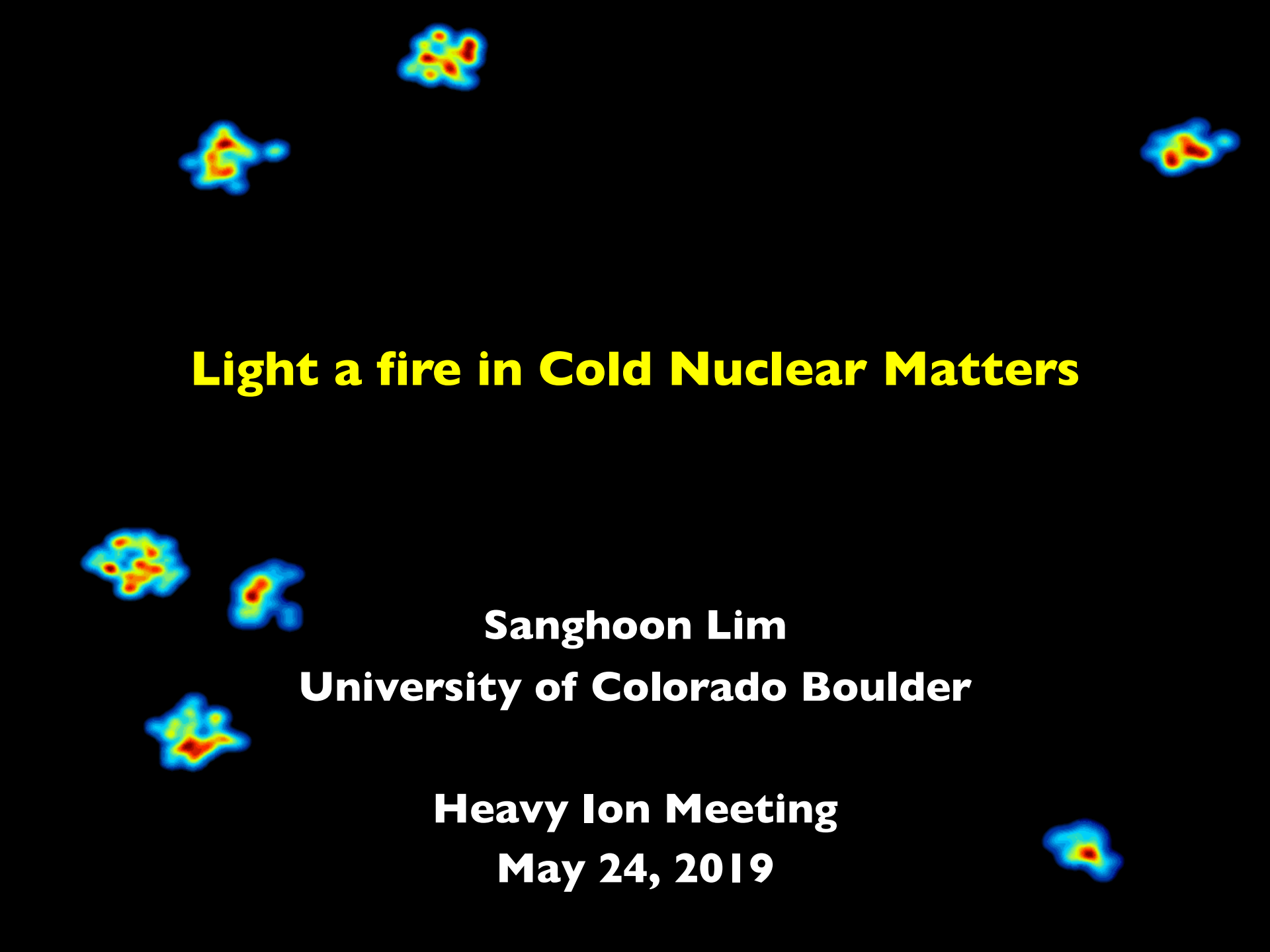

Light a fire in Cold Nuclear Matters

Sanghoon Lim
University of Colorado Boulder

Heavy Ion Meeting
May 24, 2019

ANTICANCER BLOCKBUSTER? • RISE AND FALL OF THE SLIDE RULE

SCIENTIFIC AMERICAN

Bringing **DNA Computers** to Life

MAY 2006
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Quark Soup

PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**

Stopping **Alzheimer's**

Birth of **the Amazon**

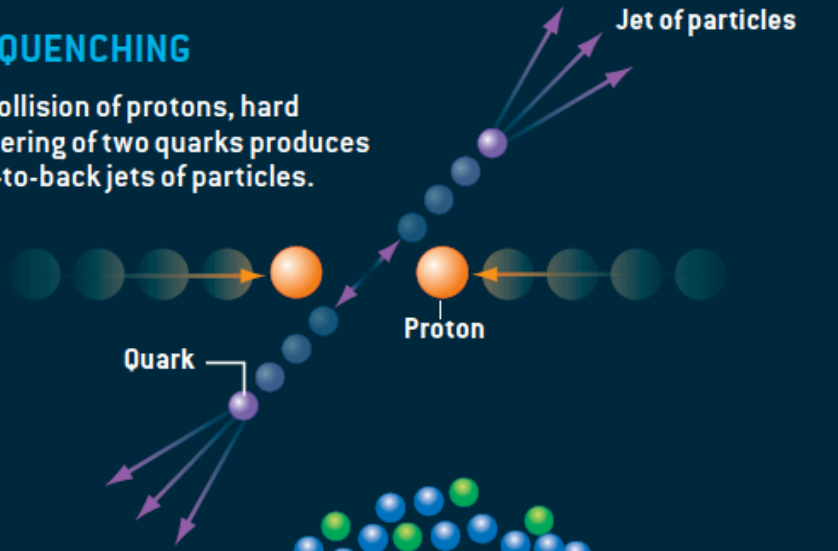
Future **Giant Telescopes**

EVIDENCE FOR A DENSE LIQUID

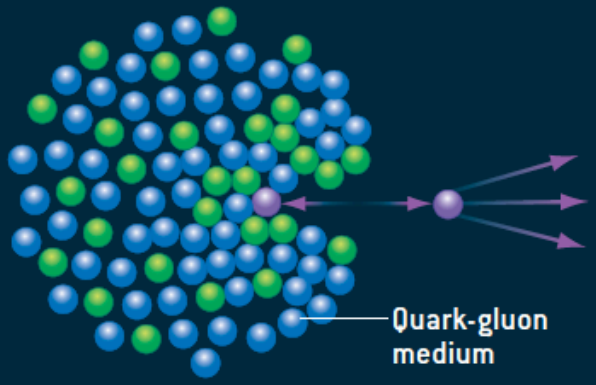
Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

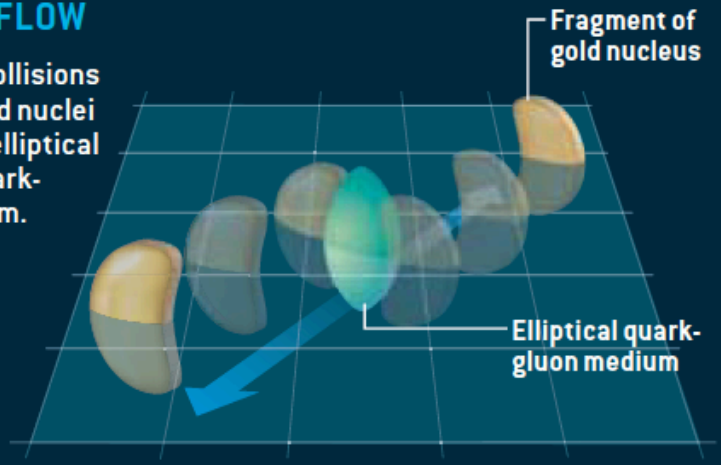


In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

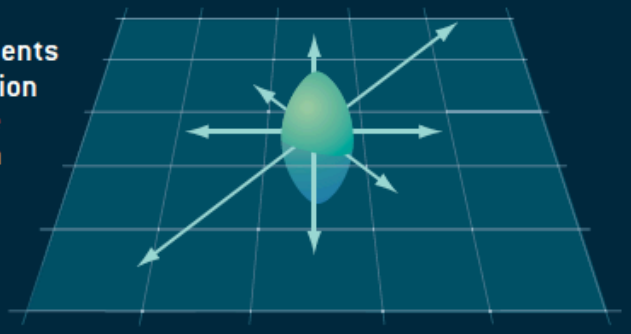


ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

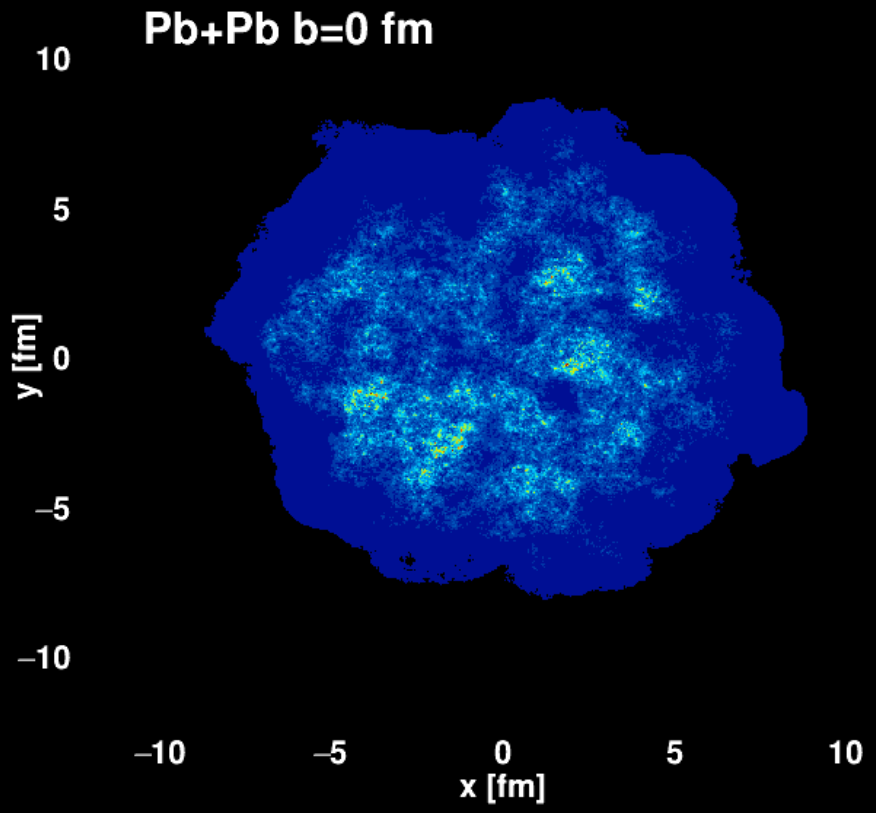


The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).



