

NEW RESULTS FOR NON-PERTURBATIVE QUANTUM FIELD THEORY



Carleton
University

Department of Physics

Collaborators: Yang Bai, Hassan Easa,
Carlos de Lima, Jonathan Ponnudurai,
and Cyrus Robertson Orkish.

DANIEL STOLARSKI

ABOUT ME

Grew up in Dallas,
TX, USA.

Liked, chemistry,
physics, and math
in high school.



ABOUT ME

Went to Caltech for undergrad.

Found chemistry, boring, math difficult.

Majored in physics.

Advisor: David Politzer.



ABOUT ME

Undergrad research
working on CMS for
LHC.

Went to Berkeley
wanting to do
particle physics.

Experiment was
hard, chose theory.



TASI 2009

Theoretical
Advanced Study
Institute was a
great experience.

The screenshot shows the INSPIRE HEP website interface. At the top, there is a search bar with the text 'conferences' and a magnifying glass icon. To the right are links for 'Help' and 'Submit'. The main content area features the title 'Theoretical Advanced Study Institute in Elementary Particle Physics: Physics of the Large and the Small (TASI 2009)' and the dates '1-26 June 2009. Boulder, CO, United States (C09-06-01.3)'. Below this, it states 'Part of the TASI series' and provides contact information 'Contact: tasi@colorado.edu'. There are also links for 'website' and 'proceedings'. A bar chart titled 'Papers' shows the distribution of papers by citation count. The x-axis represents citation ranges (0, 1-9, 10-49, 50-99, 100-249, 250-499, 500+ Citations) and the y-axis represents the number of papers. The bars are blue and labeled with their respective counts: 0, 0, 5, 3, 1, 1, 1. To the right of the chart, it says '4 contributions'. Below the chart, there are three contribution entries, each with a title, author, date, and citation count. The first entry is 'Inflation' by Daniel Baumann, published in July 2009, with 1,244 citations. The second entry is 'The Higgs as a Composite Nambu-Goldstone Boson' by Roberto Contino, published in May 2010, with 497 citations. The third entry is 'A Holographic View of Beyond the Standard Model Physics' by Tony Gherghetta, published in August 2010, with 137 citations. Each entry includes links for 'pdf', 'DOI', 'cite', and 'reference search'.

Citation Range	Number of Papers
0	0
1-9	0
10-49	5
50-99	3
100-249	1
250-499	1
500+ Citations	1

Rank	Title	Author	Date	Citations
#1	Inflation	Daniel Baumann (Princeton, Inst. Advanced Study and Harvard U., Phys. Dept.)	Jul, 2009	1,244
#2	The Higgs as a Composite Nambu-Goldstone Boson	Roberto Contino (Rome U. and INFN, Rome)	May, 2010	497
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iNSPIRE HEP conferences | Help Submit

Theoretical Advanced Study Institute in Elementary Particle Physics: Physics of the Large and the Small (TASI 2009)

1-26 June 2009. Boulder, CO, United States (C09-06-01.3)

Part of the [TASI series](#)
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[website](#) [proceedings](#)

4 contributions

Papers

— Citeable — Published

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0	0
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Inflation #1

[Daniel Baumann](#) (Princeton, Inst. Advanced Study and Harvard U., Phys. Dept.) (Jul, 2009)
Contribution to: [TASI 2009](#), 523-686 • e-Print: [0907.5424](#) [hep-th]

[pdf](#) [DOI](#) [cite](#) [reference search](#) [1,244 citations](#)

The Higgs as a Composite Nambu-Goldstone Boson #2

[Roberto Contino](#) (Rome U. and INFN, Rome) (May, 2010)
Contribution to: [TASI 2009](#), 235-306 • e-Print: [1005.4269](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [reference search](#) [497 citations](#)

A Holographic View of Beyond the Standard Model Physics #3

[Tony Gherghetta](#) (Melbourne U.) (Aug, 2010)
Contribution to: [TASI 2009](#), 165-232 • e-Print: [1008.2570](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [reference search](#) [137 citations](#)

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[SERIES-TASI](#)
[website](#) [proceedings](#)

Papers: Citeable (blue), Published (orange)

Citation Range	Citeable	Published
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4 contributions

#1
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reference search 1,244 citations

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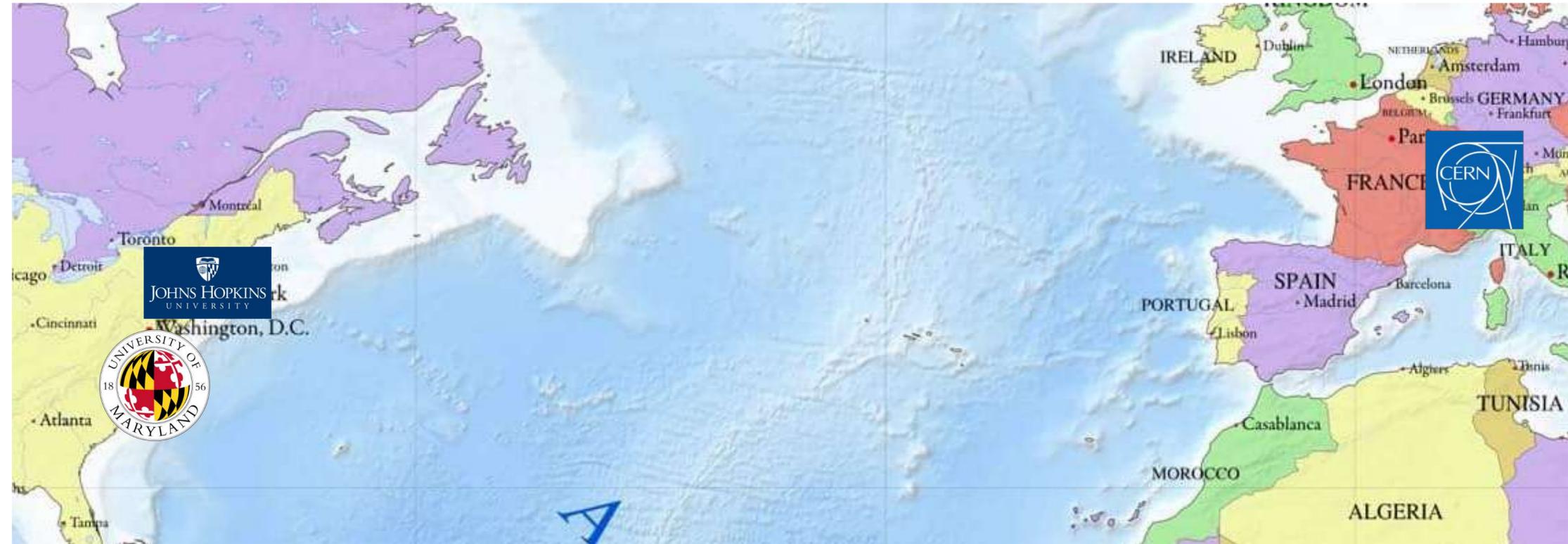
pdf DOI cite reference search citations



POSTDOCS

First postdoc joint
at University of
Maryland and Johns
Hopkins.

