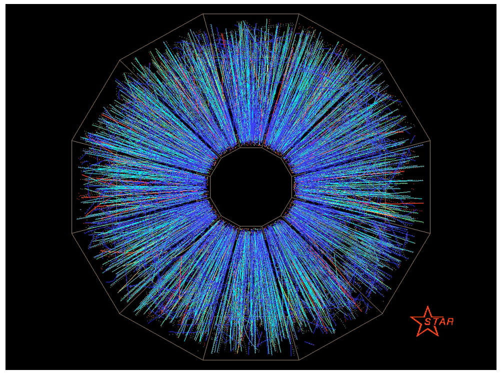
K. Zhou, L.-G. Pang, N. Su, V. Vovchenko, HP, H. Stöcker, X.-N. Wang, Nature Commun. 9 (2018) no.1, 210

Inspired from Brain/CNN

- As in image recognition, raw (p_T,Φ) data is classified

„DOG“

„CAT“

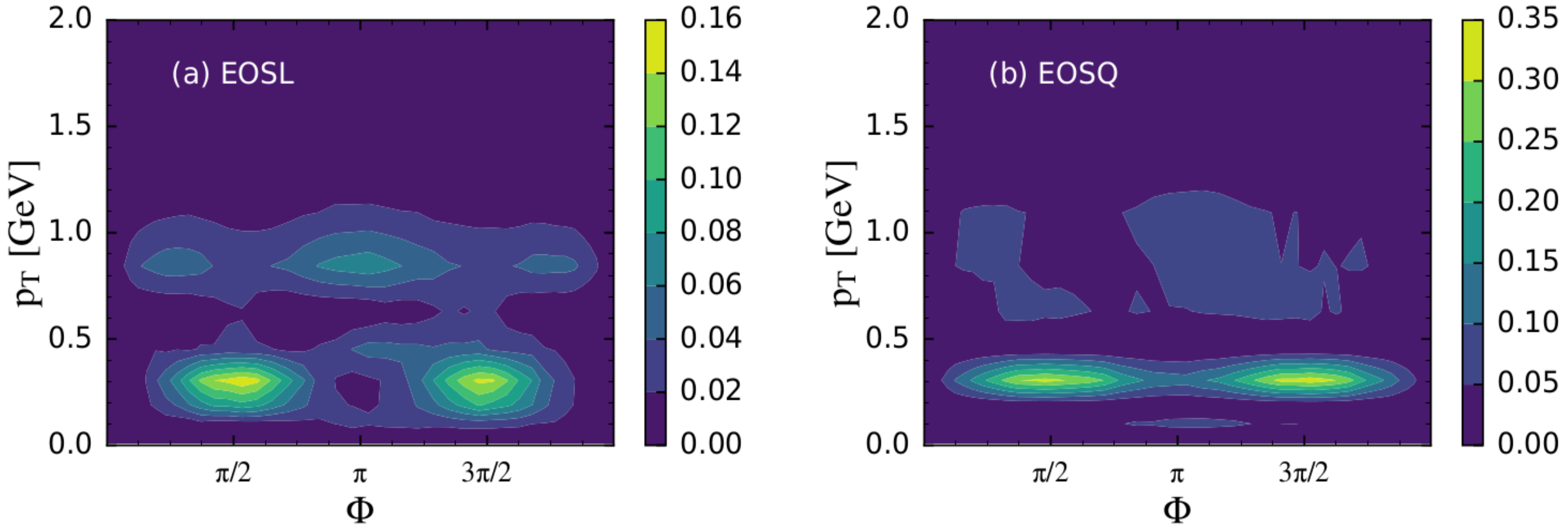


Cross-Over „(0,1)“

First-Order „(1,0)“

Importance Maps

- By replacing individual pixels, one can extract crucial features



- Helpful to understand sensitivities and device new observables

Summary

- Heavy ion collisions at low beam energies reach the high density region to **explore structures** in phase diagram
- **Hybrid** hydrodynamic + transport approaches are successfully employed to describe the dynamics
  - Equation of state is a direct input
  - Transport coefficients are crucial (not discussed here)
  - **Directed flow** poses a challenge to theory interpretations
  - Numerical solutions need to be thoroughly verified
- Deep learning techniques might help to identify **new sensitive** observables
- New results by BNL-BES I and NA61 at SPS and **exciting future** experimental programs coming up at BNL -BES II, FAIR, NICA and JPARC-HI

Open Issues

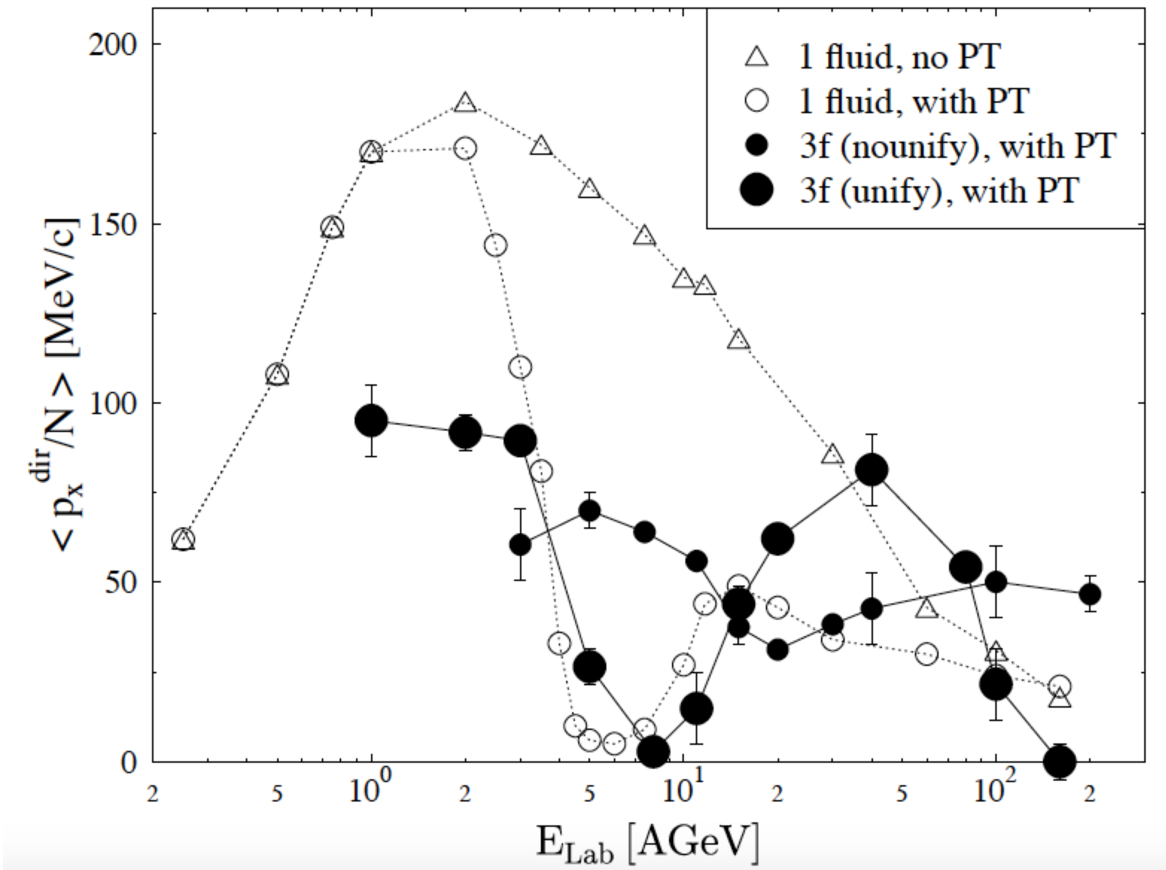
- Does the symmetry matter? Different isospin in heavy ion collisions compared to heavy ion collisions
- Equation of state is always in equilibrium, even if viscous hydrodynamics is applied, is this a problem? Especially, when now moving to anisotropic hydrodynamics?
- Possible related future work:
  - Study neutron skin effects on heavy ion observables, e.g. electromagnetic emission and charge correlations
  - New attempt of Bayesian Danielewicz constraint

