(Cambridge seminar. May 7, 2021)

Instanton/Sphaleron processes, in hadronic, heavy ion collisions and Big Bang

Edward Shuryak

How to observe the QCD instanton/sphaleron processes at hadron colliders?
Edward Shuryak   Ismail Zahed
e-Print: 2102.00256

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"Gauge topology" summer series seminars
(Simons Center, Stony Brook)
June-Aug.2020 very successful, will be repeated from June 2021

Topological landscape in pure gauge: the sphaleron path

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Instantons effects in QCD vacuum and hadrons

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production of hadronic clusters with
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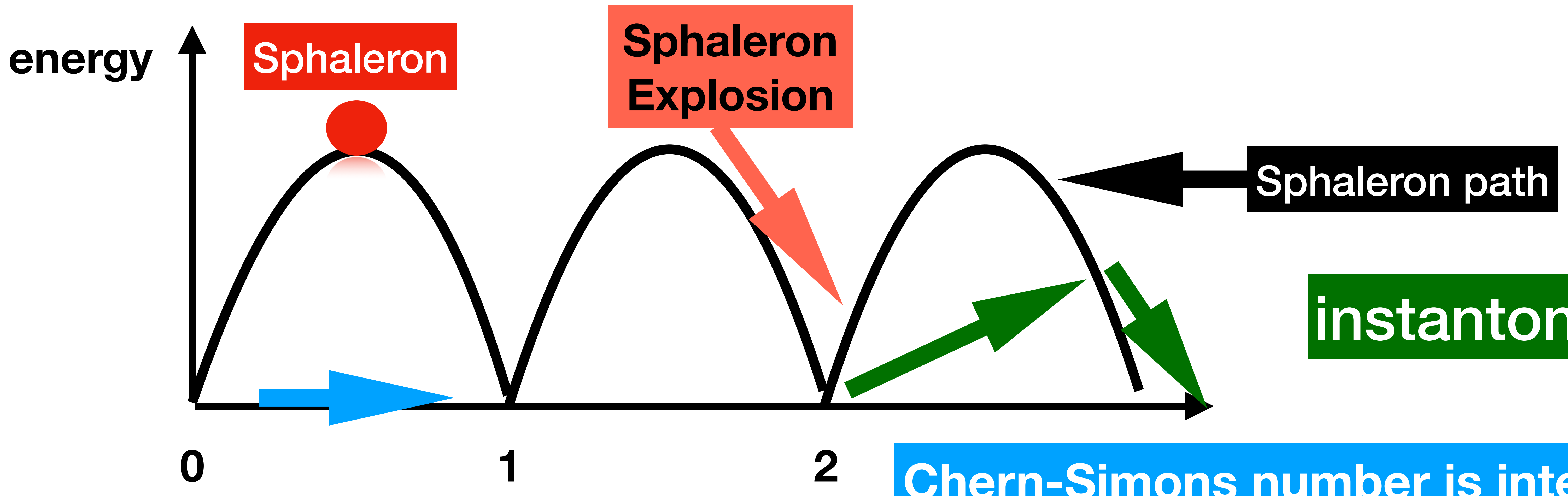
Inverse cascades in magnetohydrodynamics seeded by e/w sphalerons

the topological lanscape

Terminology of the topological landscape



instanton-sphaleron process

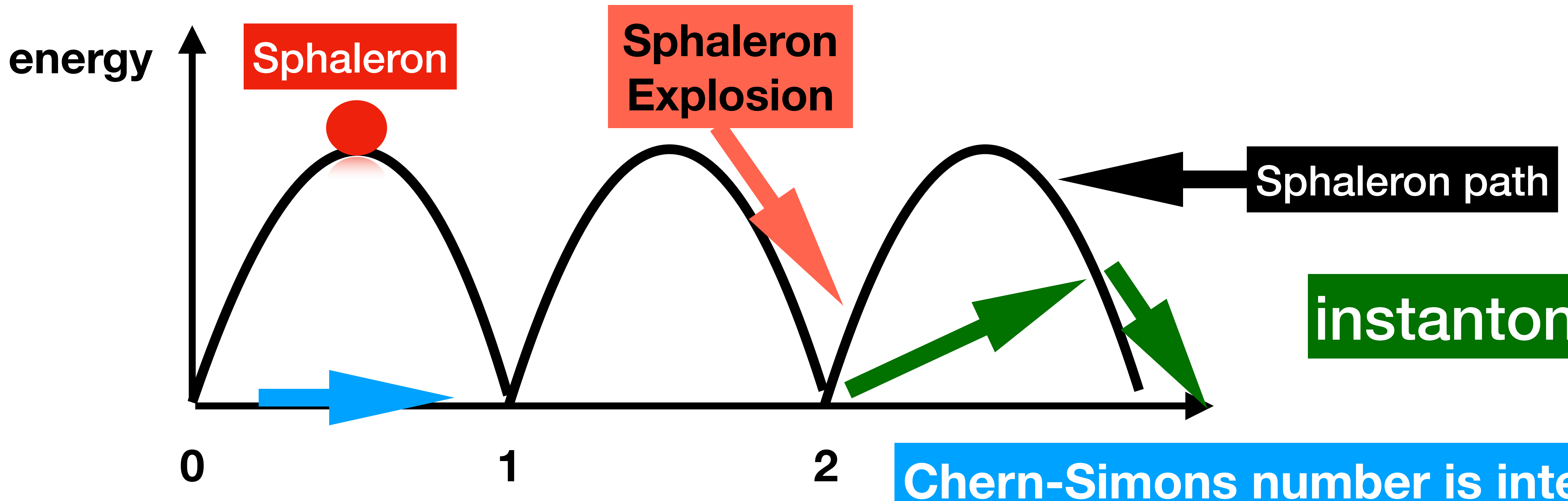
Chern-Simons number is integer at the “valleys”

Instanton is Tunneling at Zero energy

Sphaleron is static purely magnetic object
The name in Greek means
“ready to fall” (Klinkhamer and Manton)

Sphaleron path consists of configurations
Which are minima in all directions in Hilbert space
except one
Like streams going from mountain tops
to the bottom of the valley

Terminology of the topological landscape



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We do have analytic results for
All of them
In pure gauge theory
Which is not widely known

Instantons in the QCD VACUUM and HADRONS

"Instanton liquid model" , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

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hep-ph/0008048.

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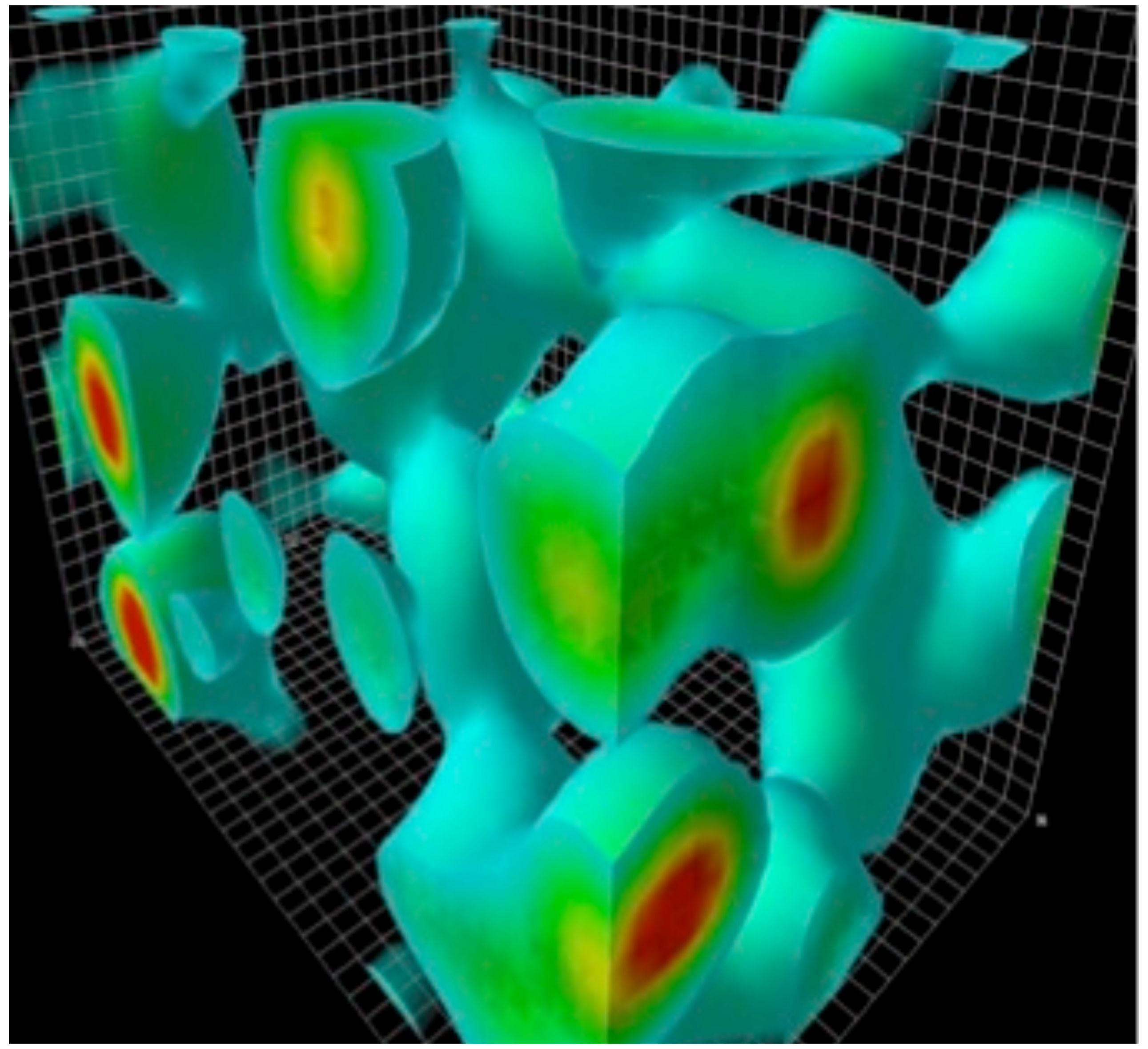

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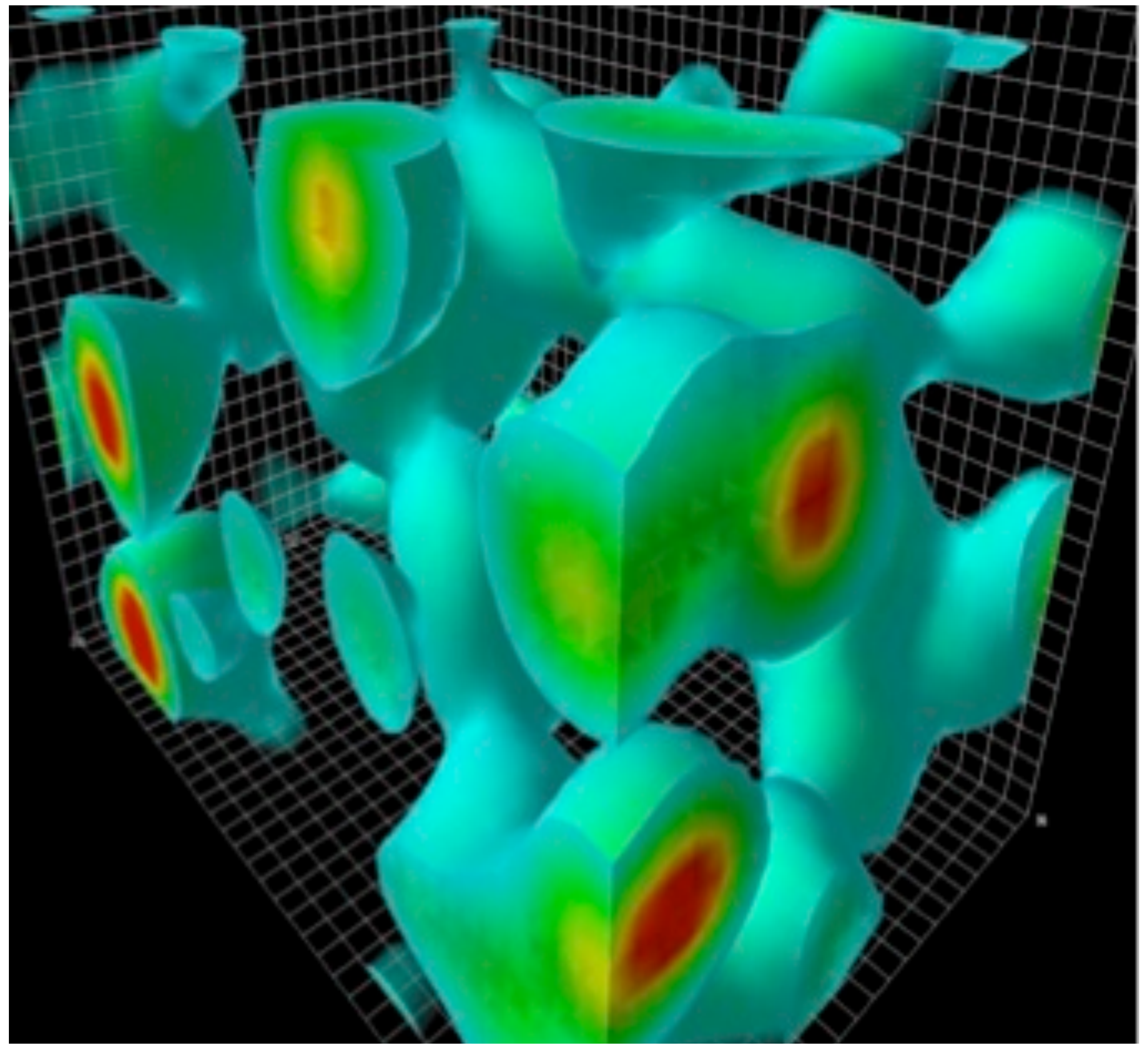
Multiple correlation functions



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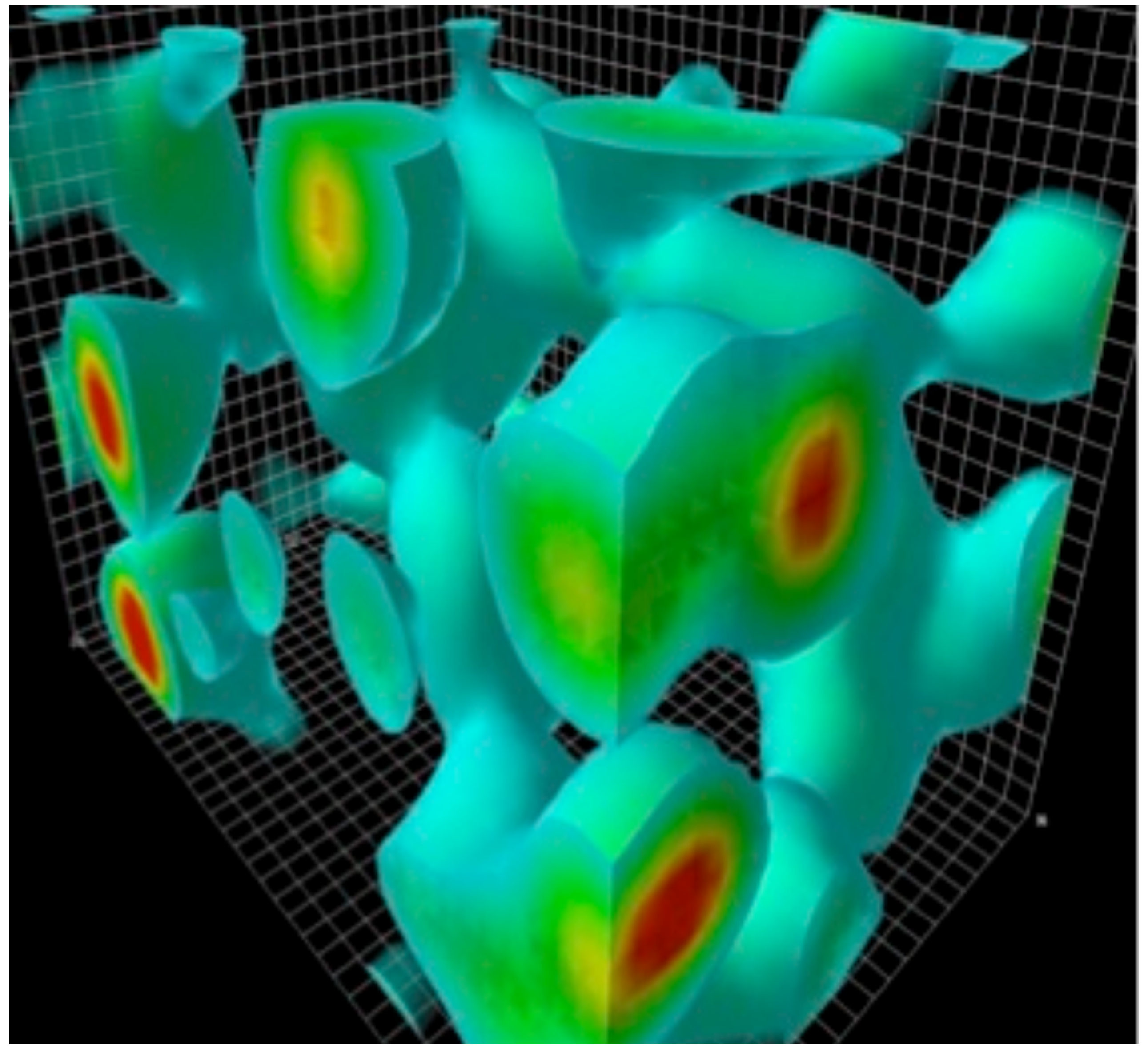

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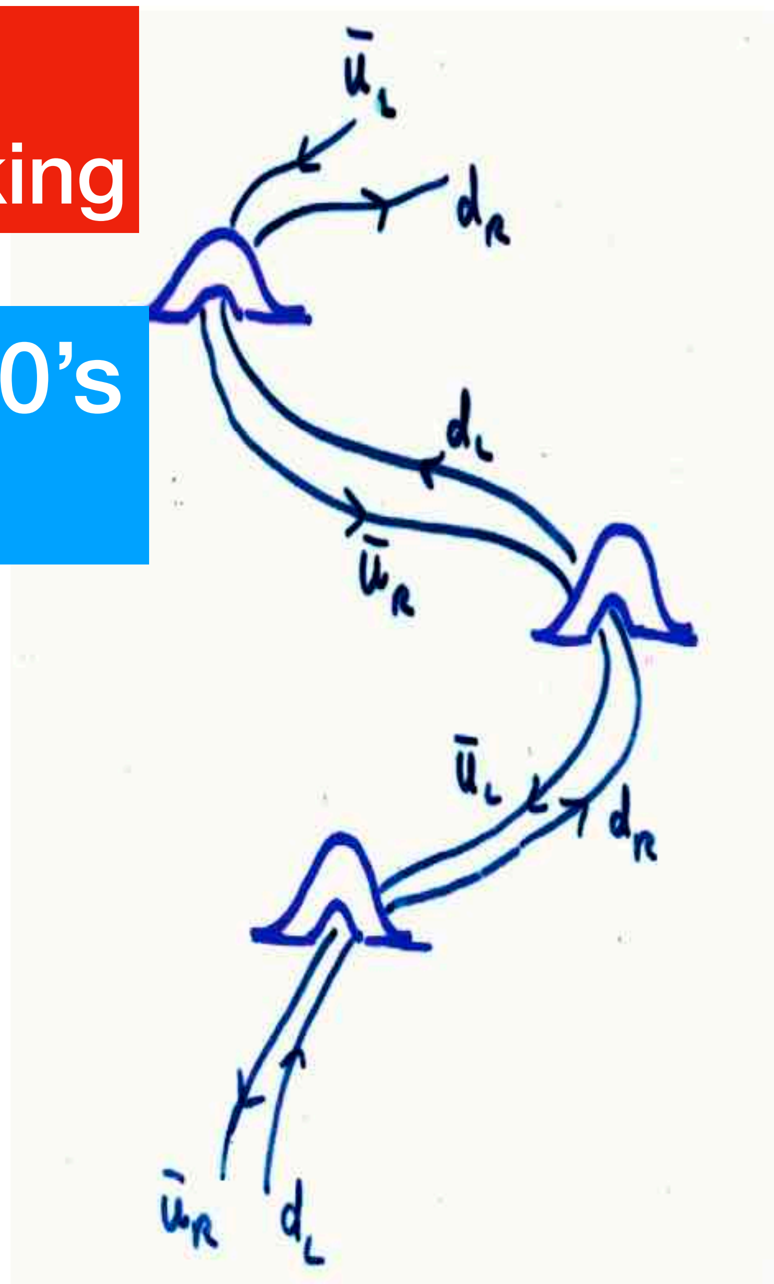

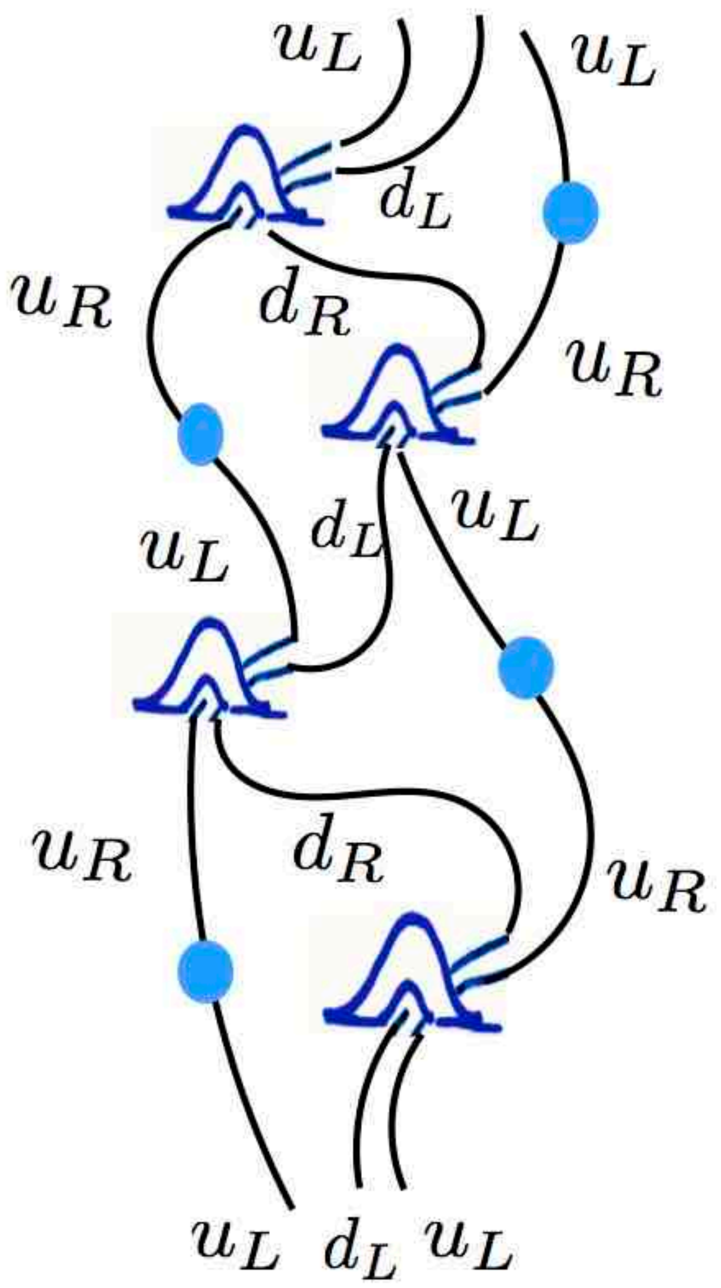

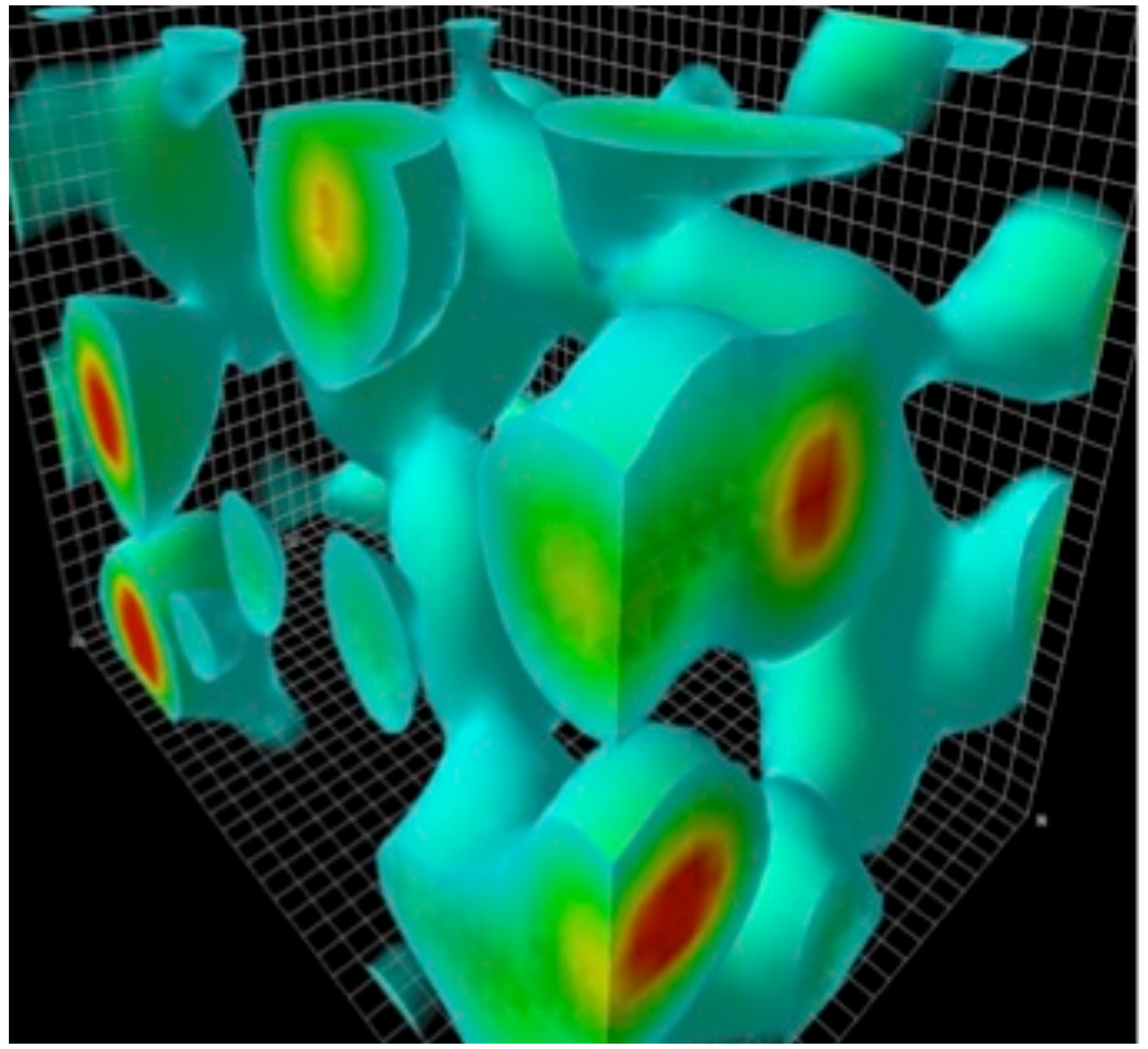

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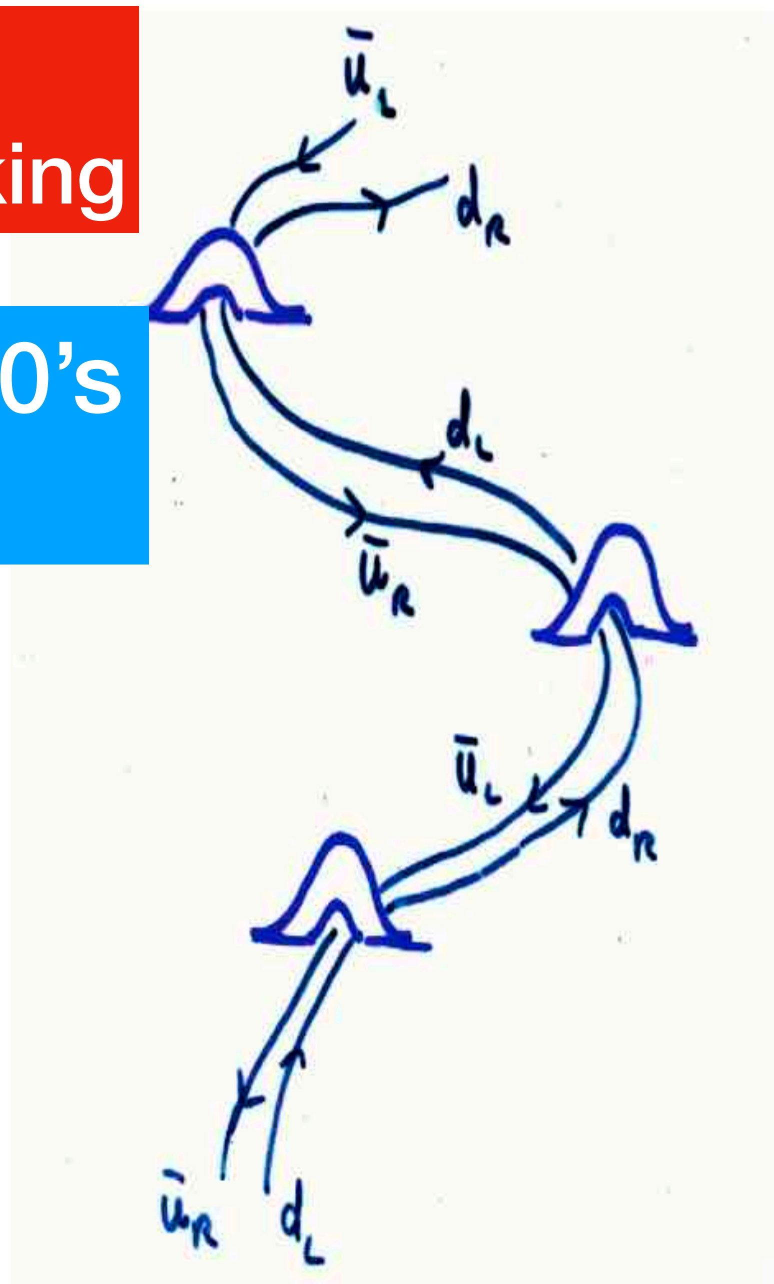

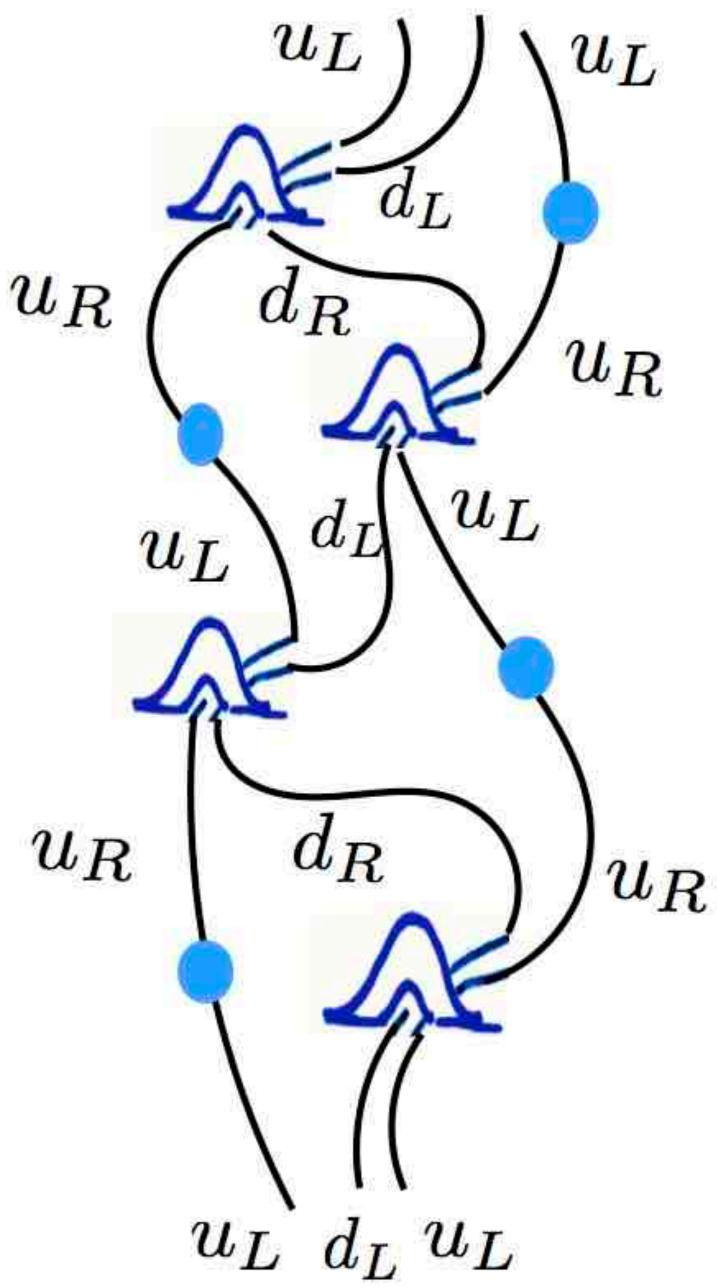

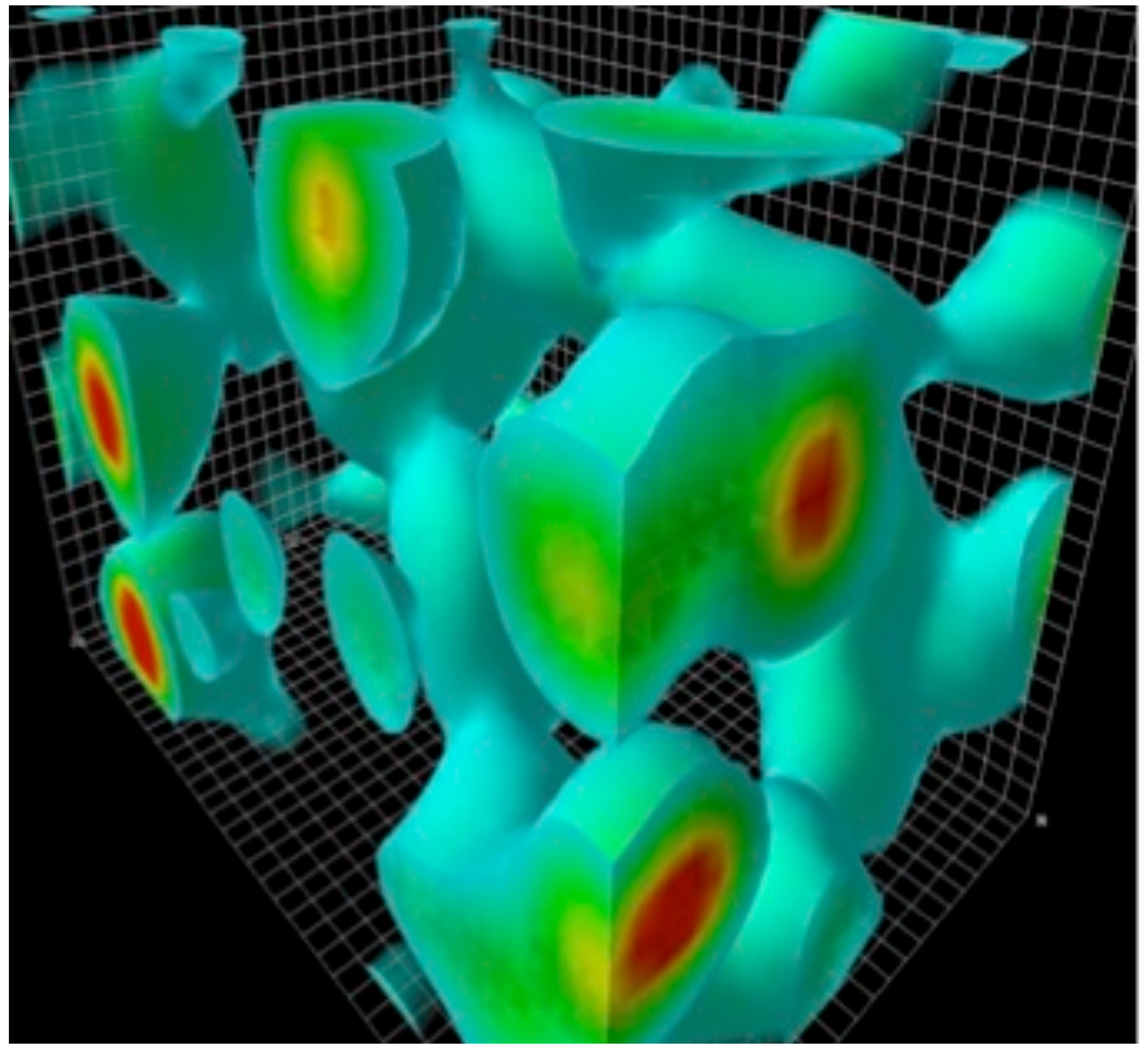

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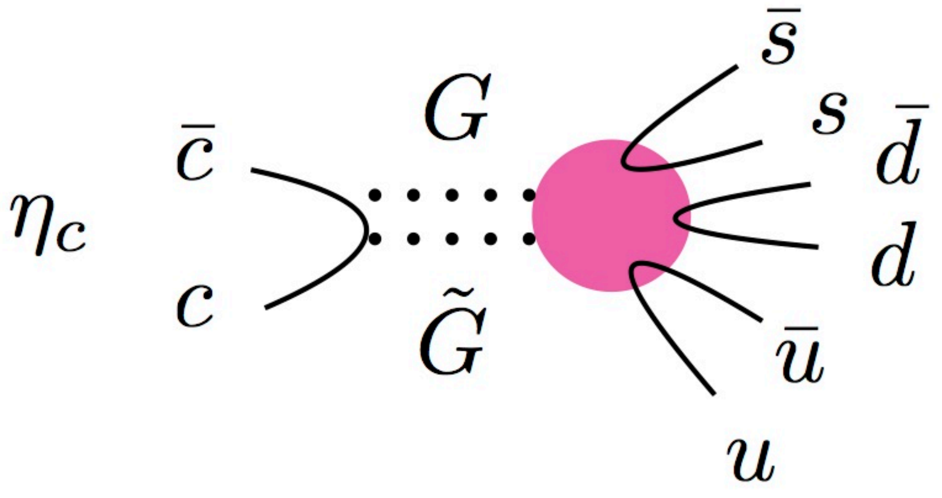

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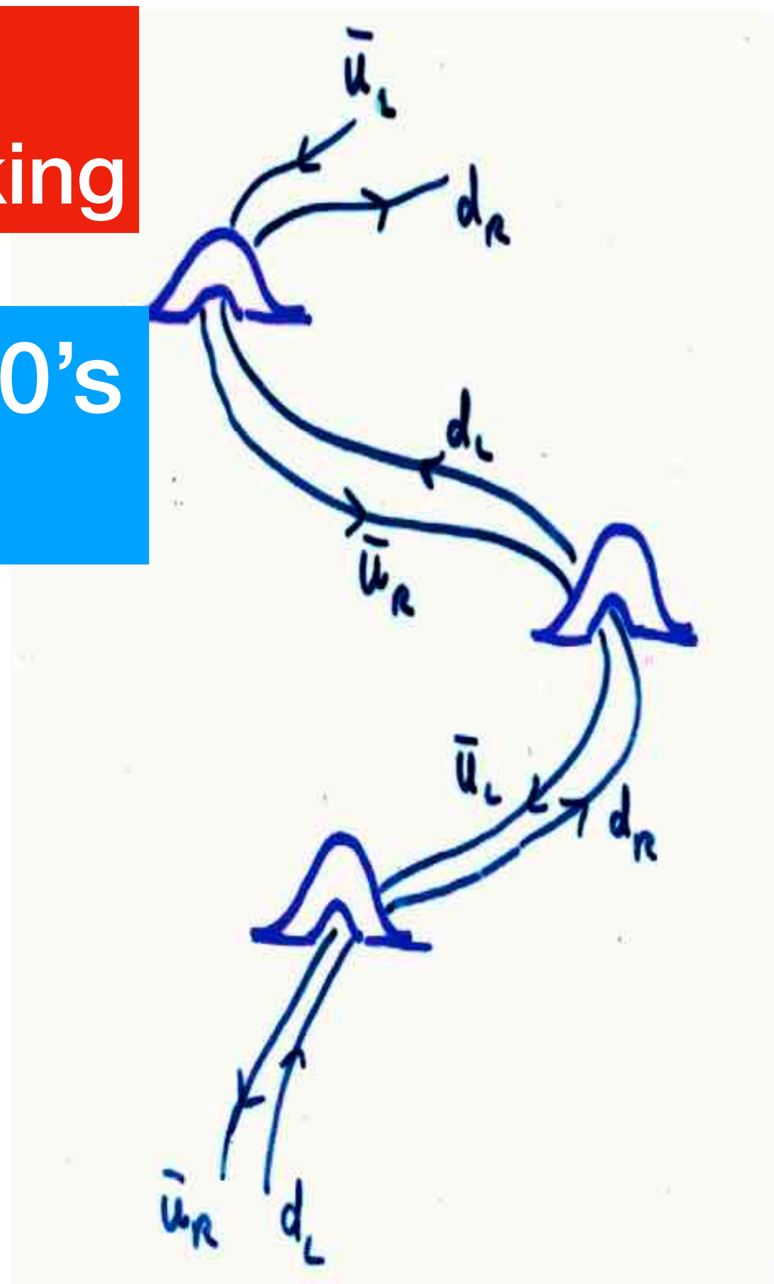

