Toward the theory of strongly coupled Quark-Gluon Plasma (sQGP)

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Outreach of the field is exponentially expanding…

- Why do we think we have strongly coupled quark-gluon plasma (sQGP) at T=(1-2)Tc?

(4 slides, a summary of main arguments)

- Flows and near-perfect liquid
- classical strongly coupled non-Abelian plasma and its first molecular dynamics (MD)
- ``New spectroscopy'' at T>Tc: mesons, colored pairs, baryons, electric chains…
- Topology and ``post-confinement'': monopoles, instantons =>Nc dyons => flux tubes => large potentials at T> Tc ? (connections to N=2 SUSY YM)
- Summary
- (Comment: lessons from AdS/CFT with strongly coupled N=4 theory are spread all over the talk)

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- 1d: very strong jet quenching, including charm, again well beyond pQCD, no Casimir scaling…

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- 2d: **Polymeric "electric" chains of gluons barQ - g - g … Q**

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- (3e: a **complete gravity dual to RHIC**, with black hope production =>ES,Sin+Zahed, sorry no time on that)

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- **New conjecture: sQGP is a plasma of both electric and magnetic charges (to be studied)**

Flows and transport properties at RHIC

Magdeburg hemispheres 1656

(recall here
pumped out
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- **We cannot pump the QCD vacuum out, but we can pump in something else, namely the Quark-Gluon Plasma**

- **QGP proposed in 1970's was expected to be simple near-ideal gas.**

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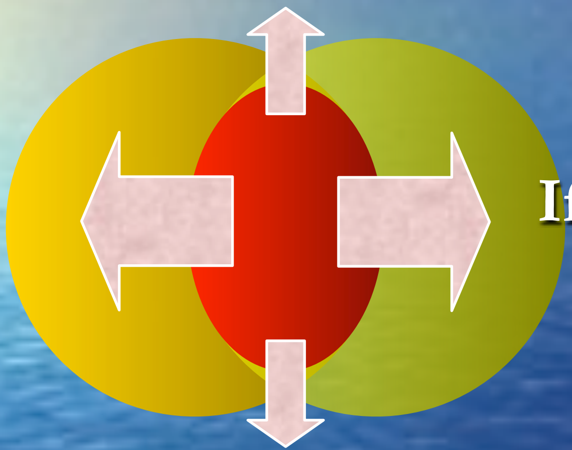
We believed if we increase the energy density, we should eventually get weakly interacting QGP. But something else was found on the way...

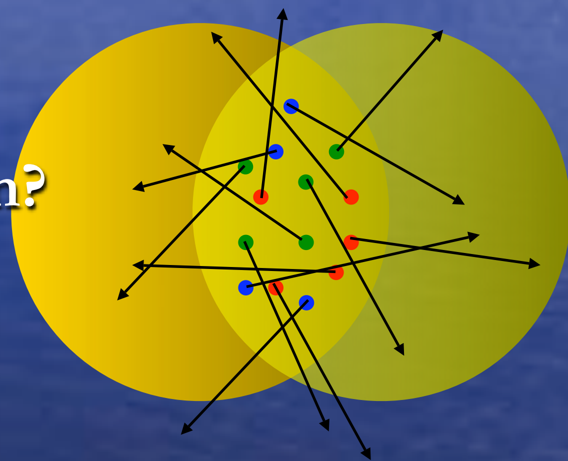
How Hydrodynamics Works at RHIC

Elliptic flow

How does the system respond to initial spatial anisotropy?



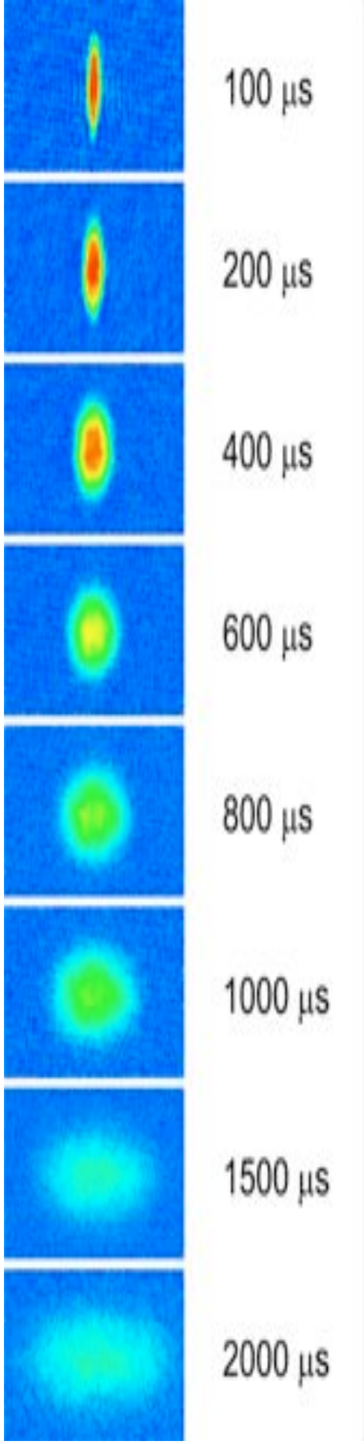
Dense or dilute?
If dense, thermalization?
If thermalized, EoS?



$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots)$$

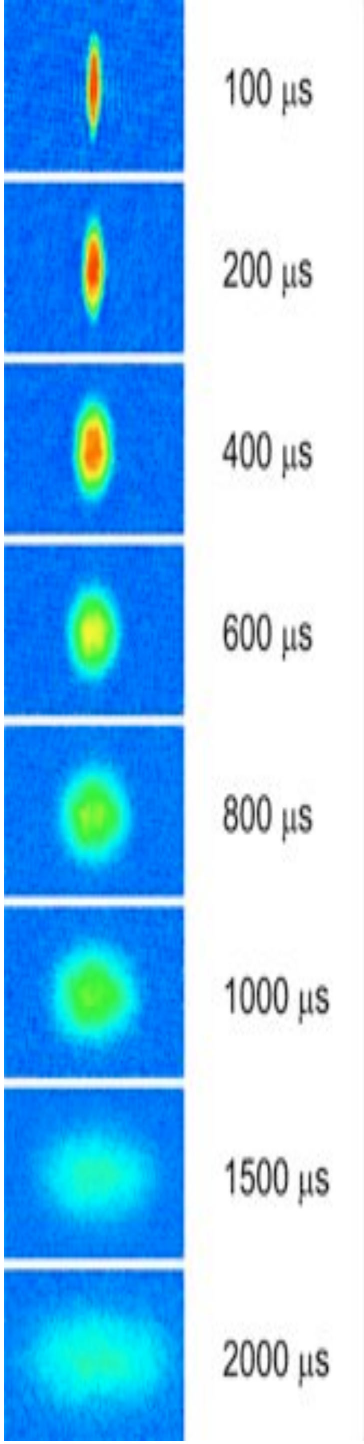
$$v_2(p_T, y) = \frac{\int d\phi \cos(2\phi)\frac{dN}{p_T dp_T dy d\phi}}{\int d\phi \frac{dN}{p_T dp_T dy d\phi}} = \langle\cos(2\phi)\rangle$$

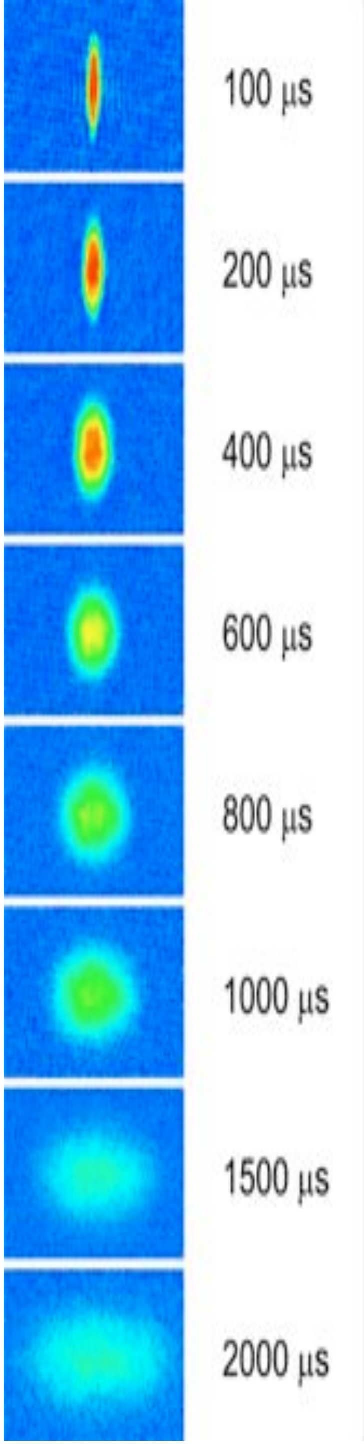
v_4


100 μs
200 μs
400 μs
600 μs
800 μs
1000 μs
1500 μs
2000 μs

The coolest thing on Earth, T=10 nK or 10^(-12) eV can actually produce a

Micro-Bang ! (O'Hara et al, Duke)





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Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime

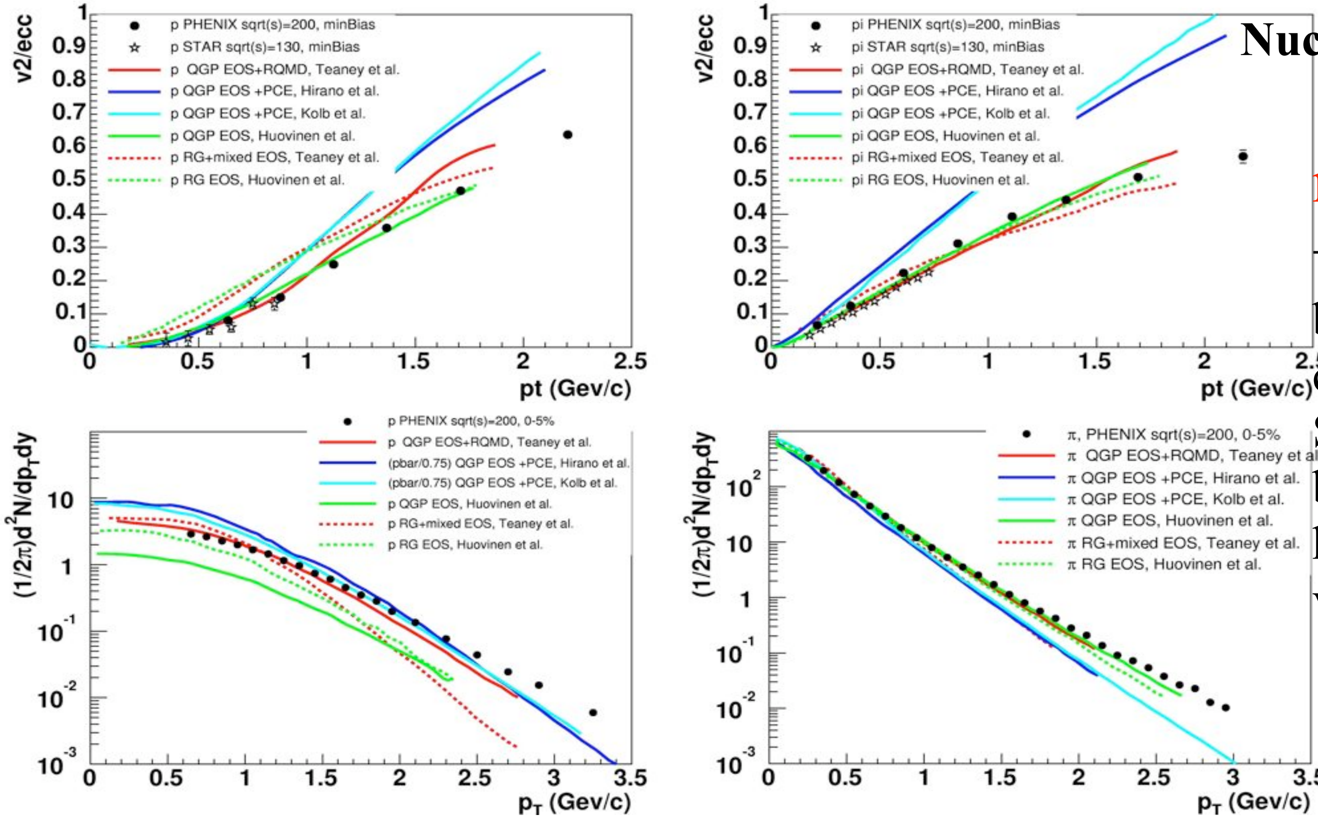
The system is extremely dilute, but can be put into a hydro regime, with an elliptic flow, if it is specially tuned into a strong coupling regime via the so called Feshbach resonance

Similar mechanism was proposed (Zahed and myself) for QGP, in which a pair of quasiparticles is in resonance with their bound state at the "zero binding lines"

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

proton pion

PHENIX, Nucl-ex/0410003



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

(D.Teaney,2003)

Viscosity reduces v2 and changes its pt dependence:

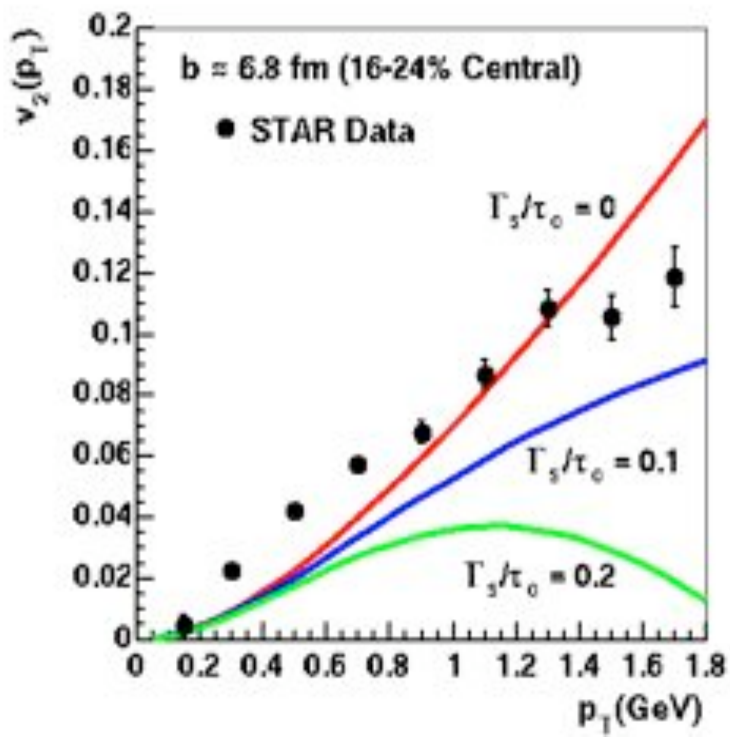
QGP at RHIC seem to be the most ideal fluid known, viscosity/entropy =.1 or so

water would not flow if only a drop with 1000 molecules be made

Correction ↖⊤ $(\eta/s)p_t^2$

=>η/s ℑ .1-.3

(1/4Pi <=AdS/CFT)



Sonic boom from quenched jets Casalderrey,ES,Teaney,

- the energy deposited by jets into liquid-like strongly coupled QGP must go into conical shock waves
- We solved relativistic hydrodynamics and got the flow picture
- If there are start and end points, there are two spheres and a cone tangent to both

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Wake effect or "sonic boom"

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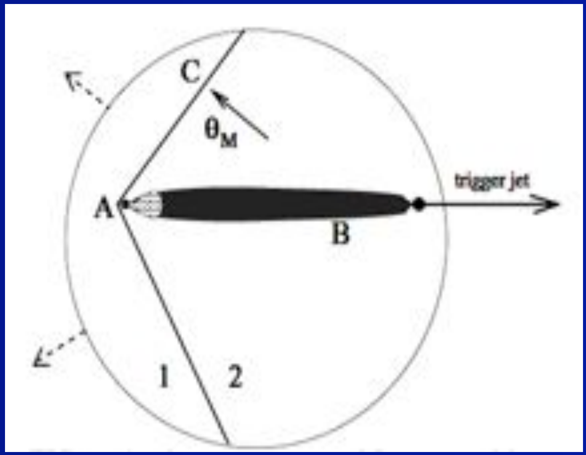

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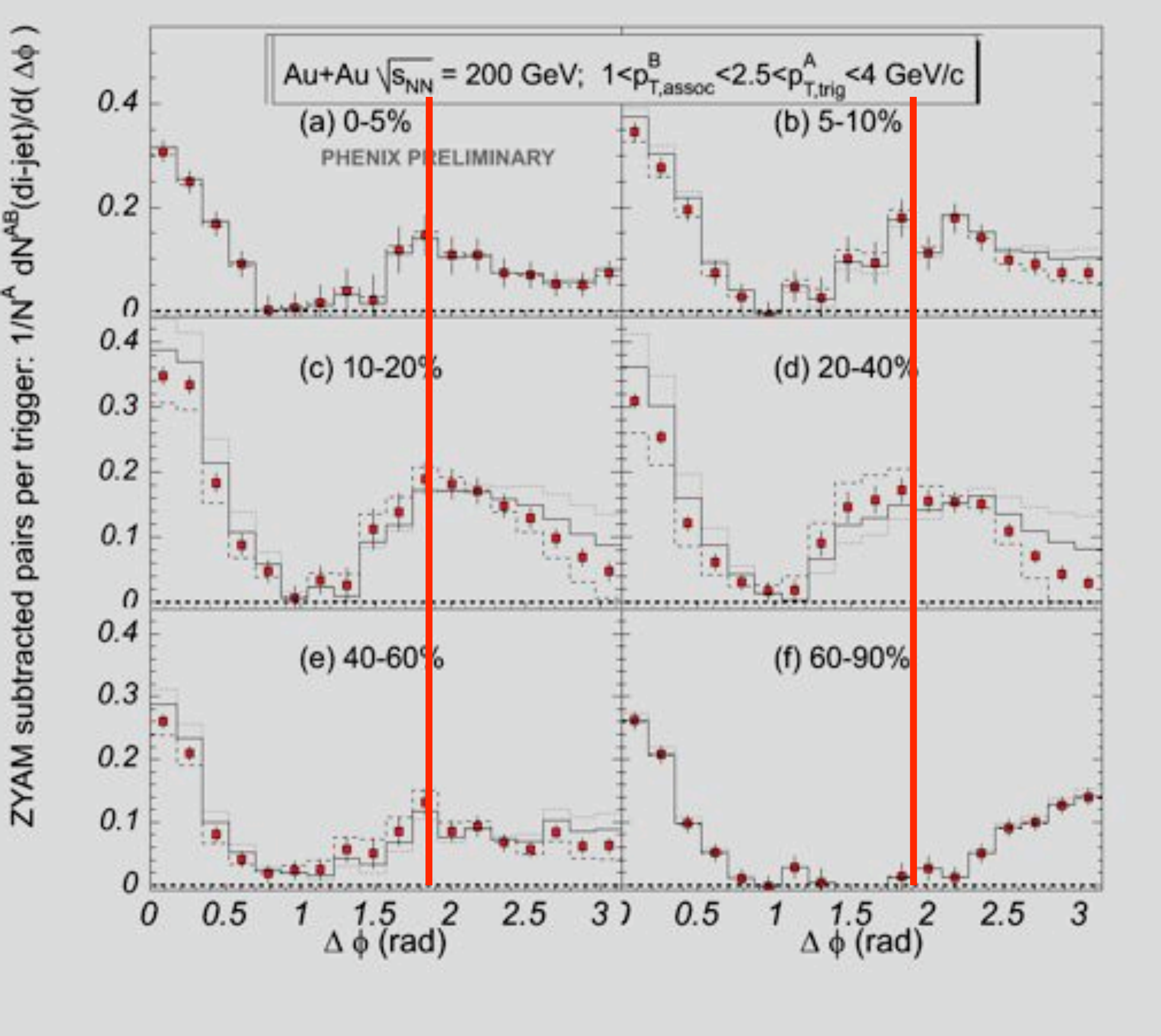
PHENIX jet pair distribution



Note: it is only projection of a cone on phi

Note 2: more recent data from STAR find also a minimum in <p_t(\phi)> at 180 degr., with a value Consistent with background

Studies of a charge moving in sQGP at strong coupling (AdS/

- AdS/CFT allows to study a charge moving

With fixed velocity in a system:

A string pending and falling into the black hole

- L.Yaffe talk here, and also D.Teaney and J.Casalderrey found such solution at nonzero T calculating dE/dx (the drag force) , sonic boom etc

Explaining transport in sQGP:

Classical QGP and its Molecular Dynamics

(B.Gelman,ES,I.Zahed,

- For $SU(2)$ charge Q is a unit vector, $\vec{Q} = (Q^1, Q^2, Q^3)$

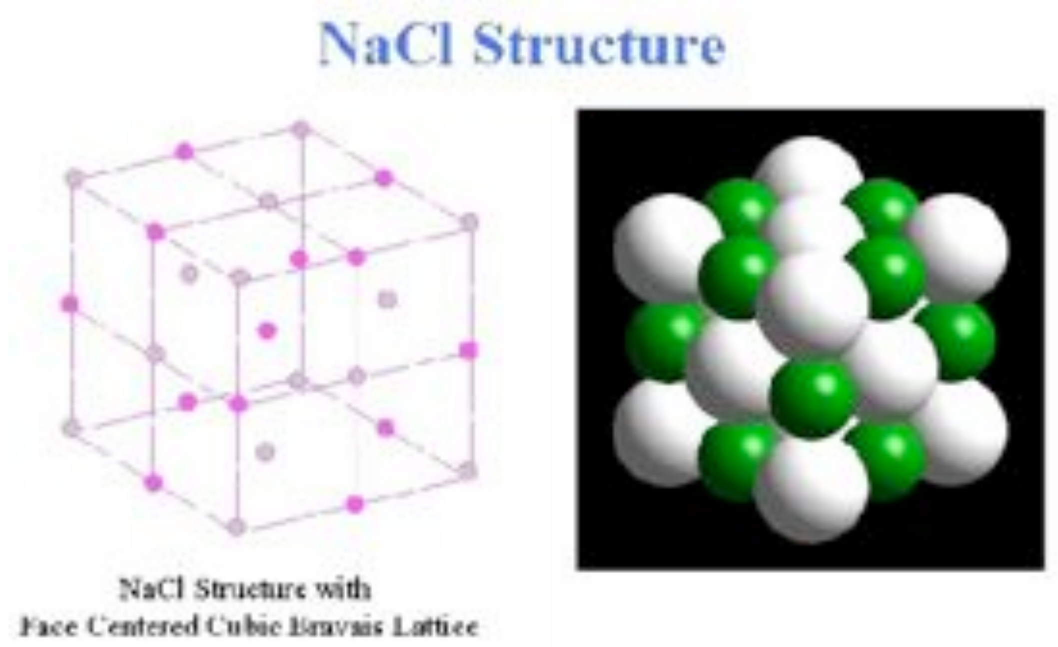
$$dx_i/dt = p_i/m,$$
$$dp_i/dt = (g^2/4\pi)\sum \vec{Q}_i \cdot \vec{Q}_j / r_{ij}^2,$$
$$d\vec{Q}_i/dt = (g^2/4\pi)\sum \vec{Q}_i \times \vec{Q}_j / |r_{ij}|$$

- Note: $d\vec{Q}_i^2/dt = 0$

Wong eqn **can be rewritten as**
x-p canonical pairs, 1 pair for SU(2), 3 for SU(3),
(as a so called Darboux variables).
We do su(2) => C is a unit vector on a sphere O(3)

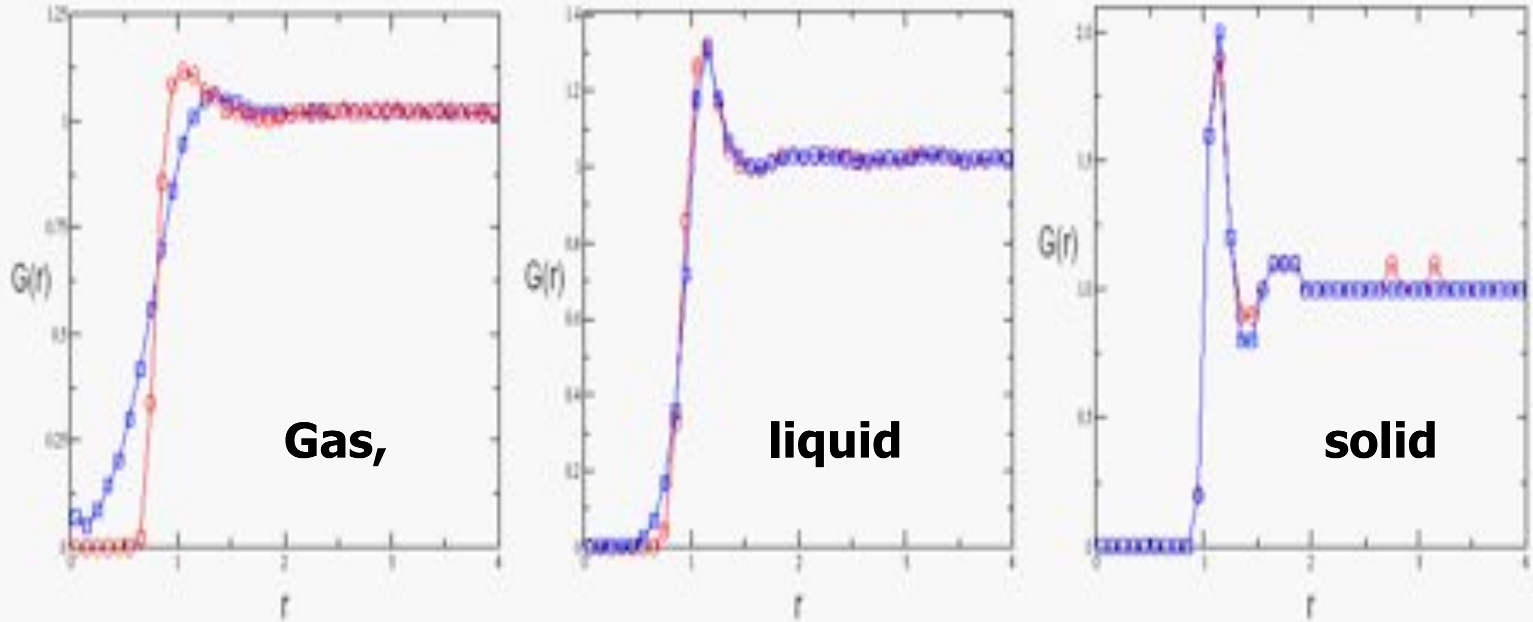
As Gamma= <|Epot|>/<Ekin> grows gas => liquid => solid

- **This is of course for +/- Abelian charges,**
- **But ``green" and ``anti-green" quarks do the same!**



•local order would be preserved in a liquid also, as it is in molten solts (strongly coupled TCP with <pot>/<kin>=O(60), about 3-10 in sQGP)

Structure factor for cQGP



- G_d correlation function for $\Gamma = 0.83, 31.3, 131$, respectively; red circles correspond to $t^* = 0$, and blue squares correspond to $t^* = 6$
- $\Gamma = 0.83$ is a weak correlation between the particles; relaxes rather quickly with time
- The correlation is more robust for $\Gamma = 31.3$ (*liquid*)
- For $\Gamma = 131$ correlation is very stable (*solid*)