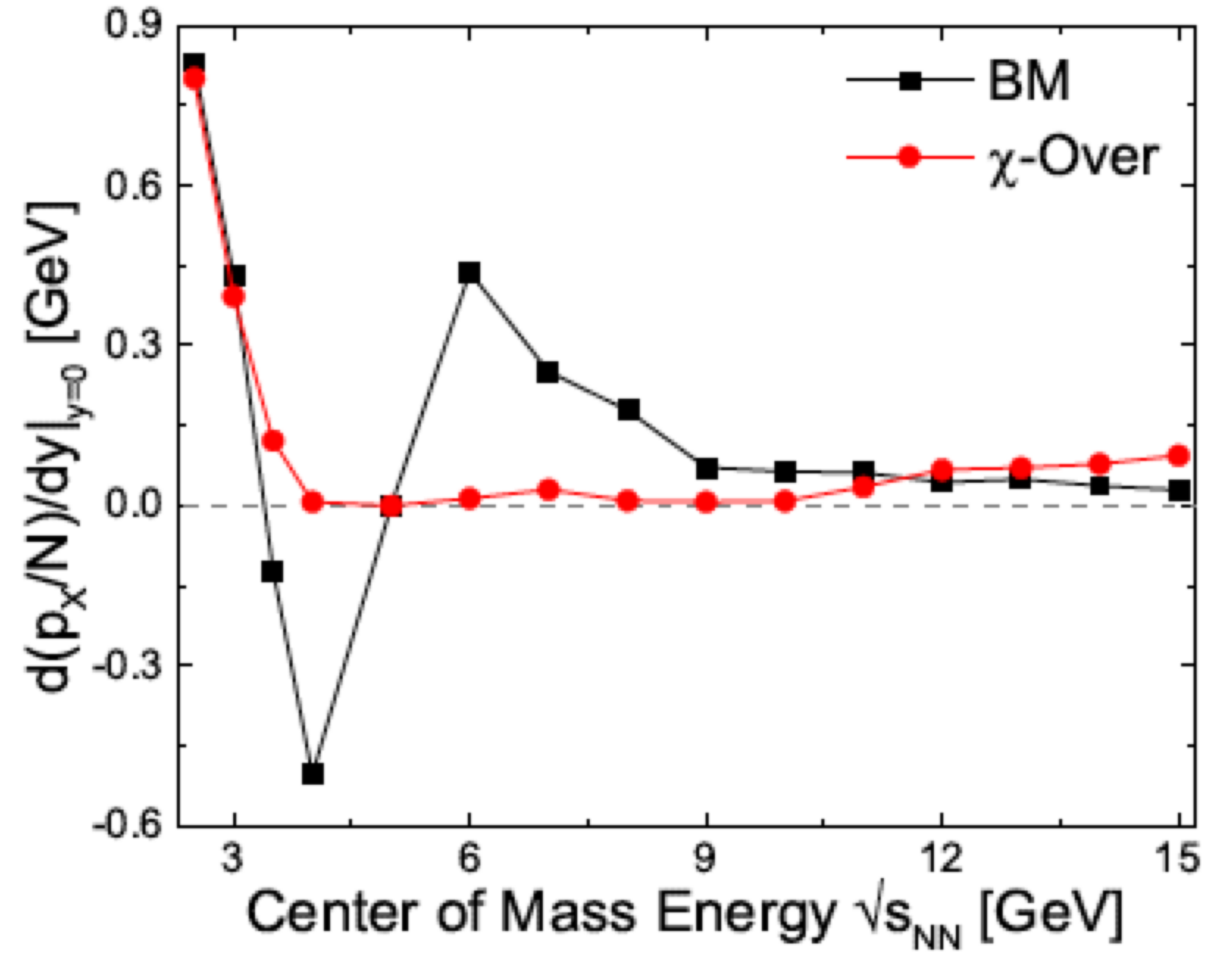
Backup

Pure Fluid Calculations

- Negative slope is reproduced in fluid dynamic calculation

J.Brachmann et al., Phys.Rev. C, 61, 2000



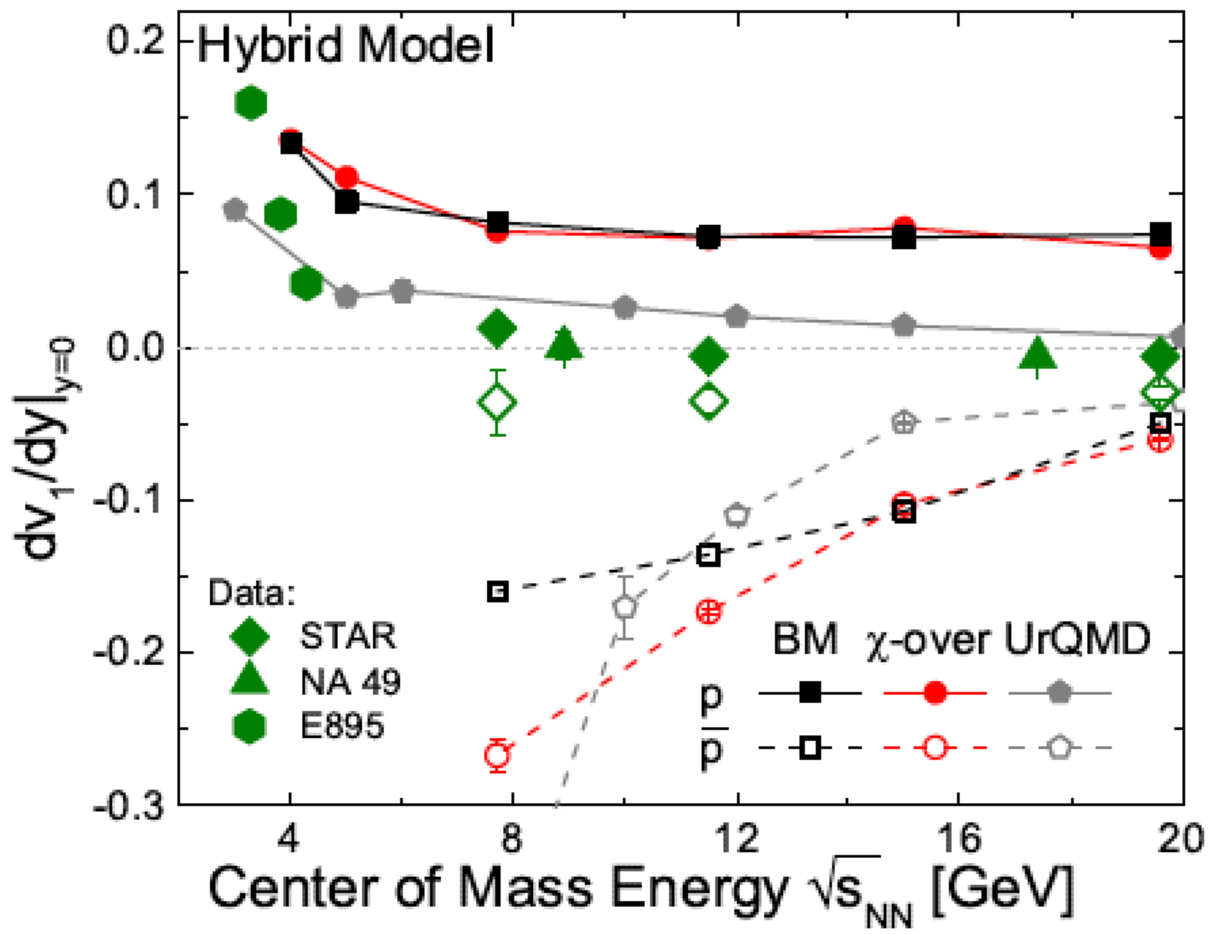


- Assumptions
  - Cold nuclear matter initialization (no pre-equilibrium transport)
  - Direct integration of momentum in x-direction without hadronic rescattering

J. Steinheimer, J. Auvinen, HP, M. Bleicher and H. Stöcker, Phys.Rev. C89 (2014) 054913

Full Hybrid Approach

- Hybrid approach with different equations of state shows similar results



- Alternative calculations within transport/3fluid dynamics confirm complexity of this observable

