Dynamical Models & the fluid nature of the QGP

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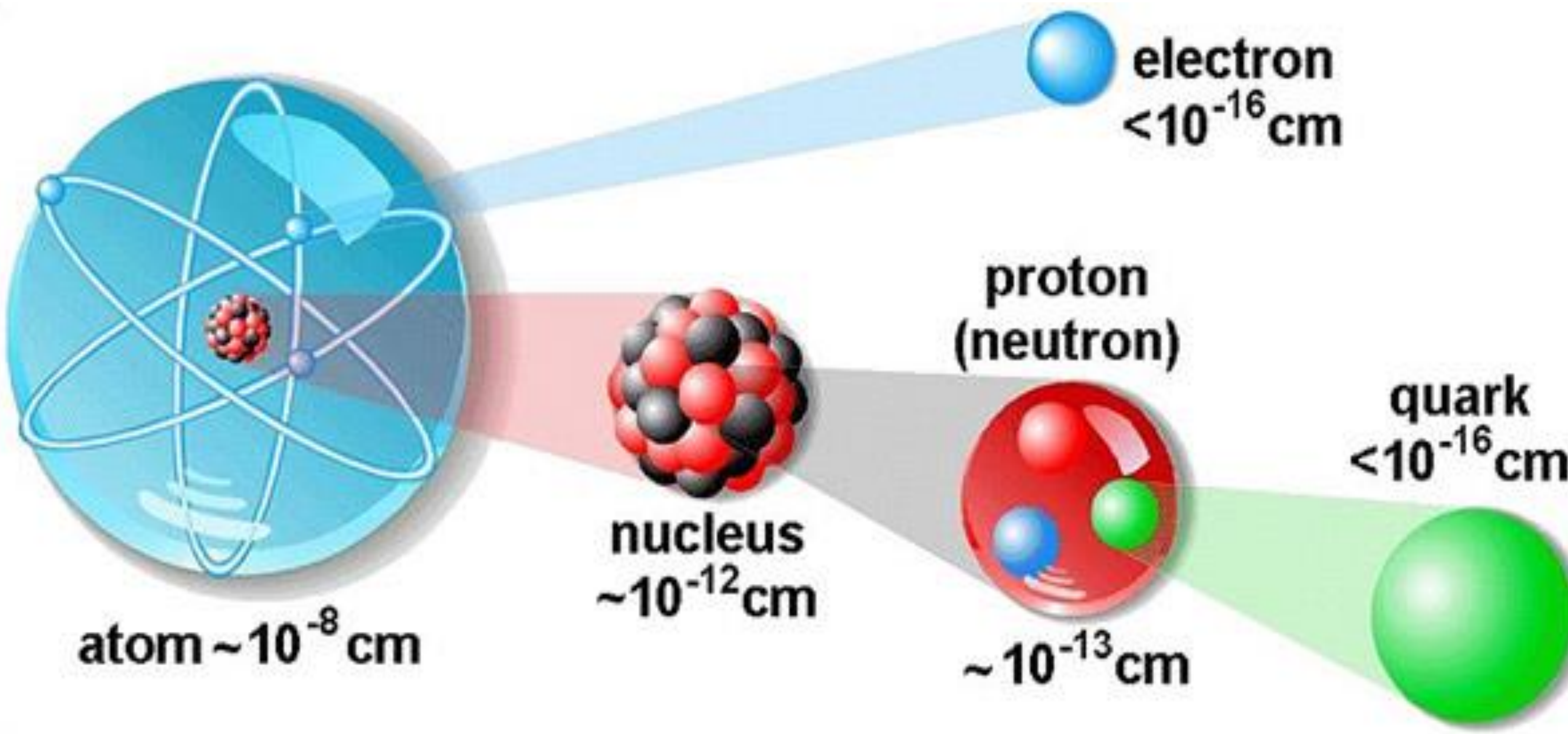
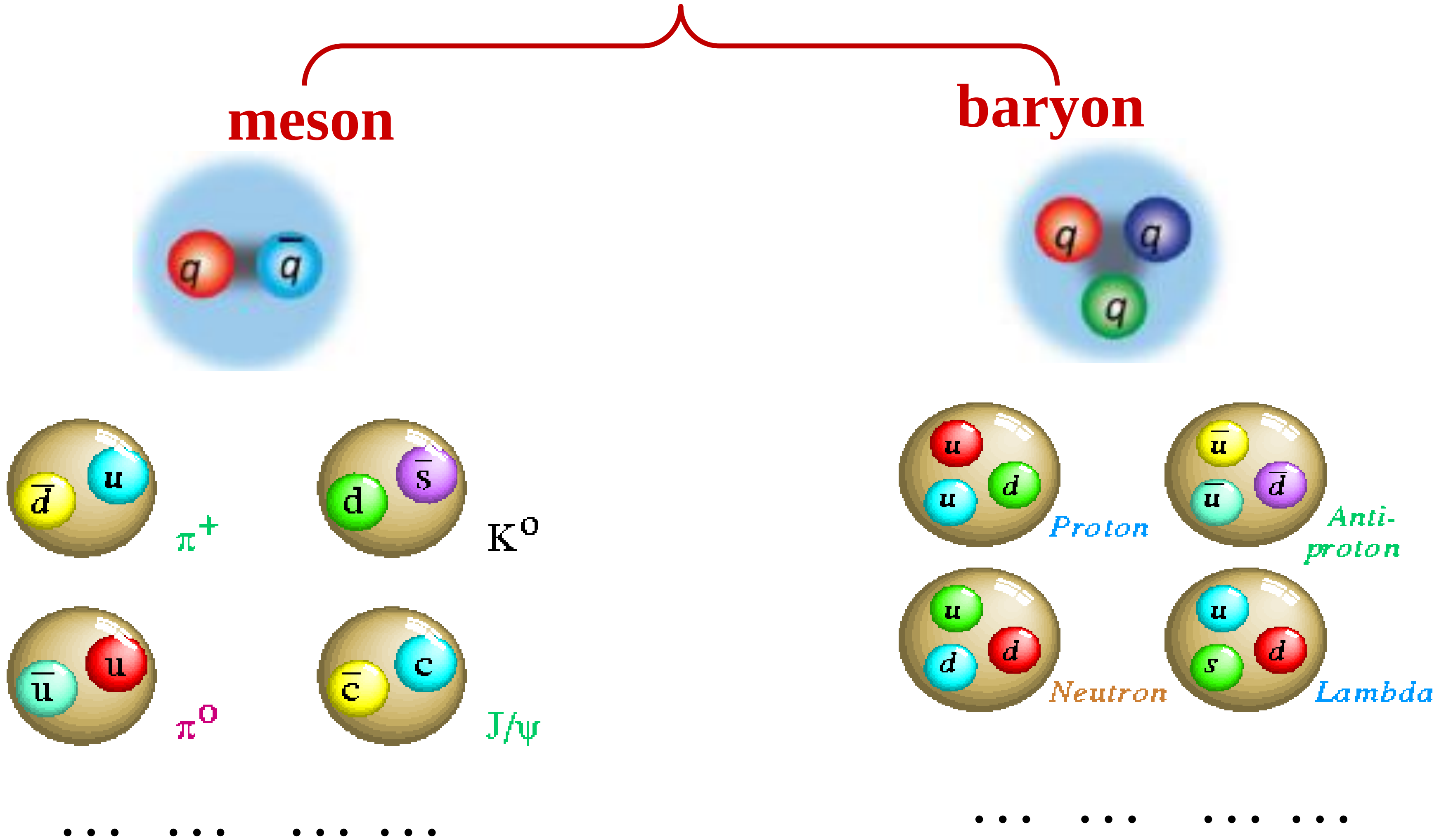
原子核结构与中高能重离子碰撞交叉学科理论讲习班，湖州，2021年7月9-24日

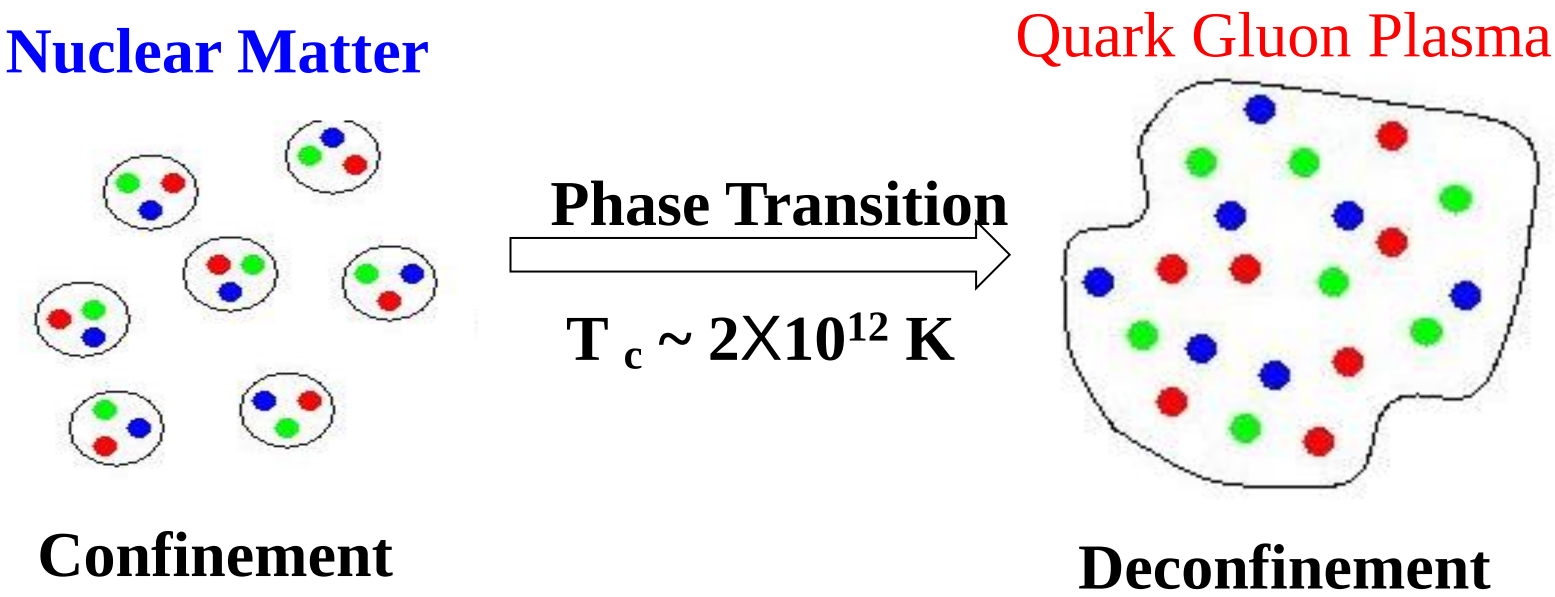
July 13 2021


electron
<10^-16 cm
proton
(neutron)
quark
<10^-16 cm
nucleus
~10^-12 cm
atom ~10^-8 cm
~10^-13 cm

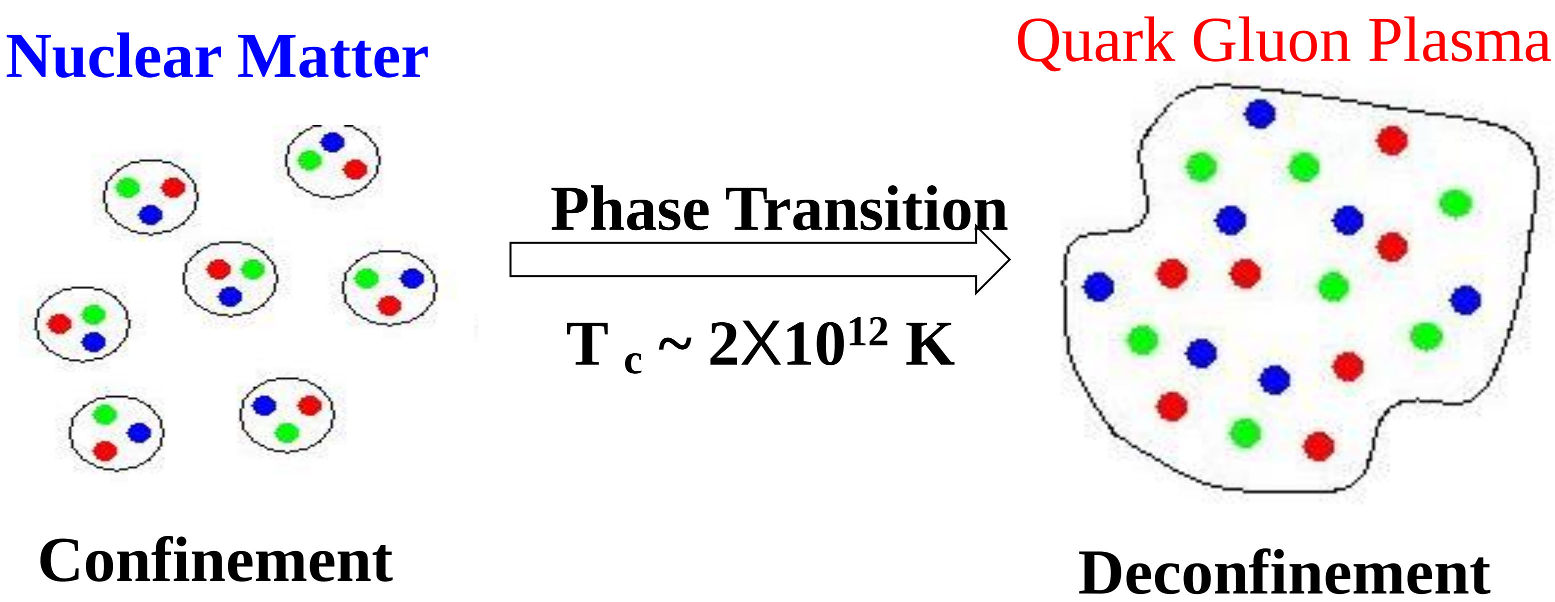
Hadrons



Quark and Gluons: confined in hadrons through strong forces described by QCD



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



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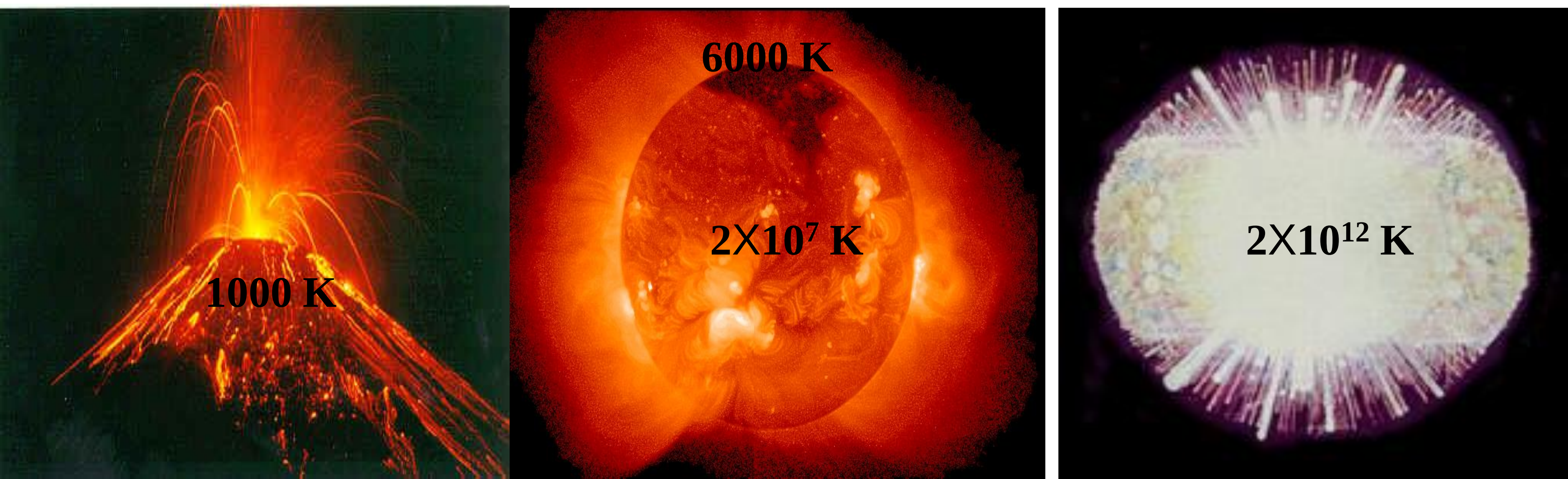
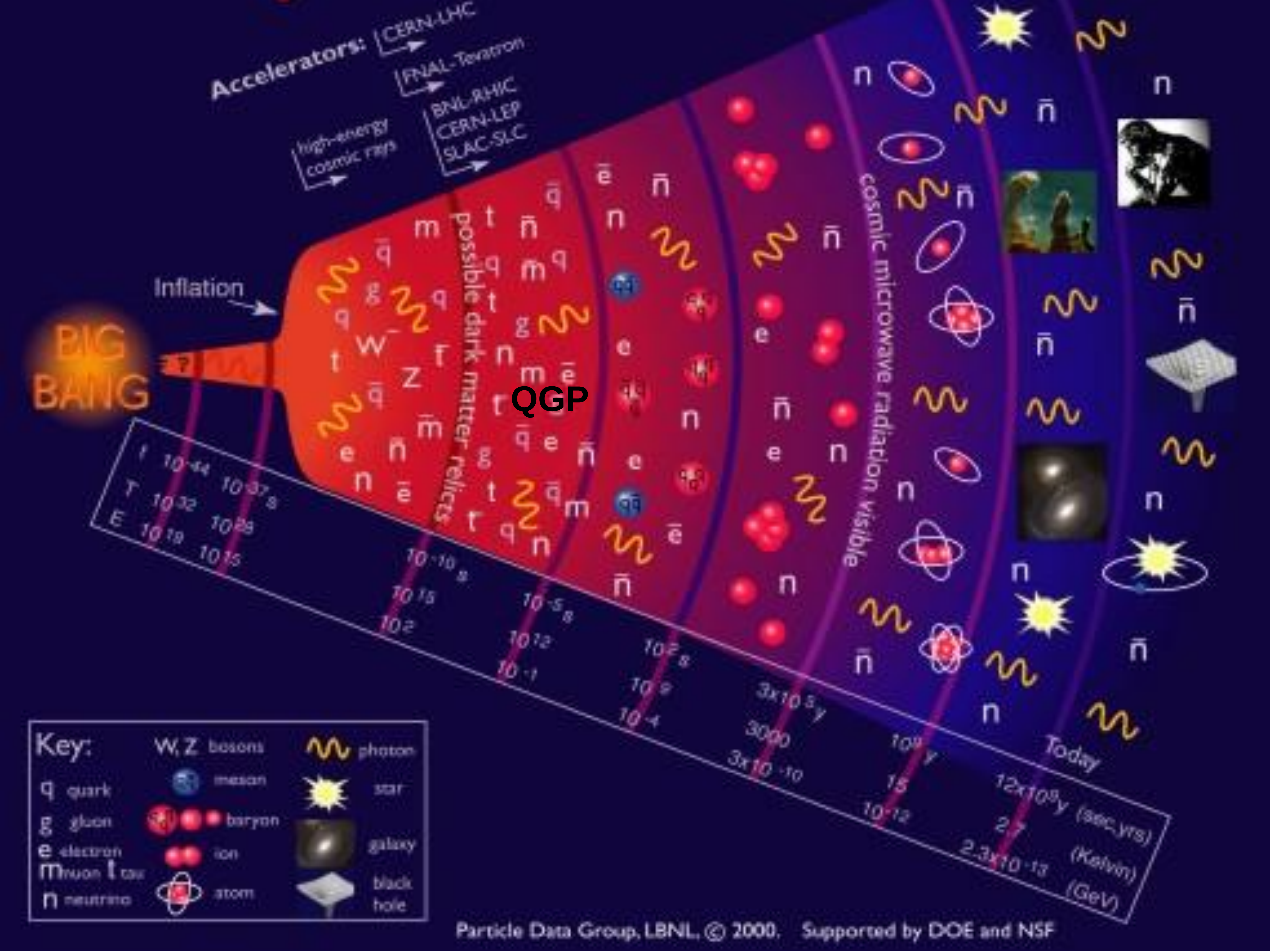
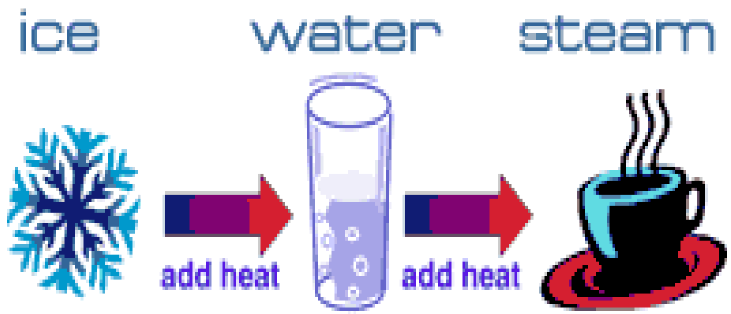
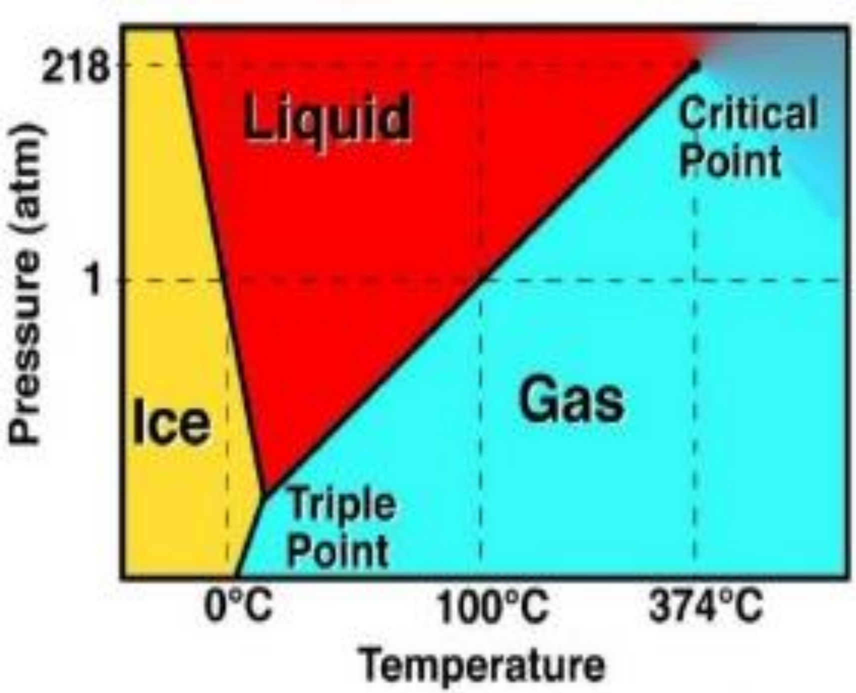



Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
QGP
cosmic microwave radiation visible
t
T
E
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
galaxy
m muon t tau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

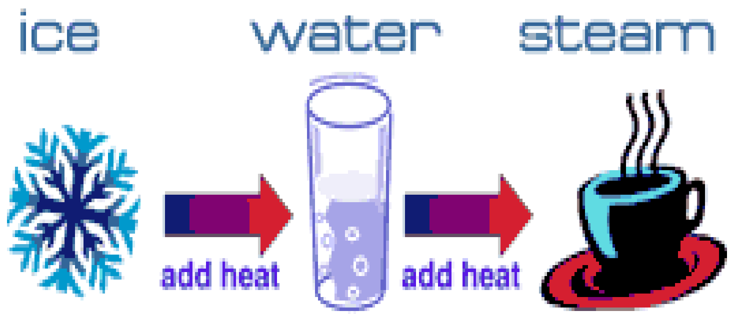
Phases diagram

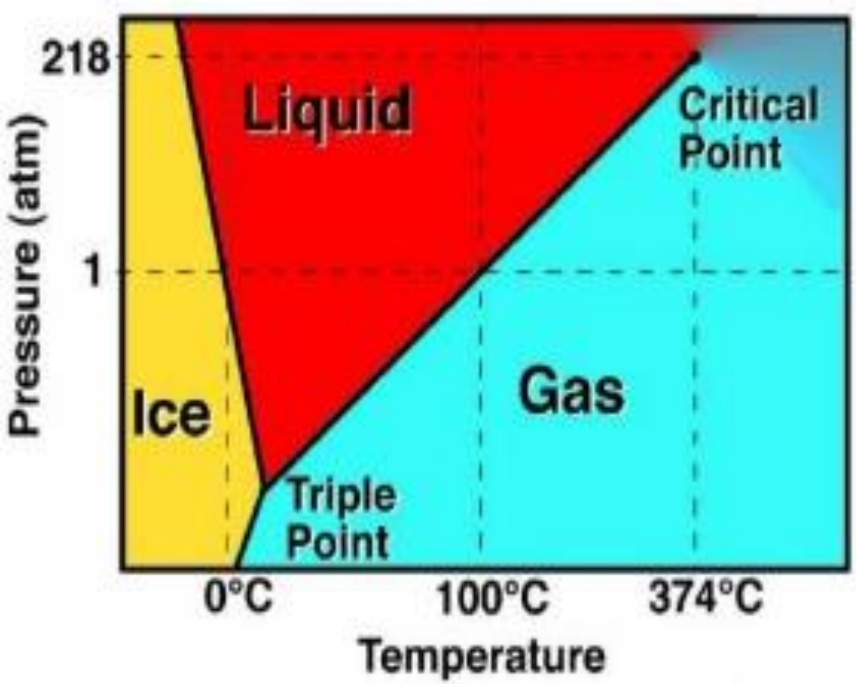




determined by electromagnetic interactions

Phases diagram





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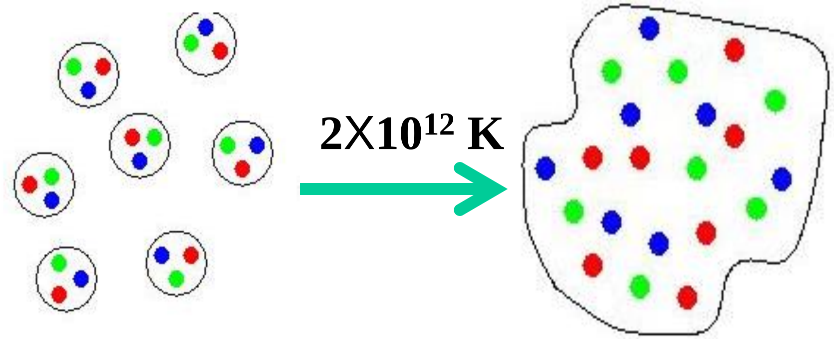
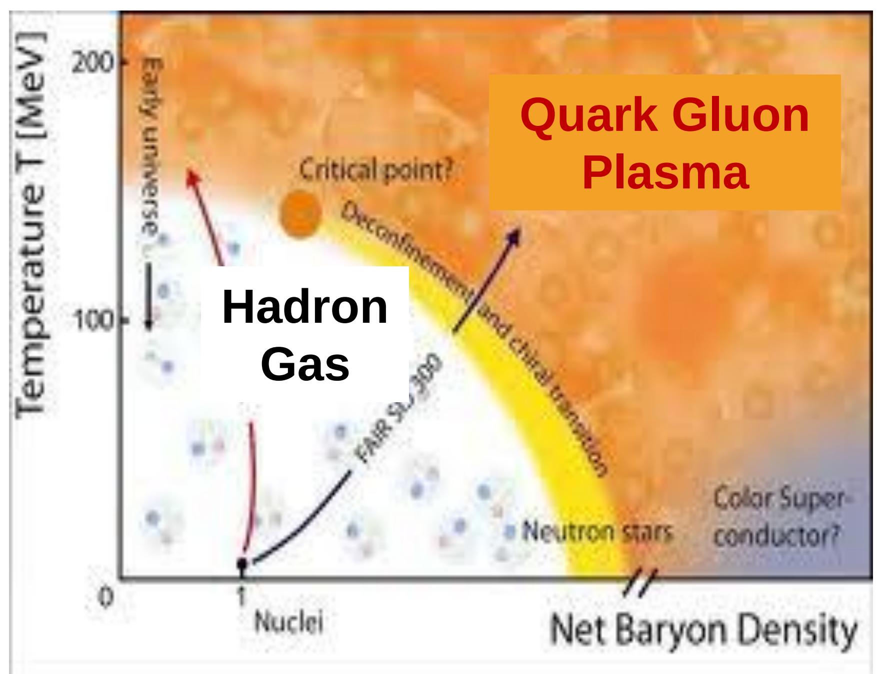
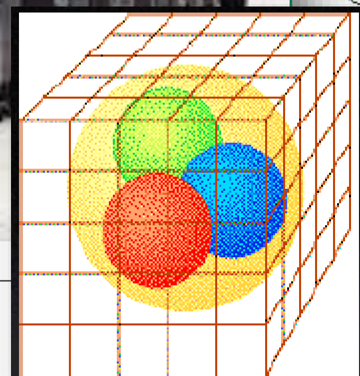
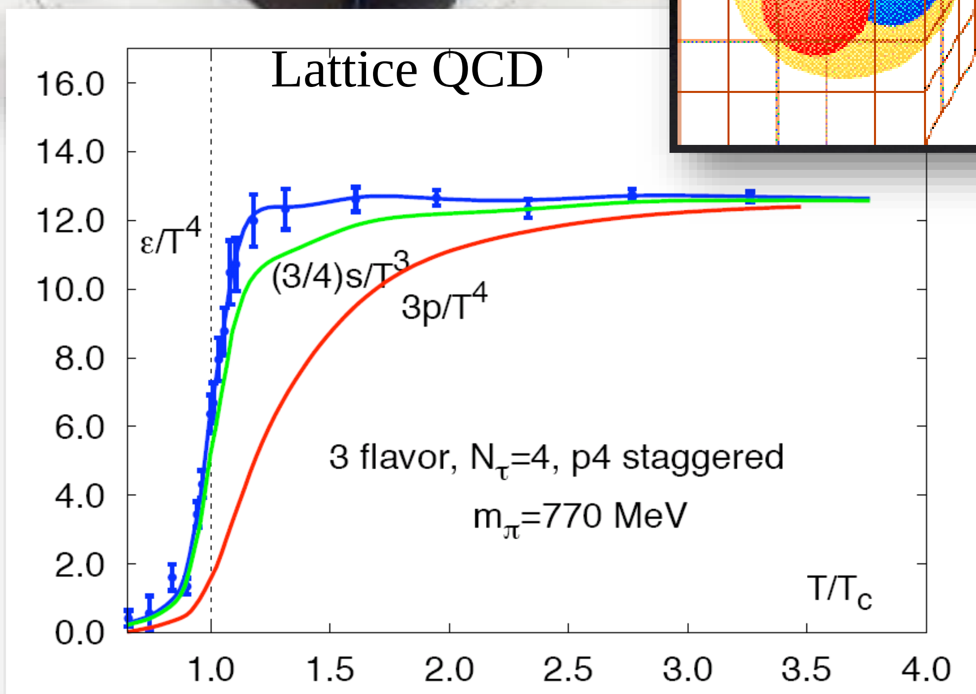


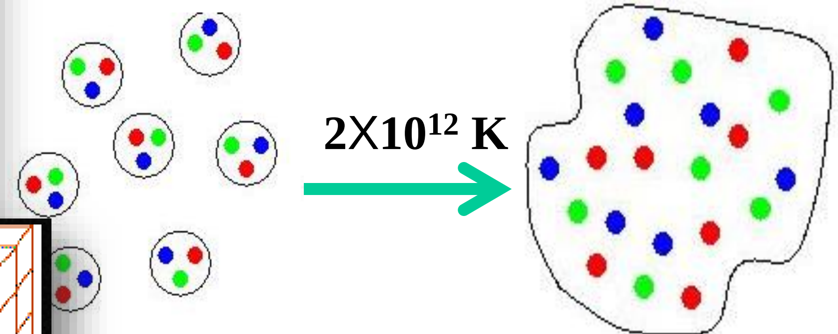


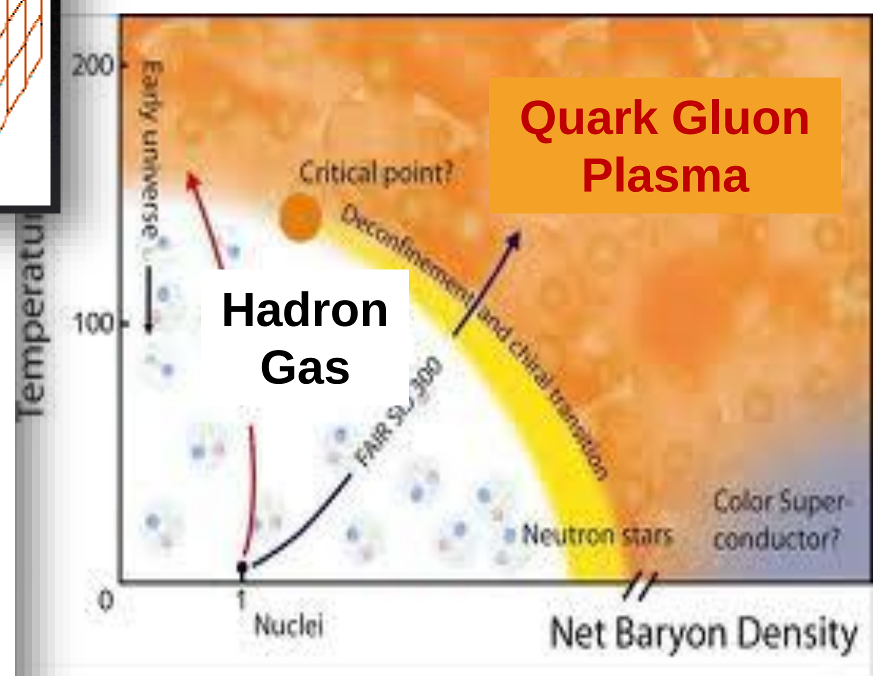
determined by strong interactions

s diagram









determined by **strong** interactions

QCD Phase transition

$\boldsymbol{\varepsilon = g\frac{\pi^2}{30}T^4}$	Energy density for "g" massless d.o.f.
$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$	Hadronic Matter: 3 π with spin=0
$\varepsilon = 37\cdot\frac{\pi^2}{30}T^4$	Quark Gluon Plasma:

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$$\varepsilon = g\frac{\pi^2}{30}T^4$$

$$= \left\{2\cdot 8_g + \frac{7}{8}\cdot 2_s\cdot 2_a\cdot 2_f\cdot 3_c\right\}\frac{\pi^2}{30}T^4$$

$$= 37\cdot\frac{\pi^2}{30}T^4$$

8 gluons, 2 spins;
2 quark flavors, anti-quarks,
2 spins, 3 colors

d.o.f : 3→ 37 (!)

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

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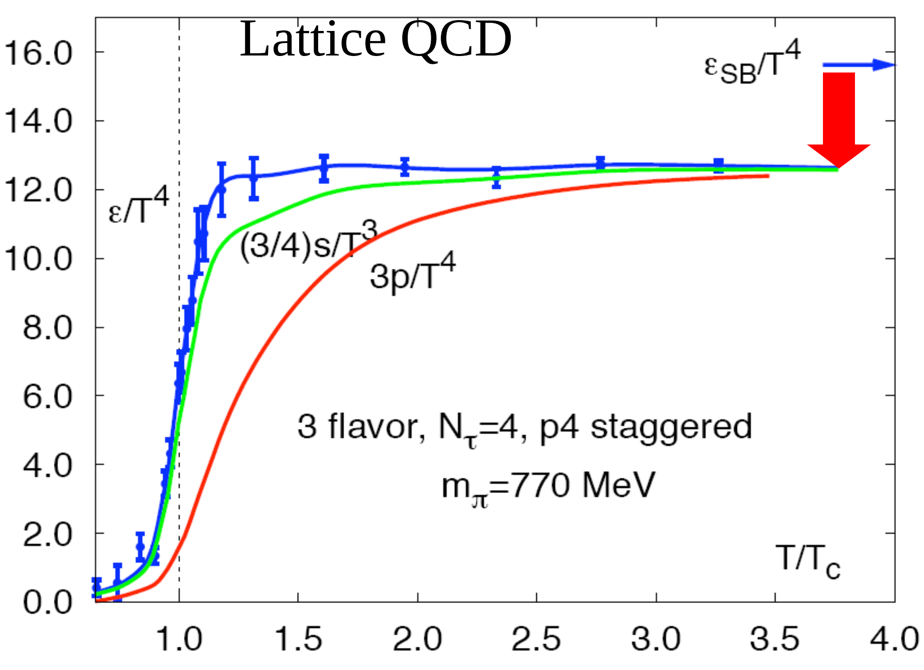
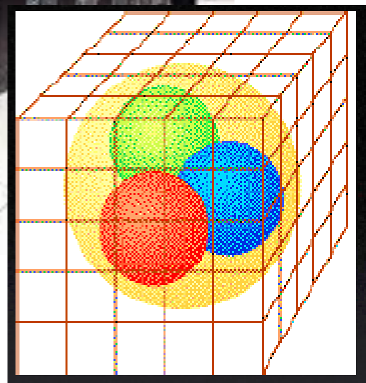




A brief history of relativistic heavy ion physics

1974: Workshop on “BeV/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)

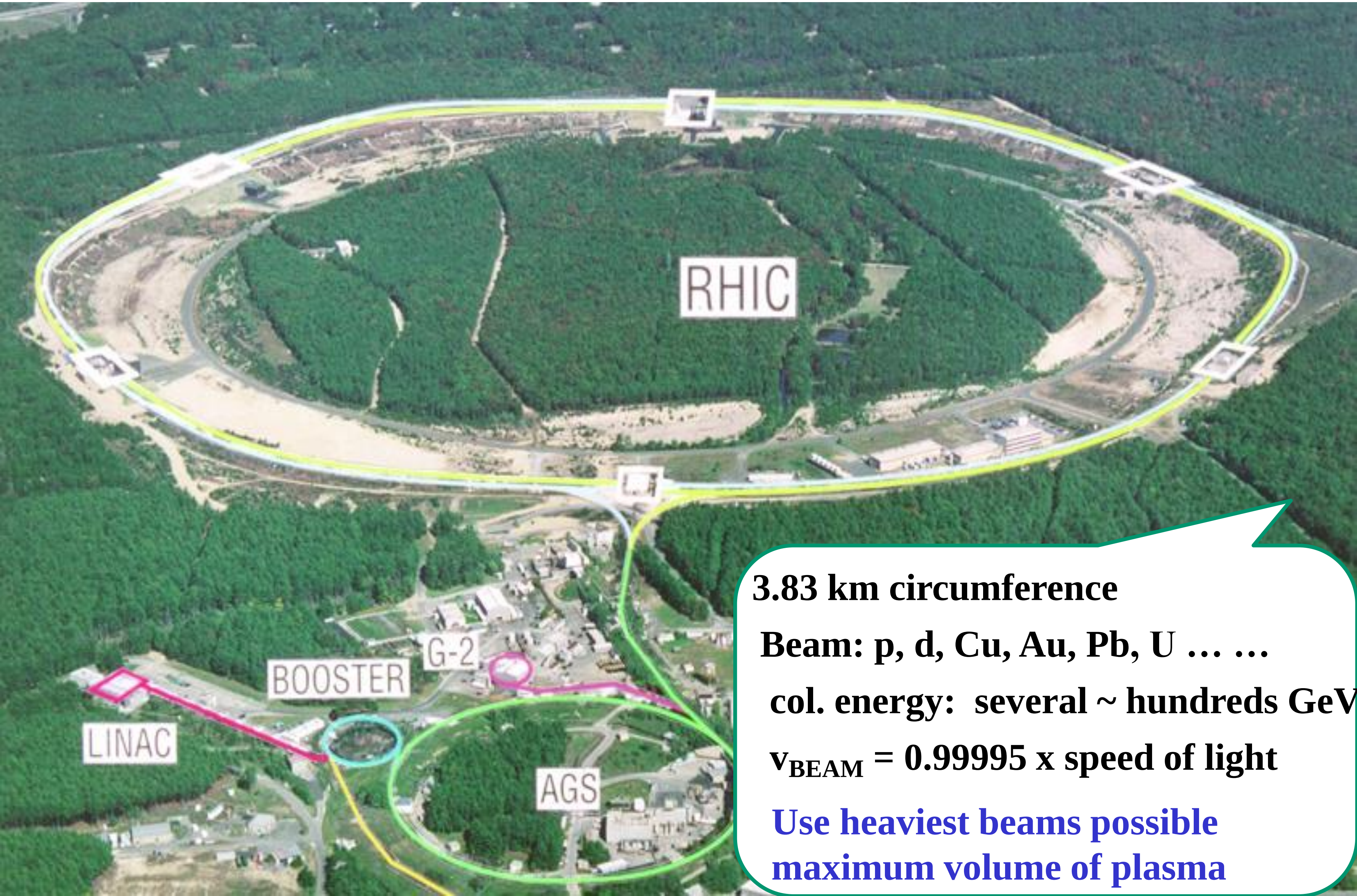
1986: AGS stars, (end 2000)

2000: RHIC starts

2010: LHC starts

Future: FAIR & NICA

Brookhaven National Laboratory



3.83 km circumference

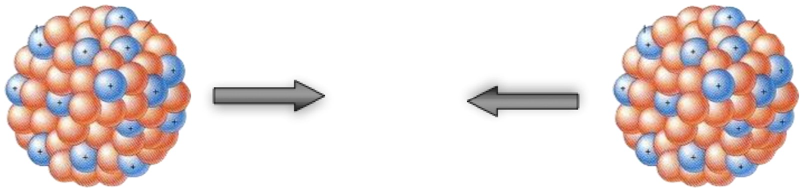
Beam: p, d, Cu, Au, Pb, U … …

col. energy: several ~ hundreds GeV

v_{BEAM} = 0.99995 x speed of light

Use heaviest beams possible
maximum volume of plasma

- RHIC = Relativistic Heavy Ion Collider
- Located at Brookhaven National Laboratory



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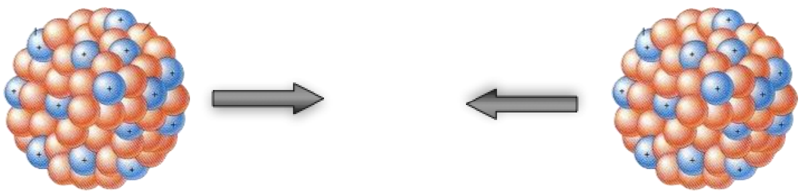
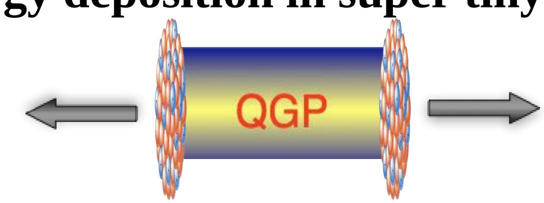
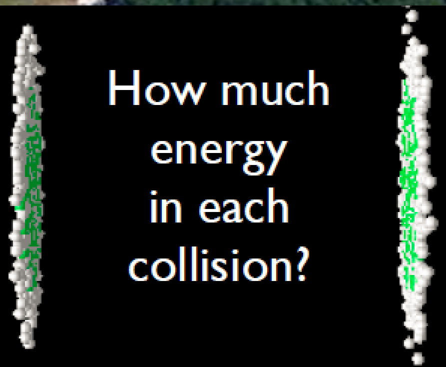


v_{BEAM} = 0.99995 x speed of light

Energy deposition in super tiny volume

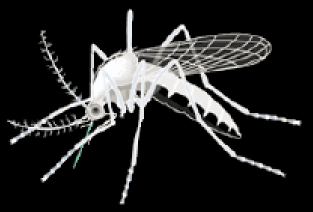




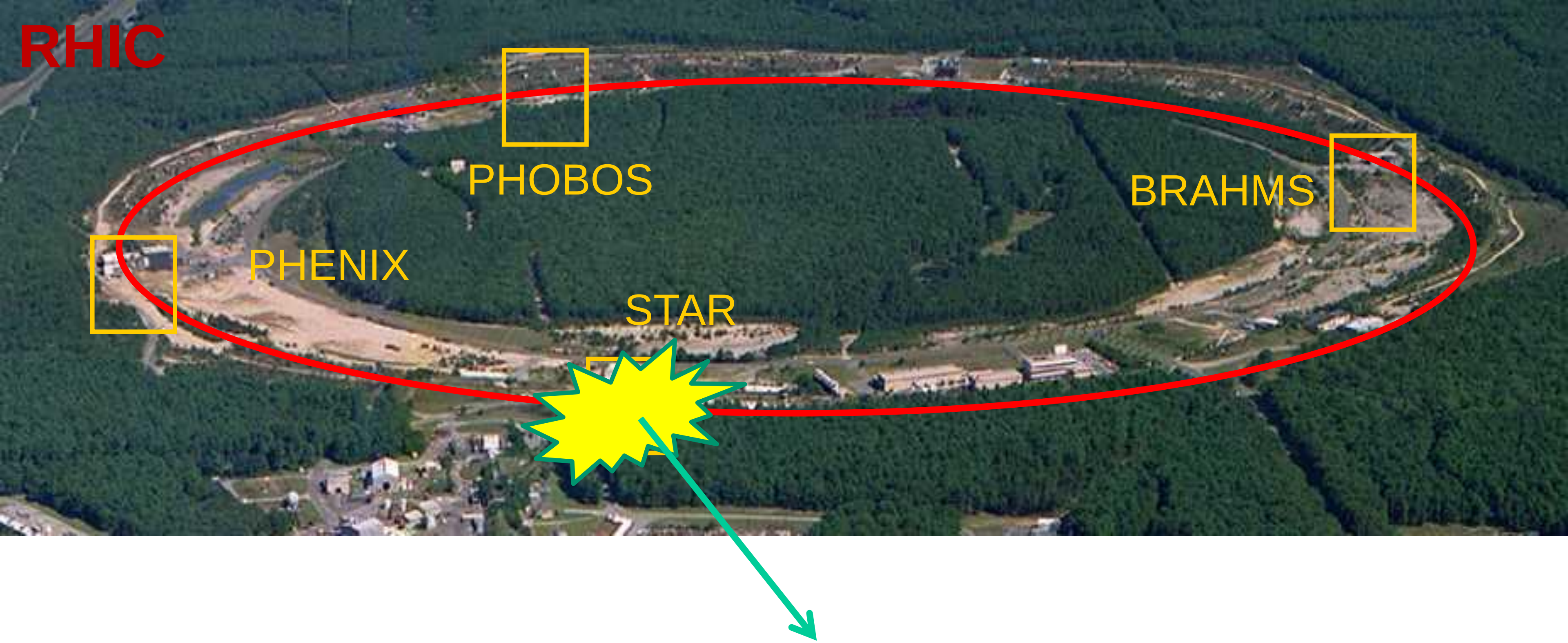
How much
energy
in each
collision?

