QGP fireballs: from the smallest, to the largest

Edward Shuryak
Stony Brook

Colloquium in Max Plank Institute
Heidelberg, April 15,2015

Dedicated to 60-th birthday
of Johanna Stachel

we met about 30 years ago
in Germany

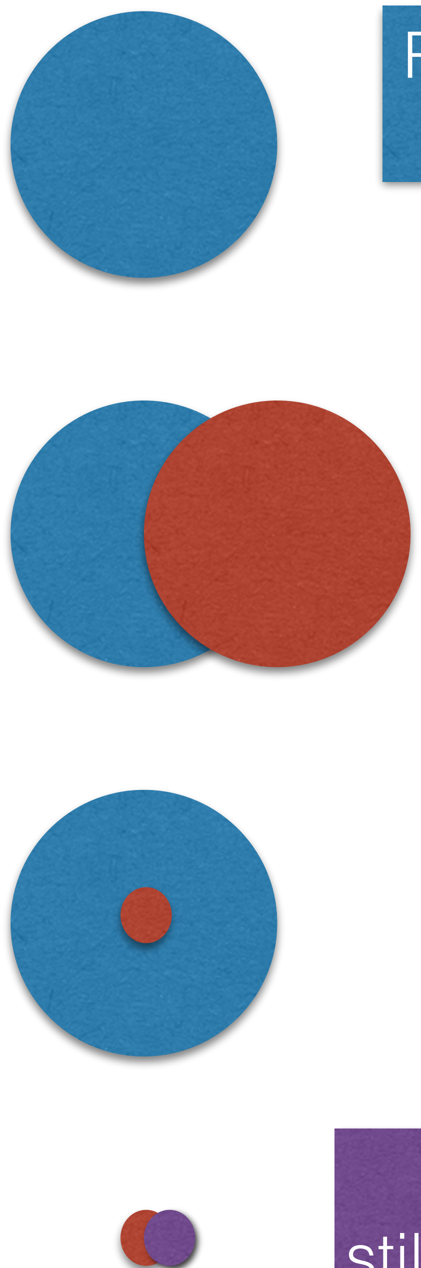
Iohanna was key organizer of QM88 in Lenox
Peter, Johanna took Gerry Brown and me,in their car,
to Stony Brook after the end of it…

In 1990 I moved
to Stony Brook myself
here they are at our home

outline

- Fireballs: Large, small and the smallest
- high multiplicity pp: HBT, radial flow, flow in HBT
- pA: Pomerons, strings, spaghetti, Lund model spaghetti collapse
- the penetrating probe of the Big Bang
- inverse acoustic cascade
- sound+sound => gravity wave

Fireballs: large, small and the smallest



R=6-7 fm
central

Large (AA):
AuAu… UU at RHIC,Brookhaven
PbPb collisions at LHC,CERN

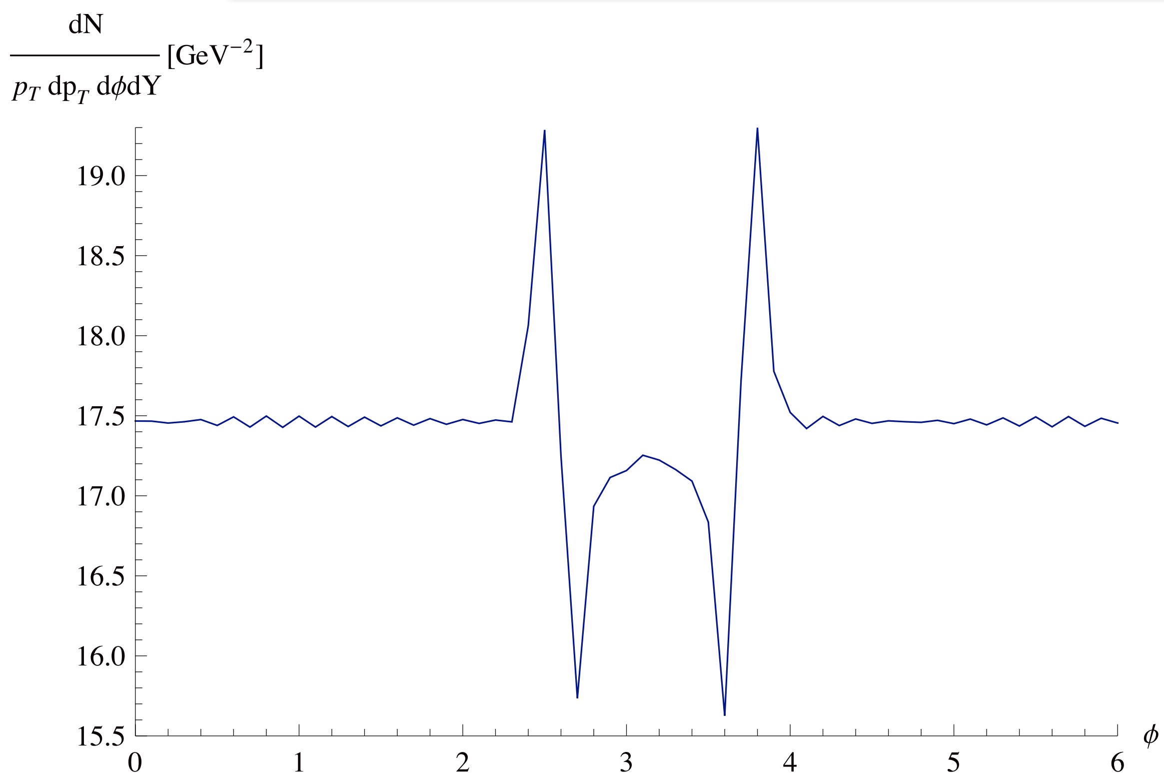
Hydrodynamical explosion
studied in detail since 2000
angular harmonics till m=6
are sounds with wave length R/m

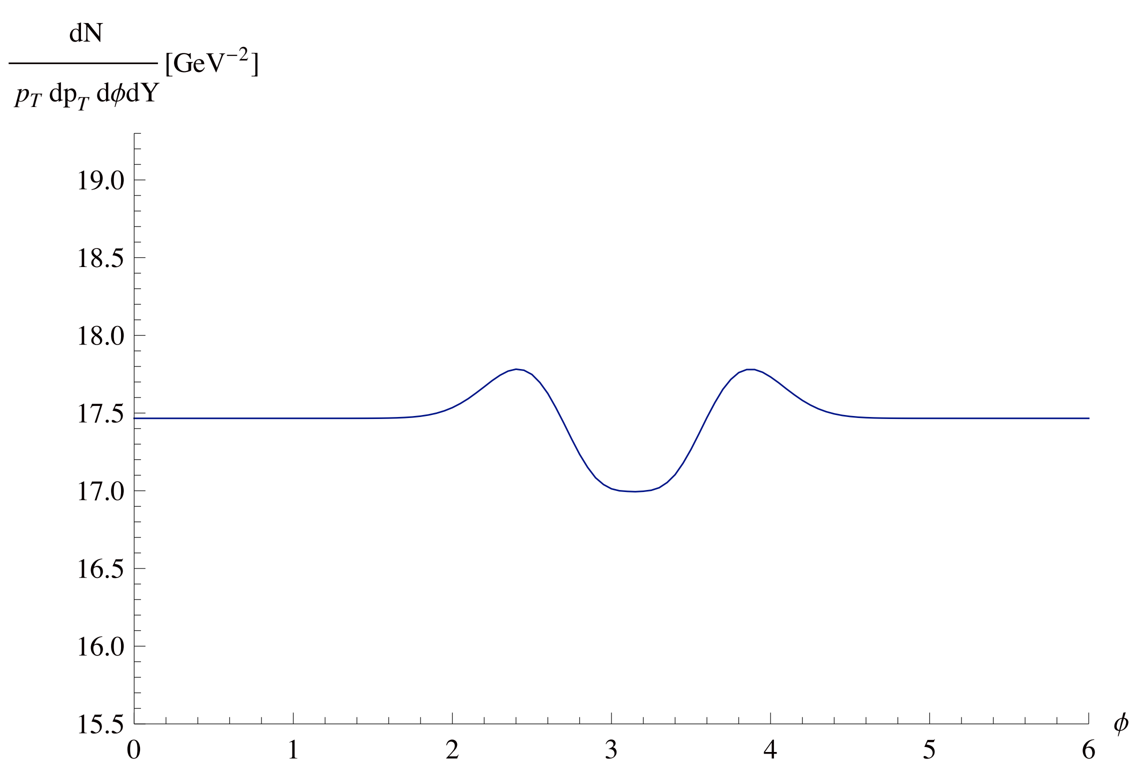
peripheral: b -> 2R
and size decreases to 0

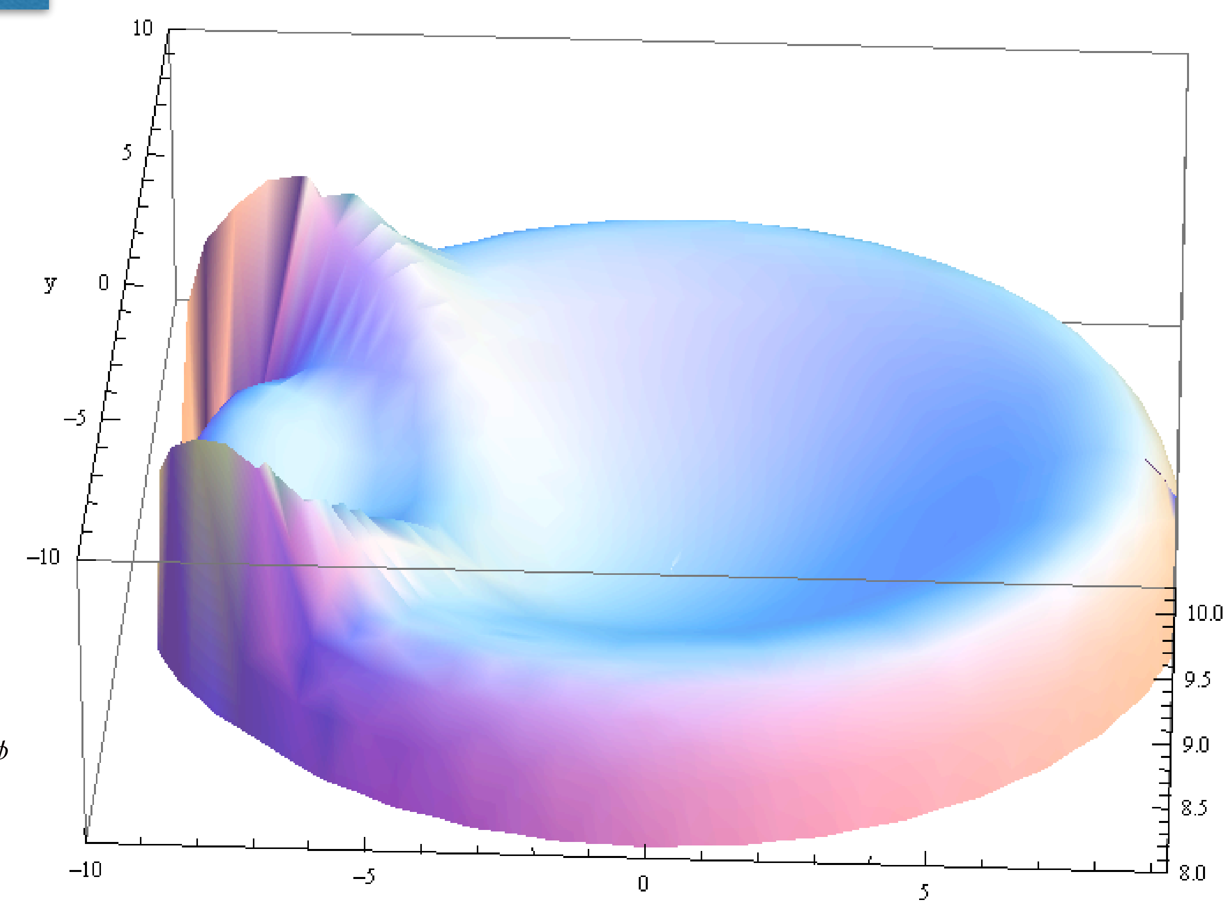
small: central pA
one nucleon collides with
about 20 others

The smallest: pp R=1 fm
still explodes at high multiplicity!

