Robust predictions of the hydrodynamic framework

by
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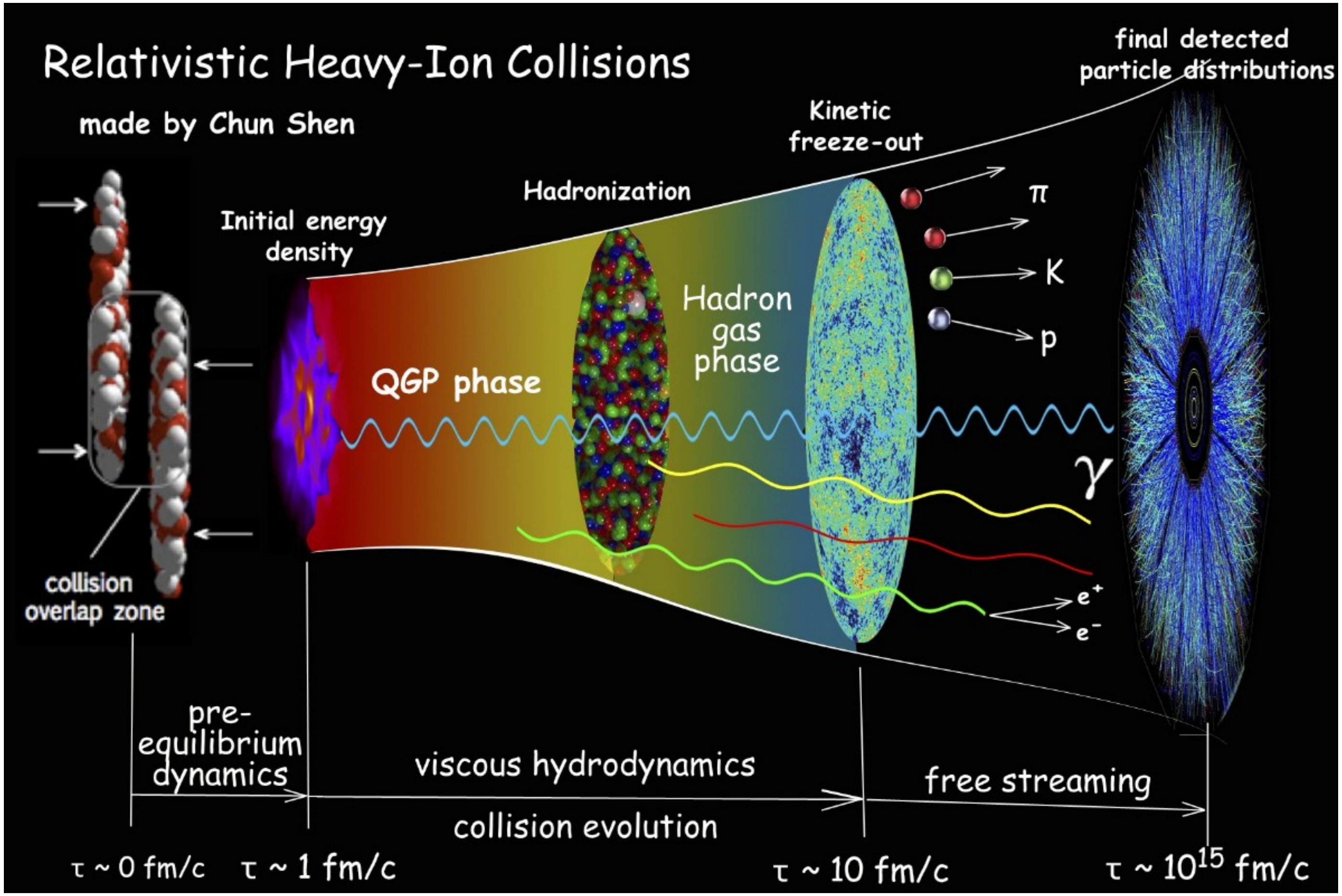
A very complex problem. A lot of modeling…..



It is crucial to point out generic features of hydrodynamics which allow for <u>universal predictions</u>, i.e., predictions which do not depend on any detail of model calculations.

In other words, it is crucial to understand to what extent details matter!

<u>In this talk, I show that hydro is a robust framework, and that for most of what we do, details do not matter at all.</u>

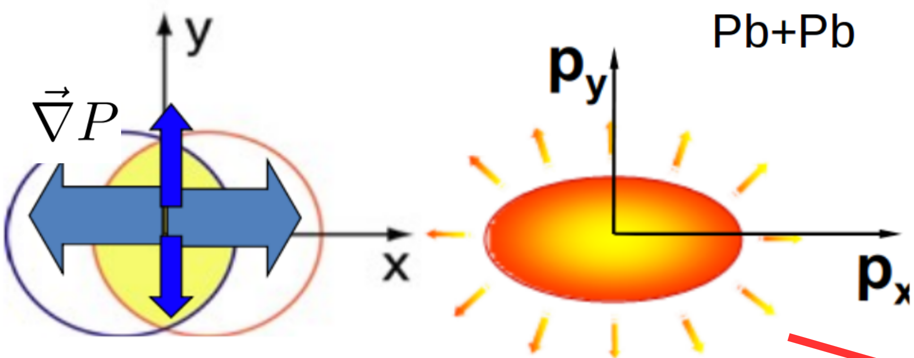
The paradigm of hydrodynamics:

Anisotropy is driven by geometry

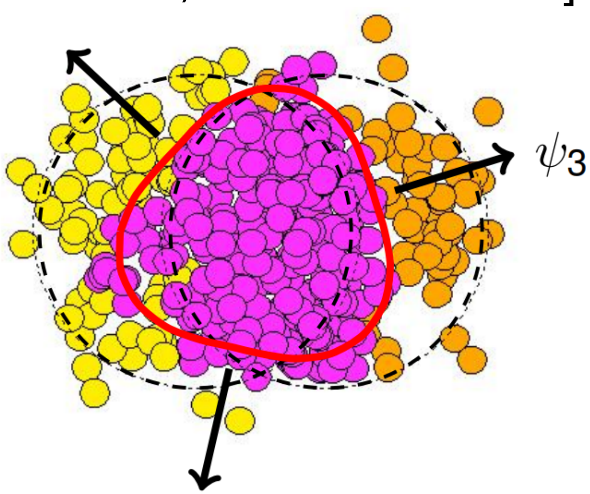
$$P(\phi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} \boxed{V_n} e^{-in\phi}$$

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \vec{\nabla} \vec{v} \right) = -\vec{\nabla} P$$

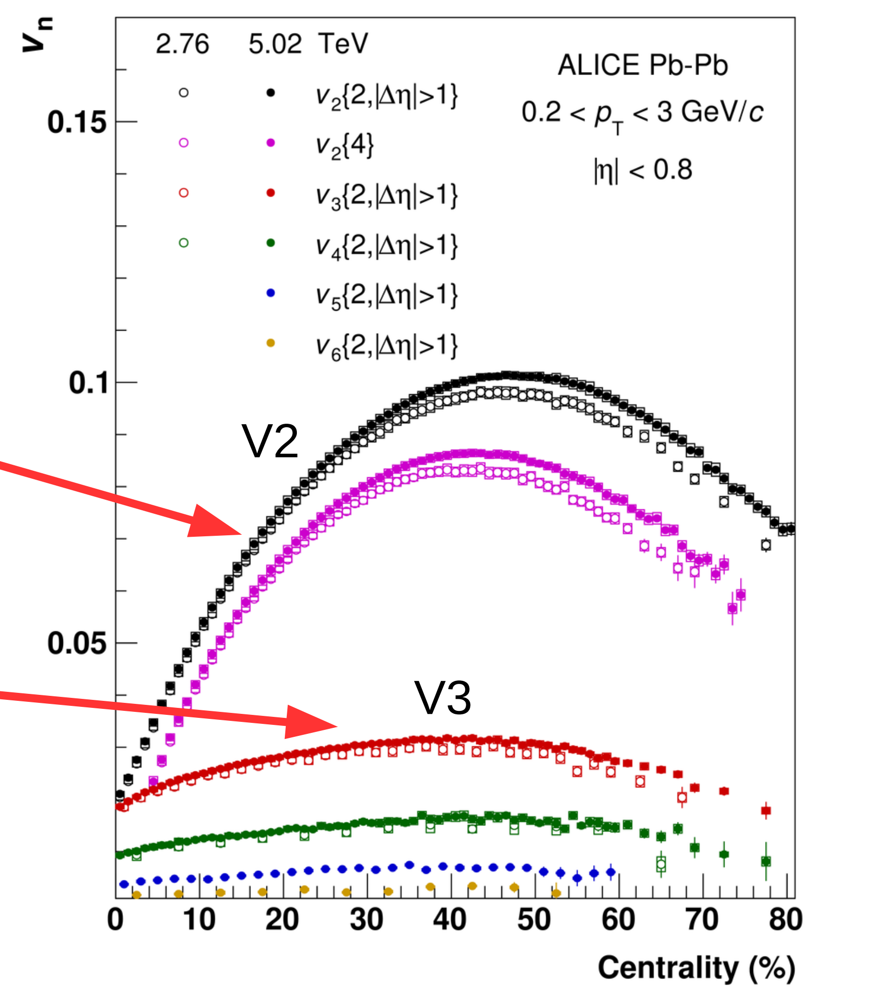
[Ollitrault, 1992]



[Alver and Roland, **arXiv 1003:0194**]



[ALICE collaboration, **arXiv 1804:02944**]



The simplest example of “robust predictions”.