$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200 GeV \sim 6 \mu J$$

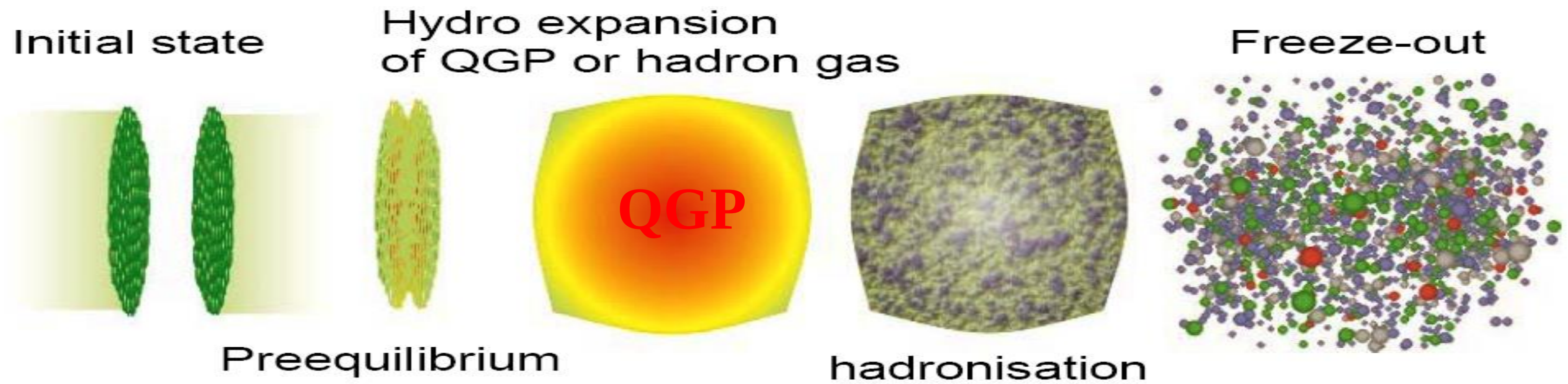
Consider
two mosquitos
colliding...

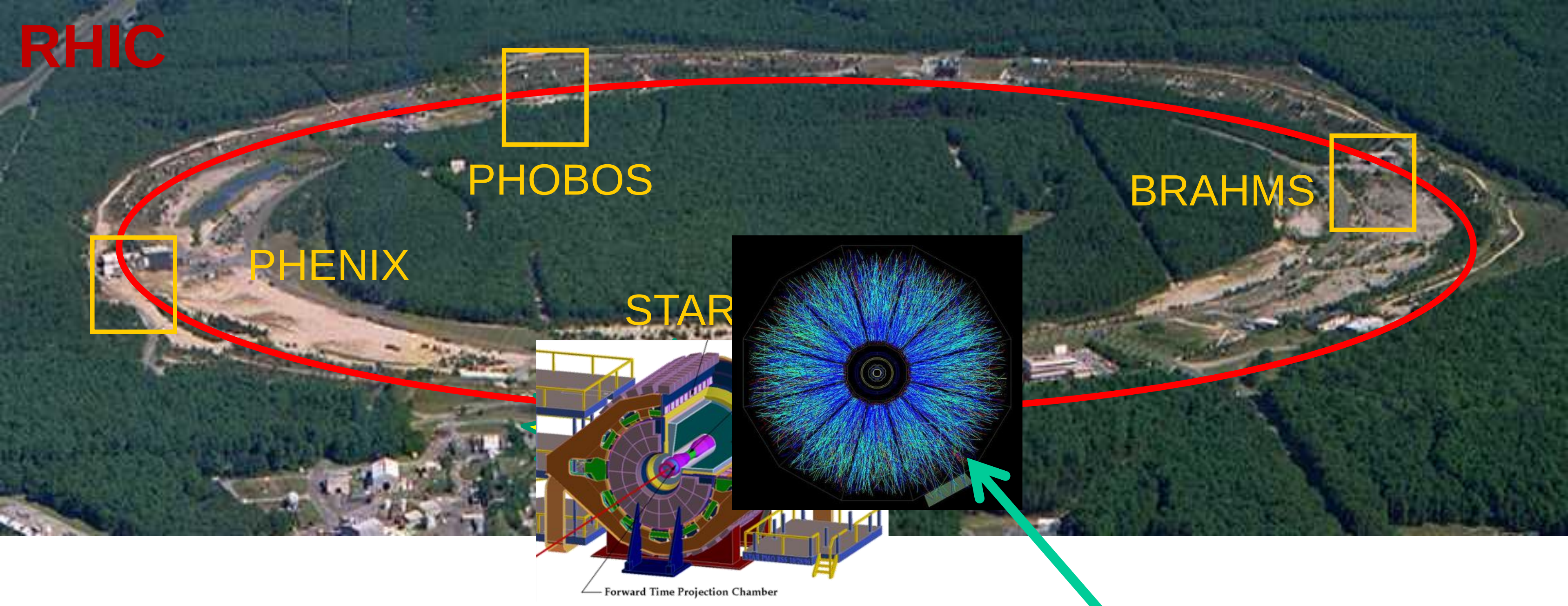


$$2 \times \frac{1}{2} m v^2 = (2.5 mg) \times (2.5 km/h)^2 = 1.2 \mu J$$



<u>little bang</u>: the different stage for a relativistic heavy ion collisions





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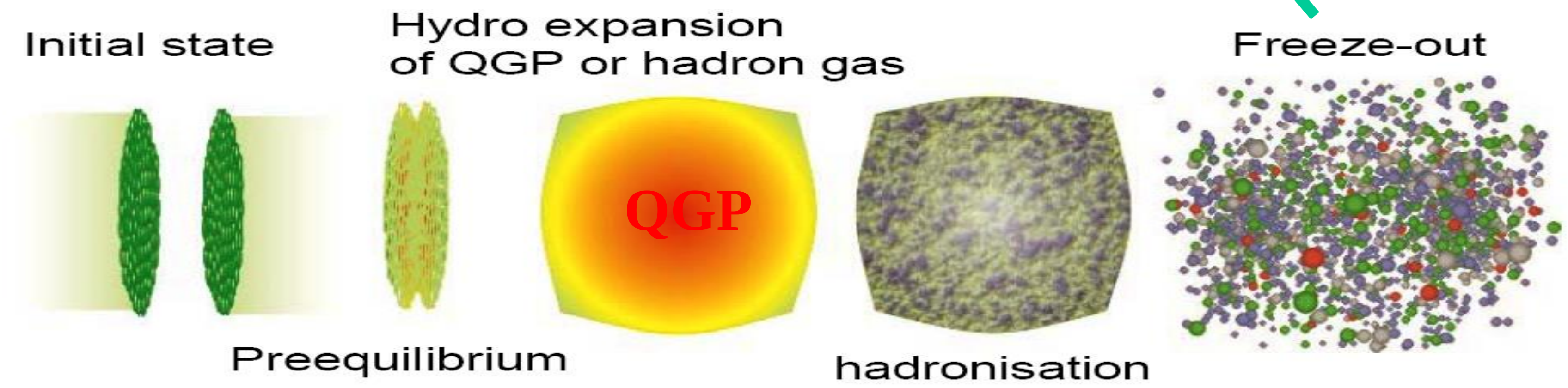
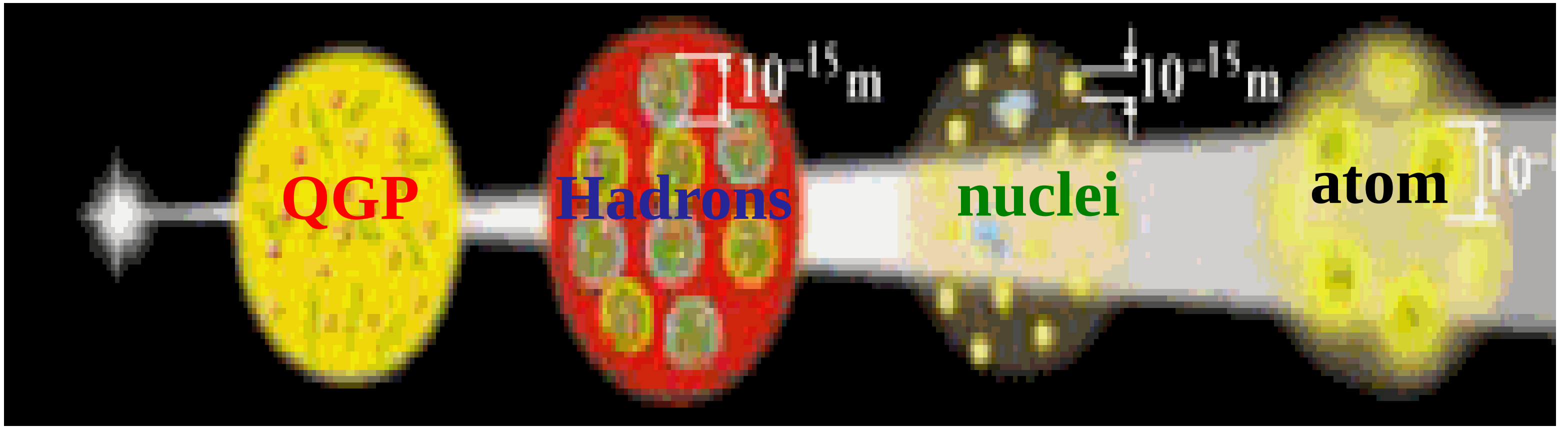


big bang: the very early history of the universe



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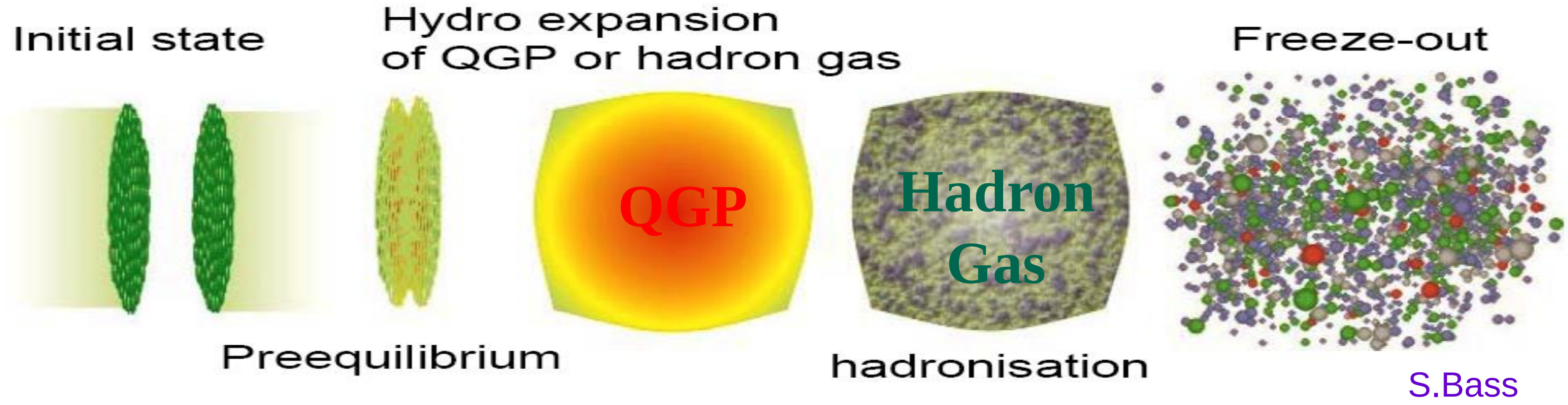


QGP-the most perfect fluid in the world

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."

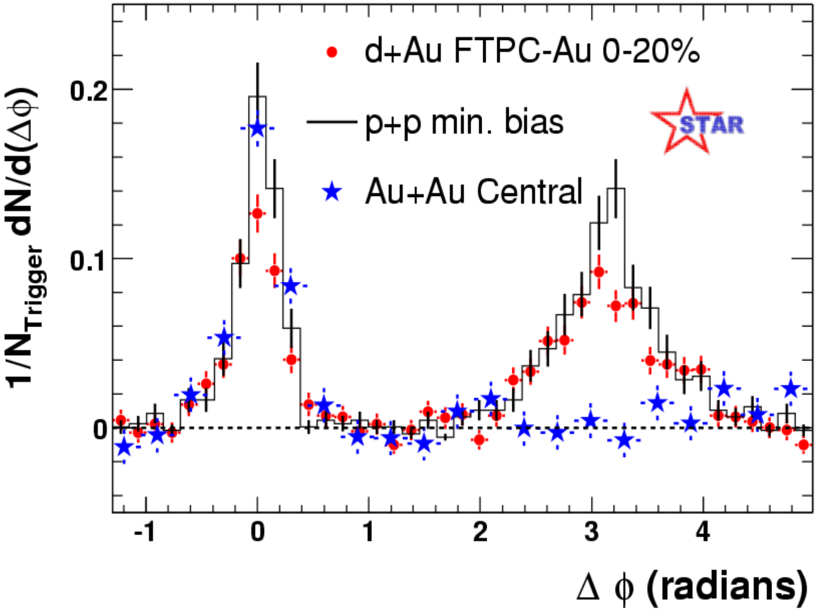
Secretary of Energy Samuel Bodman

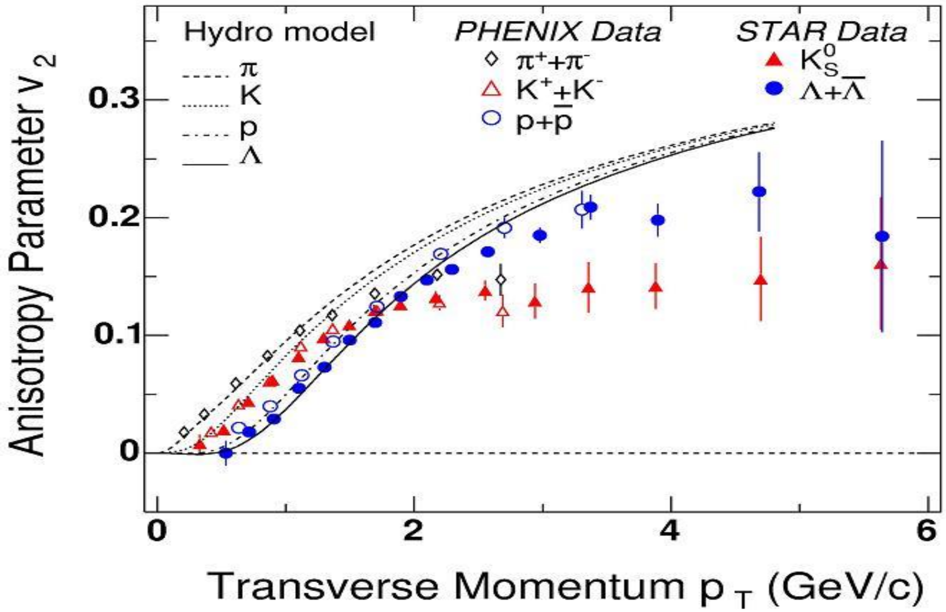
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

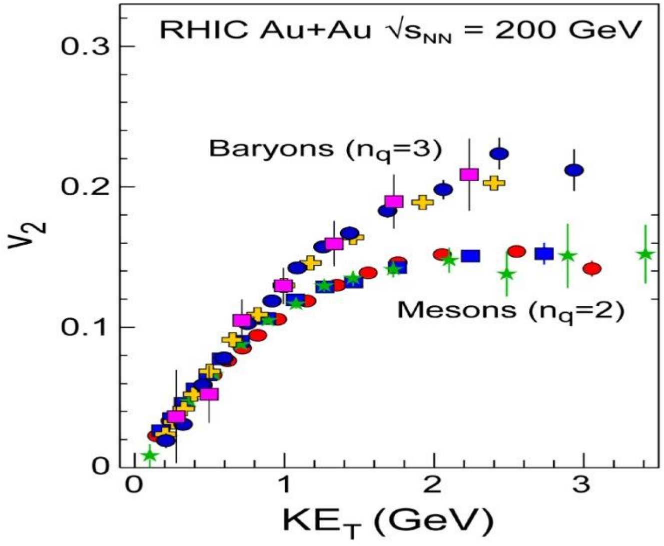
Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

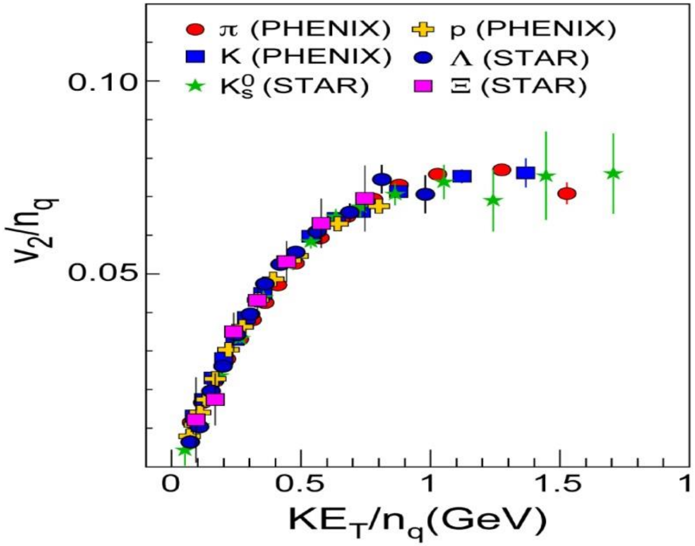
The QGP was discovered

RHIC (2000--   )









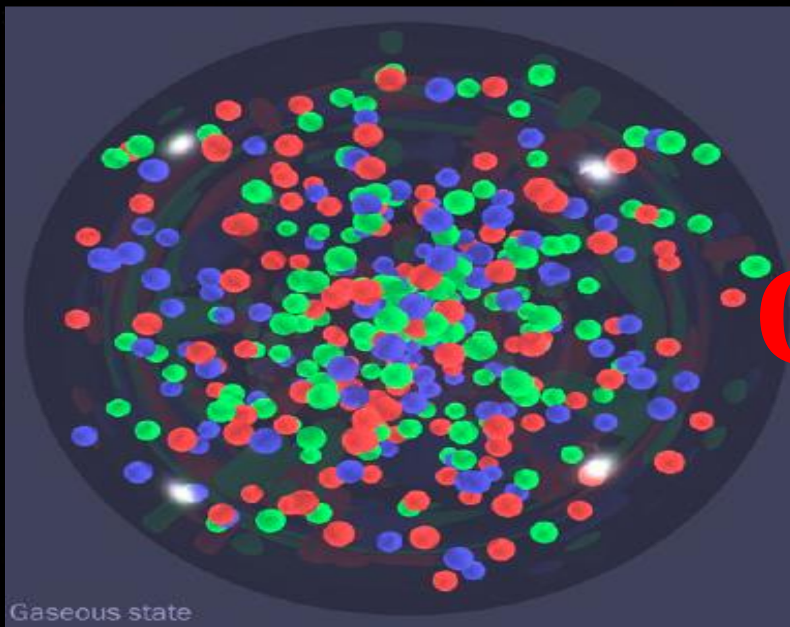
What State of Matter?

QGP

Does it act
like an ideal gas?

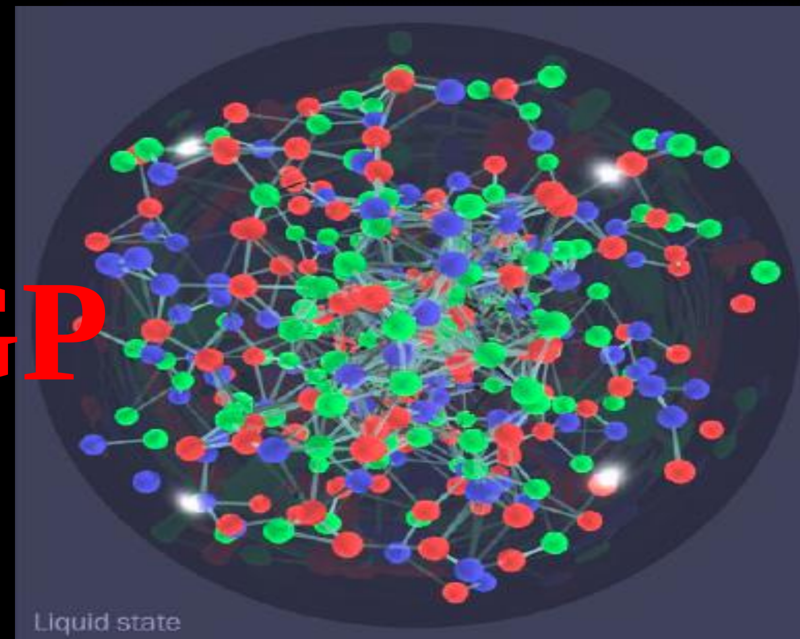
Does it flow,
like a (compressible) liquid?

What State of Matter?



Gas: particles only know about each other when they bump

QGP

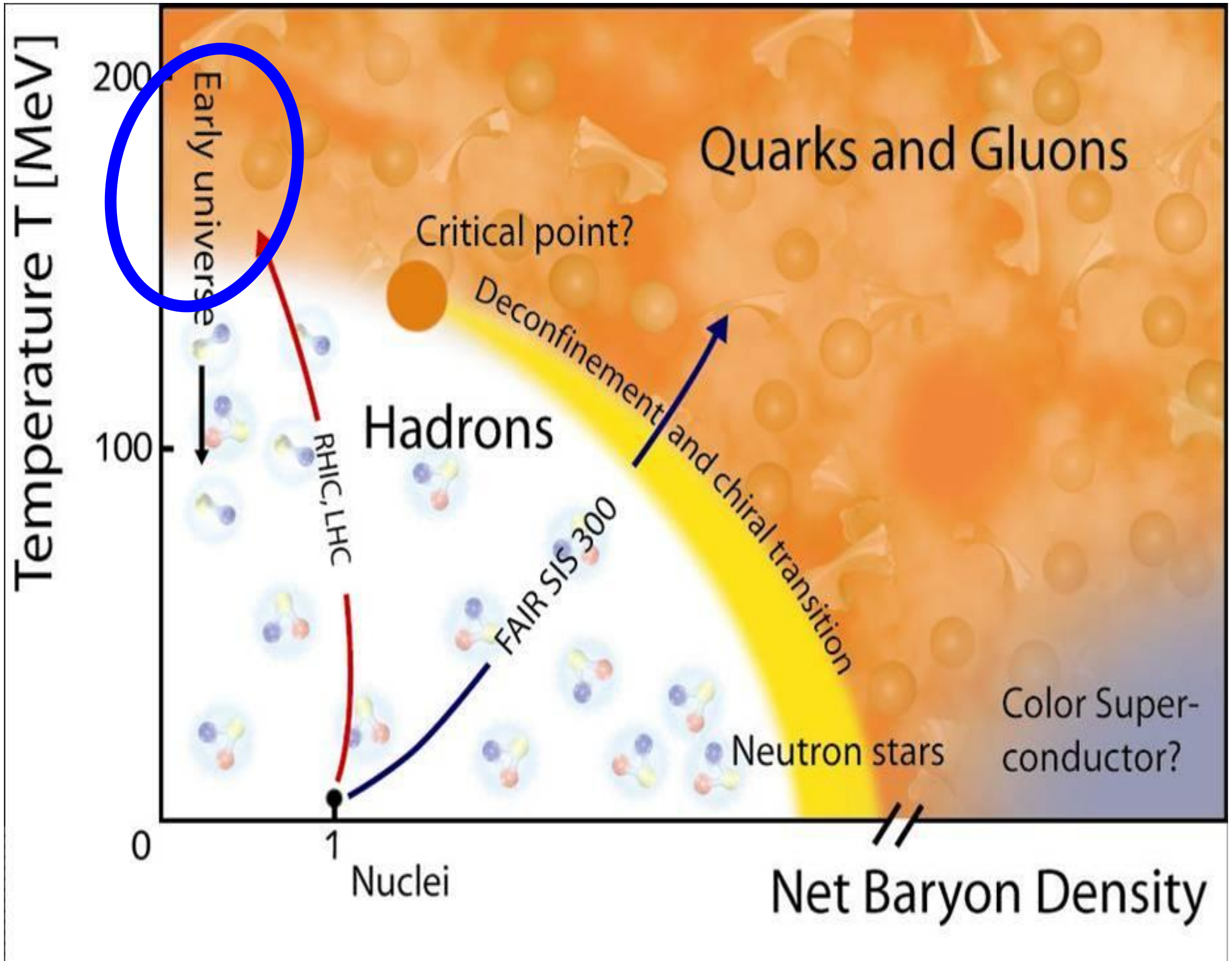


Liquid: particles exert forces on one another all the time, flows in a coordinated fashion 6

Does it act
like an ideal gas?

Does it flow,
like a (compressible) liquid?

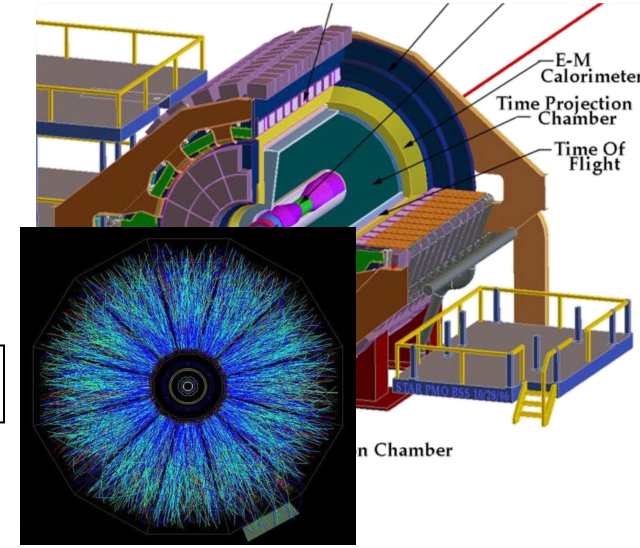
Hydrodynamics & flow at top RHIC & LHC energies



Life time~ 10^{-23} s

size~ 10^{-14} m

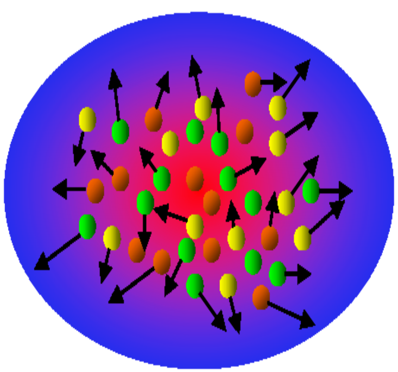
Numerical simulation



Dynamical Model

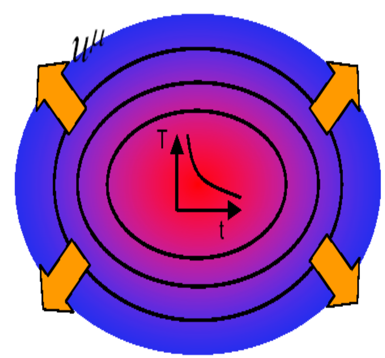
Boltzmann approach

microscopic view



Hydrodynamics

macroscopic view



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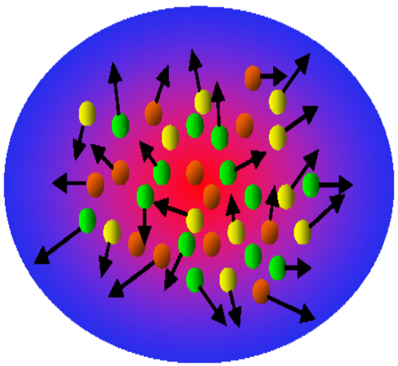

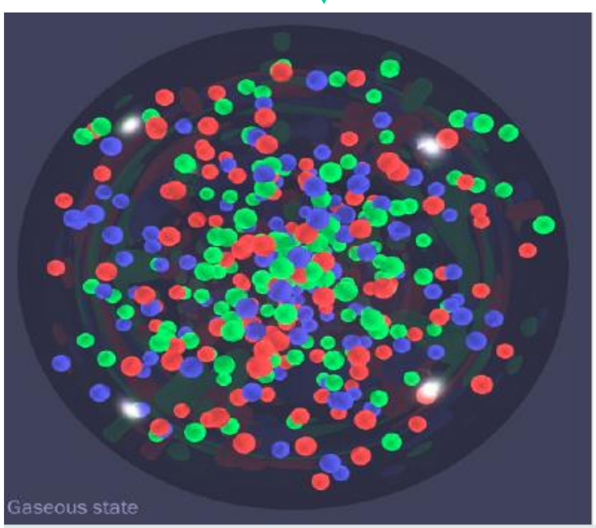

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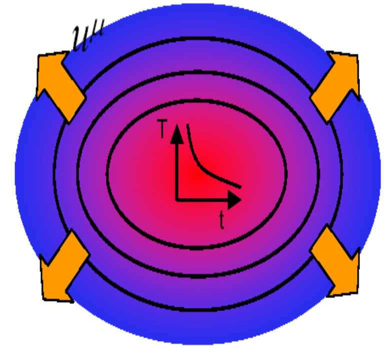
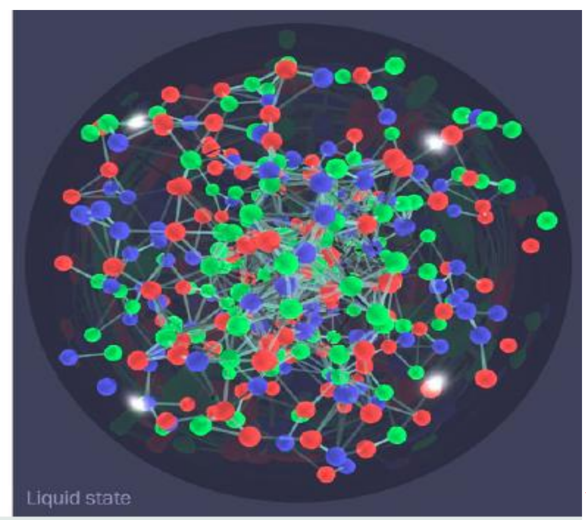
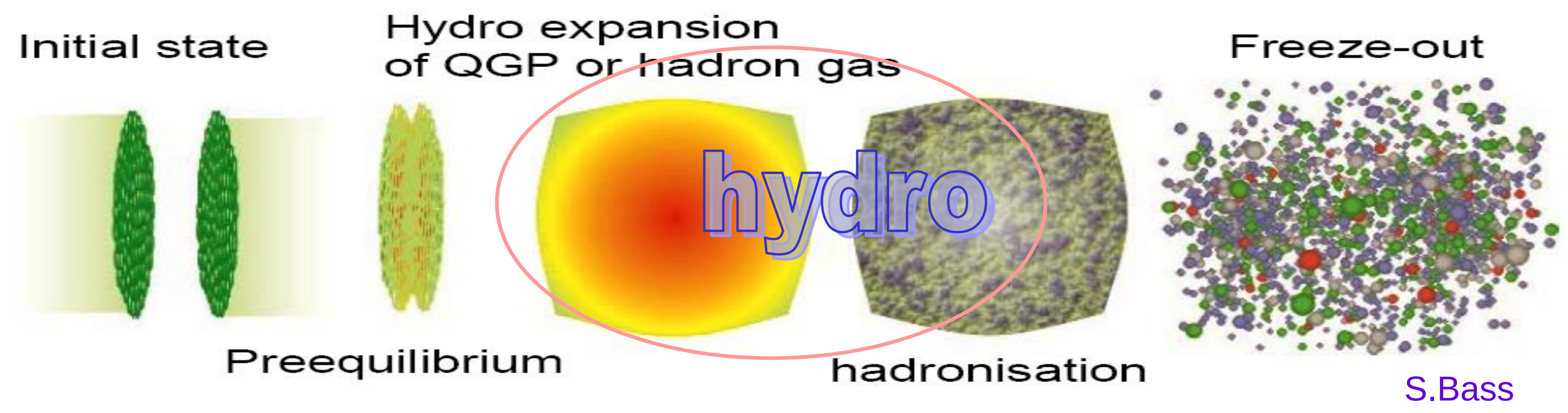




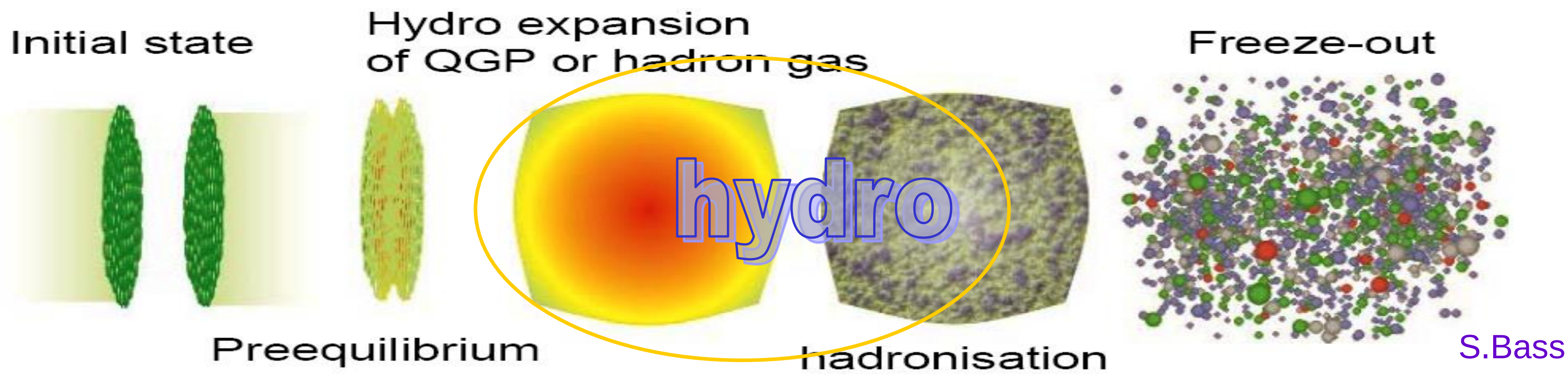
Liquid: particles exert forces on one another all the time, flows in a coordinated fashion

Hydrodynamics

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



Viscous hydrodynamics



Conservation laws:

$$\partial_\mu T^{\mu\nu}(x) = 0 \qquad T^{\mu\nu} = (e + p + \Pi)u^\mu u^\nu - (p + \Pi)g^{\mu\nu} + \pi^{\mu\nu}$$

$$\tau_\pi \Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\lambda\left(\frac{\tau_\pi}{\eta T}u^\lambda\right)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta(\partial \cdot u) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

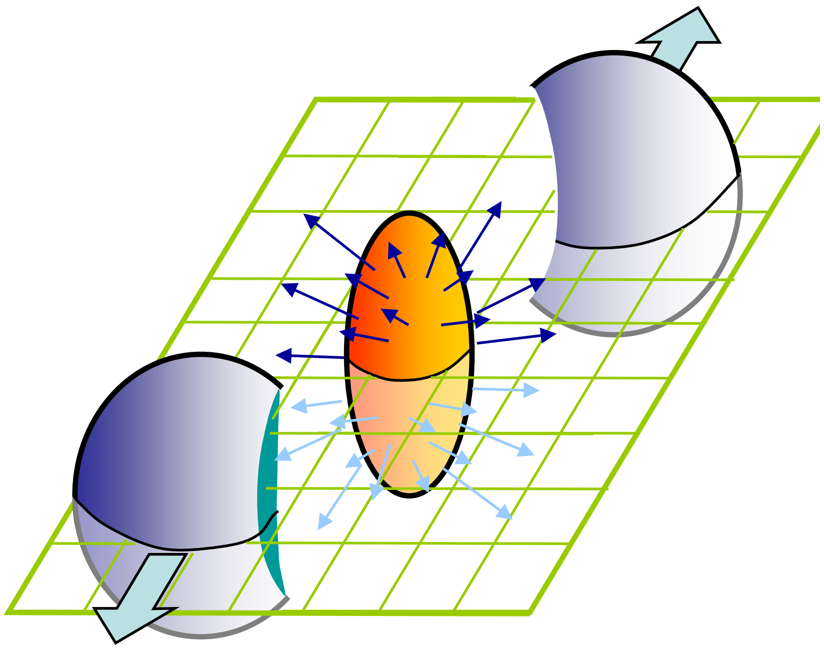
- Israel-Stewart eqns.

$$\partial_\mu S^\mu \geq 0$$

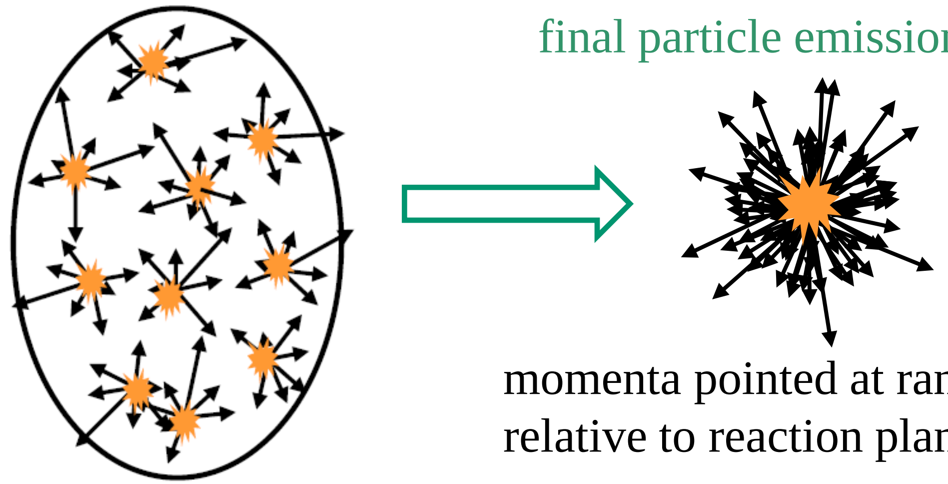
Input: “EOS” $\varepsilon = \varepsilon(p)$ initial and final conditions

Bjorken appro. : $v_z = z/t$ reduces (3+1)-d hydro to (2+1)-d hydro

Collective expansion

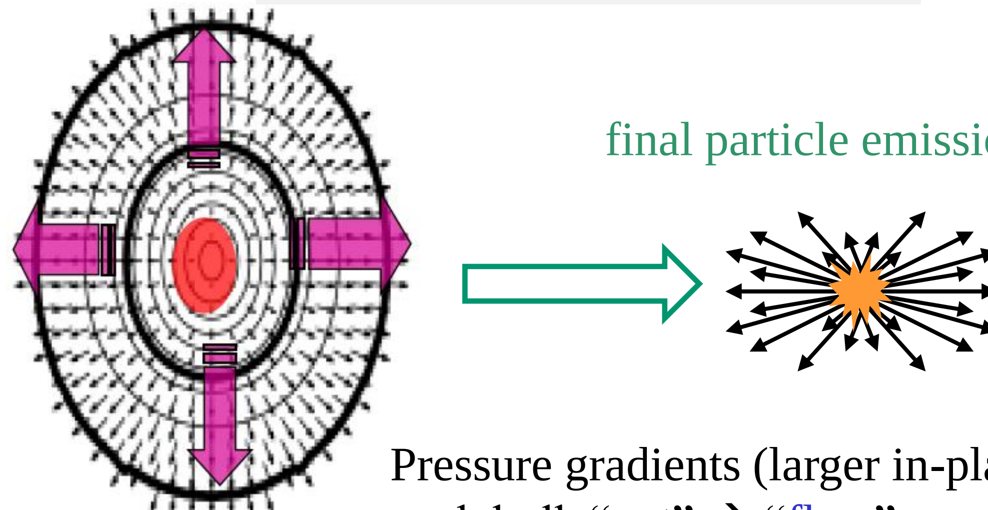


Superposition of independent p+p:



momenta pointed at random relative to reaction plane

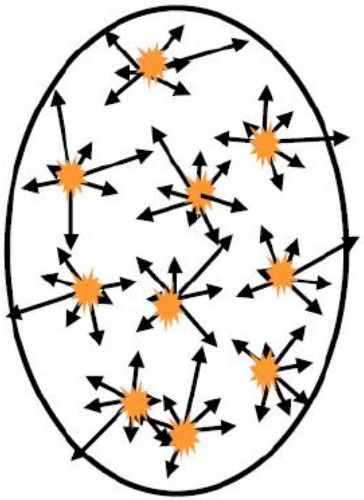
Evolution as a bulk system



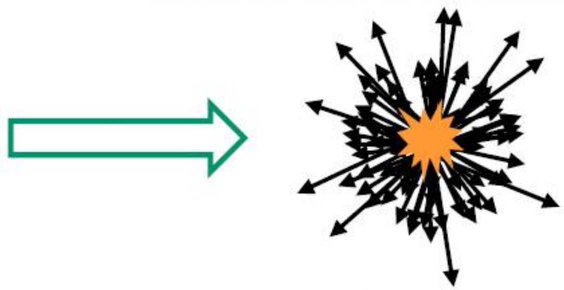
Pressure gradients (larger in-plane) push bulk "out" → "flow"

