Imprints of nucleon structure in high-energy nuclear collisions

by

GIULIANO GIACALONE

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Follow-up of: Giacalone, Schenke, Shen, Phys. Rev. Lett. 128 (2022) 4, 042301

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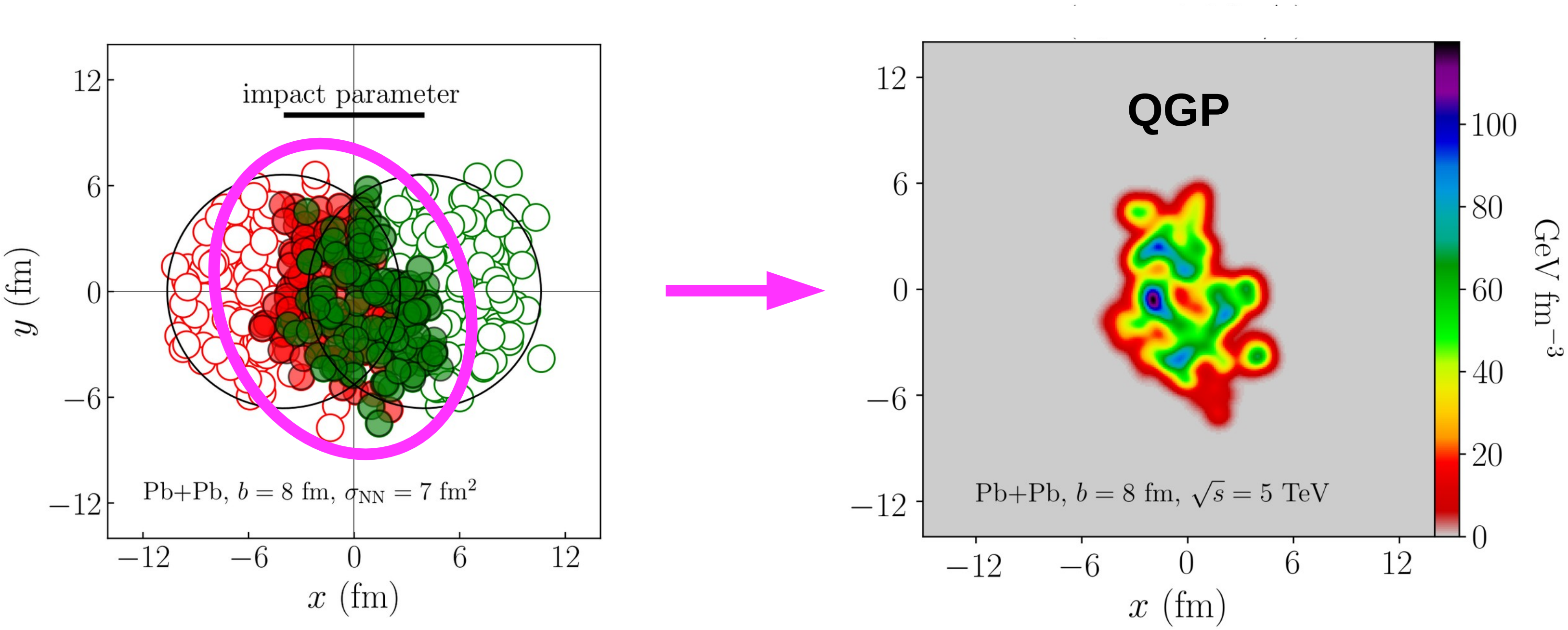
OUTLINE

- 1. Primordial fluctuations in the Little Bang.
- 2. Nucleon structure in heavy-ion collisions: Historical overview.
- 3. Observables for a consistent picture.
- 4. Consequences/prospects.
- Conclusion.

1.

Primordial fluctuations in the Little Bang

Heavy-ion collisions: Reproducing the early Universe in the lab.



Effective description: relativistic fluid. [Romatschke & Romatschke, 1712.05815]

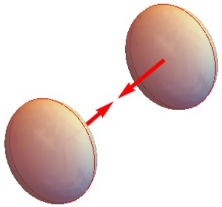
$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ + small viscous corrections ($\eta/s, \zeta/s$, ...) **+** $\partial_\mu T^{\mu\nu} = 0$

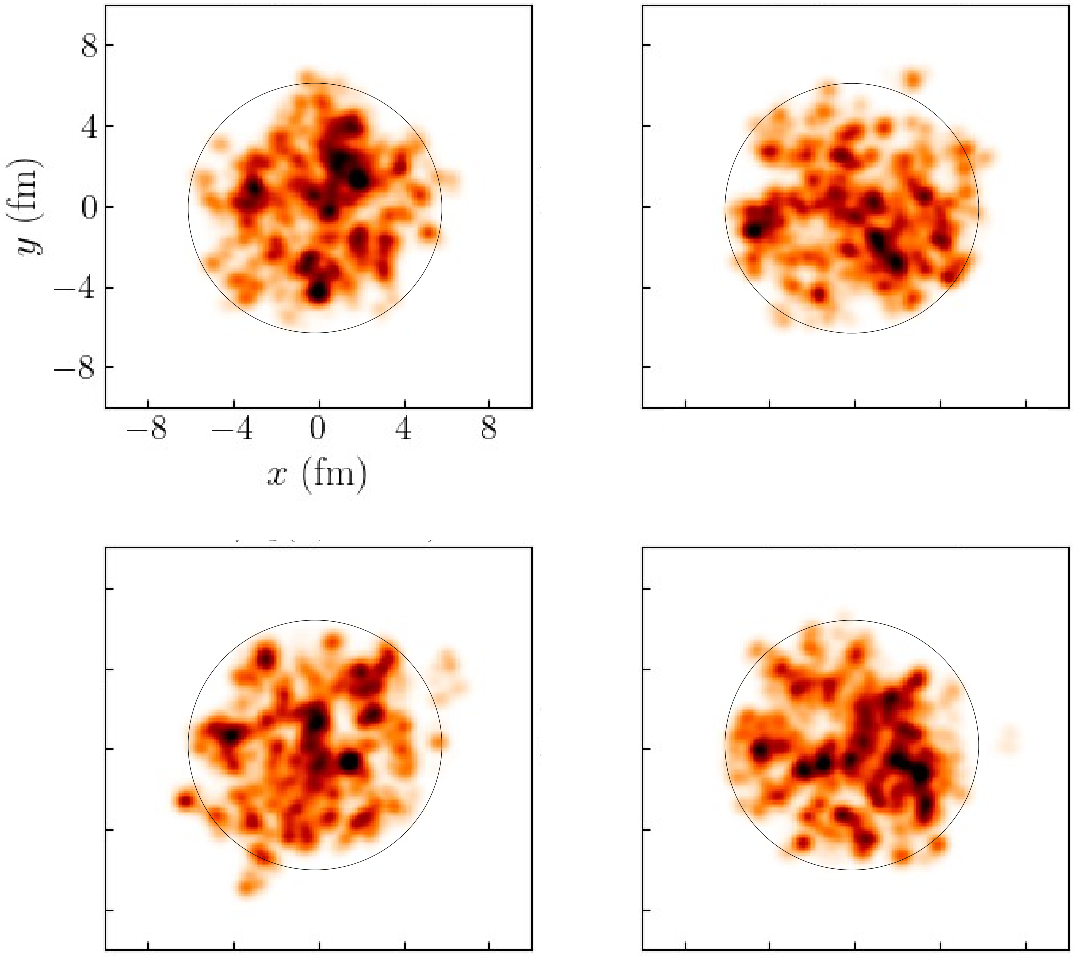
EOS from lattice QCD (T > 156 MeV, μ_B=0). Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

Primordial energy density fluctuations on all scales.

Four ^{129}Xe+^{129}Xe collisions at b=0.





Fluctuations in the interaction region:

- nuclear scales (size ~ R_A)
- nucleon scales (size ~ 1 fm)
- sub-nucleon scales (size ~< 0.5 fm)

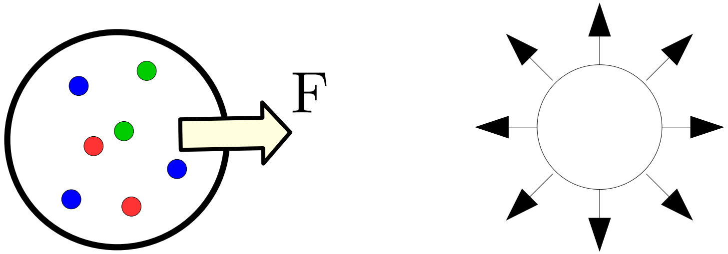
Mapping of initial-state geometry to final-state observables.

Shape-flow transmutation via pressure-gradient force.

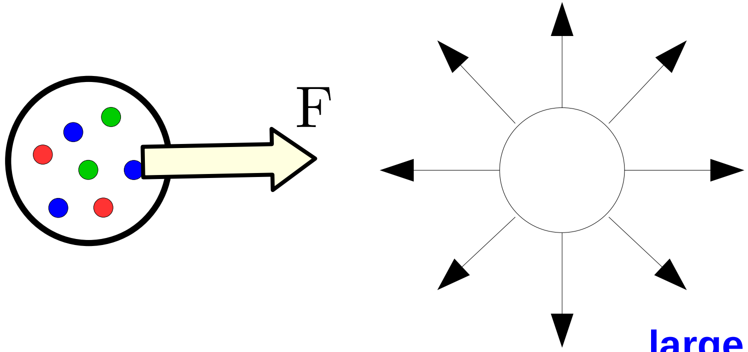
$$F = -\nabla P$$

v_n = Fourier coefficient of emission in n^{th} harmonic

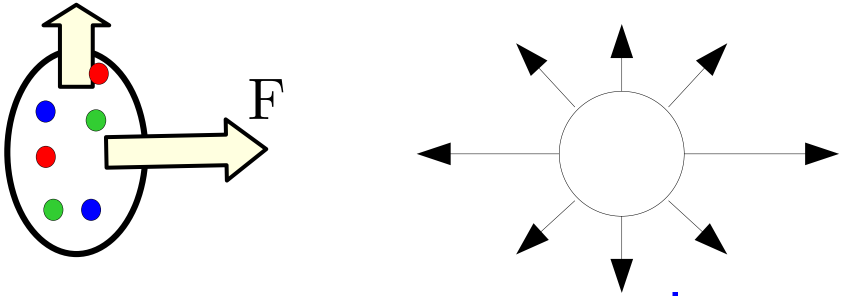
initial state (x) **final state (p)** **initial state (x)** **final state (p)**



