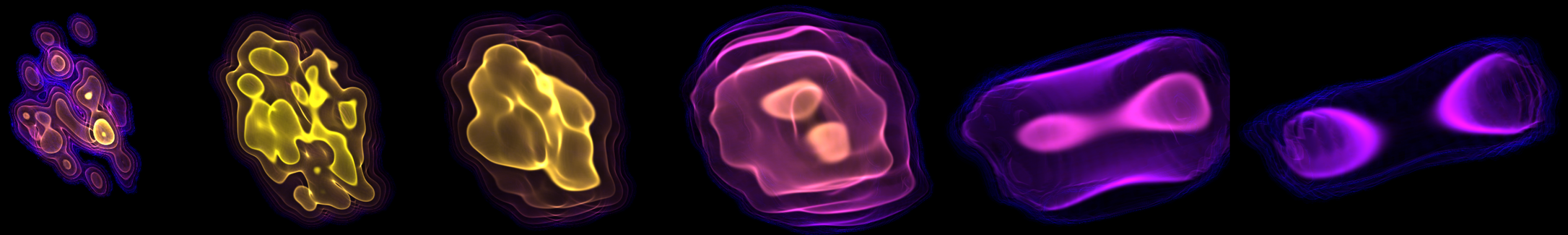
RBRC
RIKEN BNL Research Center

BEST COLLABORATION

JETSCAPE

INTRODUCTION TO THE COLLECTIVE QGP

CHUN SHEN

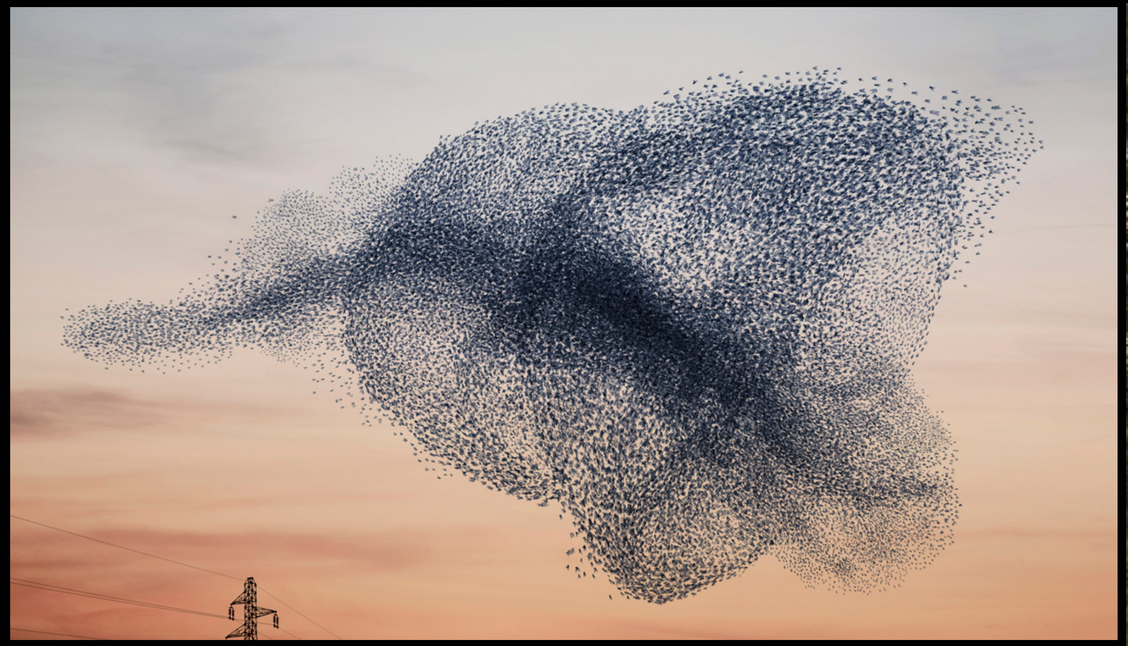


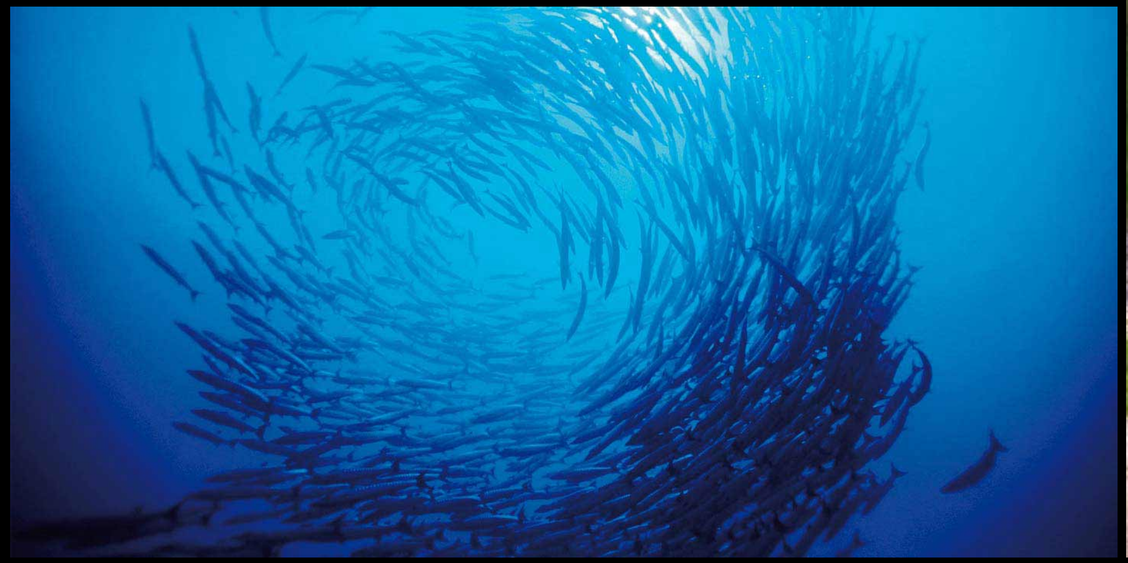
JETSCAPE Summer School
July 21, 2021

Post your questions in the slack channel:

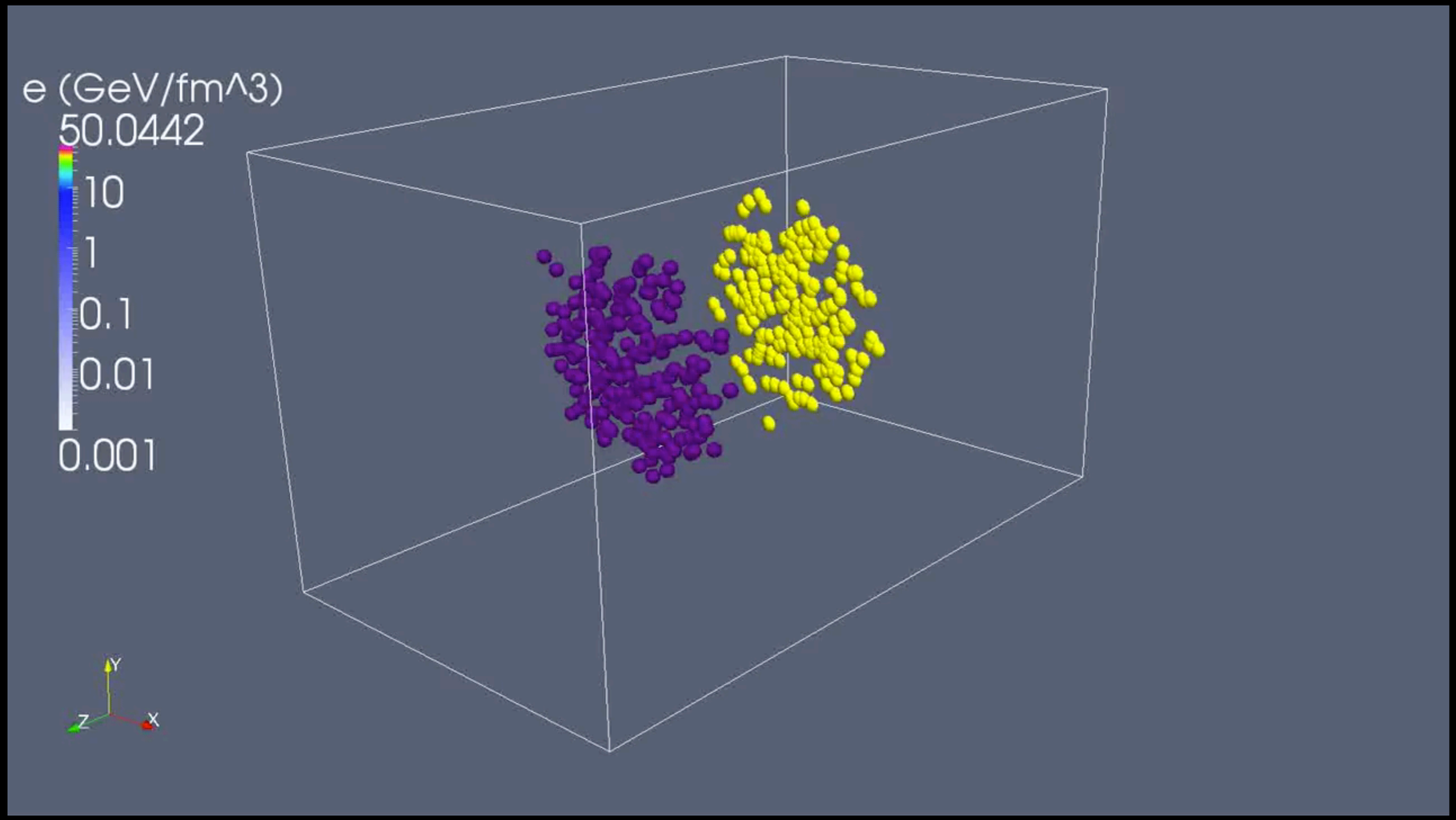
#jul21-jul22-hydro

MORE IS DIFFERENT!





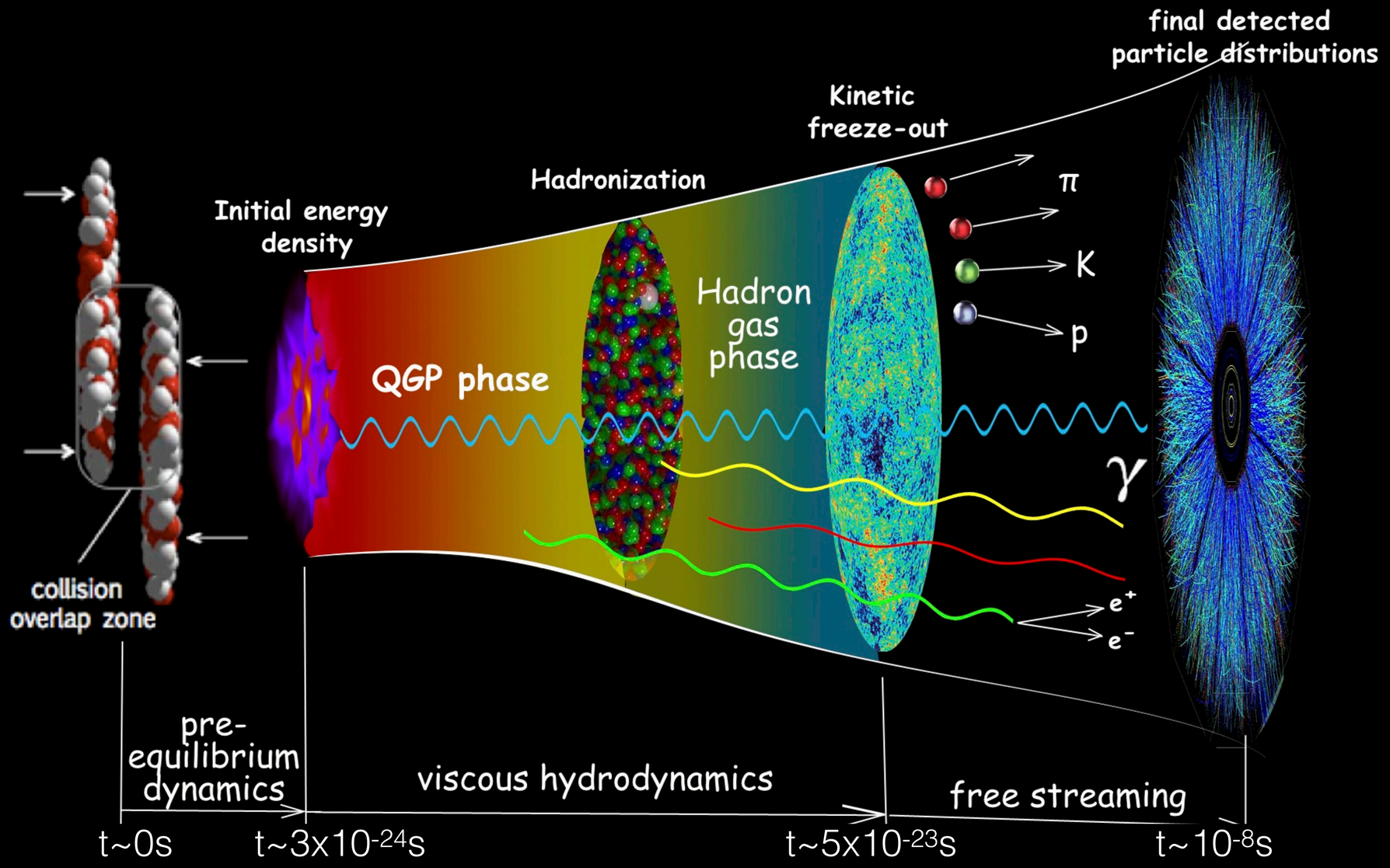
A “LITTLE BANG”



http://youtu.be/W3h5vQOUJTg

A PB+PB COLLISION AT THE LARGE HADRON COLLIDER

RELATIVISTIC HEAVY-ION COLLISIONS



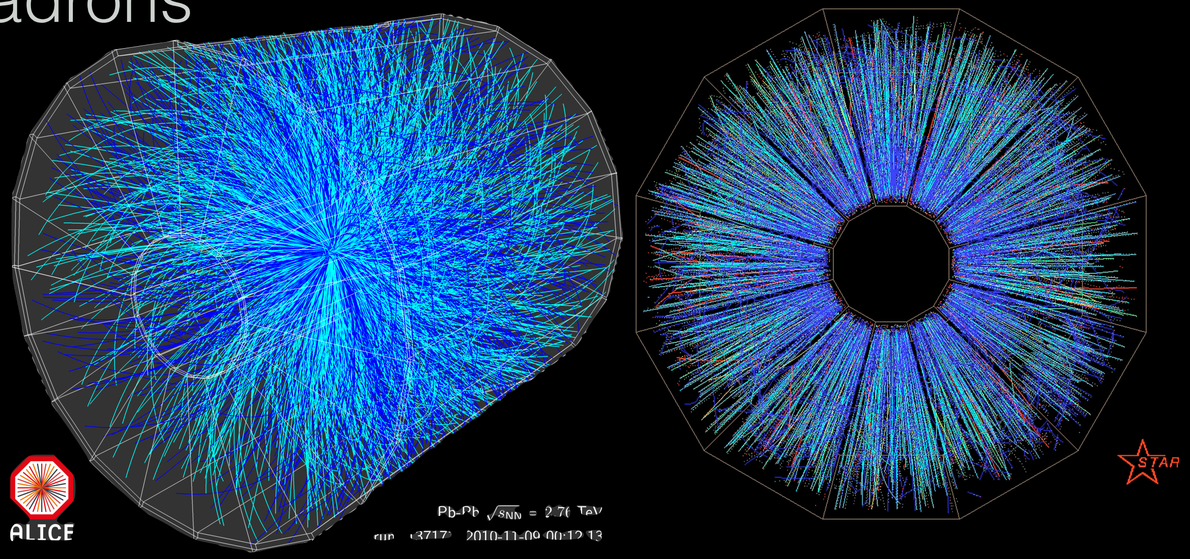
1 yoctosecond = 10^{-24} s

Complex dynamics driven by multiple length scales

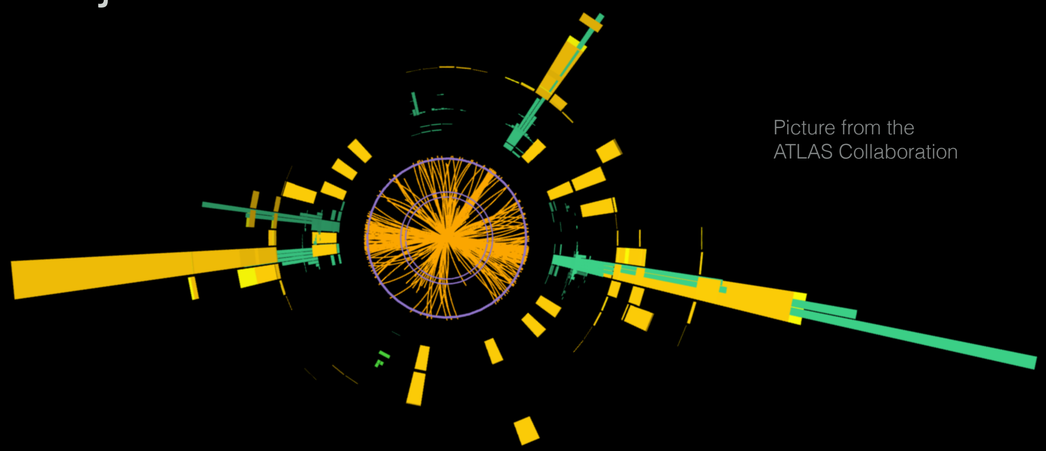
Hybrid multi-stage modeling with event-by-event fluctuations