Azimuthal distributions

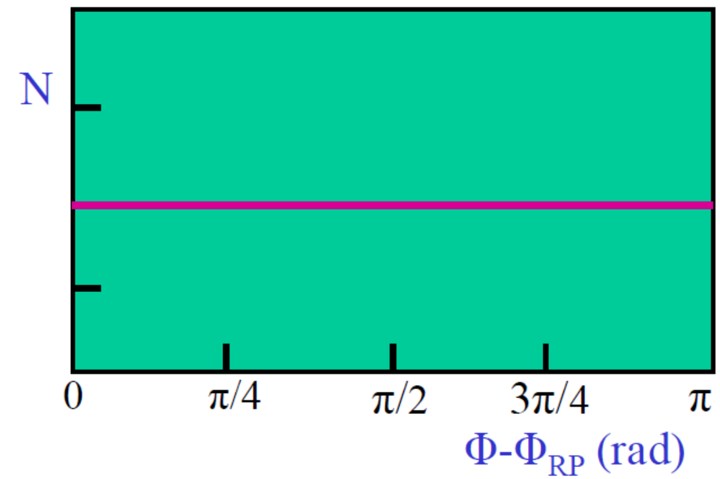
Superposition of independent p+p:



final particle emission



momenta pointed at random
relative to reaction plane



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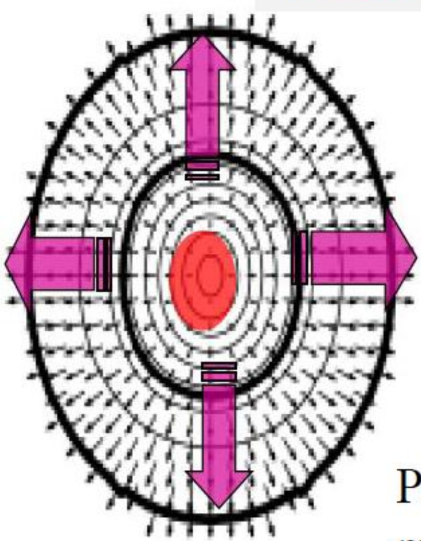
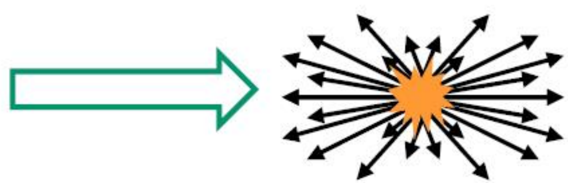


final particle emission



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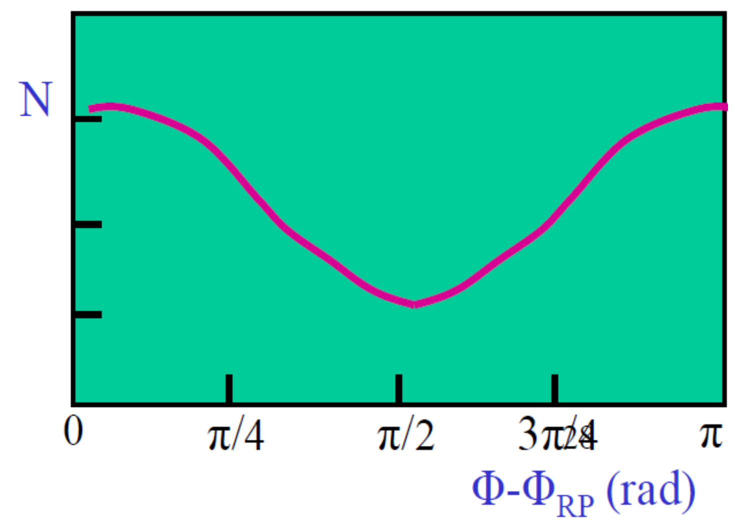
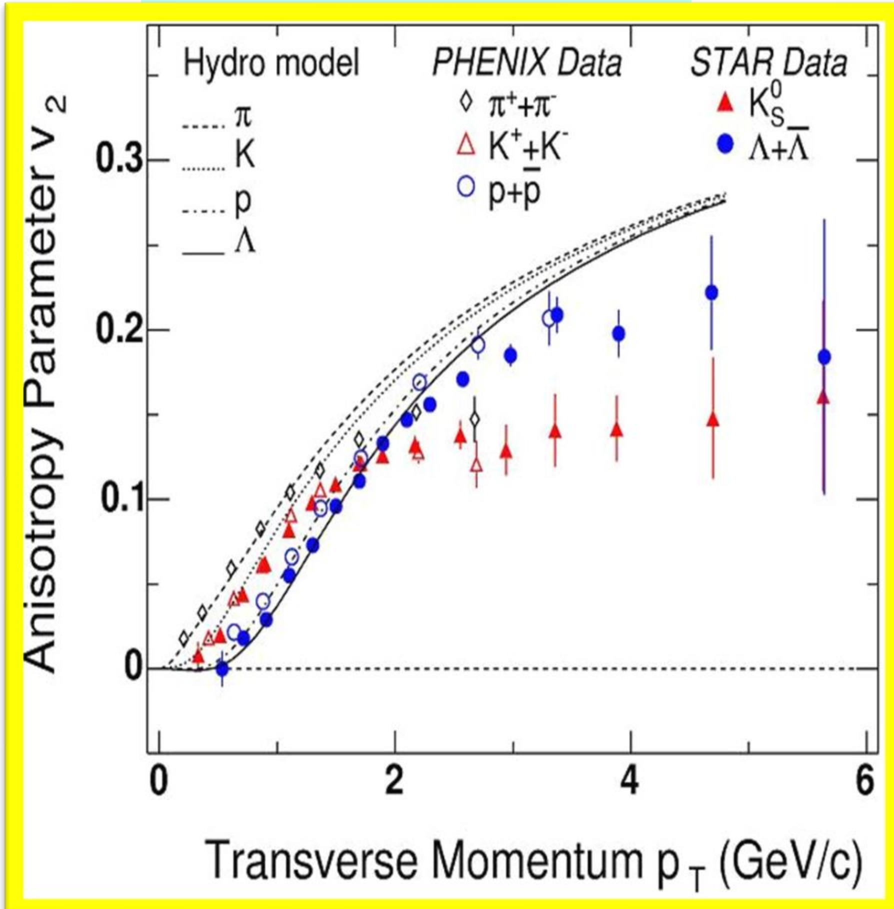
push bulk "out" → "flow"

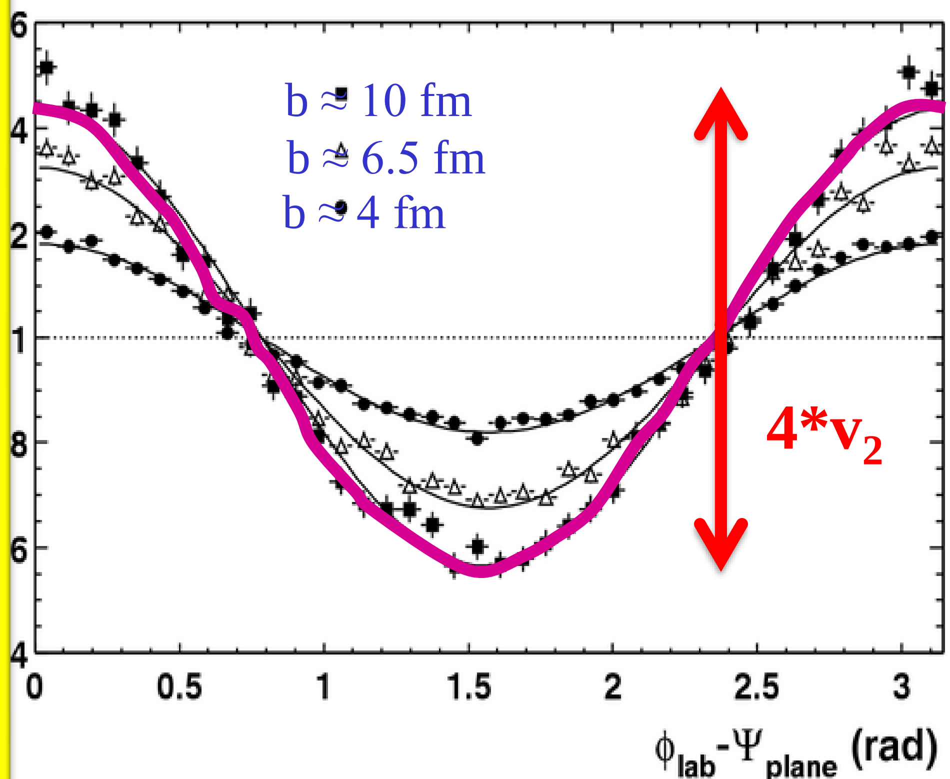


Elliptic Flow



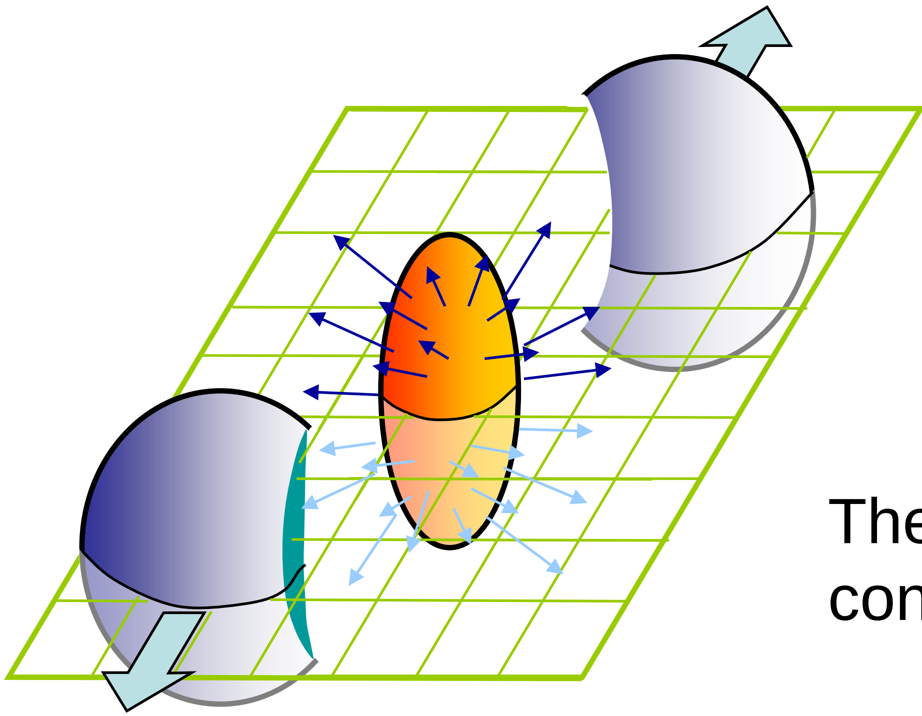
Azimuthal distributions

STAR, PRL**90** 032301 (2003)



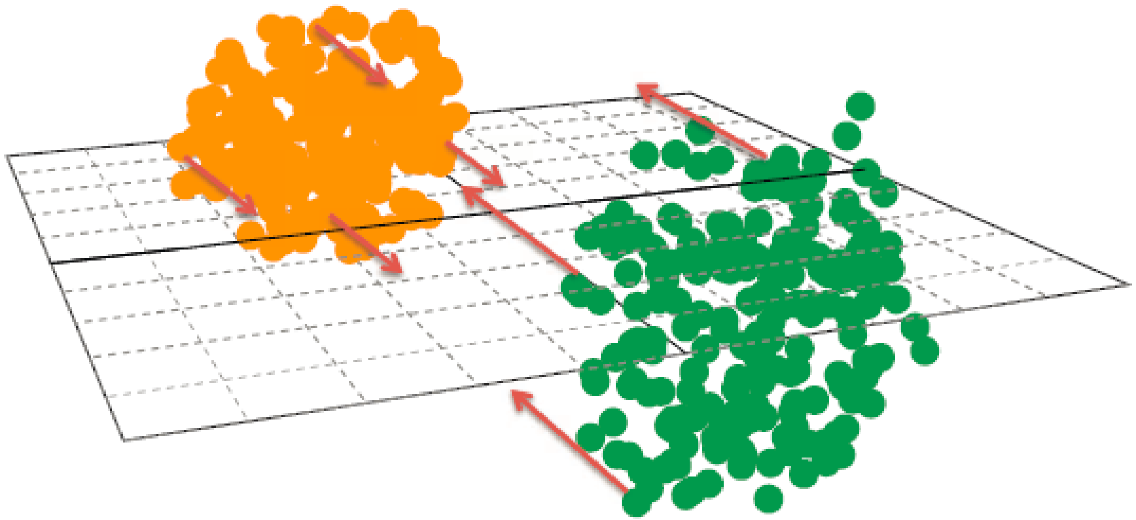
$$E\frac{dN}{d^3p}=\frac{dN}{dyp_Tdp_Td\varphi}=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_2(p_T,b)\cos(2\varphi)+...]$$

Instead of two smooth colliding nuclei

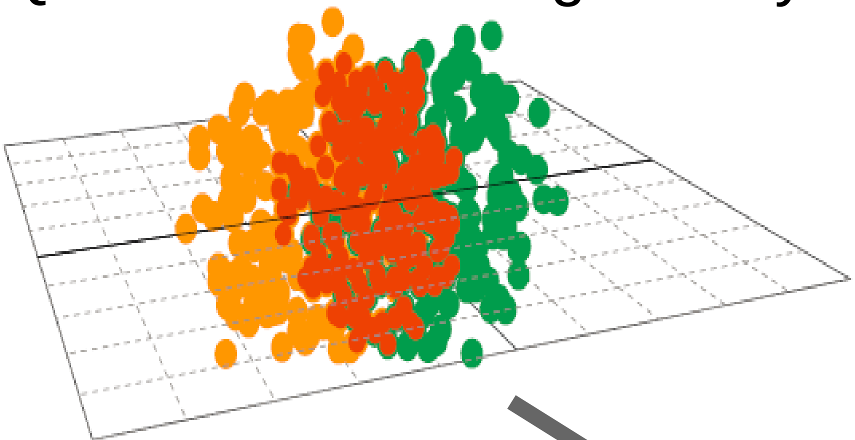


Initial stage fluctuations

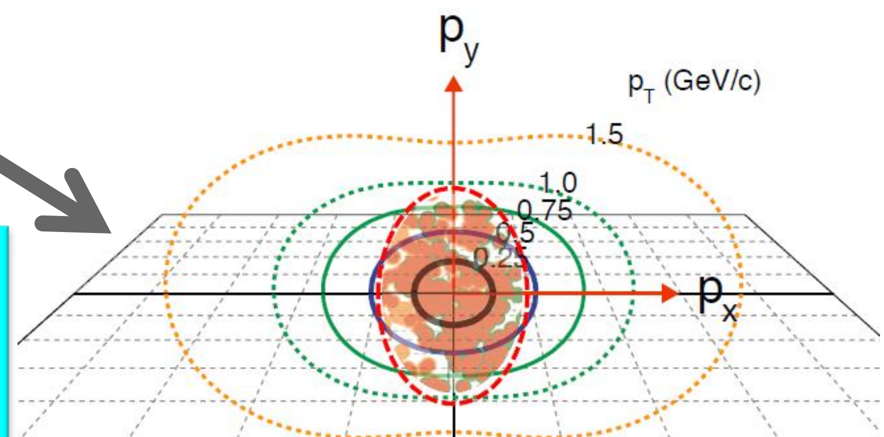
The position of initial nucleons constantly fluctuate



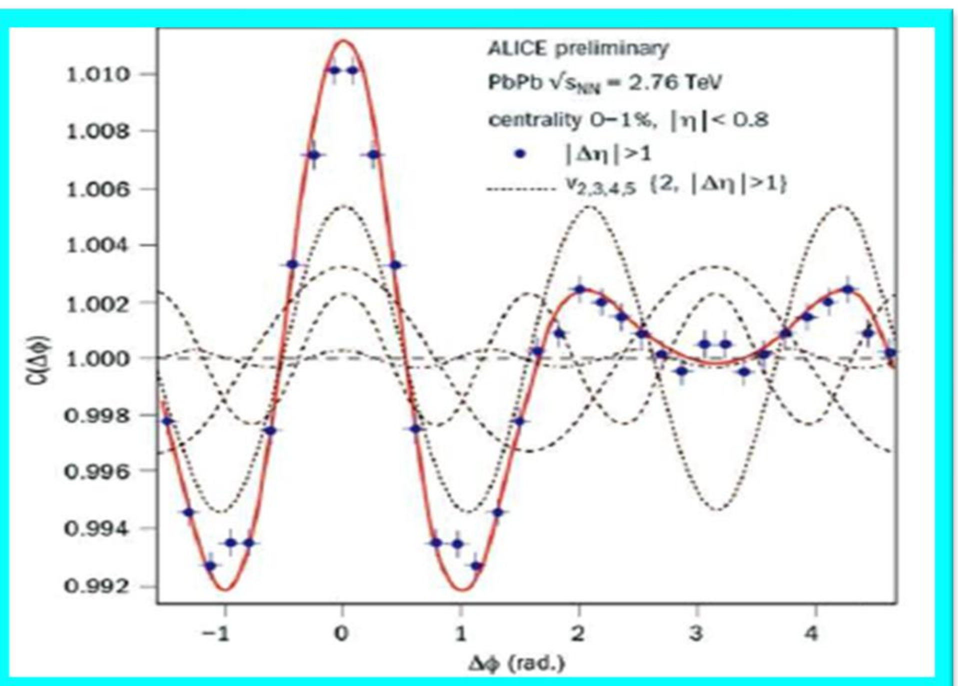
QGP with fluctuating density



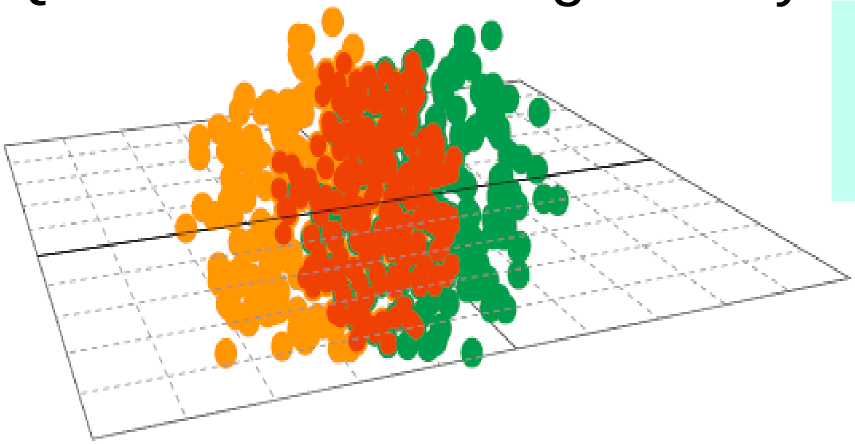
Azimuthal distribution in p-space



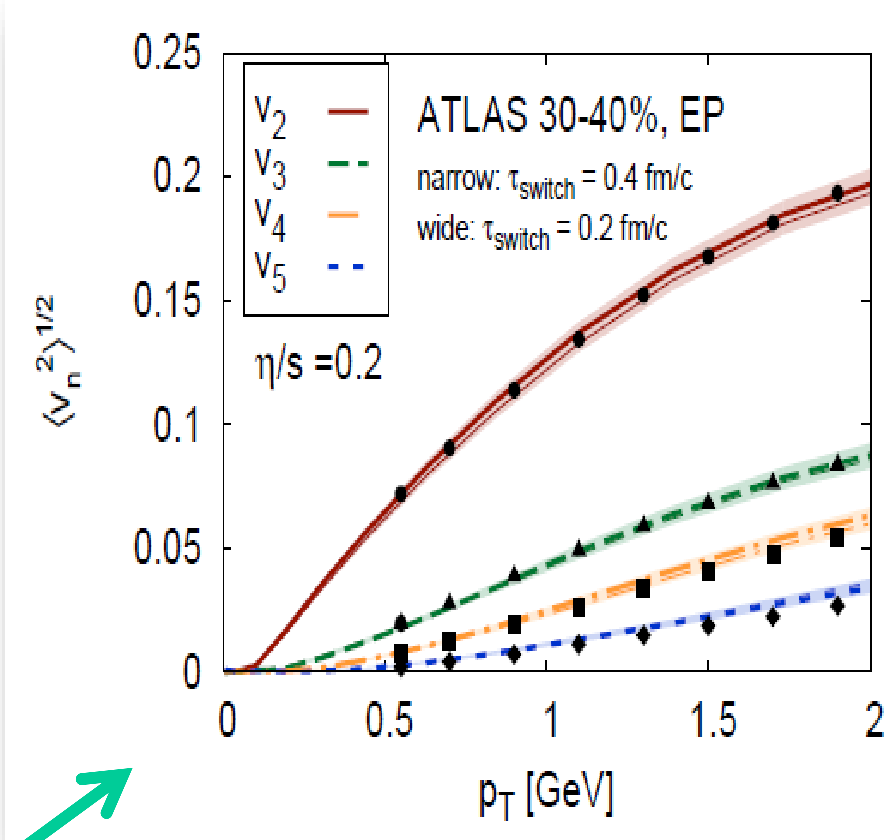
→measured flow: v_n



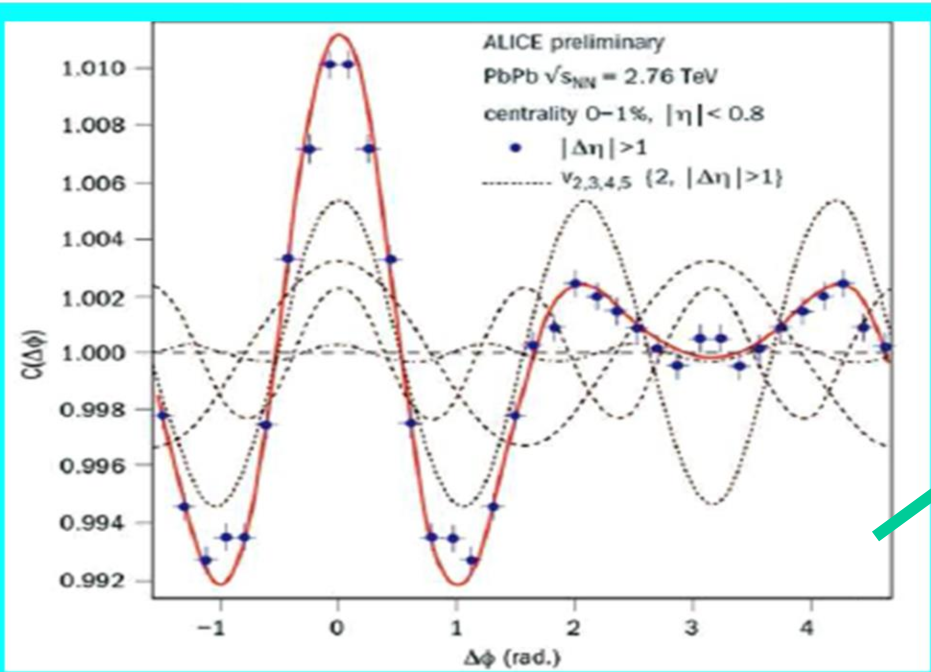
QGP with fluctuating density



Elliptic Flow & higher order flow harmonics

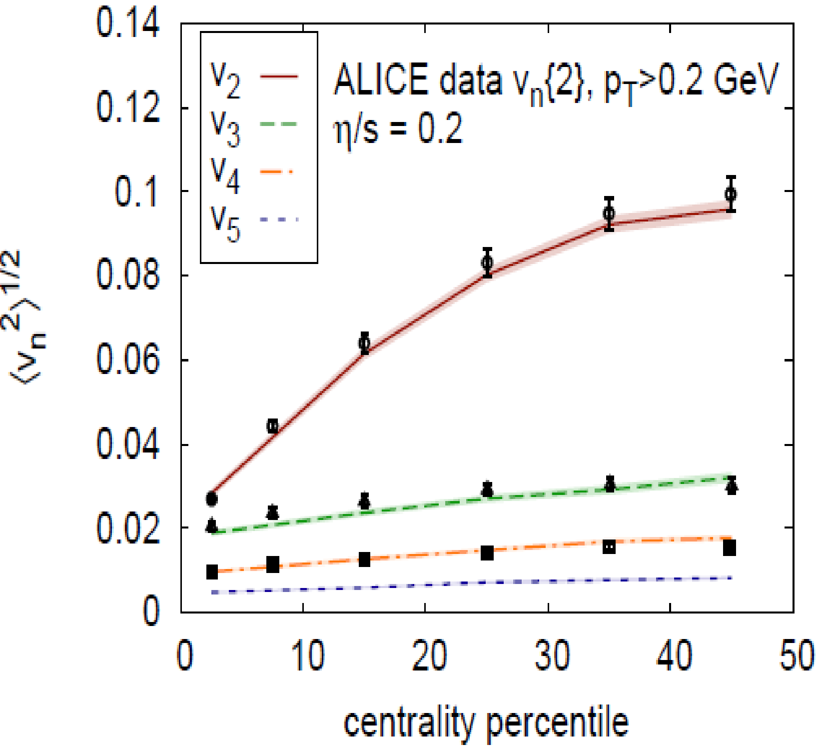


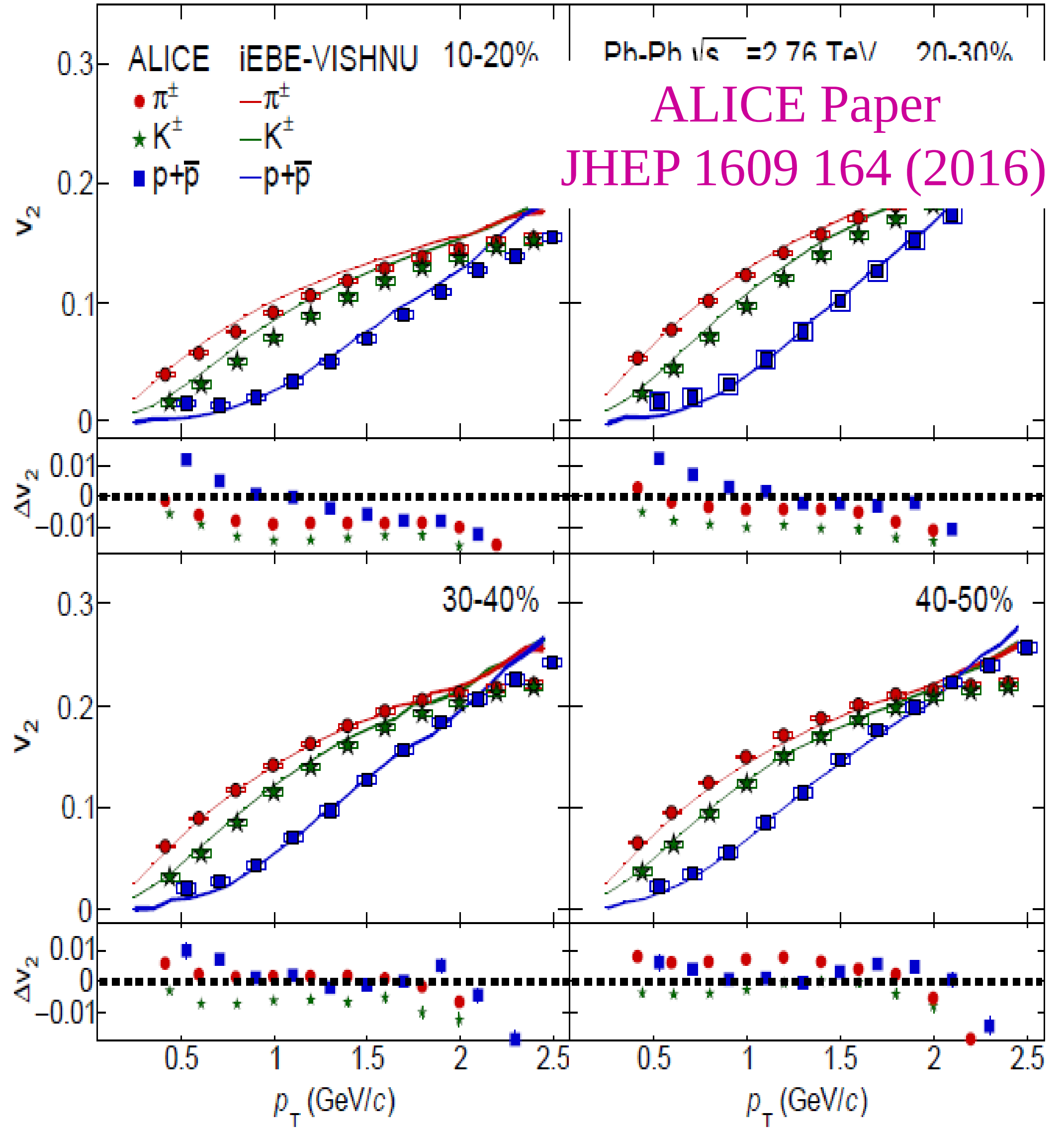
→measured flow: v_n



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

The Success of Hydrodynamics in Pb+Pb collisions





ALICE Paper
JHEP 1609 164 (2016)

-Hydro + IP-Glasma

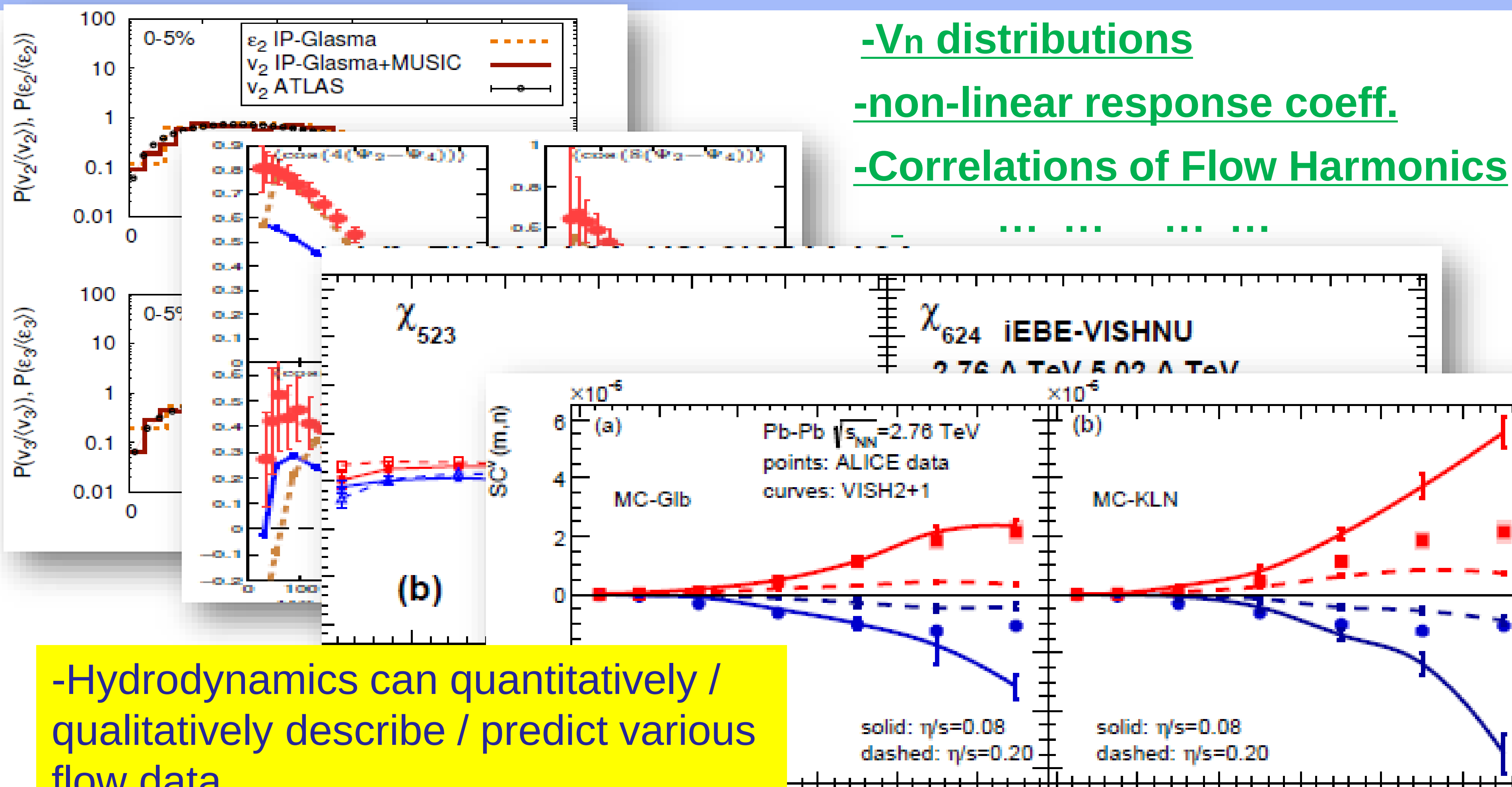
Gale, et. Al, PRL2013

-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



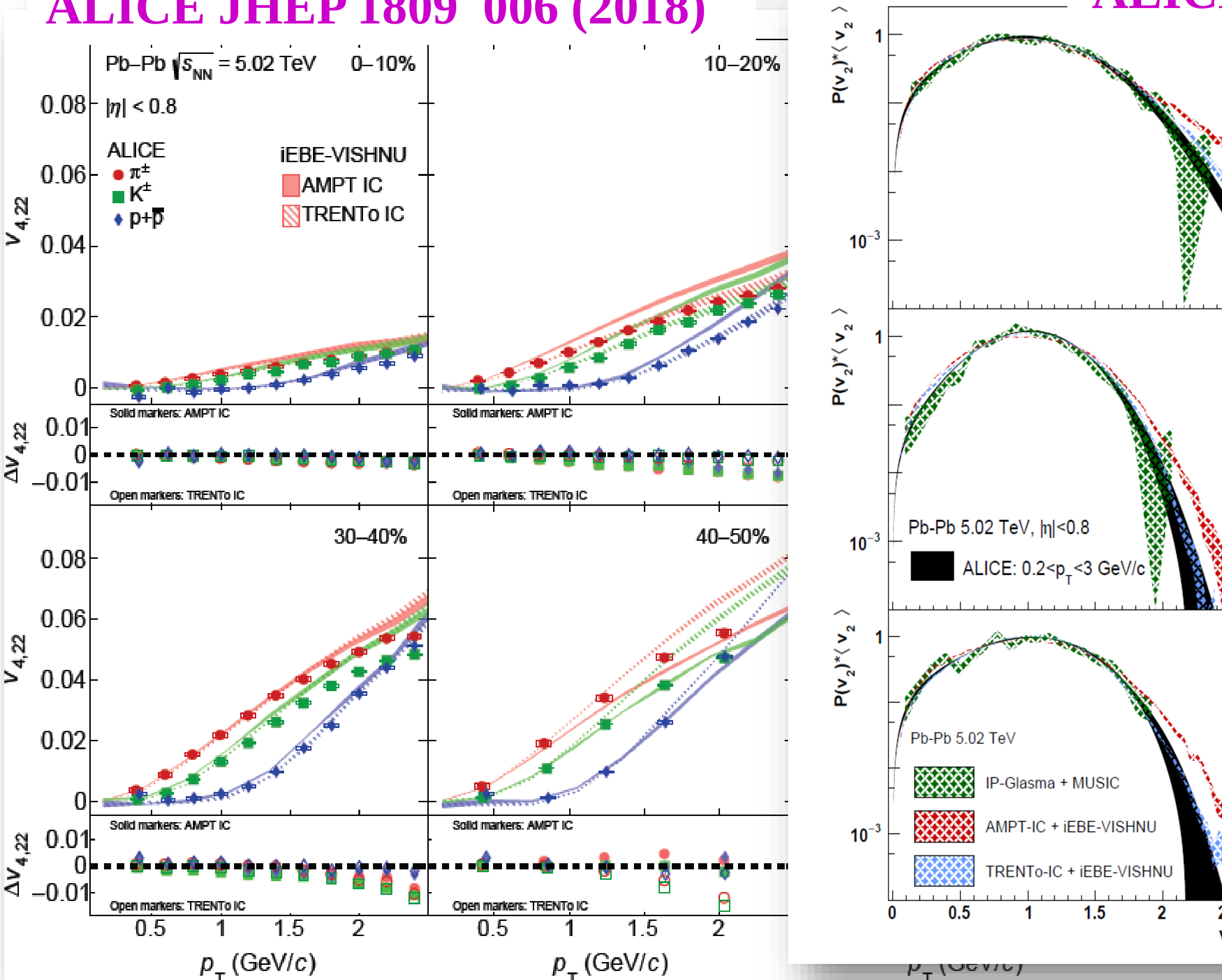
- **-Vn distributions**
- **-non-linear response coeff.**
- **-Correlations of Flow Harmonics**
- **… … … …**

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

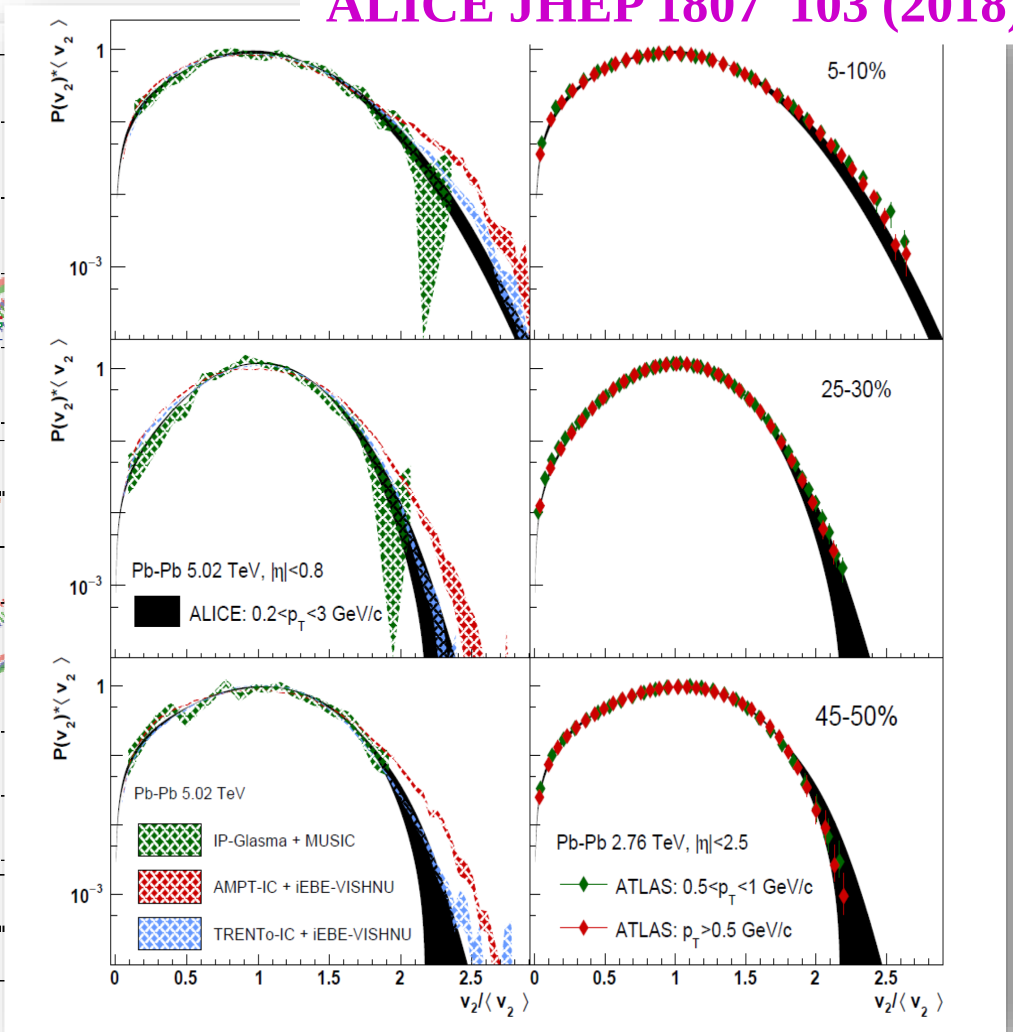
H. Xu, Z. Li and H. S*, Phys. Rev. C93, no. 6, 064905 (2016); W. Zhao, H. Xu and **H. S*,** Eur. Phys. J. C 77, no. 9, 645 (2017); X. Zhu, Y. Zhou, H. Xu and **H. S*,** Phys. Rev. C95, no. 4, 044902 (2017); W. Zhao, L. Zhu, H. Zheng, C. M. Ko and **H. S*.,** Phys. Rev. C 98, no. 5, 054905 (2018); Li,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

Predictions from Hydro & Comparison with EXP data

ALICE JHEP 1809 006 (2018)



ALICE JHEP 1807 103 (2018)



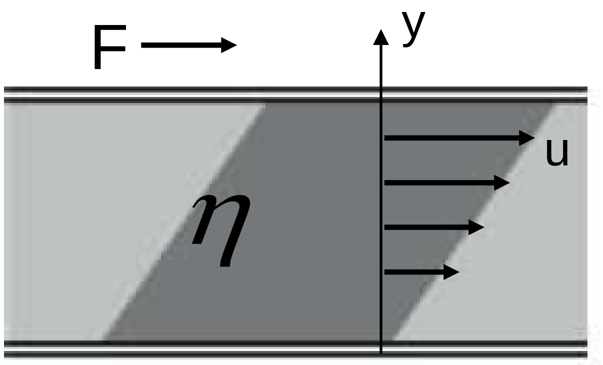
iEBE-VISHNU calculations: W. Zhao, H. Xu and **H. S*,** EPJC 77, no. 9, 645 (2017)
ALICE measurements: JHEP 1807 103 (2018); JHEP 1809 006 (2018), etc

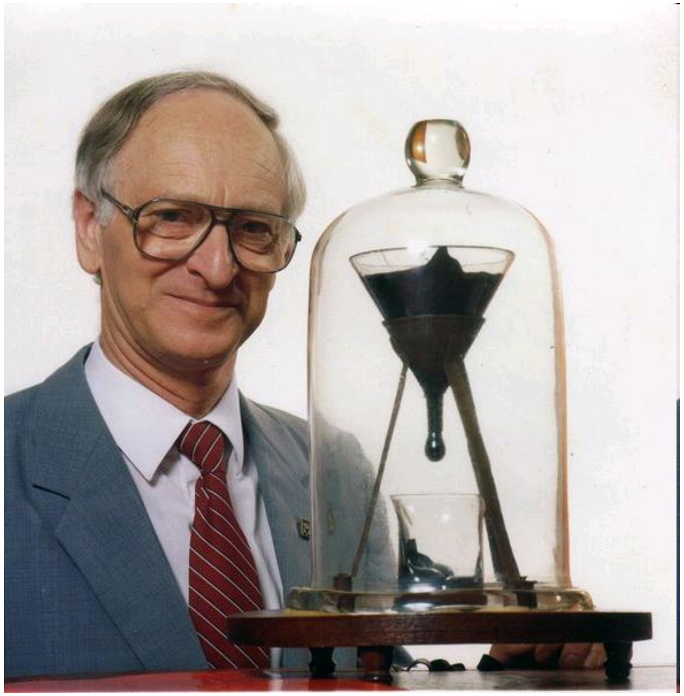
The viscosity of the QGP

Shear Viscosity

-classical definition:

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





<u>A supper viscous liquid - Pitch</u>

Pitch has viscosity approximately 230 billion times that of water.

