Hydrodynamic flow in heavy-ion collisions at RHIC and LHC

Pasi Huovinen

Uniwersytet Wrocławski

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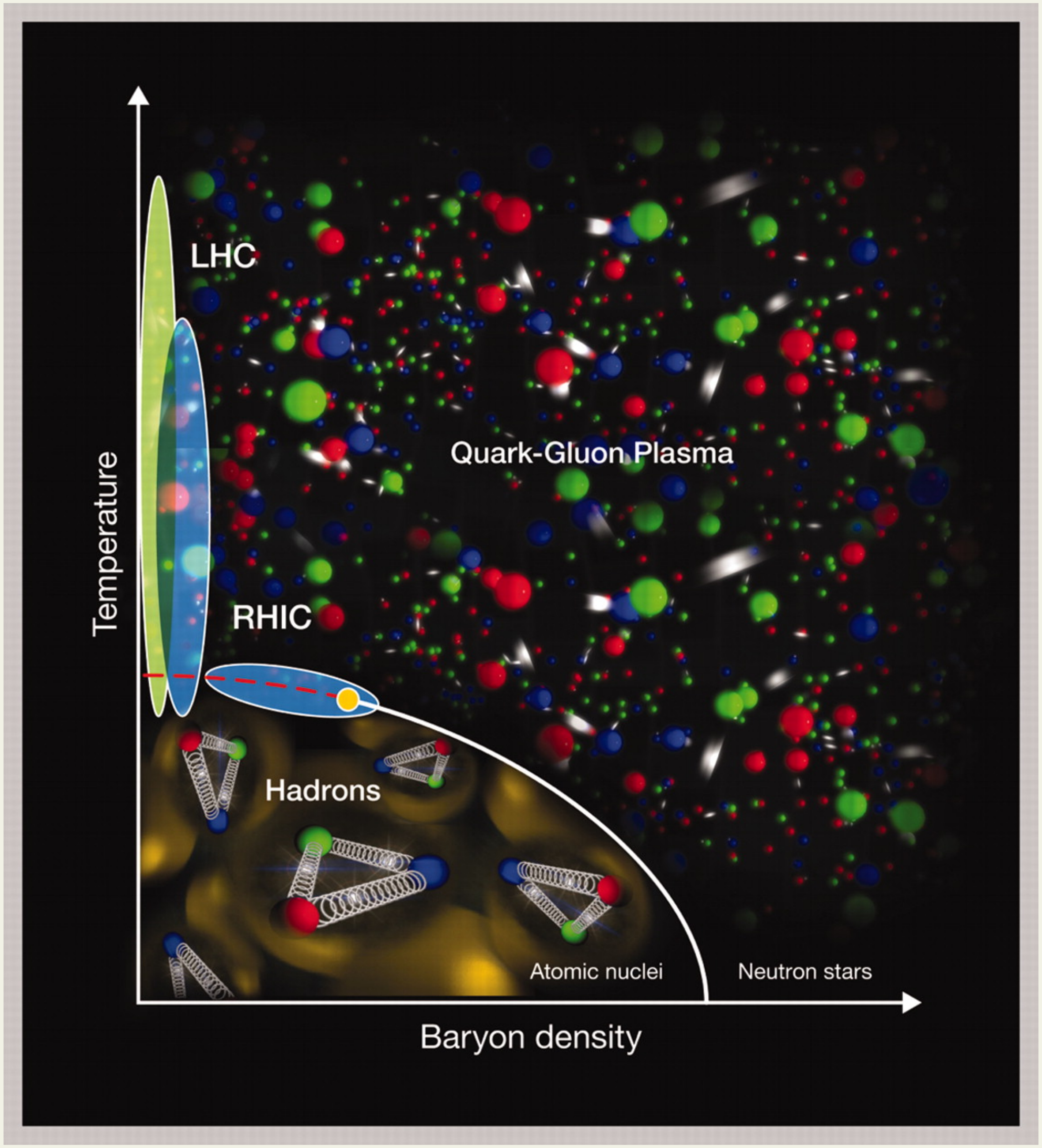
Strongly interacting matter

- interaction between constituents QCD, not QED
- matter in condensed matter physics sense
- so many particles that thermodynamical concepts
  - temperature
  - pressure
  - etc.

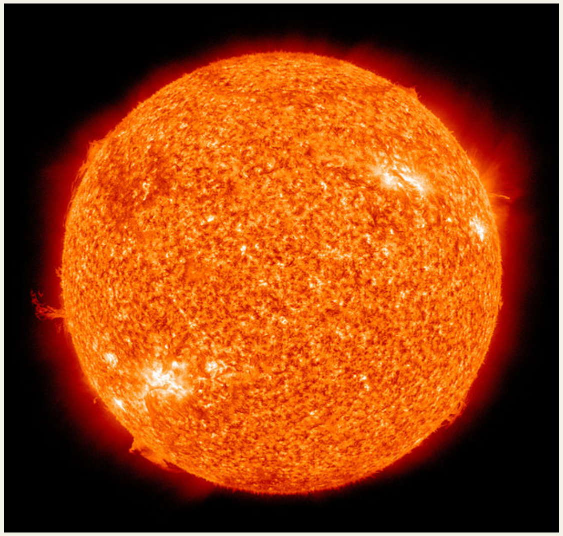
  apply

Phase diagram of strongly interacting matter

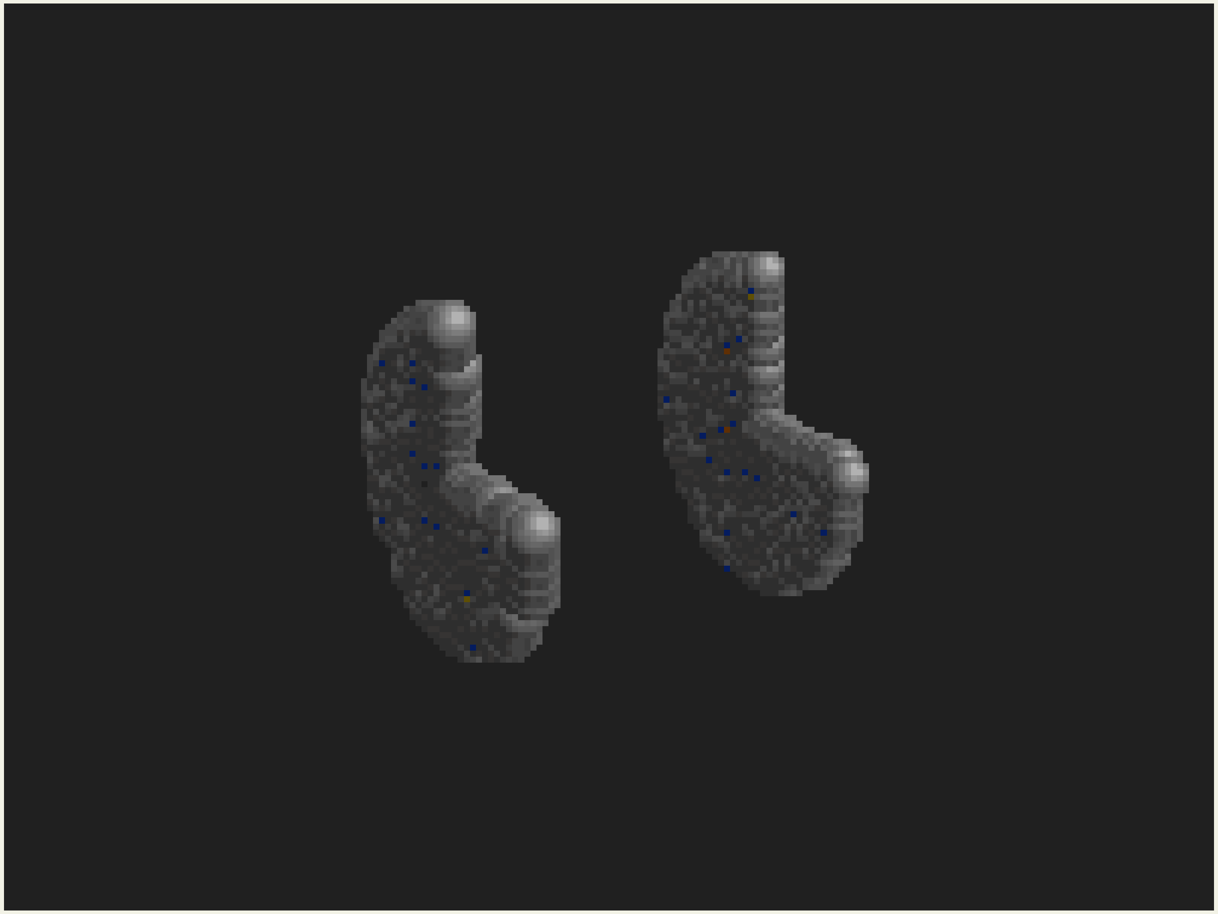


Transition temperature from hadrons to QGP $\sim 2 \cdot 10^{12}$ K, ~ 160 MeV

- **temperature on the surface of the Sun ~ 5800 K**
- **temperature in the core of the Sun $\sim 1.6 \cdot 10^{7}$ K**



Heavy-ion collision



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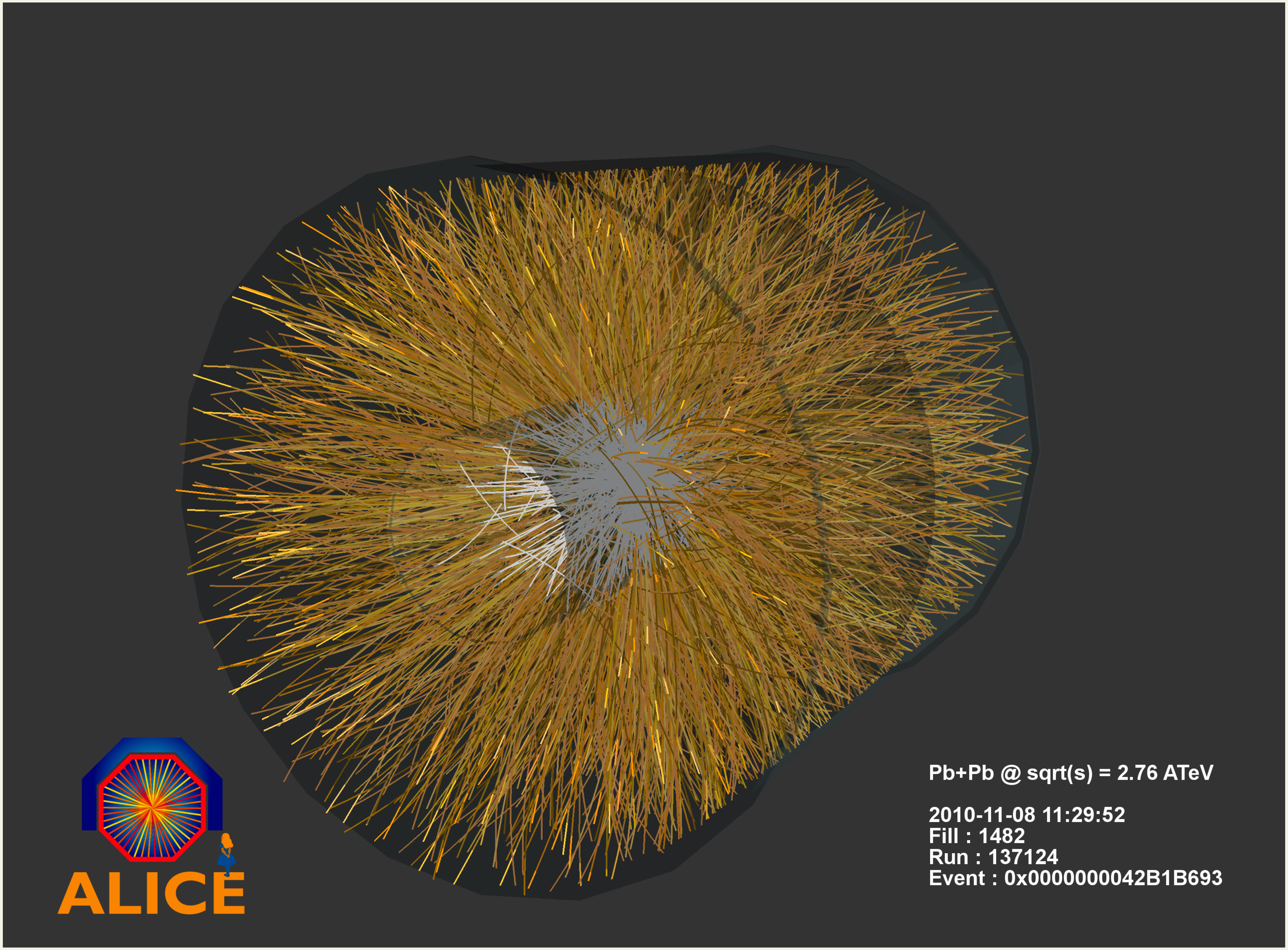

