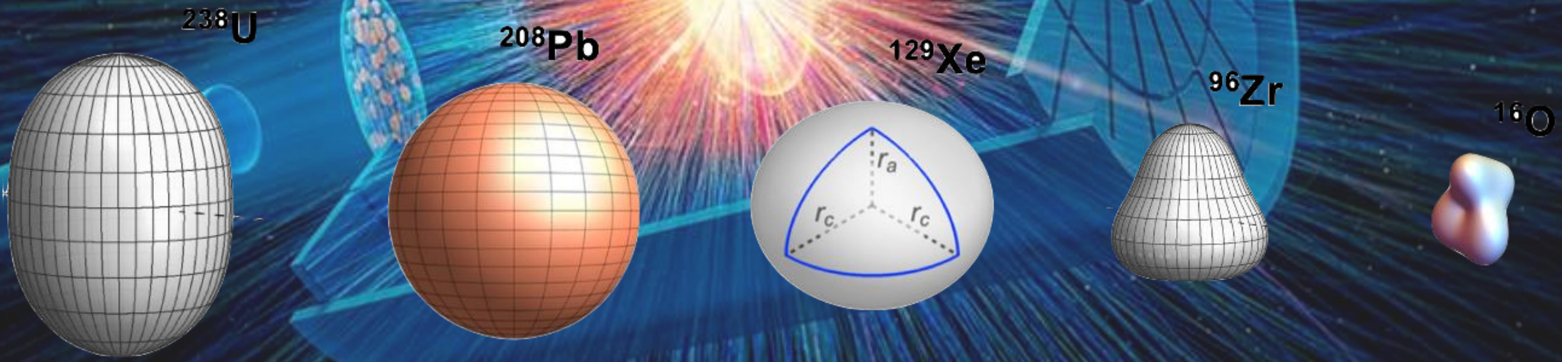
Stony Brook University

Collectivity: Prospects and Future Directions

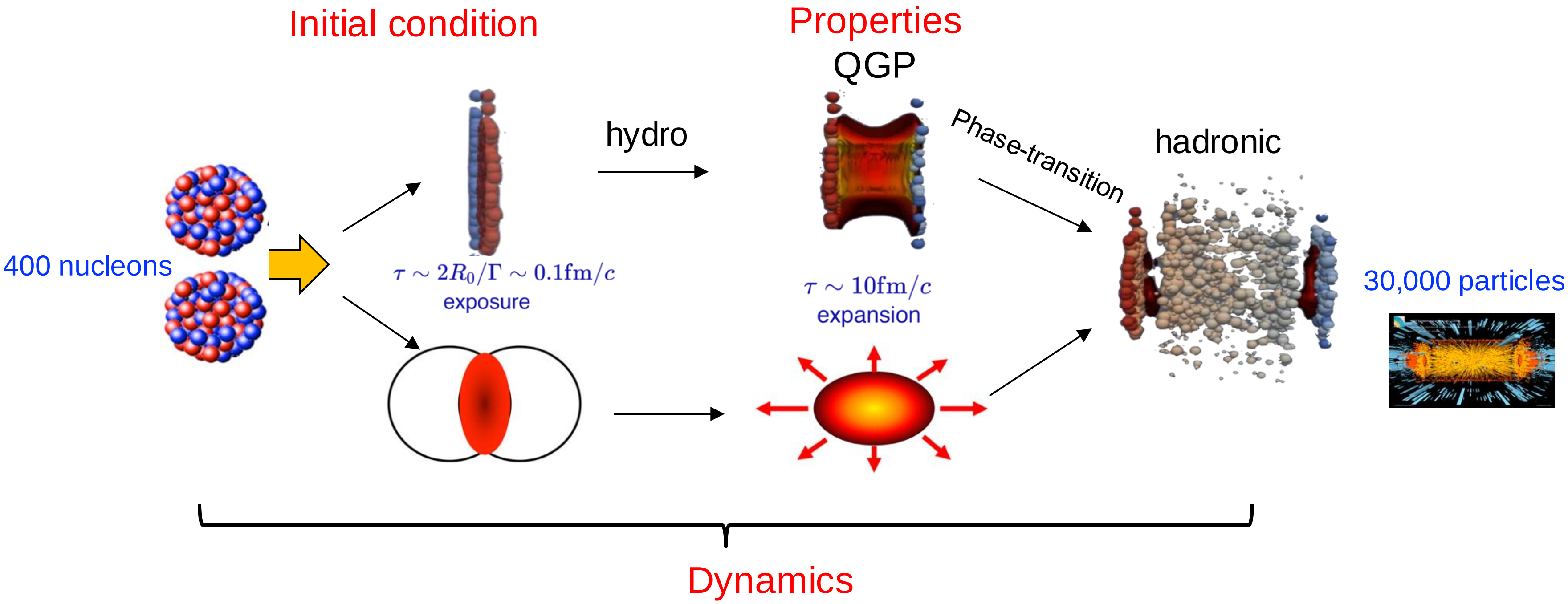
Jiangyong Jia

Oct 21, 2024



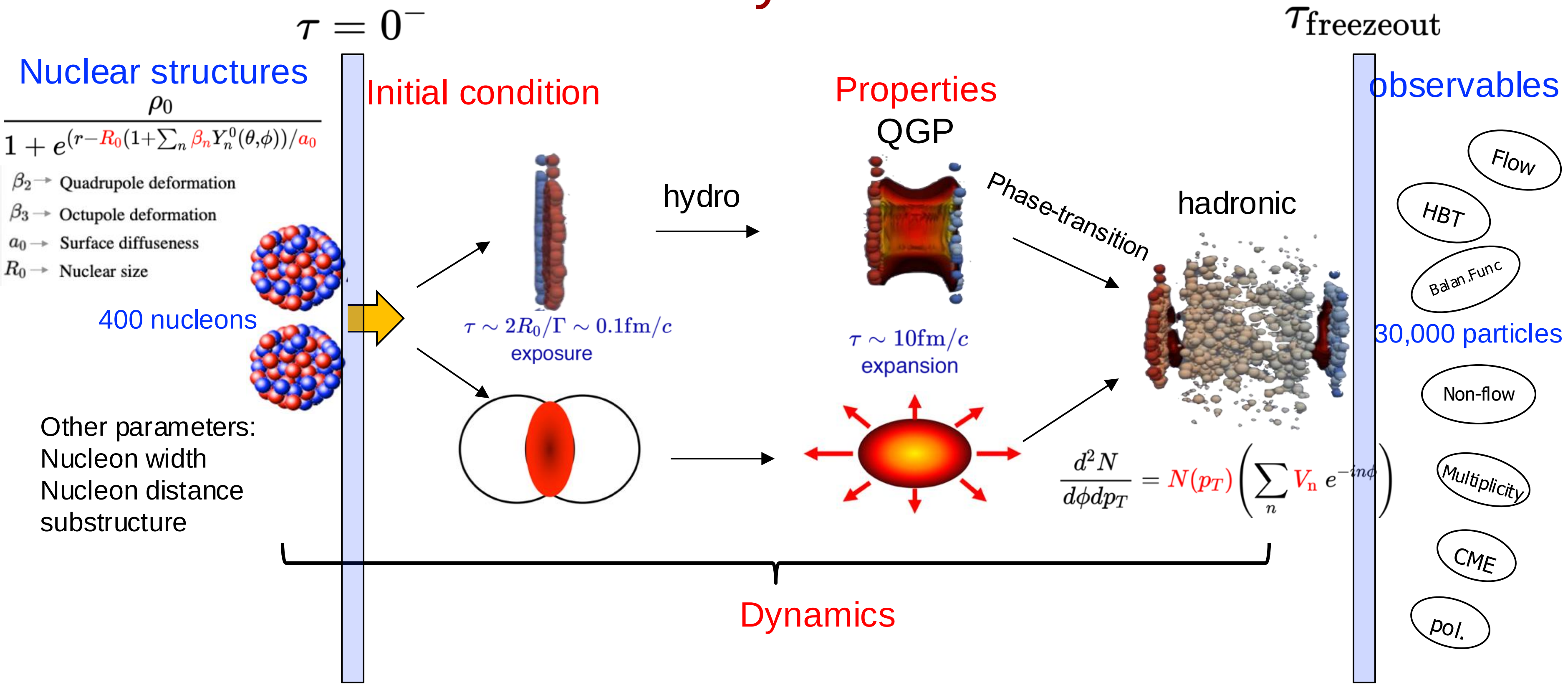
Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics

Heavy ion collisions



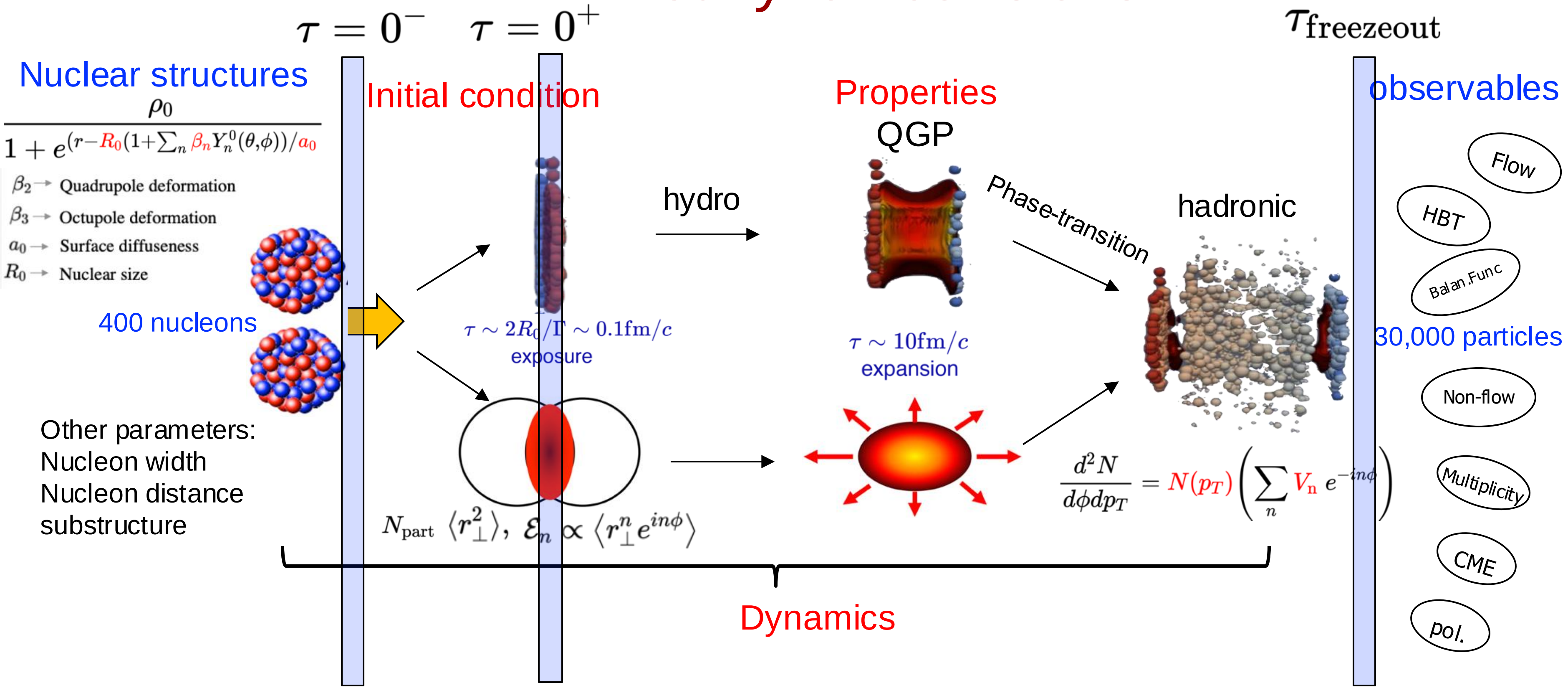
Three pillars of understanding: Properties, Dynamics, Initial condition

