Dynamical Models & the fluid nature of the QGP

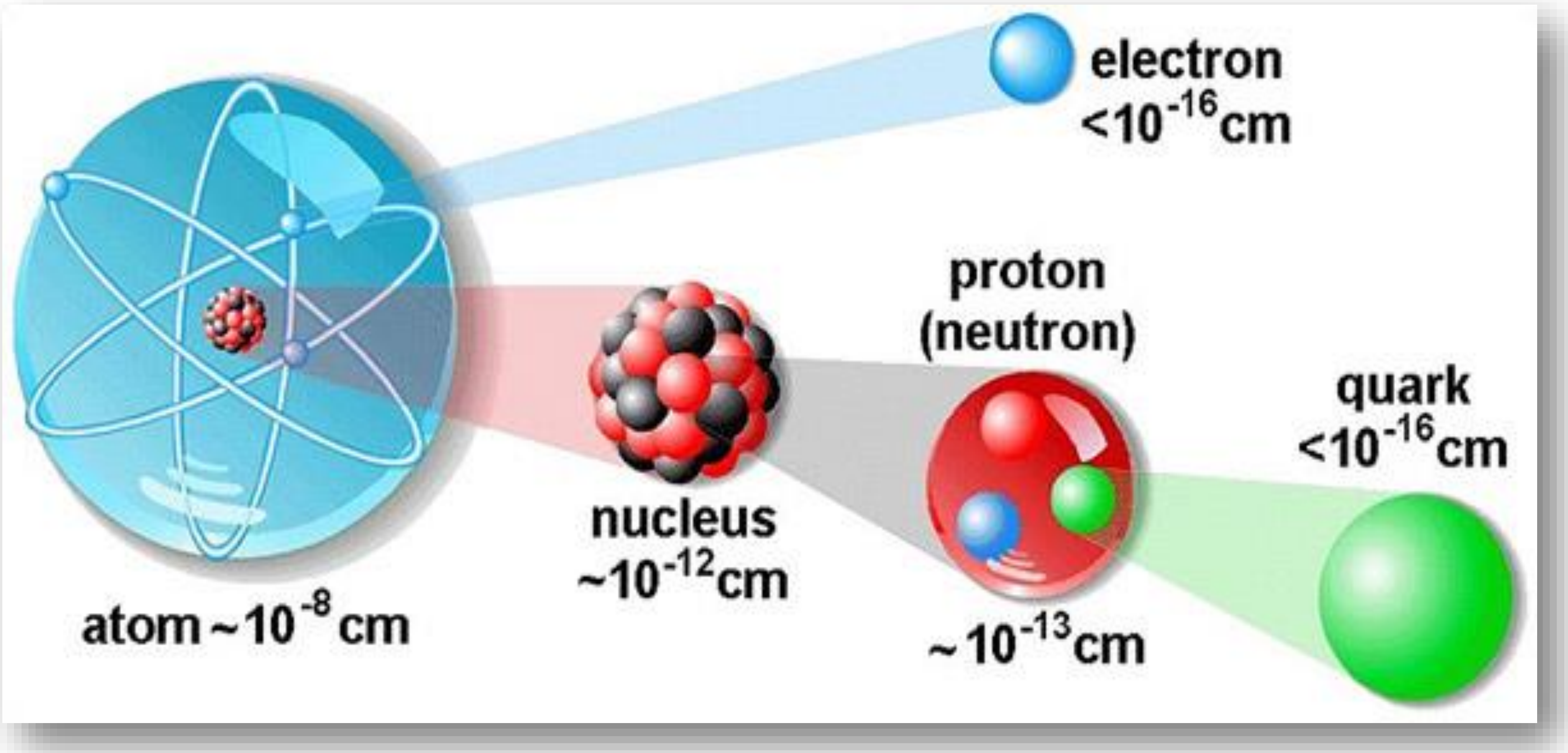
宋慧超

北京大学 物理学院

第10届华大QCD讲席班

线上，2022年10月30-11月4日

Oct 30 2022


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

Landscape of nuclear physics

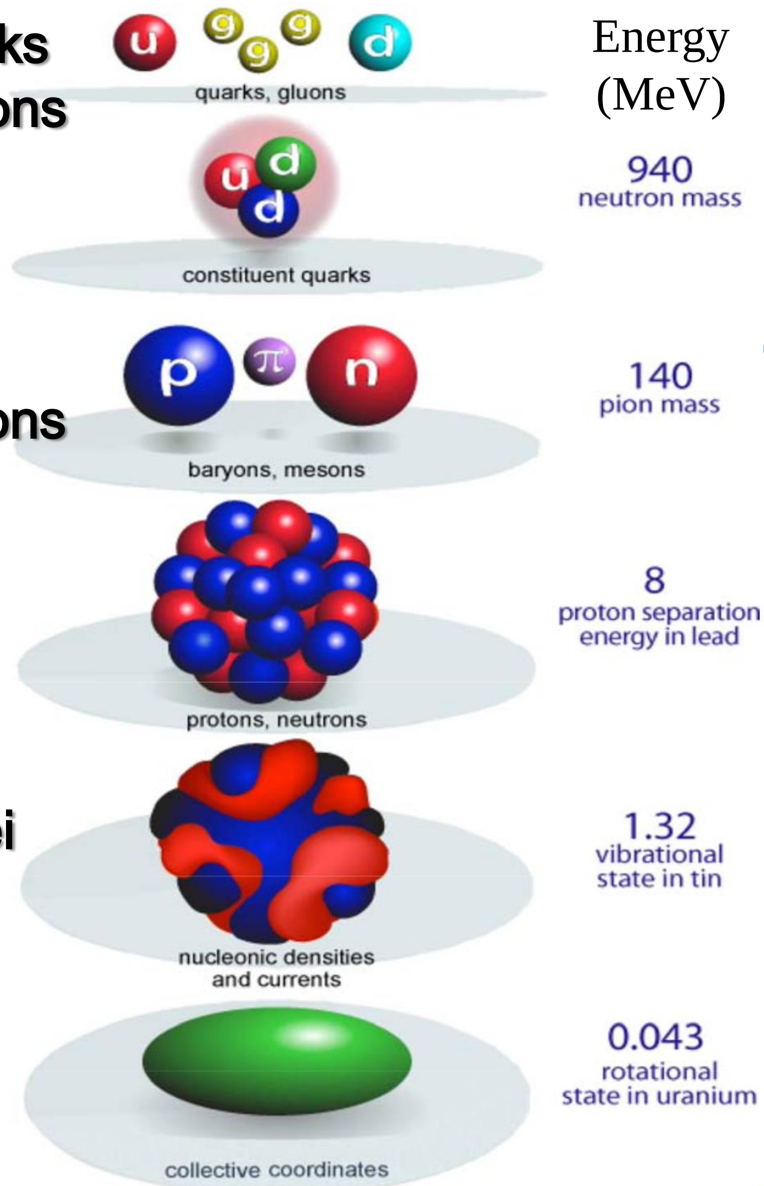
degrees of freedeom

quarks & gluons

hadrons

nuclei

Energy (MeV)



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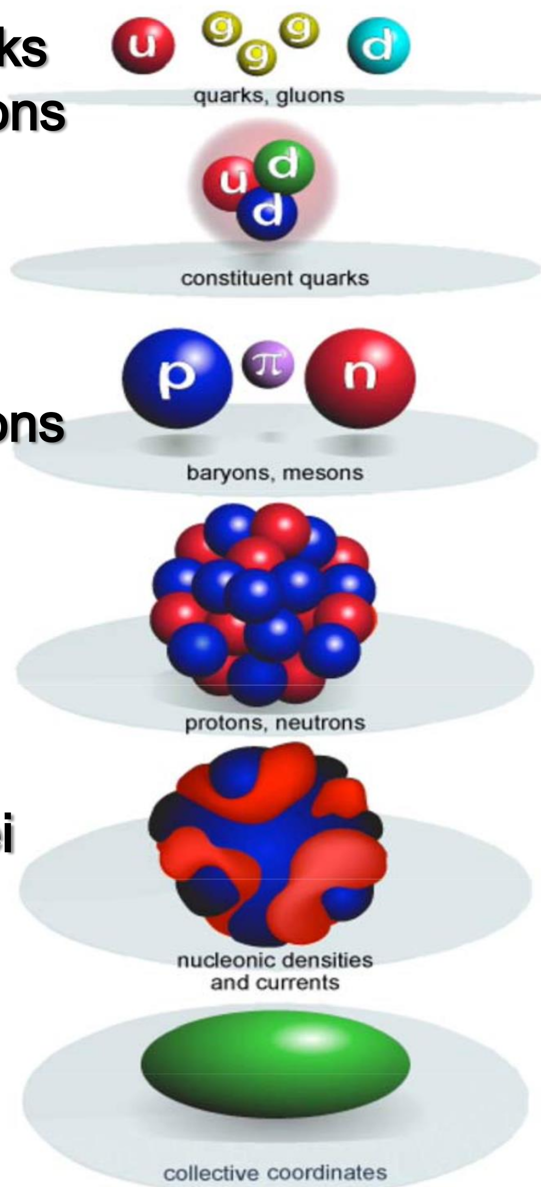


Energy (MeV)

940
neutron mass

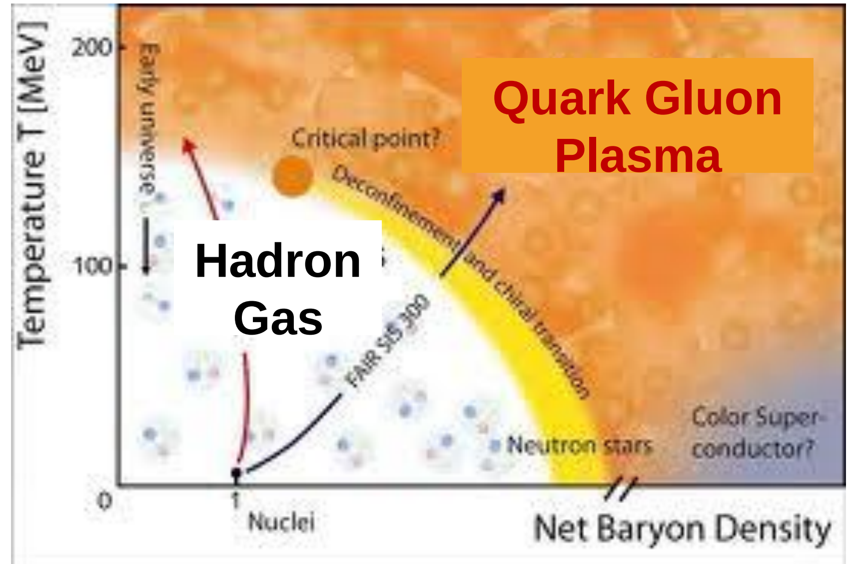
140
pion mass

8
proton separation energy in lead

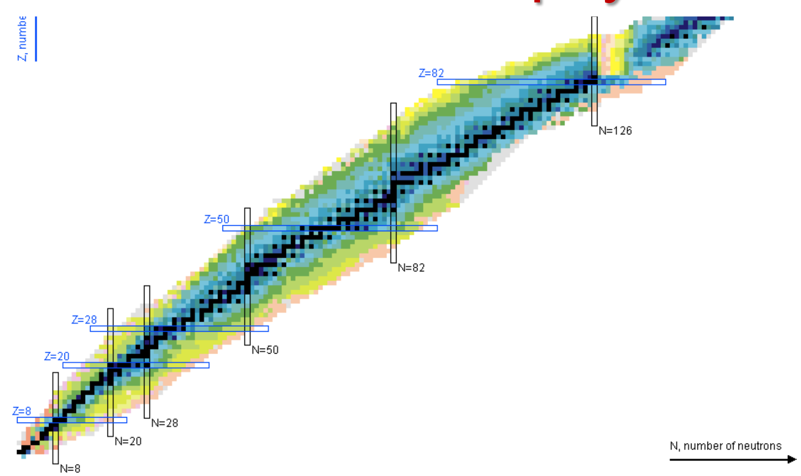
1.32
vibrational state in tin

0.043
rotational state in uranium

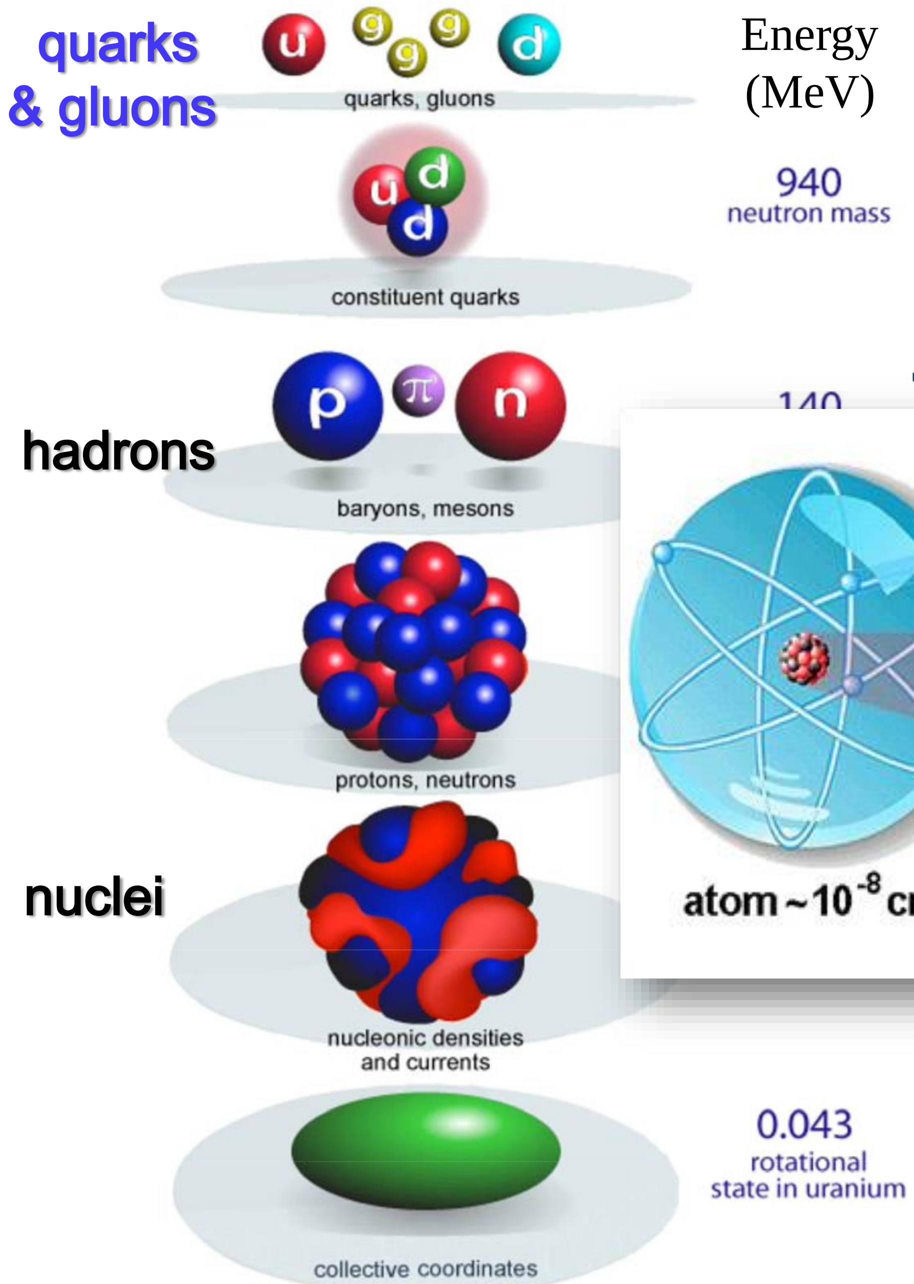
-intermediate and high energy nuclear physics



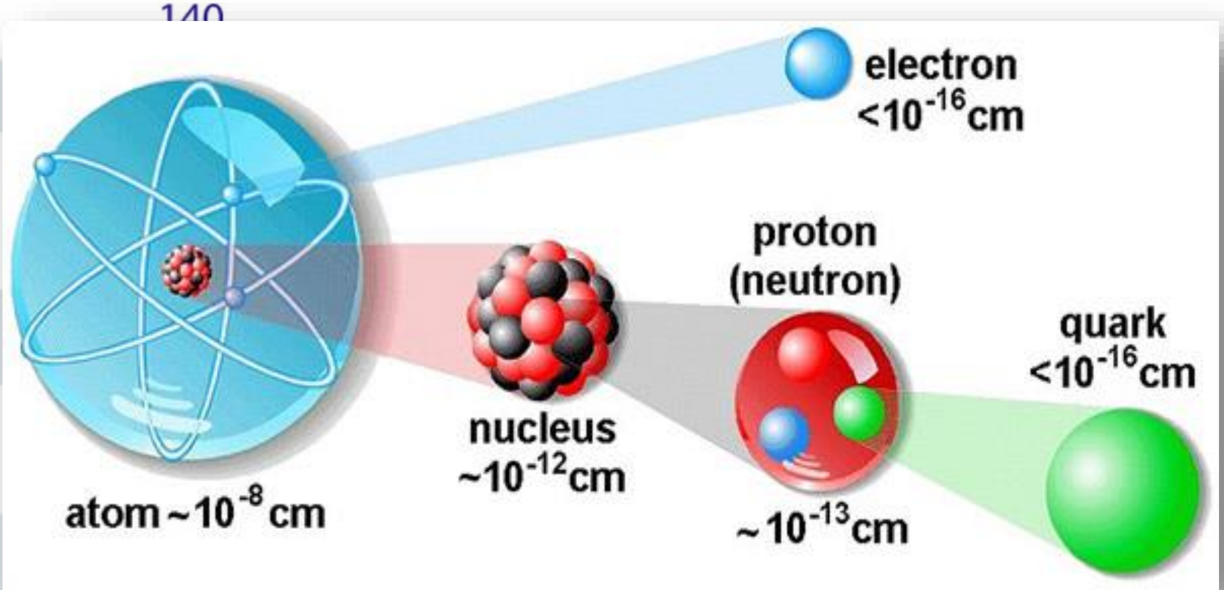
-nuclear structure physics

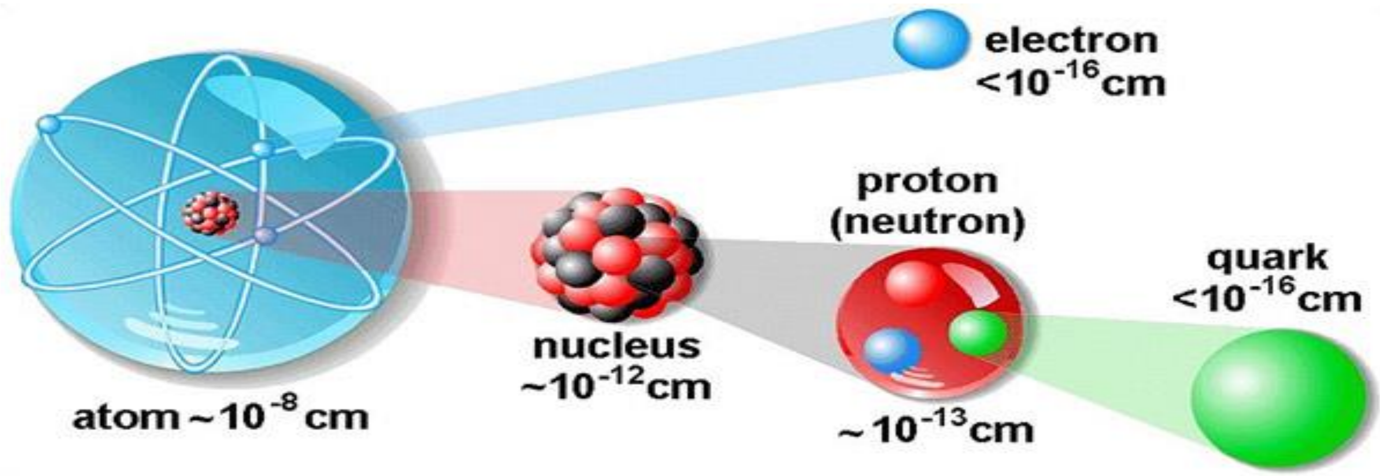


degrees of freedeom



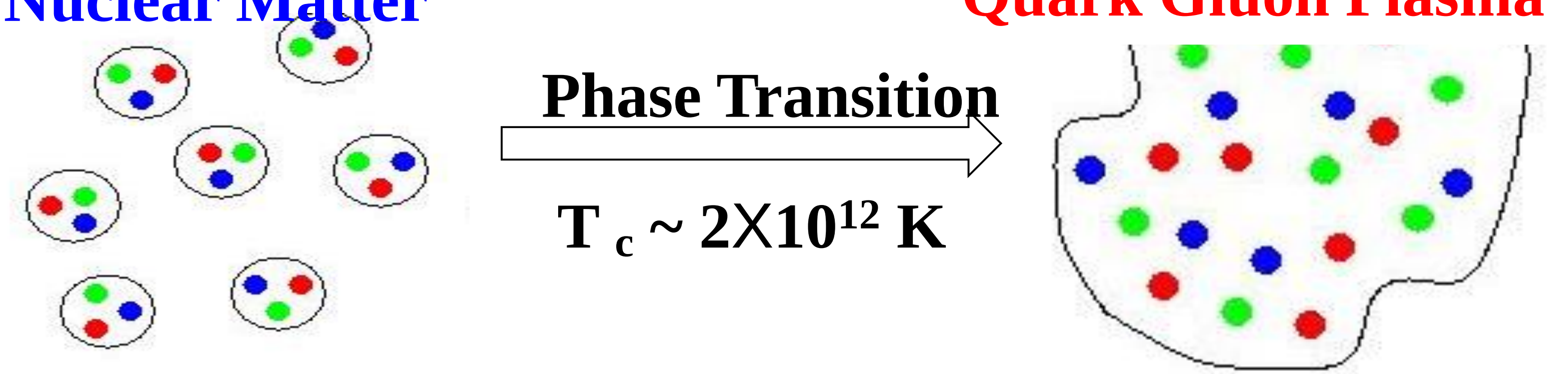
Quark and Gluons: confined in proton and neutrons through strong forces described by QCD





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

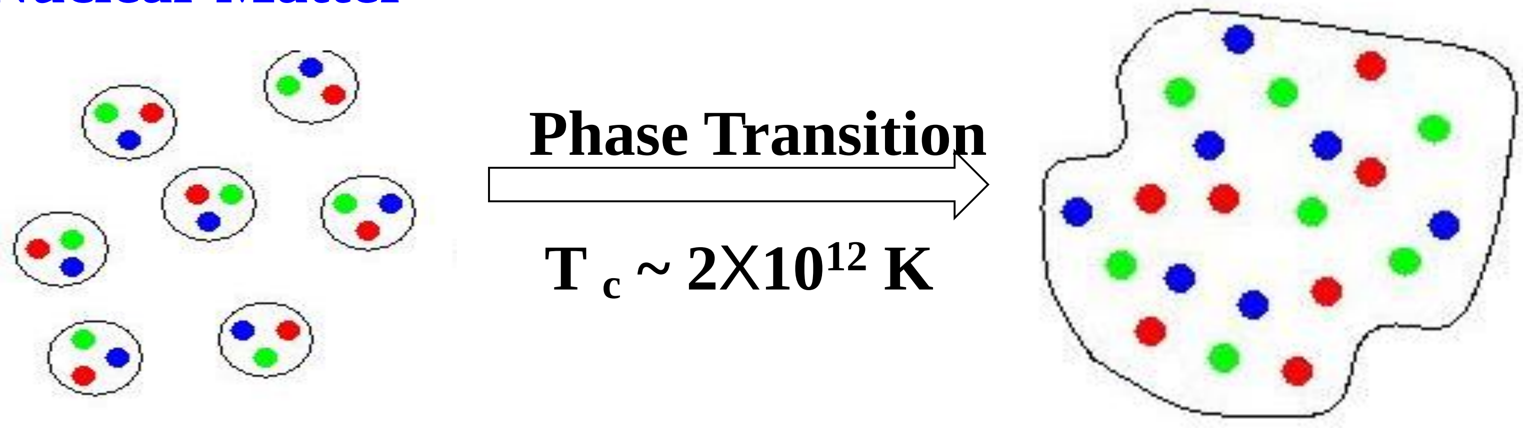
Nuclear Matter **Quark Gluon Plasma**



Confinement **Deconfinement**

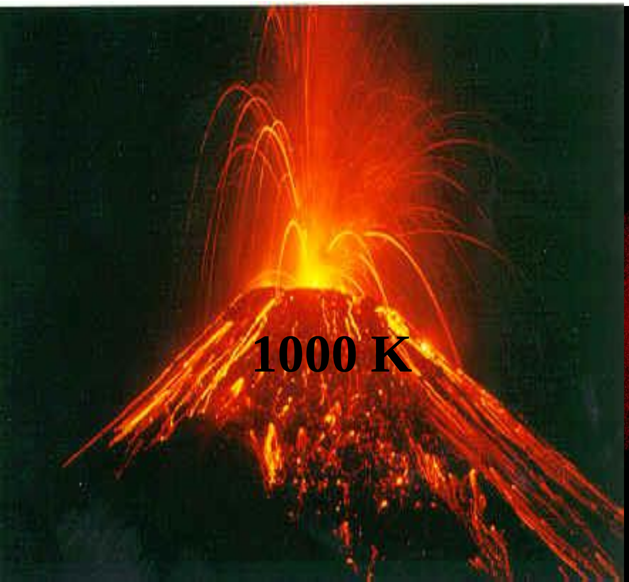
QGP (quark gluon plasma): a deconfinement phase of the QCD matter

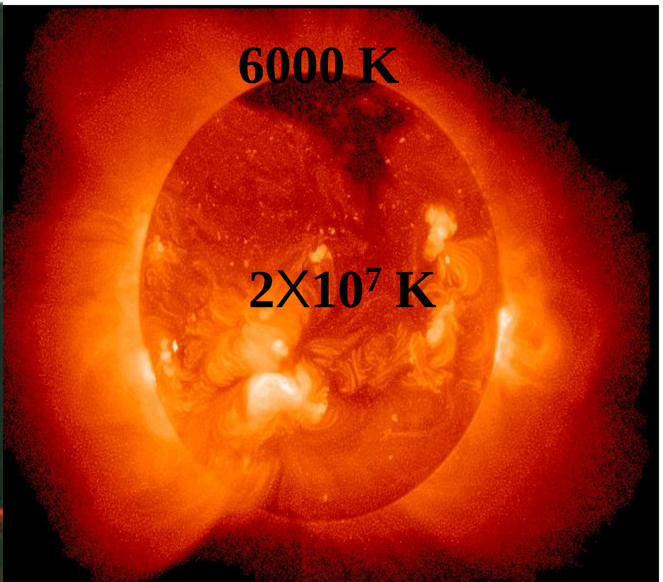
Nuclear Matter Quark Gluon Plasma

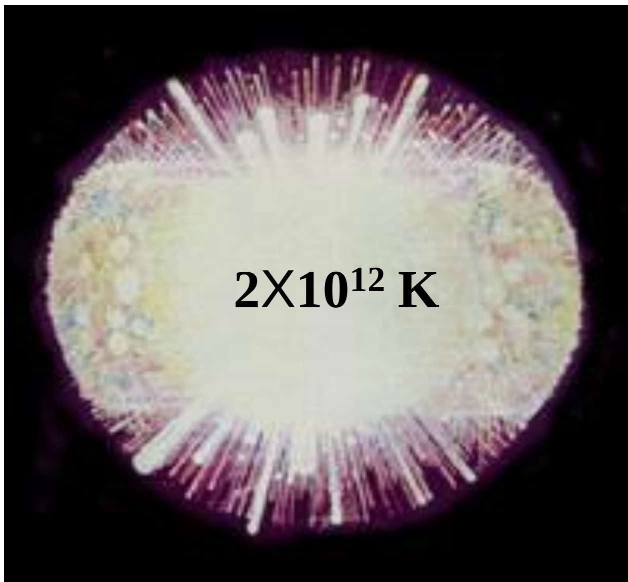


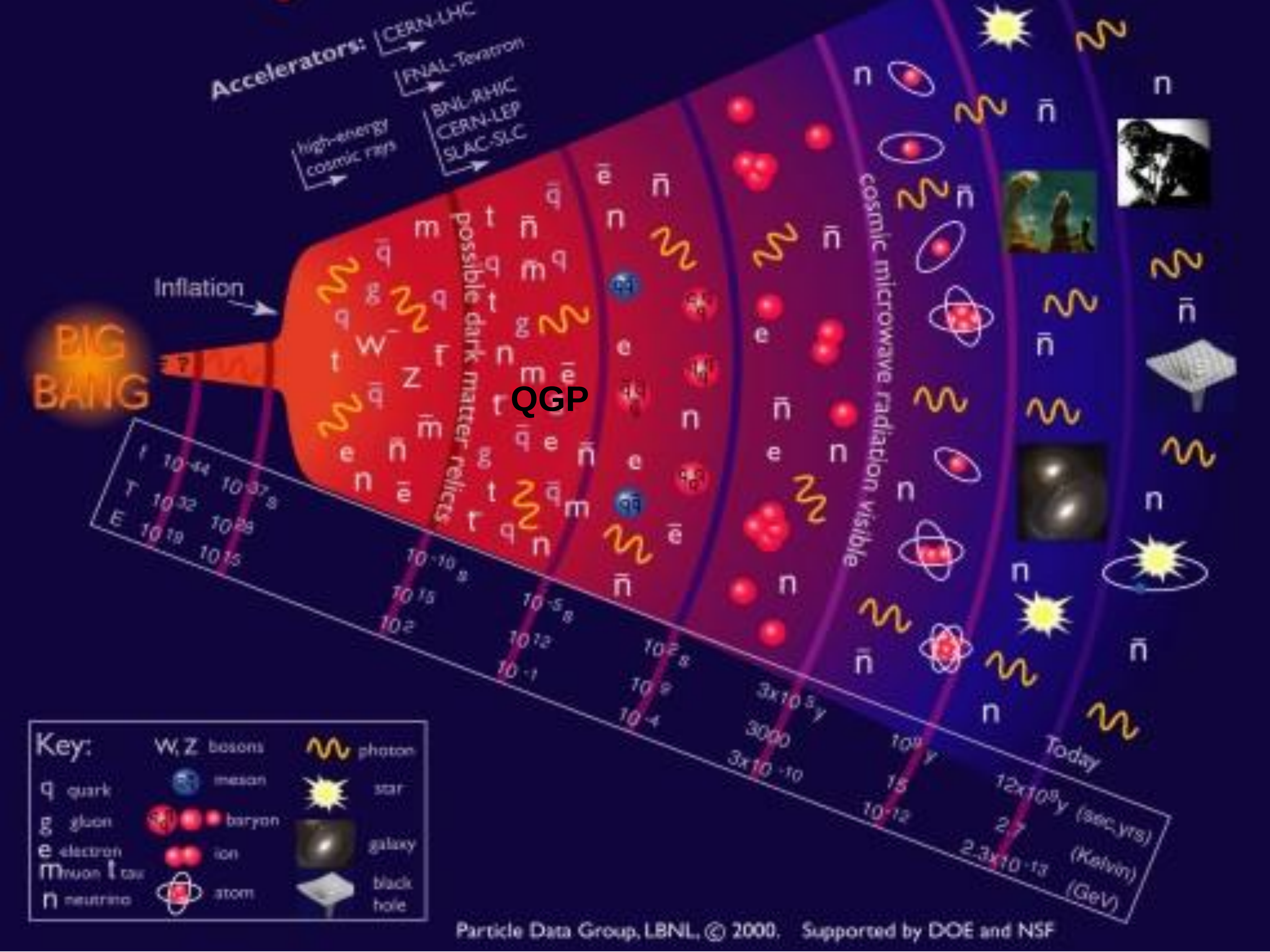
Confinement **Deconfinement**

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

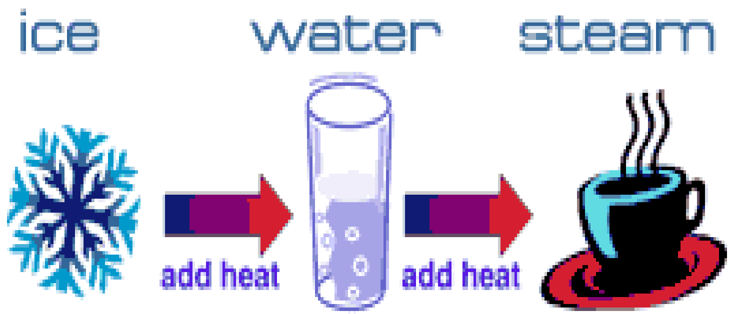


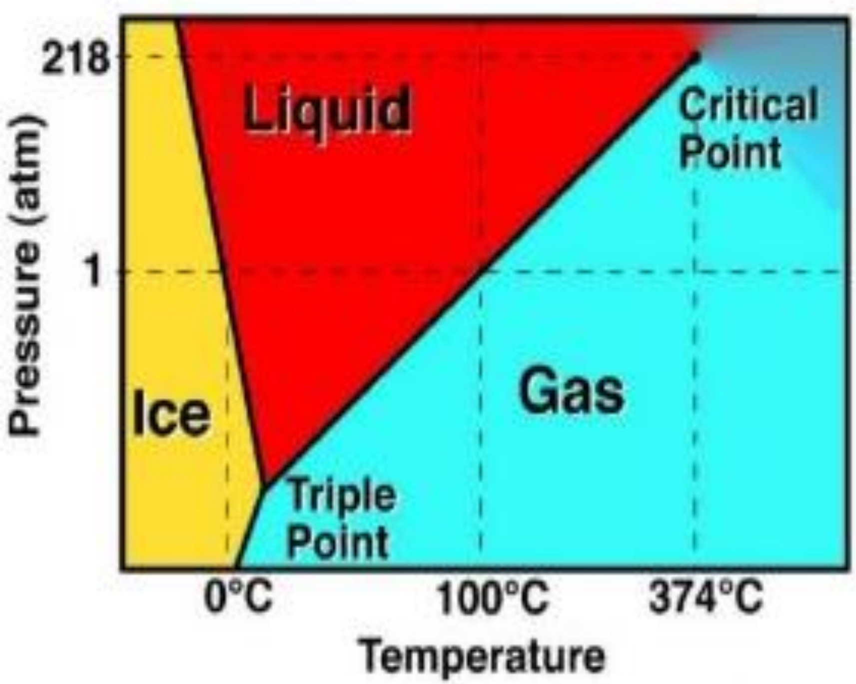




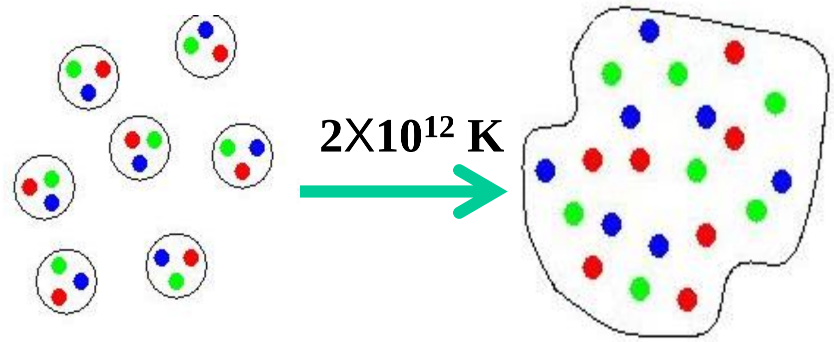

Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
QGP
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec, yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon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