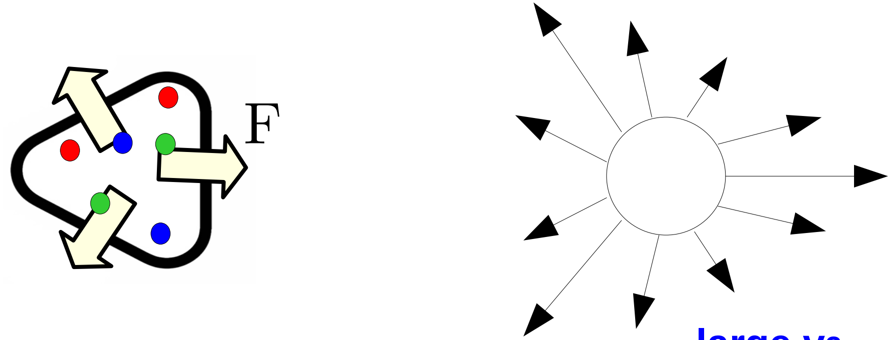
small <p>



large <p>

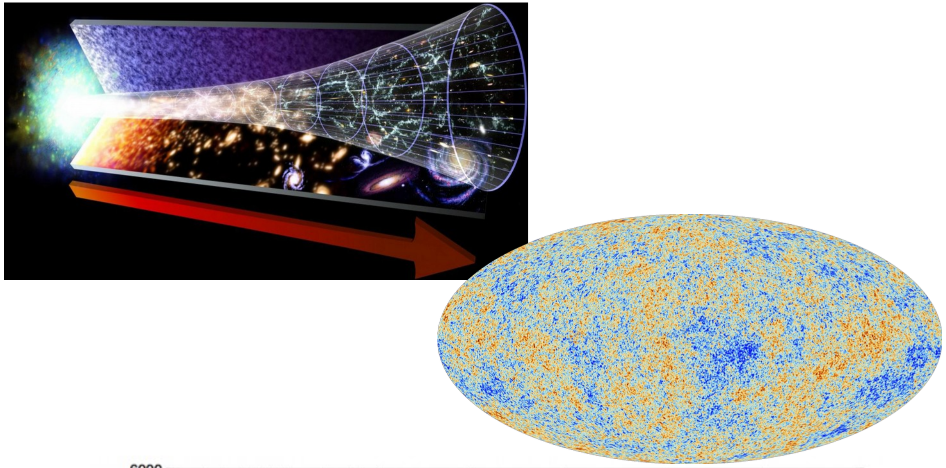


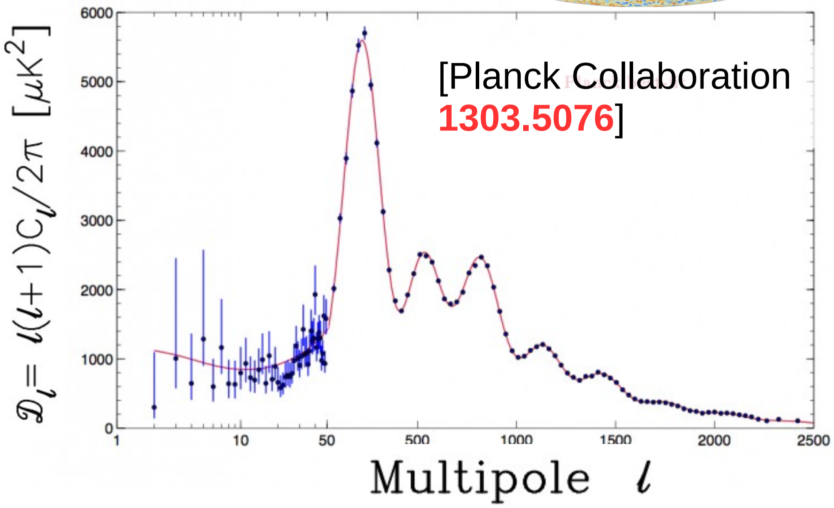
large v_2



large v_3

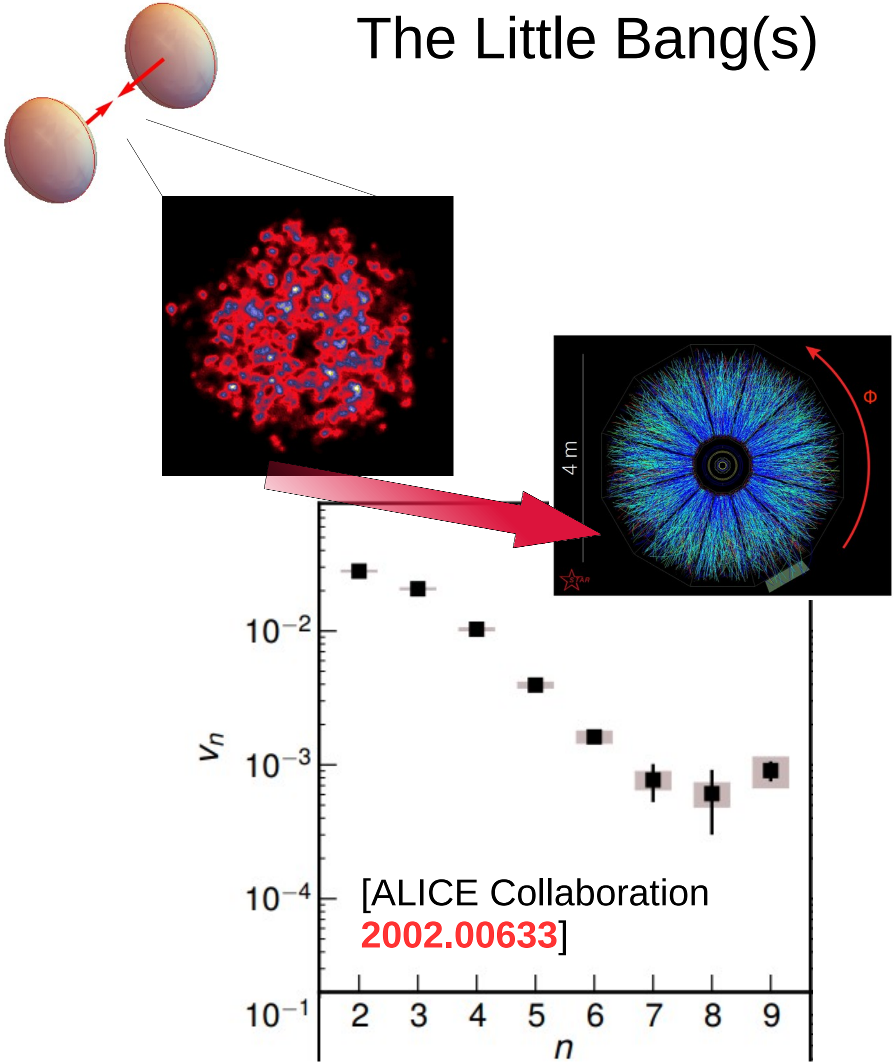
The Big Bang





[Planck Collaboration **1303.5076**]

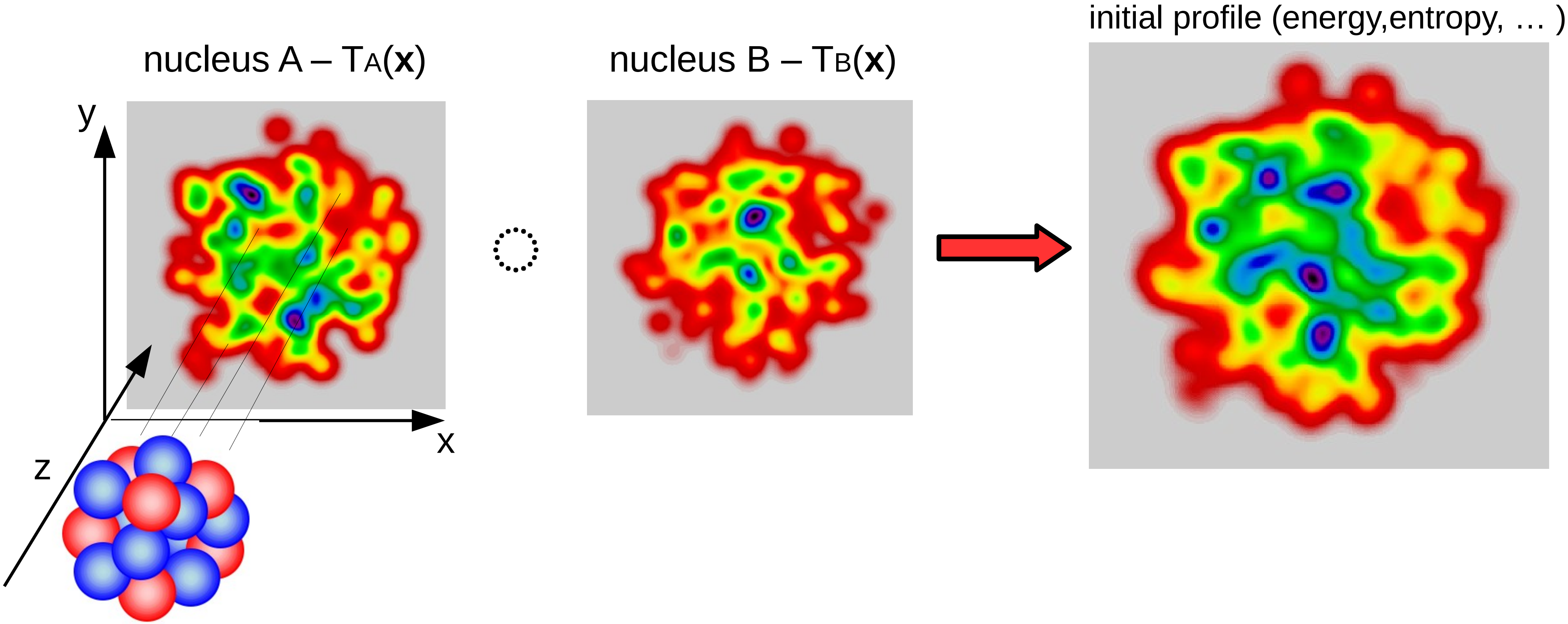
The Little Bang(s)



[ALICE Collaboration **2002.00633**]

Origin of primordial fluctuations?

Encoded in the colliding ions.



nucleus A – $T_A(\mathbf{x})$

nucleus B – $T_B(\mathbf{x})$

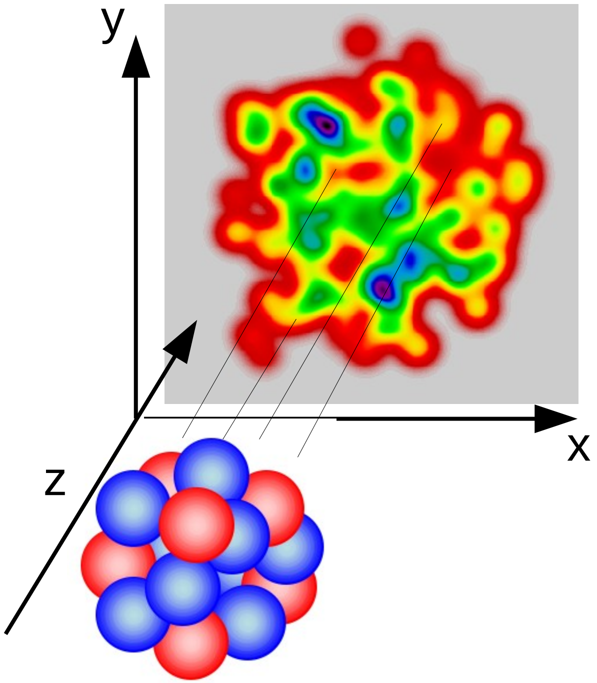
initial profile (energy,entropy, …)

◌ = some operation

Origin of primordial fluctuations?

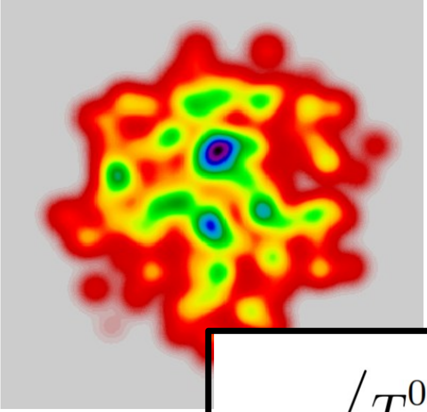
Encoded in the colliding ions.

nucleus A – $T_A(\mathbf{x})$

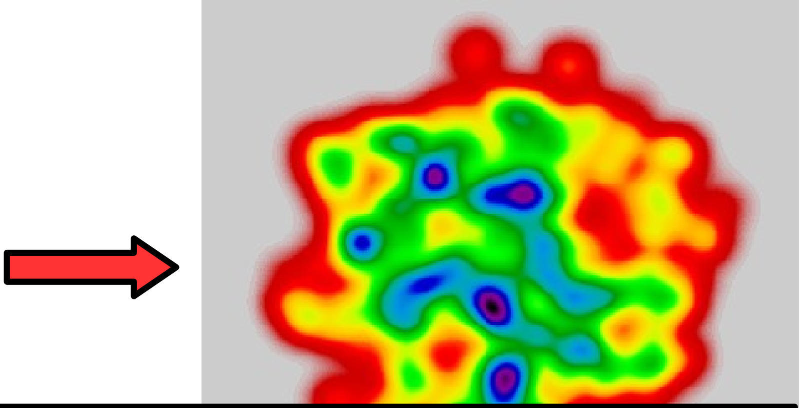


◌

nucleus B – $T_B(\mathbf{x})$



initial profile (energy,entropy, …)



◌ = some operation

$$\left\langle T^{00}(\mathbf{x},\tau=0^+)\right\rangle \propto \Big(T_A(\mathbf{x})T_B(\mathbf{x})\Big)^q$$

q=1 → prediction of the color glass condensate (CGC).

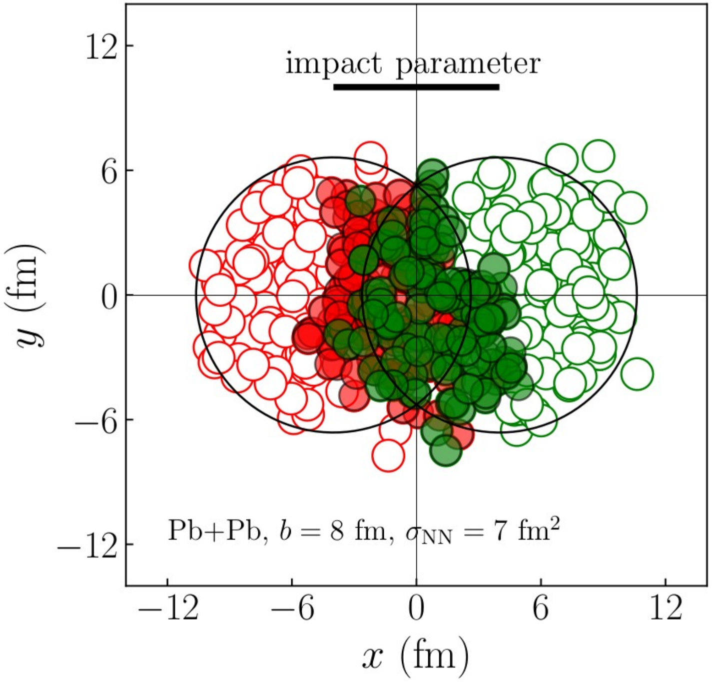
[Lappi hep-ph/0606207]

q=1/2 → Only TRENTo parametrization of the form $T_A{*}T_B$. Strongly favored by Bayesian analyses.

[Bass, Bernhard, Moreland 1412.4708, 1605.03954, Nature Phys. 15 (2019)]

Inner structure of the colliding objects.

Starting point: Glauber Monte Carlo approach.

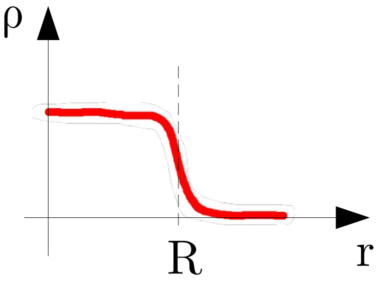


Independent nucleons in Woods-Saxon profile (ground state).

