Dynamical Models
& the fluid nature of the QGP

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2023年7月10-25日

July 18 2023

Landscape of nuclear physics

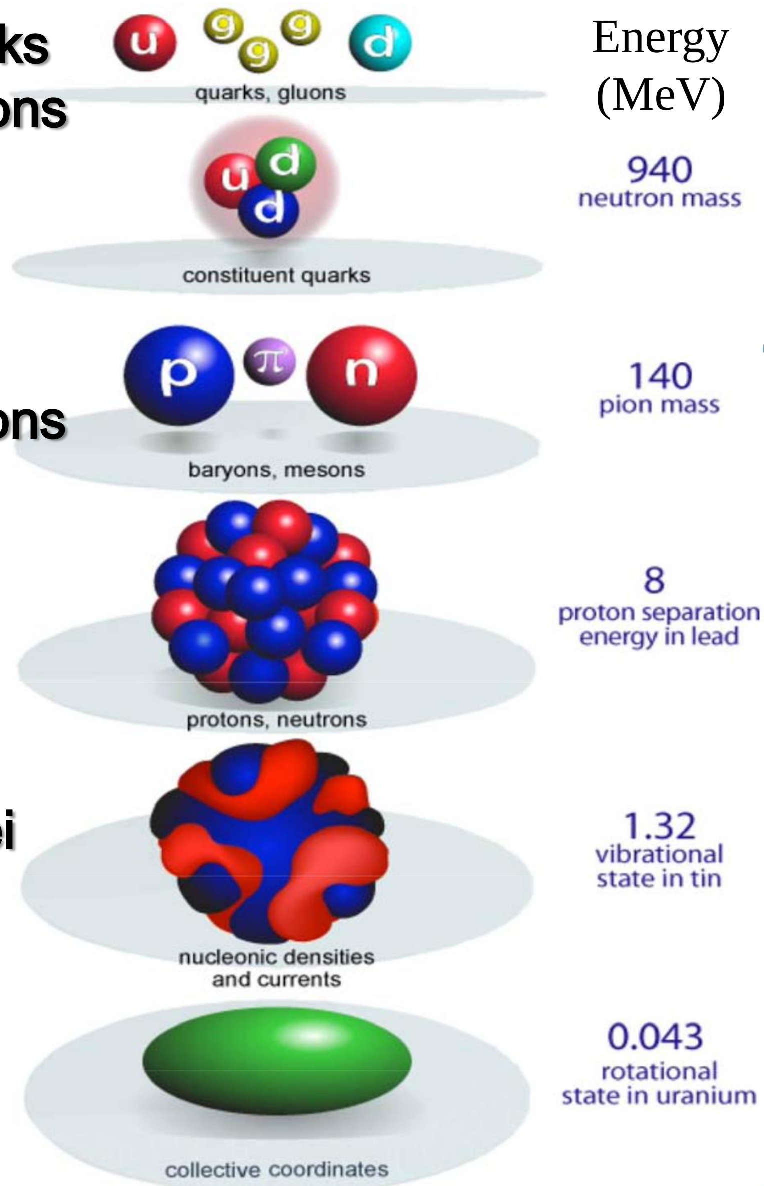
degrees of freedeom

Energy (MeV)

quarks & gluons

hadrons

nuclei



Landscape of nuclear physics

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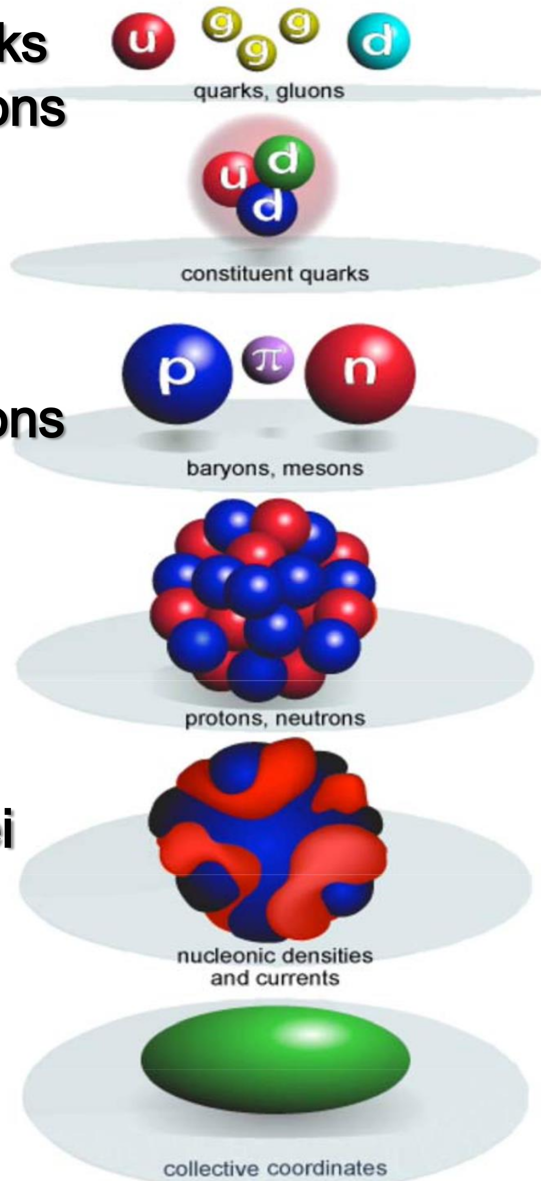


Energy (MeV)

940
neutron mass

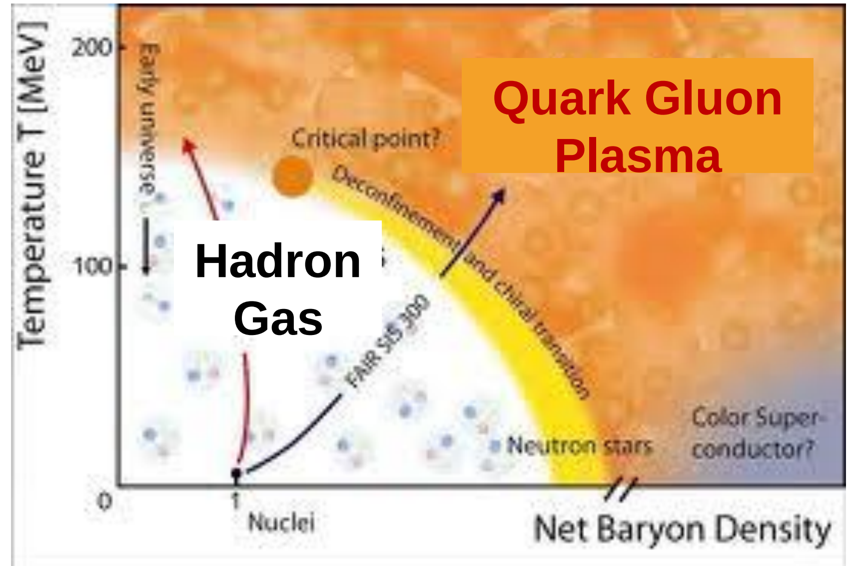
140
pion mass

8
proton separation energy in lead

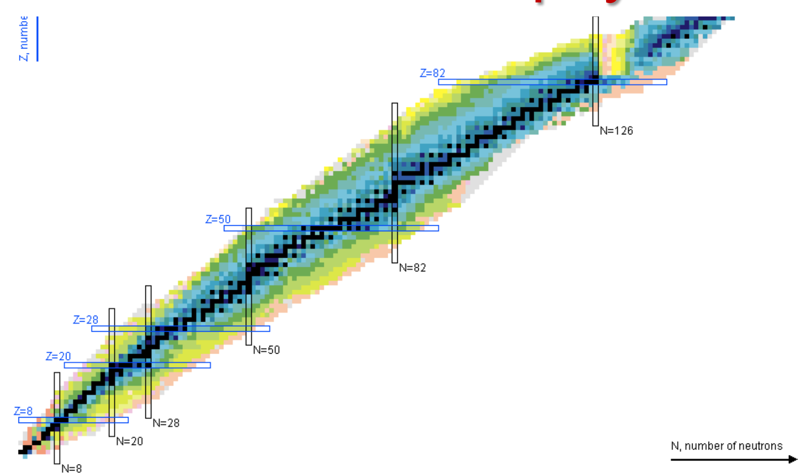
1.32
vibrational state in tin

0.043
rotational state in uranium

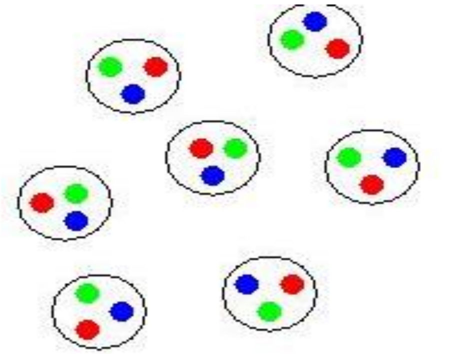
-intermediate and high energy nuclear physics



-nuclear structure physics



Nuclear Matter

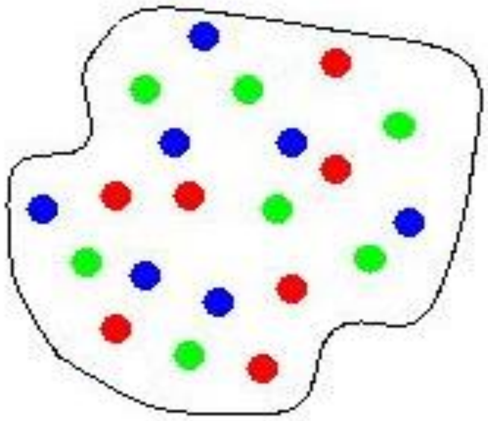


Confinement

Phase Transition

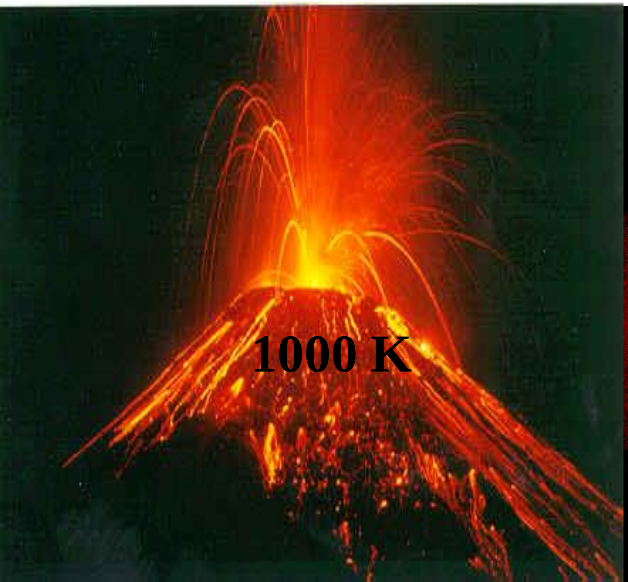
$T_c \sim 2X10^{12}$ **K**

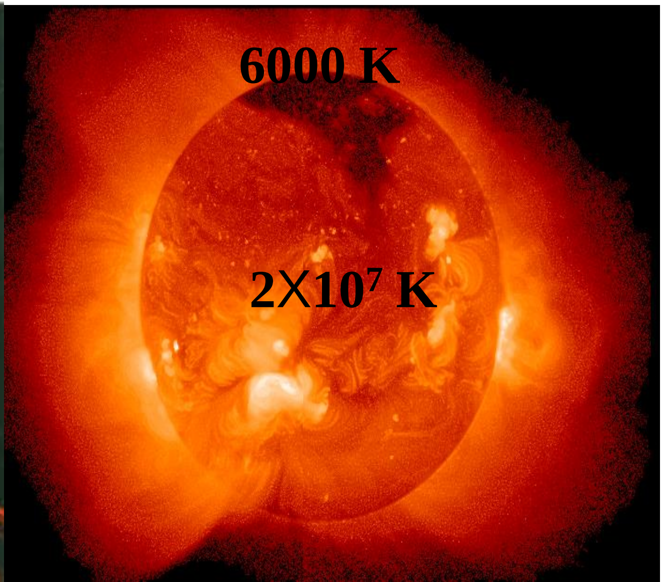
Quark Gluon Plasma

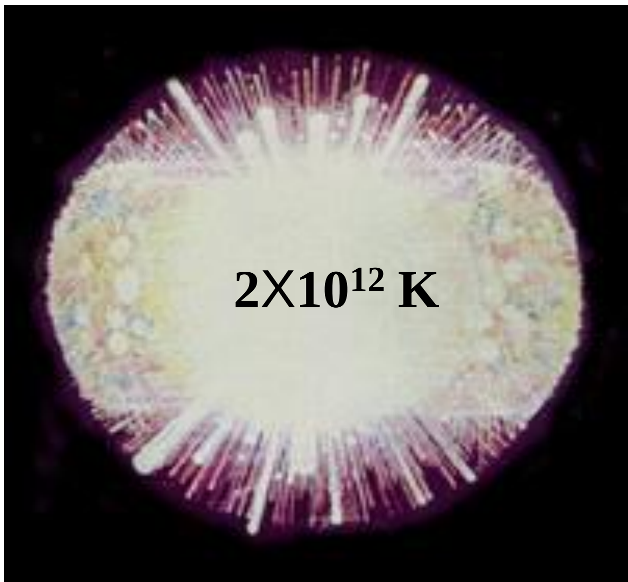


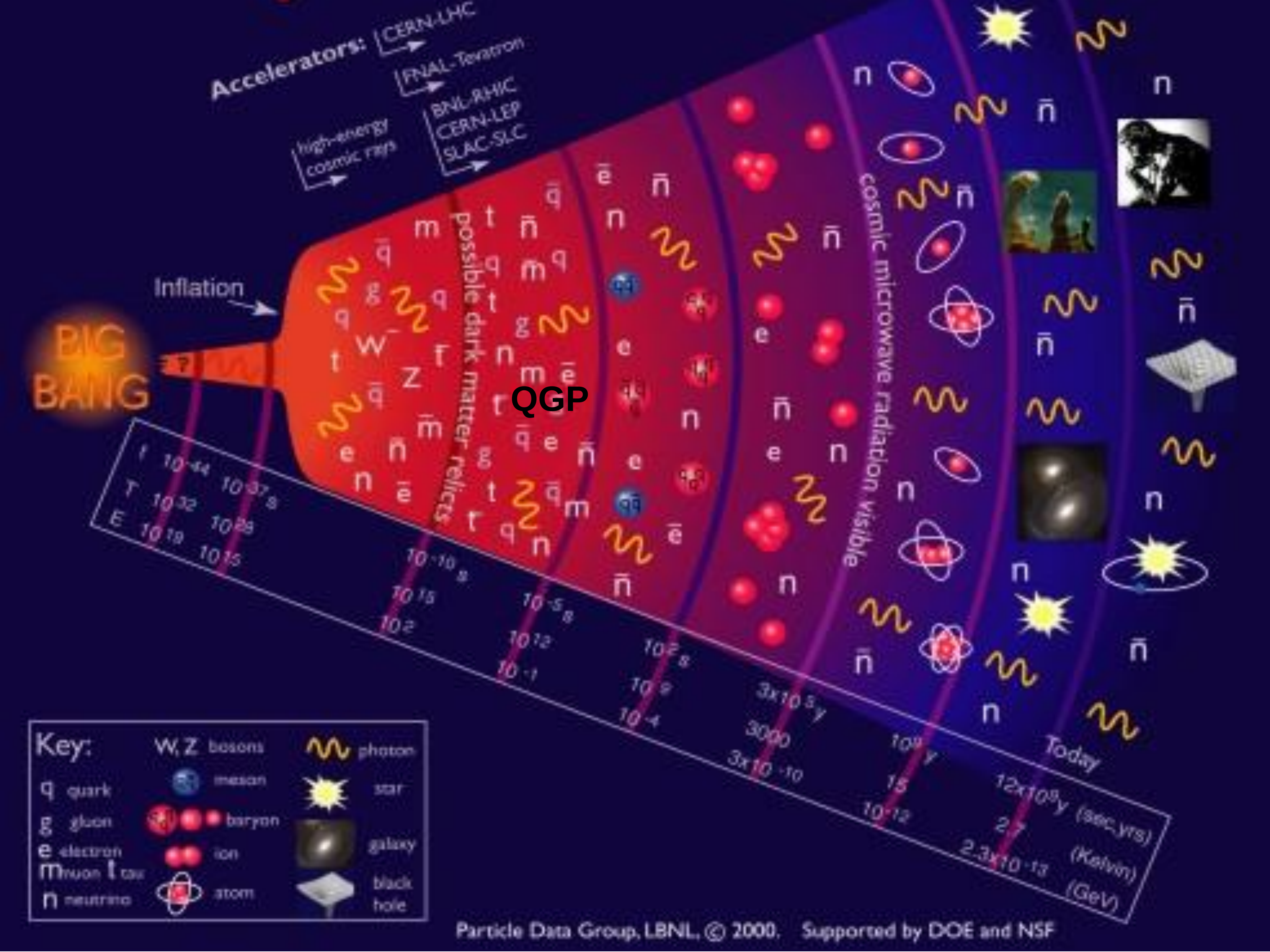
Deconfinement

QGP (quark gluon plasma): a deconfinement phase of the QCD matter

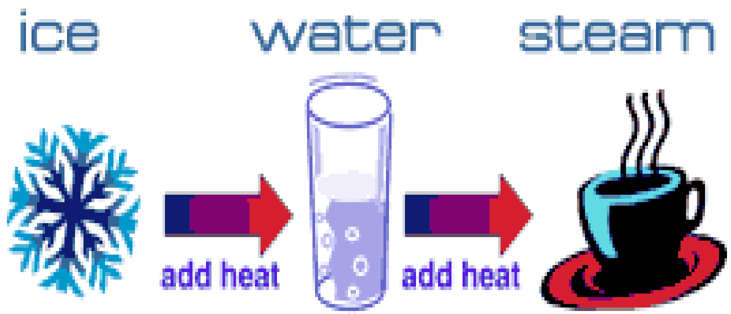


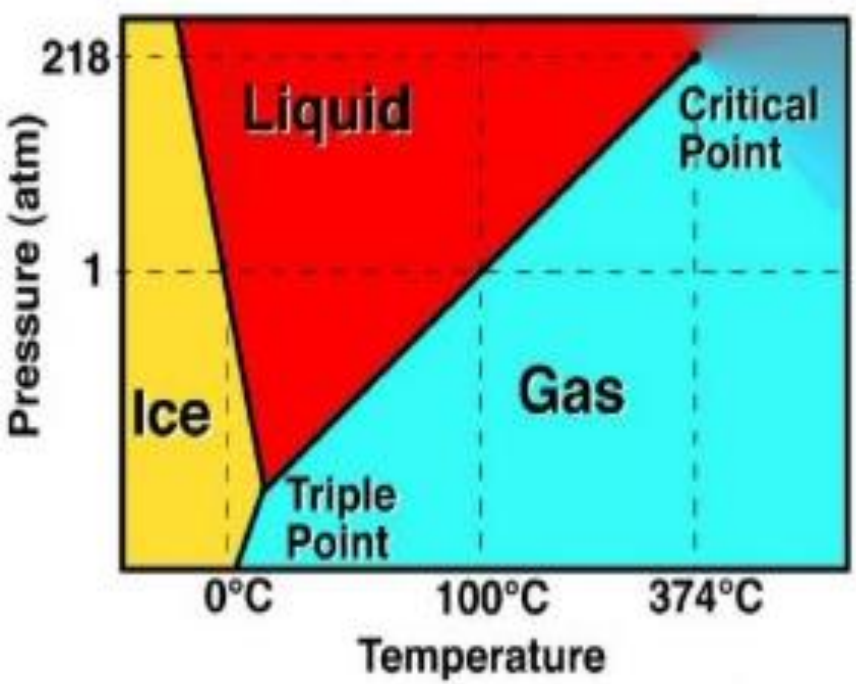




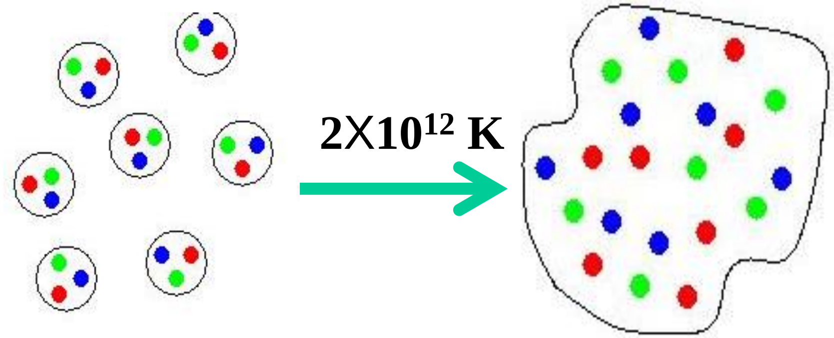

Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
QGP
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec, yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

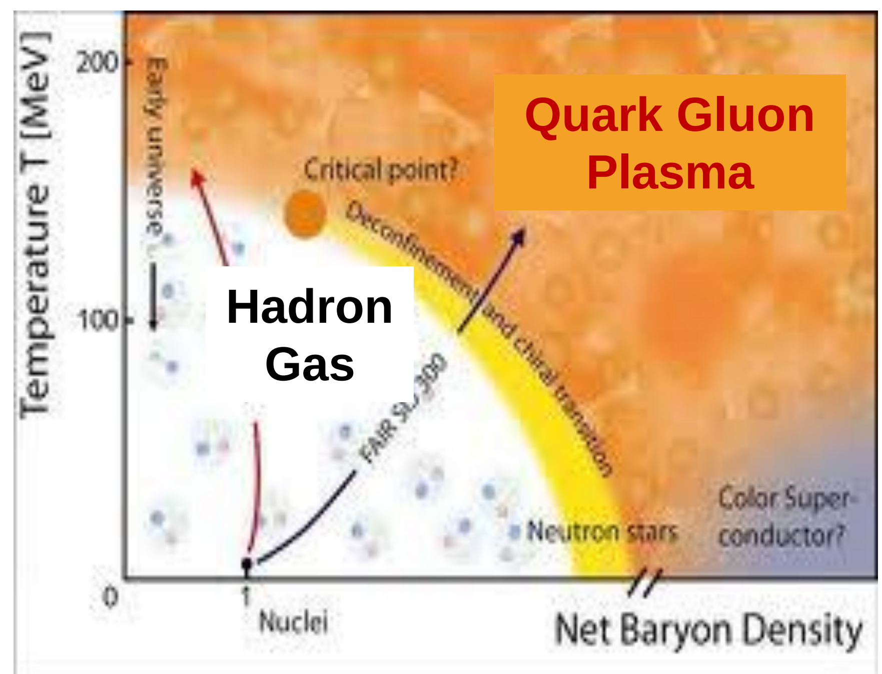
Phases diagram





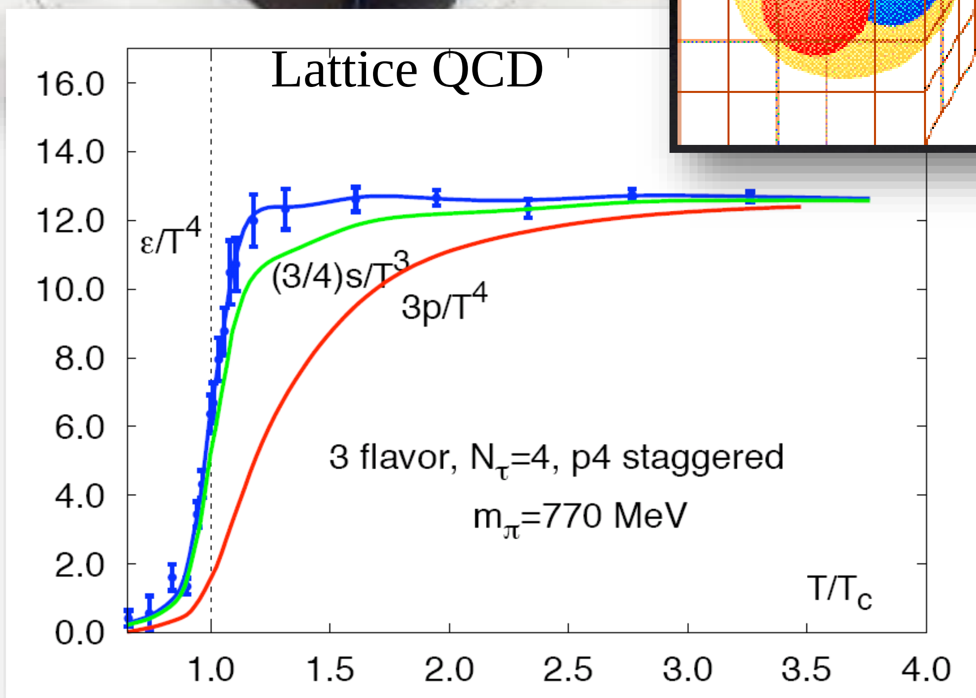
determined by electromagnetic interactions

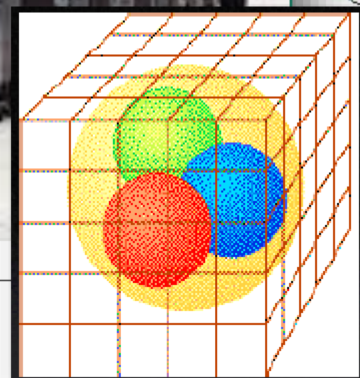


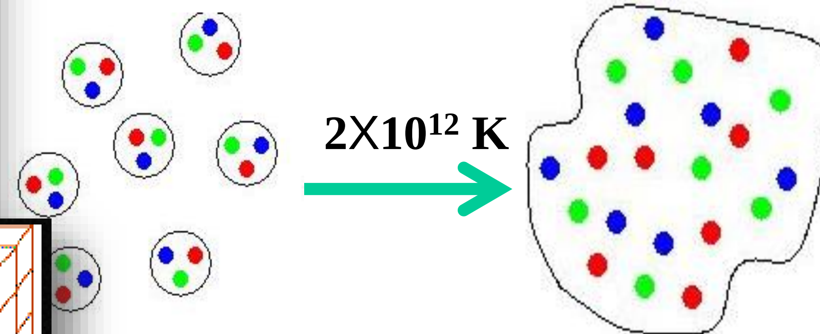


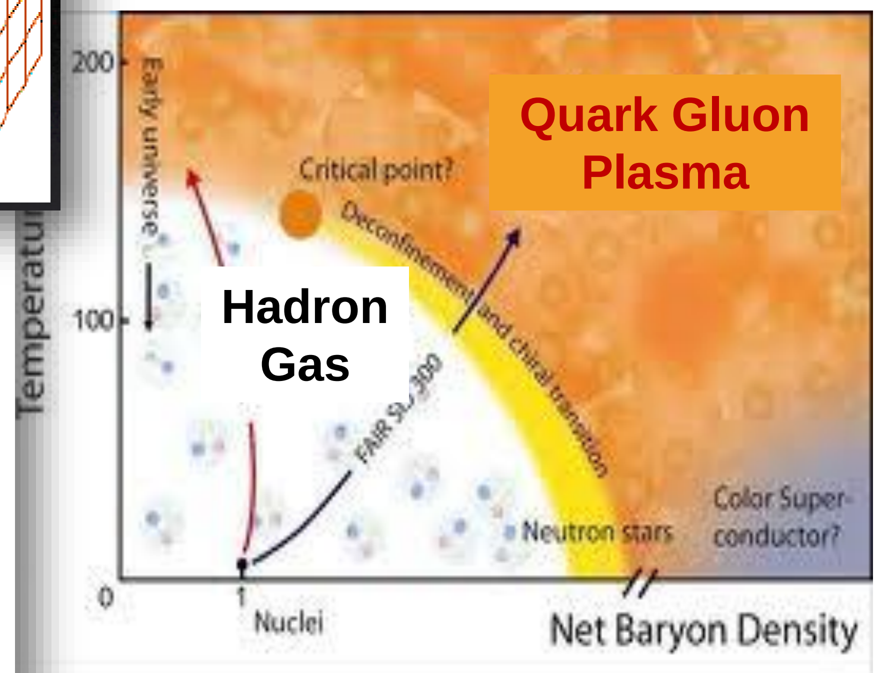
determined by strong interactions

s diagram









determined by **strong** interactions

A brief history of relativistic heavy ion physics

1974: Workshop on "GeV/nucleon collisions of heavy ions"

We should investigate.... phenomena by distributing energy of high nucleon density of a relatively large volume"
---T.D.Lee

1984: SPS starts, (end 2003)

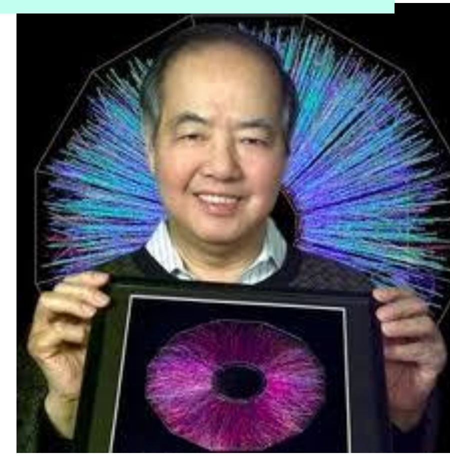
1986: AGS stars, (end 2000)

2000: RHIC starts

2010: LHC starts

Future: FAIR & NICA

A brief history of relativistic heavy ion physics



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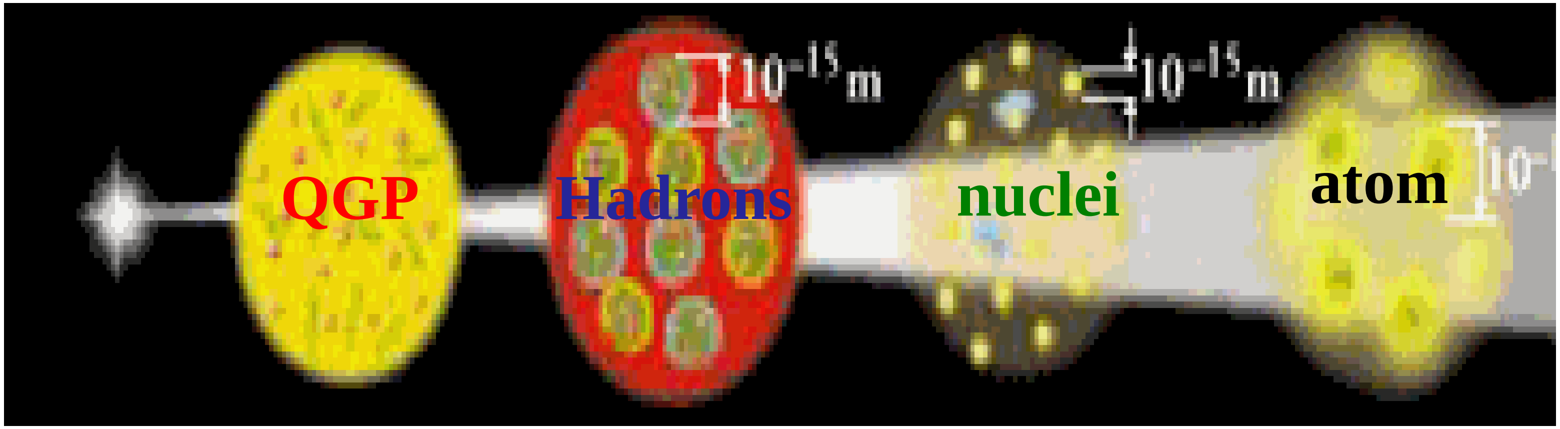
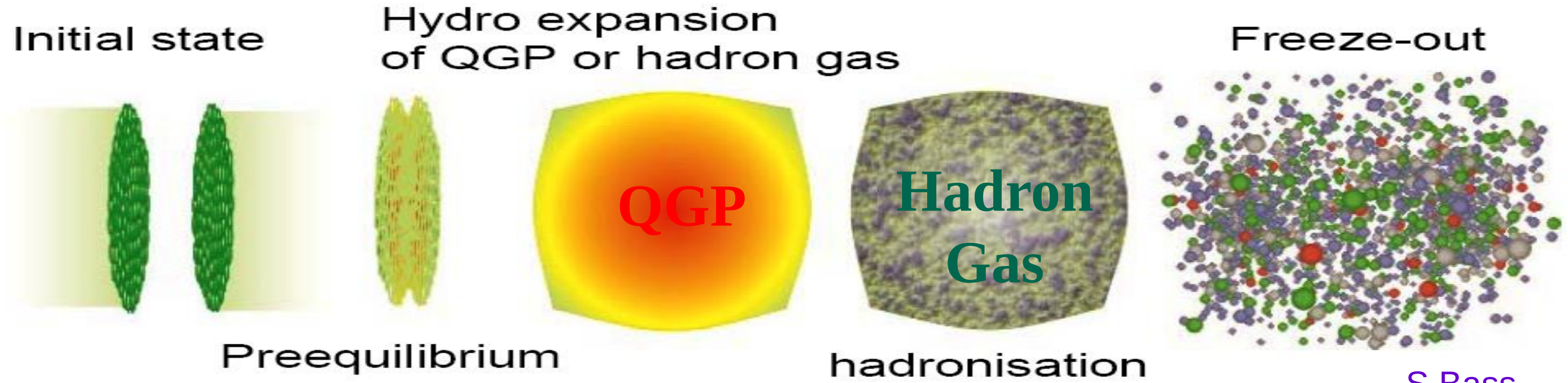
核子重如牛，对撞生新态

big bang: the very early history of the universe



little bang: the different stage for a relativistic heavy ion collisions



S.Bass

QGP-the most perfect fluid in the world

BNL News, 2005

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've 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. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

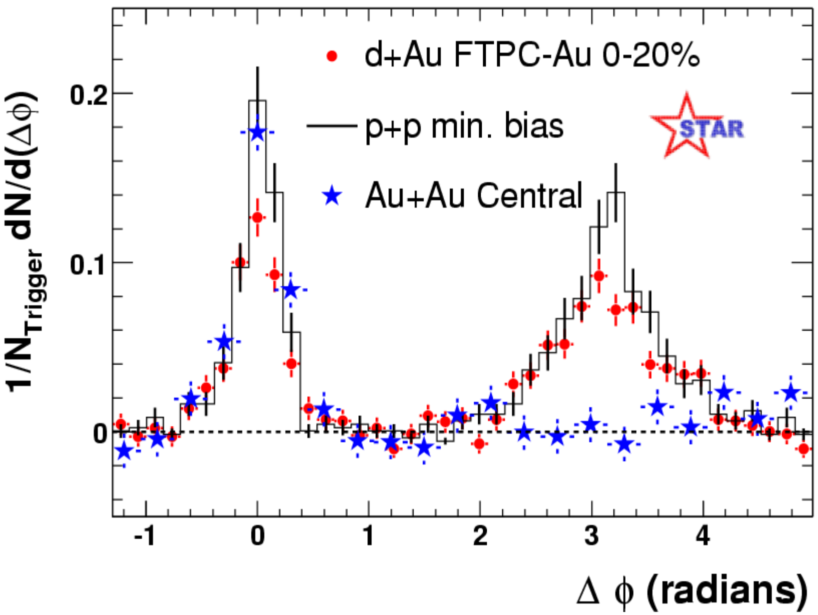
Secretary of Energy Samuel Bodman

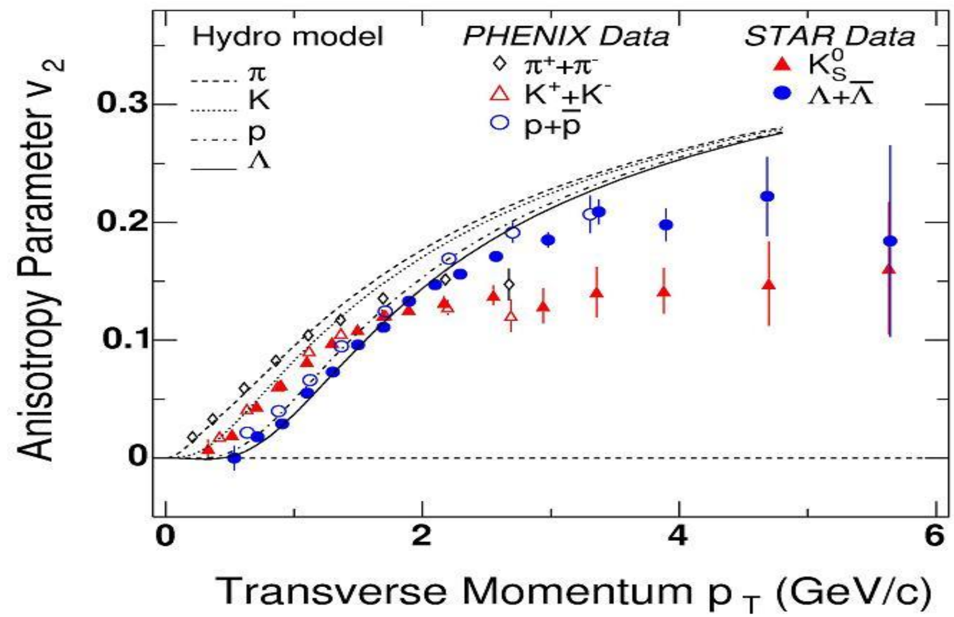
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

