Viscosity versus Causality

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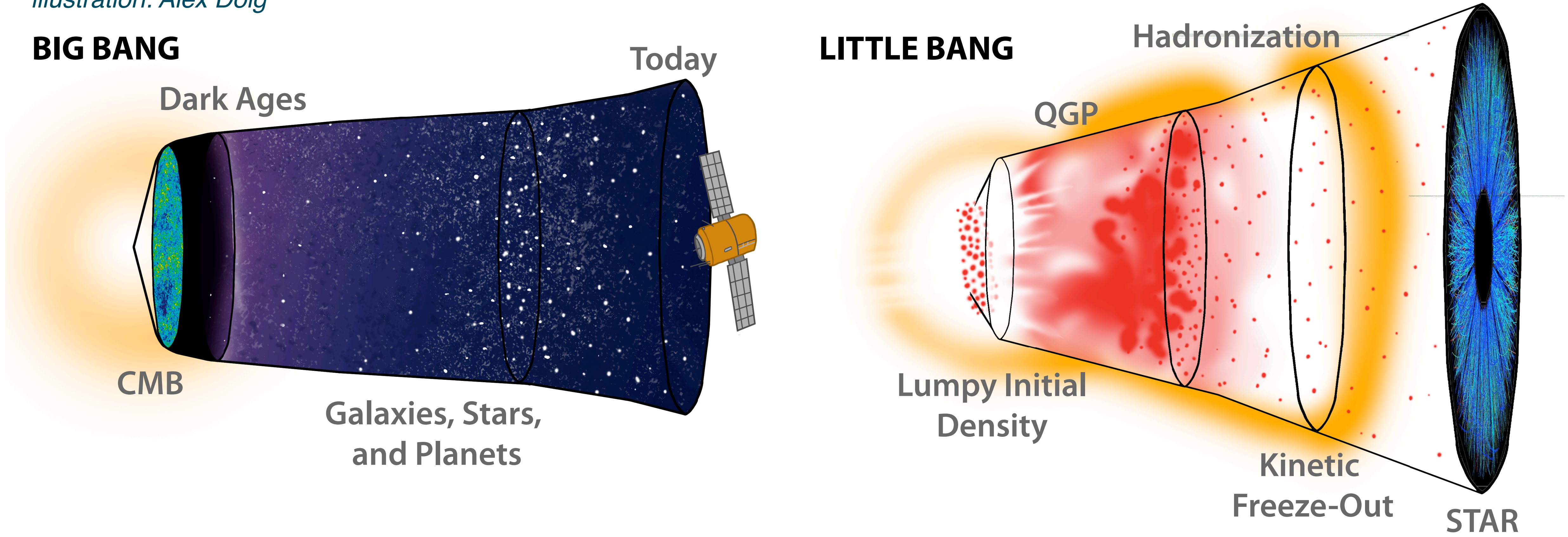
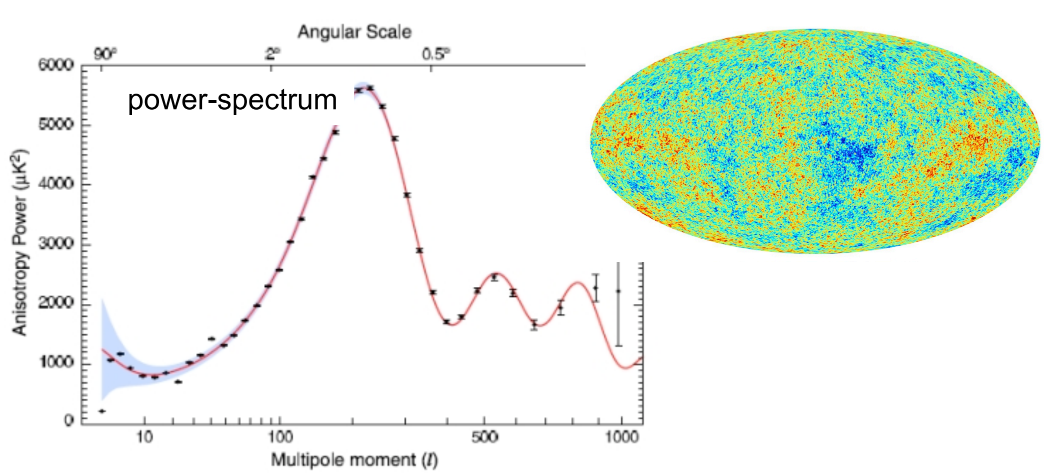
Analogy with the Early Universe

illustration: Alex Doig



Quantum fluctuations from the early universe show up as hotspots in the CMB.

Analogy for heavy-ion collisions?



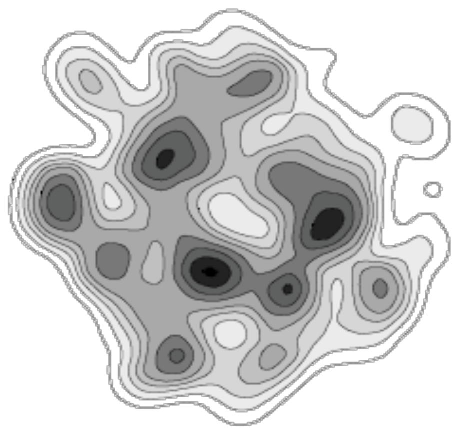
We expect fluctuations from the beginning of the little bangs show up in the data.

Lumpy Initial State

Expect: Initial density is inhomogeneous.

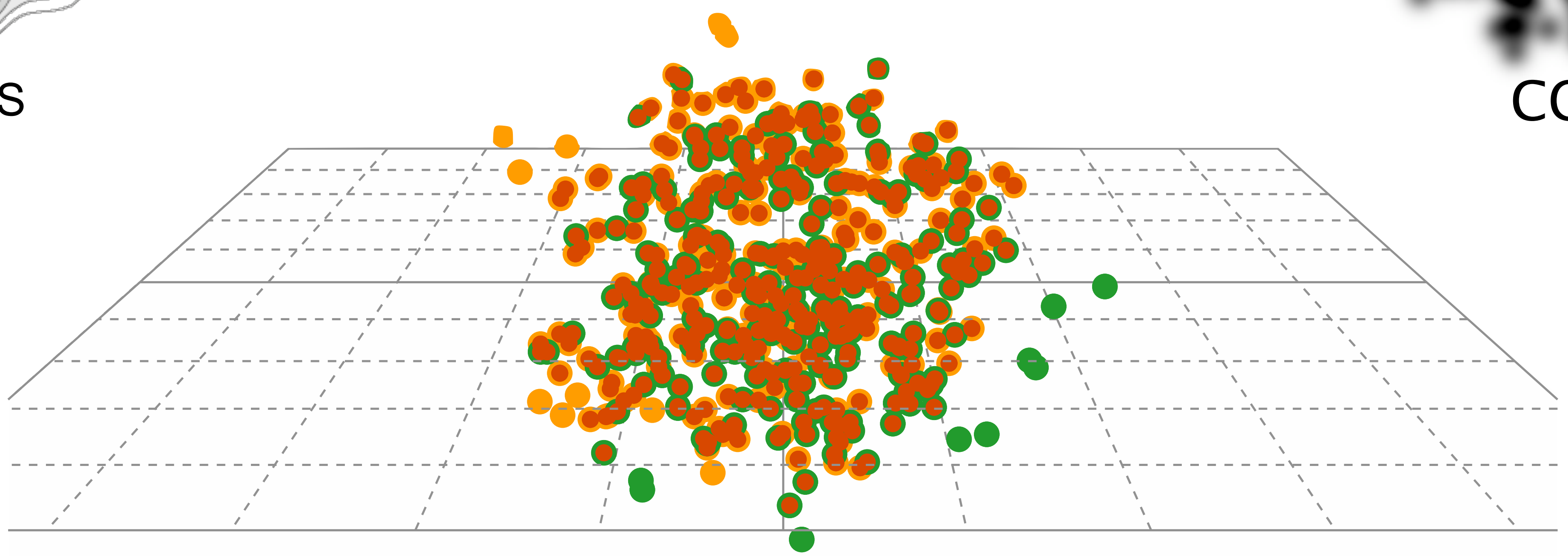
predicted by several models

transverse projection of a central collision generated in



NEXUS

CGC



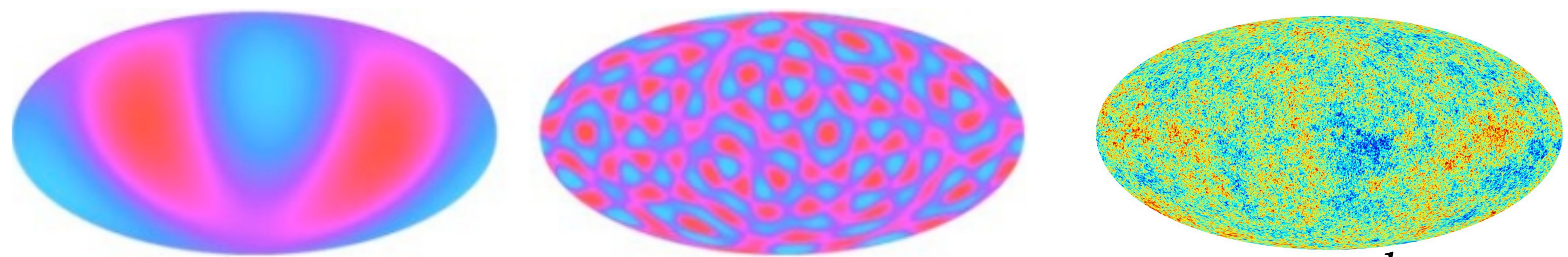
Glauber

How much of the initial inhomogeneity is transferred to the final state?

Length Scales

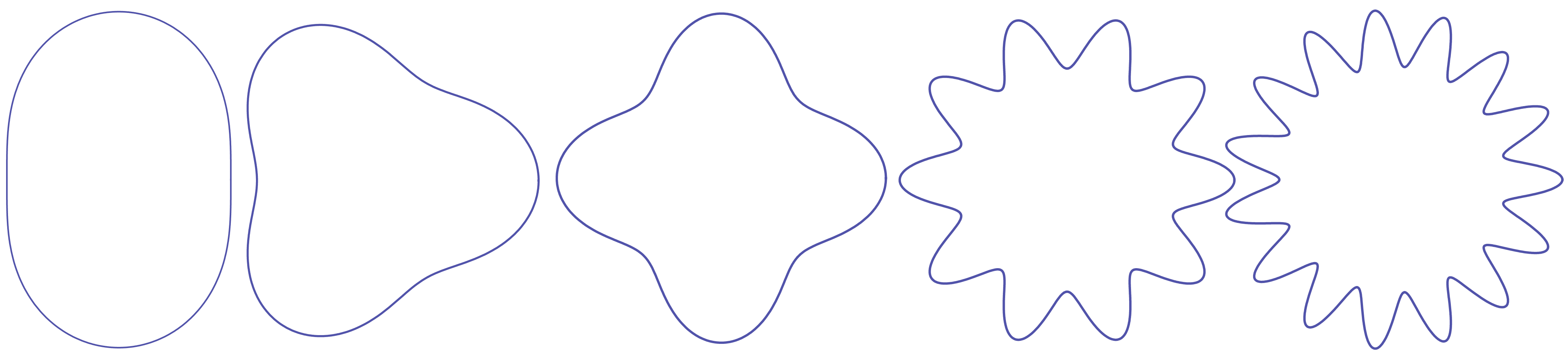
Higher harmonics probe smaller length-scales.

Spherical harmonic expansion of CMB



$\ell = 2$ $\ell = 16$ *sum l*

Fourier expansion of HIC



n=2 n=3 n=4 n=10 n=15

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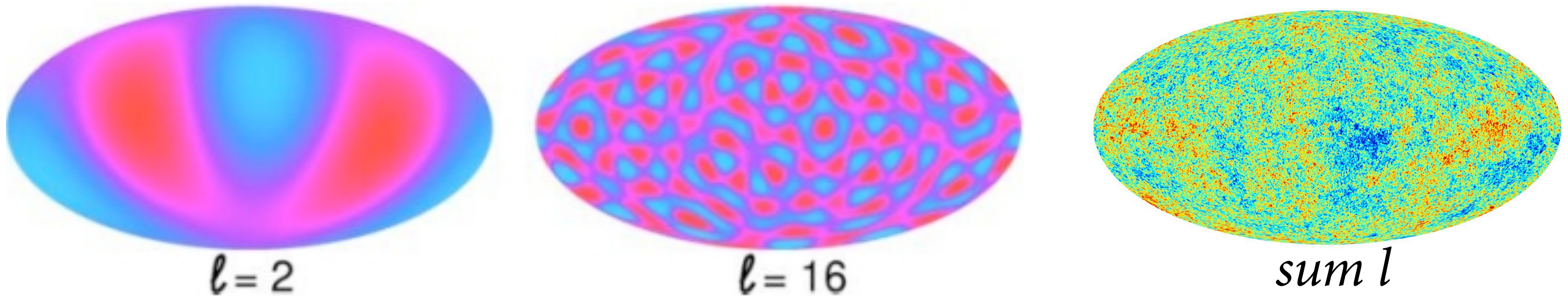

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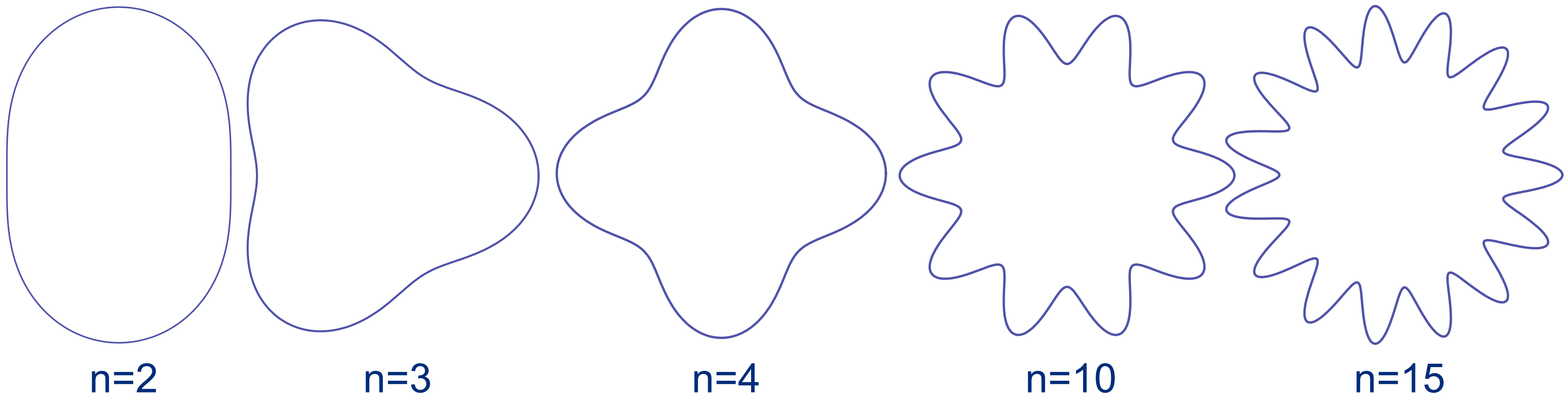

- Efficiency of conversion depends on the relation of various length scales, like the l_{mfp} to the scale probed at n

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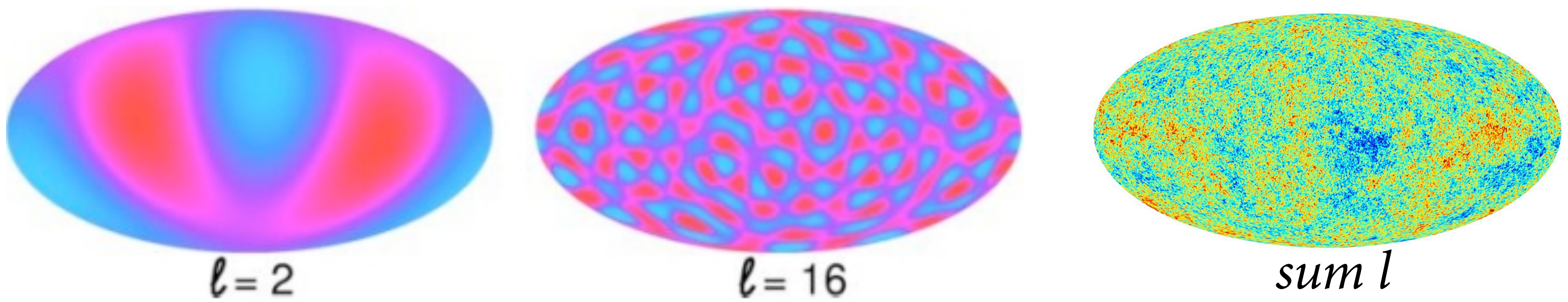

