Colour meets Flavour

Conference in Honor of

A. Khodjamirian's 60th Birthday

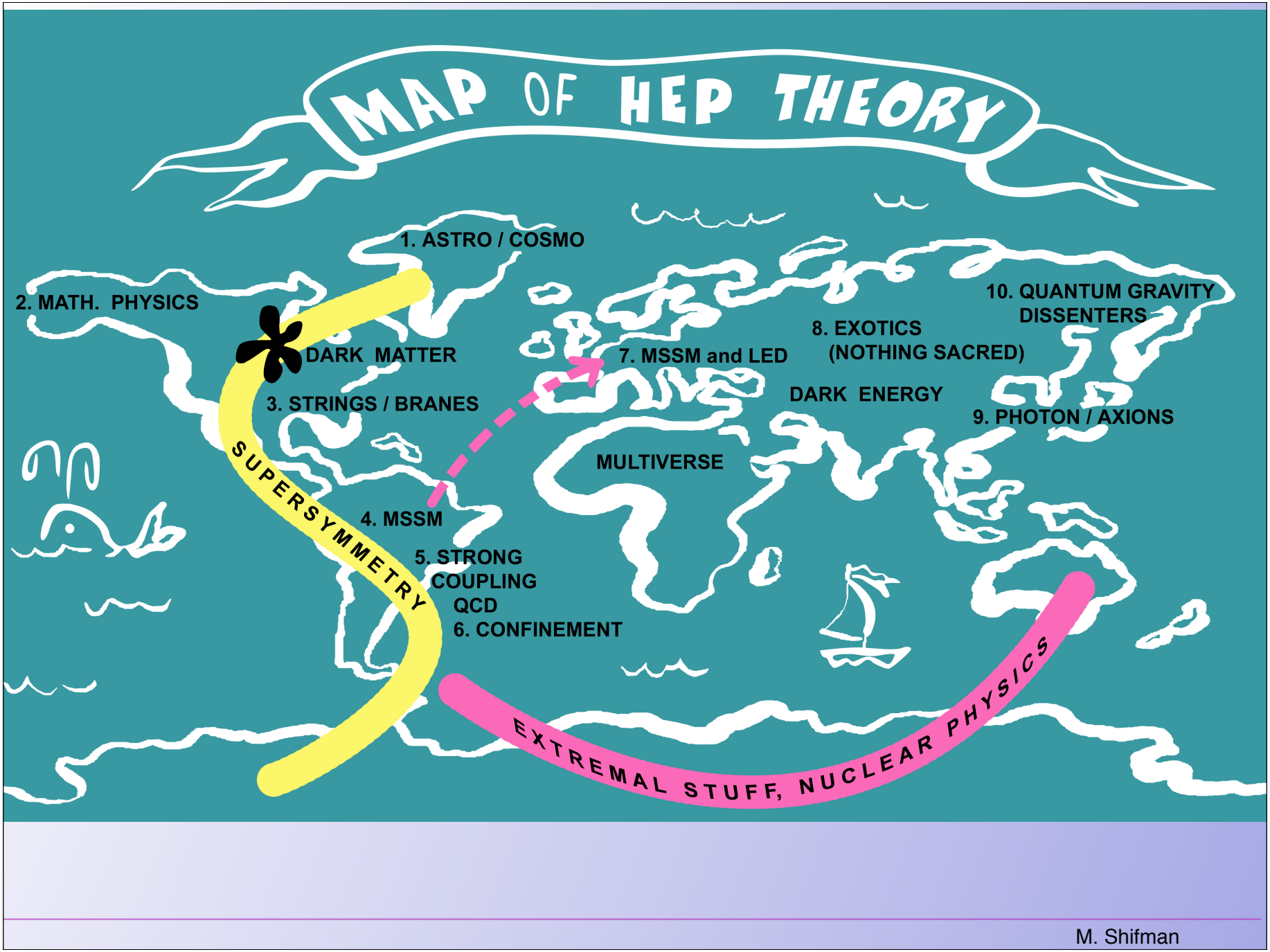
13th – 14th October 2011,

University of Siegen

M. Shifman

W.I. Fine Theoretical Physics Institute, University of Minnesota

Theory of strong interactions: Four decades of development


MAP OF HEP THEORY
1. ASTRO / COSMO
2. MATH. PHYSICS
DARK MATTER
3. STRINGS / BRANES
SUPERSYMMETRY
4. MSSM
5. STRONG
COUPLING
QCD
6. CONFINEMENT
7. MSSM and LED
MULTIVERSE
8. EXOTICS
(NOTHING SACRED)
DARK ENERGY
9. PHOTON / AXIONS
10. QUANTUM GRAVITY
DISSENTERS
EXTREMAL STUFF, NUCLEAR PHYSICS

M. Shifman

Gell-Mann & Fritzsch, 16 HEP Conf., 1972

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu\, a} + \sum_f \bar{\psi}_f \left(i \mathcal{D}_\mu \gamma^\mu - m_f \right) \psi^f$$