Inside the article

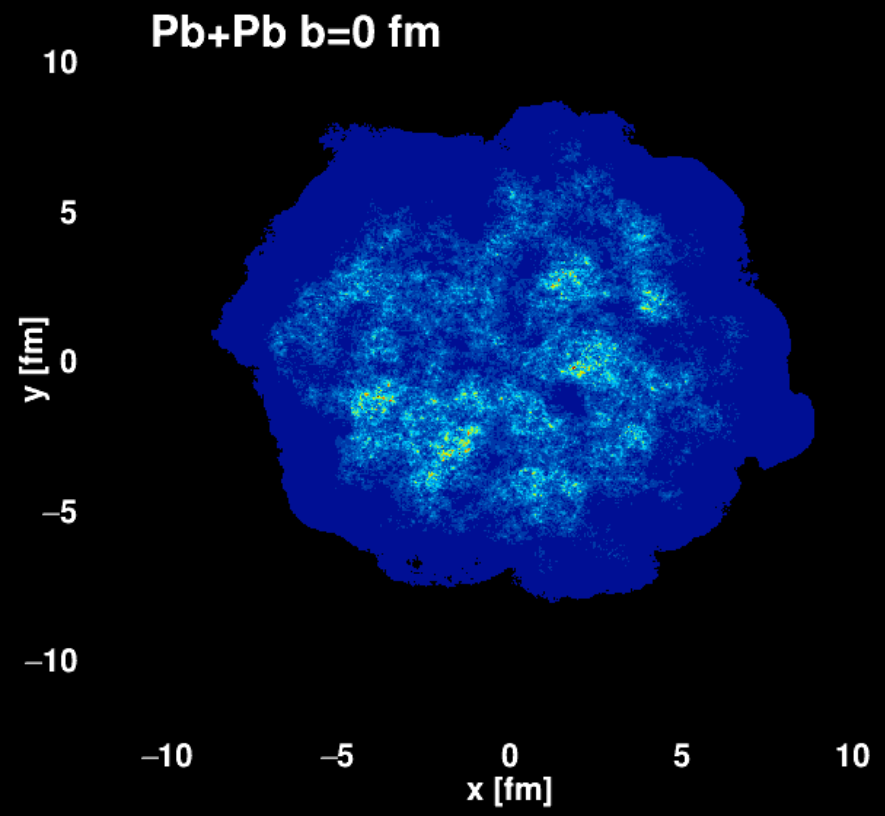
Recipe for Quark Soup

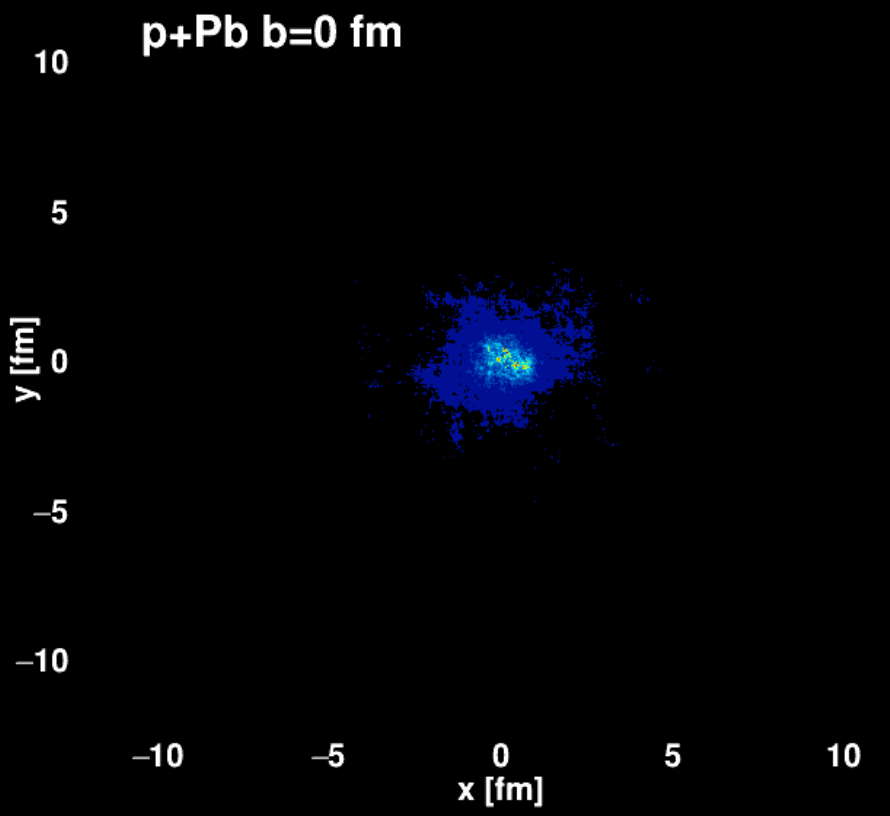


IP-Glasma

Excellent recipe for Quark-Gluon Plasma !

Recipe for Quark Soup

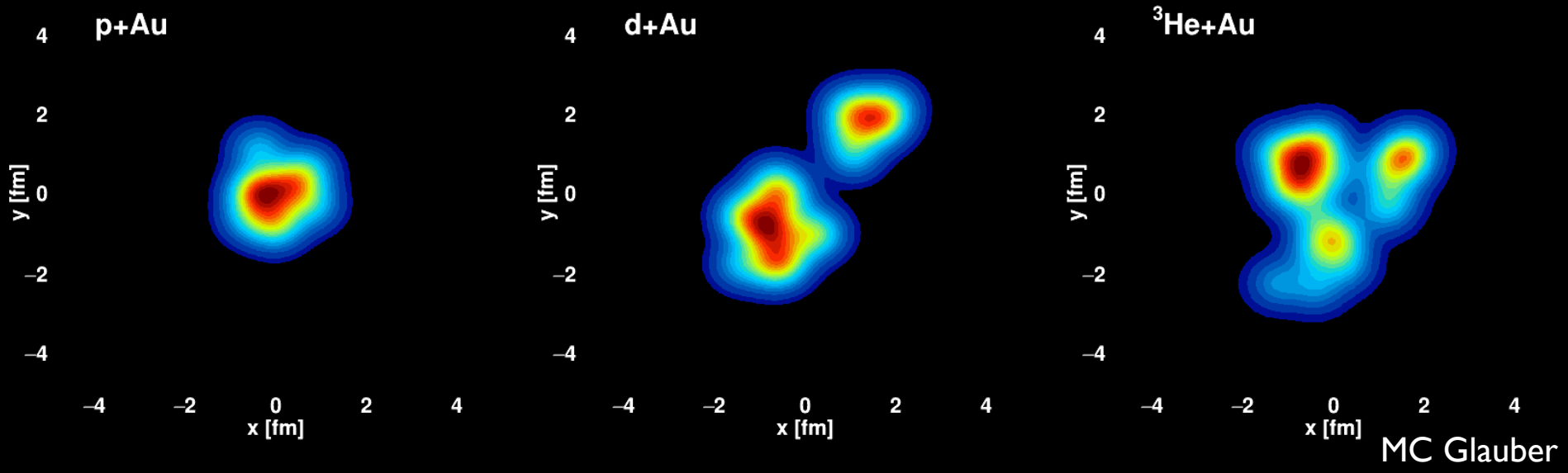




IP-Glasma

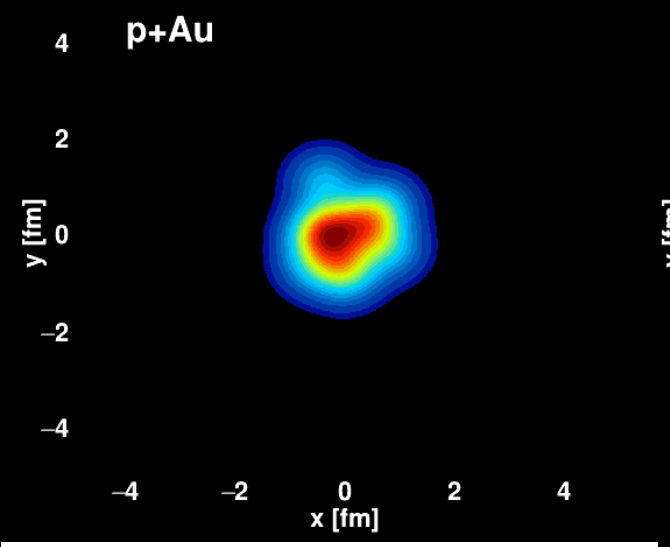
How about this new recipe ?

