

Influences of nuclear structure on the "little bangs" from ultrarelativistic heavy ion collisions

Jacquelyn Noronha-Hostler

^{238}U +Sievert, Wertepny, Rao, Carzon, Luzum in prep
 ^{129}Xe +Giacalone, Luzum, Ollitrault Phys.Rev. C97 (2018)
no.3, 034904



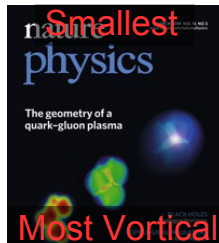
RUTGERS
UNIVERSITY

Jefferson Lab
April 22nd 2018

Nature's Most Extreme Fluid

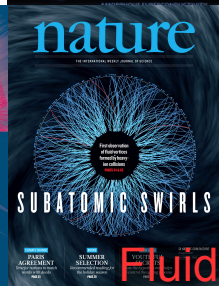
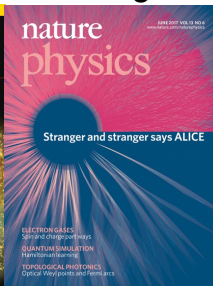
The Quark
Gluon
Plasma is
the ...

Hottest



Most Perfect

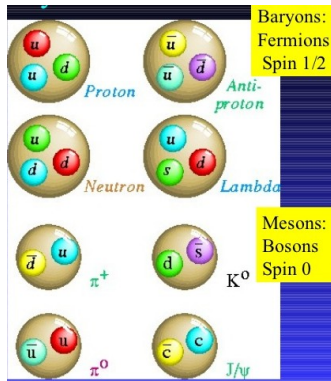
Strange



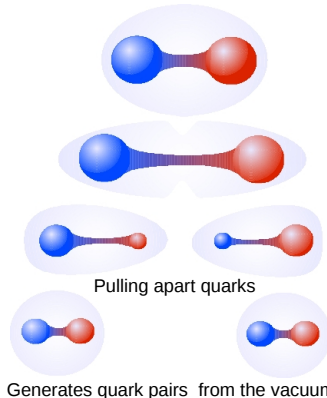
Strongest force at the smallest scales

Quantum Chromodynamics (QCD)- David Politzer, Frank Wilczek and David Gross 1973 (2004 Nobel Prize for Physics)

Bound states=Hadrons

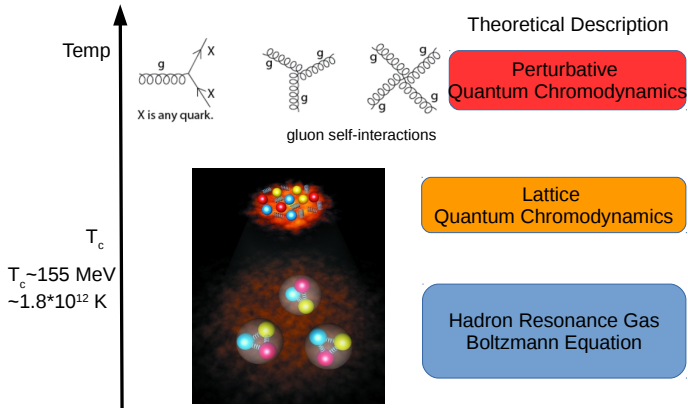


Confinement- quarks always stick together



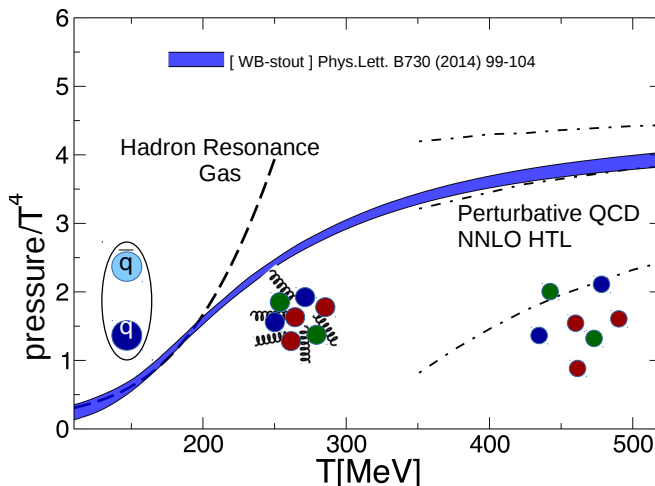
Solving Quantum Chromodynamics

$$L_{QCD} = \underbrace{-\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu}}_{\text{Gluon Interactions}} + \underbrace{\bar{\psi}^q (i\gamma_\mu D^\mu - m_q) \psi^q}_{\text{Quark Interactions}} \text{ where } D^\mu = \partial^\mu - \underbrace{ig A^\mu(x)}_{\text{Gluons}}$$



