# Lessons and open questions from heavy-ion experiments & small x

Jacquelyn Noronha-Hostler
University of Illinois Urbana-Champaign

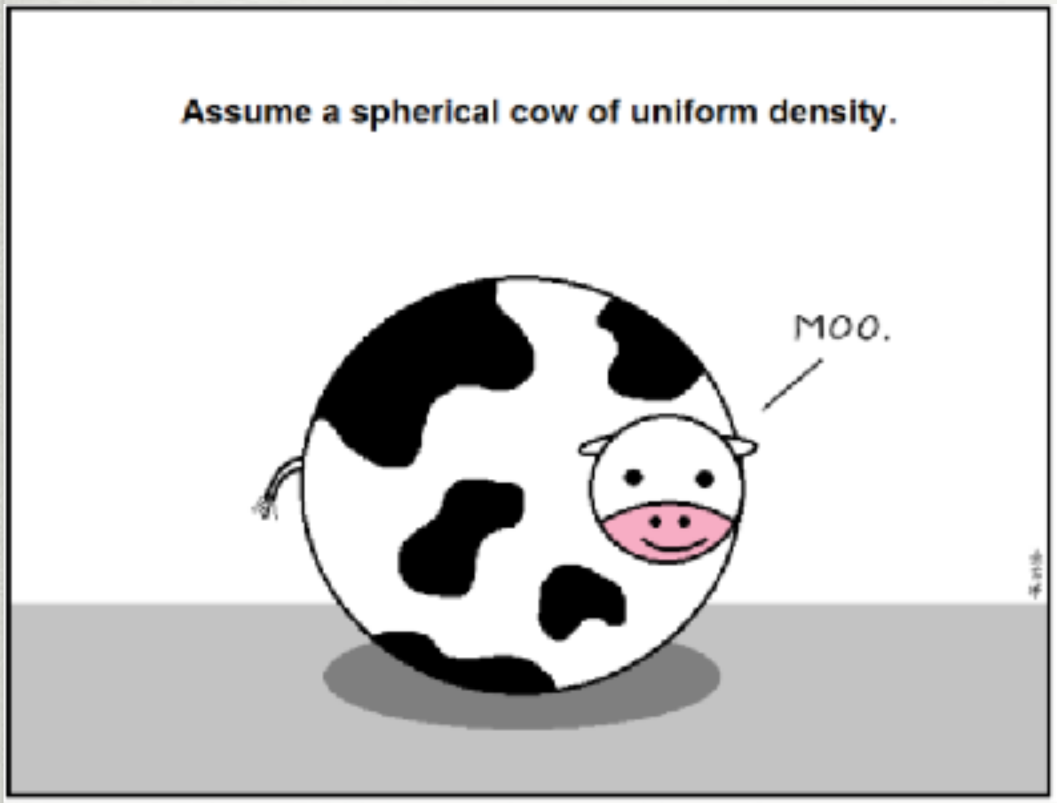
Small-x Physics in the EIC Era 2021

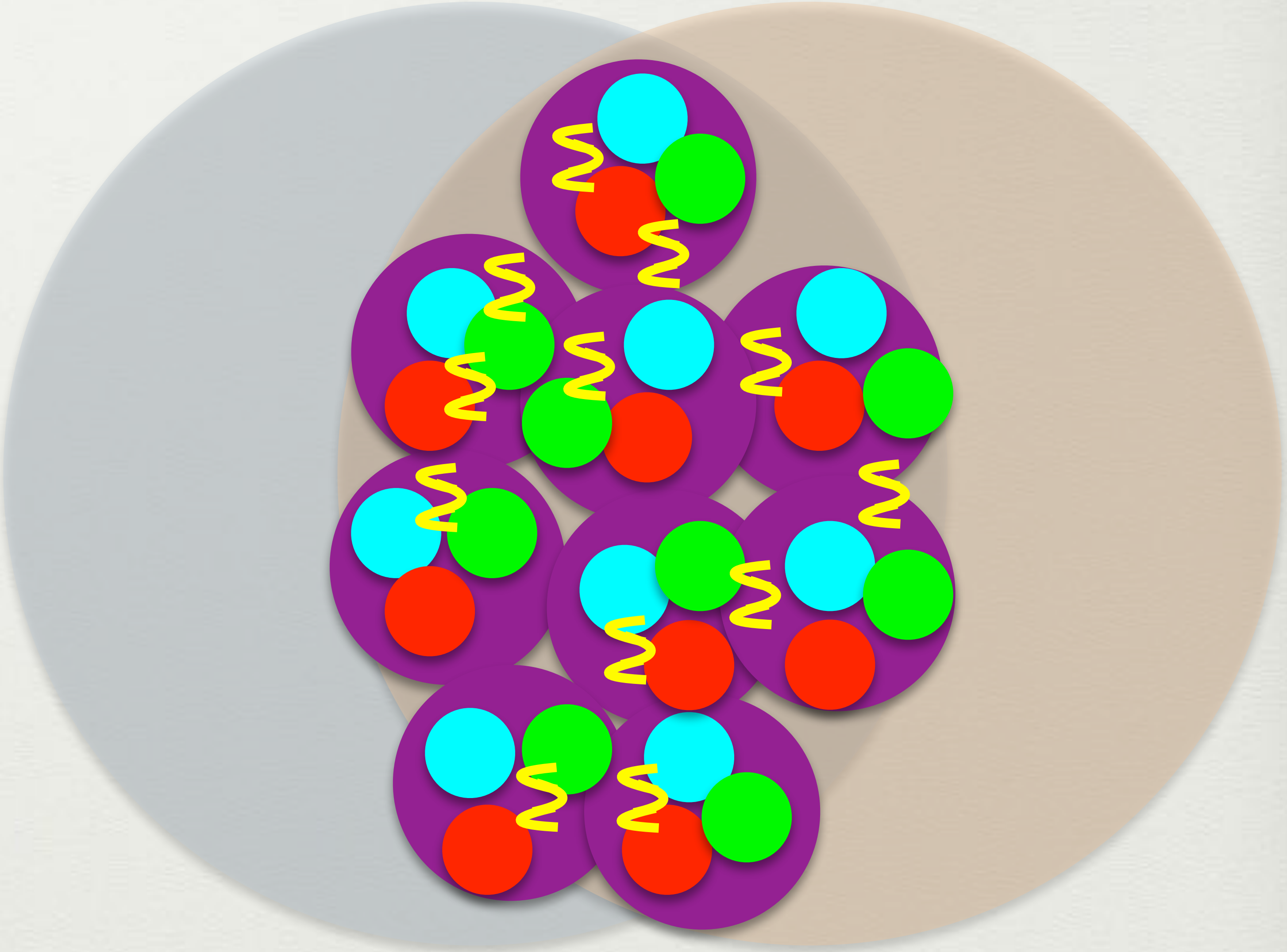
# Lessons from Heavy-Ion Collisions

- The spherical cow has bumps: $v_3$ and event-by-event fluctuations
- Shutting off the Quark-Gluon Plasma is hard (impossible?): flow harmonics won't go away
- Hydro is great but not perfect:
  initial state → hydro = acausal behavior?
- Quarks are quirky: sea quarks in heavy-ion simulations?

Caveat: jets and heavy-flavor should really be discussed, but hopefully others get to these interesting topics!

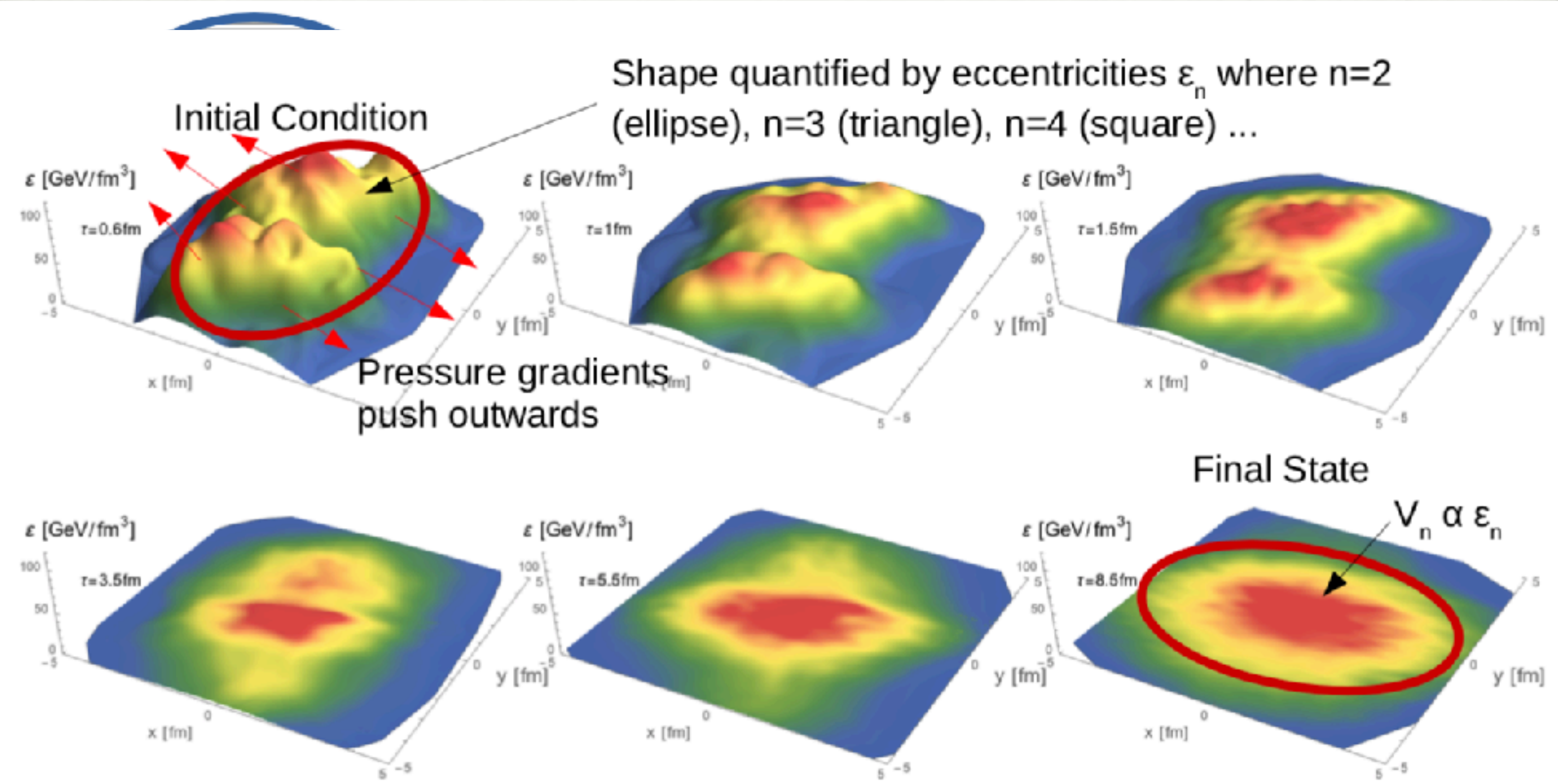
# The spherical cow has bumps:
# From optical Glauber to event-by-event fluctuations



Sub-nucleonic Fluctuations

# Initial conditions: $\varepsilon_{n,m} \equiv \dfrac{\int r^m e^{in\phi}\rho(r,\phi)rdrd\phi}{\int r^m \rho(r,\phi)rdrd\phi}$

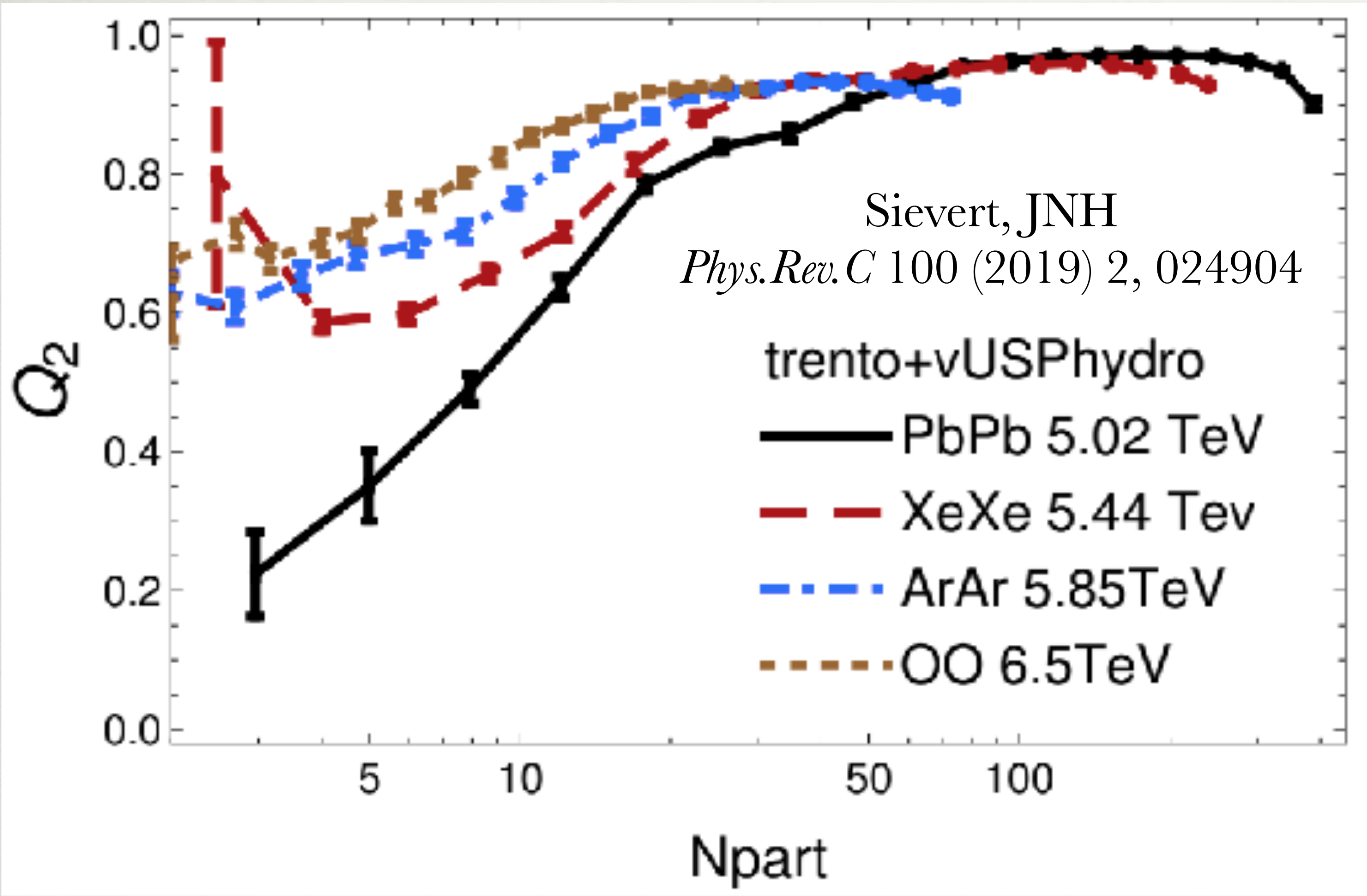



Eccentricities $\varepsilon_2$'s are directly related to the final measured flow observables $v_n$'s

# Linear response: Initial to final state

Initial state: $\mathcal{E}_n = \varepsilon e^{in\phi_n}$
Final state: $V_n = v_n e^{in\psi_n}$

Pearson Coefficient: $Q_n = \dfrac{Re\langle V_n \mathcal{E}_n^* \rangle}{\langle |V_n|^2 \rangle \langle |\mathcal{E}_n|^2 \rangle}$



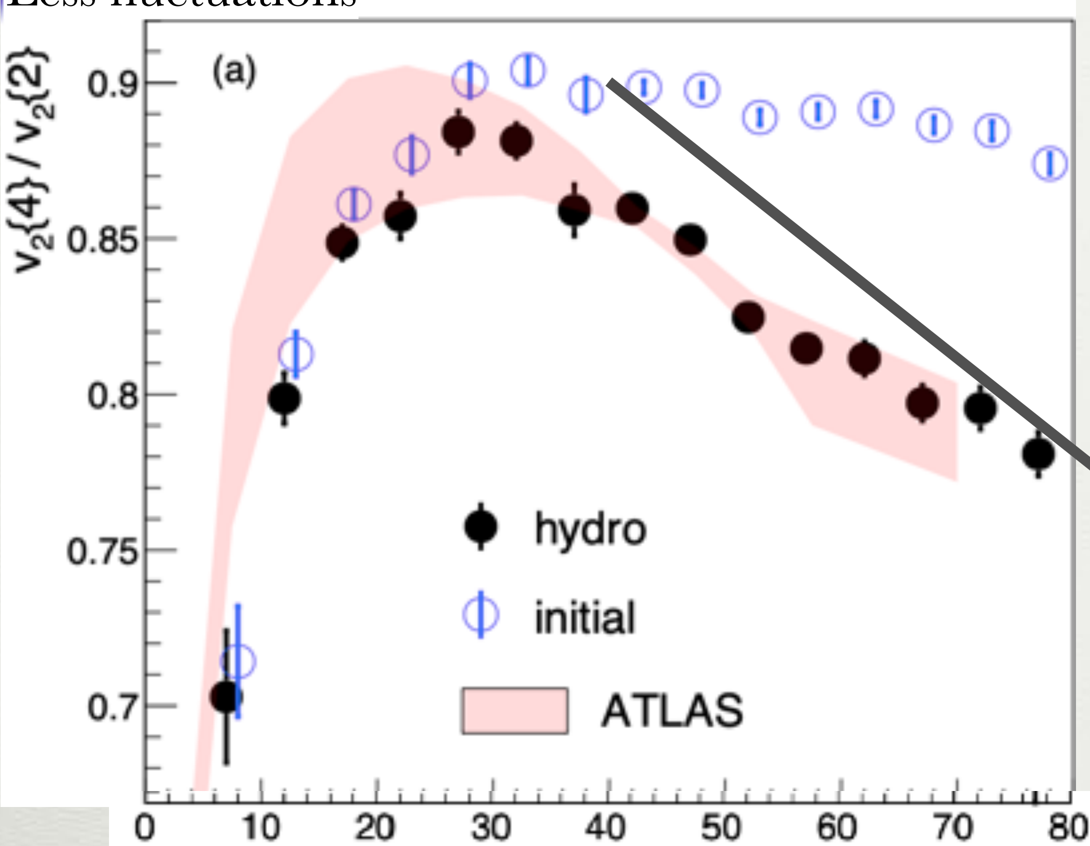

$V_n \sim \kappa_n \mathcal{E}_n$

- Strong linear responses from initial to final state
- Possible to define observables where medium response approximately cancels

# Advantage of fluctuations: medium insensitive observables

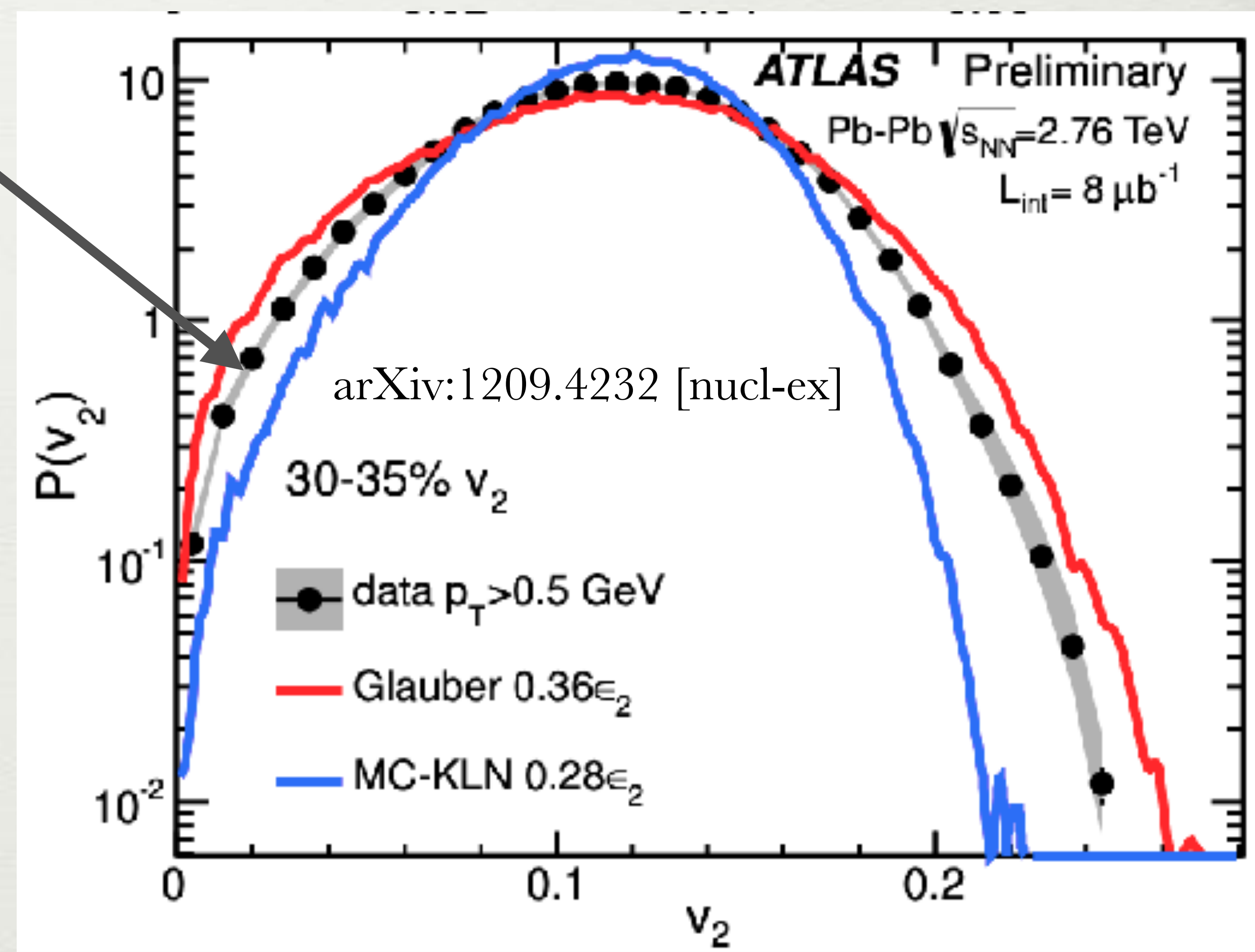
Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

Less fluctuations



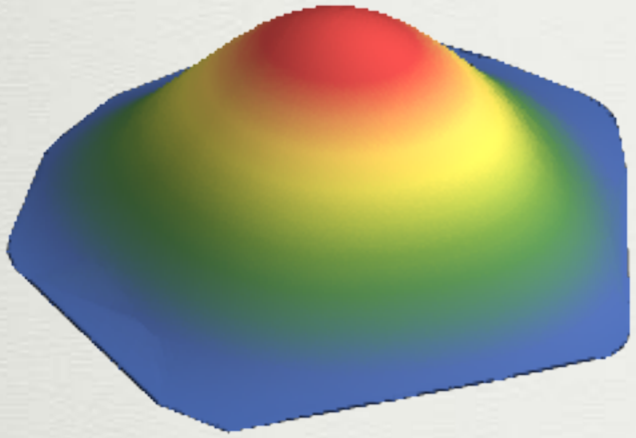

More fluctuations

Ratio connects to the width of $P(v_n)$




$$\frac{v_n\{4\}}{v_n\{2\}} \sim \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}}$$

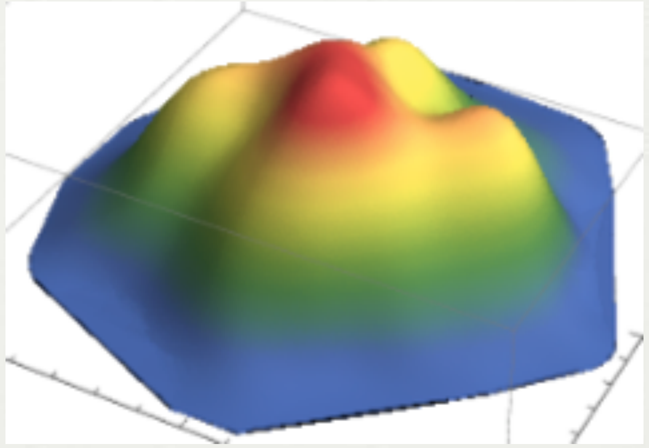
# A Tale of Scales: Initial State in heavy-ions



Nuclear Structure

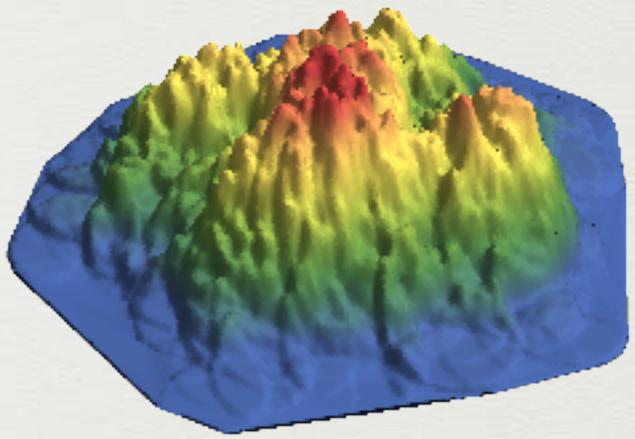
- Radius
- Deformations

Shape at small-x?