Second postdoc at
CERN.



POSTDOCS

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Hopkins.

Second postdoc at
CERN.



Emerging Jets

[Pedro Schwaller](#) (CERN), [Daniel Stolarski](#) (CERN), [Andreas Weiler](#) (CERN and DESY)

Feb 18, 2015

44 pages

Published in: *JHEP* 05 (2015) 059

Published: May 12, 2015

e-Print: [1502.05409](#) [hep-ph]

DOI: [10.1007/JHEP05\(2015\)059](#)

Report number: CERN-PH-TH-2015-031, DESY-15-026

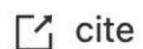
View in: [ADS Abstract Service](#), [CERN Document Server](#)



pdf



links



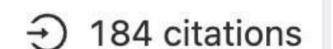
cite



claim



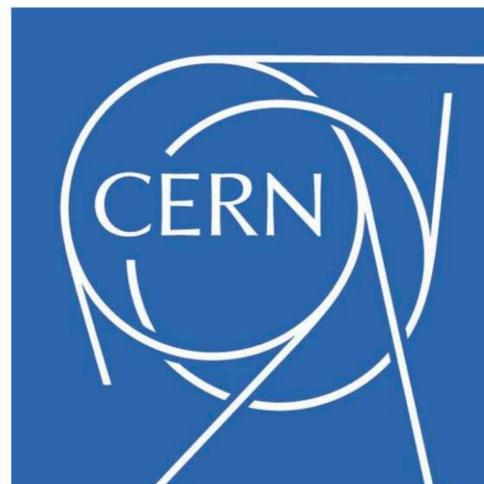
reference search



184 citations

PREVIOUS VISIT

EMERGING JETS

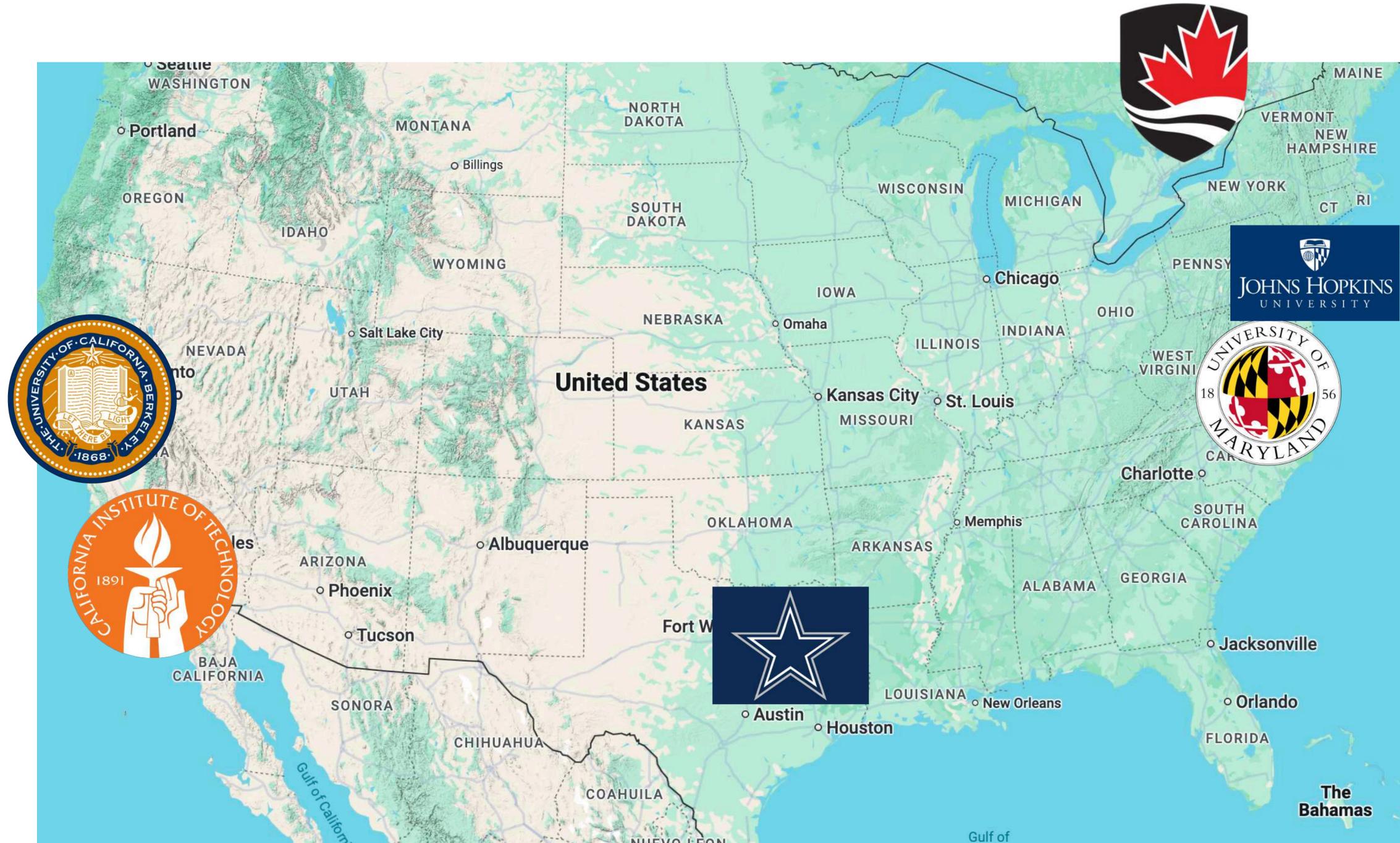


DANIEL STOLARSKI
WITH PEDRO SCHWALLER
AND ANDREAS WEILER

To appear

Mainz December 16, 2014

Faculty at Carleton University.