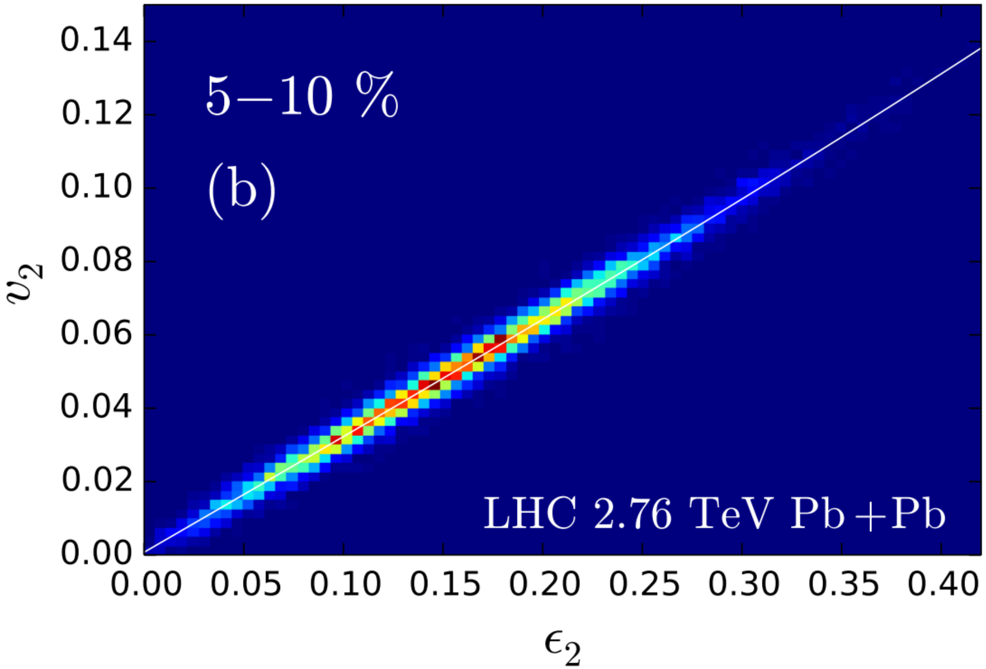
Initial anisotropies quantified by ε_n. [Teaney and Yan, **arXiv 1010:1876**]

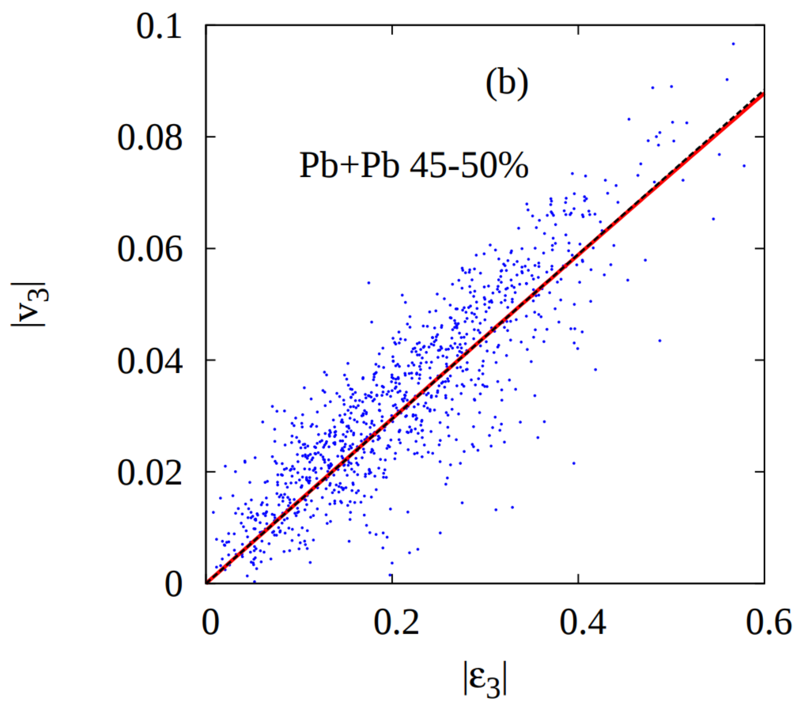
For n=2,3 hydrodynamic simulations show:

$$v_n = k_n \varepsilon_n$$

- eps2 quantifies the ellipticity of the initial density profile (almond shape + fluctuations)
- eps3 quantifies the triangularity (fluctuations)

[Niemi, Eskola, Patelaainen, **arXiv 1505:02677**]





[Noronha-Hostler, Yan, Gardim, Ollitrault, **arXiv 1511:03869**]

Let us understand data using this simple relation.
We compare (208)Pb+Pb to (129)Xe+Xe.