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:52
Fill : 1482
Run : 137124
Event : 0x0000000042B1B693
ALICE

Hydrodynamics

local conservation of energy, momentum and baryon number:

$$\partial_\mu T^{\mu\nu}(x) = 0 \quad \textbf{and} \quad \partial_\mu N^\mu(x) = 0$$

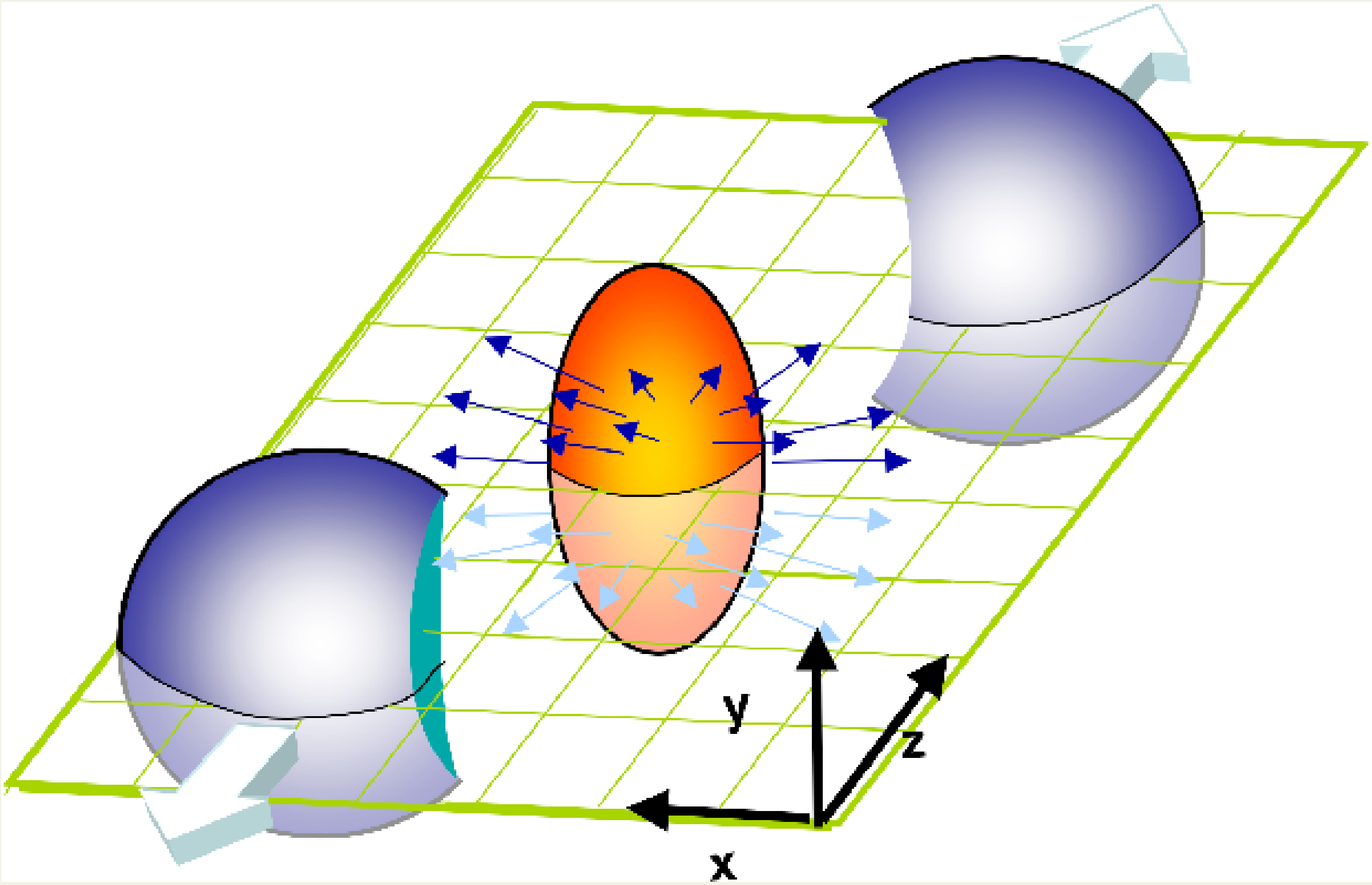
$$\begin{aligned} T^{\mu\nu} &= (\epsilon + P)u^\mu u^\nu - (P + \Pi)g^{\mu\nu} + \pi^{\mu\nu} \\ N^\mu &= n u^\mu + \nu^\mu \end{aligned}$$

local, macroscopic variables: **energy density** $\epsilon(x)$
pressure $P(x)$
flow velocity $u^\mu(x)$

matter characterized by: **equation of state** $P = P(T, \{\mu_i\})$
transport coefficients $\eta = \eta(T, \{\mu_i\})$
$\zeta = \zeta(T, \{\mu_i\})$
$\kappa = \kappa(T, \{\mu_i\})$

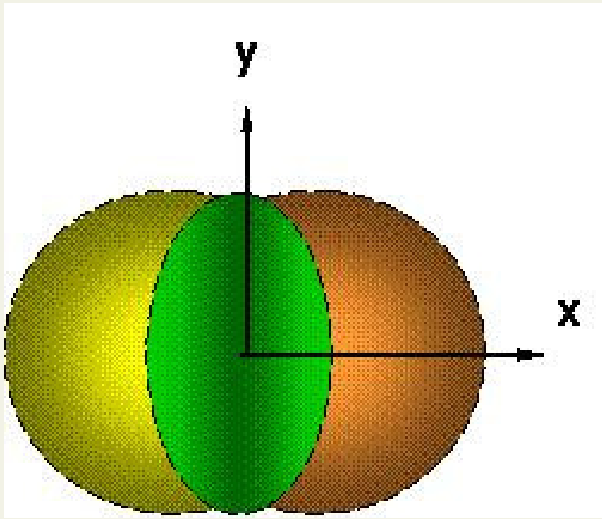
Unknowns: **initial state, final state**