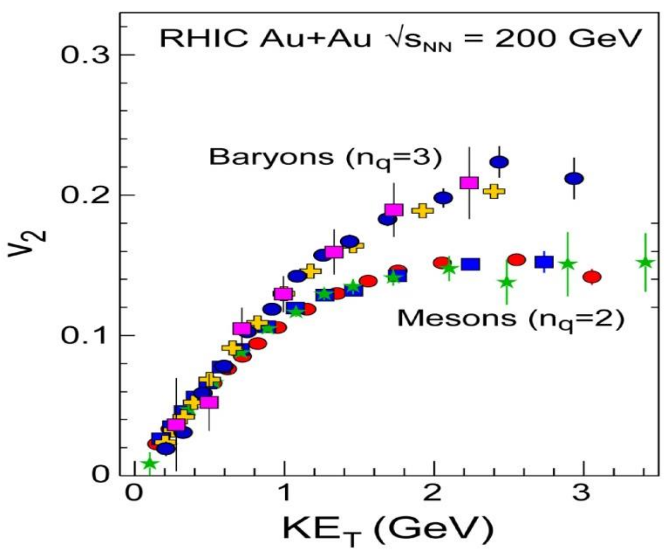
Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

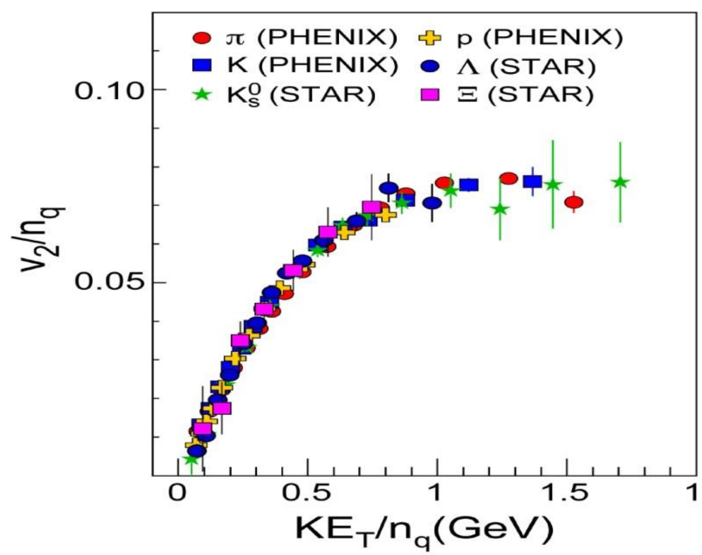
The QGP was discovered

RHIC (2000--   )







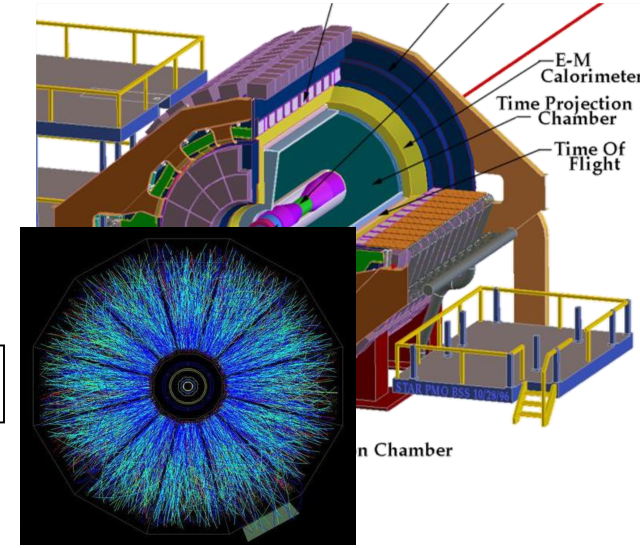


Theoretical tools for QGP evolution

Life time~ 10^{-23} s

size~ 10^{-14} m

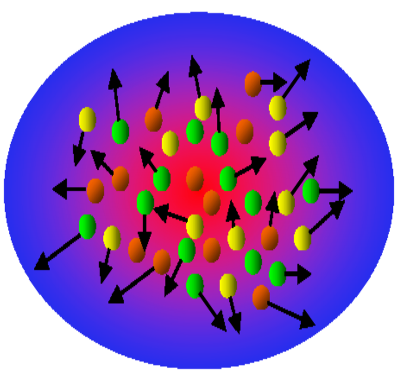
Numerical simulation



Dynamical Model

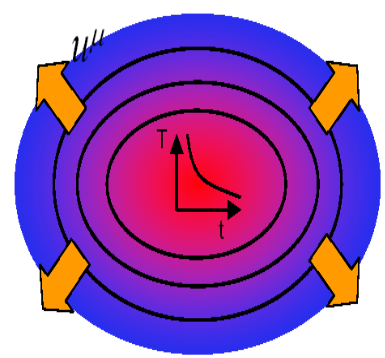
Boltzmann approach

microscopic view



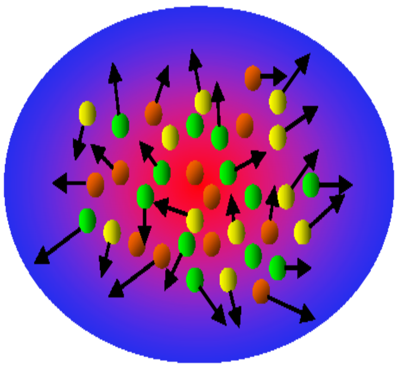
Hydrodynamics

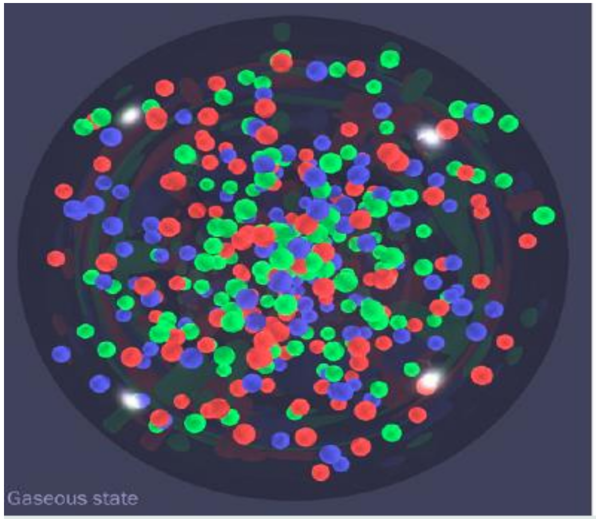
macroscopic view



Boltzmann approach

microscopic view

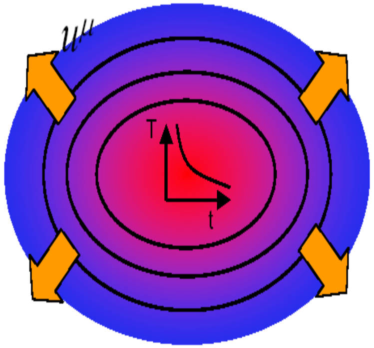


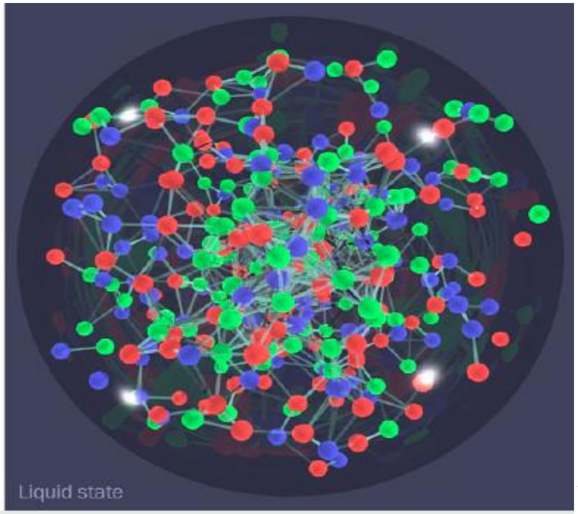


Gas: particles only know about each other when they bump

Hydrodynamics

macroscopic view

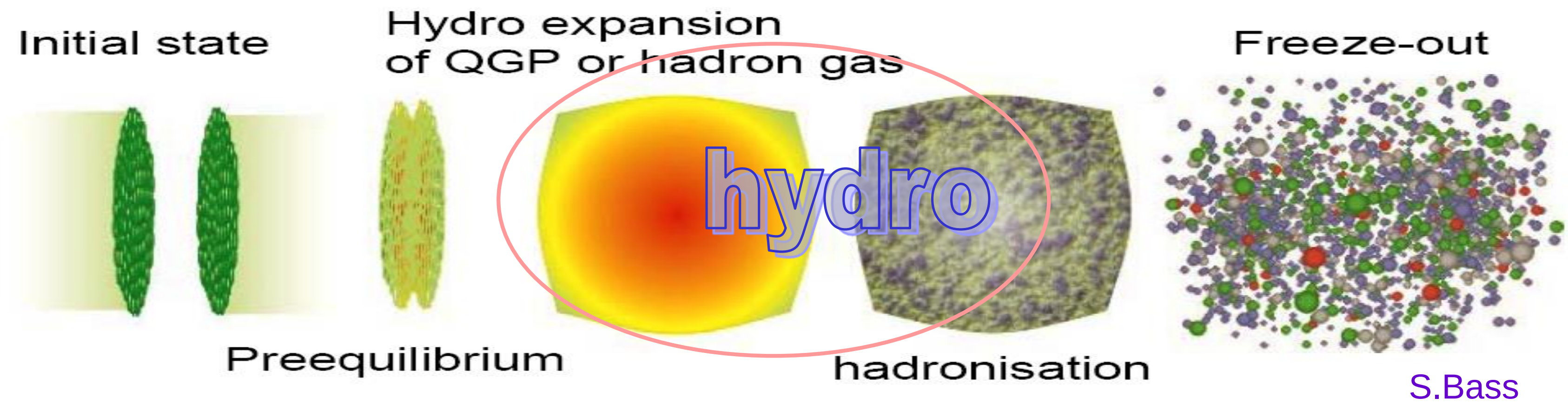




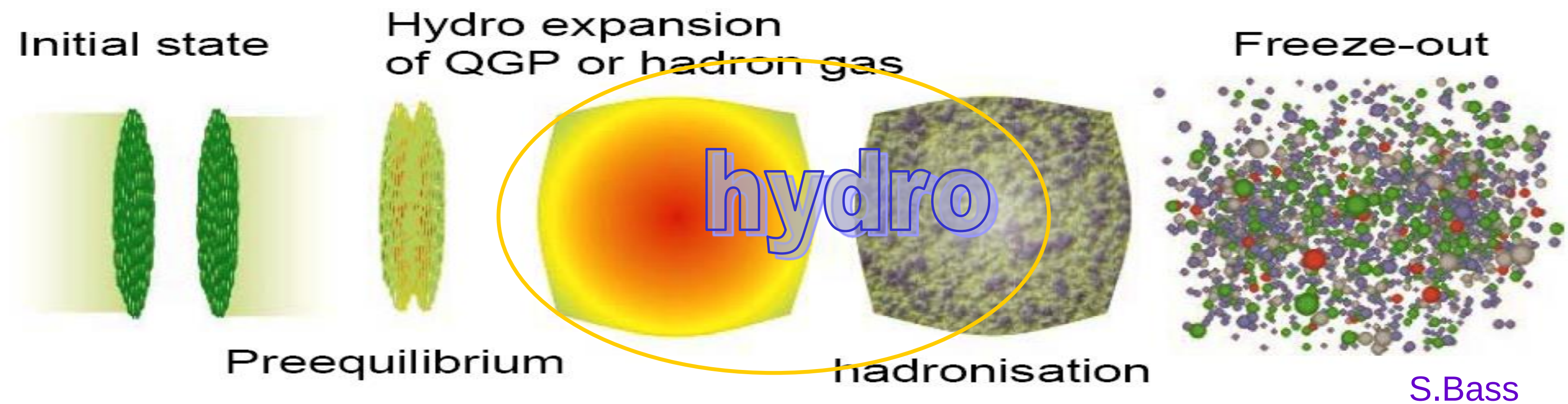
Liquid: particles exert forces on one another all the time, flows in a coordinated fashion

Hydrodynamics

ideal hydro	**viscous hydro**
$\partial_\mu S^\mu = 0$	$\partial_\mu S^\mu \geq 0$
Local equilibrium system	**Near equilibrium** system
$e(x)$ $p(x)$ $n(x)$ $u^\mu(x)$	$e(x)$ $p(x)$ $n(x)$ $u^\mu(x)$
	$\pi^{\mu\nu}(x)$ $\Pi(x)$



hydrodynamics



Hydrodynamics:

-A macroscopic tool to describe the expansion of QGP or hadronic matter

Conservation laws

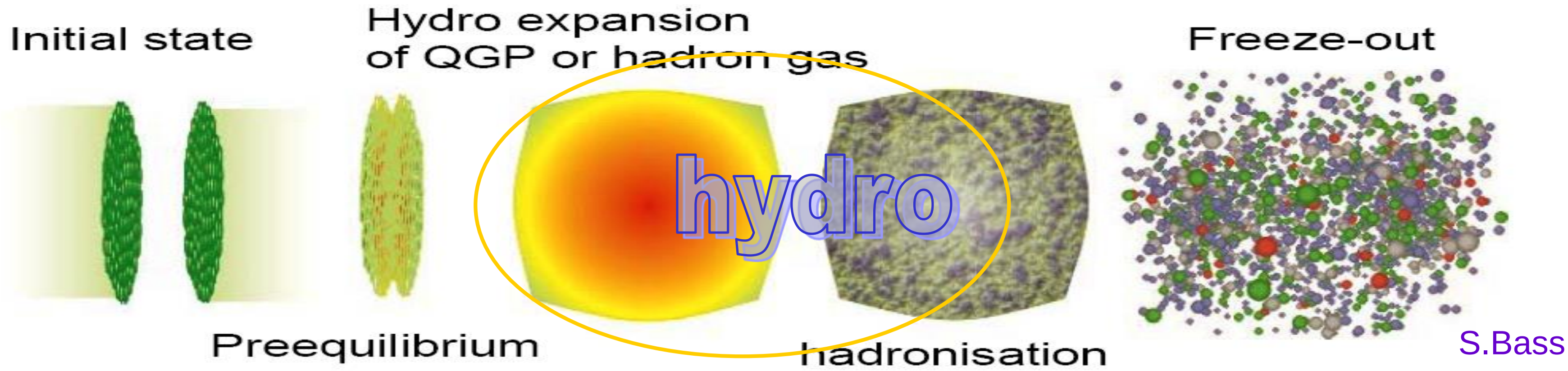
$$\partial_\mu N^\mu(x) = 0$$

$$\partial_\mu T^{\mu\nu}(x) = 0$$

5 equ. 14 independent variables

- reduce # of independent variables (ideal hydro)
- or provide more equations? (viscous hydro)

Viscous hydrodynamics



Conservation laws:

$$\partial_\mu T^{\mu\nu}(x) = 0\,. \qquad \partial_\mu N_i^\mu(x) = 0\,,$$

2nd order I-S equ:

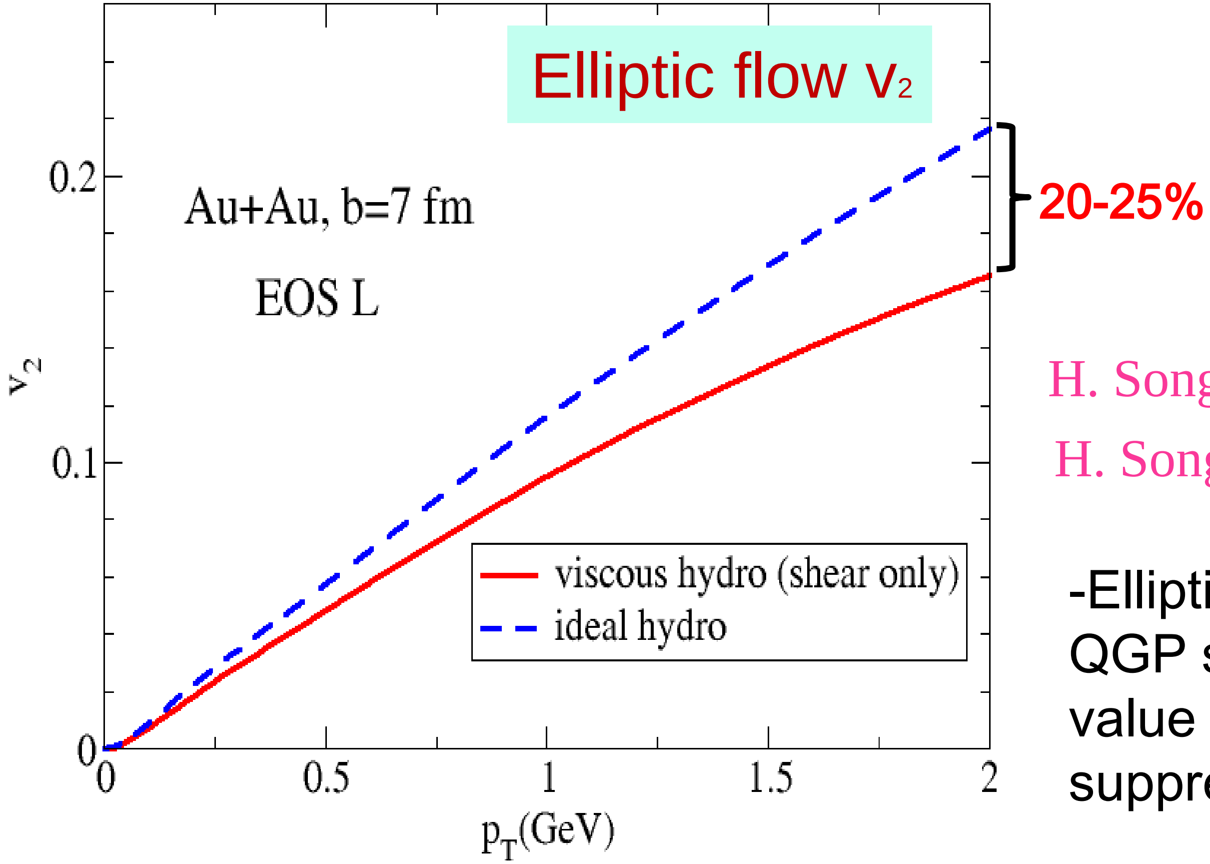
$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\Big[\Pi + \zeta\theta - l_{\Pi q}\nabla_\mu q^\mu + \Pi\zeta T\partial_\mu\big(\frac{\tau_\Pi u^\mu}{2\zeta T}\big)\Big],$$

$$\Delta^\mu_\nu \dot{q}^\nu = -\frac{1}{\tau_q}\Big[q_\mu + \lambda\frac{nT^2}{e+p}\nabla^\mu\frac{\nu}{T} + l_{q\pi}\nabla_\nu\pi^{\mu\nu} + l_{q\Pi}\nabla^\mu\Pi - \lambda T^2 q^\mu\partial_\mu\big(\frac{\tau_q u^\mu}{2\lambda T^2}\big)\Big],$$

$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\Big[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - l_{\pi q}\nabla^{\langle\mu}q^{\nu\rangle} + \pi_{\mu\nu}\eta T\partial_\alpha\big(\frac{\tau_\pi u^\alpha}{2\eta T}\big)\Big],$$

Input: "EOS" $\boldsymbol{\varepsilon = \varepsilon(p)}$ initial and final conditions

Viscous hydro: Shear viscosity η & elliptic flow V2



$\frac{\eta}{s} = \frac{1}{4\pi}$

H. Song and U. Heinz, PLB08

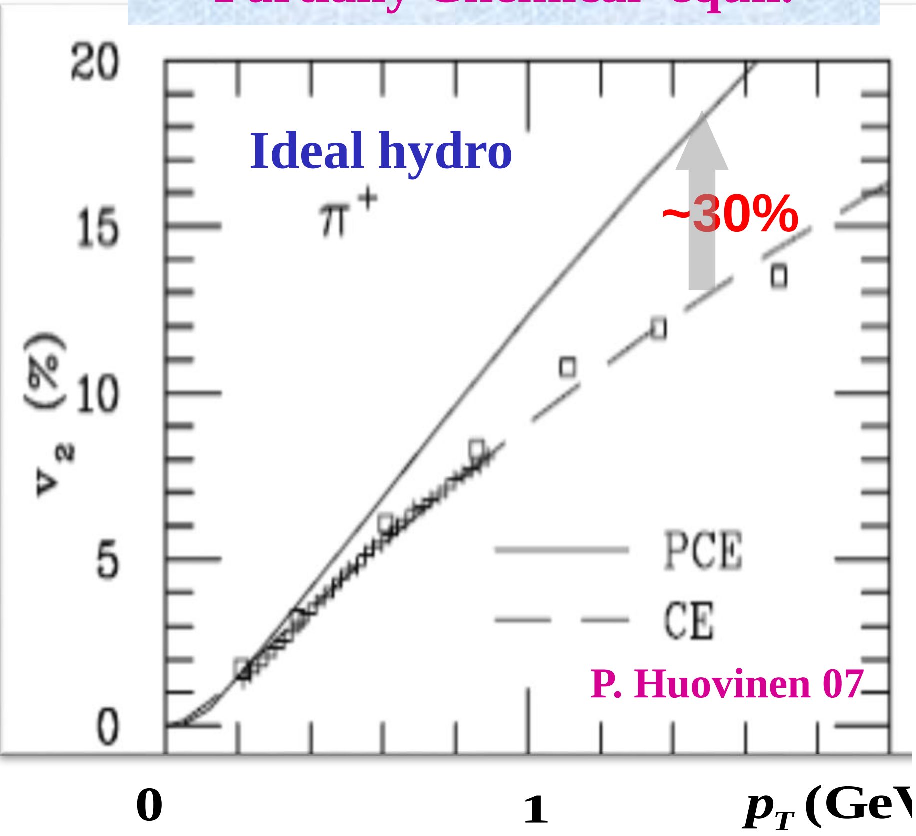
H. Song and U. Heinz, PRC08

-Elliptic flow is sensitive to the QGP shear viscosity, minimal value of η/s lead to 20-30% V_2 suppression

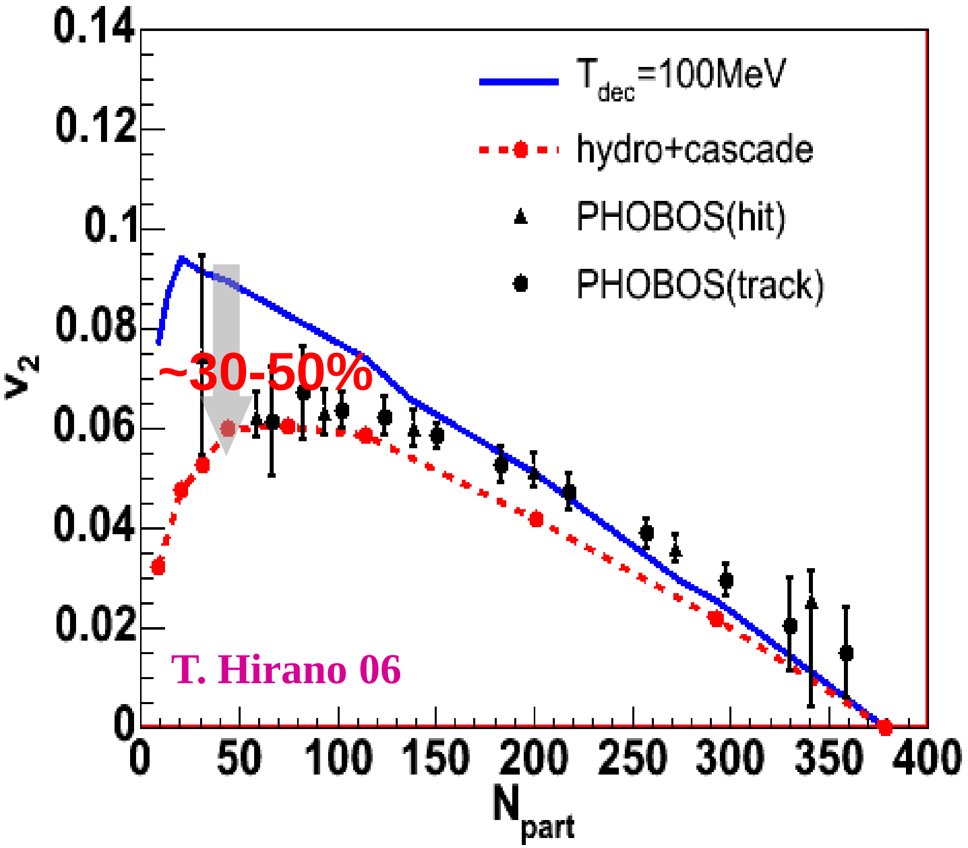
-**V2** can be used to extract the QGP shear viscosity

Effect from Hadronic evolution

Partially Chemical equil.



hadronic dissipative effects

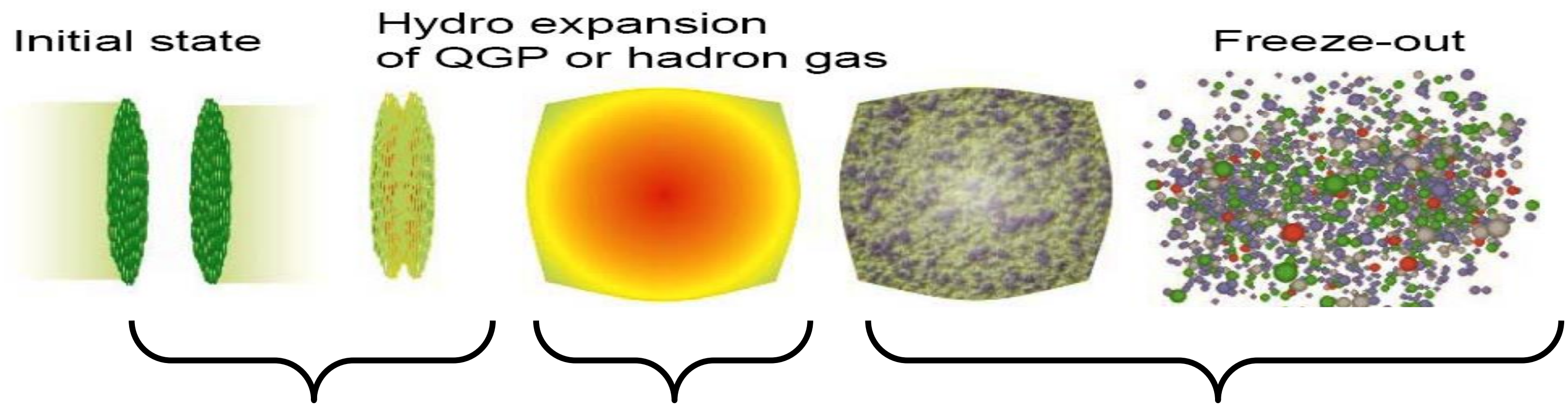


-These two HRG effects are not included in early viscous hydro calculations

→ **viscous hydro + hadron cascade (URQMD) hybrid approach**

URQMD includes the partially chemical equilibrium nature & hadronic dissipative effects

VISHNU & iEBE-VISHNU hybrid approach



Initial conditions **viscous hydro** **hadron cascade**

VISHNU: H. Song, S. Bass, U. Heinz, PRC2011

-initial conditons

-Viscous hydro (VISH2+1)

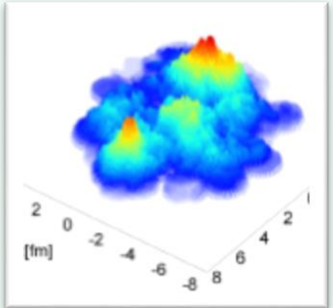
-Hadron Cascade

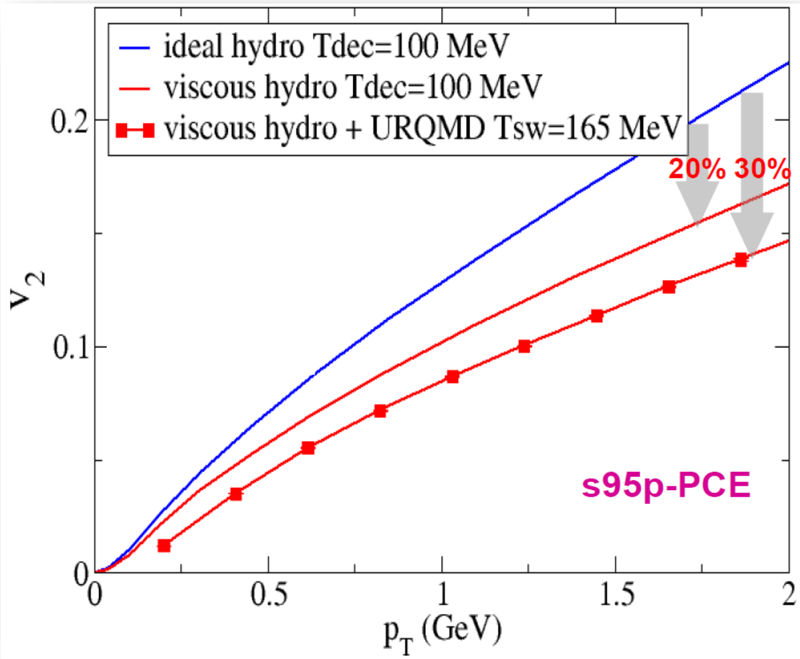
-EoS: (s95p-PCE, etc)

iEBE- VISHNU:

-Event-by-Event VISHNU

Shen, Qiu, Song et al CPC2016

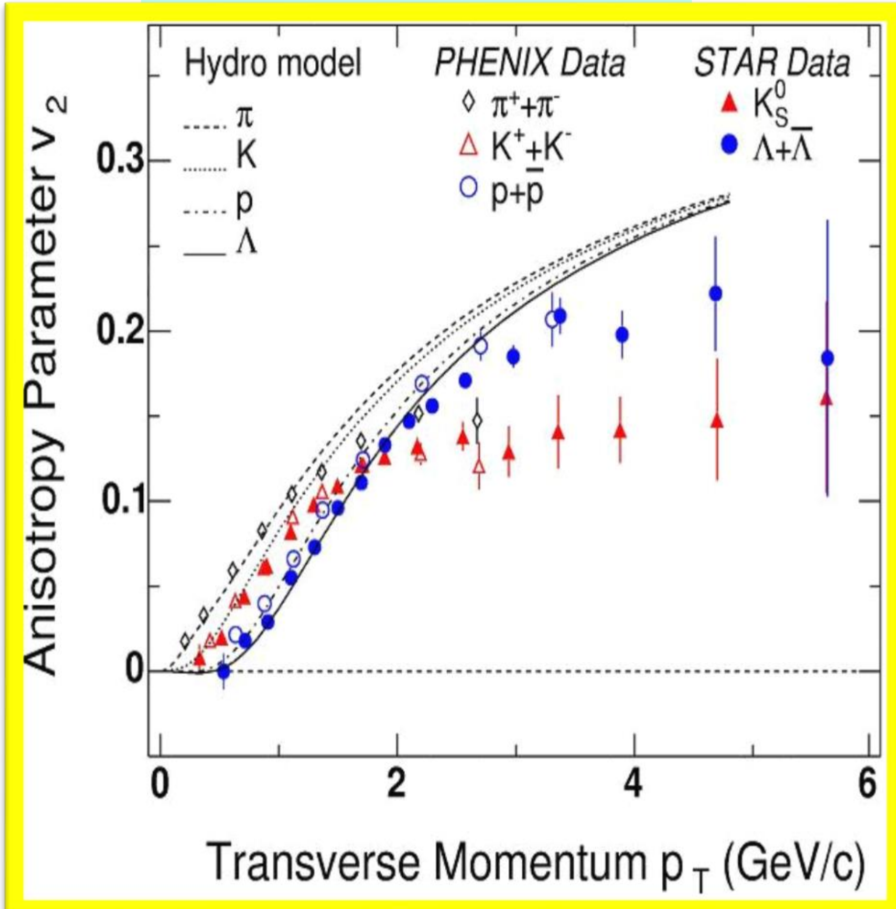


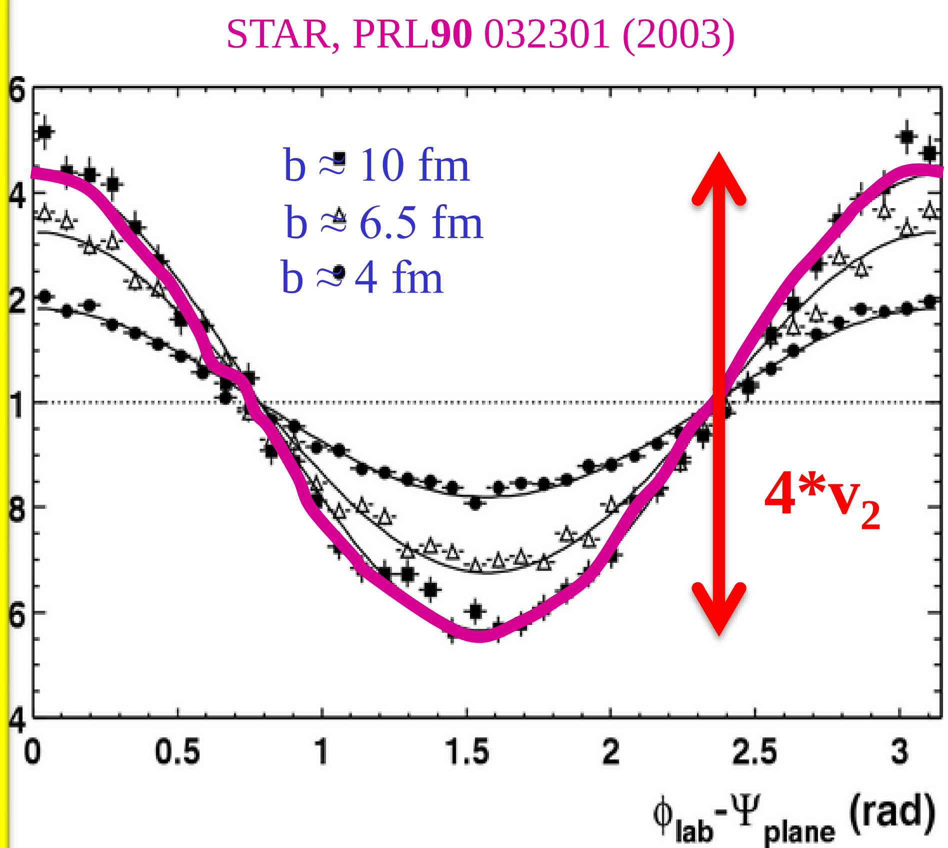


Collective Flow

Elliptic Flow

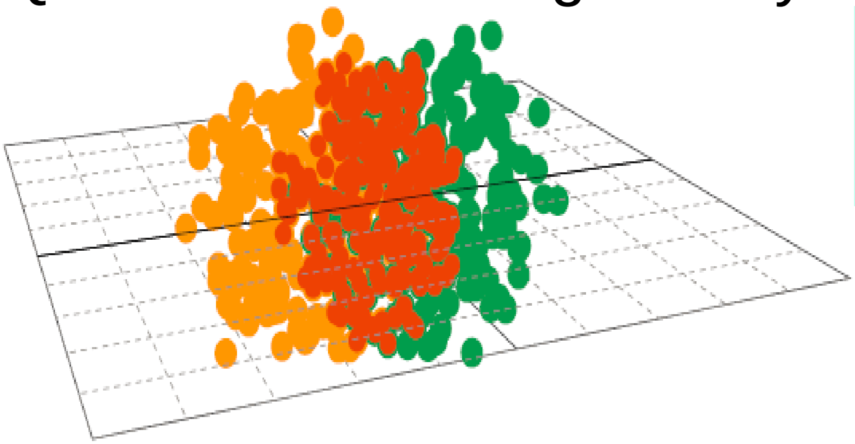
Azimuthal distributions





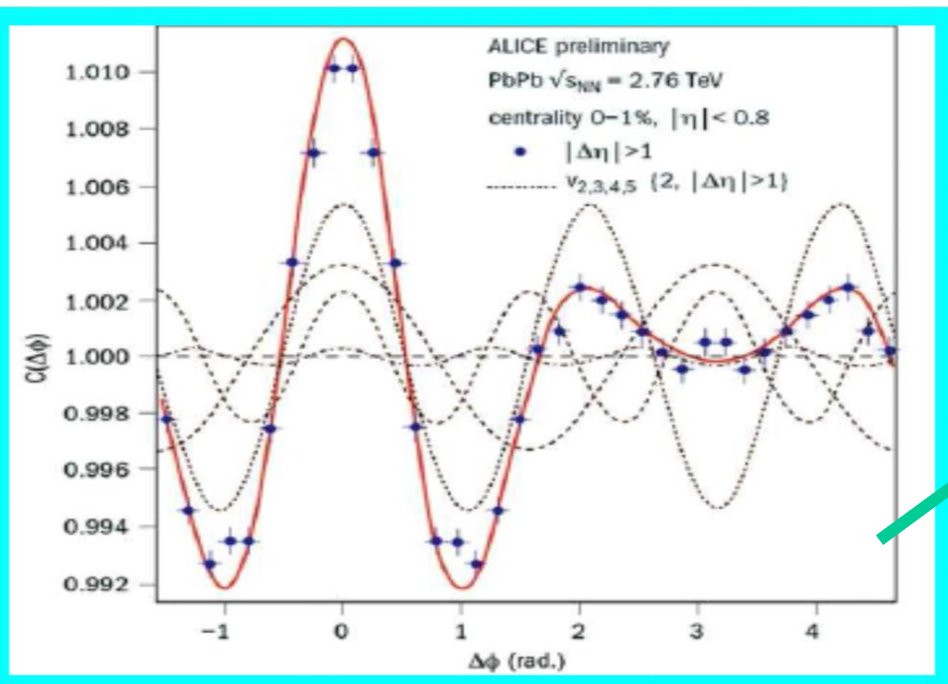
$$E\frac{dN}{d^3p} = \frac{dN}{dyp_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{dyp_T dp_T}[1 + 2v_2(p_T, b)\cos(2\varphi) + ...]$$

