Experimental results on collective flow in small system collisions at RHIC

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What are we trying to learn?

Are QGP droplets formed in small collisions?
Is the pre-hydrodynamic state strongly, weakly, un-coupled?
What are the factors for initial entropy production?

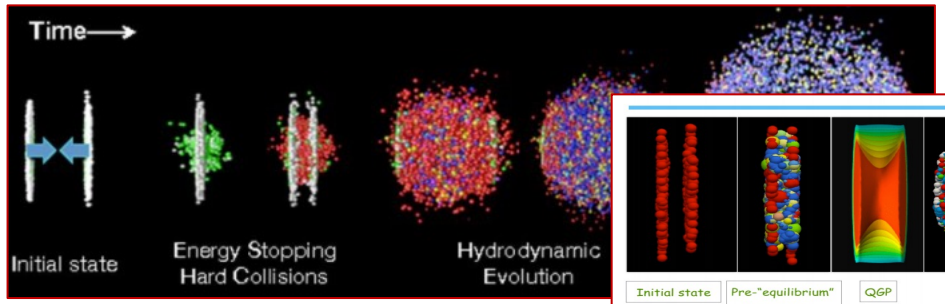
Do we have a well-formulated plan to gain this knowledge?

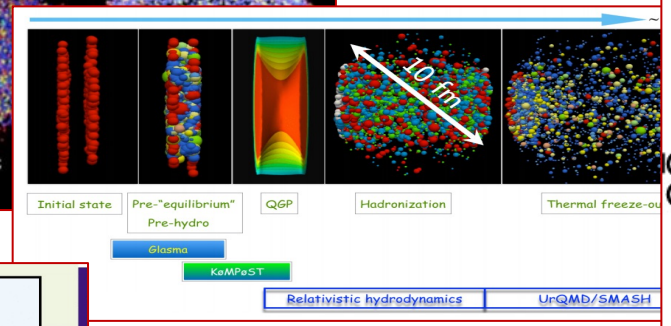
We thought so → *p/d/^{3}He+Au collisions*
→ *d+Au beam energy scan*
More data at RHIC?

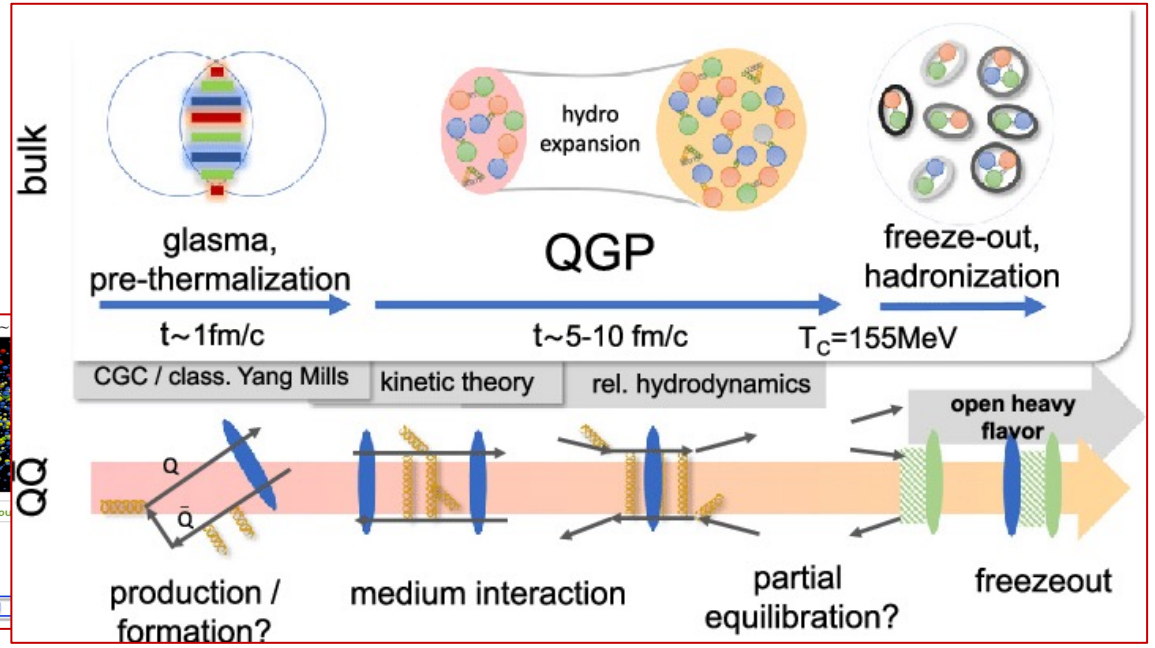
Where does this knowledge gained lead us?

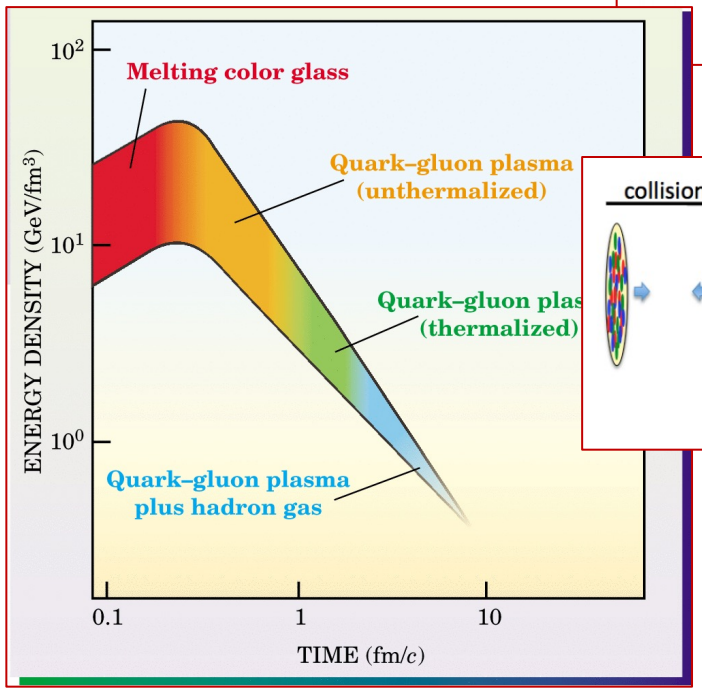
Let's wait until the end… which is soon…

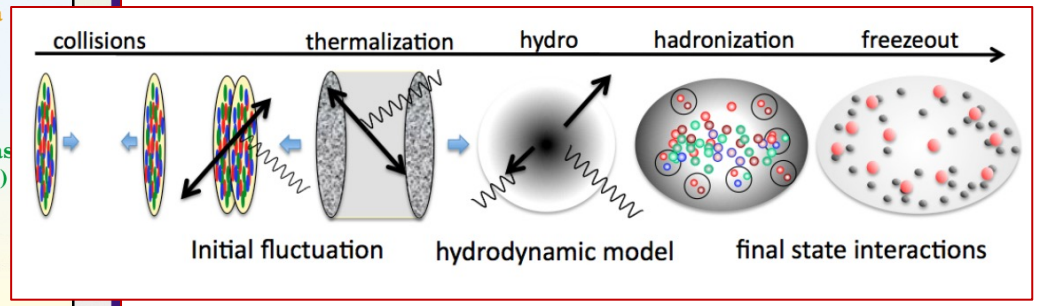
What is the standard evolution model of heavy ion collisions?