Elliptic flow v_2

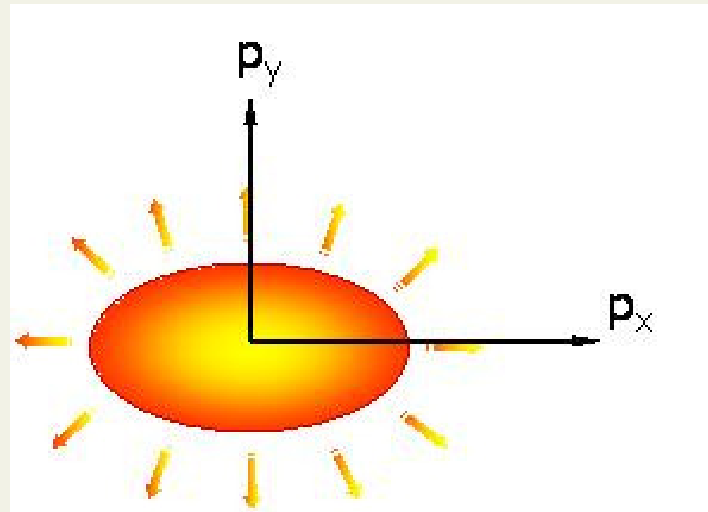


Elliptic flow v_2

spatial anisotropy $\rightarrow$ final azimuthal momentum anisotropy



$\Rightarrow$

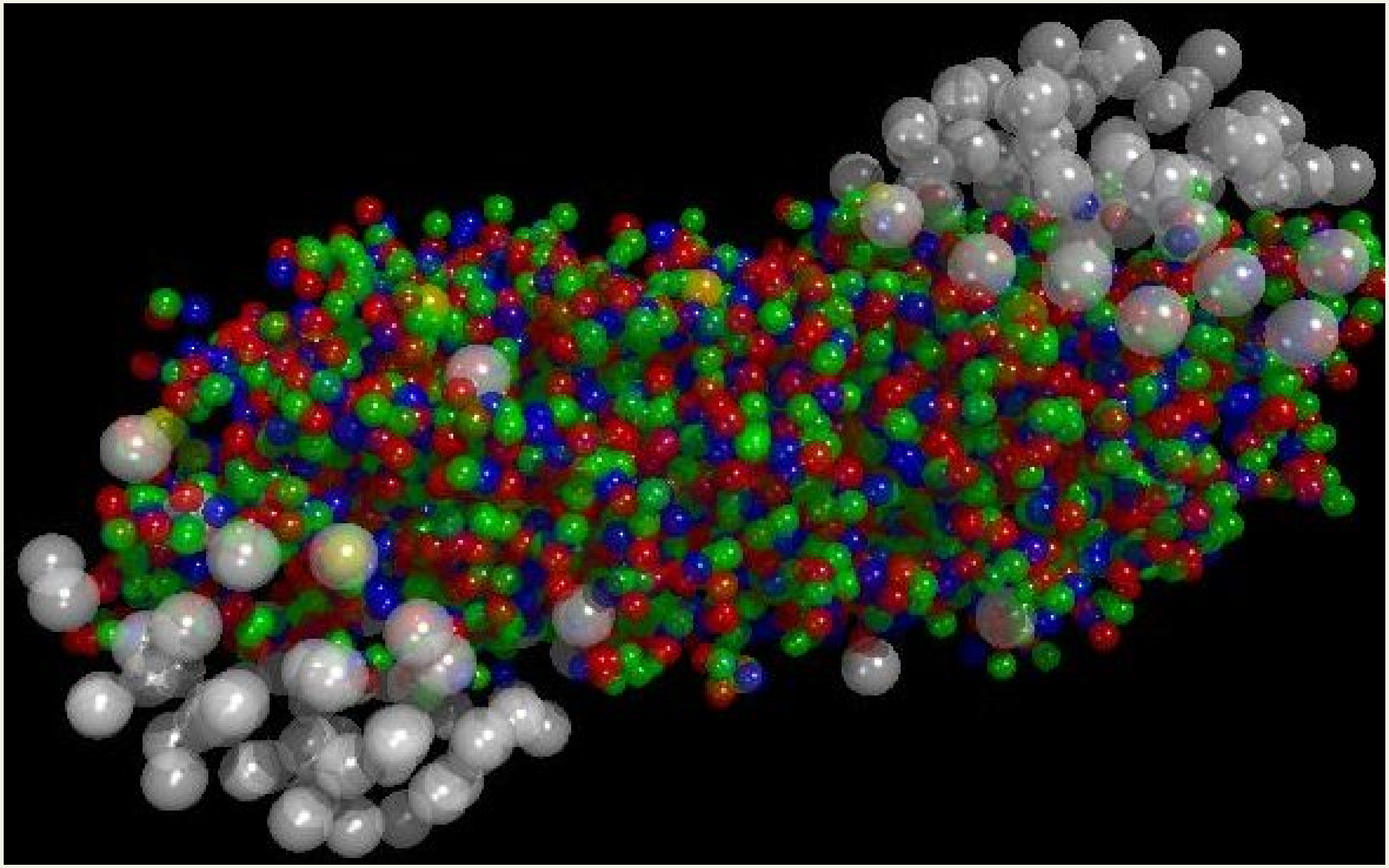


- Anisotropy in coordinate space + rescattering

$\Rightarrow$ Anisotropy in momentum space

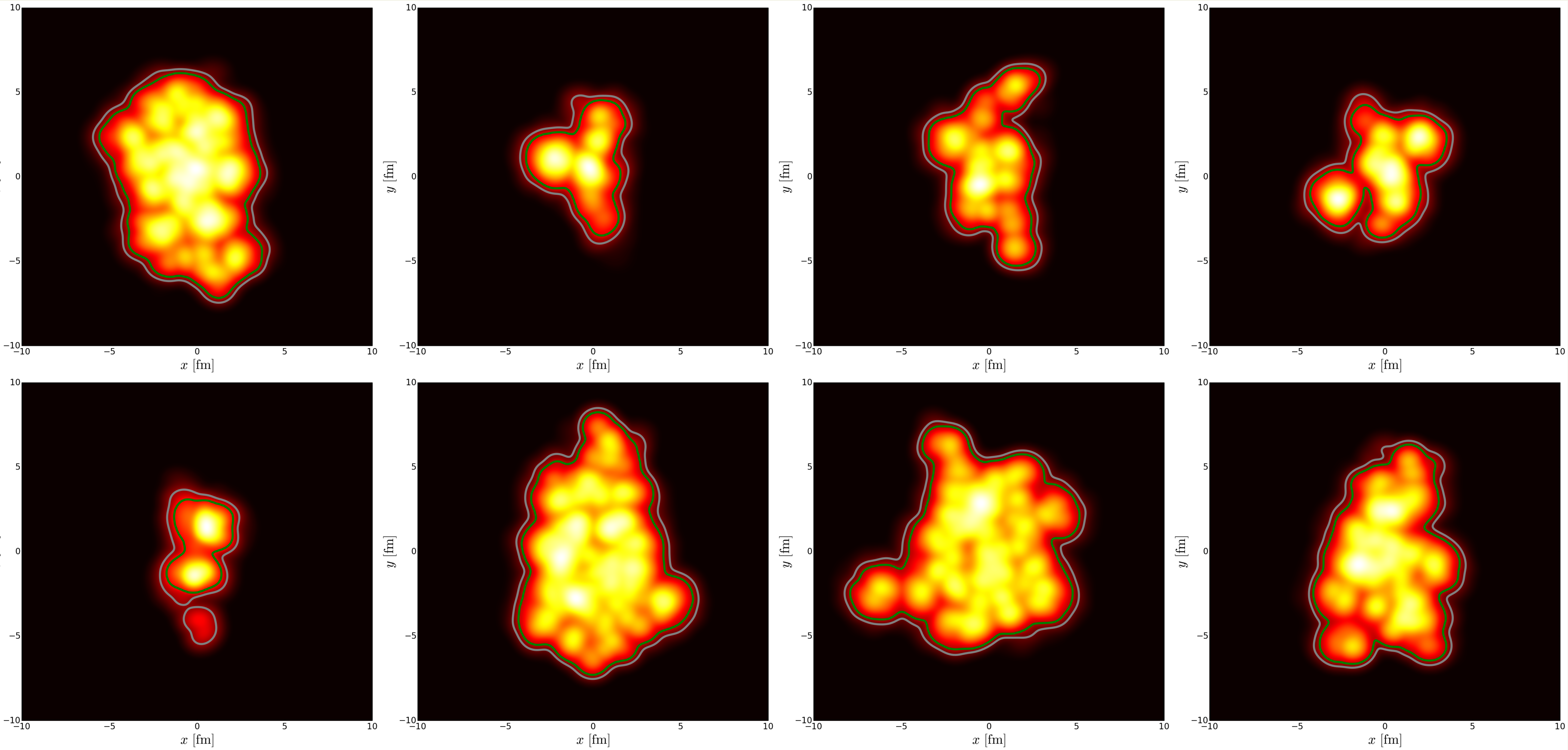
- pressure gradients convert spatial anisotropy to momentum anisotropy

  sensitive to speed of sound $c_s^2 = \partial p / \partial e$ and shear viscosity η



Initial state fluctuates

temperature profiles in transverse plane



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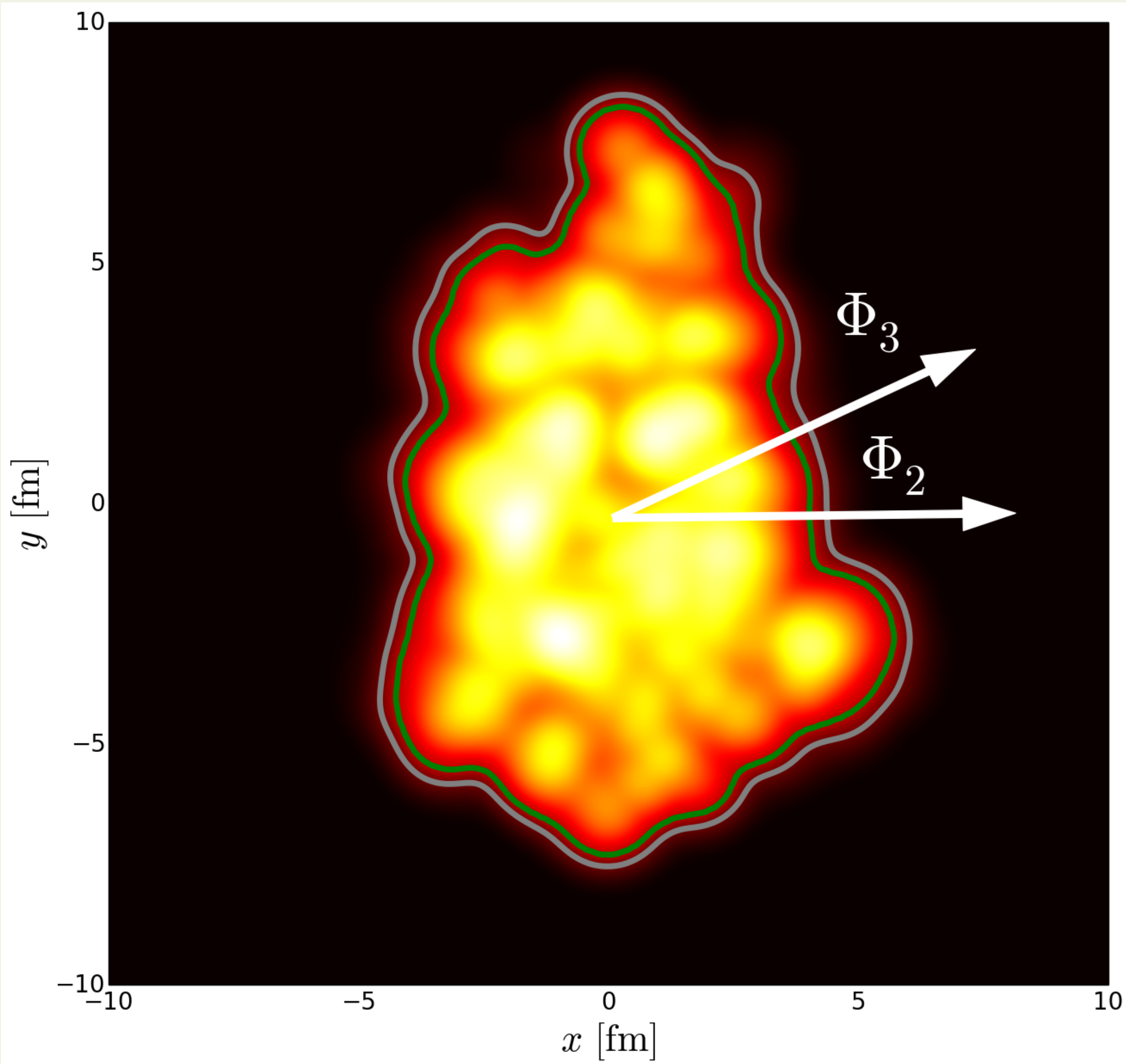
Characterising initial state



Shape of the initial density quantified by eccentricities:

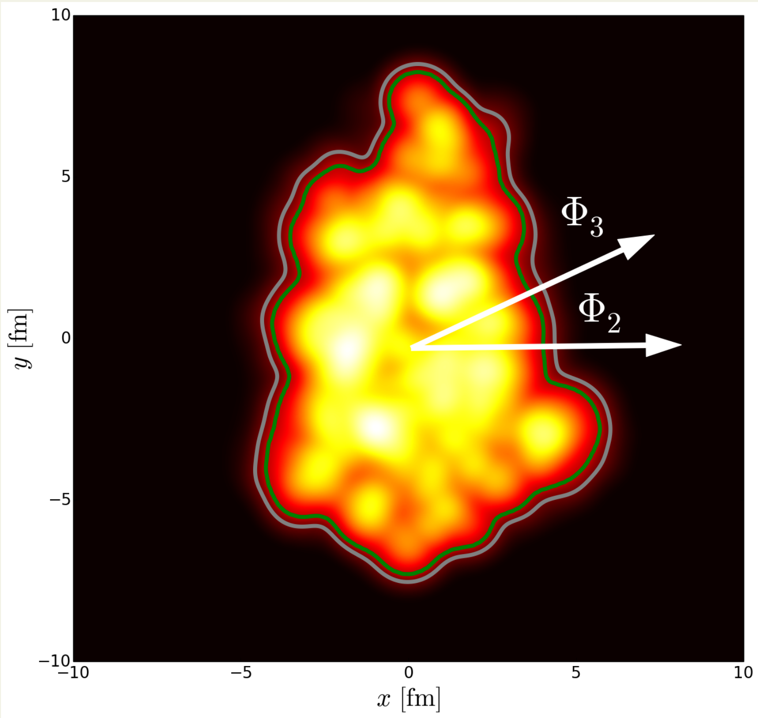
$$\epsilon_n e^{in\Phi_n} = -\frac{\{r^n e^{in\phi}\}}{\{r^n\}}$$

$$\{\ldots\} = \int \mathrm{d}x\,\mathrm{d}y\, e(x, y, \tau_0)(\ldots)$$

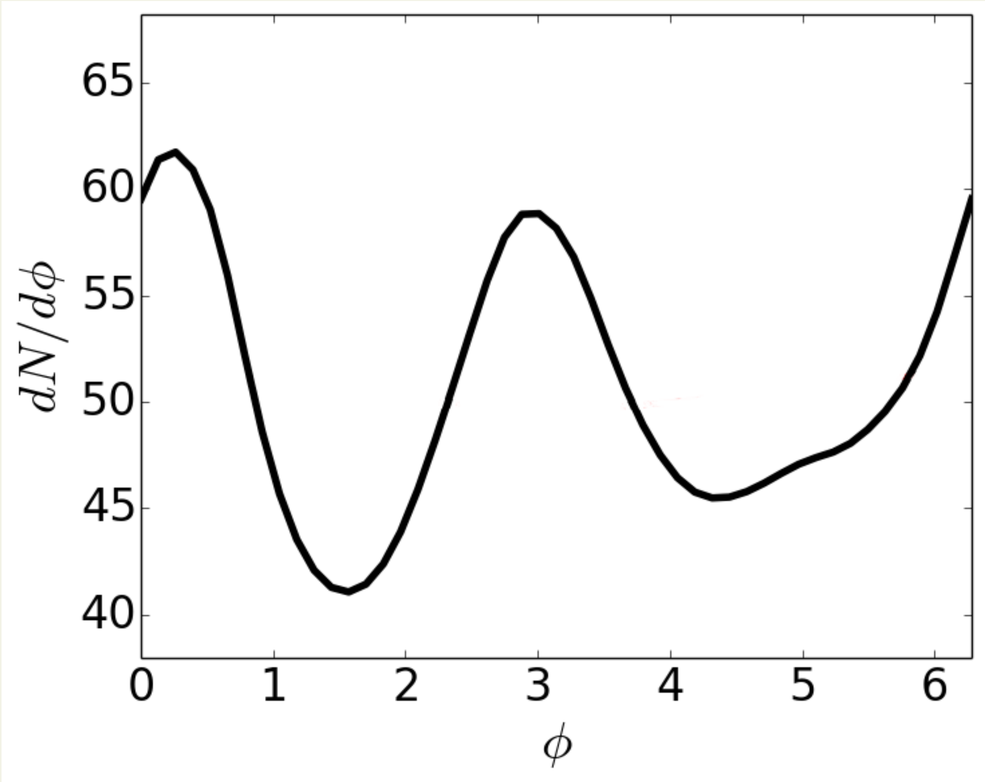
ϵ_n **eccentricity**

Φ_n **"participant plane" angle**

From fluid to distribution



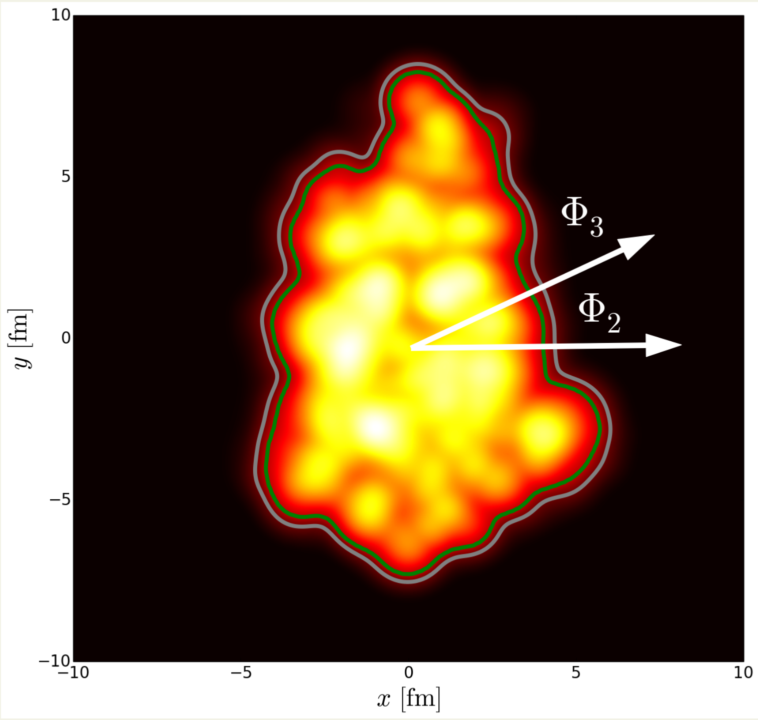
$\Longrightarrow$



$$\epsilon_n, \Psi_n \Longrightarrow v_n, \Phi_n$$

$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}\phi} = \frac{\mathrm{d}N}{\mathrm{d}y}\left[1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))\right]$$