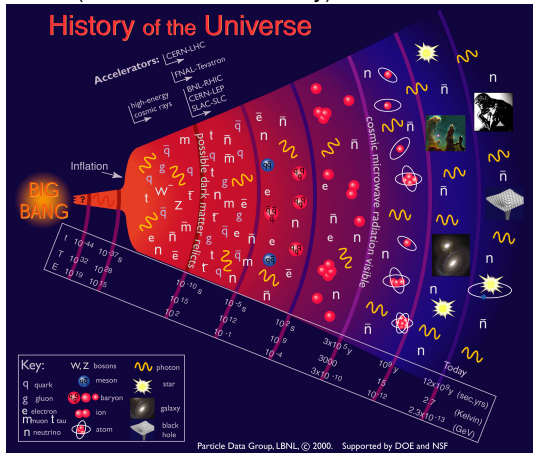
Lattice QCD: Phase Transition

Cross-over phase transition $T_c \sim 155$ MeV



Deconfined Quarks and Gluons in the Early Universe

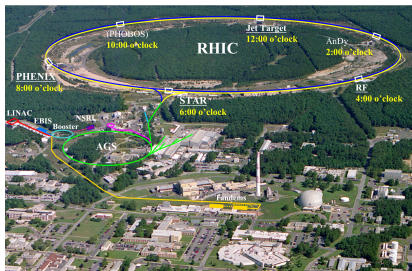
Quark Gluon Plasma: After the Big Bang a plasma of deconfined Quarks and Gluons was formed (1975 Collins and Perry)



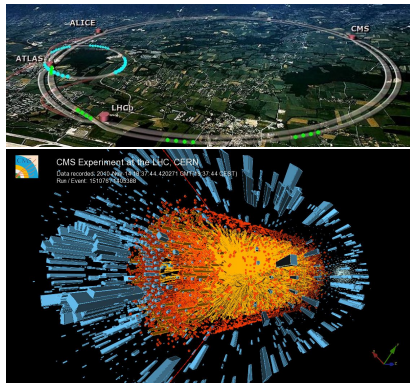
However, most signatures are washed out by the following epochs

Experiments at high temperatures

The Large Hadron Collider and RHIC create "little bangs" → deconfined quarks and gluons in the lab

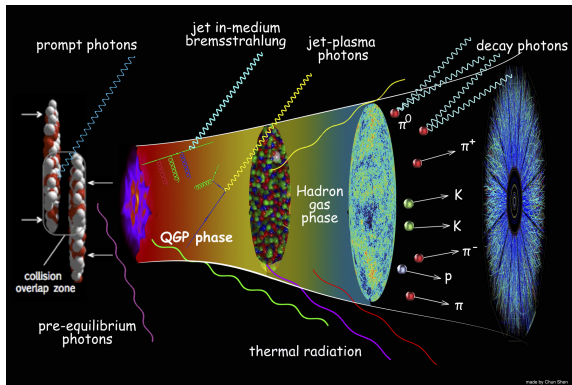


T=4 trillion degrees Celsius



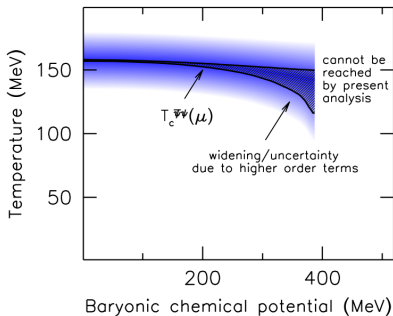
Heavy-ion collisions (Little Bangs)

Smashing two gold ions at the speed of light = deconfined (strongly interacting) quarks and gluons



Limitations of Lattice QCD

Fermi Sign Problem (Large Baryon Densities)



[WB] R. Bellwied et al., Phys.Lett. B751 (2015) 559-564

- Taylor Expansion
(only works for small densities)

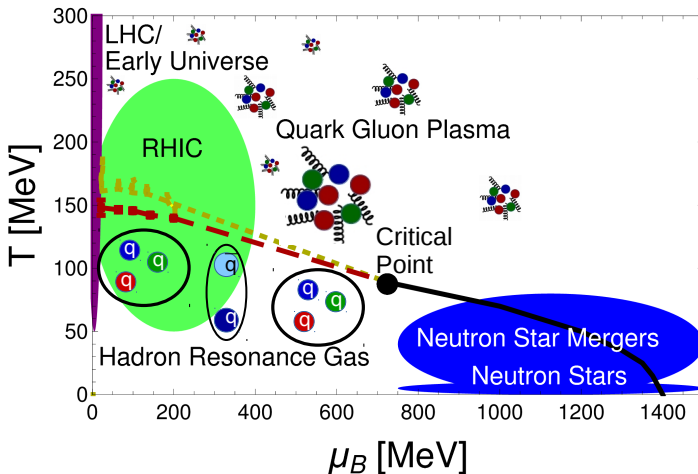
Real Time Dynamics

- Transport coefficients
- Dynamical description of QCD

Effective models

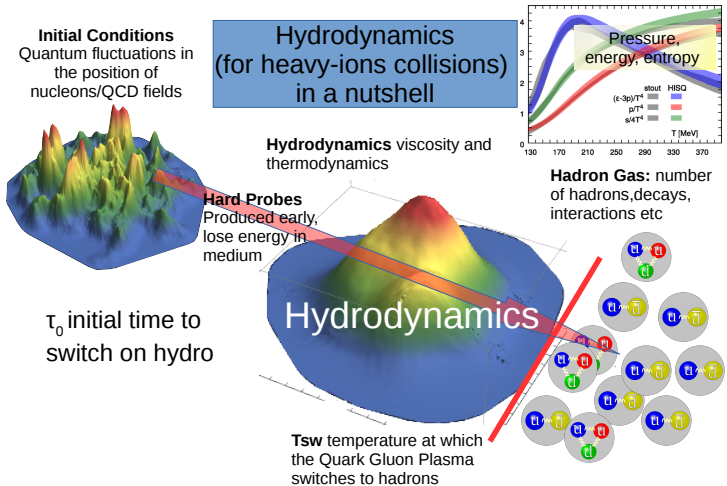
The Quark Gluon Plasma can be well described dynamically using **Relativistic Hydrodynamics** followed by a hadronic afterburner

