The Angular Power Spectrum of Heavy-Ion Collisions

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Outline

- Introduction
- Map and Angular Power Spectrum
  - Mapping particles
  - Averaged power spectrum
    - Cut effects
    - Odd modes & power law
  - Only $m \neq 0$
- Flow extraction
- Summary

anisotropy

Origin

ἀν : negative prefix
an

GREEK

ίσοω : equal
isos

τρόπος : way
tropos

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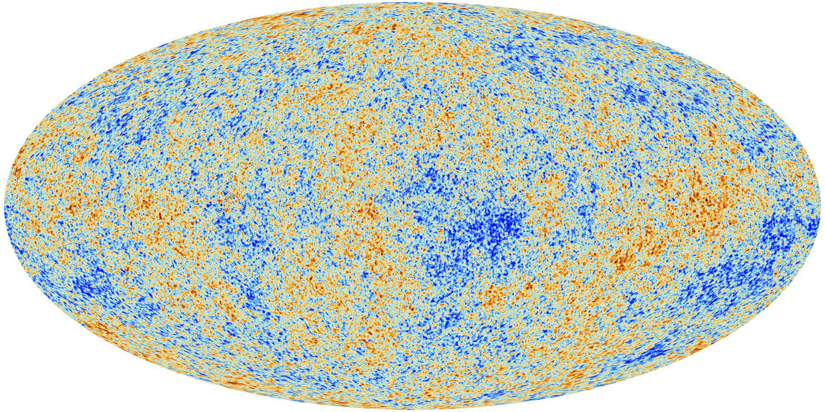
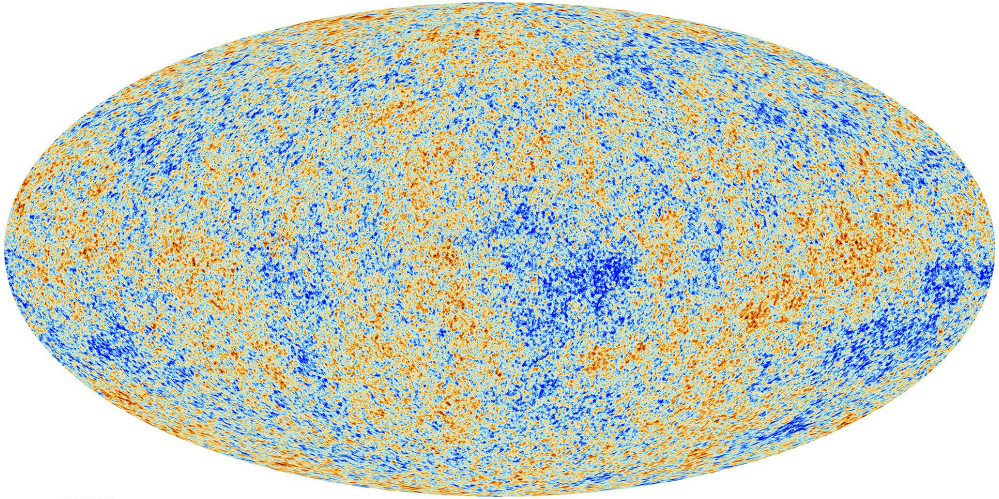
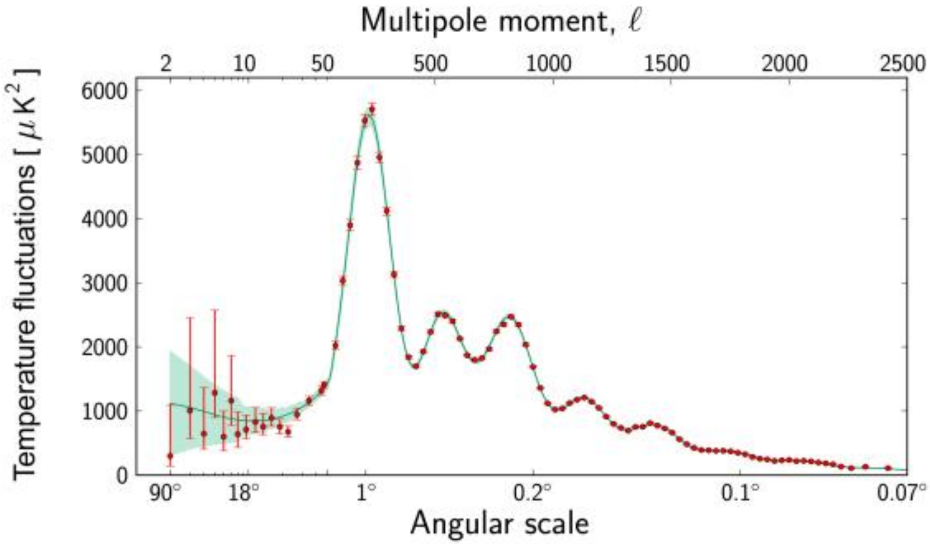


The CMB

❖ Anisotropies are the seeds of future structures





❖ In the sky, the diameter of the moon measures ~0.5º

From: ESA and Planck

At the LHC…

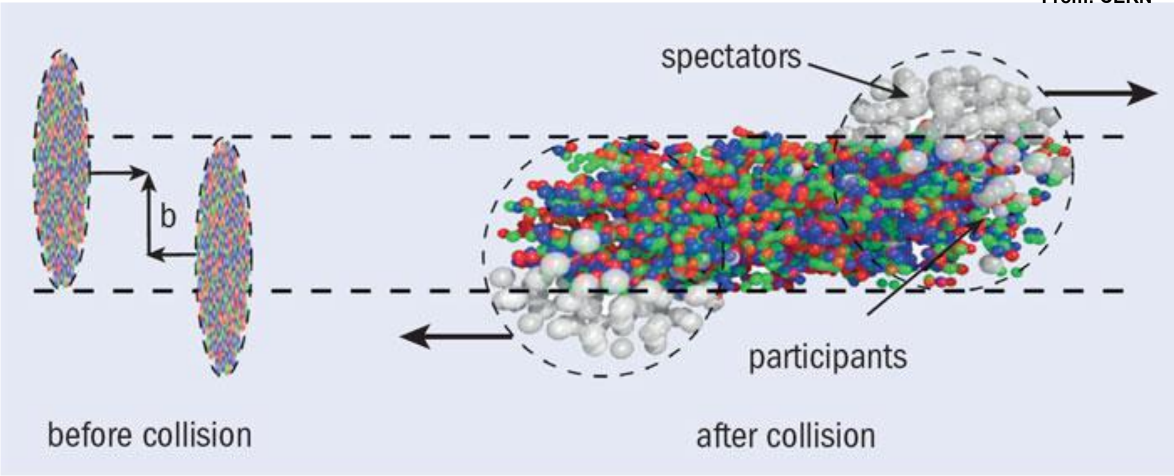
- Matter in hot and dense state
  - Explosive expansion!