From fluid to distribution



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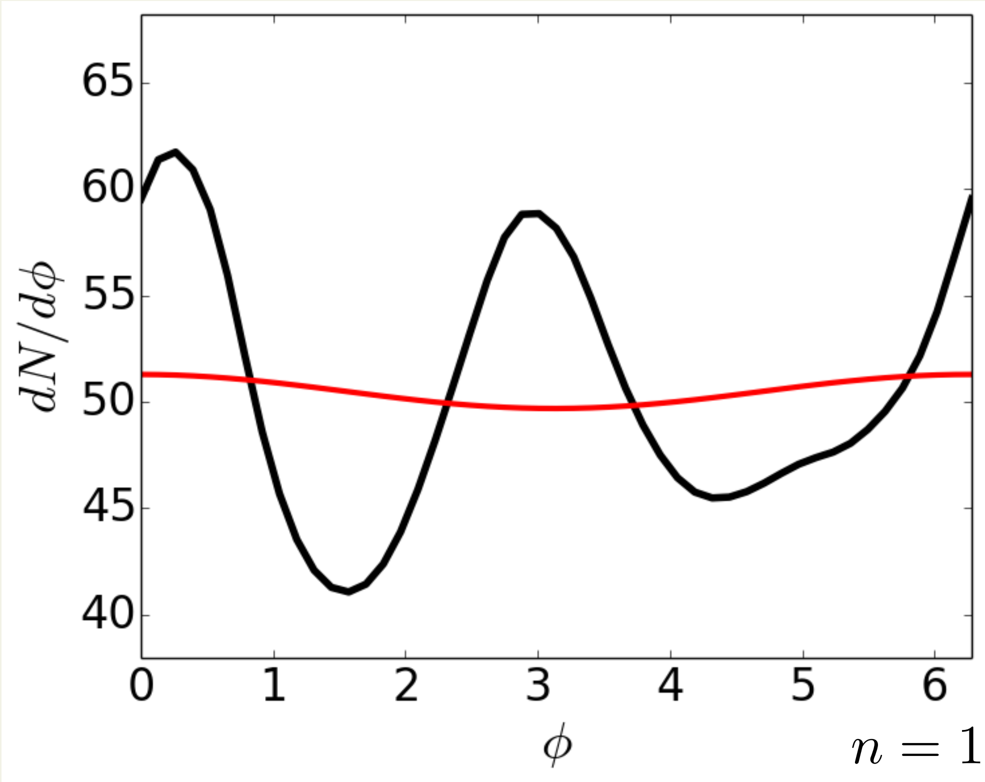

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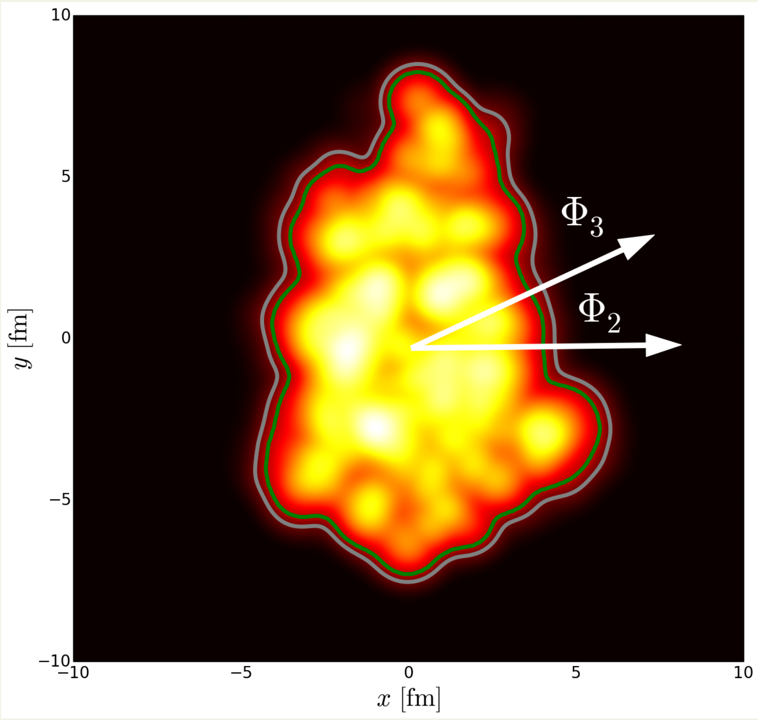

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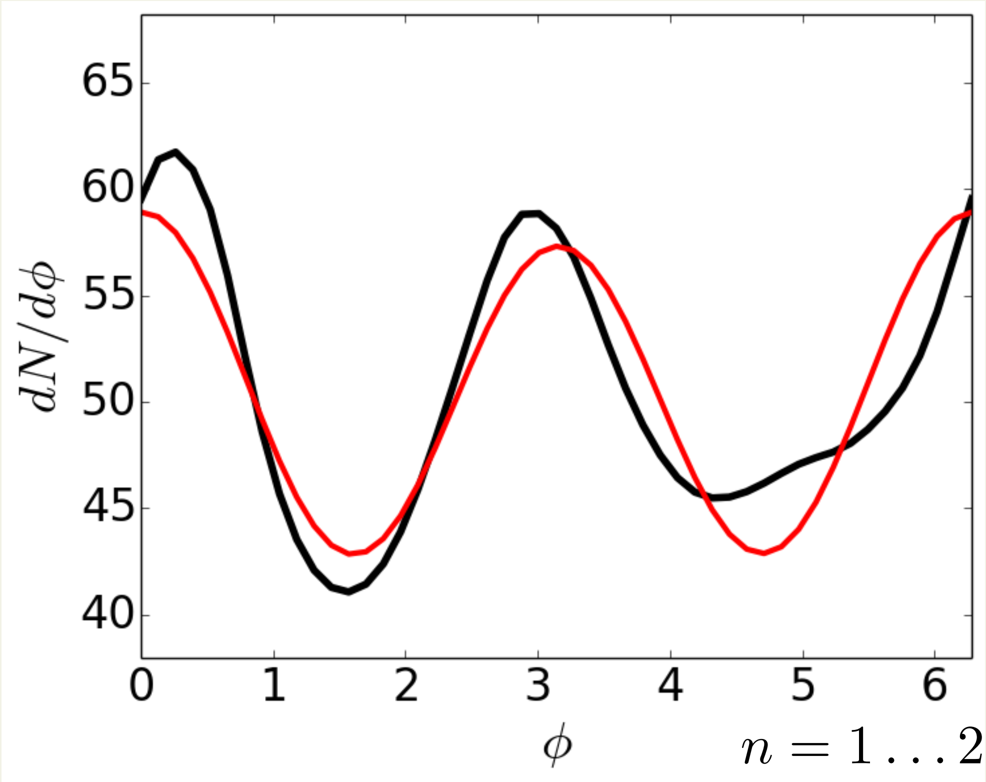

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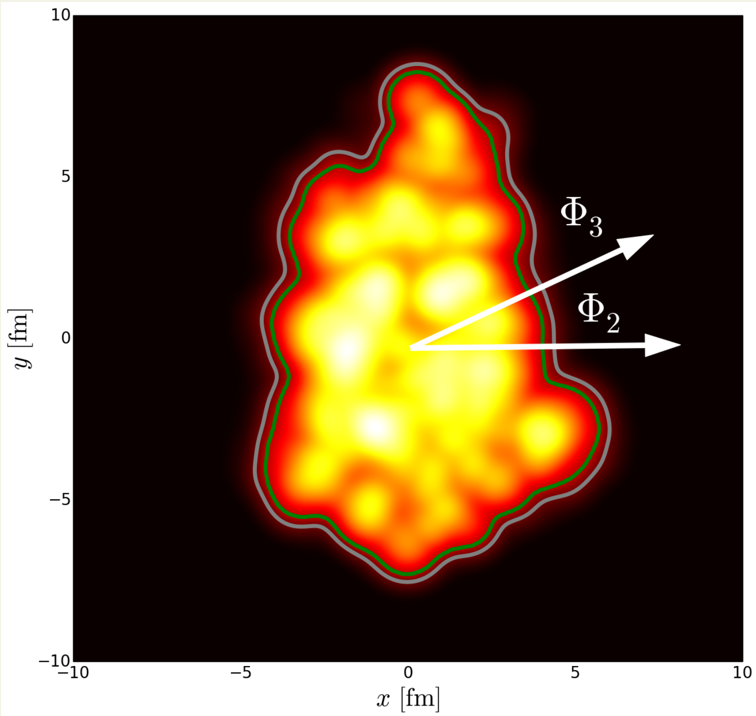

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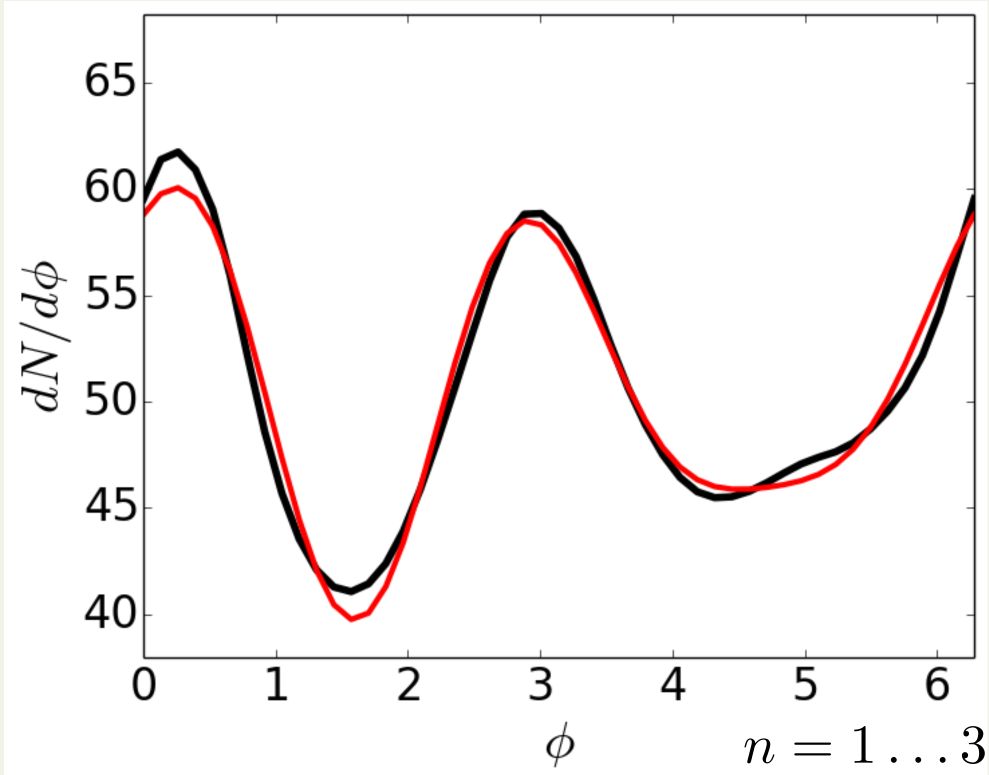

