Anisotropic flow in heavy-ion collisions at high and low beam energies

Hannah Elfner

March 14th 2024, DPG Meeting, Gießen

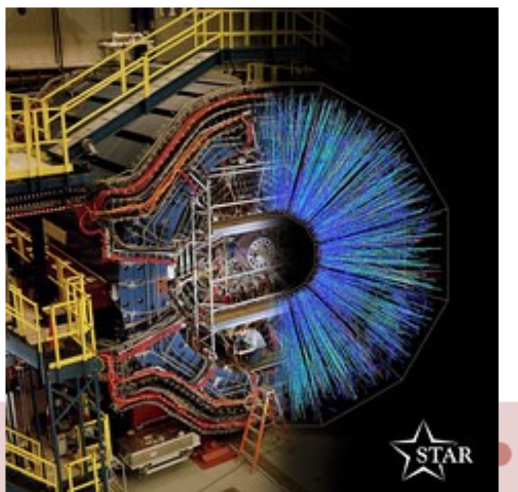
Outline

- High beam energies (LHC/RHIC+BES)
  - Anisotropic flow and transport coefficients
  - Bayesian analysis results
  - Density dependence of shear viscosity
- Low beam energies (SIS-18)
  - Equation of state of nuclear matter
  - Transport theory results
  - Momentum dependent potentials
  - SMASH vs. FOPI/HADES data
  - Flow of dileptons
- Comprehensive dynamical models are required that enable to extract properties of interest from high quality data

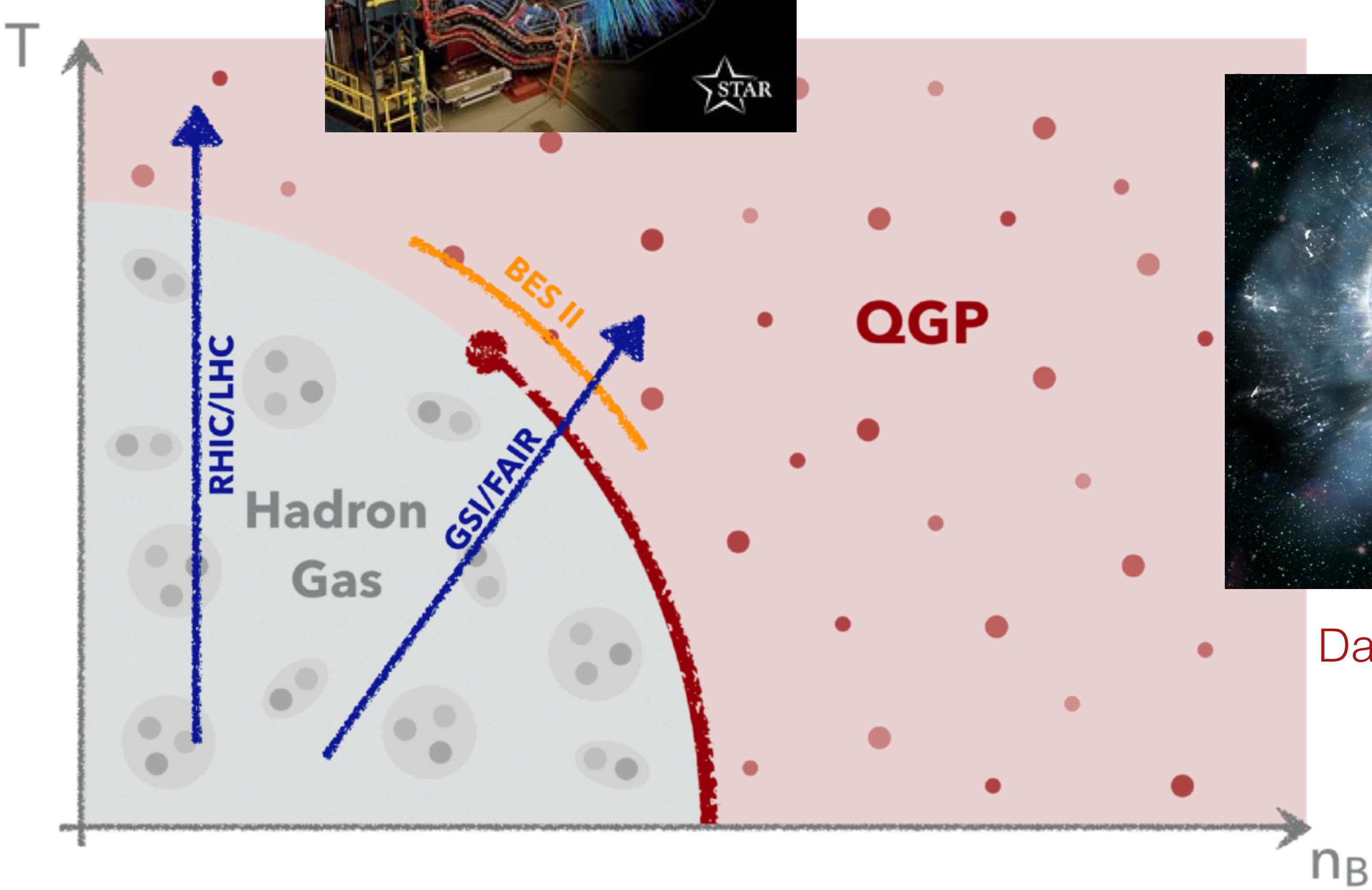
The QCD Phase Diagram

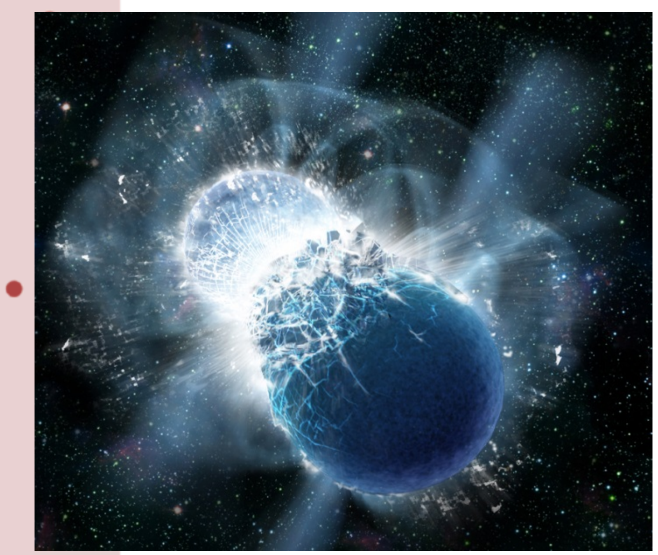
- **Main goals** of heavy-ion research:

STAR experiment at RHIC



- What are the relevant degrees of freedom at high densities?
- Phase transition, critical endpoint?
- Properties of neutron star mergers?



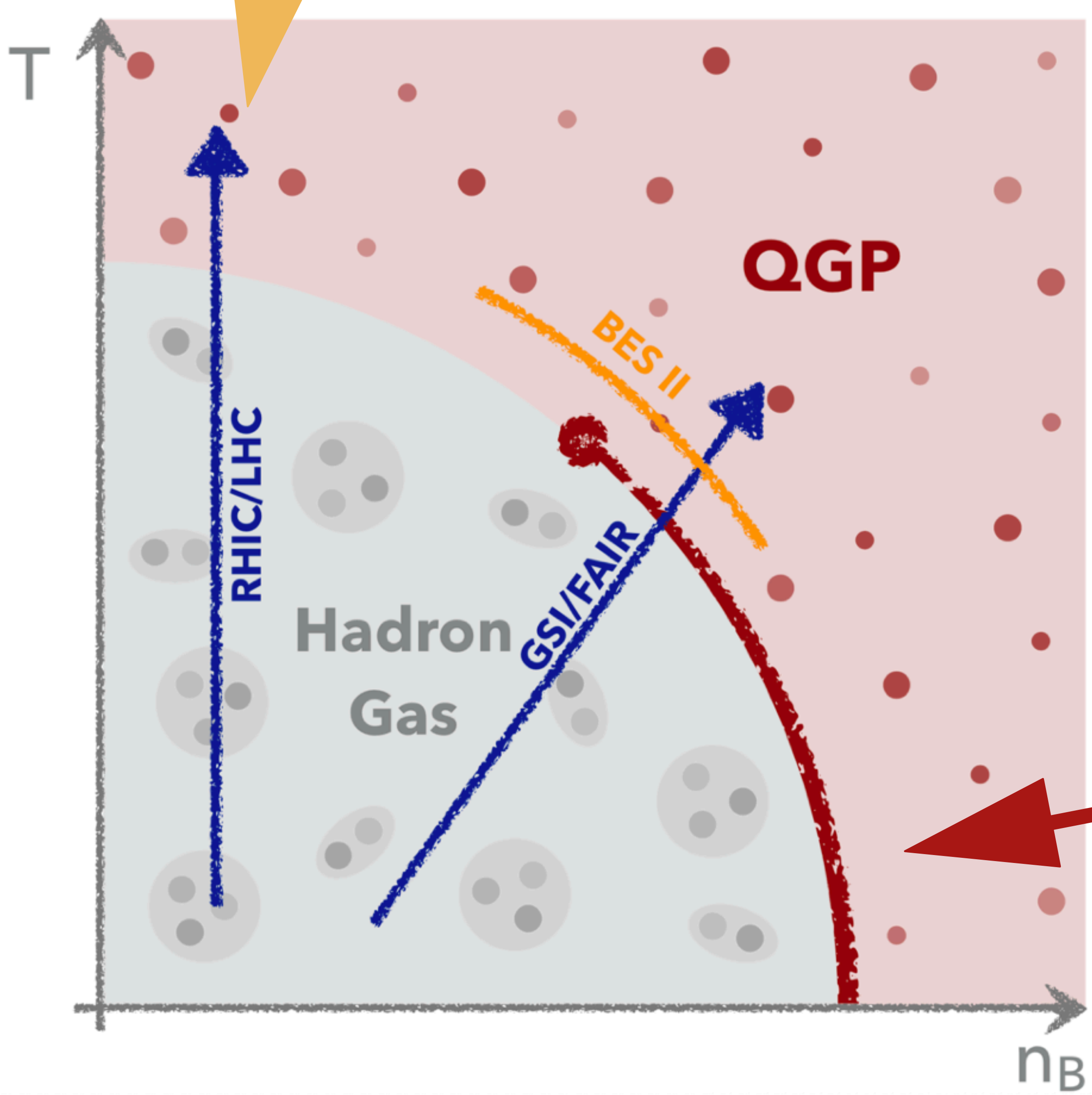


Dana Berry, SkyWorks Digital, Inc

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

The Phase Diagram

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



- Two regimes with well-established approaches
- Goals:
  - Extract the properties of the quark-gluon plasma in terms of transport coefficients
  - Constraints on the equation of state of nuclear matter

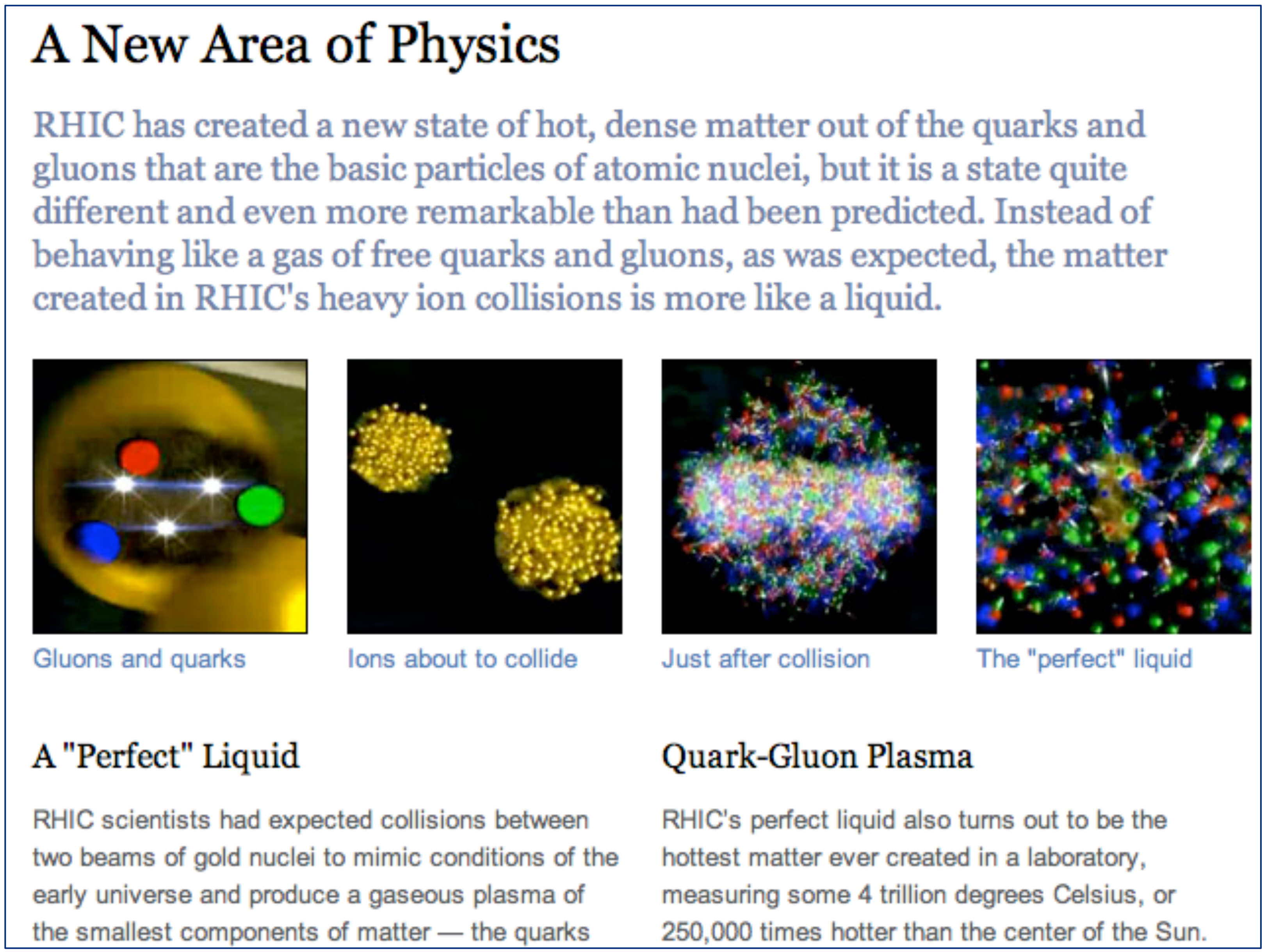
Standard approach at low beam energies
- Hadronic transport approaches
- Resonance dynamics
- Nuclear potentials

smash

Transport Coefficients of Hot and Dense QCD Matter

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.