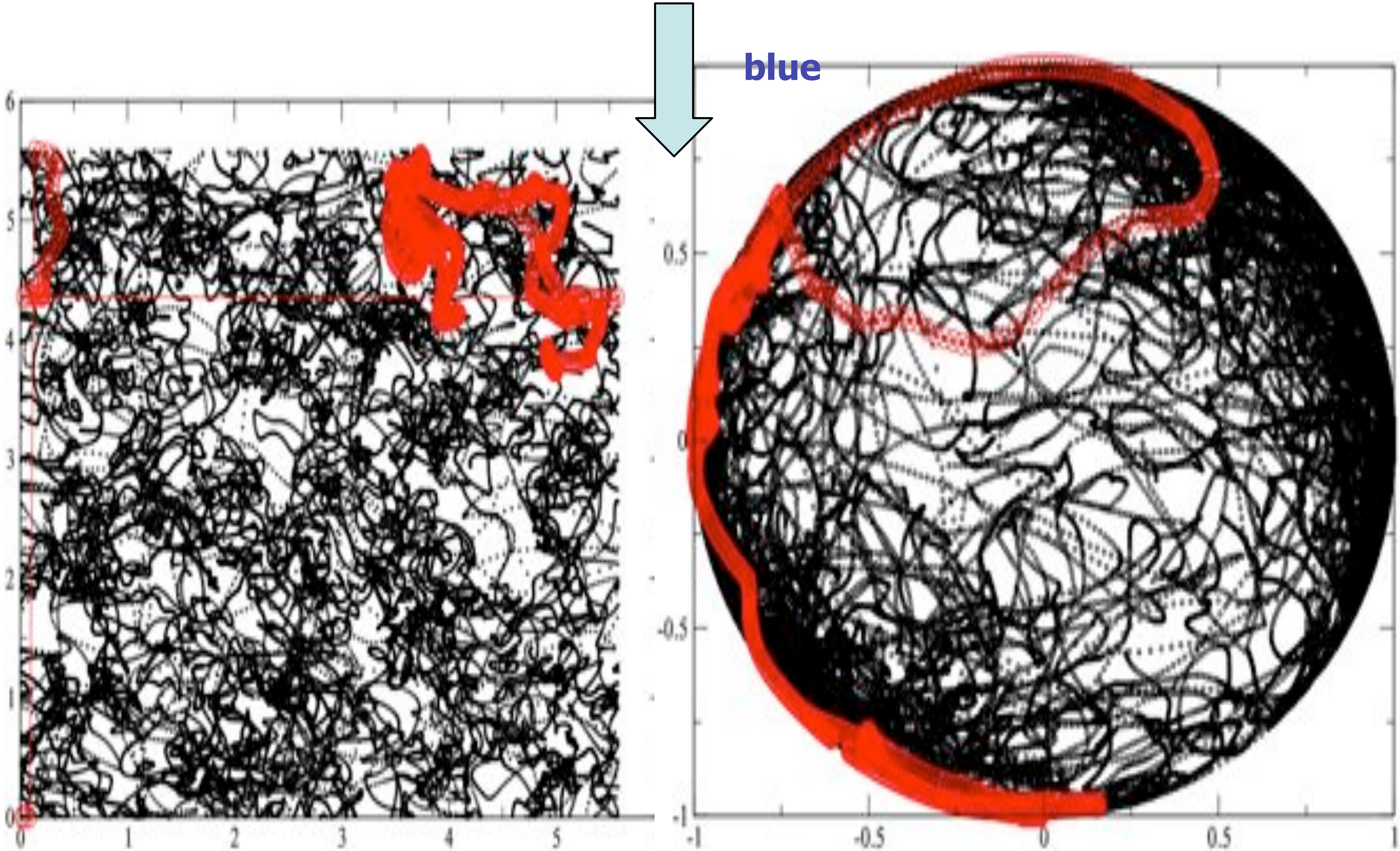
cQGP made of 64 colored particles,

projecttion of a cube on x-y plane,

red is the path of particle #1.

strong coupling,
Gamma is about 100
close to freezing

Color -> red

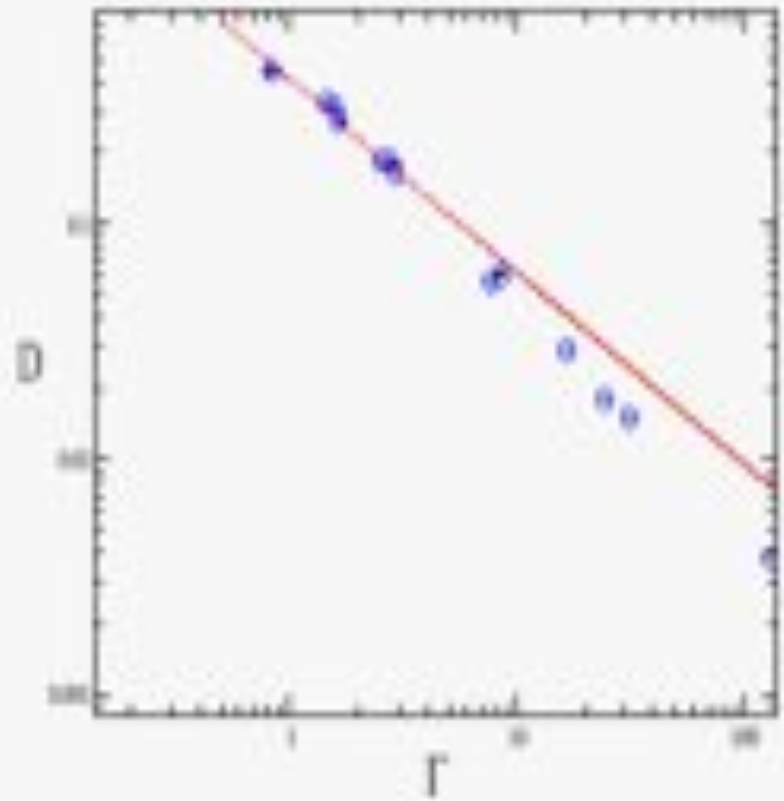


Self-diffusion

$$D(\tau) = \frac{1}{3N}\left\langle \sum_{i=1}^{N} \vec{v}_i(\tau)\cdot\vec{v}_i(0) \right\rangle$$

$$D = \int_0^{\infty} D(\tau)\, d\tau$$

$$D \approx \frac{0.4}{\Gamma^{4/5}}$$



Shear viscosity

- Green-Kubo relation for viscosity

$$\eta = \int_0^\infty \eta(\tau)\, d\tau$$

$$\eta(\tau) = \frac{1}{3TV} \left\langle \sum_{x<y} \sigma_{xy}(\tau)\, \sigma_{xy}(0) \right\rangle$$

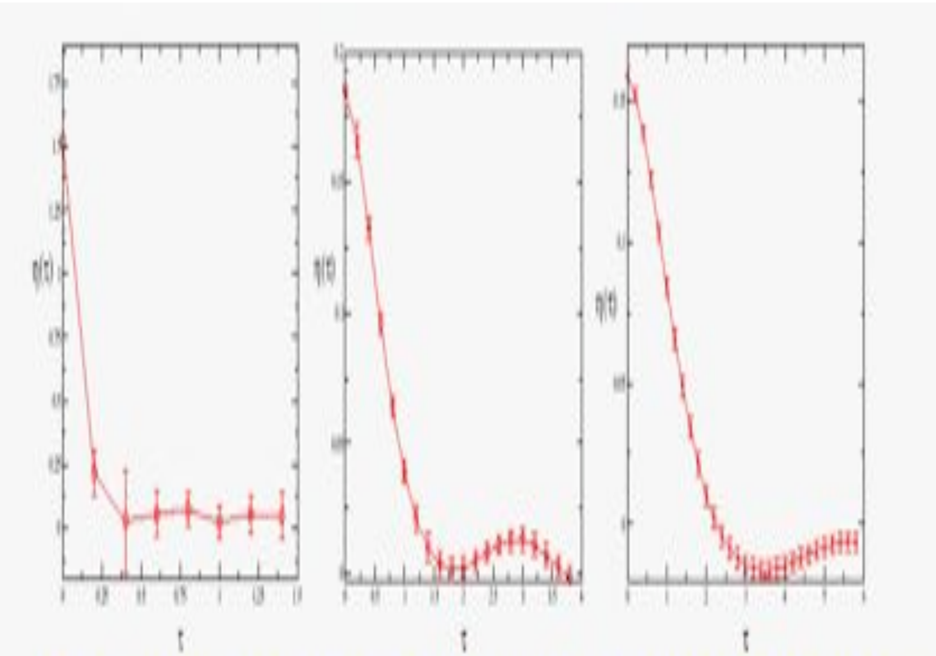
$\sum_{x<y}$—a sum over the three pairs of distinct tensor components (xy, yz and zx); the stress-energy tensor are given by

$$\sigma_{xy} = \sum_{i=1}^{N} m_i v_{ix} v_{iy} + \frac{1}{2} \sum_{i \neq j} r_{ij,x} F_{ij,y}$$

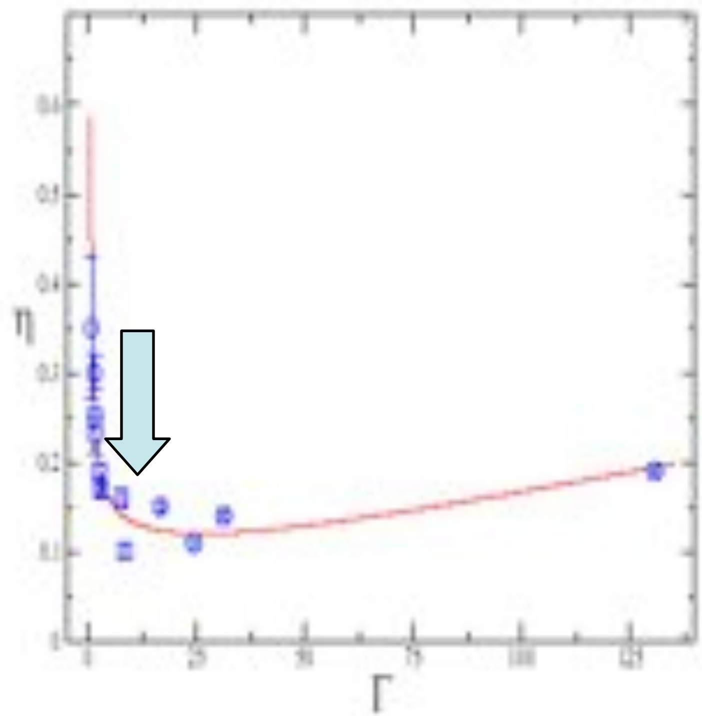
$\vec{F}_{ij}$ is the force on particle i due to particle j

First results on viscosity:

QGP (blue arrow) is about the best liquid one can possibly make



- Stress-tensor autocorrelation correlation function $\eta(t)$ for Γ = 0.83, 31.3, 131



$$\eta \approx 0.001\,\Gamma + \frac{0.242}{\Gamma^{0.3}} + \frac{0.072}{\Gamma^{2}}$$

``New spectroscopy” in sQGP

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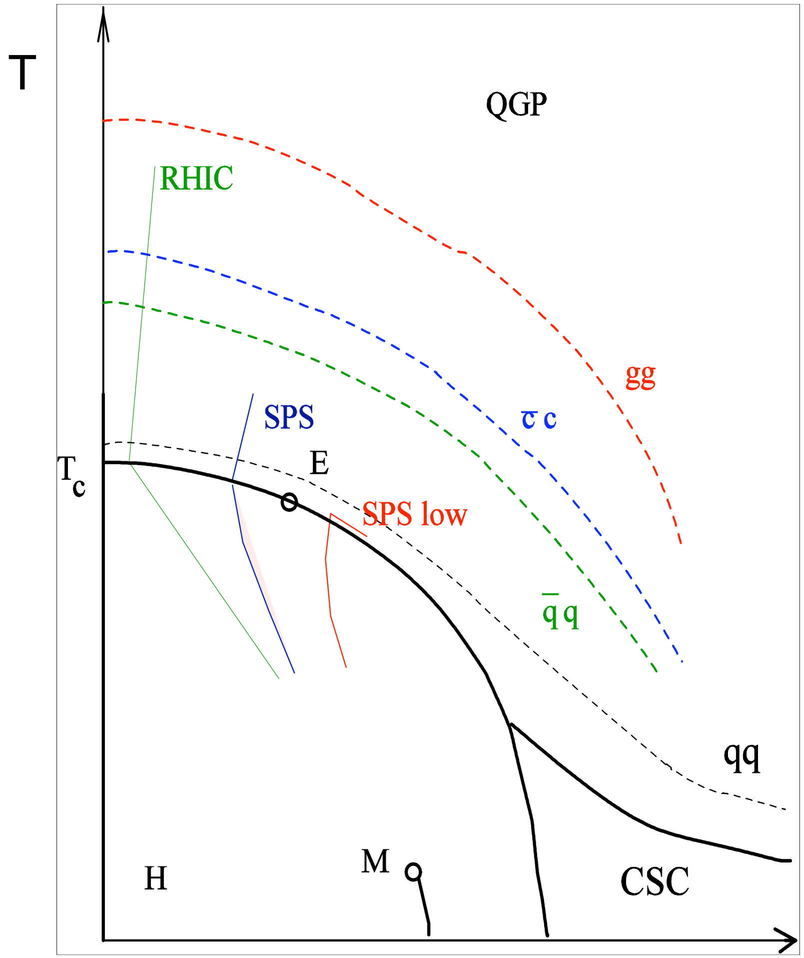
2003: Can mesons survive deconfinement?