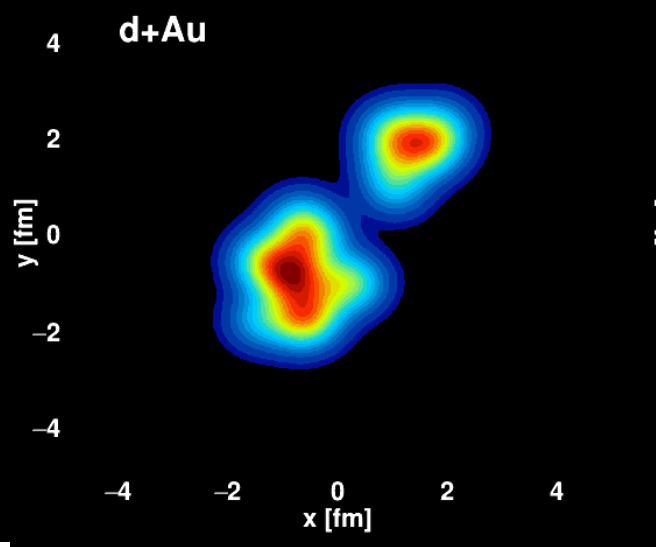
Control initial geometry

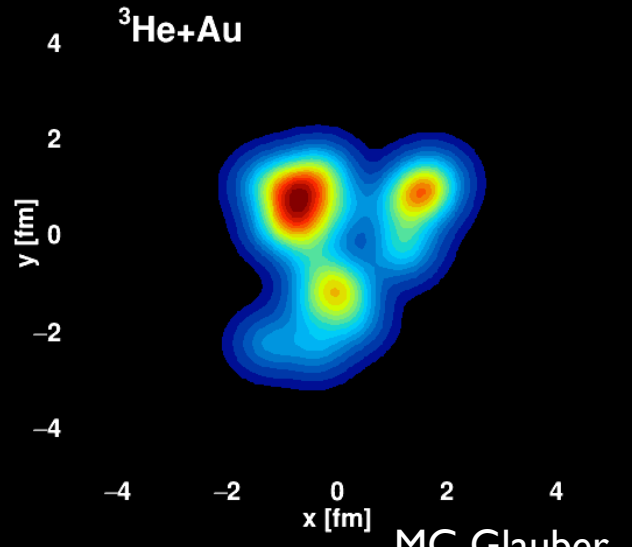


MC Glauber

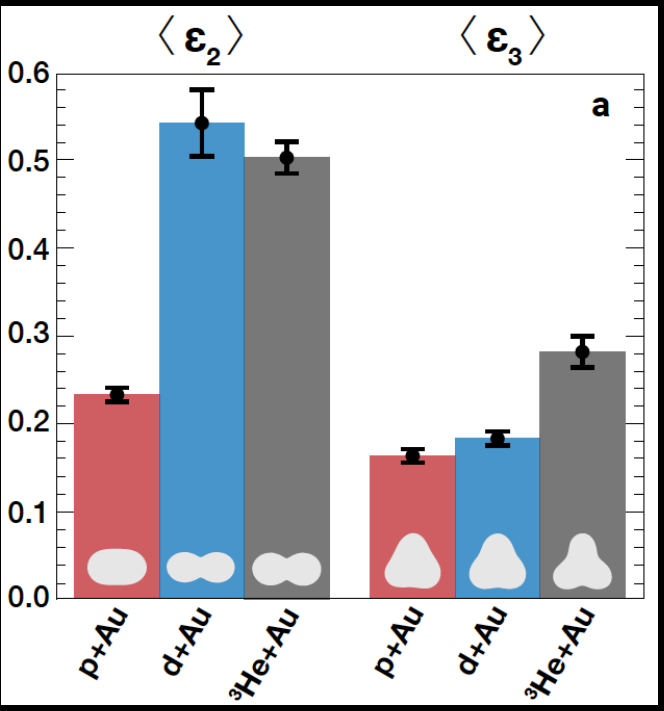
Control initial geometry







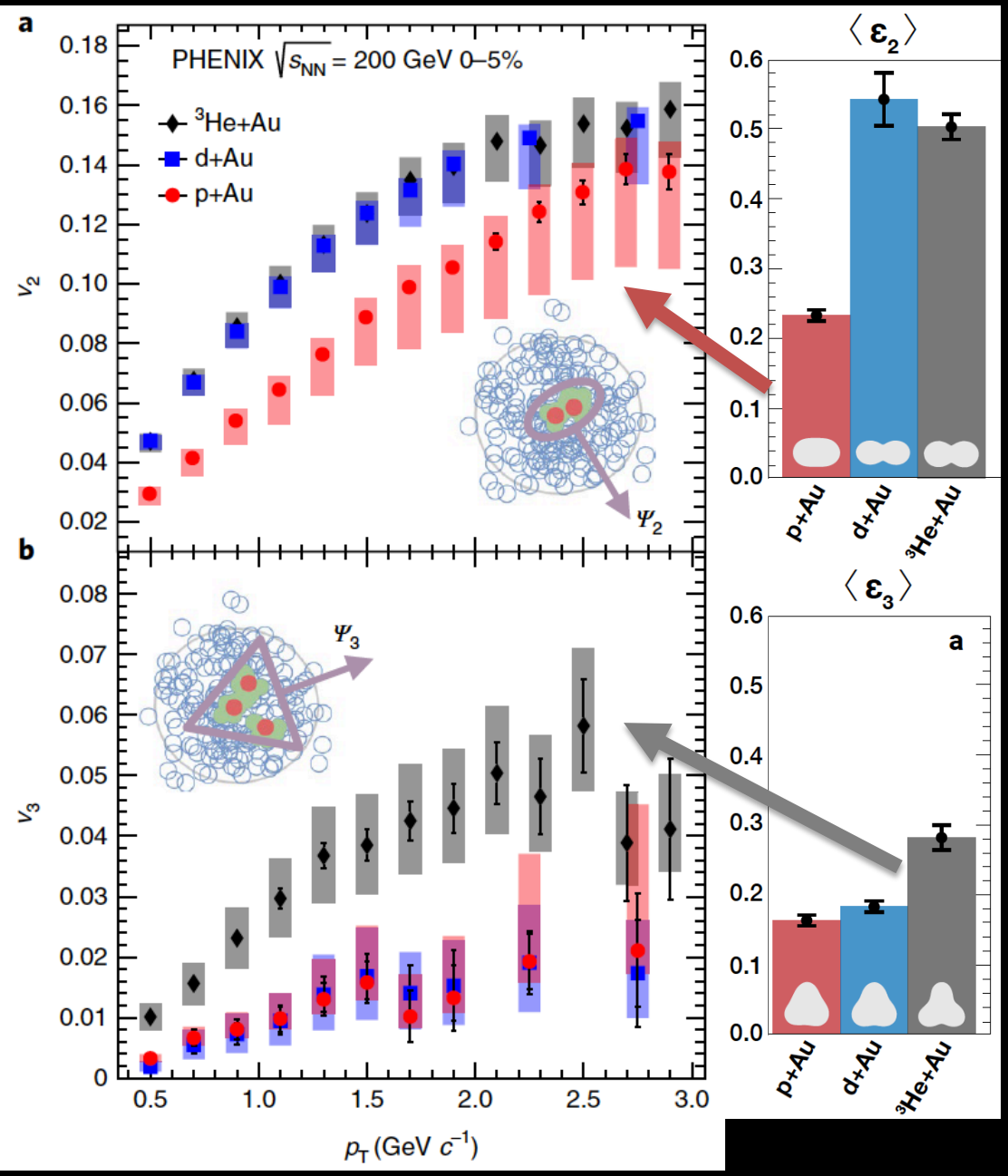
MC Glauber



- **Clearly different initial geometry in p+Au, d+Au, and ^{3}He+Au collisions**
- ***Smaller $\langle\varepsilon_2\rangle$ in p+Au***
- ***Larger $\langle\varepsilon_3\rangle$ in ^{3}He+Au***

Nature Physics 15, 214 (2019)

Control initial geometry

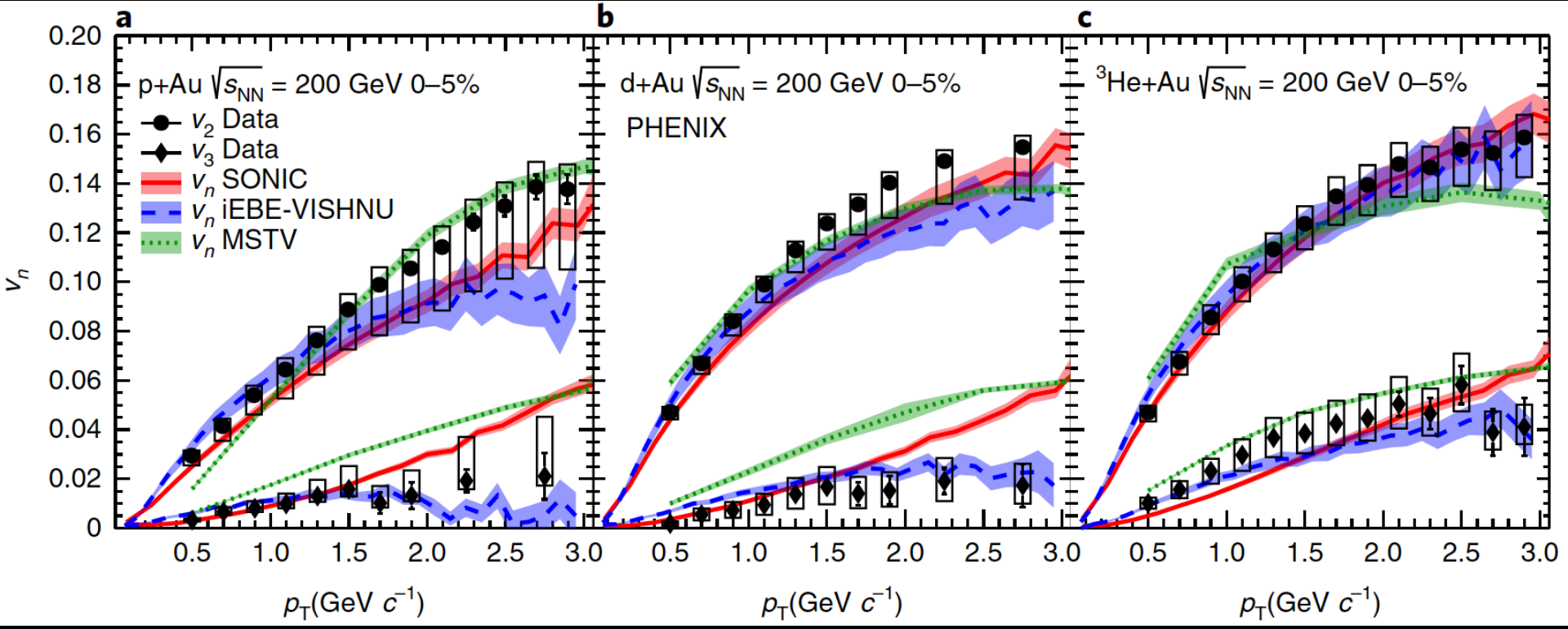


- ***Smaller $\langle\varepsilon_2\rangle$ in p+Au***
- ***Larger $\langle\varepsilon_3\rangle$ in ^{3}He+Au***

- ***Smaller v_2 in p+Au***
- ***Larger v_3 in ^{3}He+Au***

Nature Physics 15, 214 (2019)

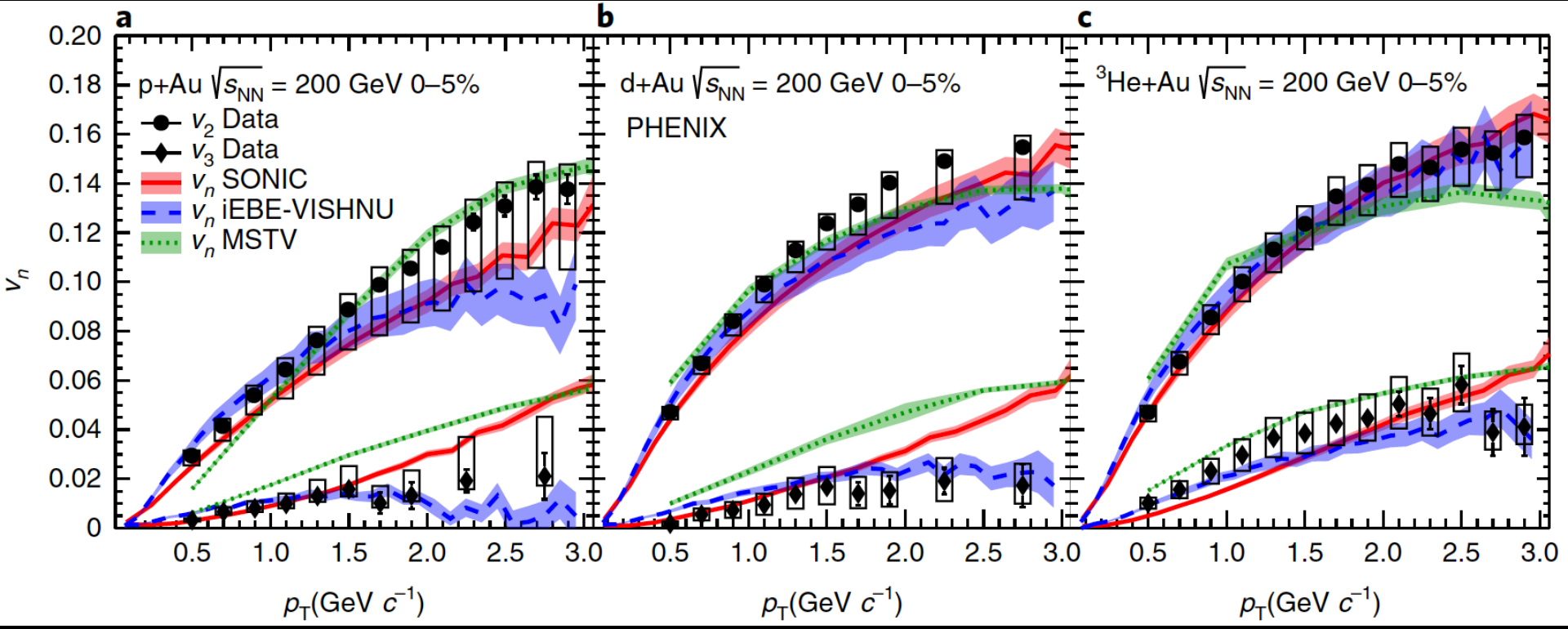
Comparison with models



Nature Physics 15, 214 (2019)

- *Hydrodynamic models* can reproduce the data quite well
- *Initial state correlation model* give the right v_2 system ordering, but a poor overall description

Comparison with models



Nature Physics 15, 214 (2019)

- *Hydrodynamic models* can reproduce the data quite well
- ~~*Initial state correlation model* give the right v_2 system ordering, but a poor overall description~~

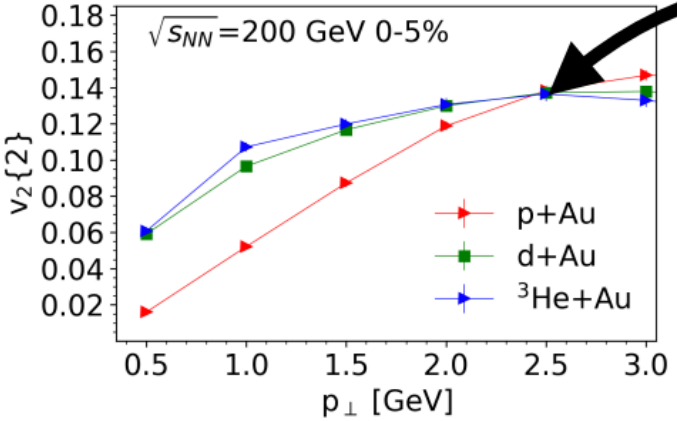
➔***Incorrect!***

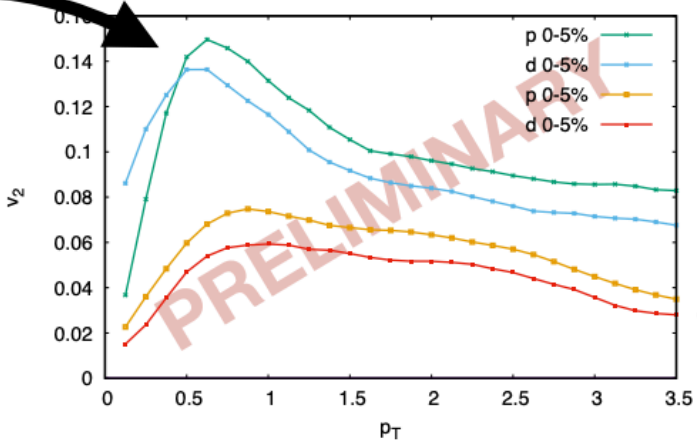
$$\frac{dN}{d^2k}[\mathrm{GeV}^{-2}] \stackrel{!}{=} f(k')[\mathrm{fm}^2]$$

Effectively, all results were off by in momenta factor of $\hbar c$

What does this mean

Effectively, nuclei were *zoomed in on* by incorrectly considering only small momenta