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

half-width radius

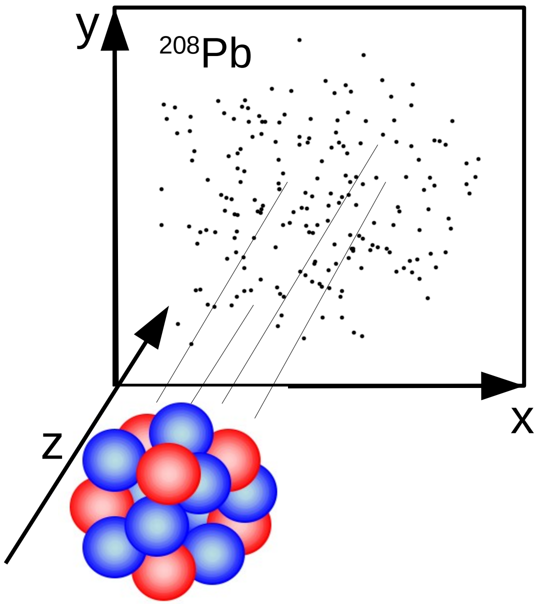
diffusivity



Spherical approximation can be relaxed.

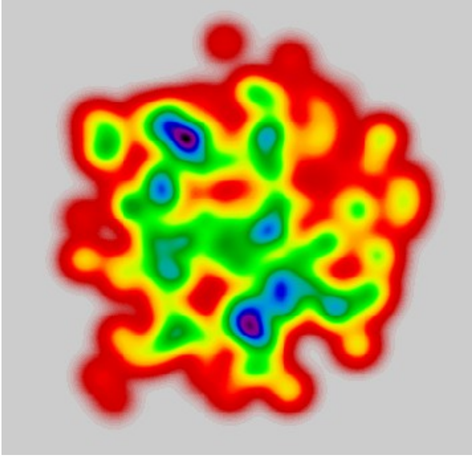
[Miller, Reygers, Sanders, Steinberg, nucl-ex/0701025]

Nuclear structure only gives us the coordinates of point-like nucleons. We need an extra step.



boosted ion

nucleus A – $T_A(\mathbf{x})$



HOW?
The standard prescription:

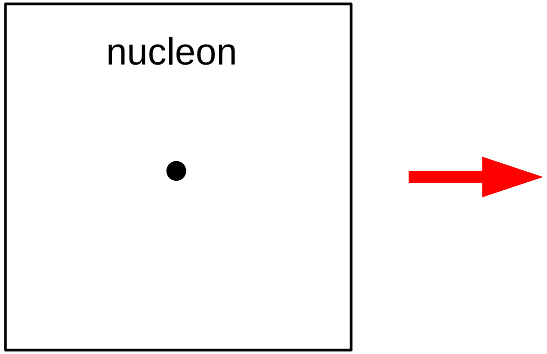
$$t_A(x) = \sum_j \lambda_j g(x; x_j, w)$$

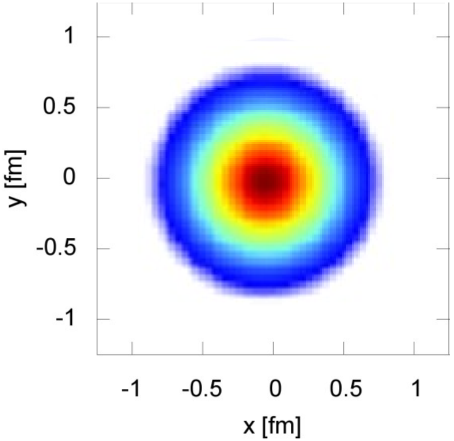
jth nucleon

random normalization (Q_s fluctuation)

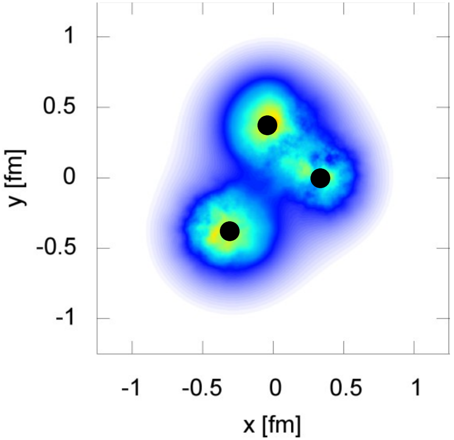
Gaussian of width *w*

One way or another, the structure of nucleons must be implemented.





OR



Effective (emergent?) description:

- **nucleon size.**
- **number of constituents.**
- **size of the constituent.**

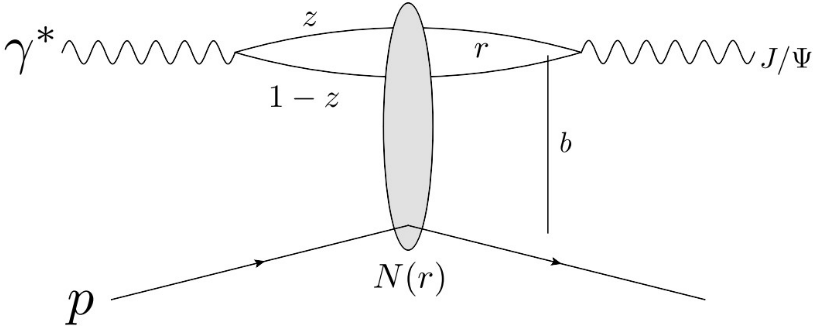
[Schenke 2102.11189]

2.

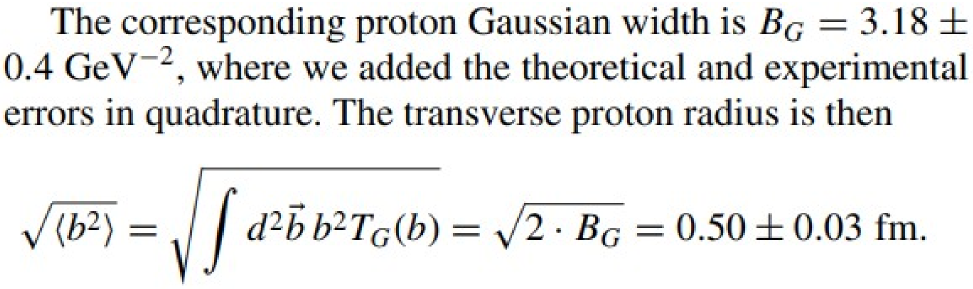
Nucleon structure in heavy-ion collisions: Historical overview

Relevant proton radius for e-p collisions inferred from diffractive J/ψ production.

$$\frac{d\sigma_{q\bar{q}}}{d^2b} \propto r^2\,\alpha_s(\mu^2)\,xg(x,\mu^2)\,T(b)$$



[Caldwell, Kowalsky, PRC ‘09]


The corresponding proton Gaussian width is $B_G = 3.18 \pm 0.4\ \text{GeV}^{-2}$, where we added the theoretical and experimental errors in quadrature. The transverse proton radius is then

$$\sqrt{\langle b^2\rangle} = \sqrt{\int d^2\vec{b}\, b^2 T_G(b)} = \sqrt{2\cdot B_G} = 0.50 \pm 0.03\ \text{fm}.$$

→ 0.5 fm /sqrt(2) ~ 0.35 fm

Took as input for original IP-Glasma implementation.

[Schenke, Tribedy, Venugopalan, 1202.6646, 1206.6805]

2016 – First Bayesian analysis of Duke group.

[Bass, Bernhard, Moreland, 1605.03954]

Fit of Pb-Pb data.

$$\boxed{\frac{dS}{dy} \propto (T_A T_B)^{1/2}}$$

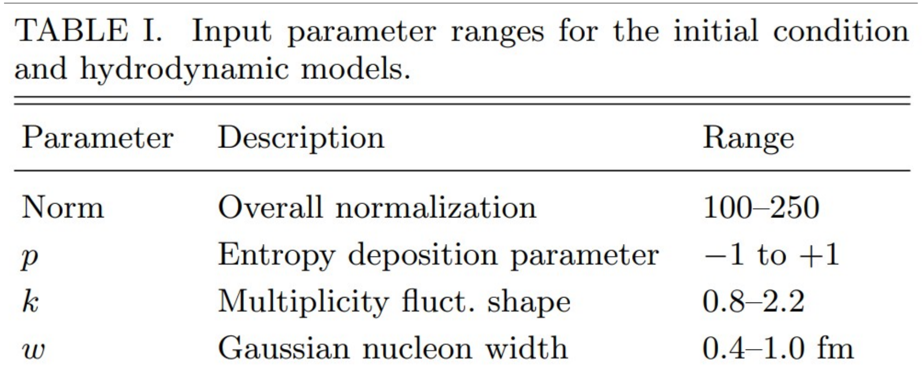
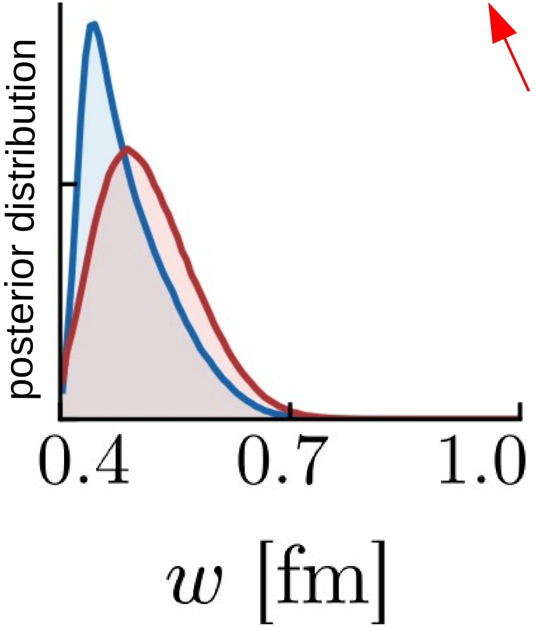
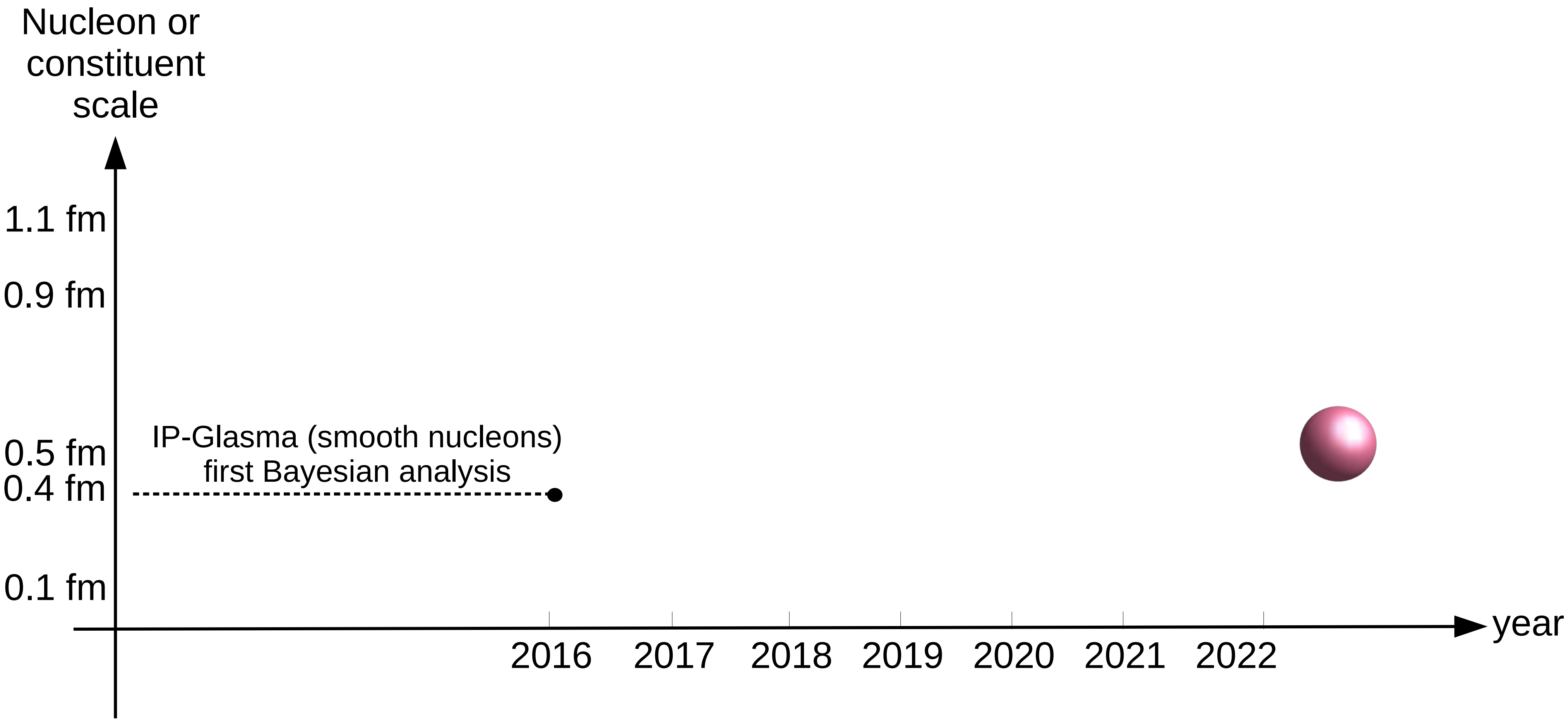


TABLE I. Input parameter ranges for the initial condition and hydrodynamic models.