Nucleon fluctuations

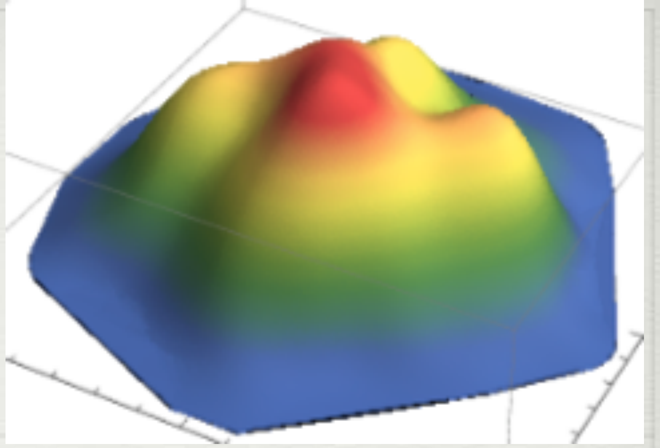
- Fluctuations
- Nucleon width



Substructure

- # of hotspots
- Eccentric nucleons

# Initial state: Color Glass Condensate vs phenomenology?



Entropy should be proportional to some combination of $T_A$ and $T_B$

$$s \propto f(T_A, T_B)$$

Model-agnostic approach (TRENTO)+ Bayesian analysis found

$$s \propto \sqrt{T_A, T_B}$$

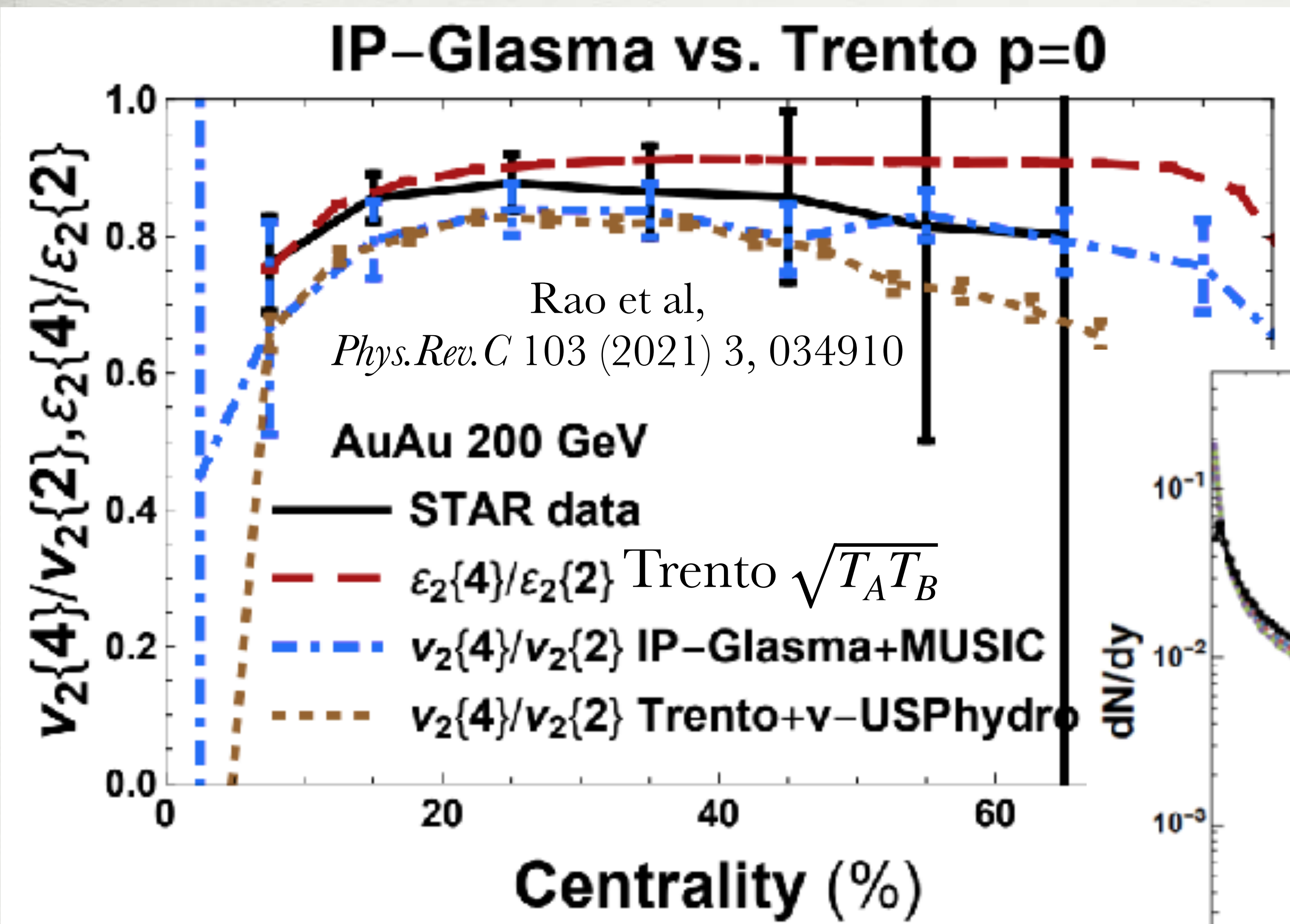
J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev.C92, 011901 (2015), 1412.4708; J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, Phys. Rev.C94, 024907(2016), 1605.03954

Color Glass Condensate approach

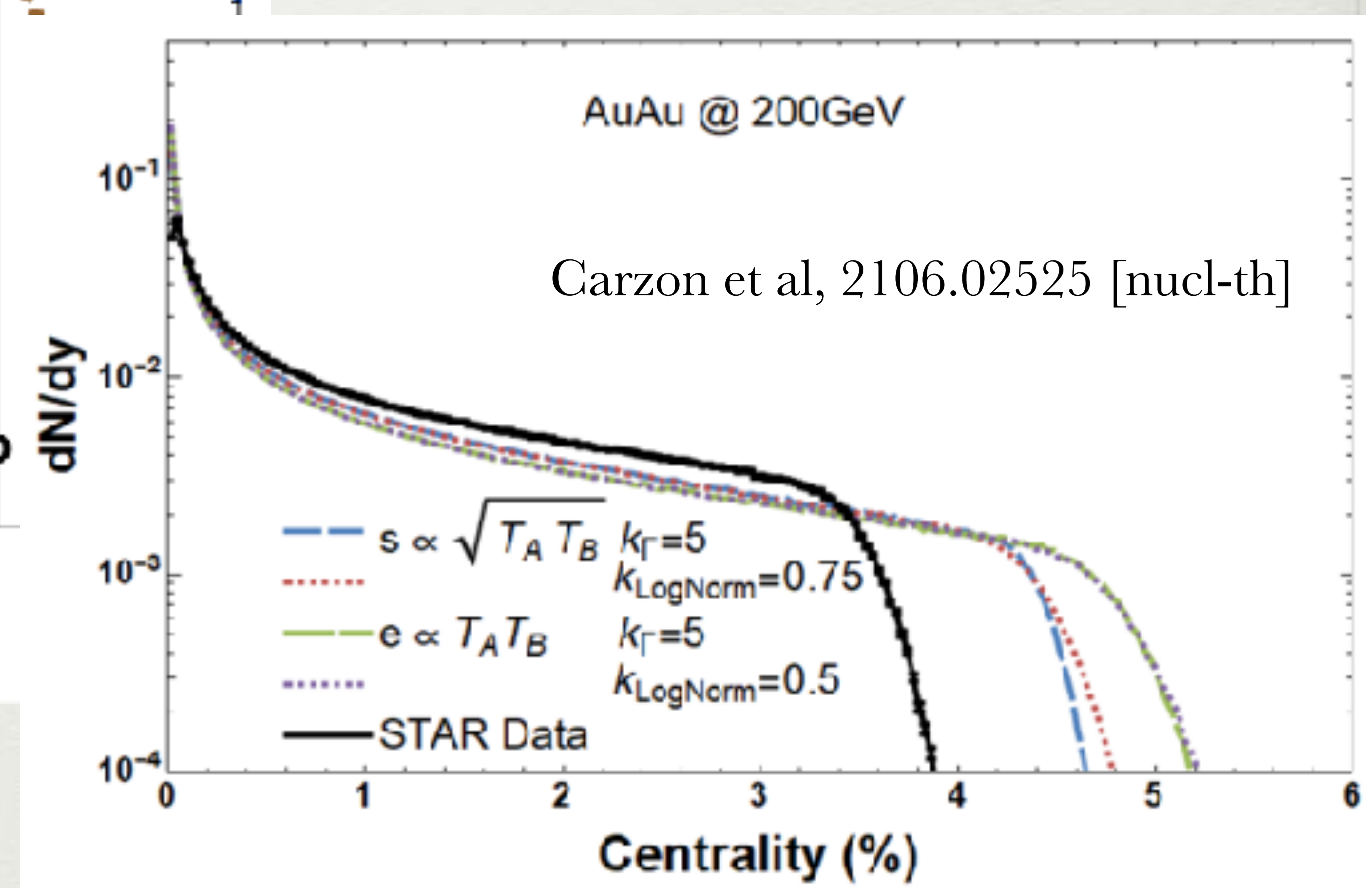
$$\varepsilon \propto T_A T_B$$

J. L. Nagle and W.A. Zajc,[arXiv:1808.01276[hep-th]], T. Lappi, Phys. Lett. B643, 11 (2006), arXiv: hepph/0606207 [hep-ph]; G. Chen, R. J. Fries, J. I. Kapusta and Y. Li, [arXiv:1507.03524 [nucl-th]], P. Romatschke and U. Romatschke, [arXiv:1712.05815 [nucl-th]]

# A-A: Constraining initial conditions



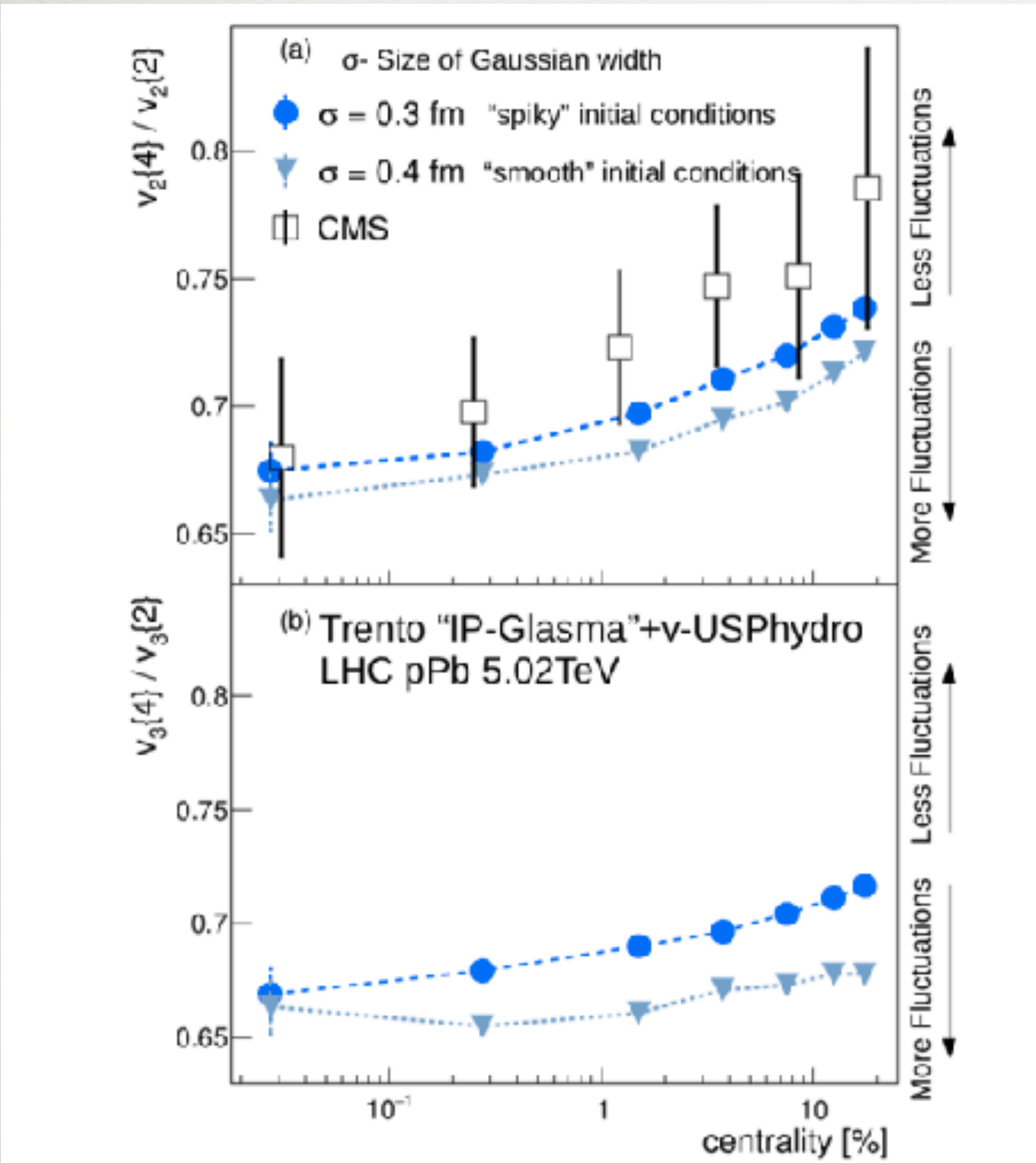

Multiplicity fluctuations off




Original $v_2\{4\}/v_2\{2\}$: Giacalone, JNH, Ollitrault, Phys.Rev. C95 (2017) no.5, 054910;
IP-Glasma+MUSIC: Schenke et al, *Phys.Rev.C* 99 (2019) 4, 044908

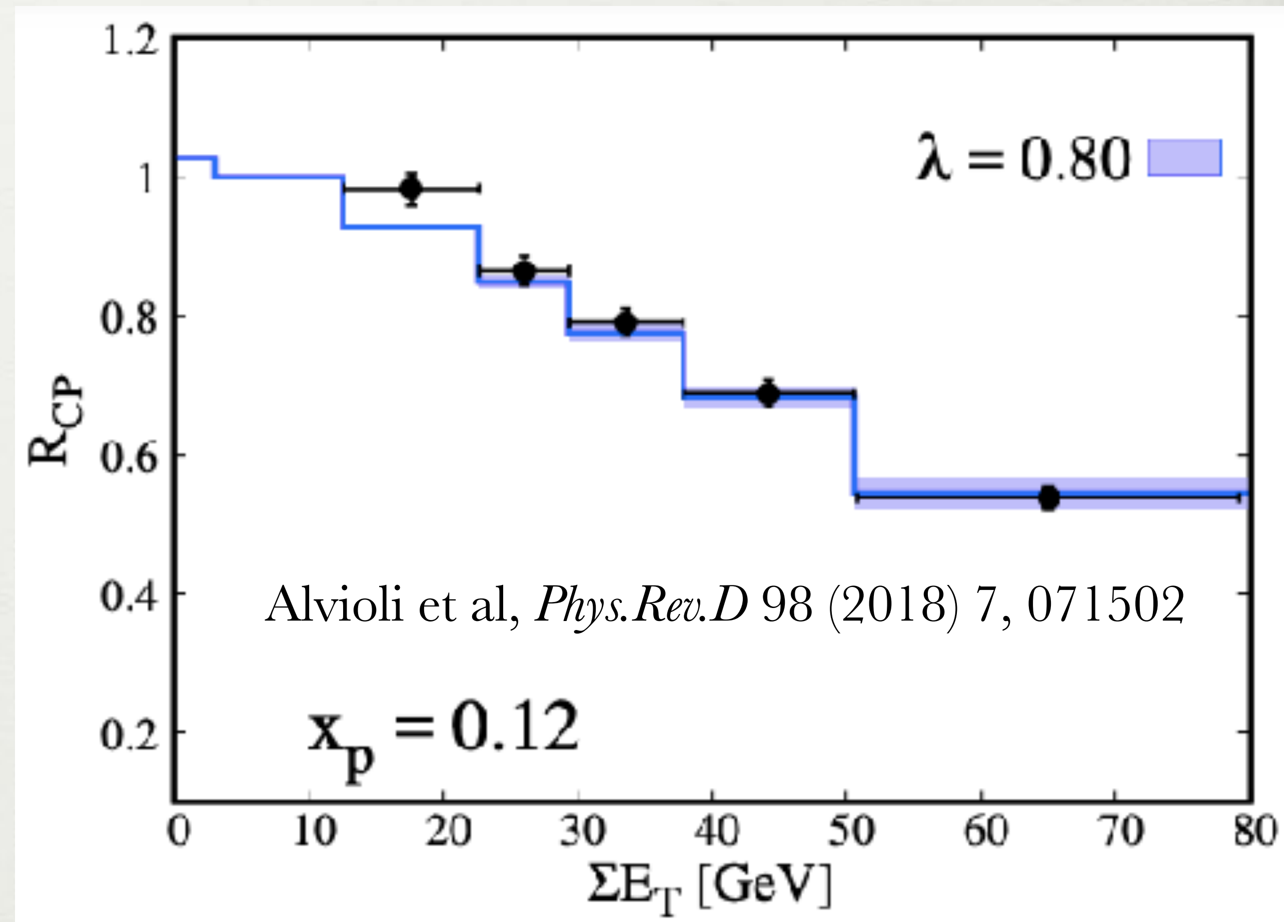
Difference at LHC:[CMS] Phys.Rev.C 100 (2019) 4, 044902 p vs. p

# Nucleon width in HIC?




Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.1, 014913

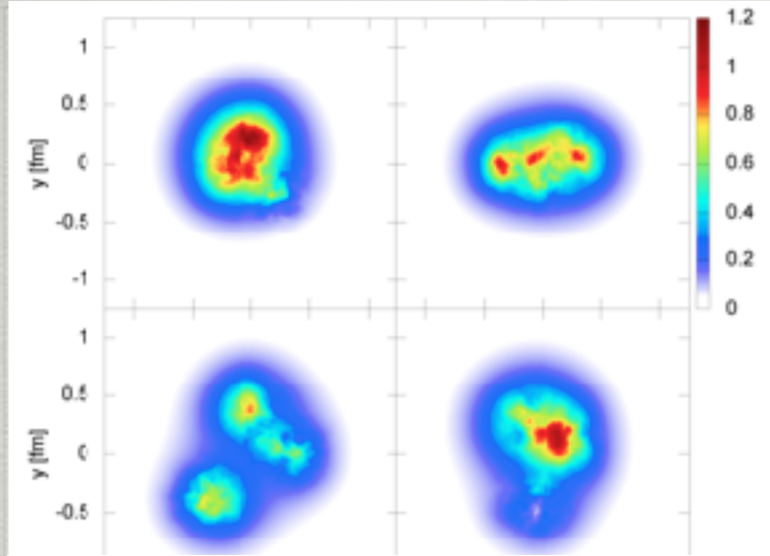
$$\lambda(x_p) = \langle \sigma_{NN}^{MB}(x_p) \rangle / \sigma_{NN}^{MB}.$$




No x dependence, $R_{CP} \to 1$

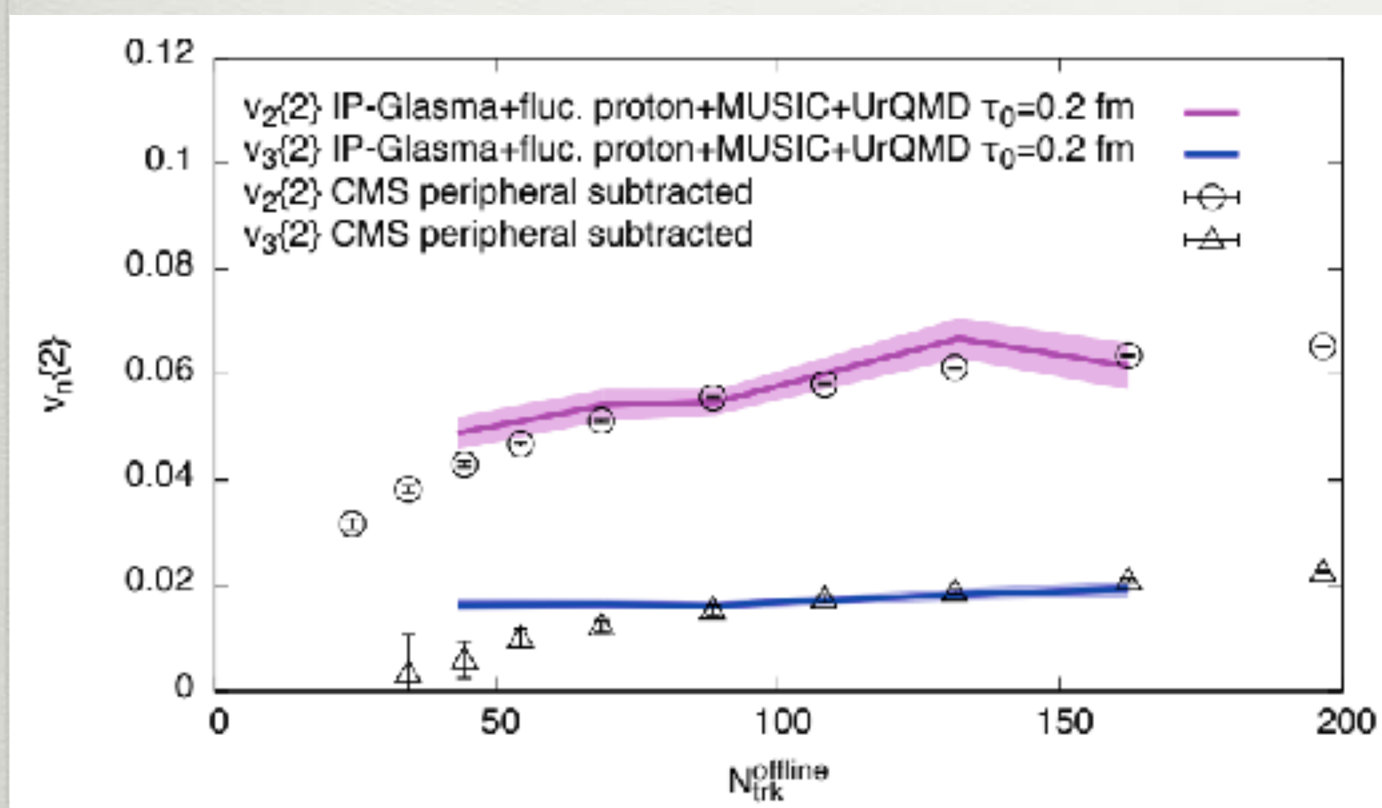
See also: McGlinchey et al, Phys.Rev.C 94 (2016) 2, 024915

