(CERN TH Coll. Dec. 16, 2020)

Sphalerons and instantons,
In hadrons, collisions and Big Bang

Edward Shuryak

"Gauge topology" meetings:

I.Aug.2015 , Simons Center, Stony Brook
II.Nov.2016,ECT*,Trento
III. May 28-June 01 2018,ECT* Trento
Summer seminar June-Aug.2020
iV June 2020 -> June 2021,Simons Center

Topological landscape. Instantons and the Sphaleron path

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Looking for sphalerons using Chiral Magnetic Effect in QGP

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Looking for sphalerons using Chiral Magnetic Effect in QGP

Sphalerons in cosmological electroweak phase transition

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Looking for sphalerons using Chiral Magnetic Effect in QGP

Sphalerons in cosmological electroweak phase transition

Semiclassical theory of sphaleron explosions, sound and gravity wave production

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barI configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Looking for sphalerons using Chiral Magnetic Effect in QGP

Sphalerons in cosmological electroweak phase transition

Semiclassical theory of sphaleron explosions, sound and gravity wave production

CP violation during sphaleron explosions, and Baryon Asymmetry of Universe

Topological landscape. Instantons and the Sphaleron path

Instantons in QCD vacuum and hadrons

Instanton effects in high energy elastic collisions

I-barl configurations and sphaleron production

Double Diffractive production of clusters and UA8 experiment

Looking for sphalerons using Chiral Magnetic Effect in QGP

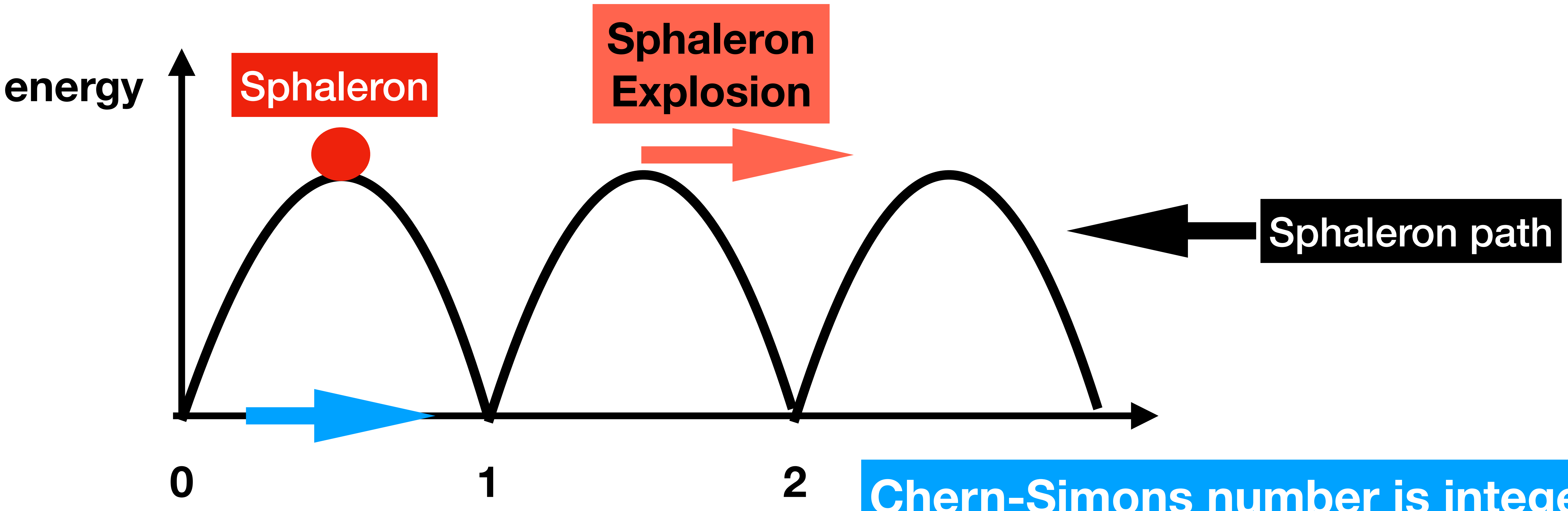
Sphalerons in cosmological electroweak phase transition

Semiclassical theory of sphaleron explosions, sound and gravity wave production

CP violation during sphaleron explosions, and Baryon Asymmetry of Universe

W-Z-top bags

Terminology of the topological landscape



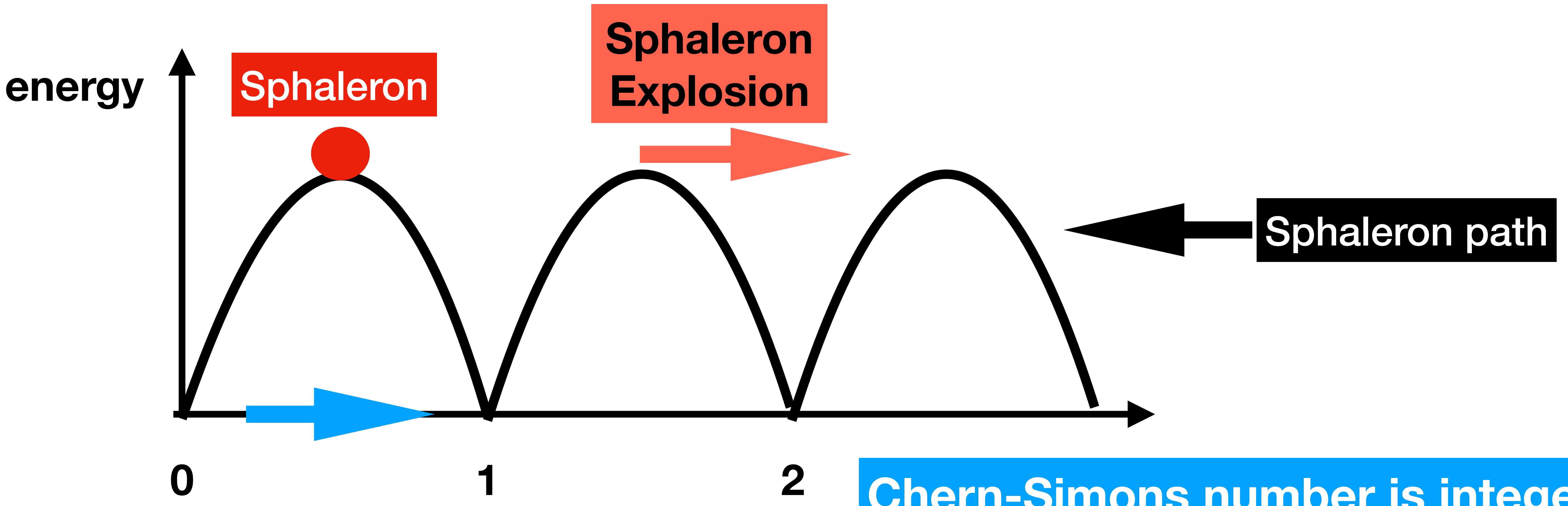
Chern-Simons number is integer at the “valleys”

Instanton
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



energy

Sphaleron

Sphaleron Explosion

Sphaleron path

0

1

2

Chern-Simons number is integer at the “valleys”

Instanton Tunneling at Zero energy

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

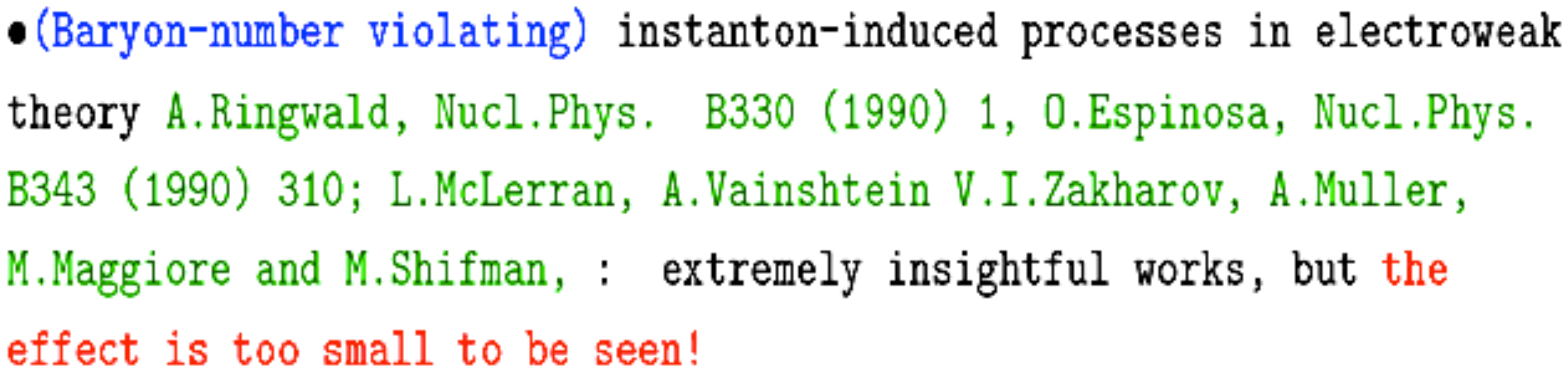
Sphaleron path consists of configurations
Which are minima in all directions in Hilbert space
except one
Like streams going from mountain tops
to the bottom of the valley

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

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

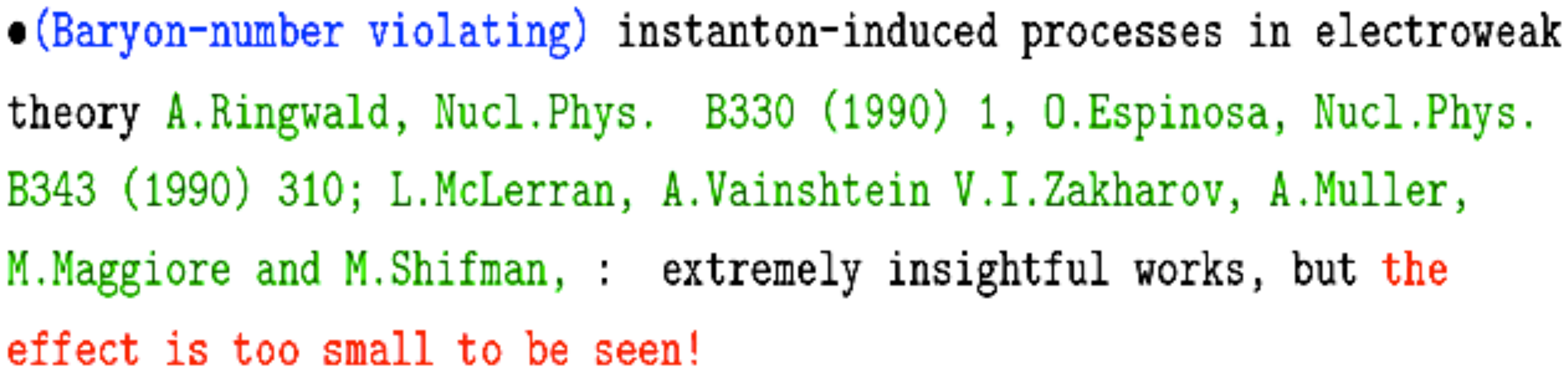


- (Baryon-number violating) instanton-induced processes in electroweak theory A.Ringwald, Nucl.Phys. B330 (1990) 1, O.Espinosa, Nucl.Phys. B343 (1990) 310; L.McLerran, A.Vainshtein V.I.Zakharov, A.Muller, M.Maggiore and M.Shifman, : extremely insightful works, but the effect is too small to be seen!

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

Mass of QCS sphalerons
Is about 3 GeV or larger!
This is to be discussed here



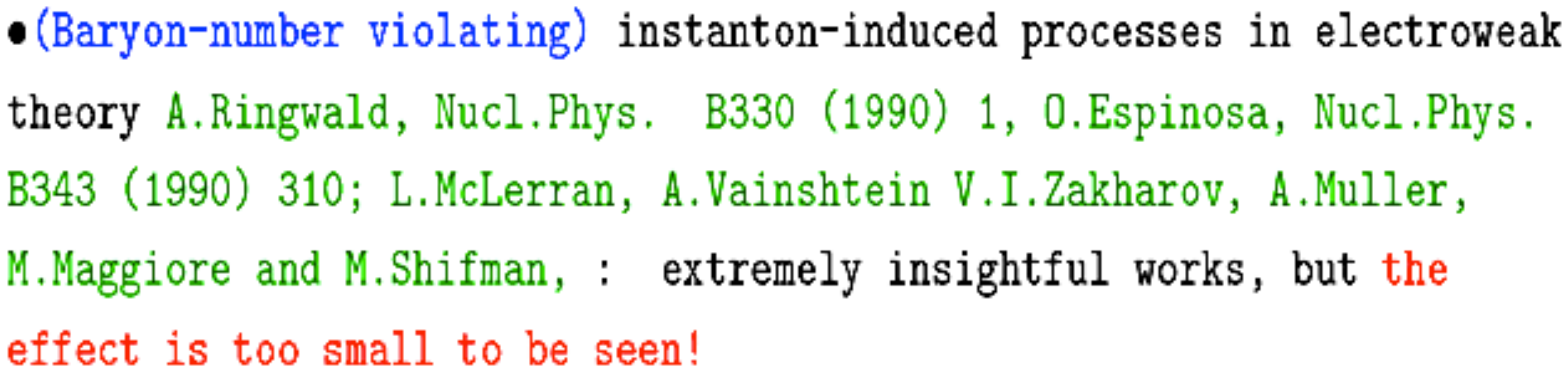
- (Baryon-number violating) instanton-induced processes in electroweak theory A.Ringwald, Nucl.Phys. B330 (1990) 1, O.Espinosa, Nucl.Phys. B343 (1990) 310; L.McLerran, A.Vainshtein V.I.Zakharov, A.Muller, M.Maggiore and M.Shifman, : extremely insightful works, but the effect is too small to be seen!

electroweak sphalerons
have a mass of about 8 TeV (>> Tew)
can they be produced in high energy pp collisions at LHC or beyond?

Mass of QCS sphalerons
Is about 3 GeV or larger!
This is to be discussed here

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

QCD sphalerons are **copiously produced in high energy hadronic collisions, creating chiral imbalance**
We will discuss experiments looking for that



- (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!

Instantons in the QCD VACUUM and HADRONS

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

…

hep-ph/0008048.

Instantons in the QCD VACUUM and HADRONS

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

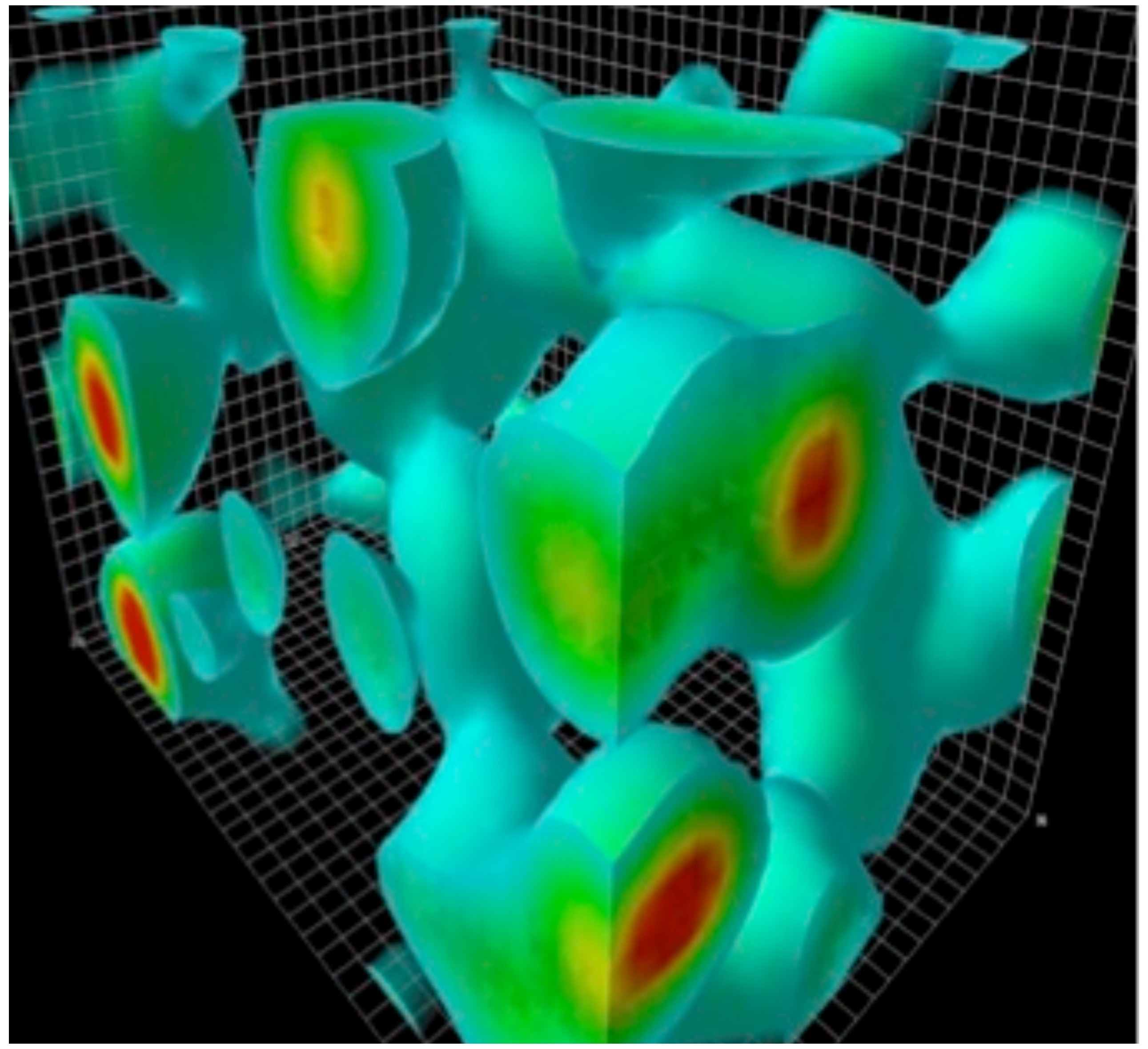
A snapshot of lattice G-dual G

...

hep-ph/0008048.

Instantons in the QCD VACUUM and HADRONS

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



A snapshot of lattice G-dual G

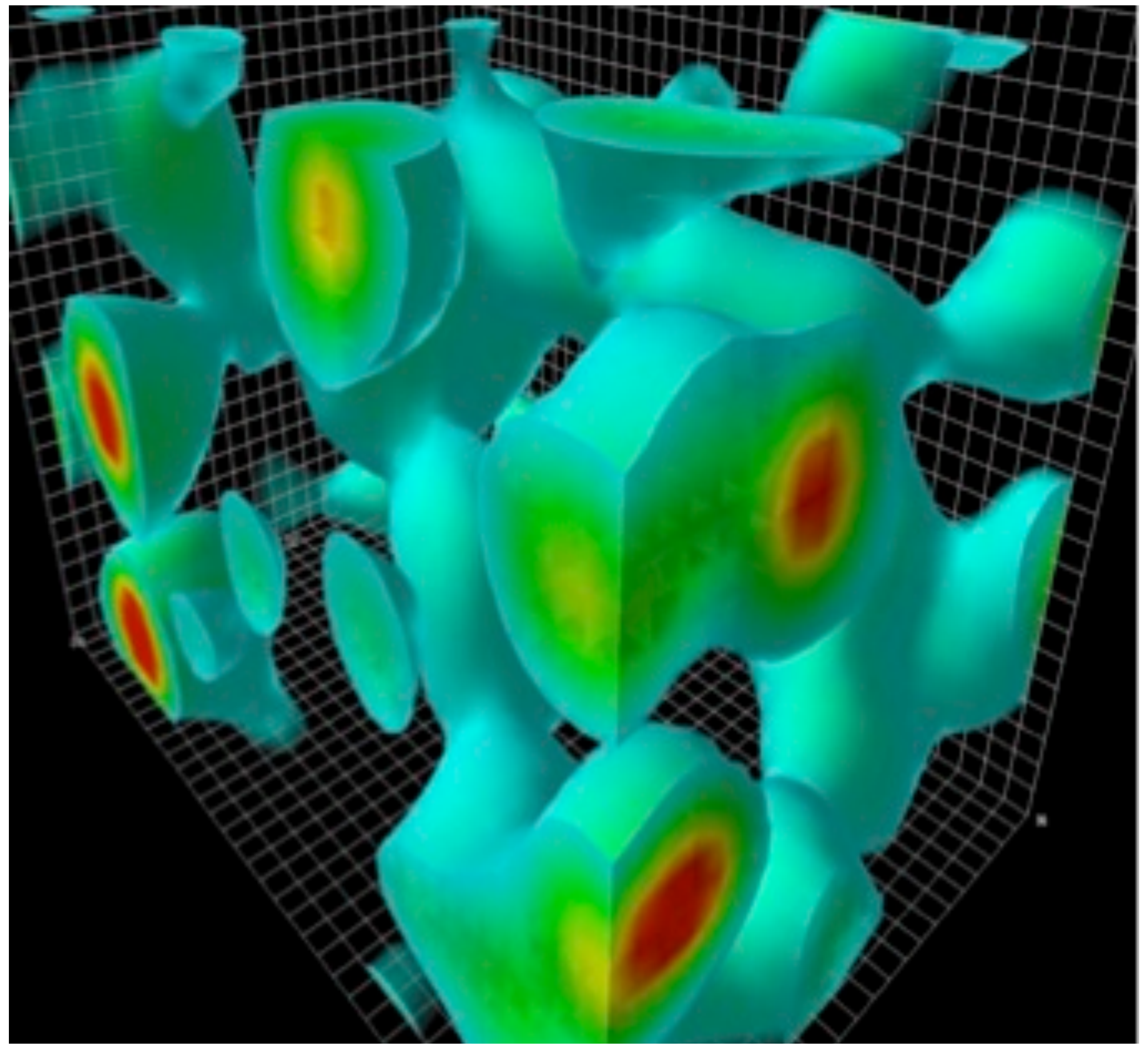
...

hep-ph/0008048.

Instantons in the QCD VACUUM and HADRONS

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

Interacting ensemble of instantons - 1990’s
Multiple correlation functions



A snapshot of lattice G-dual G

…

hep-ph/0008048.

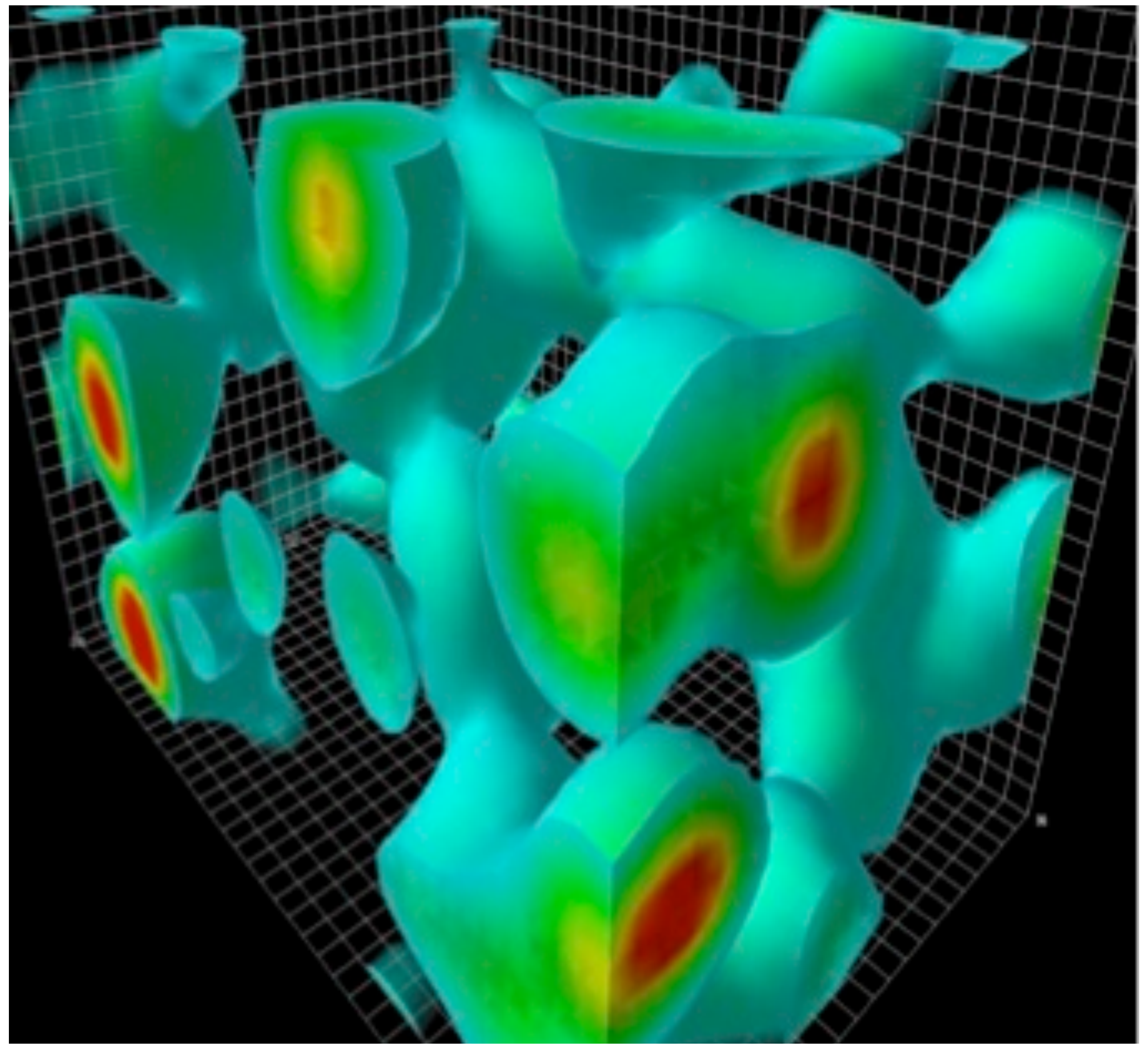
Instantons in the QCD VACUUM and HADRONS

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

Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

…



A snapshot of lattice G-dual G

hep-ph/0008048.