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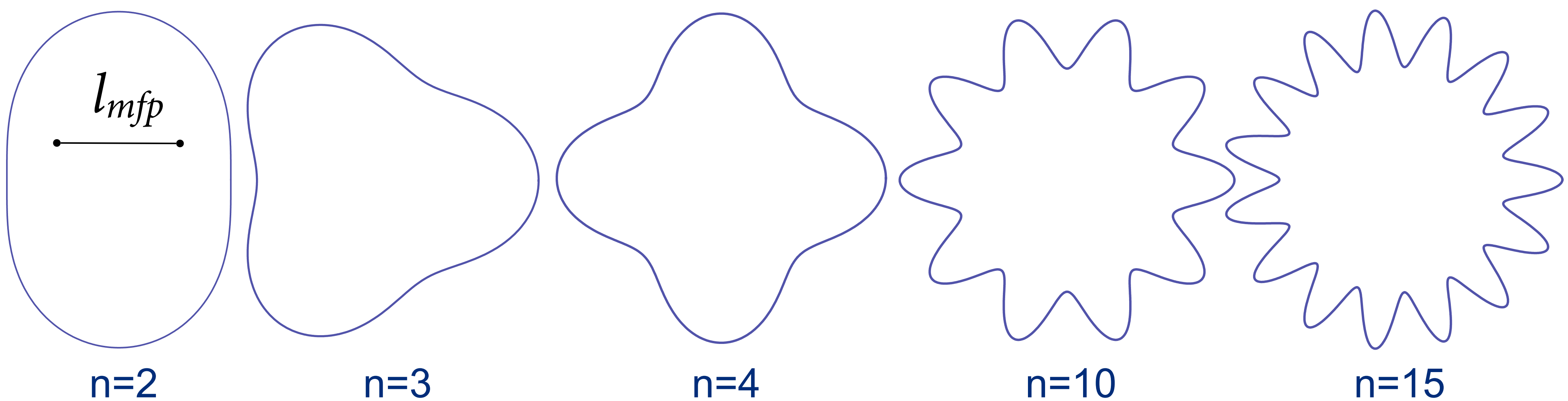

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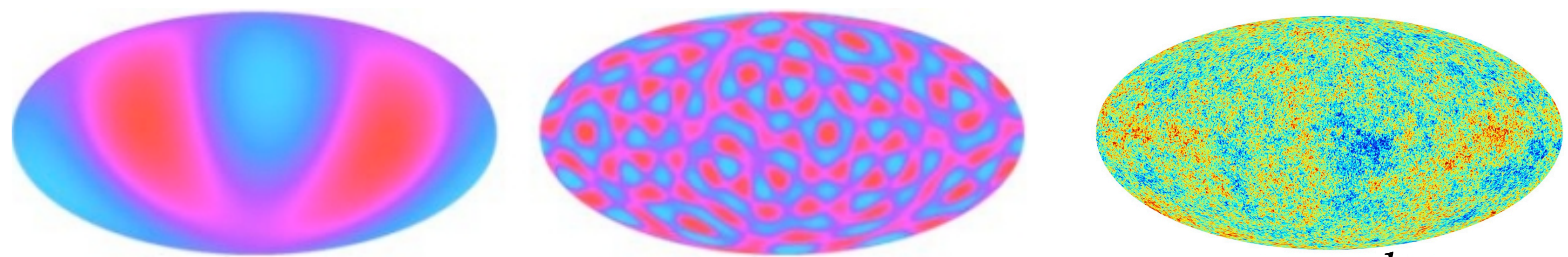

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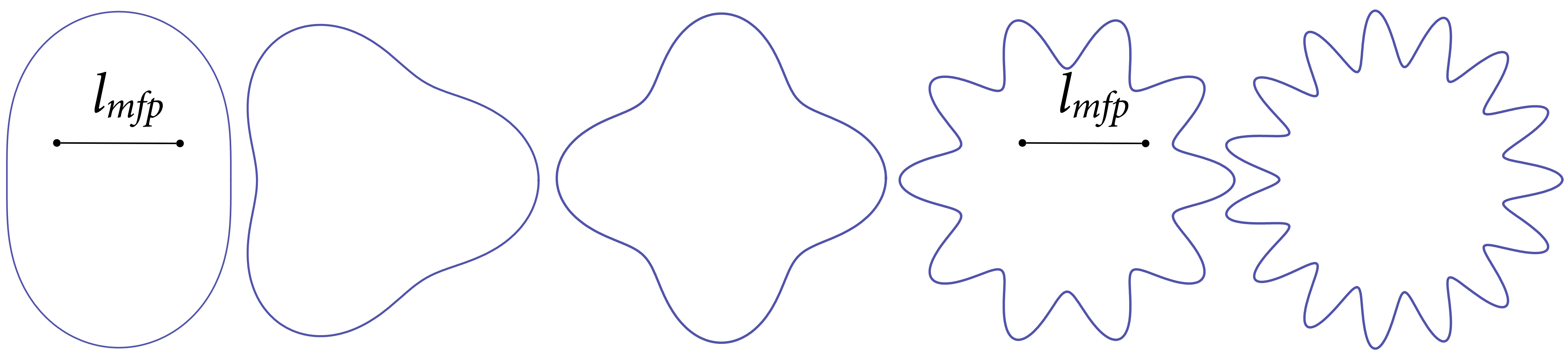

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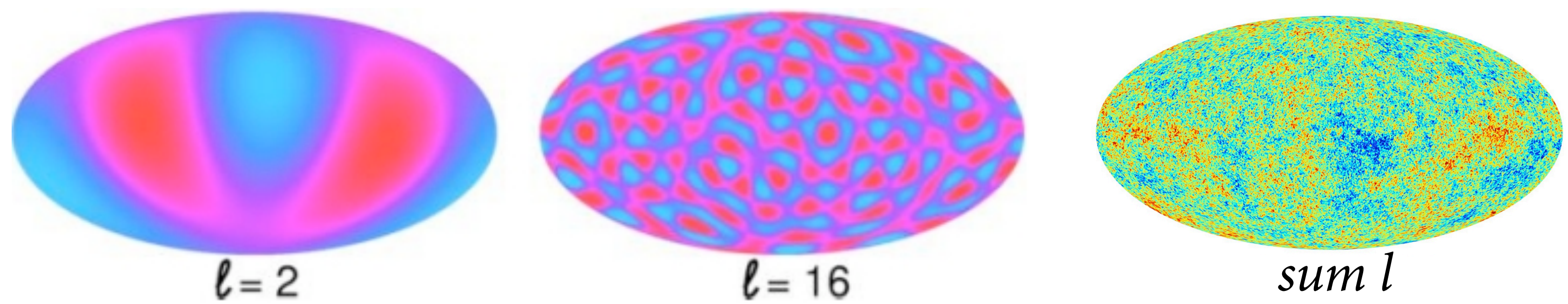
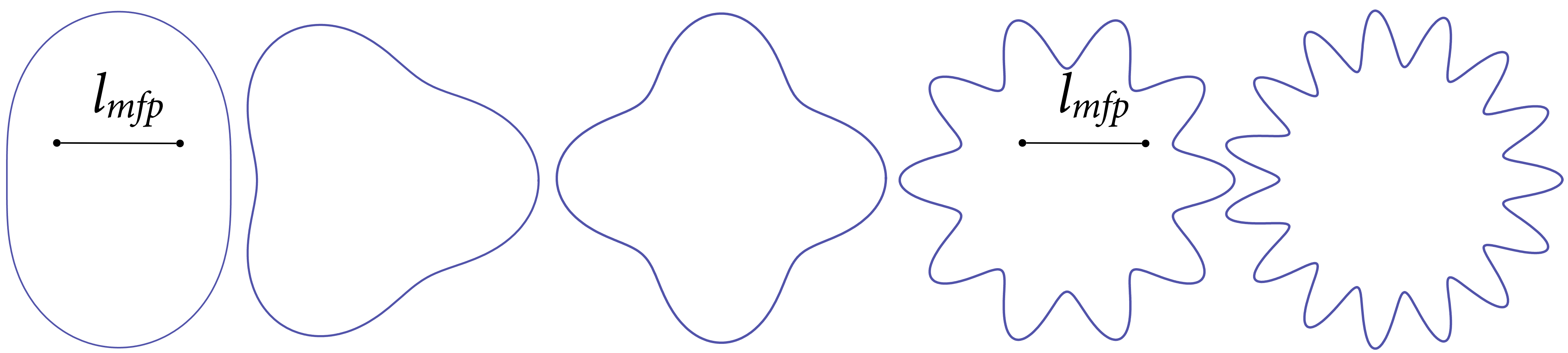


Fourier expansion of HIC



n=2 n=3 n=4 n=10 n=15

- Efficiency of conversion depends on the relation of various length scales, like the l_{mfp} to the scale probed at n

- Power spectrum measures how much anisotropy is in each harmonic n

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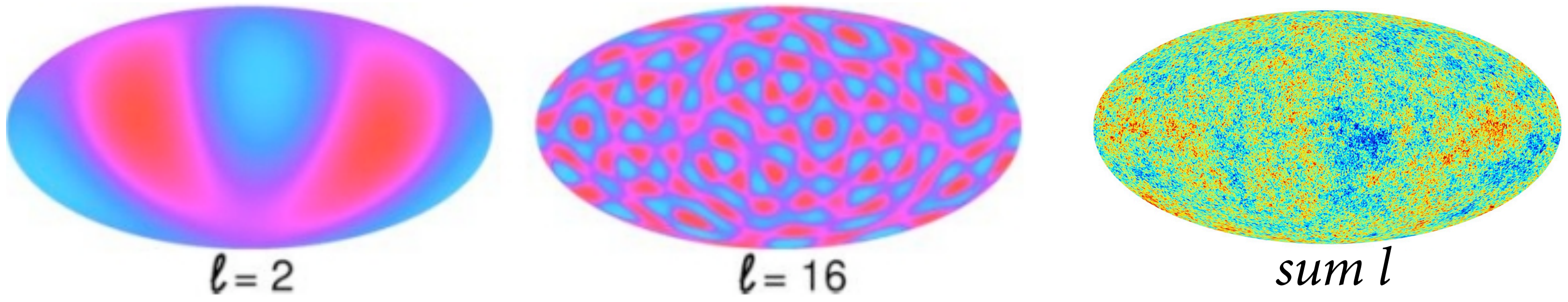
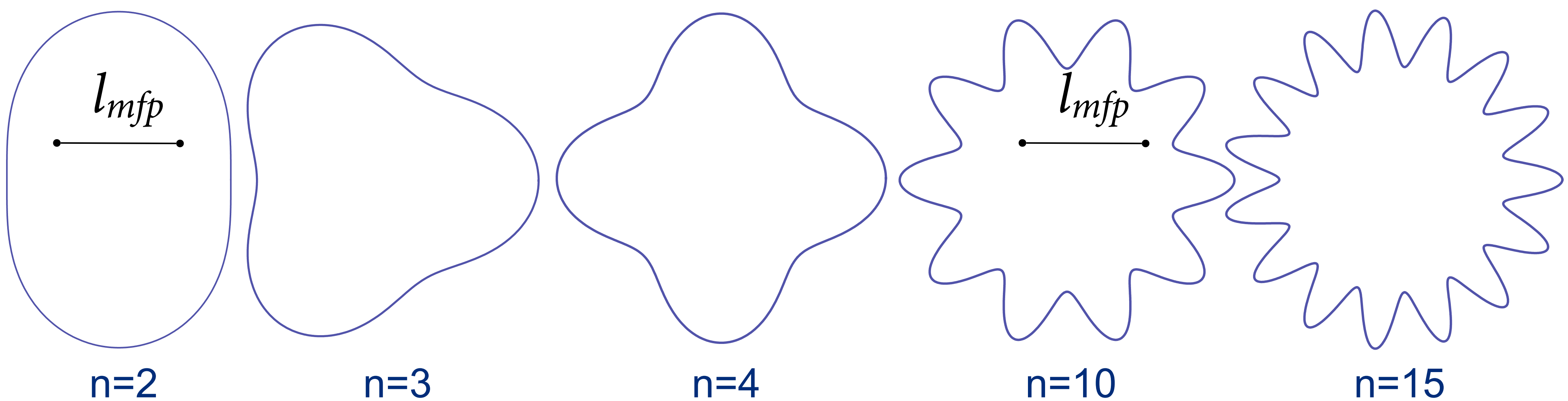


Fourier expansion of HIC

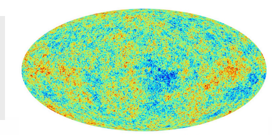


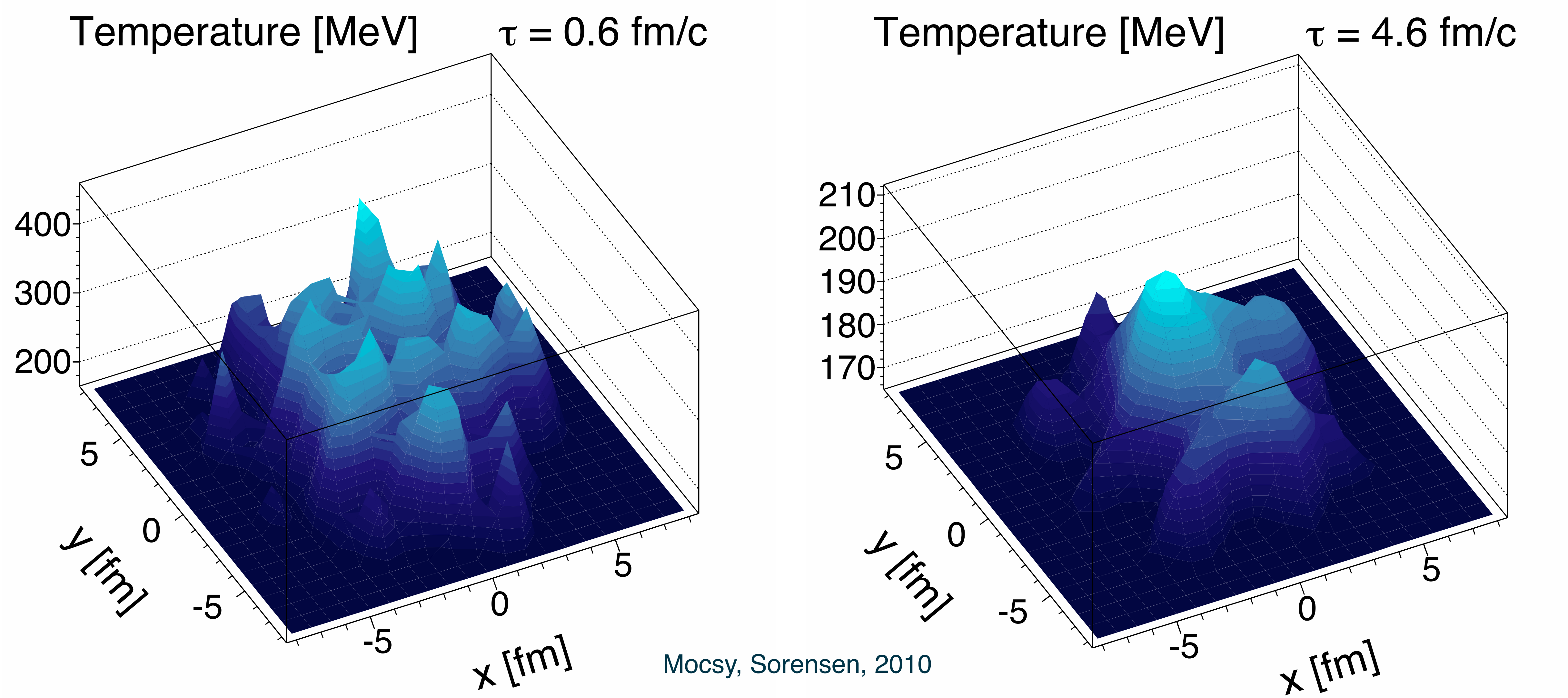
- Efficiency of conversion depends on the relation of various length scales, like the l_{mfp} to the scale probed at n

- Power spectrum measures how much anisotropy is in each harmonic n

- Can we obtain (constrain) the l_{mfp} ?

