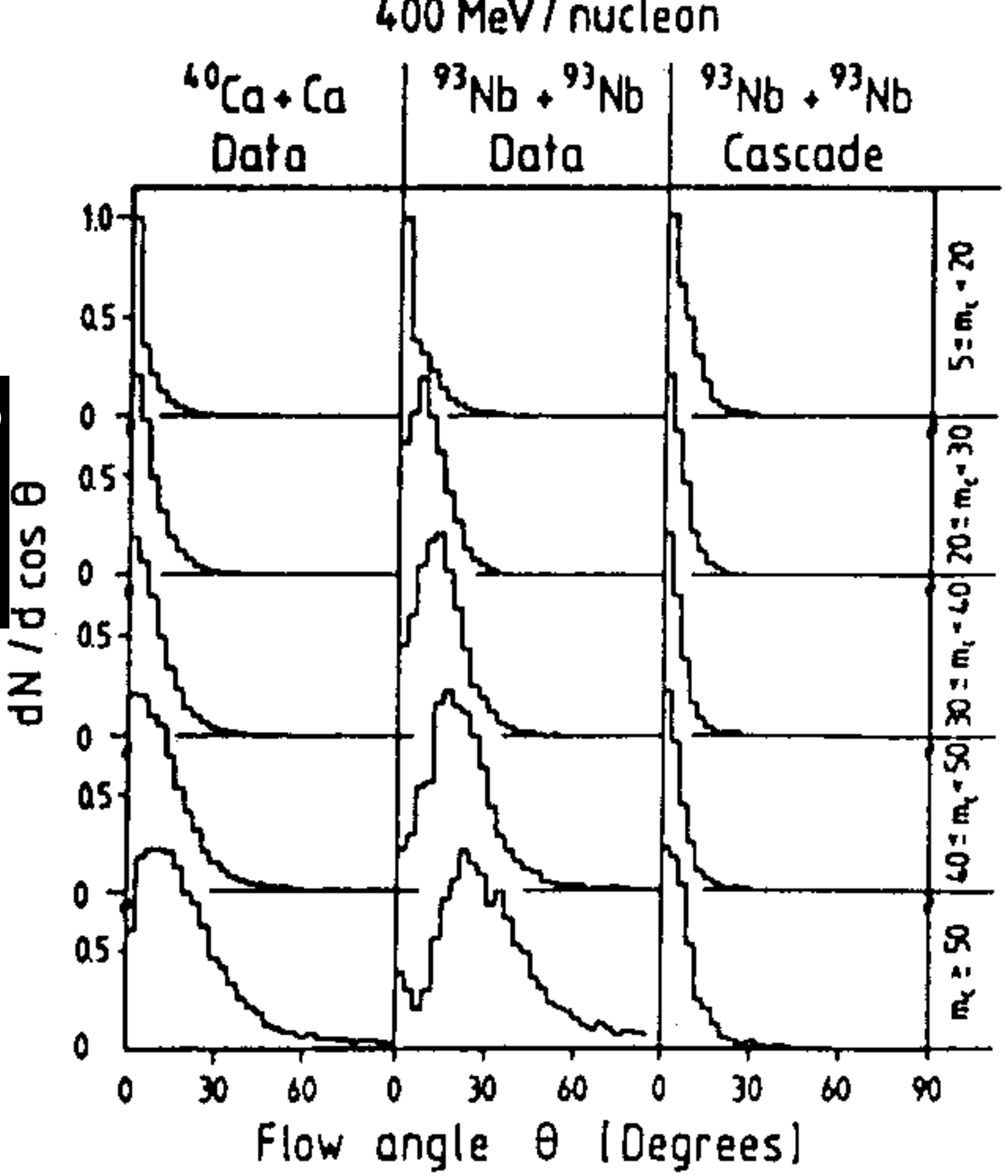
Collective flows and Sounds of the Little and Big Bangs

(presented at LBL Art Poskanzer memorial meeting,
Dec.10 2022)

Edward Shuryak, Center for Nuclear Theory, Stony Brook

Pioneering BEVALAC experiments
plastic Ball 1980’s
aimed at collective flow

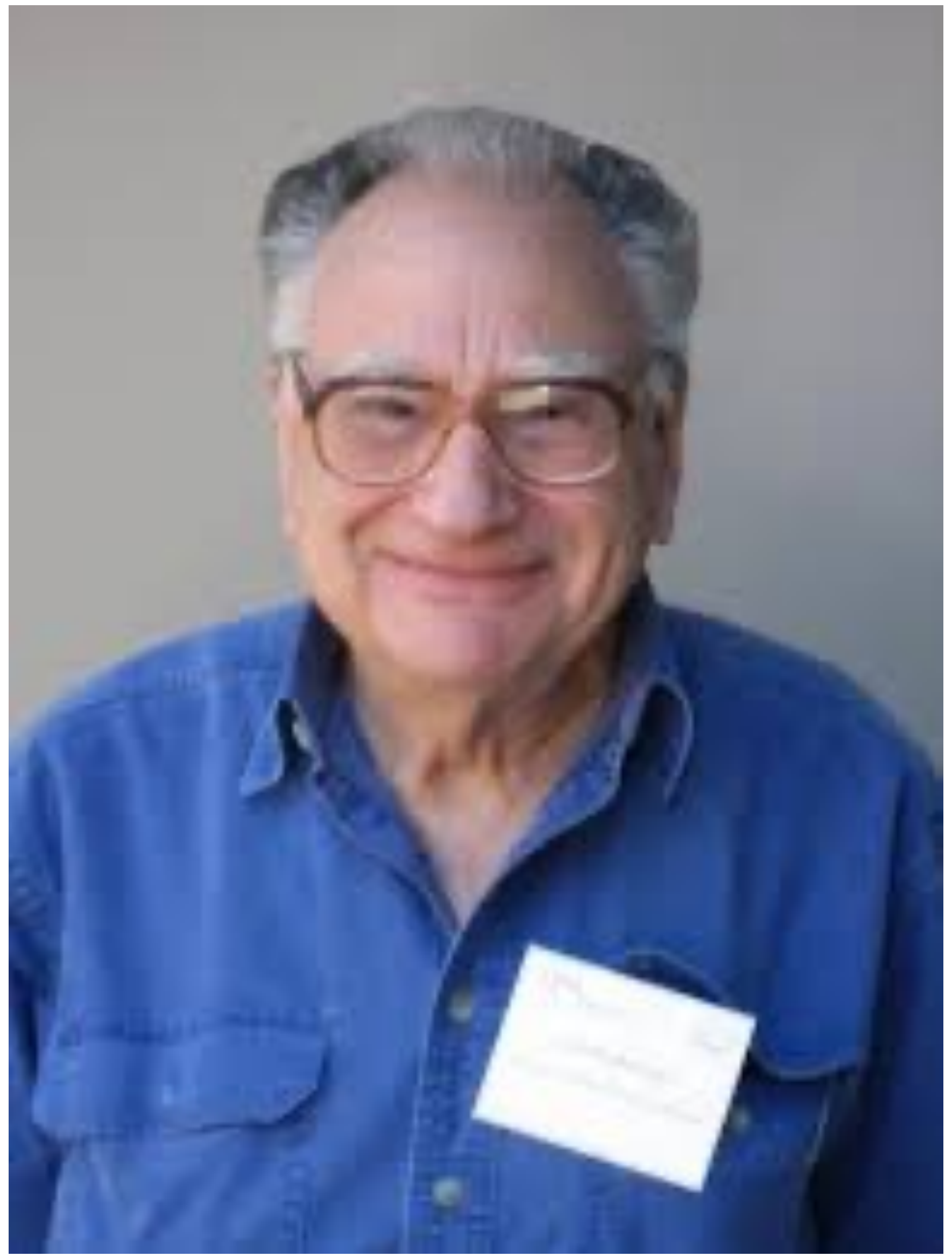
“A striking difference between Ca and Nb
the distribution of the flow angles
for the Ca data is peaked at 0 deg.
For Nb there is a finite deflection angle”



Invited paper presented at the 5th Adriatic International Conference on Nuclear Physics, Hvar, Yugoslavia, September 24-29, 1984

COMPRESSION AND EXPANSION AT THE BEVALAC

A.M. Poskanzer, K.G.R. Doss, H.-A. Gustafsson, H.H. Gutbrod, B. Kolb, H. Löhner, B. Ludewigt, T. Renner, H. Riedesel, H.G. Ritter, A. Warwick, and H. Wieman



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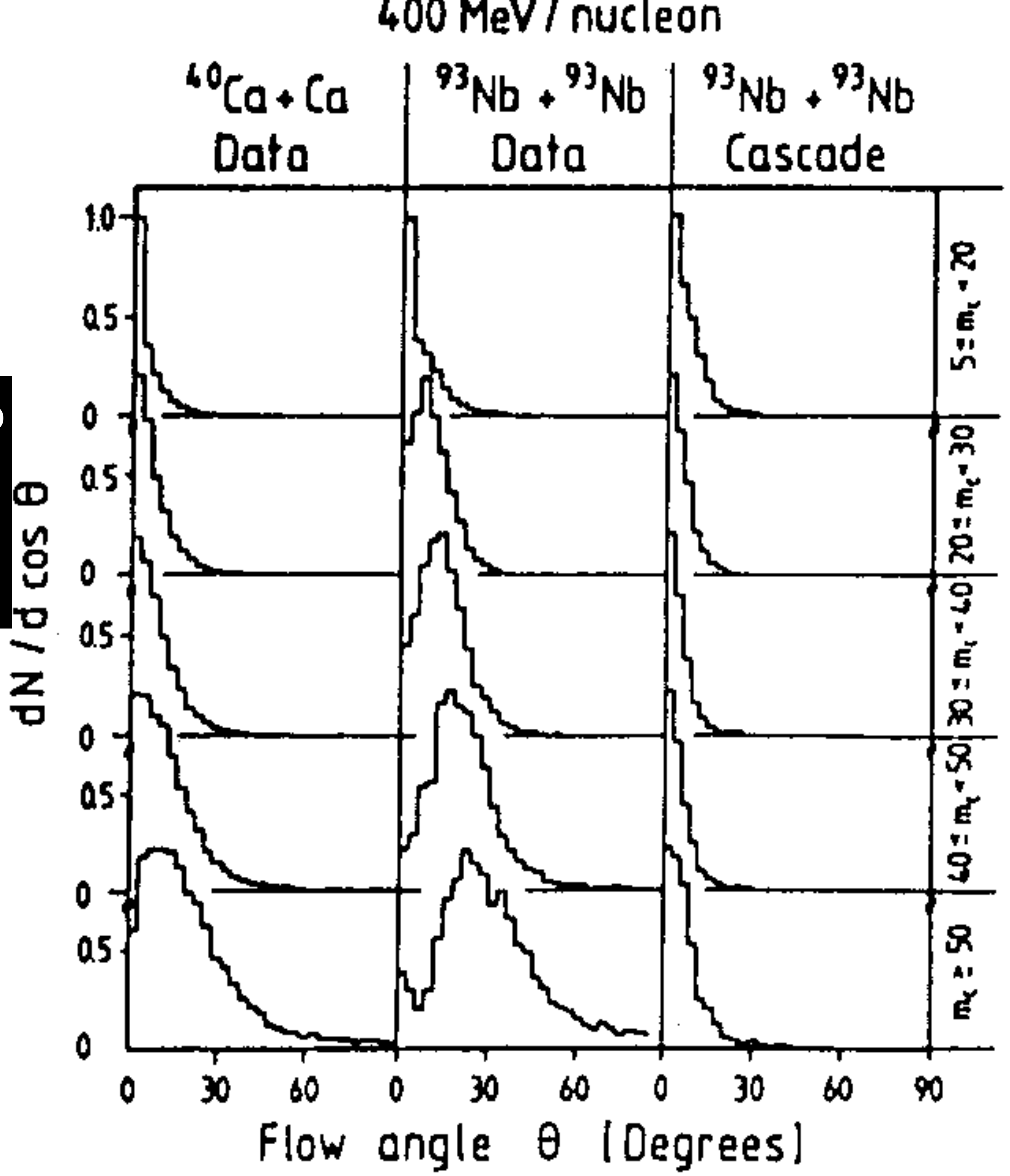

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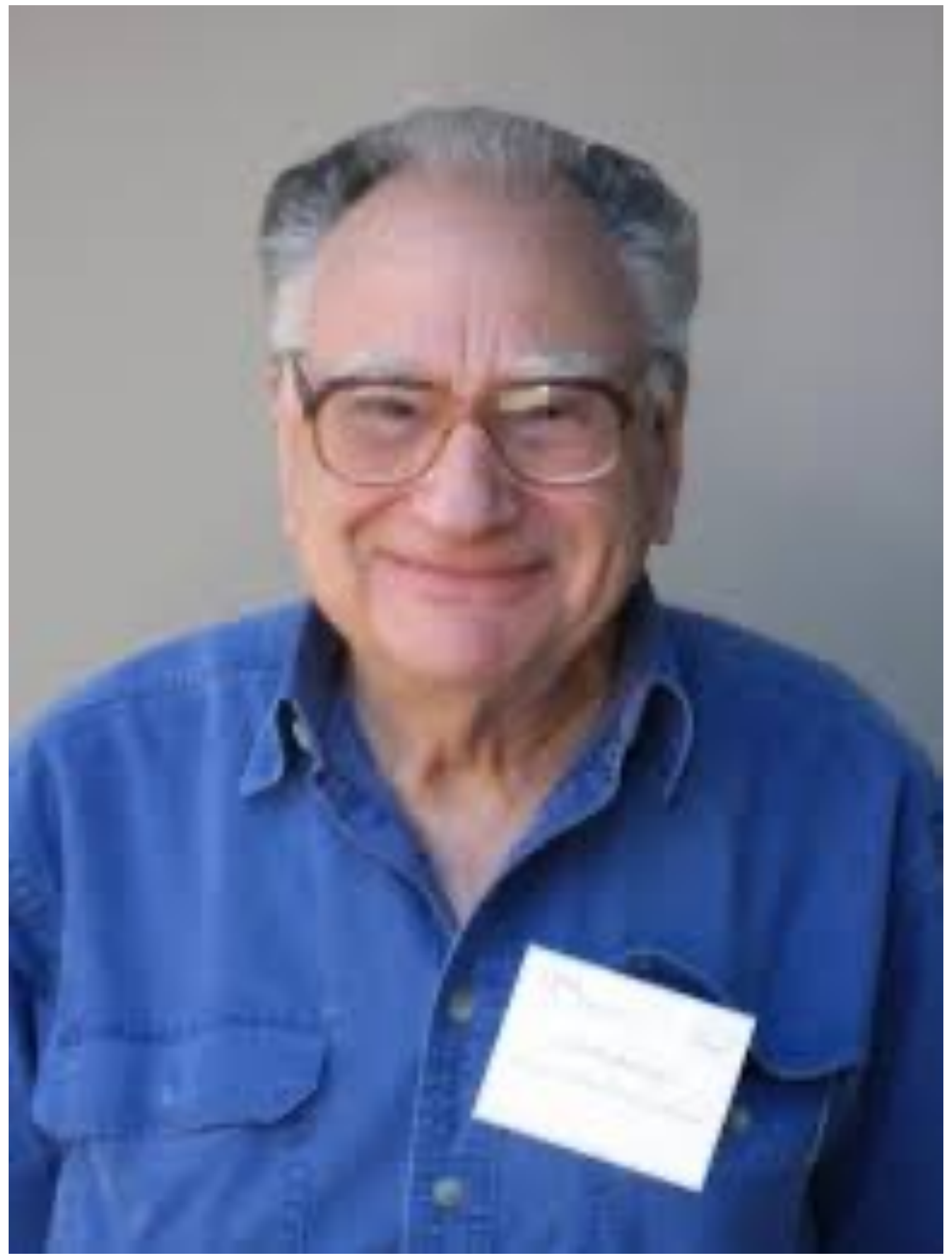

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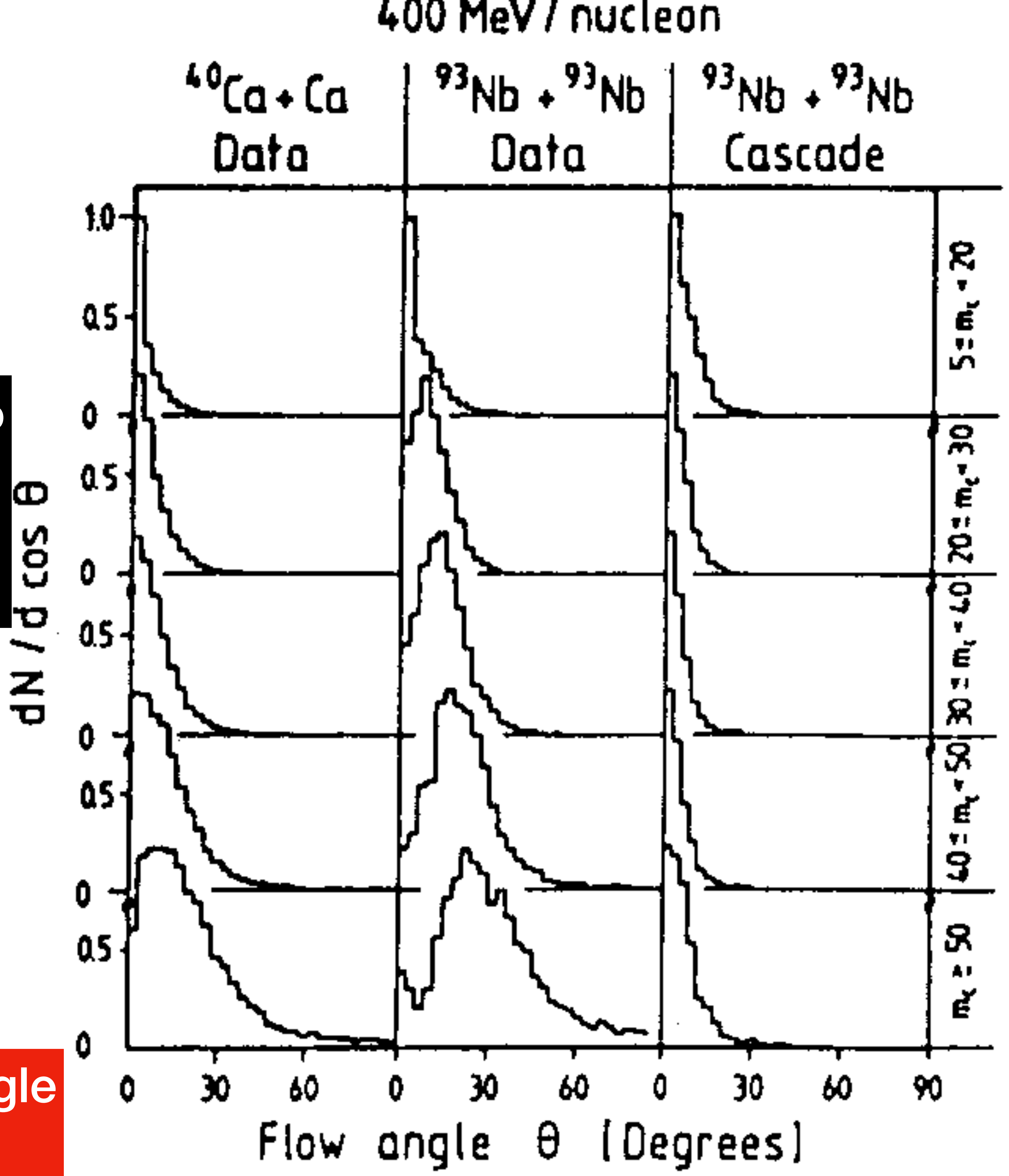
"a new collective phenomenon definitely appears in the larger-mass system which is not accounted for by the present cascade models."

" hydrodynamical prediction of the flow angle seems to be qualitatively in agreement with the measurement



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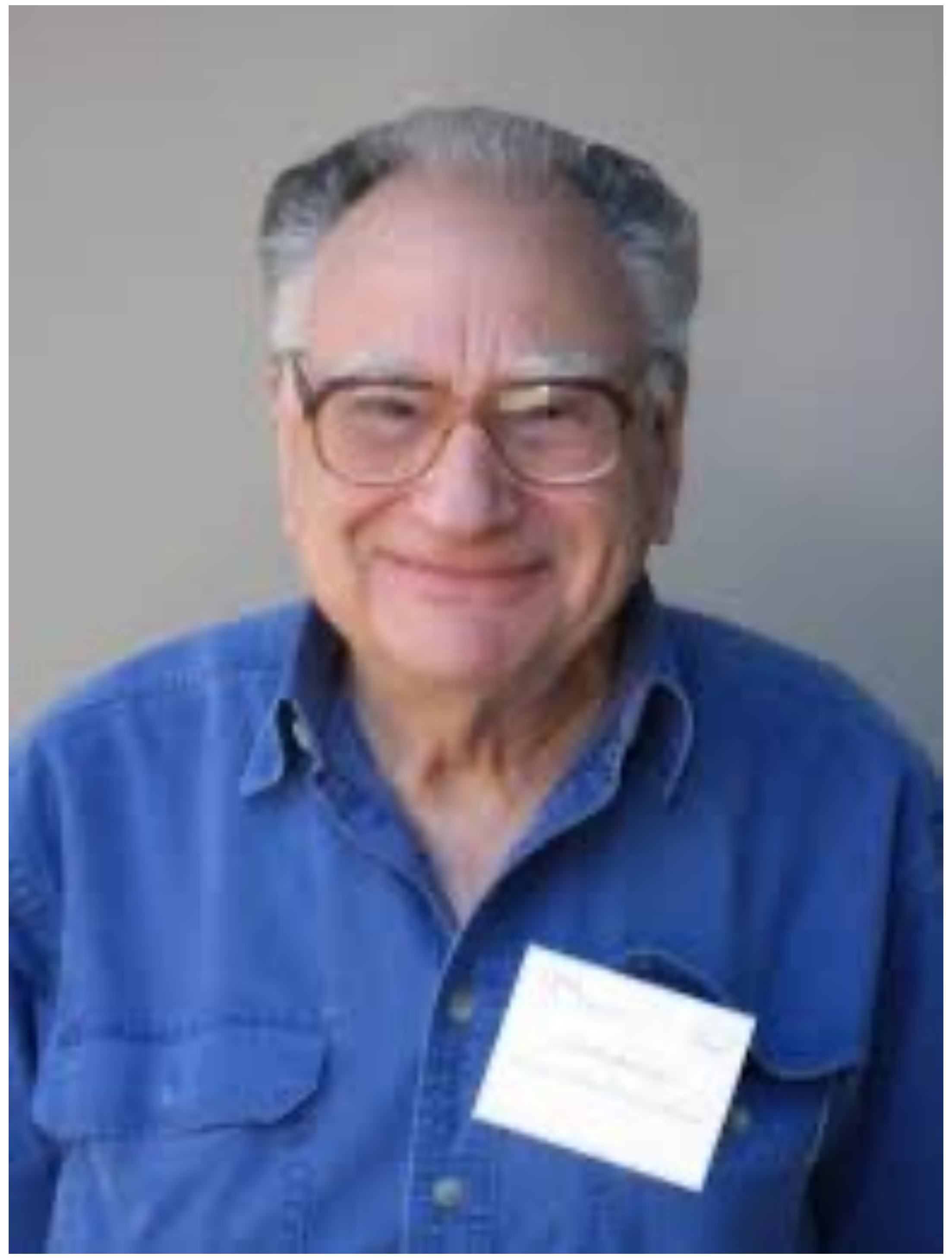
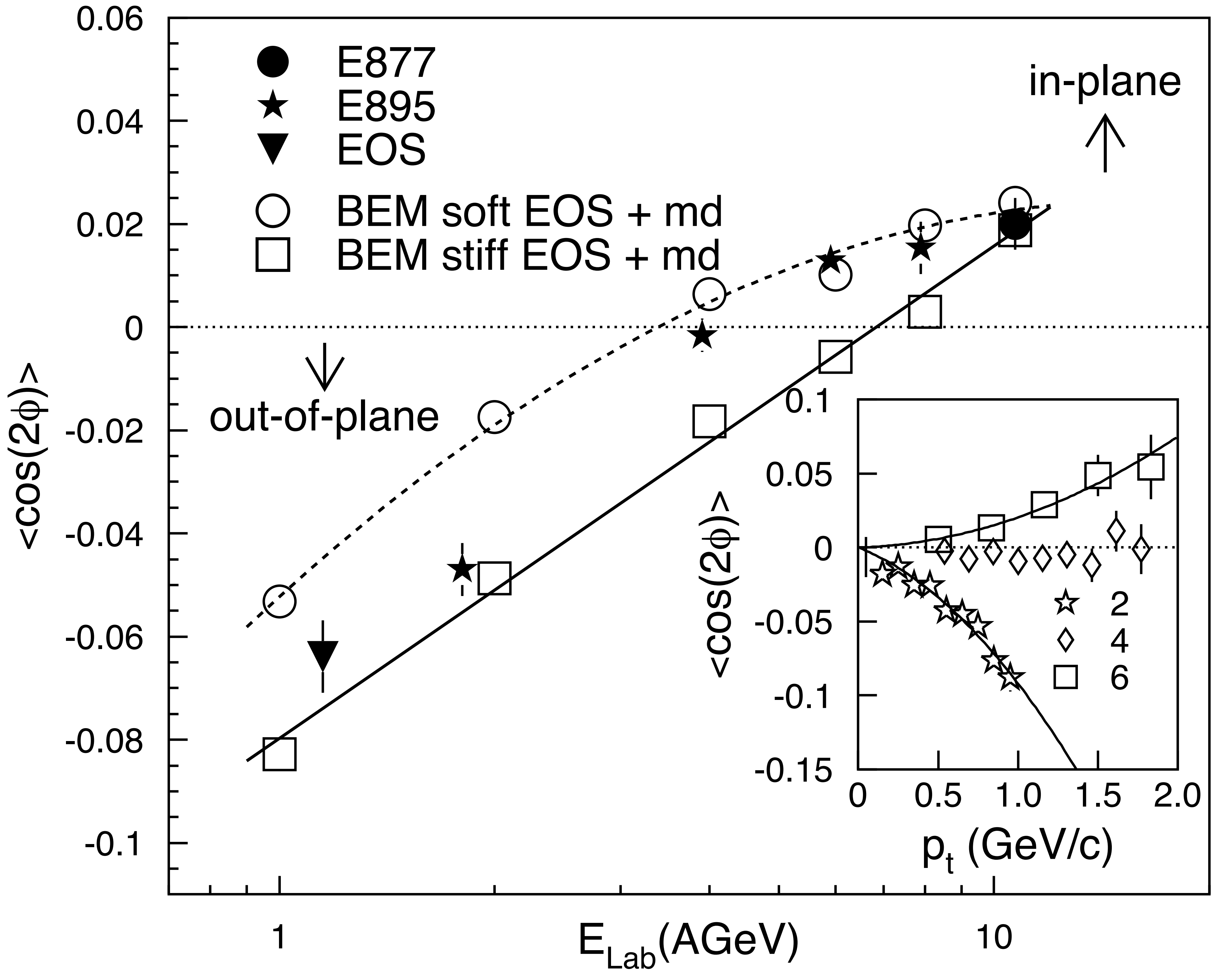


negative v2 is due to shadowing by spectator matter

At AGS/SPS the elliptic flow changes sign!
it grows with p_t and yet it remains small