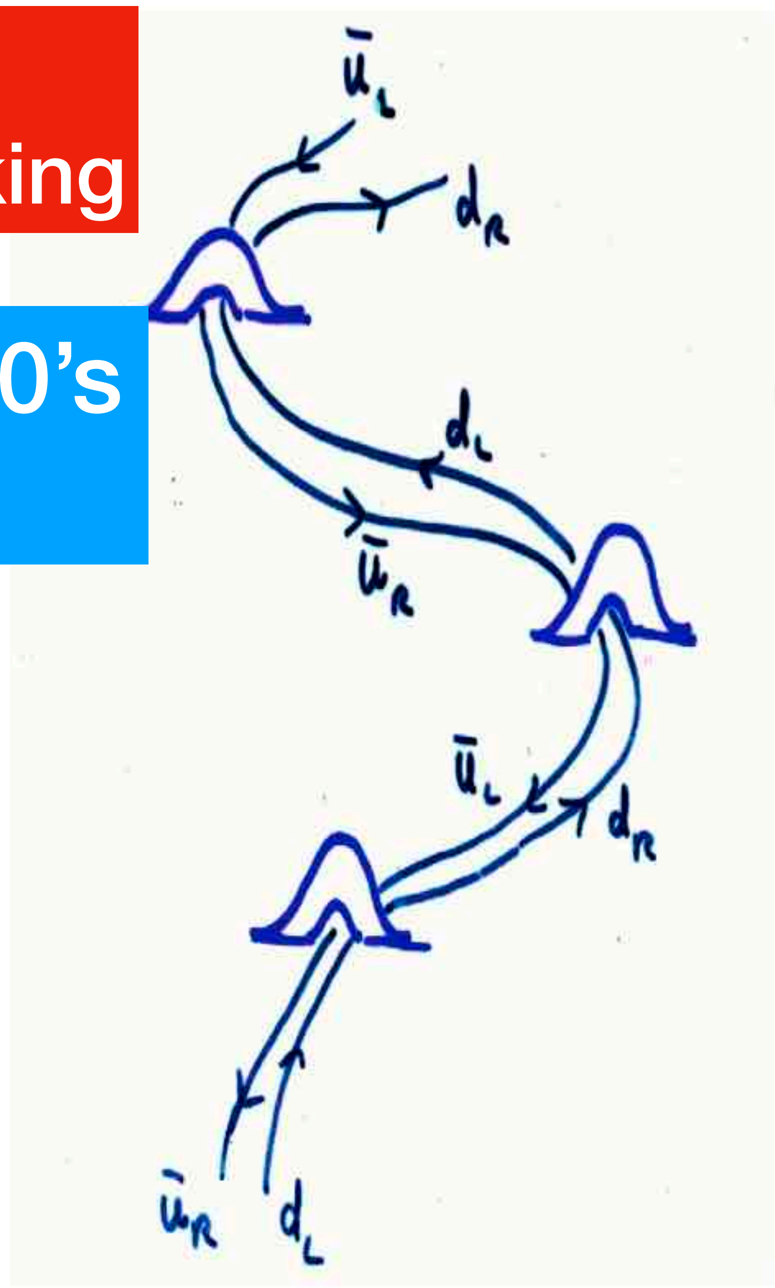
Instantons in the QCD VACUUM and HADRONS

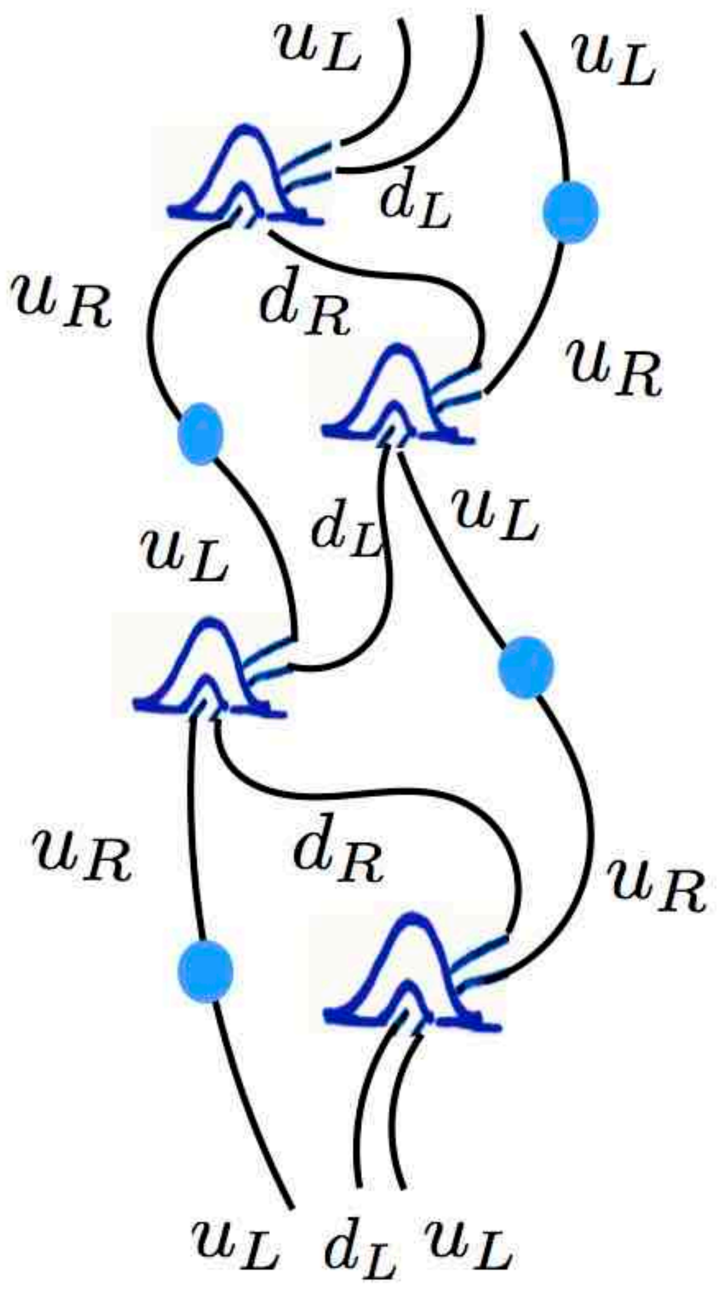
"Instanton liquid model" , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

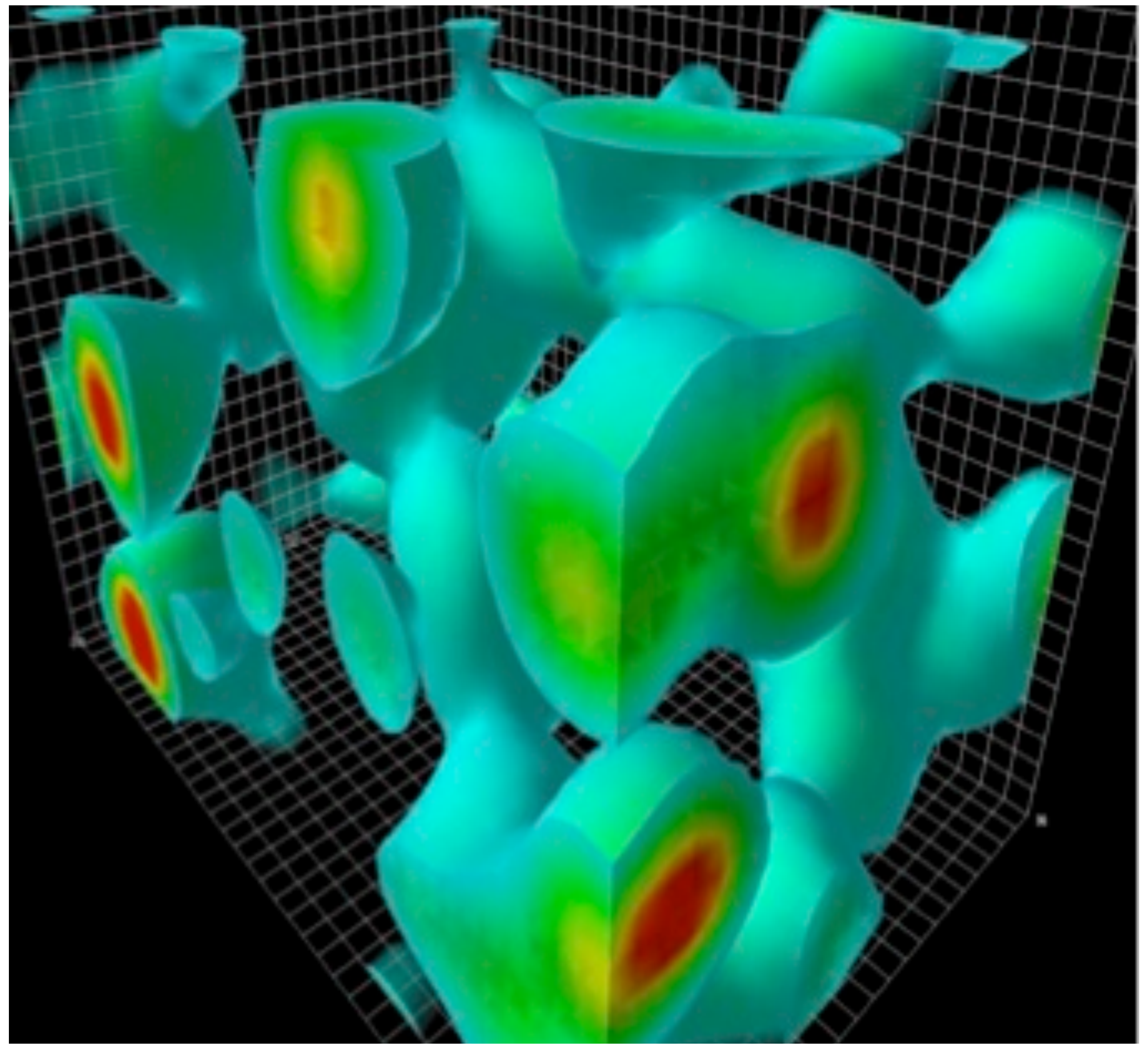
Interacting ensemble of instantons - 1990's
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

...







A snapshot of lattice G-dual G

hep-ph/0008048.

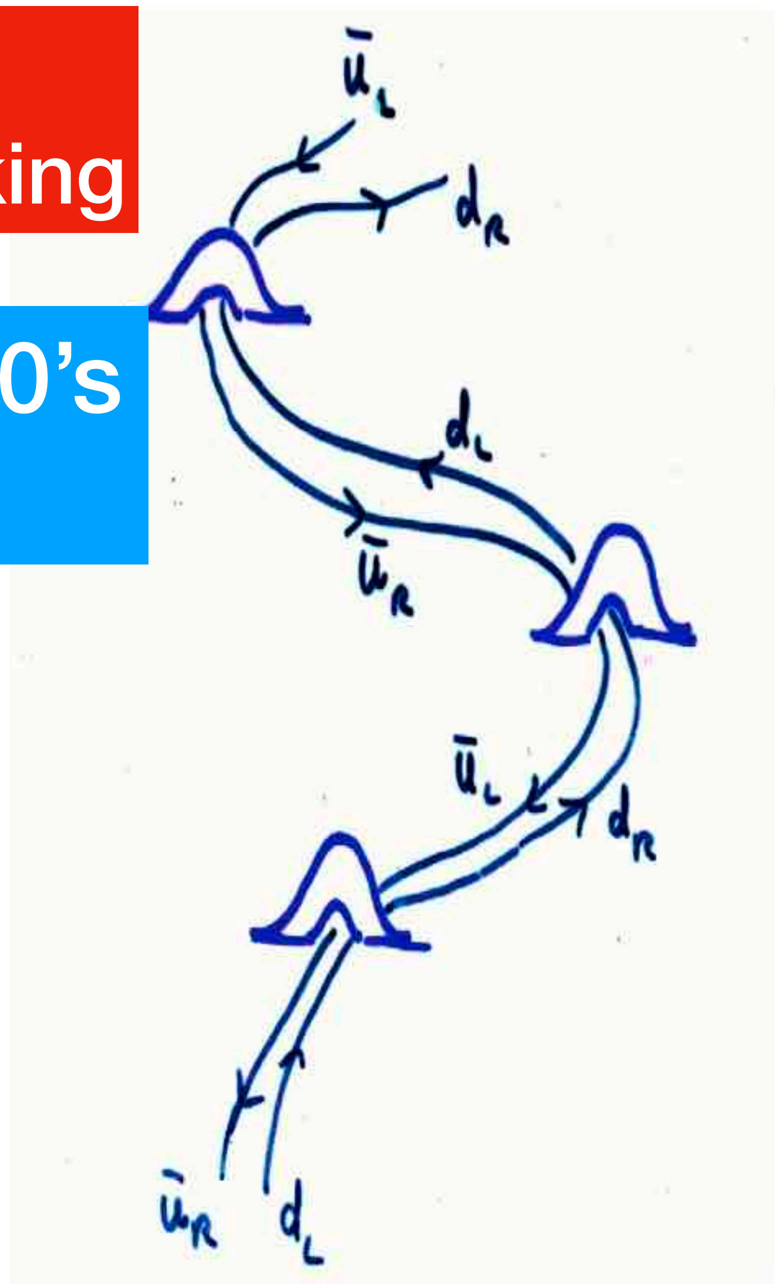
Instantons in the QCD VACUUM and HADRONS

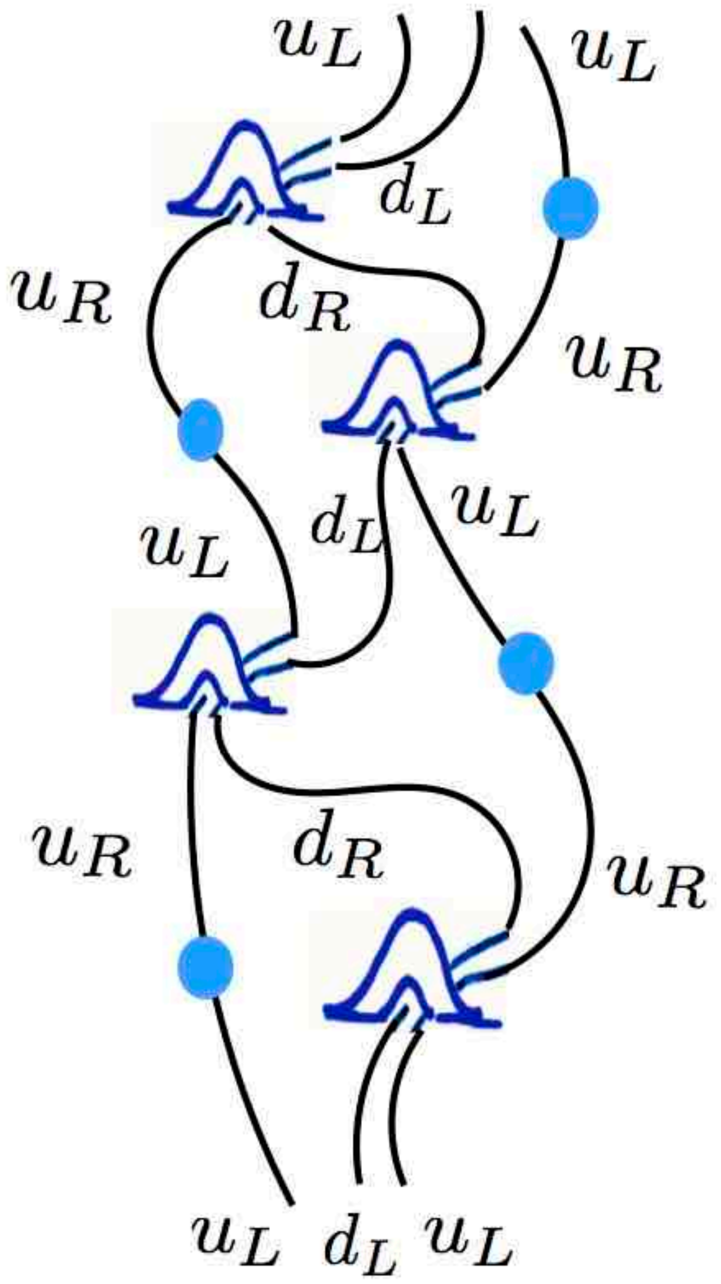
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

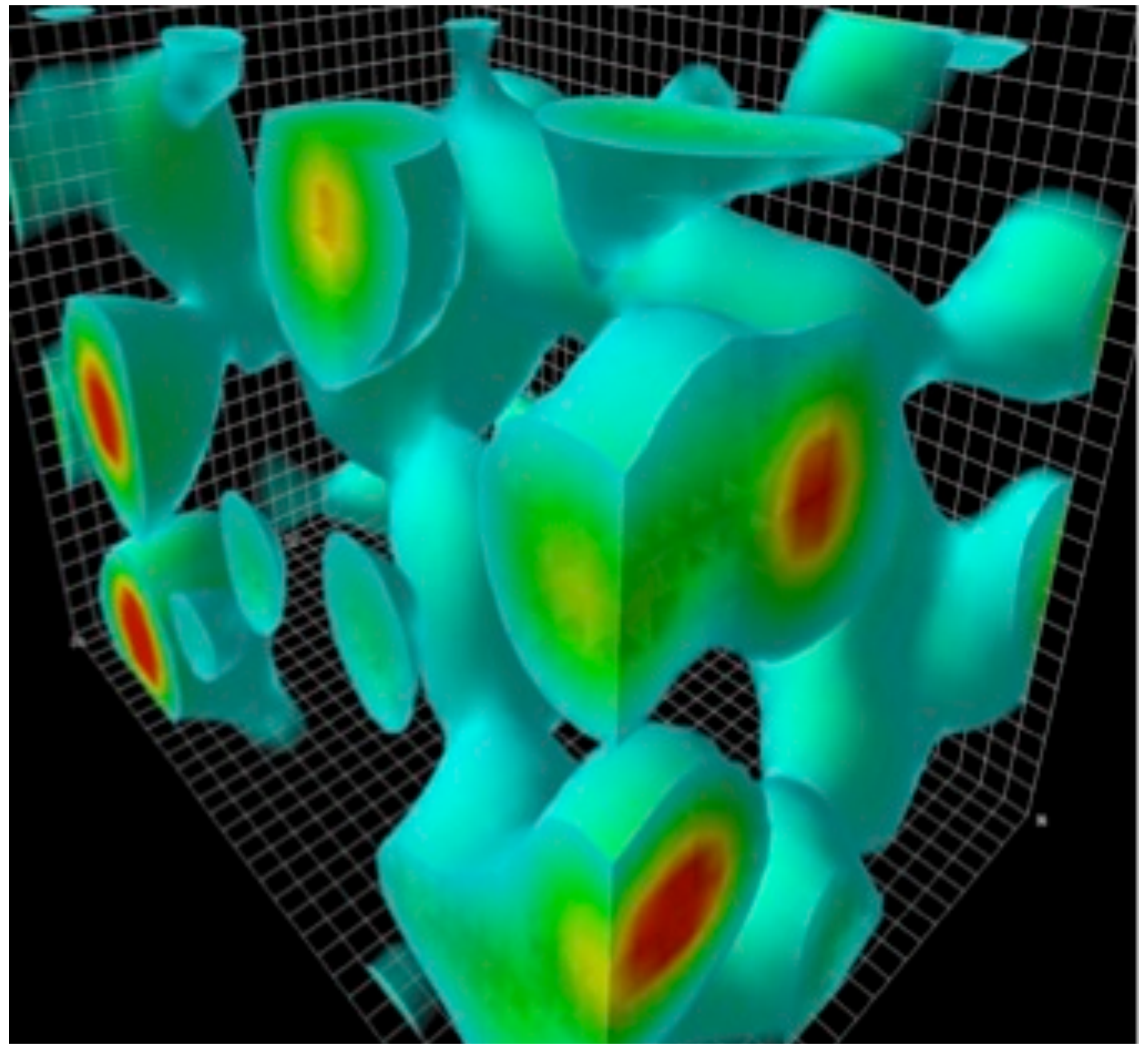
Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

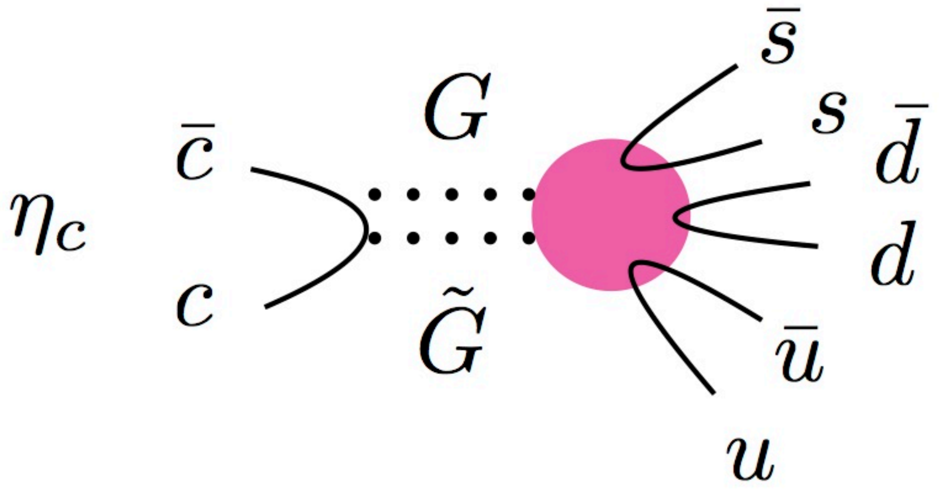
...







A snapshot of lattice G-dual G



hep-ph/0008048.

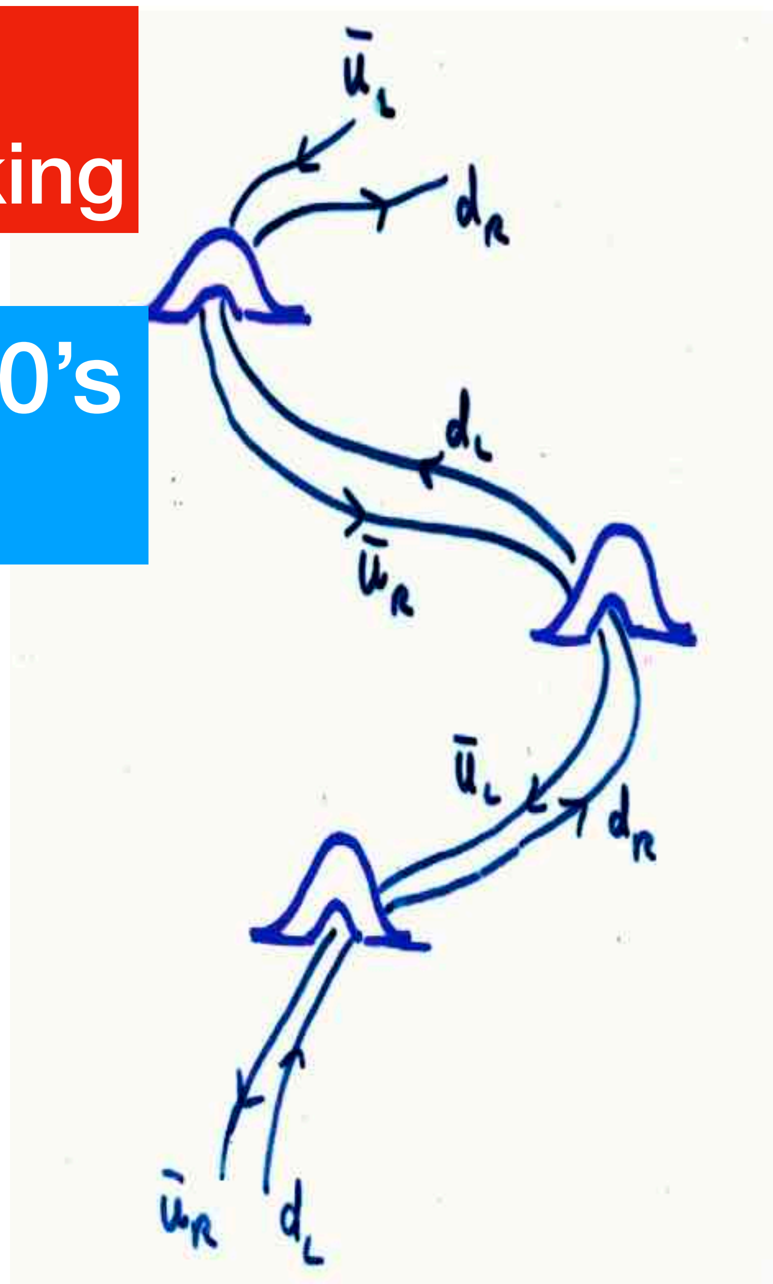
Instantons in the QCD VACUUM and HADRONS

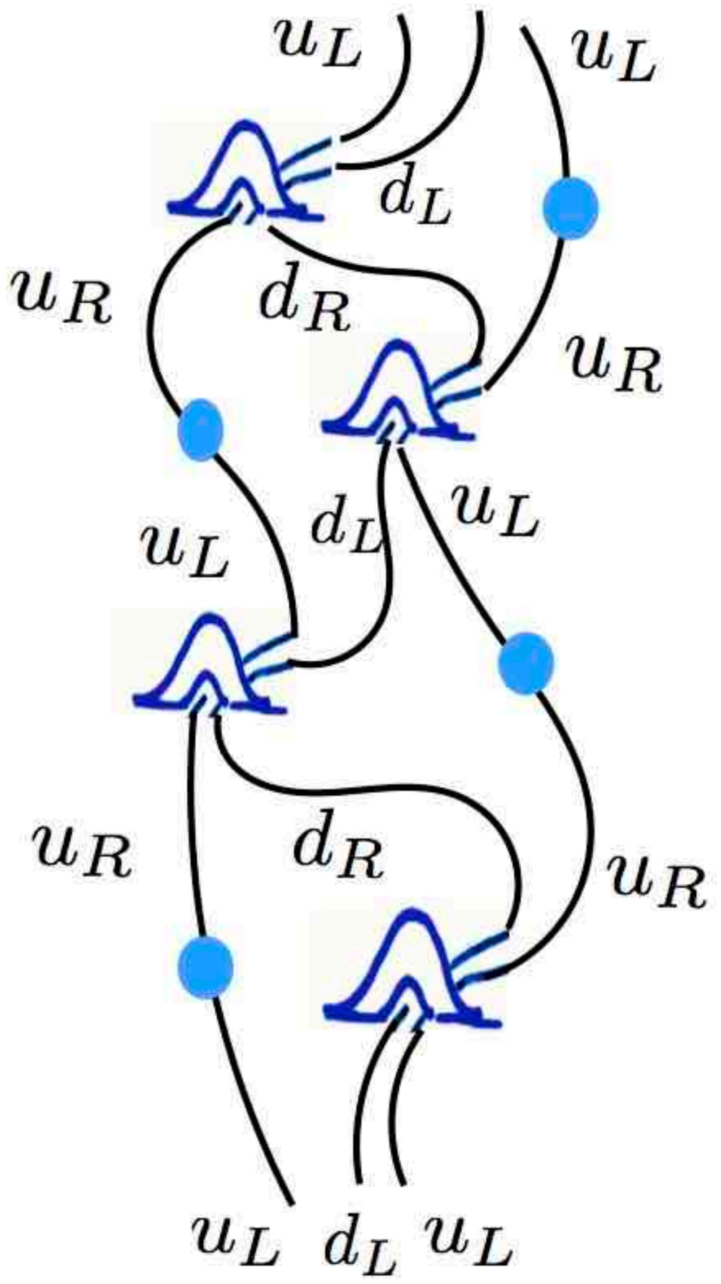
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

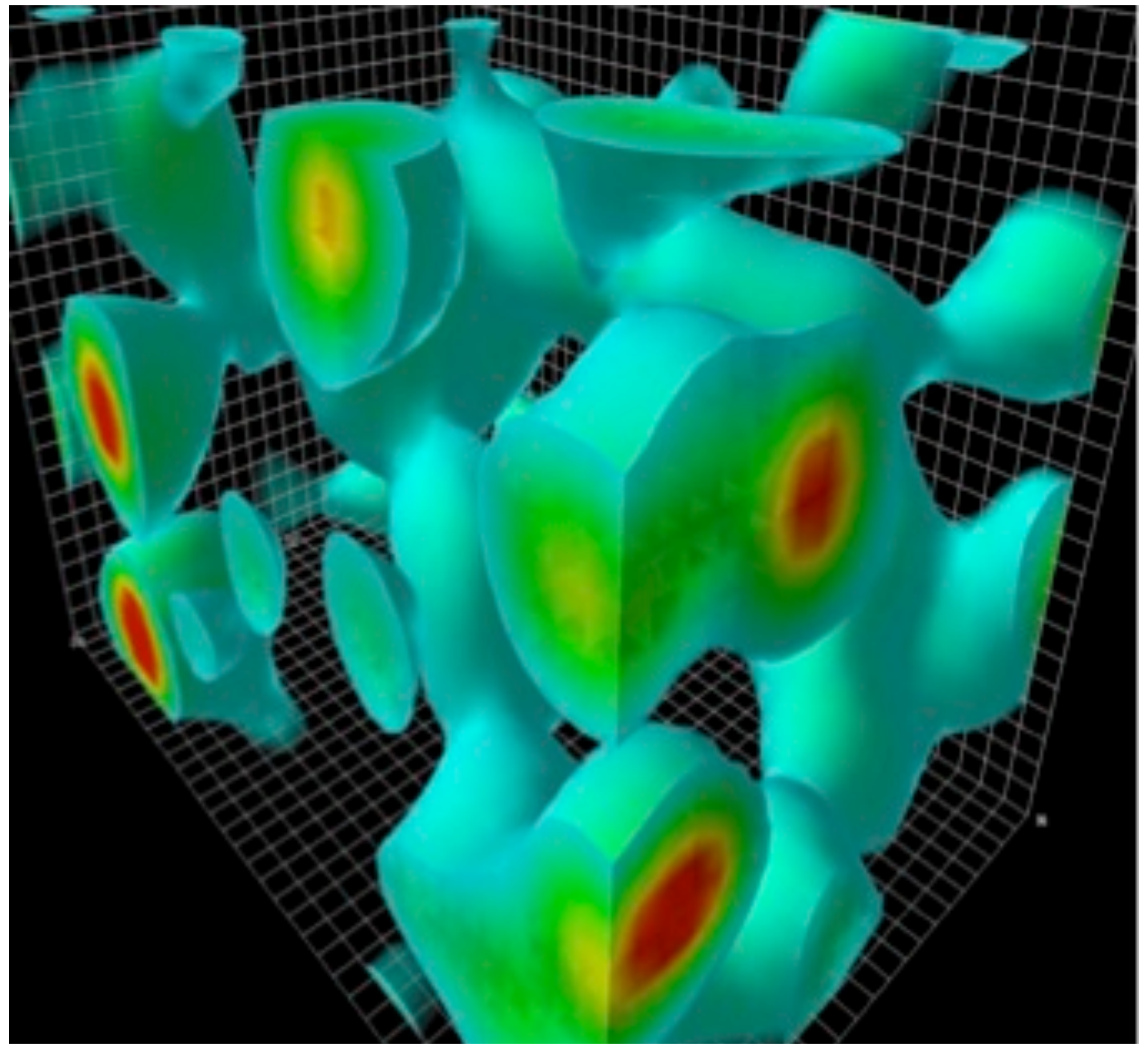
Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

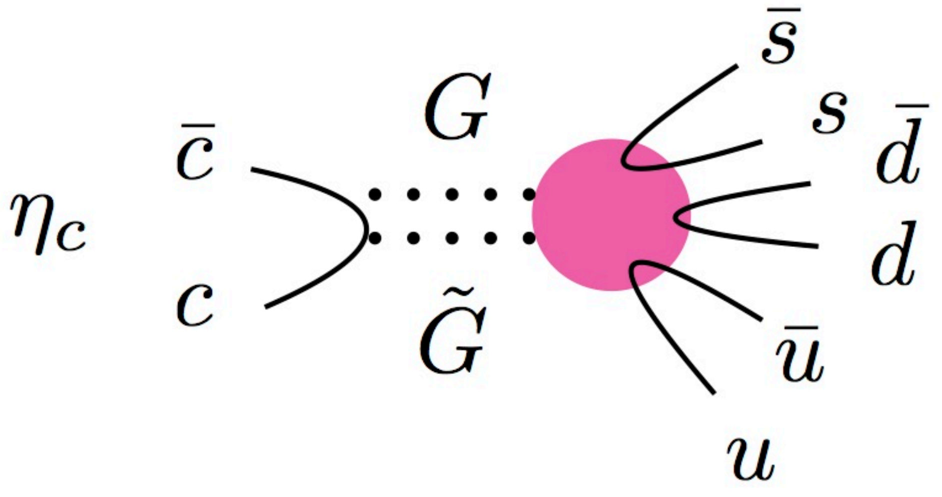
...







A snapshot of lattice G-dual G



$$\eta_c \to K K \pi; \;\; \pi\pi\eta; \;\; \pi\pi\eta'$$

hep-ph/0008048.