Temperature Fluctuations in Model

HIC analog of the CMB map 



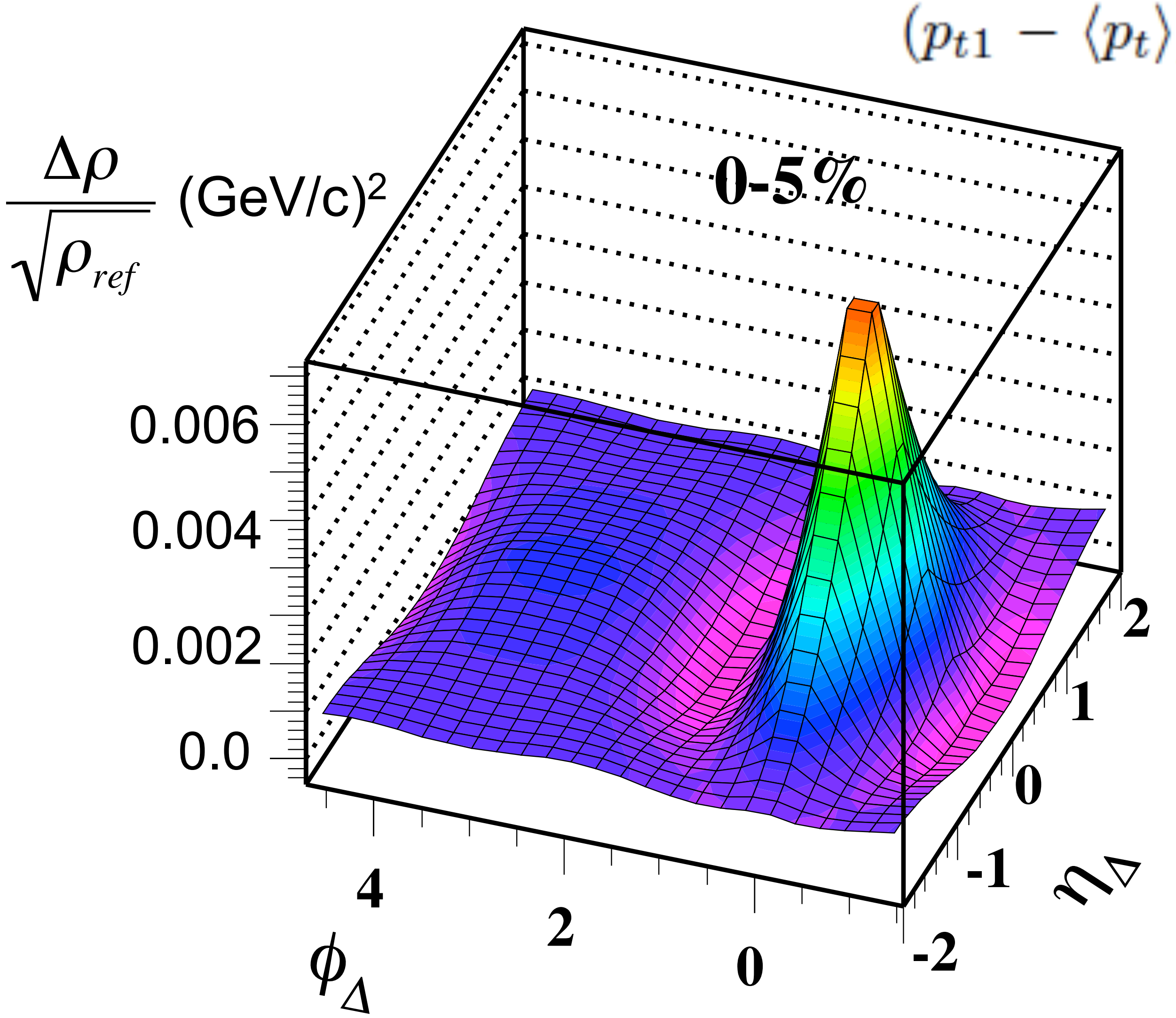
Mocsy, Sorensen, 2010

Au+Au collisions may initially contain hotspots of ~ 1.5 fm and remnants of these may persist

Temperature Fluctuations in Data

- We look for evidence for hotspots in p_t-p_t correlations

$(p_{t1} - \langle p_t \rangle)(p_{t2} - \langle p_t \rangle)$ sensitive to T-T correlations



STAR Collaboration J. Phys. G 32, L37 (2006)

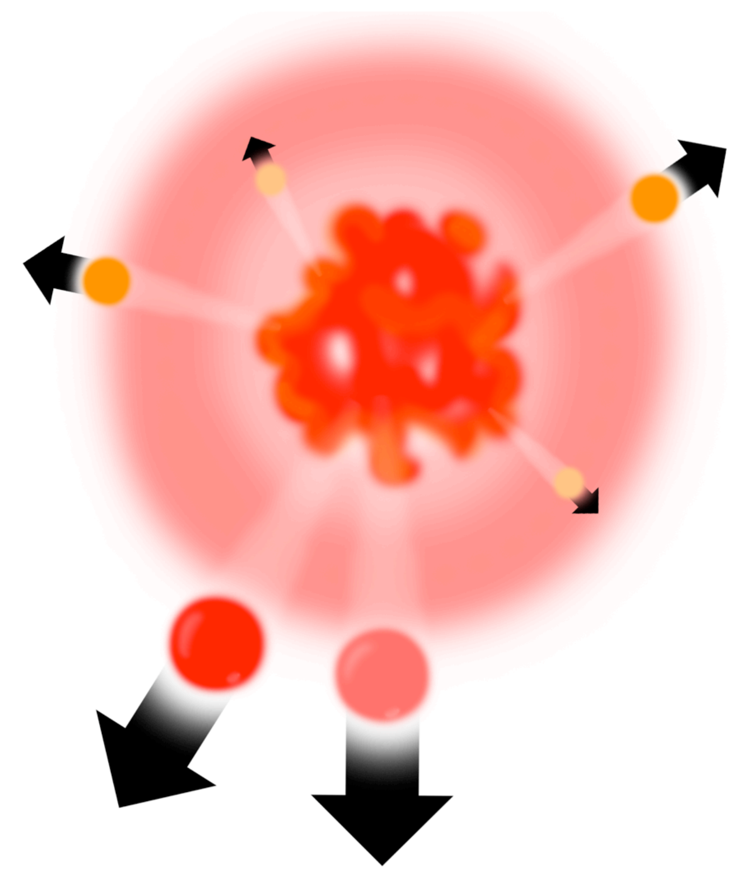


illustration: Alex Doig

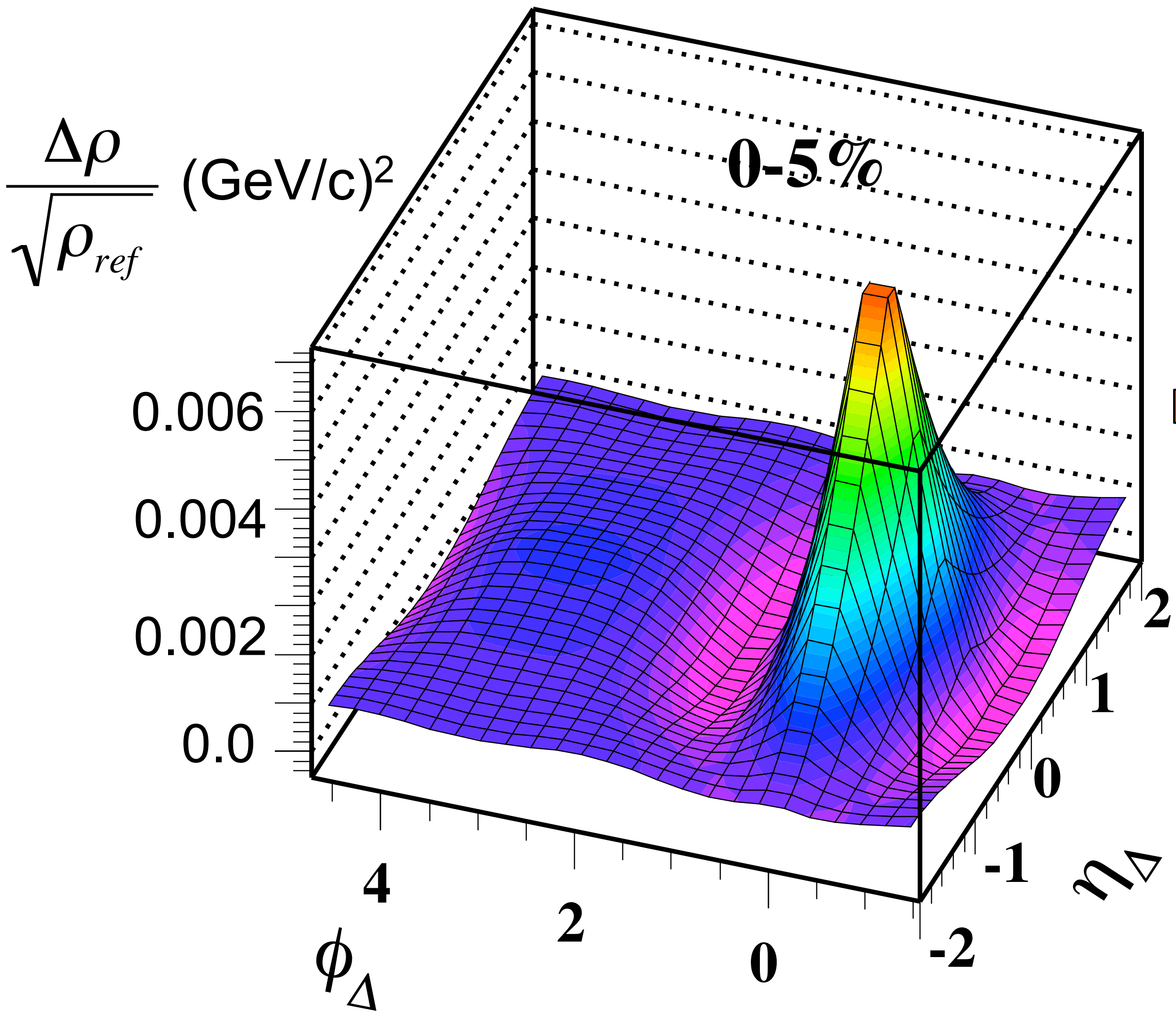
Peak indicates:

-- particles with above average momentum tend to come out together

-- consistent with being born out of the same high T lump (hotspot)

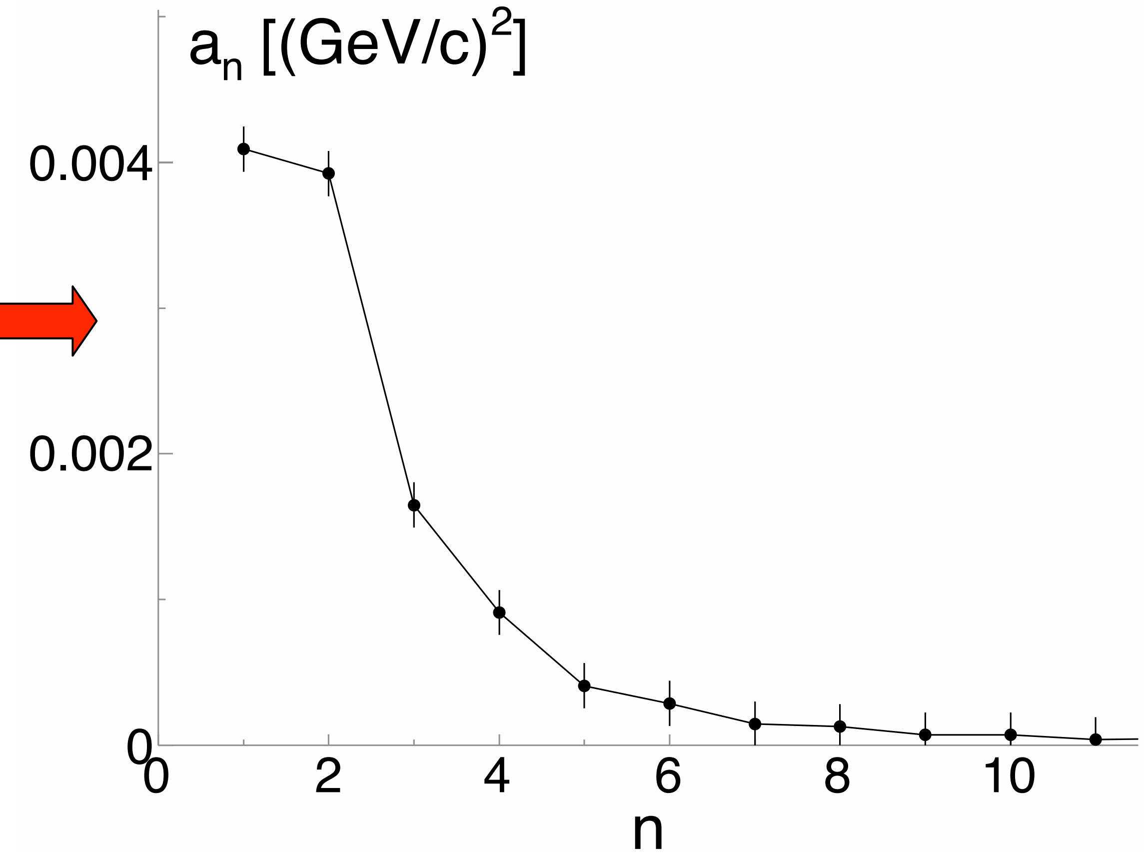
Power Spectrum

Au+Au at 200 GeV



STAR Collaboration J. Phys. G 32, L37 (2006)

$\Delta\eta = 0$

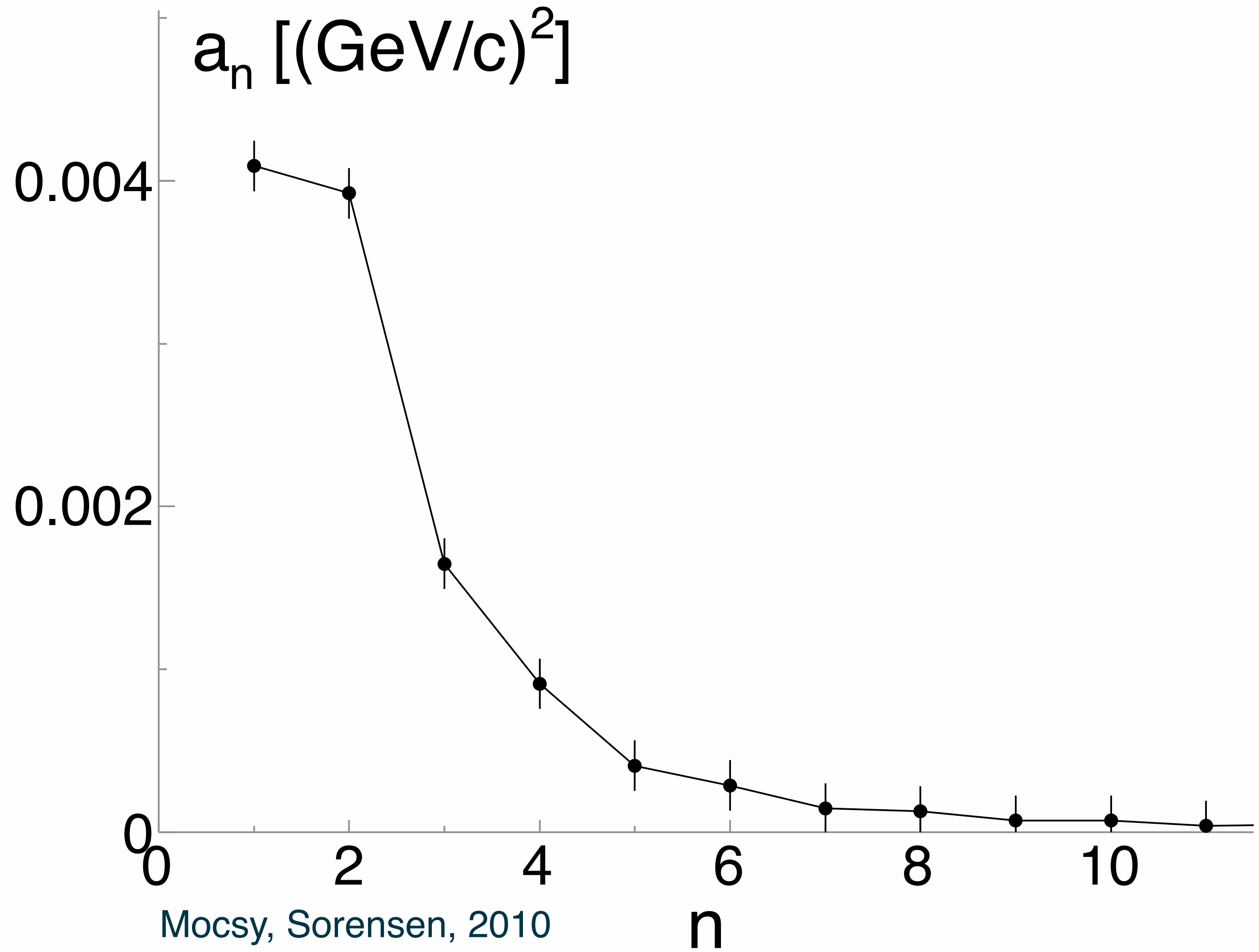


$$a_n = \frac{2}{\pi}\int_0^\infty f(\Delta\phi)\cos(n\Delta\phi)d(\Delta\phi)$$

This is the power of the harmonic n.