Konchakovski et al, Phys.Rev. C90 (2014) 014903

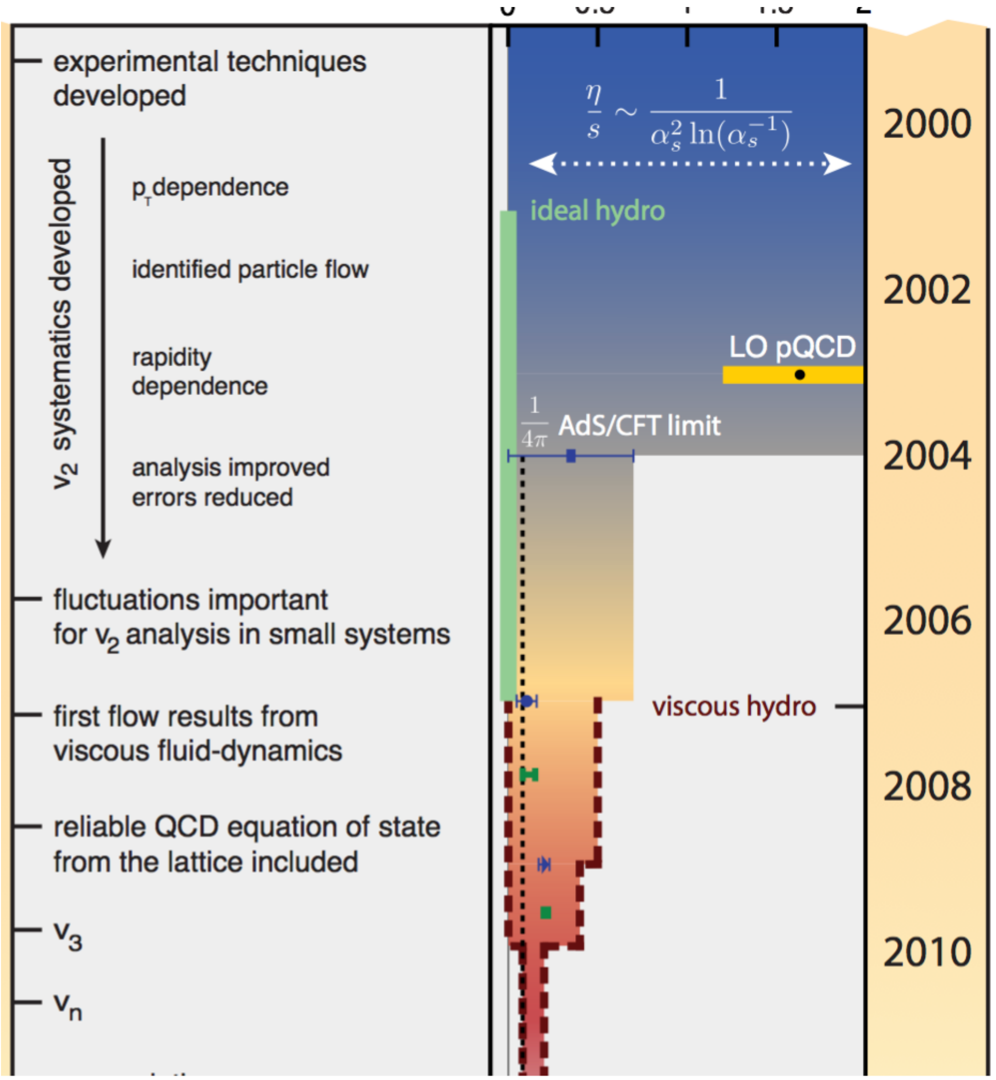
- **Additional issues** that influence the energy dependence like nucleon potentials, interactions with spectators have to be sorted out by looking at different particle species and the centrality dependence

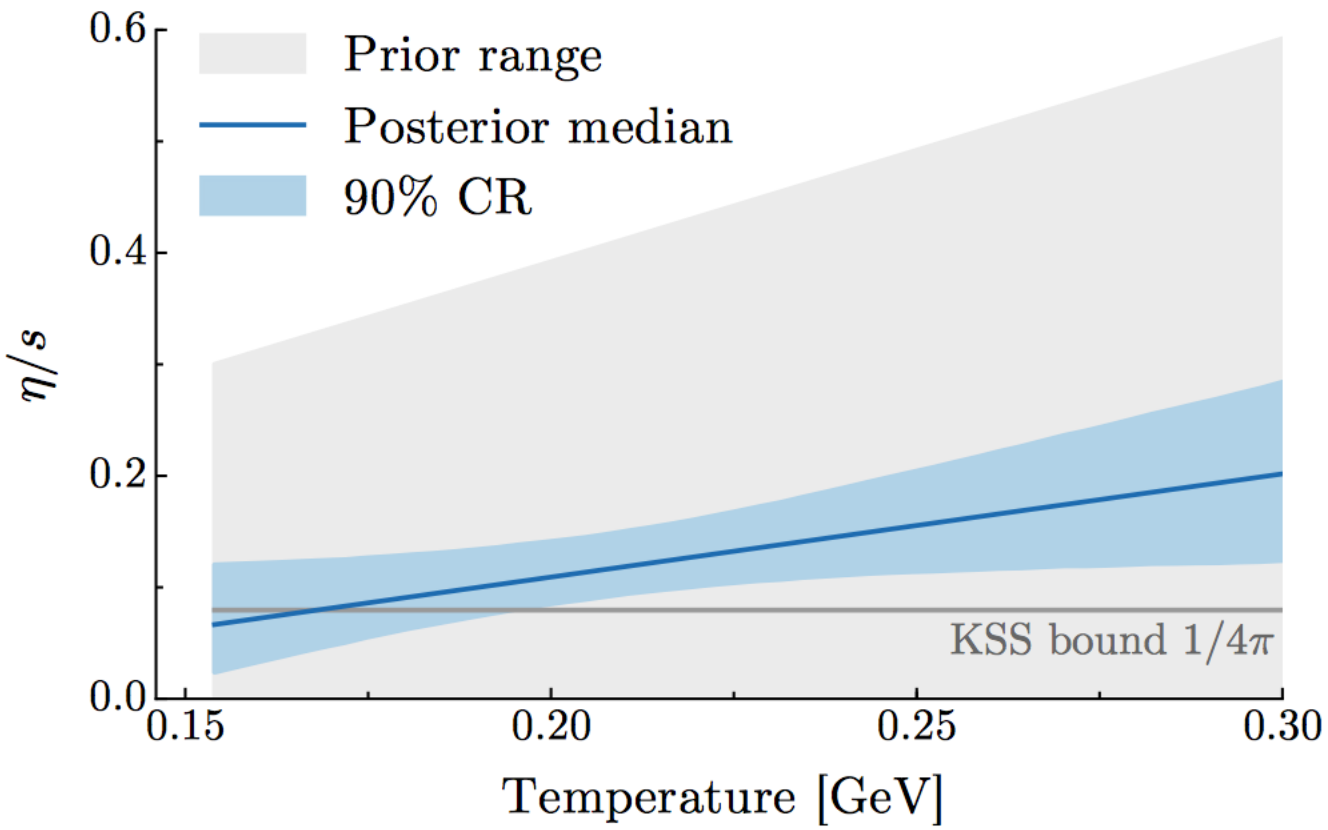
J. Steinheimer, J. Auvinen, H.P., M. Bleicher and H. Stöcker, PRC 89 (2014) 054913

Transport Coefficients

- Within hydrodynamics/hybrid approaches the shear viscosity is an input parameter

RHIC White paper, 2012





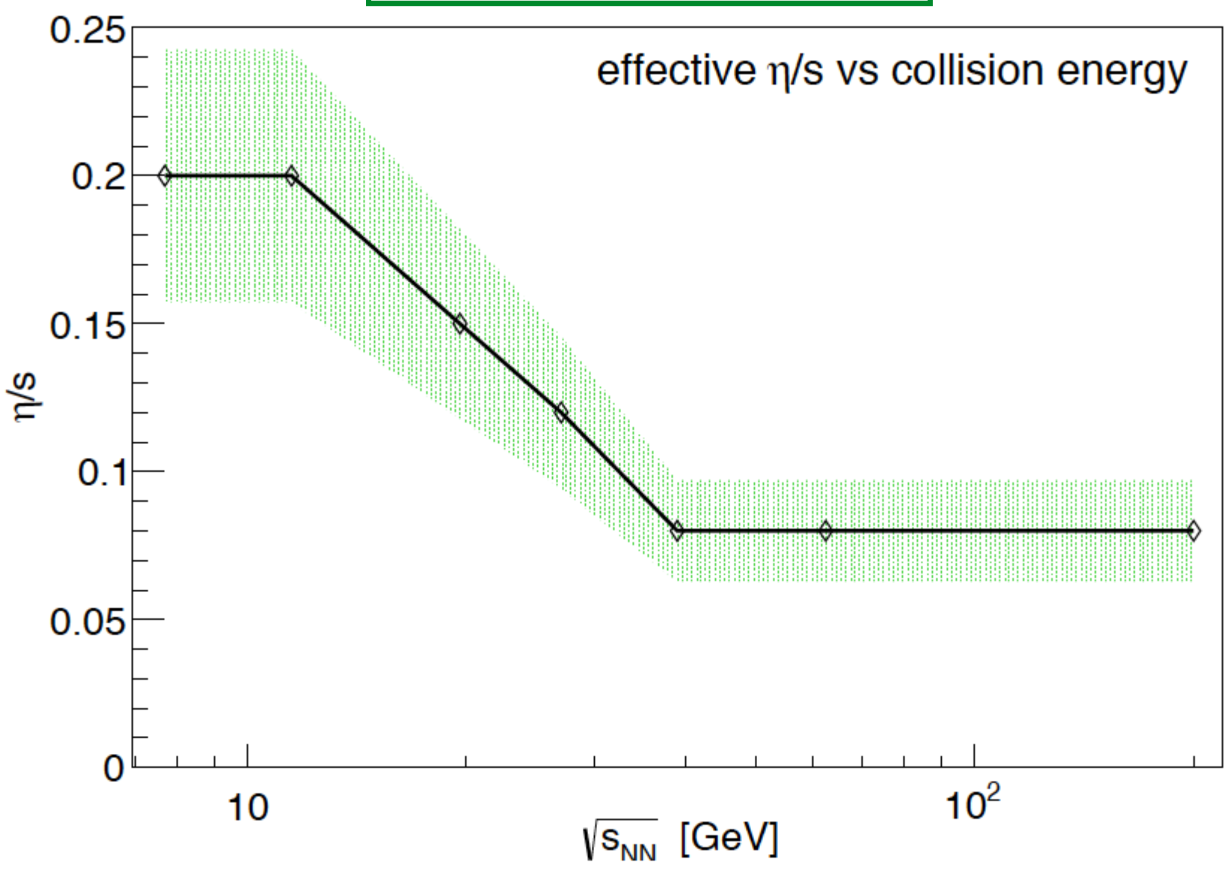
J. Bernhard et al, Phys.Rev. C94 (2016)