Parameter	Description	Range
Norm	Overall normalization	100–250
p	Entropy deposition parameter	-1 to $+1$
k	Multiplicity fluct. shape	0.8–2.2
w	Gaussian nucleon width	0.4–1.0 fm



Width of 0.45 fm from A-A data only!

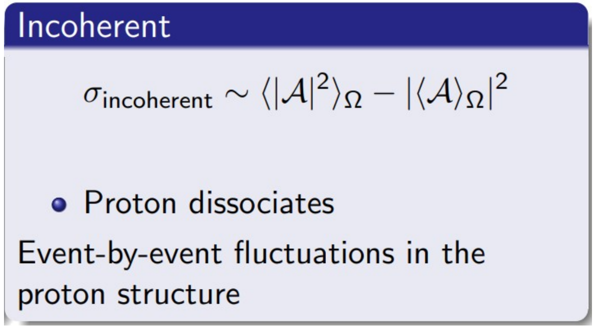


IP-Glasma (smooth nucleons)
first Bayesian analysis

Flow is observed in small systems. IP-Glasma requires nucleon structure.

[Schenke, Venugopalan **1405.3605**]

Constraints from J/ψ photoproduction at HERA (incoherent diffraction).



Incoherent

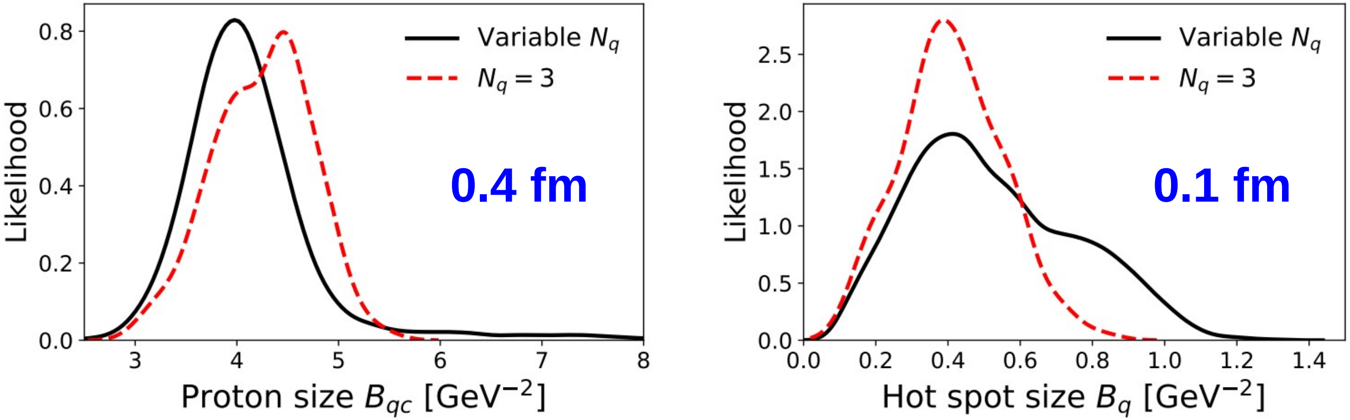
$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

- Proton dissociates

Event-by-event fluctuations in the proton structure

[Mäntysaari, Schenke **1603.04349**, **1607.01711**]

Bayesian inference. Sizes well constrained. Constituent number poorly constrained.



[Mäntysaari, Schenke,
Shen, Zhao **2203.05846**]

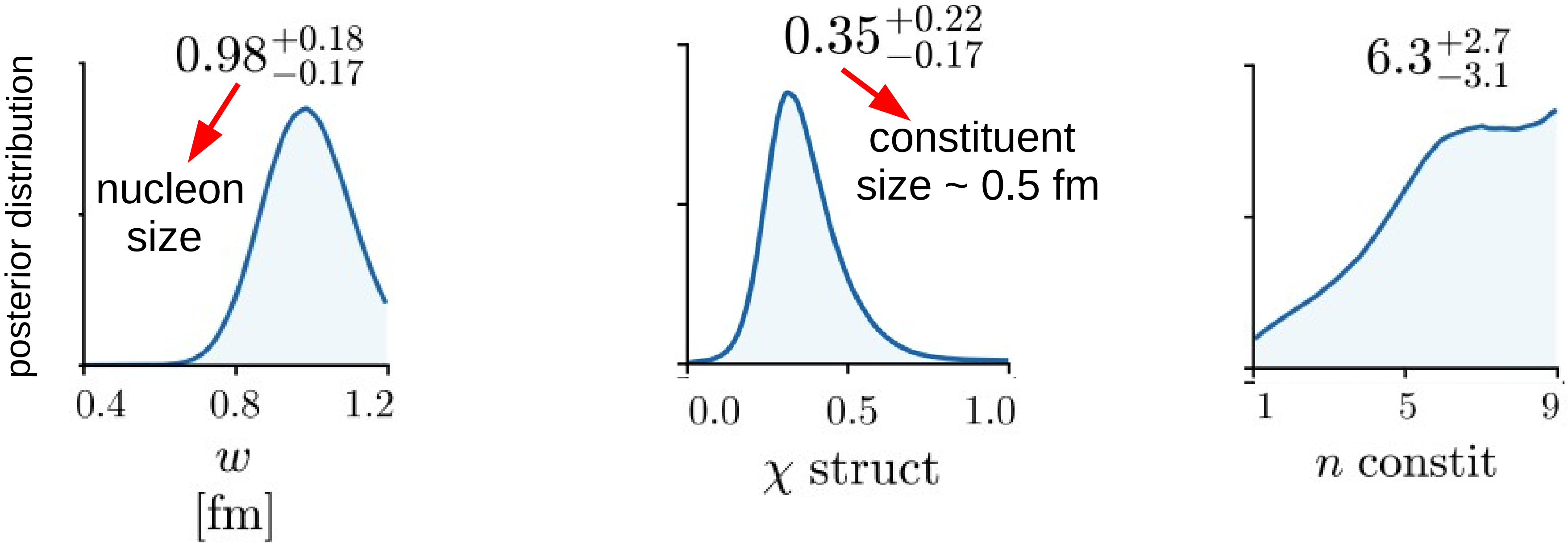
Similar conclusion reached in the TRENTo model or other codes for small systems.

[see e.g. Zhao, Zhou, Murase, Song, 2001.06742]

Constraining substructure: combined fit of p-A and A-A data.

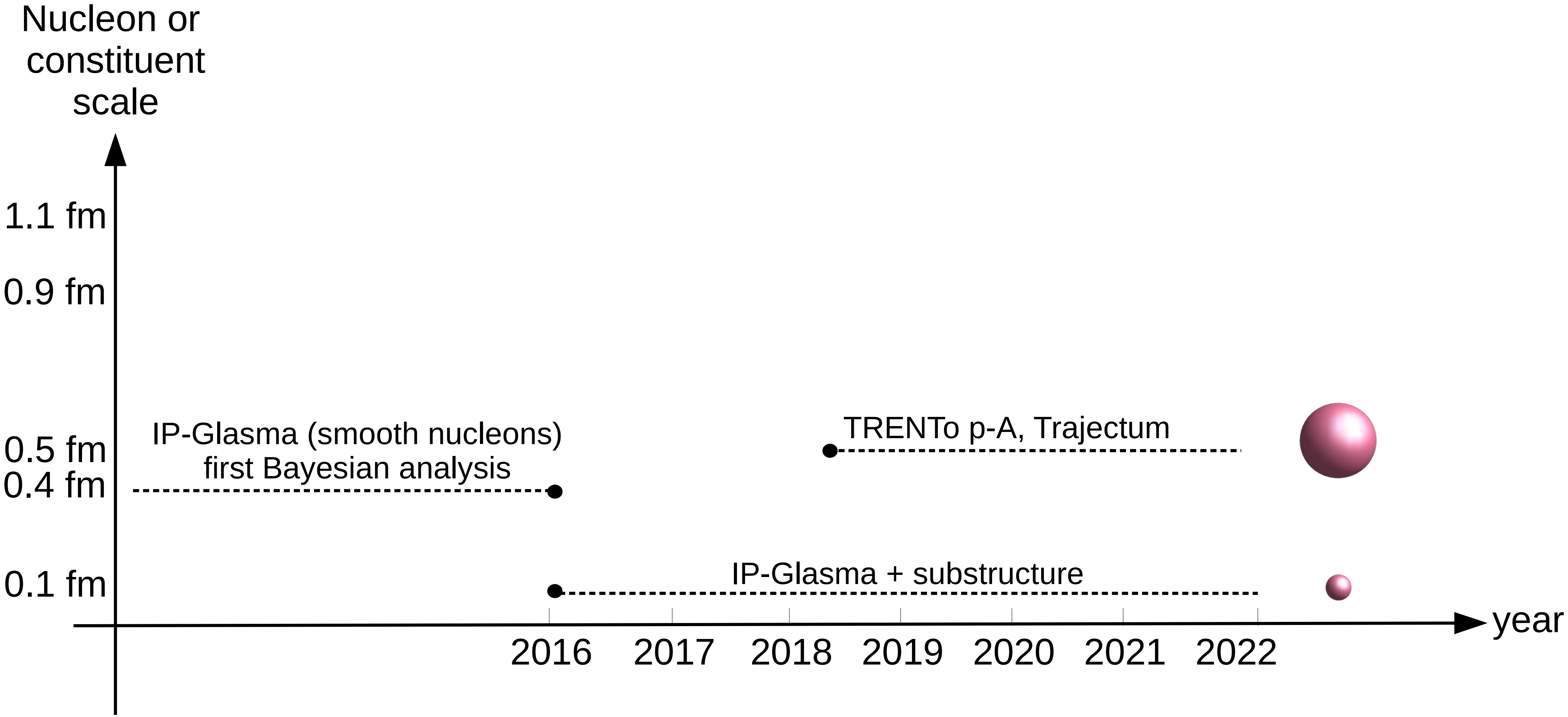
[Bass, Bernhard, Moreland **1808.02106**]
[Nijs, van der Schee, Gürsoy, Snellings **2010.15130**, **2010.15134**]

Once again, no strong constraint on constituent number.



nucleon size

constituent size ~ 0.5 fm


Nucleon or constituent scale
1.1 fm
0.9 fm
0.5 fm
0.4 fm
0.1 fm
IP-Glasma (smooth nucleons)
first Bayesian analysis
TRENTo p-A, Trajectum
IP-Glasma + substructure
2016
2017
2018
2019
2020
2021
2022
year

2019 – New Pb-Pb-only analyses with more observables and parameters.

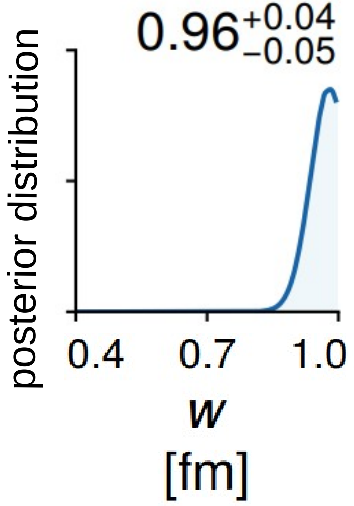
Unexpected results!

NB: TRENTo model now used for the energy.

prior range is always [0.4-1.0 fm]

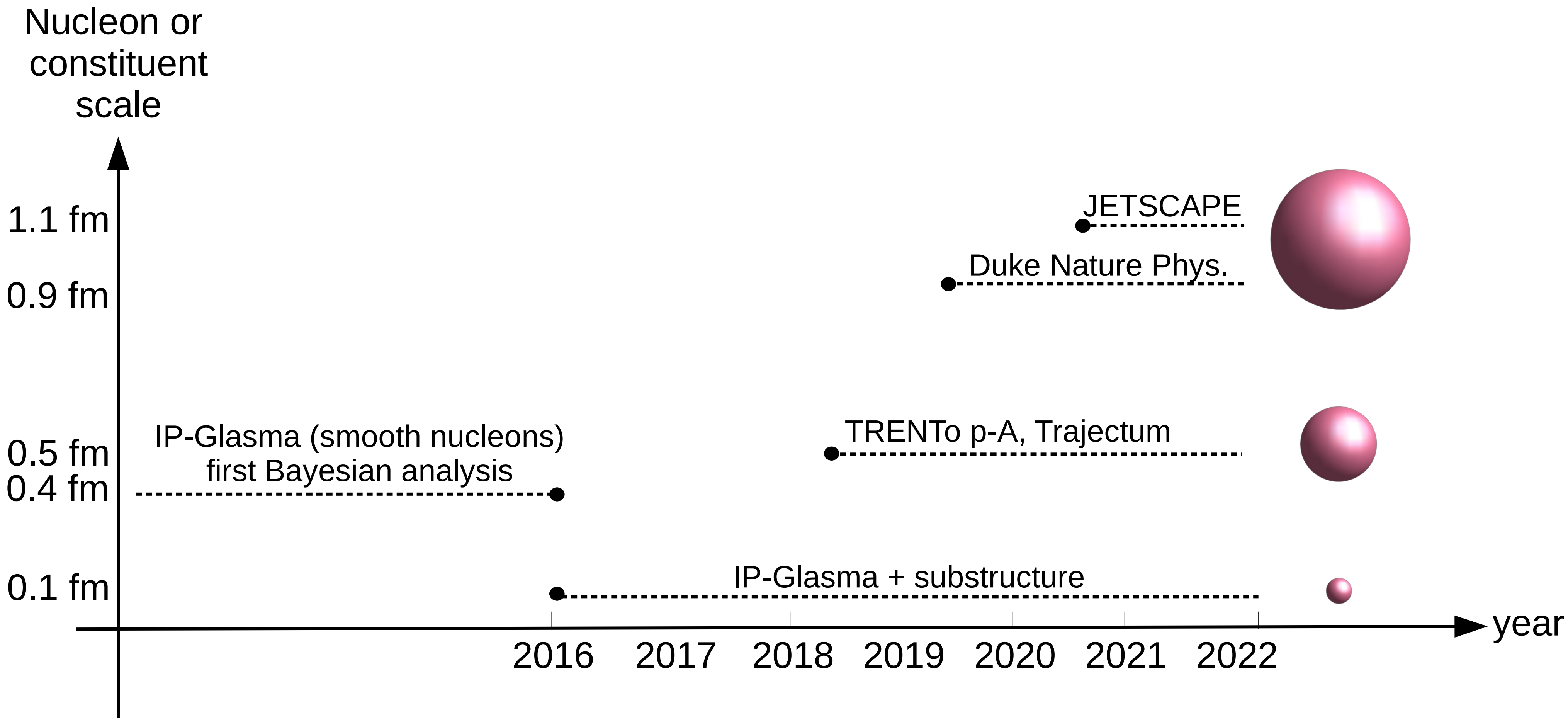
$$\boxed{\frac{dE}{dy} \propto \left(T_A T_B\right)^{1/2}}$$

[Bass, Bernhard, Moreland **Nature Phys. 15 (2019)**]



JETSCAPE collaboration confirm large sizes!