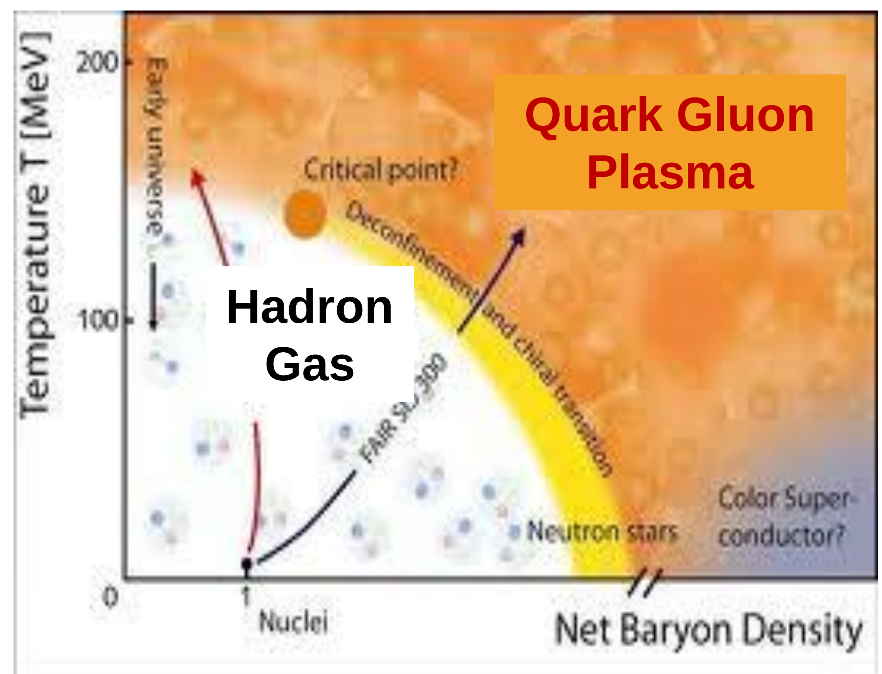
Phases diagram





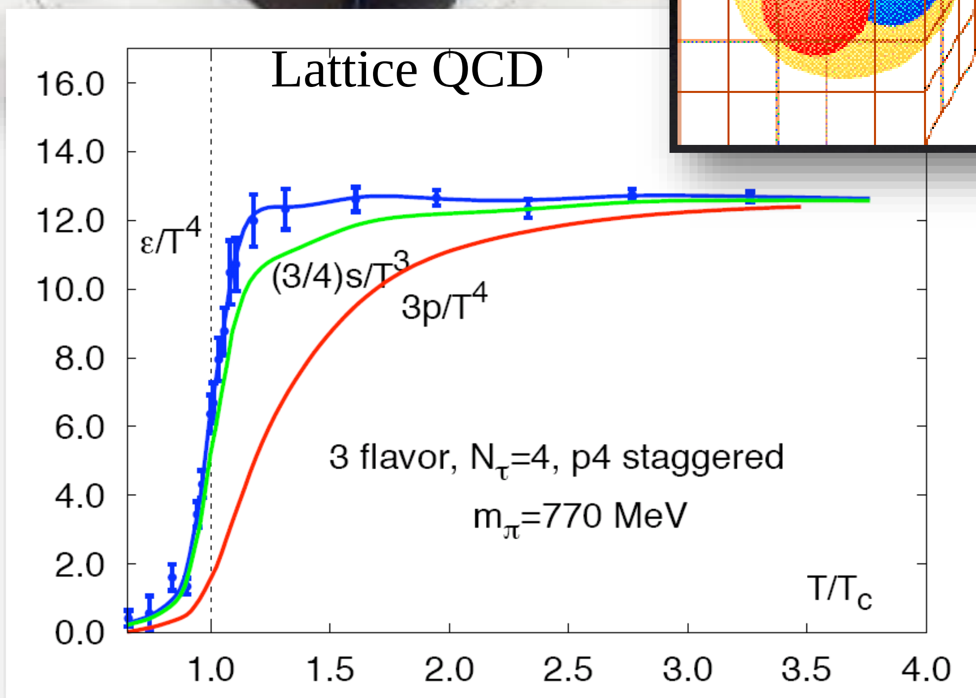
determined by electromagnetic interactions

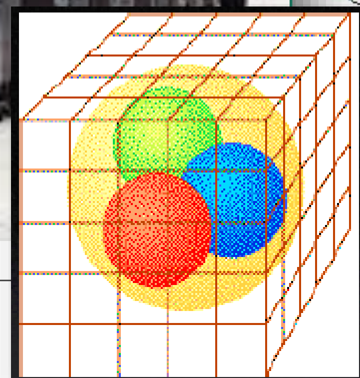


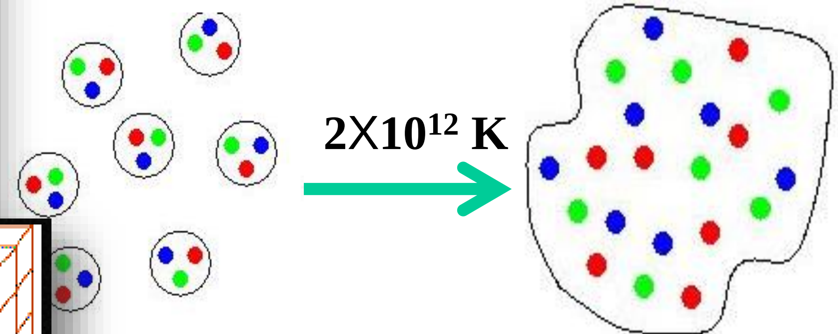


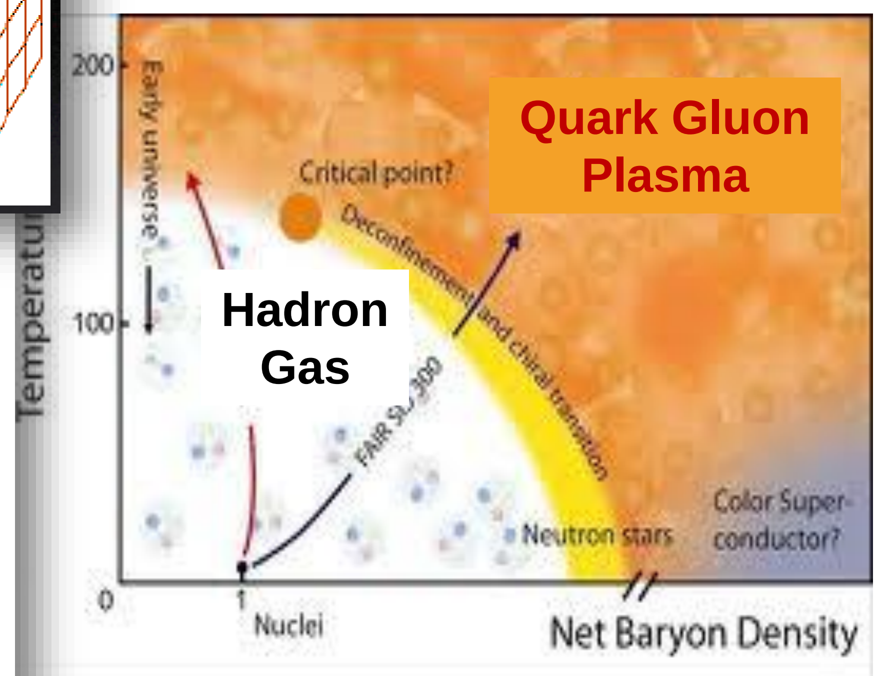
determined by strong interactions

s diagram









determined by strong interactions

QCD Phase transition

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

$$\varepsilon = g\frac{\pi^2}{30}T^4$$ Energy density for "g" massless d.o.f.

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Hadronic Matter:
3 π with spin=0

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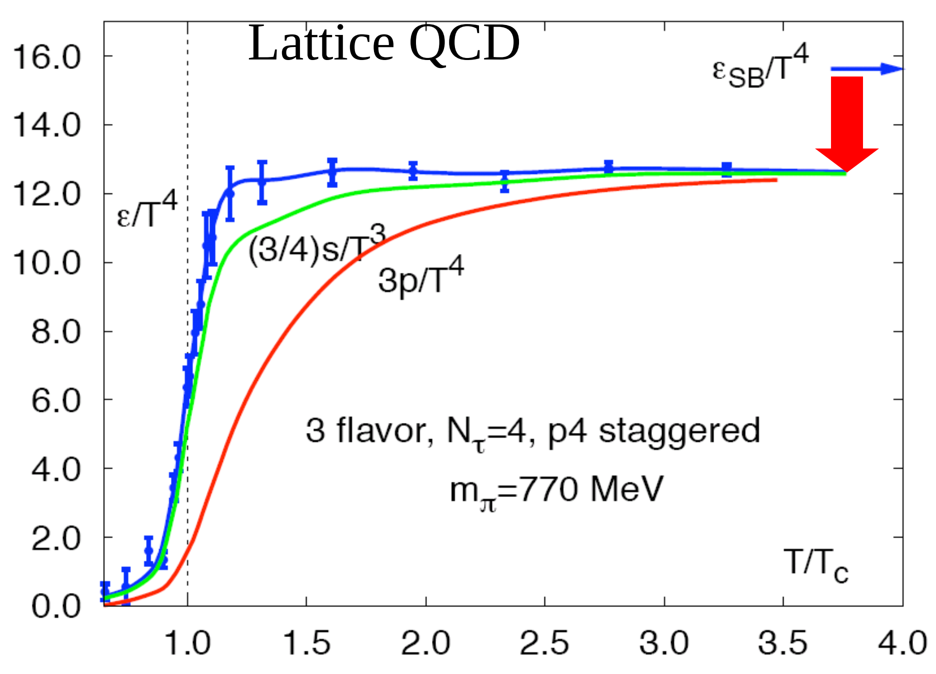
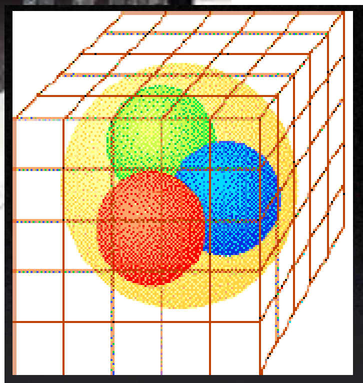




A brief history of relativistic heavy ion physics

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)

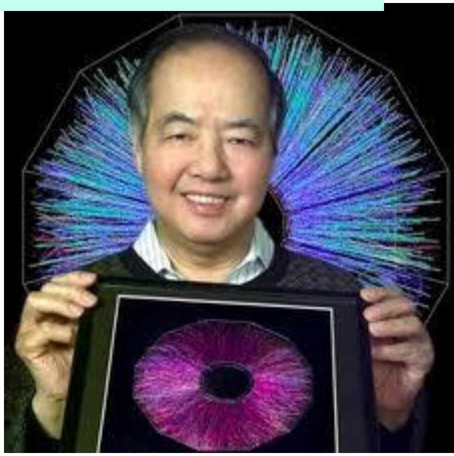
1986: AGS stars, (end 2000)

2000: RHIC starts

2010: LHC starts

Future: FAIR & NICA

A brief history of relativistic heavy ion physics



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LHC, CERN

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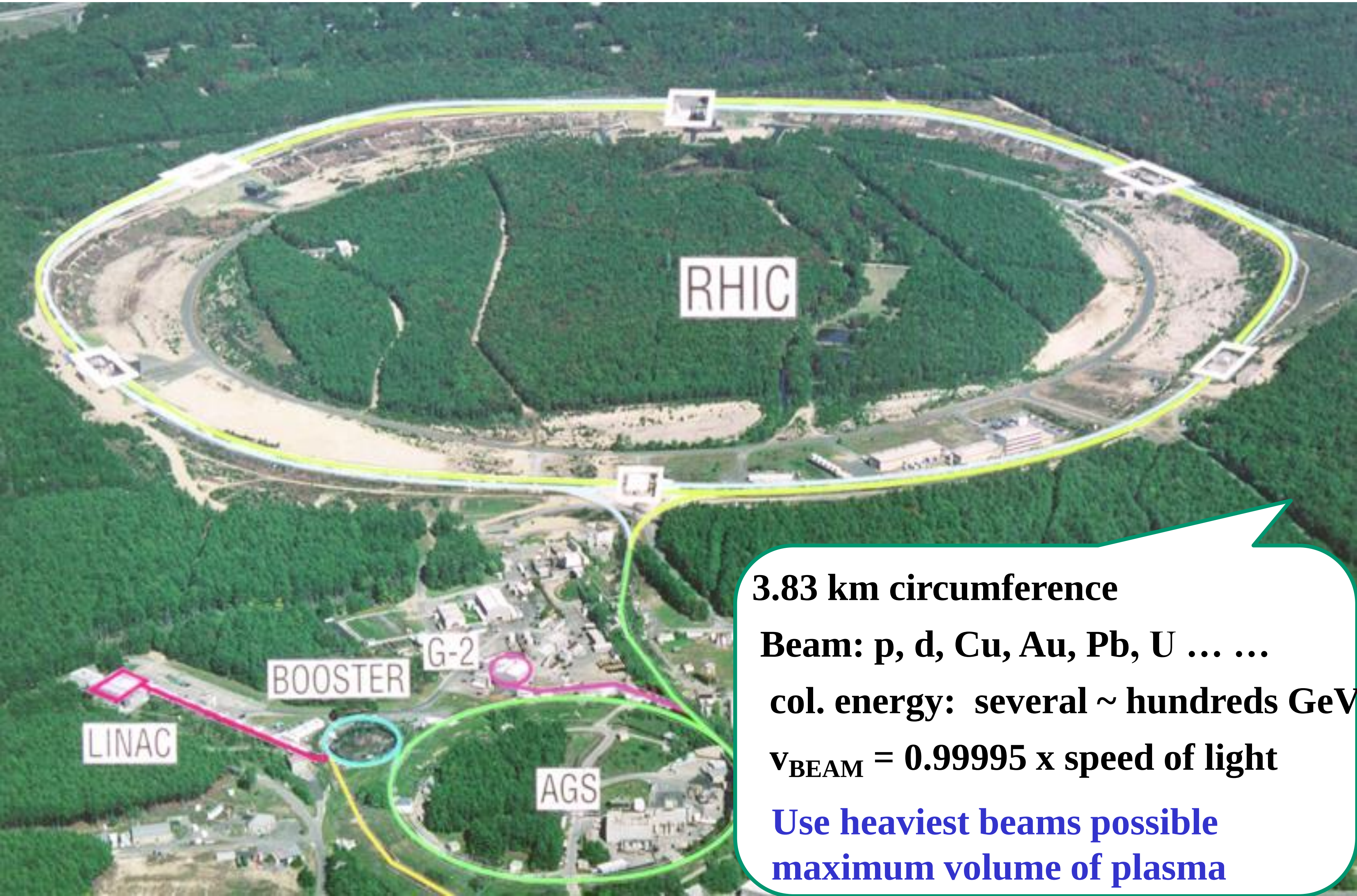
核子重如牛，对撞生新态

Relativistic Heavy Ion Collider



3.83 km circumference

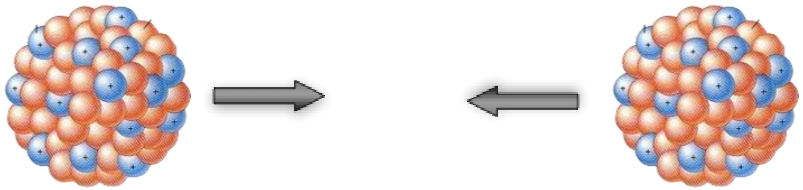
Beam: p, d, Cu, Au, Pb, U … …

col. energy: several ~ hundreds GeV

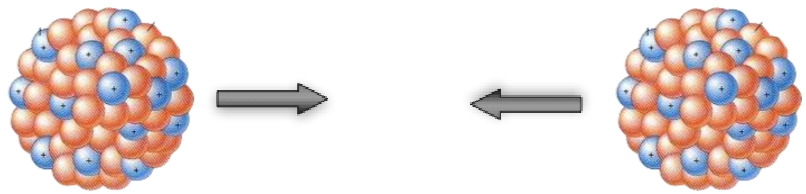
v_{BEAM} = 0.99995 x speed of light

Use heaviest beams possible
maximum volume of plasma

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

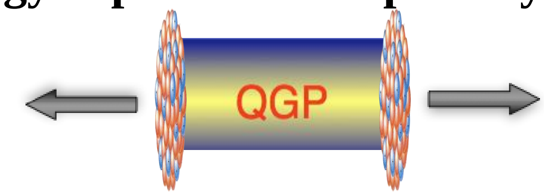


v_{BEAM} **= 0.99995 x speed of light**

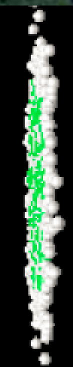


v_{BEAM} = 0.99995 x speed of light

Energy deposition in super tiny volume

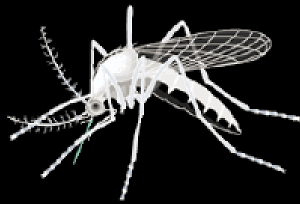


How much energy in each collision?



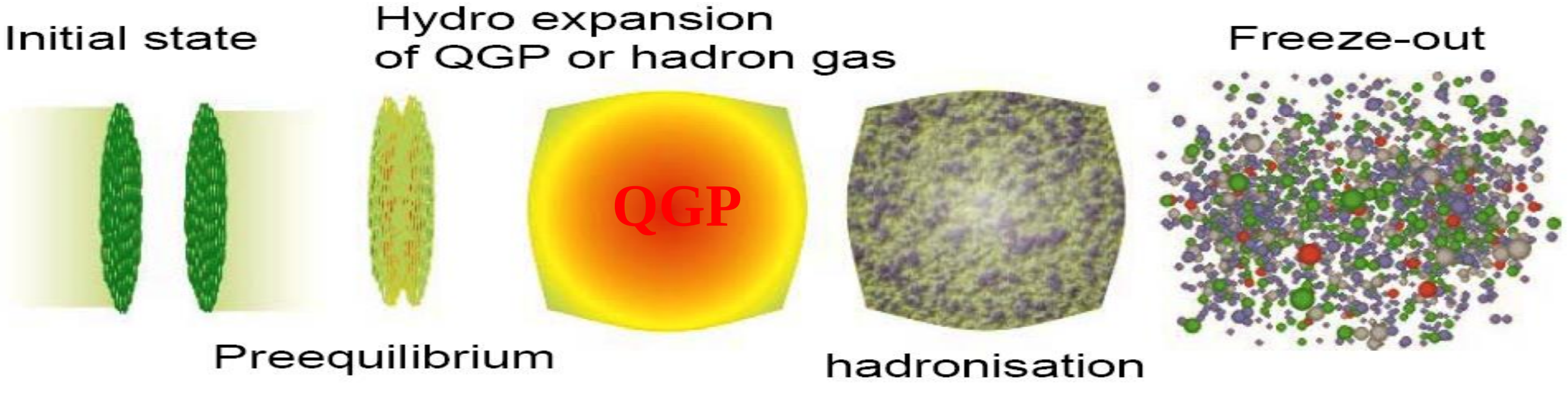
$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200GeV \sim 6\mu J$$

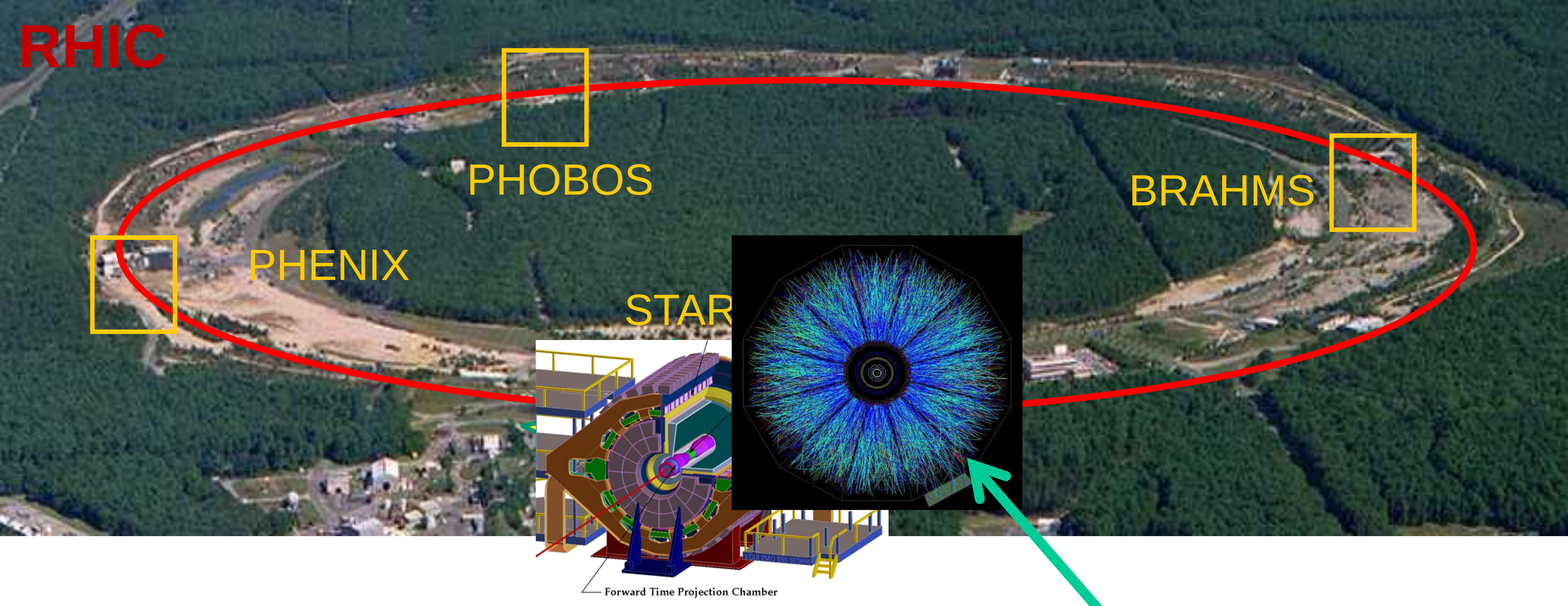
Consider two mosquitos colliding...



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

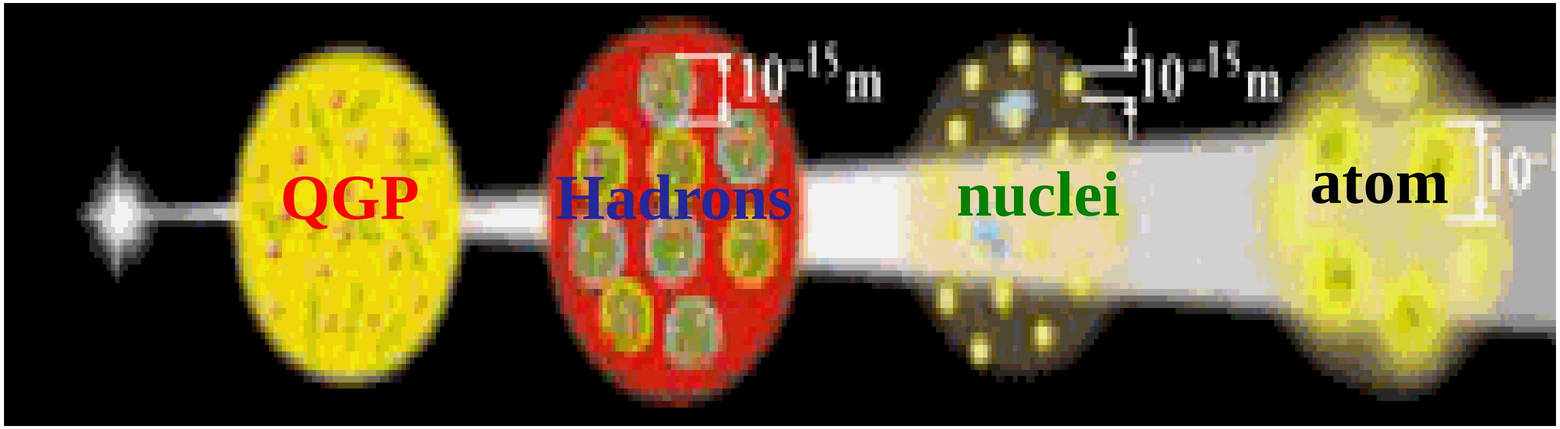
<u>little bang</u>: the different stage for a relativistic heavy ion collisions



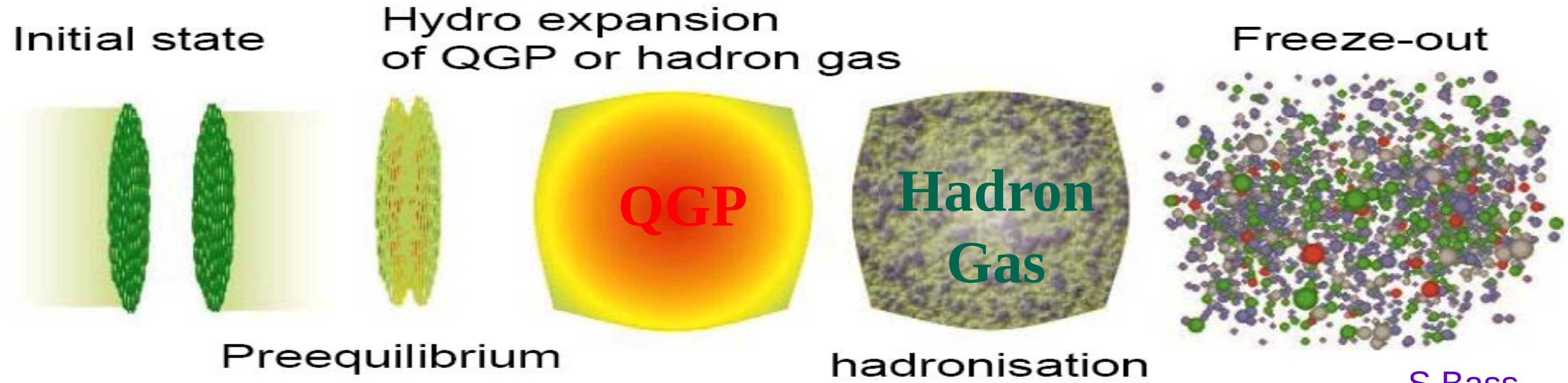


little bang: the different stage for a relativistic heavy ion collisions

<u>big bang</u>: the very early history of the universe



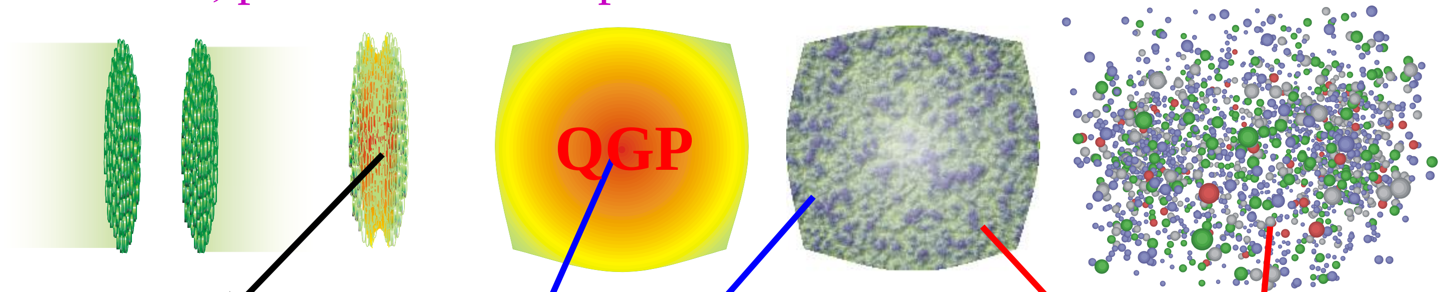
<u>little bang</u>: the different stage for a relativistic heavy ion collisions



S.Bass

Different stages for heavy ion collisions

ε, pressure builds up



Hard scattered or heavy q,g probes of plasma formed

γ, $\gamma^* \rightarrow e^+e^-$, $\mu^+\mu^-$

Real and virtual photons emitted as thermal radiation.

π, K, p, n, ϕ, Λ, Δ, Ξ, Ω, d,

Hadrons reflect (thermal) properties when inelastic collisions stop (chemical freeze-out).

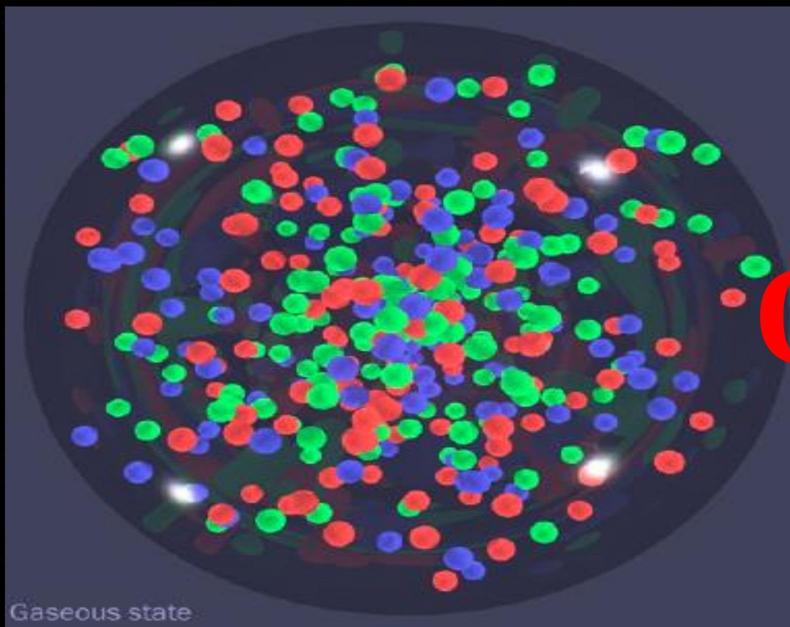
What State of Matter?

QGP

Does it act
like an ideal gas?

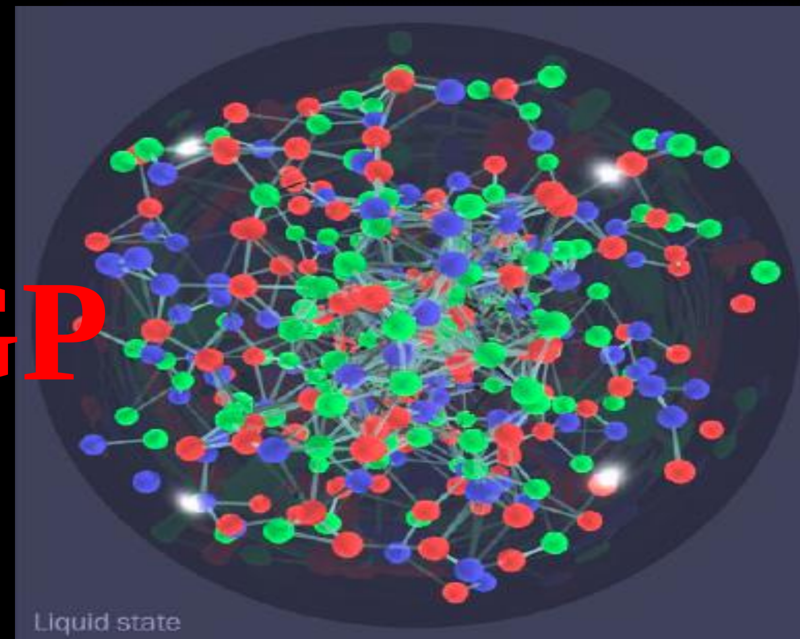
Does it flow,
like a (compressible) liquid?

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

Does it act like an ideal gas?

Does it flow, like a (compressible) liquid?

Movie

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*.