Same reference bin

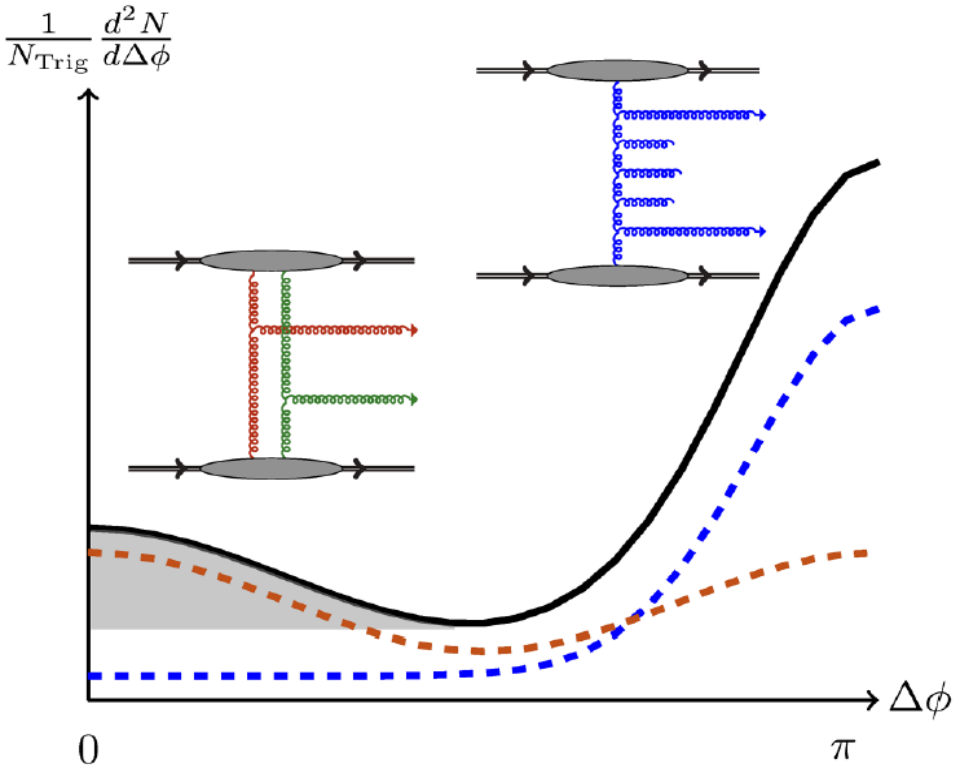
0.5-3 GeV ref bin

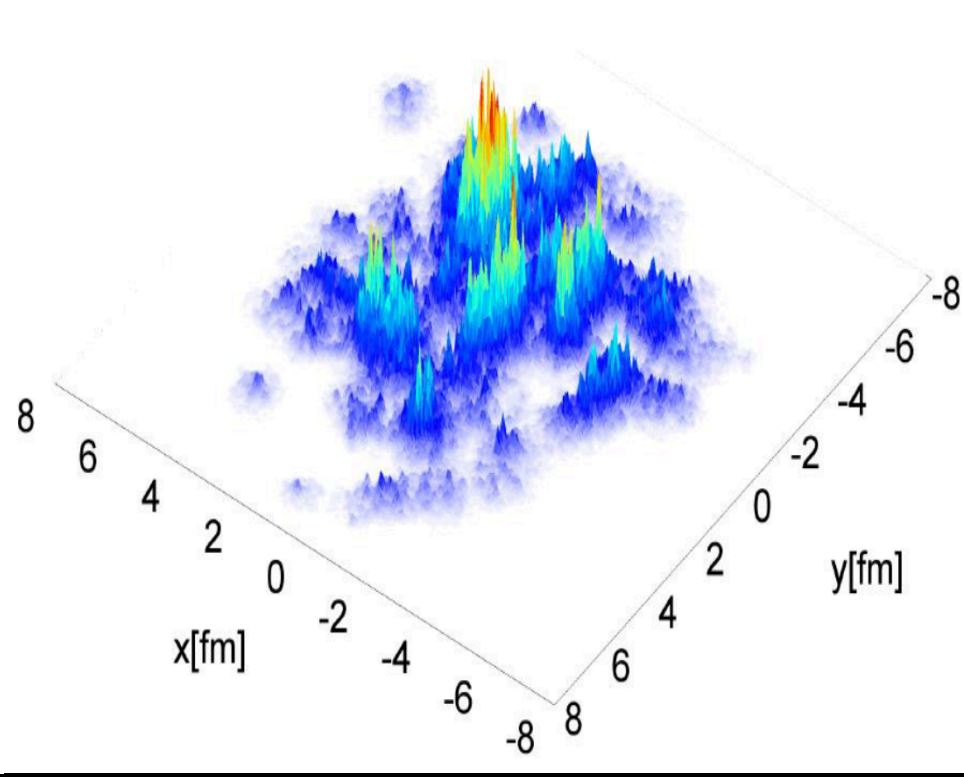
With corrections to momenta factors (including reference bin), CGC appears to be unable to describe data systematics, i.e.

$$v_2(\text{p 0-5\%}) > v_2(\text{d 0-5\%}) > v_2(^3\text{He 0-5\%})$$

Mark Mace's slides in INT 2019

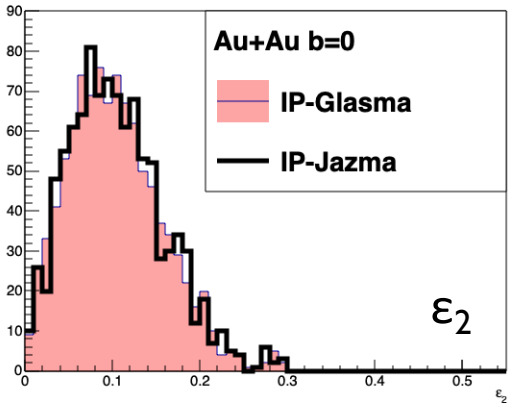
Searching for colorful domain

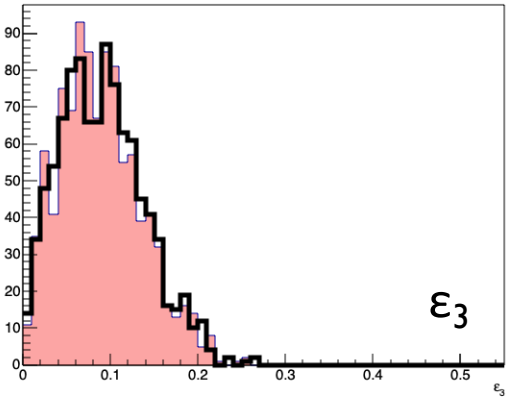


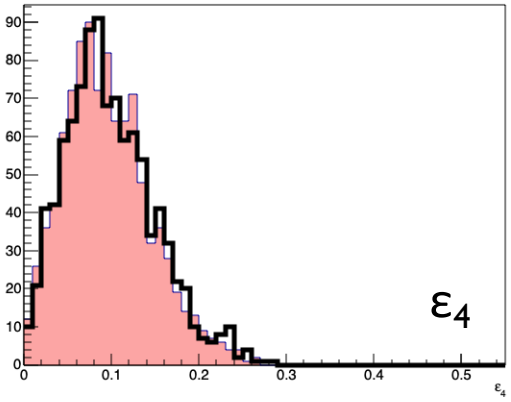


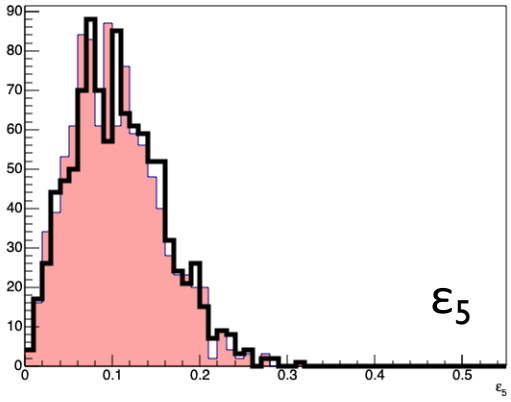
- The effect from CGC model can be studied by comparing another model including other phenomenological pieces (*IP-Jazma*, arXiv:1808.01276)
  - MC Glauber for nucleons
  - IP-Sat for Q_s
  - Multiplication of gluon densities in two nuclei for energy density

