QCD matter under extreme conditions: The role of hadronic interactions

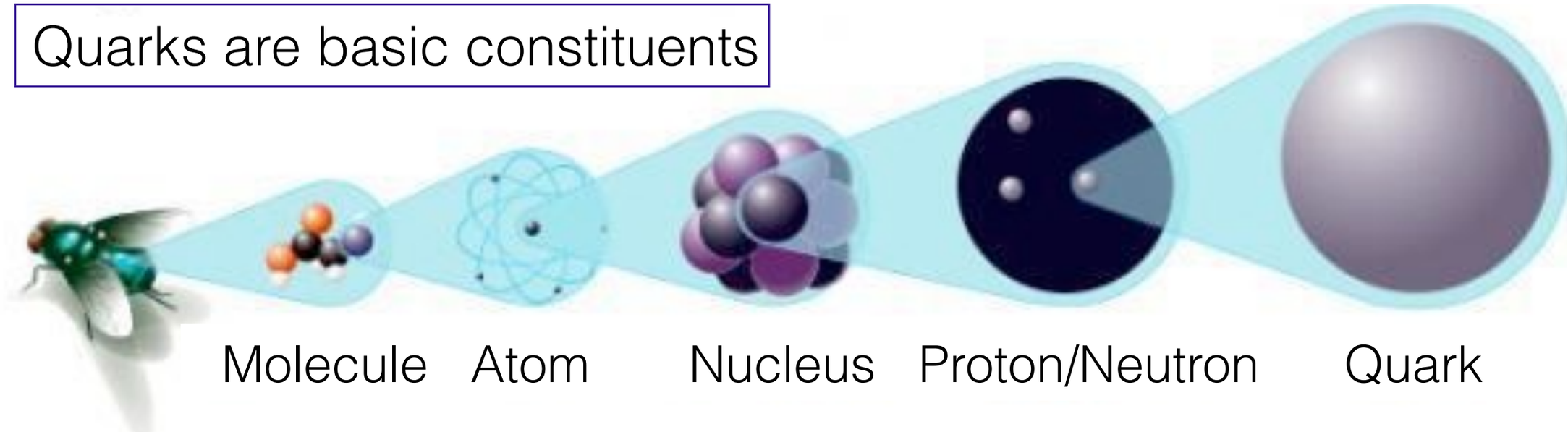
Hannah Elfner

December 5th 2019, Colloquium Eötvös University, Budapest

Quantum Chromodynamics (QCD)

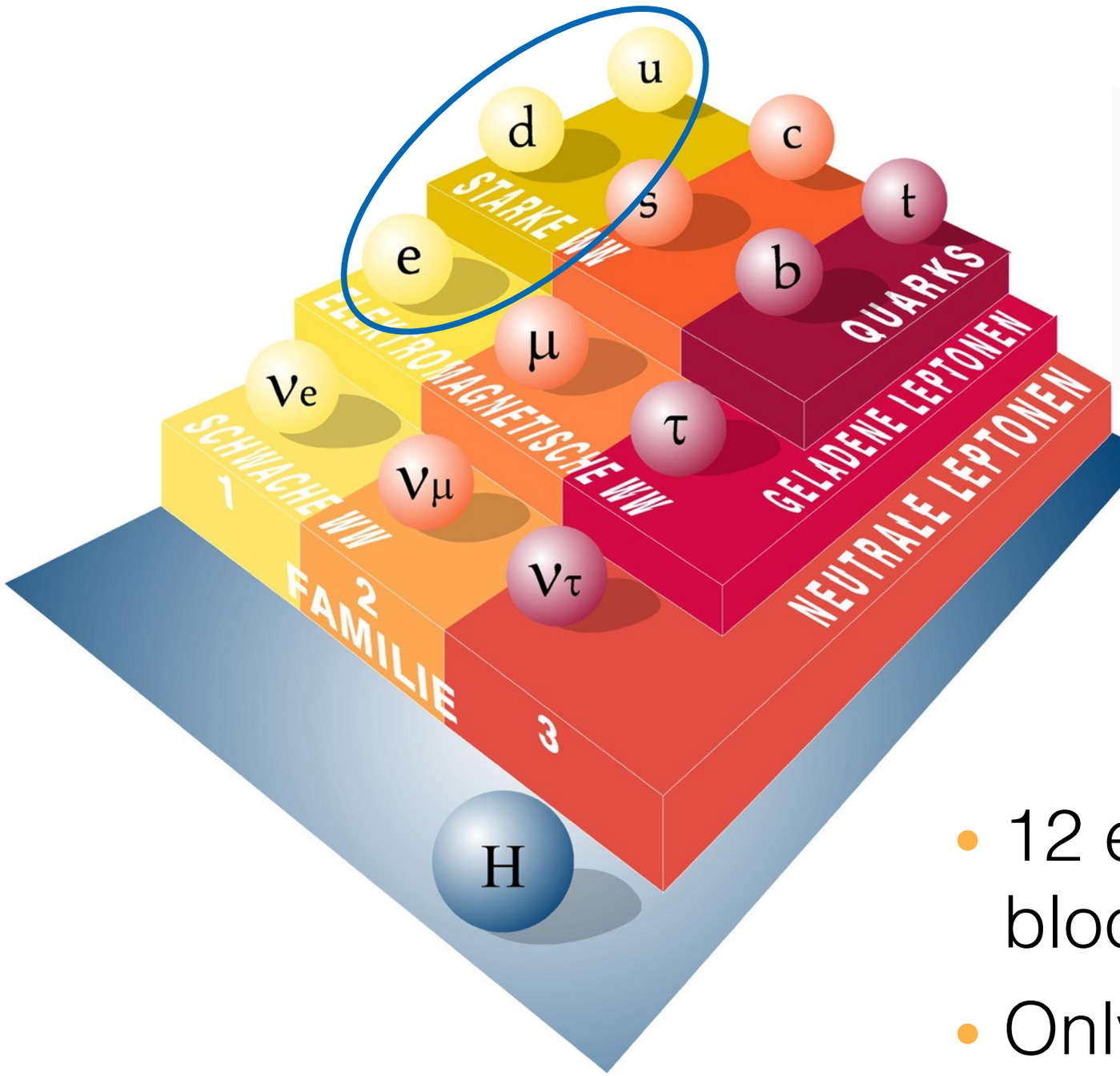
What Matter is Made of…

Quarks are basic constituents



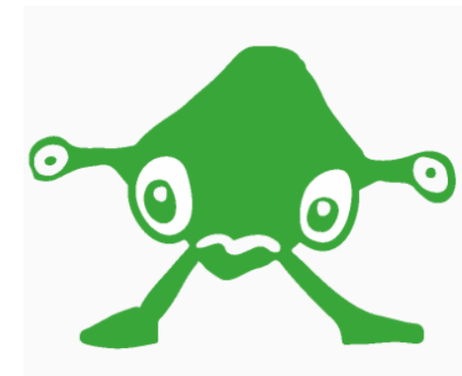
scale
10^5

Standard Model of Particle Physics



Up-Quarks

Down-Quarks

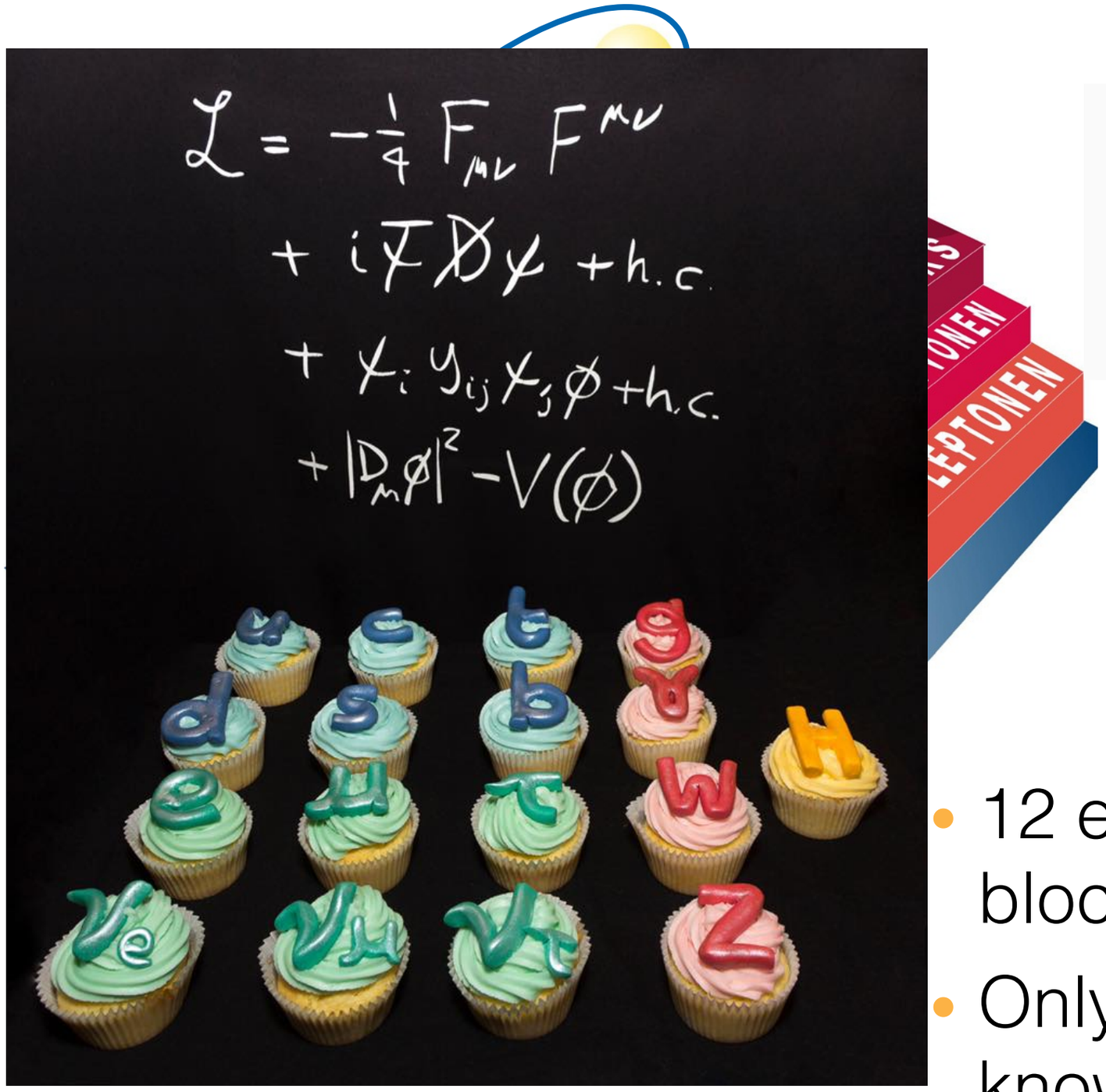


Electron

- 12 elementary building blocks
- Only 3 are needed for known matter (u, d, e)

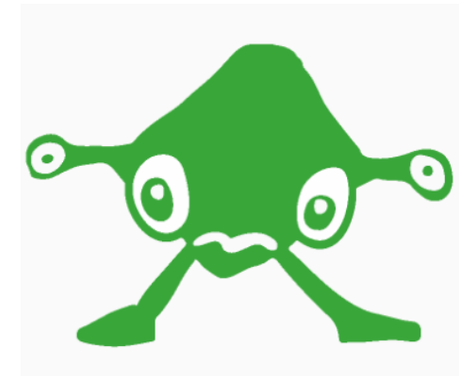
Picture: DESY and Teilchenzoo

Standard Model of Particle Physics



Up-Quarks

Down-Quarks



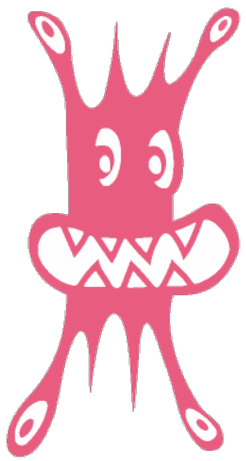
Electron

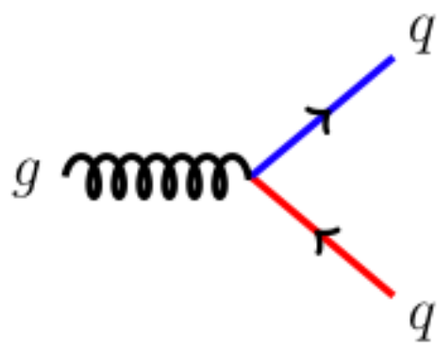
- 12 elementary building blocks
- Only 3 are needed for known matter (u, d, e)

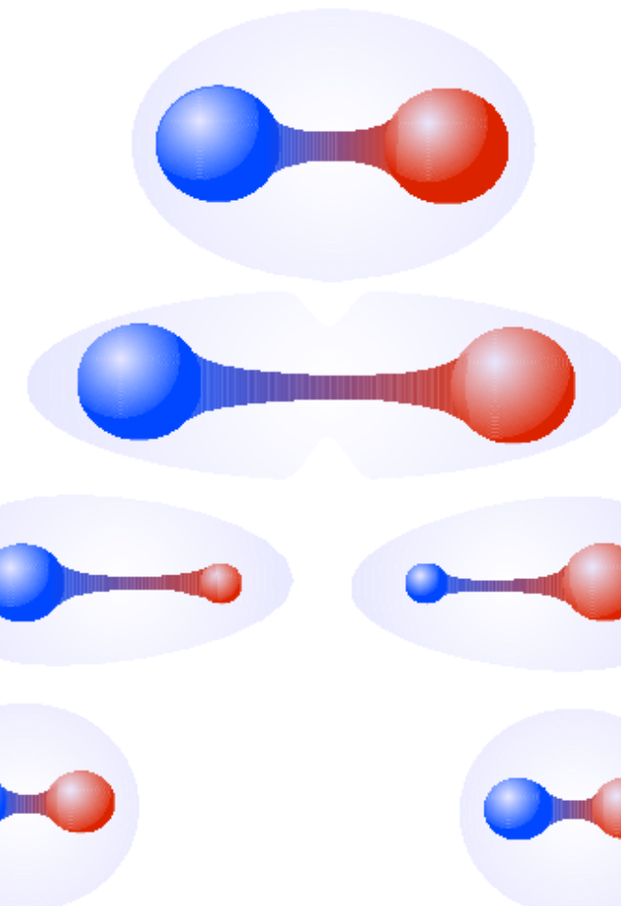
Picture: DESY and Teilchenzoo

The Strong Force

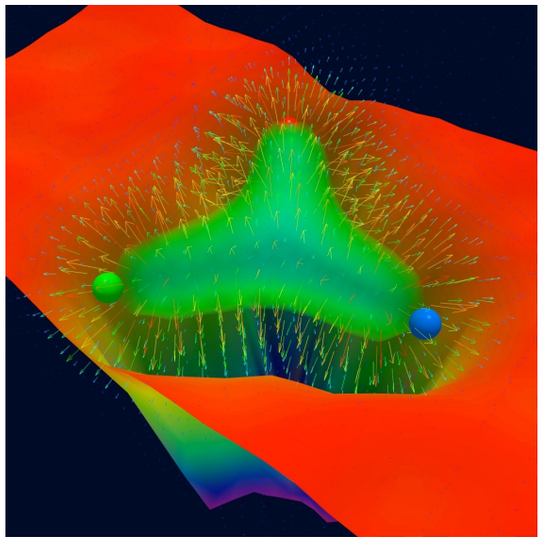
- Gluons act like a string and prevent quarks from roaming around freely







Gluon



quantumdiaries.org,
Desy-Teilchenzoo

Production of quark-antiquark pairs out of vacuum

Constituents of Matter

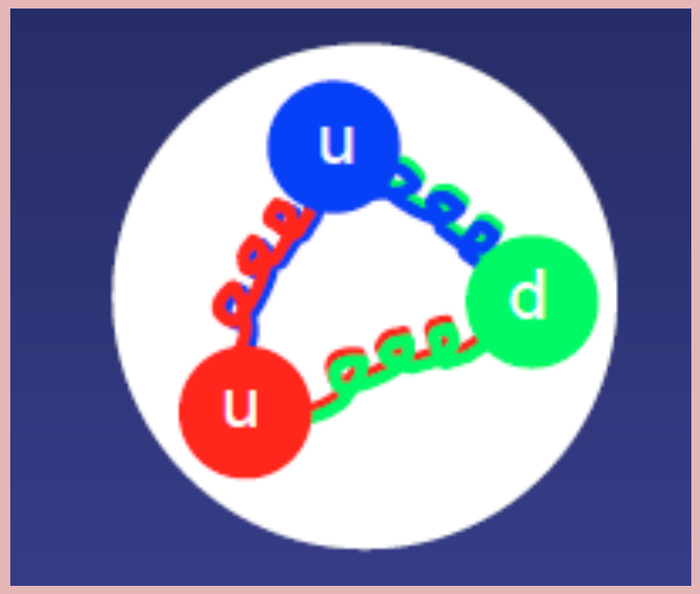
- Chroma (Χρωμα) = ‚Color' (Greek)
- Analogy to electric color, possible states are ‚white'

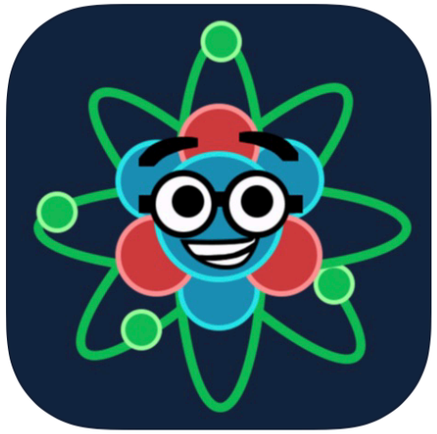
Mesons ($q\bar{q}$)

e.g. pions ($u\bar{u}$,$d\bar{d}$,$d\bar{u}$,$u\bar{d}$)…

Baryons (qqq)

e.g. proton (uud)
neutron (udd)…





Quantum 3 4+

Match-3 Quantum Physics Fun

Michigan State University GEL Lab

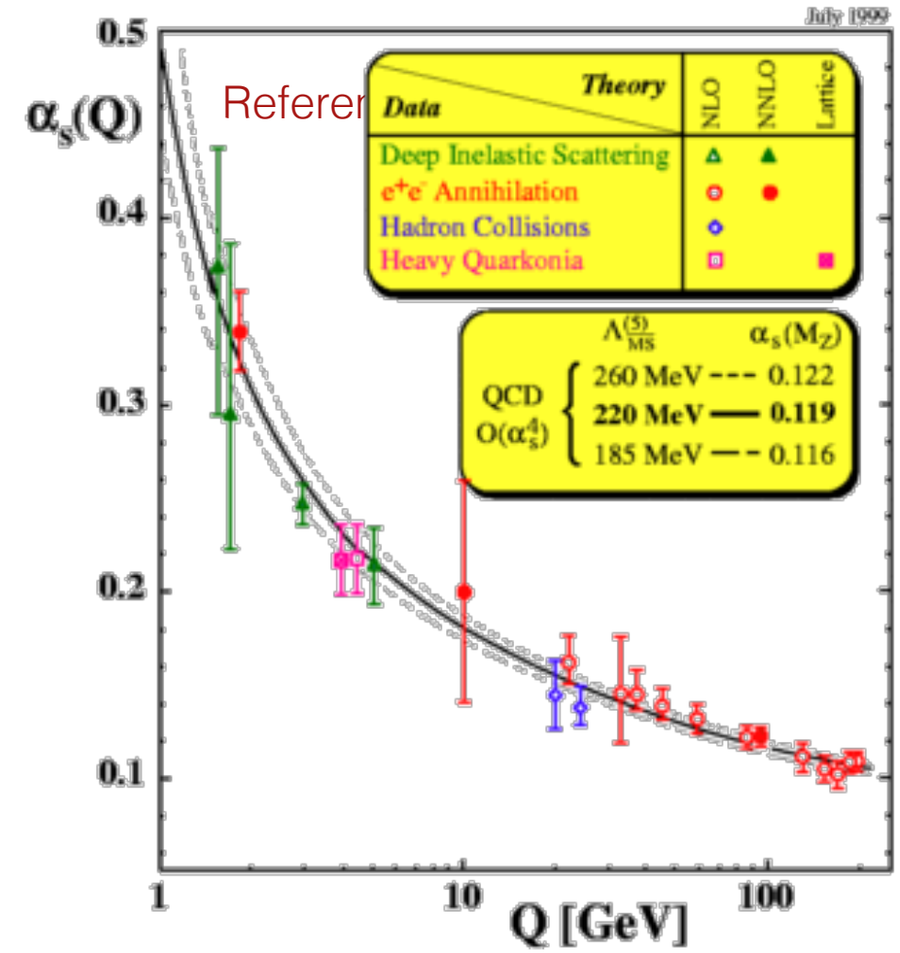
★★★★★ 5.0, 12 Ratings

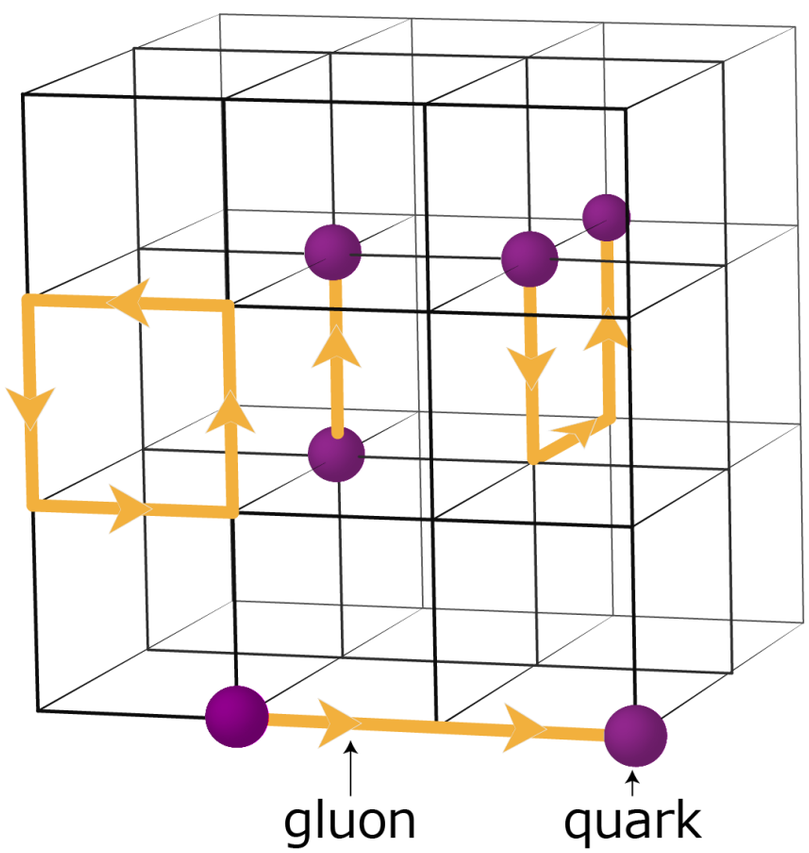
Free

https://apps.apple.com/us/app/quantum-3/id1406630529

Quantum Chromodynamics

- Coupling is strong in the regime of interest
- Perturbation theory is not valid
- Hadronization is one of the unsolved big questions





- With expensive lattice calculations thermodynamic properties can be calculated
- Many-body non-equilibrium dynamics is not solvable from first principles

The Origin of Mass

DESY-Teilchenzoo

- Higgs is only responsible for a small part, the bare mass (~2% of the proton mass)
- 3 +3 +5 << 1000

Nobel prize 2013

		u	d	s	c	b	t
M_{weak}	$[MeV/c^2]$	3	5	80	1200	4500	176000
M_{strong}	$[MeV/c^2]$	350	350	350	350	350	350
M_{total}	$[MeV/c^2]$	350	350	450	1500	4800	176000