Faculty at Carleton University.

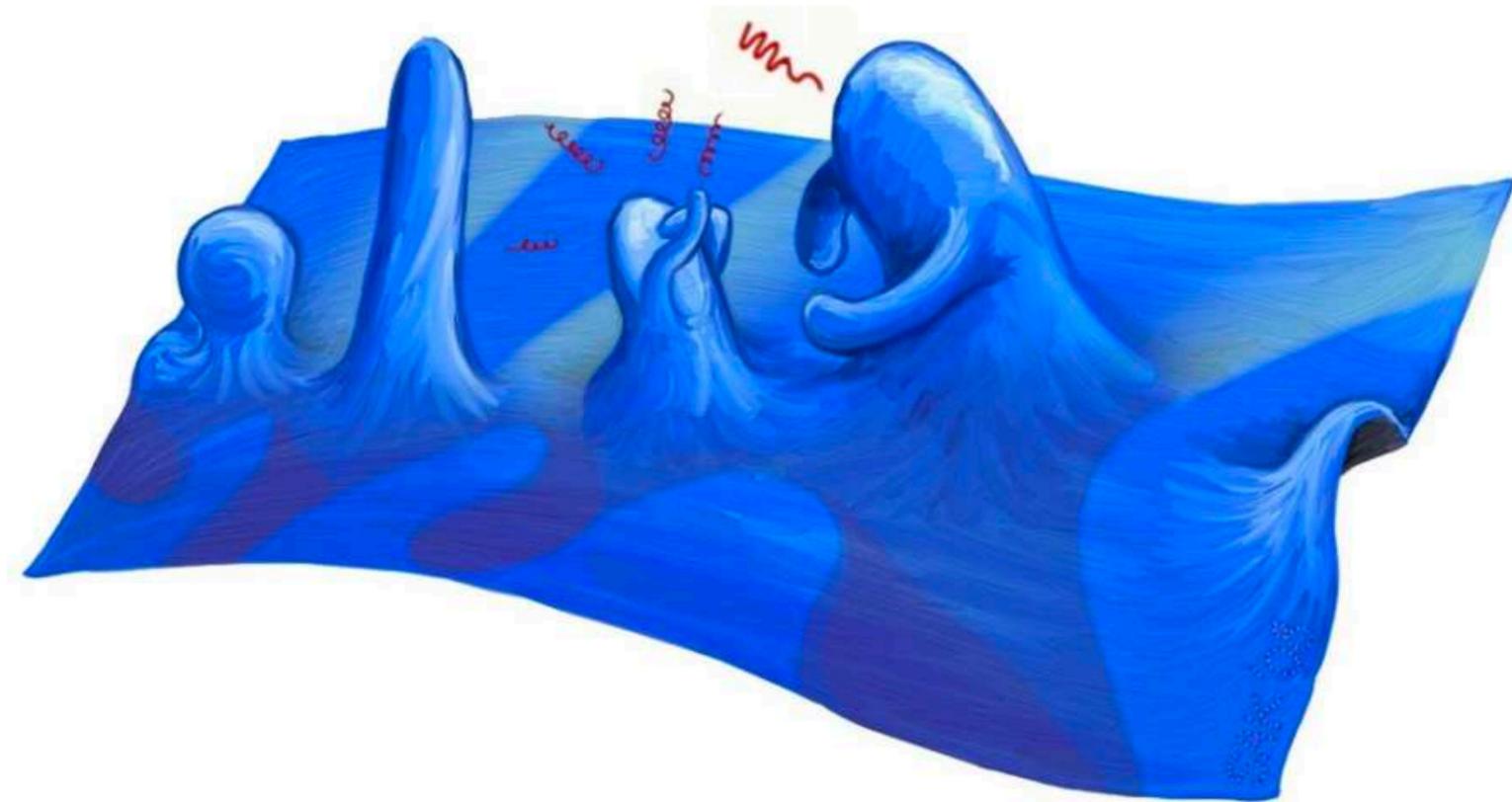


QUANTUM FIELD THEORY

Combination of quantum mechanics and special relativity.

All objects represented as fields (e.g. electric and magnetic field).

Particles are excitations in the field.



David Tong

PERTURBATIVE QFT

QFT is hard.

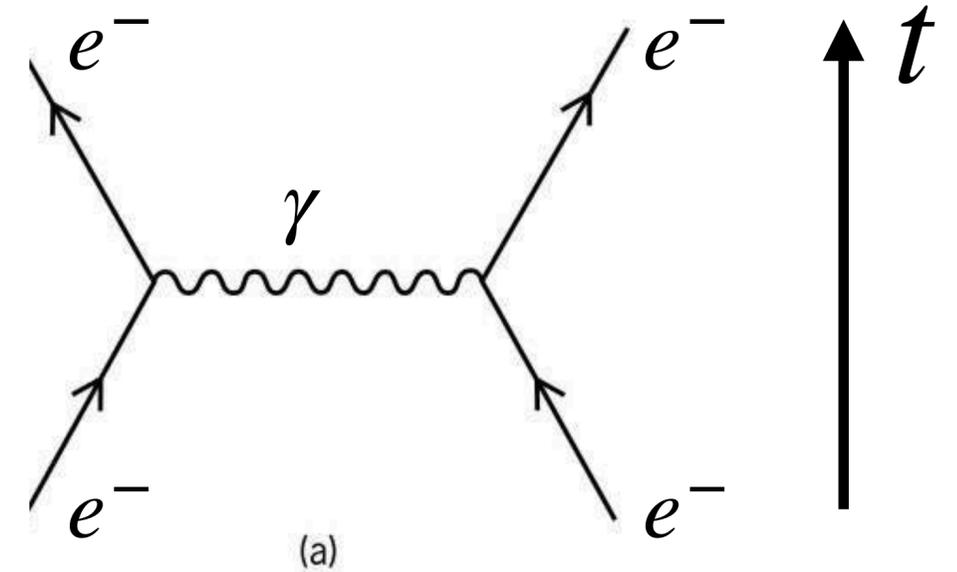
Most successful tool is
perturbation theory.