Heavy ion collisions



Two snap-shots: Final state particles, Nuclear structures

Heavy ion collisions



Two snap-shots: Final state particles, Nuclear structures

→Measure more observables or collide more systems

A plethora of observables

- Single particle distribution

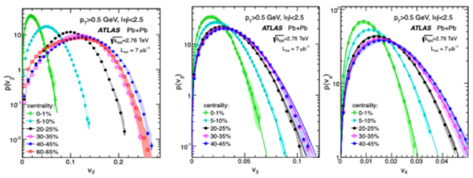
Flow vector: $\boldsymbol{V}_n = v_n e^{in\Psi_n}$

$$\frac{d^2N}{d\phi dp_T} = N(p_T)\left[1 + 2\sum_n v_n(p_T)\cos n(\phi - \Psi_n(p_T))\right]$$

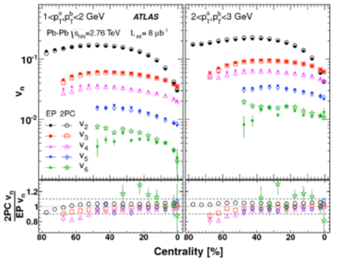
$$= N(p_T)\left[\sum_{n=-\infty}^{\infty} V_n(p_T)e^{in\phi}\right]$$

Radial flow ↗   ↖ Anisotropic flow

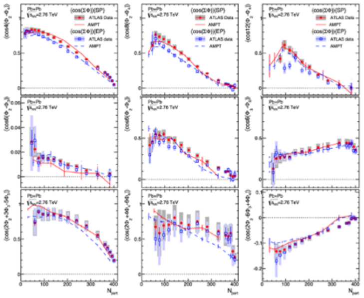
E-by-E flow amplitude distribution $p(v_n)$



Higher-harmonics v_2-v_6



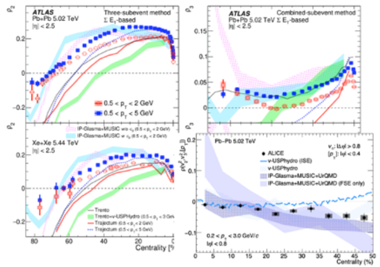
Event-plane correlation $p(\Psi_n,\Psi_m,\Psi_k)$



- Two-particle correlation function

$$\left\langle \frac{d^2N_1}{d\phi dp_T}\frac{d^2N_2}{d\phi dp_T}\right\rangle \quad Þ \quad \langle \boldsymbol{V}_n(p_{T1})\boldsymbol{V}_n^*(p_{T2})\rangle \qquad n - n = 0$$

v_n-p_T correlation $p(v_n, p_T)$



- Multi-particle correlation function

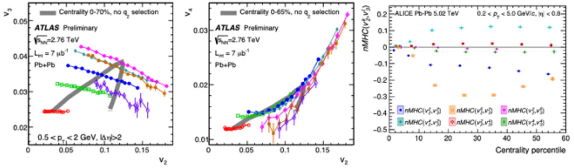
$$n_1 + n_2 + \ldots + n_m = 0$$

$$\left\langle [p_T]^k \frac{d^2N_1}{d\phi dp_T}\cdots\frac{d^2N_m}{d\phi dp_T}\right\rangle \Rightarrow \langle [p_T]^k \boldsymbol{V}_{n_1}\boldsymbol{V}_{n_2}\ldots\boldsymbol{V}_{n_m}\rangle$$

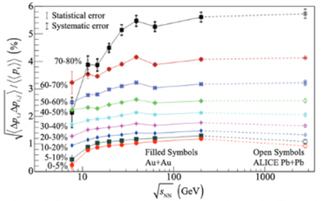
↓

$$p([p_T],\boldsymbol{V}_2,\boldsymbol{V}_3\ldots) = \frac{1}{N_{\rm evts}}\frac{dN_{\rm evts}}{d[p_T]d\boldsymbol{V}_2 d\boldsymbol{V}_3\ldots}$$

v_n amplitude correlation $p(v_n,v_m)$



p_T fluctuations $p(p_T)$



EbyE fluctuations of initial volume, size and shape

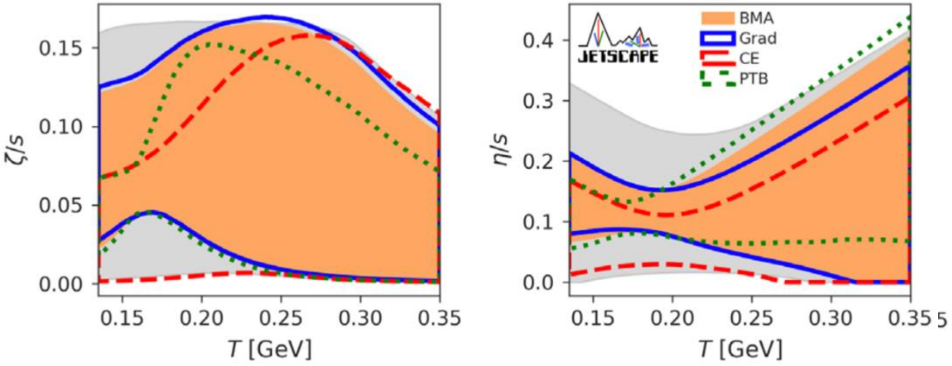
From Weiyao Ke, Jetscape

Uncertainty quantification

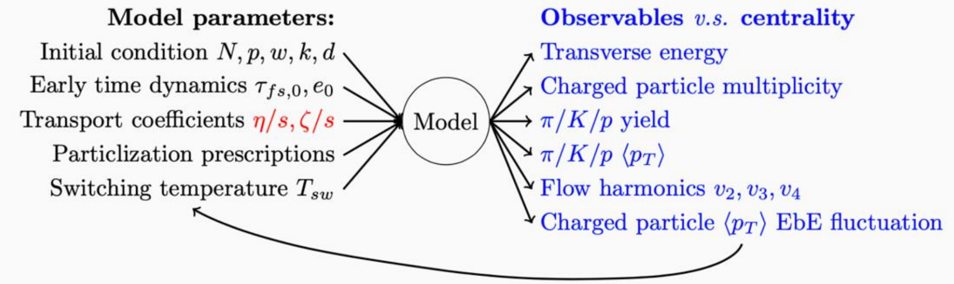
PRL.126.24230

Norm. Pb-Pb 2.76 TeV	N[2.76 TeV]	[10, 20]
Norm. Au-Au 200 GeV	N[0.2 TeV]	[3, 10]
generalized mean	p	[–0.7, 0.7]
nucleon width	w	[0.5, 1.5] fm
min. dist. btw. nucleons	$d^3_{\rm min}$	[0, 1.7^3] fm^3
multiplicity fluctuation	σ_k	[0.3, 2.0]
free-streaming time scale	τ_R	[0.3, 2.0] fm/c
free-streaming energy dep.	α	[–0.3, 0.3]
particlization temperature	$T_{\rm sw}$	[0.135, 0.165] GeV

temperature of (η/s) kink	T_η	[0.13, 0.3] GeV
(η/s) at kink	$(\eta/s)_{\rm kink}$	[0.01, 0.2]
low temp. slope of (η/s)	$a_{\rm low}$	[–2, 1] GeV^{-1}
high temp. slope of (η/s)	$a_{\rm high}$	[–1, 2] GeV^{-1}
shear relaxation time factor	b_π	[2, 8]
maximum of (ζ/s)	$(\zeta/s)_{\max}$	[0.01, 0.25]
temperature of (ζ/s) peak	T_ζ	[0.12, 0.3] GeV
width of (ζ/s) peak	w_ζ	[0.025, 0.15] GeV
asymmetry of (ζ/s) peak	λ_ζ	[–0.8, 0.8]

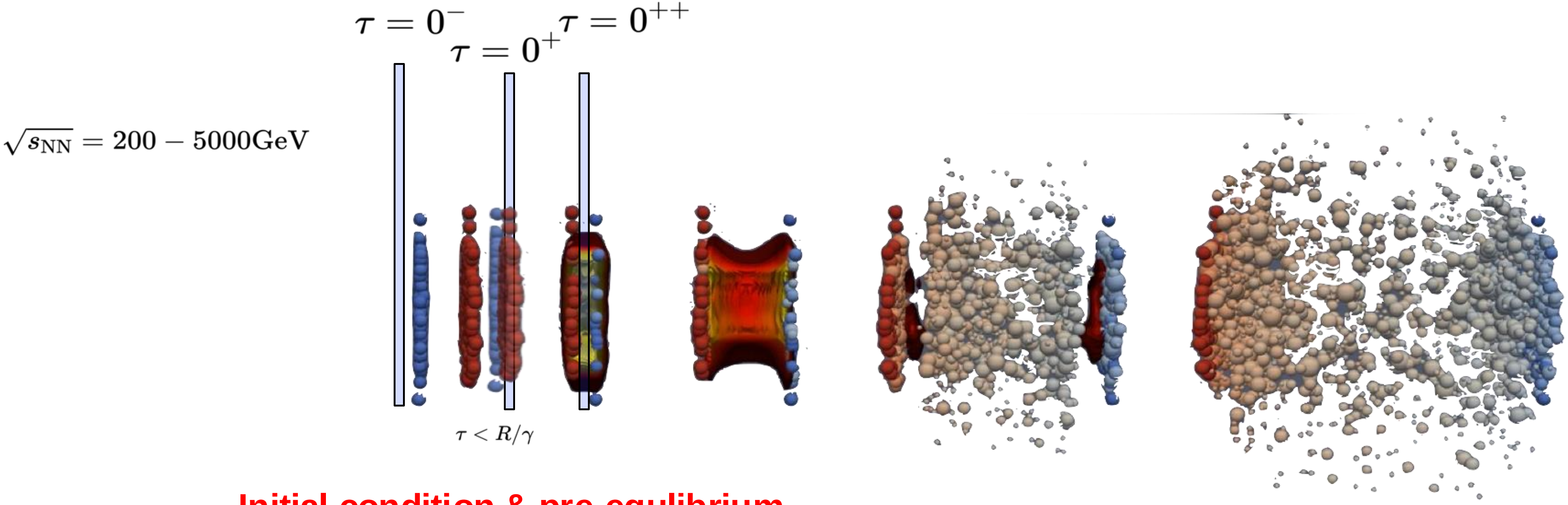


Only a subset of observables are used



- Extraction of QGP properties is limited by the initial condition
- At this moment, more observables do not necessarily improve the situation.