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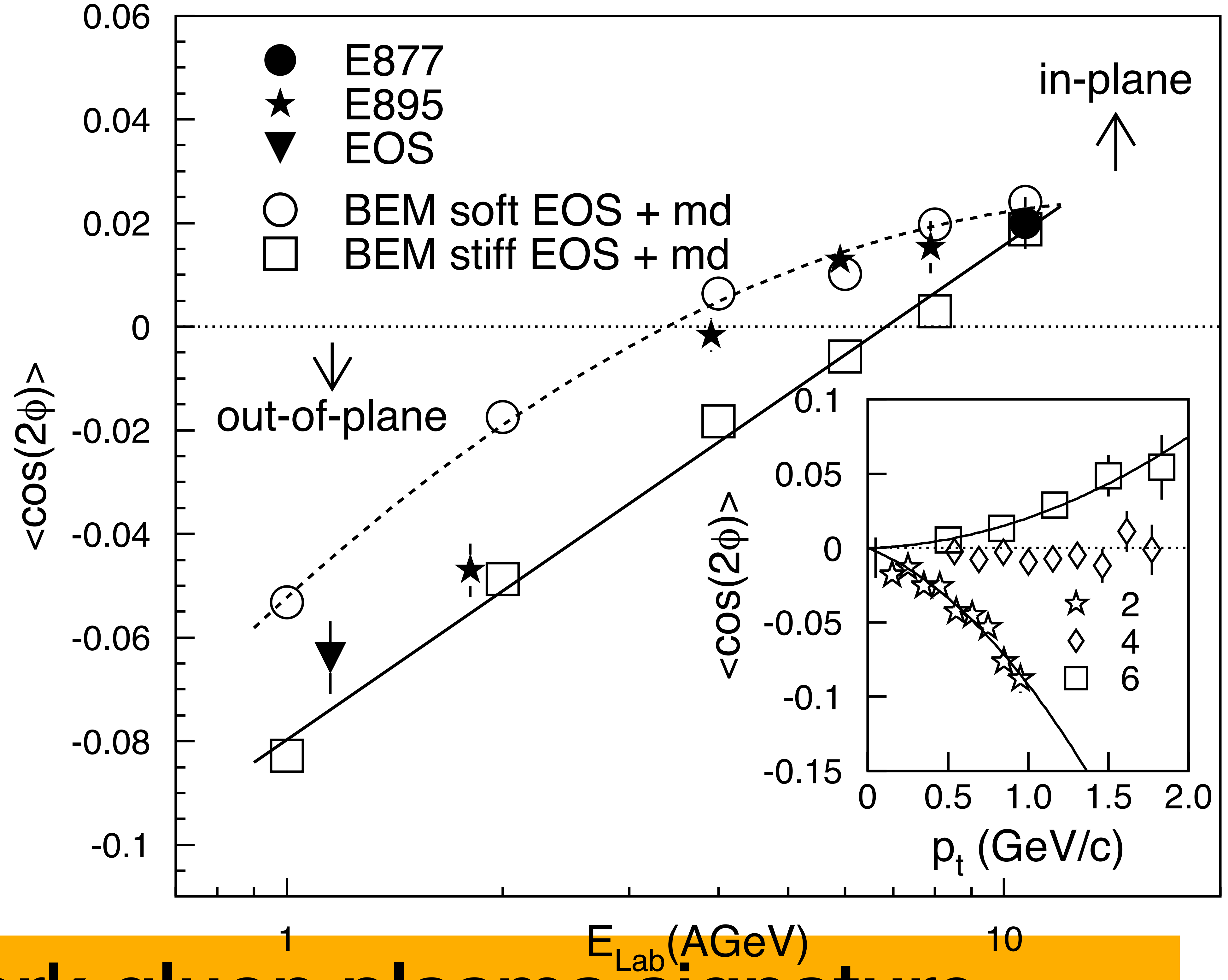
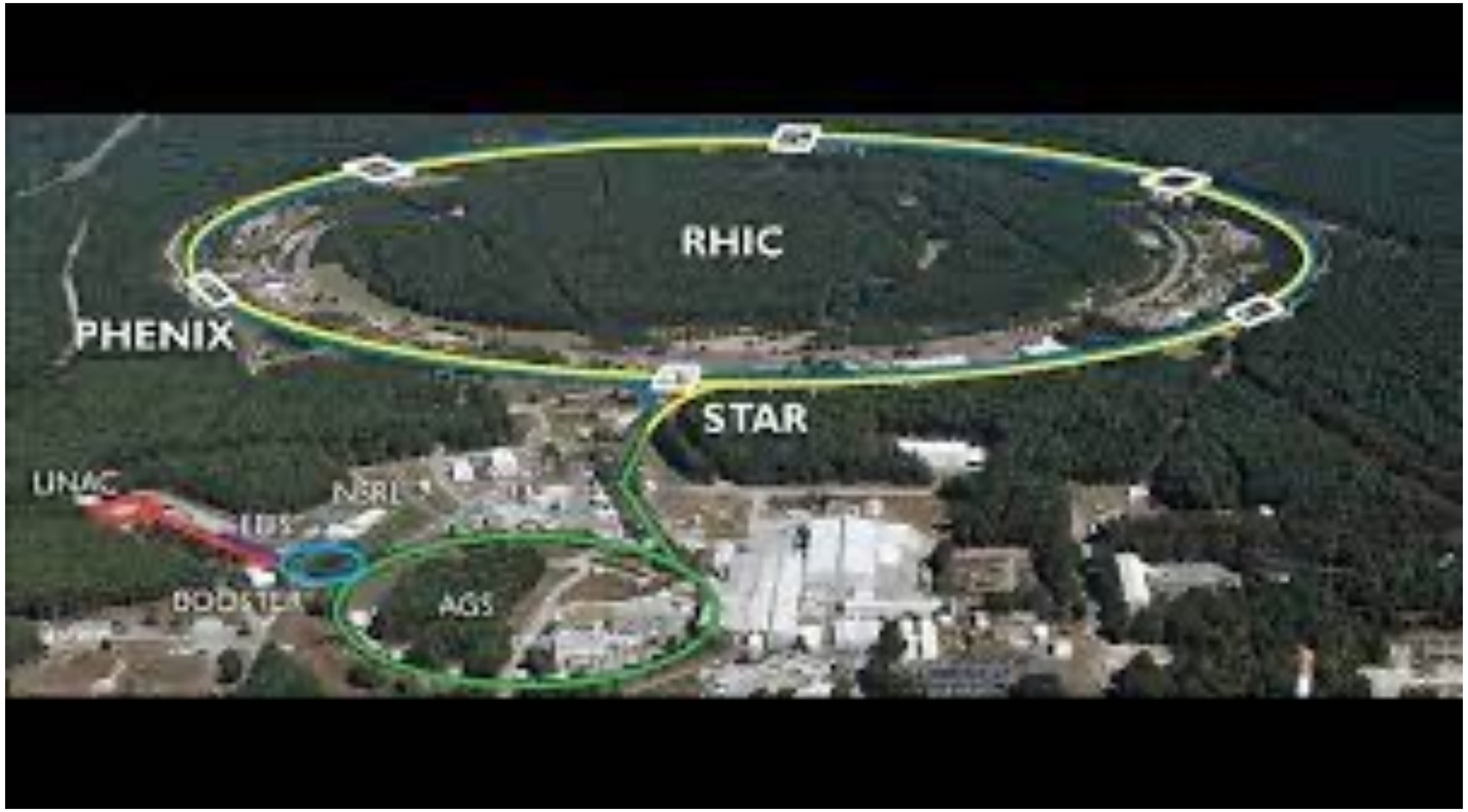


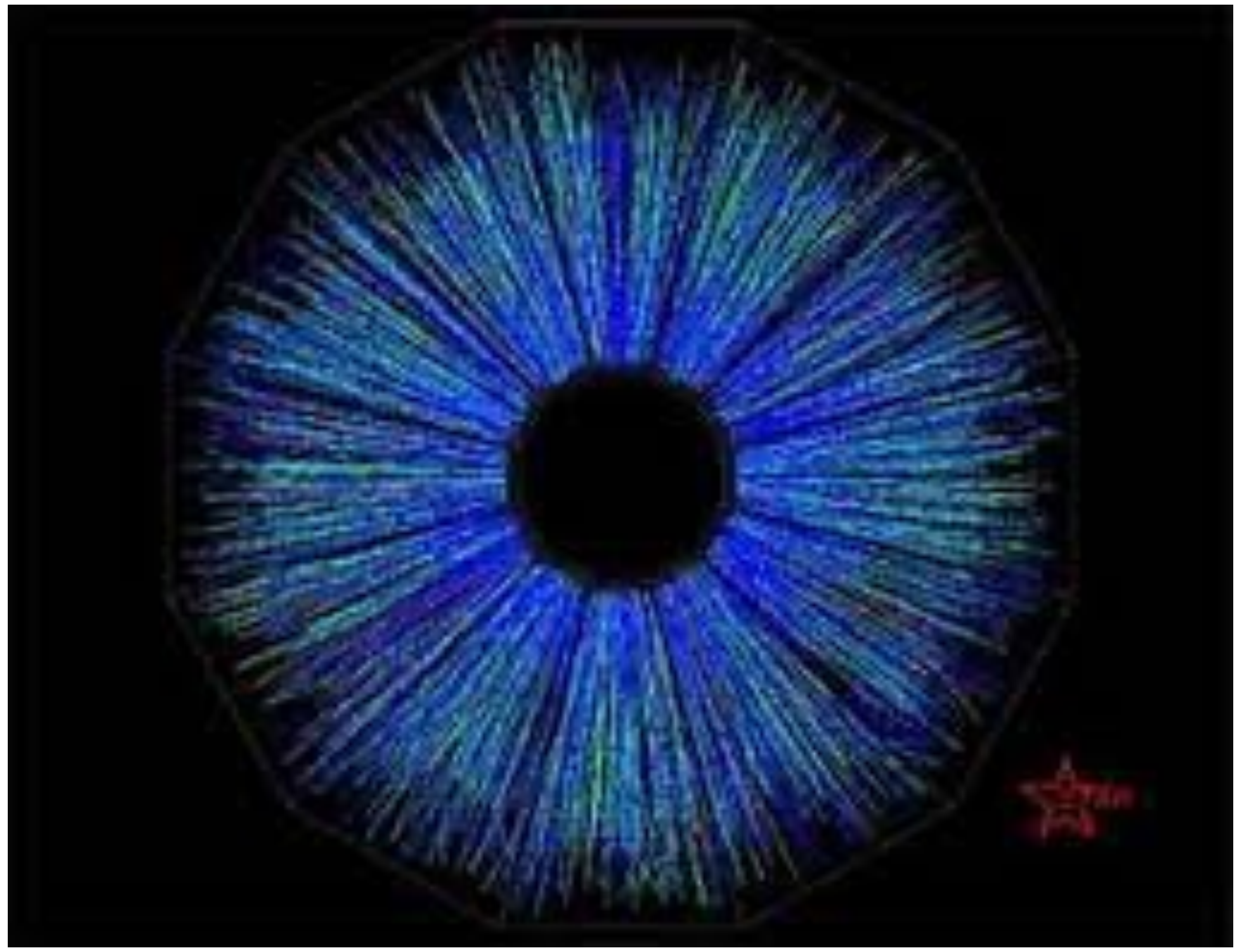
Flow at the SPS and RHIC as a quark gluon plasma signature

D. Teaney, J. Lauret, Edward V. Shuryak (Nov, 2000)

Phys.Rev.Lett. 86 (2001) 4783-4786 • e-Print: nucl-th/0011058

contrary to predictions of cascades (RQMD,URQMD)
elliptic flow at RHIC should be much stronger
because matter is not hadronic but QGP !


RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

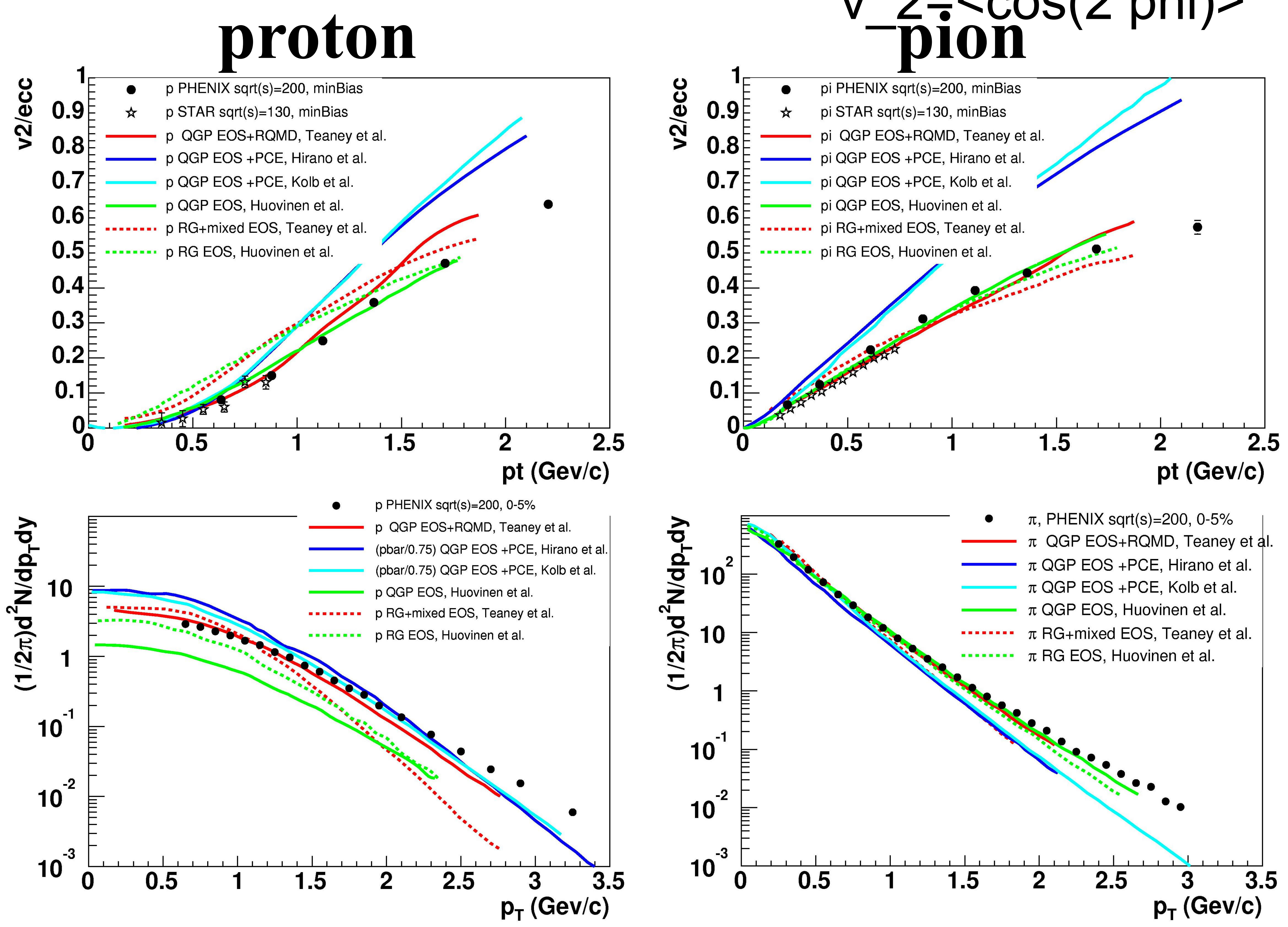


2001-2005: hydro describes radial and elliptic flows for all secondaries , pt<2GeV, centralities, rapidities, A (Cu,Au)…

Experimentalists were very sceptical but were convinced and ``near-perfect liquid” is now official,

=>AIP declared this to be discovery #1 of 2005 in physics

v_2=<cos(2 phi)>



PHENIX,

Nucl-ex/0410003

red lines are for ES +Lauret+Teaney done before RHIC data, never changed or fitted, describes SPS data as well! It does so because of the correct hadronic matter /freezout via (RQMD)

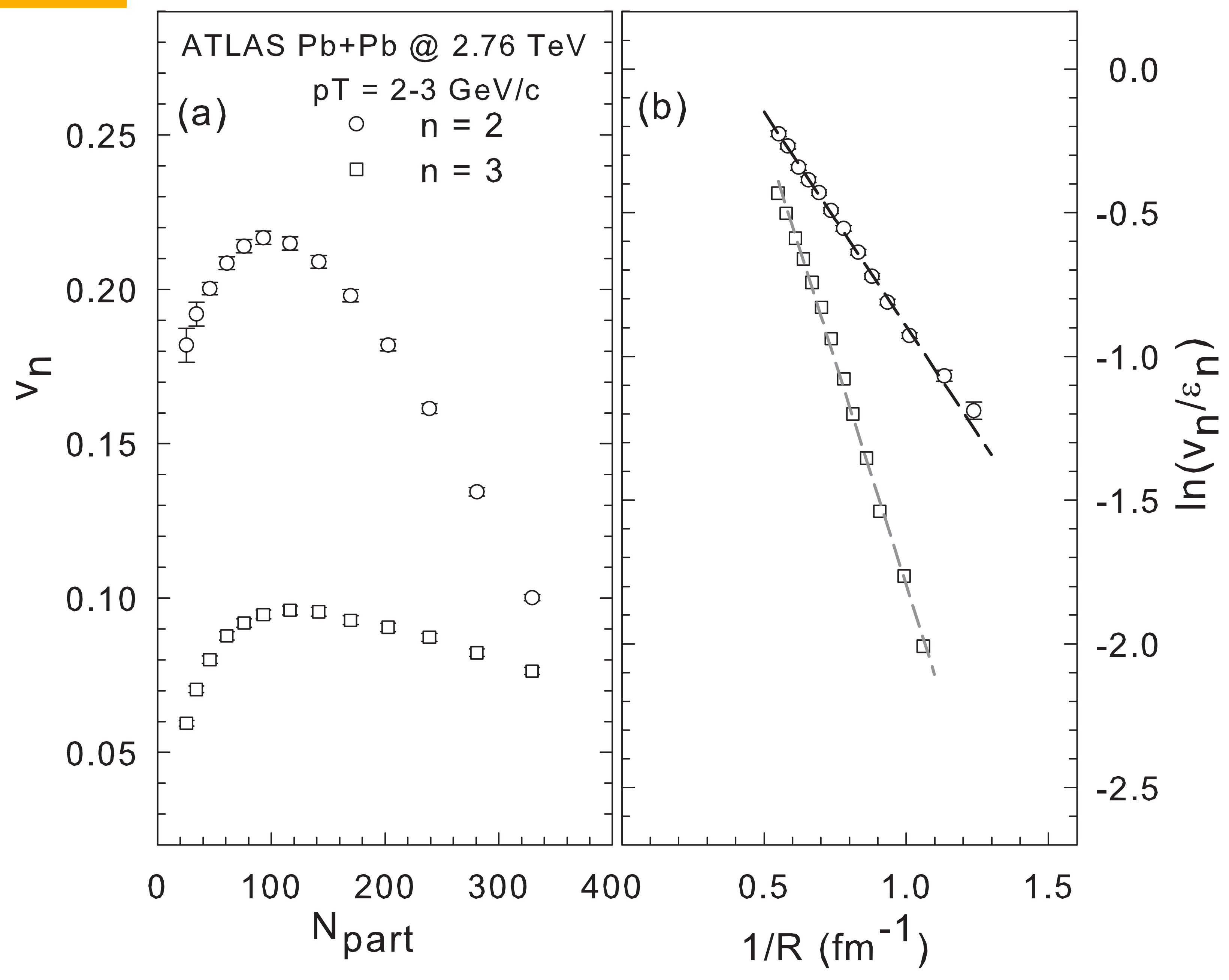
note that we did not dare to calculate beyond 1.7 GeV or so

the acoustic systematics works!

$$\frac{v_n}{\epsilon_n} \sim \exp\left[-Cn^2\left(\frac{\eta}{s}\right)\left(\frac{1}{TR}\right)\right]$$

Shuryak,Staig,2011
product of two small parameters
n^2 from gradient squared

dependence on R



dependence on n

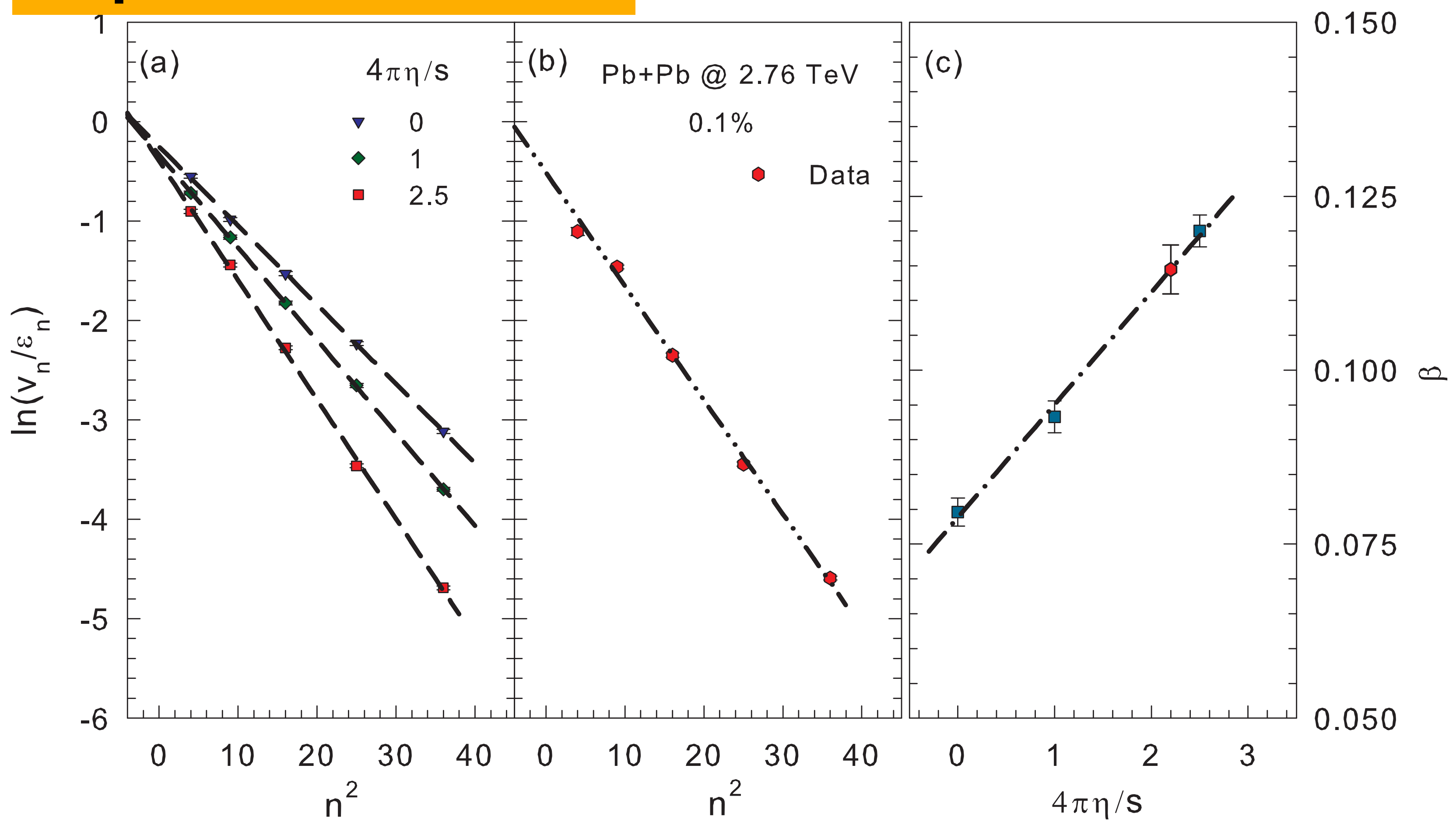
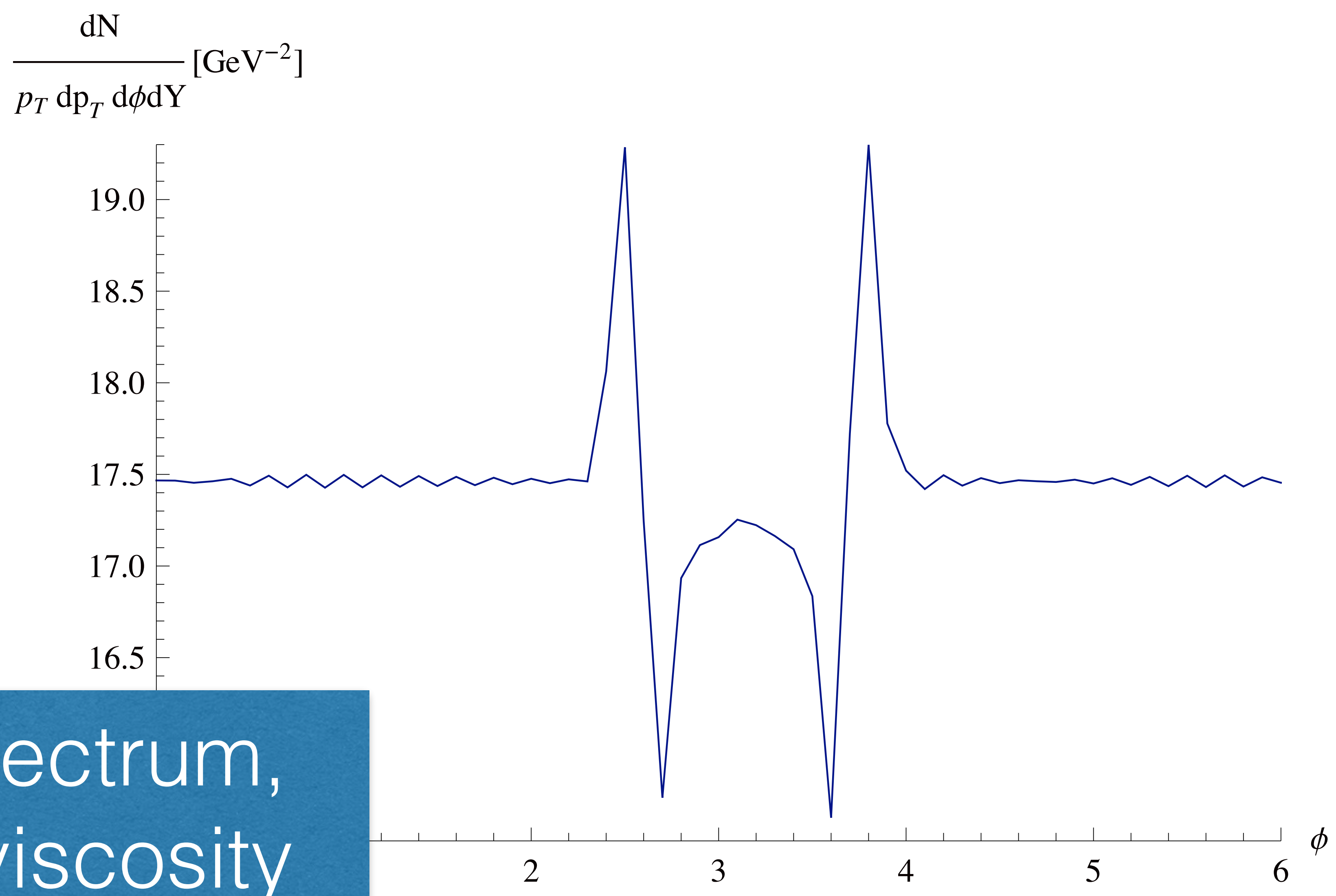