# Hotspots in the proton



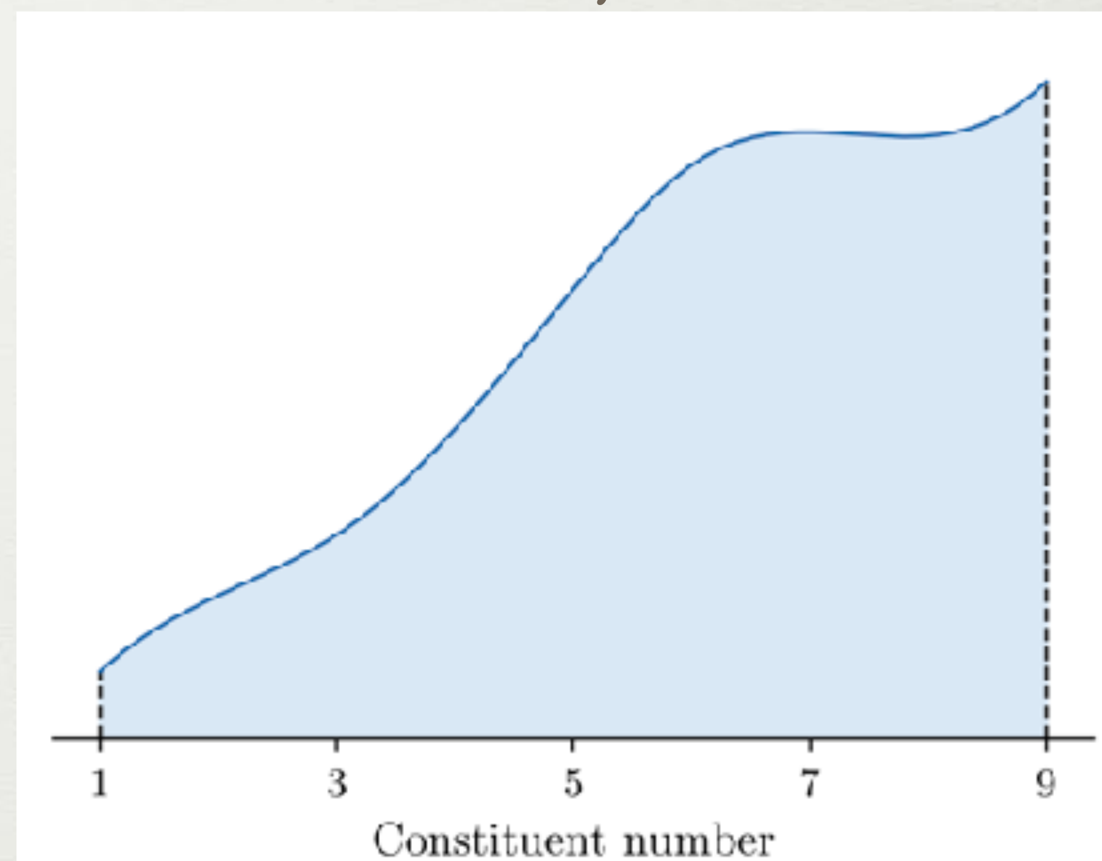

Mäntysaari, Schenke Phys.Rev.Lett. 117 (2016) 5, 052301

## Proton fluctuations, constrained by HERA data



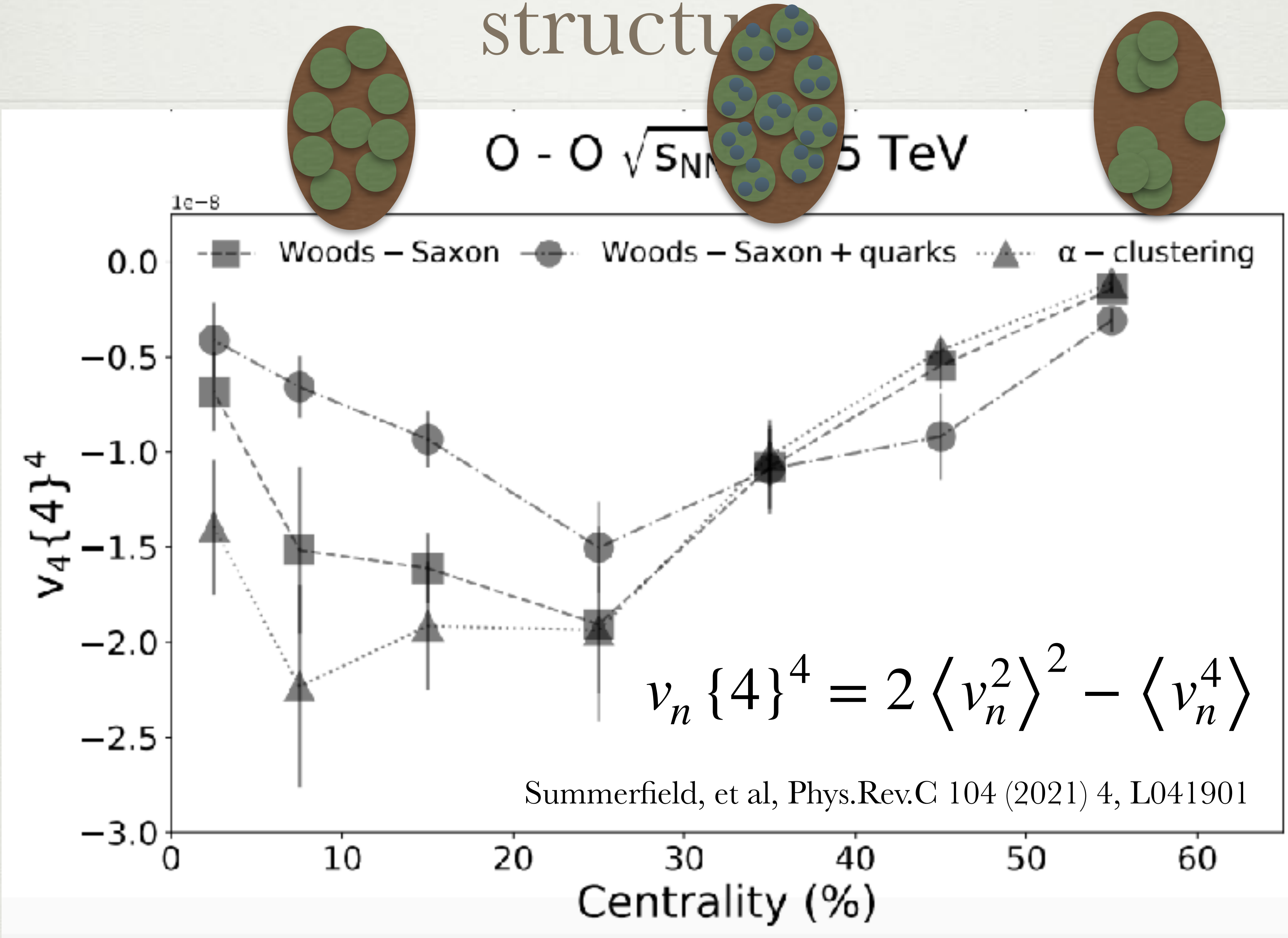

Mäntysaari et al Phys.Lett.B 772 (2017) 681-686; Phys.Lett.B 772 (2017) 832-838; Phys.Rev.D 94 (2016) 3, 034042; Schenke, Venugopalan Phys. Rev. Lett. 113, 102301 (2014)

## Posterior from Bayesian Analysis




Moreland et al, *Phys.Rev.C* 101 (2020) 2, 024911

# Fluctuations in $v_4$ disentangle structure

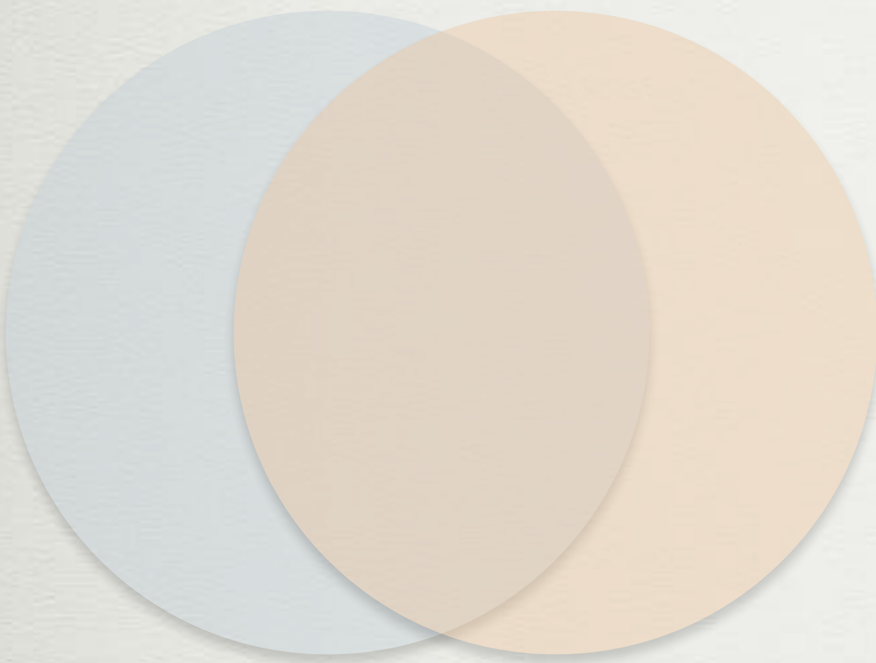



$$v_n\{4\}^4 = 2\left\langle v_n^2 \right\rangle^2 - \left\langle v_n^4 \right\rangle$$

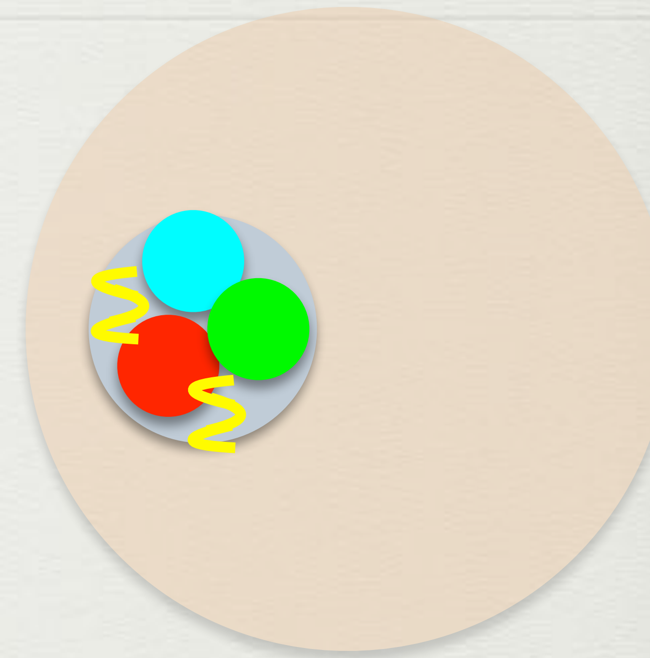
Summerfield, et al, Phys.Rev.C 104 (2021) 4, L041901

Further $v_4\{4\}^4$ may be interesting in even smaller systems

# Shutting off the Quark Gluon Plasma is hard (impossible?): flow harmonics won't go away

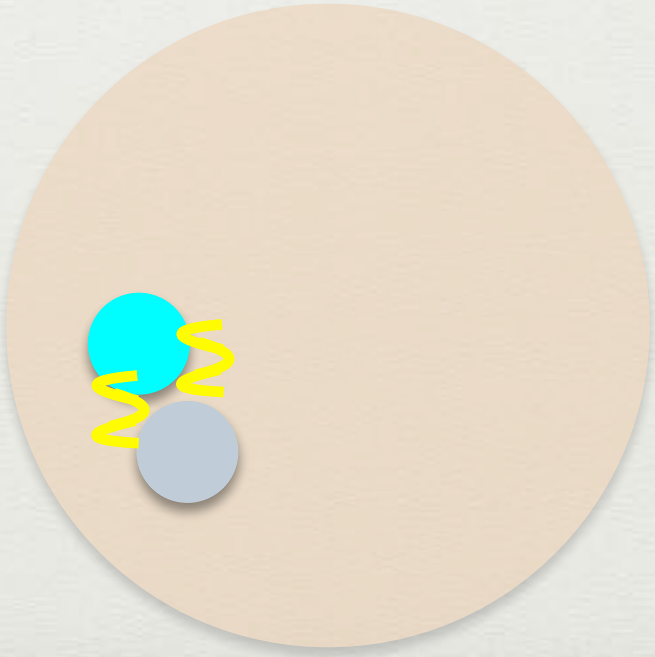


A-A collisions

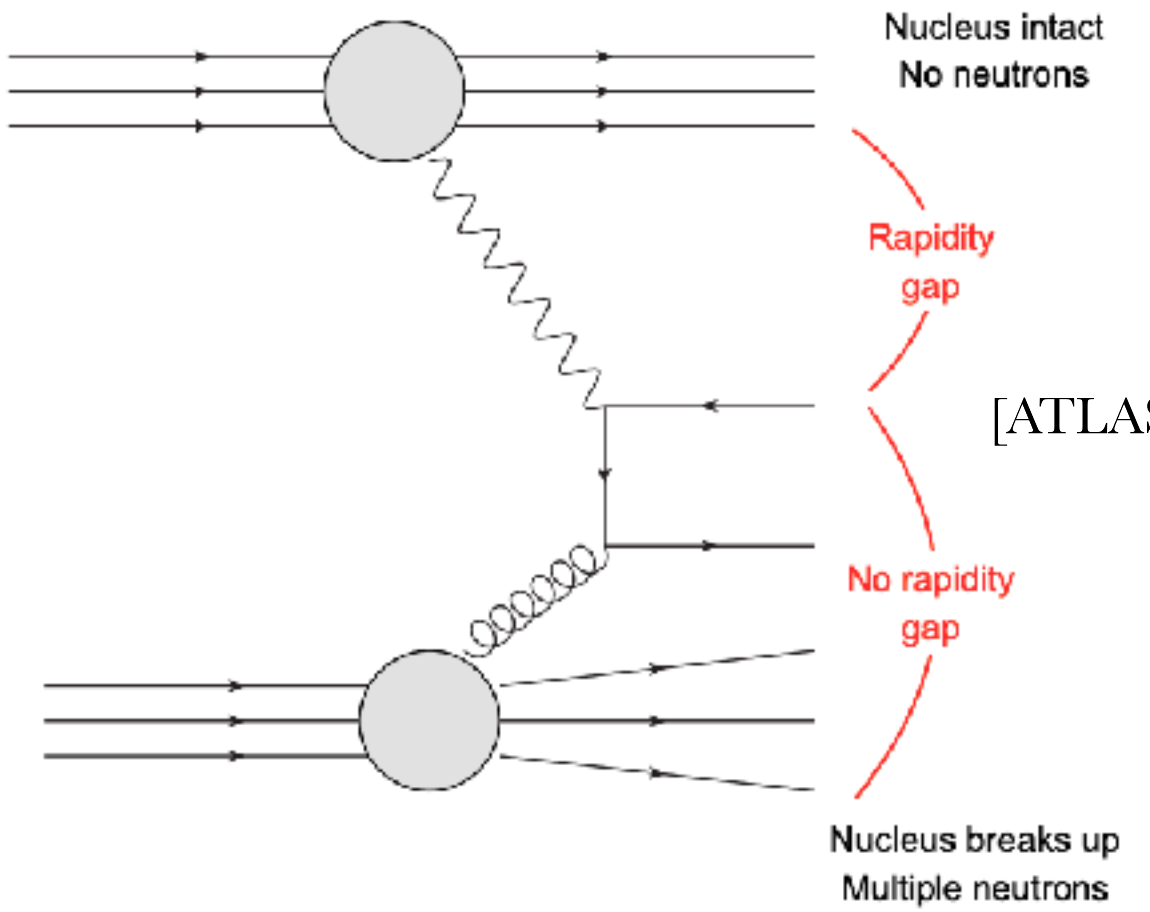


p-A collisions

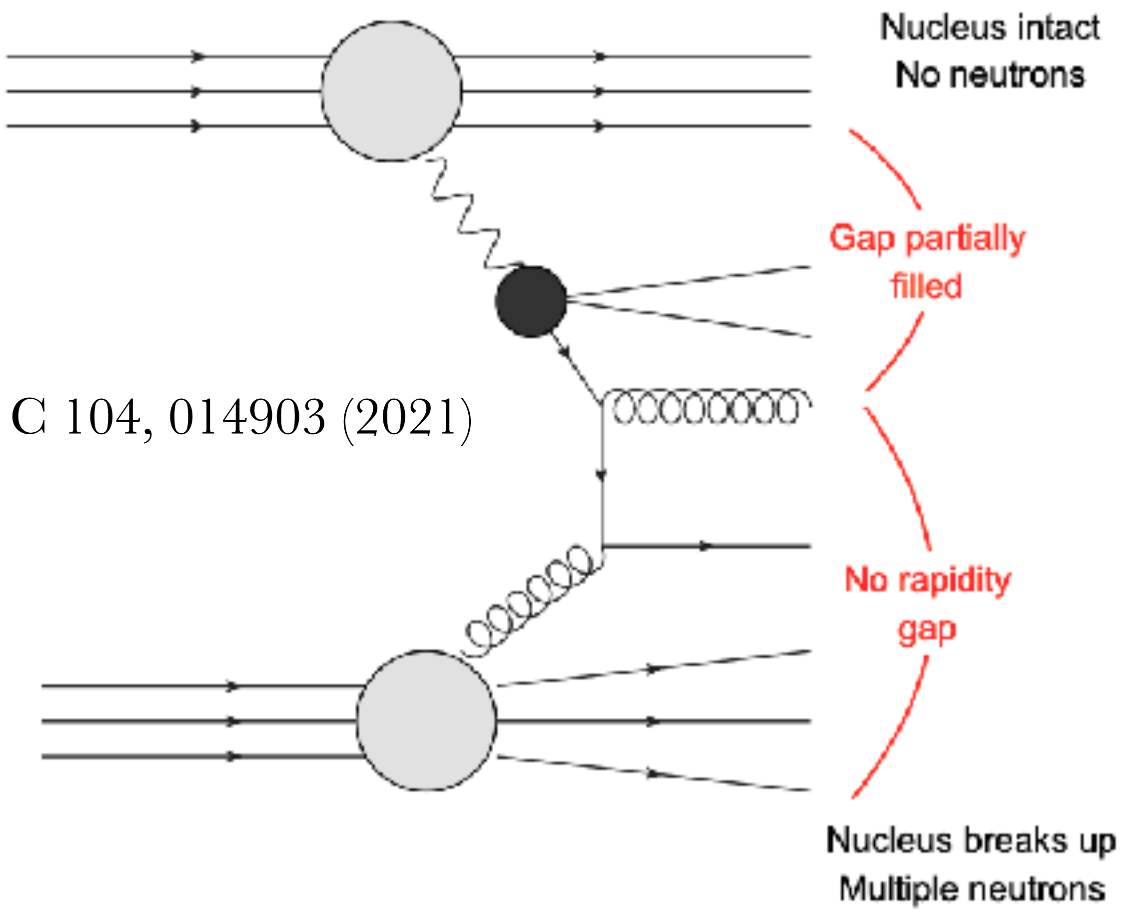
$\gamma$-A collisions



# Super tiny systems: Ultra peripheral collisions



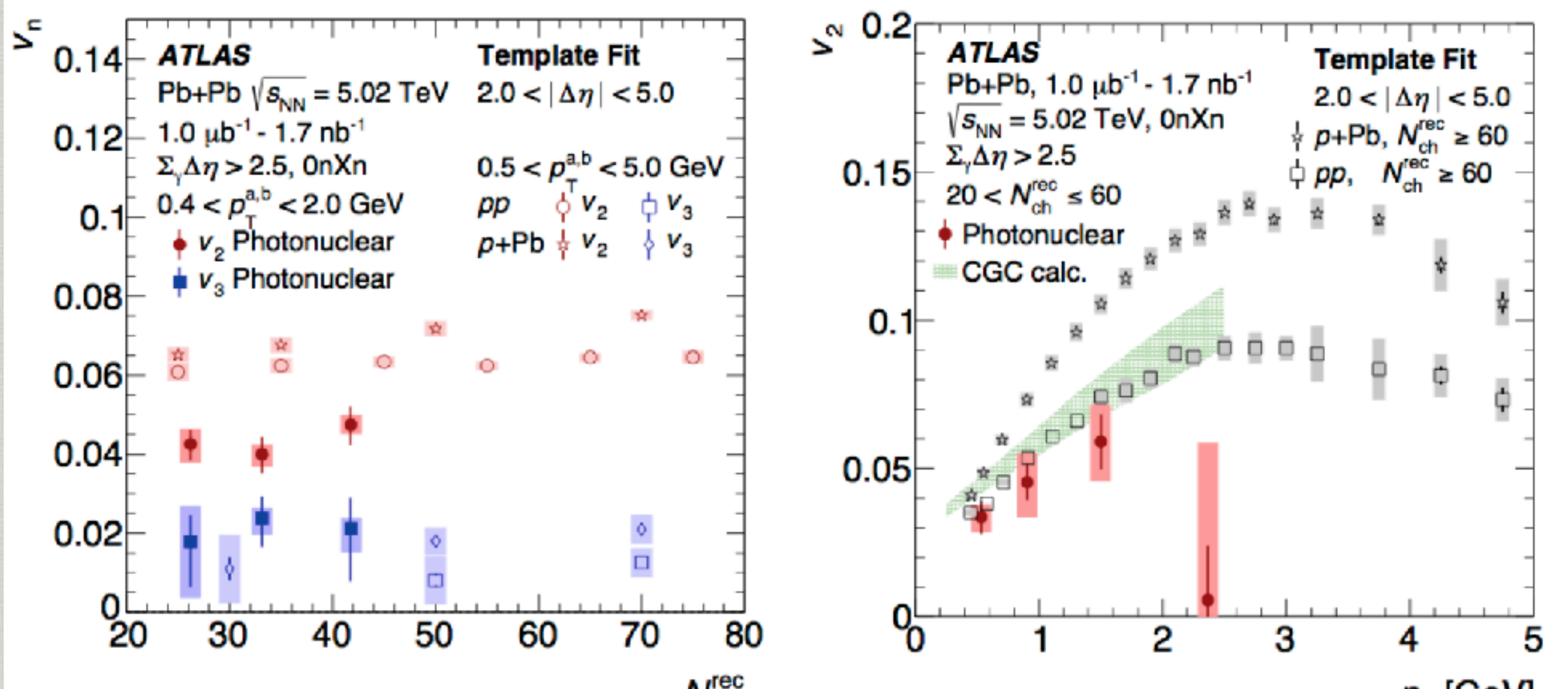

[ATLAS] Phys. Rev. C 104, 014903 (2021)