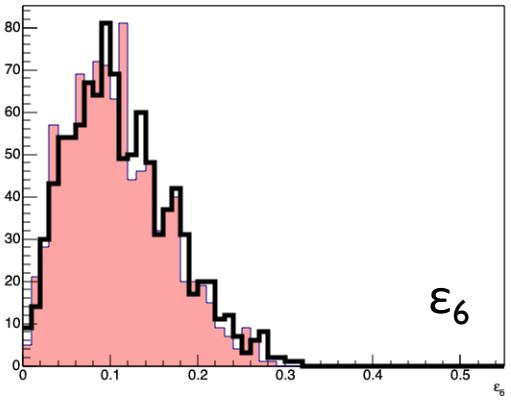
Searching for colorful domain





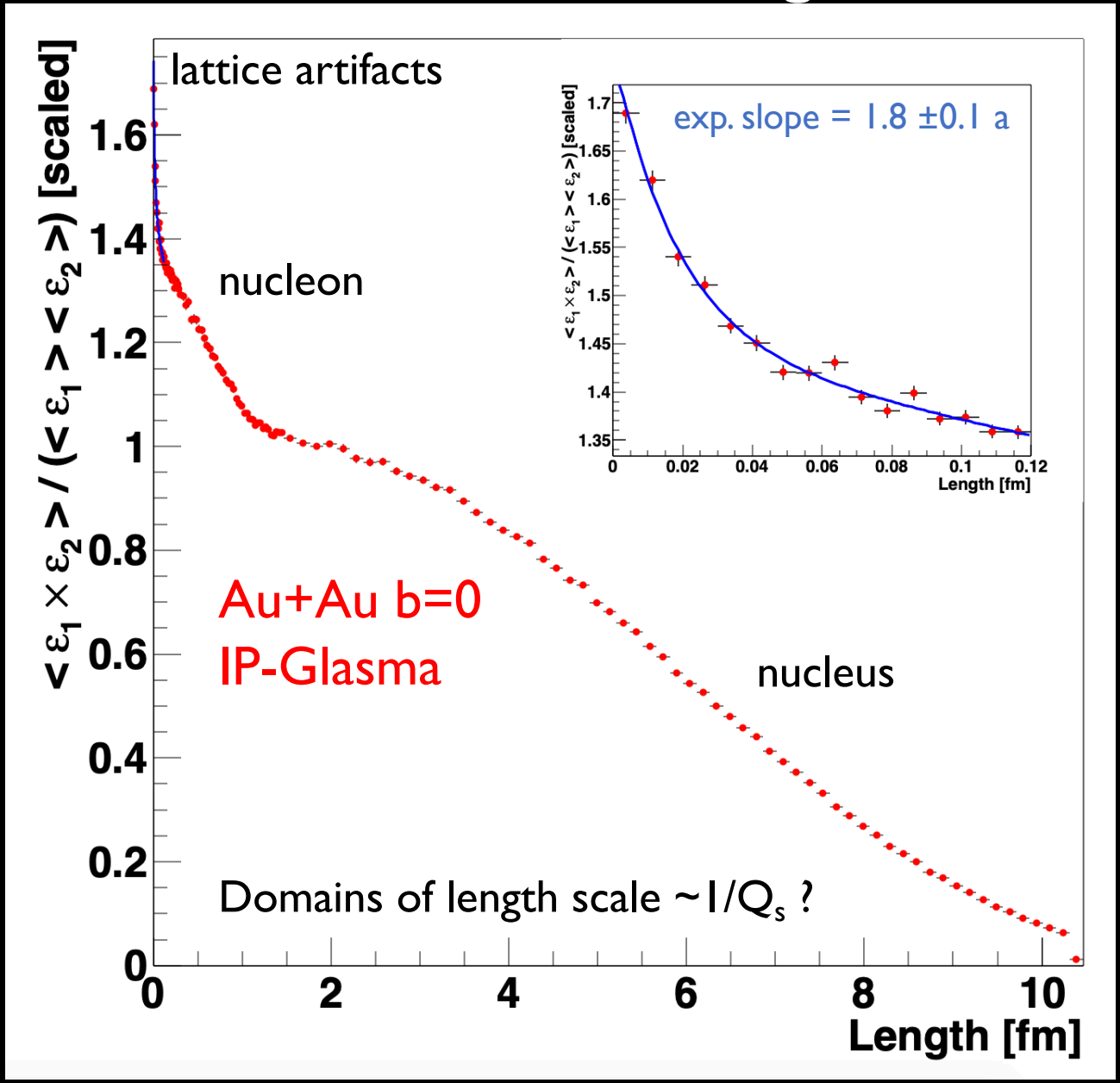




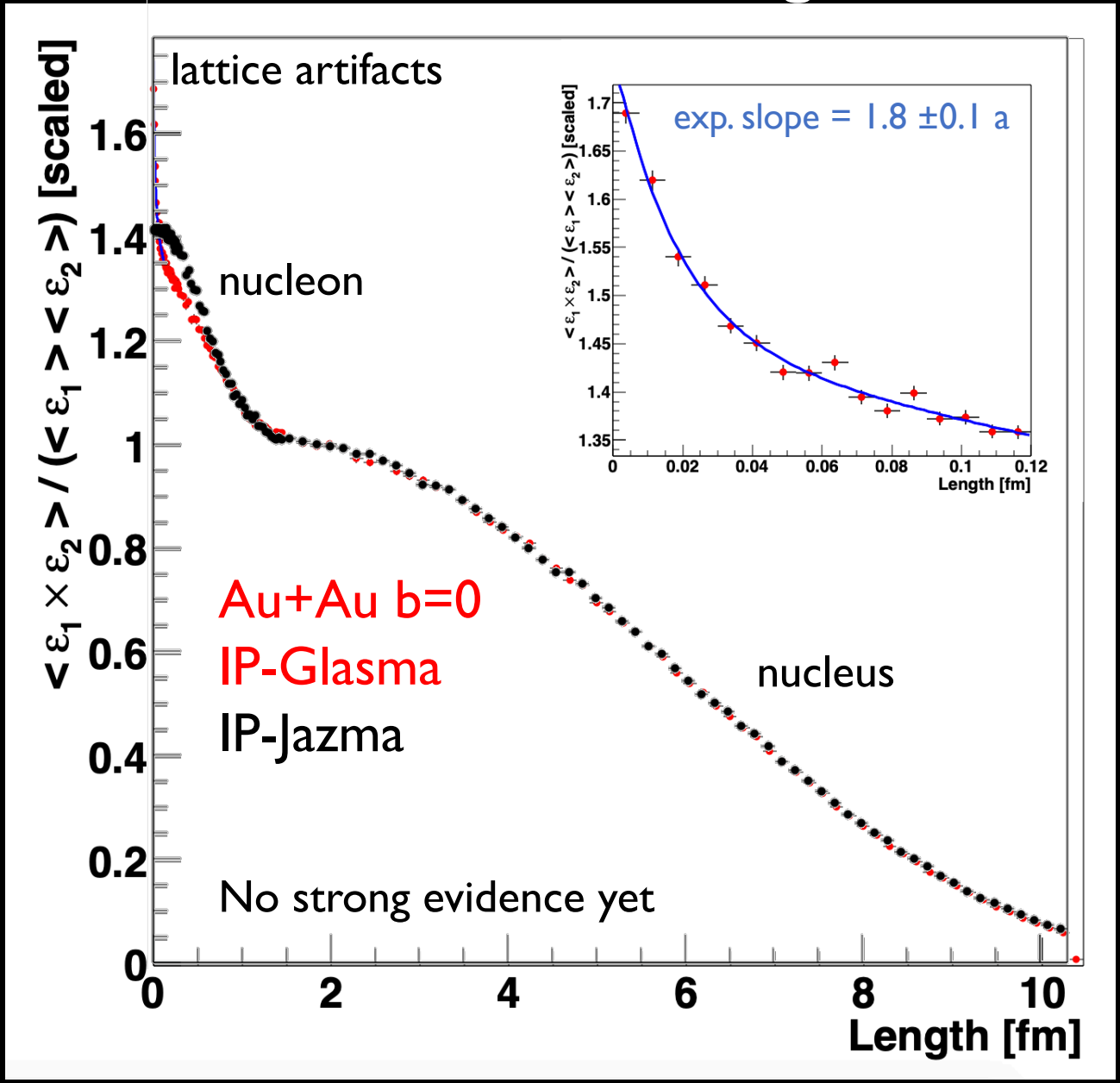


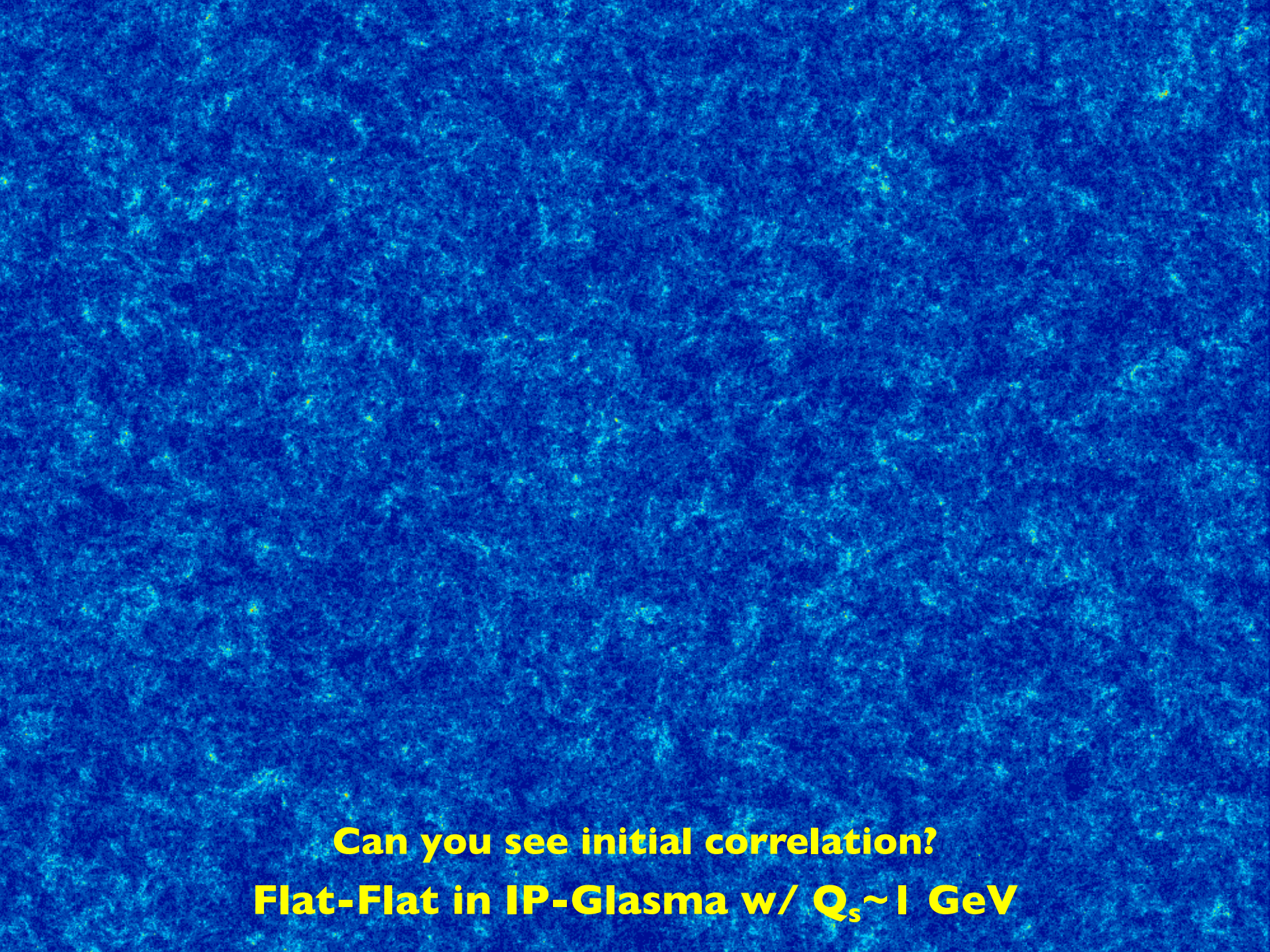
- ***Quite consistent initial geometry***

