Primordial fluctuations in relativistic nuclear collisions

by

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with :
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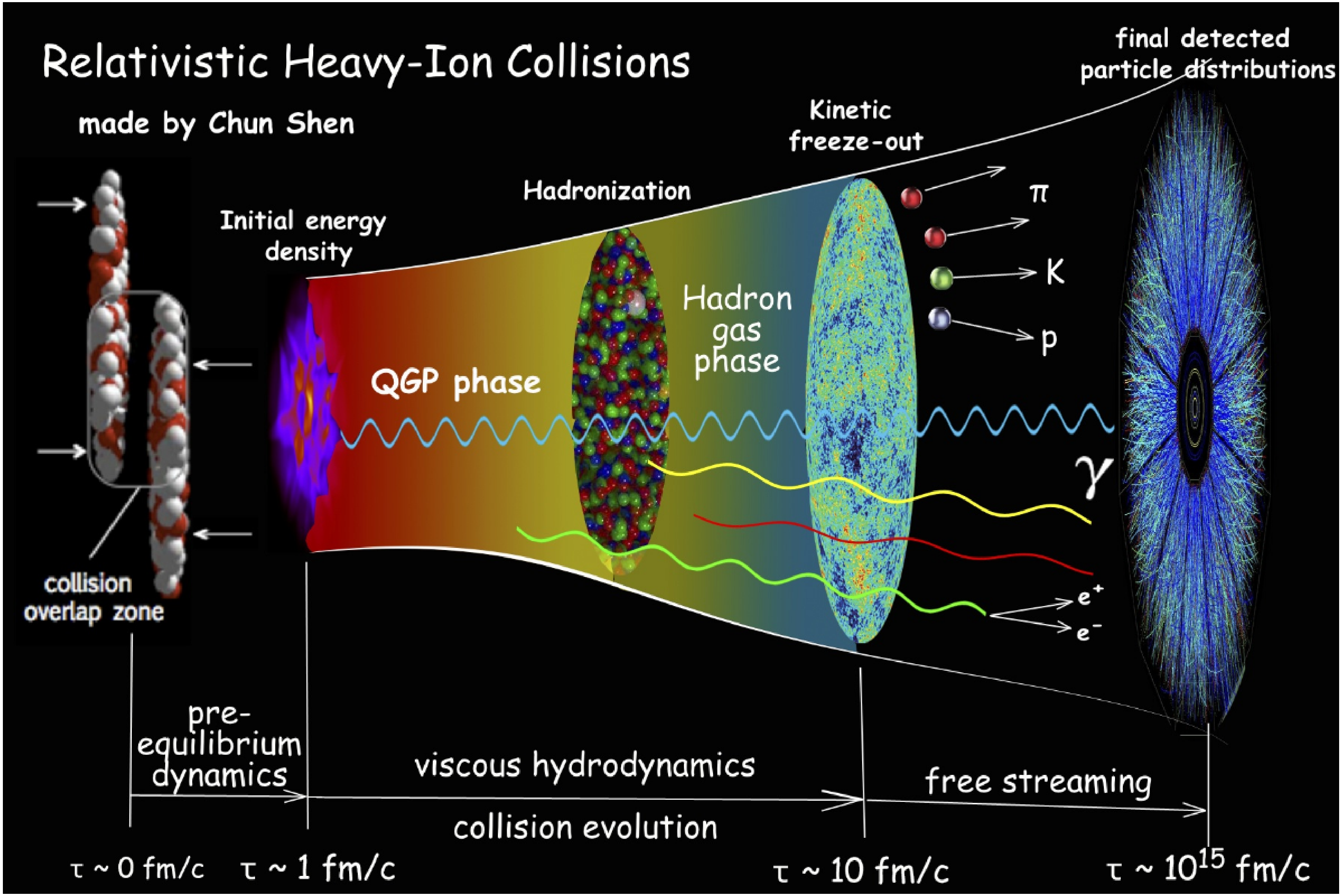
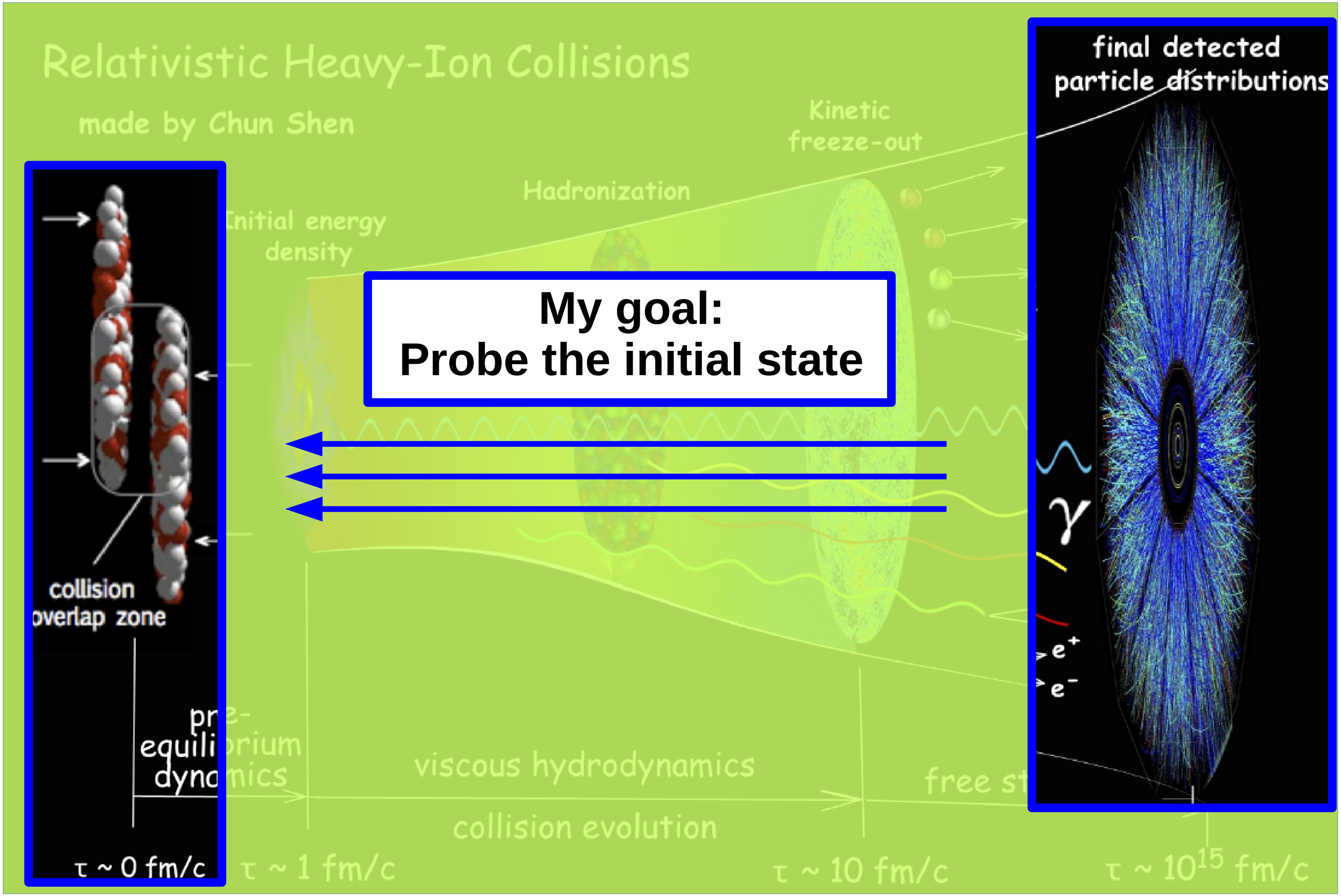

Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c



Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected
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Kinetic
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Hadronization
Initial energy
density
My goal:
Probe the initial state
collision
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pre-
equilibrium
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τ ~ 0 fm/c
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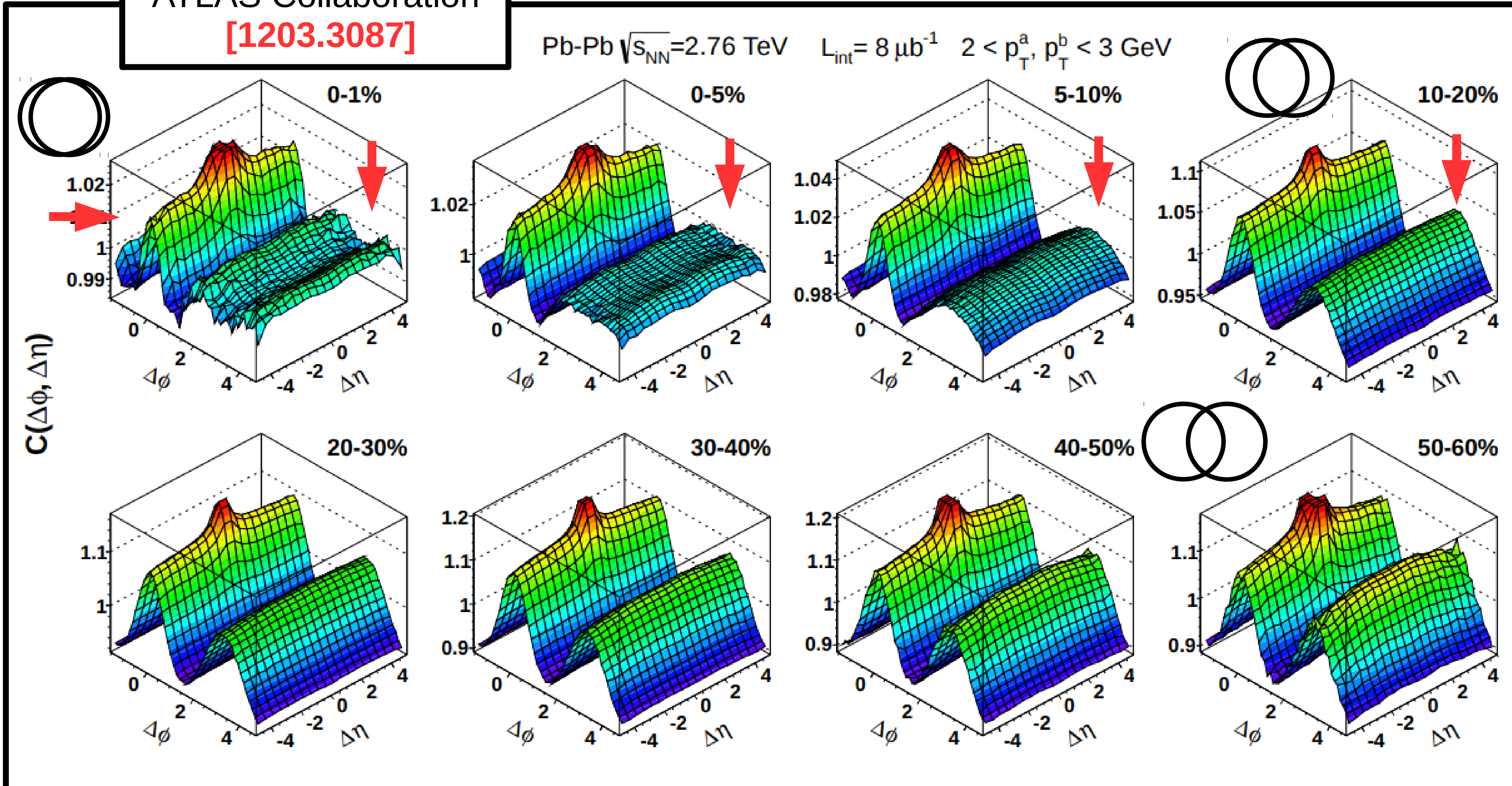
γ
e+
e−

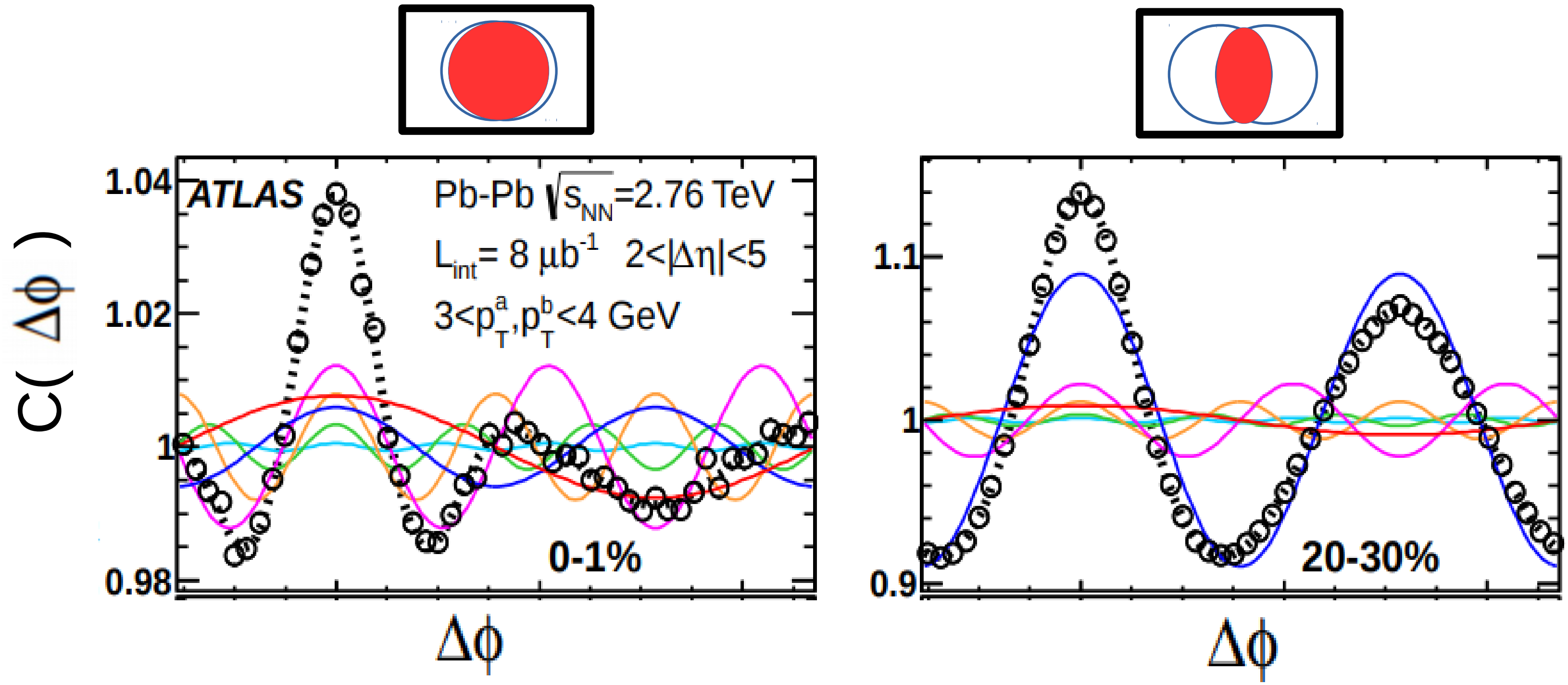
How?