$\gamma A$ Collision

$(q\bar{q})A$ Collision
$(\gamma \to q\bar{q})$

# Flow in super tiny systems!



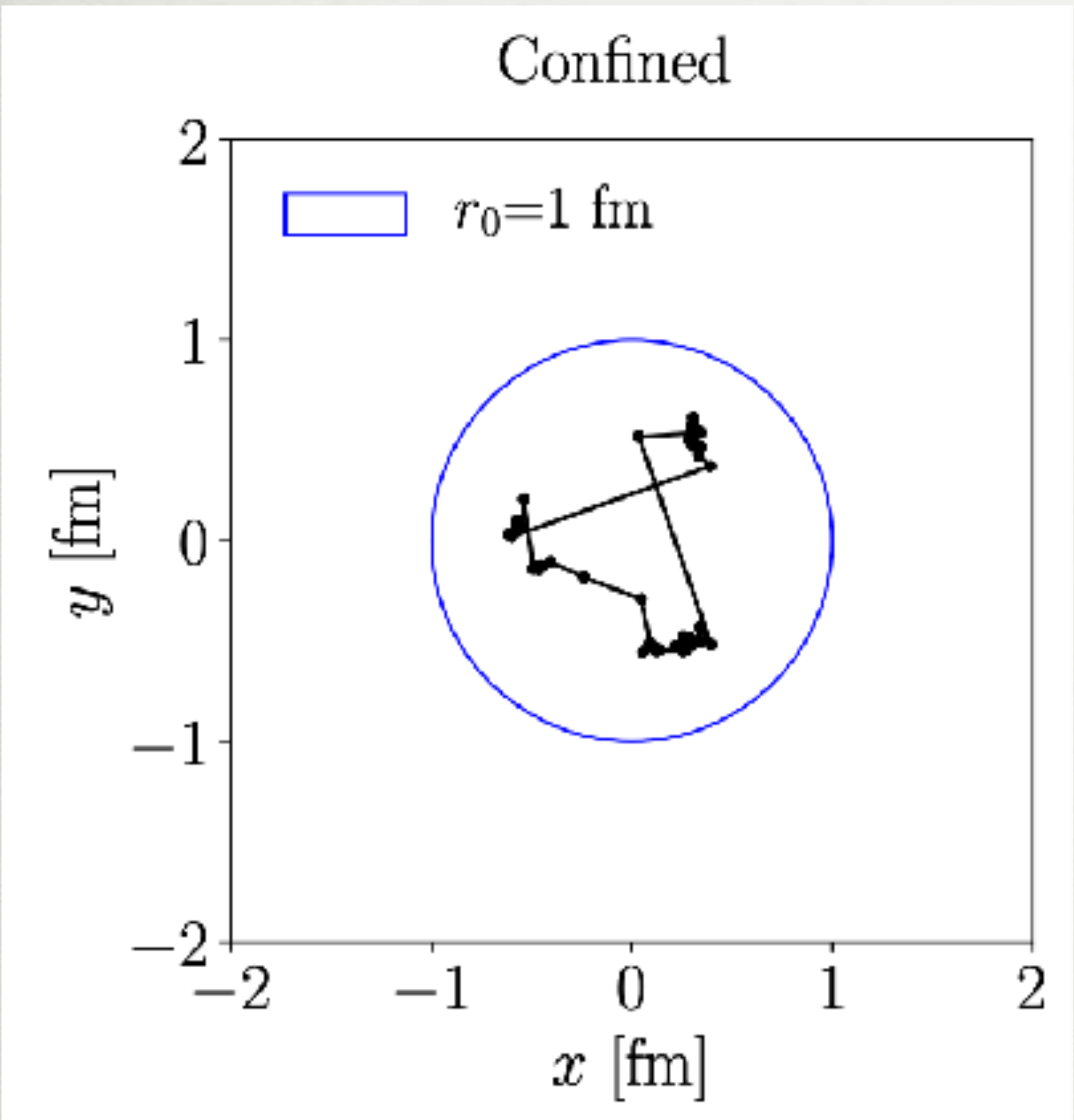

[ATLAS] Phys. Rev. C 104, 014903 (2021)

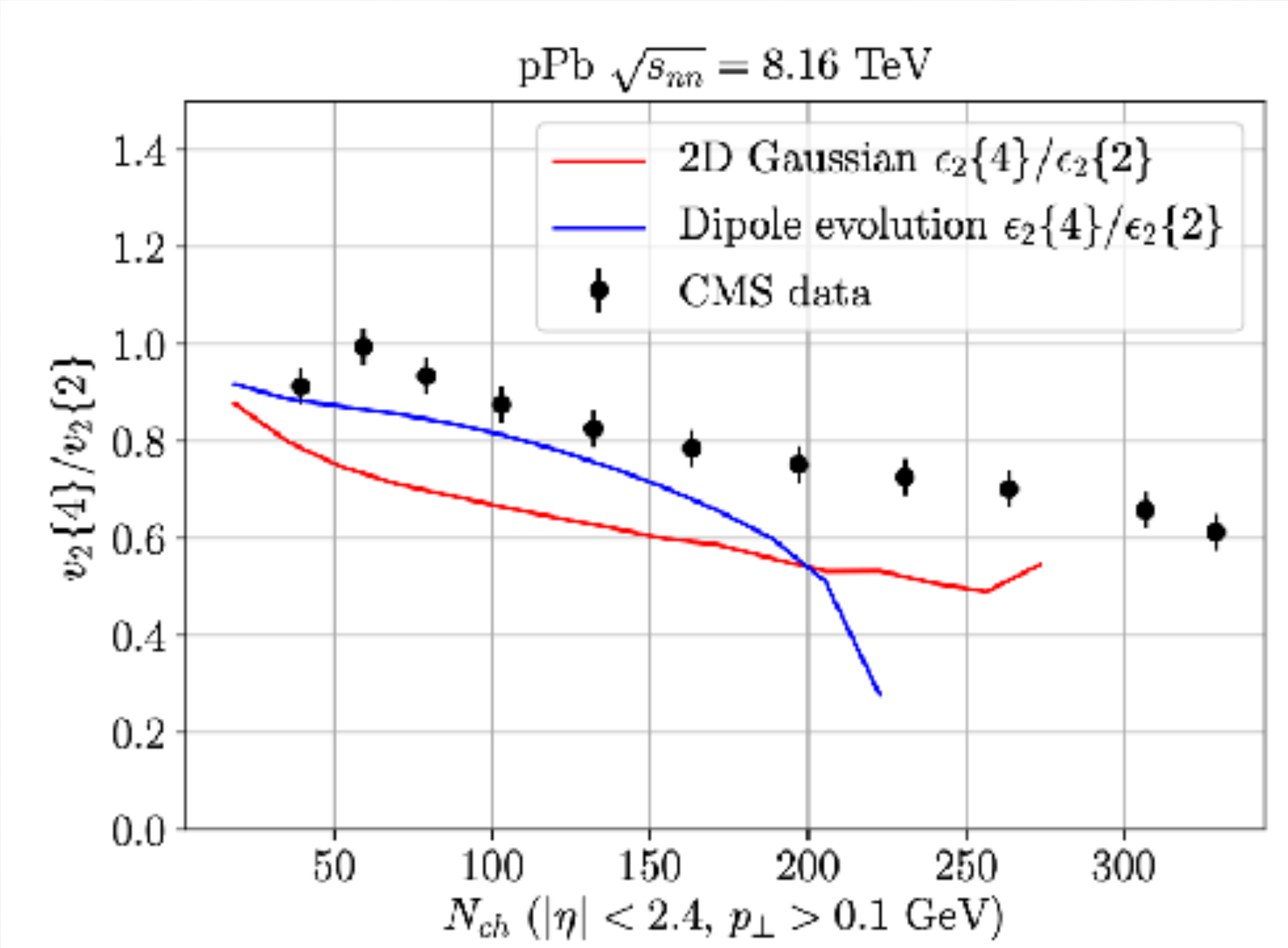
Possibility of flow at the Electron Ion Collider!?

# First steps towards $\gamma^*A$ initial conditions

Bierlich & Rasmussen JHEP 10 (2019) 026

Proton as 3 dipoles

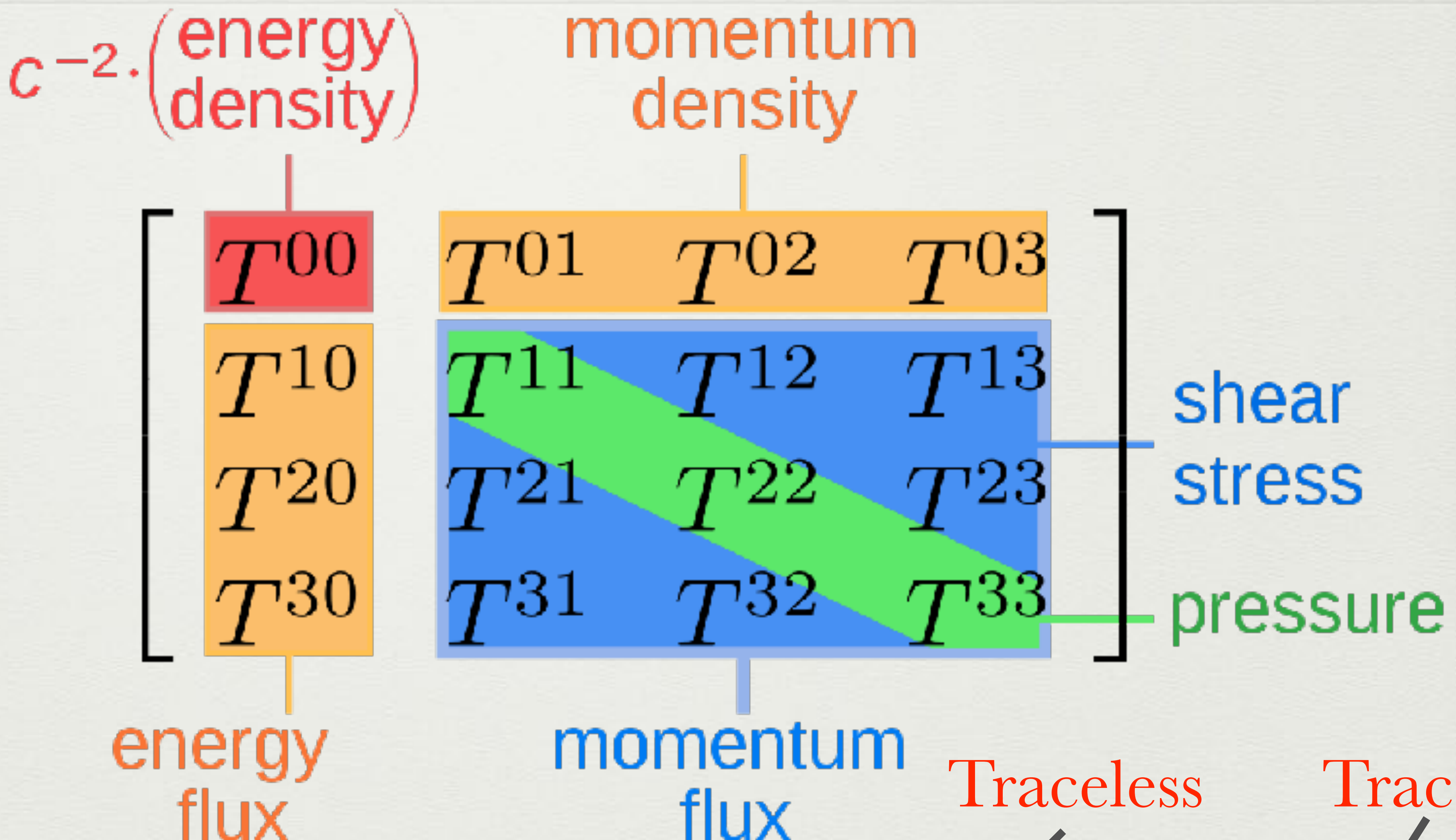



Lots more to do here…

# Initial conditions out-of-equilibrium

$T^{\mu\nu} =$




Traceless Trace

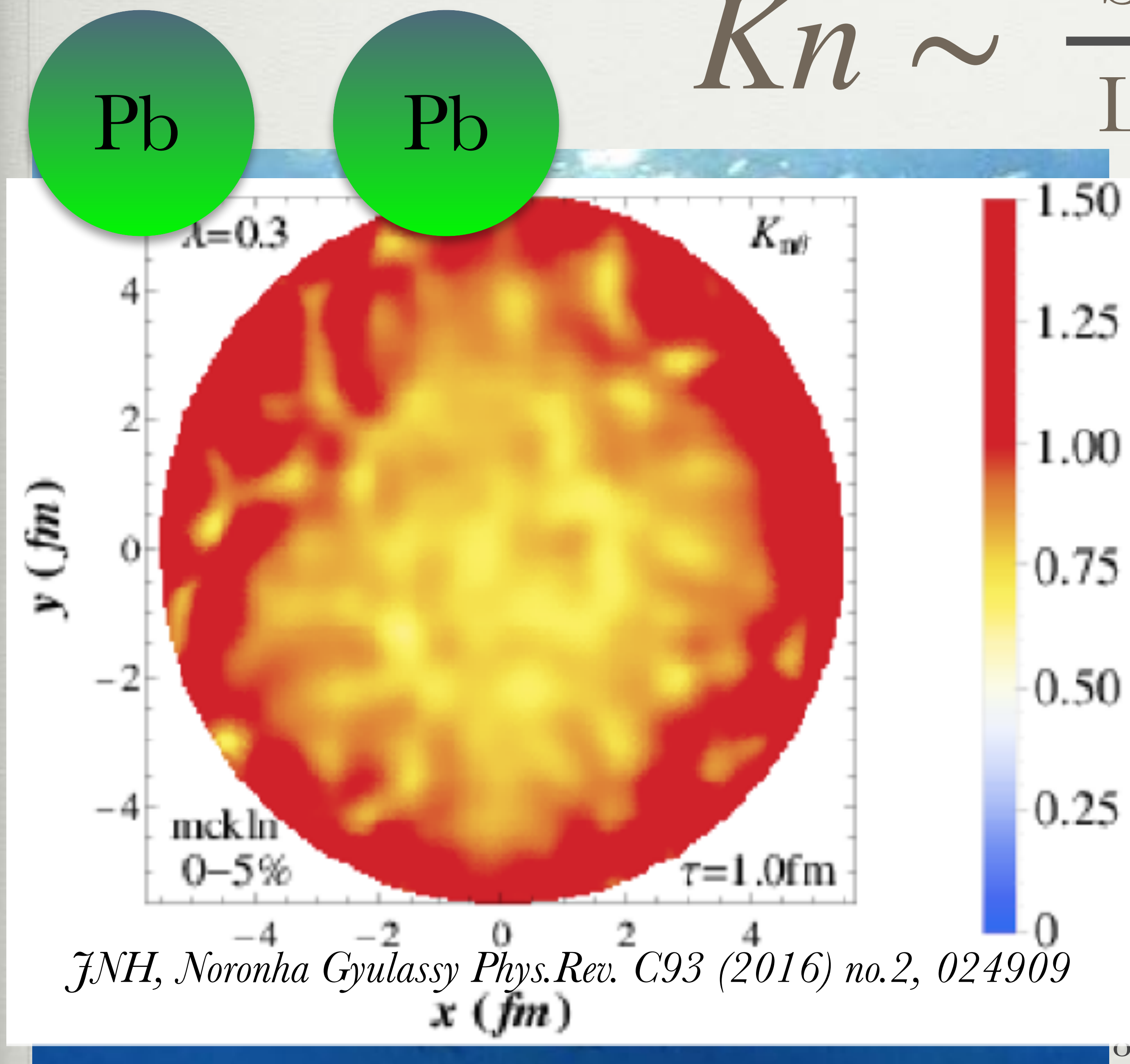
$$T^{\mu\nu} = T^{\mu\nu}_{ideal} + \Pi^{\mu\nu}_{visc}$$

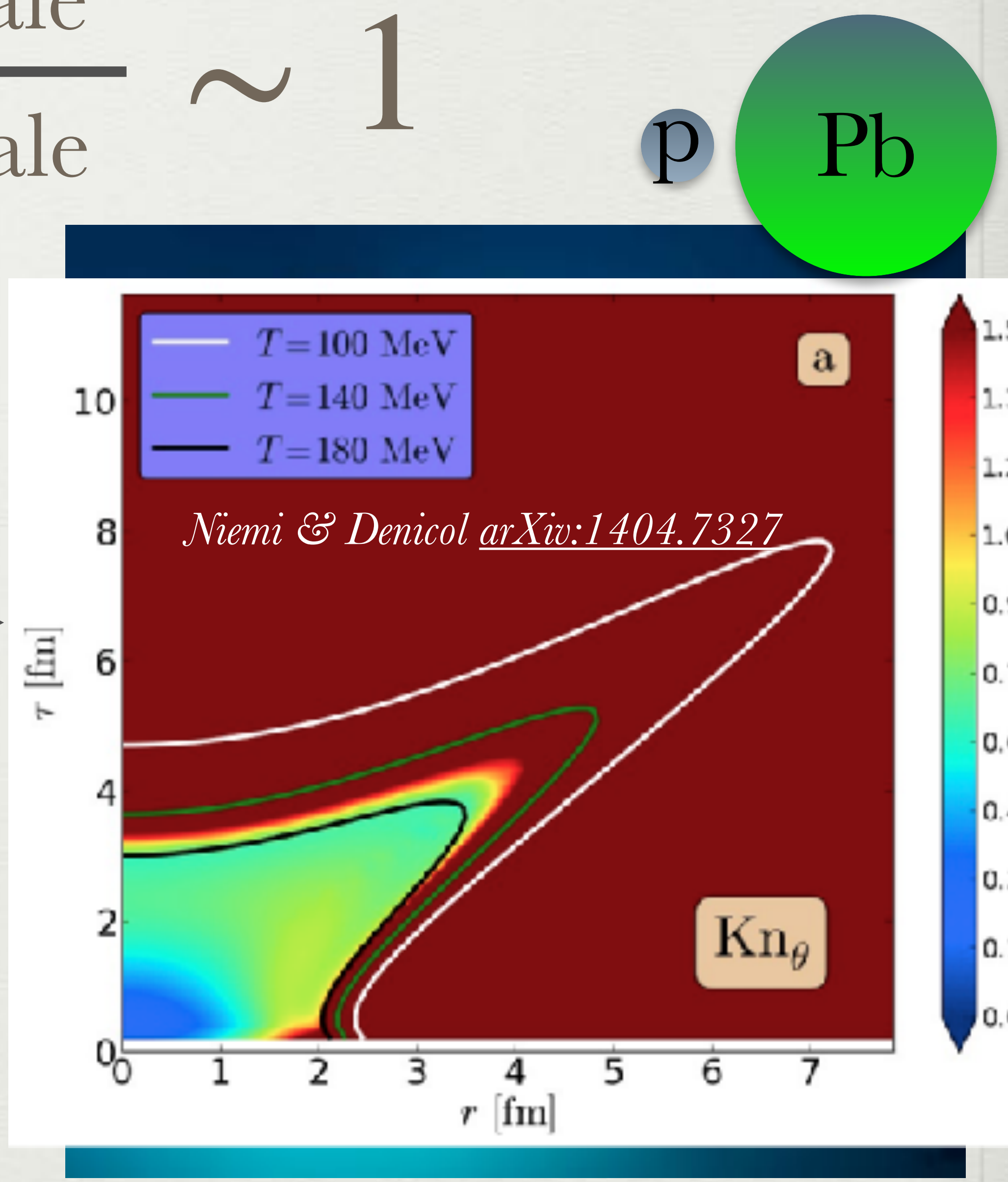
$$\Pi^{\mu\nu}_{visc} = \underbrace{\pi^{\mu\nu}}_{shear} + \Delta^{\mu\nu} \underbrace{\Pi}_{bulk}$$

# Fluids the size of a nucleus? A proton?

When do you have too few particles to use hydrodynamics?

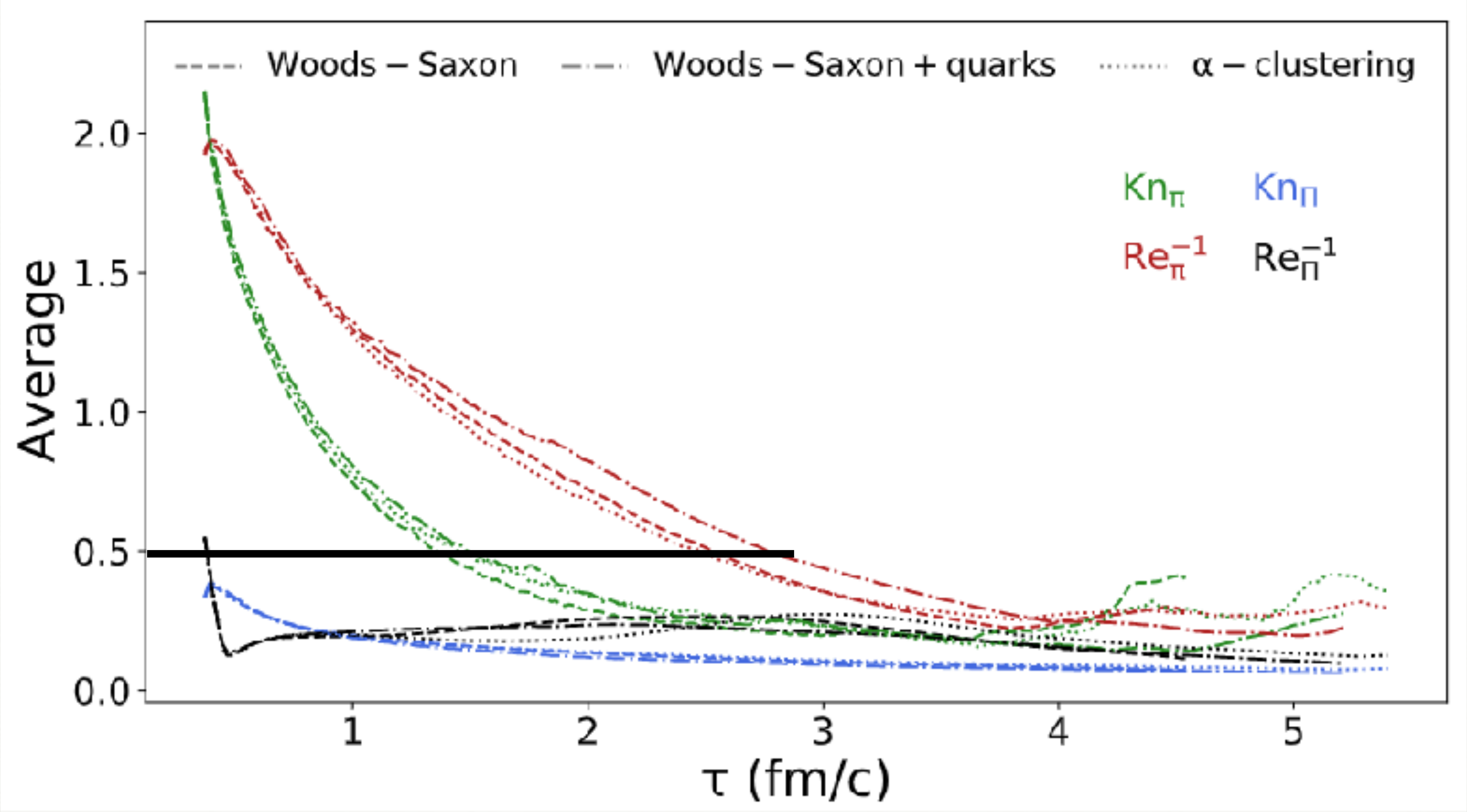
$$Kn \sim \frac{\text{Small scale}}{\text{Large scale}} \sim 1$$



# Oxygen-Oxygen collisions: Kn/$Re^{-1}$

Experimental: N. Summerfield & A. Timmins, Theory: C. Plumberg & JNH, Lattice EFT: B-N Lu & D. Lee




Hydro only applicable after $\tau \sim 3\ fm/c$?