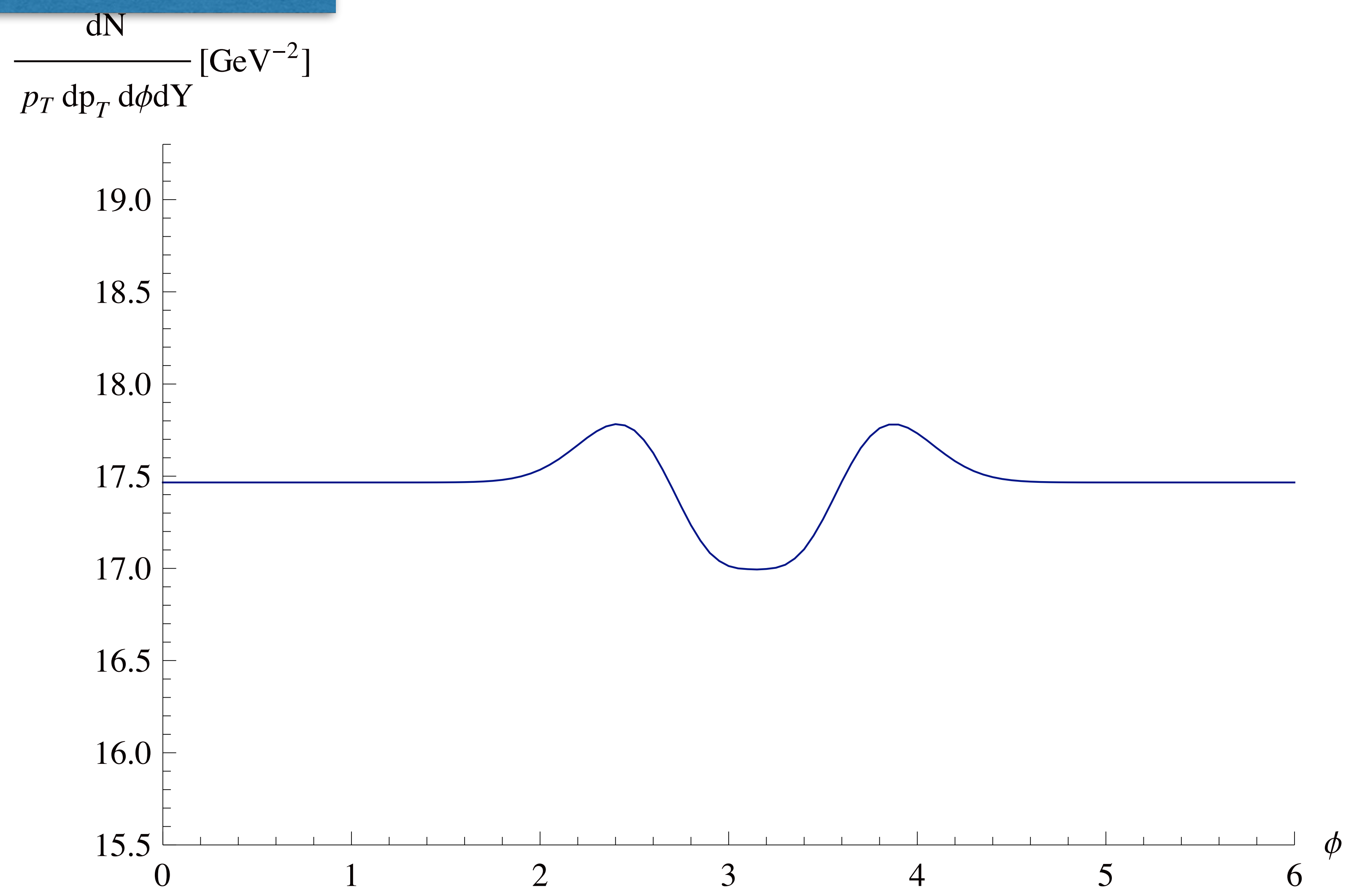
FIG. 3: (a) $ln(v_n/\epsilon_n)$ vs. n^2 from viscous hydrodynamical calculations for three values of specific shear viscosity as indicated. (b) $ln(v_n/\epsilon_n)$ vs. n^2 for Pb+Pb data. The $p_\perp$ -integrated v_n results in (a) and (b) are from ATLAS 0.1% central Pb+Pb collisions at sNN $= 2.76$ TeV; the curves are linear fits. (c) exponent vs. viscosity-to-entropy ratio $4?/s$ for curves shown in (a) and (b).

R.Lacey et al, 2013

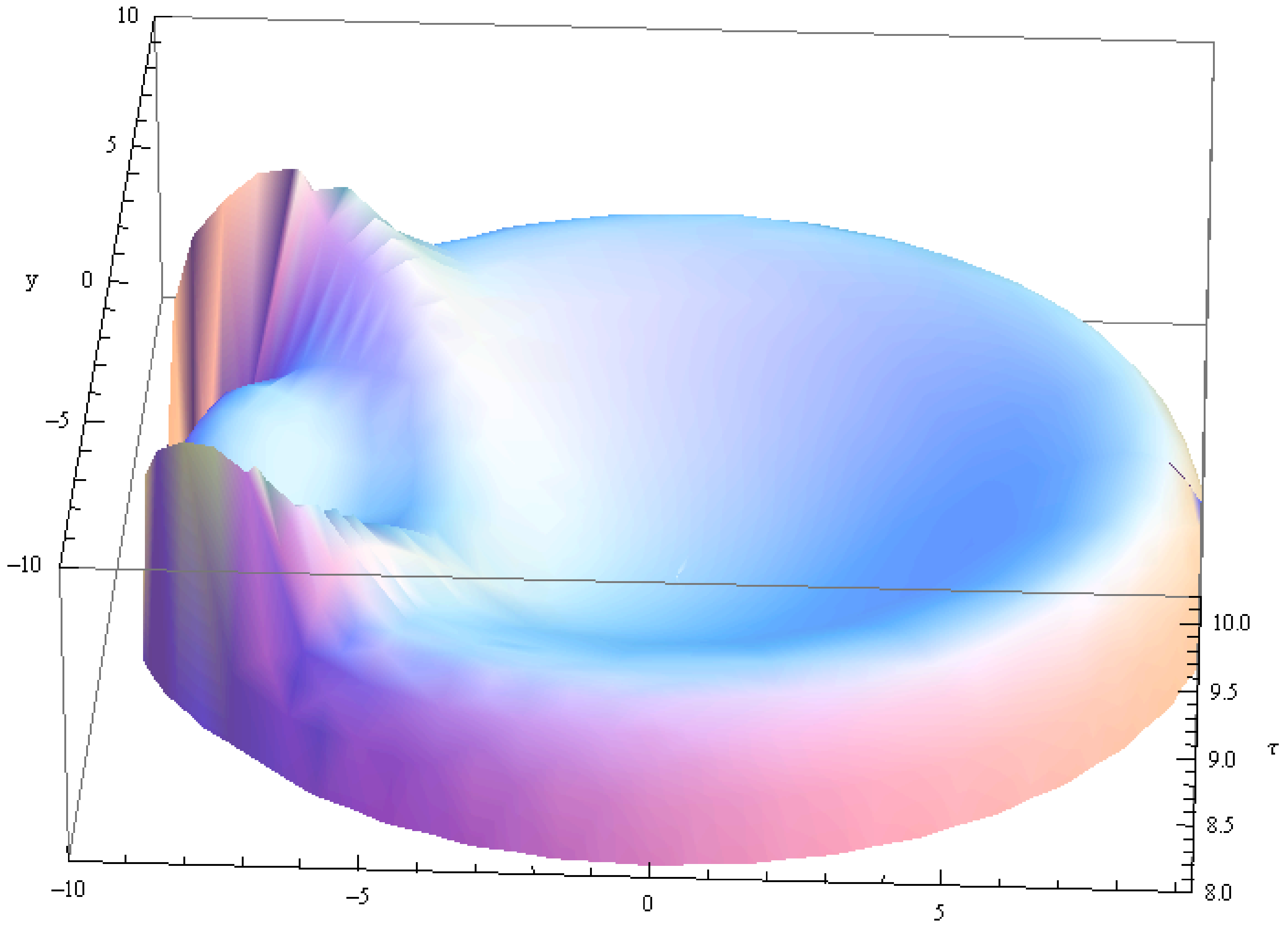
Shuryak,Staig,2011
a frozen sound wave
on top of Gubser flow



Single particle spectrum,
without and with viscosity

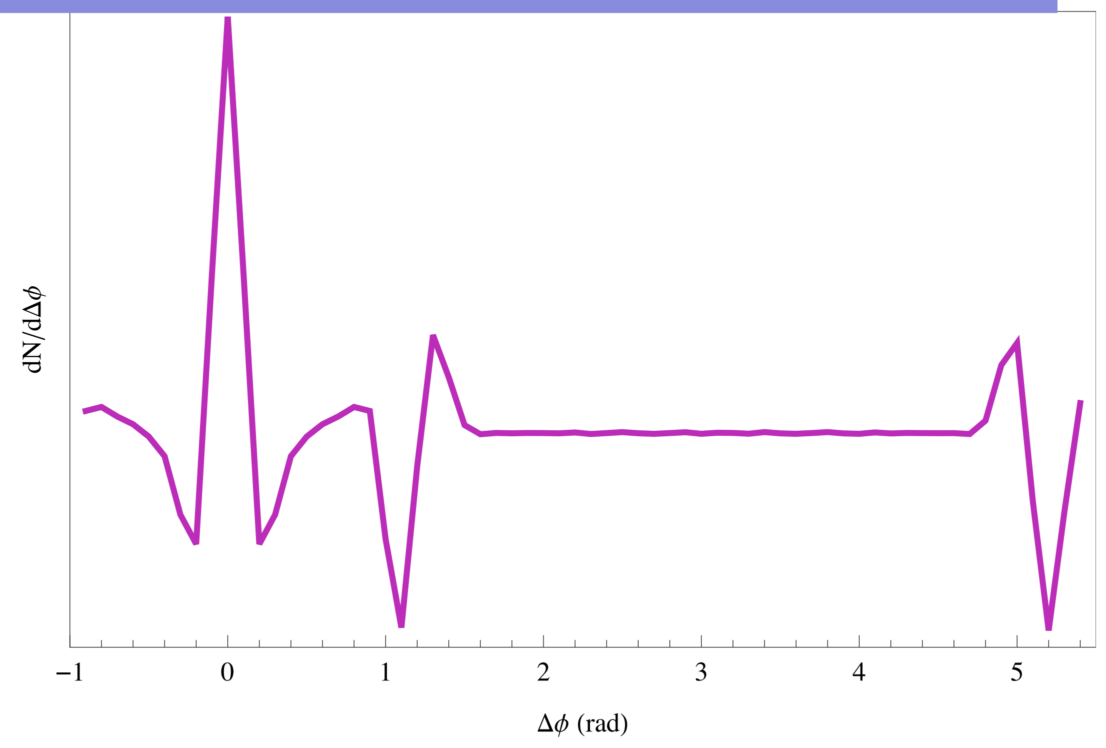


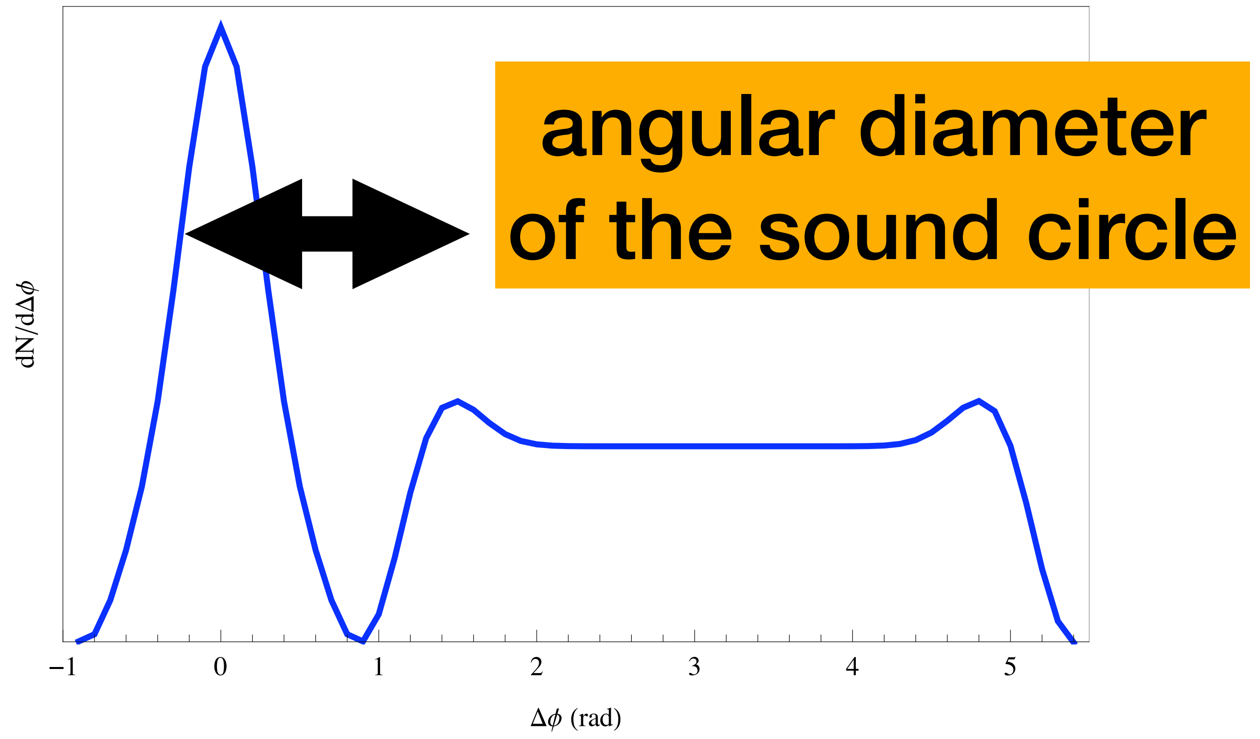
"horns" where sounds
"go ashore"



The modified freezeout
Surface (right) leads to
A modified angular distribution
Of particles, with and without viscosity
(left)

Left:4 pi eta/s=0, 2
Note shape change





this result has been
reported at QM11
before the data
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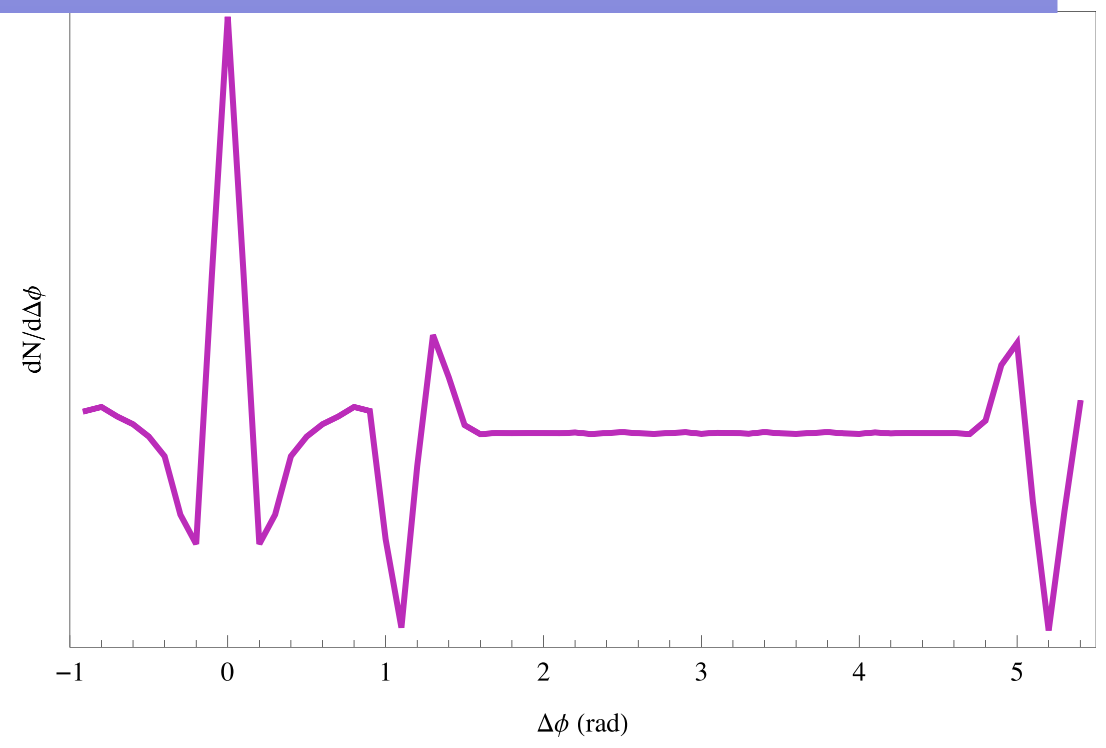

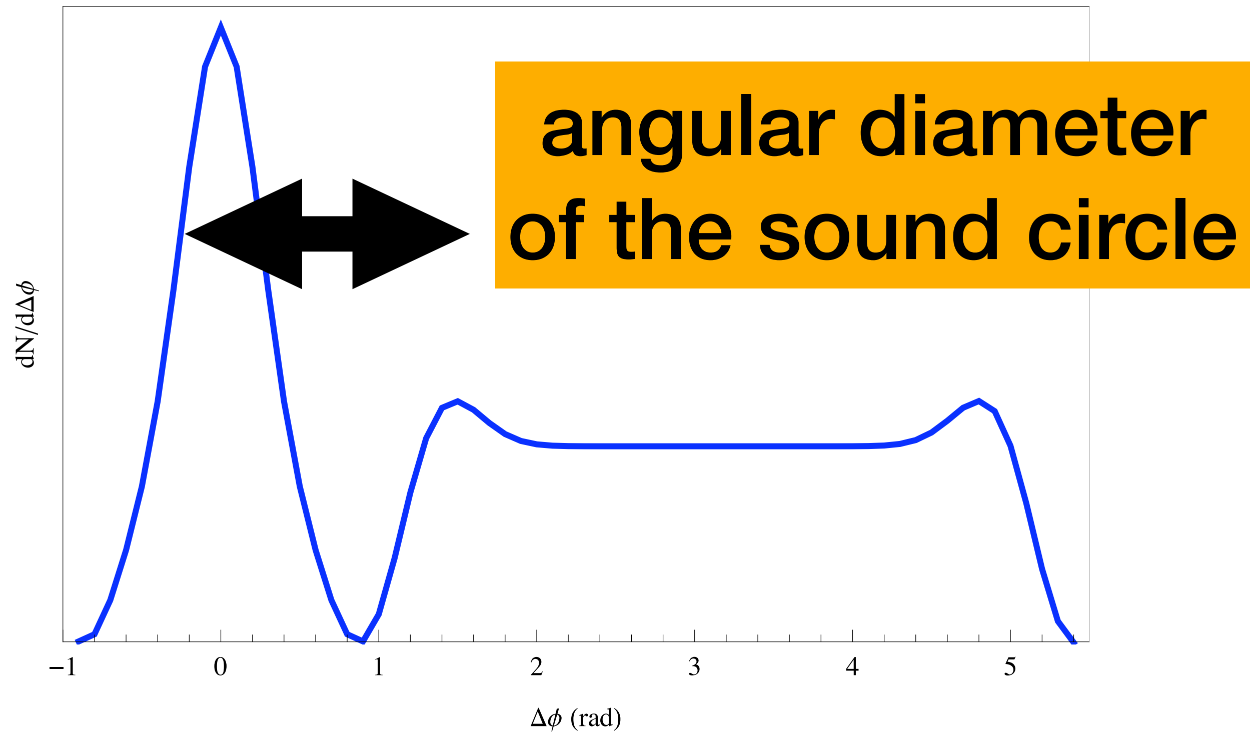

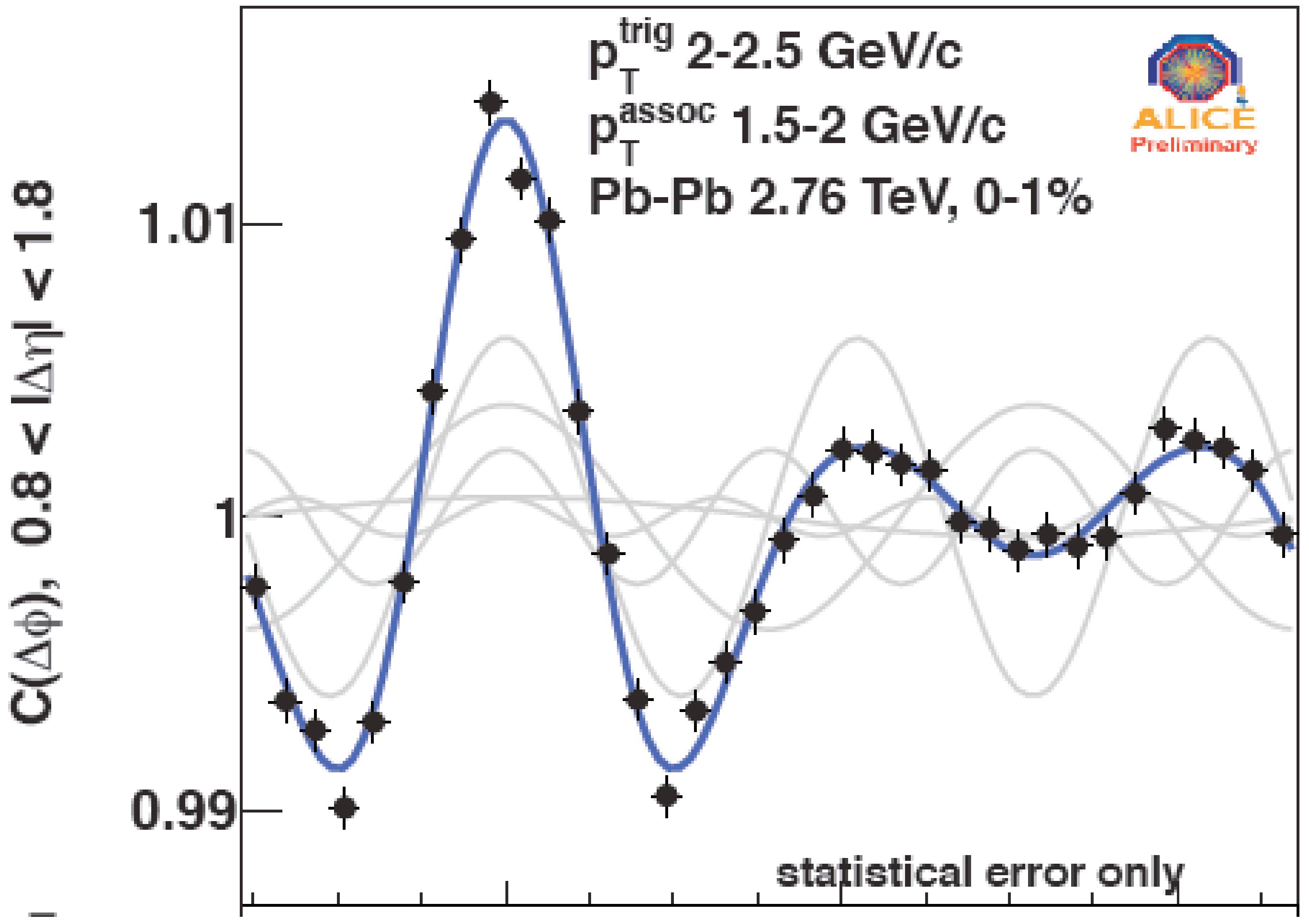

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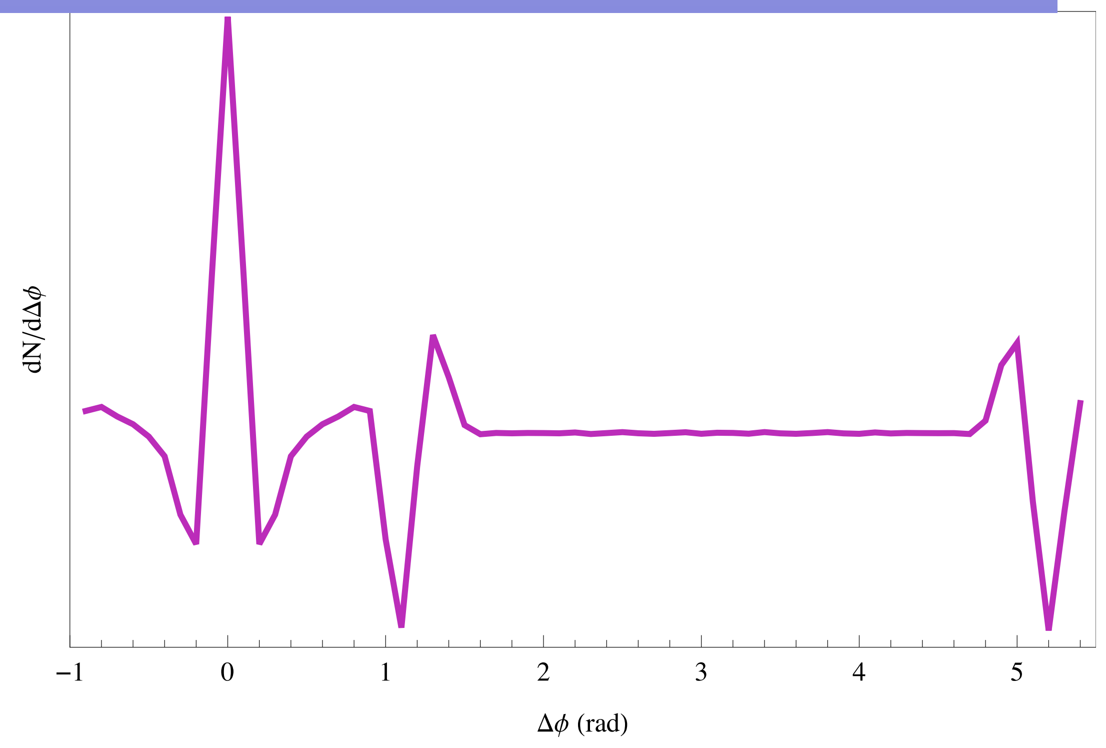