- Application of Bayesian techniques allows extraction of temperature dependence

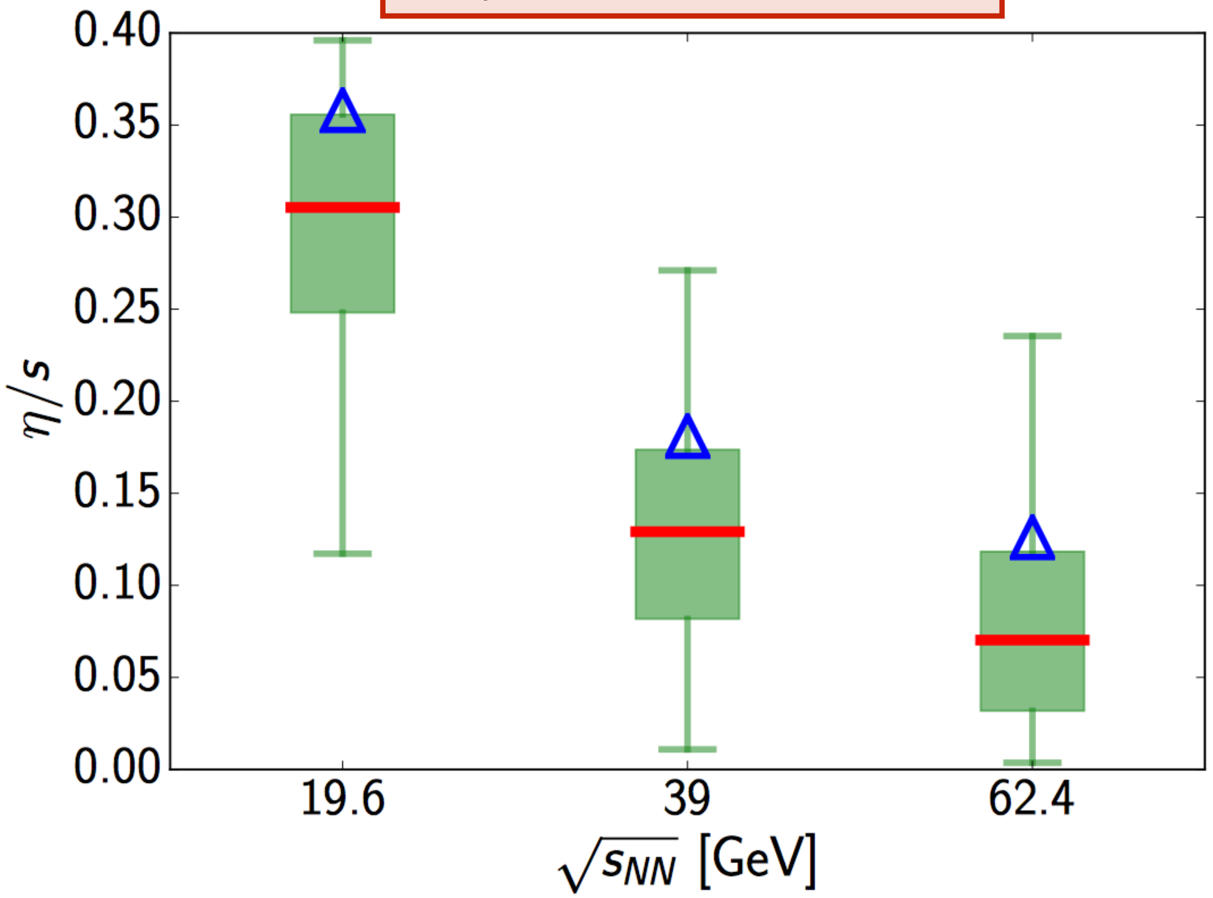
Shear Viscosity and v3

- Viscous UrQMD hybrid fitted to beam energy scan and SPS data allows to extract **effective** shear viscosity of the hydrodynamic stage

Analysis „by eye“



Bayesian framework



J. Auvinen et al., arXiv:1610.00590

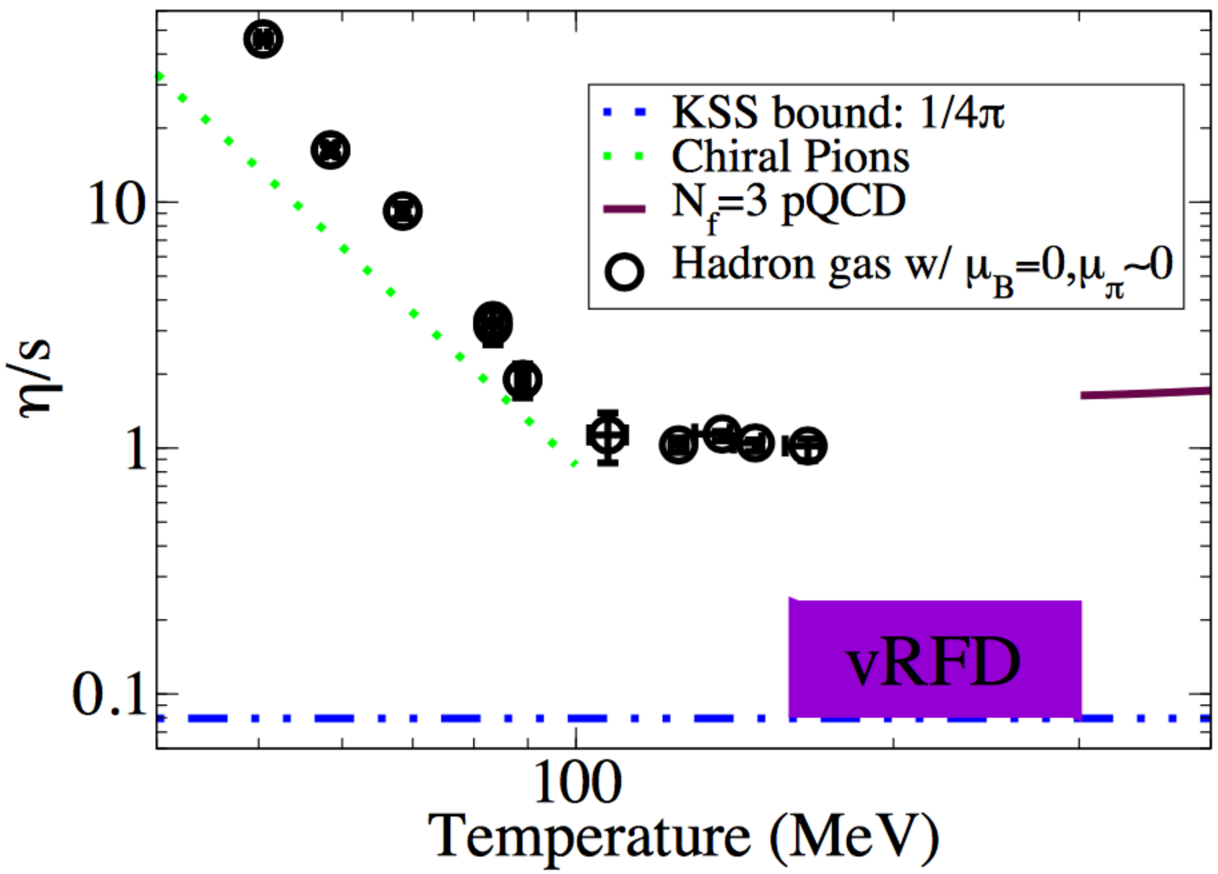
Y. Karpenko, P. Huovinen, HP, M. Bleicher, Phys.Rev. C91 (2015) no.6, 064901