Secretary of Energy Samuel Bodman

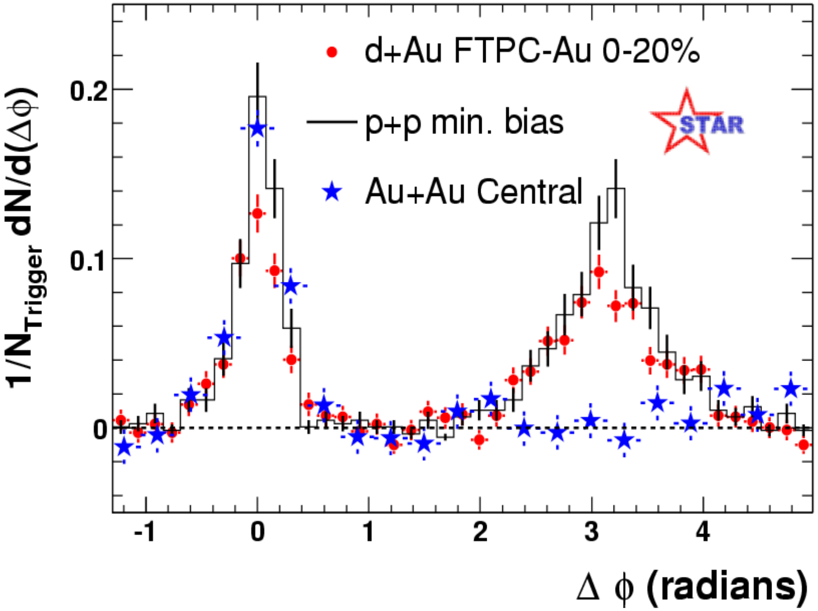
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics.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

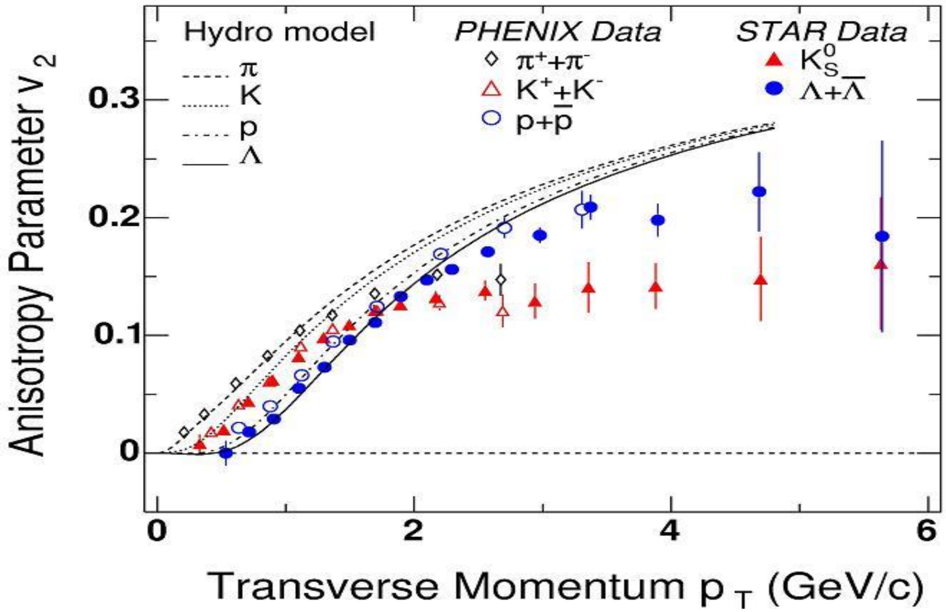
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

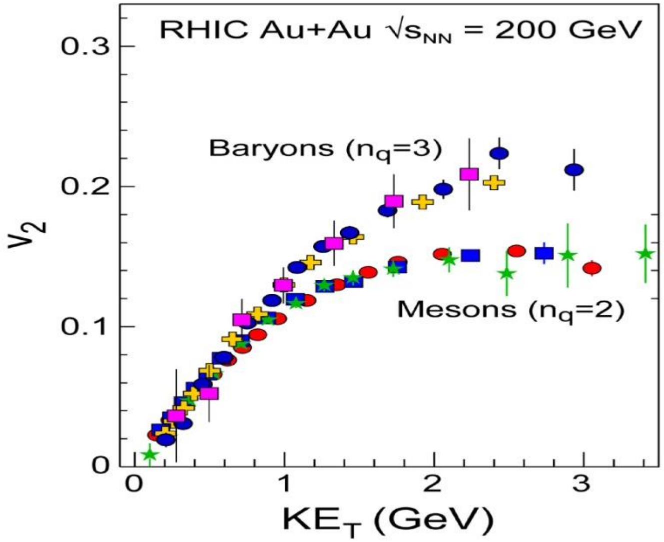
Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

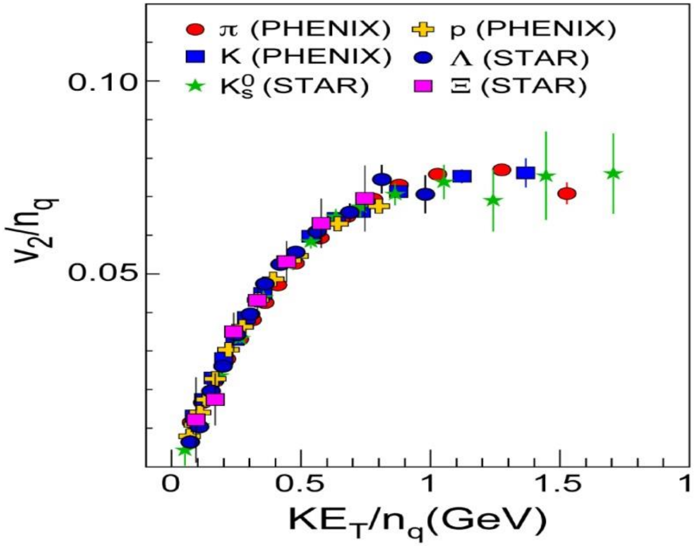
The QGP was discovered

RHIC (2000--   )







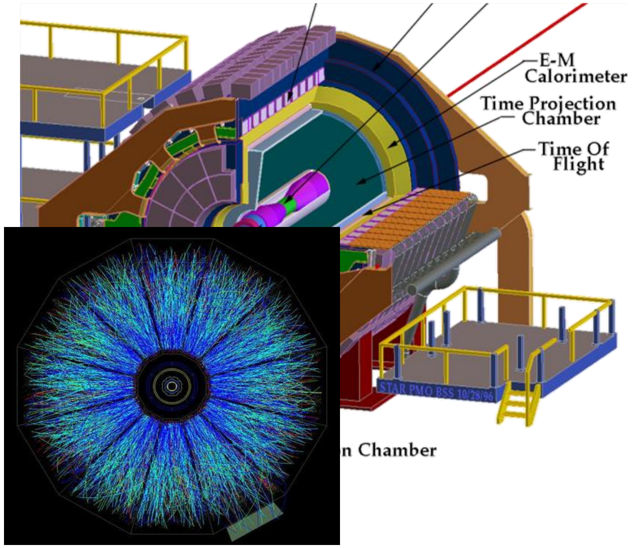


Theoretical tools for QGP evolution

Life time~ 10^{-23} s

size~ 10^{-14} m

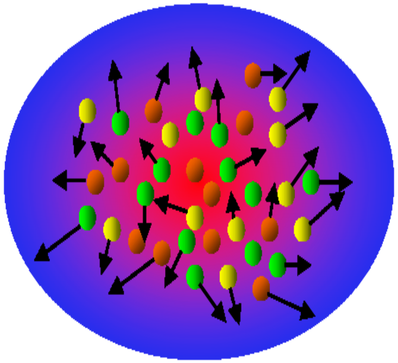
Numerical simulation



Dynamical Model

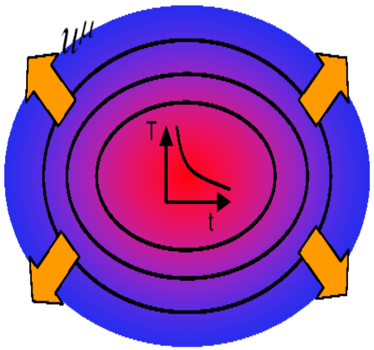
Boltzmann approach

microscopic view



Hydrodynamics

macroscopic view



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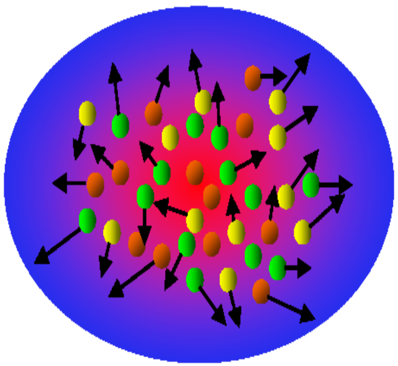

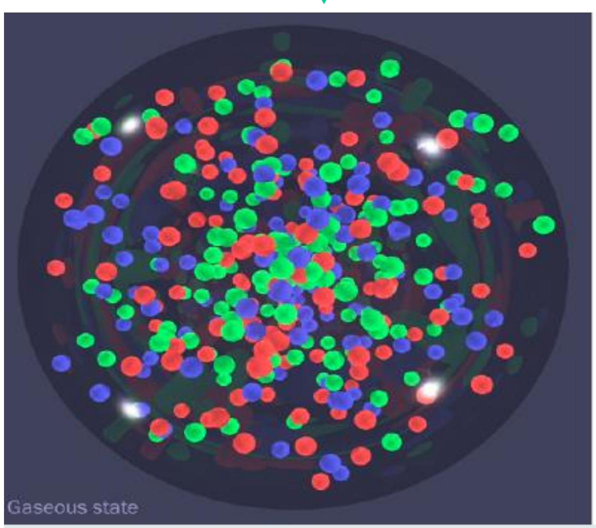

Gas: particles only know about each other when they bump

Hydrodynamics

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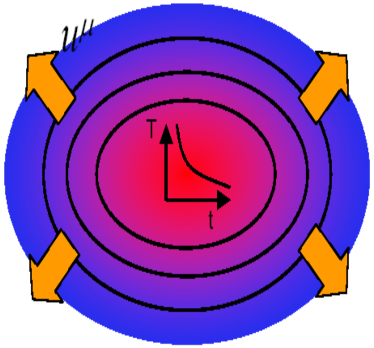
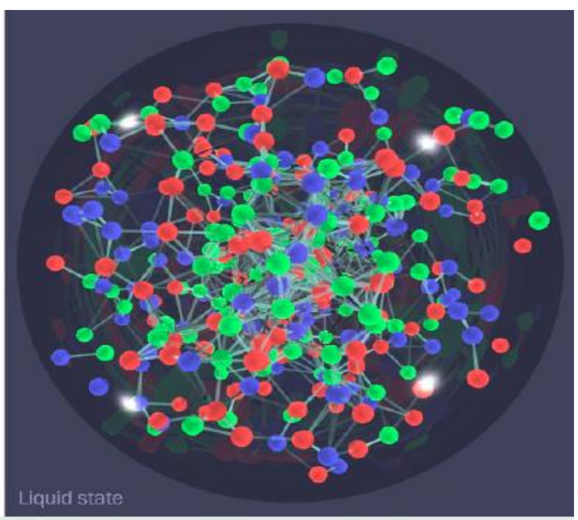
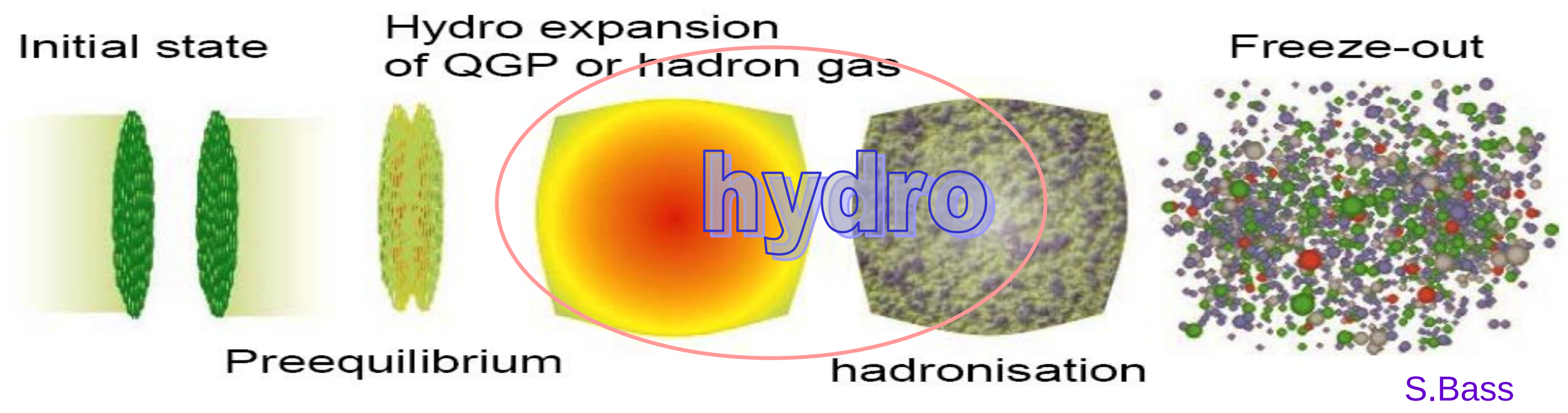




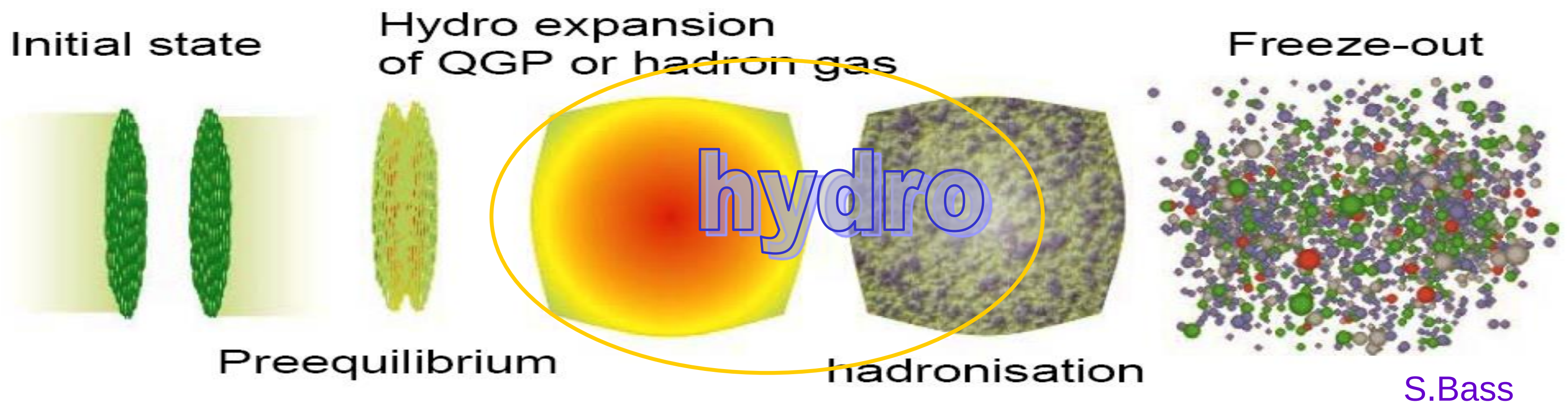
Liquid: particles exert forces on one another all the time, flows in a coordinated fashion

Hydrodynamics

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



hydrodynamics



Hydrodynamics:

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

Conservation laws

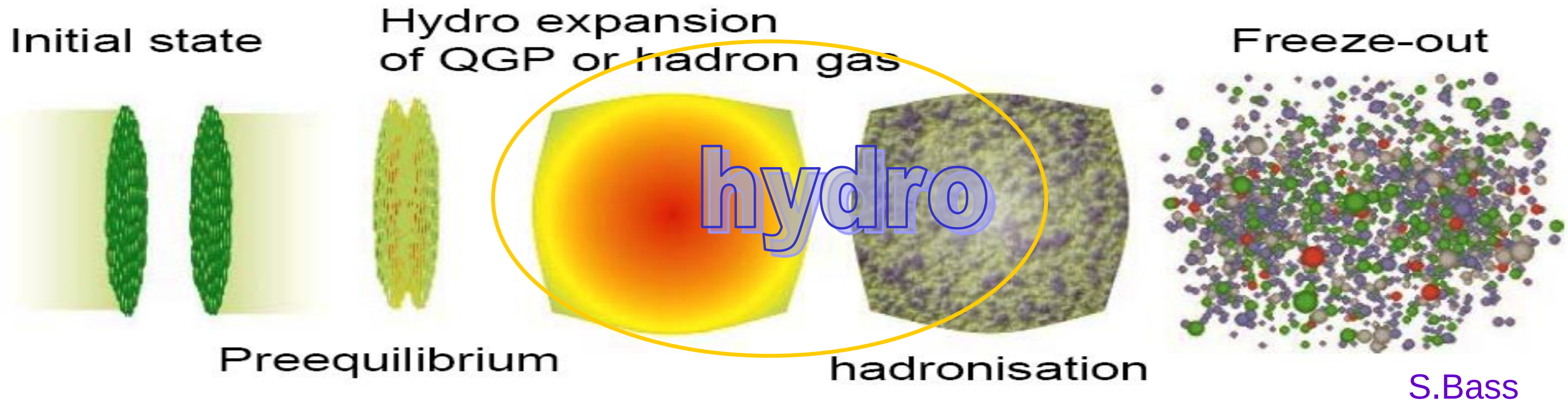
$$\partial_\mu N^\mu(x) = 0$$

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

5 equ. 14 independent variables

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

Ideal hydrodynamics



S.Bass

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Ideal hydrodynamics:

$$N^\mu = n u^\mu$$

$$T^{\mu\nu} = (\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$

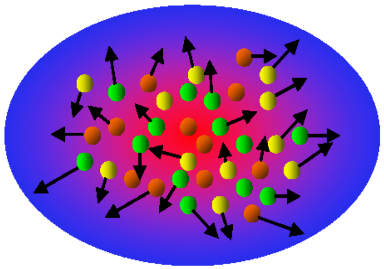
Input: "EOS" $\varepsilon = \varepsilon(p, n)$

$$\overbrace{N^\mu(4), T^{\mu\nu}(10)}^{(14)} \longleftrightarrow \overbrace{e, p, n, u(3)}^{(6)}$$

A brief comment on ideal hydro

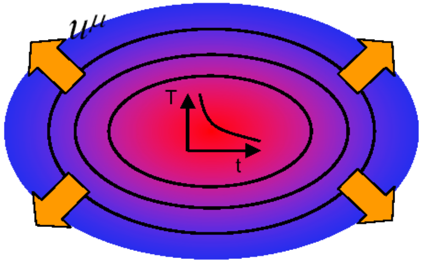
The basic assumption of ideal hydrodynamics : local equilibrium

microscopic view



$l_{m.f.p.} << L$

macroscopic view



Particle scattering rate >> flow expansion rate

-entropy is conserved $\partial_\mu S^\mu = 0$

-the independent variables is reduced $T^{\mu\nu}, \quad N^\mu$

$$f_{eq}(x,p) = \frac{1}{e^{[p.u(x)+\mu(x)]/T(x)} \pm 1}$$

$$T^{\mu\nu}(x) = \int \frac{d^3p}{E} p^\mu p^\nu (f_{eq} + \bar{f}_{eq}) = (\varepsilon + p)u^\mu u^\nu - p g^{\mu\nu}$$

$$N^\mu(x) = \int \frac{d^3p}{E} p^\mu (f_{eq} + \bar{f}_{eq}) = n u^\mu$$

$$\overbrace{N^\mu(4), T^{\mu\nu}(10)}^{(14)} \longleftrightarrow \overbrace{e, p, n, u(3)}^{(6)}$$

Ideal hydro vs viscous hydro

The basic assumption of ideal hydrodynamics : local equilibrium

-entropy is conserved $\partial_\mu S^\mu = 0$

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$$\overbrace{N^\mu(4), T^{\mu\nu}(10)}^{(14)} \longleftrightarrow \overbrace{e, p, n, u(3)}^{(6)}$$

The basic assumption of viscous hydro : near equilibrium

$$f(x,p) = f_{eq}(x,p) + \delta f(x,p)$$

$$T^{\mu\nu}(x) = \int \frac{d^3p}{E} p^\mu p^\nu (f + \bar{f}) = T^{\mu\nu}_{eq} + \delta T^{\mu\nu}$$

$$N^\mu(x) = \int \frac{d^3p}{E} p^\mu (f - \bar{f}) = N^\mu_{eq} + \delta N^\mu$$

Dissipative flow

Viscous hydrodynamics--theory

Tensor decomposition in frame of u^μ

$$N^\mu = nu^\mu + V^\mu \qquad (\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu)$$

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + (W^\mu u^\nu + W^\nu u^\mu) - \Pi\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$S^\mu = su^\mu + \phi^\mu$$

$$V^\mu u_\mu = 0 \qquad W^\mu u_\mu = 0 \qquad W^\mu = \frac{e+P}{n}V^\mu + q^\mu$$

$$\pi^{\mu\nu} u_\nu = 0 \qquad \pi^\mu_\mu = 0 \qquad \phi^\mu u_\mu = 0$$

Viscous terms

- V^μ charge flow
- W^μ energy flow
- Π bulk pressure
- $\pi^{\mu\nu}$ shear pressure tensor
- ϕ^μ entropy flow
- q^μ heat flow

$$N^\mu(4) \to n, V^\mu(3) \qquad T^{\mu\nu}(10) \to (p+\Pi), \varepsilon, W^\mu(3), \pi^{\mu\nu}(5)$$

Viscous hydrodynamics--theory

Choice of frame:

Eckart frame: $u_E^\mu = \dfrac{N^\mu}{\sqrt{N \cdot N}}$ $\quad V^\mu = 0, \qquad q^\mu = W^\mu$

Landau frame: $u_L^\mu = \dfrac{T_\nu^\mu u_L^\nu}{\sqrt{u_L^\alpha T_\alpha^\beta T_{\beta\gamma} u_L^\gamma}}$ $\quad W^\mu = 0, \qquad q^\mu = -\dfrac{e+p}{n} V^\mu$

-RHIC & LHC, low net baryon density– choose Landau frame: $W^\mu = 0,$

-The previous 3 independent variables in $W^\mu(3)$ are then replaced by $u^\mu(3)$

General conservation laws

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

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

more equ. for these viscous terms

-Phenomenologically: $\partial_\mu S^\mu \geq 0$

-From kinetic theory $p^\mu d_\mu f(\vec{x}, t, \vec{p}) = C(x)$

I-S formulism: phenomenological approach

-Thermodynamics: $s = \beta p - \alpha n + \beta e$ $\quad Ts = p - \mu n + e, \quad \alpha = \mu / T, \beta = 1/T$

-Relativistic, equilibrium: $S^{\mu} = p\beta^{\mu} - \alpha N_{eq}{}^{\mu} + \beta_{\nu} T_{eq}{}^{\mu\nu}$ $\quad \alpha = \mu / T, \beta^{\mu} = u^{\mu} / T$

-Relativistic, off equilibrium: $S^{\mu} = p\beta^{\mu} - \alpha(N_{eq}{}^{\mu} + \delta N^{\mu}) + \beta_{\nu}(T_{eq}{}^{\mu\nu} + \delta T^{\mu\nu})$

$+ Q^{\mu}(\delta N^{\mu}, \delta T^{\mu\nu})$

$$T\partial_{\mu} S^{\mu} \geq 0$$

2nd order and higher order corrections

I-S formulism: phenomenological approach

-Thermodynamics: $s = \beta p - \alpha n + \beta e \qquad Ts = p - \mu n + e, \quad \alpha = \mu / T, \beta = 1/T$

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$+ Q^\mu(\delta N^\mu, \delta T^{\mu\nu})$

2nd order and higher order corrections

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

$$T\partial_\mu S^\mu = \prod X - q^\mu X_\mu + \pi^{\mu\nu} X_{\mu\nu} + T\partial_\mu Q^\mu \geq 0$$

$$X \equiv -\theta = -\nabla \cdot u, \quad X^\mu \equiv -\frac{nT}{e+p} \nabla^\mu \left(\frac{\mu}{T}\right), \quad X^{\mu\nu} = \nabla^{<\mu} u^{\nu>} \equiv \sigma^{\mu\nu}$$

$$Q_\mu = 0$$

$$\Pi = -\zeta\theta = \zeta X$$

$$q^\mu = \kappa\left(\nabla^\mu T - T\dot{u}^\mu\right) = \kappa X^\mu$$

$$\pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} = 2\eta X^{\mu\nu}$$

I-S formulism: phenomenological approach

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-a simple case for second order theory (without heat flow& bulk pressure)

$$T\partial_{\mu} S^{\mu} = \prod X - q^{\mu} X_{\mu} + \pi^{\mu\nu} X_{\mu\nu} + T\partial_{\mu} Q^{\mu} \geq 0$$

$$Q^{\mu} = -\left(\beta_2 \pi^{\lambda\nu} \pi_{\lambda\nu}\right)\frac{u^{\mu}}{2T}, \quad (\Pi = 0, \ q^{\mu} = 0)$$

A. Muronga 00-04 W. Israel, J.Stewart 79

$$T\partial_{\mu} S^{\mu} = \pi^{\alpha\beta}[\sigma_{\alpha\beta} - \beta_2 \Delta^{\mu\alpha}\Delta^{\nu\beta} D\pi_{\mu\nu} + \frac{T}{2}\partial_{\lambda}\left(\frac{\beta_2}{T}u^{\lambda}\right)\pi_{\alpha\beta} - 2\pi^{\alpha(\mu}\omega_{\alpha}^{\nu)}]$$

$$T\partial_{\mu} S^{\mu} = \frac{\pi_{\alpha\beta}\pi^{\alpha\beta}}{2\eta} \geq 0$$

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

I-S formulism: phenomenological approach

-Thermodynamics: $s = \beta p - \alpha n + \beta e$ $\quad Ts = p - \mu n + e, \quad \alpha = \mu / T, \beta = 1/T$

-Relativistic, equilibrium: $S^{\mu} = p\beta^{\mu} - \alpha N_{eq}{}^{\mu} + \beta_{\nu} T_{eq}{}^{\mu\nu}$ $\quad \alpha = \mu / T, \beta^{\mu} = u^{\mu} / T$

-Relativistic, off equilibrium: $S^{\mu} = p\beta^{\mu} - \alpha(N_{eq}{}^{\mu} + \delta N^{\mu}) + \beta_{\nu}(T_{eq}{}^{\mu\nu} + \delta T^{\mu\nu})$
$+ Q^{\mu}(\delta N^{\mu}, \delta T^{\mu\nu})$

<u>-full second order theory</u> A. Muronga 00-04 W. Israel, J.Stewart 79

$$Q^{\mu} = -(\beta_0 \Pi^2 - \beta_1 q^{\mu} q_{\mu} + \beta_2 \pi_{\mu\nu}\pi^{\mu\nu})\frac{u^{\mu}}{2T} - \frac{\alpha_0 \Pi q^{\mu}}{T} + \frac{\alpha_1 \pi^{\mu\nu} q_{\nu}}{T},$$

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

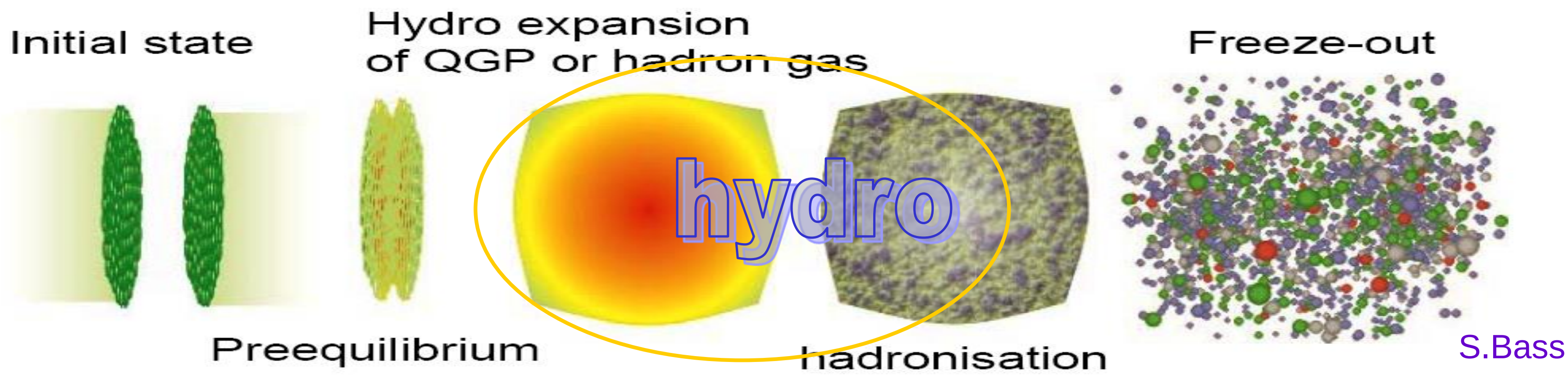
$$\Delta^{\mu}_{\nu}\dot{q}^{\nu} = -\frac{1}{\tau_q}\left[q_{\mu} + \lambda\frac{nT^2}{e+p}\nabla^{\mu}\frac{\nu}{T} + l_{q\pi}\nabla_{\nu}\pi^{\mu\nu} + l_{q\Pi}\nabla^{\mu}\Pi - \lambda T^2 q^{\mu}\partial_{\mu}\left(\frac{\tau_q u^{\mu}}{2\lambda T^2}\right)\right],$$

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

$\Big\}\; T\partial_{\mu} S^{\mu} \geq 0$

$\tau_{\Pi} = \zeta\beta_0, \quad \tau_q = \lambda T\beta_1, \quad \tau_{\pi} = 2\eta\beta_2 \qquad \tau_0 = \zeta\alpha_0, \quad \tau_1 = \lambda T\alpha_1, \quad \tau_2 = 2\eta\alpha_1$

Viscous hydrodynamics



Conservation laws:

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

2nd order I-S equ:

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

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

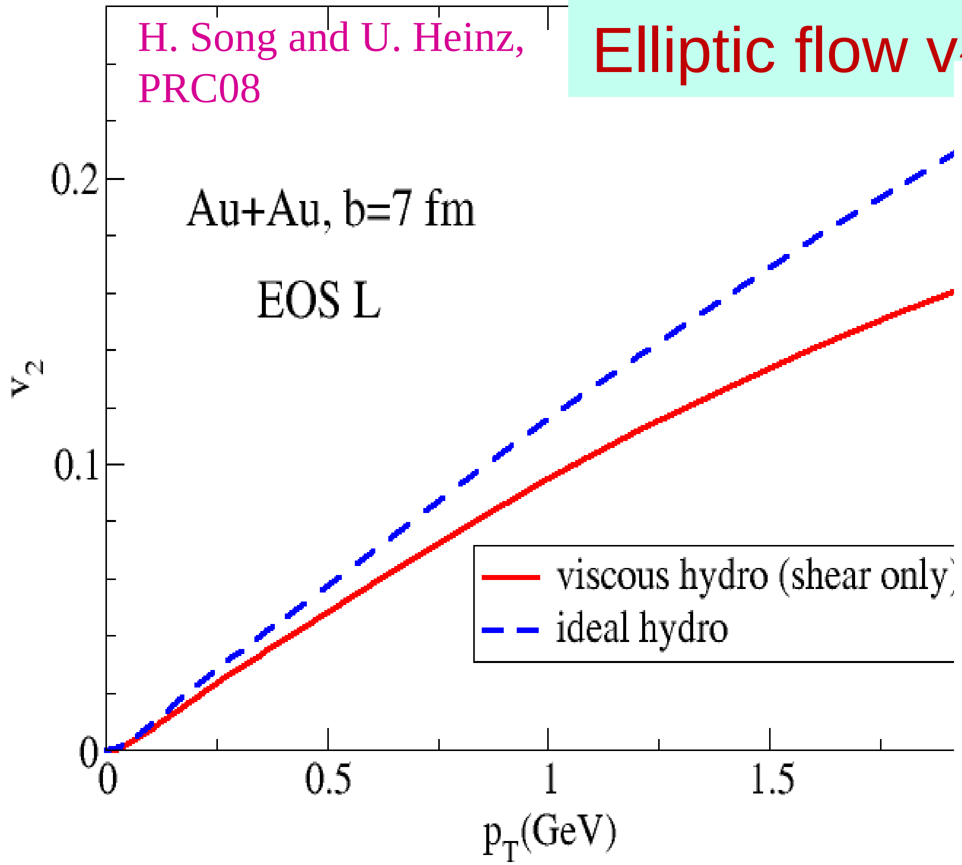
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - l_{\pi q}\nabla^{\langle\mu}q^{\nu\rangle} + \pi_{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

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

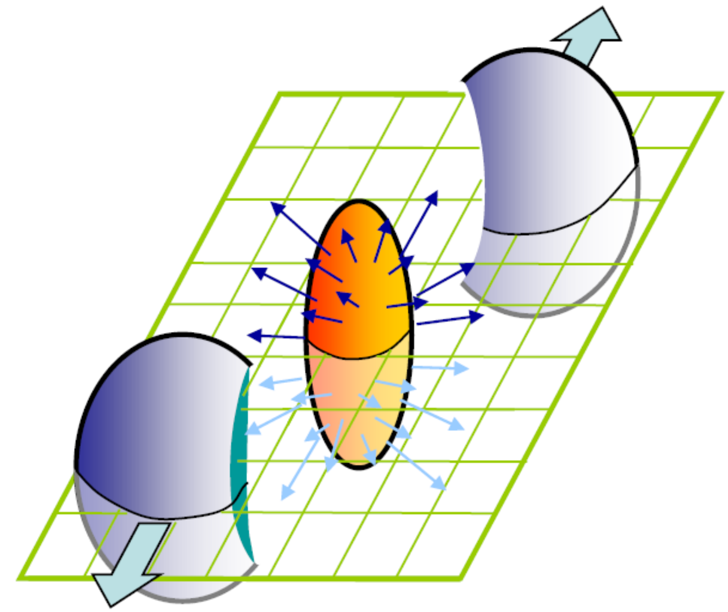
Viscous hydro: Shear viscosity η & elliptic flow v_2