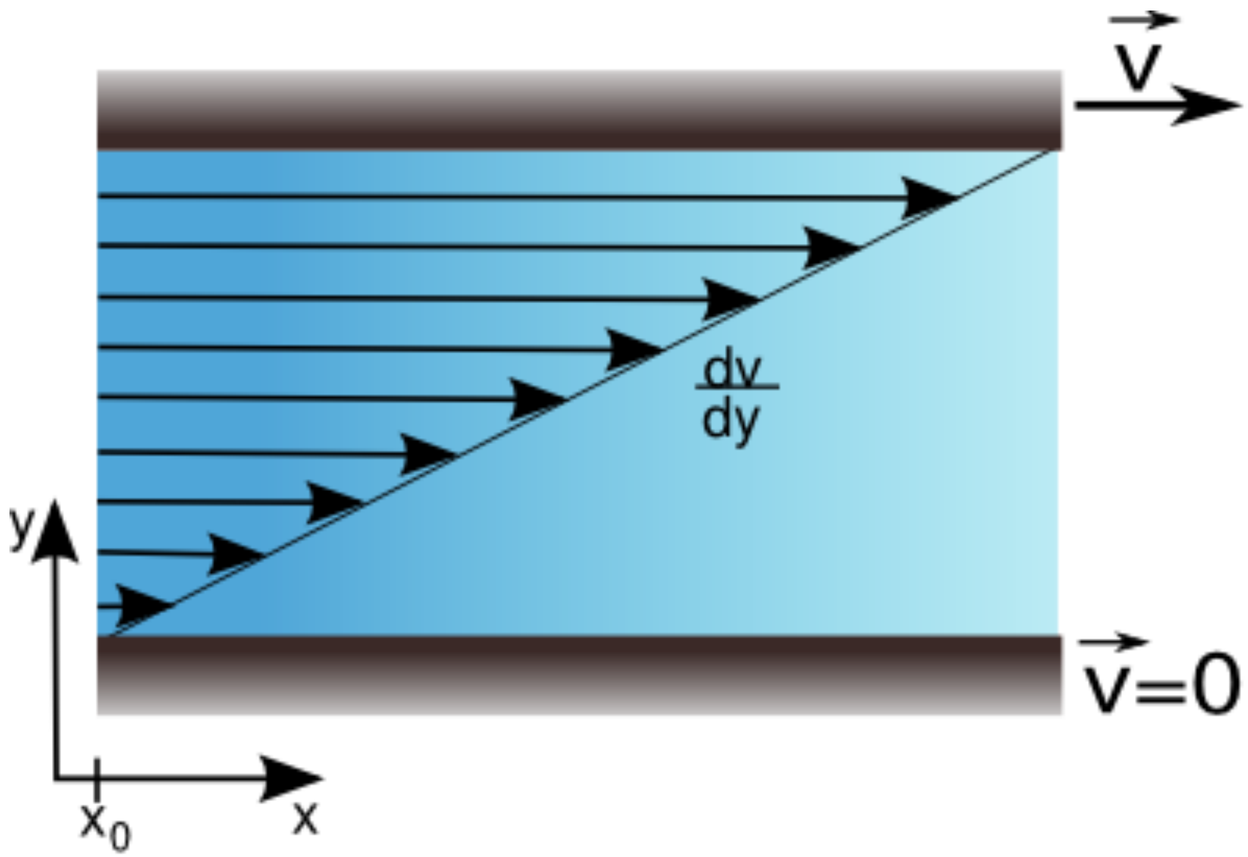
Webpage RHIC at BNL

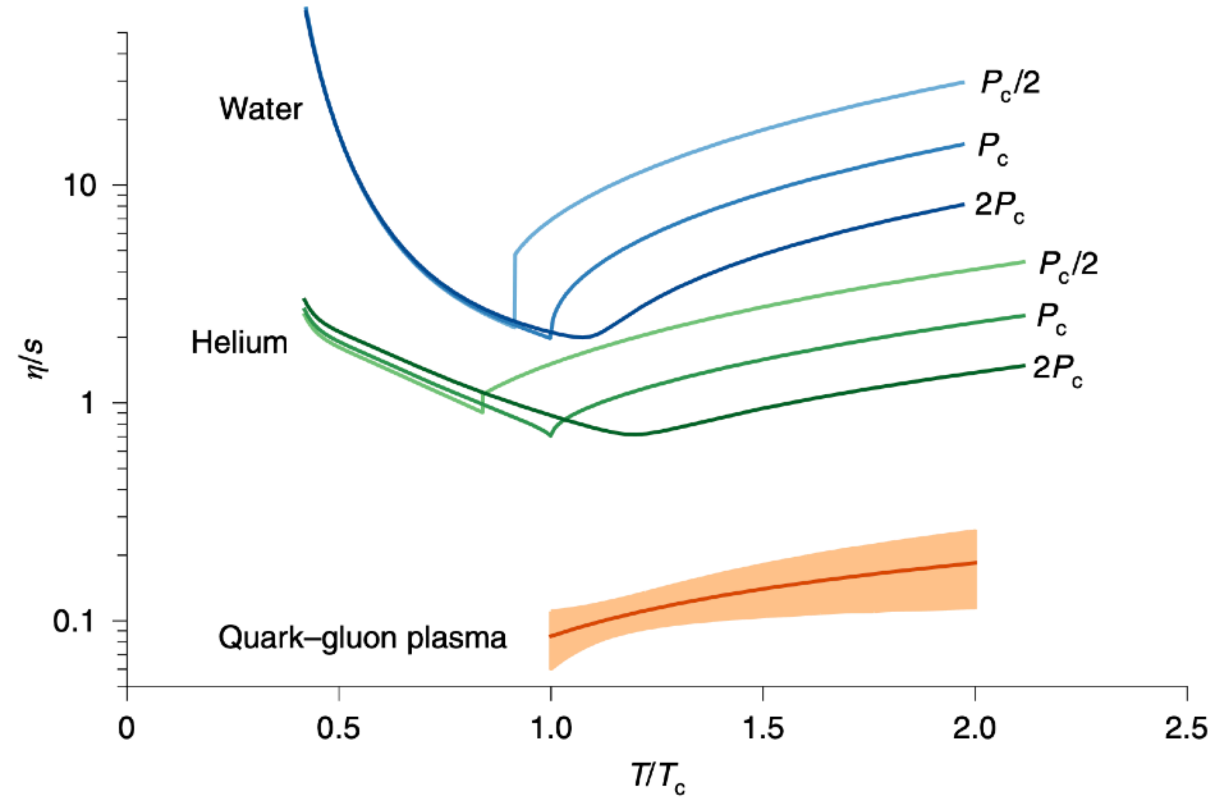
Google image search for 'perfect liquid'

Here is the heavy-ion reaction

Shear Viscosity

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





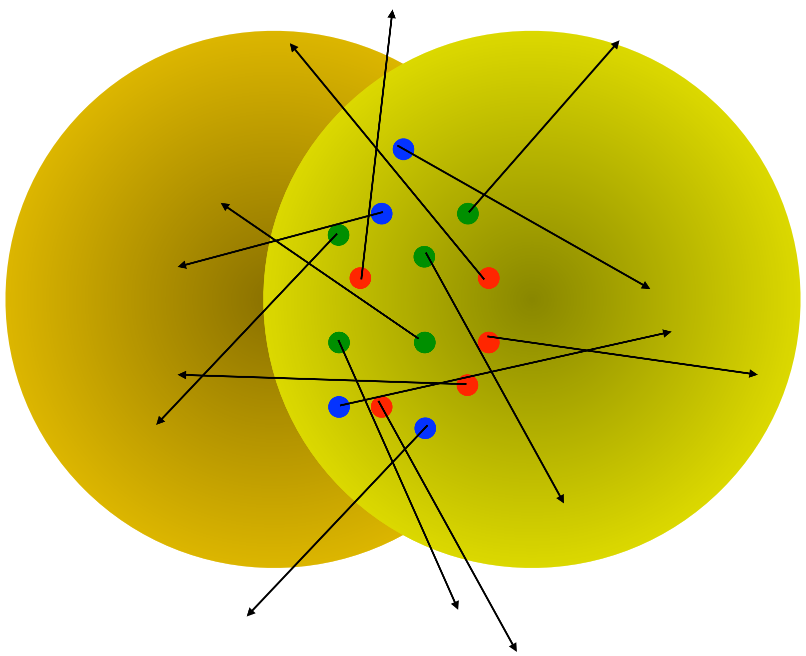
J. Bernhard et al., Nature Physics 15 (2019)

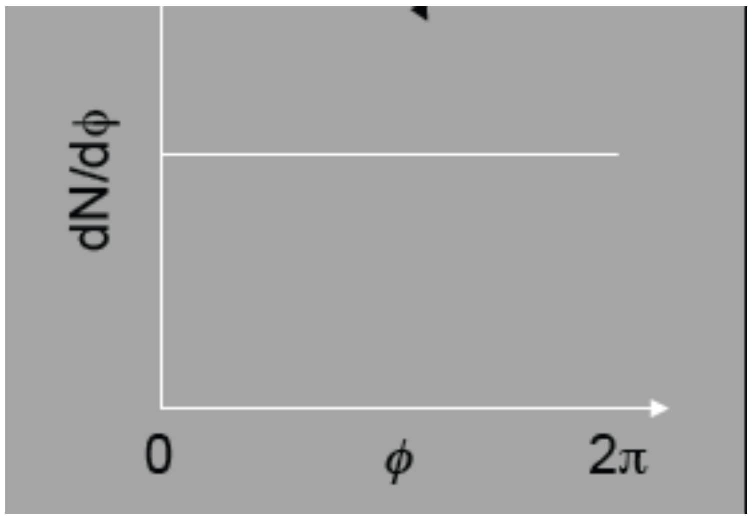
- Small viscosity → strongly coupled system
- Large viscosity → few interactions

Collective Behaviour

- Response of the system to initial spatial anisotropy

No secondary interactions
mean free path λ→∞





Spatial anisotropy

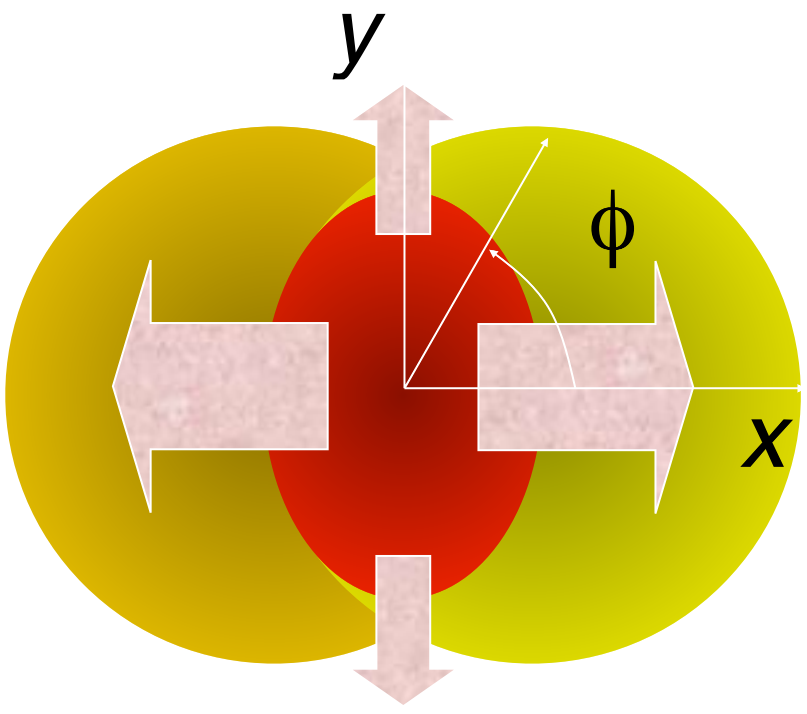
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