Existing Results - Discrepancy

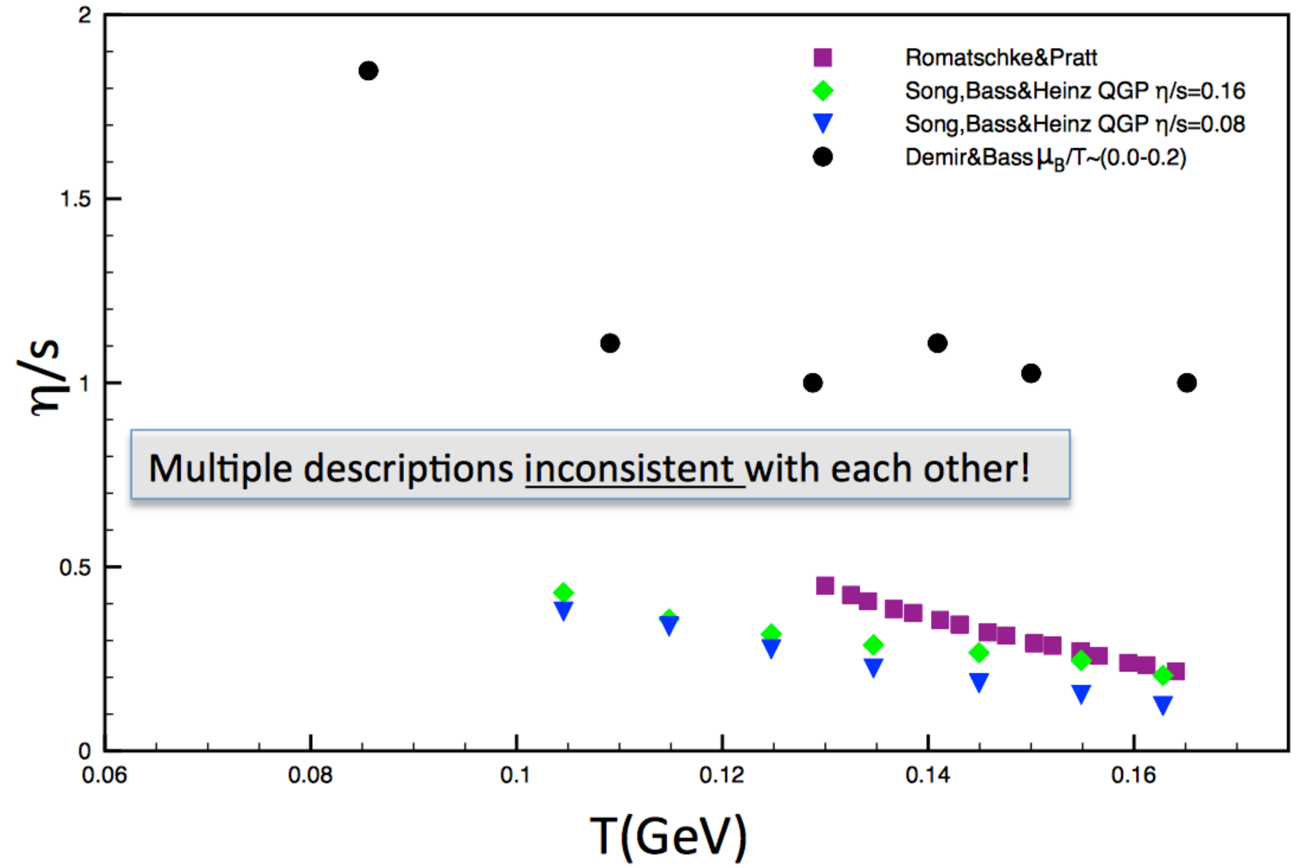
- Long standing question: Why are the results so different from each other?

Green-Kubo formalism UrQMD

Discrepancy with hydro-inspired B3D and VISHNU



N. Demir and S.A. Bass, Phys.Rev.Lett. 102 (2009)



-Romatschke & Pratt, arXiv:1409.0010v1
-Song, Bass & Heinz, Phys. Rev. C83 (2011) 024912
-Demir & Bass, Phys.Rev.Lett. 102 (2009) 172302

Shear Viscosity over Entropy Density

- Box with periodic boundary condition in chemical and thermal equilibrium
- Entropy is calculated via Gibbs formula from thermodynamic properties
- The shear viscosity is extracted following the Green-Kubo formalism:

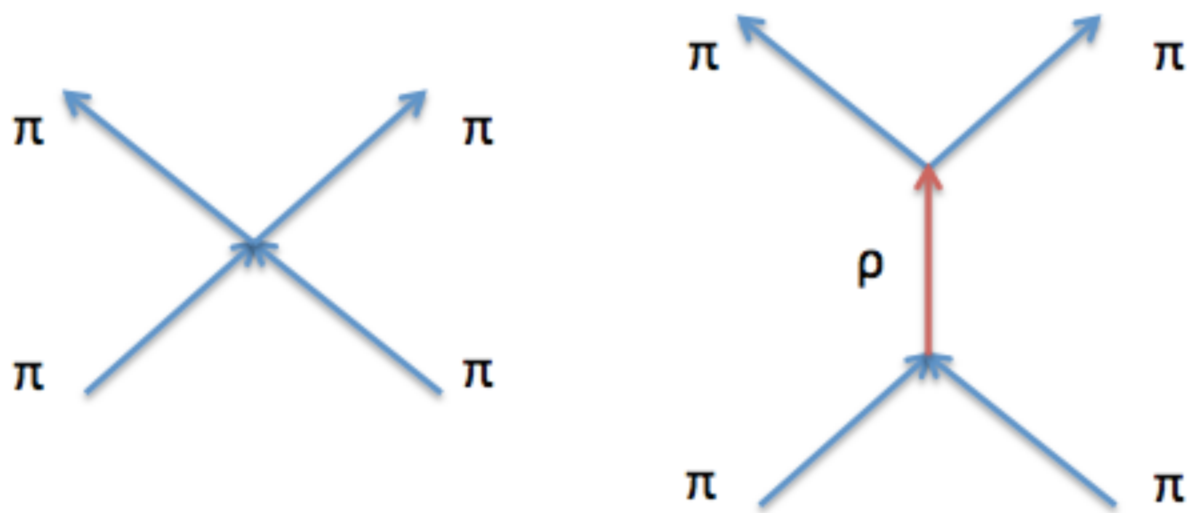
$$\eta = \frac{V}{T}\int_0^\infty C^{xy}(t)dt \qquad C^{xy}(t) = \frac{1}{N}\sum_s^N T^{xy}(s)T^{xy}(s+t)$$