H. Song and U. Heinz, PRC08

Elliptic flow v_2



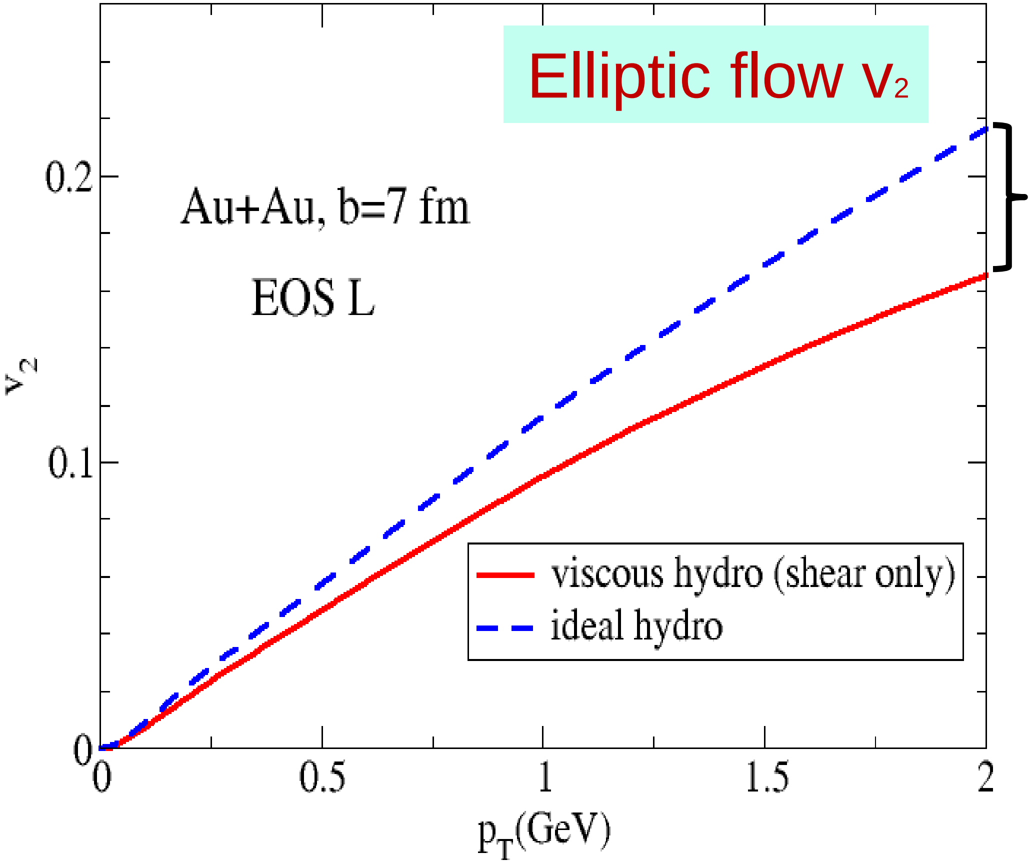
Elliptic flow



$$E\frac{dN}{d^3p}=\frac{dN}{dyp_Tdp_Td\varphi}$$

$$=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_2\cos(2\varphi)+...]$$

Viscous hydro: Shear viscosity η & elliptic flow V2



20-25% v_2 suppression $\frac{\eta}{s} = \frac{1}{4\pi}$

H. Song and U. Heinz, PLB08

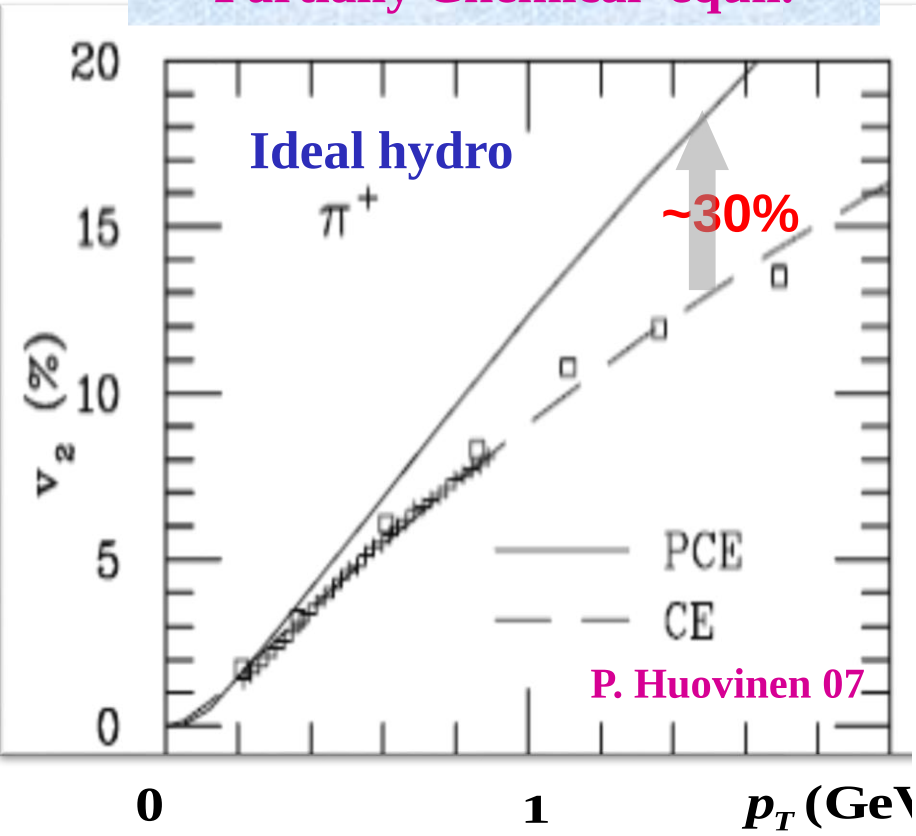
H. Song and U. Heinz, PRC08

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

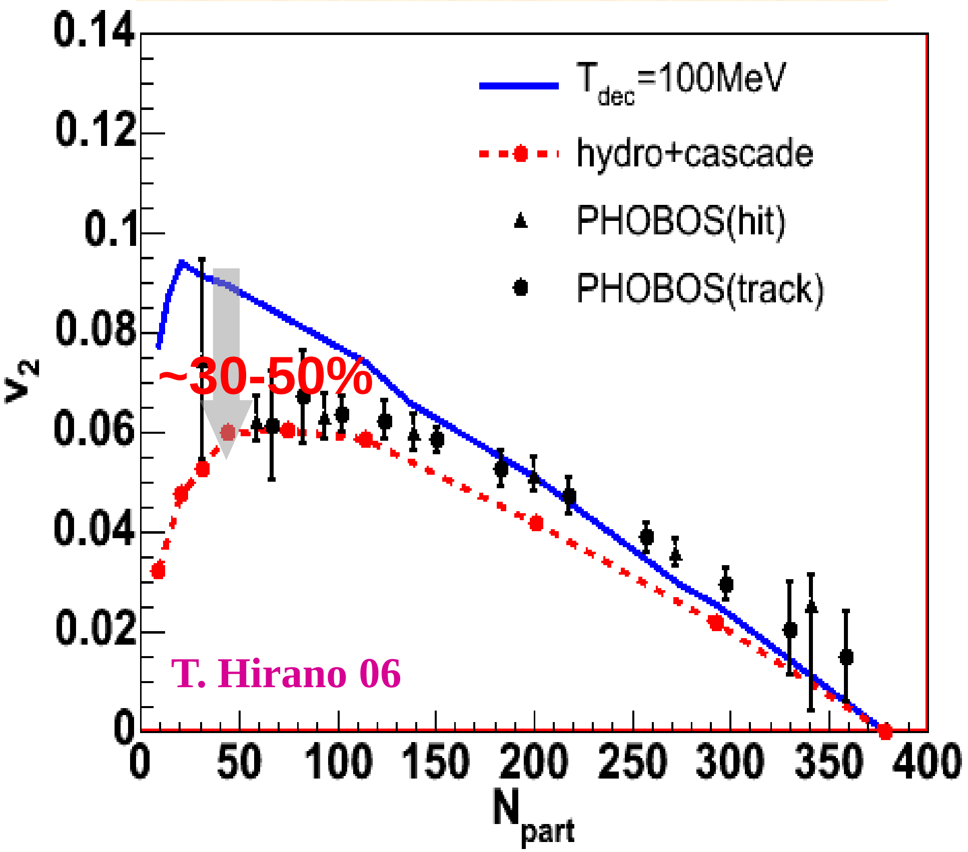
-**V2** can be used to extract the QGP shear viscosity

Effect from Hadronic evolution

Partially Chemical equil.



hadronic dissipative effects

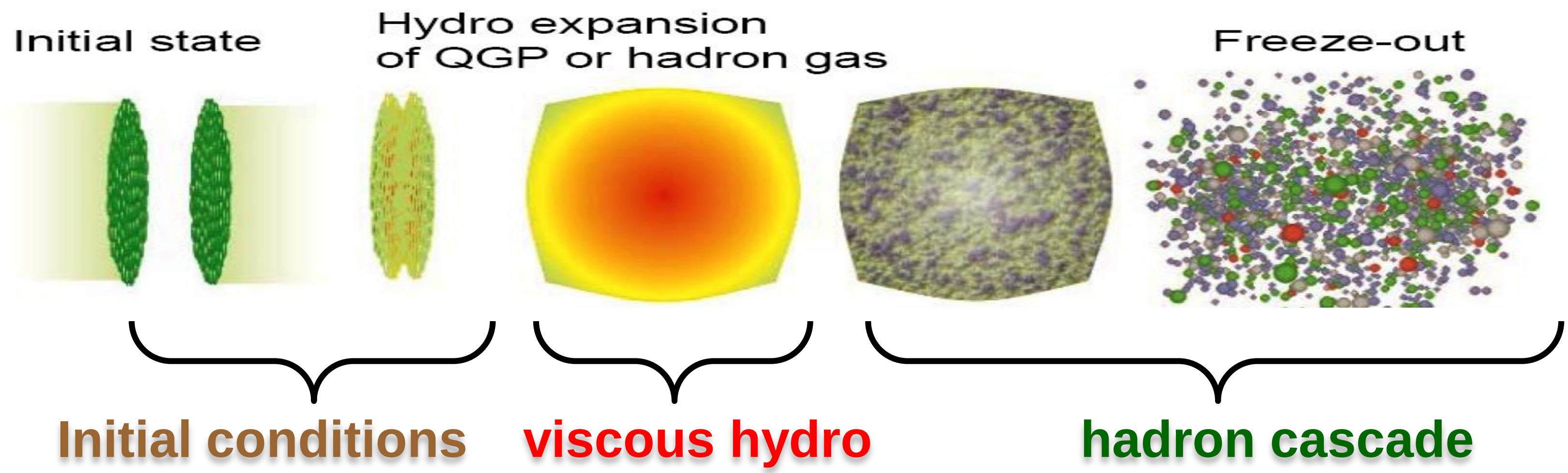


-These two HRG effects are not included in early viscous hydro calculations

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

URQMD includes the partially chemical equilibrium nature & hadronic dissipative effects

VISHNU & iEBE-VISHNU hybrid approach



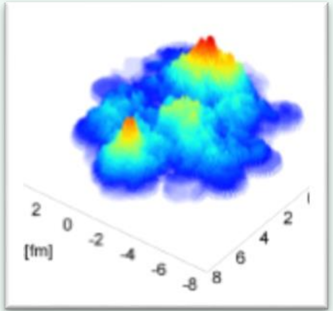
VISHNU: H. Song, S. Bass, U. Heinz, PRC2011

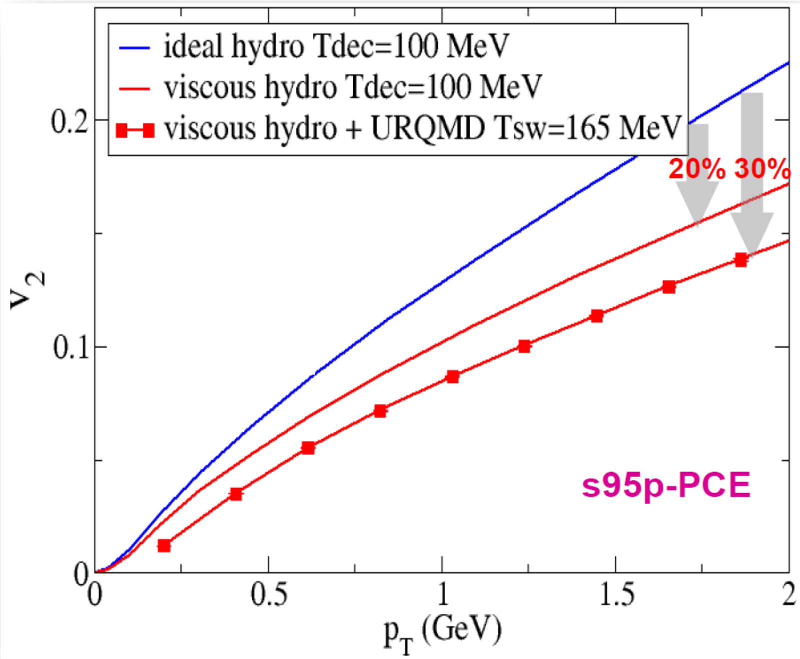
- -initial conditons
- -Viscous hydro (VISH2+1)
- -Hadron Cascade
- -EoS: (s95p-PCE, etc)

iEBE- VISHNU:

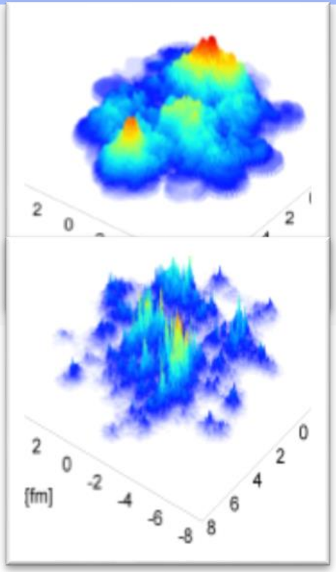
- -Event-by-Event VISHNU

Shen, Qiu, Song et al CPC2016





Initialization Models



-fluctuations of nucleon positions:

MC-Glauber:
MC-KLN: } T. Hirano & Y. Nara, Phys. Rev. C 79 064904 (2009)

-fluctuations of color charges or gluon number

IP-Glasma: Schenke, Tribedy & Venugopalan PRC, PRL2012

-early flow & fluctuations from dynamical models:

URQMD initialization: H.Petersen & M. Bleicher, Phys. Rev. C81, 044906,2010

AMPT initialization: L. Pang, Q.Wang & X.Wang, PRC 2012
H. Xu Z.Li and H. Song PRC2016

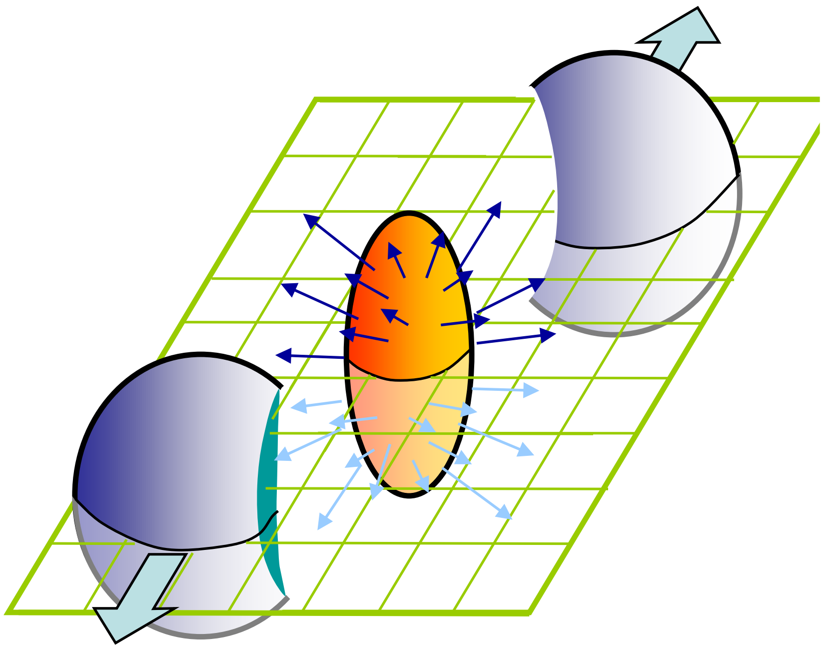
EPOS/NEXUS initialization: K. Werner et al., Phys. Rev. C83:044915,2011;
H. J. Drescher et, al., Phys.Rev. C65 , 054902 (2002)

-Parameterized initial condition:

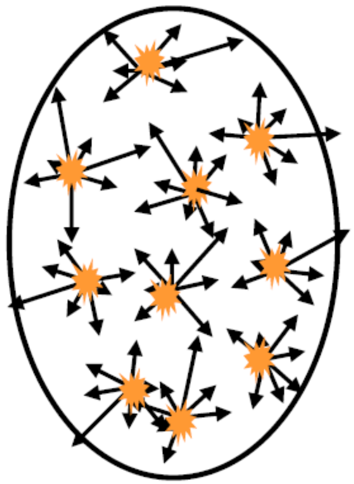
Trento initialization: S. Moreland, J. E. Bernhard and S.A. Bass, Phys. Rev. C92no.1, 011901 (2015)

Collective Flow

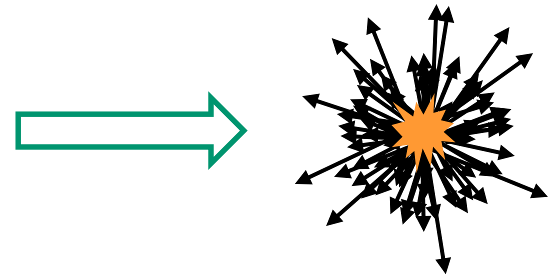
Collective expansion



Superposition of independent p+p:

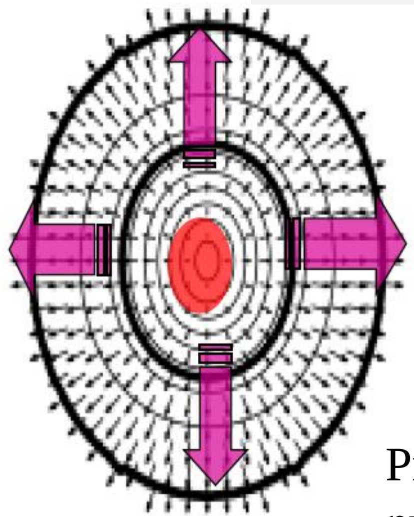


final particle emission

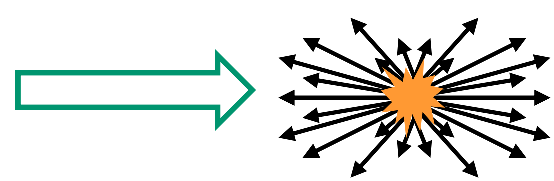


momenta pointed at random relative to reaction plane

Evolution as a bulk system



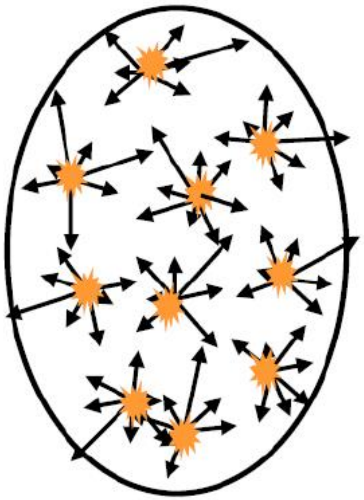
final particle emission

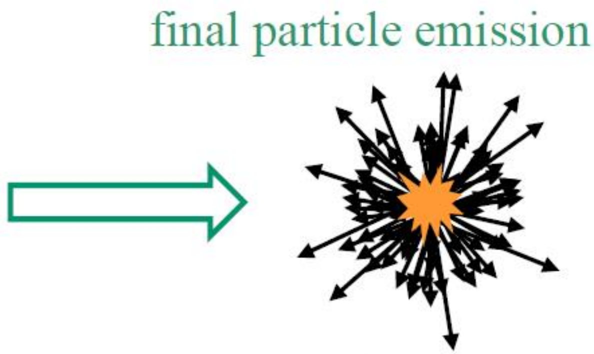


Pressure gradients (larger in-plane) push bulk "out" → "flow"

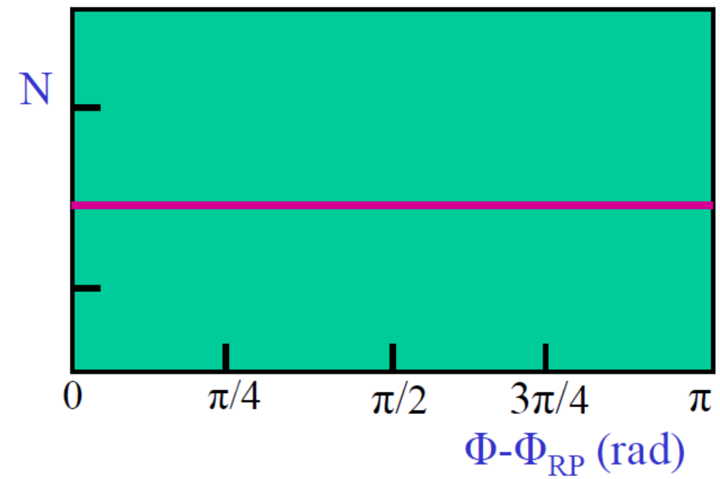
Azimuthal distributions

Superposition of independent p+p:

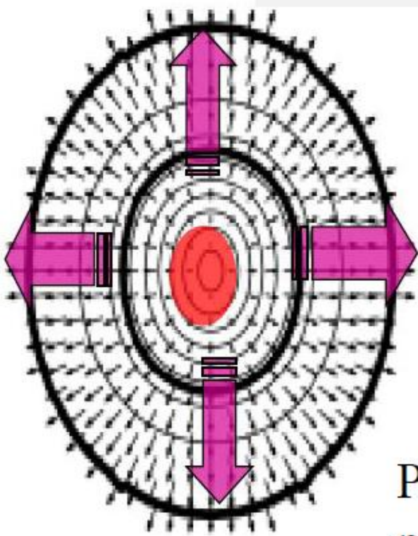


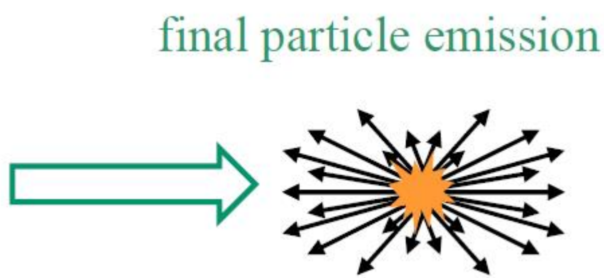


momenta pointed at random
relative to reaction plane

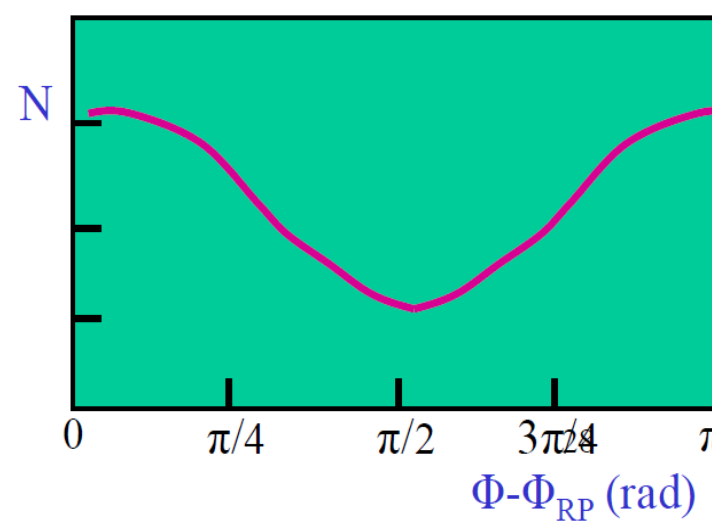


Evolution as a bulk system



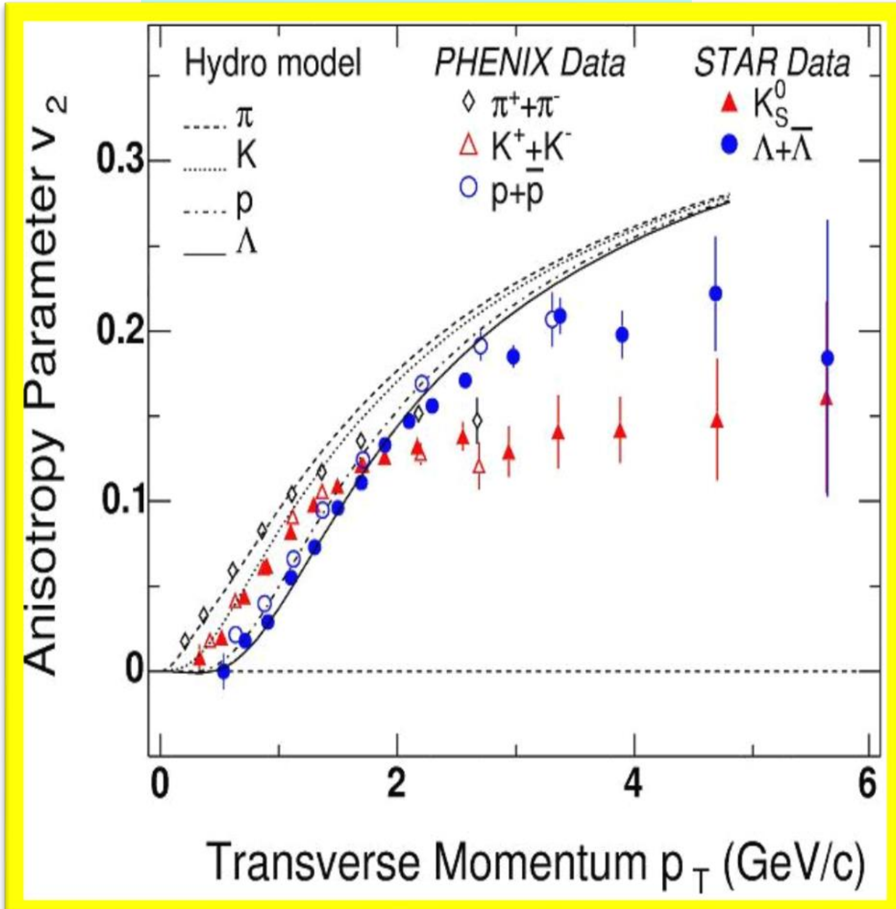


Pressure gradients (larger in-plane)
push bulk "out" → "flow"

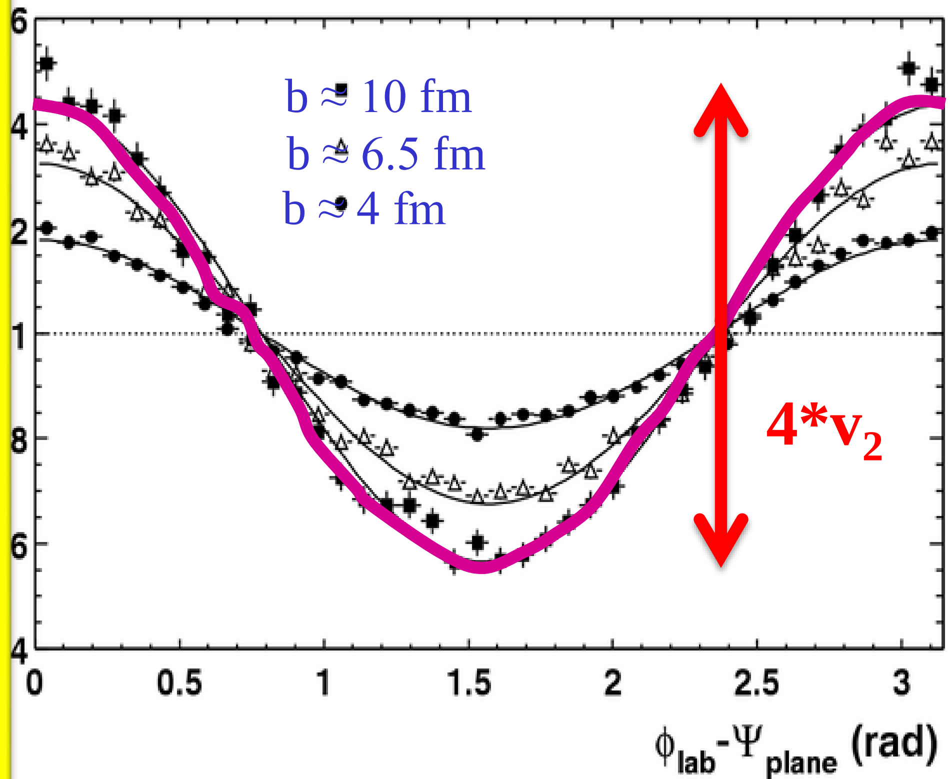


Elliptic Flow

Azimuthal distributions

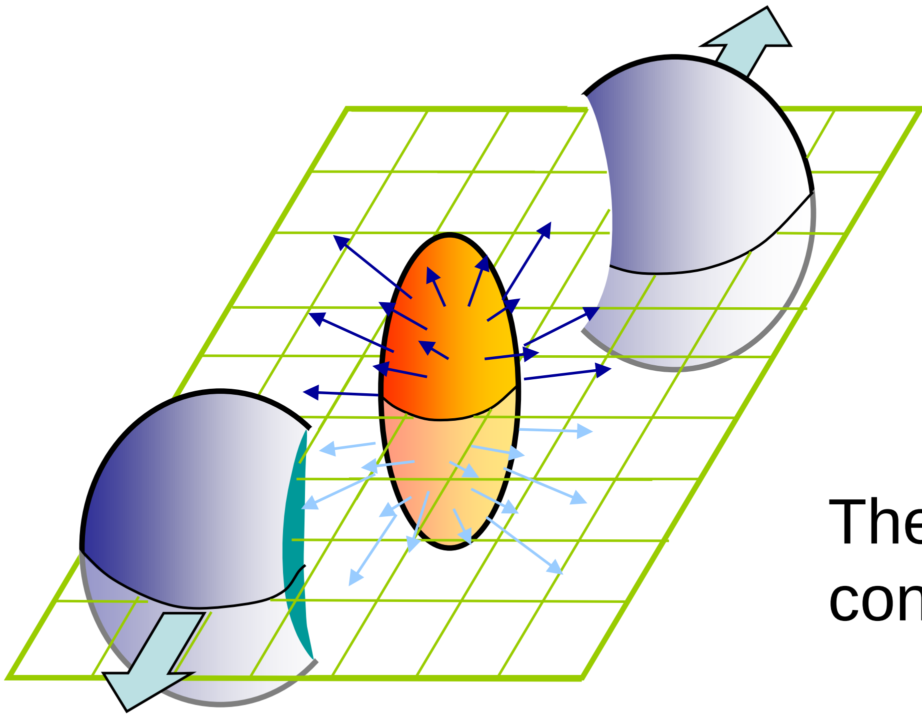


STAR, PRL**90** 032301 (2003)



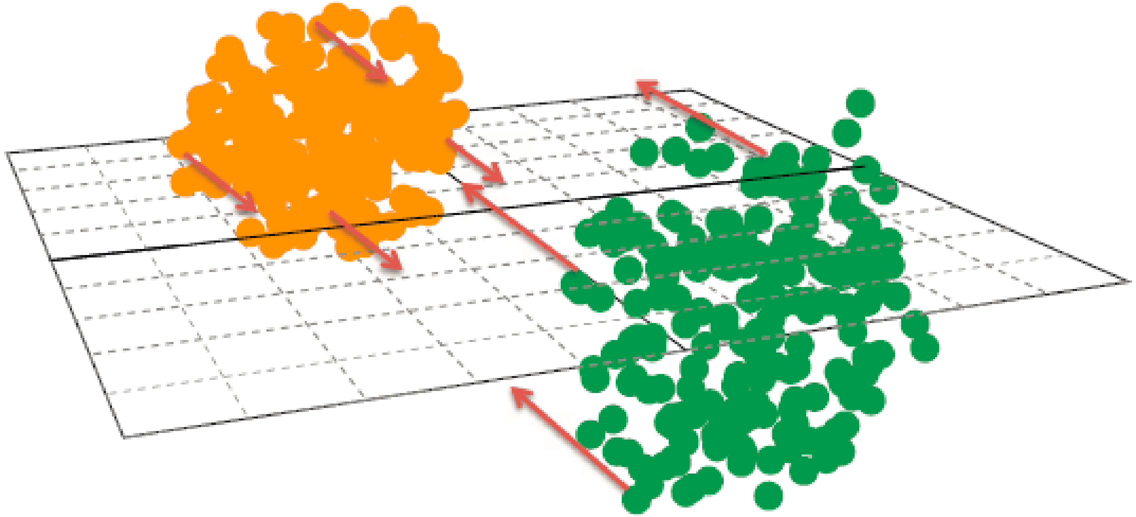
$$E\frac{dN}{d^3p}=\frac{dN}{dyp_Tdp_Td\varphi}=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_2(p_T,b)\cos(2\varphi)+\ldots]$$

Instead of two smooth colliding nuclei

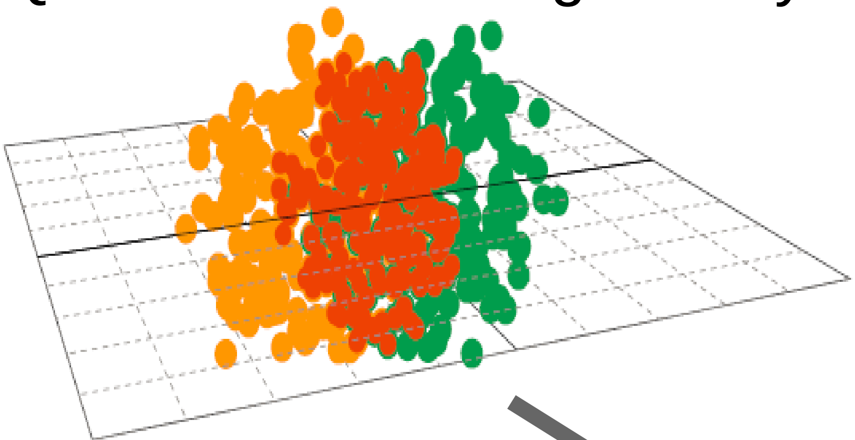


Initial stage fluctuations

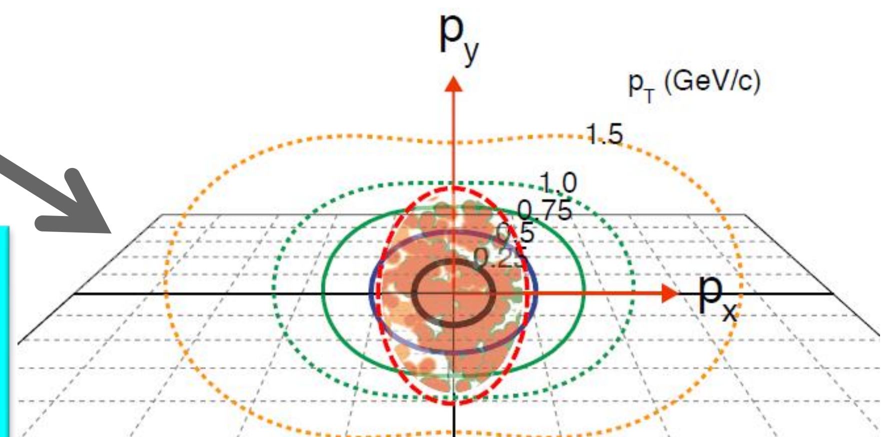
The position of initial nucleons constantly fluctuate