Terms in series represented
by Feynman diagrams.

Electron scattering:

$$\mathcal{M} \sim e^2$$

$$\sigma_{\text{Born}} \sim e^4$$



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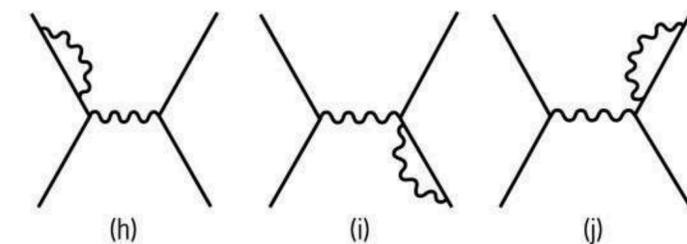
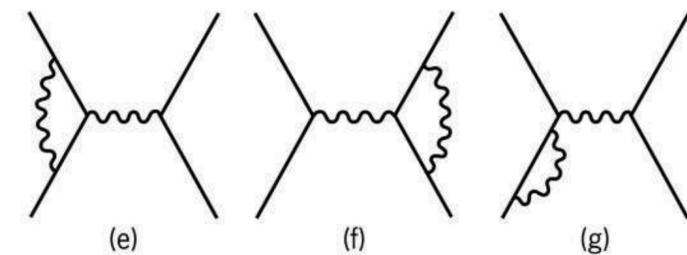
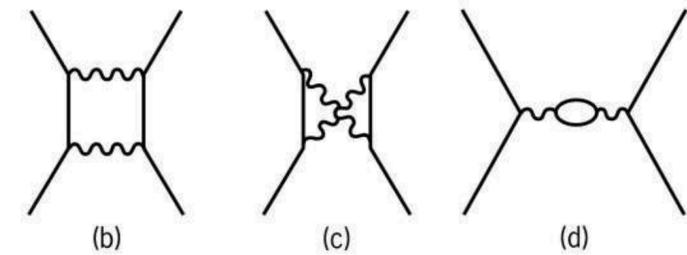
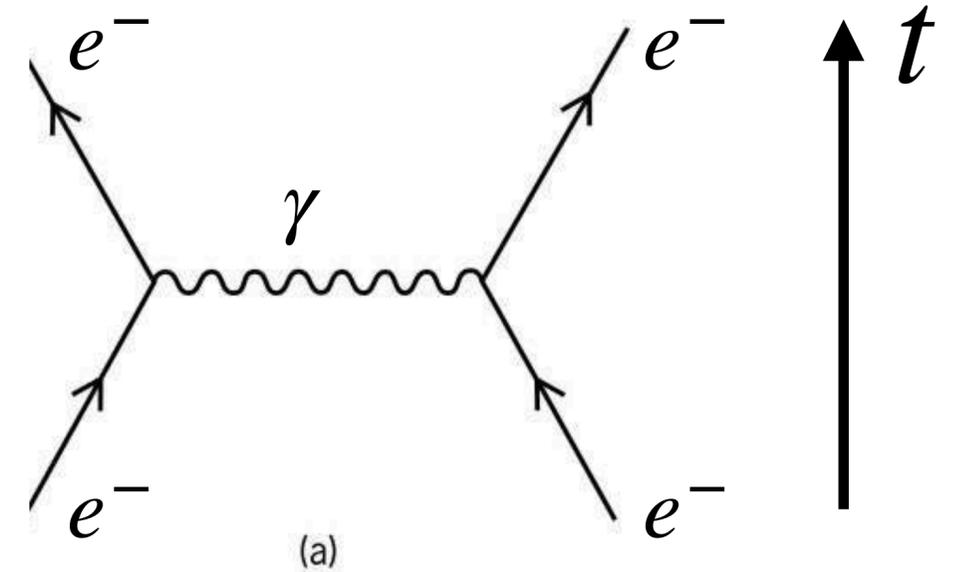
Electron scattering:

$$\mathcal{M} \sim e^2$$

$$\sigma_{\text{Born}} \sim e^4$$

$$\mathcal{M} \sim e^2 + e^4$$

$$\sigma_{\text{NLO}} \sim e^4 + e^6$$



ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

$$g = 2 \quad \text{Dirac, 1928}$$

$$(i\gamma^\mu \partial_\mu - m)\psi(x) = 0$$

ELECTRON MAGNETIC MOMENT

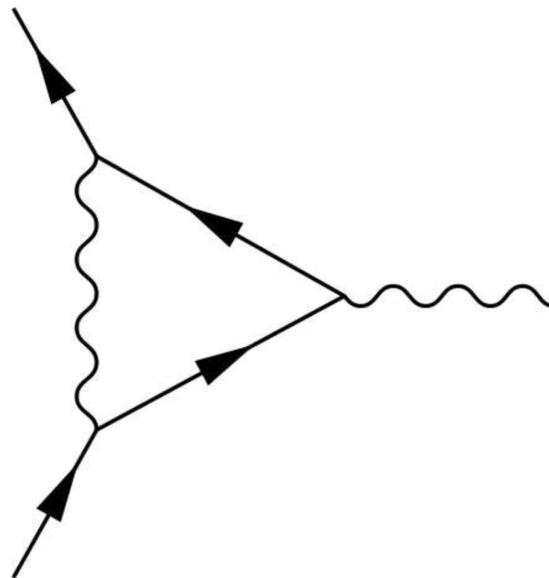
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$$g = 2 \left(1 + \frac{\alpha}{2\pi} \right)$$