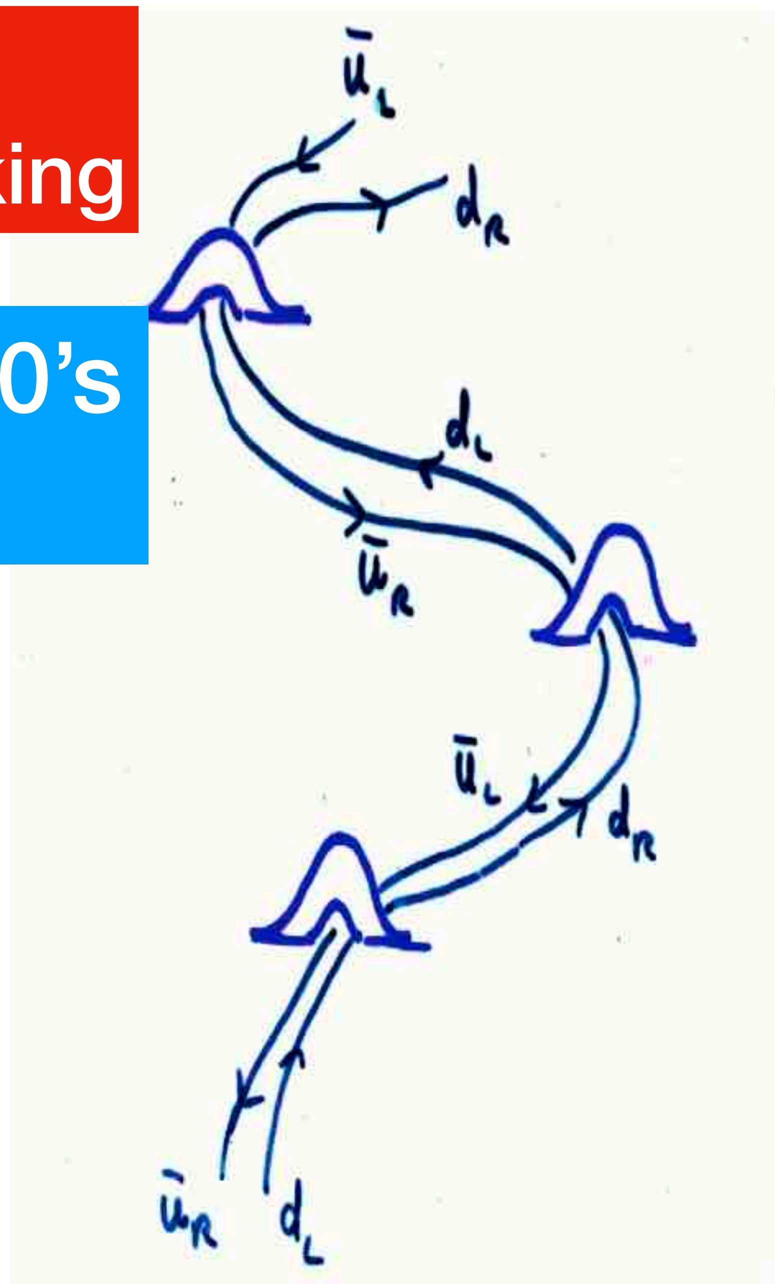
Instantons in the QCD VACUUM and HADRONS

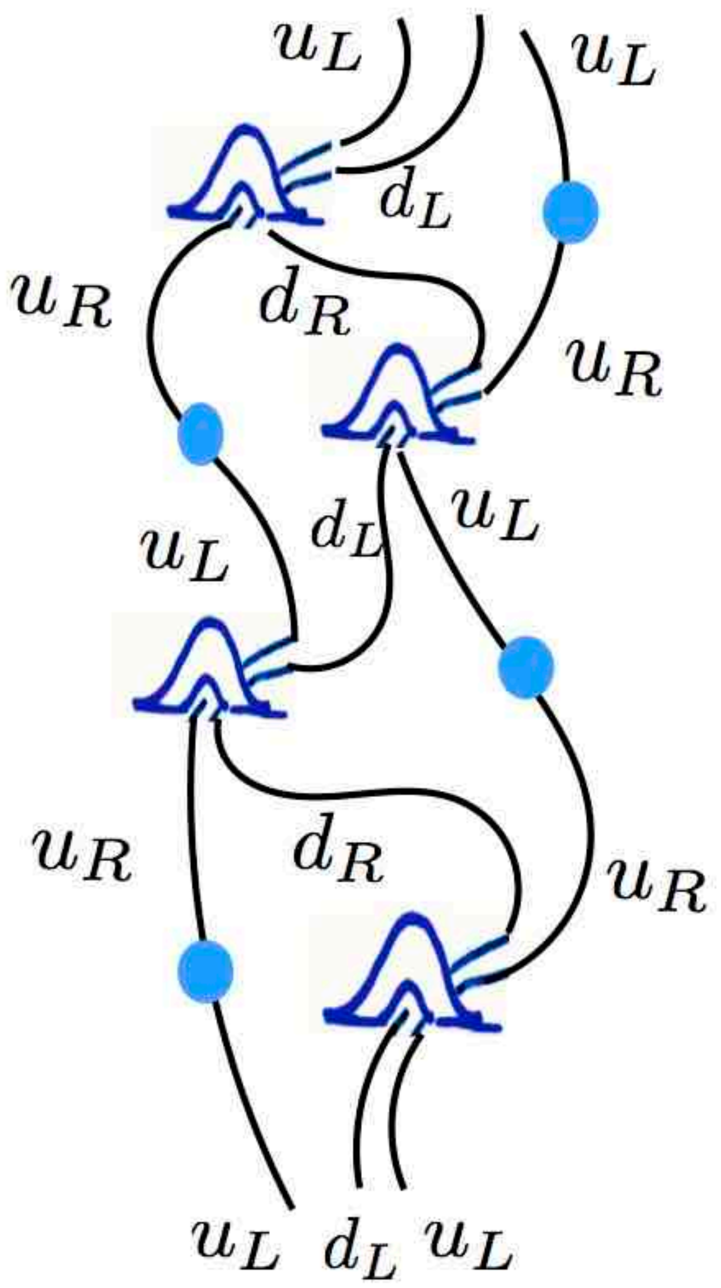
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

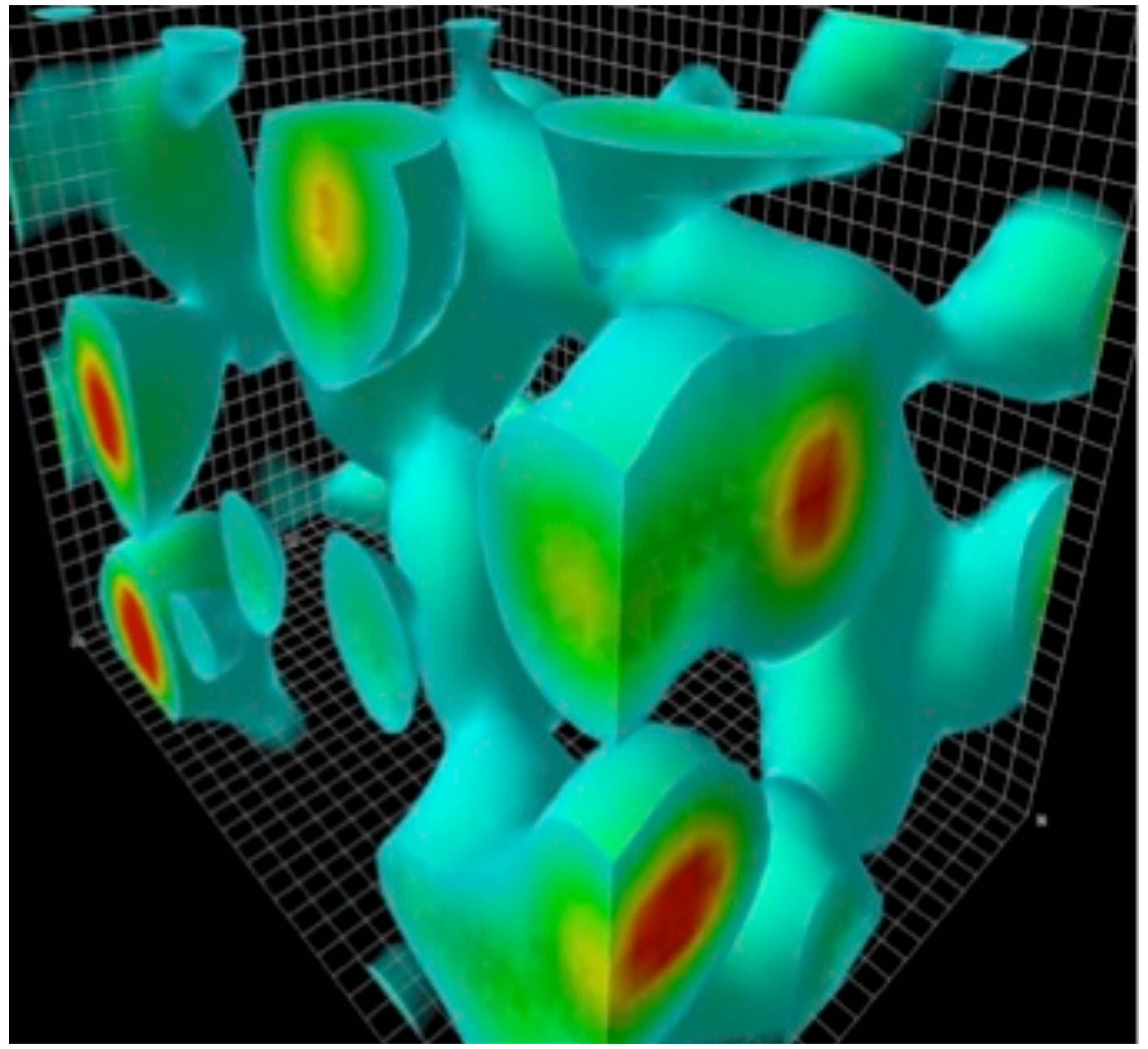
Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

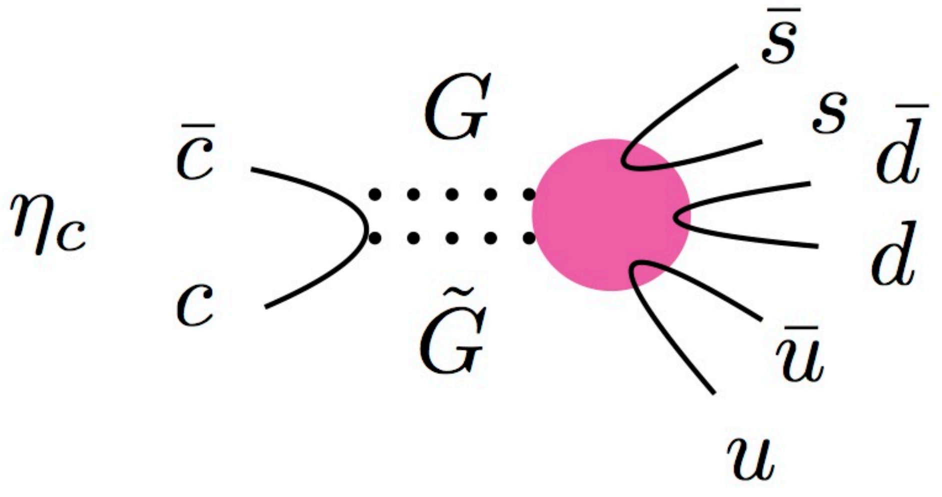
…







A snapshot of lattice G-dual G



$$\eta_c \to KK\pi;\ \ \pi\pi\eta;\ \ \pi\pi\eta'$$

hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

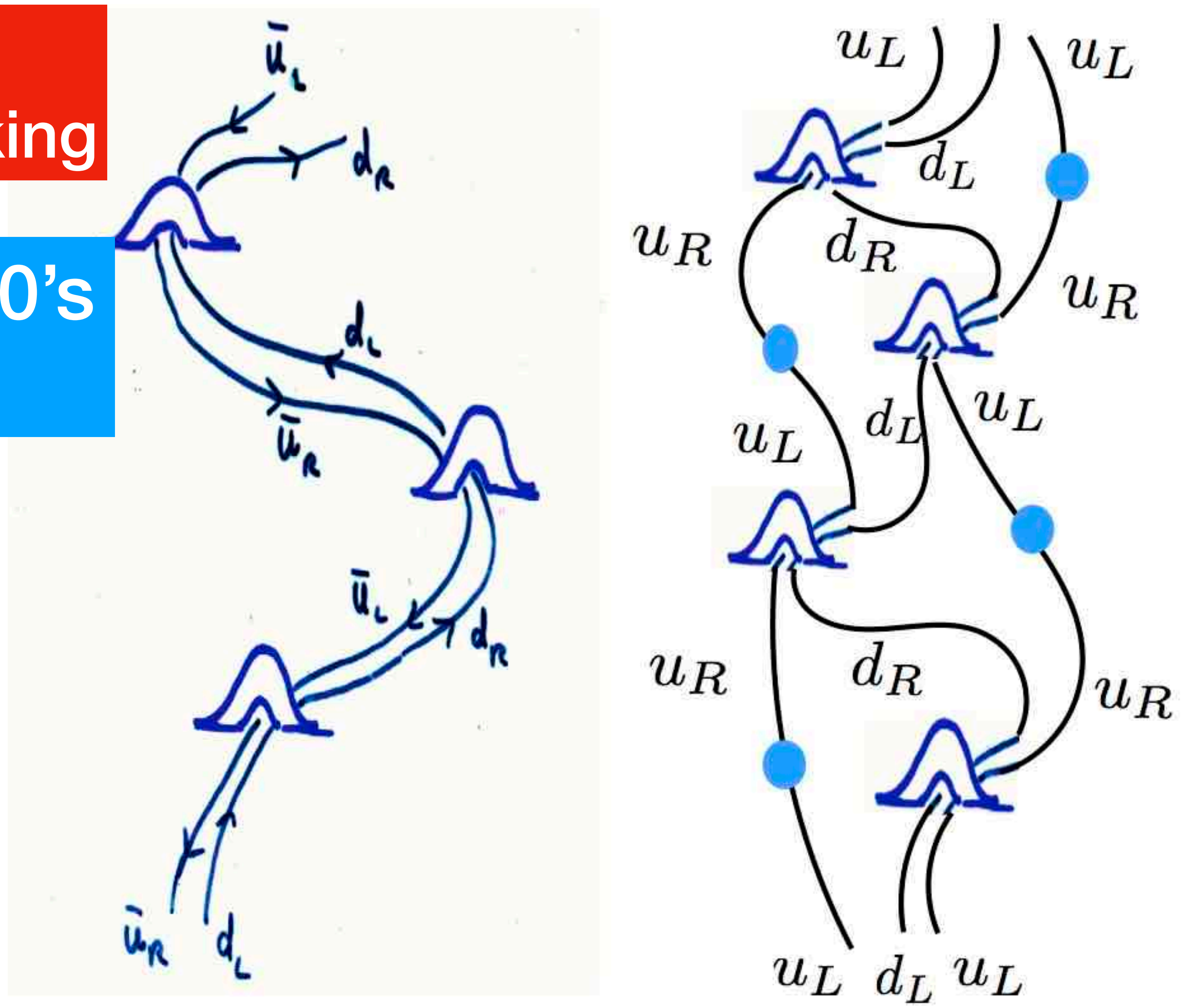
Instantons in the QCD VACUUM and HADRONS

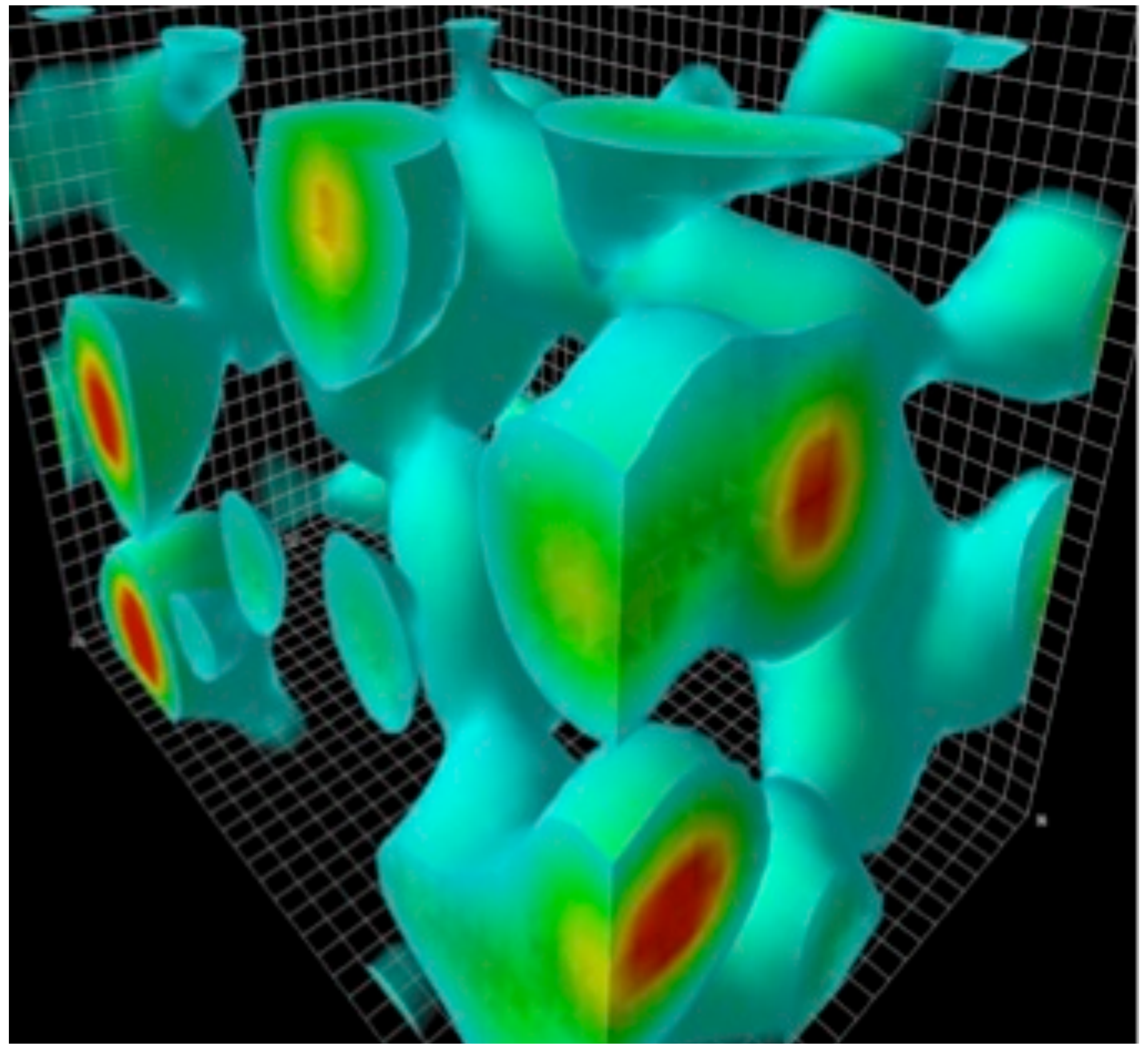
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

Interacting ensemble of instantons - 1990’s
Multiple correlation functions

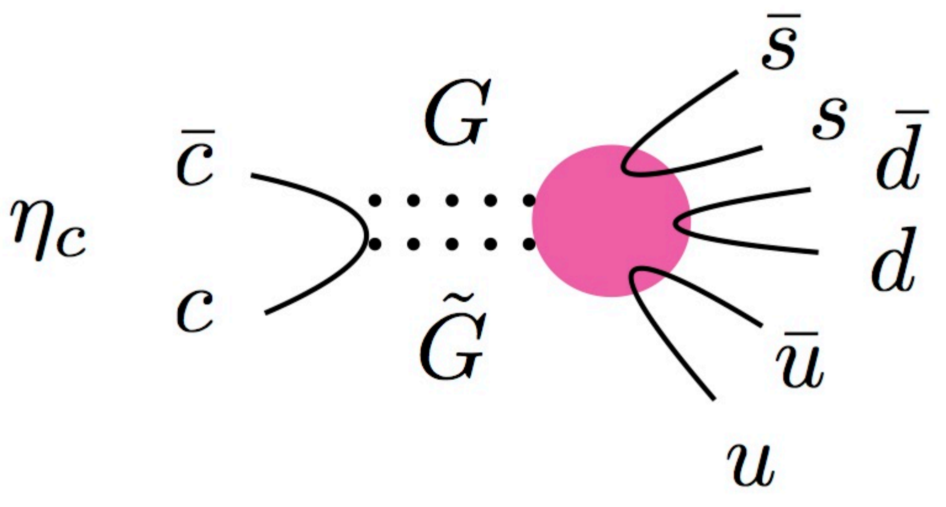
Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

...





A snapshot of lattice G-dual G



$\eta_c \to KK\pi;\quad \pi\pi\eta;\quad \pi\pi\eta'$ Bjorken, J. D hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

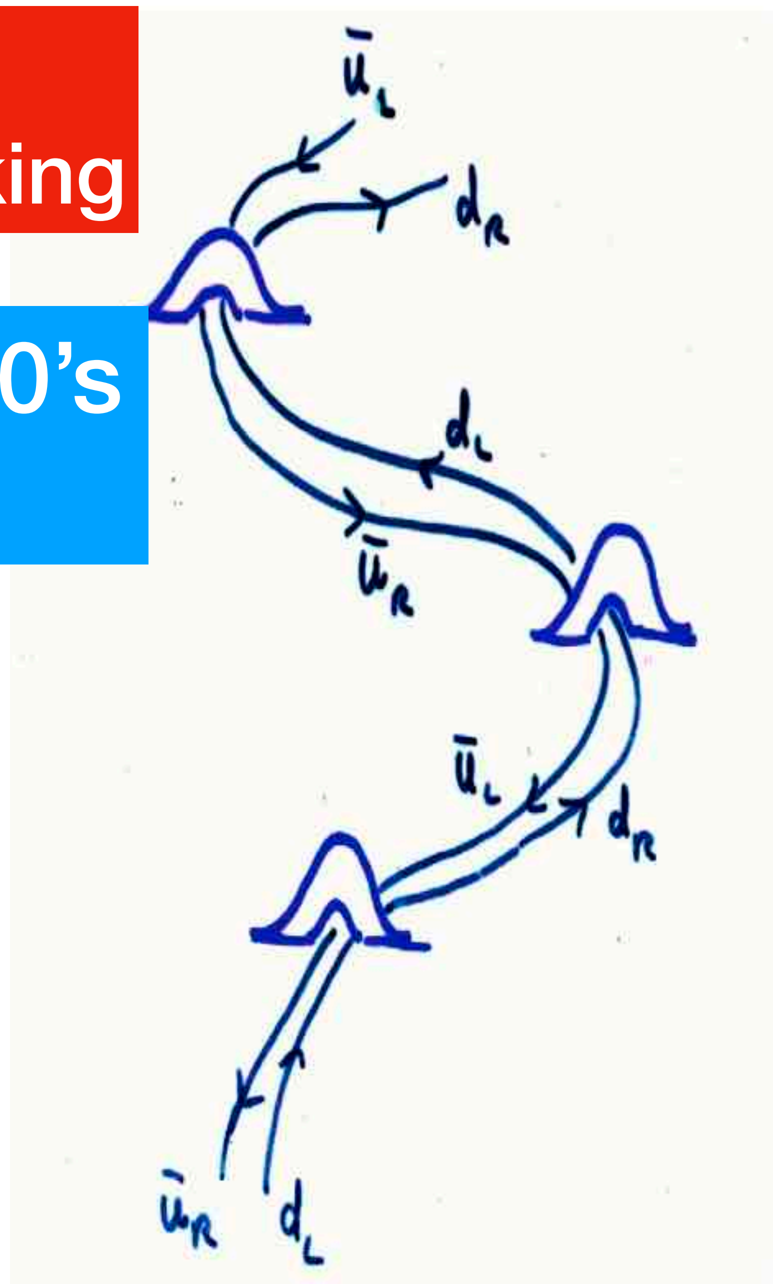
Instantons in the QCD VACUUM and HADRONS

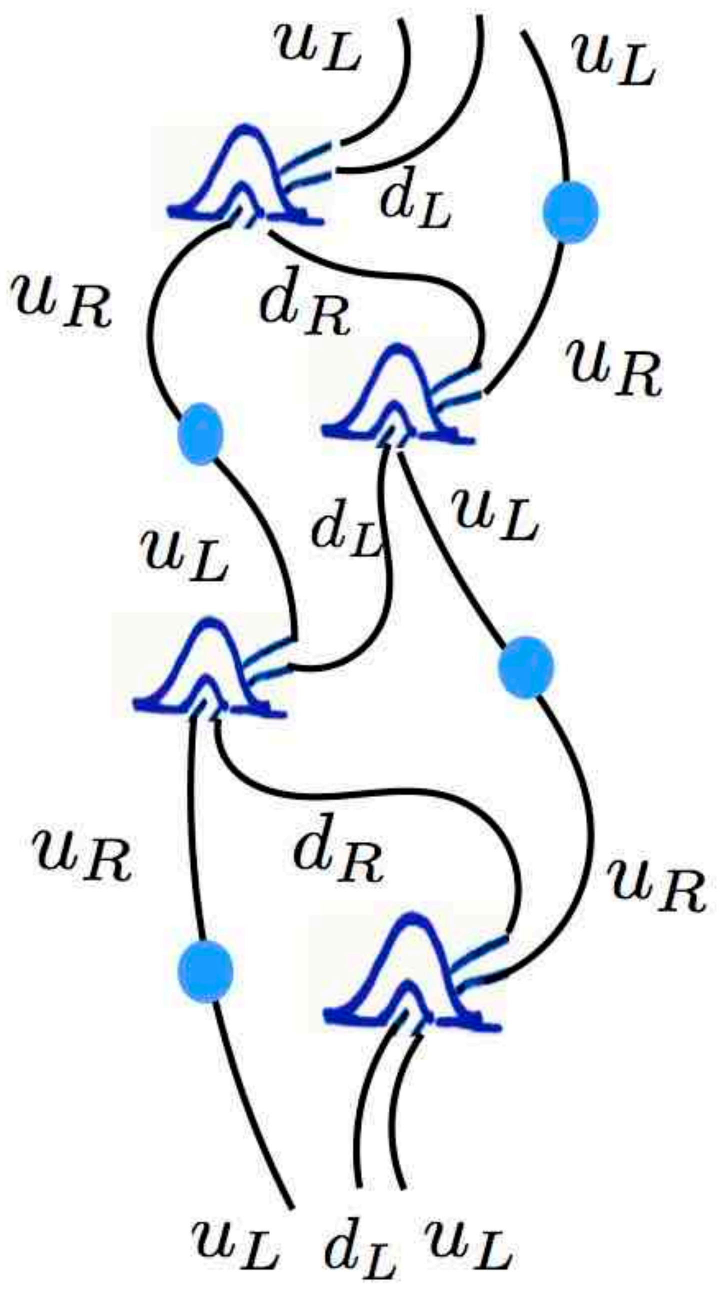
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

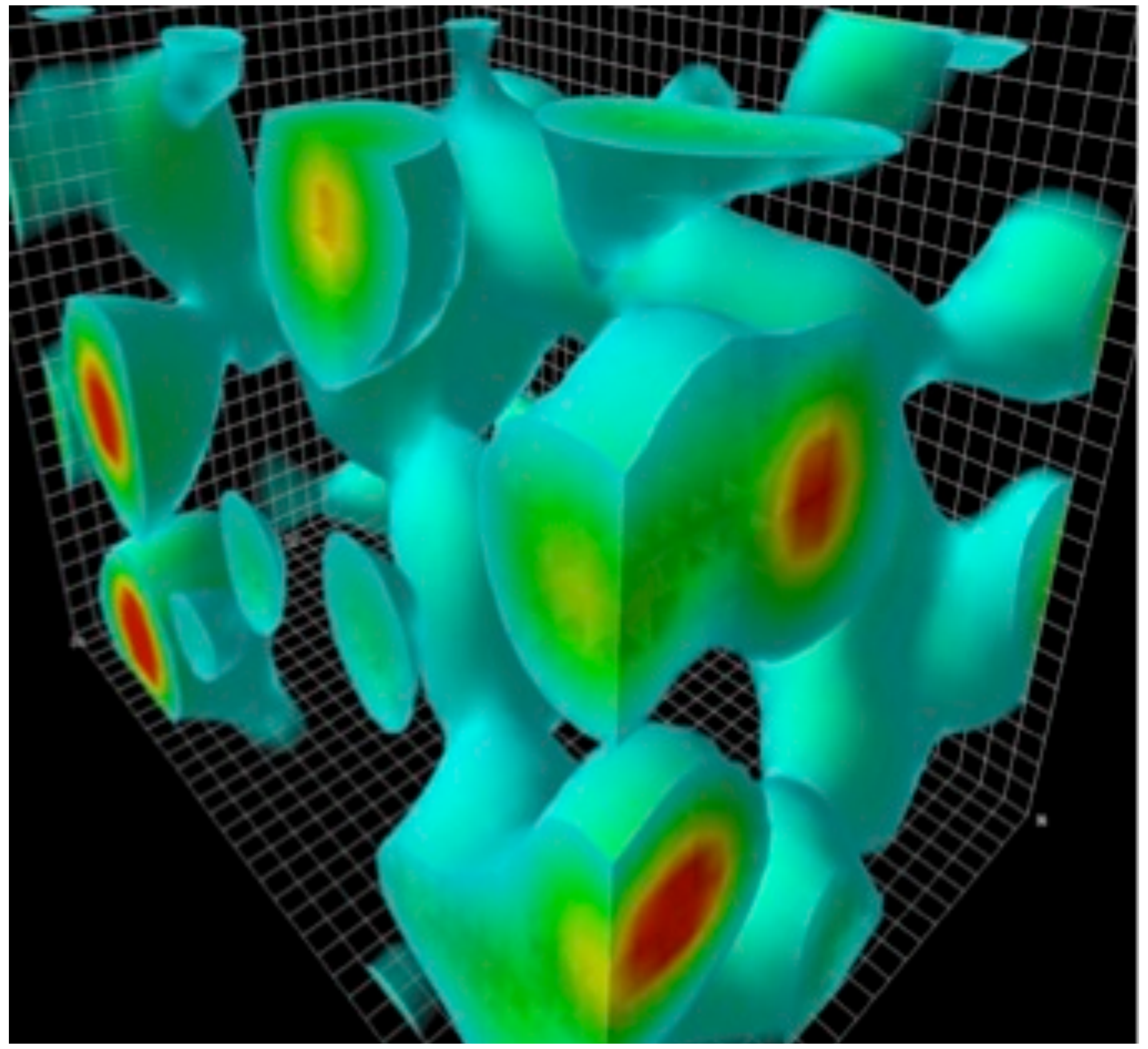
Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

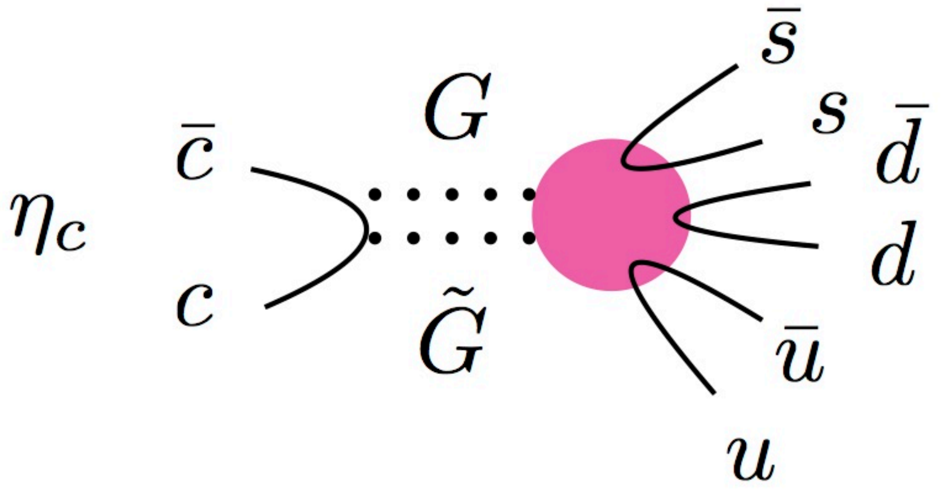
…







A snapshot of lattice G-dual G



$\eta_c \to KK\pi;\ \ \pi\pi\eta;\ \ \pi\pi\eta'$ Bjorken, J. D hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