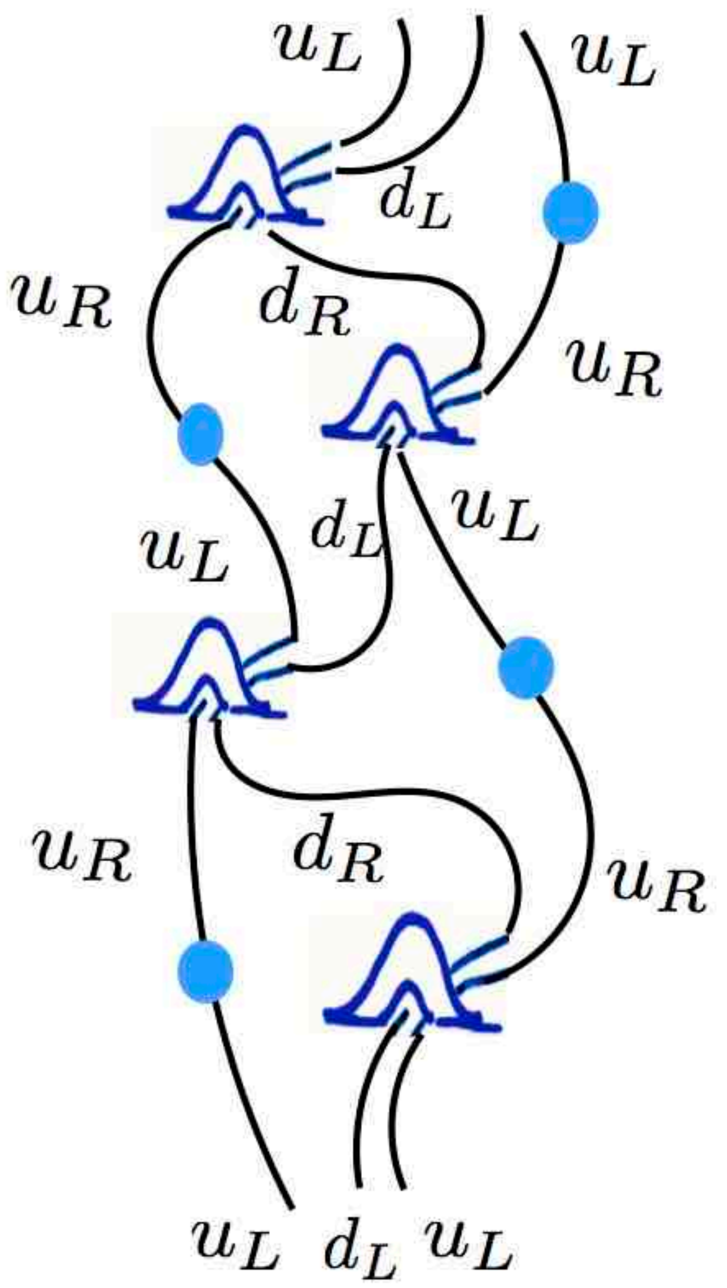

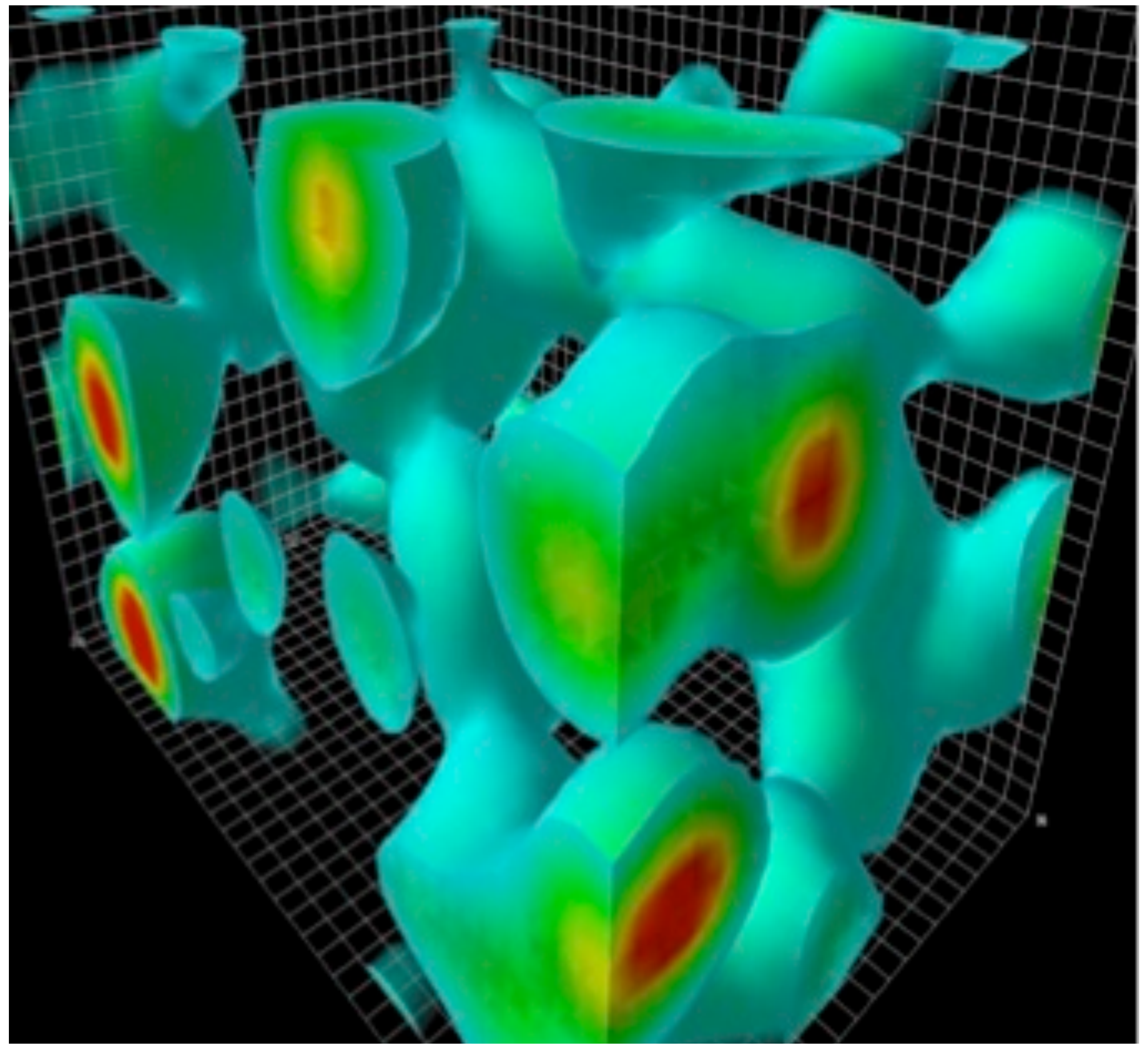

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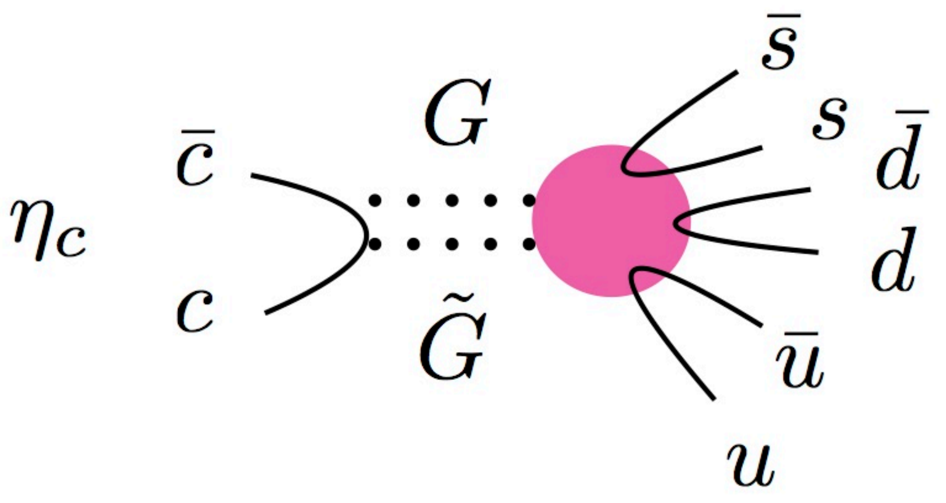

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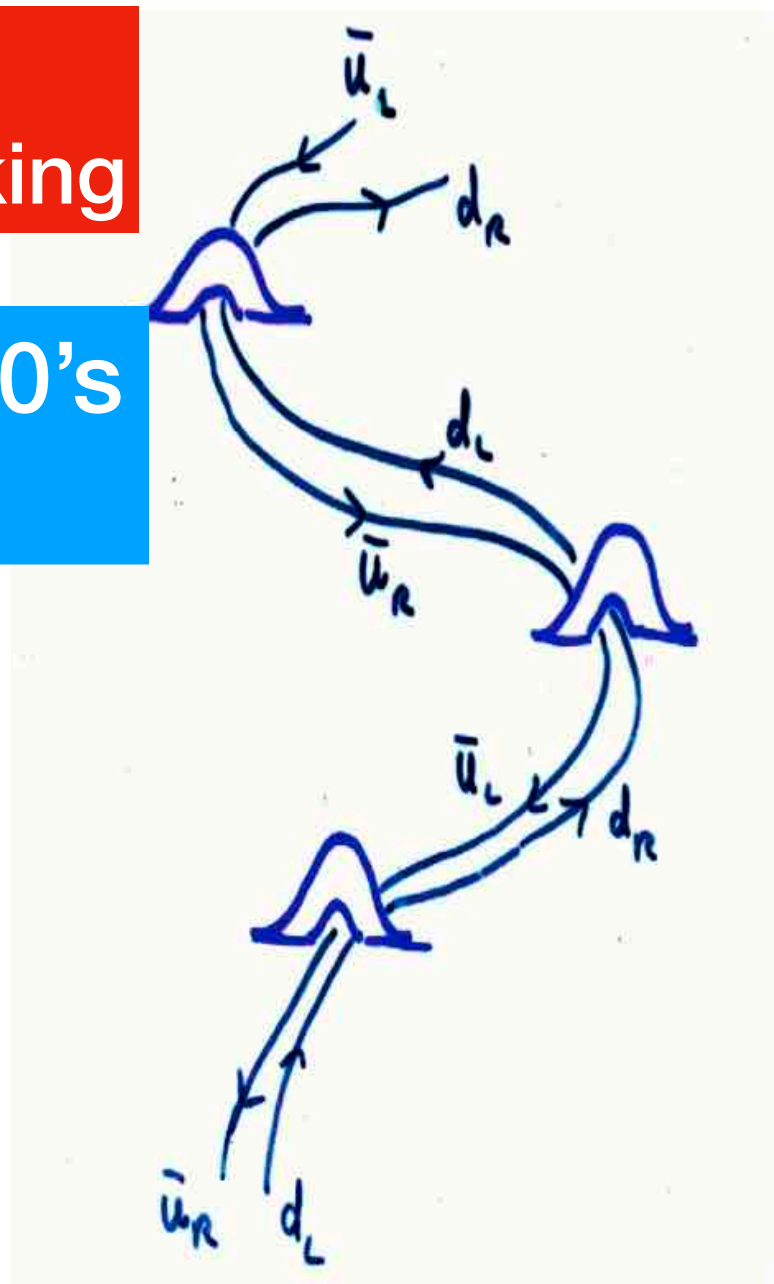

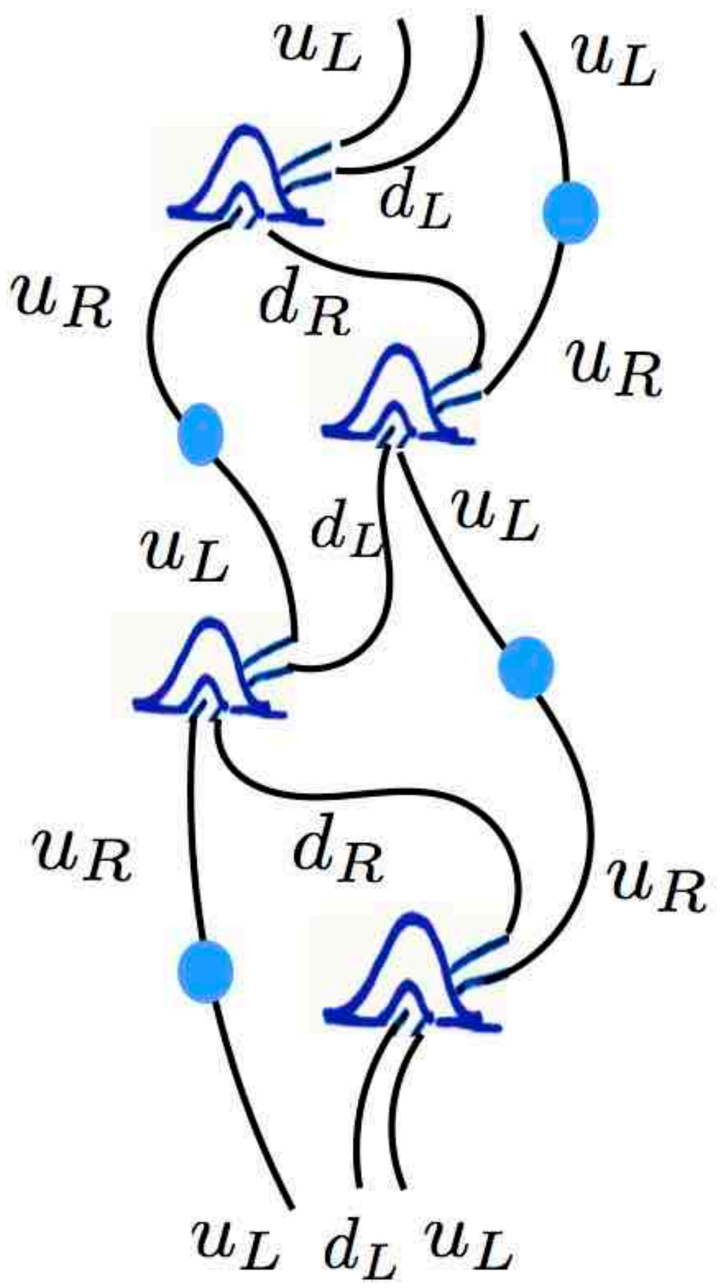

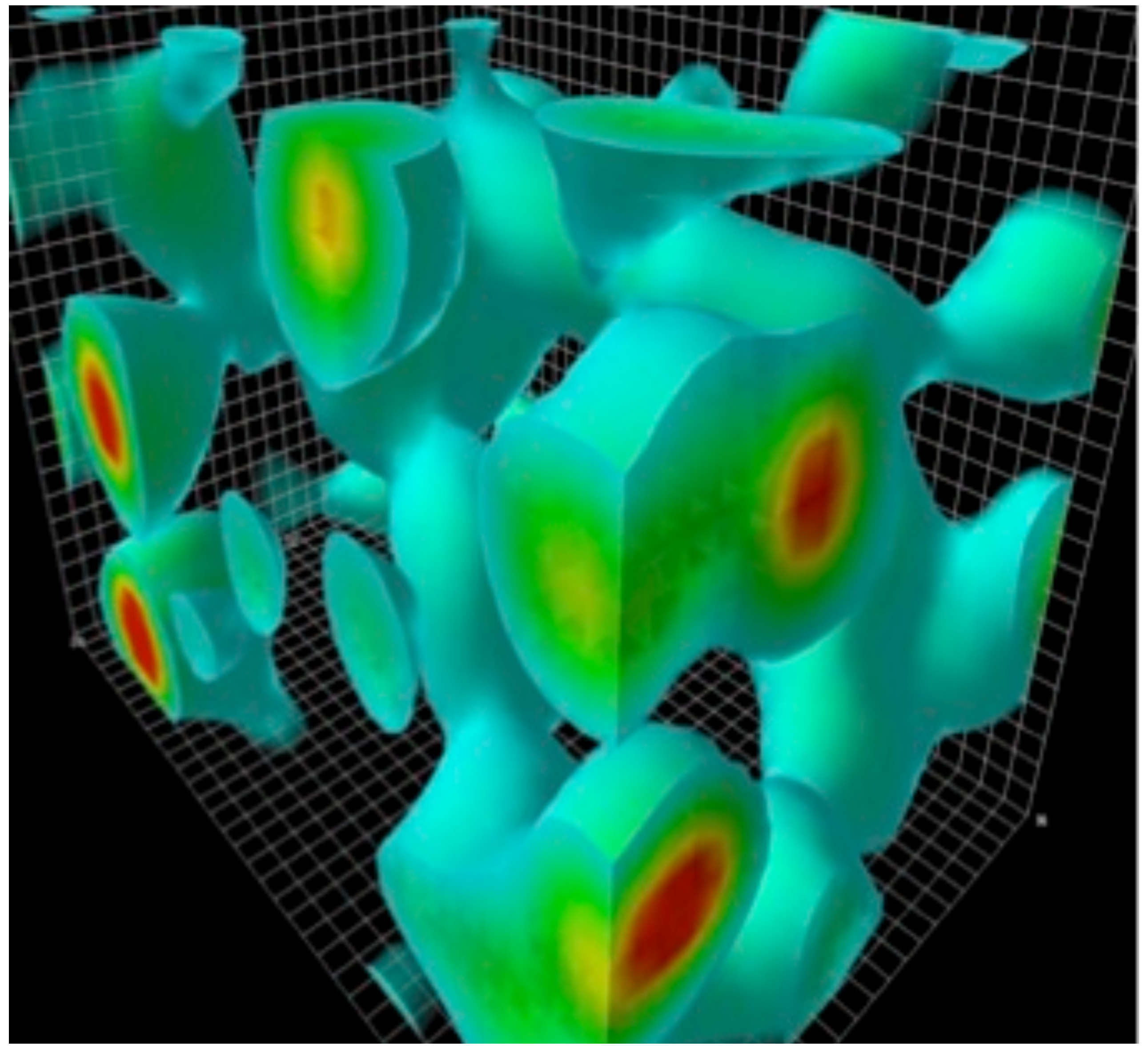

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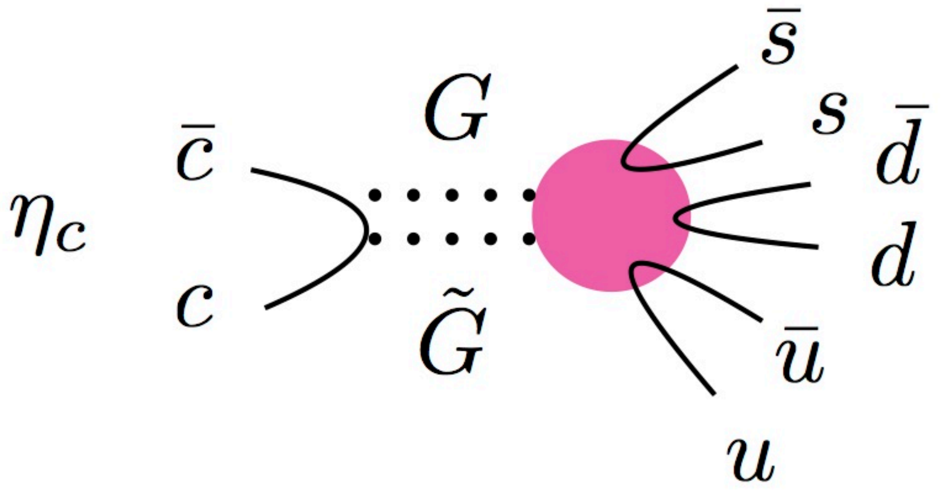

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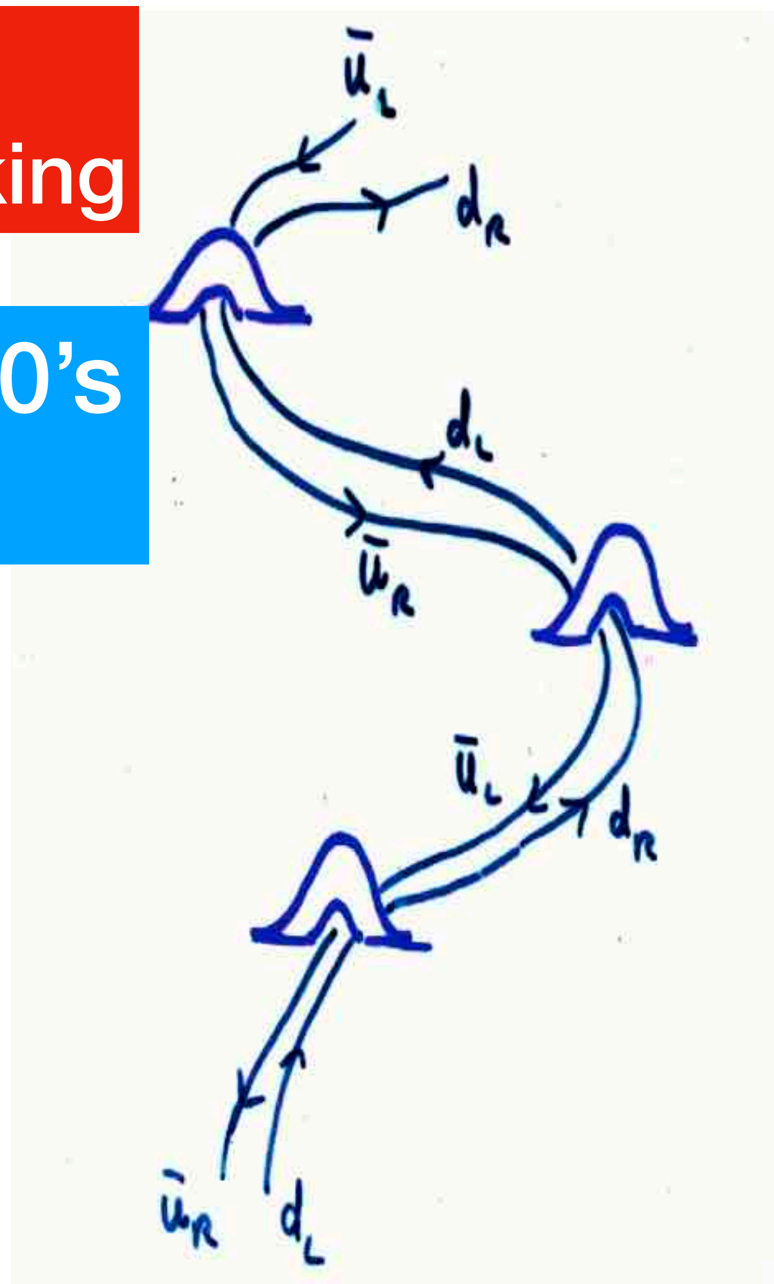

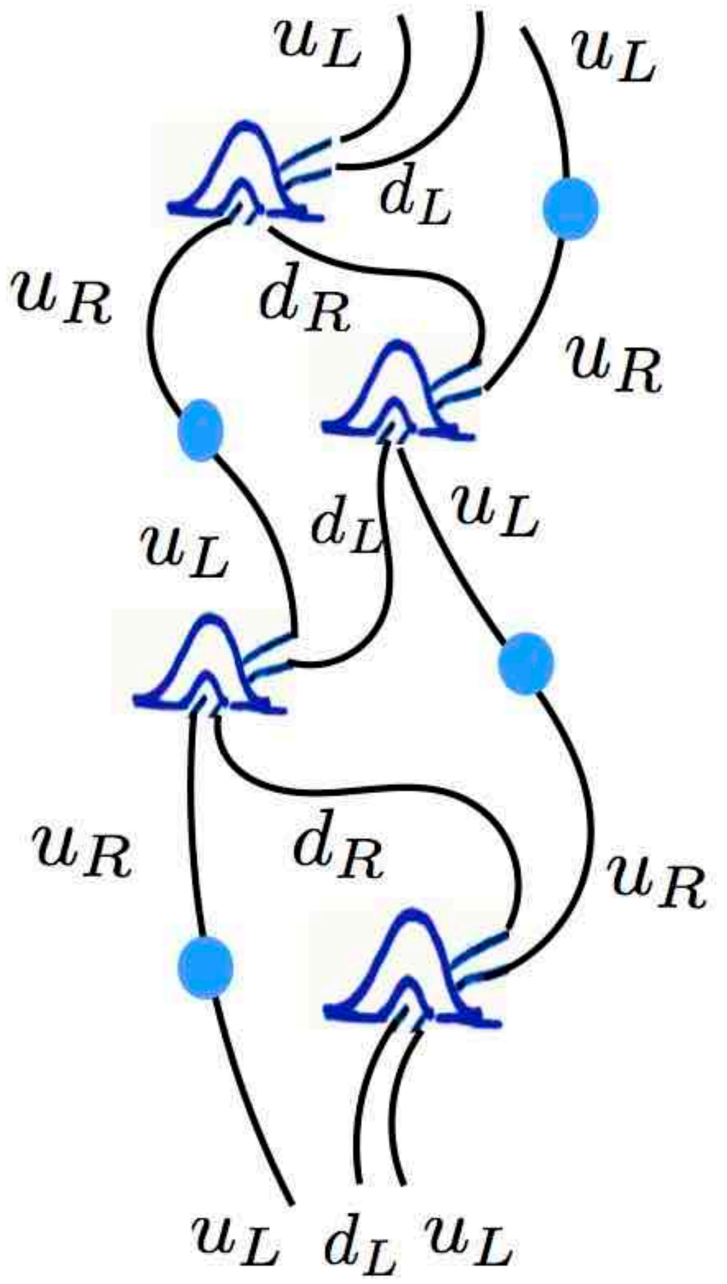

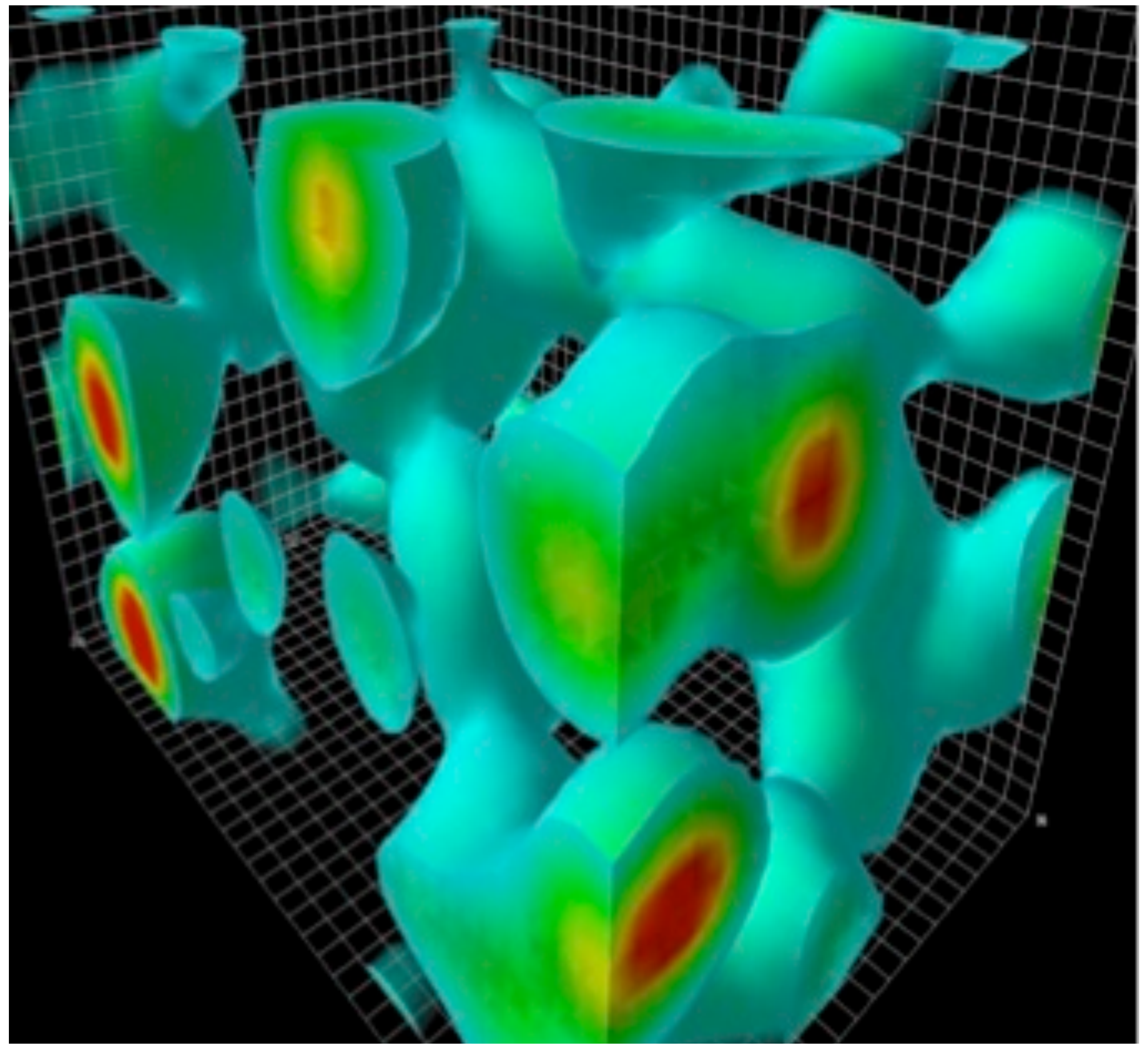

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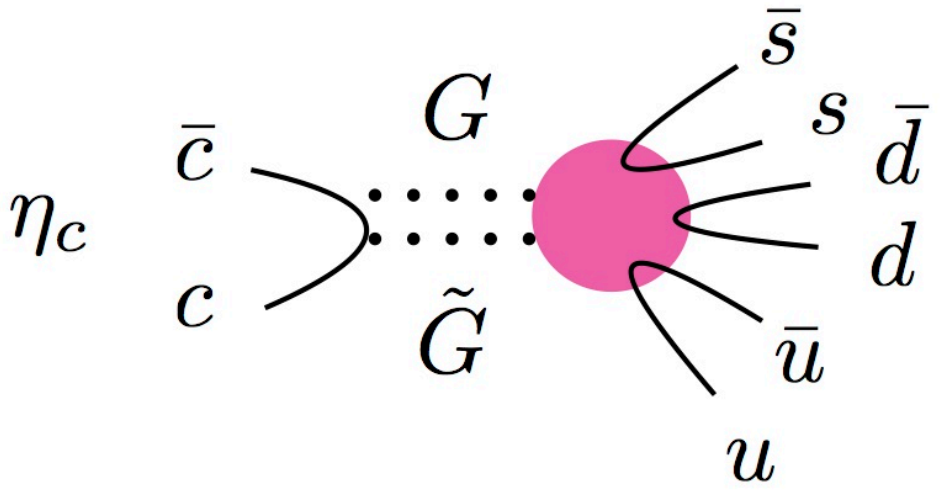

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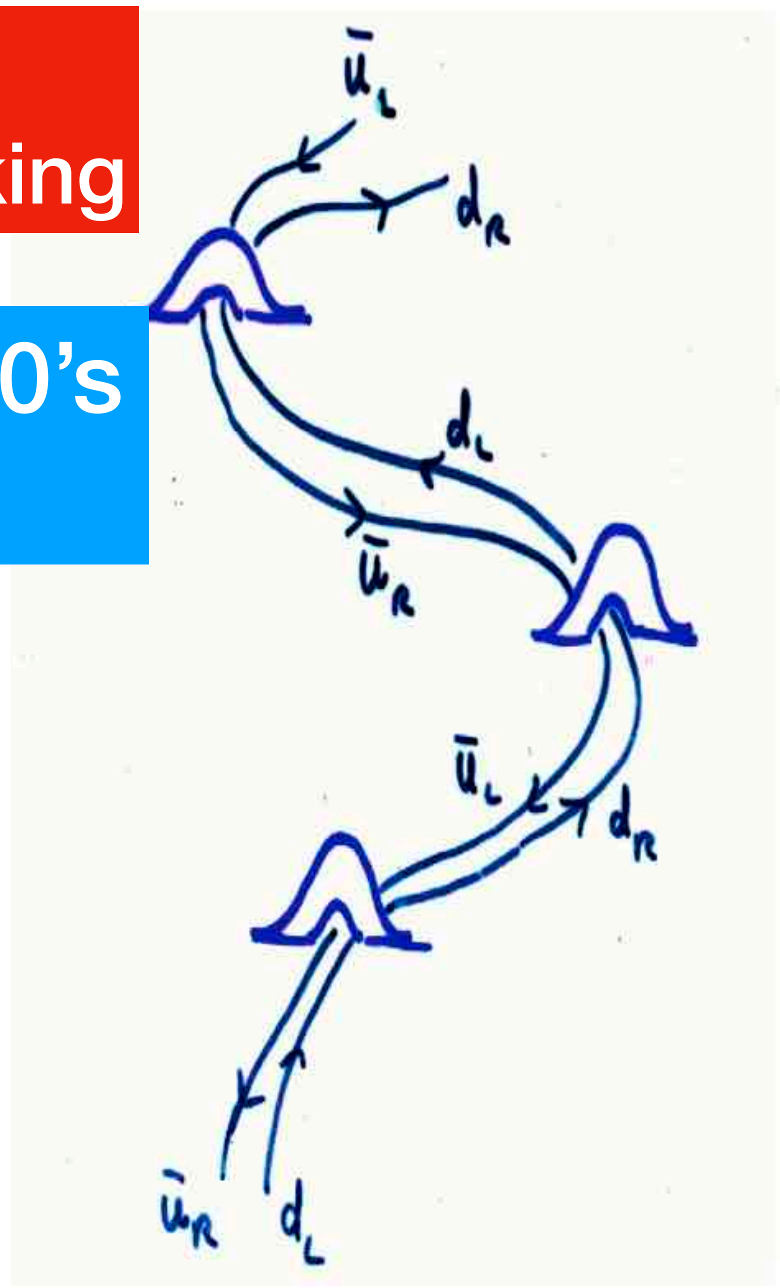

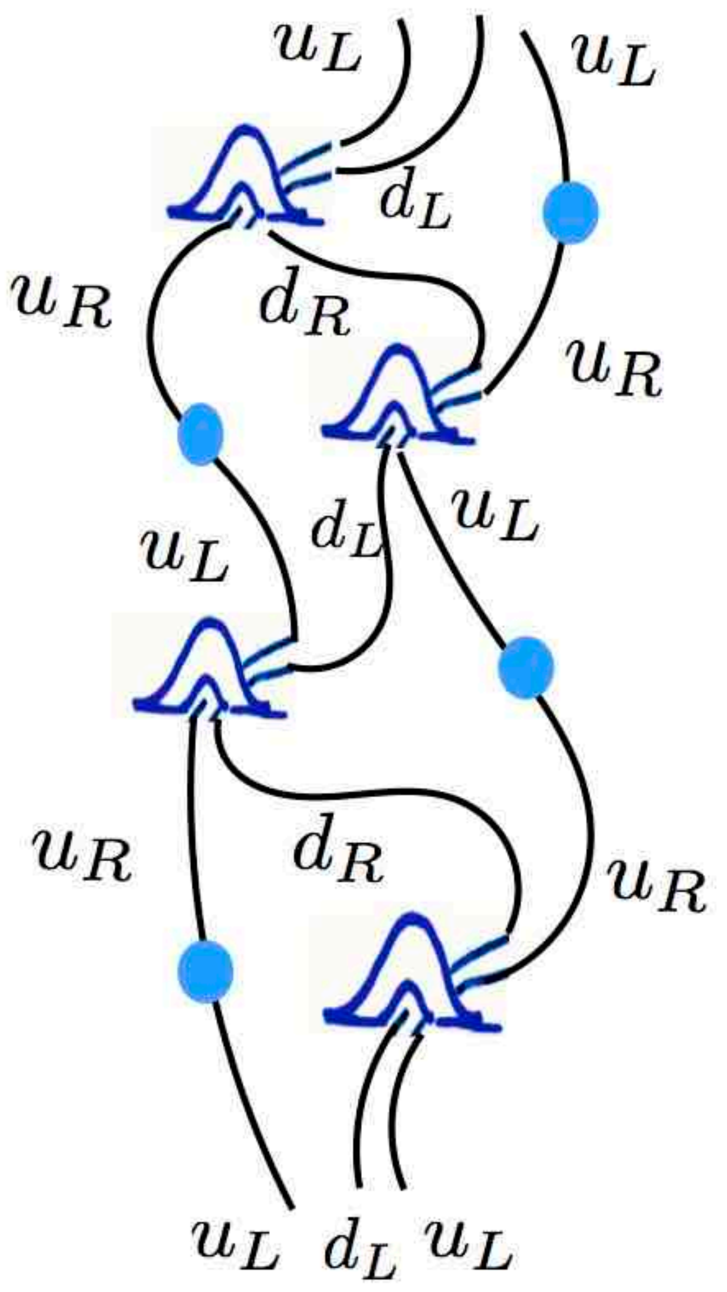

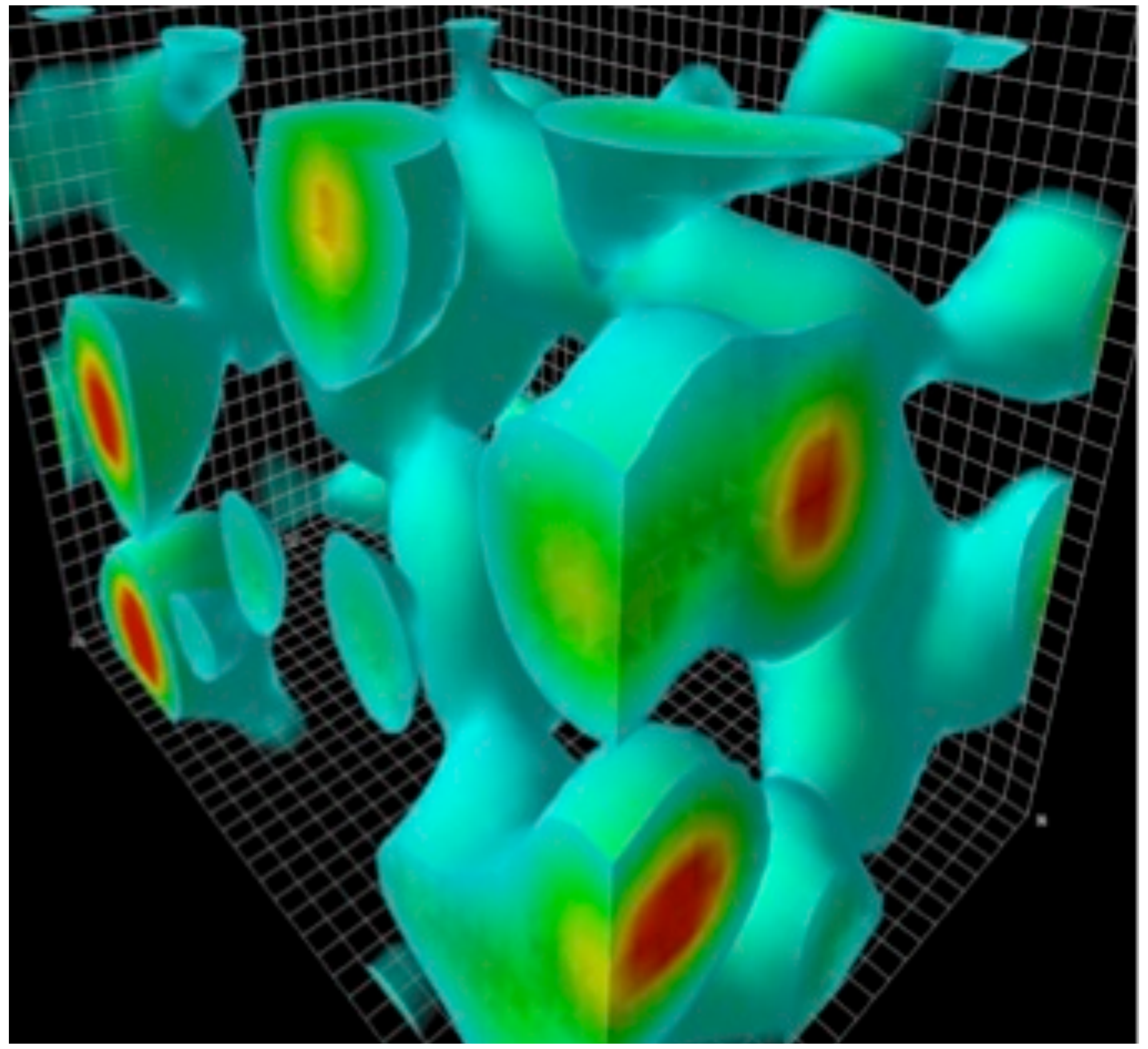

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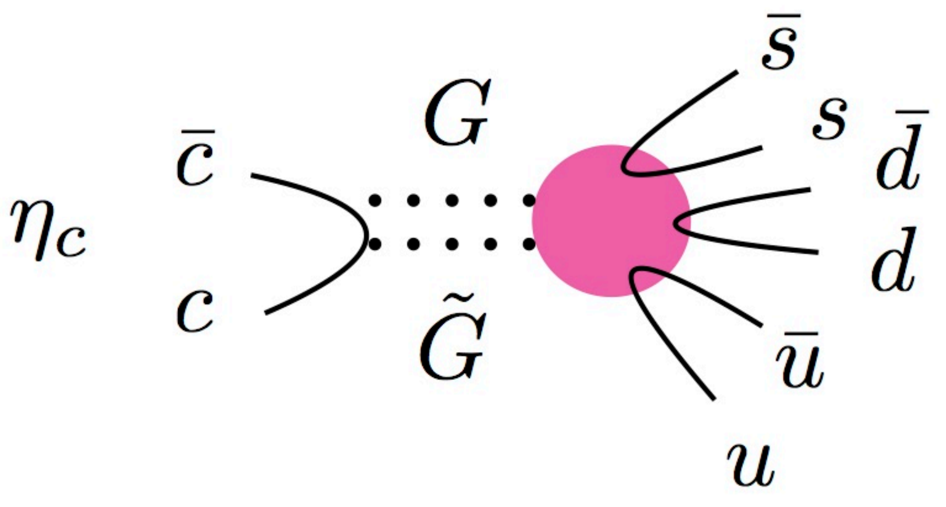

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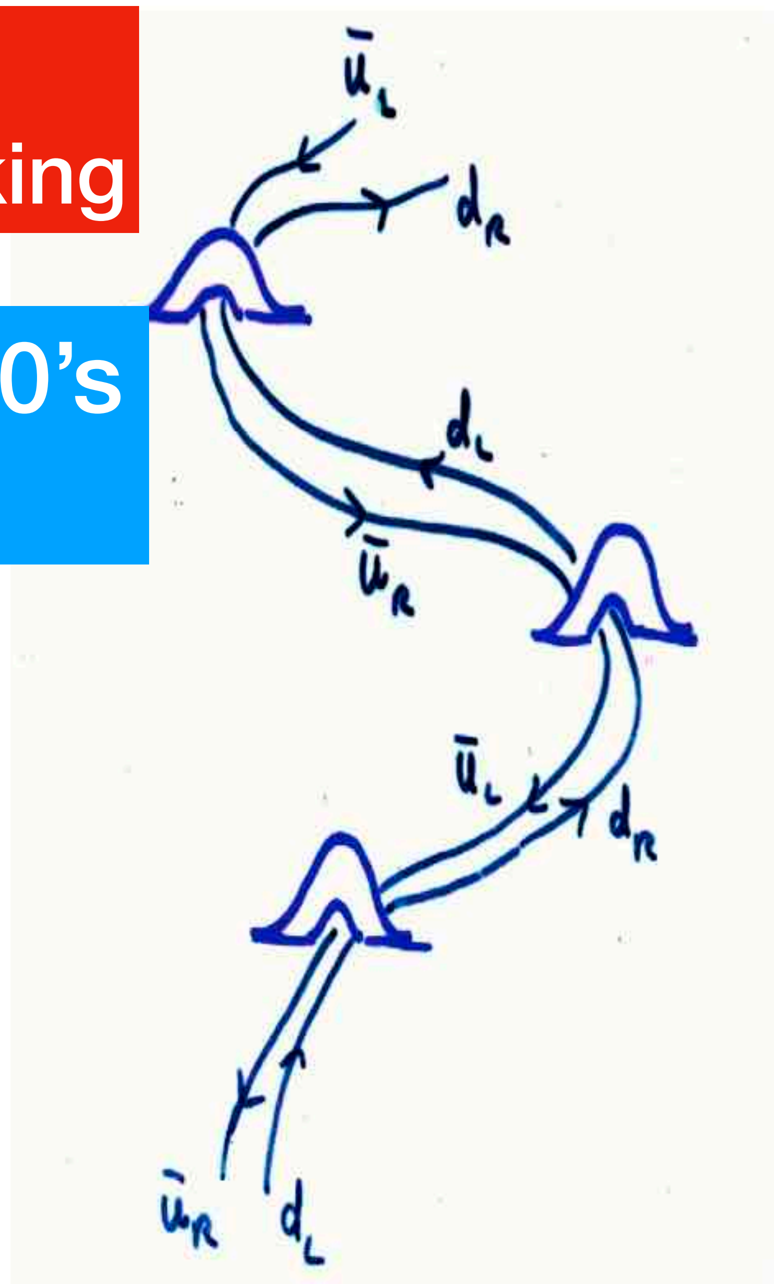

