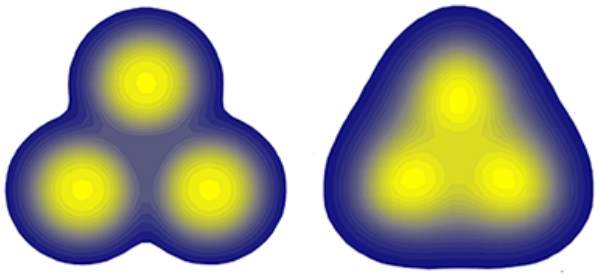
# Lowest-energy nuclear structure from highest-energy nuclear collisions

**Wojciech Broniowski**

Institute of Physics, UJK

19 March 2014



[more details in WB& E. Ruiz Arriola, **arXiv:1312.0289**, Phys. Rev. Lett. 112, 112501]

## NEWS AND COMMENTARY IN PHYSICS

"An Untested Window into Nuclear Structure"
http://journals.aps.org/prl/

# Instead of outline

(WPCF 2013 in Catania $\rightarrow \alpha$)

**Two phenomena are related:**

$\alpha$ clustering in light nuclei

$\updownarrow$

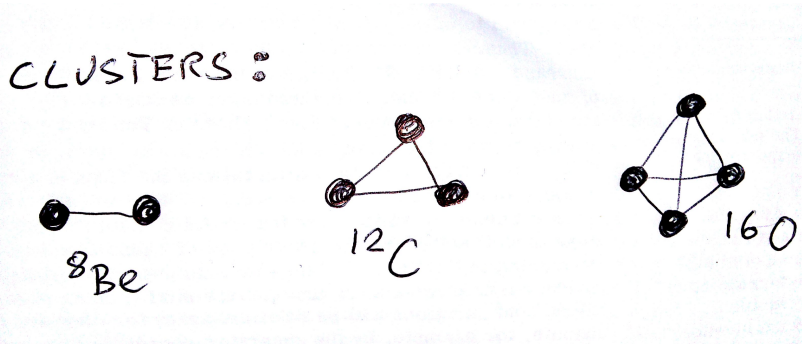
harmonic flow in ultra-relativistic A+B collisions

**Surprising link:**

low-energy structure $\longleftrightarrow$ highest energy reactions

# Some history

David Brink: *After Gamow's theory of $\alpha$-decay it was natural to investigate a model in which nuclei are composed of $\alpha$-particles. Gamow developed a rather detailed theory of properties in his book "Constitution of Nuclei" published in 1931 before the discovery of the neutron in 1932. He supposed that 4n-nuclei like $^{8}Be$, $^{12}C$, $^{16}O$ ... were composed of $\alpha$-particles*



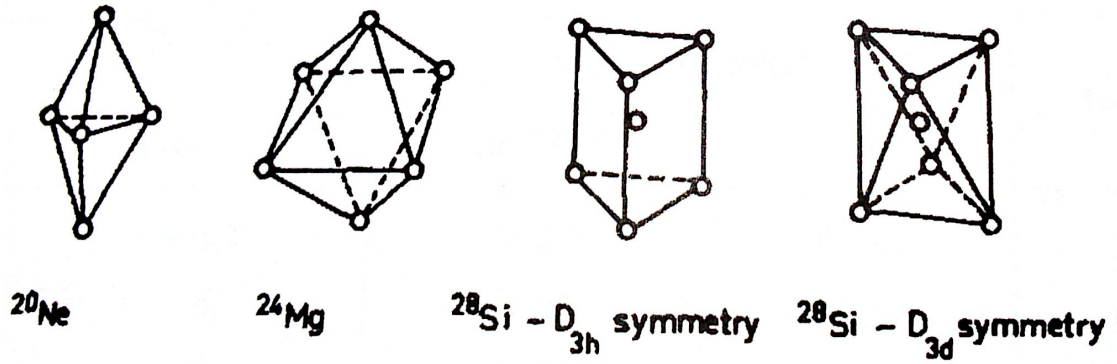




**Fig. 1. Alpha-particle configuration for some 4N nuclei.**

# Shell model and its problems

Michael P. Carpenter: *However, in the 1960s, excited states in nuclei that comprise equal numbers of protons and neutrons, (e.g., $^{12}C$ and $^{16}O$) were identified that could not be described by the shell model, and it was suggested by Ikeda and others that these states could be associated with configurations composed of $\alpha$ particles*

Also: problems with $\alpha$ decay of $^{212}$Po
shell model predicts a way too small decay width
spectroscopy: $^{212}\text{Po} = {}^{208}\text{Pb}+\alpha$ [Astier et al. 2014]

# Fragmentation

Evidence from dissociation in nuclear track emulsions

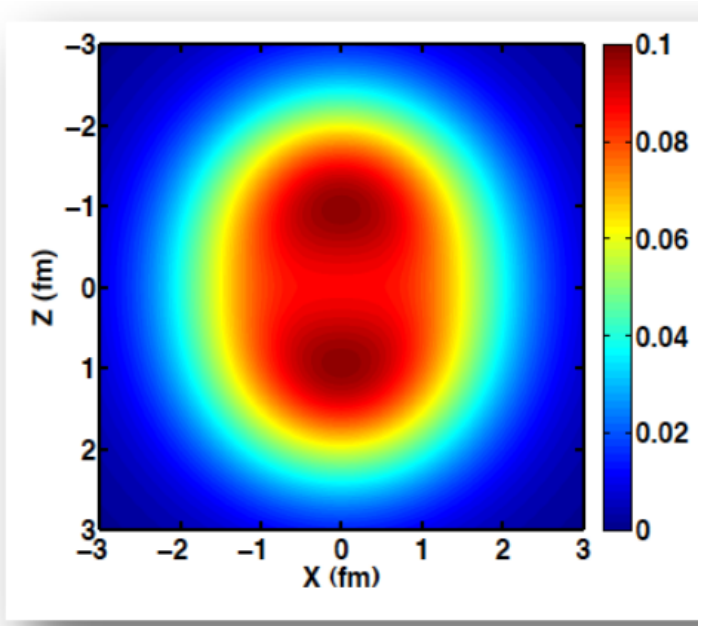
[Zarubin 2013 (BECQUEREL)]

Example: dissociation of $^7$Li (energy of a few A GeV)

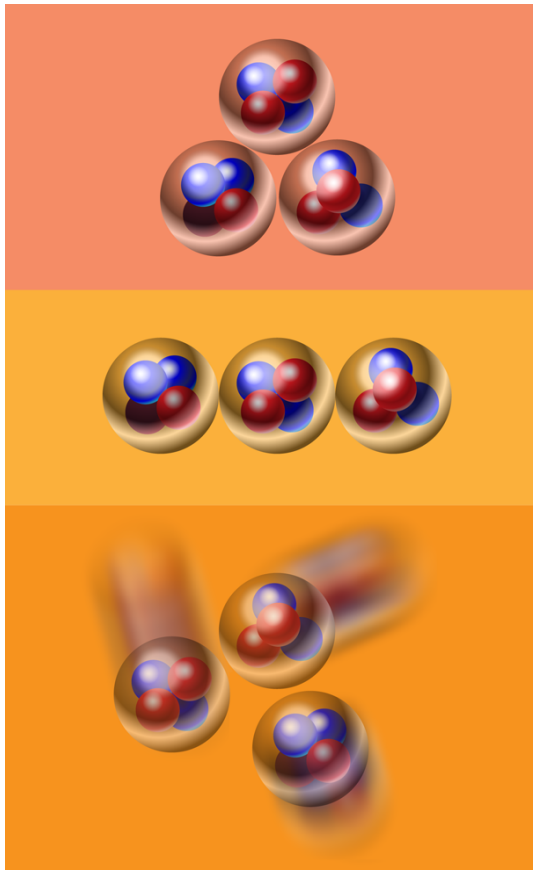
| channel | $^4$He+$^3$He | $^3$He+$^3$He | $^4$He+$2p$ | $^4$He+$d$+$p$ | $^3$He+$2p$ | $^3$He+$d$+$p$ | $^3$He+$2d$ | $^3$He+$t$+$p$ | $3p$+$d$ | $^6$Li+$p$ |
|---|---|---|---|---|---|---|---|---|---|---|
| N | 30 | 11 | 13 | 10 | 9 | 8 | 1 | 1 | 2 | 9 |
| % | 31 | 12 | 14 | 11 | 10 | 9 | 1 | 1 | 2 | 10 |

Numerous ongoing experiments (GANIL, Osaka, ...)