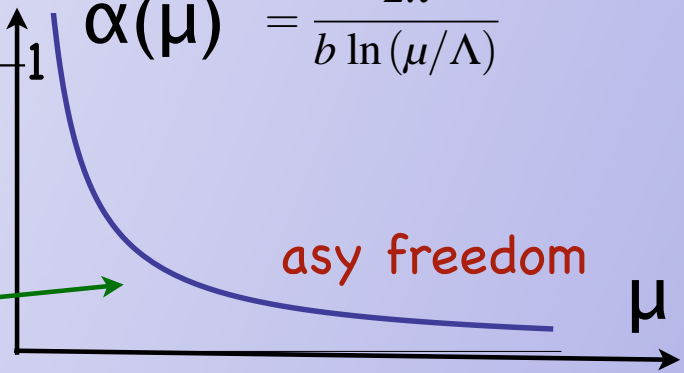
$$G^a{}_{\mu\nu} = \partial_\mu A^a{}_\nu - \partial_\nu A^a{}_\mu + g\, f^{abc}\, A^b{}_\mu\, A^c{}_\nu \,,$$

$$D_\mu = \partial_\mu - i\, g\, T^a\, A^a{}_\mu$$

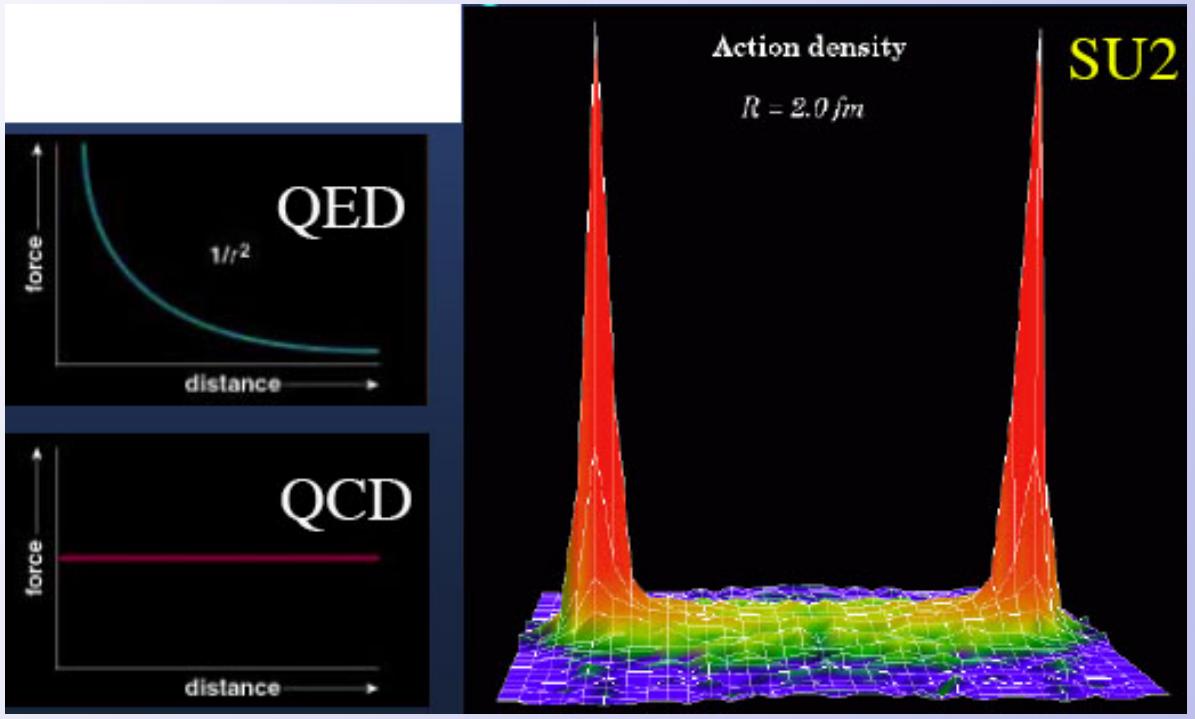
★ For strong interaction physics this is the same as the Schrödinger equation for chemistry

★ ★ This simple formula encodes all information about matter that builds our world

$$\alpha(\mu) = \frac{2\pi}{b \ln(\mu/\Lambda)}$$



Gross, Wilczek, and Politzer

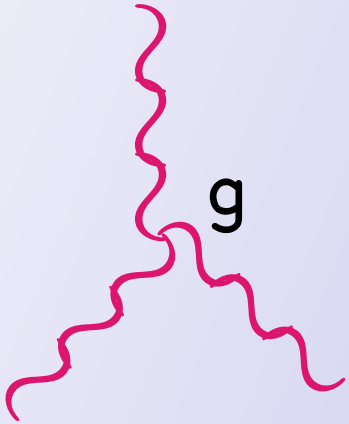


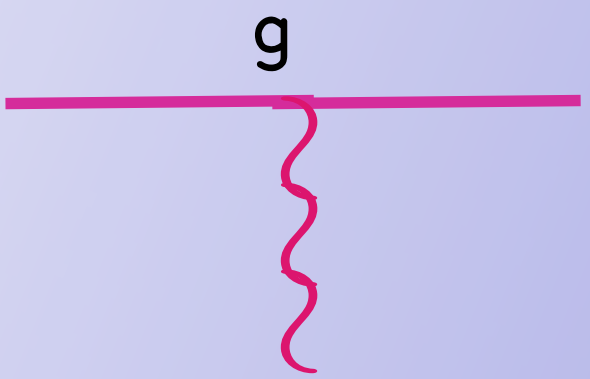
Gross, Wilczek & Politzer, 1973

The most salient feature: quark inseparability

8 gluons

3-colored quarks





Nonlinearity: "charged" gluons emit gluons!