[JETSCAPE Collaboration **2011.01430**, **2010.03928**]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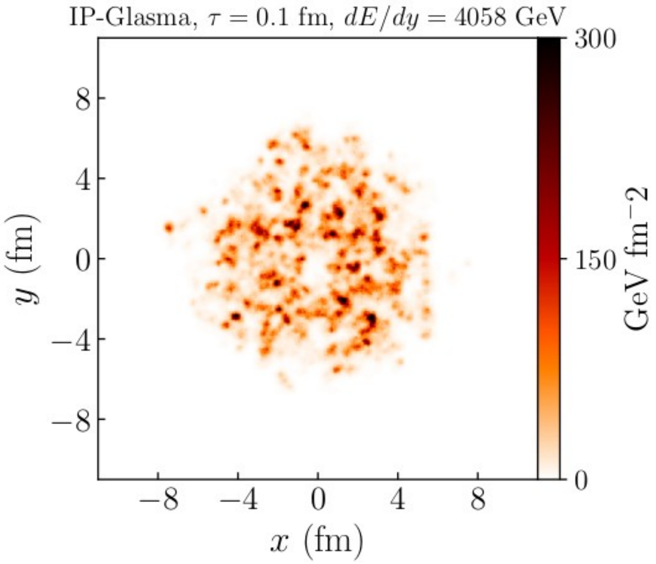
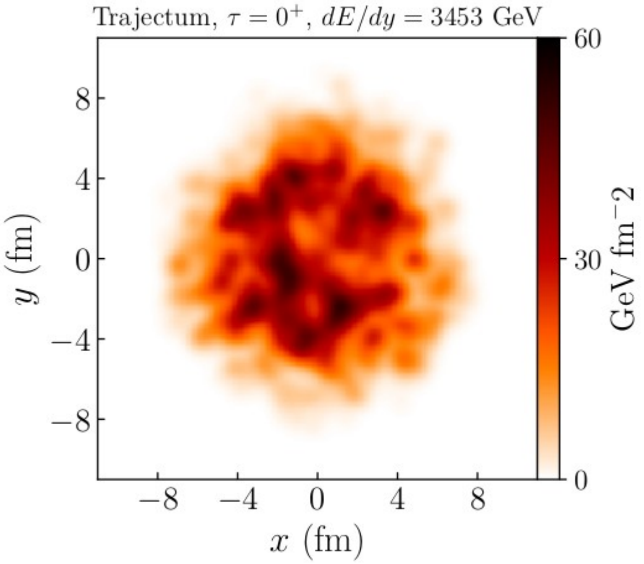
CURRENT STATUS OF INITIAL CONDITIONS



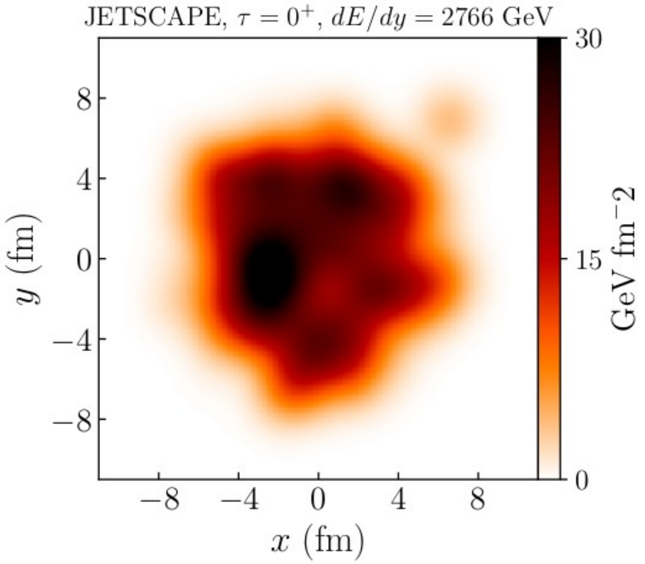
[Schenke, Shen, Tribedy 2005.14682]



[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

[Nijs, van der Schee 2110.13153,2112.13771]

[Bass, Bernhard, Moreland 1808.02106]

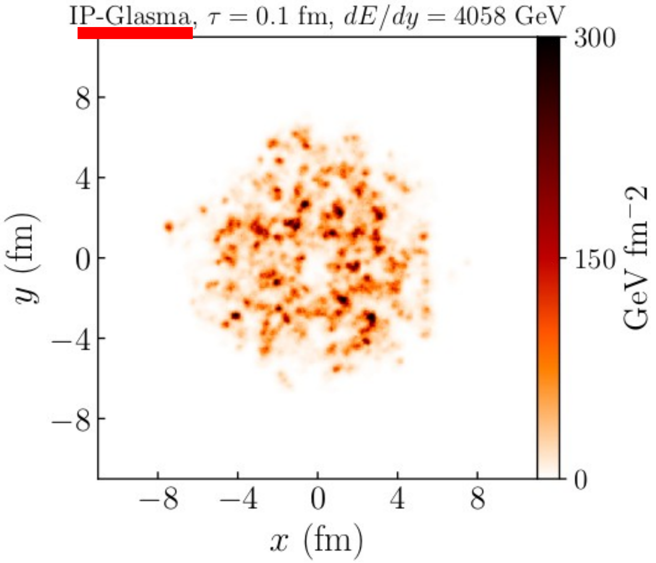


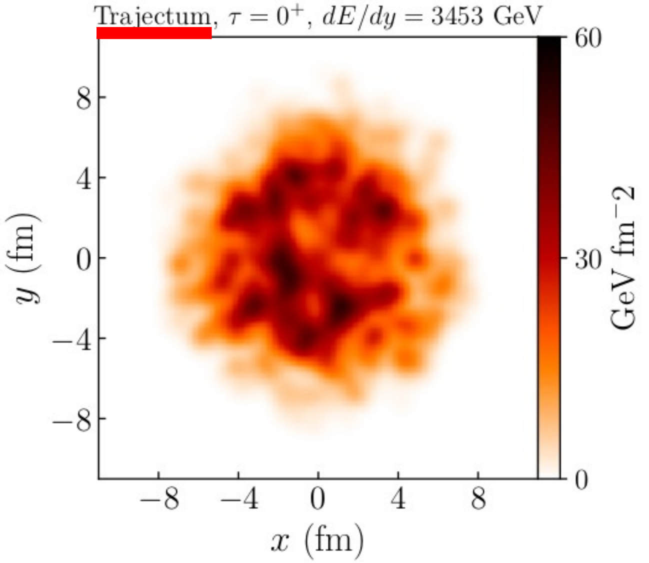
[Parkkila, Onnerstad, Taghavi, Mordasini, Bilandzic 2111.08145]

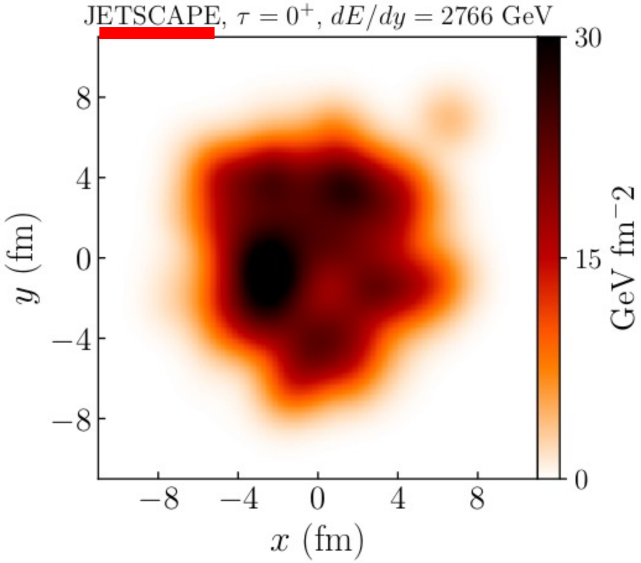
[Parkkila, Onnerstad, Kim 2106.05019]

[JETSCAPE Collaboration 2011.01430, 2010.03928]

[Bass, Bernhard, Moreland Nature Phys. 15 (2019)]


IP-Glasma, $\tau = 0.1$ fm, $dE/dy = 4058$ GeV

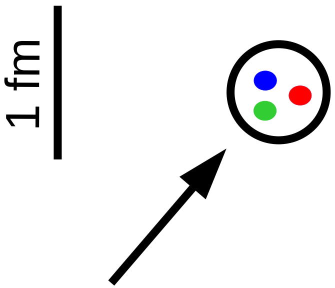

Trajectum, $\tau = 0^+$, $dE/dy = 3453$ GeV


JETSCAPE, $\tau = 0^+$, $dE/dy = 2766$ GeV

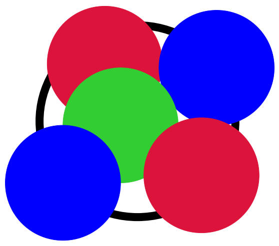
L~0.1 fm

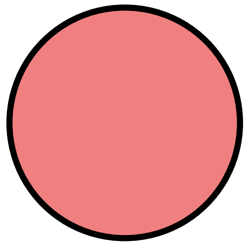
L~0.5 fm

L~1 fm



NUCLEON



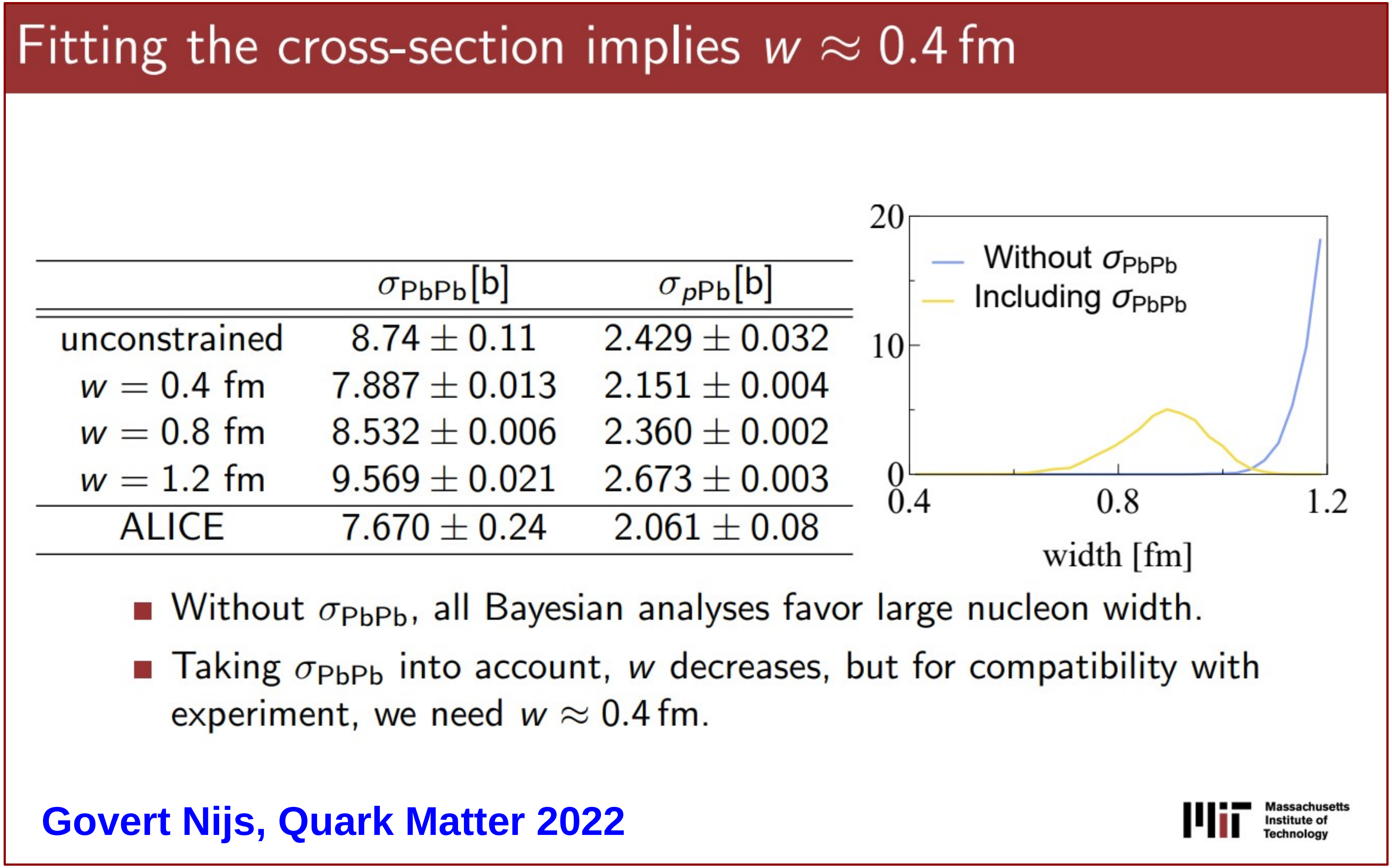


Highly degenerate in regard to final observables … can we make some order?