Not seen in the control group
The J/psi decays

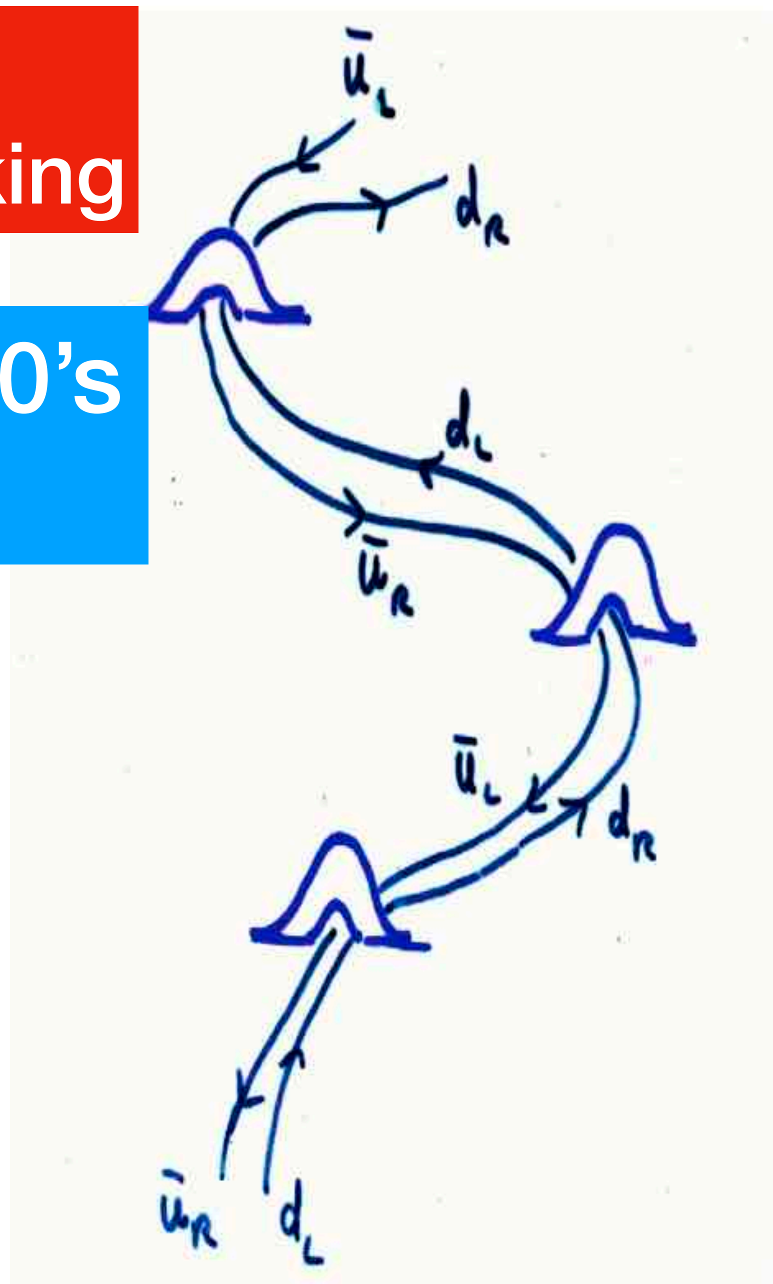
Instantons in the QCD VACUUM and HADRONS

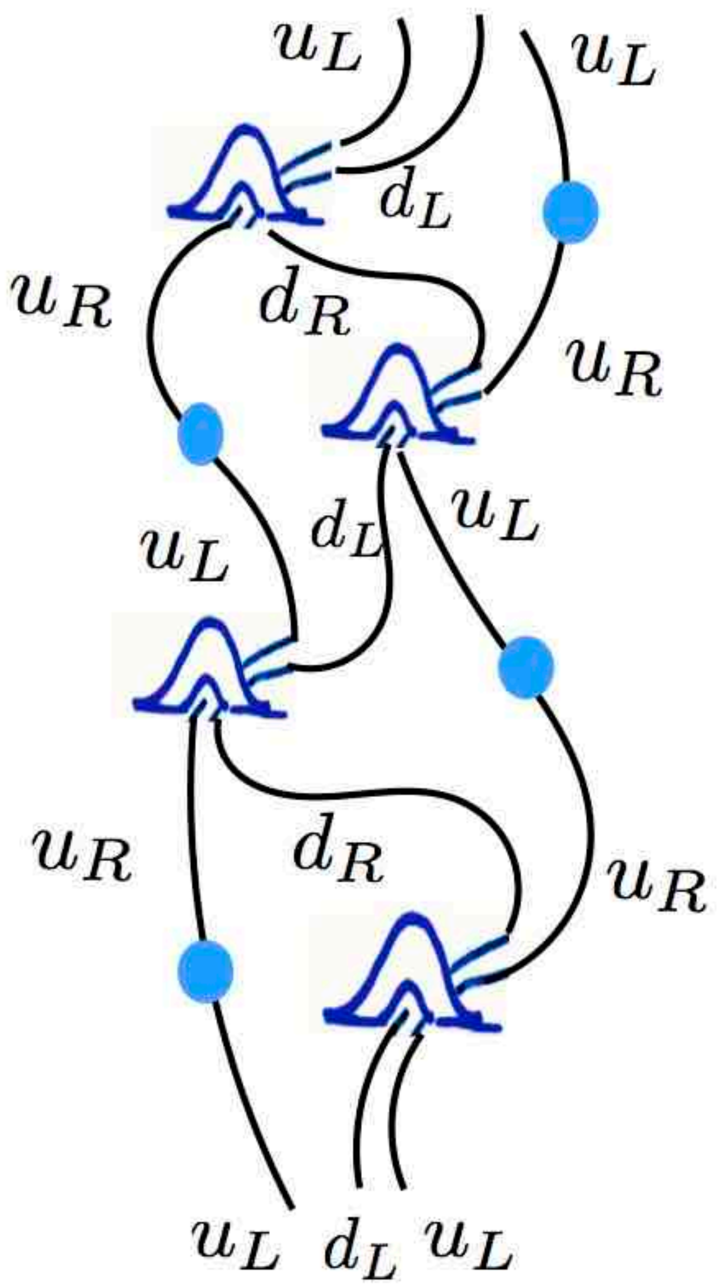
“Instanton liquid model” , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

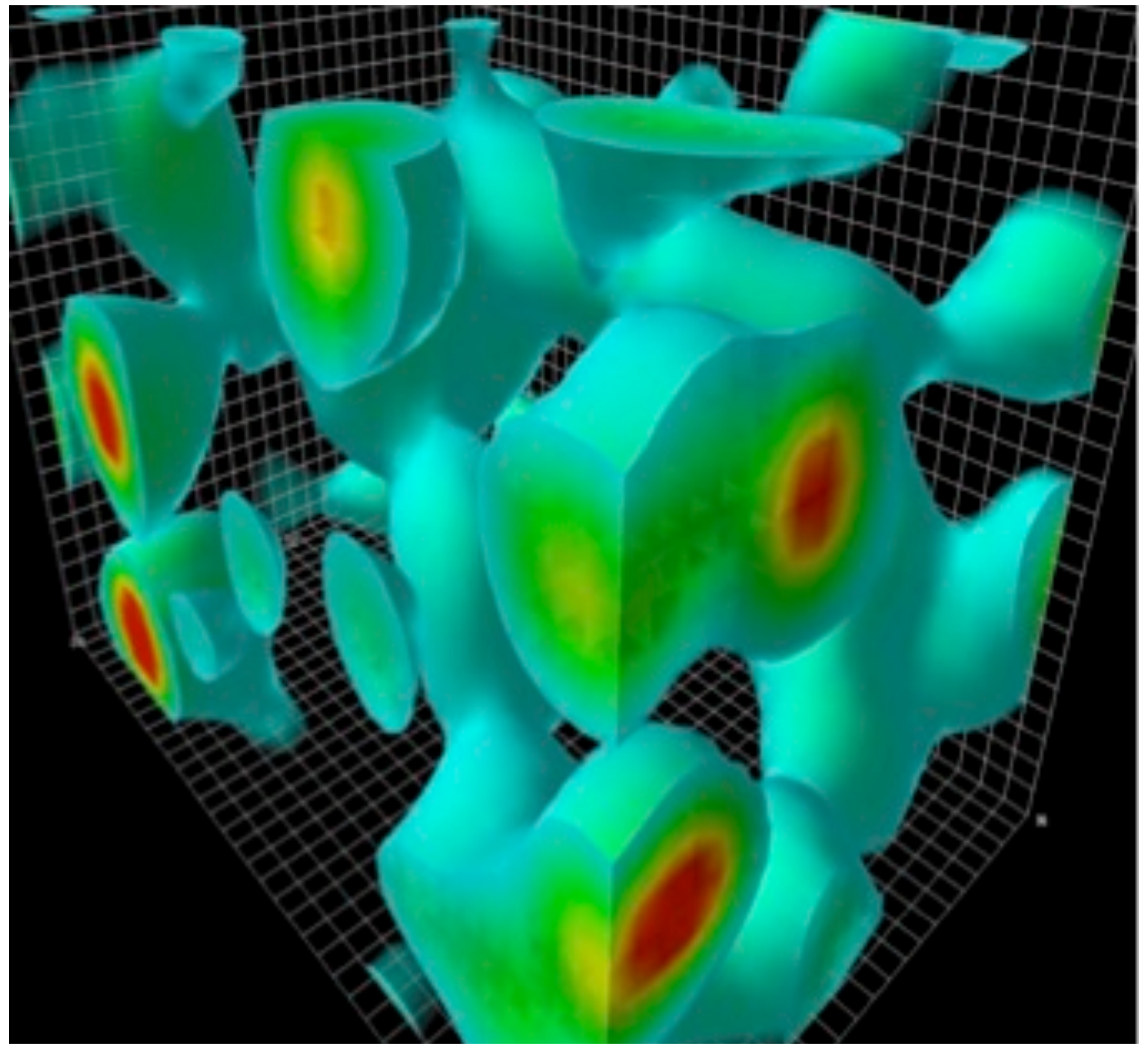
Interacting ensemble of instantons - 1990’s
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

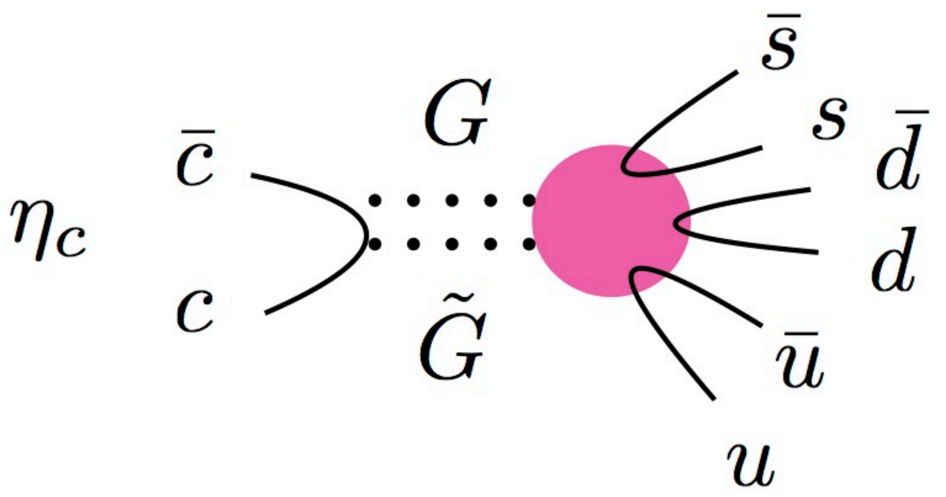
…







A snapshot of lattice G-dual G



$\eta_c \to KK\pi;\ \ \pi\pi\eta;\ \ \pi\pi\eta'$ Bjorken, J. D hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

Not seen in the control group
The J/psi decays

Zetocha, V. and Schafer, T. (2003). Instanton contribution to scalar charmonium and glueball decays. Phys. Rev., D67:114003. hep-ph/0212125.

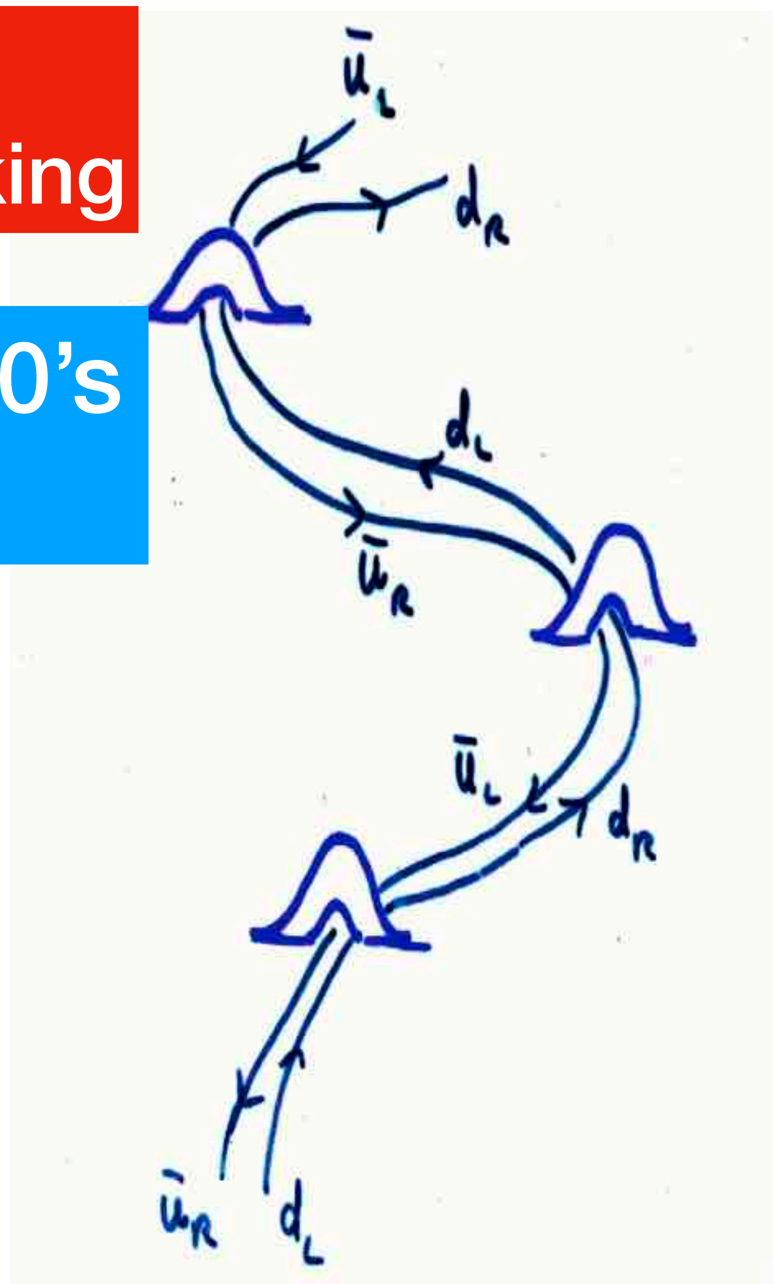
Instantons in the QCD VACUUM and HADRONS

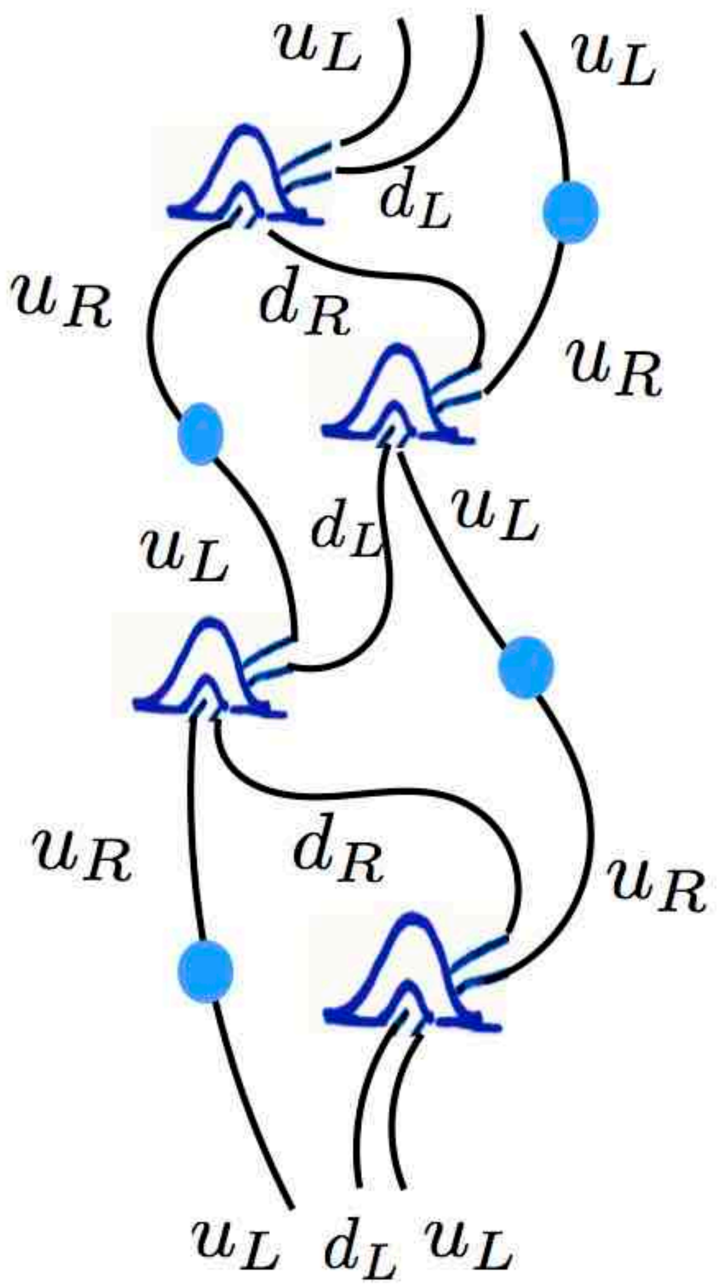
"Instanton liquid model" , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

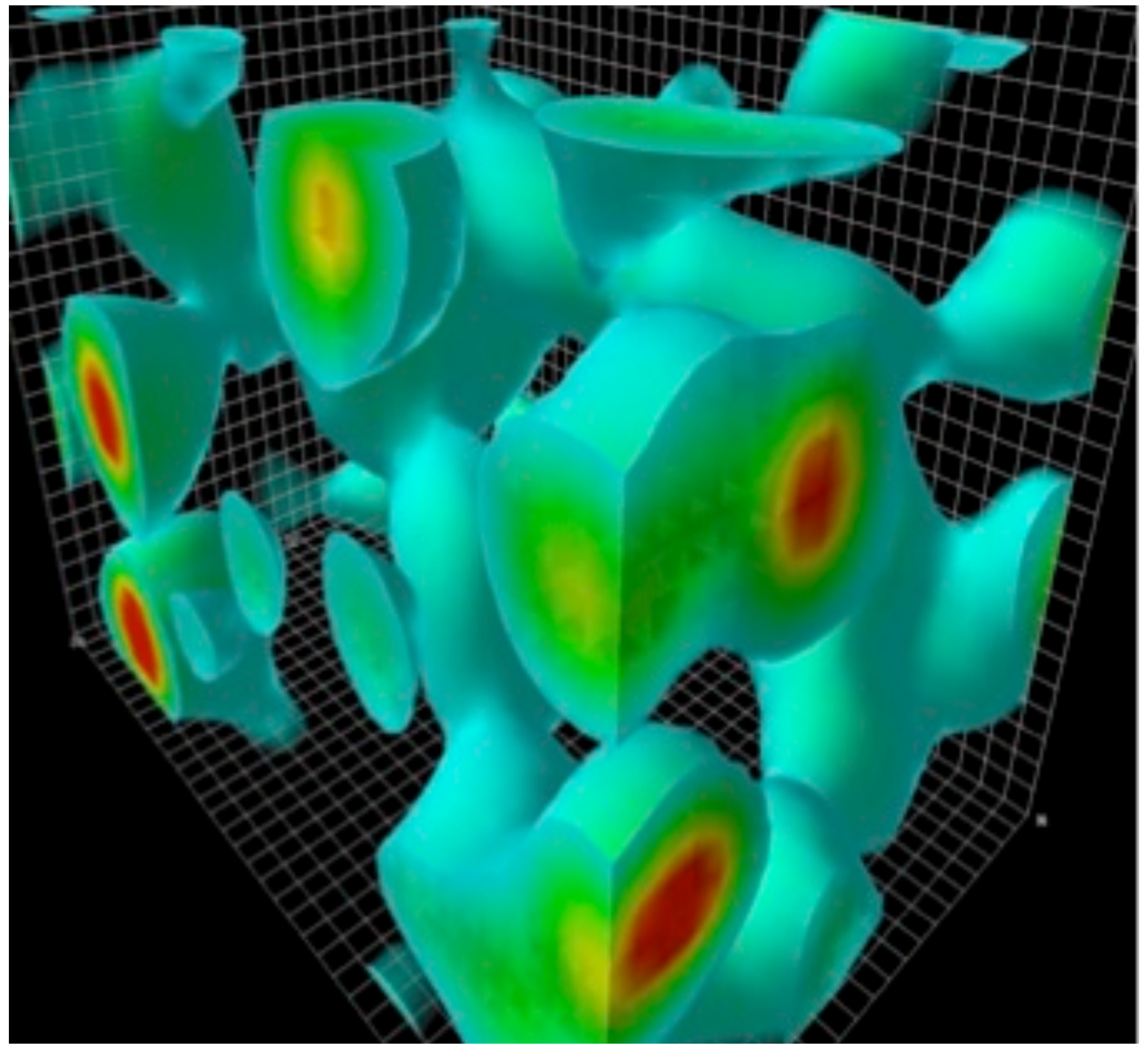
Interacting ensemble of instantons - 1990's
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

...

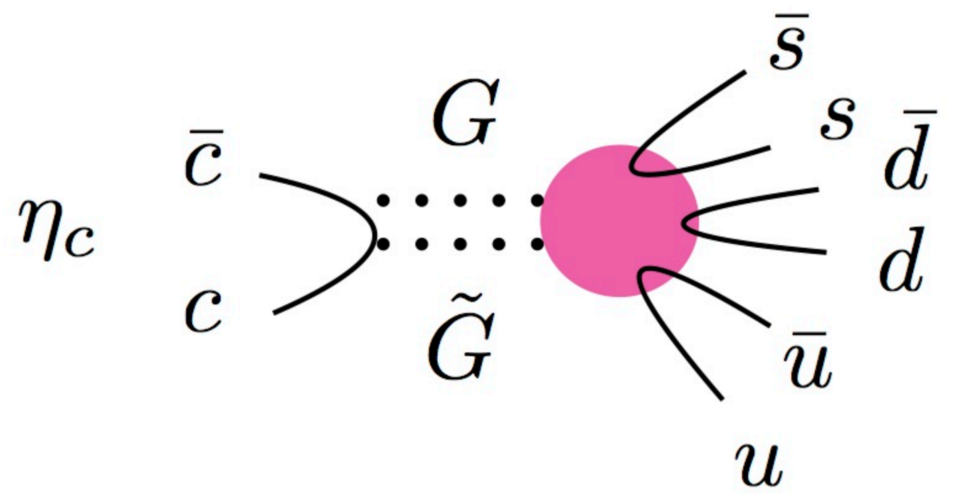






A snapshot of lattice G-dual G

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



$\eta_c \to KK\pi;\ \ \pi\pi\eta;\ \ \pi\pi\eta'$ Bjorken, J. D hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

Not seen in the control group
The J/psi decays

Zetocha, V. and Schafer, T. (2003). Instanton contribution to scalar charmonium and glueball decays. Phys. Rev., D67:114003. hep-ph/0212125.

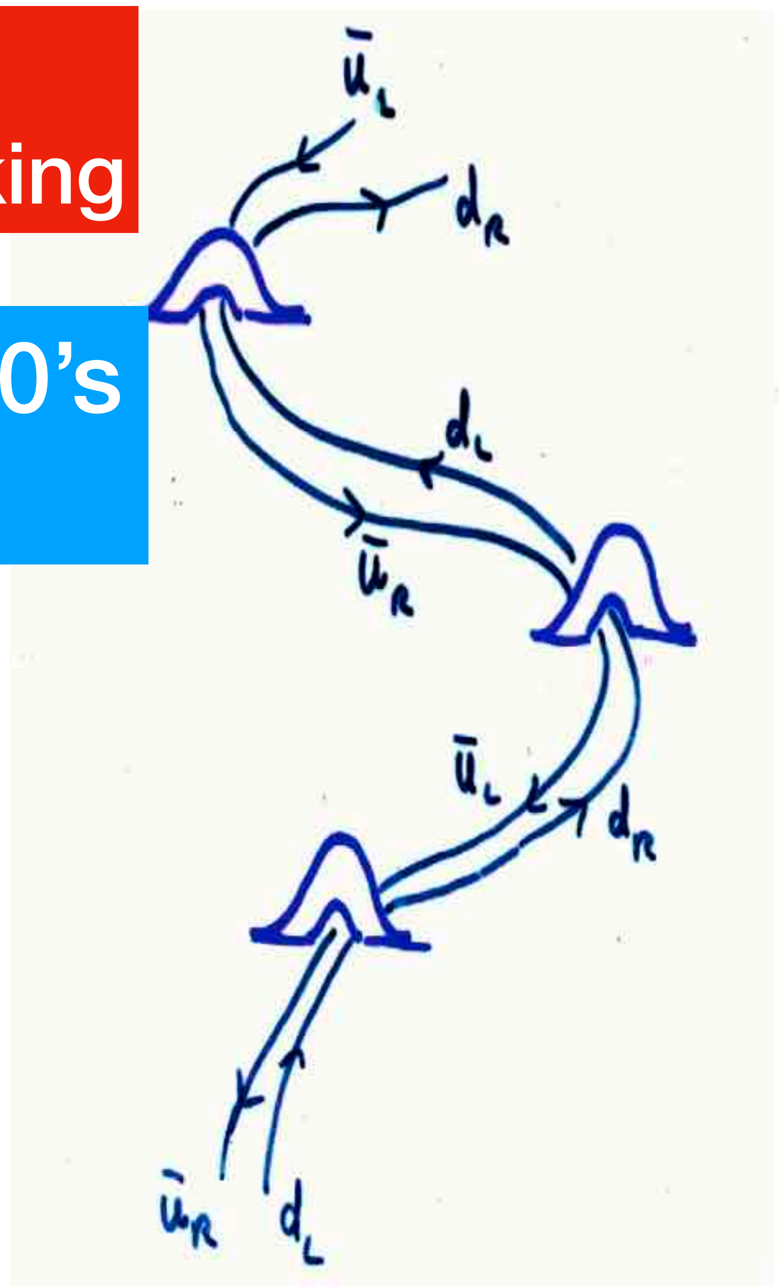
Instantons in the QCD VACUUM and HADRONS

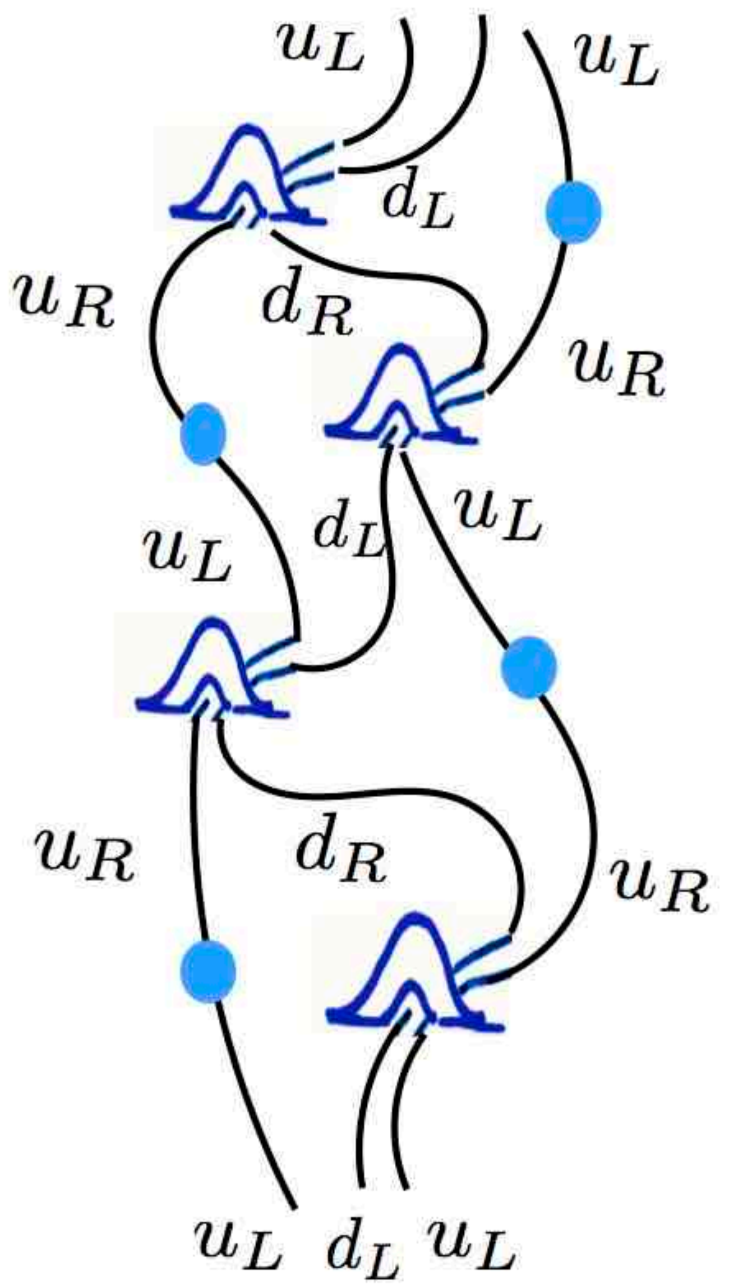
"Instanton liquid model" , Shuryak, 1981
n=1/fm^4, rho=1/3 fm => chiral symmetry breaking

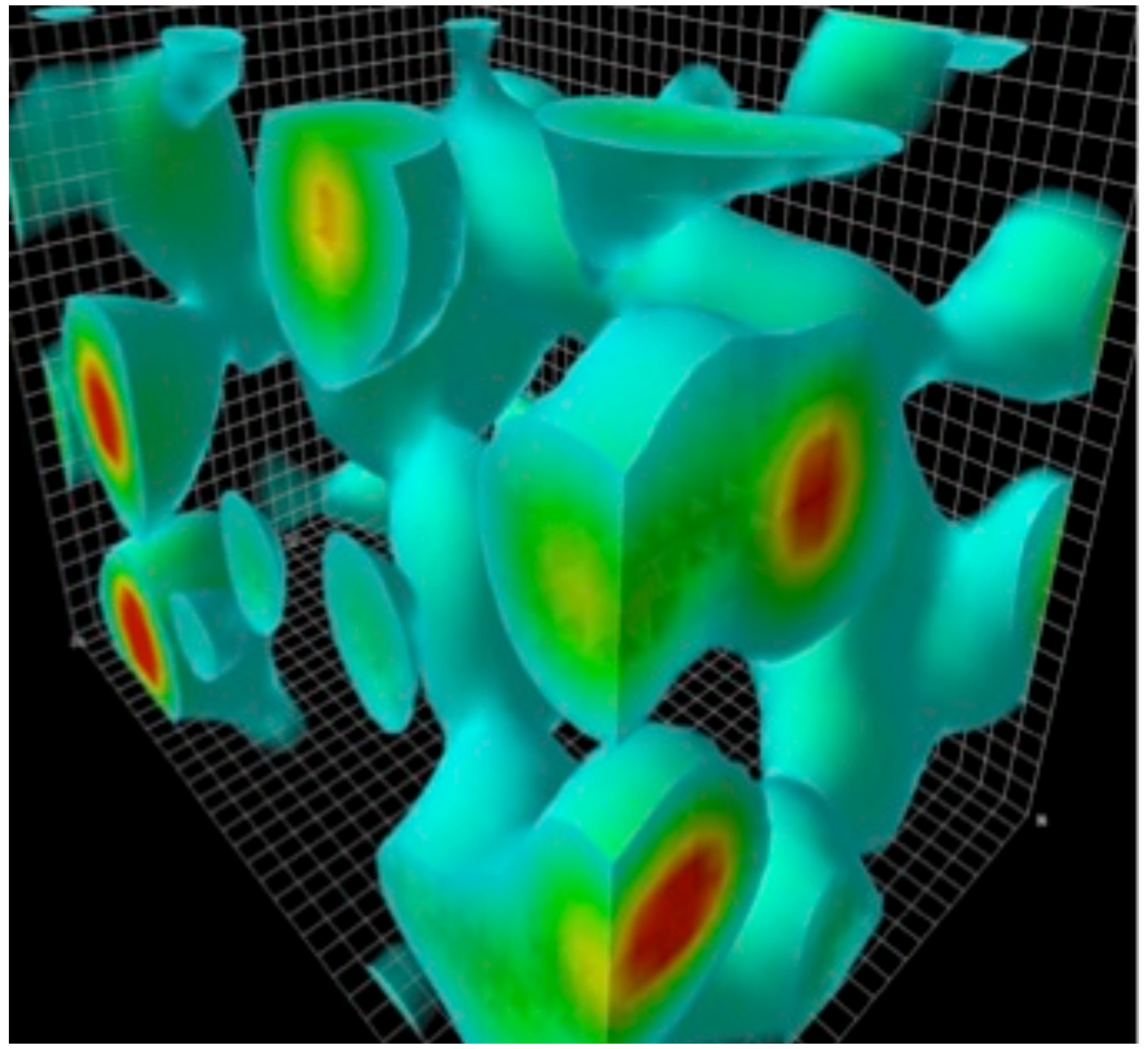
Interacting ensemble of instantons - 1990's
Multiple correlation functions

Diquark formation inside nucleons
(but not Deltas)
Color superconductivity 1998

...