Schwinger, 1948



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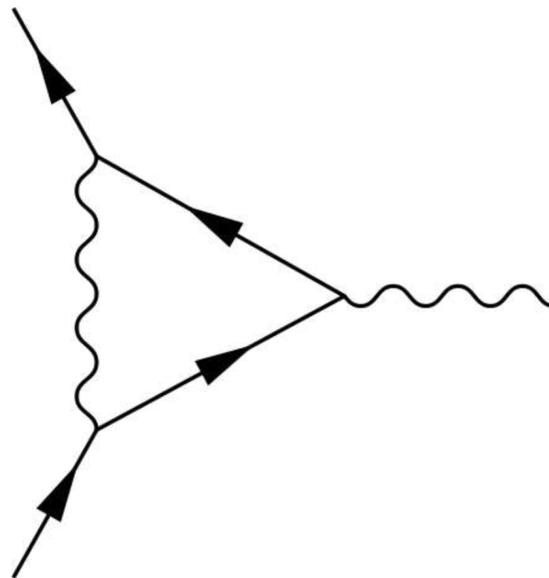
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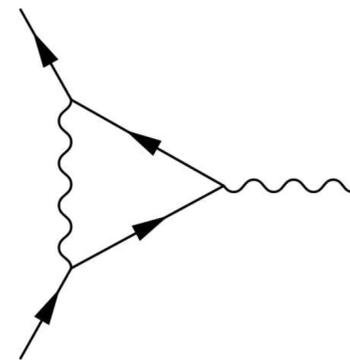
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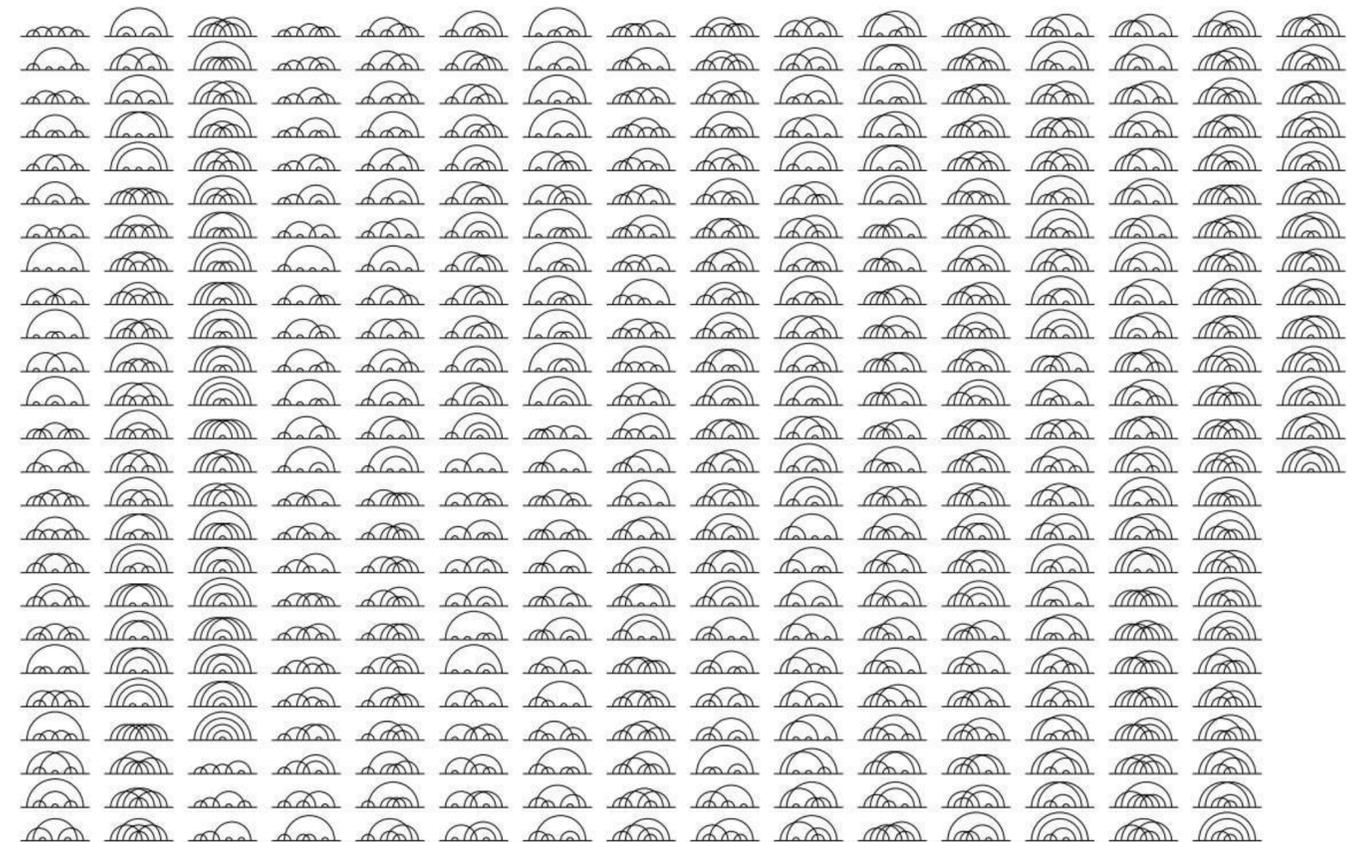
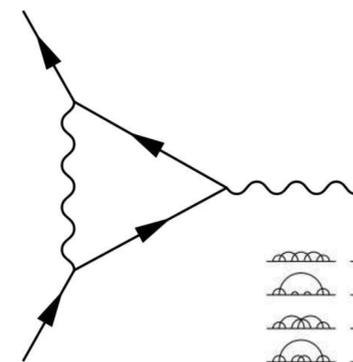
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$$g_{\text{th}} = 2(1 + 0.0011596521816) \quad \text{Kinoshita et al, 2014}$$