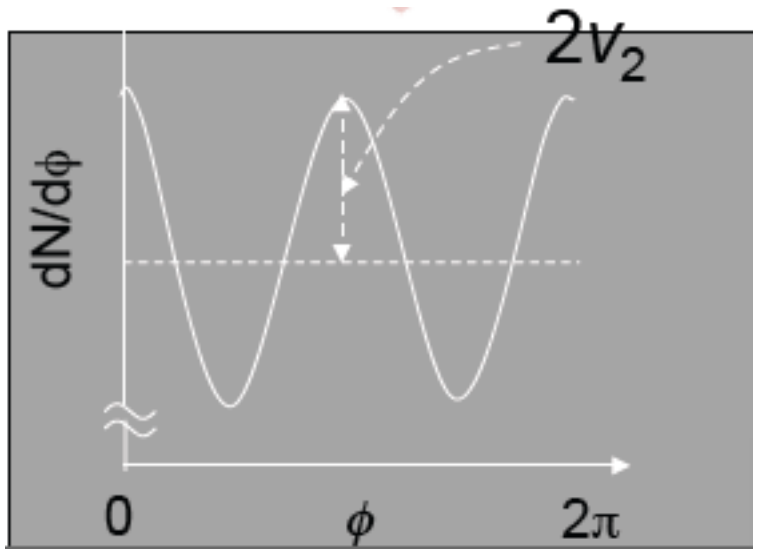
Interactions between particles

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

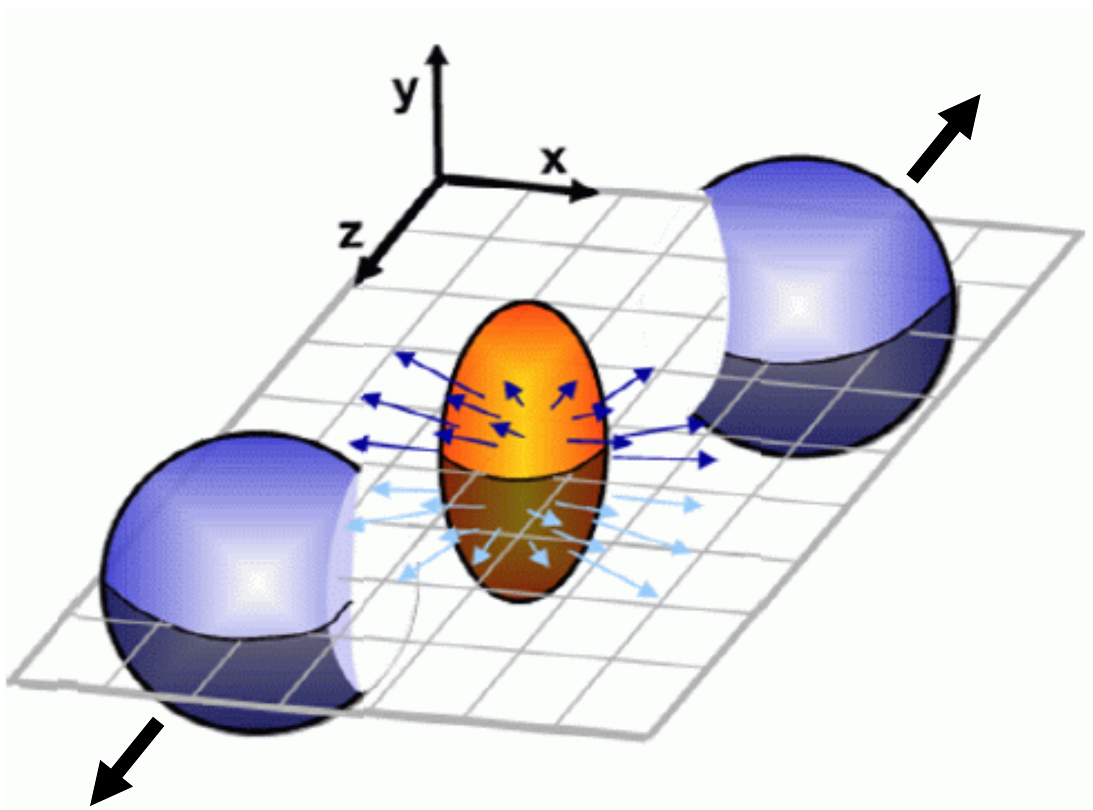


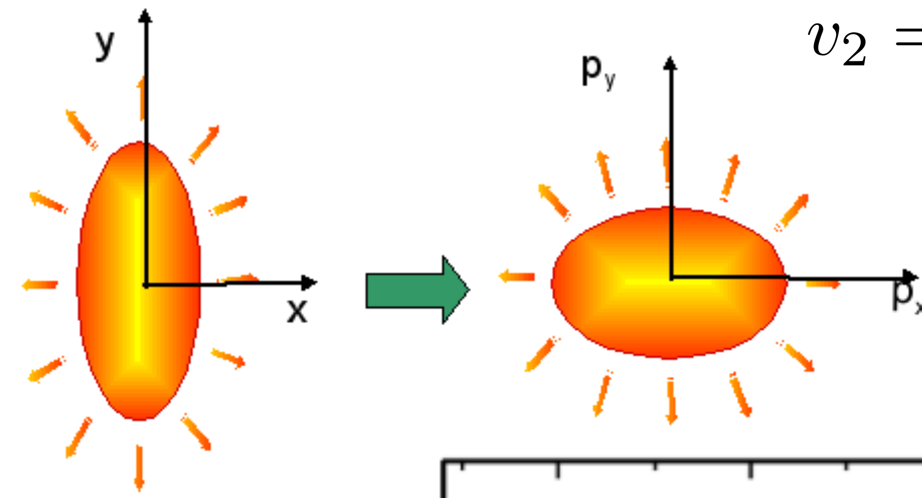


Elliptic Flow

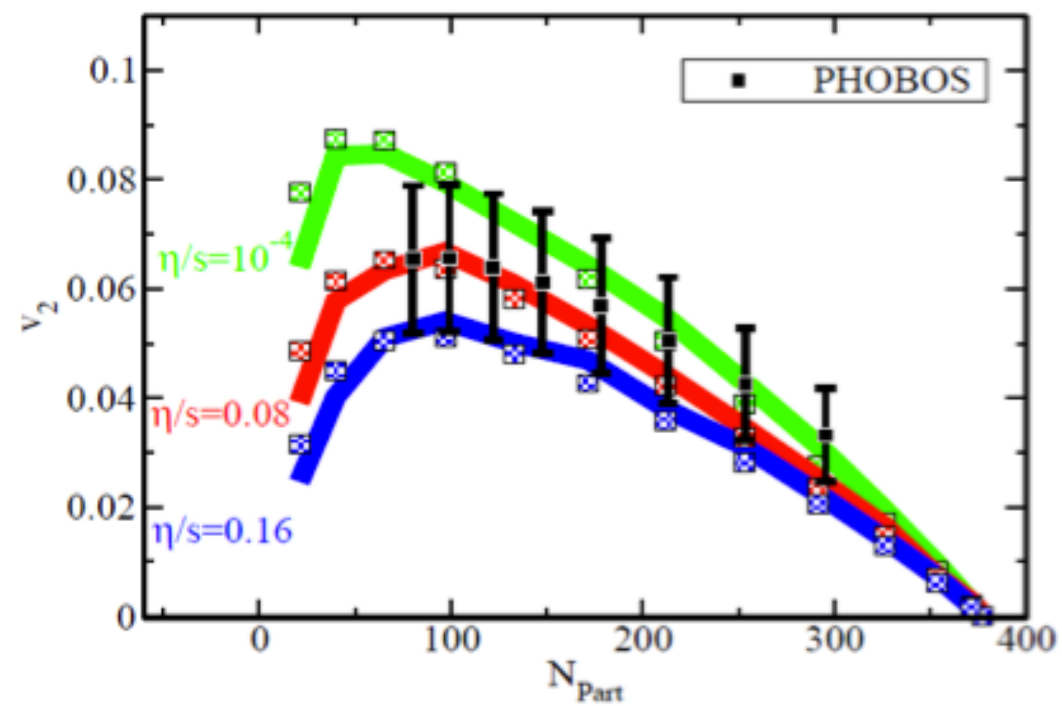
- Second coefficient of the Fourier expansion of the azimuthal particle distribution:

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





Coordinate space asymmetry
→momentum space anisotropy

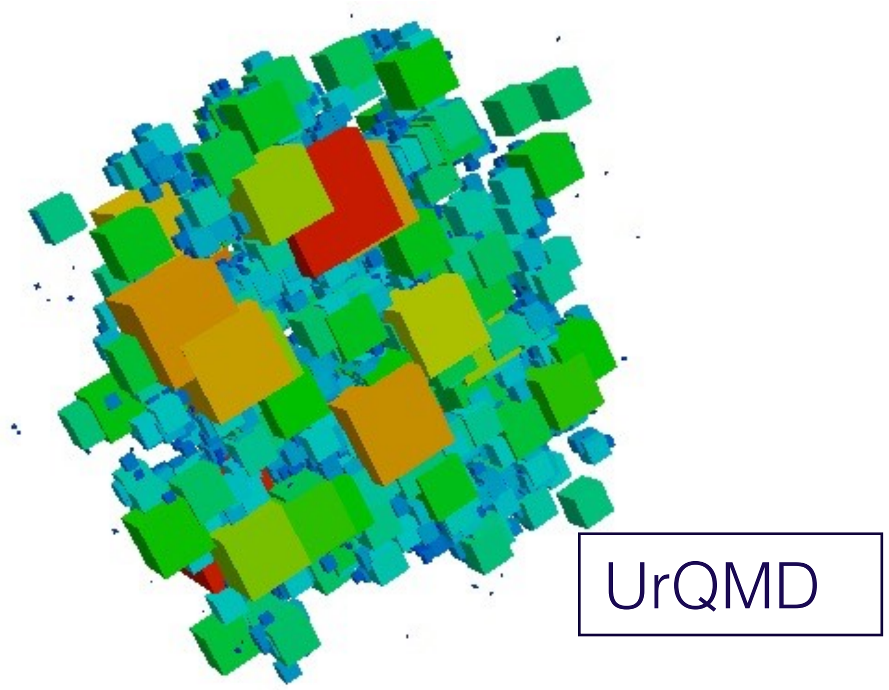


- Relativistic fluid dynamics with very low viscosity describes elliptic flow at RHIC (and LHC)

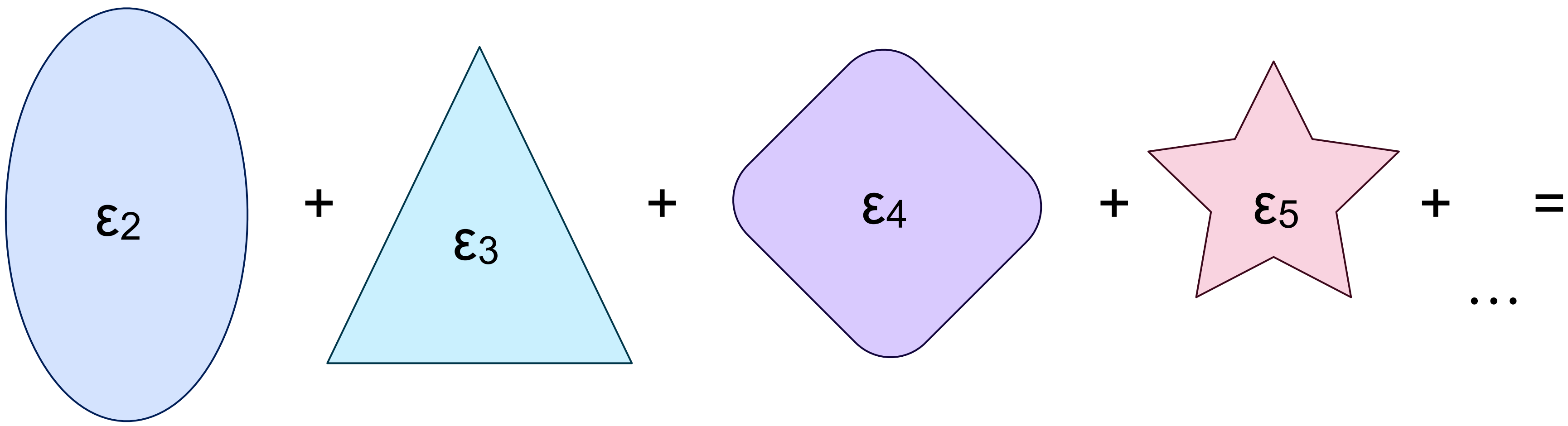
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

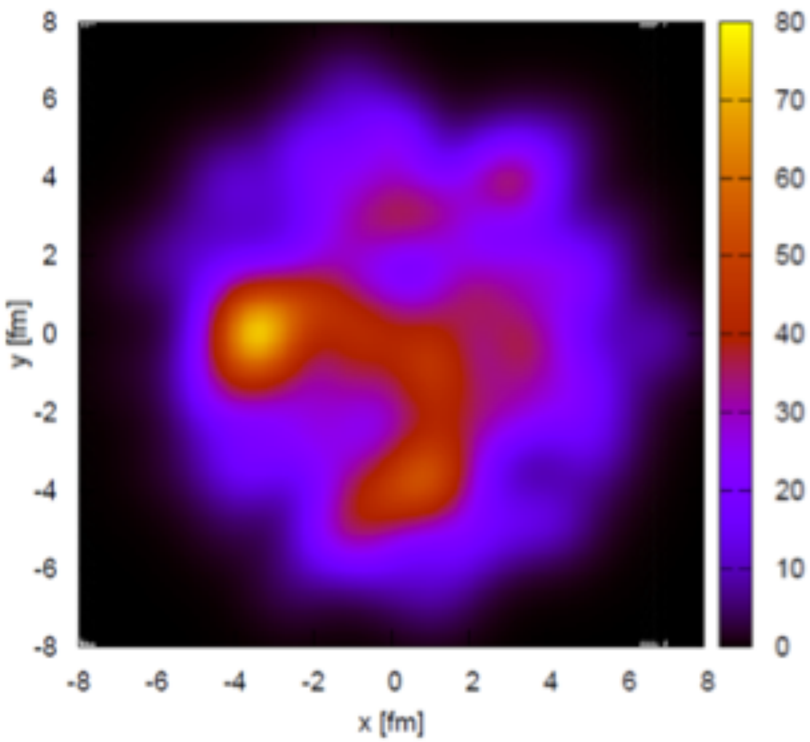
Initial State Fluctuations

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



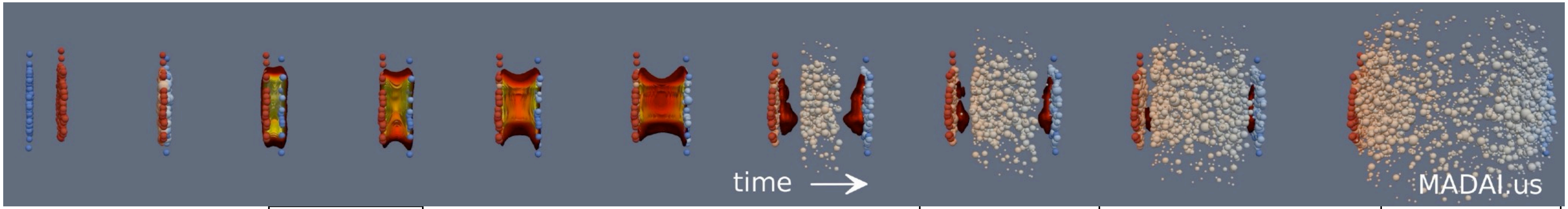
- Differences in form and fluctuations are quantified:
  – Fourier expansion in coordinate space





Time Evolution of Heavy-Ion Collisions

- Detailed dynamical modeling is essential to learn something about hot and dense QGP stage



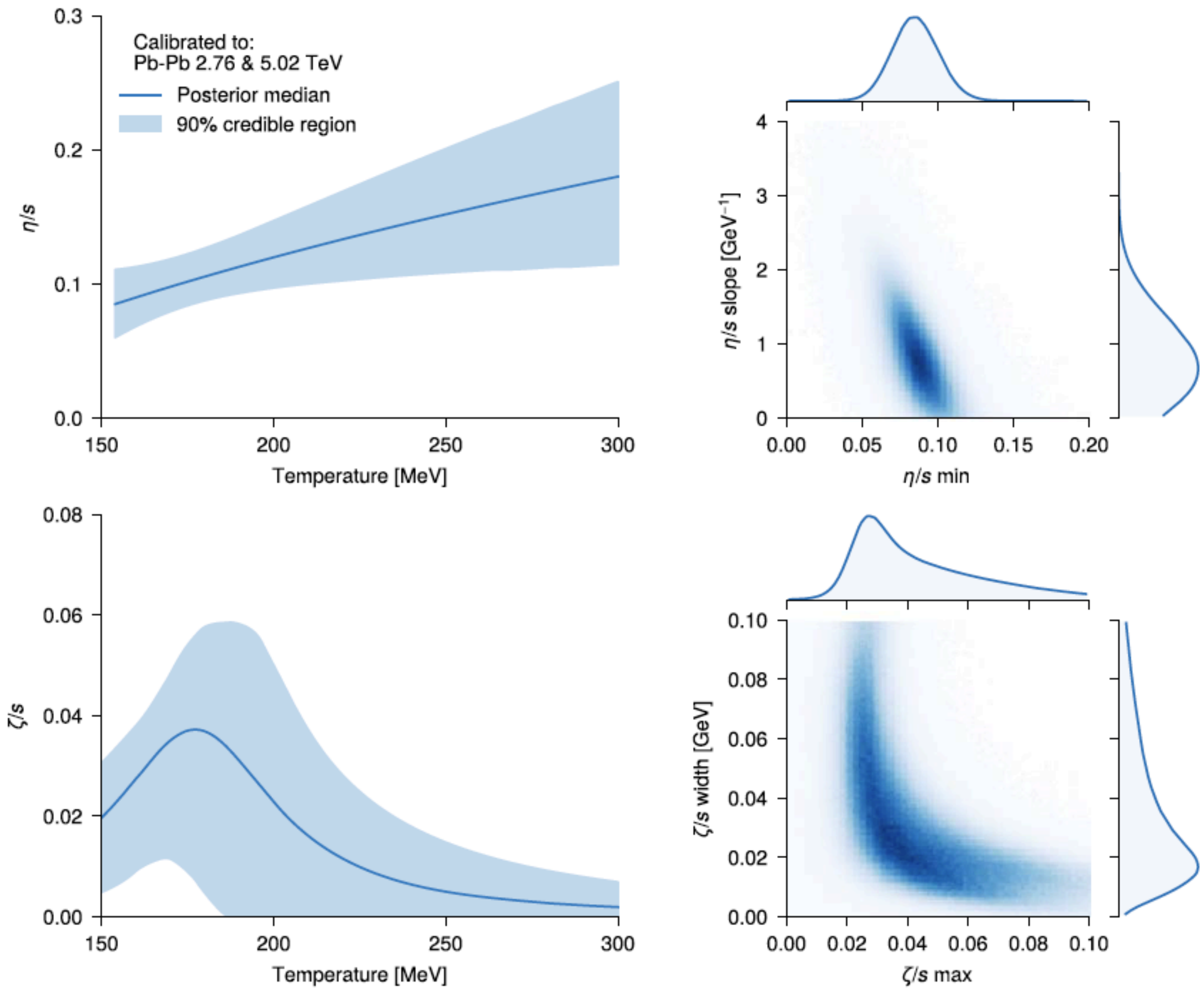
1x 10^{-23} s | 10 x 10^{-23} s | 30 x 10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