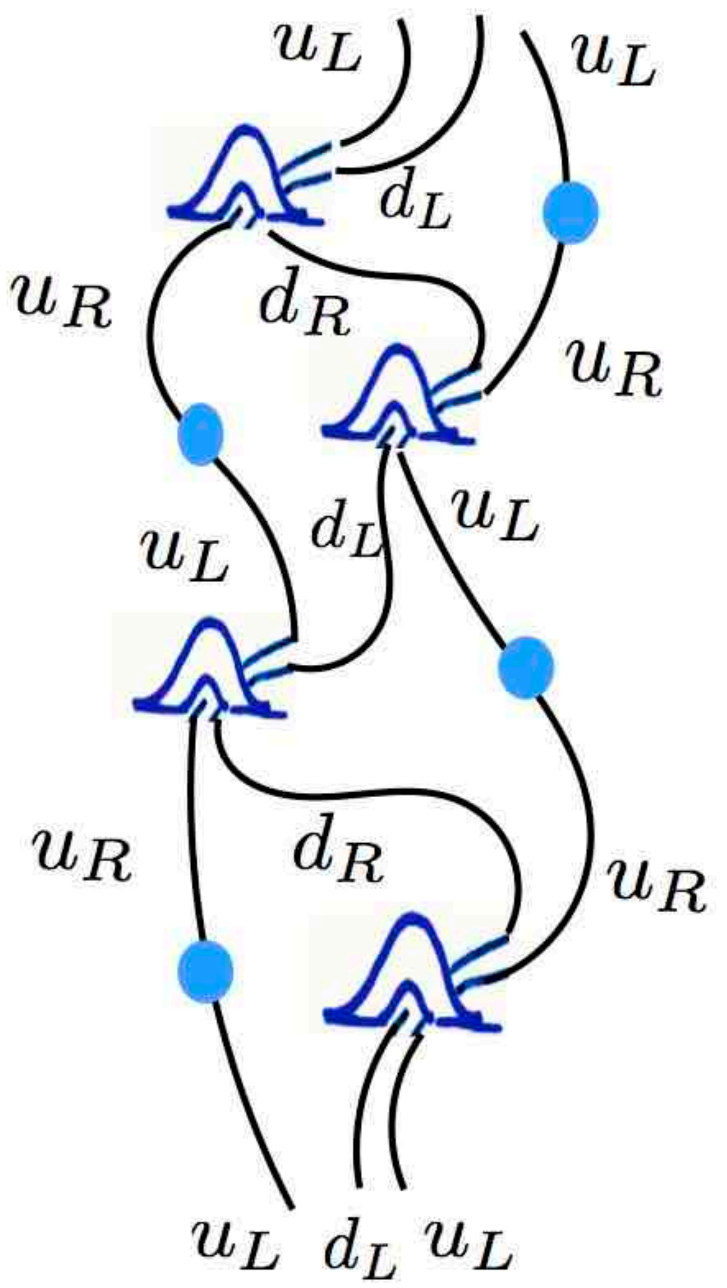

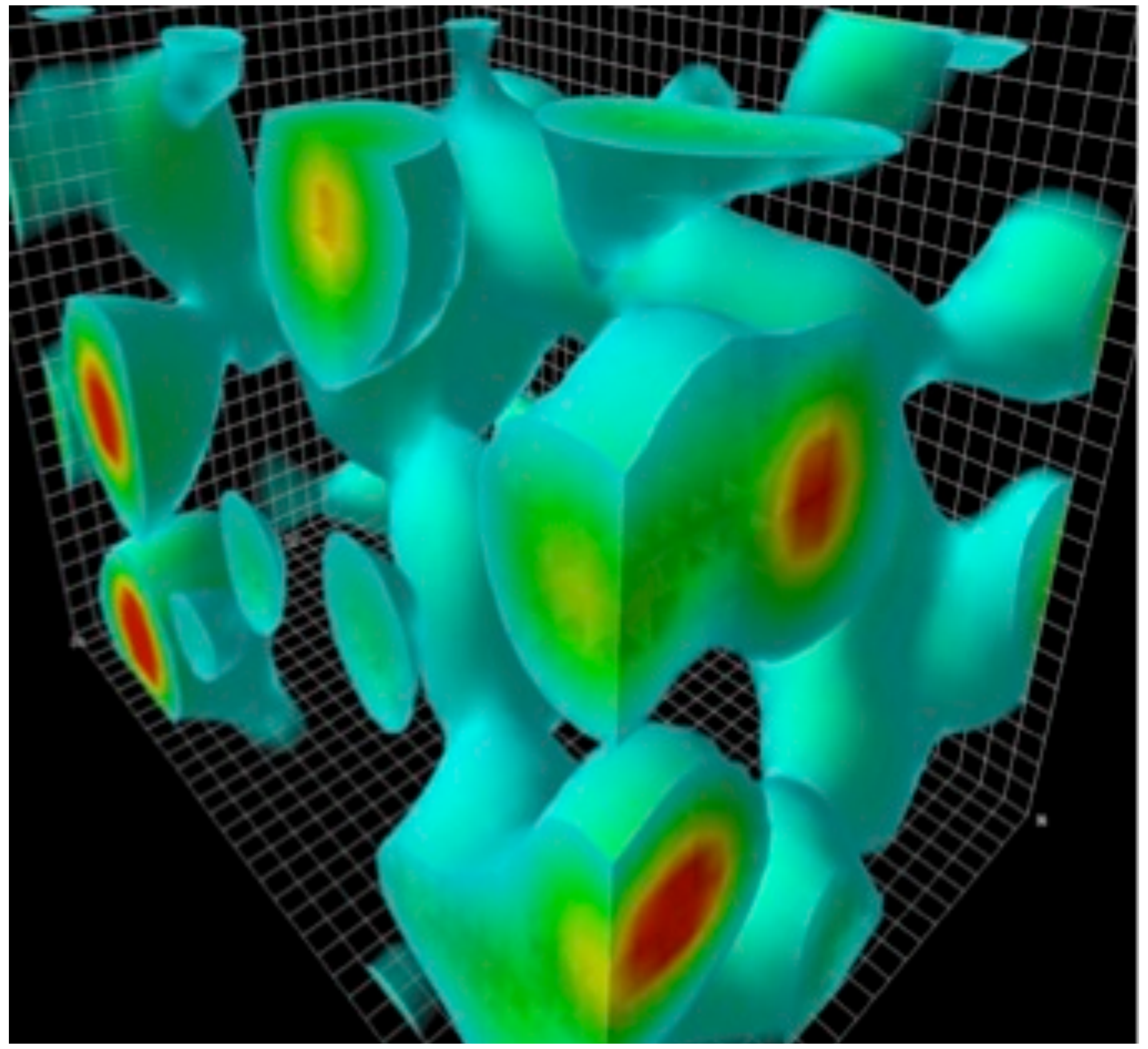

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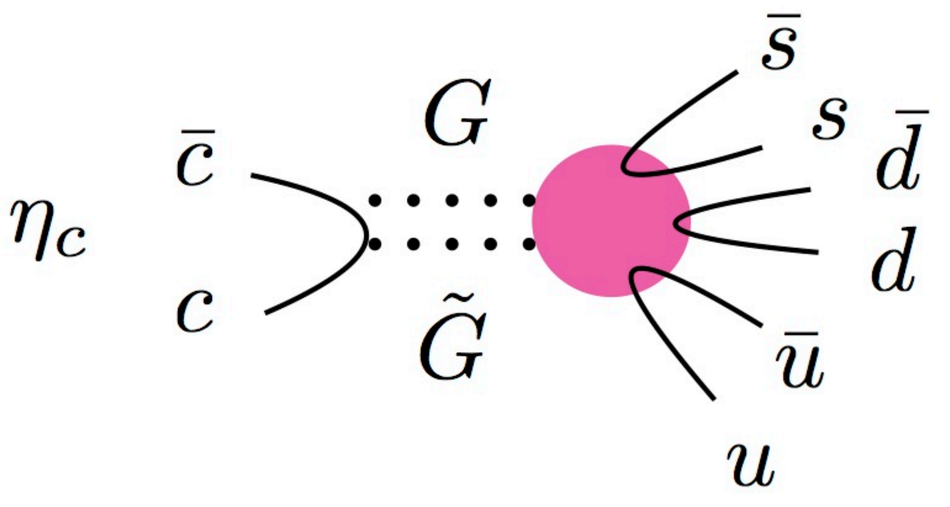

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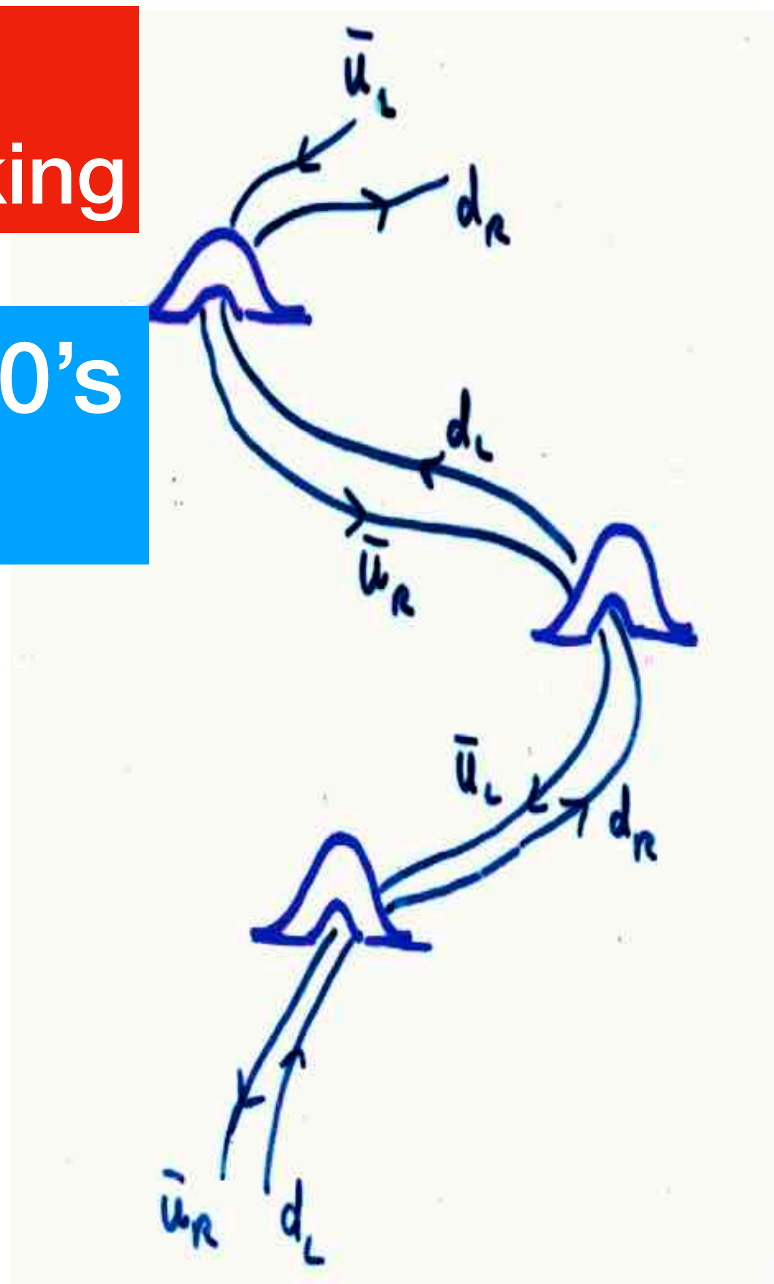

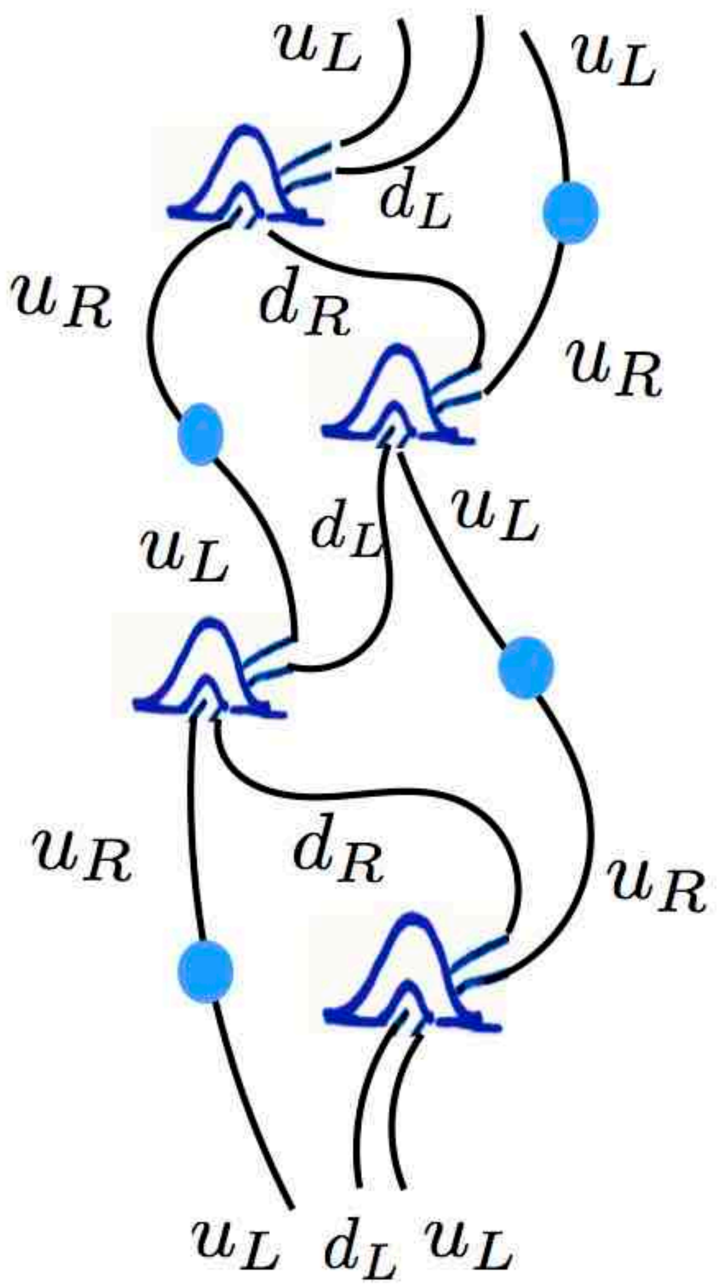

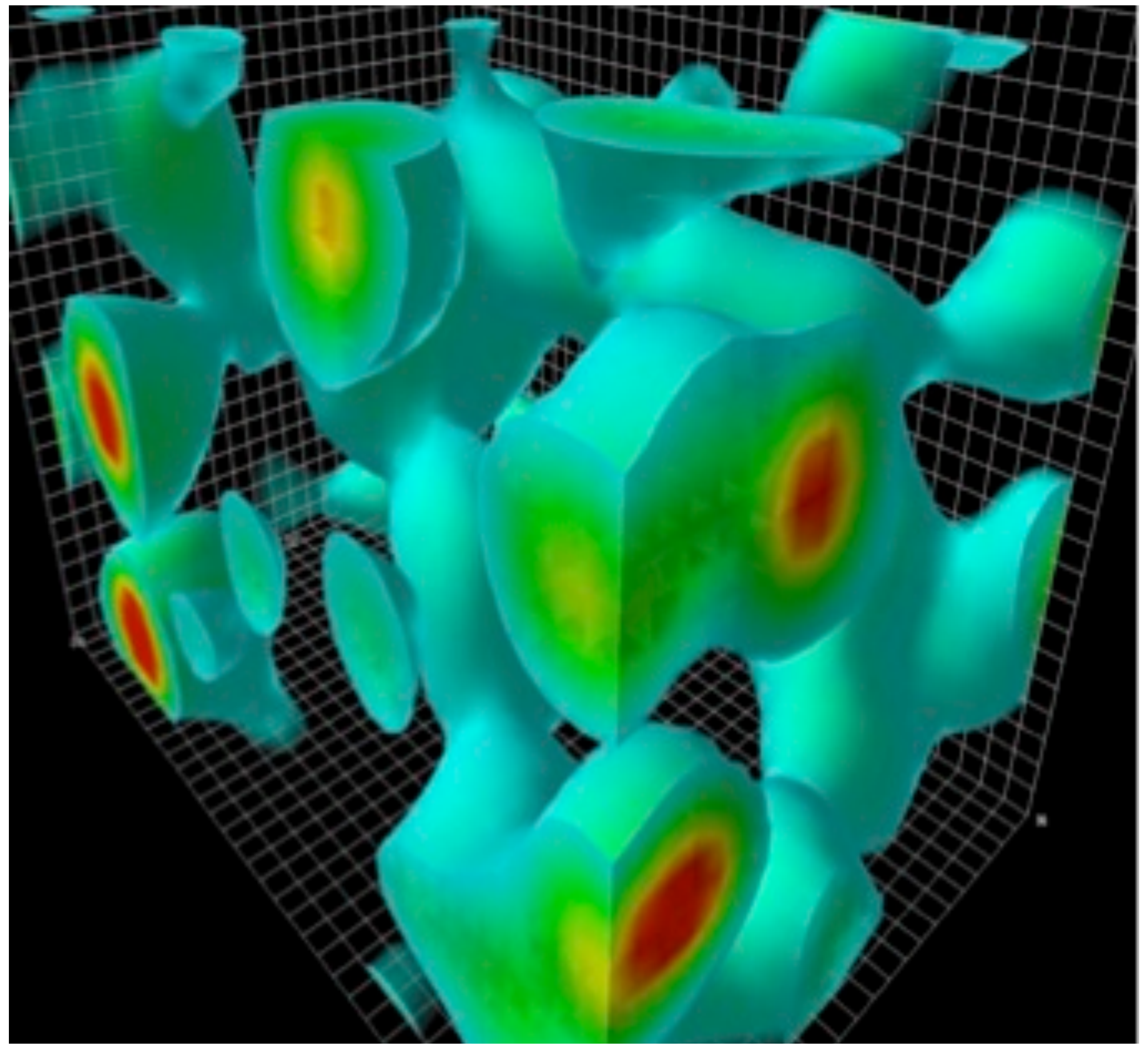

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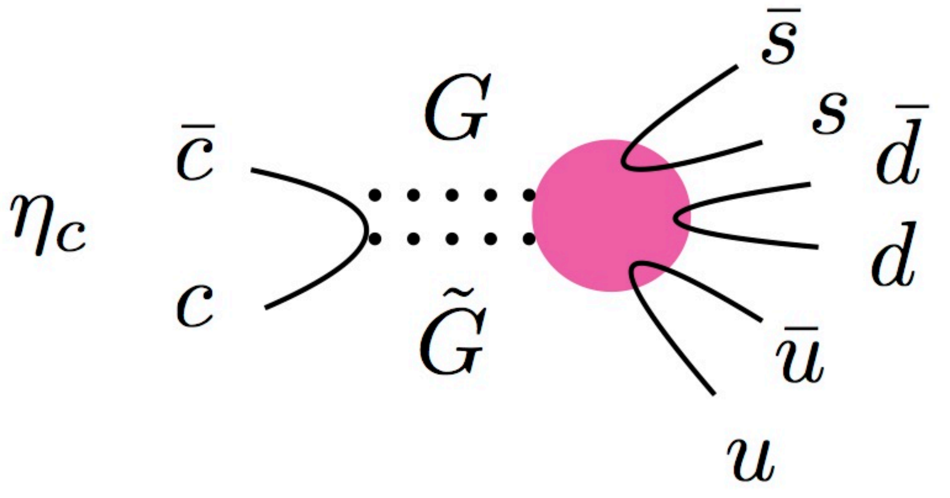
Light-front wave functions of mesons, baryons, and pentaquarks with topology-induced local four-quark interaction
ES,*Phys.Rev.D* 100 (2019) 11, 114018 • e-Print: 1908.10270



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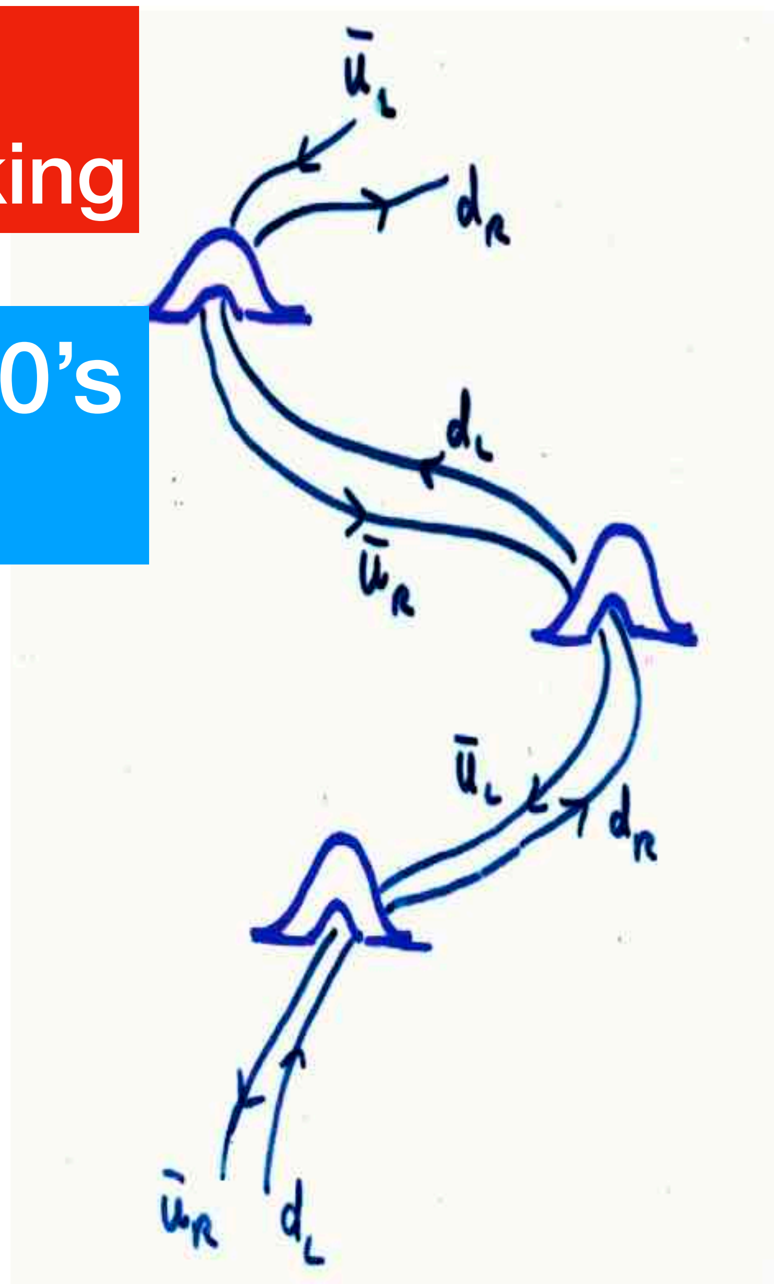

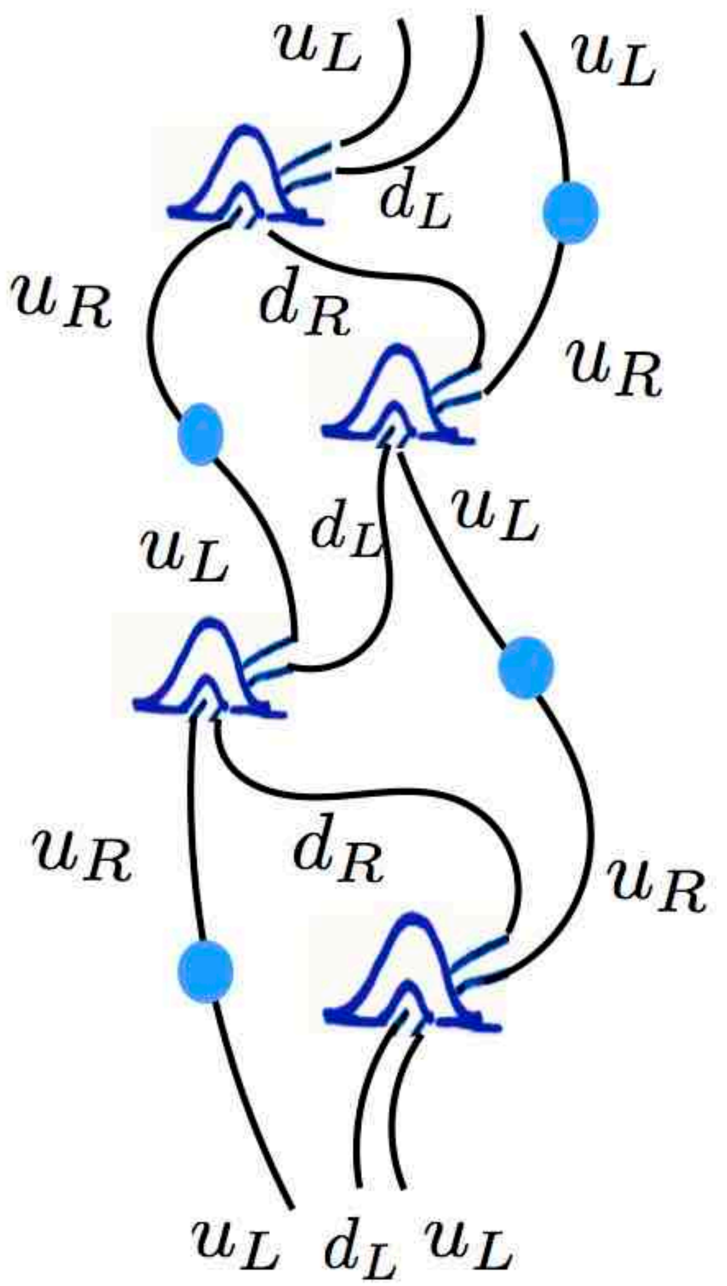

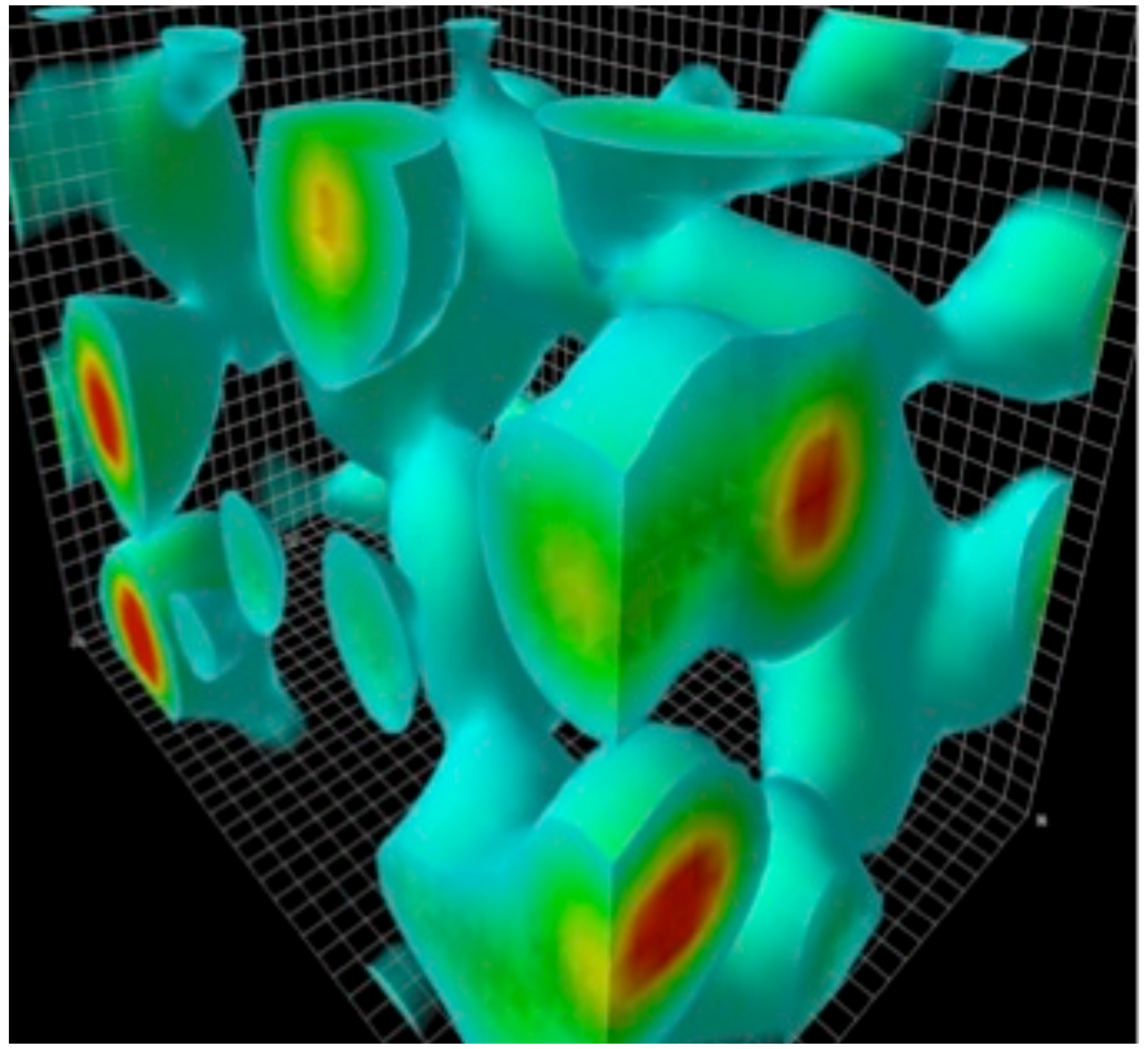

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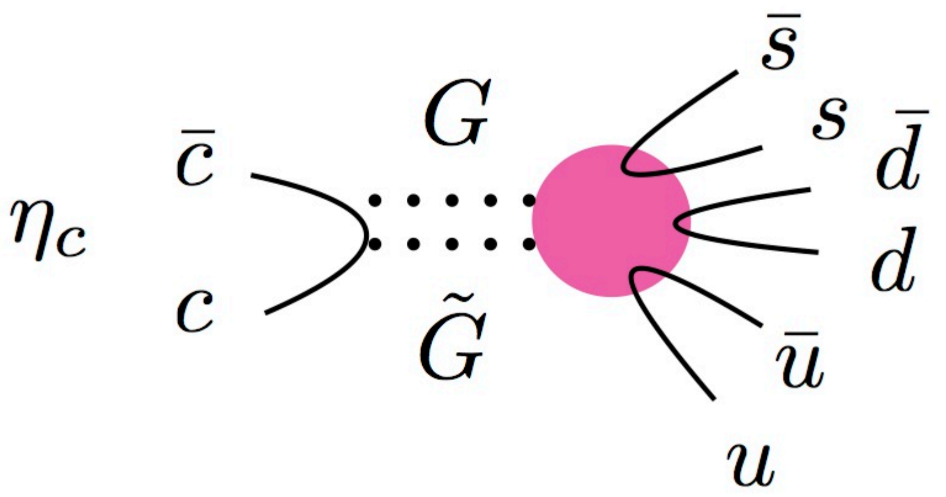
Nonperturbative quark-antiquark interactions in mesonic form factors ES, Ismail Zahed , 2008.06169



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topological landscape configurations in pure gauge theory were historically derived in three different ways.

Here is number 1: reduction to 3d from 4d instanton-antiinstanton configuration

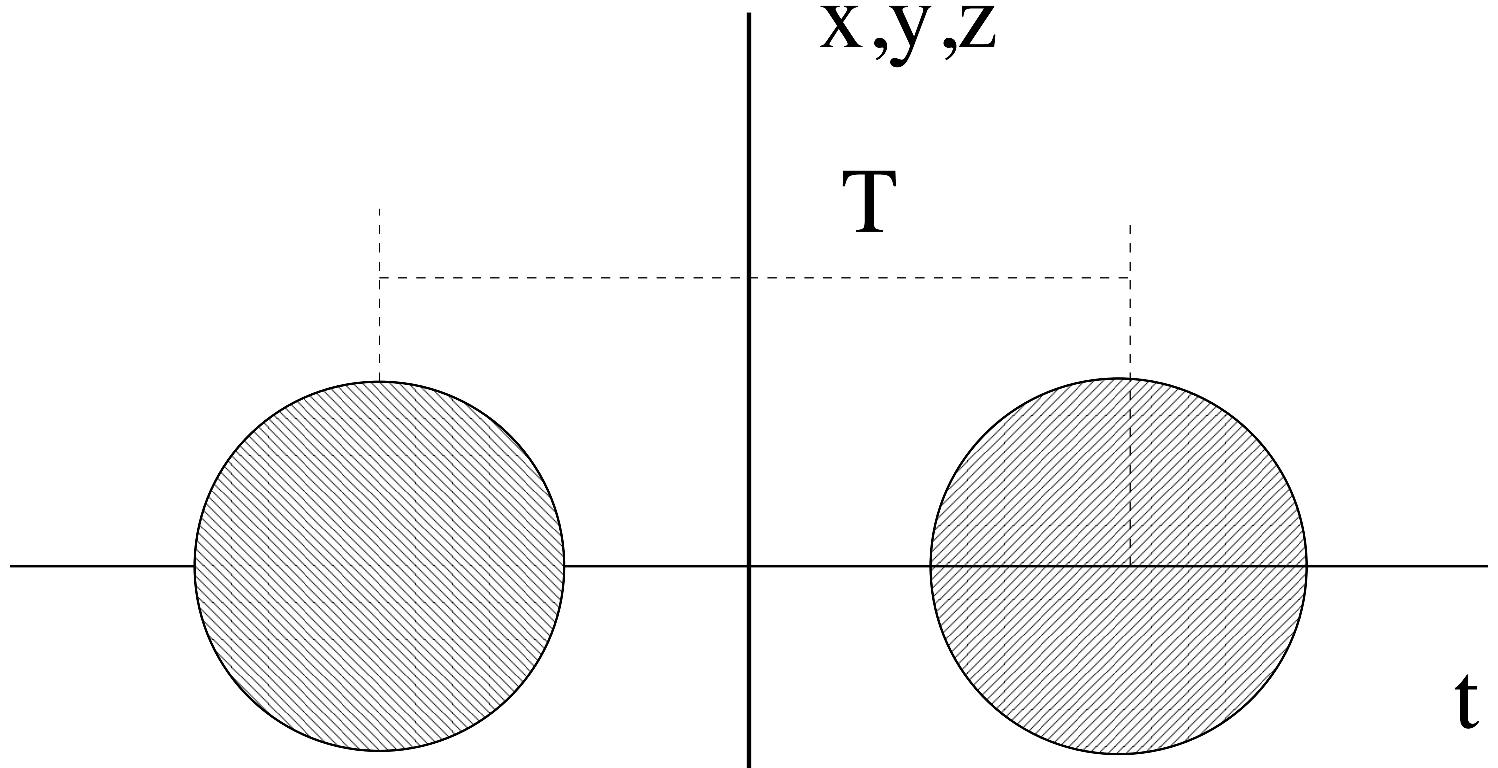
Forced Tunneling and Turning State Explosion in Pure Yang-Mills Theory

D. M. Ostrovsky[1], G. W. Carter[2], and E. V. Shuryak[1]

[1] *Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800*

[2] *Department of Physics, Box 351560, University of Washington, Seattle, WA 98195-1560*

(18 April 2002)



selfdual

anti-selfdual

Unitarity Cut

t is the Euclidean time here, t=0 is the "unitarity cut" On which E=0, only B And Minkowskian path into the Real world starts from it!

One can see that, in the simplest case of identical sizes and orientations for the I and $\bar{I}$, time reflection symmetry $t \rightarrow -t$ of the problem is indeed manifest, so that

$$\mathcal{A}_0^a(\vec{r}, t=0) = 0\,, \quad \mathcal{E}_m^a(\vec{x}, t=0) = 0\,. \qquad (21)$$

topological landscape configurations in pure gauge theory were historically derived in three different ways.

Here is number 1: reduction to 3d from 4d instanton-antiinstanton configuration

Forced Tunneling and Turning State Explosion in Pure Yang-Mills Theory

D. M. Ostrovsky[1], G. W. Carter[2], and E. V. Shuryak[1]
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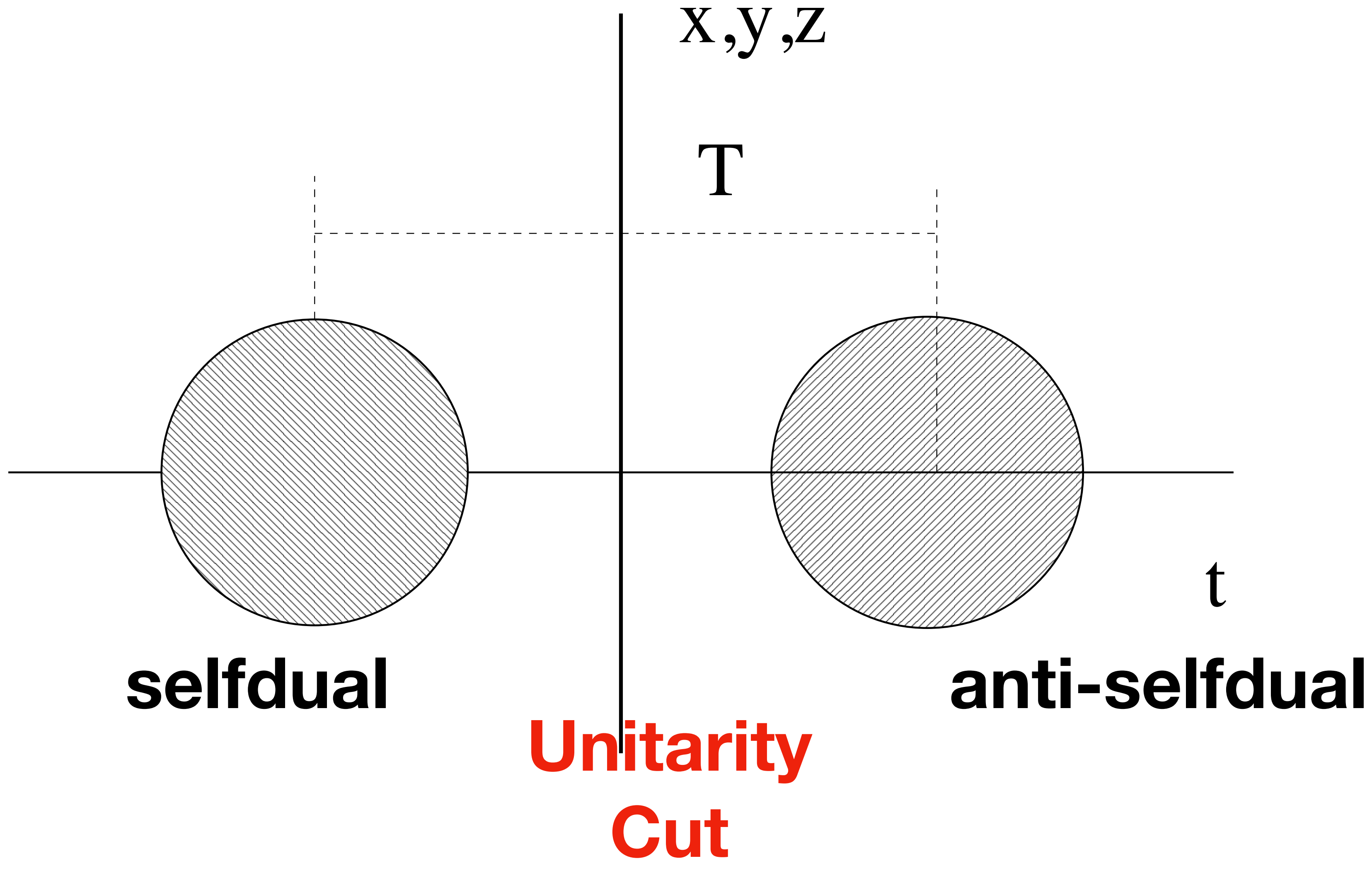

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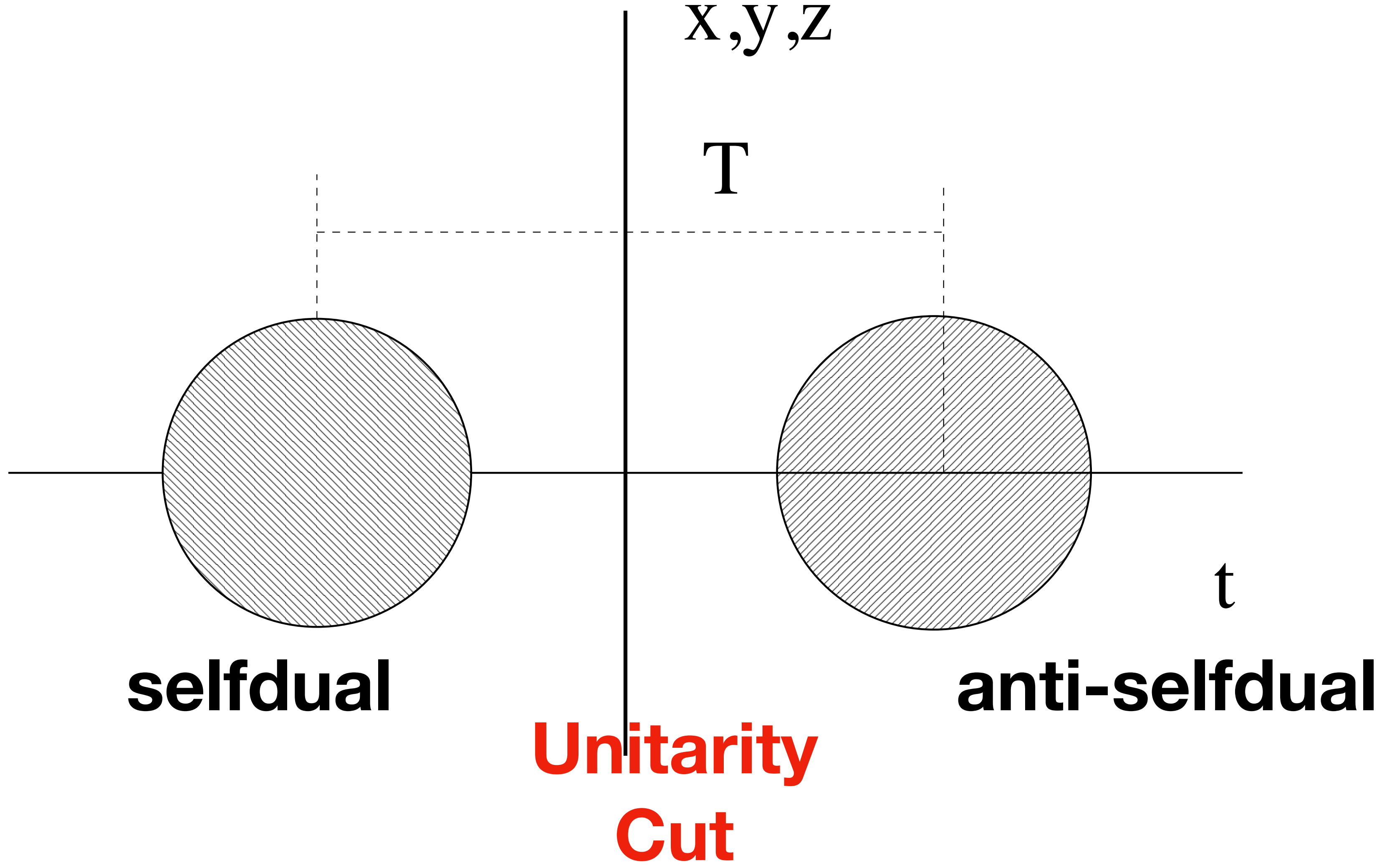

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but only Yung's ansatz worked,
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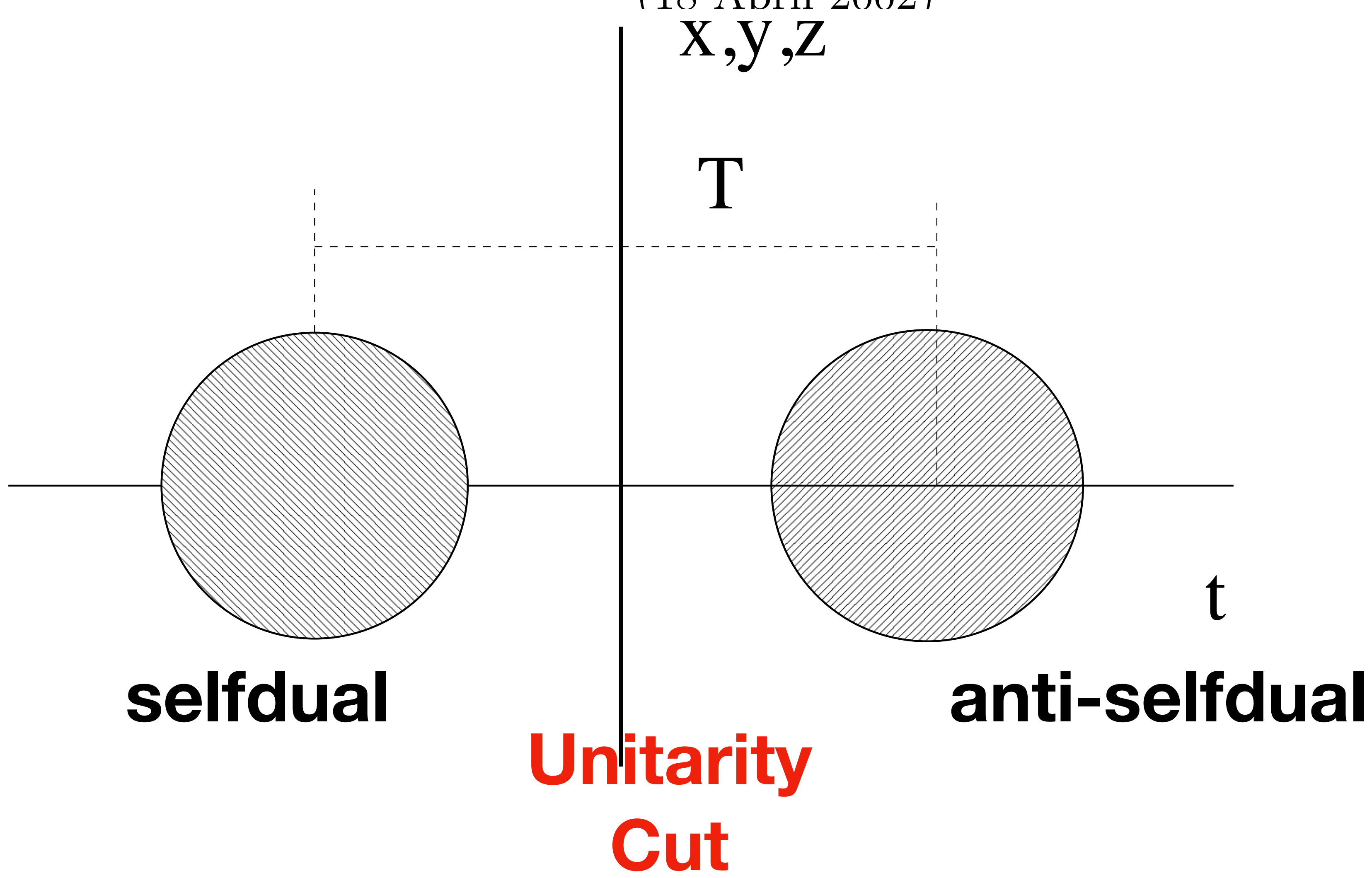

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t is the Euclidean time here,
t=0 is the “unitarity cut”
On which E=0, only B
And Minkowskian path into the
Real world starts from it!