# Present theory status




$^{9}$Be



$^{12}$C

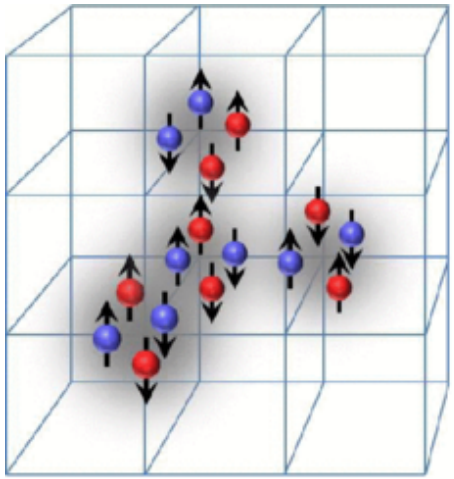
ground

Hoyle $0^+$

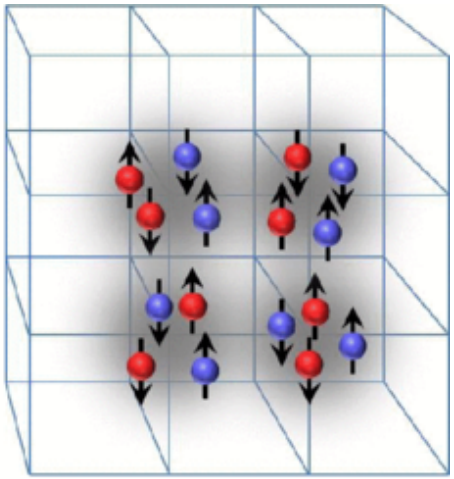
other excited, $2^+$ ...

[M. Freer: WPCF13, H. Fynbo+Freer: Physics 4 (2011) 94]

Ab initio calculations of $^{16}O$ with chiral NN force (Juelich 2014)
$\rightarrow$ strong $\alpha$ clusterization



(a) Initial state "A",
8 equivalent orientations.

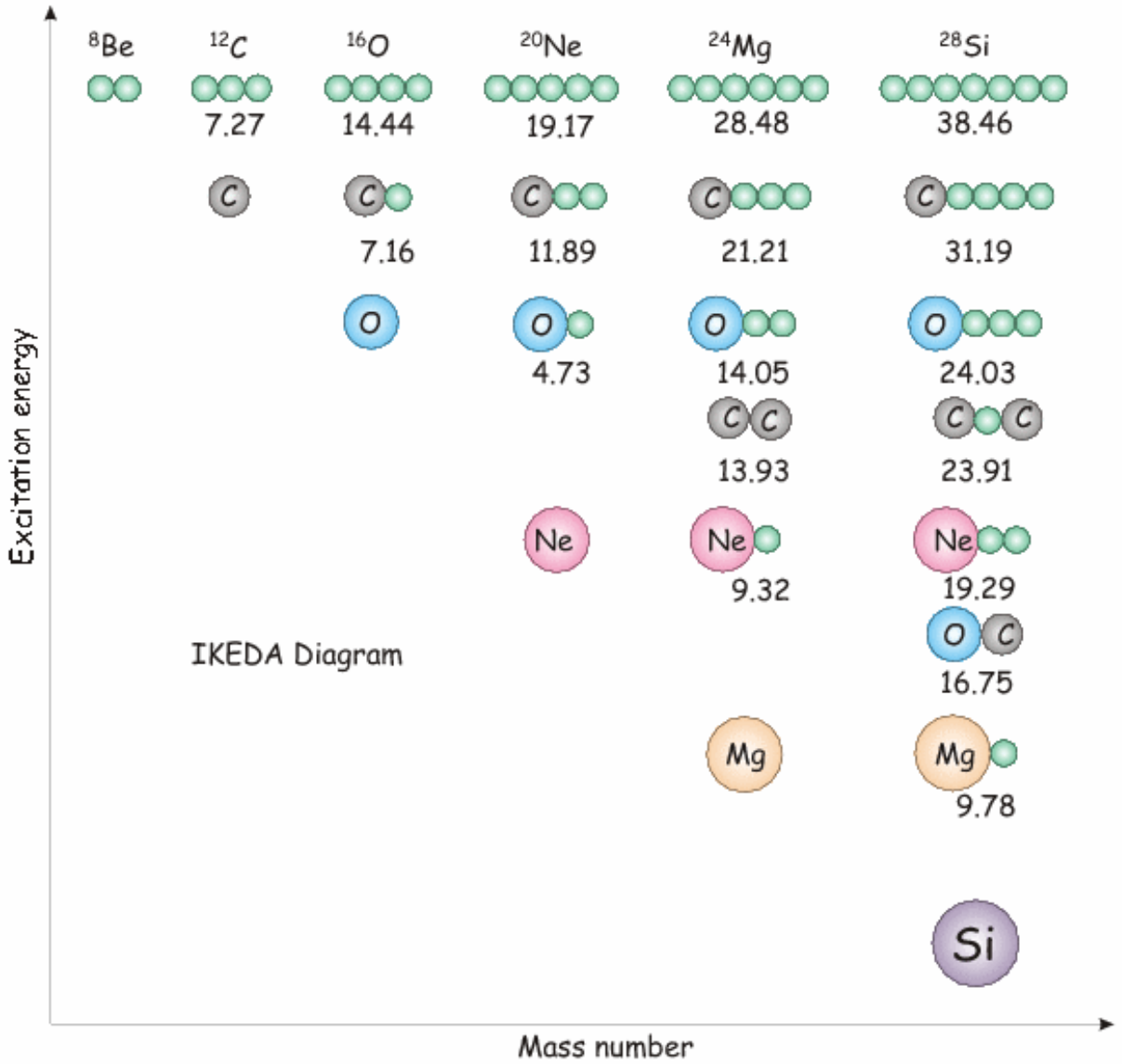


(b) Initial states "B" and "C",
3 equivalent orientations.

ground state

excited

# Ikeda diagram



# $\alpha$ condensation

Funaki et al.: *certain states in self-conjugated nuclei ... can be described as product states of $\alpha$ particles, all in the lowest $0S$ state. We define a state of condensed $\alpha$ particles in nuclei as a bosonic product state in good approximation, in which all bosons occupy the lowest quantum state of the corresponding bosonic mean-field potential* ($\alpha$BEC)

Another approach: Fermionic Molecular Dynamics (FMD)

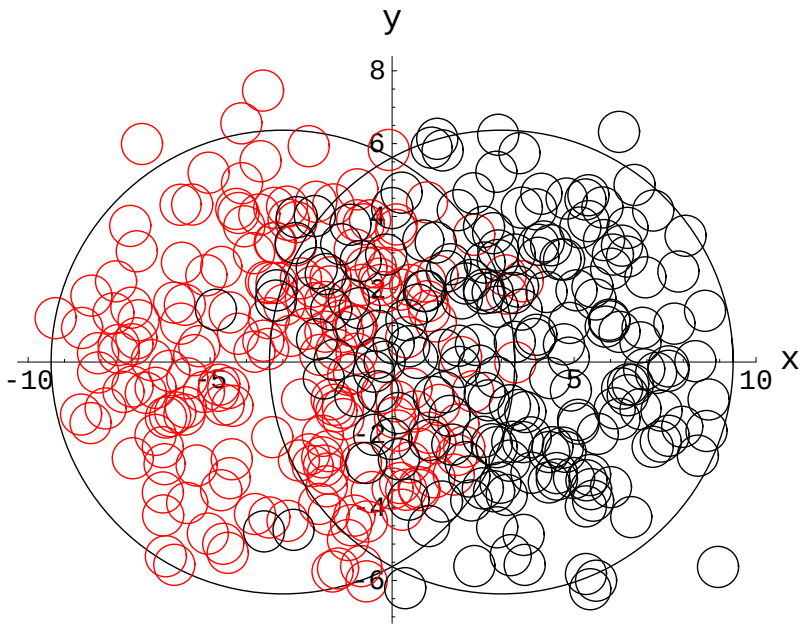
A=2-12:
Quantum Variational Monte Carlo (with 2- and 3-body forces)
[Robert Wiringa, `http://www.phy.anl.gov/theory/research/density/`]

**All approaches give clusters**

**Goal:**

reproduce ground-state energy, excitation spectrum, EM form factor, ...