3.

Observables for a consistent picture

Simple facts first.



Fitting the cross-section implies $w \approx 0.4\,\mathrm{fm}$

	$\sigma_{\mathrm{PbPb}}[\mathrm{b}]$	$\sigma_{p\mathrm{Pb}}[\mathrm{b}]$
unconstrained	8.74 ± 0.11	2.429 ± 0.032
$w = 0.4$ fm	7.887 ± 0.013	2.151 ± 0.004
$w = 0.8$ fm	8.532 ± 0.006	2.360 ± 0.002
$w = 1.2$ fm	9.569 ± 0.021	2.673 ± 0.003
ALICE	7.670 ± 0.24	2.061 ± 0.08

- Without σ_{PbPb}, all Bayesian analyses favor large nucleon width.
- Taking σ_{PbPb} into account, w decreases, but for compatibility with experiment, we need $w \approx 0.4\,\mathrm{fm}$.

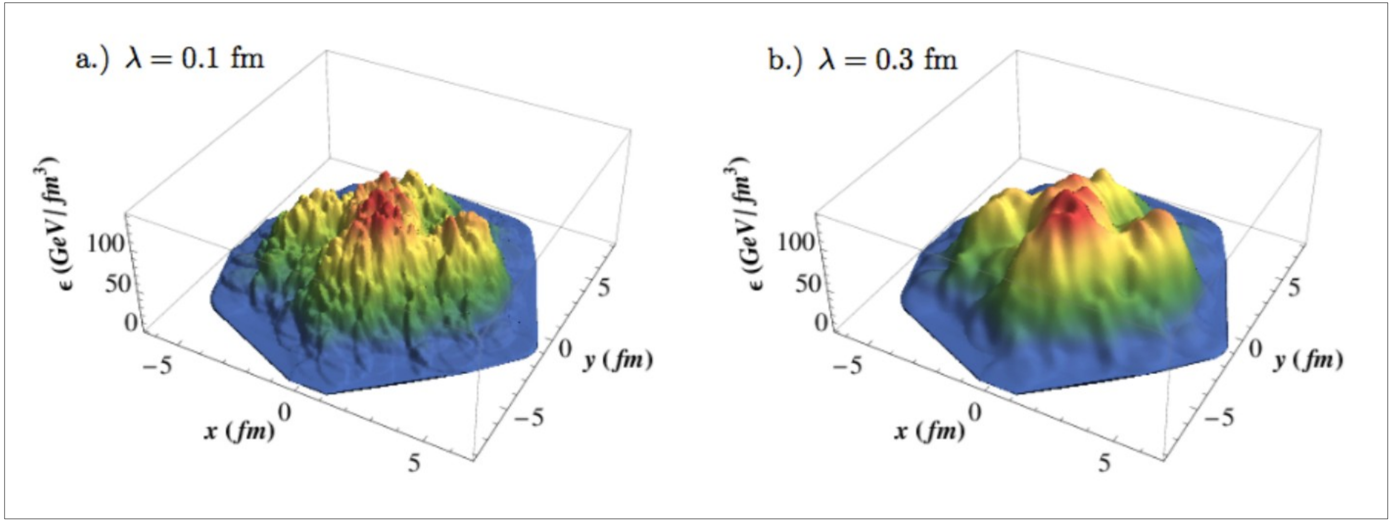
Govert Nijs, Quark Matter 2022

Massachusetts
Institute of
Technology

More “dynamical” observables (related to hydrodynamic flow)?

No visible sensitivity in A-A collisions unless for very peripheral events (>60%).

[Noronha-Hostler, Noronha, Gyulassy, **1508.02455**]
[Gardim, Grassi, Ishida, Luzum, Magalhães, **1712.03912**]



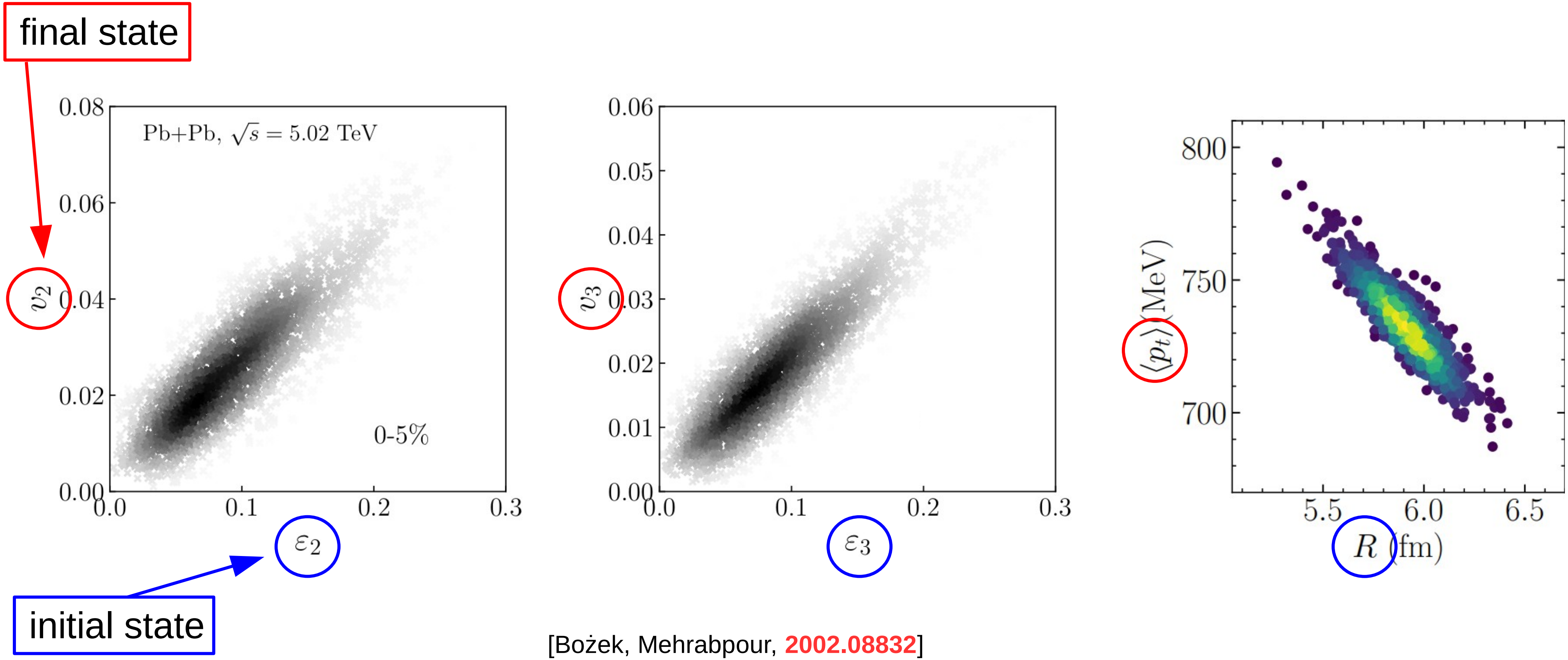
Observable not considered in previous studies: Correlation between v_n and mean p_t.

$$\rho(v_n^2,[p_t]) = \frac{\langle \delta v_n^2 \delta[p_t]\rangle}{\sqrt{\langle(\delta v_n^2)^2\rangle\langle(\delta[p_t])^2\rangle}}$$

[Bożek, **1601.04513**]

Physical meaning:
correlation between shape and size of QGP.

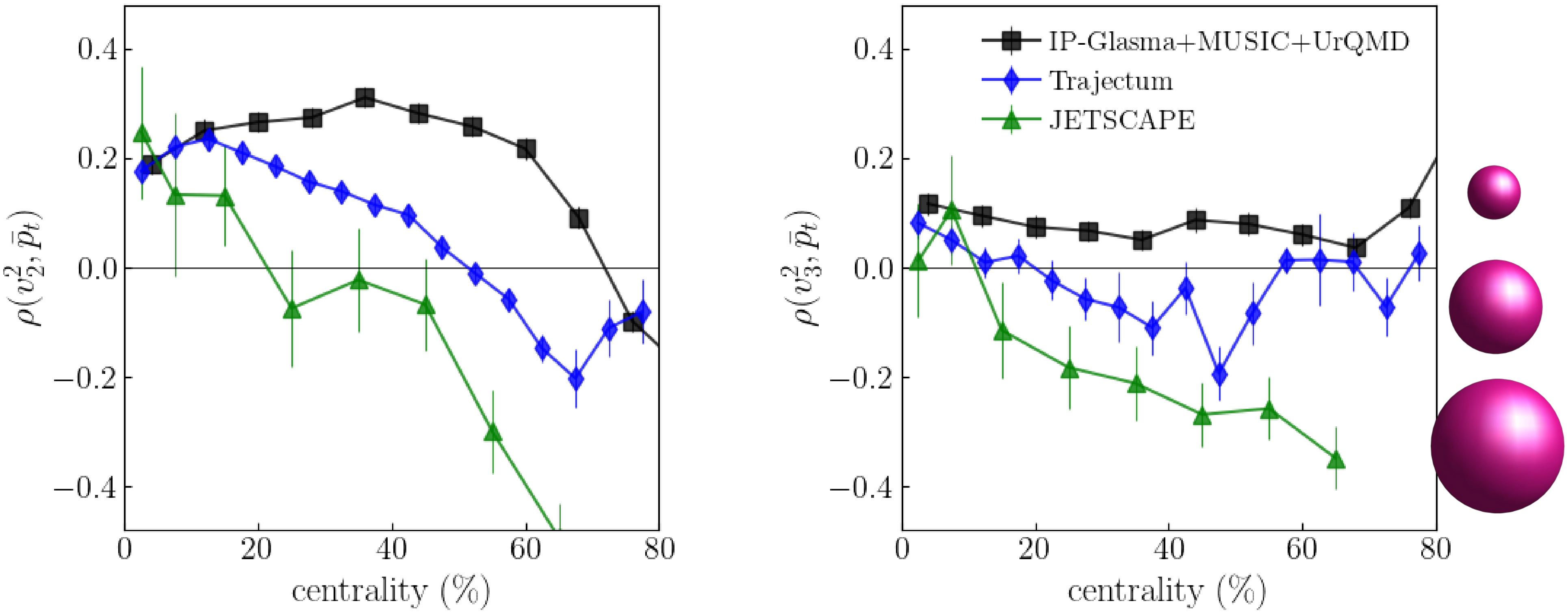
$$\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta[p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}$$


final state

initial state

[Bożek, Mehrabpour, **2002.08832**]
[Schenke, Shen, Teaney, **2004.00690**]
[Gardim, Giacalone, Noronha-Hostler, Ollitrault **2004.01765**]

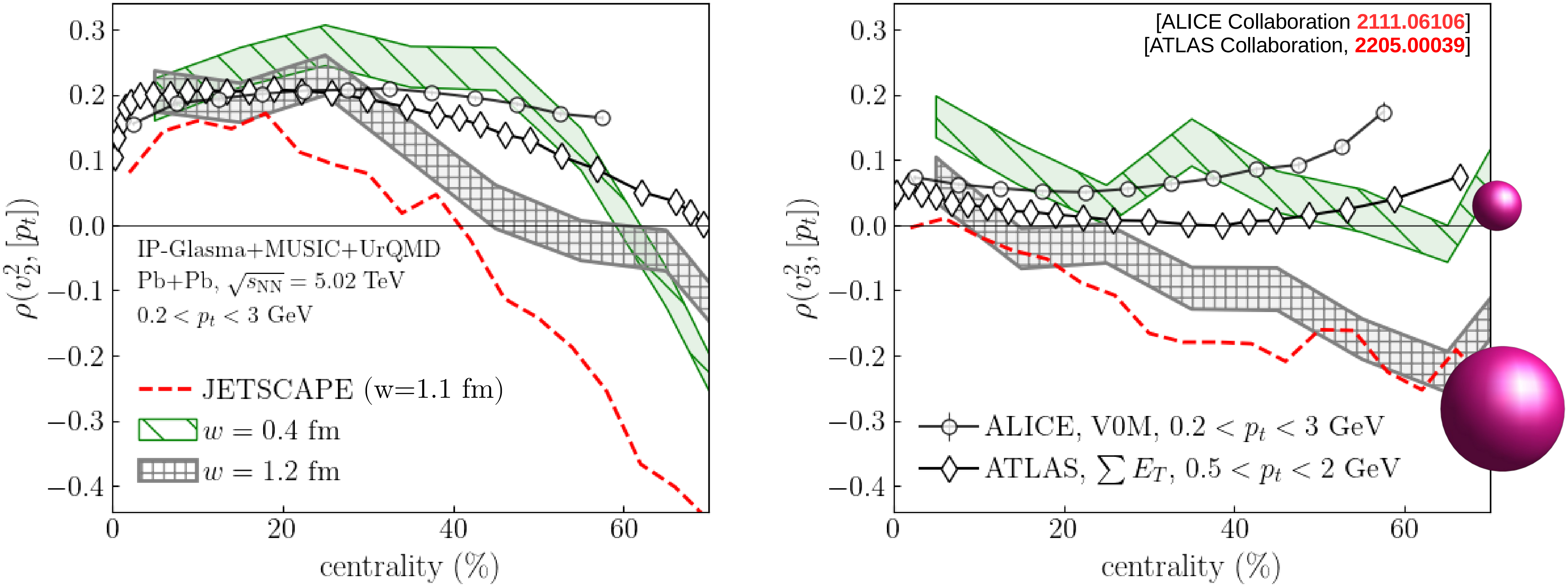
The observable is strongly model-dependent… rare feature.