CENTRAL COLLISIONS
<u>FLUCTUATIONS DOMINATE</u>

Fluctuations scale like $1/\sqrt{N}$

A good proxy for N is # of nucleons

$$\sqrt{\frac{208}{129}} = 1.27$$

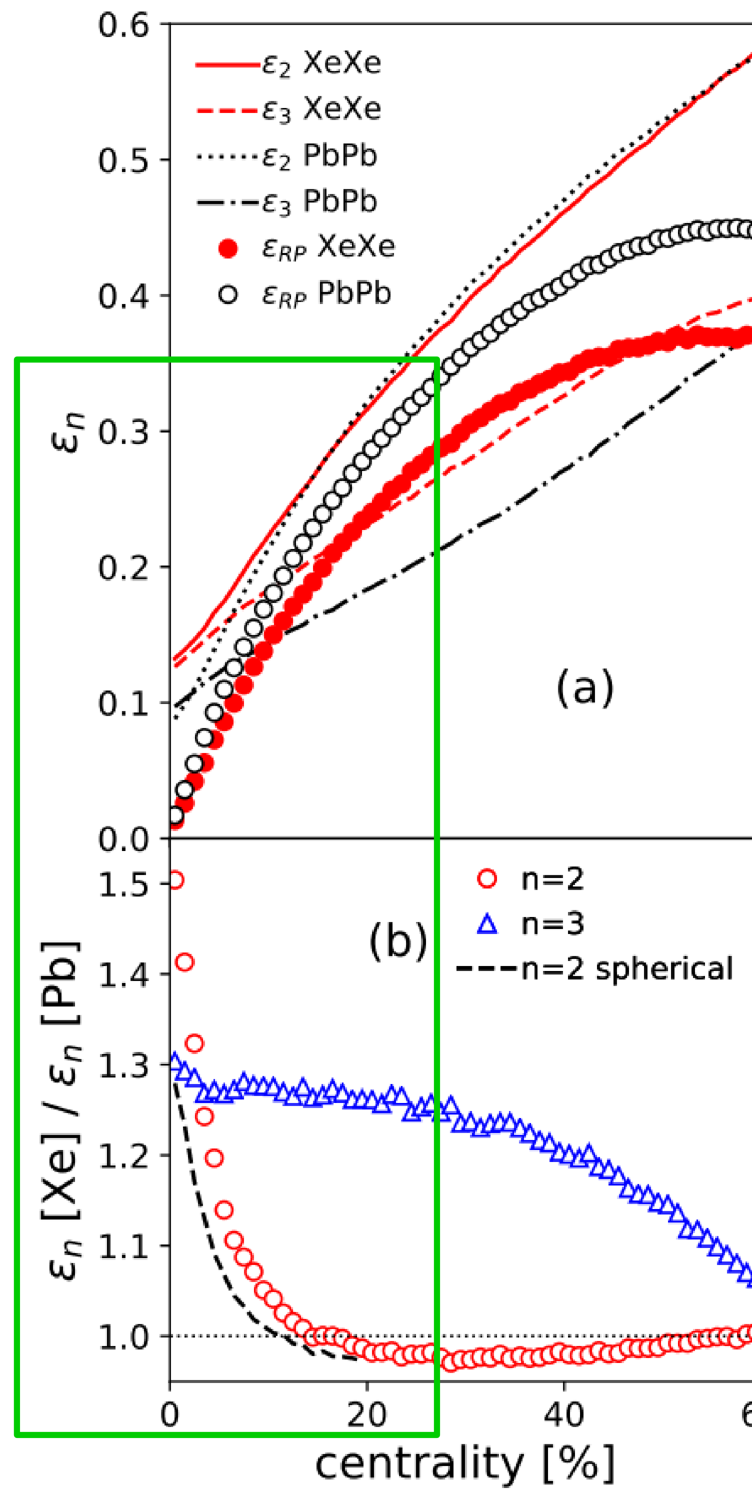
- e3 in XeXe should be larger by that factor.
- e2 is affected by deformation, typically 20% effect, so the ratio is even larger.

And do not forget viscosity:

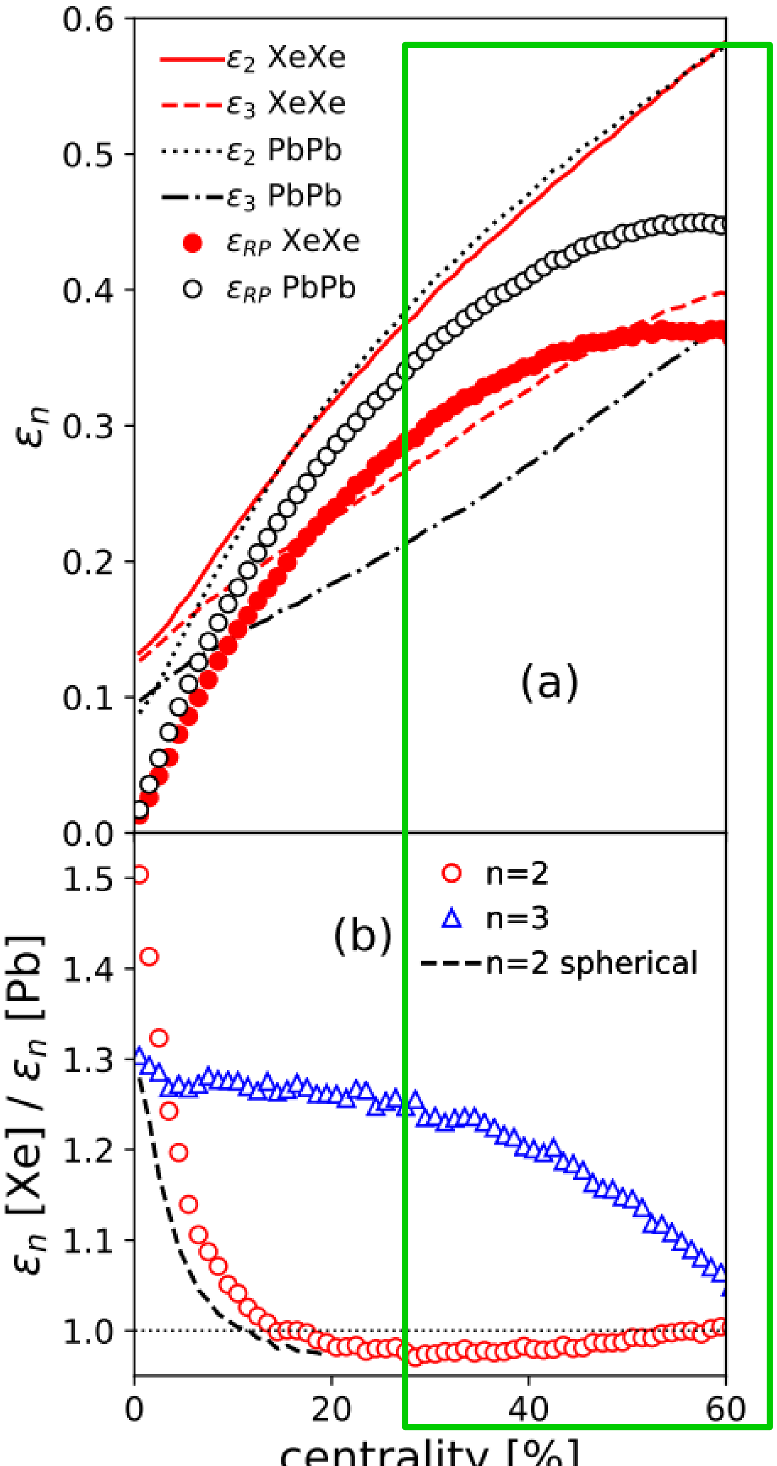
$$\rho\left(\frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\vec{\nabla}\vec{v}\right) = -\vec{\nabla}P + \boxed{\eta\nabla^2\vec{v}}$$