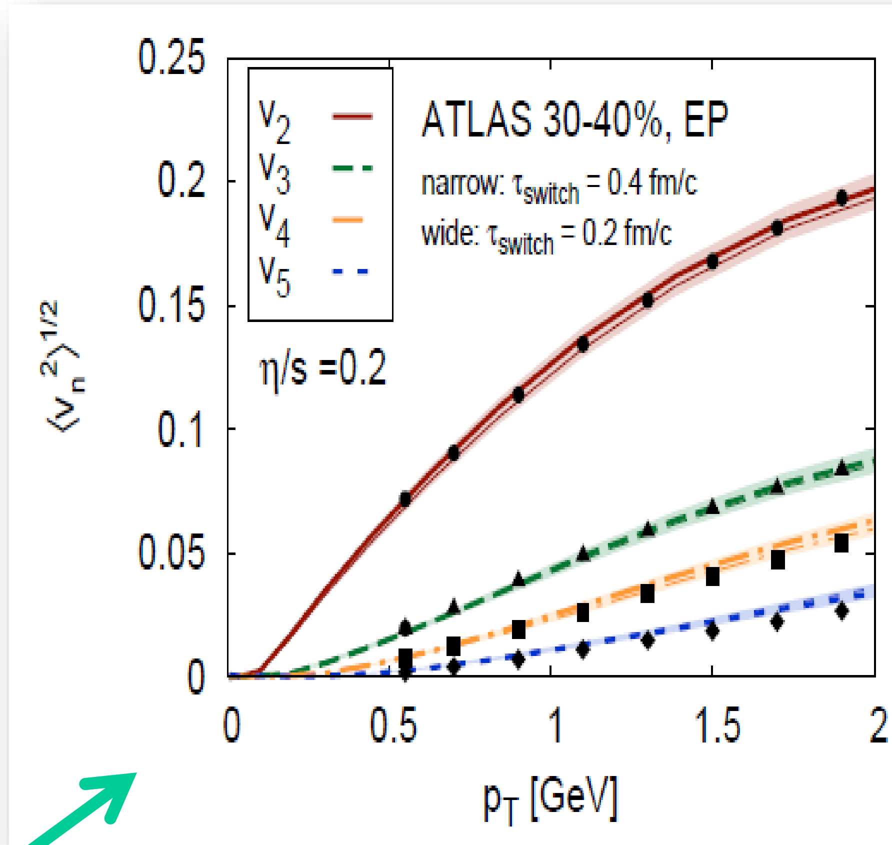
QGP with fluctuating density



Elliptic Flow & higher order flow harmonics

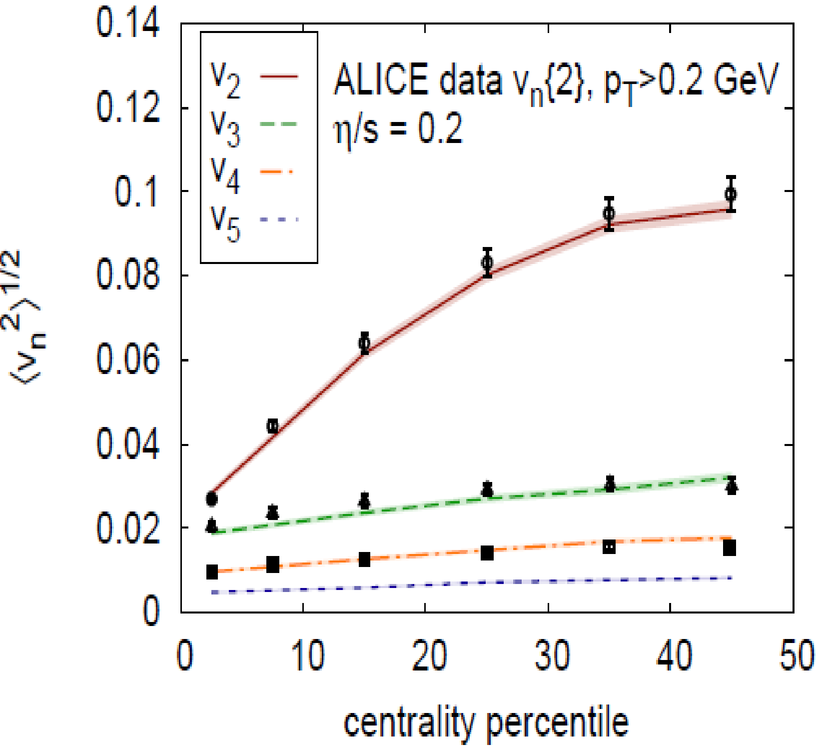
→measured flow: v_n

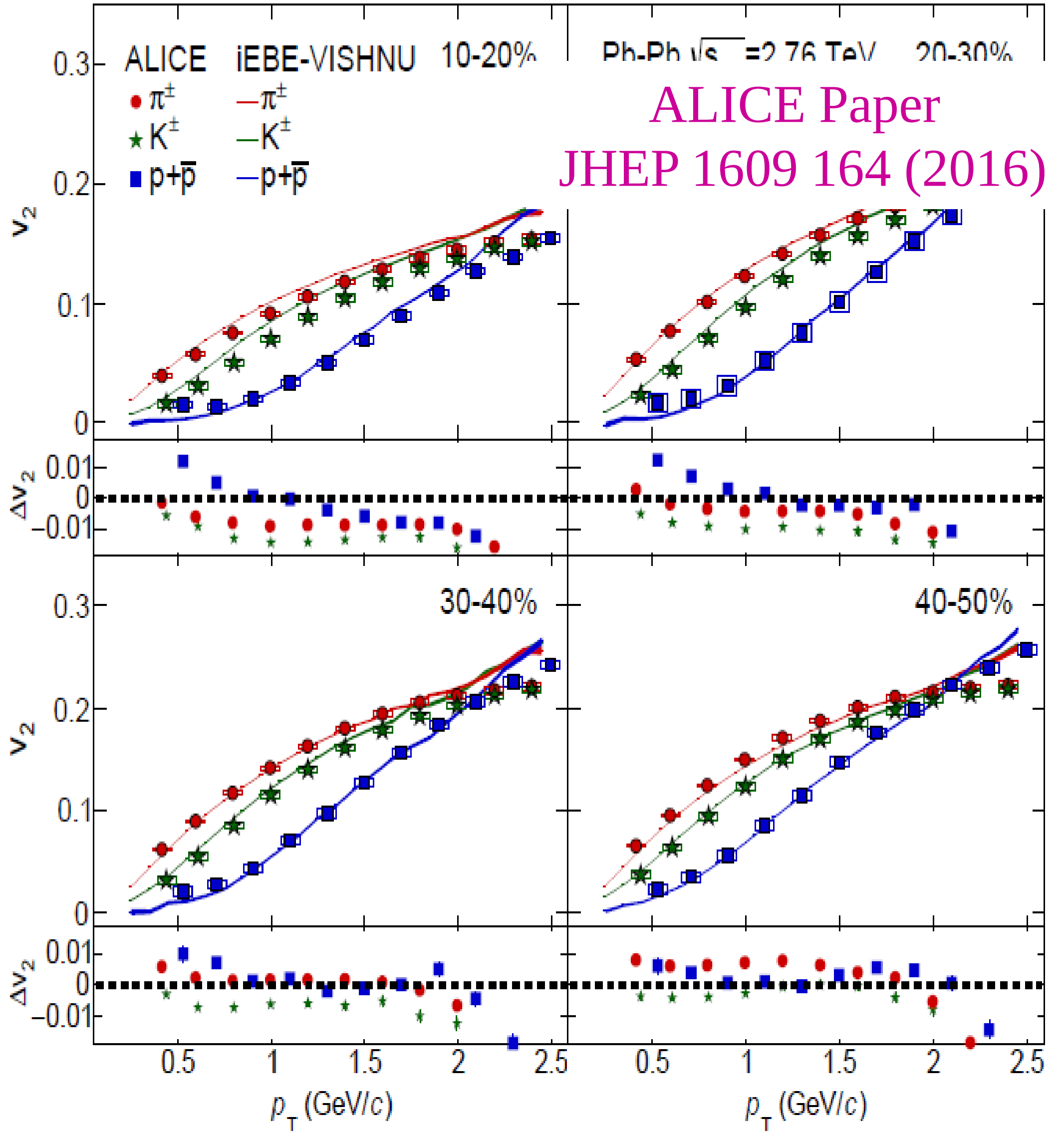




$$N(\phi) \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$

The Success of Hydrodynamics





ALICE Paper
JHEP 1609 164 (2016)

-Hydro + IP-Glasma

Gale, et. Al, PRL2013

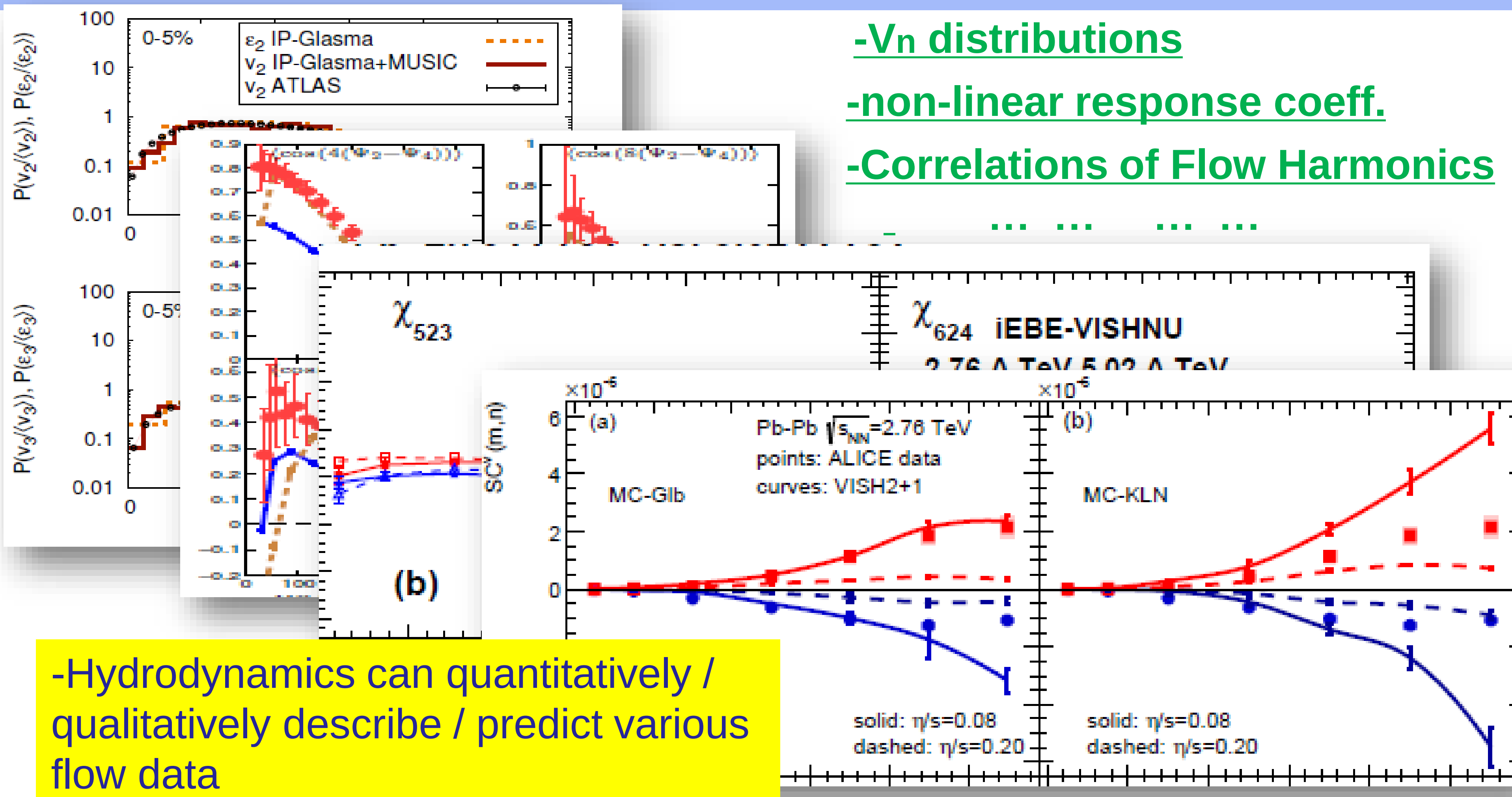
-iEBE-VISHNU + AMPT

Xu, Li, **H. S***, PRC 2016

-hydrodynamics nice describe of integrated and differential V_n of all charged and identified hadrons

Various Flow Predictions ftom Hydrodynamics

- -Vn distributions
- -non-linear response coeff.
- -Correlations of Flow Harmonics
- - … … … …

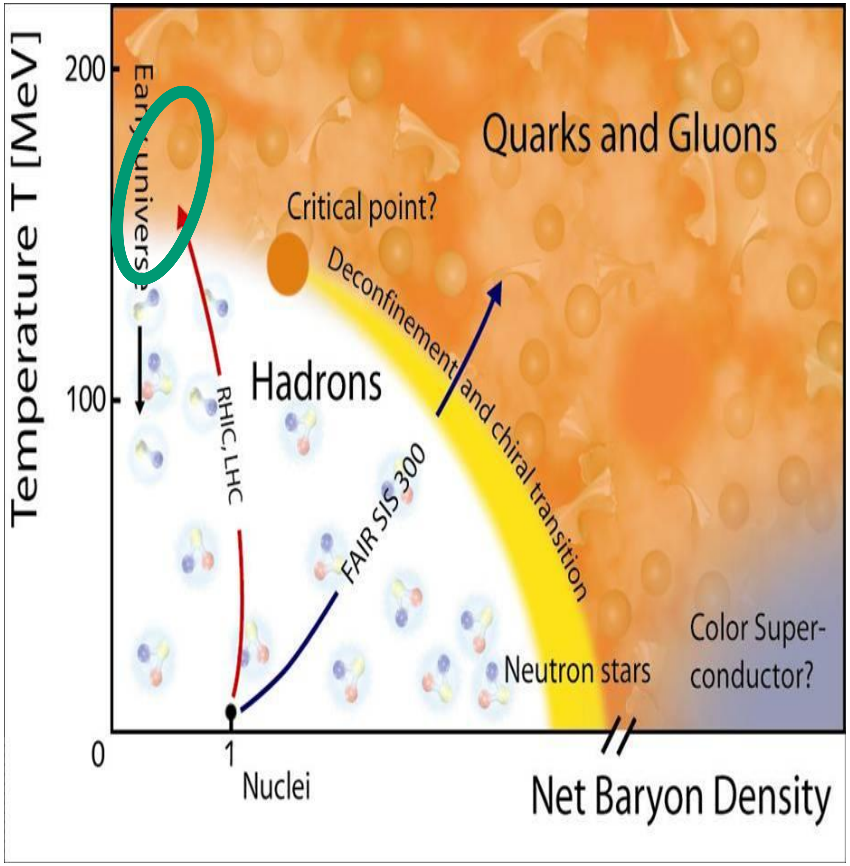


-Hydrodynamics can quantitatively / qualitatively describe / predict various flow data

H. Xu, Z. Li and H. S*, Phys. Rev. C93, no. 6, 064905 (2016); W. Zhao, H. Xu and **H. S*,** Eur. Phys. J. C 77, no. 9, 645 (2017); X. Zhu, Y. Zhou, H. Xu and **H. S*,** Phys. Rev. C95, no. 4, 044902 (2017); W. Zhao, L. Zhu, H. Zheng, C. M. Ko and **H. S*.,** Phys. Rev. C 98, no. 5, 054905 (2018); Li, Zhao, Zhou, **H.S***, in preparation (2020) … … … …

Flow & QGP viscosity

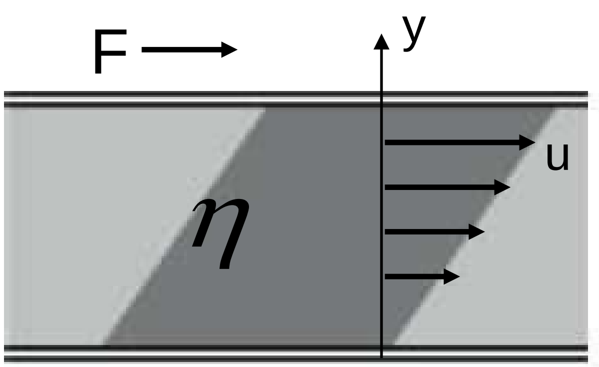
@ top RHIC and LHC energies



Lowest bound of specific shear viscosity

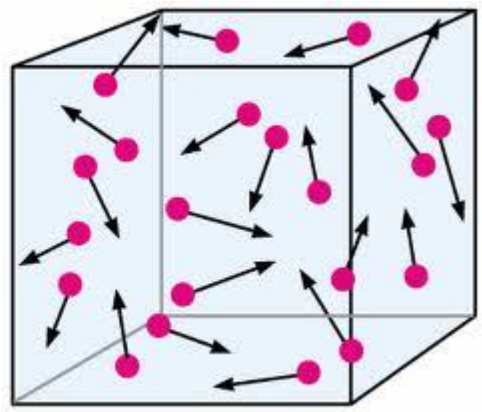
-classical definition:

$$\frac{F}{A} = \eta \frac{du}{dy}$$



-kinetic theory:

$$\eta \sim mn\bar{v}l_{mfp}$$

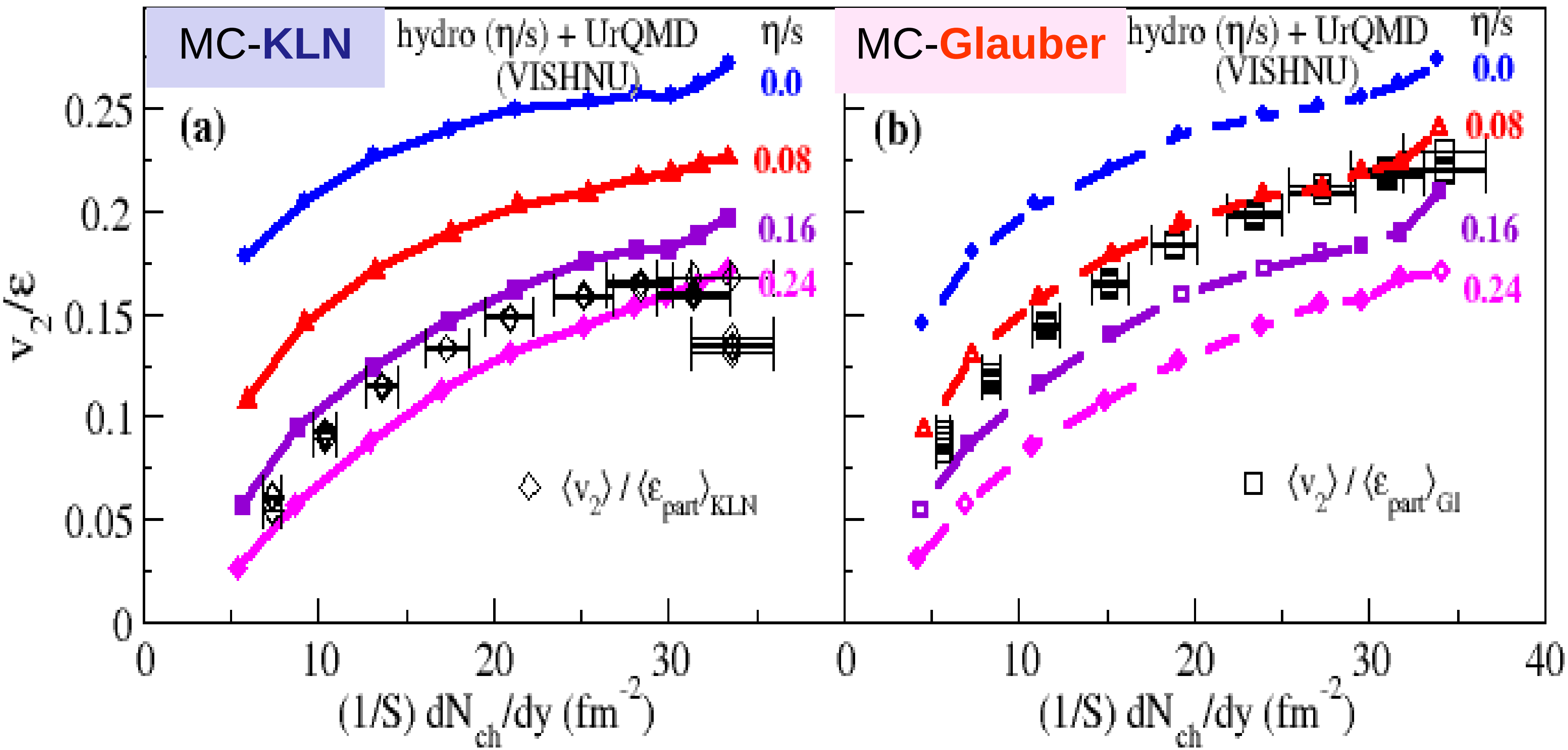


$$\frac{\eta}{s} \sim \frac{1}{k_B}\bar{v}ml_{mfp} \sim \frac{1}{k_B}(\frac{1}{2}m\bar{v}^2)(\frac{l_{mfp}}{\bar{v}}) \sim \frac{e\tau}{k_B} \qquad (s \sim k_B n)$$

uncertainty principle: ⇨ $\frac{\eta}{s} \geq \frac{h}{k_B}$

Extracting QGP viscosity-early attempt

H. Song,et.al, PRL2011



$$1\times(1/4\pi)\leq(\eta/s)_{QGP}\leq 2.5\times(1/4\pi)$$

Extract QGP properties from bulk observ.

-massive data evaluation

Exp Observables

- particle yields
- spectra
- elliptic flow
- triangular flow & higher order flow harmonics
- event by event V_n distributions
- higher-order event plane correlations

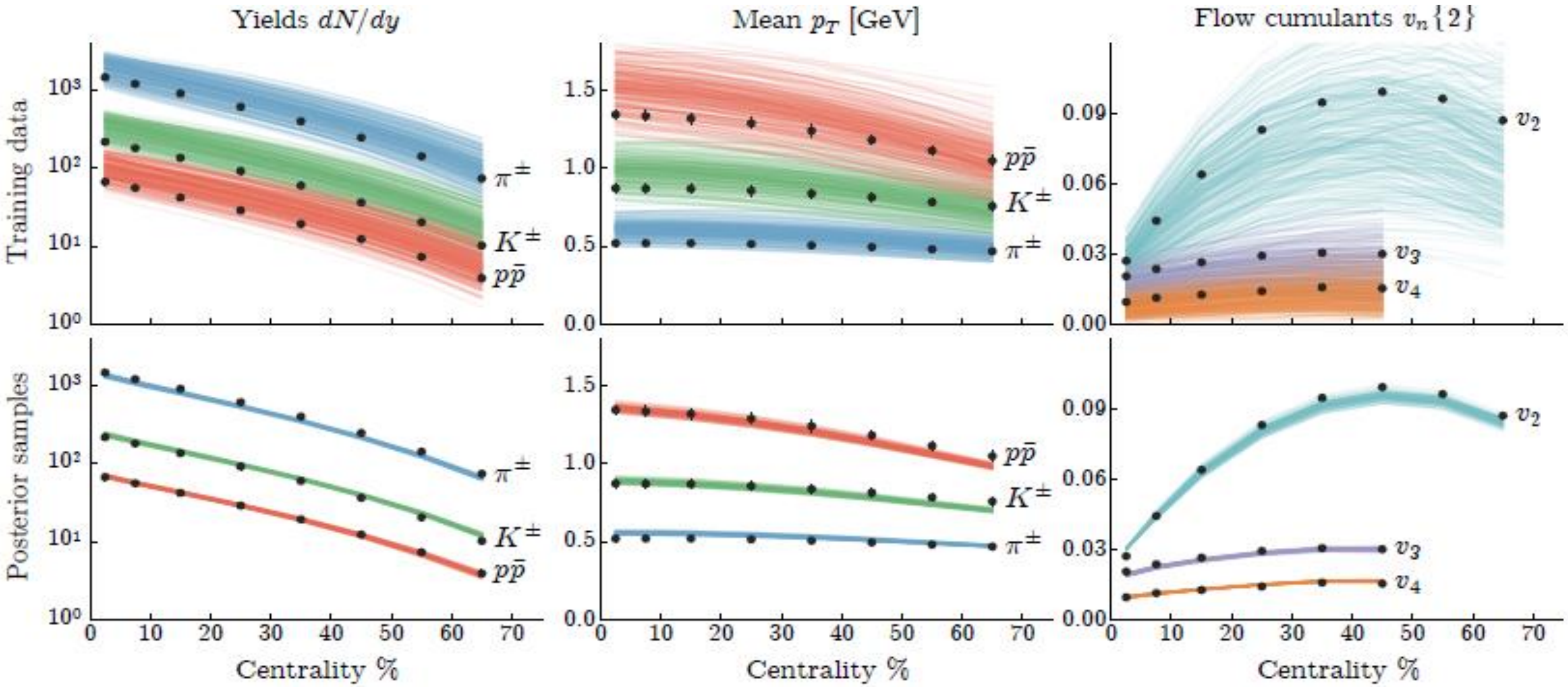
… ... … …

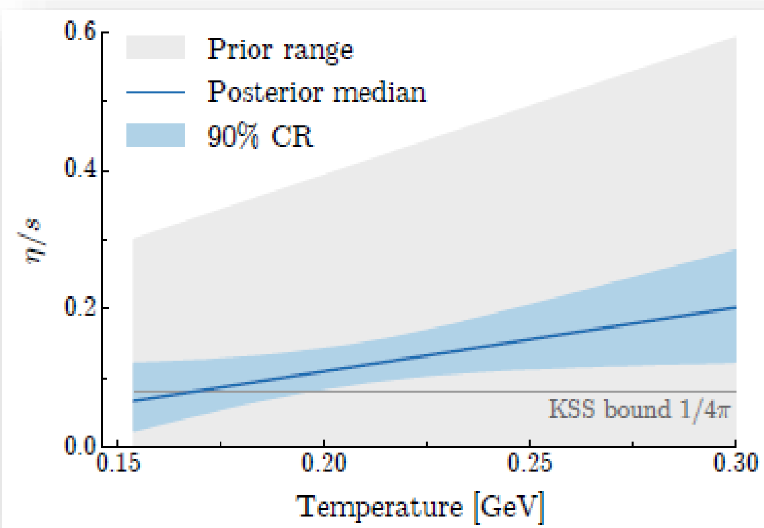
Hydro model & its Inputs:

-Initial conditions
-EoS
- shear viscosity
- bulk viscosity
- Heat conductivity
- relaxation times
- freeze-out/switching cond.