Current QCD Phase Diagram



- Critical Point from Black hole engineering: Critelli et al Phys.Rev. D96 (2017) no.9, 096026
- Cross-over from fluctuations: Alba et al, PLB738 (2014) 305-310; JNH, Parotto, Portillo, Ratti to appear soon
- Neutron Stars (Mergers): Dexheimer, arXiv:1711.09030

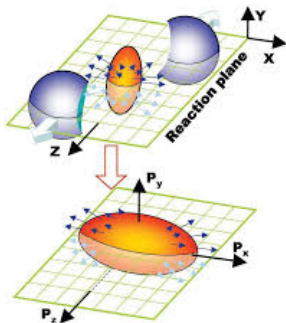
Modelling Little Bangs



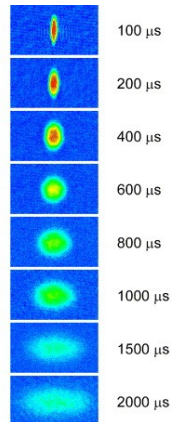
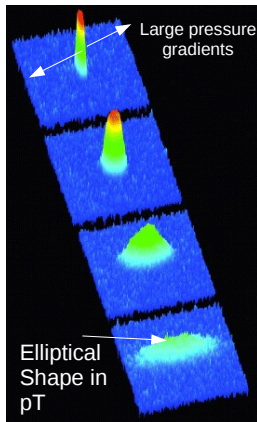
Initial Conditions

Hydrodynamics: eccentric initial state to elliptical flow

Assuming Gold ions are spheres...



Cold Atoms



Spherical Nuclei

Sample nucleons over a Wood Saxon density distribution

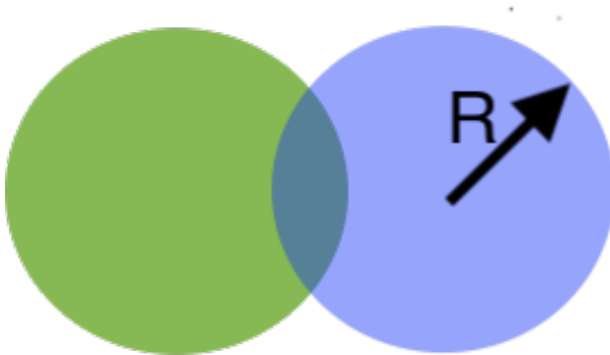
$$\rho = \rho_0 \left[1 + \exp \left(\frac{r - R_0}{a} \right) \right]^{-1}$$

Radius of nucleus R_0

a - surface diffusion parameter

ρ_0 - normal nuclear density

Centrality: pre-2010



Peripheral
collisions

Centrality: pre-2010



Mid-central
collisions

Centrality: pre-2010



Central collisions

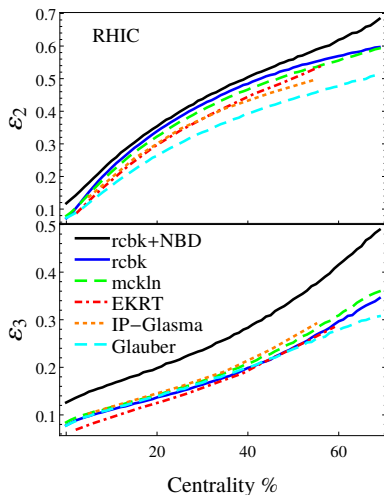
Eccentricities

Eccentricities:

$$\varepsilon_n e^{i\Phi_n} = \frac{\int d^2\mathbf{r} r^n e^{in\phi} \epsilon(\tau_0, \mathbf{r})}{\int d^2\mathbf{r} r^n \epsilon(\tau_0, \mathbf{r})}$$

Variance in the Eccentricities

Different initial conditions with varying underlying physical assumptions







Measuring collective flow

The distribution of particles can be written as a Fourier series

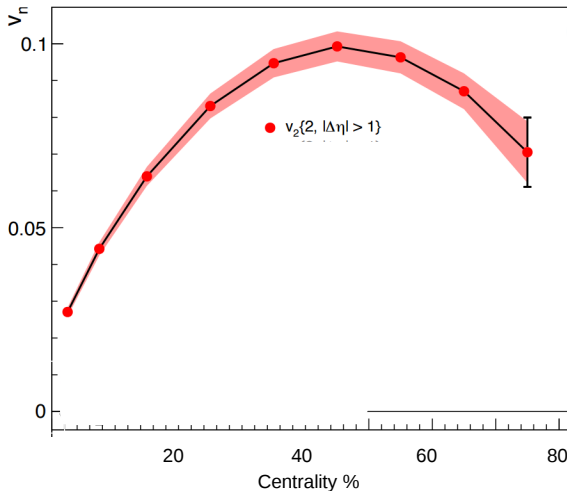
$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left[1 + \sum_n 2v_n \cos[n(\phi - \psi_n)] \right]$$