MULTI-MESSENGER HEAVY-ION PHYSICS

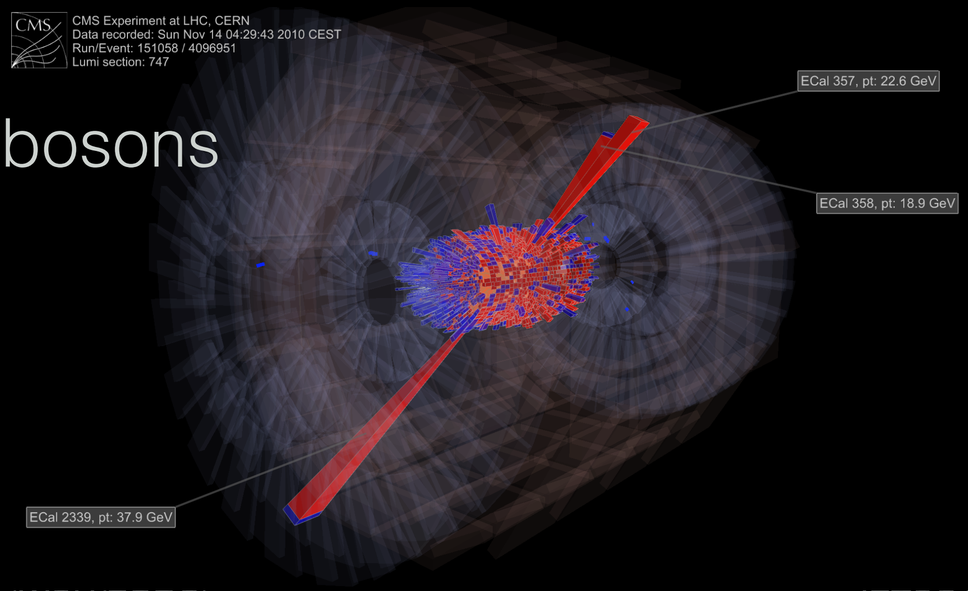
Hadrons



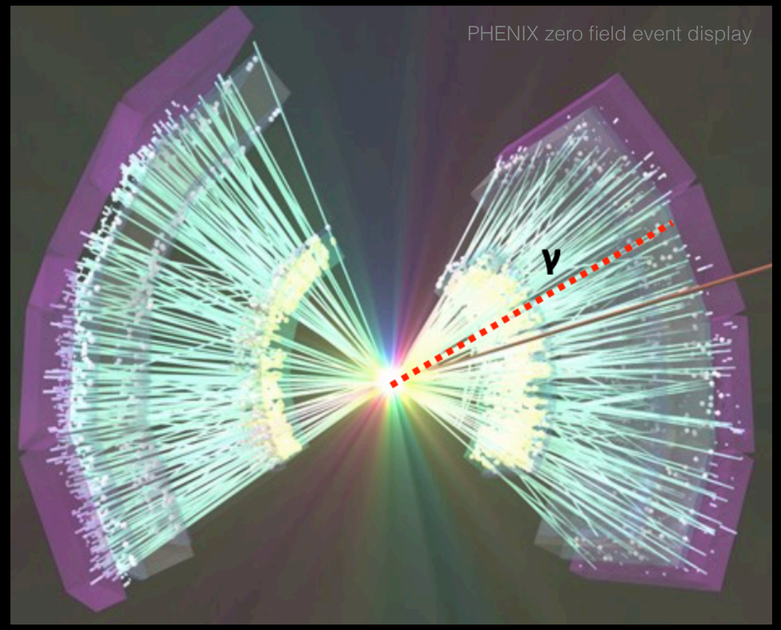
QCD jets



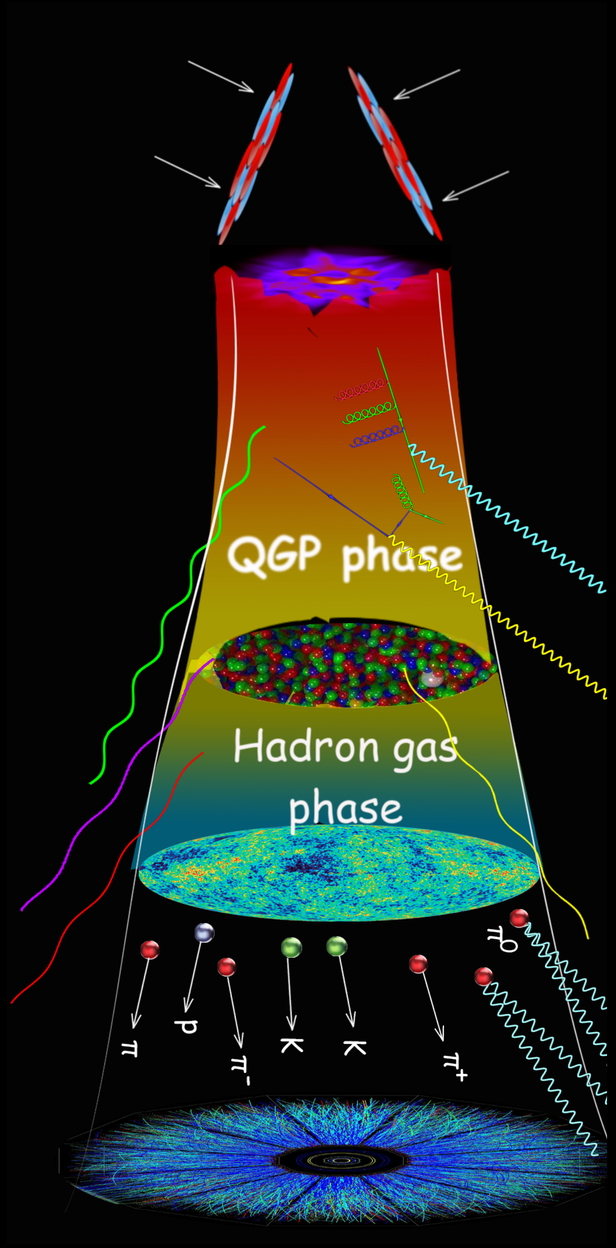
EW bosons



EM radiations



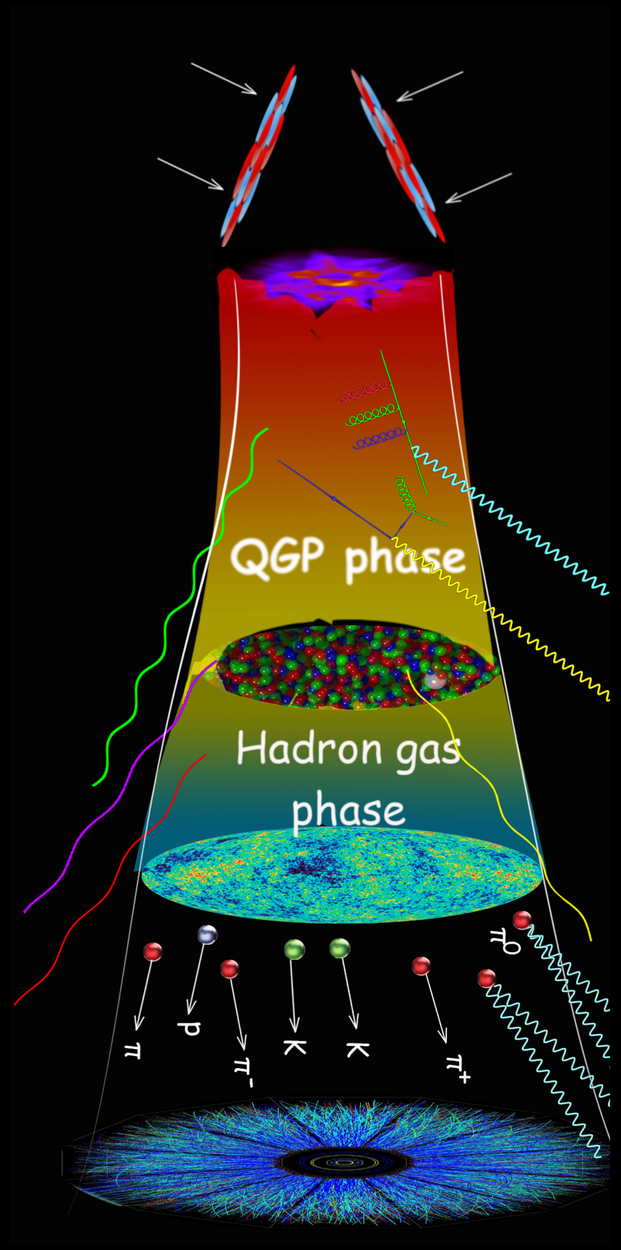
DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$ $c_s^2 = \partial P/\partial e\|_{s/n}$	Spectra, collective flow, femtoscopy
Shear and bulk viscosities $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$	Anisotropic flow v_n Flow correlations
Charge diffusion D_B, D_Q, D_S	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$c_s^2 = \partial P/\partial e|_{s/n}$

LQCD

Shear and bulk viscosities
$\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Energy-momentum transport
$\hat{q}, \hat{e}, \hat{e}_2, \ldots$

Spectra, collective flow, femtoscopy

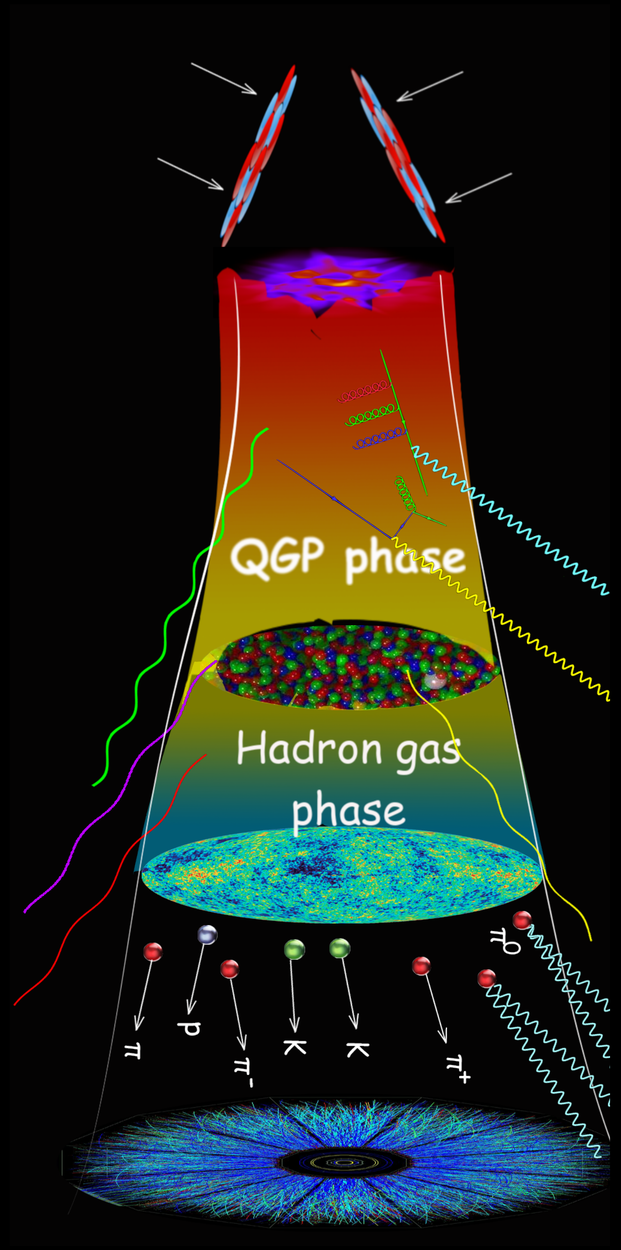
Anisotropic flow v_n
Flow correlations

Balance functions

Photons and dileptons

Jets and heavy-quarks

DEFINING THE QUARK-GLUON PLASMA



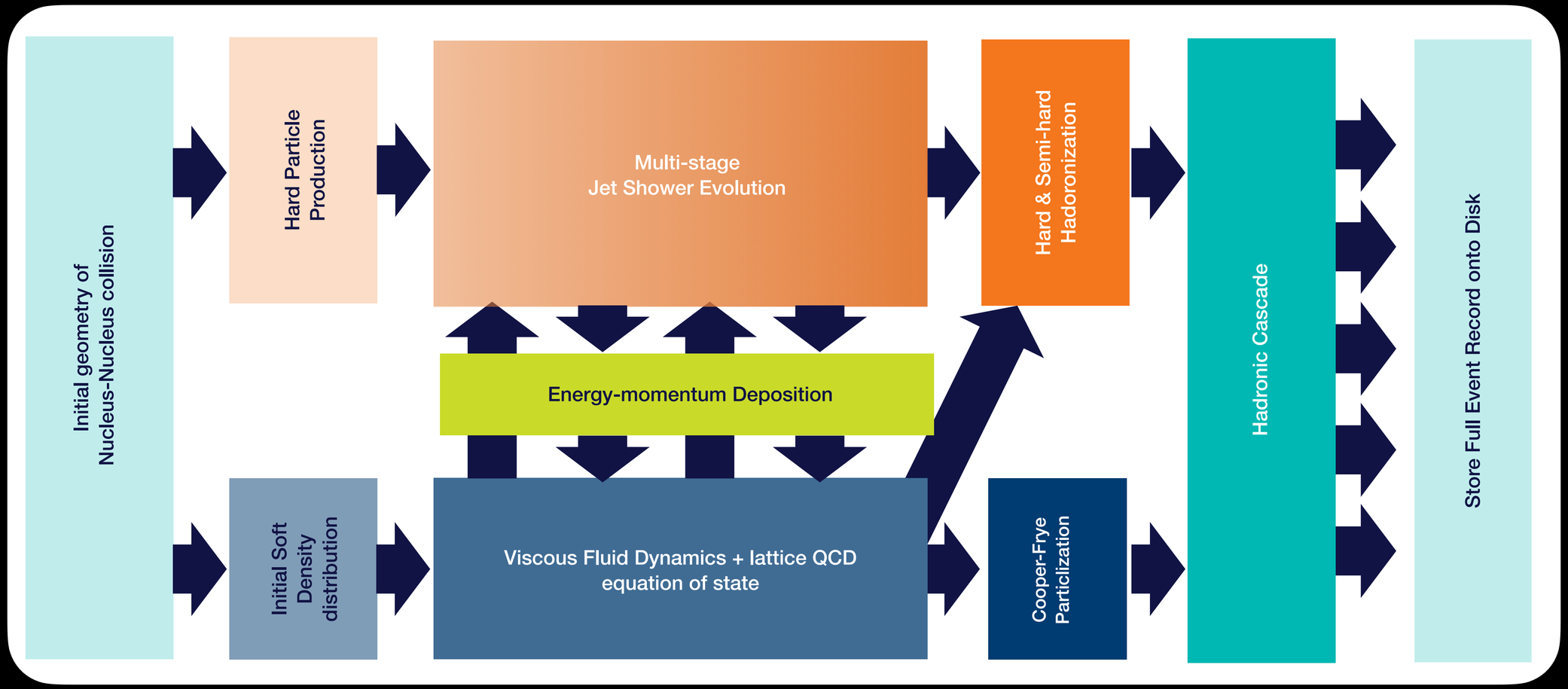
Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$ $c_s^2 = \partial P/\partial e\|_{s/n}$ **LQCD**	Spectra, collective flow, femtoscopy
Shear and bulk viscosities $\eta/s(T,\mu_B),\ \zeta/s(T,\mu_B)$	Anisotropic flow v_n Flow correlations
Charge diffusion $D_B,\ D_Q,\ D_S$	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

THE JETSCAPE FRAMEWORK

"The JETSCAPE framework," arXiv:1903.07706 [nucl-th]