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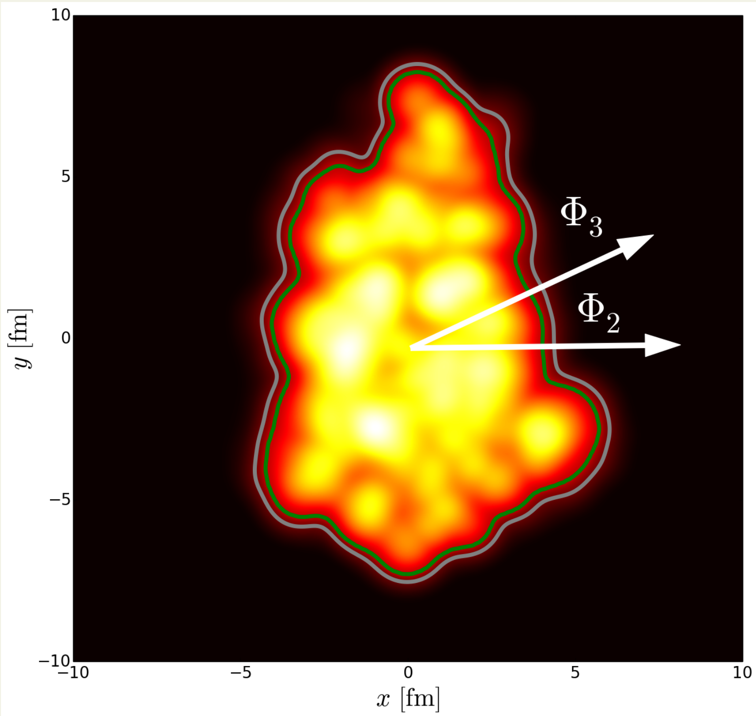

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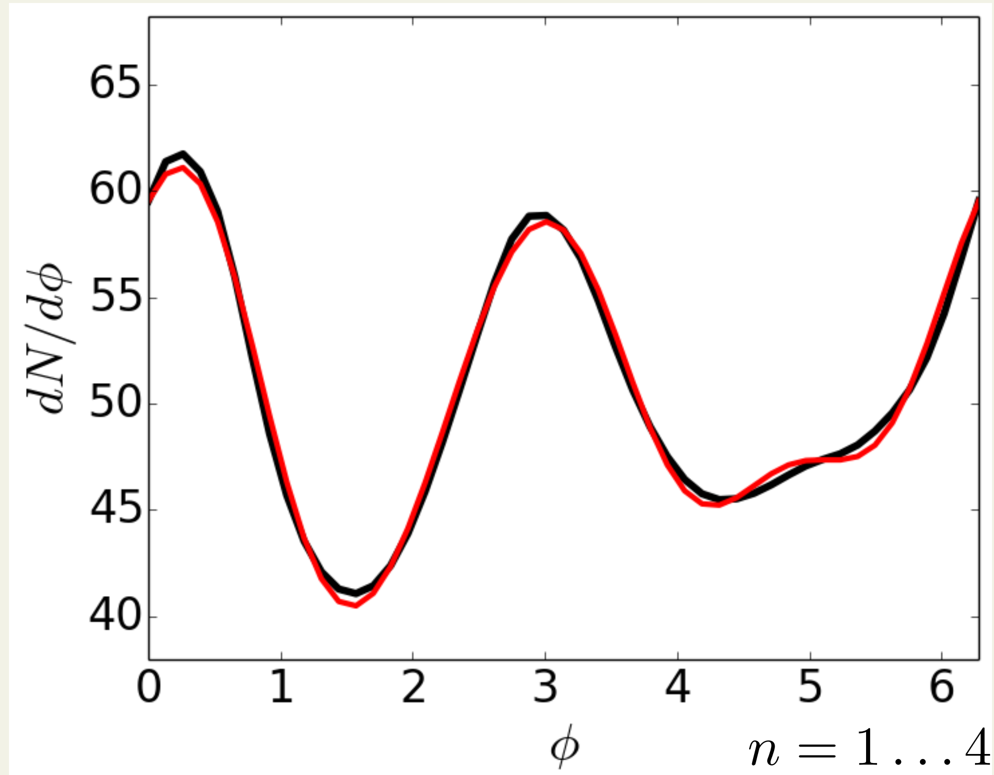

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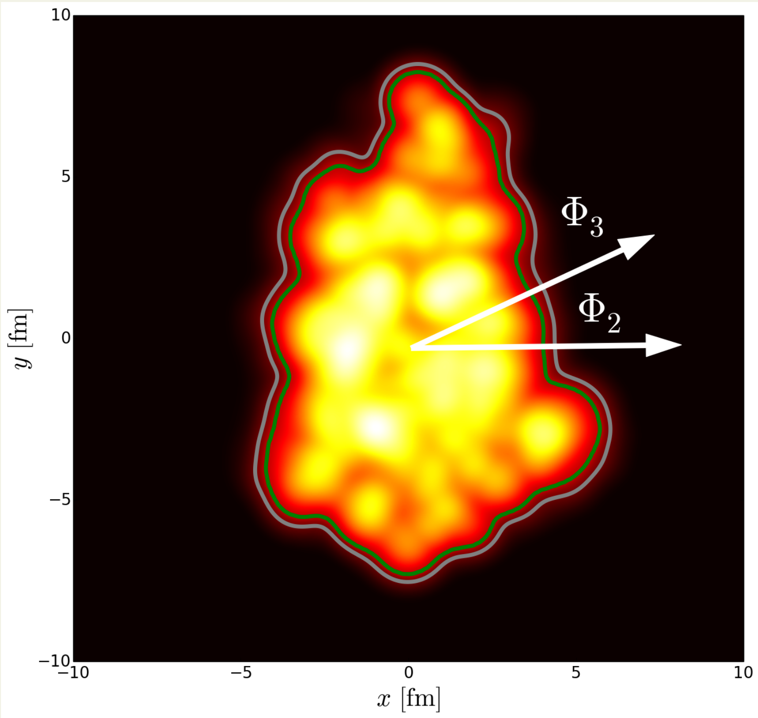

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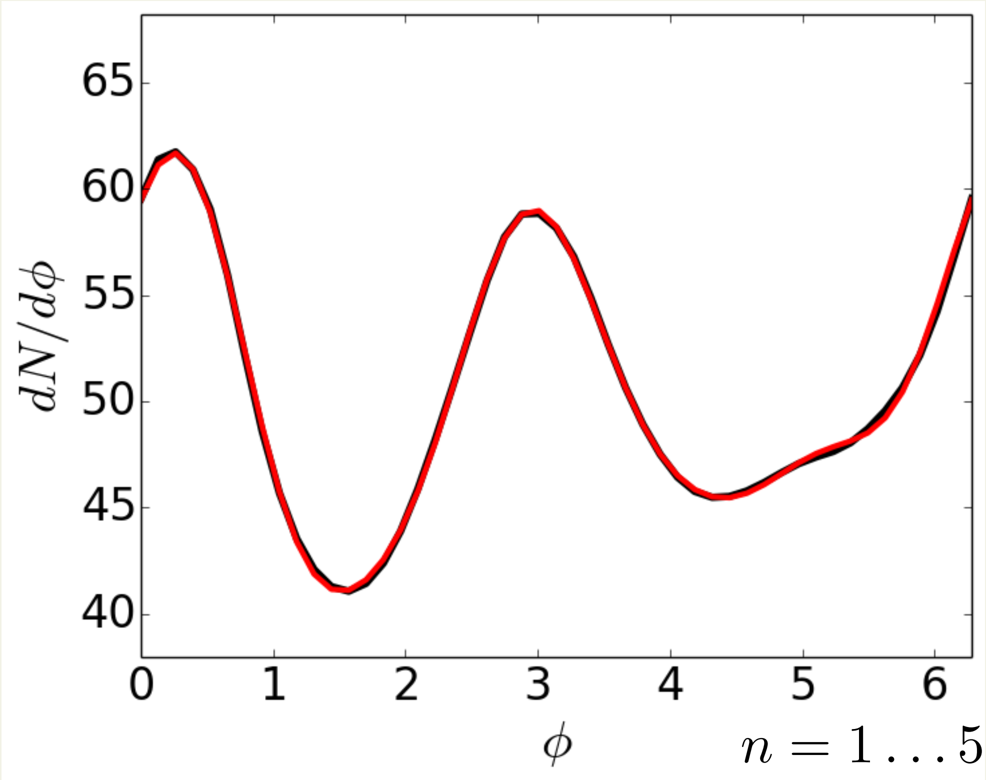

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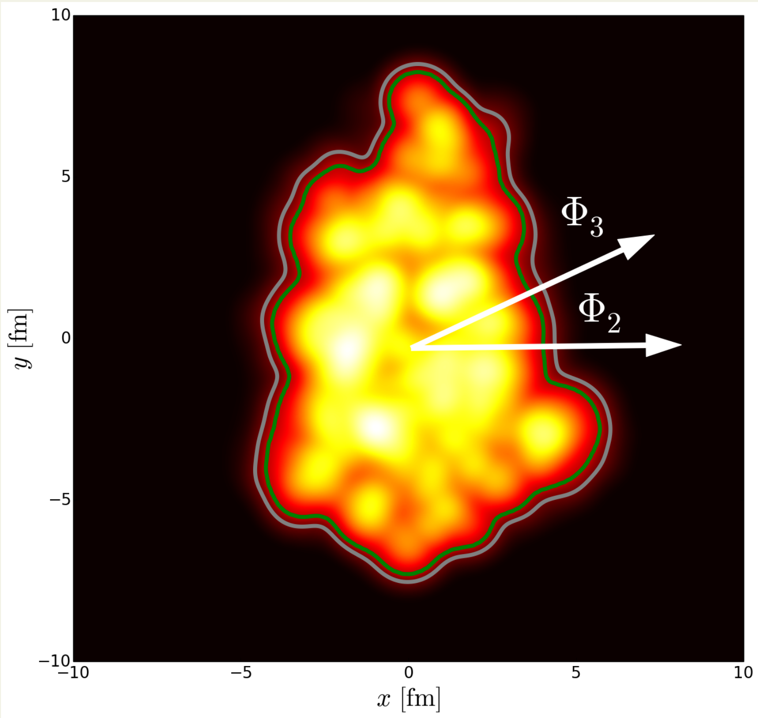

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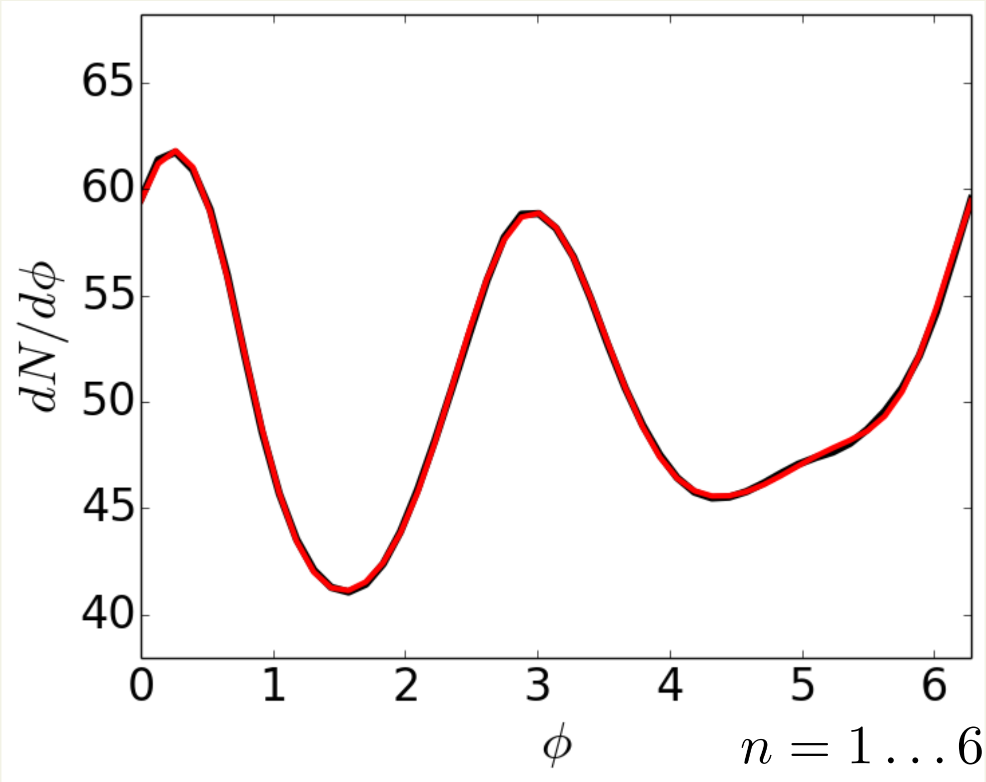