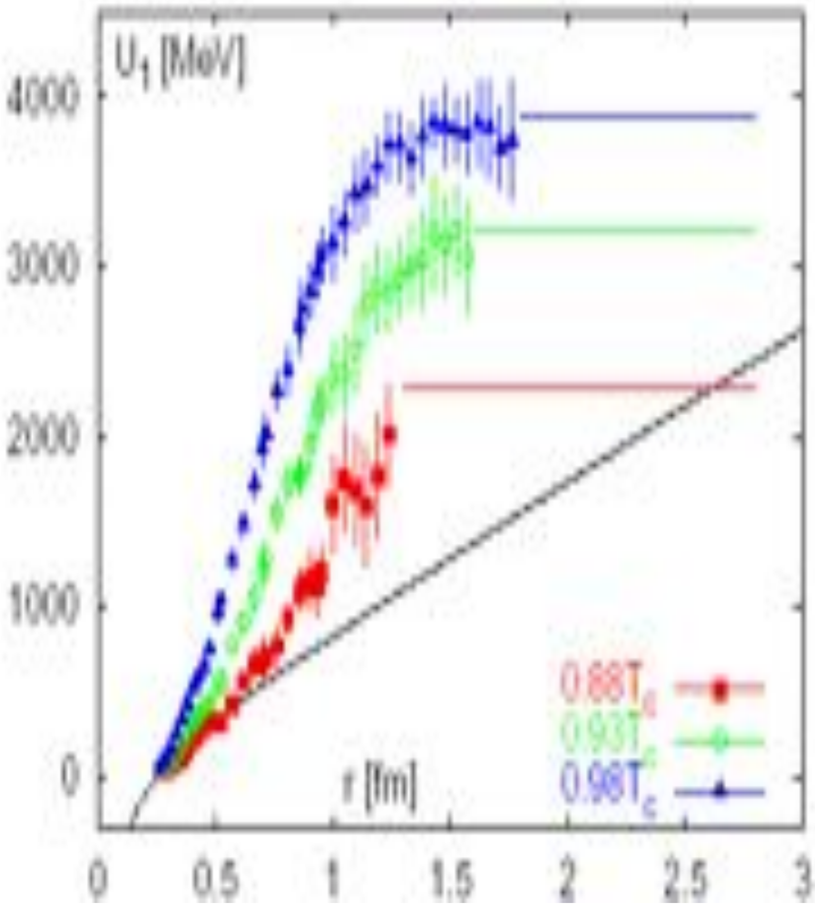


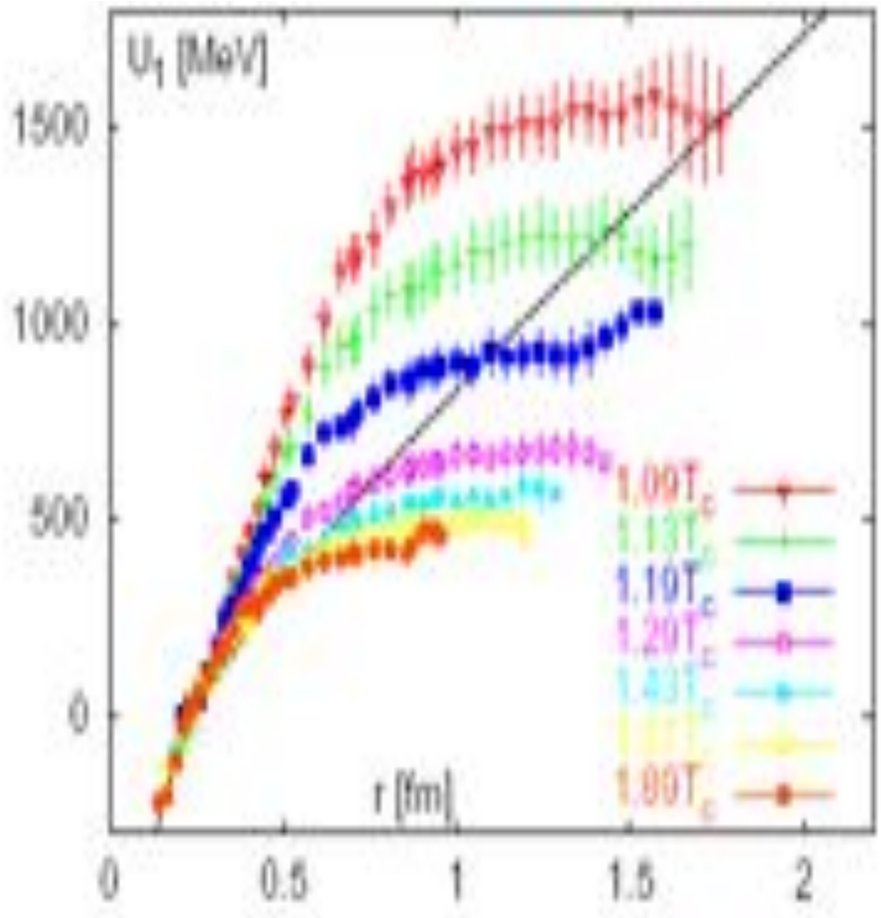
Chemical potential
mu

Can resonance scatering help explain small m.f.p.? (It does for atoms)

Are regions of meson binding the divider between wQGP and sQGP? (ES+I.Zahed,``rethinking" paper PRC 2003, the beginnig of sQGP…):

``Postconfinement”
potential energy of a static dipole
at T=(1-2)Tc and r=.5-1 fm is even larger





Solving for the bound states ES+I.Zahed, hep-ph/0403127

- **Charmonium remains bound till 2Tc => confirmed by lattice correlators and now by direct RHIC J/Psi data**
- **In QGP there is no confinement => Hundreds of colored channels SHOULD have bound states as well**

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

the strongest

The usual

weak

- gg color 8*8=64=27+2*10+2*8+1: only the 2 color octets $(gg)_8$ have $(16 * 3_s * 3_s = 144)$ states.

Baryons at T>Tc ? Polymer chains?

J.Liao+ES,05

- **Lattice favors ``potential-like" (b) behavior of the potentials for baryons.**
- **(a)= V(1j)+V(2j)+V(3j) (j=junction)**
- **(b)=(V(12)+V(13)+V(23))(1/2) Casimir**
- **Fortunately <V>(a) and <V>(b) do not differ by more than 15%!**

- **polymeric chains \bar q g … gq , with color indices convoluted as writte**

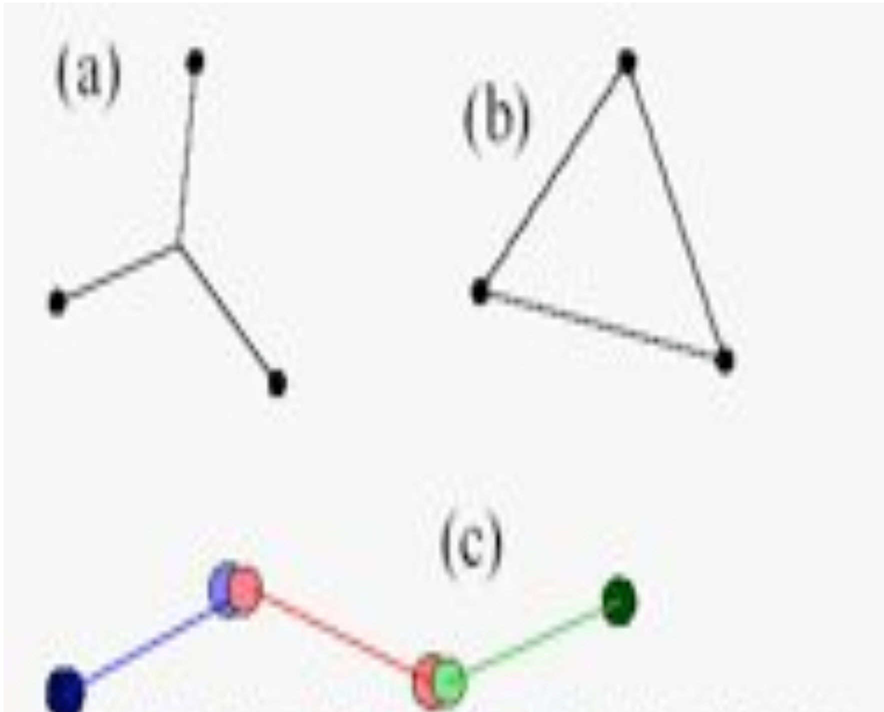
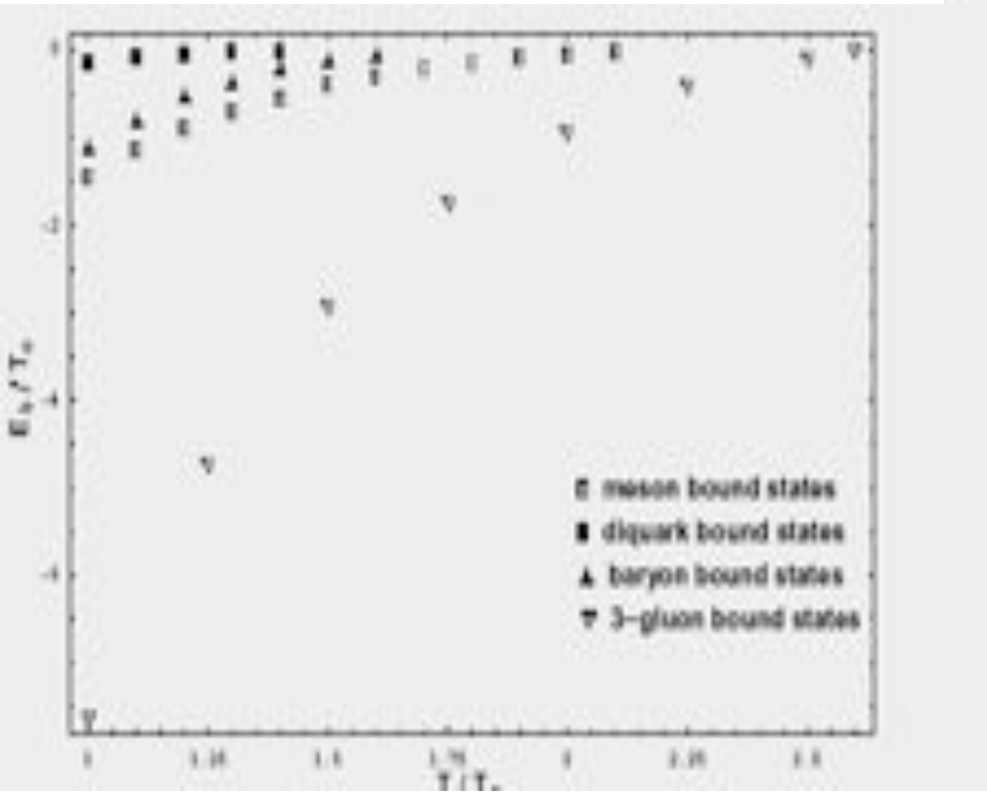


FIG. 1. The interaction in baryons for "string-like" interaction (a) versus the "potential-like" interaction (b). The double circles with different colors (online) in (c) represent gluons, and it is an example of 4-chain $\bar{q}ggq$.

Bindings from variational calculation for baryons and ggg chain (J.Liao+ES, 05)

electric chains have the same binding as mesons per link



structure	-body	G	E_b at T_c	T_m
$\bar{q}q$	2	1	-1.45	2.1
$\bar{q}g\cdots gq$ olymer chain)	N	1	-1.45*(N-1)	2.1
ggg losed chain)	3	1	-7.64	2.6
qq	2	1/2	-0.13	1.4
qqq close chain)	3	1/2	-1.10	1.6

Polymeric chains in strongly coupled Higgsed N=4 (J.Minahan 98)

Nc branes are put not at the same point, but say 2 lumps Nc/2 +Nc/2 =>

Massive gluons

String solutions with a string oscillating between the lumps

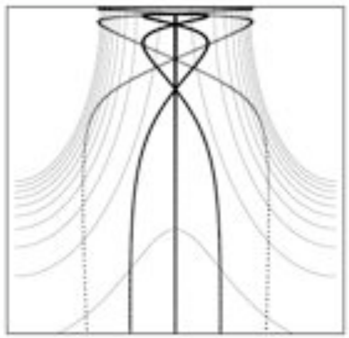
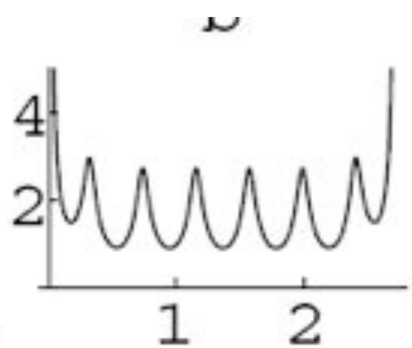


Fig. 2: *Geodesics with six half oscillations. As L is increased, the geodesic approaches the concatenation of the BPS geodesics of two quarks and a five Ws.*