Power Spectrum

Au+Au at 200 GeV

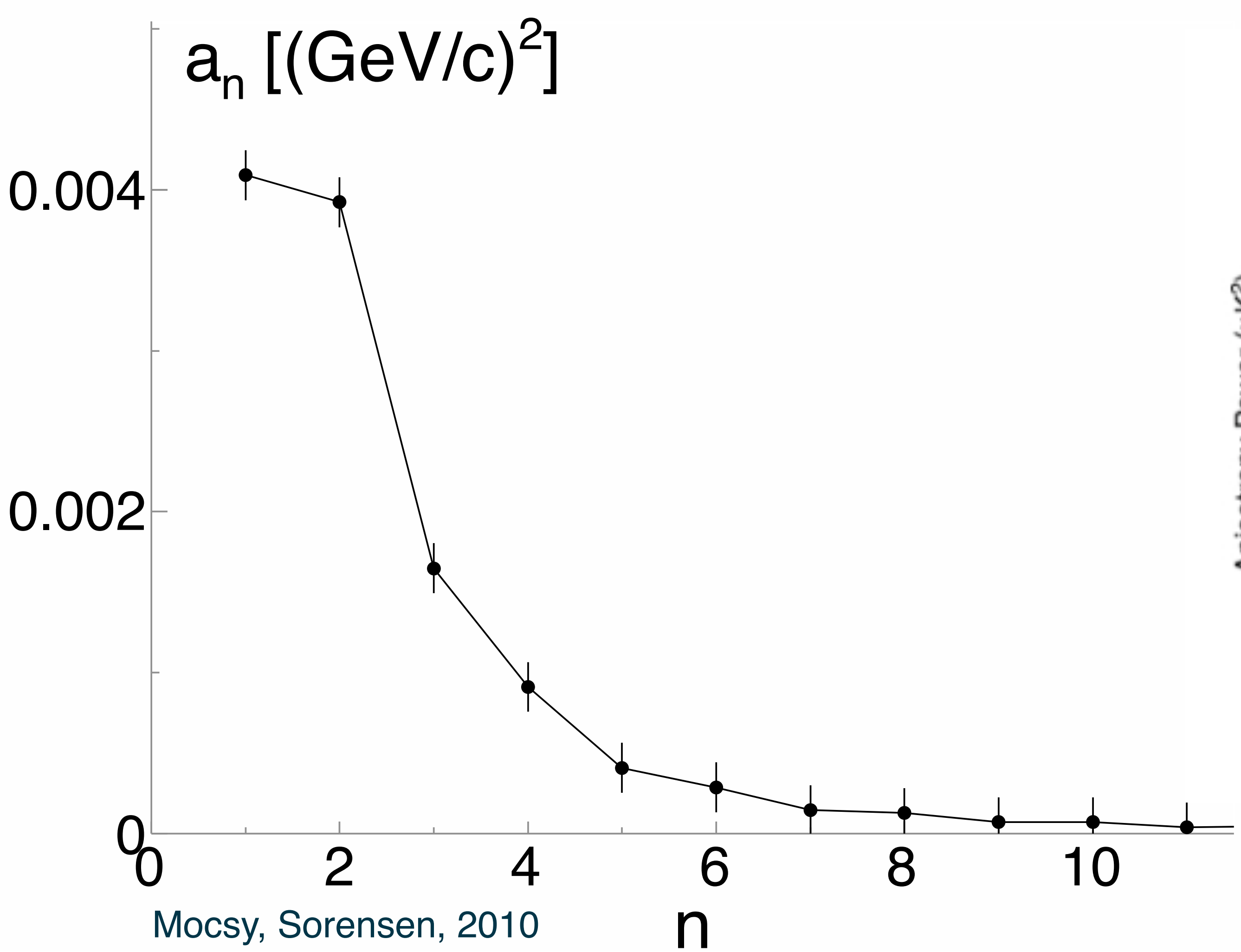


Most power in lowest modes.
Power drops off rapidly with n

Appears to be dominated by **viscous**(-like) **effects**

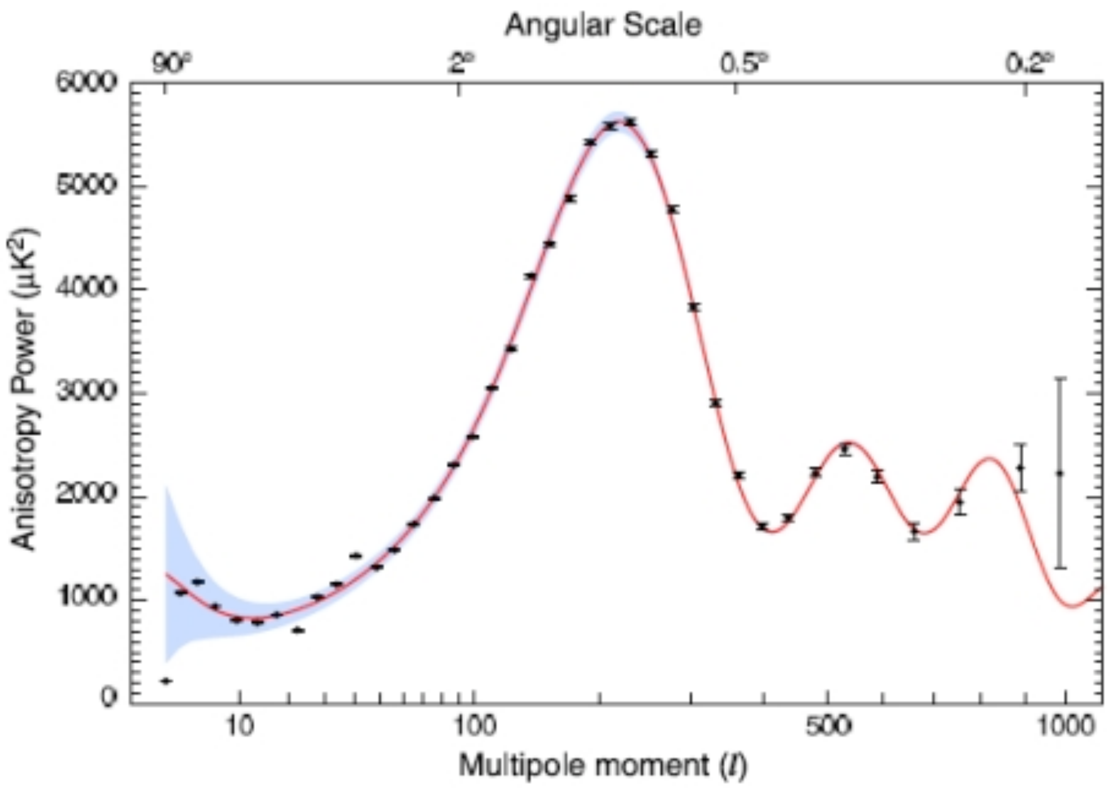
Power Spectrum

Au+Au at 200 GeV



Mocsy, Sorensen, 2010

Our universe



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Appears to be dominated by **viscous**(-like) **effects**

Low modes suppressed
Acoustic oscillations at high modes.

Effects of horizon apparent

Power Spectrum

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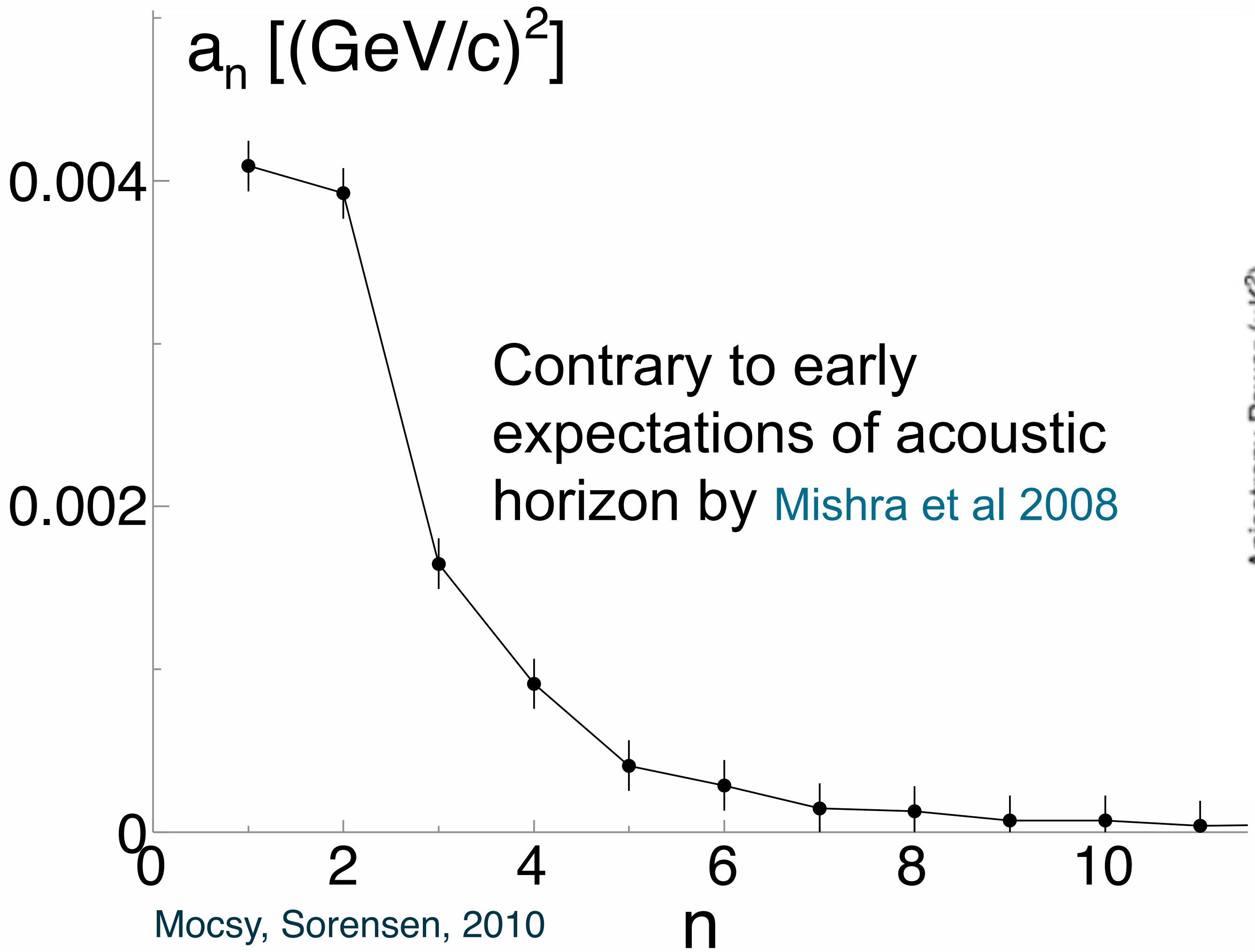

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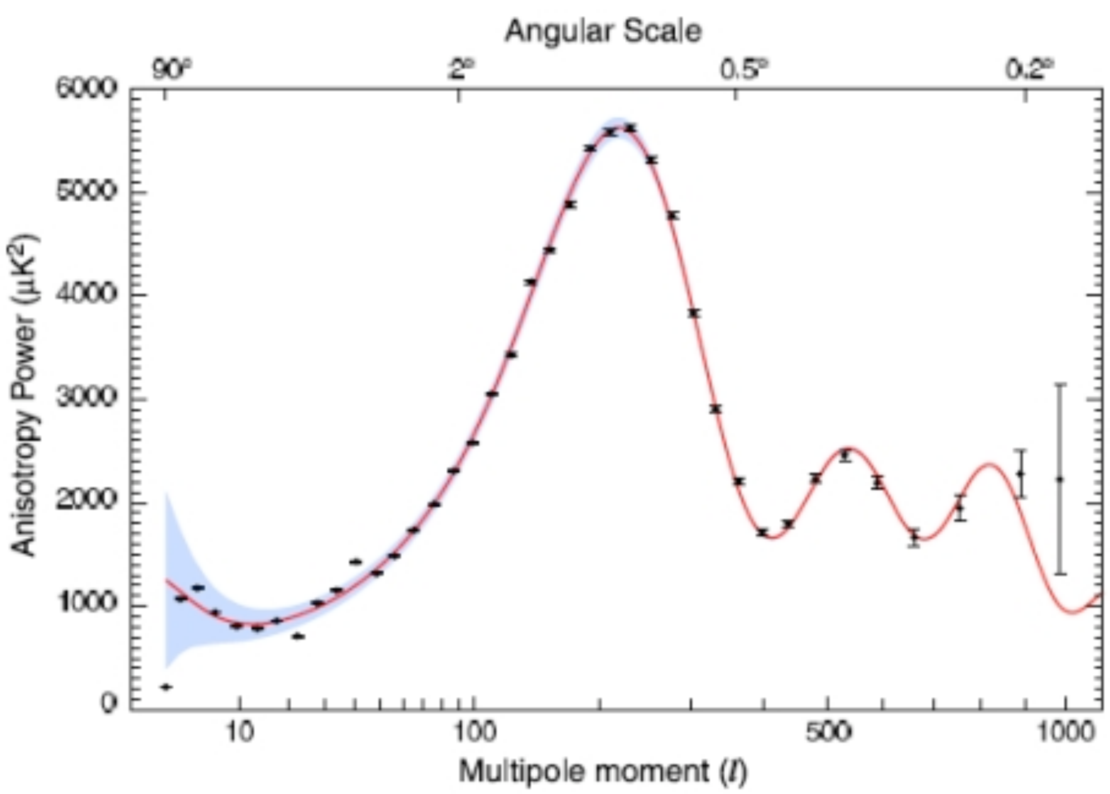


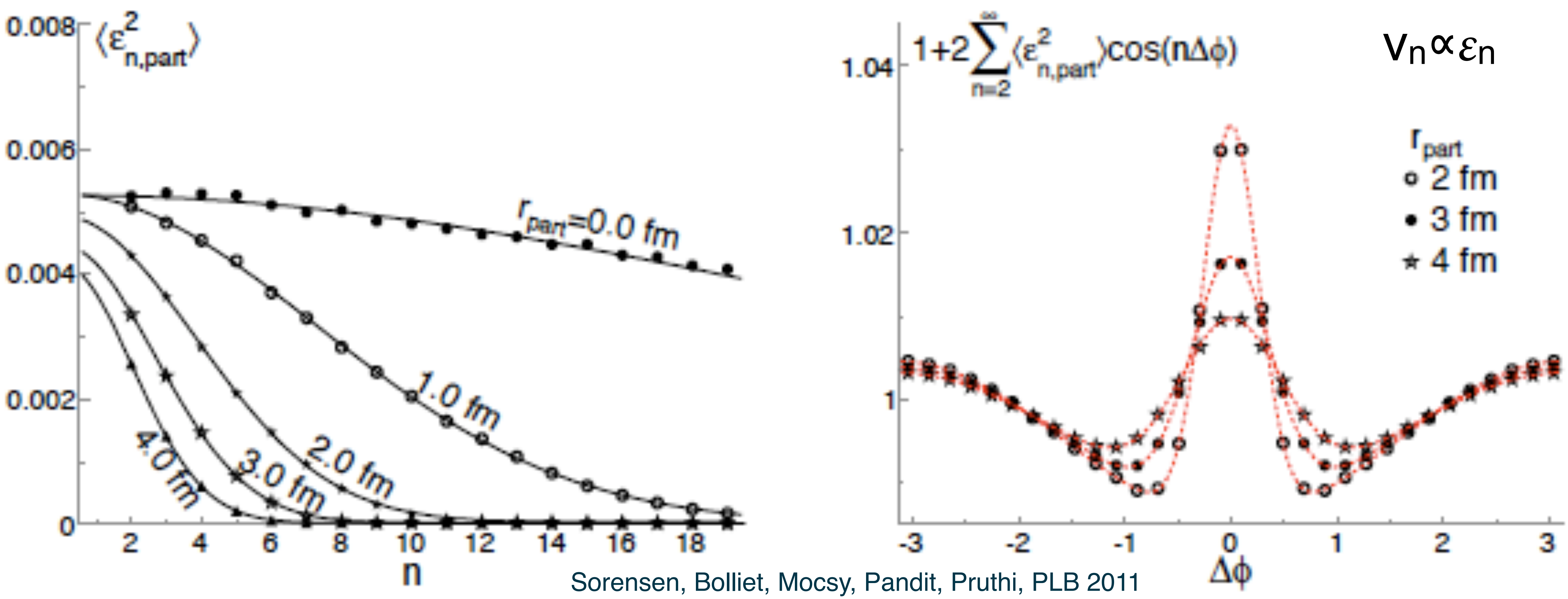
Most power in lowest modes. Power drops off rapidly with n	Low modes suppressed Acoustic oscillations at high modes.

Appears to be dominated by **viscous**(-like) **effects**

Effects of horizon apparent

Eccentricity and Correlations

Eccentricity at different harmonics leads to two-particle correlations similar to those observed in the data



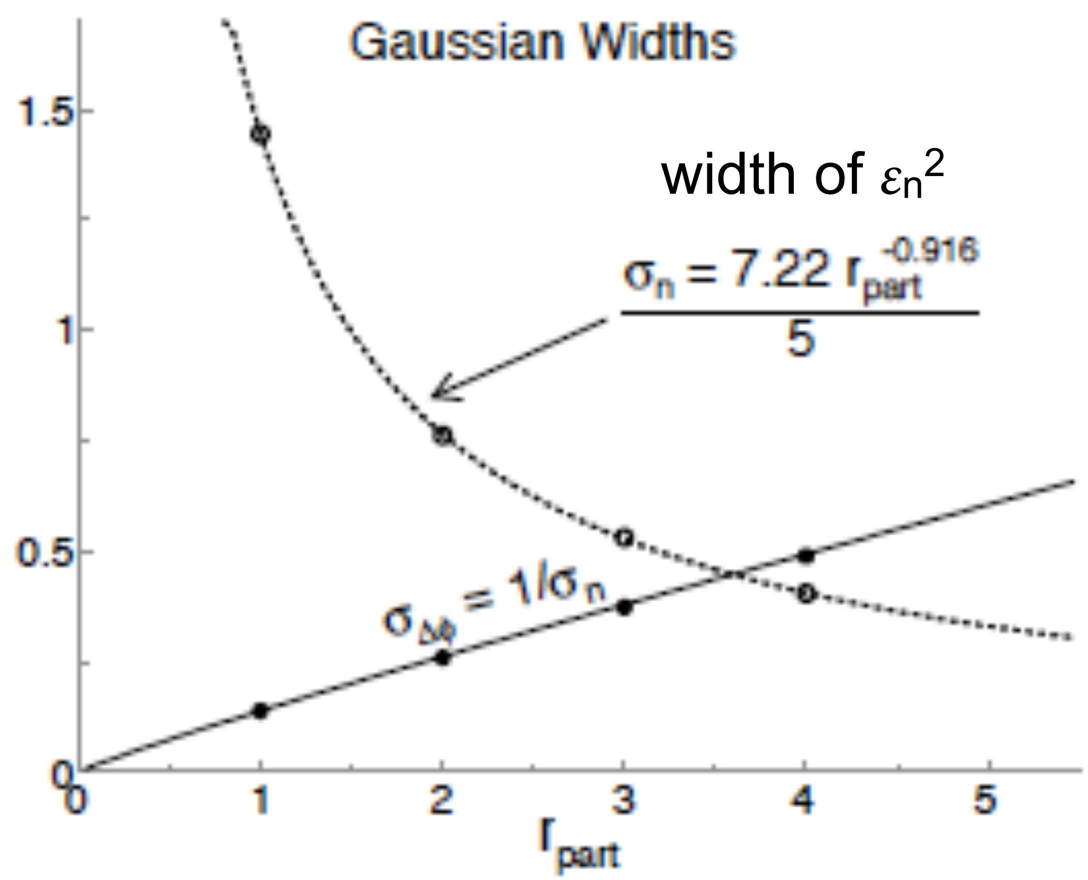
Sorensen, Bolliet, Mocsy, Pandit, Pruthi, PLB 2011