Similar to QED

★ Ordinary QFT like QED: almost harmonic oscillators, expansion in weak anharmonicity

★ ★ In QCD *Unhaprmonicity* is huge and dominant!

Vacuum structure is *Complicated*

THREE STRATEGIES:

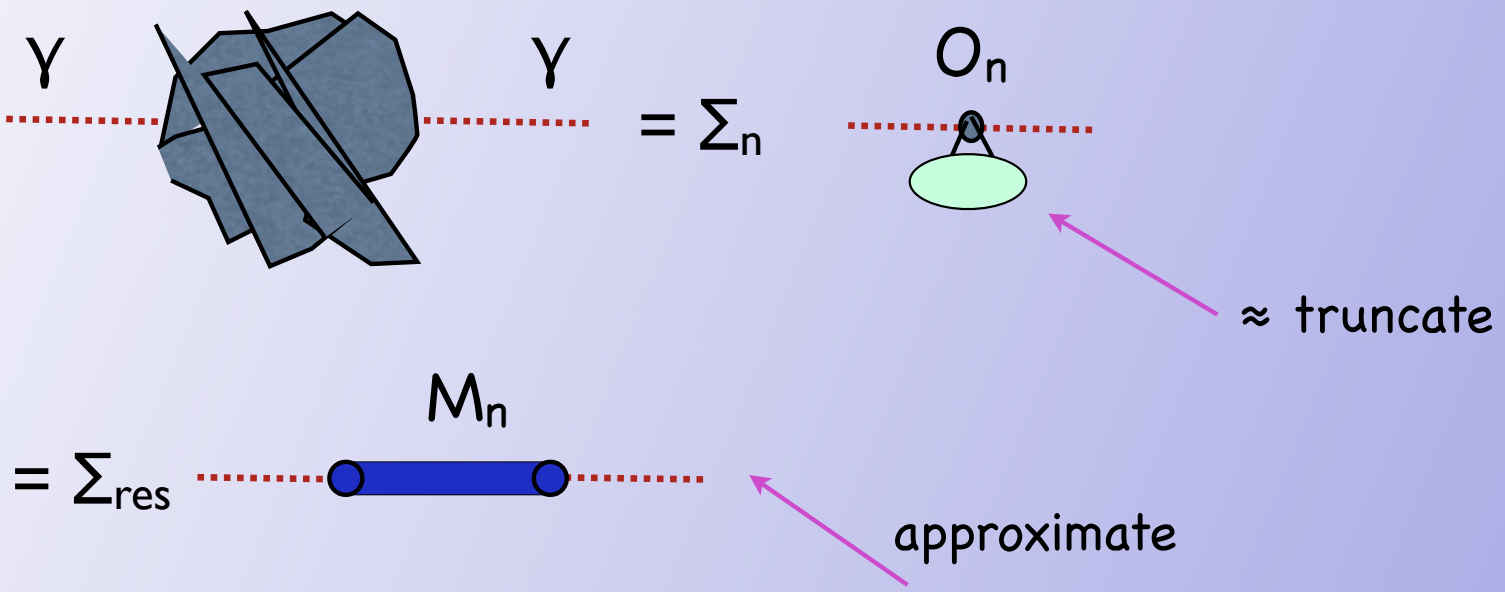
a) Accept confinement, parametrize vacuum complexity by few basic condensates, and extract as much profit as possible→ QCD SR (A.K.!☺)

b) Brute force: Build a *Huge* computer, crush everything you can;

c) develop an understanding of dynamics→ convert to quantitive models as close to QCD as possible ✌ ✈

Basic idea:

QCD vacuum structure is complicated. For limited purposes one can try to approximate it by a few vacuum expectation values in an intermediate domain of distances - between short and asymptotically large



Confinement is assumed!

Operator Product Expansion

Wilson, 1969; Polyakov, unpubl.

$$T\{A(x)B(0)\} = \Sigma_n \; C^{AB}{}_n(x) \; O_n(0)$$

expansion in singularities

In this form Wilson designed it for theories with a UV fixed point at $\alpha \neq 0$. All x dependence is encoded in the set $C^{AB}{}_n(x)$. The operators $O_n(0)$ were defined as local.

OPE (fusion rules) in the above form are perfect for the conformal theories (Polyakov et.al.) where dynamics at all scales is the same.
In 2D the fusion rules are powerful enough to solve some CFTs.
In 4D N=4 super-YM conformal symmetry leads to miracles.

QCD is extremely rich:

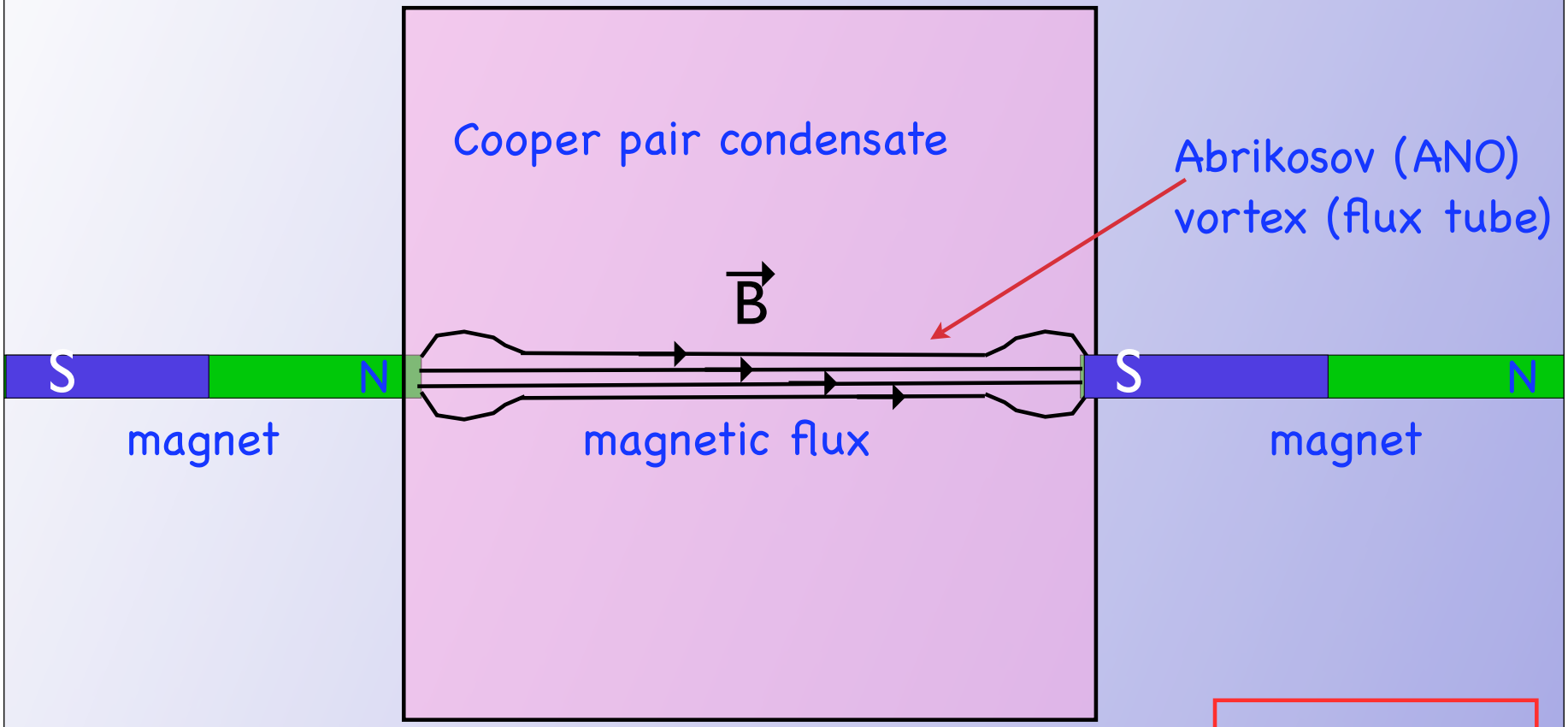
- Nuclear Physics
  - Regge behavior
    - QGM: high-T/high μ (neutron stars)
      - Richness of the hadronic world:

- chiral;
- light & heavy quarkonia;
- glueballs & exotics;
- exclusive & inclusive phenomena;
- interplay between strong forces & weak interactions...

That's why I do not expect **FULL** analytic solution to QCD to be found

Are we aware of precedents?

☞ Yes, the Meissner effect! 1930s, 1960s

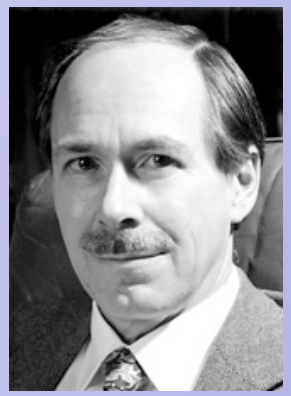


Superconductor of the 2nd kind

Abelian ☚

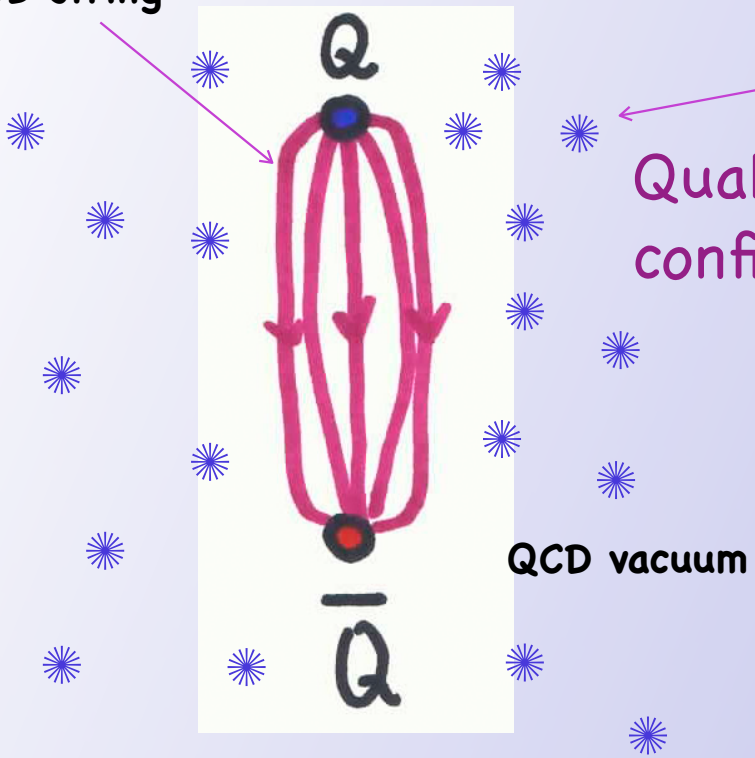
Dual Meissner effect for confinement conjectured