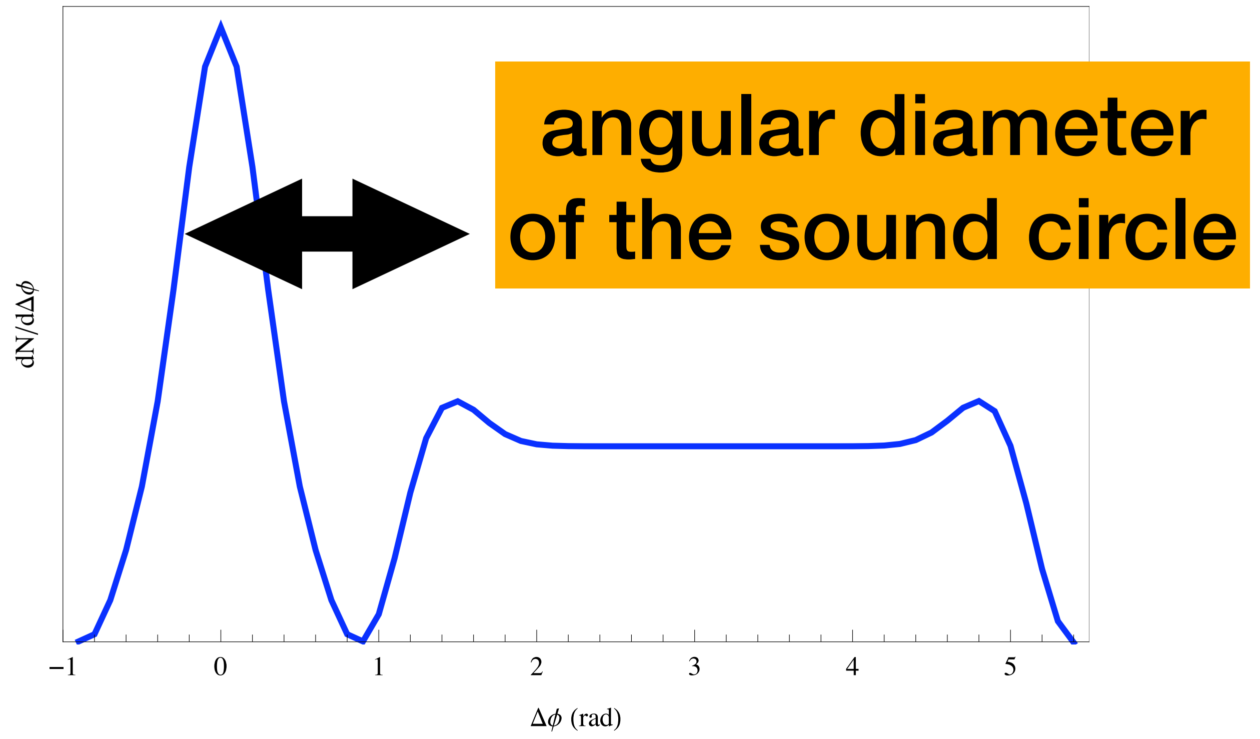

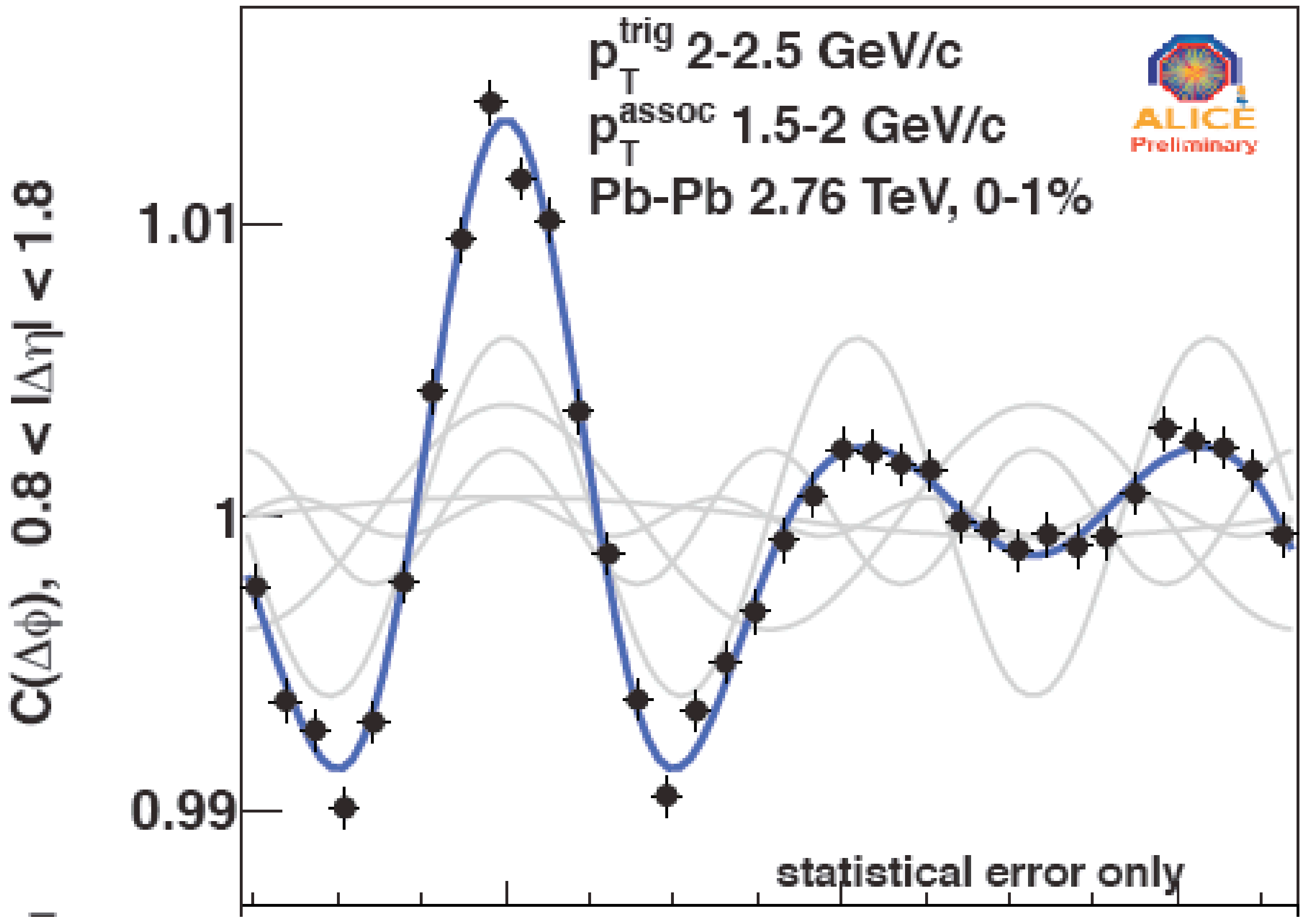

ALICE central 1% correlators
Note shape agreement
No parameters, just Green Function from a delta function

this result has been reported at QM11 before the data were presented

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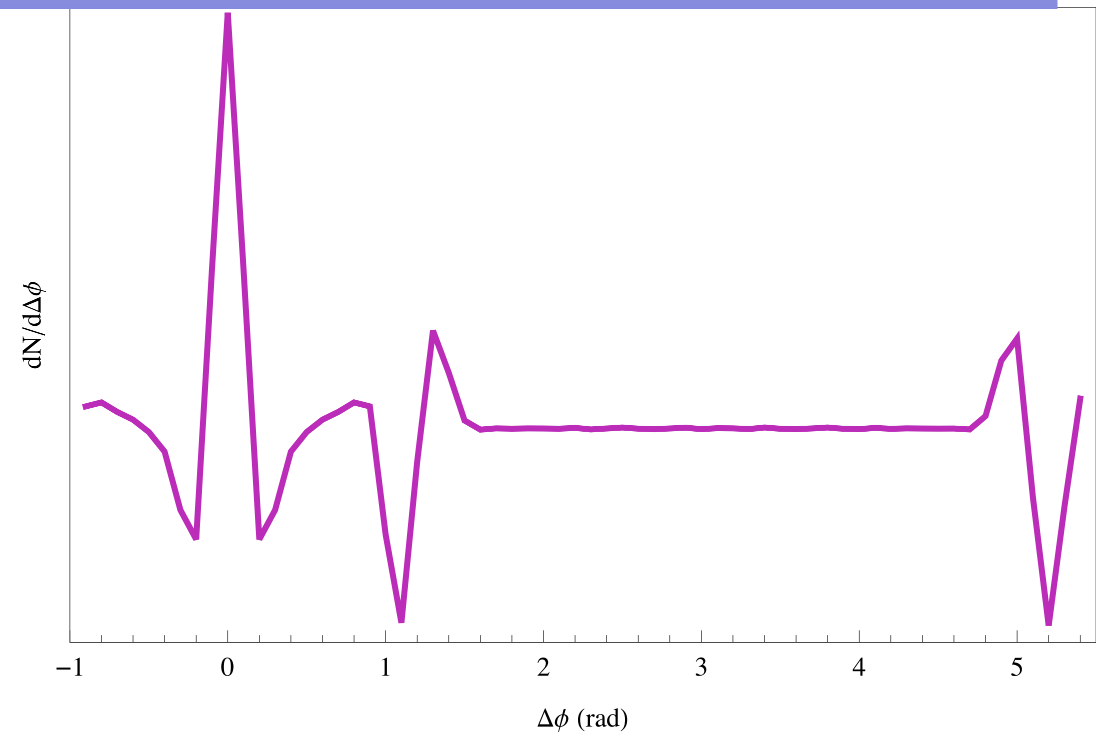

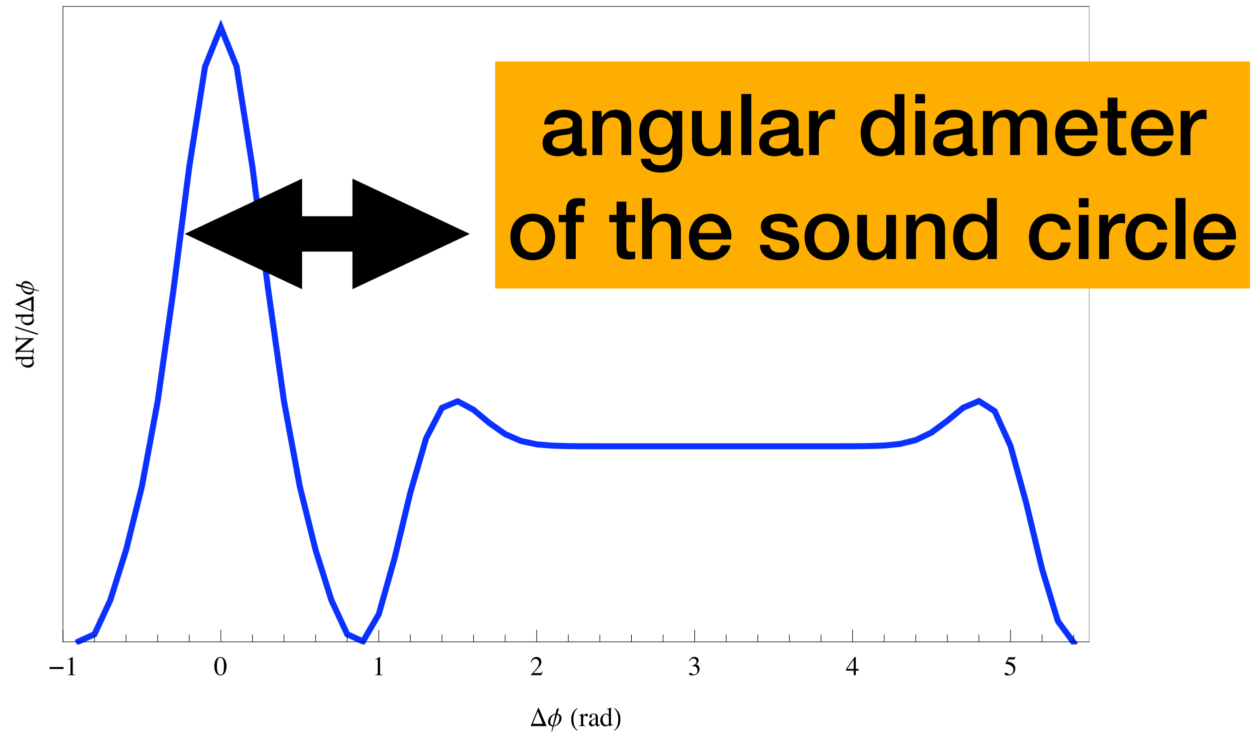

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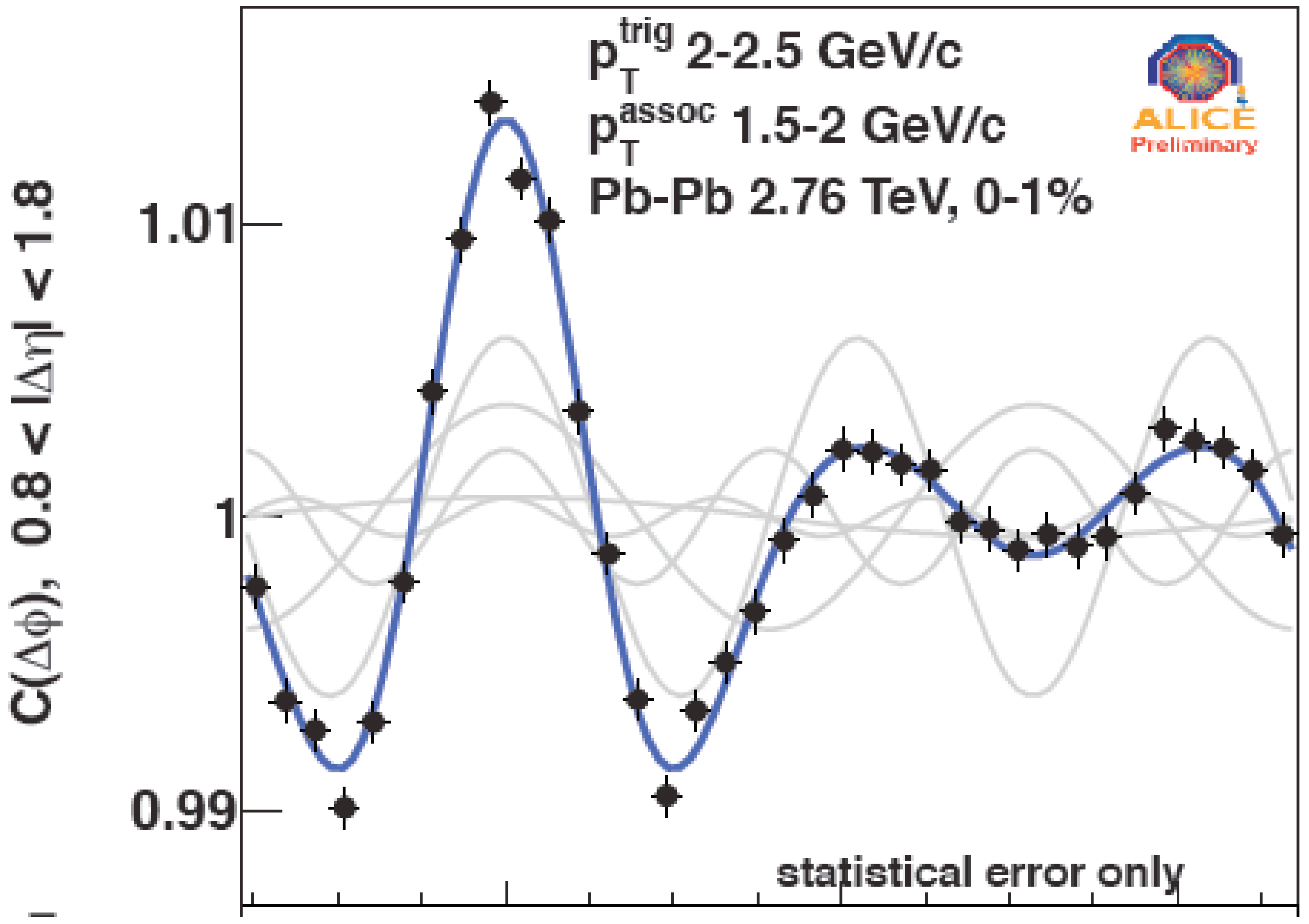

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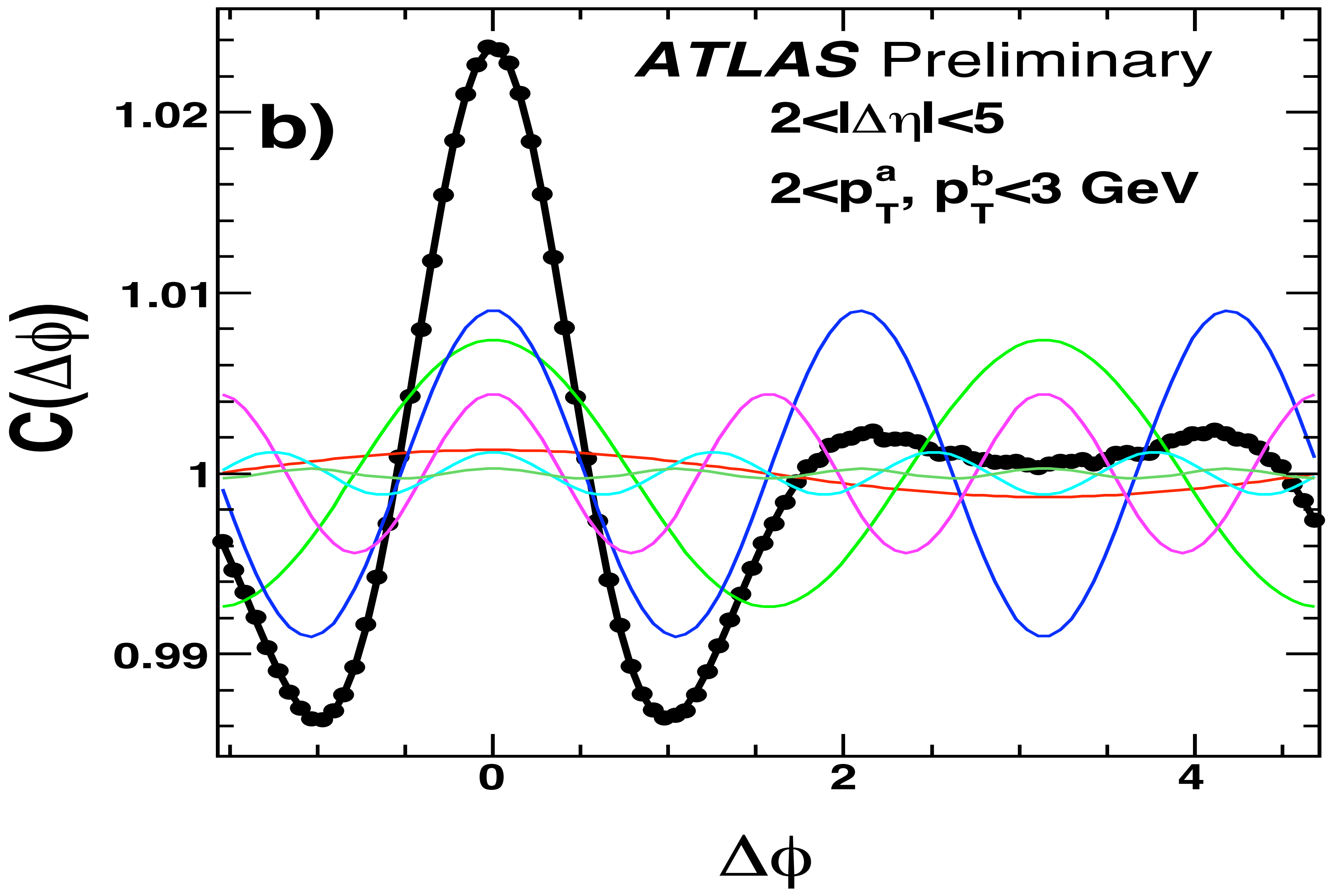

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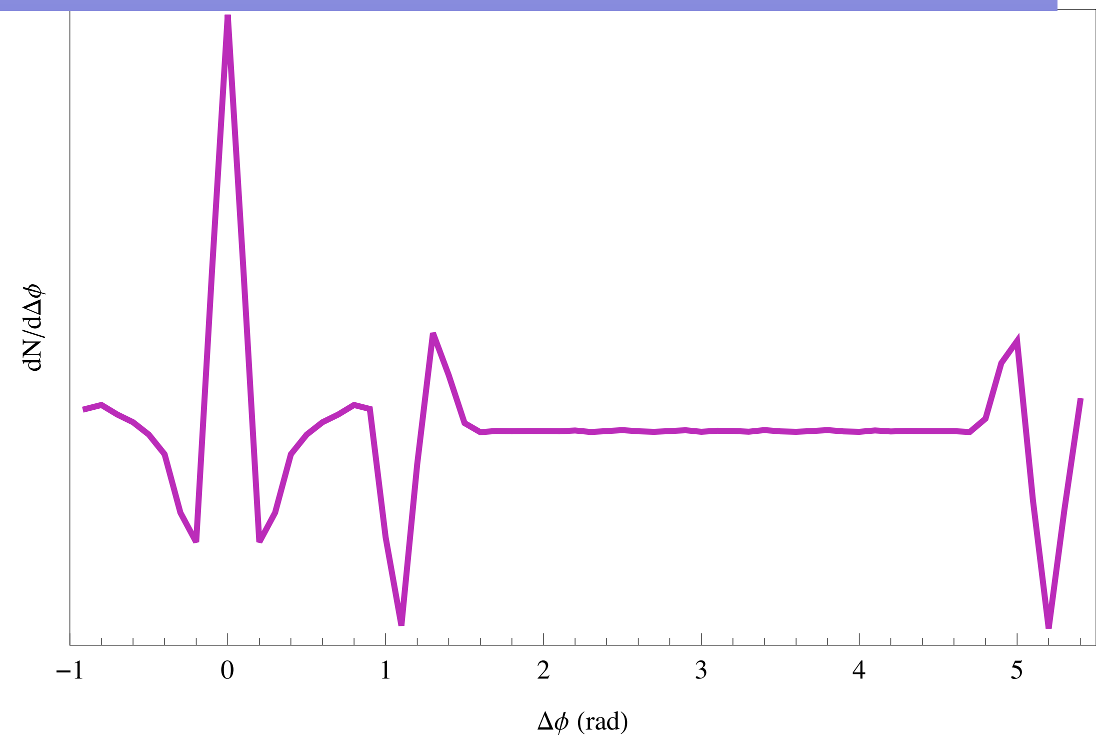