Smearing out the positions of participants
- washes out higher harmonics
- broadens the near-side peak

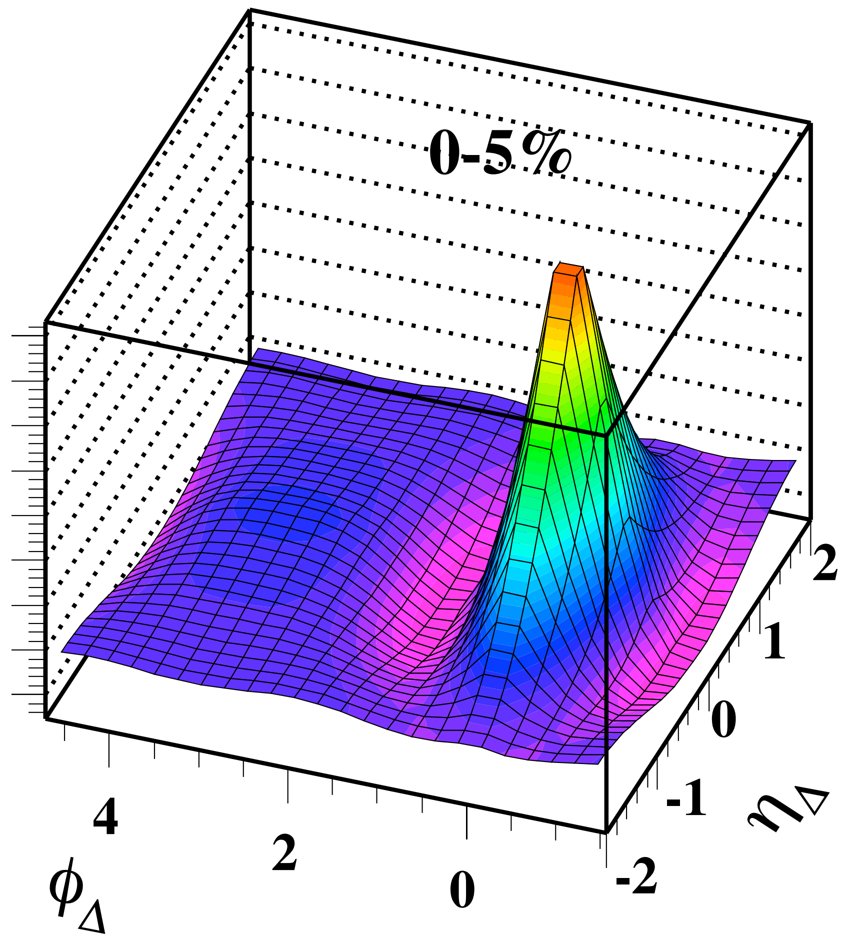
Several effects (like viscosity, free streaming) can have the same effect.

Width of the Correlations

The width depends on the length scales



Sorensen, Bolliet, Mocsy, Pandit, Pruthi, PLB 2011



STAR Collaboration J. Phys. G 32, L37 (2006)

length scale $l = \left(7.22\sigma_{\Delta\varphi}\right)^{1.09}$

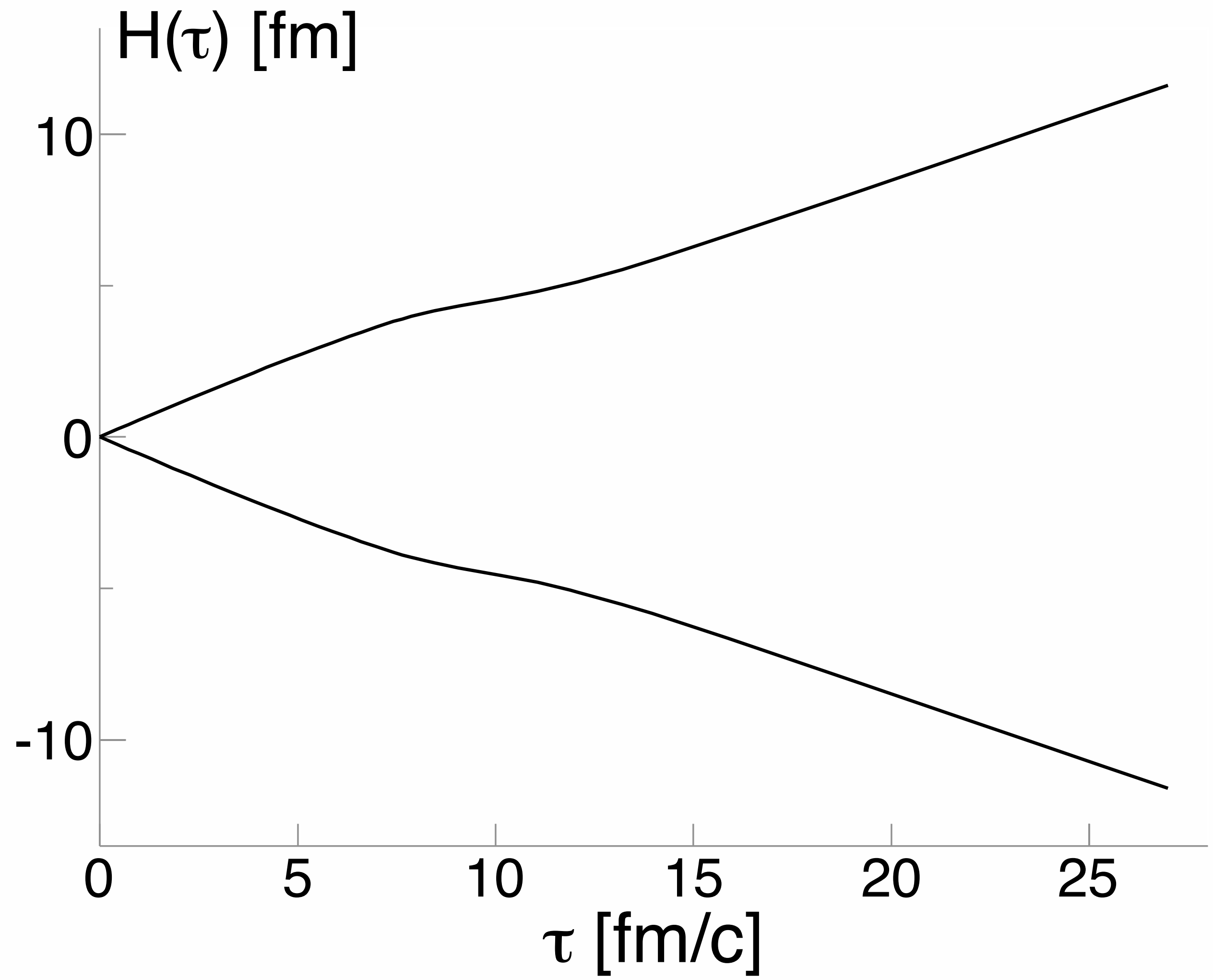
Width of pt correlations consistent with a length scale of 4-5 fm

Not a small viscosity?!

But width can reflect many effects (e.g. thermal at hadronization)

Acoustic Horizon

- Another important length scale:
  H = distance density perturbations will have travelled



$$H(\tau) = \int_0^{\tau_{fo}} c_s(\tau) d\tau$$

Mocsy, Sorensen, 2010
also Staig, Shuryak, 2010

$c_s(e)$ from lattice QCD

Huovinen, Petreczky, Nucl. Phys.A (2010)

$e(t)$ from hydro to get $c_s(t)$

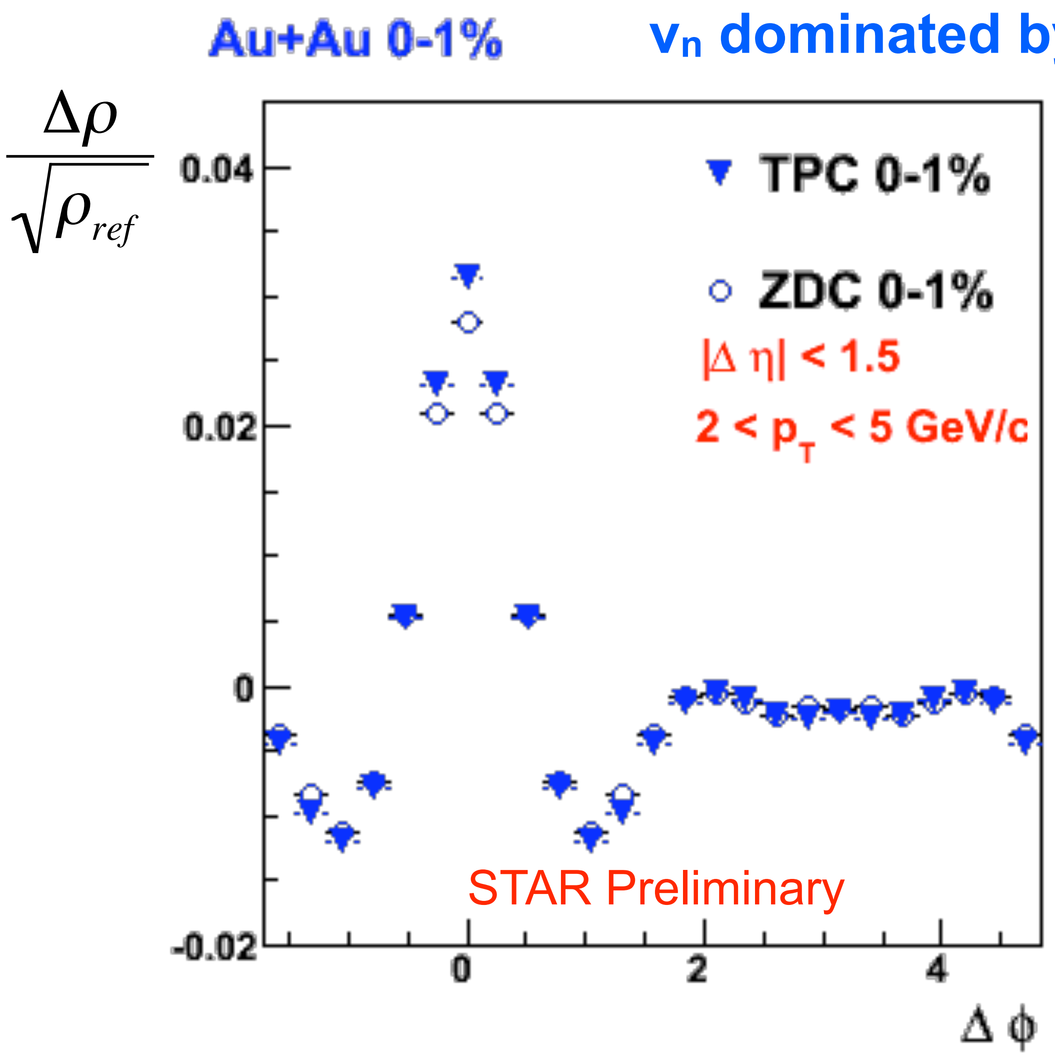
Kolb, Heavy Ion Phys. (2004)

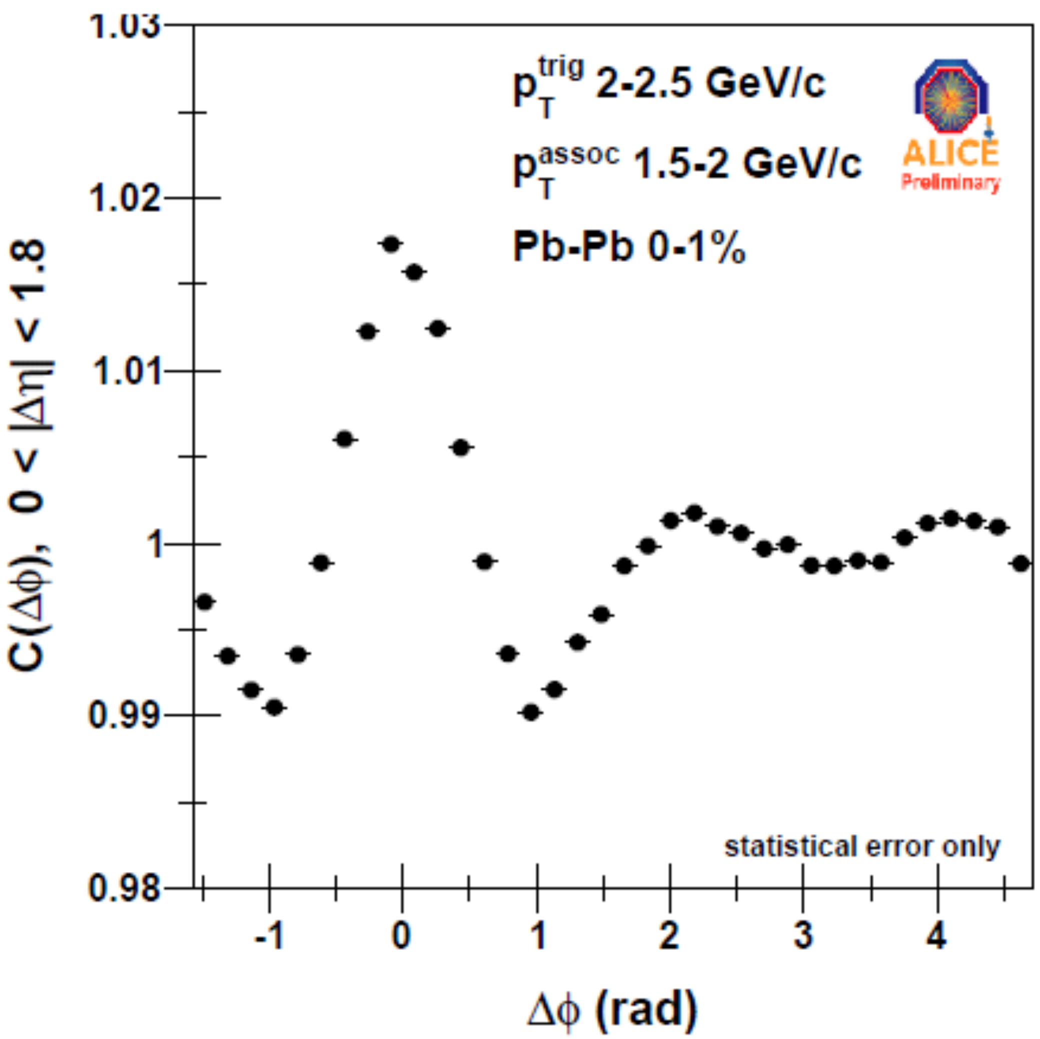
- Effects of H freeze-out should show up in the power spectrum:
  lengthscales larger than the horizon remain super-horizon

Effect of the Acoustic Horizon?