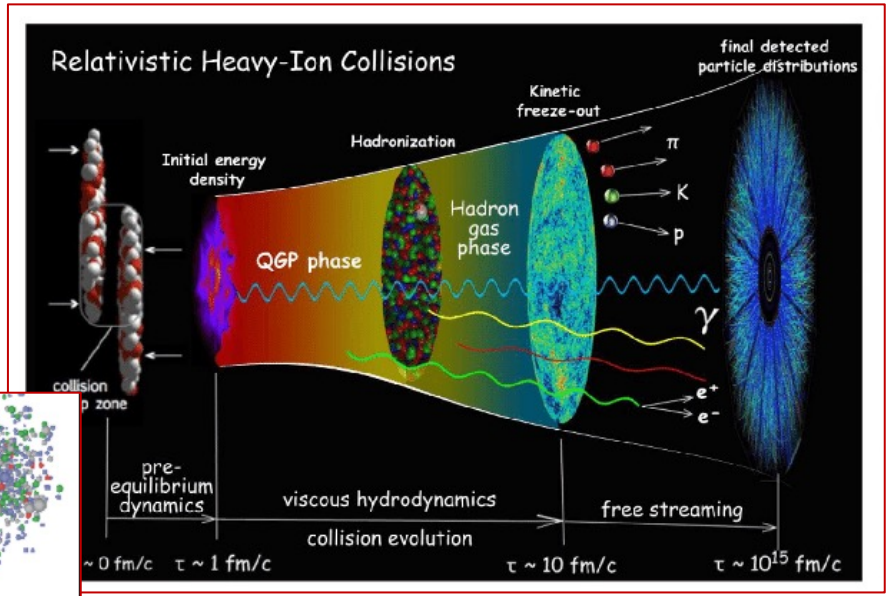


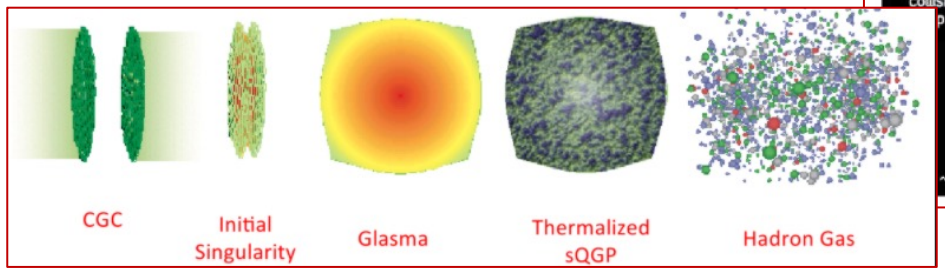












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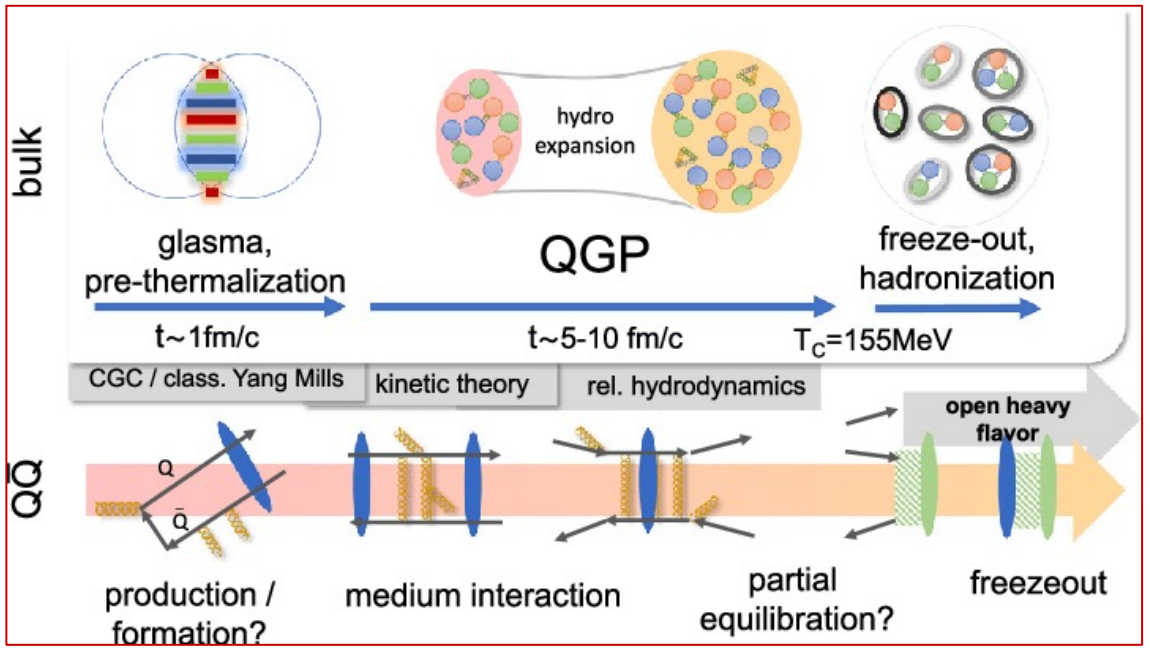


Pre-equilibrium, pre-thermalization → Pre-hydrodynamization

The field has still not come fully to grips with the fact that the QGP never equilibrates. Remember all the conference sessions on the “fast equilibration puzzle”?

After 20 years, is there really any experimental evidence for very weakly coupled initial state (glasma, CGC, free stream)?

Just like strangeness as a QGP signal, pushing to smaller (pp, pA) systems has been insightful. How do small system collisions fit into this timeline?

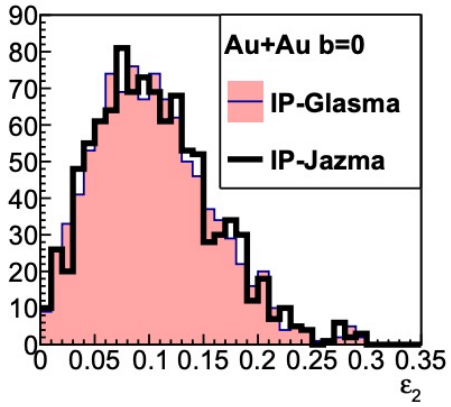
Weak versus Strong Coupling in Initial State?

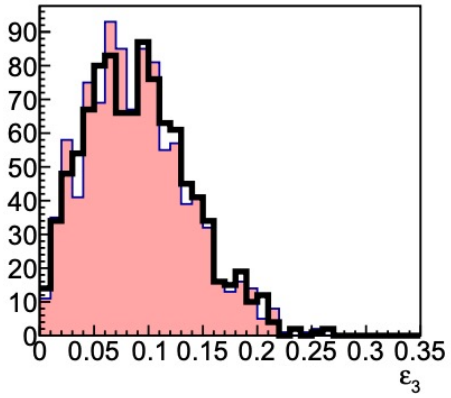
No Coupling - free streaming (too often used)

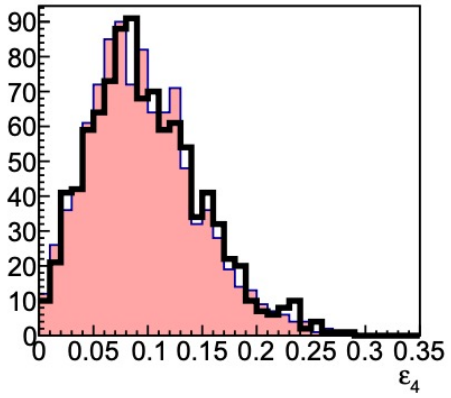
Weak coupling – Color Glass Condensate / Glasma ($\alpha_s \rightarrow 0$)

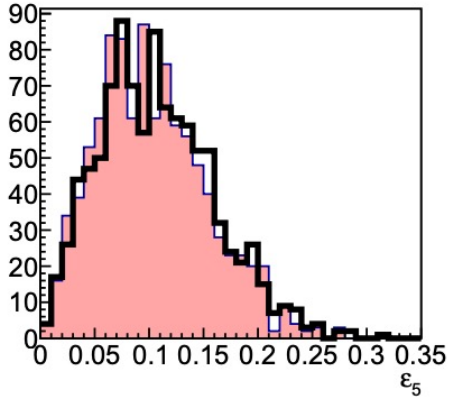
Strong Coupling – AdS/CFT ($\alpha_s \rightarrow \infty$)

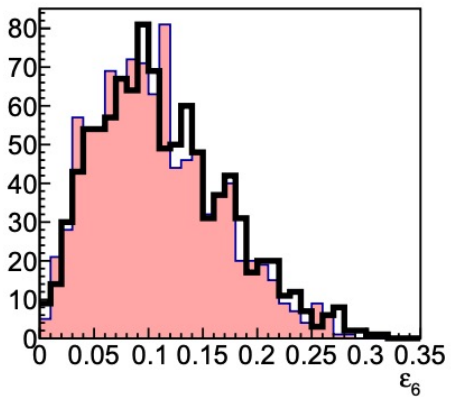
No evidence for weakly coupled initial state in A+A Collisions