- Flow Harmonics at mid-rapidity

$$v_n(p_T) = \frac{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi} \cos[n(\phi - \psi_n)]}{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi}}$$

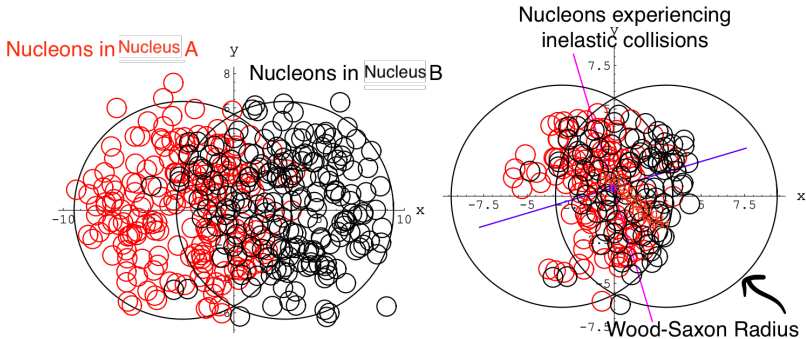
where $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin[(n\phi)] \rangle}{\langle \cos[(n\phi)] \rangle}$

Flow Harmonics across Centrality



ALICE Phys.Rev.Lett. 107 (2011) 032301

Event-by-Event: Radius $\rightarrow$ Participating nucleons



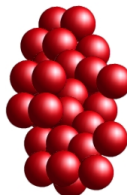
Keep the **participating** nucleons that collide in the overlap region

Centrality

Head on collisions ("central collisions")

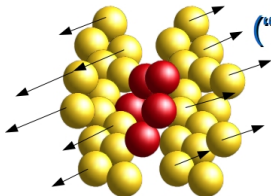
- More partons (protons and neutrons) = larger density
- More circular shape

J. Noronha-Hostler



Grazing collisions ("peripheral collisions")

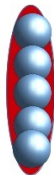
- Fewer partons = small density
- Elliptical shape



Same density (centrality), different shapes

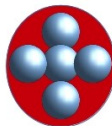
Centrality bins by the density, but for the same density..

“Event-by-Event” Holding the number of partons (density) constant for the same types of collisions, different shapes can be formed.



Ellipsoid=
Large
eccentricity (ϵ_2)

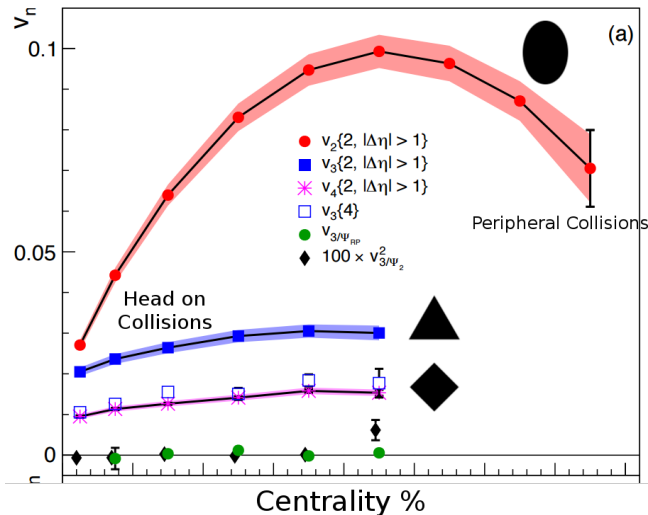
For the
same 5
participants

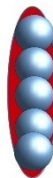
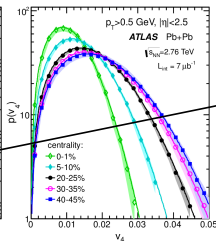


Circle=
Small
eccentricity (ϵ_2)

Triangles, squares etc can even appear...

Flow Harmonics across Centrality

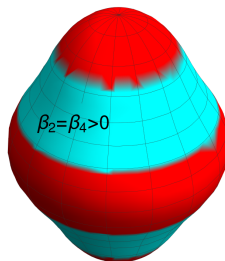
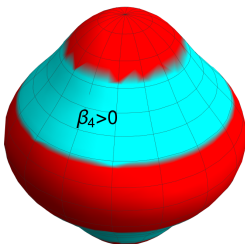
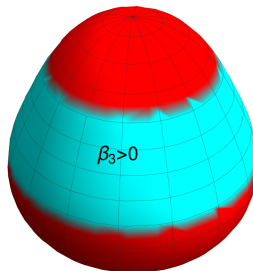
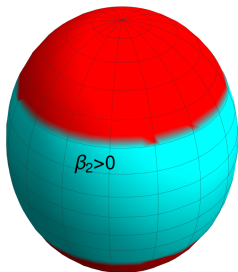




ATLAS JHEP 1311, 183 (2013)

What happens when nuclei aren't perfect
spheres?