The unitarity cuts are
Like ``turning points” in QM,
They are in between
Virtual motion
Under the barrier
And real one above the barrier

we tried sum ansatz,
ratio ansatz
but only Yung’s ansatz worked,
as shown by Verbaarschot 91

Energy density is E^2+B^2
In Euclidean time E^2=> -E^2
So e.g. in instantons the energy density (and all T_\mu\nu) vanishes at every point, since E=iB

But in our 3d turning configurations E=0 and therefore energy >0
In fact there was 1-parameter set
Of configurations, depending on distance
Between the centers of the instantons

When we made a parametric plot,
Energy versus their Chern-Simons number,
We observed the profile of the sphaleron pass
Across the topological mountain

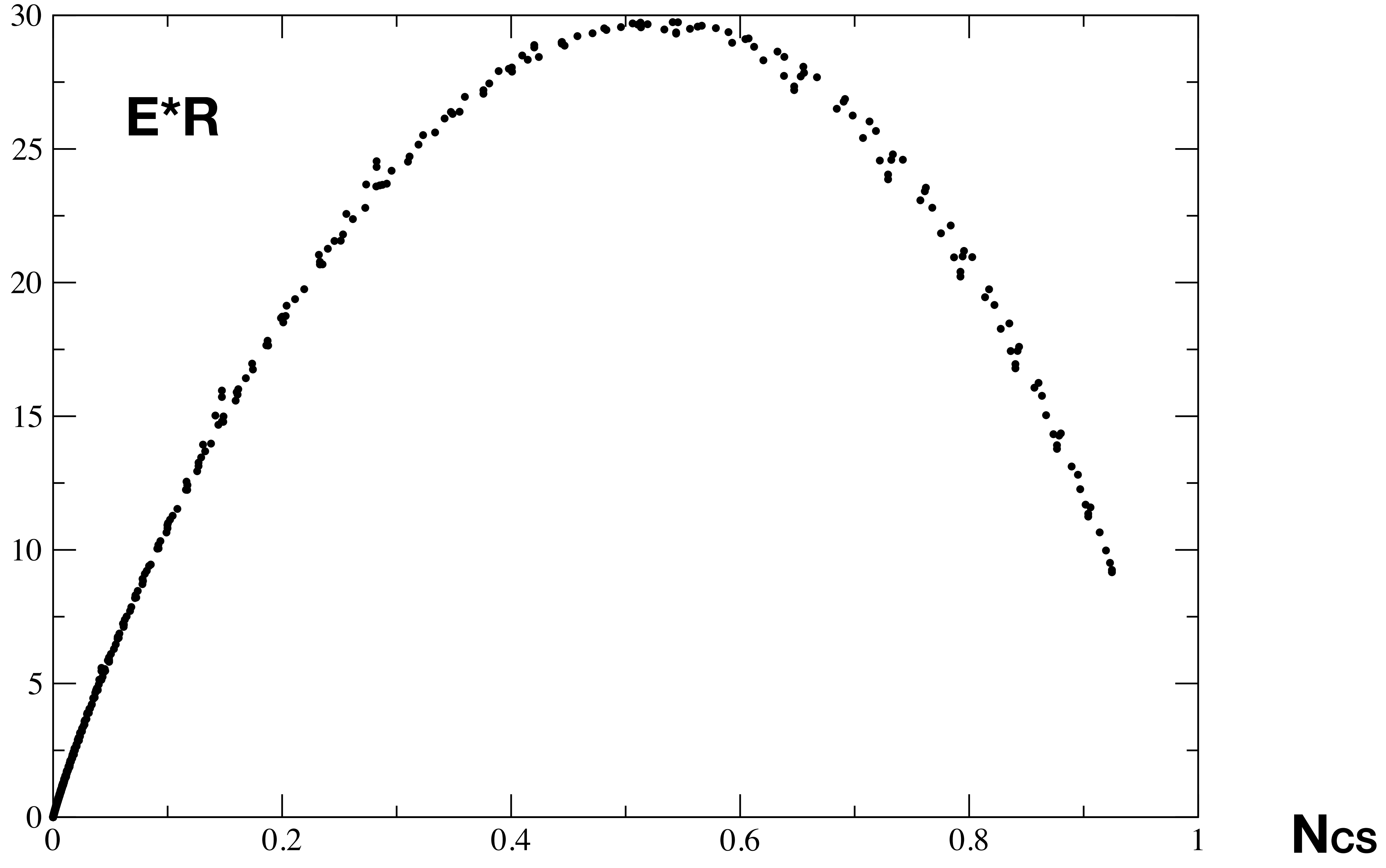


FIG. 6. The normalized energy, ER, versus the Chern-Simons number for the Yung ansatz. Plot (a) shows the positions of the turning states for various T, while (b) combines many points along the path ($t \neq 0$); their small spread means that Yung ansatz is nearly going directly up-hill, thus passing via the same points for different T.

Sphaleron production cross section
Is given by action : see below

Here is derivation number 2: constrained minimization

Carter-Ostrovsky,ES: QCD sphalerons

- What is the minimal potential energy of static Yang-Mills field, consistent with the constraints:

(i) the given value of (corrected) Chern-Simons number.

(ii) the given value of the r.m.s. size $< r^2 >= \int d^3x r^2 B^2 / \int d^3x B^2$

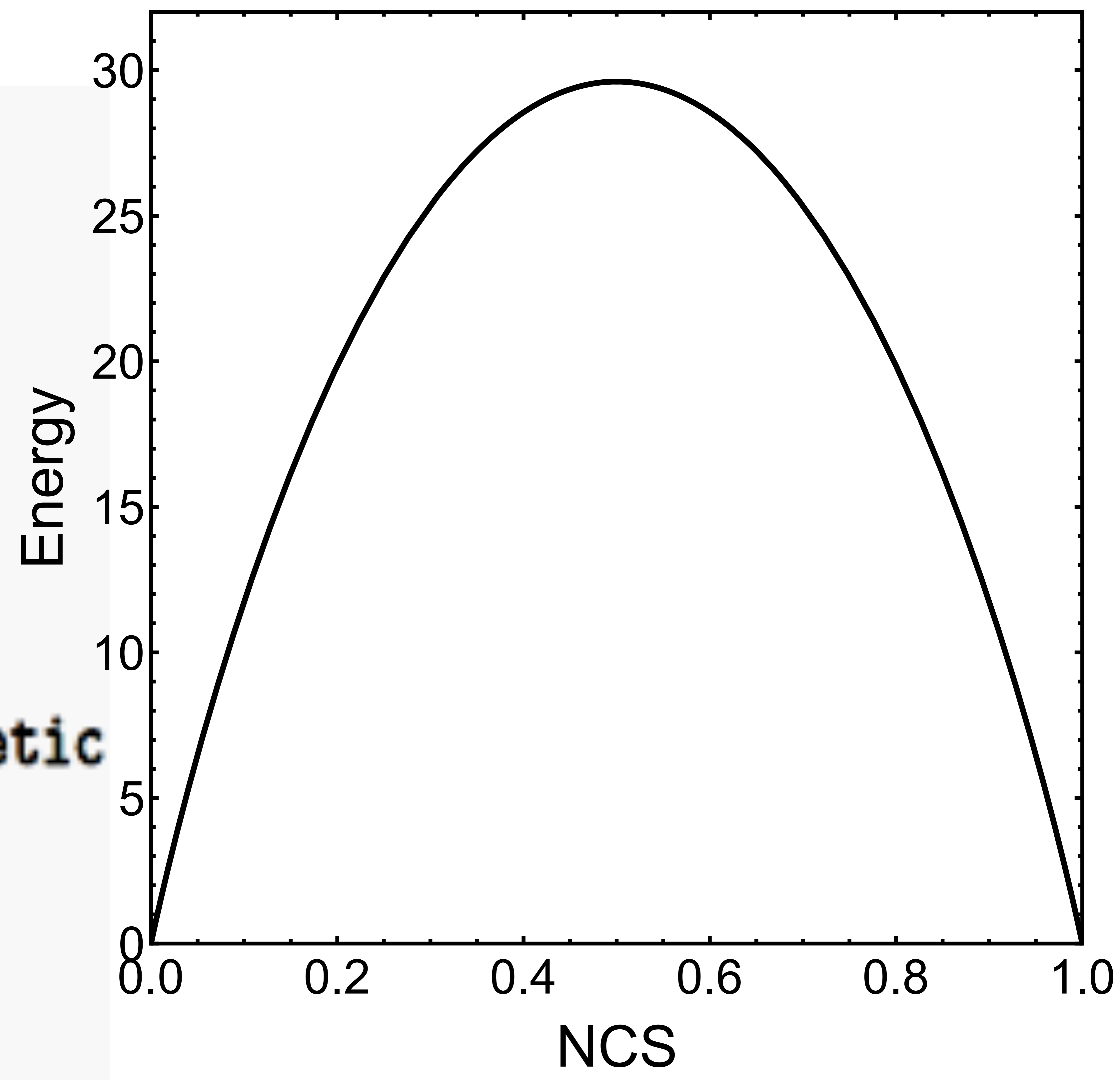
- Solution (found by D.Ostrovsky) is a ball made of three magnetic gluon fields (out of 8 in SU(3)) rotated around x,y,z axes

$B^2/2 = 24(1-\kappa^2)^2\rho^4/(r^2+\rho^2)^4$

$E_{stat} = 3\pi^2(1-\kappa^2)^2/(g^2\rho)$ $\tilde{N}_{CS} = \mathrm{sign}(\kappa)(1-|\kappa|)^2(2+|\kappa|)/4.$

Eliminating κ one gets the topological potential energy,

$\kappa = 0$ gives the sphaleron



We so far discussed only pure gauge theory which is scale invariant
But as the size rho gets large, vacuum structure needs to be take into account

In electroweak theory one has to include the Higgs scalar and its VEV v
as known from Klinkhammer and Manton (1984)
M(size) grows at large sizes, rho^4 v^4, and thus there is a minimum
=> the original electroweak sphaleron

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In QCD the sitation is in fact similar
if rho increases one has to include
the field and VEV of the dual Higgs ,
a Bose-Einstein condensate of monopoles.
It suppresses large sizes of
flux tubes,
instantons and sphalerons

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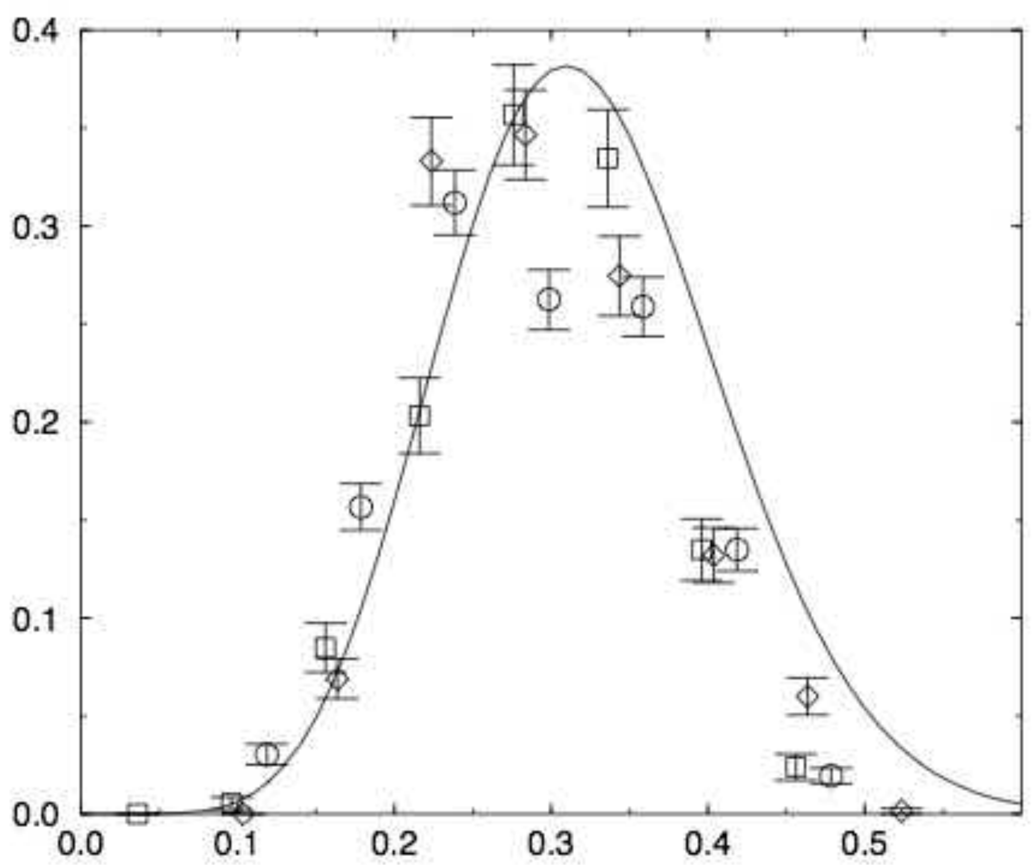

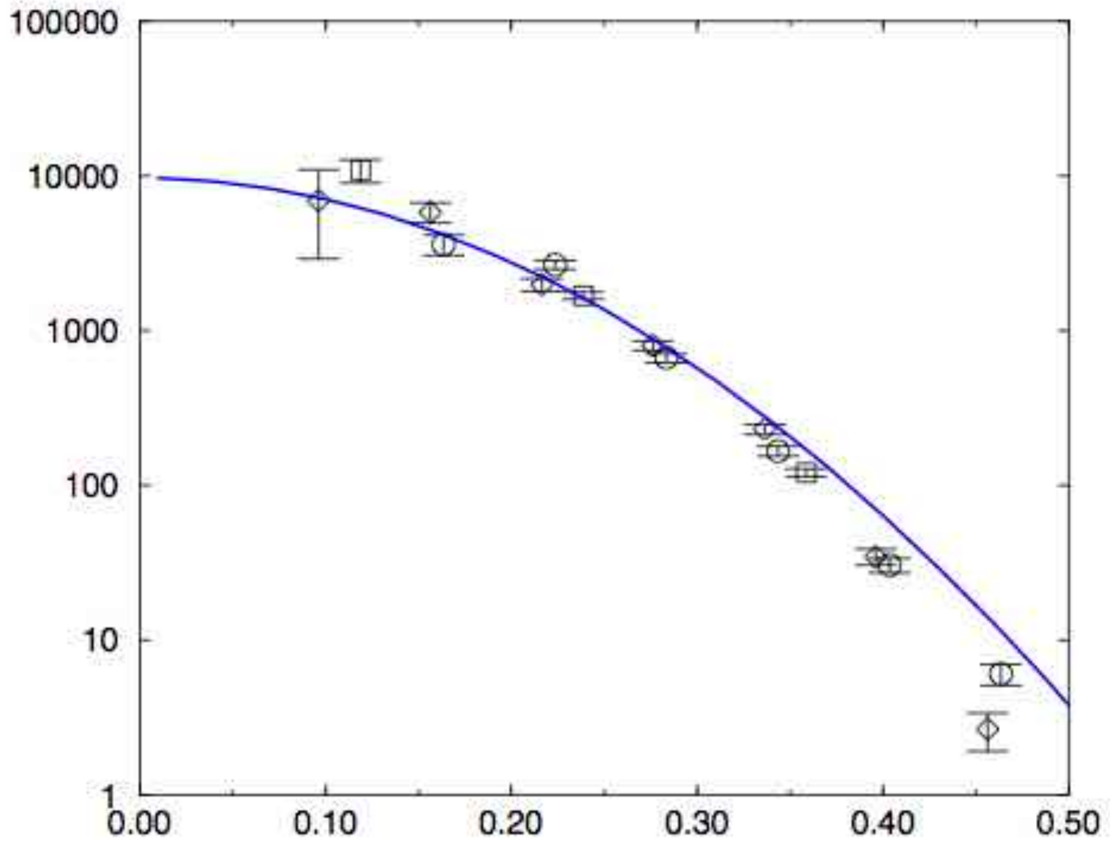

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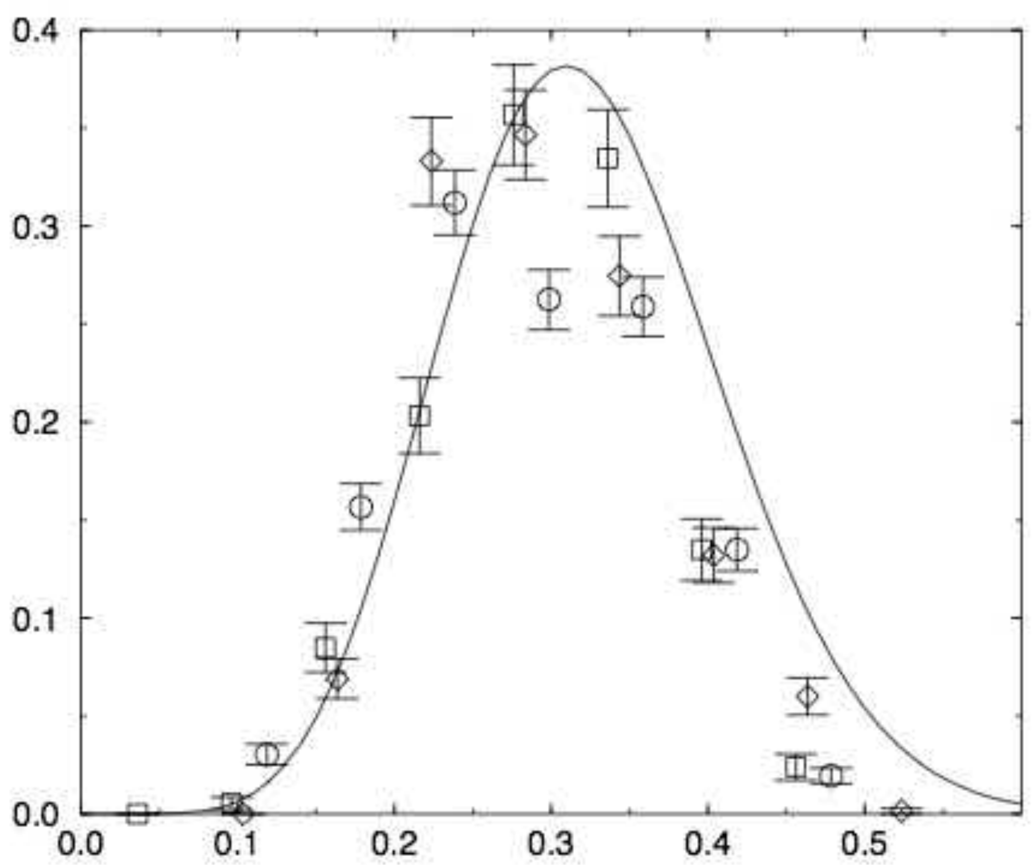

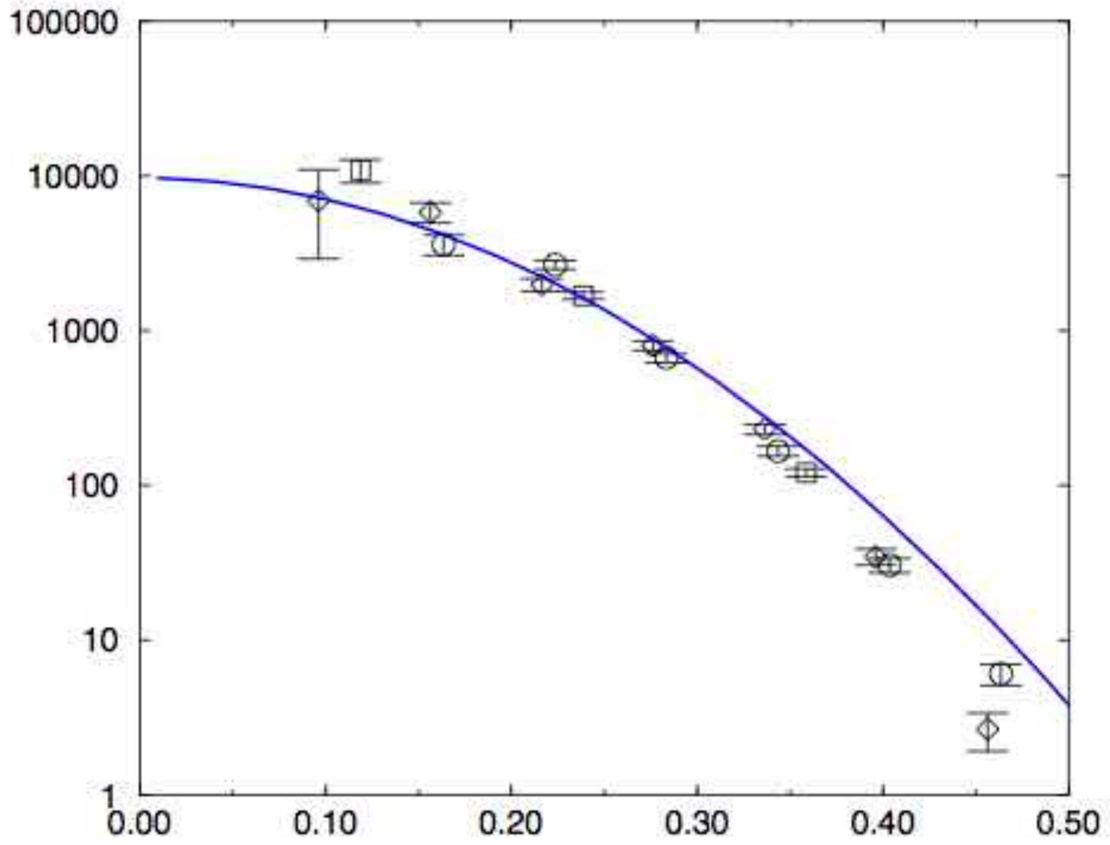

distribution of instanton sizes rho (fm) in the QCD vacuum

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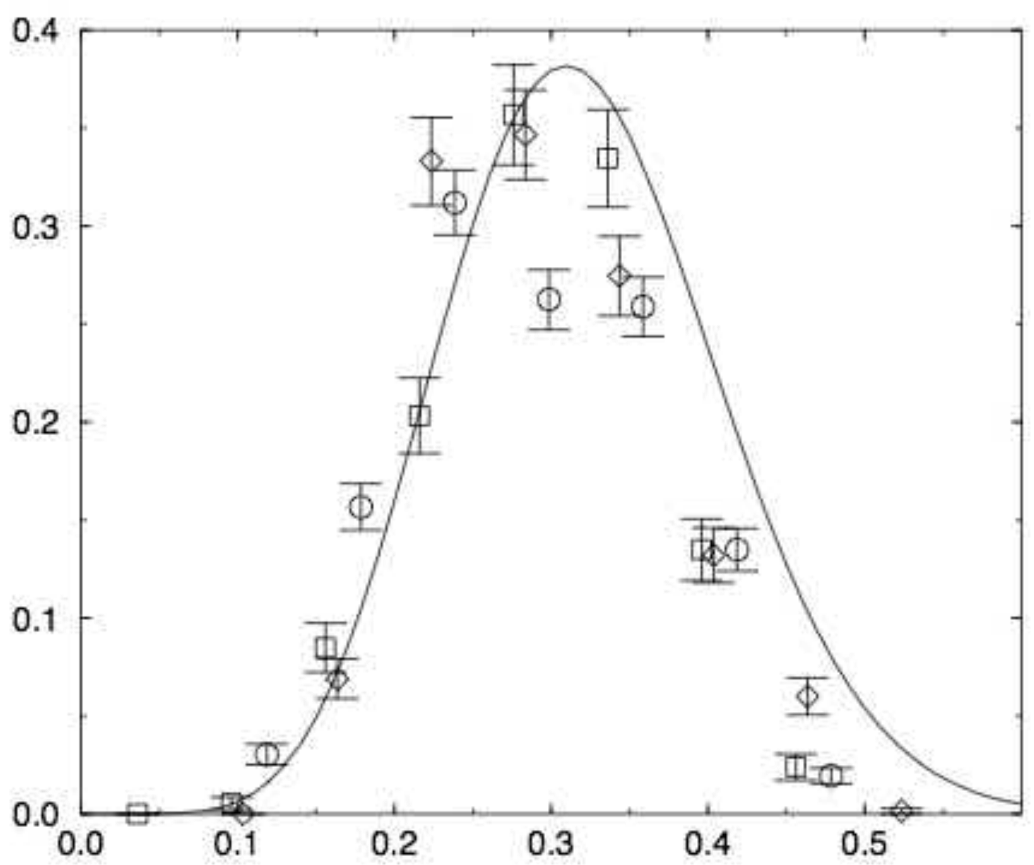

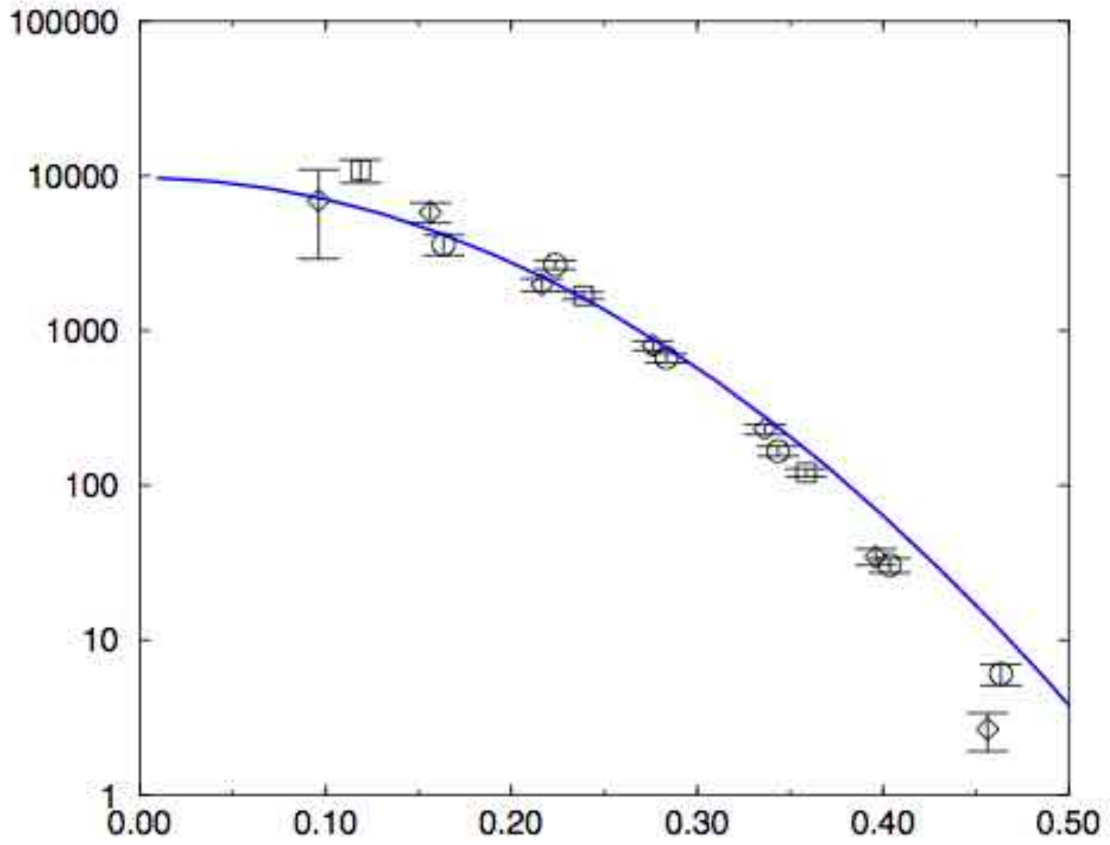

both lines correspond to the following formula

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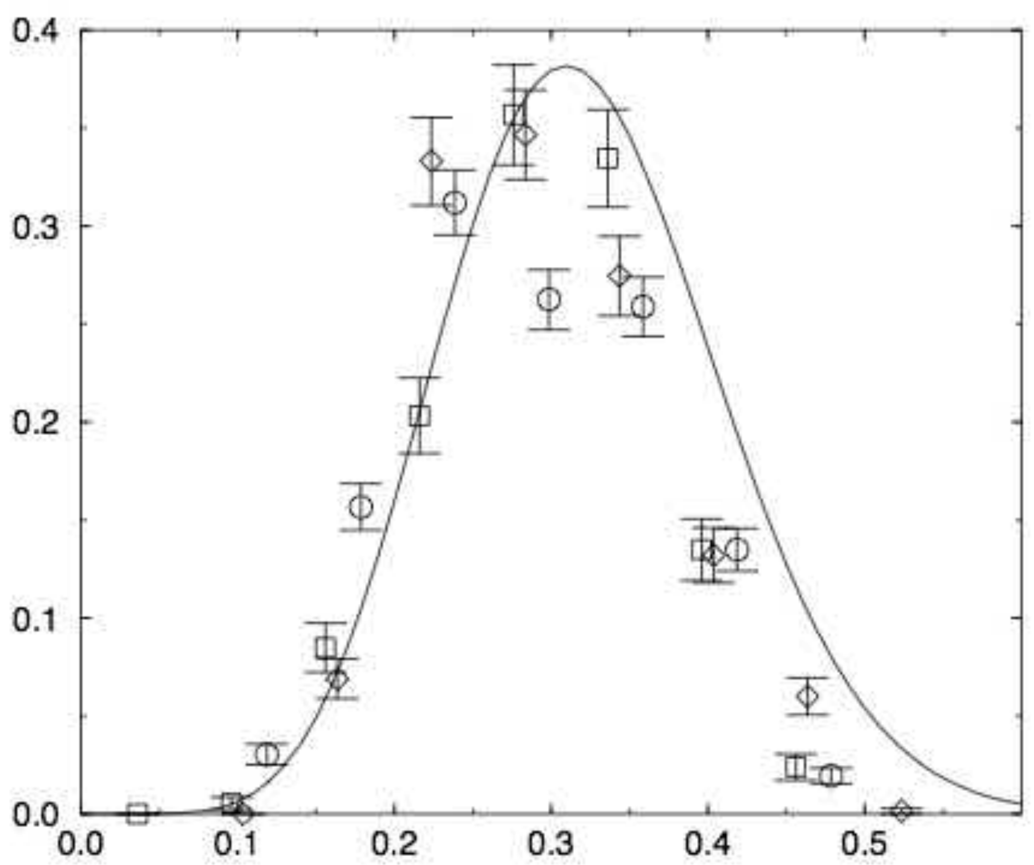

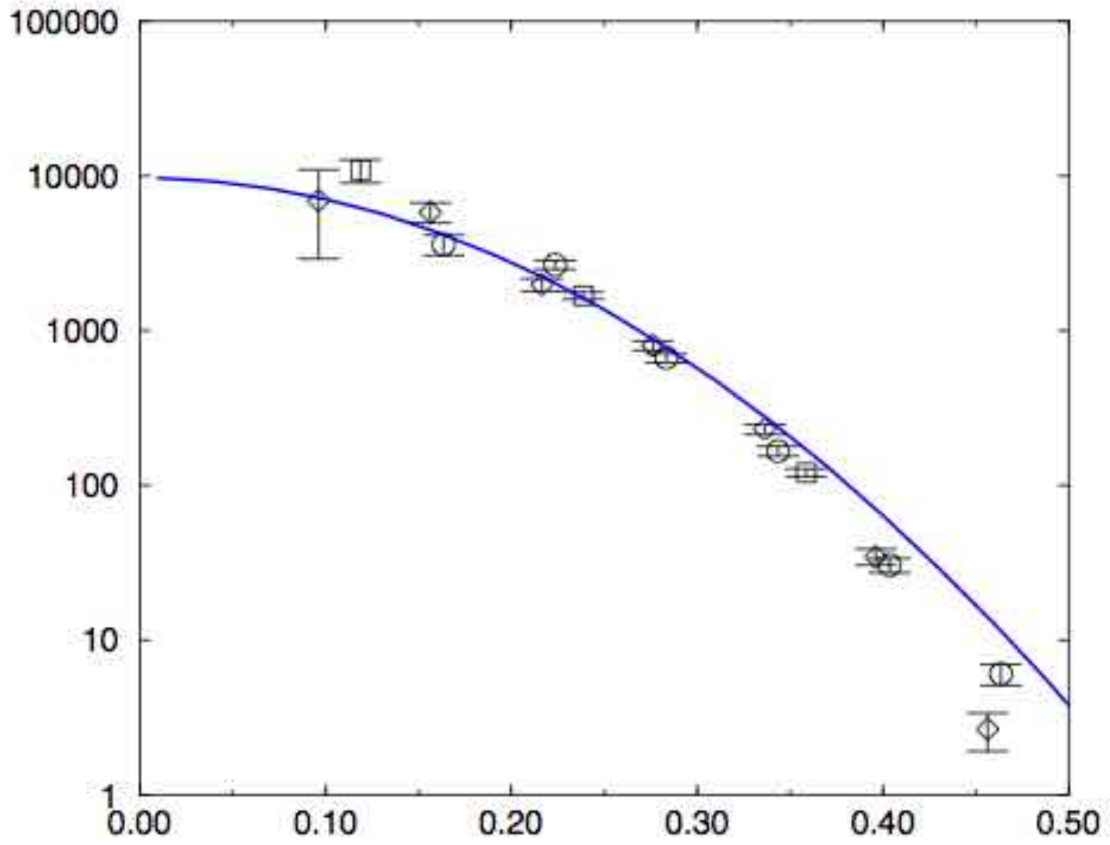

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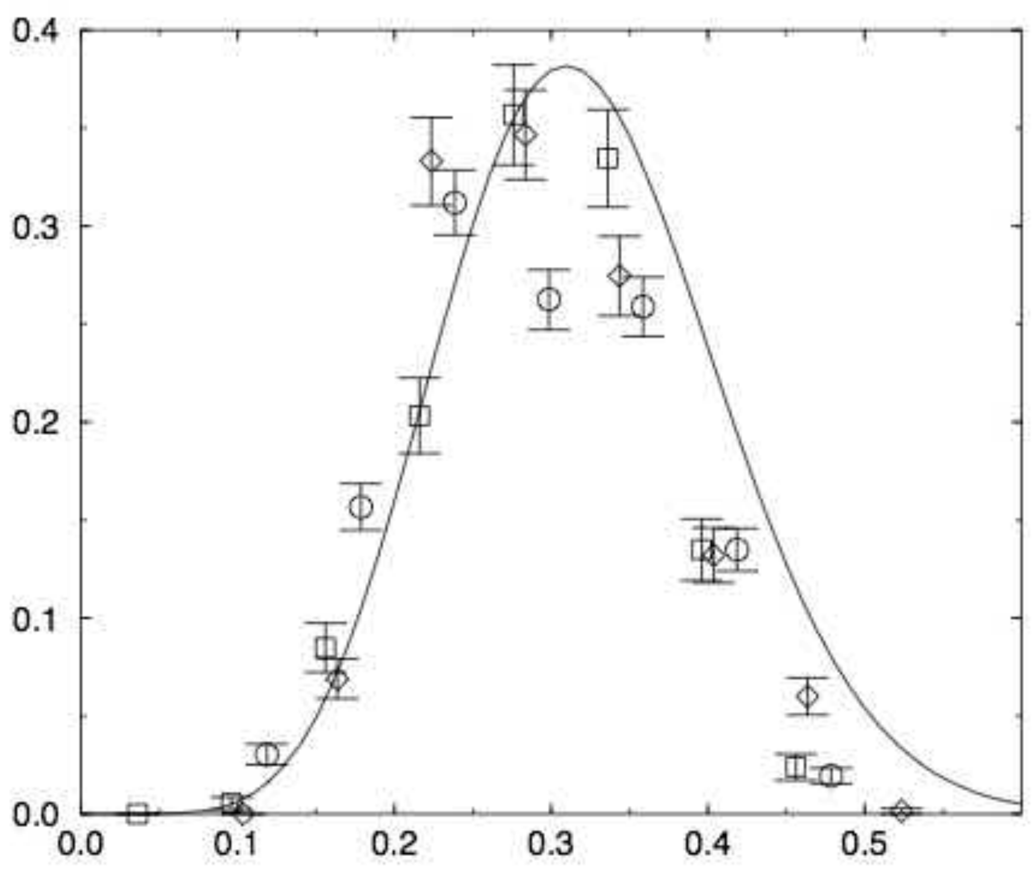

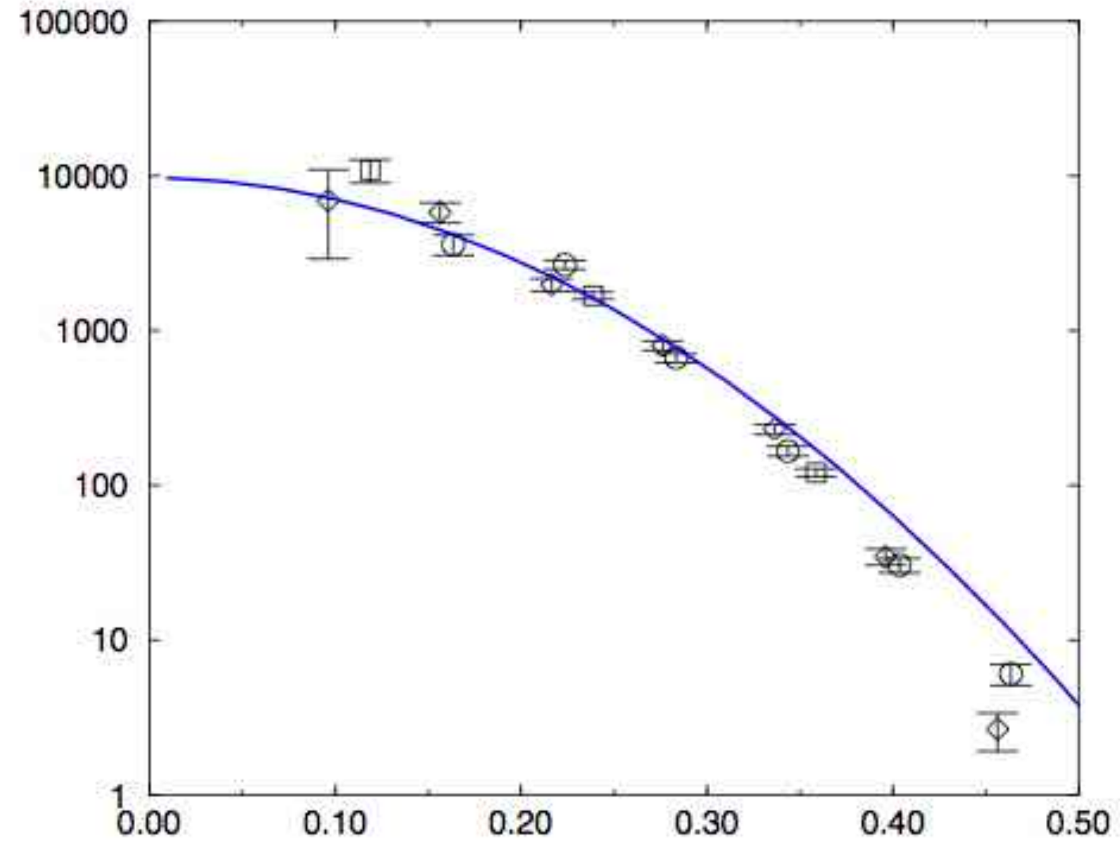

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the string tension
sigma stands for v^2