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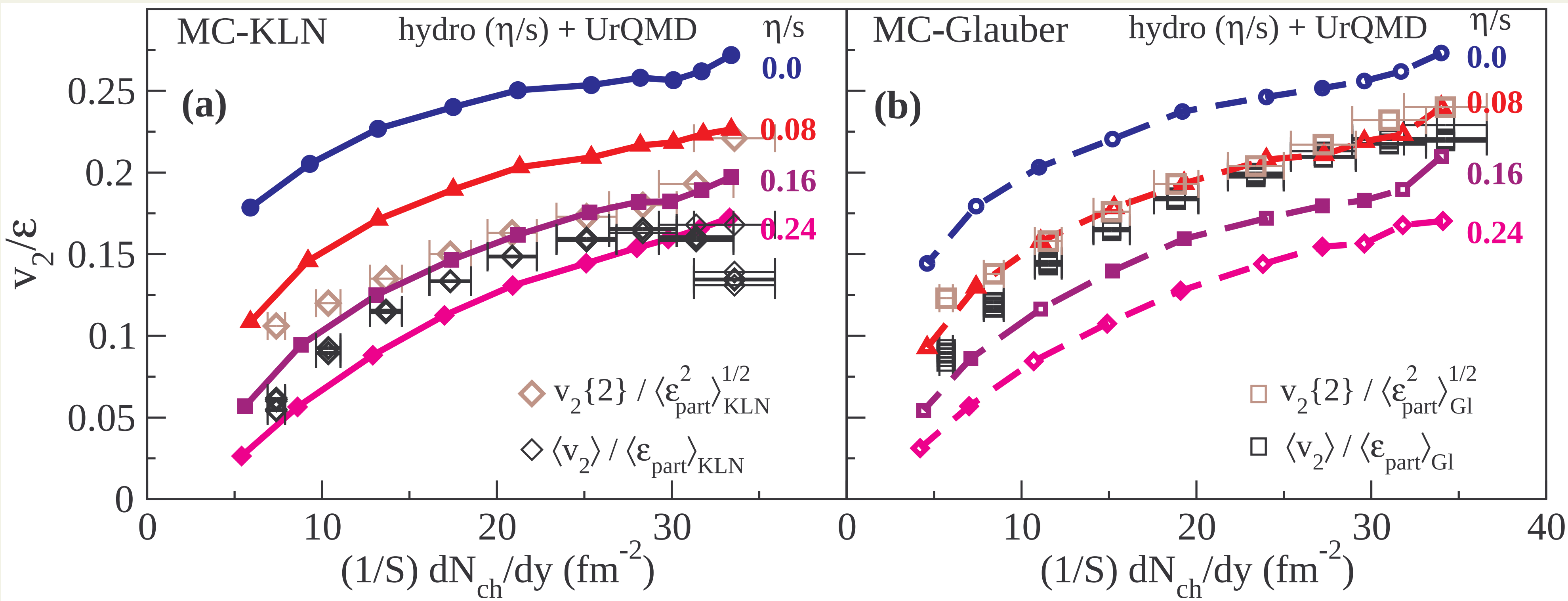
η/s from v_2

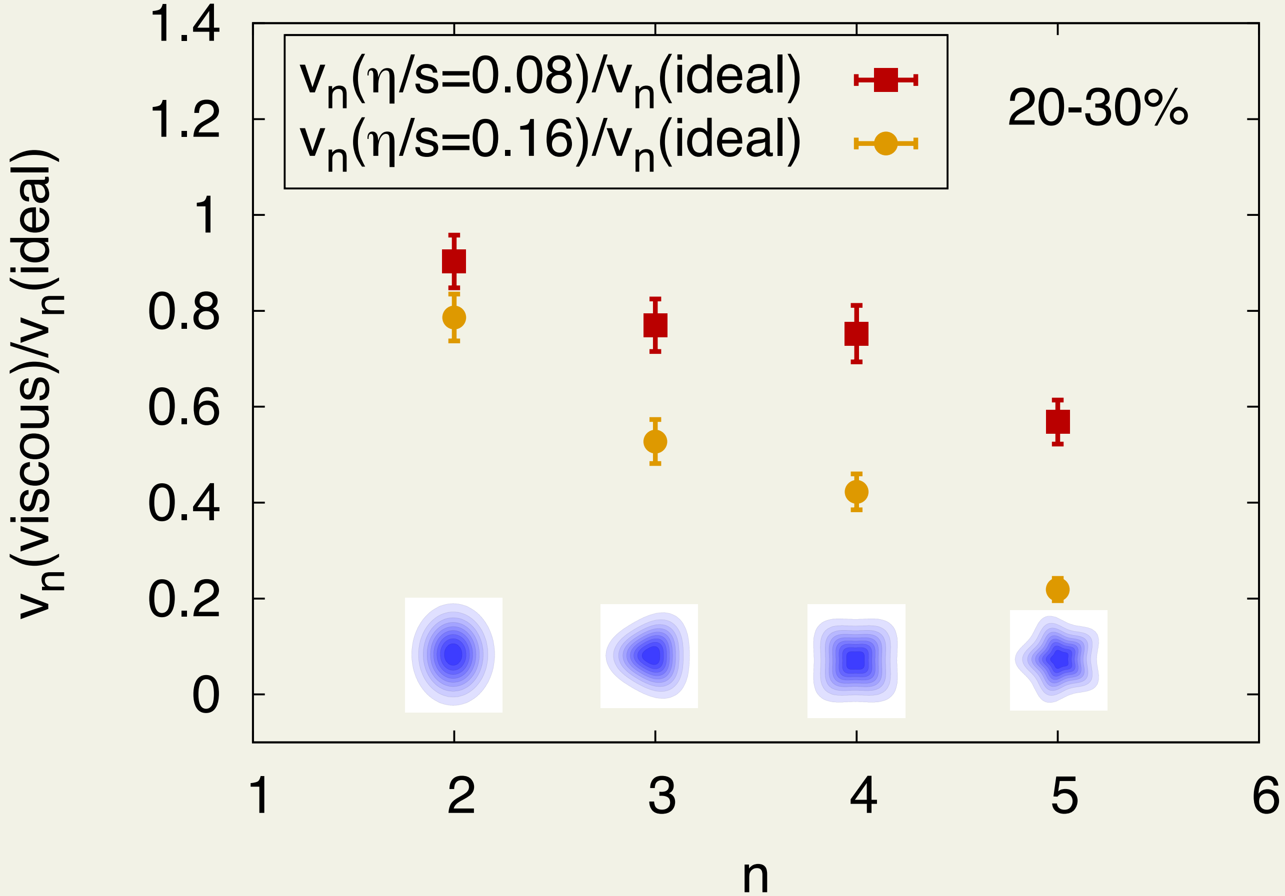
Shen *et al.* J.Phys.G38:124045,2011



- **MC-Glauber initialization:** $\eta/s = 0.08$
- **MC-KLN initialization:** $\eta/s = 0.2$

Sensitivity to η/s

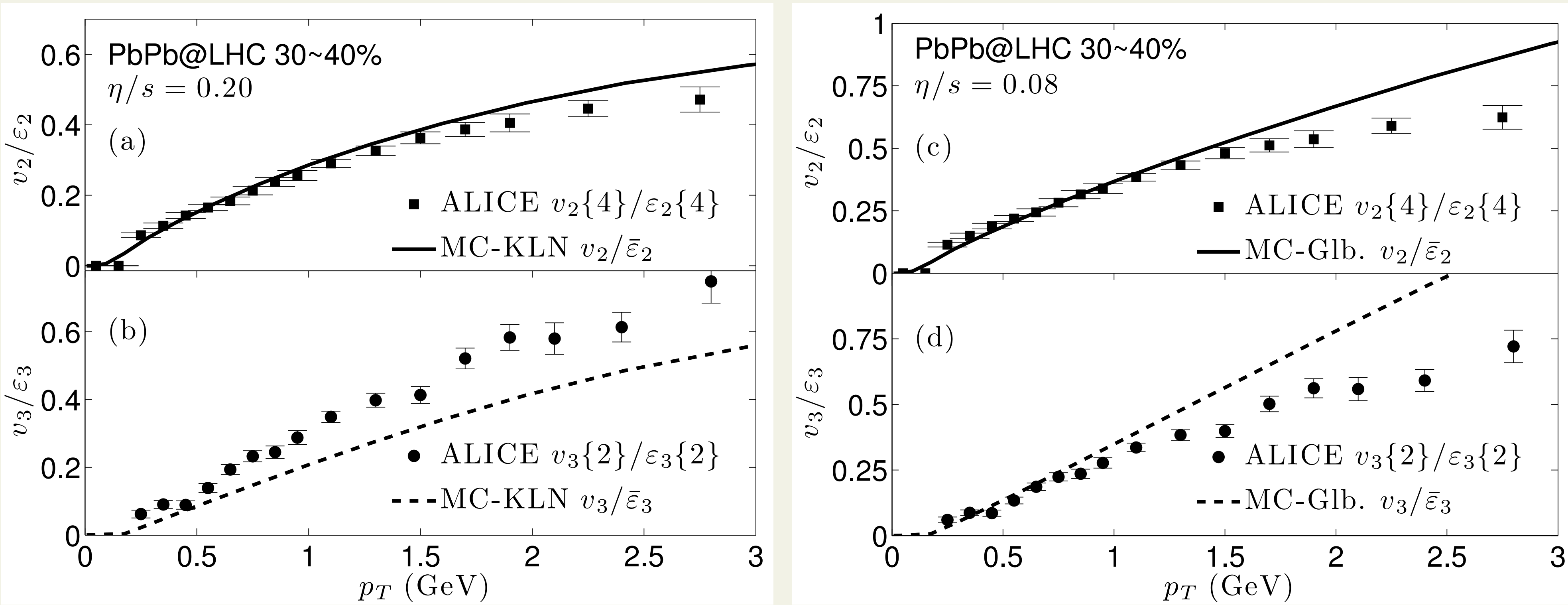
Schenke *et al.* Phys.Rev.C85:024901,2012



- higher coefficients are suppressed more by dissipation

v_3

Qiu *et al.* Phys.Lett.B707:151,2012



- **models can be distinguished**
- **MC-Glauber slightly favoured**

Distributions of v_n event-by-event

Scale out the average

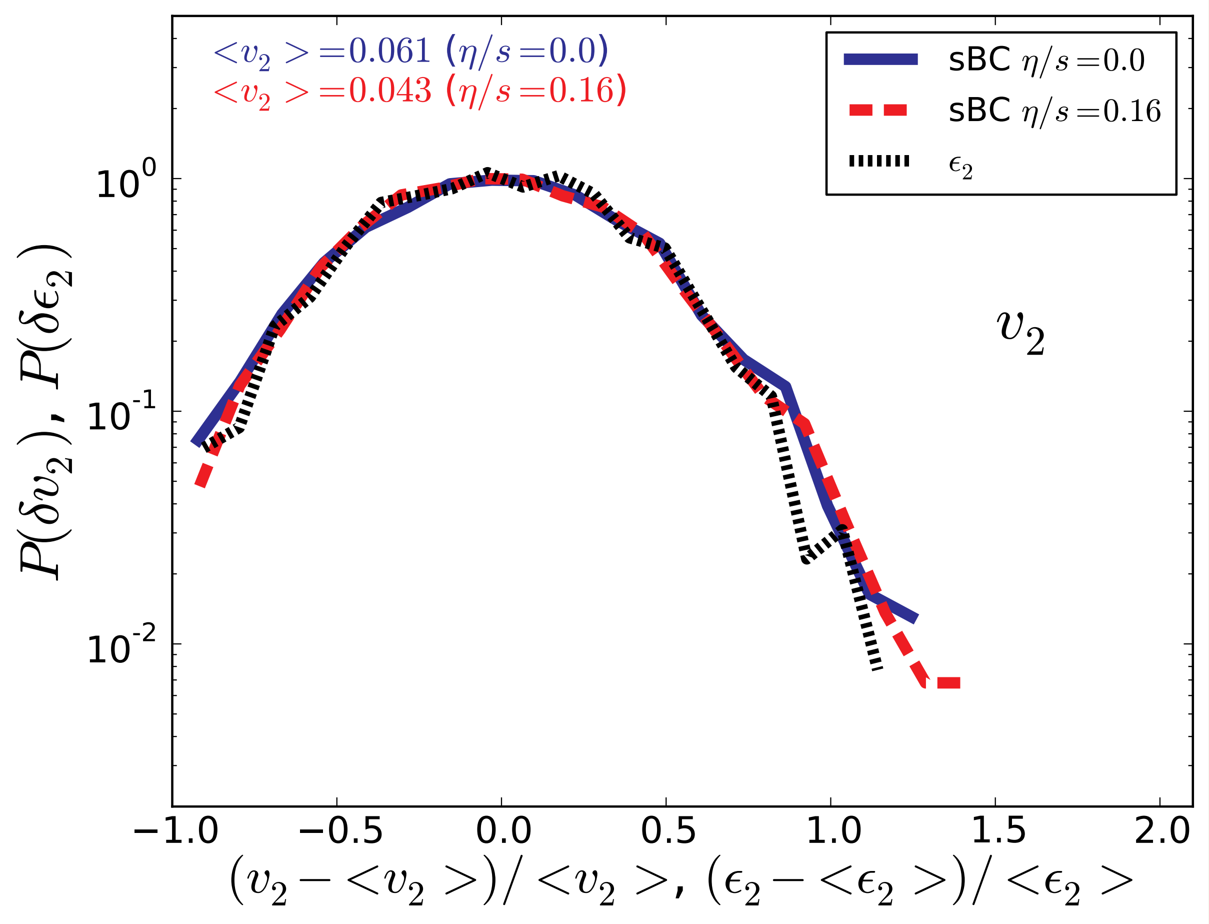
$$\delta v_2 = \frac{v_2 - \langle v_2 \rangle}{\langle v_2 \rangle}$$