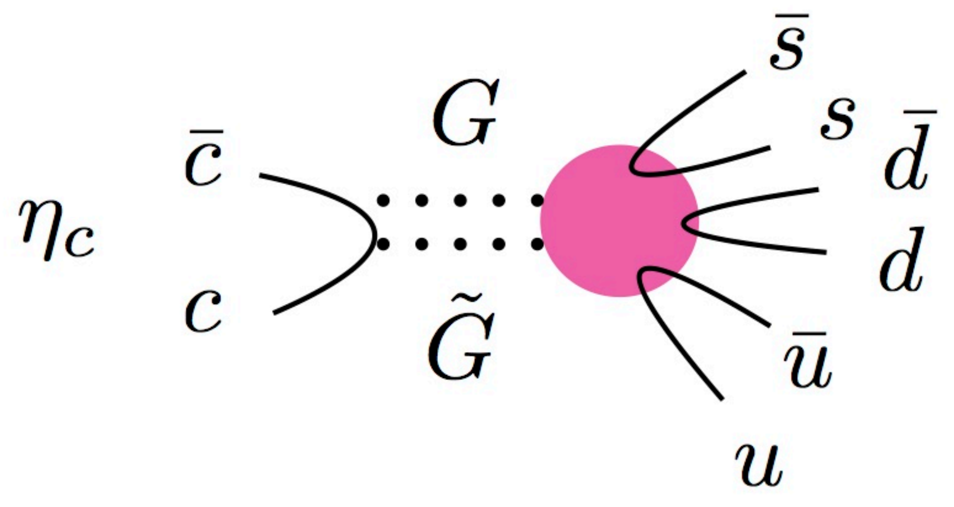




A snapshot of lattice G-dual G

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

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



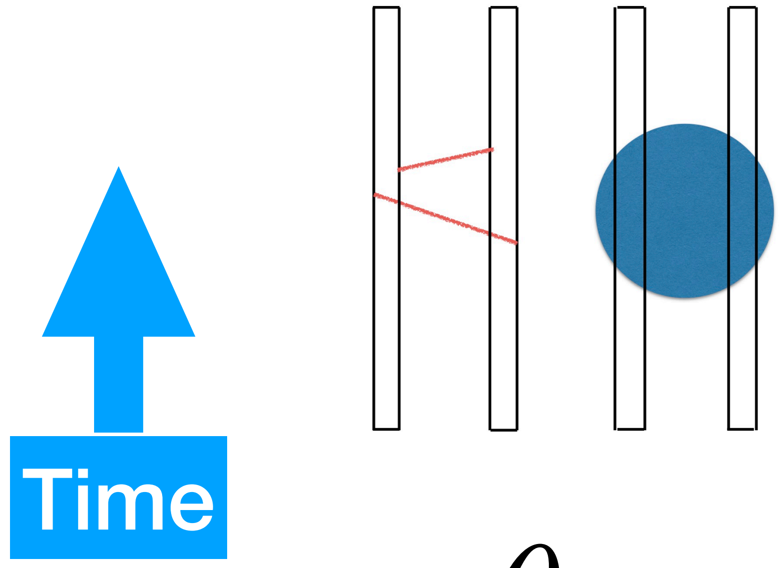
$\eta_c \to KK\pi;\ \ \pi\pi\eta;\ \ \pi\pi\eta'$ Bjorken, J. D hep-ph/0008048.

But no pi,pi,pi or other 3-body decays

Not seen in the control group
The J/psi decays

Zetocha, V. and Schafer, T. (2003). Instanton contribution to scalar charmonium and glueball decays. Phys. Rev., D67:114003. hep-ph/0212125.

Instanton-induced elastic dipole-dipole high energy scattering

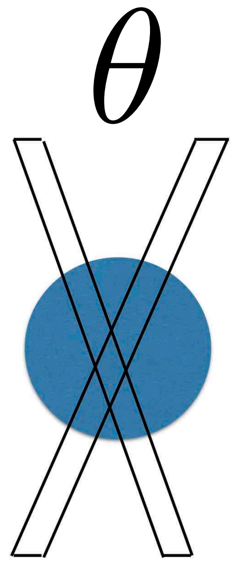


$$\langle \vec{E}^2(\tau_1)\vec{E}^2(\tau_2)\rangle \sim \frac{1}{[R^2+(\tau_1-\tau_2)^2]^4}$$

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



$$\theta \rightarrow iy$$

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*.

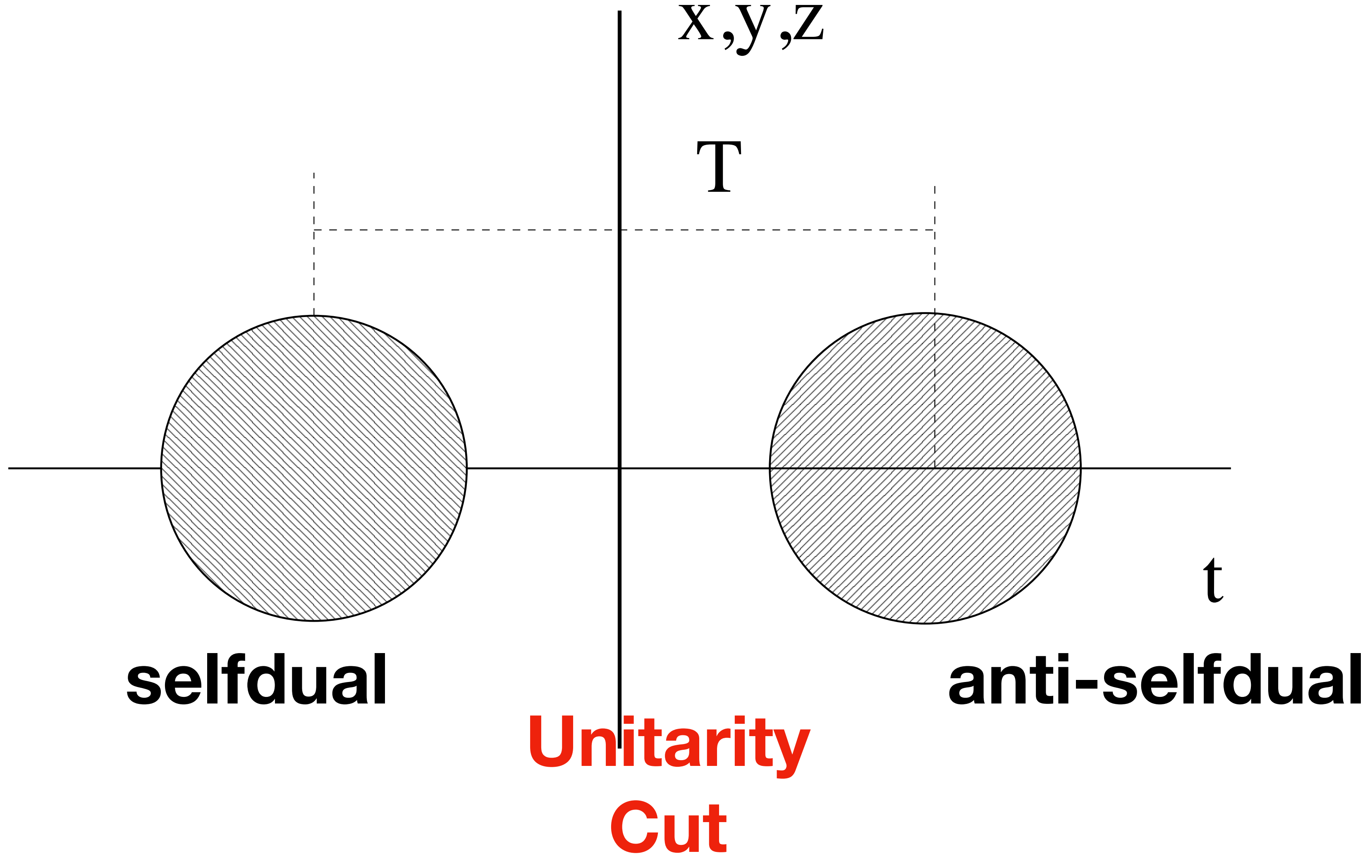
Istead of showing complicated formulae
Let me just say the cross section is larger
than 2-gluon change

sphaleron path configurations 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)



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

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

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!

sphaleron path configurations were historically derived in three different ways.

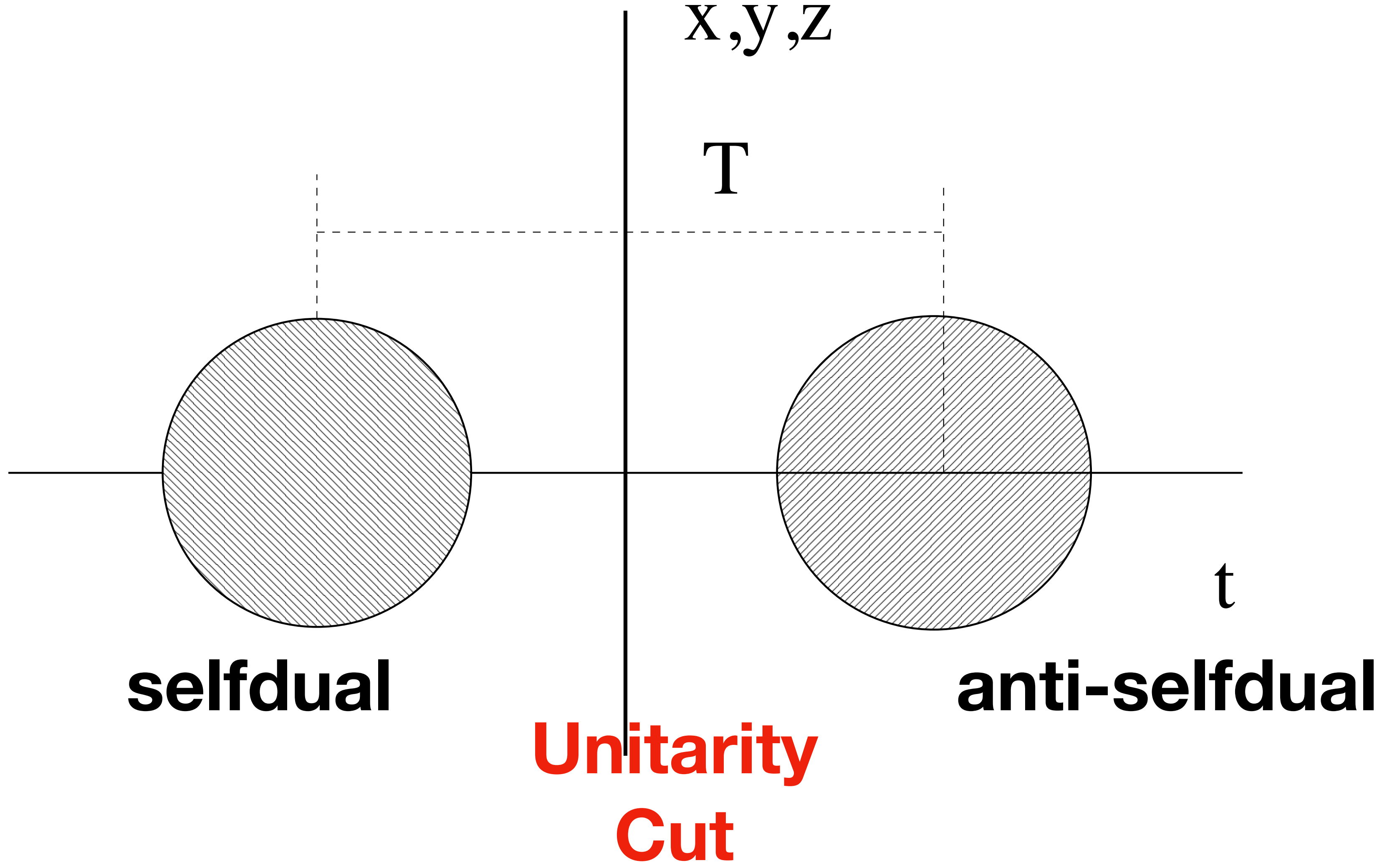
Here is number 1: reduction to 3d from 4d instanton-antiinstanton configuration

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)

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!



selfdual

anti-selfdual

Unitarity
Cut

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

Superposition of I and anti-I has
its own history,
1983``streamline configurations”for double well
Balitsky+Yung, streamline eon
Now we know they are “Lefschits timbles”

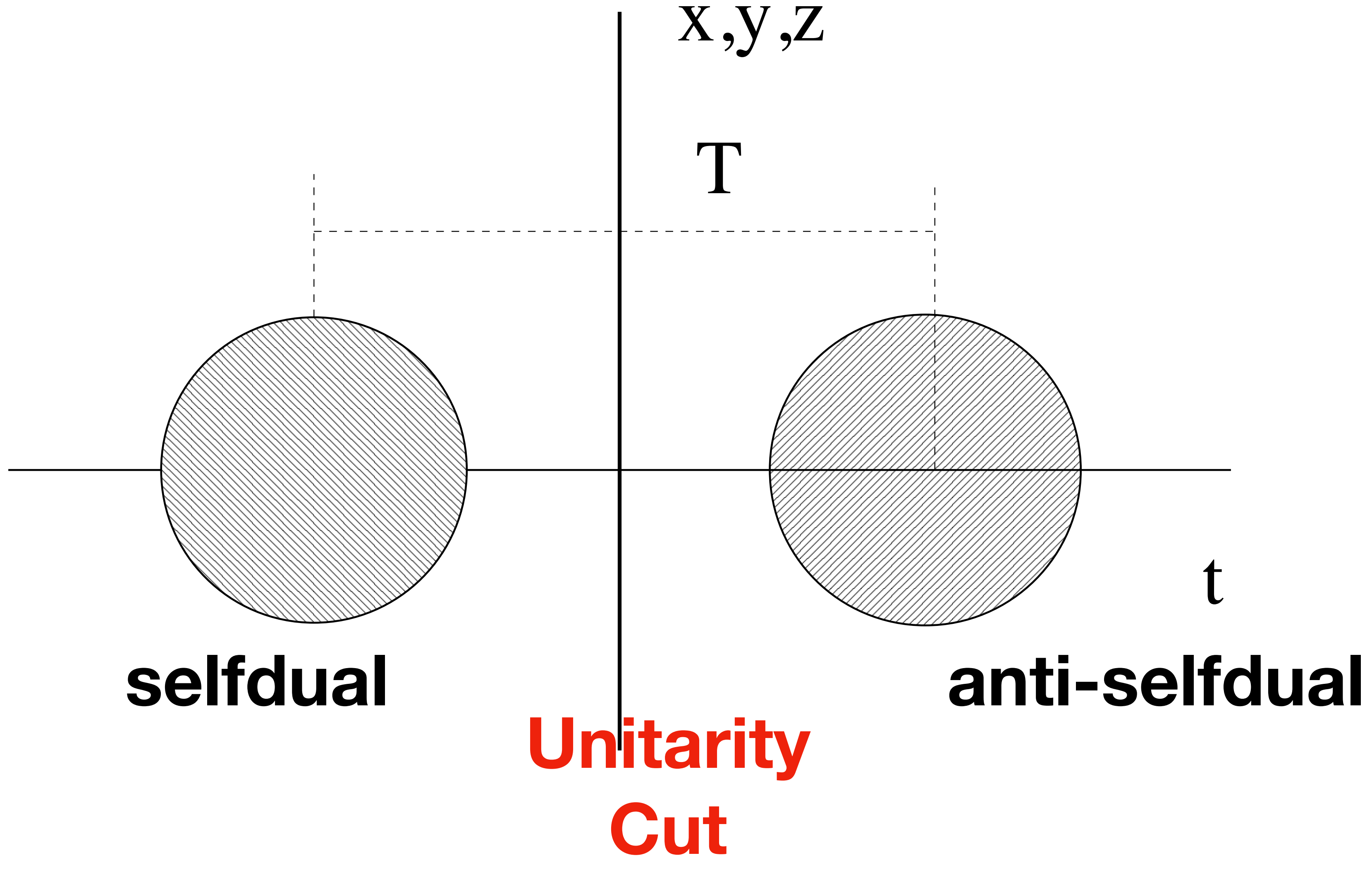
sphaleron path configurations were historically derived in three different ways.
Here is number 1: reduction to 3d from 4d instanton-antiinstanton configuration

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!

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)



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

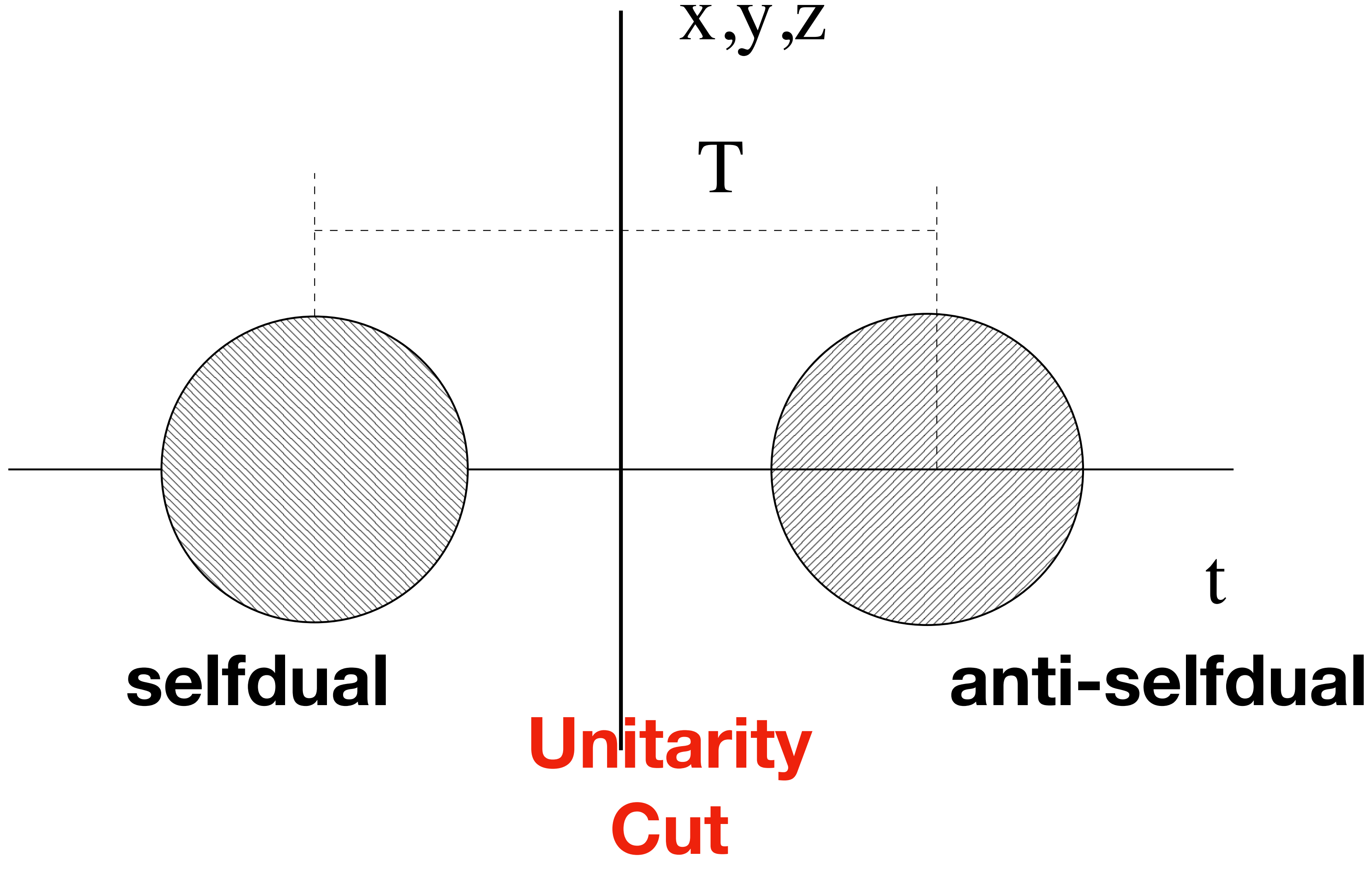
Superposition of I and anti-I has
its own history,
1983``streamline configurations”for double well
Balitsky+Yung, streamline eon
Now we know they are “Lefschits timbles”

we tried sum ansatz,
ratio ansatz
but only Yung’s ansatz
Approximately worked,
(as shown by Verbaarschot 91
Khoze and Ringwald,91)

sphaleron path configurations 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)



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

Superposition of I and anti-I has
its own history,
1983``streamline configurations”for double well
Balitsky+Yung, streamline eon
Now we know they are “Lefschits timbles”

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
Approximately worked,
(as shown by Verbaarschot 91
Khoze and Ringwald,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, 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

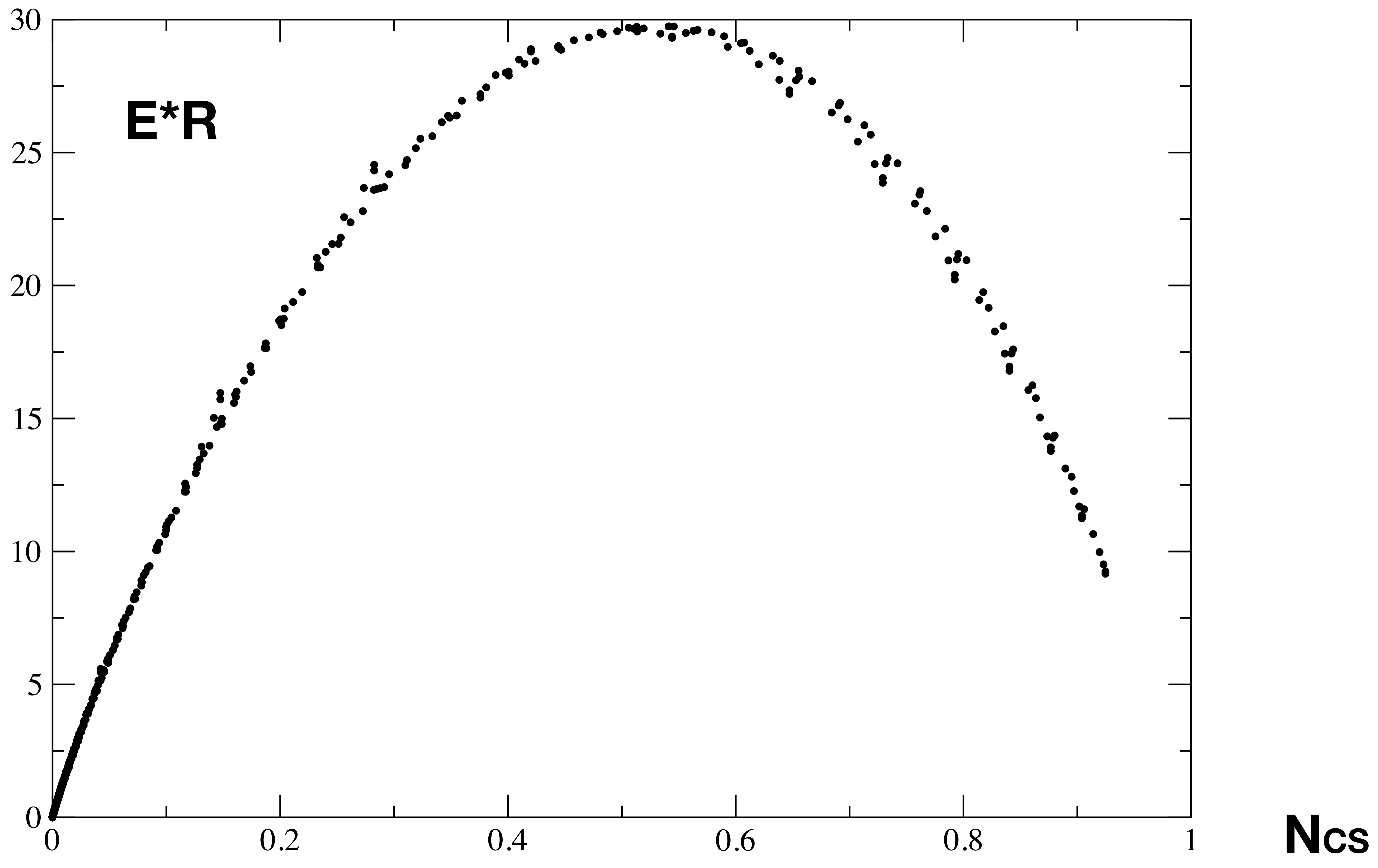
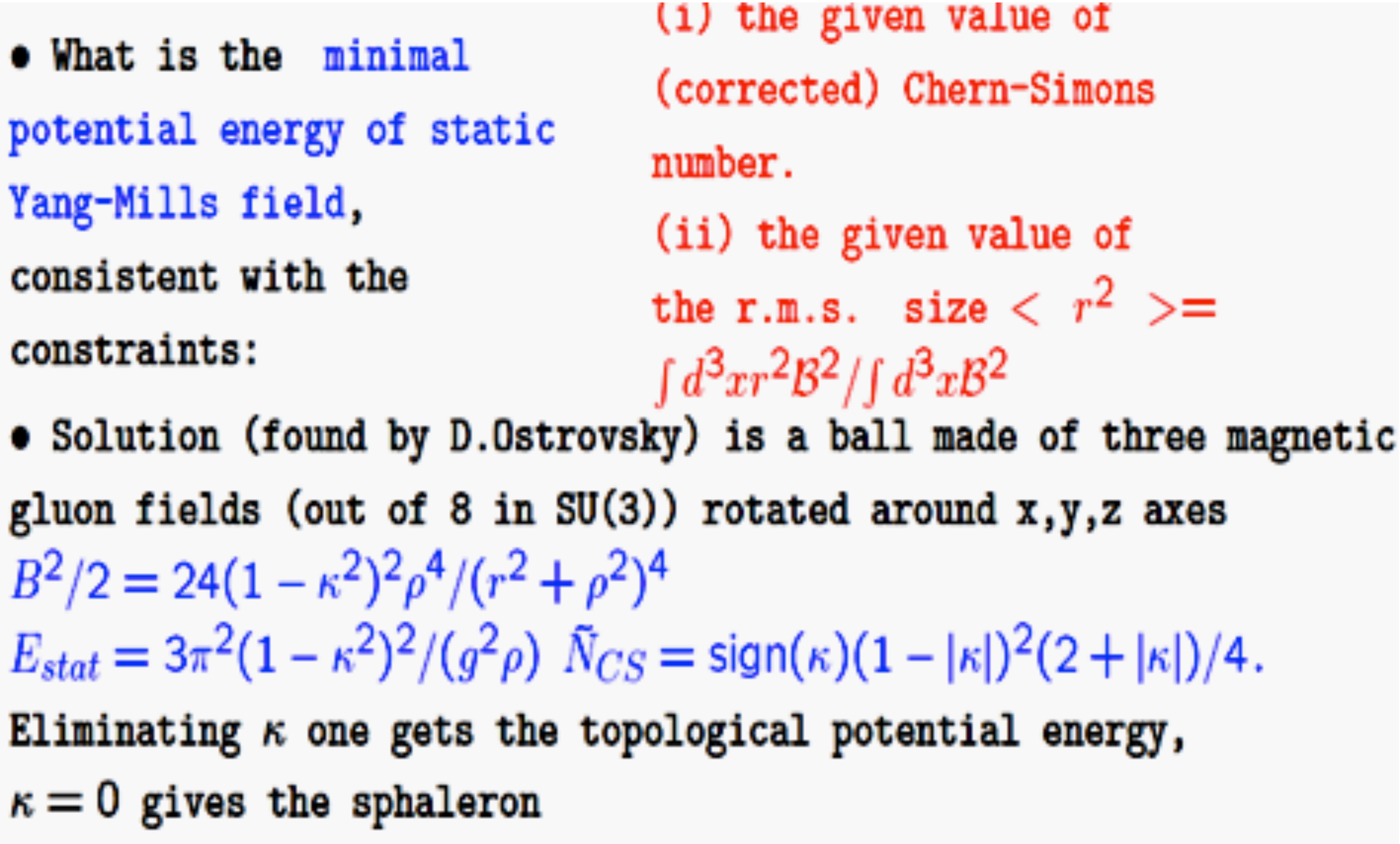