- A unified event-generator for the high energy nuclear physics community

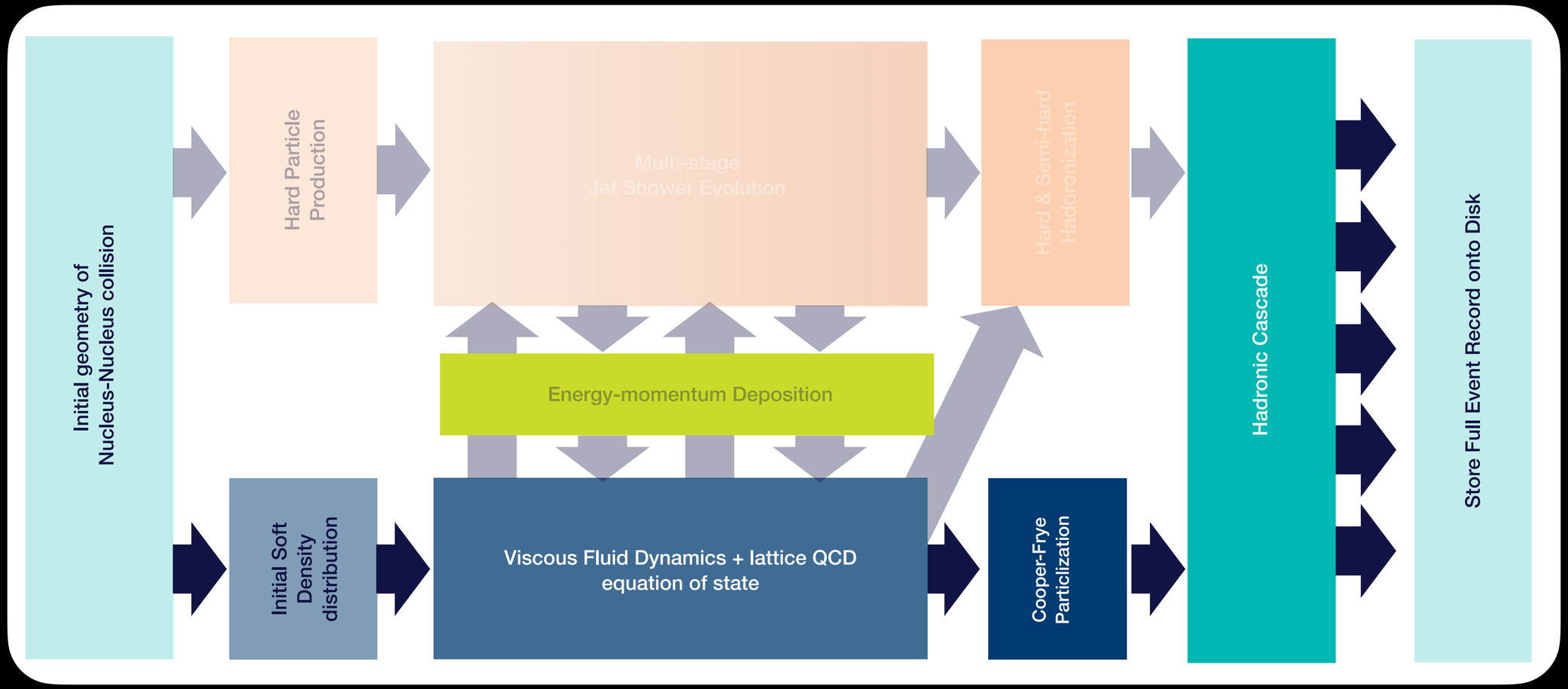


@ Y. Tachibana

THE JETSCAPE FRAMEWORK

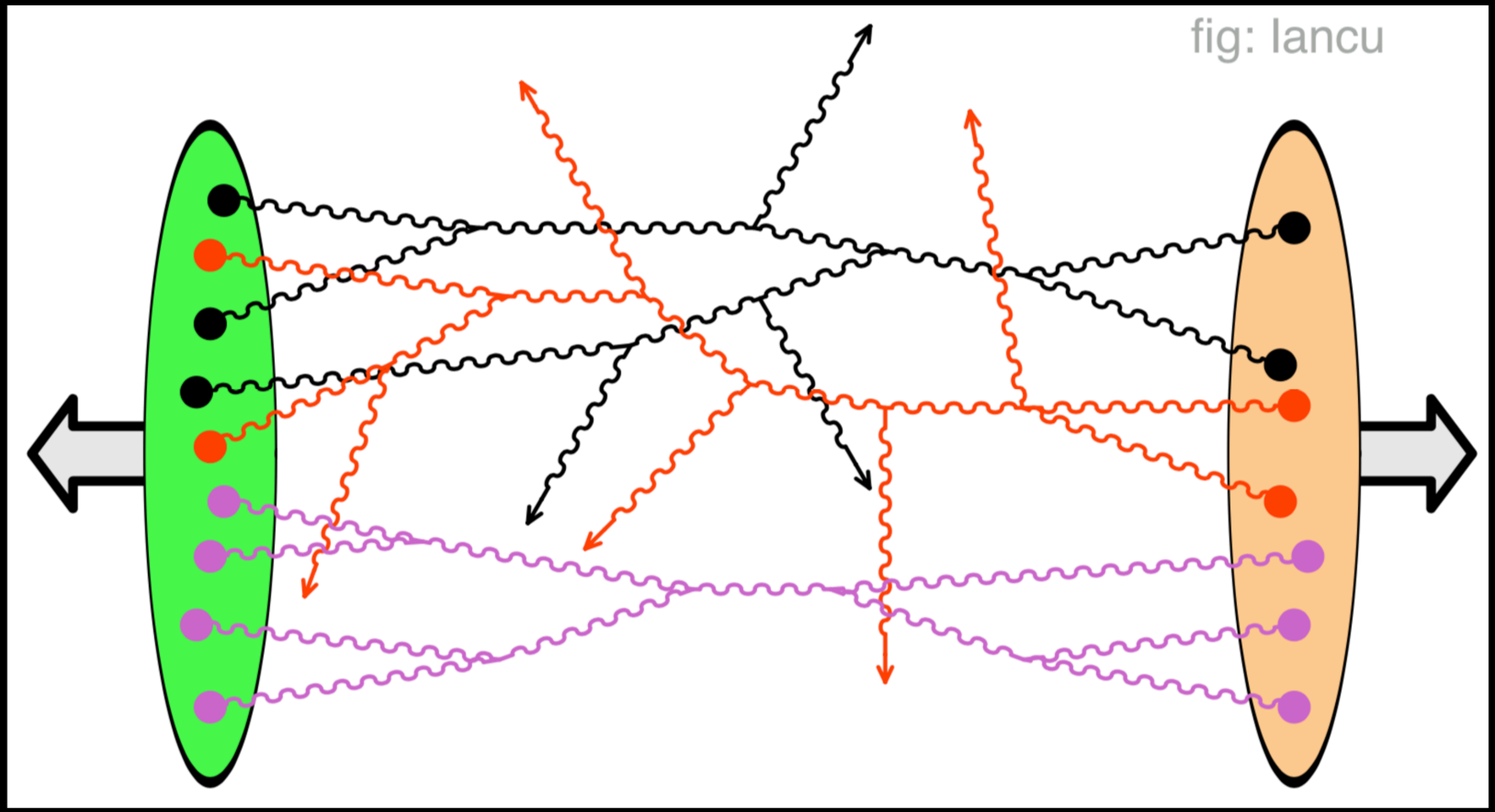
"The JETSCAPE framework," arXiv:1903.07706 [nucl-th]

- A unified event-generator for the high energy nuclear physics community



@ Y. Tachibana

INITIAL-STATE OF RELATIVISTIC NUCLEAR COLLISIONS



- Multiple scattering & soft processes dominate

highly non-perturbative

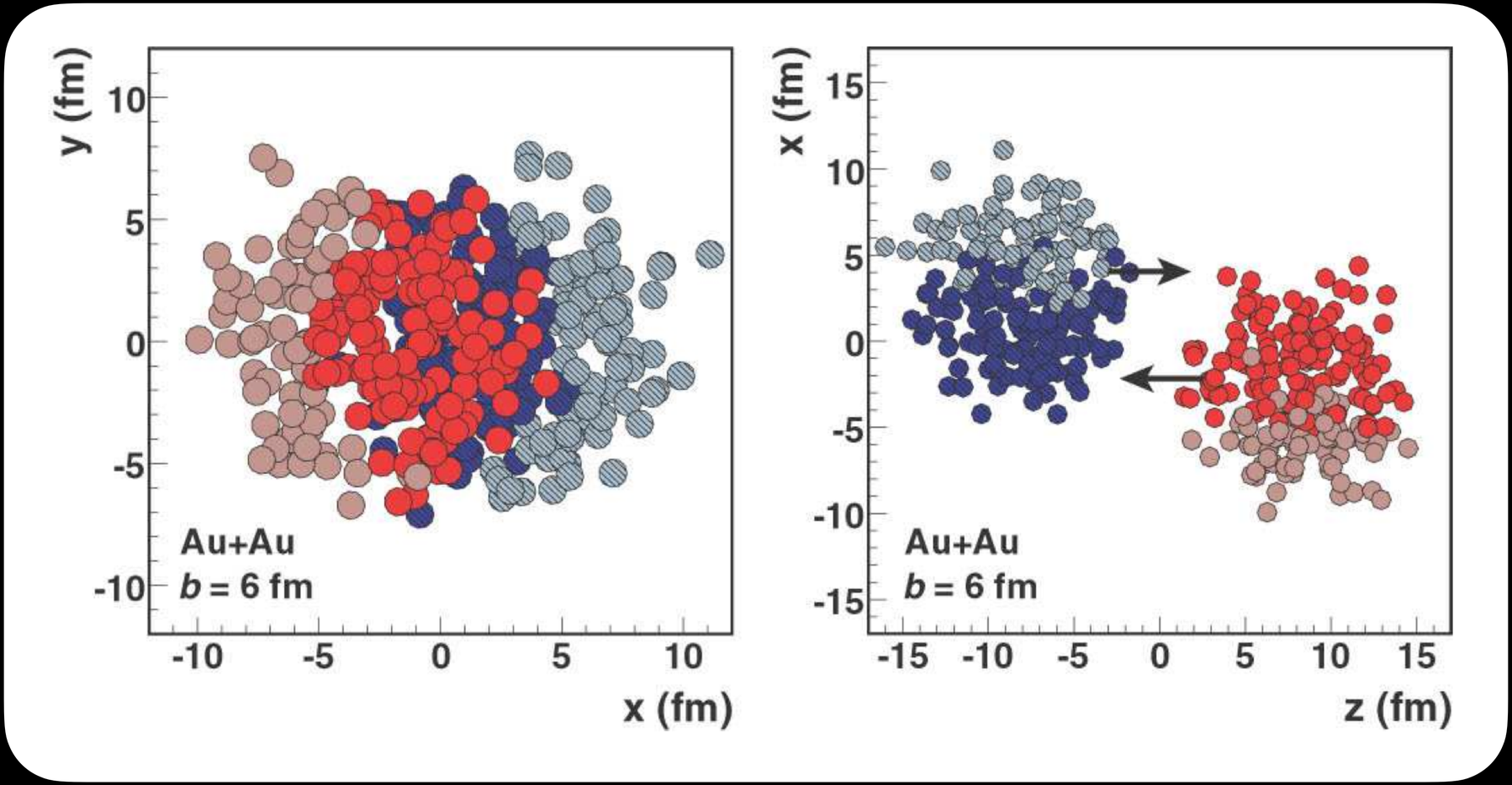
A ZOO OF INITIAL-STATE MODELS

by P. Tribedy

COLLISION GEOMETRY

Miller, Reygers, Sanders, Steinberg
Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)

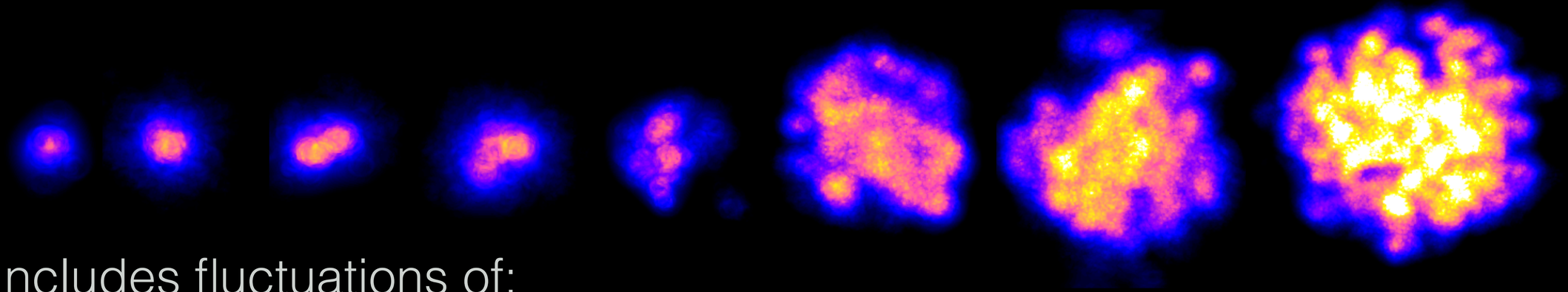
The Glauber model:



Participants in dark colors, spectators in light colors

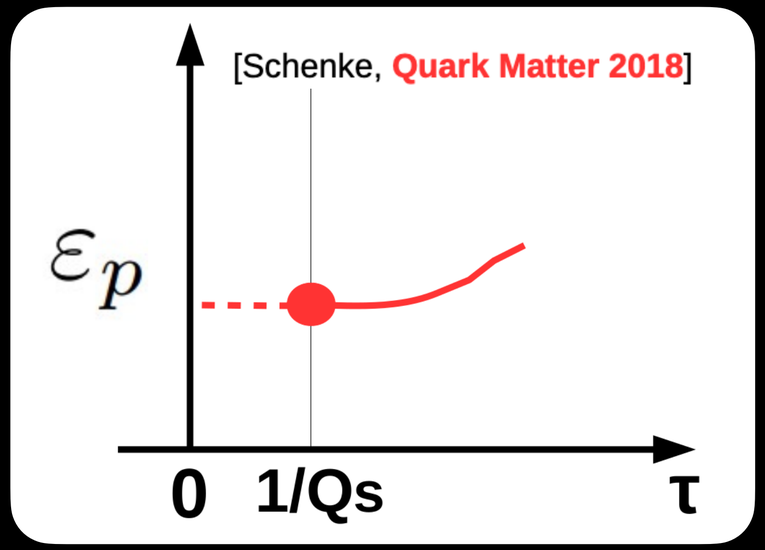
INITIAL STATE AND PRE-EQUILIBRIUM DYNAMICS: IP-GLASMA

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)



Includes fluctuations of:

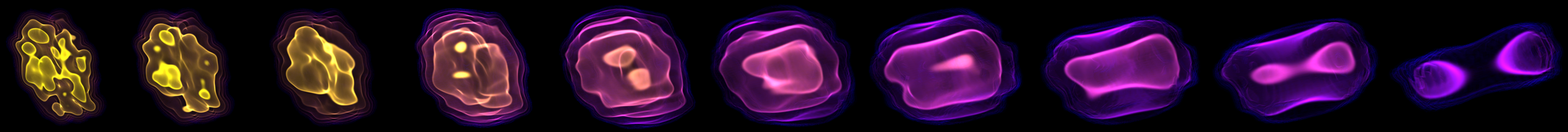
Impact parameter, nucleon positions, quark positions, color charge normalization, color charges



- The Color Glass Condensate (CGC) predicts anisotropic particle productions because of
  1. Local anisotropies in the color fields
  2. Local density gradients
  3. Quantum interference effects

$$\mathscr{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy} \rangle + i\langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$

THE HYBRID THEORETICAL FRAMEWORK



$T^{\mu\nu}$ 0^+ 0.5-1 τ (fm)

Initial State +
Pre-equilibrium dynamics

Hydrodynamics

Hadronic Transport

$$T^{\mu\nu}_{\text{pre. eq}} = T^{\mu\nu}_{\text{hydro}}$$

+ Landau Matching with lattice EoS

Cooper-Frye particlization

- Continuously connect the system's energy-momentum tensor $T^{\mu\nu}$ between different stages

COLLECTIVITY & HYDRODYNAMICS

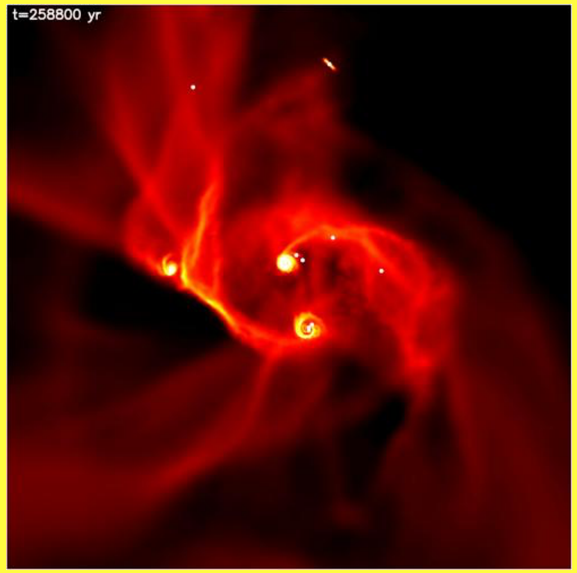
A long wavelength effective description of interacting systems