Types of deformed nuclei



Wood Saxon Distribution

Wood Saxon density distribution

$$\rho = \rho_0 \left[1 + \exp \left(\frac{r - R}{a} \right) \right]^{-1}$$

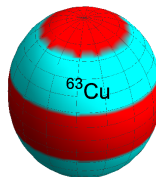
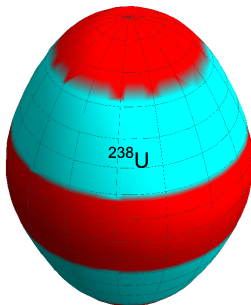
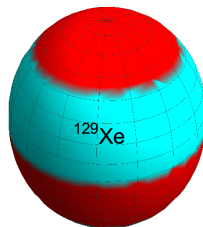
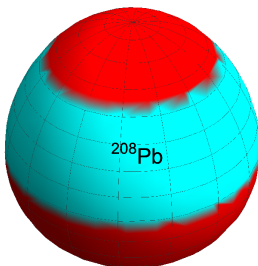
Radius of nucleus R_0

$$R = R_0 \left(1 + \underbrace{\beta_2 Y_{20}(\theta)}_{\text{Quadrupole}} + \underbrace{\beta_4 Y_{40}(\theta)}_{\text{Hexadecapole}} \right)$$

a - surface diffusion parameter

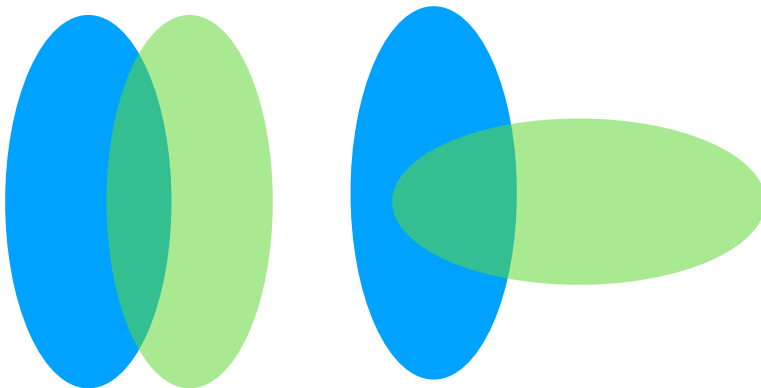
ρ_0 - normal nuclear density

Common heavy ions used in collisions



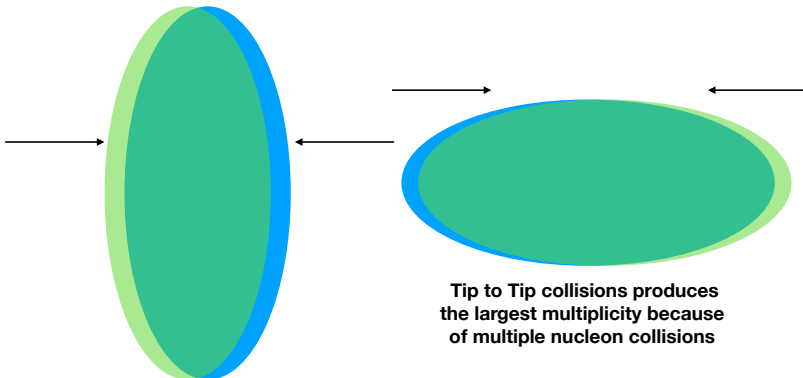
Deformed mid-central

Mid-central insensitive to deformed nuclei



Deformed ultra-central

Only ultra central collisions are sensitive to deformations



**Body to Body collisions
produces the largest elliptical
flow**

**Tip to Tip collisions produces
the largest multiplicity because
of multiple nucleon collisions**

side-side collisions

tip-tip collisions

v_2

0.125% Most Central ZDC Selection

0.85 0.9 0.95 1 1.05 1.1 1.15

Mult/(Mult)

U+U

Au+Au

Glauber $x_{\text{hard}}=0.13$

Glauber Const. Quarks

CGC-IPGlasma

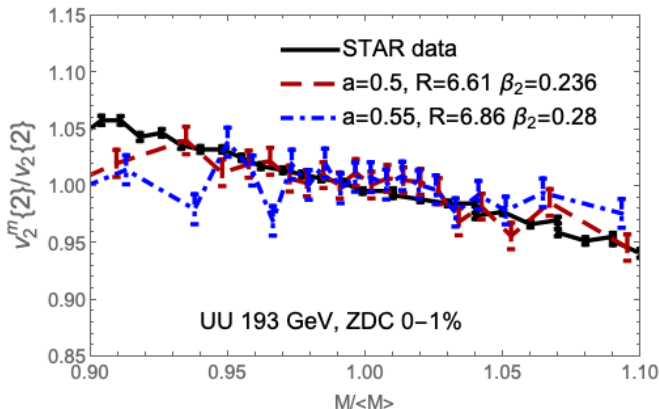
A set of small navigation icons typically found in Beamer presentations, including symbols for back, forward, search, and other slide controls.

Testing different parameterizations of ²³⁸U

$a=0.5$, $R=6.61$, $\beta_2 = 0.236$ Data Nucl. Data Tabl. 109-110, 1 (2016); Giacalone Phys.Rev.