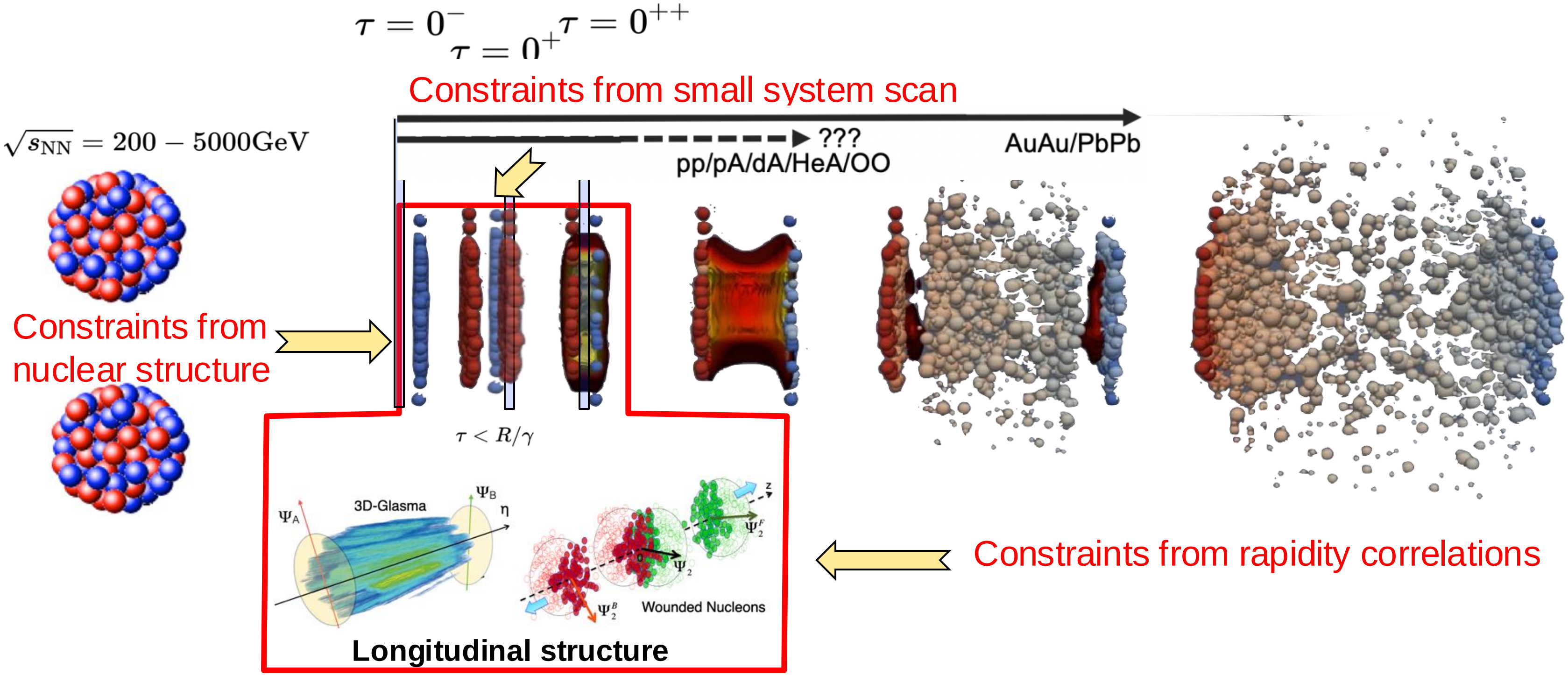
Isolating the impact of initial condition



Initial condition & pre-equlibrium

What is the nature of quantum fluctuations?
How is the energy deposited?
What are the DoFs?
How does the system hydrodynamize/thermalize? timescales?

Isolating the impact of initial condition

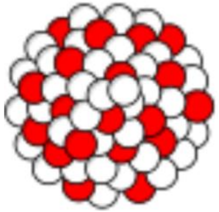


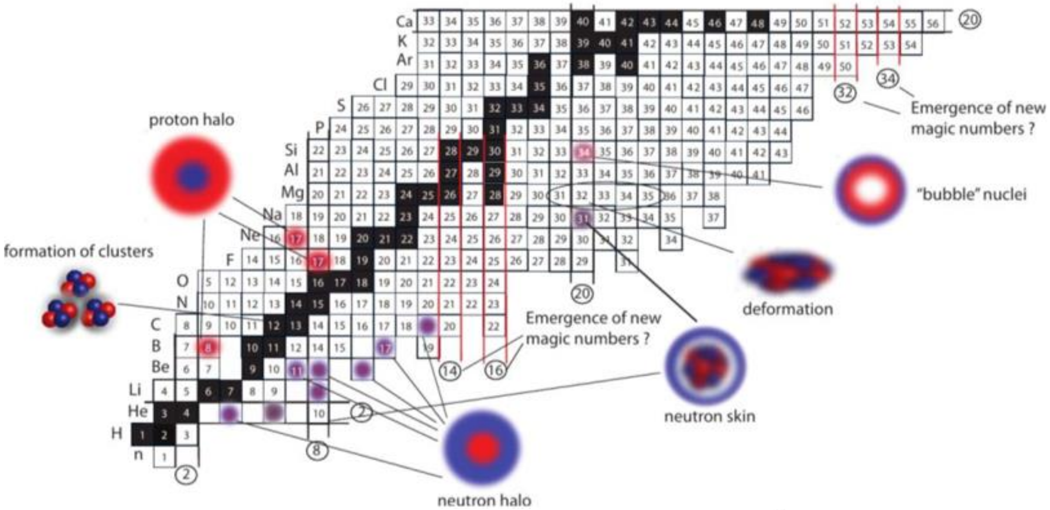
What is the nature of quantum fluctuations?
How is the energy deposited?
What are the DoFs?
How does the system hydrodynamize/thermalize? timescales?

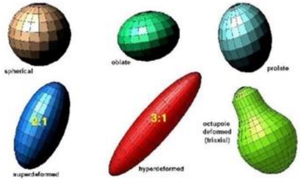
Three experimental approaches:

- Explore nuclear structure
- Longitudinal correlation
- Small system scan

1) Constraints from nuclear structure







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

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

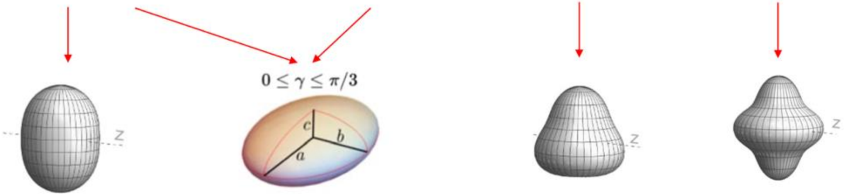
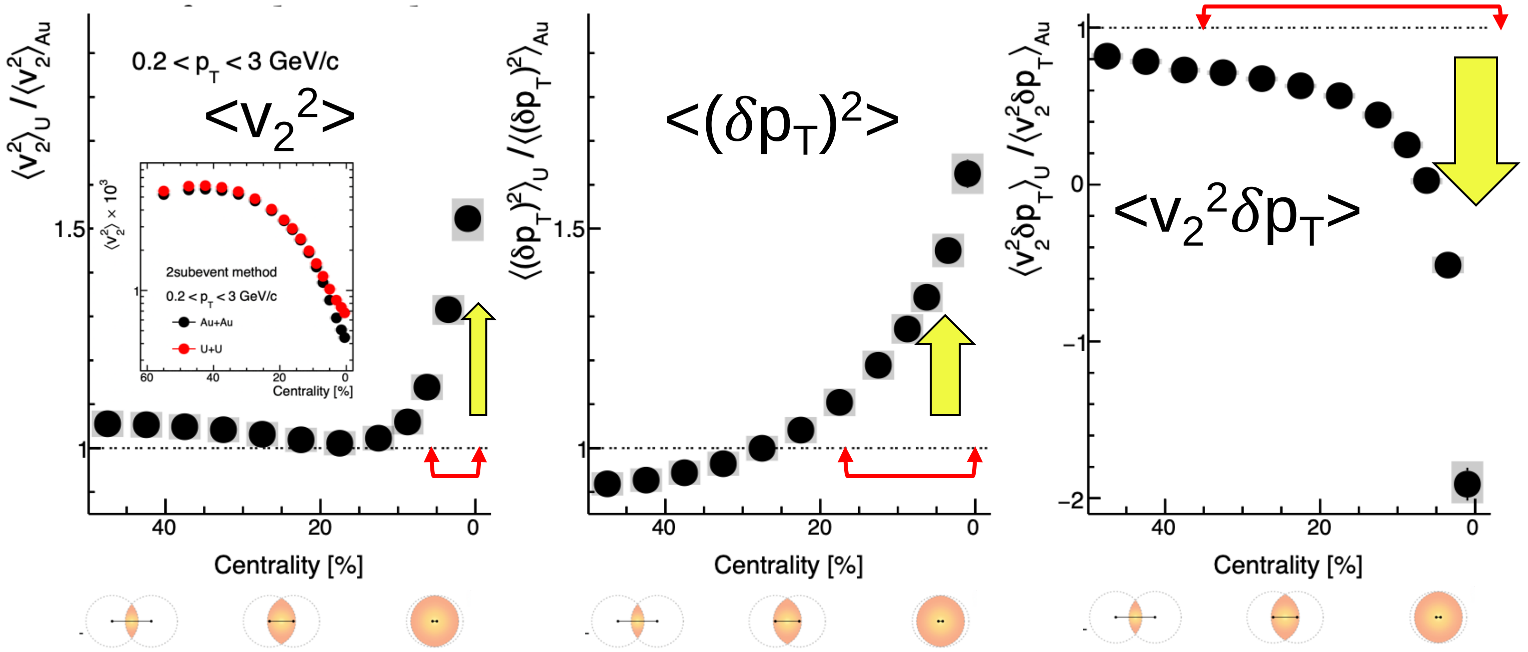