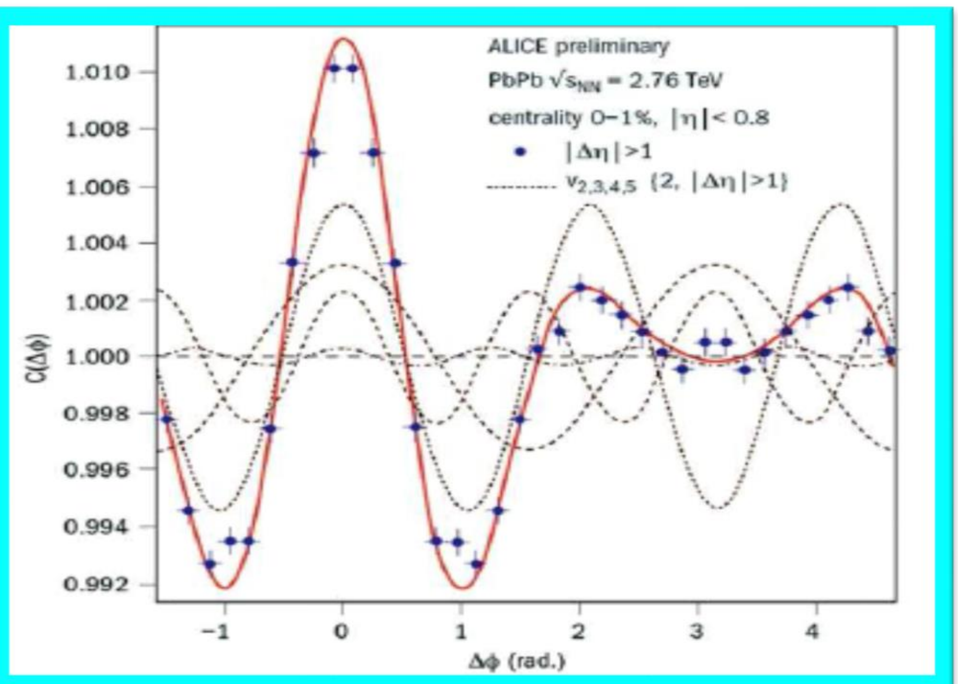
QGP with fluctuating density



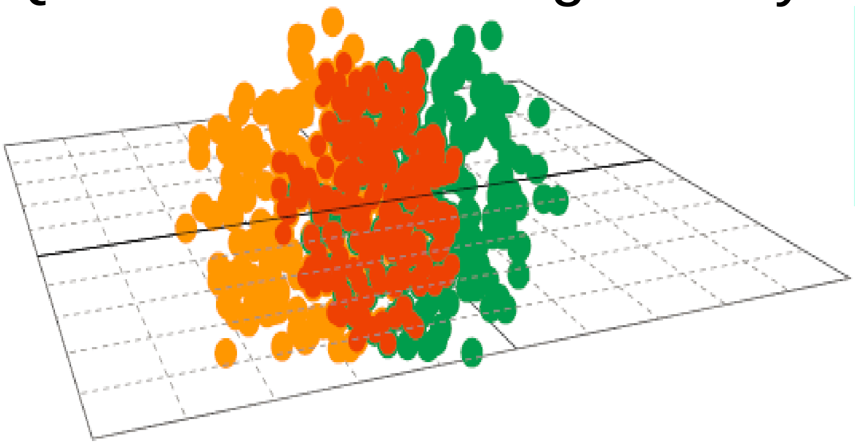
Azimuthal distribution in p-space



→measured flow: v_n

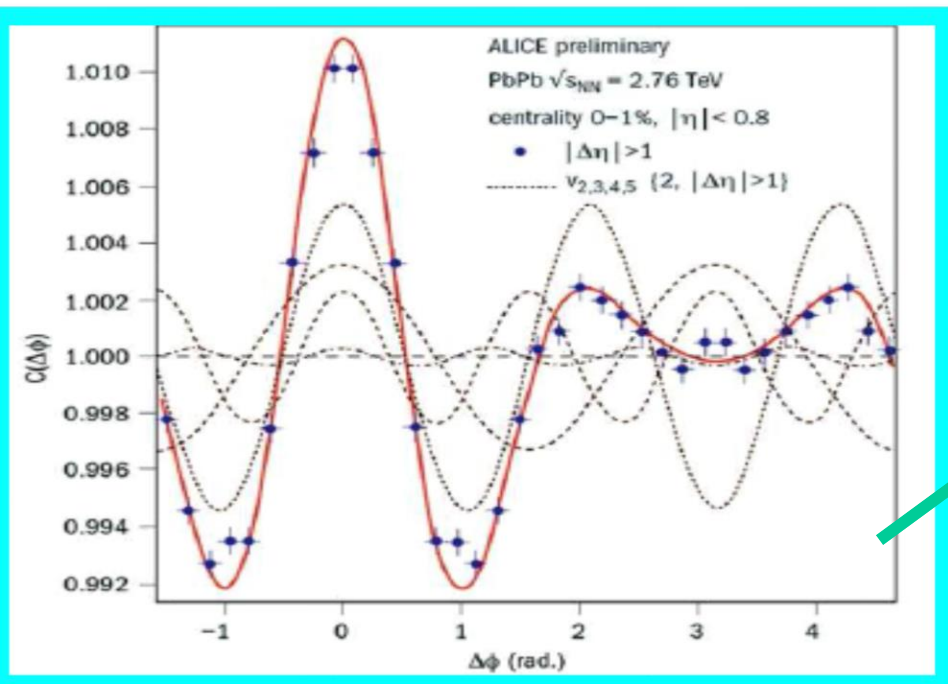


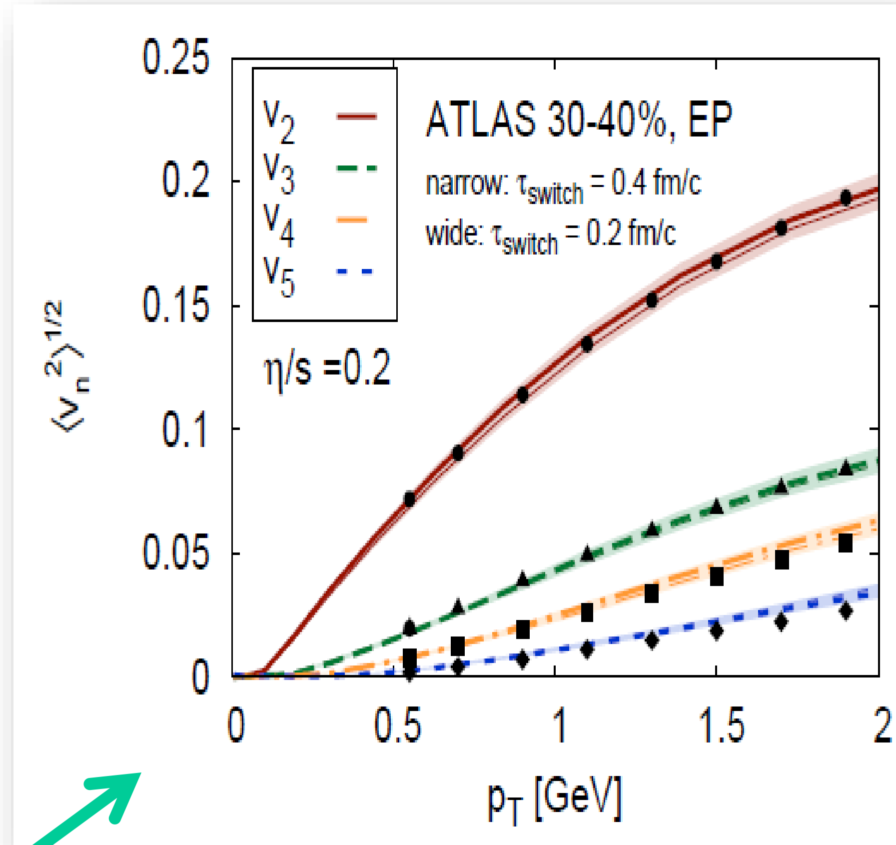
QGP with fluctuating density



Elliptic Flow & higher order flow harmonics

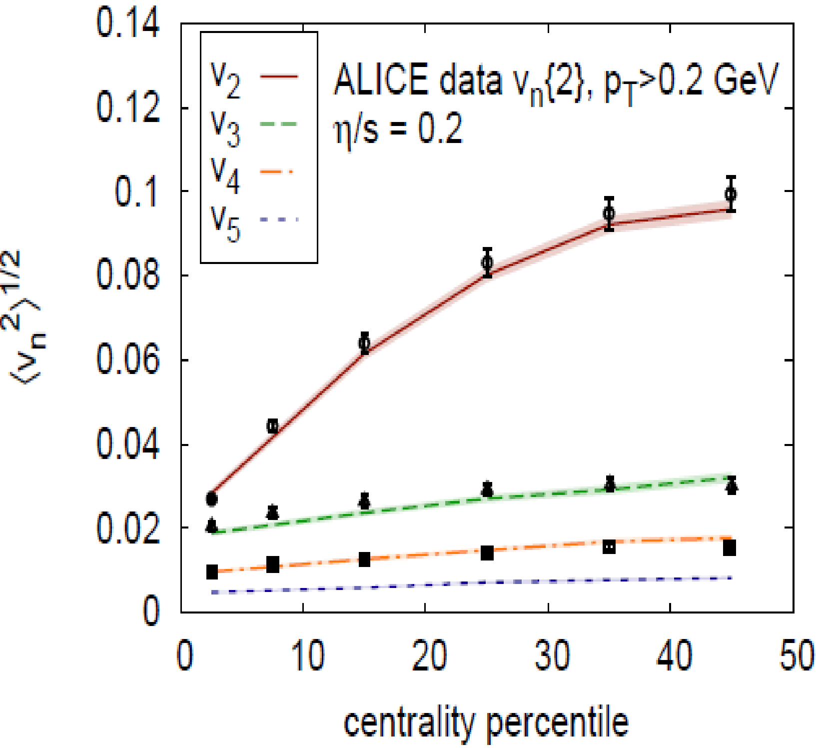
→measured flow: v_n

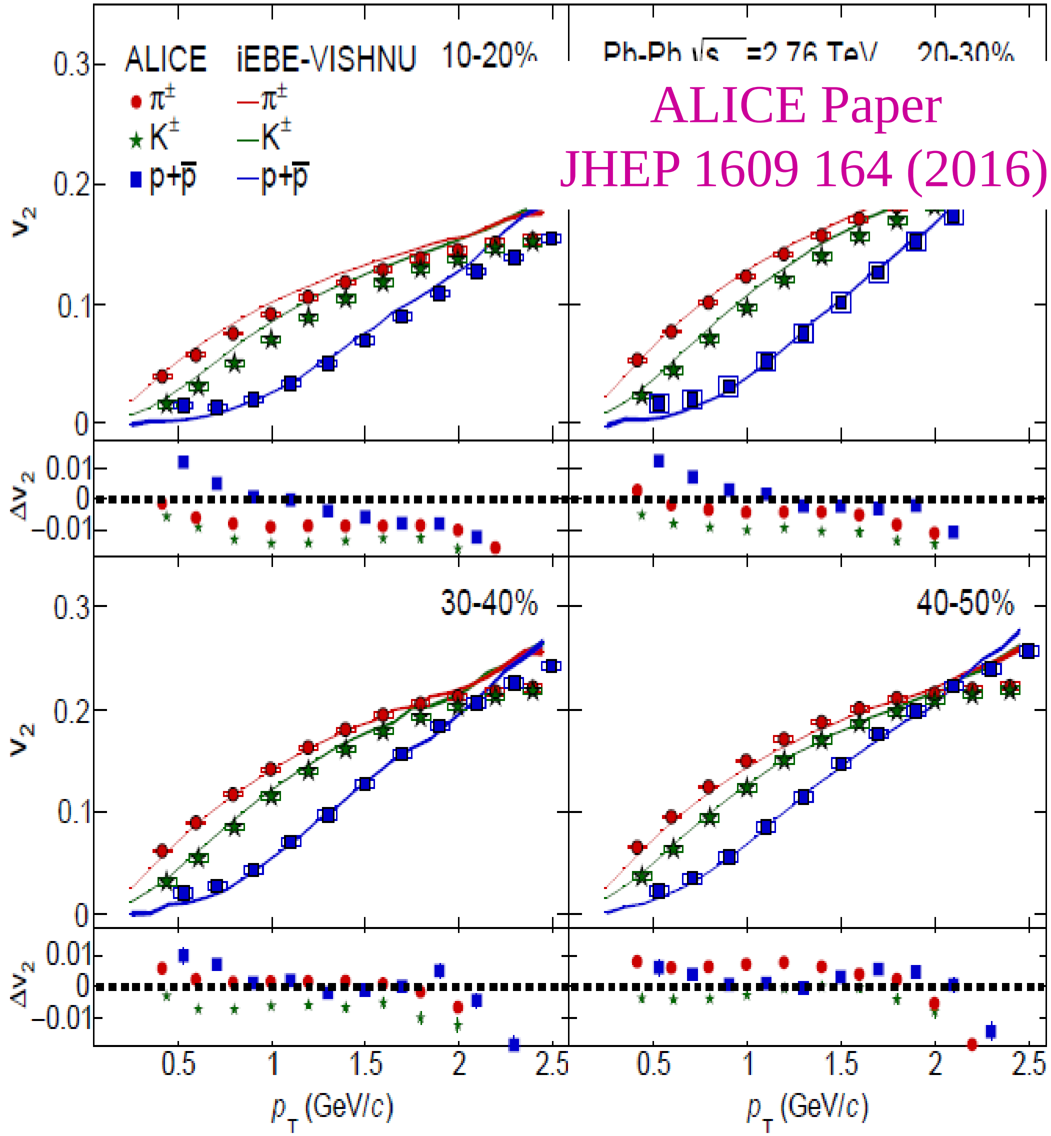




$$N(\phi) \propto 1 + 2v_1 \cos(\phi) + 2{\color{red}v_2} \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots$$

The Success of Hydrodynamics





ALICE Paper
JHEP 1609 164 (2016)

-Hydro + IP-Glasma

Gale, et. Al, PRL2013

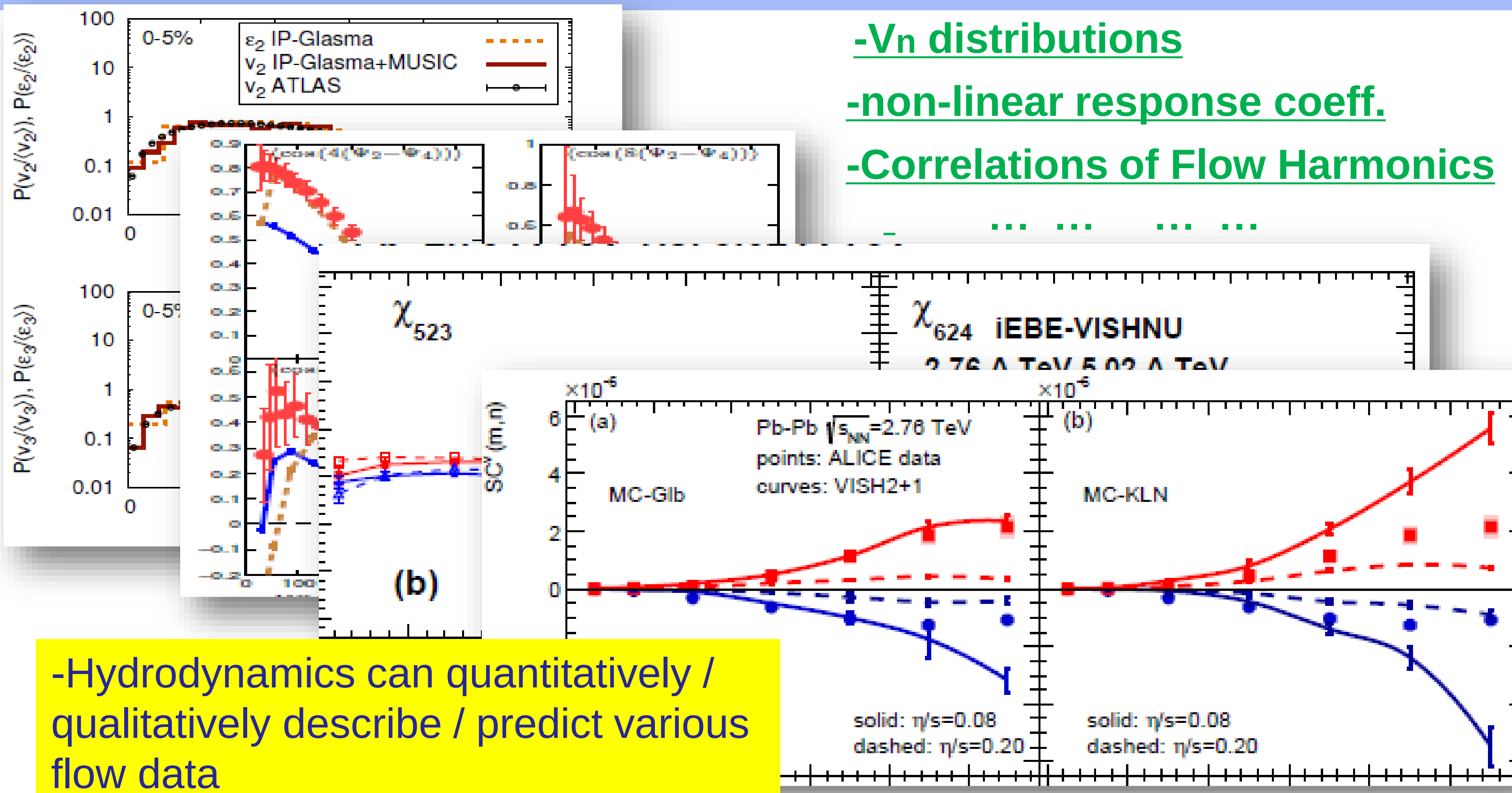
-iEBE-VISHNU + AMPT

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**
- **… … … …**

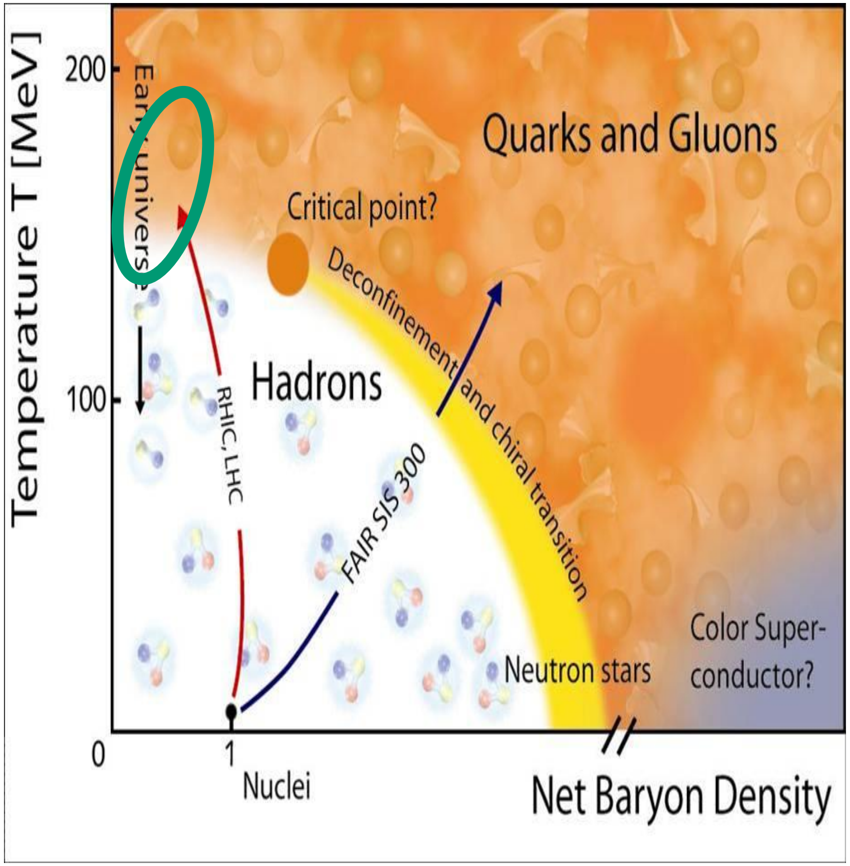


-Hydrodynamics can quantitatively / qualitatively describe / predict various flow data

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

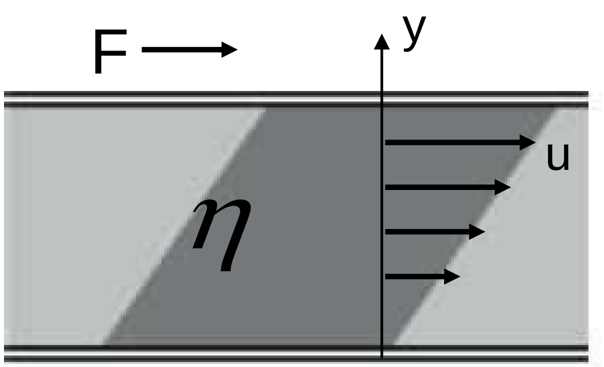
@ top RHIC and LHC energies

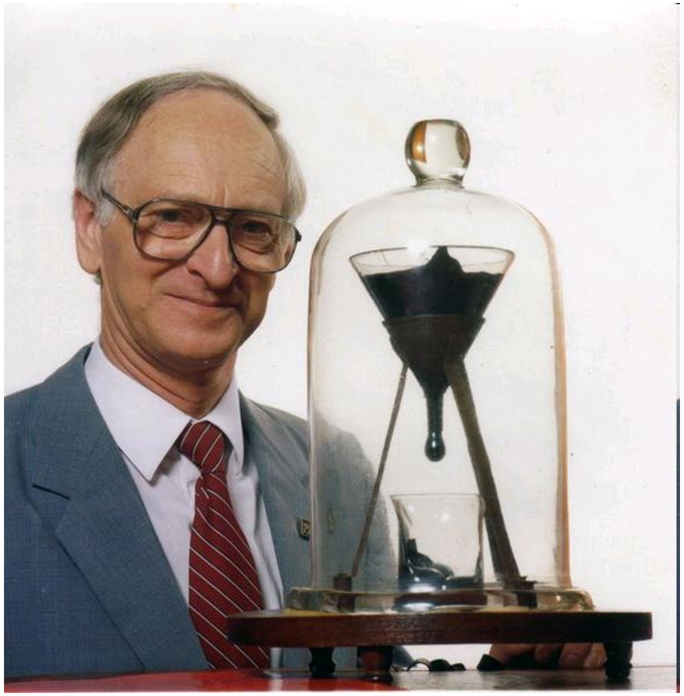


Shear Viscosity

-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.

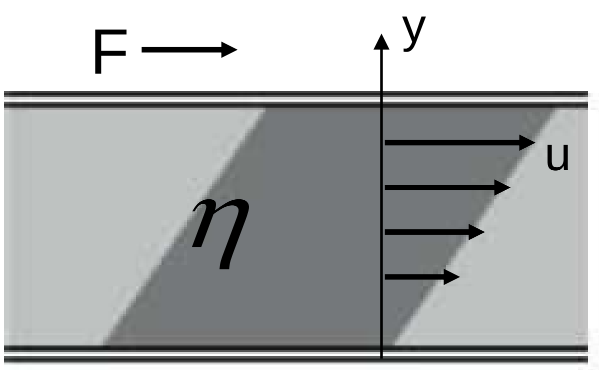
Longest running experiment (1927-present)
8 drops so far, none ever seen fall!

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

Lowest bound of specific shear viscosity

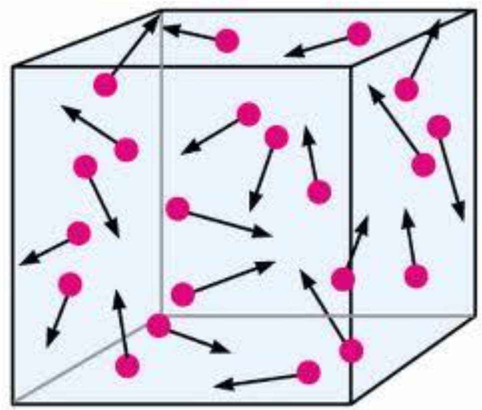
-classical definition:

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



-kinetic theory:

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

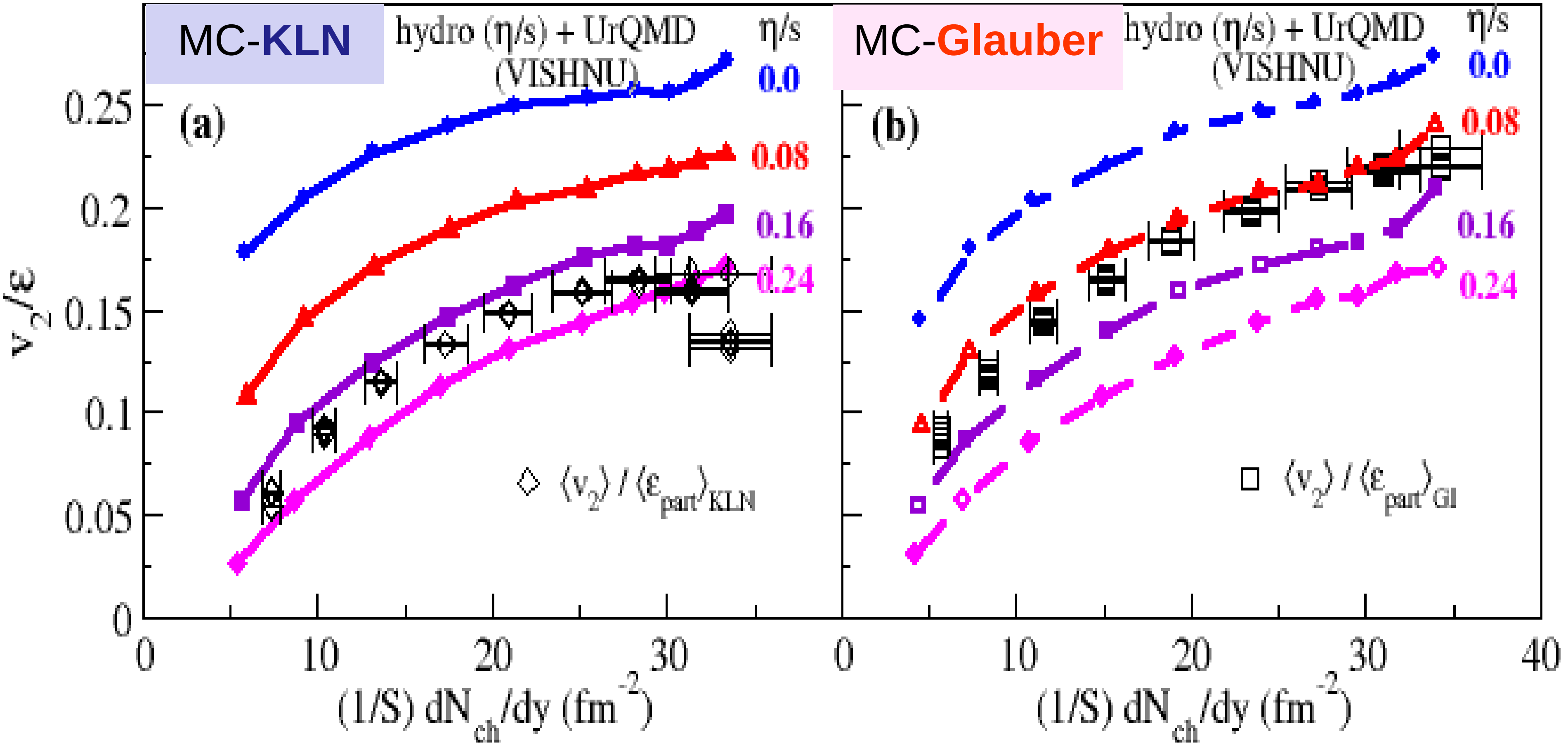


$$\frac{\eta}{s} \sim \frac{1}{k_B}\bar{v}ml_{mfp} \quad \sim \frac{1}{k_B}(\frac{1}{2}m\bar{v}^2)(\frac{l_{mfp}}{\bar{v}}) \sim \frac{e\tau}{k_B} \quad (s \sim k_B n)$$

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

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

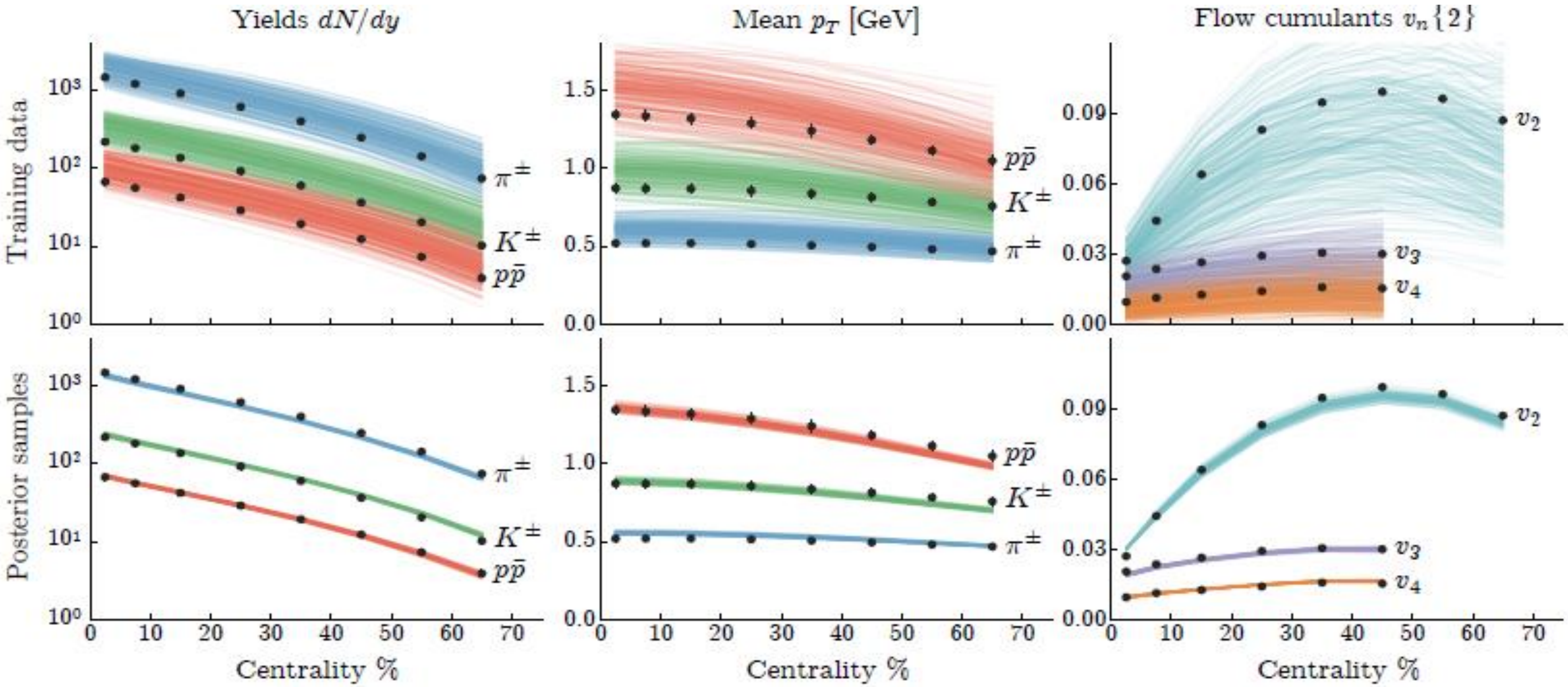
… ... … …

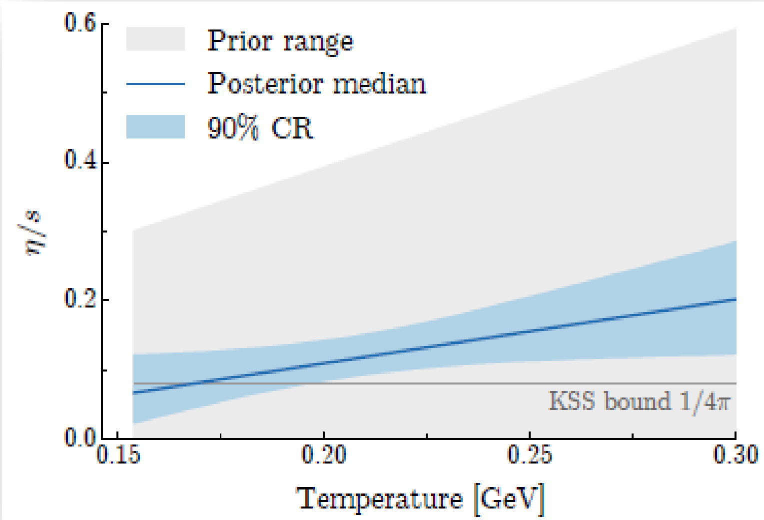
Hydro model & its Inputs:

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

… … … …

An quantitatively extraction of the QGP viscosity



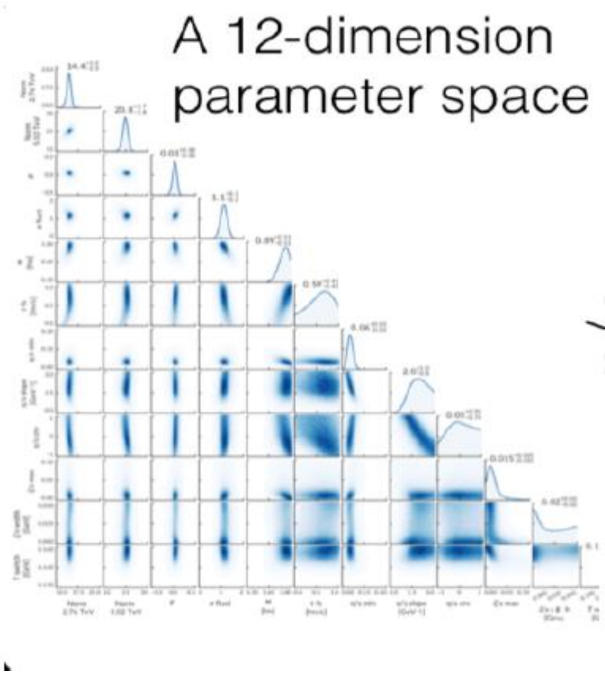


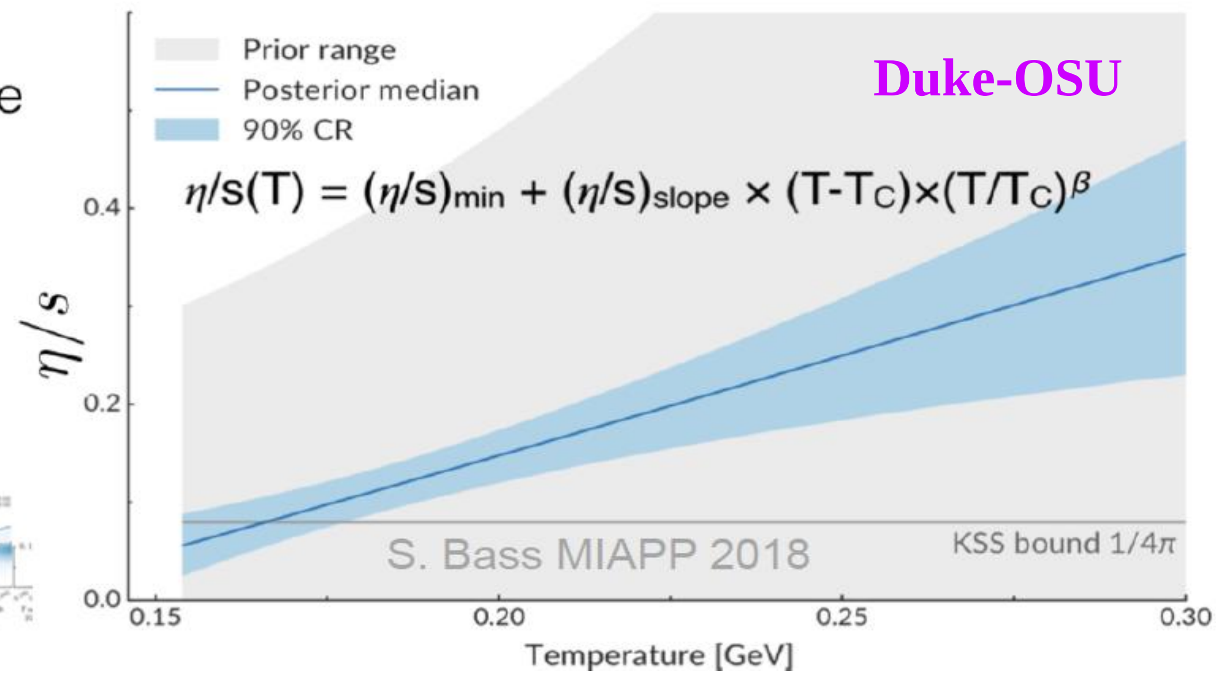
-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