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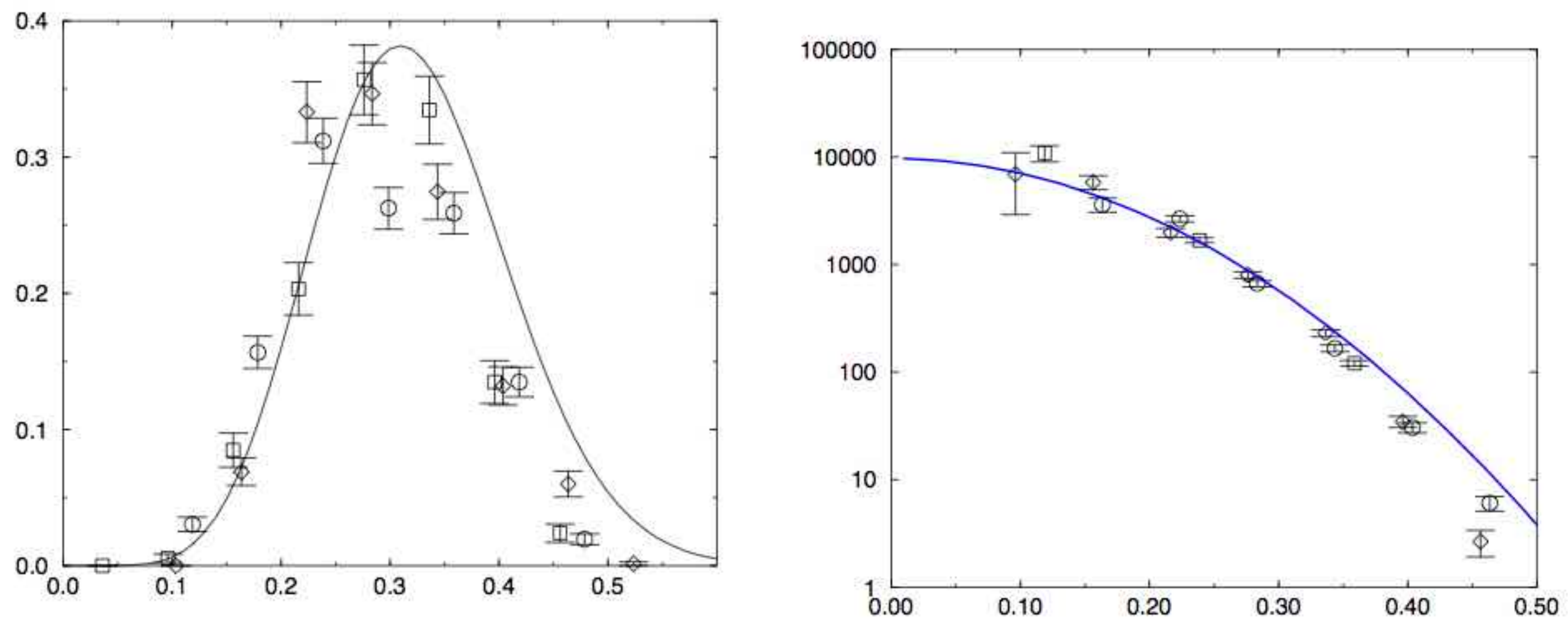

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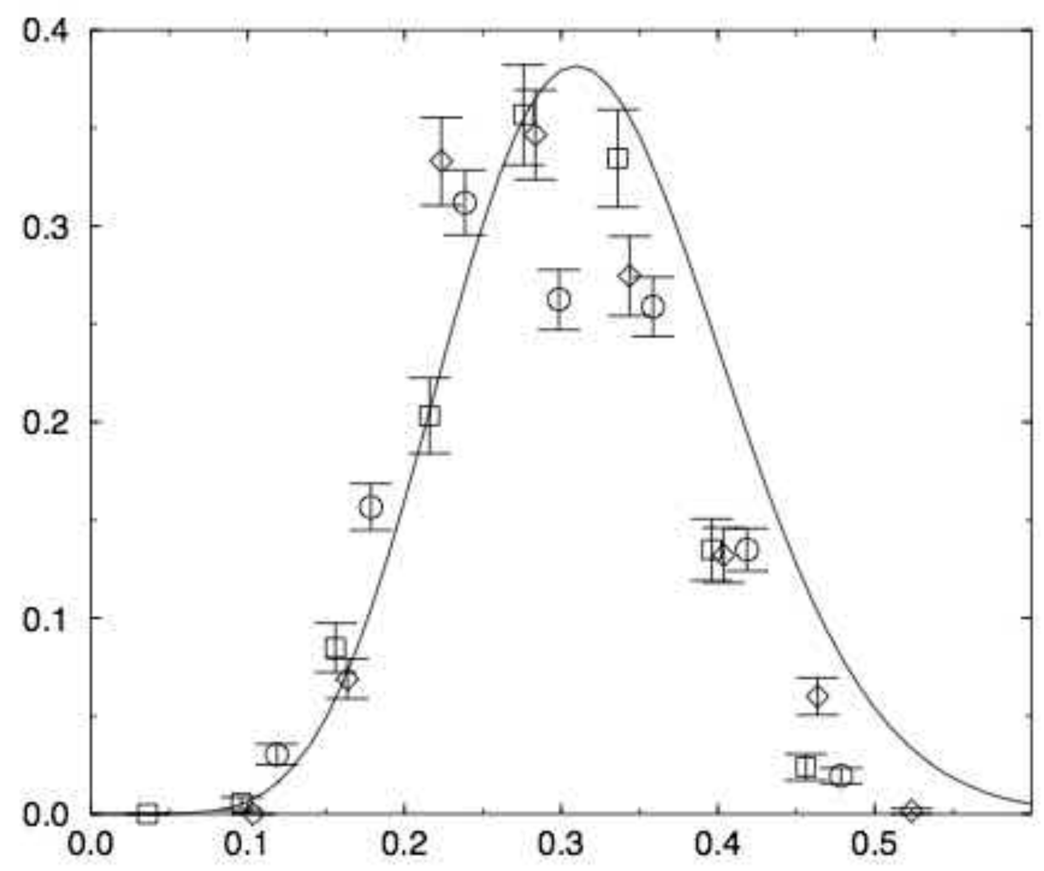

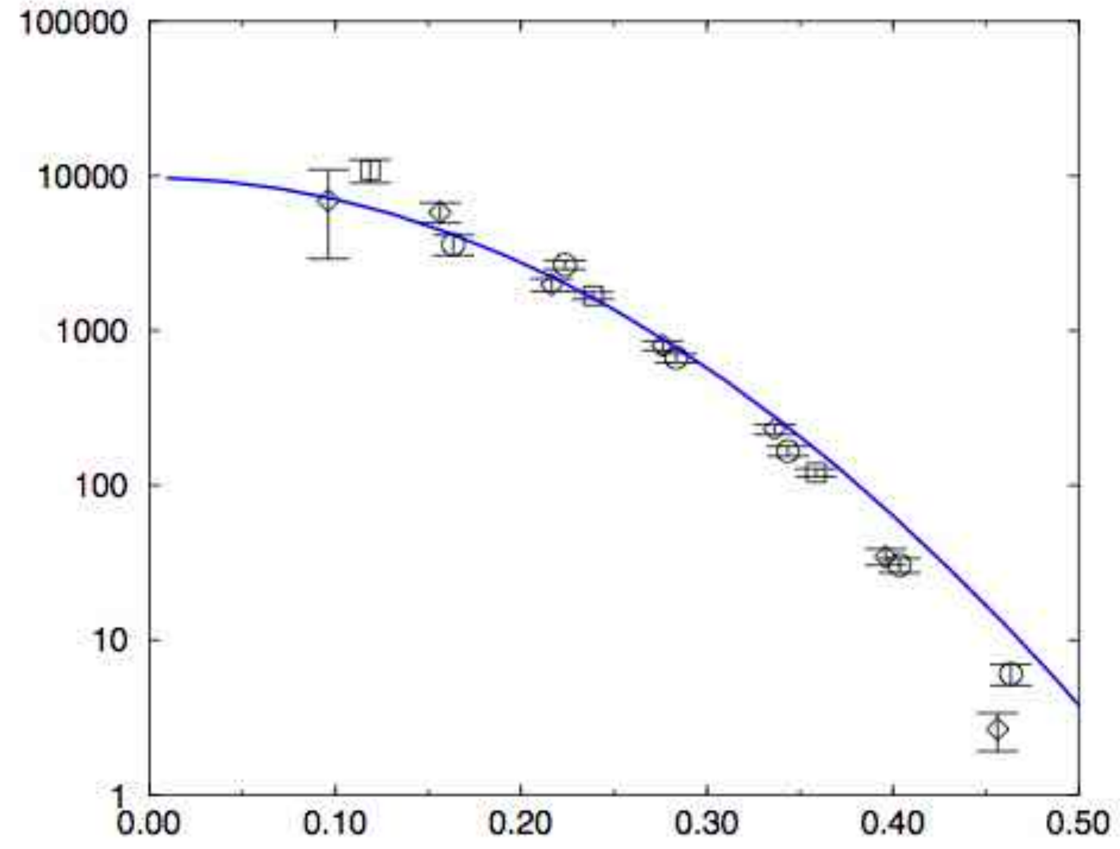

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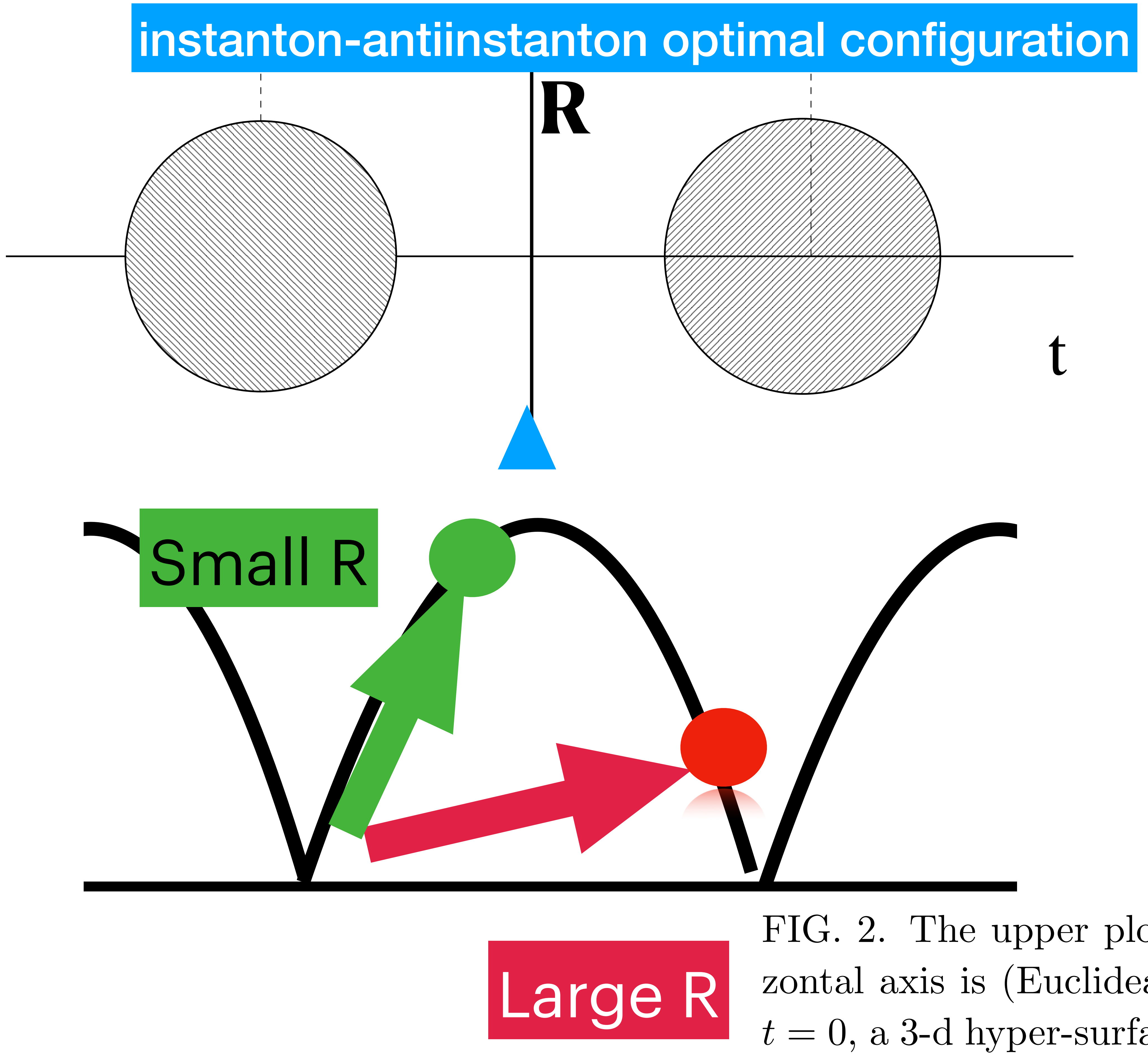
Lattice data, A.Hazenfratz,1999

How to observe instanton/sphaleron processes at LHC and RHIC

$$\sigma \sim \left[\frac{\text{entrance}}{\text{factor}}\right]\left[\frac{\text{semiclassical}}{\text{prefactor}}\right]\left[e^{-S_{cl}}\right]\left[B(\text{final state})\right]$$

Now, when we understand the mountain landscape, we need to carefully select the place for a tunnel



shorter tunnel saves action,
on which probability of the process
depends exponentially,
but if NCS<1/2
the produced ball will roll
back to the original valley

FIG. 2. The upper plot shows a schematic picture of the instanton-antiinstanton configuration. The horizontal axis is (Euclidean) time t, and R is the distance between their centers. The blue triangle indicates $t = 0$, a 3-d hyper-surface in which the produced magnetic object resides. The lower plot with the red arrow, refers to the "reclined tunnel" corresponding to large R. The green arrow on the left indicates tunneling for small R, with a Chern-Simons number of the produced object $N_{CS} < 1/2$. For this last case, the classical explosion returns the system to the original valley.

How much action is compensated by usage of a “reclined” tunneling to NCS=1/2?

ScI

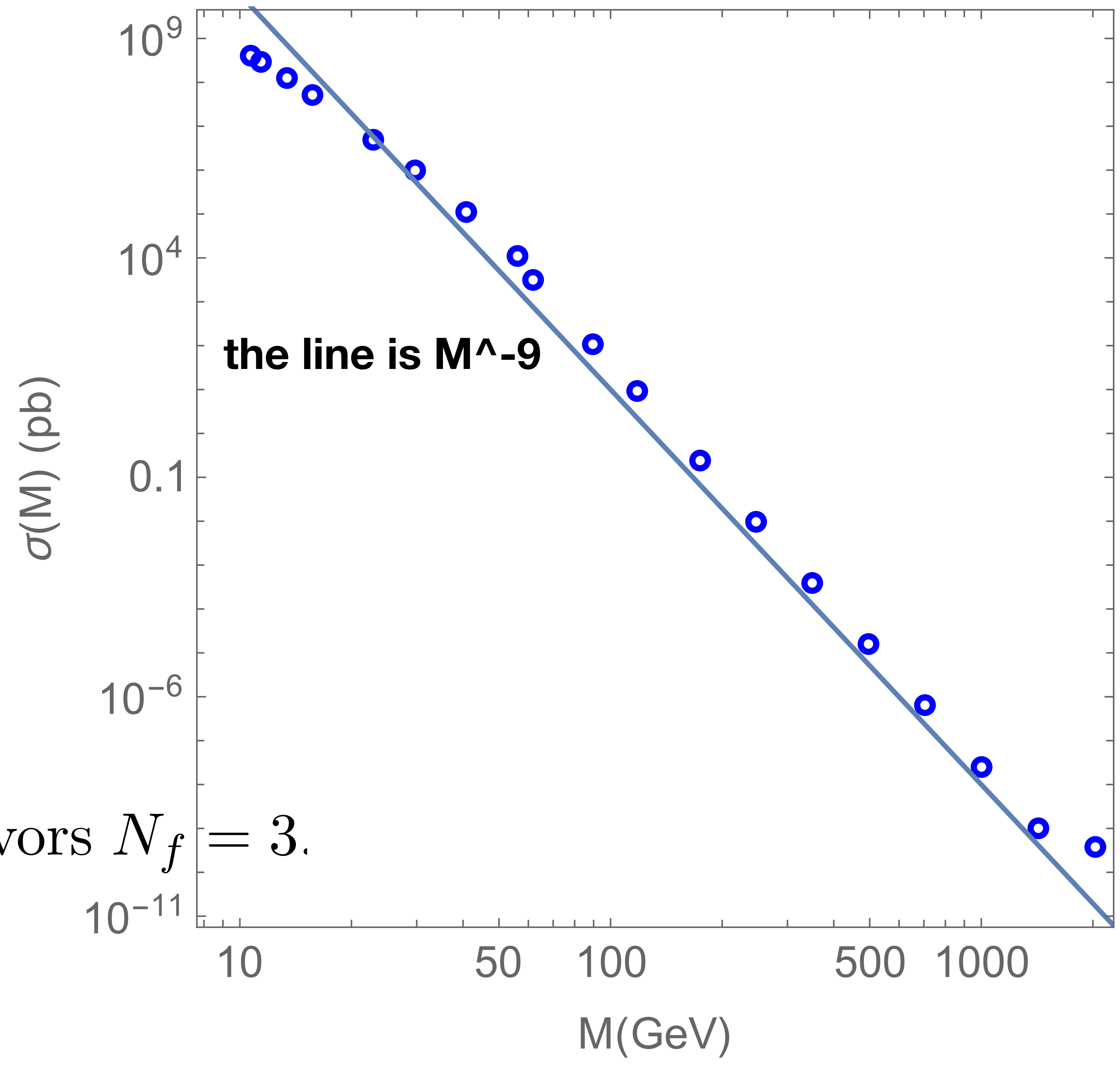
Khoze, Ringwald 1991
Shuryak, Verbaarschot 1991
proposed to use I bar-I valley

here is recent integration of the cross section versus the sphaleron mass (Khose et al, arXiv:1911.09726)

$$\sigma \sim \frac{1}{M^2}\left(\frac{\Lambda_{QCD}}{M}\right)^{b(2-\Delta S/S_0)}$$

$\frac{\Delta S}{S_0} \approx 1$

$b = (11/3)N_c - (2/3)N_f$, or 9 if the number of light flavors $N_f = 3$.



$$\Rightarrow \quad \frac{\Delta S}{S_0} \approx 1$$

the reclined tunneling to the top, NCS=1/2, compensates HALF of the instanton-antiinstanon action

Branchings of the final state

Flavor structure
and explicit t' Hooft Lagrangian
rewritten and NOT containing

$$f^{abc}\lambda^a\lambda^b\lambda^c, \quad d^{abc}\lambda^a\lambda^b\lambda^c$$

Small masses M=3-10 GeV

$$(\bar{u}_R u_L)(\bar{d}_R d_L)(\bar{s}_R s_L) + (L \leftrightarrow R)$$

$$Q = \overline{q}_R q_L \qquad Q_{\mu\nu} = \overline{q}_R \sigma_{\mu\nu} q_L$$

$$\boxed{\begin{aligned}\mathcal{V}^{L+R}_{qqq} = & \frac{\kappa}{N_c(N_c^2-1)}\left(\frac{2N_c+1}{2(N_c+2)}\det(UDS)\right.\\ & \left. + \frac{1}{8(N_c+1)}\Big(\det(U_{\mu\nu}D_{\mu\nu}S) + \det(U_{\mu\nu}DS_{\mu\nu}) + \det(UD_{\mu\nu}S_{\mu\nu})\Big)\right) + (L \leftrightarrow R)\end{aligned}}$$

whatever form of the Lagrangian is used, one needs to include ALL diagrams

three-meson channels including ALL diagrams for eta_c decays

middle columns are branching ratios in %

		PDG2020	input [34]	—M—
$K\bar{K}\pi$	$K^+K^-\pi^0$	7.3 ± 0.4 (all 4)	5.5 ± 1.7 (all 4)	$5.07\ K_K^2 K_\pi$
	$K^+\bar{K}^0\pi^-$			$7.27\ K_K^2 K_\pi$
	$K^0\bar{K}^0\pi^0$			$5.07 K_K^2 K_\pi$
	$K^-K^0\pi^+$			$7.27 K_K^2 K_\pi$
$\pi\pi\eta$	$\pi^+\pi^-\eta$	1.7 ± 0.5	4.9 ± 1.8 (both)	$4.92\ K_\pi^2 K_\eta^s$
	$\pi^0\pi^0\eta$			$2.46 K_\pi^2 K_{\eta'}^s$
$\pi\pi\eta'$	$\pi^+\pi^-\eta'$	4.1 ± 1.7 (both)	4.1 ± 1.7 (both)	$5.20\ K_\pi^2 K_{\eta'}^s$
	$\pi^0\pi^0\eta$			$2.60 K_\pi^2 K_{\eta'}^s$
$\bar{K}K\eta$	$K^+K^-\eta$	1.36 ± 0.15 (both)		$3.68\ K_K^2 F_\eta^q$
	$K^0\bar{K}^0\eta$			$3.68\ K_K^2 F_\eta^q$
$\bar{K}K\eta'$	$K^+K^-\eta'$			$3.53\ K_K^2 F_{\eta'}^q$
	$K^0\bar{K}^0\eta'$			$3.53\ K_K^2 F_{\eta'}^q$
$\eta\eta\eta$				$1.32 (K_\eta^q)^2 K_\eta^s$

the WF at the origin
=> K_i
all are known from
phenomenology
we keep it like this
to have clean predictions
of the ratios

TABLE I. The first column gives the generic names of the decay channels of η_c, while the second column records the specific channels. The third column contains the corresponding branching ratio (percents) according to the Particle Data Table 2020. For comparison, we show in the fourth column the corresponding numbers used in [34]. The last column gives the decay matrix elements. The meson-specific constants (wave function at the origin) are defined in Appendix A.

also production of SU(3) singlet baryons…

Method number 3: conformal off-center transformation, +Mikowski continuation gives explosion

Prompt quark production by exploding sphalerons

ES, Zahed: *Phys.Rev.D* 67 (2003) 014006 • e-Print: hep-ph/0206022

Starts from 4d spherical solution in Euclidean time,
Then off-center conformal transformation,
Then continuation to Minkowski

In QCD sph explosion creates 2Nf=6 units of axial charge

In the EW theory sph. explosion
Produce 9 quarks and 3 leptons
Or B=L=3

At t=0 they have zero energy and belong to the Dirac sea, And then are accelerated by radial E To positive energy

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Important bonus:
zero mode of the 4d spherical solution Mapped into Minkowskian solution Of the Dirac eqn Describes the wave function Of the outgoing fermions

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Branchings of the final state

medium masses M=10-20 GeV

$$(\bar{u}u)(\bar{d}d)(\bar{s}s)(\bar{c}c)$$

appearence of charm quark pairs produced a la Schwinger mechanism via radial electric field E(x)

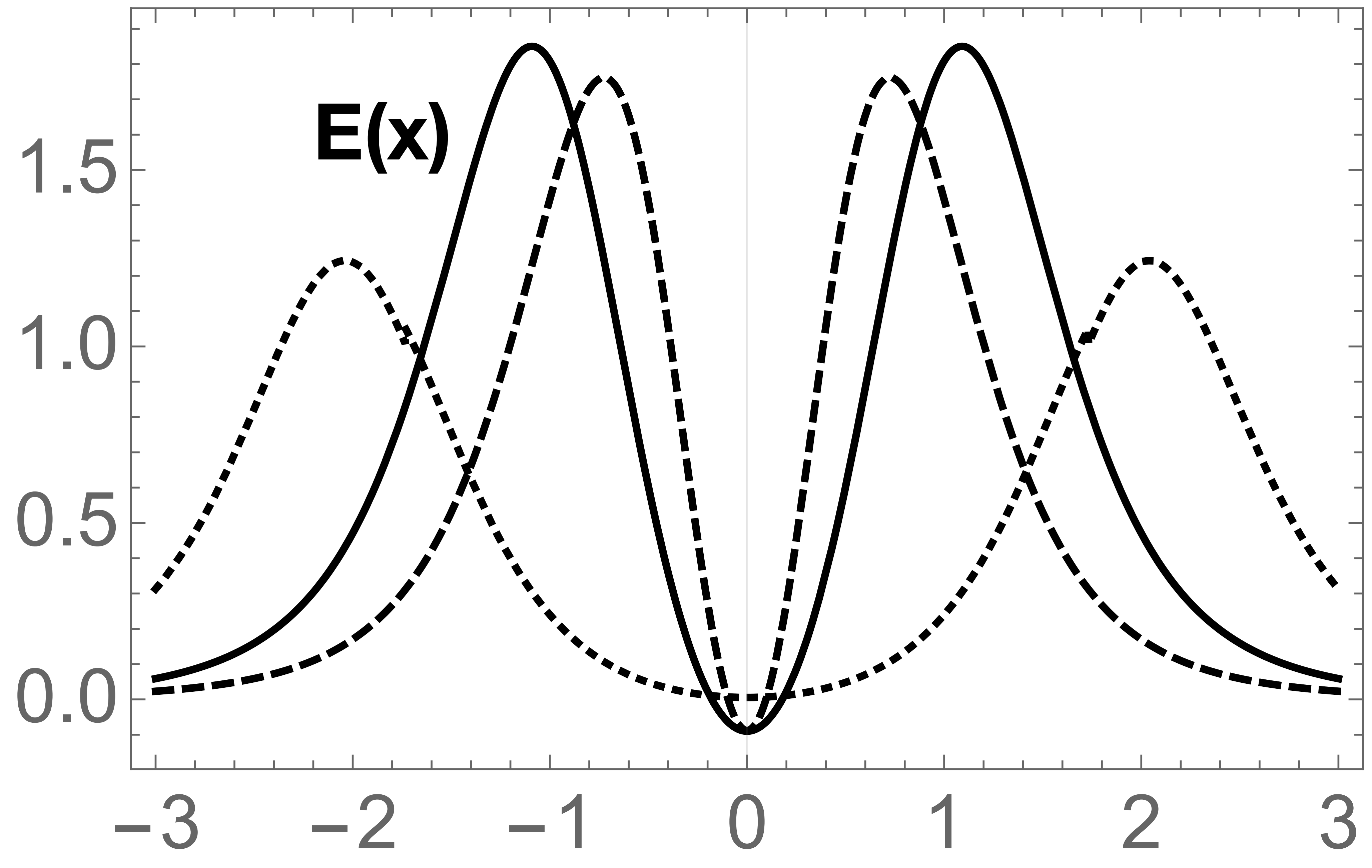

FIG. 6. The snapshots of the electric field component $E_3^3(r,t)$ in units of $1/g\rho^2$, as a function of x^3/ρ, for times $t/\rho = 0.5$ (dashed), $t/\rho = 1$ (solid) and $t/\rho = 2$ (dotted) curves.

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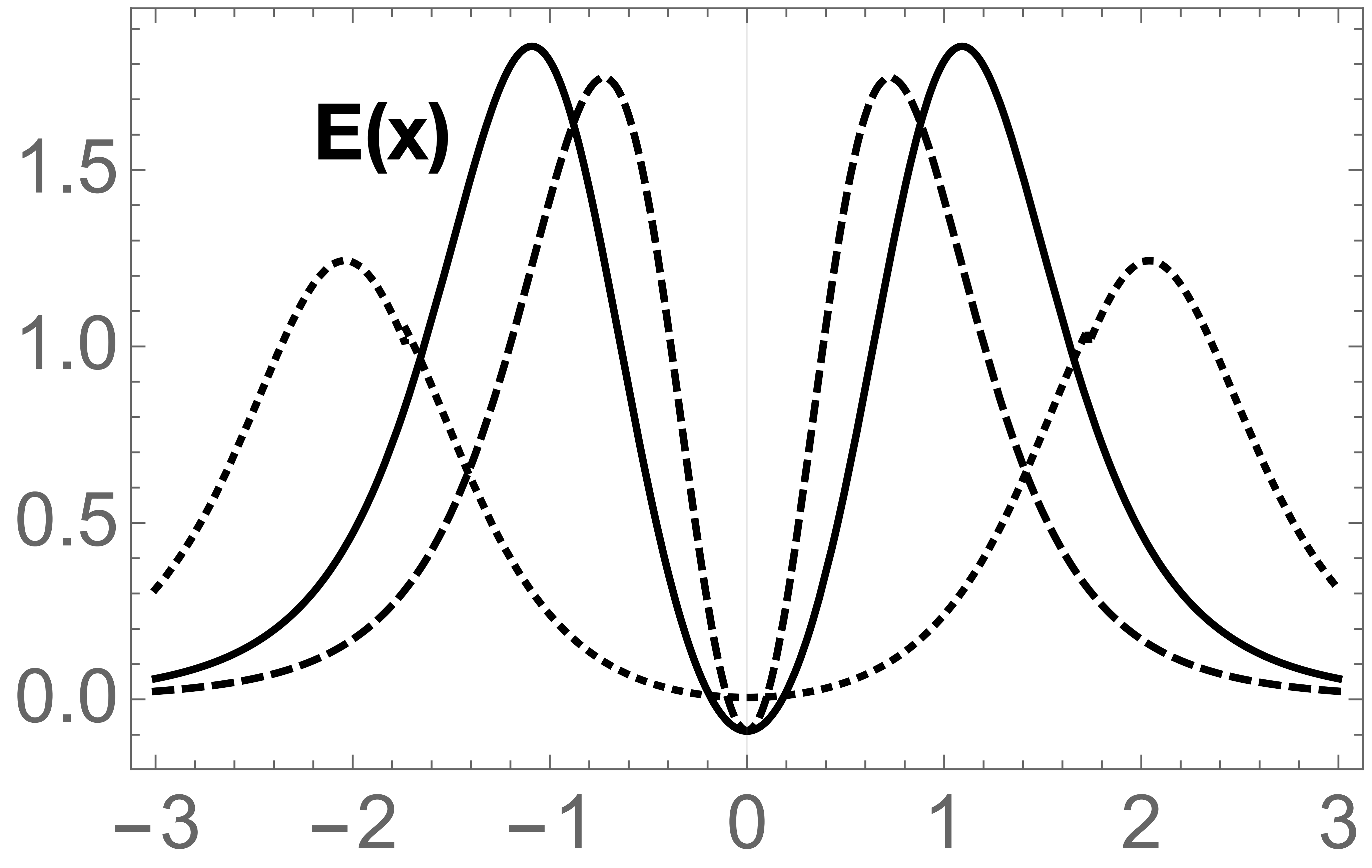

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O(10) gluons should lead to several glueballs, with calculable spectrum

Branchings of the final state

large masses M=O(100 GeV)

about a dosen jets emitted isotropically
unusual fragmentation function
since QCD flux tubes do not
point to the origin

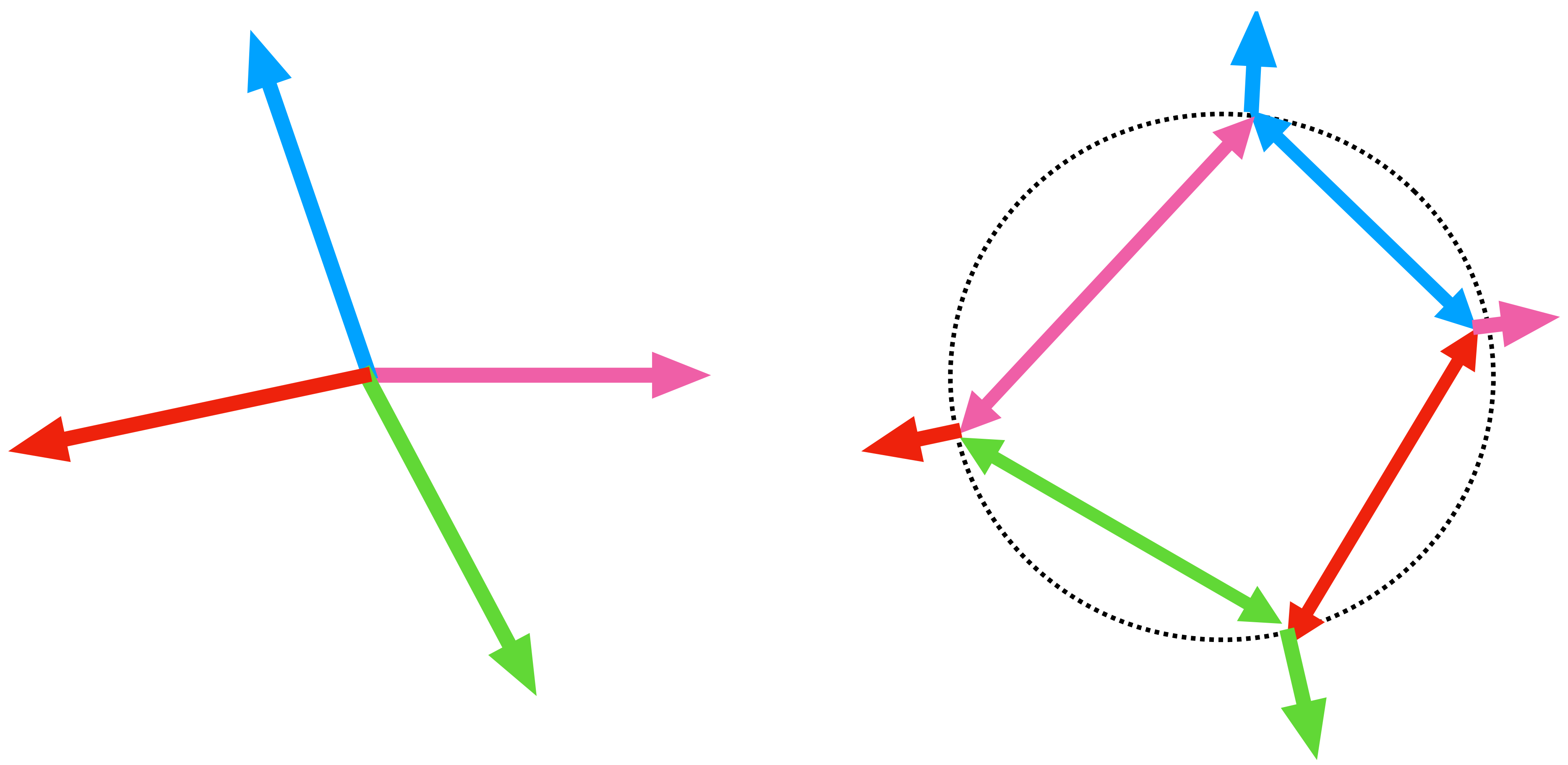


FIG. 7. Schematic picture illustrating the configuration of QCD strings in four-jet events. The left corresponds to the usual case, when jets originate from collisions at the origin in the transverse plane. The right corresponds to an exploding sphaleron in which the strings are not connected to the origin, but are close to the expanding shell (dotted circle).

How to observe instanton/sphaleron process in pp collisions?

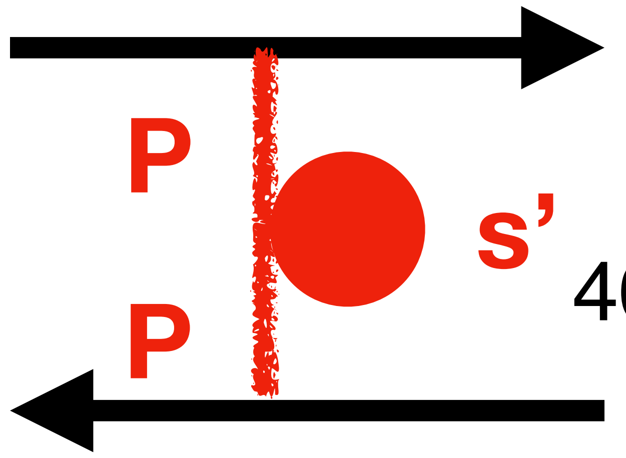
to reduce background, we proposed to use double-diffractive events (Pomeron-Pomeron collisions)

UA8 and double-Pomeron production

A Study of Inclusive Double–$\mathcal{P}$omeron–Exchange in $p\bar{p} \rightarrow pX\bar{p}$ at $\sqrt{s} = 630$ GeV

A. Brandt[1], S. Erhan[a], A. Kuzucu[2], M. Medinnis[3], N. Ozdes[2,4], P.E. Schlein[b], M.T. Zeyrek[5], J.G. Zweizig[6]
University of California*, Los Angeles, California 90024, U.S.A.

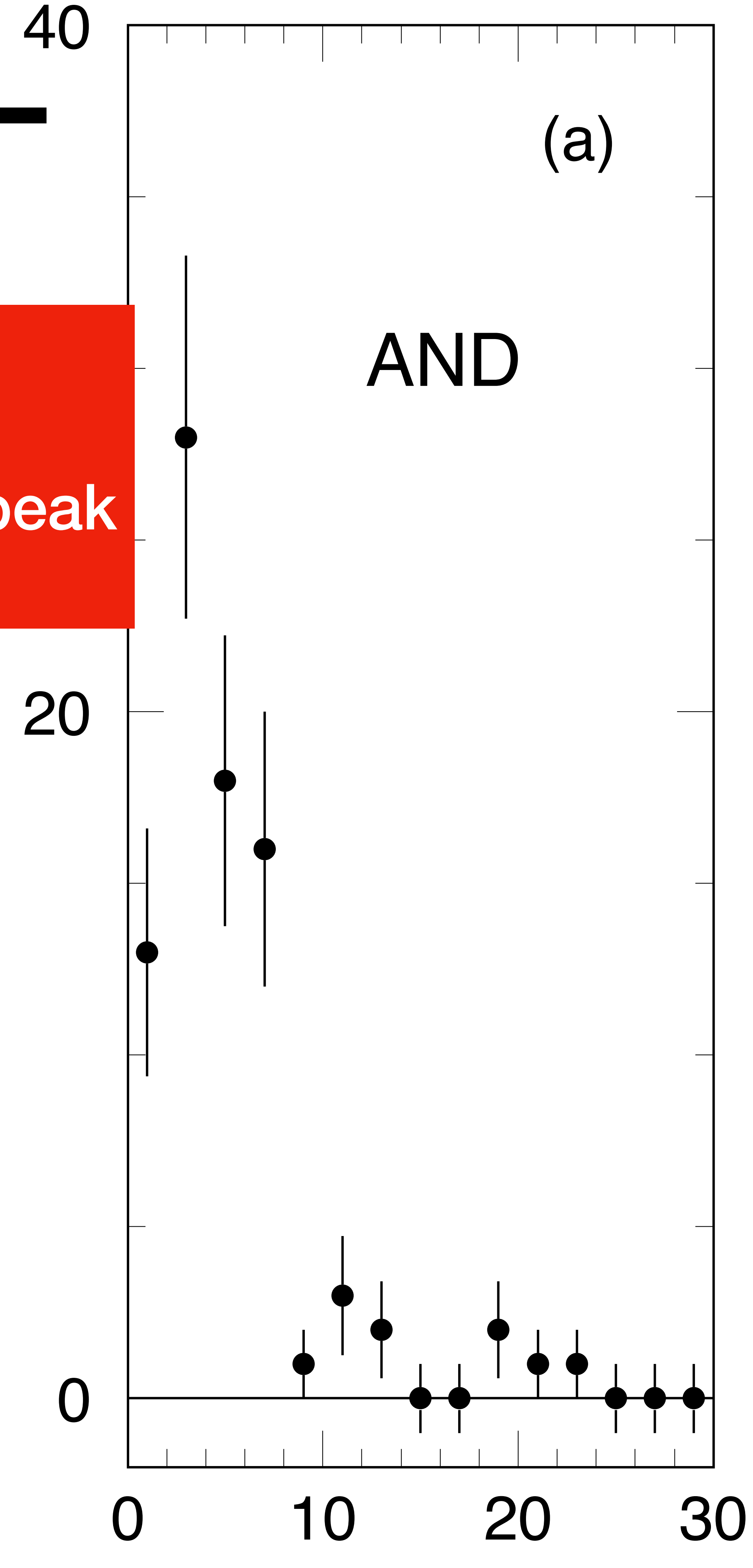
J.B. Cheze, J. Zsembery
Centre d'Etudes Nucleaires-Saclay, 91191 Gif-sur-Yvette, France.