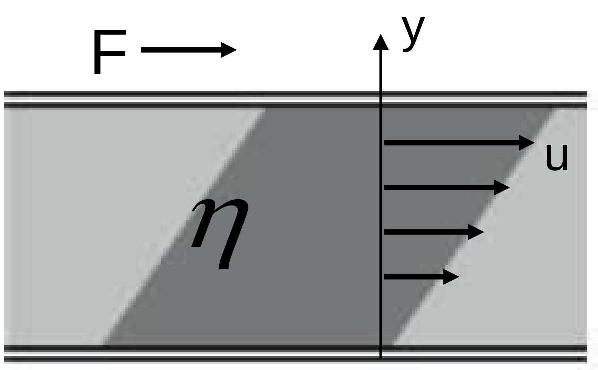
Longest running experiment (1927-present)
8 drops so far, none ever seen fall!

http://en.wikipedia.org/wiki/Pitch_drop_experiment

Lowest bound of specific shear viscosity

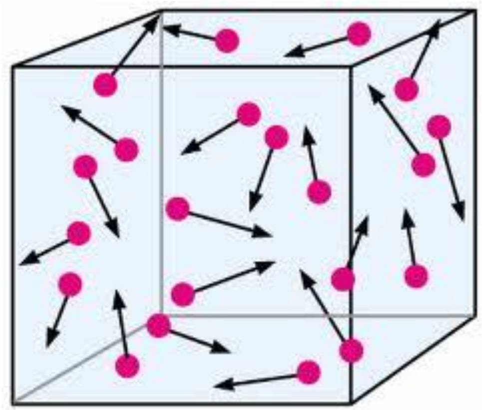
-classical definition:

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



-kinetic theory:

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

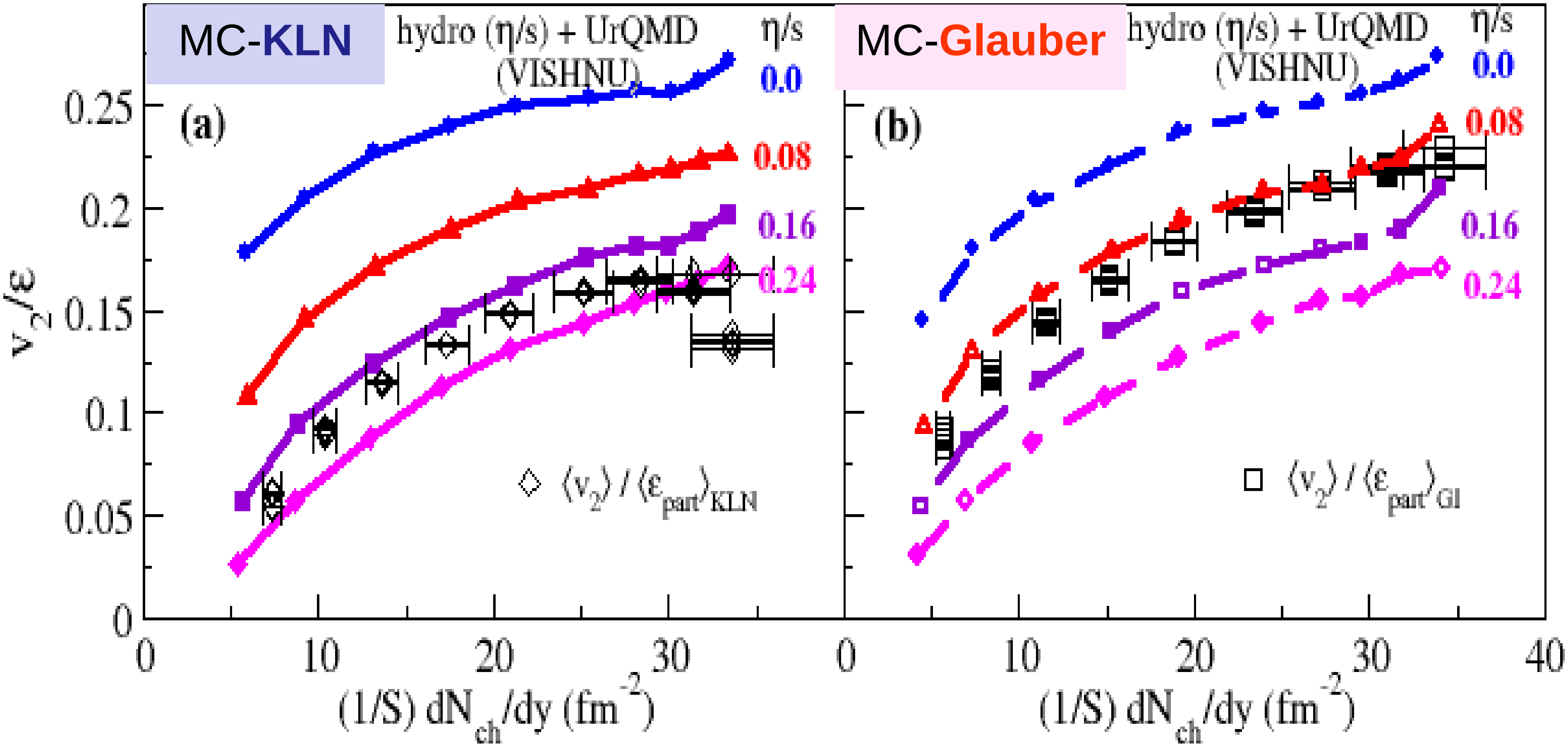


$$\frac{\eta}{s} \sim \frac{1}{k_B}\bar{v}ml_{mfp} \sim \frac{1}{k_B}\left(\frac{1}{2}m\bar{v}^2\right)\left(\frac{l_{mfp}}{\bar{v}}\right) \sim \frac{e\tau}{k_B} \qquad (s \sim k_B n)$$

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

Extracting QGP viscosity with hydrodynamical model

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

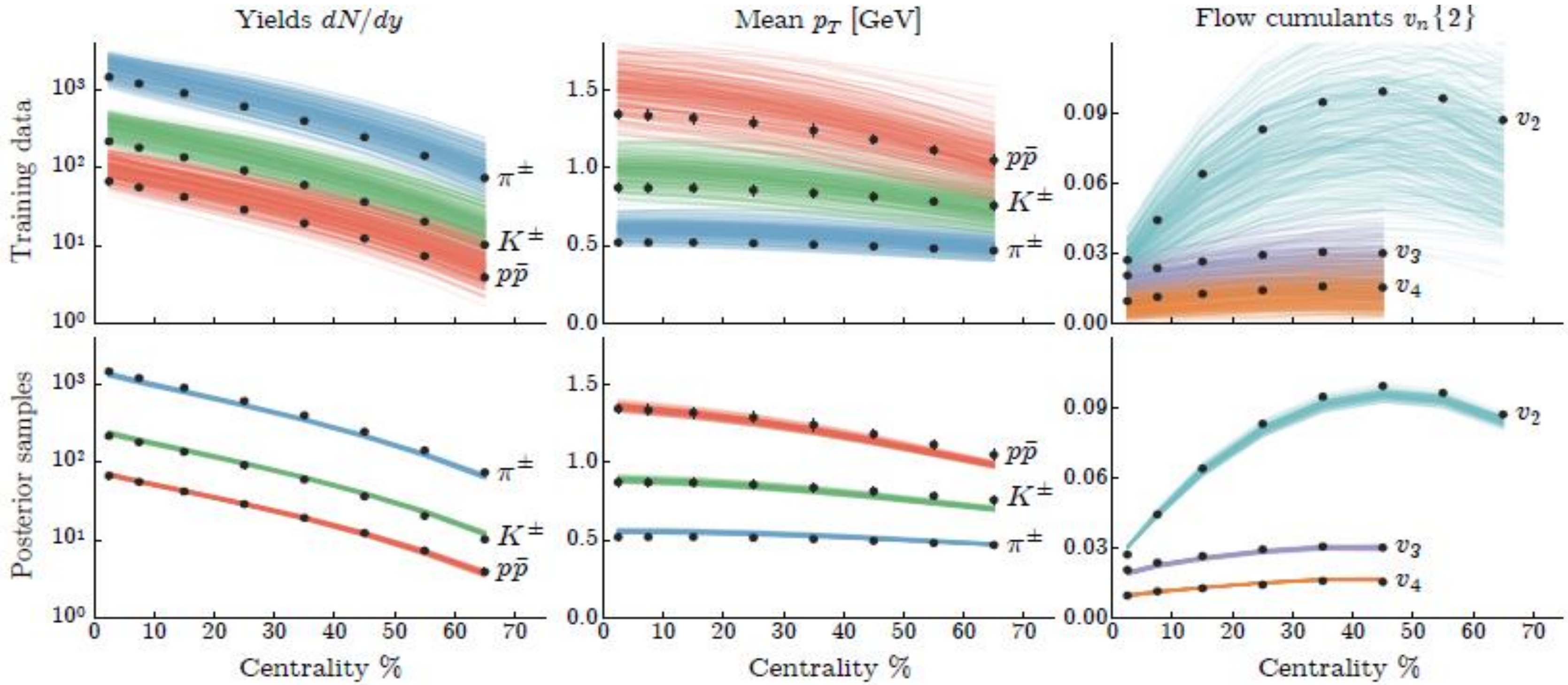
… ... … …

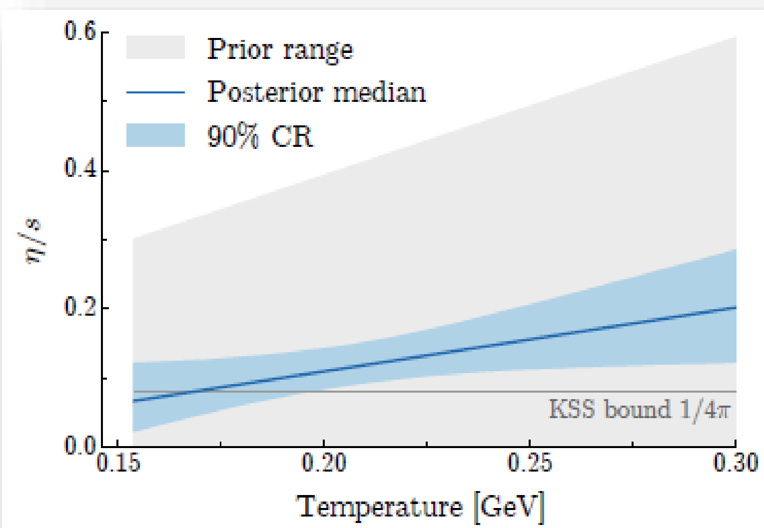
Hydro model & its Inputs:

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

… … … …

An quantitatively extract the QGP viscosity



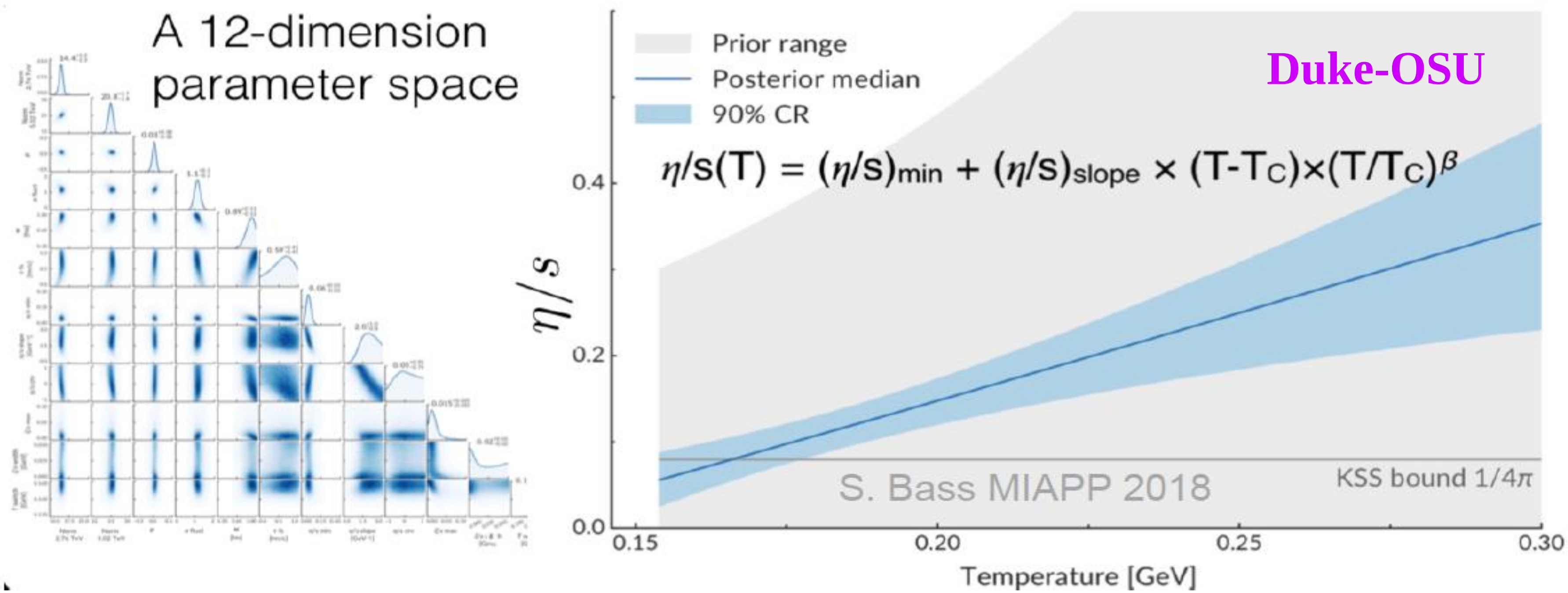


-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

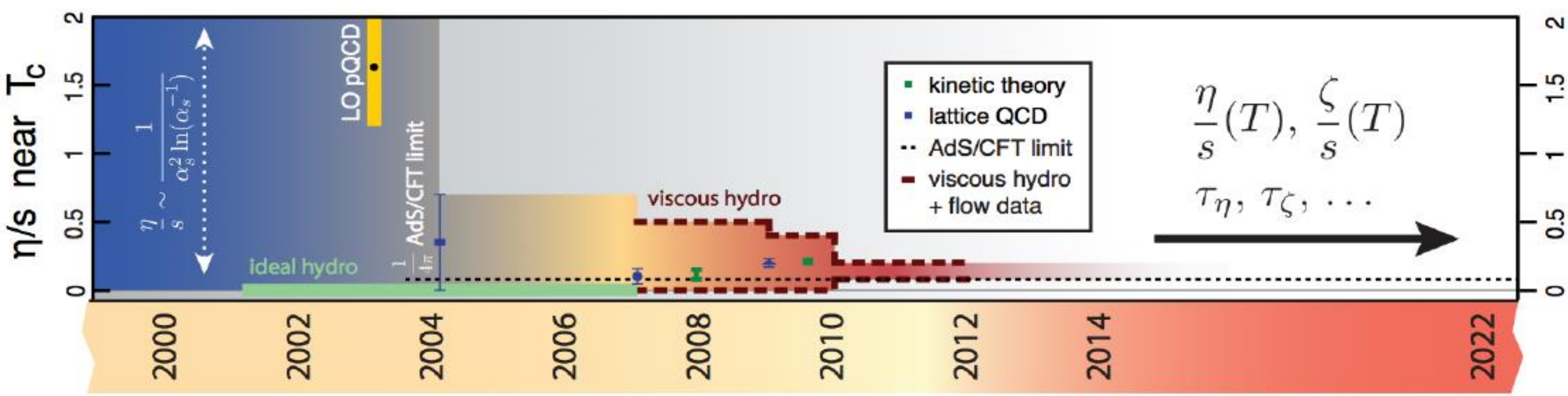
-$\eta/s(T)$ is very close to the KSS bound of $1/4\pi$

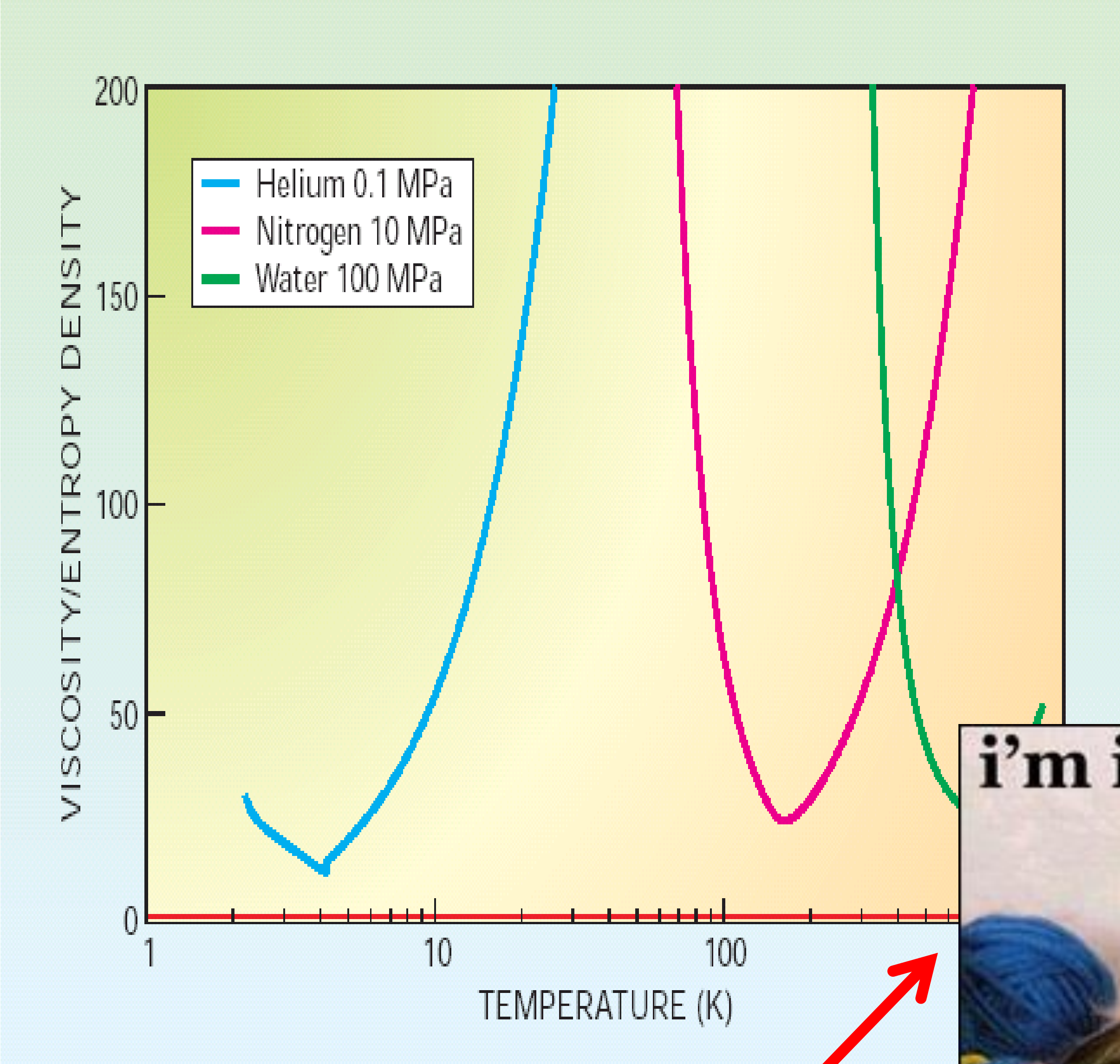
J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

Extracting QGP viscosity with massive data evaluation



Extracted QGP viscosity with ever increasing precision



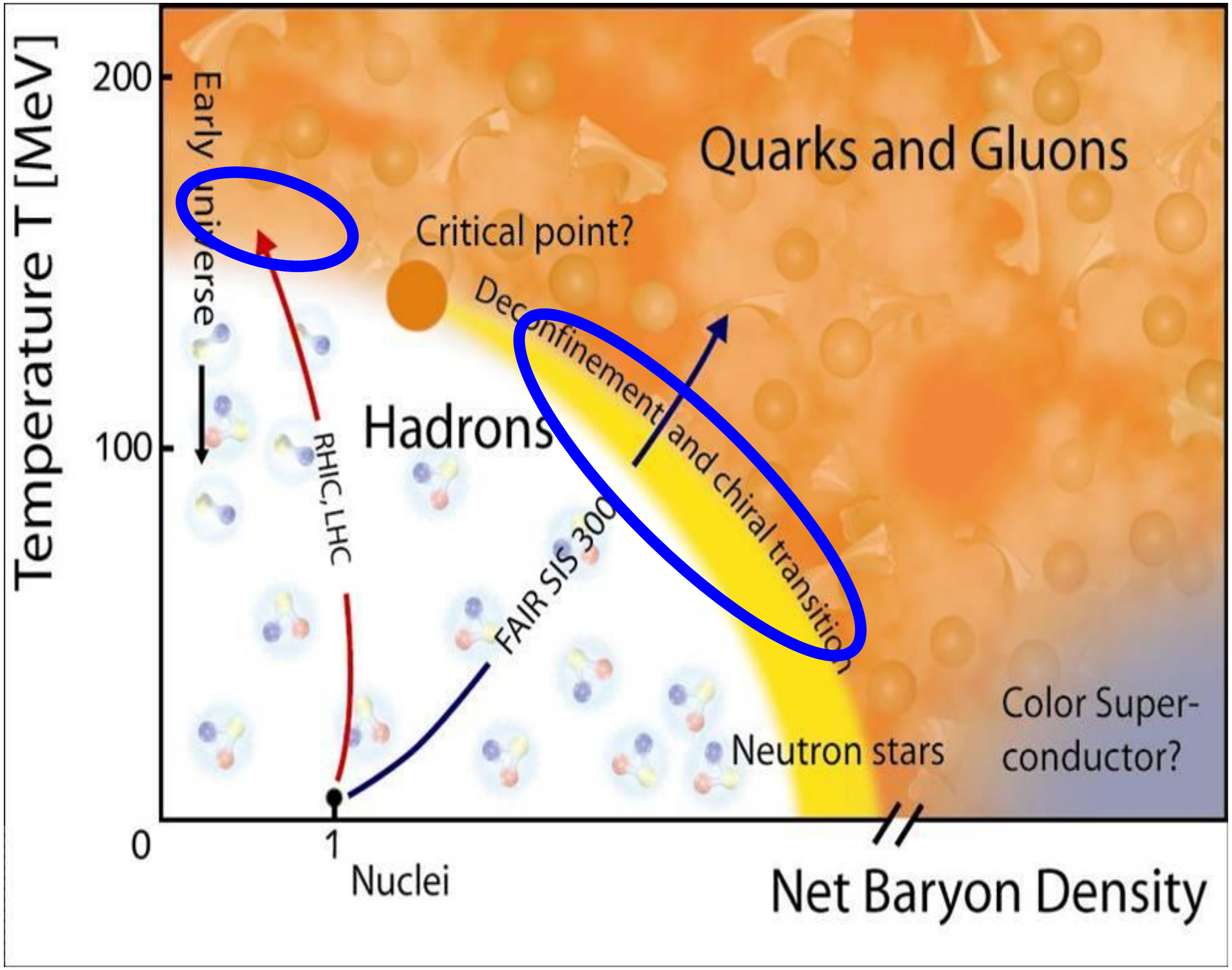


AdS/CFT

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

QGP specific shear viscosity
Extracted from exp data

Dynamical models at various collision energy & system sizes



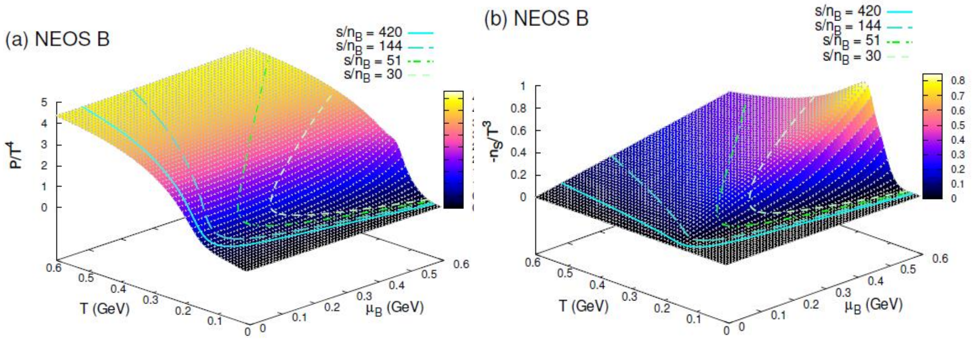
Recent development of hybrid model for RHIC BES

Dynamical initial conditions

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

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

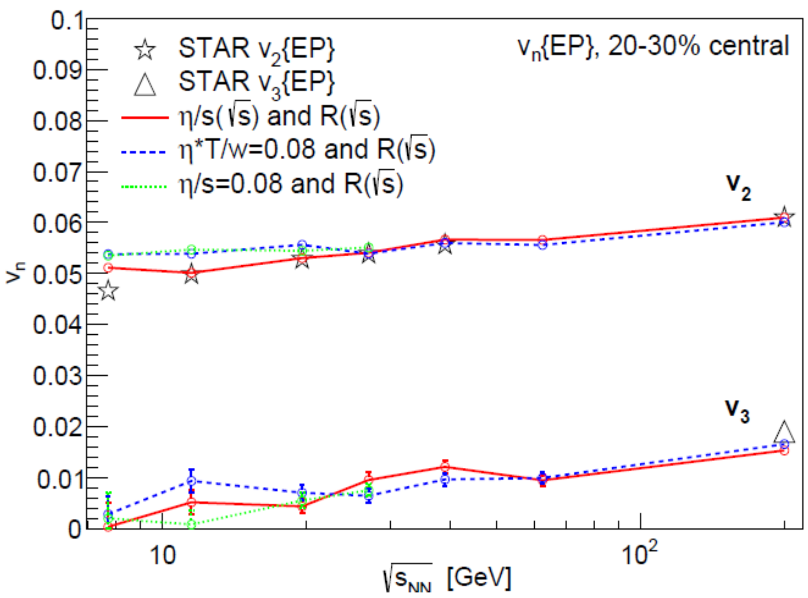
$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu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

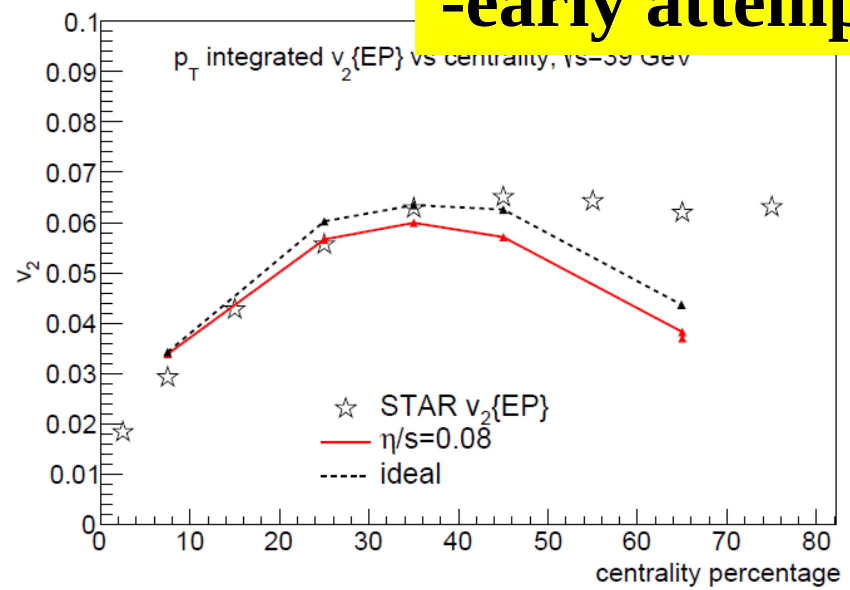
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\sigma^{\nu\rangle}}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi^{\langle\mu}{}_\alpha \pi^{\nu\rangle\alpha}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

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 η/s($\sqrt{s}$) from RHIC BES (I)

-early attempt





<u>Data</u>

- RHIC BES Au+Au 7.7-200 A GeV

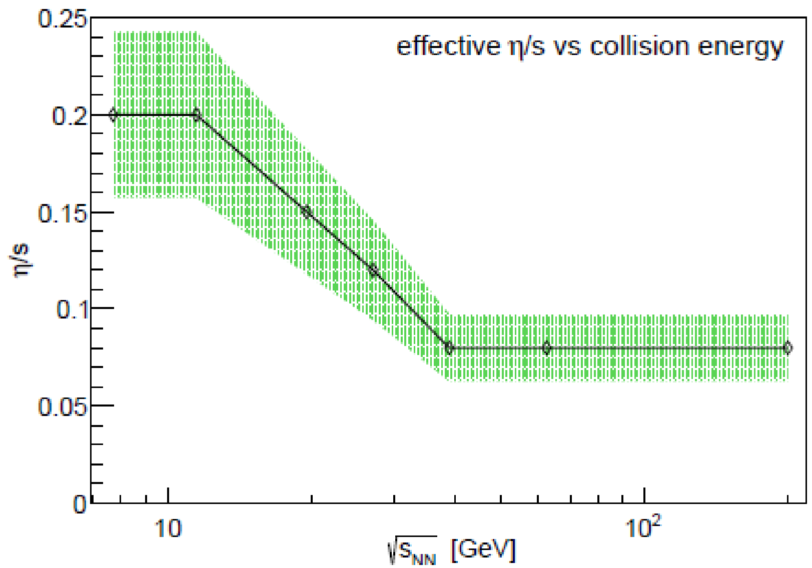
<u>Model</u>

-3+1d viscous hydro + UrQMD

-pre-equilibrim stage UrQMD

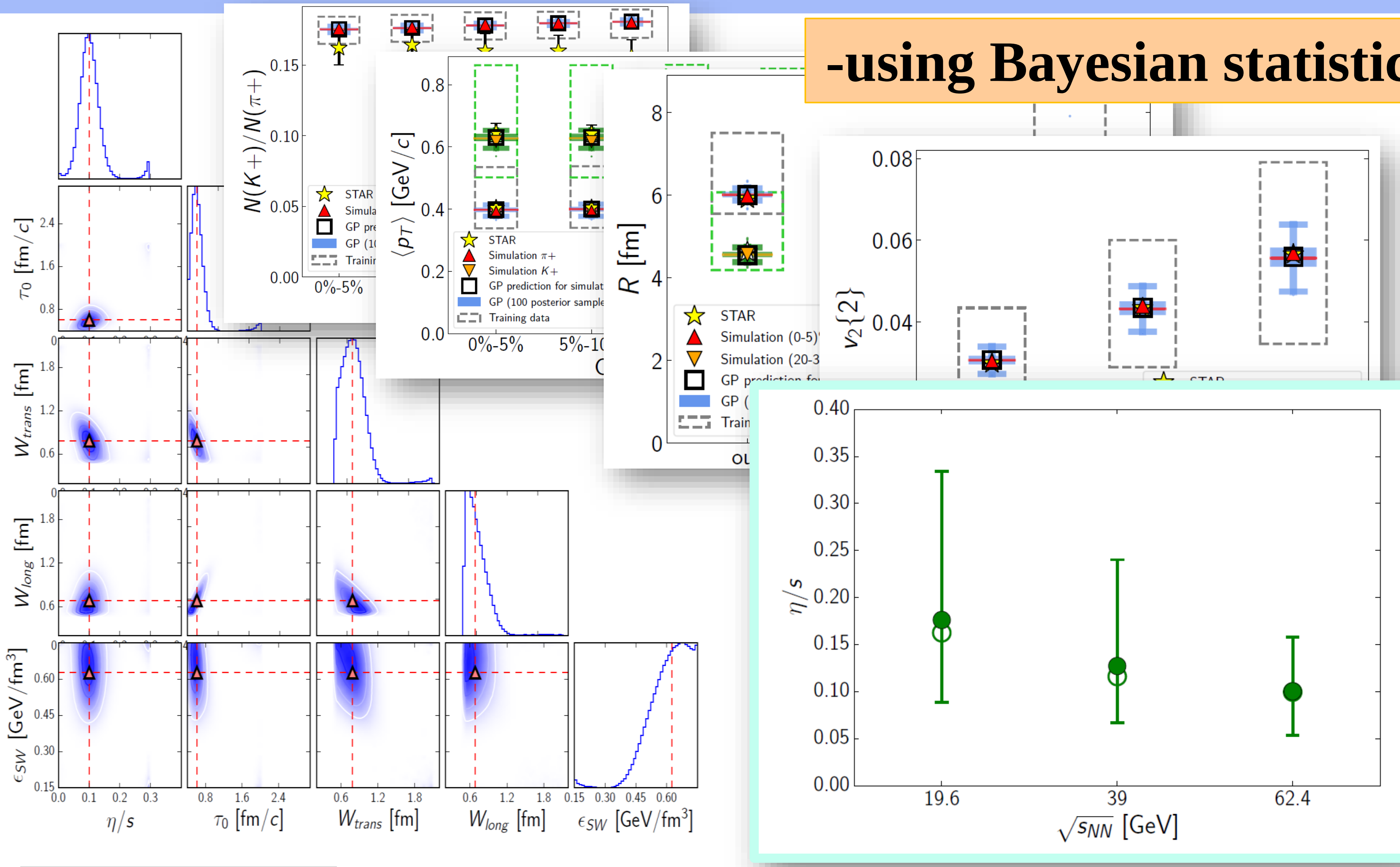
-EoS (Chiral Model with T, μ)

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)

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

Effects of heat conductivity

Net baryon diffusion

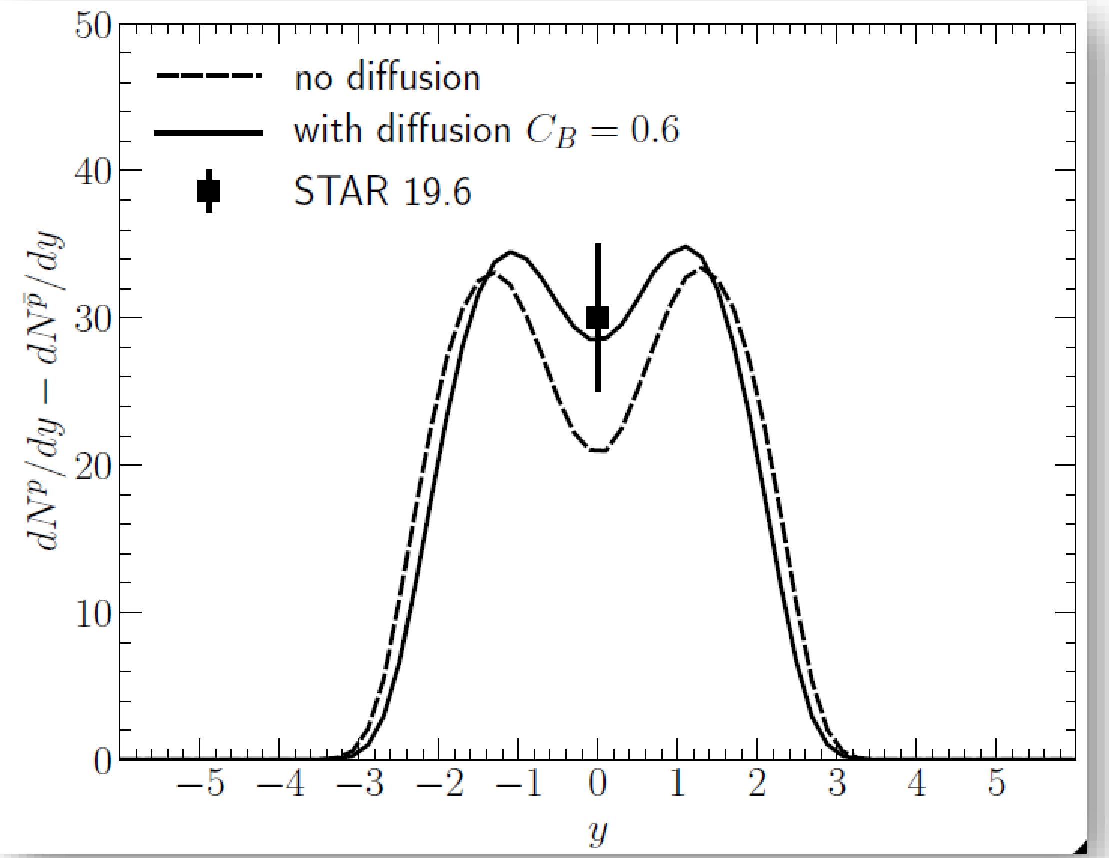
$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_q}{\tau_q} \cdots$$

$$+\frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla \cdots$$

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu} \cdots\right.$$

$$-\frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi} \cdots$$

$$+\frac{l_{\pi q}}{\tau_\pi}\nabla^{\langle\mu} q^{\nu\rangle} + \frac{\lambda_{\pi q}}{\tau_\pi} \cdots$$



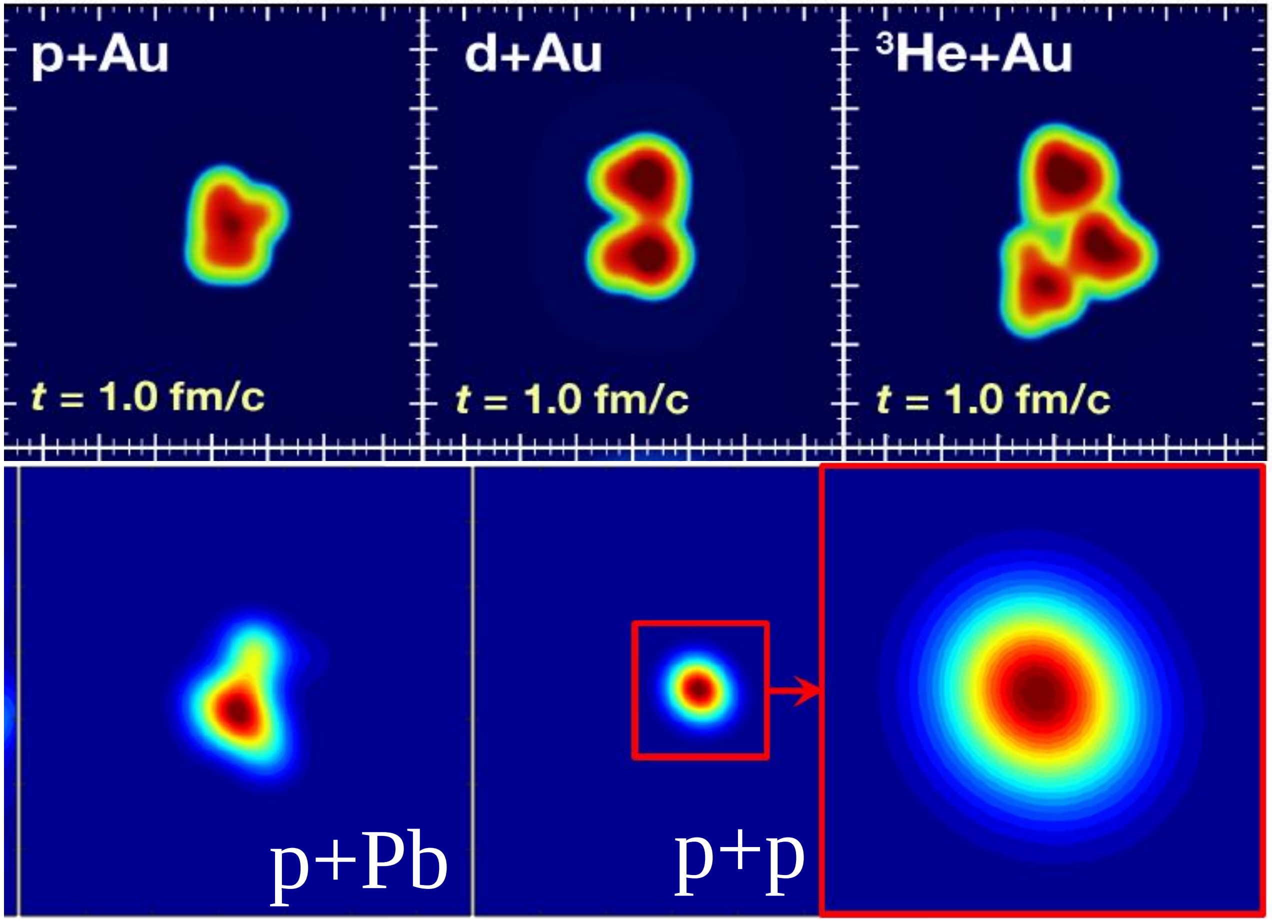
G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018) ; M. Li and C. Shen, Phys. Rev. C98, 064908 (2018)

-Net baryon diffusion transports more baryon numbers to the mid-rapidity region

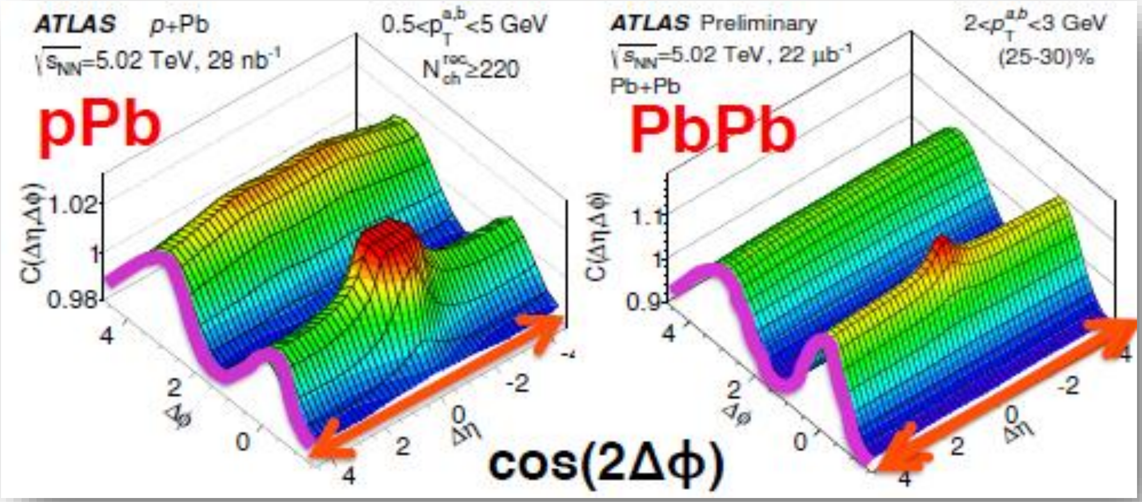
-Need a systematical study of various flow data in the near future

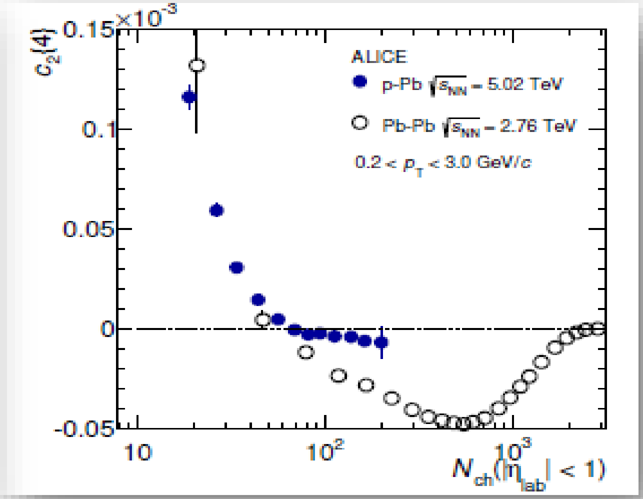
-Extracting heat conductivity in the future