Single particle spectrum, without and with viscosity

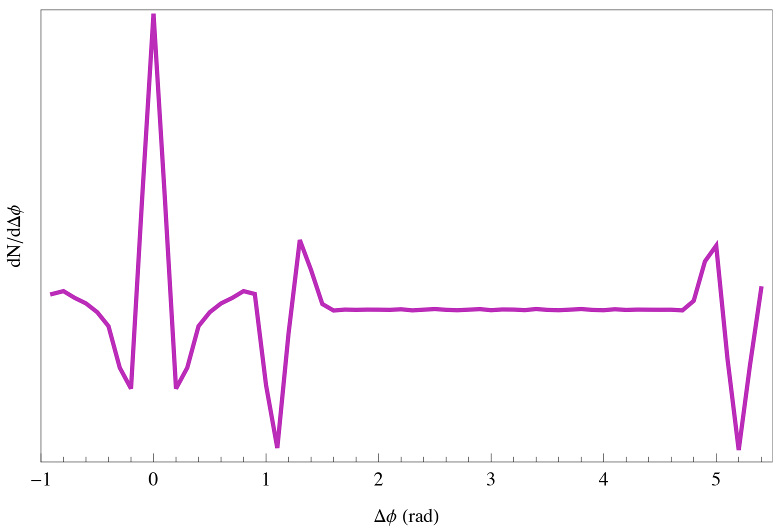


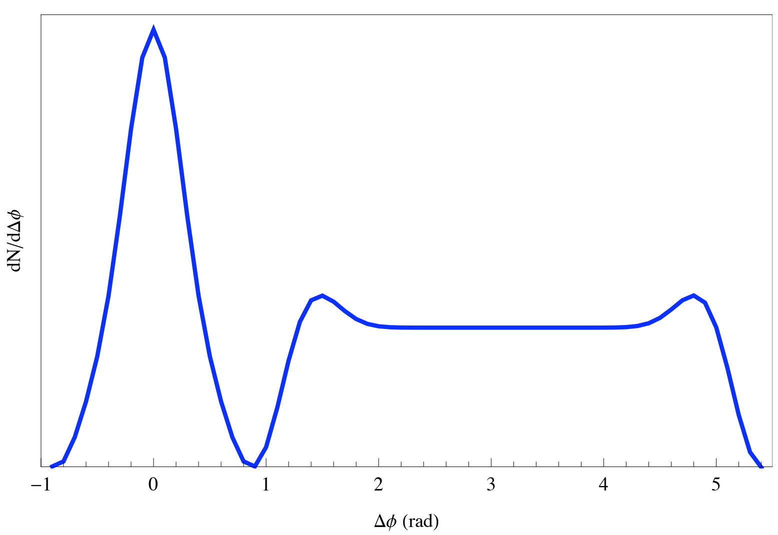


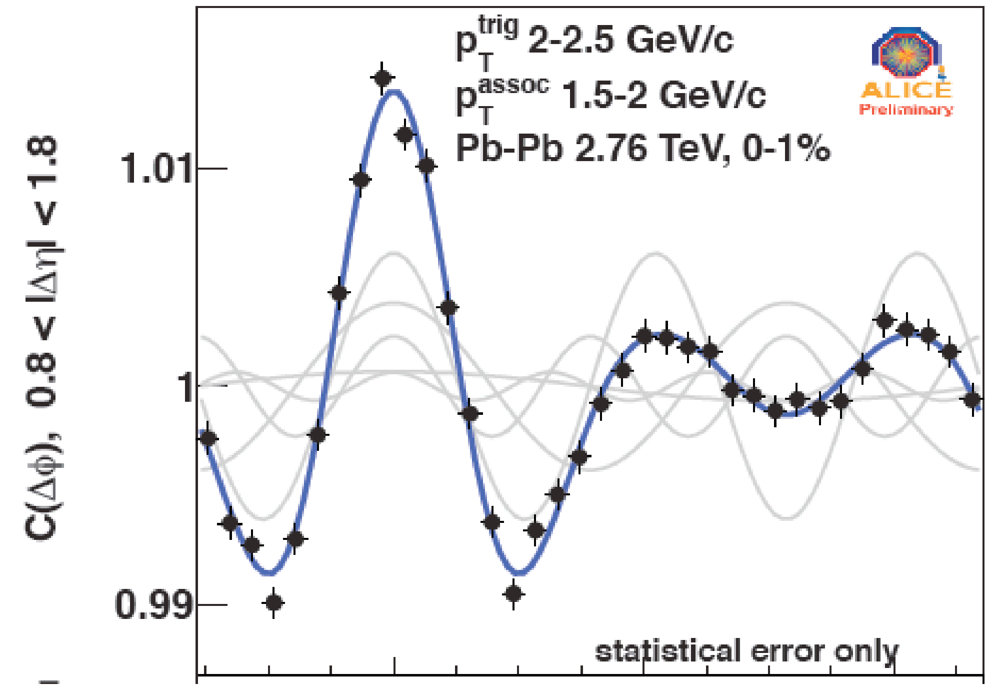


The modified freezeout Surface (right) leads to A modified angular distribution Of particles, with and without visco (left)