- Mandelstam, 1975
- Nambu, 1974
- 't Hooft, 1975



QCD string

condensed magnetic monopoles

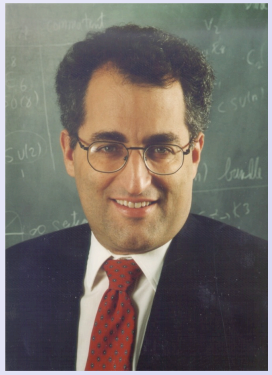


QCD vacuum

Qualitative explanation of color confinement: Dual Meissner effect:

★ "...[monopoles] turn to develop a non-zero vacuum expectation value. Since they carry color-magnetic charges, the vacuum will behave like a superconductor for color-magnetic charges. What does that mean? Remember that in ordinary electric superconductors, magnetic charges are connected by magnetic vortex lines ... We now have the opposite: it is the color charges that are connected by electric flux tubes."
G. 't Hooft (1976)

☺ First demonstration of the dual Meissner effect: Seiberg & Witten, 1994 ☺



- gluons+complex scalar superpartner
- two gluinos
- Georgi-Glashow model built in

N=2 (extended) SUSY → SU(2) →U(1), monopoles →

Monopoles become light → N=1 deform. forces M condensatition →

U(1) broken, electric flux tube formed →

☹ ☹ Dynamical Abelization ... dual Abrikosov string

analytic continuation

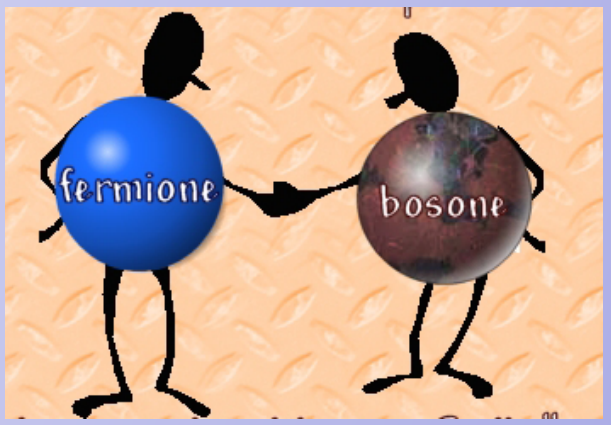
$$E = mc^2$$

Cultural icon of the 20th century

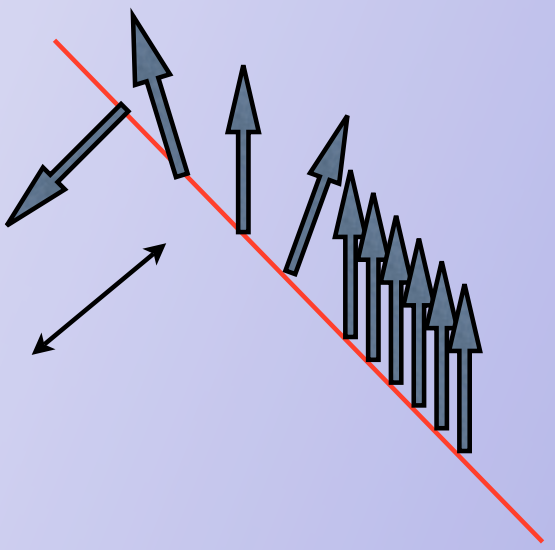
$$\{\bar{Q}_{\dot{\alpha}}, Q_{\beta}\} = 2\sigma^{\mu}_{\dot{\alpha}\beta} P_{\mu}$$ ⟵ Of the 21st ?

Supersymmetry entails that for every particle that has been found there are mirror particles that are identical in all respects except for their spin. Bosons of spin 1 — the photon, W, Z, and gluon — have spin 1/2 partners called the photino, wino, and gluino. Fermions of spin 1/2 — leptons and quarks — have spin 0 partners called the sleptons and squarks.

Fermion *Boson*



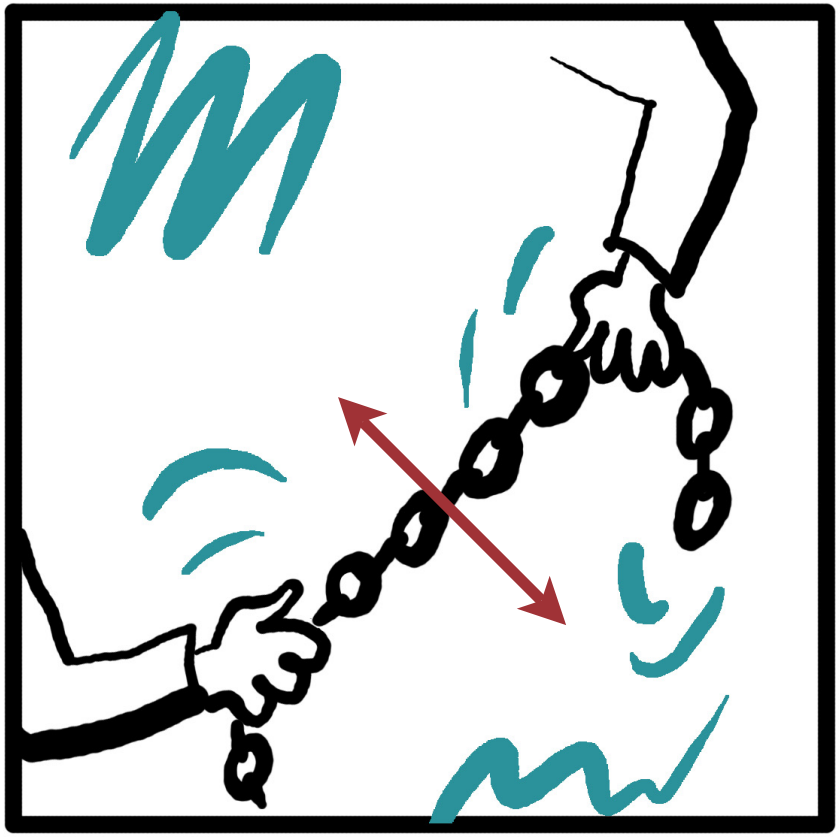
"Non-Abelian" string is formed if all non-Abelian degrees of freedom participate in dynamics at the scale of string formation