# Nonlinear Causality Constraints

Bemfica et al, *Phys.Rev.Lett.* 126 (2021) 22, 222301

**Necessary:**
If conditions violated, $v > c$!

$$(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{1}{2}\tau_{\pi\pi}|\Lambda_1| \geq 0$$

$$\varepsilon + P + \Pi - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{4\tau_\pi}\Lambda_3 \geq 0,$$

7 total (5 not shown)

**Sufficient:**
If conditions satisfied, $v \leq c$!

$$(\varepsilon + P + \Pi - |\Lambda_1|) - \frac{1}{2\tau_\pi}(2\eta + \lambda_{\pi\Pi}\Pi) - \frac{\tau_{\pi\pi}}{2\tau_\pi}\Lambda_3 \geq 0,$$

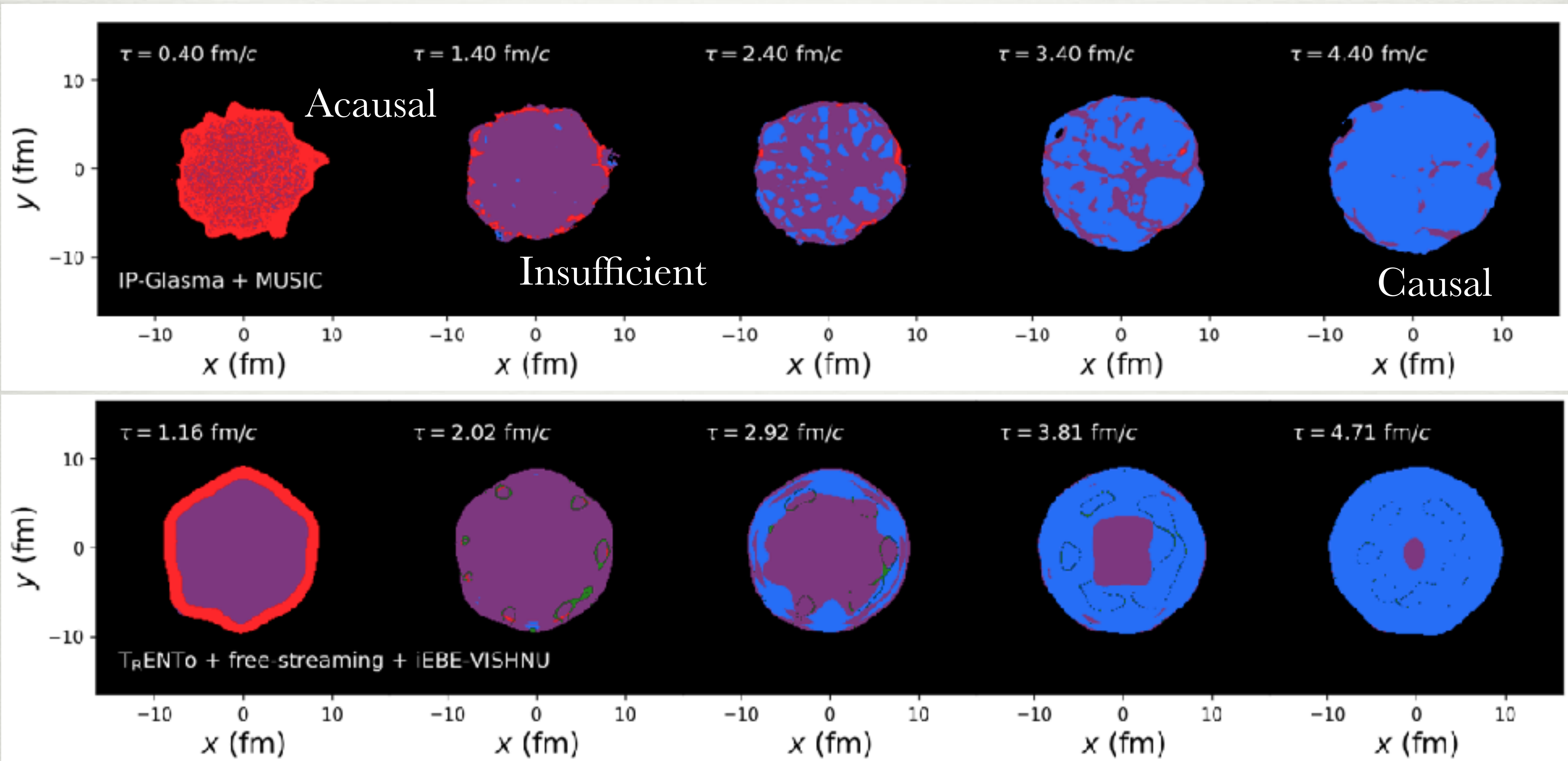
$$(2\eta + \lambda_{\pi\Pi}\Pi) - \tau_{\pi\pi}|\Lambda_1| > 0,$$

8 total (6 not shown)

**Insufficient:** necessary satisfied, but 1+ sufficient fail

# Hydro is great but not perfect: initial state → hydro = acausal behavior?

Plumberg, Almaalol, Dore, Noronha, JNH rXiv:2103.15889v1 [nucl-th]



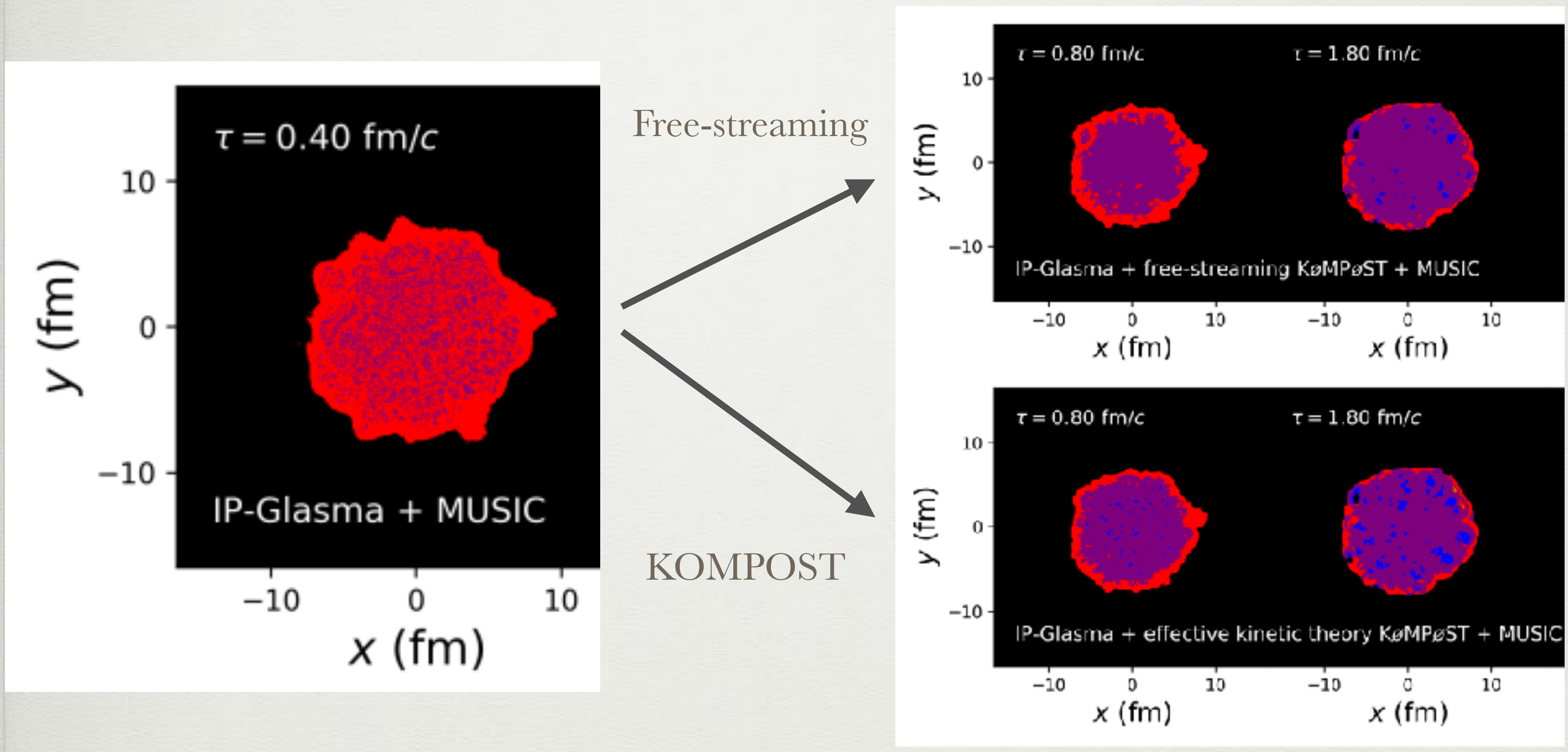

Connection between initial state → hydrodynamics, causality violation

Constraints derived in

Bemfica et al, *Phys.Rev.Lett.* 126 (2021) 22, 222301

# Pre-equilibrium may save the day

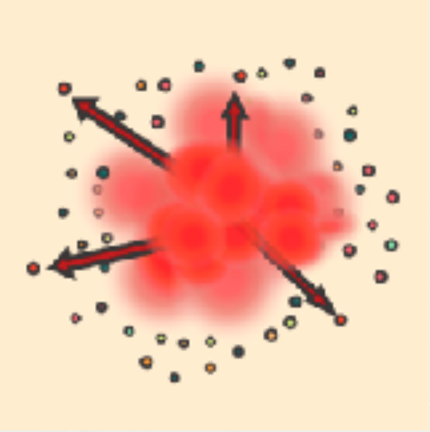
Plumberg, Almaalol, Dore, Noronha, JNH rXiv:2103.15889v1 [nucl-th]



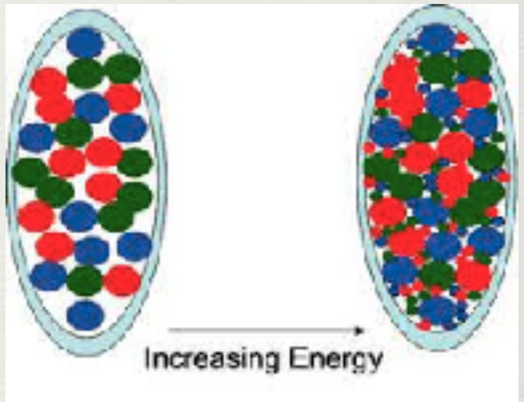

But a "ring of fire" remains in IP-Glasma and TRENTO

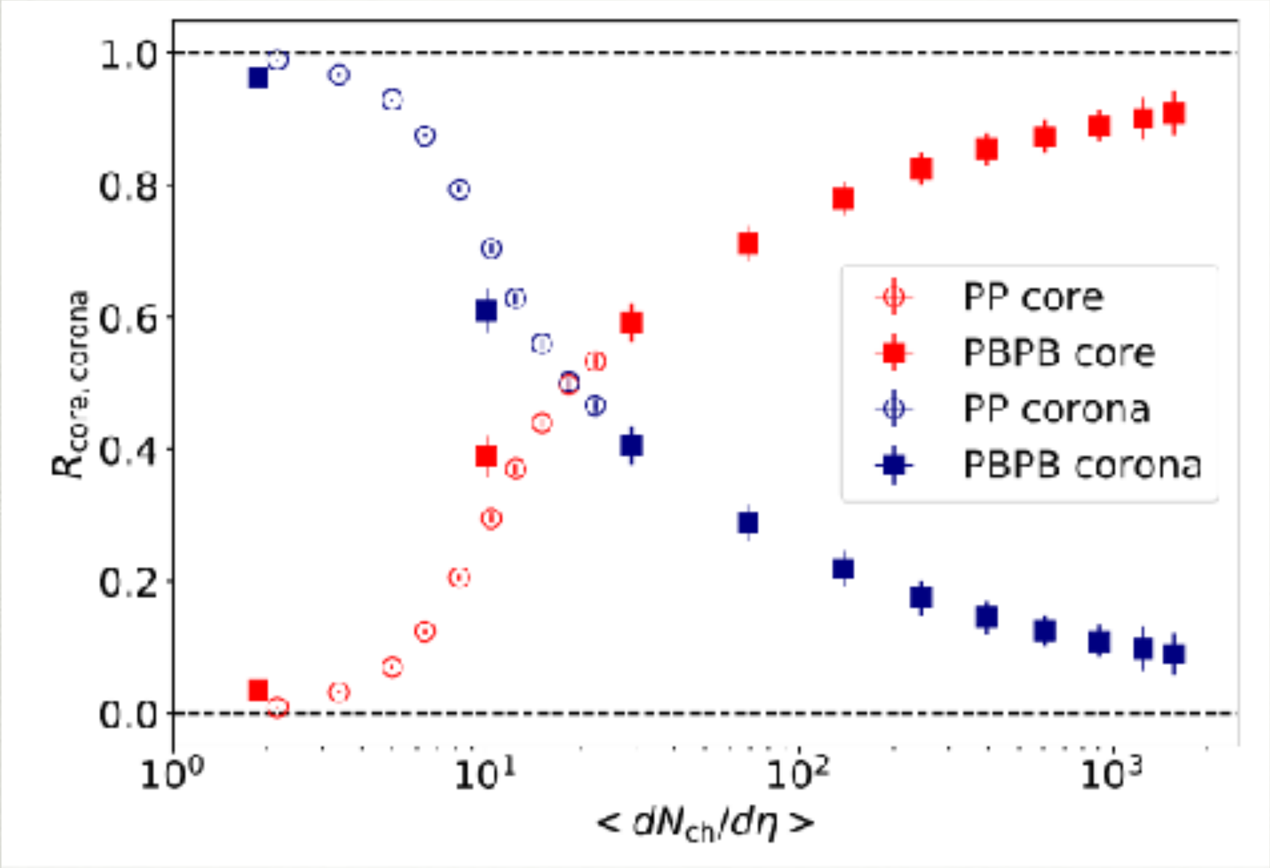
# Core-Corona? CGC+parton evolution?