Conservation laws

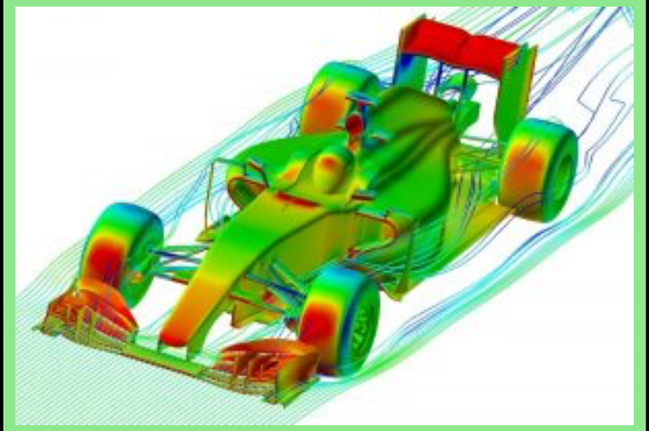
+

Equation of State

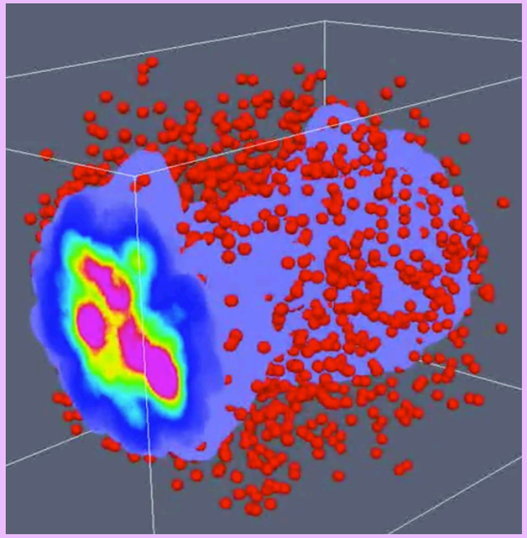
Star formation



Air dynamics of race car

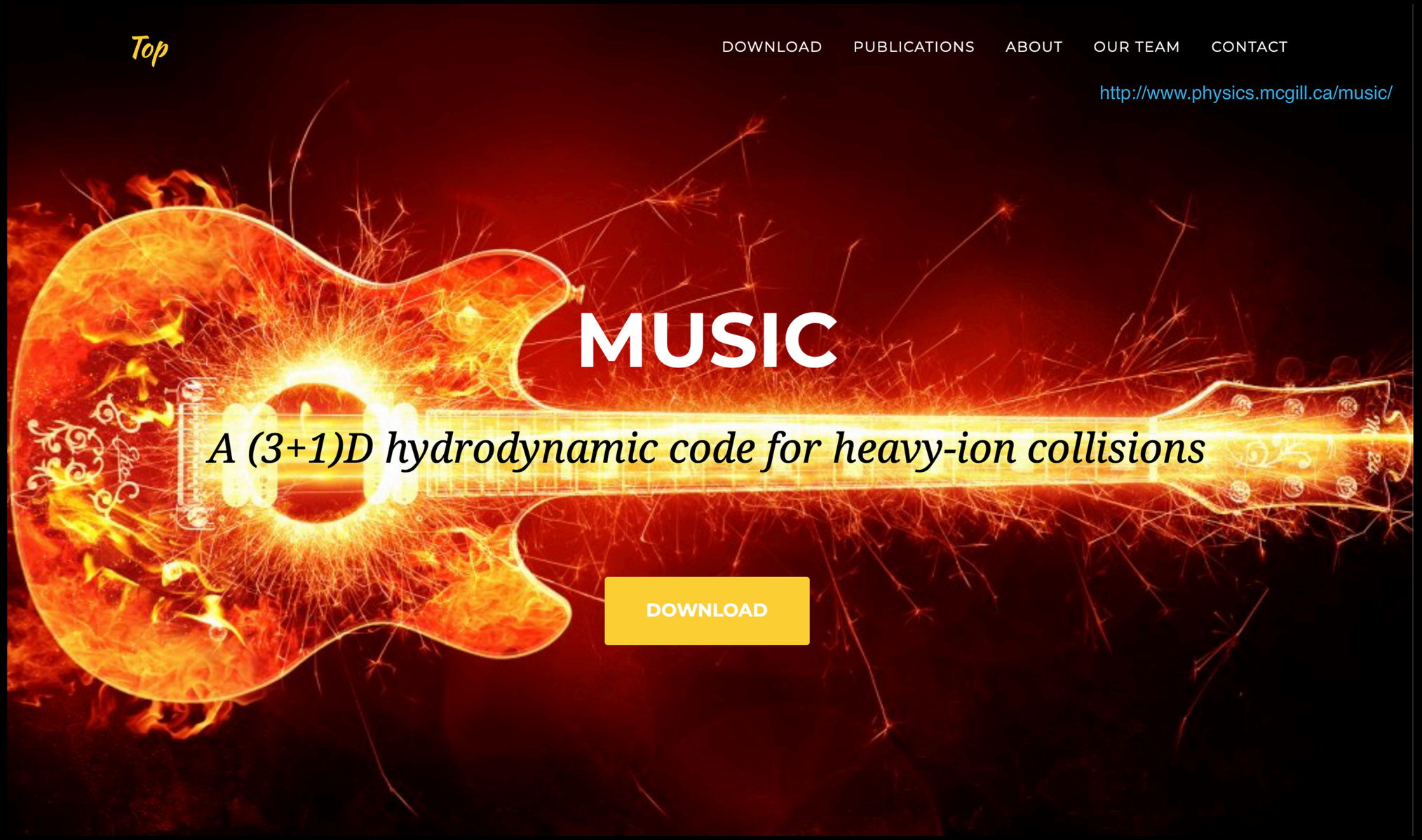


Quark-Gluon Plasma



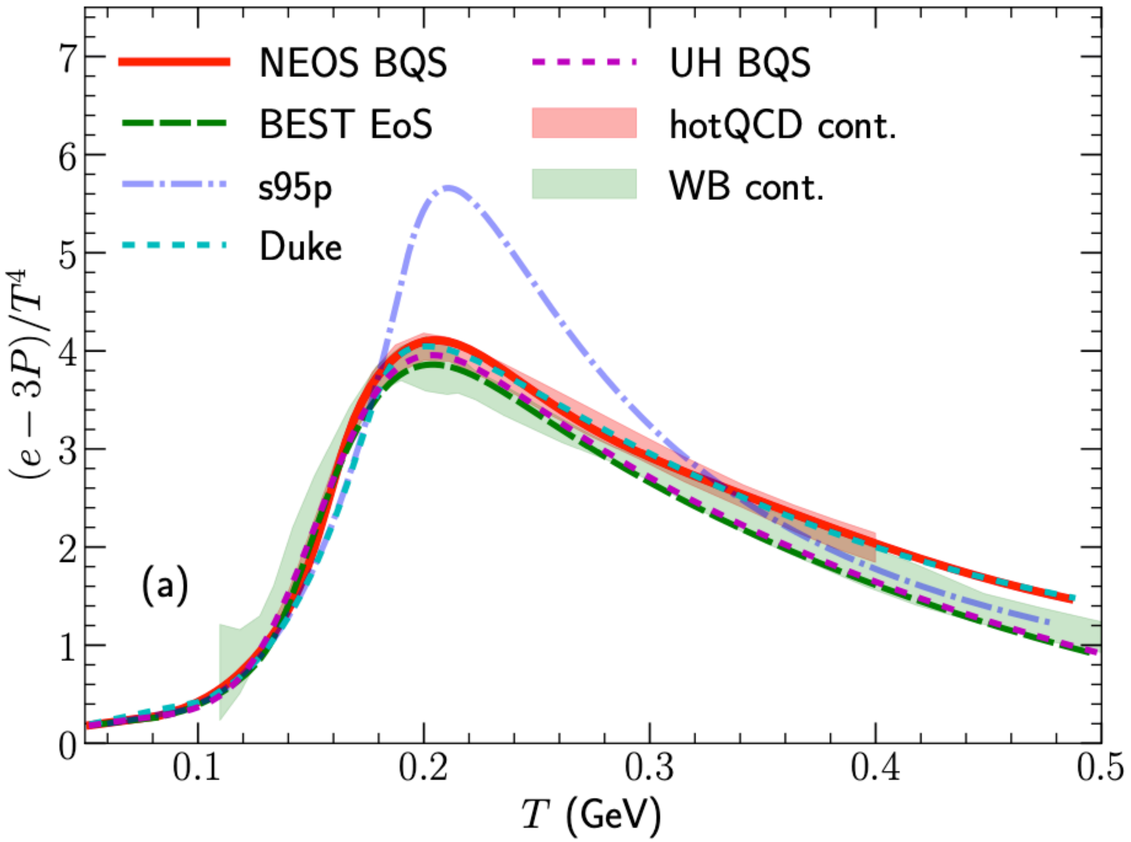
Studying collective phenomena in heavy-ion collisions has been leading the theory frontier of developing causal viscous relativistic hydrodynamics

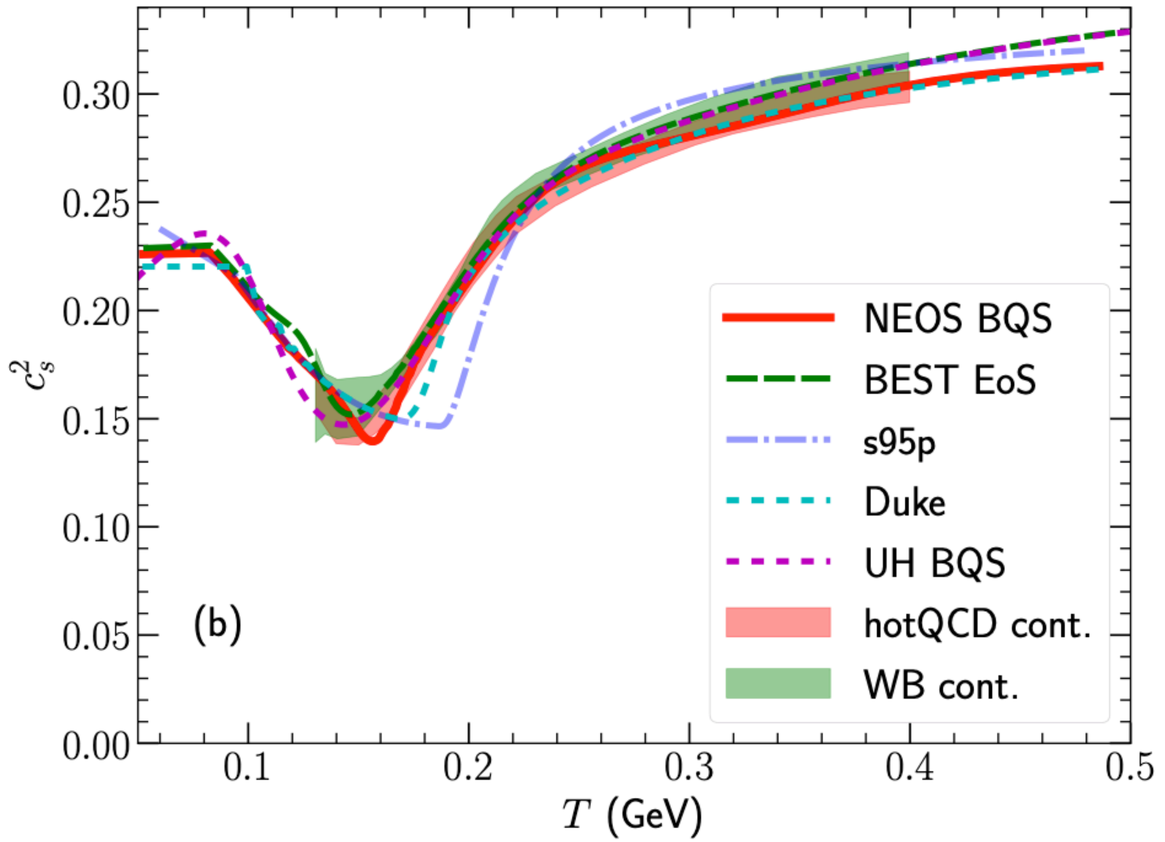
A REALIZATION OF RELATIVISTIC HYDRODYNAMICS



QCD EQUATION OF STATE

A. Monnai, B. Schenke and C. Shen, Int. J. Mod. Phys. A36, 2130007 (2021)





- QCD equation of state are constrained by Lattice QCD calculations

PRESSURE GRADIENTS DRIVEN DYNAMICS

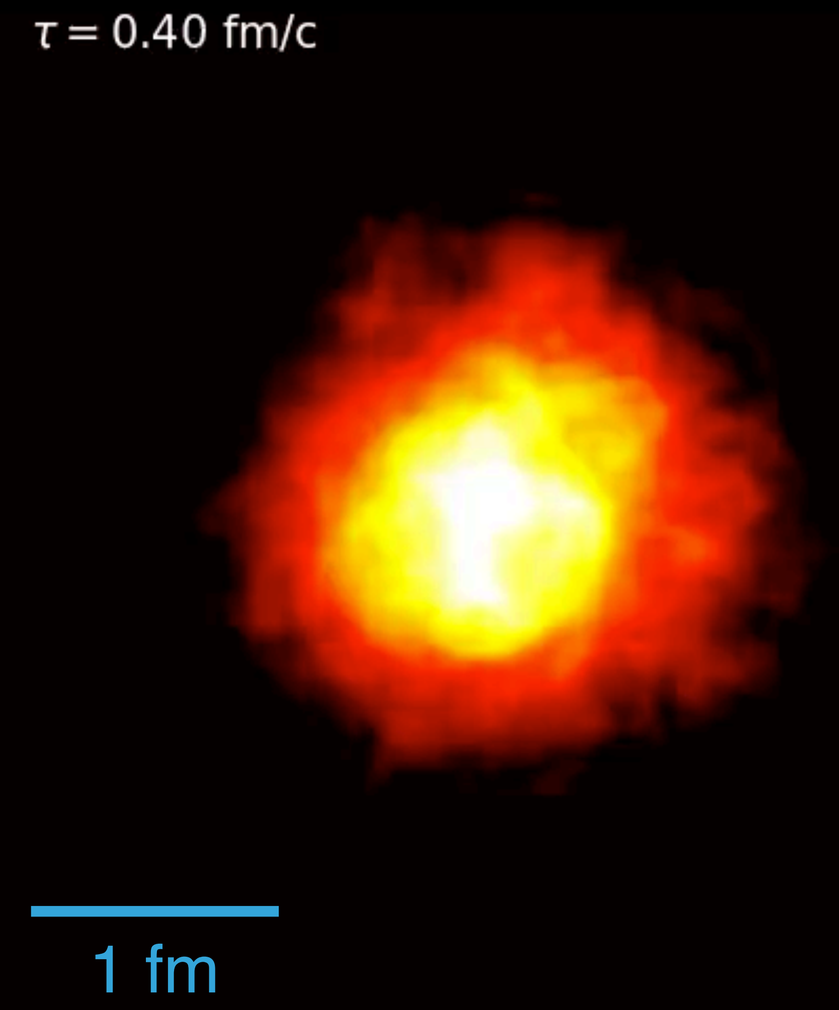
force

$$Du^\mu = \frac{\nabla^\mu P}{e + P}$$

acceleration

moment of inertia

Spatial imhomogeneity → Flow velocity

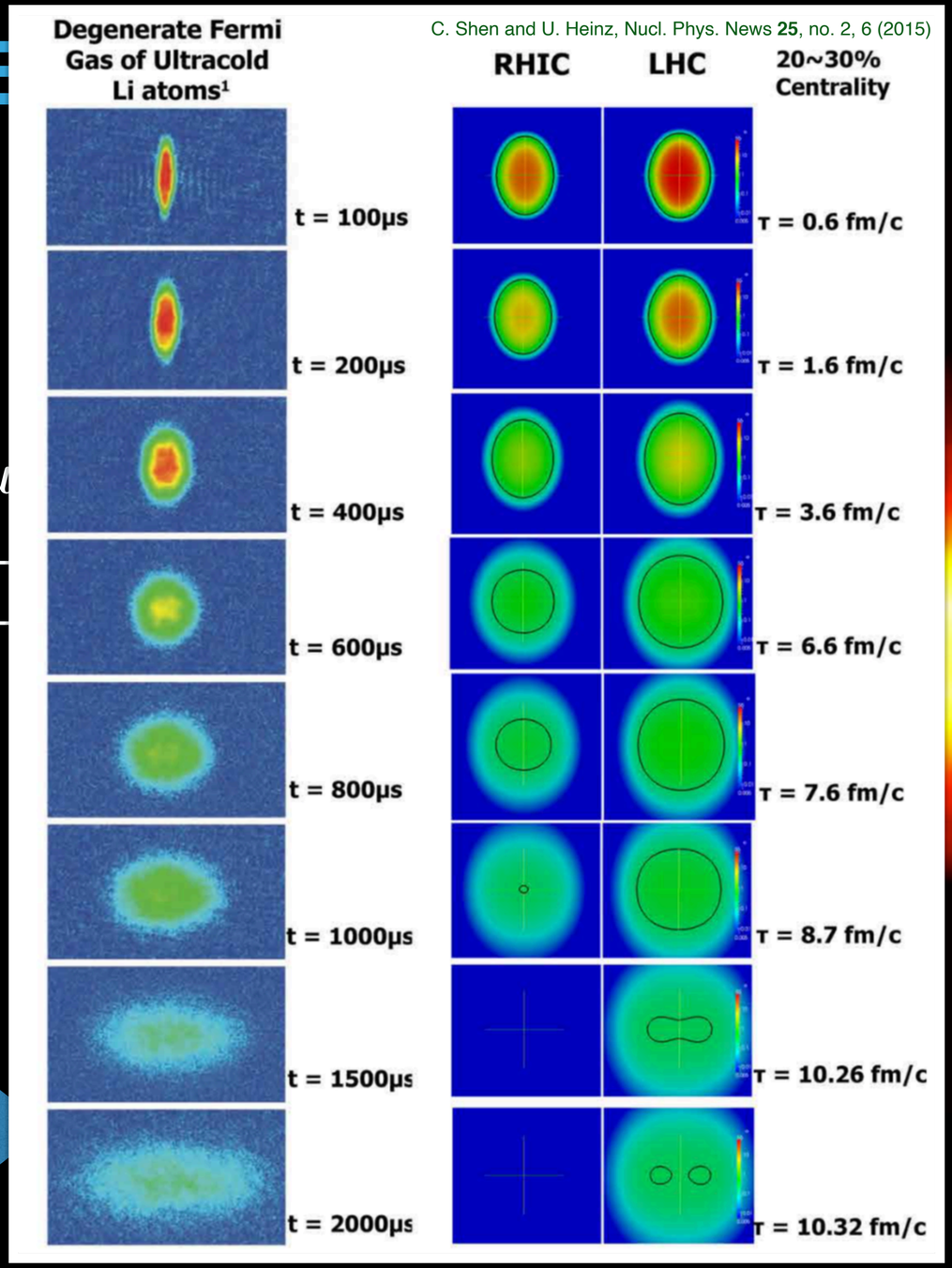


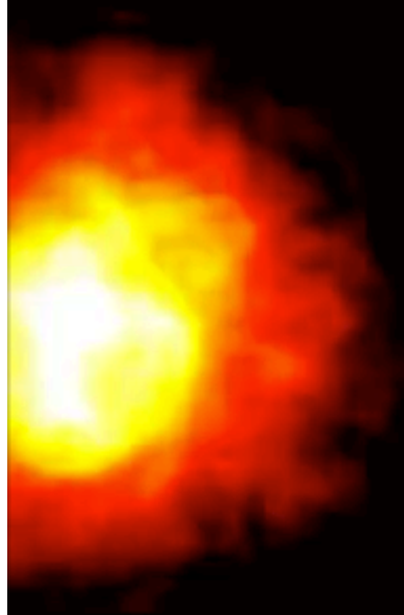
PRESSURE DYNAMICS

$$Du^\mu = \frac{\nabla^\mu}{e +}$$

acceleration

Spatial imhomogeneity





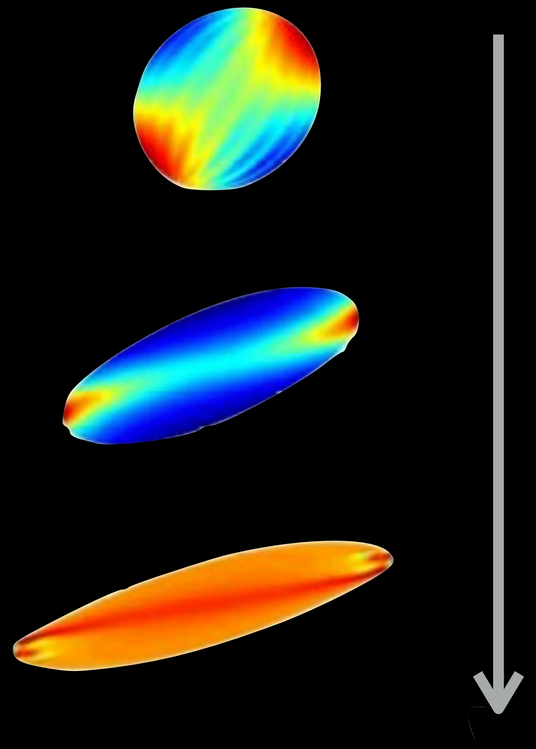
STUDY QGP TRANSPORT PROPERTIES

https://youtu.be/G-Fbon0YQak

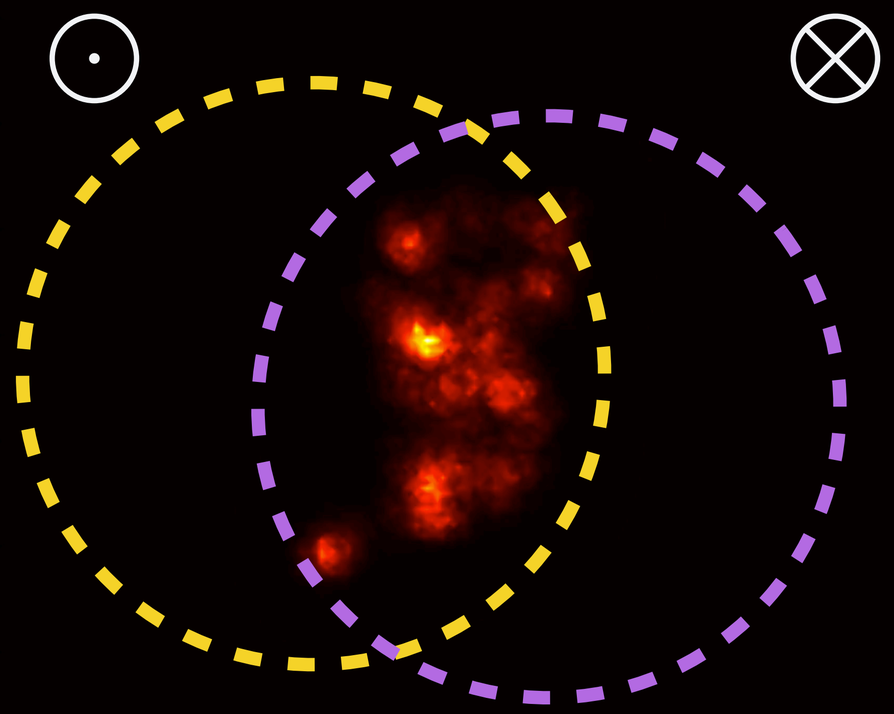
Shear viscosity

Resistance to deformation

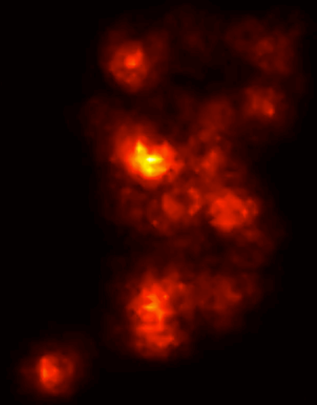
$\sim 2\eta\nabla^{\langle\mu}u^{\nu\rangle}$