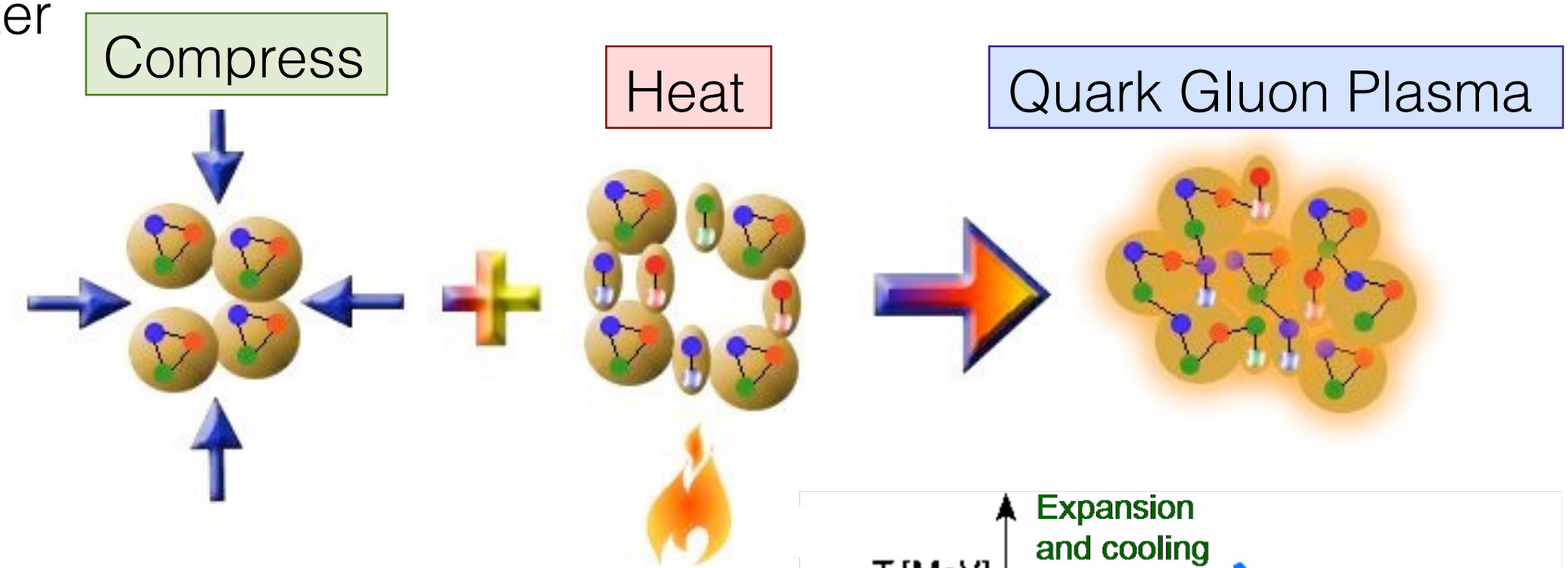
C. Fischer

- The strong interaction generates the same amount of mass for all quark species

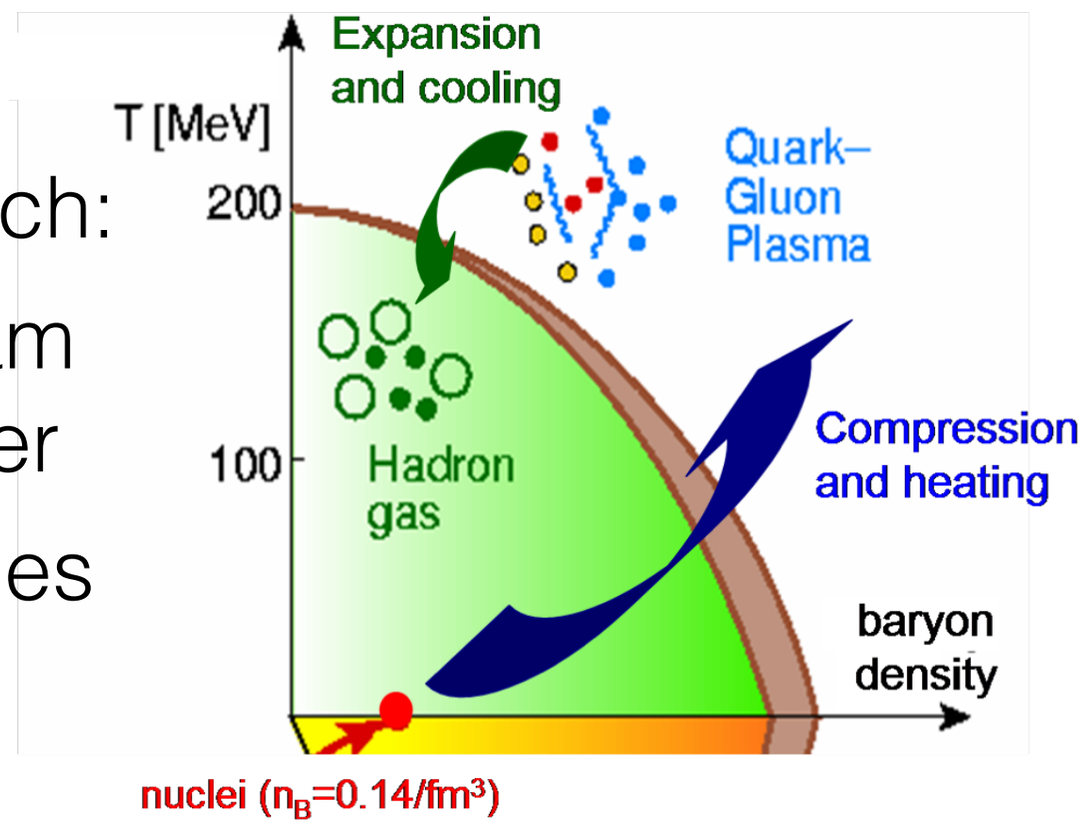
Big Bang in the Laboratory

A New State of Matter

High densities and temperatures change the properties of nuclear matter

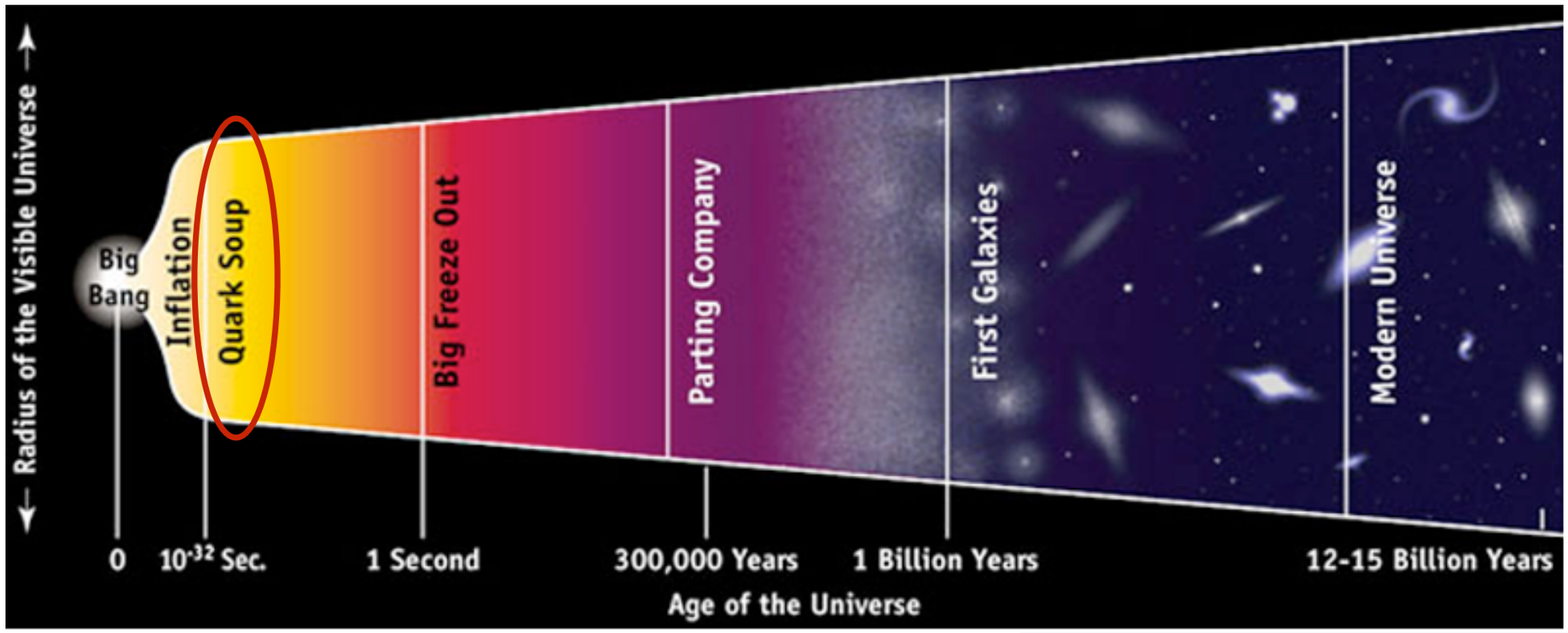


- Major goals of heavy ion research:
  - Exploring the phase diagram of strongly interacting matter
  - Understanding the properties of the quark gluon plasma

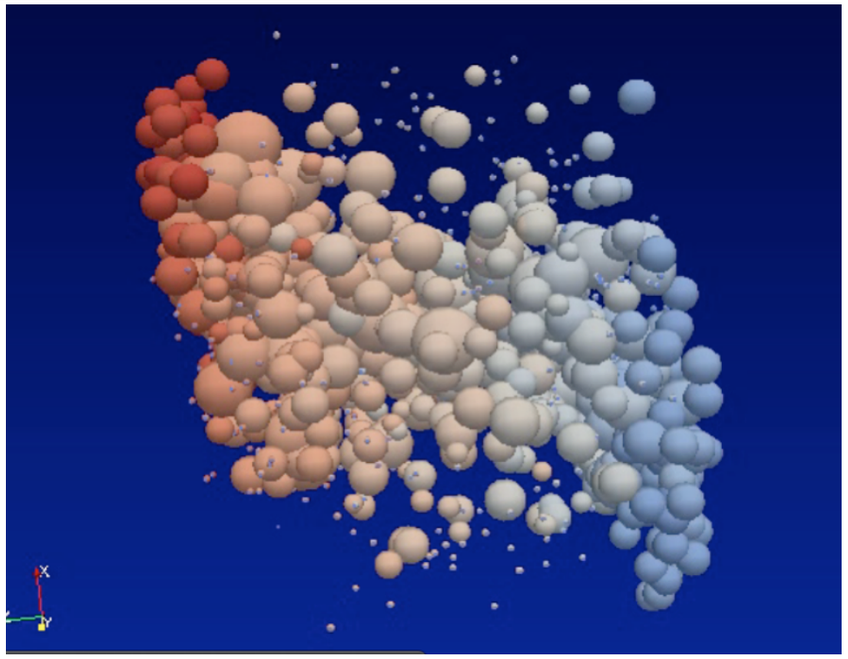


The Big Bang in the Laboratory

- Microseconds after the Big Bang the whole universe was in the quark gluon plasma phase



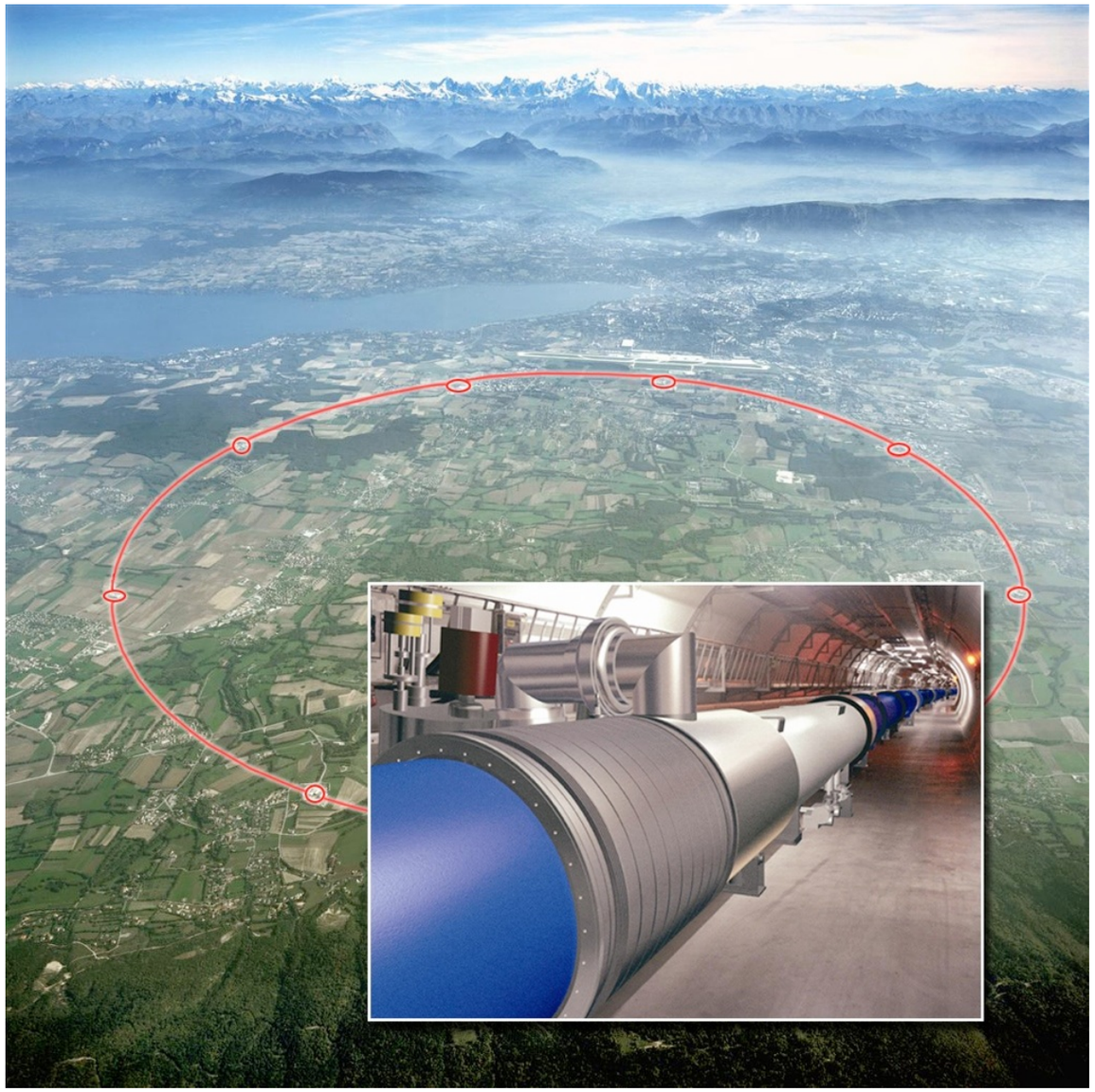
Heavy ion collisions provide hot and dense nuclear matter, the quark gluon plasma in the laboratory

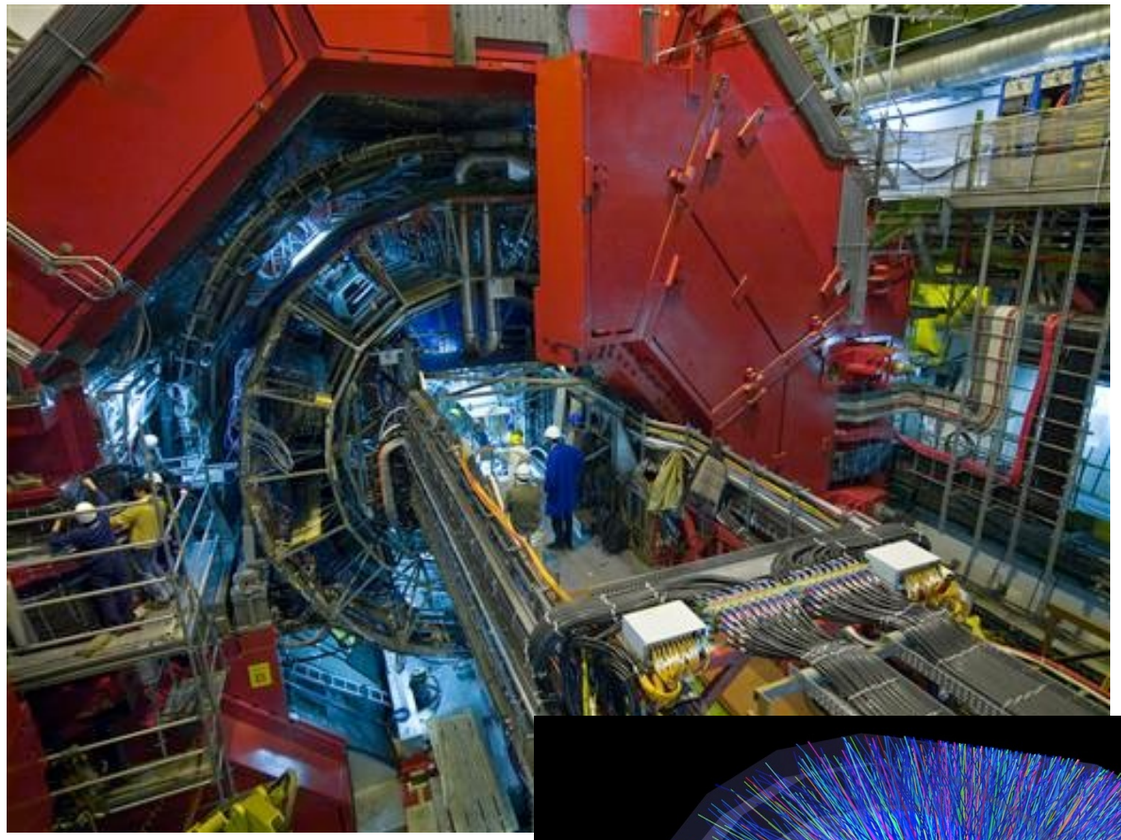


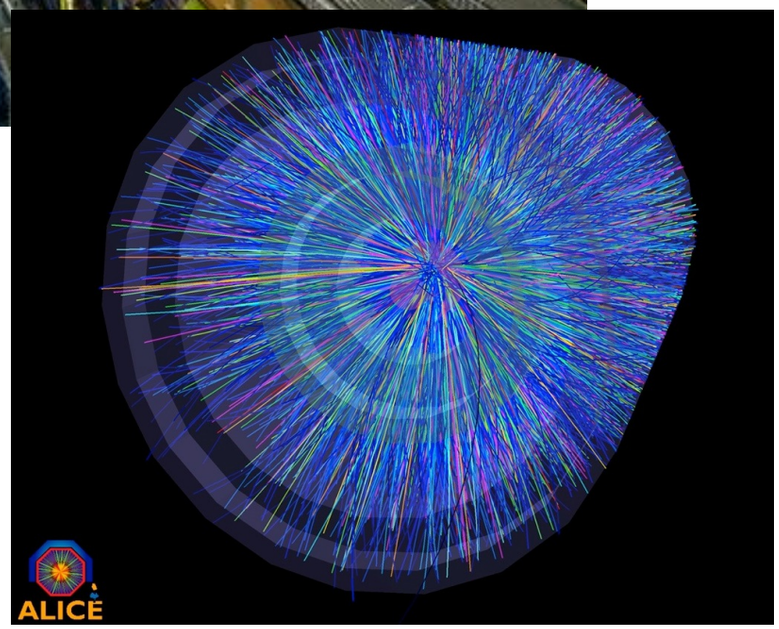
‚Free' Color Charges

- ‚White' nuclei produce colored plasma

Creating the QGP in the Lab

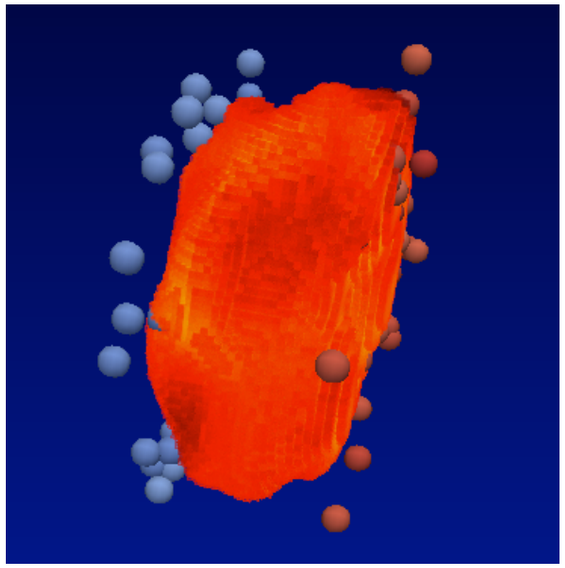




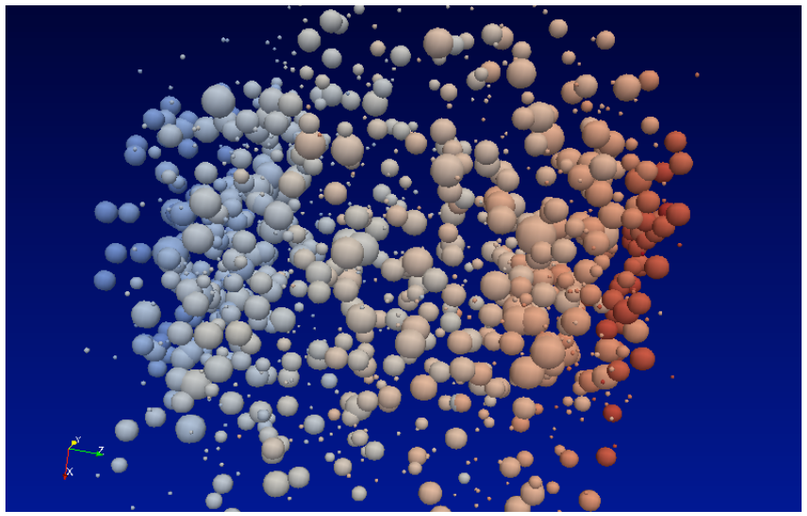


- ALICE at **Large Hadron Collider**, CERN
- How to find relics of the QGP in the traces of thousands of hadrons?

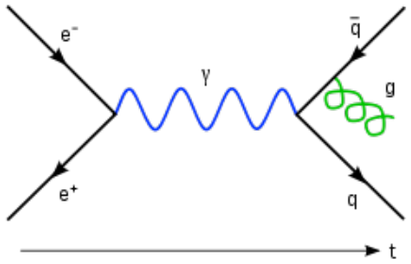
Theoretical Description



Dynamical description of heavy ion reactions

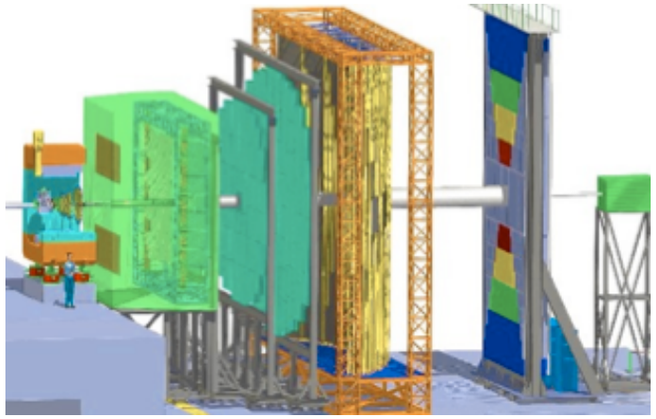


Fundamental field theory of strong interactions (QCD)



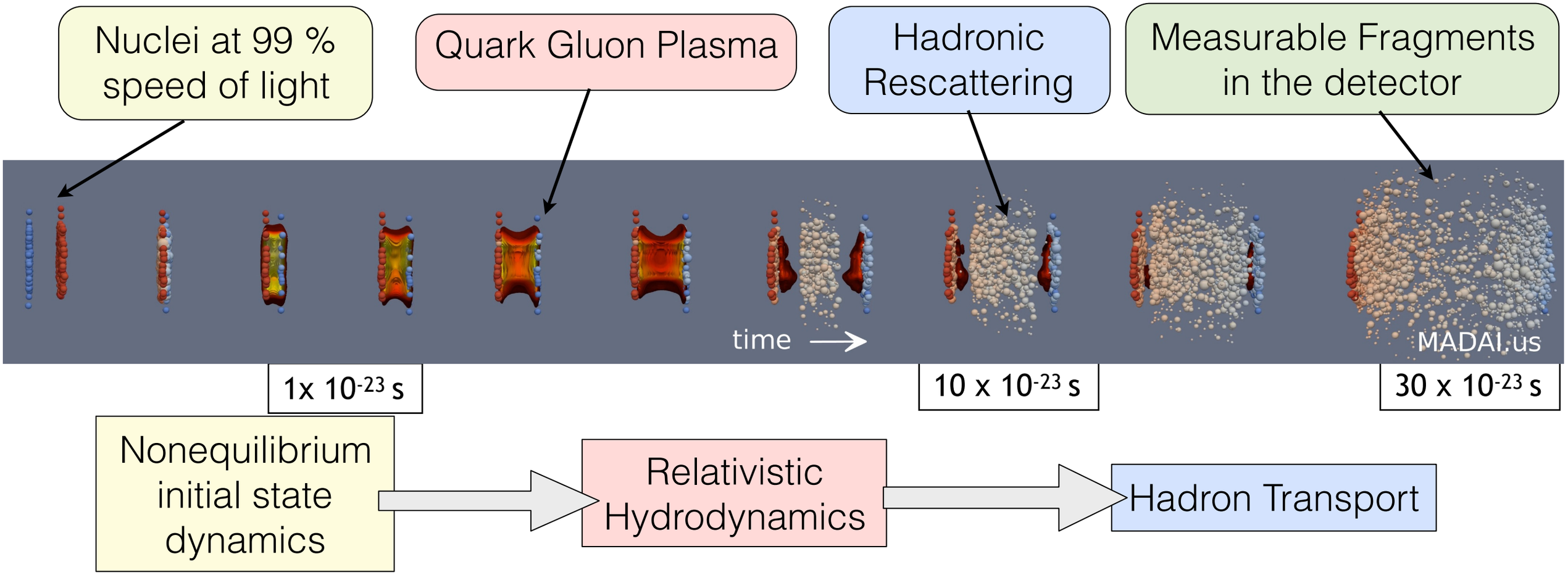
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Measurements in the detector (CBM@FAIR)



- **Theoretical models** are essential to gain insights about the properties of the quark gluon plasma

Time Evolution of Heavy Ion Collisions



- Due to the short time scale of 10^{-22} seconds and the tiny volume $(10 \times 10^{-15}\text{m})^3$ the quark gluon plasma escapes direct detection

Dynamic description of heavy ion collisions has to capture all the stages of the reaction

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

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

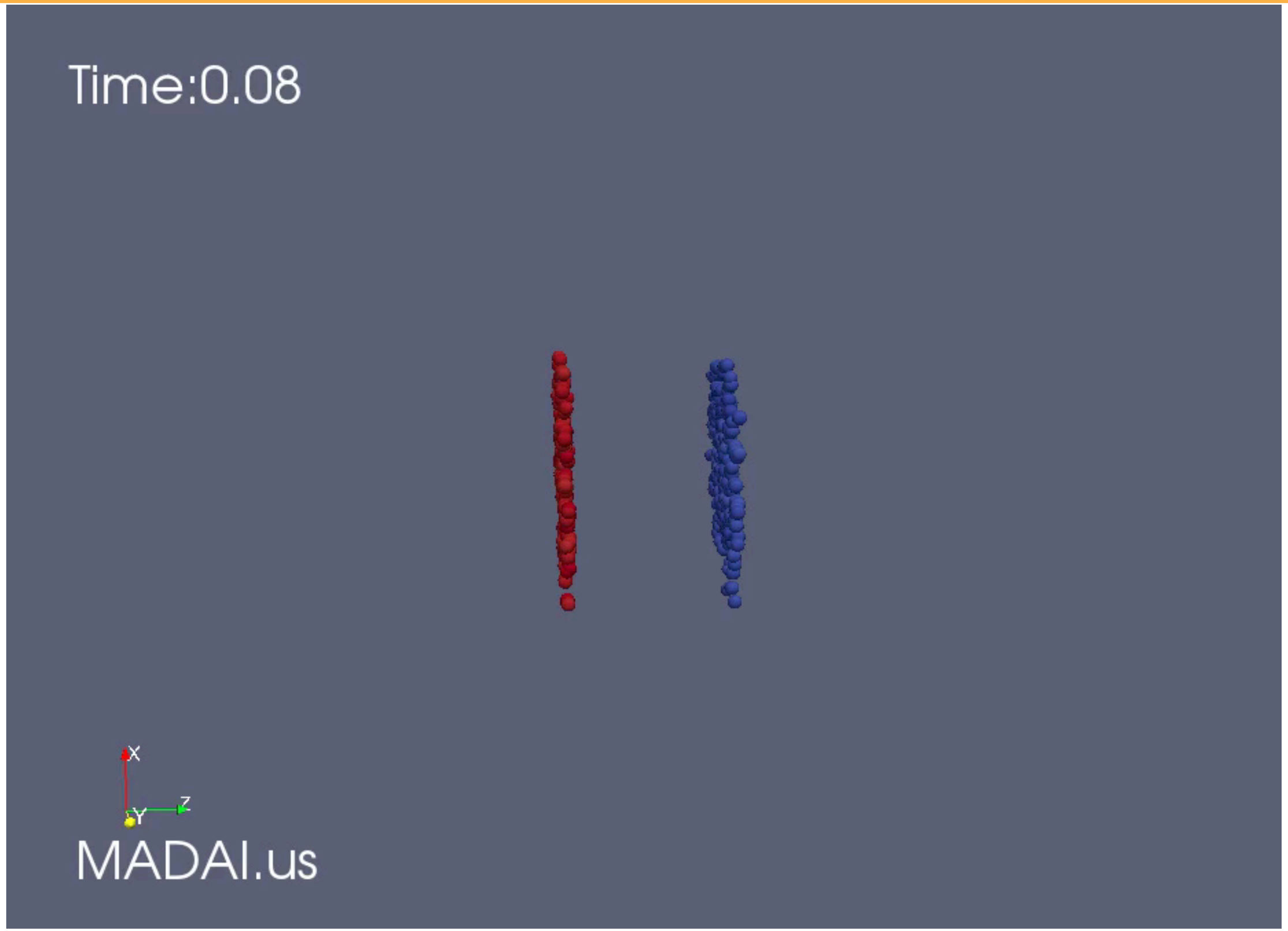
Propagation according to conservation laws

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

One Event at RHIC Energies



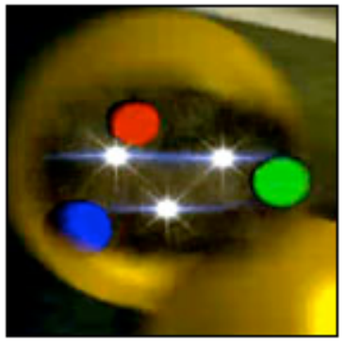
Why Hybrid Approaches?