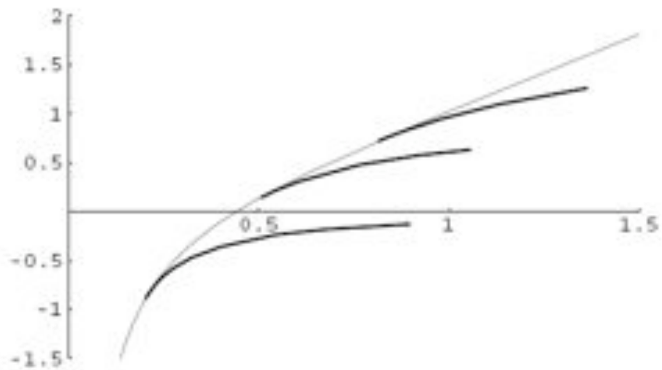
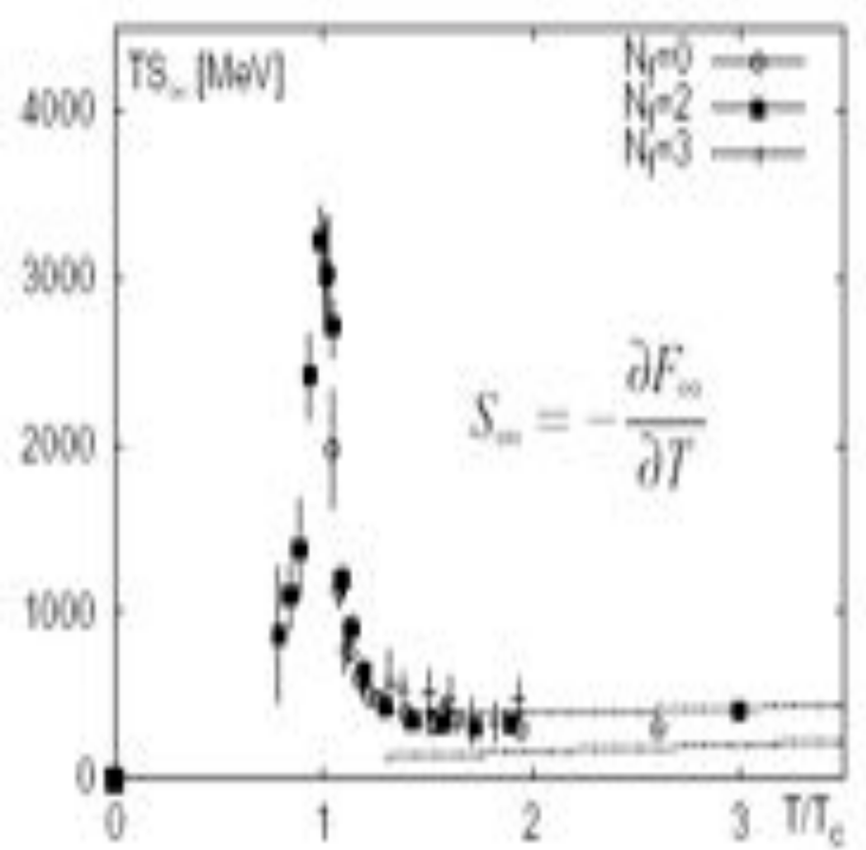


Fig. 3: *Plot of E vs. L for the saddle branch and the first three coulomb branches. E is plotted in units of the W mass, m_W, and L is in units of R^2/m_W. The first and third branches are doubly degenerate. The second branch is a $\mathbb{Z}_2$ symmetric branch.*

13

Entropy associated with a static dipole gets huge! (shown at large r vs T/Tc)



- **S/charge =O(10)**
- **#(states) =exp(10)**

What those states may be?

- **string picture**

(Polyakov 78 => Klebanov,Maldacena,Thorn et al hep-th/0602255)

- **electric polymers (Liao,ES 05 … Ads/CFT Minahan 98)**
- **trapped monopoles?**

Postconfinement and monopoles at T>Tc

monopoles in QGP

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- Dual superconductivity as a confinement mechanism (‘tHooft, Mandelstam 1980’s) require monopole condesation (nonzero VEV)

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monopoles in QGP

- Dual superconductivity as a confinement mechanism ('tHooft, Mandelstam 1980's) require monopole condesation (nonzero VEV)
- But maybe we better look at T>Tc and study dyon dynamics without condensation when they are heavy/classical enough?
- Lorentz force on monopoles makes them reflect from a region with E, or even rotate around the E flux => compresses E into flux tubes even in classical plasma!

Can a flux tube exist without a dual superconductor?

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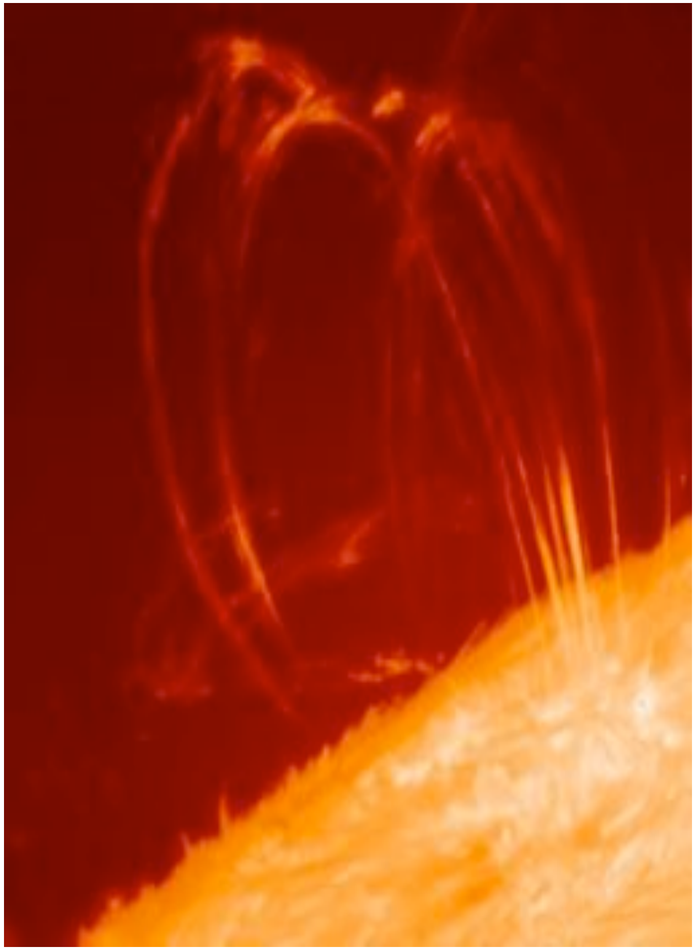
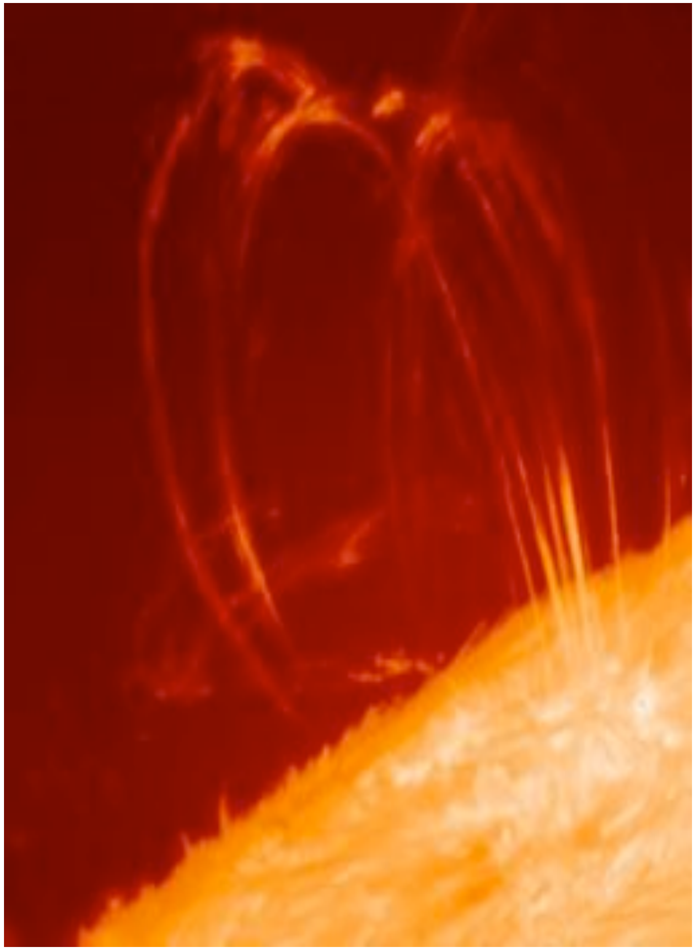


Can a flux tube exist without a dual superconductor?

- **Here are magnetic flux tubes at the Sun,**



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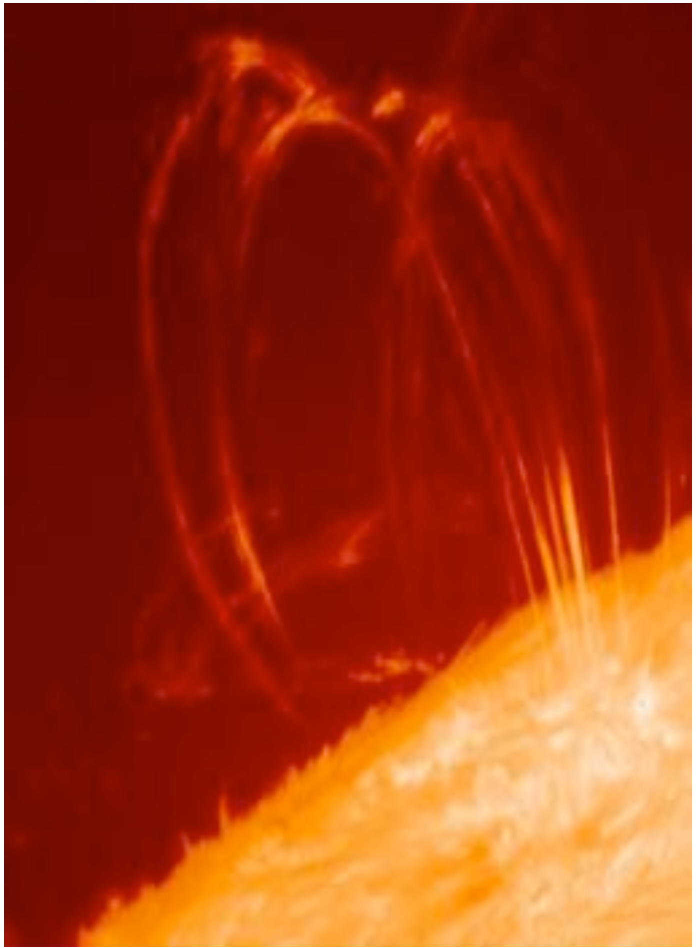

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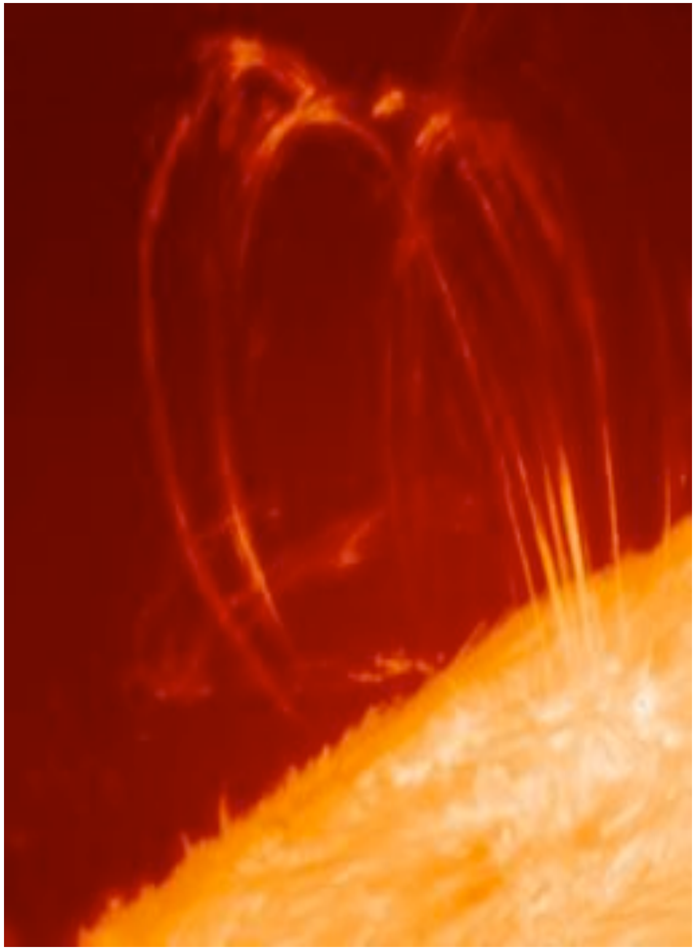

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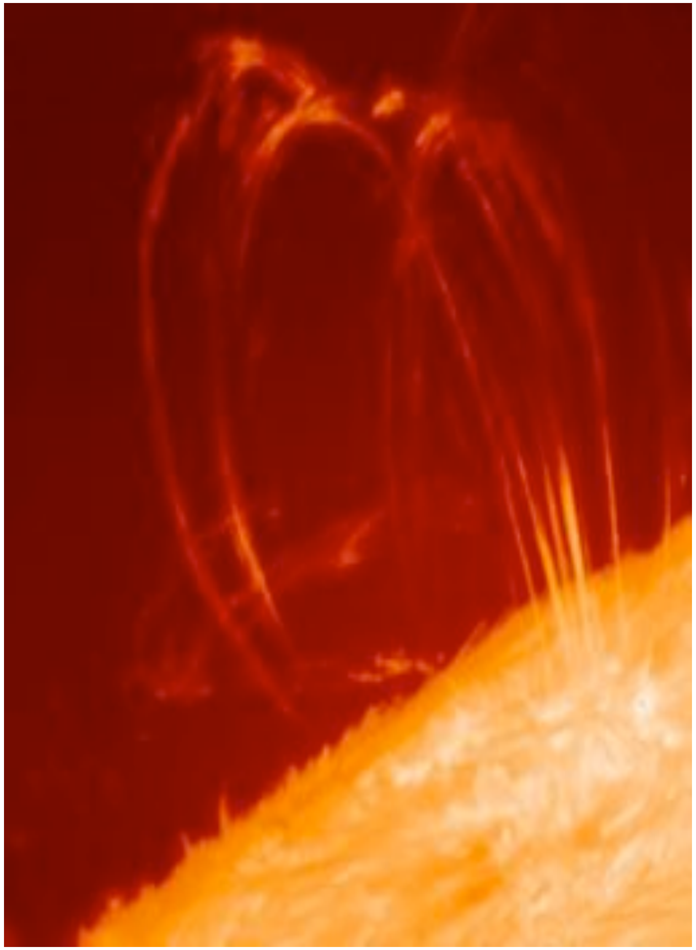