no shear viscosity



with shear viscosity



Shear viscosity smears out the fine flow patterns

Flow anisotropy is imprinted to final state particle momenta

EFFECTS OF BULK VISCOSITY

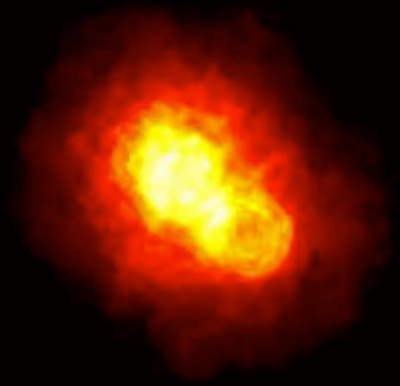
https://youtu.be/G-Fbon0YQak

Bulk viscosity

Resistance to expansion

$\sim -\zeta \partial_\mu u^\mu$

no bulk viscosity

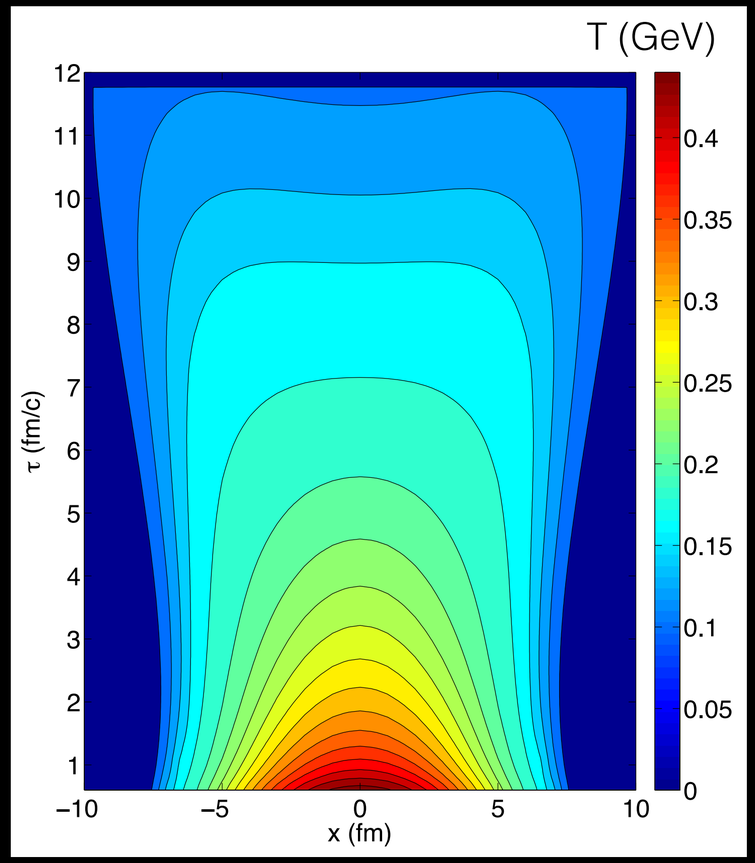


with bulk viscosity

- Bulk viscosity slows down radial expansion and produces more entropy

WHEN TO END?

- Particles are observed, not fluid elements
- How and when to convert fluid to particles (evaporation)
- How far is hydrodynamics valid?



Kinetic equilibrium requires

Scattering rate $\gg$ expansion rate

$\tau_{\rm sc}^{-1} \sim \sigma n \propto \sigma T^3 \quad \theta = \partial_\mu u^\mu$

Fluid description breaks down at

$$\tau_{\rm sc}^{-1} = \theta$$

Approximation: decouple takes place at a fixed temperature

$$T = T_{\rm fo} \propto \left(\frac{\theta}{\sigma}\right)^{1/3}$$

COOPER-FRYE PARTICLIZATION

Sample particles on the freeze-out surface (surface of constant (low) energy density) according to

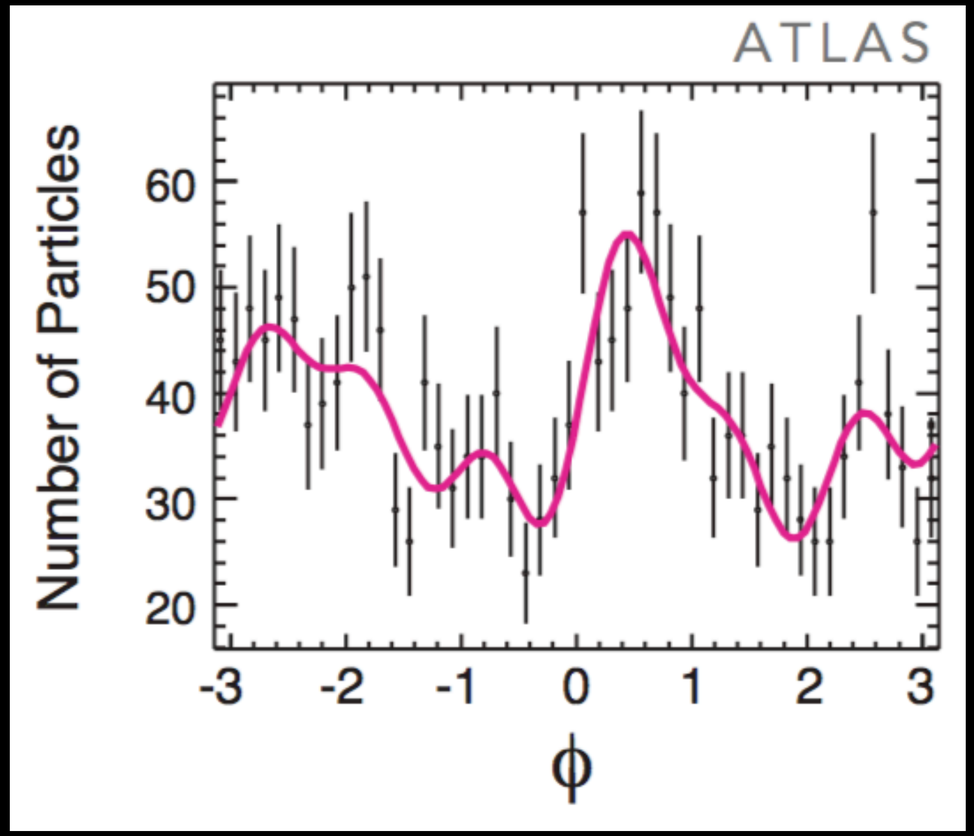
$$E\frac{dN_i}{d^3p} = \frac{g_i}{(2\pi)^3}\int_{\Sigma(T_{\rm fo})} d^3\sigma_\mu p^\mu \left(f^i_{\rm eq}\left(\frac{p^\mu u_\mu}{T}\right) + \delta f^i \right)$$

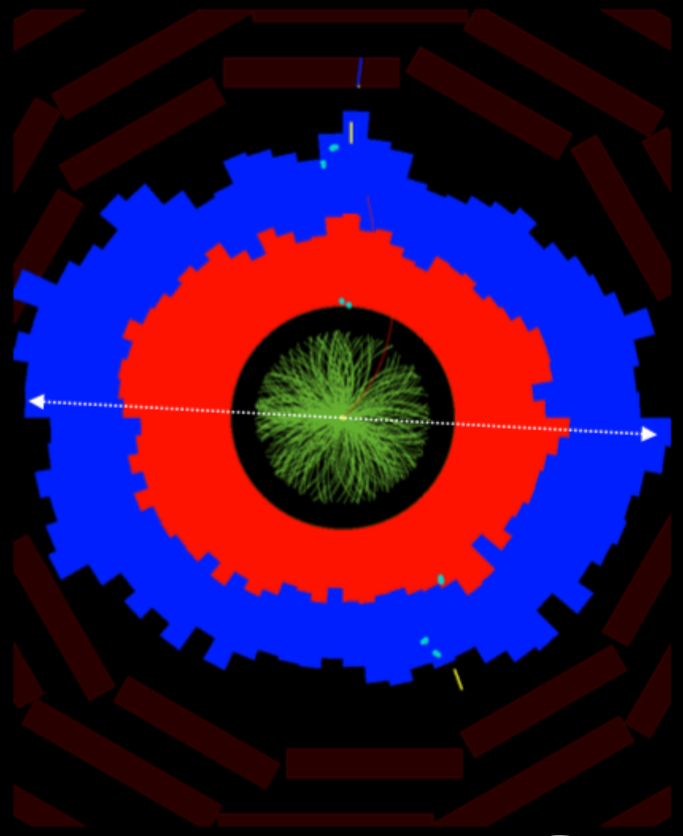
then feed particles into hadronic cascade (UrQMD/SMASH)

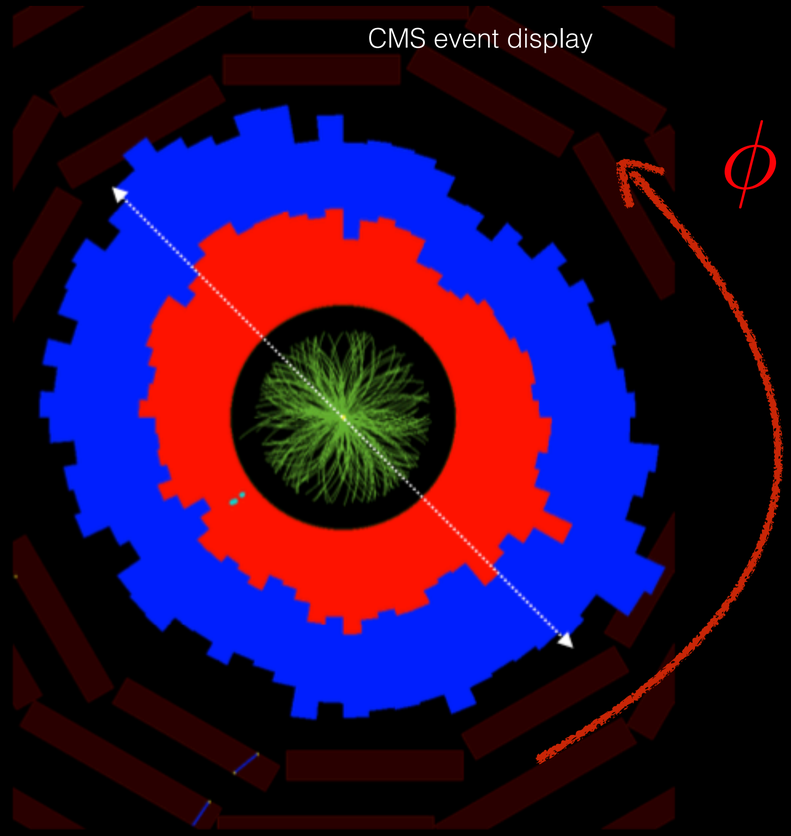
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255–369 (1998)
M. Bleicher et al., J. Phys. G25, 1859–1896 (1999)
J. Weil, et al. Rev. C 94, 054905 (2016)

which performs resonance decays and scattering according to hadronic cross sections

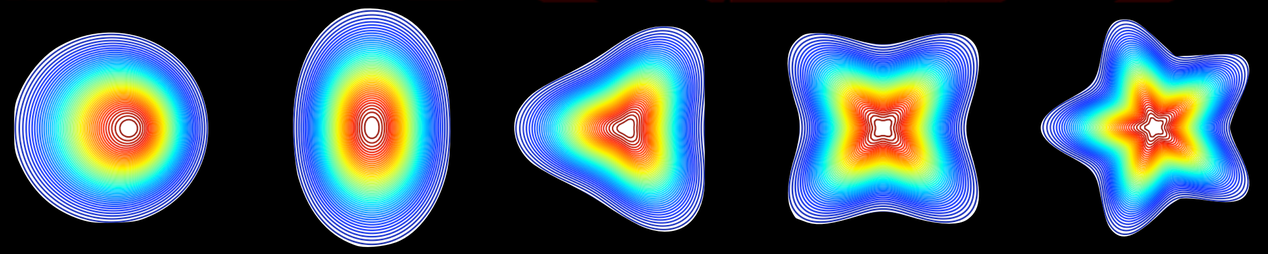
ANISOTROPIC FLOW



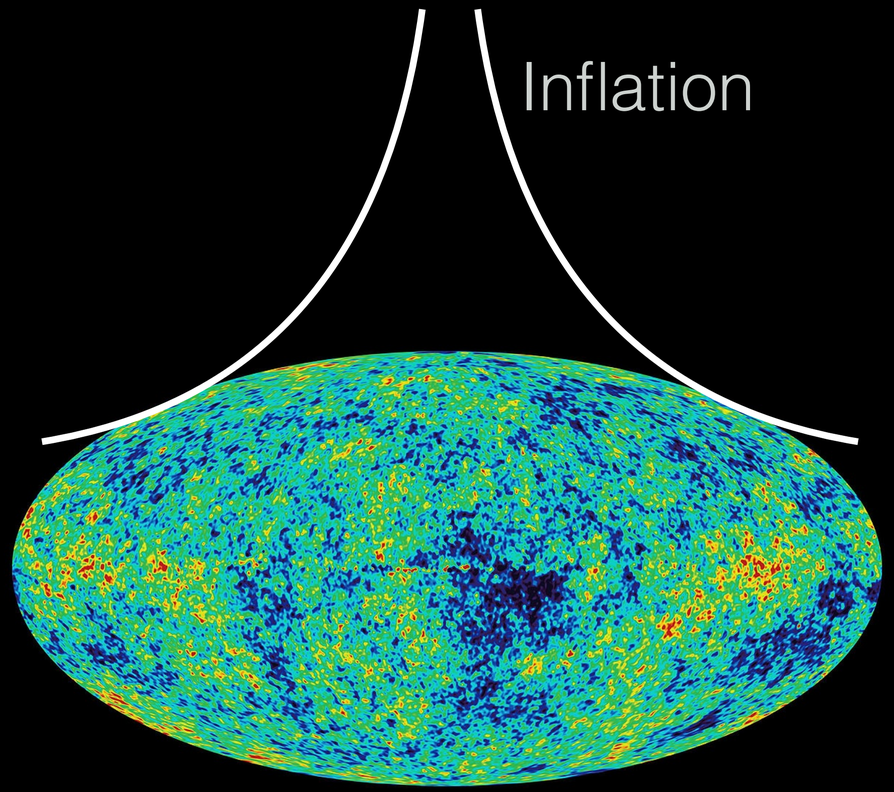


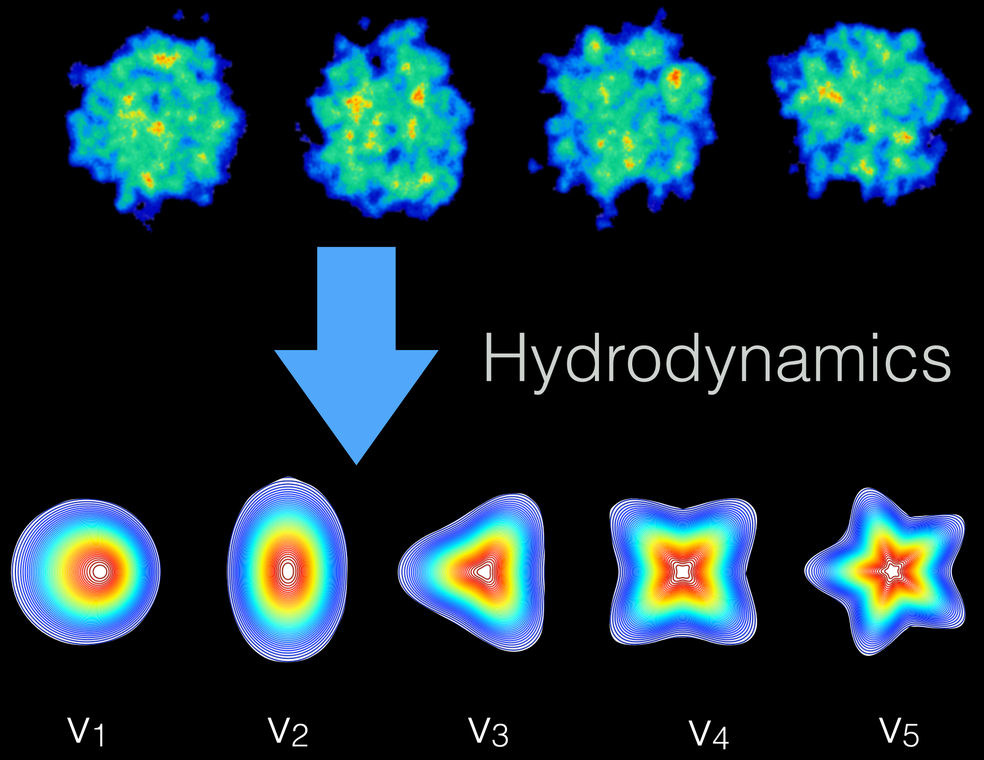


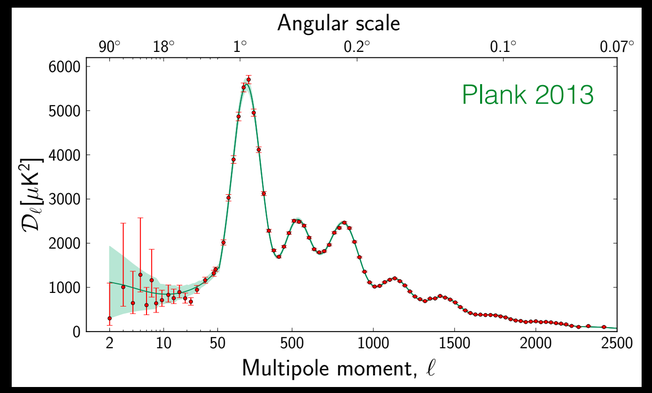
$$\frac{dN}{d\phi} = \frac{N}{2\pi}(1 + 2\sum_{n=1}^{\infty} v_n \cos(\phi - \Psi_n))$$