Same ordering as implemented nucleon sizes.

Final-state observable driven by the nucleon size?

[Giacalone, Schenke, Shen **2111.02908**]

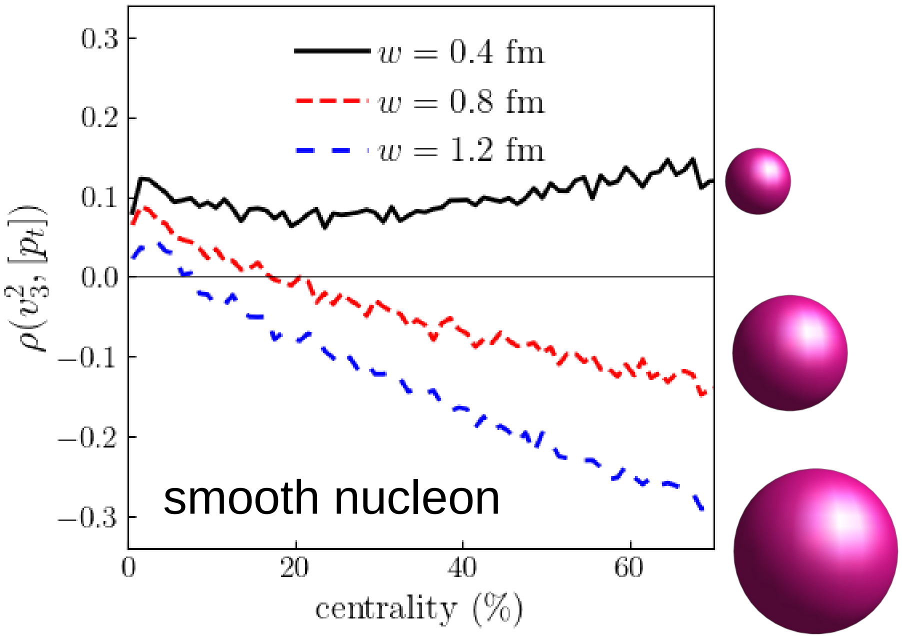


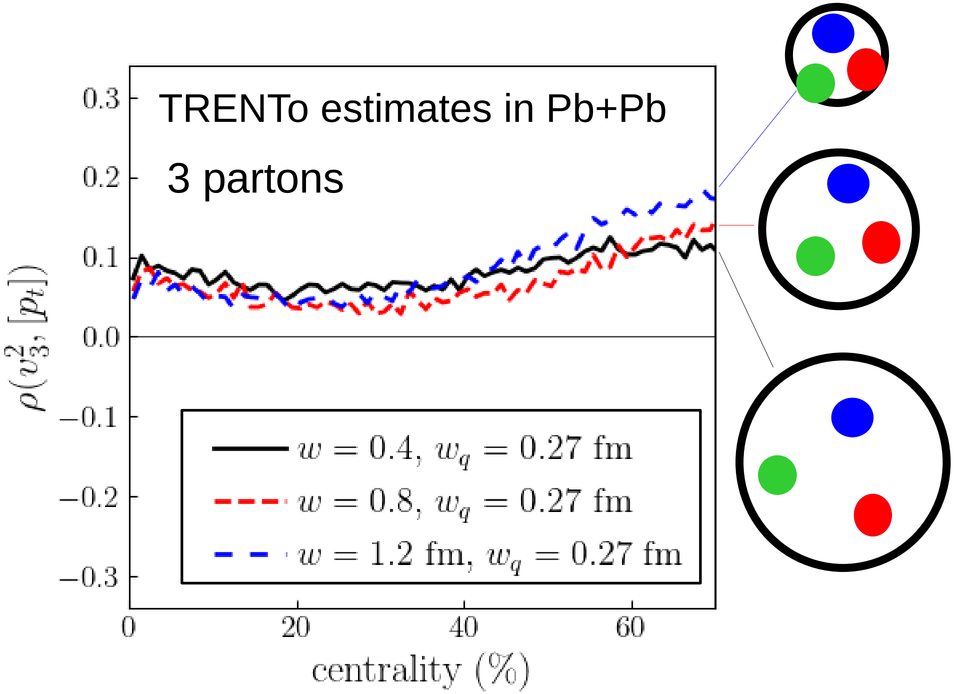
[ALICE Collaboration **2111.06106**]
[ATLAS Collaboration, **2205.00039**]

Experimental data does not support a large size, ρ_3>0.
Size estimates in Bayesian analyses are not OK. Fitted data is not enough.

Role of subnucleonic structure – constituent size

[Giacalone, Schenke, Shen 2111.02908]



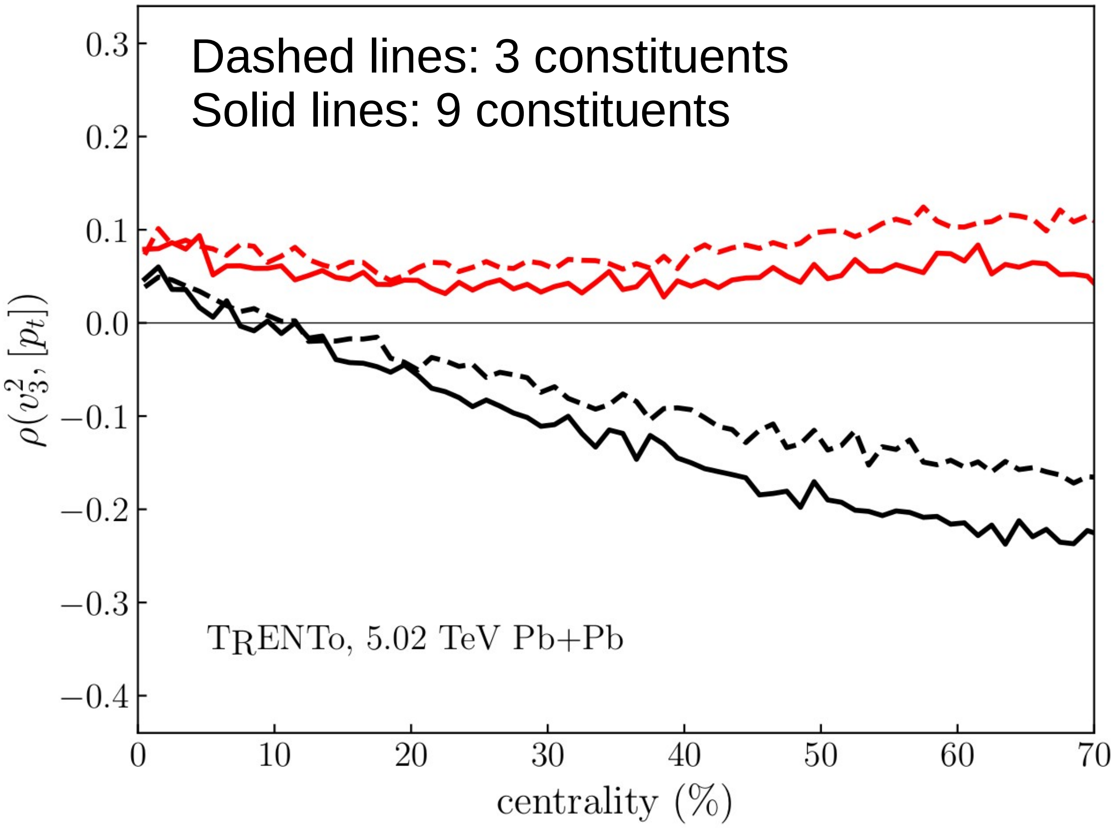


Full sensitivity to constituent size:

IMPORTANT: goes beyond the nucleon size constraint from AA cross section!

Role of subnucleonic structure – constituent number

[Giacalone, Schenke, Shen in progress]



Dashed lines: 3 constituents
Solid lines: 9 constituents

Constituent size: 0.27fm

Constituent size: 0.80fm

Little sensitivity to constituent number:

How do we understand this? Supplementing Bayesian analyses.
Field theoretical approach?

[Floerchinger, Wiedemann, 1307.7611]
[Blaizot, Broniowski, Ollitrault, 1405.3572]
[Bhalerao, Giacalone, Ollitrault 1904.10350]

$\rho(z)$ → energy density

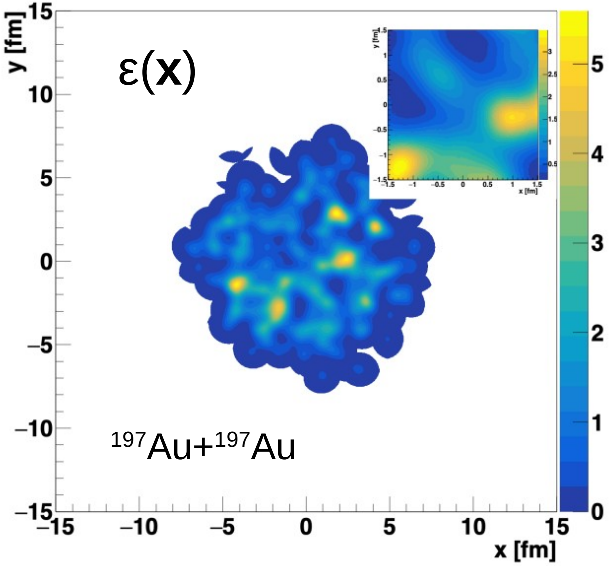
$$S(z_1, z_2) \equiv \langle \rho(z_1)\rho(z_2) \rangle - \langle \rho(z_1) \rangle \langle \rho(z_2) \rangle$$

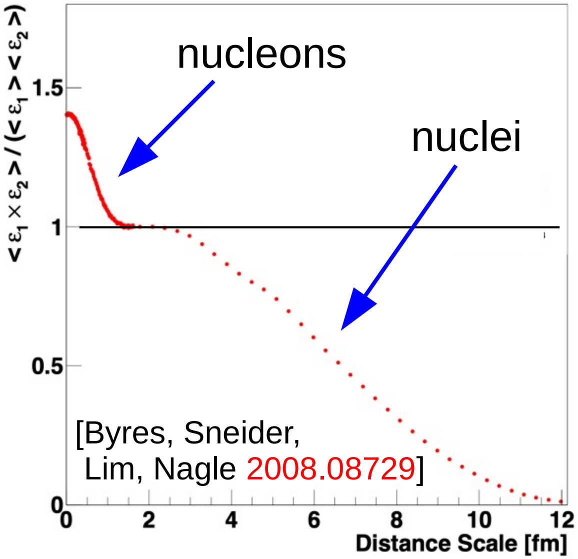
→ **average**

$$S(z_1, z_2) = A(z)h(s), \qquad z \equiv \frac{z_1 + z_2}{2}, \quad s \equiv z_1 - z_2$$

fluctuation amplitude

correlation length



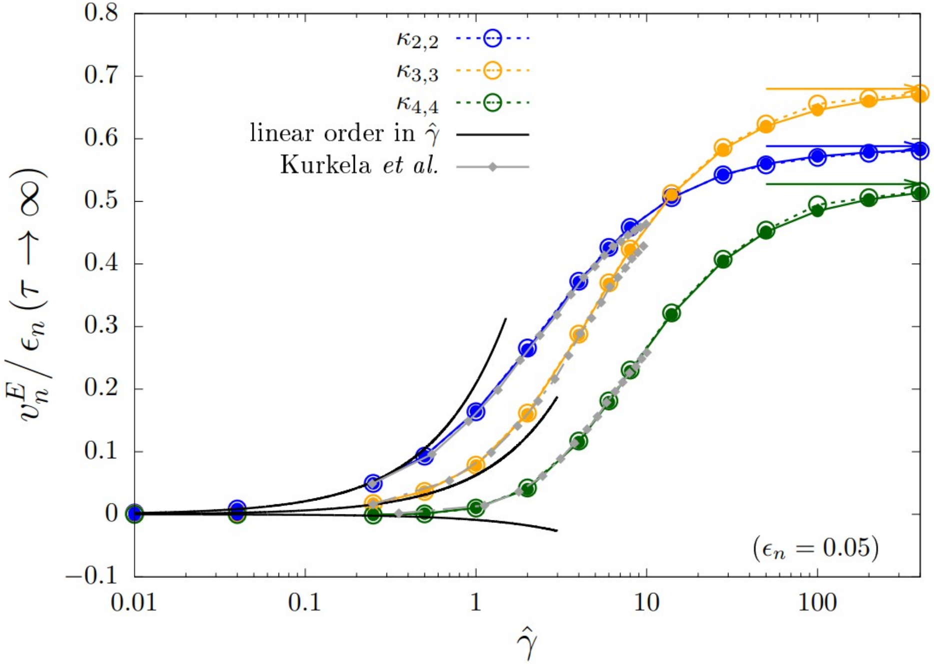


[Byres, Sneider,
Lim, Nagle 2008.08729]

4.
Consequences/prospects

1 – Small system geometry

Dynamical evolution of small systems raises many questions.
But one needs an initial geometry!