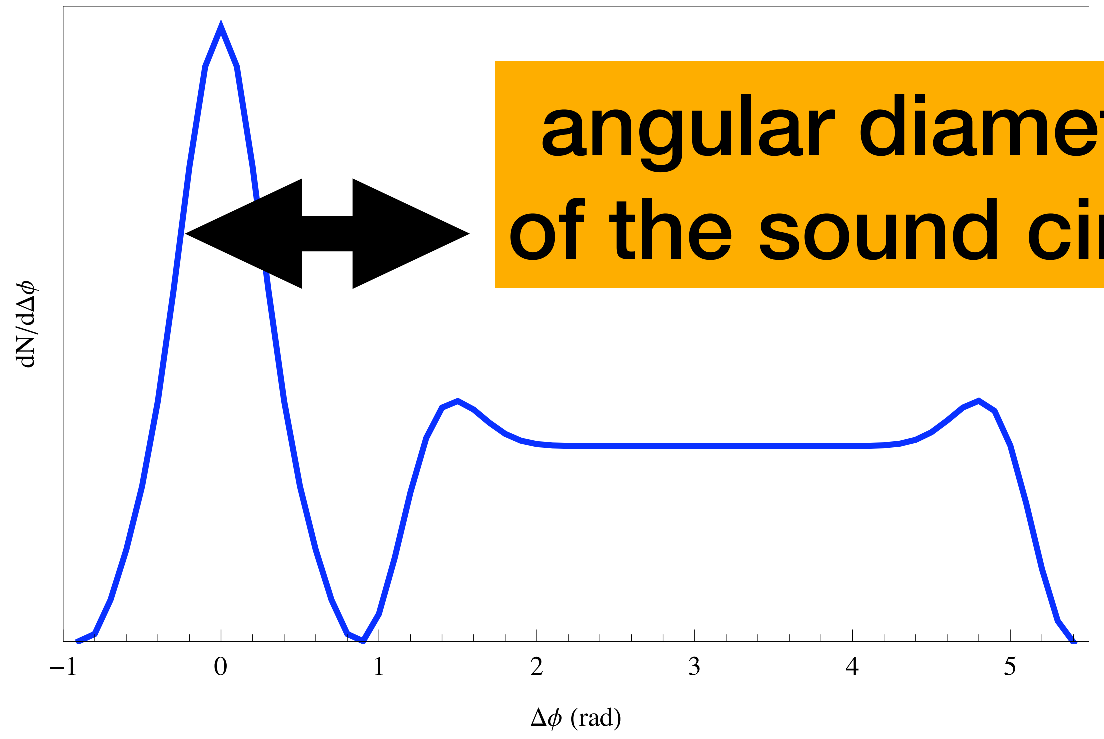

angular diameter
of the sound circle

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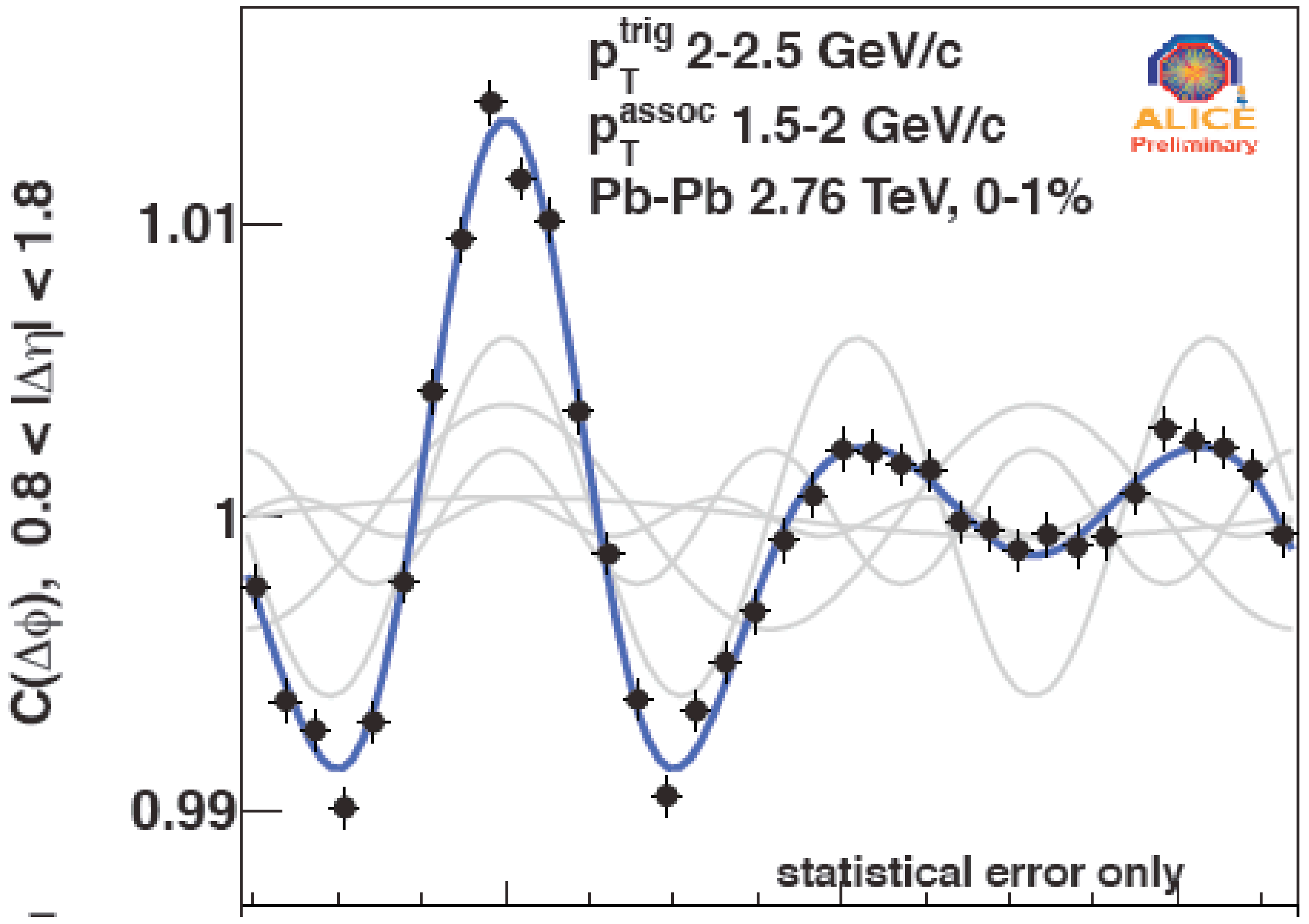

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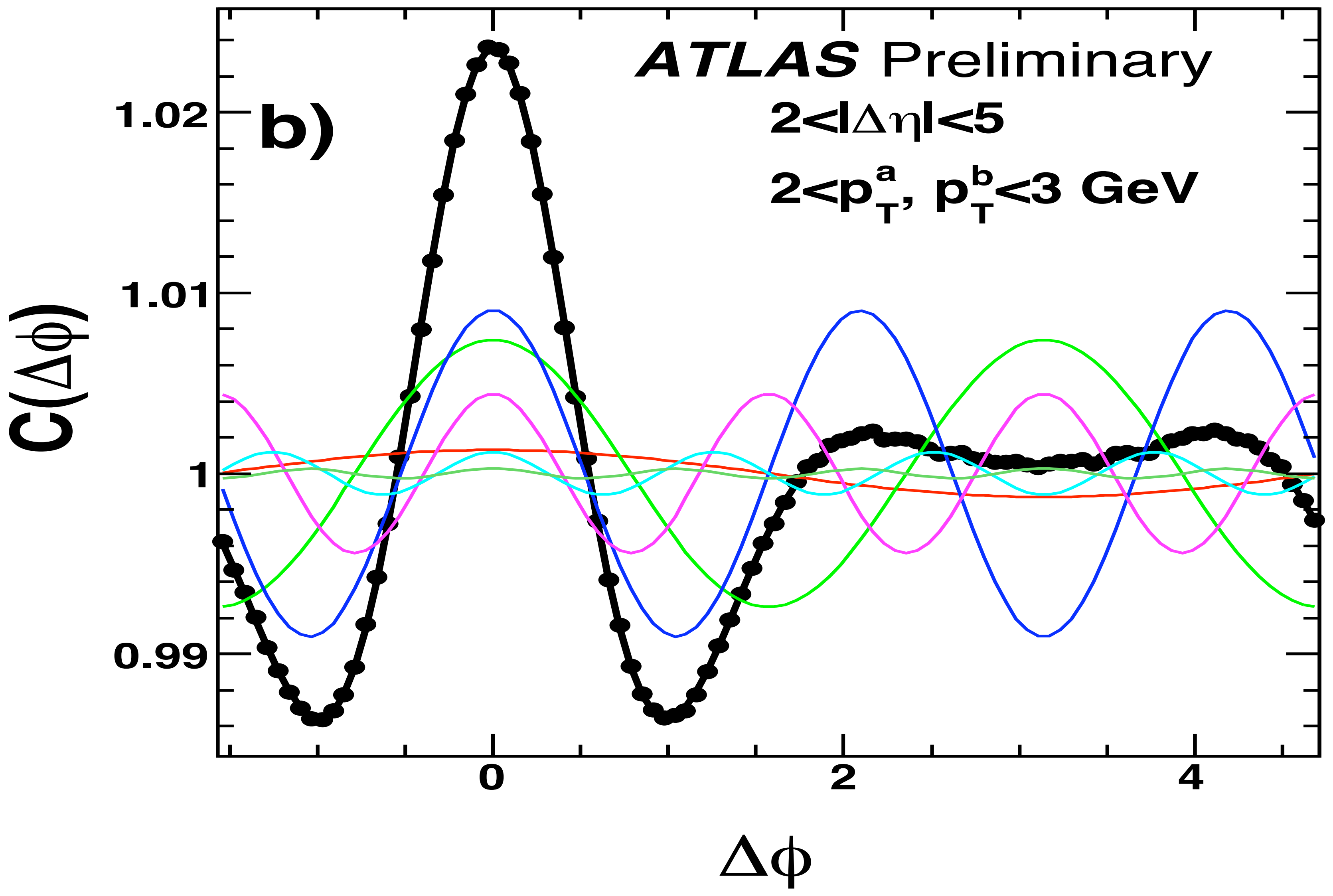
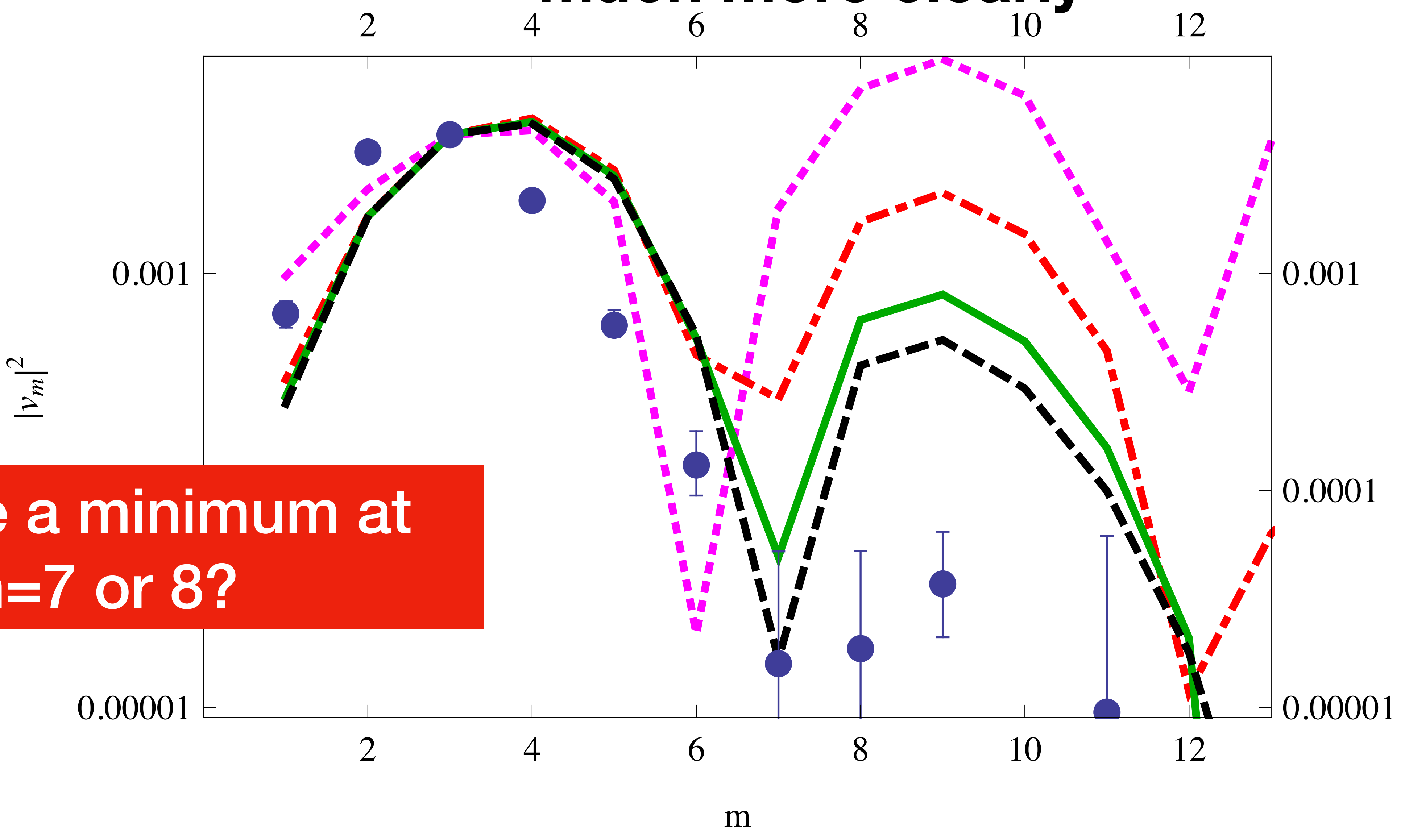


note that
it is the n=3
triangular
harmonics
which is
the strongest

the spectrum of azimuthal harmonics show the effect of viscous damping much more clearly

data from ATLAS coll



Is there a minimum at n=7 or 8?

data from ATLAS coll

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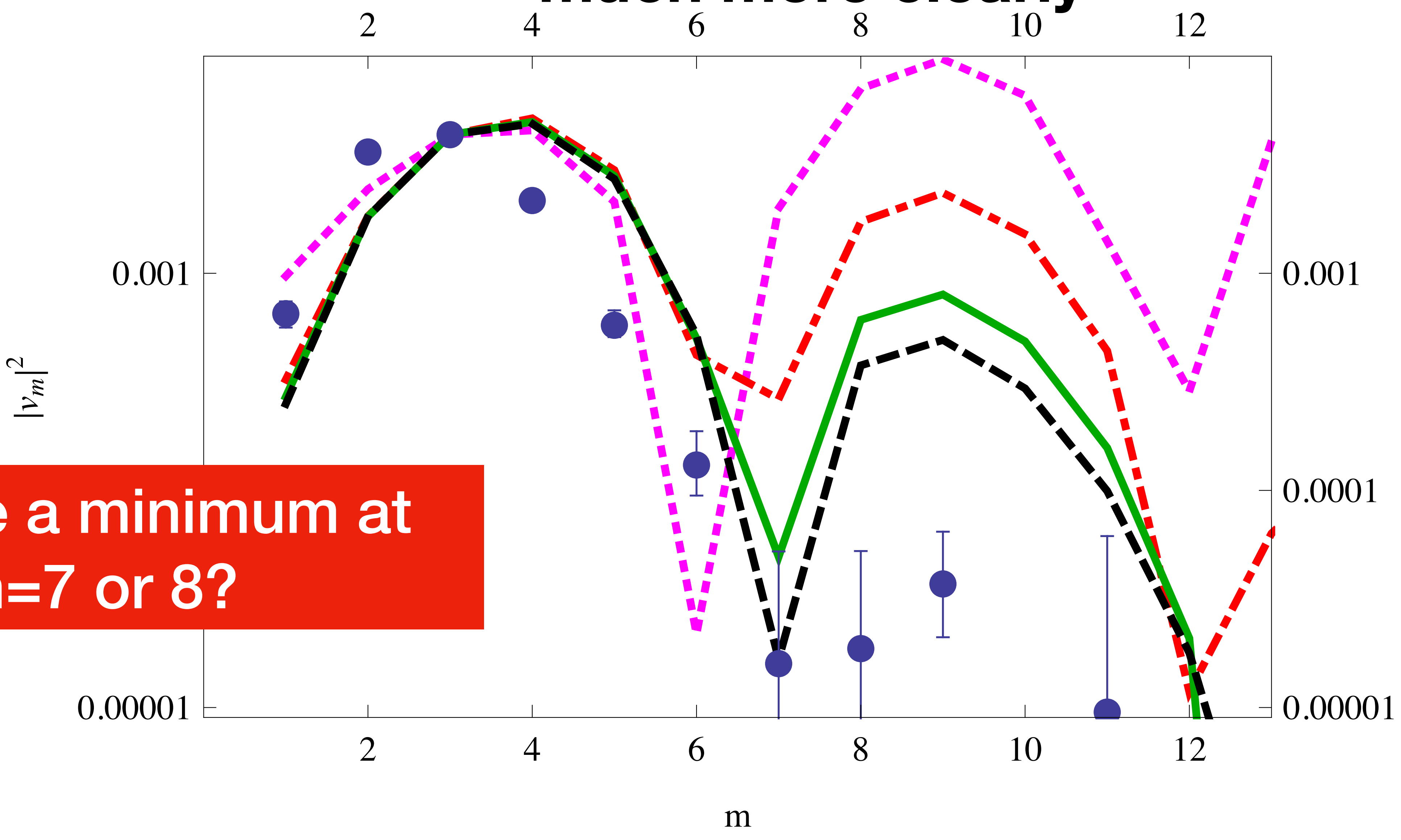
ALICE, 2020
yes, the minimum seems to be there



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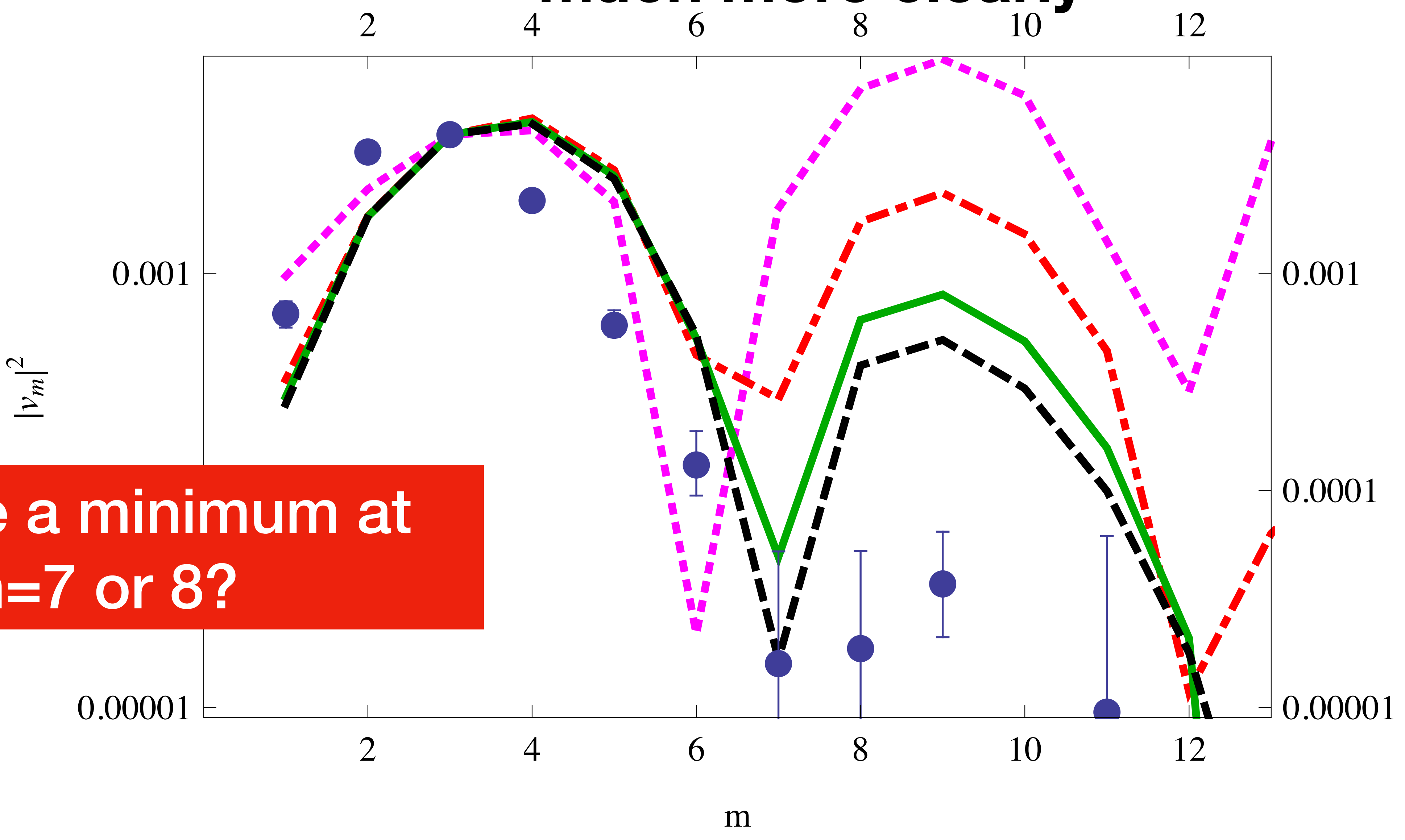

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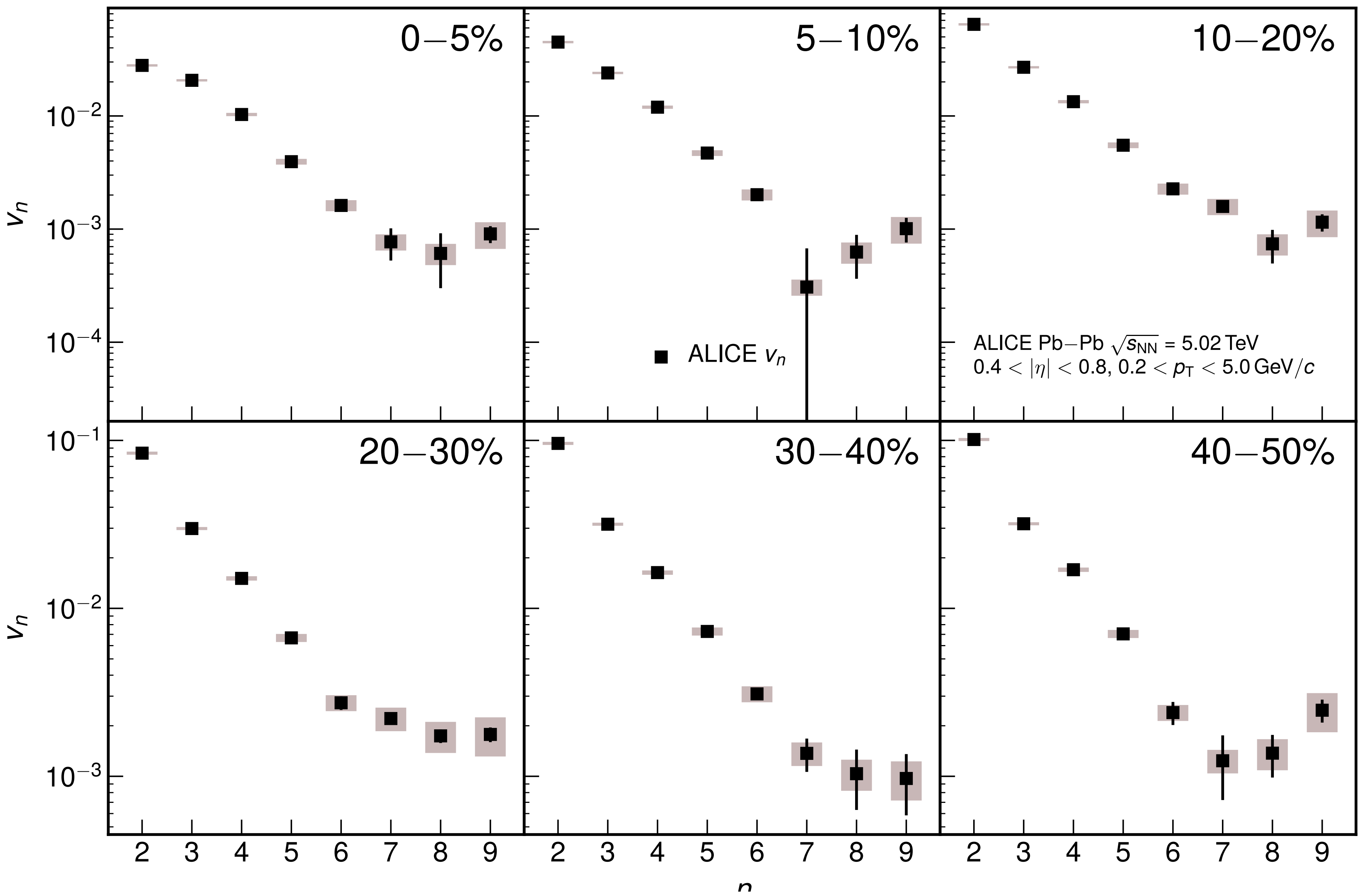