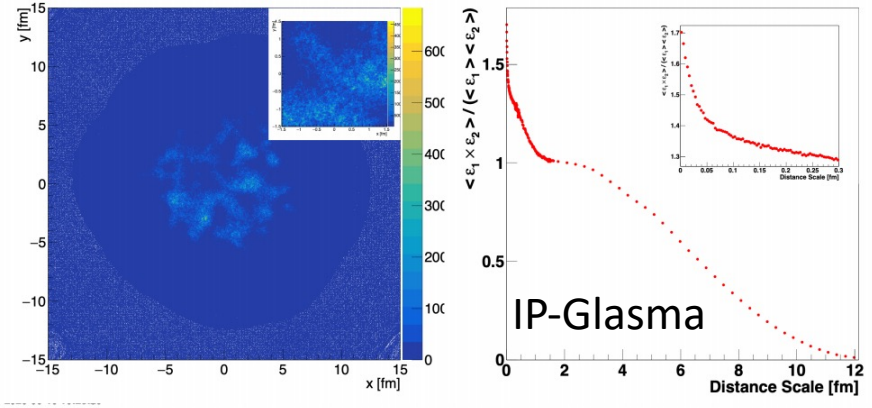


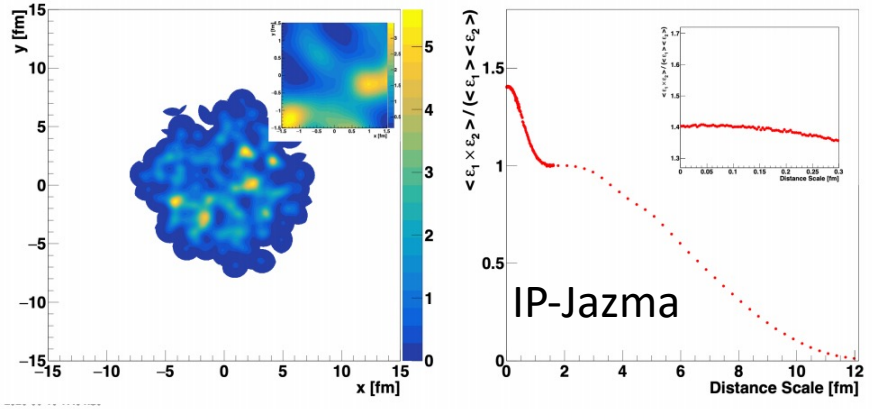










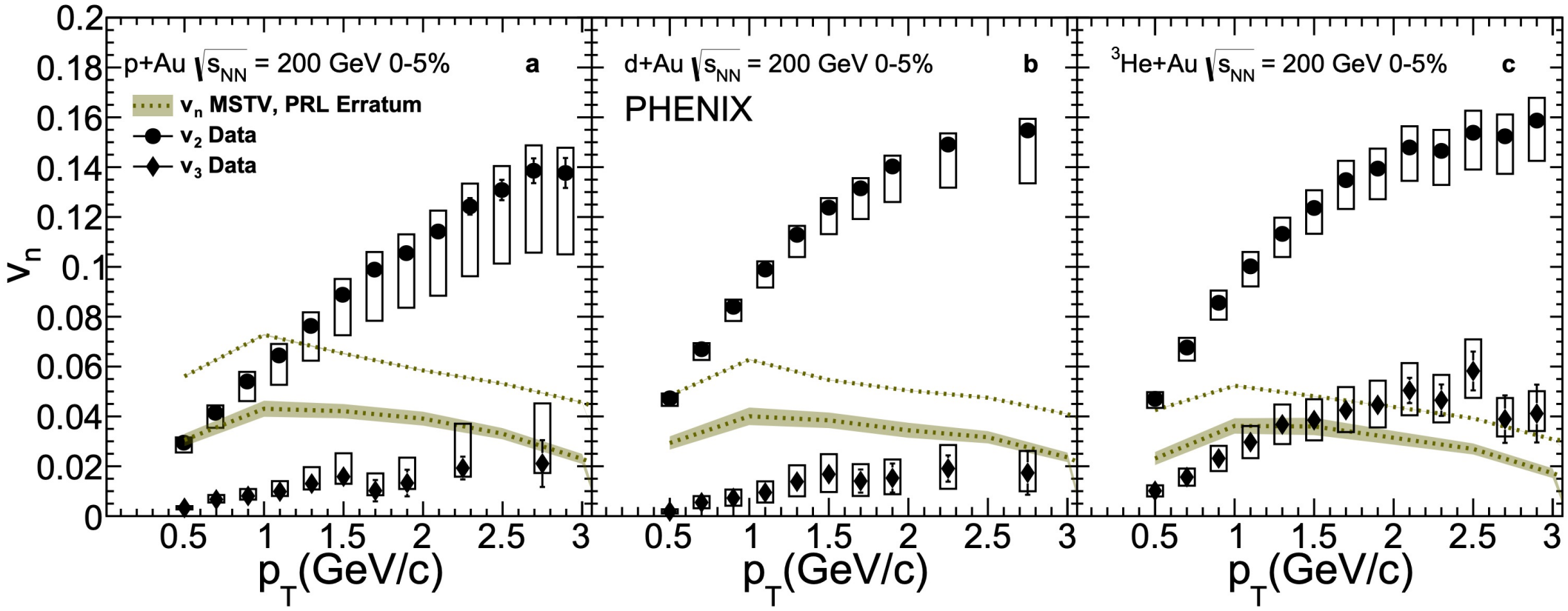


IP-Glasma as part of evolution package has been very successful (see for example https://arxiv.org/abs/2005.14682); however, that really has nothing to do with weak coupling, color domains, etc.

Essentially just T_{AB} scaling of Gaussian nucleons or 3 quarks and Q_s^2 fluctuations put in by hand (also in IP-Glasma).

https://arxiv.org/abs/2008.08729

No evidence for weakly coupled initial state in small collisions systems

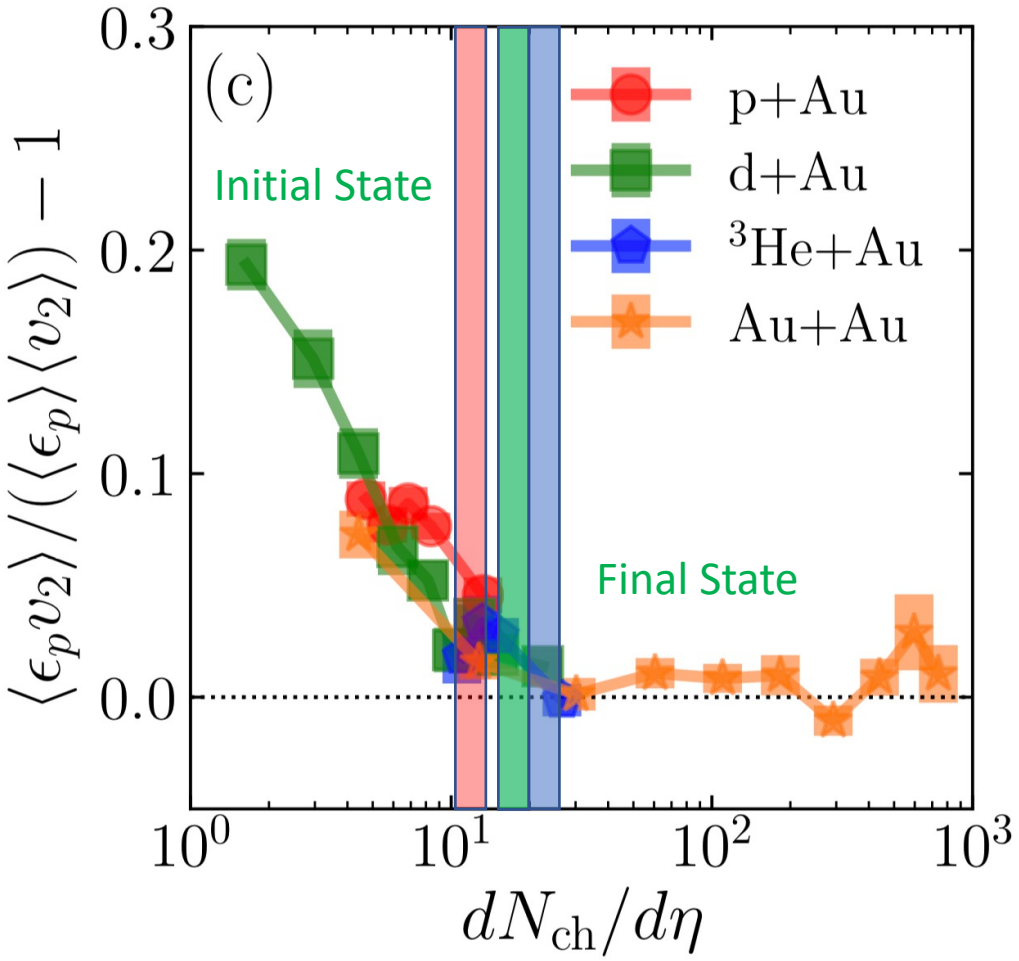


"In summary, due to the numerical error specified,
the hierarchy of $v_2;_3$ seen in the PHENIX data is not seen in our model.
It cannot therefore provide a viable description of the data."

Erratum: Phys.Rev.Lett. 121 (2018) no.5, 052301
Corrigendum: Phys.Lett. B788 (2019) 161-165