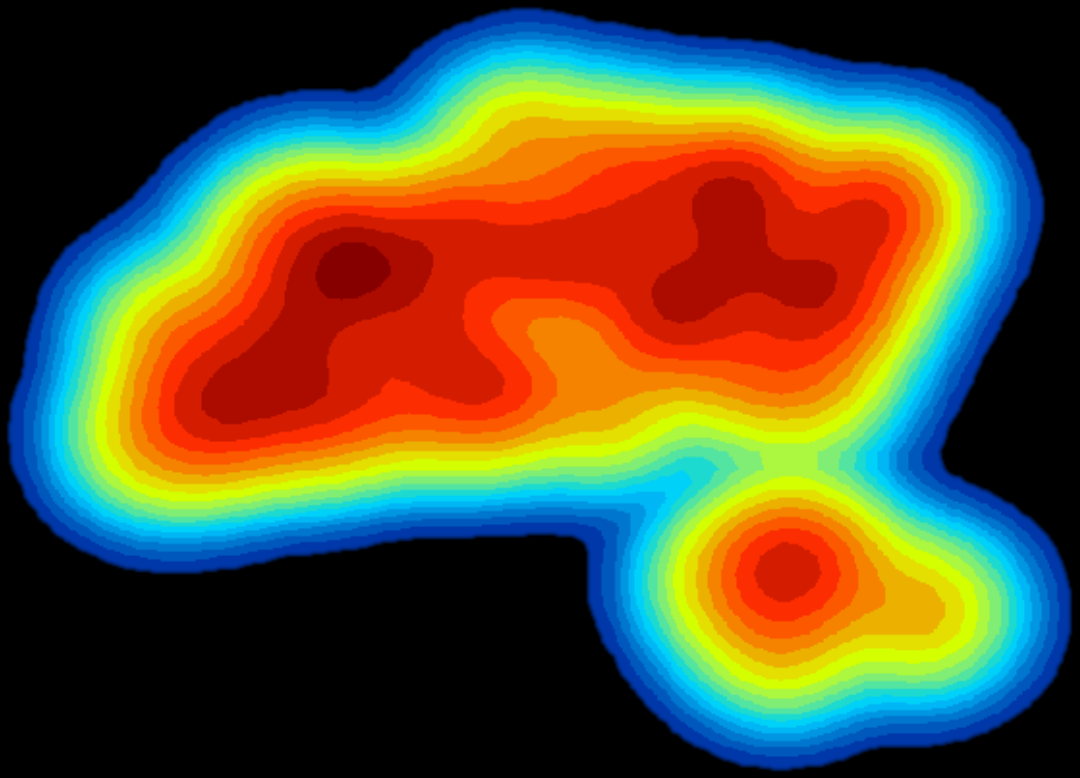
Searching for colorful domain



Searching for colorful domain

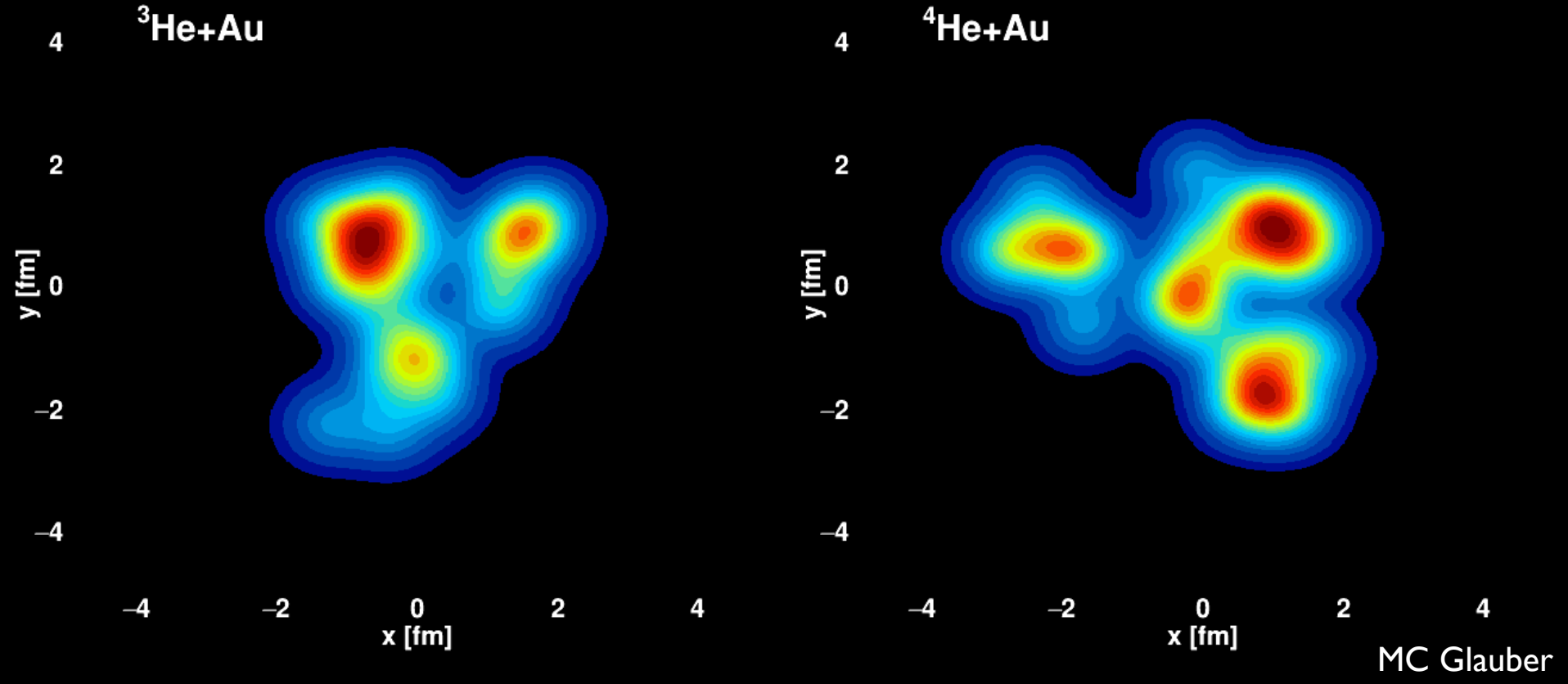



Can you see initial correlation?
Flat-Flat in IP-Glasma w/ Q_s~1 GeV



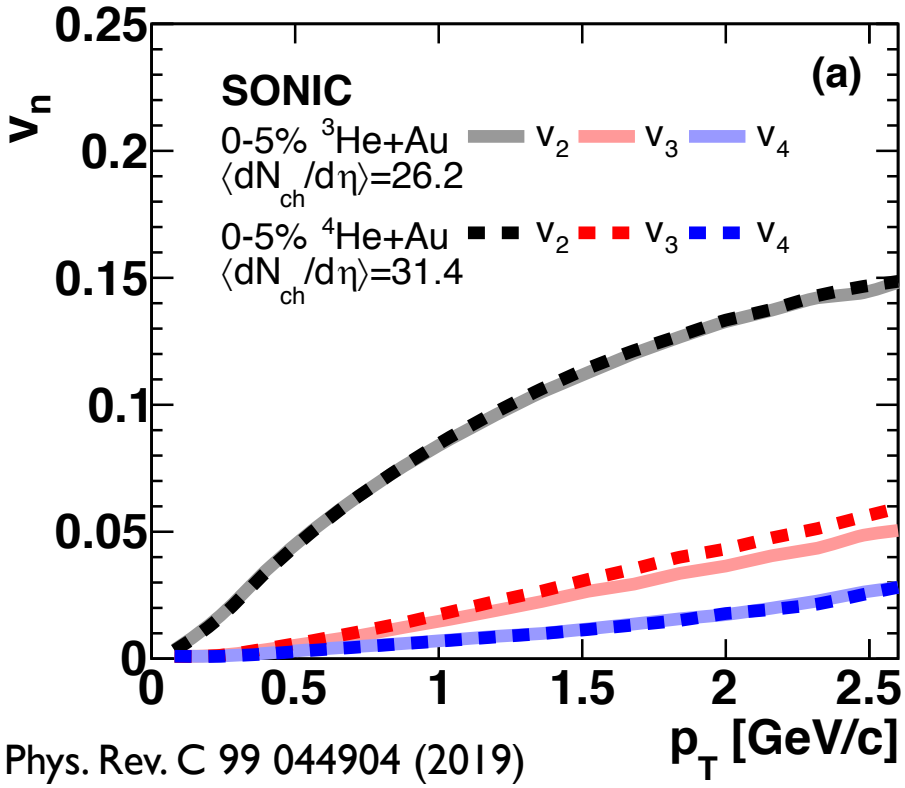
Imagine new geometry!

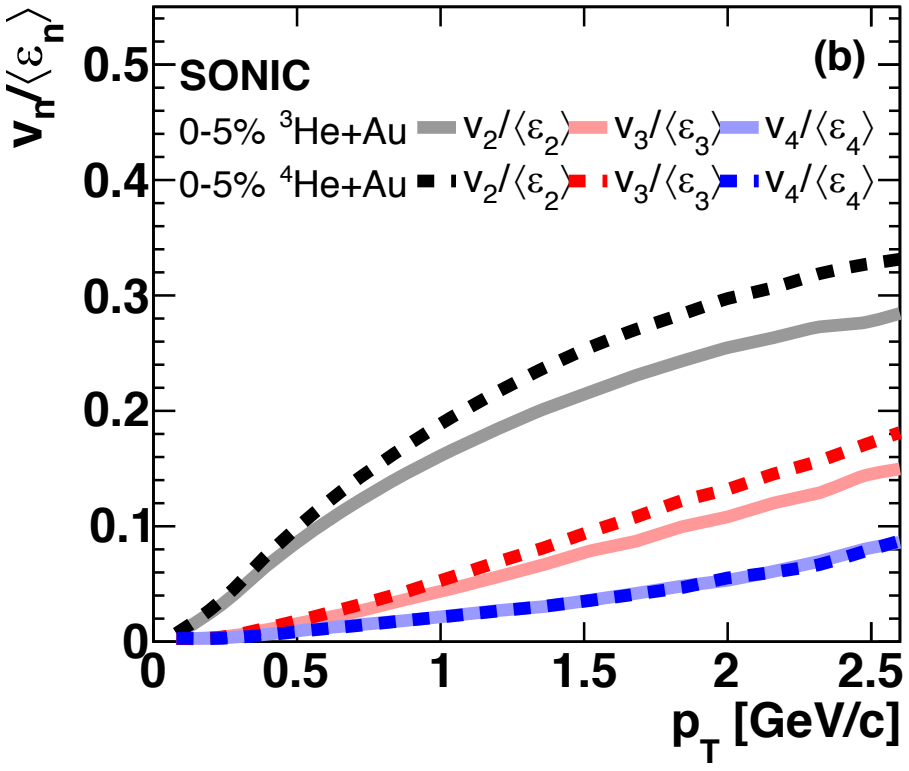
How about ^{4}He?



- Even with additional nucleon in ^{4}He, the size is more compact than ^{3}He
  - RMS for nucleon central coordinates: *1.46 fm for ^{4}He and 1.57 fm for ^{3}He*

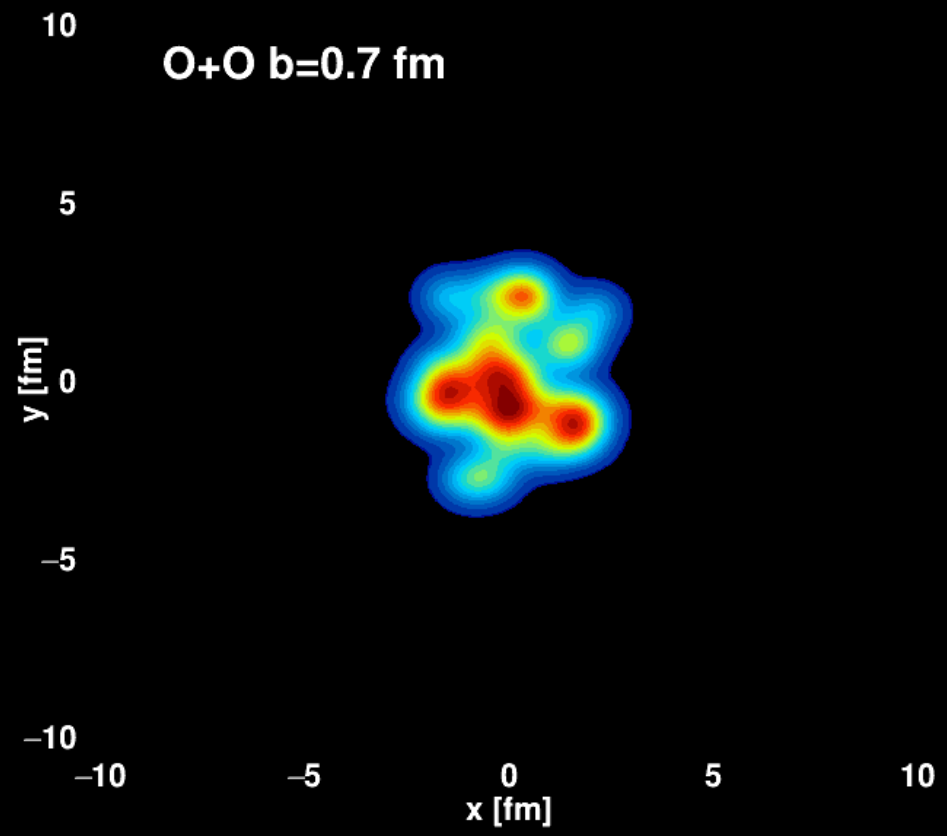
Collectivity in ^{4}He+Au 200 GeV

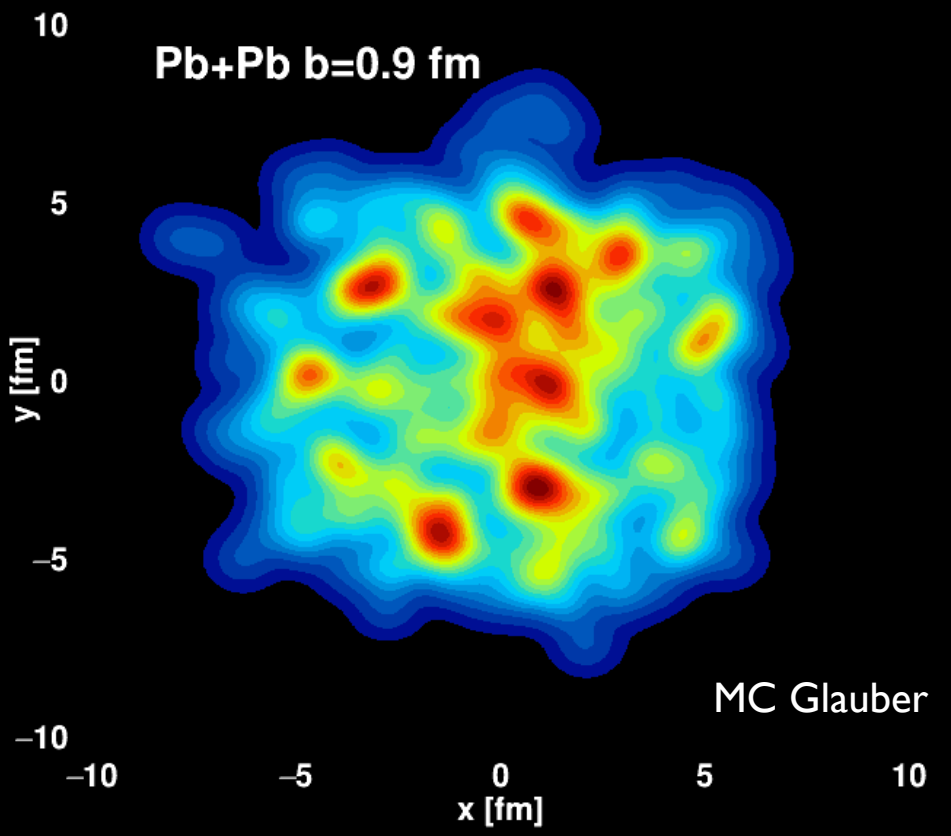




- v_n relative to initial geometry ($v_n/\langle\varepsilon_n\rangle$) in ^{4}He+Au is larger
- *More compact ^{4}He induced hot spot leads to larger translation of geometry to v_n*