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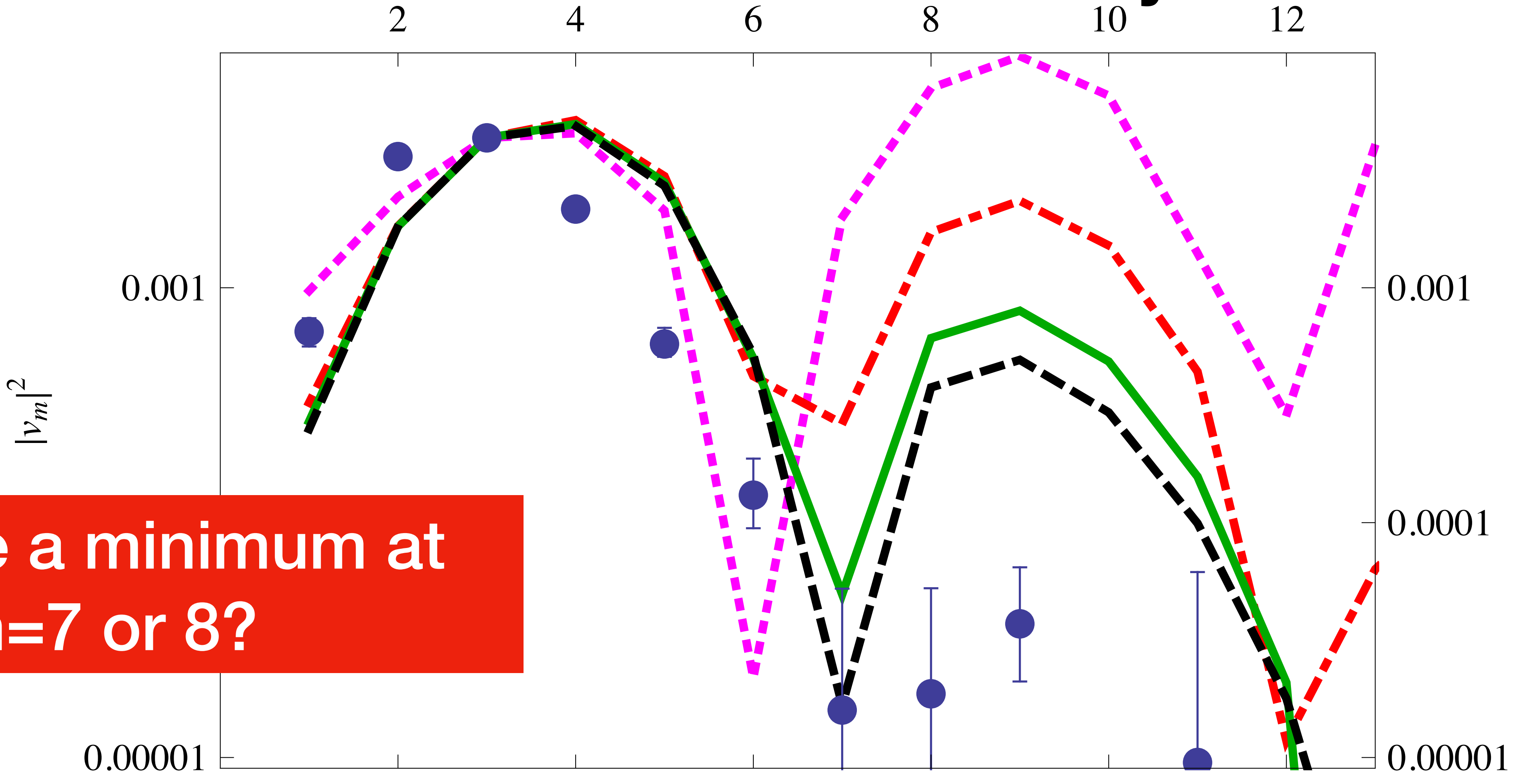

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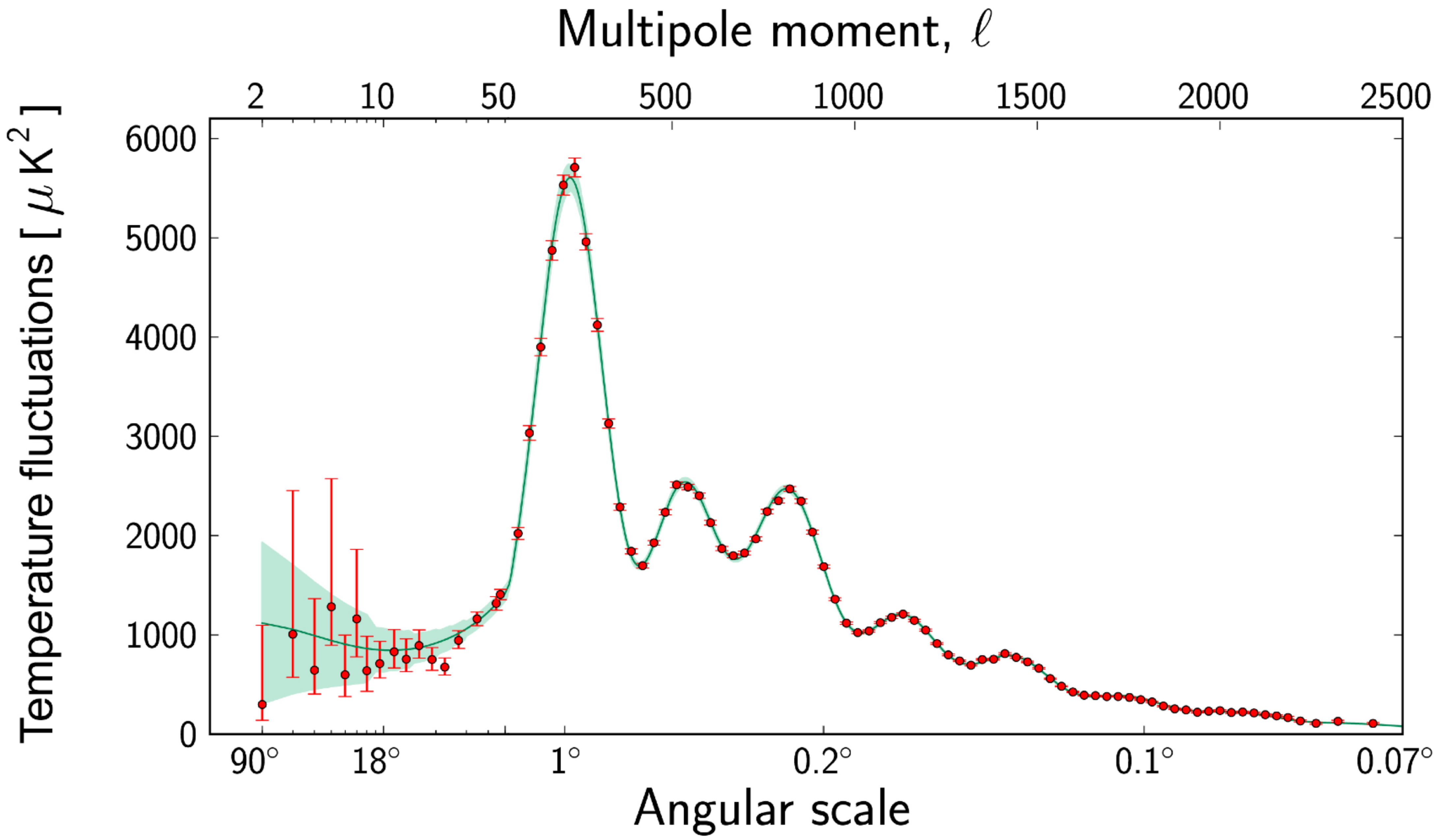

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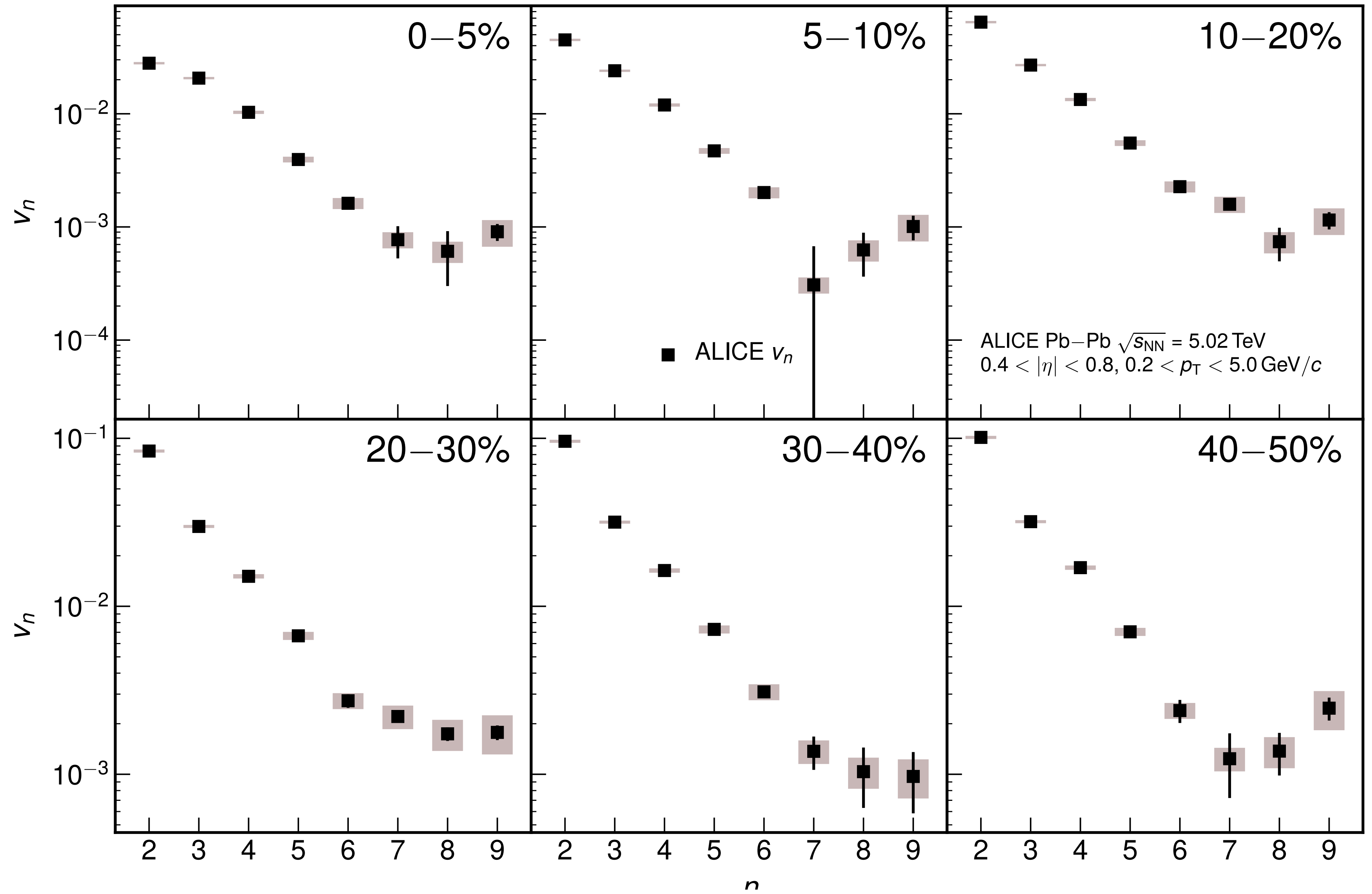

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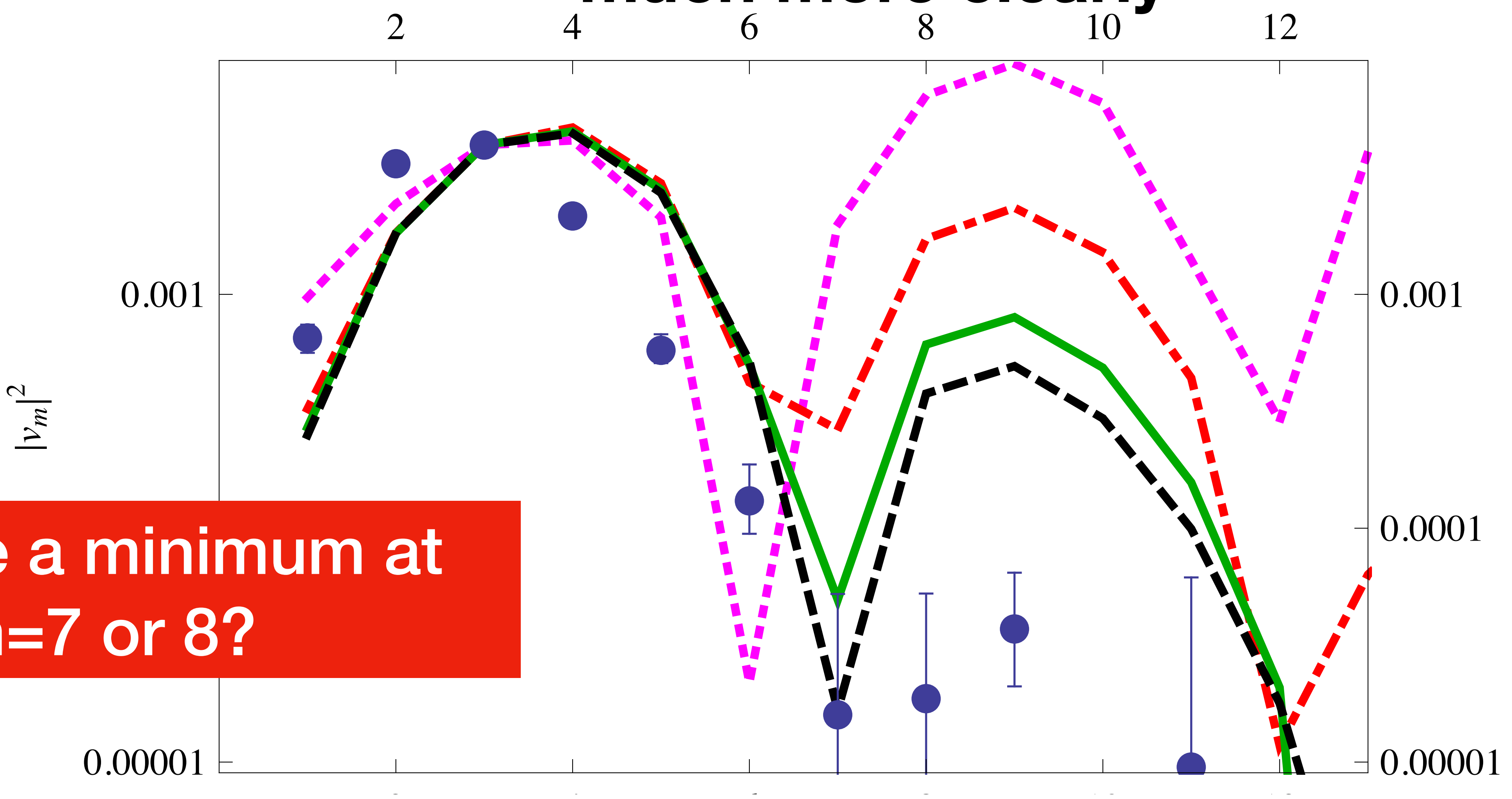

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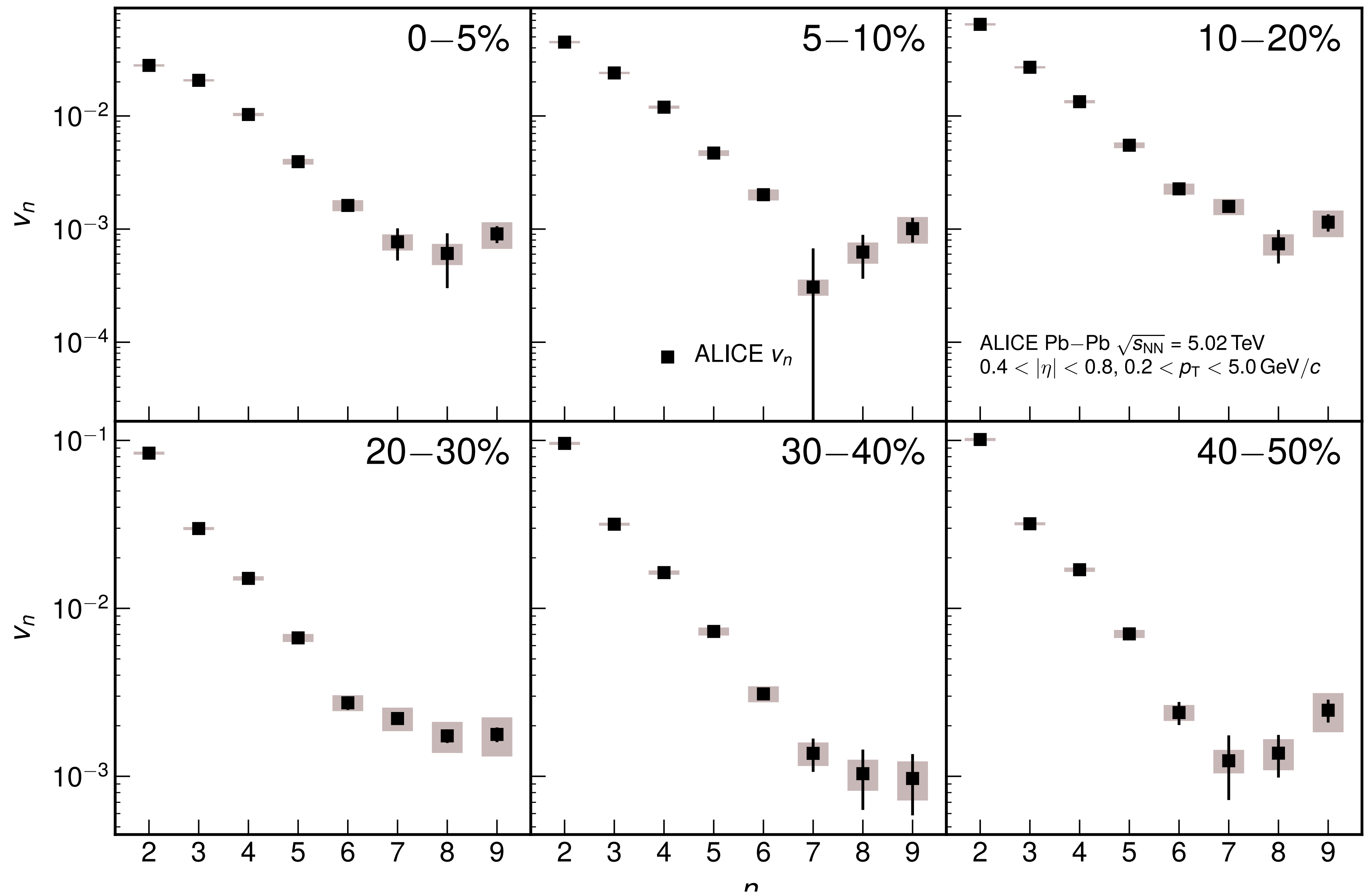

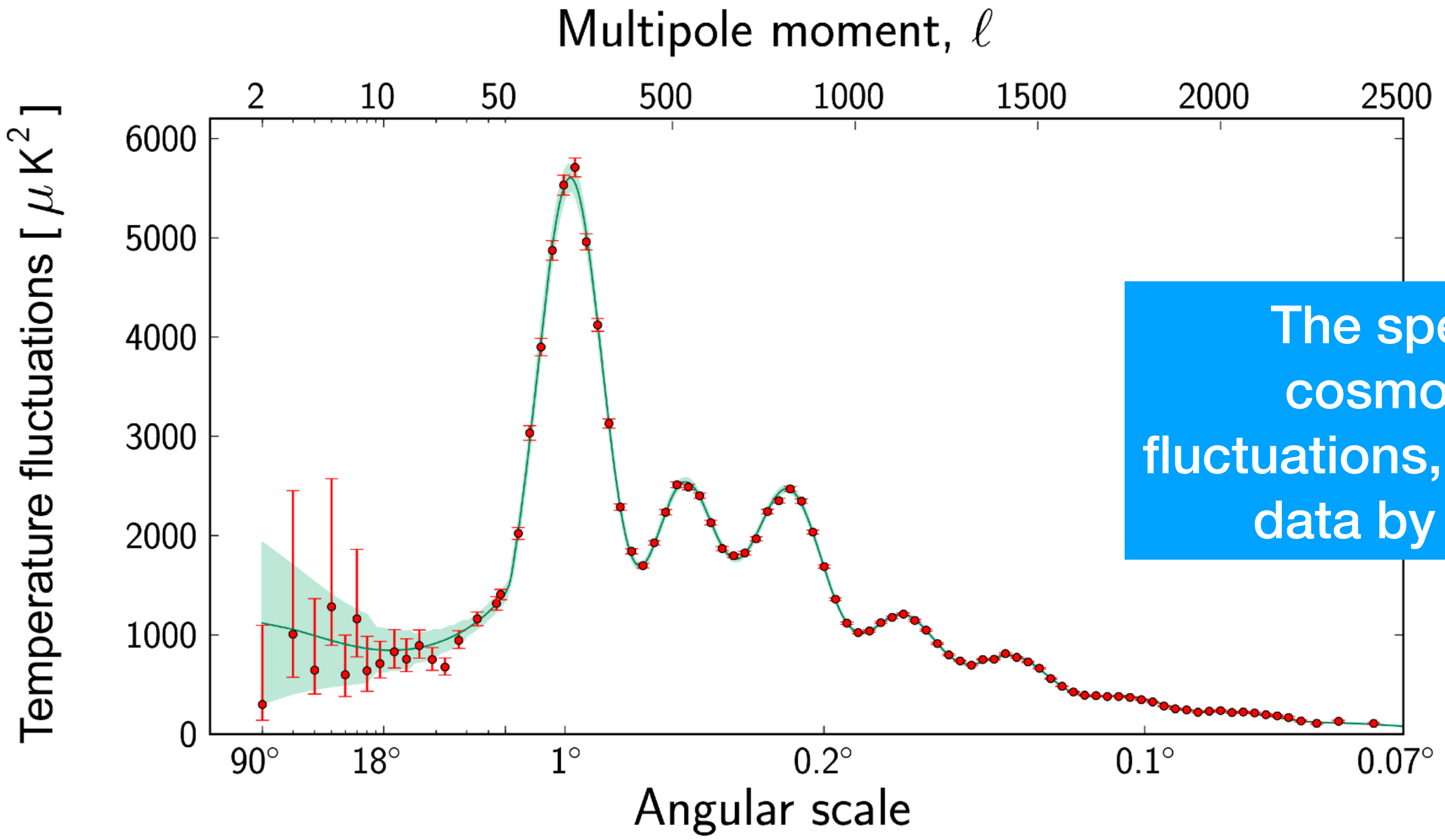

The spectrum of cosmological T fluctuations, from the CMB data by Plank coll

data from ATLAS coll

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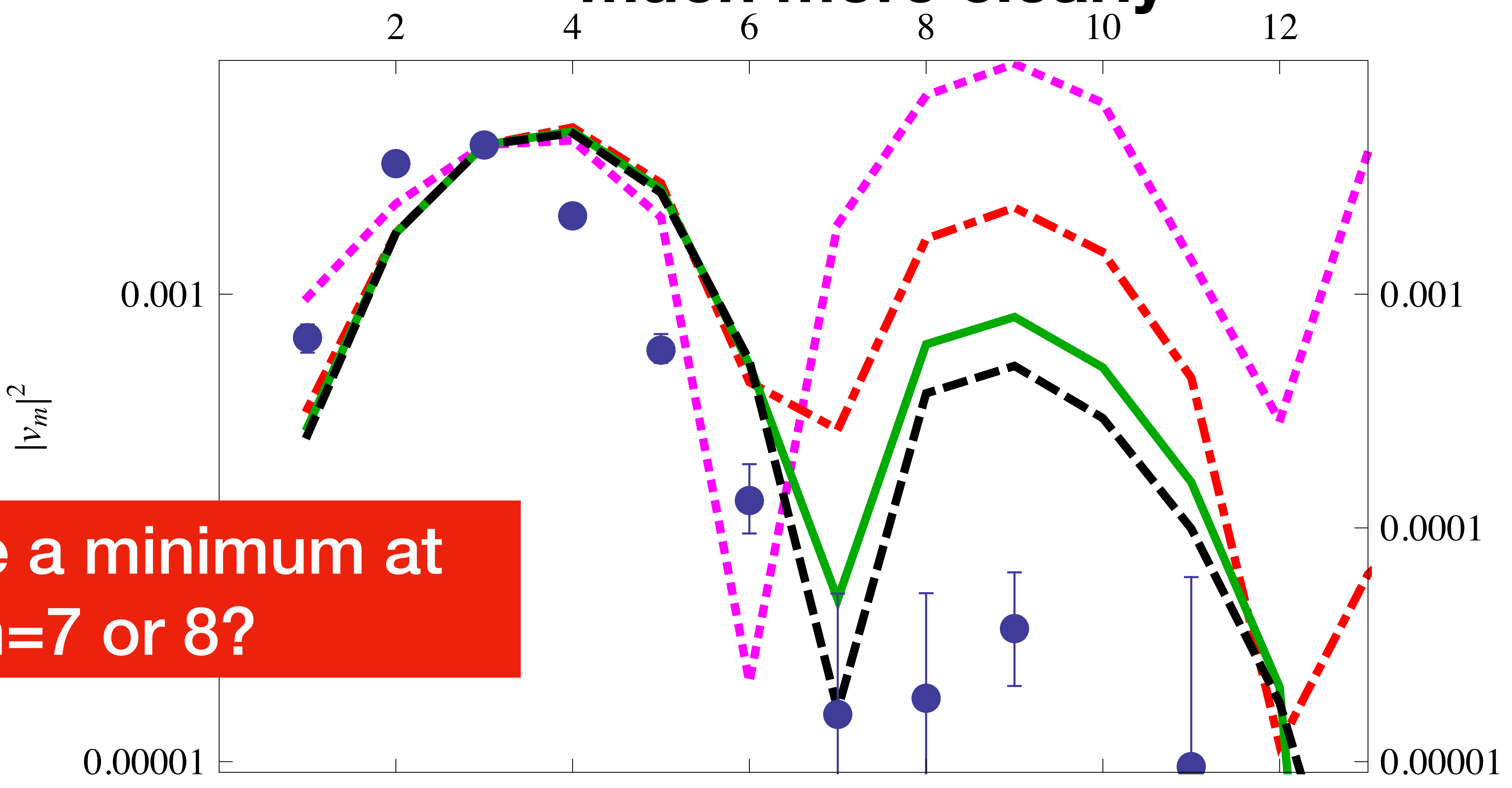