ATLAS Collaboration
[1203.3087]



Long-range azimuthal correlations: A new feature of high-energy physics.

Integrated over eta.

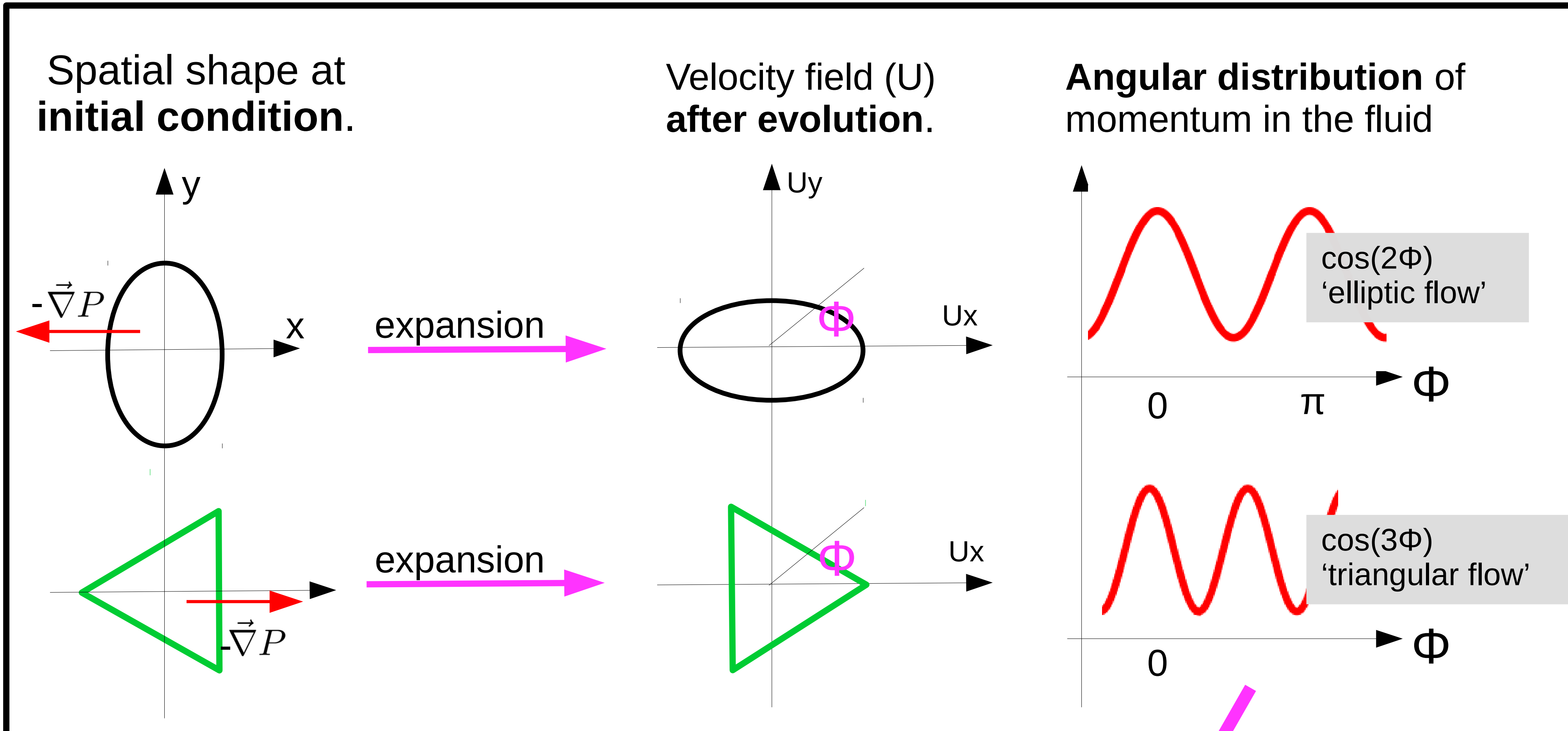


Harmonic decomposition:

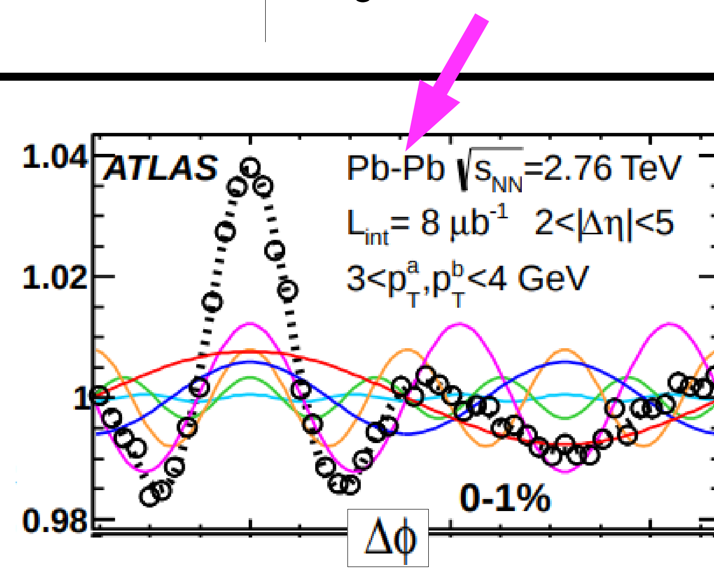
$$\frac{dN}{p_t dp_t d\phi} = \frac{dN}{p_t dp_t} \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{in\phi}, \qquad V_{-n} = V_n^*$$