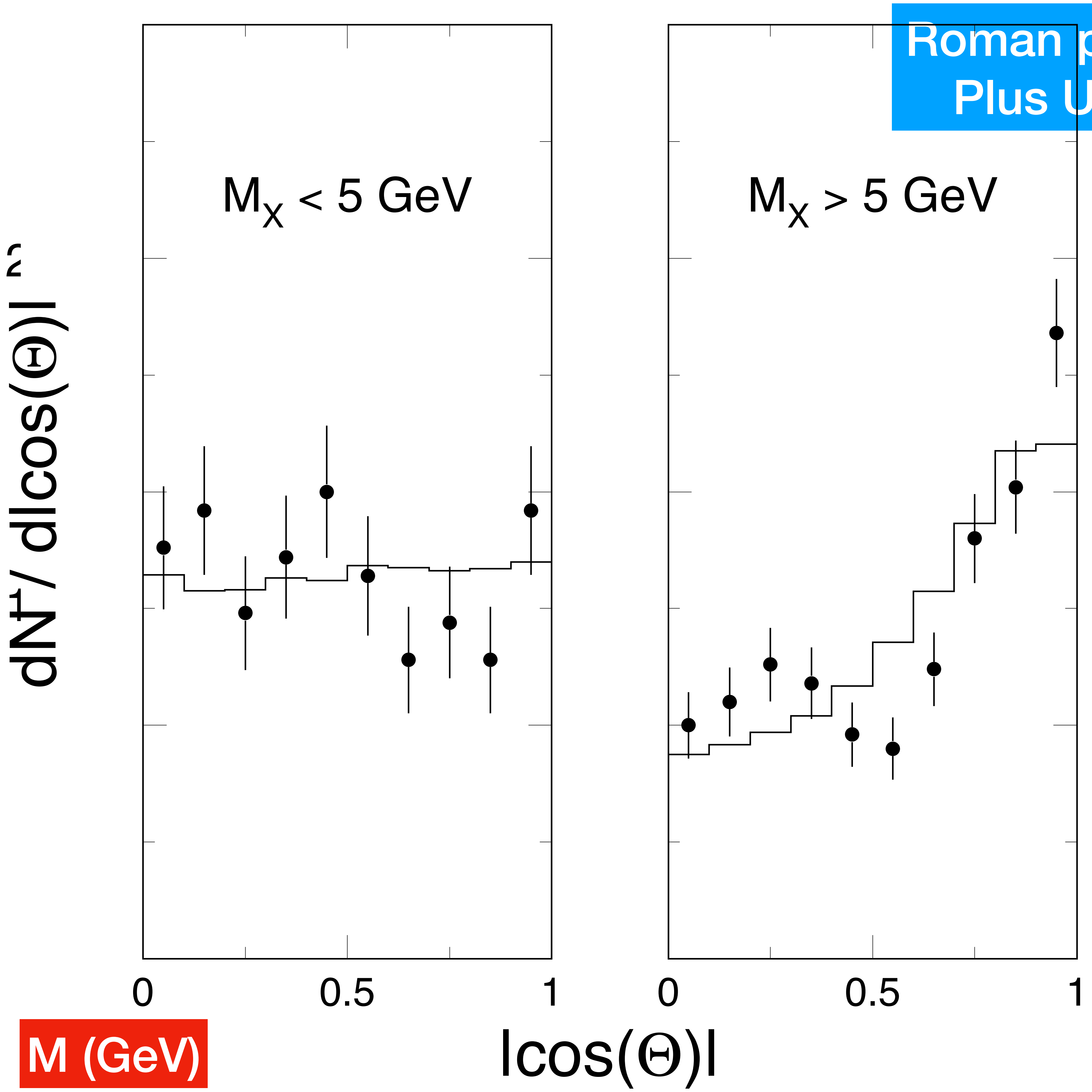
$$\frac{d^6\sigma_{DPE}}{d\xi_1 d\xi_2 dt_1 dt_2 d\phi_1 d\phi 2} = F_{\mathcal{P}/p}(t_1,\xi_1)\cdot F_{\mathcal{P}/p}(t_2,\xi_2)\cdot \sigma^{tot}_{\mathcal{PP}}(s').$$

s'=M^2 is the cluster mass squared

Mass Distribution Has unpredicted peak At 2-8 GeV



Roman pots on both sides (AND) Plus UA2 central calorimeter



Small and large M Production is different In magnitude and Angular distributions

Low mass clusters decay isotropically In their rest frame

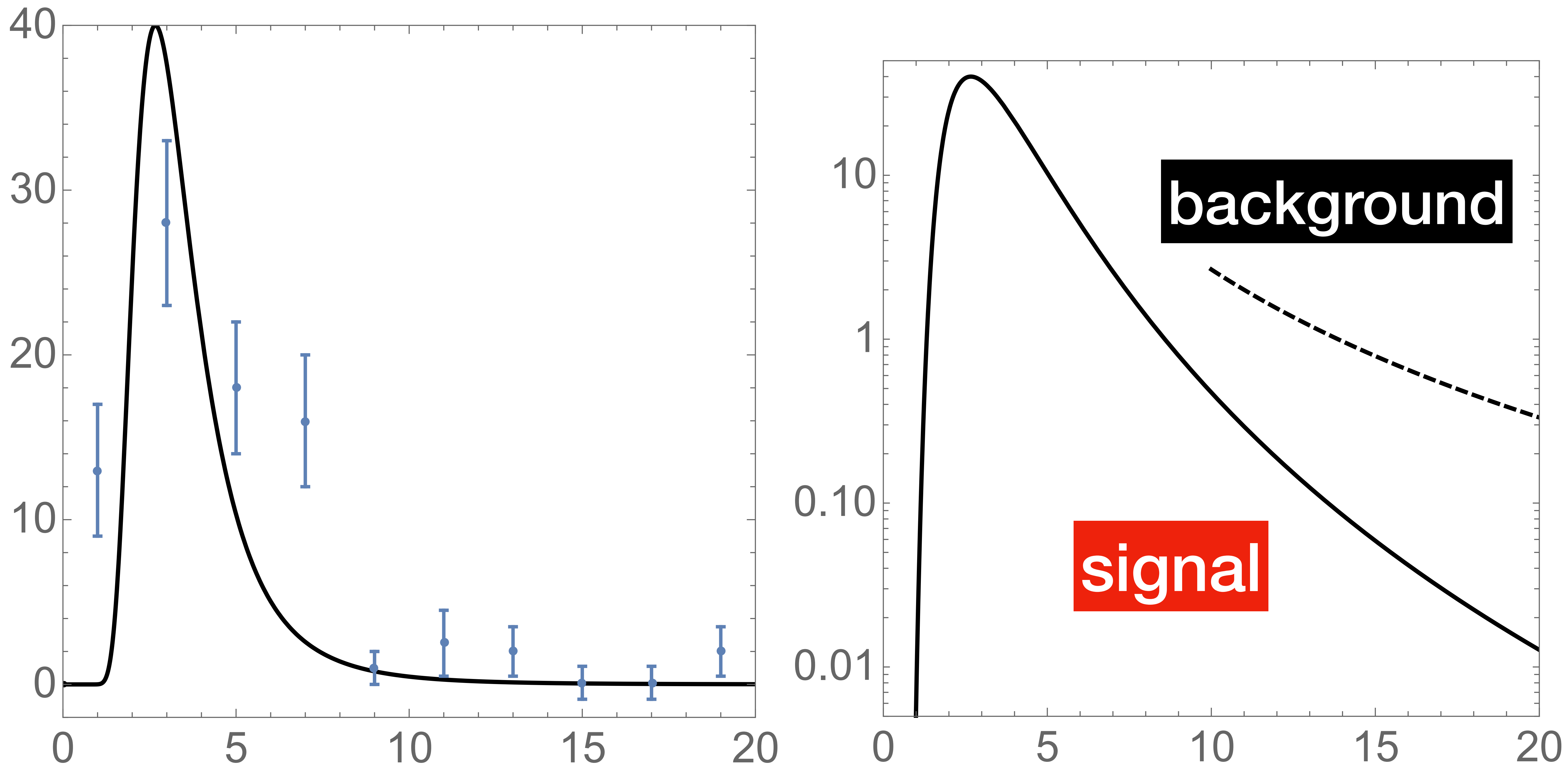


FIG. 9. Left plot: Semiclassical distribution over the cluster mass M (GeV), compared to the data points from the UA8 experiment; Right plot is the logarithmic representation of the same curve (solid), now compared with the dashed line representing the perturbative background.

We suggest
M<5 GeV clusters are
The QCD sphalerons!
the curve is from
vacuum instanton size
distribution

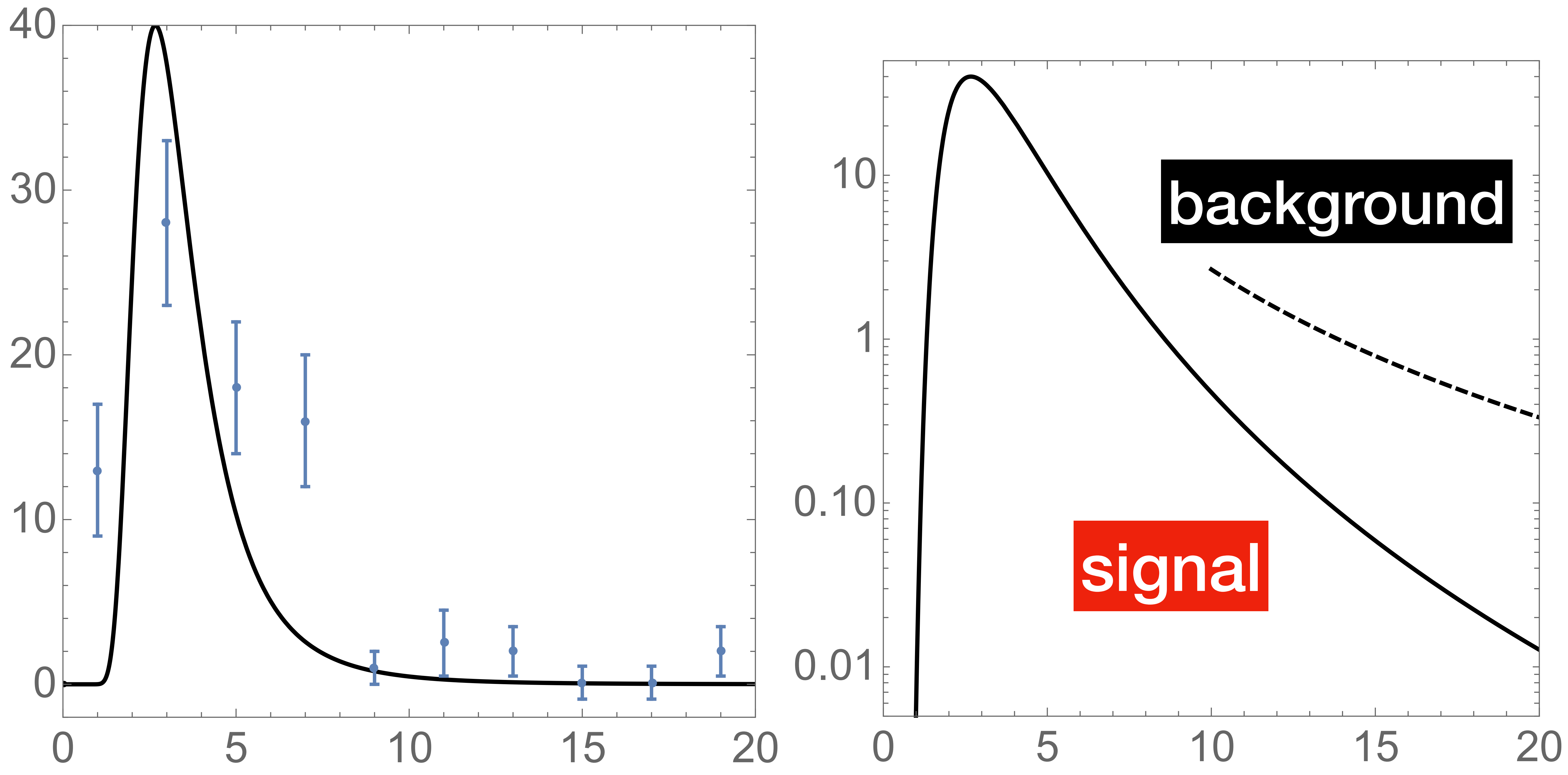
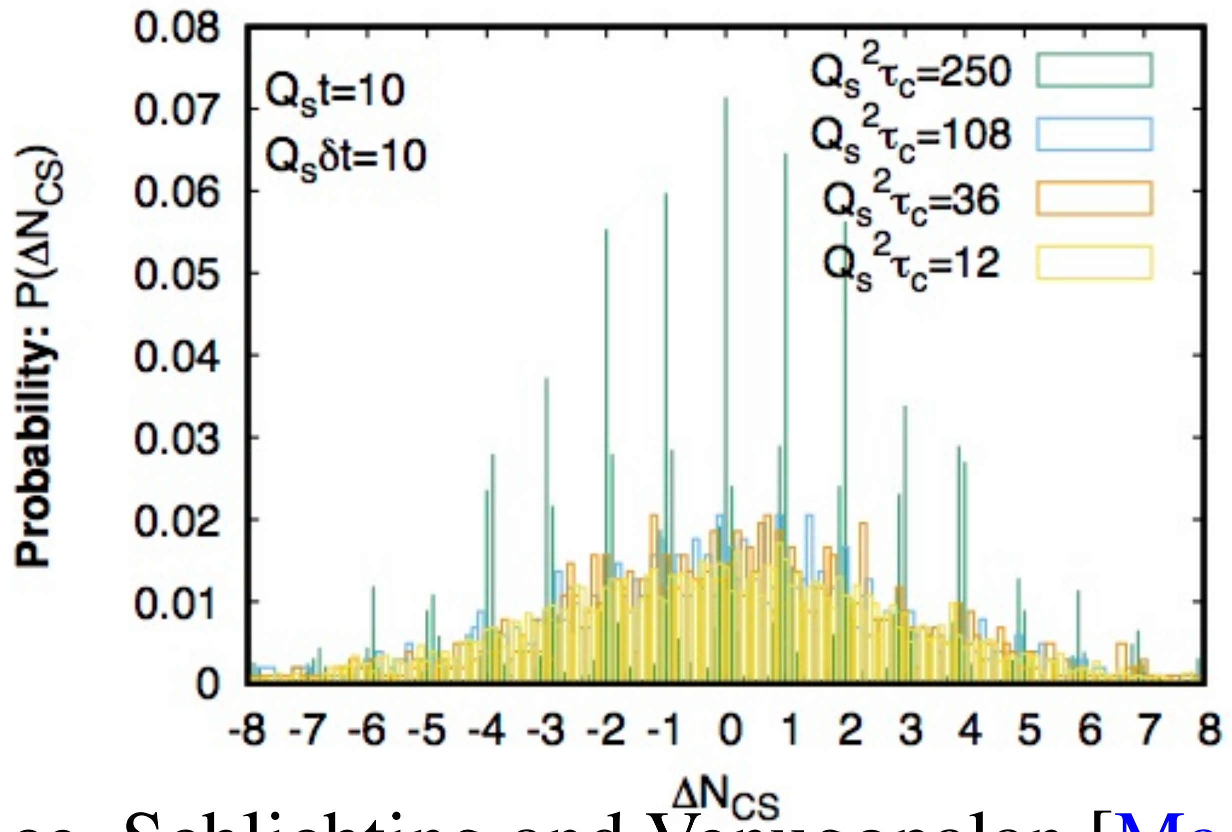


FIG. 9. Left plot: Semiclassical distribution over the cluster mass M (GeV), compared to the data points from the UA8 experiment; Right plot is the logarithmic representation of the same curve (solid), now compared with the dashed line representing the perturbative background.

How can one observe sphalerons in heavy ion collisions?

Searching for topological fluctuations in heavy ion collisions at RHIC via CME



Mace, Schlichting and Venugopalan [Mace et al., 2016]

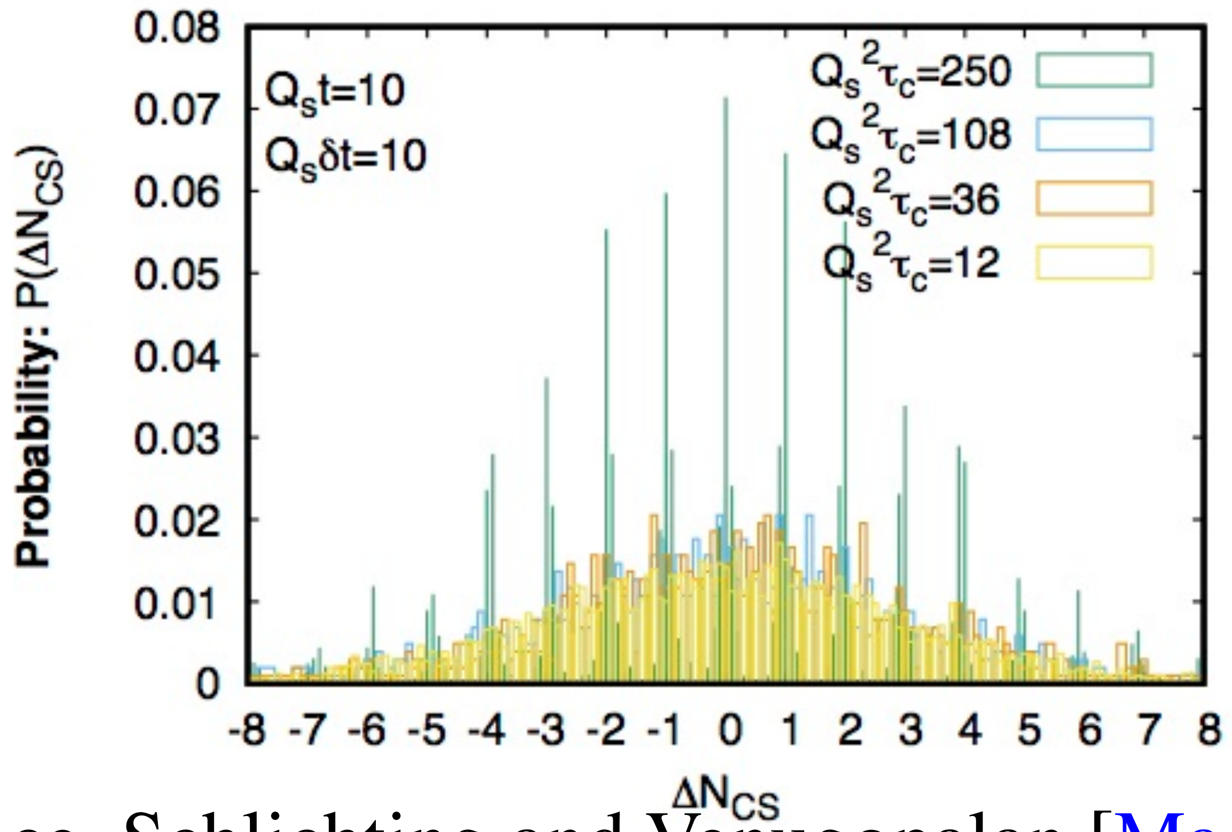
Diffusion in Chern-Simons number in GLASMA

Change of 1 =>
6 units of axial charge
So total r.m.s. is +- 25

CME (Kharzeev et al) $$\vec{J} \sim \mu_5 \vec{B}$$

Non-dissipative current
Recently observed In semimetals

Searching for topological fluctuations in heavy ion collisions at RHIC via CME



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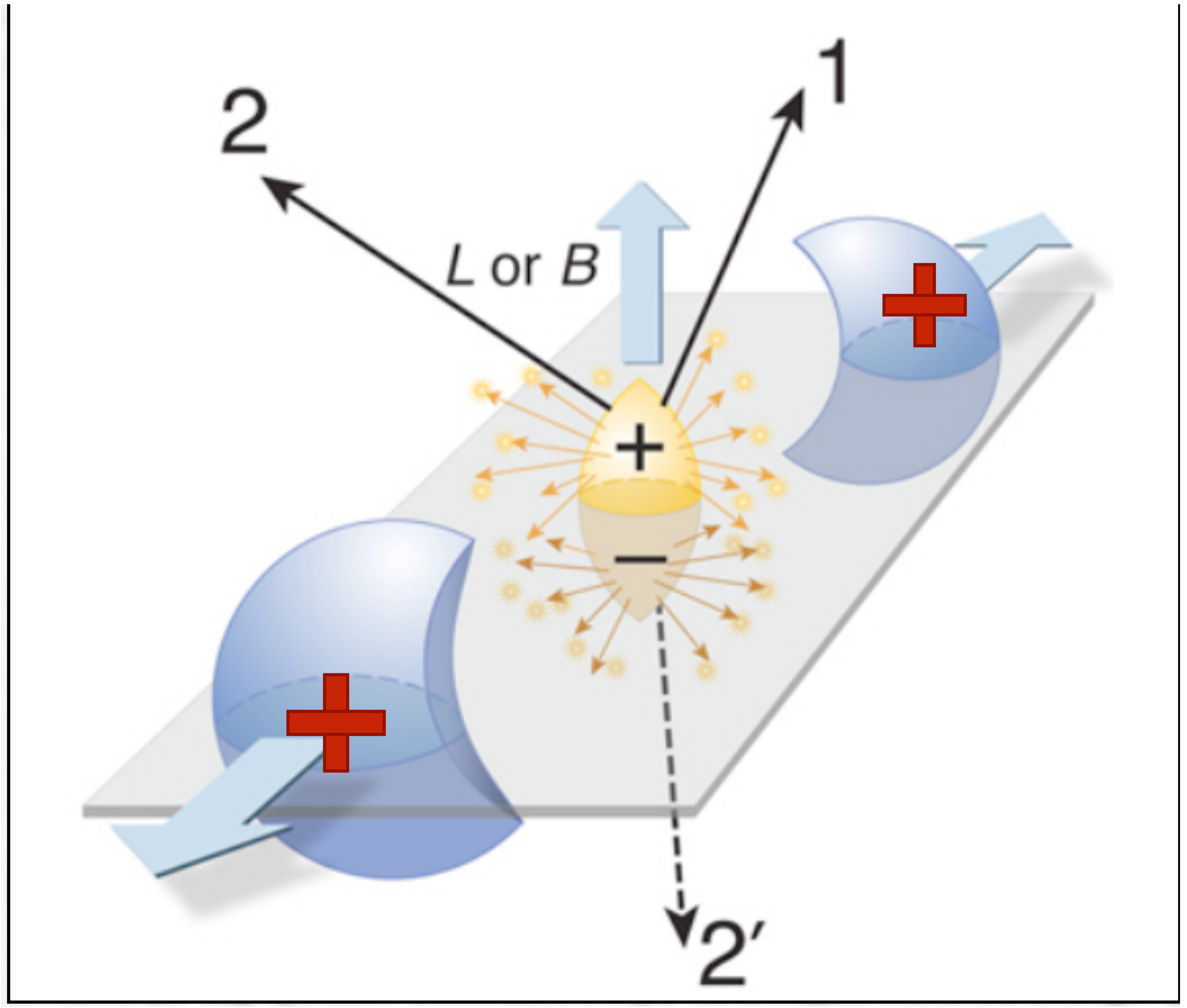

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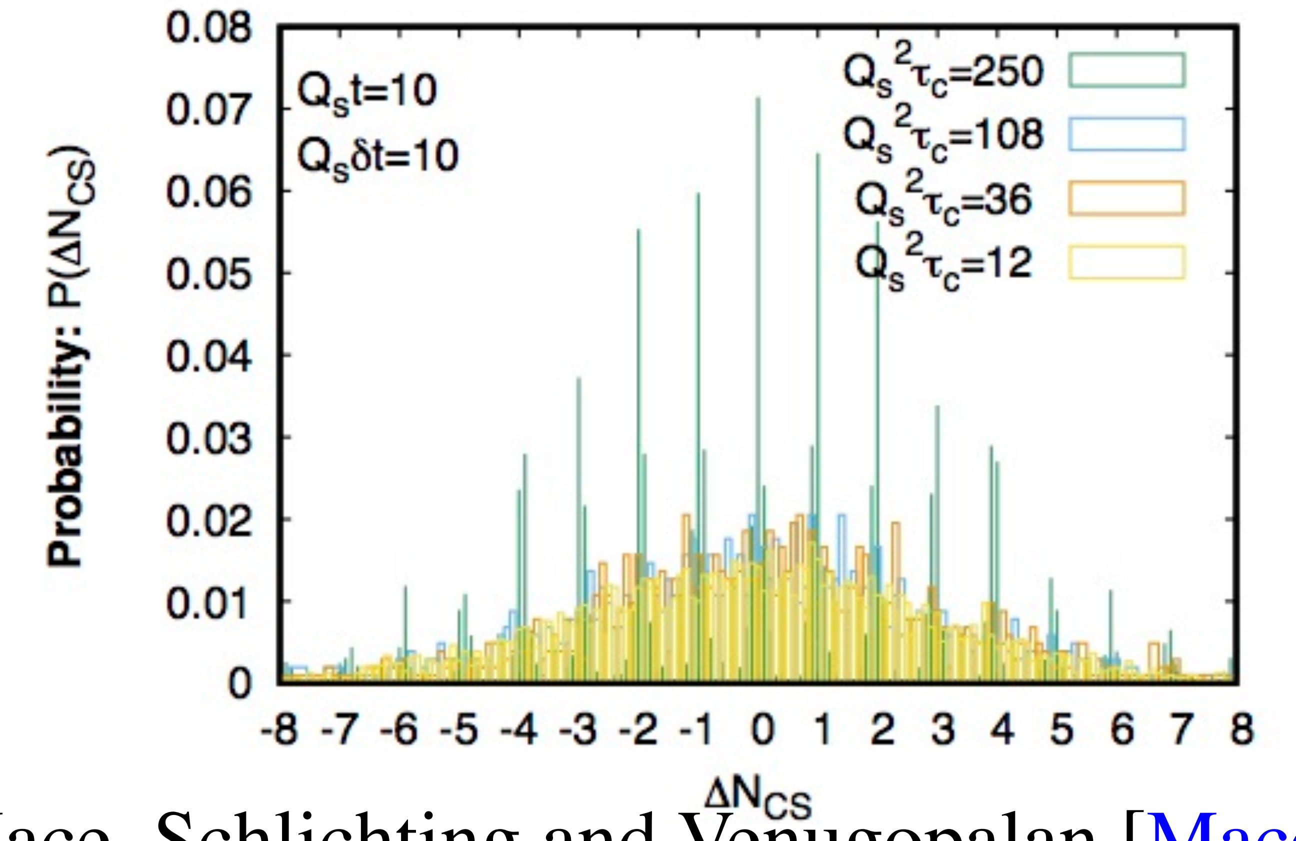

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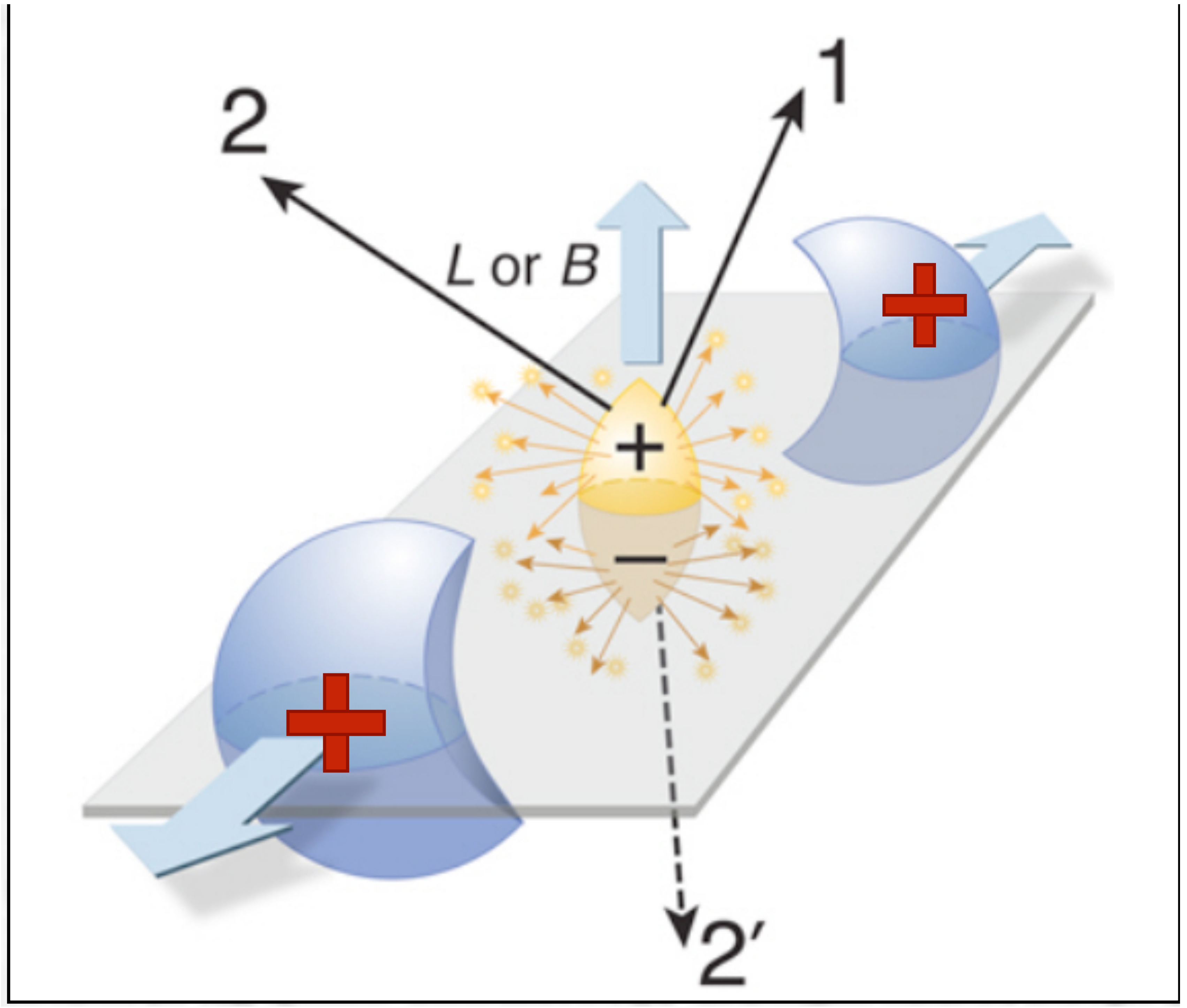

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Non-dissipative current
Recently observed In semimetals

One needs QGP
WHICH IS “CHIRAL MATTER”
AS AT T>TC NO <QQ>!

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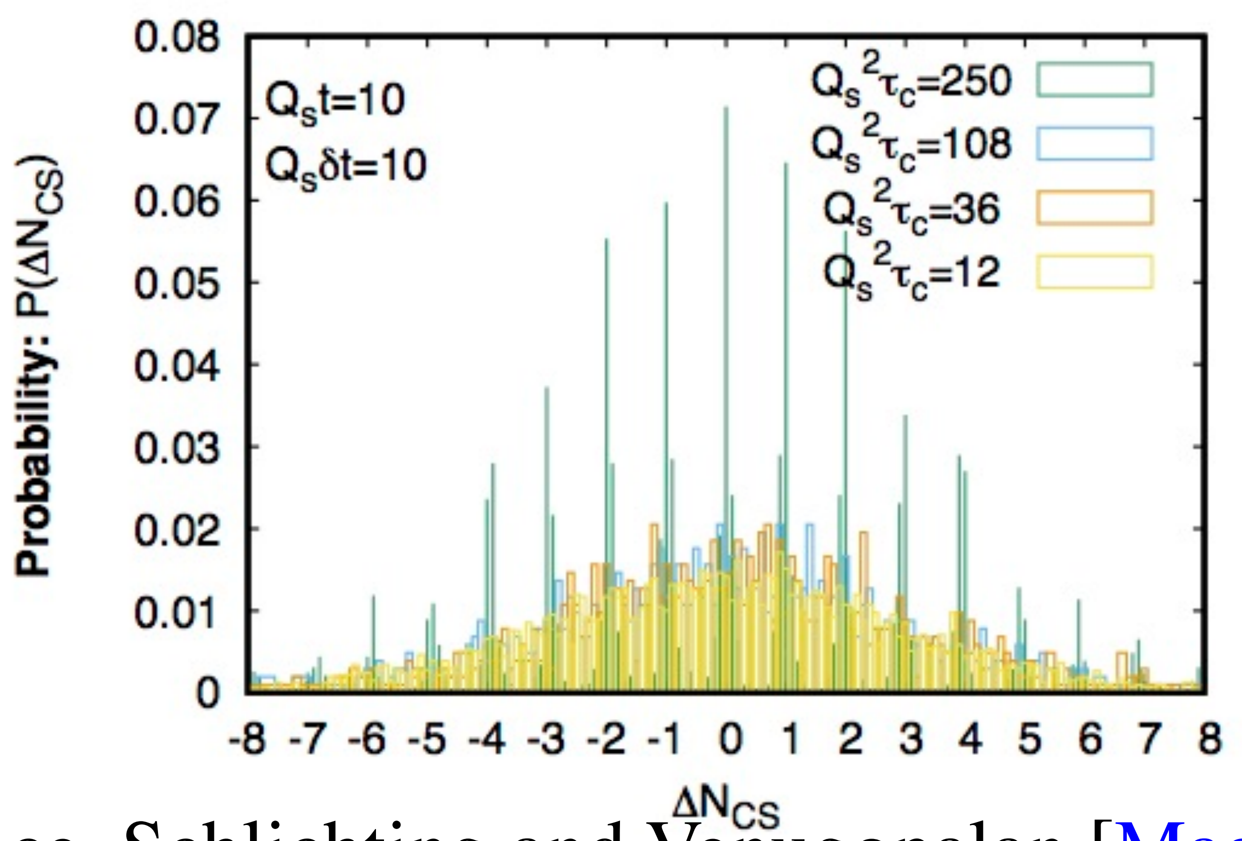

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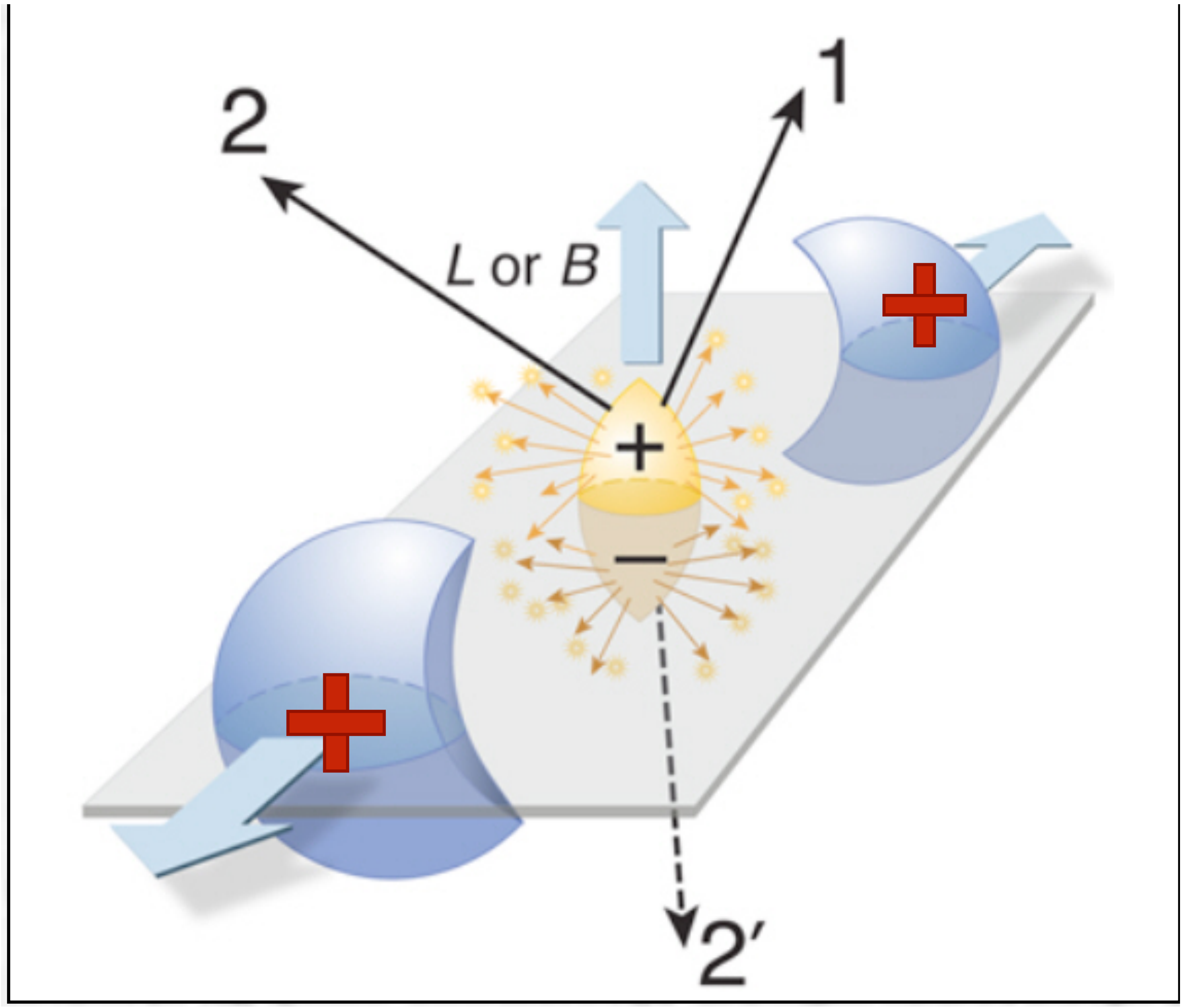

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$$Ru^{96}_{44} + Ru^{96}_{44} \;\; and \;\; Zr^{96}_{40} + Zr^{96}_{40}$$

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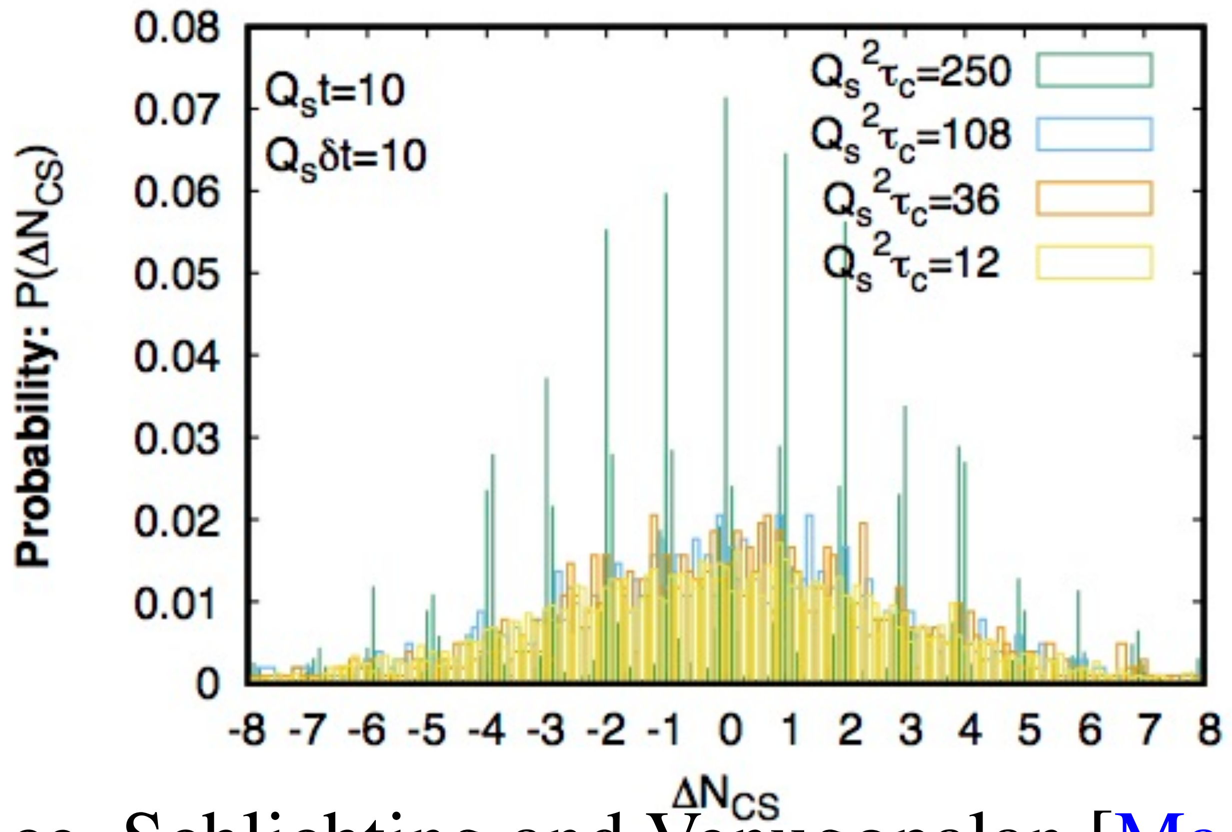

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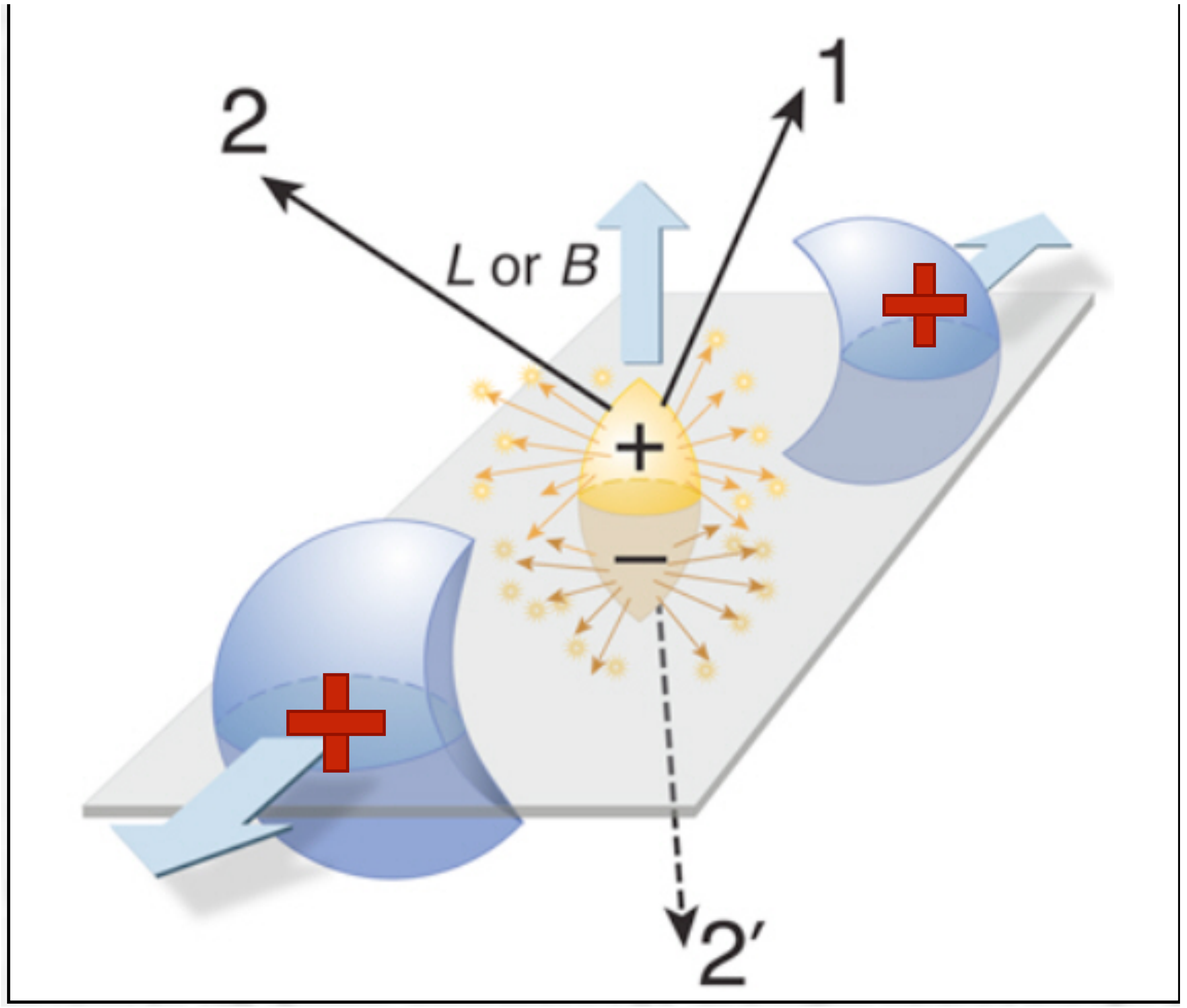

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LATEST RHIC run done, not yet analyzed

sounds in the Little and Big Bangs

(introductory heavy ion collisions vs cosmology)

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

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

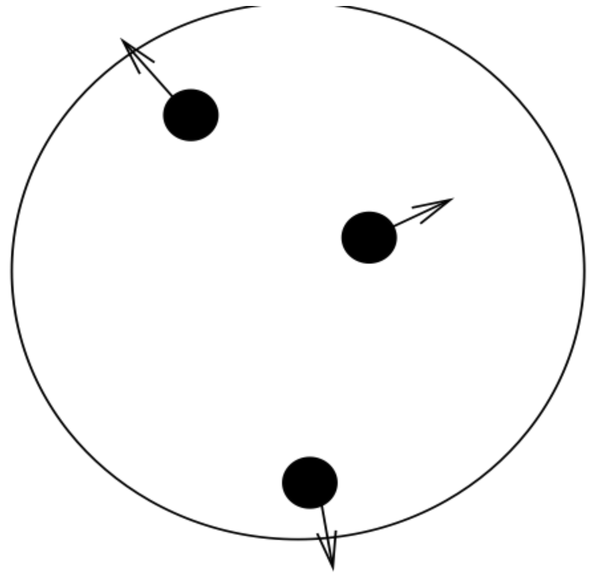
$$l_{maximum} \approx 210$$

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

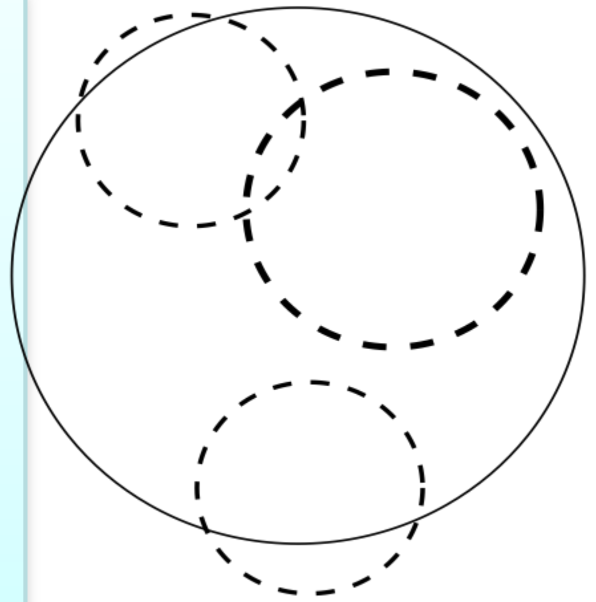
They are literally circles on the sky, around primordial density perturbations

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

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



Cylindrical (extended in z) at FO surface tau$_f$=2R and sound velocity is ½ => radius is about R => Azimutal harmonics m=O(1) Angle about 1 radian



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)

Perhaps shumerians had managed to see them somehow...., why else had they introduced 1°?