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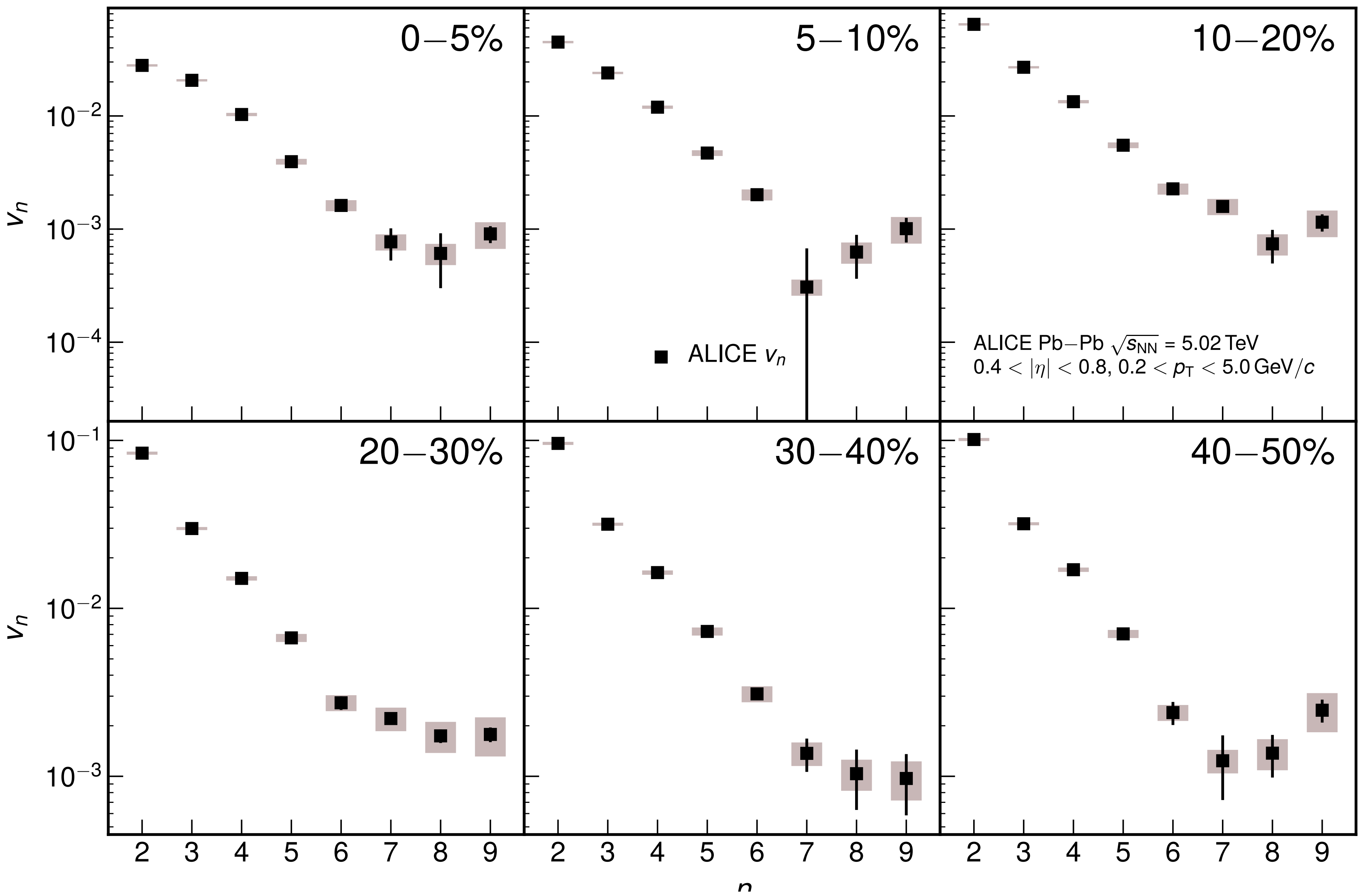
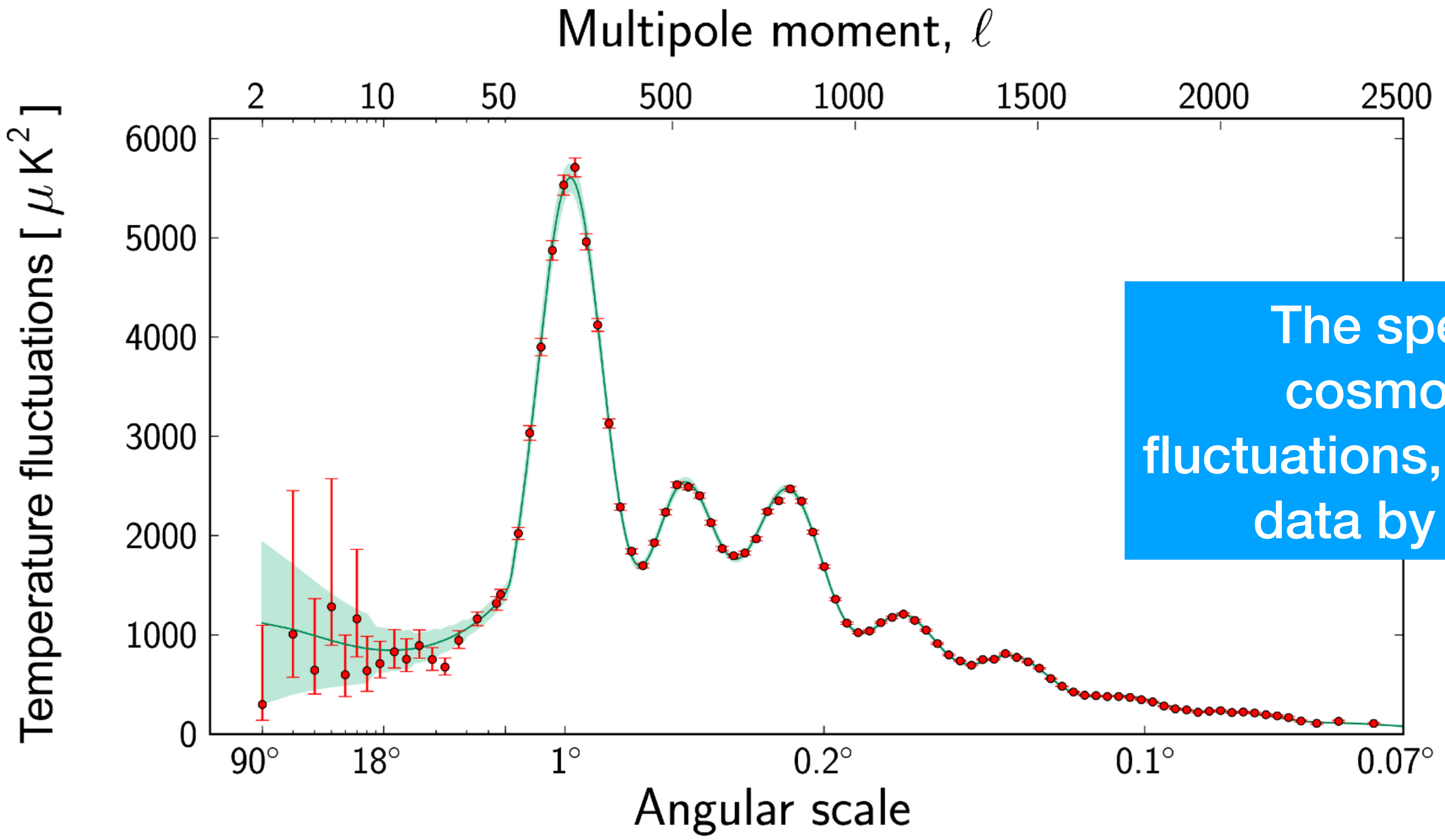




The spectrum of cosmological T fluctuations, from the CMB data by Plank coll

the sounds of the Little and Big Bang have very similar physics!

Perturbations of the Big and the Little Bangs

Frozen sound (from the era long gone) is seen on the sky, both in CMB and in distribution of Galaxies

$$\frac{\Delta T}{T} \sim 10^{-5}$$

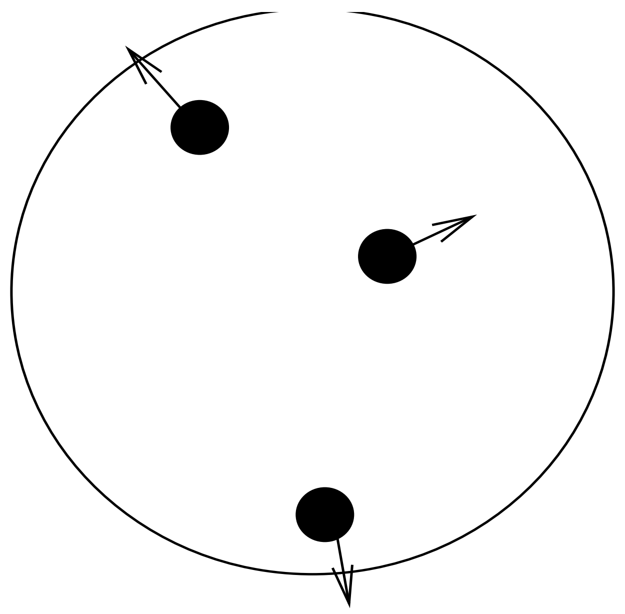
$$l_{maximum} \approx 210$$

$$\delta\phi \sim 2\pi/l_{maximum} \sim 1^o$$

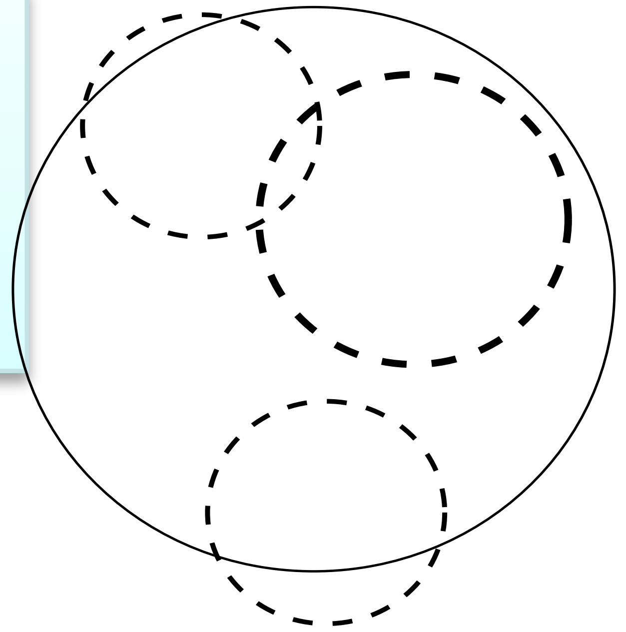
They are remnants of the sound circles on the sky, around the primordial density perturbations Freezeout time O(100000) years

Initial state fluctuations
in the positions of participant nucleons
lead to perturbations of the Little Bang also

$$\frac{\Delta T}{T} \sim 10^{-2}$$



Freezeout time about 12 fm/c
Radius of the circle about 6 fm,
Comparable to the fireball size



PHYSICAL REVIEW C **80**, 054908 (2009)

Fate of the initial state perturbations in heavy ion collisions

Edward Shuryak
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA
(Received 20 July 2009; revised manuscript received 14 October 2009; published 13 November 2009)

ACOUSTIC PEAK SEEN ON THE SKY, ON CMB and galaxy distribution

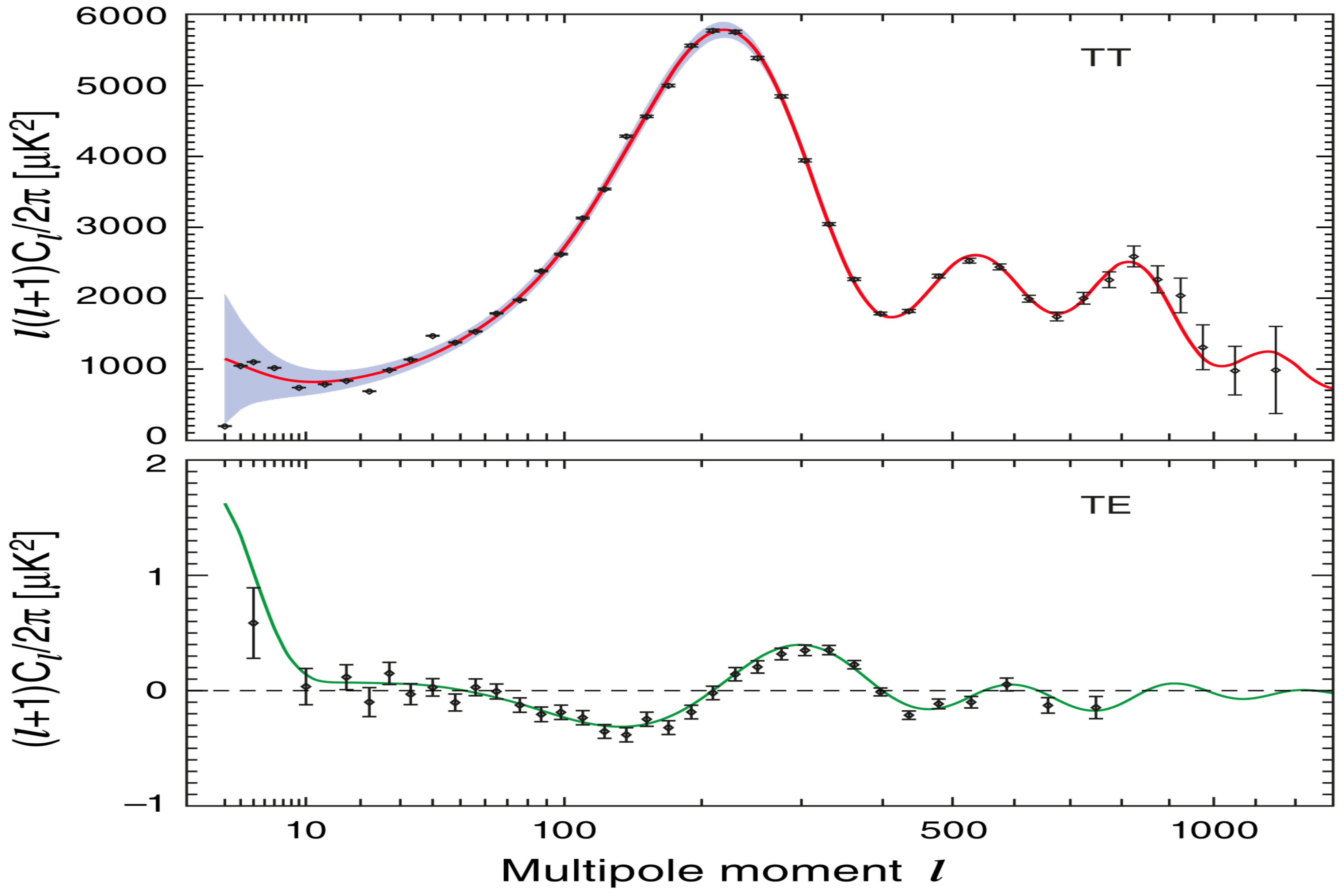


Fig. 9.— The temperature (TT) and temperature-polarization(TE) power spectra for the seven-year *WMAP* data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty in the model spectrum arising from cosmic variance. The model parameters are: $\Omega_b h^2 = 0.02260 \pm 0.00053$, $\Omega_c h^2 = 0.1123 \pm 0.0035$, $\Omega_\Lambda = 0.728^{+0.015}_{-0.016}$, $n_s = 0.963 \pm 0.012$, $\tau = 0.087 \pm 0.014$ and $\sigma_8 = 0.809 \pm 0.024$.

DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

Daniel J. Eisenstein[1,2], Idit Zehavi[1], David W. Hogg[3], Roman Scoccimarro[3], Michael R. Blanton[3], Robert C. Nichol[4], Ryan Scranton[5], Hee-Jong Seo[1], Max Tegmark[6,7], Zheng Zheng[8], Scott F. Anderson[9], Jim Annis[10], Neta Bahcall[11], Jon Brinkmann[12], Scott Burles[7], Francisco J. Castander[13], Andrew Connolly[5], Istvan Csabai[14], Mamoru Doi[15], Masataka Fukugita[16], Joshua A. Frieman[10,17], Karl Glazebrook[18], James E. Gunn[11], John S. Hendry[10], Gregory Hennessy[19], Zeljko Ivezić[9], Stephen Kent[10], Gillian R. Knapp[11], Huan Lin[10], Yeong-Shang Loh[20], Robert H. Lupton[11], Bruce Margon[21], Timothy A. McKay[22], Avery Meiksin[23], Jeffery A. Munn[19], Adrian Pope[18], Michael W. Richmond[24], David Schlegel[25], Donald P. Schneider[26], Kazuhiro Shimasaku[27], Christopher Stoughton[10], Michael A. Strauss[11], Mark SubbaRao[17,28], Alexander S. Szalay[18], István Szapudi[29], Douglas L. Tucker[10], Brian Yanny[10], & Donald G. York[17]

Submitted to The Astrophysical Journal 12/31/2004

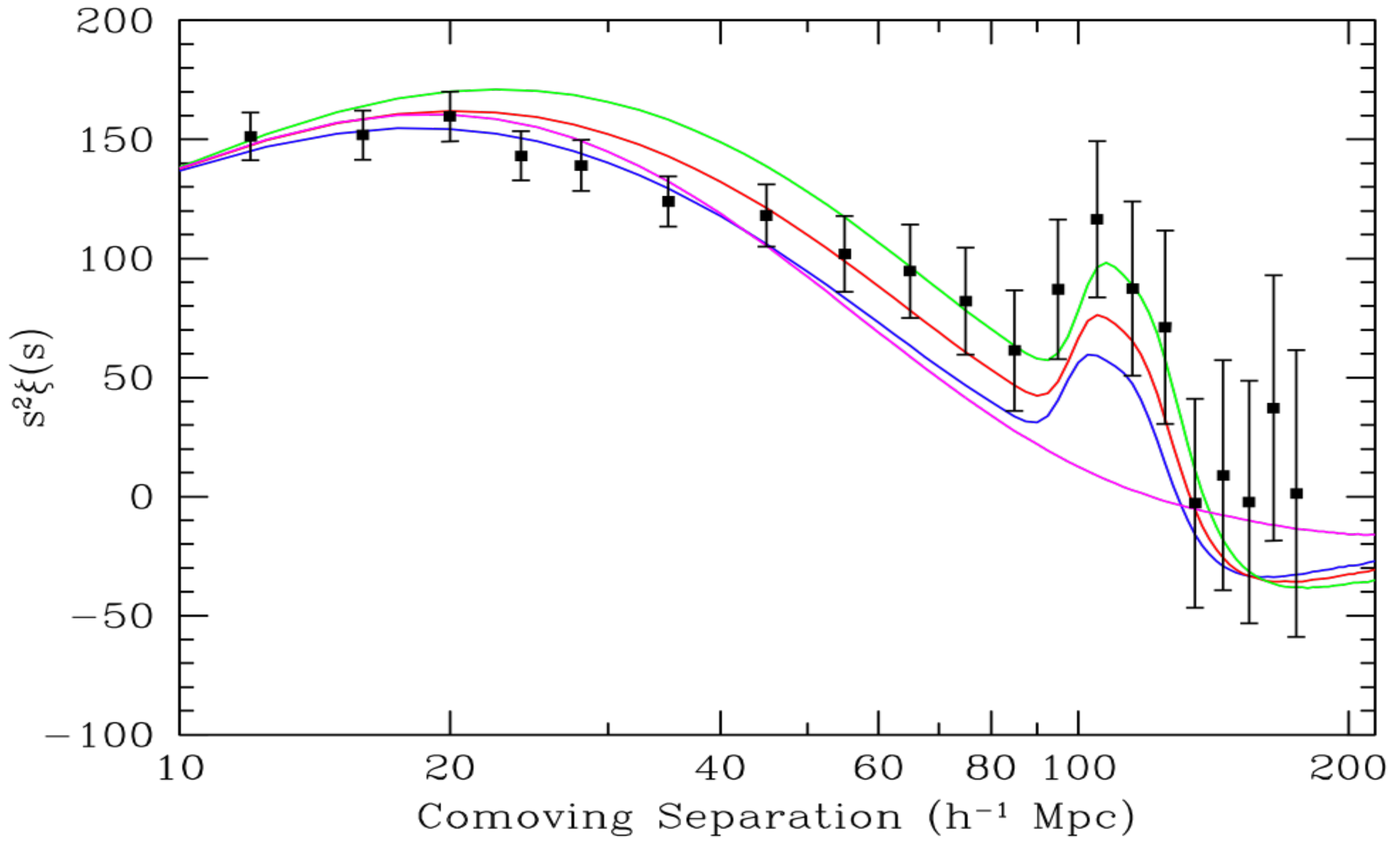


Fig. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

The stages of Big Bang to be mentioned

neutralization of plasma
production of CMB
T(then) about 1 eV
T(now) =2.7K
t(CMB) about 10^5 years

QCD phase transition
(no confinement and hadrons
for T<Tc=155 MeV

$$ct_{QCD} \sim 10km$$

$$t_{QCD} \sim 10^{-4}sec$$

electroweak phase transition
(no Higgs VEV at T<Tc)
Tc =160 GeV

$$t_{EW} \sim 0.9 \cdot 10^{-11} s, \quad ct_{EW} \approx 2.7\,\mathrm{mm}$$

Gravity waves generated by sounds from big bang phase transitions

Tigran Kalaydzhyan   Edward Shuryak

Phys.Rev.D 91 (2015) 8, 083502 • e-Print: 1412.5147

- QGP is transparent to dileptons/photons, Early Universe is likewise transparent to **gravity waves (GW)**. **Can those be used as "penetrating probes"?**
- long wave sounds, once produced, have very long lifetime. What are their interactions? Cascades?
- Can they be converted by the reaction sound+sound=> **GW** during this long time? **What is the expected amplitude?**
- **at what frequencies and how one can observe it?**

Gravity waves are the only penetrating probes of the Big Bang

$$\Omega_{GW} \sim \left(\frac{T}{M_P}\right)^2 (t_{life} T)$$

fraction of the GW energy density to total radiated from thermal particles if just thermal radiation
not observable!

$$tT \sim \frac{M_P}{T} \cdot \frac{1}{N_{DOF}^{1/2}} \sim 10^{18}$$

IR

UV

from Friedmann eqns for radiation-dominated era

macro-to-micro factor is very large,
but it cannot cancel smallness of the coupling:

perhaps other mechanism
of GW generation can do better!