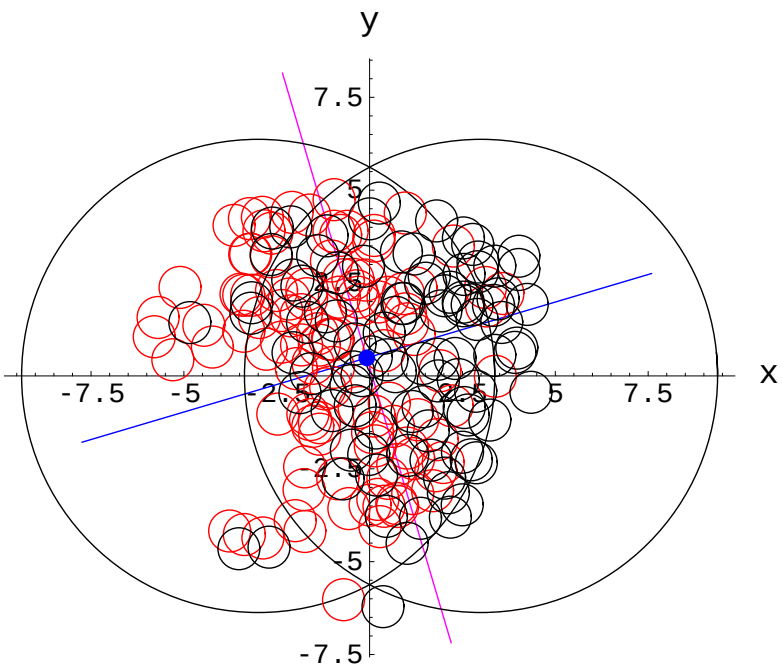
# A+A collisions




Au+Au collision at RHIC

# Harmonic flow

Participants:




- initial fireball is asymmetric in the transverse plane from 1) geometry 2) fluctuations
- collectivity! – **flow generated**
- strong elliptic flow, triangular flow from fluctuations, higher-order flow

"Initial shape – final flow" transmutation detectable in the asymmetry of the momentum distribution of detected particles

# Harmonic flow

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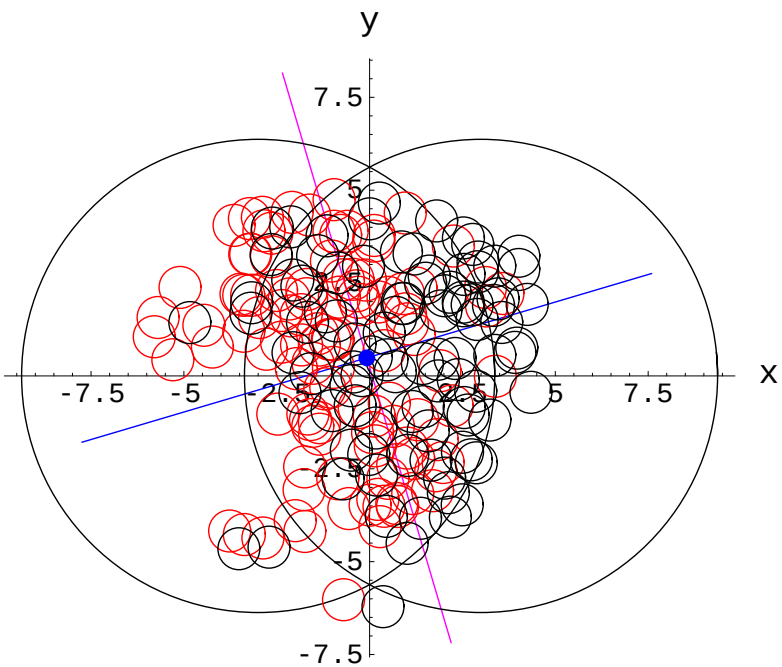


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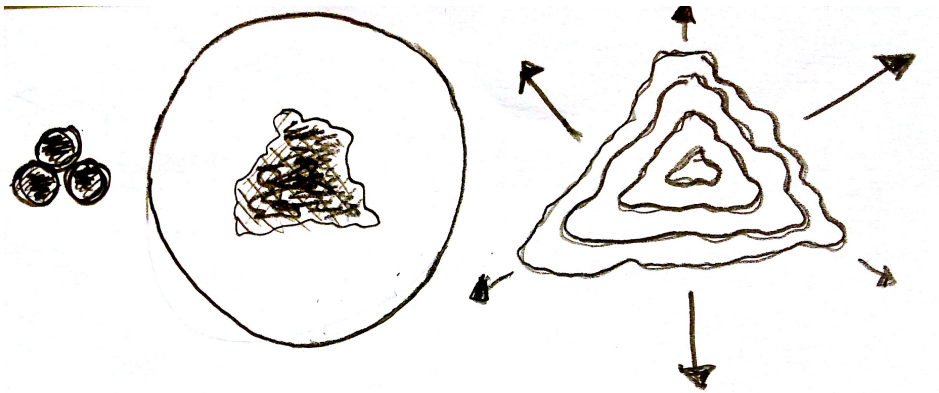
**Merge the two ideas ($\alpha$'s and flow)** $\rightarrow$

# From $\alpha$ clusters to flow in relativistic collisions

$\alpha$ clusters $\rightarrow$ asymmetry of shape $\rightarrow$ asymmetry of initial fireball $\rightarrow$
$\rightarrow$ hydro or transport $\rightarrow$ collective harmonic flow

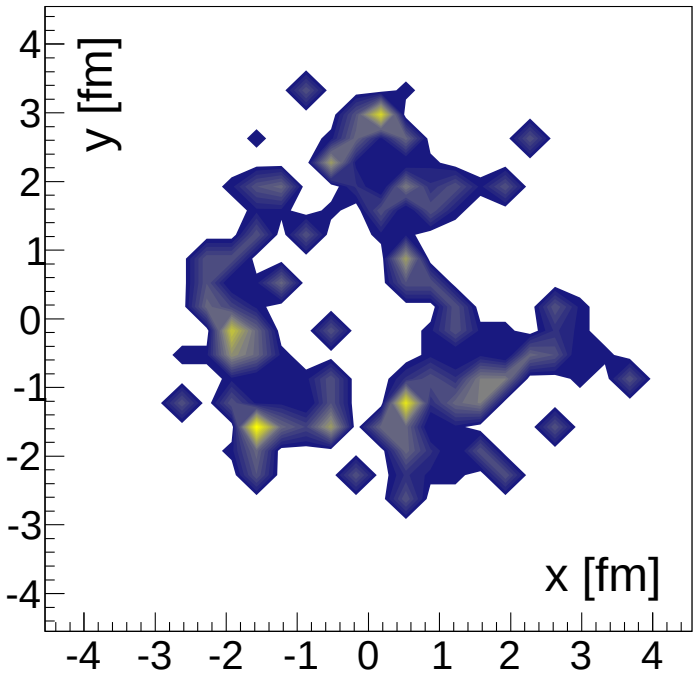


nuclear triangular geometry $\rightarrow$ fireball triangular geometry $\rightarrow$ triangular flow

What are the chances of detection?

Related idea: triton/$^3$He–Au at RHIC in 2015 [Sickles (PHENIX) 2013]
The case of light nuclei is more promising, as it leads to abundant fireballs