- Many parameters: initial time, smearing widths, transport coefficients, switching energy density,…
- Many observables: Yields, Spectra, Flow and their correlations
- -> Bayesian analysis

Bayesian Analysis

Analysis in a hybrid approach only based on LHC data



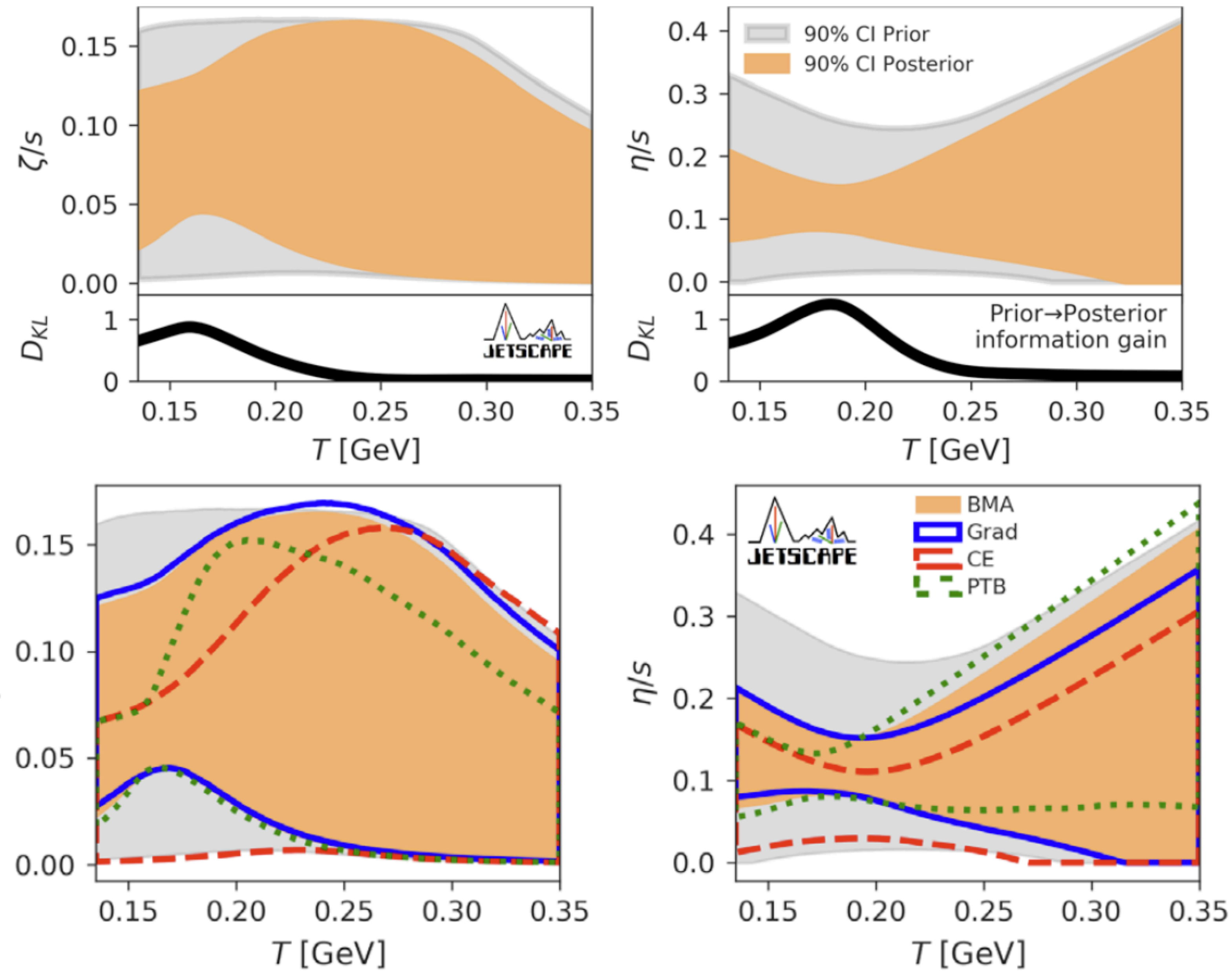
- Select model and parameters (+priors)
- Run model in parameter space according to Latin-Hypercube sampling
- Select observables
- PCA to select orthogonal components
- Construct an emulator
- MCMC to determine posterior distribution
- Tests and validation of setup
- Requires large computational resources

Pioneered by the MADAI collaboration
Results from J. Bernhard et al., Nature Phys. 15, 2019
For an introduction HE, B. Müller, JPG 50, 2023
and a review J.-F. Paquet, arXiv:

Sensitivity to Model Assumptions

JETSCAPE collaboration, PRL 126, 2021

- JETSCAPE performed a Bayesian analysis on soft bulk observables from RHIC and LHC
- Mainly sensitive to temperature region from T=150-250 MeV
- Dependence on assumptions for delta f contribution is displayed
- Other groups choose different sets of observables and different model ingredients
- Can we combine them all together?



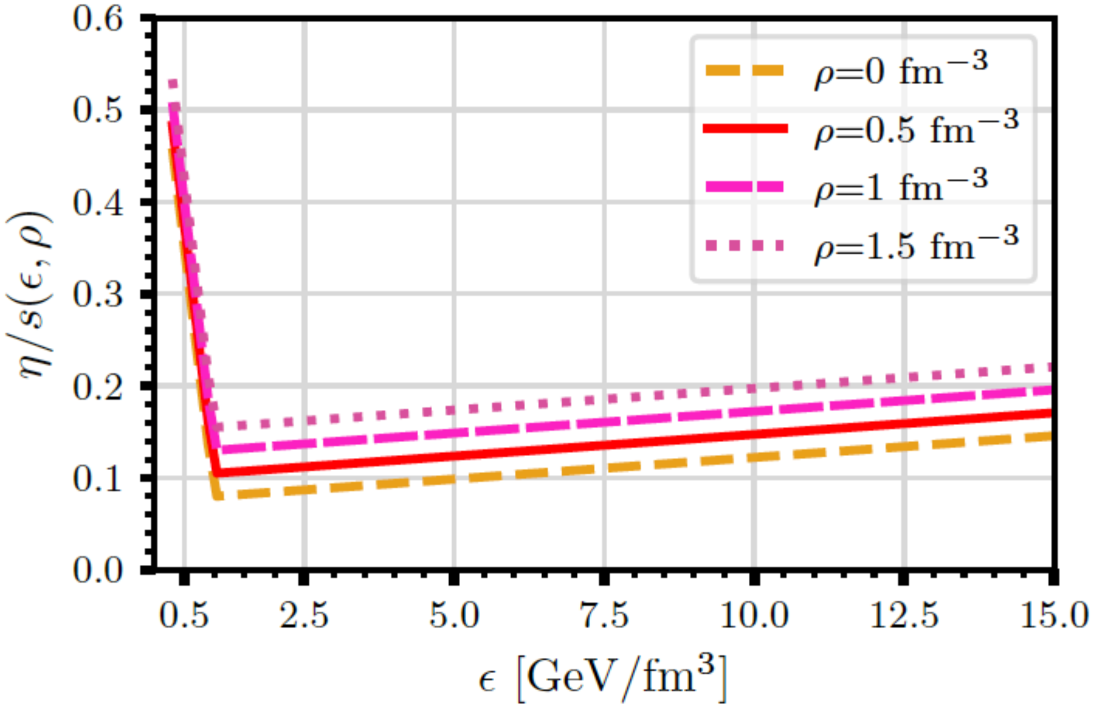
Other efforts include
J. Auvinen et al., PRC 102, 2020, different parametrizations;
TRAJECTUM, PRL 126 and PRC 103, 2021, pT dependence
J.E. Parkkila et al., PLB 835, 2022, correlations of flow observables

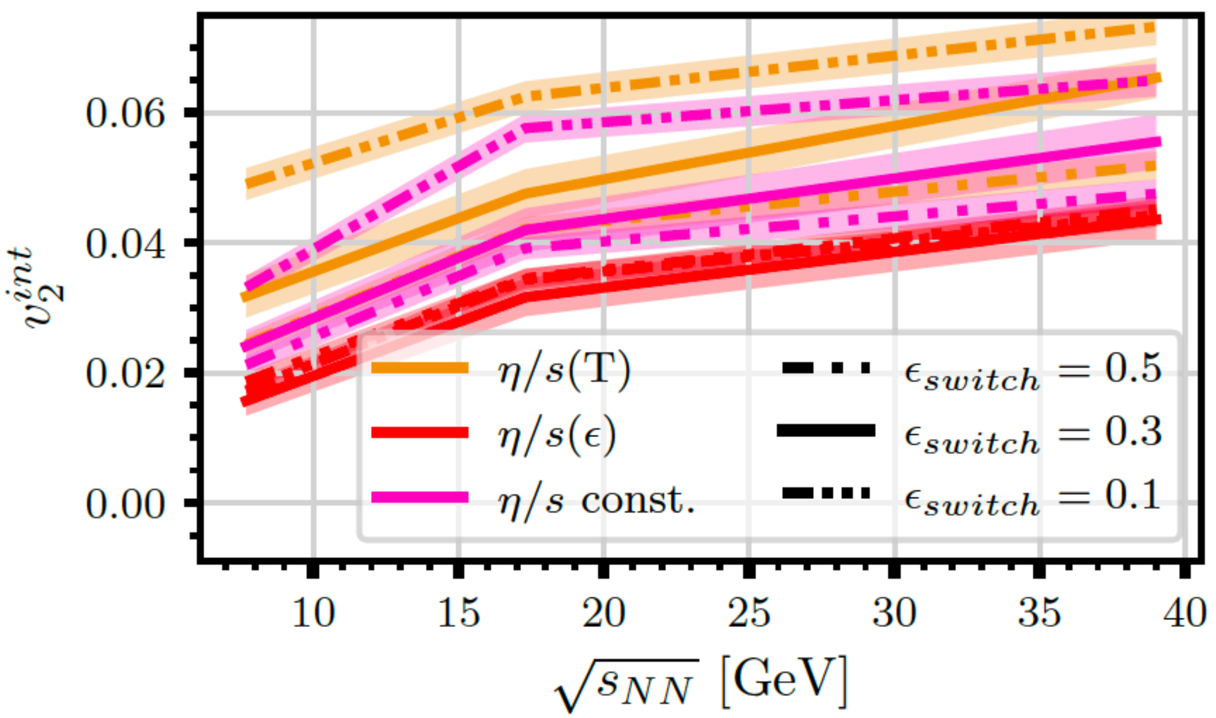
Density Dependence

- At lower beam energies the system reaches finite net baryon chemical potential

N. Götz, HE, *Phys.Rev.C* 106 (2022)

- Within the SMASH-vHLLE hybrid approach the density dependence of the shear viscosity has been explored





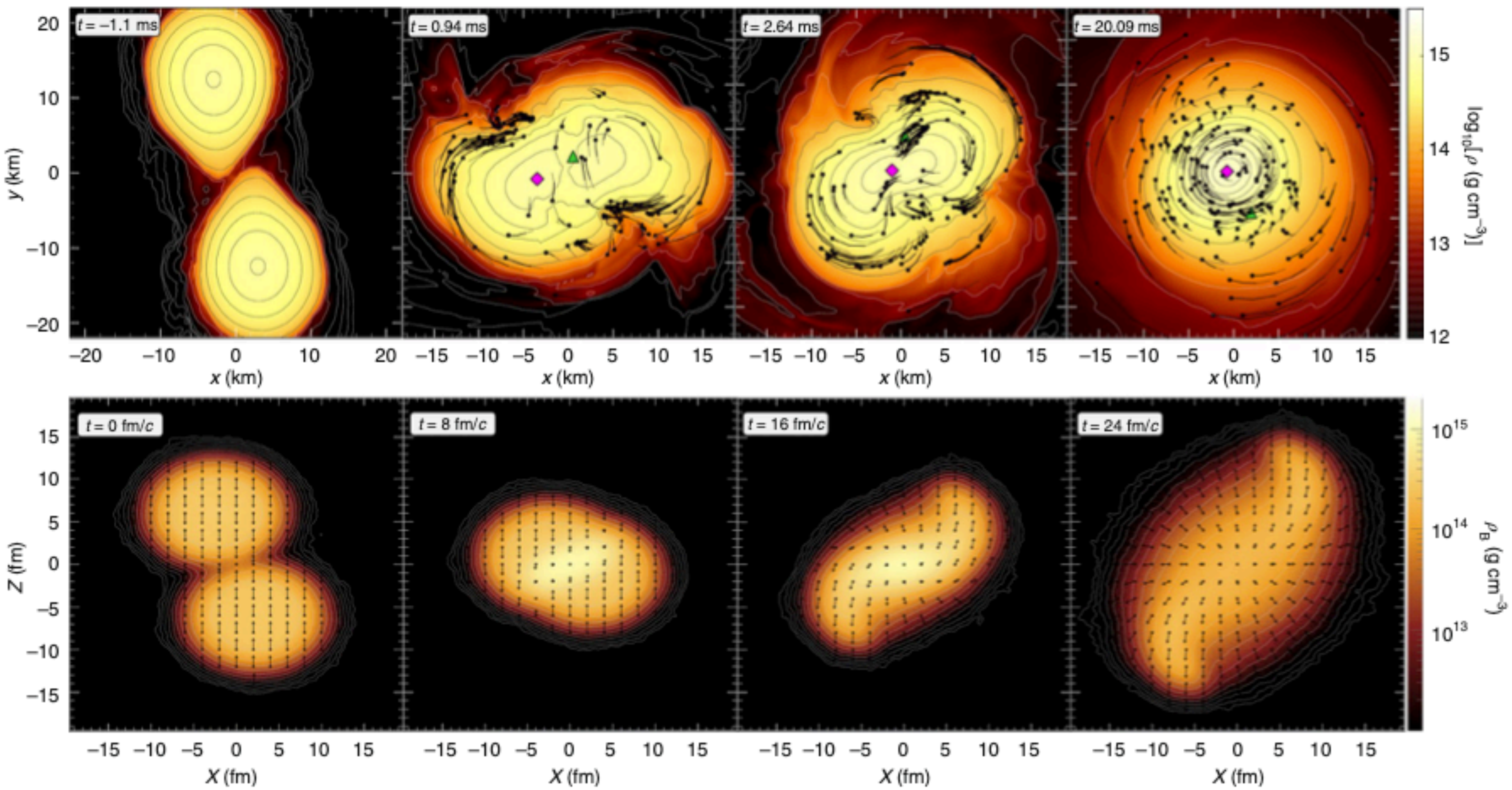
- Choosing the parametrization as a function of energy density allows for results that are independent of the switching transition between hydrodynamics and transport

https://github.com/smash-transport/smash-vhlle-hybrid

Equation of State of Nuclear Matter

Matter at Extreme Densities

- 18 orders of magnitude in scales, still similar temperature up to ~80 MeV and densities up to 2-4 times nuclear ground state density