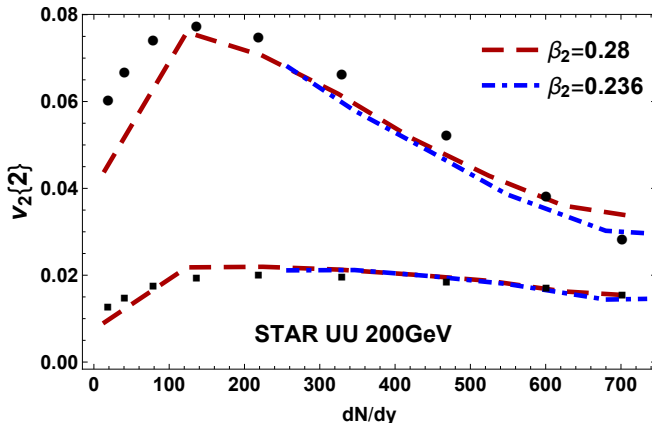
C99 (2019) no.2, 024910

$a=0.55$, $R=6.86$, $\beta_2 = 0.28$ Schenke, Shun, Tribedy Phys.Rev. C99 (2019) no.4, 044908



Effects of the quadrupole (ultracentral collisions only)

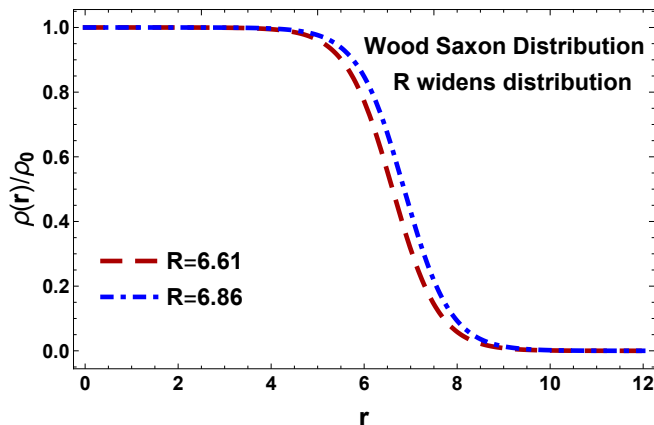
Keep $R=6.86$ and $a=0.600$ constant, vary β_2



STAR, L. Adamczyk et al., Phys. Rev. Lett. 115 (2015) 222301, 1505.07812; v-USPhydro JNH et al Phys.Rev. C90 (2014) no.3, 034907, Phys.Rev. C88 (2013) no.4, 044916 ;TRENTO Moreland et al Phys.Rev. C92 (2015) no.1, 011901

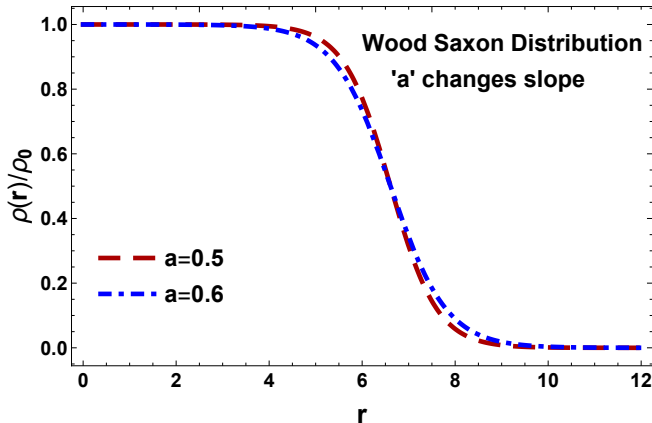
Density distribution (Wood Saxon)

Varying the radius $\rho = \rho_0 \left[1 + \exp\left(\frac{r-R}{a}\right) \right]^{-1}$



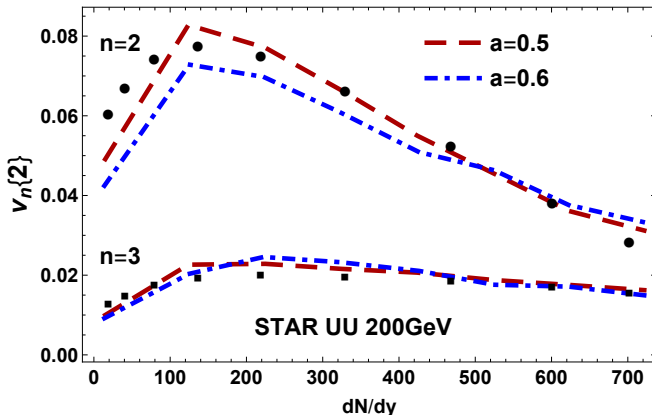
Density distribution (Wood Saxon)

Varying the diffusion $\rho = \rho_0 \left[1 + \exp \left(\frac{r-R}{a} \right) \right]^{-1}$



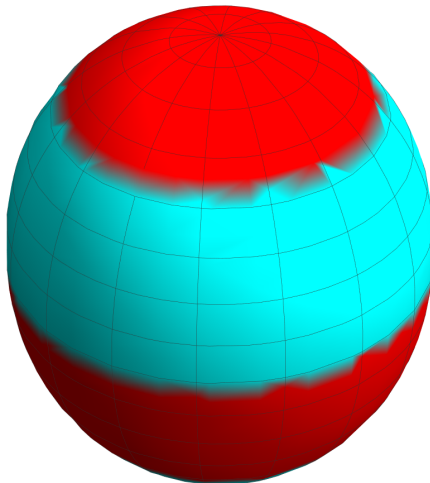
Effects of the diffusion (significant in peripheral collisions)