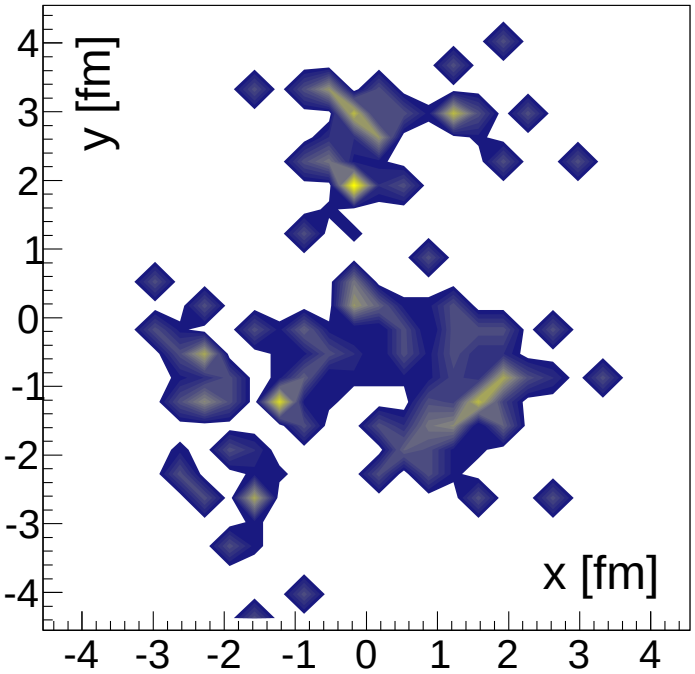
# $^{12}$C-$^{208}$Pb – single event



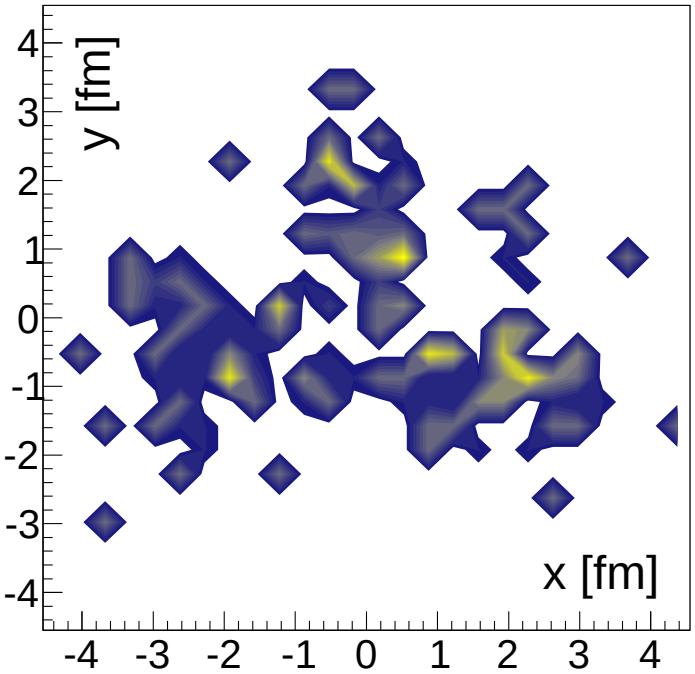

Imprints of the $\alpha$ clusters clearly visible

[simulations with GLISSANDO 2: GLauber Initial-State Simulation AND mOre..., M. Rybczyński, G. Stefanek, WB, P. Bożek]

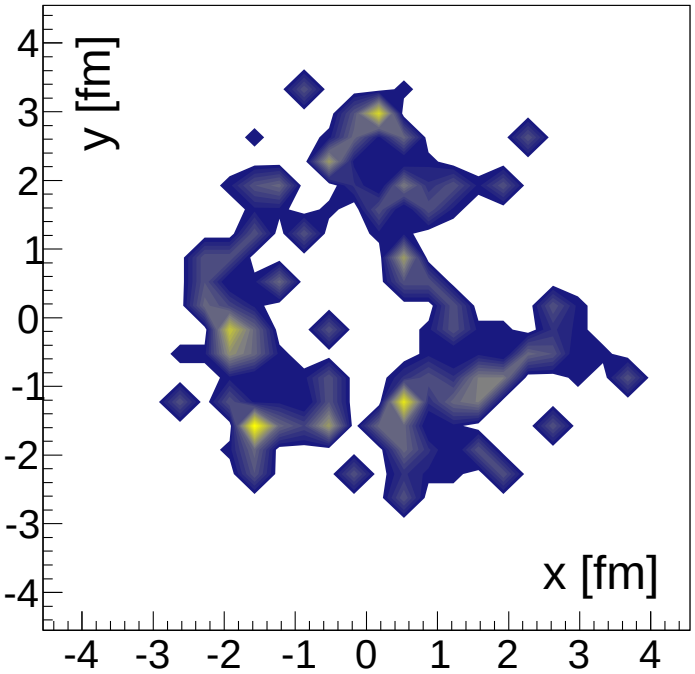
# ... more events



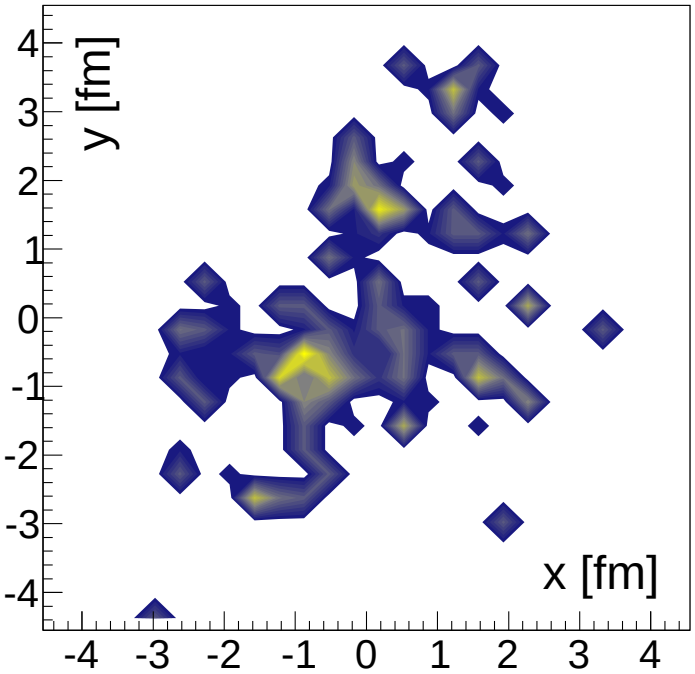
# ... more events



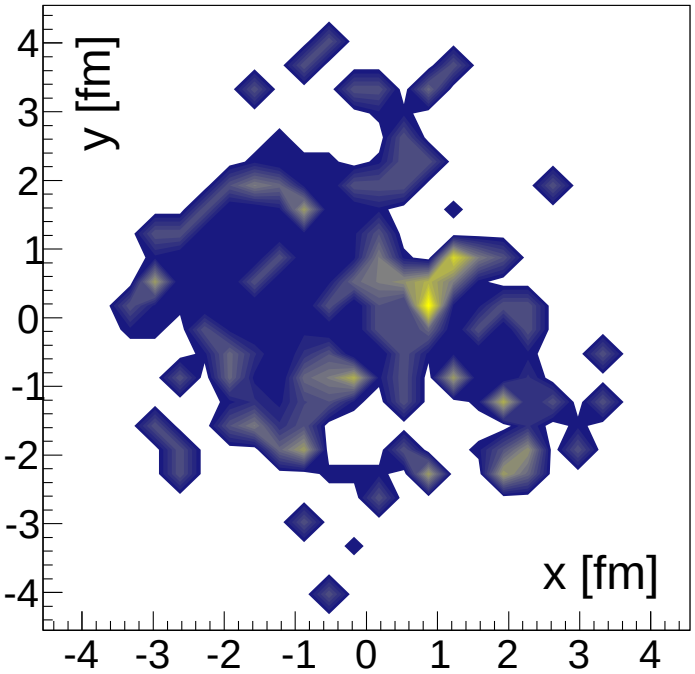
# ... more events



# ... more events



# ... more events



# The meaning of *intrinsic*

Ground-state nuclei are (mostly) in $0^+$ states (rotationally symmetric wave functions). The meaning of *deformation* concerns multiparticle correlations between the nucleons

**Superposition over orientations:**

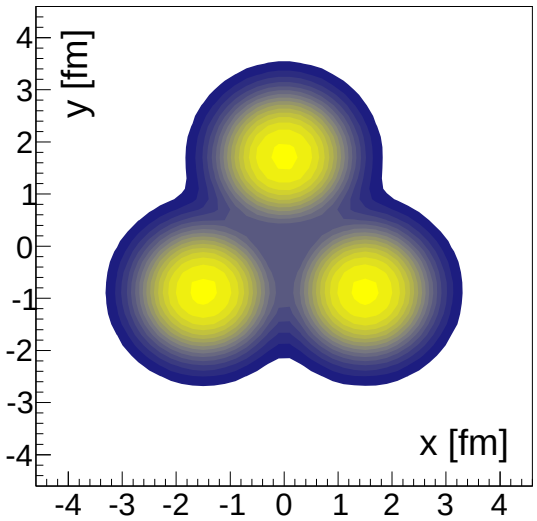
$$|\Psi_{0^+}(x_1,\ldots,x_N)\rangle = \frac{1}{4\pi}\int d\Omega \Psi_{\rm intr}(x_1,\ldots,x_N;\Omega)$$

(holds from deuterium to U)

The *intrinsic* density of sources of rank $n$ is defined as the average over events, where the distributions in each event have aligned principal axes: $f_n^{\rm intr}(\vec{x}) = \langle f(R(-\Phi_n)\vec{x})\rangle$. Brackets indicate averaging over events and $R(-\Phi_n)$ is the inverse rotation by the principal-axis angle in each event