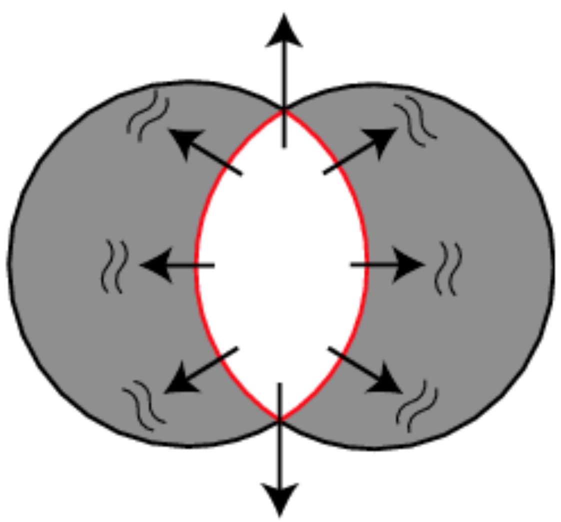


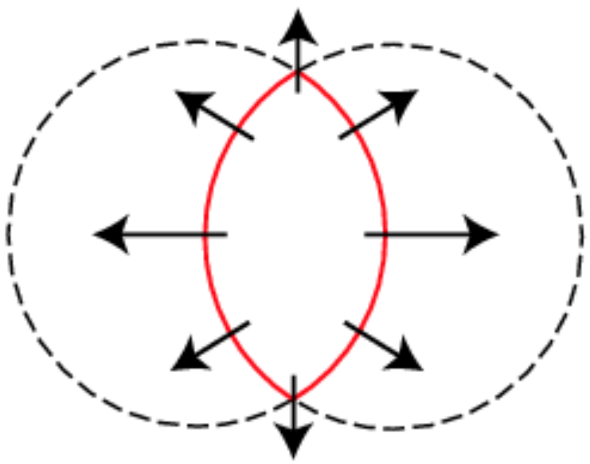
- Binary neutron star mergers: First detected events are GW170817, GW19042
- Heavy-ion collisions: Ongoing experiments: RHIC-BES, NA61, HADES, BM@N, FAIR Phase-0

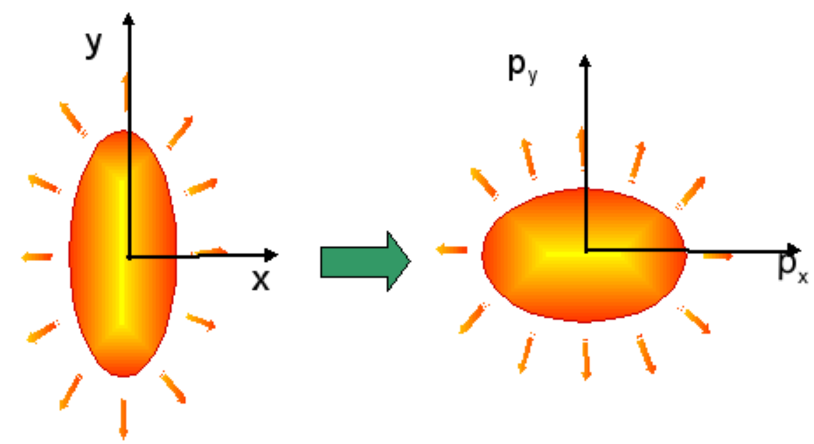
HADES collaboration, Nature Physics 15, 1040-1045 (2019)

Elliptic flow

- Two competing effects lead to different signs of v2:







Squeeze-out

$p_y^2 > p_x^2$

$\rightarrow v_2 < 0$

In-plane flow

$p_x^2 > p_y^2$

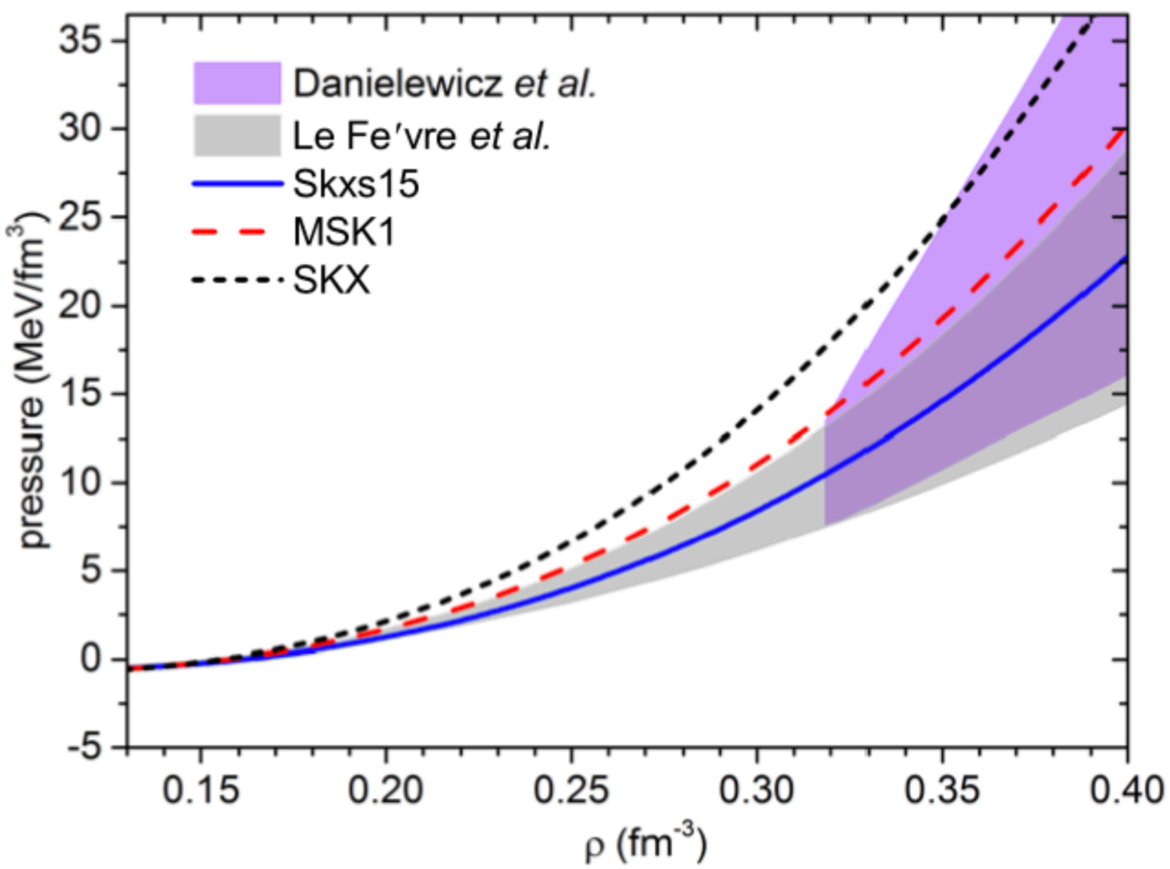
$\rightarrow v_2 > 0$

- Conversion from coordinate space to momentum space

- Sensitive to properties of the matter created in heavy-ion collisions, e.g. transport coefficients and mean fields/EoS

Nuclear Matter Equation of State

- ‚Danielewicz constraint' and newer constraints ->varying mean field parameters to fit flow observables best

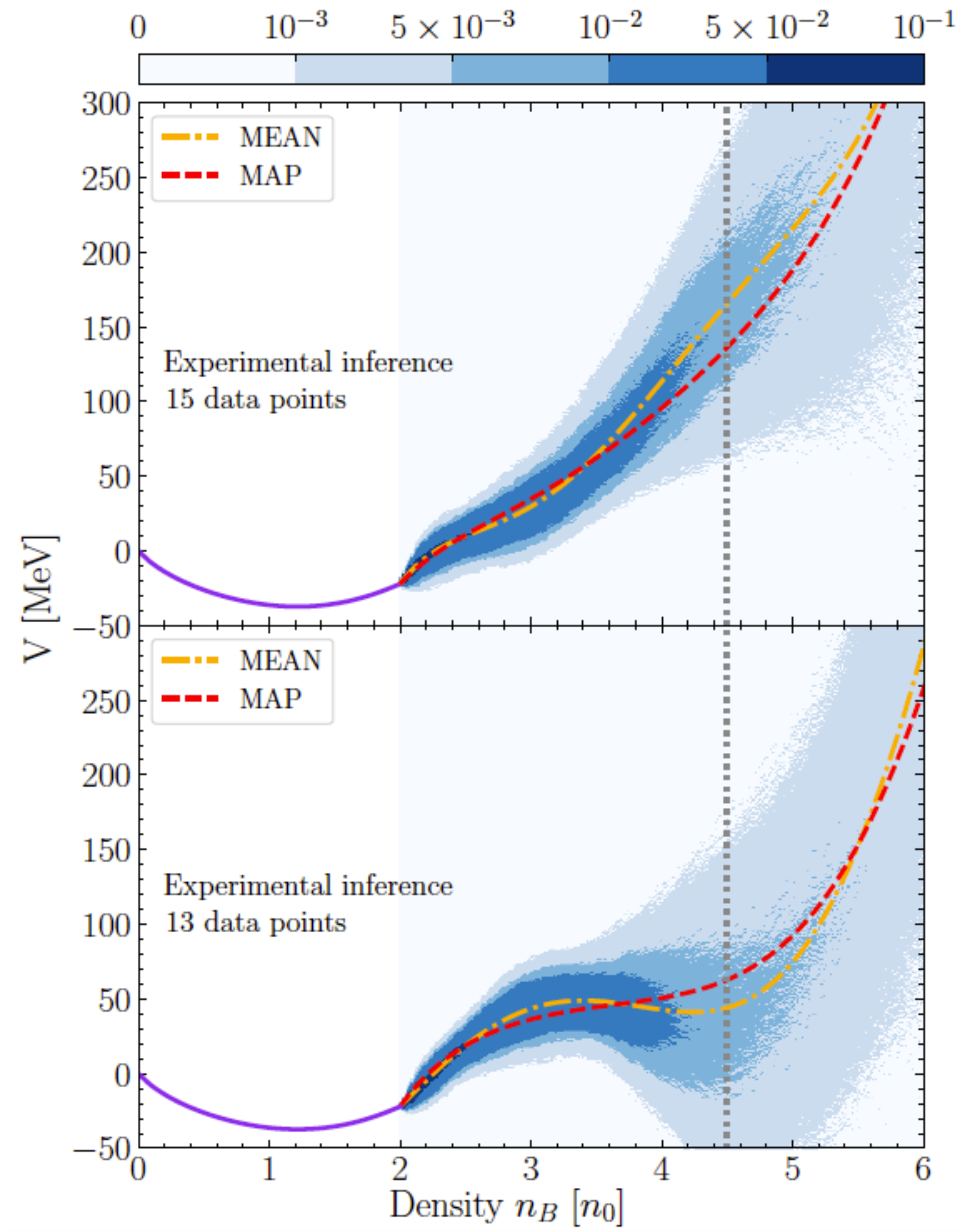


Y. Wang et al, arXiv:1804.04293
A. Hombach et al, Eur.Phys.J.A 5 (1999)
Show importance of resonances

- Open issues: Results are dependent on details of transport code and in particular mean field properties, e.g. BUU vs QMD, cluster formation, form of the potential…

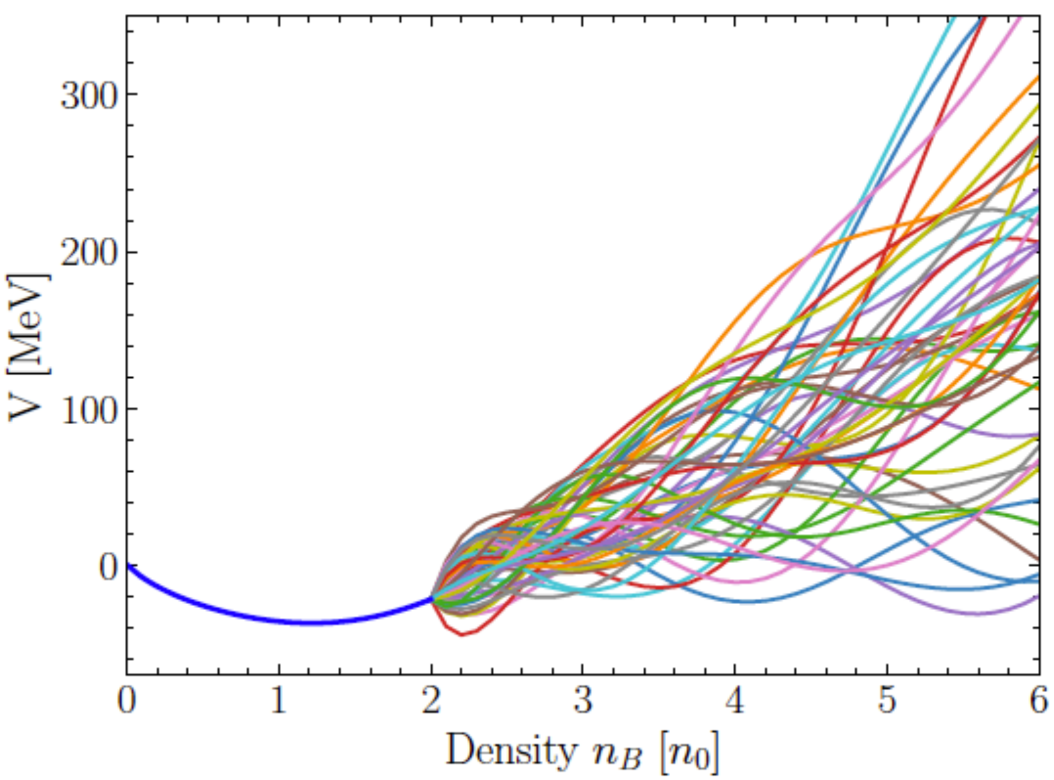
TMEP collaboration, e.g. Prog.Part.Nucl.Phys. 125 (2022)