- An acoustic horizon should suppress lower harmonics compared to higher harmonics (Mishra et al); the opposite of viscous effects (Mocsy, Sorensen)

v_n dominated by fluctuations alone

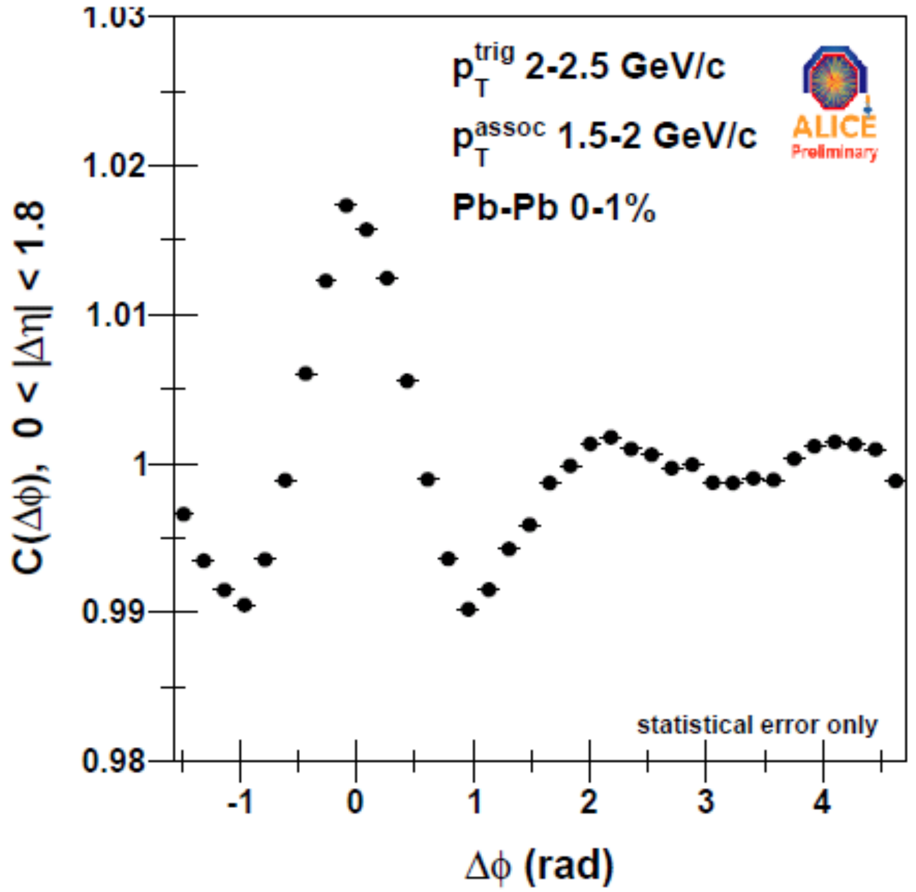


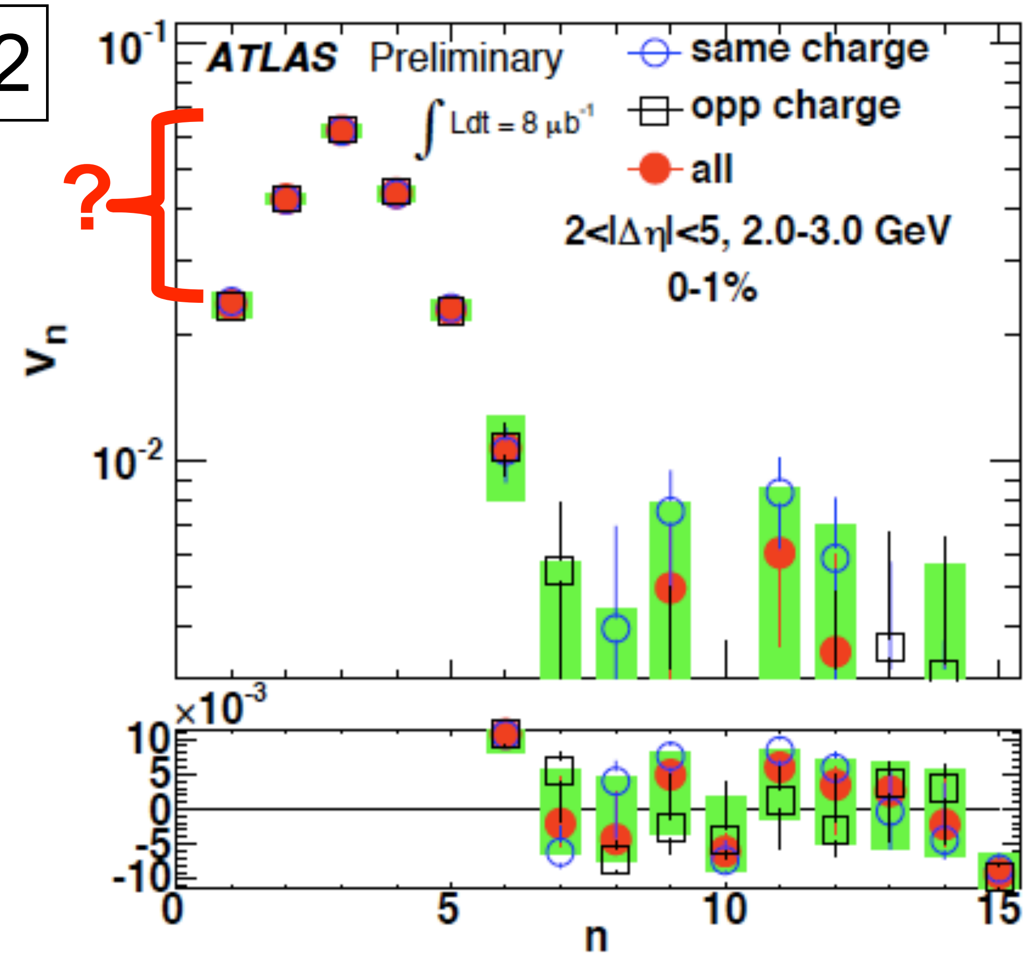


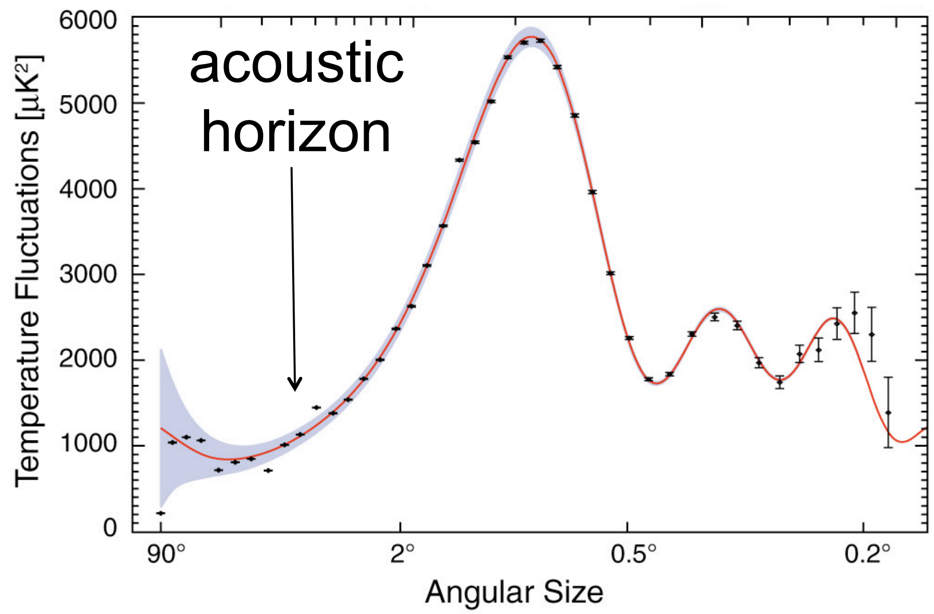
- At both RHIC and LHC, intermediate p_T correlations in very central collisions exhibit a strong n=3 modulation

Power Spectrum at Intermediate pt

n=3 larger than n=2





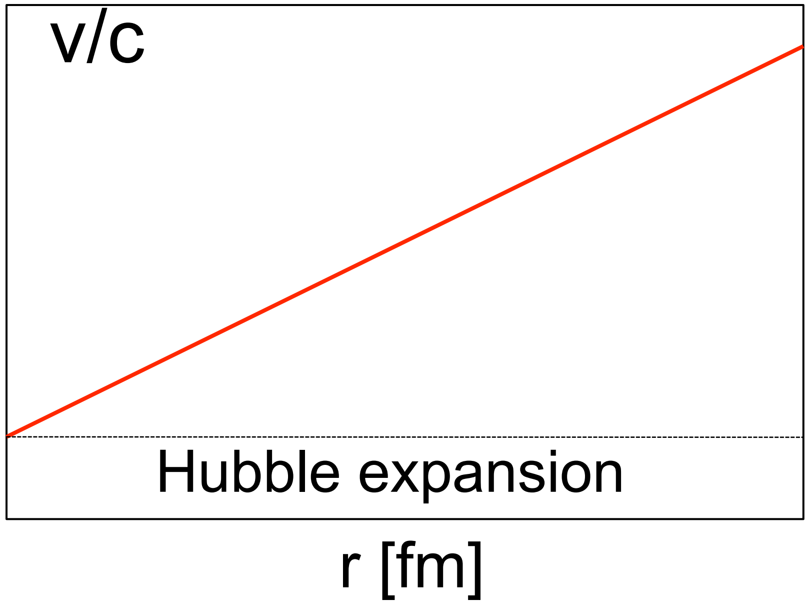


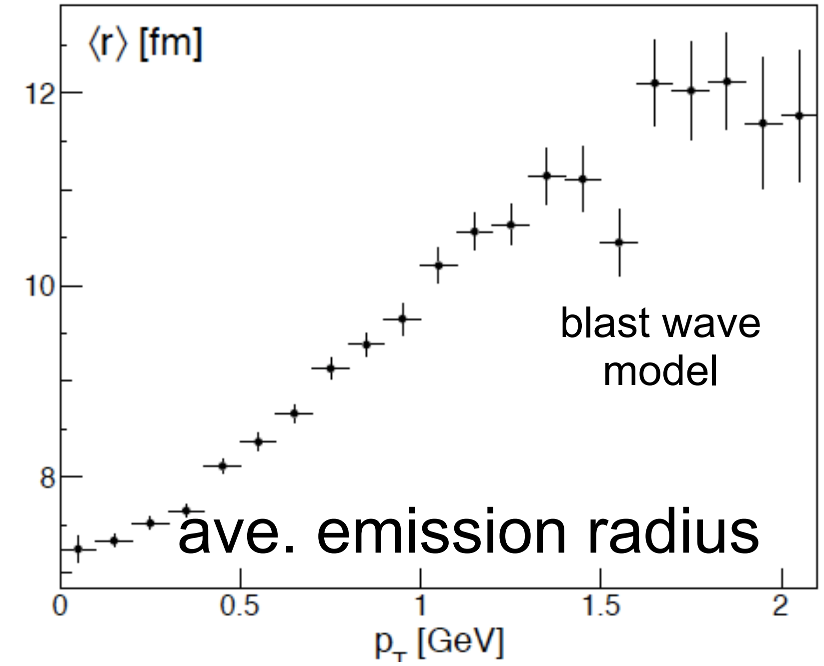
Is this caused by the acoustic horizon?

What other possible explanations?

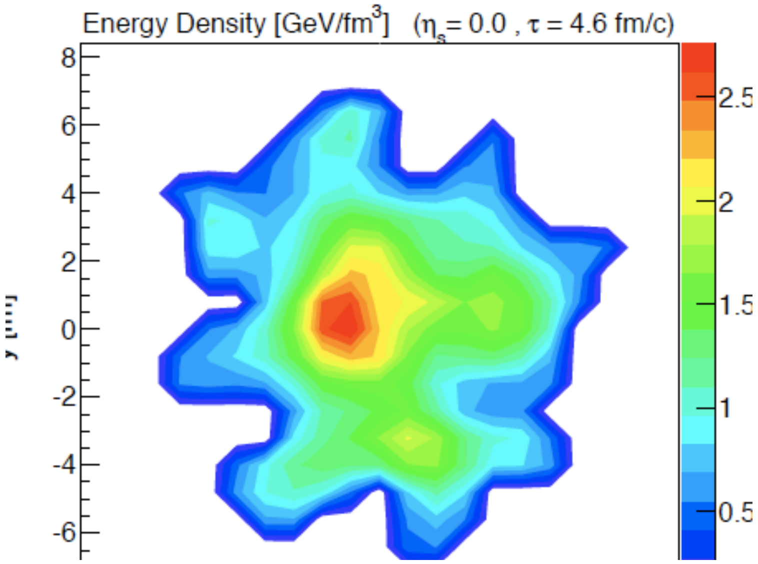
Why only at intermediate p_T?

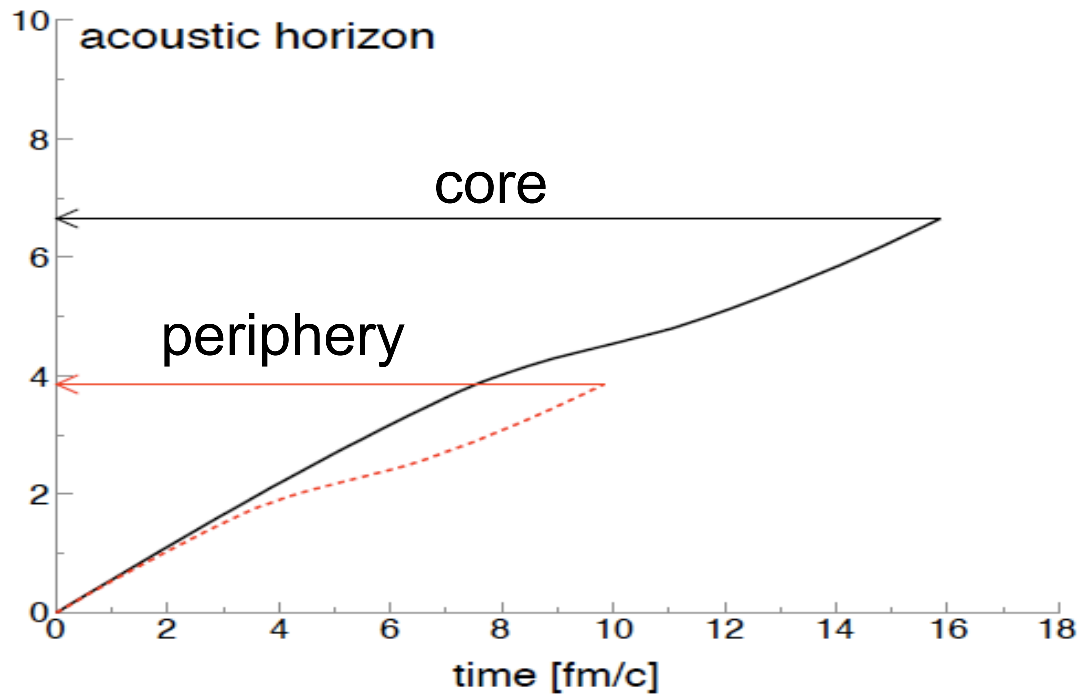
n=3 larger than n=2 Possible Explanation





In a medium undergoing hubble expansion, intermediate p_T particles are preferentially emitted from the periphery





Horizon should be smaller on the periphery, perhaps leading to n=3 > n=2

Summary/Conclusion

The power spectrum of heavy ion collisions shows that higher harmonics are suppressed: as expected for finite size participants and viscous effects

Identified a relevant large scale ~ 4-5 fm (implies a rather large viscosity)

mean free path? free-streaming? thermal broadening?

Correlations can reflect a competition between causality (horizon) and viscosity

viscous effects suppress higher harmonics
causality suppresses lower harmonics

Identified the acoustic horizon as a possible explanation for $v_3 > v_2$ at intermediate p_T

The End

Final Note

Á.M., P. Sorensen arXiv: 1008.3381 [hep-ph]
Á.M., P. Sorensen arXiv: 1101.1926 [hep-ph]
P. Sorensen, B. Bolliet, Á.M., Y. Pandit, N. Pruthi arXiv: 1102.1403 [nucl-th]
and
www. soundofthelittlebang.com

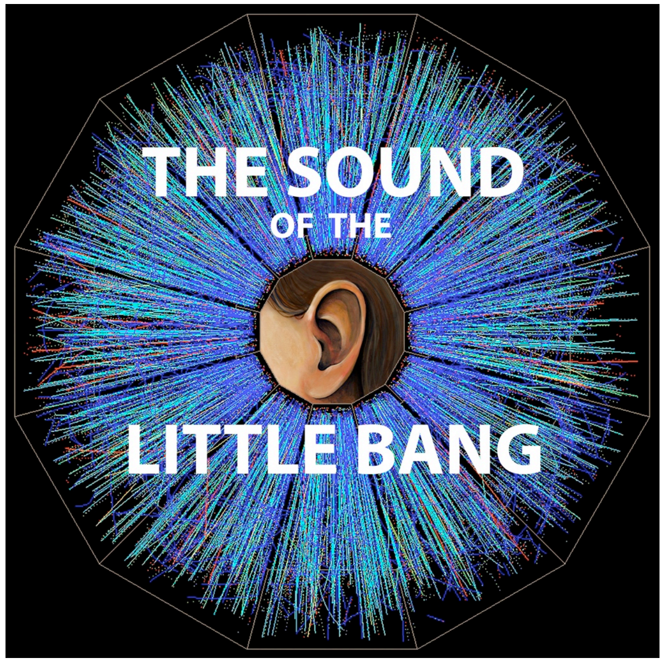


illustration: Alex Doig

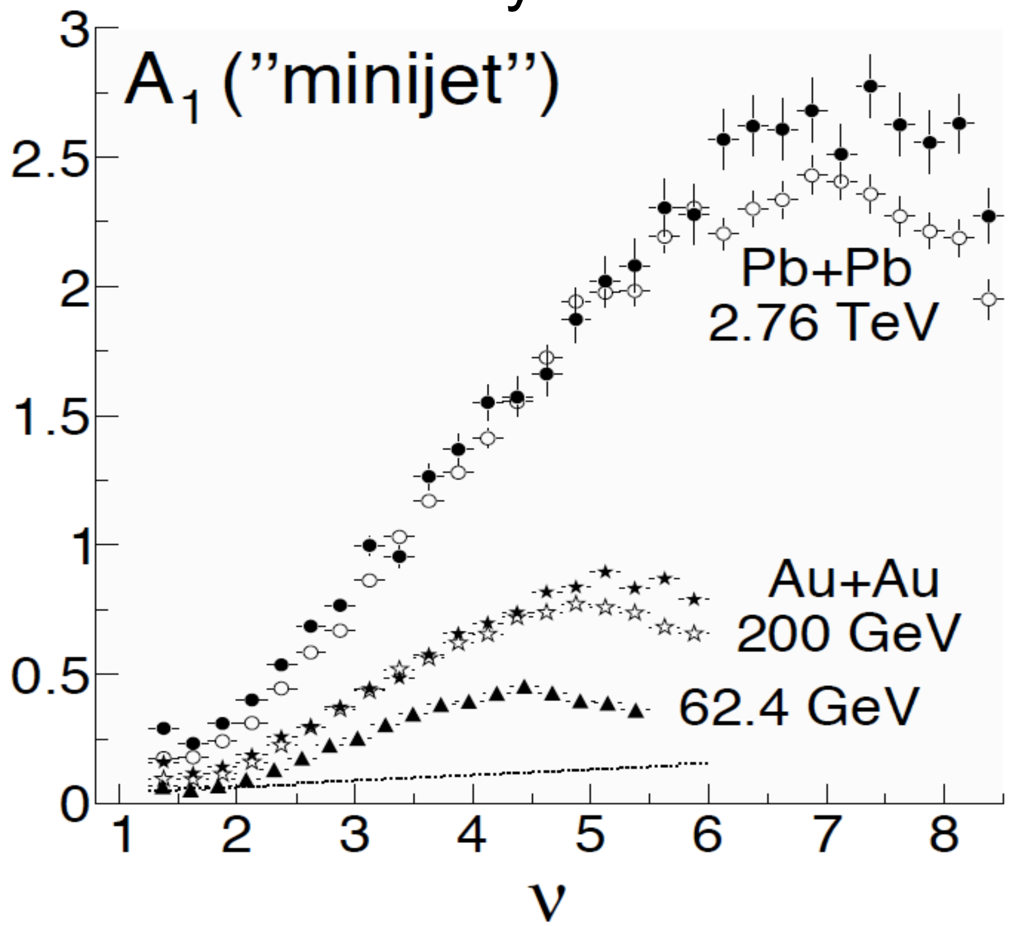
Backups

We demonstrated that eccentricity fluctuations naturally lead to ridge-like correlations with a width dependent on the length-scales in the system