# $^{12}$C – intrinsic density

Intrinsic distributions in $^{12}$C: 3 $\alpha$'s in a triangular arrangement

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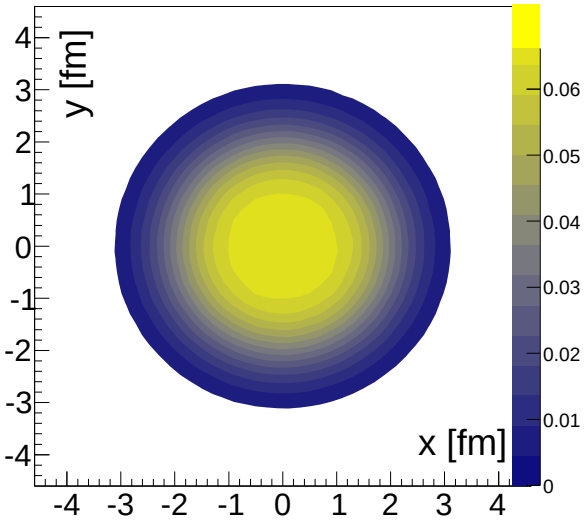


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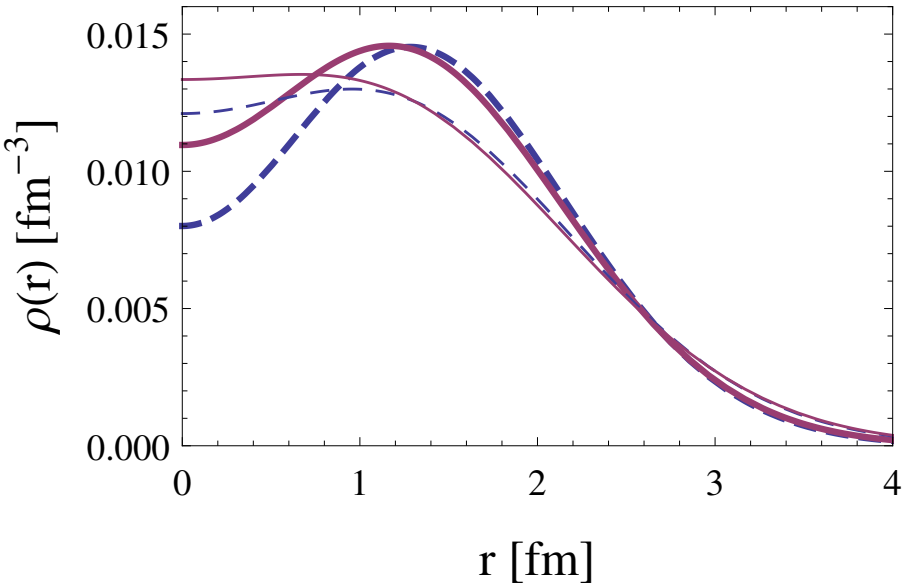
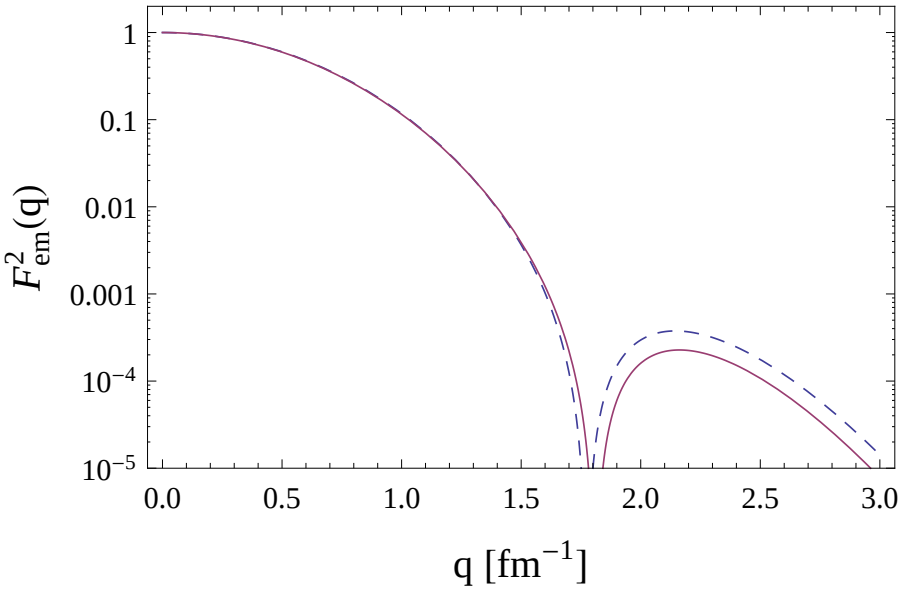
# Constraints from EM form factor

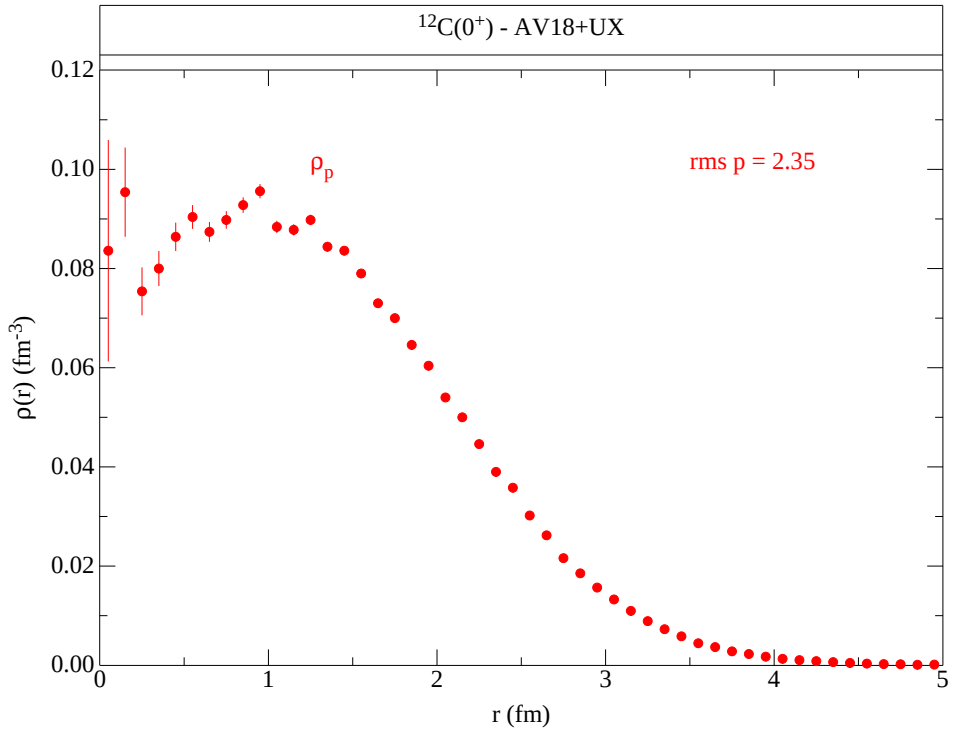



Electric charge density (thin lines) and the corresponding distribution of the centers of protons (thick lines) in $^{12}$C for the data and BEC calculations (dashed lines), and for the FMD calculations (solid lines), plotted against the radius. **BEC agrees with the experimental data**