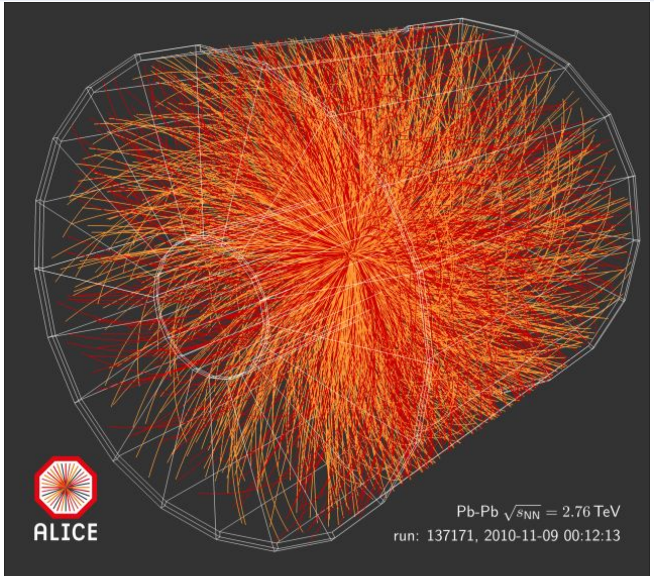
QGP!