Viscous corrections go as 1/R.

<u>In the data, all these ratios will get suppressed because Xe is smaller.</u>



[Giacalone, Noronha-Hostler, Luzum, Ollitrault, arXiv 1711:08499]



PERIPHERAL COLLISIONS
<u>GEOMETRY+VISCOSITY DOMINATE</u>

Only difference is that now e2 is dominated by almond shape.

- We do not expect much to happen for e3, the ratio should be rather constant.

- We expect PbPb to have sharper shape, that compensate larger fluctuations in XeXe, so the ratio should stay close to 1.

Any strong centrality dependence has to be due to viscous damping:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\vec{\nabla}\vec{v}\right)=-\vec{\nabla}P+\boxed{\eta\nabla^2\vec{v}}$$

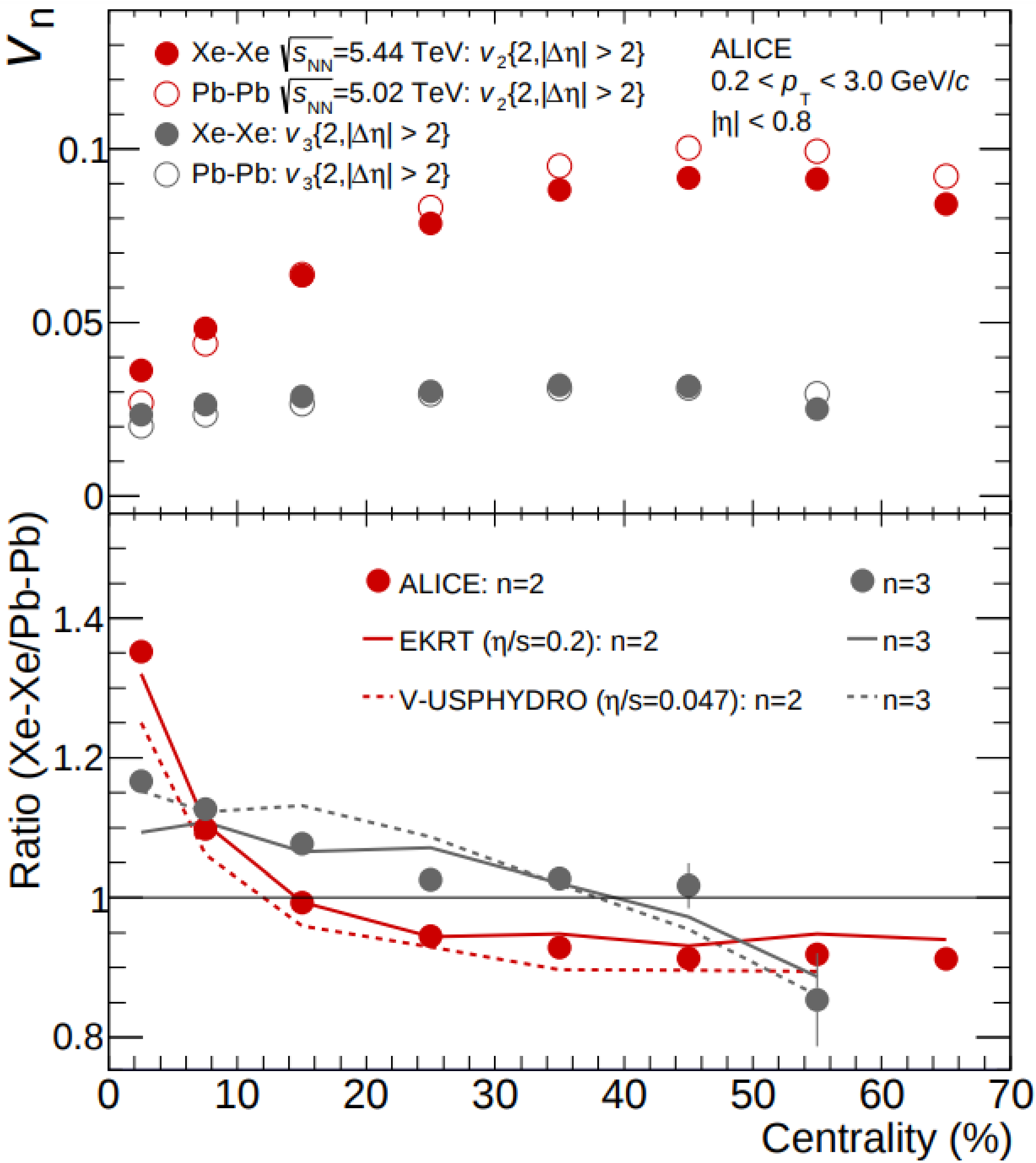
Stronger in peripheral events (1/R)