2003: Hanany, Tong
Auzzi et al.
Yung + M.S.

classically gapless excitation

SU(2)/U(1) = CP(1)~O(3) sigma model

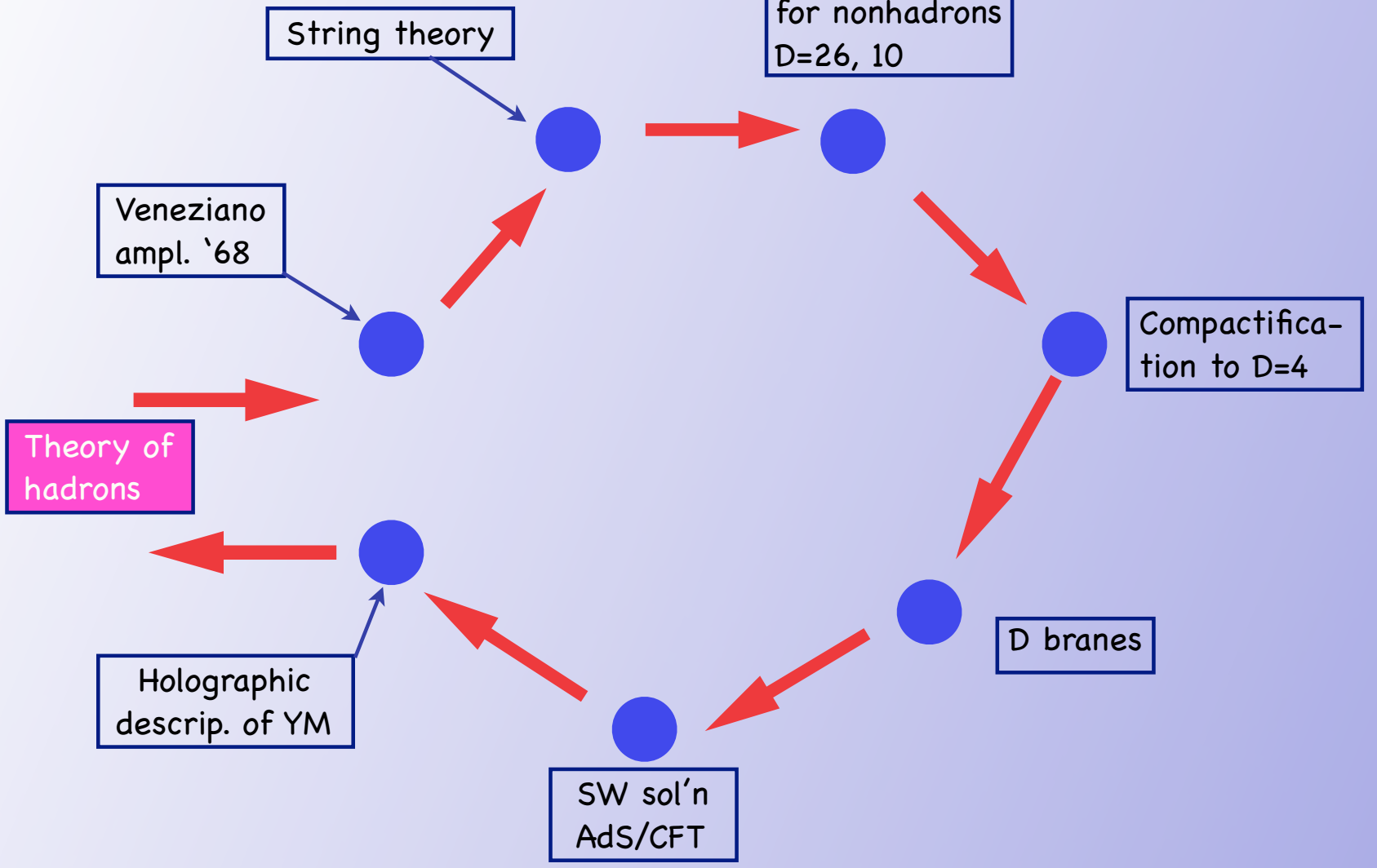


5. STRONG COUPLING

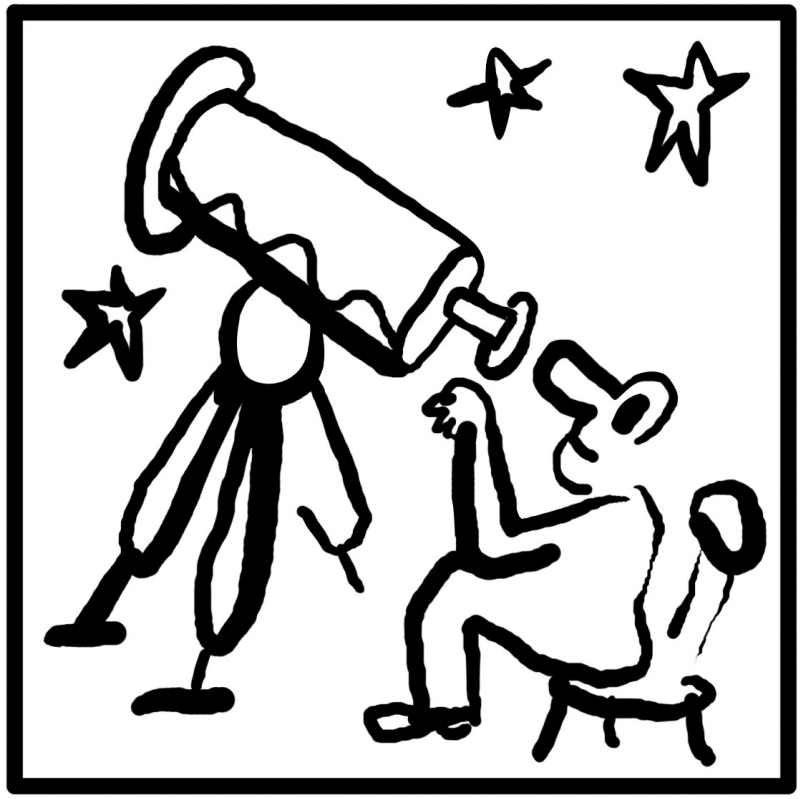
6. CONFINEMENT