- Early fluctuations propagate fluid dynamically→initial geometry preserved

- Decoupled hadrons accessible experimentally

From: CERN

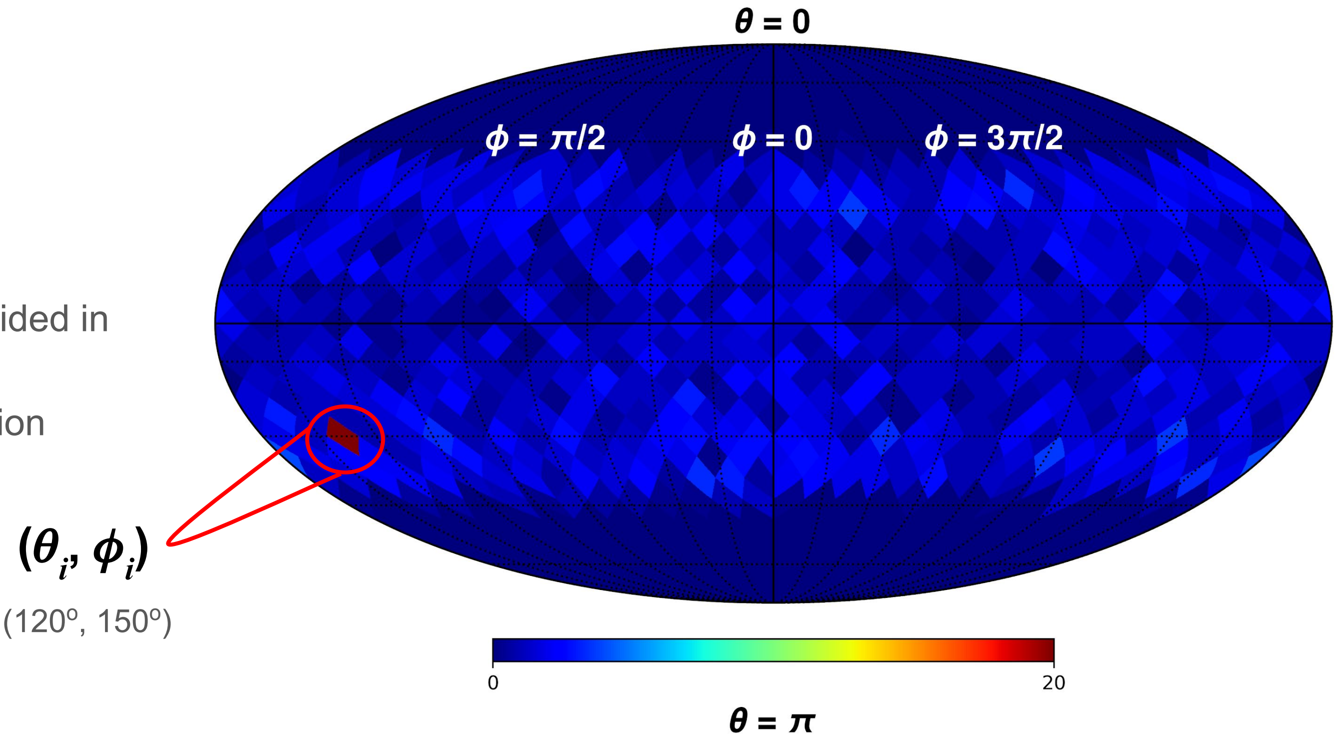




Mapping Particles

- $(\eta, \phi) \rightarrow (\theta, \phi)$

- Surface of sphere divided in pixels of equal area
  - Dep. on resolution

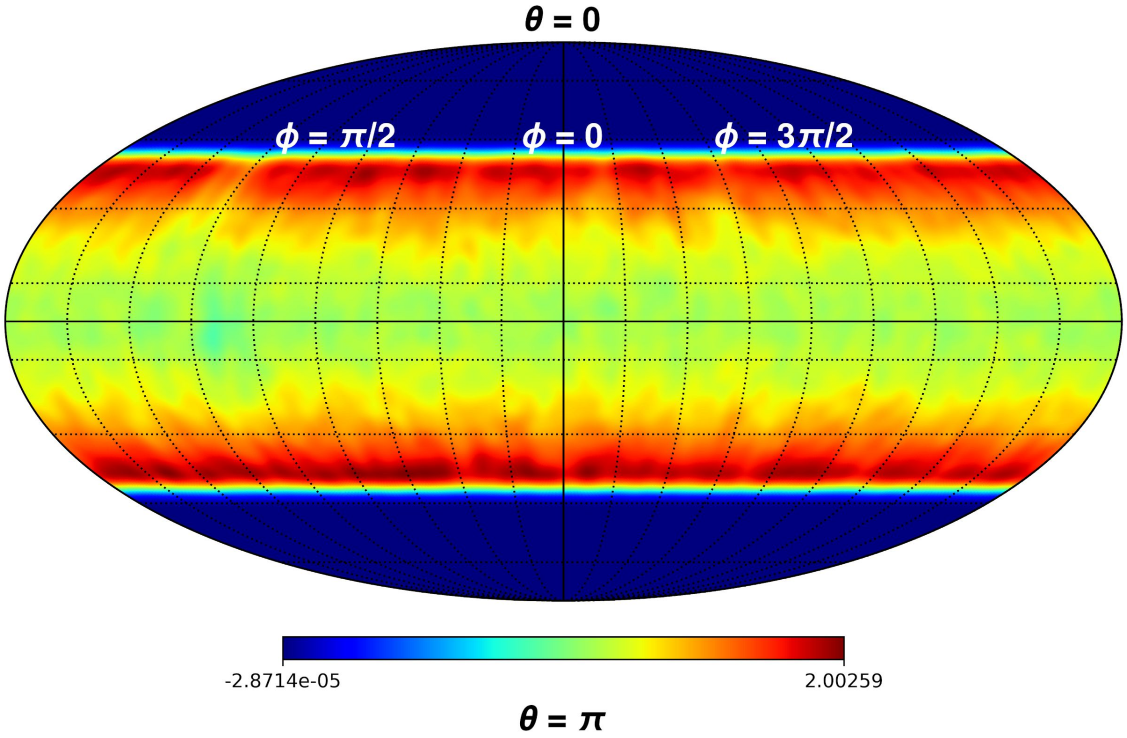


Mapping Particles

- ALICE data from *CERN Open Data portal* extracted with https://github.com/cbourjau/alice-rs

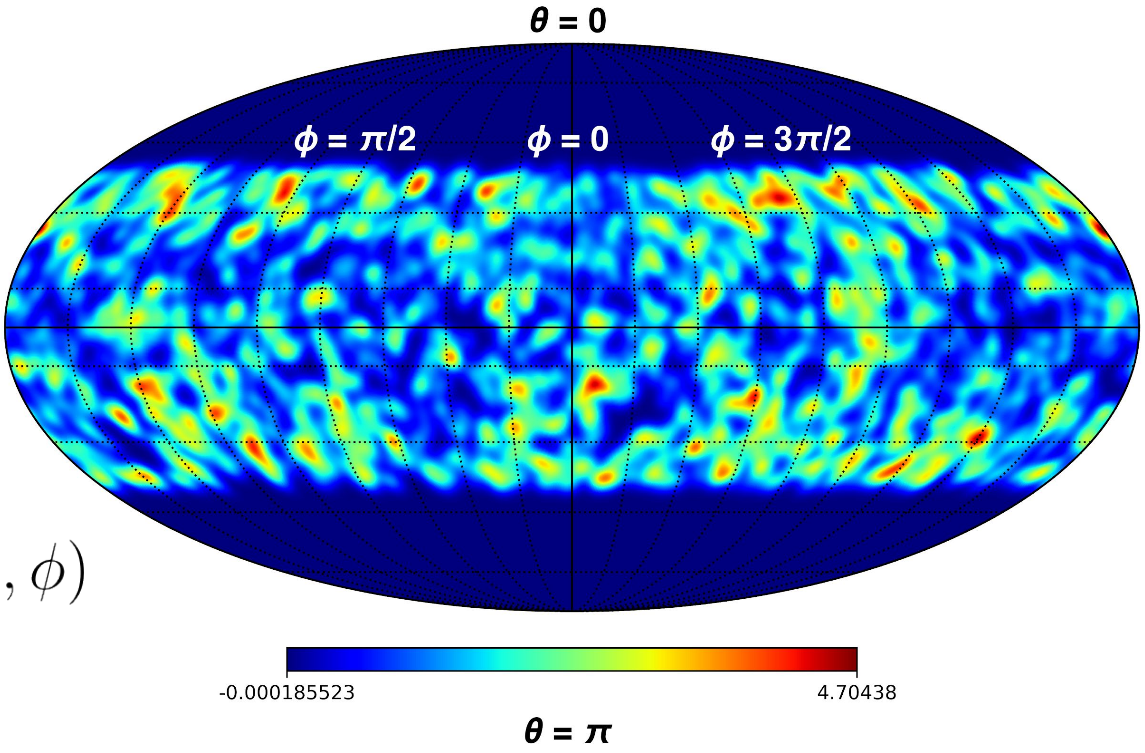
- At $\sqrt{s_{NN}}$ = ***2.76TeV*** with $|\eta| < 0.9$