… … … …

An quantitatively extraction of the QGP viscosity



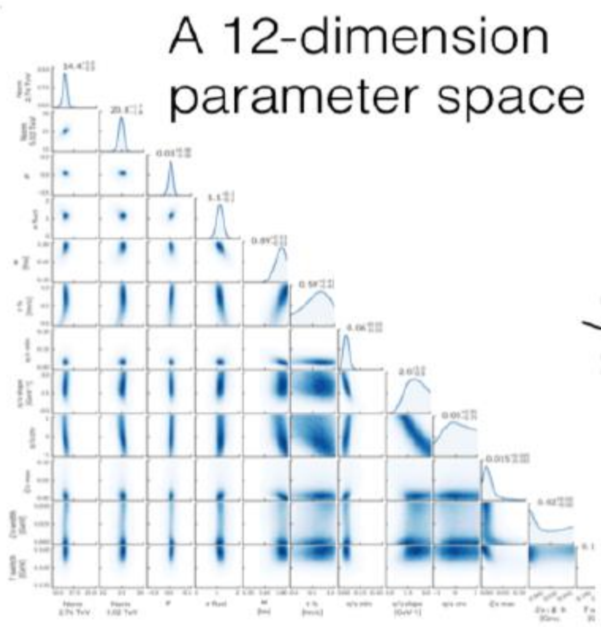


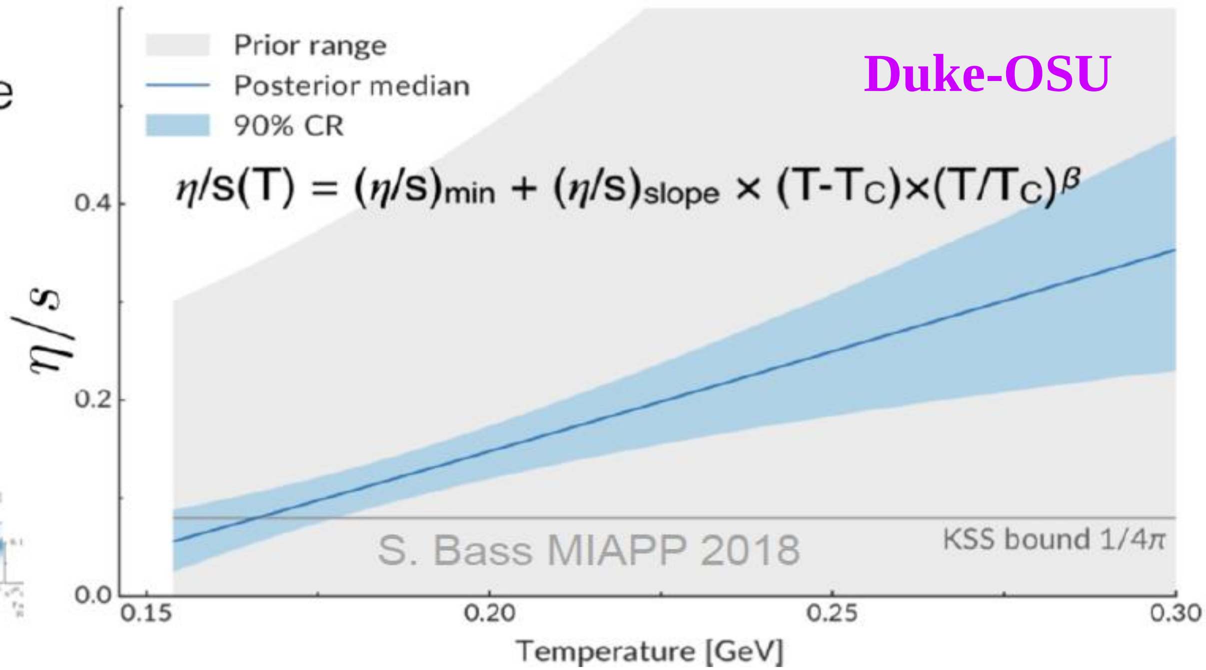
-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

-η/s(T) is very close to the KSS bound of 1/4π

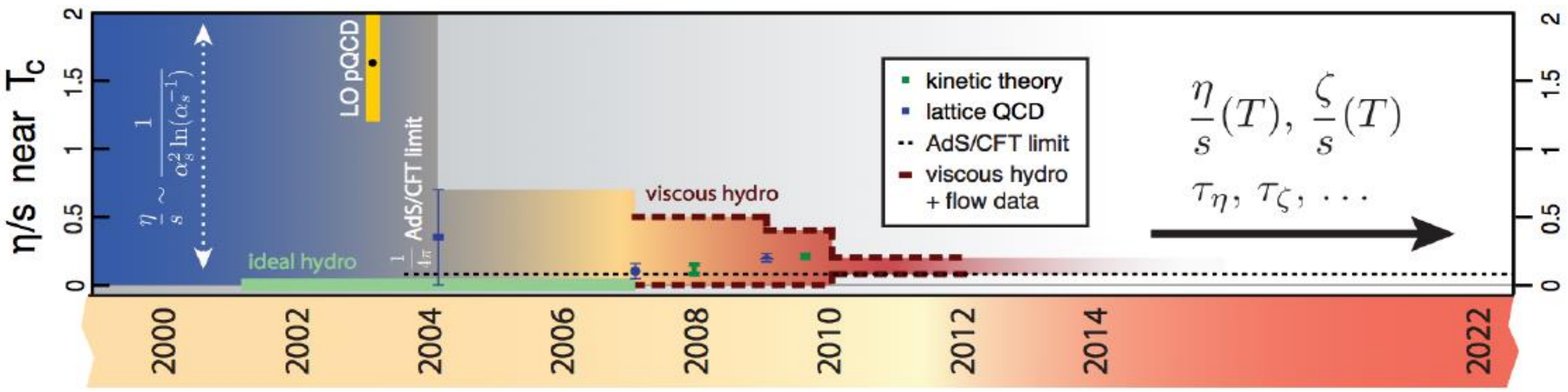
J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

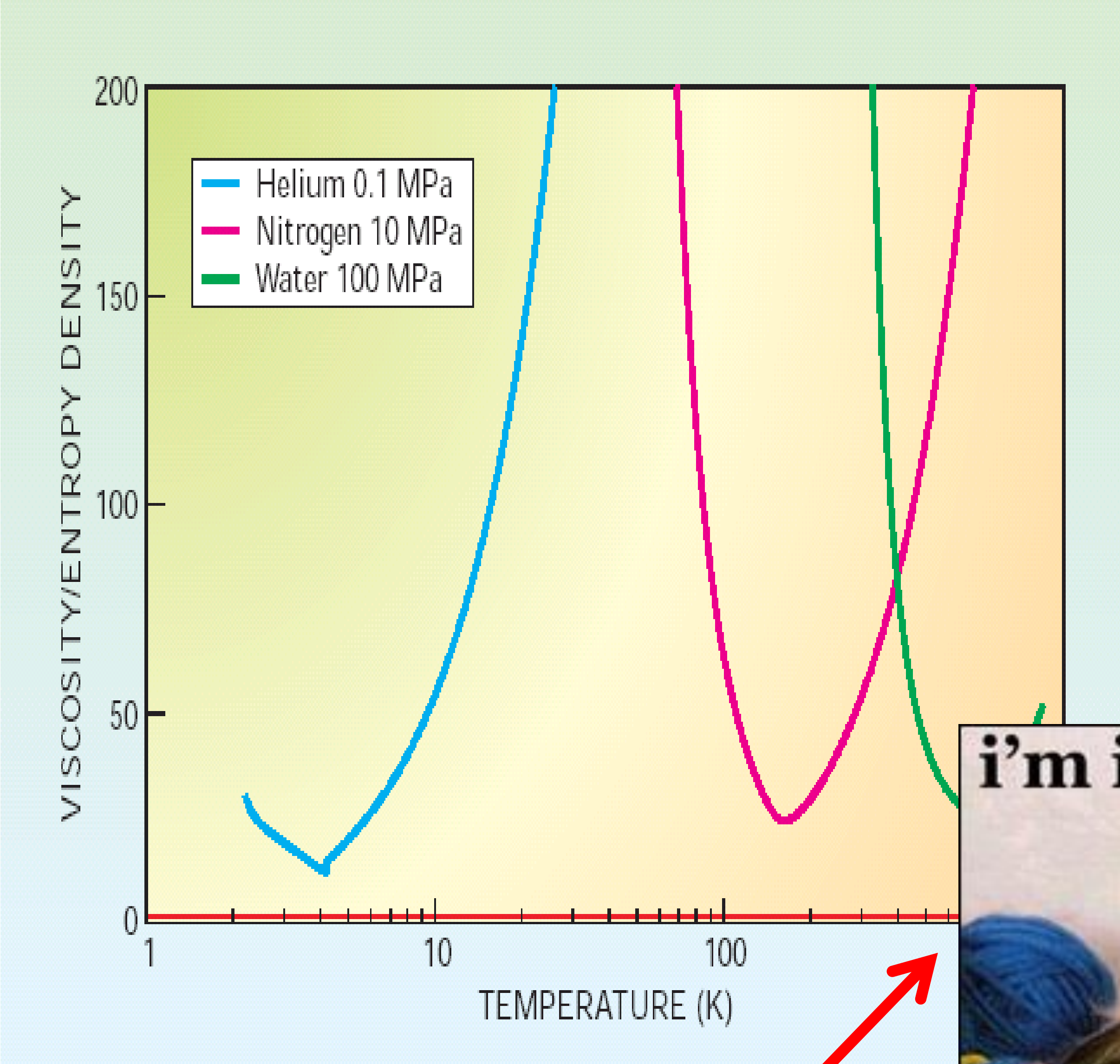
Extracting QGP viscosity with massive data evaluation





Extracted QGP viscosity with ever increasing precision



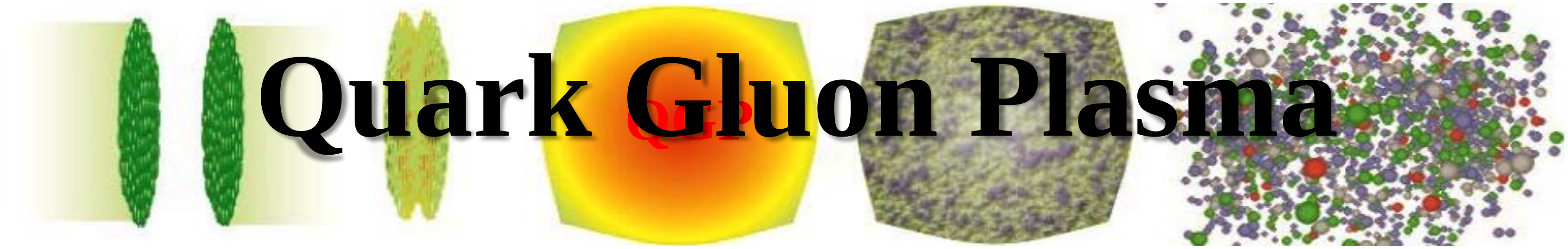


AdS/CFT

$$\frac{\eta}{s} \geq \frac{h}{k_B}$$

QGP specific shear viscosity
Extracted from exp data

Quark Gluon Plasma



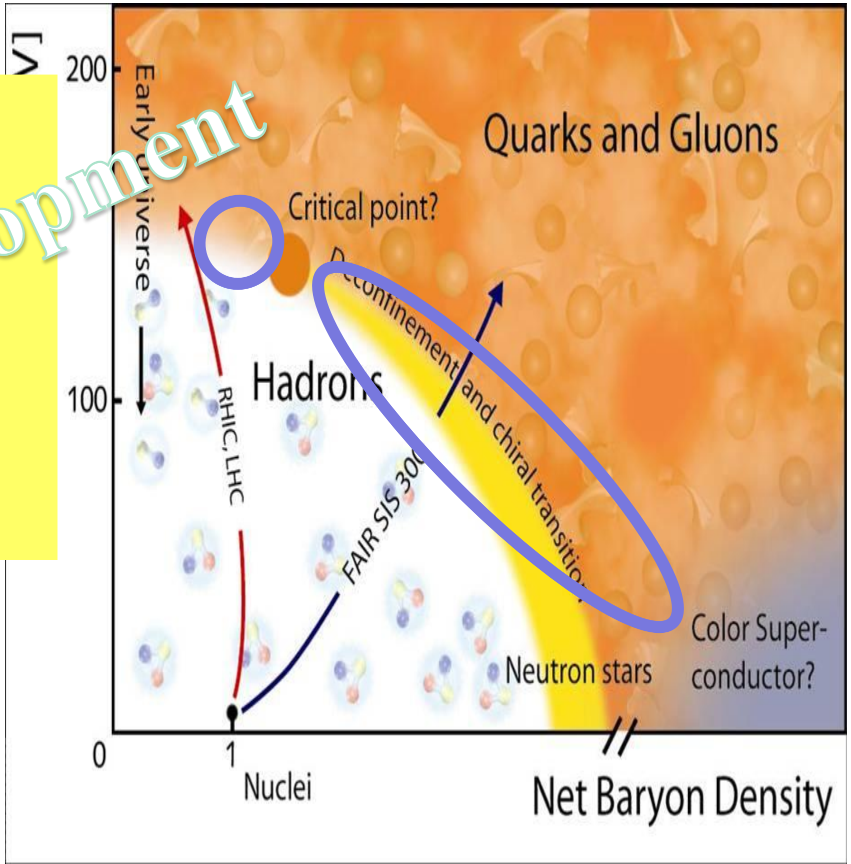
Hottest Matter on Earth

Flow & viscosity at RHIC-BES

Hybrid model for RHIC BES

- proper initial condition
  (dynamical initial cond.,…)
- 3+1-d hydro
  (effects from heat conductivity …)
- hadronic afterburner
- EoS with T & μ

Still under-development



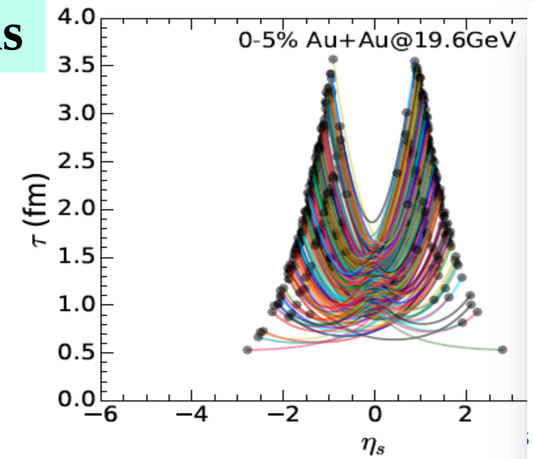
Recent model development for RHIC BES

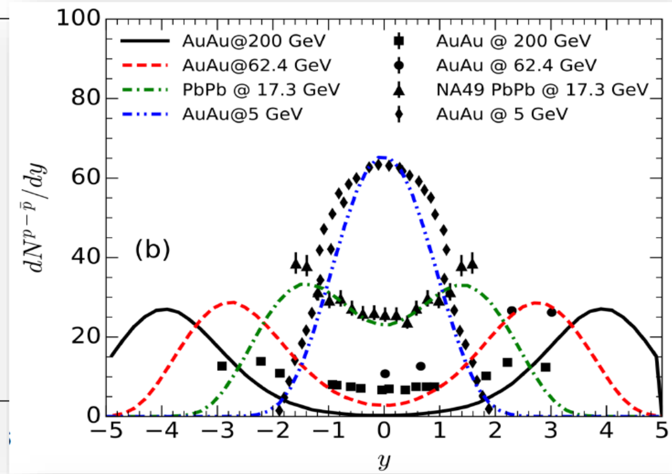
Dynamical initial conditions

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

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

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

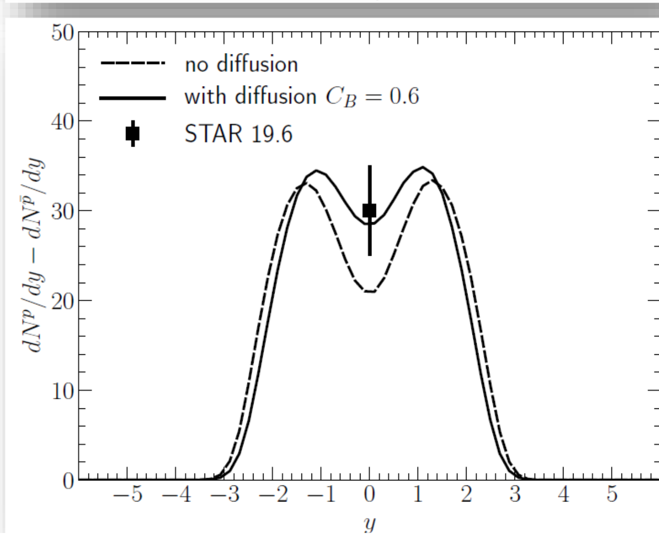




Net baryon diffusion

$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu \frac{\mu_B}{T}, \quad (13)$$

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi^{\langle\mu}{}_\alpha\pi^{\nu\rangle\alpha} + \frac{l_{\pi q}}{\tau_\pi}\nabla^{\langle\mu}q^{\nu\rangle} + \frac{\lambda_{\pi q}}{\tau_\pi} q^{\langle\mu}\nabla^{\nu\rangle}\frac{\mu_B}{T}.$$



G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018) ; M. Li and C. Shen, Phys. Rev. C98, 064908 (2018)

Net baryon diffusion transports more baryon numbers to the mid-rapidity region / extracting heat conductivity In the future

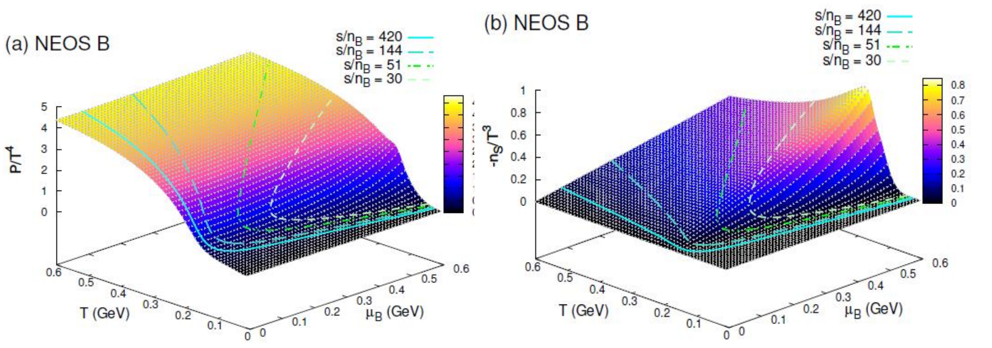
Recent development of hybrid model for RHIC BES

Dynamical initial conditions

$$\partial_\mu T^{\mu\nu} = J^\nu_{\mathrm{source}}$$
$$\partial_\mu J^\mu = \rho_{\mathrm{source}}.$$

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

EoS with finite T & μ



A. Monnai, B. Schenke and C. Shen, arXiv:1902.05095 [nucl-th].

Net baryon diffusion

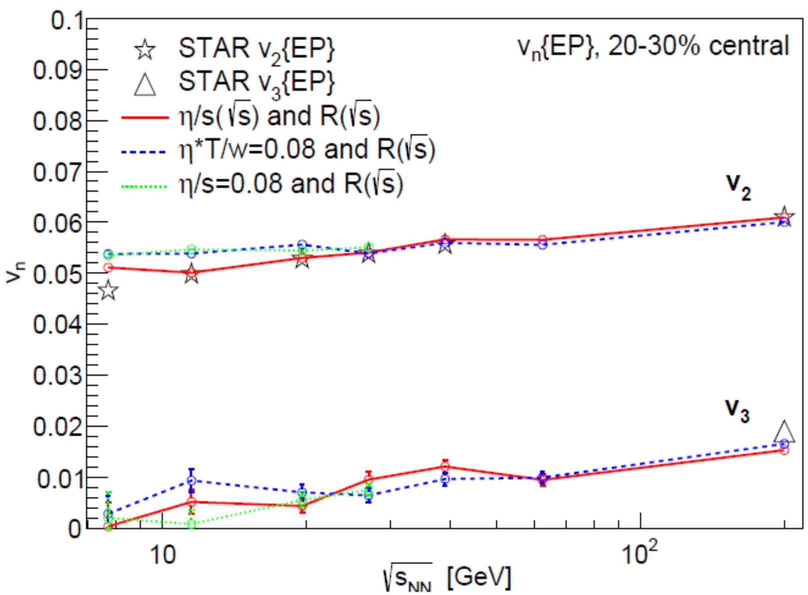
$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu \frac{\mu_B}{T}, \qquad (13)$$

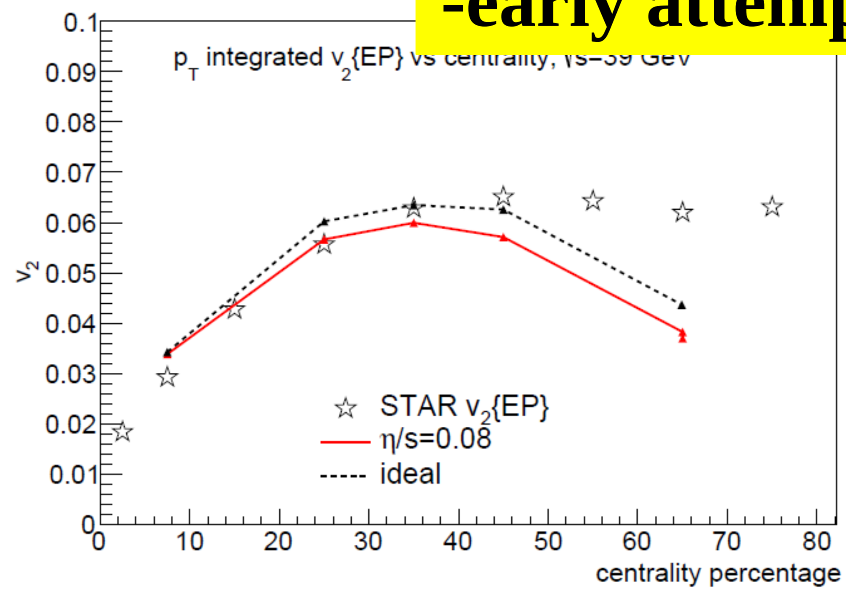
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\sigma}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi^{\langle\mu}{}_\alpha \pi^{\nu\rangle\alpha} + \frac{l_{\pi q}}{\tau_\pi}\nabla^{\langle\mu} q^{\nu\rangle} + \frac{\lambda_{\pi q}}{\tau_\pi} q^{\langle\mu}\nabla^{\nu\rangle}\frac{\mu_B}{T}. \qquad (14)$$

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018) ; M. Li and C. Shen, Phys. Rev. C98, 064908 (2018)

Extracting $\eta/s(\sqrt{s})$ from RHIC BES (I)

-early attempt





<u>Data</u>

- RHIC BES Au+Au 7.7-200 A GeV

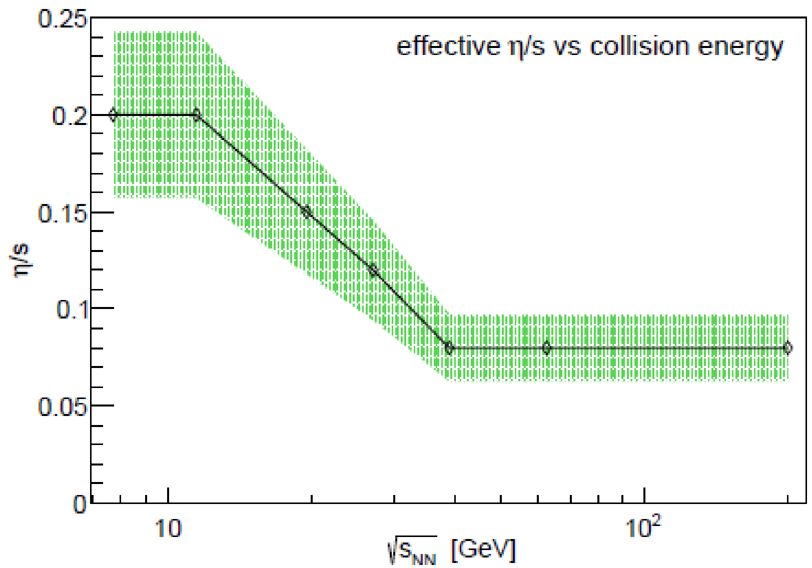
<u>Model</u>

-3+1d viscous hydro + UrQMD

-pre-equilibrim stage UrQMD

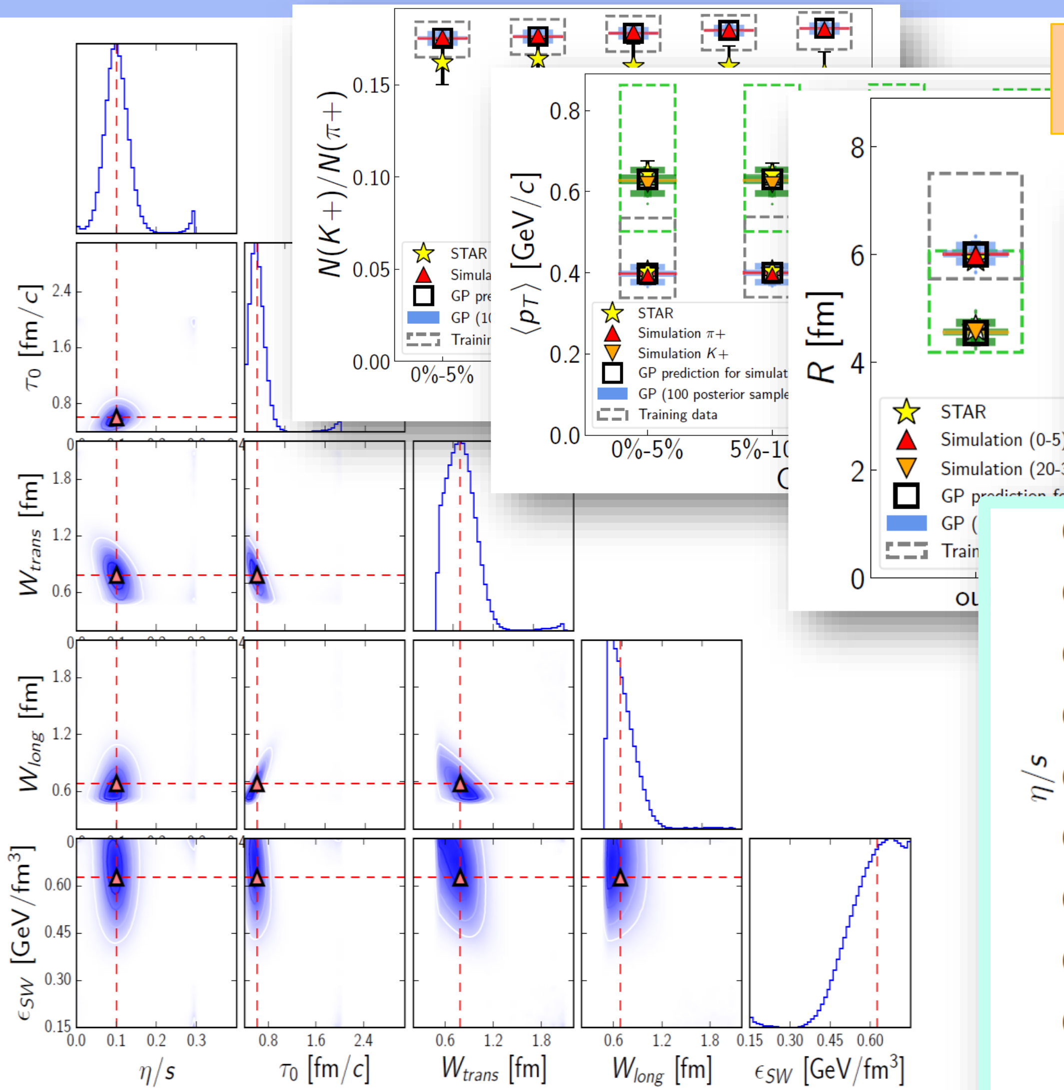
-EoS (Chiral Model with T, μ)

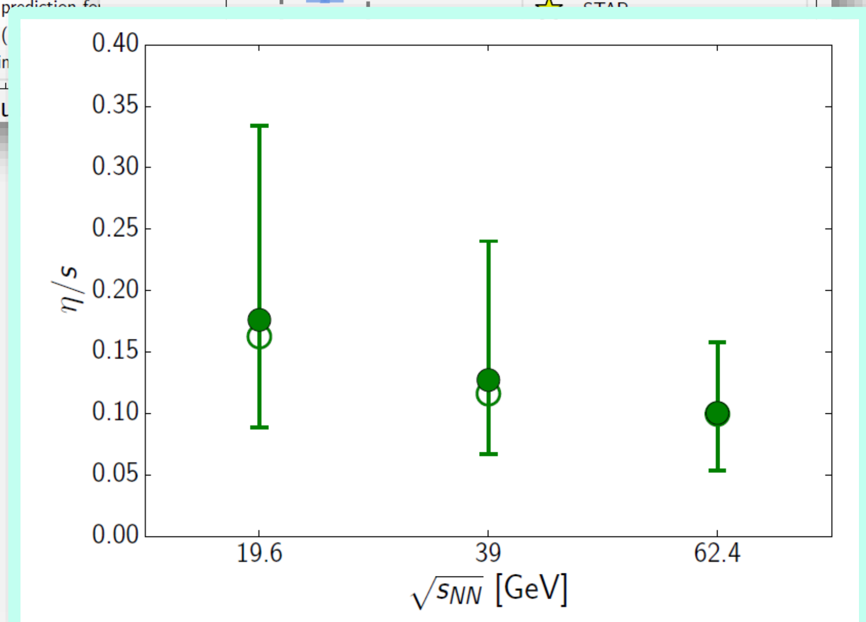
I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91, no. 6, 064901 (2015)



Extracting η/s($\sqrt{s}$) from RHIC BES (II)

-using Bayesian statistics

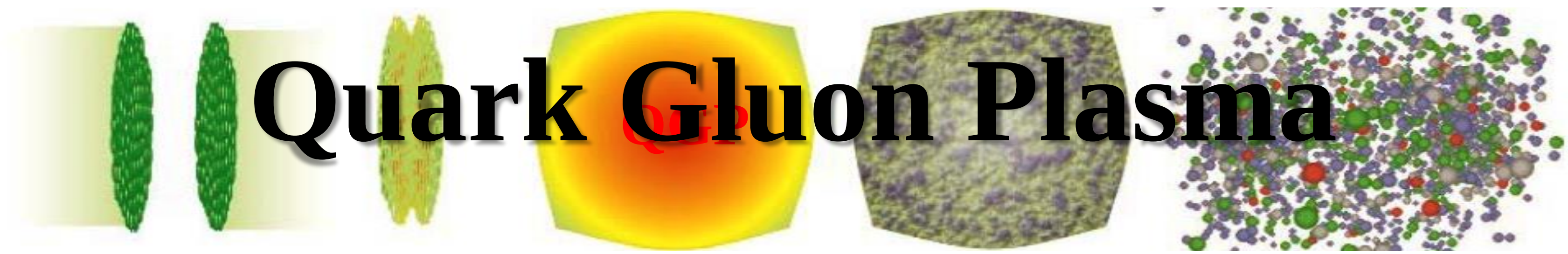




Future:
η/s(T,μ) ζ/s(T,μ) K/s(T,μ)

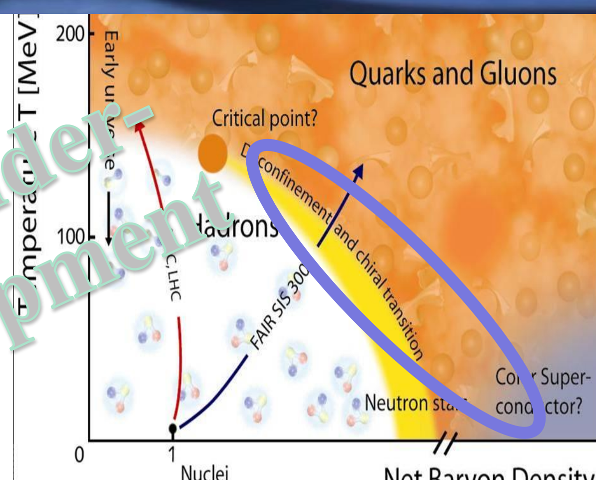
J. Auvinen, J. E. Bernhard, S. A. Bass and I. Karpenko, Phys. Rev. C97, no. 4, 044905 (2018)