☺ Happy birthday, Alik! Many happy returns of the day! ☺

Conclusions:



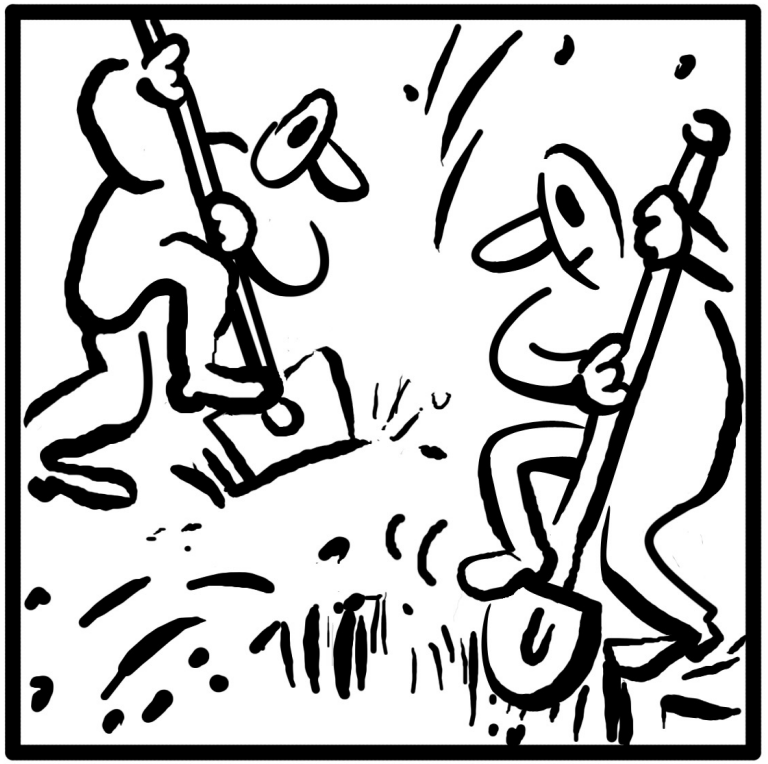
After 1998: Back-to-roots stage



1. ASTRO / COSMO

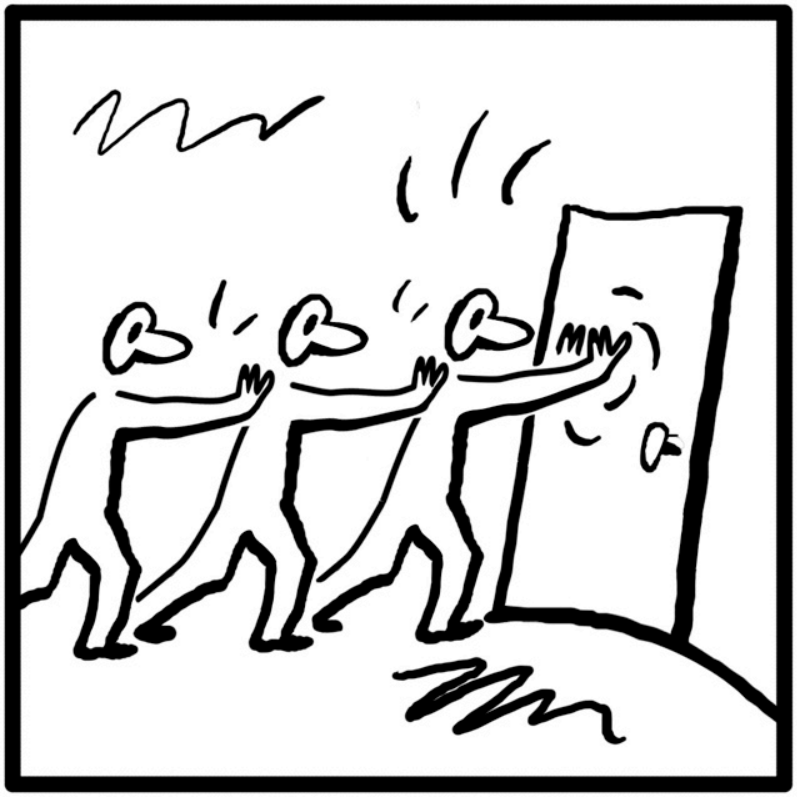
8. EXOTICS (NOTHING SACRED)