Rise and Fall of the Ridge

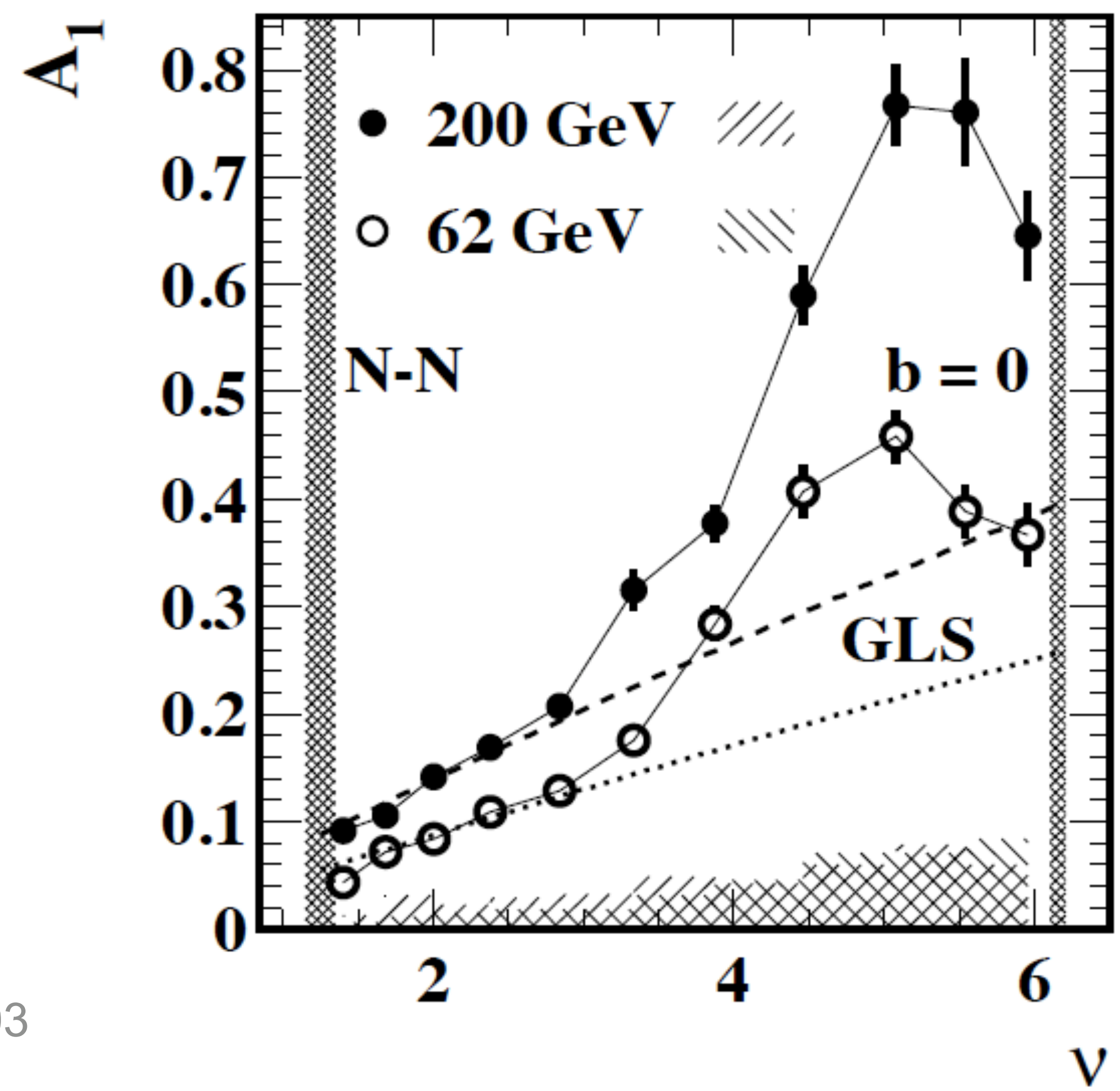
The ridge amplitude A_1 exhibits a drop in central collisions. The drop is natural for eccentricity fluctuations.

Prediction from eccentricity fluctuations



P. S., B. Bolliet, A. Mocsy, Y. Pandit, N. Pruthi, arXiv:1102.1403

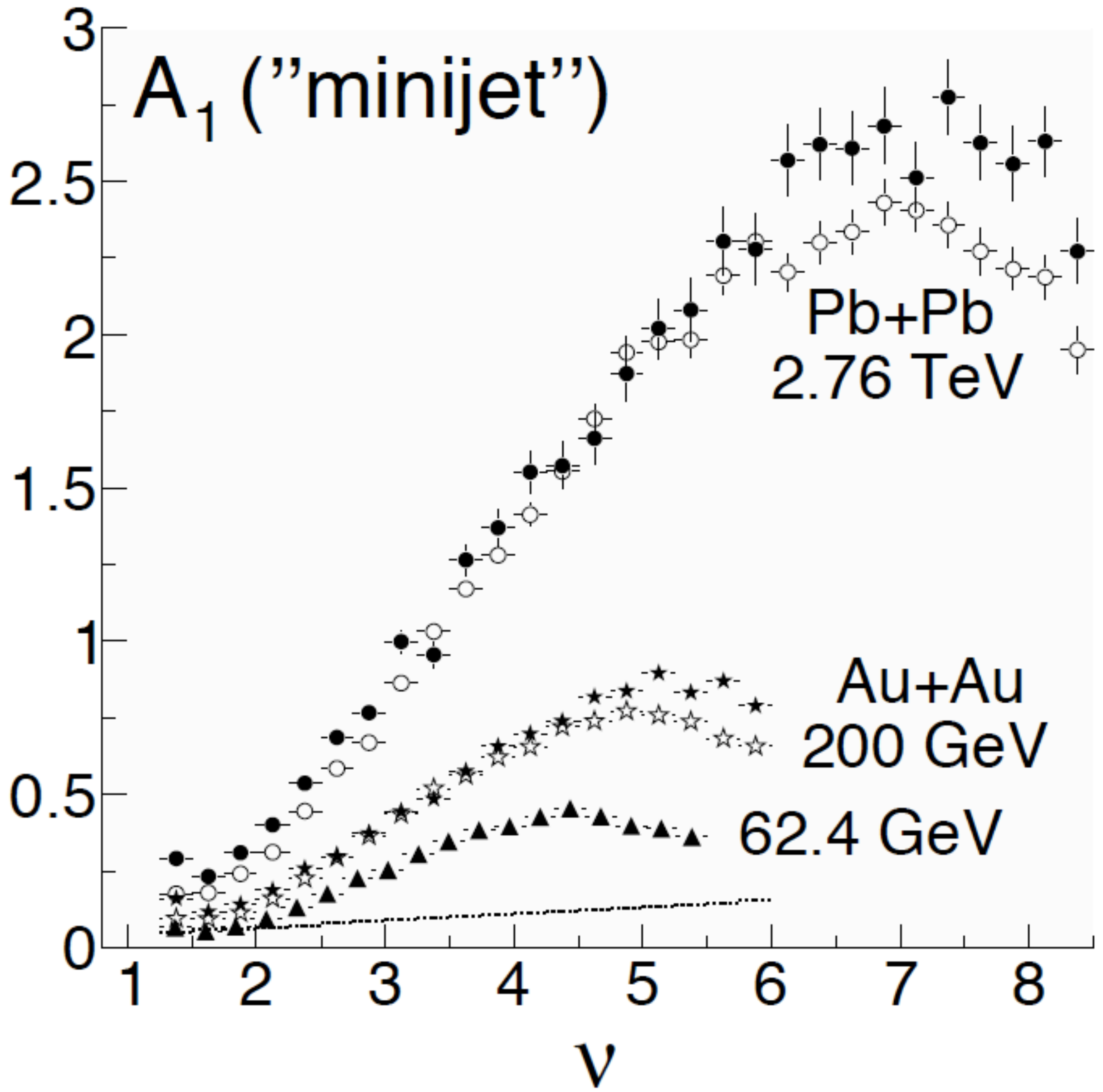
STAR Data http://arxiv.org/abs/1109.4380



Prediction: rise and fall of the ridge will be present at all energies: *it's a feature of the overlap geometry*

LHC Predictions

A_1 will be several times larger at the LHC: *driven by increased multiplicity and flow*



P. S., B. Bolliet, A. Mocsy, Y. Pandit, N. Pruthi, arXiv:1102.1403

Data seems to favor eccentricity fluctuations as the explanation for the ridge

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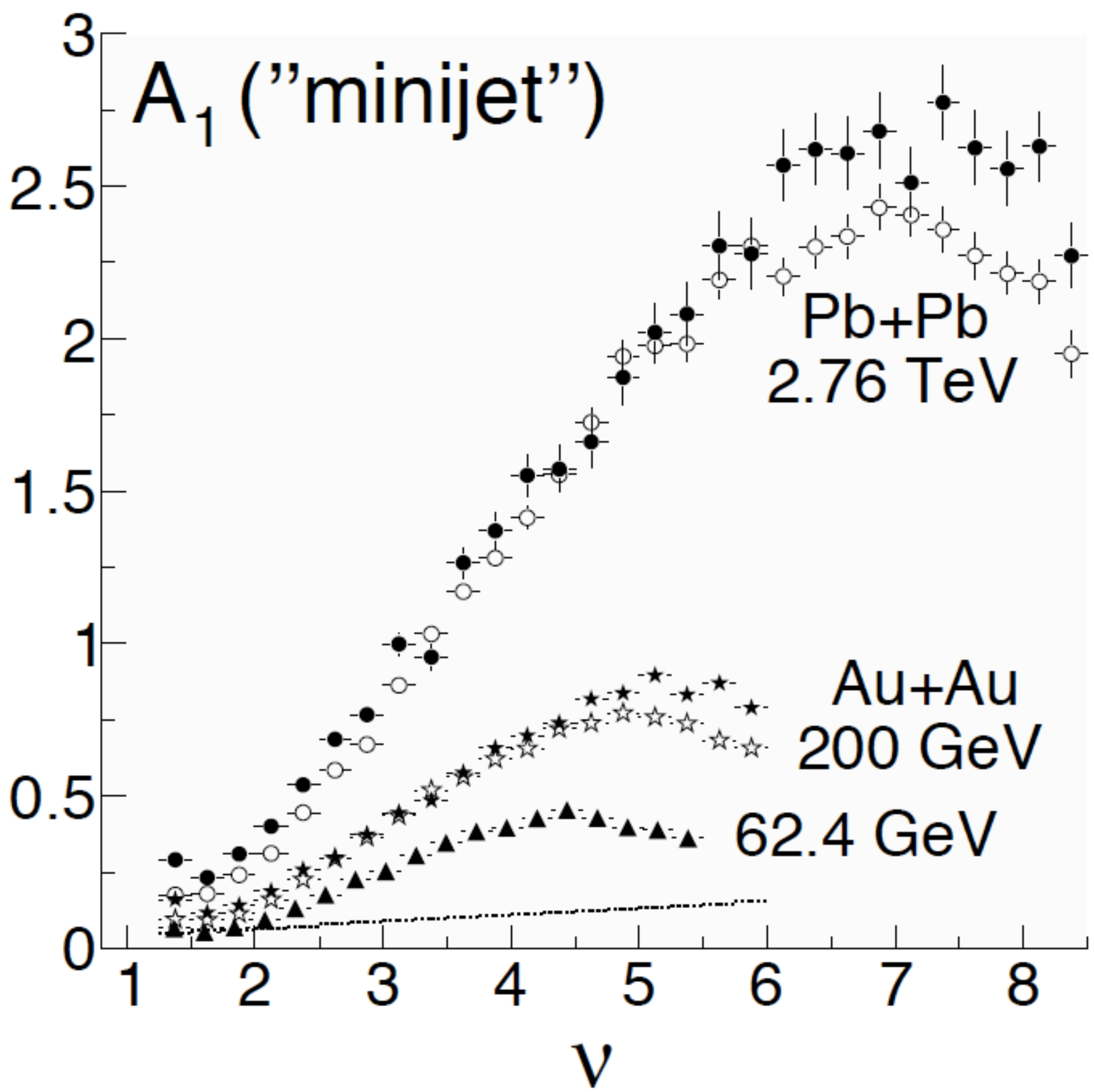
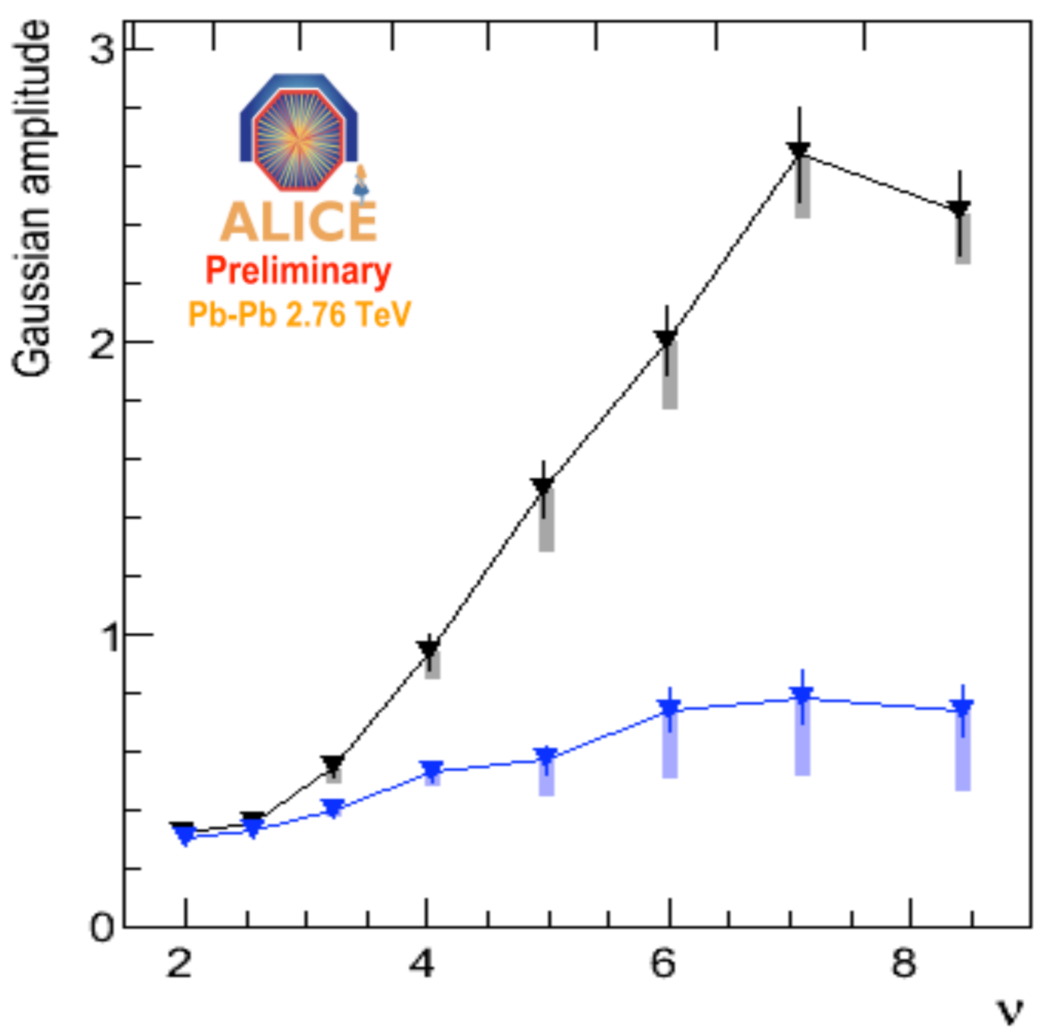