Central depletion

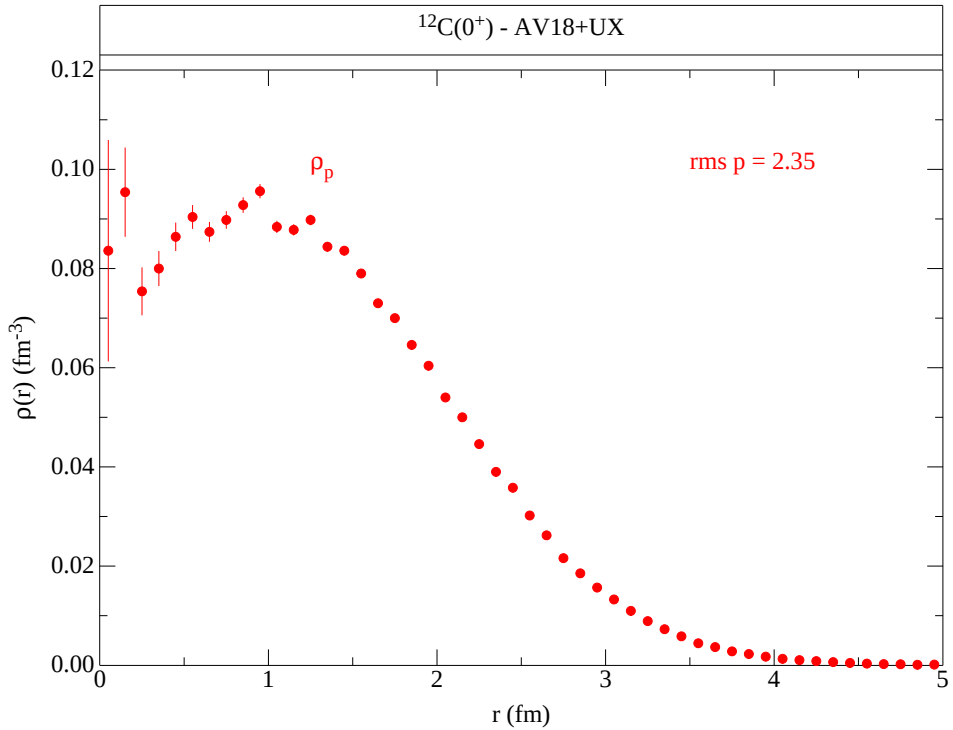
# $^{12}$C from Wiringa




Distribution of the centers of protons = neutrons in $^{12}$C

Central depletion

# $^{12}$C from Wiringa




Distribution of the centers of protons = neutrons in $^{12}$C

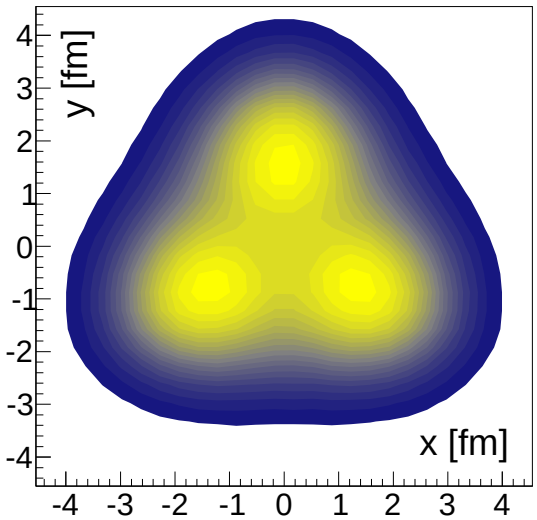
Central depletion

**Have good distributions → carry out detailed simulations**

# $^{12}$C–$^{208}$Pb collision

Mixed Glauber model at SPS conditions: $n \sim \frac{1-a}{2} N_{\mathrm{w}} + a N_{\mathrm{bin}}, \quad a = 0.12$

*Intrinsic* distributions in the *transverse plane* of the fireball with $N_w > 70$ – large multiplicity

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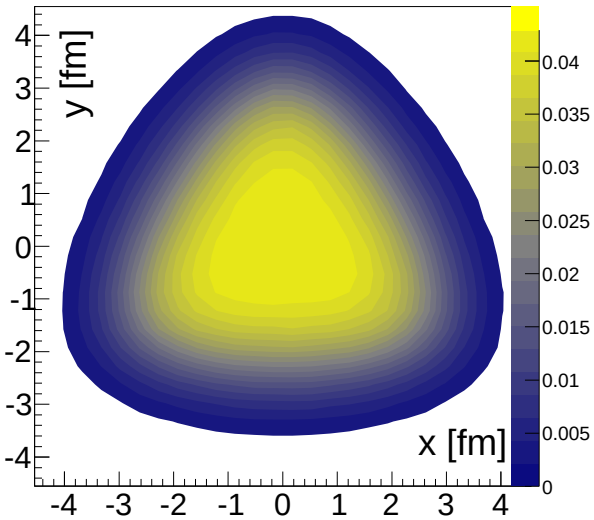


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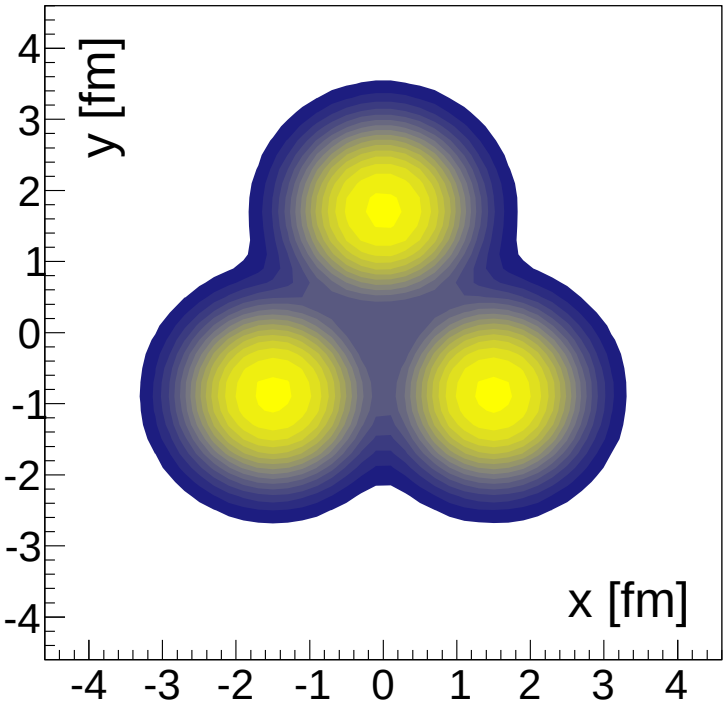
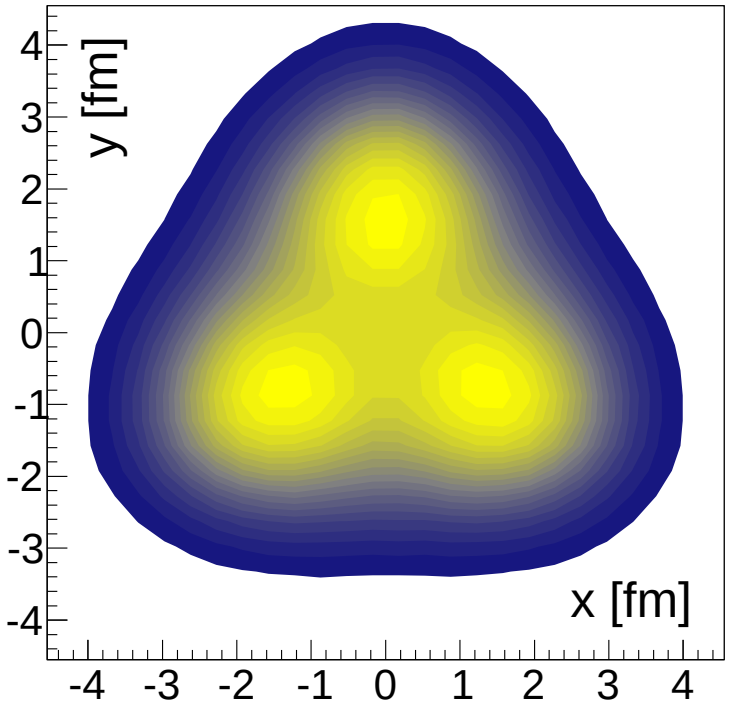
# Geometry of nucleus $\rightarrow$ geometry of fireball




intrinsic density of $^{12}$C $\rightarrow$




geometry of the fireball

# Eccentricity parameters

Eccentricity parameters $\epsilon_n$,

$$\epsilon_n e^{in\Phi_n} = \frac{\sum_j \rho_j^n e^{in\phi_j}}{\sum_j \rho_j^n},$$

describe the shape of each event ($j$ labels the sources in the event, $n$=rank, $\Phi_n$ is the principal axis angle)

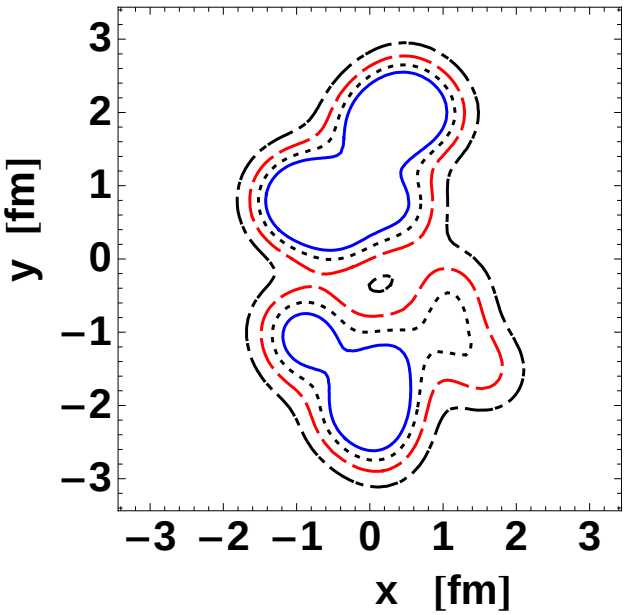
Two components:

- intrinsic (from existent mean deformation of the fireball)
- from fluctuations

# Digression: d-Pb by Bożek

The deuteron has an intrinsic dumbbell shape with very large deformation: rms $\simeq 2$ fm