$$\Downarrow$$

$$P(\delta v_2) = P(\delta \epsilon_2)$$

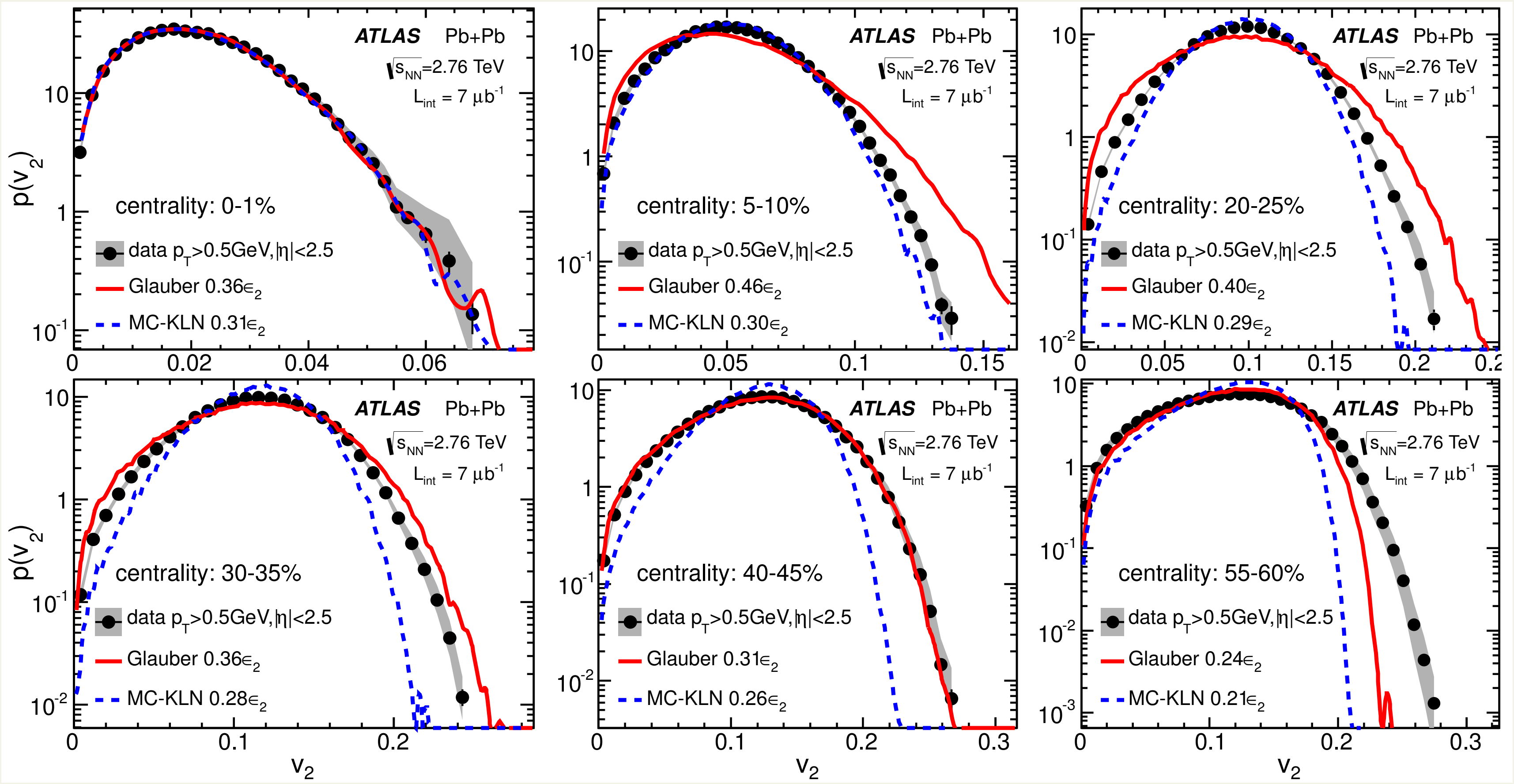
independent of viscosity

Niemi *et al.* Phys.Rev.C87,054901,2013



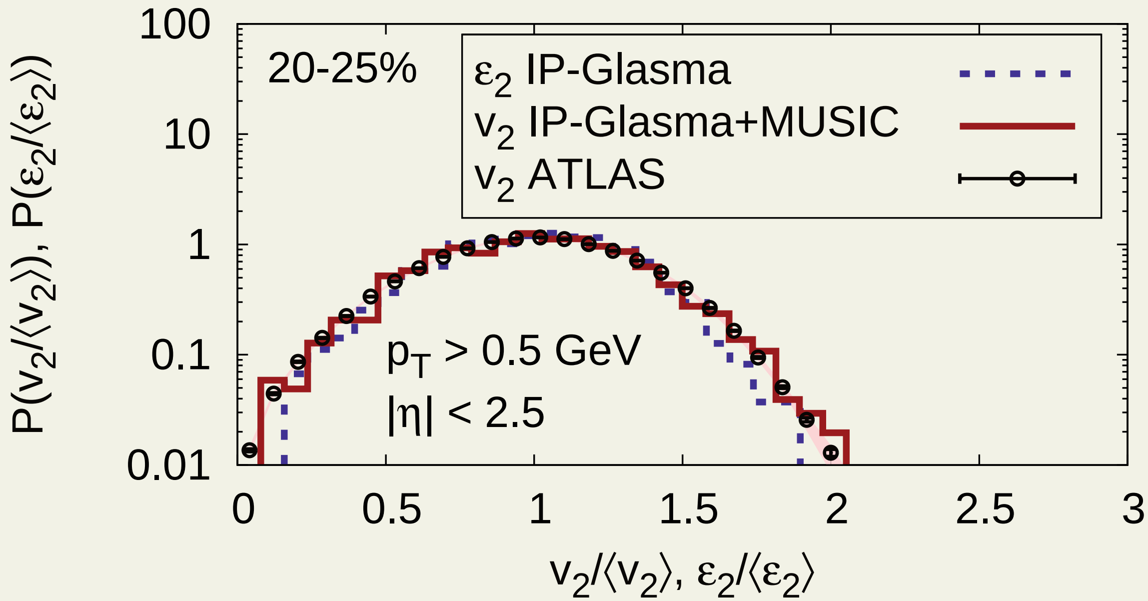
Flow fluctuations

Aad *et al.* [ATLAS Collaboration] JHEP 1311:183,2013



- $P(v_2)$ **compared to MC-Glauber and MC-KLN** $P(\varepsilon_2)$
- **MC-Glauber initialization: too wide**
- **MC-KLN initialization: too narrow**

Gale *et al.*, PRL 110, 012302 (2013)



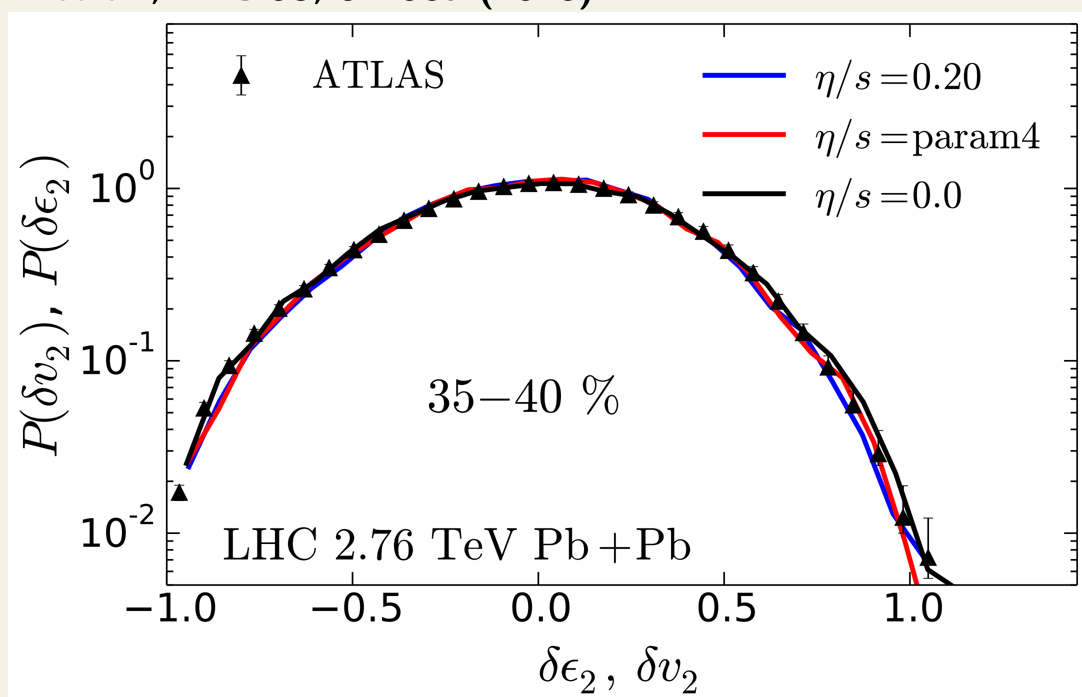
•IP-Glasma (Color Glass + Yang-Mills)

and

•EKRT (pQCD + saturation)

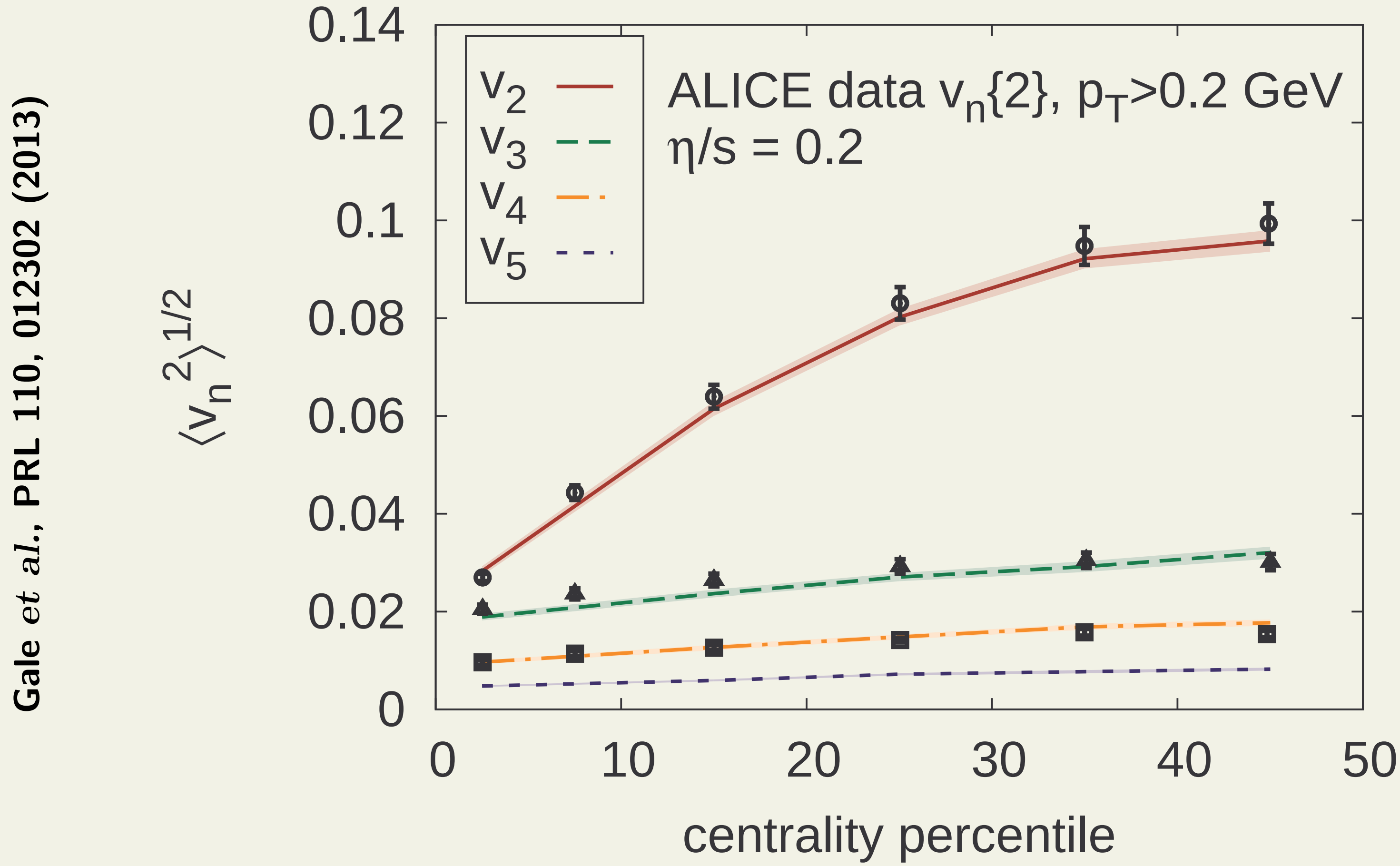
initial states work

Niemi *et al.*, PRC 93, 024907 (2016)