- Map of all events from 0-5% centrality ⇢ artificial anisotropies



Mapping Particles

- Central event at $\sqrt{s_{NN}}$ = ***2.76TeV***
- Normalized map

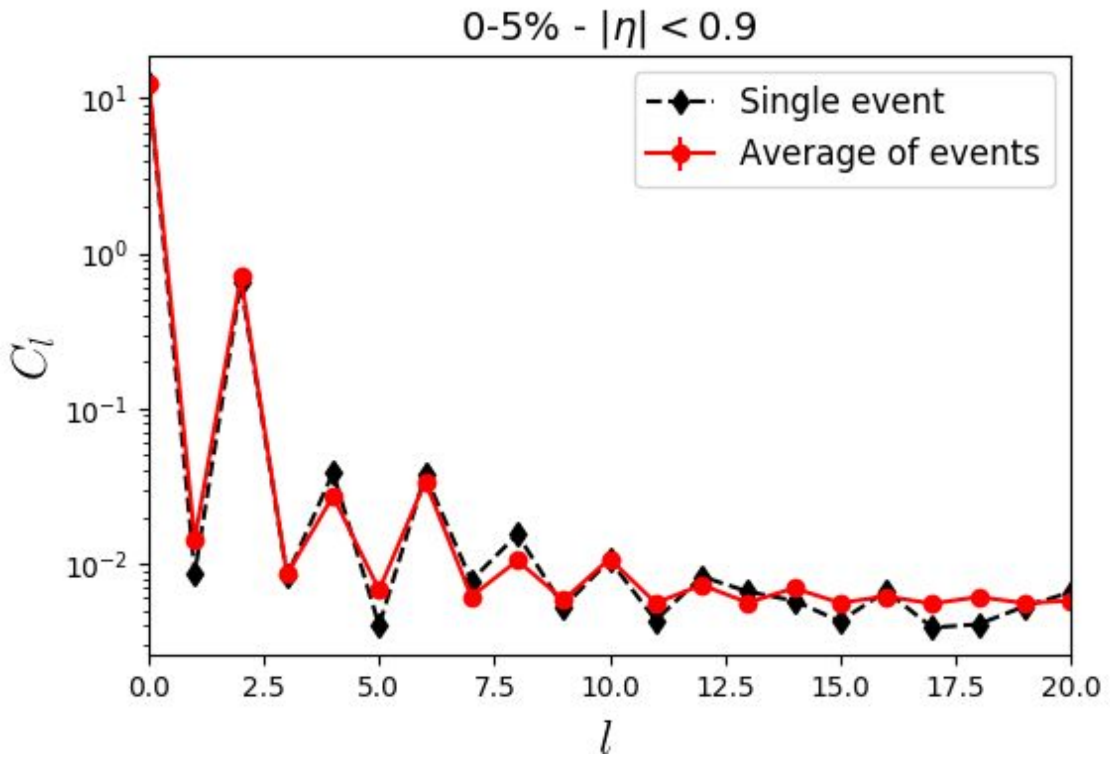


$$f(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{lm}Y_{lm}(\theta,\phi)$$

$$C_l=\frac{1}{2l+1}\sum_{m=-l}^{m=l}|a_{lm}|^2$$

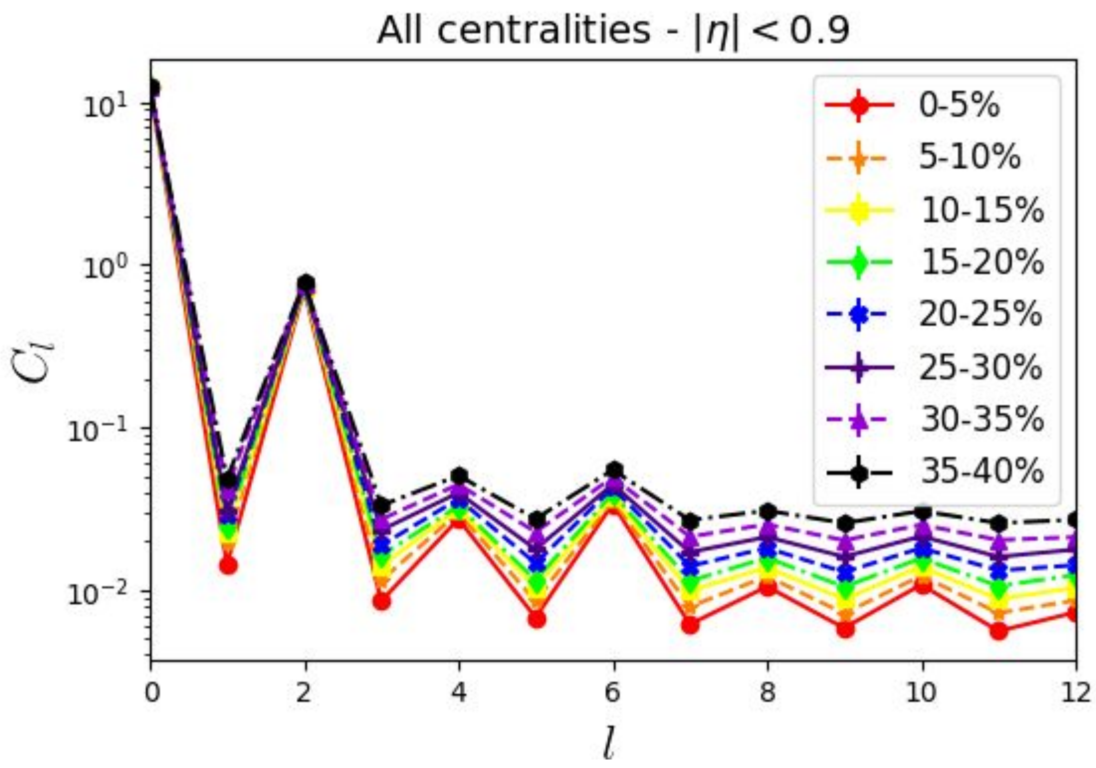
Angular Power Spectrum

- Even modes enhanced relative to odd ⇢ symmetry
- $l = 4n$, $n = 1, 2, \ldots$ modes suppressed relative to other even



Angular Power Spectrum

- Same features in each centrality
- Order of C_l for high l depends on multiplicity
- Cut effects?