Quark Gluon Plasma



Hottest Matter on Earth

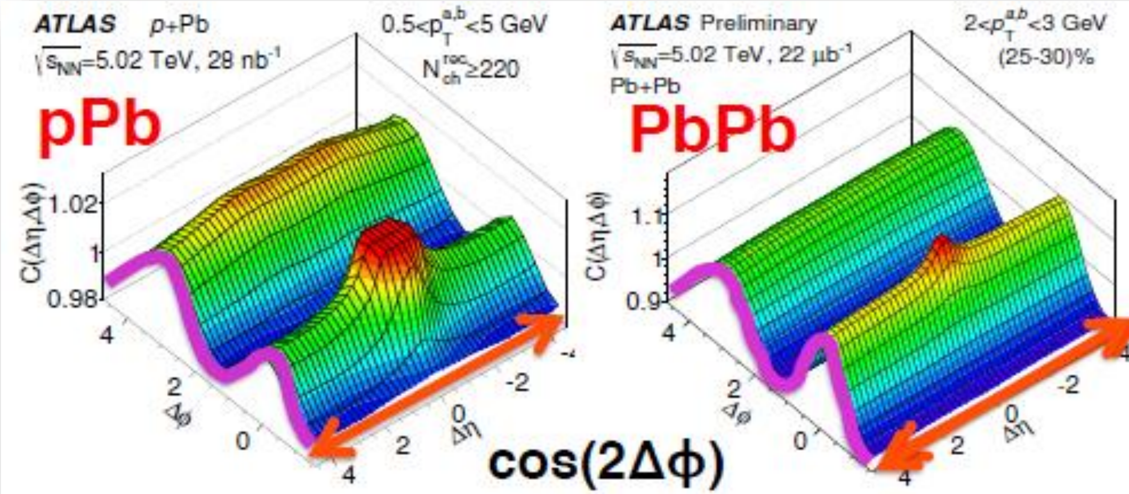
Most Perfect Liquid

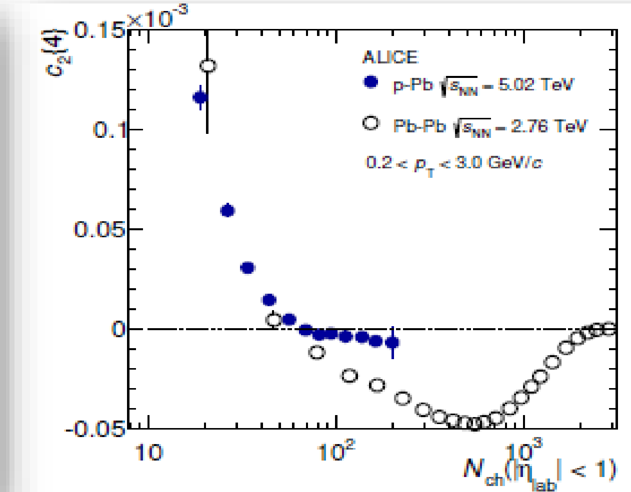


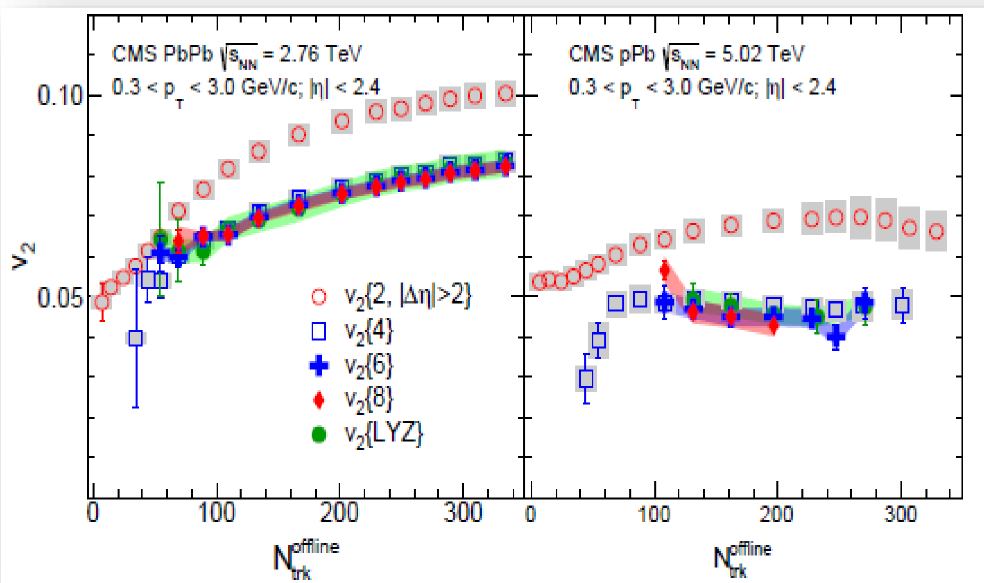
Still under-development

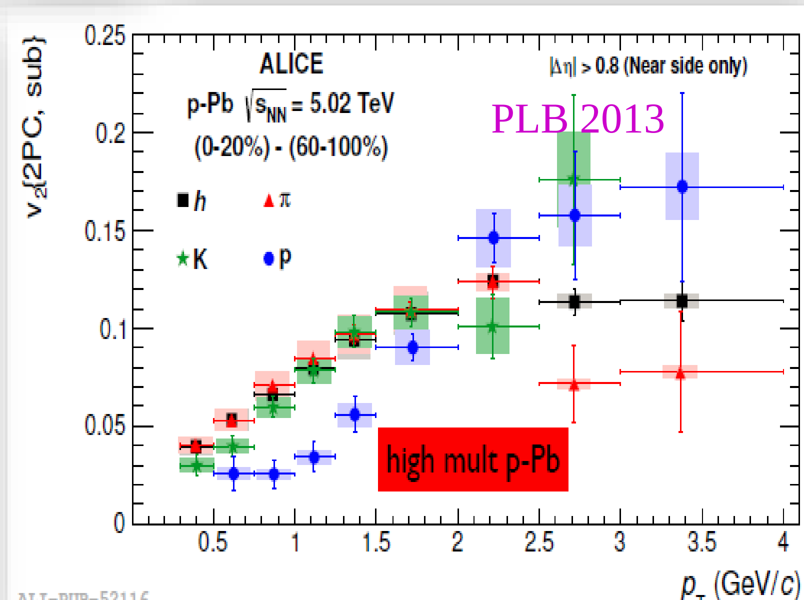
Flow and QGP signals at small systems

Correlations & Flow in p-Pb collisions



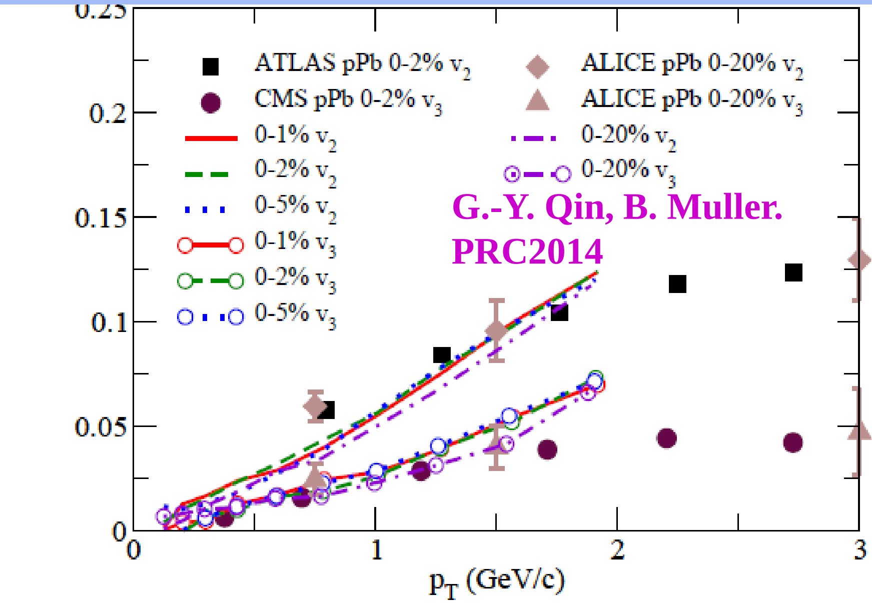


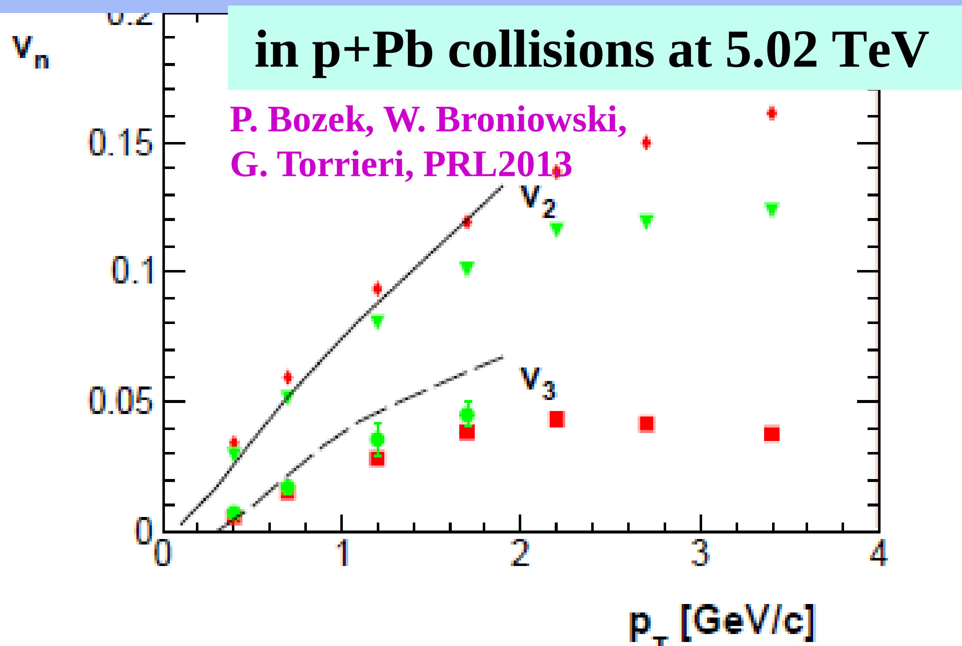


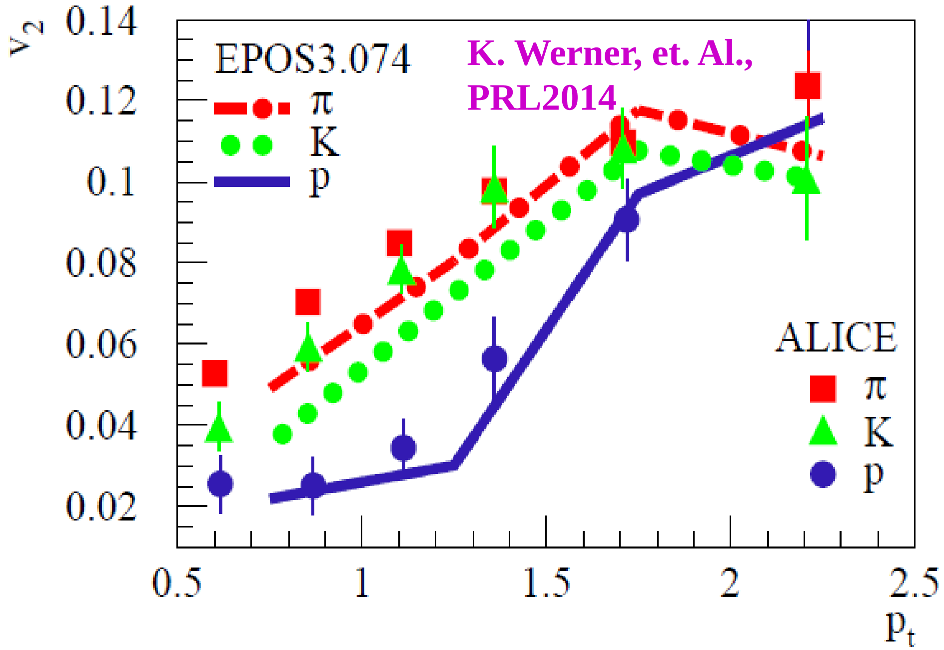


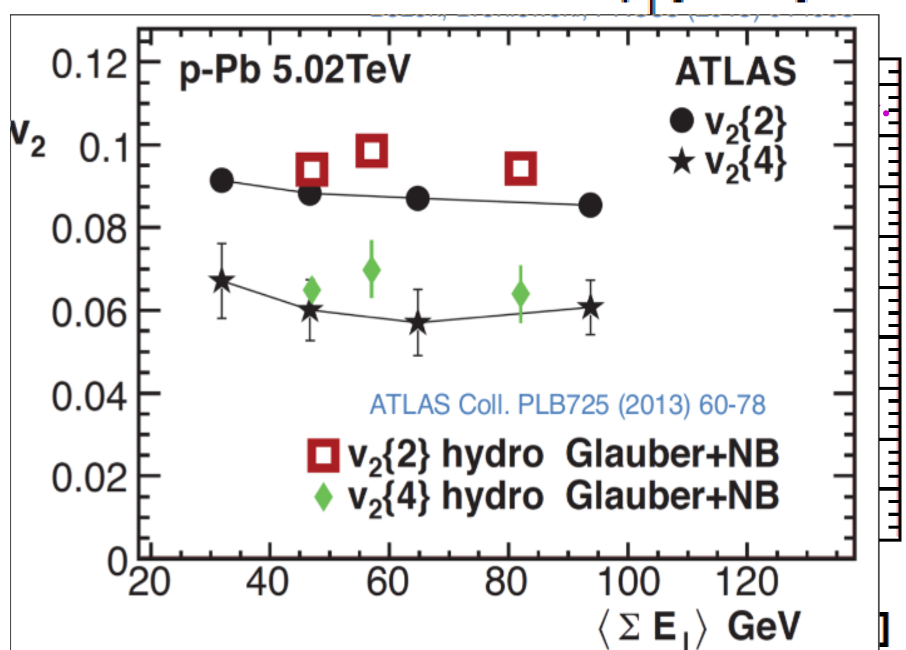
-Many flow-like signals have been observed in high multiplicity p-Pb collisions

Flow in p-Pb -- Hydrodynamics Simulations









Initial state or Final state effects?

Initial state effects: – Various Models interpolations

-K. Dusling and R. Venugopalan, PRL 2012, PRD2013, NPA 2014

-A. Dumitru and A. V. Giannini, NPA 2015, A. Dumitru and V. Skokov PRD2015

-B. Schenke, S. Schlichting, P. Tribedy, and R. Venugopalan, PRL2016

-K. Dusling et al, Phys. Rev. Lett 120 042002 (2018)

-C. Zhang, et al Phys. Rev. Lett. 122, no. 17, 172302 (2019).

… … … …

Final state interactions:

-P. Bozek, W. Broniowski, G. Torrieri, PRL2013

-K. Werner, et. Al., PRL2014

-G.-Y. Qin, B. Muller. PRC2014

-Y. Zhou, X. Zhu, P. Li, and H. Song, PRC2015

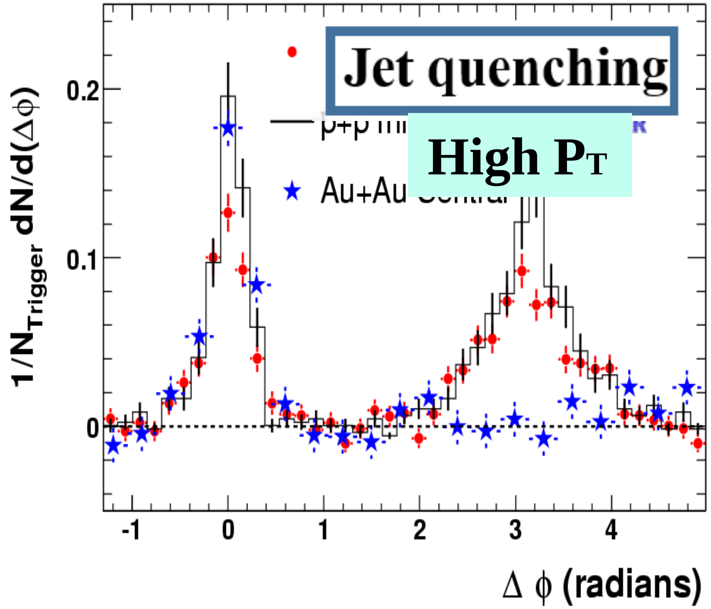
- P. Bozek, A. Bzdak, and G.-L. Ma, PLB2015

- P. Romatschke, Eur.Phys.J. C77 21(2017)

-W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018)

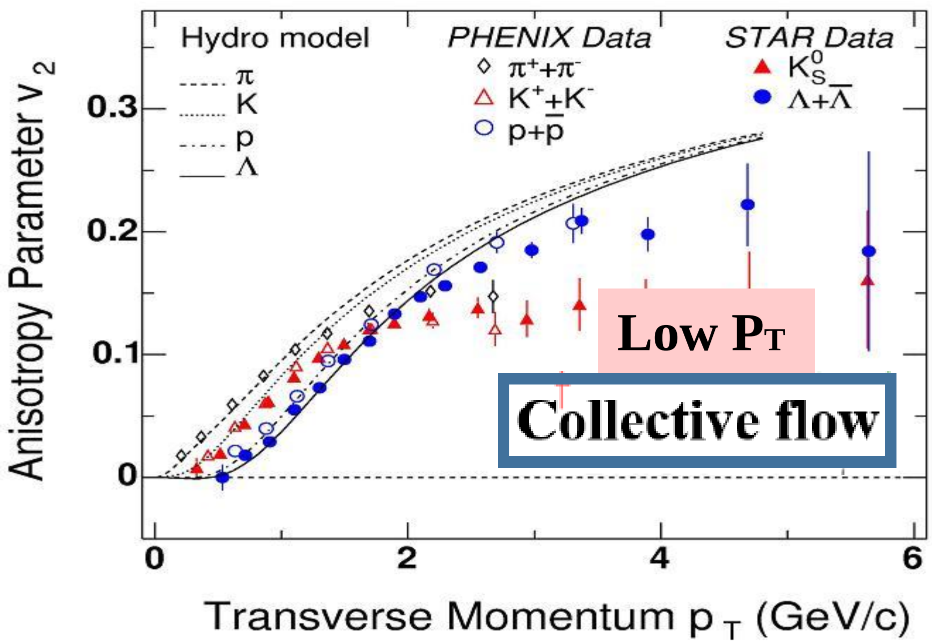
… … … …

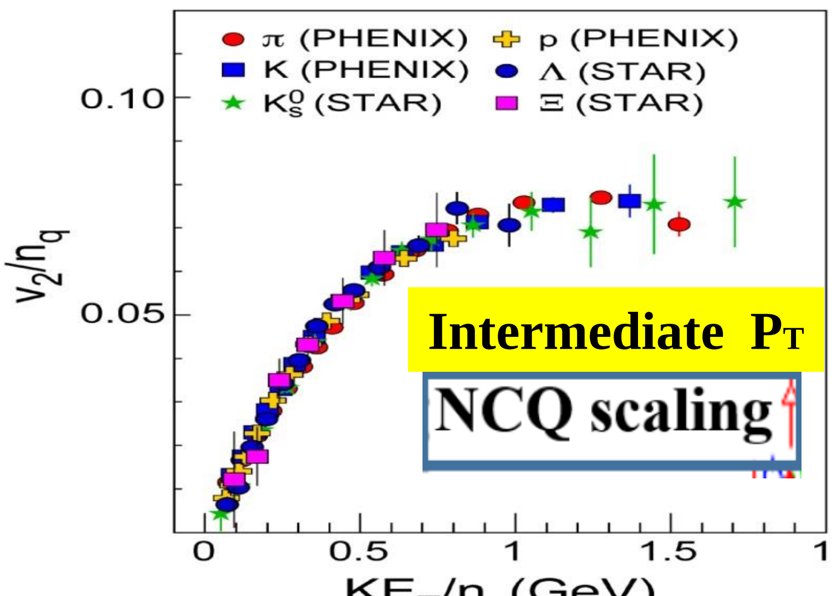
Reminder : QGP signals in large systems



Au+Au / Pb+Pb

- -strong elliptic flow
- -jet quenching
- -NCQ scaling of elliptic flow





NCQ scaling of v2 in p-Pb collisions

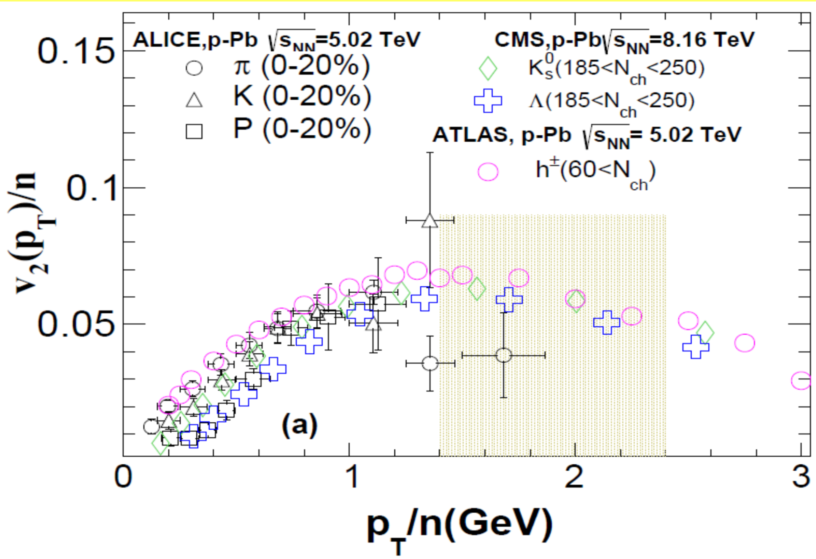
Low P_T | Intermediate P_T | High P_T

0 | 2 GeV | 6 GeV | P_T

Collective Flow:
Hydrodynamics
final states interaction
Initial state effects
(strong debate)

NCQ Scaling of V2:
-Recent Exp measurements--need systematic theoretical investigation

Hard Probes:
~~no longer leave obvious hints due to the limited size.~~



ALICE data: PLB,726, 164 (2013).
CMS data: PRL, 121, 082301 (2018).
ATLAS data: PRC, 96, 024908 (2017).

-Where does such approximate NCQ scaling of v2 come from

-Is it an indication of partonic degree of freedom?

coalescence model & NCQ scaling of v2

Coalescence model Zhao, Ko, Liu, Qin & Song, PRL 125 7 072301 (2020).

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y},\mathbf{k}) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)$$

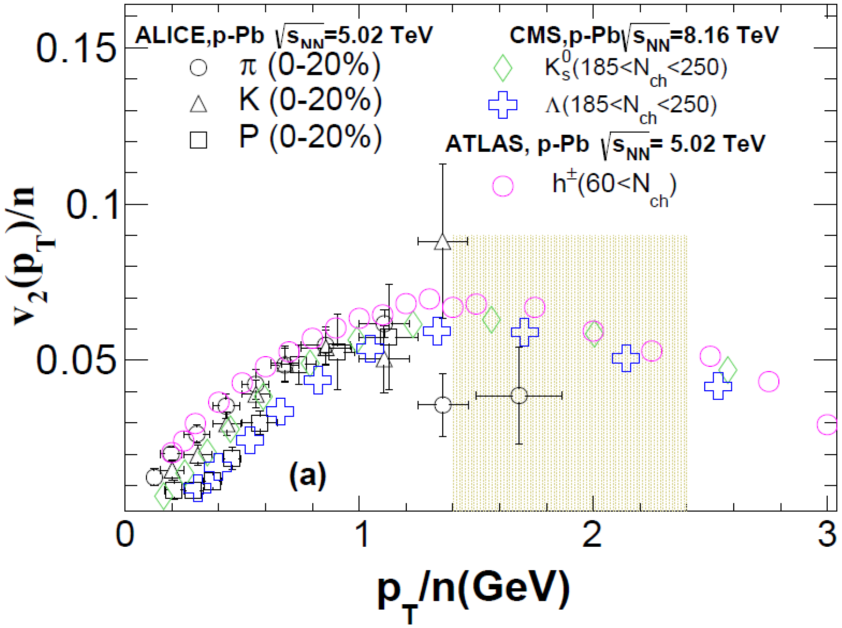
$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3)$$

Thermal & hard Partons:

- Thermal partons generated by hydro
- Hard partons generated by PYTHIA8, then suffered with energy loss by LBT

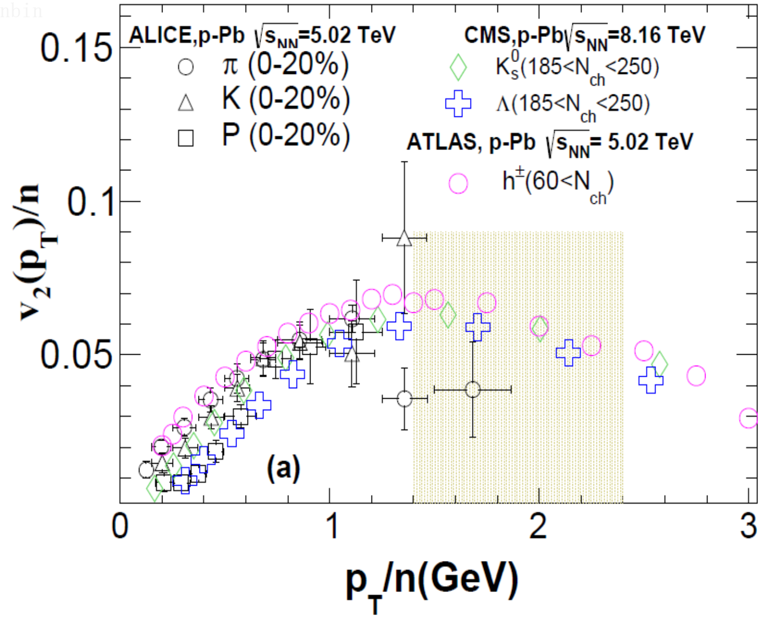
Coalesence processes:

- thermal - thermal parton coalescence
- thermal - hard parton coalescence
- hard - hard parton coalescence



Hydro-Coal-Frag Hybrid Model

Zhao, Ko, Liu, Qin & Song, PRL 125 7 072301 (2020).



Thermal hadrons (VISH2+1):

- generated by hydro. with Cooper-Frye.

Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

Coalescence hadrons (Coal Model):

-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

Fragmentation hadrons (LBT):

-the remnant hard quarks feed to fragmentation .

UrQMD afterburner:

-All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays

Main Parameters:

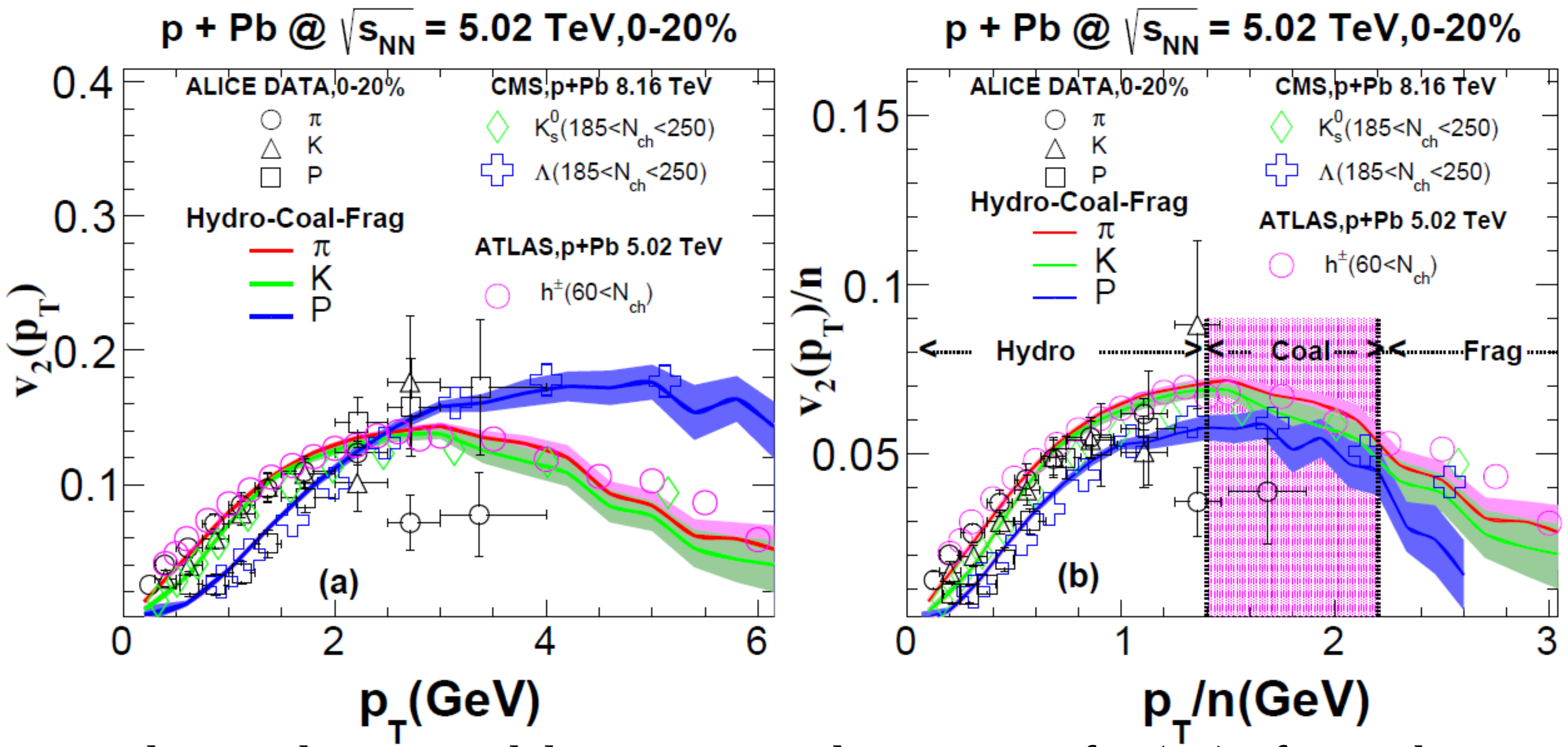
***-Thermal partons from* hydro with $P_T > P_1$.**

***-Hard partons from LBT* with $P_T > P_2$.**

Fixed by the pT spectra

p_{T1} = 1.6GeV and p_{T2} = 2.6GeV

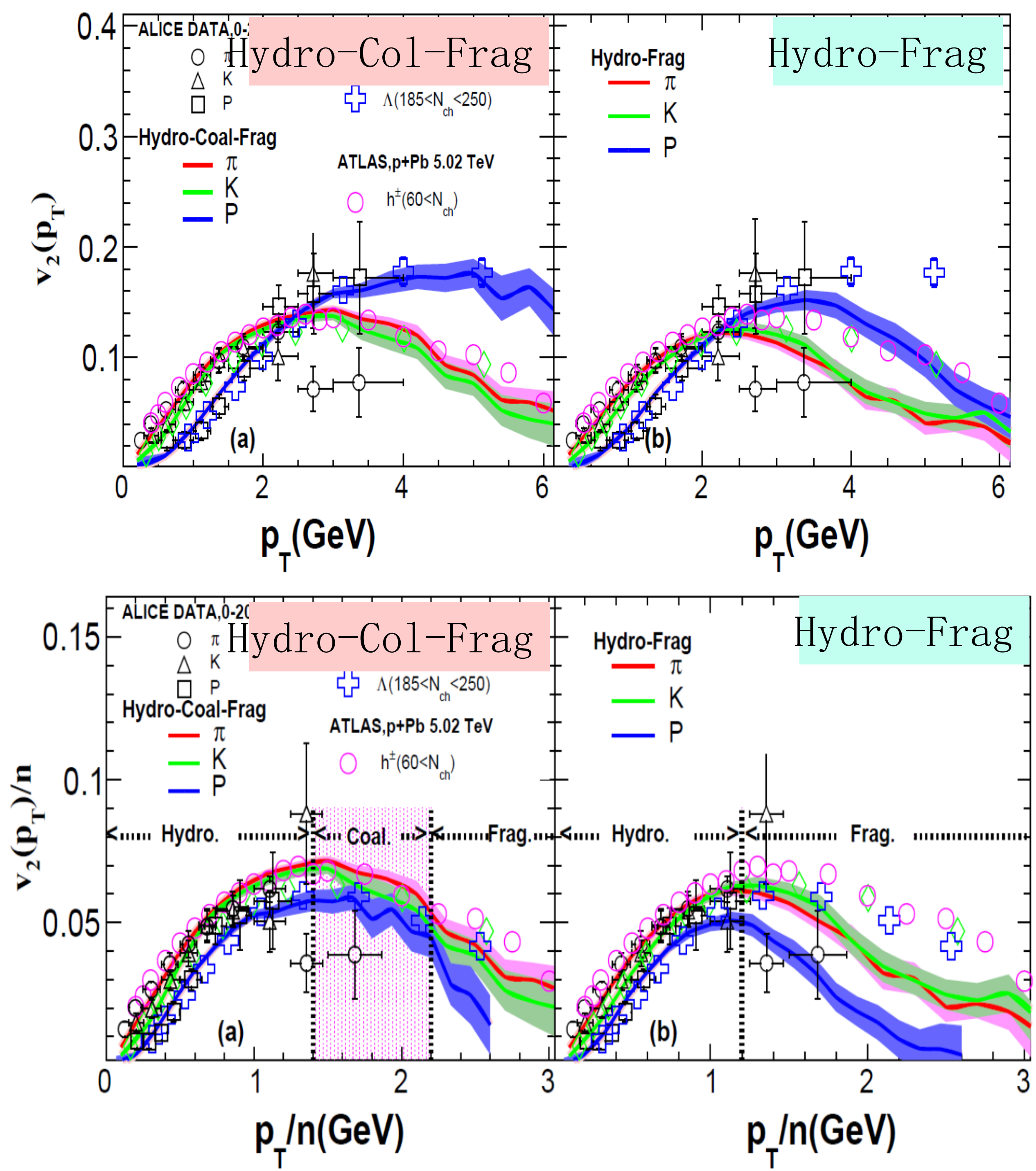
v2(pT) and NCQ scaling



-Hydro-Coal-Frag model gives a nice description of $v_2(p_T)$ of pion, kaon and proton over p_T from 0 to 6 GeV.

-At intermediate p_T, Hydro-Coal-Frag model can obtain an approximate NCQ scaling as shown by the data.

Zhao, Ko, Liu, Qin & Song,PRL 125 7 072301 (2020).



Zhao, Ko, Liu, Qin & Song,PRL 125 7 072301 (2020

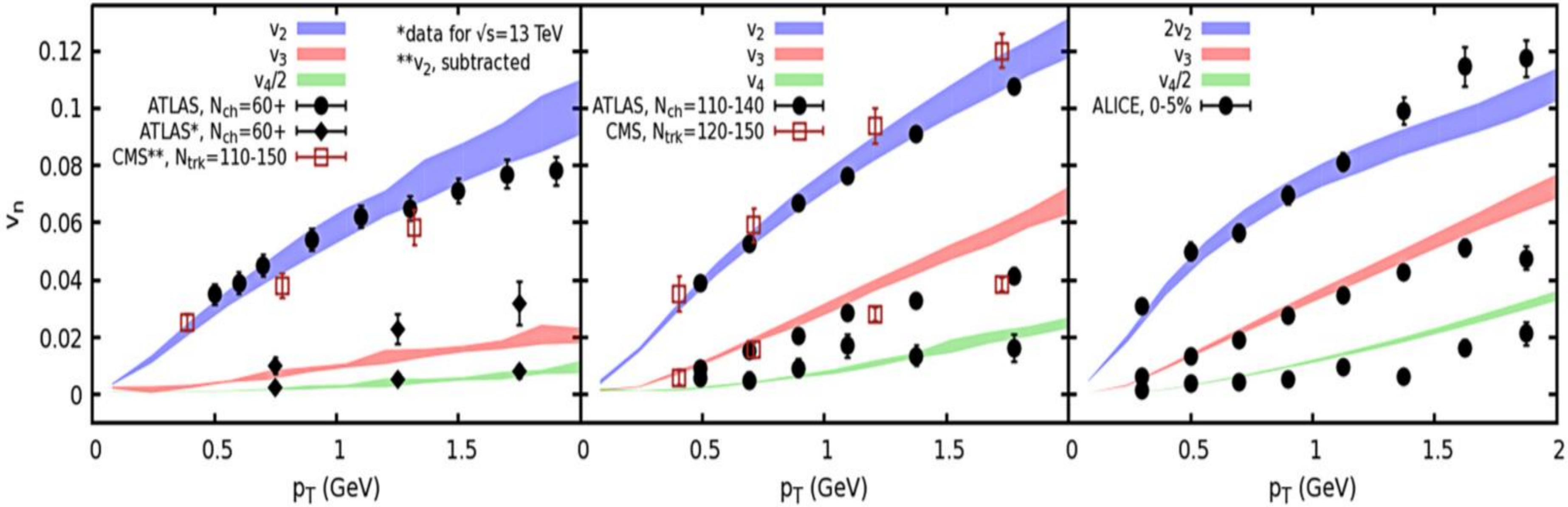
The importance of Partonic flow in p-Pb collisions

Without coalescence, Hydro-Frag largely underestimates the v2(pT)at intermediate pT, violating the NCQ Scaling of v2

Is the underlying physics identical in small and large systems?

Can one fluid rule it all? (for p-p p-Pb and Pb-Pb collisons)

Low P_T region



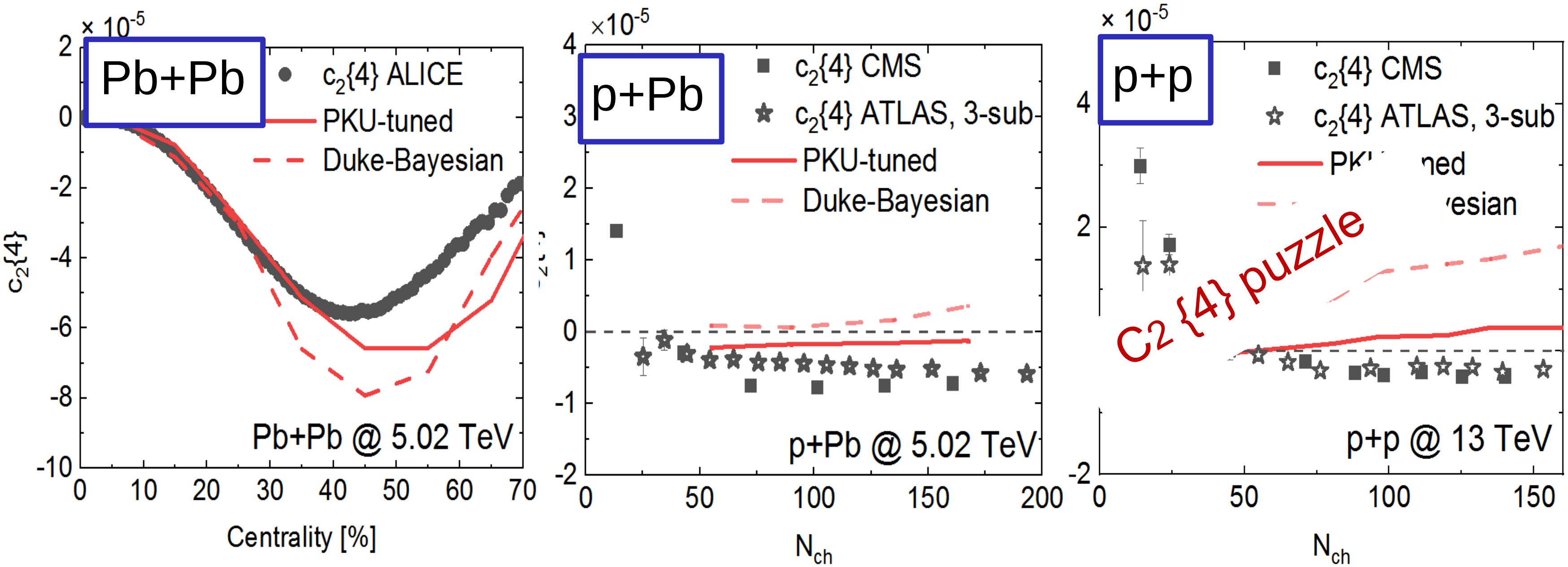
-Hydrodynamics can simultaneously describe v2, v3 and v4 for p-p, p-Pb and Pb-Pb collisions.

R.D.Weller and P.Romatschke,Phys. Lett. B 774 (2017), 351

Is the underlying physics identical in small and large systems?

Can one fluid rule it all? (for p-p p-Pb and Pb-Pb collisons)

Low P_T region



-**However**, the description of C2{4} become worse and worse from p-Pb to p-p collisions

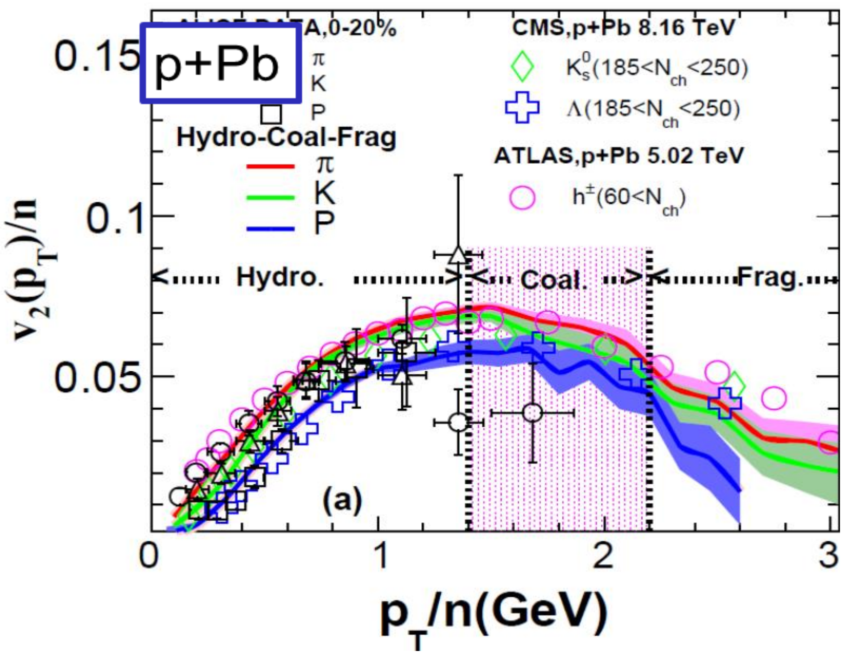
B.Fu & H.Song, paper in preparation.

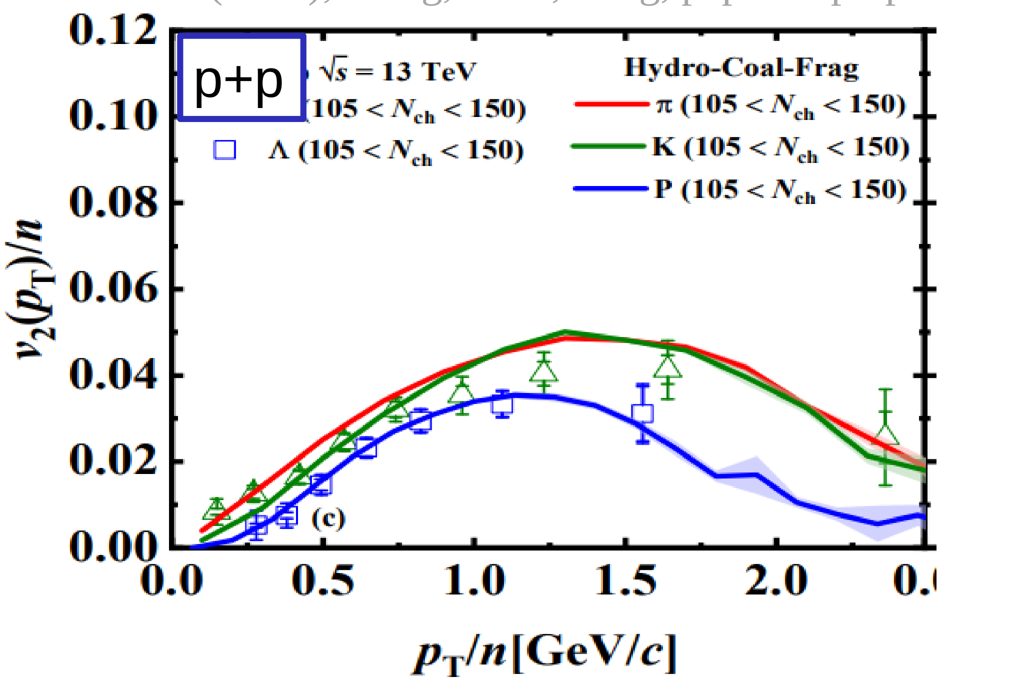
Is the underlying physics identical in small and large systems?