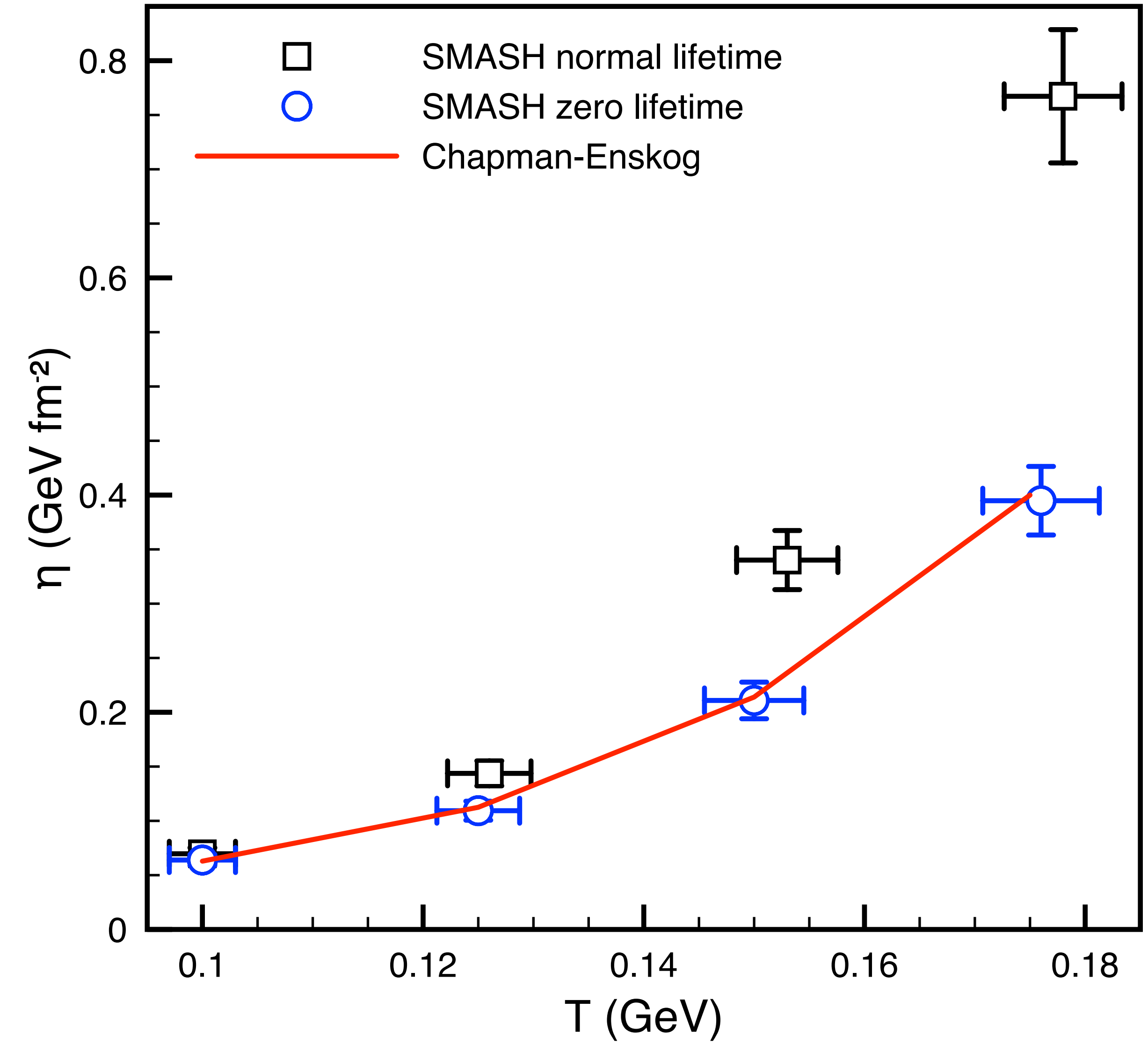
$$T^{\mu\nu} = \frac{1}{V}\sum_i^{N_{part}} \frac{p_i^\mu p_i^\nu}{p_i^0} \qquad C^{xy}(t) \simeq C^{xy}(0)\exp\left(-\frac{t}{\tau}\right)$$

$$\eta = \frac{VC^{xy}(0)\tau}{T}$$

Resonance Dynamics

- Energy-dependence of cross-sections is modelled via resonances
- Point-like in analytic calculation and finite lifetime in transport approach