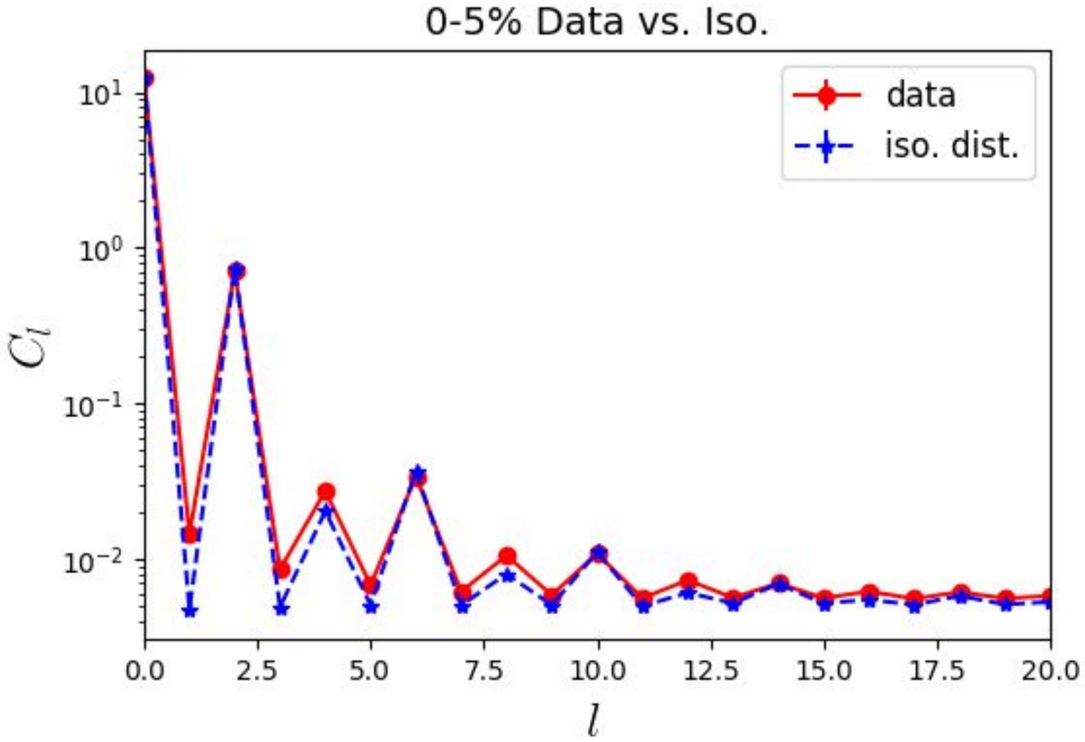


Cut effects

- Generate isotropic distributions as basis

- Apply $|\eta| < 0.9$ cut

- Compare with data ⇢ cut effects indeed!

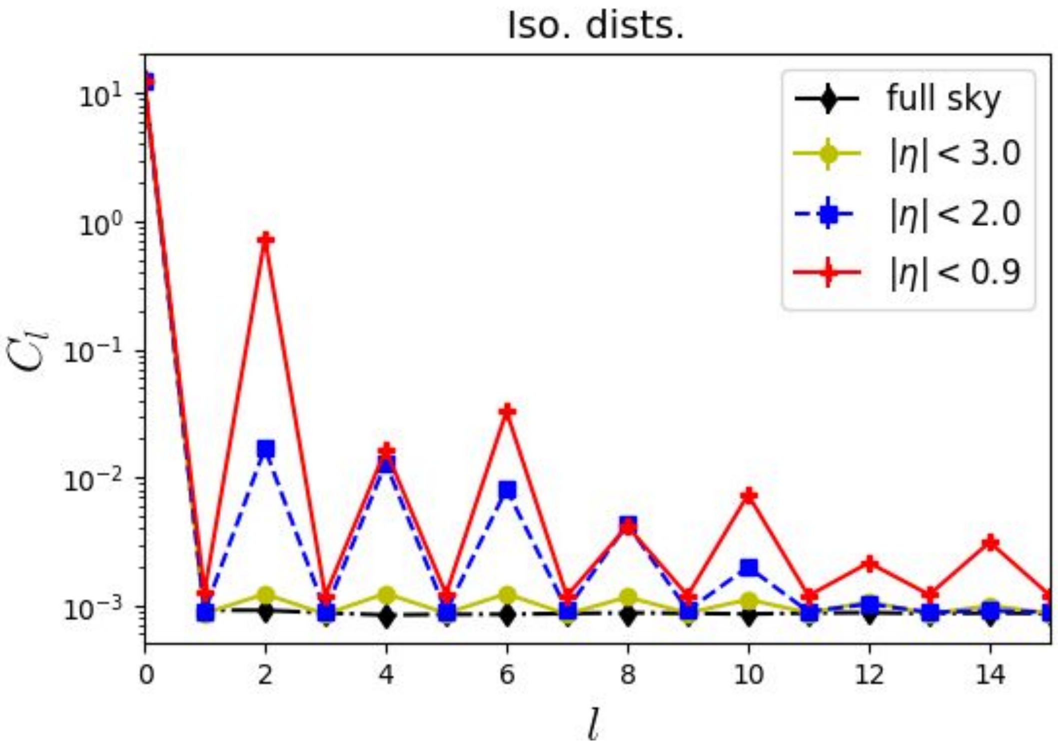


Cut effects

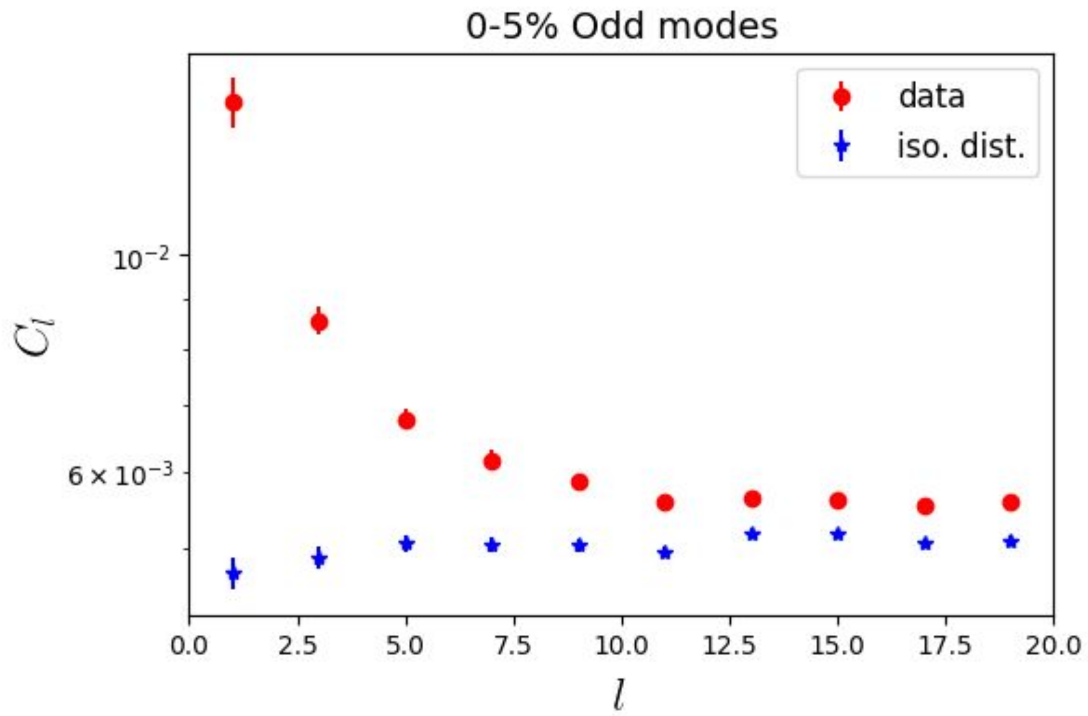
- ❖ Generate **more** isotropic distributions