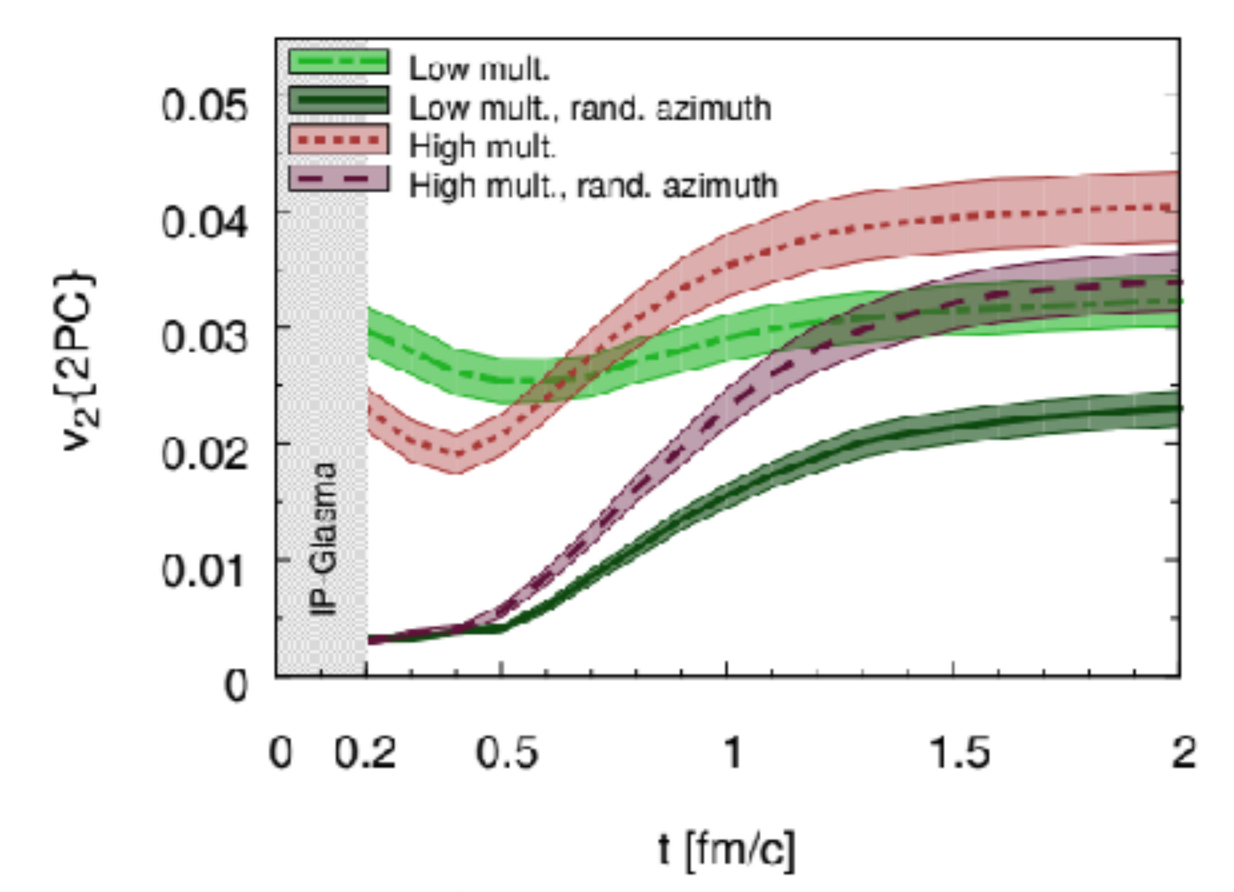
Core-corona



CGC+BAMPS



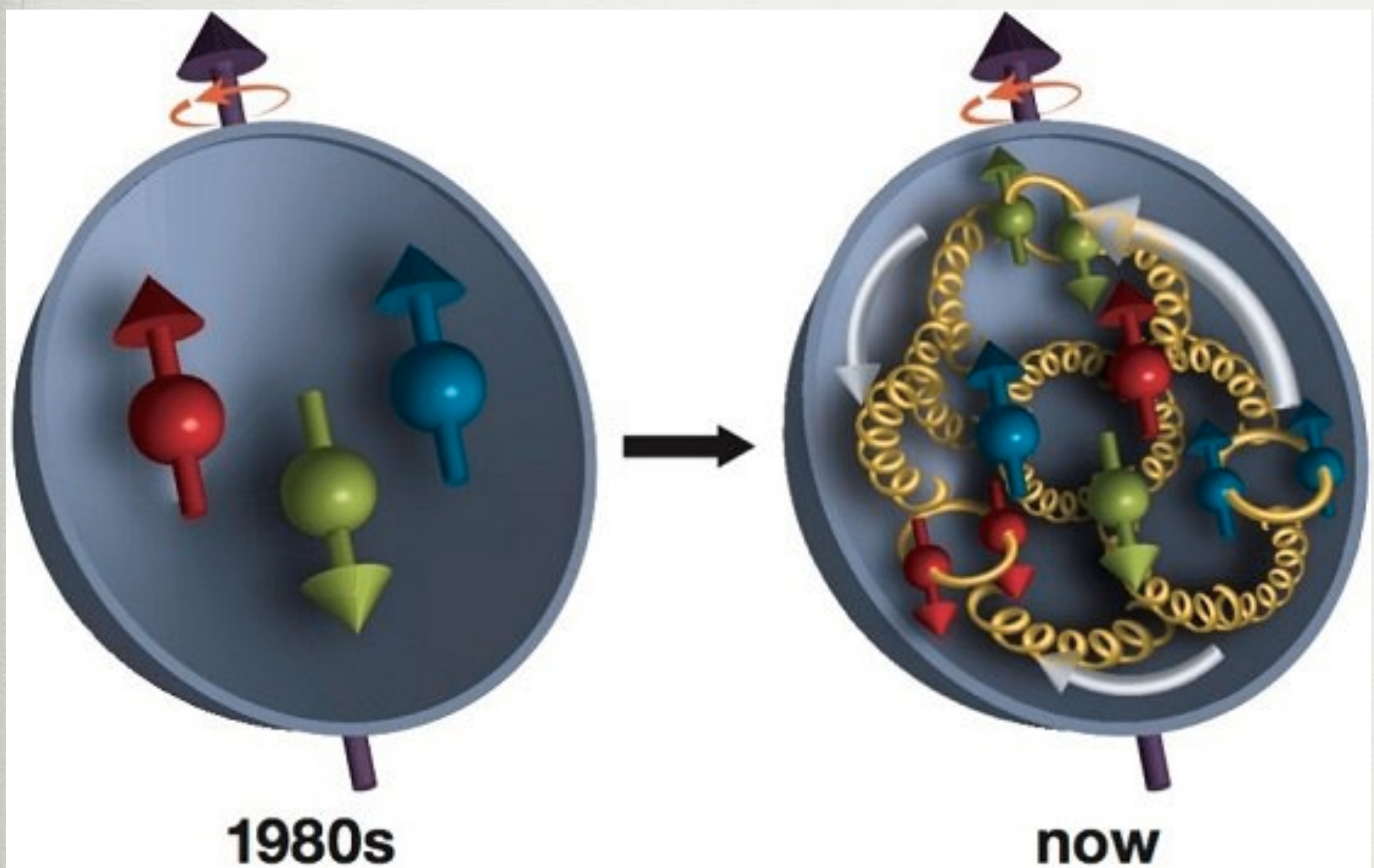



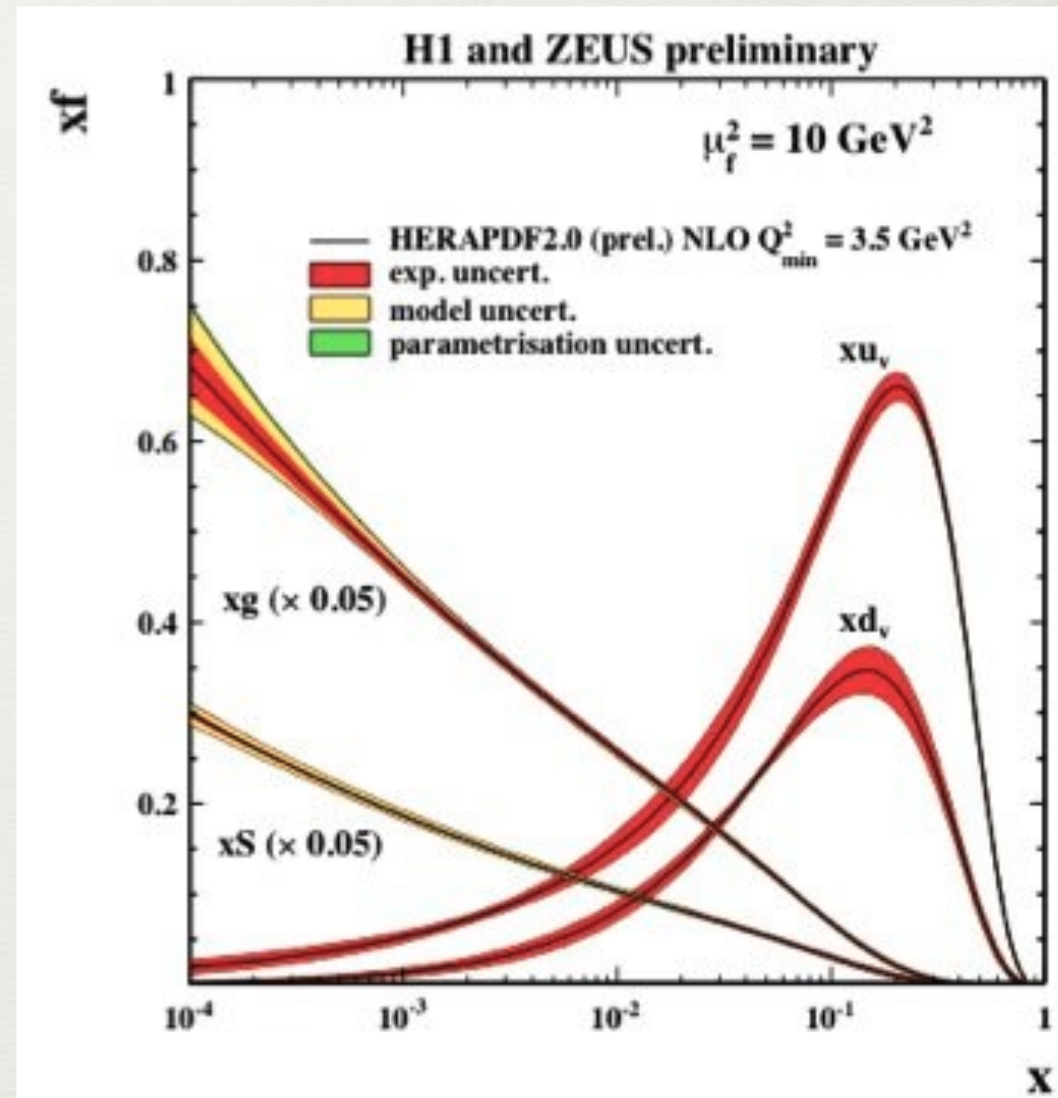




Kanakubo et al, Phys.Rev.C 101 (2020) 2, 024912; 2108.07943

Greif et al, *Phys.Rev.D* 96 (2017) 9, 091504

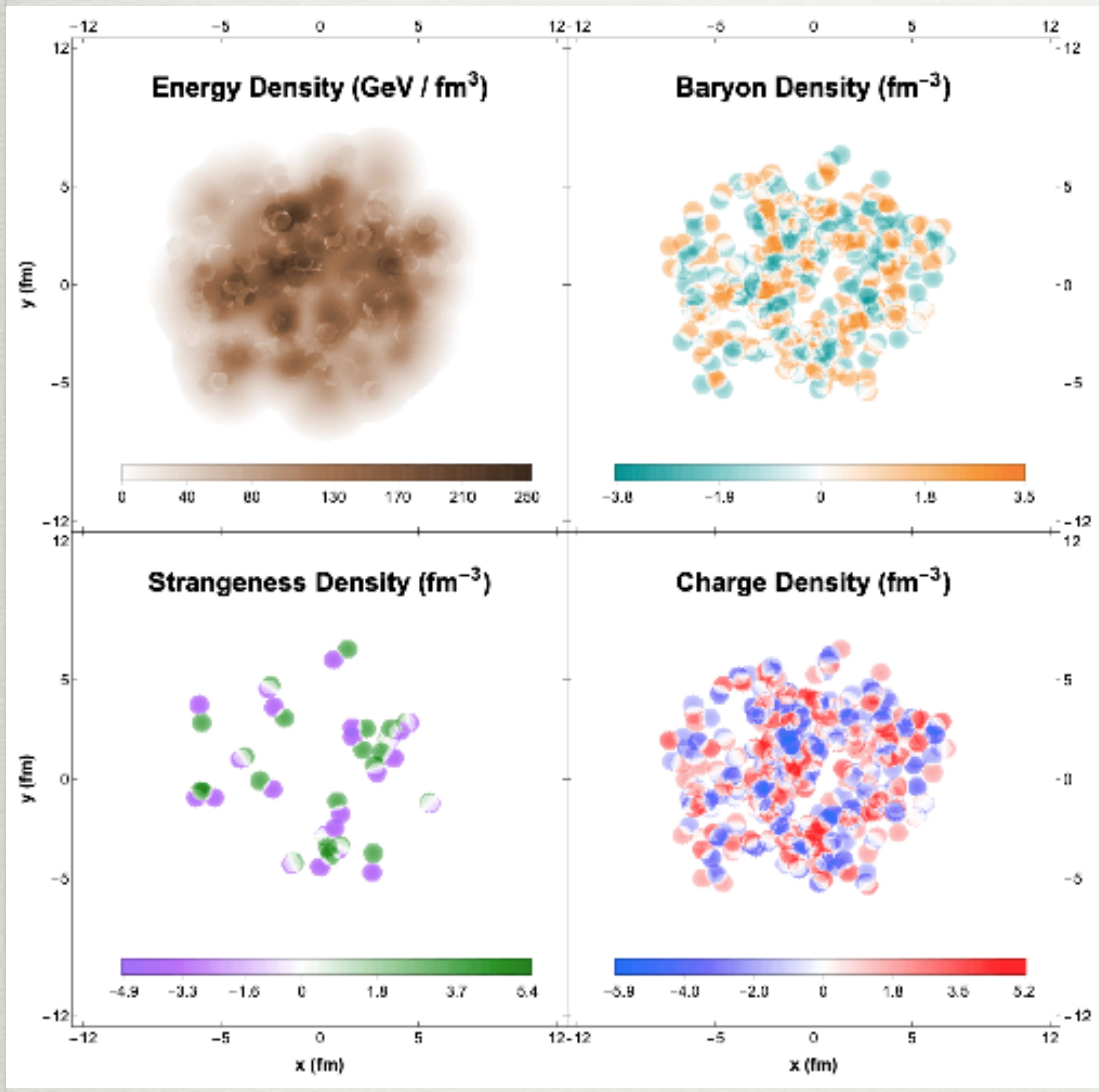
# Quarks are quirky: sea-quarks?



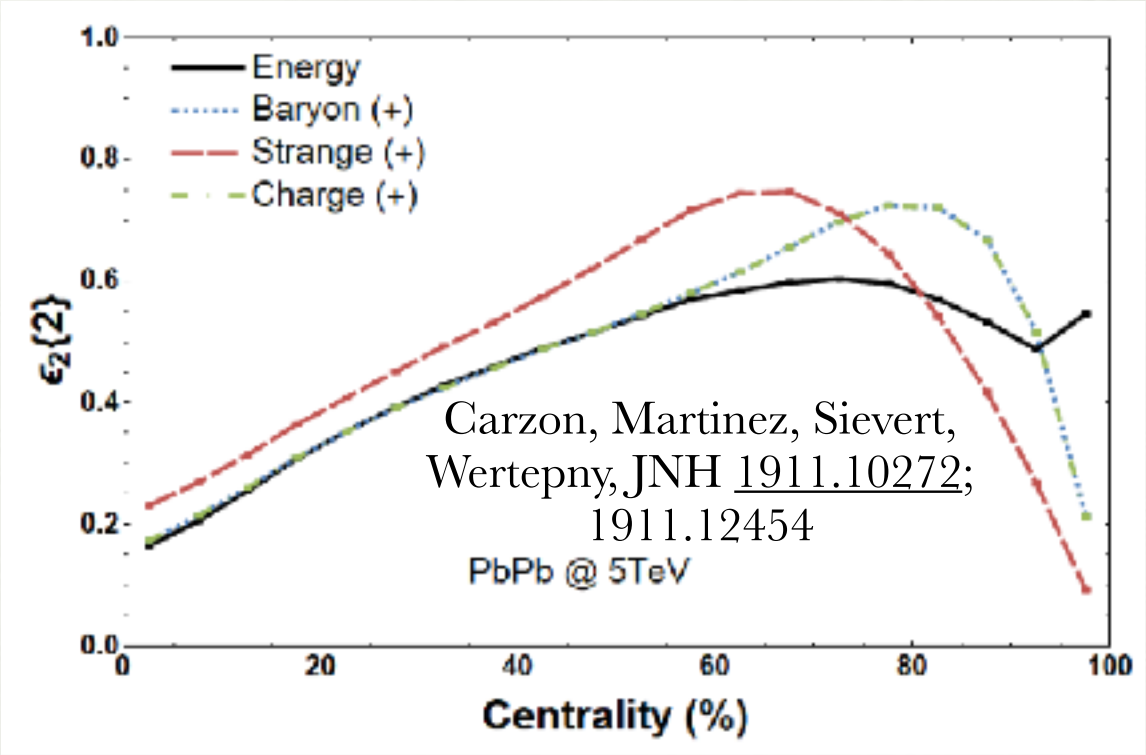

Status Quo: initial conditions include gluon saturation, no sea quarks

# **Initial conditions:** ICCING- Initializing Conserved Charges in Nuclear Geometries




Theoretical development
**Martinez, Sievert, Wertepny**
JHEP 02 (2019) 024;JHEP 1807 (2018) 003

$$g \leftrightarrow q\bar{q}$$




Carzon, Martinez, Sievert, Wertepny, JNH 1911.10272; 1911.12454

BSQ hydrodynamics needed for direct comparisons to data

# Lessons from heavy-ion collisions

- Remember your assumptions: moving on from optical Glauber took years
- Flow signals don’t like to switch off
- Event-by-event fluctuations can be feature, not a bug
- Hydrodynamics is not infallible, still need to understand the “ring of fire”

# HIC to EIC: Open-questions from small-x

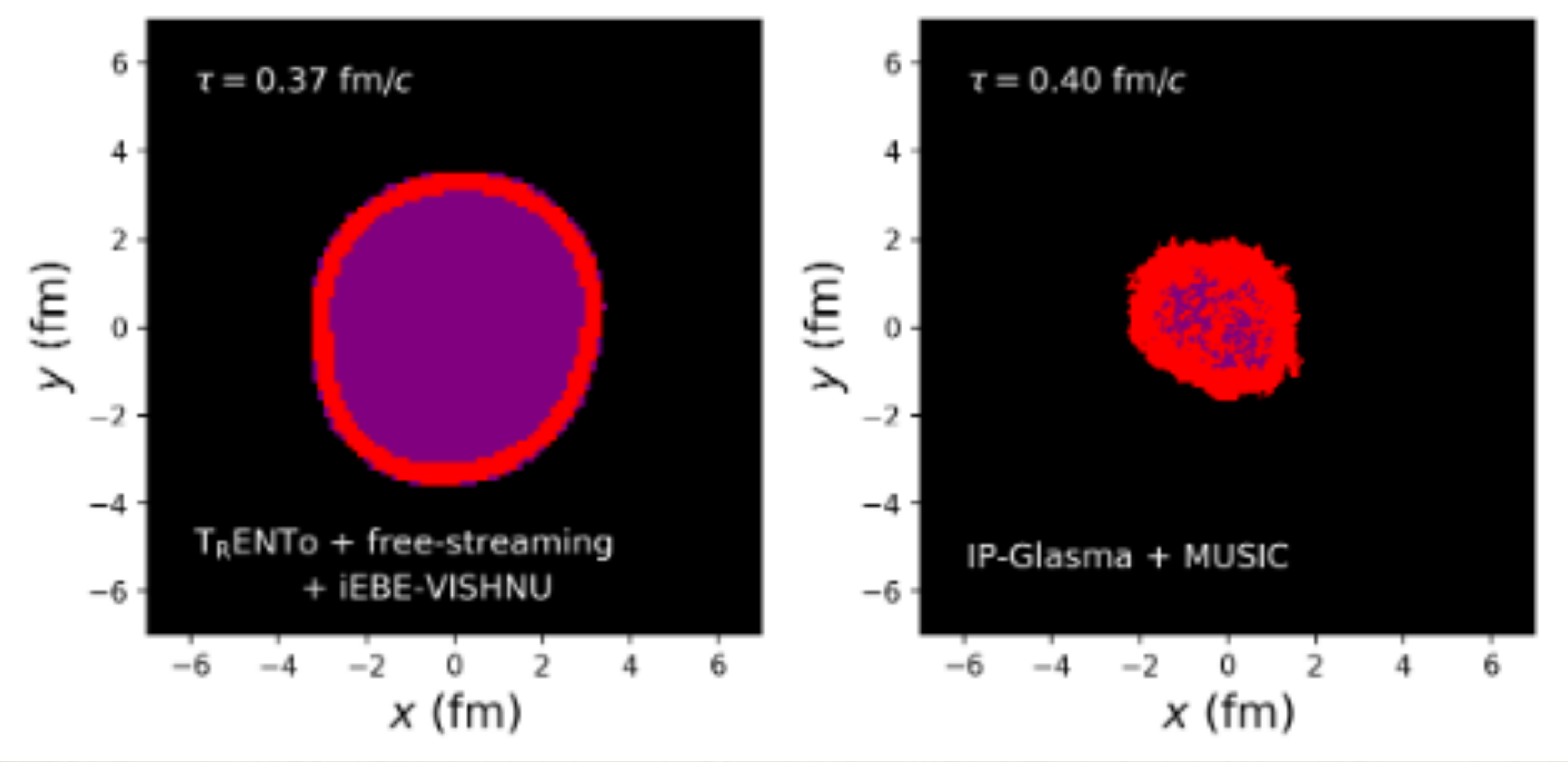
- $\gamma - A$ (Ultra-peripheral collisions): What's going on? Is this CGC or hydro? Would hydro be completely causal there? Will there be a $v_3$ at the EIC?
- Nucleon size at small-x? Influence of nucleon substructure?
- Final word on initial state? We understand the geometry, but do we know the correct theory?
- Charge/quark distributions? Synergy between high and low energy physics
- D & B mesons flow at EIC? What would that mean?
- Nuclear structure: synergy between BNL and FRIB? What does a nucleus look like a small-x?

# Backup

# Causality in small systems

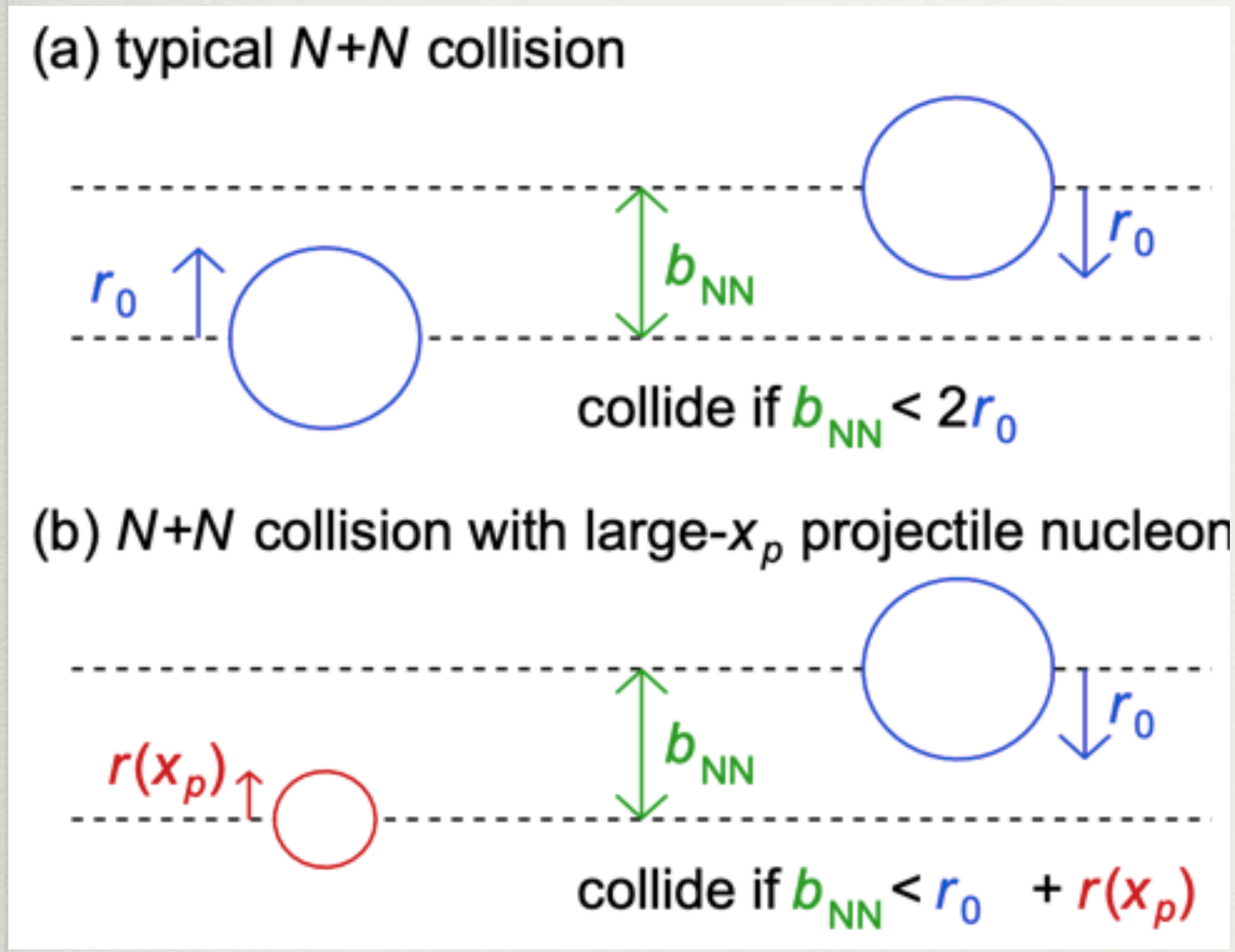
Plumberg, Almaalol, Dore, Noronha, JNH rXiv:2103.15889v1 [nucl-th]

pPb produces similar results, “ring of fire” still remains

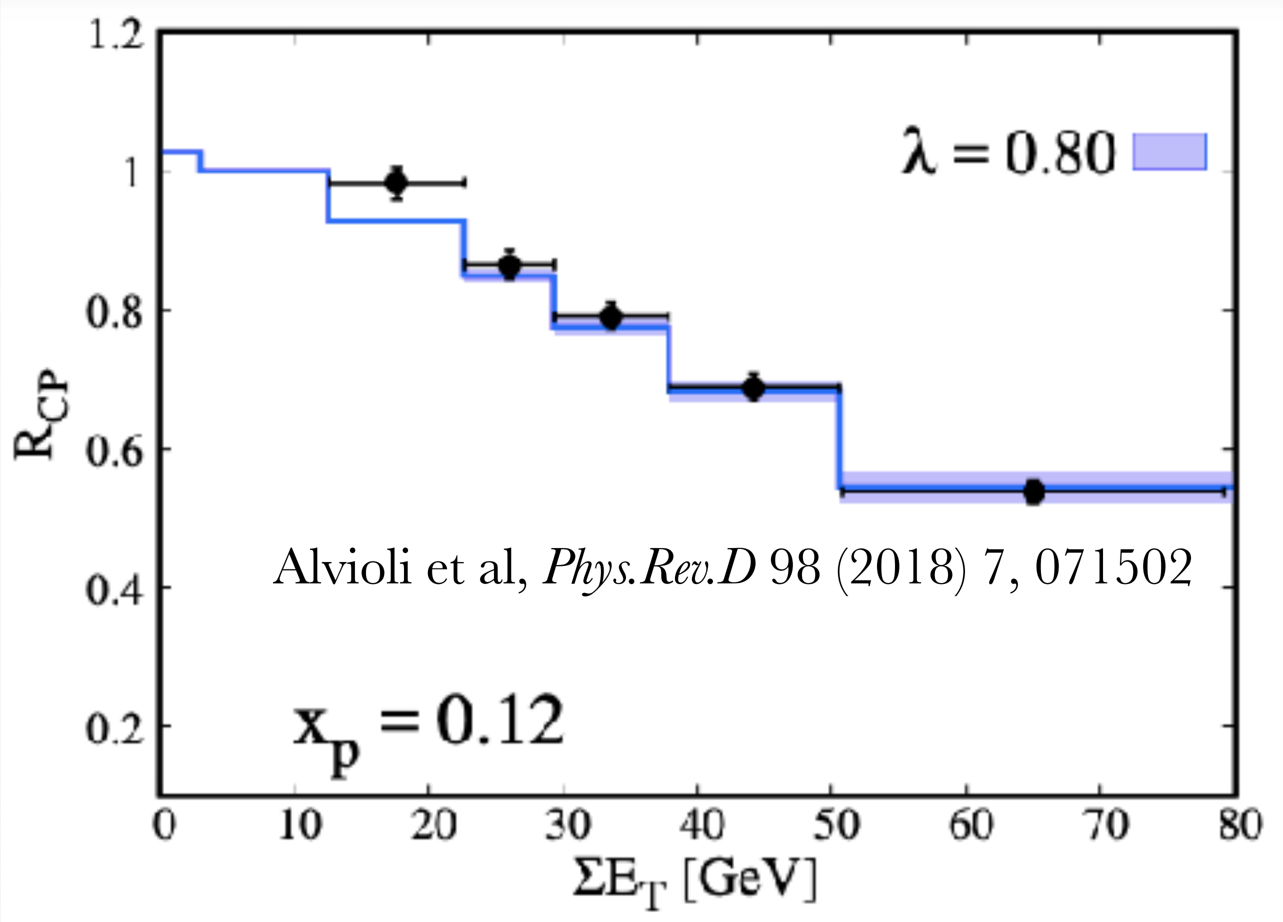


# Proton size fluctuations?

$$\lambda(x_p) = \left\langle \sigma_{NN}^{MB}(x_p) \right\rangle / \sigma_{NN}^{MB}.$$