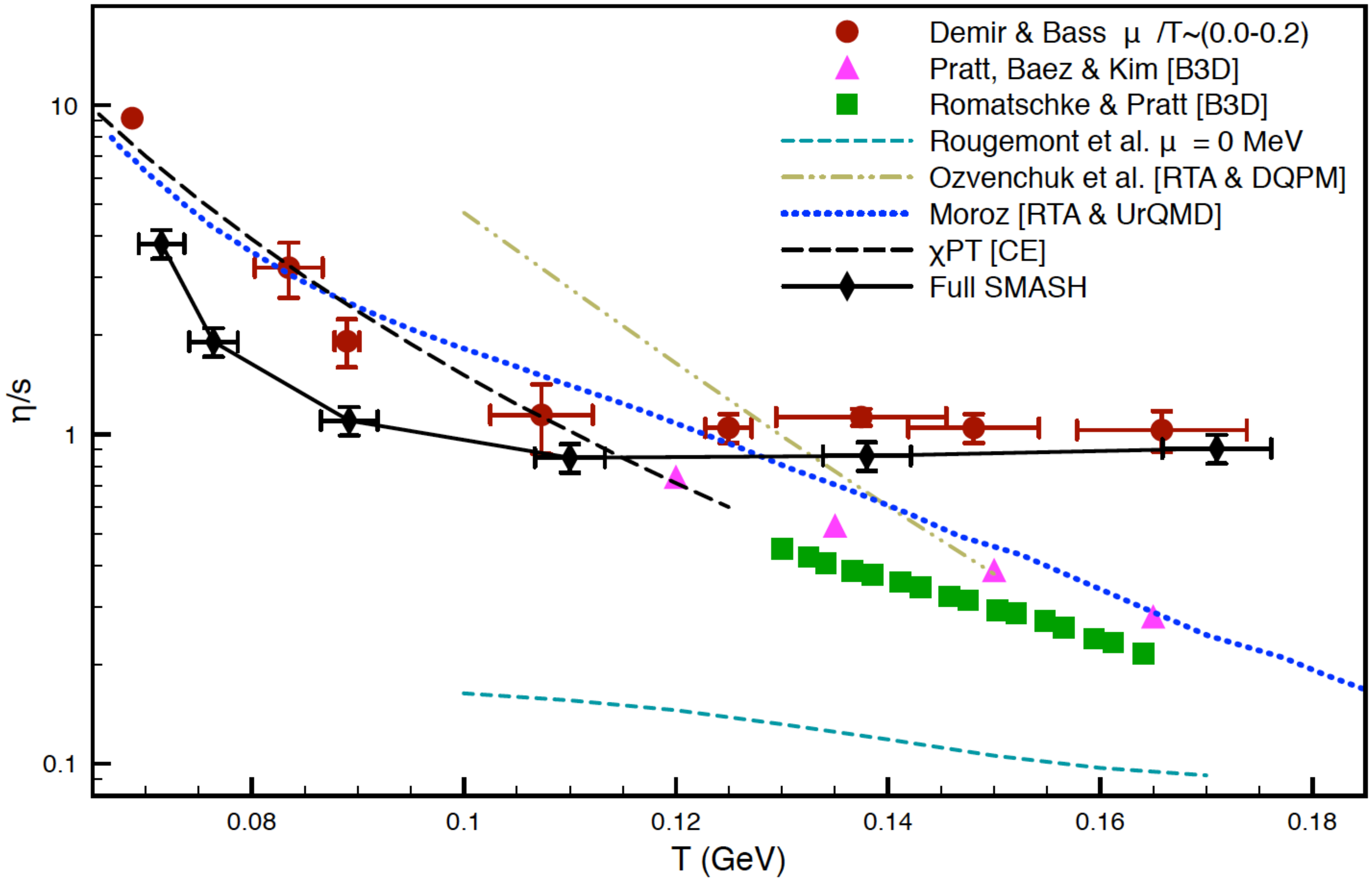




- Agreement recovered by decreasing ρ meson lifetime

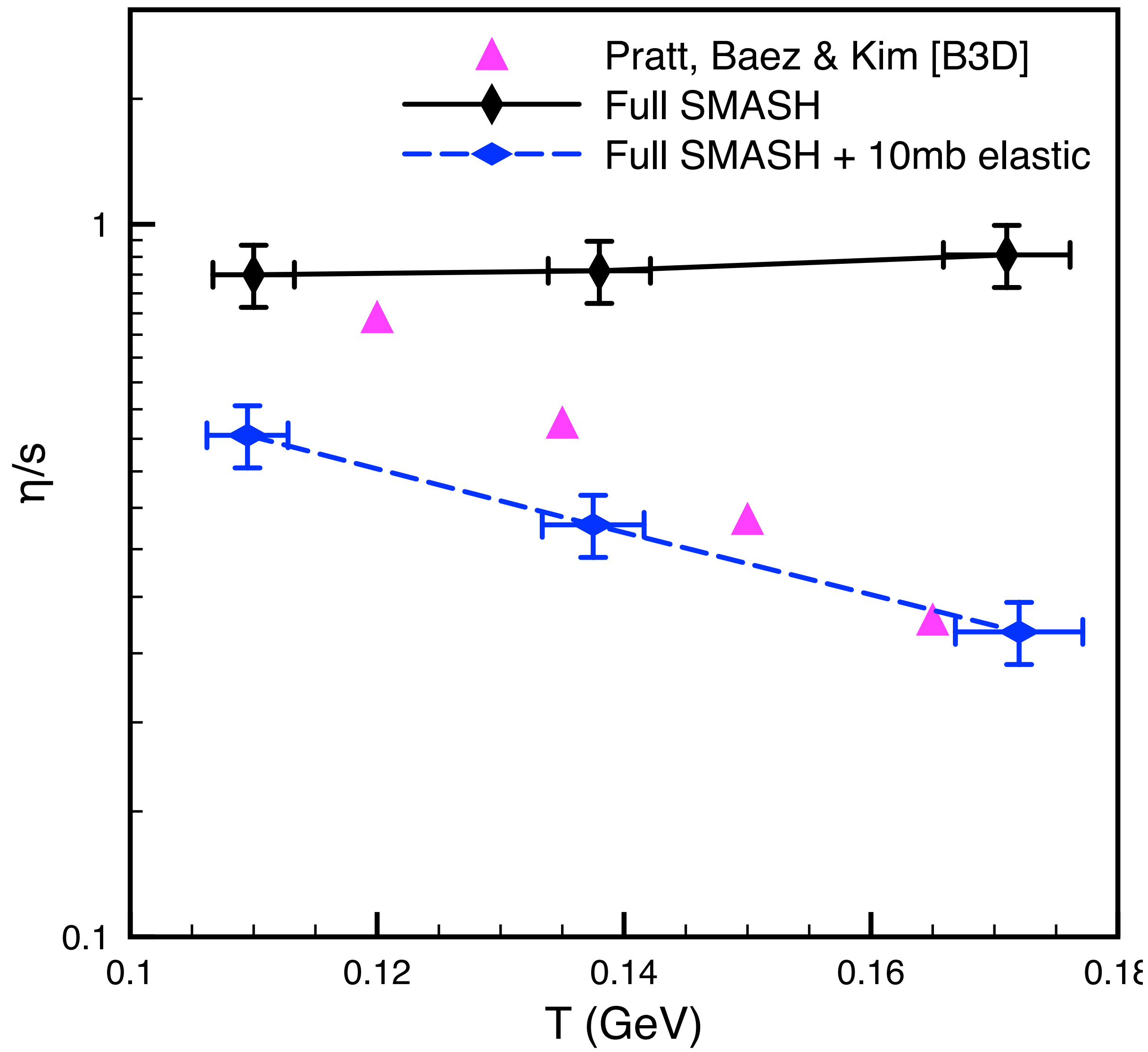
Comparison to Literature

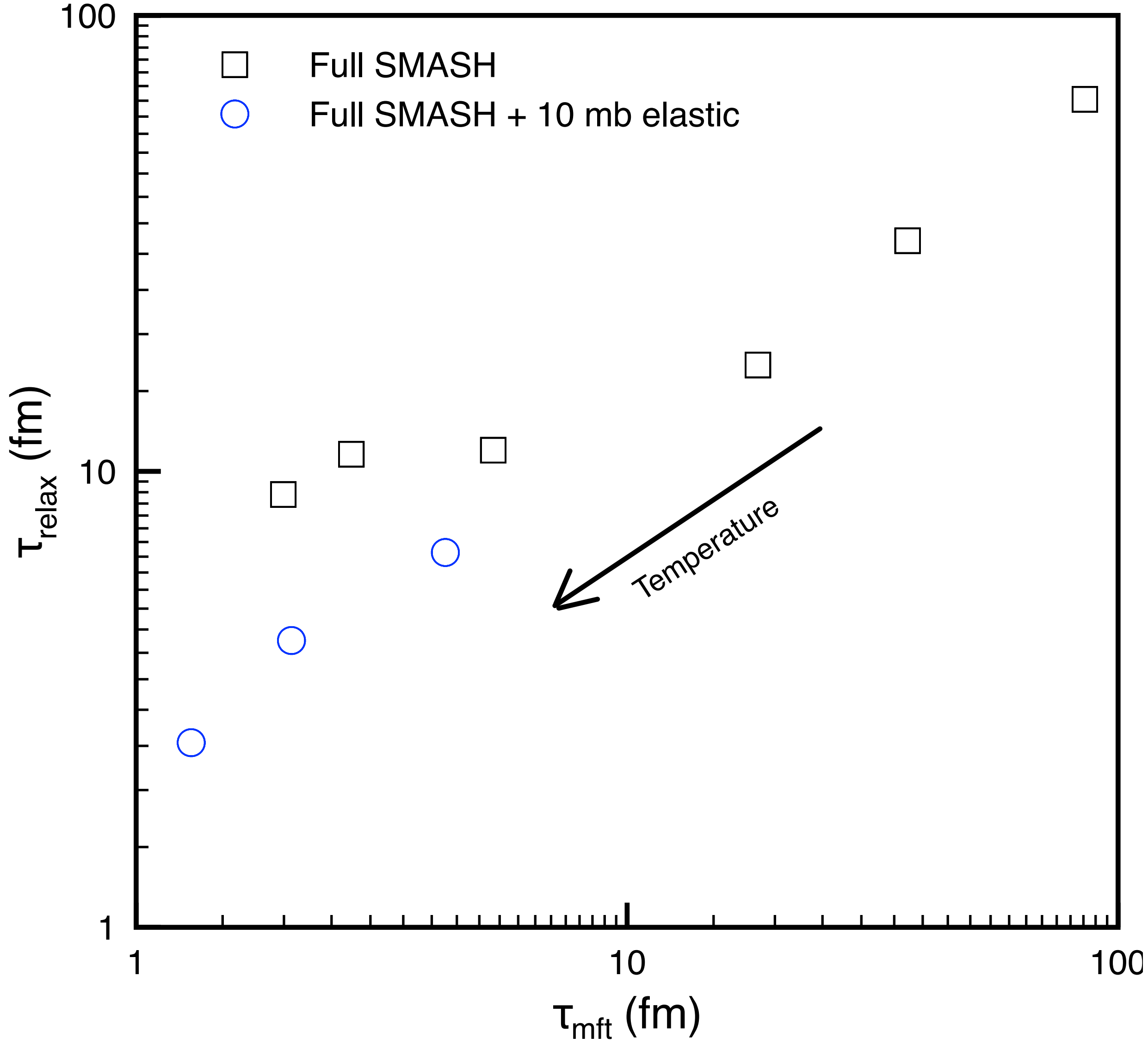
- Cl ectedted



Point-like Interactions

- Adding a constant elastic cross section leads to agreement with B3D result





- Approximately linear relationship between relaxation time and mean free time is recovered