Can one fluid rule it all? (for p-p p-Pb and Pb-Pb collisons)

Intermediate PT region

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301(2020); Wang, Zhao, Song, paper in preparation.



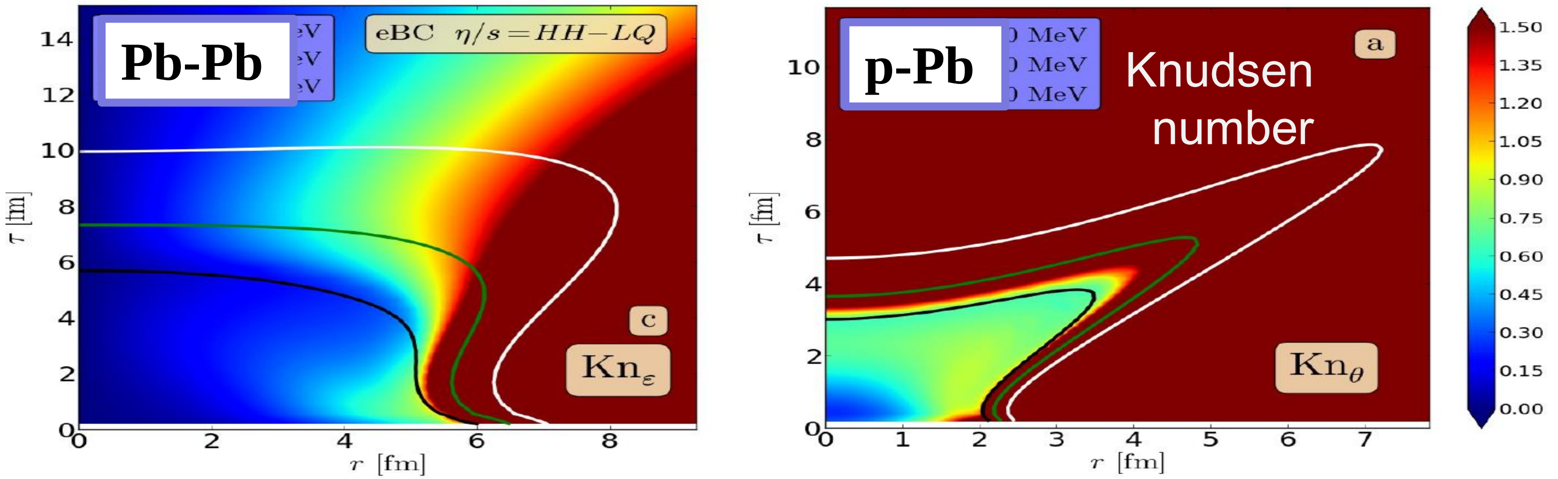


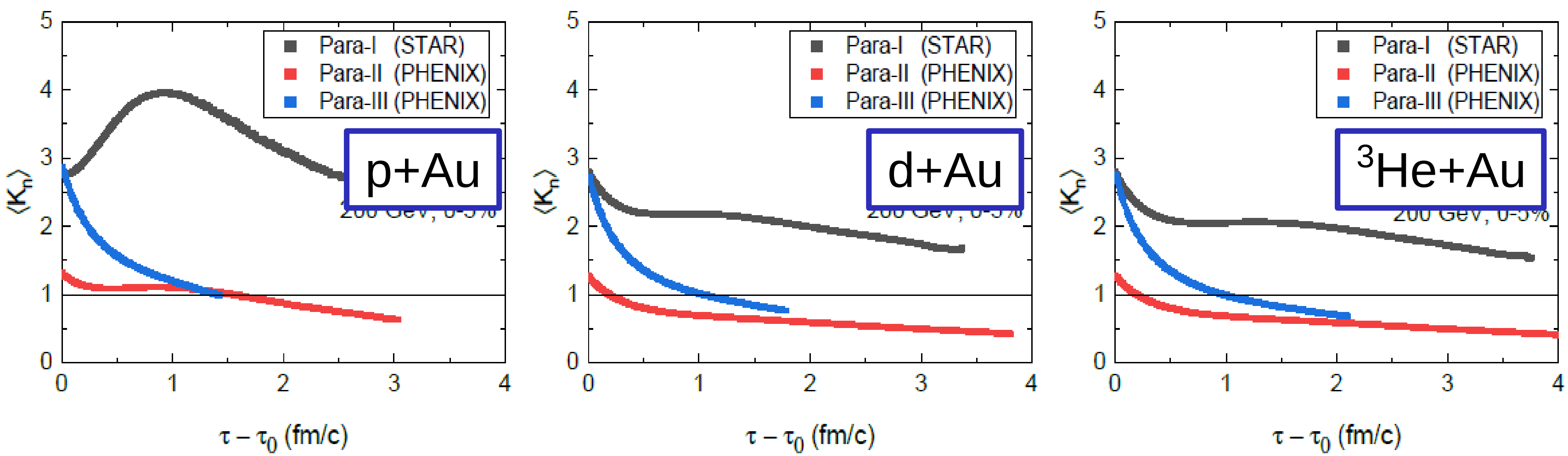
-The NCQ scaling become worse from p-Pb to p-p collisions

-Fragmentation become important tends to break-up the NCQ scaling

Large systems : traditional hydrodynamics are great success

Small systems : hydrodynamics and the fluid behavior is not that good





-Small systems may approach or beyond the limit of hydro; The situation is worse for smaller systems

Wu … Song, paper in preparation.

Is the underlying physics identical in small and large systems?

Can one fluid rule it all? (for p-p p-Pb and Pb-Pb collisons)

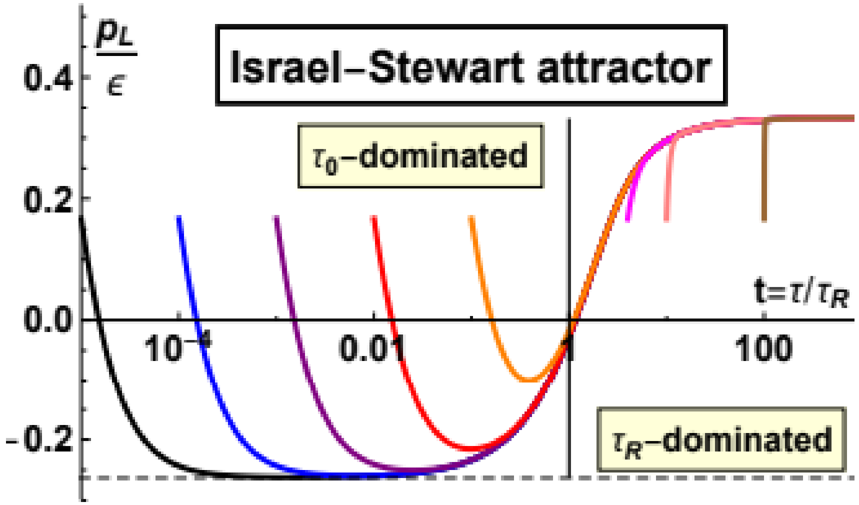
Small systems :

-Phonemically, hydrodynamics and the fluid behavior is not that good

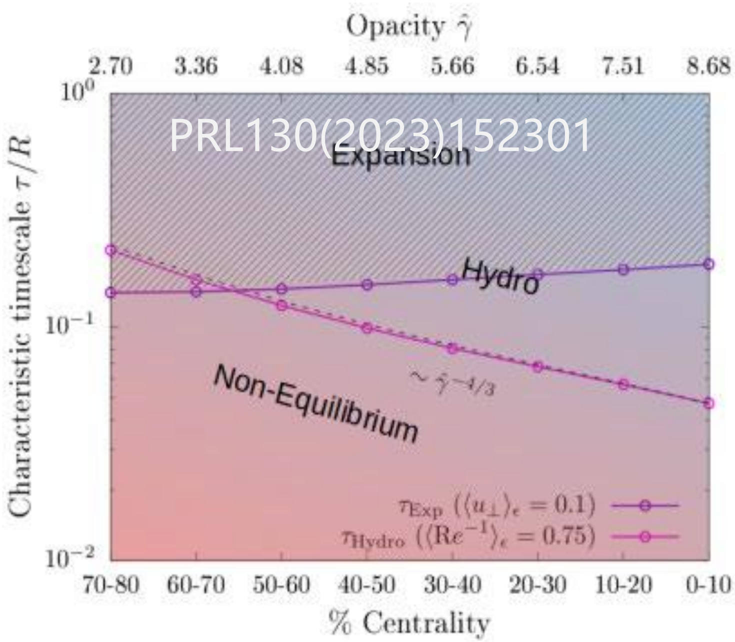
-Fragmentation/mini-jets become more & more important for smaller systems

-Small systems may approach or beyond the limit of hydro

-Isotropization & thermalizations is slower for small systems



A. Kurkela, W. van der Schee, U. A. Wiedemann, PRL124(2020)102301



Comments & Discussions

Hydrodynamic side:

-Isotropization & thermalizations for Large and small systems (need more efforts)

-Properly treat pre-equilibrium stage /isotropization for small systems

-Anisotropic hydrodynamics

M. Alqahtani, et al Phys. Rev. Lett. 119(2017)042301 … …

-Hybrid approach IP-Glasma+hydro

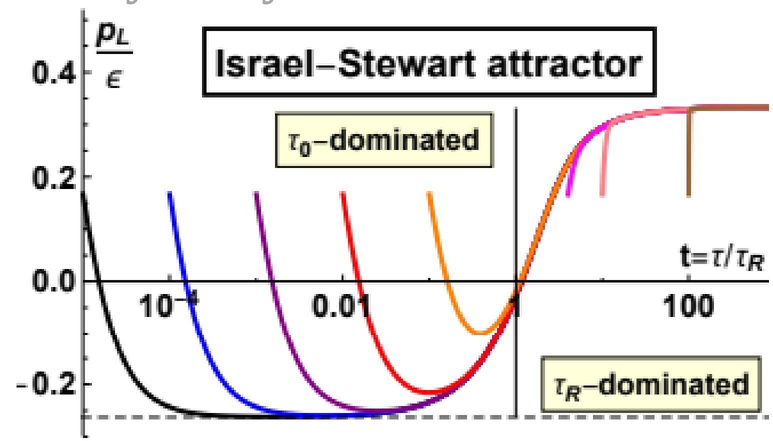
B.Schenke, et al Phys Lett B 803 (2020) 135322 …

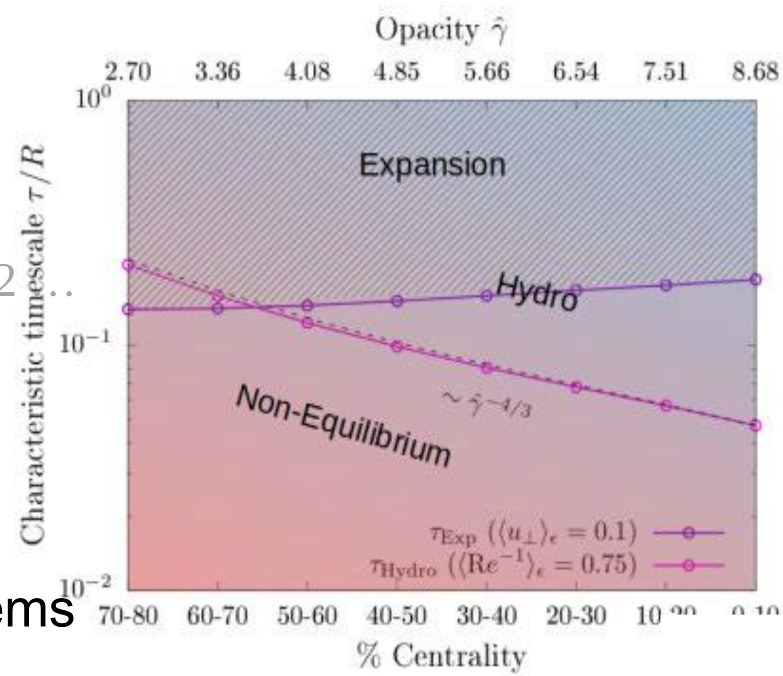
-Hybrid approach core+ corona

Y. Kanakubo, Y. Tachibana, T. Hirano. Phys.Rev.C 106 (2022) 5, 054908 … …

-initial state fluctuations for various systems

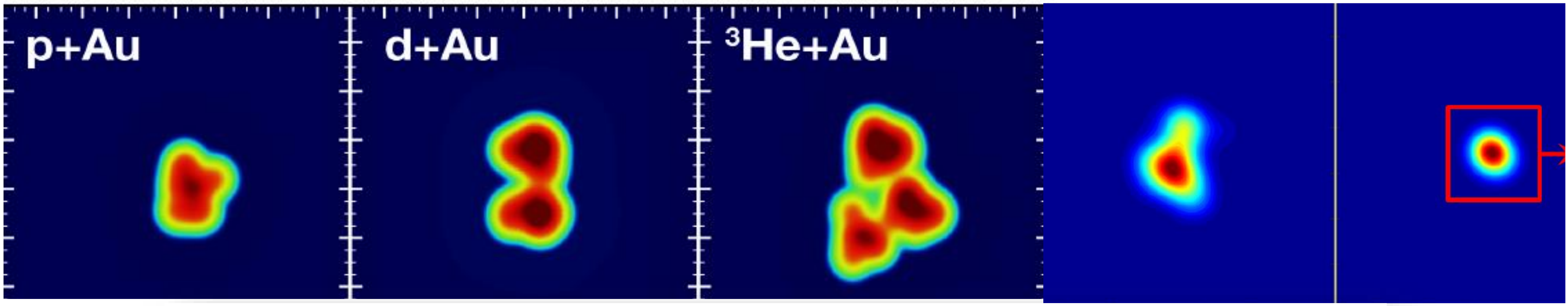
Hydrodynamic attractor

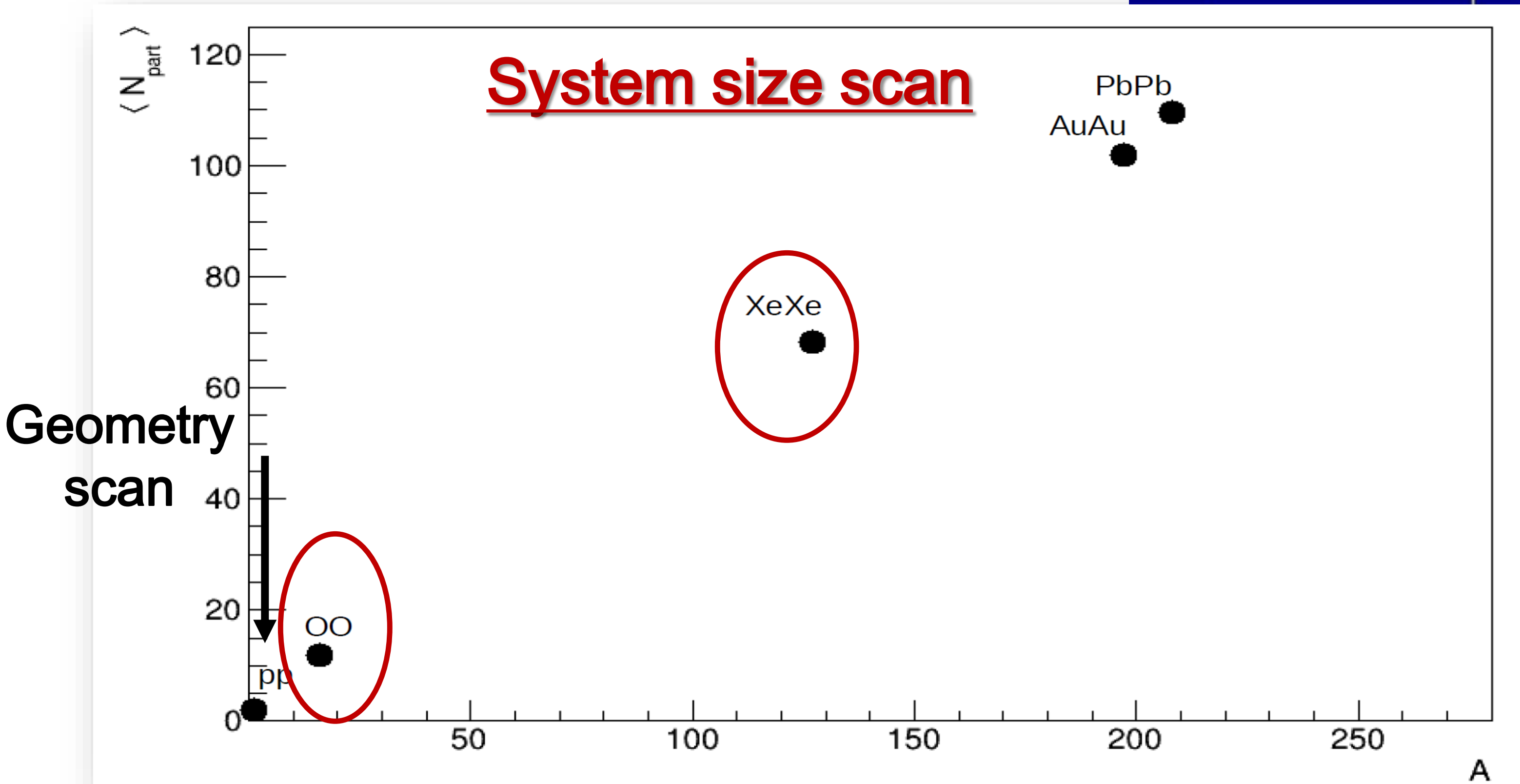




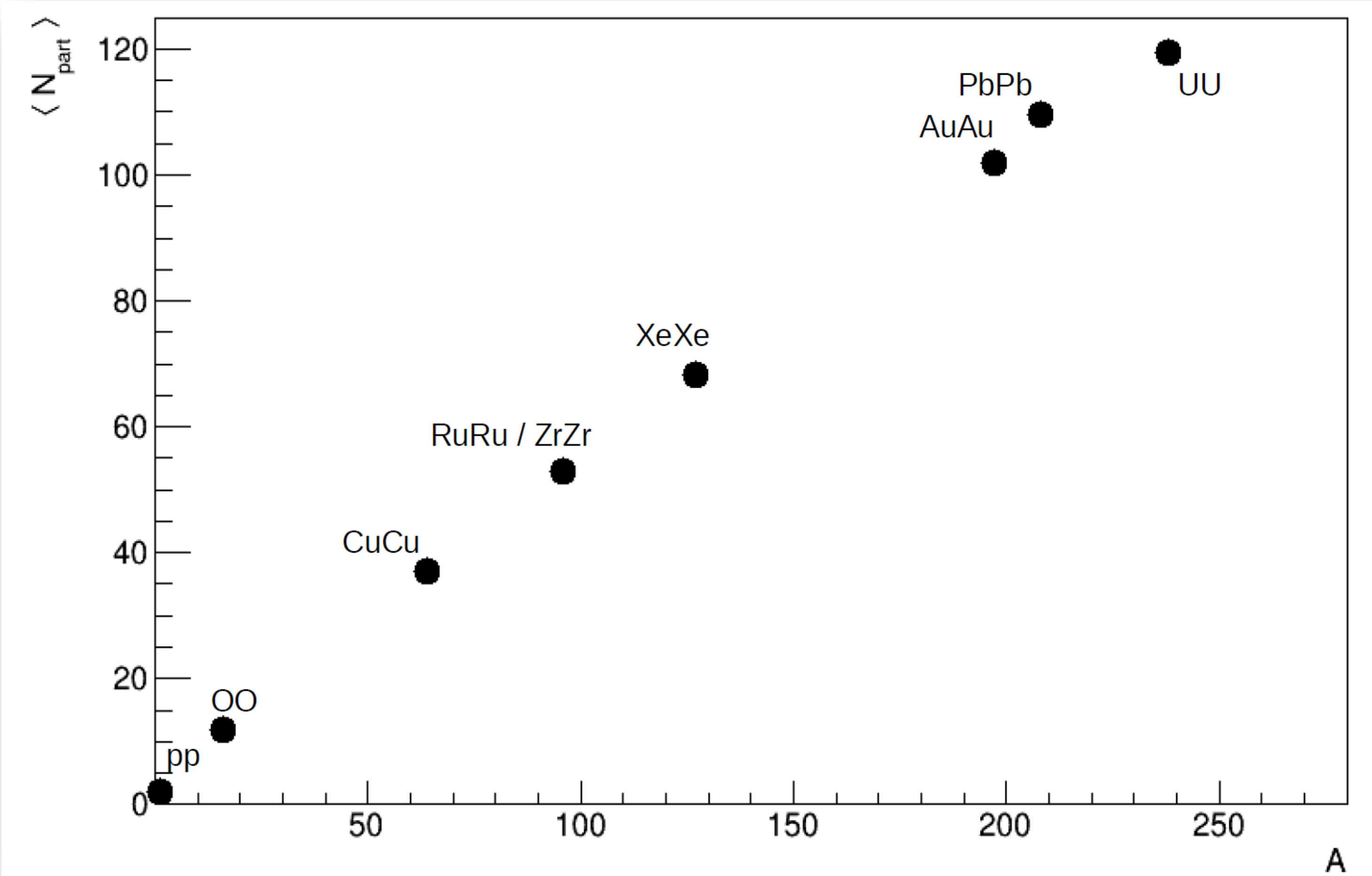
Exploring the small collision systems

Geometry scan



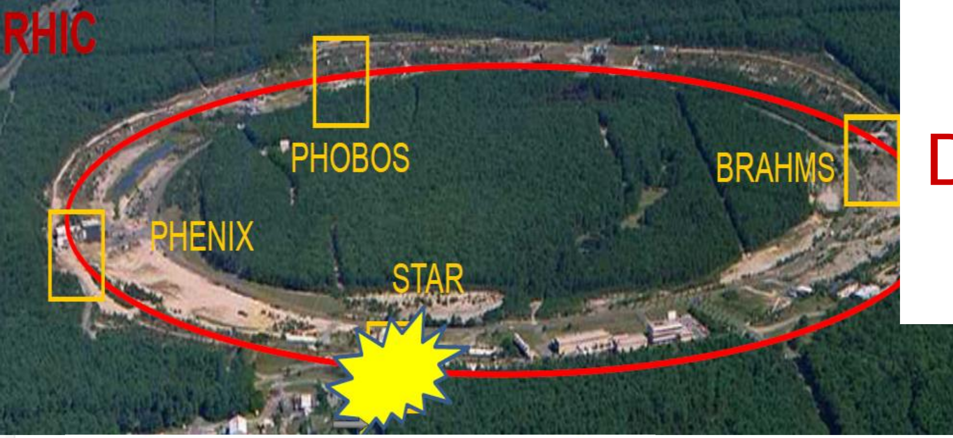


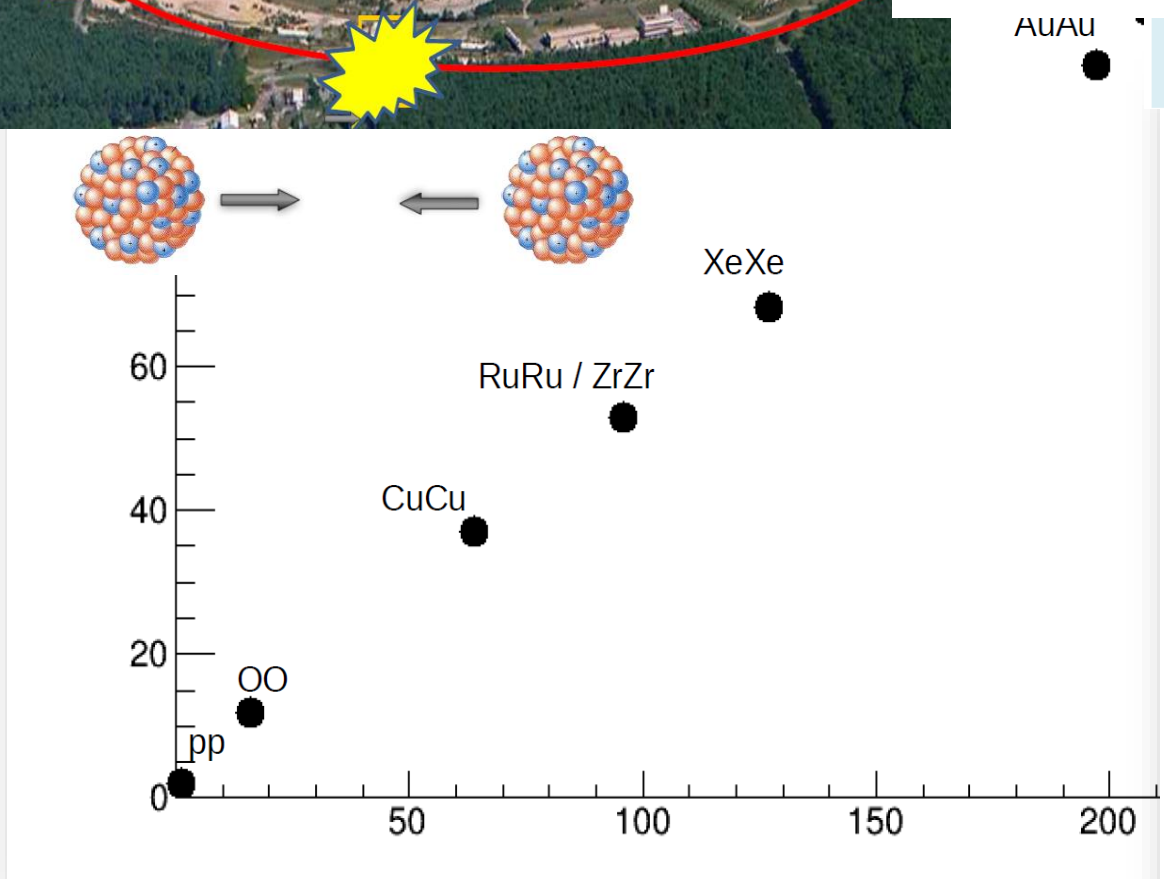
Rich collision systems at RHIC and the LHC

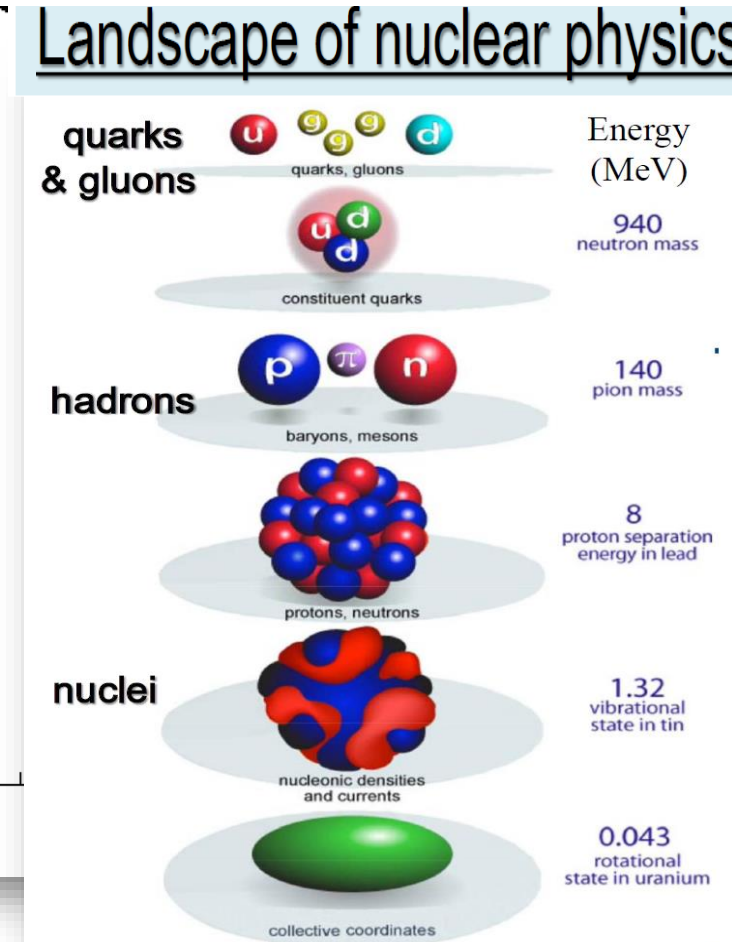


^{197}Au+^{197}Au、^{238}U+^{238}U、^{208}Pb+^{208}Pb、^{129}Xe+^{129}Xe、^{96}Zr+^{96}Zr、^{96}Ru+^{96}Ru、^{64}Cu+^{64}Cu 、 ^{16}O+^{16}O 、p+^{208}Pb、p+p ……

Probe the Nuclear Deformation with high energy nucleus-nucleus collisions



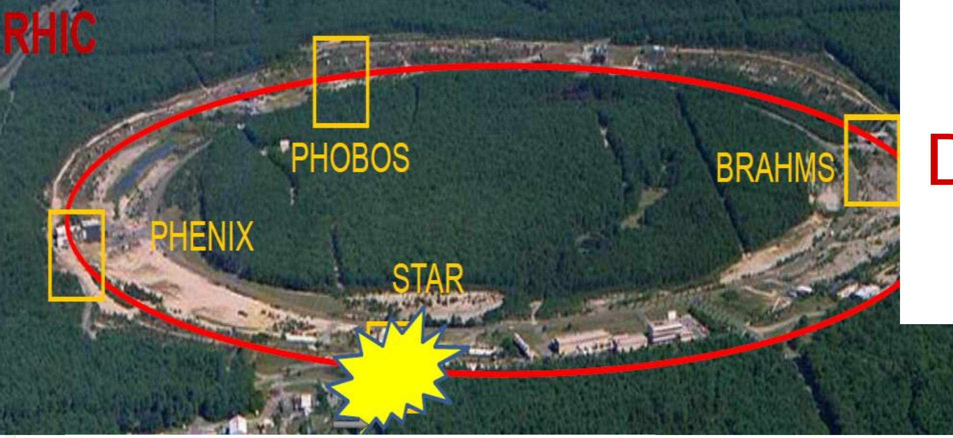


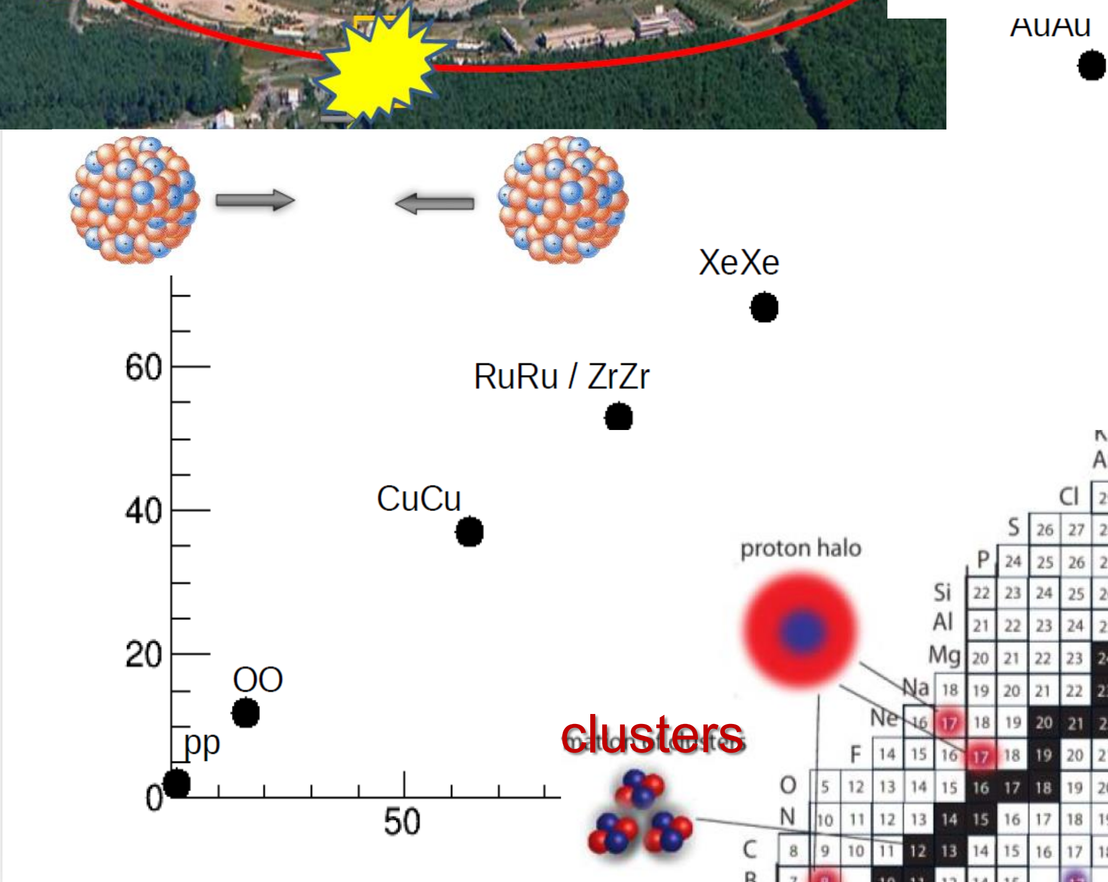


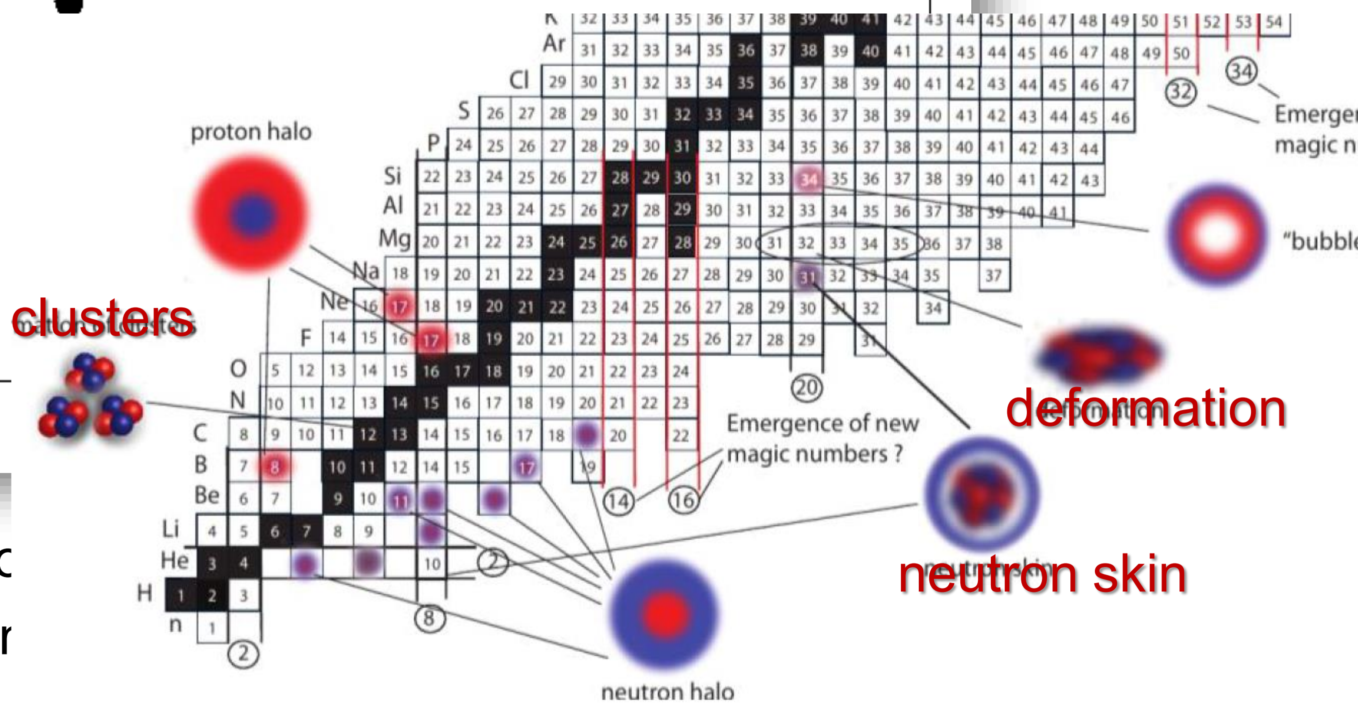
-Relativistic heavy collisions start from nuclei