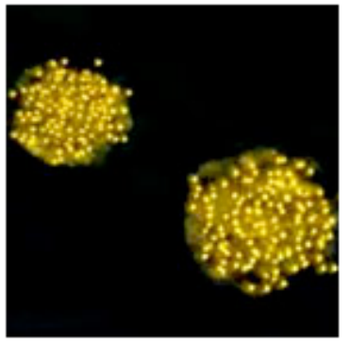
The Ideal Fluid

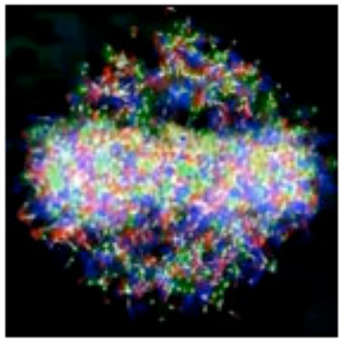
- Press release of Brookhaven National Lab (2005):
  - At RHIC a new state of matter has been formed that acts like an ideal fluid

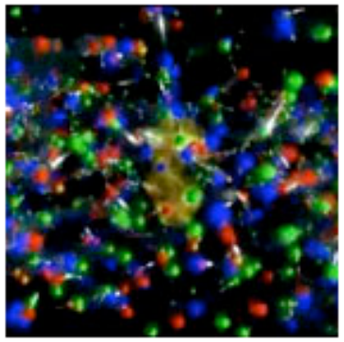
A New Area of Physics

RHIC has created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. Instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions is more like a liquid.


Gluons and quarks


Ions about to collide


Just after collision


The "perfect" liquid

A "Perfect" Liquid

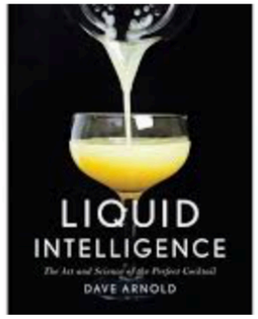
RHIC scientists had expected collisions between two beams of gold nuclei to mimic conditions of the early universe and produce a gaseous plasma of the smallest components of matter — the quarks

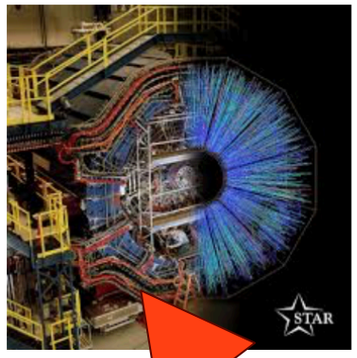
Quark-Gluon Plasma

RHIC's perfect liquid also turns out to be the hottest matter ever created in a laboratory, measuring some 4 trillion degrees Celsius, or 250,000 times hotter than the center of the Sun.

Webpage RHIC at BNL

Google image search for 'perfect liquid'



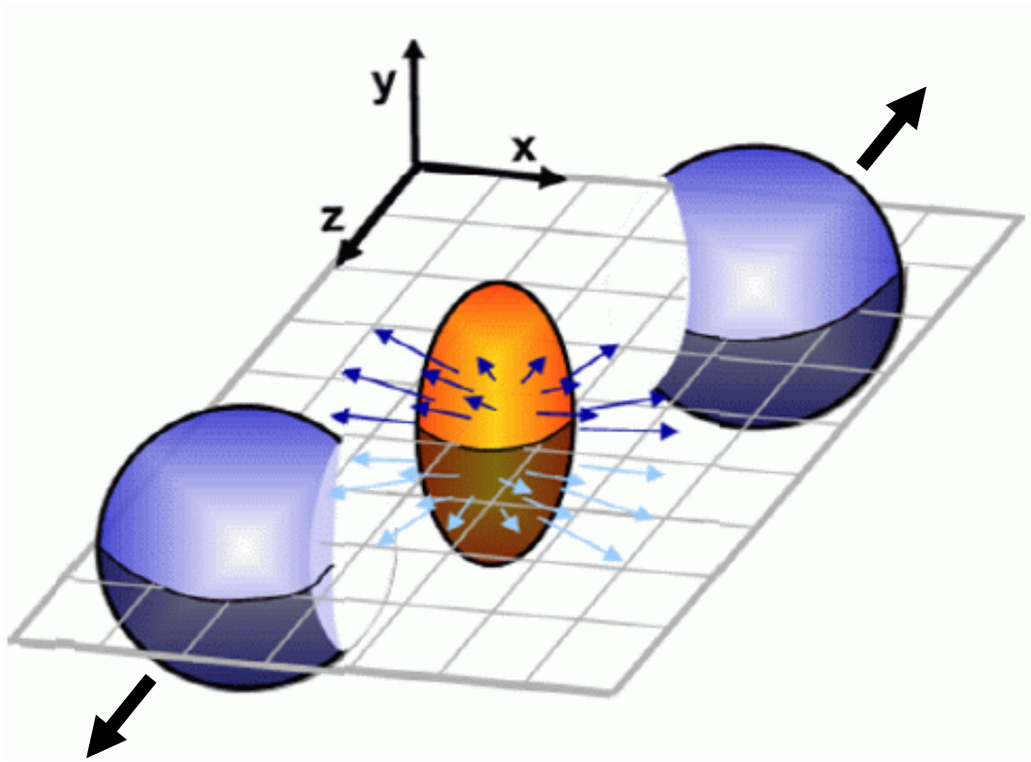


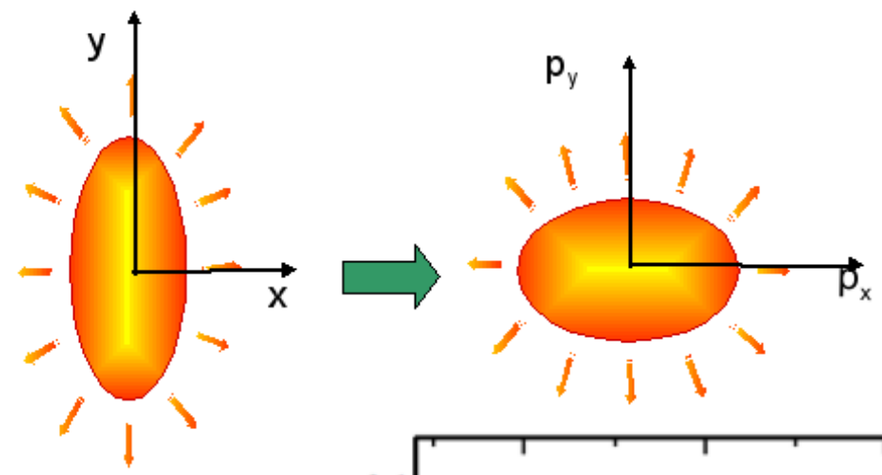
Here is the heavy-ion reaction

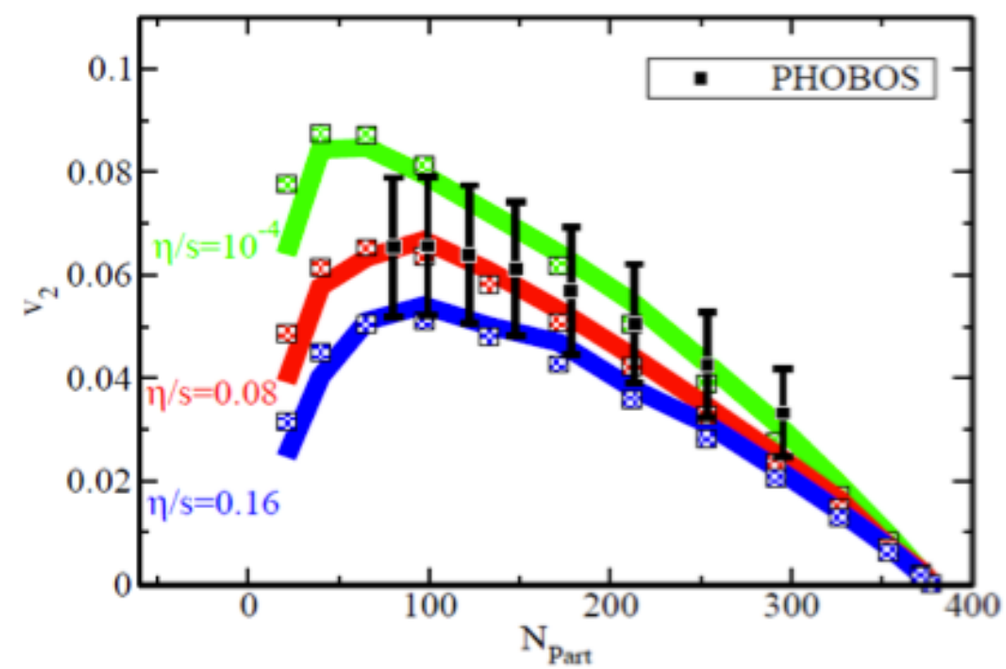
Elliptic Flow

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

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







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

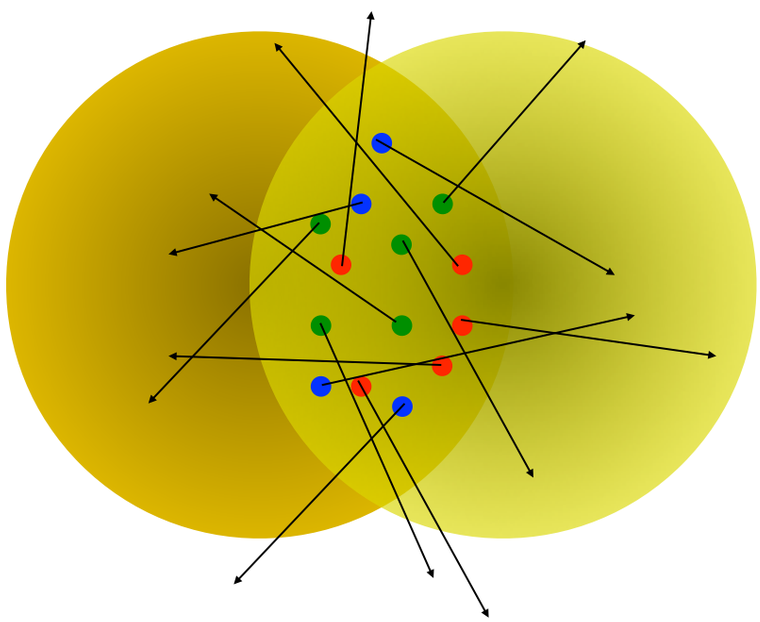
Coordinate space asymmetry
→momentum space anisotropy

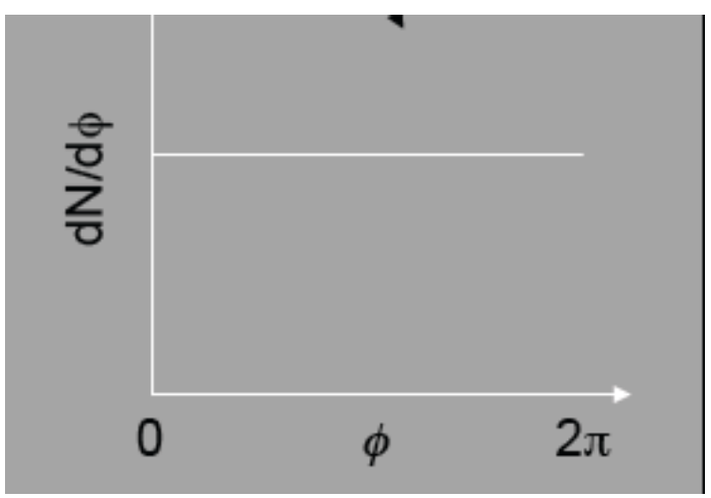
- Relativistic fluid dynamics with very low viscosity describes elliptic flow at RHIC (and LHC)

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path $\lambda \rightarrow \infty$





Spatial anisotropy

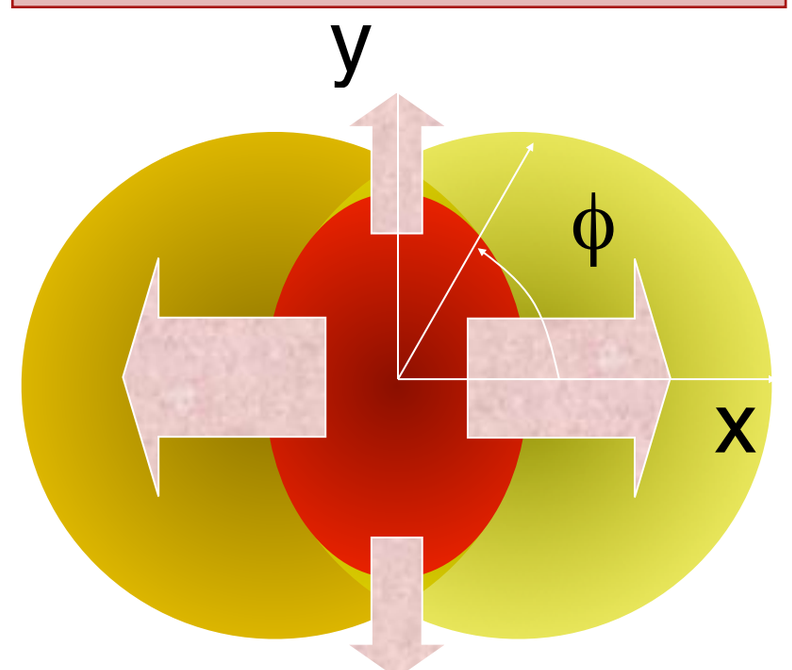
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

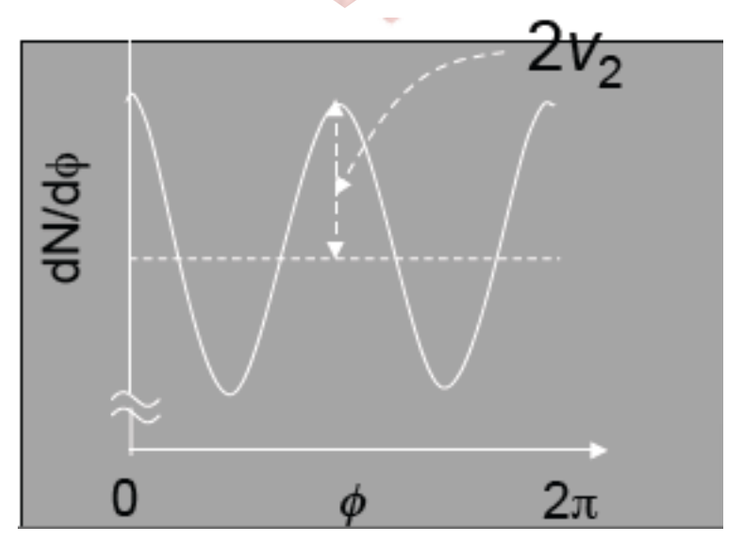
Interactions between particles

Momentum anisotropy

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

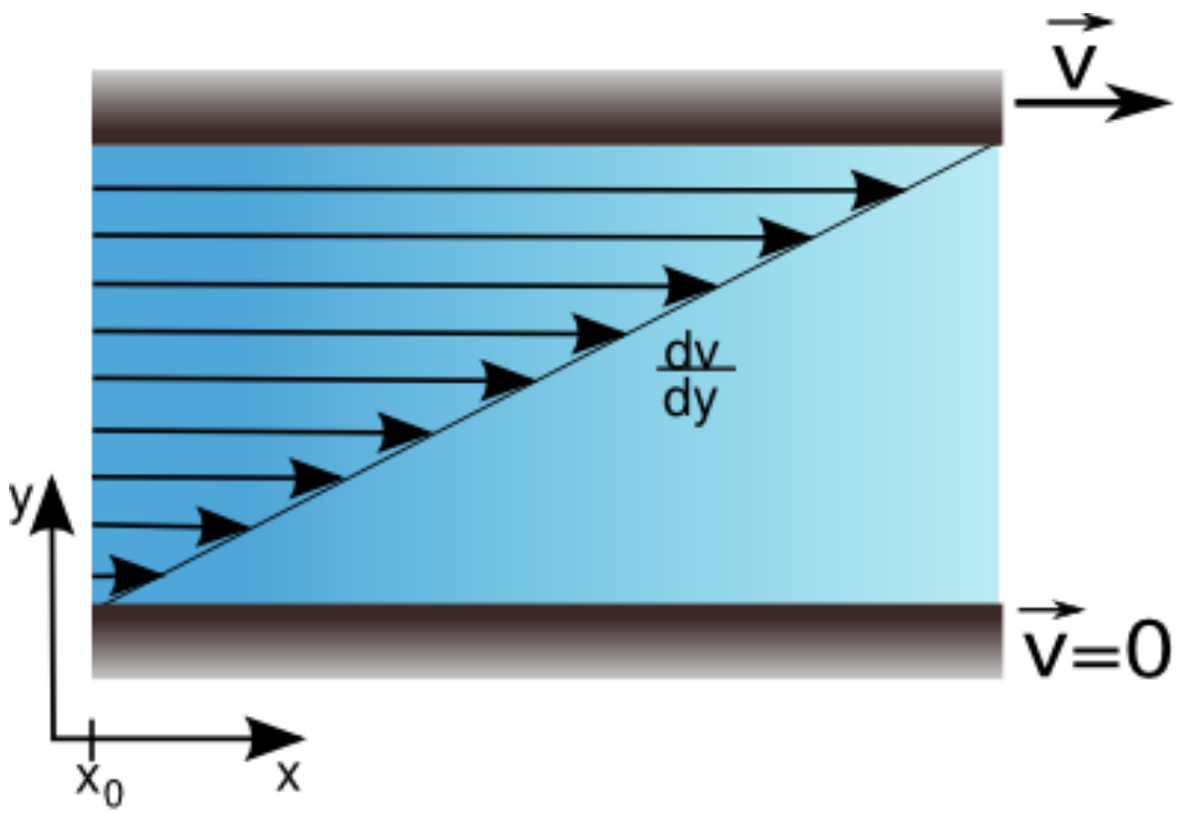
Hydrodynamic behaviour
mean free path $\lambda \rightarrow 0$

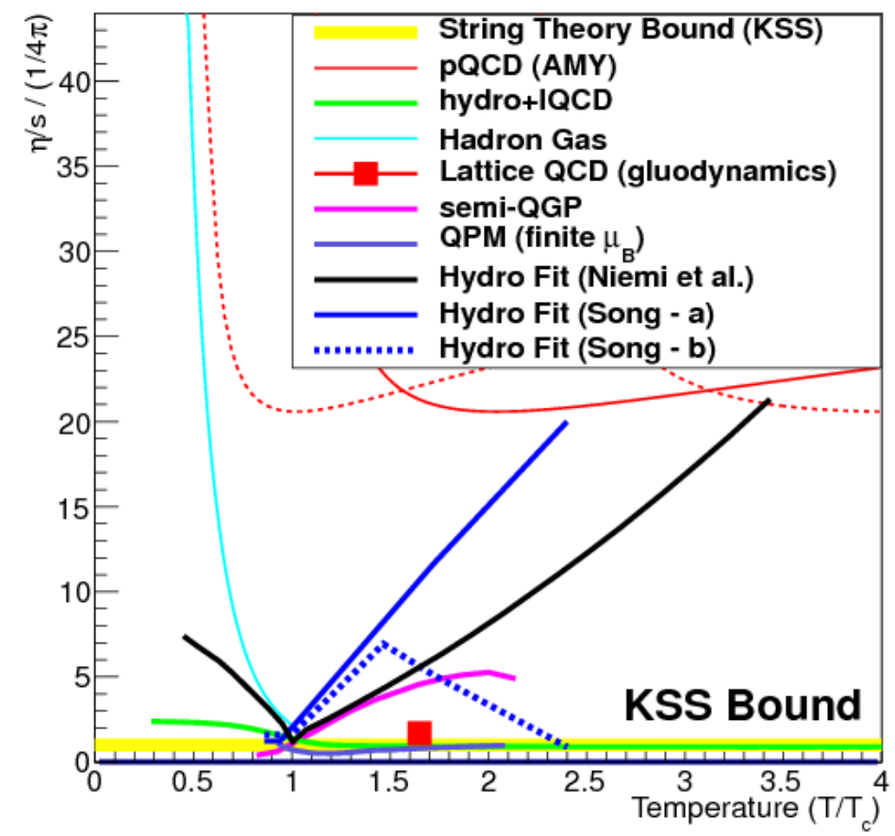




Shear Viscosity

- Transport coefficient of the quark-gluon plasma
  - Measures momentum transfer orthogonal to direction of motion

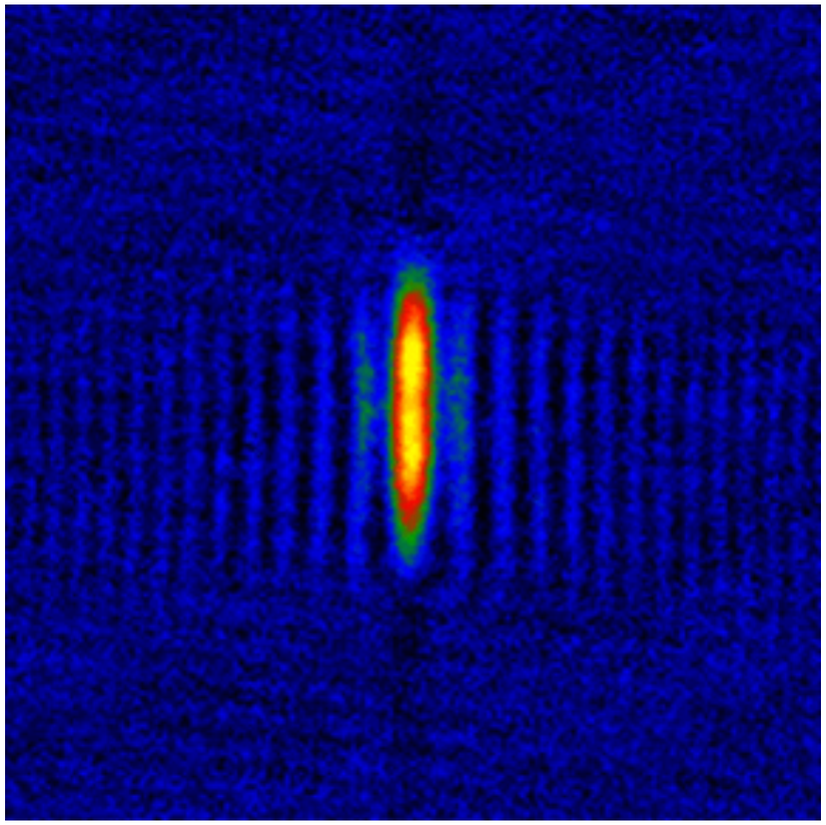


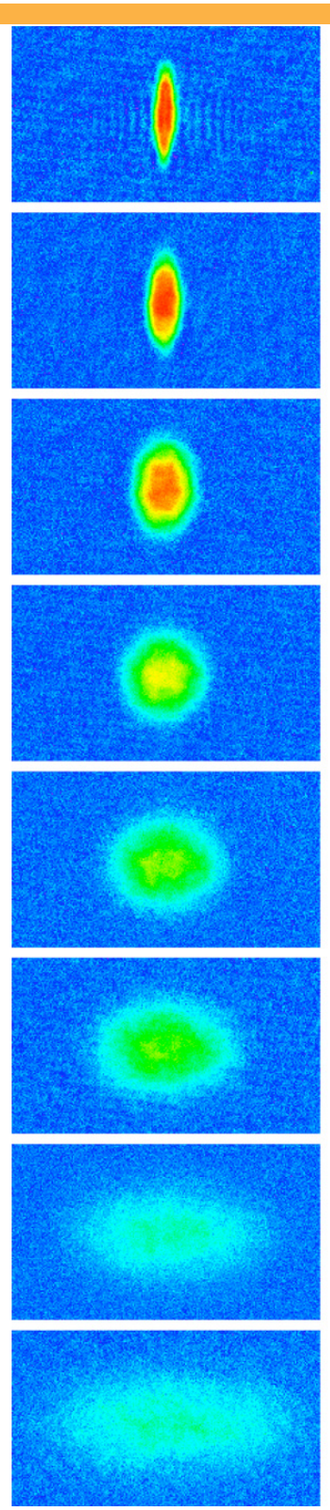


- Small viscosity → strongly coupled system
- Large viscosity → few interactions

Other Perfect Fluids in Nature…

- Lithium atoms at release from an optical trap:
  - Initial almond shape is similar to interaction region in heavy ion collisions
  - One can actually observe the build up of elliptic flow through differences in pressure gradients