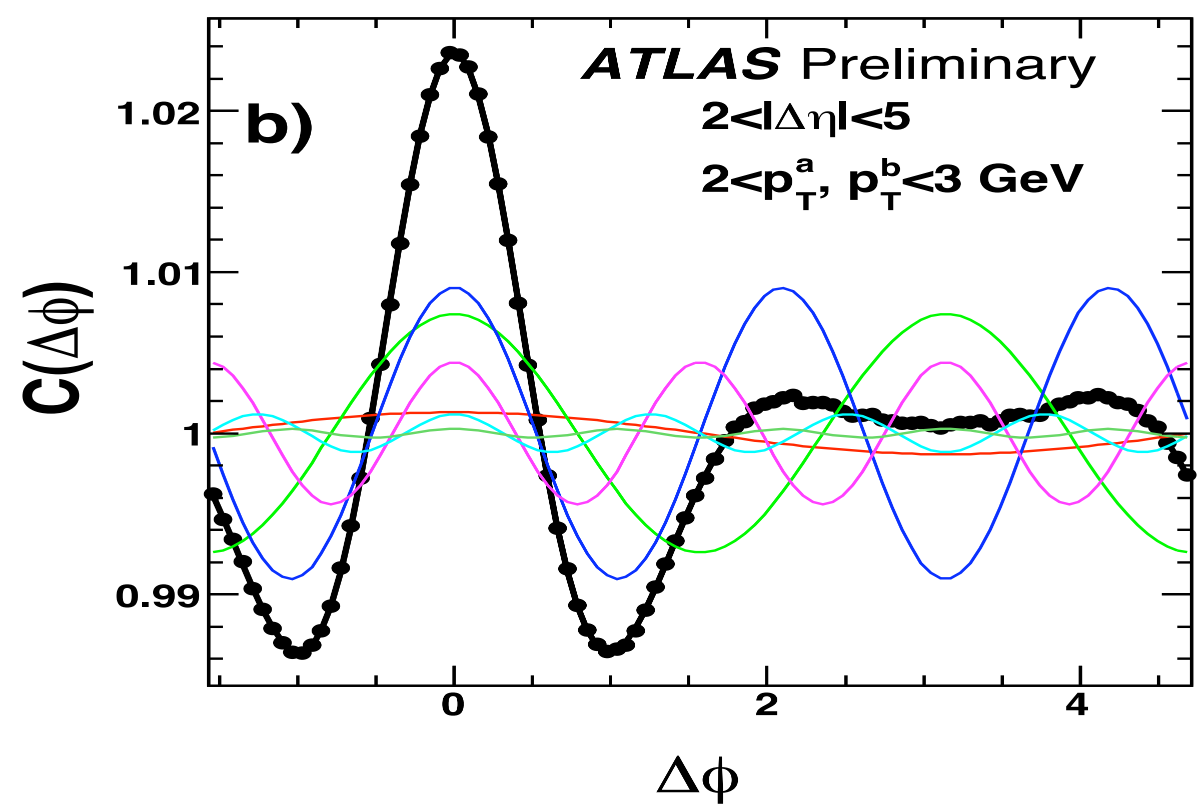
Left:4 pi eta/s=0, 2
Note shape change







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

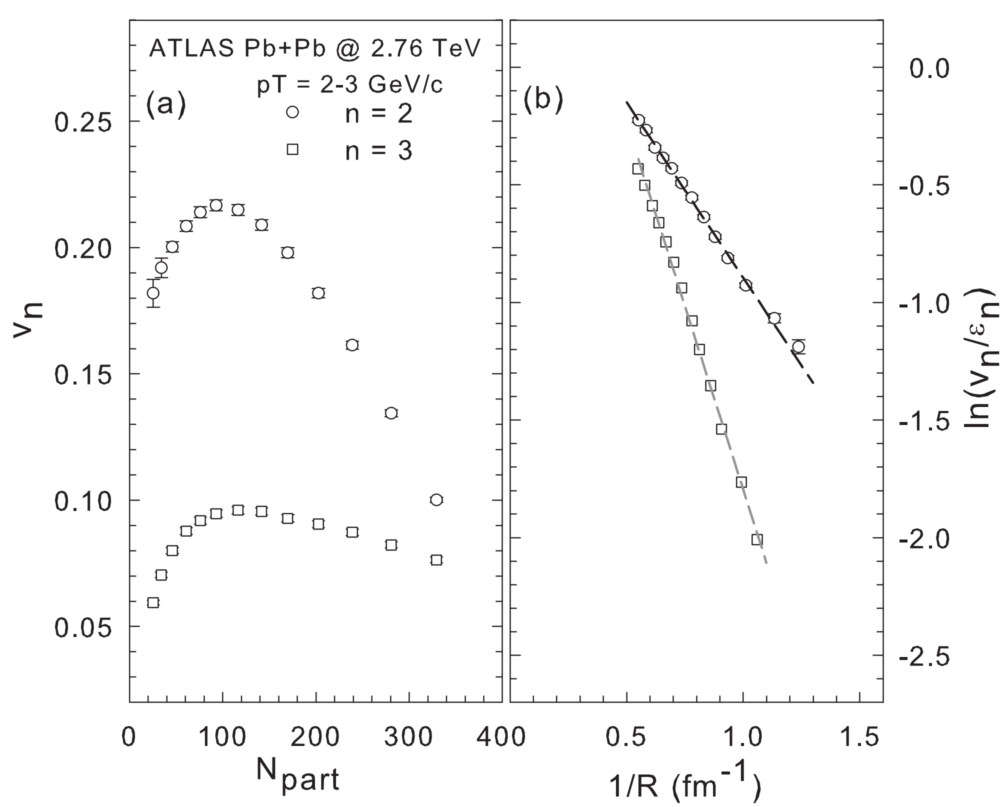


this result has been reported at QM before the data were presented

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



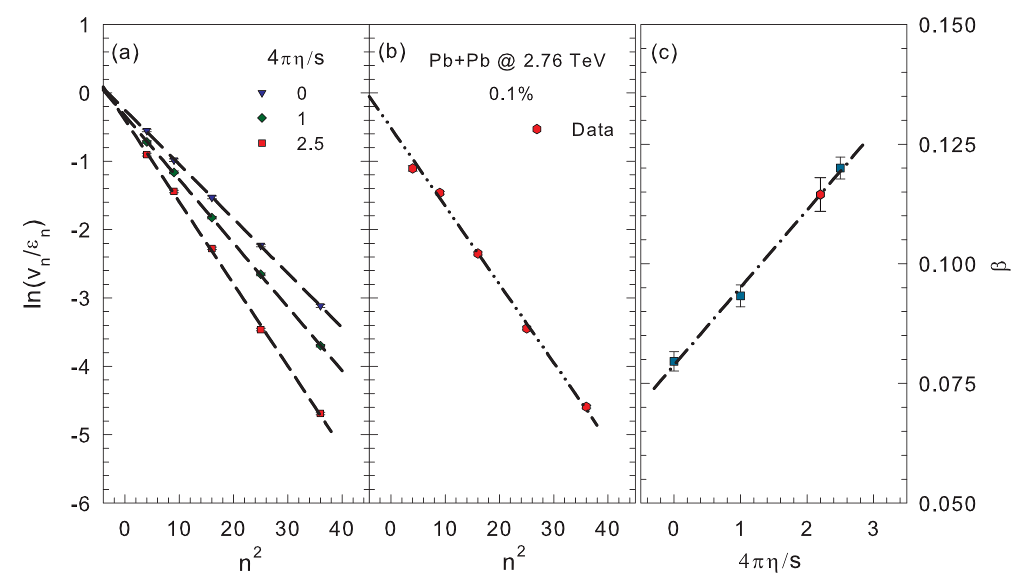


FIG. 3: (a) $ln(v_n/\epsilon_n)$ vs. n^2 from viscous hydrodynamical calculations for three values of specific shear viscosity as indicated. (b) $ln(v_n/\epsilon_n)$ vs. n^2 for Pb+Pb data. The $p_\perp$ -integrated v_n results in (a) and (b) are from ATLAS 0.1% central Pb+Pb collisions at sNN = 2.76 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

why is it important to study these small fireballs?

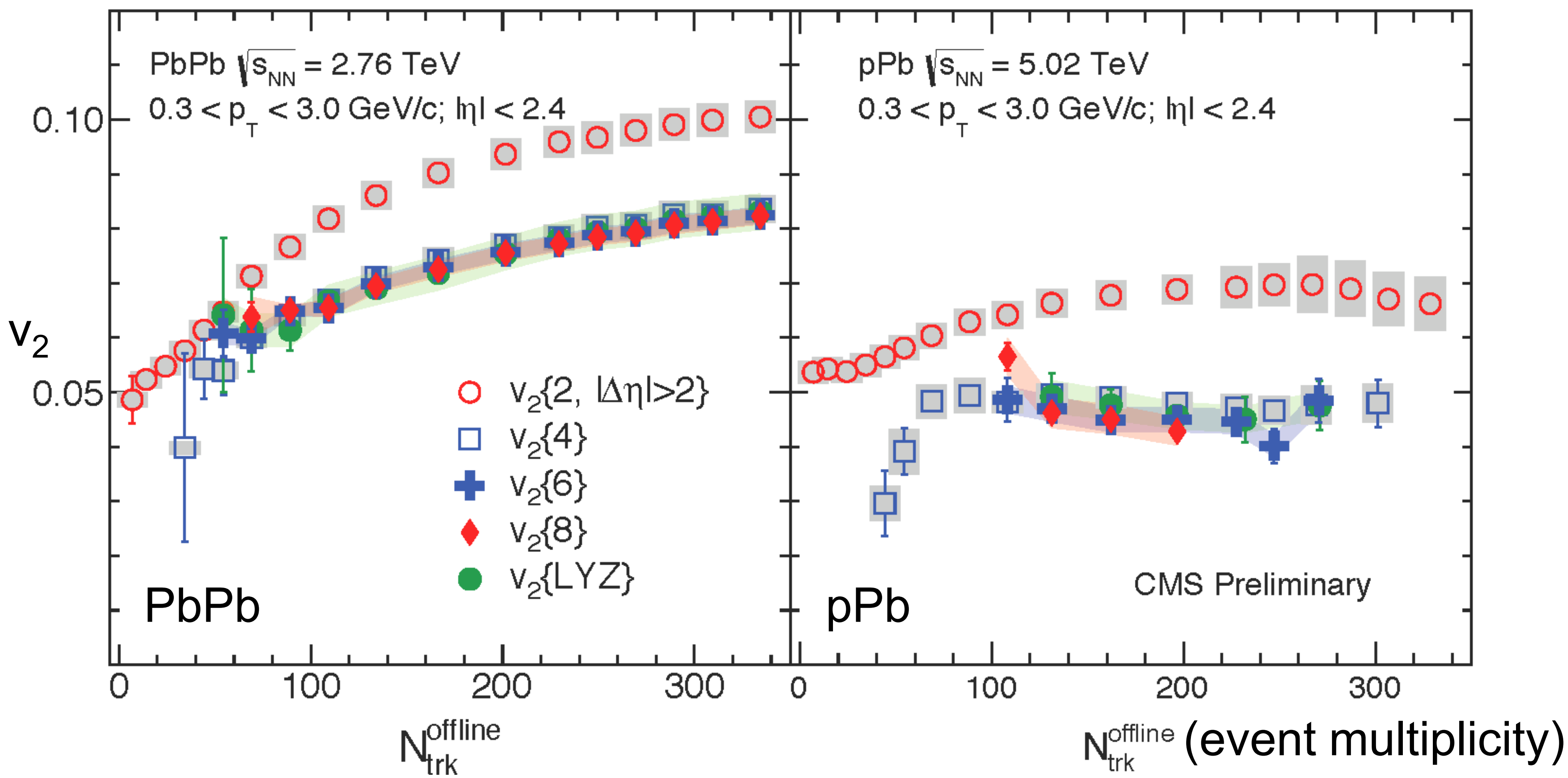
- The usual fluids (such as air, water) can be taken to an atomic scale, at which they are no longer fluids

- Quark-Gluon Plasma (QGP) is, in the first approximation, **“scale invariant”**. It is made of massless quarks and gluons and the only parameter is the temperature T: **p=O(T^4),density=O(T^3),viscosity=O(T^3) rescaling R->R/k,T->kT changes nothing**

- (Only in the **second (quantum loops) approximation** the so called running of the coupling appears, and **very very hot QGP** will become weakly coupled, due to ``asymptotic freedom”. This is seen in lattice numerical simulations but we will never see it in experiment since such T is too high)

- These small fireballs are the hottest object ever produced in laboratory!
Hydrodynamics at its edge is of theoretical interest:
it is holographically dual to small quantum black holes which string theorists want to study but cannot reach

Collectivity of the elliptic flow:



The second harmonics V2 of the azimuthal flow can be measured using 2,4,6,8… particle correlators
If the result is the same, ALL particles have this features
This works for peripheral AA but also for pA!

The v2 magnitude tells us about fluctuations in the initial state in AA it is Glauber wounded nucleons: what is it in pA and pp?

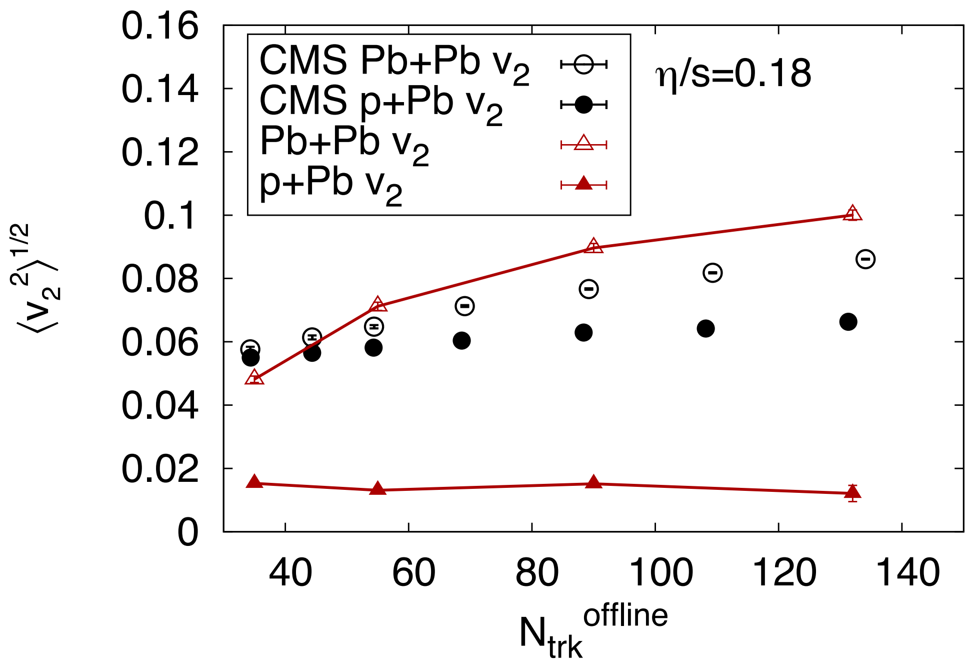
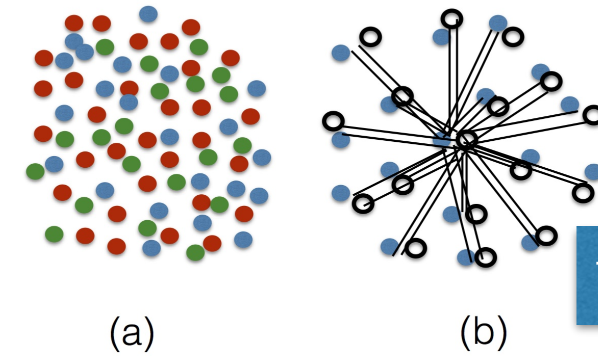


FIG. 25: (Color online) Multiplicity dependence of the root-mean-square elliptic flow coefficient v2 in Pb+Pb (open symbols) and p+Pb collisions (filled symbols) from the IP-Glasma+music model (connected triangles) compared to experimental data by the CMS collaboration.