In conclusion, we are able to guess the behavior of experimental data with **simple** statements about fluctuations, geometry, scaling rules, dimensional analysis.

We just know how experimental data will look like!
without running any model calculation, and without any detail.

So, time to look at the data!

[ALICE collaboration, arXiv 1805:01832]



All the previous features are in the data!

WE

UNDERSTAND

EVERYTHING!

….which also implies that the crazy details of the models do not matter for the overall picture!!!

What about smaller systems? We can play the same game!
But one comment is in order.

Let us go 'backwards':

Final-state v_n ⇉ Initial-state ε_n ⇉ initial density fluctuations

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\vec{\nabla}\vec{v}\right)=-\vec{\nabla}P+\boxed{\eta\nabla^2\vec{v}}$$

⇇ stronger gradients

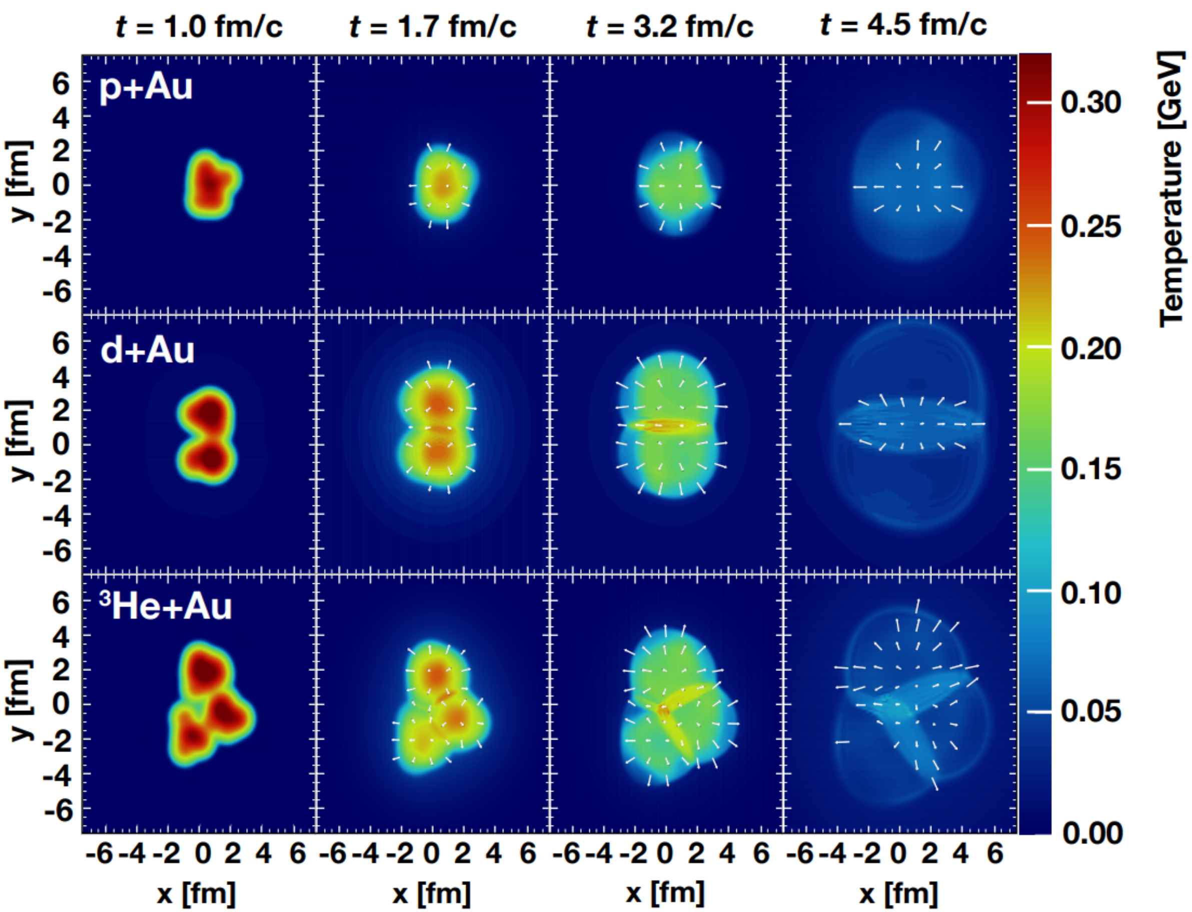
Larger viscous corrections!!