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

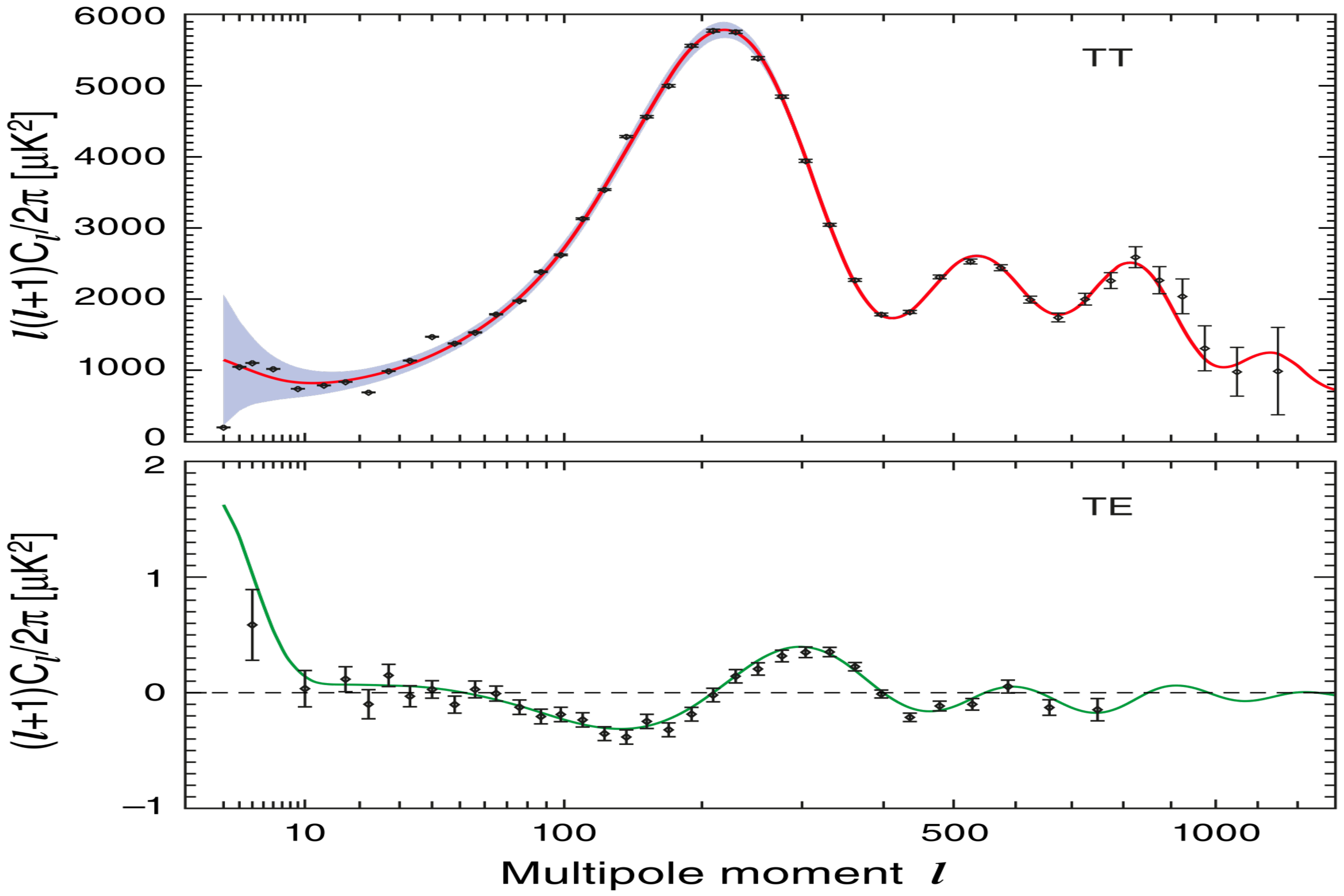


Fig. 9.— The temperature (TT) and temperature-polarization(TE) power spectra for the seven-year *WMAP* data set. The solid lines show the predicted spectrum for the best-fit flat ΛCDM model. The error bars on the data points represent measurement errors while the shaded region indicates the uncertainty 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

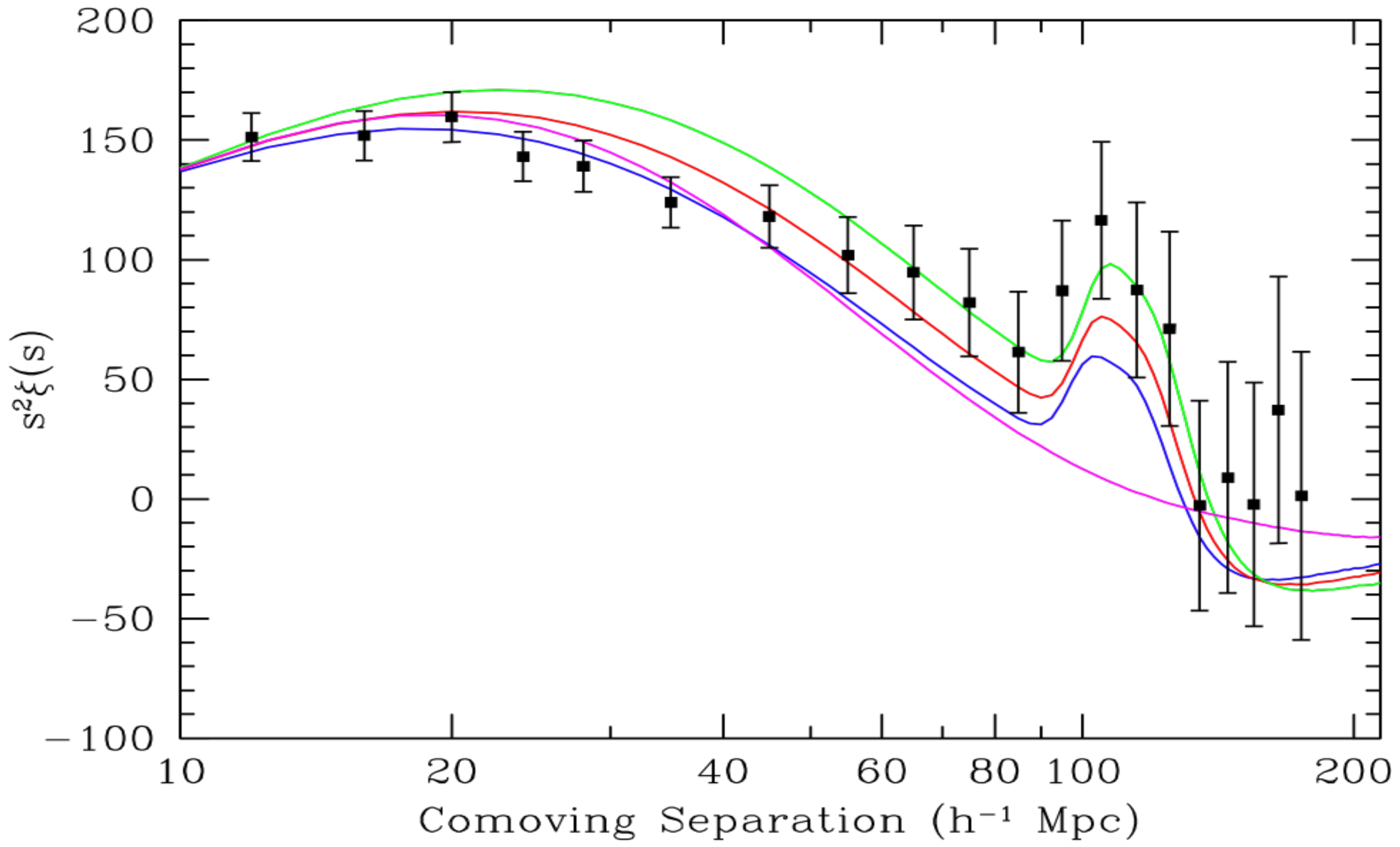


Fig. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting 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 Fate of the Initial State Fluctuations in Heavy Ion Collisions. III The Second Act of Hydrodynamics

Pilar Staig and Edward Shuryak

Comoving coordinates with Gubser flow:

Gubser and Yarom, arXiv:1012.1314

$$\sinh\rho = -\frac{1-q^2\tau^2+q^2r^2}{2q\tau}$$

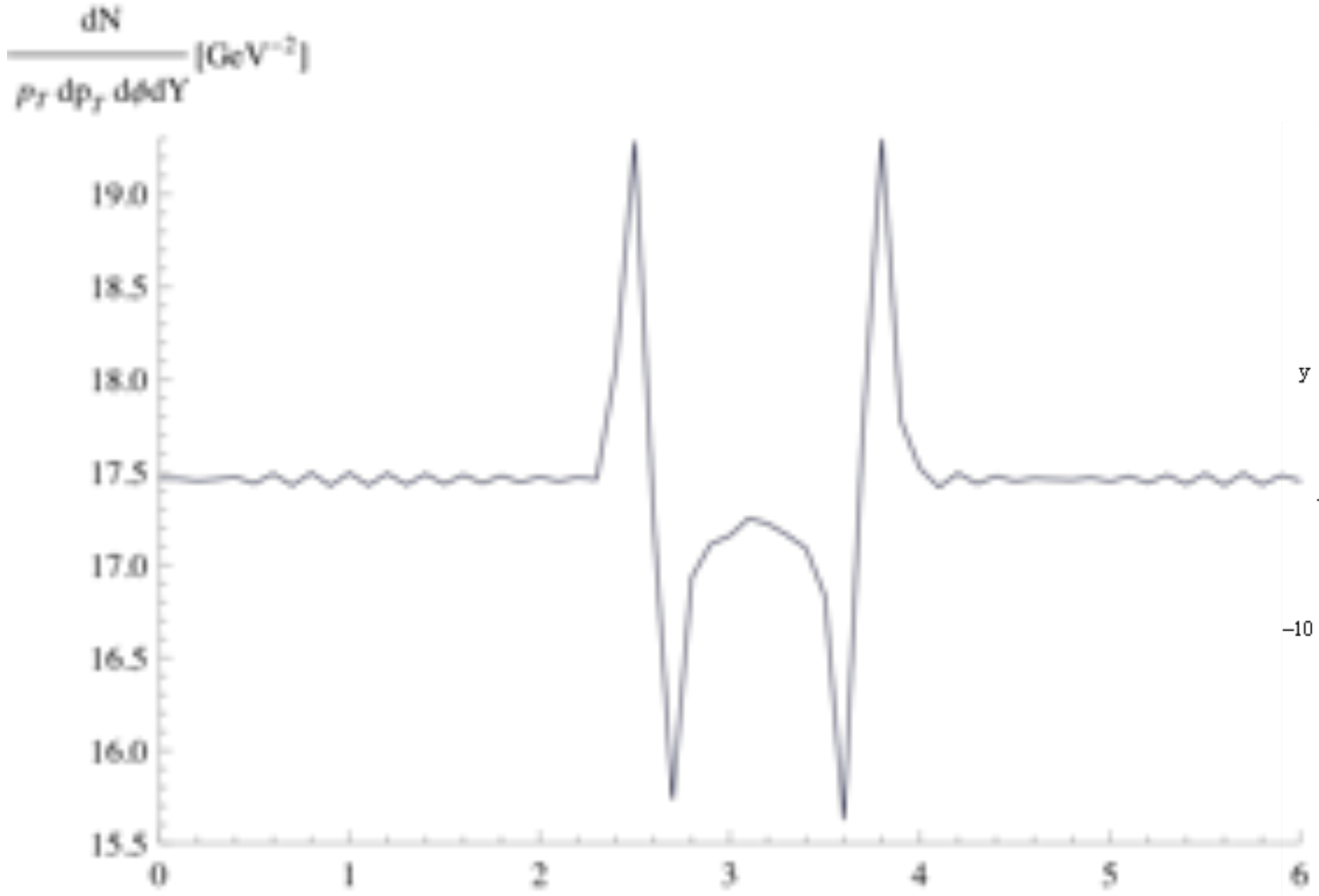
$$\tan\theta = \frac{2qr}{1+q^2\tau^2-q^2r^2}$$

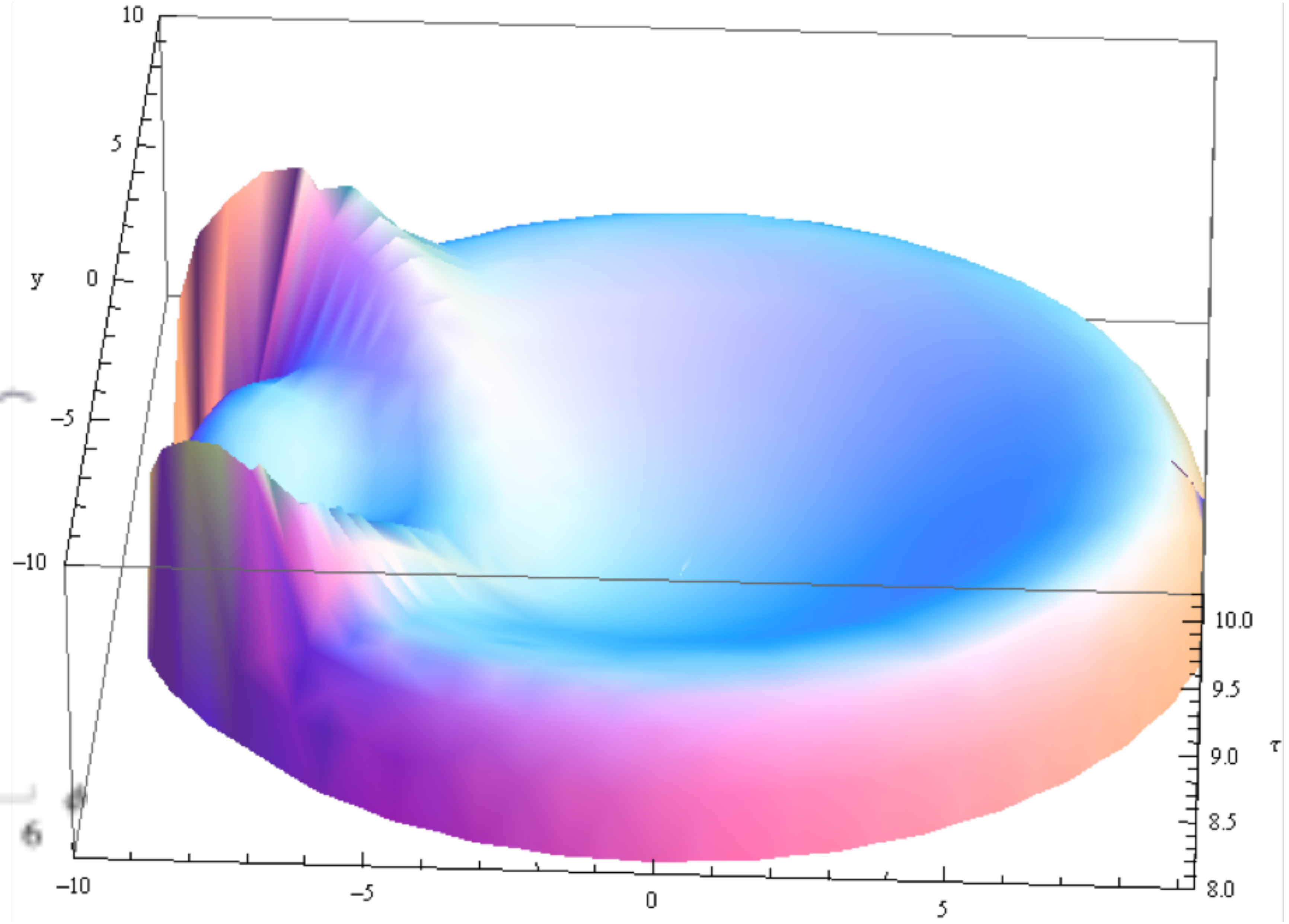
$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho} = 0 \qquad (3.16)$$

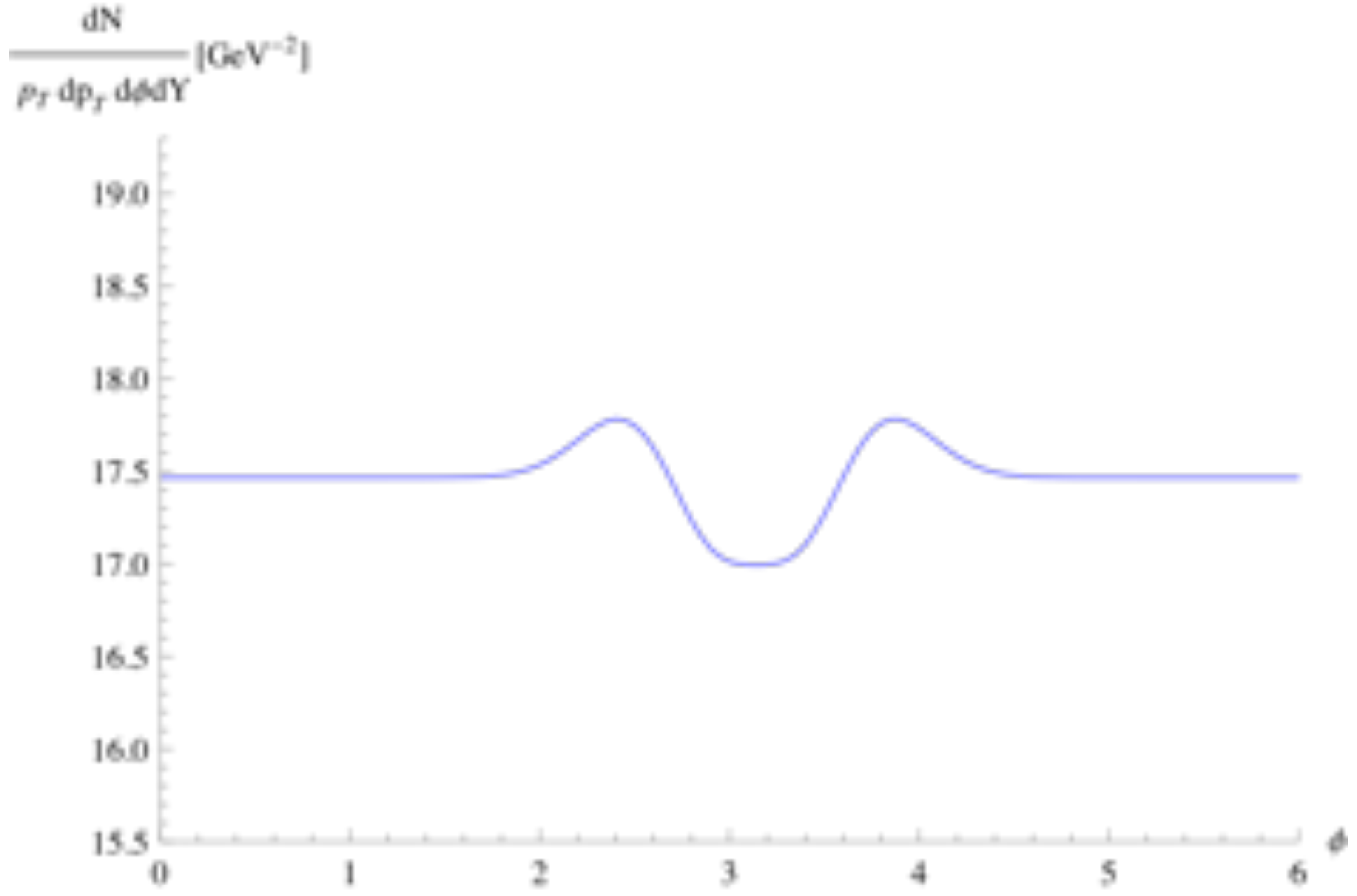
We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

$$\begin{aligned} R(\rho) &= \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}} \\ \Theta(\theta) &= C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta) \\ \Phi(\phi) &= C_5 e^{im\phi} + C_6 e^{-im\phi} \end{aligned} \qquad (3.26)$$

where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.





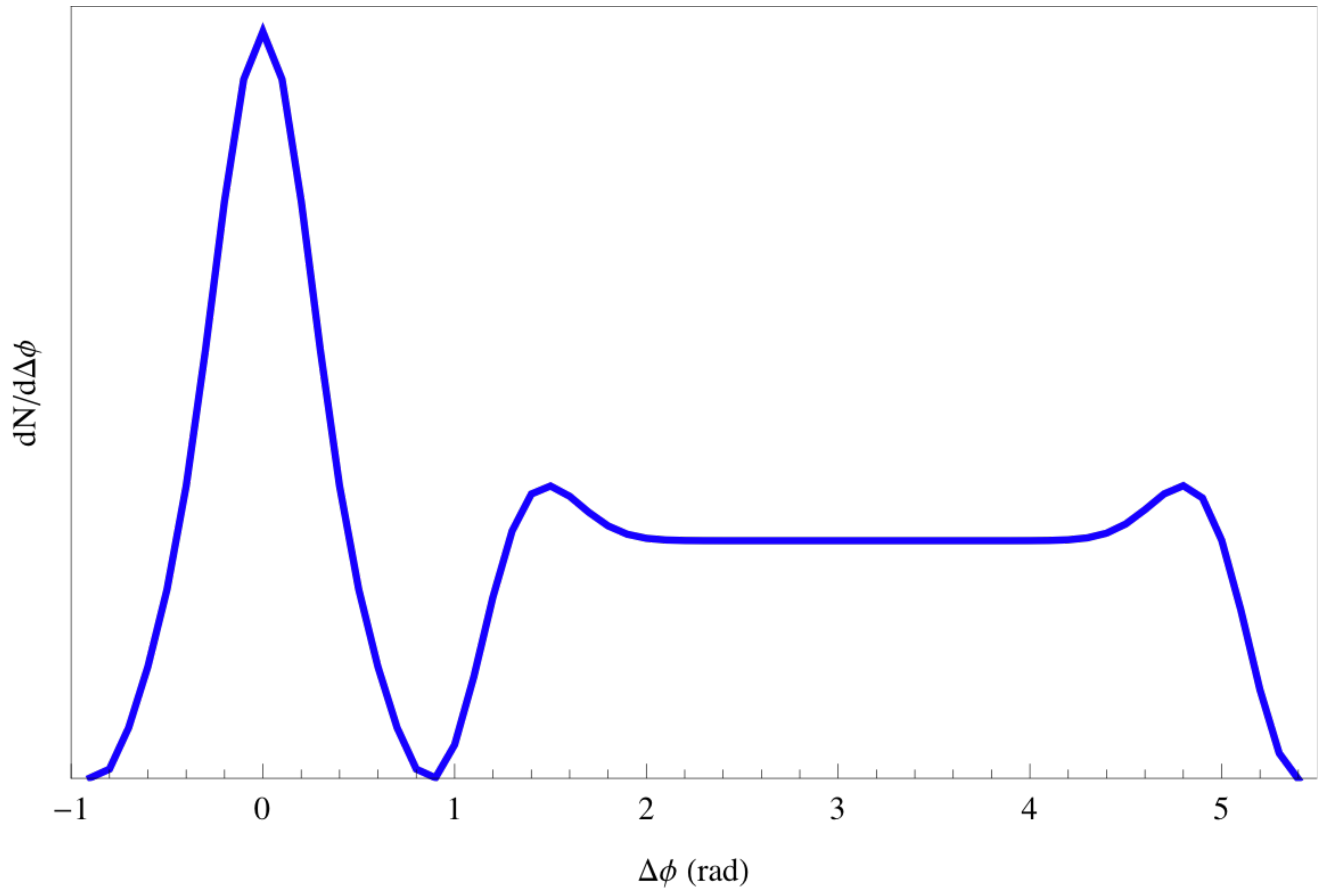


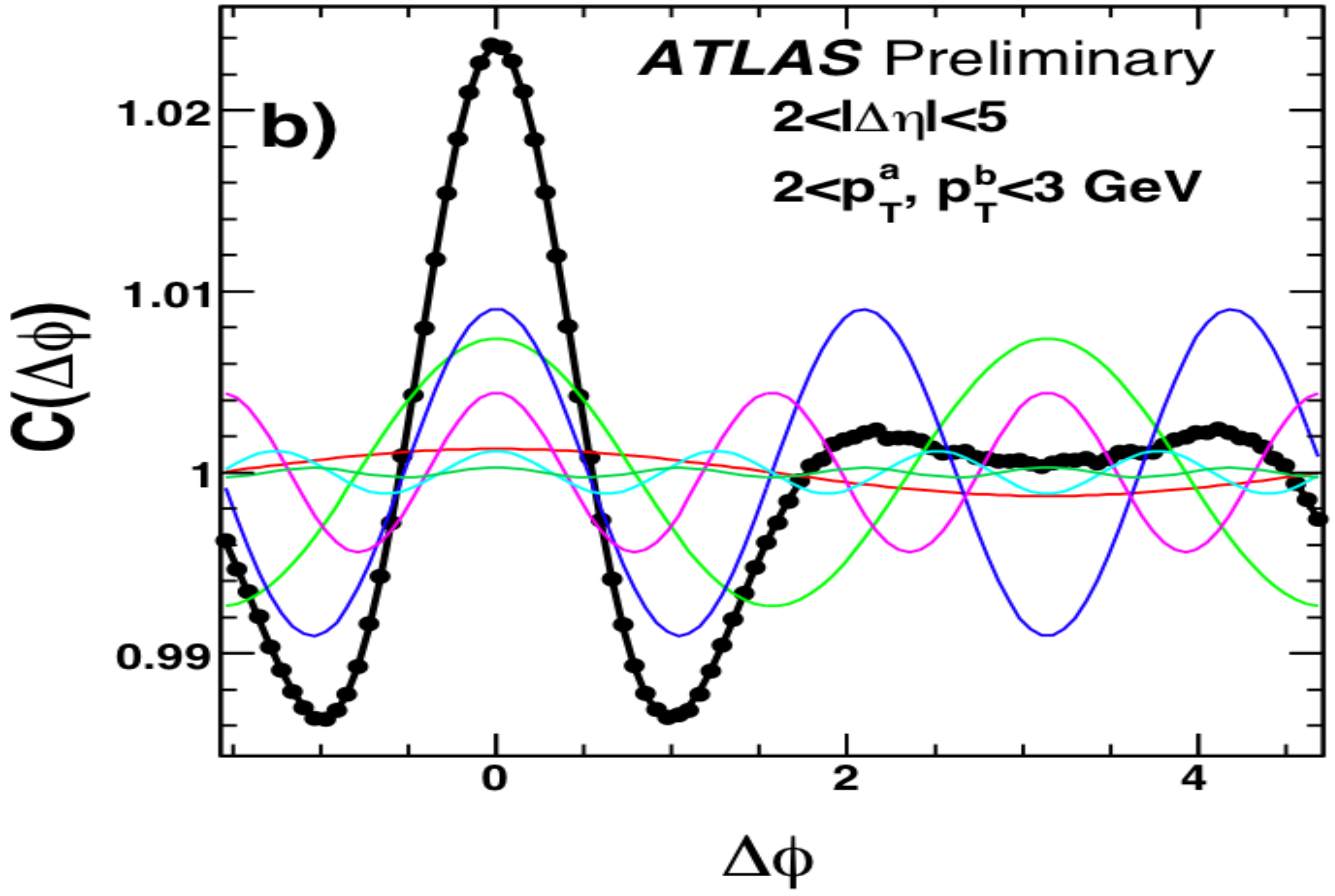
The modified freezeout
Surface (right) leads to
A modified angular distribution
Of particles, with and without viscosity
(left)

the effect of viscosity was seen by eye
for the first time

our theoretical prediction for two-particle correlator

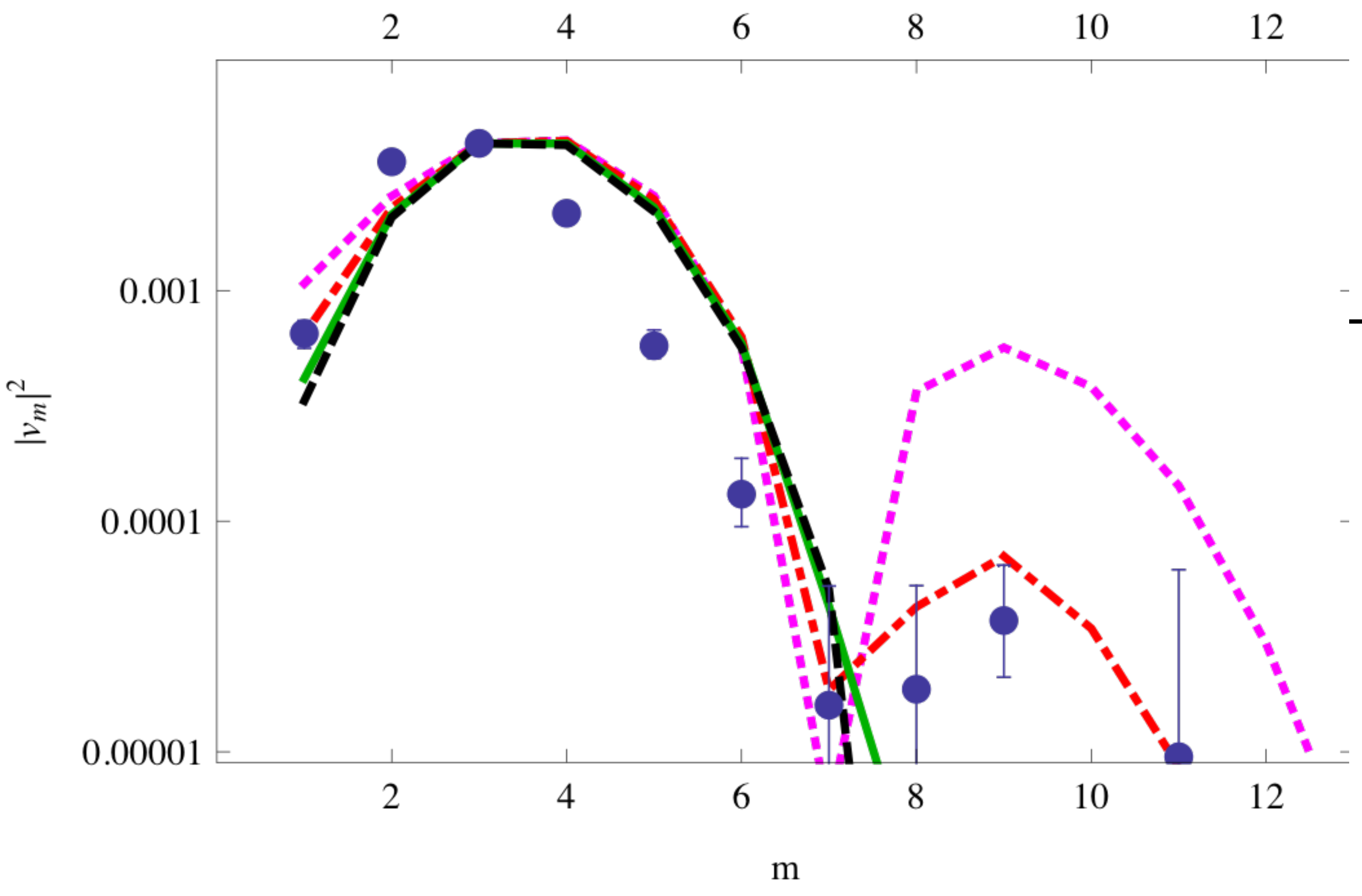
soon confirmed by ATLAS measuremnts



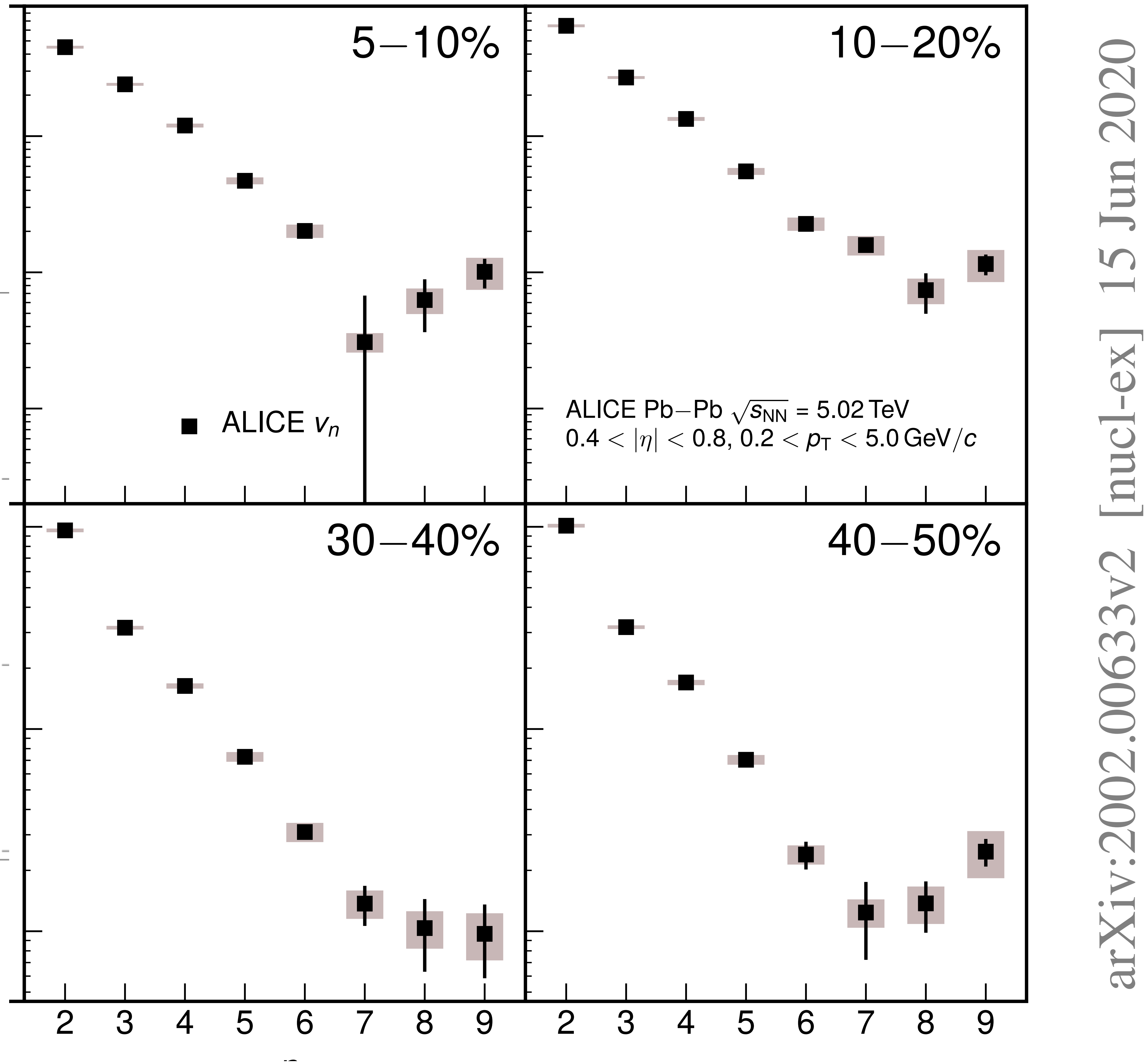


colored curves are expansion in harmonics

our paper 2011:
fixed QGP viscosity and predicted
the first minimum at m=7
and maximum at 9



points are ATLAS 2011, preliminary



ALICE MEASUREMENTS 2020:
yes, the minimum is confirmed

Sphalerons in

QCD AND ELECTROWEAK PHASE TRANSITIONS

Cosmological electroweak phase transition (EWPT)

$$T_{EW} = (159 \pm 1)\,\mathrm{GeV}$$
$$t_{EW} \sim 0.9 \cdot 10^{-11} s, \quad ct_{EW} \approx 2.7\,\mathrm{mm}$$

crossover: M. D'Onofrio, K. Rummukainen and A. Tranberg,
Phys. Rev. Lett. 113, no. 14, 141602

If Higgs mass be small,
it is the first order,
thus studies of bubbles etc in 1980s.
But now we know it is
a smooth crossover

W,Z,quarks and leptons
Are all massless at T>Tc

At later time
Higgs VEV appears, v^2
Approximately linearly in T

$$\frac{v^2(140\,\mathrm{GeV} < T < T_{EW})}{T^2} \approx 9\left(1 - \frac{T}{T_{EW}}\right)$$

In the fully broken
phase at T=0
v=246 GeV

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In the fully broken
phase at T=0
v=246 GeV

Note that the critical temperature
for QCD transition is nearly
exactly 1000 times smaller, 155 MeV

Sphalerons in cosmological electroweak transition

Change in baryon number:
each sphaleron explosion creates
9 quarks and 3 leptons
Is related to sphaleron rate
Per dt d^3x

$$\frac{1}{N_B}\frac{dN_B}{dt} = \frac{39\,\Gamma}{4T^3}.$$

$$\Gamma = \kappa\left(\frac{gT}{m_D}\right)^2 \alpha_W^5 T^4,$$

At T>Tc (early Universe)
The rate is only power suppressed
And is about 10^9 times the rate of expansion
Erasure of earlier baryon
asymmetry is therefore a problem

$$\frac{\Gamma}{T^4} = (18 \pm 4)\alpha_{EW}^5 \approx 1.5 \cdot 10^{-7}$$

Lattice simulations

$$\log\left(\frac{\Gamma(T < T_{EW})}{T^4}\right) =$$

$$-(147.7 \pm 1.9) + (0.83 \pm 0.01)\left(\frac{T}{\mathrm{GeV}}\right)$$

M. D'Onofrio, K. Rummukainen and A. Tranberg, Phys. Rev. Lett. **113**, no. 14, 141602 (2014) doi:10.1103/PhysRevLett.113.141602 [arXiv:1404.3565 [hep-ph]].

sphaleron transitions become irrelevant when the temperature is below

$$T_{\text{decoupling}} = 131.7 \pm 2.3\,\mathrm{GeV}. \qquad (9)$$

also about 1000 times freezeout temperature of heavy ion collisions

The sphaleron size distribution

D.Kharzeev, E.S, I.Zahed *Phys.Rev.D* 102 (2020) 7, 073003 • e-Print: 1906.04080

Small sizes:

Are limited by growing mass

$$M_{sph}(\rho) = \frac{3\pi^2}{g^2\rho}$$

$$\Gamma \sim e^{-M_{sph}/T}$$

Large sizes:

Are limited by weak magnetic screening

$$M_m(T) \approx 0.457 g^2 T$$

Lattice

$$\frac{\Gamma}{T^4} \sim \exp\Big(-(0.457)^2\pi^2 g^2 T\rho\Big)$$

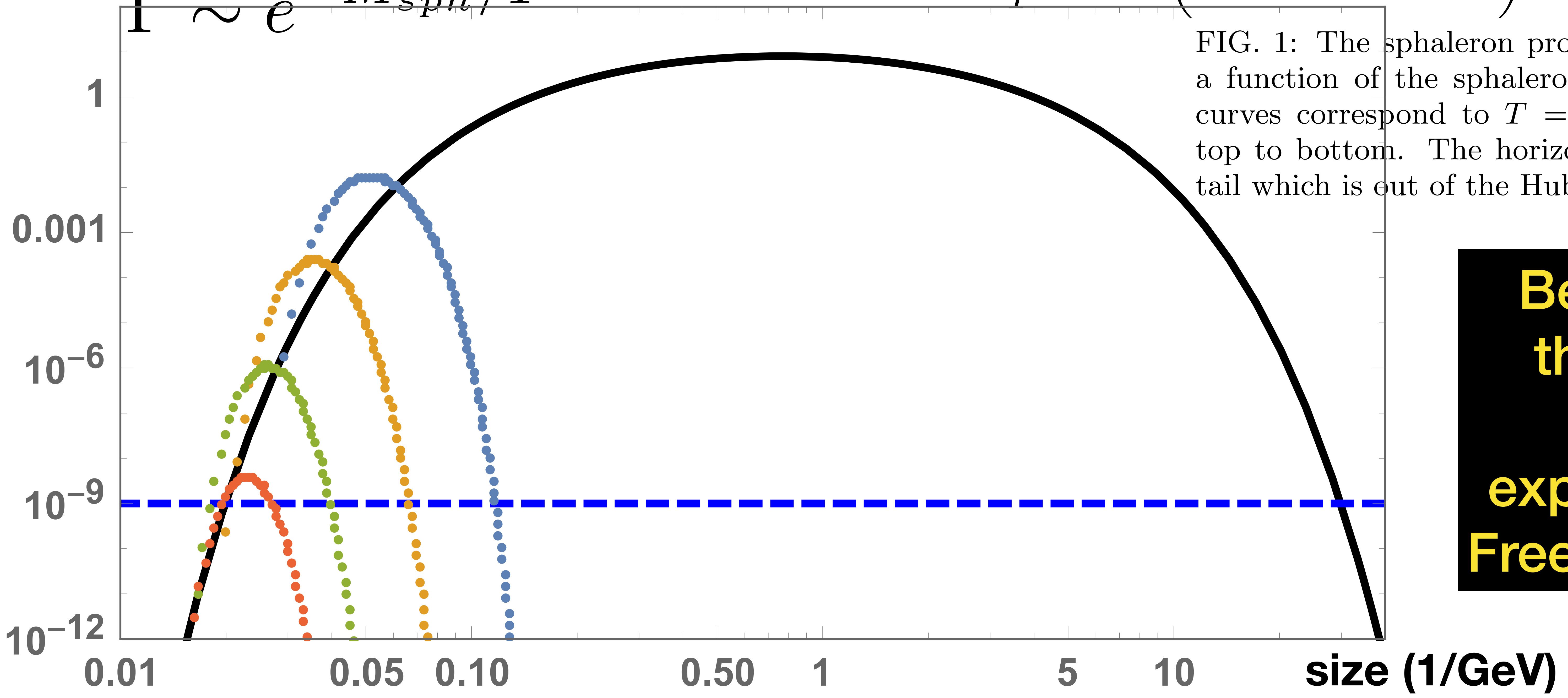

FIG. 1: The sphaleron probability distribution as a function of the sphaleron size $\rho(\mathrm{GeV}^{-1})$. The curves correspond to $T = 159, 150, 140, 130\,\mathrm{GeV}$, top to bottom. The horizontal line separates the tail which is out of the Hubble expansion rate.