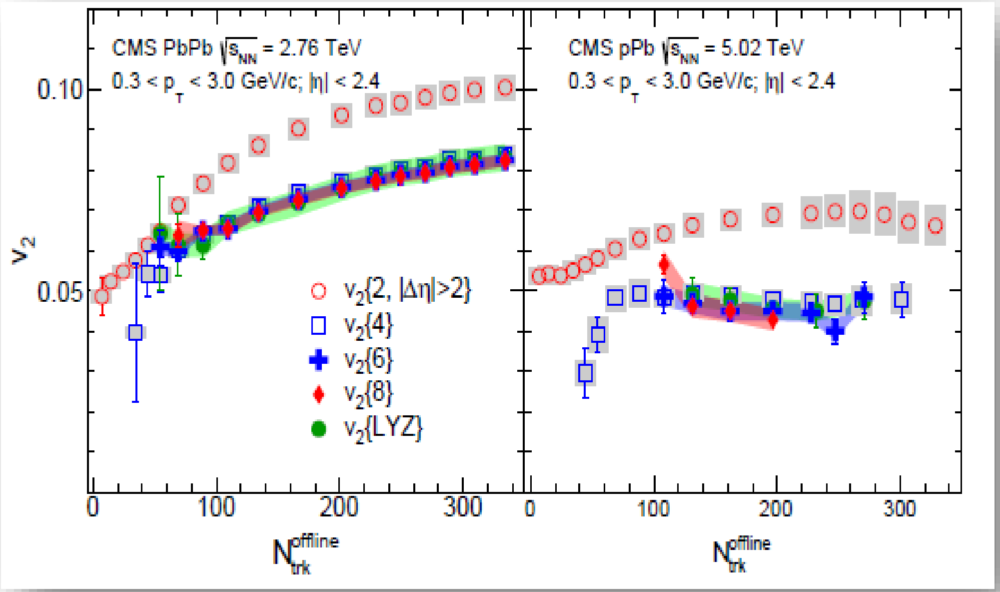
Collectively & QGP signatures in small systems

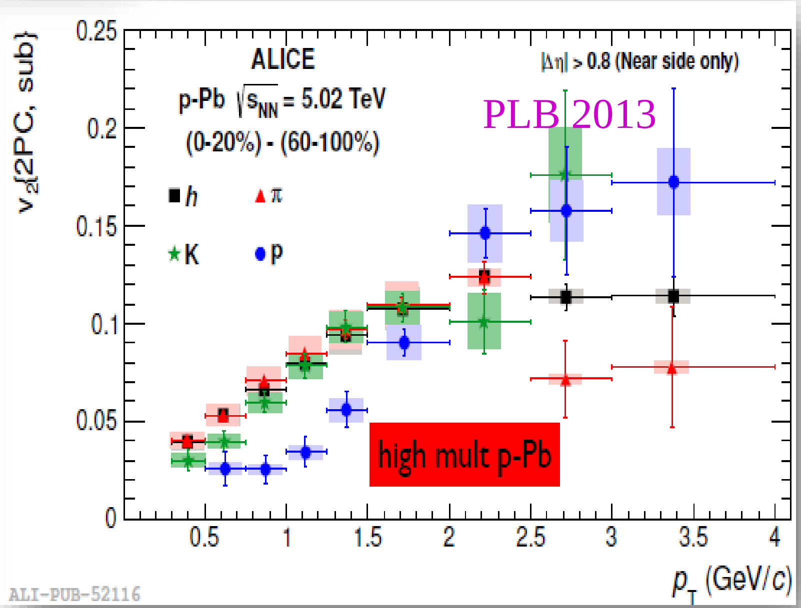


Correlations & Flow in p-Pb collisions



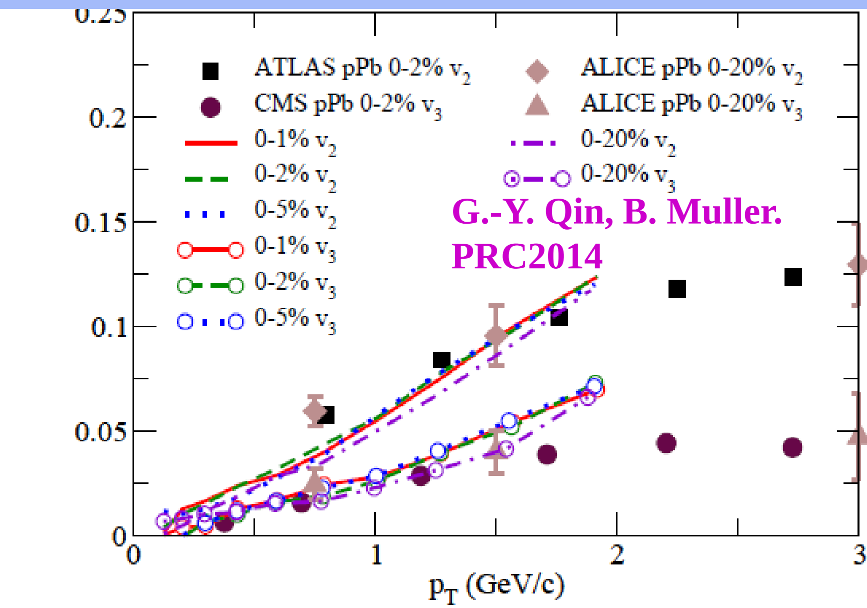




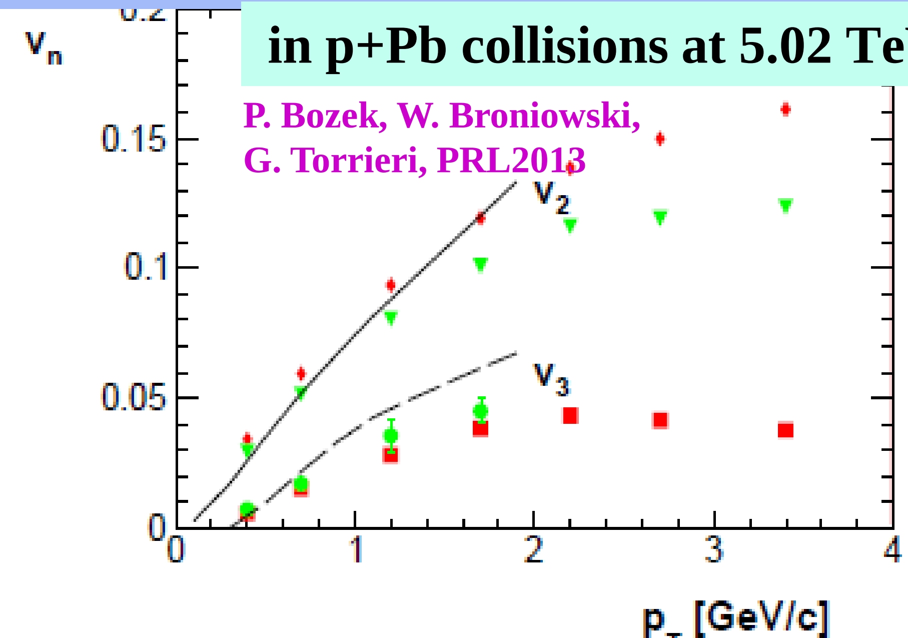


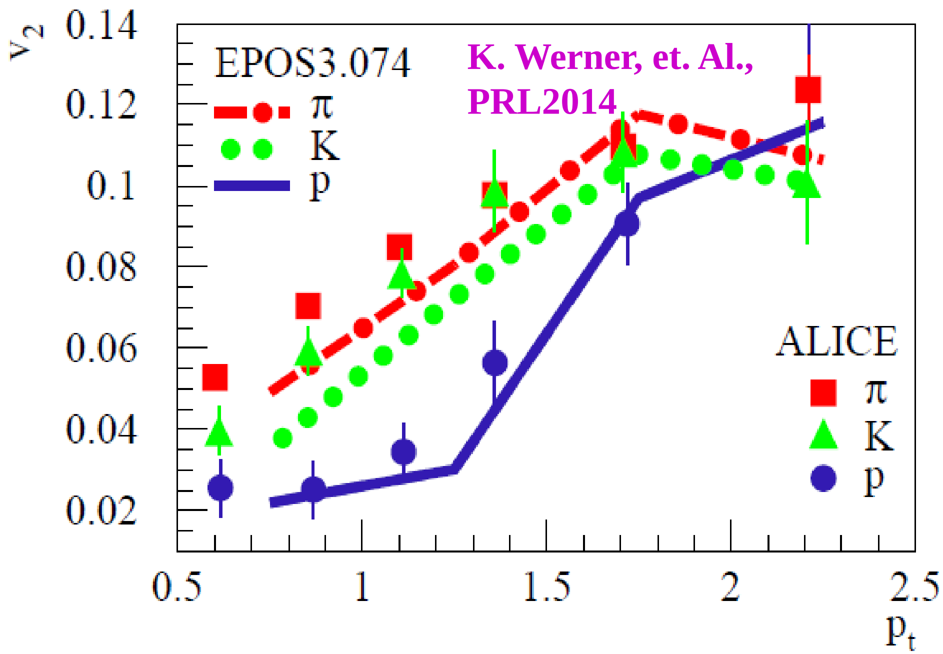
-Many flow-like signals have been observed in high multiplicity p-Pb collisions

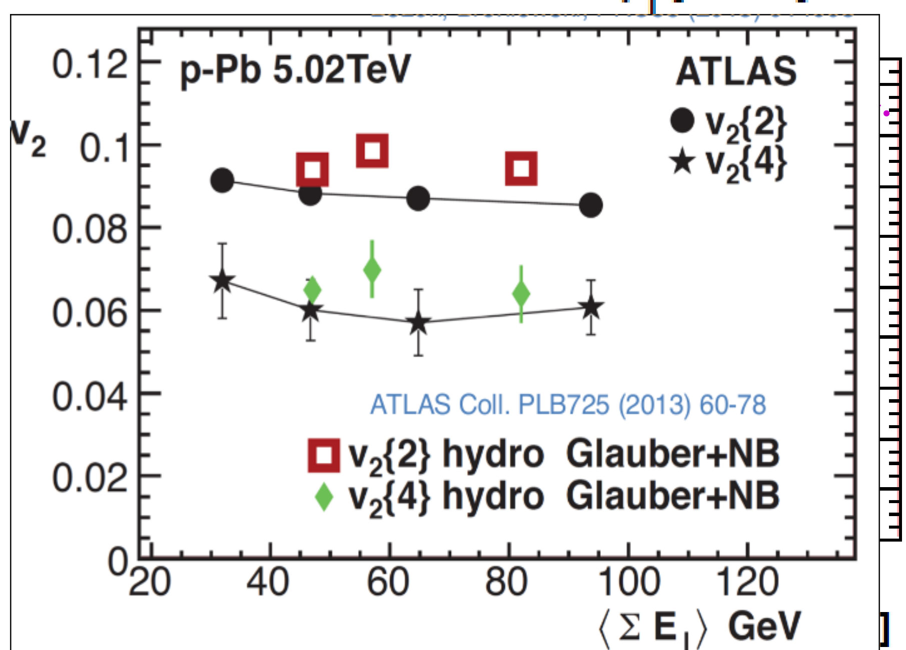
Flow in p-Pb -- Hydrodynamics Simulations



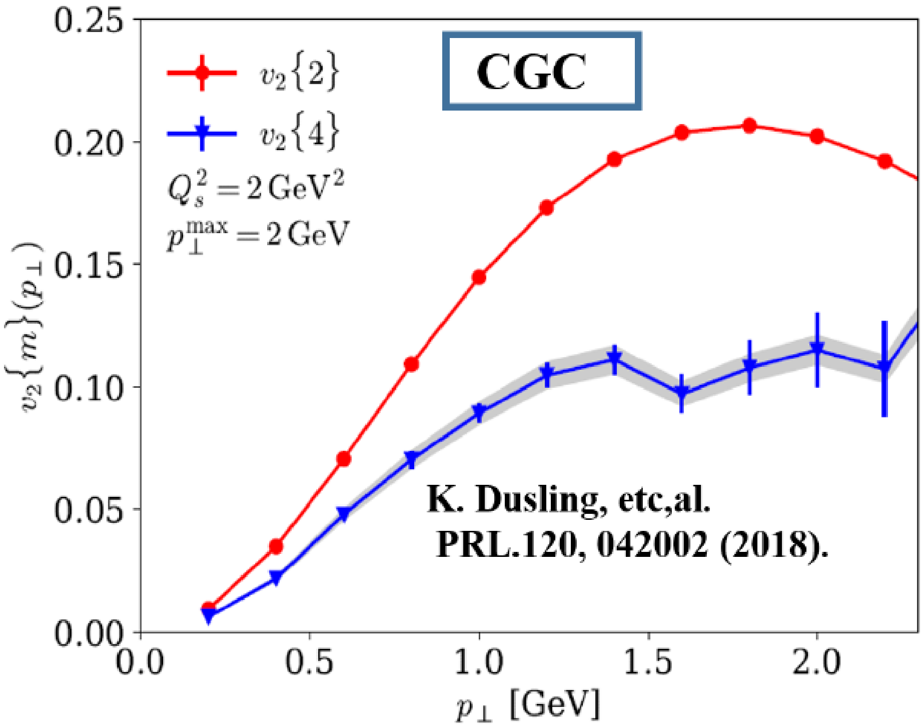
in p+Pb collisions at 5.02 TeV

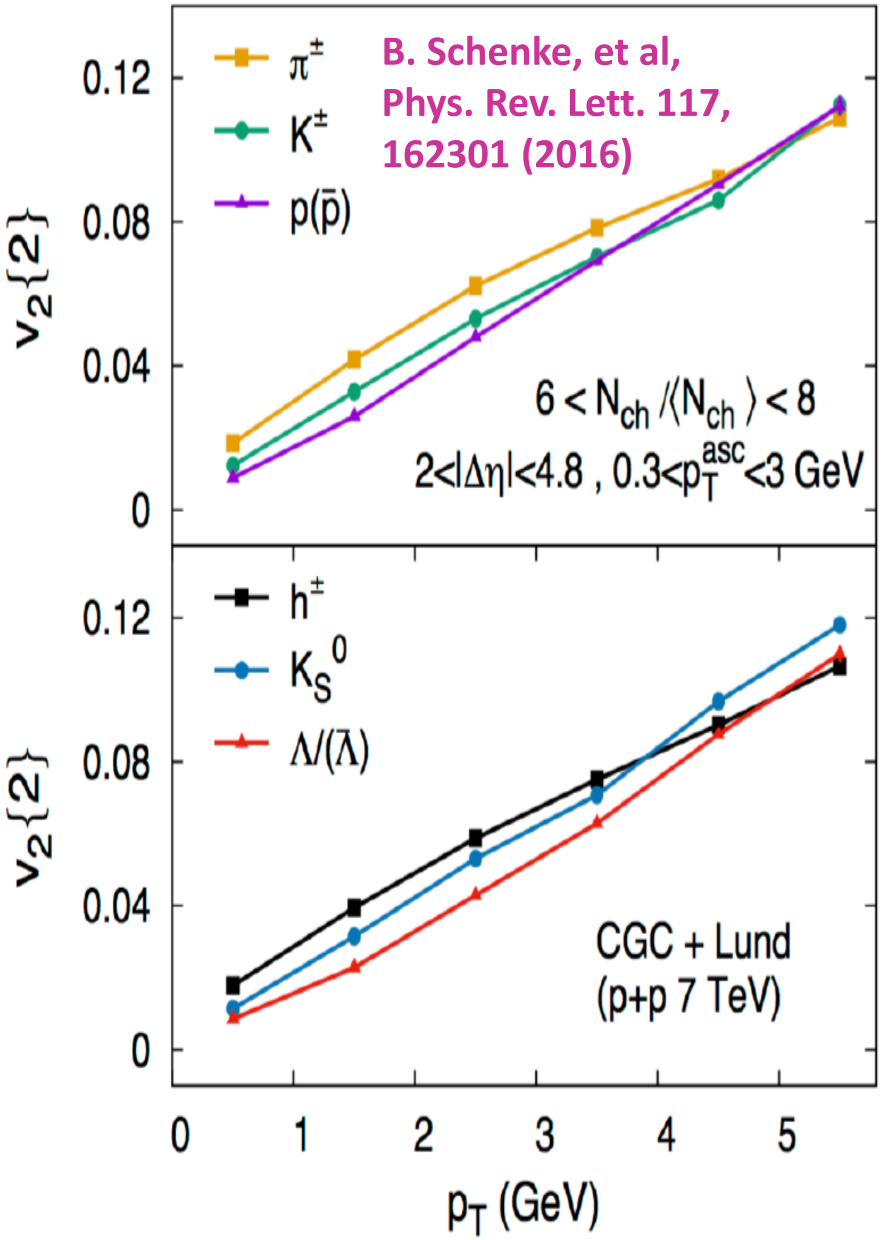






Flow-like signals: initial state effects

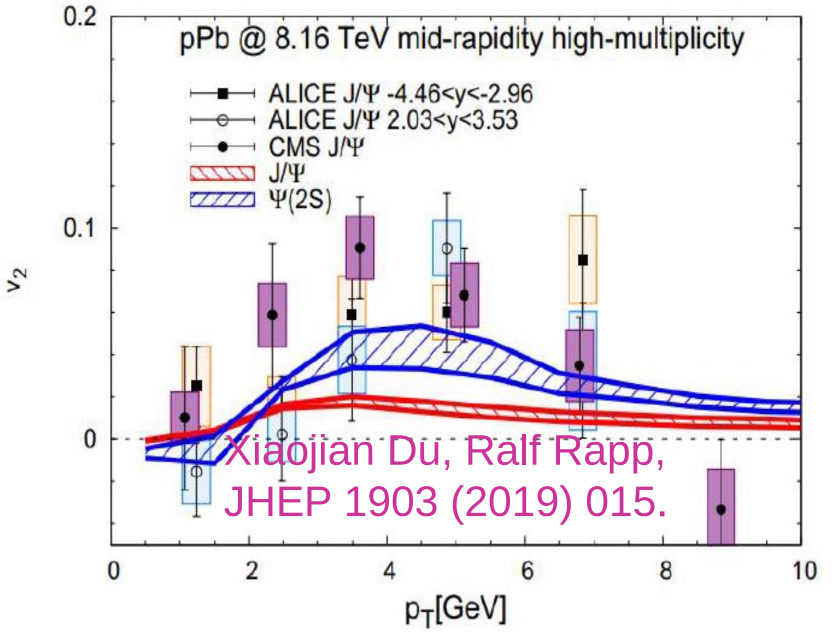


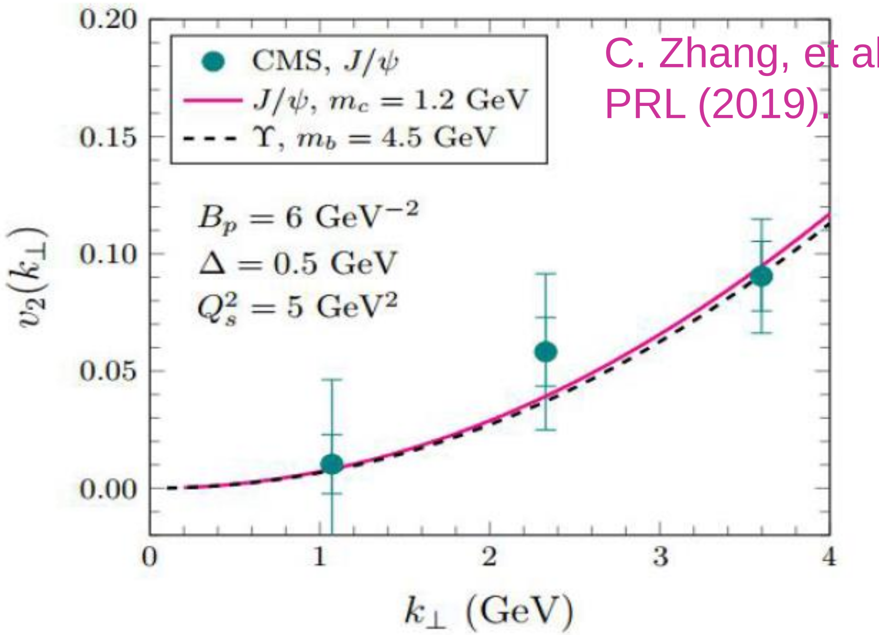


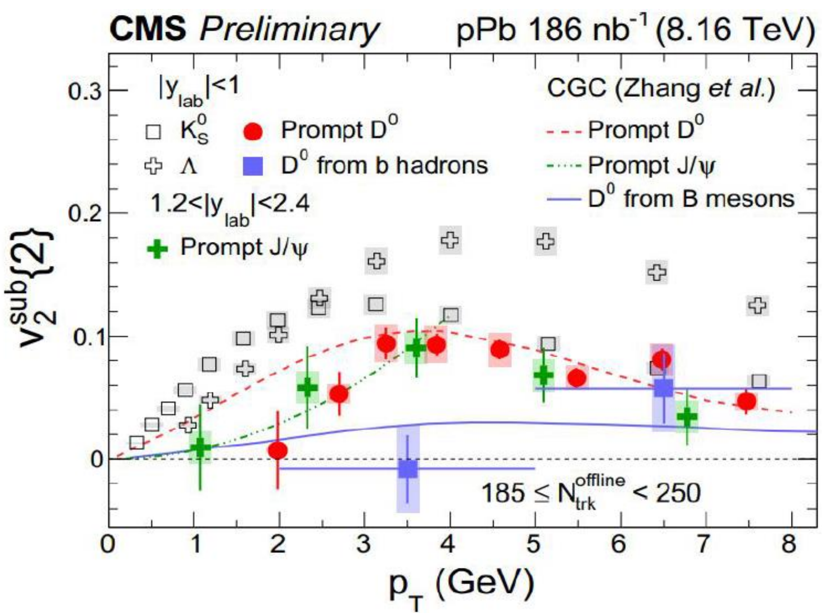
-Qualitative features of v2{2} and v2{4} have been reproduced with the initial state model with localized domains of color charge

- Mass splitting can also explained within CGC + Lund string fragmentation where the string gives the common boost

Flow-like signals: Heavy quarkonia & open heavy flavor







-The observed v2 of J/Ψ cannot be explained by final-state effects alone,

-Heavy quarkonia & open heavy flavor can have a significant v2 in pPb due to azimuthal angular correlations from the initial state effects (CGC).

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, PRL2(…)

-K. Werner, et. Al., PRL2014

-G.-Y. Qin, B. Muller. PRC201(…)

-Y. Zhou, X. Zhu, P. Li, a(…) PRC2015

- P. Bozek, A. Bzda(…) Ma, PLB2015

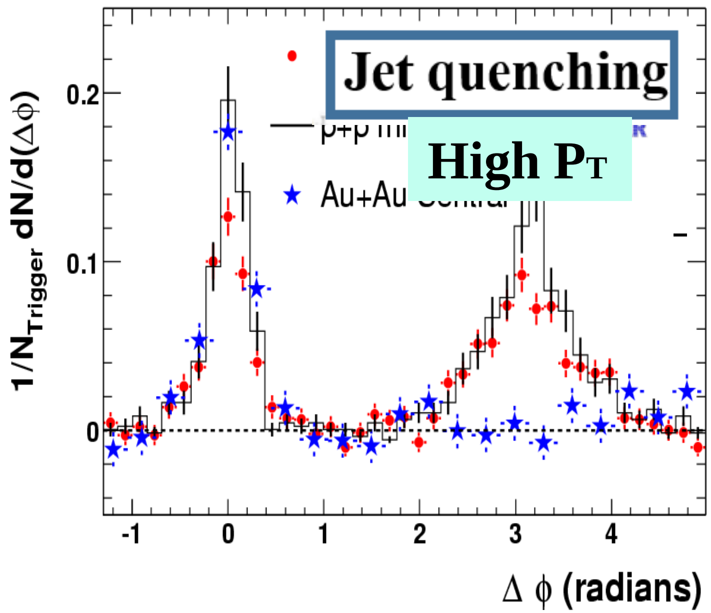
- P. Romatsc(…) J. C77 21(2017)

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

… … … …

Is QGP formed in the small systems?

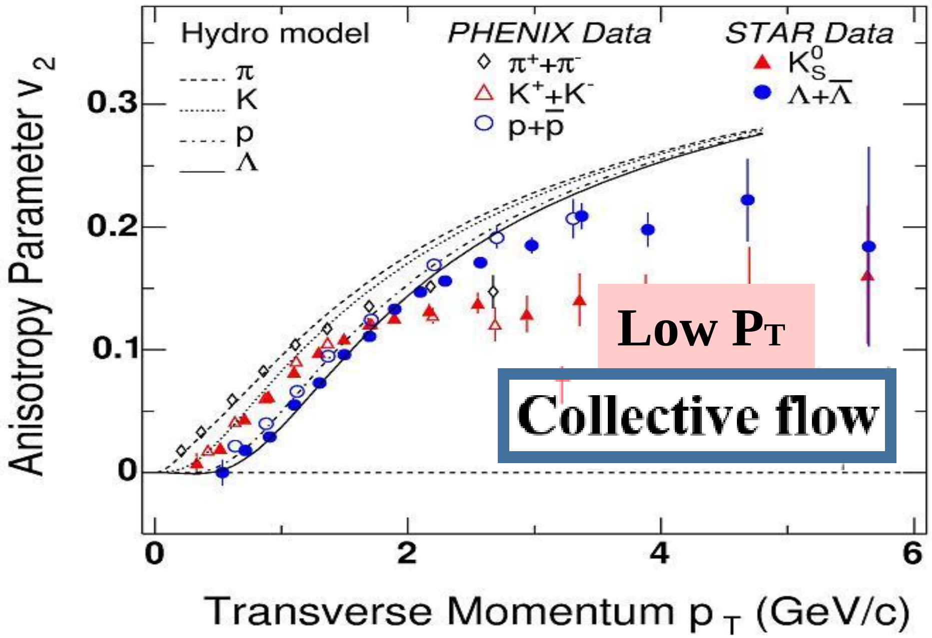
Reminder: QGP signals in large systems

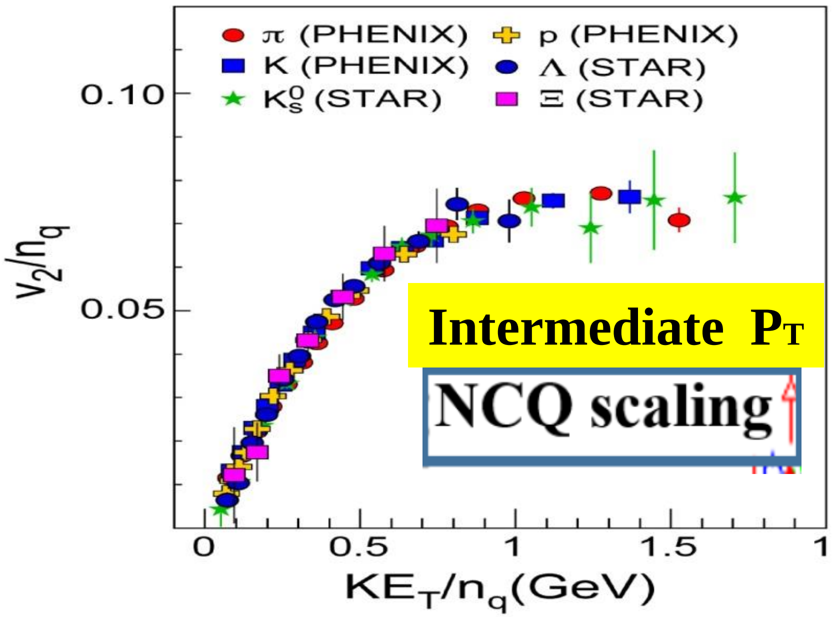


Au+Au / Pb+Pb

QGP was discovered @RHIC & LHC

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





QGP signals 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**）

.

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

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)

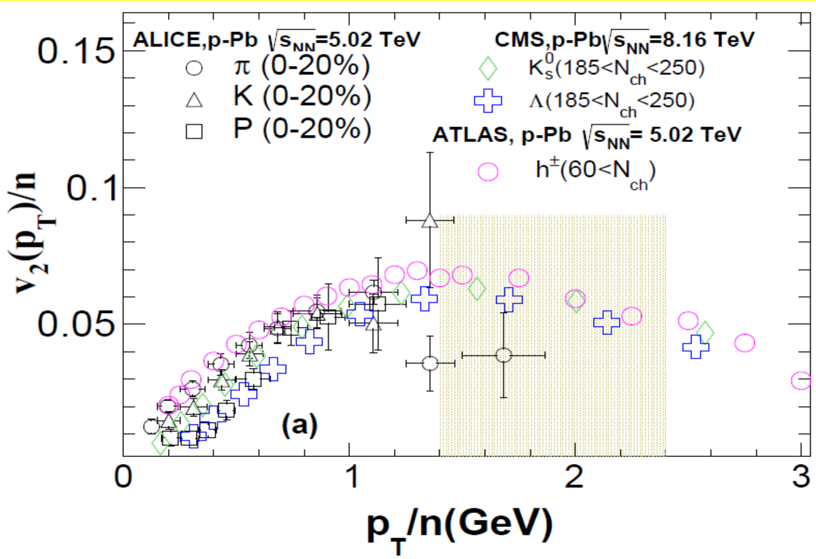
NCQ Scaling of V2:

-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).

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

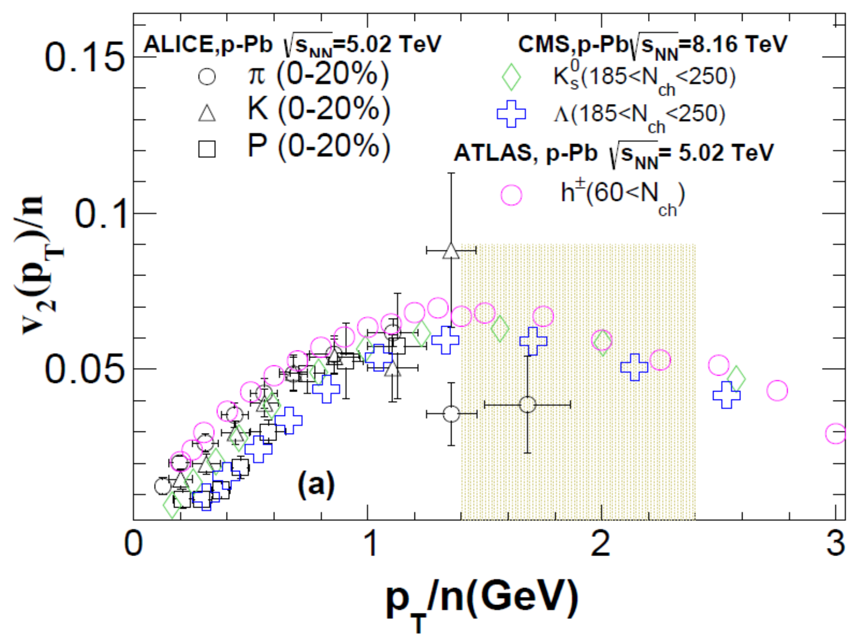
$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2)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

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):

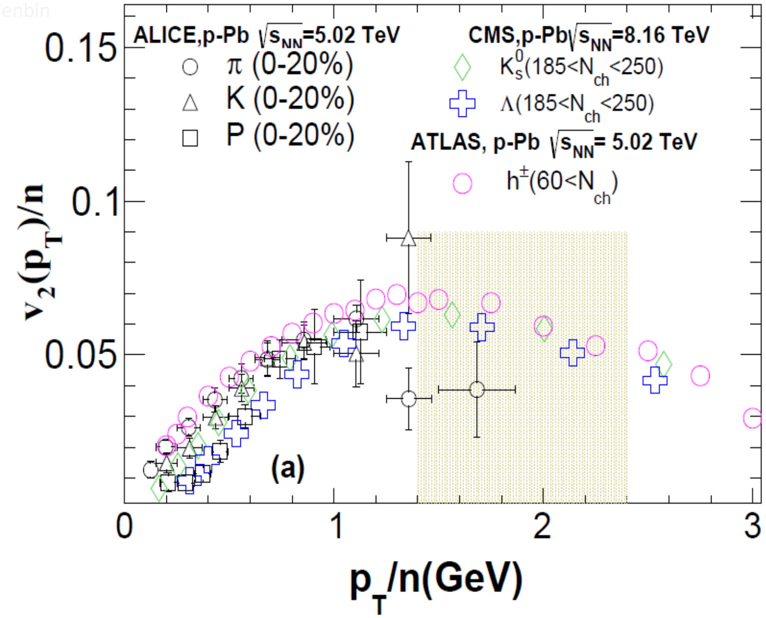
-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

Fragmentation hadrons (LBT):

-the remnant hard quarks feed to fragmentation .

UrQMD afterburner:

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



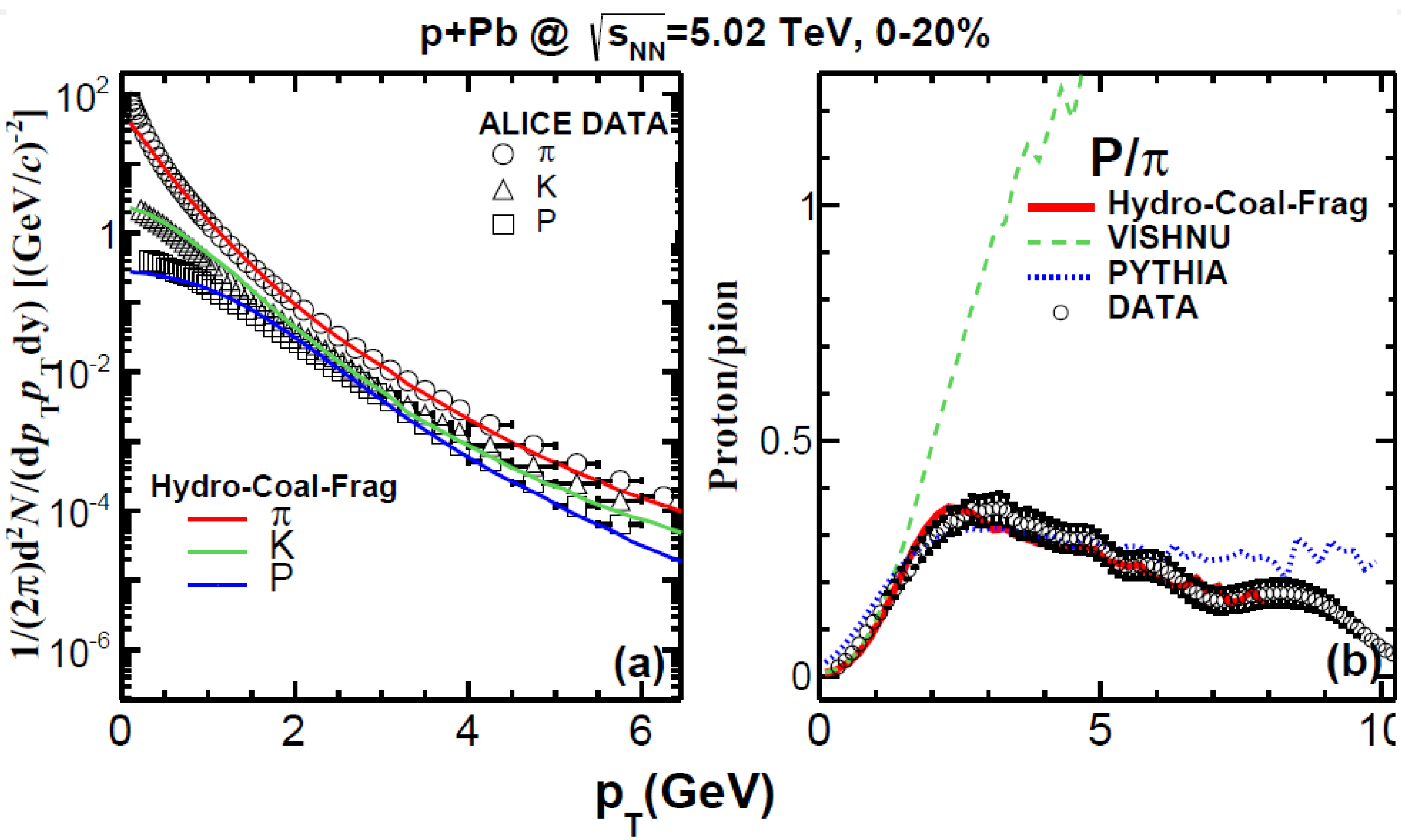
Main Parameters:

***-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

Spectra of pions, kaons and protons

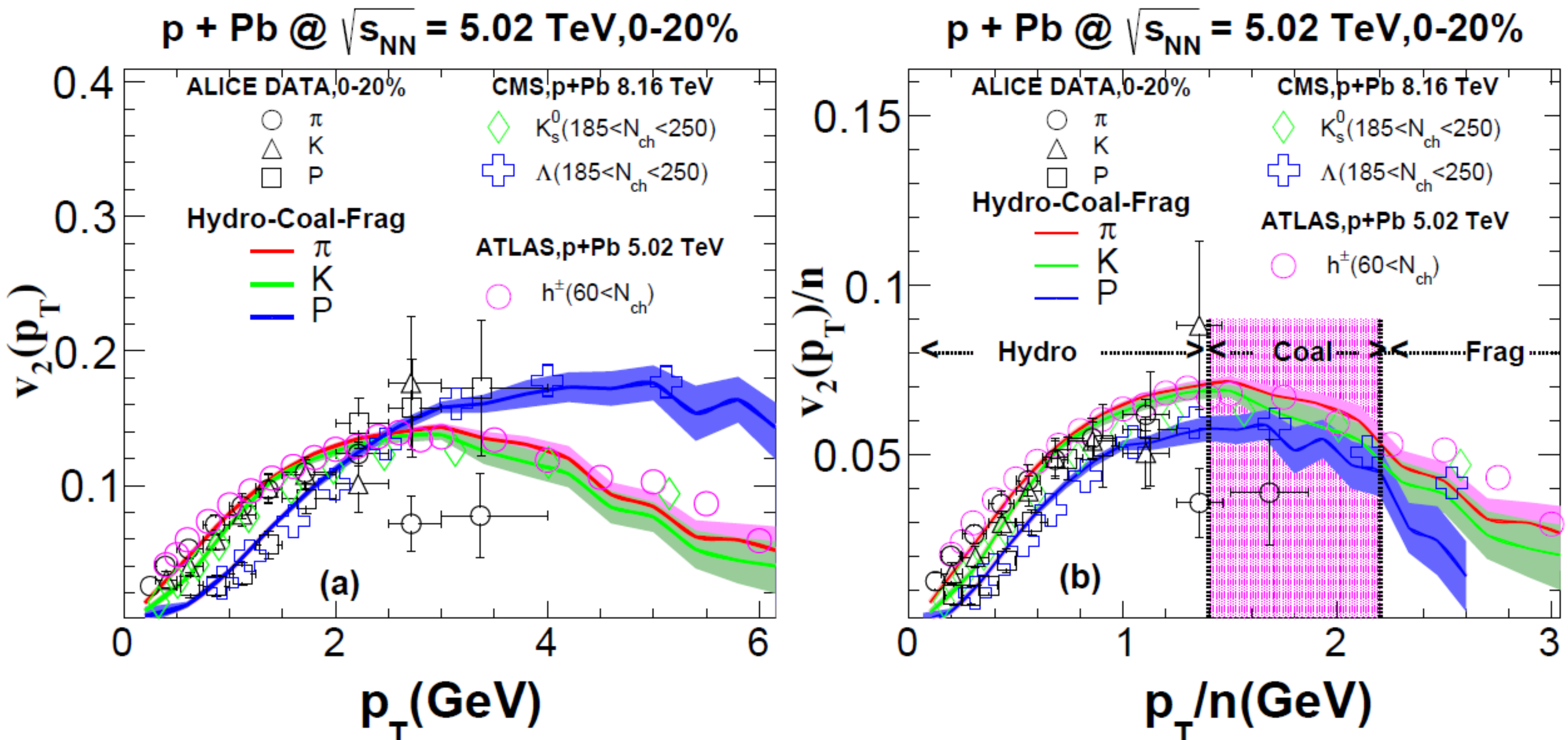


Our combined model, Hydro-Coal-Frag, gives a nice description of spectra of pion, kaon and proton as well as the P/π over p_T from 0 to 6 GeV.

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

Wenbin

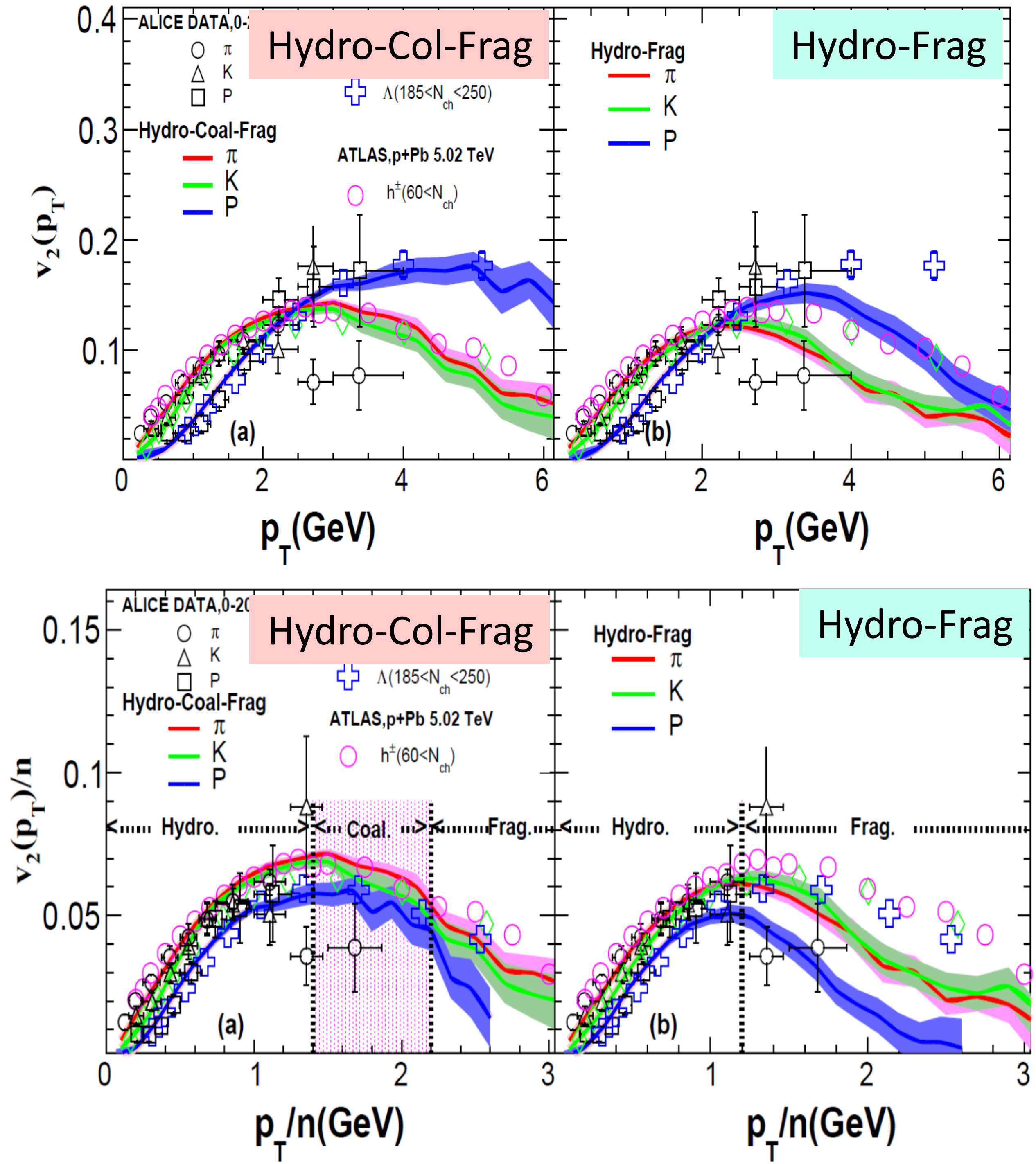
v2(pT) and NCQ scaling



-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).