IP glasma



16 Pomerons

FIG. 27: Sketch of the initial state in central pA collisions. The plot (a) corresponds to IP-glasma model, with colored circles representing multiple gluons. Fig.(b) is for $N_p = 16$ Pomerons, each represented by a pair of cold strings. The open circles are quarks and filled blue circles are diquarks.

where $N = N_p N_g$ for (a) and only $N = N_p$ for (b).

$$\epsilon_n \sim \frac{1}{\sqrt{N}} \qquad \frac{\epsilon_n^{(b)}}{\epsilon_n^{(a)}} \sim \frac{1}{\sqrt{N_g}} \sim 4$$

conclusion: no glasma in pA but Pomerons/strings instead

femtoscopy of
THE SMALLEST DROPS OF QGP
shows they are different:

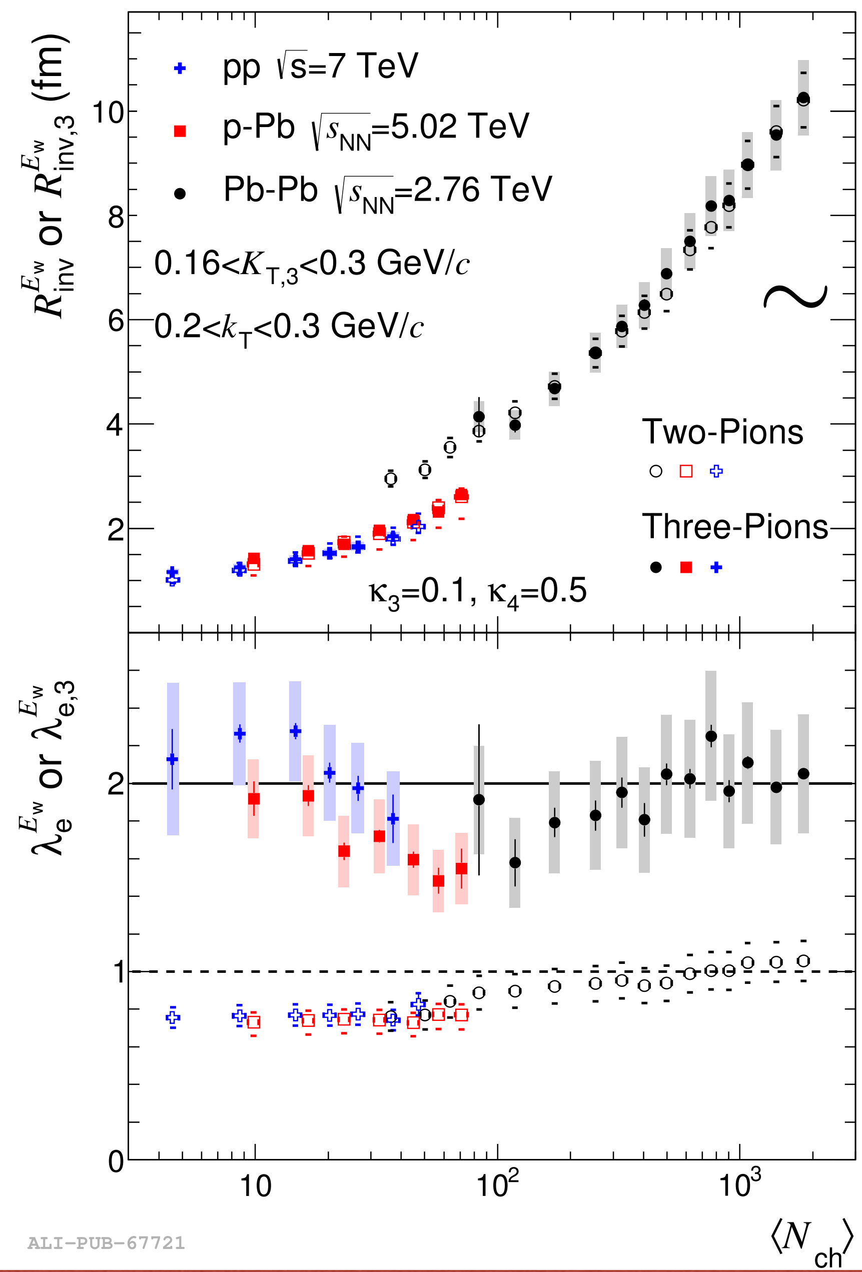
AA data follow N^1/3 curve => fixed freeze out density

Yet the pp, pA data apparently fall on a different line

Why do those systems get frozen at higher density, than those produced in AA?
(hint #1)

$$< n\sigma v >= \tau_{coll}^{-1}(n) \sim \tau_{expansion}^{-1} = \frac{dn(\tau)/d\tau}{n(\tau)}$$

So, more “explosive” systems, with larger expansion rate, freezeout earlier, at higher density.



$\sim N_{ch}^{1/3}$

(up-
unc-

Where is the room for that, people usually ask, given that even the final size of these objects is not large but even smaller than in peripheral AA, which has weak radial flow.
Well, the only space left is at the beginning: those systems must start accelerating earlier, from even smaller size,

Femtoscopic Signature of Strong Radial Flow in High-multiplicity *pp* Collisions

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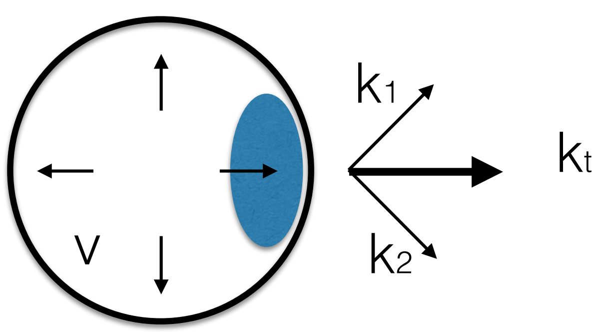
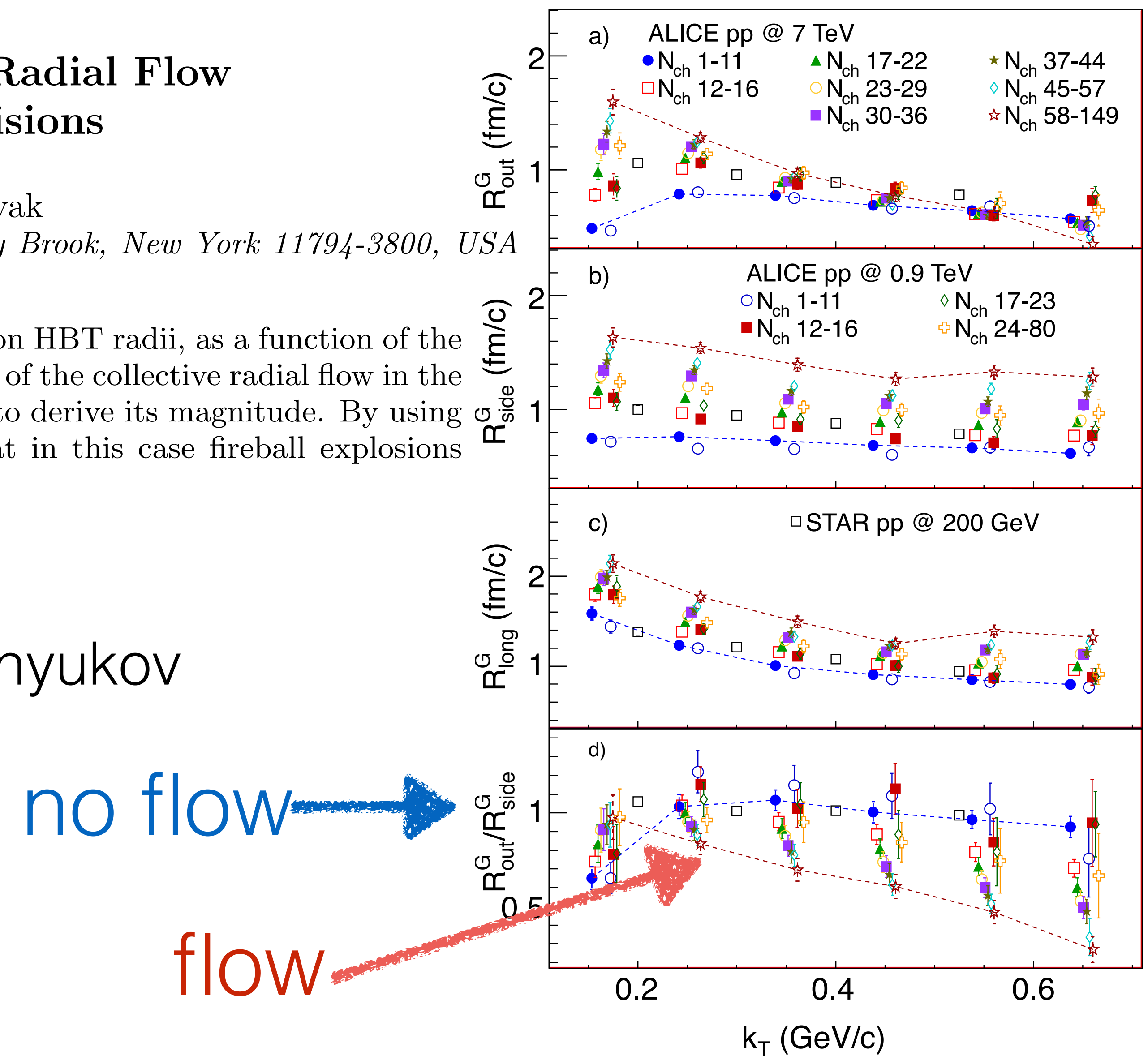
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

(Dated: December 2, 2014)

Hydrodynamic simulations are used to calculate the identical pion HBT radii, as a function of the pair momentum k_T. This dependence is sensitive to the magnitude of the collective radial flow in the transverse plane, and thus comparison to ALICE data enables us to derive its magnitude. By using hydro solutions with variable initial parameters we conclude that in this case fireball explosions starts with a very small initial size, well below 1 fm.



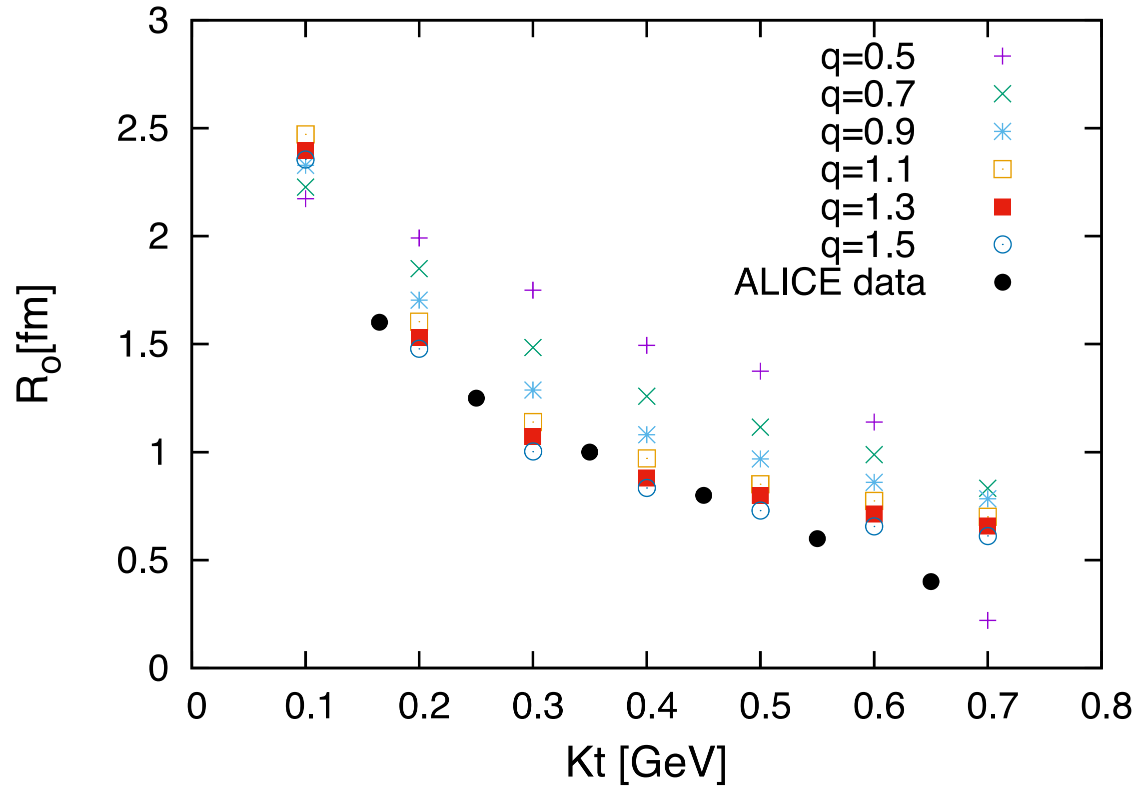
Makhlin,Sinyukov



blue-shifted source has a different shape and size

For most multiplicity bins the radii do not depend on kt of the pair, but the largest multiplicity one shows strong reduction: this is a signature of the radial flow