"anisotropic flow" coefficients

Natural explanation in a fluid paradigm. $F = -\nabla P$ [Ollitrault, 1992]



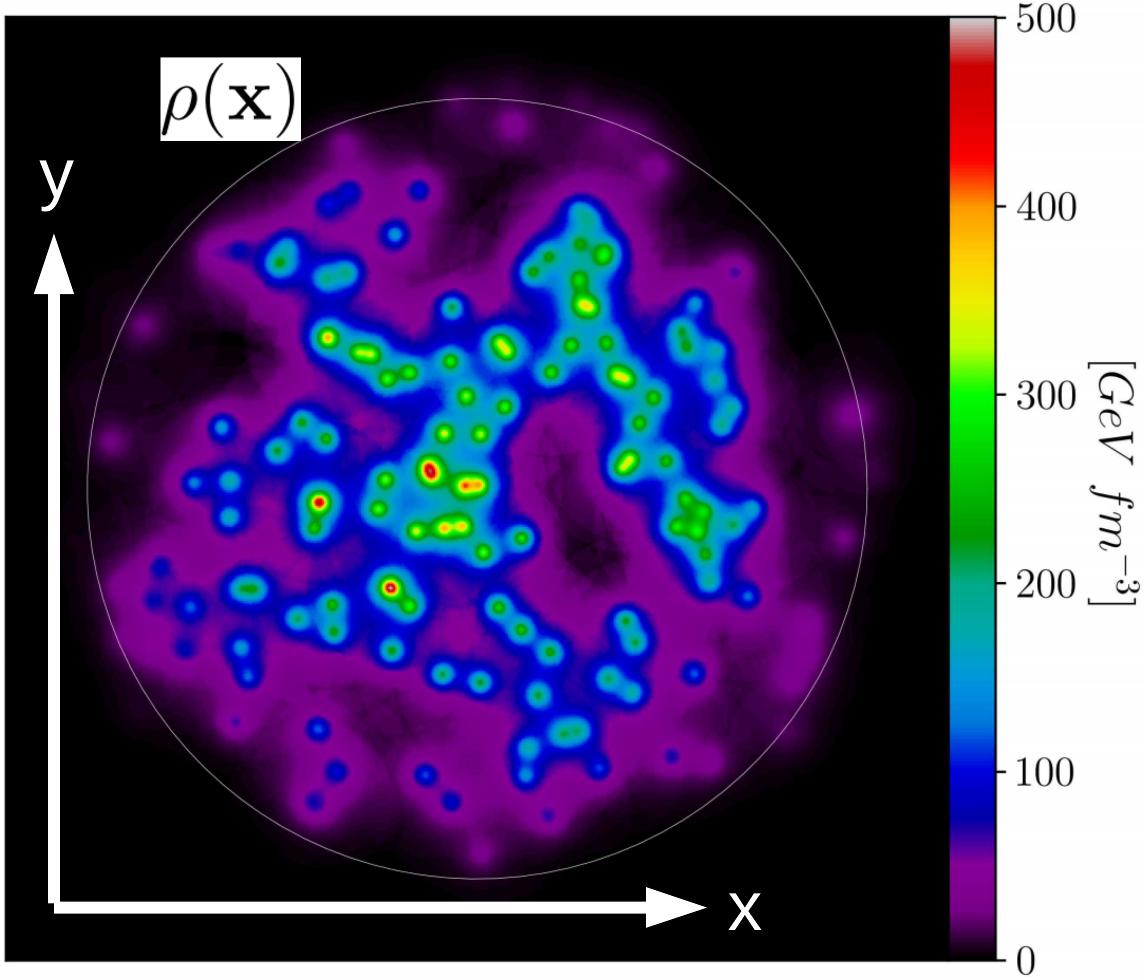
ANISOTROPIC FLOW



Initial-state (primordial) anisotropy. A 2D analysis.

Fluctuations generate anisotropy to all orders!

[Alver, Roland **1003.0194**]



[Gelis, Giacalone, Guerrero-Rodriguez, Marquet, Ollitrault, **1907:10948**]

Anisotropy of large scale structures.

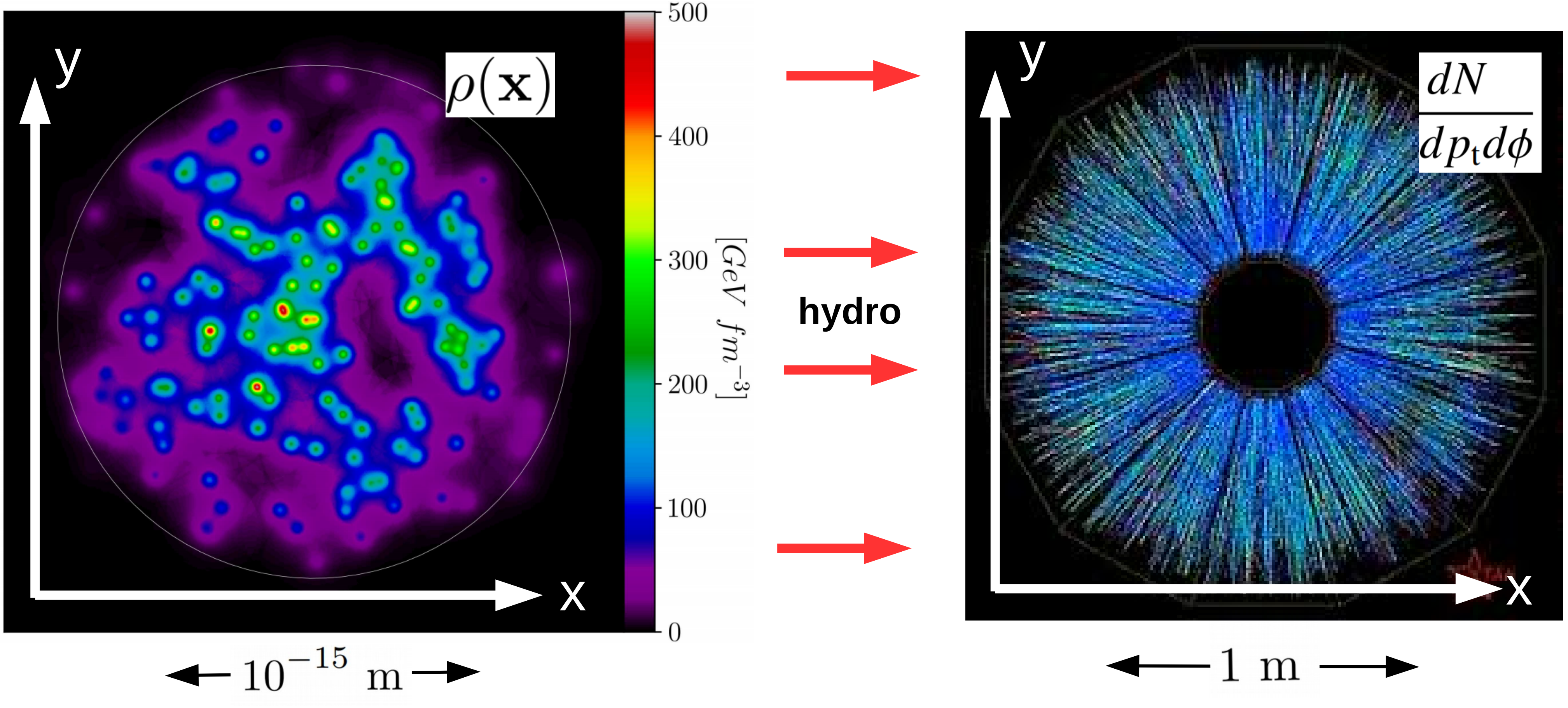
[Teaney, Yan **1010.1876**]