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

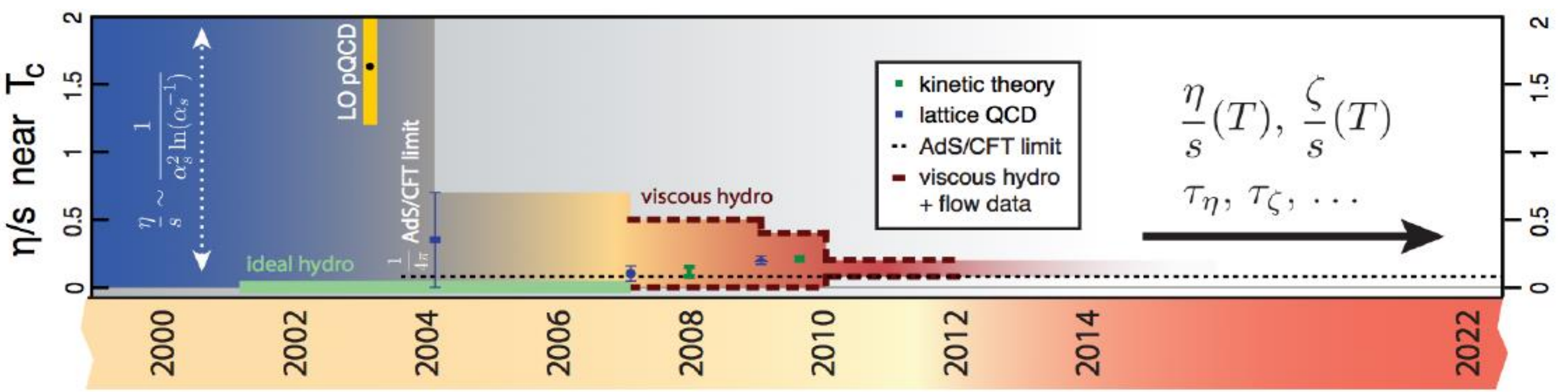
J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

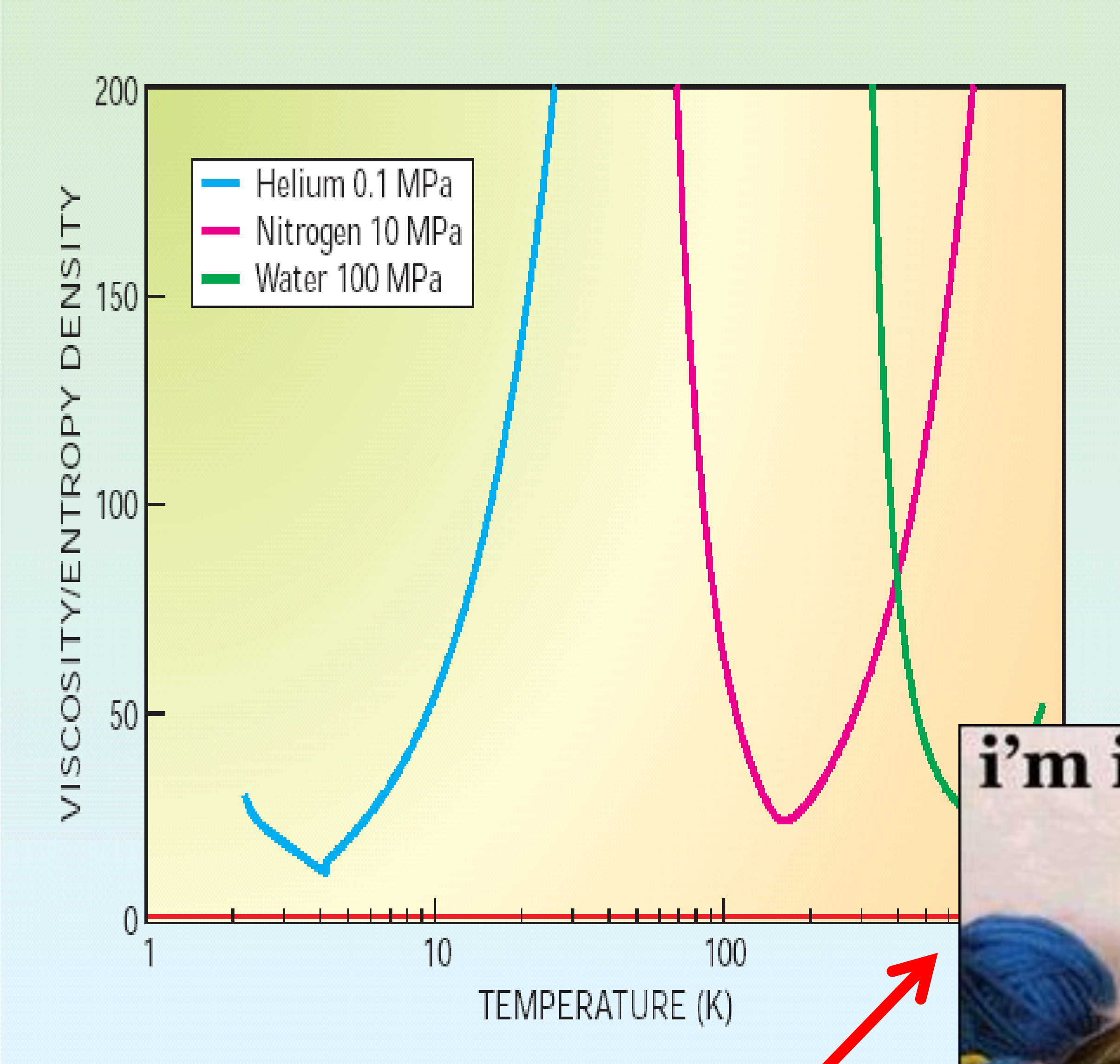
Extracting QGP viscosity with massive data evaluation





Extracted QGP viscosity with ever increasing precision





AdS/CFT

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

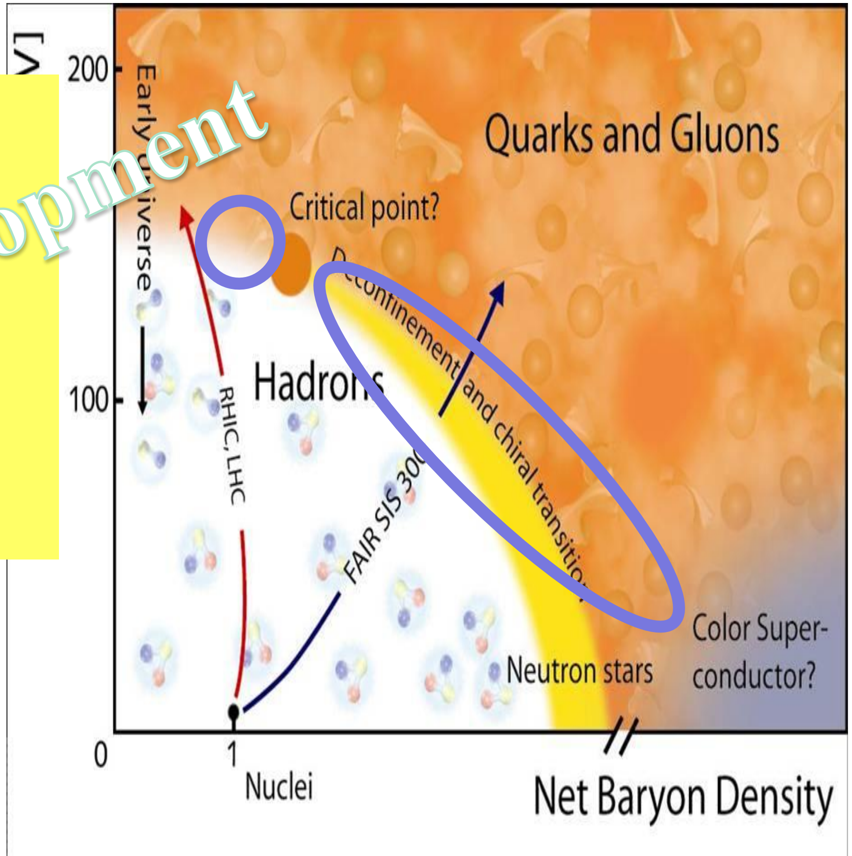
QGP specific shear viscosity
Extracted from exp data

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



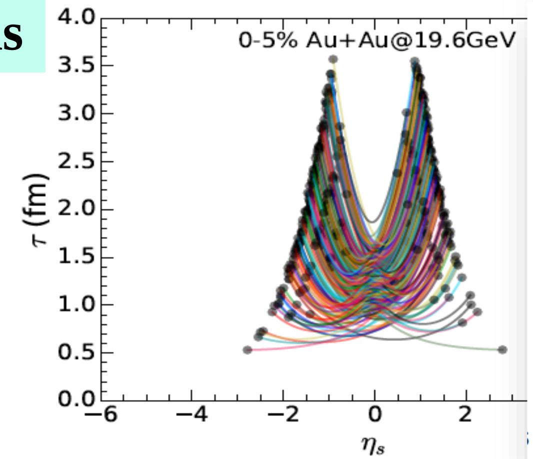
Recent model development for RHIC BES

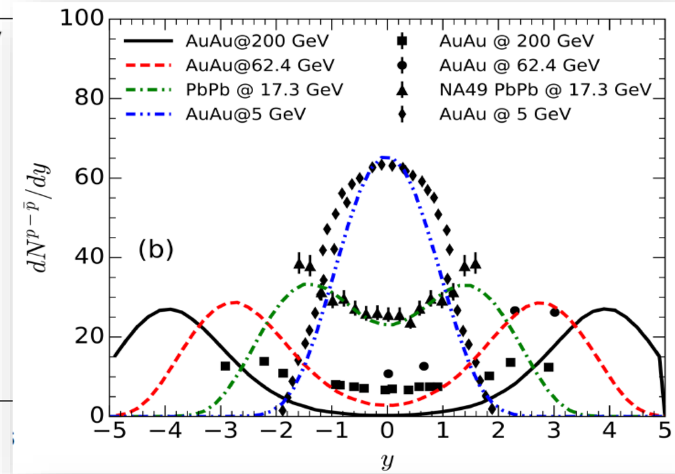
Dynamical initial conditions

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

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

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



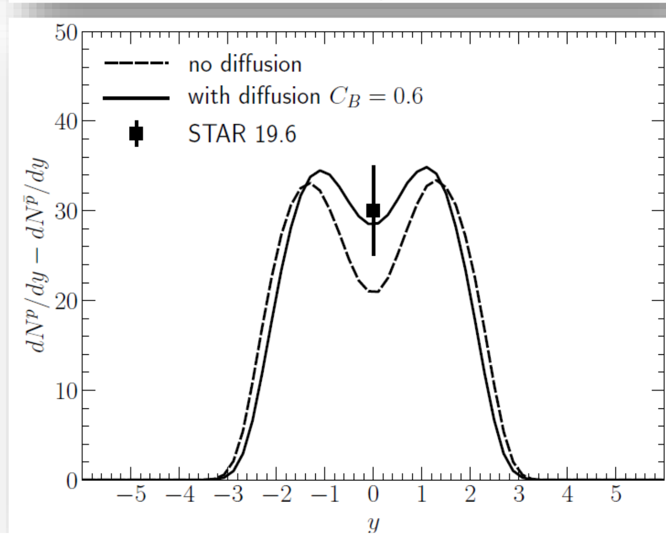


Net baryon diffusion

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

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

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

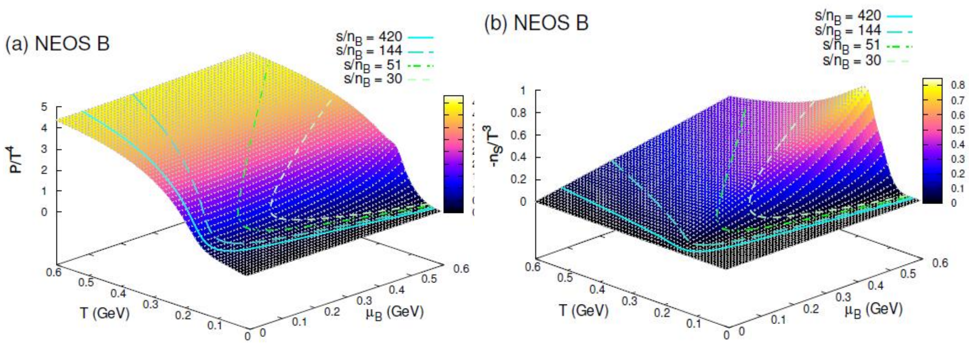
Recent development of hybrid model for RHIC BES

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

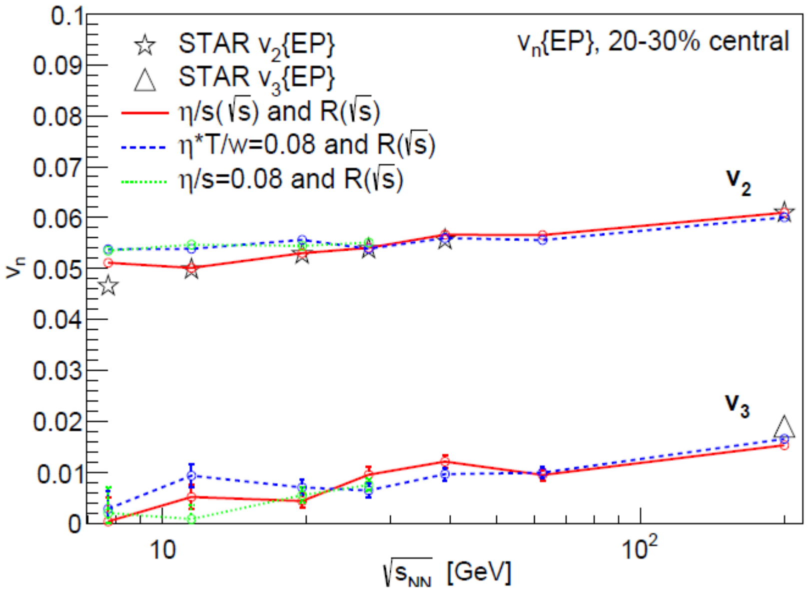
$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu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

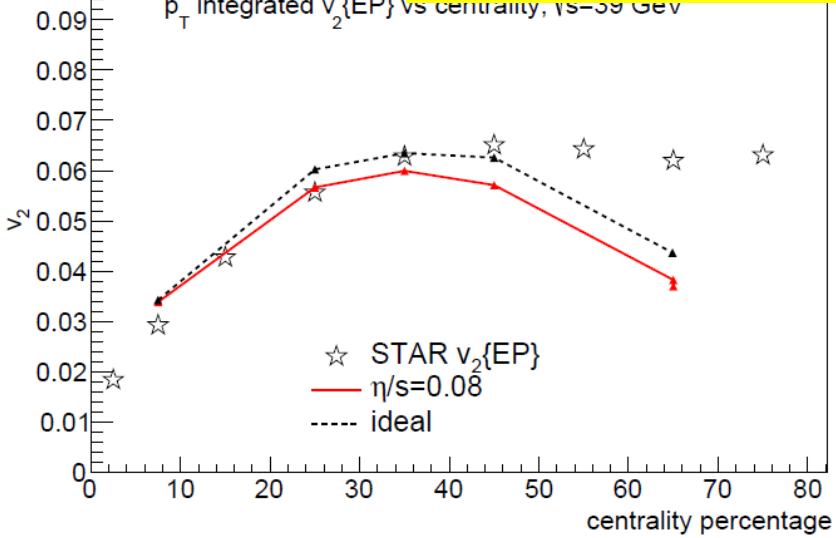
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi^{\langle\mu}{}_\alpha \pi^{\nu\rangle\alpha}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

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(√s) from RHIC BES (I)

-early attempt

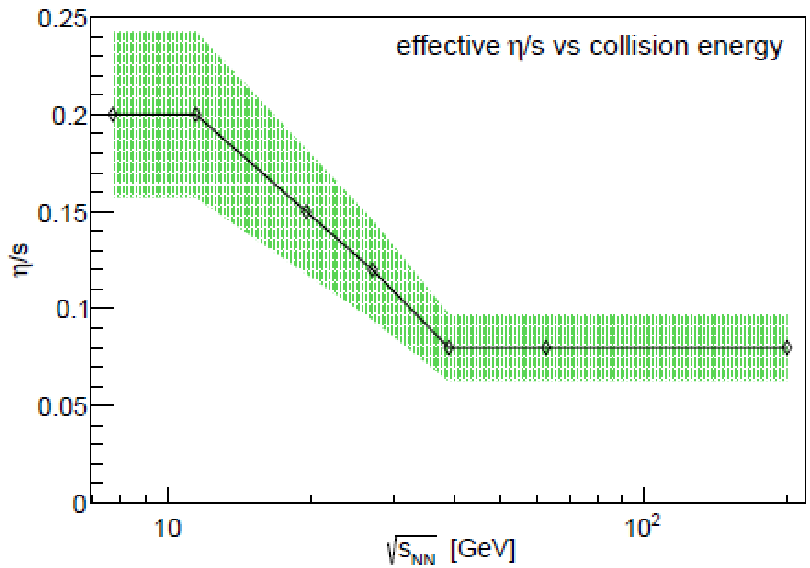




<u>Data</u>
- RHIC BES Au+Au 7.7-200 A GeV

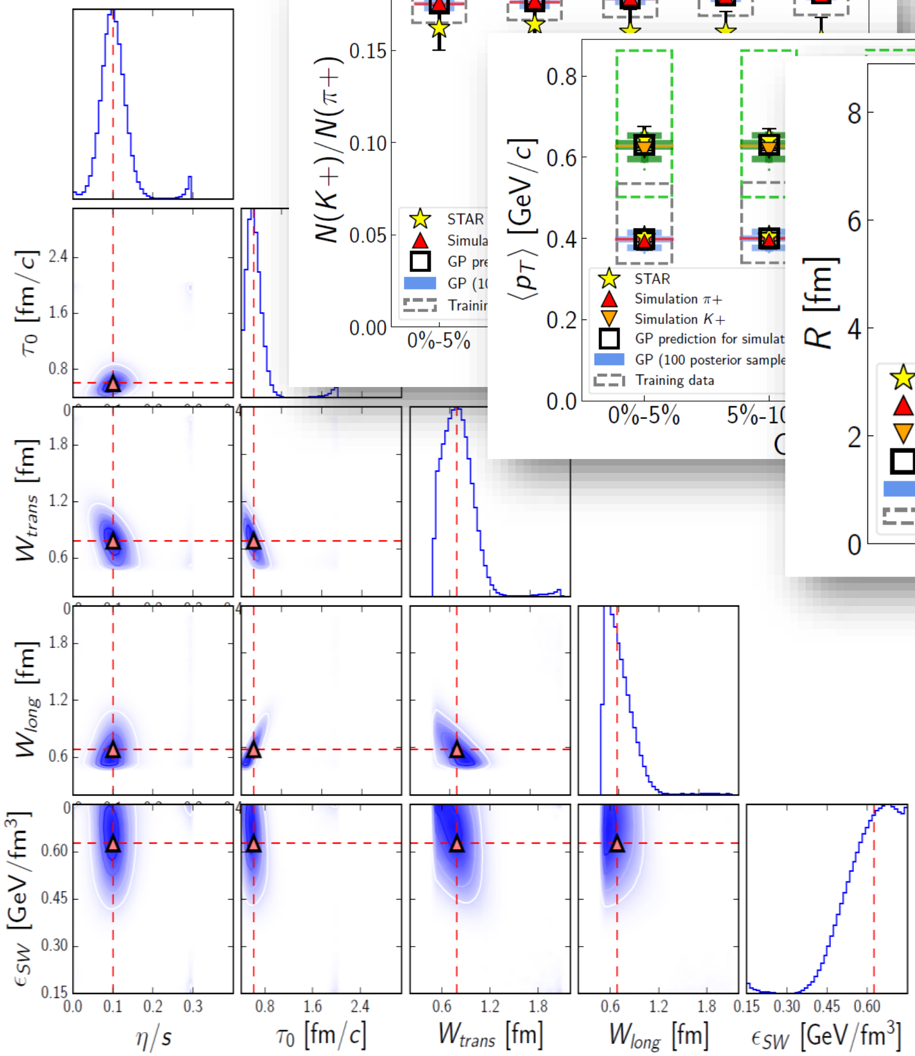
<u>Model</u>
-3+1d viscous hydro + UrQMD
-pre-equilibrim stage UrQMD
-EoS (Chiral Model with T, μ)

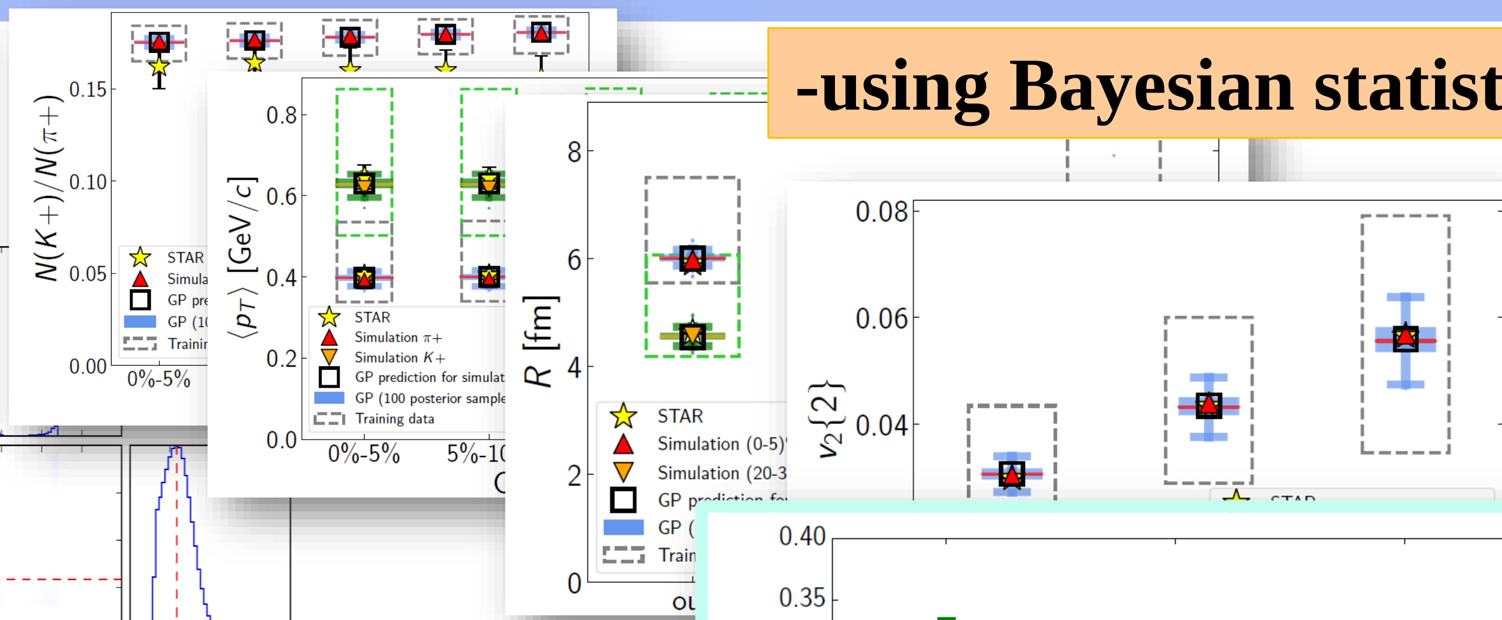
I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91, no. 6, 064901 (2015)

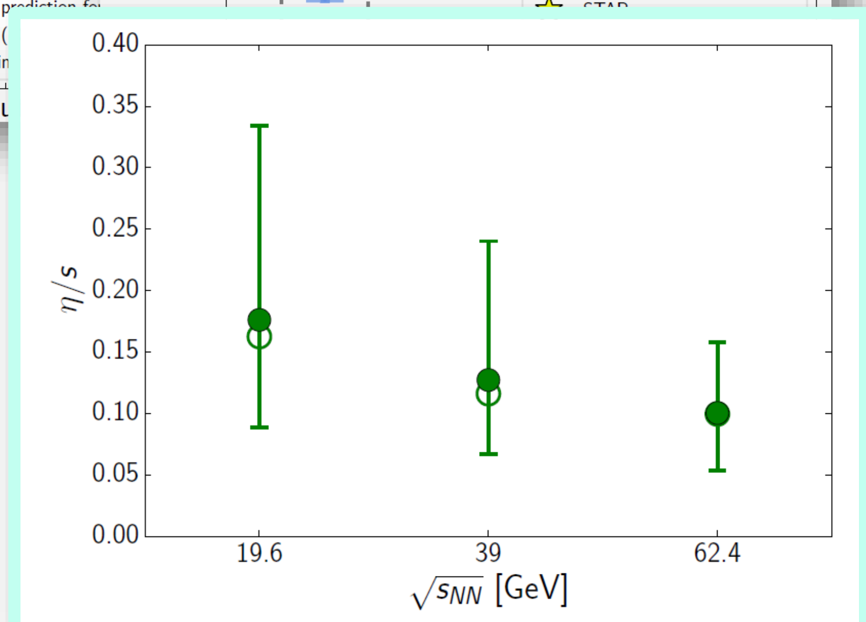


Extracting η/s($\sqrt{s}$) from RHIC BES (II)

-using Bayesian statistics





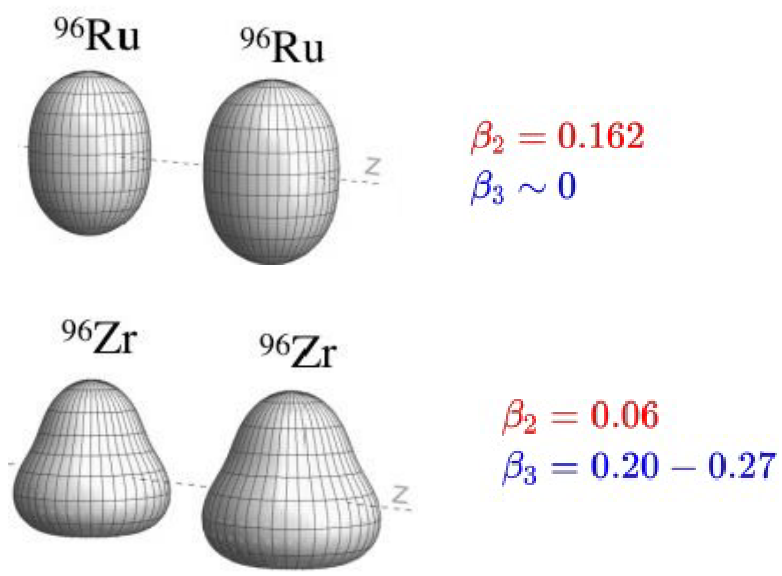


Future:

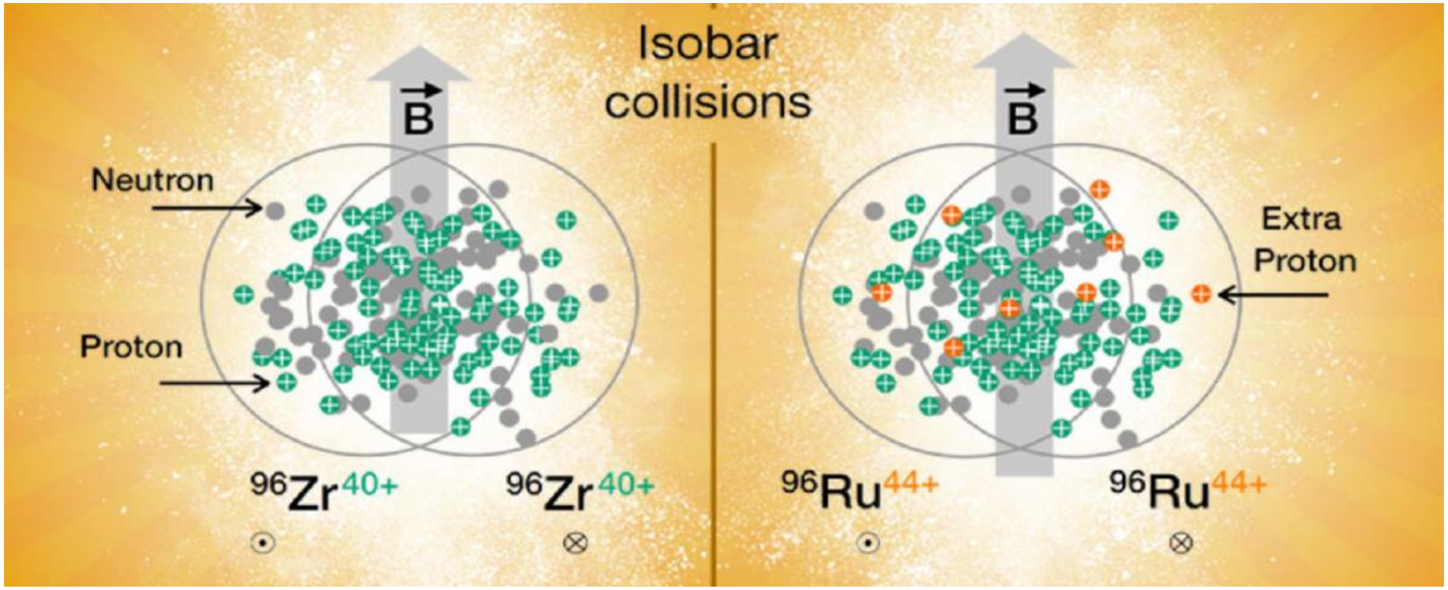
η/s(T,μ) ζ/s(T,μ) K/s(T,μ)

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

Probe the Nuclear Deformation with high energy nucleus-nucleus collisions

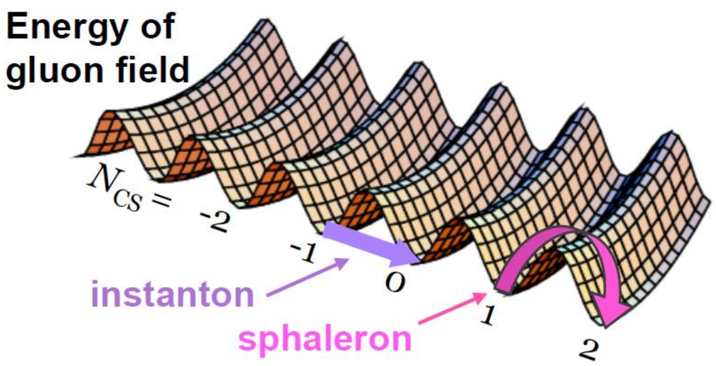


$^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$ Collisions @ RHIC isobar run

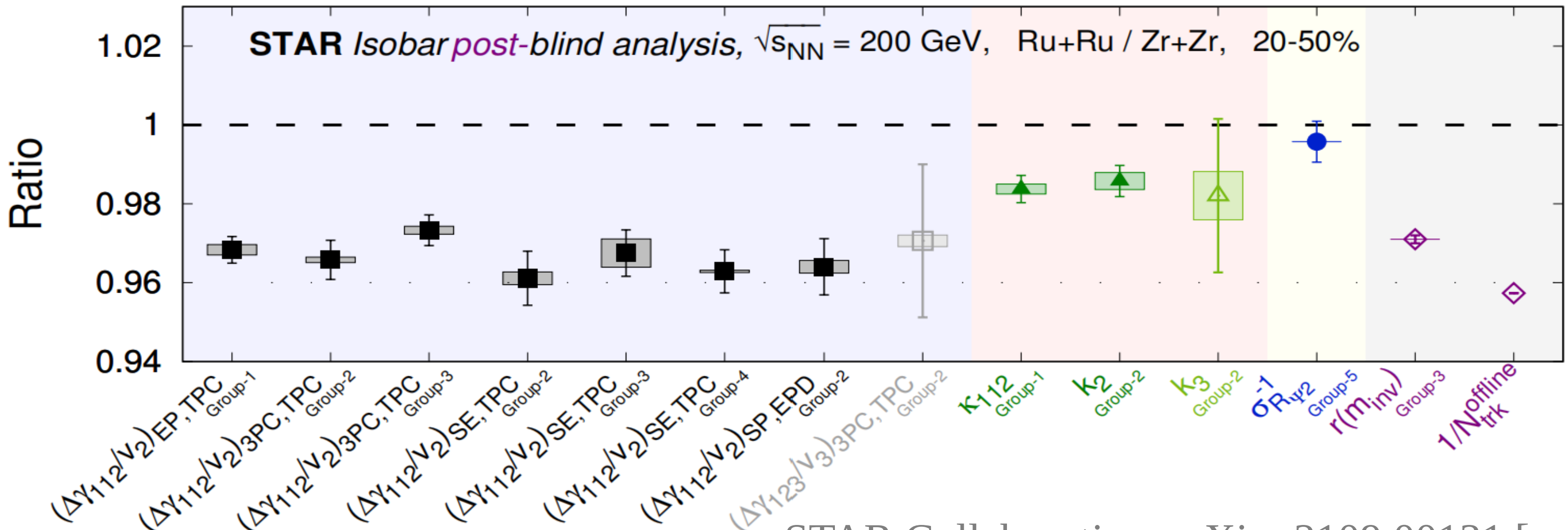


-Obviously different early magnetic field for Ru+Ru and Zr+Zr collisions

-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.