Initial entropy density in a d-Pb collision with $N_{\rm part} = 24$ [Bożek 2012]

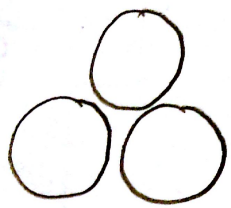



Resulting large elliptic flow confirmed with the later RHIC data

# Geometry vs multiplicity correlations in $^{12}$C-Pb

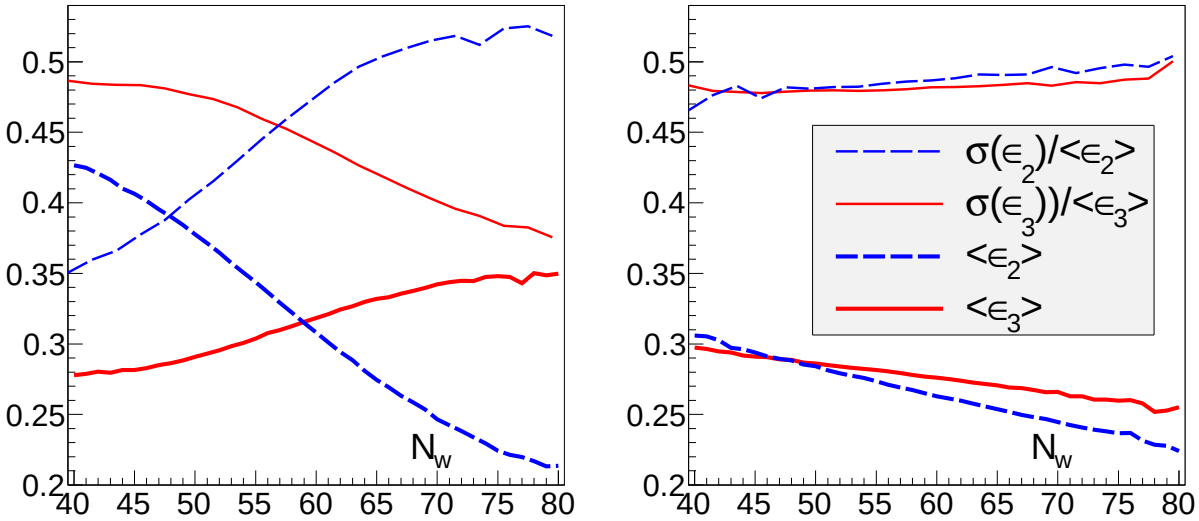
A very specific feature of the $^{12}$C collisions:

The cluster plane parallel or perpendicular to the transverse plane:



| higher multiplicity | lower multiplicity |
|---|---|
| higher triangularity | lower triangularity |
| lower ellipticity | higher ellipticity |

# Ellipticity and triangularity vs multiplicity

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**Clusters:**

When $N_w \nearrow$ then $\langle\epsilon_3\rangle \nearrow$ and $\langle\epsilon_2\rangle \searrow$

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$ tending to $\sqrt{4/\pi - 1} \sim 0.52$

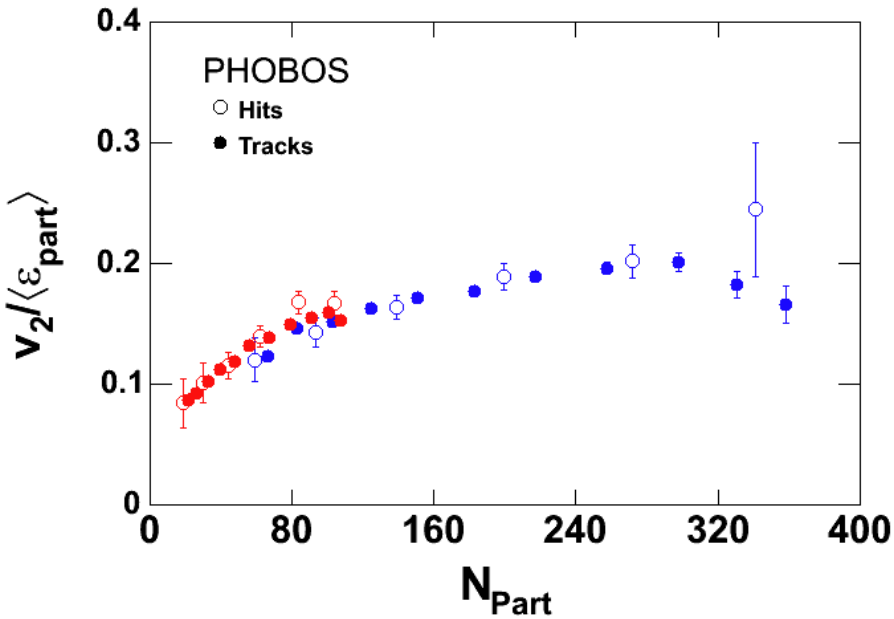
**No clusters:**

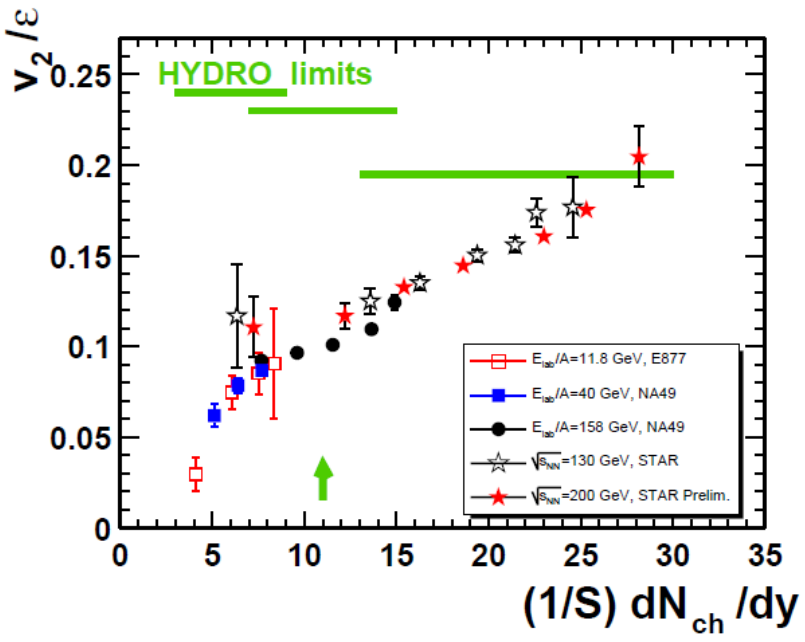
similar behavior for $n = 2$ and $n = 3$

# Shape-flow transmutation

The eccentricity parameters are transformed (in all models based on collective dynamics) into asymmetry of the transverse-momentum flow. It has been found that