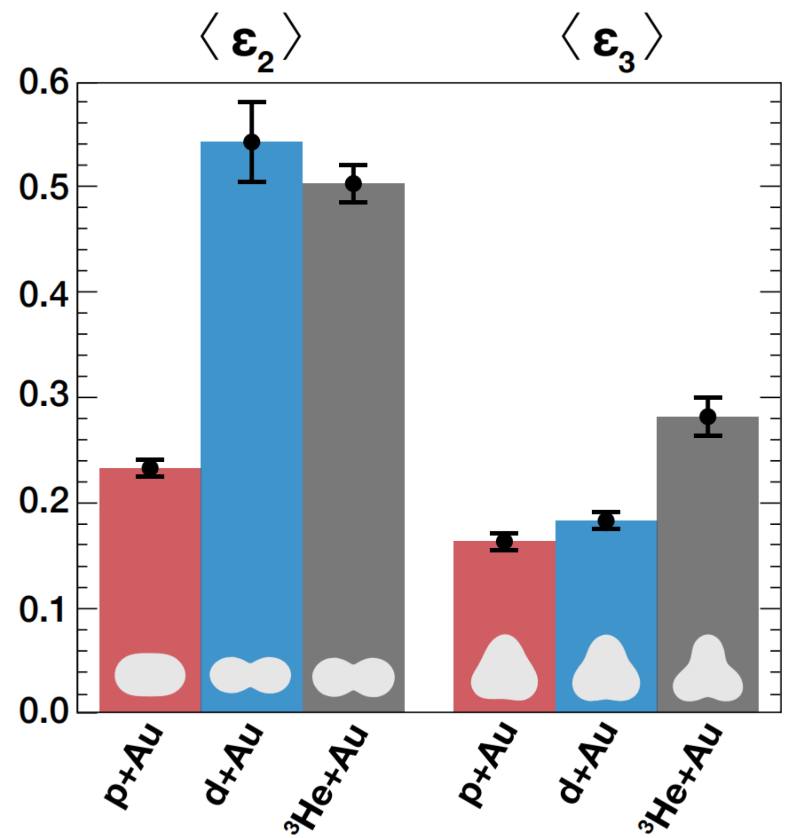
How far can we go before hydro breaks down?

Essentially, a whole new field of research.

Assuming fluid dynamics is **OK**… let us play the game

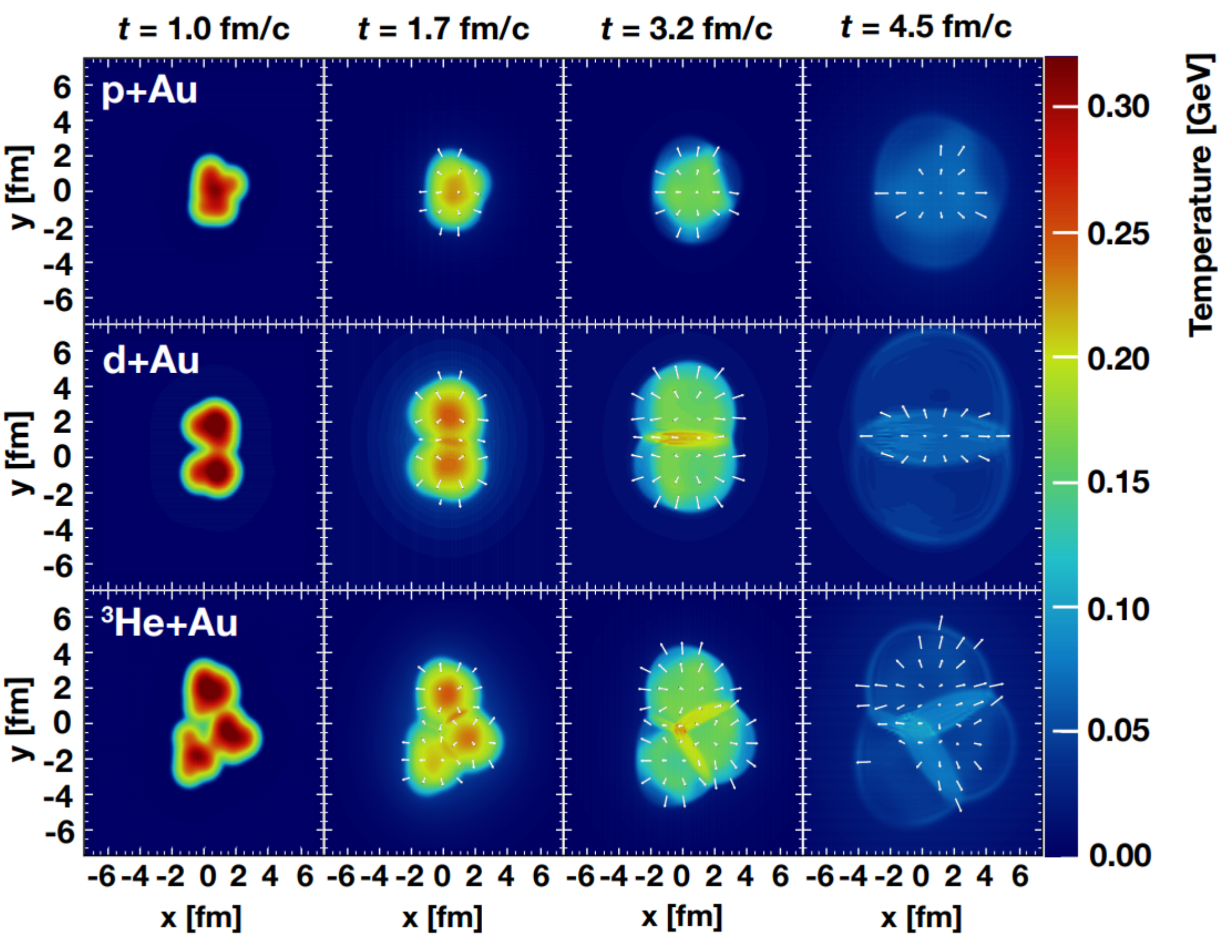
[PHENIX collaboration, **arXiv 1805:02973**]