Image U shape via Isobar-like U+U vs Au+Au collisions

2401.06625, accepted by Nature

$R_{\mathcal{O}} = \langle\mathcal{O}\rangle_{U+U} / \langle\mathcal{O}\rangle_{Au+Au}$ →Insensitive to final state parameters



U deformation dominates the ultra-central collisions

→50%-70% modification on $\langle v_2^2\rangle$ and $\langle(\delta p_T)^2\rangle$, 300% for $\langle v_2^2\delta p_T\rangle$

Image U shape via Isobar-like U+U vs Au+Au collisions

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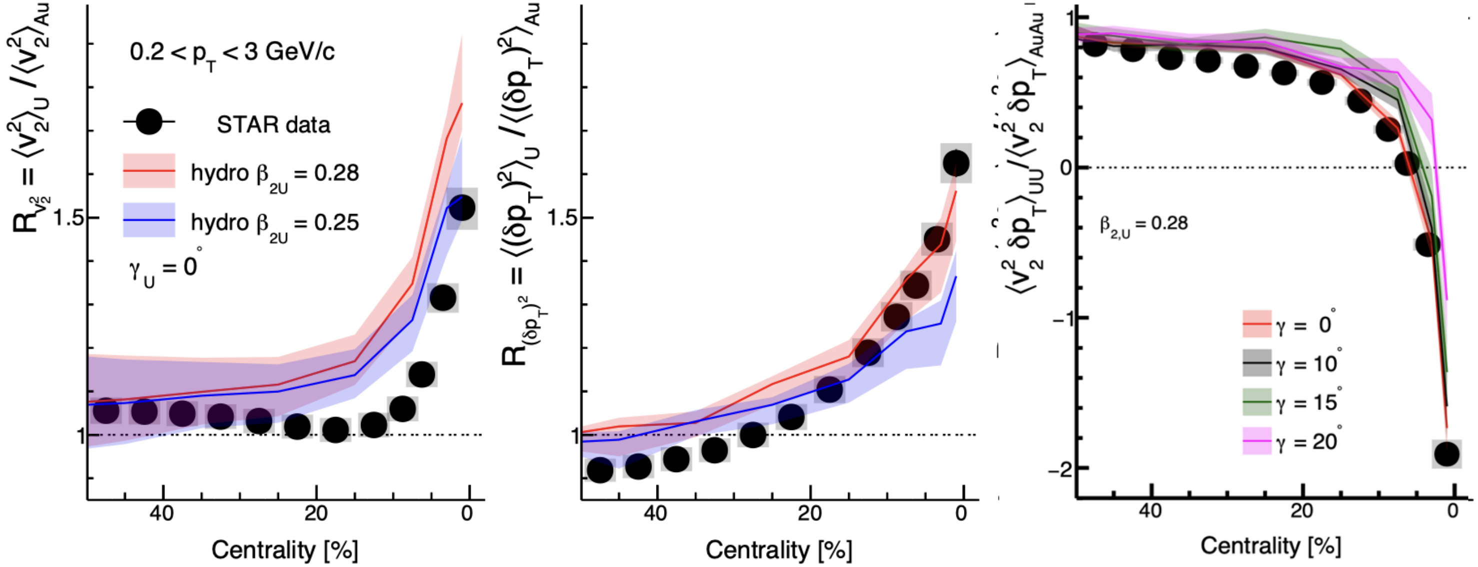
$R_{\mathcal{O}} = \langle \mathcal{O} \rangle_{\mathrm{U+U}} / \langle \mathcal{O} \rangle_{\mathrm{Au+Au}}$ →Insensitive to final state parameters

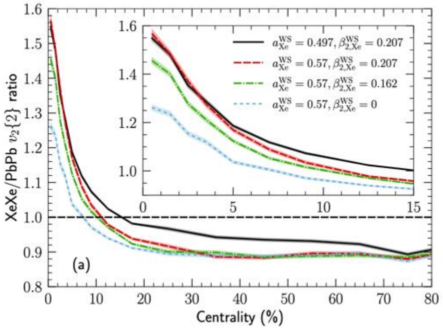


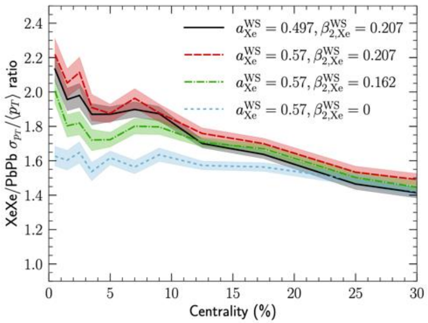
Reasonable agreement with IPGlasma+Music+UrQMD hydro model 2005.14682

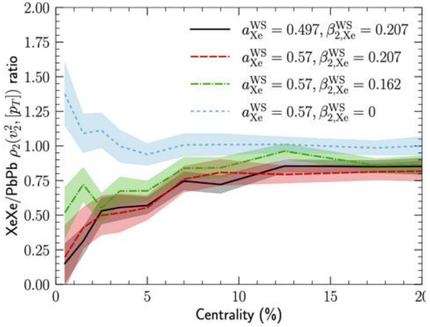
Constraints from $\langle \delta p_T^2 \rangle$ and v_2-p_T : $\beta_{2U} = 0.297 \pm 0.015$ $\gamma_U = 8.5° \pm 4.8°$

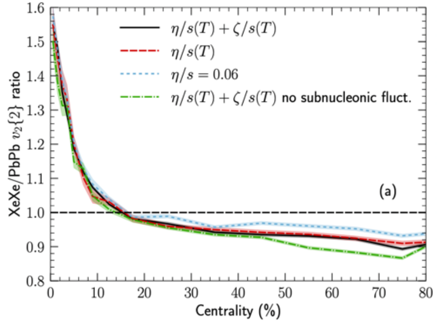
Image Xe shape via Xe+Xe vs Pb+Pb collisions

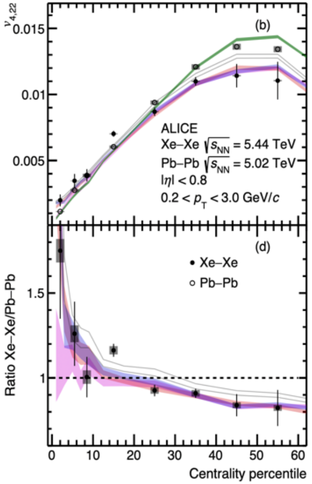
2409.19064

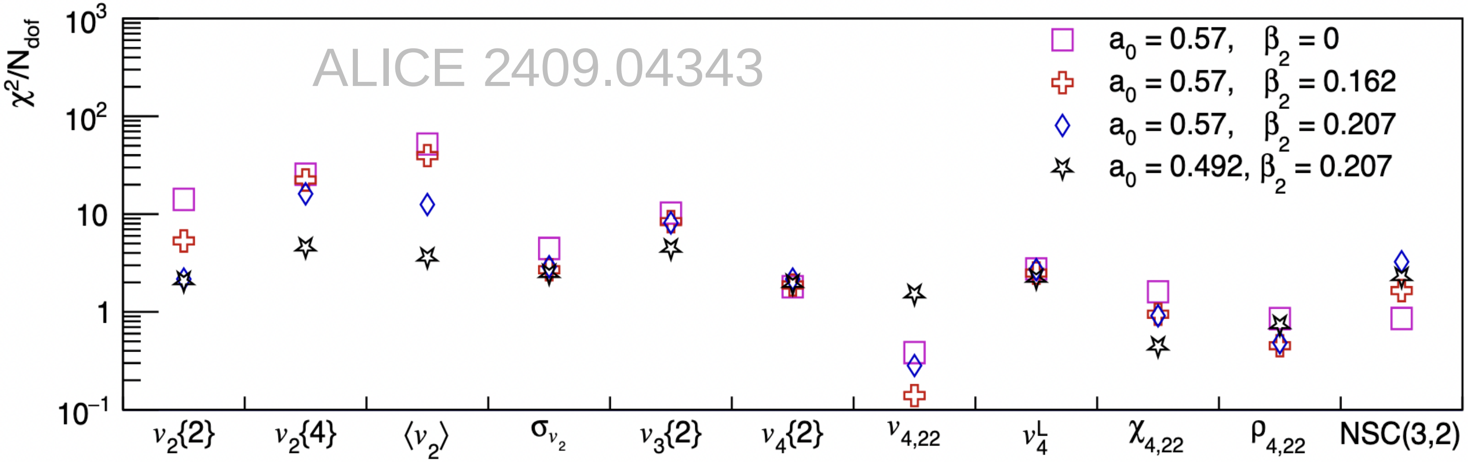












Isobar ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions at RHIC 200 GeV

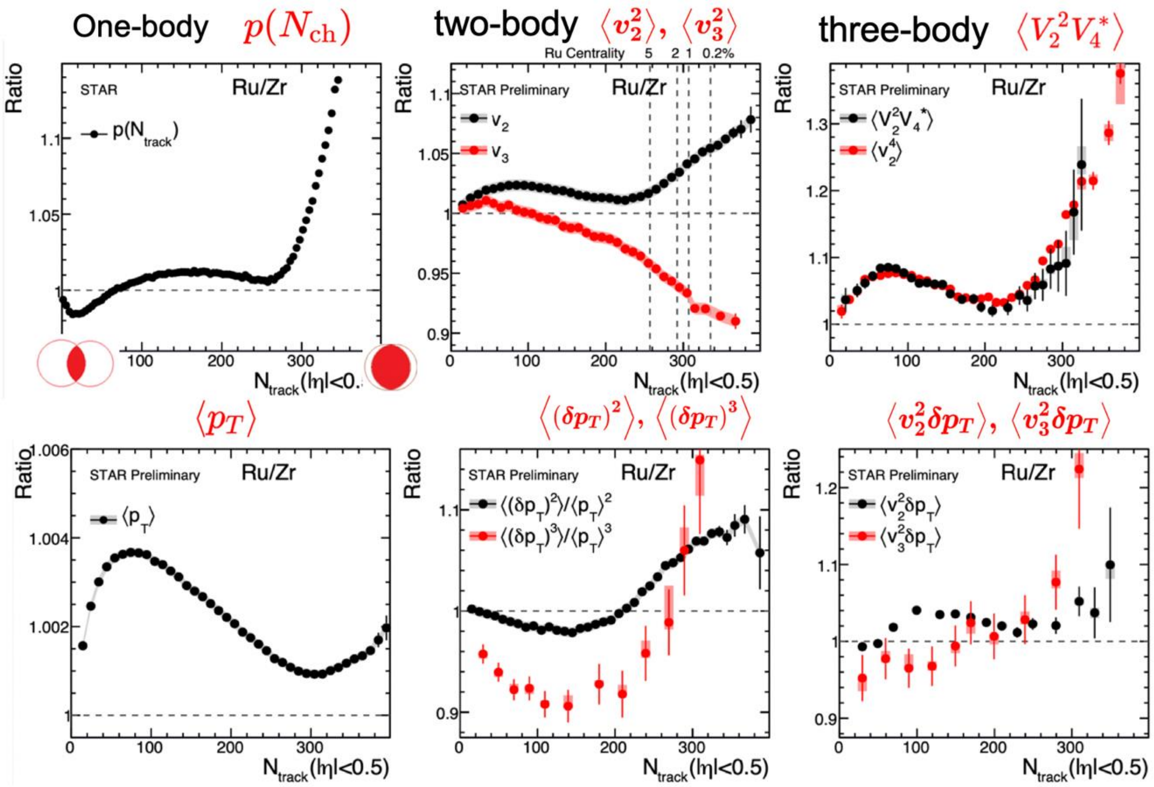
$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}}$$