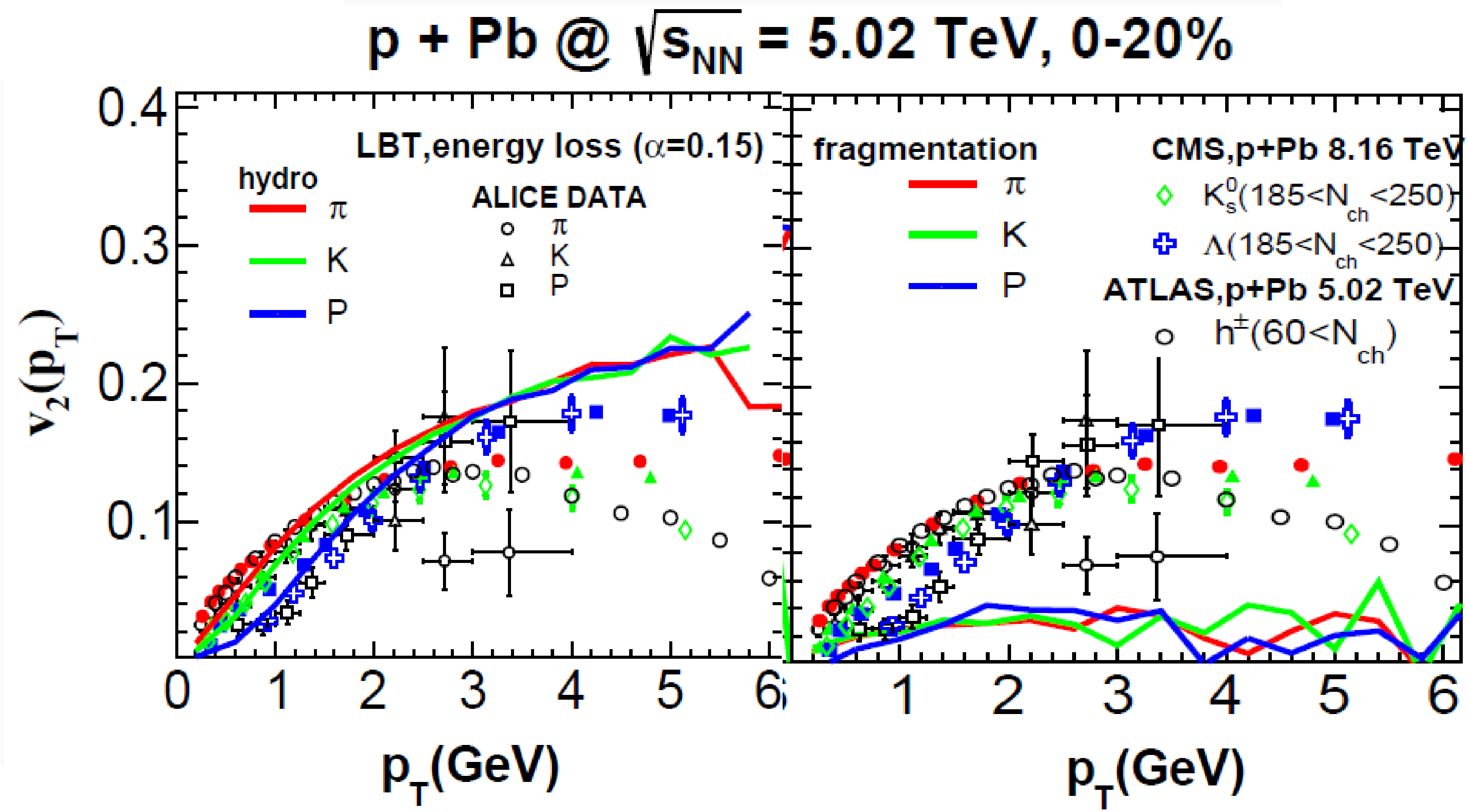


Zhao, Ko, Liu, Qin & Song,PRL 125 7 072301 (2020).

The importance of quark coalescence in p-Pb collisions

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

$v_2(P_T)$ from hydro or fragmentation alone



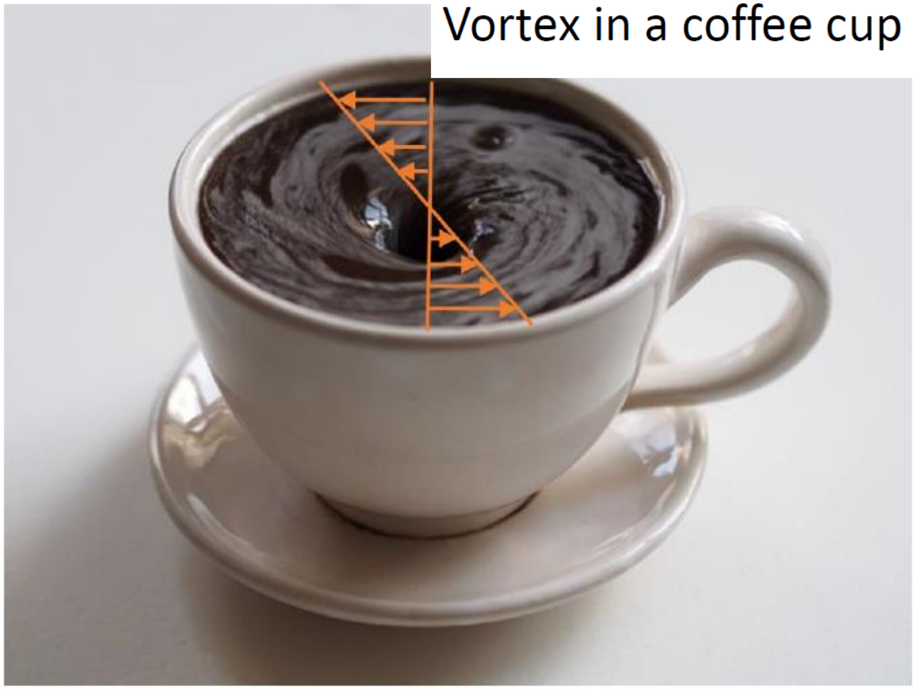
Hydro or Fragmentation alone can not describe v2(PT) in high multiplicy p-Pb colissions

Vorticity and spin polarization

What is vorticity

Non-Relativistic Case:

Vortex in a coffee cup

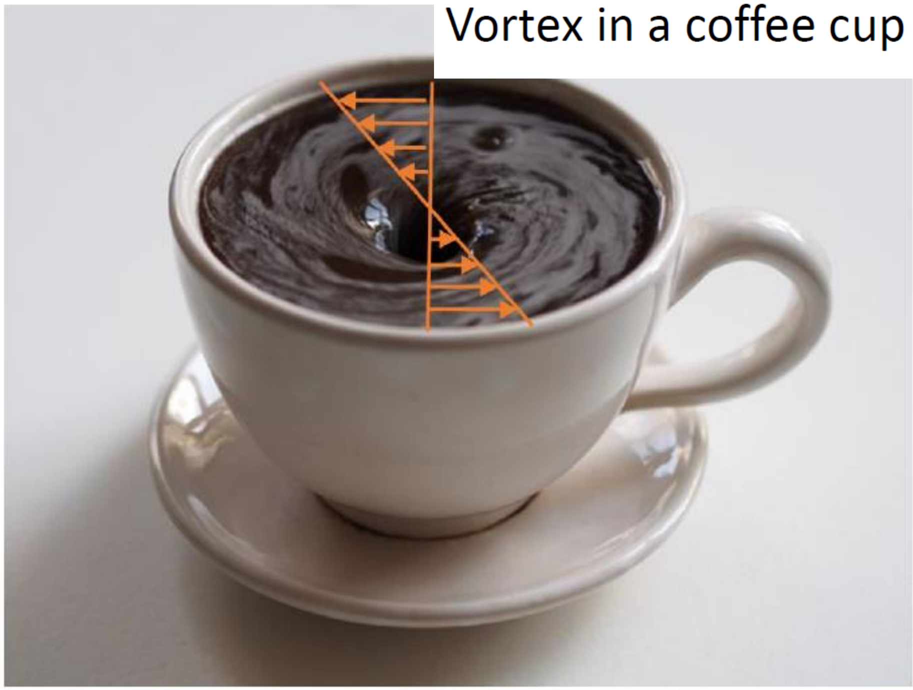


Fluid vorticity

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

(Local angular velocity)

Vorticity & spin polarization

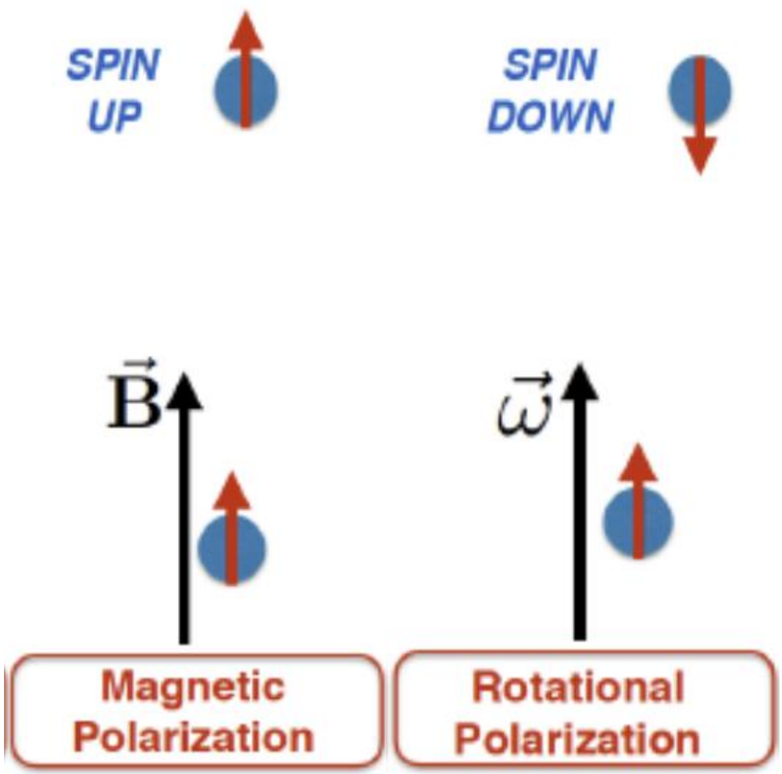


Fluid vorticity

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

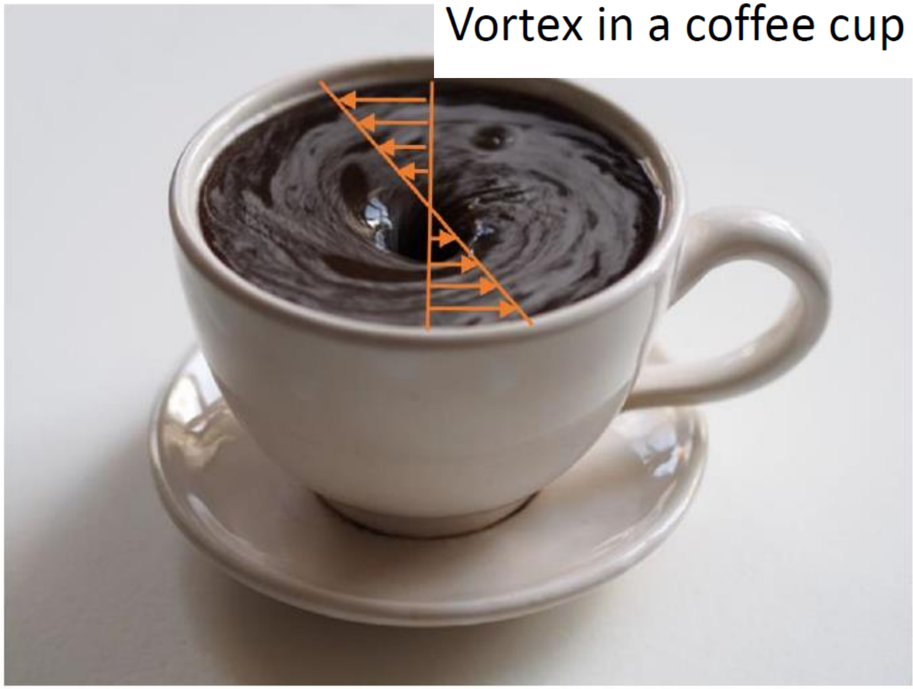
(Local angular velocity)

Non-Relativistic Case:



$$H = -\boldsymbol{\mu}_{\mathrm{B}} \cdot \boldsymbol{B} - \boldsymbol{S} \cdot \boldsymbol{\omega}$$

Vorticity & spin polarization

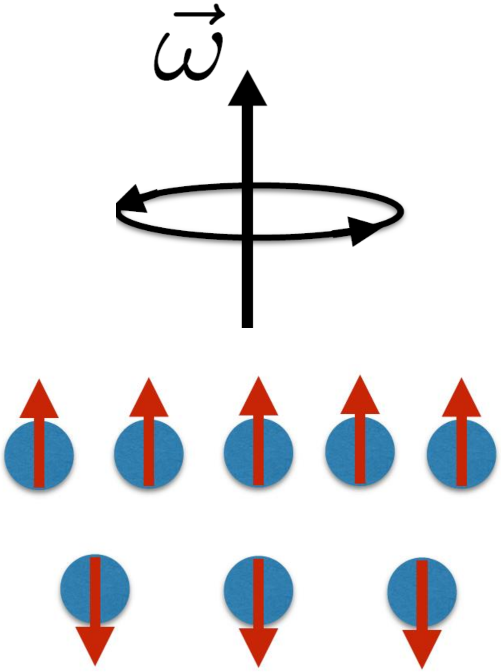


Fluid vorticity

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

(Local angular velocity)

Non-Relativistic Case:



$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S}$$

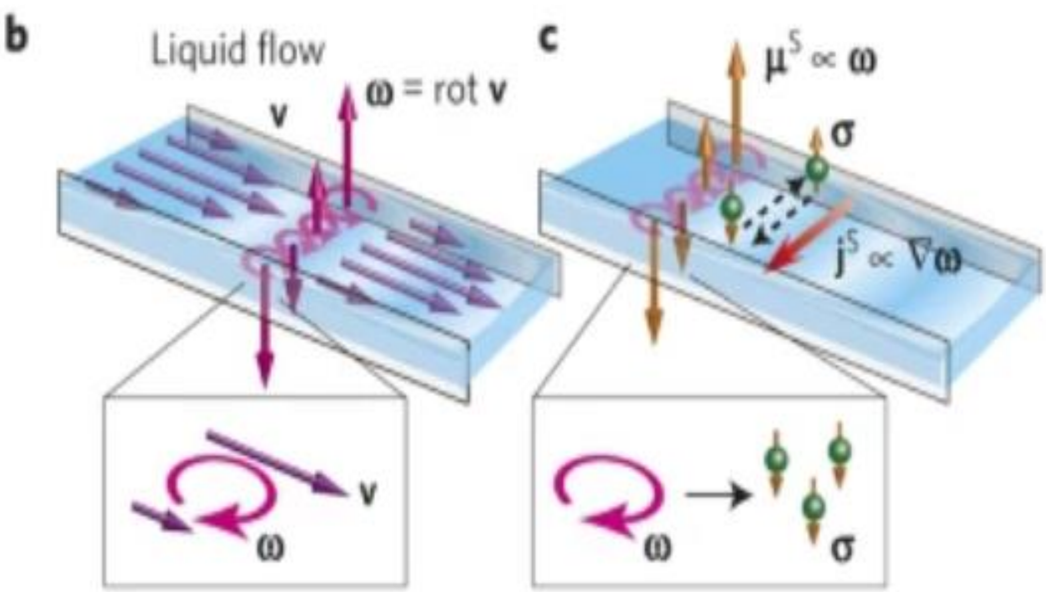
$$\frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega}\cdot\boldsymbol{S})/T}$$

Rotational Polarization in Condense Matter

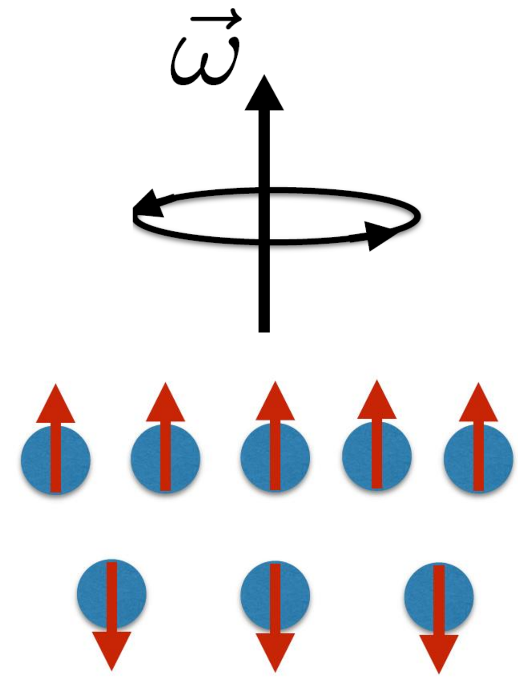
Spin hydrodynamic generation

R. Takahashi, M. Matsuo, M. Ono, K. Harii, H. Chudo, S. Okayasu, J. Ieda, S. Takahashi, S. Maekawa & E. Saitoh

Nature Physics **12**, 52–56(2016) | Cite this article



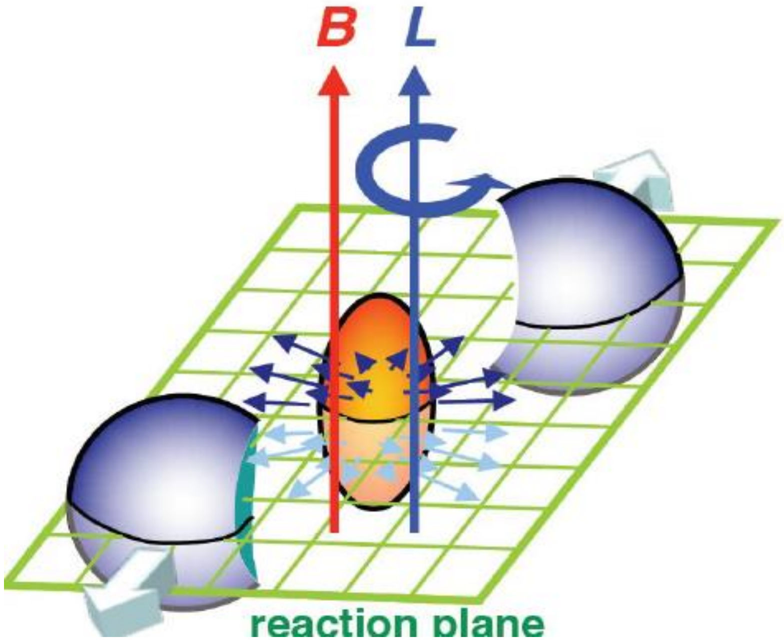
Non-Relativistic Case:

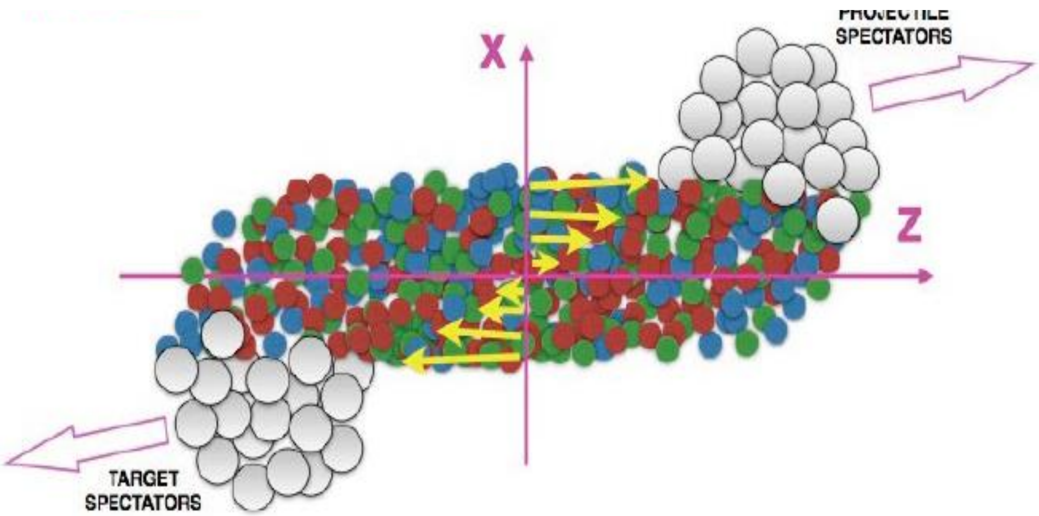


$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S}$$

$$\frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S})/T}$$

Vorticity in relativistic heavy ion collisions





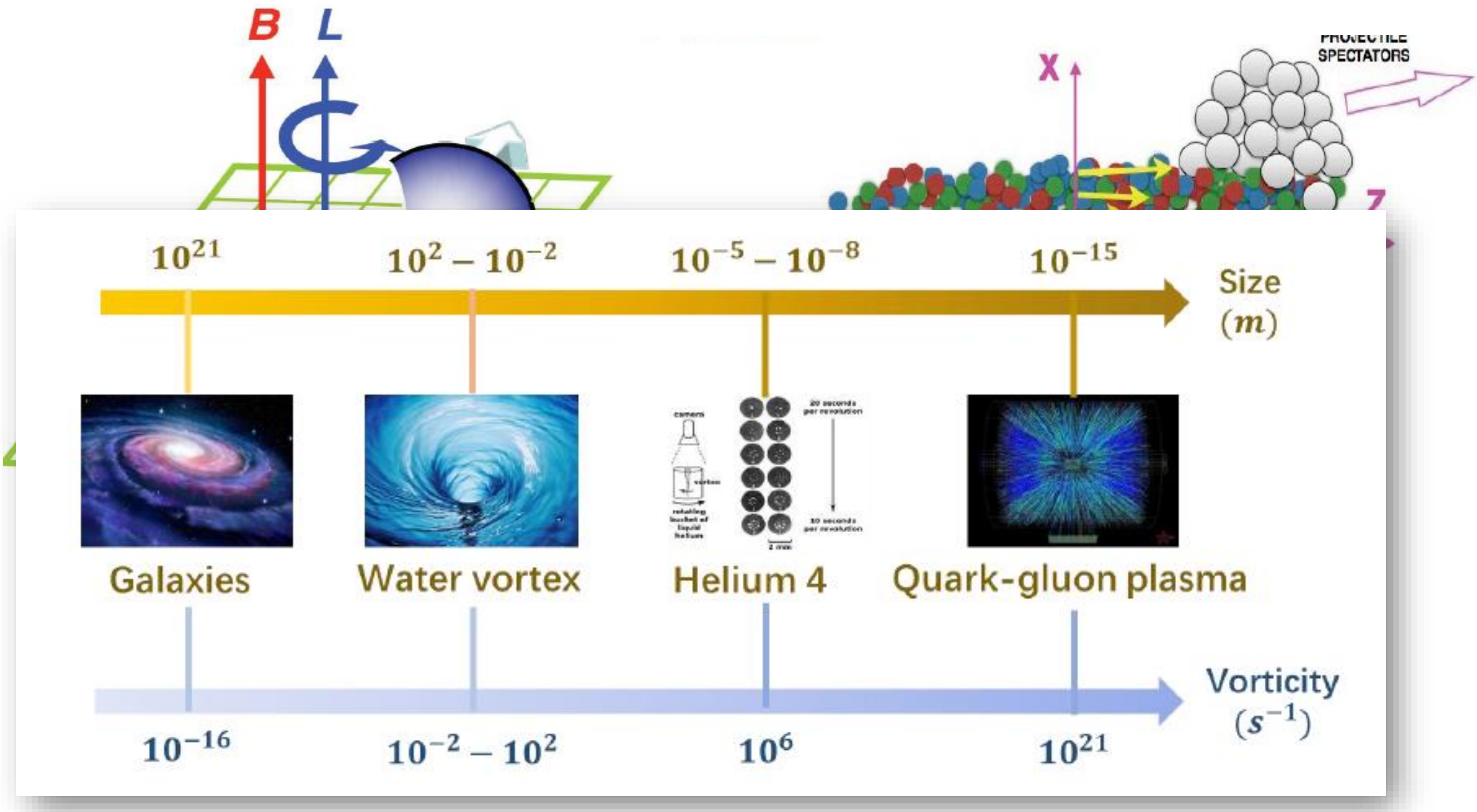
$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

very large global angular momentum

$$eB \sim \gamma \alpha_{\text{EM}} \frac{Z}{b^2} \sim 10^{18}\ \text{G}$$

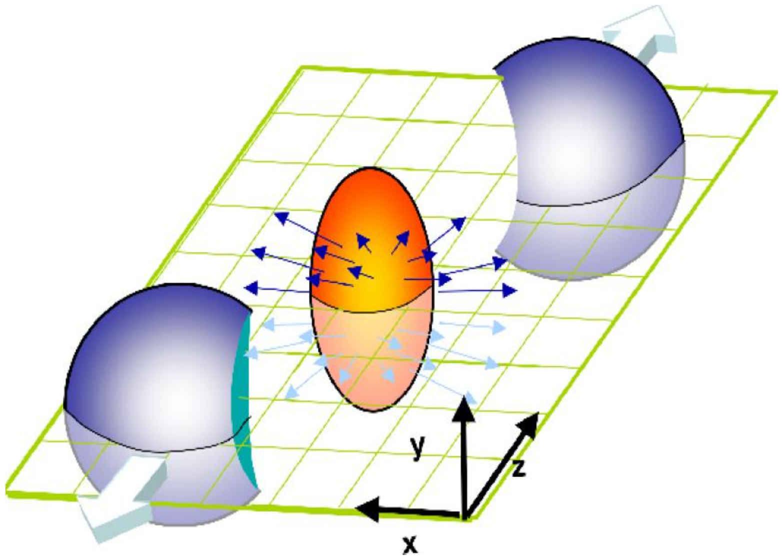
strong magnetic field

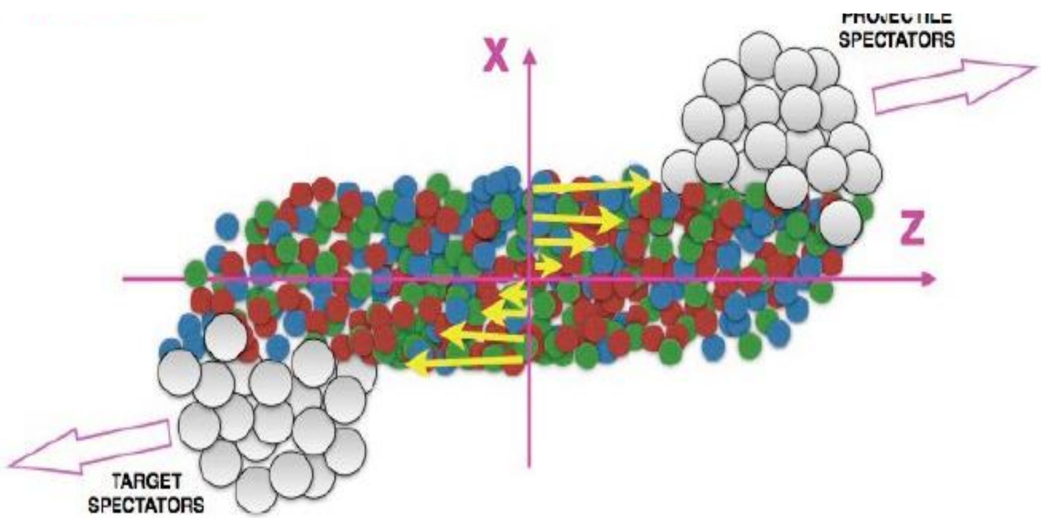
Vorticity in relativistic heavy ion collisions



QGP: smallest but most vortical fluid

Vorticity in relativistic heavy ion collisions





Non-Relativistic illustration:

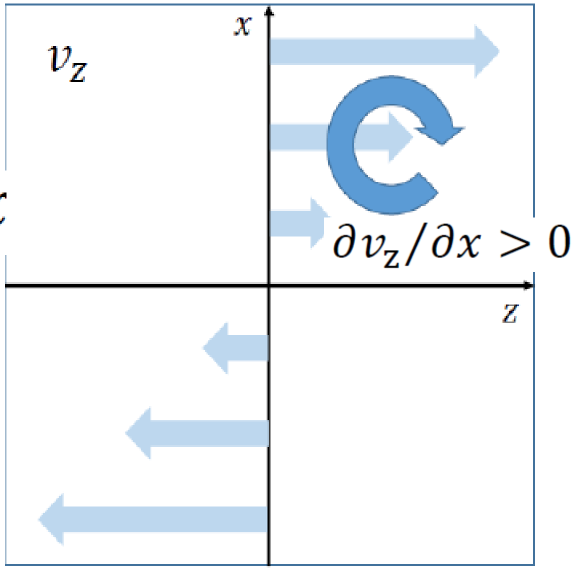
$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

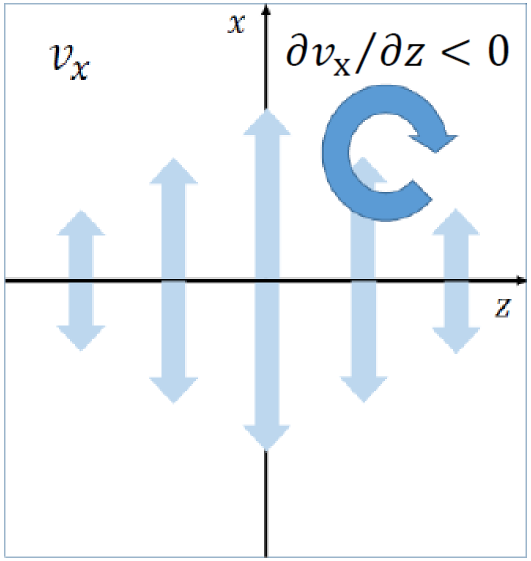
$$\omega_y = \partial v_x/\partial z - \partial v_z/\partial x$$

$$\omega_y < 0$$

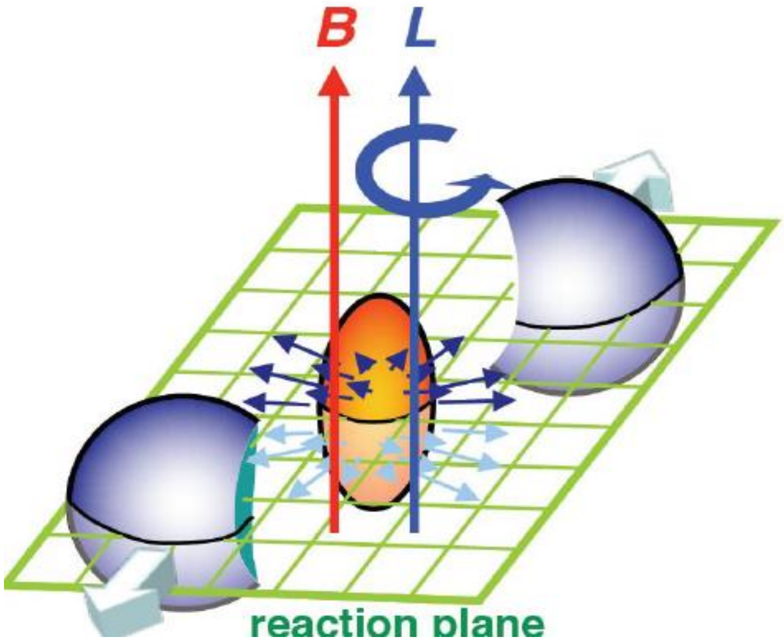
$$\longrightarrow P_y < 0$$

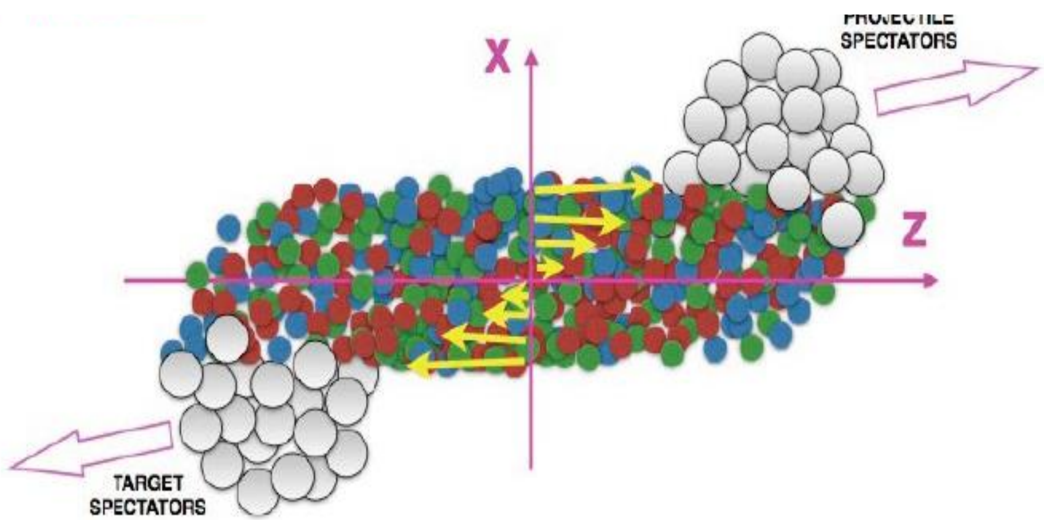
Global polarization





Global angular momentum & global polarization





The earlier but very pioneering work:

Global polarization of Λ and spin alignment of vector mesons from spin-orbital coupling

Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94 (2005) 102301, Phys.Lett.B 629 (2005) 20-26

Motivate the spin polarization measurements in experiments!

Spin-orbital coupling

Global quark polarization

Final hadron polarization
(recombination/fragmentation)

Global polarization measurements in heavy ion collisions

'self-analyzing' of hyperon

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\mathrm{H}} \mathbf{P}_{\mathrm{H}} \cdot \mathbf{p}_{\mathbf{p}}^*)$$

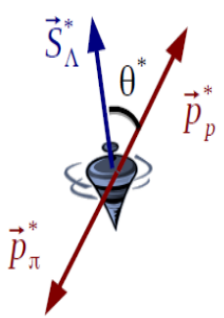
P_H: Λ polarization

p_p^*: proton momentum in the Λ rest frame

α_H: Λ decay parameter

α_Λ=0.642±0.013 → α_Λ=0.732±0.014

P.A. Zyla et al. (PDG), PTEP2020.083C01



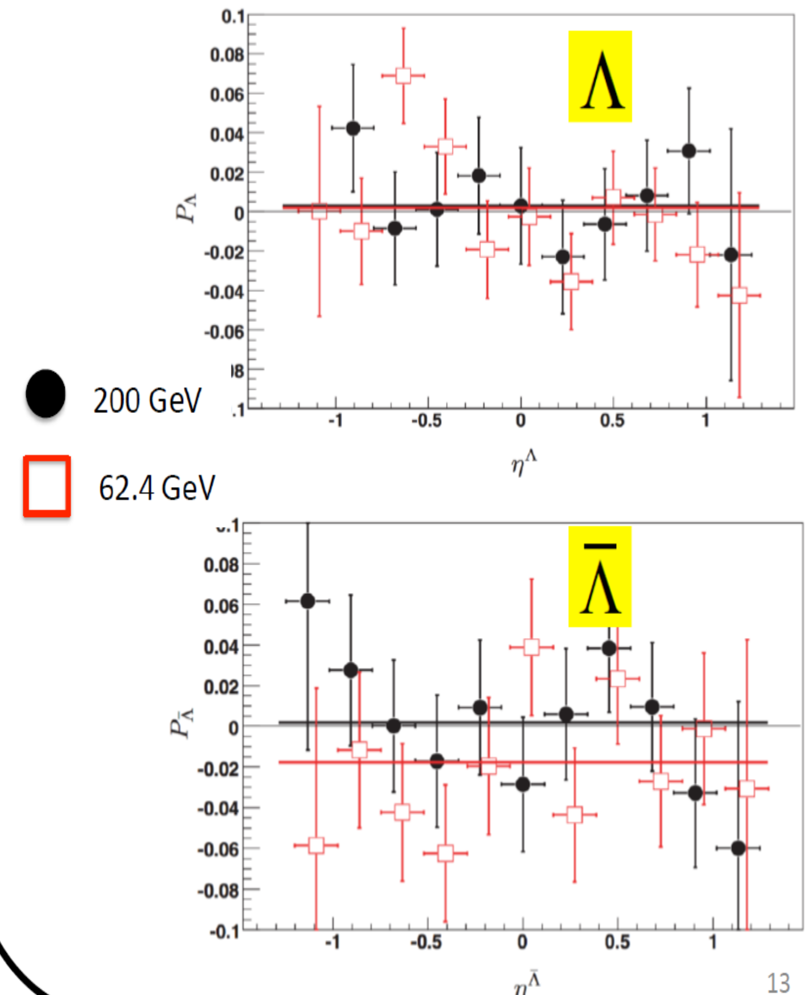
$$\Lambda \to p + \pi^-$$

(BR: 63.9%, cτ~7.9 cm)

S. Voloshin and T. Niida, PRC 94.021904 (2016)

No signal at high energy

Phys. Rev. C **76**, 024915 (2007)



Global polarization measurements in heavy ion collisions

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$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)$$

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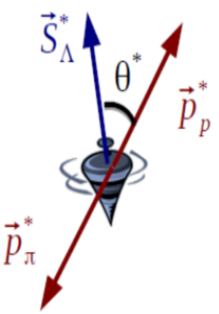


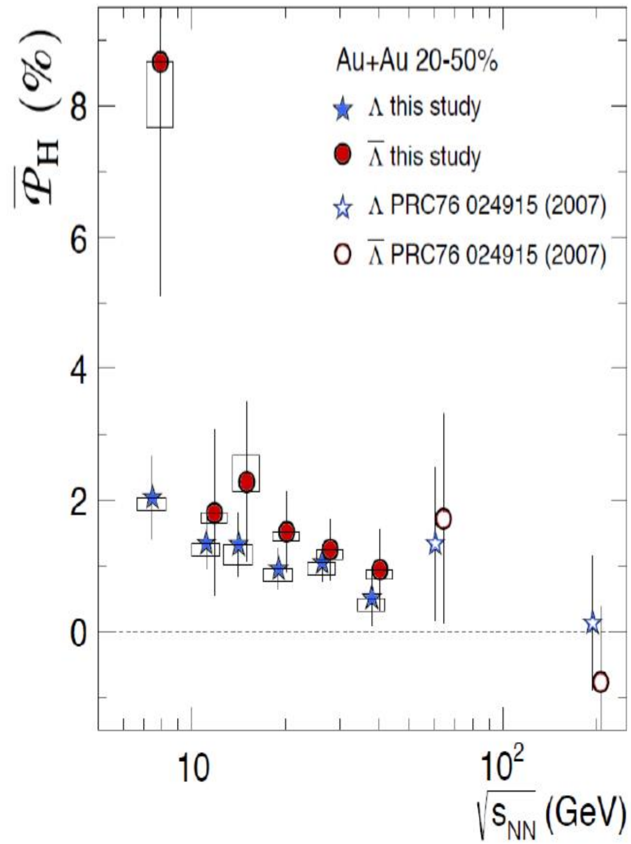
$$\Lambda \rightarrow p + \pi^-$$

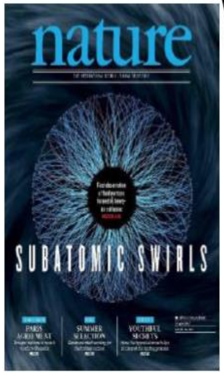
(BR: 63.9%, cτ~7.9 cm)

S. Voloshin and T. Niida, PRC 94.021904 (2016)

Most vortical fluid!

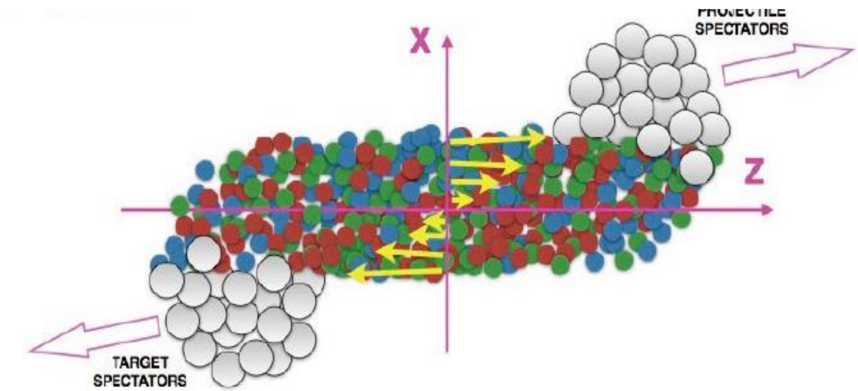
STAR Collaboration, Nature 548, 62 (2017)





$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22} s^{-1}$$

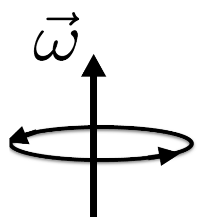
Theoretical frameworks: thermal vorticity & polarization

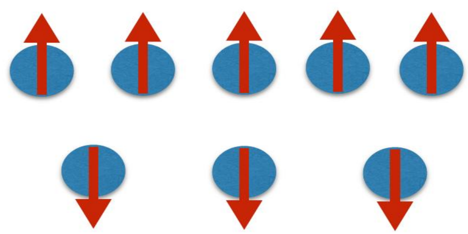


Non-Relativistic case:

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

Landau & Lifshitz, Statistical Physics





$$H = H_0 - \boldsymbol{\omega}\cdot\boldsymbol{S} \qquad \frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega}\cdot\boldsymbol{S})/T}$$

$$\langle \vec{\omega}_{\mathrm{QGP}} \rangle \| \vec{L}_{\mathrm{QGP}} \Rightarrow \langle \vec{S}_{\vec{\omega};\,\mathrm{hadrons}} \rangle \| \vec{L}_{\mathrm{QGP}}$$

Relativistic case:

F. Becattini, et al. Annal Phys. 338 32 (2013)

Thermal vorticity:

$$\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right) \qquad \beta_\mu = u_\mu / T$$

Spin polarization:

$$S^\mu(x,p) = -\frac{1}{2m}\frac{S(S+1)}{3}\left[1 - f(x,p)\right]\epsilon^{\mu\nu\rho\sigma} p_\sigma \varpi_{\nu\rho}$$

global equil. → local equil.