McGlinchey et al, Phys.Rev.C 94 (2016) 2, 024915




Alvioli et al, *Phys.Rev.D* 98 (2018) 7, 071502

No x dependence, $R_{CP} \rightarrow 1$

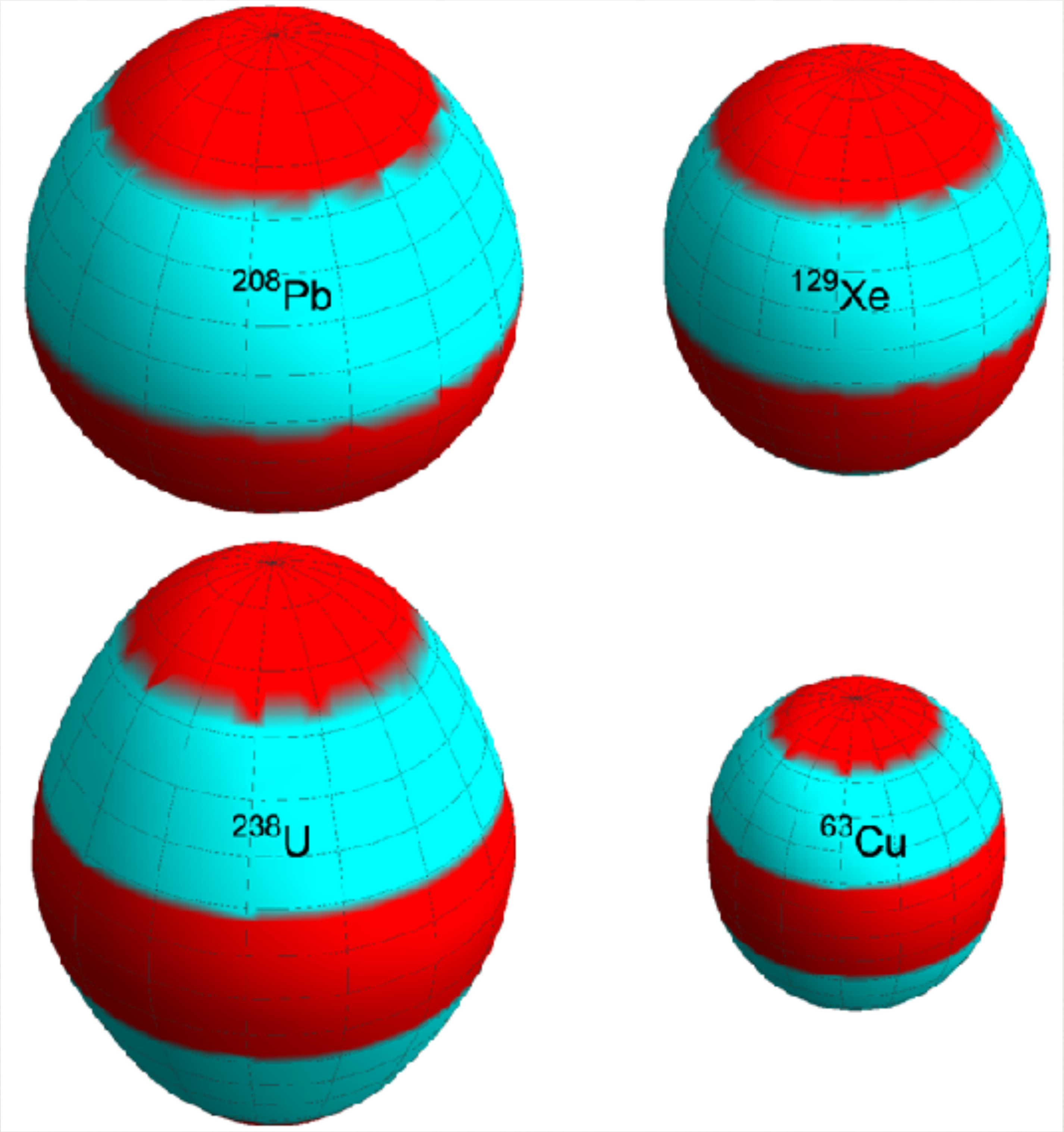
N. Summerfield & A. Timmins
Theory: C. Plumberg & JNH
Lattice EFT: B-N Lu & D. Lee

Duke Bayesian analysis set-up
*Bernhard et al, Nature Phys.* 15 (2019) 11, 1113-1117

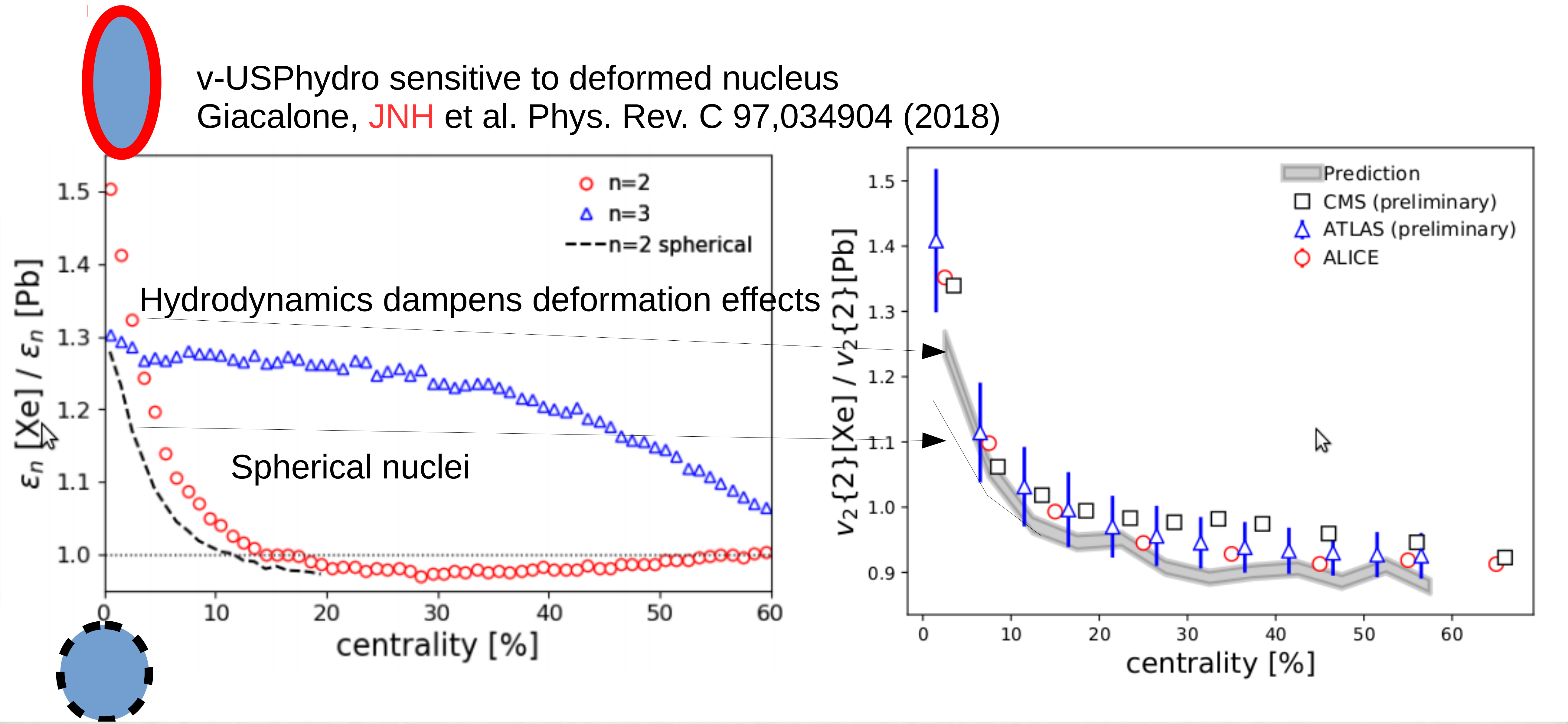
# C… angling large … cture

- OO Wood-Saxon from Sievert, JNH Phys.Rev. C100 (2019) no.2, 024904
- OO+$\alpha$ clustering from lattice effective field theory Moreland et al, *Phys.Rev.C* 101 (2020) 2, 024911
- OO+sub-nucleonic structure (Trento 2.0) Lu, et al, Phys. Lett. B 797, 134863 (2019)

# Influence of nuclear structure

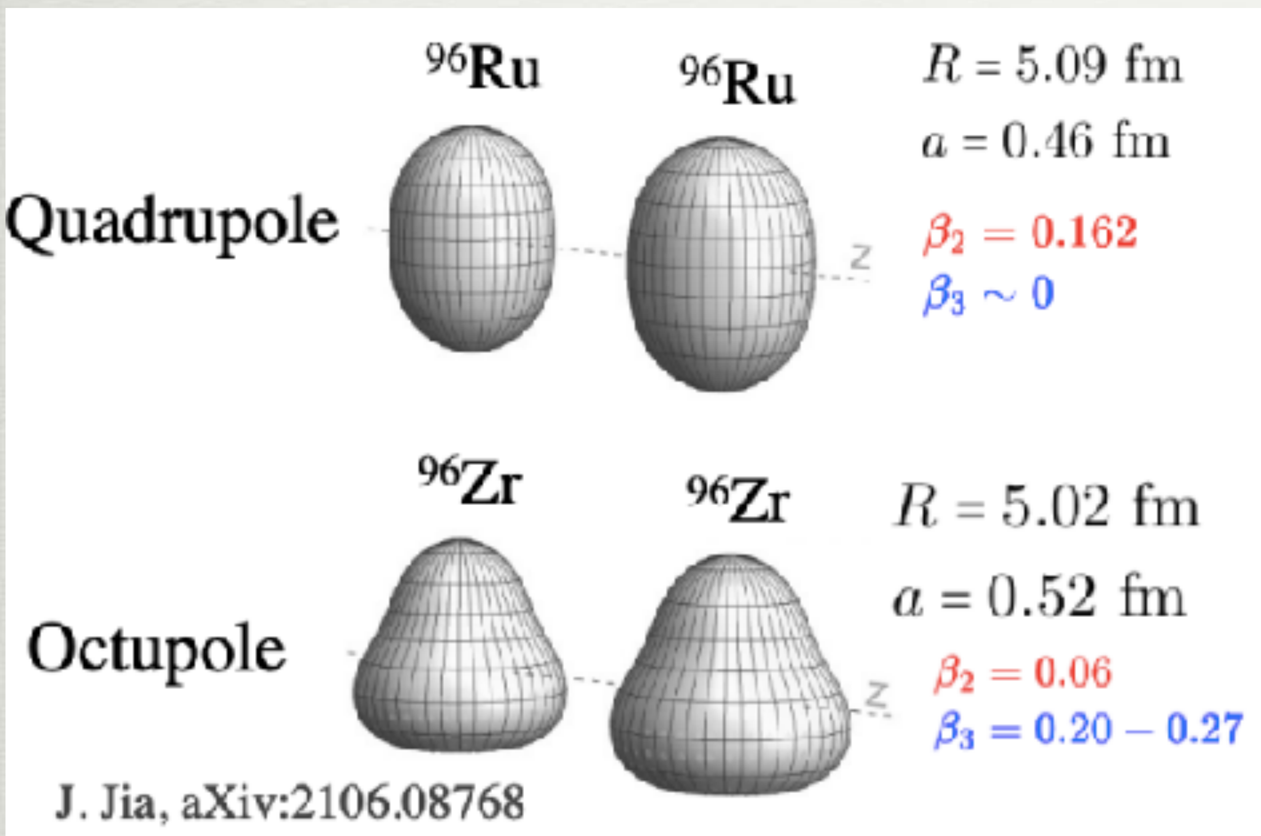


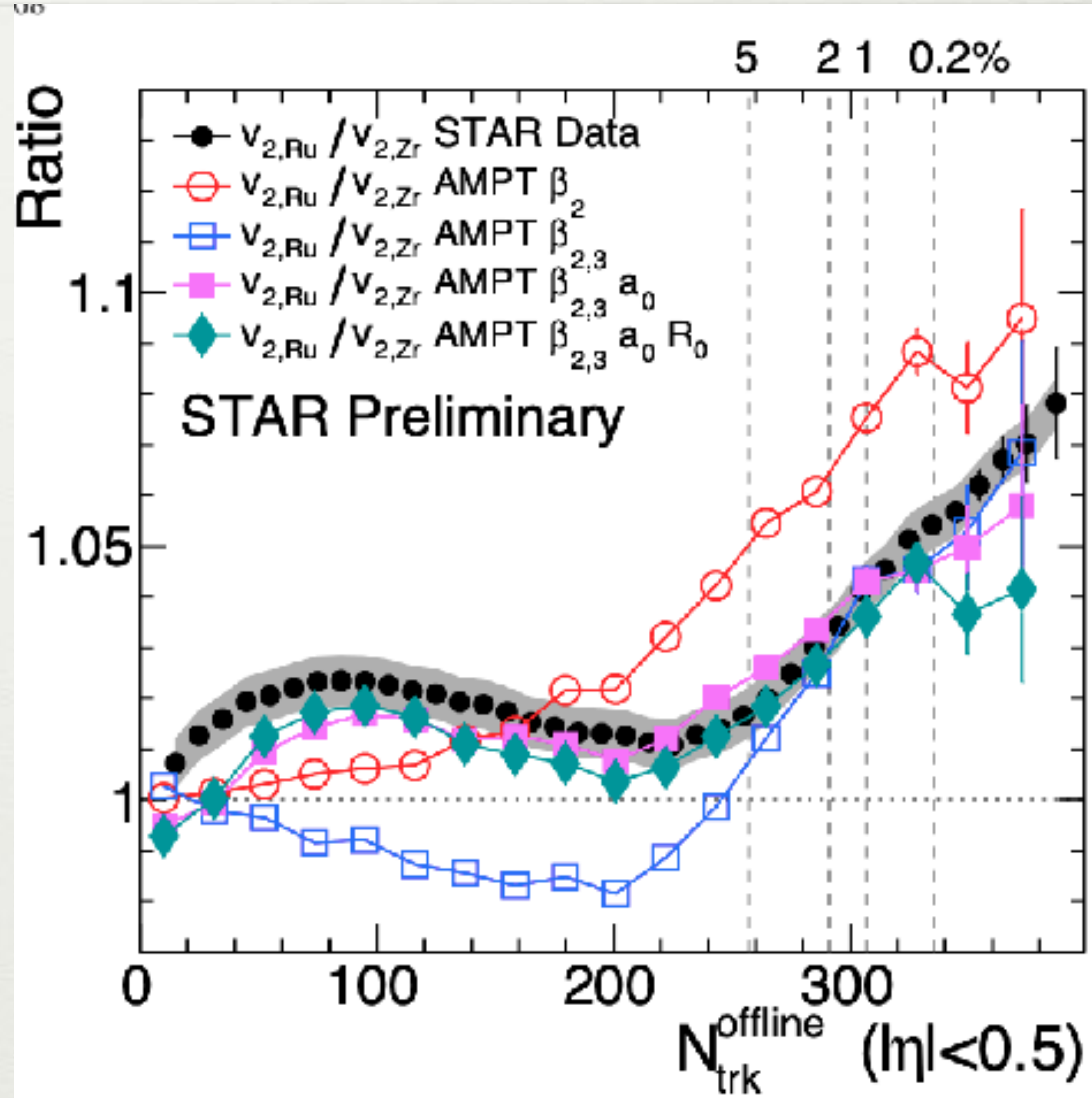
# Finding a deformation in $^{129}Xe$




Deviation from experimental data: possible constraints on nuclear structure?

# Isobar ($^{96}Zr$ & $^{96}Ru$) run at RHIC



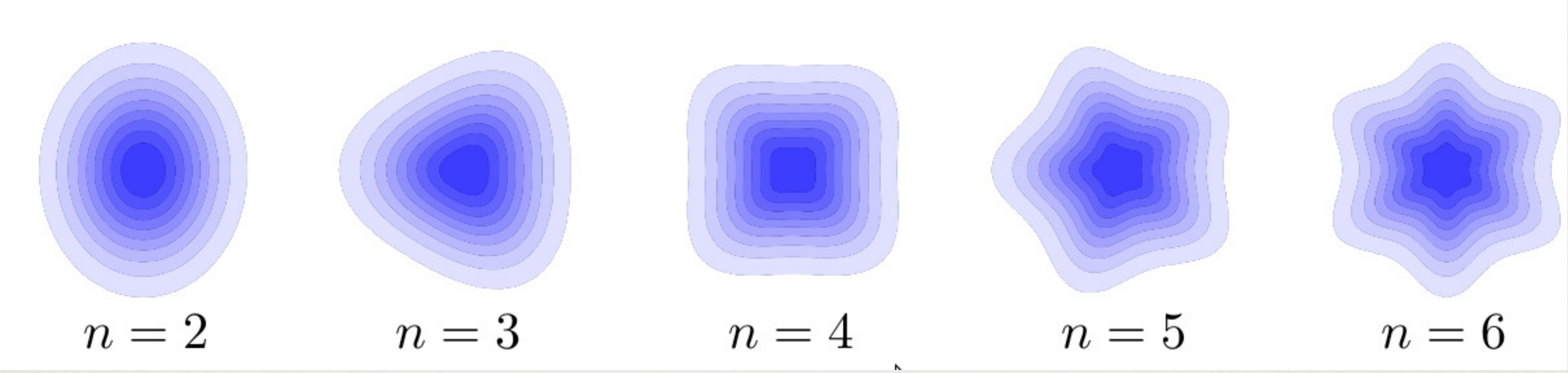




See work from: Guiliano Giacalone, Jiangyong Jia, Anthony Timmins, Wojciech Broniowski, Jean-Yves Ollitrault, Bjoern Schenke, Chun Shen, Wei Li

# Quantifying flow

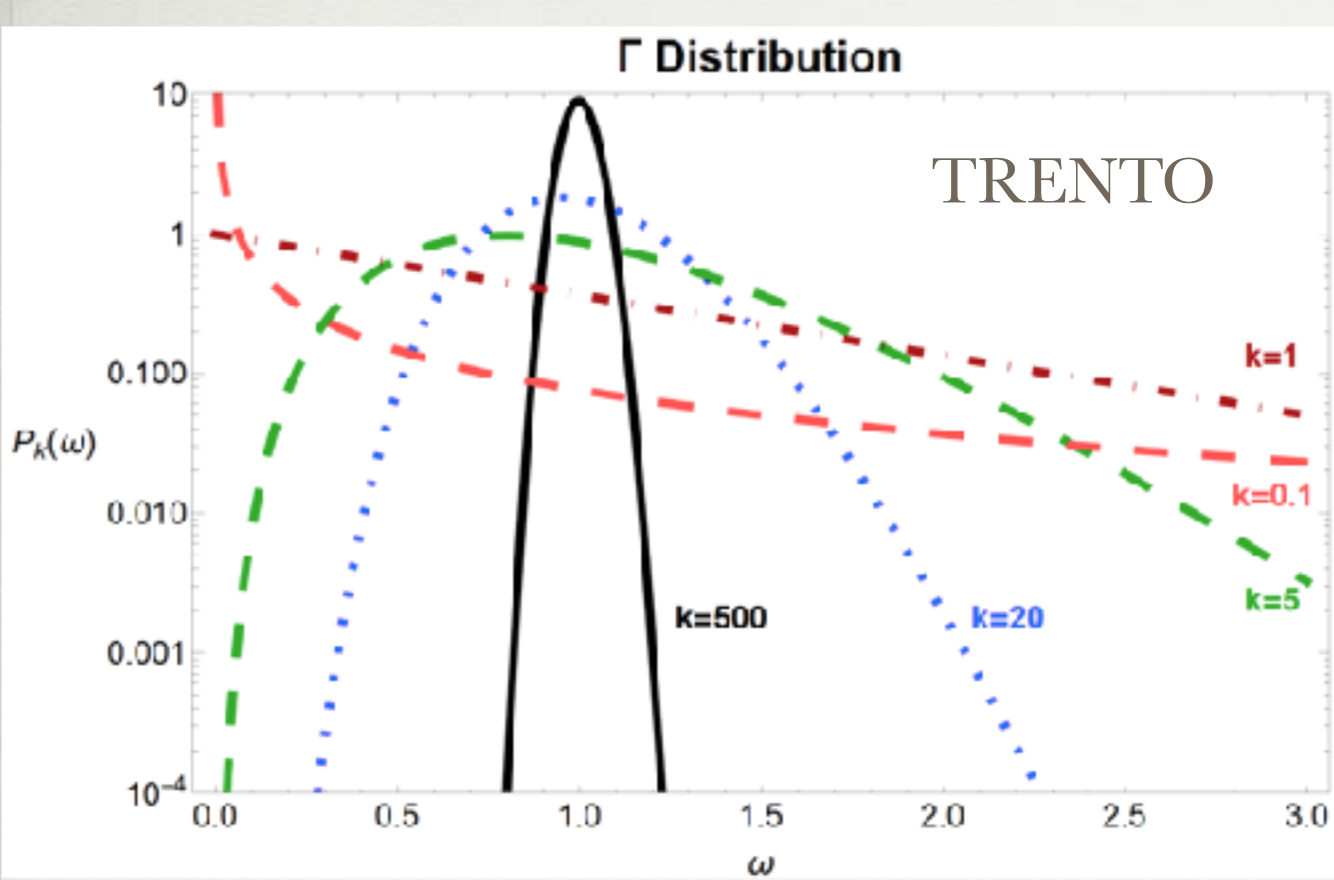
The distribution of particles can be written as a Fourier series

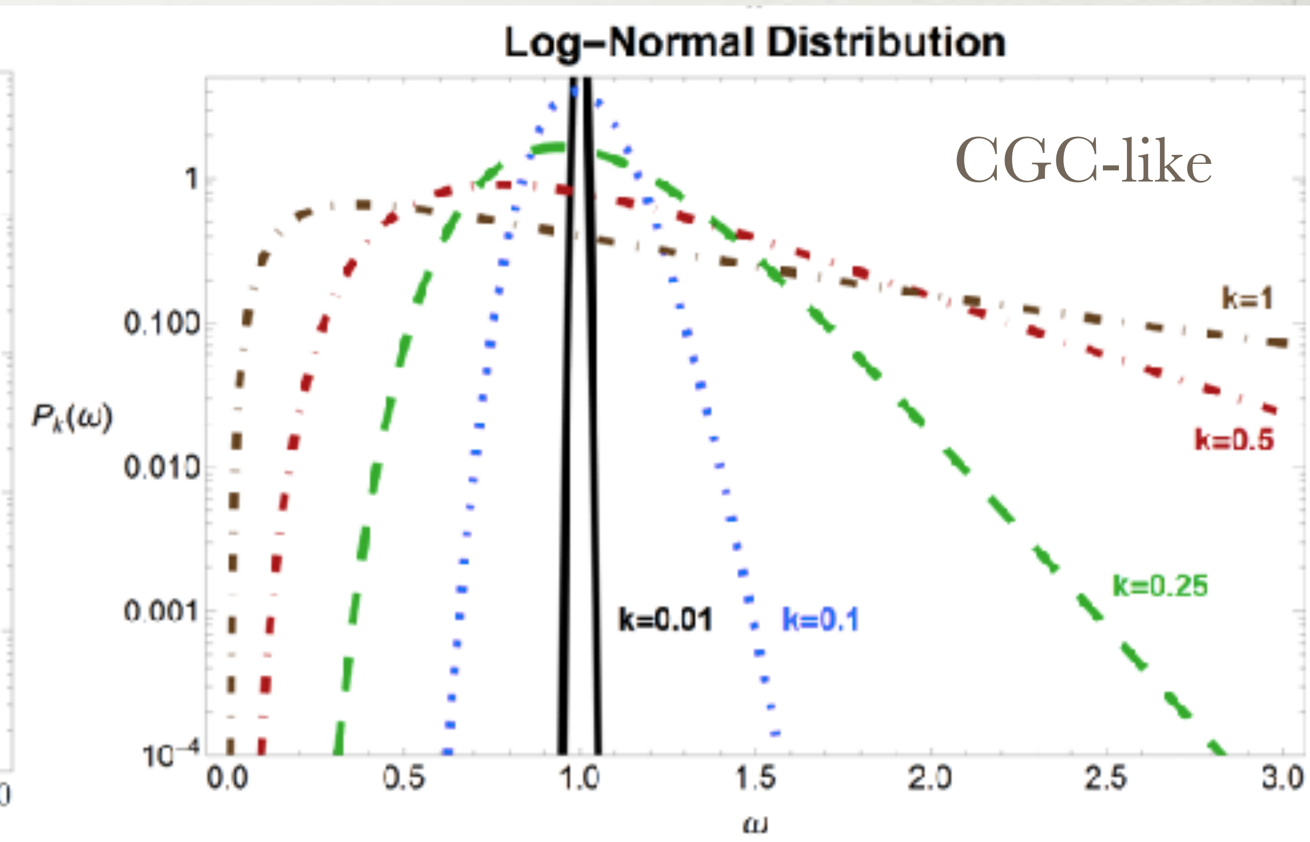
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$