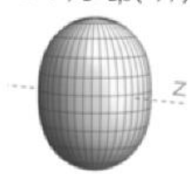
-Observed differences in both multiplicity and v2 imply that **CME background are different for ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr Collisions** at matching centralities

Nuclear Deformation

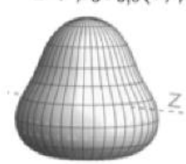
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$

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

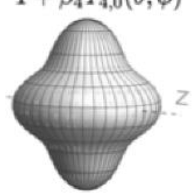
$1 + \beta_2 Y_{2,0}(\theta,\phi)$

Quadrupole: 

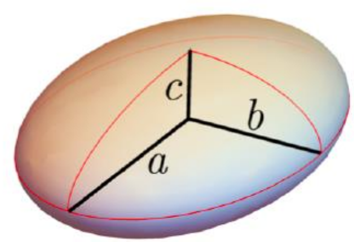
$1 + \beta_3 Y_{3,0}(\theta,\phi)$

Octupole: 

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

Hexadecapole: 

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



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

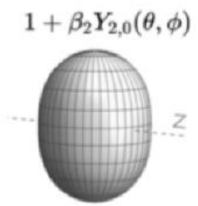
Prolate: a=b<c → β_2, $\gamma=0$
Oblate: a<b=c → β_2, $\gamma=\pi/3$ or $-\beta_2$, $\gamma=0$

Nuclear Deformation

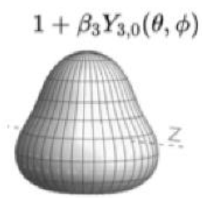
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

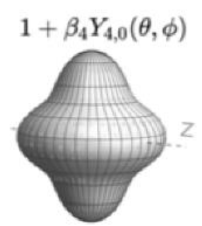
Quadrupole:

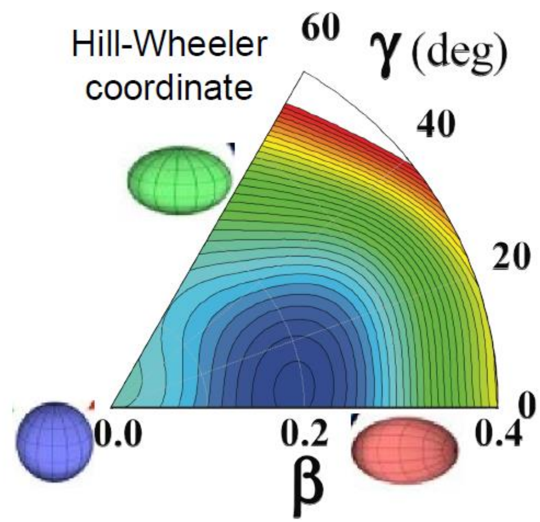


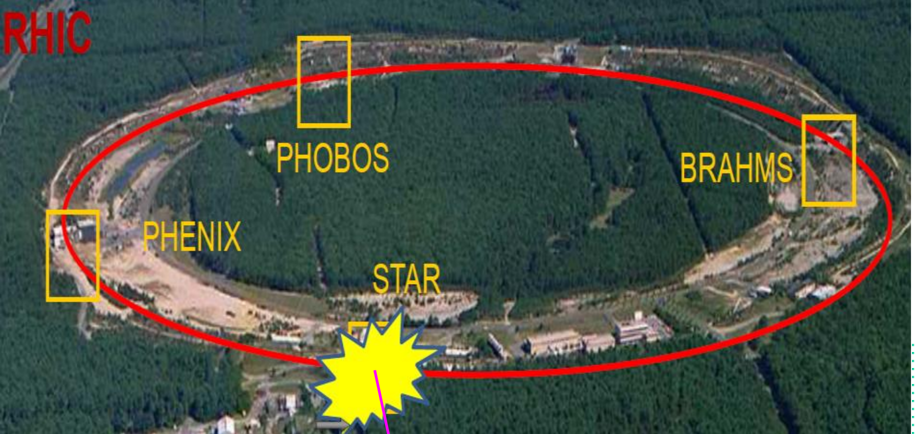
Octupole:



Hexadecapole:



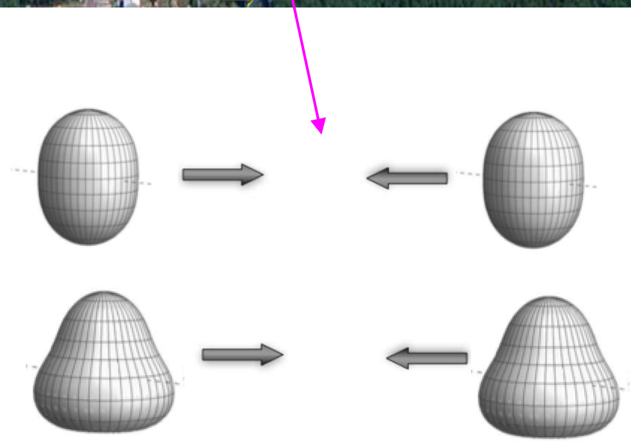




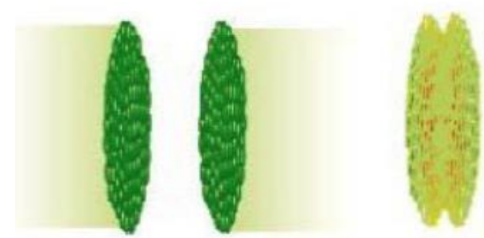
Relativistic heavy ion collision can probe the nuclear deformation

- Relativistic heavy collisions start from nuclei

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

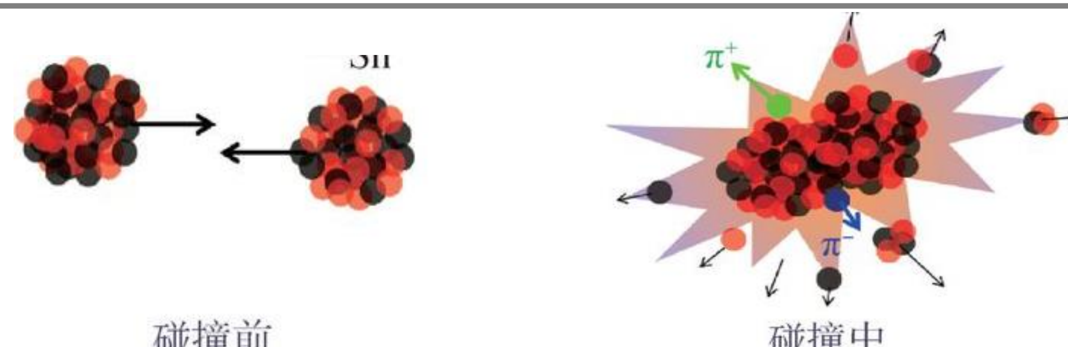


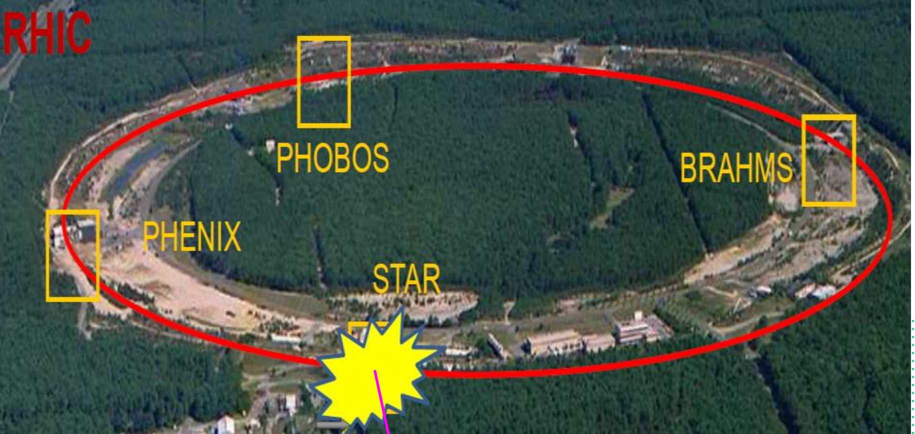
initial conditions:
(with deformations)



Collision time < 10^{-24} s

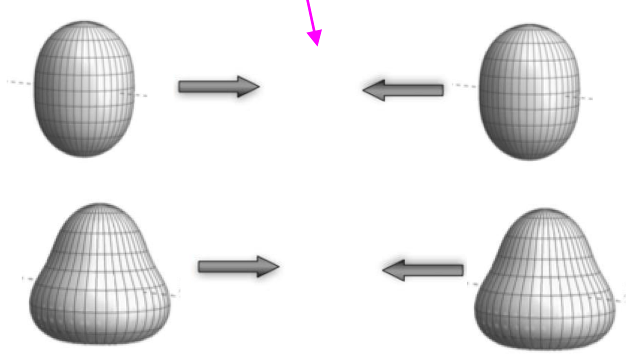
heavy ion collision at intermediate energies excites nuclei during the collision





Relativistic heavy ion collision can probe the nuclear deformation

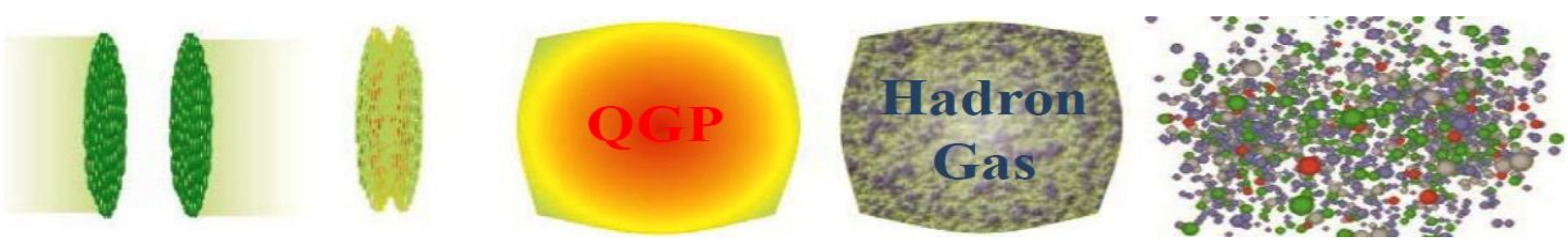
- Relativistic heavy collisions start from nuclei
- Collision time < 10^{-24} s directly probe the ground state of nuclei
- Well calibrated calculations to focus on the initial state effects from the succeeding evolution



initial conditions: (with deformations)

Well calibrated calculations

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



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

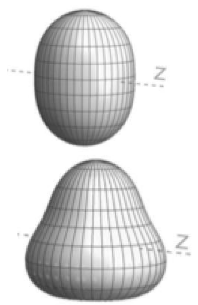
PHYSICAL REVIEW C VOLUME 42, NUMBER 3 SEPTEMBER 1990

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 $B(E3; 0_1^+ \to 3_1^-)$

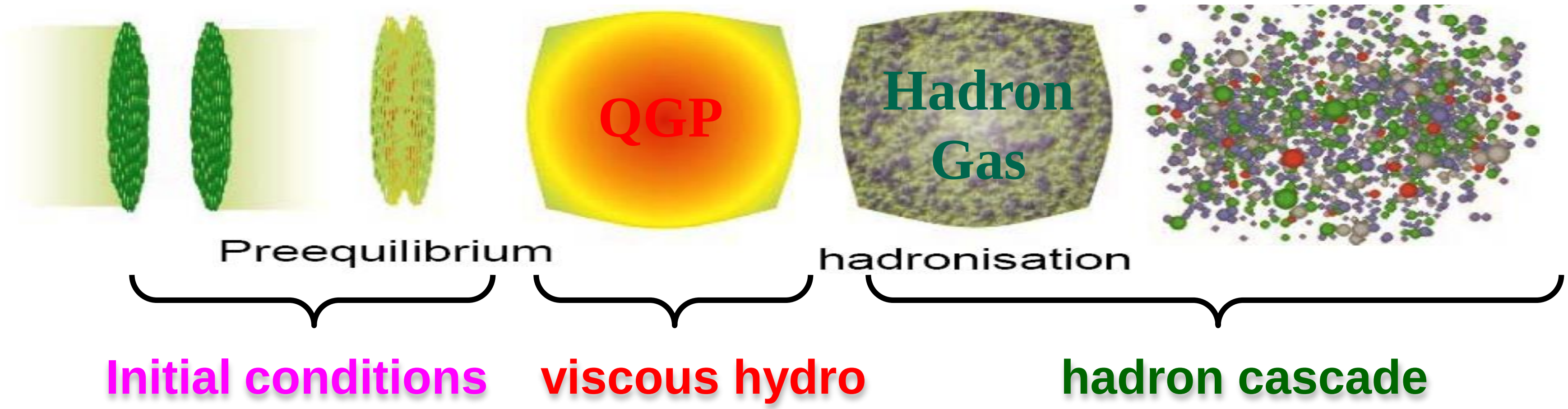
Conversion from B(En) to β_n via: $\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}}$, $\beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$

	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



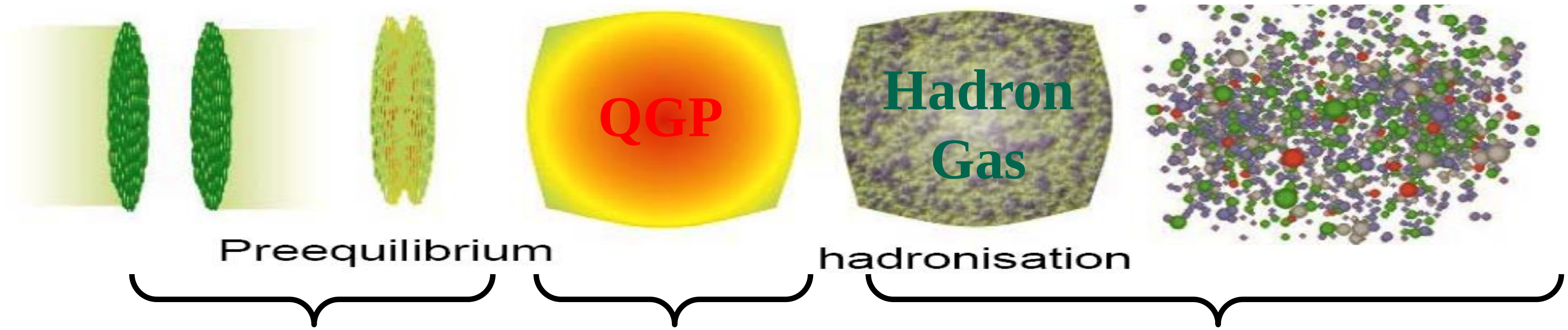
Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

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

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

Hydrodynamic calculation with initially deformed nuclei



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

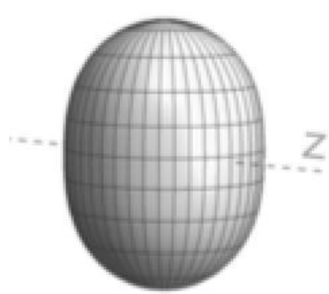
Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}} \qquad R(\theta,\phi) = R_0(1+\beta_2 Y_{2,0}+\beta_3 Y_{3,0})$$

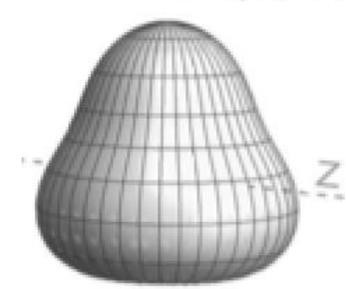
$1+\beta_2 Y_{2,0}(\theta,\phi)$

Quadrupole:

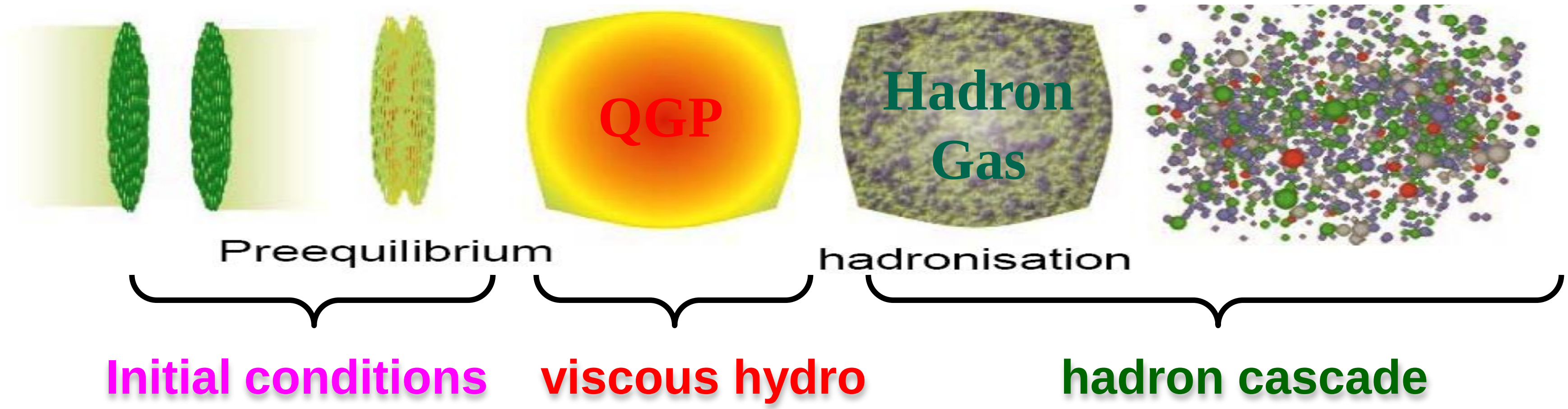


$1+\beta_3 Y_{3,0}(\theta,\phi)$

Octupole:



Hydrodynamic calculation with initially deformed nuclei



Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R_0(1+\beta_2 Y_{2,0}+\beta_3 Y_{3,0}))/a_0}}$$

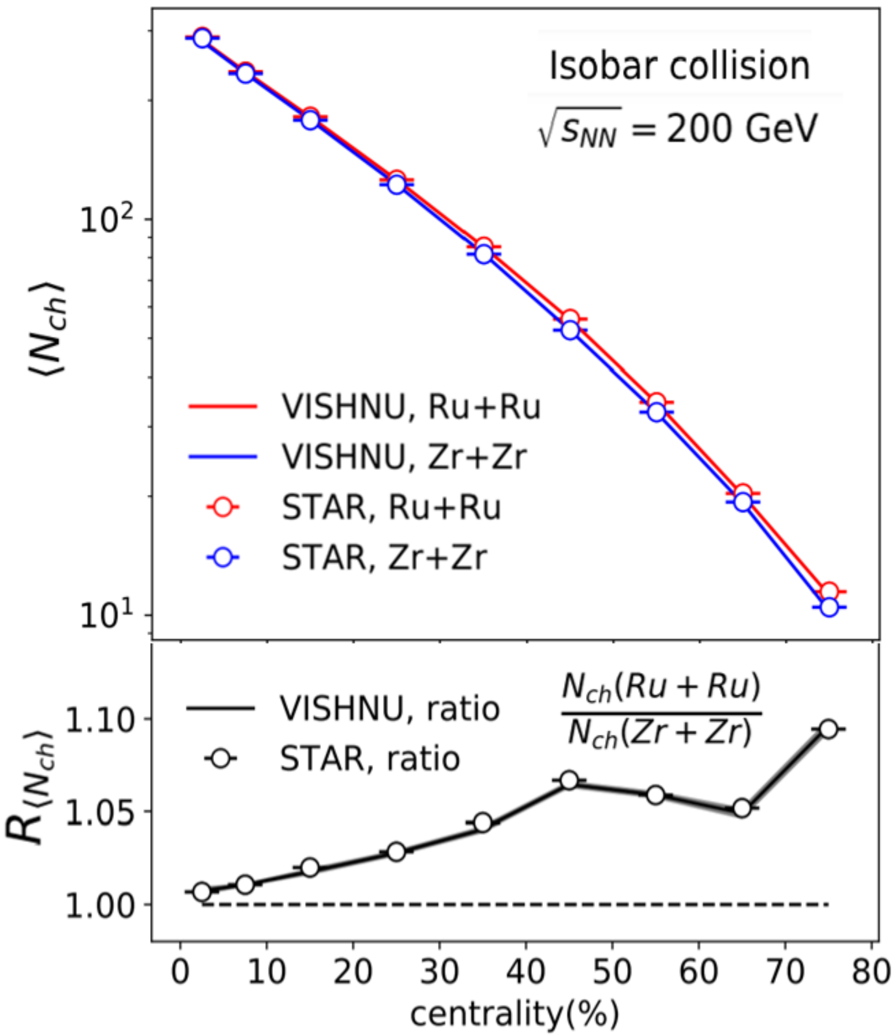
	β_2	β_3	R_0	a
Ru-para-I	0.12	0.00	5.093	0.487
Ru-para-II	0.16	0.00	5.093	0.471
Zr-para-I	0.00	0.16	5.021	0.524
Zr-para-II	0.00	0.20	5.021	0.517

Parameters are refer to:

G. Fricke, et al. Atom. Data Nucl. Data Tabl. 60, 177 (1995).B. Pritychenko, et al. Atom. Data Nucl. Data Tabl. 107, 1 (2016).T Kib´edi and R. H Spear, Atom. Data Nucl. Data Tabl. 80, 35 (2002).

(H. Xu, et al., Phys. Lett. B 819, 136453 (2021)J. Jia, et al. arXiv: 2111.15559 [nucl-th])

Nch for Ru+Ru and Zr+Zr collisions

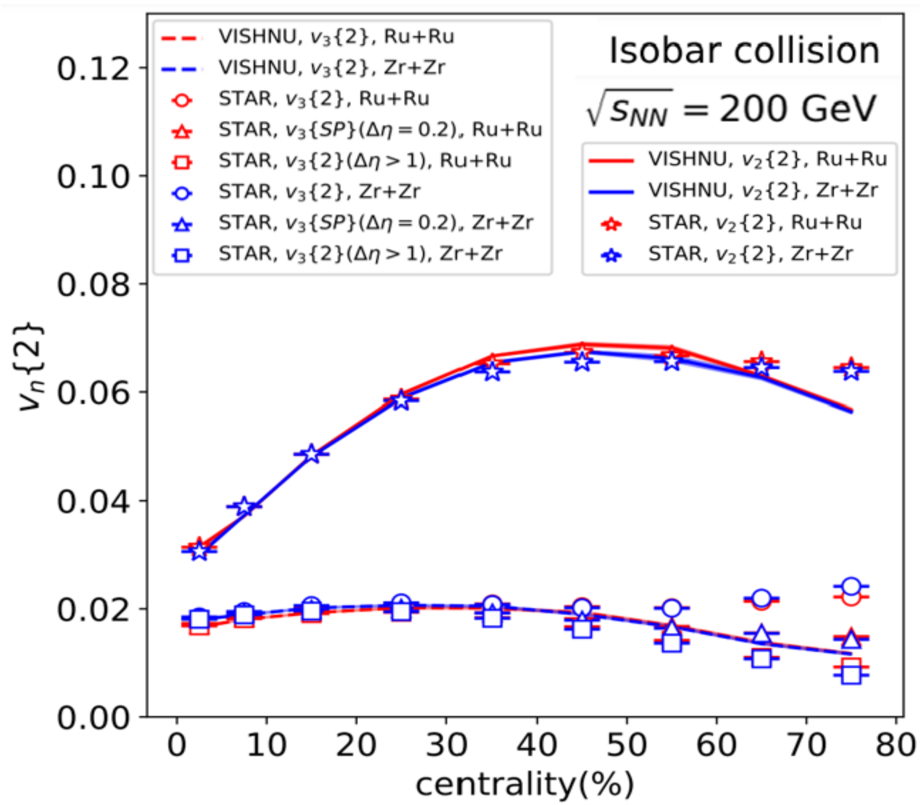


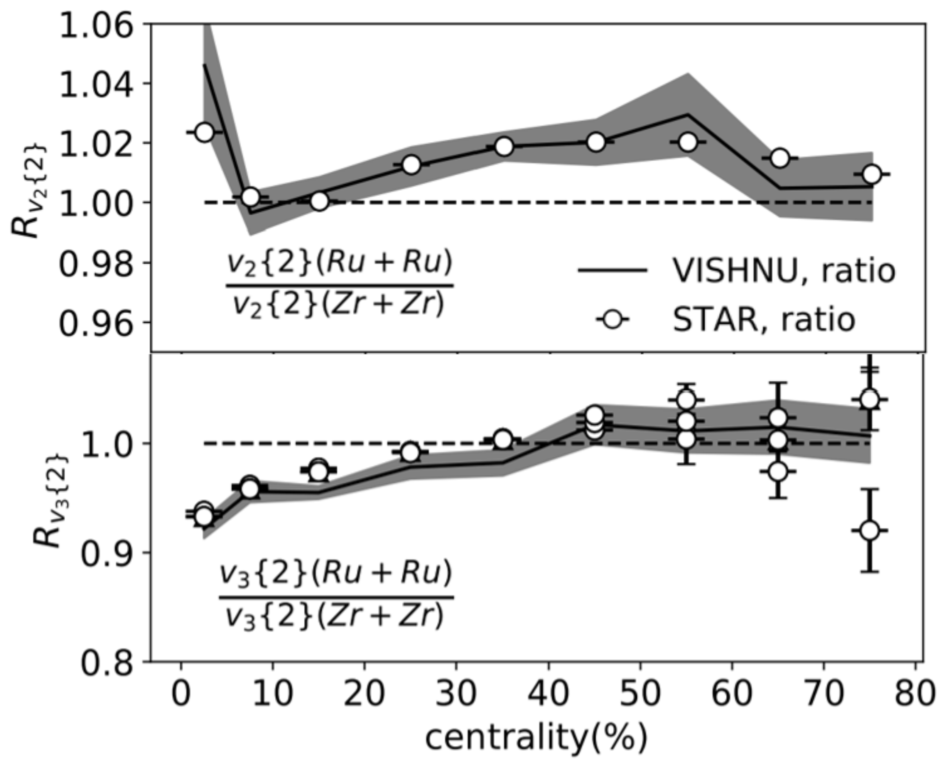
"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

-With fine tuning parameters, iEBE-VISHNU fits Nch for Ru+Ru collisions

-Using $\beta_2 \beta_3$ in table1, it "predicts" Nch for Zr+Zr collisions & the Nch ratio between the two systems (the data are nicely described).

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



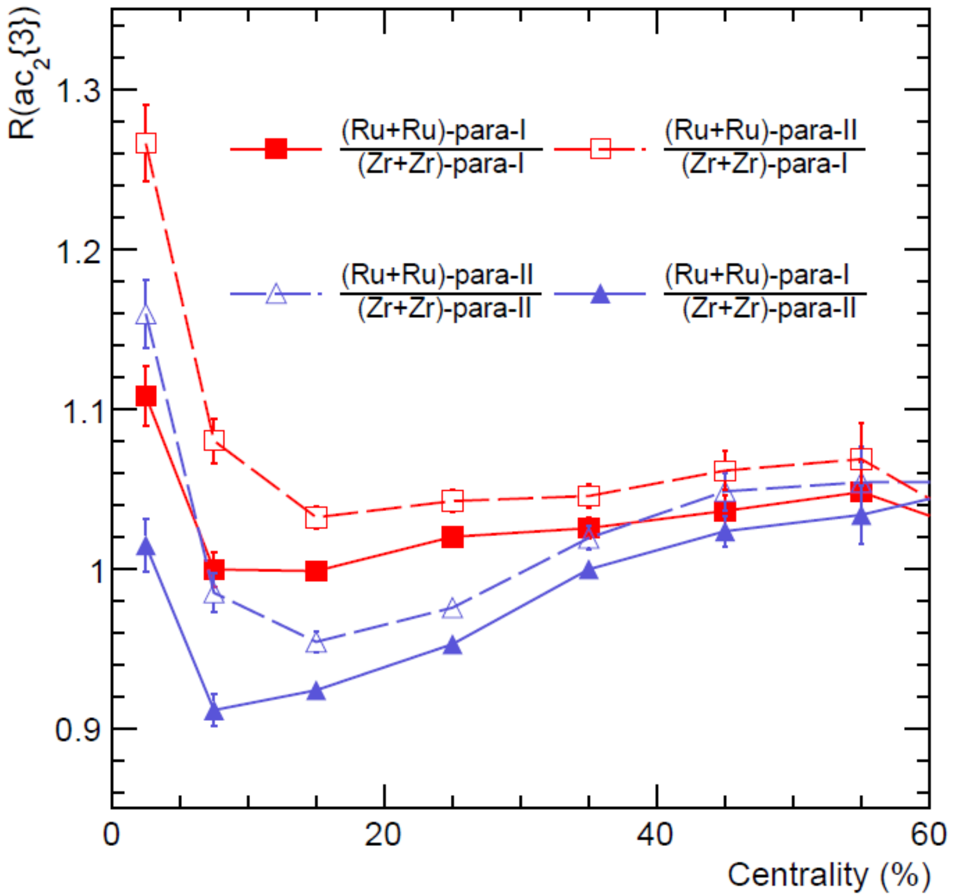


-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

-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

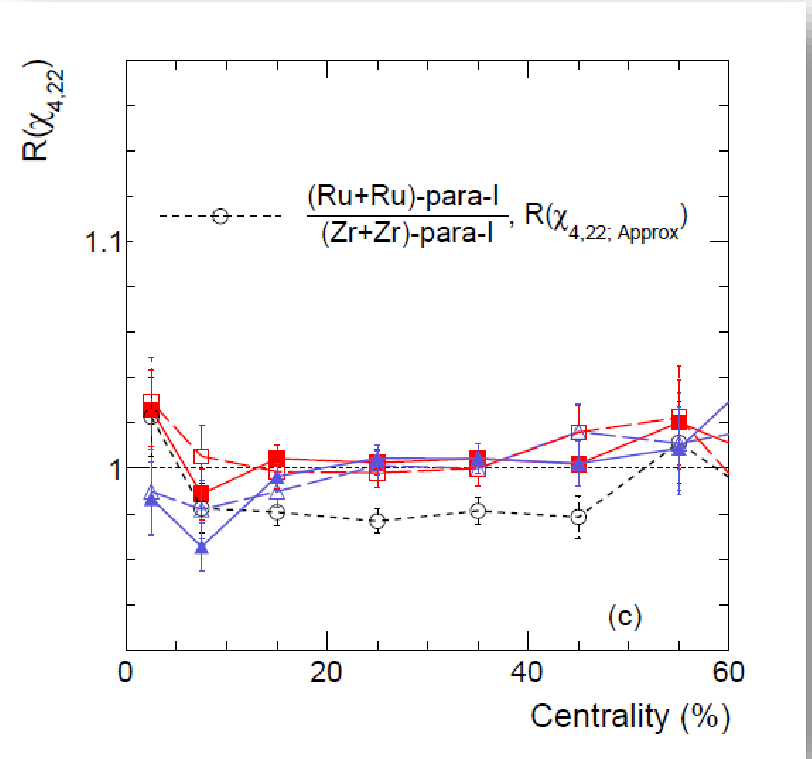
ac{3}for Ru+Ru and Zr+Zr collisions



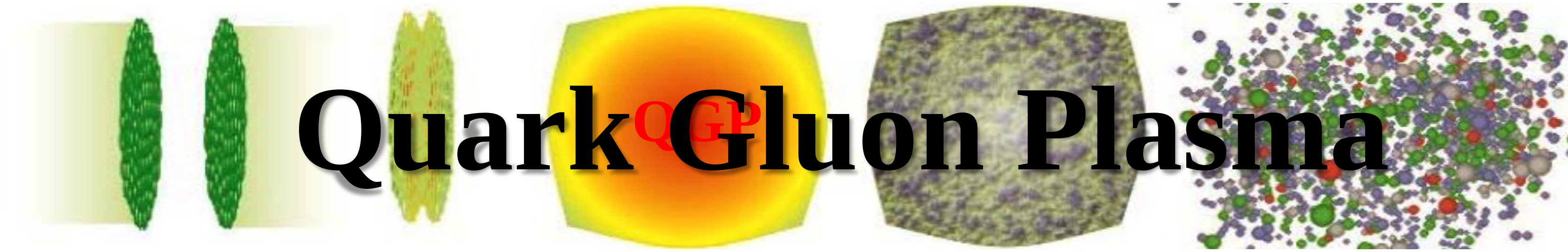
$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle,$$

$$\chi_{4,22} \equiv \frac{ac_2\{3\}}{\langle v_2^4\rangle} = nac_2\{3\}\sqrt{\frac{v_4\{2\}^2}{2v_2\{2\}^4 - v_2\{4\}^4}}.$$

ac{3} is sensitive to quadrupole and octupole deformations



Quark Gluon Plasma



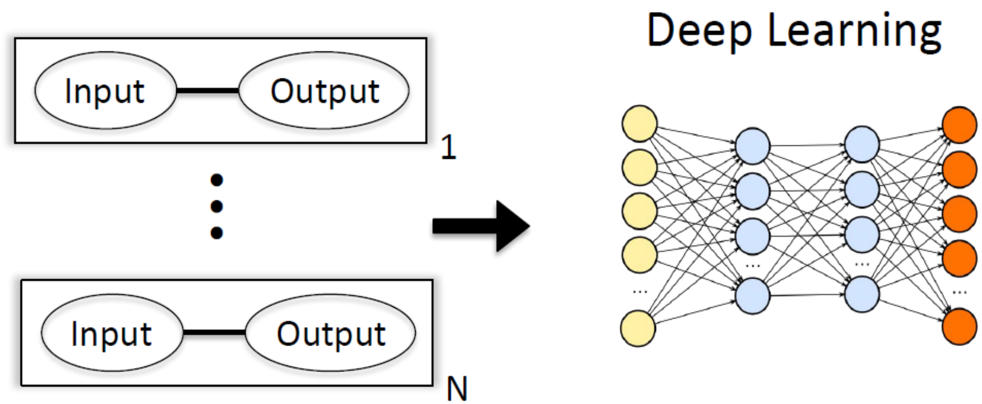
Hottest Matter on Earth

Most Perfect Liquid

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."

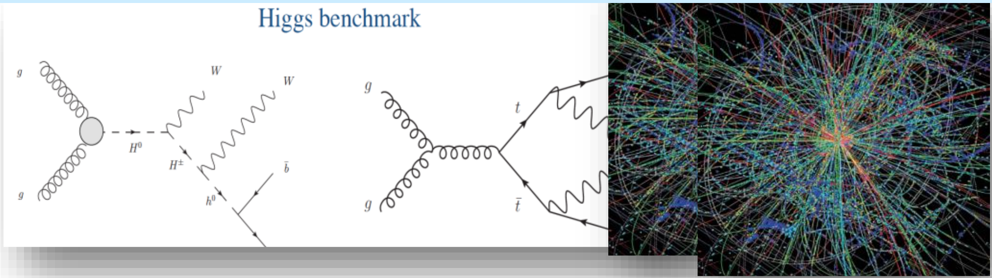


Can "Black-box" models learn patterns and models solely from data without relying on scientific knowledge?