momentum
rom ALIC



Gubser solution at early time +numerical hydro at later stages

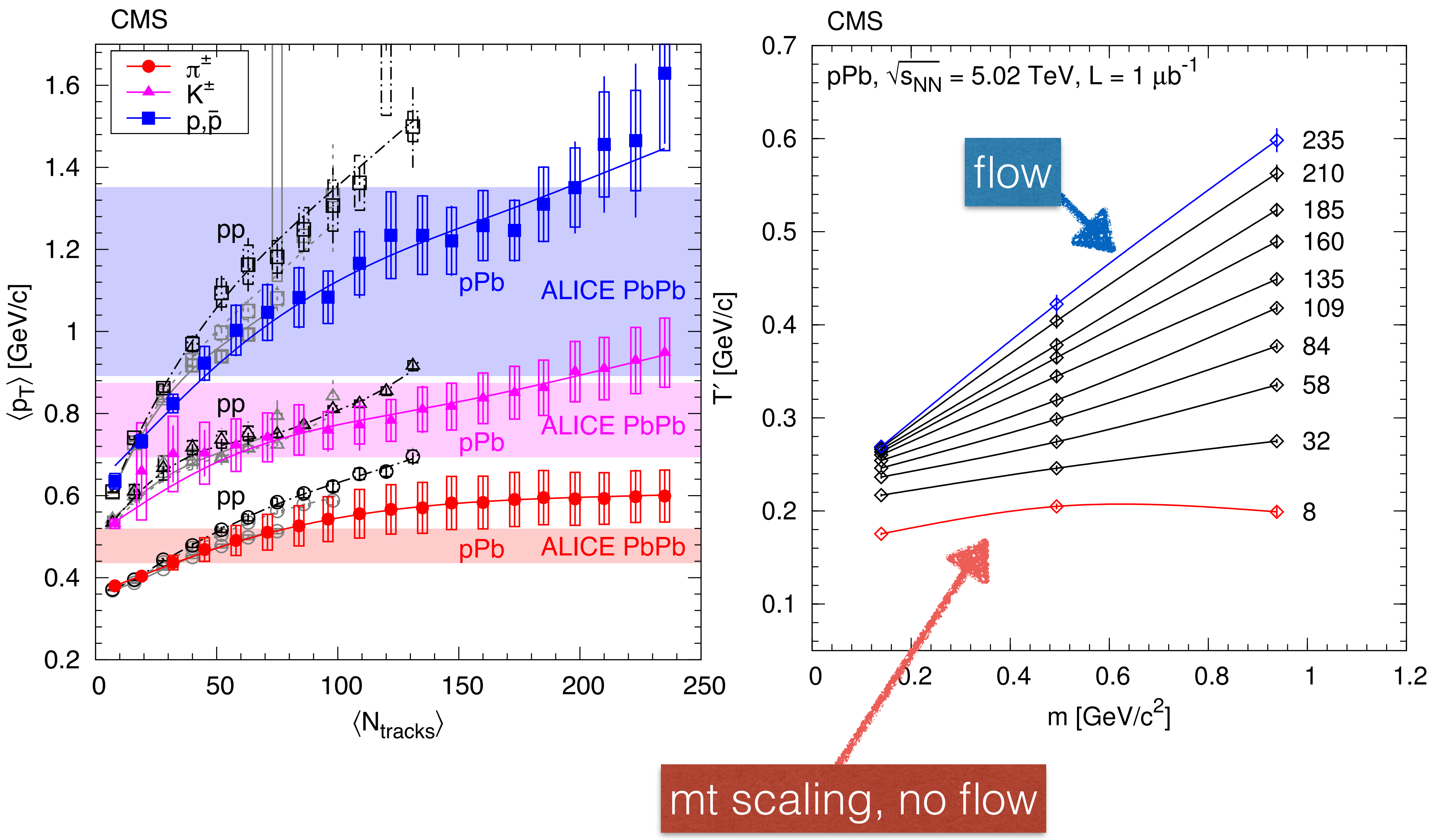
$$t = q\bar{\tau}, \quad r = q\bar{r}$$

$$\frac{\epsilon}{q^4} = \frac{\hat{\epsilon}_0 2^{8/3}}{t^{4/3}\left[1 + 2(t^2 + r^2) + (t^2 - r^2)^2\right]^{4/3}}$$

$$v_\perp(t, r) = tanh(y_\perp) = \frac{2tr}{1 + t^2 + r^2}$$

conclusion: in order to describe ALICE femtoscopy pp data one needs very strong flow
=> surprisingly small initial size1/q=2/3 fm

the radial flow



PHYSICAL REVIEW C **88**, 044915 (2013)

High-multiplicity *pp* and *pA* collisions: Hydrodynamics at its edge

Edward Shuryak and Ismail Zahed

We predicted the radial flow in pp/pA to be even stronger than in central AA

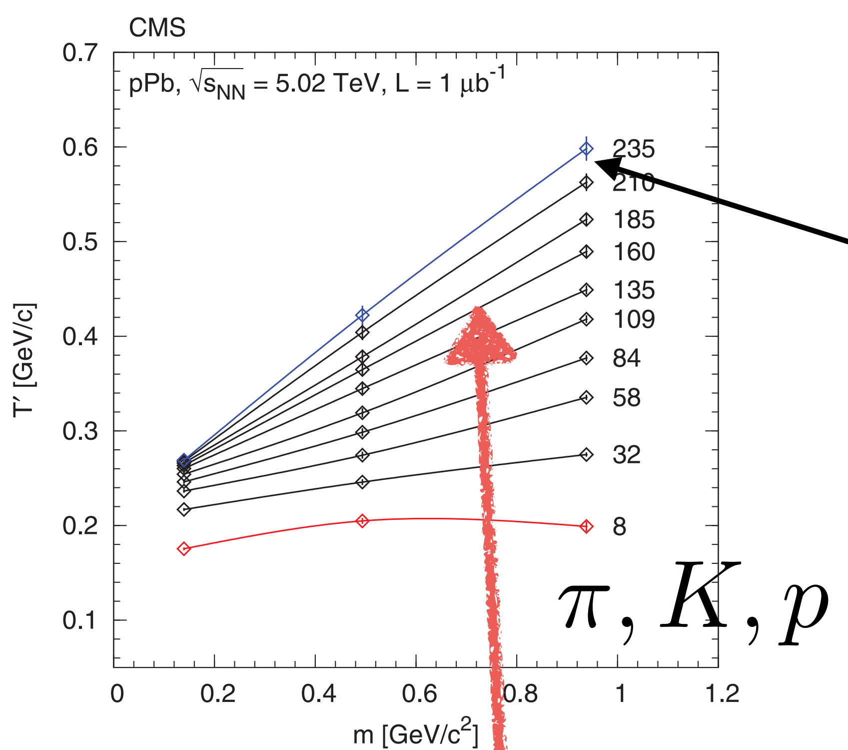


FIG. 8. (Color online) The slopes of the $m_\perp$ distribution T' (GeV) as a function of the particle mass, from [13]. The numbers on the right

Not the Mt scaling at large Ntr => not a large Qs but a collective flow: p=m v

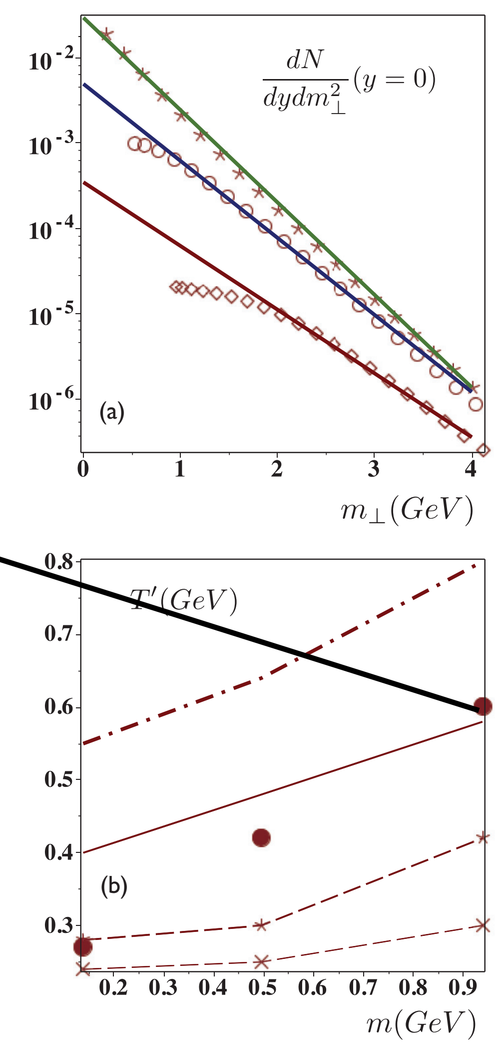


FIG. 9. (Color online) (a) A sample of spectra calculated for π, K, p, top-to-bottom, versus $m_\perp$ (GeV), together with fitted exponents.(b) Comparison of the experimental slopes $T'(m)$ versus the particle mass m (GeV). The solid circles are from the highest multiplicity bin data of Fig. 8, compared to the theoretical predictions. The solid and dash-dotted lines are our calculations for freeze-out temperatures $T_f = 0.17, 0.12$ GeV, respectively. The asterisk-marked dashed lines are for Epos LHC model, diagonal crosses on the dashed line are for AMTP model.

some hydro underpredict the radial flow

the strength of flow does not follow the (naive) ordering of the entropy density

Let us summarize those (naive) estimates: in terms of the initial entropy density one expects the following order of the densities

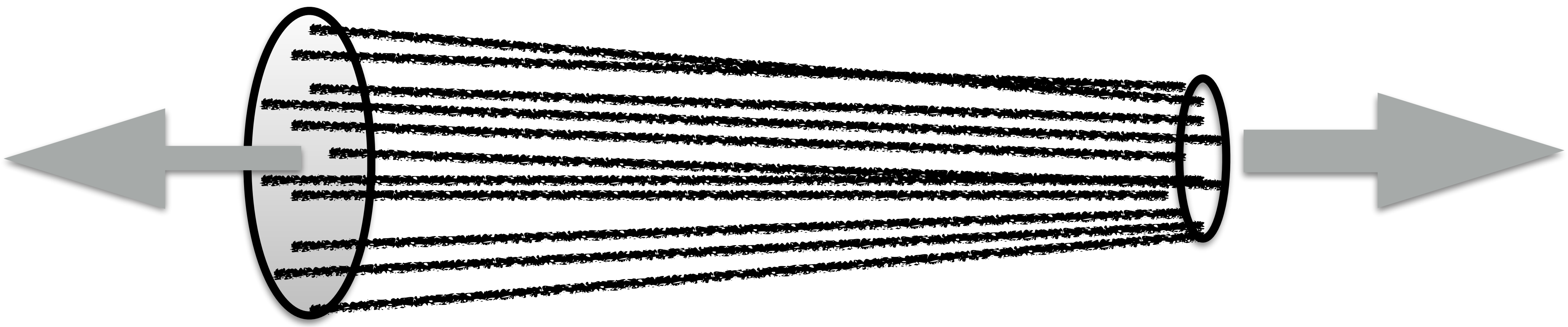
$$\frac{dN^{pA}_{maximal}}{dA_\perp} \sim \frac{dN^{AA}_{peripheral}}{dA_\perp} \ll \frac{dN^{AA}_{central}}{dA_\perp} \ll \frac{dN^{pp}_{maximal}}{dA_\perp} \quad (27)$$

and may thus expect that the radial flow follows the same pattern. The data however show it is *not* the case.