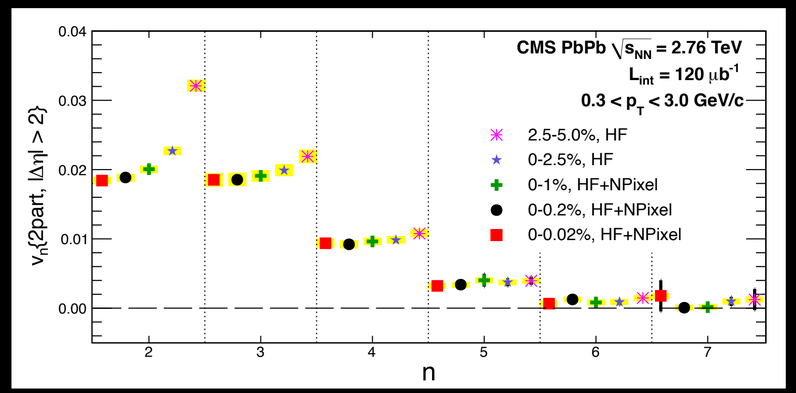


FLUCTUATION POWER SPECTRUM



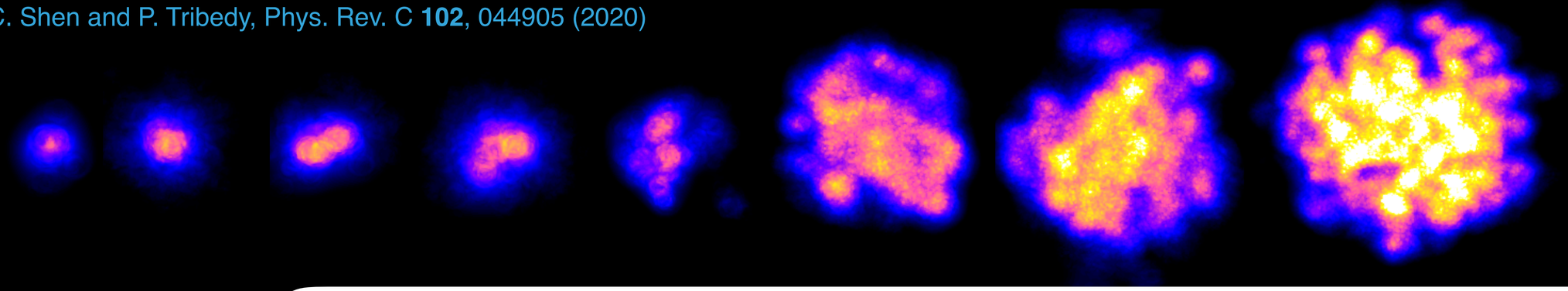






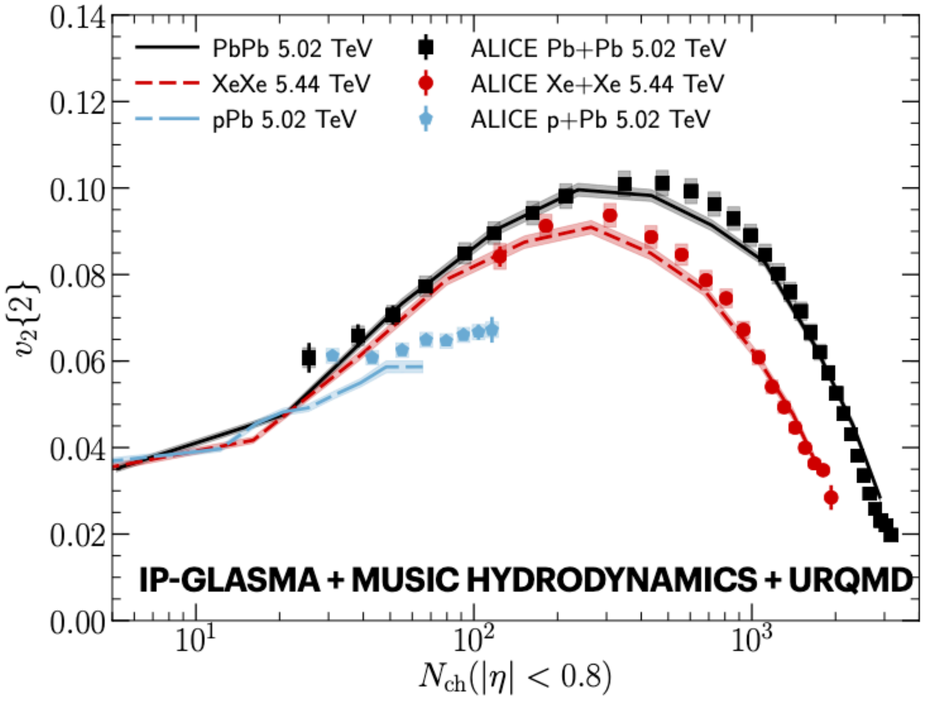
RUNNING THE GAMUT OF HIGH ENERGY NUCLEAR COLLISIONS

B. Schenke, C. Shen and P. Tribedy, Phys. Rev. C **102**, 044905 (2020)

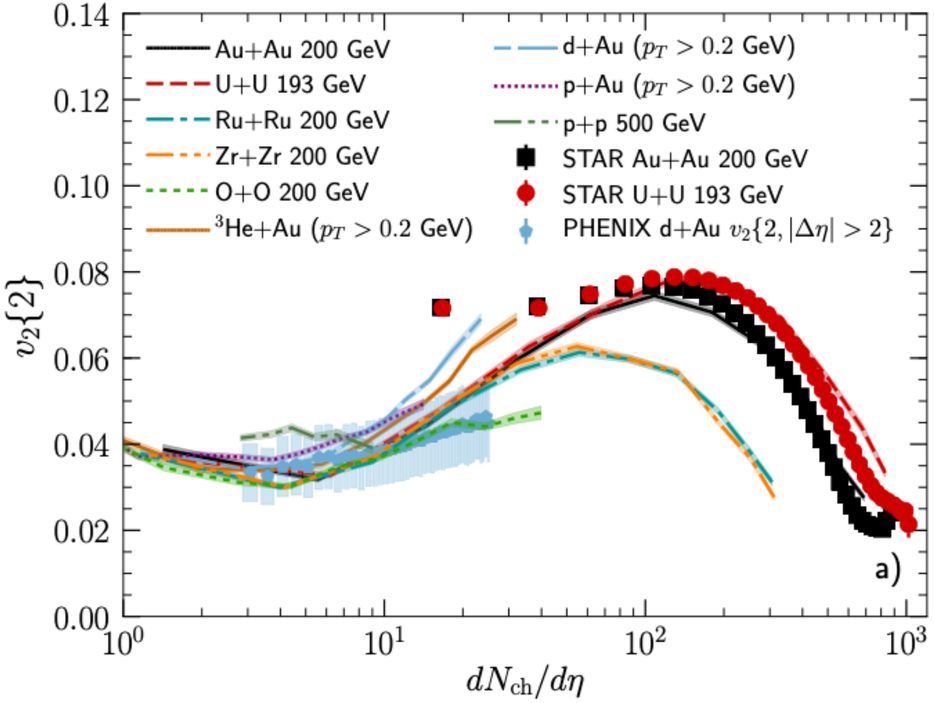


- One single set of model parameters for *ALL* types of collisions at the top RHIC and LHC energies

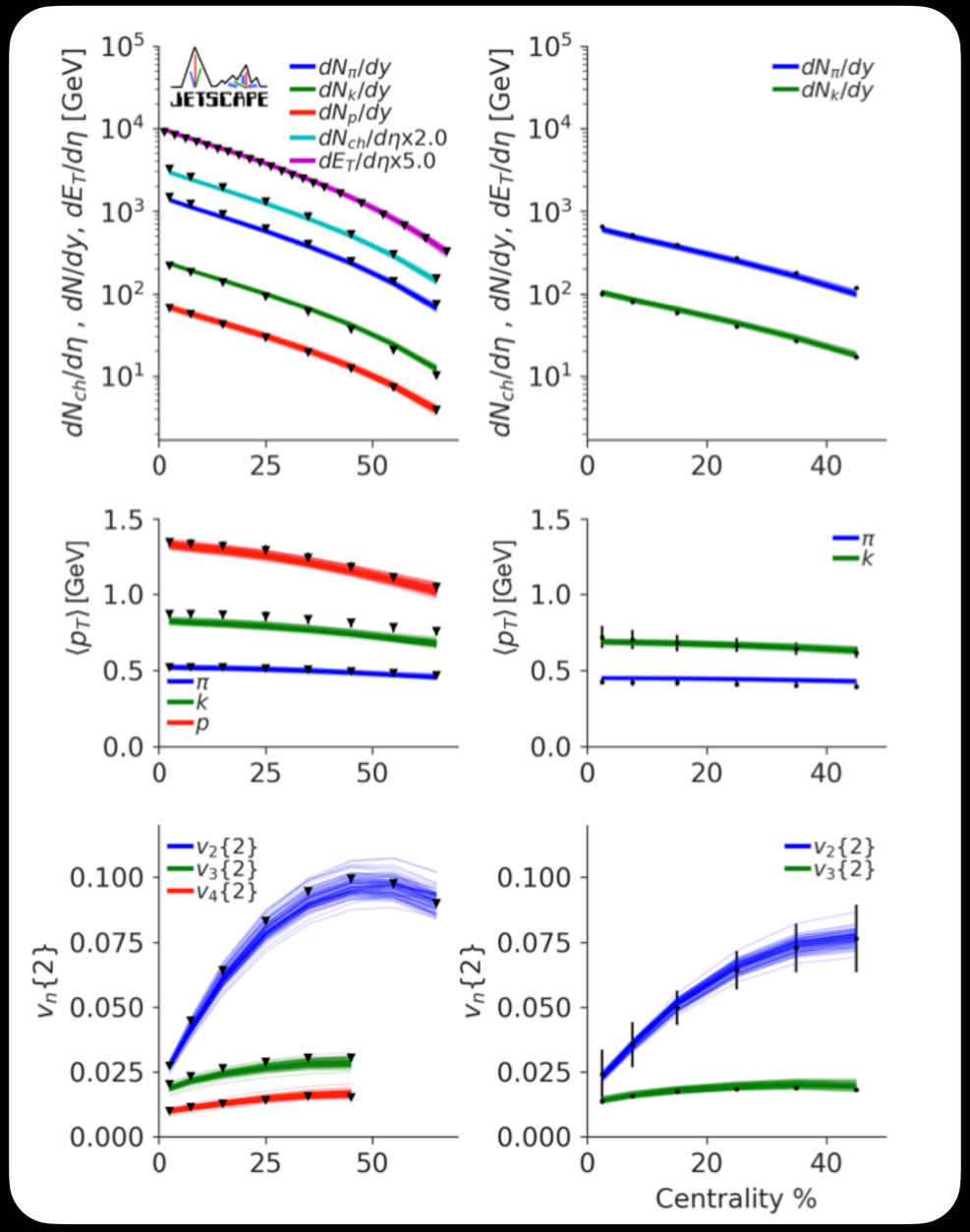
LHC



RHIC



GLOBAL BAYESIAN CONSTRAINTS ON QGP VISCOSITY



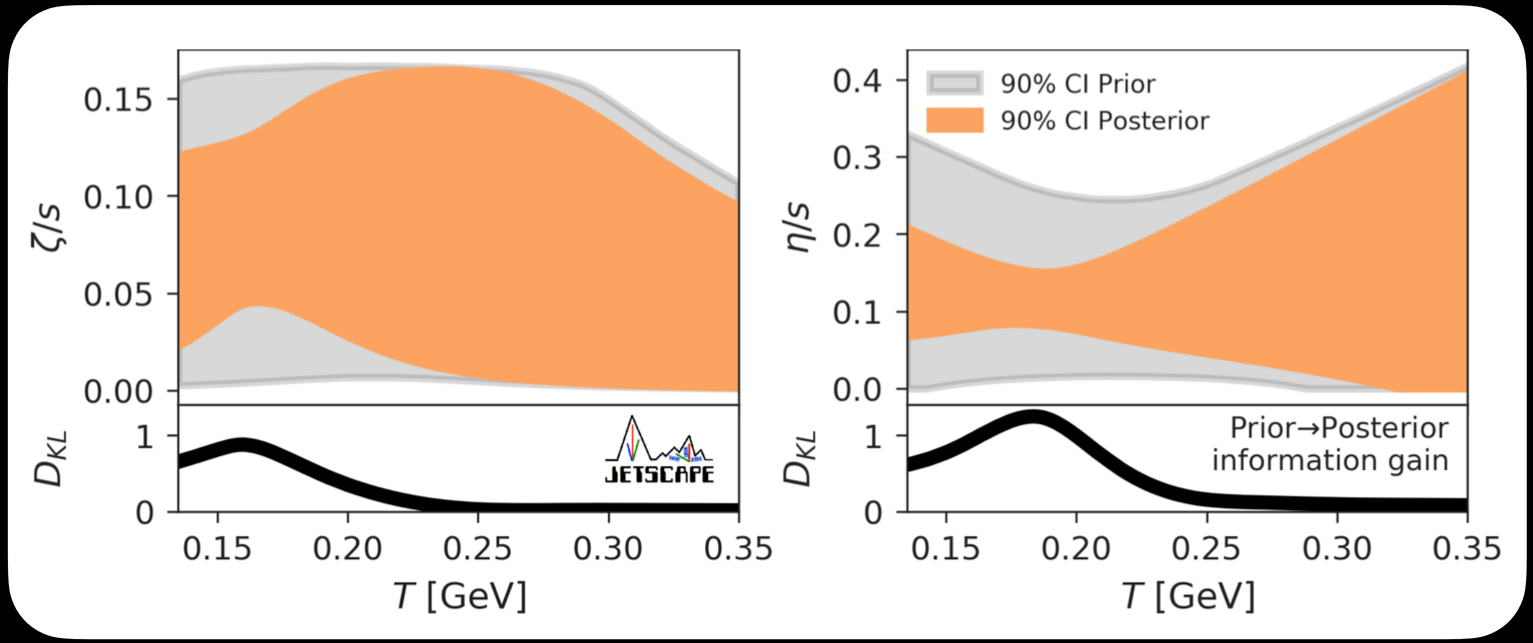
S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Phys. Rev. Lett. 114, 202301 (2015)

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C94, 024907 (2016)

J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, 1113-1117 (2019)

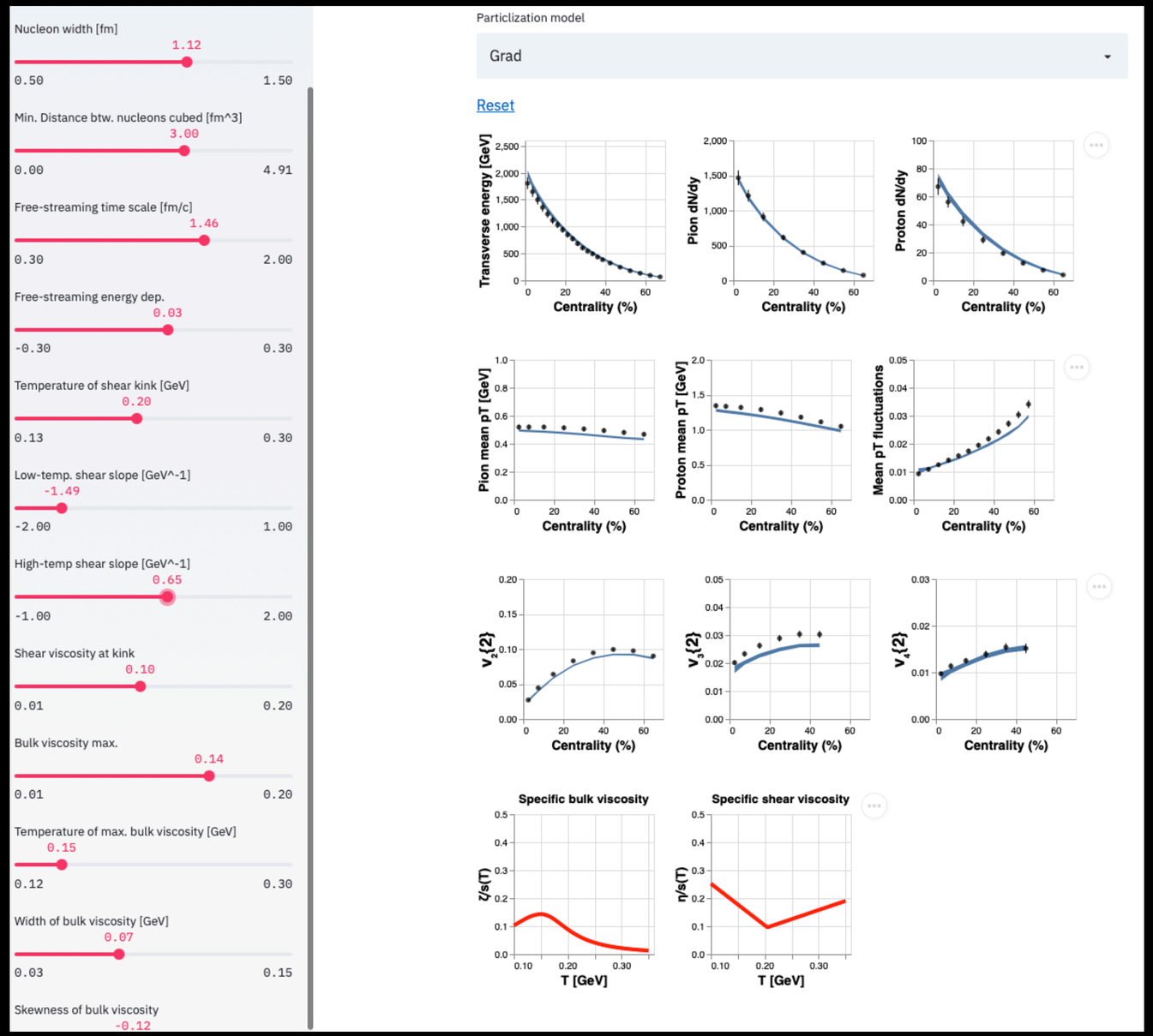
G. Nijs, W. Van Der Schee, U. Gursoy and R. Snellings,
Phys. Rev. Lett. 126, 202301 (2021) & Phys. Rev. C103, 054909 (2021)