FIG. 6. The normalized energy, ER, versus the Chern-Simons number for the Yung ansatz. Plot (a) shows the positions of the turning states for various T, while (b) combines many points along the path ($t \neq 0$); their small spread means that Yung ansatz is nearly going directly uphill, thus passing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

Sphaleron production
Is given by action : see other talks

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

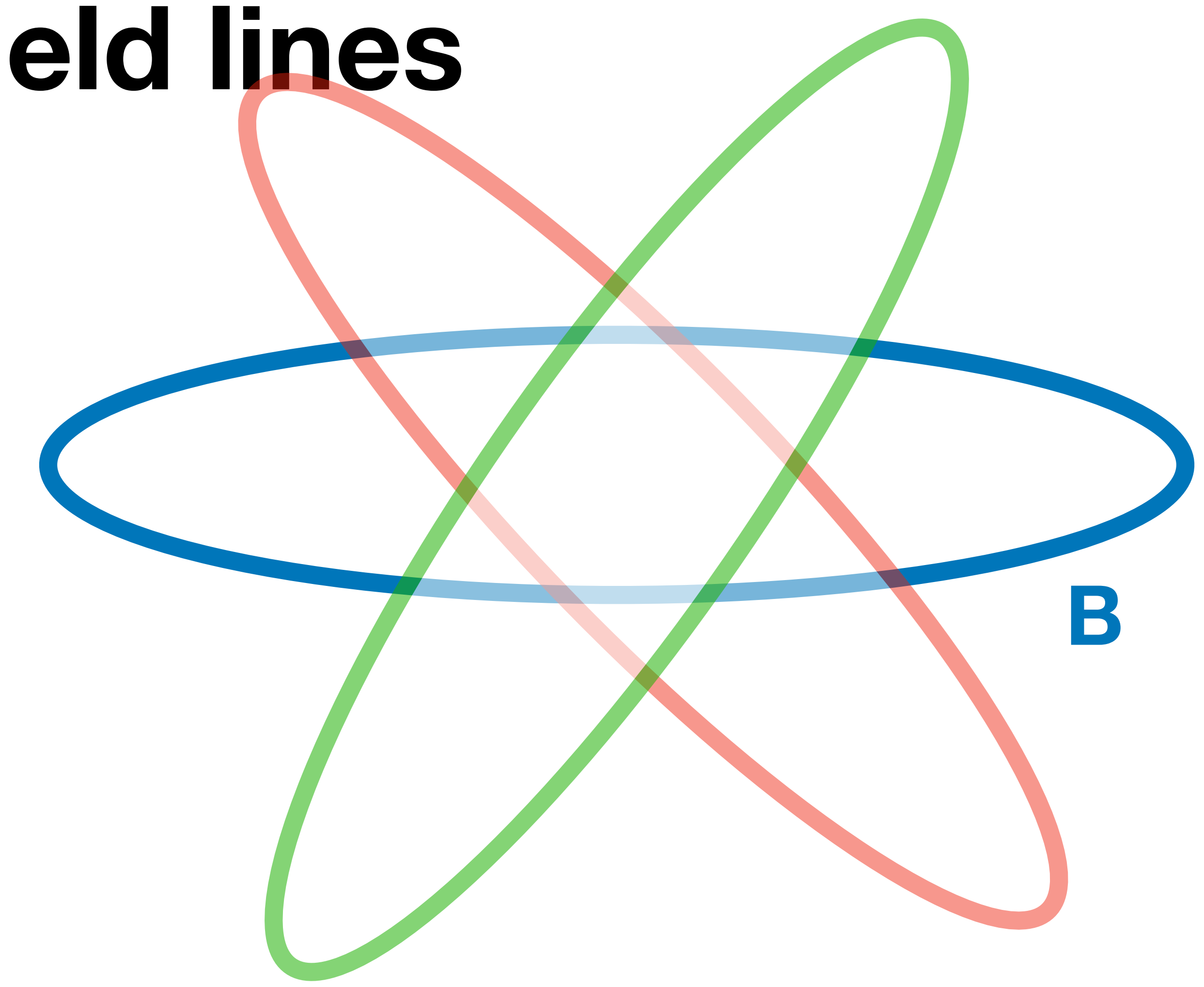
$B^2/2 = 24(1-\kappa^2)^2\rho^4/(r^2+\rho^2)^4$

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

Eliminating κ one gets the topological potential energy,

$\kappa = 0$ gives the sphaleron

sphaleron fields are static magnetic
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

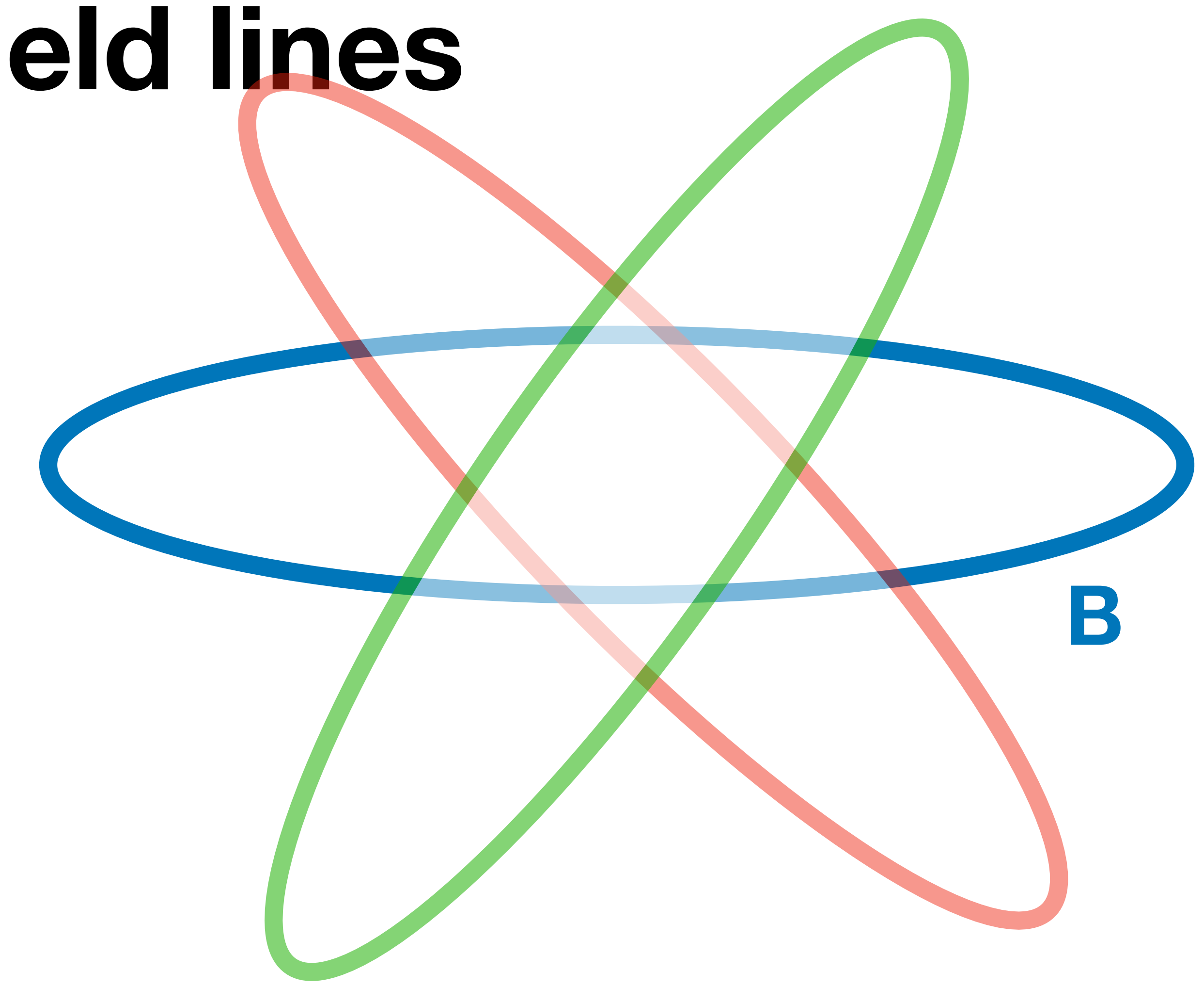
$$B^2(r) = \frac{48\rho^4}{g^2(r^2+\rho^2)^4}$$

Solution is unstable,
basically a magnetic bomb
waiting to explode
Approach with care!

sphaleron fields are static magnetic
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

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

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



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

Solution is unstable,
basically a magnetic bomb
waiting to explode
Approach with care!

Method number 3: conformal off-center transformation

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

Method number 3: conformal off-center transformation

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

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

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

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].

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

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

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

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

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

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

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

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

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

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

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

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

dn is the elliptic function

the gauge field is given explicitly

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

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

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

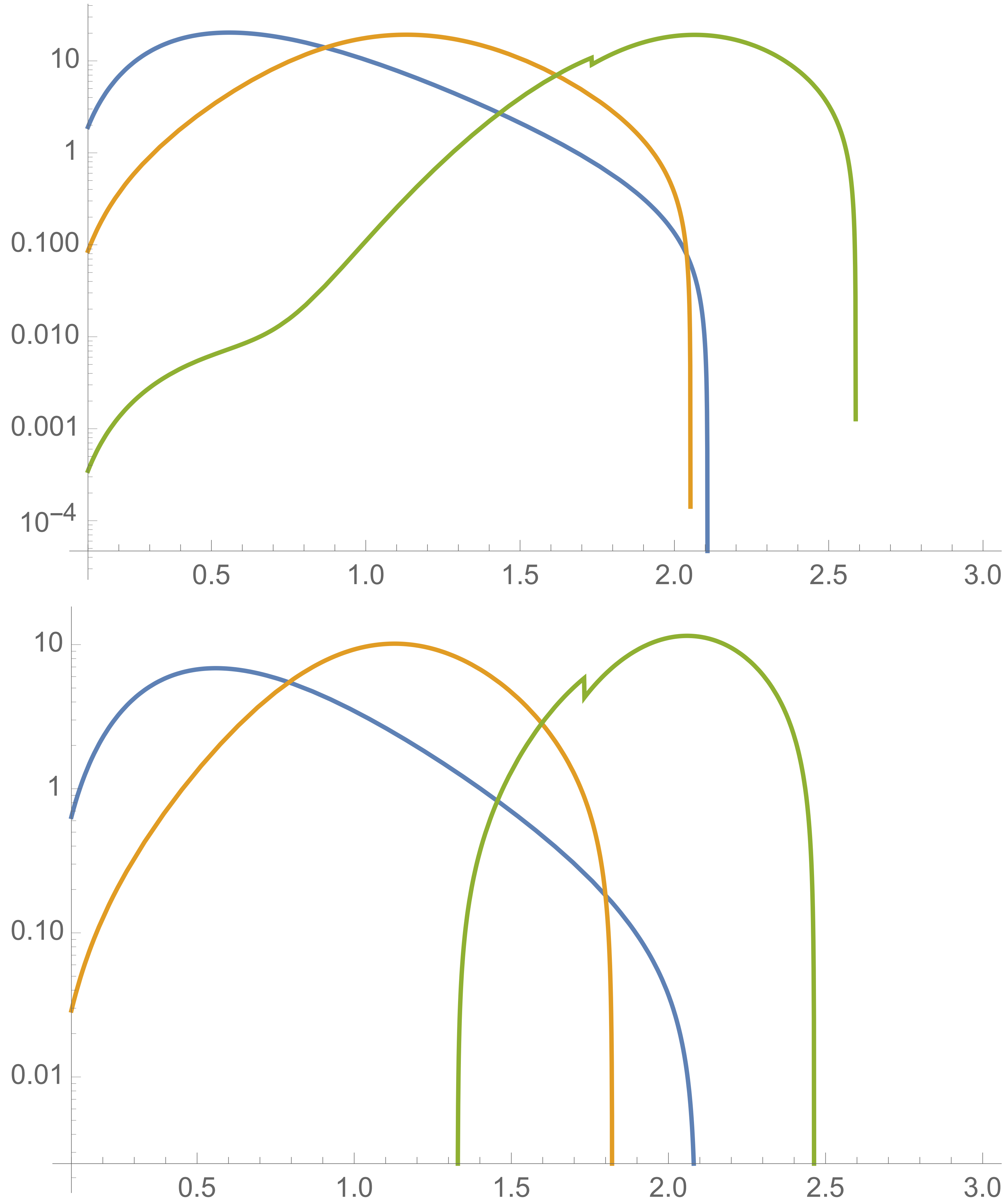


FIG. 2: Componenents of the stress tensor (times r^2, namely $r^2T^{00}(t,r)$ upper plot, $r^2T^{33}(t,r)$ lower plot) as a function of r, the distance from the center, at times $t/\rho = 0.1, 1, 2$, left to right.

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

Snapshots of the explosion

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

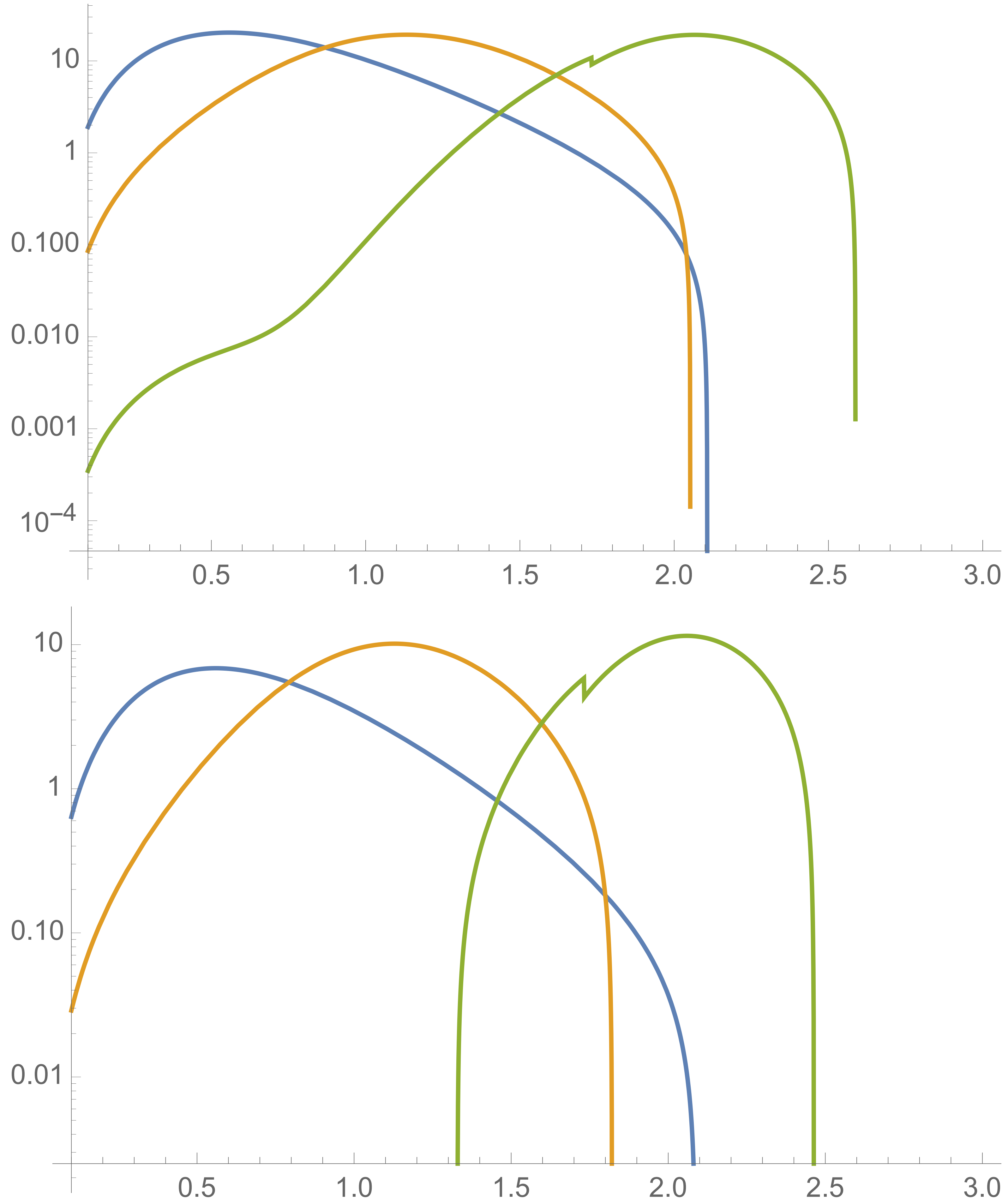


FIG. 2: Componenents of the stress tensor (times r^2, namely $r^2T^{00}(t,r)$ upper plot, $r^2T^{33}(t,r)$ lower plot) as a function of r, the distance from the center, at times $t/\rho = 0.1, 1, 2$, left to right.

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

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

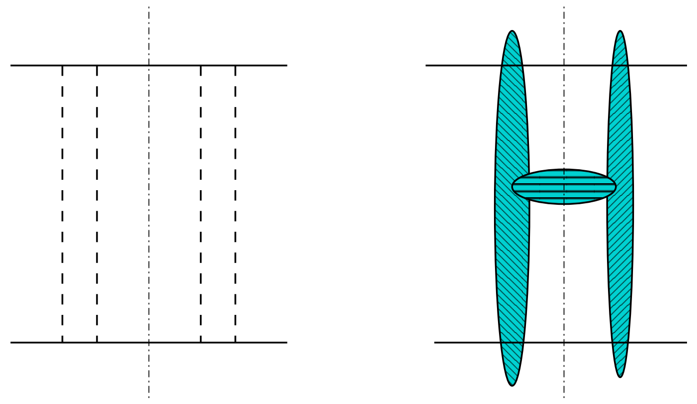
At T<Tc VEV of Higgs is nonzero
Weinberg angle mixes Z and photons
And also makes explosion elliptic =>
Direct generation of
Gravity waves

Collisions of sound waves leads to
Indirect production of
gravity waves
Kalaydzhyan +ES

Semiclassical Double-Pomeron Production of Glueballs and η′

Edward Shuryak and Ismail Zahed

arXiv:hep-ph/0302231v1 25 Feb 2003



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

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

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

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

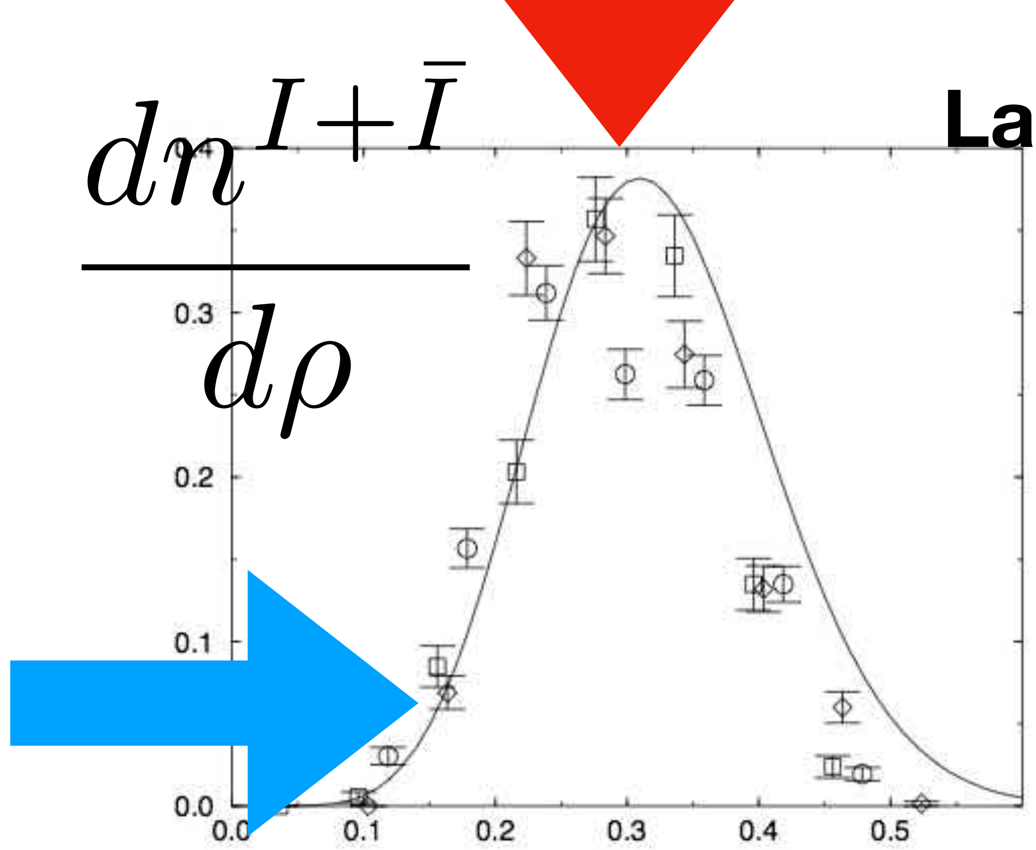
with

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

which is purely imaginary,

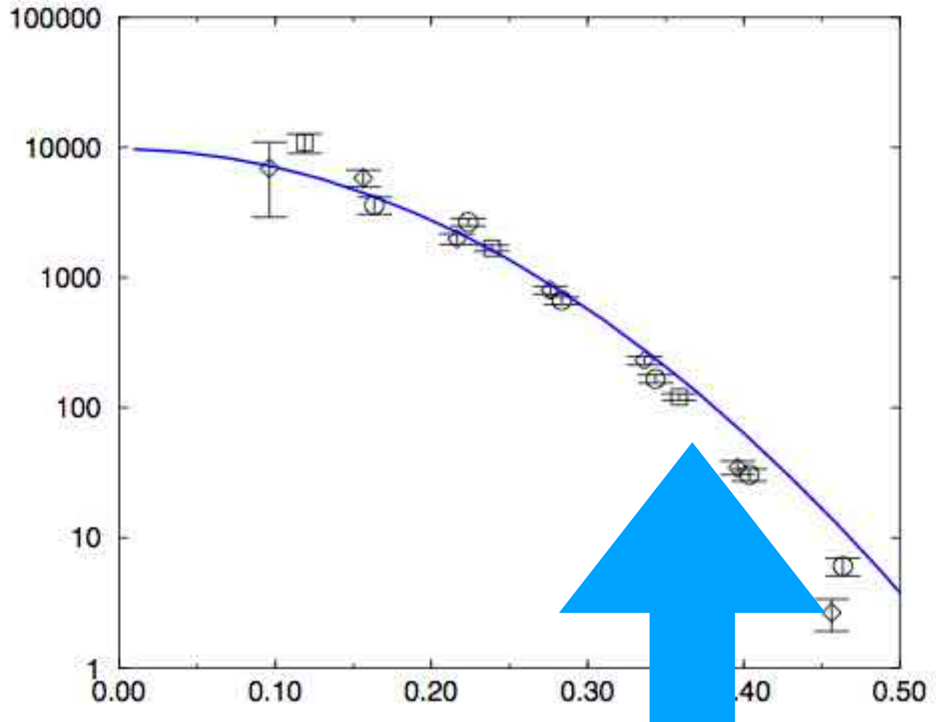
$$\mathbf{J}(q_\perp) = -i\frac{\hat{q}_\perp}{\sqrt{q_\perp}} \int_0^\infty dx\, J_{3/2}(q_\perp x) \times \left((2\,\pi x)^{3/2} \sin\left(\frac{\pi\,|x|}{\sqrt{x^2+\rho_0^2}}\right)\right)\ .$$

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



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

Lattice data, A.Hazenfratz



Dual Higgs model

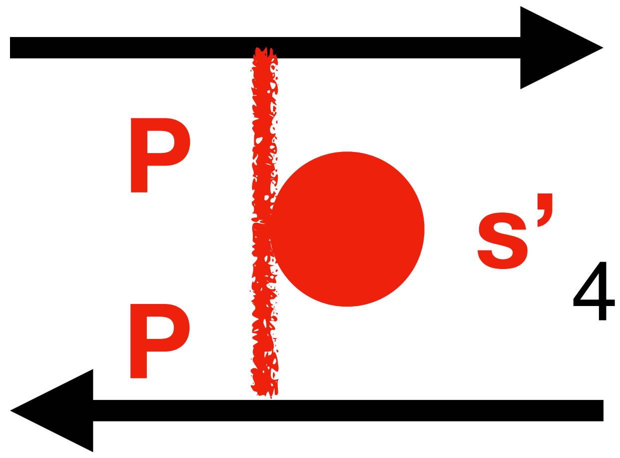
$$\frac{dn}{d\rho} = \frac{dn}{d\rho}\Big|_{semiclassical} \cdot e^{-2\pi\sigma\rho^2}$$

UA8 and double-Pomeron production

A Study of Inclusive
Double–$\mathcal{P}$omeron–Exchange
in $p\bar{p} \to pX\bar{p}$ 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.

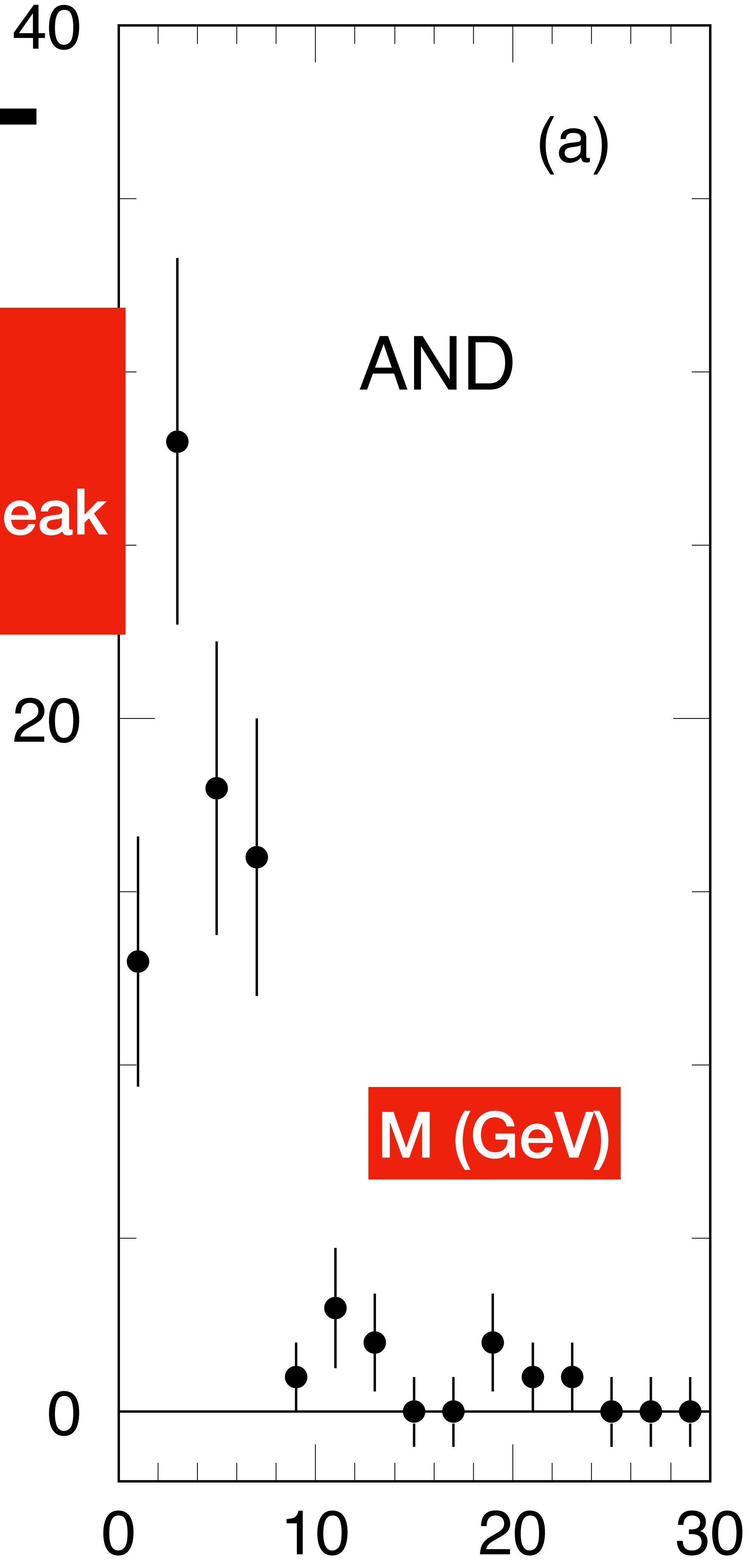
J.B. Cheze, J. Zsembery
Centre d'Etudes Nucleaires-Saclay, 91191 Gif-sur-Yvette, France.