-Rich collision systems to explore the nuclear structure

Probe the Nuclear Deformation with high energy nucleus-nucleus collisions

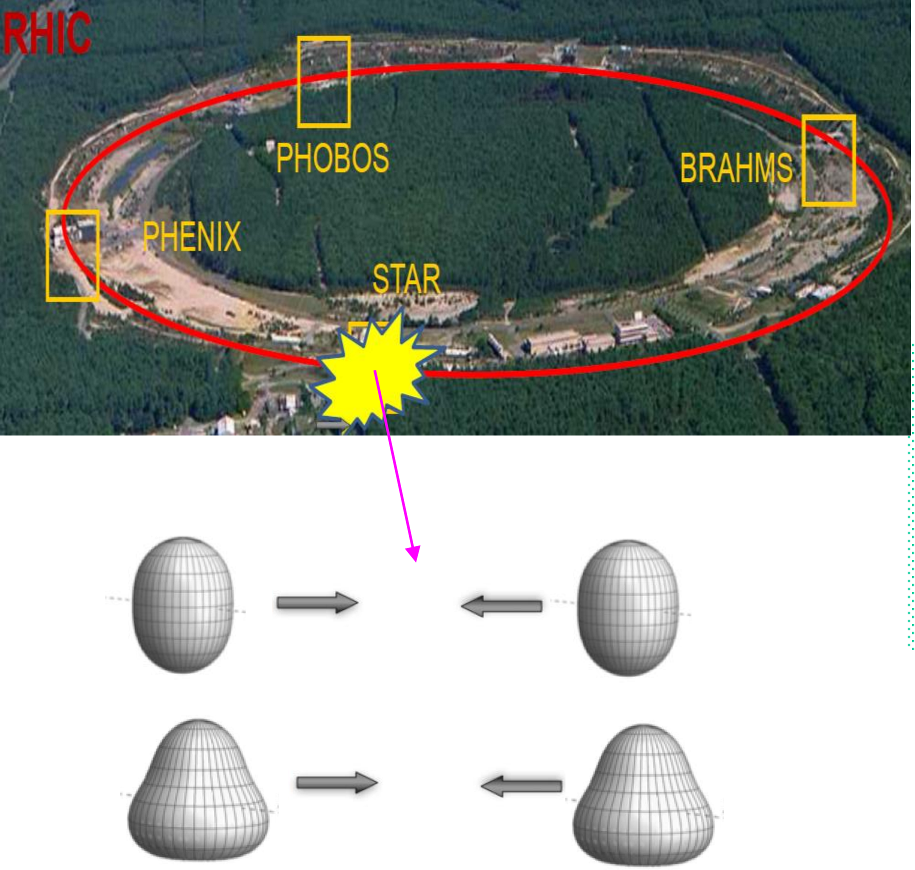






-Relativistic heavy co

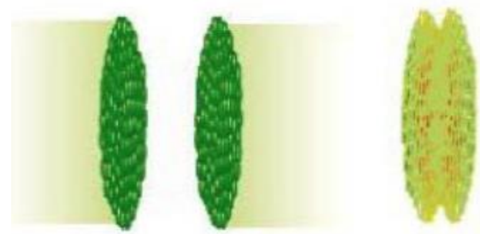
-Rich collision syster



Relativistic heavy ion collision can probe the nuclear deformation

- Relativistic heavy collisions start from nuclei

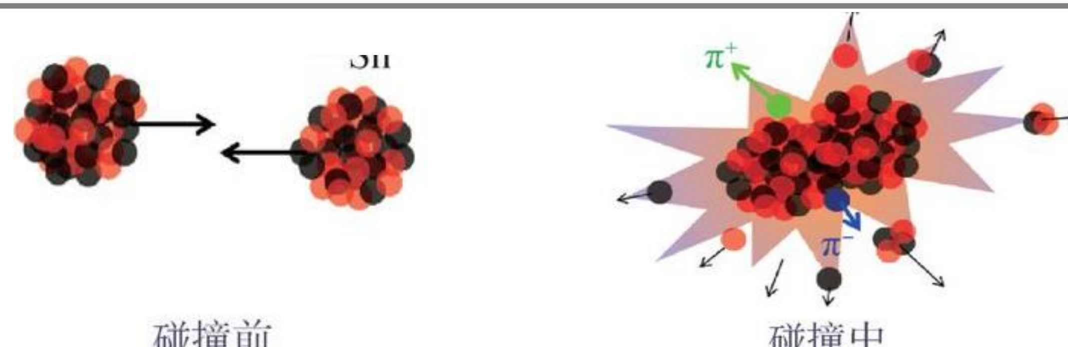
-Collision time < 10^{-24} s
directly probe the ground state of nuclei

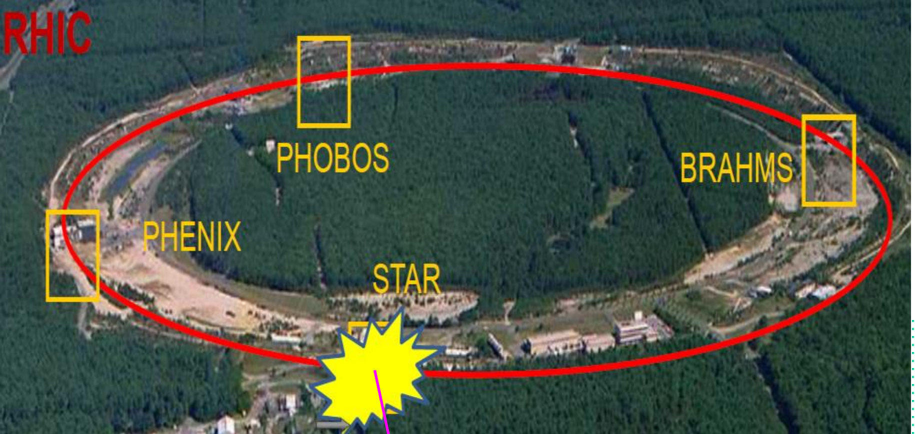


initial conditions:
(with deformations)

Collision time < 10^{-24} s

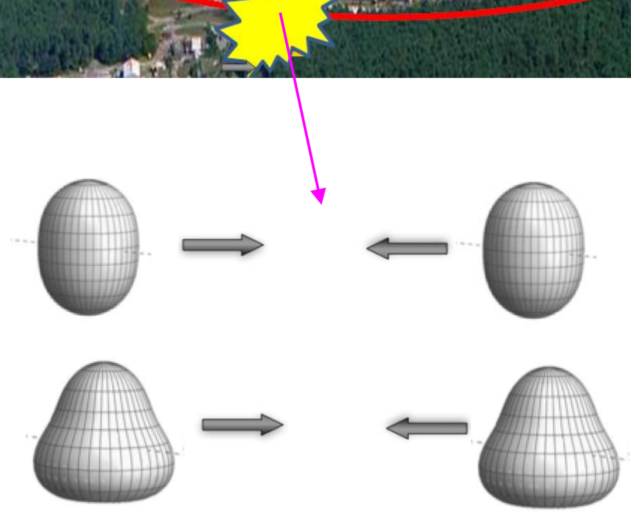
heavy ion collision at intermediate energies excites nuclei during the collision





Relativistic heavy ion collision can probe the nuclear deformation

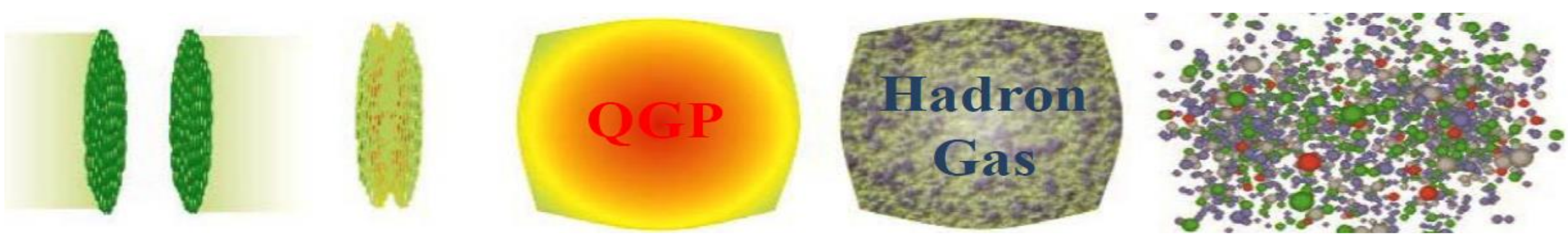
- Relativistic heavy collisions start from nuclei
- Collision time < 10^{-24} s directly probe the ground state of nuclei
- Well calibrated calculations to focus on the initial state effects from the succeeding evolution



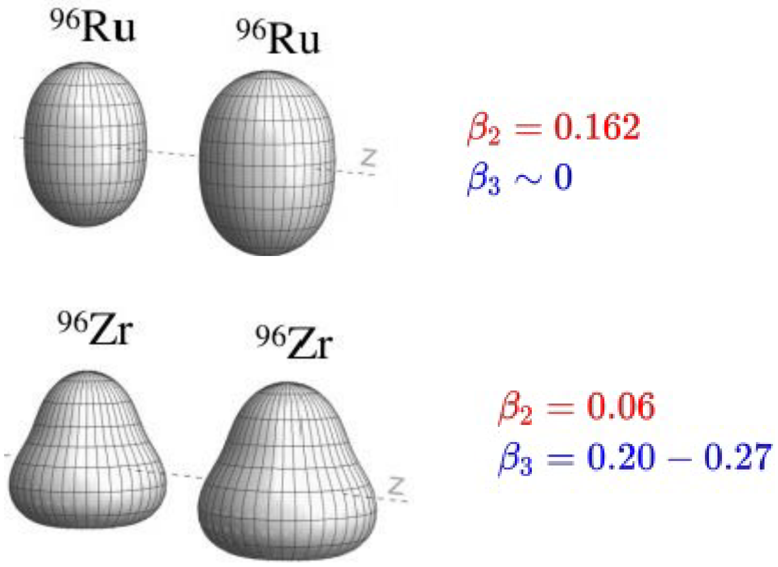
initial conditions:
(with deformations)

Well calibrated calculations

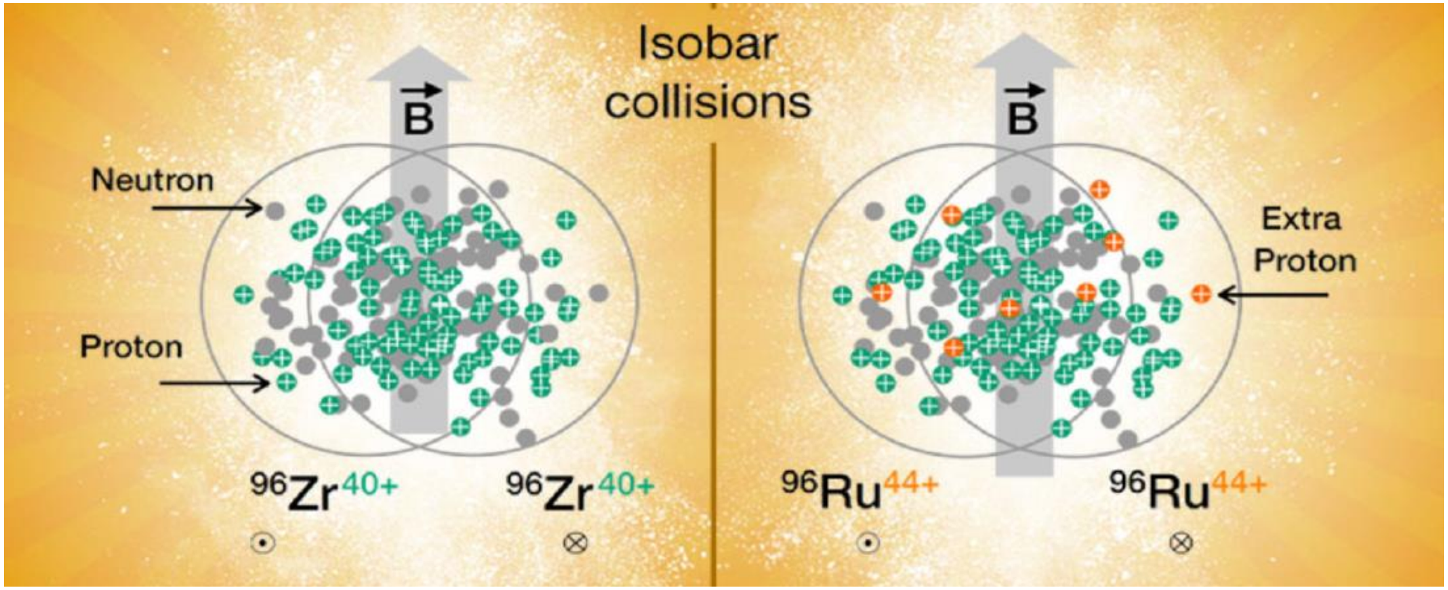
Initial conditions | viscous hydro | hadron cascade



Probe the Nuclear Deformation with Isobar collisions

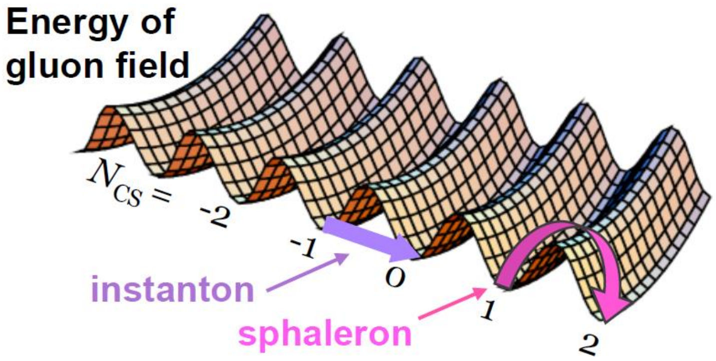


$^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$ Collisions @ RHIC isobar run

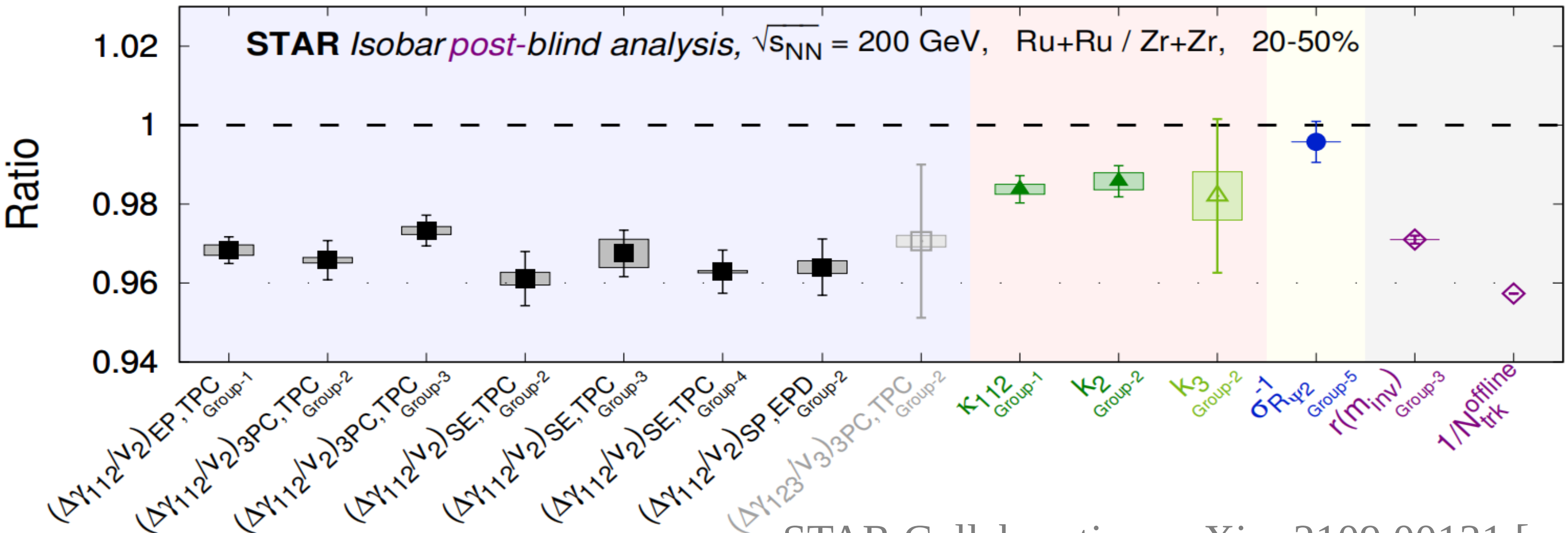


-Obviously different early magnetic field for Ru+Ru and Zr+Zr collisions

-Aim to search the Chiral Magnetic Effect (CME) and probe nontrivial structure of the QCD vacuum



Search CME with Isobar collisions



STAR Collaboration. arXiv: 2109.00131 [nucl-ex]

between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

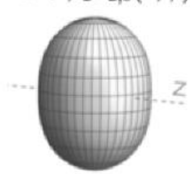
-Observed differences in both multiplicity and v2 imply that **CME background are different for ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr Collisions** at matching centralities

Nuclear Deformation

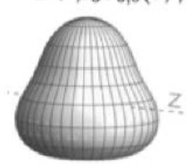
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0\left(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^{3} \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^{4} \alpha_{4,m} Y_{4,m}\right)$$

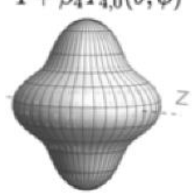
Quadrupole: $1 + \beta_2 Y_{2,0}(\theta,\phi)$



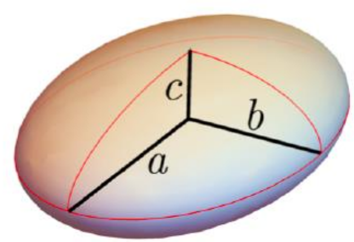
Octupole: $1 + \beta_3 Y_{3,0}(\theta,\phi)$



Hexadecapole: $1 + \beta_4 Y_{4,0}(\theta,\phi)$



Triaxial spheroid: $a \neq b \neq c$.



$0 \leq \gamma \leq \pi/3$

Prolate: a=b<c → β_2, γ=0
Oblate: a<b=c → β_2, $\gamma=\pi/3$ or $-\beta_2$, γ=0

Deformation of ^{96}Ru and ^{96}Zr

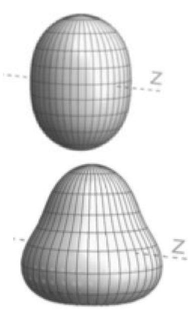
PHYSICAL REVIEW C VOLUME 42, NUMBER 3 SEPTEMBER 1990

Strong octupole and dipole collectivity in ^{96}Zr: Indication for octupole instability in the $A=100$ mass region

^{96}Zr has very large octupole deformation from $B(E3;0_1^+ \rightarrow 3_1^-)$

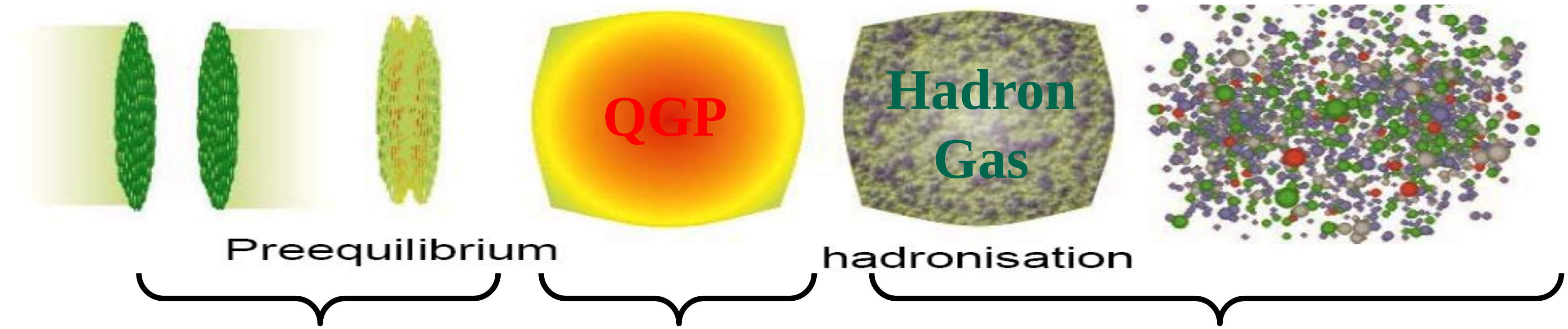
Conversion from B(En) to β_n via: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90



ADNDT107,1 (2016) ADNDT80,35(2002)

Hydrodynamic calculation with initially deformed nuclei

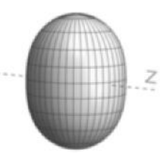


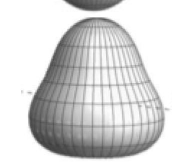
Initial conditions **viscous hydro** **hadron cascade**

Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

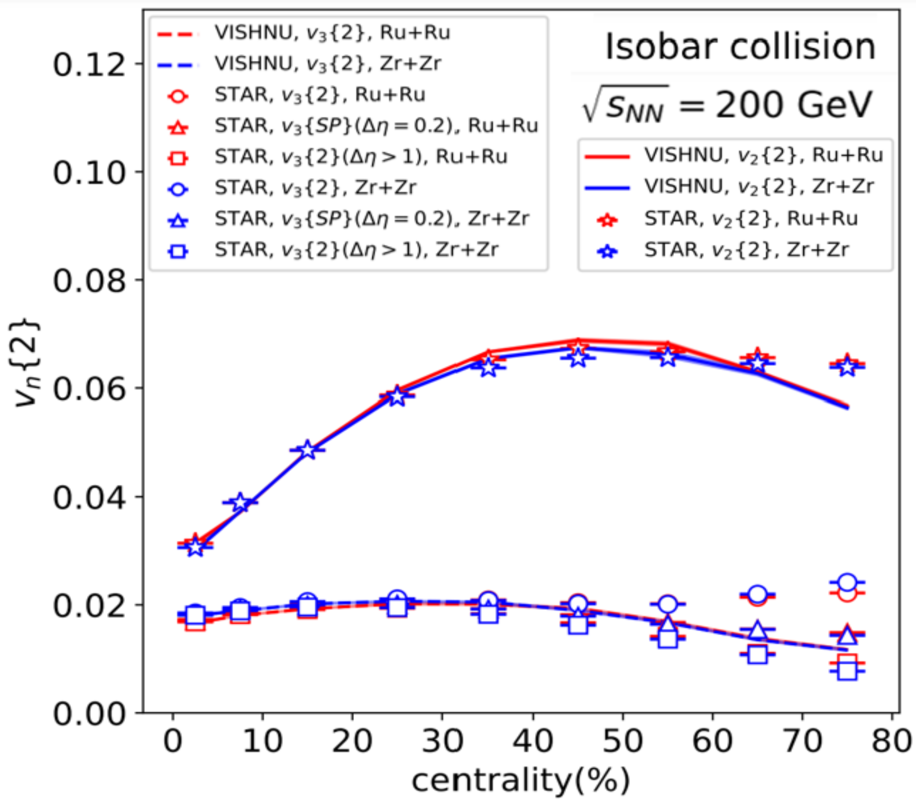
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

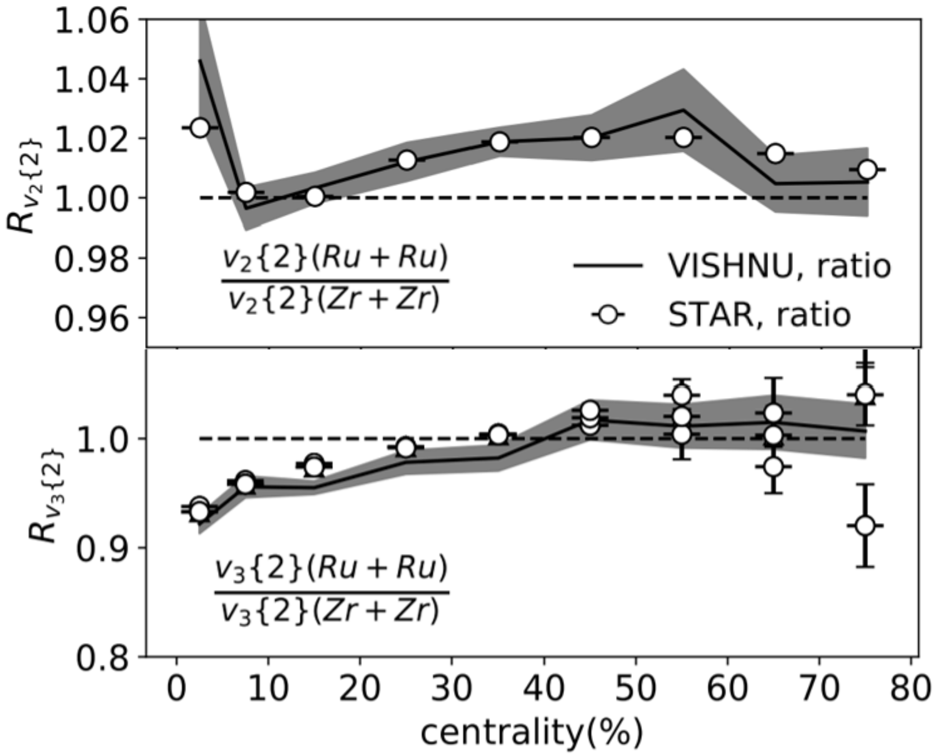
Quadrupole: 

Octupole: 

$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}] + \beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m} + \beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

V_2 and V_3 for Ru+Ru and Zr+Zr collisions



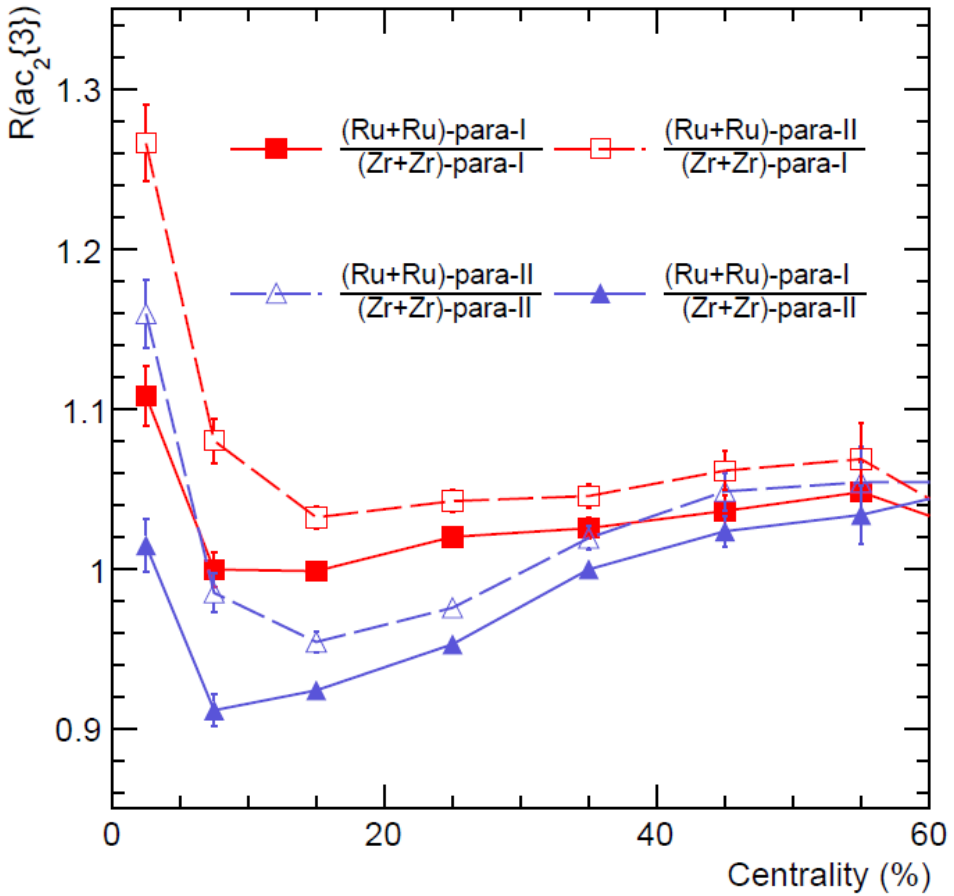


-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

-Using β_2 β_3 in table1, it "predicts" V_2 & V_3 for Zr+Zr collisions & the related ratio -- (the data are roughly described).

"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

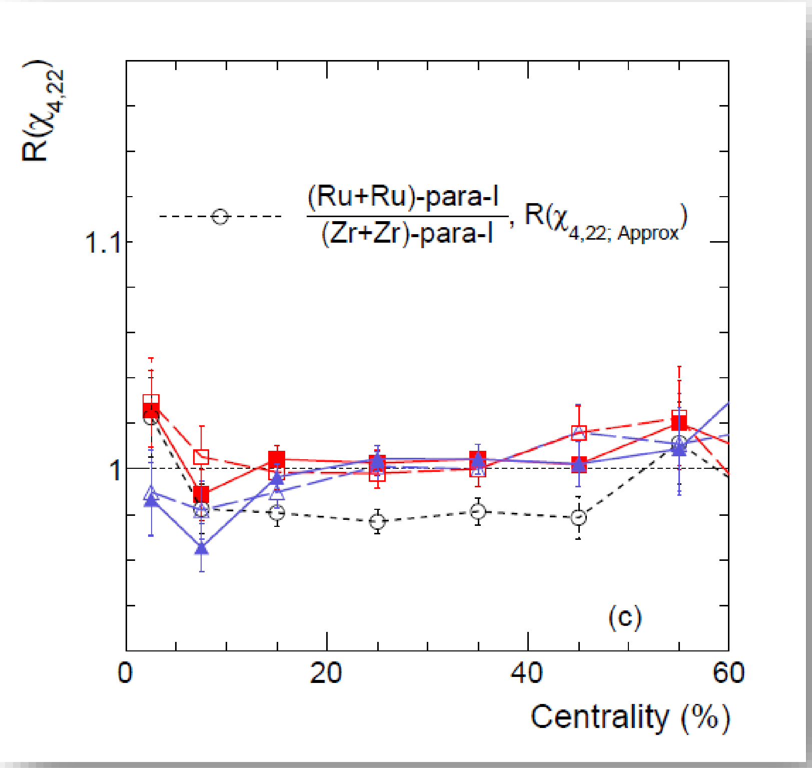
ac{3}for Ru+Ru and Zr+Zr collisions



$$\mathrm{ac}_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$

$$\chi_{4,22} \equiv \frac{\mathrm{ac}_2\{3\}}{\langle v_2^4\rangle} = \mathrm{nac}_2\{3\}\sqrt{\frac{v_4\{2\}^2}{2v_2\{2\}^4 - v_2\{4\}^4}}.$$

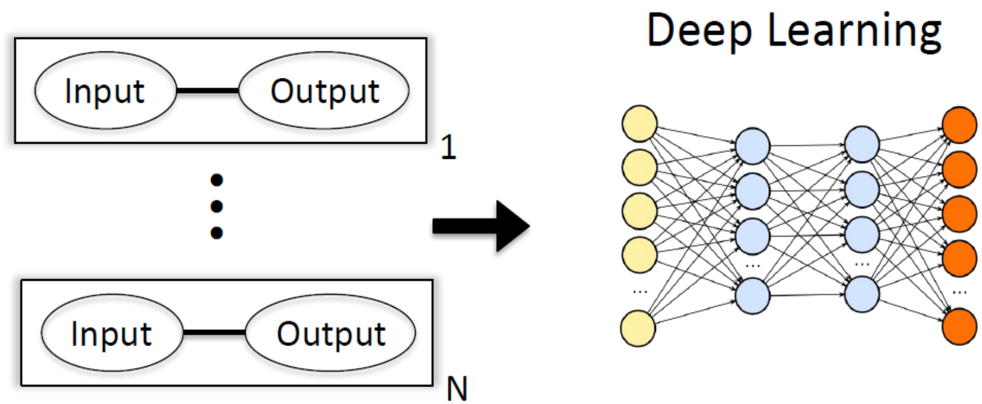
ac{3} is sensitive to quadrupole and octupole deformations



Applications of Deep Learning in Relativistic Hydrodynamics

Why Deep Learning in Physics?

"Unlike earlier attempts … Deep Learning systems can see patterns and spot anomalies in data sets far larger and messier than human beings can cope with."

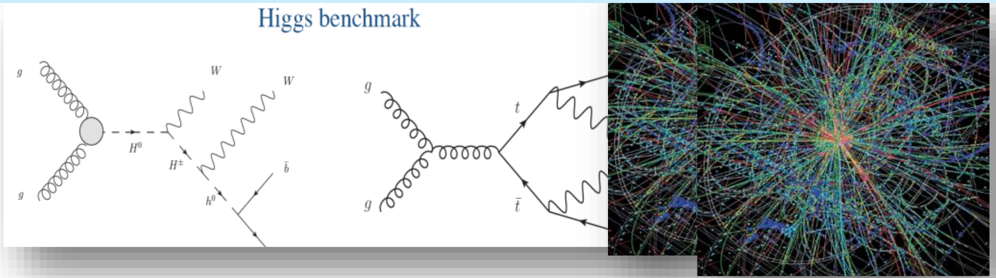


Can "Black-box" models learn patterns and models solely from data without relying on scientific knowledge?

Applications of Deep Learning in Physics

- Y. D. Hezaveh, L. Perreault Levasseur and P. J. Marshall, Nature 548, 555 (2017)
- J. Carrasquilla and G. R. Melko, Nature Phys. 13, 431 (2017)
- Carleo et al., Science 355, 602-606 (2017)
- E. P. L. van Nieuwenburg, Y. H. Liu, S. Huber, Nature Phys. 13, 435 (2017)
- Pierre Baldi, Peter Sadowski, and Daniel Whiteson, Nature Commun. 5 (2014) 4308
- Luke de Oliveira, Michela Paganini, and Benjamin Nachman, Comput Softw Big Sci (2017) 1: 4
- Long-Gang Pang et al., Nature Commun. 9 (2018) no.1, 210
- . . ., . . .,
- . . .