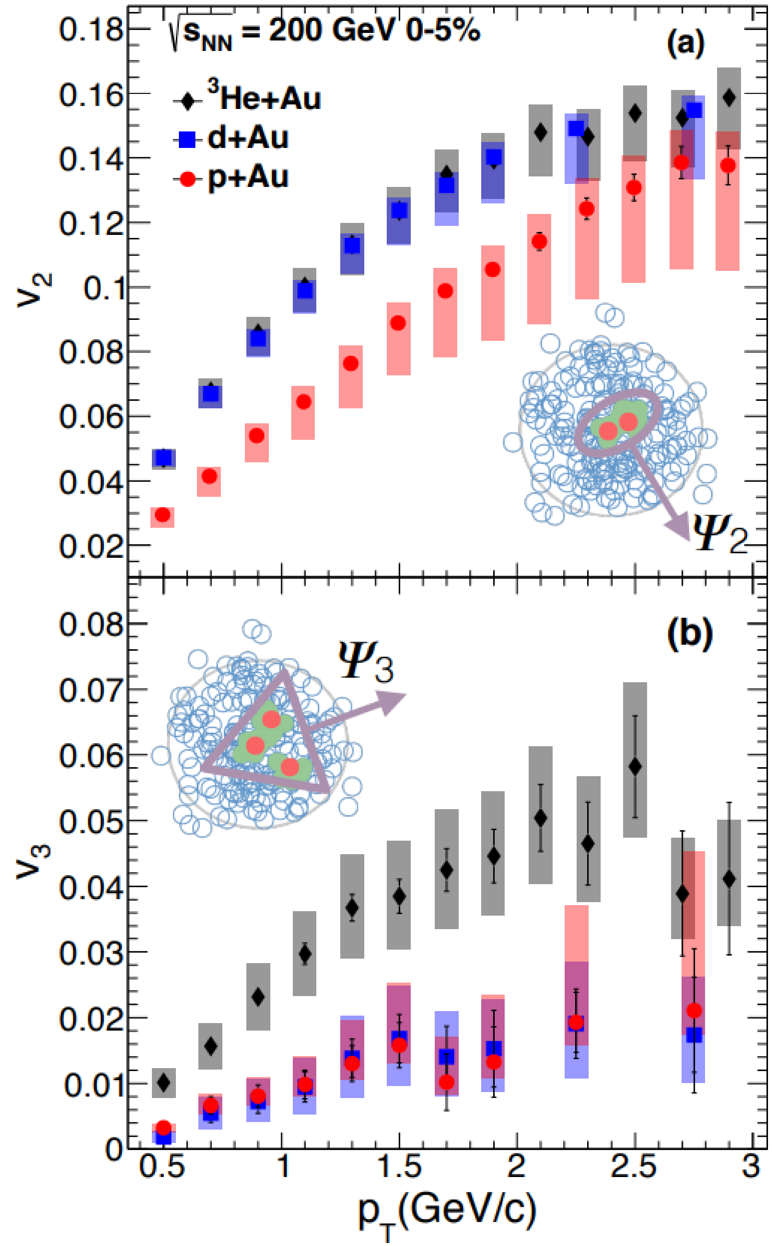




...expected hierarchies (highly nontrivial)...

[PHENIX collaboration, arXiv 1805:02973]





...spectacular confirmation in the data!

- Conclusive remarks.
- I hope I convinced hydrodynamics provides a solid framework which explains data **regardless of details and model calculations.**
- This is why hydrodynamics works so well!
- I could have gone much beyond the results I have been discussing here! In both p+A and A+A, very generic behavior is observed in more involved observables (fluctuations of flow coefficients).
- Thank you all!