New idea: weakly coupled initial state in small collisions systems

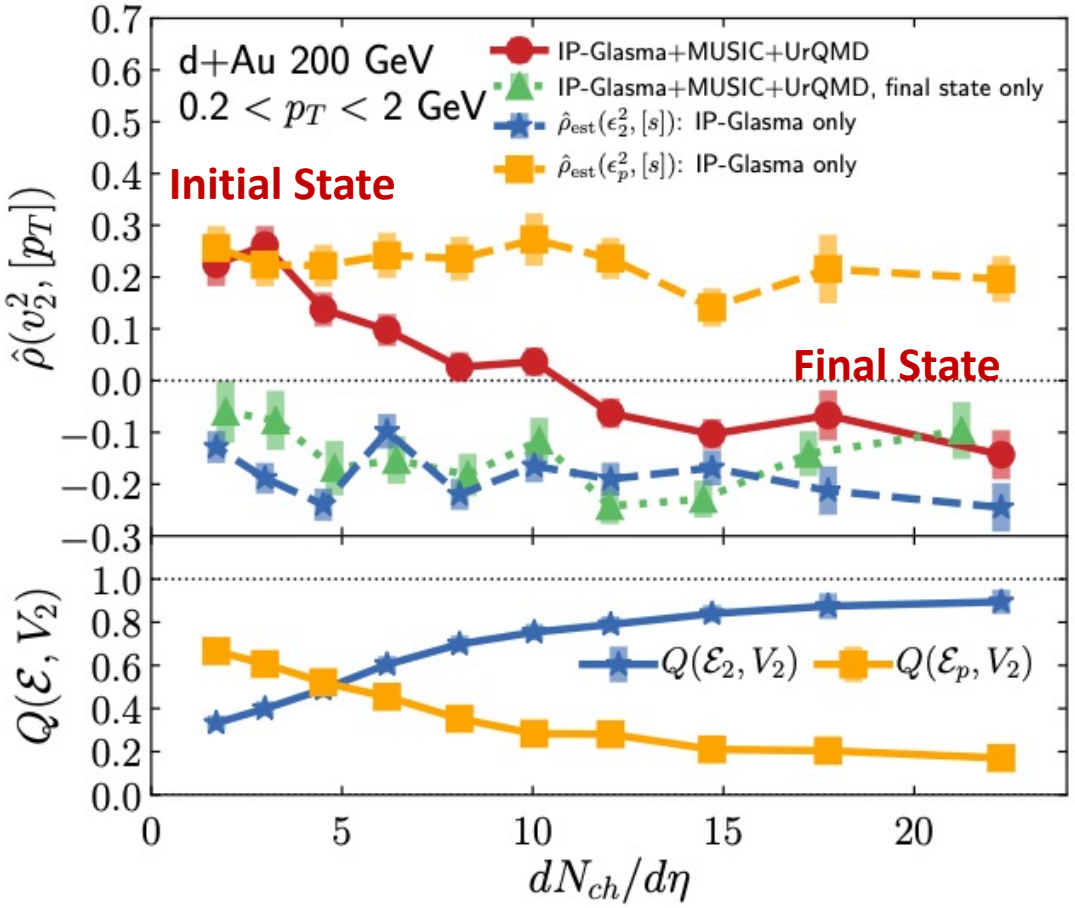
https://arxiv.org/abs/1908.06212



0-5% Central pAu dAu ^{3}HeAu

PHENIX: Phys.Rev.Lett. 121 (2018) no.22, 222301

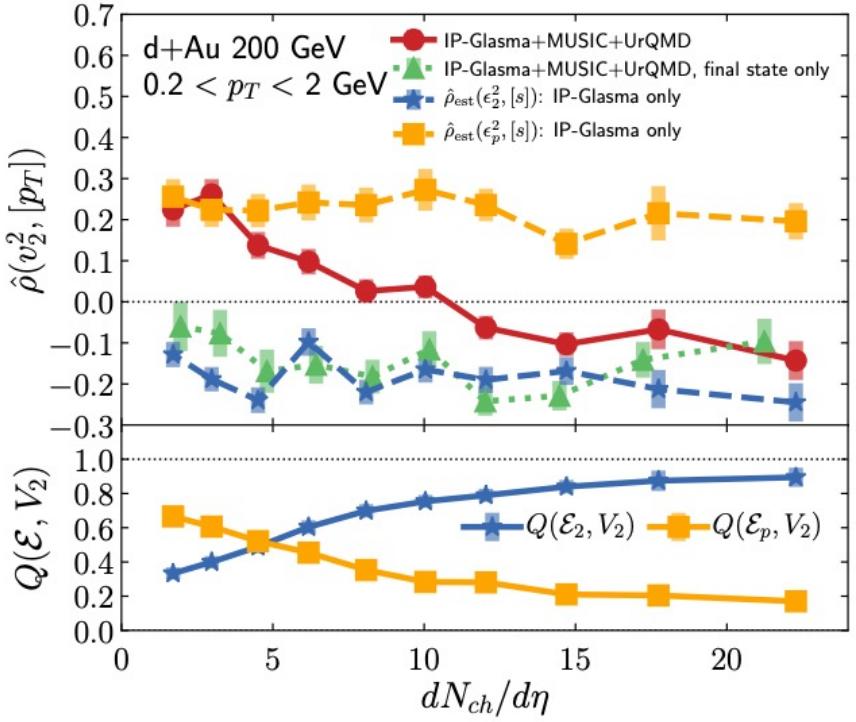
https://arxiv.org/abs/2006.15721



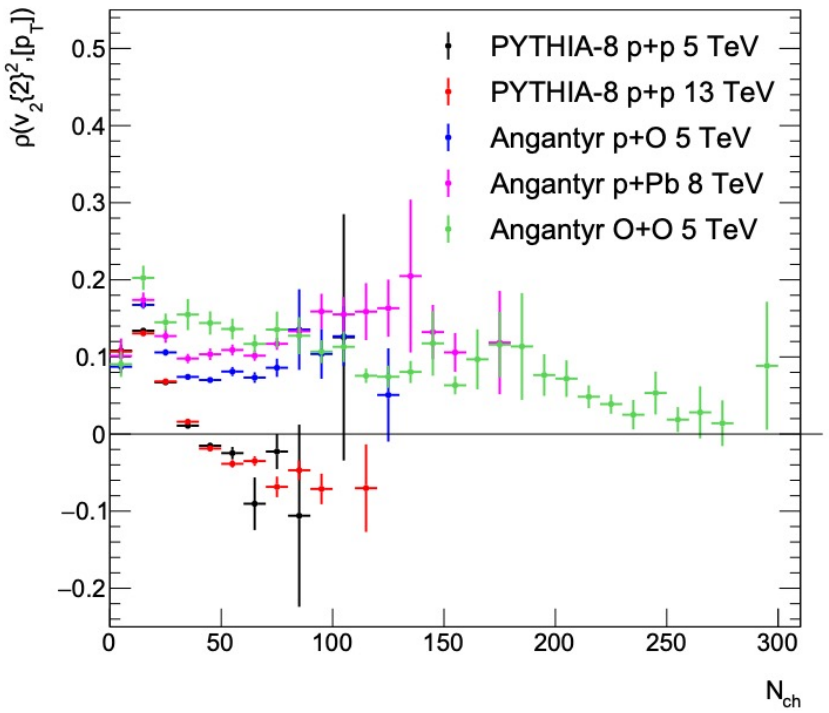
$p_T - v_n$ Correlator

Forwards or Backwards?

https://arxiv.org/abs/2006.15721



https://arxiv.org/abs/2103.01348
https://arxiv.org/abs/2102.05200



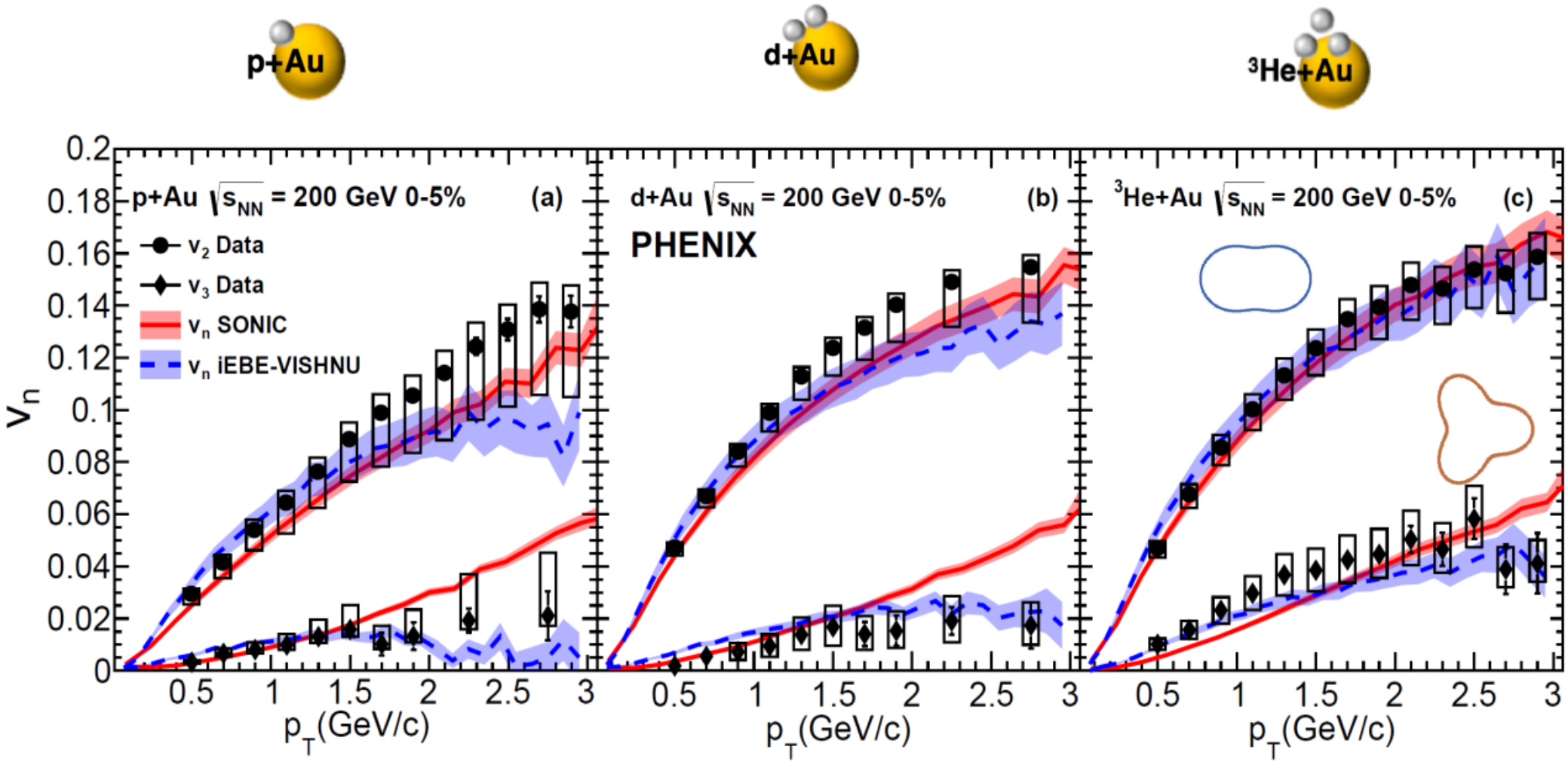
Odd to propose a clean signature for "exotic" glasma diagrams
as positive ρ at $dN_{ch}/d\eta$ ~ 2-6
when standard QCD hard scattering diagrams (PYTHIA)
produce the same sign effect.