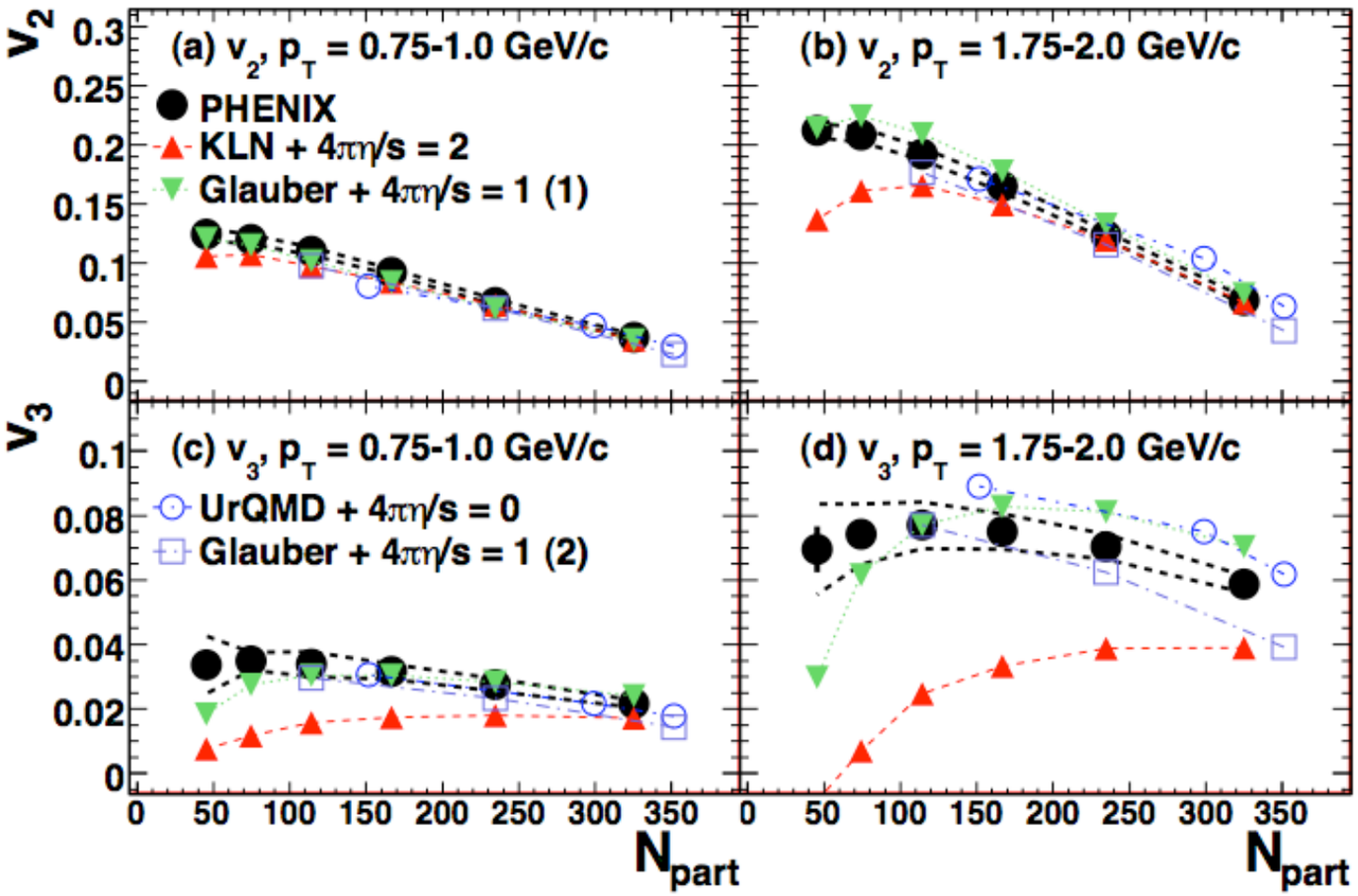


Hottest and coldest matter on earth exhibits **similar features** associated with strongly coupled systems

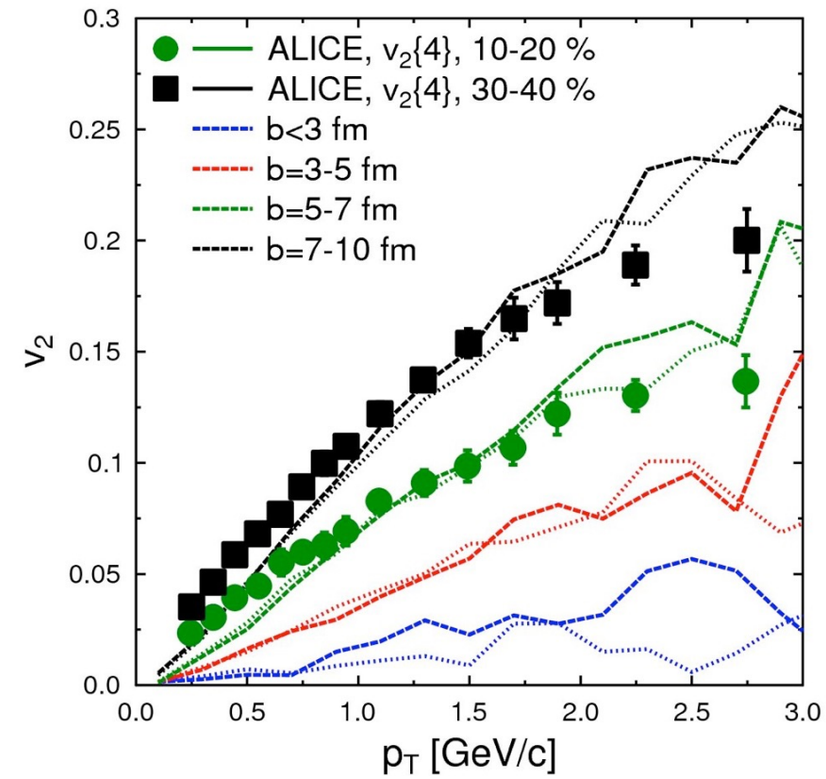
Reference to K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, J. E. Thomas: Science **298** (2002) 2179

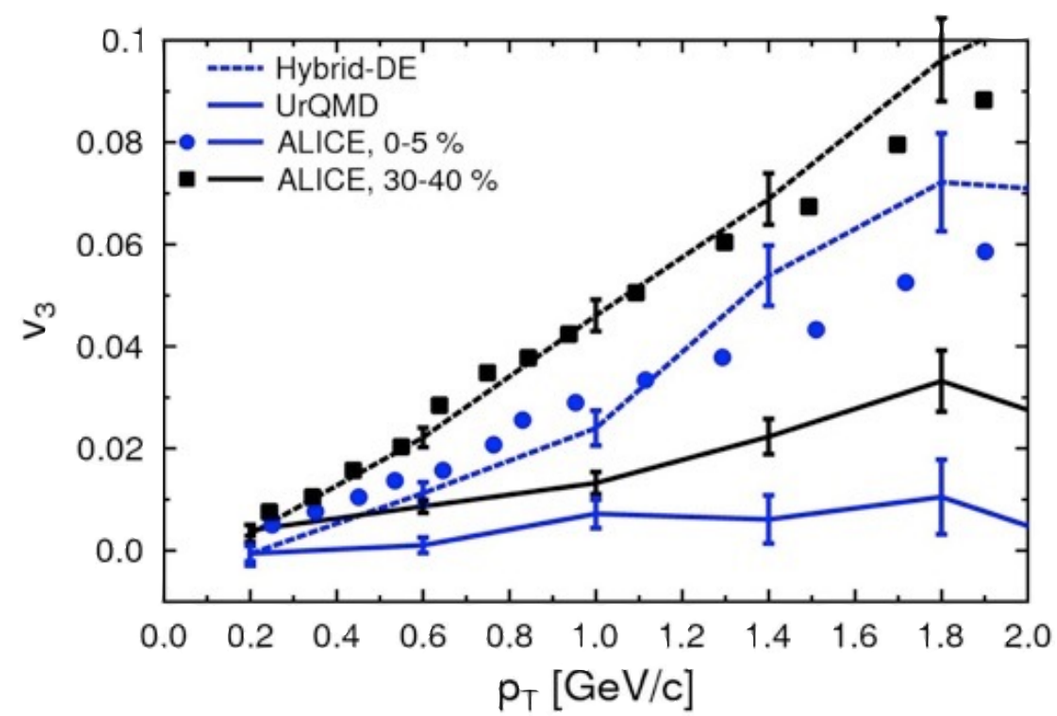
Comparison to Experimental Data

PHENIX collaboration, Phys.Rev.Lett. 107 (2011) 252301



HP (now Elfner), PRC84 (2011) 034912





- Fluctuations from nucleon positions and energy deposition in binary collisions included
- Without tuning anything v_3 at RHIC and flow at LHC in agreement with experimental data

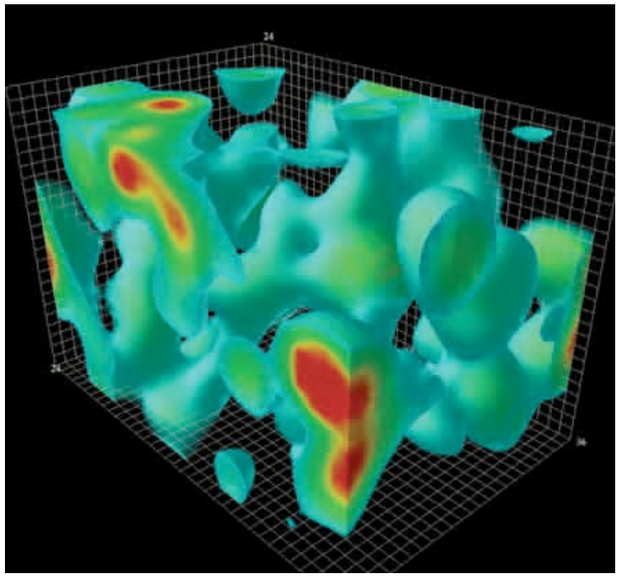
Event-by-event Fluctuations

Origin of Fluctuations

Underlying question:

Why do collisions of undistinguishable nuclei in the ground state exhibit different properties?

- Controllable differences:
  - Change of beam energy
  - Selection of centrality
  - Different system sizes (ion species)
- But: Quantum fluctuations are **unavoidable**



The challenge:

Fluctuations affect the observables of the quark-gluon plasma

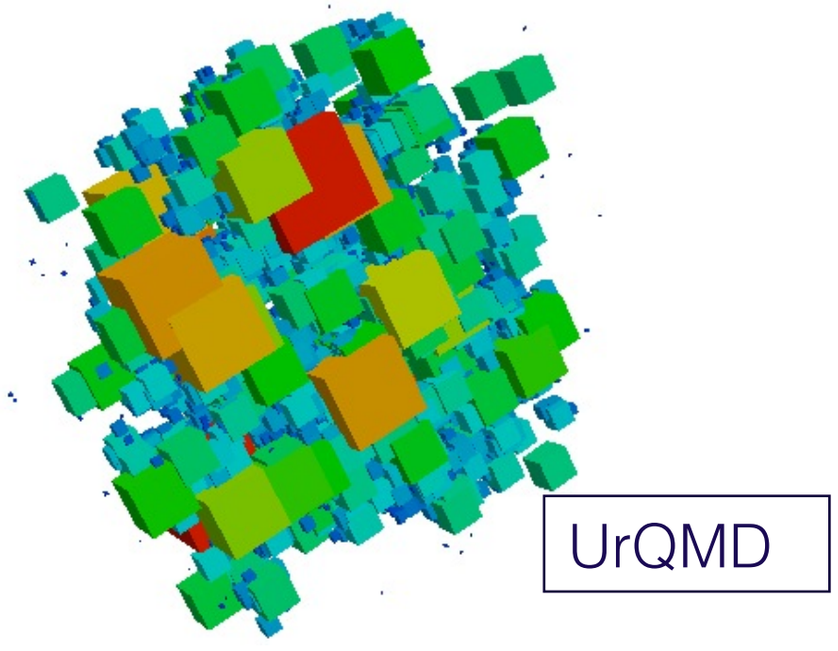
And **opportunity**:

Initial state fluctuations constrain transport coefficients

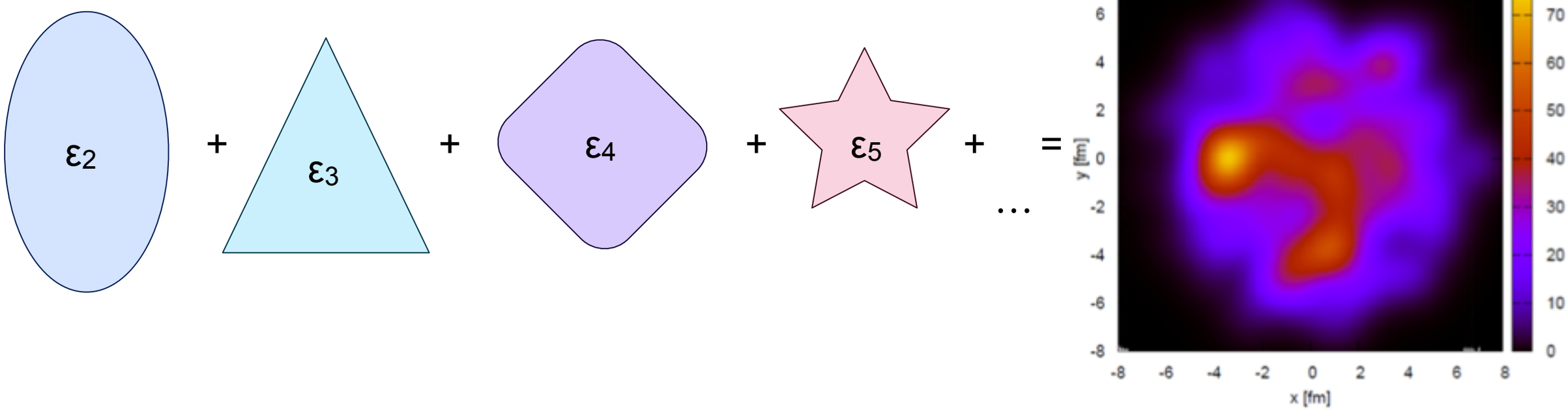
Event-by-event measurements in heavy-ion reactions contribute to the understanding of initial state of highly excited nuclei

Sources of Fluctuations

- **Granularity** is influenced by
  - Nucleon positions
  - Distribution of collisions
  - Type of interaction
  - Degree of thermalisation



- Differences in form and fluctuations are quantified:
  - Fourier expansion in coordinate space

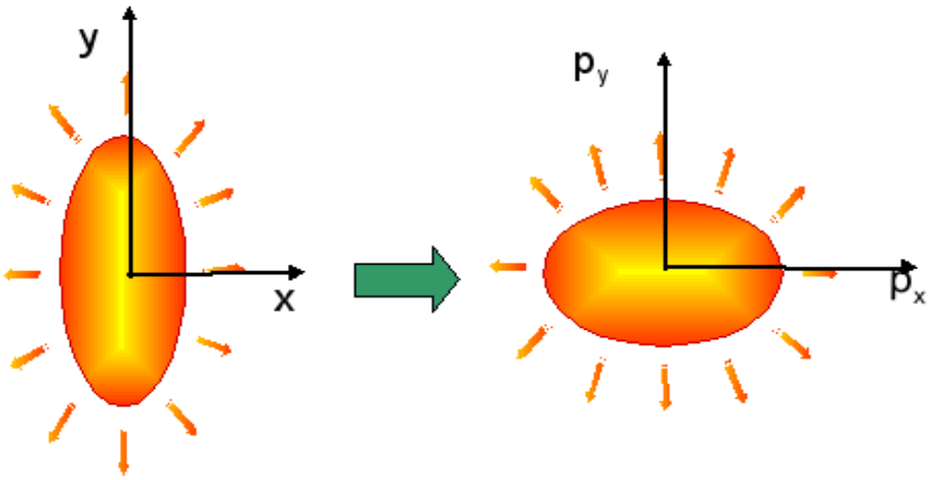


Anisotropic Flow - Higher Coefficients

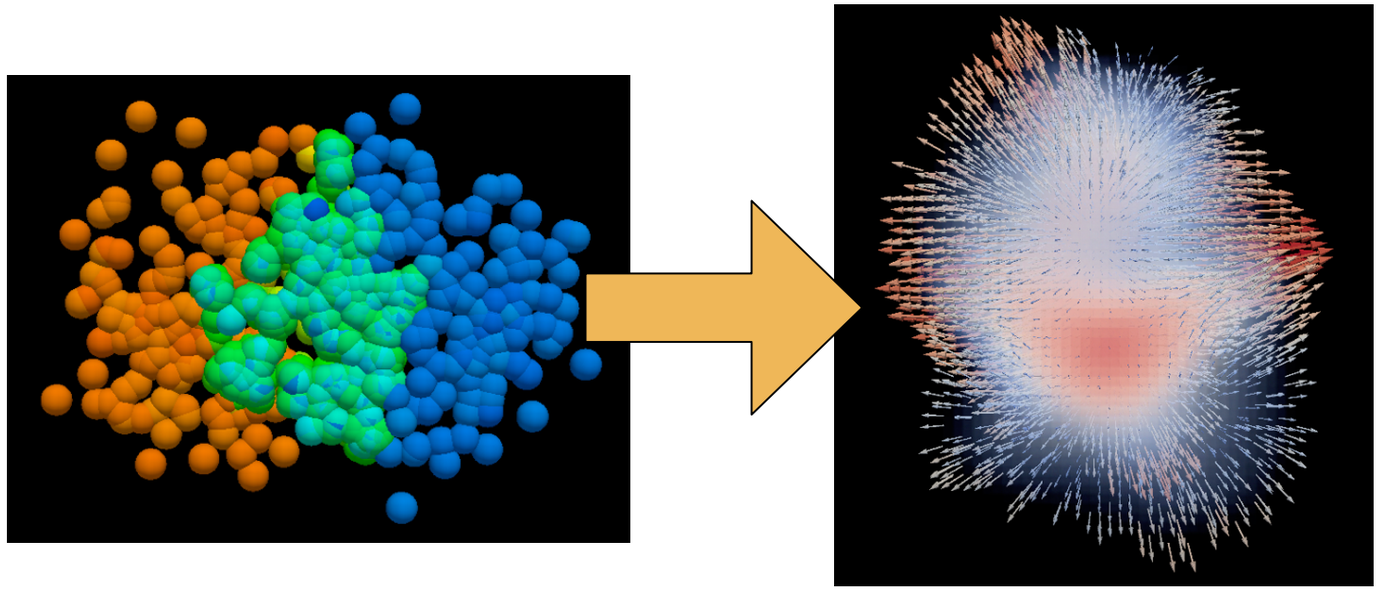
Simplified picture:

Coordinate space anisotropy → Momentum space anisotropy

Status 2010



With fluctuations in event-by-event calculations



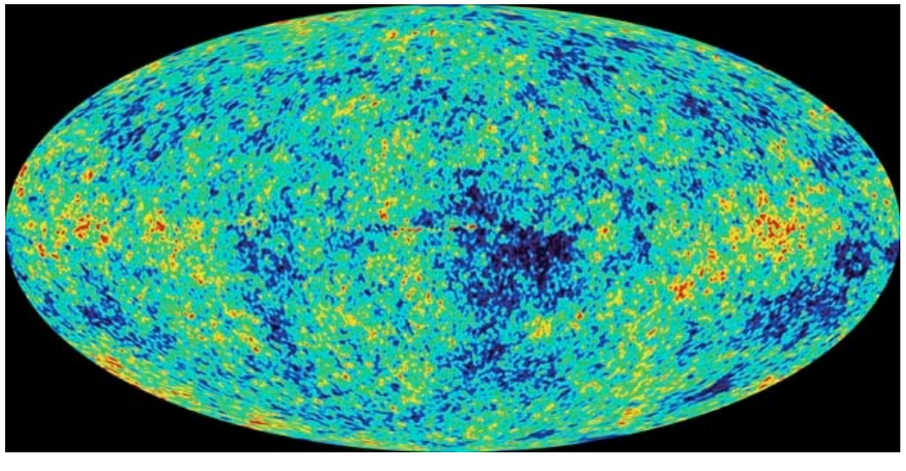
by MADAI.us

A multitude of new observables has been defined and requires event-by-event calculations

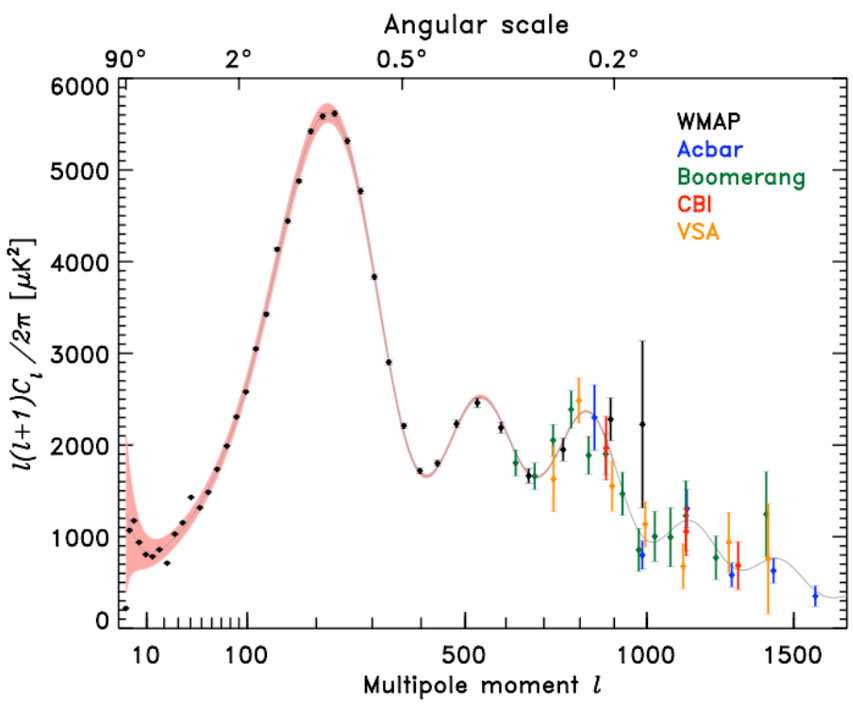
Topical Review in J. Phys. G, M. Luzum, HP (now Elfner), arXiv:1312.5503