Bayesian Constraints



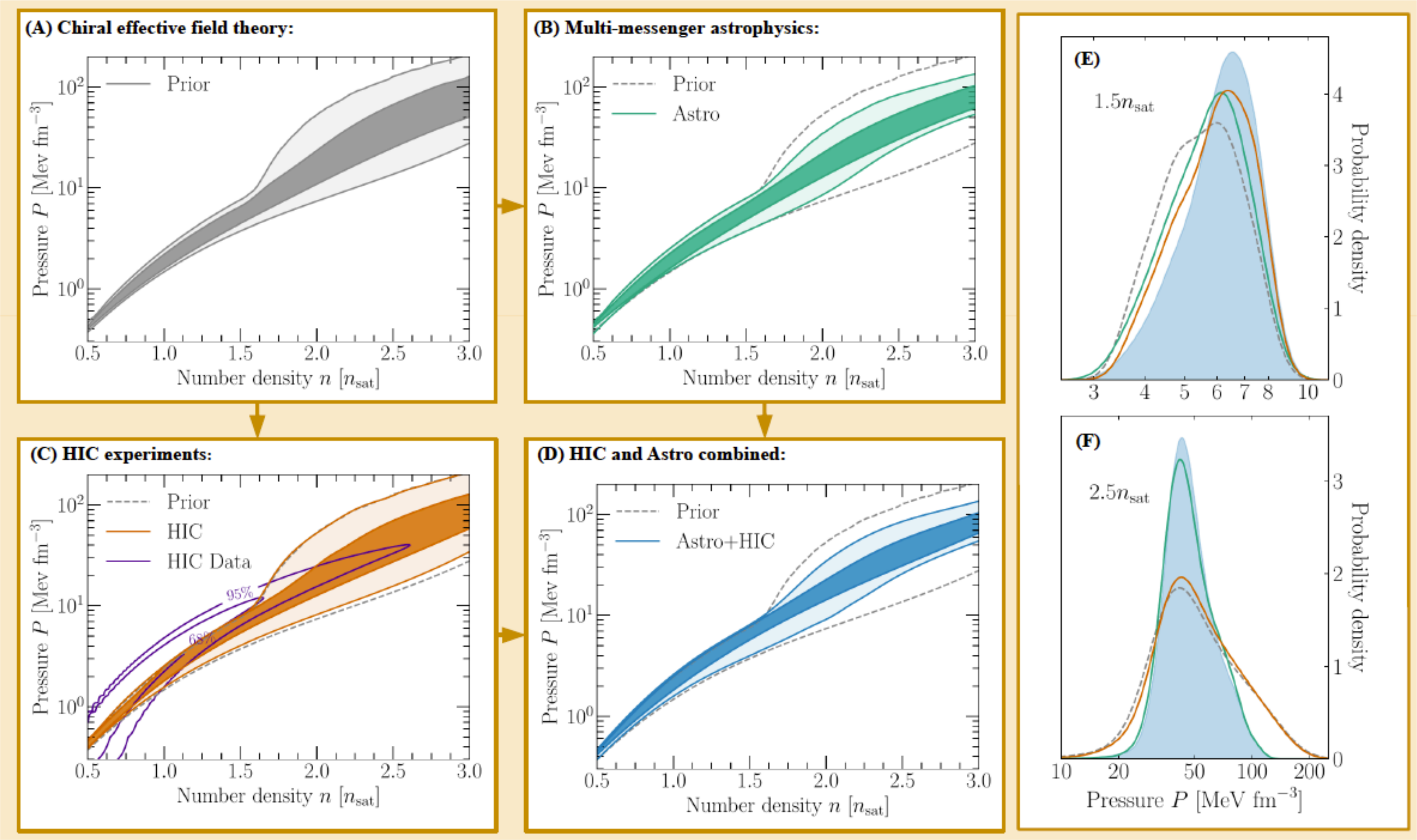
M. Omana Kuttan et al., PRL 131, 2023

- Chiral mean field in UrQMD allows to vary equation of state -> Bayesian analysis is performed and indicates dependence on which observables are used
- Mean transverse mass and elliptic flow from $\sqrt{s_{NN}}$ = 3-9 GeV



Combing with Astrophysics

- Combination of analysis of heavy-ion data and astrophysical constraints



- Dependence of results on prior based on chiral effective field theory

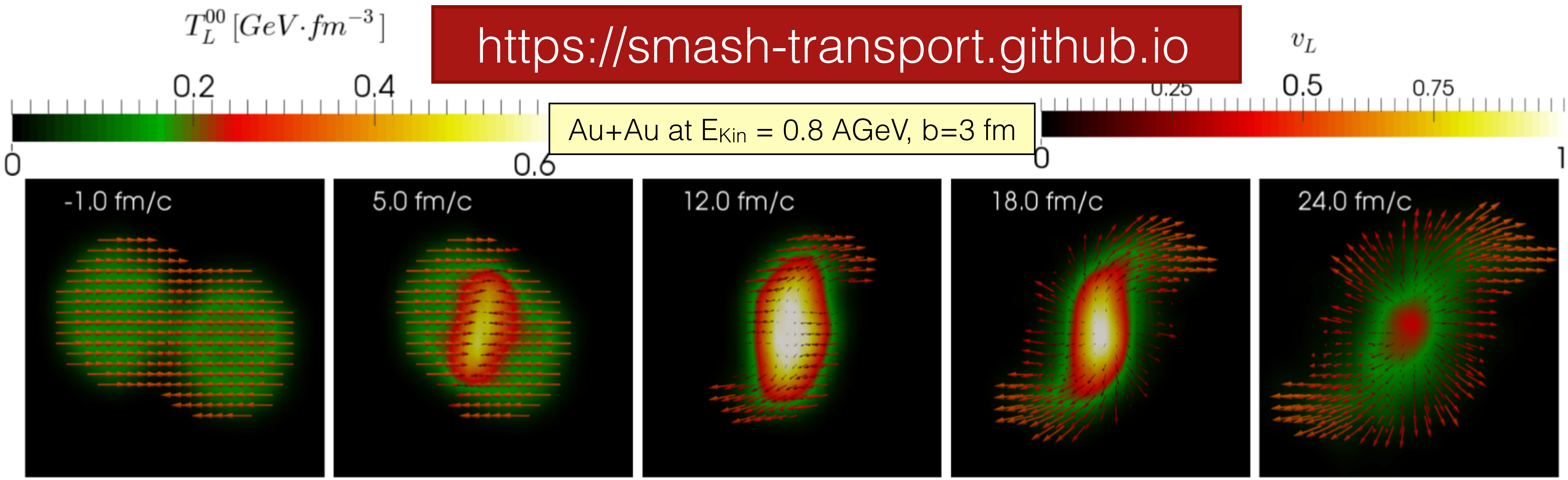
S. Huth et al., Nature 606, 2022

SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, ROOT, HepMC, RIVET
  - Used as a library by many groups for afterburner

https://smash-transport.github.io



* Simulating Many Accelerated Strongly-Interacting Hadrons

Potentials in SMASH

- Simple form of Skyrme and symmetry potential is used
- Coulomb potential can be employed as well
- Densities and their derivatives are required
- BUU method with test particles and parallel ensembles
- Densities are calculated using Gaussian smearing kernel

$$U_{\mathrm{Sk}} = A\left(\frac{\rho_B}{\rho_0}\right) + B\left(\frac{\rho_B}{\rho_0}\right)^{\tau}$$

$$U_{\mathrm{Sym}} = \pm 2S_{\mathrm{pot}}\frac{\rho_{I_3}}{\rho_0}$$

$$f(\mathbf{r},\mathbf{p}) = \frac{1}{N_{\mathrm{test}}}\sum_{i=1}^{N_{\mathrm{test}}} K(\mathbf{r}-\mathbf{r}_i)\delta(\mathbf{p}-\mathbf{p}_\mathbf{i})$$

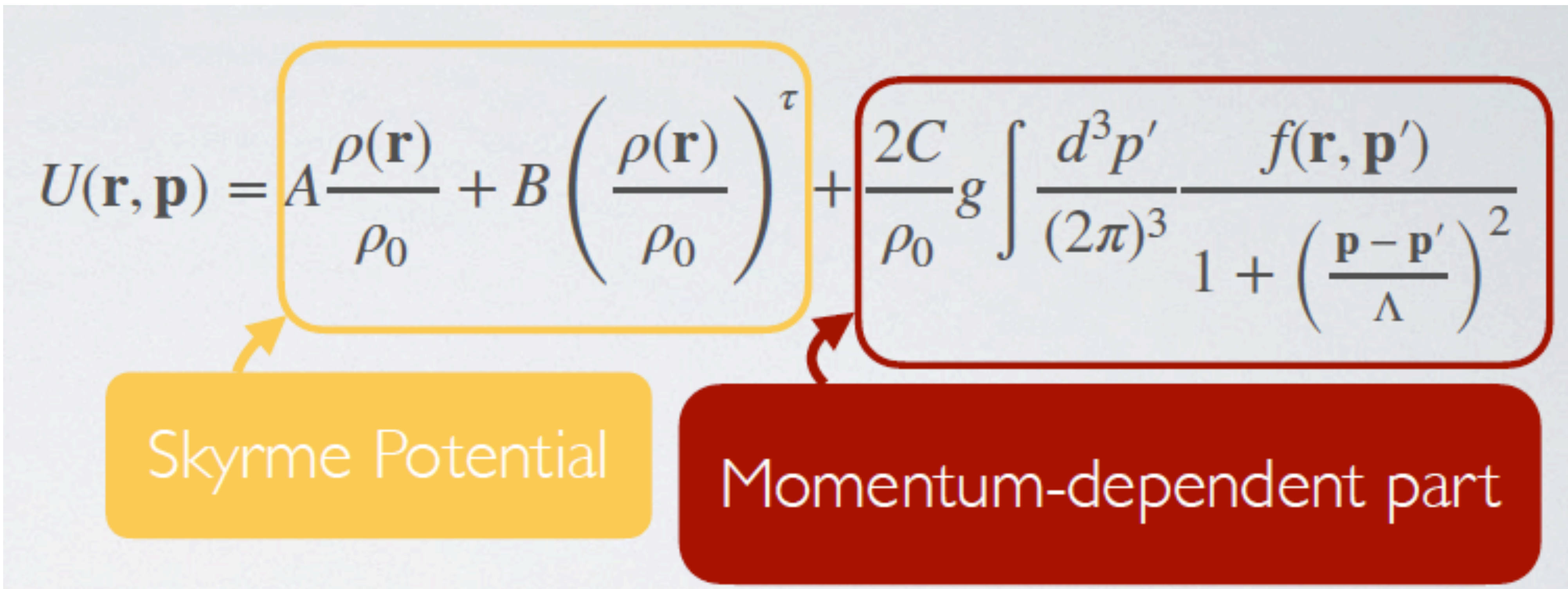
$$K(\mathbf{r}) = (2\pi\sigma^2)^{-\frac{3}{2}}\gamma\exp\left(-\frac{r^2+(\mathbf{r}\cdot\mathbf{u})^2}{2\sigma^2}\right)$$

J. Mohs at NUSYM 2023

Momentum Dependence

- Nuclear potential should include momentum dependence
- Implemented following Welke et al.

G. M. Welke et al. Phys.Rev.C 38 (1988)
Used in GiBUU: O. Buss et al. Phys.Rept. 512 (2012)



$$U(\mathbf{r},\mathbf{p}) = A\frac{\rho(\mathbf{r})}{\rho_0} + B\left(\frac{\rho(\mathbf{r})}{\rho_0}\right)^{\tau} + \frac{2C}{\rho_0} g \int \frac{d^3p'}{(2\pi)^3} \frac{f(\mathbf{r},\mathbf{p}')}{1+\left(\frac{\mathbf{p}-\mathbf{p}'}{\Lambda}\right)^2}$$

- Integral simplified by assuming cold nuclear matter

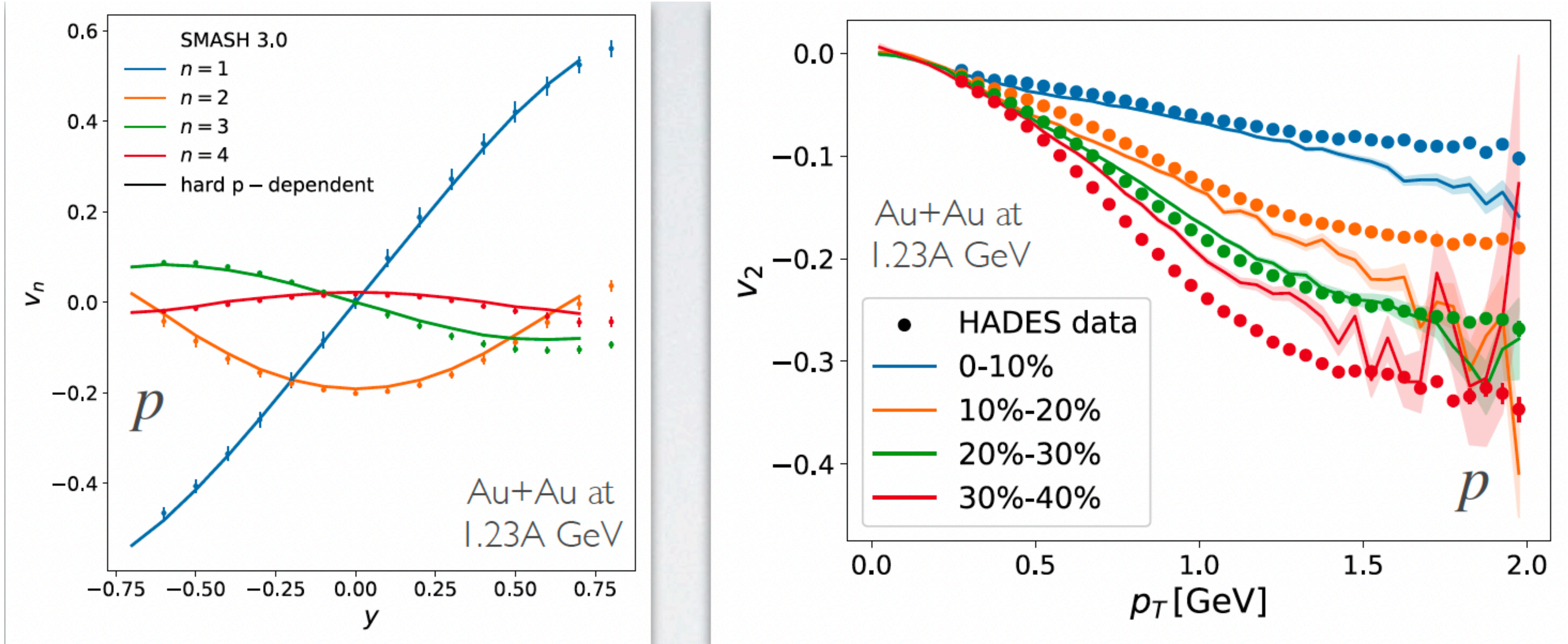
$$f(\vec{r},\vec{p}) = \Theta(p_F - p)$$

- Single particle energy evaluated in local rest frame for equation of motion $\dot{\vec{p}} = -\nabla E$

J. Mohs at NUSYM 2023

Flow Overview

- Hard momentum dependent equation of state yields good agreement with HADES data



HADES data
Phys. Rev. Lett. 125 (2020)