New collision system at the LHC

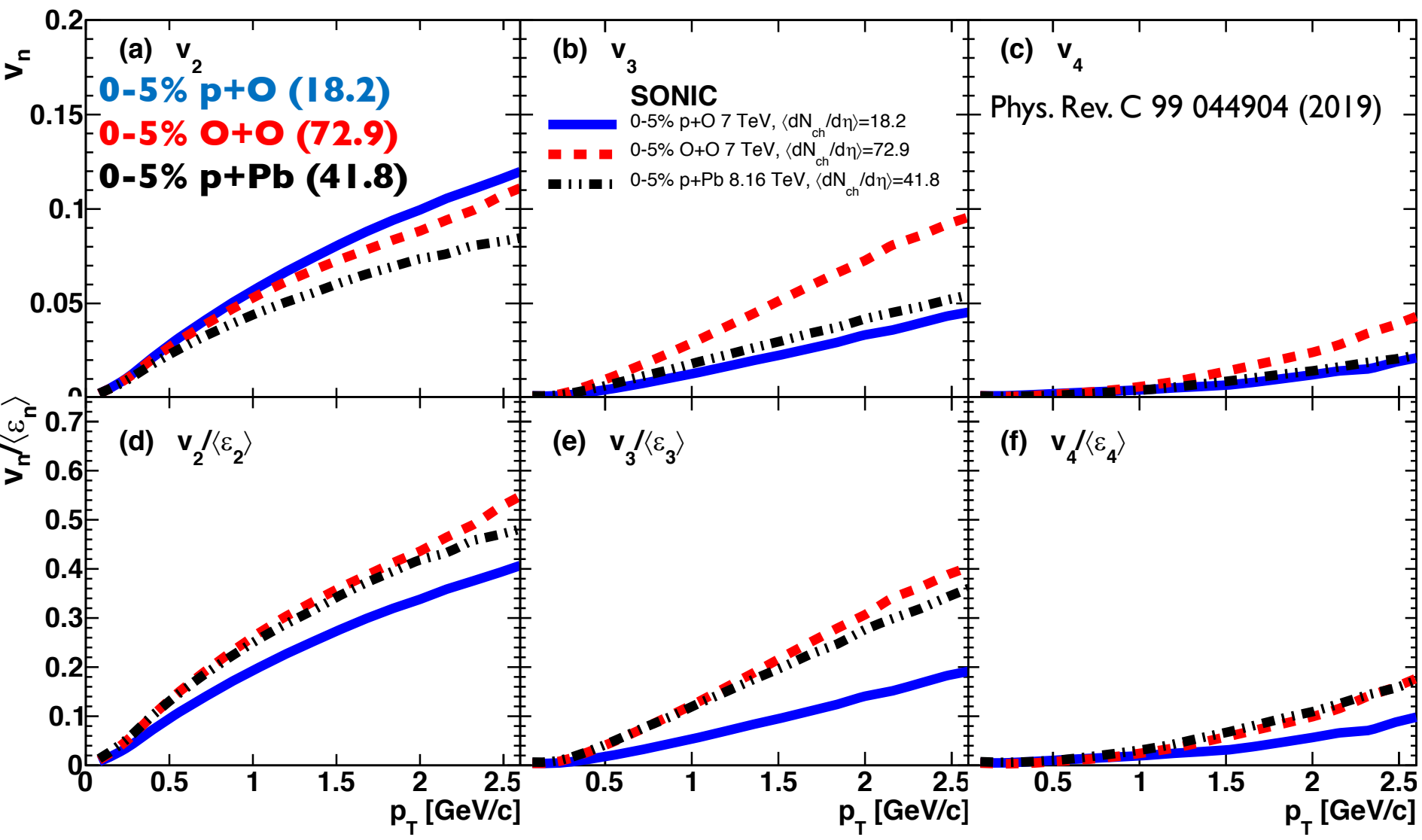




Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	$2.3\ \mathrm{nb}^{-1}$
	pp 5.5 TeV	1 week	$3\ \mathrm{pb}^{-1}$ (ALICE), $300\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $25\ \mathrm{pb}^{-1}$ (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	$3.9\ \mathrm{nb}^{-1}$
	O–O, p–O	1 week	$500\ \mu\mathrm{b}^{-1}$ and $200\ \mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	$0.6\ \mathrm{pb}^{-1}$ (ATLAS, CMS), $0.3\ \mathrm{pb}^{-1}$ (ALICE, LHCb)
	pp 8.8 TeV	few days	$1.5\ \mathrm{pb}^{-1}$ (ALICE), $100\ \mathrm{pb}^{-1}$ (ATLAS, CMS, LHCb)

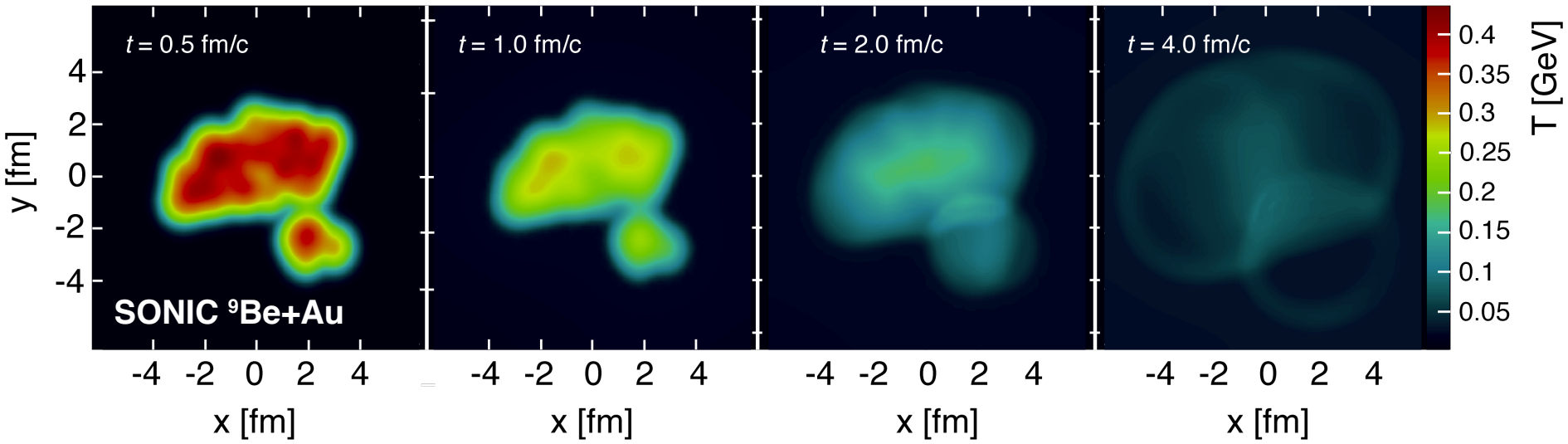
arXiv:1812.06772

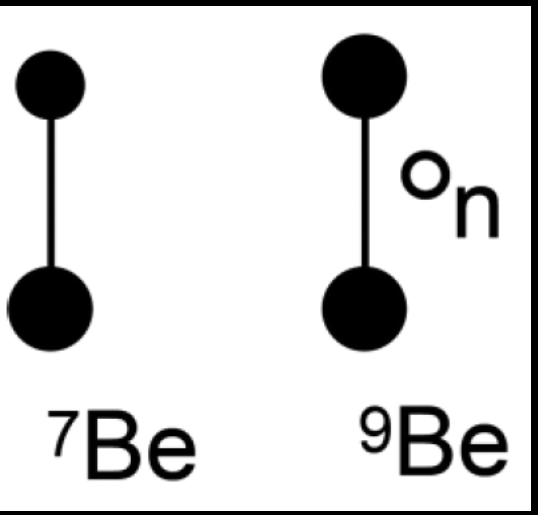
Collectivity in p/O+O 7 TeV



- *Similar $v_n/\langle\varepsilon_n\rangle$ between p+Pb and O+O and smaller in p+O*

α-clustering in ^{9}Be+Au





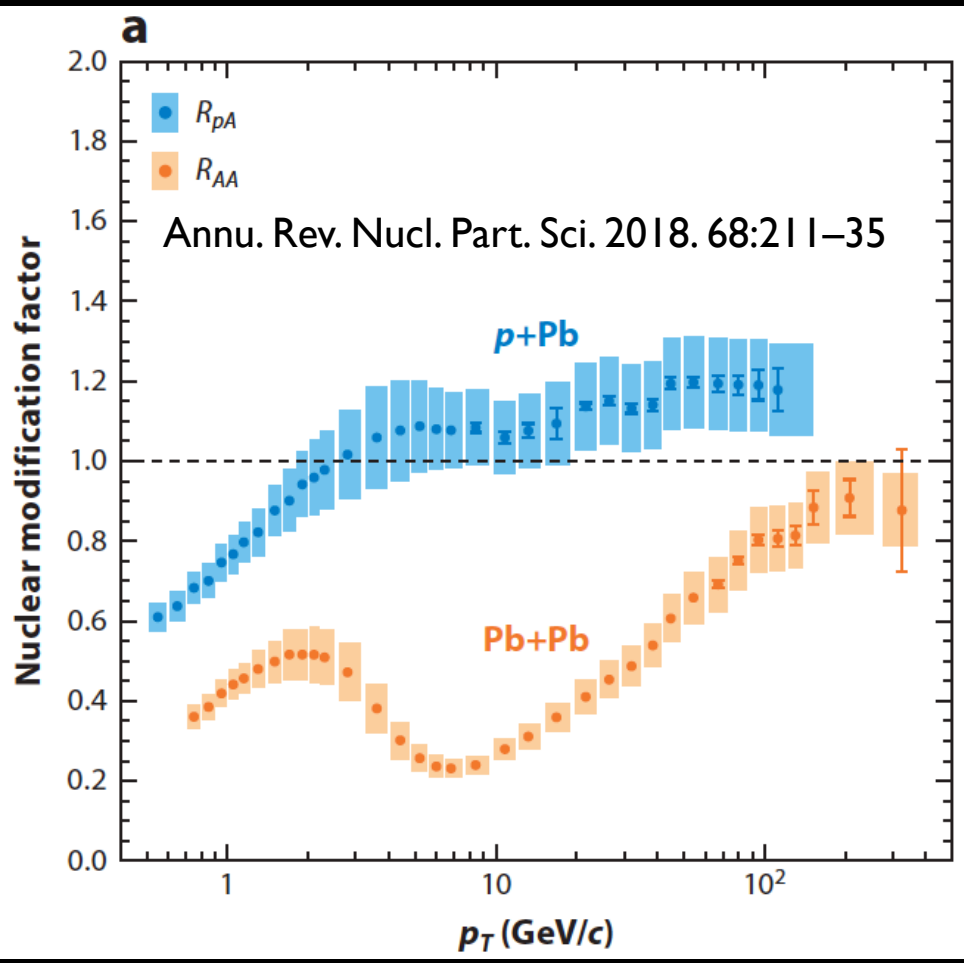
- In collisions between ^{7,9}Be and large nucleus, a significant deformation of ellipticity with ^{9}Be because of additional neutron