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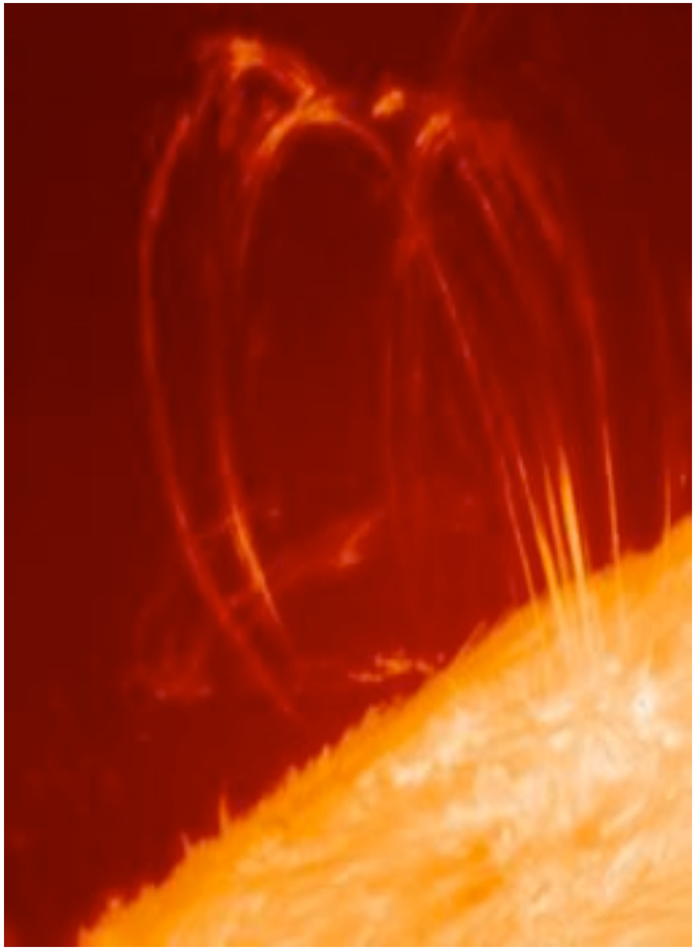

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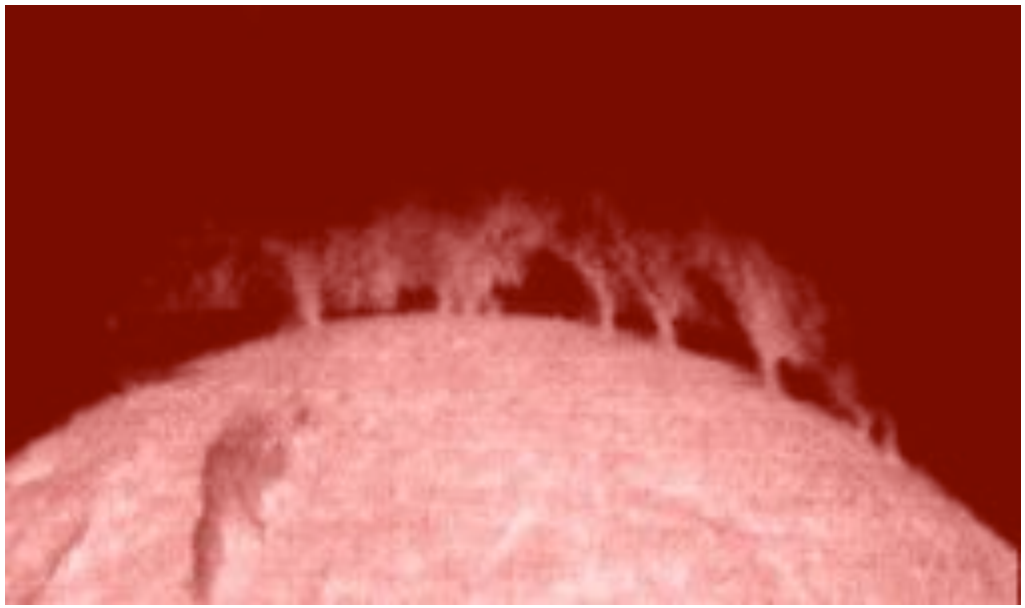
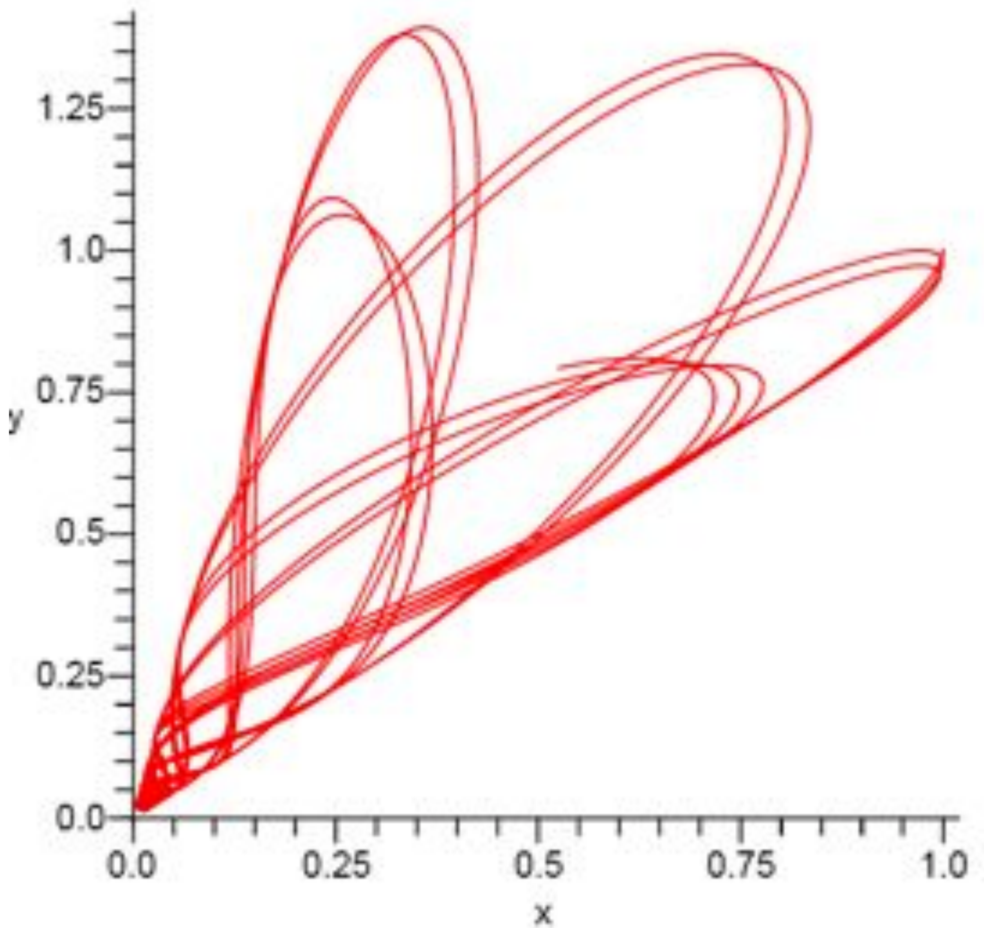


Let us however start with one monopole (dyon)+ one charge

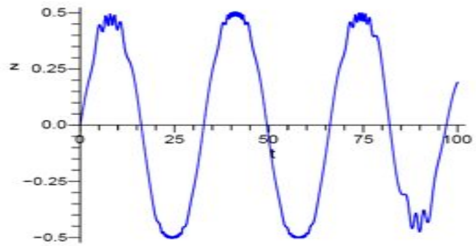
A.Poincare 110 years ago had explained that there is angular momentum of the field J || to r
and that the motion is restricted to a cone

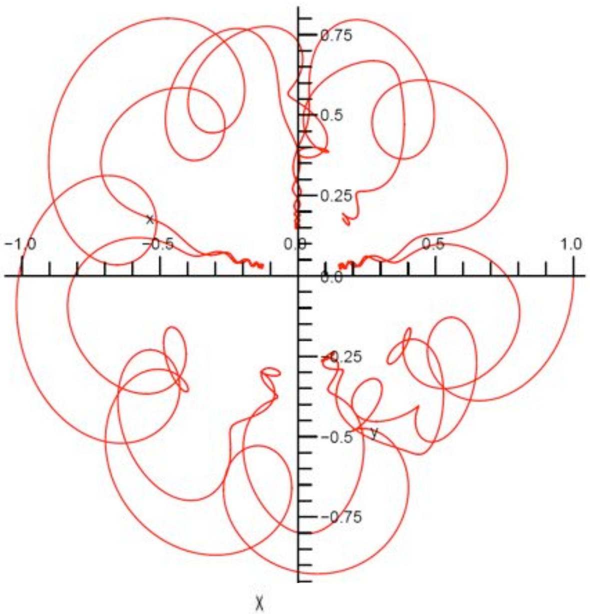
Monopole repels from a charge



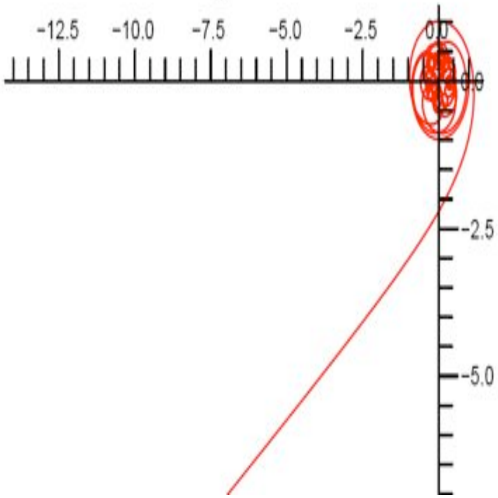
Here is my solution for a dyon with Attractive charge, preventing the escape to large r
Quantum system is like H atom…

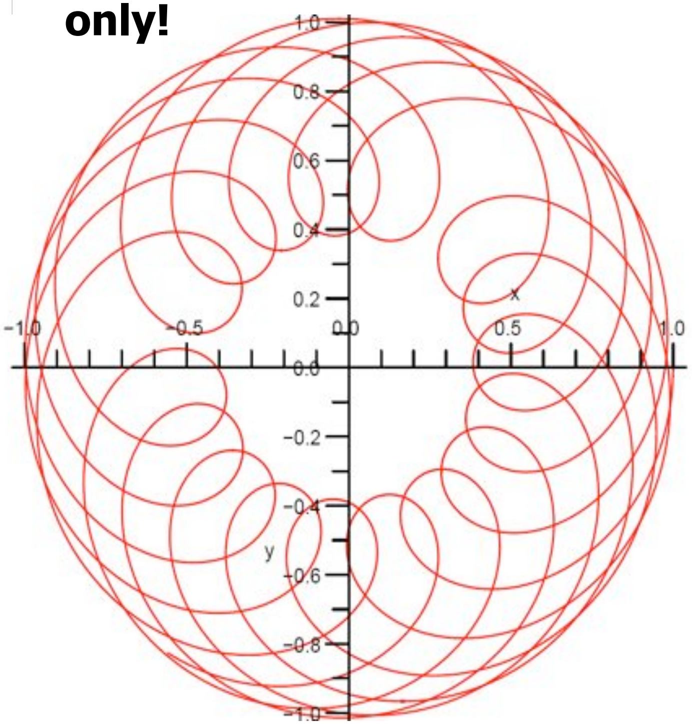
I found that two charges play ping-pong by a monopole without even moving!





Chaotic, regular and escape trajectories for a monopole, all different in initial condition by 1/1000 only!