Below the horizontal line the rate does not match the Universe expansion rate (Hubble) => Freezeout, out of equilibrium

After T<Tc=160 GeV Higgs VEV appears, Strongly suppressing sphalerons

As mountains grow, everything from slopes falls down

Explosion of pure gauge sphalerons was solved analytically By conformal off-center transformation and continuation into Minkowski time

$$gA^a_\mu = \eta_{a\mu\nu}\partial_\nu F(y)$$

$$F(y) = 2\int_0^{\xi(y)} d\xi' f(\xi')$$

E. Shuryak and I. Zahed, Phys. Rev. D **67**, 014006 (2003) doi:10.1103/PhysRevD.67.014006 [hep-ph/0206022].

$$S_{\rm eff} = \int d\xi \left[\frac{\dot{f}^2}{2} + 2f^2(1-f)^2\right]$$

$$f(\xi) = \frac{1}{2}\left[1 - \sqrt{1+\sqrt{2\epsilon}}\,\mathrm{dn}\left(\sqrt{1+\sqrt{2\epsilon}}(\xi - K), \frac{1}{\sqrt{m}}\right)\right]$$

dn is the elliptic function

$$\xi_E \to -i\xi_M = \arctan\left(\frac{2\rho t}{t^2 - r^2 - \rho^2}\right)$$

the gauge field is given explicitly

$$gA^a_4 = -f(\xi)\frac{8t\rho x_a}{[(t-i\rho)^2 - r^2][(t+i\rho)^2 - r^2]}$$

$$gA^a_i = 4\rho f(\xi)\frac{\delta_{ai}(t^2 - r^2 + \rho^2) + 2\rho\epsilon_{aij}x_j + 2x_i x_a}{[(t-i\rho)^2 - r^2][(t+i\rho)^2 - r^2]}$$

Explosion of pure gauge sphalerons was solved analytically By conformal off-center transformation and continuation into Minkowski time

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$$gA^a_4 = -f(\xi)\frac{8t\rho x_a}{[(t-i\rho)^2 - r^2][(t+i\rho)^2 - r^2]}$$

$$gA^a_i = 4\rho f(\xi)\frac{\delta_{ai}(t^2 - r^2 + \rho^2) + 2\rho\epsilon_{aij}x_j + 2x_i x_a}{[(t-i\rho)^2 - r^2][(t+i\rho)^2 - r^2]}$$

The fermion zero mode Becomes production Mode of 12 fermions

Snapshots of the explosion

D.Kharzeev, E.S, I.Zahed *Phys.Rev.D* 102 (2020) 7, 073003 • e-Print: 1906.04080

from A_\mu => G_{\mu\nu} => T^{\mu\nu}
leads to lengthy expressions,
here are snapshots

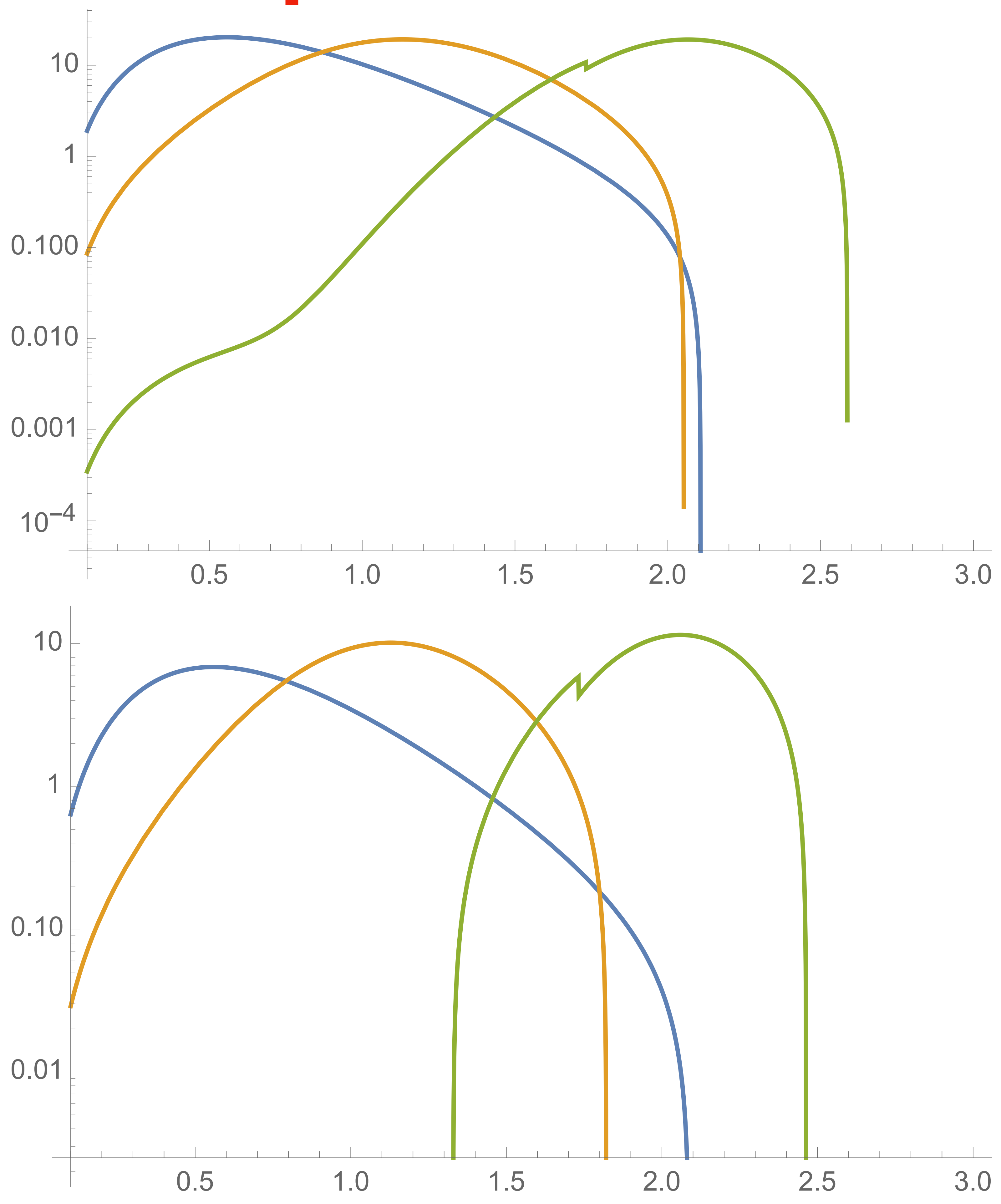


FIG. 2: Componenents of the stress tensor (times r^2, namely $r^2T^{00}(t,r)$ upper plot, $r^2T^{33}(t,r)$ lower plot) as a function of r, the distance from the center, at times $t/\rho = 0.1, 1, 2$, left to right.

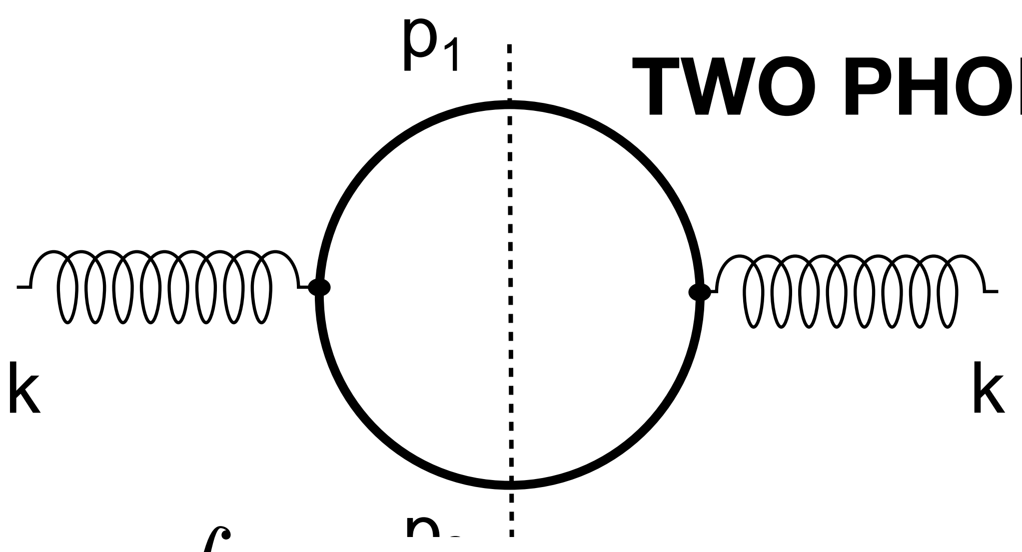
Even in smooth EWPT
There are explosions! At T>Tc
sphalerons explode spherically,
Producing sound waves in matter

At T<Tc VEV of Higgs is nonzero
Weinberg angle mixes Z and photons
And also makes explosion elliptic =>
Direct generation of
Gravity waves

Inverse acoustic cascade and gravitational wave production

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

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



TWO PHONONS IN THE LOOP

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

IN FACT GRAVITY WAVES WITH SUCH PERIOD WERE RECENTLY REPORTED BY OBSERVATION OF PULSAR TIMING COLLABORATION

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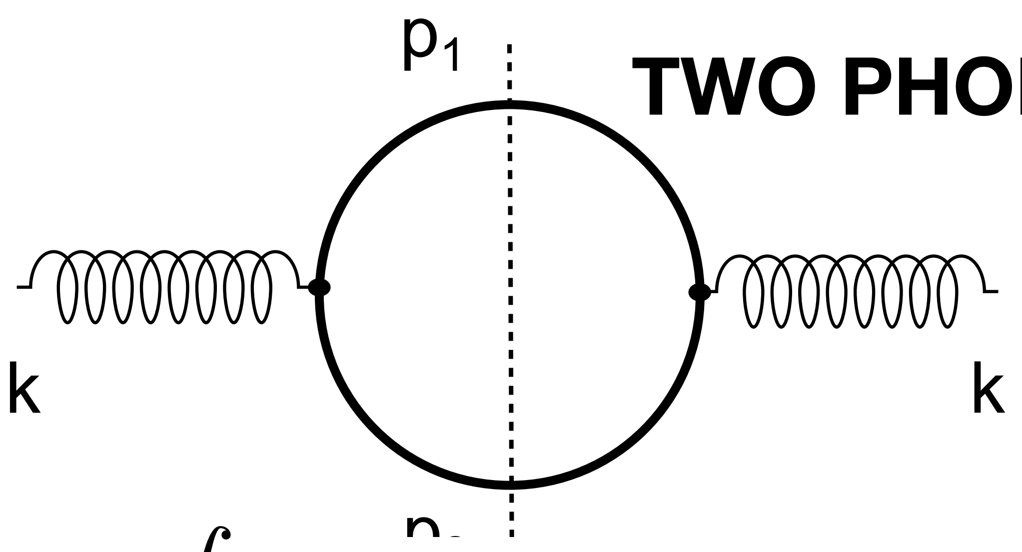

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Collisions of two sound waves leads to
direct production of gravity waves
IN THE CASE OF QCD TRANSITION
THE CHARACTERISTIC TIME IS 1 YEAR
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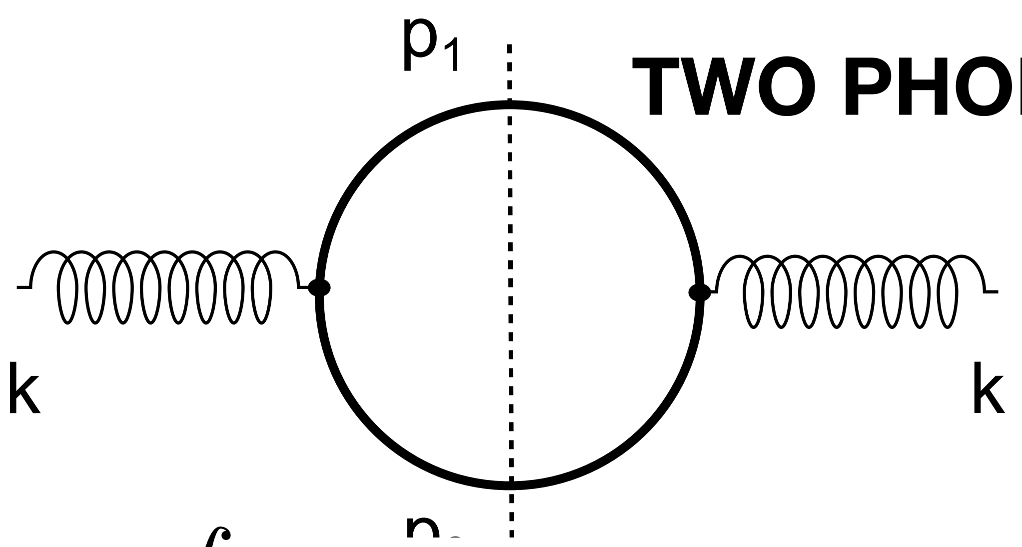

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Searching For Gravitational Waves From Cosmological Phase Transitions With The NANOGrav 12.5-year dataset
NANOGrav Collaboration•Zaven Arzoumanian(CRESST, Greenbelt and NASA, Goddard) et al. (Apr 28, 2021)
e-Print: 2104.13930

Helical magnitogenesis

The symmetry breaking by the Higgs VEV at $T < T_c$ leads to mass separation of the original non-Abelian field A^3_μ into a massive Z_μ and a massless a_μ, related by a rotation involving the Weinberg angle. The expanding outer shell of the sphaleron explosion contains massless photons and near-massless quarks and leptons u, d, e, ν.

The anomaly relation implies that the non-Abelian Chern-Simons number during the explosion defines the chiralities of the light fermions, which can be transferred to the so-called "magnetic helicity" (Chern-Simons three-form):

$$\int d^3x \vec{A}\vec{B} \sim B^2\xi^4. \tag{38}$$

The configurations with nonzero (38) correspond to chiral knots of magnetic flux, and are called *helical*.

The size growth of the chiral (linked) magnetic cloud is diffusive. For a magnetically driven plasma with a large electric conductivity σ, a typical magnetic field $\vec{B}$ diffuses as

$$\frac{d\vec{B}}{dt} = D\nabla^2\vec{B} \tag{40}$$

with the diffusion constant $D = 1/(4\pi\sigma) \sim 1/T$. It follows that the magnetic field size grows as

$$R^2(t) = D\Delta t \sim \frac{\Delta t}{T} \tag{41}$$

where the inverse cascade time Δt is limited by

Intergalactic magnetic fields should be
Of cosmological origin
most likely seeded by sphalerons
Magnetic helicity is conserved
CME makes it also an inverse cascade

Summary

Electroweak sphalerons have M of about 8 TeV
And is hard to produce: thus cosmology
they may seed sounds and magnetic fields

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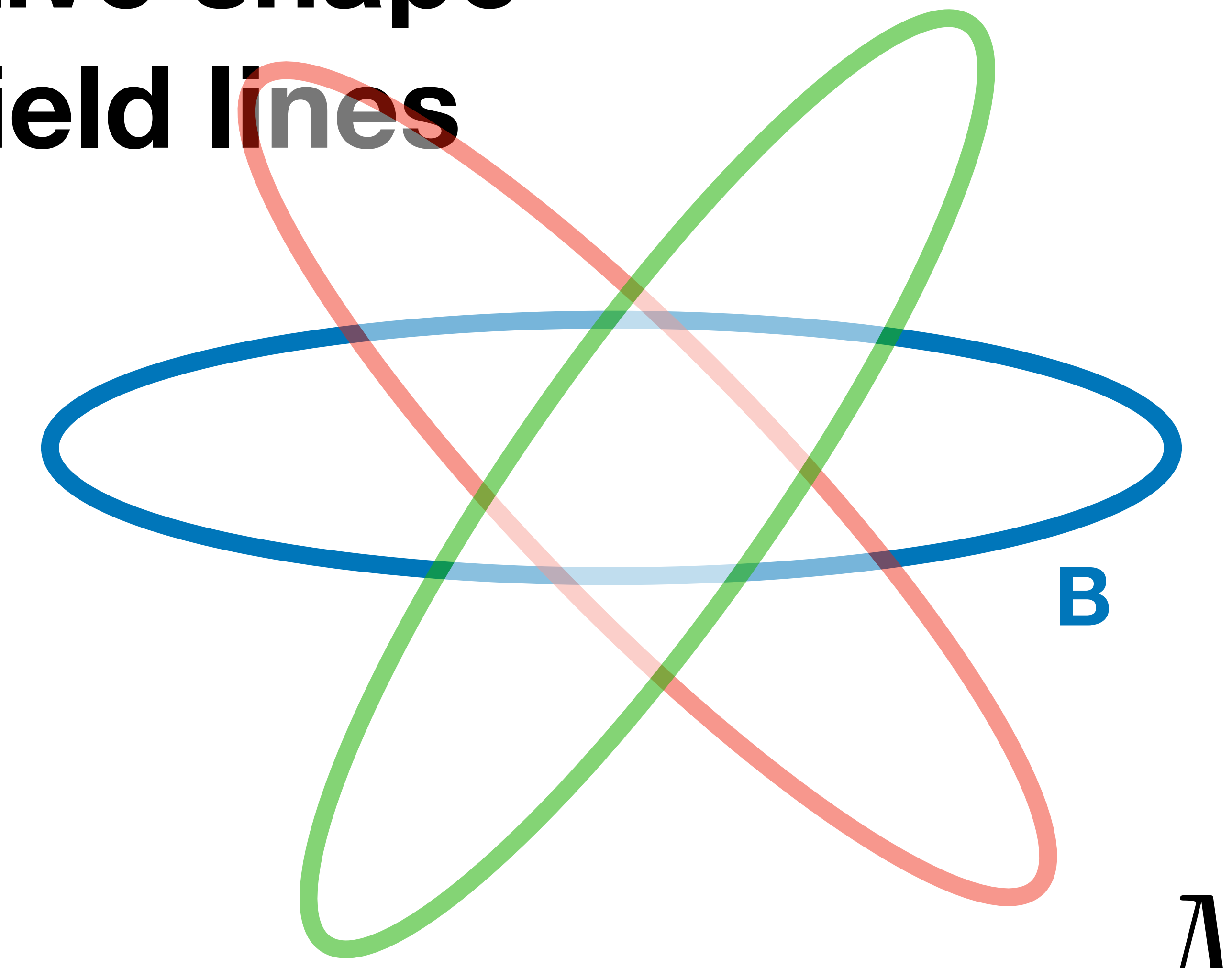
SCENARIO WITH inverse acoustic cascade
and gravity wave production may explain
recent discovery of 1-year period
gravity waves

sphaleron path field configurations
are static magnetic balls
in SU(2) there are three generators
(which are not ``colors", but W+,W-,Z
yet shown by red, blue and green below)
here is the qualitative shape
of the magnetic field lines



sum over colors makes
it spherically symmetric
in pure gauge it is a ball of size rho
for kappa=0 it is

$$B^2(r) = \frac{48\rho^4}{g^2(r^2+\rho^2)^4}$$

$$M_{sph} = U_{\min}\left(\frac{1}{2}, \rho\right) = \frac{3\pi^2}{g^2\rho}$$

these ``turning points" are unstable,
basically magnetic bombs
waiting to explode
Approach with care!

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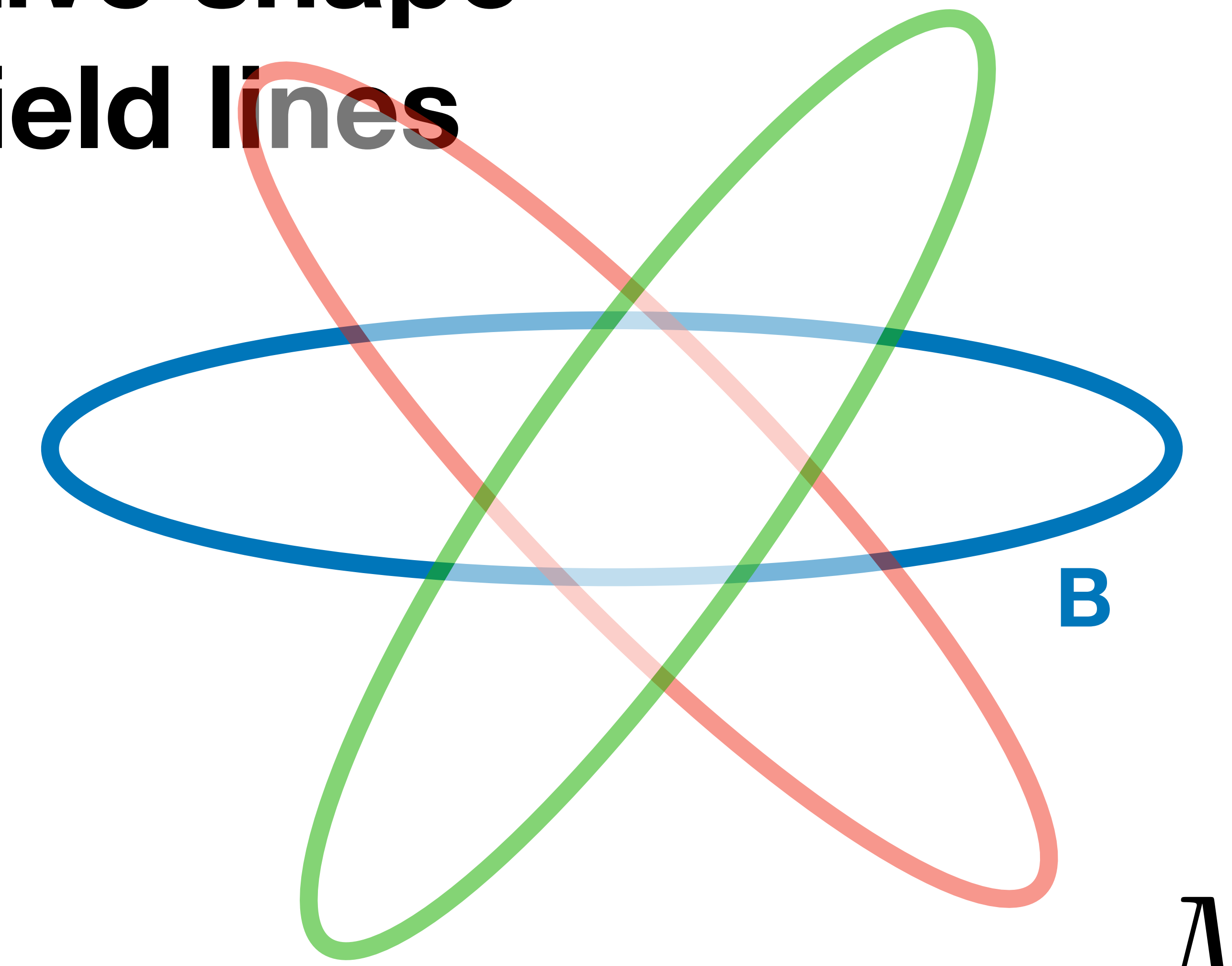

unlike another famous 3d magnetic soliton,
t’Hooft-Polyakov monopole,
fields are not radial, thus no magnetic charge!

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electroweak sphalerons

have a mass of about 8 TeV (>> Tew)

can they be produced in high energy pp collisions at LHC or beyond?

Producing hundreds of W's
And making them coherent soliton
Is very hard
Study QCD sphaleron production is
Much more promising

• (Baryon-number violating) instanton-induced processes in electroweak theory A.Ringwald, Nucl.Phys. B330 (1990) 1, O.Espinosa, Nucl.Phys. B343 (1990) 310; L.McLerran, A.Vainshtein V.I.Zakharov, A.Muller, M.Maggiore and M.Shifman, : extremely insightful works, but the effect is too small to be seen!

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QCD sphalerons should be
produced in high energy hadronic collisions, creating chiral imbalance
We will discuss experiments looking for that

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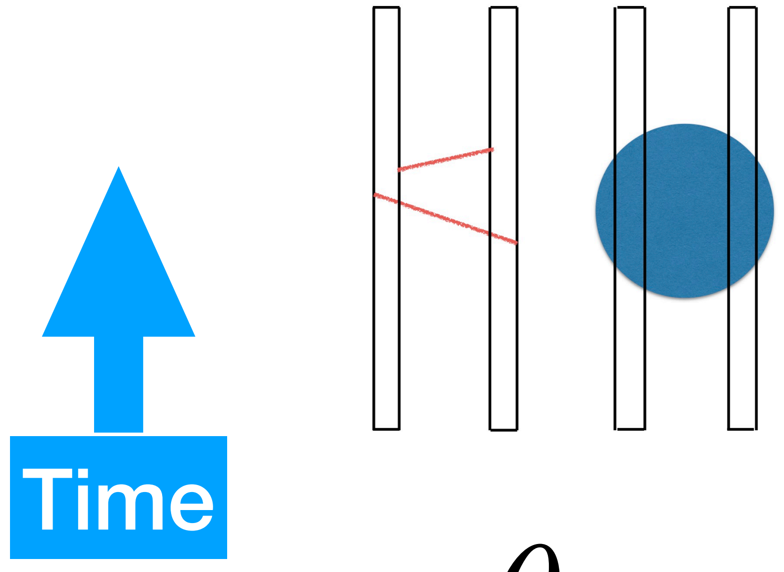
extra slides

Baryogenesis

- Sakharov (1967) had formulated 3 conditions => **B-violation, CP-violation, non-equilibrium**
- All 3 are there in the Standard Model (SM)
- And yet we do not know how $n_B/n_\gamma = 6*10^{-10}$ has been obtained… as way too small numbers are obtained
- beyond the SM? (very popular)
  or beyond the standard cosmology instead?

Instanton-induced elastic dipole-dipole high energy scattering



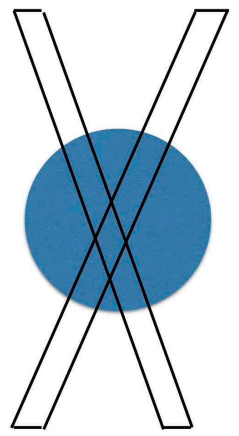
$$\langle \vec{E}^2(\tau_1)\vec{E}^2(\tau_2)\rangle \sim \frac{1}{[R^2+(\tau_1-\tau_2)^2]^4}$$

Integrating over time difference Gives 1/R^7, Casimir-Polder

$$W(\vec{r}) = cos(\frac{\pi r}{\sqrt{r^2+\rho^2}}) + \frac{\vec{r}\vec{\tau}}{r} sin(\frac{\pi r}{\sqrt{r^2+\rho^2}})$$

Wilson line for instanton can be Calculated analytically

θ



$$\theta \to iy$$

where y is the Minkowski rapidity difference between the colliding objects. It has been checked in [Meggiolaro:1997dy, 1998; Shuryak and Zahed, 2000] and elsewhere that in that it works correctly for perturbative amplitudes.

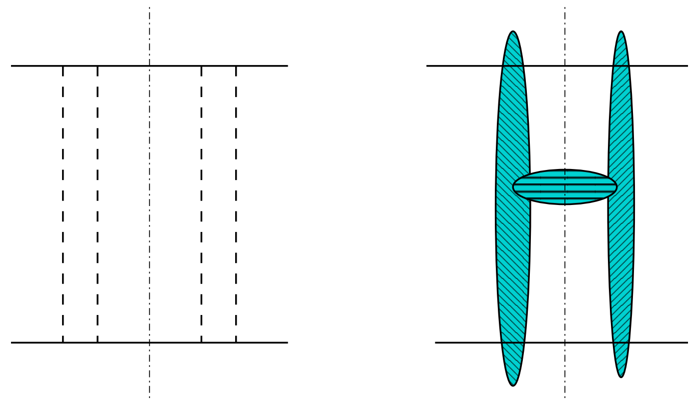
scattering of two small dipoles correspond to elastic double scattering

For example, future lepton collider can be used as a collider of two virtual photons γ*γ*.

Istead of showing complicated formulae Let me just say the cross section is larger than 2-gluon change

Semiclassical Double-Pomeron Production of Glueballs and η′

Edward Shuryak and Ismail Zahed



Central cluster = sphaleron path states

For sufficiently small mass
Of about 2 GeV it can go into
A single hadron
ETA', 0^- or 2^+ GLUEBALLS

The mean mass is related to
mean instanton size
M(sphaleron) =
3pi^2/g^2(\rho)\rho \sim 3\, GeV

$$\sigma(s) \approx \mathbf{C}_S\, \pi\, \rho^2 \ln s \int dq_{1\perp}\, dq_{2\perp}\; \mathbf{K}(q_{1\perp}, q_{2\perp})$$
$$\times \int_{(q_{1\perp}+q_{2\perp})^2}^{\infty} dM^2\; \sigma_S(M)\ .$$

$$\sigma_S(Q) = \mathrm{Im} \int dT\, e^{QT-\mathbf{S}(T)} \approx \kappa\, e^{\frac{4\pi}{\alpha}\,(\mathbf{F}(Q)-\mathbf{F}(M_s))}\ ,$$

$$\mathbf{K}(q_{1\perp}, q_{2\perp}) = |\mathbf{J}(q_{1\perp})\cdot\mathbf{J}(q_{2\perp}) + \mathbf{J}(q_{1\perp})\times\mathbf{J}(q_{2\perp})|^2$$

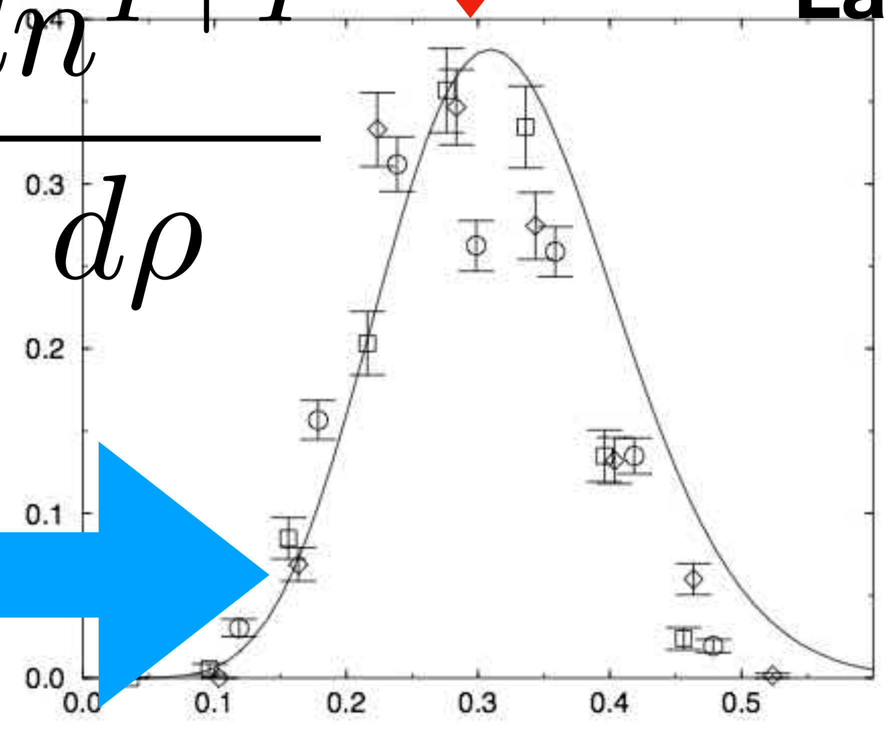
with

$$\mathbf{J}(q_\perp) = \int dx_3\, dx_\perp\, e^{-iq_\perp x}\, \frac{x_\perp}{|x|}\, \sin\left(\frac{\pi\,|x|}{\sqrt{x^2+\rho_0^2}}\right)\ .$$

which is purely imaginary,

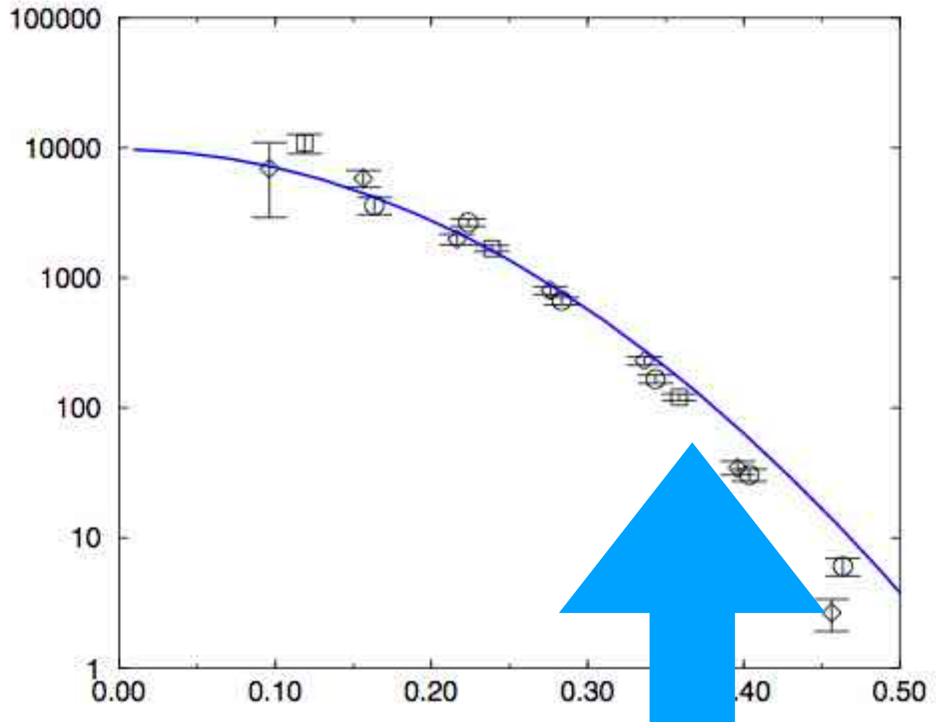
$$\mathbf{J}(q_\perp) = -i\frac{\hat{q}_\perp}{\sqrt{q_\perp}} \int_0^\infty dx\, J_{3/2}(q_\perp x)$$
$$\times \left((2\,\pi x)^{3/2} \sin\left(\frac{\pi\,|x|}{\sqrt{x^2+\rho_0^2}}\right)\right)\ .$$

$$\frac{dn^{I+\bar{I}}}{d\rho}$$



$$\sim \rho^{b-5} \sim \rho^4$$

Lattice data, A.Hazenfratz



Dual Higgs model

$$\frac{dn}{d\rho} = \frac{dn}{d\rho}\Big|_{semiclassical} \cdot e^{-2\pi\sigma\rho^2}$$

earlier scenario using small momentum quarks

G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. D *50*, 774 (1994) [hep-ph/9305275].

was criticized because of gluon scattering on quarks

one cannot keep momentum small for long!

M. B. Gavela, P. Hernandez, J. Orloff and O. Pene, Mod. Phys. Lett. A *9*, 795 (1994) [hep-ph/9312215].
P. Huet and E. Sather, Phys. Rev. D *51*, 379 (1995) [hep-ph/9404302].

The second argument is based on the emergence of a "thermal Klimov-Weldon" quark mass

$$M_{KW} = \frac{g_s T}{\sqrt{6}} \sim 50\,\mathrm{GeV} \qquad (34)$$

induced by the real part of the forward scattering amplitude of a gluon on a quark.

The third argument which is stronger, was given in [33, 34]. It is based on the *decoherence* suffered by a quark while traveling in a thermal plasma, as caused by the imaginary part of the forward scattering amplitude (related by unitarity to the cross section of *non-forward* scatterings on gluons). Basically, they argued that if a quark starts with a small momentum, it will not be able to keep it small for necessary long time, due to such scattering. The imaginary part is about

$$\mathrm{Im}(M_q) \sim \alpha_s T \sim 20\,\mathrm{GeV} \qquad (35)$$

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Unlike momenta, topological Dirac zero modes do survive plasma corrections (such as gluon rescattering)!

tested e.g. on the lattice for instantons and instanton-dyons

$$i\not{D} = (i\not\partial + gA_\mu)\hat{1} + gA_\mu(\hat{M}_{CKM} - \hat{1}) \; + M_{KW}$$

Nonperturbative A=O(1/g)

LL small **not small but does not kill zero mode**

LR $M_{LR}\dfrac{1}{i\not\partial + M_{KW}}M^\dagger_{RL}$

Klimov-Weldon mass remains in the R (right) part so the effective mass term create **flavor-dependent phases**

$$\phi_Q = \frac{m_Q^2|x_1 - x_2|}{M_{KW}}$$

Outgoing quarks have two interactions with W, there are two CKM matrics in amplitude 4 in the probability

$$\overline{A}A_{U0} \sim \sum_{D1,U,D2} Tr\hat{P}_{U0}W(x_1)\hat{V}^*_{CKM}S^{D1,D1}(x_1,x_2) \times W(x_2)\hat{V}^T_{CKM}\tilde{S}^{U1,U1}(x_2,x_3)W(x_3)\hat{V}^*_{CKM}S^{D2,D2}(x_3,x_4)W(x_4)\hat{V}^T_{CKM}\hat{P}_{U0}$$

for light u and d the CP asymmetry between quark and antiquark production is

$$2J\frac{(m_b^2 - m_s^2)(m_c^2 - m_u^2)}{M_\rho^4} \quad \sim 0.25 \cdot 10^{-9}$$

which is much larger than for nonzero modes!

signs for u and d are opposite but there is no symmetry due to Higgs VEV

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Baryon asymmetry is due to out-of-equilibrium sphalerons,

Which have probabilities different from antisphalerons

Due to CP-odd effects: CKM in quark determinant (?) or others (?)

$$\left(\frac{n_B}{s}\right) = 3A_{CP} \times \left[\frac{\Gamma\, F_{\rm freezeout}}{T_{EW}\, s_{EW}}\right] \times \left[T_{EW} t_{EW}\right] \times \left[\frac{t_{FO} - t_{EW}}{t_{EW}}\right]$$

$\approx 2.2 \cdot 10^{15}$ $\quad\approx 0.5$

$$\left(\frac{n_B}{n_\gamma}\right) = 7.6 \cdot 10^{-2} A_{CP}$$

$$A_{CP} \approx 0.8 \cdot 10^{-8}$$

Such CP violation is needed to explain BAU our estimate based on CKM gave

$$\sim 0.25 \cdot 10^{-9}$$

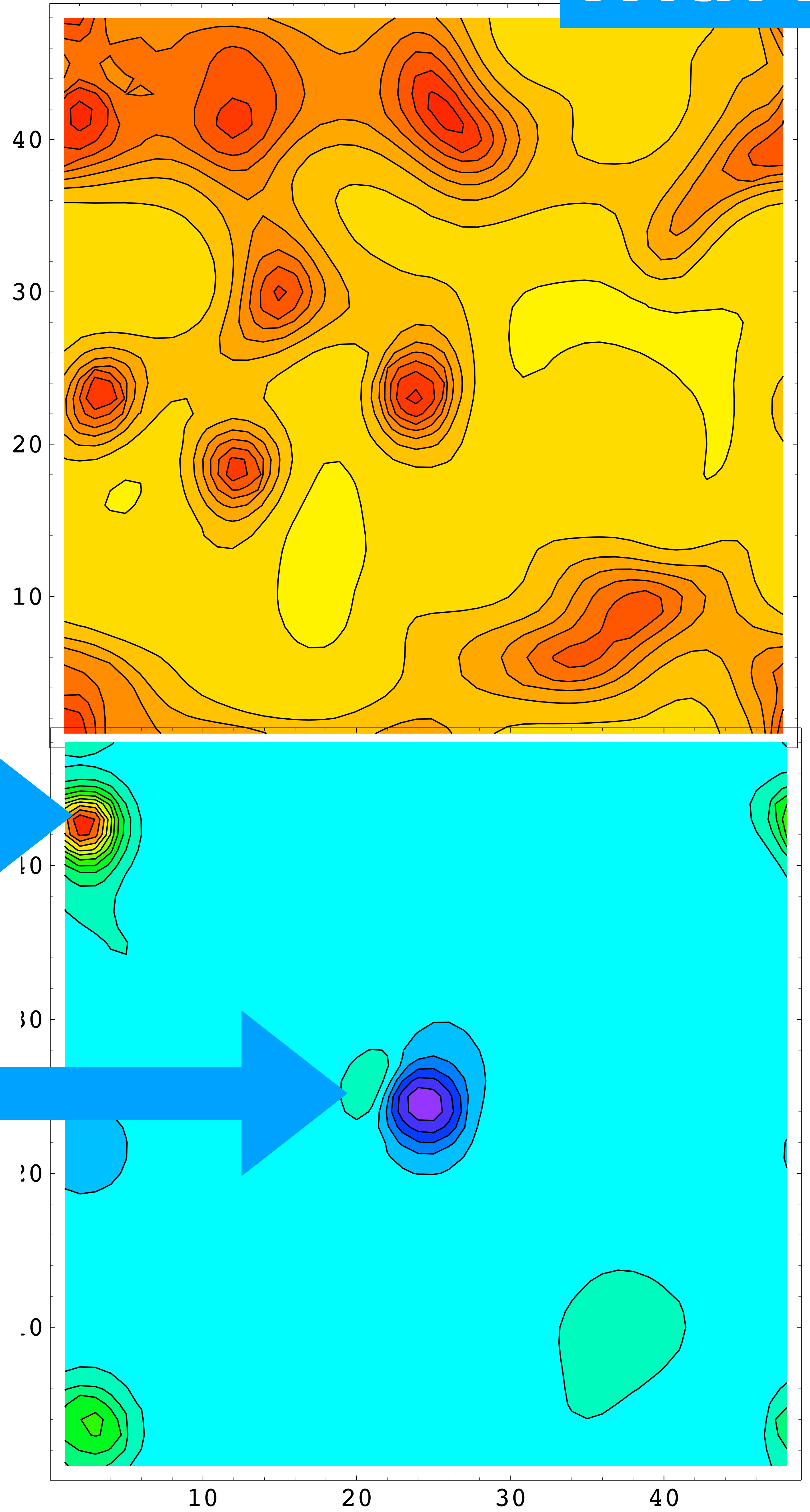
which is in the right ballpark, within the accuracy of our crude estimates!

Issue needs more studies ...

Hybrid (cold) scenario

With huge fluctuations

- **Topological charge Q** = GG_{dual} is also localized
- The topological transitions happen **only inside (some of) the "hot spots"**
- **Hot spots take volume fraction of few percents, sphalerons in them also have P of few percents**
- $=>\Gamma/T^4$ about $10^{-4,}$
- Integrated in time 10^{-3}



Map of Higgs VEV
In red spots it is depleted

$|\phi|$

T m=19
The same
Time and
place

Q(x)

The W-Z-Top Bags

Marcos P. Crichigno[1], Victor V.Flambaum[2], Michael Yu.Kuchiev[2] and Edward Shuryak[1]

Why should one study these multi-quanta states? From a methodical point of view, they are a new class of manybody systems, beyotnd atoms and nuclei

- C. D. Froggatt and H. B. Nielsen, Surveys High Energ. Phys. 18, 55 (2003), hep-ph/0308144;
  12 t make bound state via Higgs exchange

M. Y. Kuchiev, V. V. Flambaum and E. Shuryak, Phys. Rev. D 78, 077502 (2008) arXiv 0808.3632

- Not with realistic Higgs mass M_H>50 GeV

We calculated lowest states of W/Z and tops
In Higgs-Depleted bags
Unfortunately no bound multi-tops for any number
With W/Z in the lowest mode there are bound bags
But one needs hundreds of quanta!

Can be ``dorway states”
facilitating production of electroweak Sphalerons