If he cannot guess your weight, you can win anything…
"Anything in this three inches. Right in here, this area, that includes the Chiclets, but not the erasers."

So now we can only see CGC effects in collisions with $dN_{ch}/d\eta \sim 2$

I must be missing something about dense packing of gluons…

Who knows which movie this is from?



PHENIX, **Nature Phys. 15 (2019) no.3, 214-220**

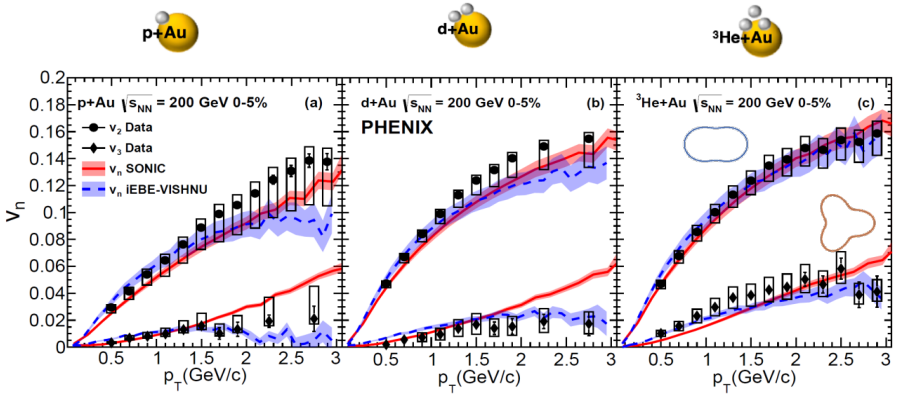
(More) Definitive Proof of Geometry & Hydrodynamics

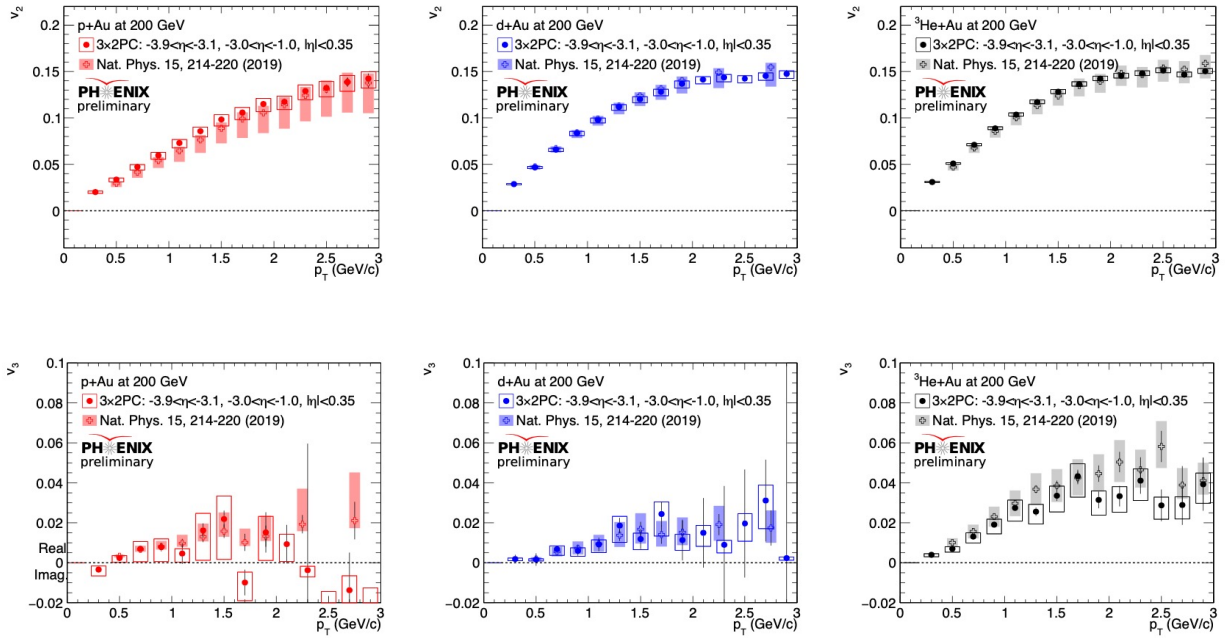
Are we done?

1) At QM19 in Wuhan the STAR Collaboration challenged the validity of the PHENIX measurements

PHENIX has carried out a new, 3 x PC analysis for all systems with (a) a new code base, (b) different analyzer, (c) FVTX tracks instead of hits, (d) additional systematic checks.

Nature Physics measurements confirmed. PHENIX manuscript with these results and additional kinematic selections to be submitted in the next month.





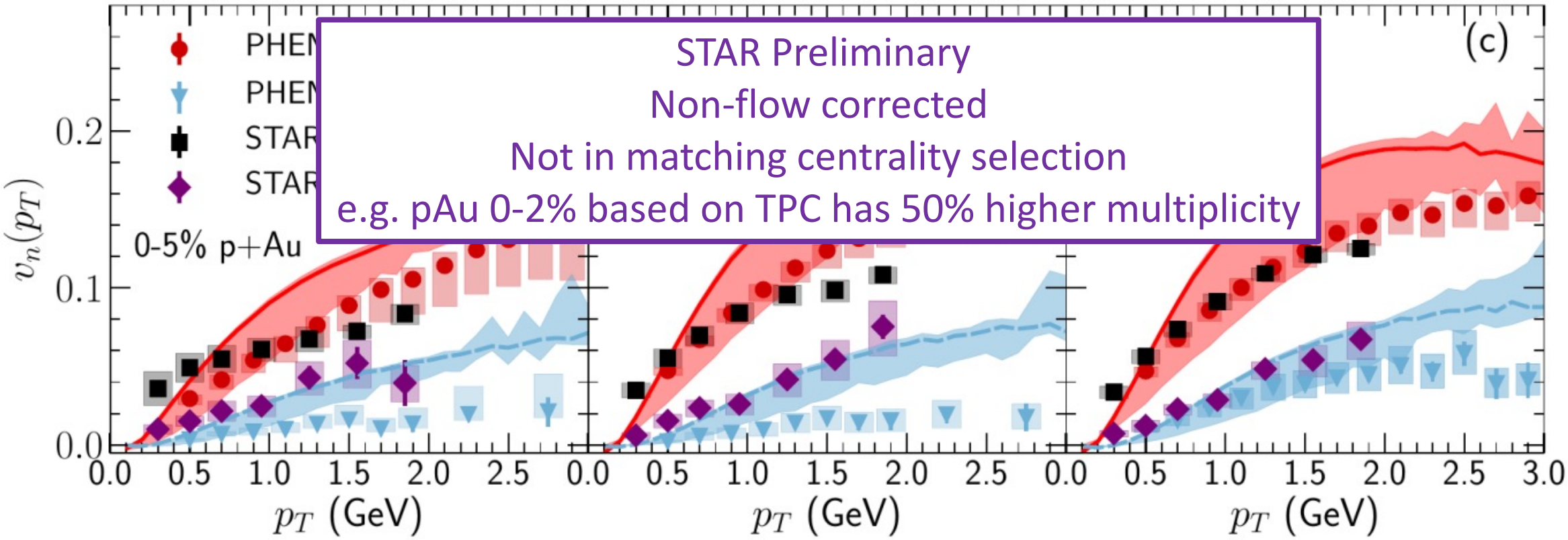
Are we done?

2) At QM19 in Wuhan the STAR Collaboration showed new preliminary experimental results.

v_2 results "consistent", tension in pAu/dAu

v_3 results "differ" in pAu, dAu

→ How to understand, resolve?