- Insensitive to parameters in the final state
- Deviation from one reflects differences in nuclear structure

Structure influences everywhere

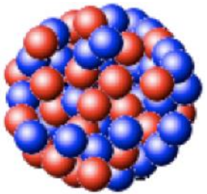
Nuclear structure is inherently part of Heavy ion problem

Talk by Chunjian Zhang Wednesday

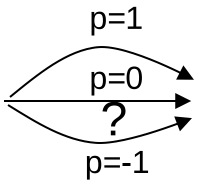


Isobar ratio constraints on the initial condition

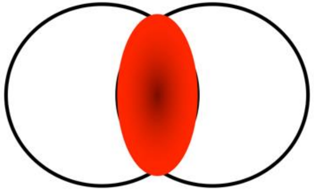
Nucleus

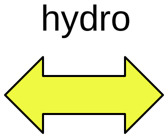


$$T \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$

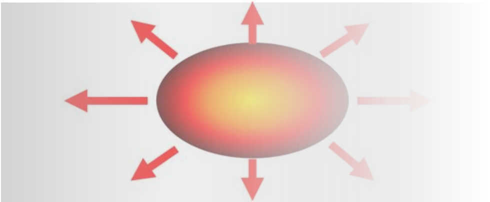


Initial condition

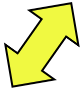




Final state

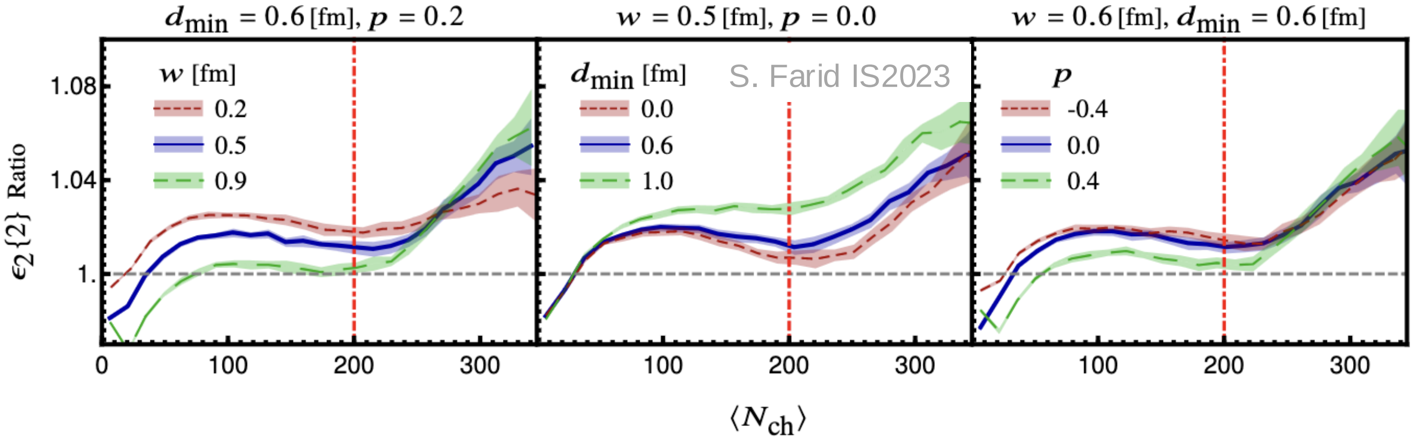


$$T_A(x,y) = \int \rho(x,y,z)dz$$



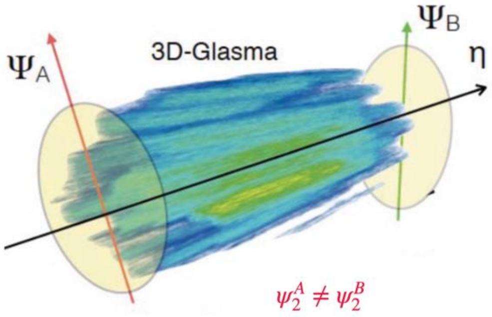
$$\frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

c_n relates nuclear structure and initial condition

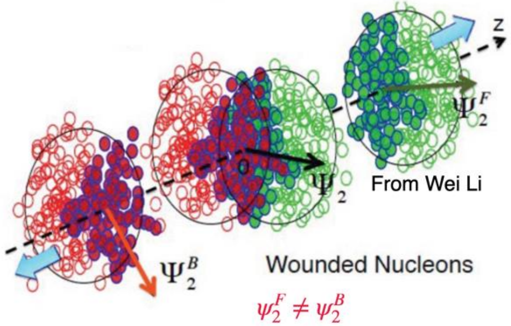


2) Longitudinal structure

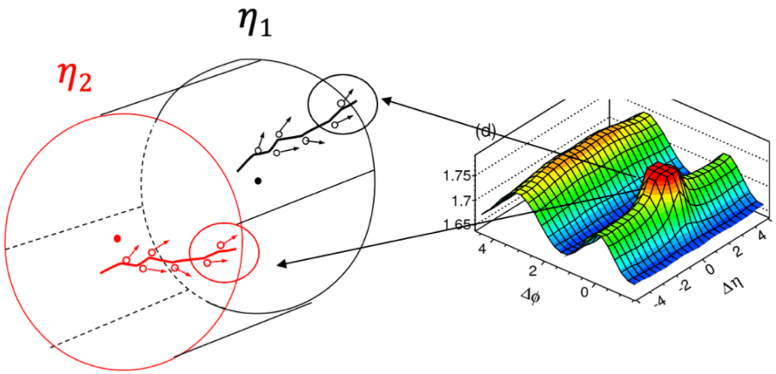
- Sensitive to stopping and entropy production mechanism
- Varying the timescales $\tau \sim e^{-\Delta\eta}$
- Short-range structure sensitive to hydrodynamization (also non-flow)



Bjorn Schenke, Soren Schlichting
Phys. Rev. C 94 (2016) 4, 044907

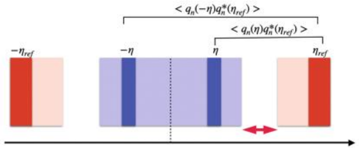


Jiangyong Jia, Peng Huo
Phys. Rev. C 90 (2014) 034905



Long-range sees geometry, short-range sees microscopic origin of collectivity

Traditional observables are insufficient, e.g.



$$r_2(\eta)_{\eta_{\rm ref}} = \frac{\langle V_2(-\eta)V_2^*(\eta_{\rm ref})\rangle}{\langle V_2(\eta)V_2^*(\eta_{\rm ref})\rangle} \equiv \frac{R(-\eta,\eta_{\rm ref})}{R(\eta,\eta_{\rm ref})}$$

Decorrelation is non-linear!!

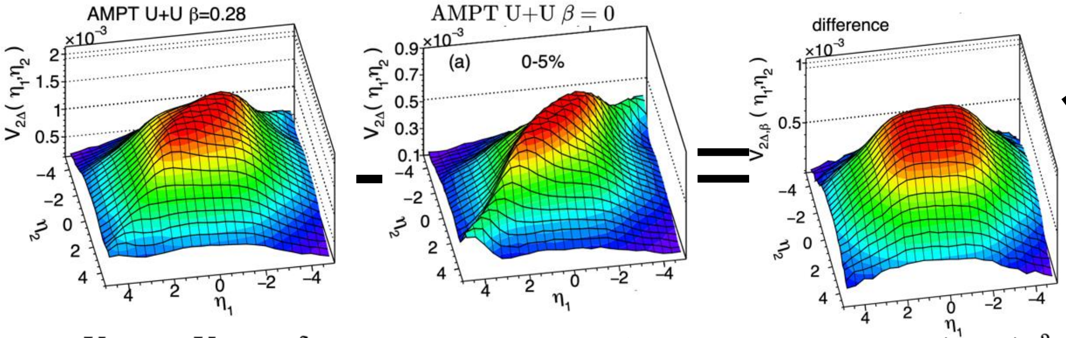
We want: $$R(\eta_1,\eta_2) = \frac{\langle V_2(\eta_1)V_2^*(\eta_2)\rangle}{\sqrt{\langle V_2(\eta_1)V_2^*(\eta_1)\rangle\langle V_2(\eta_2)V_2^*(\eta_2)\rangle}}$$

How to deal with non-flow?

Deformation-assisted study of longitudinal structure

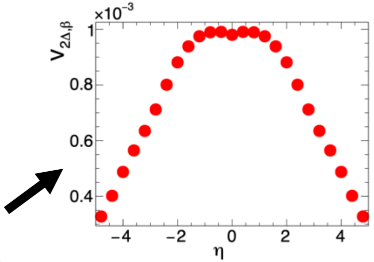
2405.08749

$$V_{2\Delta} = V_{2\Delta,\mathrm{sp}} + V_{2\Delta,\beta} + \delta_{\mathrm{nf}} \qquad V_{2\Delta}(\eta_1,\eta_2) = \langle V_2(\eta_1)V_2^*(\eta_2)\rangle$$



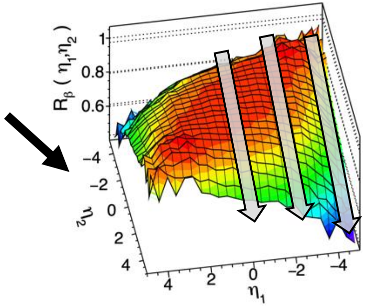
$V_{2\Delta,\mathrm{sp}} + V_{2\Delta,\beta} + \delta_{\mathrm{nf}}$ $\quad V_{2\Delta,\mathrm{sp}} + \delta_{\mathrm{nf}}$ $\quad V_{2\Delta,\beta} = b(\eta_1,\eta_2)\beta^2$