2. MATH. PHYSICS

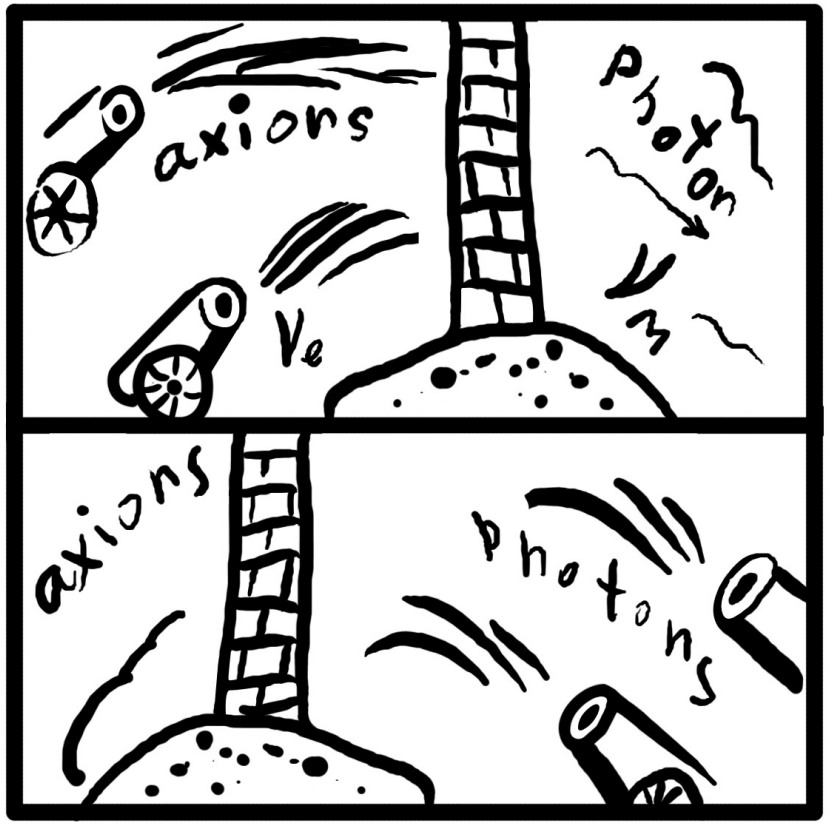


3. STRINGS / BRANES

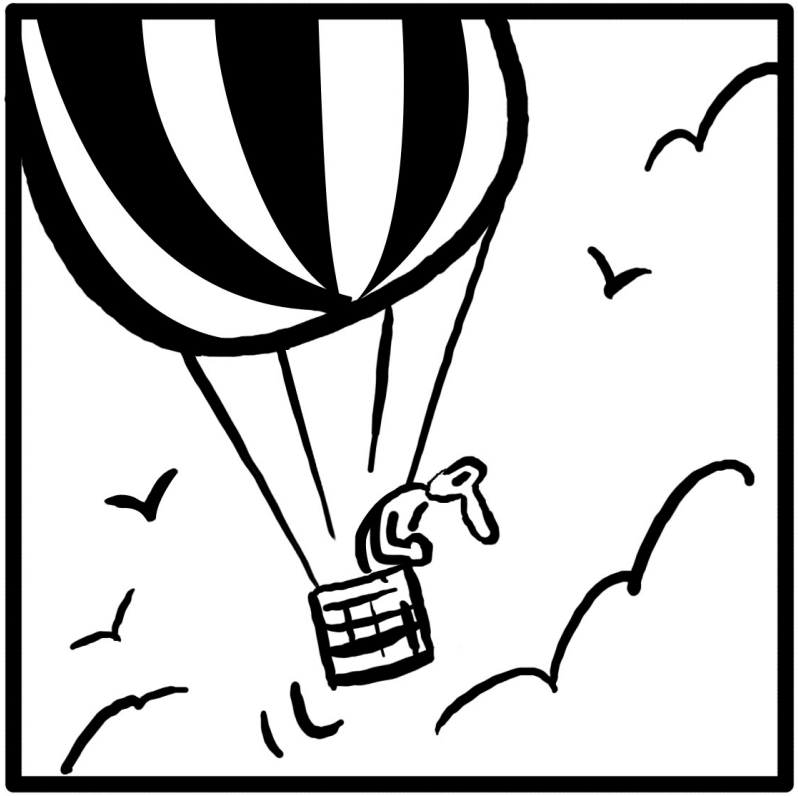
4



7. MSSM and LED



9. PHOTON / AXIONS



10. QUANTUM GRAVITY DISSENTERS