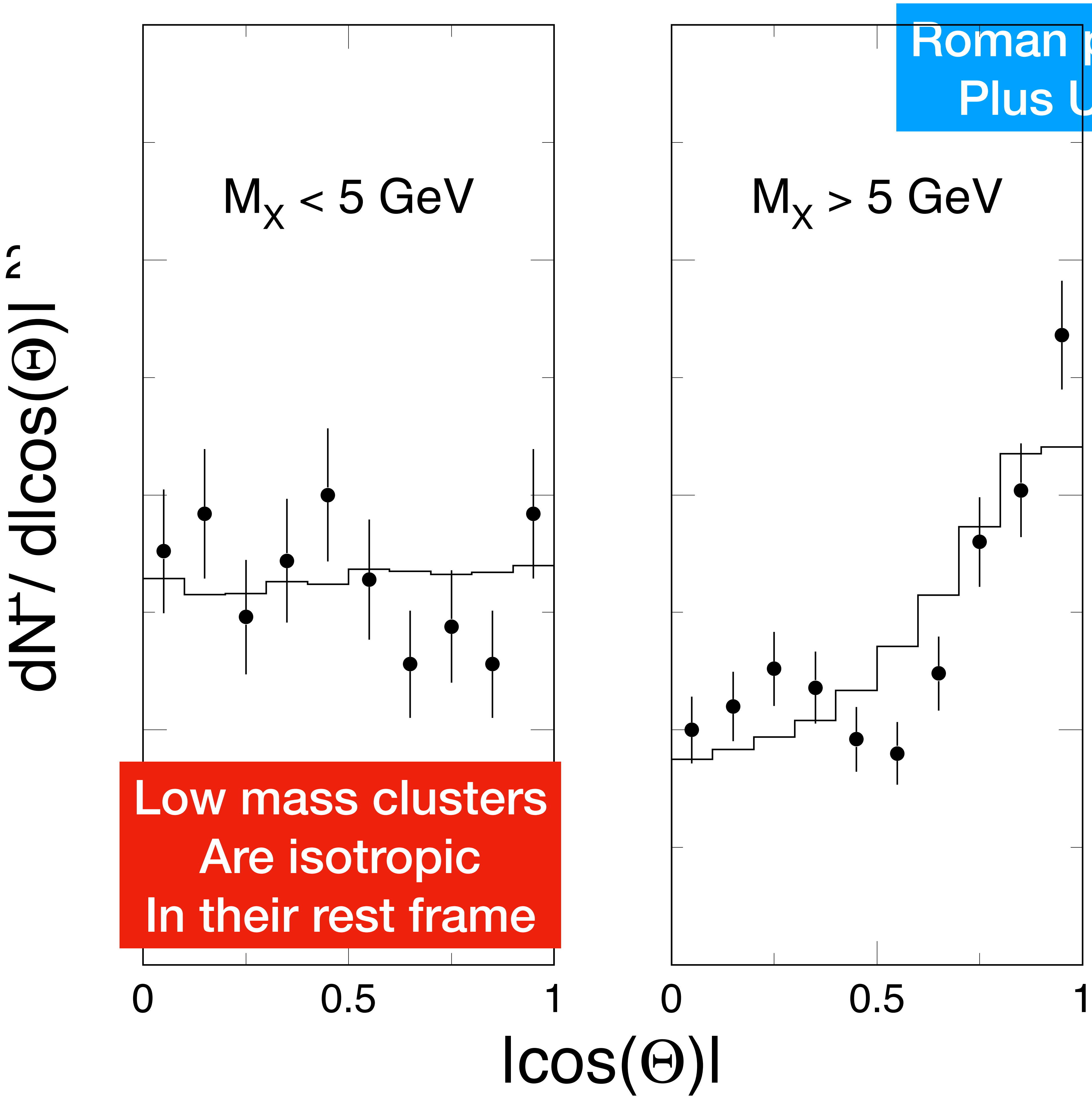
$$\frac{d^6\sigma_{DPE}}{d\xi_1 d\xi_2 dt_1 dt_2 d\phi_1 d\phi 2} = F_{\mathcal{P}/p}(t_1,\xi_1)\cdot F_{\mathcal{P}/p}(t_2,\xi_2)\cdot\sigma^{tot}_{\mathcal{PP}}(s').$$

s'=M^2 is the cluster mass squared

Mass
Distribution
Has unpredicted peak
At 2-8 GeV



Low mass clusters
Are isotropic
In their rest frame



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

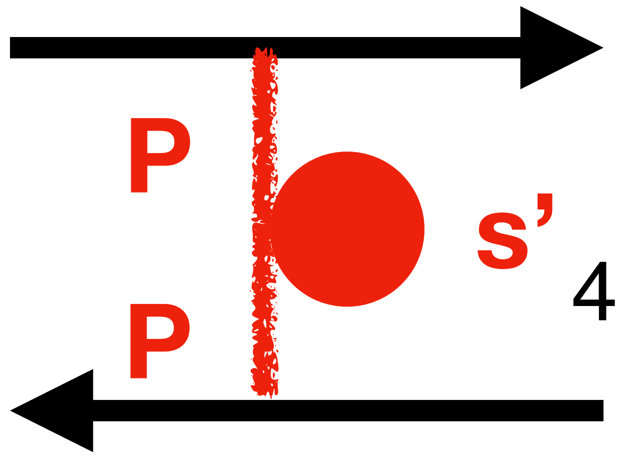
Small and large M
Production is different
In magnitude and
Angular distributions

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

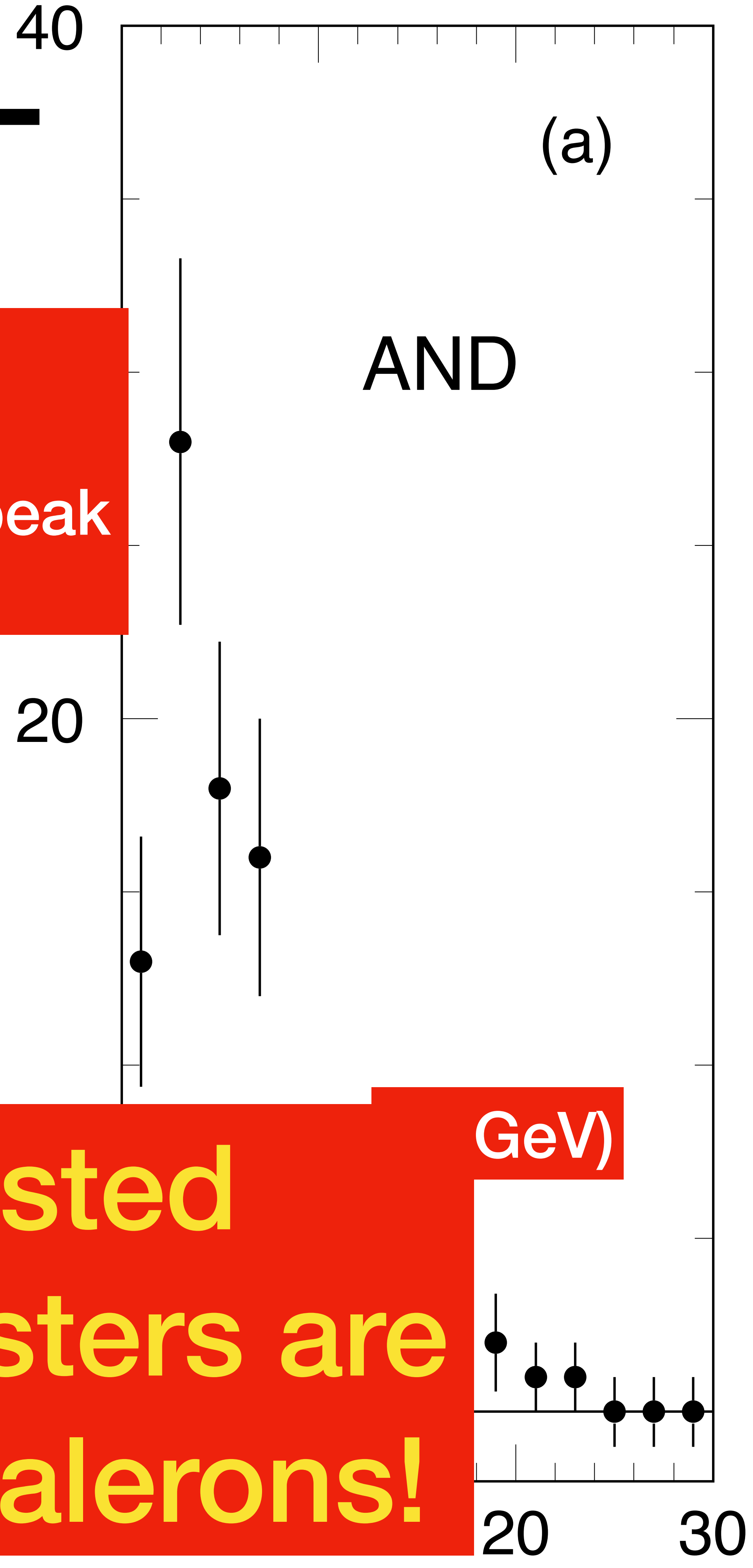
A. Brandt[1], S. Erhan[a], A. Kuzucu[2], M. Medinnis[3],
N. Ozdes[2,4], P.E. Schlein[b], M.T. Zeyrek[5], J.G. Zweizig[6]
University of California*, Los Angeles, California 90024, U.S.A.

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



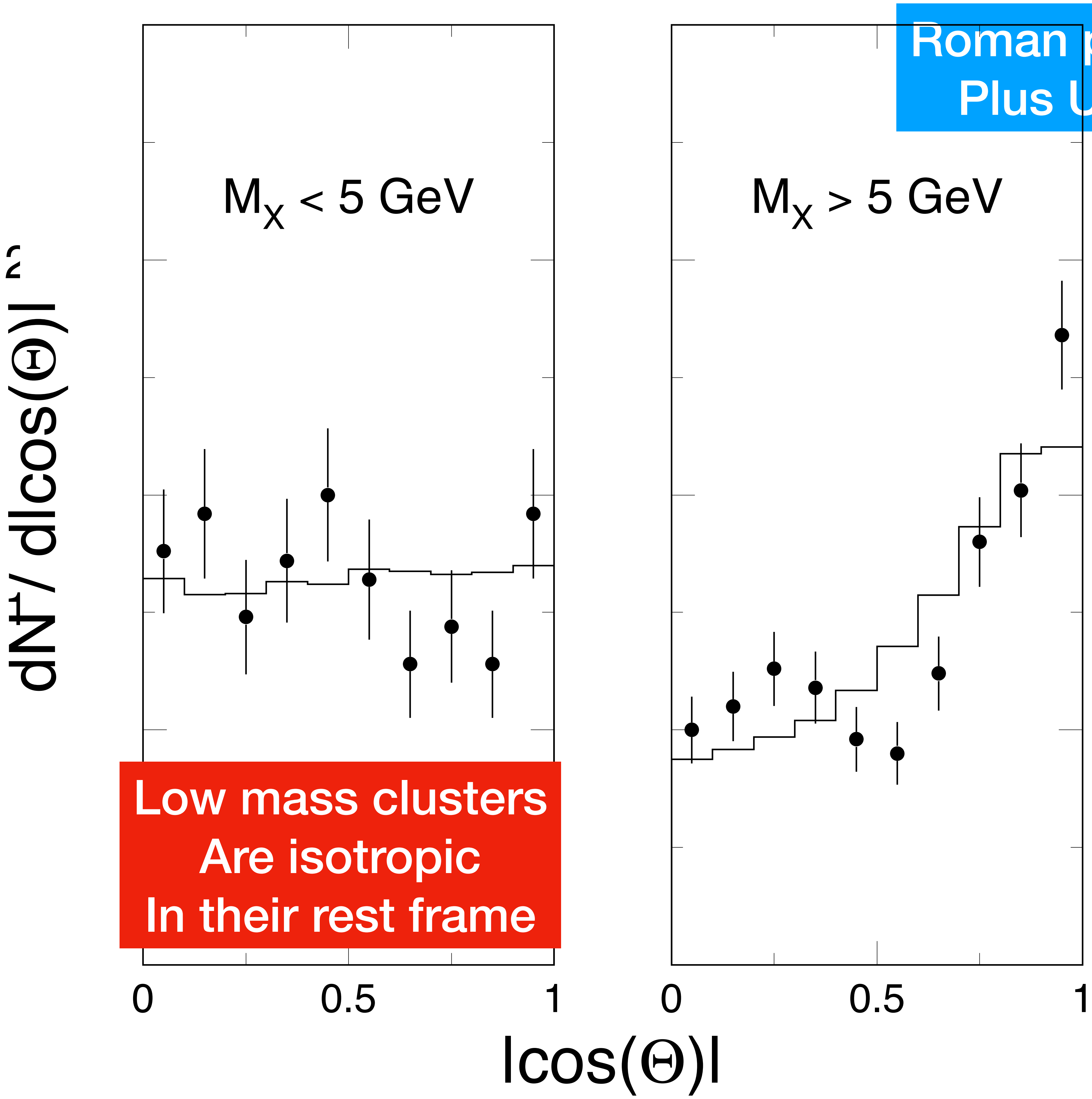
$$\frac{d^6\sigma_{DPE}}{d\xi_1 d\xi_2 dt_1 dt_2 d\phi_1 d\phi 2} = F_{\mathcal{P}/p}(t_1,\xi_1)\cdot F_{\mathcal{P}/p}(t_2,\xi_2)\cdot\sigma^{tot}_{\mathcal{PP}}(s').$$

s'=M^2 is the cluster mass squared



Mass
Distribution
Has unpredicted peak
At 2-8 GeV

We suggested
M<5 GeV clusters are
The QCD sphalerons!



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

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

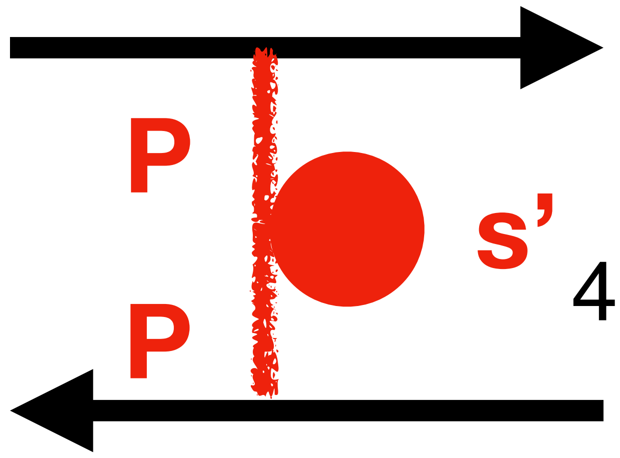
Low mass clusters
Are isotropic
In their rest frame

UA8 and double-Pomeron production

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

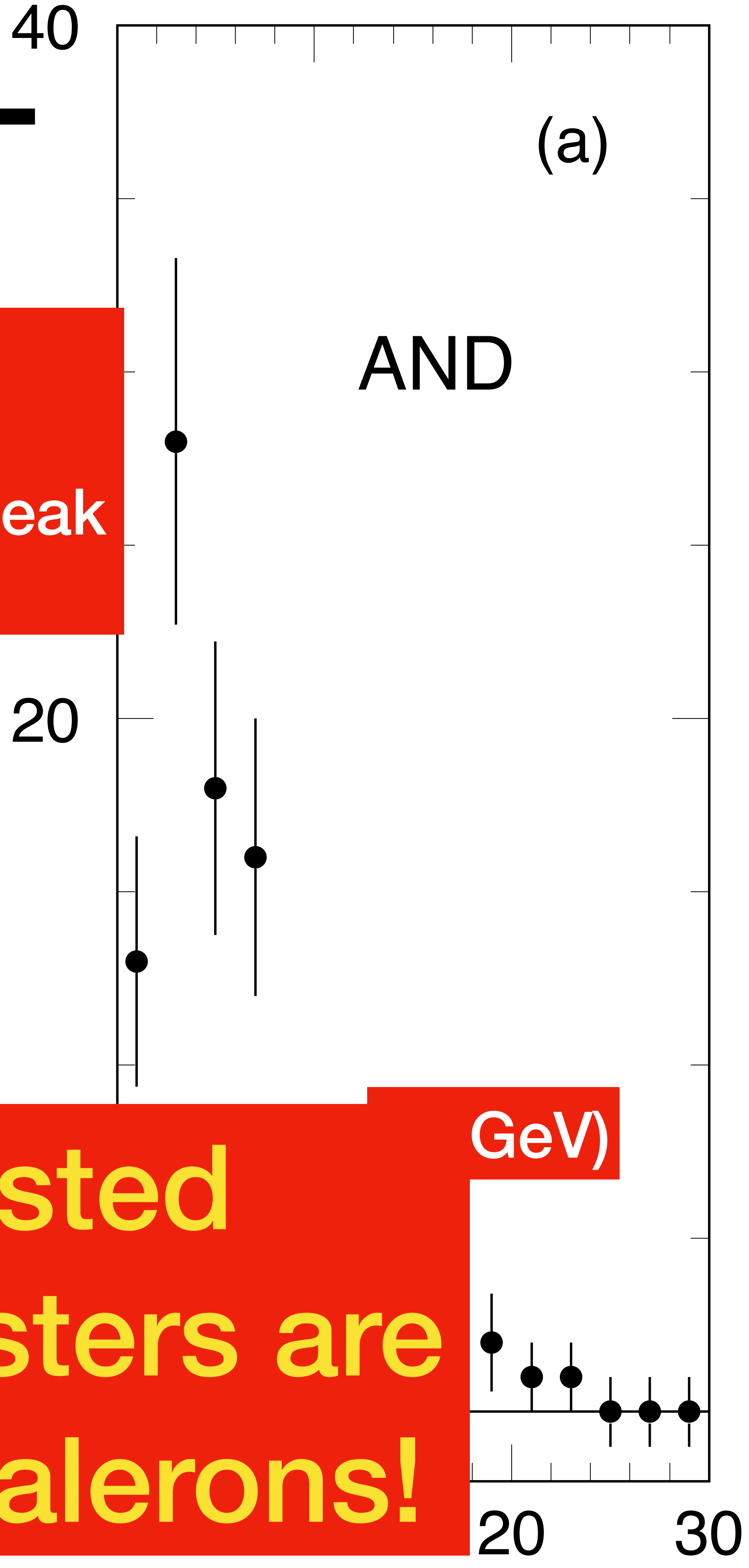
A. Brandt[1], S. Erhan[a], A. Kuzucu[2], M. Medinnis[3],
N. Ozdes[2,4], P.E. Schlein[b], M.T. Zeyrek[5], J.G. Zweizig[6]
University of California*, Los Angeles, California 90024, U.S.A.

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



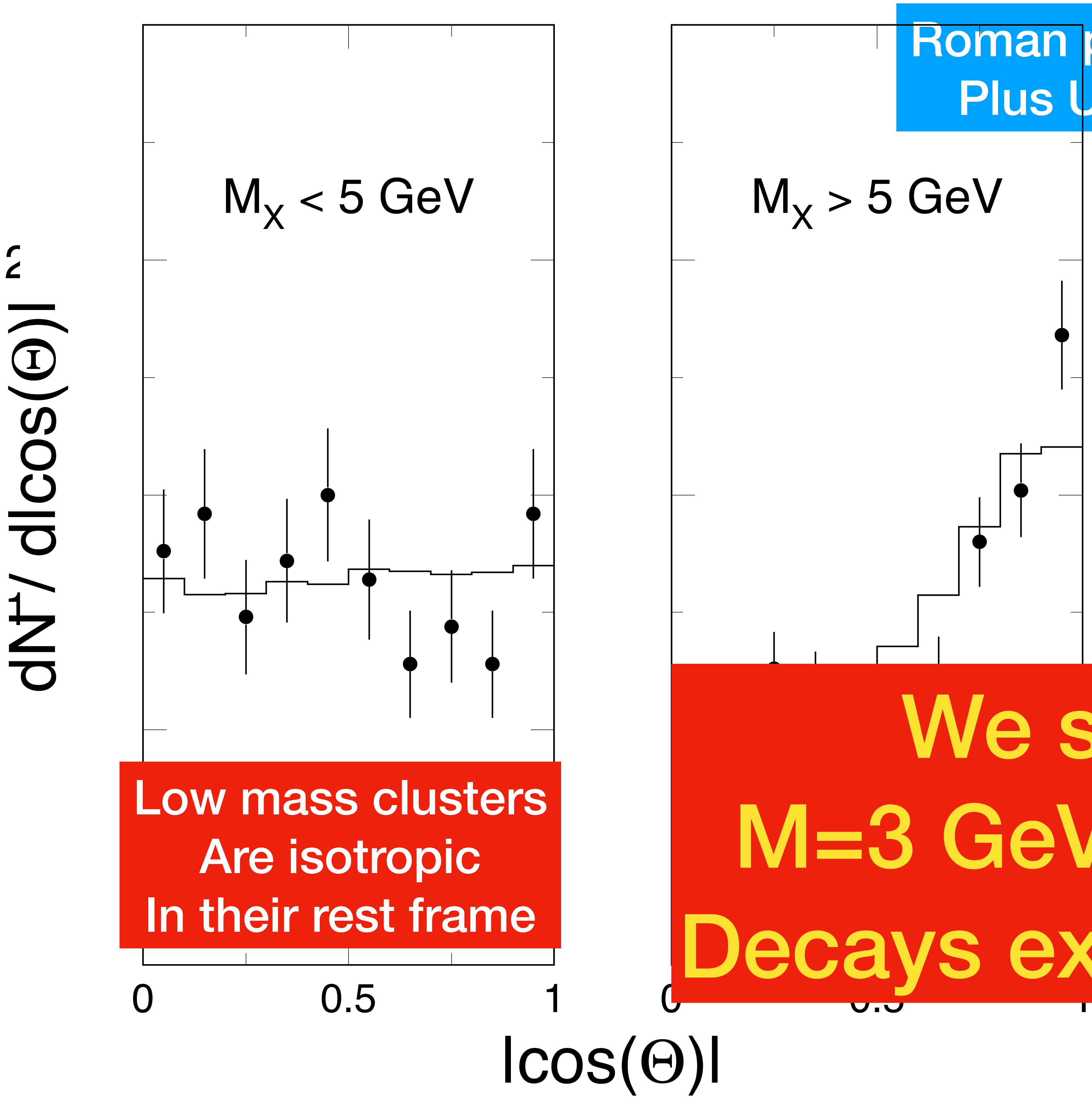
$$\frac{d^6\sigma_{DPE}}{d\xi_1 d\xi_2 dt_1 dt_2 d\phi_1 d\phi 2} = F_{\mathcal{P}/p}(t_1,\xi_1)\cdot F_{\mathcal{P}/p}(t_2,\xi_2)\cdot \sigma^{tot}_{\mathcal{P}\mathcal{P}}(s').$$

s'=M^2 is the cluster mass squared



Mass
Distribution
Has unpredicted peak
At 2-8 GeV

We suggested
M<5 GeV clusters are
The QCD sphalerons!



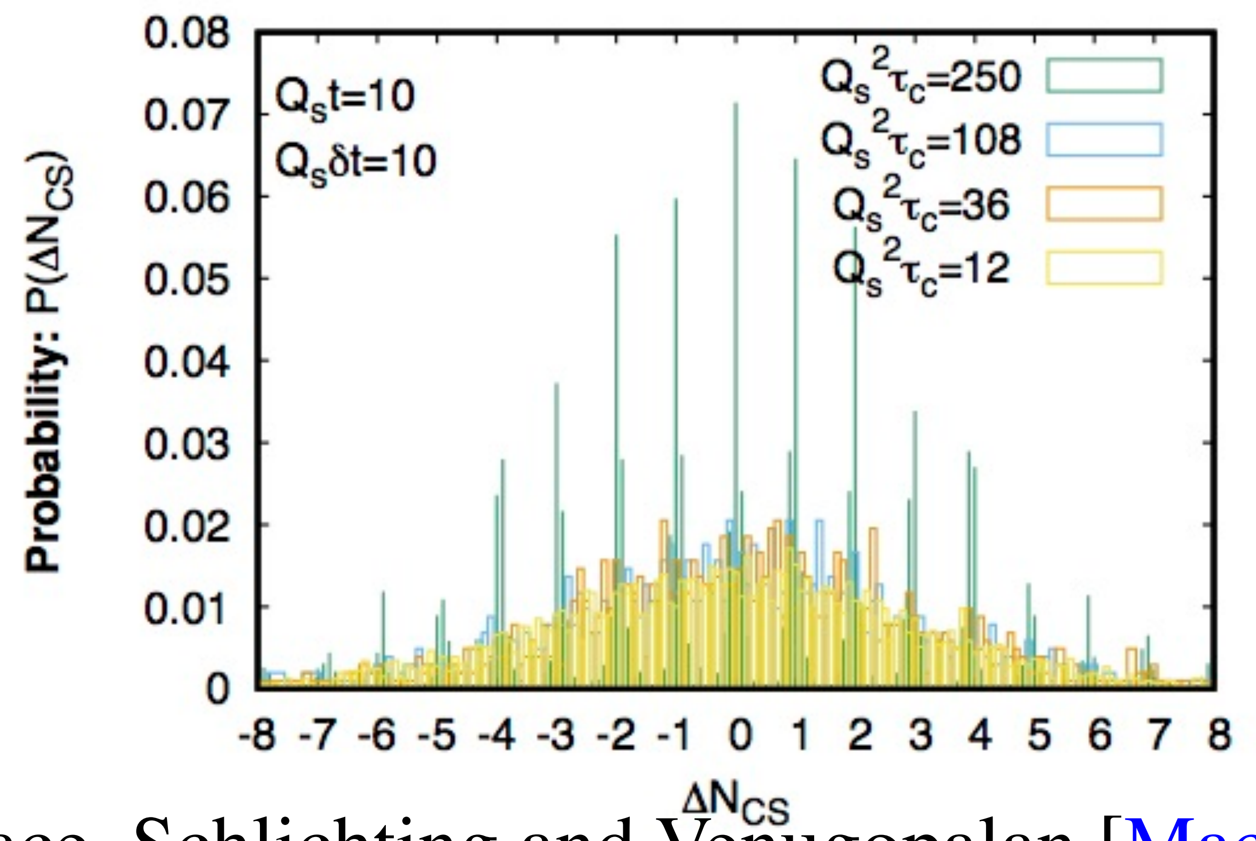
Roman pots on both sides (AND)
Plus UA2 central calorimeter

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

Low mass clusters
Are isotropic
In their rest frame

We suggested
M=3 GeV clusters have
Decays exactly like eta_c

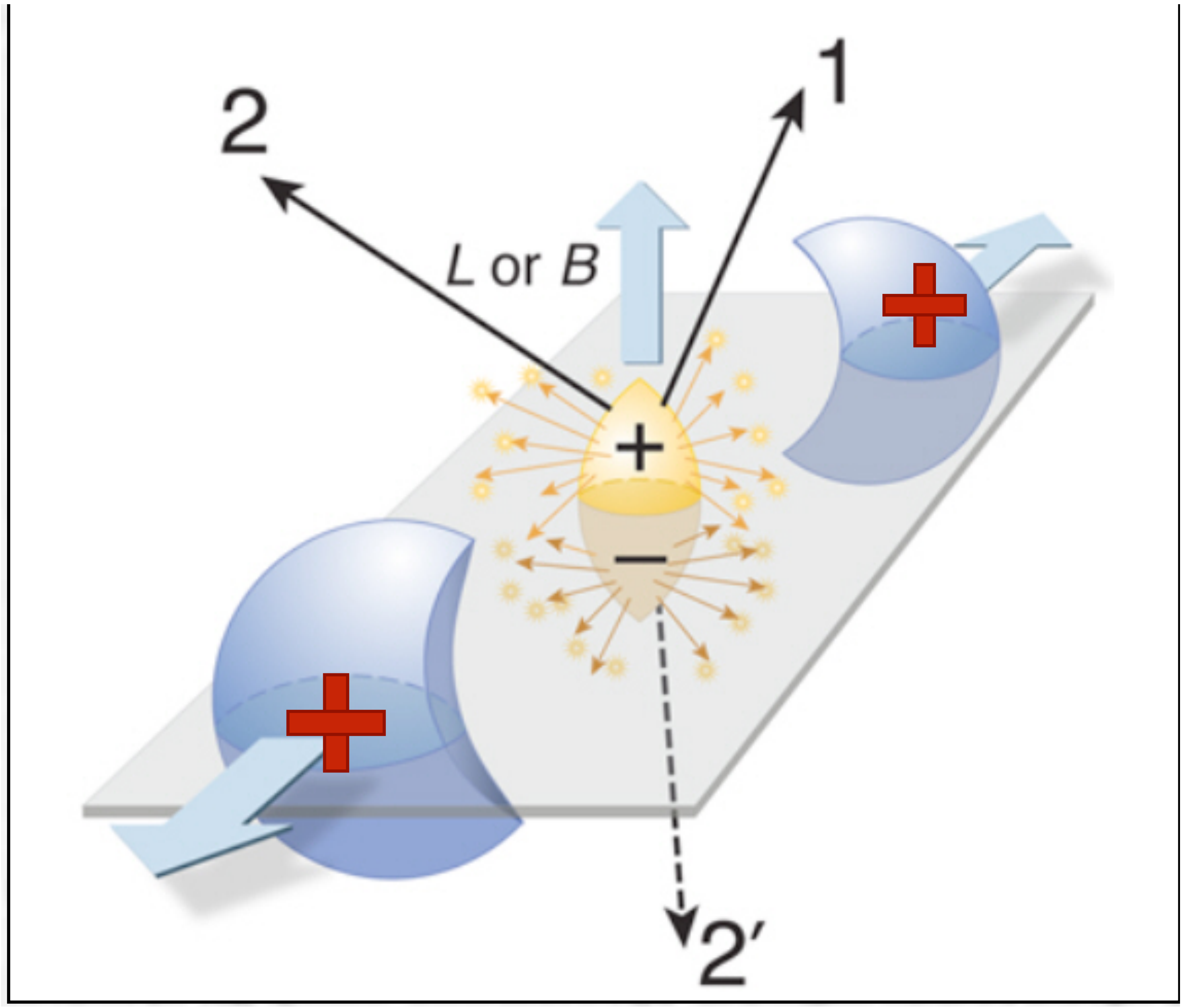
Searching for topological fluctuations in heavy ion collisions at RHIC via CME