The "radial flow puzzle" for central pA

the simplest multi-string state: the spaghetti

$2N_P$



N(strings)=2N(Pomerons)

in small multiplicity bins strings are broken independently (the Lund model),

but one should obviously think about their interaction if their number grows

string interaction via sigma meson exchange

our fit uses
the sigma mass
600 MeV

$$\frac{\langle \sigma(r_\perp) W \rangle}{\langle W \rangle \langle \sigma \rangle} = 1 - C K_0(m_\sigma \tilde{r}_\perp)$$

$$\tilde{r}_\perp = \sqrt{r_\perp^2 + s_{string}^2}$$

T. Iritani, G. Cossu and S. Hashimoto, arXiv:1311.0218

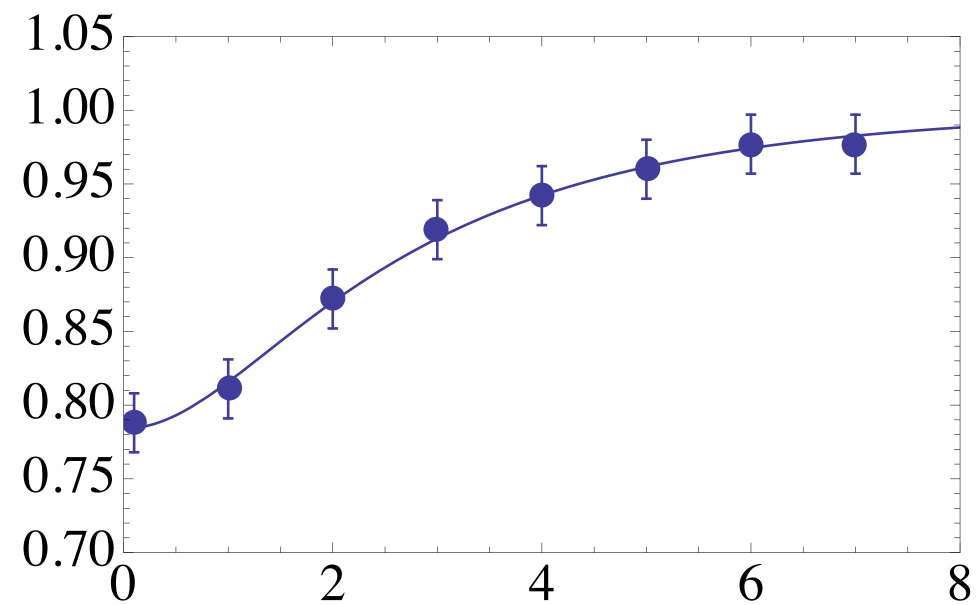


FIG. 2. (Color online). Points are lattice data from [12], the curve is expression (8) with $C = 0.26$, $s_{string} = 0.176$ fm.

So the sigma cloud around a string is there!

Reminder: sigma-related attraction holds together atomic nuclei
nucleons resist compression, but strings do not

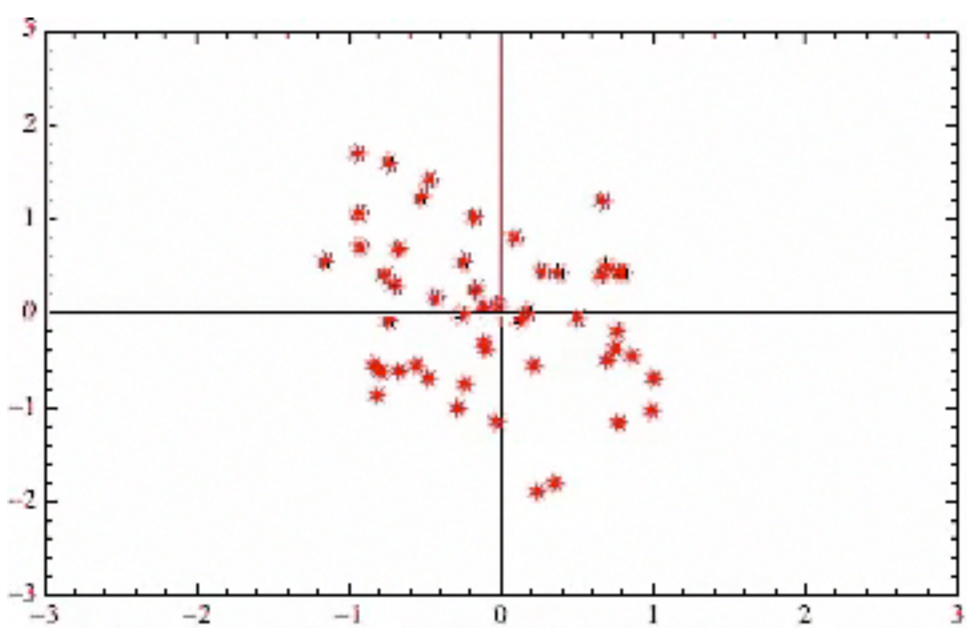
2d spaghetti collapse

Basically strings can be viewed as a 2-d gas of particles with unit mass and forces between them are given by the derivative of the energy (8) , and so

$$\ddot{\vec{r}}_i = \vec{f}_{ij} = \frac{\vec{r}_{ij}}{\tilde{r}_{ij}}(g_N \sigma_T) m_\sigma 2 K_1(m_\sigma \tilde{r}_{ij}) \qquad (19)$$

$$E_{tot} = \sum_i \frac{v_i^2}{2} - 2 g_N \sigma_T \sum_{i>j} K_0(m_\sigma r_{ij})$$

with $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and “regularized” $\tilde{r}$ (9).



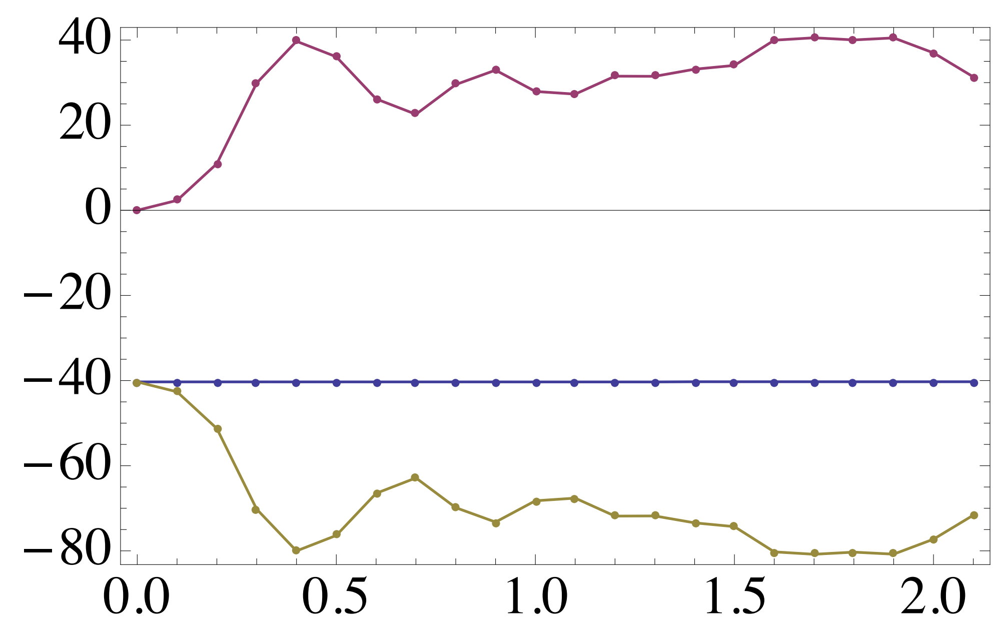


FIG. 4. (Color online) The (dimensionless) kinetic and potential energy of the system (upper and lower curves) for the same example as shown in Fig. 6, as a function of time t(fm). The horizontal line with dots is their sum, namely E_{tot}, which is conserved.

the penetrating probes of the Little Bang

- quarks and gluons have small mean free path, but **photons/dileptons** have little re-scattering: thus they can bring us an information about the whole evolution, not just at the freezeout (ES,1978)

e.g. photon production is due to strong Compton and annihilation $qg \to q\gamma, \bar{q}g \to \bar{q}\gamma, \bar{q}q \to g\gamma$ is

$$dN_\gamma / d^4x \sim \alpha\alpha_s T^4 \quad (4)$$

and thus their accumulated density normalized to the entropy density of matter $s_{QGP} \sim T^3$ is of the order of

$$\frac{\int dt dN_\gamma / d^4x}{s_{QGP}} \sim \alpha\alpha_s (t_{life} T) \quad (5)$$

where t_{life} is the fireball lifetime. Small QED and QCD coupling constants in front are thus partly compensated by large $(t_{life} T) \gg 1$, called "macro-to-micro ratio",

If one puts QGP in a can for a long time a lot of photons can be produced

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

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

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 some enhancement mechanism of GW generation can be invented, to make it detectable…

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

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

→

3*10^7s=1 year

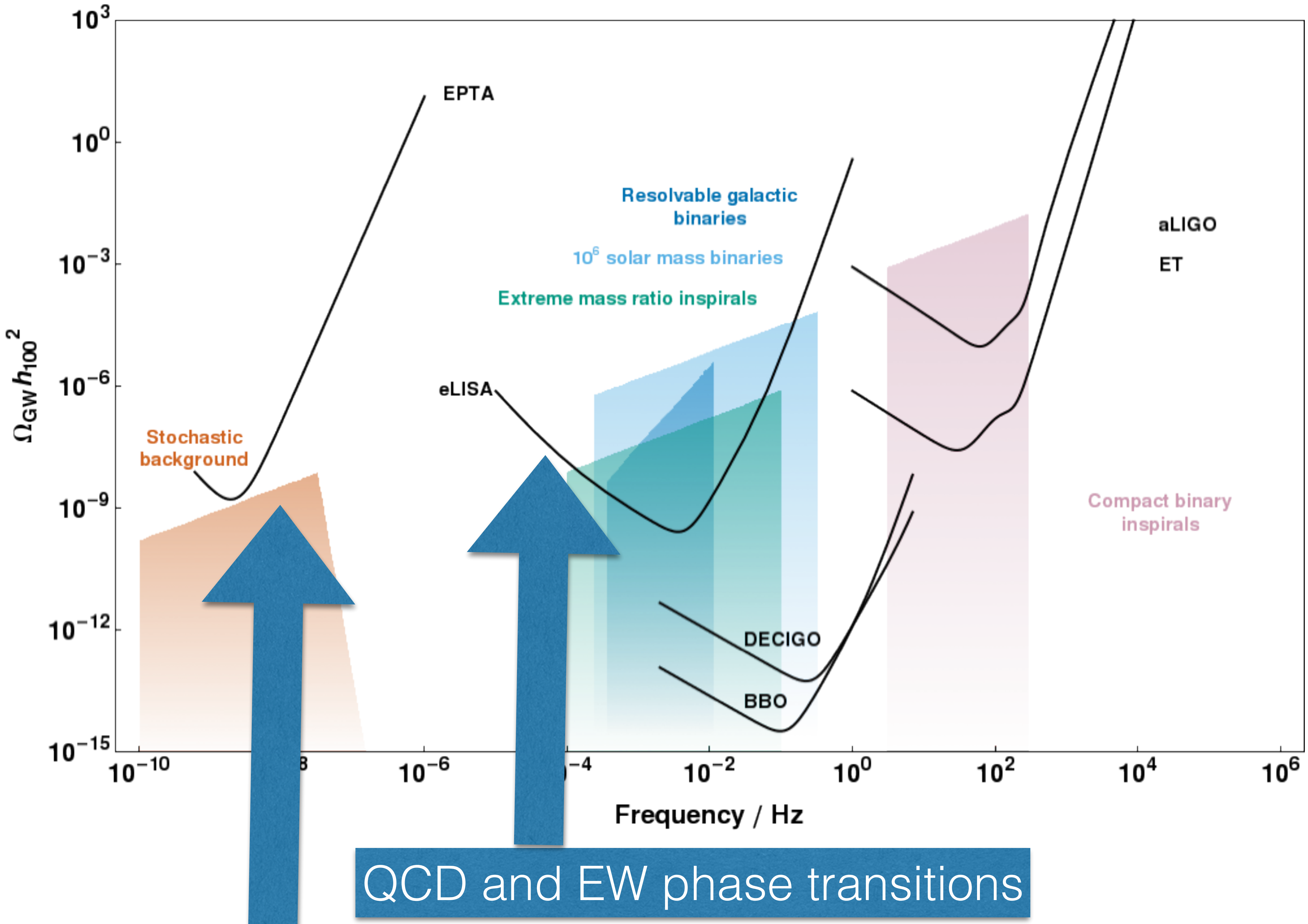
so it cannot be observed by conventional
GW detectors such as LEGO or space-based eLISA
since they have completely different frequencies

