Generation of confinement and other nonperturbative effects by infrared gluonic degrees of freedom

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Infrared gluonic degrees of freedom – will focus on:

Vortices
Monopoles
Instantons, Calorons, Merons

Review: J. Greensite, hep-lat/0301023

But first, what else has been happening on confinement . . .

What else has been happening:

- Confinement in the Coulomb gauge
  $\longrightarrow$ J. Greensite, Š. Olejník, D. Zwanziger, hep-lat/0401003
  $\longrightarrow$ K. Langfeld, L. Moyaerts, hep-lat/0406024
- Confinement in the Landau gauge, Kugo-Ojima confinement criterion
  $\longrightarrow$ S. Furui, H. Nakajima, hep-lat/0403021
  $\longrightarrow$ P. O. Bowman, U. M. Heller, D. B. Leinweber, M. B. Parappilly, A. G. Williams, hep-lat/0402032
  $\longrightarrow$ A. Cucchieri, T. Mendes, A. R. Taurines, hep-lat/0406020
  $\longrightarrow$ J. Gattnar, K. Langfeld, H. Reinhardt, hep-lat/0403011
- Confinement in models with exceptional gauge groups
  $\longrightarrow$ K. Holland, P. Minkowski, M. Pepe, U.-J. Wiese, hep-lat/0302023
  $\longrightarrow$ K. Holland, M. Pepe, U.-J. Wiese, hep-lat/0312022
- SU(2) vs. SO(3)
  $\longrightarrow$ A. Barresi, G. Burgio, M. D'Elia, M. Müller-Preussker, hep-lat/0405004
  $\longrightarrow$ P. de Forcrand, O. Jahn, hep-lat/0211004

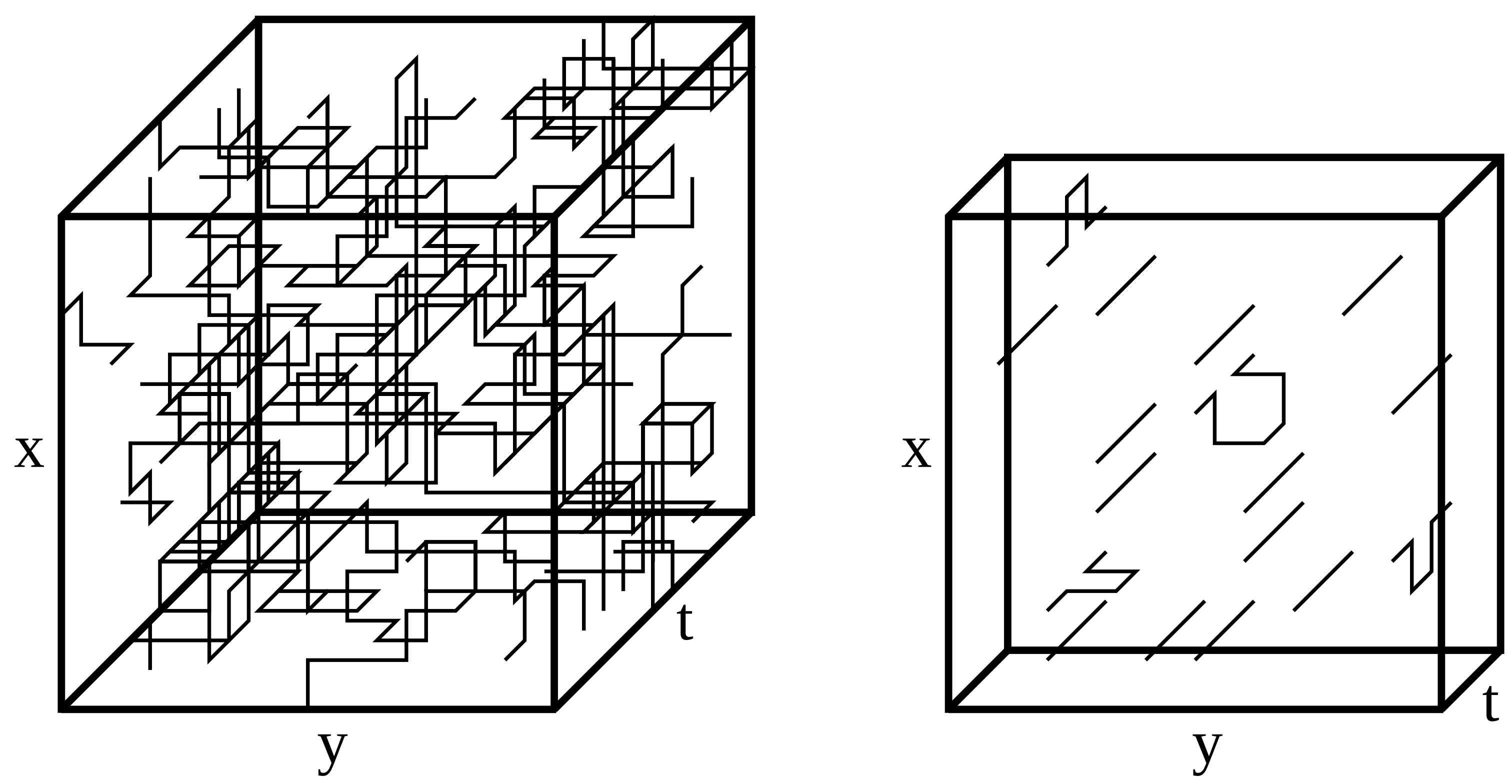
- Higher representation Wilson loops
  - ⟶ B. Lucini, M. Teper, U. Wenger, hep-lat/0404008
  - ⟶ L. Del Debbio, H. Panagopoulos, E. Vicari, hep-lat/0308012
- Connecting short to long scales by decimations
  - ⟶ E. T. Tomboulis, hep-lat/0311022
- String breaking
  - ⟶ S. Kratochvila, P. de Forcrand, hep-lat/0306011
  - ⟶ V. Bornyakov et al (DIK collaboration), hep-lat/0401014
- Stringy behavior of the QCD flux tube
  - ⟶ M. Lüscher, P. Weisz, hep-lat/0207003
  - ⟶ K. J. Juge, J. Kuti, F. Maresca, C. Morningstar, M. Peardon, hep-lat/0309180
  - ⟶ K. J. Juge, J. Kuti, C. Morningstar, hep-lat/0401032
  - ⟶ M. Caselle, M. Hasenbusch, M. Panero, hep-lat/0403004
  - ⟶ M. Caselle, M. Pepe, A. Rago, hep-lat/0406008
  - ⟶ P. Majumdar, hep-lat/0211038
  - ⟶ Y. Koma, M. Koma, P. Majumdar, hep-lat/0311016
  - ⟶ O. Jahn, P. de Forcrand, hep-lat/0309115 (baryonic configurations)