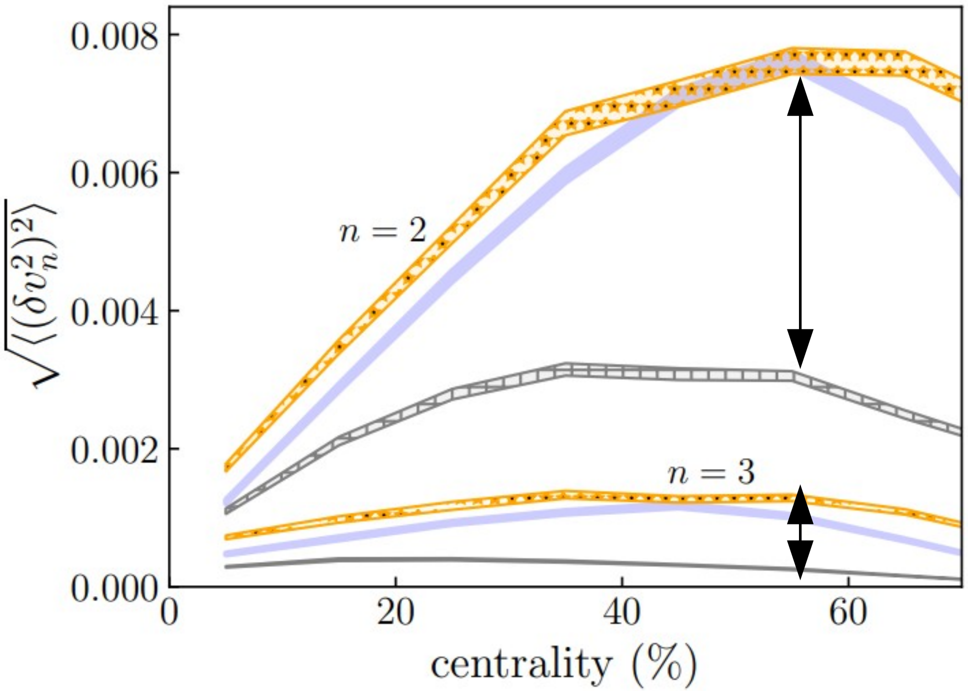
[Kurkela, Taghavi, Wiedemann, Wu, 2007.06851]
[Kurkela, Mazeliauskas, Törnkvist, 2104.08179]
[Ambrus, Schlichting, Werthmann, 2109.03290]

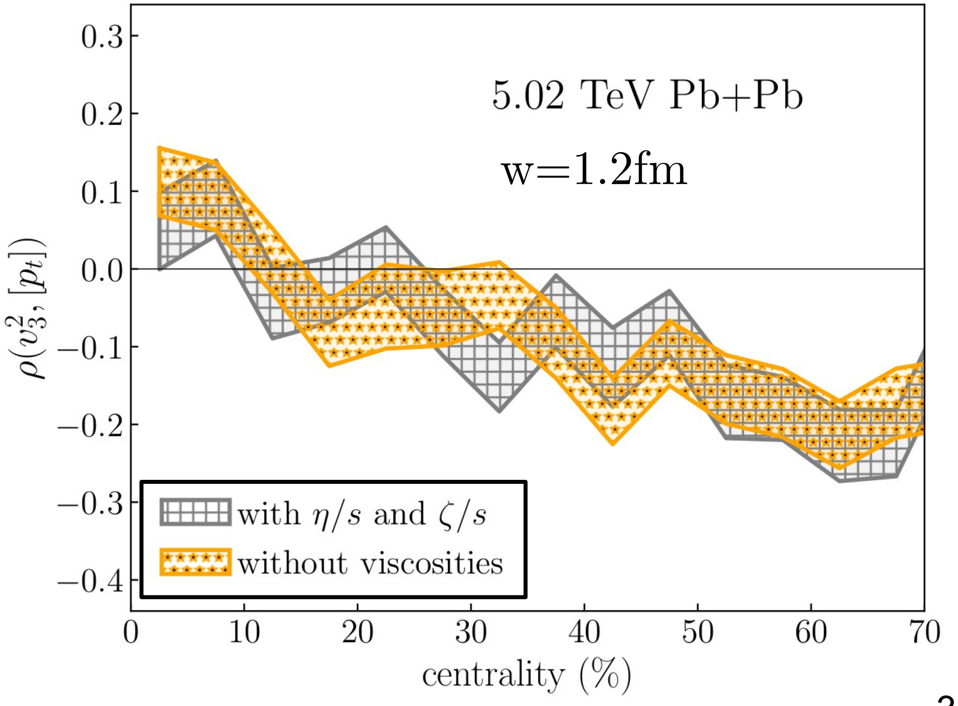
We can constrain it from A-A data alone!

2 – The fate of the bulk viscosity.

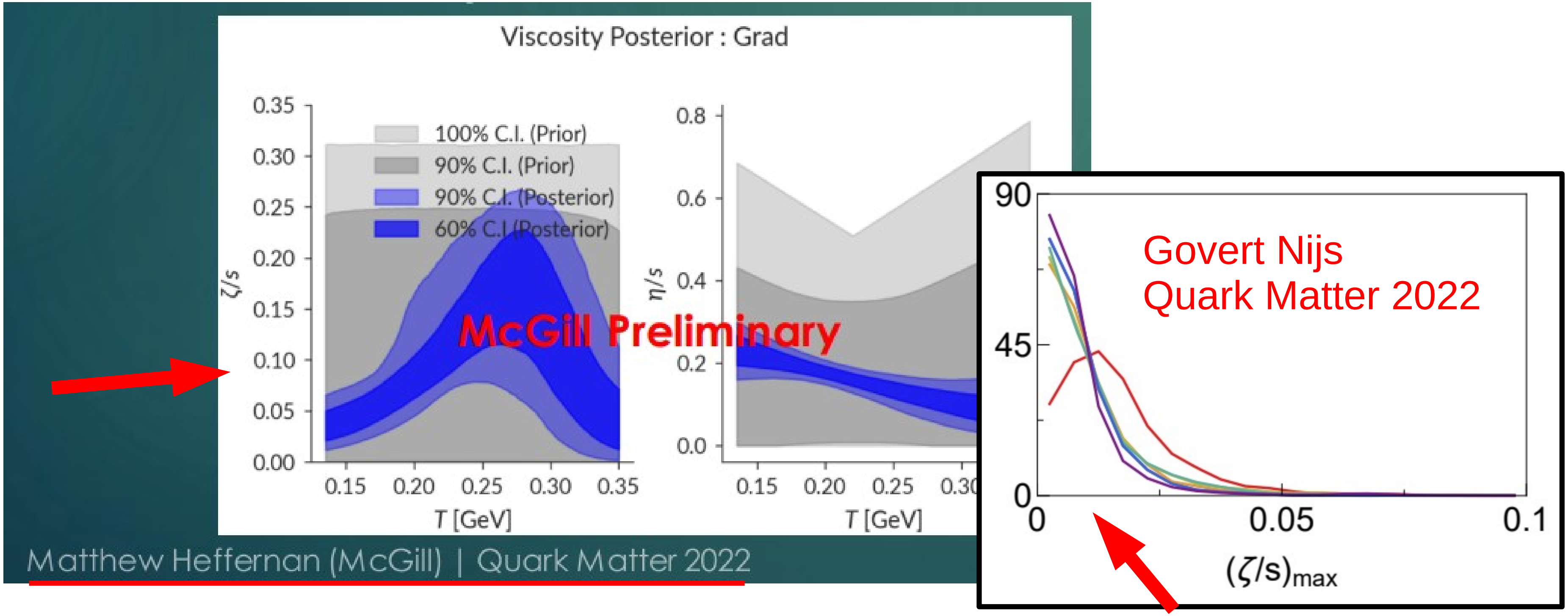
Unlike flow coefficients, sensitive to nucleon size but not to viscosity!
Genuine probe of initial state.

[Giacalone, Schenke, Shen **2111.02908**]





Bulk viscosity? Literature is inconsistent.



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Govert Nijs
Quark Matter 2022

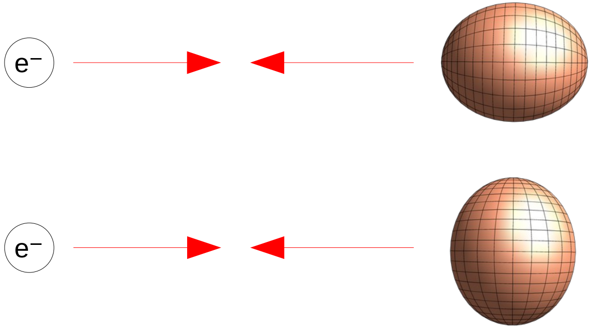
Once nucleon structure is fixed, this is a matter of:

CGC **AdS/CFT**

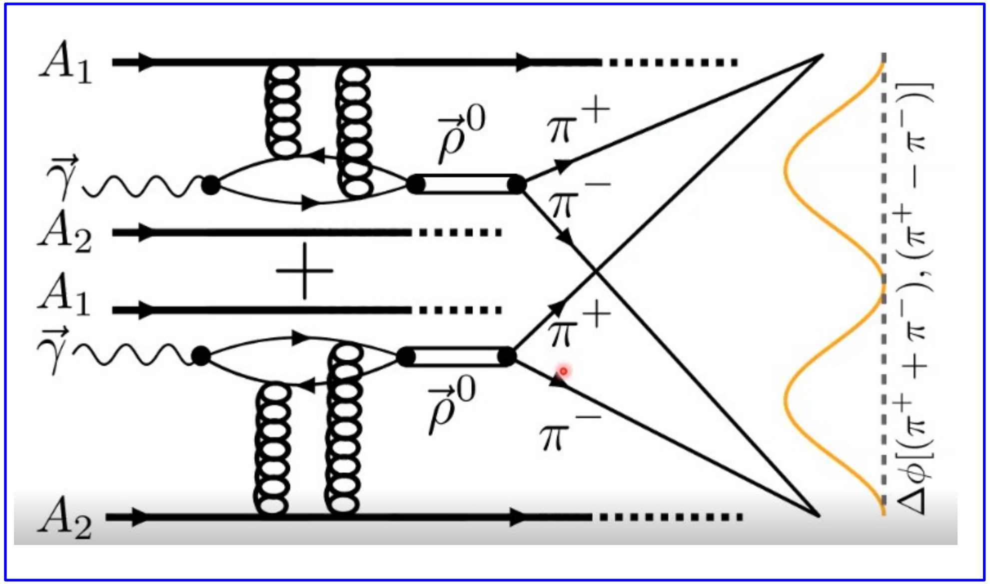
$$\frac{dS}{dy} \propto \quad (T_A T_B)^{1/2} \quad (T_A T_B)^{1/3} \quad ?$$

3 – Towards EIC?

Check consistency between A-A and e-A data.



First steps in UPC?



[STAR collaboration, **2204.01625**]

Woods-Saxon radii for gluons:

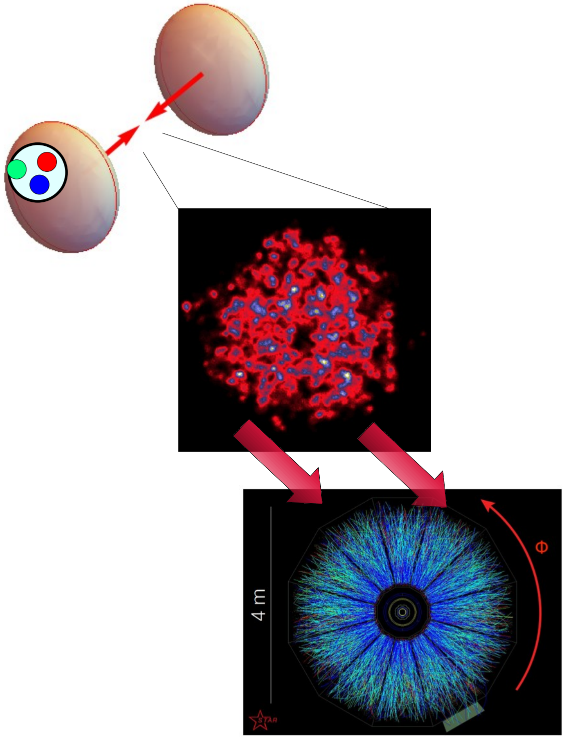
$R\ {}^{197}\mathrm{Au} = 6.53$ fm

$R\ {}^{238}\mathrm{U} = 7.29$fm

Can we extract an effective nucleon size?

[Bally, Giacalone, in progress]

CONCLUSION



- QGP fluctuates on all scales and we see that.
- Effective model of nucleon structure at high energy.
  Little attention given to nucleon/subnucleon size over the years.
- v_n-$\langle p_t \rangle$ correlations sensitive to nucleon/subnucleon size.
- Experimental data supports a size ~0.4fm.
  Bayesian analysis can pin down the constituent scale.
- **We constrain the impact of nucleon structure from A-A data.**
  Broad consequences.

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

Jan 23rd - Feb 24th 2023

INSTITUTE for
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