But GW in this frequency range can be observed by monitoring pulsar phases. GR effectively are seen as stochastic change of the distance to pulsars. There are three ongoing experiments

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

$\Omega_{GW} h_{100}^2 < 10^{-9}$ → early in BB < 10^-5

sources and sensitivity



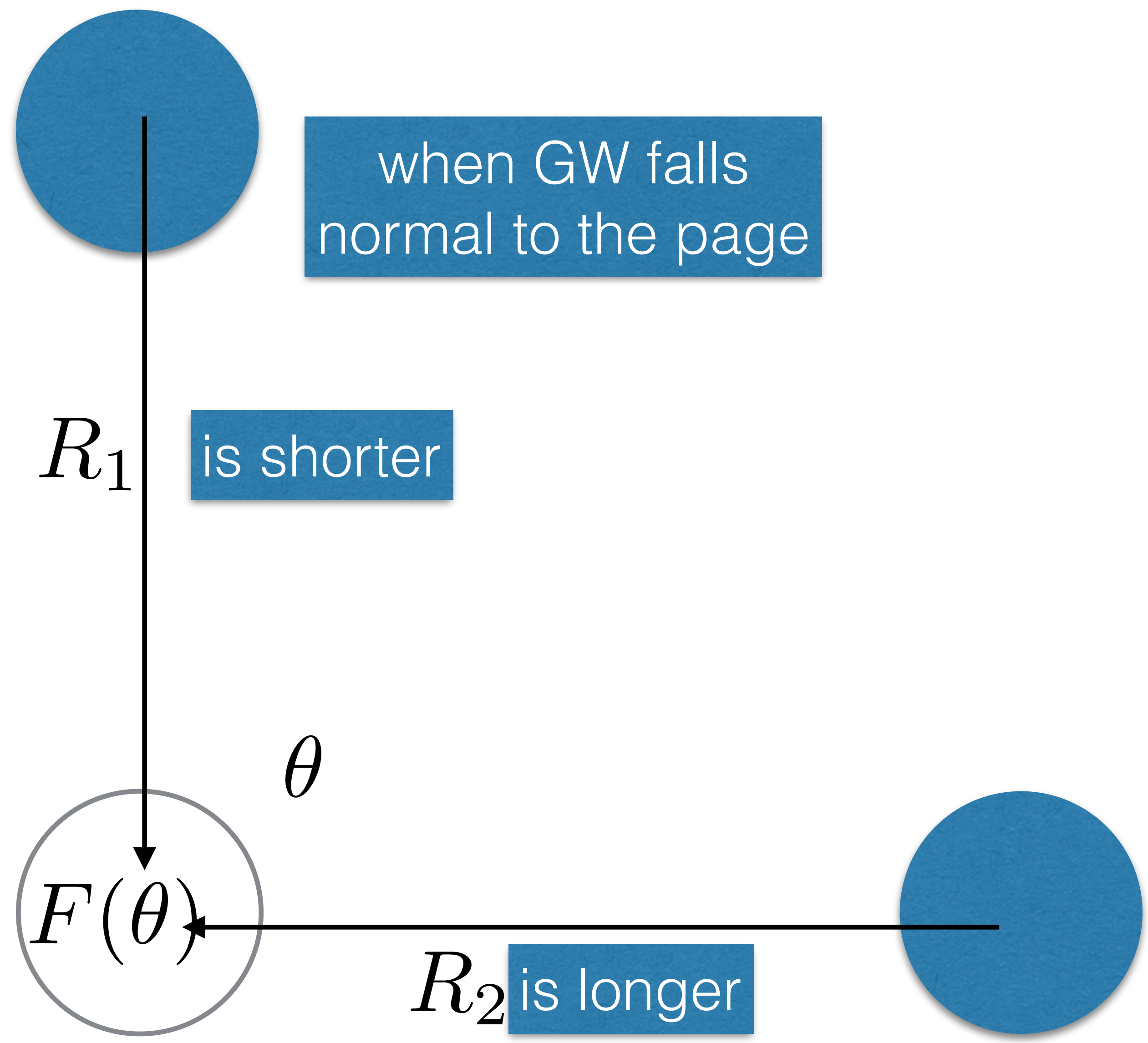
QCD and EW phase transitions

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

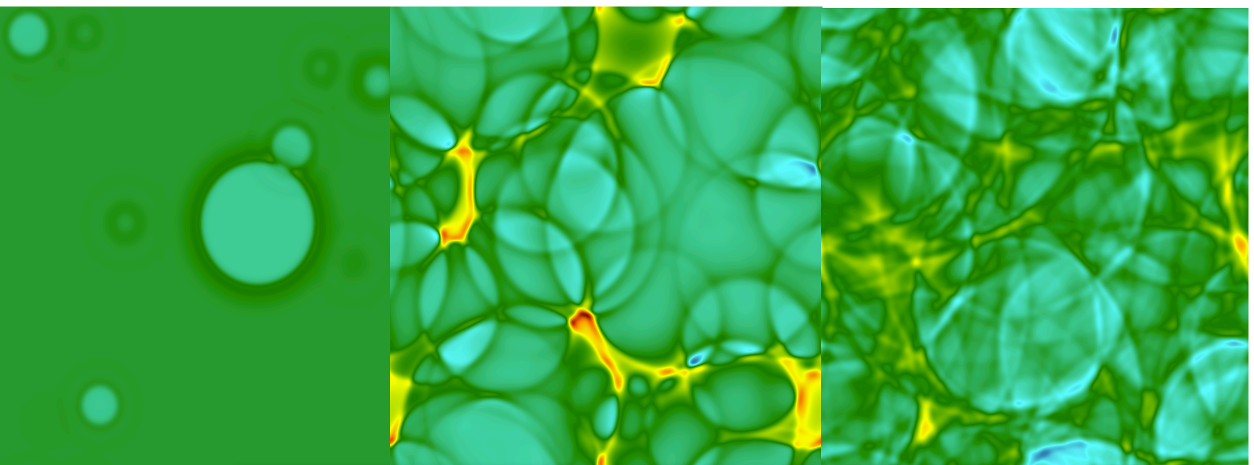
If Earth is in GW
and say R1 slightly
increases, then R2
at 90 degrees decreases



observer correlates phase
timing of all known millisec pulsar pairs

1st order cosmological transition, bubble coalescence,
gravity waves: Witten PRD 30, 272 (1984)
Hogan Mon.Not.Roy.Astron.Soc 218, 629 (1986)

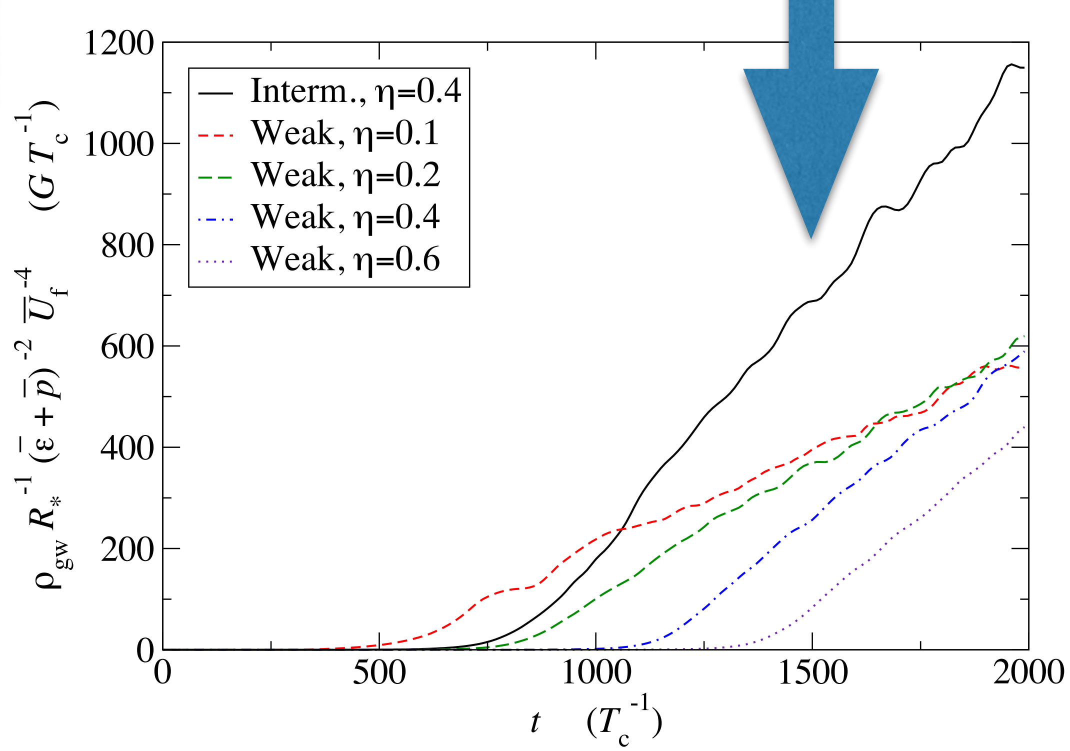
Numerical studies of the 1st order (?) electroweak ph.tr.
hydro+Higgs, bubbles collide and disappear but the
GW production rate stays the same long after!



bubbles => sound circles

last year paper
which triggered our work

Hindmarsh, Huber, Rummukainen, Weir (2013)



our point: **a single sound circle does not work but two colliding sound waves - at certain angle - produce GW with a simple calculable rate**