Keep $R=6.62$ and $\beta_2 = 0.236$ constant, vary diffusion

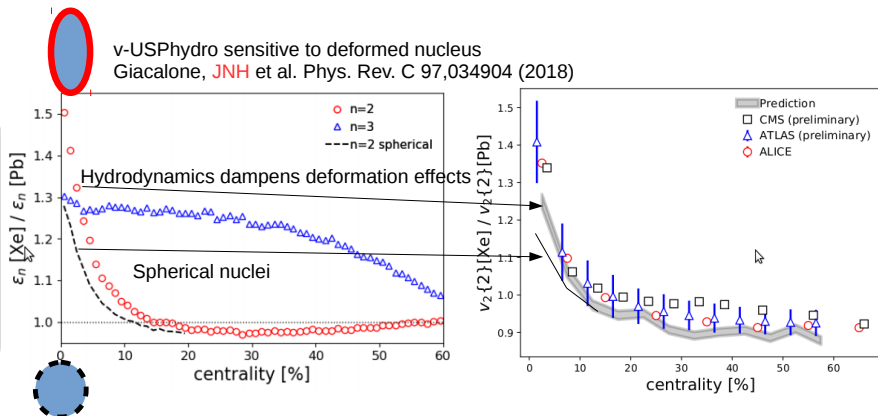


Xe¹²⁹ nucleus

$A = 129$, $R = 5.42$ fm, $a = 0.57$ fm, $\beta_2 = 0.162$ and $\beta_4 = -0.003$
Data Nucl. Data Tabl. 109-110, 1 (2016)



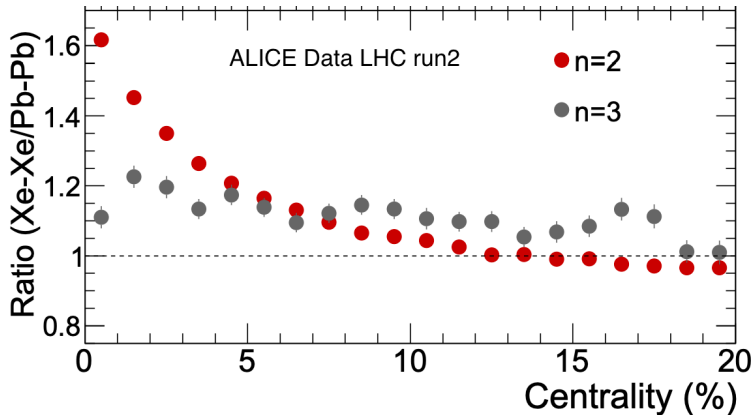
Deformed Xe^{129} nucleus



Initial conditions

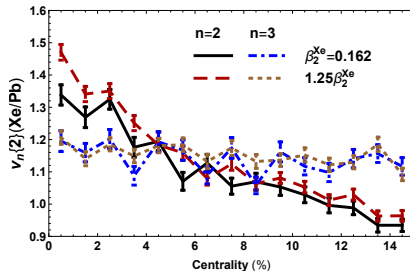
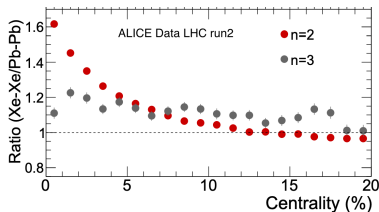
- Questions still remain in central collisions, possible insights into nuclear structure?
- Centrality still dominate factor

Xenon ultra-central



Xenon ultra-central

Given an approximate 25% error on β_2 still isn't quite elliptical enough for data



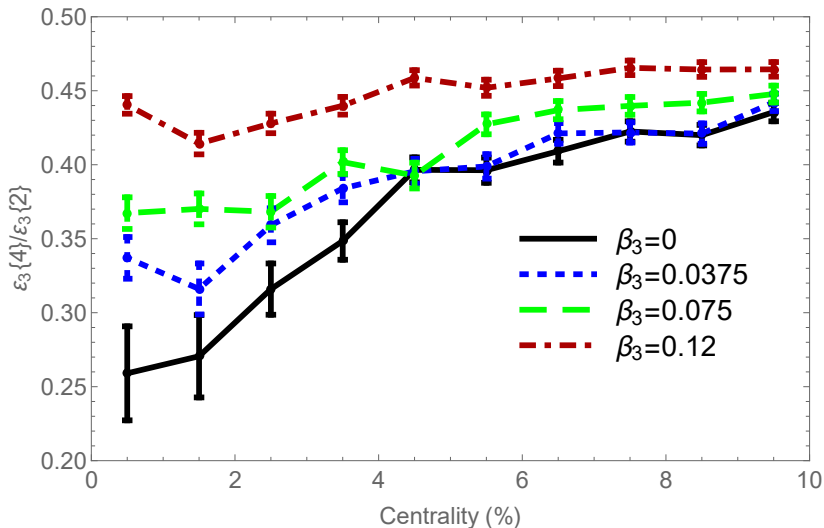
Could deformation effects look different at high energies? Initial time/initial flow?