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

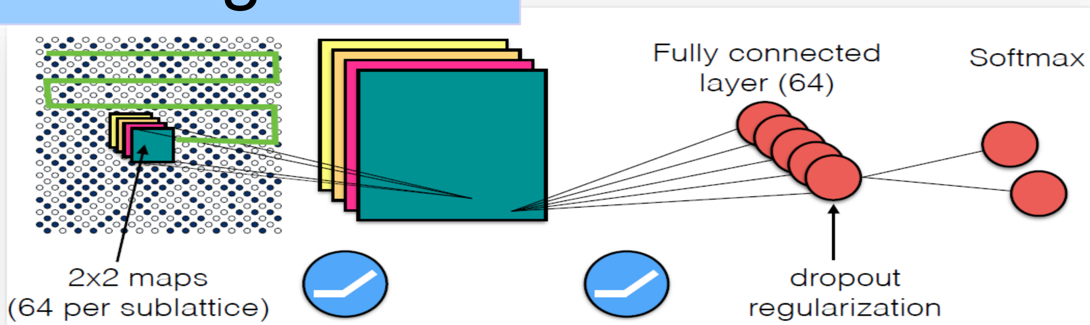
P. Baldi, P. Sadowski, & D. Whiteson
Nature Commun. 5, 4308 (2014)

Classifying the Phase of Ising Model

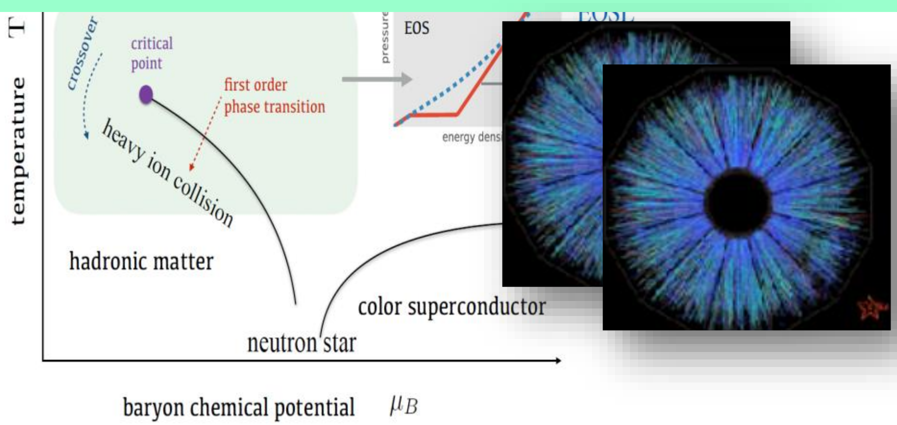
For the case of Ising gauge theory

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

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



Identify QCD Phase Transition with Deep Learning

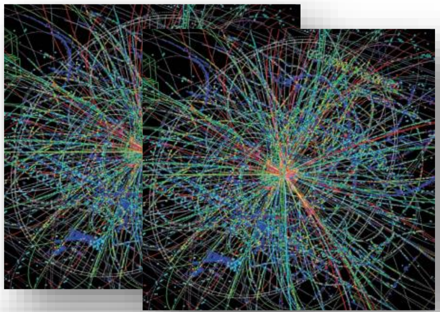


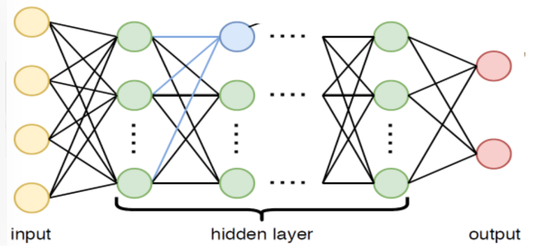
DNN efficiently decode the EOS information from the complex final particle info event by event

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

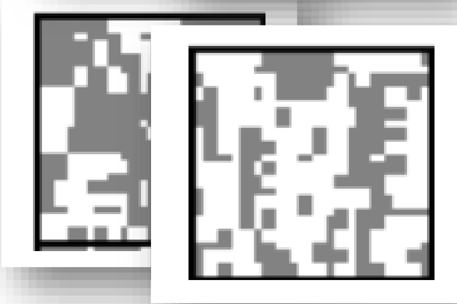
Image identification

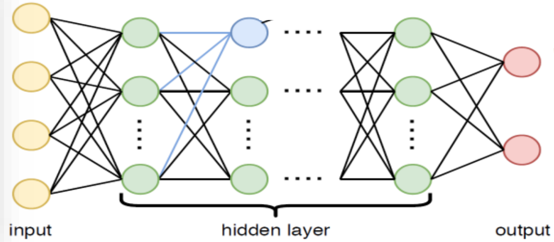




Higgs signal or background?

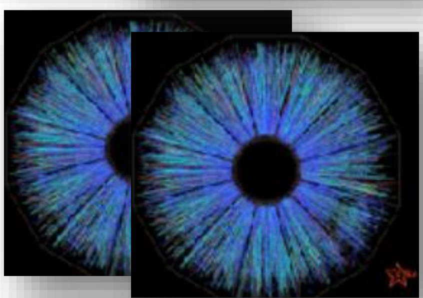
P.Baldi,et al,Nature Commun.(2014)

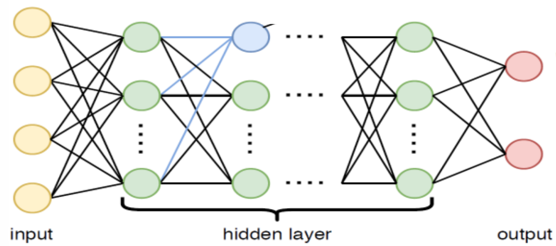




High temperature or low temperature phase?

Carrasquilla & Melko. Nature Physics (2017)





EoS L or EOSQ ?

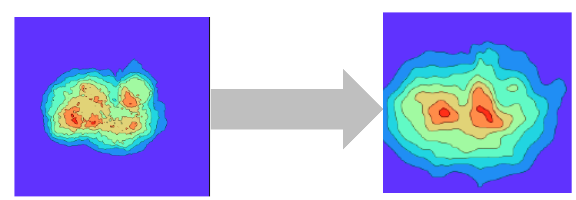
Pang,et al Nature Commun.(2018)

"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

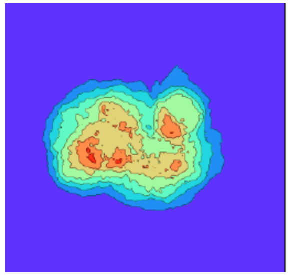


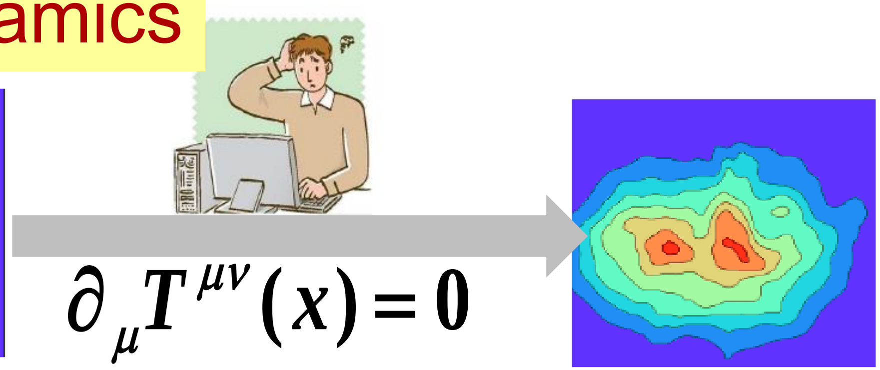
For the non-linear hydro system, can the black-box network could learn pattern transformations solely from data without relying on scientific knowledge?
(conservation laws)

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)

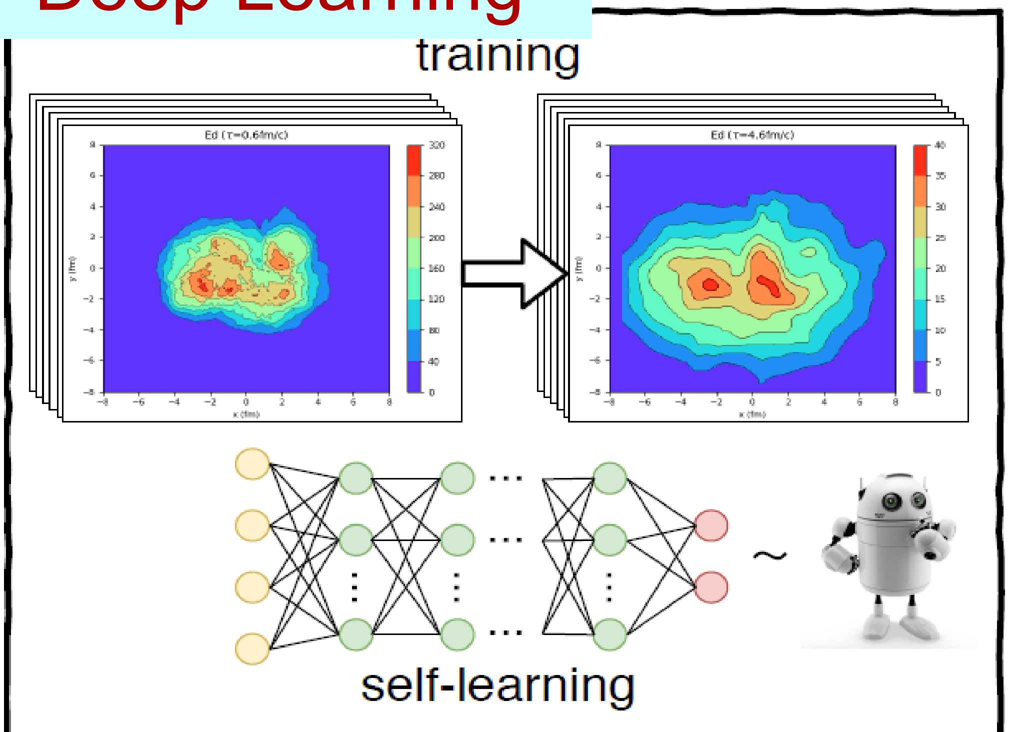
Traditional hydrodynamics

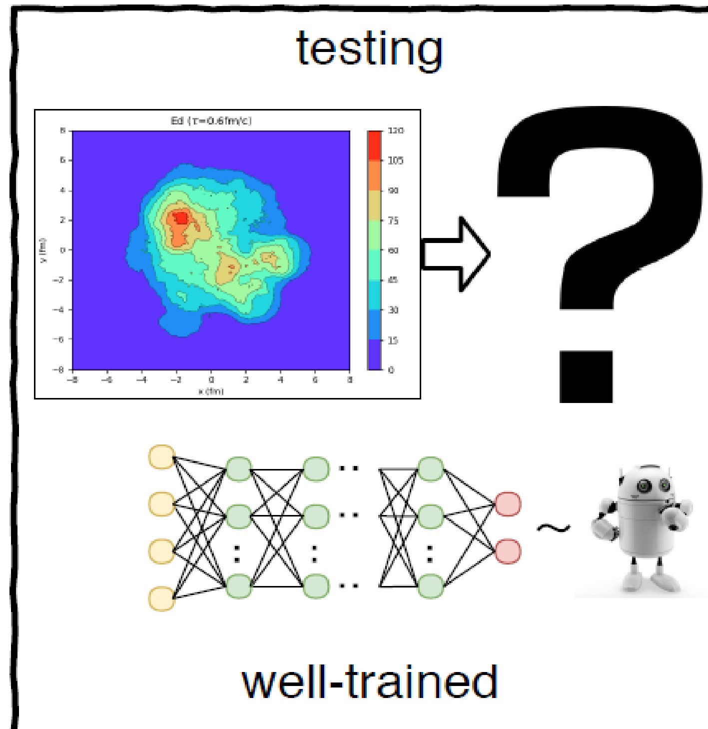




$$\partial_\mu T^{\mu\nu}(x) = 0$$

Deep Learning

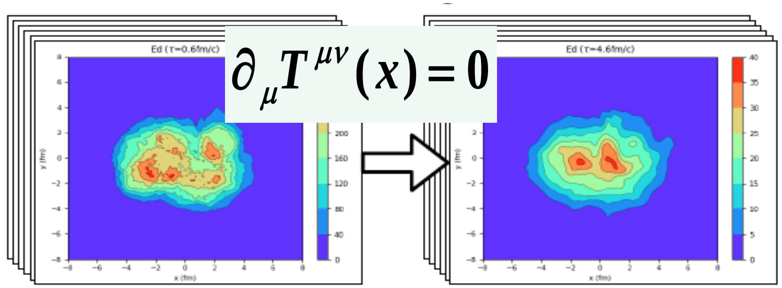




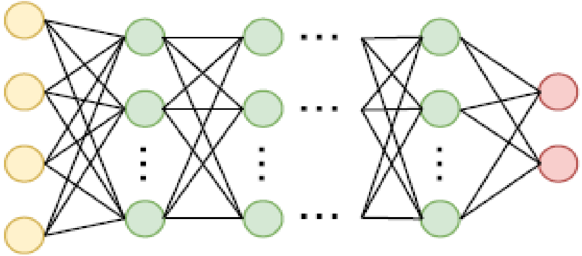
-Such deep learning systems do not need to be programmed with the hydro equation $\partial_\mu T^{\mu\nu}(x) = 0$ **Instead, they learn on their own**

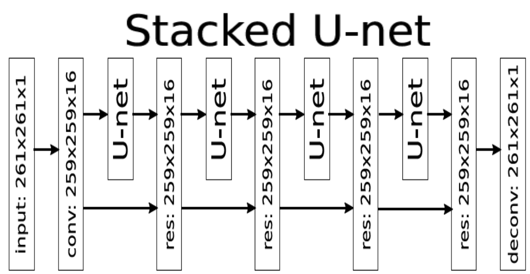
Deep Learning

Step1) Generate the training/testing data sets from hydro



Step2) Design & train the deep neural network

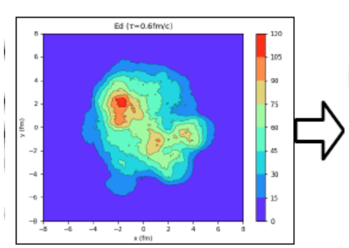




The Training Data Sets

hydro VISH2+1	MC-Gl
	10000

Step3) Test the deep neural network

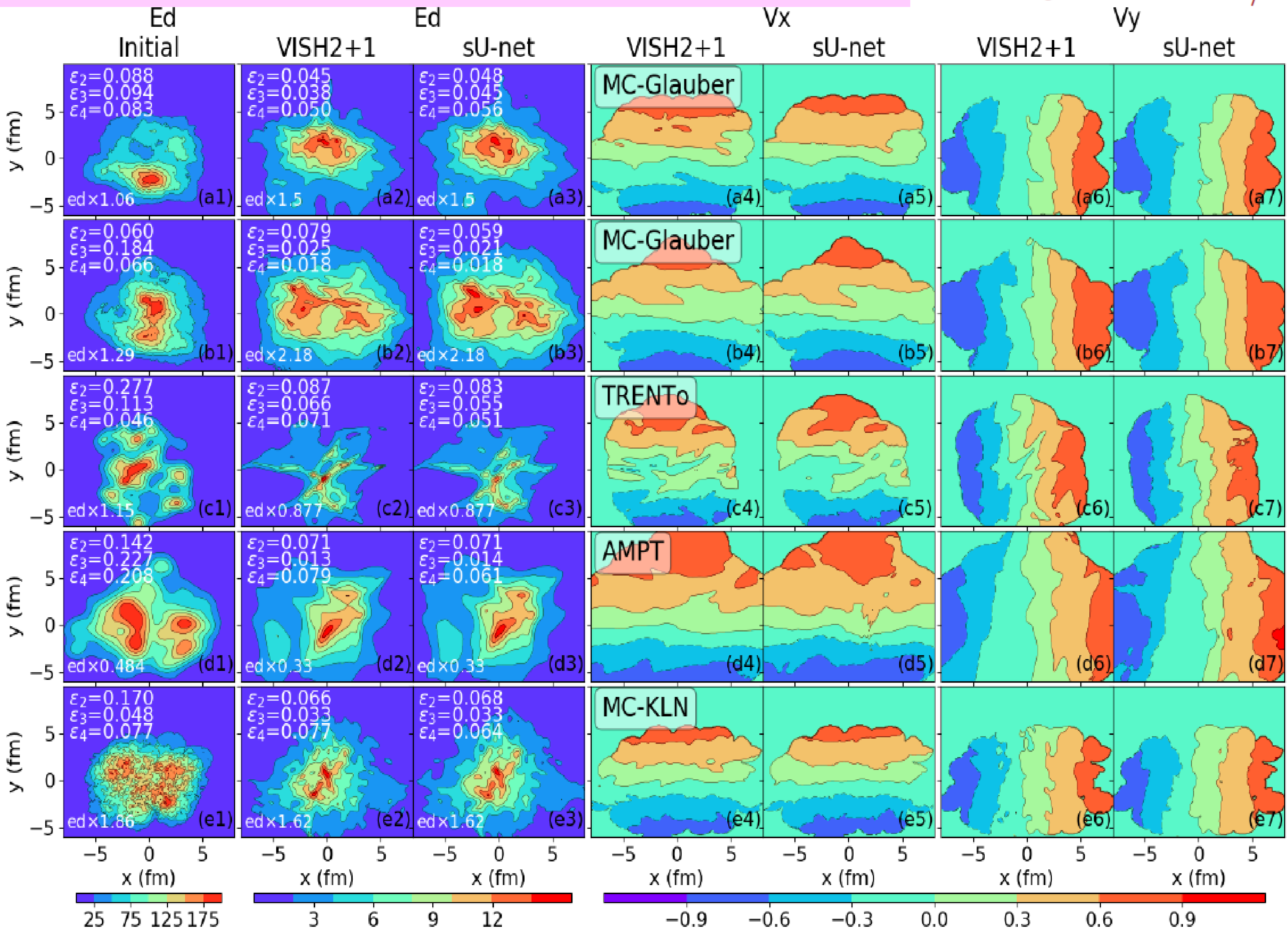


The Testing Data Sets

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

sUnet prediction vs. hydro simulations

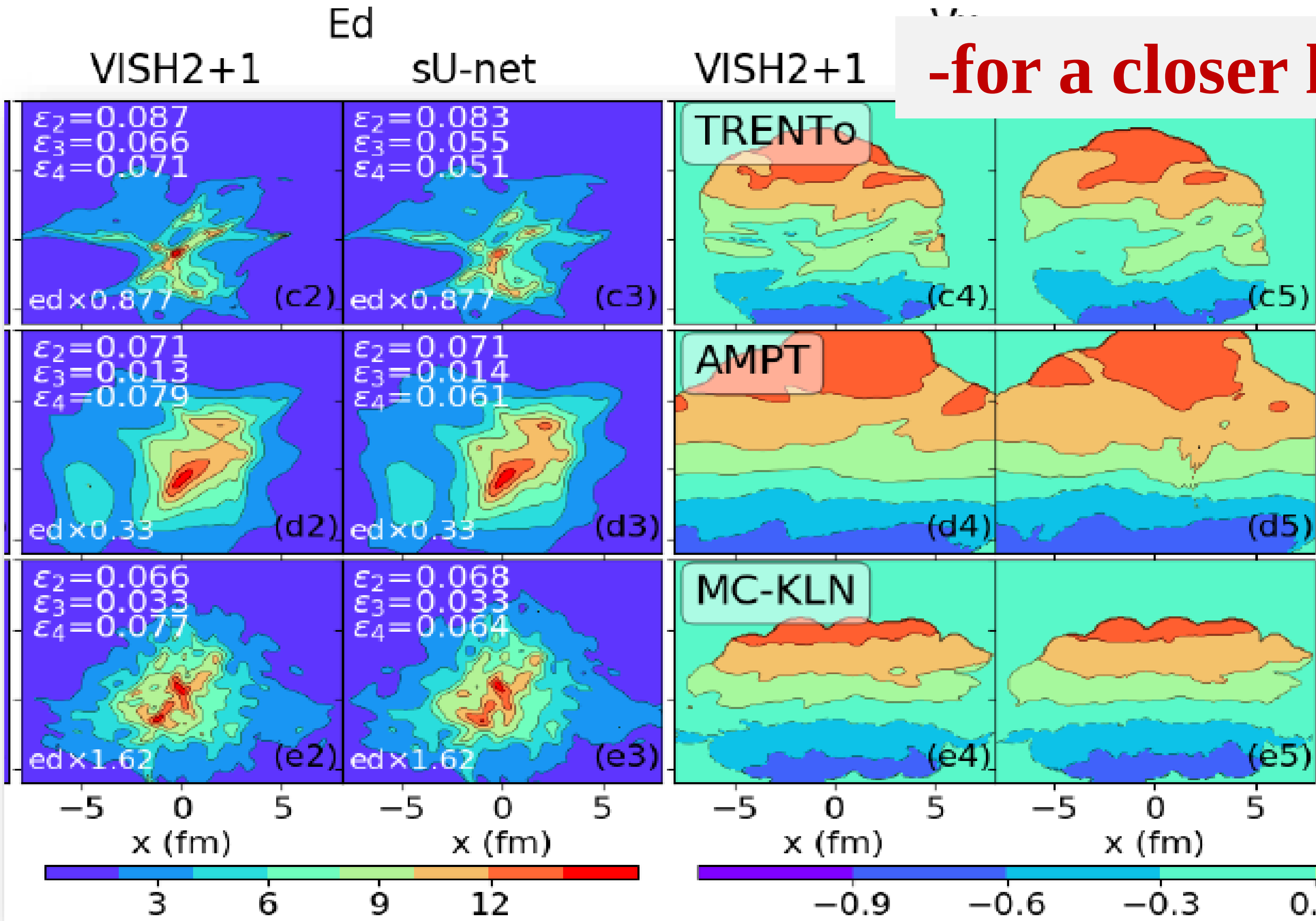
$\tau - \tau_0 = 6.0 fm/c$



sUnet prediction vs. hydro simulations

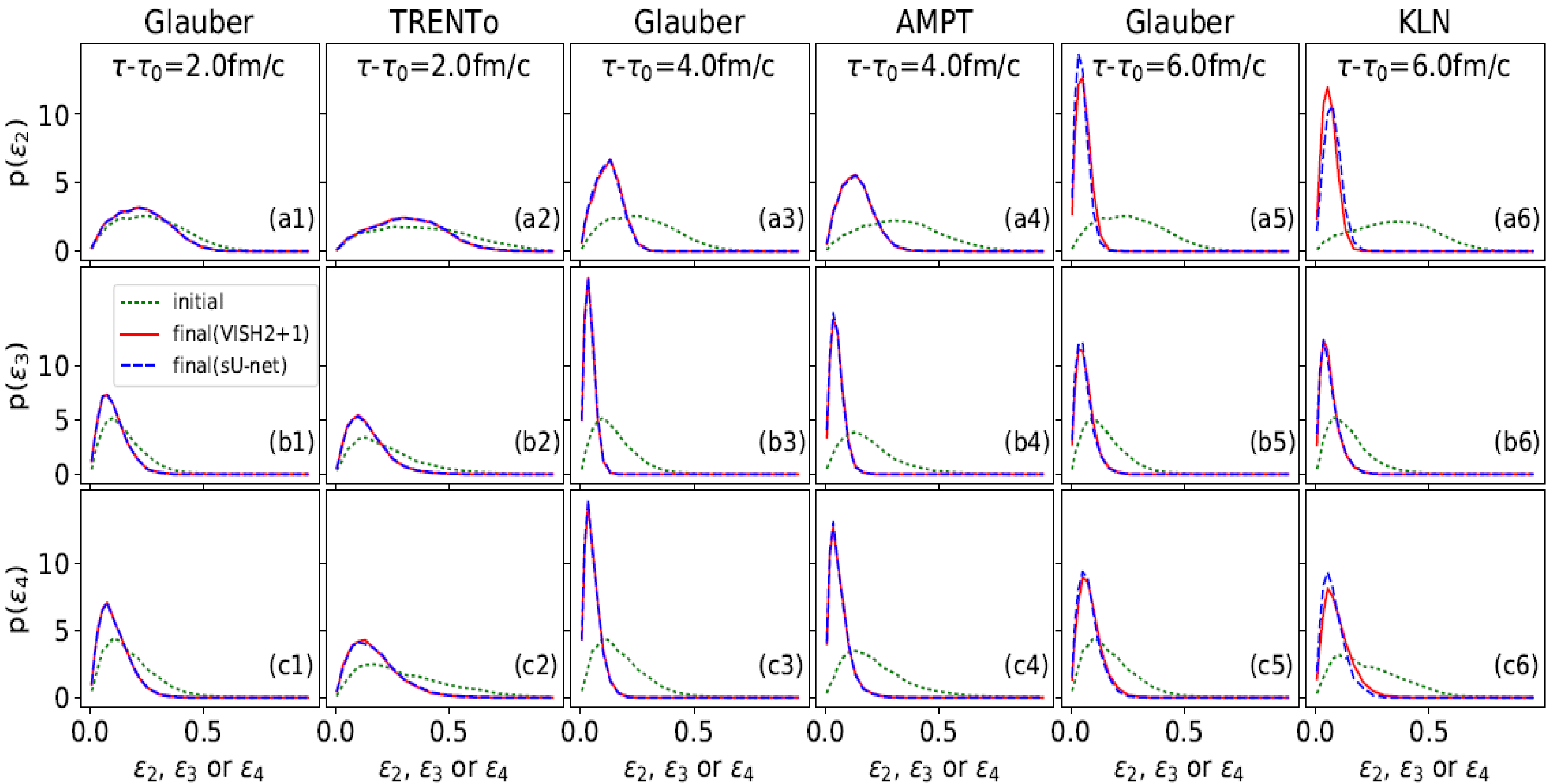
$\tau - \tau_0 = 6.0fm/c$

-for a closer look

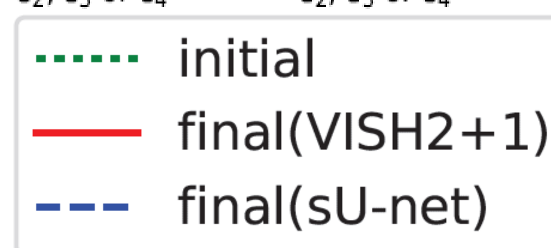


sUnet prediction vs. hydro simulations

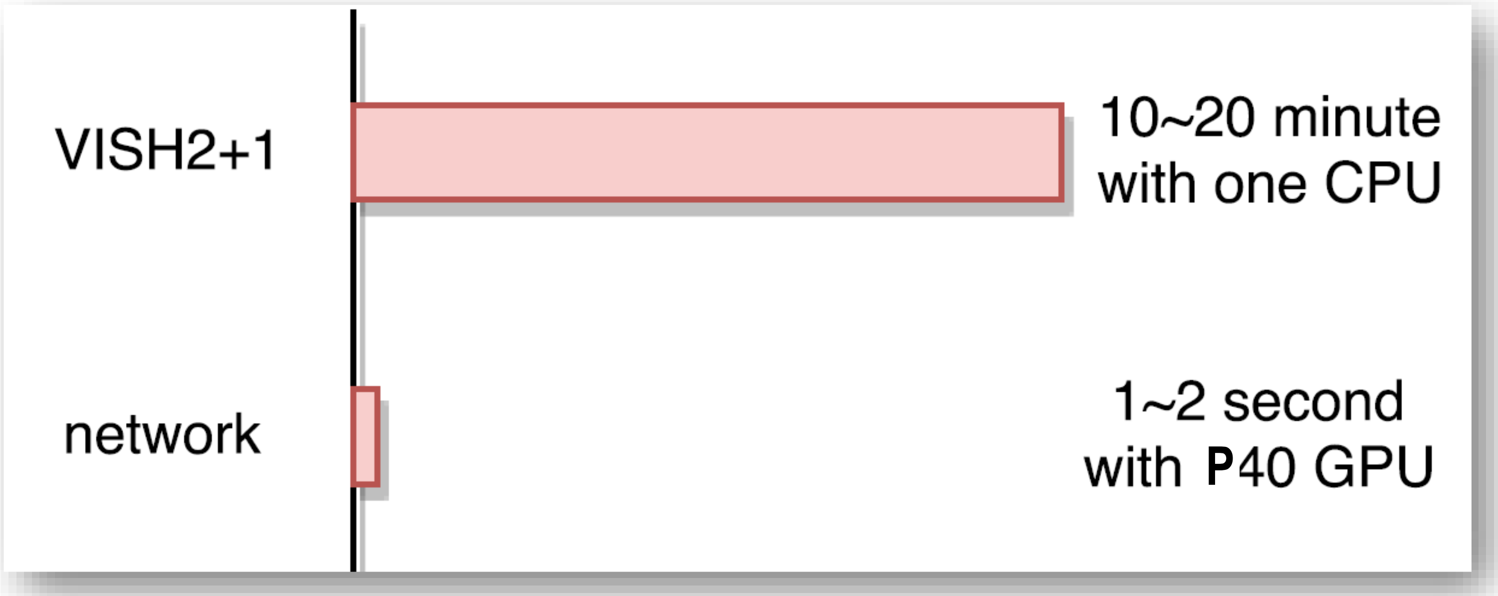
Eccentricity distributions:

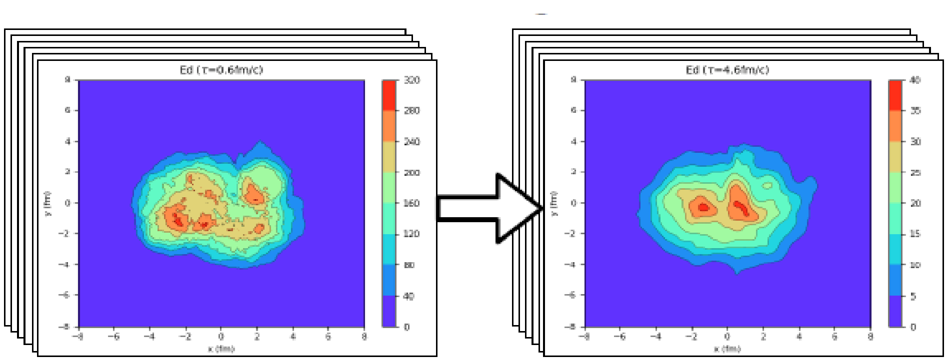


$$\varepsilon_n e^{in\Phi_n} = -\frac{\int dxdyr^2 e^{in\phi} e(x,y)}{\int dxdyr^2 e(x,y)}$$



Simulation time: sUnet vs. hydro





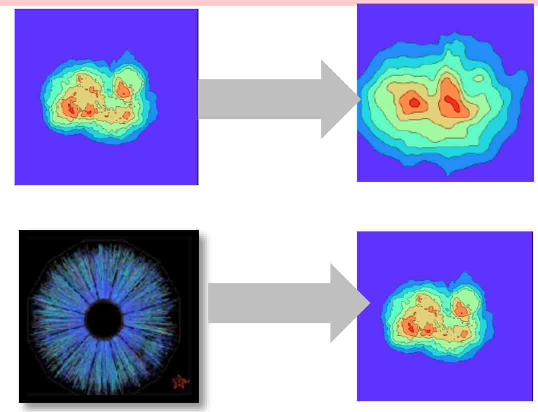
With the well trained network, the final state profiles can be quickly generated from the initial profiles.

Outlook

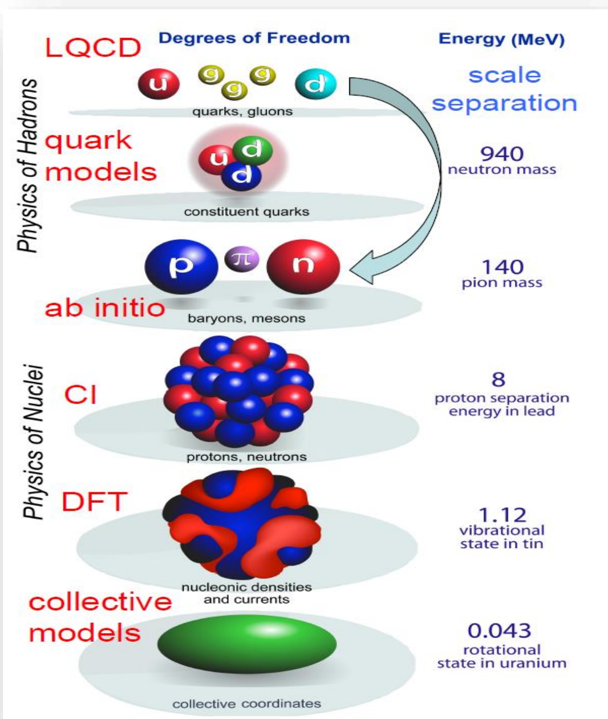
For hydrodynamics

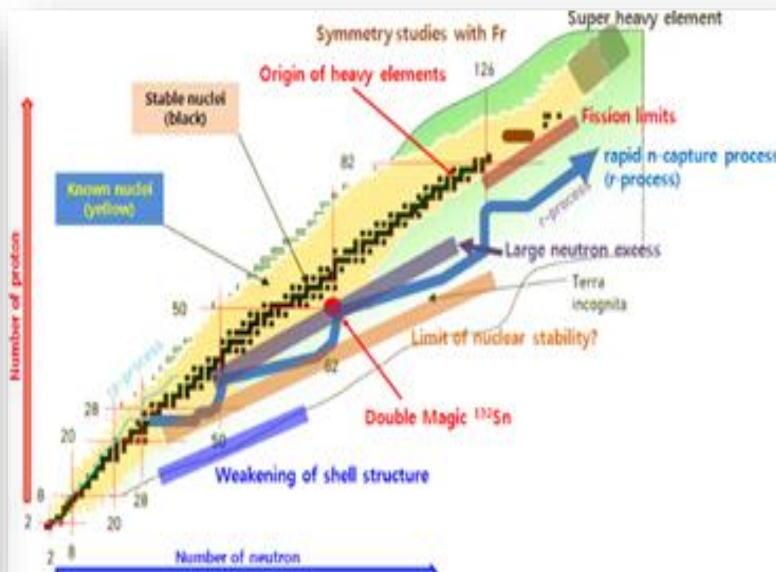
Initial energy density profiles
-------- > final energy density velocity profiles

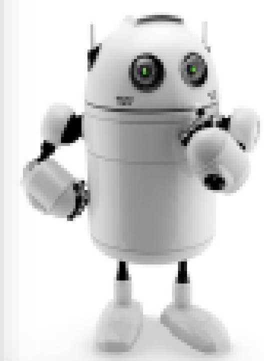
Final particle profiles
-------- > Initial energy density profiles



For Nuclear Physics







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