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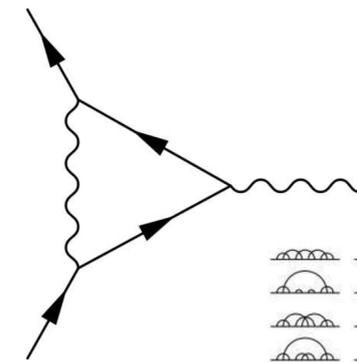
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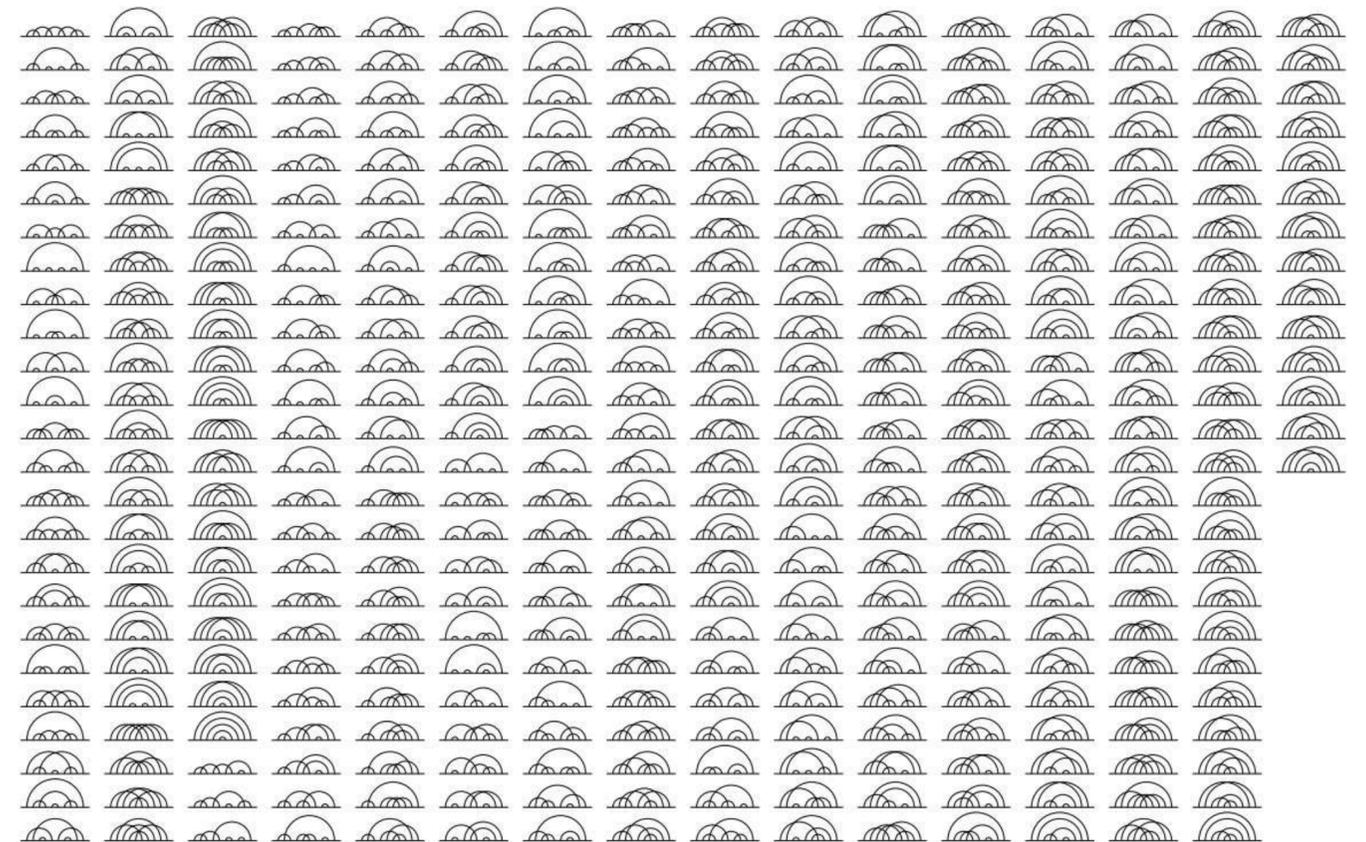


$$g_{\text{th}} = 2(1 + 0.0011596521816)$$

Kinoshita et al, 2014

$$g_{\text{exp}} = 2(1 + 0.0011596521806)$$

Fan et. al. 2023



RUNNING COUPLINGS

Quantum electrodynamics

characterized by charge of electron: e .

Often use dimensionless fine structure

constant: $\alpha = \frac{e^2}{4\pi \epsilon_0 \hbar c} \approx \frac{1}{137}$

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Fun fact: the fine structure constant is
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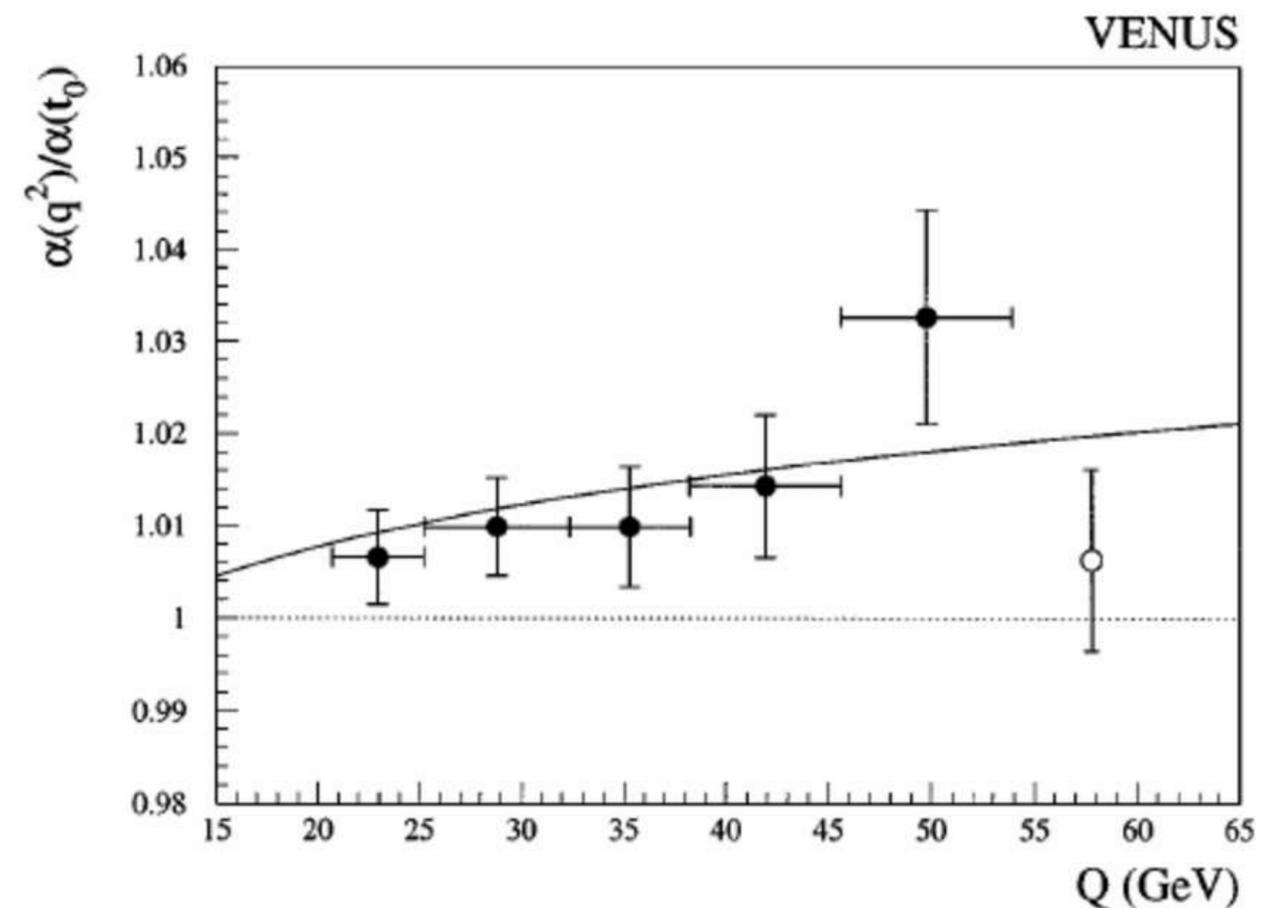
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Venus Collaboration, 1998.