Isolate the decorrelation map of deformation-induced flow



η dependence of flow

$$V_{2\Delta,\beta}(\eta,\eta) = \langle v_{2,\beta}^2(\eta)\rangle$$



Decorrelation of flow

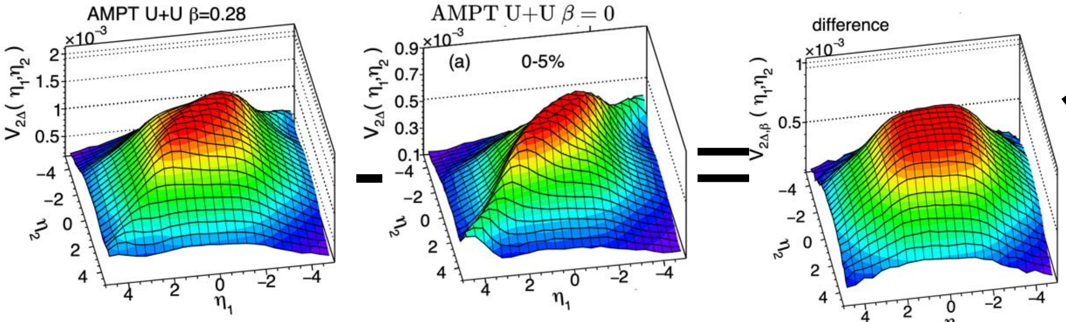
$$R_\beta(\eta_1,\eta_2)$$

Deformation-assisted study of longitudinal structure

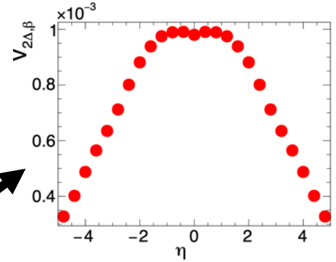
2405.08749

$V_{2\Delta} = V_{2\Delta,\mathrm{sp}} + V_{2\Delta,\beta} + \delta_{\mathrm{nf}}$

$V_{2\Delta}(\eta_1,\eta_2) = \langle V_2(\eta_1)V_2^*(\eta_2)\rangle$



$V_{2\Delta,\mathrm{sp}} + V_{2\Delta,\beta} + \delta_{\mathrm{nf}}$ $V_{2\Delta,\mathrm{sp}} + \delta_{\mathrm{nf}}$ $V_{2\Delta,\beta} = b(\eta_1,\eta_2)\beta^2$



η dependence of flow

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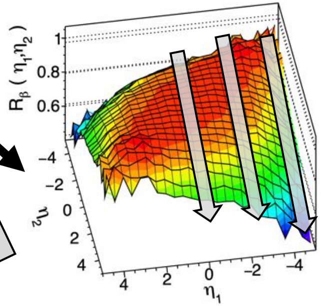
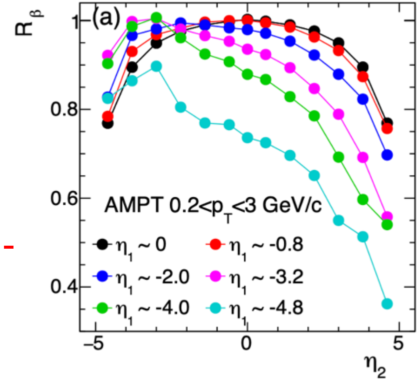
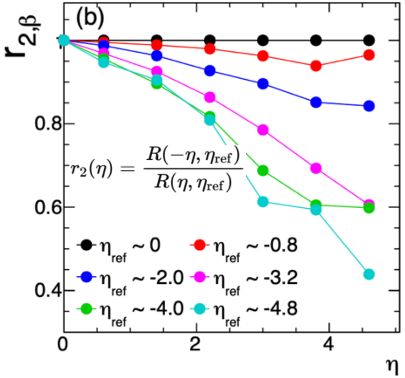


Decorrelation of flow

$R_\beta(\eta_1,\eta_2)$

Isolate the decorrelation map of deformation-induced flow





Decorrelation stronger in forward η_{ref}.

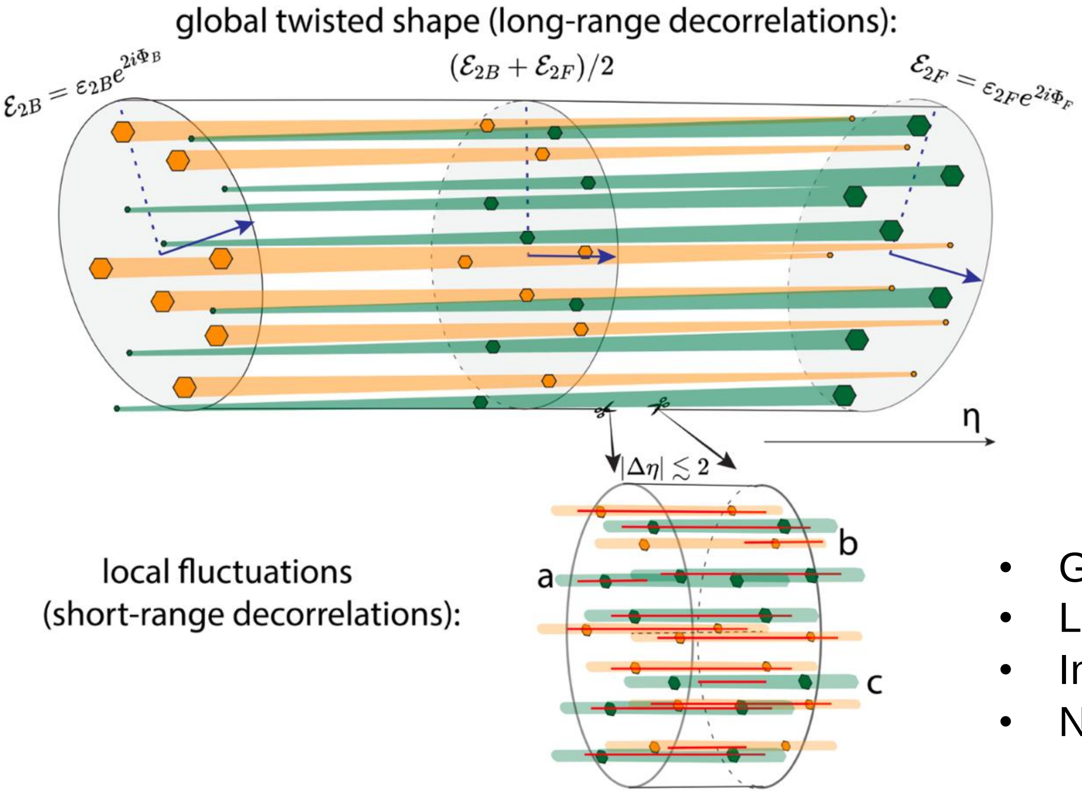
Longitudinal structure is non-linear and not factorizable

Projection in slices→normal r_2. Some decorr. is cancelled, and residual decorr. depends on η_{ref}.

Can not be interpreted as decor between $-\eta$ and η

Sources of longitudinal fluctuations

Expectation from string picture

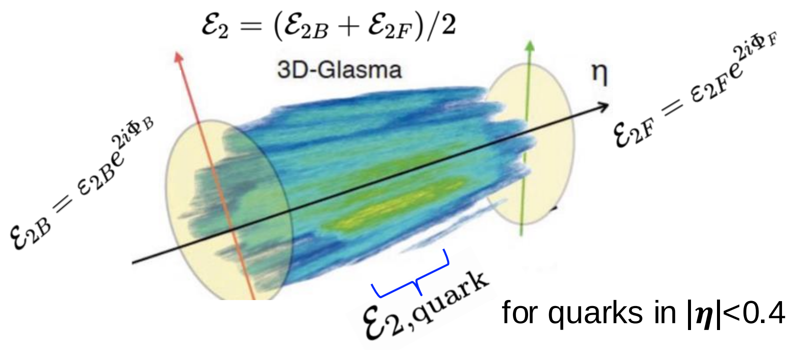


2408.15006

Many sources with different structures

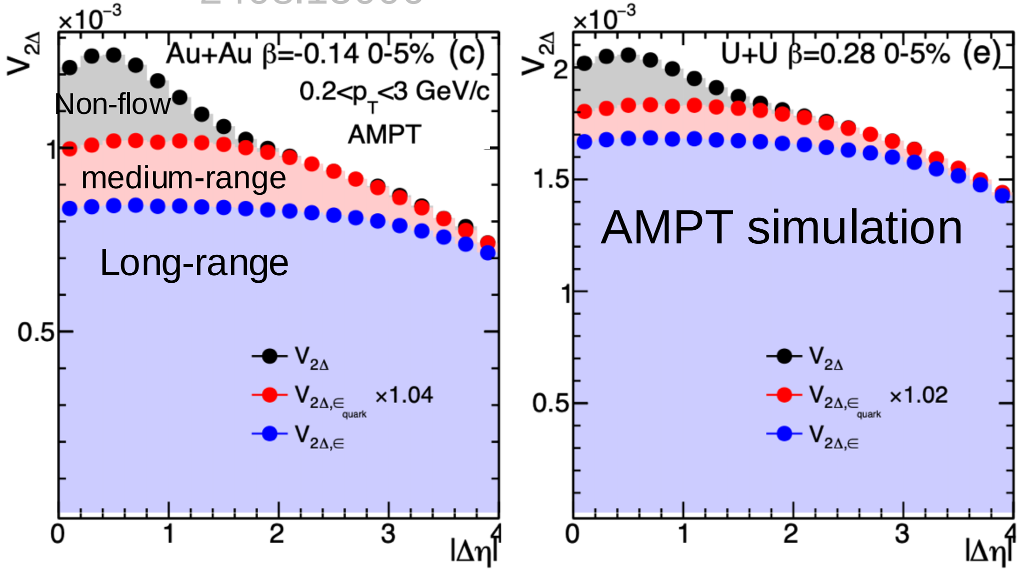
- Geometry from ϵ_F and ϵ_B: long-range
- Local hot spots: short- to medium- range
- Initial momentum anisotropy: short-range?
- Non-flow: short-range

Sources of longitudinal fluctuations



for quarks in $|\eta|<0.4$

2408.15006



Three ways of calculating elliptic flow:

2PC method: $V_{2\Delta}(\eta_1, \eta_2) = \langle V_2(\eta_1) V_2^*(\eta_2) \rangle$

Projection flow to eccentricities:

$$v_{2,\varepsilon}(\eta) \equiv \frac{\langle V_2(\eta)\mathcal{E}_2^* \rangle}{\sqrt{\langle \mathcal{E}_2 \mathcal{E}_2^* \rangle}}, \quad v_{2,\varepsilon_{\mathrm{quark}}}(\eta) \equiv \frac{\langle V_2(\eta)\mathcal{E}_{2,\mathrm{quark}}^* \rangle}{\sqrt{\langle \mathcal{E}_{2,\mathrm{quark}} \mathcal{E}_{2,\mathrm{quark}}^* \rangle}}$$

Long-range only Long- & short-range

1. Convolute to get contributions to 2PC

$$V_{2\Delta,\varepsilon}(\Delta\eta) = \frac{1}{4}\int_{-2}^{2} v_{2,\varepsilon}(\eta_1) v_{2,\varepsilon}(\eta_2) \delta(\eta_1 - \eta_2) d\eta_1 d\eta_2$$

2. Decomposition:

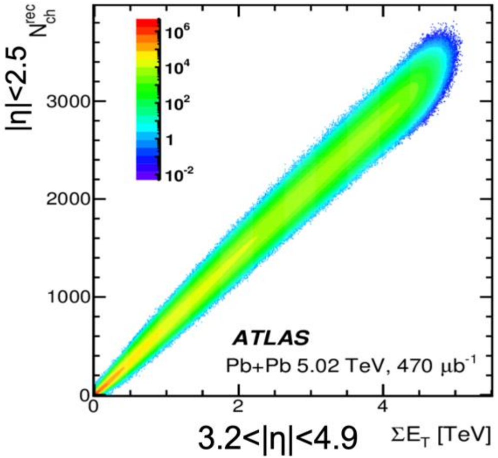
$V_{2\Delta}$ = long + medium + non-flow

Observables for long-range collectivity

- n^{th}-order long-range correlations are azimuthal flow harmonics v_n.
  - Most studies of collectivity use this, in particular small system.