$$\langle v_n \rangle \simeq A \langle \epsilon_n \rangle$$



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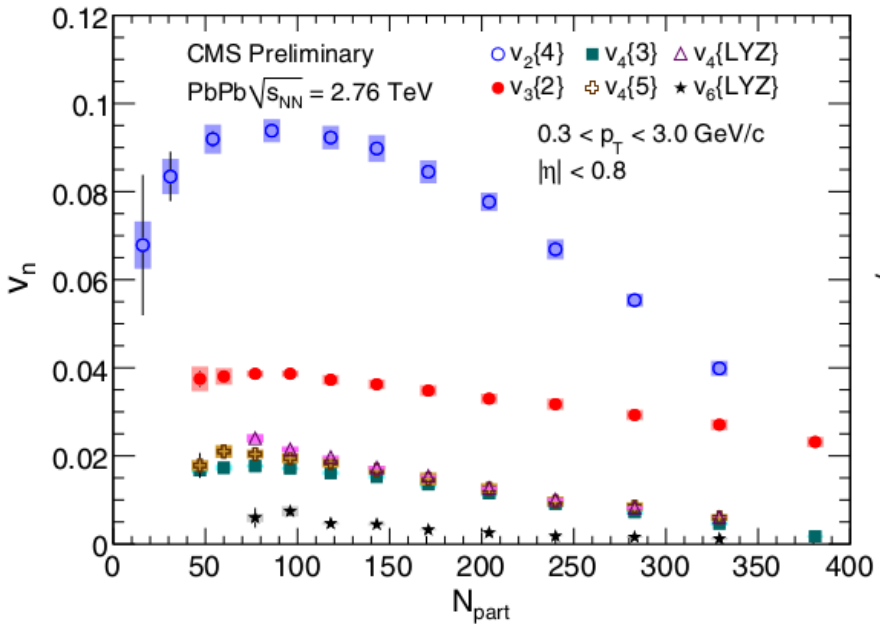
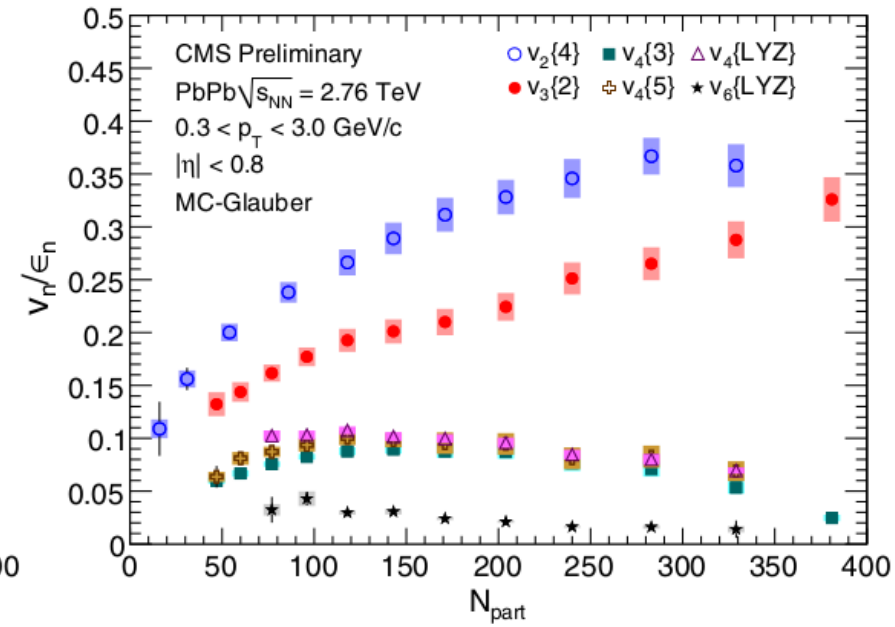
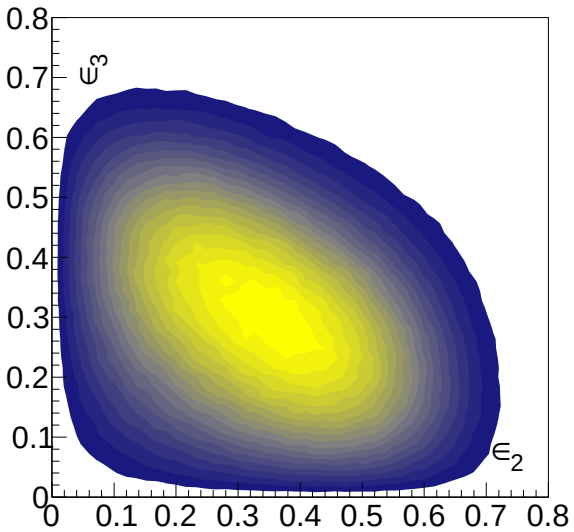


# Triangularity vs ellipticity

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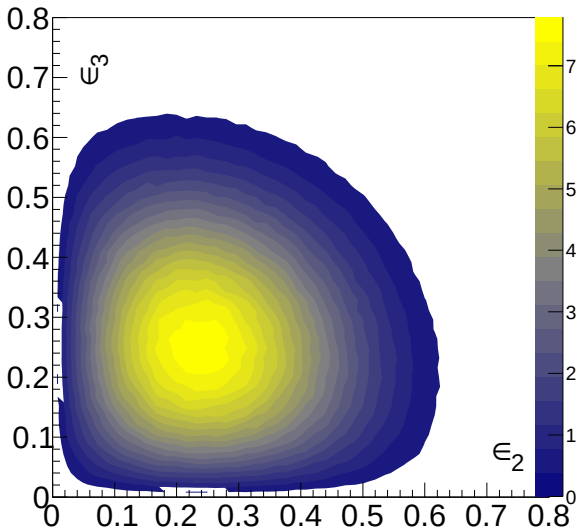


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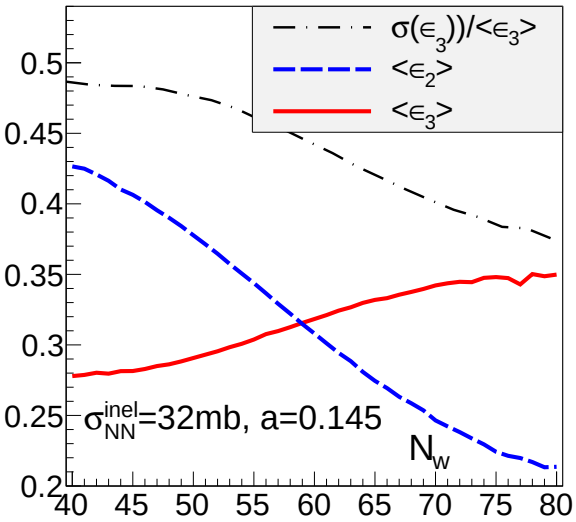
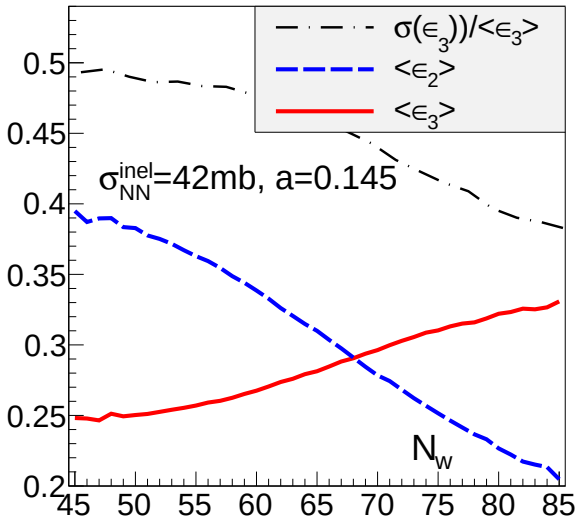
**Clusters:**

Anticorrelation: $\rho(\epsilon_2, \epsilon_3) \simeq -0.3$

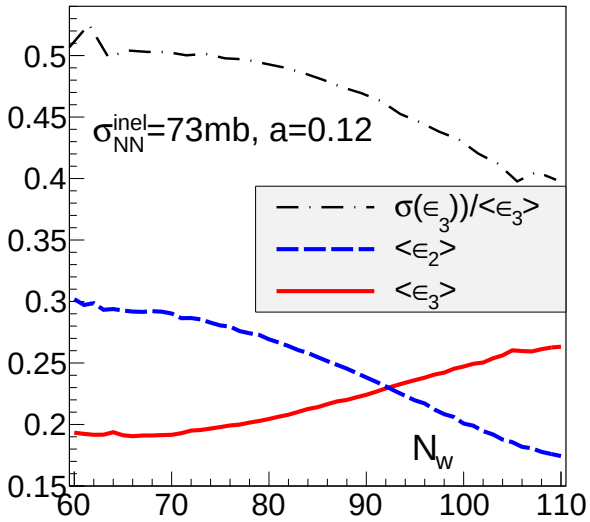
# Dependence on the collision energy




32mb (SPS)




42mb (RHIC)




72mb (LHC)

Qualitative conclusions hold from SPS to the LHC

# Why small on big?

## small on big

small nucleus $\rightarrow$ large deformation from clusters
big nucleus $\rightarrow$ large fireball, collectivity

## small on small

more difficult evolution / particle production, other signatures if any

## big on big

(U+U, Cu+Au) $\rightarrow$ possible signatures of nuclear deformation (but not clustering) [Filip, Volshin 2010, Rybczyński, WB, Stefanek 2011]

ultra-relativistic collisions at central rapidities $\rightarrow$ tested evolution codes exist

# New method: nuclear structure snapshots from ultra-fast heavy ion collisions / Geometry of the ground st. $\rightarrow$ flow

**Signatures** (qualitative and quantitative) of clustered $^{12}$C-$^{208}$Pb collisions

- Increase of $\epsilon_3$ and $v_3$ with multiplicity for the highest multiplicity events
- Decrease of scaled variance $\epsilon_3$ and $v_3$ with multiplicity for the highest multiplicity events
- Anticorrelation of $\epsilon_2$ and $\epsilon_3$, or $v_2$ and $v_3$

**Extensions**

- Other systems and other possible signatures (work in progress at UJK)
- More detailed modeling (involving hydrodynamics)

Possible future data (NA61, RHIC?) in conjunction with a detailed knowledge of the dynamics of the evolution of the fireball would allow to place constrains on the $\alpha$-cluster structure of the colliding nuclei. Conversely, the knowledge of the clustered nuclear distributions may help to verify the fireball evolution models