Analogy to Cosmology

Temperature fluctuations in early universe

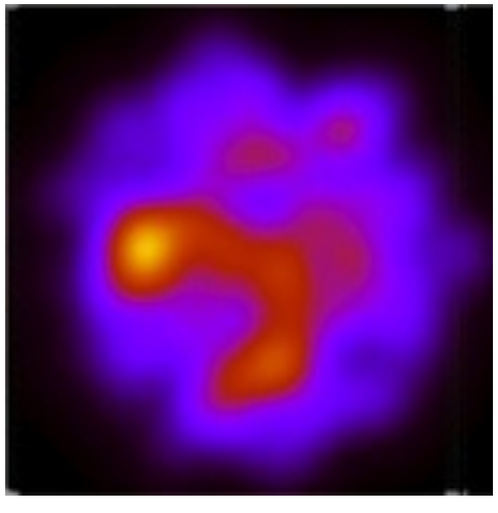


Analysis of multipol moments

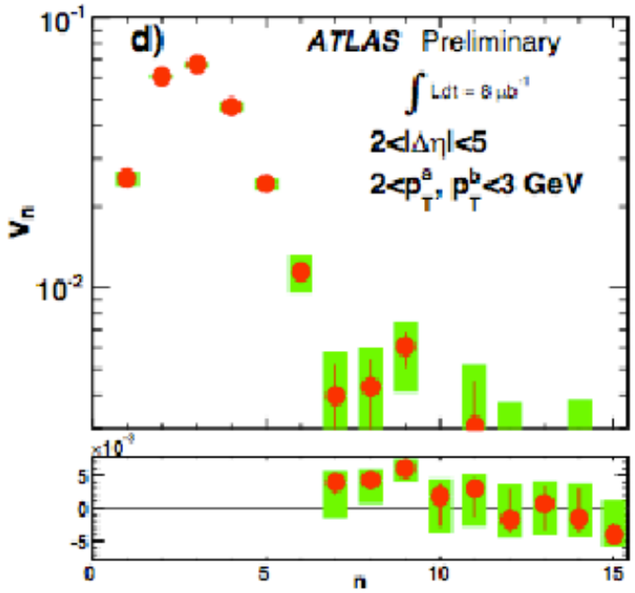


→ Matter content of the universe

Energy density fluctuations in nuclear collisions



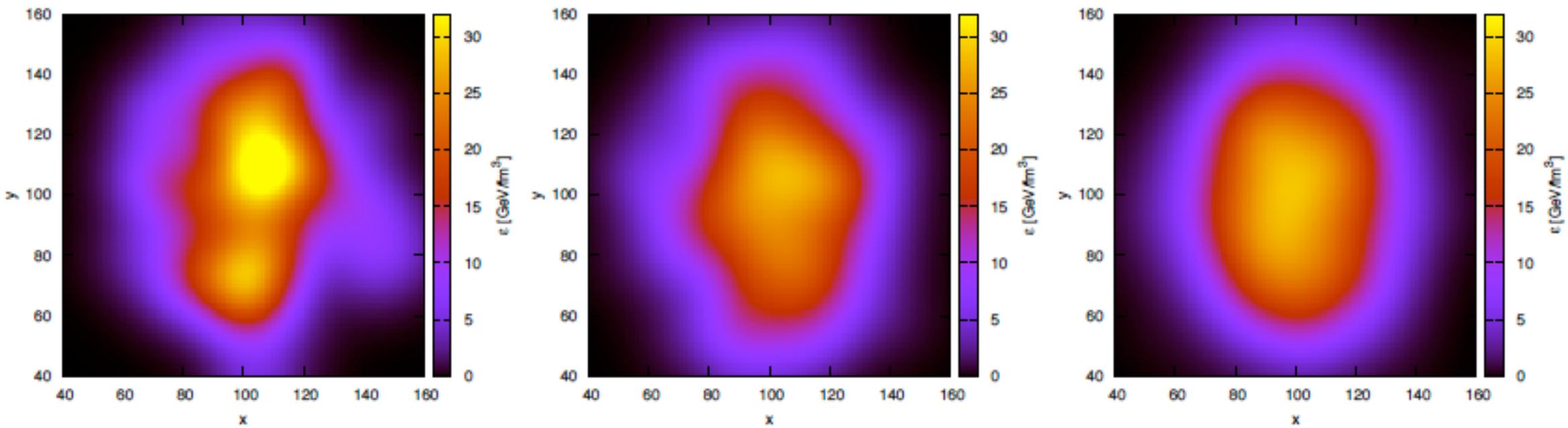
Analysis of anisotropic flow



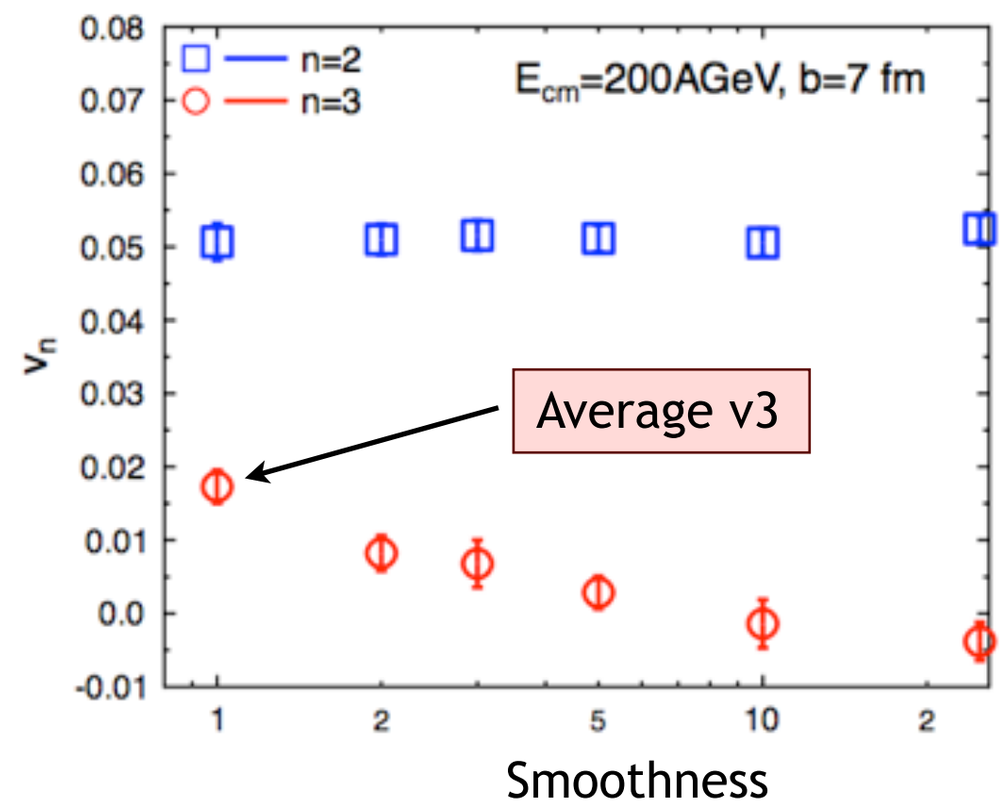
→ Transport properties of QCD matter

Sensitivity to Fluctuations

Energy density distribution in the transverse plane



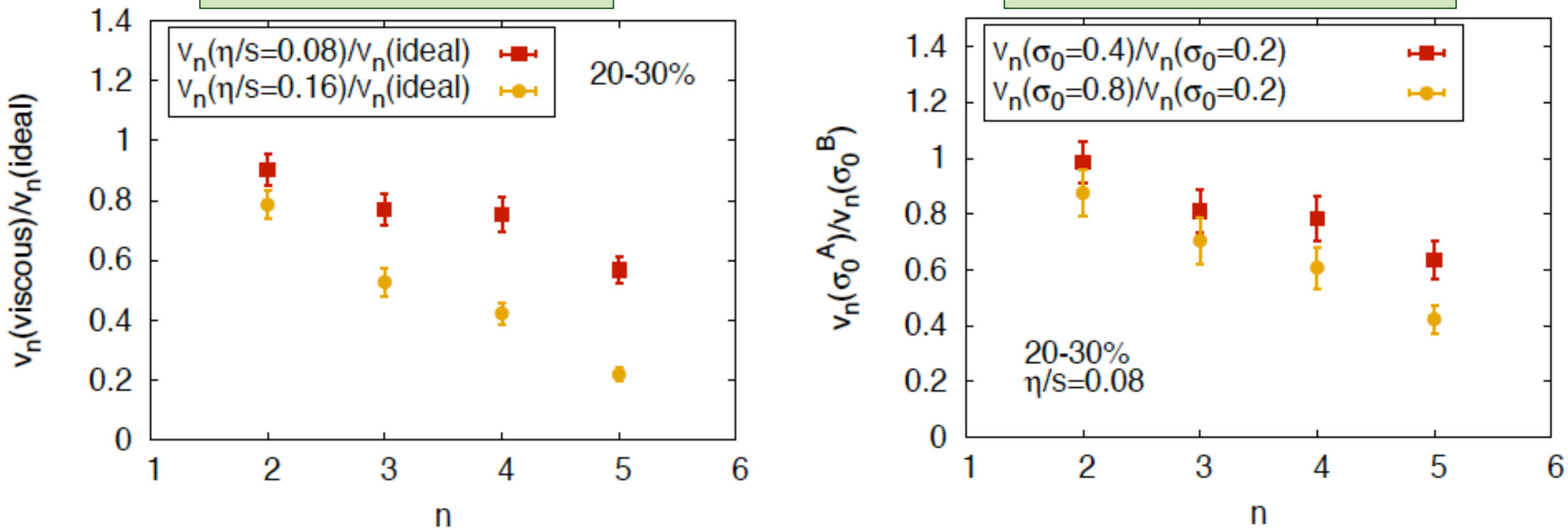
- Triangular flow is **very sensitive** to amount of initial state fluctuations
- Demonstrated in event-by-event calculation with different granularities



HP (now Elfner) et al, JPG G39 (2012)2016

Fluctuations and Viscosity

Variation of viscosity



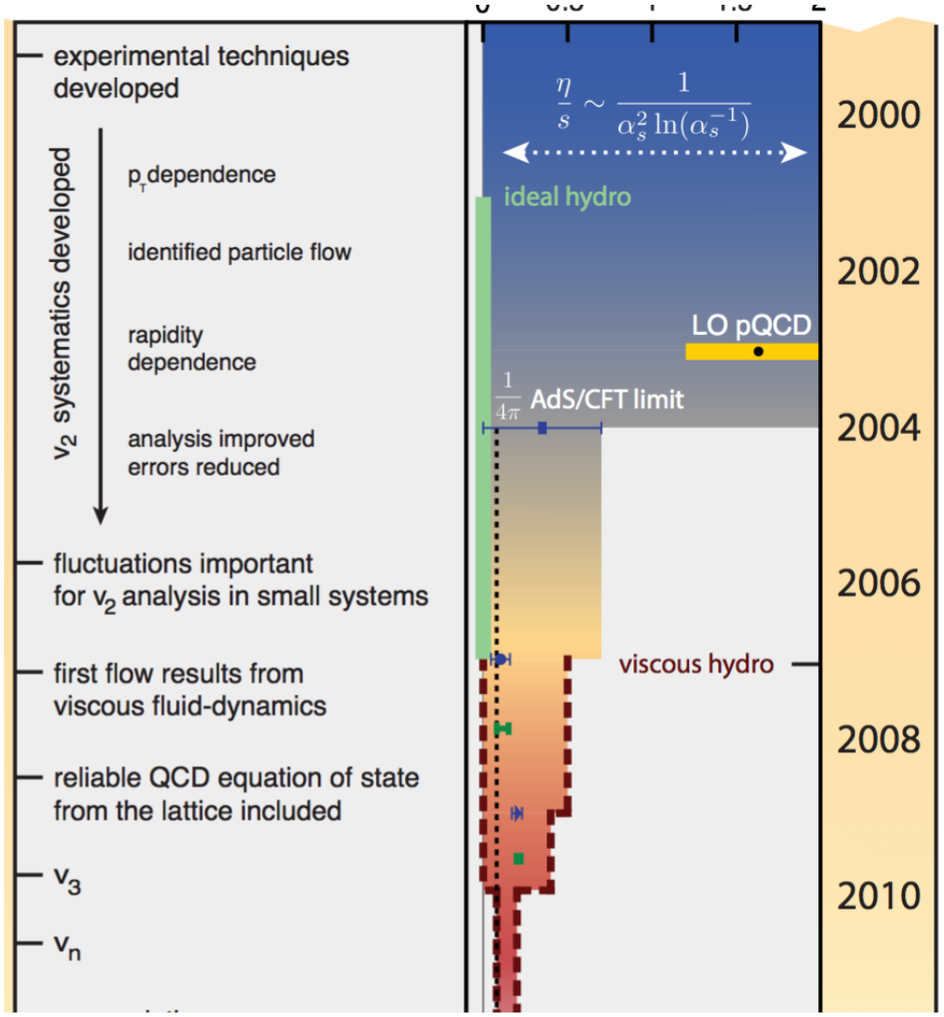
Variation of granularity

B. Schenke et al, Phys.Rev. C85 (2012) 024901

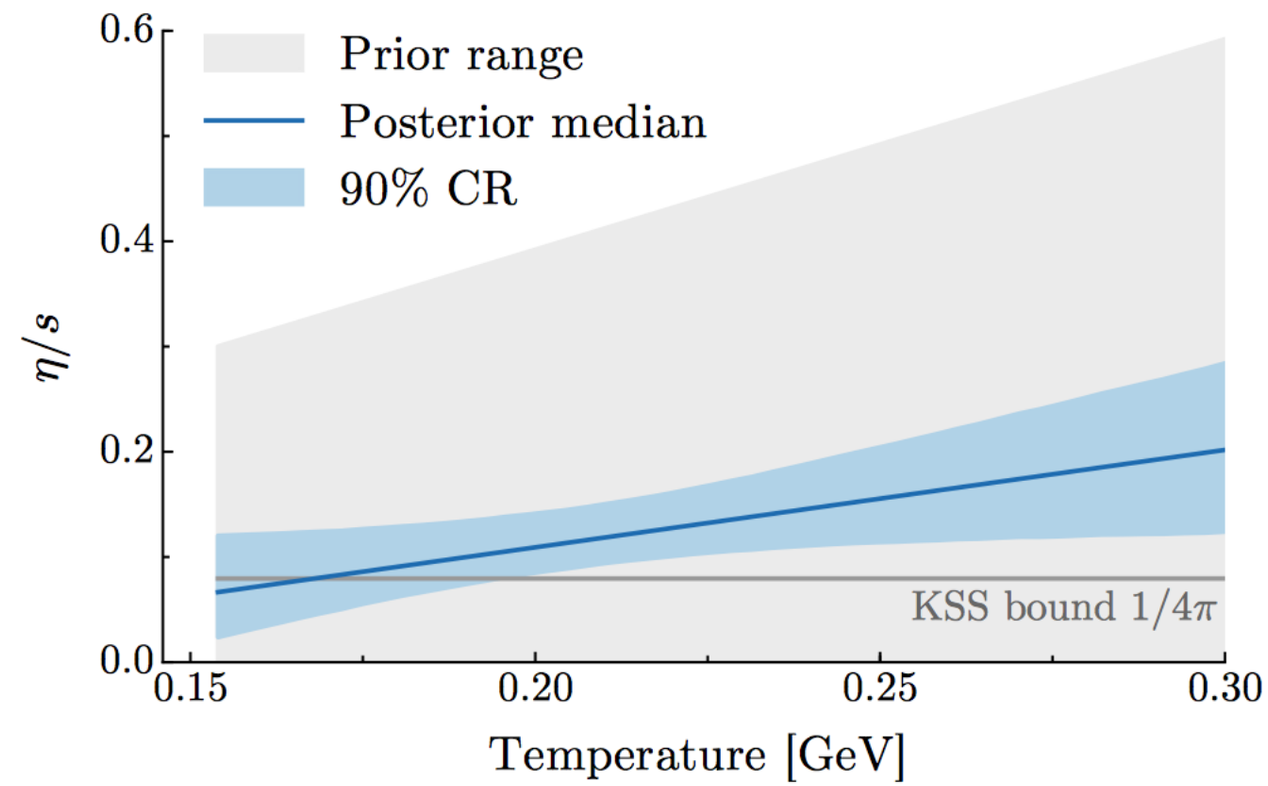
- Interplay of viscosity and fluctuations in the initial state:
  - Large structures and ideal fluid dynamics
    = small structures and viscous hydrodynamics
- Event-by-event calculations with many parameters required

Transport Coefficients

- Shear viscosity has been constrained over many years



RHIC White paper, 2012



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

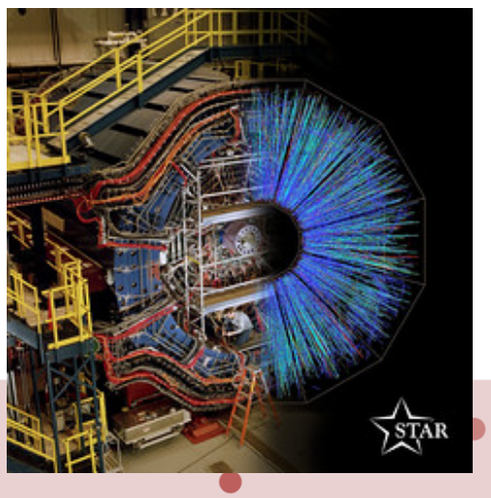
- Bayesian multi-parameter analysis yields confidence interval for temperature dependence of shear viscosity to entropy ratio

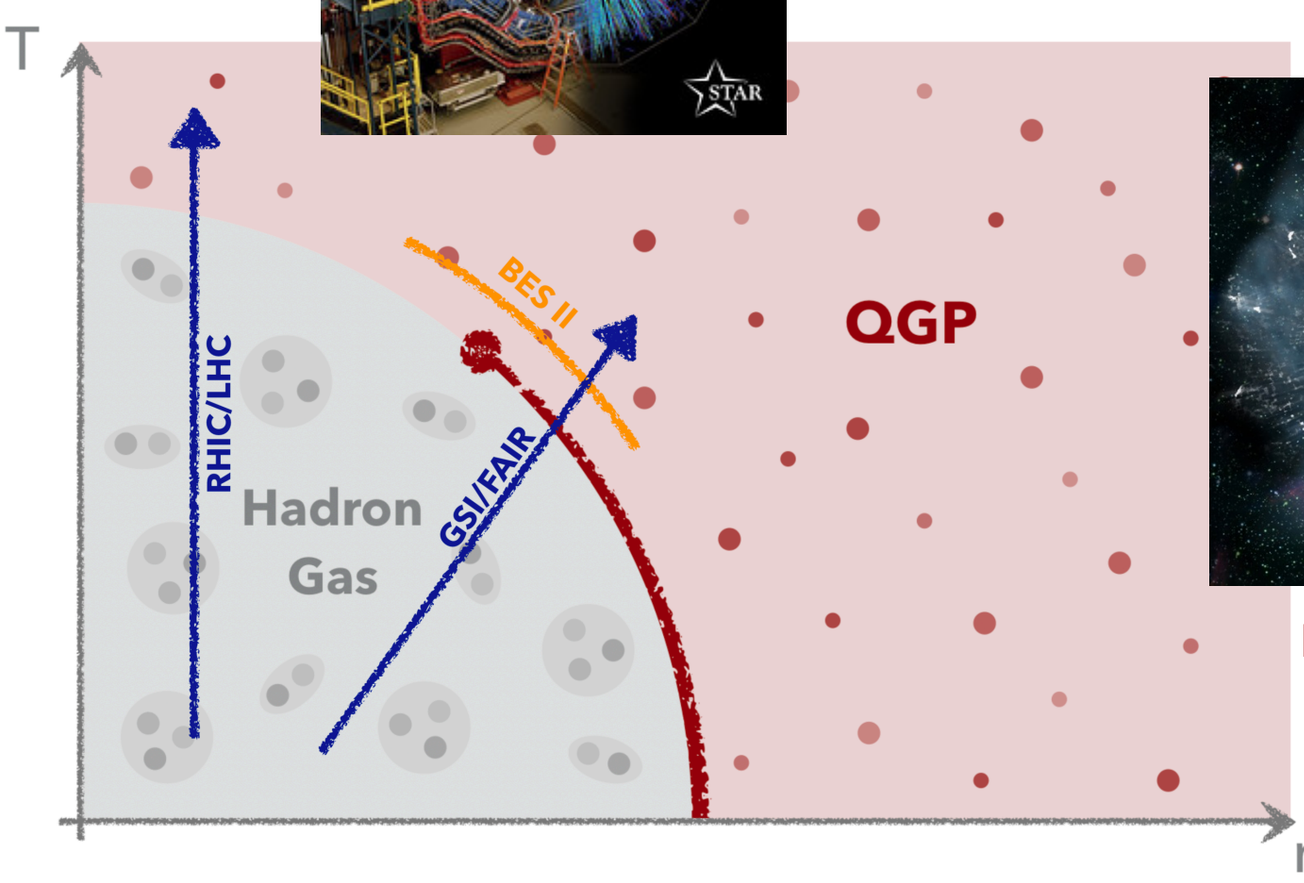
Towards Finite μ_B

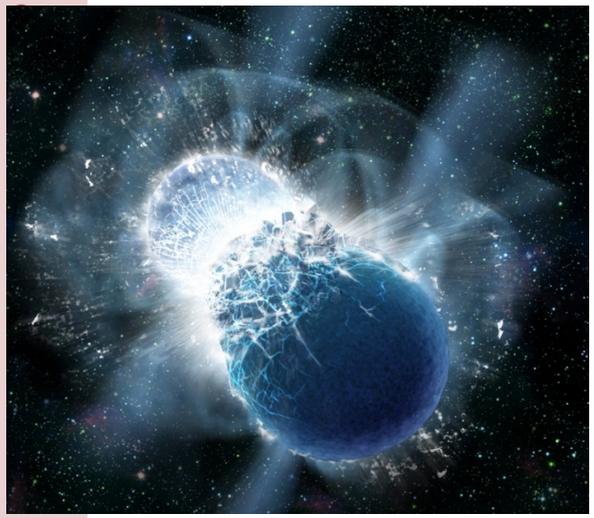
The QCD Phase Diagram

- Lattice QCD cannot be employed at finite densities due to the sign problem —> many interesting questions:
  - What are the relevant degrees of freedom at high densities?
  - Phase transition, critical endpoint?
  - Properties of neutron star mergers?

STAR experiment at RHIC







Dana Berry, SkyWorks Digital, Inc

Relevant for neutron star mergers as detected by gravitational waves (GW170817)

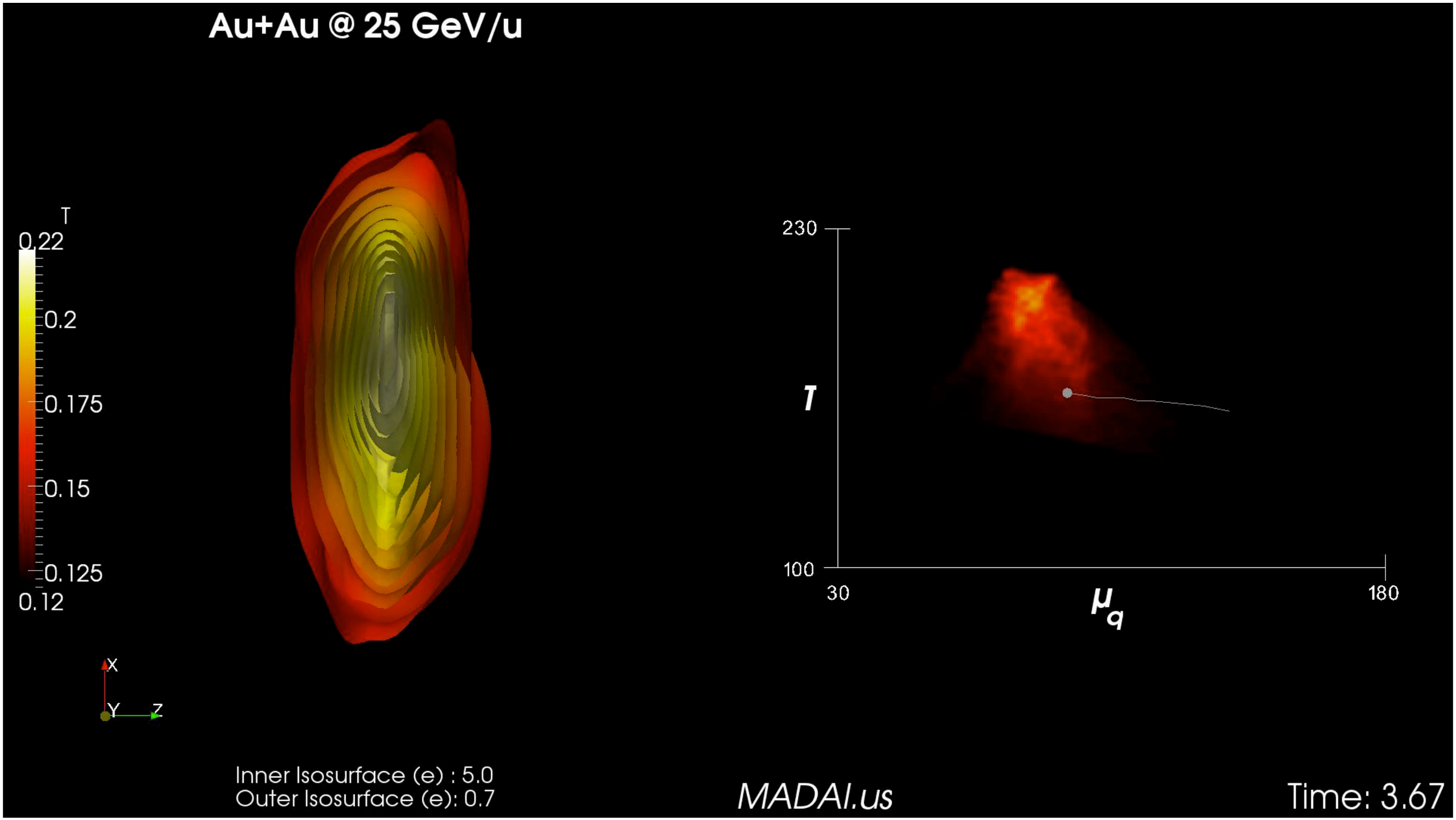
Construction Site FAIR

GSI webpage, August 2019

- Creation of densest matter world-wide
- High collision rates
- Starting ~2025

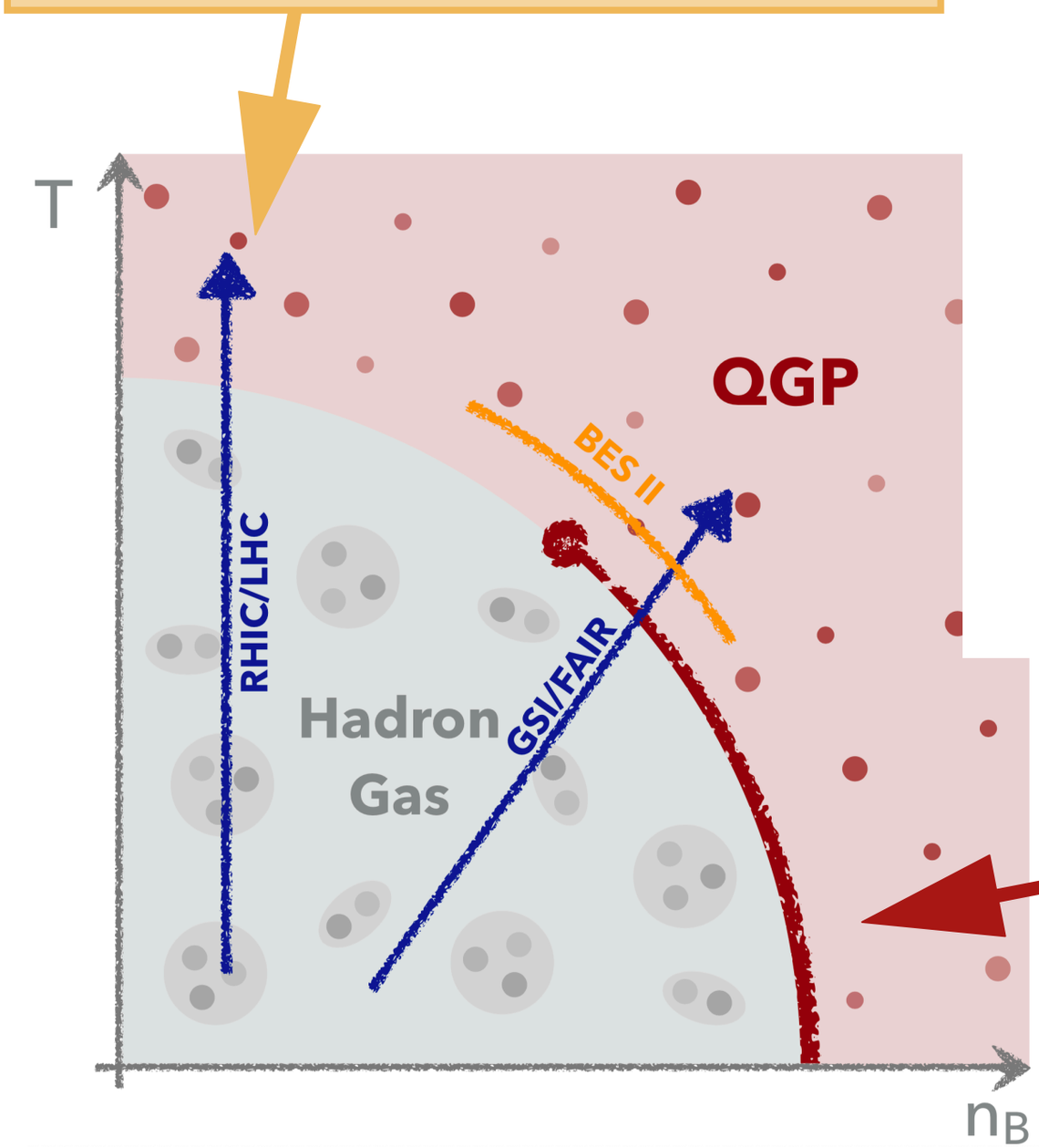
Facility for **A**nti-Proton and **I**on **R**esearch in Darmstadt-Wixhausen