Infrared gluonic degrees of freedom

- **Can they generate the nonperturbative effects characterizing the strong interaction in the infrared? How?**
- **Is it realistic to assume them to be weakly coupled/correlated?**
- **How can they be studied in lattice gauge theory?**
- **Results of such studies?**

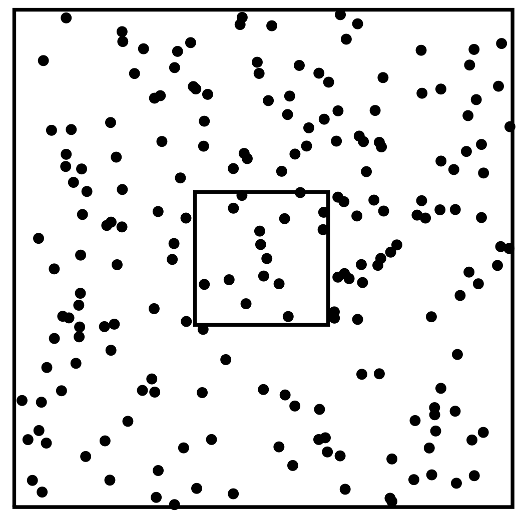
Center Vortices

Two-dimensional closed world-surfaces of chromomagnetic flux quantized such as to contribute a center phase to any Wilson loop it is linked to (SU(N): N-1 types of flux).