- ❖ Different η ranges

...and other even modes will rise!

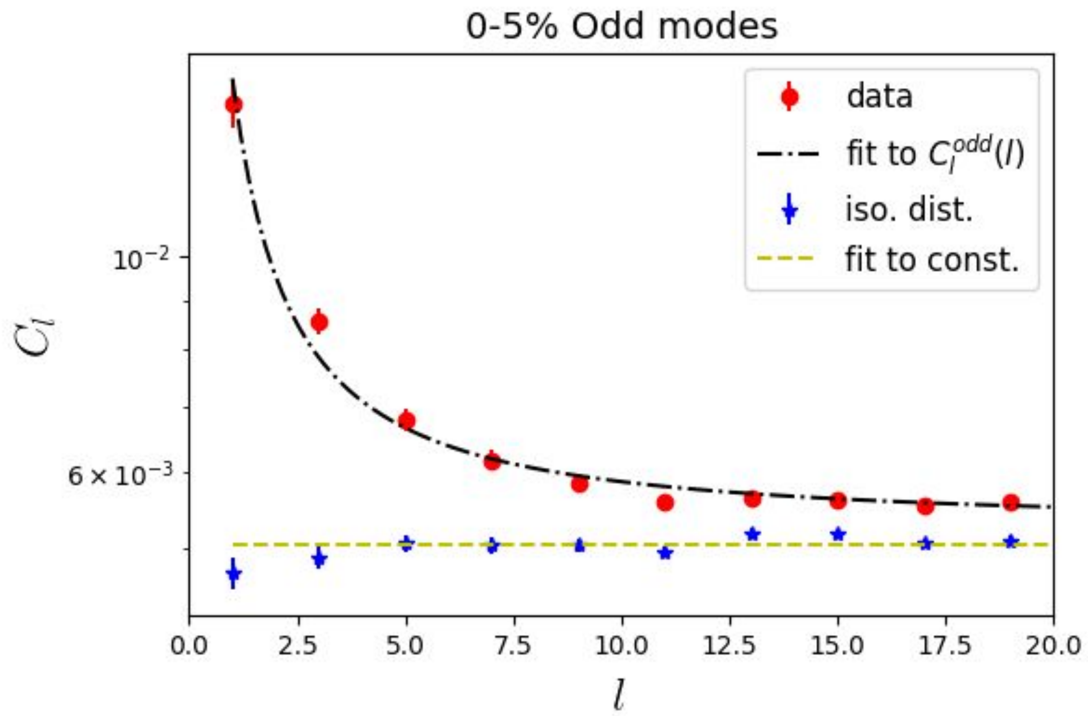


Odd modes & power law



❖ Influenced by anisotropies in ϕ

Odd modes & power law



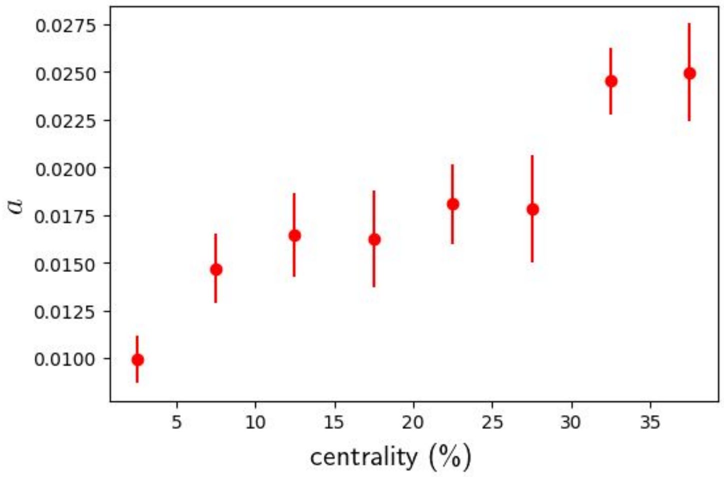
❖ Influenced by anisotropies in ϕ

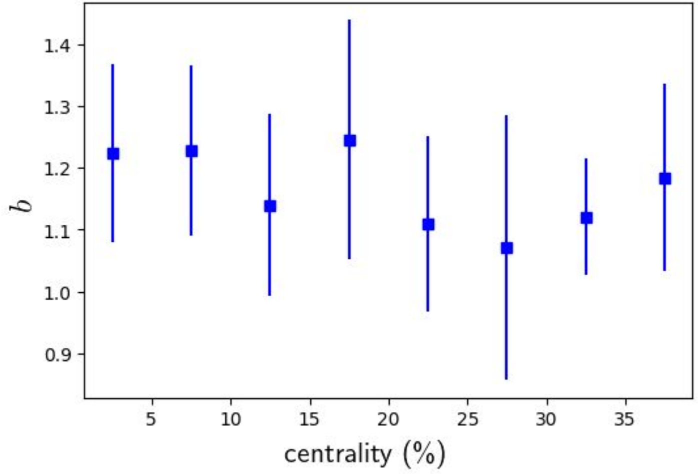
❖ Power Law behavior of odd modes

$$C_l^{odd} = a \cdot l^{-b} + c$$

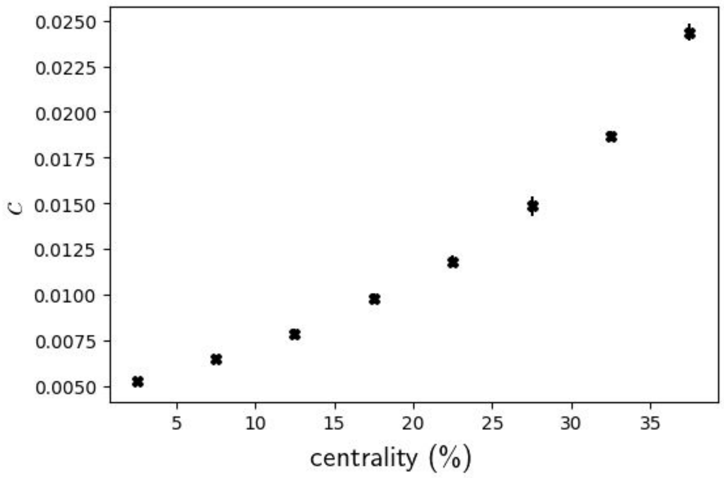
Odd modes & power law

- Power law fit to odd modes for other centralities





- Proportionate scaling of each other?



$$C_l = a \cdot l^{-b} + c$$

If even modes become enhanced with the cut, how do event anisotropies contribute to them?

Only $m \neq 0$

$$a_{lm} = \int d\Omega f(\theta,\phi) Y^*_{lm}(\theta,\phi)$$

$$Y_{lm}(\theta,\phi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_{lm}(\cos(\theta)) e^{im\phi}$$