Exploring the Phase Diagram



The Phase Diagram

Standard approach at high energies
- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic rescattering



- Two regimes with well-established approaches
- Goals:
  - Constraints on the equation of state of nuclear matter
  - Determine limit of applicability of hadronic transport approach
  - Qualitative signatures of first order phase transition

Standard approach at low beam energies
- Hadronic transport approaches
- Resonance dynamics
- Nuclear potentials

smash

SMASH

A Hadron Transport Approach

Simulating Many Accelerated Strongly-Interacting Hadrons

- Hadronic transport approach:
  - Includes > 150 mesons and baryons
  - Based on relativistic Boltzmann equation

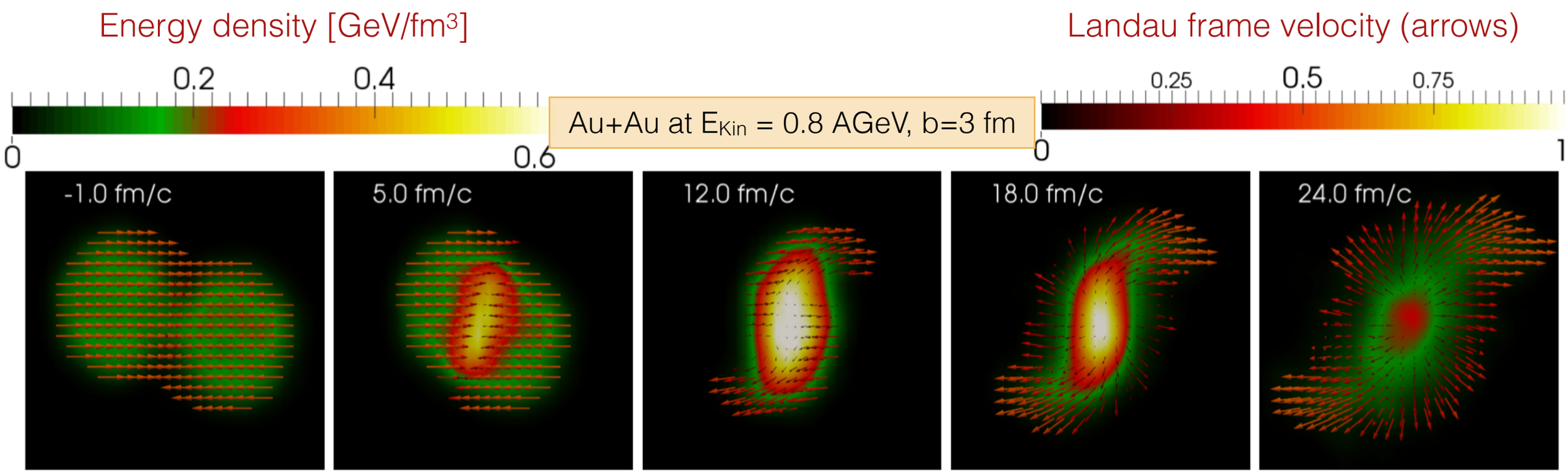
$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\text{coll}}$$

smash

https://smash-transport.github.io

J. Weil, HP (now Elfner) et al, PRC 94 (2016)

  - Open source code: C++, Git, Python Analysis Suite
  - Already used by HADES, CBM, JETSCAPE, BEST and individuals



The SMASH Team

- In Frankfurt:
  - Oscar Garcia-Montero
  - Vinzent Steinberg
  - Jean-Bernard Rose
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Natey Kübler
  - Jan Hammelmann
  - Damjan Mitrovic
  - Philip Karan
  - Martha Ege
- In US/Serbia/China:
  - Dmytro Oliinychenko
  - LongGang Pang
  - Jussi Auvinen
  - Sangwook Ryu

Subset of the group in July 2019

Degrees of Freedom

N	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^-_{1672}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^-_{2250}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}	
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}	
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}		
N_{1720}		Λ_{1830}	Σ_{2250}		
N_{1875}		Λ_{1890}			
N_{1900}		Λ_{2100}			
N_{1990}		Λ_{2110}			
N_{2060}		Λ_{2350}			
N_{2080}					
N_{2100}					
N_{2120}					
N_{2190}					
N_{2220}					
N_{2250}					

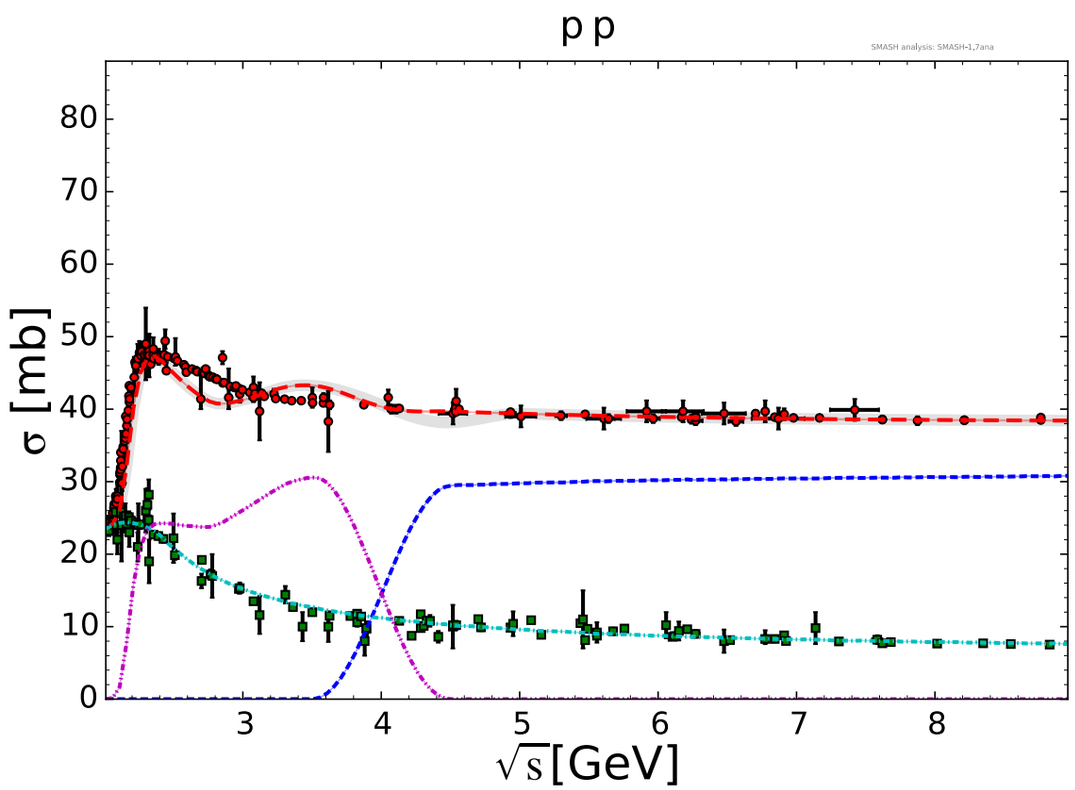
As of SMASH-1.7

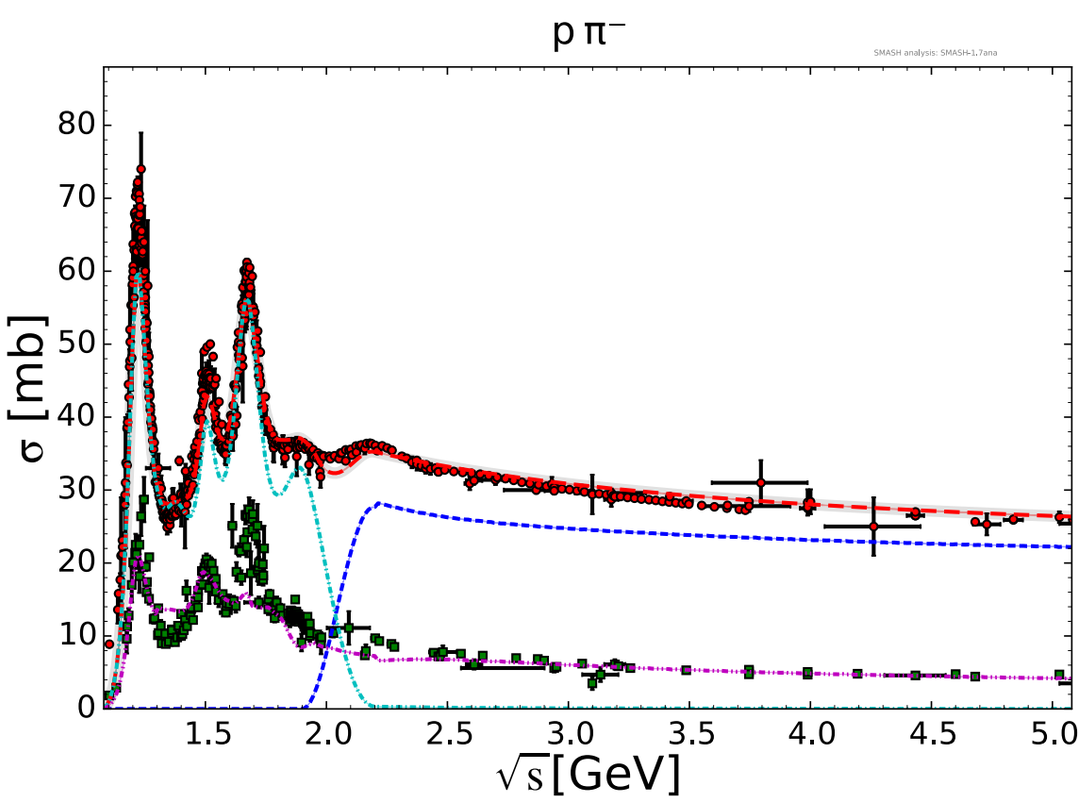
Unflavored				Strange
π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
π_{1300}	$f_{0\ 1370}$	$f_{2}'_{1525}$		K^*_{892}
π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
	$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
η_{1405}		$f_{1\ 1285}$		K^*_{1680}
η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
	ϕ_{1680}			$K_3^*{}_{1780}$
σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
	$h_{1\ 1170}$			$K_4^*{}_{2045}$
ρ_{776}		$\pi_{1\ 1400}$		
ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
ρ_{1700}				
	$a_{1\ 1260}$	$\eta_{2\ 1645}$		
ω_{783}				
ω_{1420}		$\omega_{3\ 1670}$		
ω_{1650}				

- + corresponding antiparticles
- Perturbative treatment of photons and dileptons
- Isospin symmetry

- Mesons and baryons according to particle data group
- Isospin multiplets and anti-particles are included

Elementary Cross Sections



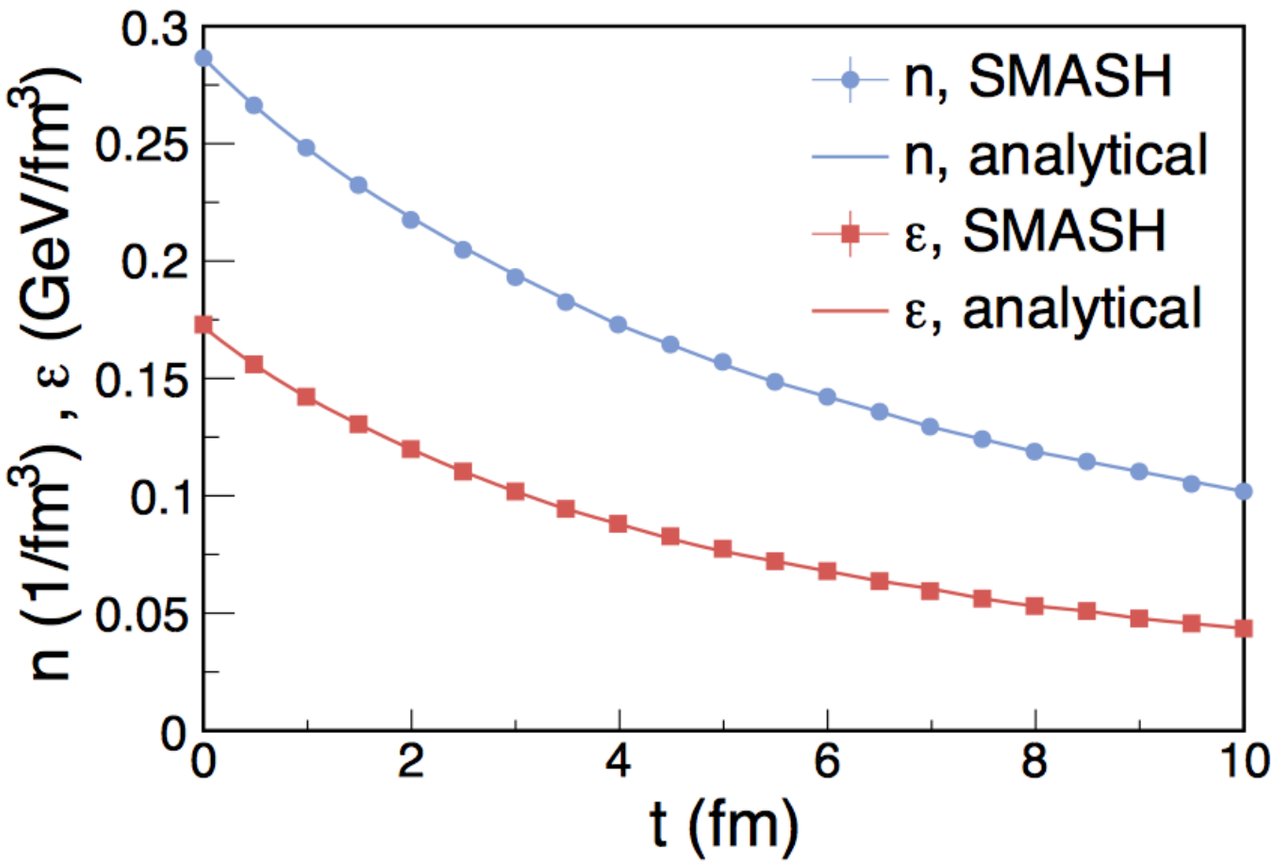


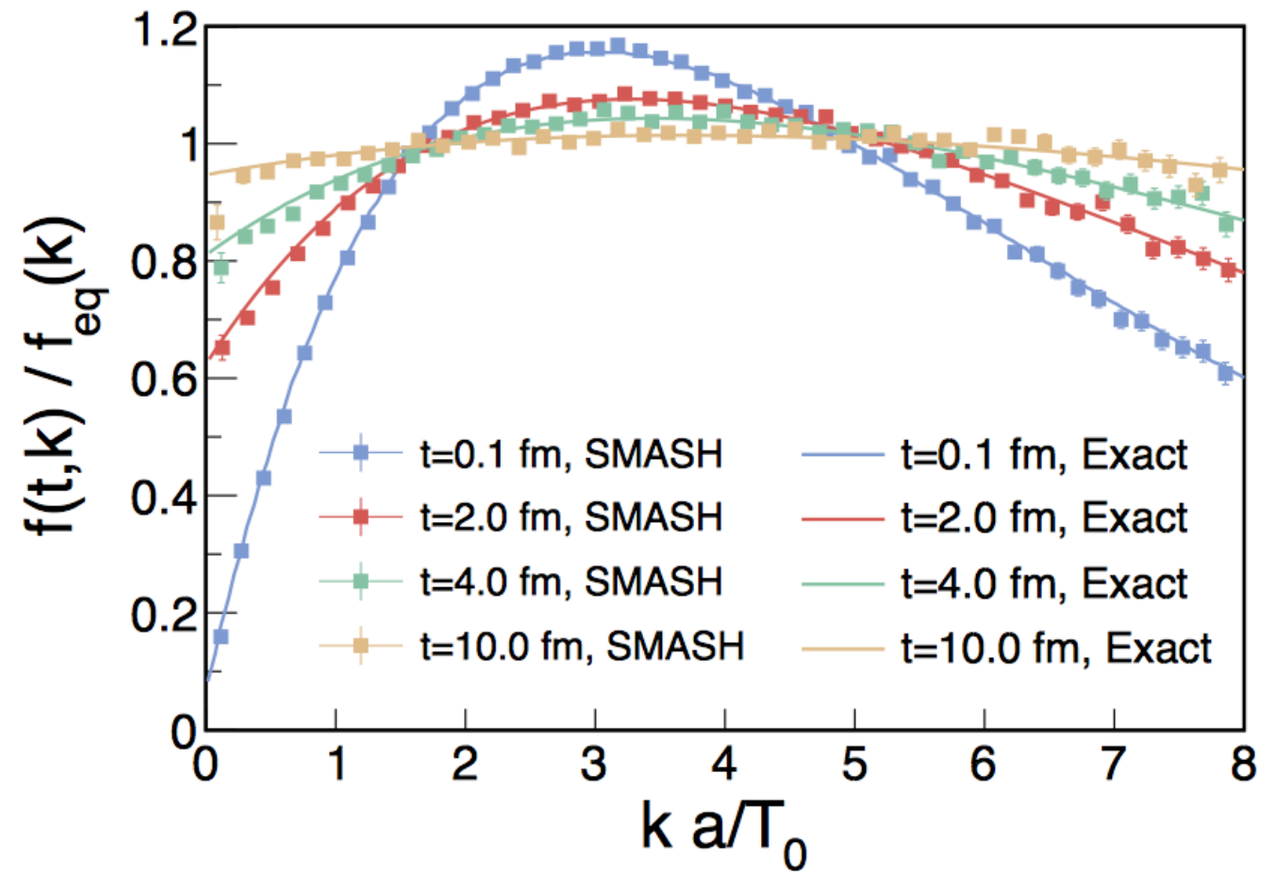
- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Transition from resonances to strings at intermediate energies

J. Weil et al, PRC 94 (2016), updated SMASH-1.7

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





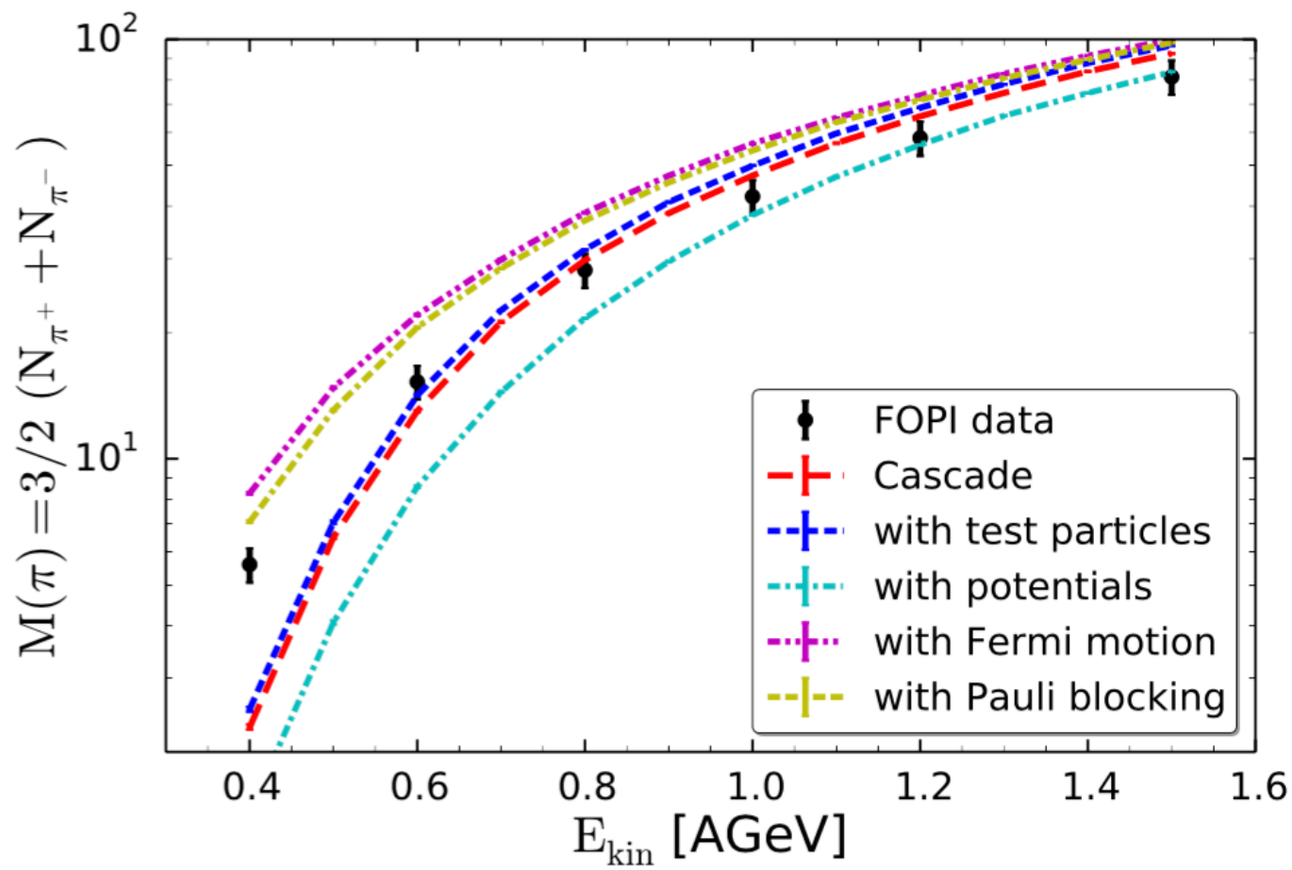
- Perfect agreement proves correct numerical implementation of collision algorithm

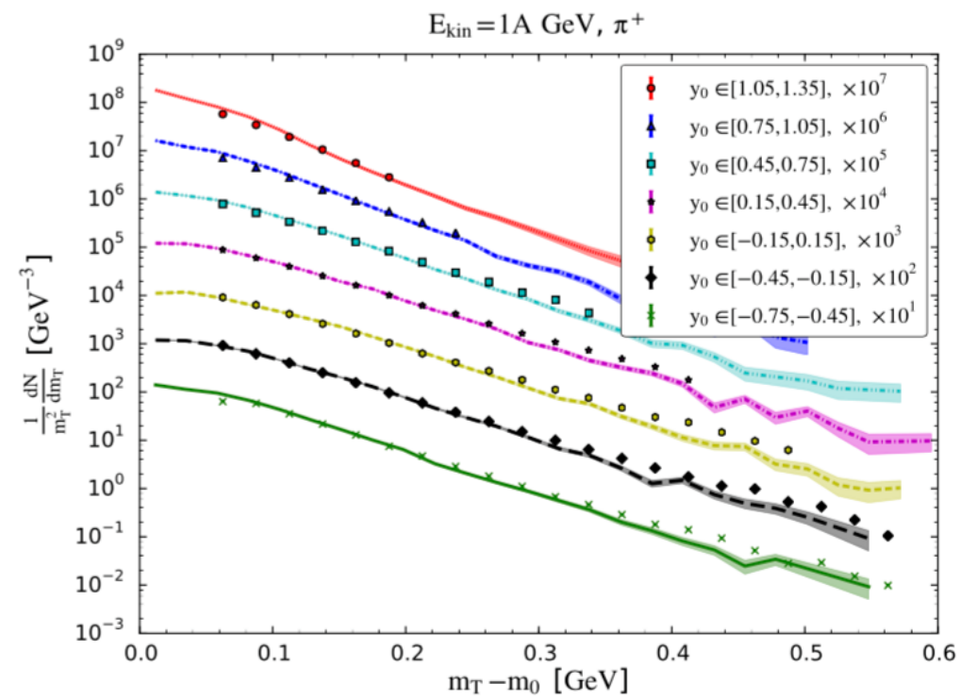
D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