Spin polarization in hydro:

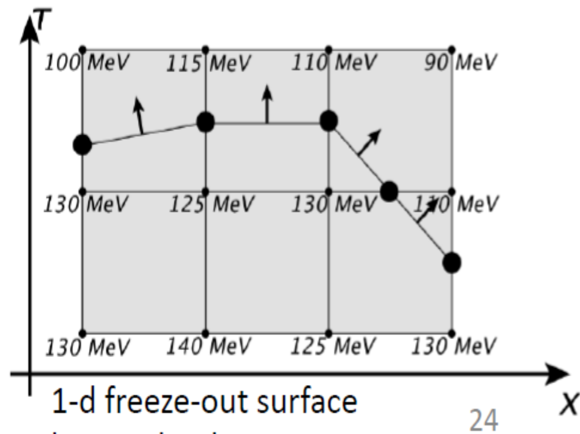
$$S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p) \langle S(x,p) \rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}$$

Integration on freeze-out surface

From thermal vorticity to polarization within hydrodynamics

AMPT → MUSIC → Freeze-out surface → iSS → UrQMD

'Spin Cooper-Frye' formula



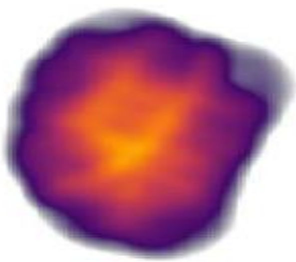
Polarization from hydrodynamics

$$S^{\mu}(p) = \frac{\int d\Sigma_{\lambda} p^{\lambda} f(x,p) \langle S(x,p) \rangle}{\int d\Sigma_{\lambda} p^{\lambda} f(x,p)}$$

$$S^{\mu}(x,p) = -\frac{1}{2m}\frac{S(S+1)}{3}[1-f(x,p)]\epsilon^{\mu\nu\rho\sigma} p_{\sigma} \varpi_{\nu\rho}$$

Boost to particle rest frame

$$\boldsymbol{S}^{*} = \boldsymbol{S} - \frac{\boldsymbol{p}\cdot\boldsymbol{S}}{E(E+m)}\boldsymbol{p}$$



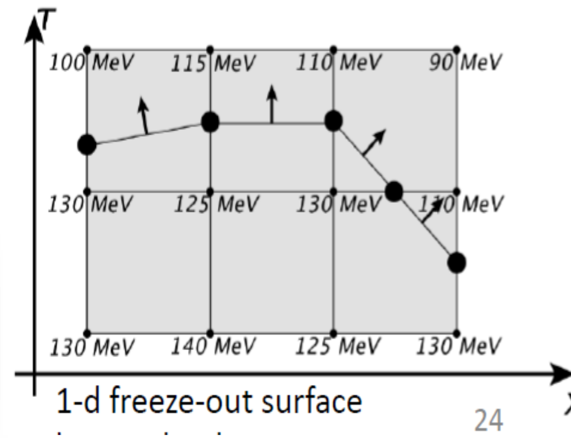
velocity fields: $u_{\mu}(x)$ → Collective flow

velocity gradients (vorticity) $\partial_{\mu} u_{\nu}(x)$ → Spin polarization

From thermal vorticity to polarization within hydrodynamics

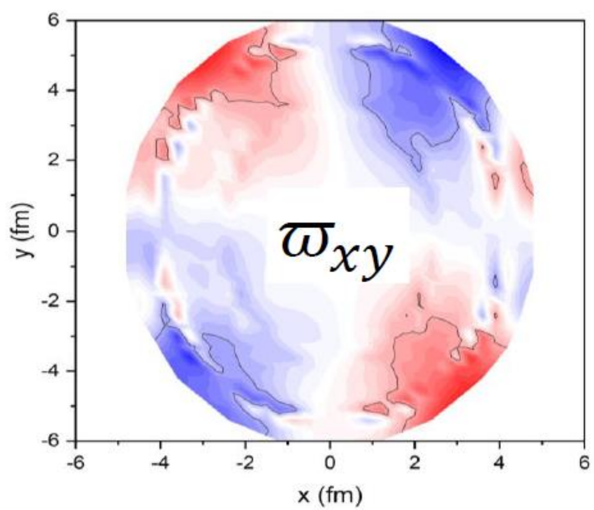
AMPT → MUSIC → Freeze-out surface → iSS → UrQMD

'Spin Cooper-Frye' formula

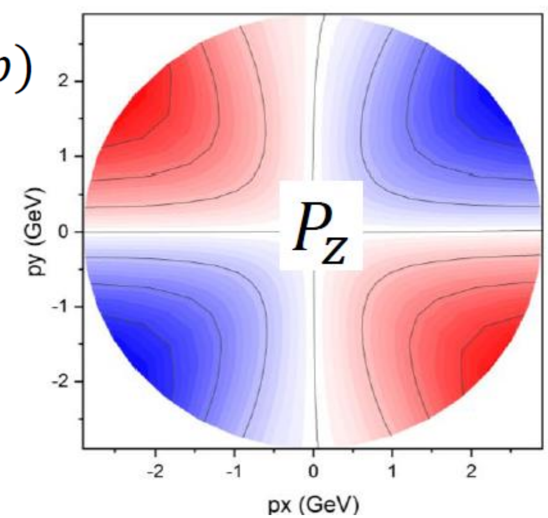


Polarization from hydrodynamics

$$S^{\mu}(p) = \frac{\int d\Sigma_{\lambda} p^{\lambda} f(x,p) \langle S(x,p) \rangle}{\int d\Sigma_{\lambda} p^{\lambda} f(x,p)}$$

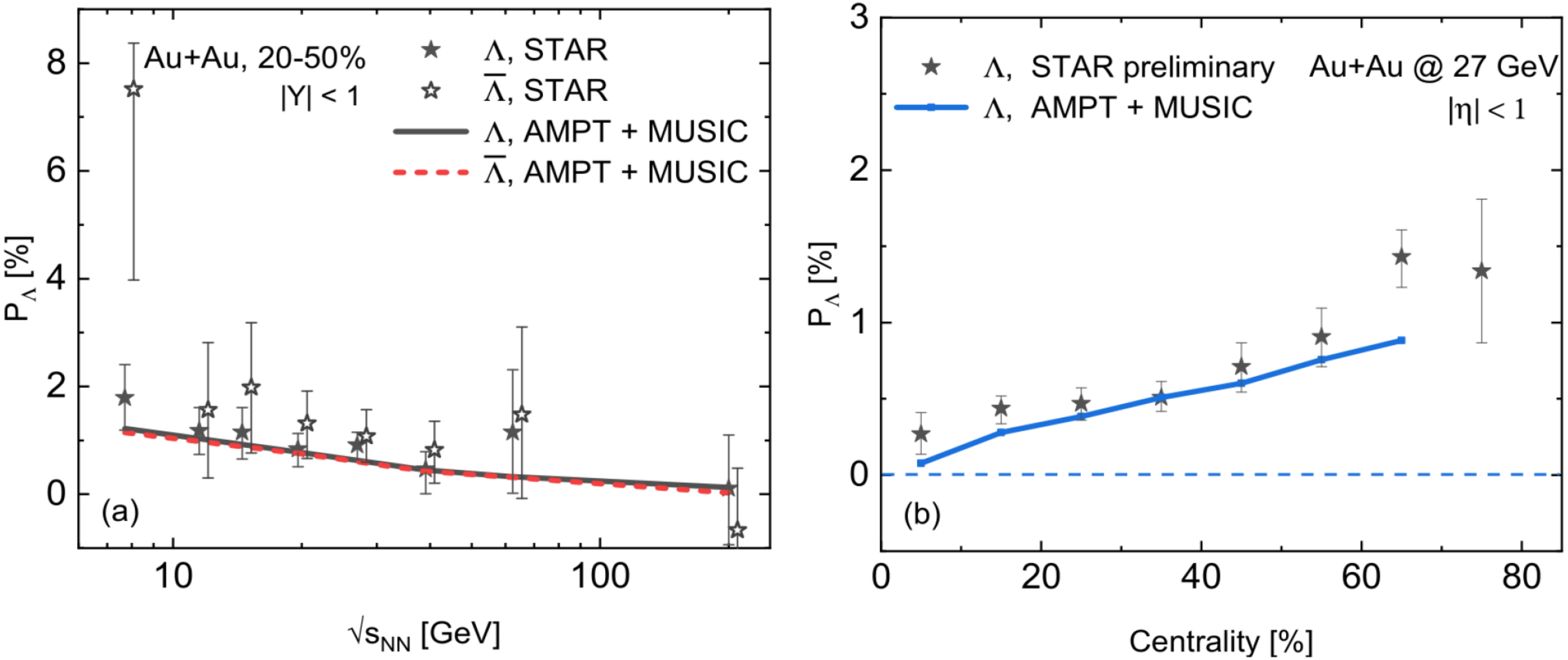


A mapping: $\varpi_{\mu\nu}(x) \rightarrow P^{\mu}(p)$



Global Λ Polarization from Hydro

B. Fu, K. Xu, X-G, Huang, H. Song, Phys.Rev.C103 2, 024903 (2021)



$$P^{\mu} = \langle P^{\mu}(p) \rangle = \frac{\int \frac{d^3p}{E} \int d\Sigma_{\nu} p^{\nu} f(x,p) P^{\mu}(x,p)}{\int \frac{d^3p}{E} \int d\Sigma_{\nu} p^{\nu} f(x,p)}$$

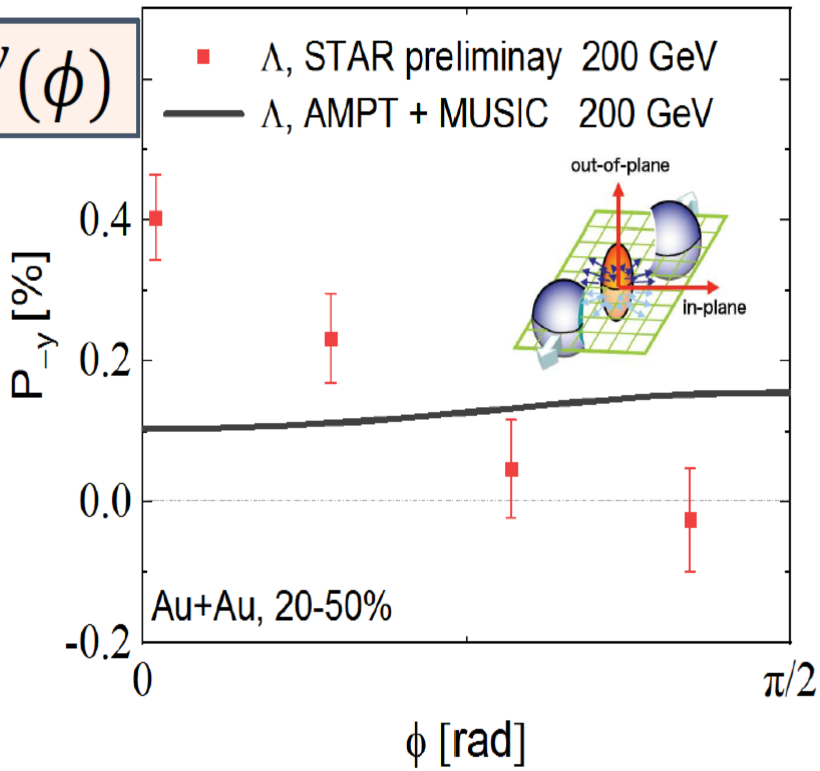
-Decrease with the collision energy; increase with centrality;

-Roughly describe the data within error bars

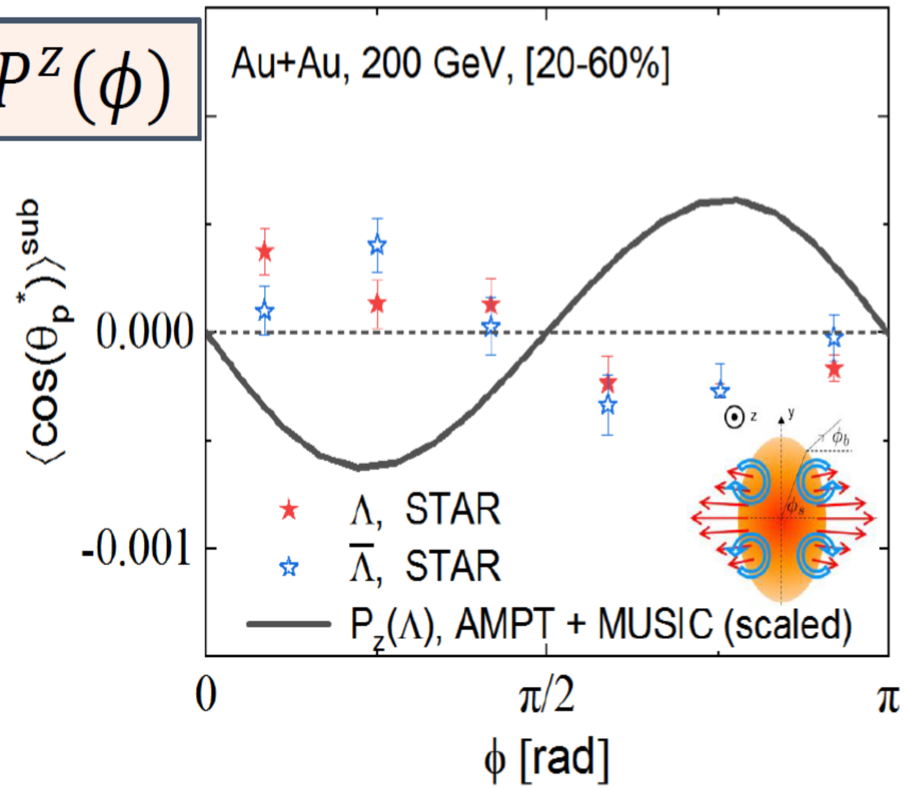
Local Λ Polarization from Hydro

B. Fu, K. Xu, X-G, Huang, H. Song, Phys.Rev.C103 2, 024903 (2021)

$P^y(\phi)$



$P^z(\phi)$



Different trend/sign in $P_y(\phi)$ and $P_z(\phi)$ results

-Local Λ Polarization Puzzle !

See also:

Karpenko, Becattini, EPJC 77 (2017) 4, 213

D. Wei, et al., PRC 99 (2019) 014905

X. Xia, et al., PRC 98 (2018) 024905

Becattini, Karpenko, PRL 120 (2018) 012302

Efforts to resolve the 'sign puzzle'

- Feed-down effects (Xia, Li, Huang, Huang, PRC 2019, Becattini, Cao, Speranza, EPJC 2019) **[no obvious influence]**
- Other spin chemical potential (Wu, Pang, Huang, Wang, PRR 2019) **[extra assumption]**
- Polarization from projected thermal vorticity (Florkowski, Kumar, Ryblewski, Mazeliauskas, PRC 2019) **[extra assumption]**
- Side-jump in CKT (Liu, Ko, Sun, PRL 2019) **[massless limit]**
- Spin as a dynamical d.o.f: **[under developing]**

  spin hydrodynamics (Florkowski, et al., PRC2017, Hattori, et al., PLB 2019, Shi, et al, PRC 2021, …)

  spin kinetic theory (Gao and Liang, PRD 2019, Weickgenannt ,et al PRD 2019, Hattori, et al PRD 2019, Wang, et al, PRD 2019, Liu, et al, CPC 2020, Hattori, et al, PRD 2019, …)
- Final hadronic interactions (Xie and Csernai, ECT talk 2020, Csernai, Kapusta, Welle, PRC 2019)
- …

Re-evaluate spin cooper fryer formular in hydrodynamics

spin cooper-fryer formula (traditional)

$$S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p)\langle S(x,p)\rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}$$

F. Becattini, et al. Annals Phys. 338 32 (2013)

$$S^\mu(x,p) = -\frac{1}{2m}\frac{S(S+1)}{3}[1-f(x,p)]\epsilon^{\mu\nu\rho\sigma}p_\sigma\varpi_{\nu\rho}$$

$$\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu\right) \qquad \beta_\mu = u_\mu/T$$

Hydrodynamic gradients

$\partial_\mu u_\nu(x)$

Anti-symmetric: vorticity

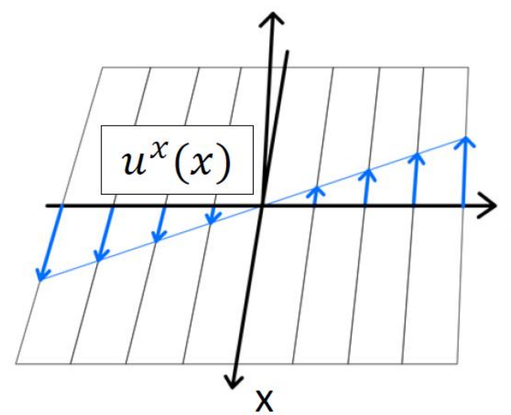
$$\omega^\mu = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}u_\nu\partial_\alpha^\perp u_\beta$$

traditional spin cooper-fryer formula

Symmetric: shear stress

$$\sigma^{\mu\nu} = \frac{1}{2}\left(\partial_\perp^\mu u^\nu + \partial_\perp^\nu u^\mu\right) - \frac{1}{3}\Delta^{\mu\nu}\partial_\perp\cdot u$$

?



[Strain induced polarization]
In **crystal physics**:

Crooker and Smith, **PRL** (2005) 94, 236601

Kissikov, et al., **Nature Comm.** (2018) 9, 1058

Shear Induced Polarization

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

Axial Wigner fu[n…]

$$\mathcal{A}^\mu = \sum_\lambda \left(\lambda p^{\mu} \ldots \right.$$

Expand $\mathcal{A}^\mu$ to …

To one-loop order (in charge neutral fluid)

$$\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial_\alpha (\beta u)_\lambda$$

Thermal vorticity

$$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu(\beta u_\mu) - \partial_\mu(\beta u_\nu))$$

$$\mathcal{A}^\mu = \frac{1}{2}\beta n_0(1-n_0)\left\{\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial^\perp_\alpha u_\lambda + 2\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha \left[\beta^{-1}(\partial_\lambda \beta)\right] - 2\frac{p_\perp^2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho} u_\nu Q_\alpha^{\ \lambda} \sigma_{\rho\lambda}\right\}$$

Vorticity — T gradient (spin Nernst effect) — Shear strength

Total P^μ = [Vorticity] + [T gradient] + [Shear]

Total P^μ = [Thermal vorticity] + [Shear]

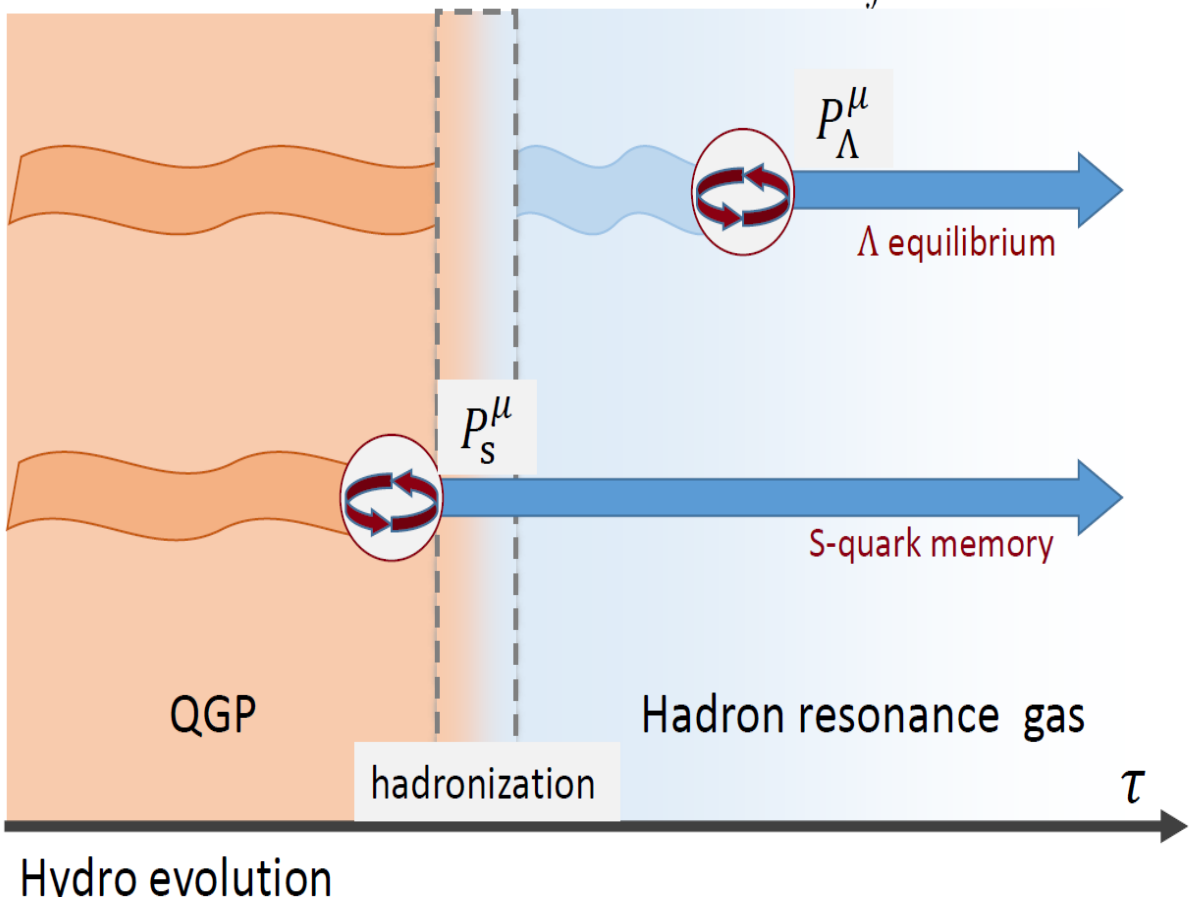
The only new effect

Similar result obtained independently by
Becattini, Buzzegoli, Palermo, arXiv: 2103.10917

‘Λ equilibrium’ vs. ‘S-quark memory’

BF, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

Spin Cooper-Frye: $$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x, \boldsymbol{p}; m)}{2m \int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)}$$



‘Λ equilibrium’

$\tau_{\text{spin},\Lambda} \to 0$

Polarization of Λ-hyperon

$P^\mu_\Lambda(p)$

F. Becattini (2013)
and later hydrodynamic(transport) calculations

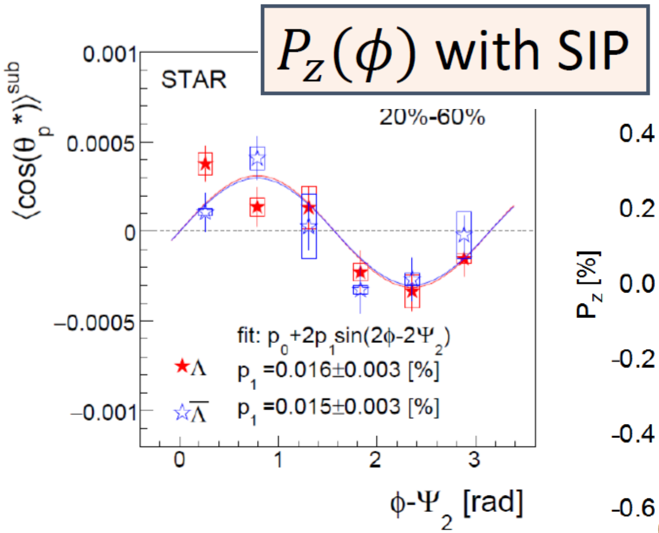
‘S-quark memory’

$\tau_{\text{spin},\Lambda} \to \infty$

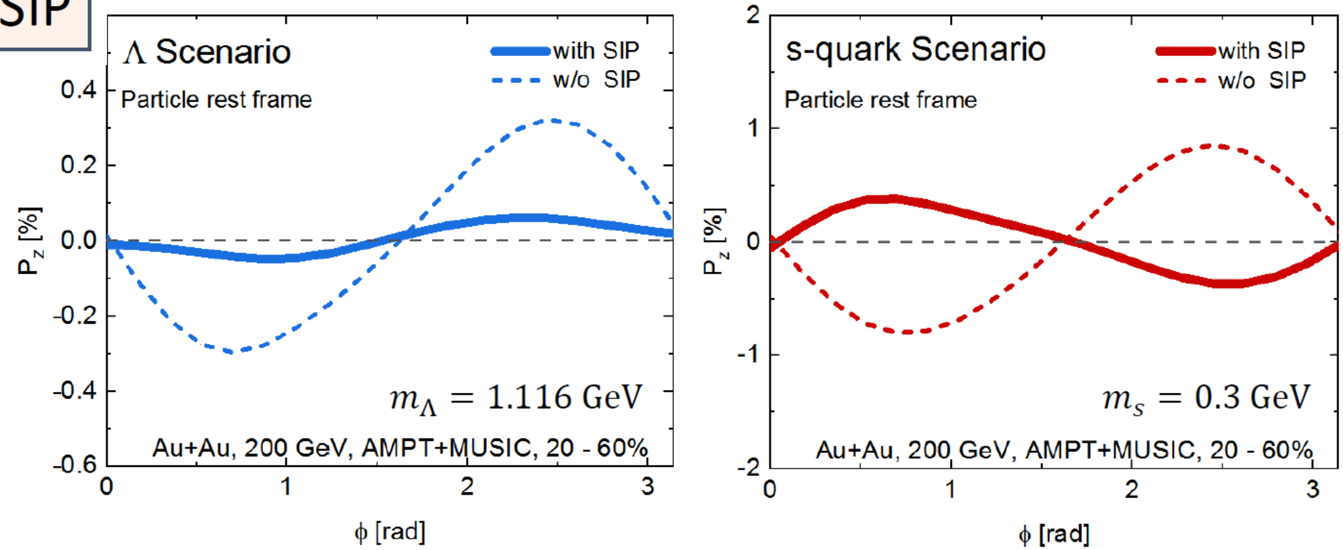
Polarization of S-quark

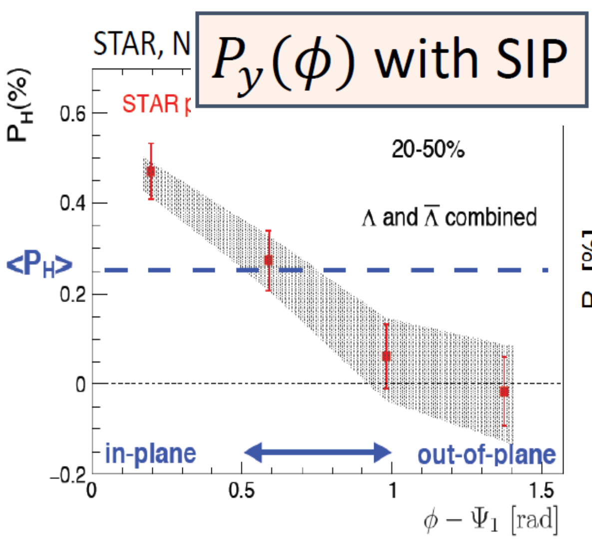
$P^\mu_\Lambda(p) = P^\mu_s(p)$

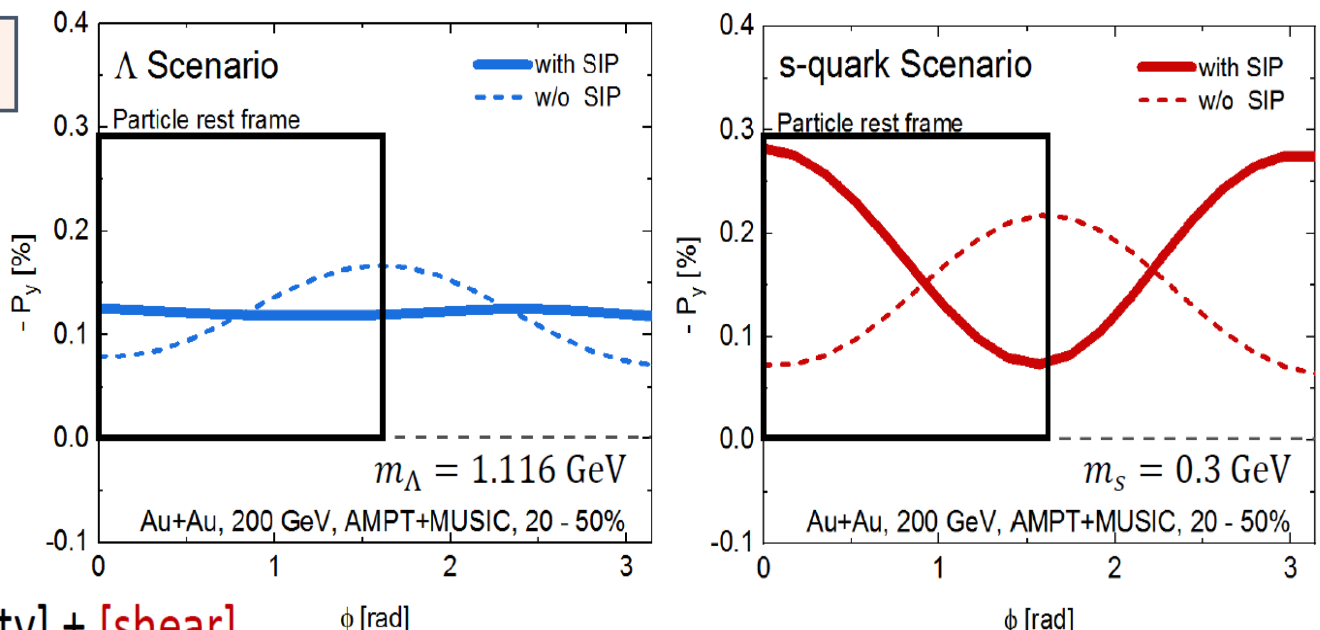
Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301



STAR, Phys.Rev.Lett. 123 (2019) 132301



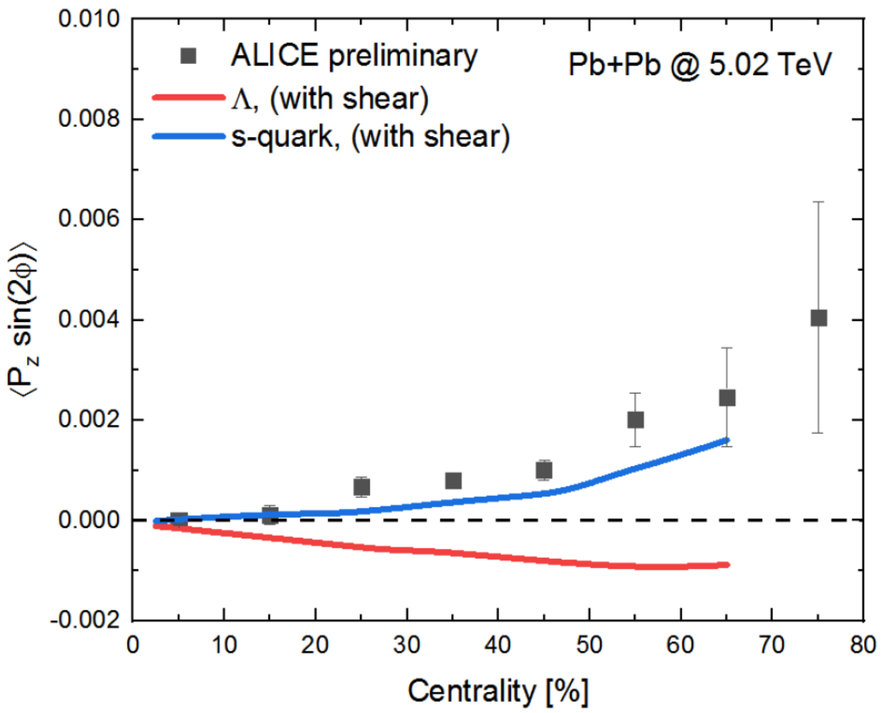


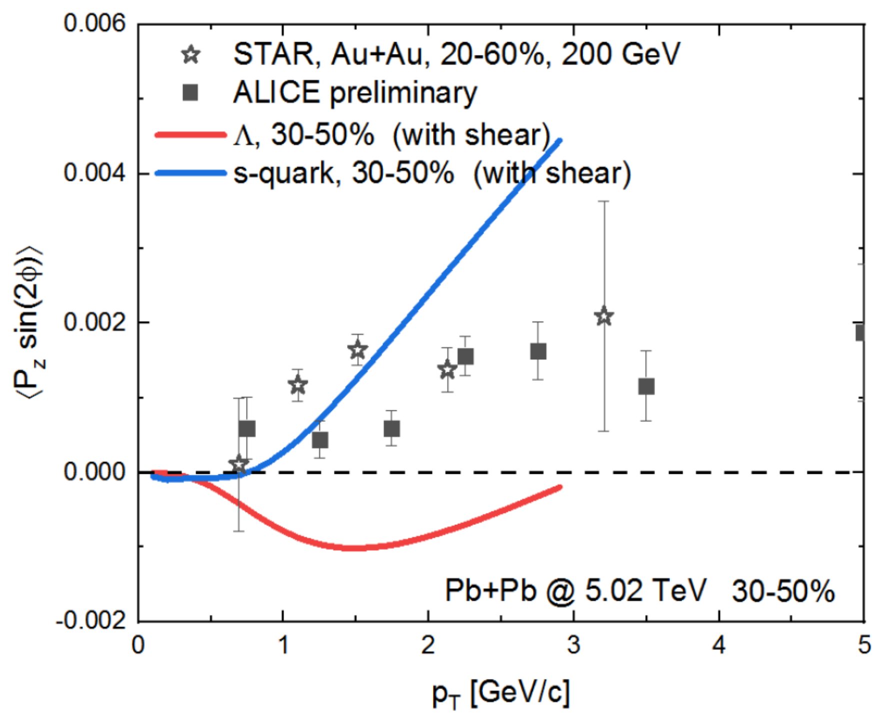


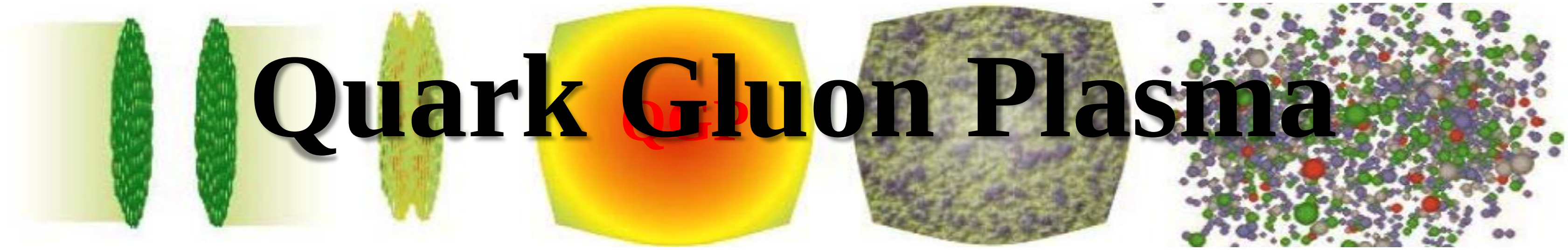
Total P^{μ} = [thermal vorticity] + [shear]

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, arXiv: 2103.10403

Local polarization at LHC energies



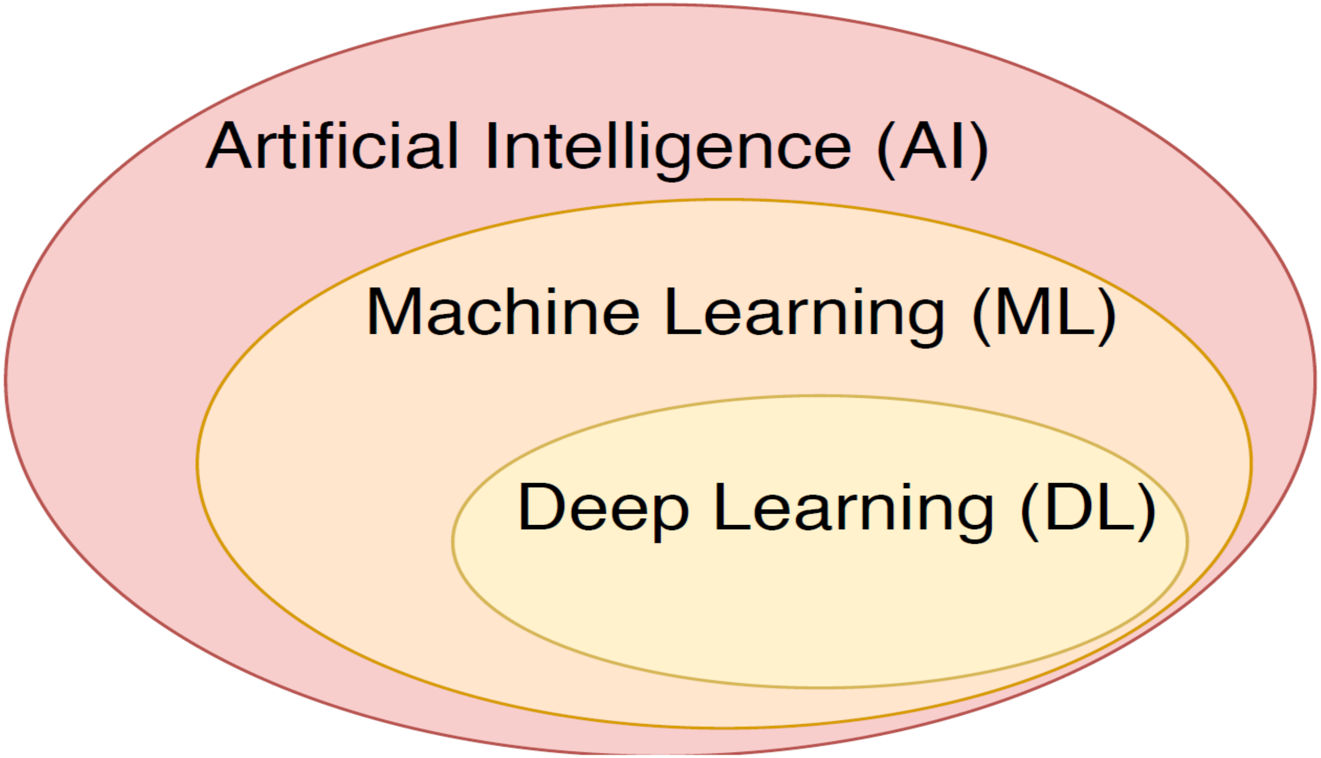




Hottest Matter on Earth

Applications of Deep Learning in Relativistic Hydrodynamics

What is deep learning?



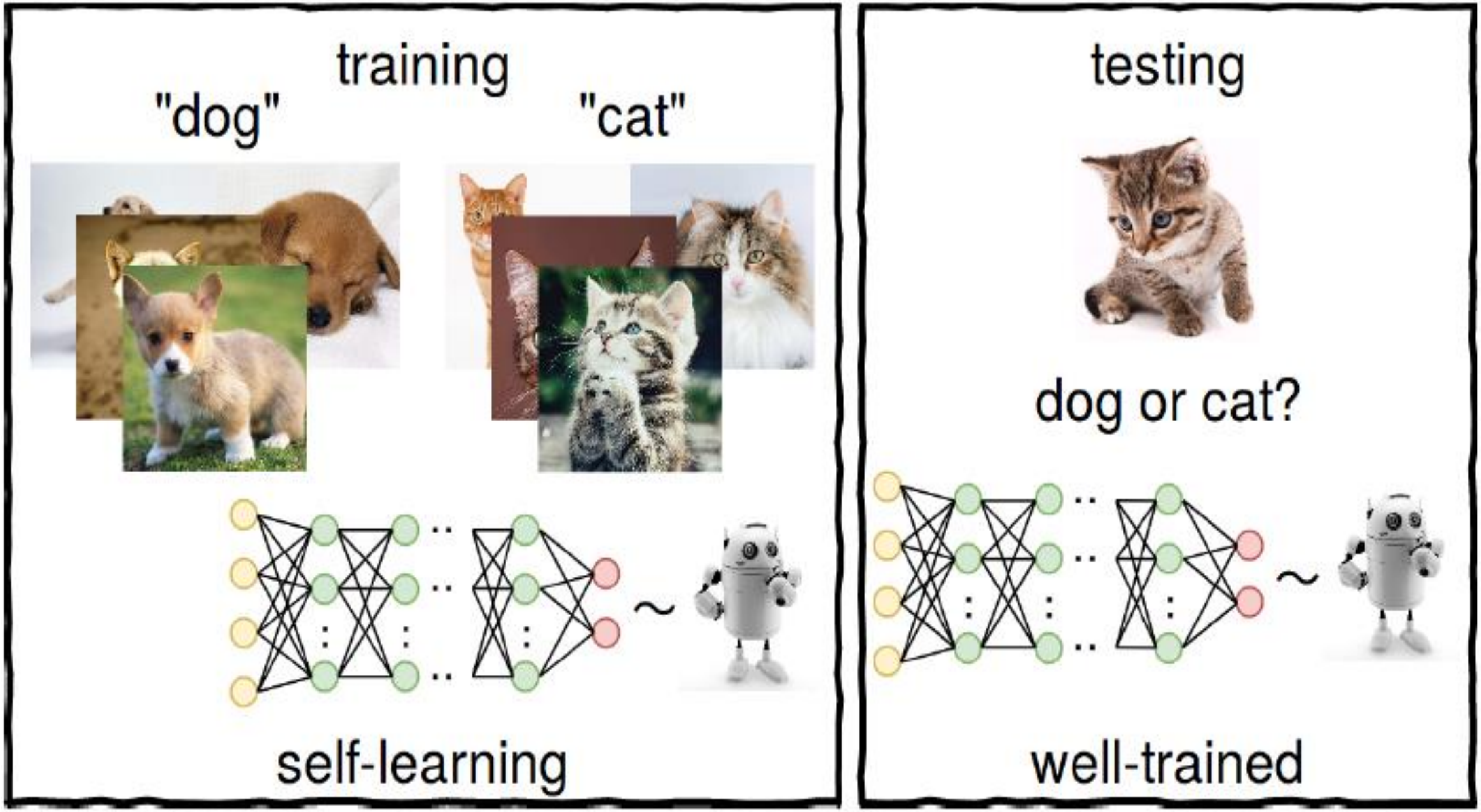
AI： the broadest term, applying to any technique that enables computers to mimic human intelligence.

ML： A subset of AI aiming at optimizing a performance criterion using example data or past experience, but without explicit instruction.

DL： A subset of ML aiming at understanding high-level representations of data using a deeper structure of multiple processing layers

An example of Deep Learning

-Identify cats and dogs



Broad Applications of Deep Learning

Computer vision

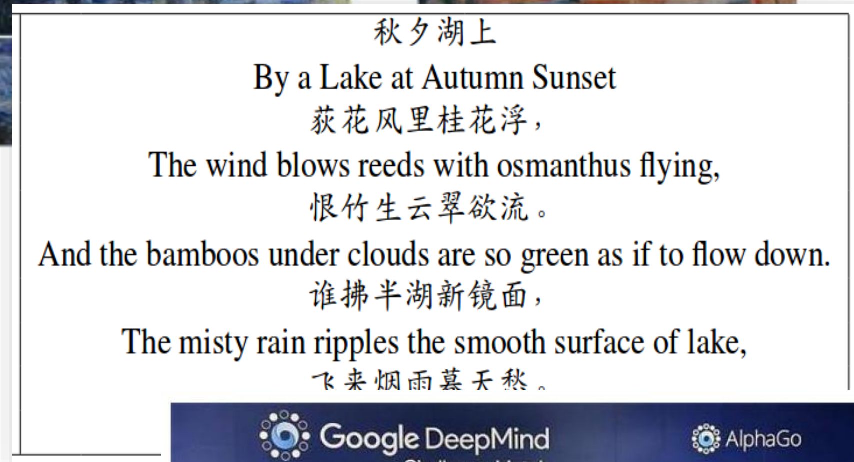
-Image identification

-Image style transition

-Image generation

… … … …

Language processing



秋夕湖上

By a Lake at Autumn Sunset

荻花风里桂花浮，

The wind blows reeds with osmanthus flying,

恨竹生云翠欲流。

And the bamboos under clouds are so green as if to flow down.