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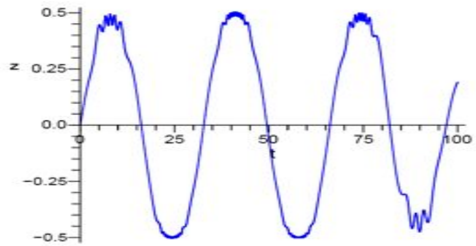

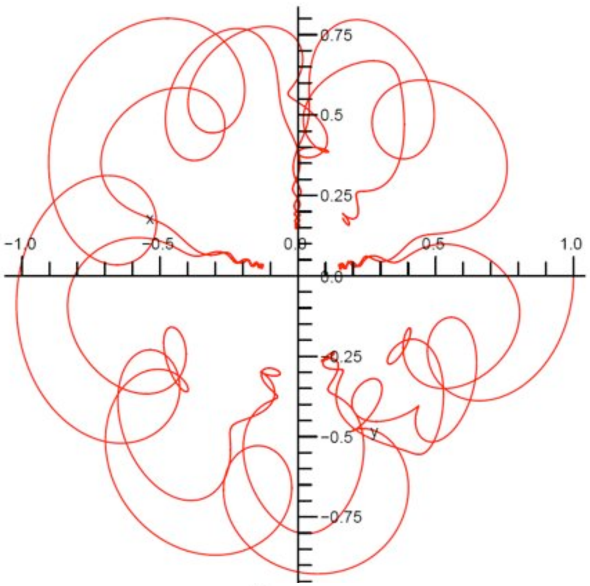

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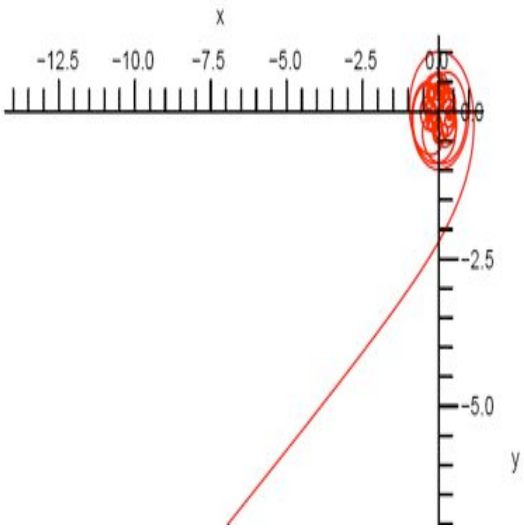
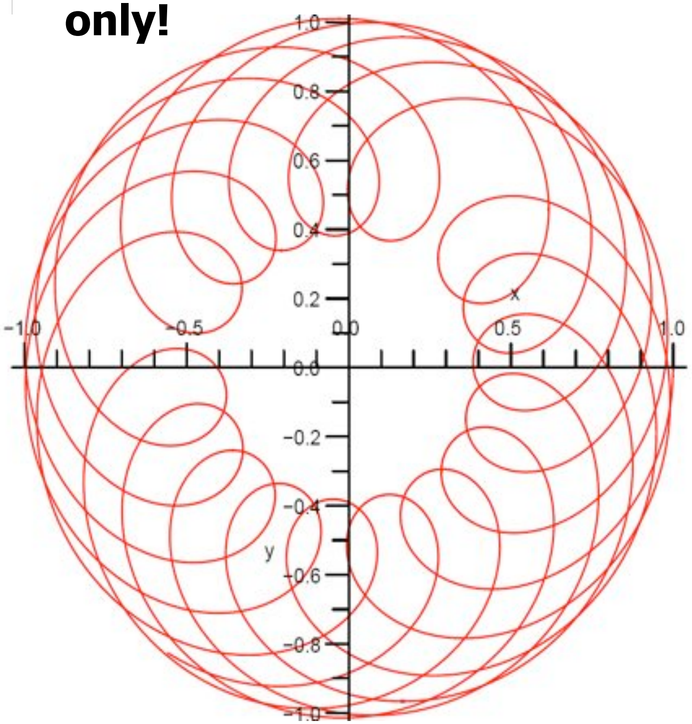
Dual to Budker's





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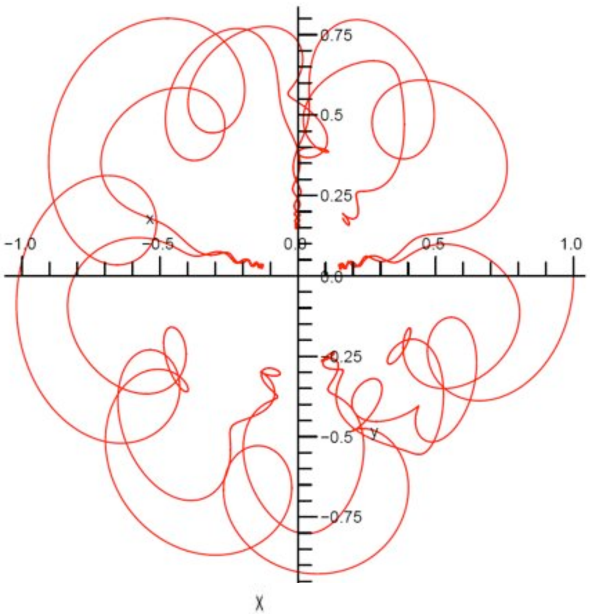

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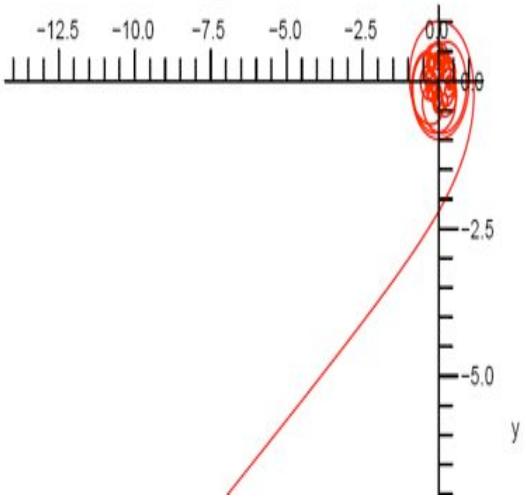

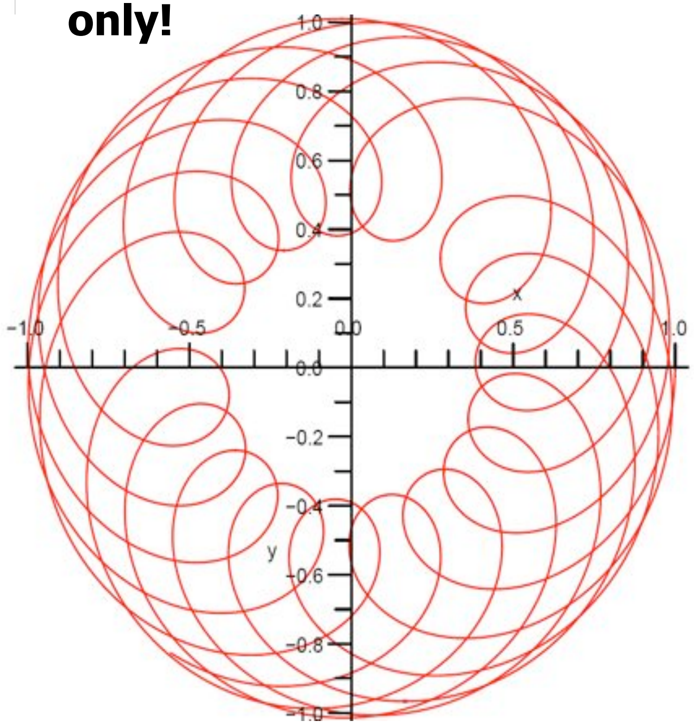

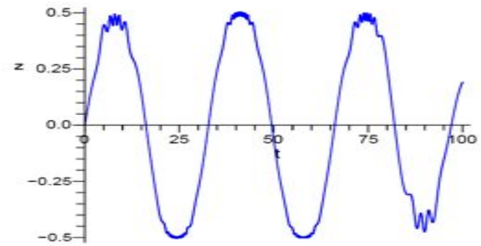

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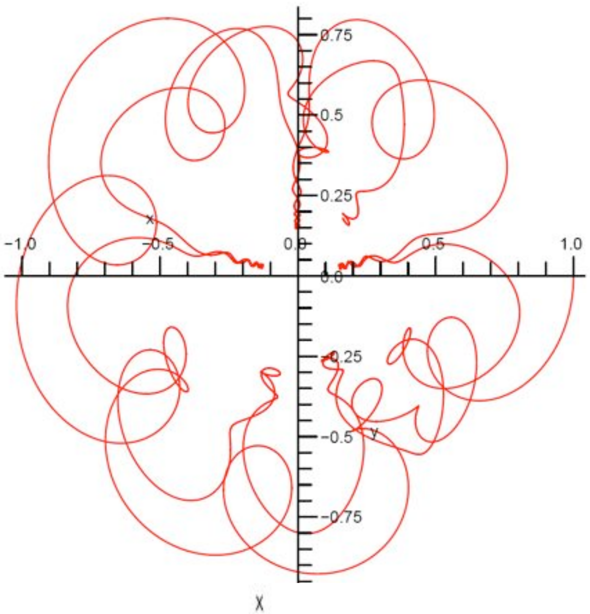

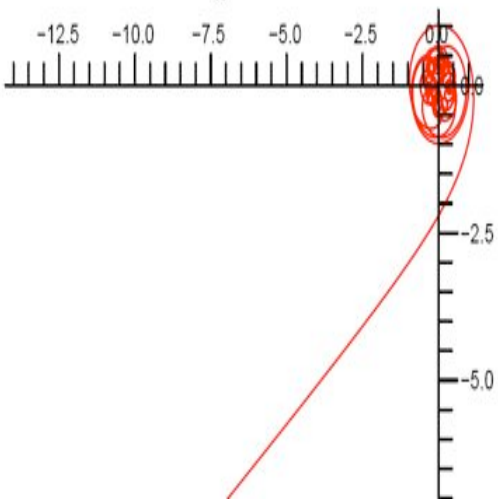

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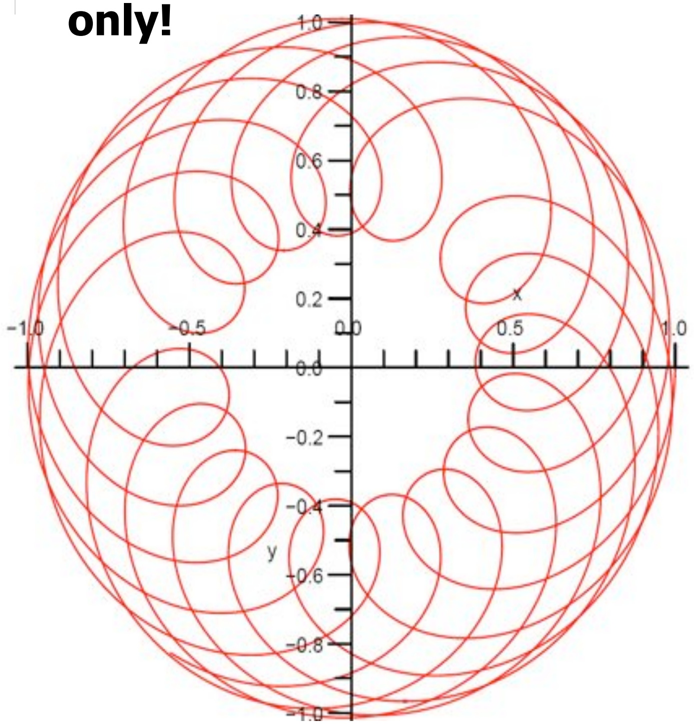

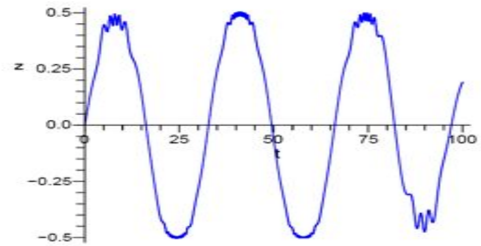

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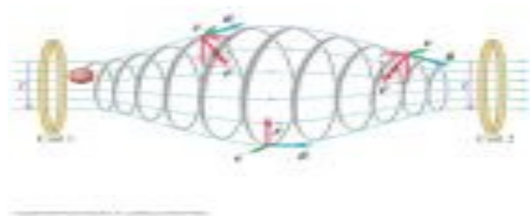

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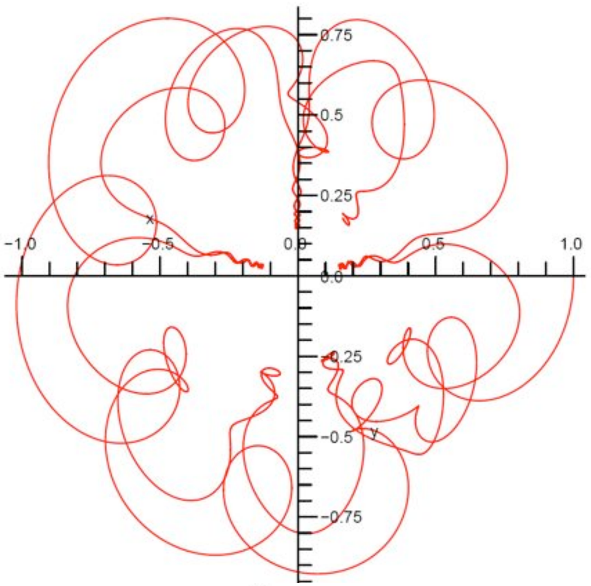

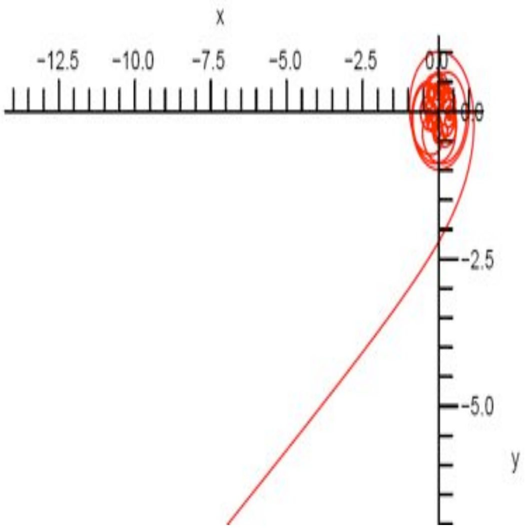

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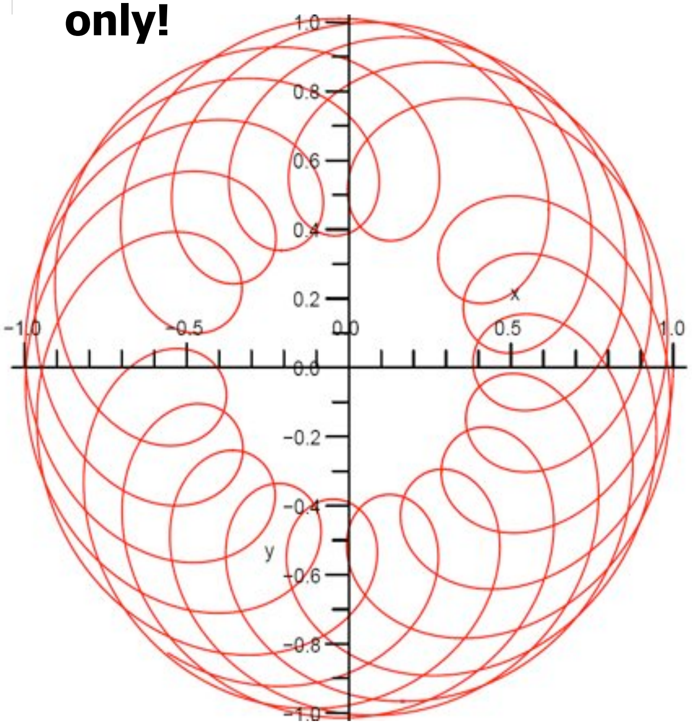