**Collective flow**: Flow harmonics, $v_n\{m\}$, are calculated by correlating m=2 to 8 particles → collective behavior

# Multiplicity fluctuations

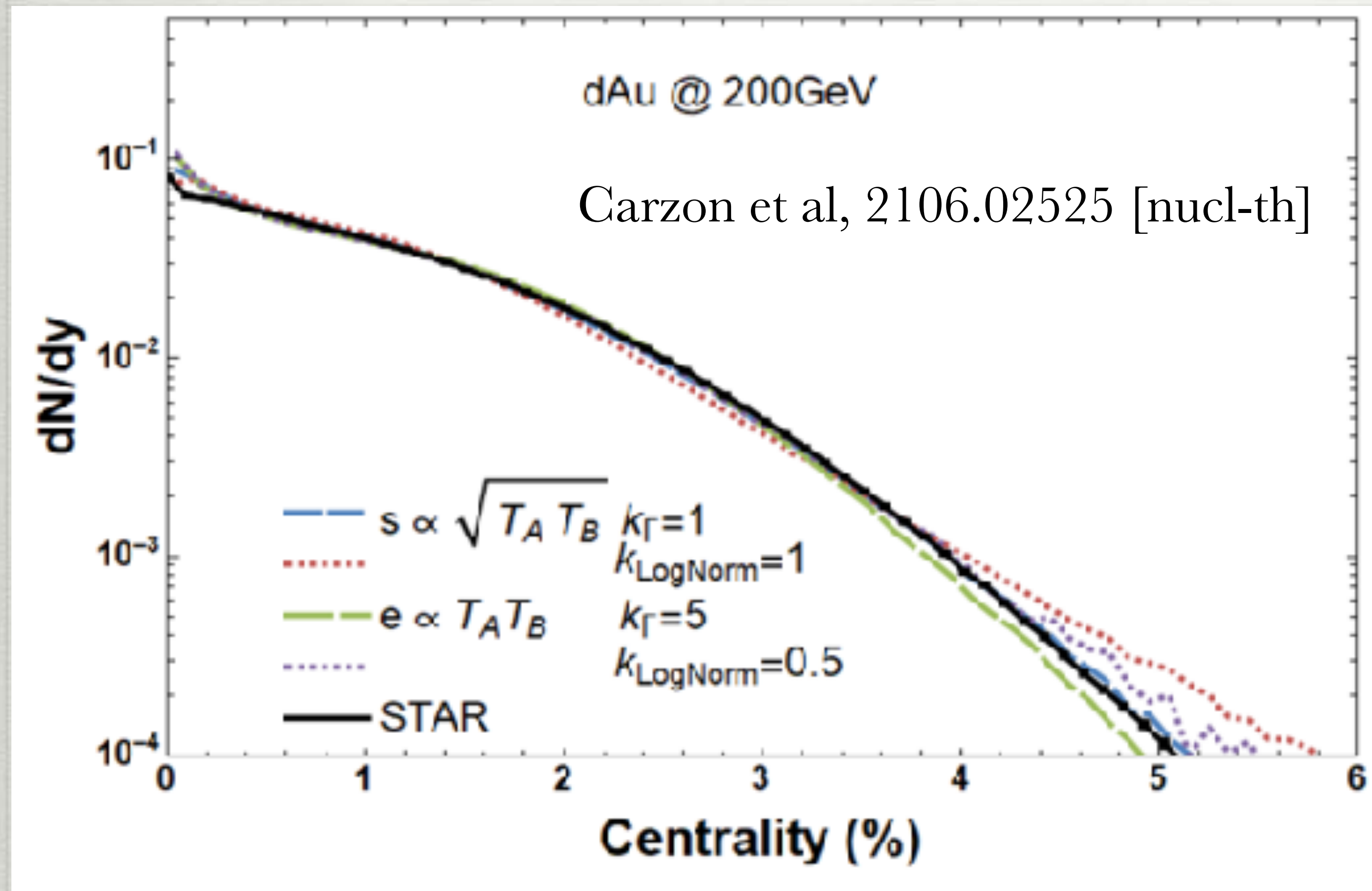


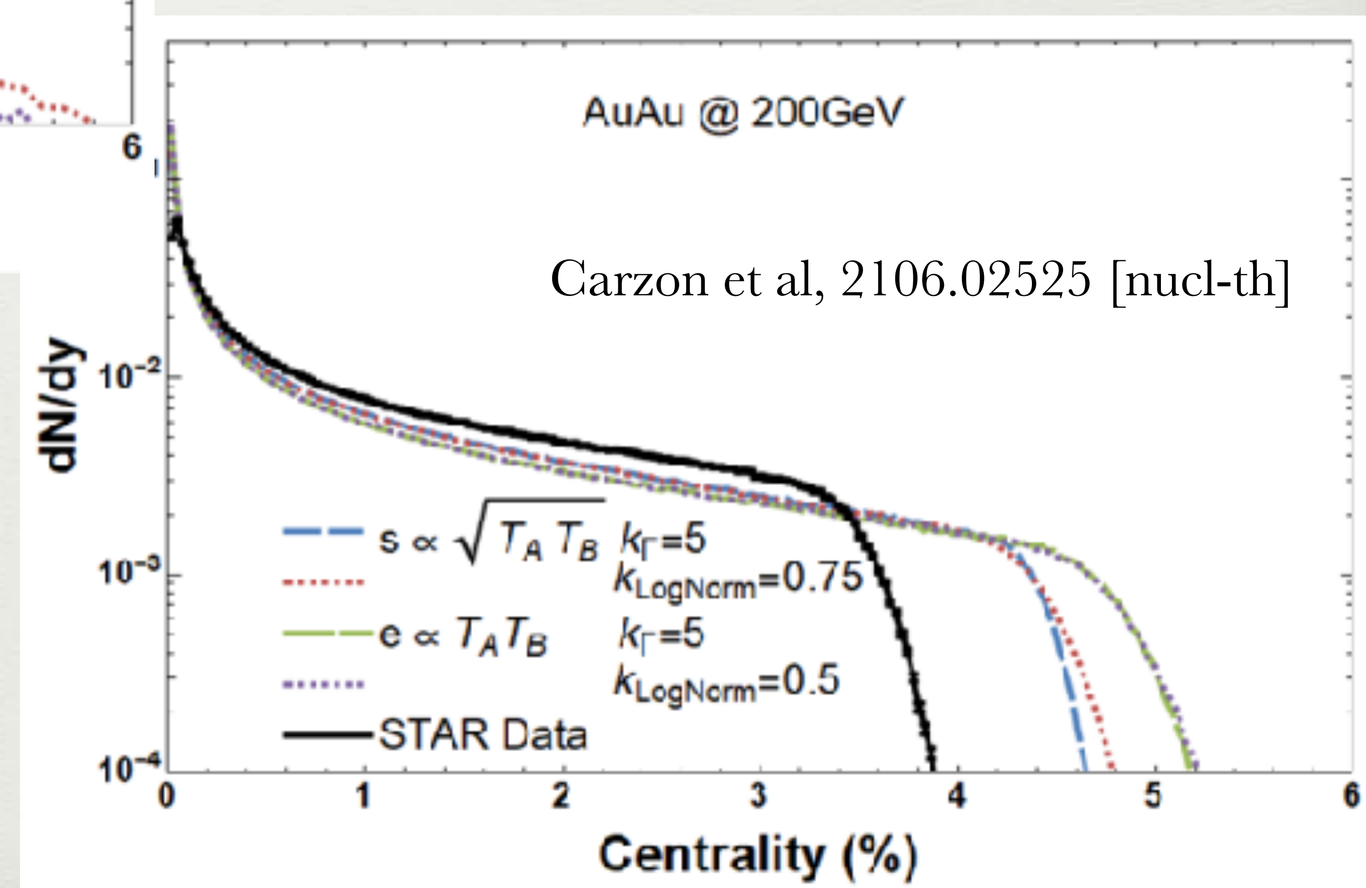

Carzon et al, 2106.02525 [nucl-th]

Current Bayesian analyses only considered Γ distribution.
Effects of Log-normal?

# Multiplicity fluctuations: small vs. large systems

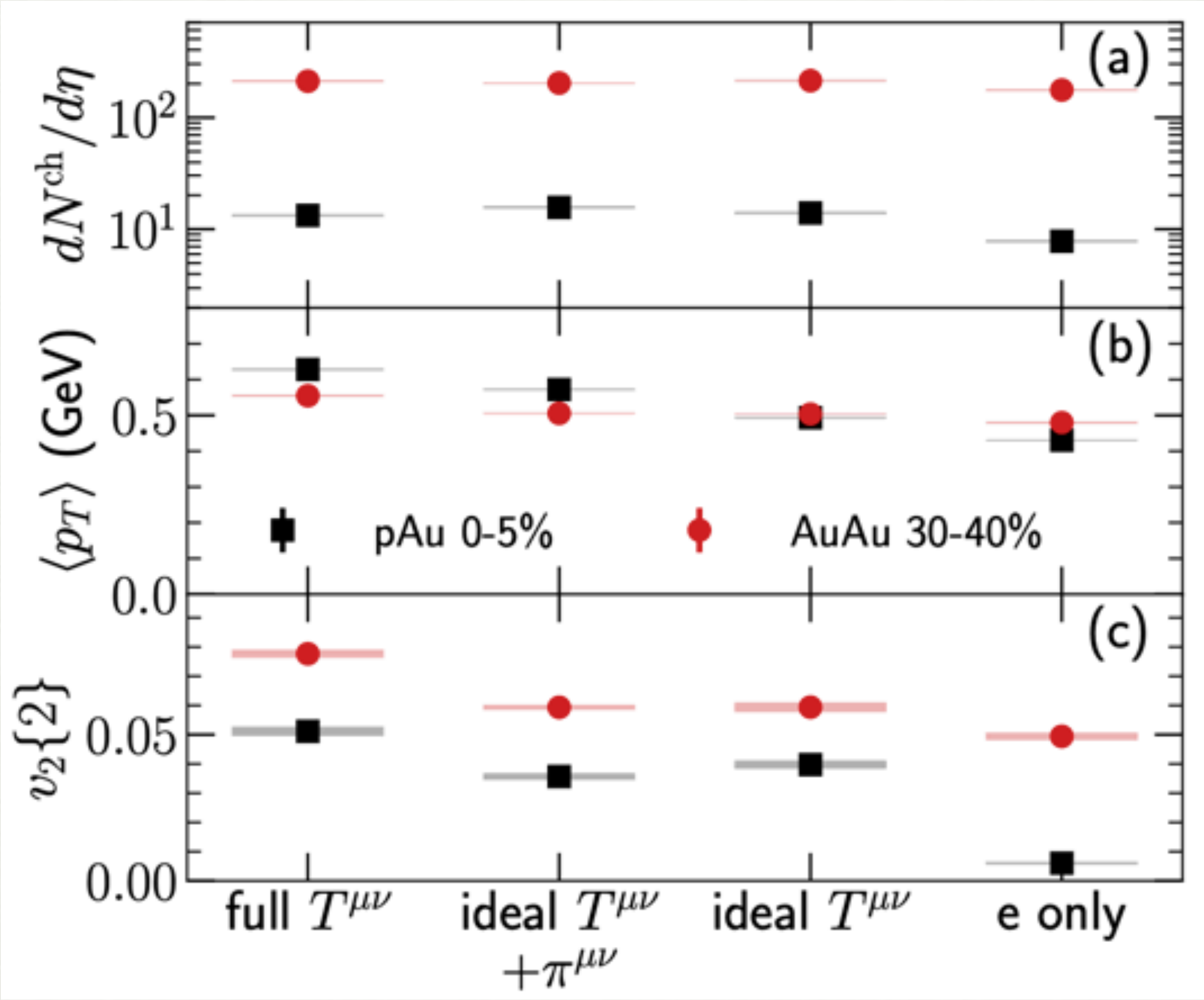



Small systems easier to fit



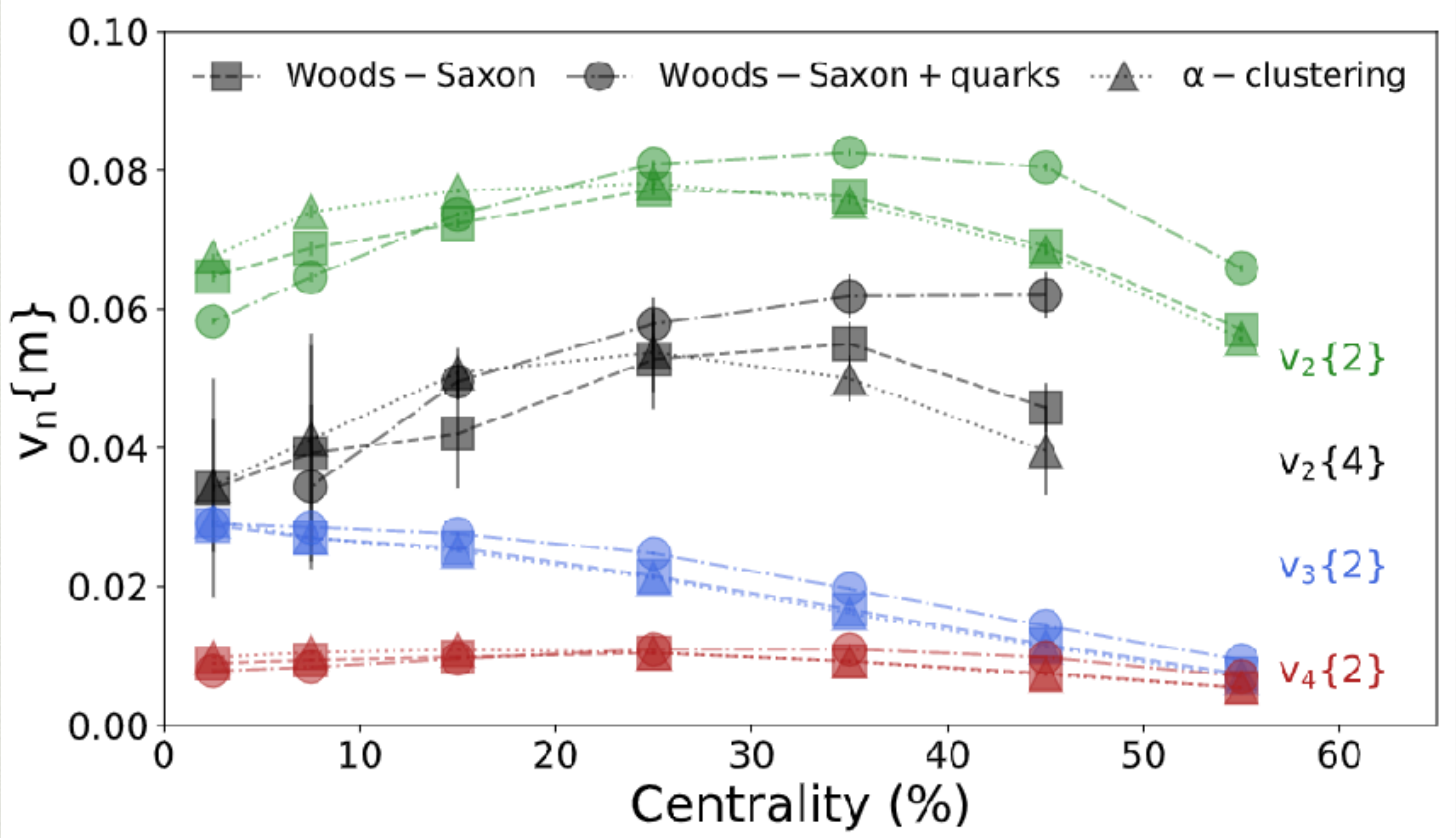

Large systems miss the data

# 3+1D Simulations: full $T^{\mu\nu}$ small effect



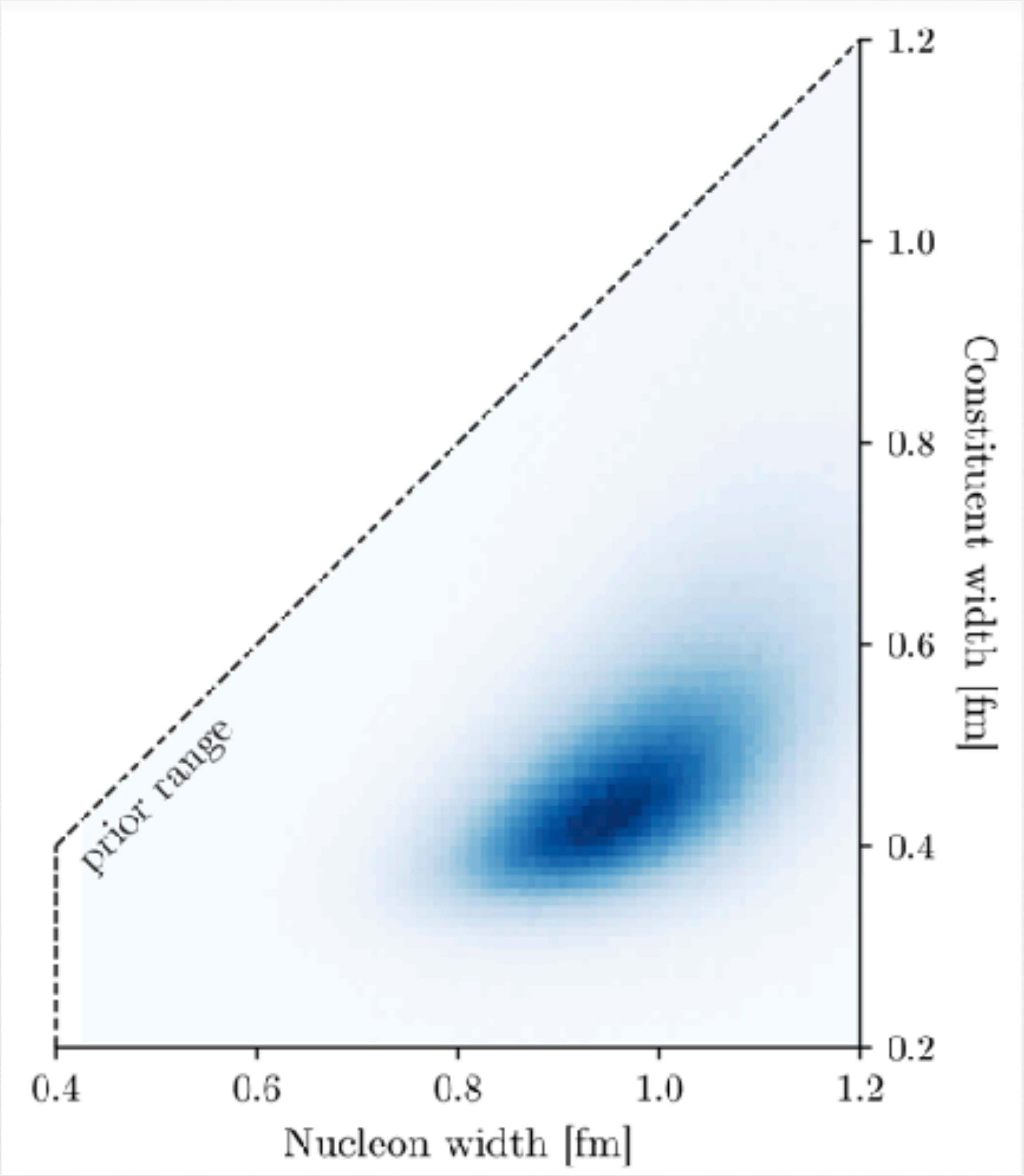

Schenke et al, *Phys.Lett.B* 803 (2020) 135322

# $^{16}O$: Lattice effective field theory and hydrodynamics




Summerfield, et al, Phys.Rev.C 104 (2021) 4, L041901

# Bayesian Analysis: nucleon width

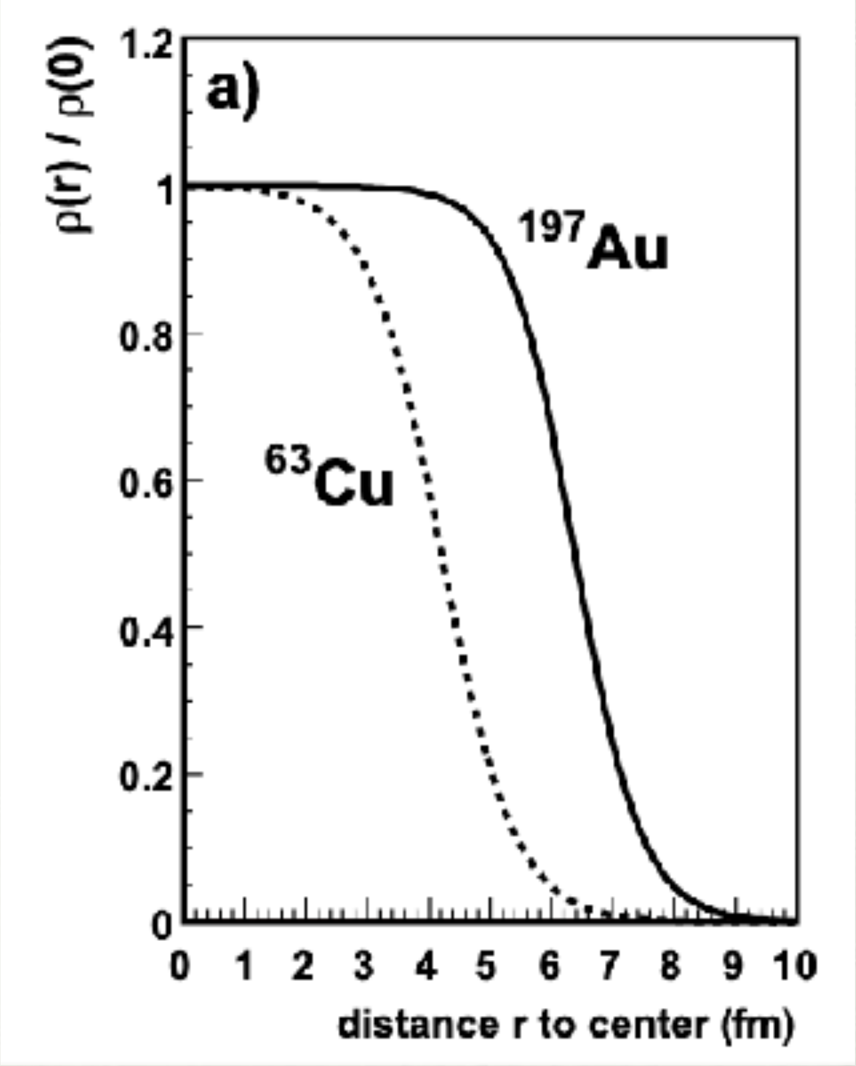



Moreland et al, *Phys.Rev.C* 101 (2020) 2, 024911

# **Initial conditions**: Nuclear structure

Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243

Initial conditions typically sample over a density distribution ( Wood-Saxon)




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

For deformed nuclei, the deformations considered via

$$R(\theta) = R_0\Big(1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta) + \ldots\Big)$$

Even Better: Nucleon configurations from lattice effective field theory