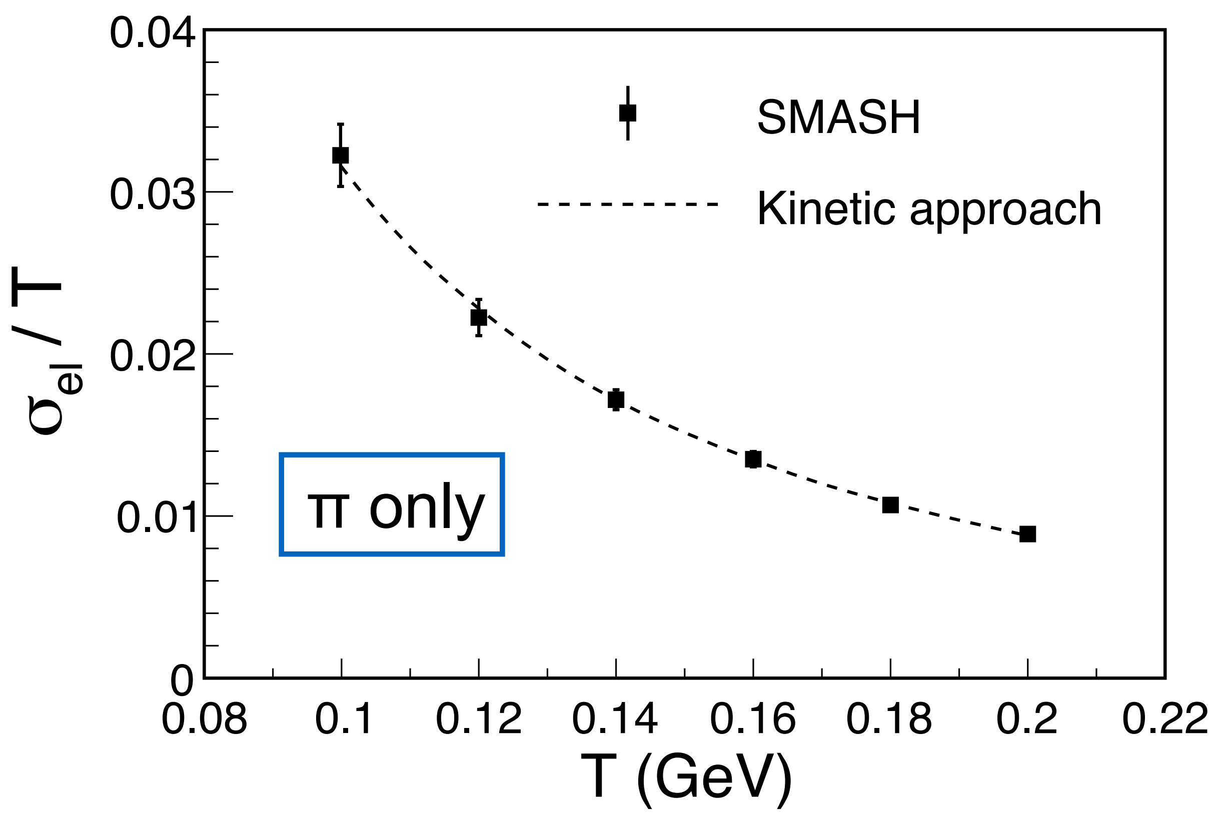
Electric Conductivity

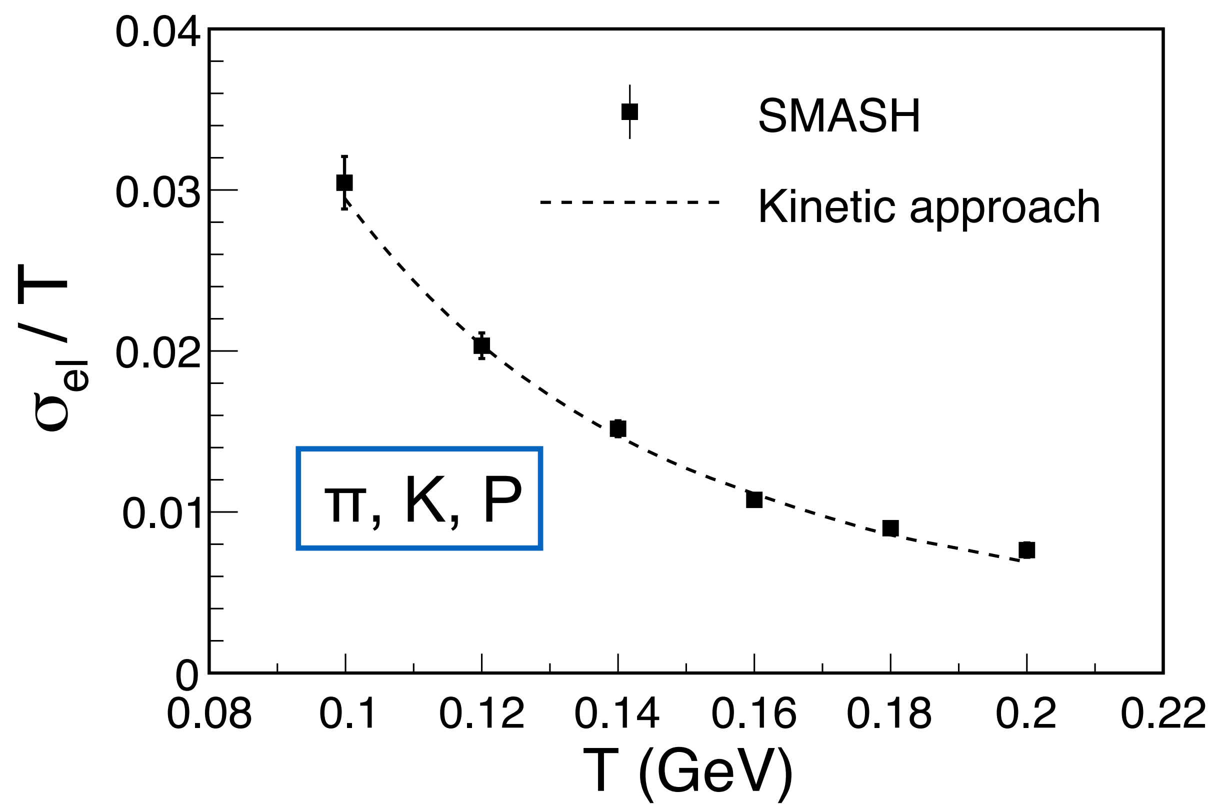
- Comparison to linear response kinetic theory to validate our approach

Greif et al, Phys.Rev. D93 (2016)

$$\sigma_{el} = \frac{V}{T}\int_0^\infty \langle j_i(0) j_i(t)\rangle dt \qquad\qquad \sigma_{el} = \frac{VC(0)\tau}{T}$$

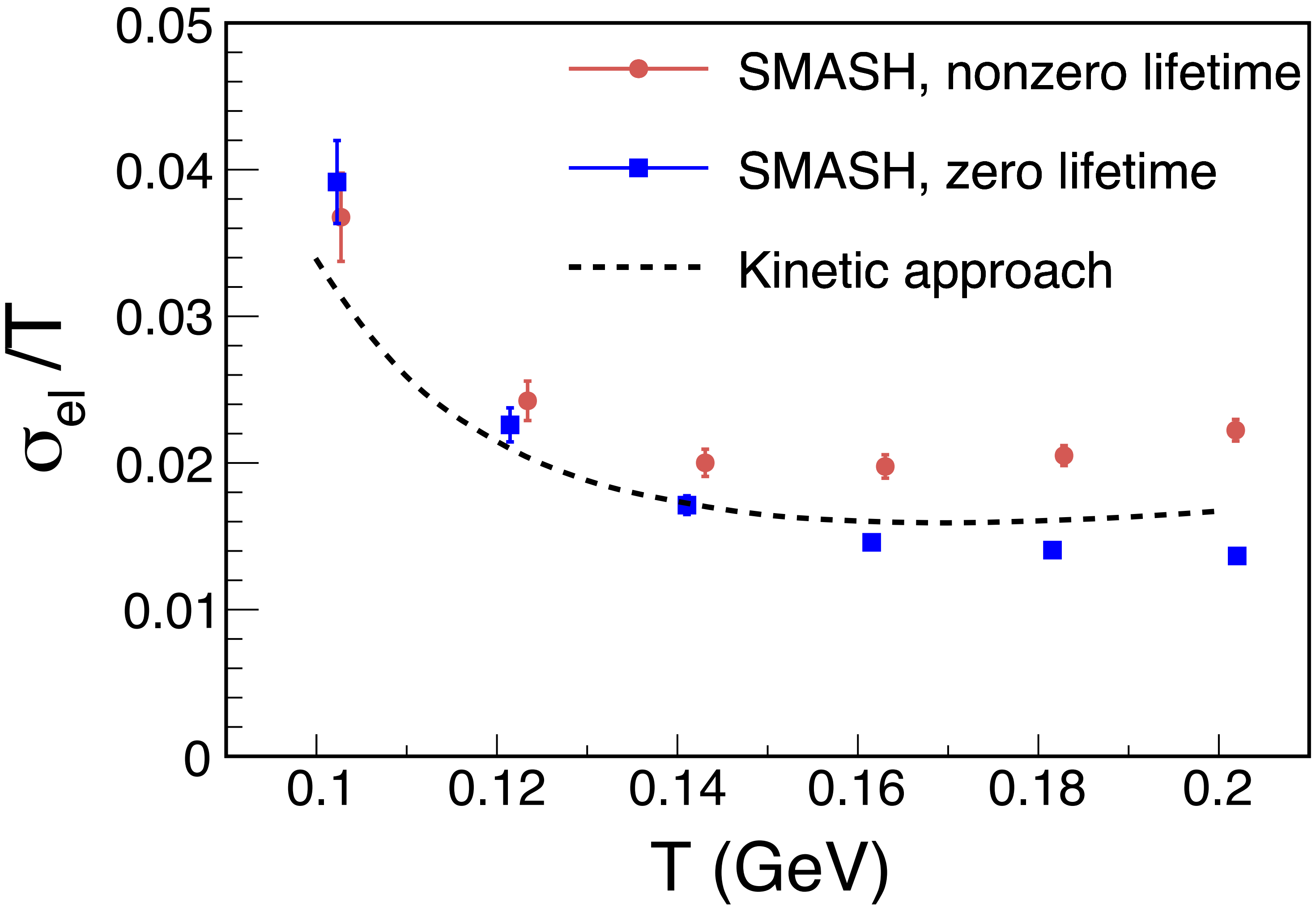
- Infinite matter with constant σ = 30 mb





Effect of Lifetime

- ρ-π system is again affected by the lifetime



- Work in progress: Understand the differences between analytic calculation and SMASH results