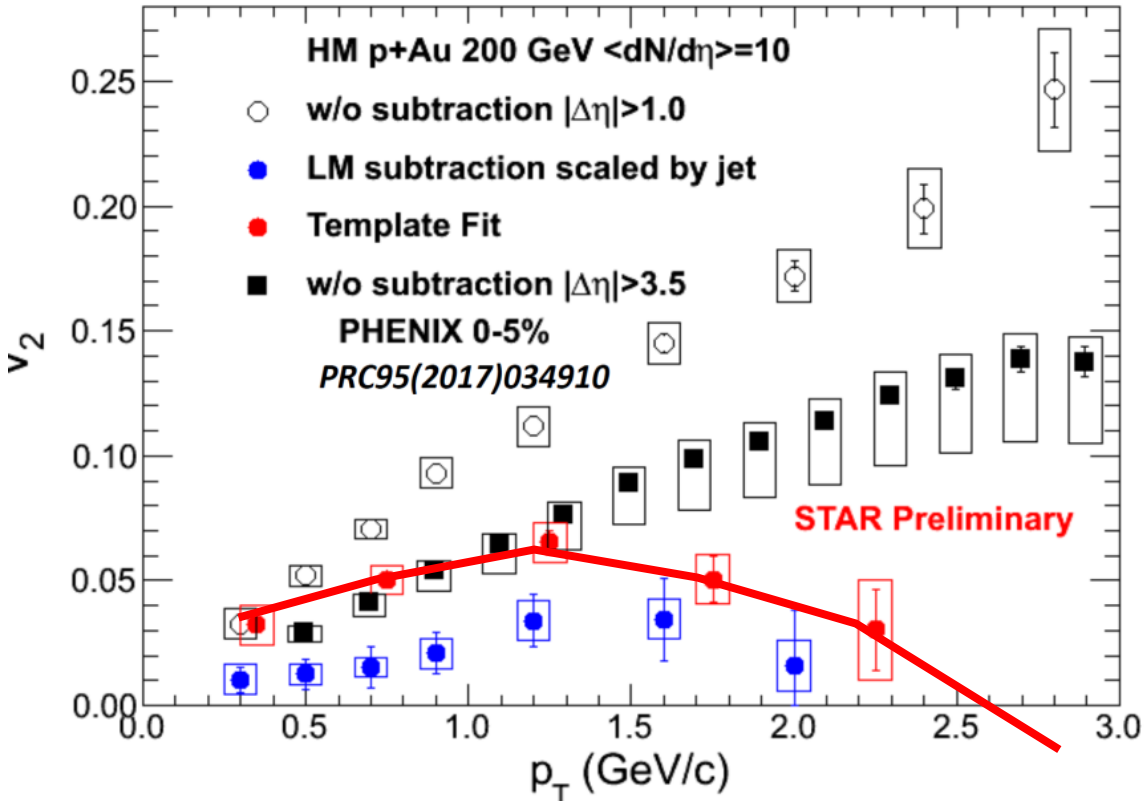
How to Address Experimentally?

PHENIX has done due diligence to confirm experimental results. PHENIX manuscript submission forthcoming. Manuscript will include tables with all 2-particle correlation coefficients (c_1, c_2, c_3, c_4) to enable future studies.

STAR is confirming their results with an independent analysis. Publication of results will be highly beneficial. Important to include results with matched PHENIX centrality selection and extend to p_T = 3 GeV to show when / where non-flow corrections break down.

Future measurements in pAu by sPHENIX and STAR could be elucidating as well. Recently taken O+O data by STAR adds significantly to the program.

How to Address Non-Flow?

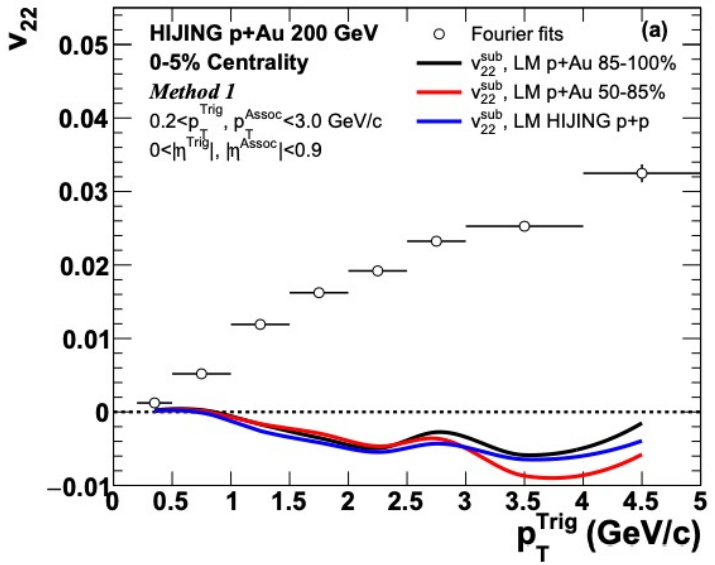


Including in published results up to p_T = 3 GeV is critical.

Examination of Flow and Non-Flow Factorization Methods in Small Collision Systems

S.H. Lim,[1] Q. Hu,[1] R. Belmont,[2] K.K. Hill,[1] J.L. Nagle,[1] and D.V. Perepelitsa[1]
[1] *University of Colorado, Boulder, Colorado 80309, USA*
[2] *University of North Carolina, Greensboro, North Carolina 27413, USA*
(Dated: March 1, 2019)

https://arxiv.org/abs/1902.11290



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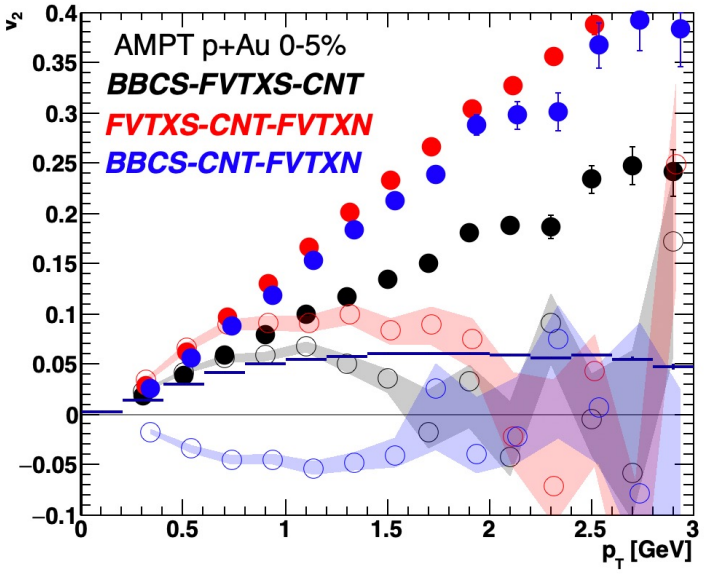
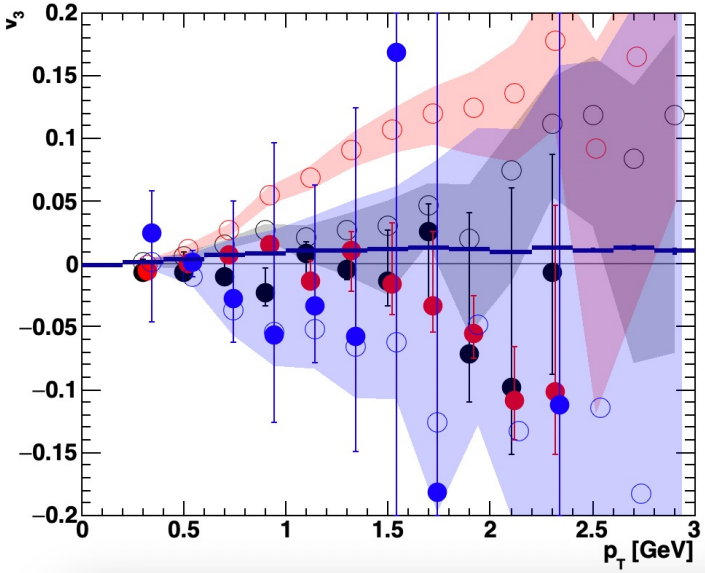




Full AMPT modeling of 3 x 2-particle correlations

Filled markers = raw

Open markers = c_1 non-flow applied

Non-flow method not validated by AMPT.

AMPT does have larger non-flow compared to data.

What are other options to test "closure" on models with both flow and non-flow?