confined phase   deconfined phase

Confinement



Universe L^4

Slice through universe L^2

Area of Wilson loop A

Number of intersection points N

Vortex density $\rho = N/L^2$

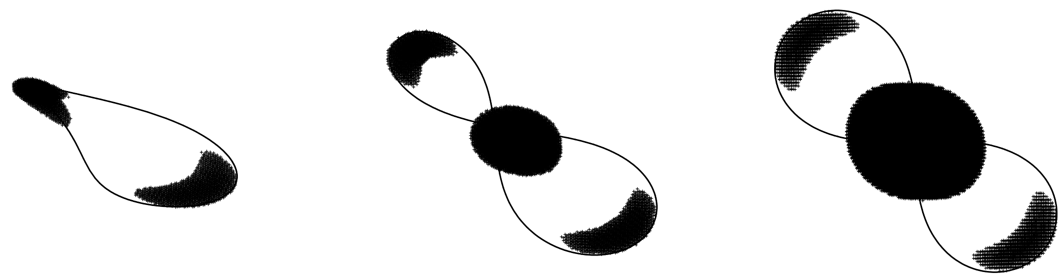
$$\langle W \rangle = \sum_{n=0}^{N} (-1)^n \binom{N}{n} \left(\frac{A}{L^2}\right)^n \left(1 - \frac{A}{L^2}\right)^{N-n} = \left(1 - \frac{2\rho A}{N}\right)^N \xrightarrow{N\to\infty} \exp(-2\rho A)$$

Confinement $\longleftrightarrow$ Vortex percolation

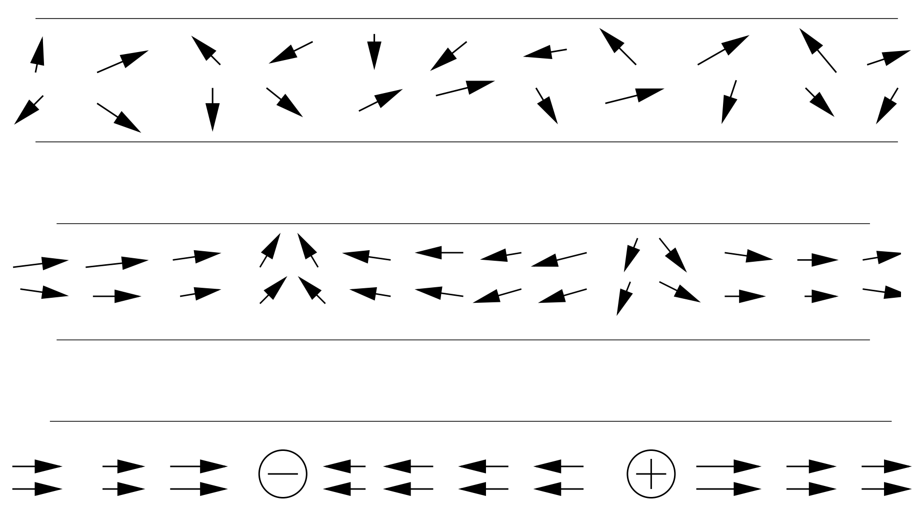
Adjoint Wilson loops insensitive to center flux

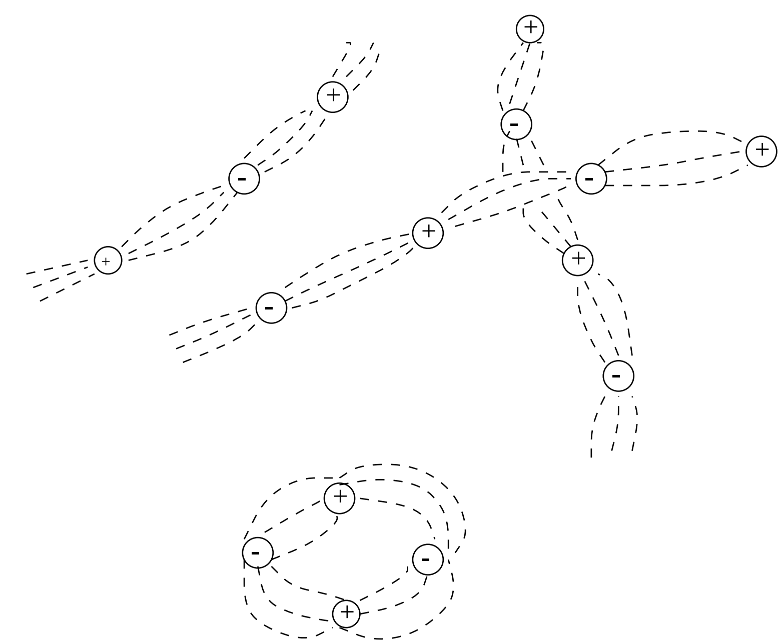
Topological charge

- Topological charge carried by vortex surface writhe and intersection points



- Generic surfaces non-orientable – in Abelian gauge, surface patches of alternating orientation separated by **monopoles**





- Only non-oriented surfaces carry global topological charge!