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{m=l} |a_{lm}|^2$$

Only $m \neq 0$

$$a_{lm} = \int d\Omega \cancel{f(\theta, \phi)} Y^*_{lm}(\theta, \phi)$$

Map

$$Y_{lm}(\theta, \phi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_{lm}(\cos(\theta)) e^{im\phi}$$

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$m = 0$

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$m = 0$

$$C_l^{m \neq 0} = \frac{1}{2l+1}\left(\sum_{m=-l}^{m=l} |a_{lm}|^2 - |a_{l0}|^2\right)$$

Only $m \neq 0$

$$a_{lm} = \int d\Omega \, \cancel{f(\theta, \phi)} Y^*_{lm}(\theta, \phi)$$

Map

$$Y_{lm}(\theta, \phi) = \sqrt{\frac{2l+1}{4\pi} \frac{(l-m)!}{(l+m)!}} P_{lm}(\cos(\theta)) \cancel{\boxed{e^{im\phi}}}$$

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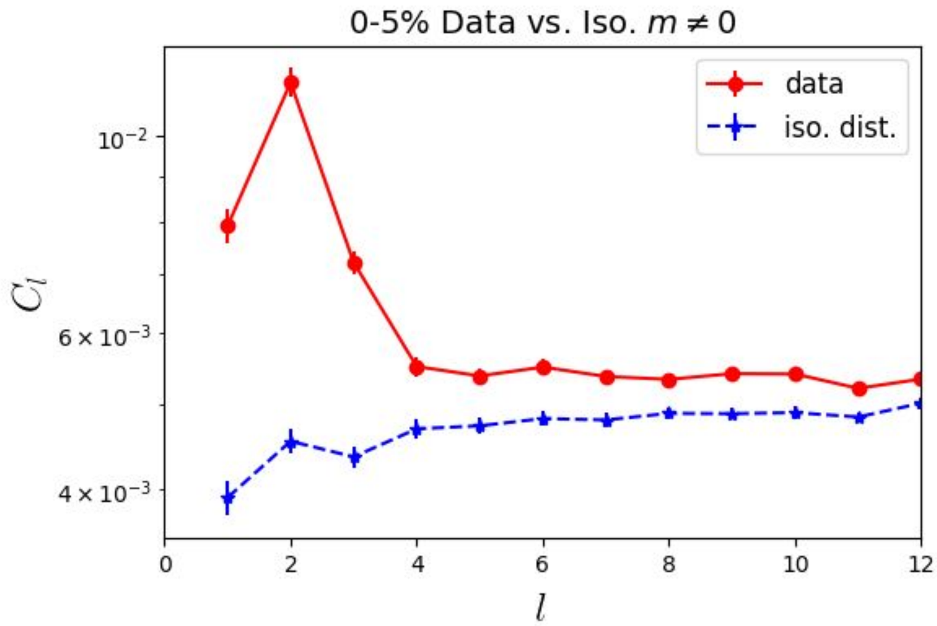
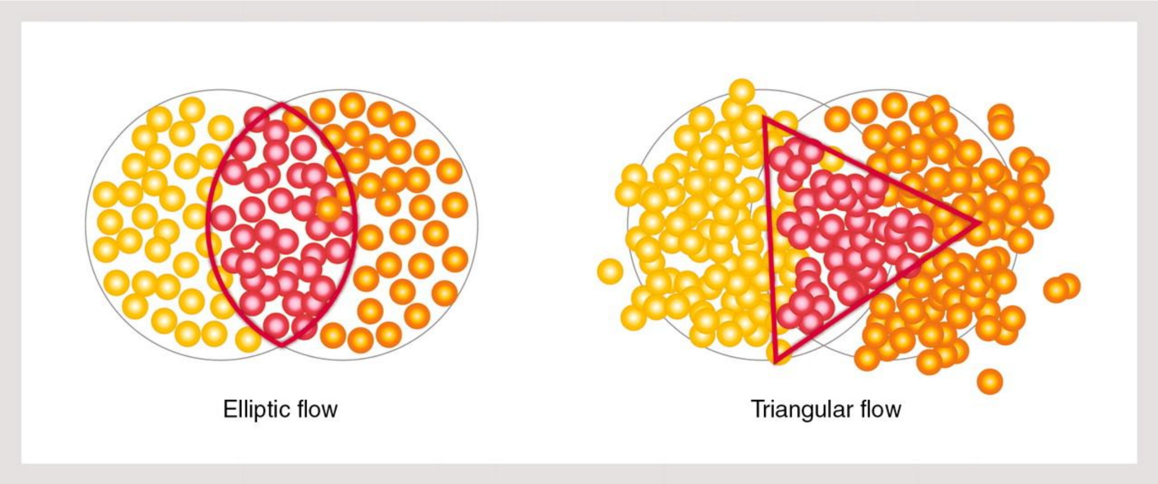