D. Everett *et al.* [JETSCAPE], Phys. Rev. Lett. 126, 242301 & Phys. Rev. C103, 054904 (2021)



- Precision hadronic measurements can systematically constrain the QGP viscosity

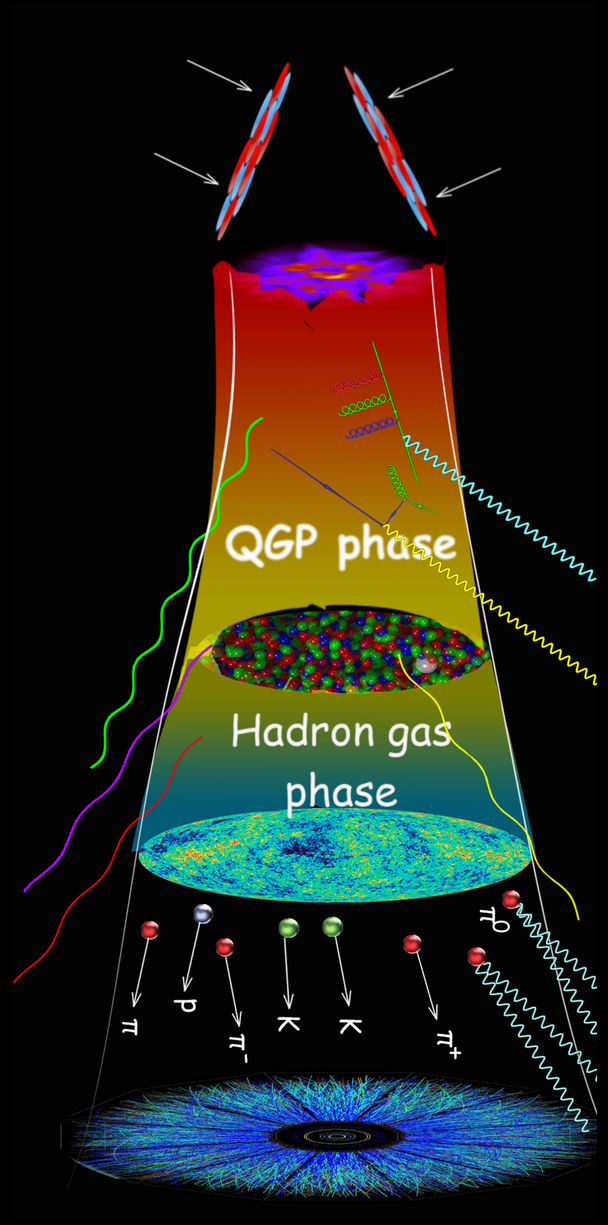
BUILDING INTUITIONS WITH THE JETSCAPE WIDGET

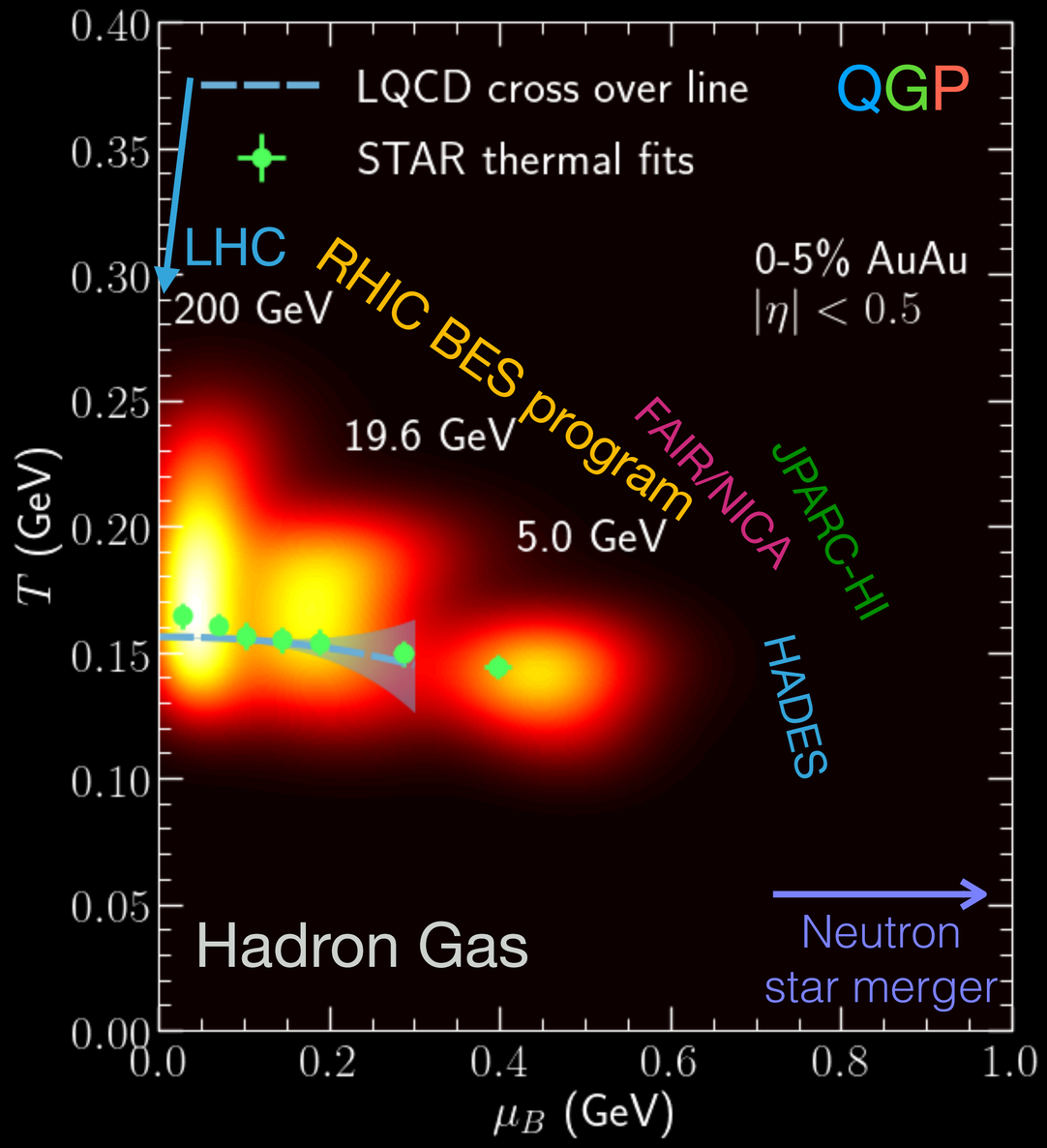


JETSCAPE Widget

http://jetscape.org/sims-widget/

PROBING THE NUCLEAR MATTER PHASE DIAGRAM



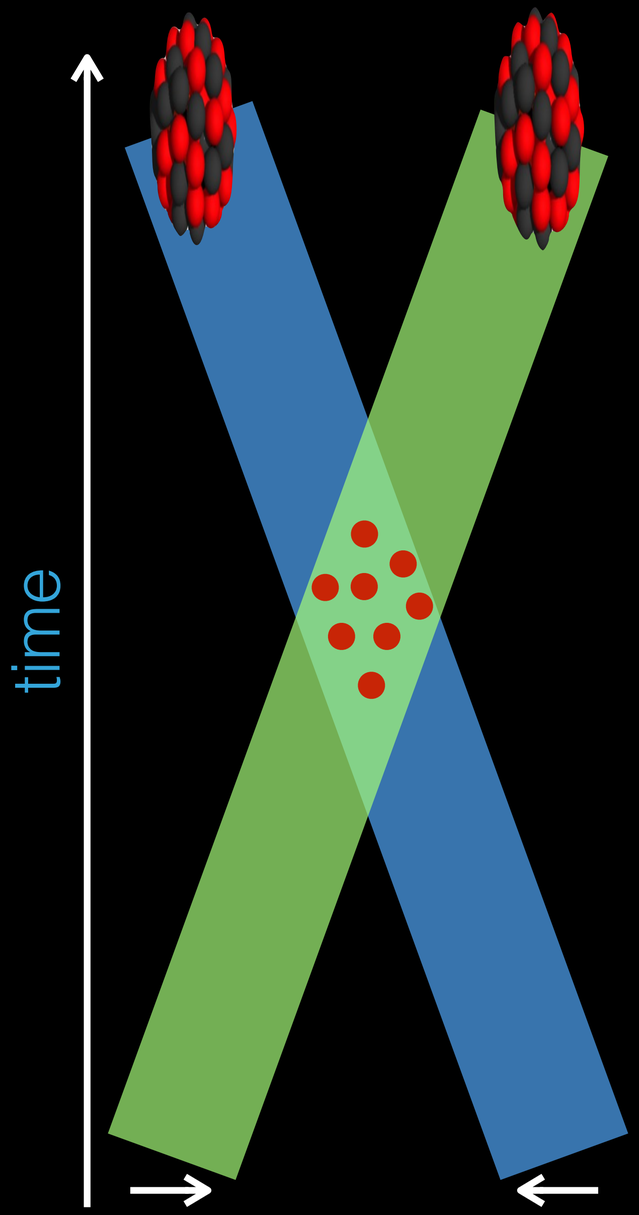


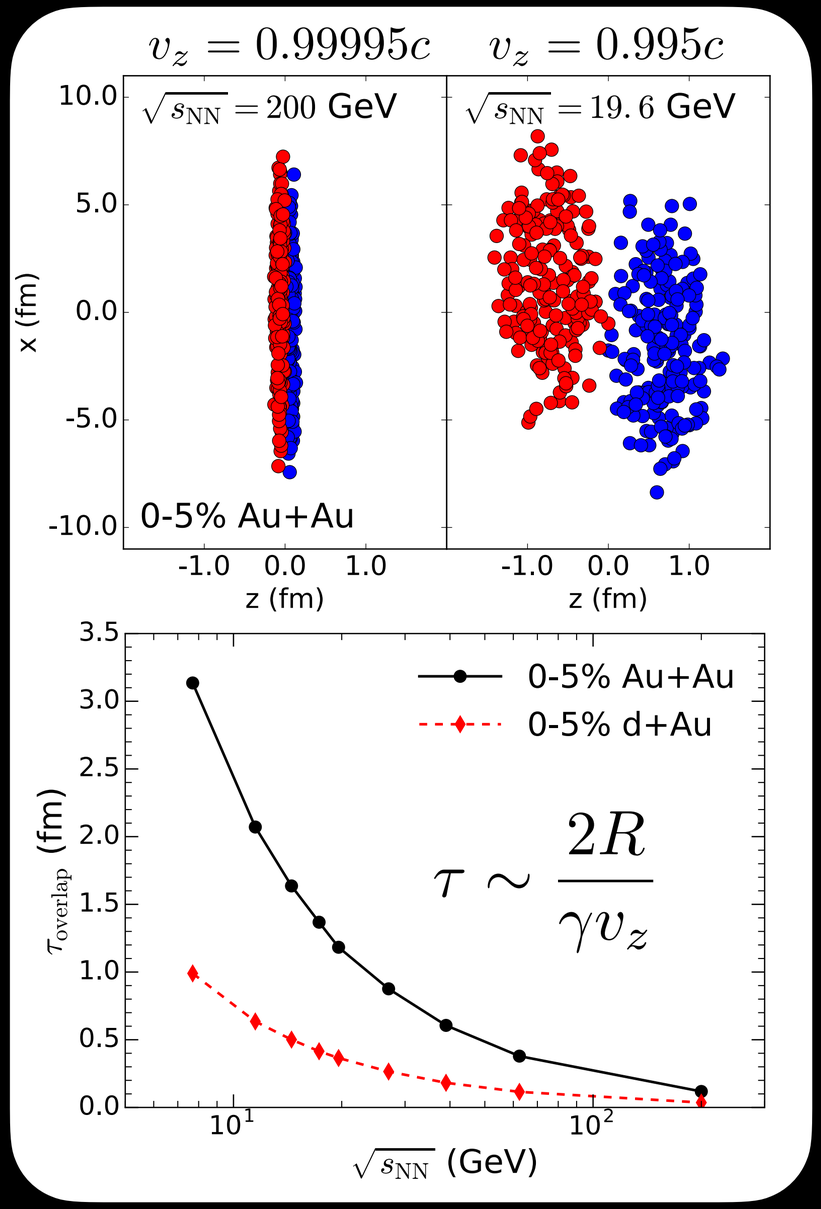
- Search for a critical point & 1st order phase transition
- How does the QGP transport property change with baryon doping?

  $(\eta/s)(T, \{\mu_q\})$, $(\zeta/s)(T, \{\mu_q\})$
- Access to new transport phenomena

  Charge diffusion

3D DYNAMICS BEYOND THE BJORKEN PARADIGM

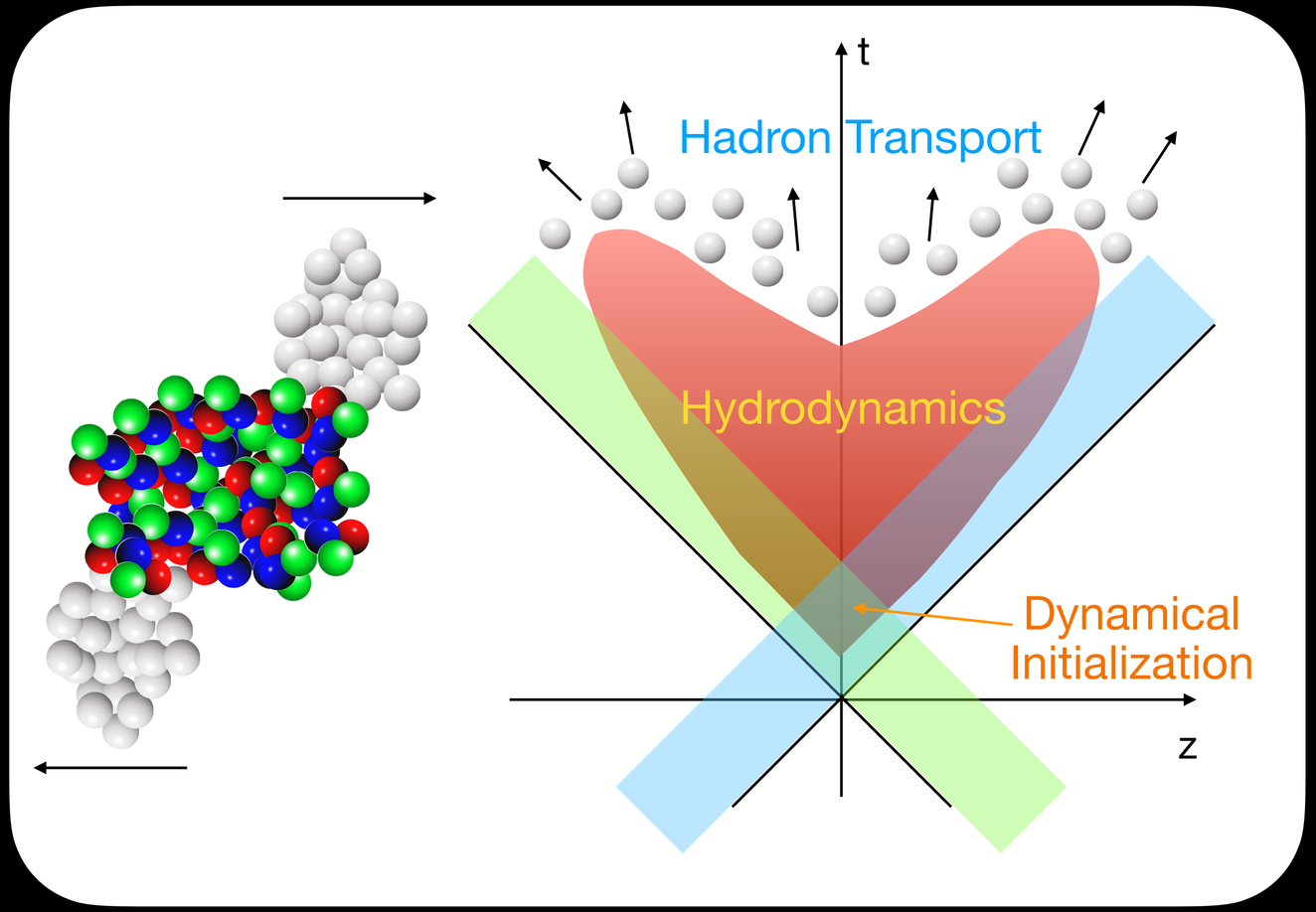




- Geometry-Based initial conditions
  - C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
- Classical string-based initial conditions
  - A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)
  - C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907
- Transport model based initial conditions
  - I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
  - L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410
- Color Glass Condensate based models
  - M. Li and J. Kapusta, Phys. Rev. C 99, 014906 (2019)
  - L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)
  - M. Martinez, M. D. Sievert, D. E. Wertepny and J. Noronha-Hostler, arXiv:1911.10272 + arXiv:1911.12454 [nucl-th]
- Holographic approach at intermediate coupling
  - M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

HYDRODYNAMICS WITH SOURCES

Energy-momentum current and net baryon density are fed into hydrodynamic simulations as source terms



$$\partial_\mu T^{\mu\nu} = J^\nu_{\rm source}$$

$$\partial_\mu J^\mu = \rho_{\rm source}$$

M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, Phys. Rev. C95, 054914 (2017)