Searching for Exotic Particles in High-Energy Physics



Deep learning can improve the power for the collider search of exotic particles

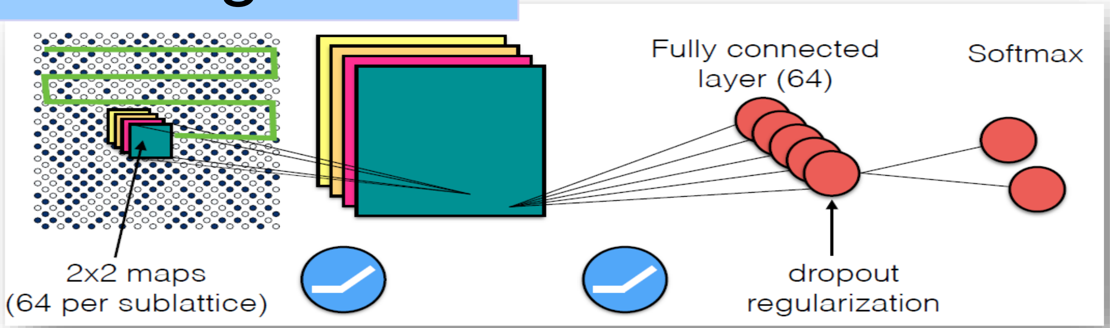
P. Baldi, P. Sadowski, & D. Whiteson
Nature Commun. 5, 4308 (2014)

Classifying the Phase of Ising Model

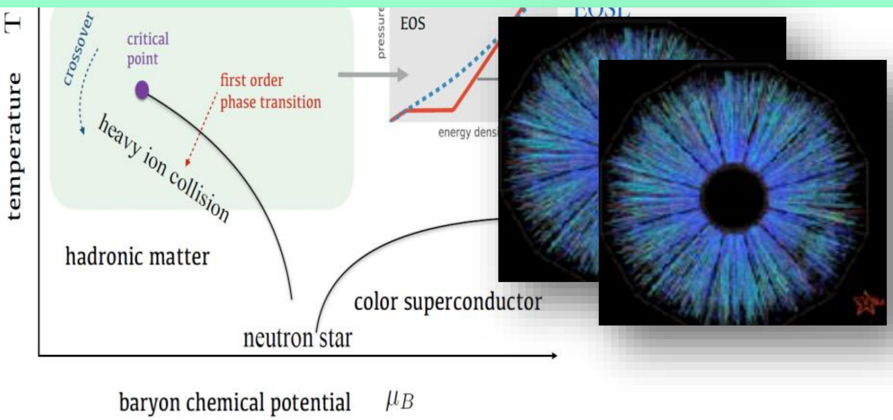
For the case of Ising gauge theory

$$H = -J \sum_p \prod_{i \in p} \sigma_i^z$$

J. Carrasquilla and R. G. Melko.
Nature Physics 13, 431–434 (2017)



Identify QCD Phase Transition with Deep Learning

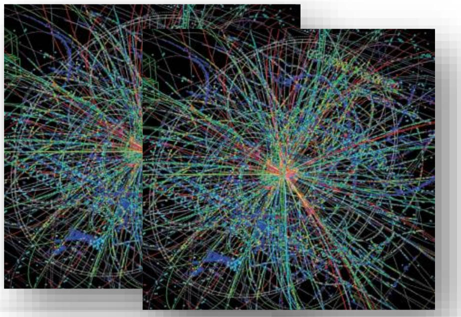
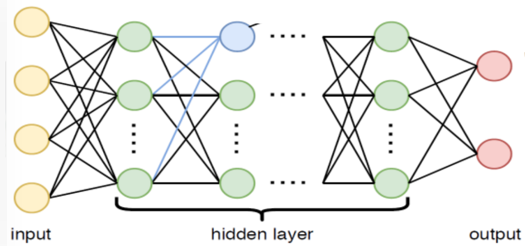


DNN efficiently decode the EOS information from the complex final particle info event by event

LG. Pang, K. Zhou, N. Su, H. Petersen, H. Stoecker, XN. Wang.
Nature Commun. 9 (2018) no. 1, 210

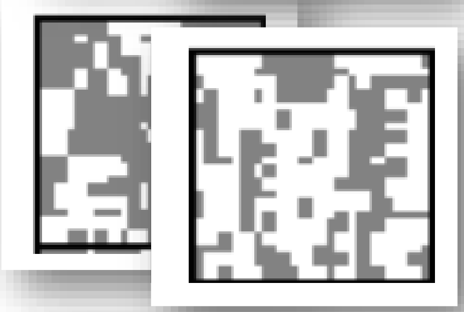
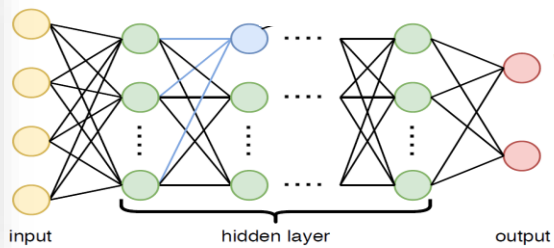
More Comments on several examples of supervised learning

Image identification

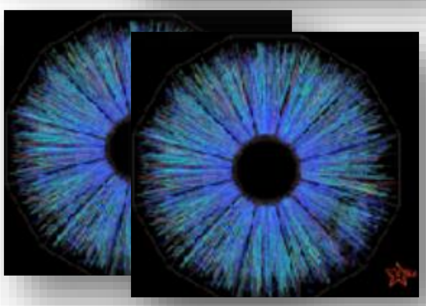
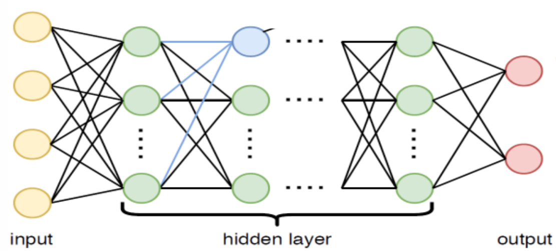
Higgs signal or background?

P.Baldi,et al,Nature Commun.(2014)

High temperature or low temperature phase?

Carrasquilla & Melko. Nature Physics (2017)

EoS L or EOSQ ?

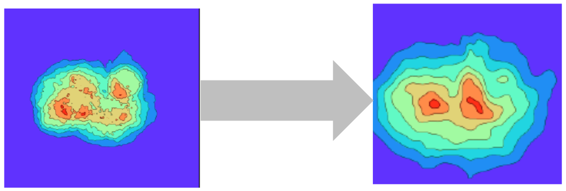
Pang,et al Nature Commun.(2018)

"Unlike earlier attempts … Deep Learning systems can see patterns and spot anomalies in data sets far larger and messier than human beings can cope with."

Image generation

For hydrodynamics can we use deep learning to learn/predict the pattern transformation between initial and final profiles?

Initial energy density profiles
-------- > final energy density velocity profiles

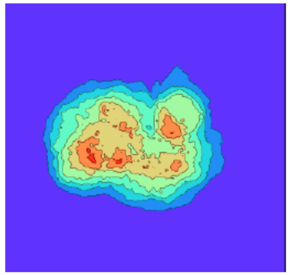


For the non-linear hydro system, can the black-box network could learn pattern transformations solely from data without relying on scientific knowledge?
(conservation laws)

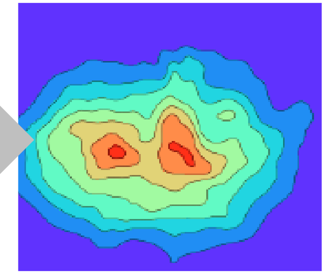
Applications of deep learning to relativistic hydrodynamics

H.Huang, B.Xiao, H.Xiong, Z.Wu, Y. Mu and H.Song; NPA 2019
Phys. Rev. Res. 3 2 023256(2021)

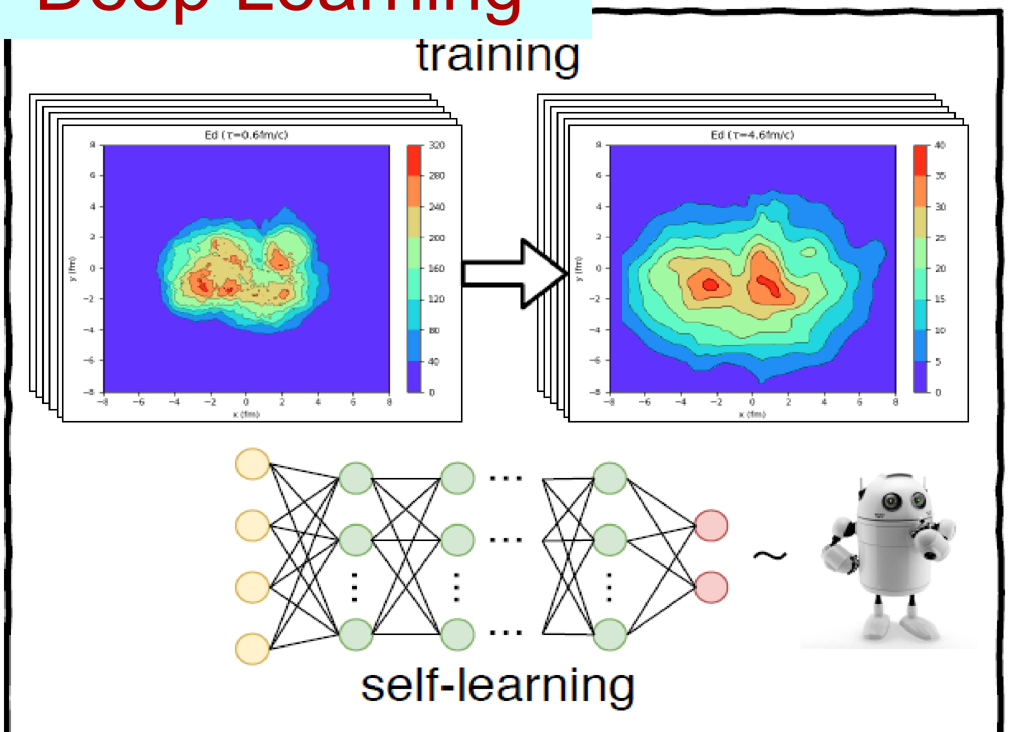
Traditional hydrodynamics

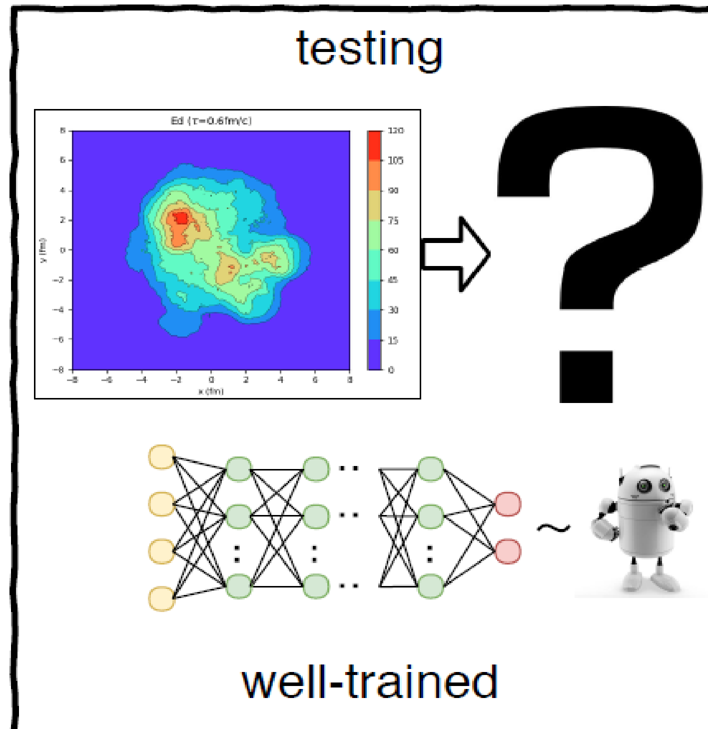


$$\partial_\mu T^{\mu\nu}(x) = 0$$



Deep Learning

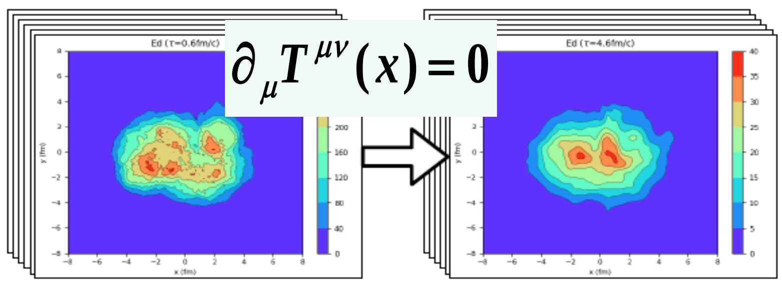




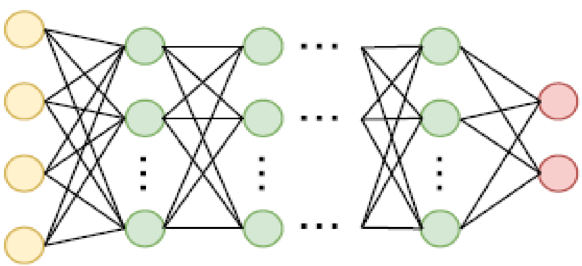
-Such deep learning systems do not need to be programmed with the hydro equation $\partial_\mu T^{\mu\nu}(x) = 0$ Instead, they learn on their own

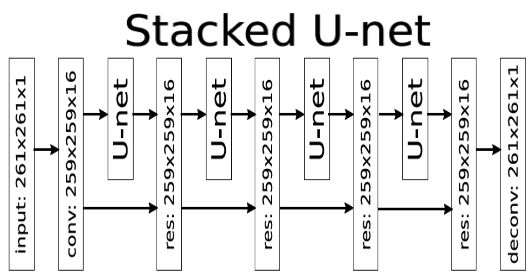
Deep Learning

Step1) Generate the training/testing data sets from hydro



Step2) Design & train the deep neural network

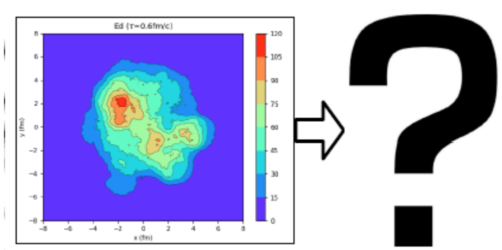




The Training Data Sets

hydro VISH2+1	MC-Gl
	10000

Step3) Test the deep neural network

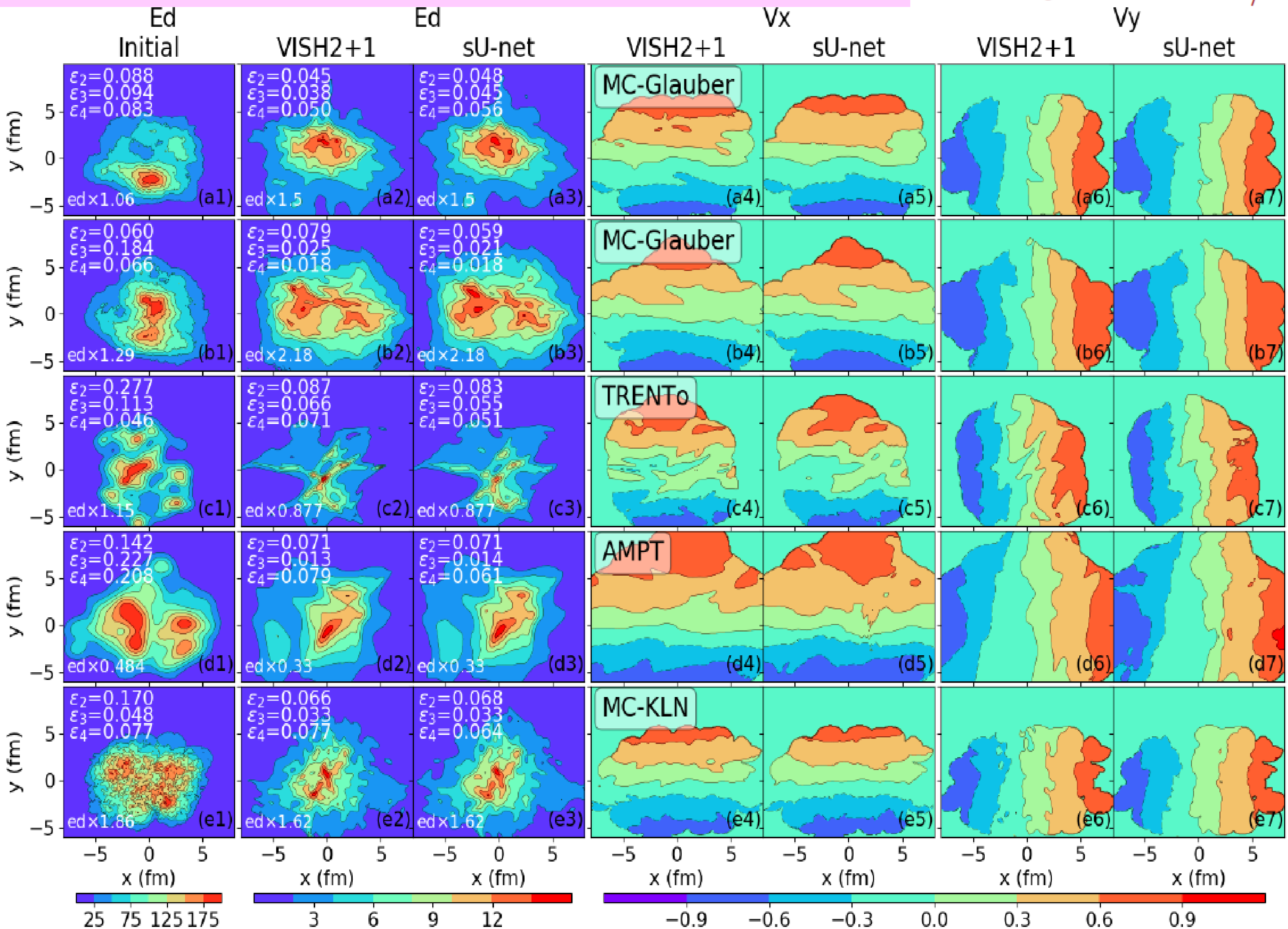


The Testing Data Sets

hydro VISH 2+1	MC-Gl	MC-KLN	AMPT	Trento
	10000	10000	10000	10000

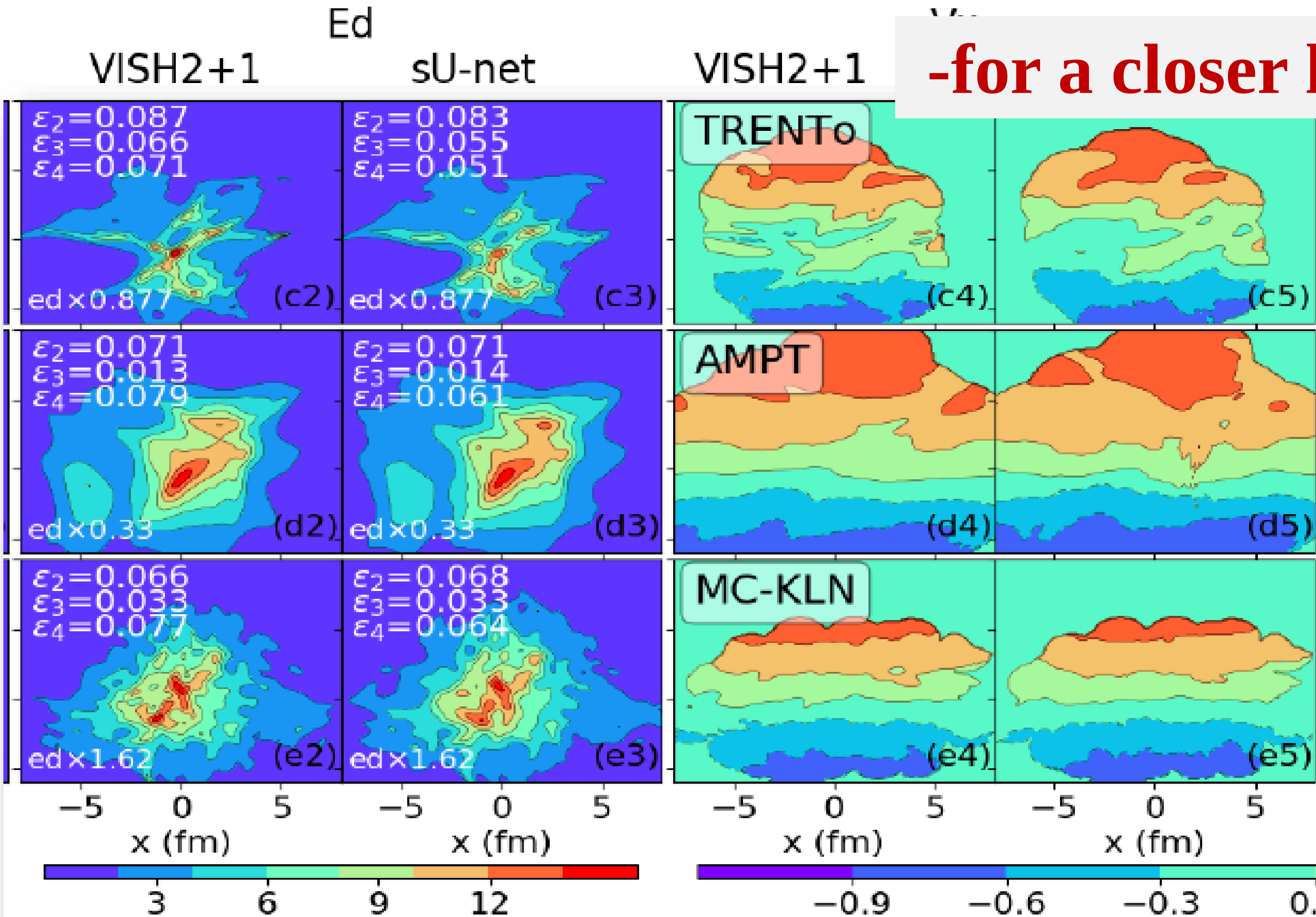
sUnet prediction vs. hydro simulations

$\tau - \tau_0 = 6.0 fm/c$



sUnet prediction vs. hydro simulations

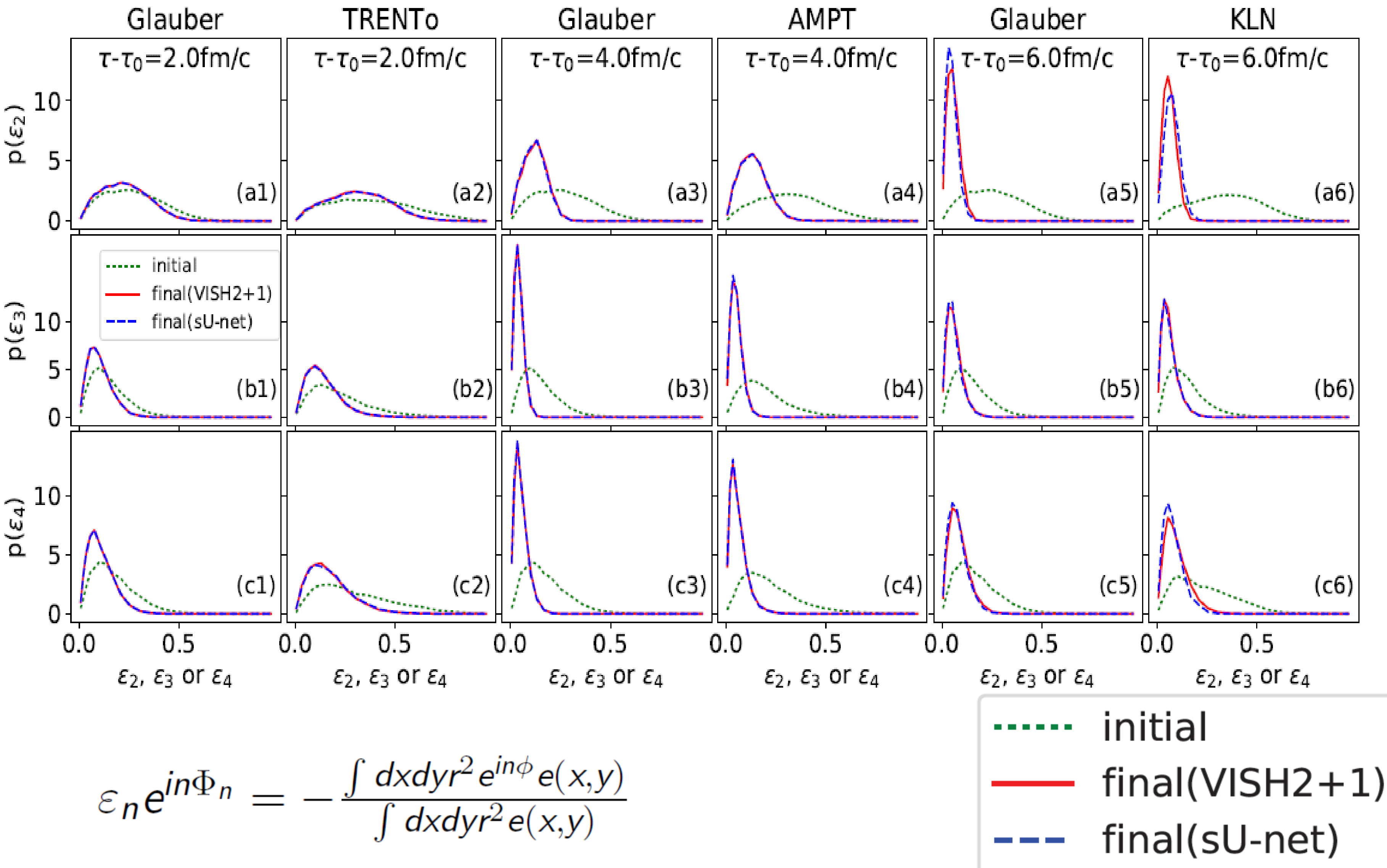
$\tau - \tau_0 = 6.0 fm/c$



-for a closer look

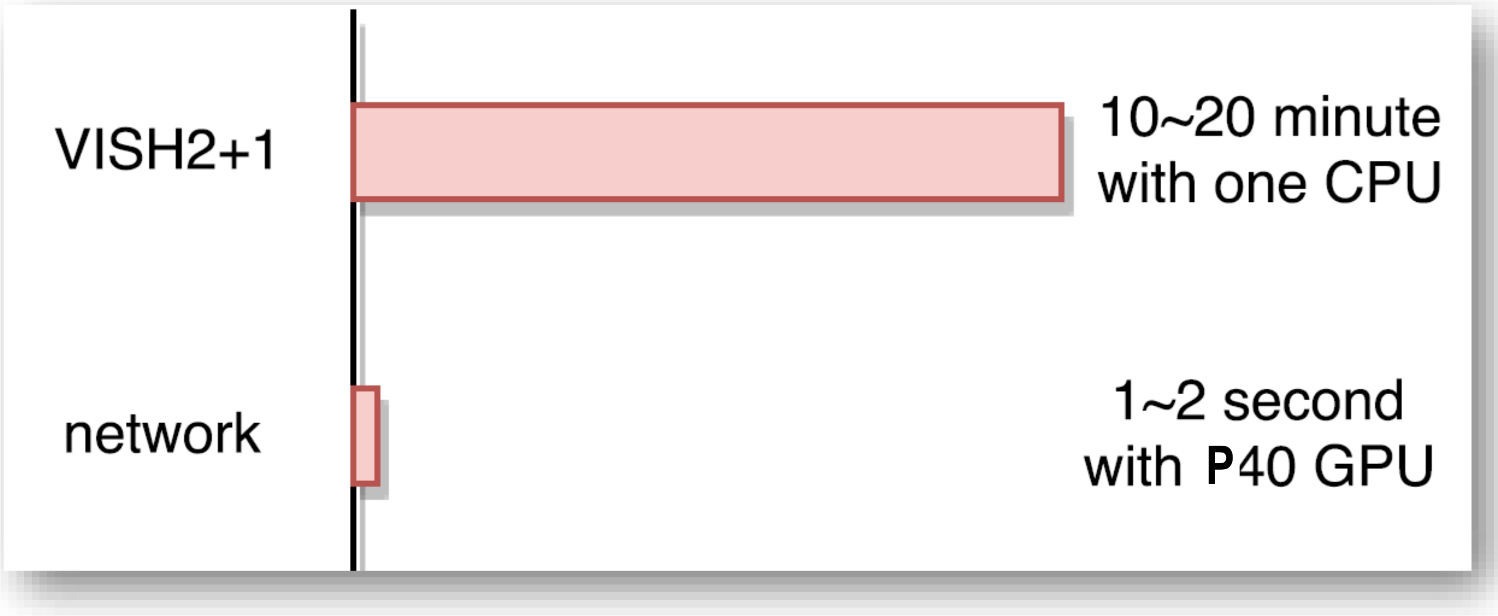
sUnet prediction vs. hydro simulations

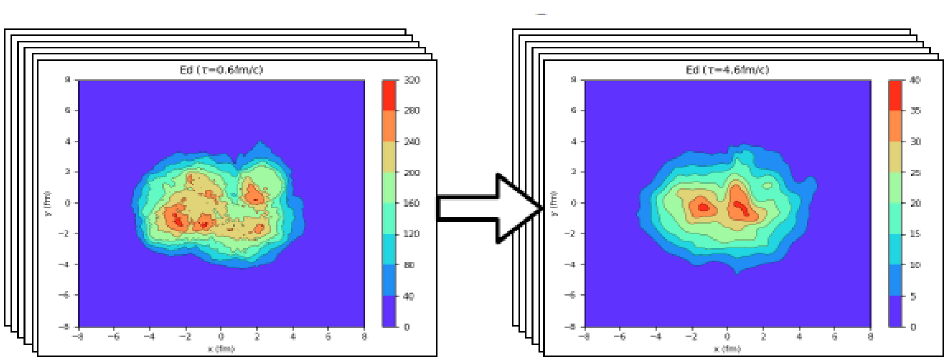
Eccentricity distributions:



$$\varepsilon_n e^{in\Phi_n} = -\frac{\int dxdyr^2 e^{in\phi} e(x,y)}{\int dxdyr^2 e(x,y)}$$

Simulation time: sUnet vs. hydro





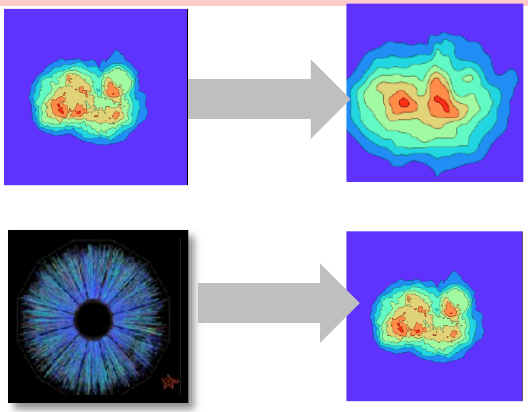
With the well trained network, the final state profiles can be quickly generated from the initial profiles.

Outlook

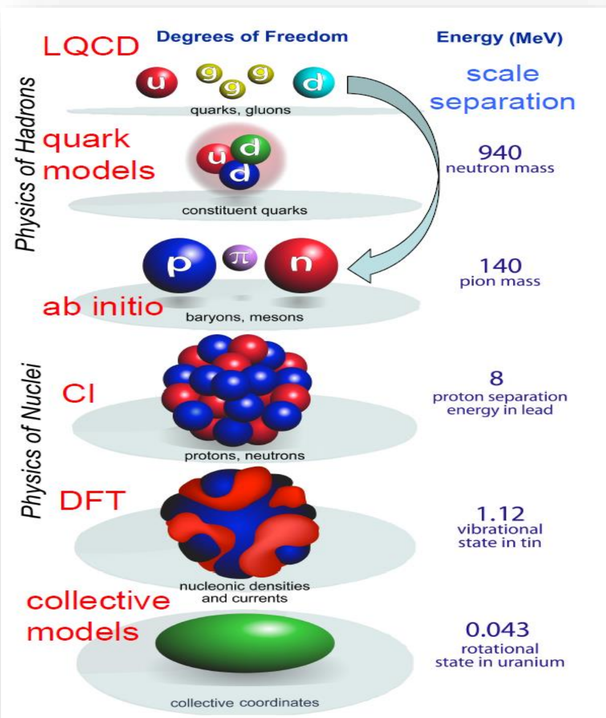
For hydrodynamics

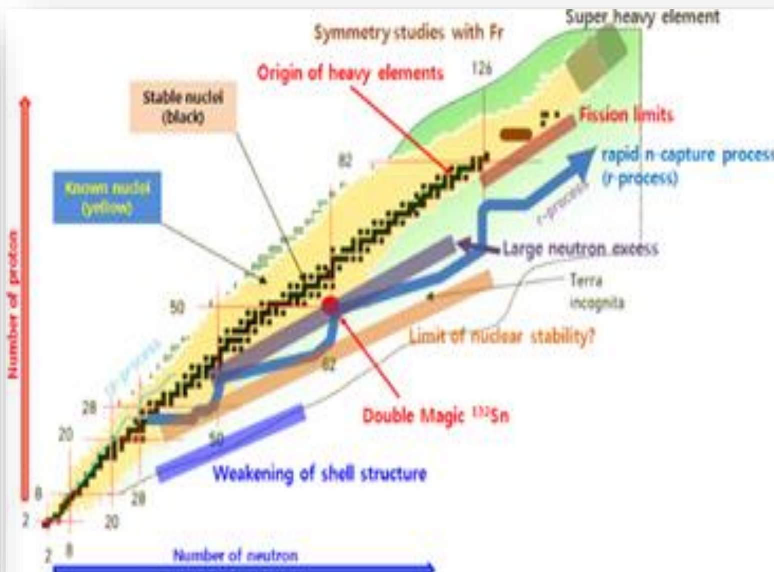
Initial energy density profiles
-------- > final energy density velocity profiles

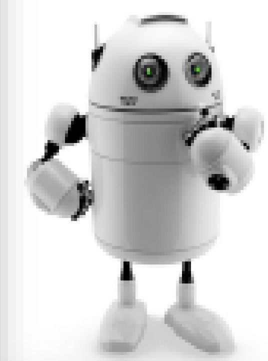
Final particle profiles
-------- > Initial energy density profiles



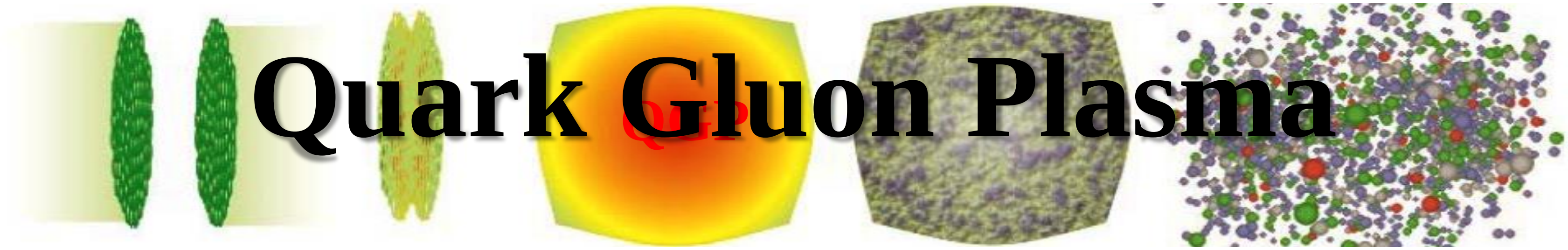
For Nuclear Physics







Many many more to explore … …
Enjoy it! have fun!



Hottest Matter on Earth