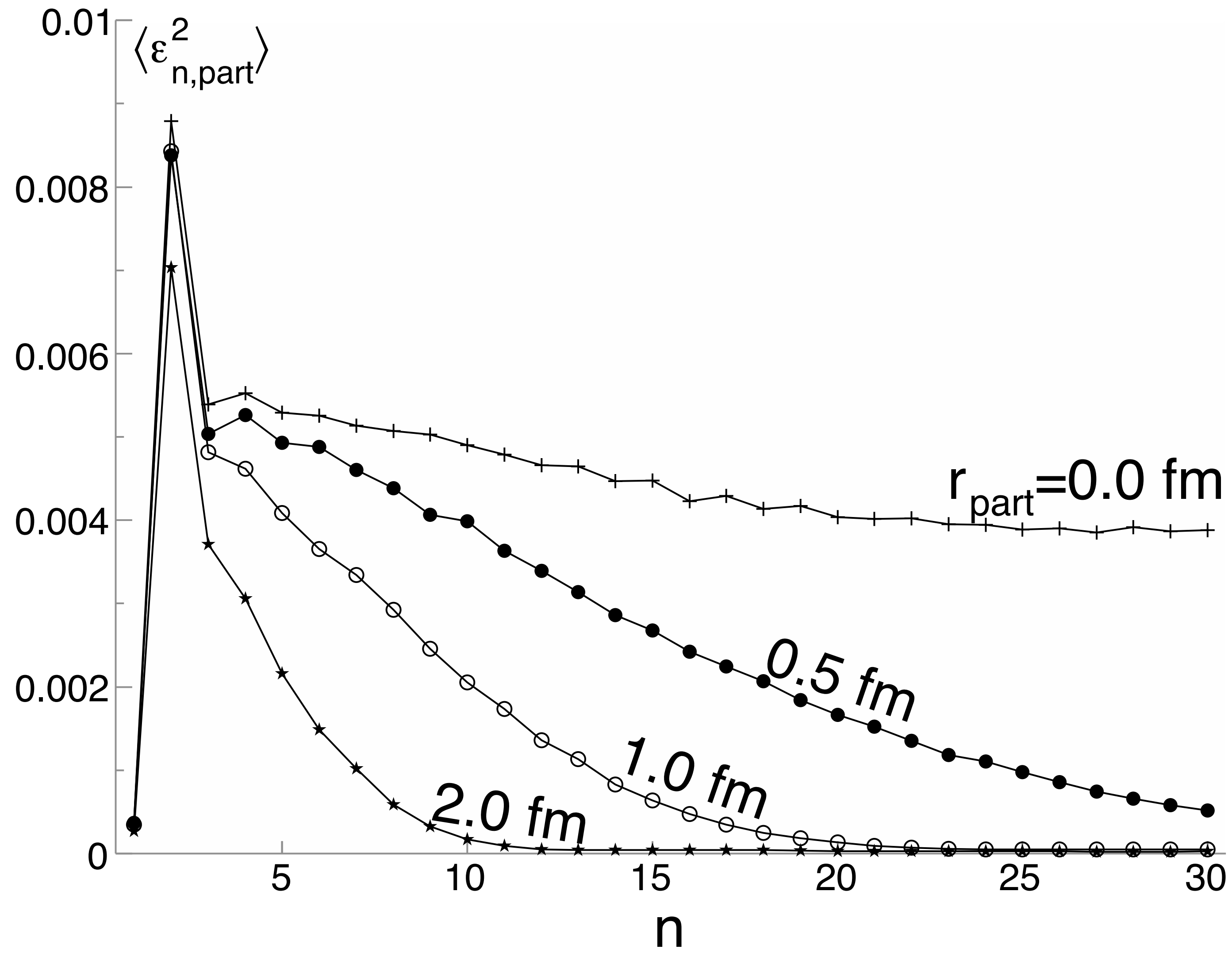
P. S., B. Bolliet, A. Mocsy, Y. Pandit, N. Pruthi, arXiv:1102.1403



A. Timmins, QM2011

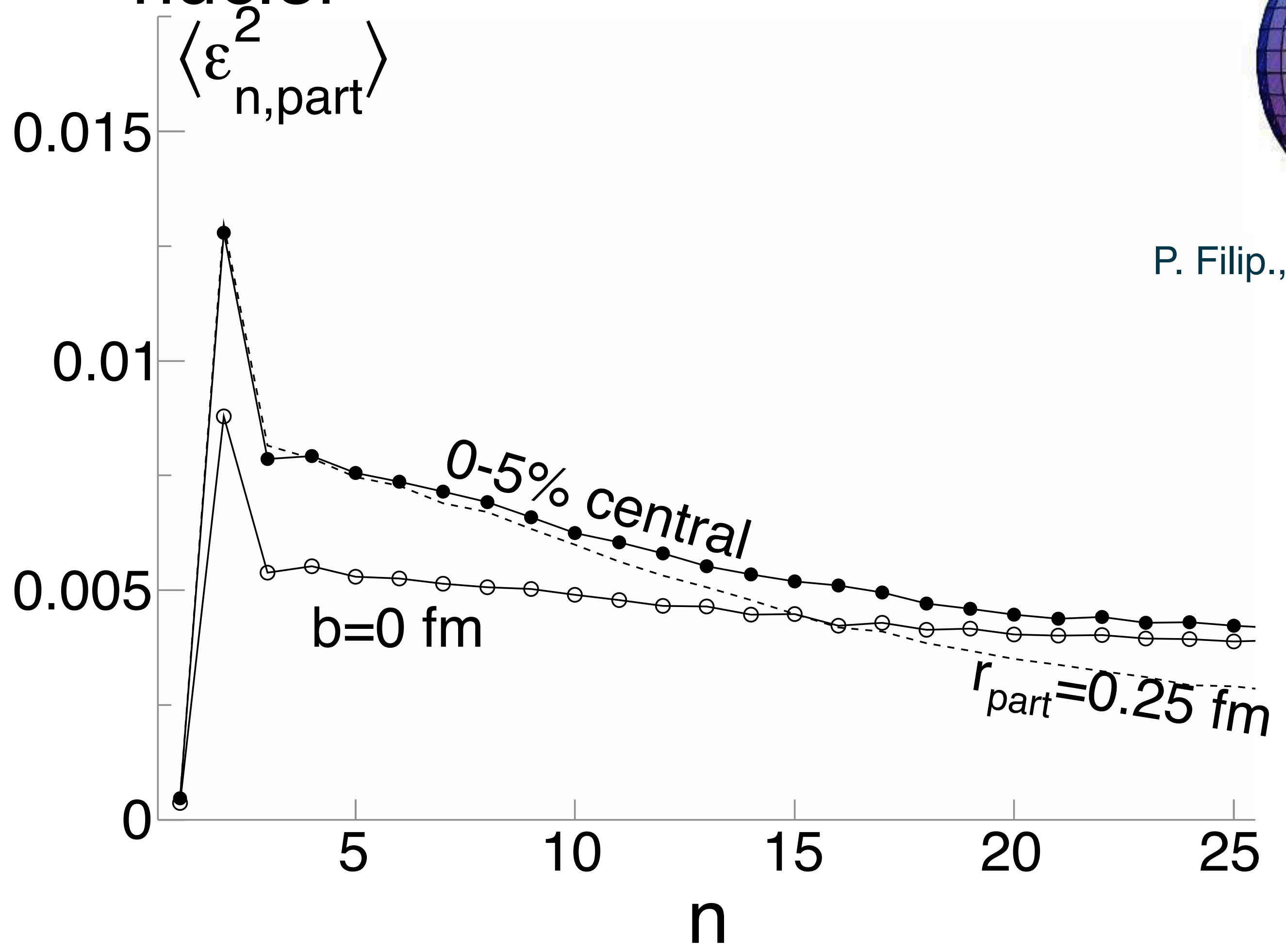
Data seems to favor eccentricity fluctuations as the explanation for the ridge

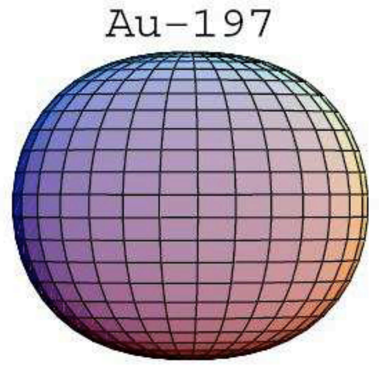
Participant size dependence



Participant Eccentricity

Monte Carlo Glauber with non-spherical Au nuclei





P. Filip., PRC 80, 054903 (2009)

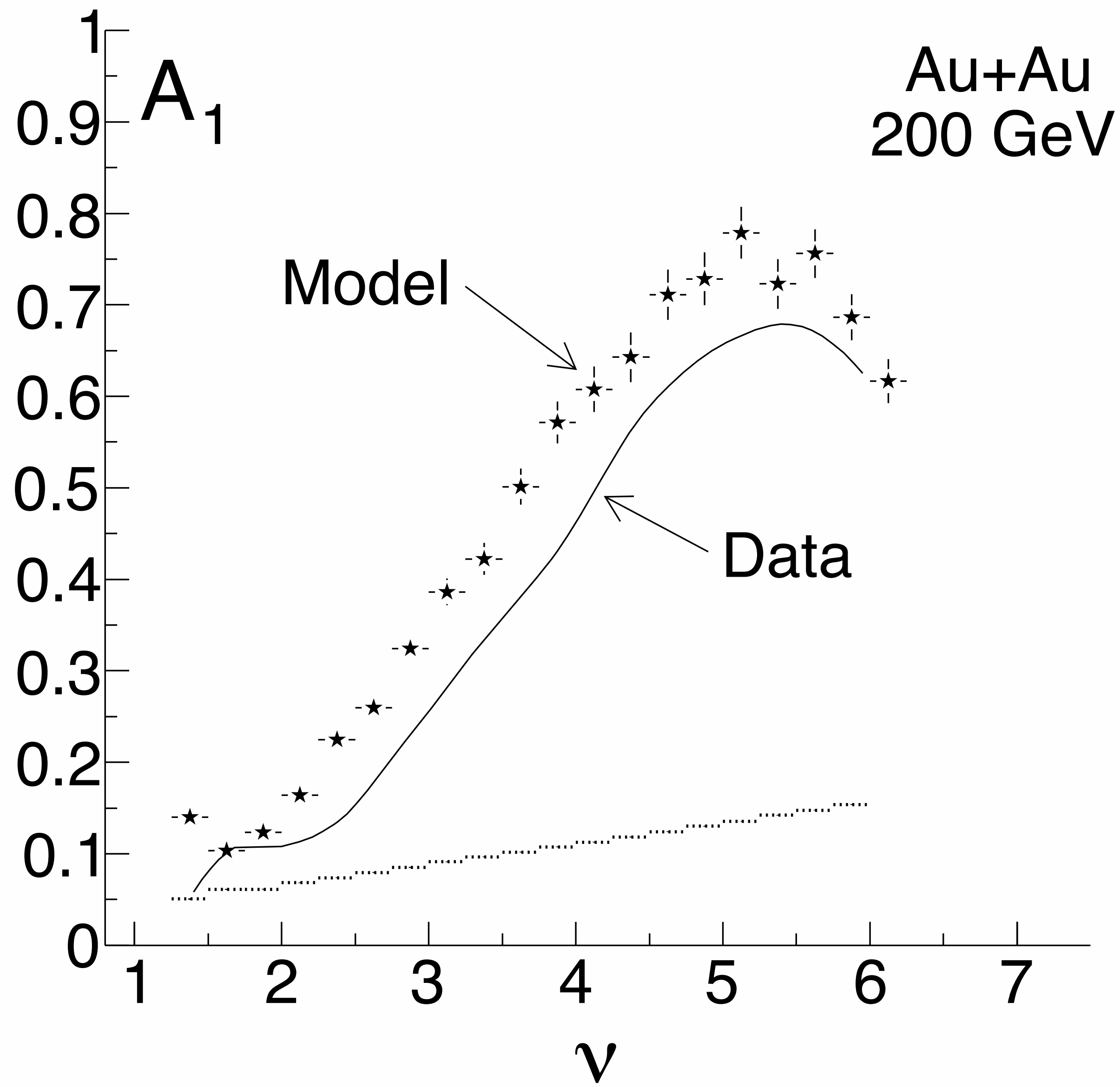
n=2 spike due to oblateness of the Au nucleus (even for b=0)

n>2 at b=0 participant eccentricity is nearly independent of n (only N_{part} dependence)

n.b. finite-sized participants or effect of free-streaming cause a drop with n

H. Petersen et al., [arXiv:1009.1847 [nucl-th]]

Correlations From Initial State



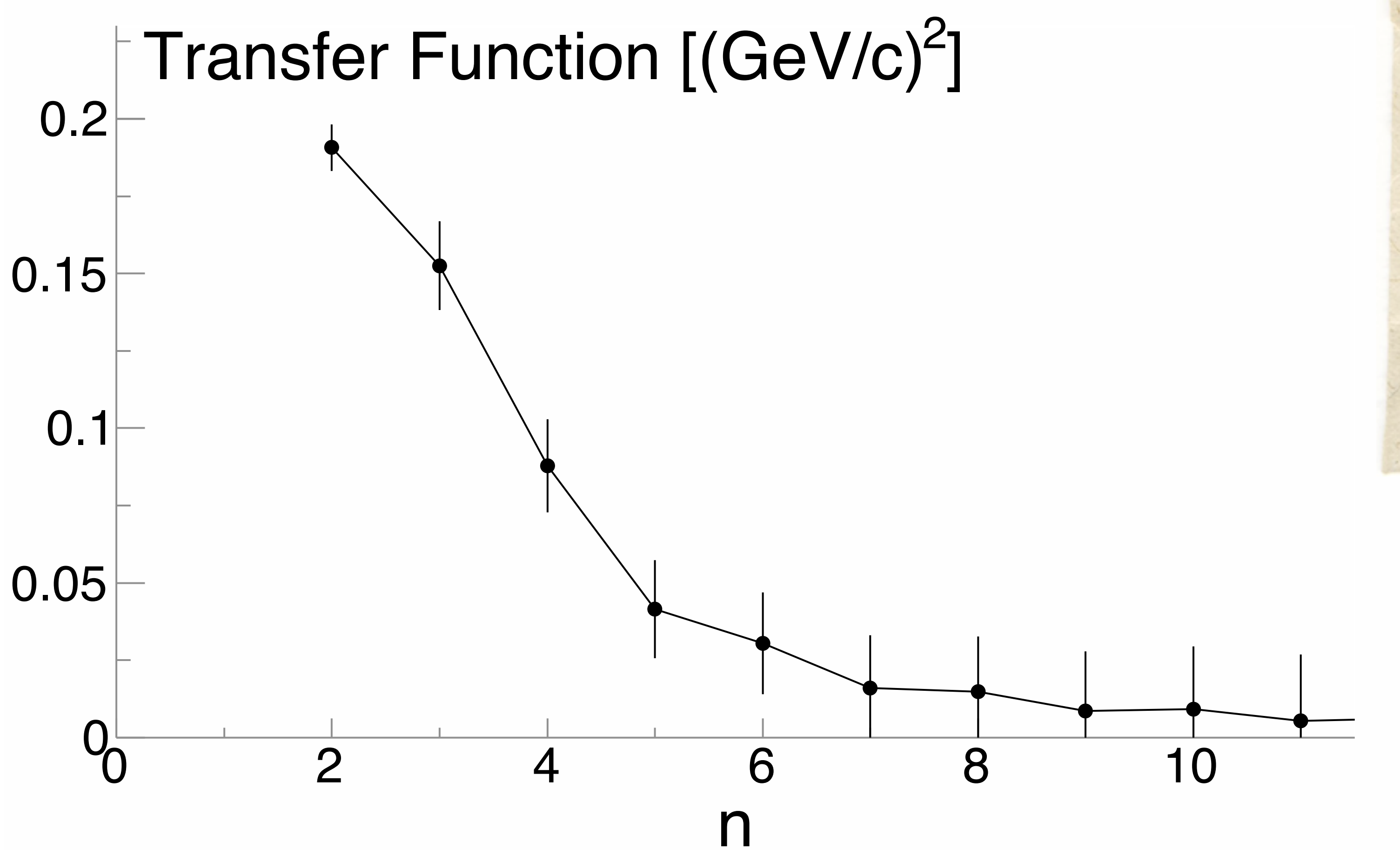
The correlations expected from the initial state density fluctuations transfered into momentum space matches the data

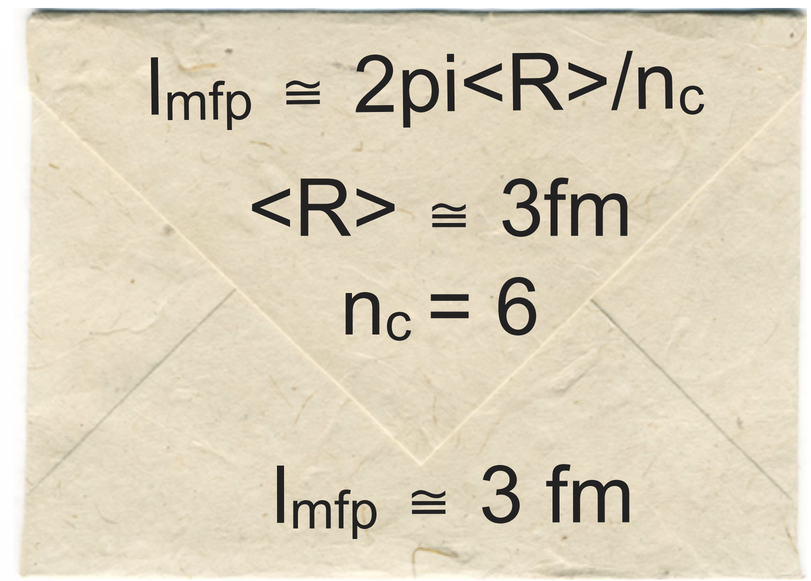
Heavy ion collisions convert spatial anisotropy to momentum anisotropy

Transfer-Function

tells how well coordinate space anisotropy is converted to momentum space

$a_n/\langle \varepsilon^2_{part,n} \rangle$





<R> average radial position of participants

Drop expected due to l_{mfp} cutting off the smaller lengthscales (high n)

Conversion is inefficient for modes n > 6

Transfer function may be used to estimate the mean free path

n.b. full simulation needed, other scales (1/Qs, 1/T, ctau, H, ...) could also be important