NON-PERTURBATIVE QFT

QED (electromagnetic force)
expansion parameter is

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What about theories where
expansion parameter is ~ 1 ?

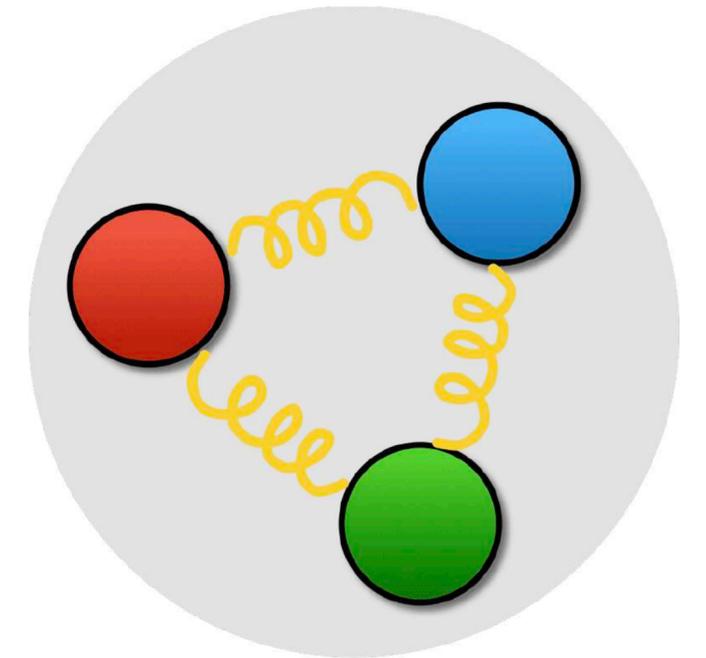
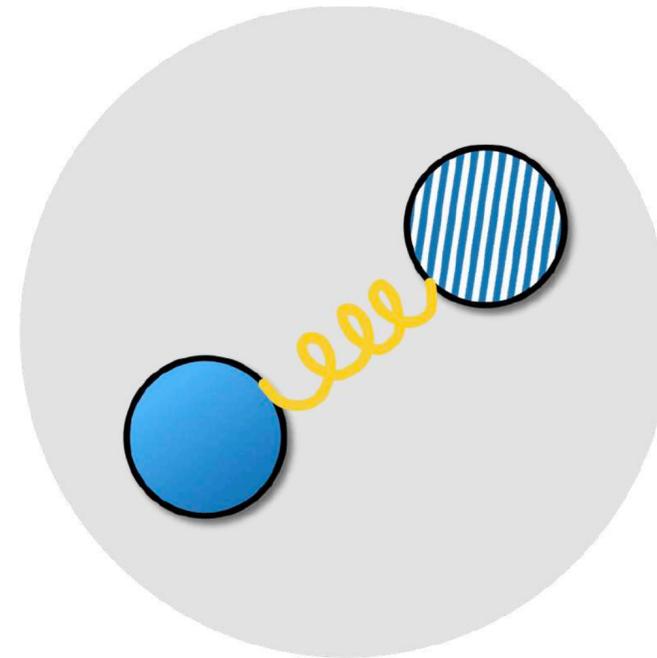
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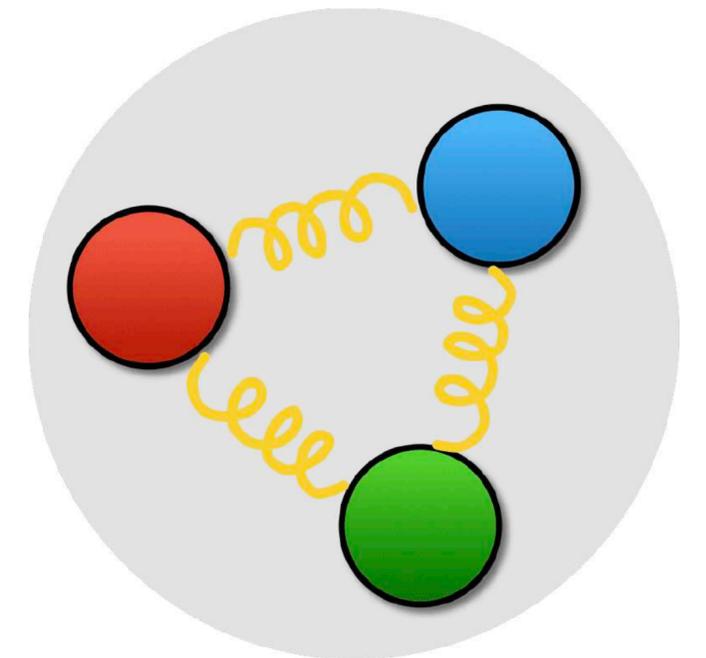
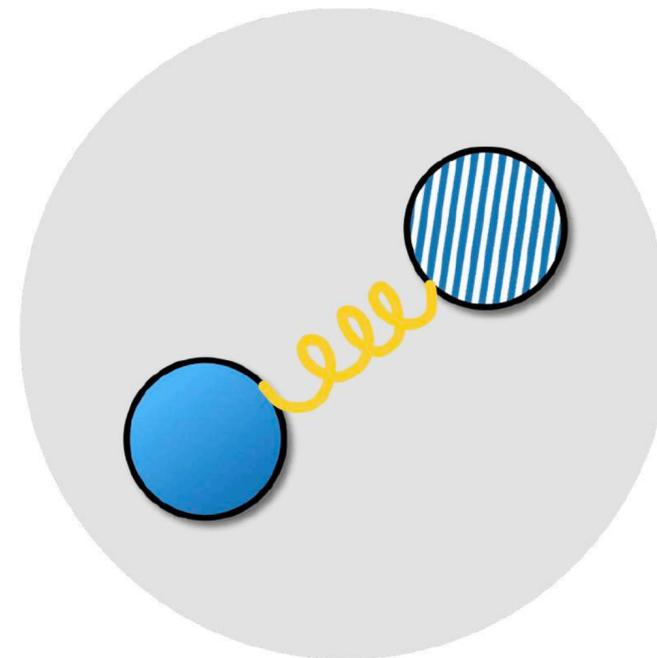