谁拂半湖新镜面，

The misty rain ripples the smooth surface of lake,

-Machine translation

-Speech recognition

-Chinese poetry generation

… … … …

Playing Games

-AlphaGo (by Google DeepMind)

… … … …

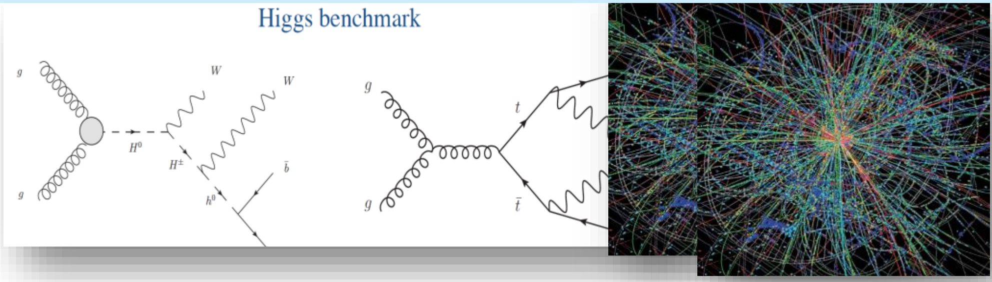
Autonomous Driving

… … … …

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

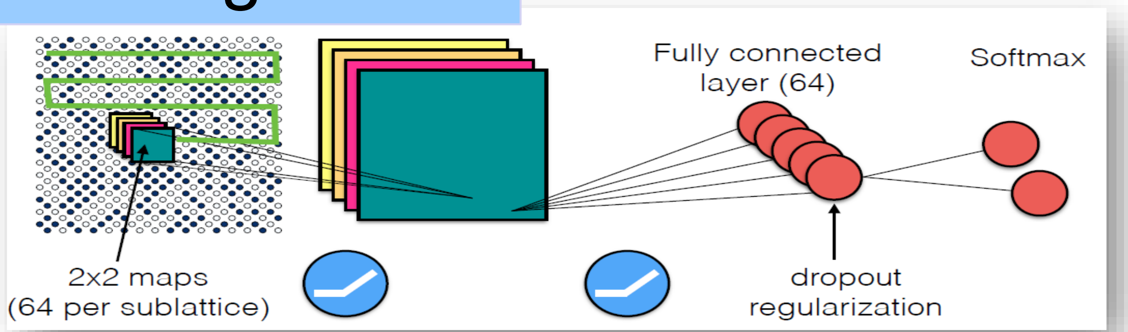
P.Baldi,P.Sadowski,& D.Whiteson Nature Commun.5, 4308 (2014)

Classifying the Phase of Ising Model

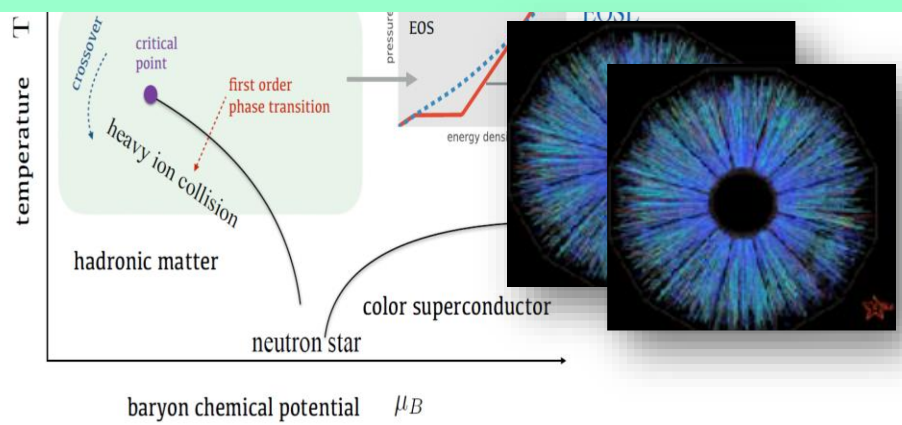
For the case of Ising gauge theory

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

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



Identify QCD Phase Transition with Deep Learning

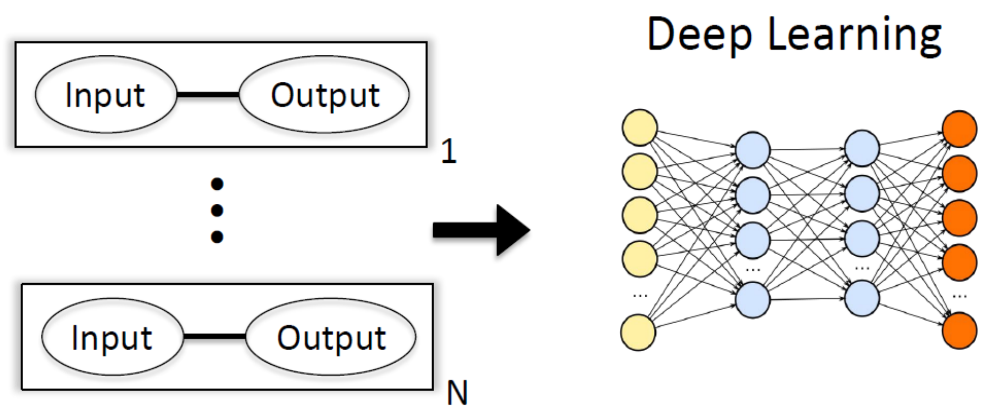


DNN efficiently decode the EOS information from the complex final particle info event by event

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

Why Deep Learning in Physics?

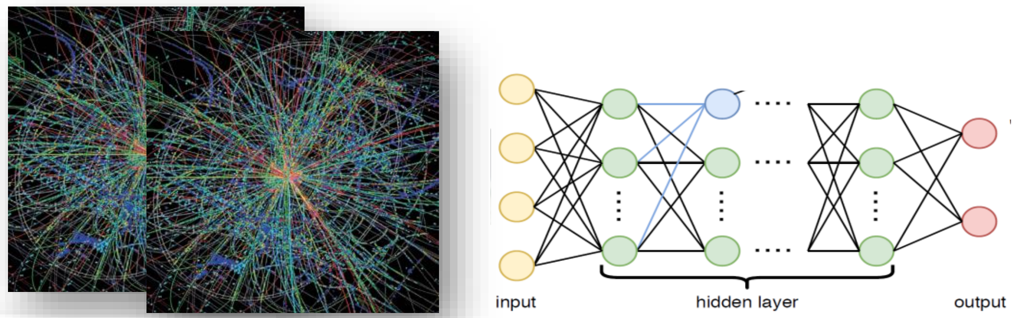
"Unlike earlier attempts … Deep Learning systems can see patterns and spot anomalies in data sets far larger and messier than human beings can cope with."



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

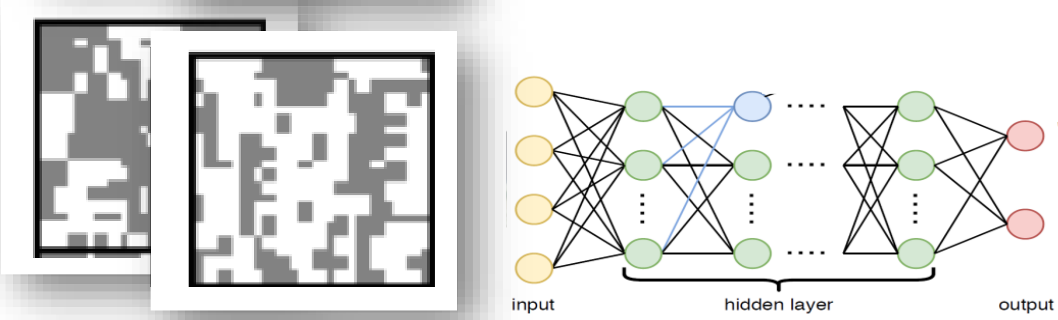
More Comments on several examples of supervised learning

Image identification



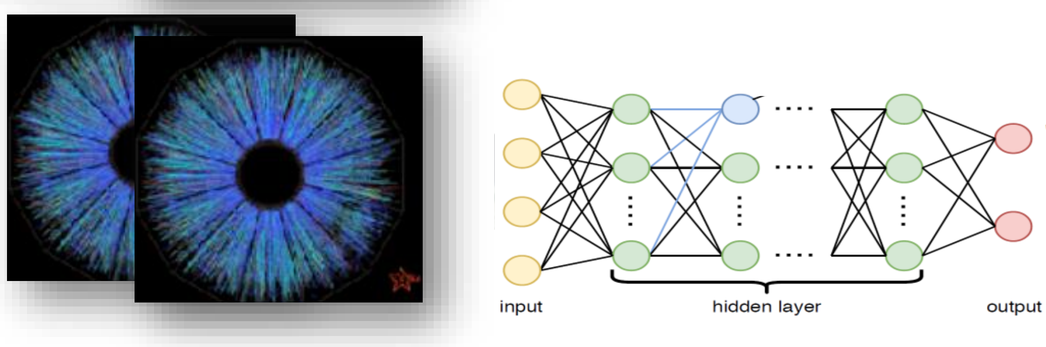
Higgs signal or background?

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)

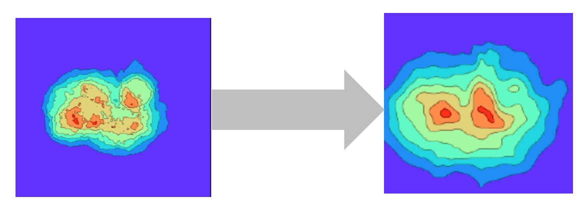
"Unlike earlier attempts … Deep Learning systems can see patterns and spot anomalies in data sets far larger and messier than human beings can cope with."

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



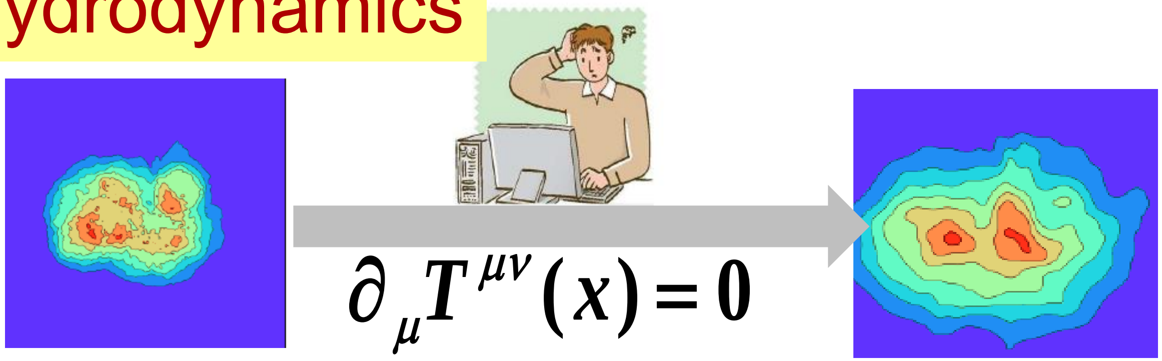
For the non-linear hydro system, can the **black-box** network could learn pattern transformations solely from data without relying on scientific knowledge?

(conservation laws)

Applications of deep learning to relativistic hydrodynamics

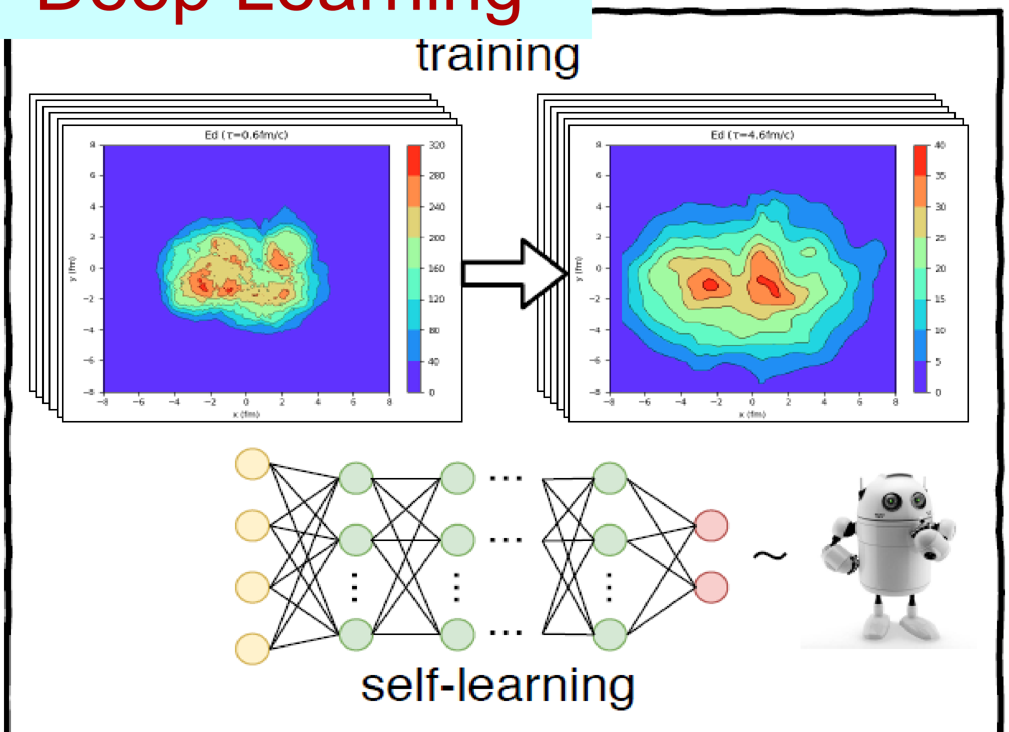
H.Huang, B.Xiao, H.Xiong, Z.Wu, Y. Mu and H.Song Phys. Rev. Res. 3 2 023256(2021)

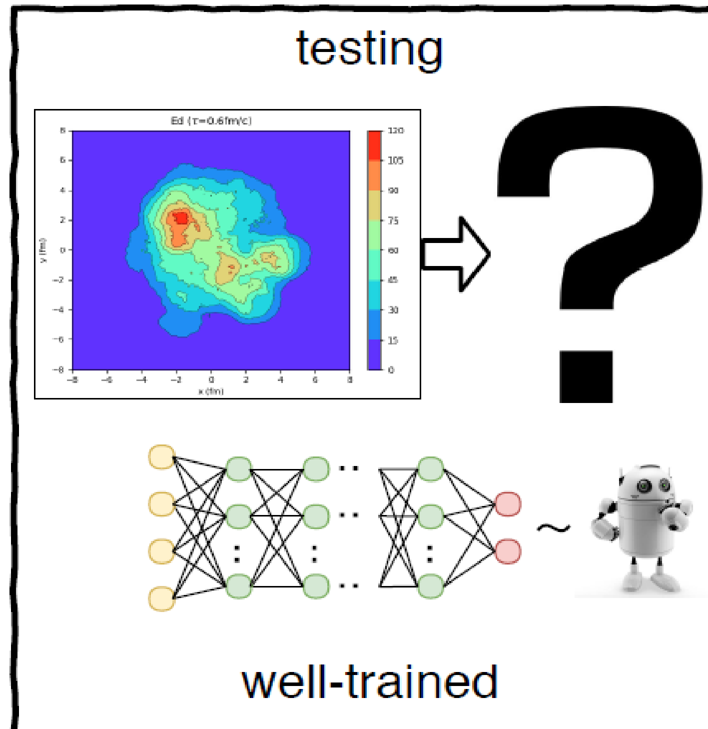
Traditional hydrodynamics



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

Deep Learning

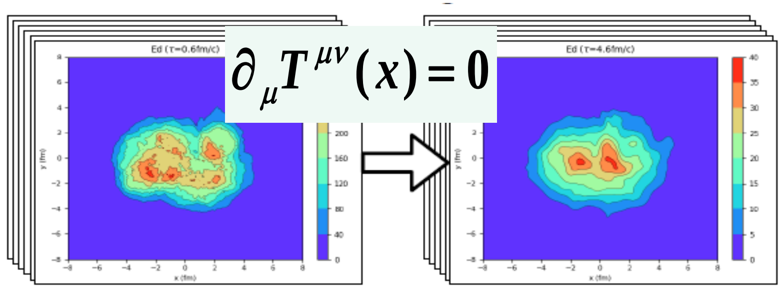




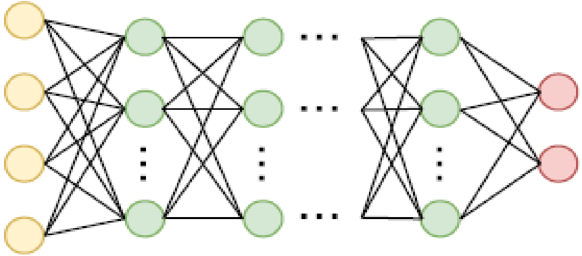
-Such deep learning systems do not need to be programmed with the hydro equation $\partial_\mu T^{\mu\nu}(x) = 0$ Instead, they learn on their own

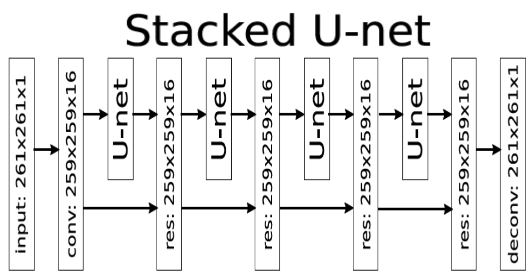
Deep Learning

Step1) Generate the training/testing data sets from hydro



Step2) Design & train the deep neural network

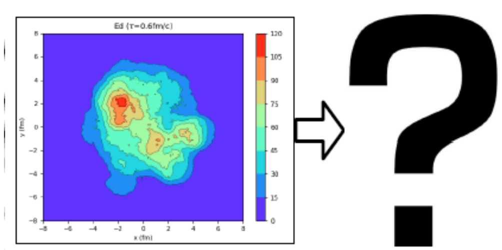




The Training Data Sets

hydro VISH2+1	MC-Gl
	10000

Step3) Test the deep neural network

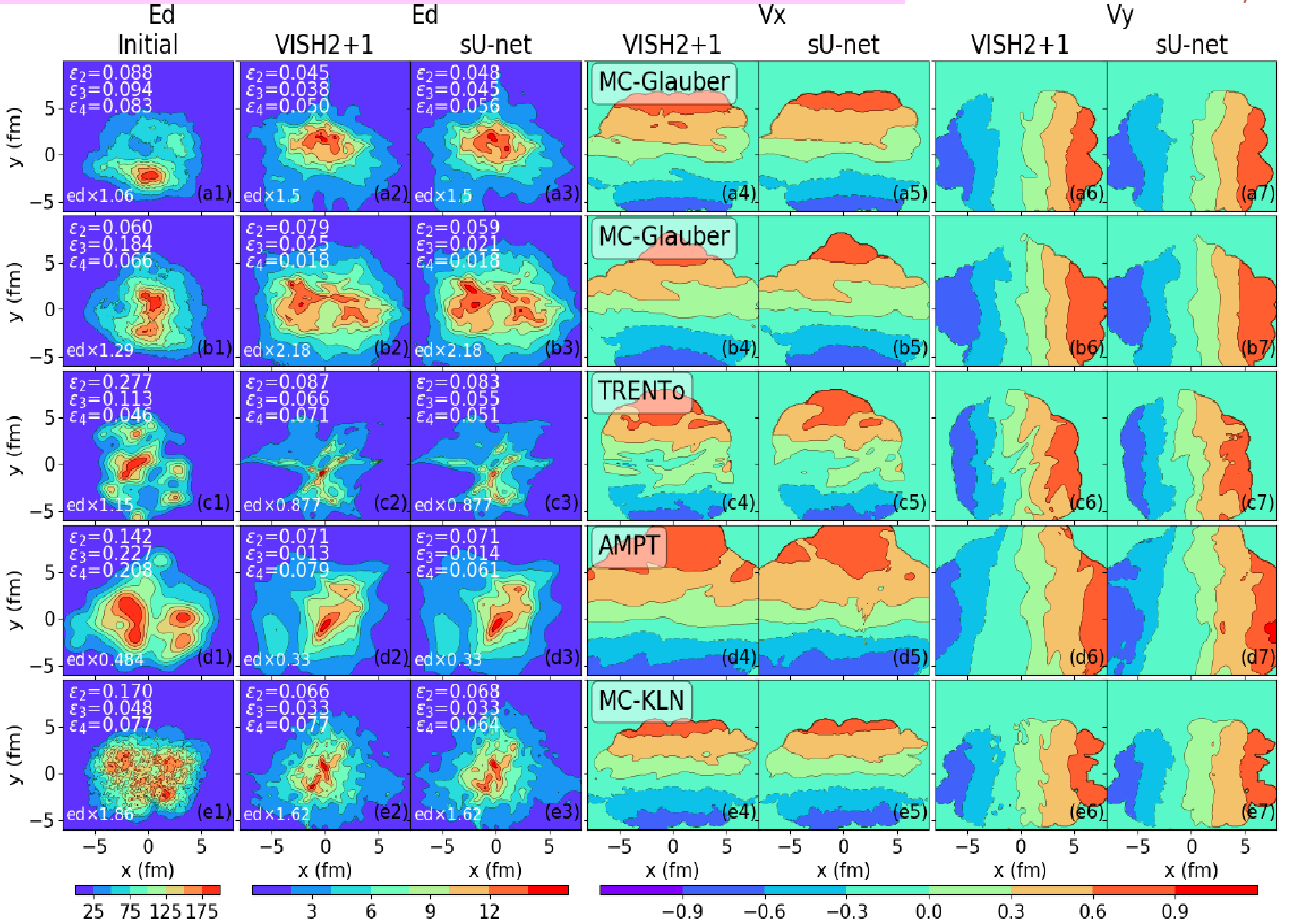


The Testing Data Sets

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

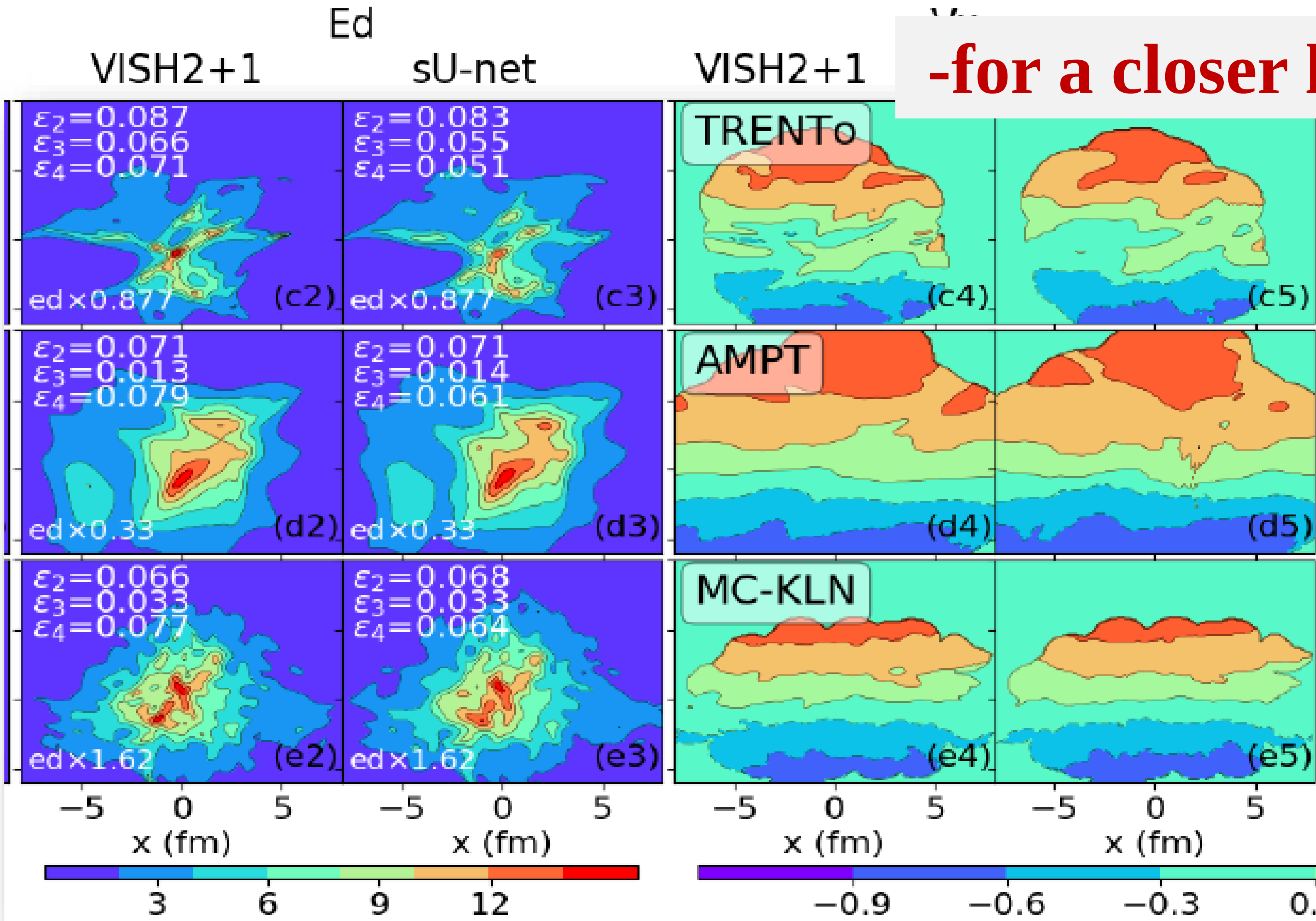
sUnet prediction vs. hydro simulations

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



sUnet prediction vs. hydro simulations

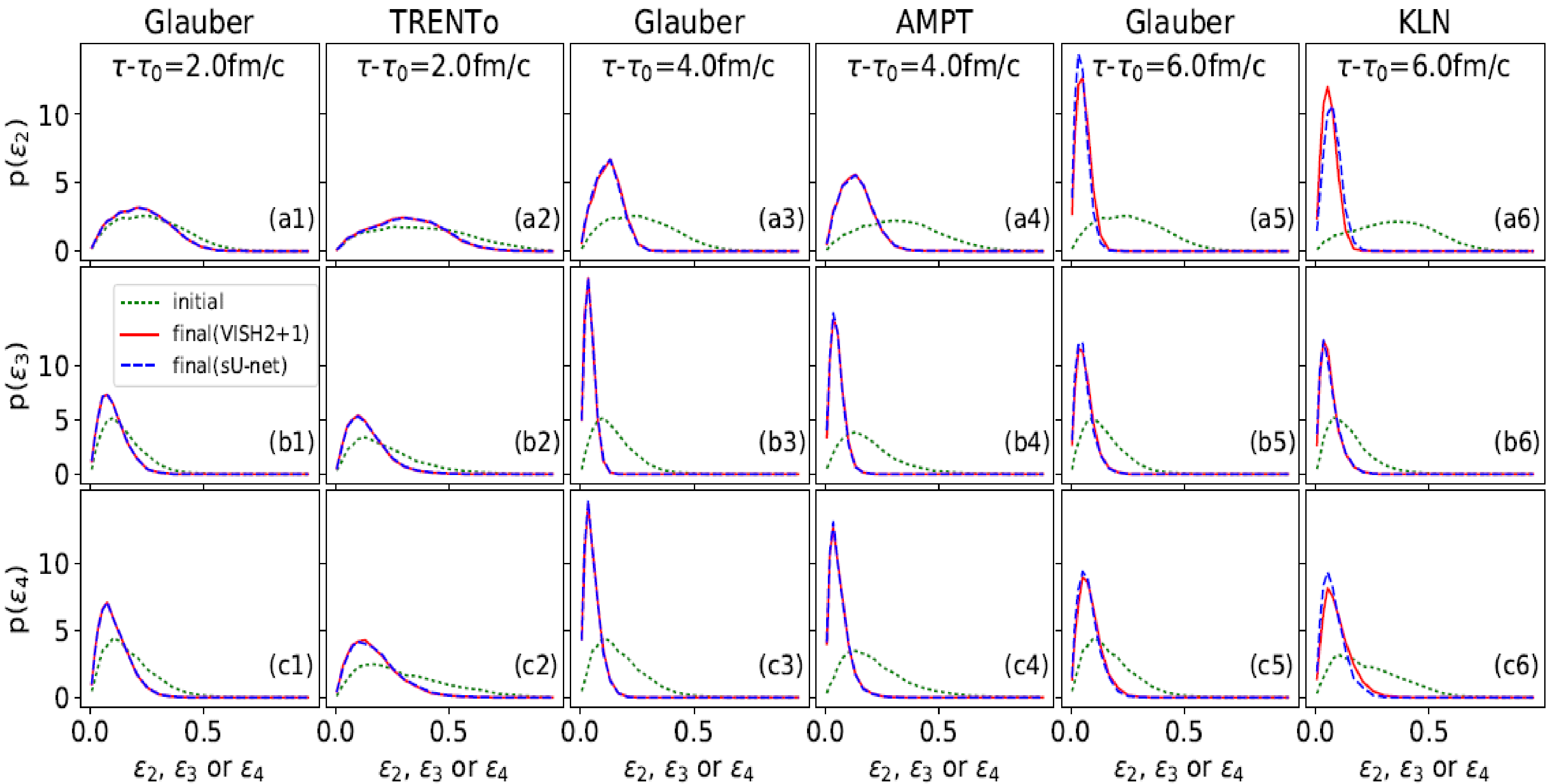
$\tau - \tau_0 = 6.0 fm/c$



-for a closer look

sUnet prediction vs. hydro simulations

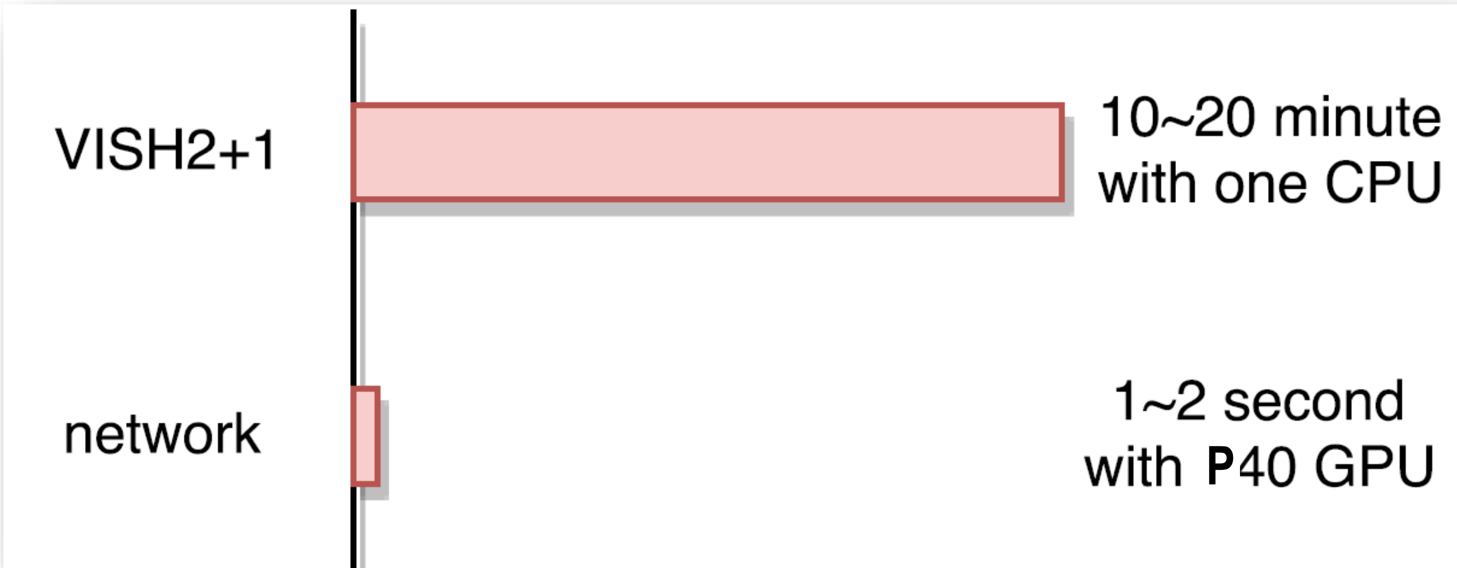
Eccentricity distributions:

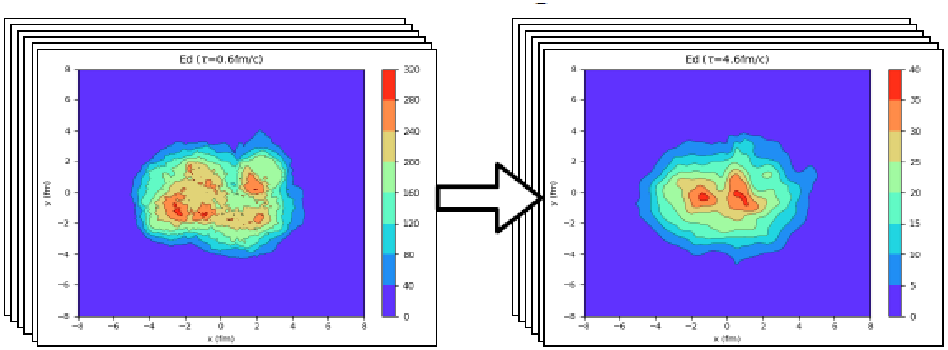


$$\varepsilon_n e^{in\Phi_n} = -\frac{\int dxdy r^2 e^{in\phi} e(x,y)}{\int dxdy r^2 e(x,y)}$$

initial
final(VISH2+1)
final(sU-net)

Simulation time: sUnet vs. hydro

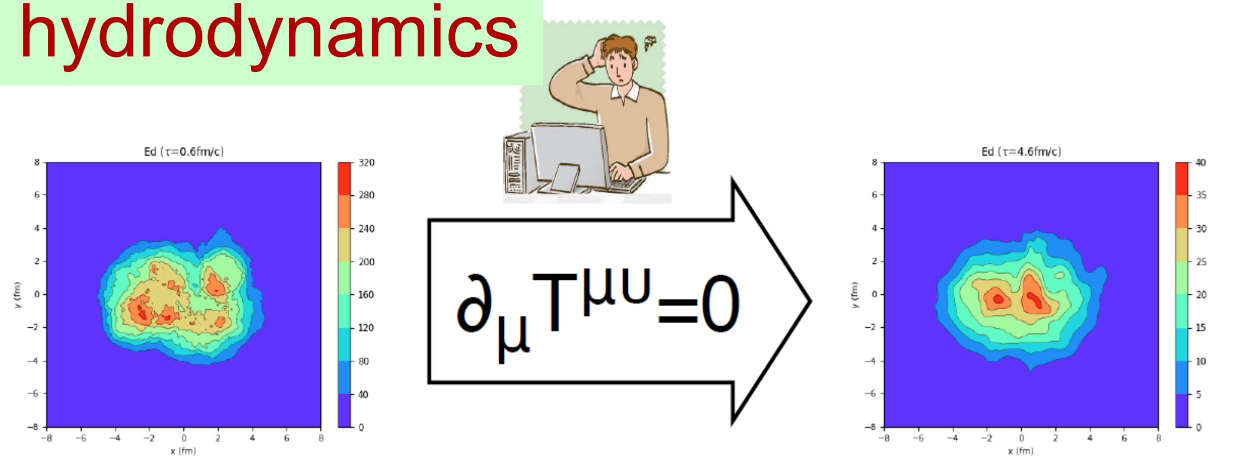




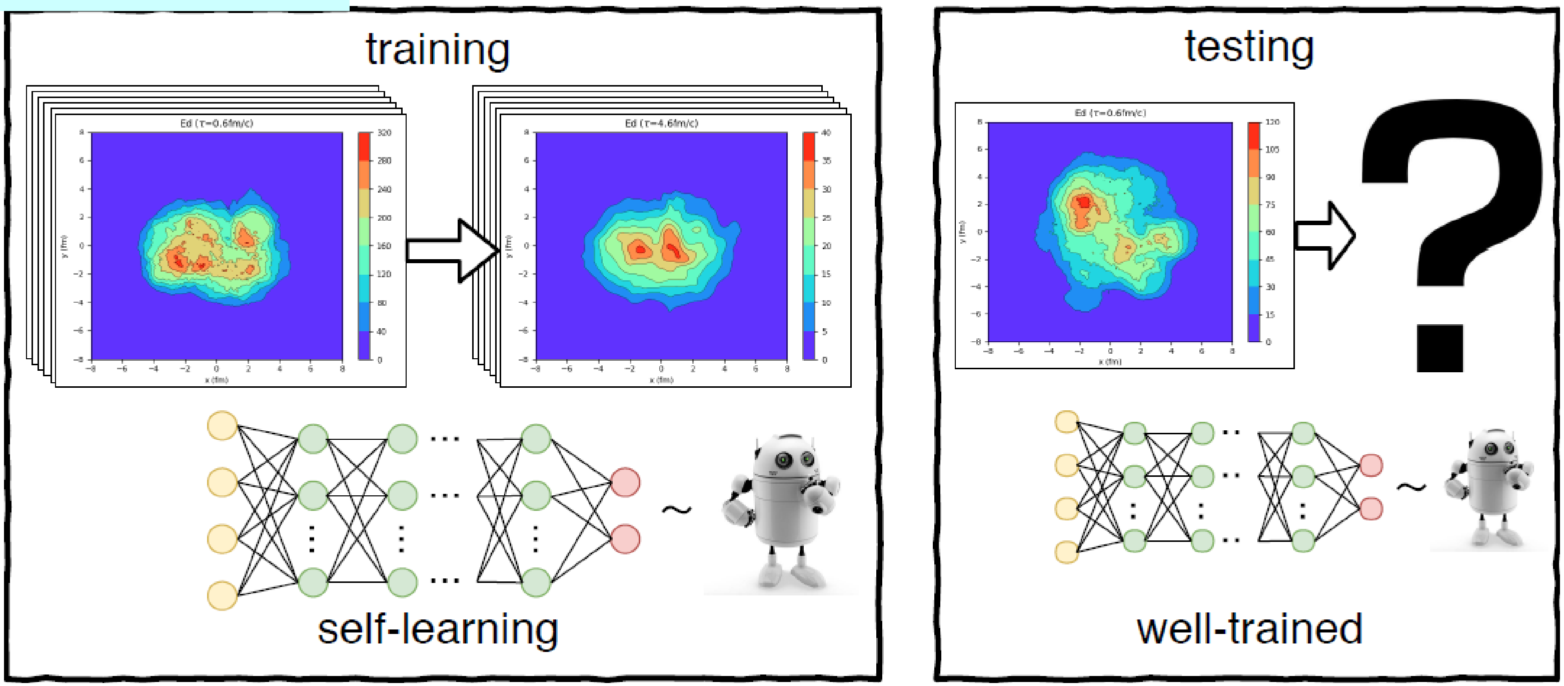
With the well trained network, the final state profiles can be quickly generated from the initial profiles.

Summary & outlook

Traditional hydrodynamics



Deep Learning

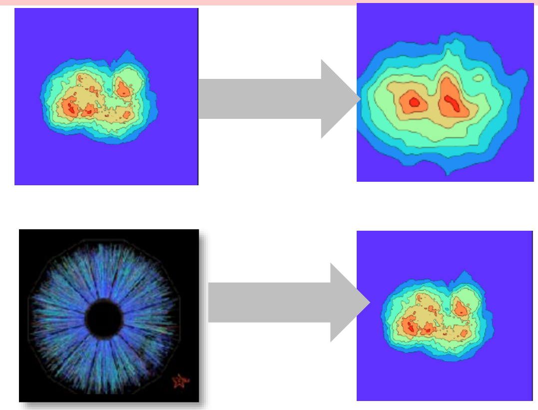


Outlook

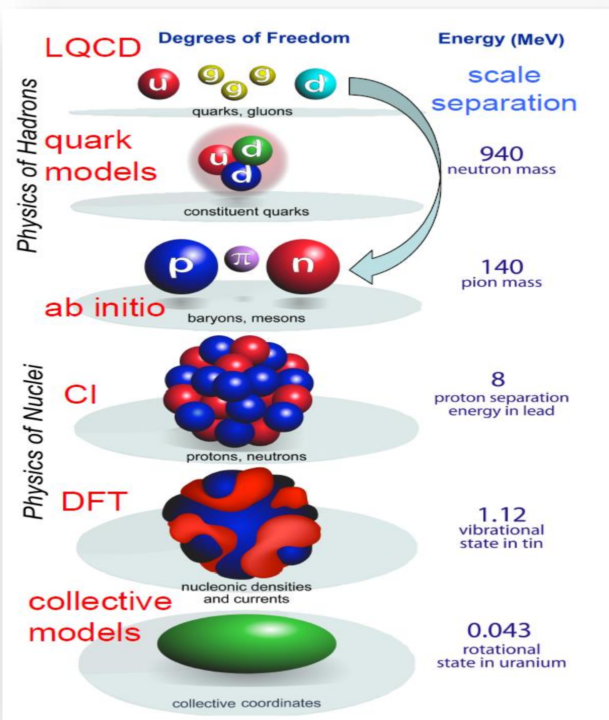
For hydrodynamics

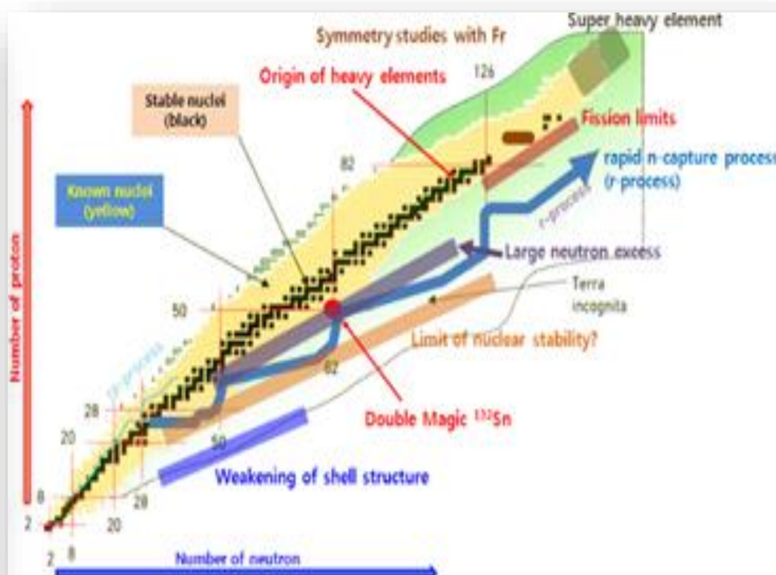
Initial energy density profiles
-------- > final energy density velocity profiles

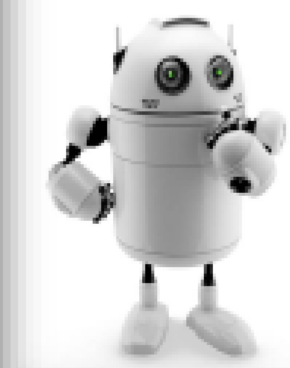
Final particle profiles
-------- > Initial energy density profiles



For Nuclear Physics







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

Flow from the QGP

$V_2(P_T)$

$v_2(p_T)$