Conclusions

- Even small deformations in nuclei is measurable in ultra-central heavy ion collisions
- ^{129}Xe appears to have a larger quadrupole deformation than expected
- ^{238}U uncertainties from radius/surface diffusion parameter
- Possible upcoming runs of ^{16}O and ^{40}Ar at the LHC
- Future: Thoughts on way the EIC could shed light on this issue

v_3 Fluctuations: improvements with β_3

Lead-Lead Collisions at 5.02 TeV



Fluctuations of Conserved Charges

Susceptibilities

$$\chi_{lmn}^{BSQ} = \frac{\delta^{l+m+n} p / T^4}{\delta(\mu_B/T)^l \delta(\mu_S/T)^m \delta(\mu_Q/T)^n}$$

where the chemical potentials are related via:

$$\begin{aligned}\mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q \\ \mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q \\ \mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S\end{aligned}$$

Thermodynamic quantities arXiv:1711.05207

π **gas** $T \leq 33.5$ MeV **HRG** $T \leq 153$ MeV **Lattice QCD**

$$\left(\frac{\varepsilon - 3p}{T^4}\right)_{all} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{\pi} - \frac{1 + \tanh\left[b(T - T_{HRG+Latt}/\pi)\right]}{2} \left[\left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG+Latt} - \left(\frac{\varepsilon - 3p}{T^4}\right)_{\pi}\right]$$

$$\left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG+Latt} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG} - \frac{1 + \tanh\left[a(T - T_{HRG/Latt})\right]}{2} \left[\left(\frac{\varepsilon - 3p}{T^4}\right)_{Latt} - \left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG}\right]$$

$$\frac{\varepsilon}{T^4} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{all} + \frac{3p}{T^4}$$

$$\frac{s}{T^3} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{all} + \frac{4p}{T^4}$$

$$c_s^2 = \frac{s}{T} \frac{dT}{ds} = \frac{dp}{d\varepsilon}$$

$$\frac{p}{T^4} = \int_0^T dT \frac{1}{T} \left(\frac{\varepsilon - 3p}{T^4}\right)_{all}$$

$$a = 0.1 \text{ MeV}^{-1}, T_{HRG/Latt} = 153 \text{ MeV}$$

$$b = 1 \text{ MeV}^{-1}, T_{HRG+Latt/\pi} = 33.5 \text{ MeV}$$

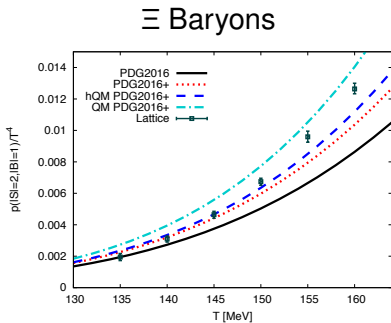
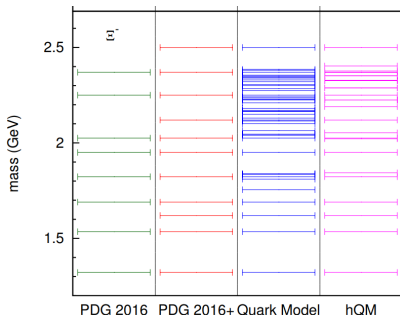
Missing hadron resonances

[WB] Phys.Rev. D96 (2017) no.3, 034517

see also [HotQCD] Phys.Rev.Lett. 113 (2014) no.7, 072001

Partial pressure can find missing strange states.

$$P_{1|2} = -\frac{1}{4} (\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}) \cosh(\hat{\mu}_B - 2\hat{\mu}_S)$$



Uncertainty in decays of heavier resonances! Extrapolated from same family.

Alba, Mantovani Sarti, JNH, P. Parotto, Portillo Vazquez, Ratti. To appear soon.

TRENTO

TRENTO Moreland, Bernhard, Bass PRC92(2015)no.1,011901

Total initial entropy profile

$$S(p; S_A, S_B) = \left(\frac{S_A^p + S_B^p}{2} \right)^{\frac{1}{p}}, \quad (1)$$

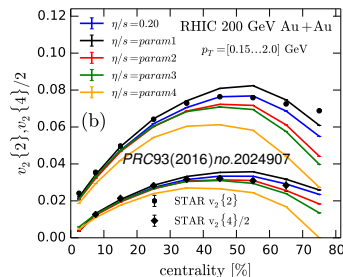
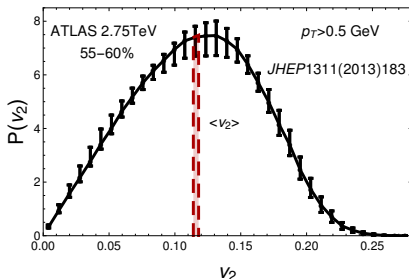
where

$$S_{A,B} = w_{A,B} \frac{1}{2\pi\sigma^2} \exp \left[-\frac{(x - x_{A,B})^2 + (y - y_{A,B})^2}{2\sigma^2} \right]. \quad (2)$$

normalization, w , is a random number which is assigned to each participant nucleon, Γ probability distribution with the width k .

Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s, \text{ EOS etc..}$



- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$



- Correlation different harmonics $SC(3,2)$



◀ ◻ ▶ ◀ ◻ ▶ ◀ ≡ ▶ ◀ ≡ ▶ ≡