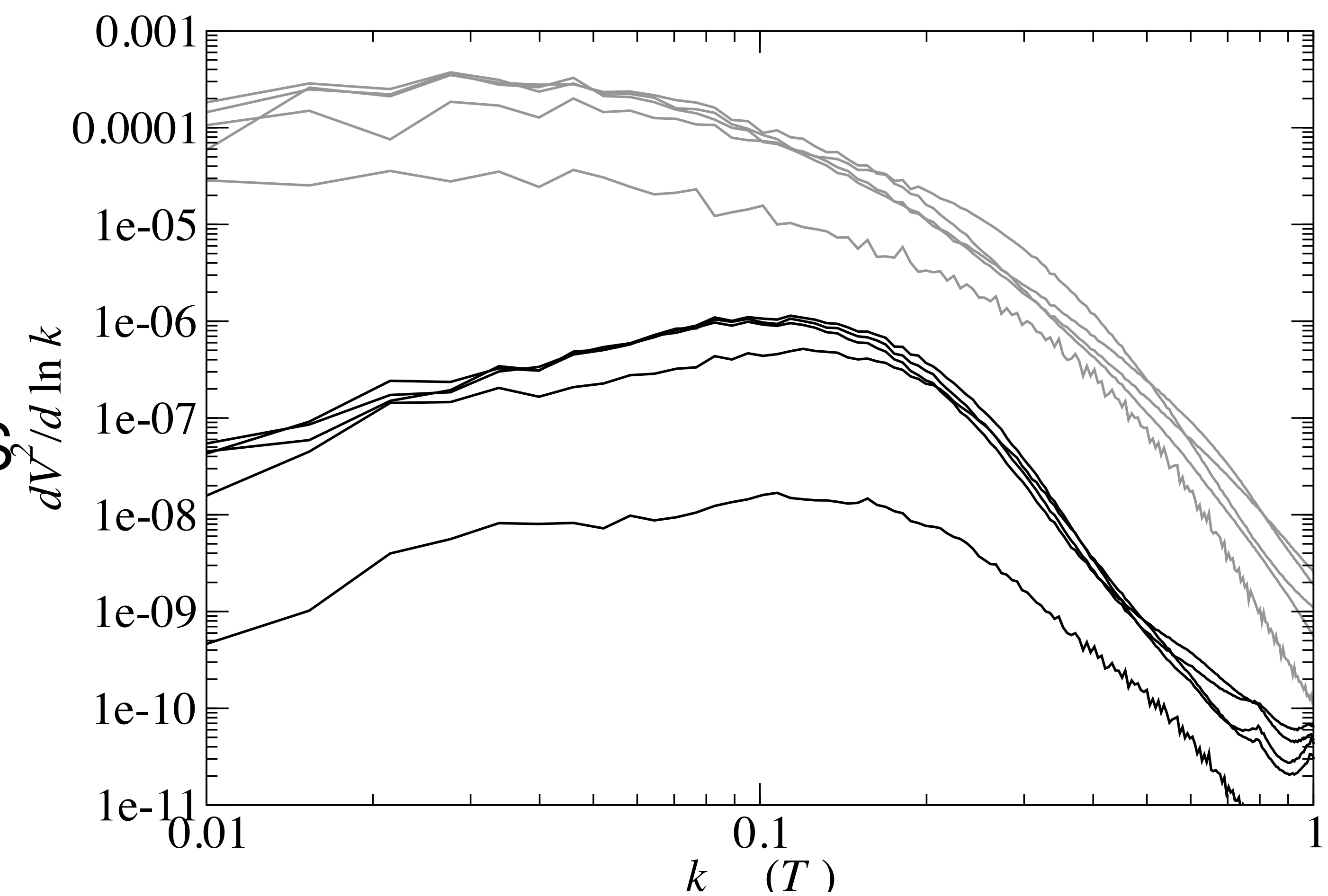
Hindmarsh, Huber, Rummukainen, Weir (2013)

Although these authors discussed EW transition, the sound cascade should be **universal**

Unfortunately the simulation is only at **scales close to UV** or sound production scale

if one still evaluate index of n_k

what happens next?
here is our main idea:
acoustic inverse cascade



spectral power of
the velocity fluctuations from hydro
grey -sounds, black -rotational mode
curves from bottom up - time

Gravity Waves generated by Sounds from Big Bang Phase Transitions

Tigran Kalaydzhyan and Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
(Dated: January 16, 2015)

Inhomogeneities associated with the cosmological QCD and electroweak phase transitions produce hydrodynamical perturbations, longitudinal sounds and rotations. It has been demonstrated by Hindmarsh *et al.* [1] that the sounds produce gravity waves (GW) well after the phase transition is over. We further argue, that, under certain conditions, an *inverse acoustic cascade* may occur and move sound perturbations from the (UV) momentum scale at which the sound is originally produced to much smaller (IR) momenta. Weak turbulence regime of this cascade is studied via Boltzmann equation, possessing stationary power and time-dependent self-similar solutions. We suggest certain indices for strong turbulence regime as well, into which the cascade eventually proceeds. Finally, we point out that two on shell sound waves can produce one on-shell gravity wave, and evaluate the rate of the process using standard *sound loop diagram*.

acoustic inverse cascade: self-focusing into small k

$$\mathrm{Re}\,\omega_k = c_s k + \delta\omega \qquad \delta\omega = A k^3 + \mathcal{O}(k^5)\,.$$

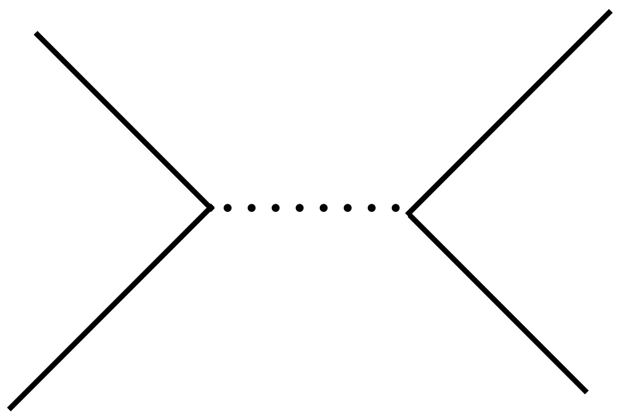
If A>0 then 1->2 decay possible, then direct cascade (to large k)

If A<0 then 2<->2 and inverse cascade

Weak turbulence: Boltzmann eqn

The $2 \leftrightarrow 2$ scattering amplitude is, schematically, a sum of the type

$$\sum_{i,j,l,m} \frac{V^*(k_i \pm k_j, k_i, k_j) V(k_l \pm k_m, k_l, k_m)}{\omega(k_i) \pm \omega(k_j) - \omega(k_i \pm k_j)} \qquad (20)$$



like gluons, dominated by small angle scattering

stationary Kolmogorov spectrum, particle flow to IR

$$n_k \sim k^{-s} \qquad s_{nondecay} = 10/3$$

Self-similar time-dependent solution

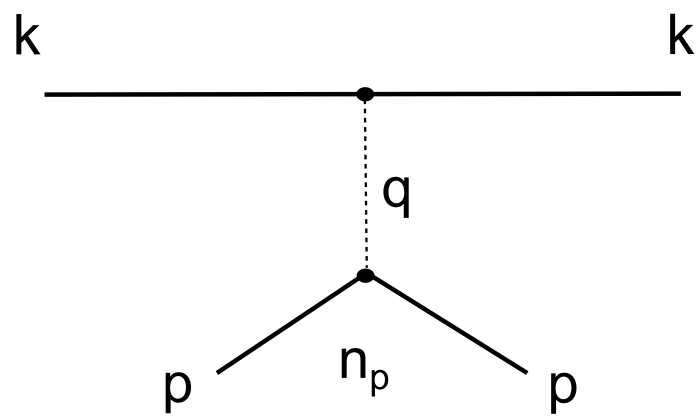
$$n_k = \hat{t}^{-q} f_s[\hat{t}^{-p}\hat{k}] = \hat{t}^{-q} f_s[\xi]\,, \qquad p = -1, \qquad q = -3\,,$$

soliton moving in scales, from UV to IR

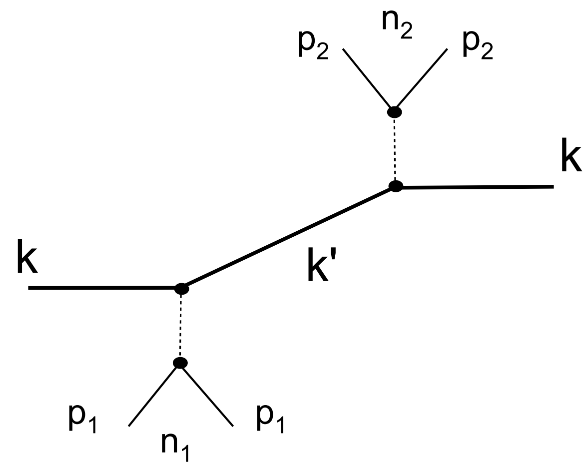
V.E. Zakharov, V.S. Lvov, G. Falkovich, "Kolmogorov spectra of turbulence I. Wave turbulence.", Springer Verlag. ISBN 3-540-54533-6.

self-focusing of sounds to small k

Strong turbulence: re-summation of diagrams



(a)



(b)

FIG. 1: Forward scattering diagrams corresponding to the (a) quartic and (b) sextic terms in the Hamiltonian (34).

Like in perturbative gluon cascade, the impact parameter is limited by the Debye screening length, which depends on the matter density

$$n_k \sim k^{-s}$$

if diagram (a) dominates then $s_{strong} = 4\,,$

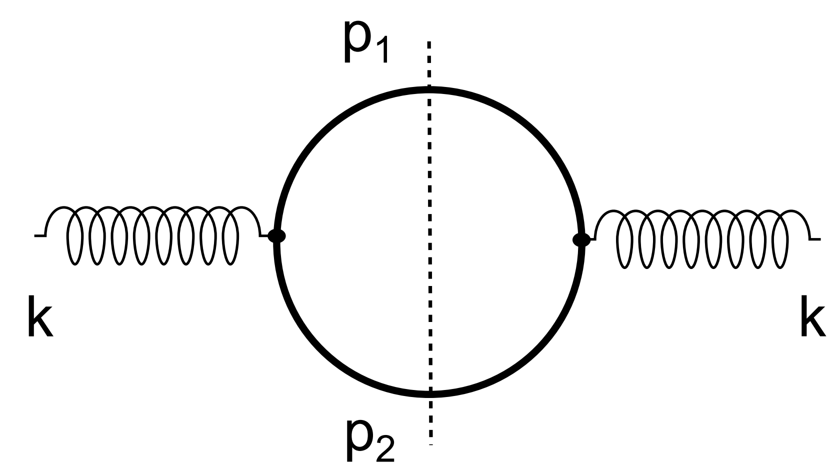
if diagram (b) dominates then $s_{strong} = 6$ (subleading)

even stronger self-focusing of sounds to small k!

GENERATION OF GRAVITY WAVES

General expressions for the GW production rate are well known, and we will not reproduce them here, proceeding directly to the main object one has to calculate, the two-point *correlator of the stress tensors*

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



Two on-shell sound waves can do it. Using notations $p_1^\mu + p_2^\mu = k^\mu$ one writes GW on-shell condition $(k^\mu)^2 = 0$ as

$$c_s^2 (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2 p_1 p_2 \cos(\theta_{12})\,, \qquad (54)$$

where c_s,θ_{12} are the sound velocity and an angle between the two sound waves, respectively. In terms of such an angle there are two extreme configurations. The first is a "symmetric case", $p_1 = p_2$, corresponding to a minimal angle. For $c_s^2 = 1/3$ this angle is $\theta_{12} = 109°$. The second, "asymmetric case", corresponds to anticollinear vectors $\vec{p}_1, \vec{p}_2$, $\theta_{12} = 180°$. Important difference from the usual textbook relativistic-invariant cases is that various θ_{12} are allowed by kinematics in our case, not only $\theta_{12} = 0°$, which is due to the fact that $c_s < 1$.

The rate is

and self-focusing to small k increases it tremendously:

recall T/k(IR) =10^18 !

summary

- **Even the smallest fireball — pp high multiplicity — shows very strong explosion, evidences from spectra and femtoscopy**
- **gravity waves are the penetrating probe of Big Bang**
- **small k sounds exist for long time, and may self-focus to smaller k. Huge natural amplifier!**
- **2 sounds => GW rate is calculated simply**
- **can perhaps be observed via pulsar time correlations**