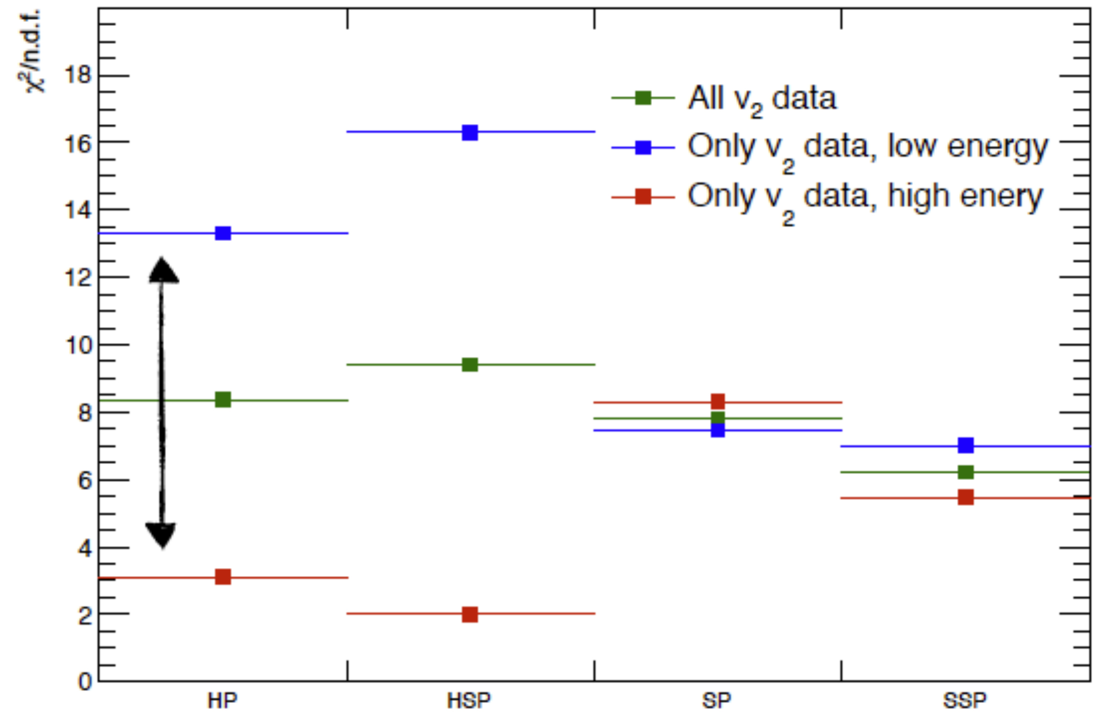
Hard momentum-dependent EOS
HADES data
Eur. Phys. J. A 59 (2023)

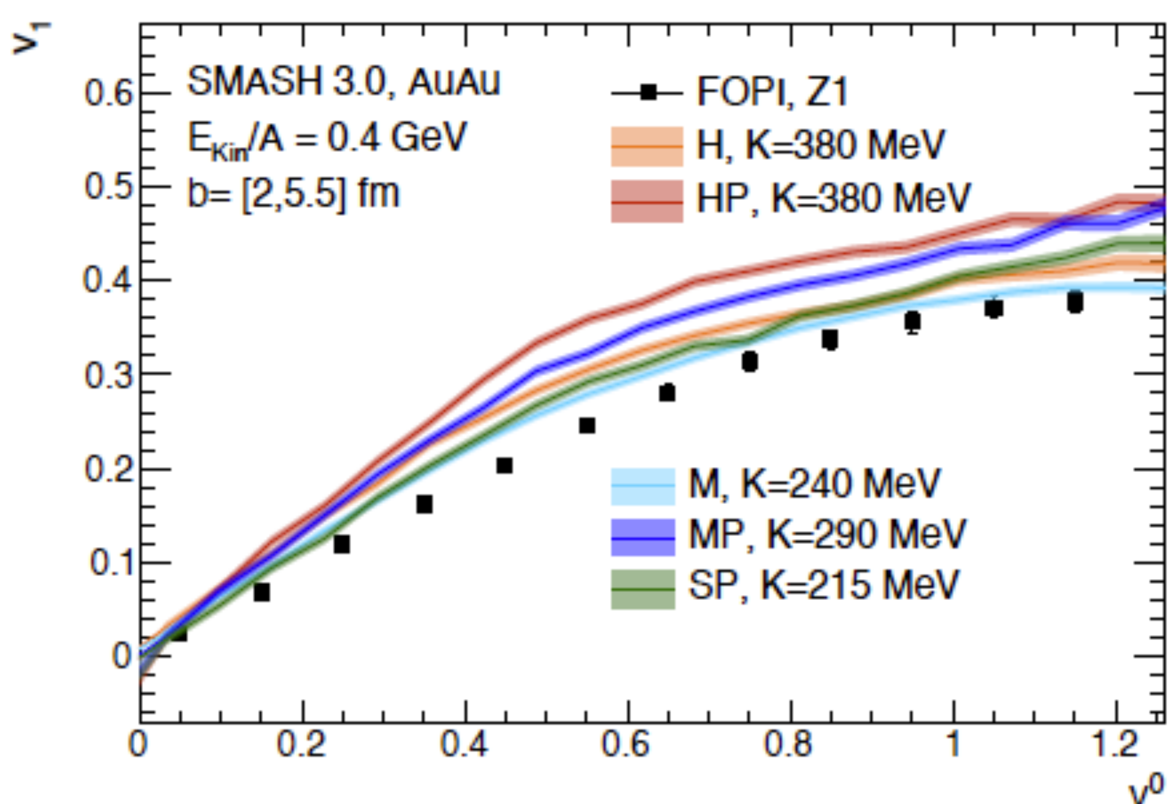
- Centrality dependence is reasonable
- Better match of centrality selection procedure is in progress

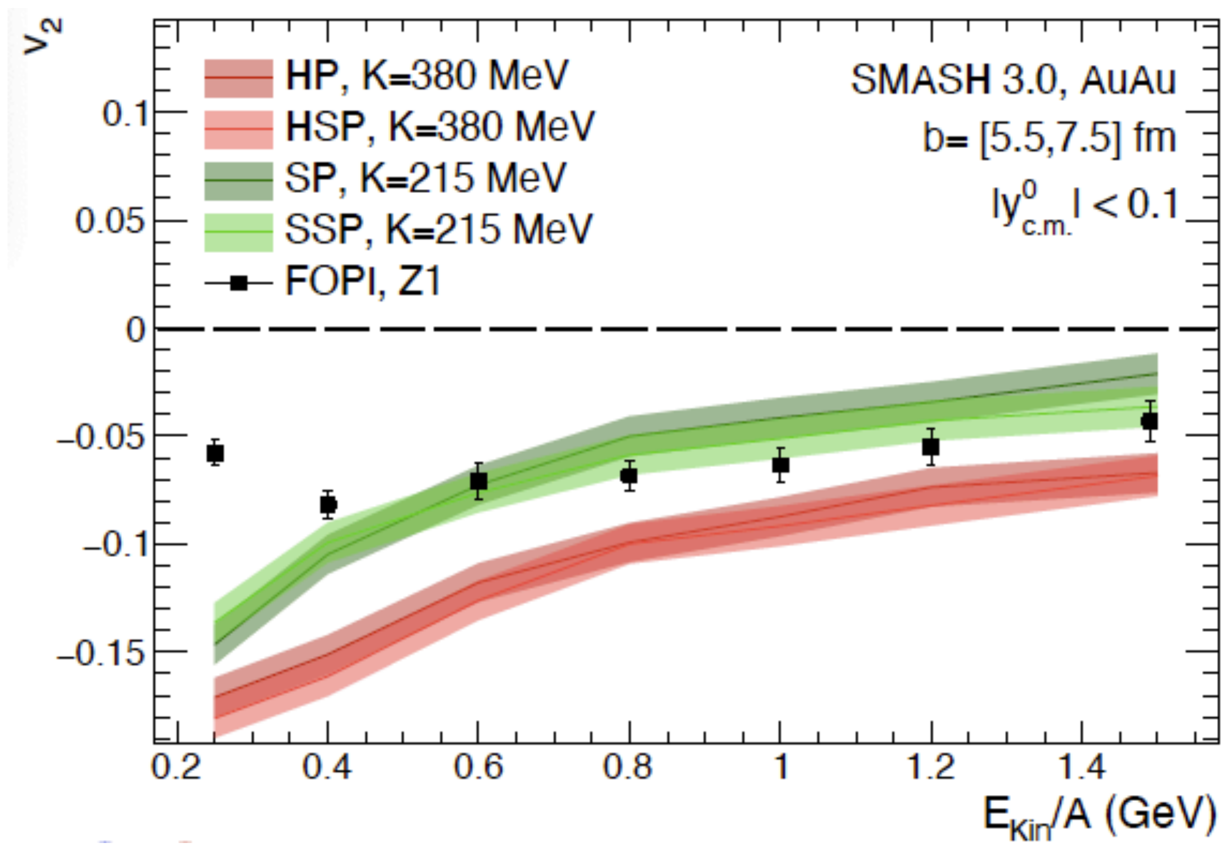
J. Mohs at NUSYM 2023

Comparison to FOPI data

- v_1 requires soft momentum dependent EoS while v_2 asks for hard momentum dependent EoS, transition as a function of energy



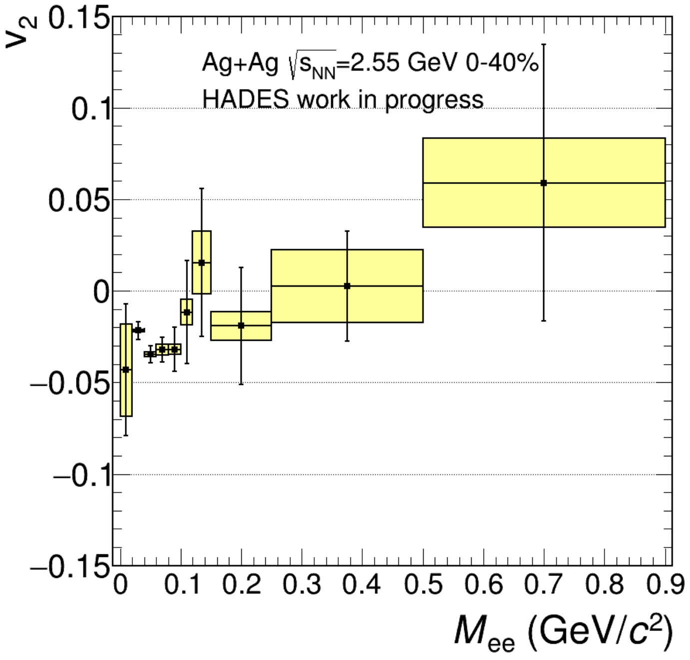


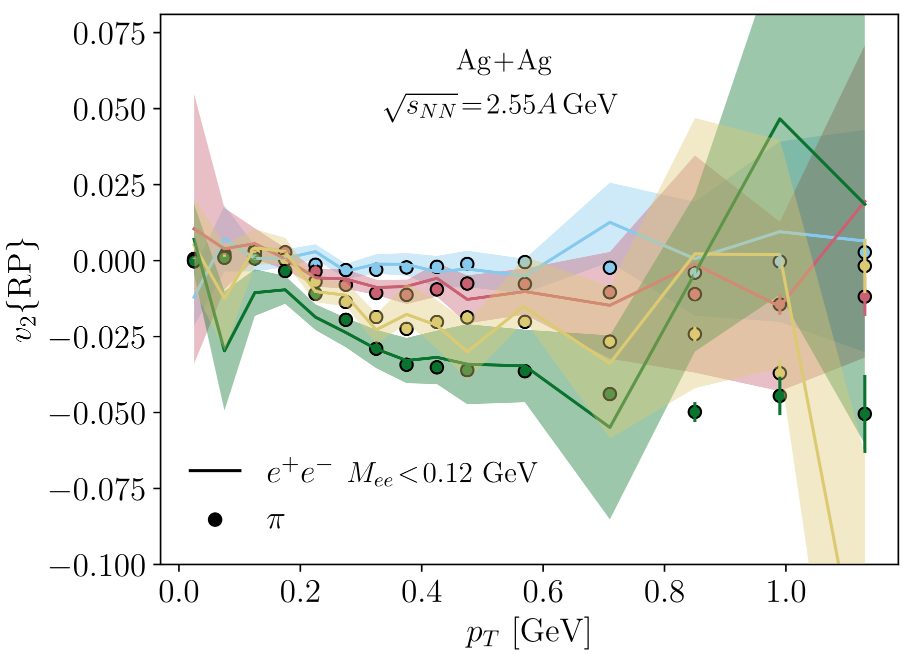


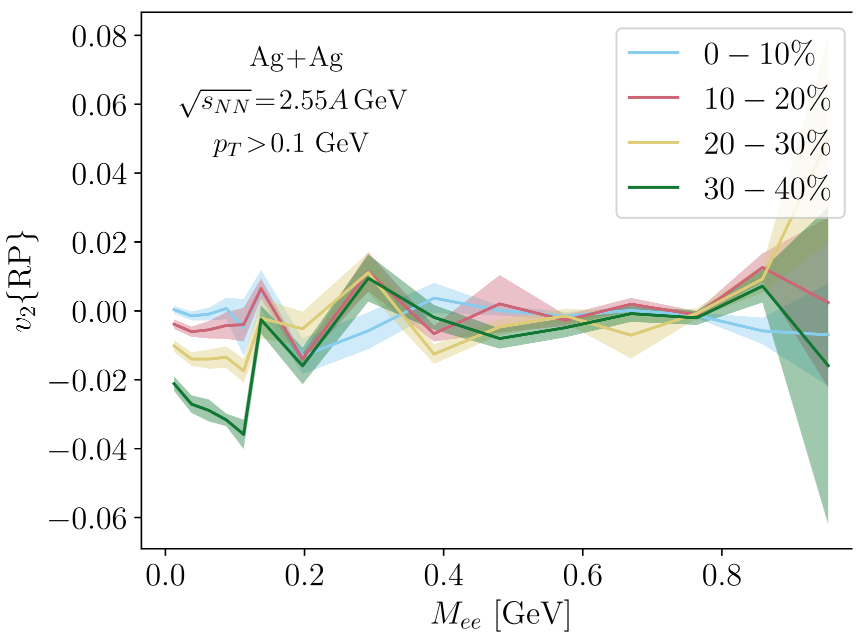
L. Tarasovic et al., in preparation, FAIR-NRW network