$$\mathcal{E}_n \equiv \frac{\int_{\mathbf{x}} |\mathbf{x}|^n e^{in\phi} \rho(\mathbf{x})}{\int_{\mathbf{x}} |\mathbf{x}|^n \rho(\mathbf{x})}$$

n=2 ellipse

n=3 triangle

Final-state anisotropy from primordial fluctuations.



$$\mathcal{E}_n \equiv \frac{\int_{\mathbf{x}} |\mathbf{x}|^n e^{in\phi} \rho(\mathbf{x})}{\int_{\mathbf{x}} |\mathbf{x}|^n \rho(\mathbf{x})} \longrightarrow \frac{dN}{p_t dp_t} \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{in\phi}$$

The relation is remarkably simple.

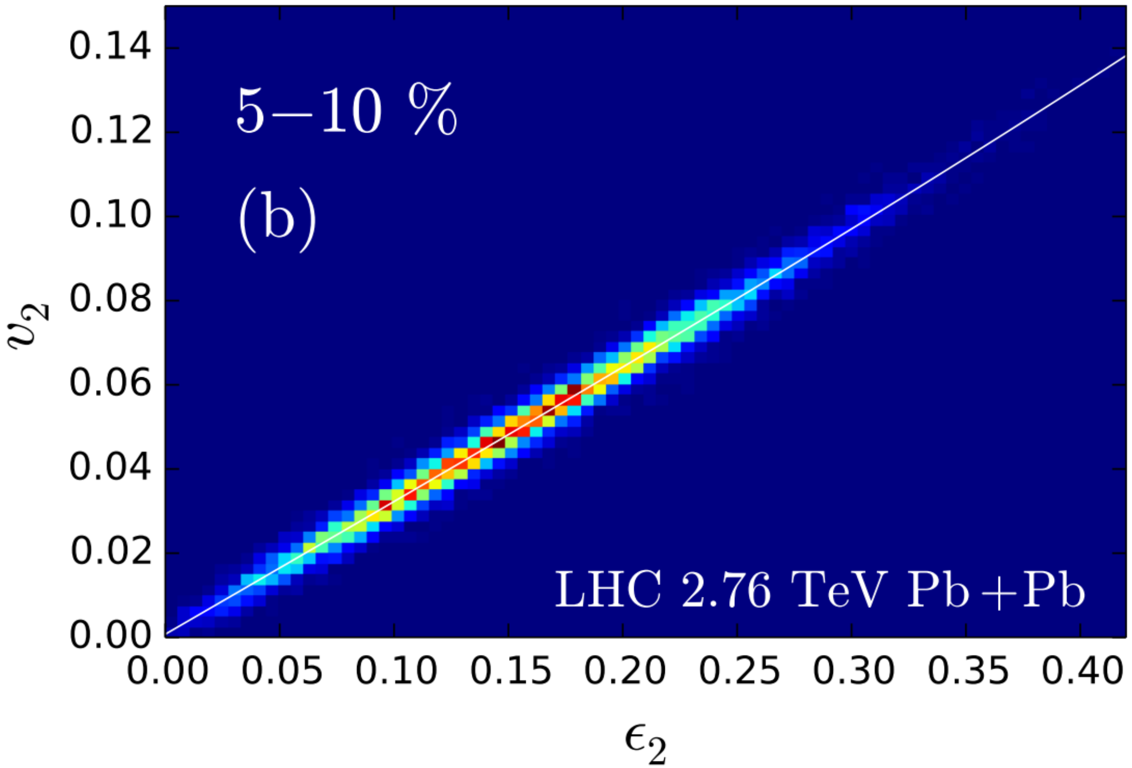
$$V_n = \kappa_n \mathcal{E}_n + \ldots$$

"hydro"

(smaller scale structures allowed by symmetry)

Confirmed by theoretical calculations.