From: American Physical Society

Flow extraction



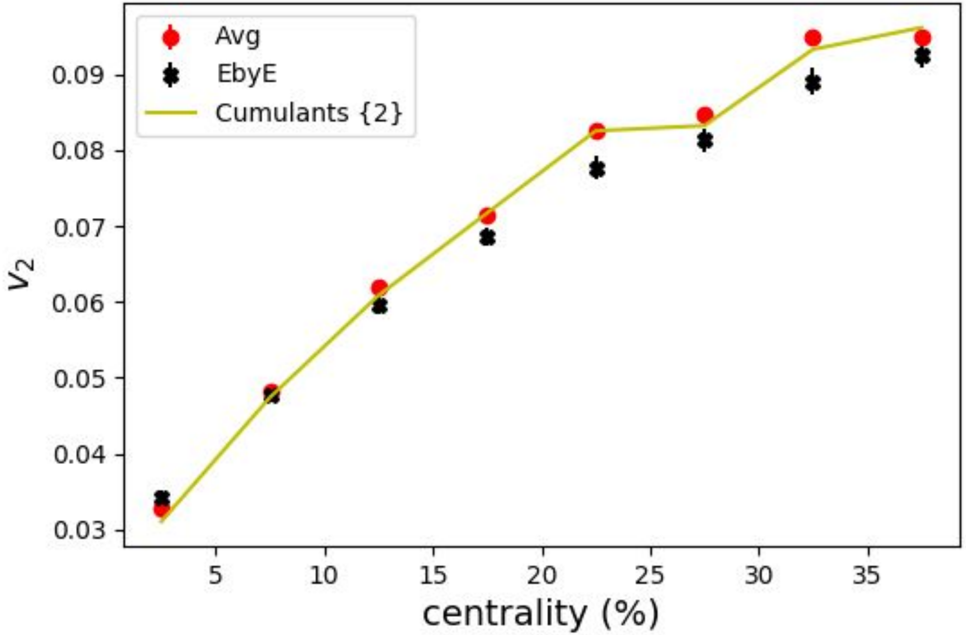
- Geometry of initial overlapping region in final distribution

- Particle distribution in the azimuthal direction

$$f(\phi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \psi_n))\right]$$

Flow extraction

$$|v_2|^2 = \frac{5}{2} \cdot \frac{C_2^{m\neq 0} - C_1^{m\neq 0[iso]}}{|a_{22}|^2} \cdot \frac{|a_{00}|^2}{C_0}$$



- Two ways:
  - Event-by-event (EbyE)
  - Direct from averaged $C_l^{m\neq 0}$(Avg)

- Comparison with flow estimation from 2nd order cumulant **[arXiv:1010.0233v2]**

Flow extraction

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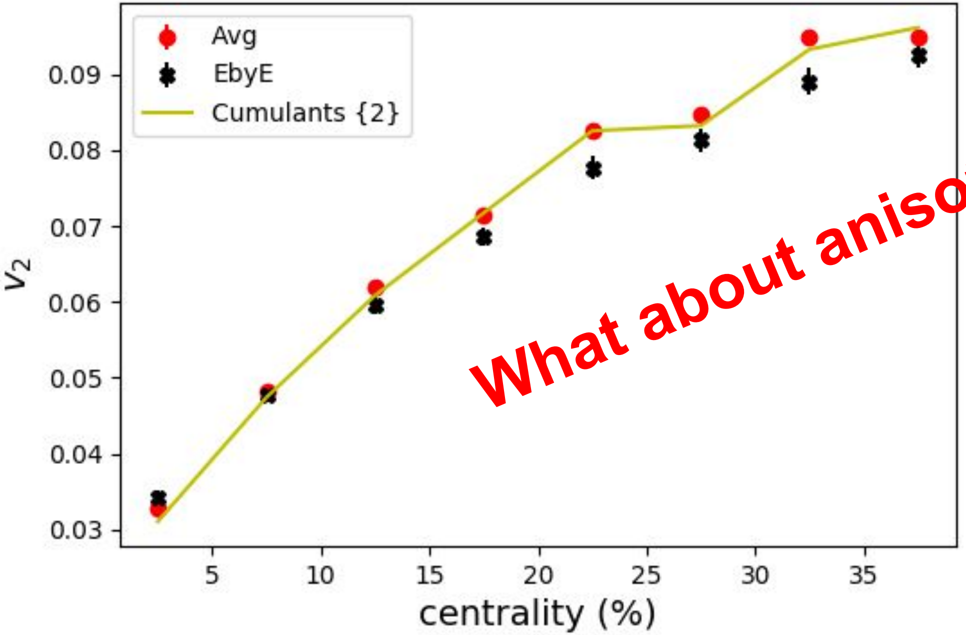

What about anisotropies in θ?

- ❖ Two ways:
  - ➢ Event-by-event (EbyE)
  - ➢ Direct from averaged $C_l^{m\neq0}$ (Avg)

- ❖ Comparison with flow estimation from 2nd order cumulant **[arXiv:1010.0233v2]**

Summary

- Anisotropies of early Universe formed the galaxies, planets, us and everything else
- Many Little Bangs vs. one Big Bang
- Search for anisotropies in heavy-ions through mapping of emitted particles
  - Angular Power Spectrum!
    - Interesting when taking $m \neq 0$!
- Extraction of elliptic flow through power spectrum
- Why the power law?
- Monte Carlo transport models could shed light to power spectrum behavior
- Longitudinal dependency? Restrict parameters of 3D+1 models?
- Still more to explore...

References

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- Emitted particles: http://cms.web.cern.ch/news/new-cms-results-heavy-ion-collisions
- Flow: http://science.sciencemag.org/content/337/6092/310.full?rss=1
- QGP plush: https://www.particlezoo.net/products/quark-gluon-plasma
- Data: http://opendata.cern.ch/search?page=1&size=20&experiment=ALICE
  https://github.com/cbourjau/alice-rs