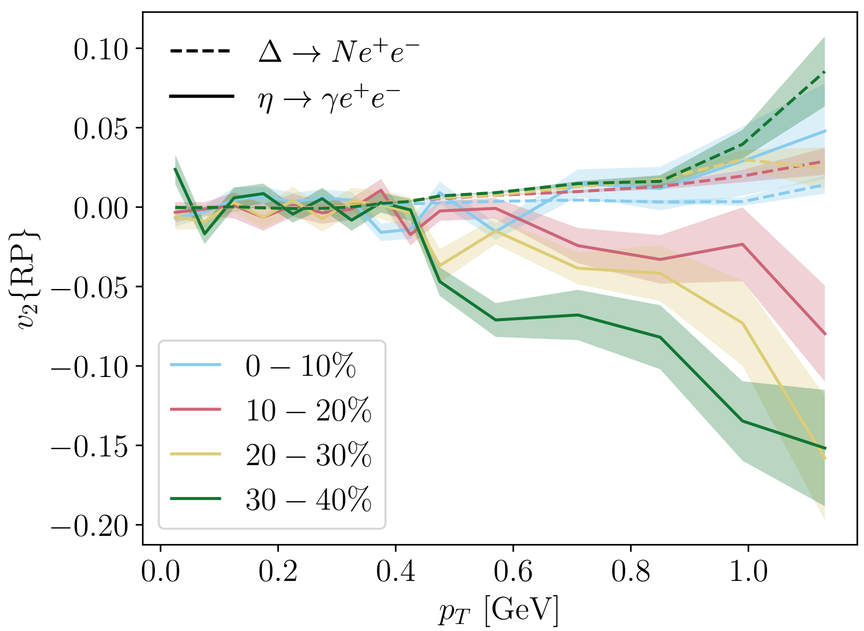
Flow of Dileptons

N. Schild, Hard Probes 2023









R. Hirayama, work in progress

- Dielectron flow for AgAg collisions at 1.76 AGeV
- SMASH calculation yields similar results as HADES data
- Different regimes as a function of invariant mass
- Employing the scalar product method allows to distinguish experimentally

$$v_2^{ll}(X) = \frac{\langle |\mathbf{q}_n^h||\mathbf{q}_n^{ll}(X)|\cos[n(\Psi_n^h - \Psi_n^{ll})]\rangle_{\text{ev}}}{\sqrt{\langle |\mathbf{q}_n^h|^2\rangle_{\text{ev}}}}$$

We can choose which hadrons to correlate with dileptons

Summary

- Collective flow is one of the most important observables in heavy-ion physics
  - At high beam energies:
    - Access to temperature (and density) dependence of transport coefficients
    - Convergence of multiple Bayesian analysis needed
  - At low beam energies:
    - Extraction of equation of state of nuclear matter at densities relevant for neutron star mergers
    - More quantitative statements require more sophisticated statistical analysis
- Detailed systematic measurements combined with theoretical dynamical approaches will lead to very interesting results in the future

The SMASH Team

- In Frankfurt:
  - Alessandro Sciarra
  - Justin Mohs
  - Niklas Götz
  - Renan Hirayama
  - Nils Saß
  - Carl Rosenkvist
  - Antonio Bozic
  - Lucas Constantin
  - Timo Füle
  - Martha Ege
  - Robin Sattler
  - Olivia Kolavandelu

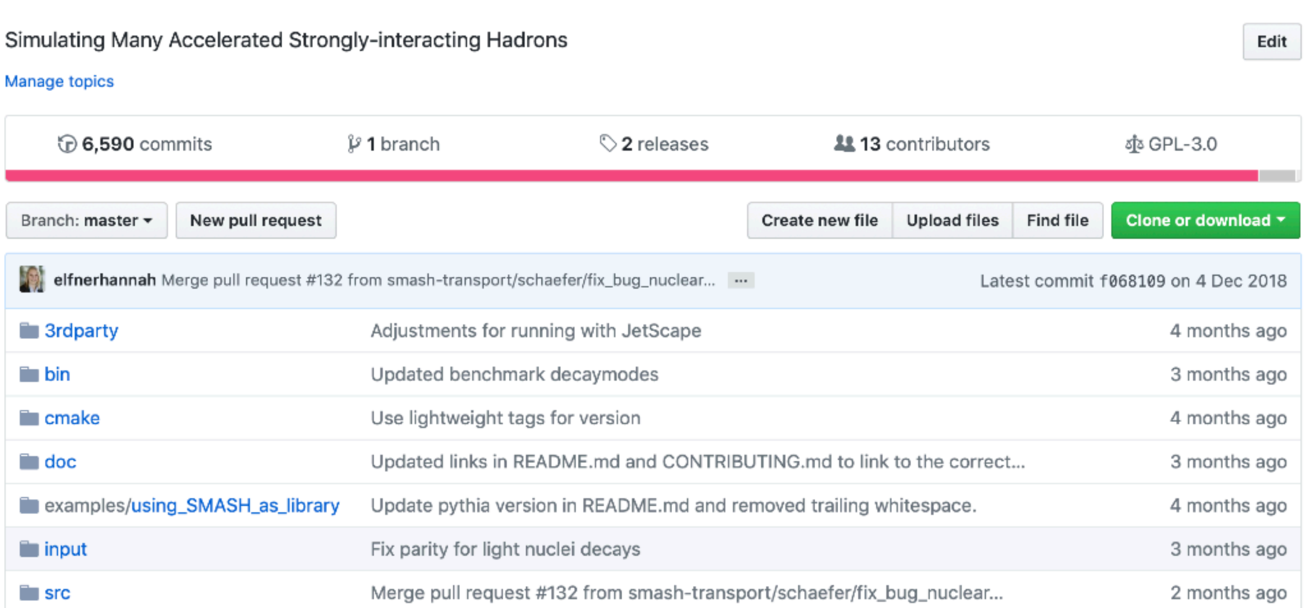
- In US/Bielefeld/Slovakia:
  - Agnieszka Sorensen
  - Oscar Garcia-Montero
  - Zuzana Paulinyova

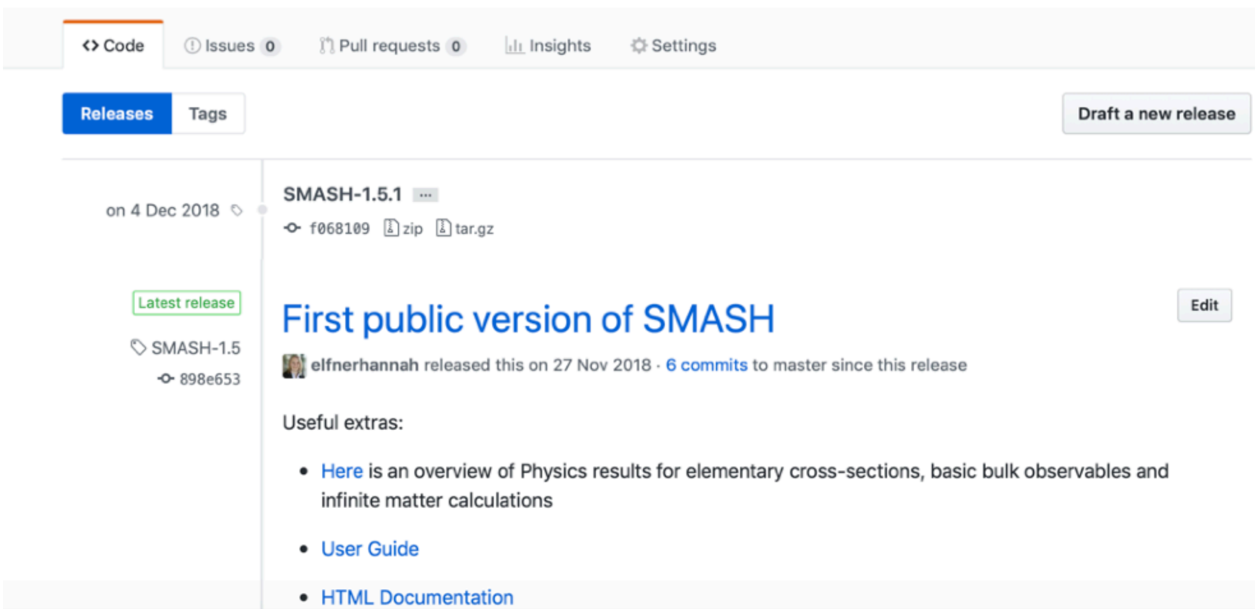
Group excursion in May 2022

Open Source Strategy

- Visit the webpage to find publications and link to SMASH-3.1 results https://smash-transport.github.io
- Download the code at https://github.com/smash-transport/smash
- Checkout the Analysis Suite at https://github.com/smash-transport/smash-analysis
- Find user guide and documentation at https://github.com/smash-transport/smash/releases
- Animations and Visualization Tutorial under https://smash-transport.github.io/movies.html

SMASH-3.0 has HepMC and RIVET

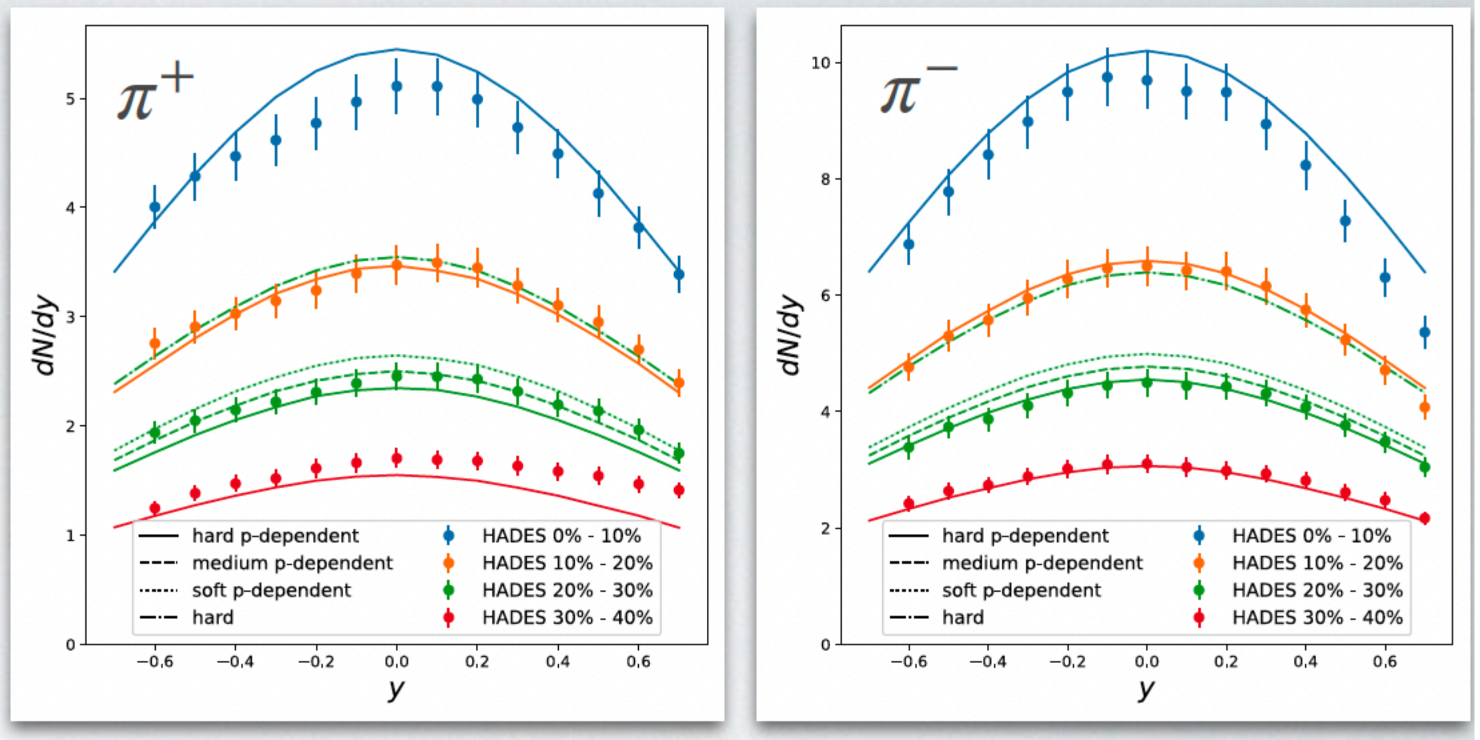




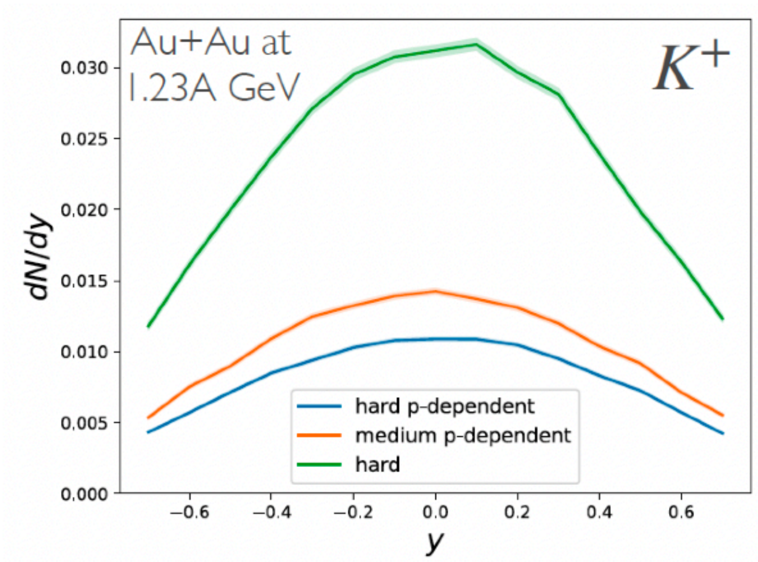
Meson Production

- Particle production is improved as well with the hard momentum dependent equation of state
- Work in progress:
  - Bayesian analysis
  - Comparison to FOPI data (with A. Andronic et al)
  - Vector density potentials by A. Sorensen

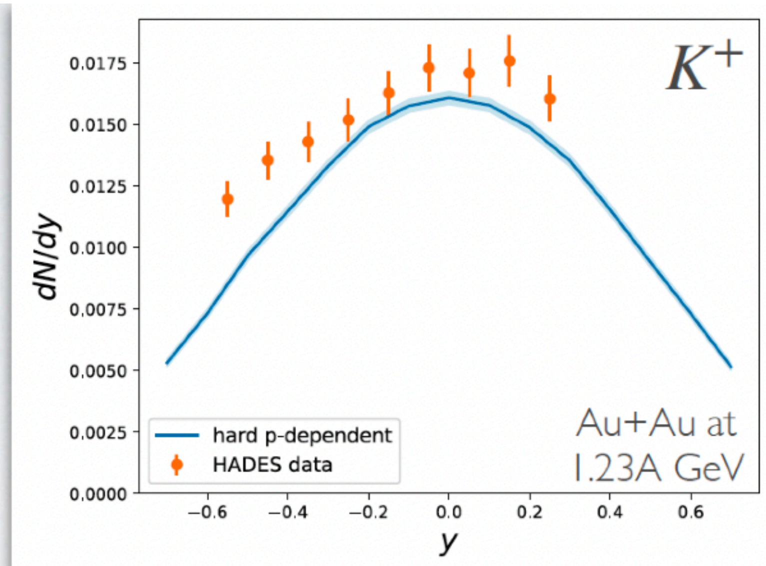
A. Sorensen and V. Koch, *Phys.Rev.C* 104 (2021)



Au+Au at 1.23A GeV
Hades data
Eur. Phys. J. A 56 (2020)



20%-30% centrality



0%-40% centrality
HADES data
Phys. Lett. B 778 (2018)

J. Mohs at NUSYM 2023