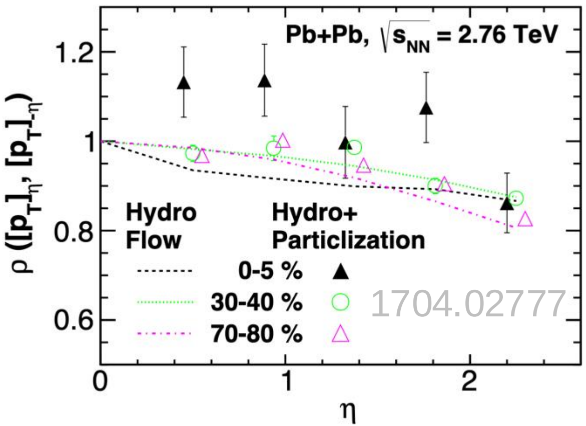
- 0^{th}-order long-range correlation is energy/multiplicity
  - Such correlation comes from boost invariance of initial condition. Does not require final state effects

- 1^{st}-order long-range correlation is $\langle p_T \rangle$ or radial flow.



$$\frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle}$$

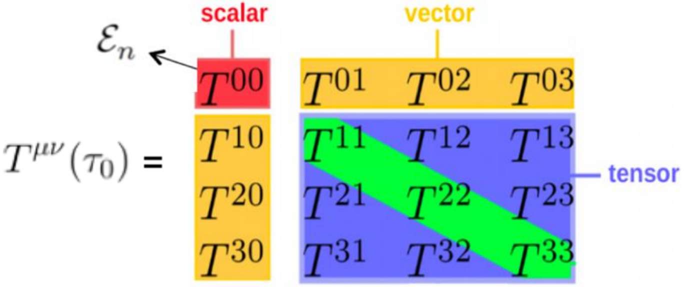
$$\frac{\langle \delta p_T(\eta_1)\delta p_T(\eta_2)\rangle}{\sqrt{\left\langle(\delta p_T)^2\right\rangle_{\eta_1}\left\langle(\delta p_T)^2\right\rangle_{\eta_2}}}$$



3) Small system scan

Why small systems

- Need to consider full energy-momentum tensor $T_{\mu\nu}(\tau = 0)$ for the initial condition



[Sousa, Luzum, Noronha, 2002.12735]

SCALAR

$$\mathcal{E}_2 = \frac{\langle x^2 - y^2 \rangle + i\langle 2xy \rangle}{\langle x^2 + y^2 \rangle}$$ ← Initial eccentricity

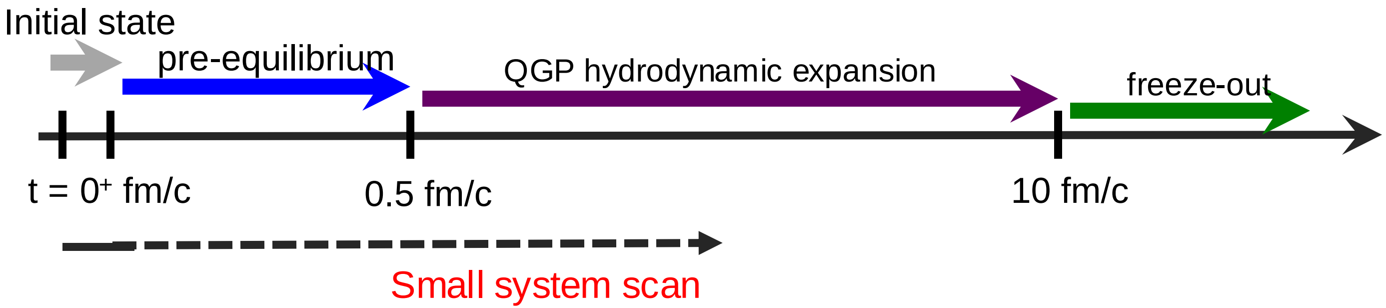
TENSOR

$$\mathcal{E}_p \equiv \frac{\langle T^{xx} - T^{yy} \rangle + i\langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$ ← Initial momentum anisotropy

2405.13600

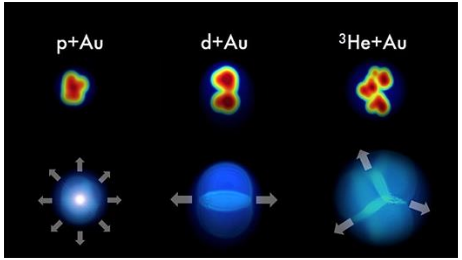
$$\mathcal{E}_n = -\frac{\int_{\vec{x}_\perp} \rho(\vec{x}_\perp)\vec{x}_\perp^{\,n}}{\int_{\vec{x}_\perp} \rho(\vec{x}_\perp)|\vec{x}_\perp|^n} \qquad \rho(\vec{x}_\perp) = T^{\tau\tau}(\vec{x}_\perp) - \alpha\partial_i T^{\tau i}(\vec{x}_\perp) + \beta\partial_i\partial_j T^{ij}(\vec{x}_\perp)$$

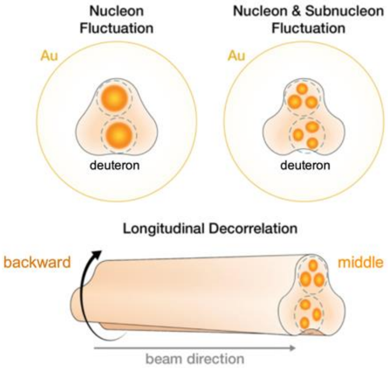
- Interplay of different sources holds key to hydrodynamization and its timescales

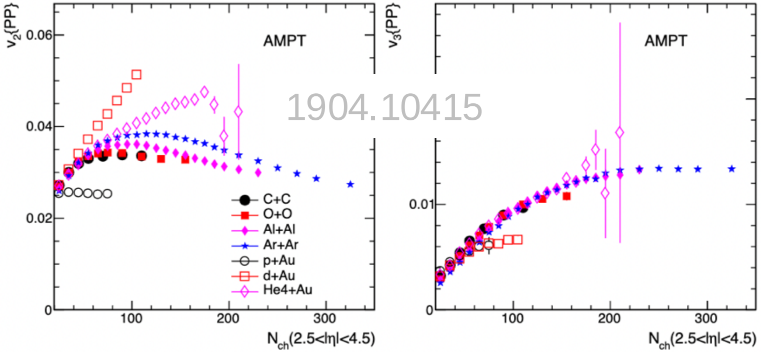


Disentangle sources of collectivities

Identifying the geometry response via geometry scan

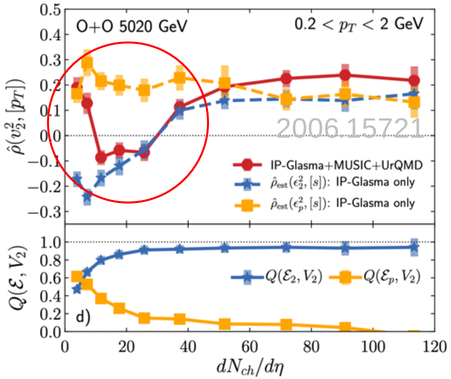


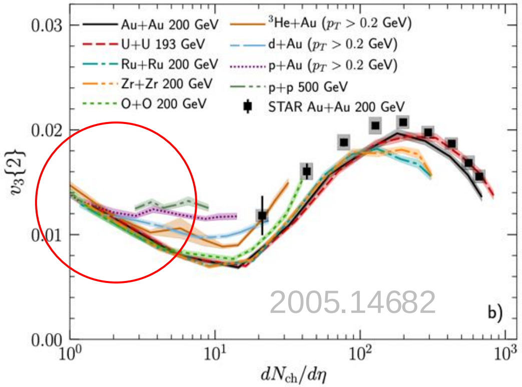




- Non-flow
- Geometry response
  - Nucleon vs subnucleon
  - Local hotspots
  - Hydro vs transport
- Initial momentum anisotropy

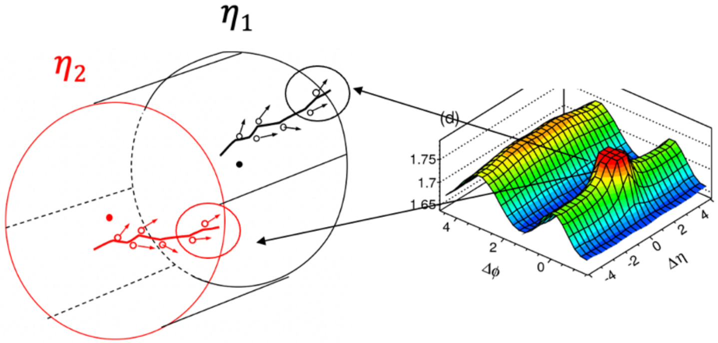
Quantify the fraction of each component





Small system scan

Examine QGP's short-range structures



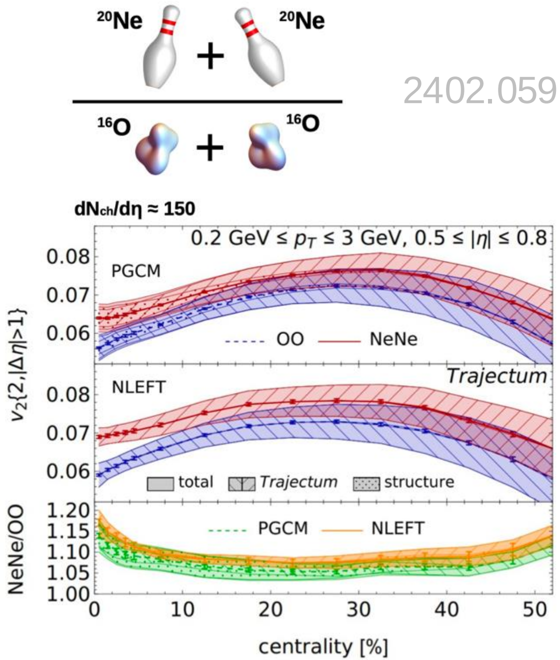
non-flow, geometry response, local hotspot
Decorrelation should be different from large systems

Compare symmetric vs asymmetric systems e.g. d+Au vs O+O

constrain the role of subnucleon fluctuations

Strategic scan from small to medium systems.