State of the art

- **IP-Glasma initial state: Color Glass plus Yang-Mills evolution**

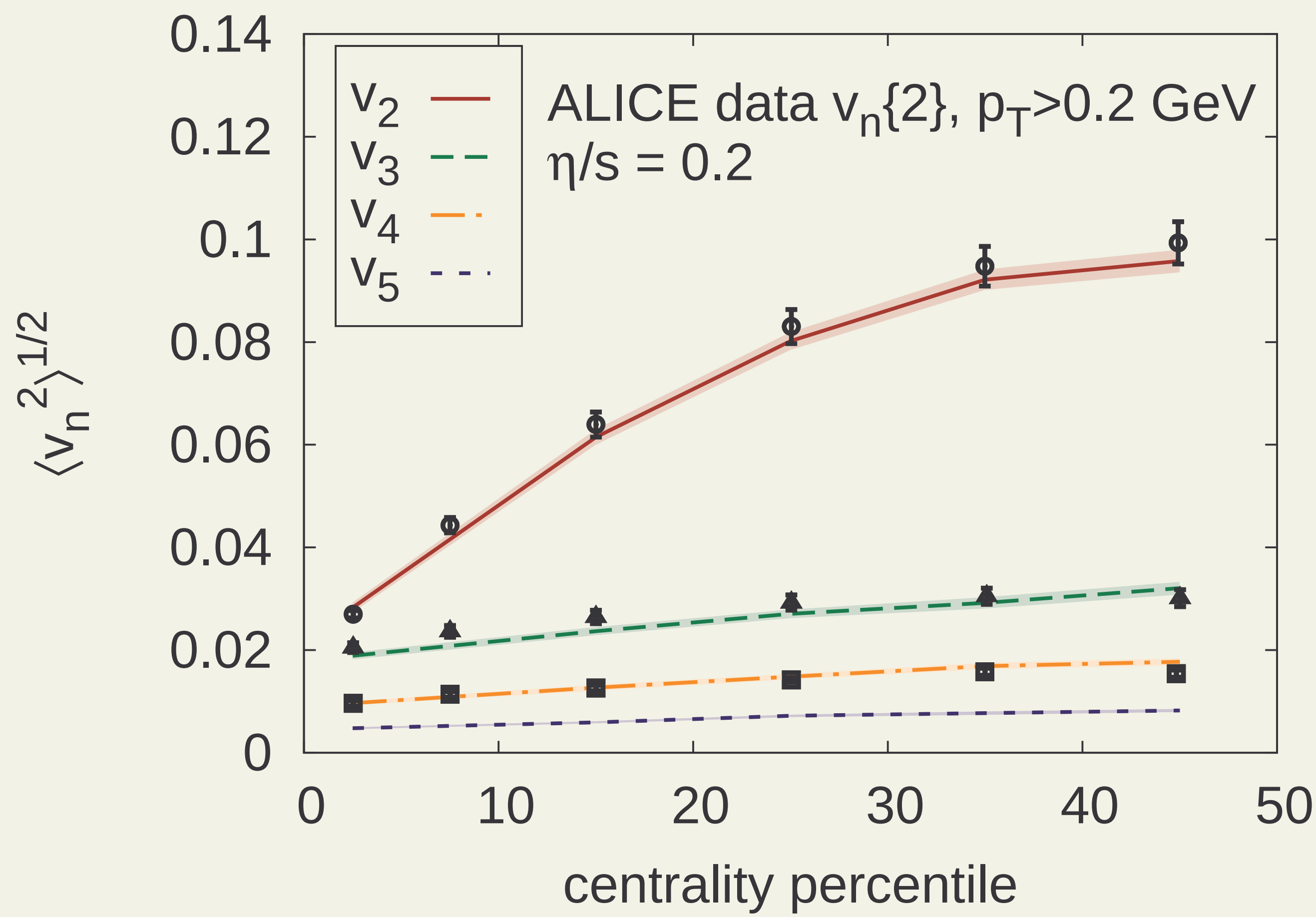


- $\eta/s = 0.2$ **favoured**

State of the art

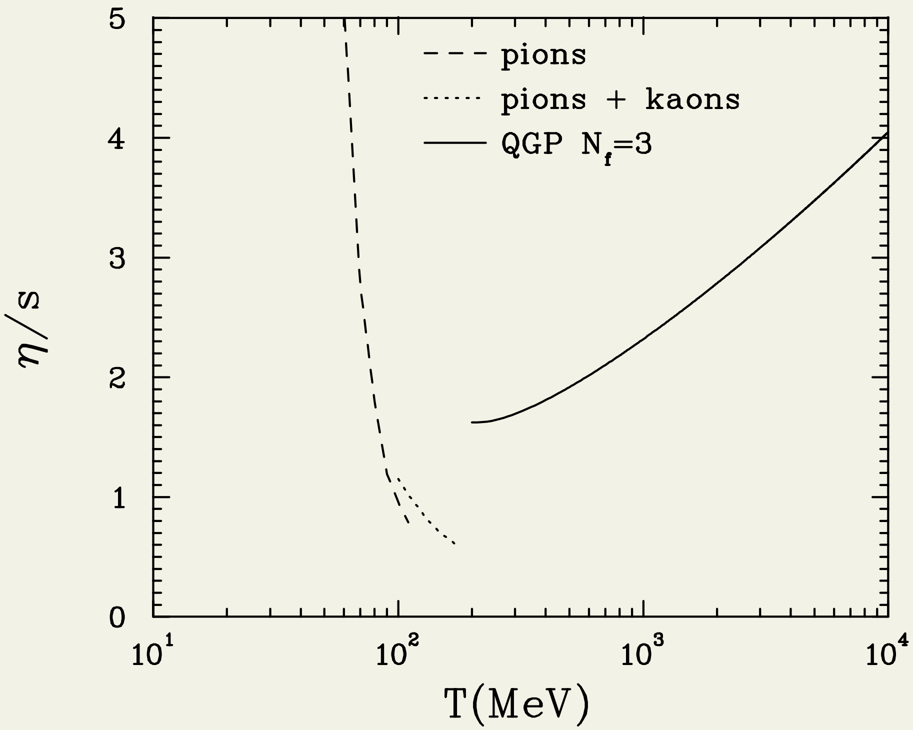
- **IP-Glasma initial state: Yang-Mills evolution plus Color Glass**

Gale *et al.*, PRL 110, 012302 (2013)



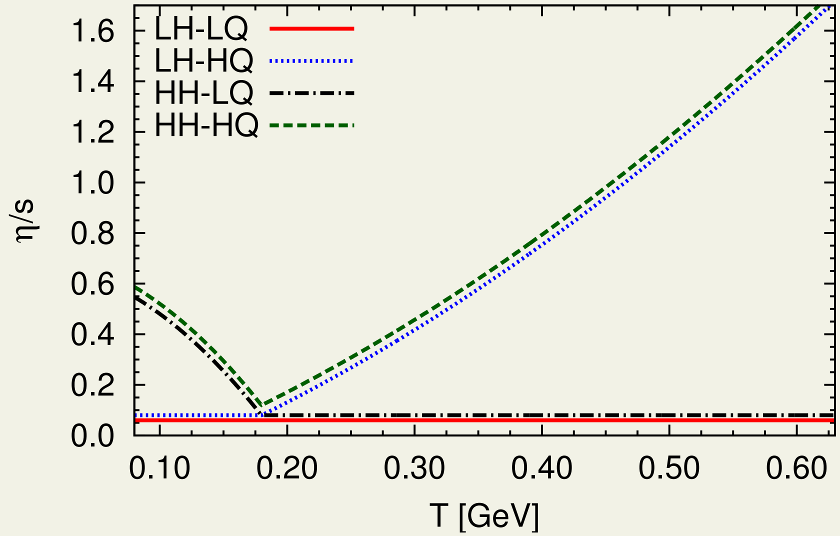
- $\eta/s = 0.2$ **favoured at LHC**
- $\eta/s = 0.12$ **favoured at RHIC**

$\eta/s = \text{const.} \longrightarrow (\eta/s)(T)$

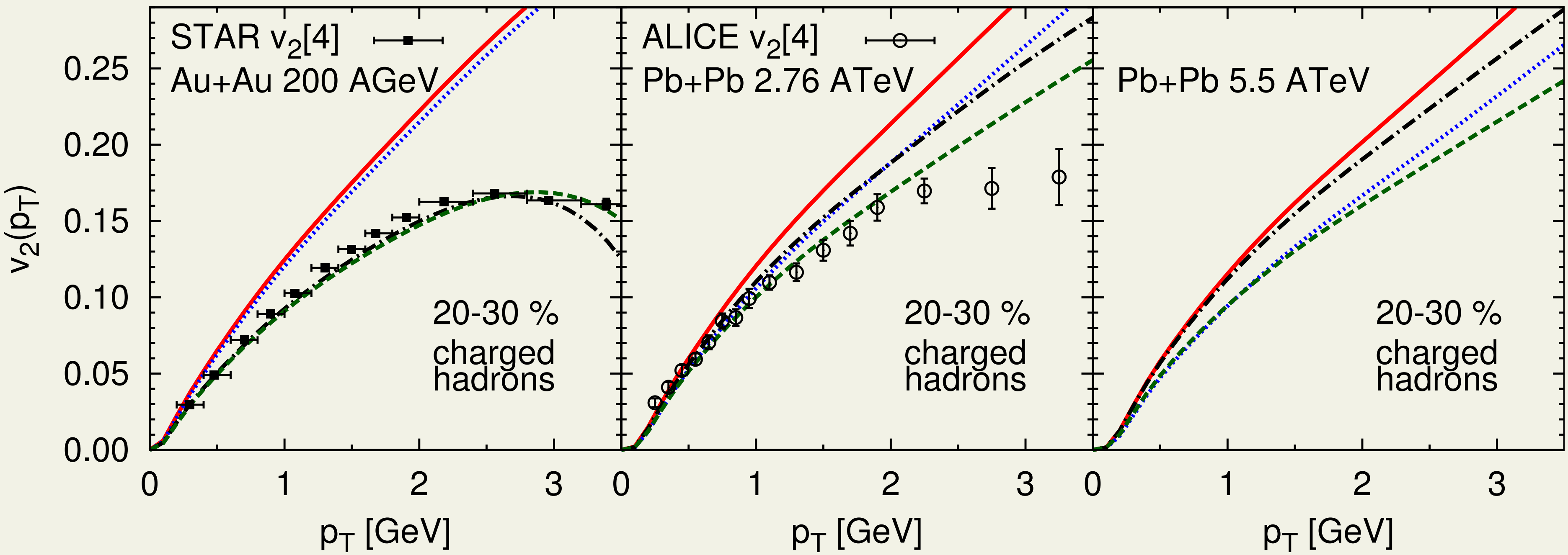


theory expectation

sensitivity to $(\eta/s)(T)$



- parametrizations of $(\eta/s)(T)$
  L="low", H="high"
  H="hadronic", Q="qgp"



- weak dependence on QGP η/s at RHIC
- increasing sensitivity to QGP η/s with collision energy at LHC
- sensitive to minimum of η/s

Summary

- hydrodynamics can describe the anisotropies of particle emission observed in ultrarelativistic heavy-ion collisions
- the minimum specific shear viscosity of matter formed in these collisions is very low, $\eta/s \lesssim 2.5/(4\pi)$
- temperature dependence of η/s is to be determined

♻ This talk consisted of 100% recycled electrons