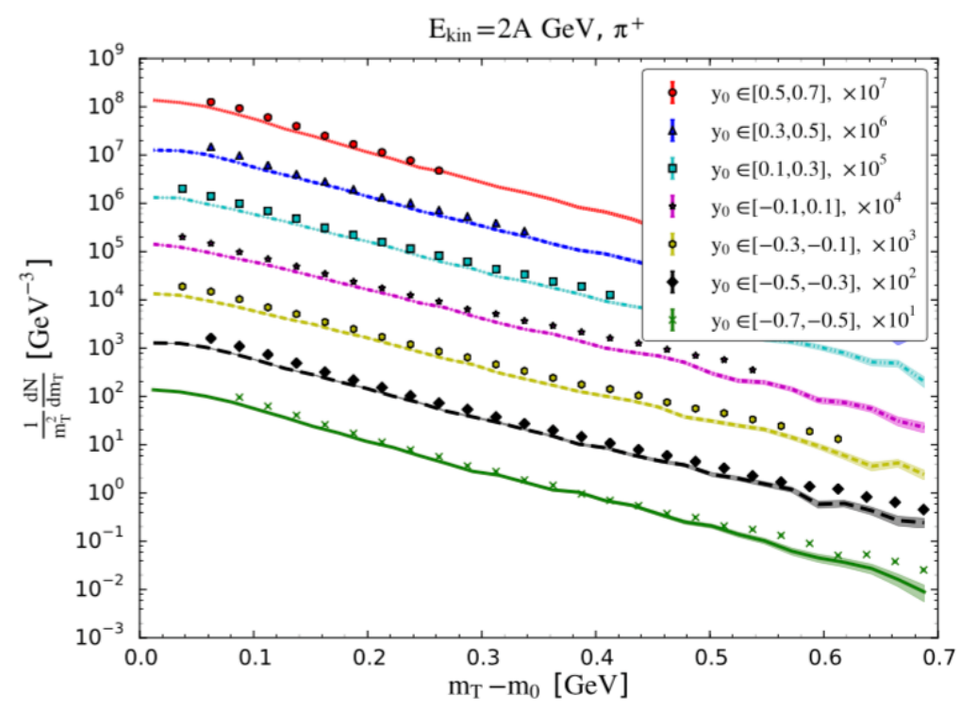
J. Tindall et al., PLB 770 (2017)

Pion Production in Au+Au

- Potentials decrease pion production, while Fermi motion increases yield
- Nice agreement with SIS experimental data





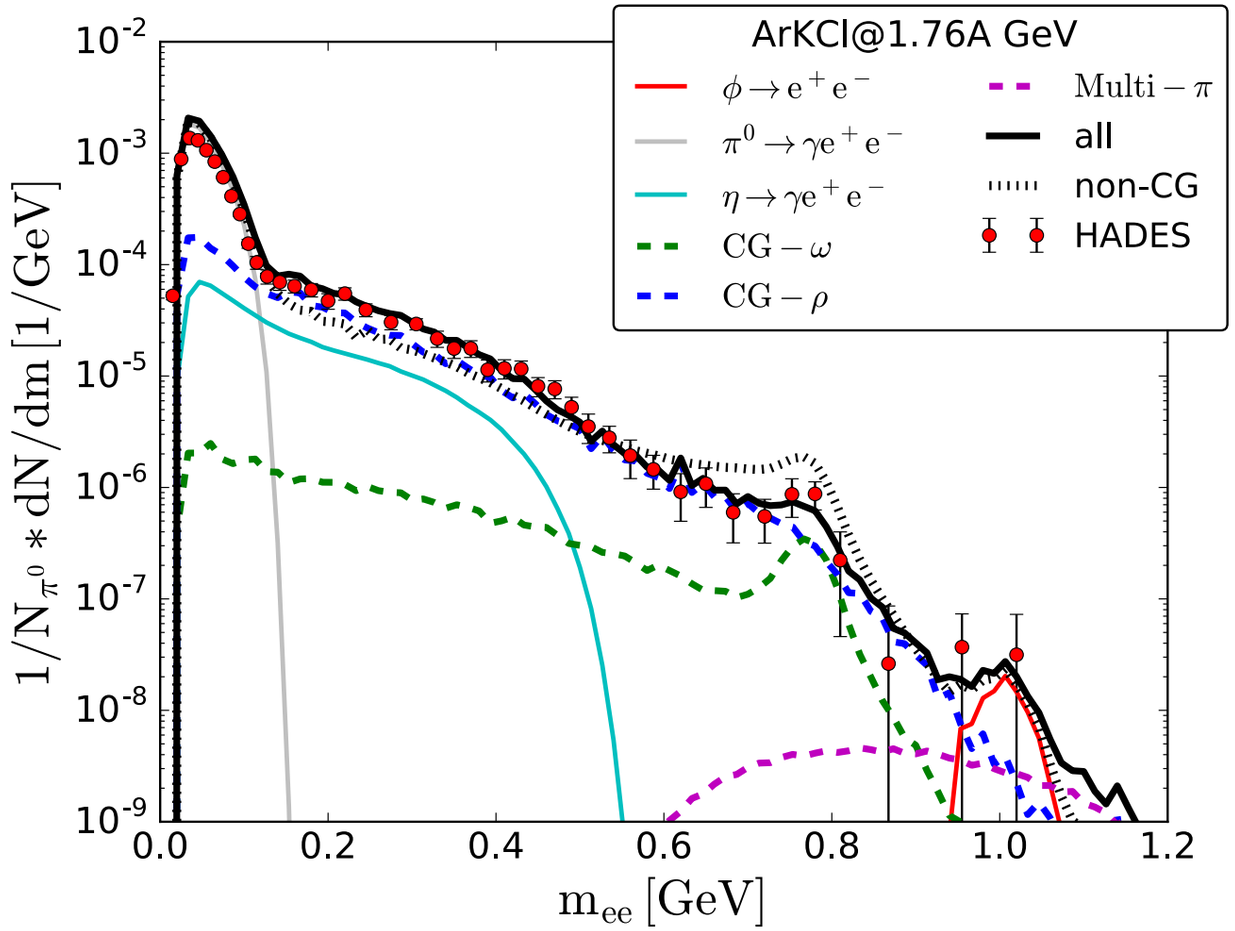


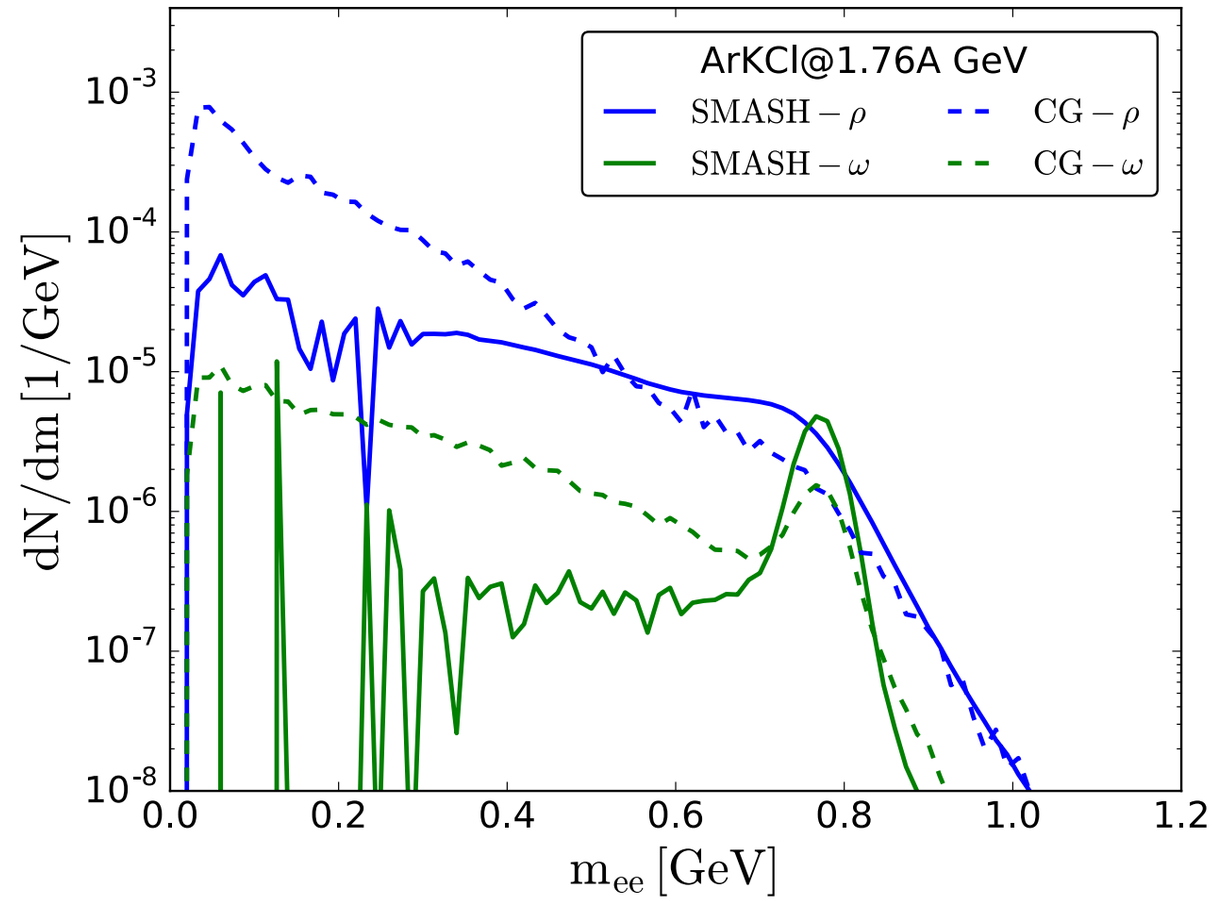
Note: consecutive addition of features

J. Weil et al, PRC 94 (2016)

Electromagnetic Probes

- Dileptons do not interact strongly and escape the interaction region





- Coarse-grained transport evolution allows for full medium-modified spectral function

S. Endres et al., PRC 92, 2015
R. Rapp et al, EPJA 6, 1999, PRC 63, 2001

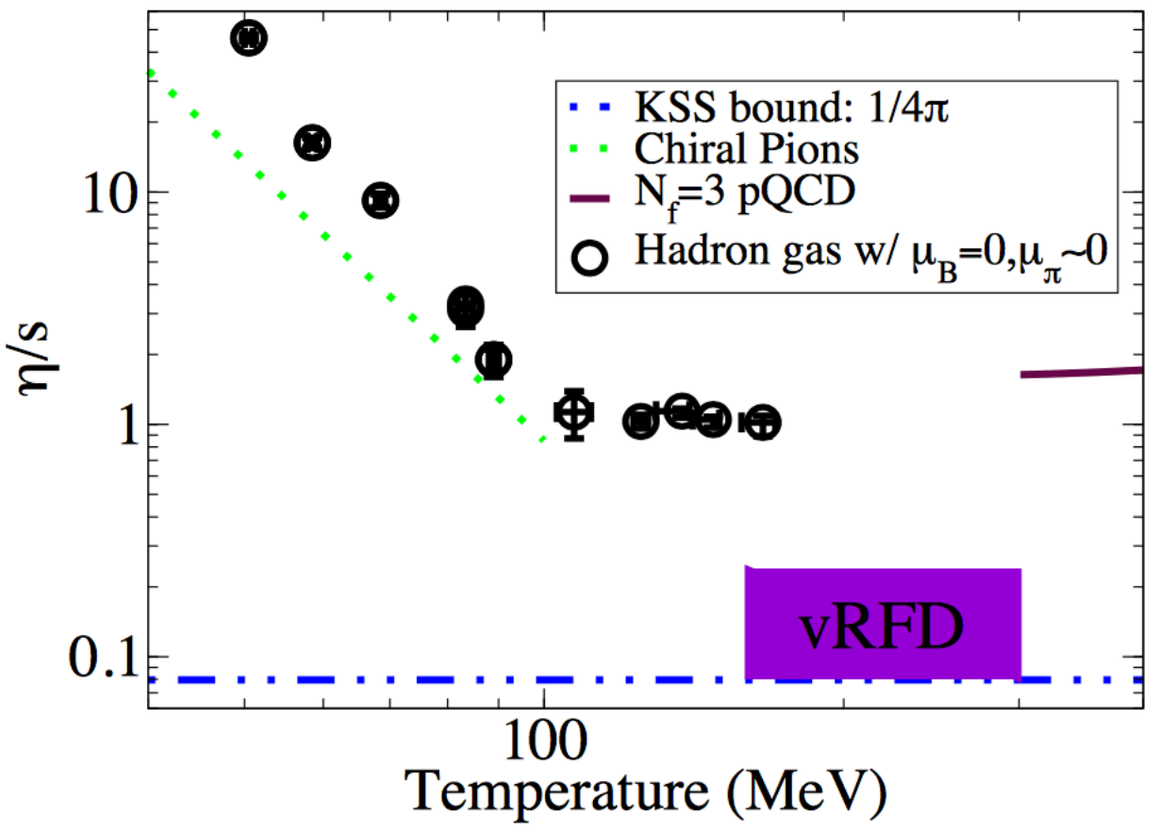
- Comparison allows for detailed investigation of medium modifications

J. Staudenmaier et al,
Phys.Rev. C98 (2018) no.5, 054908

Transport Coefficients

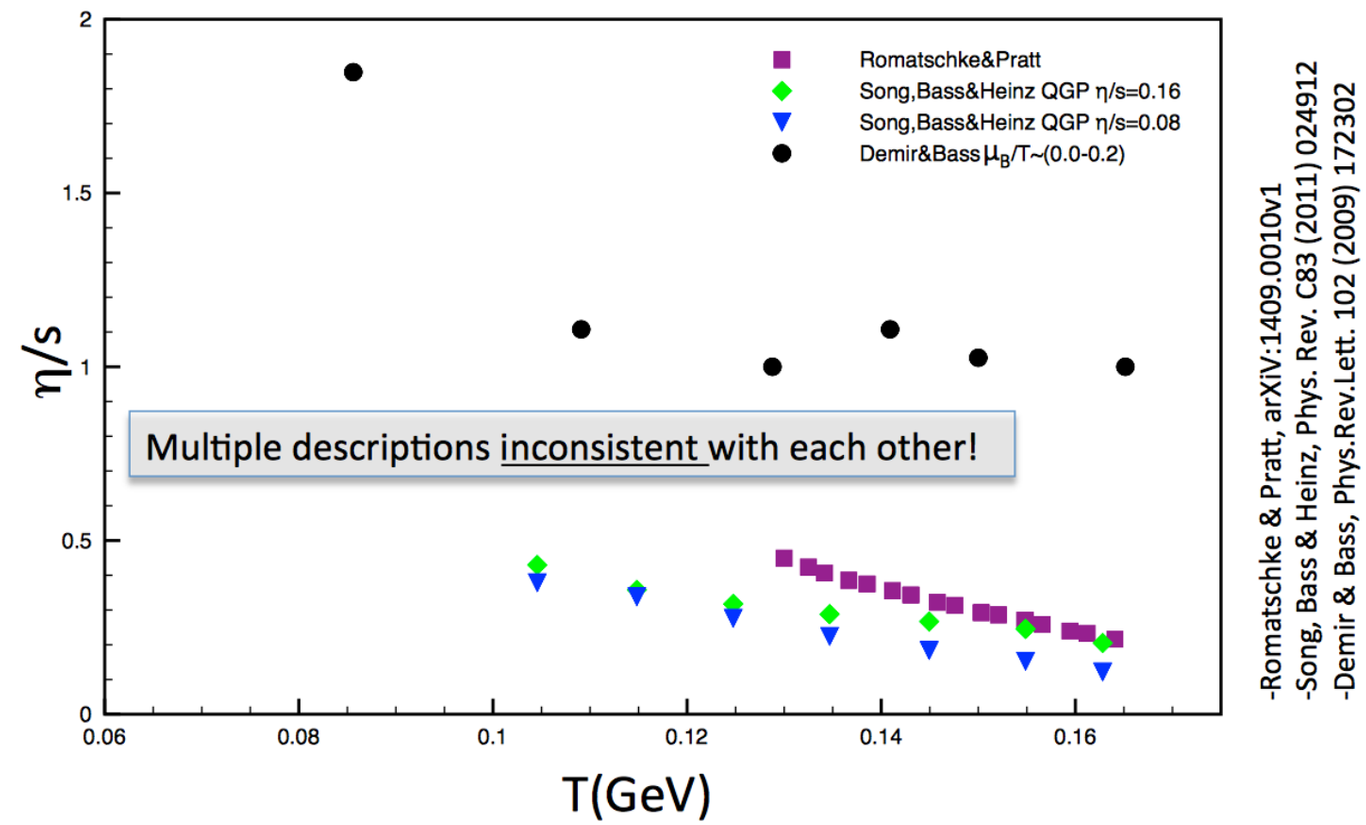
Shear Viscosity of the Hadron Gas

Green-Kubo formalism
UrQMD



N. Demir and S.A. Bass, PRL 102 (2009)

Discrepancy with
hydro-inspired B3D and VISHNU

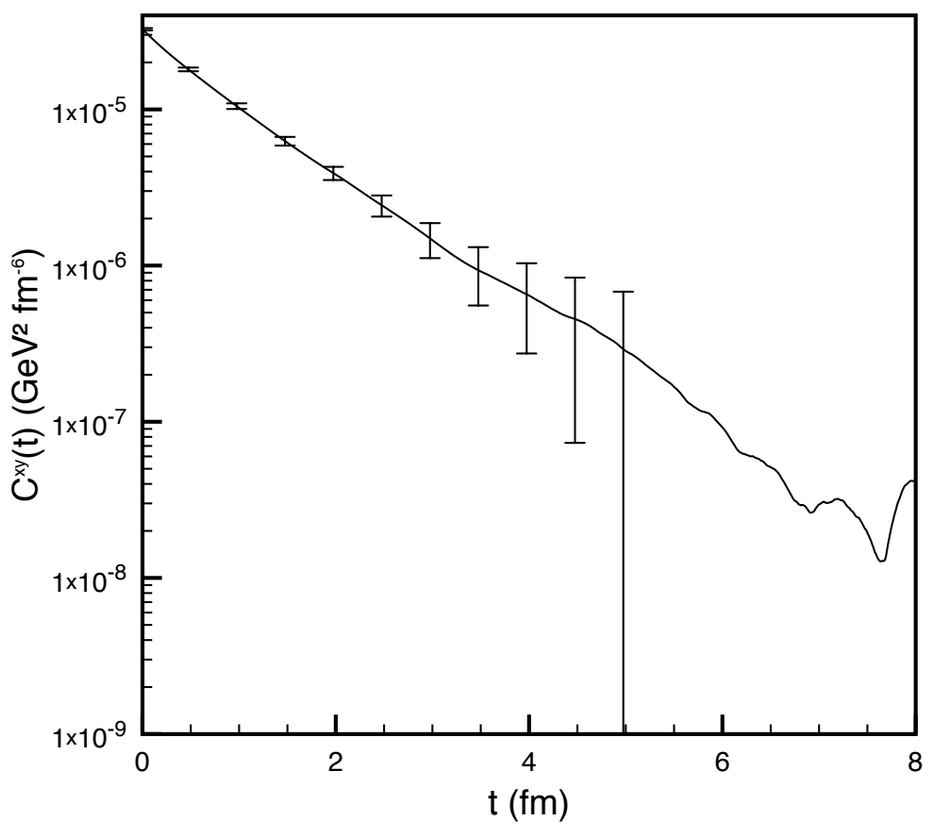


- Long standing question: Why are the results so different from each other?

J.-B. Rose, J. M. Torres-Rincon, A. Schäfer, D. Oliinychenko and HP, PRC97 (2018) and JPCS 1024 (2018)

Shear Viscosity over Entropy Density

- Hadron gas in thermodynamic equilibrium realised by box with periodic boundary conditions
- Entropy is calculated via Gibbs formula from thermodynamic properties
- The shear viscosity is extracted following the Green-Kubo formalism:



$$T^{\mu\nu} = \frac{1}{V} \sum_{i}^{N_{part}} \frac{p_i^\mu p_i^\nu}{p_i^0}$$

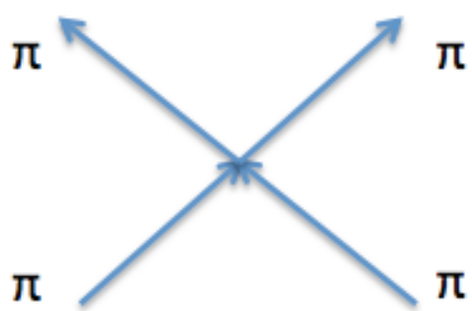
$$C^{xy}(t) = \frac{1}{N} \sum_{s}^{N} T^{xy}(s) T^{xy}(s+t)$$

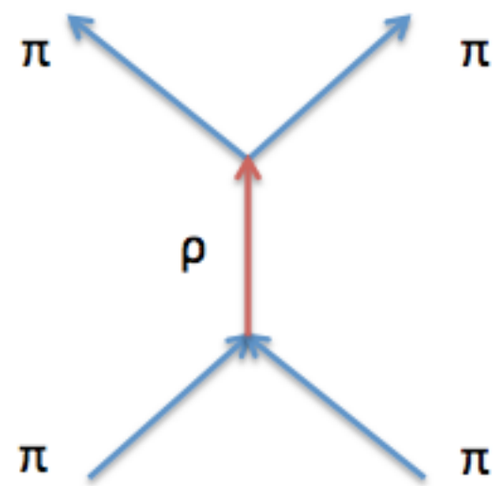
$$C^{xy}(t) \simeq C^{xy}(0) \exp\left(-\frac{t}{\tau}\right)$$