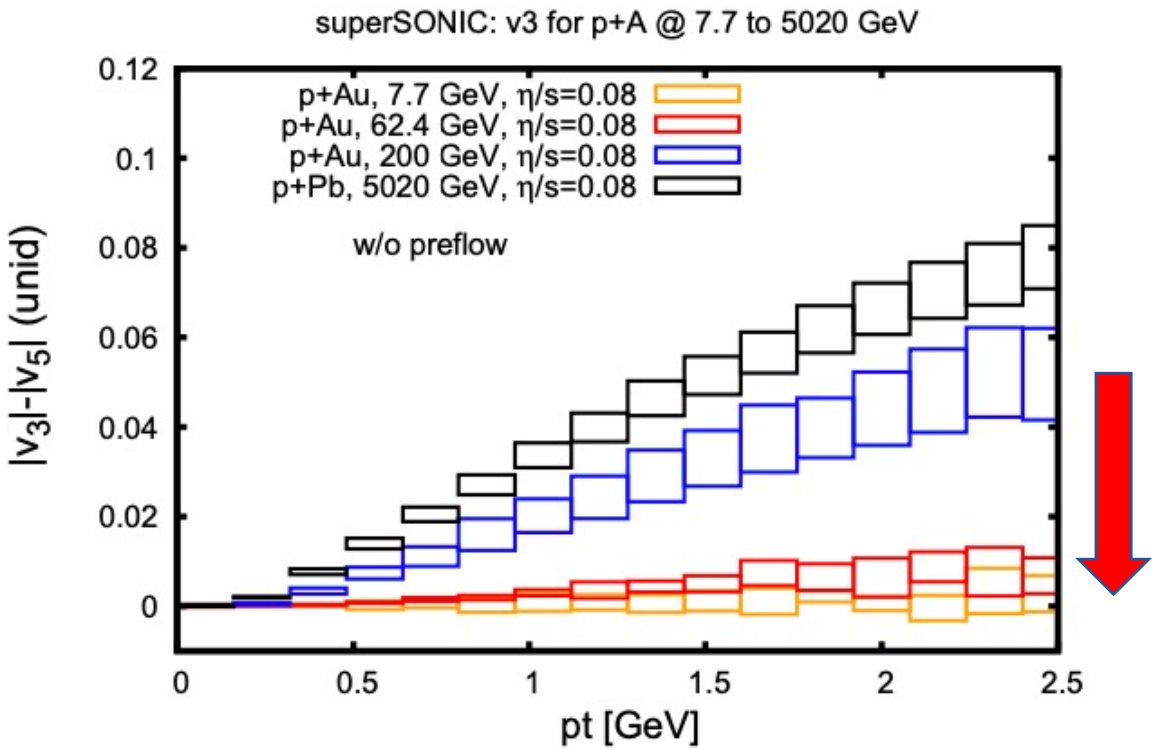
Light-heavy-ion collisions: a window into pre-equilibrium QCD dynamics?

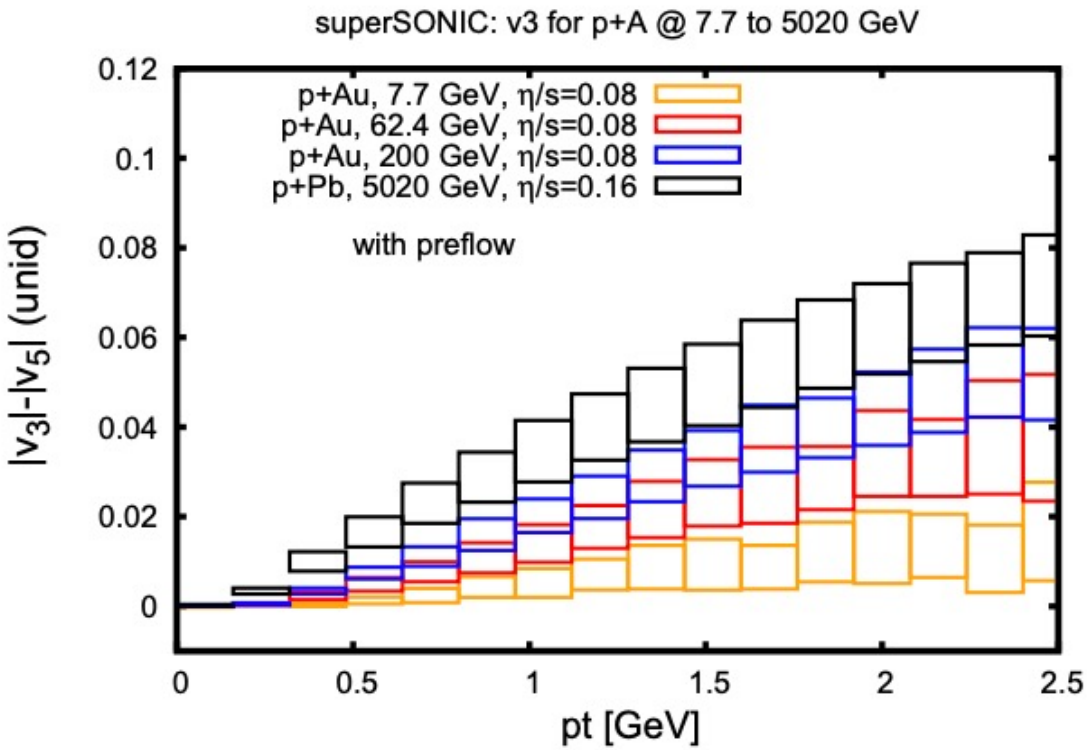
P. Romatschke[a]

University of Colorado, Boulder, USA

At some point, QGP lifetime too short and v_3 collapses

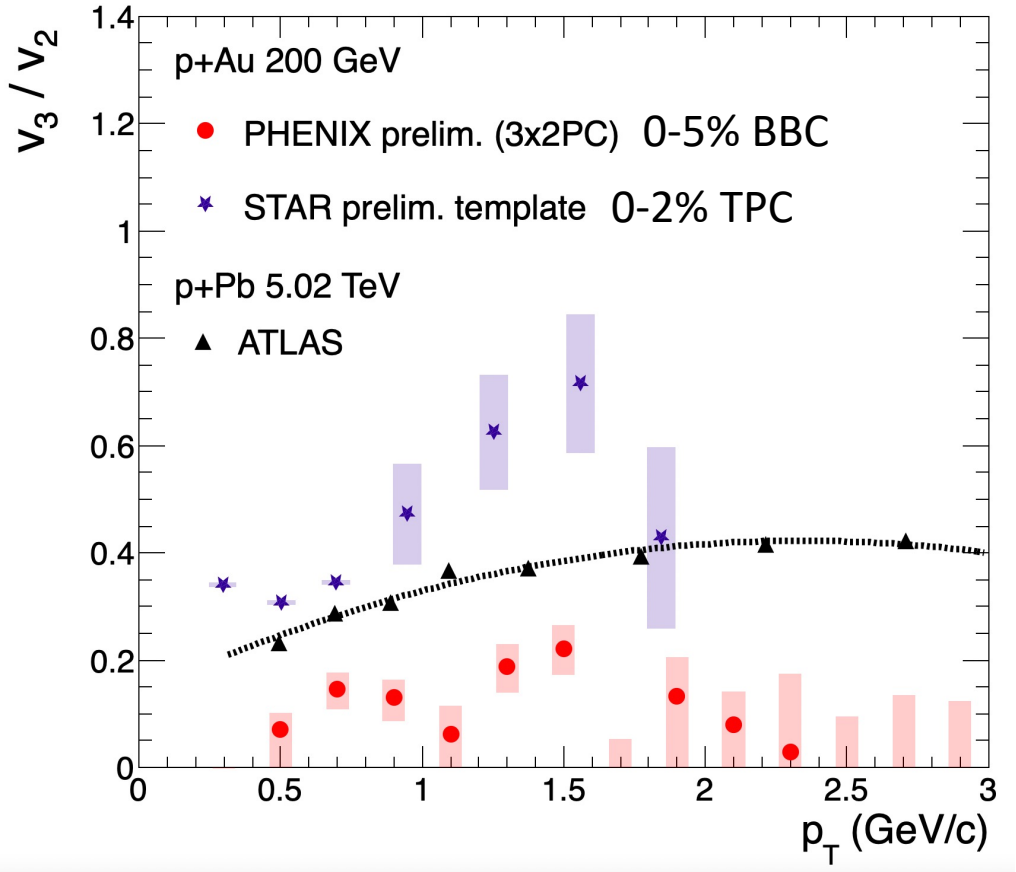
Strongly-coupled pre-flow helps mitigate this effect





How to Address Experimentally (and Theoretically)?