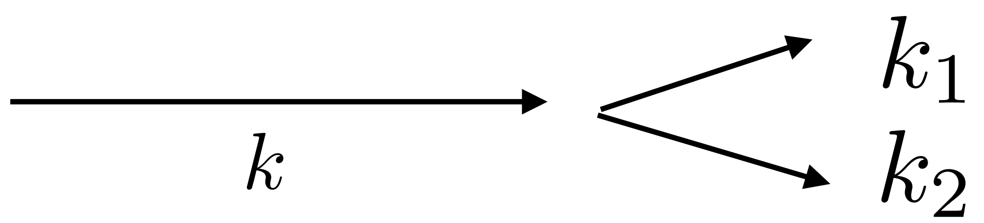
cascade of phonons leads to so called
inverse (toward IR, small k) **turbulent cascade**
which has **stationary attractor solution** known as

Kolmogorov-Zakharov power spectra

scenario 1: decay

if a^2>0, decays possible

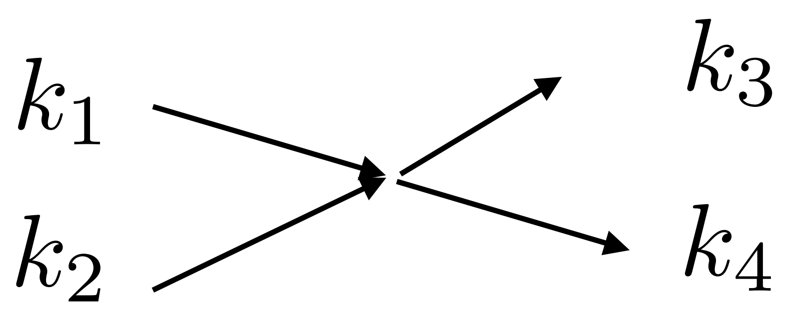
$$n_k \sim k^{-s}, \quad s_{decay} = 9/2$$



scenario 2: nodecay

if it is negative
and decays impossible
then 2<->2 scattering

$$s_{nondecay} = 10/3, 11/3$$



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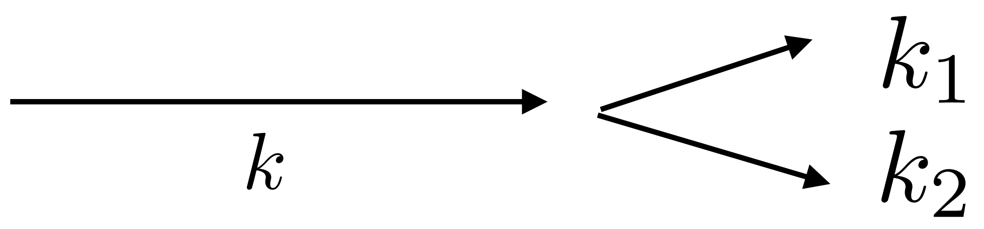

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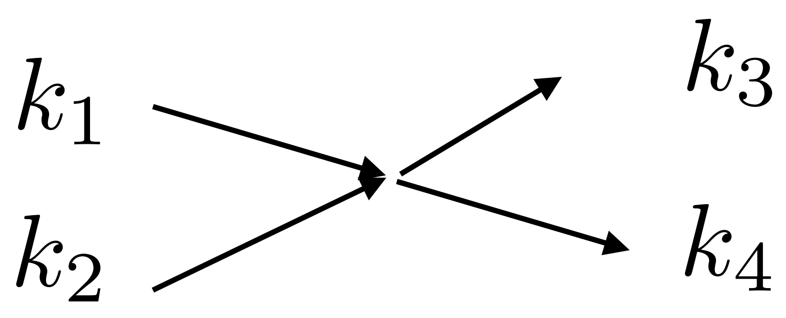

Earth's atmosphere also has
inverse cascade,
in which small vortices
add up toward IR
end of the spectrum
creating big stroms
at a cutoff scale R,
thousands of km
**Can similar cascade
goes in early Universe
up to horizon scale?**

Inverse acoustic cascade and gravitational wave production

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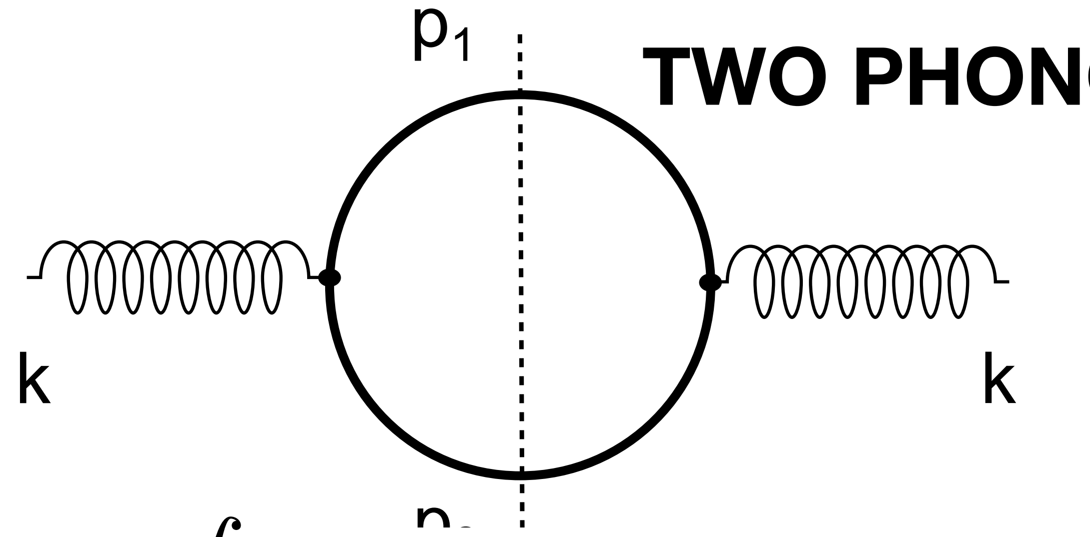
under certain conditions specified,
inverse acoustic turbulent cascade develops
producing a "large-scale storm" till
a cutoff at horizon

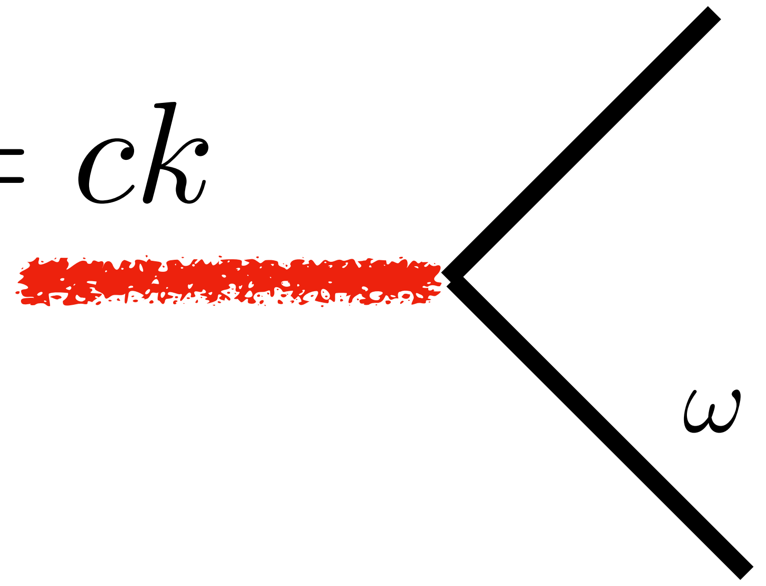
TWO PHONONS IN THE LOOP



$$G^{\mu\nu\mu'\nu'} = \int d^4x\, d^4y\, e^{ik_\alpha(x^\alpha - y^\alpha)} \langle T^{\mu\nu}(x)T^{\mu'\nu'}(y)\rangle\,.$$

phonon+phonon=> graviton

$\omega = ck$



$\omega = (c/\sqrt{3})k$

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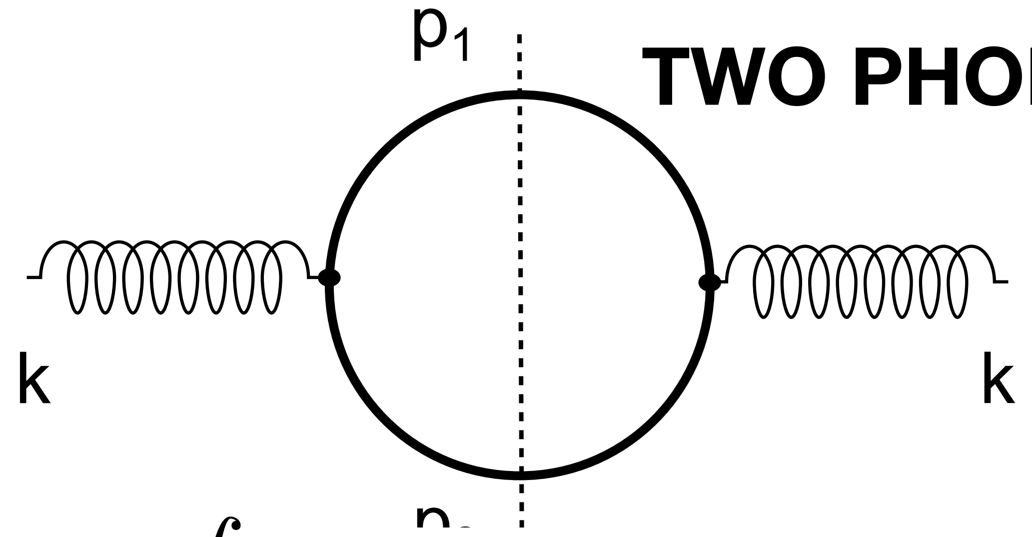

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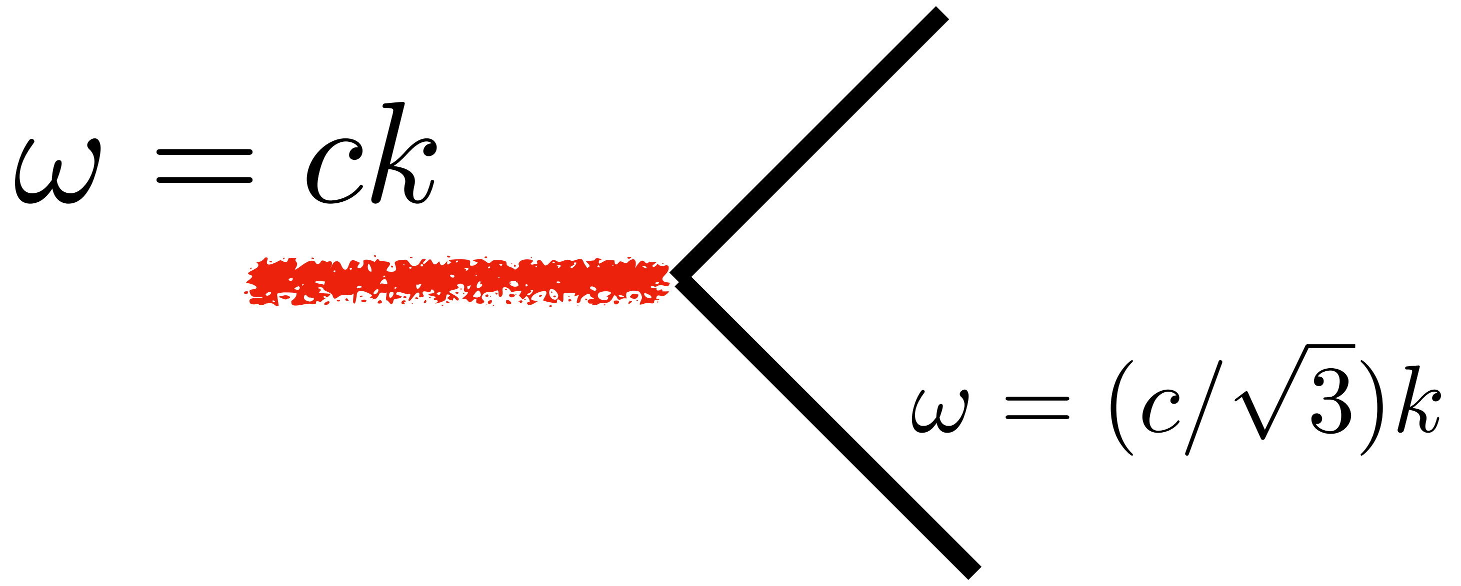
Collisions of two sound waves leads to
direct production of gravity waves
IN THE CASE OF QCD TRANSITION
THE CHARACTERISTIC TIME IS 1 YEAR
perhaps recently discovered

phonon+phonon=> graviton



Are the GW from the QCD phase transition era observable? How?

time 4 10^-5 s
redshift z =7.6*(10^11).

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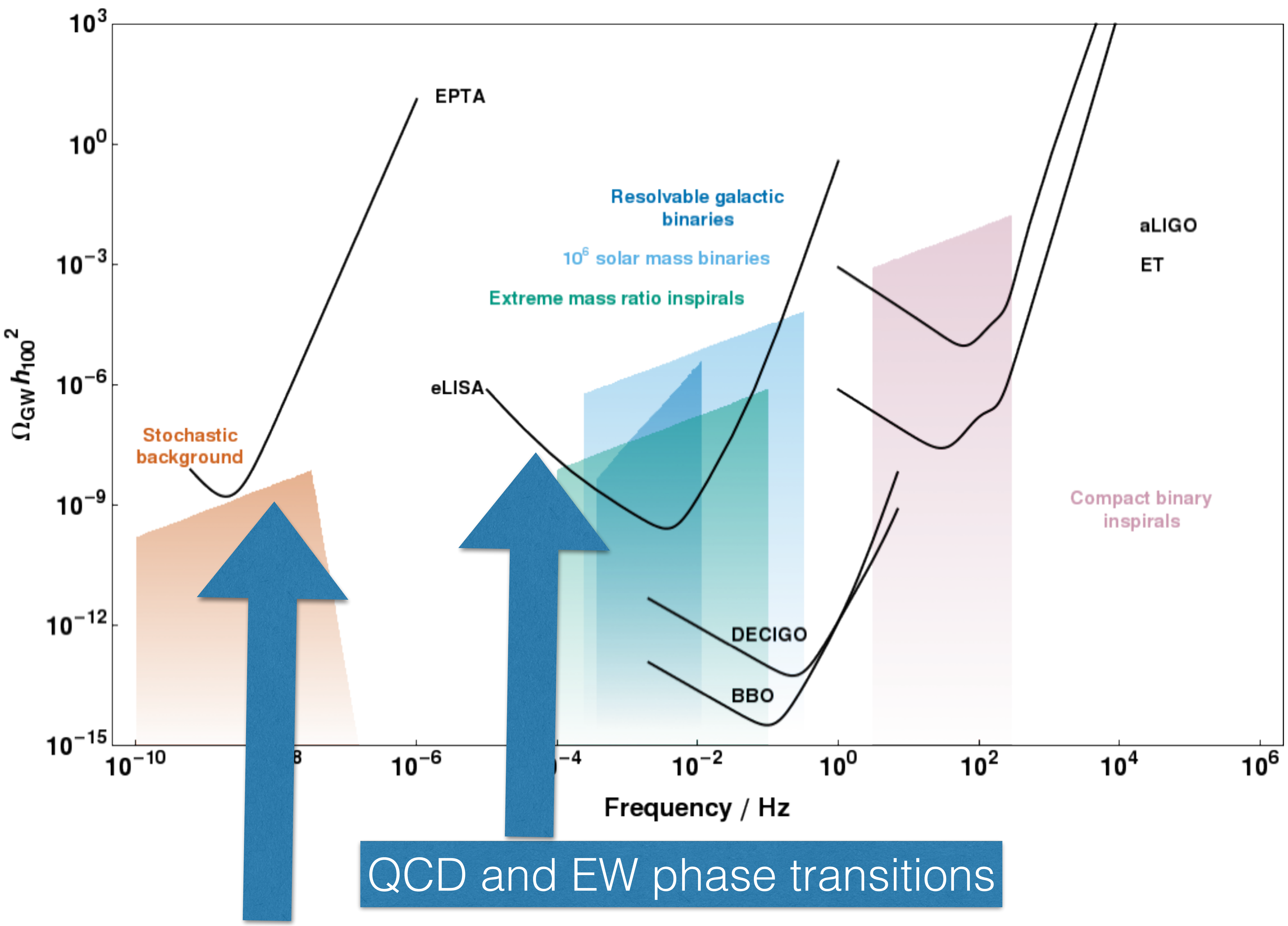
European Pulsar Timing Array
Parkes Pulsar Timing Array
North American Nanohertz Observatory for Gravitational Waves.

sources and sensitivity

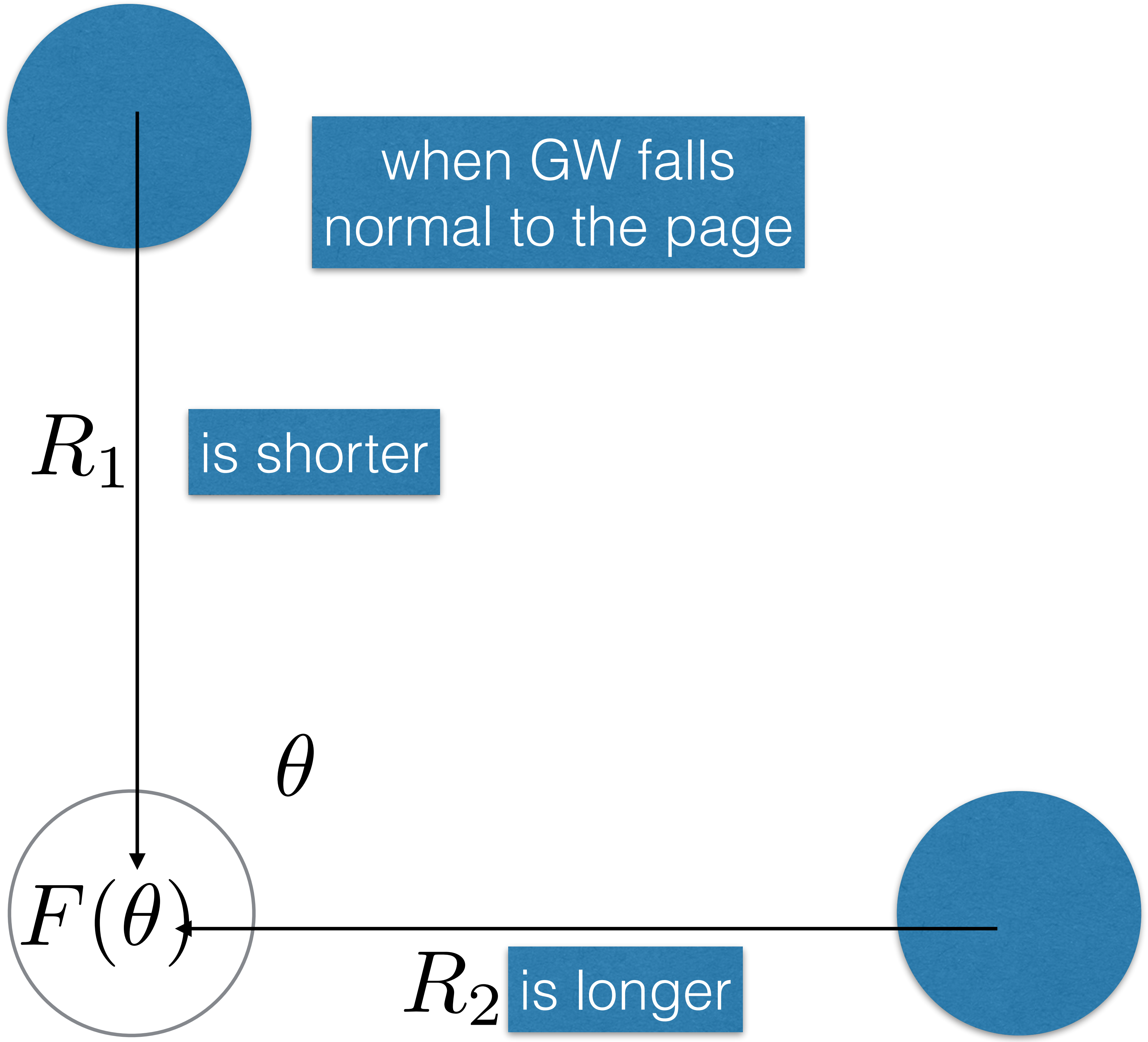


http://www.ast.cam.ac.uk/~rhc26/sources/

the idea of the pulsar method: angular correlations

there about 200
millisecond pulsars
discovered
(2013 was a record year)
30000 in Galaxy estimated

If Earth is in GW
and say R1 slightly
increases, then R2
at 90 degrees decreases



observer correlates phase
timing of all known millisec pulsar pairs

Searching for Gravitational Waves from Cosmological Phase Transitions with the NANOGrav 12.5-Year Dataset, NANOGRAV collaboration, arxiv 2104.13930

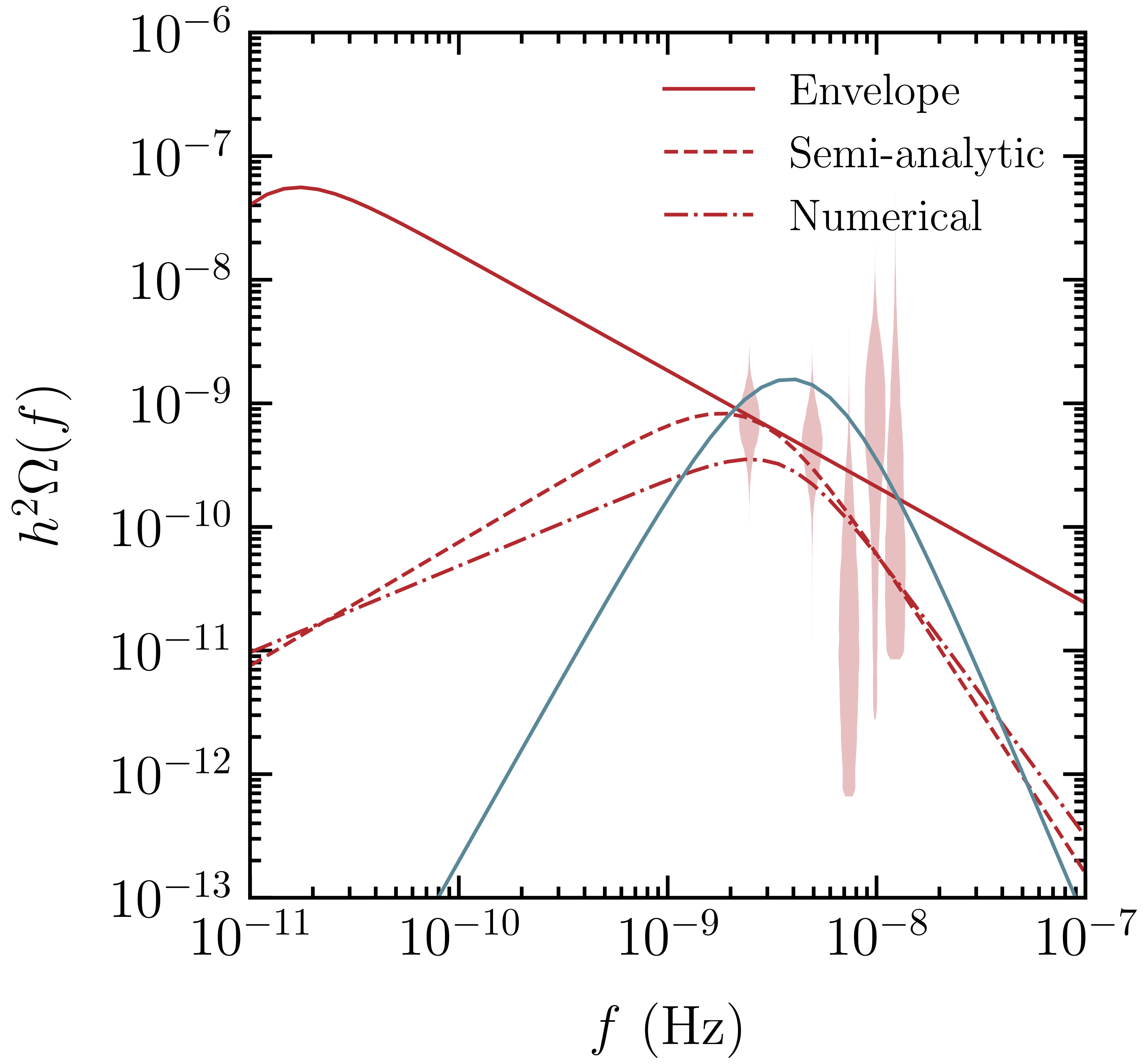


FIG. 2. Maximum likelihood GWB fractional energy-density spectrum for the BO (red) and SWO (blue) analyses compared with the marginalized posterior for the free power spectrum (independent per-frequency characterization; red violin plot) derived in NG12gwb. For the BO analysis we show the results derived by using the envelope (solid line), semi-analytic (dashed), and numerical (dot-dashed) spectral shapes. For the BO analyses the values of (α_*, T_*) for these maximum likelihood spectra are $(0.28, 0.7\,\mathrm{MeV})$ for the envelope results, $(1.2, 3.4\,\mathrm{MeV})$ for the semi-analytic results, and $(0.13, 14.1\,\mathrm{MeV})$ for the numerical results. While for the SO analysis we get $(6.0, 0.32\,\mathrm{MeV})$.

The first gravity waves with 1 year period were reported a year ago

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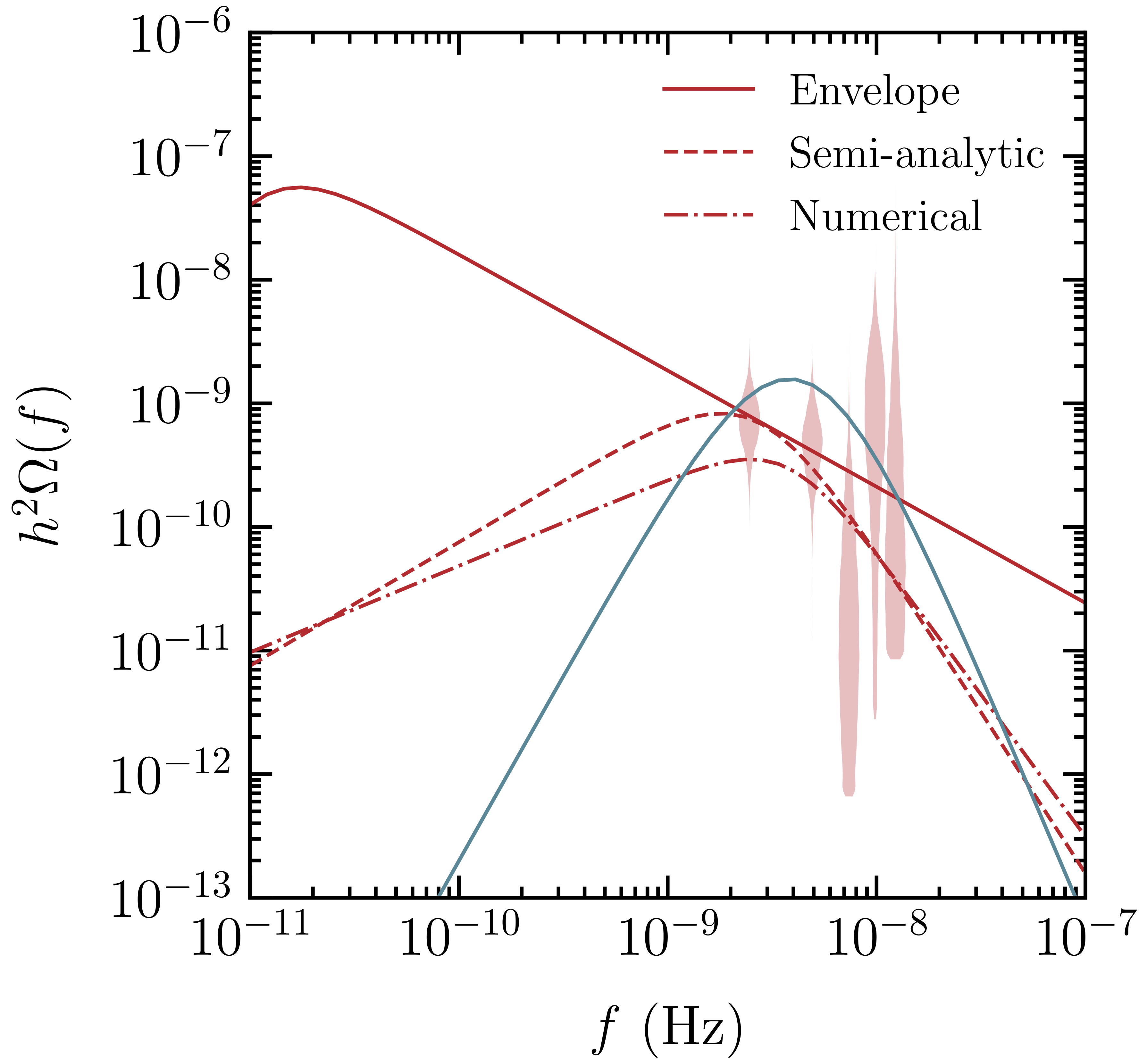

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Summary

Sounds of the Little Bang:

- are observed as azimuthal correlations
- “acoustic systematics” for harmonics of flow
- phase factor should produce oscillations
- they are well seen in Big Bang CMB
- predicted minimum at n about 7 seems to be there

- Sounds in the Big Bang
- Very long wavelength sound — limited by horizon only — have negligible dissipation: so complicated acoustic inverse cascade can take place: power spectra of the sound all the way to the IR
- The penetrating probe for Big Bang are gravity waves.
- Two sound waves on shell can produce one on shell GW. QCD transitions IR scale today is 1 year (hours).
- Pulsar timing /correlations have recently seen gravity waves at 1 year period range