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

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

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

LATEST RHIC run done, not yet analyzed

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

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

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

Sphalerons in cosmological electroweak transition

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

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

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

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

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

Lattice simulations

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]].

$$\log\left(\frac{\Gamma(T < T_{EW})}{T^4}\right) = -(147.7 \pm 1.9) + (0.83 \pm 0.01)\left(\frac{T}{\mathrm{GeV}}\right)$$

sphaleron transitions become irrelevant when the temperature is below

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

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

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

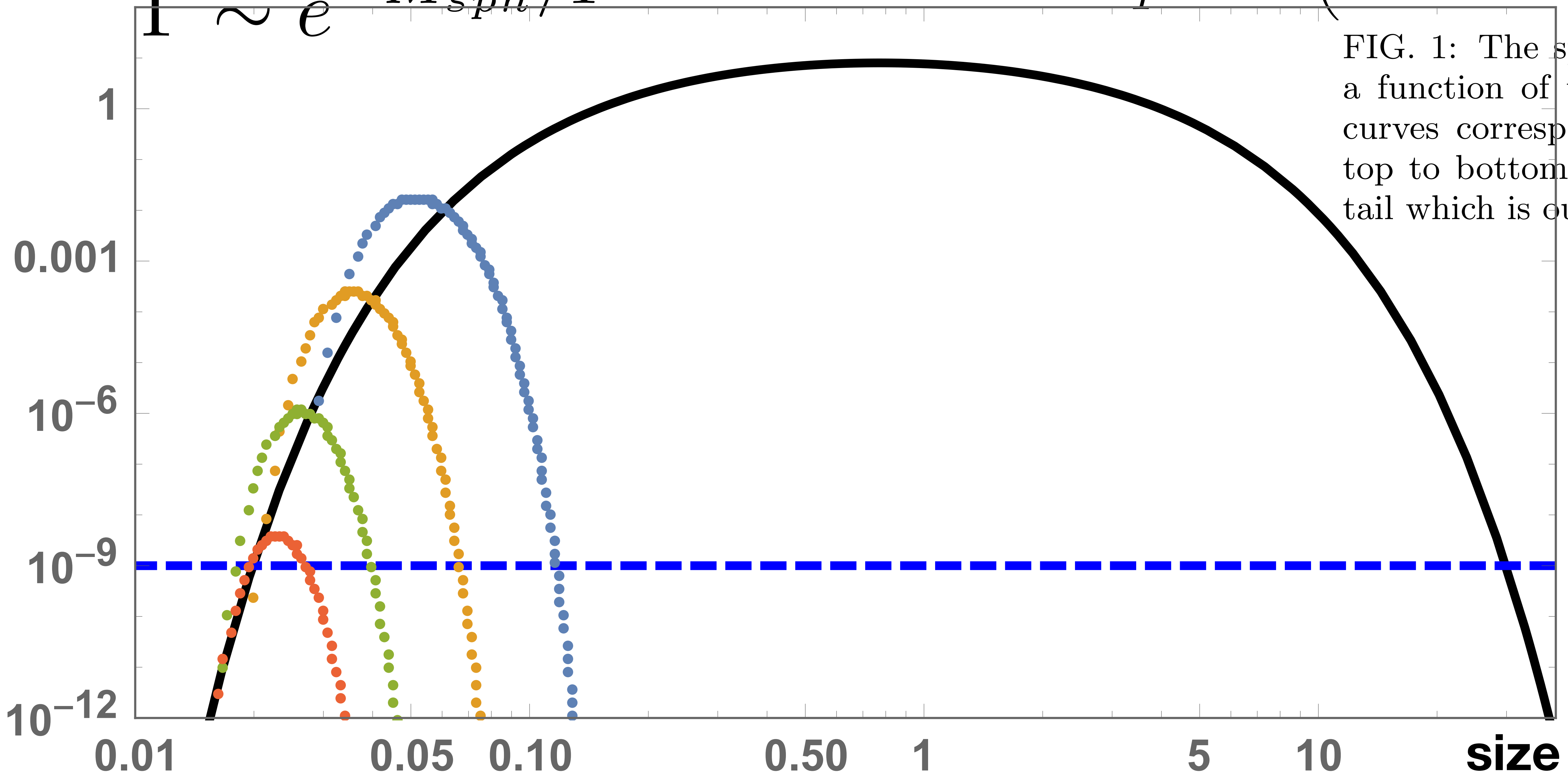


FIG. 1: The sphaleron probability distribution as a function of the sphaleron size $\rho(\mathrm{GeV}^{-1})$. The curves correspond to $T = 159, 150, 140, 130\,\mathrm{GeV}$, top to bottom. The horizontal line separates the tail which is out of the Hubble expansion rate.

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

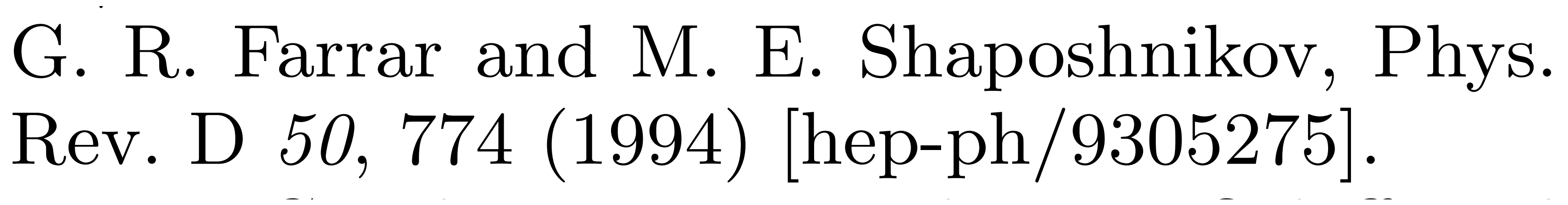
After T<Tc=160 GeV Higgs VEV appears, Strongly suppressing sphalerons

As mountains grow, everything from slopes falls down

Baryogenesis

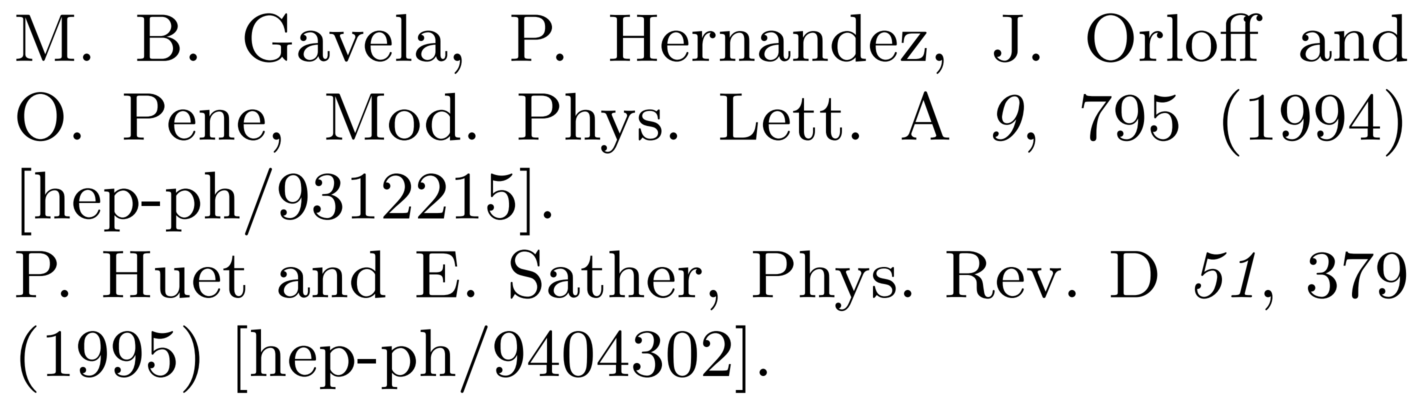
- Sakharov (1967) had formulated 3 conditions => **B-violation, CP-violation, non-equilibrium**
- All 3 are there in the Standard Model (SM)
- And yet we do not know how $n_B/n_\gamma = 6*10^{-10}$ has been obtained… as way too small numbers are obtained
- beyond the SM? (very popular)
  or beyond the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

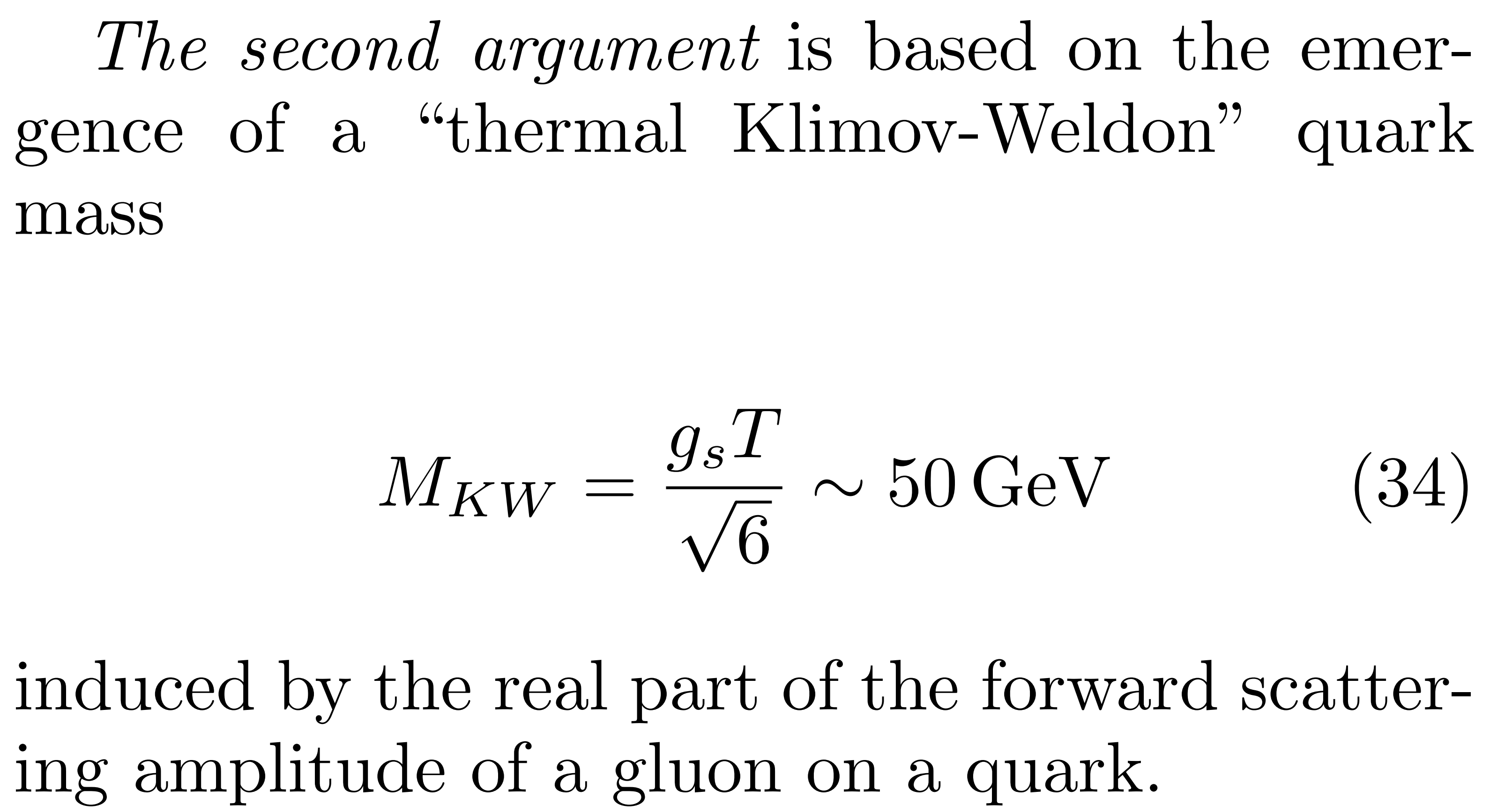
earlier scenario using small momentum quarks


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

was criticized because of gluon scattering on quarks

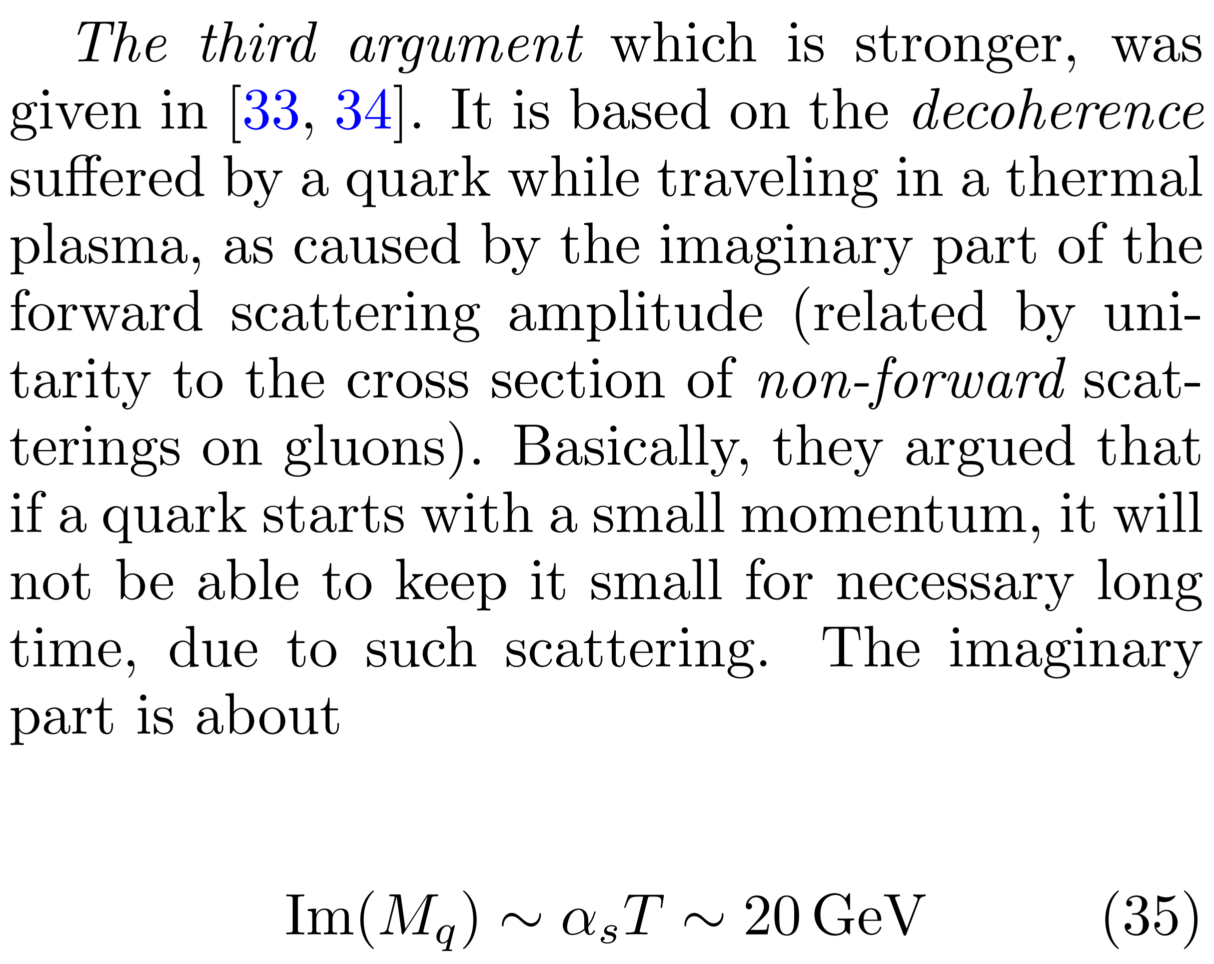
one cannot keep momentum small for long!


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

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

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

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

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

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 $$M_{LR}\frac{1}{i\not{\partial} + M_{KW}}M_{RL}^\dagger$$

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

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

which is much larger than for nonzero modes!

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

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

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 (?)

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

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

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

➡

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

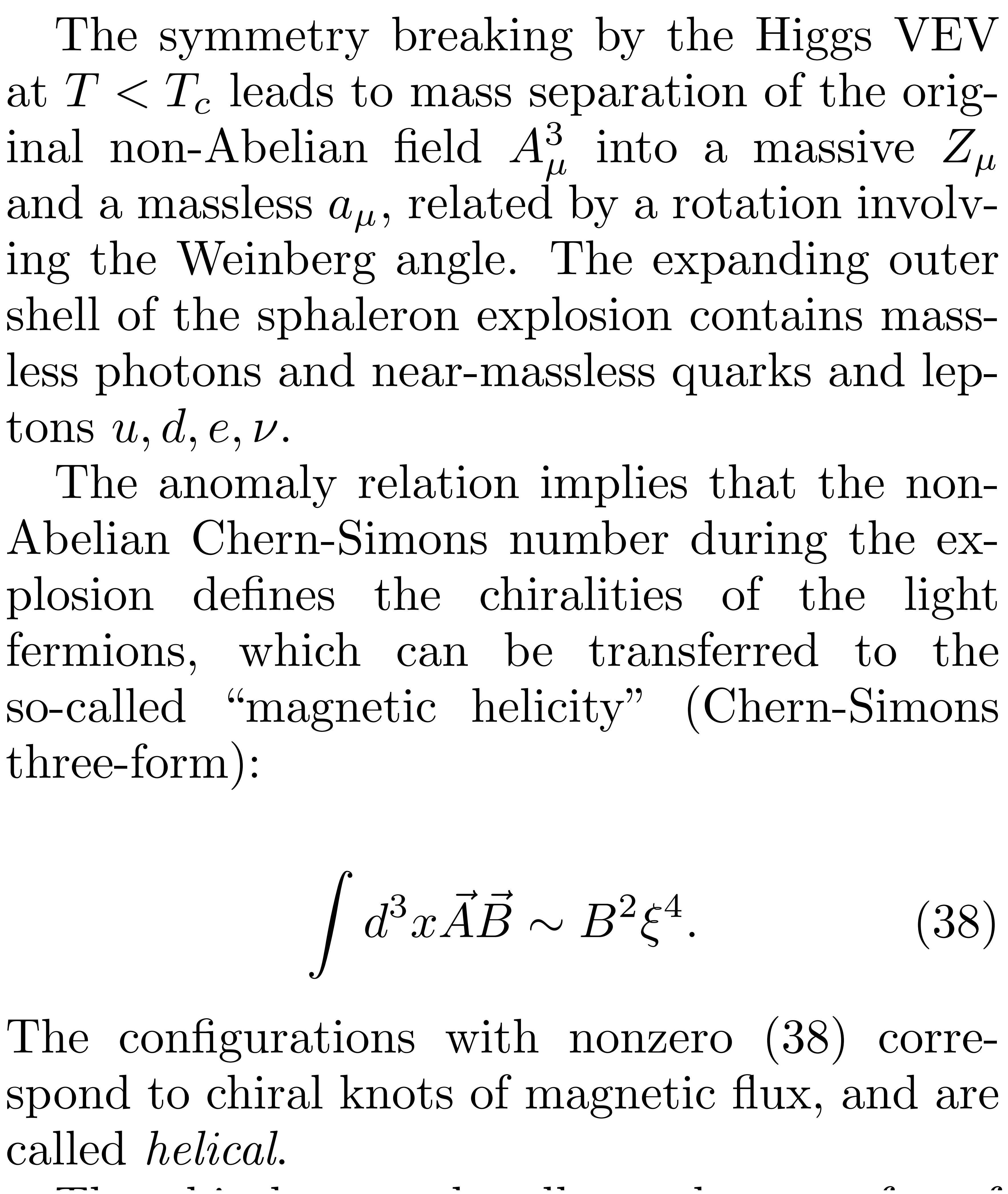
Such CP violation is needed to explain BAU our estimate based on CKM gave

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

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

Issue needs more studies …

Helical magnitogenesis

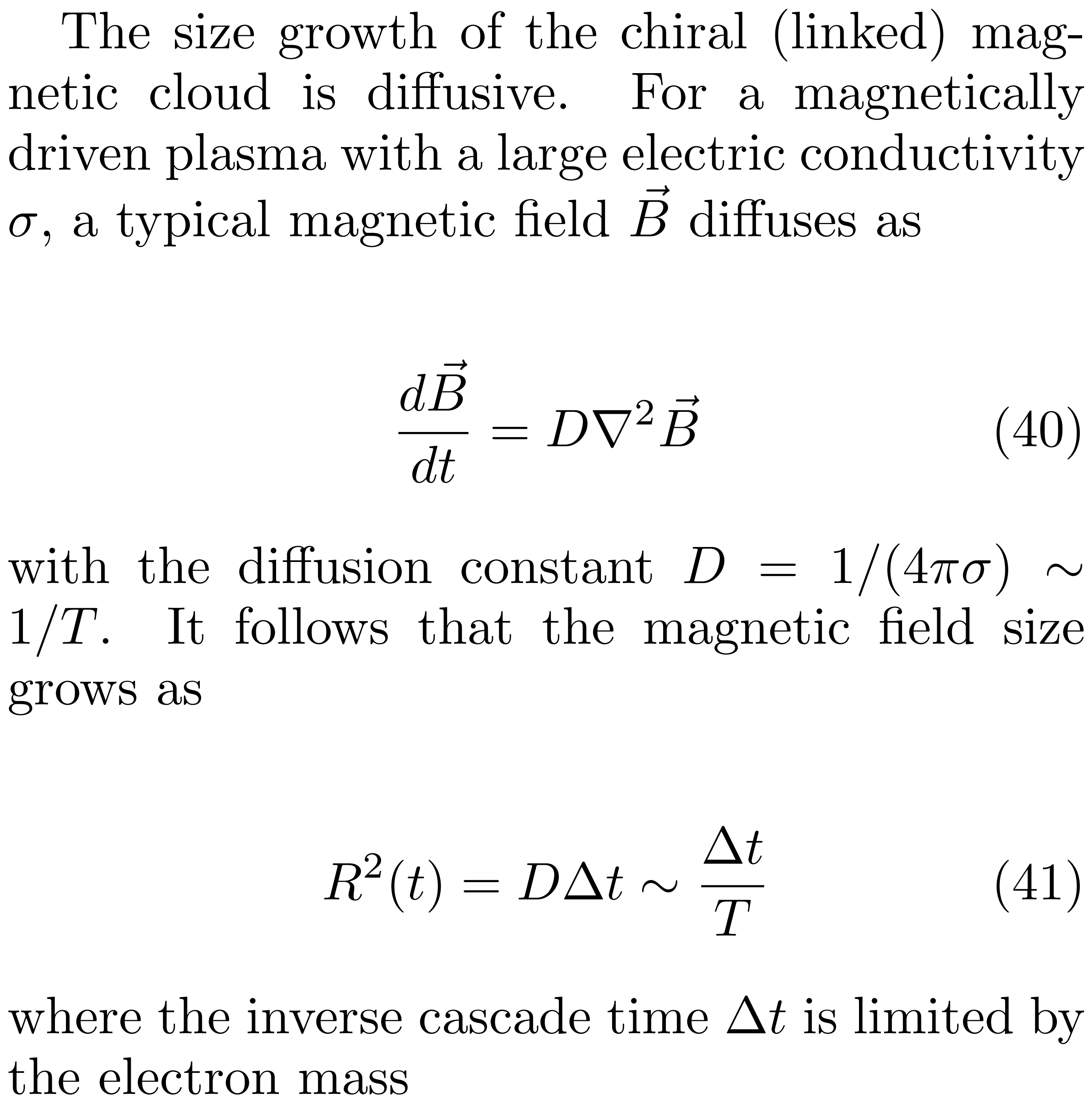


The symmetry breaking by the Higgs VEV at $T < T_c$ leads to mass separation of the original non-Abelian field A^3_μ into a massive Z_μ and a massless a_μ, related by a rotation involving the Weinberg angle. The expanding outer shell of the sphaleron explosion contains massless photons and near-massless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

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

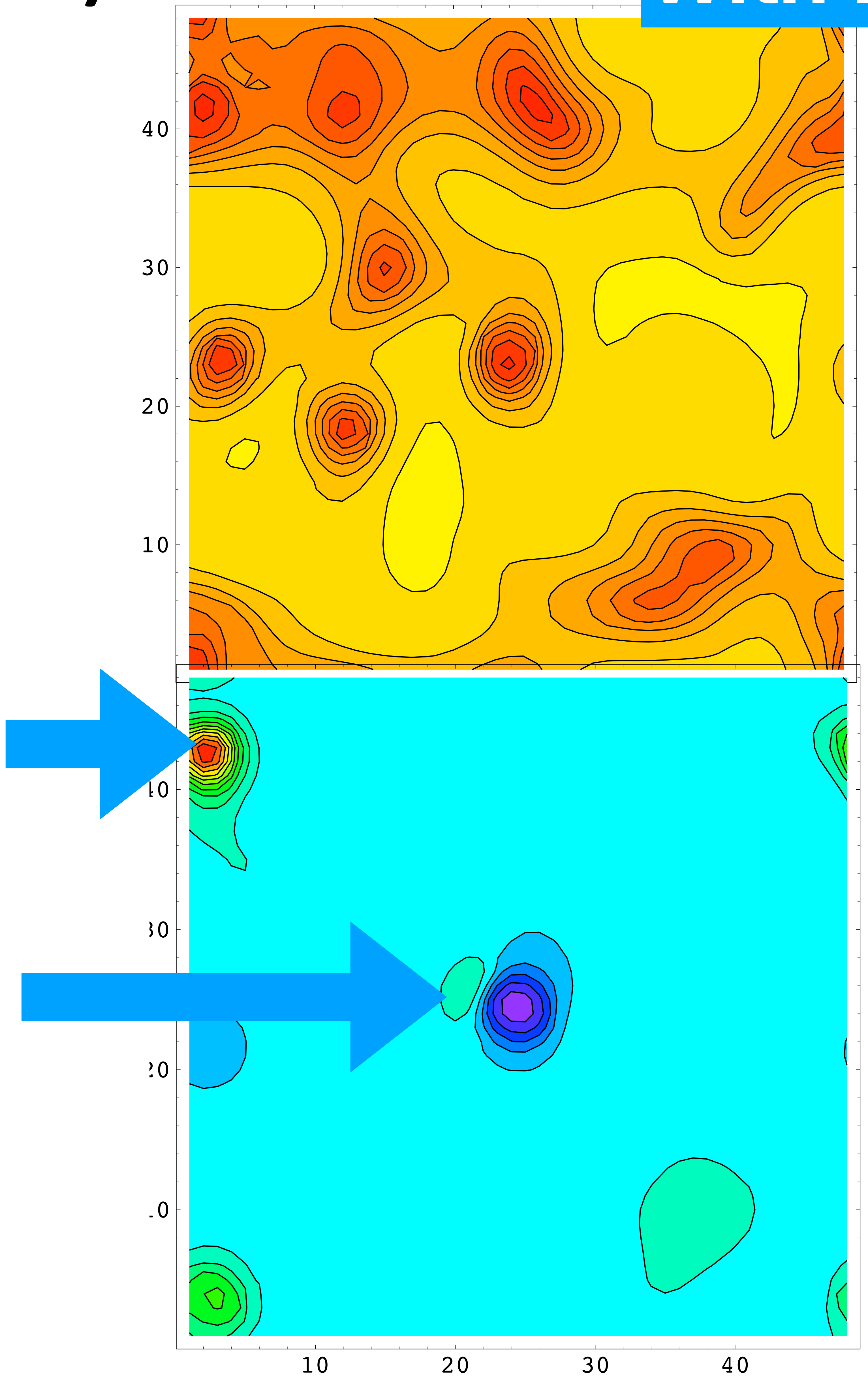
where the inverse cascade time Δt is limited by the electron mass

Intergalactic magnetic fields should be
Of cosmological origin
Magnetic helicity is conserved
CME makes inverse cascade

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**
- =>Γ/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) arXi
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

Summary

Instanton-induced processes lead to production of sphalerons

QCD sphalerons of mass >3 GeV should be produced diffractively
(And maybe they were clusters in WA8)
One may look for much higher mass and multi-gluon events at LHC

Electroweak sphalerons have M of about 8 TeV
And is hard to produce: thus cosmology

Summary

Instanton-induced processes lead to production of sphalerons

QCD sphalerons of mass >3 GeV should be produced diffractively
(And maybe they were clusters in WA8)
One may look for much higher mass and multi-gluon events at LHC

Electroweak sphalerons have M of about 8 TeV
And is hard to produce: thus cosmology

Sphaleron explosions with rate
of the order of Universe expansion rate
are out of equilibrium, +CP =>BAU

Summary

Instanton-induced processes lead to production of sphalerons

QCD sphalerons of mass >3 GeV should be produced diffractively
(And maybe they were clusters in WA8)
One may look for much higher mass and multi-gluon events at LHC

Electroweak sphalerons have M of about 8 TeV
And is hard to produce: thus cosmology

Sphaleron explosions with rate
of the order of Universe expansion rate
are out of equilibrium, +CP =>BAU

Sphaleron explosions also create polarized electrons
Which then transfer helicity to magnetic fields =>
Magnetic helicity then is conserved in plasma
And can perhaps be observable now

Summary

Instanton-induced processes lead to production of sphalerons

QCD sphalerons of mass >3 GeV should be produced diffractively
(And maybe they were clusters in WA8)
One may look for much higher mass and multi-gluon events at LHC

(*) continue searching for chiral imbalance in heavy ion collisions
Using CME in QGP (Kharzeev et al)
(*) identify a single sphaleron production in double-diffractive pp
(Zahed and ES)

Electroweak sphalerons have M of about 8 TeV
And is hard to produce: thus cosmology

Sphaleron explosions with rate
of the order of Universe expansion rate
are out of equilibrium, +CP =>BAU

Sphaleron explosions also create polarized electrons
Which then transfer helicity to magnetic fields =>
Magnetic helicity then is conserved in plasma
And can perhaps be observable now