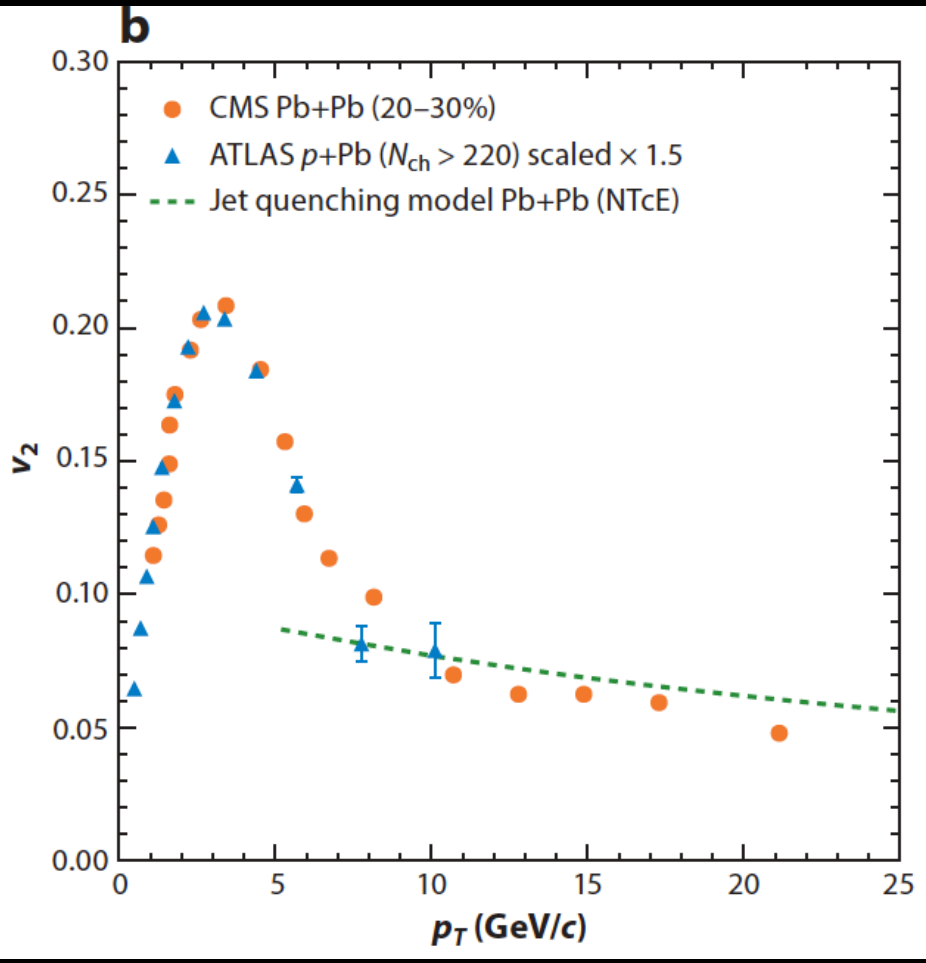
Phys. Rev. C 97 034912 (2018)

Collective behaviors have been observed everywhere!

Can we learn more by searching for particles not participating into the collective behavior?

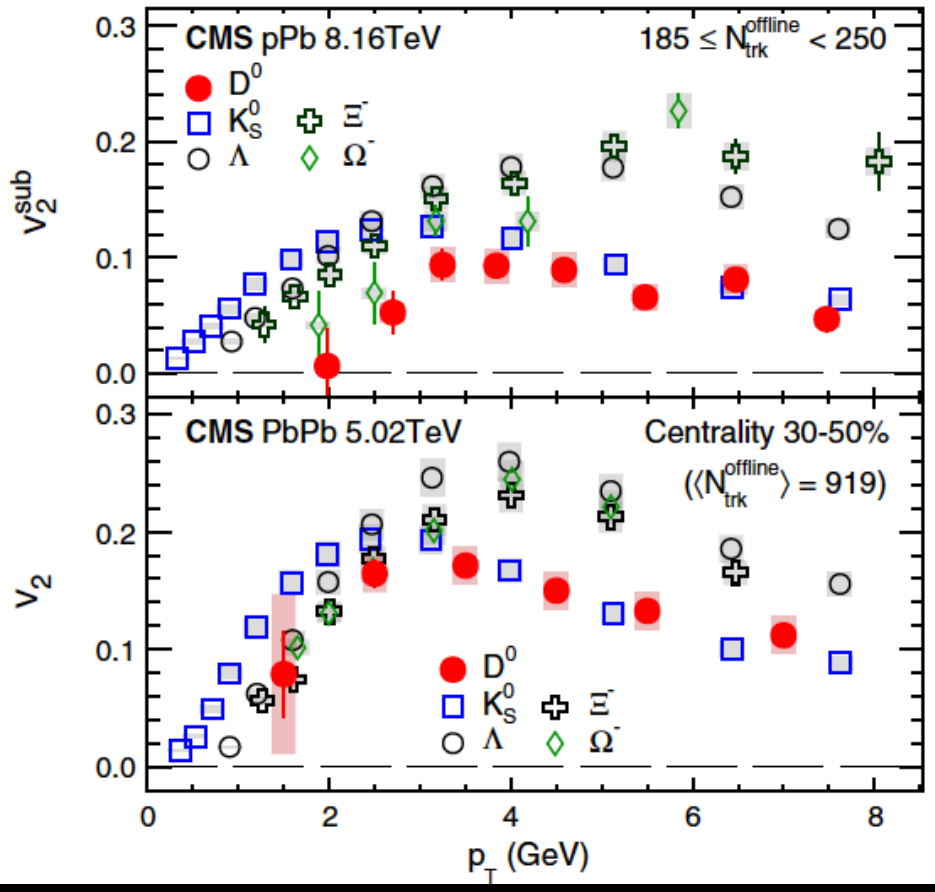
High p_T in small systems

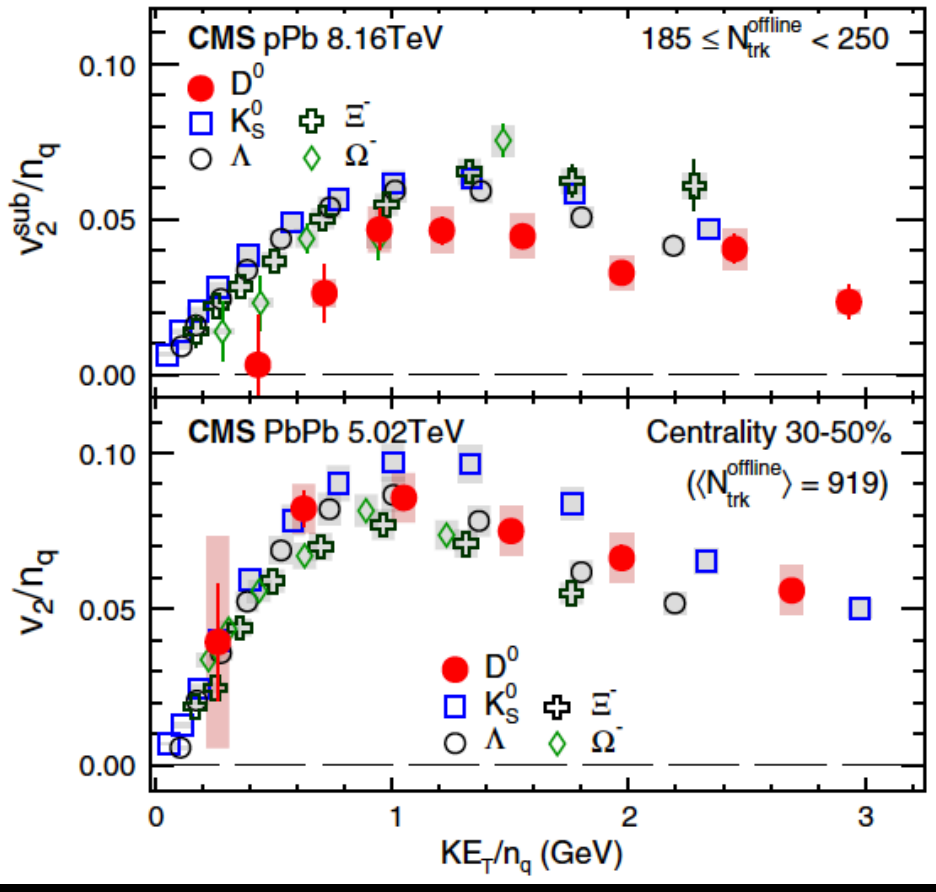




- One of explanation of high p_T v_2 in heavy-ion is differential energy loss
- Interesting study of high p_T v_2 in small systems where no clear evidence of energy loss has been observed yet

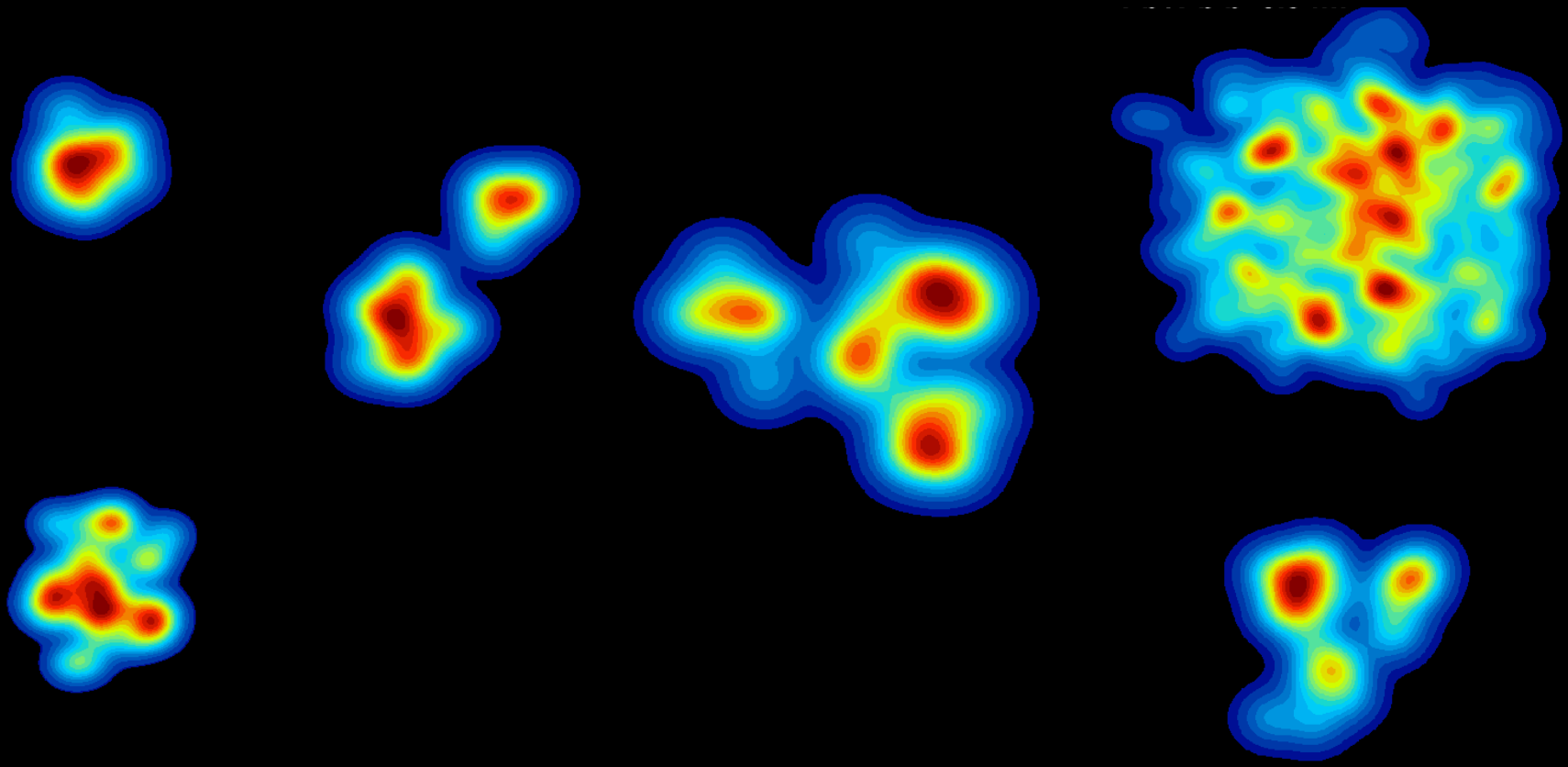
Heavier quarks





Phys. Rev. Lett. 121, 082301 (2018)

- Strong flow for charm quarks in p+Pb and Pb+Pb
- *How about bottom quarks?*



Many recipes for Quark-Gluon Soup!

Lots of efforts are on going to find out key ingredients!

BACKUP