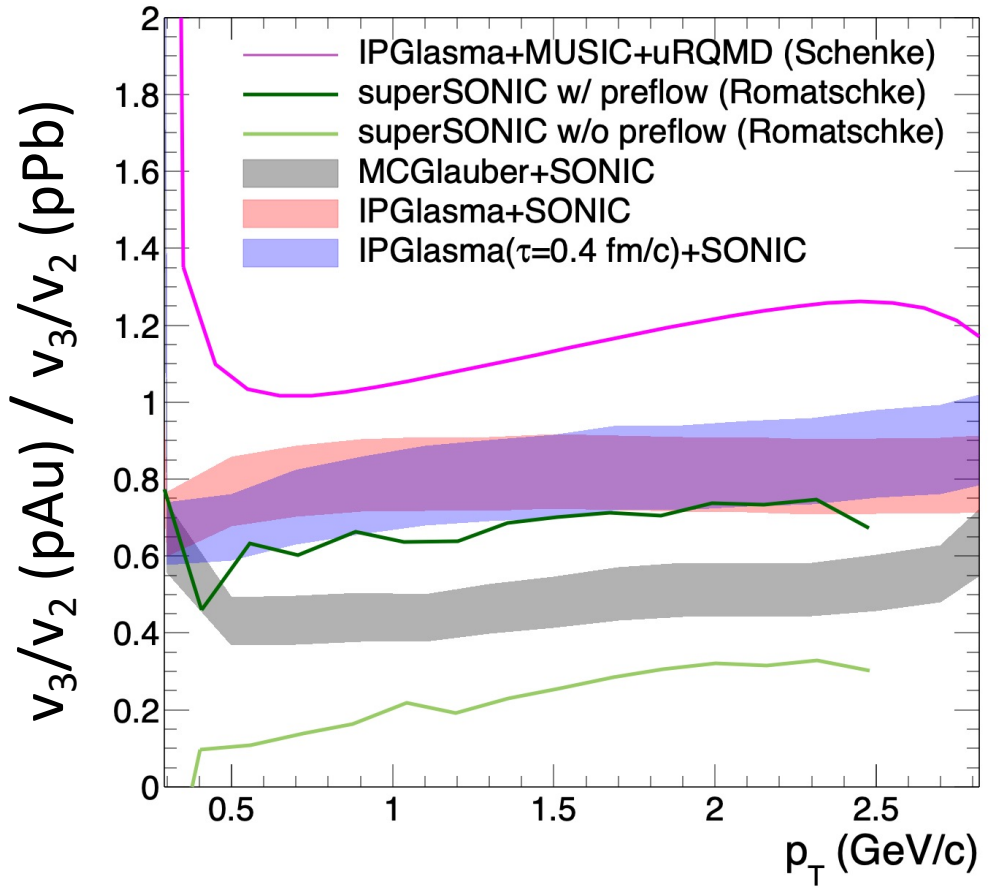
Experiment



PHENIX pAu v_3/v_2 < ATLAS pPb v_3/v_2

STAR pAu v_3/v_2 > ATLAS pPb v_3/v_2

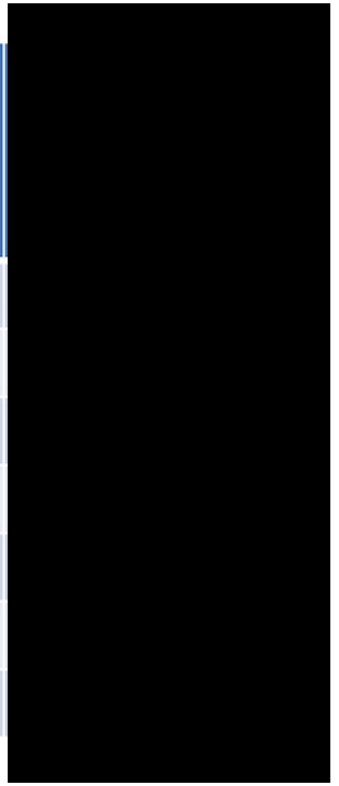
Theory



Most calculations have larger damping of higher moments at lower energy

Initial Geometry also matters…

System	Nagle Nucleons w/o NBD fluctuations	Welsh Nucleons w/ NBD fluctuations	Welsh Quarks w/ NBD and Gluon fluctuations	IPGlasma w/ Nucleons t=0	IP-Glasma w/ 3 Quarks t=0
ε_2 p+Au	0.23	0.32	0.38	**0.10**	**0.50**
ε_2 d+Au	0.54	0.48	0.51	**0.58**	**0.73**
ε_2 ^{3}He+Au	0.50	0.50	0.52	**0.55**	**0.64**
ε_3 p+Au	0.16	0.24	0.30	**0.09**	**0.32**
ε_3 d+Au	0.18	0.28	0.31	**0.28**	**0.40**
ε_3 ^{3}He+Au	0.28	0.32	0.35	**0.34**	**0.46**



Nagle et al., https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301

Welsh, Singer, Heinz, https://journals.aps.org/prc/abstract/10.1103/PhysRevC.94.024919

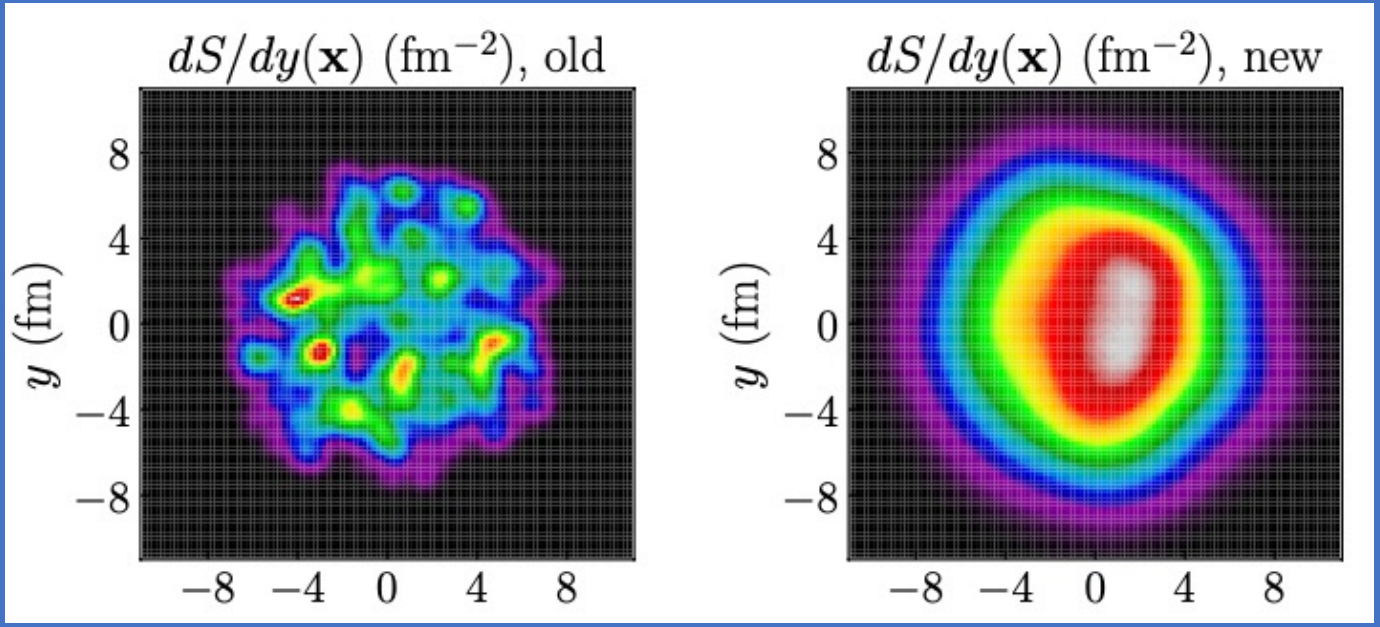
STAR QM19 Talk, https://indico.cern.ch/event/792436/contributions/3535629/

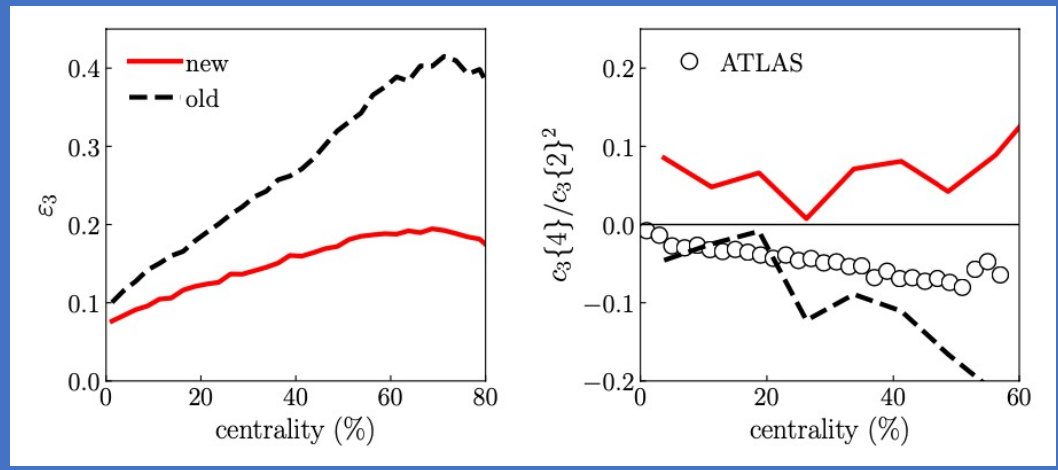
* IP-Glasma values from files generated by Sanghoon Lim with publicly available IP-Glasma code (Thanks to Bjoern Schenke)

JETSCAPE Bayesian analysis

https://journals.aps.org/prc/pdf/10.1103/PhysRevC.103.05490

From Giuliano Giacalone





New parameters:

w = 1.12 fm - really big proton

d_{min} = 1.44 fm - nice and even spacing

- cannot be hard core repulsion

Progress with Bayesian analysis, but maybe losing sight of the goal of the field

Call to action…

Plug-n-play module for free stream, IP-Glasma evolution, AdS/CFT parameterized evolution

Bayesian analysis must compare these scenarios to make strong conclusions regarding bulk viscosity for example…

Does not make sense to over-machine things without this part, particularly in small systems

Relaxation times are (often) hidden knobs. Cannot go from free streaming (weak) to QGP $\eta/s=0.08$ (strong) without some bumps in the road

What is the point of our scientific enterprise if we never learn anything?

With RHIC heavy ion running ending in a handful of years, what is the real knowledge gained from this endeavor?


Extras

From Giuliano Giacalone