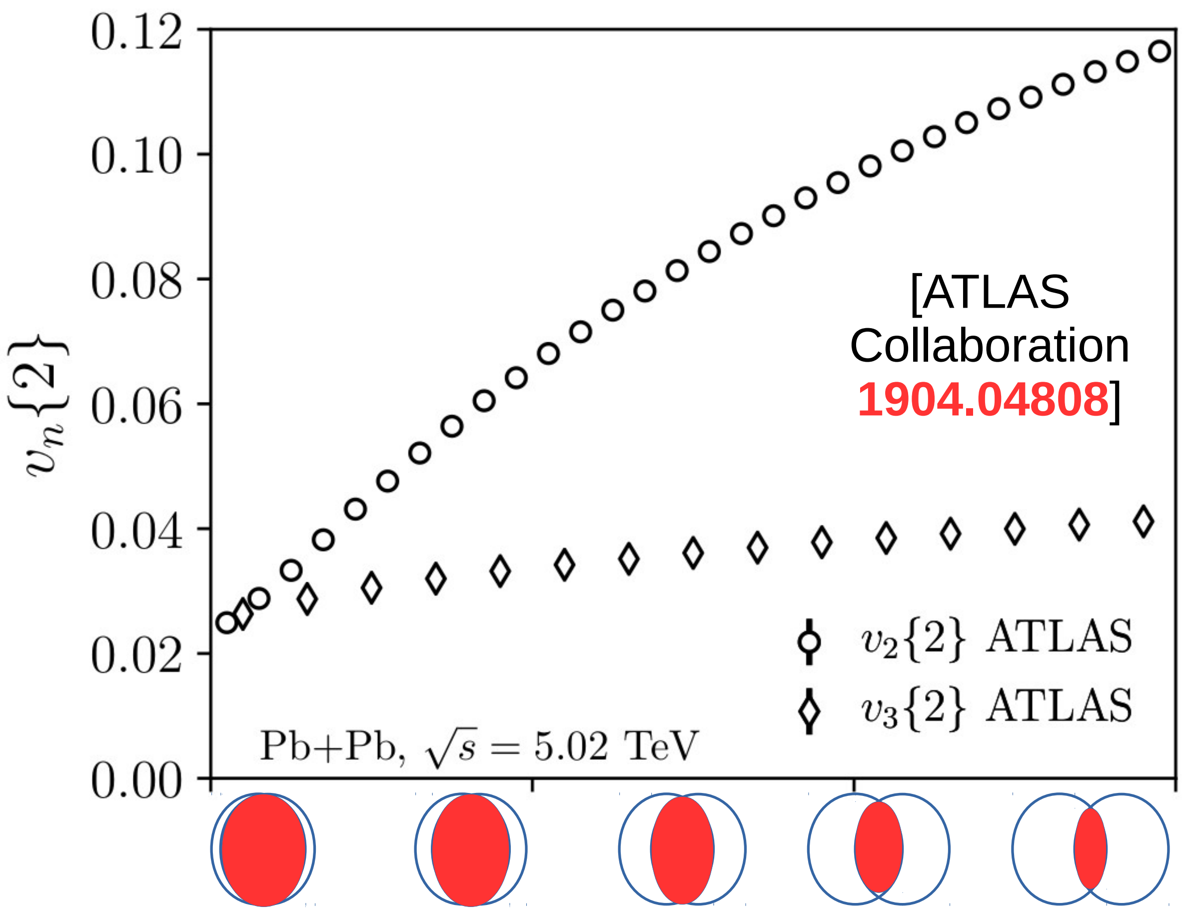
[Niemi, Eskola, Patelaainen, **1505.02677**]



Experimentally one can only measure averaged quantities:

$$\langle V_n V_n^* \rangle = \langle \cos n(\phi_1 - \phi_2) \rangle \equiv v_n\{2\}^2$$

average over
a class of events



We need a **statistical theory of anisotropy**. We follow Blaizot.

$$\langle V_n V_n^* \rangle \propto \langle \mathcal{E}_n \mathcal{E}_n^* \rangle$$

[Blaizot, Broniowski, Ollitrault, 1405.3572]

1) In heavy-ion collisions, **large-scale fluctuations are small**.

$$\rho(\mathbf{x}) = \langle \rho(\mathbf{x}) \rangle + \delta\rho(\mathbf{x}), \quad \boxed{\langle \rho(\mathbf{x}) \rangle \gg \delta\rho(\mathbf{x})}$$

2) The **correlation length is typically negligible** compared to the size of the large scale structures.

$$\langle \rho(\mathbf{x}_1)\rho(\mathbf{x}_2) \rangle - \langle \rho(\mathbf{x}_1) \rangle \langle \rho(\mathbf{x}_2) \rangle \approx \boxed{\xi(\mathbf{x})\delta(\mathbf{r})}$$

$$\mathbf{x} = \frac{\mathbf{x}_1 + \mathbf{x}_2}{2}, \quad \mathbf{r} = \mathbf{x}_1 - \mathbf{x}_2$$

3) The **observable** that we need becomes:

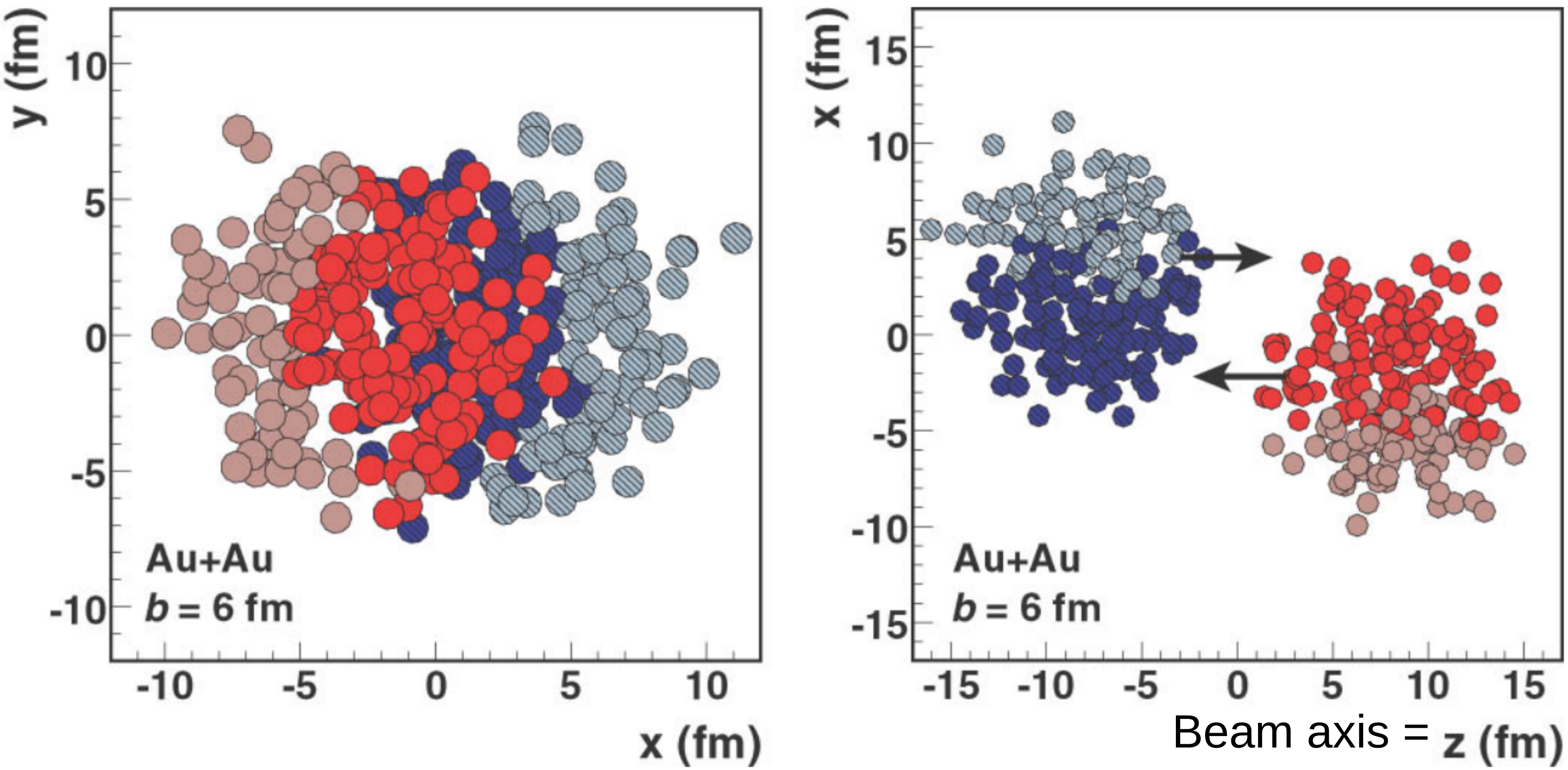
$$v_n\{2\}^2 = \langle V_n V_n^* \rangle \propto \boxed{\langle \mathcal{E}_n \mathcal{E}_n^* \rangle = \frac{\int_{\mathbf{x}} |\mathbf{x}|^{2n} \xi(\mathbf{x})}{\left[\int_{\mathbf{x}} |\mathbf{x}|^{n} \langle \rho(\mathbf{x}) \rangle\right]^2}}$$

How do we calculate these correlation functions?