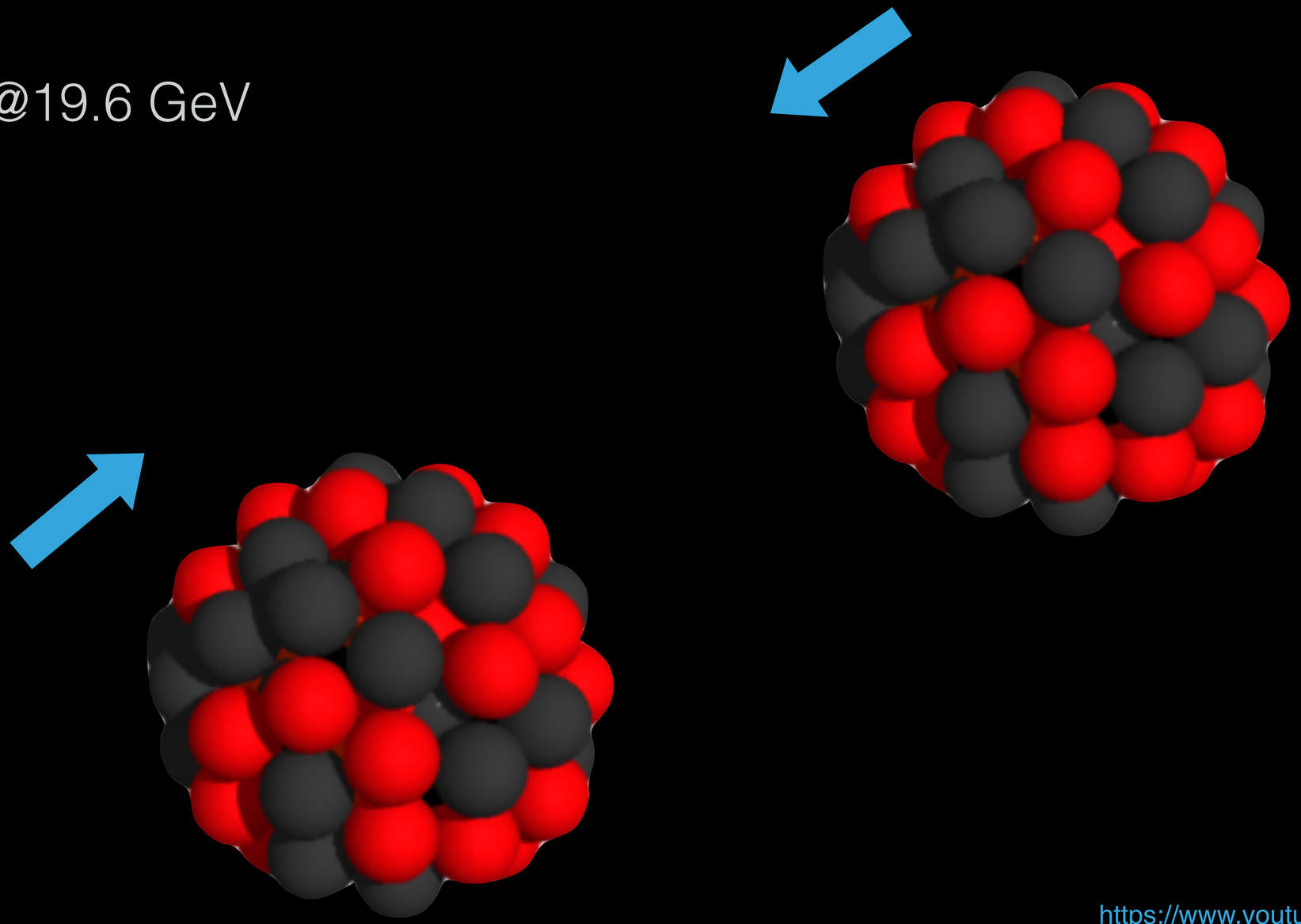
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907

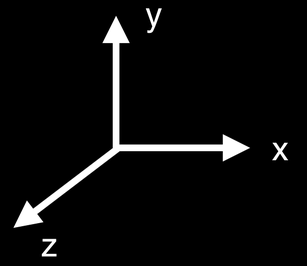
L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410

Y. Akamatsu, M. Asakawa, T. Hirano, M. Kitazawa, K. Morita, K. Murase, Y. Nara, C. Nonaka and A. Ohnishi, Phys. Rev. C98, 024909 (2018)

RELATIVISTIC HEAVY-ION COLLISIONS

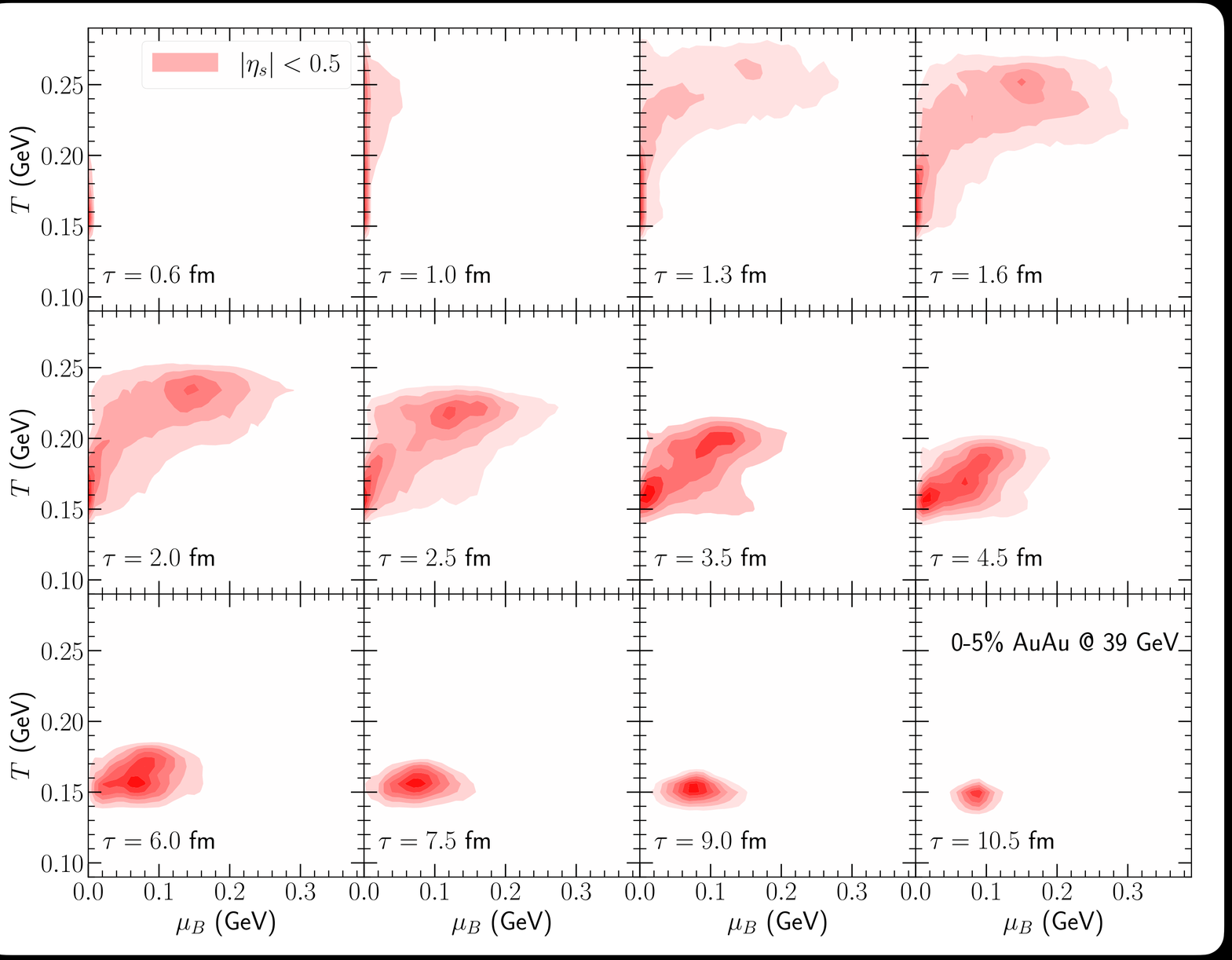
0-5% AuAu@19.6 GeV





https://www.youtube.com/watch?v=gFV-9VeqzkE

FLOWING THROUGH THE QCD CROSSOVER REGION

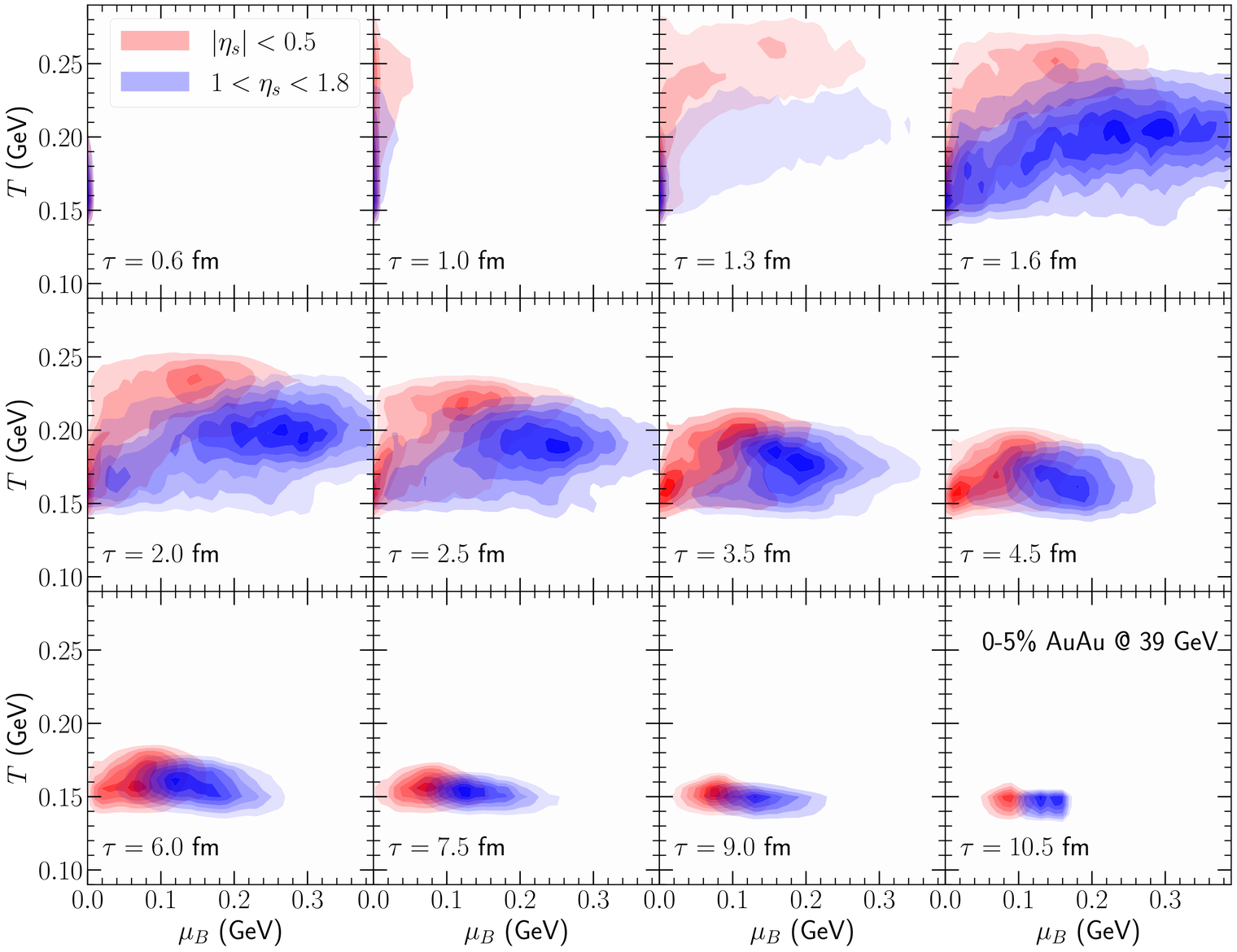


Nuclei overlap
Dynamical Initialization stage
Baryon dopping

Hydrodynamics evolution

Switching to hadronic transport

FLOWING THROUGH THE QCD CROSSOVER REGION



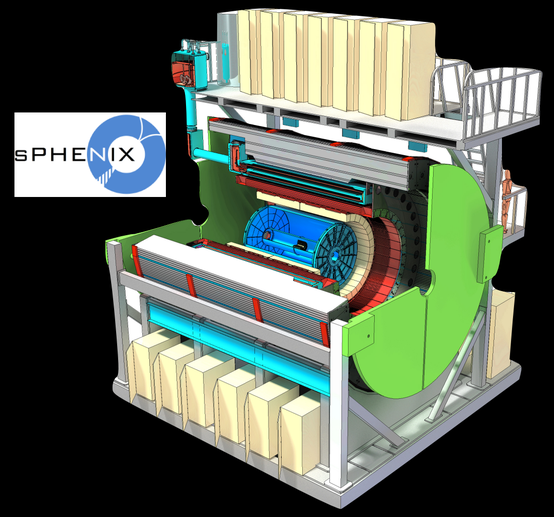
Nuclei overlap
Dynamical Initialization stage
Baryon dopping

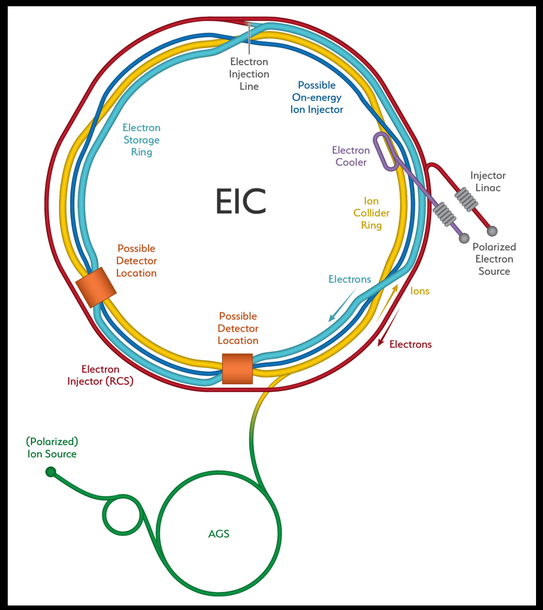
Hydrodynamics evolution

Switching to hadronic transport

THE ERA OF MULTI-MESSENGER HEAVY-ION PHYSICS

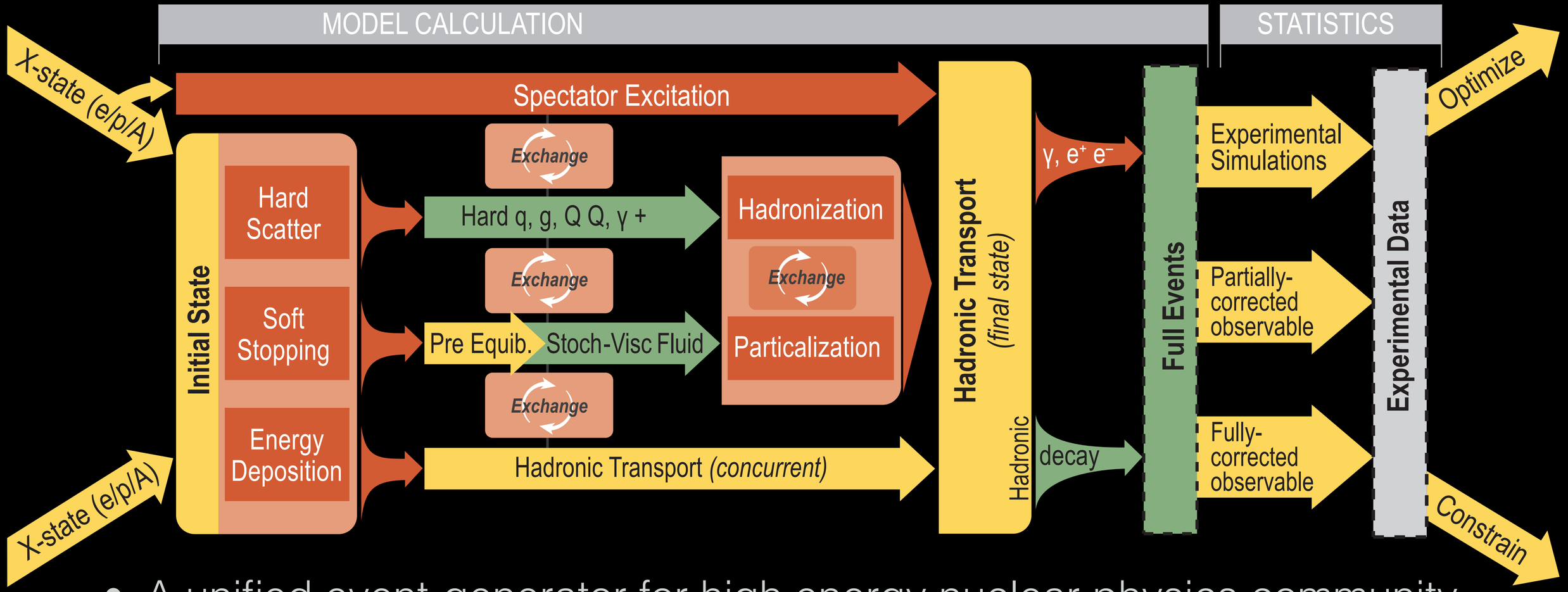
- RHIC: STAR upgrade and sPHENIX program
  - Probing QCD at high net baryon density
  - Study fully resolved jets, Upsilon states, and heavy quarks as QGP structure probes
- LHC: ALICE, CMS, ATLAS upgrades
  - High energy and high luminosity frontier
  - Precision measurements for rare probes
- HADES, FAIR, NICA, J-PAC-HI
  - Phase structure of hot QCD matter
- Future Electron-Ion Collider
  - Tomography of nucleon and nucleus





THE NEXT GENERATION JETSCAPE FRAMEWORK

- The XSCAPE Project



- A unified event-generator for high energy nuclear physics community

SUMMARY

- The vibrant experimental programs with precision measurements have been driving heavy-ion physics to the multi-messenger era

  Unified theoretical + statistical frameworks are *essential* to unravel physics

- Viscous relativistic hydrodynamics provides a **robust**, **reliable**, **efficient**, and **accurate** description of QGP evolution in heavy-ion collisions

  state-of-the-art lattice QCD inputs

  a few remarkable quantitative predictions

  model parameters has direct connection to the physics properties of the strongly-couple QGP