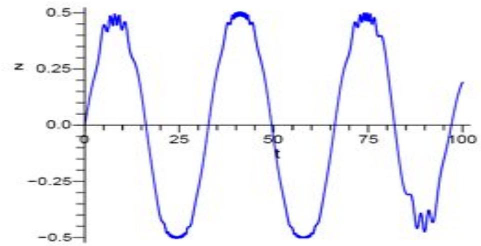

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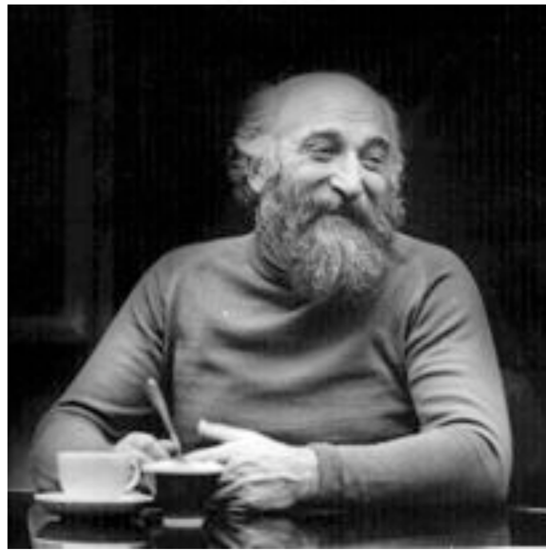


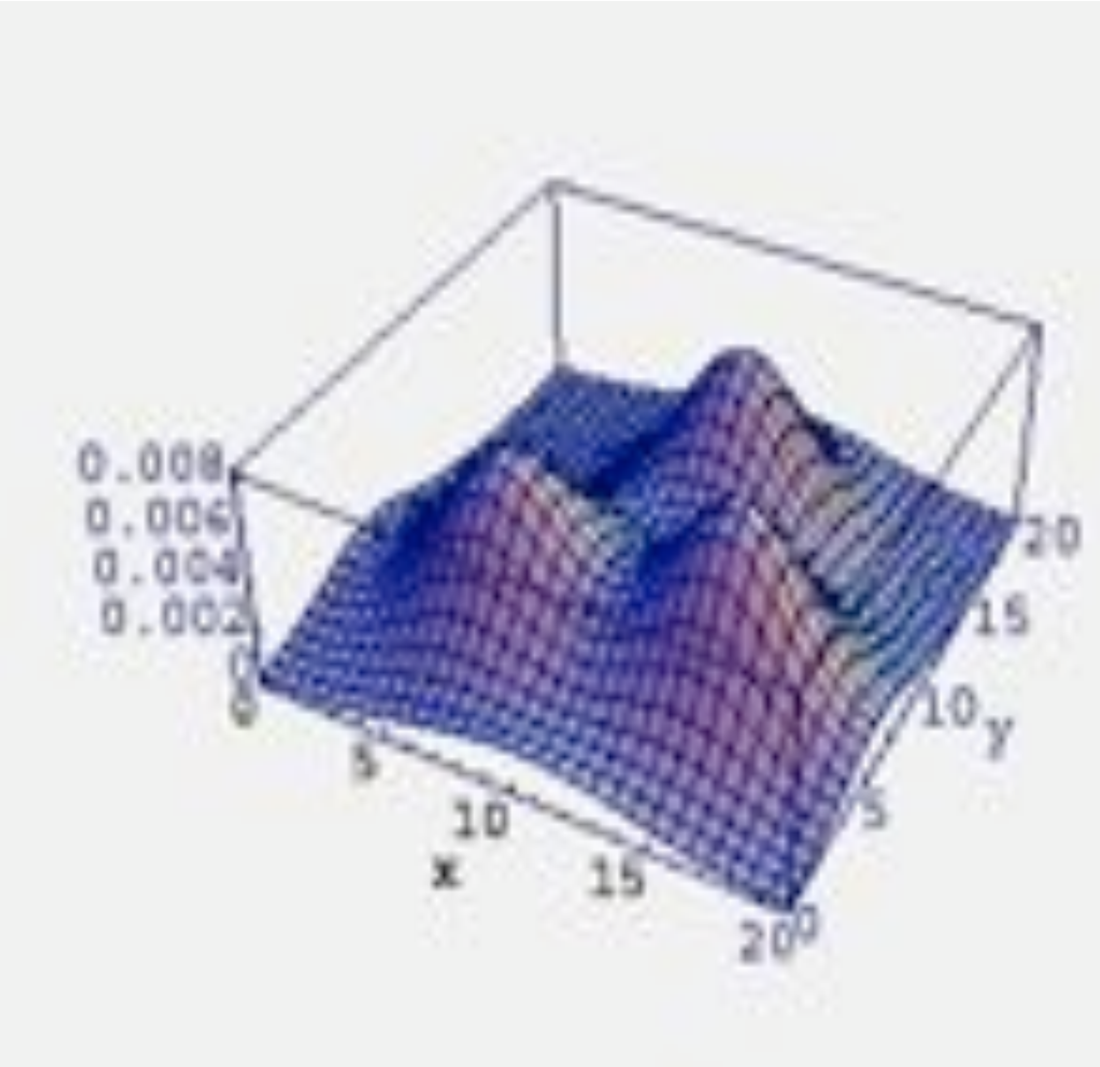
Can we see monopoles? How many are there at T>Tc?

Topology and fermionic zero modes helps

Caloron=baryon made of Nc dyons, can be seen in energy directly:

KvBLL solutions:

T. C. Kraan and P. van Baal, K. Lee and C. Lu [1998]



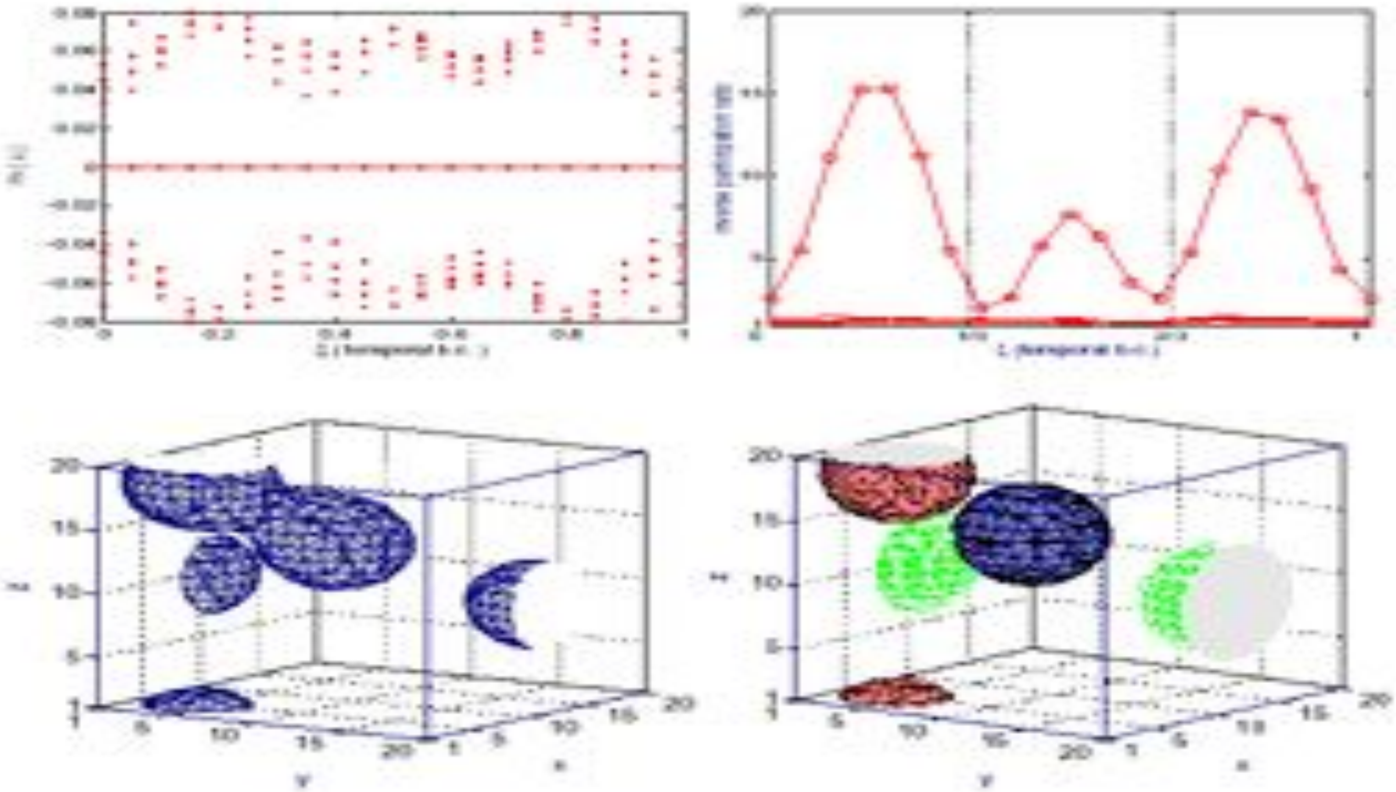
Classical solutions with the top. charge Q=1 and nonzero holonomy <P> (A_0 or Higgs VeV) =>

(long suspected because there are 4 Nc collective coordinates and monopoles have 4)

Now it has nice Ads/CFT brane derivation

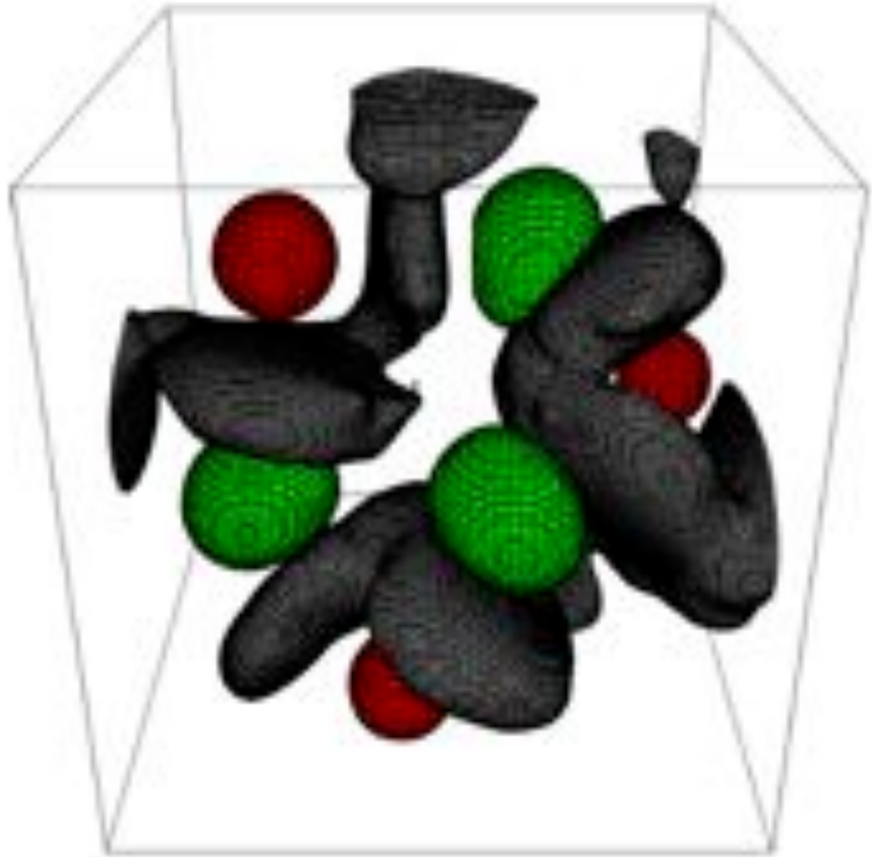
Such semiclassical self-dual dyons are even better seen in lattice configurations via fermionic zero modes

(From Ilgenfritz et al)



5: Non-trivial $Q = 1$ caloron : Spectral flow (upper left), IPR of zero-mode (breathing, upper right), action density (bottom left) and zero-mode density (bottom right), for three z's corresponding to maximal localization.

A $SU(2)$ multicaloron ring with $Q = 3$ containing 6 dyons



gure 13: A $Q = 3$ caloron with non-trivial holonomy in $SU2$: Iso-surfaces of the Polyakov loop at positive (L dyons, red) and negative values (M dyons, green). Regions of non-staticity (in dark) are separating the L and M dyons (alternating along a multicaloron ring) from each other.

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•Classical QGP and its MD:

•a strongly coupled liquid with local color and crystalline order can be studies in real time

Additional slides