Center vortex dynamics: Random vortex world-surface model

- Surfaces composed of elementary squares on a hypercubic lattice
- Fixed lattice spacing $\longleftrightarrow$ vortex thickness
- Generate random surface ensemble by Monte Carlo methods
- Reproduces:
  - Confined, deconfined phases (SU(2), SU(3) – weakly first order deconfinement transition, baryonic Y law)
  - Topological susceptibility (SU(2))
  - Quenched chiral condensate (SU(2))

M. Engelhardt, H. Reinhardt, hep-lat/9912003
M. Engelhardt, hep-lat/0004013
M. Engelhardt, hep-lat/0204002
M. Engelhardt, M. Quandt, H. Reinhardt, hep-lat/0311029
M. Engelhardt, hep-lat/0406022

Vortex detection in lattice configurations

Maximal center gauge

Choose gauge such that relevant physical information concentrated optimally on collective degrees of freedom under investigation

$$\max \sum_i |\mathrm{tr}\, U_i|^2$$

Project onto collective degrees of freedom

$$U \longrightarrow \mathrm{sign}\ \mathrm{tr}\, U$$

L. Del Debbio, M.Faber, J. Giedt, J. Greensite, Š. Olejník, hep-lat/9801027

V. Bornyakov, D. Komarov, M. Polikarpov, hep-lat/0009035 (Gribov problem)

Laplacian center gauge

Find eigenvectors for two lowest eigenvalues of lattice adjoint Laplacian; vortices are located on the two-dimensional submanifolds where they become collinear; monopoles are located on lines where eigenvector for lowest eigenvalue vanishes.

No Gribov problem

C. Alexandrou, P. de Forcrand, M. D'Elia, hep-lat/9909005

Combined approach: M.Faber, J. Greensite, Š. Olejník, hep-lat/0106017

Detection via Wilson loops? – S. Cheluvaraja, hep-lat/0405018

Lattice results

- **Center dominance** of the string tension
  $\longrightarrow$ M.Faber, J. Greensite, Š. Olejník, hep-lat/0106017
  $\longrightarrow$ P. de Forcrand, M. Pepe, hep-lat/0008016

- Vortex-limited Wilson loops – ratio of Wilson loops pierced by 1 projection vortex to Wilson loops pierced by no projection vortices approaches (-1) at infrared scales
  $\longrightarrow$ M.Faber, J. Greensite, Š. Olejník, hep-lat/0106017

- Vortex removal: $\sigma = 0$, $Q = 0$, $\langle\bar{\psi}\psi\rangle = 0$
  $\longrightarrow$ P. de Forcrand, M. D'Elia, hep-lat/9901020

- Deconfinement transition $\leftrightarrow$ percolation transition
  $\longrightarrow$ M. Engelhardt, K. Langfeld, H.Reinhardt, O. Tennert, hep-lat/9904004
  $\longrightarrow$ K. Langfeld, hep-lat/0304012

- Roughening
  $\longrightarrow$ V. Bornyakov, A. Kovalenko, M. Polikarpov, D. Sigaev, hep-lat/0209029
  $\longrightarrow$ V. Bornyakov, A. Kovalenko, M. Polikarpov, D. Sigaev, hep-lat/0309049

- Maximal Abelian gauge monopoles are located on vortices - action collimated in vortex direction at monopoles
  $\longrightarrow$ J. Ambjørn, J. Giedt, J. Greensite, hep-lat/9907021
  $\longrightarrow$ A. Kovalenko, M. Polikarpov, S.Syritsyn, V. Zakharov, hep-lat/0402017
- Topological susceptibility
  $\longrightarrow$ R. Bertle, M. Engelhardt, M. Faber, hep-lat/0104004
- SU(3)
  $\longrightarrow$ P. de Forcrand, M. Pepe, hep-lat/0008016
  $\longrightarrow$ K. Langfeld, hep-lat/0307030
- Vortices and Higgs fields – no vortex percolation in Higgs (screening) phase
  $\longrightarrow$ R. Bertle, M. Faber, J. Greensite, Š. Olejník, hep-lat/0310057