Design isobar collisions with drastically different geometry

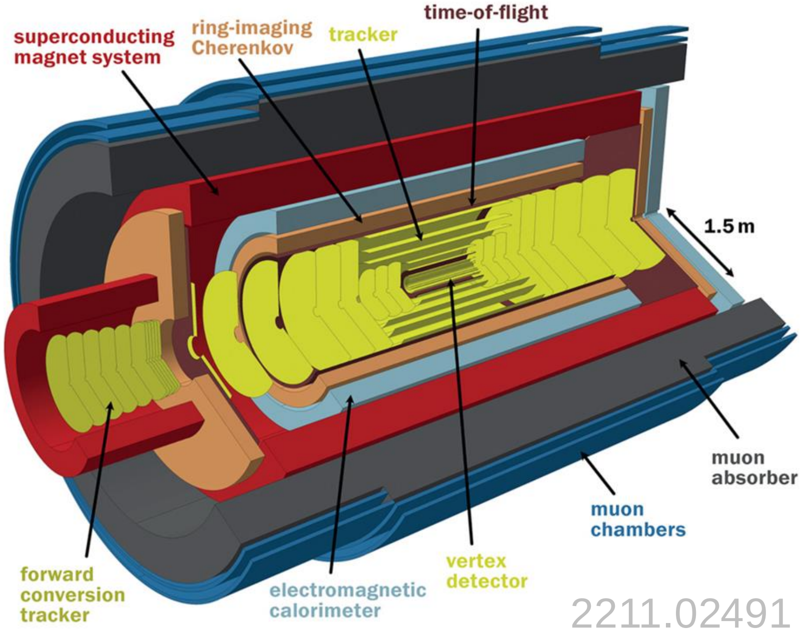


2402.05995

$$\frac{v_2\{2\}_{\mathrm{NeNe}}}{v_2\{2\}_{\mathrm{OO}}} = \begin{cases} 1.170(8)_{\mathrm{stat.}}(30)^{Traj.}_{\mathrm{syst.}}(0)^{\mathrm{str.}}_{\mathrm{syst.}} & (\mathrm{NLEFT}) \\ 1.139(6)_{\mathrm{stat.}}(27)^{Traj.}_{\mathrm{syst.}}(28)^{\mathrm{str.}}_{\mathrm{syst.}} & (\mathrm{PGCM}), \end{cases}$$

Future

Large acceptance detector and flexible collision species



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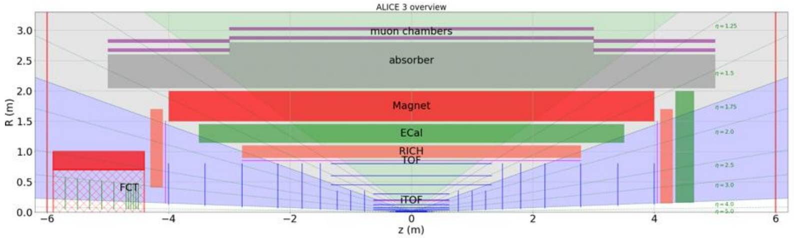
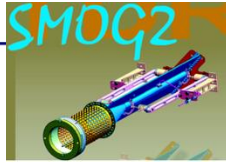


Collider mode

	B (5) Boron 10.811	O (8) Oxygen 15.9994	Ne (10) Neon 20.1797	Mg (12) Magnesium 24.305	Ar (18) Argon 39.948	Ca (20) Calcium 40.078	Kr (36) Krypton 83.80	In (49) Indium 114.818	Xe (54) Xenon 131.29
SHINE NA61++	★	★		★					
NA60+									
ALICE3					★ or	★ or	★ or	★ or	★ or
NUCLEAR PHYSICS AT LHC		★	★		★		★	★	★
CHIMERA		★			★		★		★
GAMMA FACTORY						★			

SMOG2 fixed target mode: $\sqrt{s_{NN}} = 65 - 110\text{GeV}$

Summary of possible gas targets



✌	H	validated for O(100) h/year
~✌	D	as above (not tested yet)
✌	He	
~✌	N	not tested yet, but ok from simulations
☞	O	to be validated, should be possible at least for short runs
✌	Ne	
✌	Ar	
☞	Kr	to be validated, should be possible for short runs at end of data-taking
☞	Xe	to be validated, should be possible for short runs at end of data-taking

Giacomo Graziani

any isotope for approved gas should be ok

Summary

Precision understanding of QGP properties, its initial condition, and dynamics.

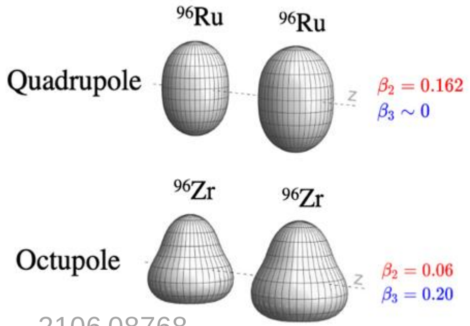
Requires all possible experimental handles.

- Exploration of the full 3D structure
  →ALICE 3, ATLAS/CMS/LHCb

- Design collision species with different geometries: shape, size, and skins
- Scan from small to medium species.
  → Enable by LHC and SMOG2

A	isobars	A	isobars	A	isobars	A	isobars	A	isobars	A	isobars
36	Ar, S	80	Se, Kr	106	Pd, Cd	124	Sn, Te, Xe	148	Nd, Sm	174	Yb, Hf
40	Ca, Ar	84	Kr, Sr, Mo	108	Pd, Cd	126	Te, Xe	150	Nd, Sm	176	Yb, Lu, Hf
46	Ca, Ti	86	Kr, Sr	110	Pd, Cd	128	Te, Xe	152	Sm, Gd	180	Hf, W
48	Ca, Ti	87	Rb, Sr	112	Cd, Sn	130	Te, Xe, Ba	154	Sm, Gd	184	W, Os
50	Ti, V, Cr	92	Zr, Nb, Mo	113	Cd, In	132	Xe, Ba	156	Gd,Dy	186	W, Os
54	Cr, Fe	94	Zr, Mo	114	Cd, Sn	134	Xe, Ba	158	Gd,Dy	187	Re, Os
64	Ni, Zn	96	Zr, Mo, Ru	115	In, Sn	136	Xe, Ba, Ce	160	Gd,Dy	190	Os, Pt
70	Zn, Ge	98	Mo, Ru	116	Cd, Sn	138	Ba, La, Ce	162	Dy,Er	192	Os, Pt
74	Ge, Se	100	Mo, Ru	120	Sn, Te	142	Ce, Nd	164	Dy,Er	196	Pt, Hg
76	Ge, Se	102	Ru, Pd	122	Sn, Te	144	Nd, Sm	168	Er,Yb	198	Pt, Hg
78	Se, Kr	104	Ru, Pd	123	Sb, Te	146	Nd, Sm	170	Er,Yb	204	Hg, Pb

Nuclear structure via v_2-ratio and v_3-ratio



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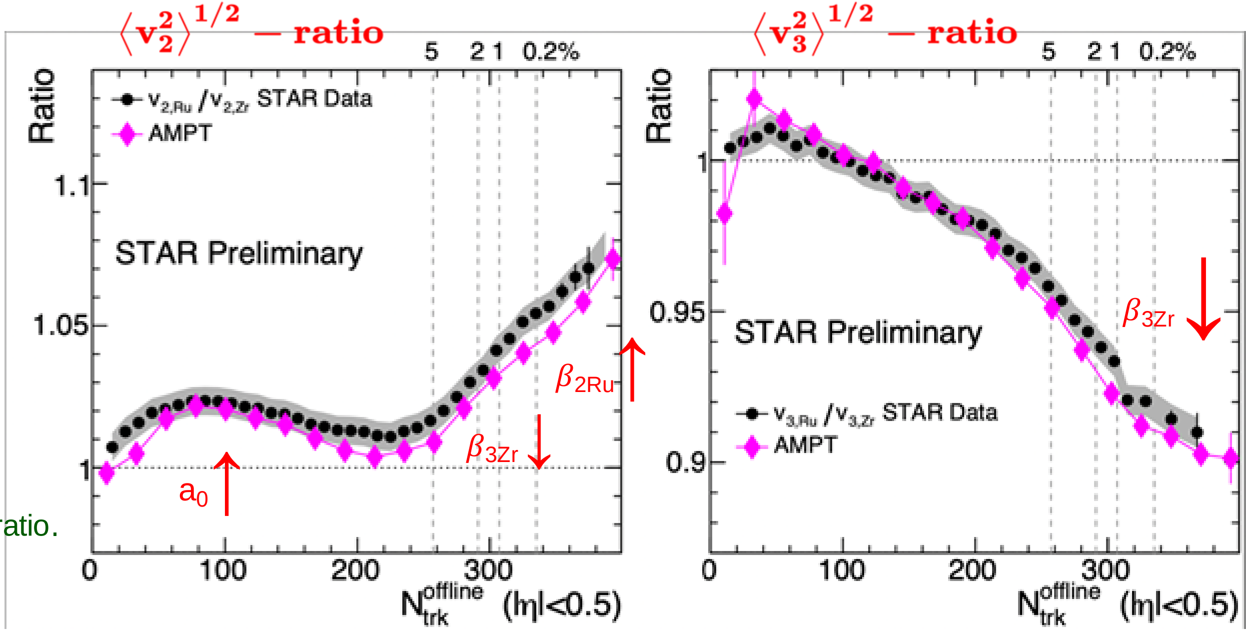
Species	β_2	β_3	a_0	R_0
Ru	0.162	0	0.46 fm	5.09 fm
Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

Simultaneously constrain four structure parameters



- β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio
- β_{3Zr} ~ 0.2 decrease v_2 and v_3 ratio
- Δa_0 = -0.06 fm increase v_2 mid-central,
- Radius ΔR_0 = 0.07 fm slightly affects v_2 and v_3 ratio.

Strategy for nuclear shape imaging

Flow observable = k ⊗ initial condition (structure)

QGP response,
a smooth function of N+Z

Structure of colliding nuclei,
non-monotonic function of N and Z

Compare two systems of similar size but different structure

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

arXiv: 2111.15559

Deviation from unity depends only on their structure differences
c_1-c_4 are function of centrality