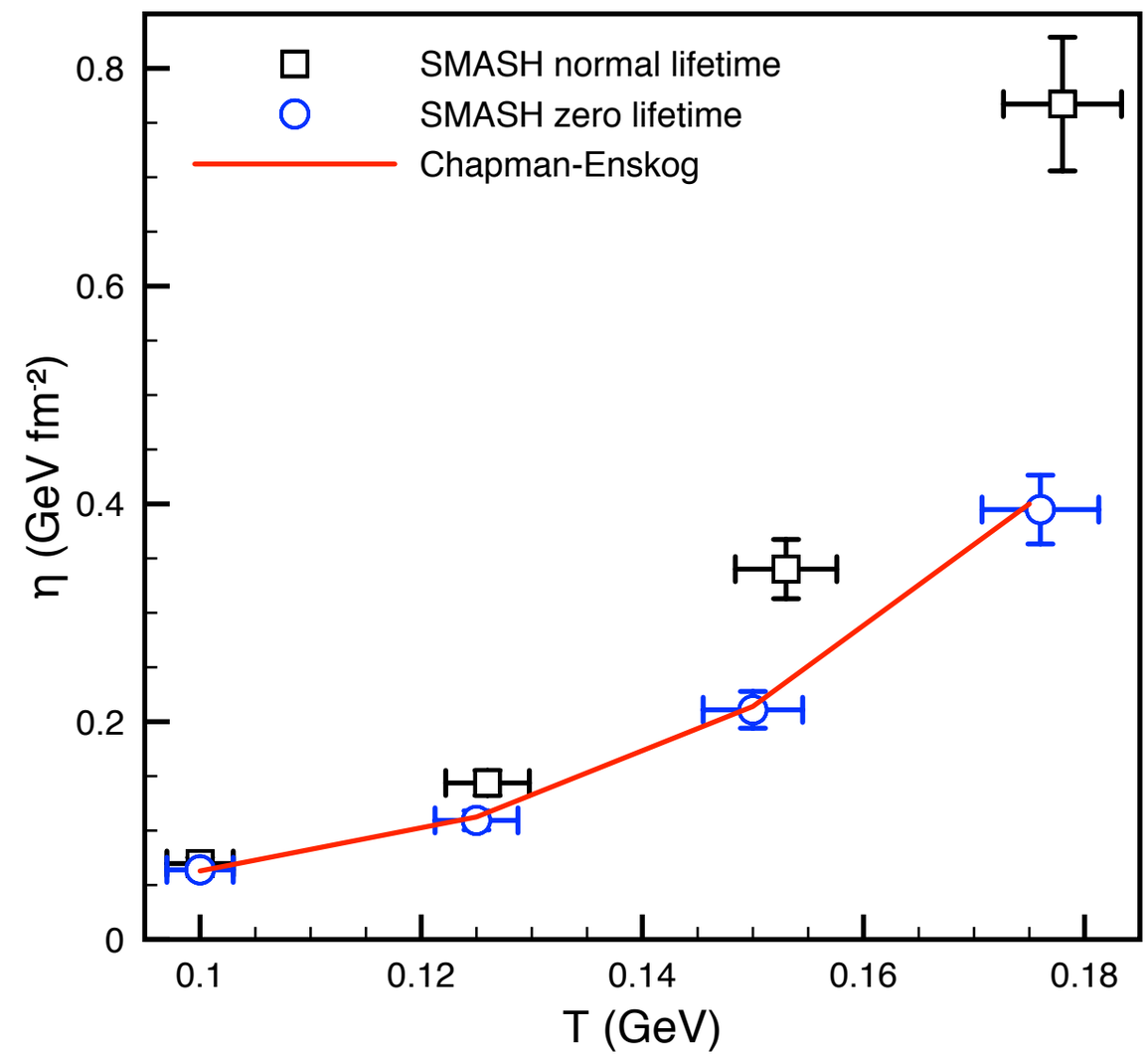
$$\eta = \frac{V C^{xy}(0) \tau}{T}$$

Resonance Dynamics

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



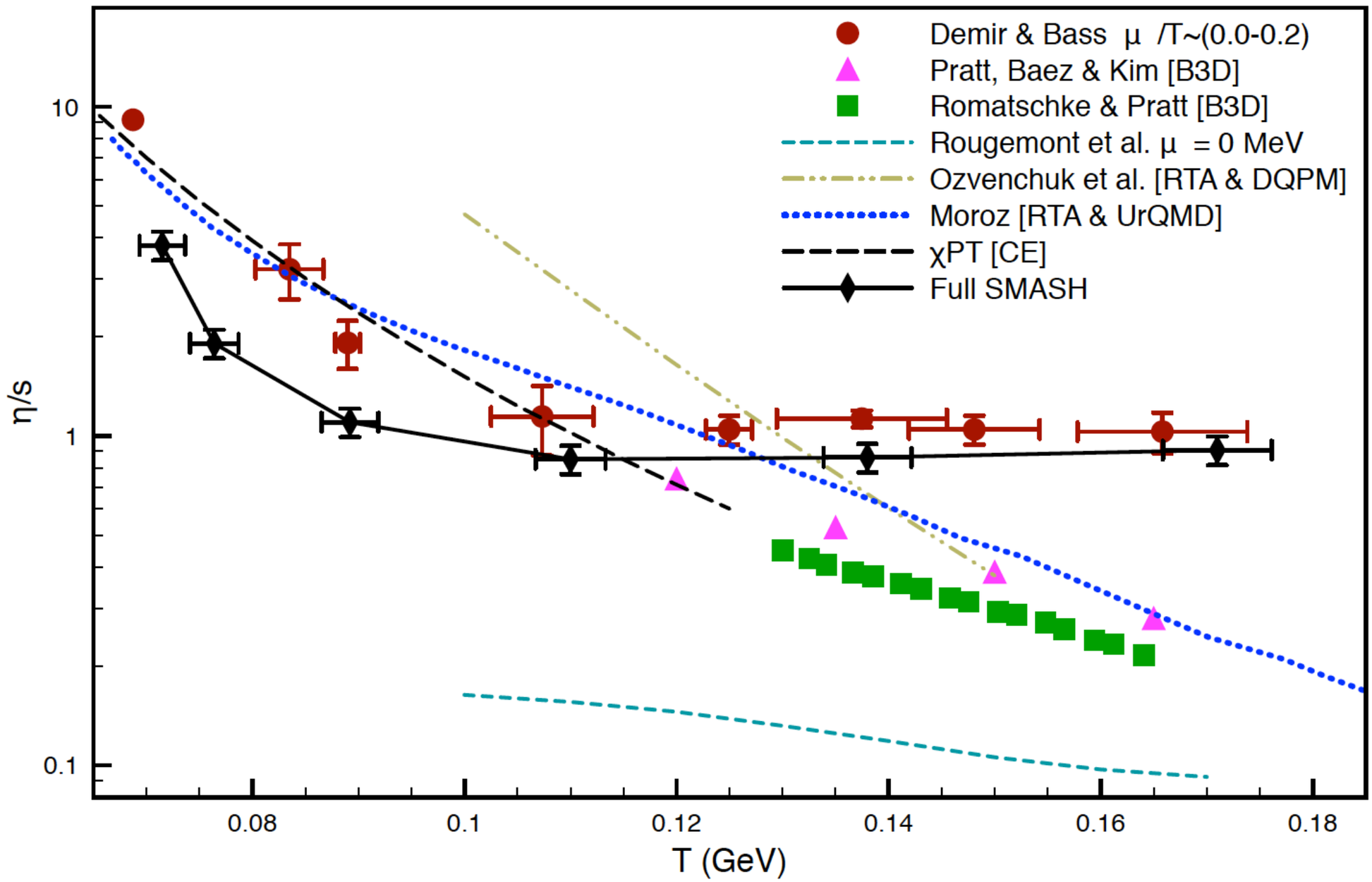




- Agreement recovered by decreasing ρ meson lifetime

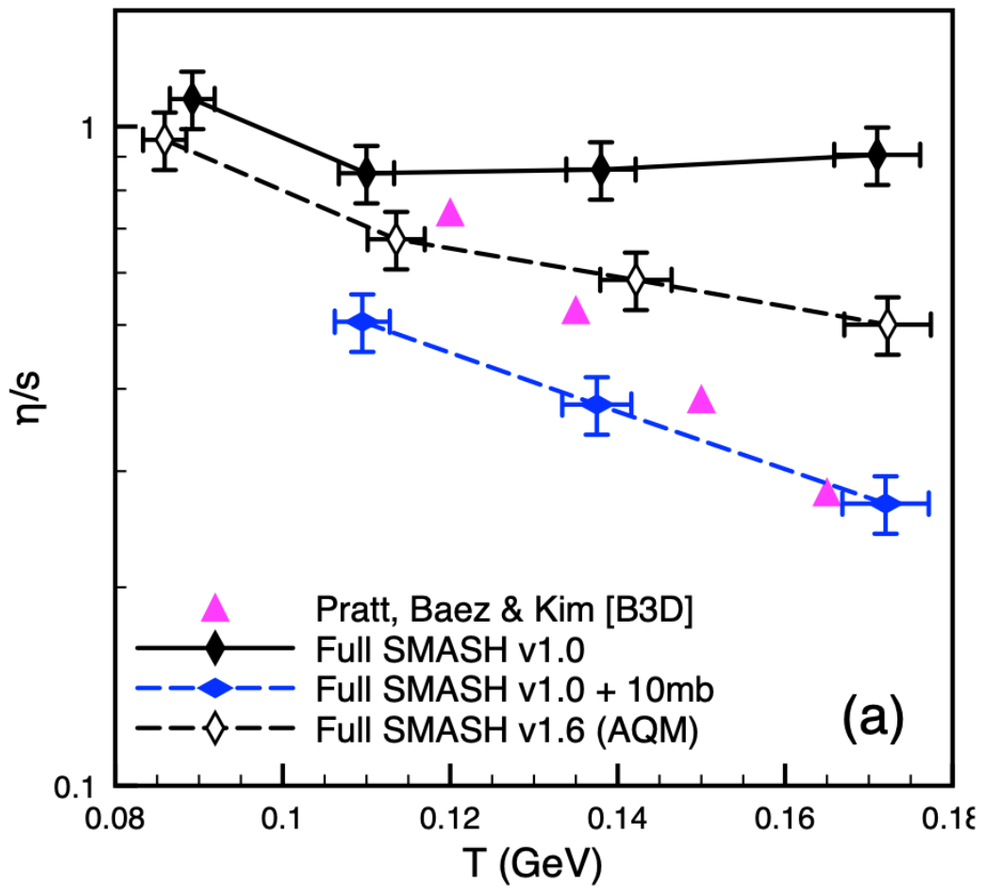
Comparison to Literature

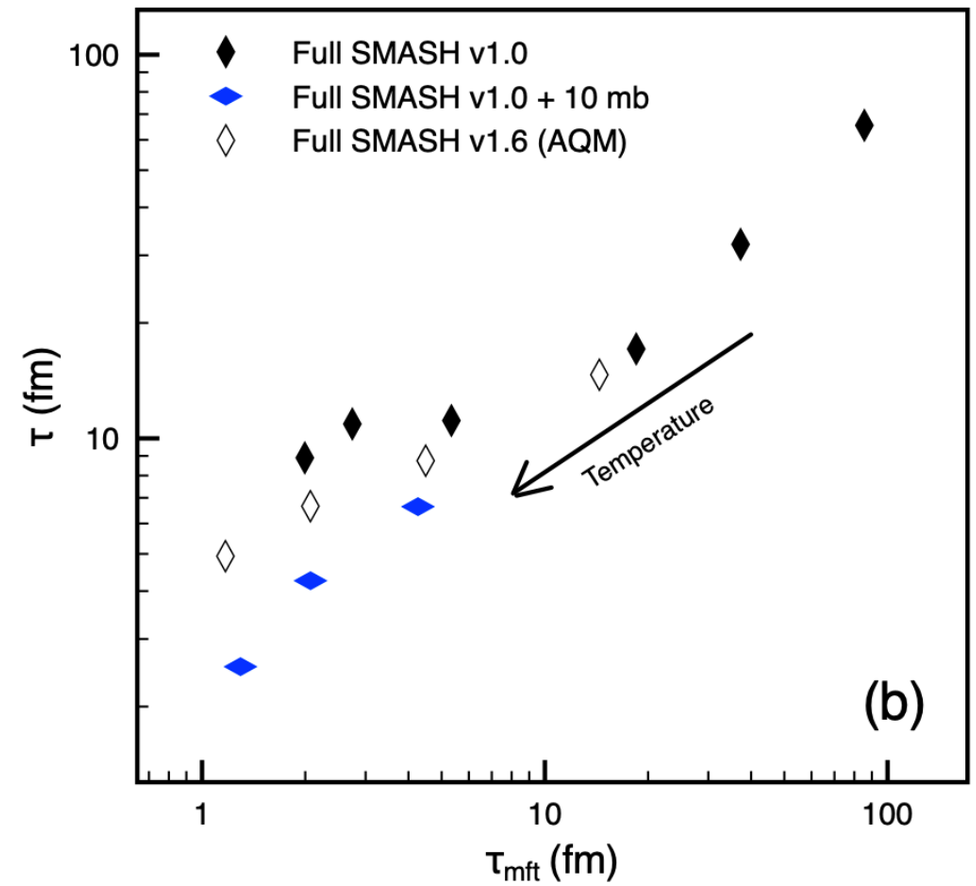
- Closest similarity to Bass/Demir result as expected



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
- Viscosity constrains the hadronic interactions

Electric Conductivity

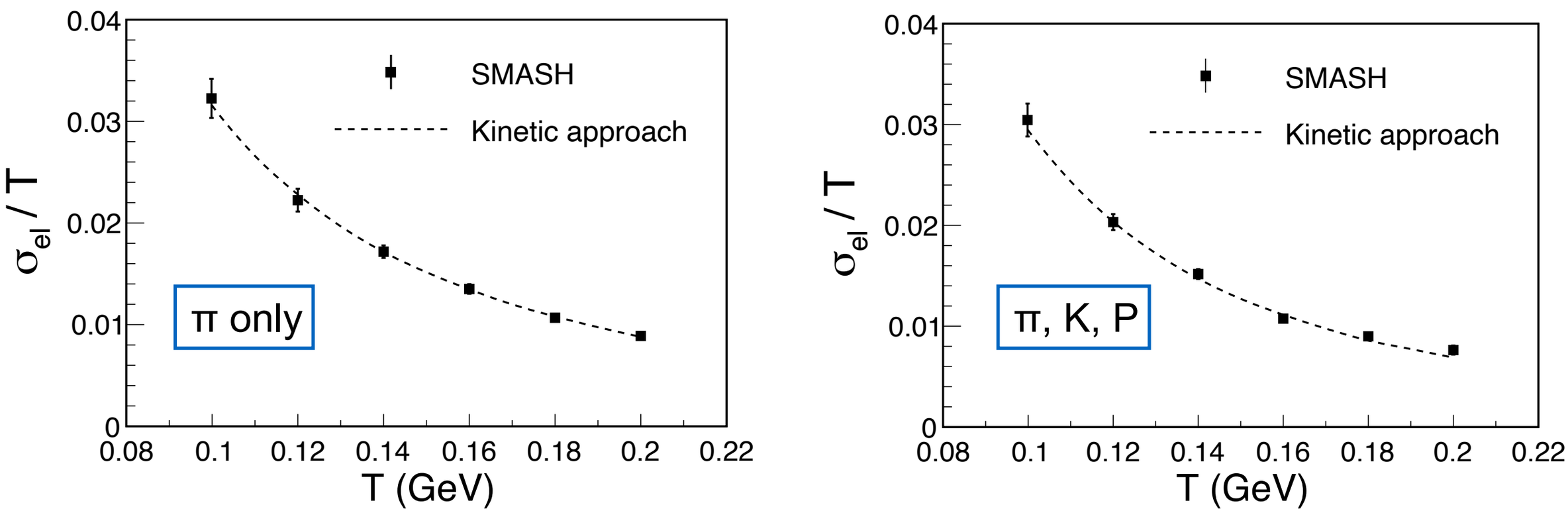
- Comparison to linear response kinetic theory to validate our approach

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

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

- Infinite matter with constant σ = 30 mb

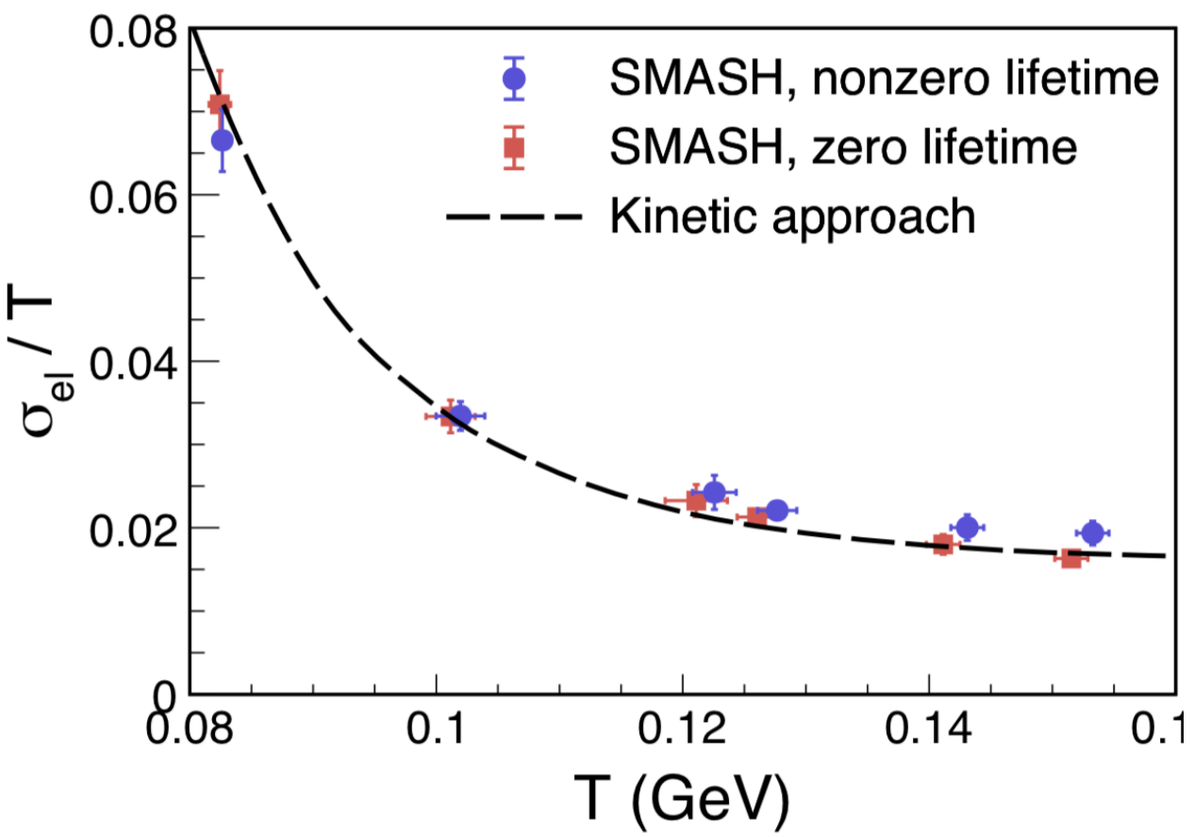
J. Hammelmann et al, Phys.Rev. D99 (2019) no.7, 076015

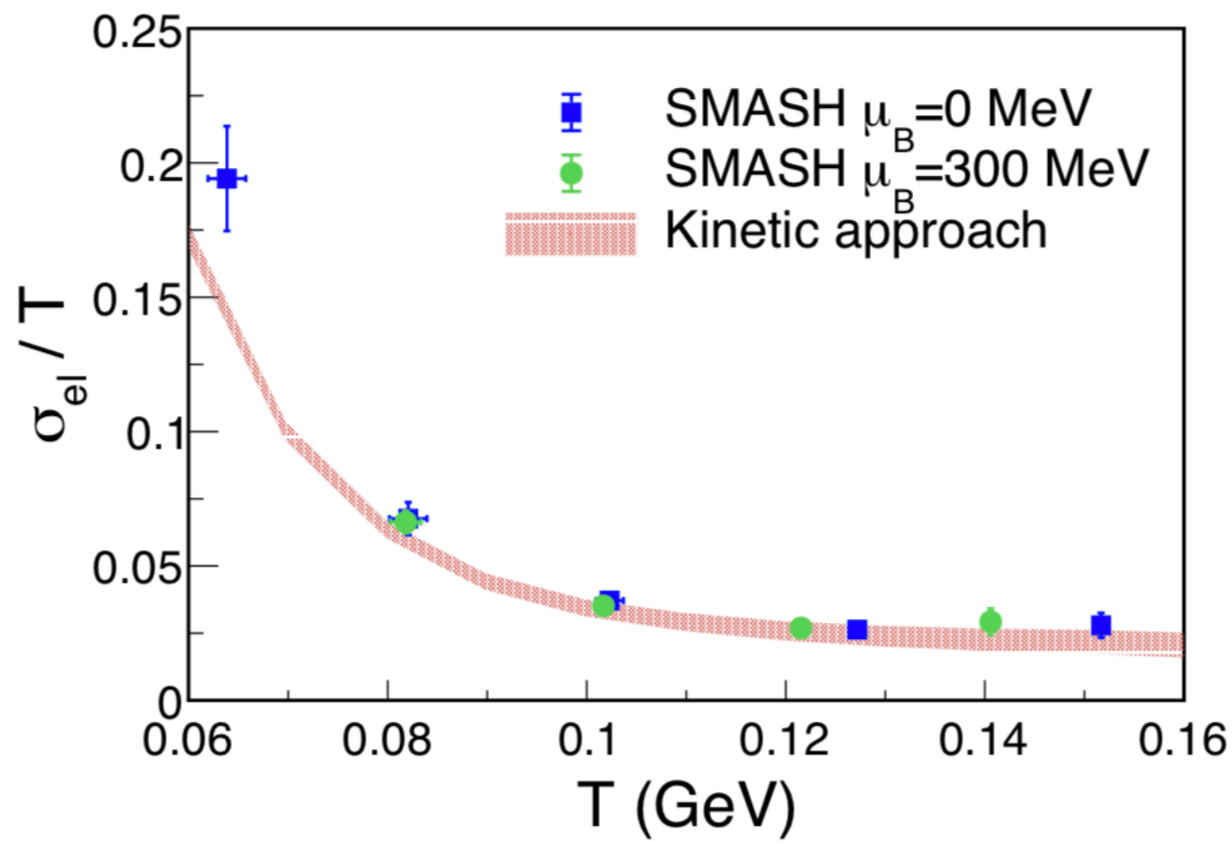


Influence of Lifetime

- Results for electric conductivity are independent of resonance lifetimes

J. Hammelmann et al, Phys.Rev. D99 (2019) no.7, 076015



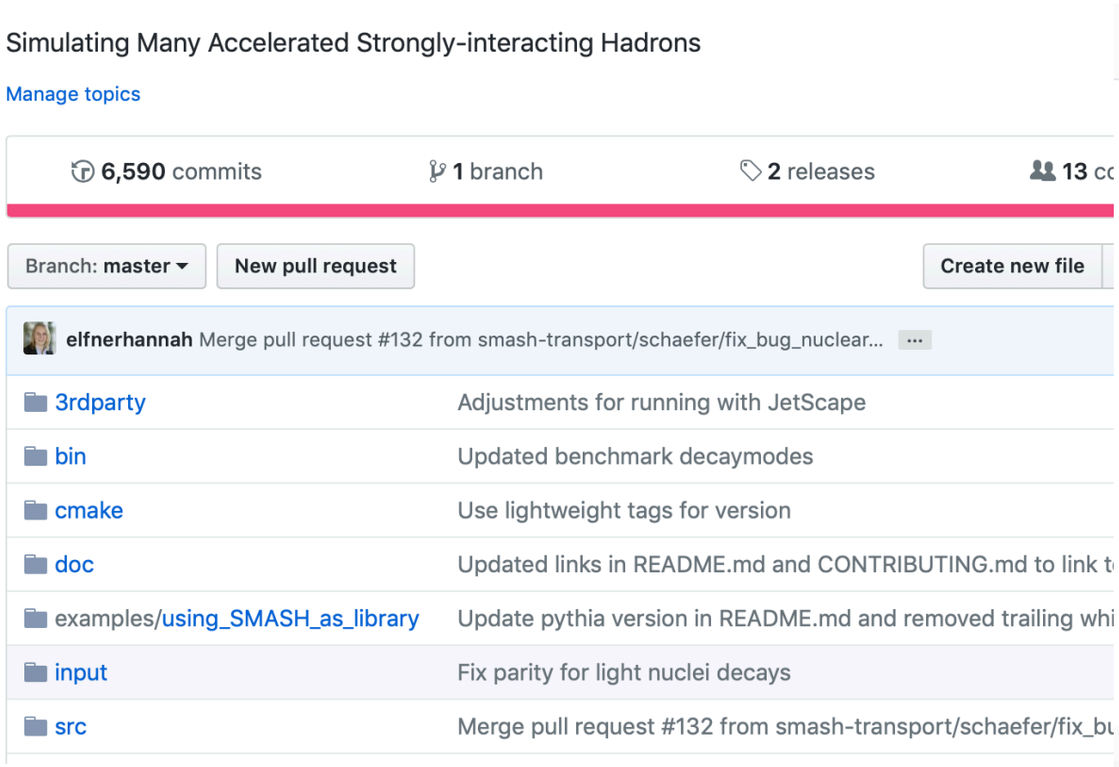


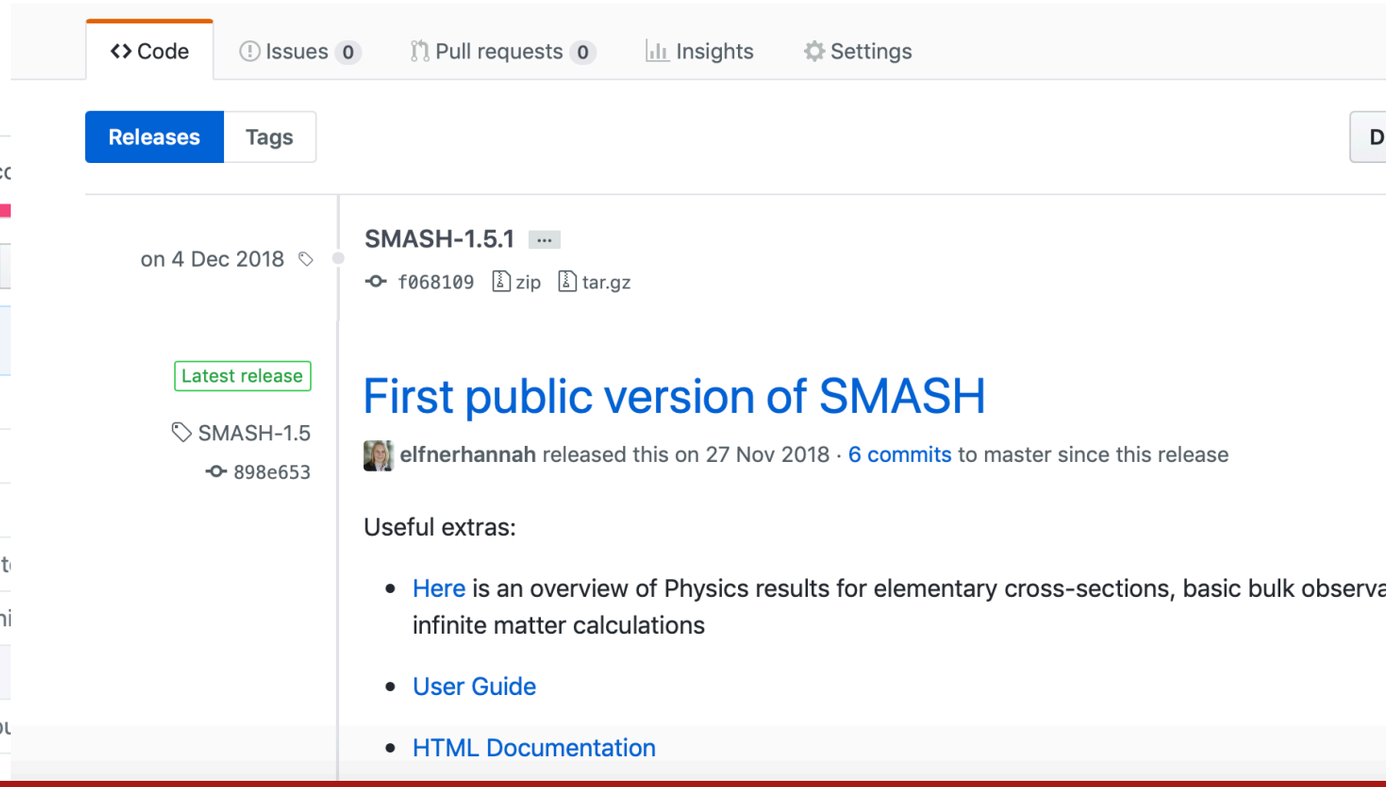
- Electric current relaxes already at formation of resonances and not only at the decay (full momentum exchange)

Summary

How to Use SMASH?

- Visit the webpage to find publications (DOI for the code 10.5281/zenodo.3484711) https://smash-transport.github.io
- Download the code at https://github.com/smash-transport/smash and https://github.com/smash-transport/smash-analysis
- Checkout the physics results at http://theory.gsi.de/~smash/analysis_suite/current/
- Find user guide and documentation at https://github.com/smash-transport/smash/releases





Summary and Outlook

- Quark-gluon plasma properties are explored in heavy-ion reactions
- At ultra-relativistic energies (LHC/RHIC) similar conditions to early universe
- Shear viscosity and initial state structures constrained by higher order flow coefficients
- Dynamical description essential to draw conclusions from experimental data
- At finite densities a first order phase transition is expected
- SMASH is a new hadronic transport approach that has been employed to study viscosity and conductivity of hot and dense hadron gas
- Importance of resonance lifetimes has been pointed out