Abelian monopoles – the dual superconductor

Select a $U(1)^{N-1}$ subgroup of $SU(N)$

($\longrightarrow$ by fixing color direction of a covariantly transforming quantity)

Monopoles: Sources of magnetic flux w.r.t. that $U(1)^{N-1}$

Ensemble of monopole world-lines $\longrightarrow$ field theory

Ginzburg-Landau theory: Dual Abelian Higgs model

$$\mathcal{L} = \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \left|(\partial_\mu + igC_\mu)\phi\right|^2 + \frac{\lambda}{4}(\phi\phi^* - v^2)^2$$

$\longrightarrow$ **Nielsen-Olesen vortices of *electric* flux**

$\rightarrow$ confinement of electric sources if monopoles condensed/percolate

$\rightarrow$ deconfinement of electric sources if no monopole condensation/percolation

$\rightarrow$ confinement also of adjoint SU(N) sources (= doubly charged w.r.t. $U(1)^{N-1}$)!

$\rightarrow$ cannot neglect off-diagonal gluons – screen adjoint sources

Topological charge

Topological charge implies the presence of monopoles:

- Only non-oriented vortices (i.e., containing monopoles) carry global topological charge
- Instantons in Abelian gauges exhibit monopoles (and vortices)
- Calorons contain monopole constituents

Conversely, monopole positions are in general not enough to specify topological charge – need to supply magnetic field emanating from them (except for special gauges, e.g. Polyakov gauge)

- Magnetic field collimated into vortices $\longrightarrow$ correct topological susceptibility in random vortex world-surface model
- Monopole Coulomb gas result for the topological susceptibility?

Chiral condensate induced by monopole Coulomb gas?

Monopole detection in lattice configurations

In general: Find eigenvalues (in color space) of any covariantly transforming quantity – Monopoles located where two eigenvalues degenerate

In practice: **Maximal Abelian gauge**

$$\max \sum_{x,\mu} \mathrm{tr}\,(U_\mu \sigma^3 U_\mu^\dagger \sigma^3) \qquad \longrightarrow \text{ fields as diagonal as possible}$$

$\longrightarrow$ A. Kronfeld, M. Laursen, G. Schierholz, U.-J. Wiese, Phys. Lett. B198 (1987) 516

Residual $U(1)$: Diagonal fields transform as photons, off-diagonal fields as charge-2 matter

Abelian projection: Keep only diagonal fields, rescaled to preserve unitarity of links
Note: No statement about form of Abelian fields – could be vortices

Monopole projection: Extract monopole positions (seek Dirac string leaving elementary cube), associate magnetic Coulomb field with monopoles
$\longrightarrow$ H. Shiba, T. Suzuki, hep-lat/9404015
$\longrightarrow$ J. Stack, S. Neiman, R. Wensley, hep-lat/9404014

Consistent definition of electric and magnetic fluxes, currents
$\longrightarrow$ R. W. Haymaker, T. Matsuki, hep-lat/0310025

Lattice results

- **Abelian dominance:** Evaluating Wilson loops using Abelian projected configuration yields (92 ± 4) % of full string tension. Adjoint sources not confined.
  $\longrightarrow$ T. Suzuki, I. Yotsuyanagi, Phys. Rev. D 42 (1990) 4257
  $\longrightarrow$ G. Bali, V. Bornyakov, M. Müller-Preussker, K. Schilling, hep-lat/9603012
- **Monopole dominance:** 87 % of full fundamental string tension recovered,
  $\longrightarrow$ H. Shiba, T. Suzuki, hep-lat/9404015
  $\longrightarrow$ J. Stack, S. Neiman, R. Wensley, hep-lat/9404014
  but: adjoint sources confined!
  $\longrightarrow$ J. Ambjørn, J. Giedt, J. Greensite, hep-lat/9907021
- Deconfined phase – Maximal Abelian gauge monopole percolation ceases
  $\longrightarrow$ V. Bornyakov et al (DIK collaboration), hep-lat/0401026 (includes $N_f = 2$)
- Monopole, photon structure of flux tube $\longleftrightarrow$ Nielsen-Olesen form (no roughening!)
  $\longrightarrow$ G. Bali, C. Schlichter, K.Schilling, hep-lat/9802005
  $\longrightarrow$ Y. Koma, M. Koma, E.-M. Ilgenfritz, T. Suzuki, M. Polikarpov, hep-lat/0302006
  $\longrightarrow$ Y. Koma, M. Koma, E.-M. Ilgenfritz, T. Suzuki, hep-lat/0308008
  $\longrightarrow$ V. Bornyakov et al (DIK collaboration), hep-lat/0310011 (includes $N_f = 2$)