The ‘standard model’ : Glauber Monte Carlo generators

[Miller, Reygers, Sanders, Steinberg, nucl-ex/0701025]

~1200 citations on INSPIRE



A 10-year old recipe:

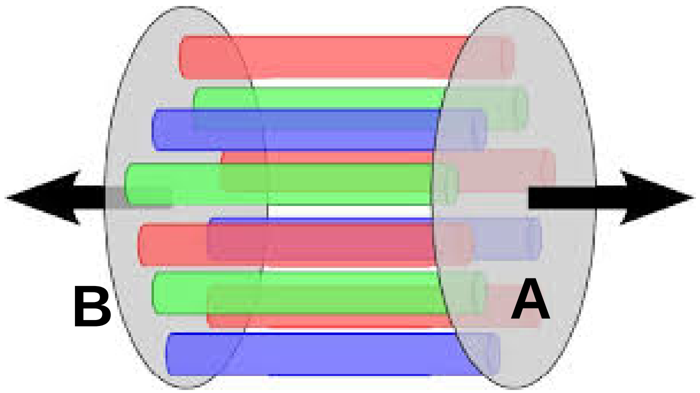
1. Sample nucleons according to the ground-state nuclear density.

2. Determine those nucleons that interact (participants).

3. Map the participants into an energy density $\rho(\mathbf{x})$.

A different approach within the Color Glass Condensate.

[Giacalone, Guerrero-Rodriguez, Luzum, Marquet, Ollitrault, 1902:07168]



Stress-energy tensor right after the overlap:

[Lappi, McLerran, hep-ph/0602189]

$$T^{\mu\nu}(\mathbf{x}, \tau = 0^+) = \rho(\mathbf{x})[\mathrm{diag}(1,1,1,-1)]^{\mu\nu}$$

Using the **McLerran-Venugopalan model** one can evaluate correlation functions: [McLerran, Venugopalan, hep-ph/9309289]

$$\langle T^{00}(\mathbf{x}, \tau = 0^+)\rangle, \; \langle T^{00}(\mathbf{x}, \tau = 0^+) T^{00}(\mathbf{y}, \tau = 0^+)\rangle$$

Precisely what we need!

The 1-point function has been known for a long time.

[Lappi, hep-ph/0606207]

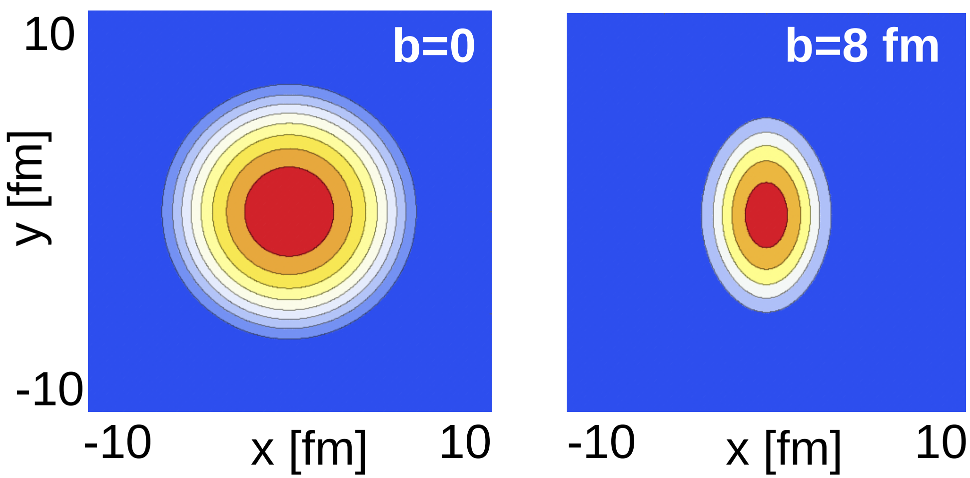
$$\langle \rho(\mathbf{x}) \rangle = \frac{4}{3g^2} Q_A^2(\mathbf{x}) Q_B^2(\mathbf{x})$$

Nuclear saturation scale:

$$Q_s^2(\mathbf{x}) = \left[Q_{s0}^2 \sim O(1\ \mathrm{GeV}^2)\right] \times \frac{[\text{density of gluons at } \mathbf{x}]}{[\text{density of gluons at } \mathbf{0}]}$$

It gives the average energy density at a given b.

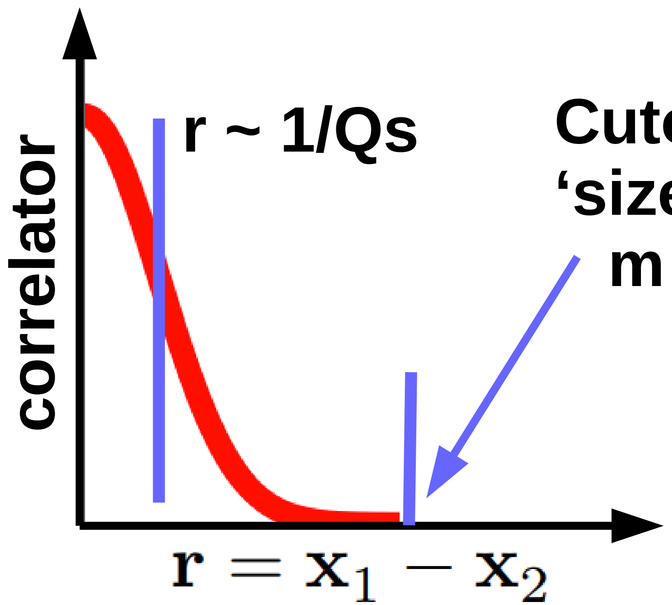
$$\langle \rho(\mathbf{x}) \rangle \longrightarrow$$



The 2-point function has been evaluated recently.