- Baryonic Y law in Abelian projection
  $\longrightarrow$ V. Bornyakov et al (DIK collaboration), hep-lat/0401026 (includes $N_f = 2$)
- Breaking of fundamental string in Abelian projection ($N_f = 2$)
  $\longrightarrow$ V. Bornyakov et al (DIK collaboration), hep-lat/0401027
- Monopole action, monopole length distribution, monopole entropy
  $\longrightarrow$ M. Chernodub, K. Ishiguro, K. Kobayashi, T. Suzuki, hep-lat/0306001
- Studies of monopole condensation (magnetic disorder parameter)
  $\longrightarrow$ J. M. Carmona et al (Pisa group), hep-lat/0309035
  $\longrightarrow$ A. Di Giacomo, hep-lat/0310021
  $\longrightarrow$ M. Chernodub, hep-lat/0308031
  $\longrightarrow$ V. A. Belavin, M. Chernodub, M. Polikarpov, hep-lat/0403013
  $\longrightarrow$ V. A. Belavin, M. Chernodub, M. Polikarpov, hep-lat/0212004
  $\longrightarrow$ J. Fröhlich, P. A. Marchetti, hep-th/0011246

- **Adjoint string breaking**
  - Abelian Higgs models – charge-2 string breaking by charge-2 matter fields
    $\longrightarrow$ T. Suzuki, M. Chernodub, hep-lat/0207018
  - Action of Abelian matter fields essential in Abelian projection
    $\longrightarrow$ M. Chernodub, K. Hashimoto, T. Suzuki, hep-lat/0311026
  - Monopoles form (vortex) chains in compact Abelian charge-2 Higgs model
    $\longrightarrow$ J. Greensite, hep-lat/0301023
    $\longrightarrow$ M. Chernodub, R. Feldmann, E.-M. Ilgenfritz, A. Schiller, hep-lat/0406015
- **Monopole trajectories not distributed as random walks**
  $\longrightarrow$ V. Bornyakov, P. Boyko, M. Polikarpov, V. Zakharov, hep-lat/0305021

Topological charge lumps – Instantons, Merons, Calorons

Merons:

$$a_\mu(x) = \frac{\eta_{a\mu\nu} x_\nu}{x^2 + \rho^2} \frac{\sigma^a}{2} \qquad (SU(2))$$

Classical solution for $\rho = 0$; topological charge $Q = 1/2$
$F_{\mu\nu} \sim 1/x^2 \quad \rightarrow$ action of single meron logarithmically singular

Can build meron gas with finite action density if color orientations correlated accordingly
$\longrightarrow$ F. Lenz, J. Negele, M. Thies, hep-th/0306105

$$A_\mu(x) = \sum_{i=1}^{M} h_i a_\mu(x - z_i) h_i^{-1}$$

Monte Carlo sum over positions z_i, color orientations h_i (nonlocal!):

- Confining potential
- Quantitative agreement of topological susceptibility (in units of string tension) with SU(2) Yang-Mills

Adjoint color sources?
Do color correlations imply higher-dimensional structures?

Instantons:

- Classical solutions with topological charge $Q = 1$, regular action
- Highly successful instanton liquid model of the $U_A(1)$ anomaly, chiral symmetry breaking, hadron phenomenology
  $\longrightarrow$ T. Schäfer, E. V. Shuryak, Rev. Mod. Phys. 70 (1998) 323 (hep-ph/9610451)

  No confinement in the instanton liquid model
- Observation of instantons and associated quark zero modes in lattice QCD $\longrightarrow$ physics of chiral symmetry breaking
  $\longrightarrow$ J. W. Negele, hep-lat/9810053
- New development (J.Negele, this conference): Instanton ensemble with proper color orientation correlations (analogous to meron ensemble) produces confinement!

Adjoint color sources?
How is instanton liquid phenomenology modified by color correlations?
Do color correlations imply higher-dimensional structures?

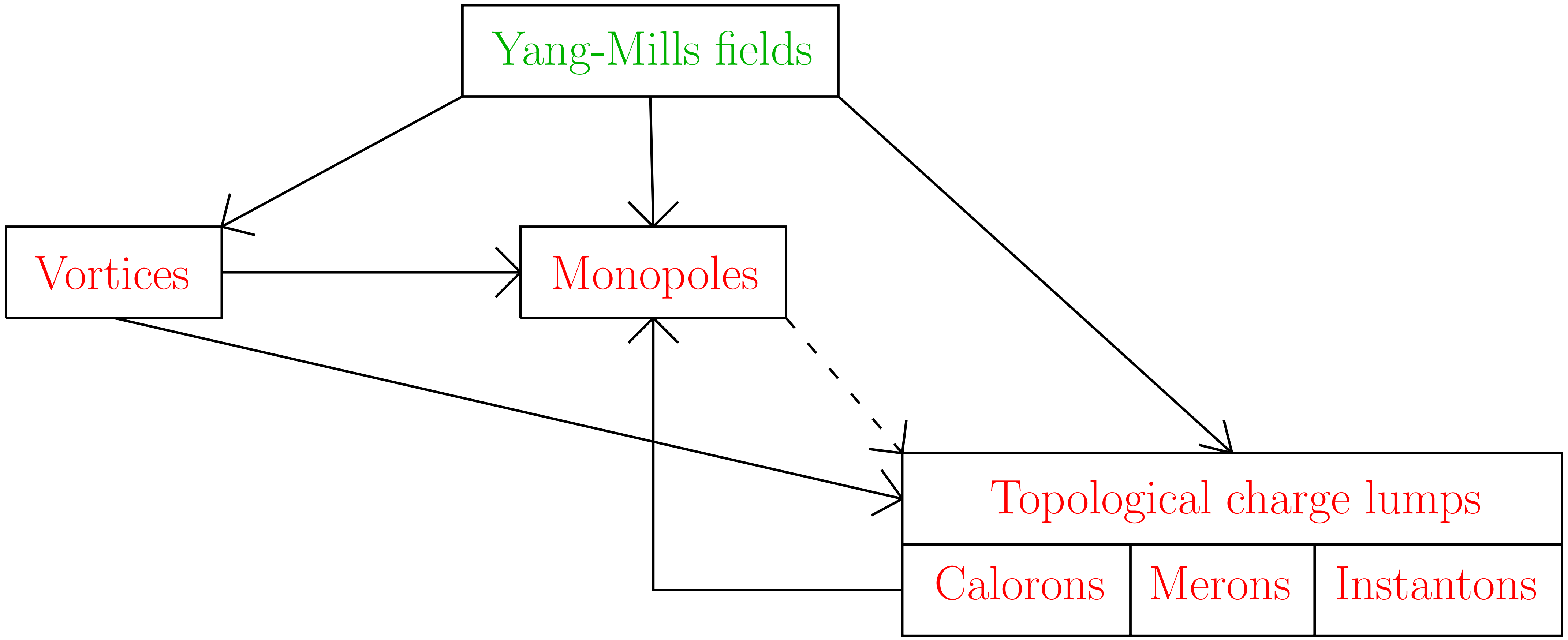
Calorons:

- Classical solutions on space-times with compact directions (finite temperature); quanta of topological charge
- Monopole substructure (⟶ relation to confinement?)
  ⟶ F. Bruckmann, M. García Pérez, D. Nógrádi, P. van Baal, hep-lat/0308017
  ⟶ F. Bruckmann, D. Nógrádi, P. van Baal, hep-th/0404210
- Calorons, monopole substructure detected in lattice configurations via cooling
  ⟶ E.-M. Ilgenfritz, B. Martemyanov, M. Müller-Preussker, A. Veselov, hep-lat/0402010
- Detection also via quark zero modes
  ⟶ C. Gattringer et al, hep-lat/0309106
  ⟶ C. Gattringer, S. Schaefer, hep-lat/0212029
  ⟶ C. Gattringer, hep-lat/0210001

…evidence suggests that topological charge distribution in the QCD vacuum is more fragmented, structured than uncorrelated instanton-like lumps …

more indications ⟶ I. Horvath et al, hep-lat/0302009
(long-range low-dimensional topological charge structure)

Synopsis:



increasing correlation needed to recover all nonperturbative physics $\longrightarrow$

increasing level of truncation $\longrightarrow$