[Albacete, Guerrero-Rodríguez, Marquet **1808.00795**]

$$\langle \rho(\mathbf{x}_1)\rho(\mathbf{x}_2)\rangle - \langle \rho(\mathbf{x}_1)\rangle\langle \rho(\mathbf{x}_2)\rangle \approx \boxed{\xi(\mathbf{x})\delta(\mathbf{r})}$$



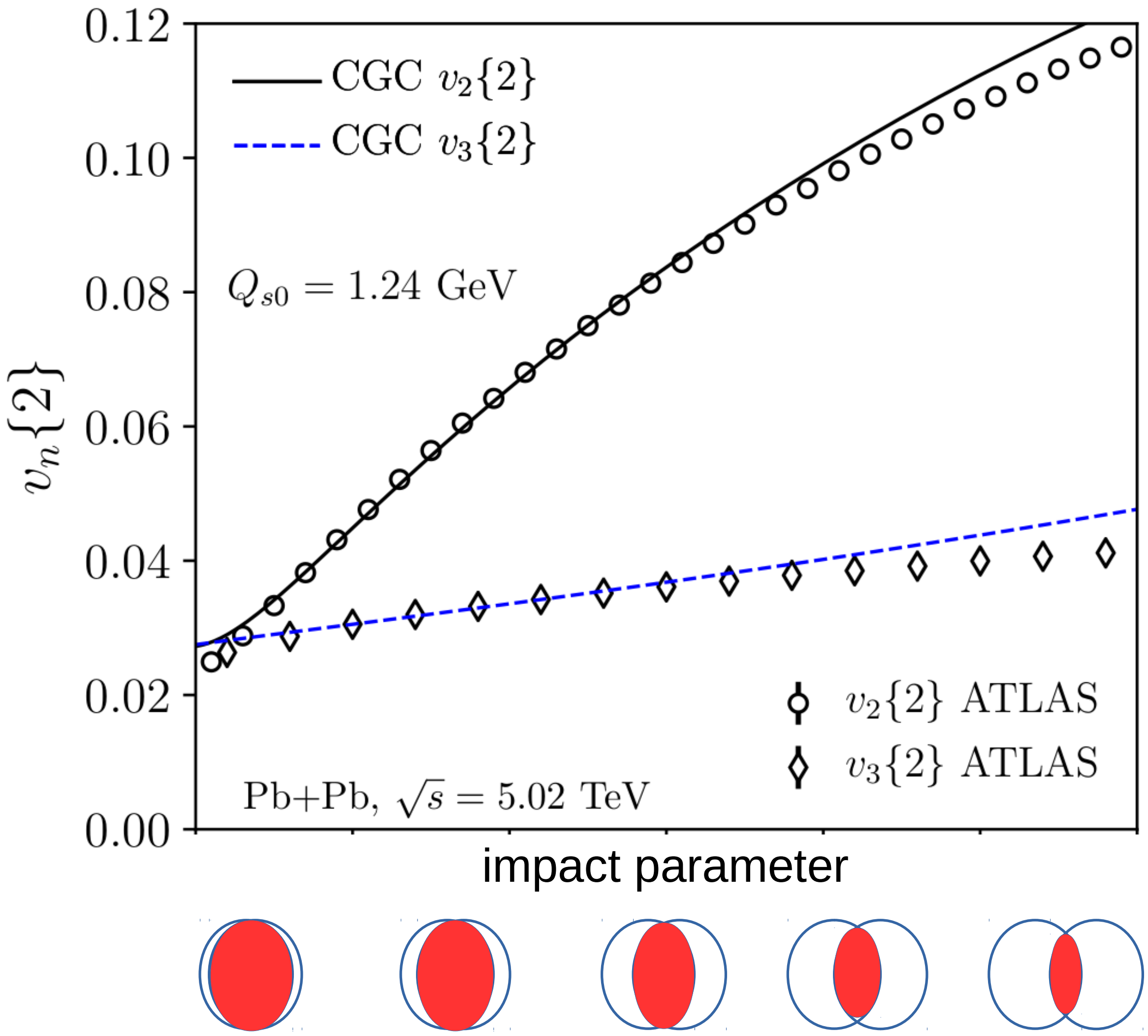
To leading logarithmic accuracy:

[Giacalone, Guerrero-Rodriguez, Luzum, Marquet, Ollitrault, **1902:07168**]

$$\xi(\mathbf{x}) = \frac{16\pi}{9g^4} Q_A^2(\mathbf{x}) Q_B^2(\mathbf{x}) \left[Q_A^2(\mathbf{x}) \ln\left(\frac{Q_B^2(\mathbf{x})}{m^2}\right) + Q_B^2(\mathbf{x}) \ln\left(\frac{Q_A^2(\mathbf{x})}{m^2}\right)\right]$$

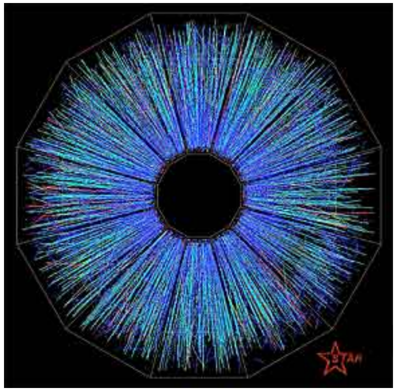
RESULTS

$$v_n\{2\}^2 = \langle V_n V_n^* \rangle \propto \langle \mathcal{E}_n \mathcal{E}_n^* \rangle = \frac{\int_{\mathbf{x}} |\mathbf{x}|^{2n} \xi(\mathbf{x})}{\left[\int_{\mathbf{x}} |\mathbf{x}|^n \langle \rho(\mathbf{x}) \rangle\right]^2}$$



[Giacalone, Guerrero-Rodriguez, Luzum, Marquet, Ollitrault, **1902:07168**]

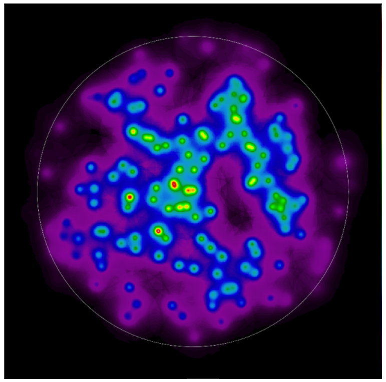
HEP-PHENOMENOLOGY FOR HEAVY IONS?



FINAL-STATE ANISOTROPY

Multi-particle azimuthal correlations

$$\langle e^{in(\phi_1-\phi_2)}\rangle,\ \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle,\ \ldots$$



PRIMORDIAL ANISOTROPY

Multi-point correlations of the density field

$$\langle\rho(\mathbf{x})\rangle,\ \langle\rho(\mathbf{x}_1)\rho(\mathbf{x}_2)\rangle,\ \langle\rho(\mathbf{x}_1)\rho(\mathbf{x}_2)\rho(\mathbf{x}_3)\rangle\ \ \ldots$$