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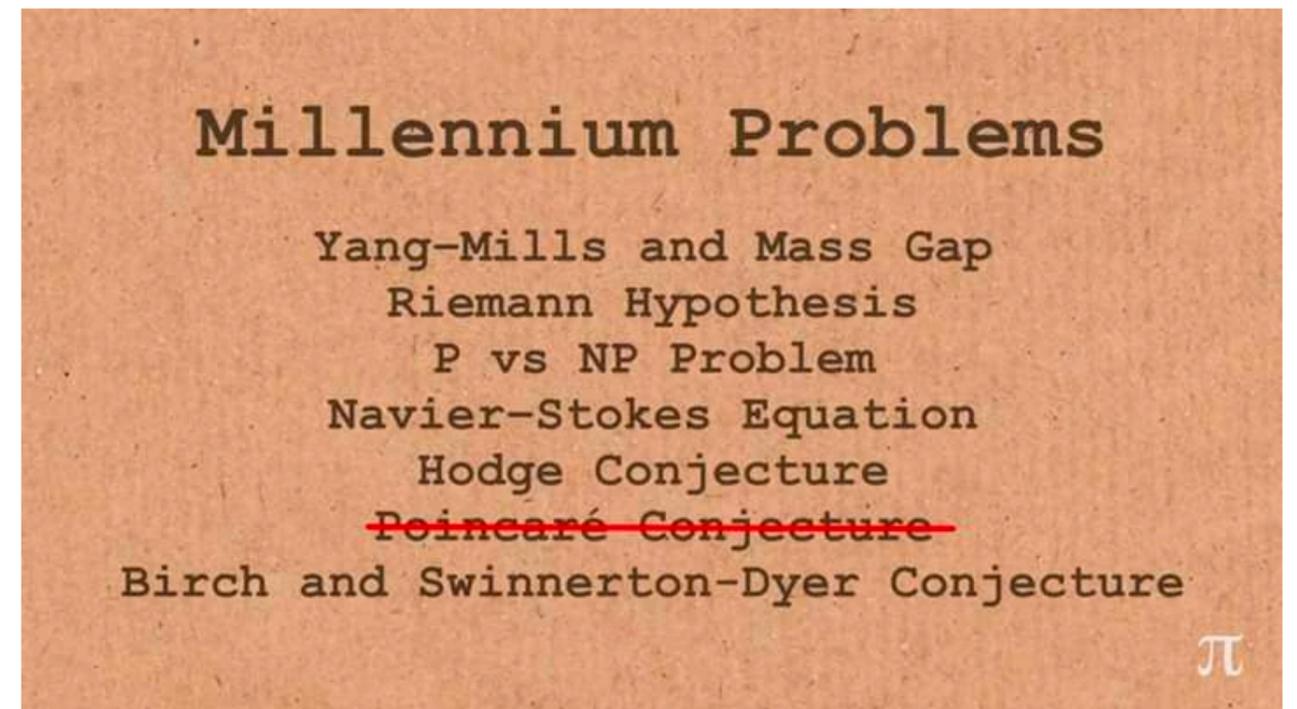
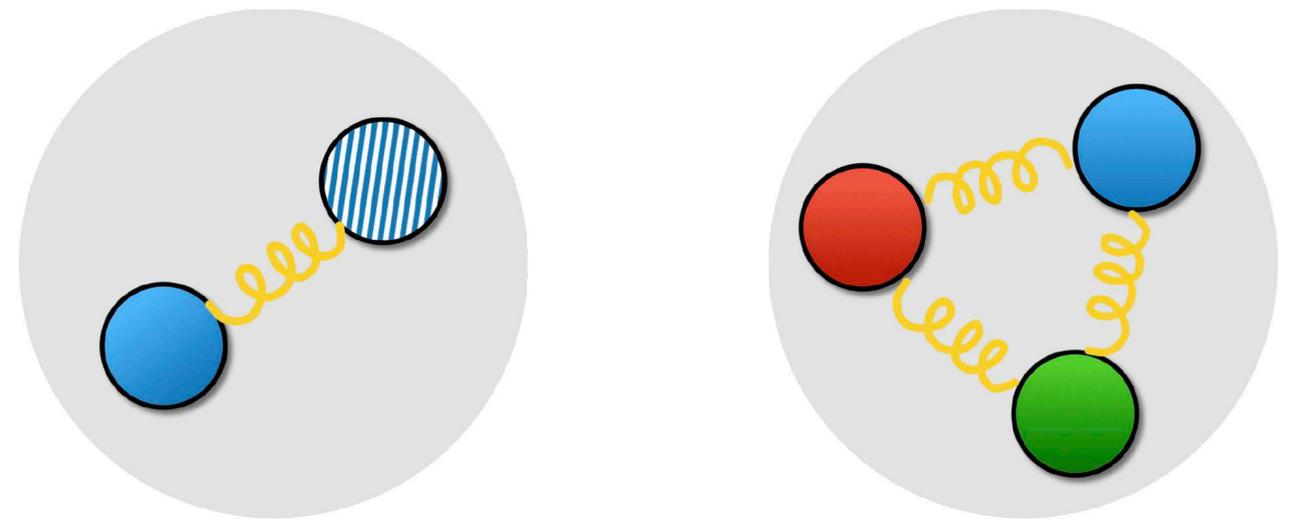
Feynman diagrams are unhelpful.

Most of our understanding of strong
force is from data.

STRONG FORCE (QCD)

Things we know about the strong force from data:

1. **Confinement**: do not see free quarks, only see **heavy** bound states.

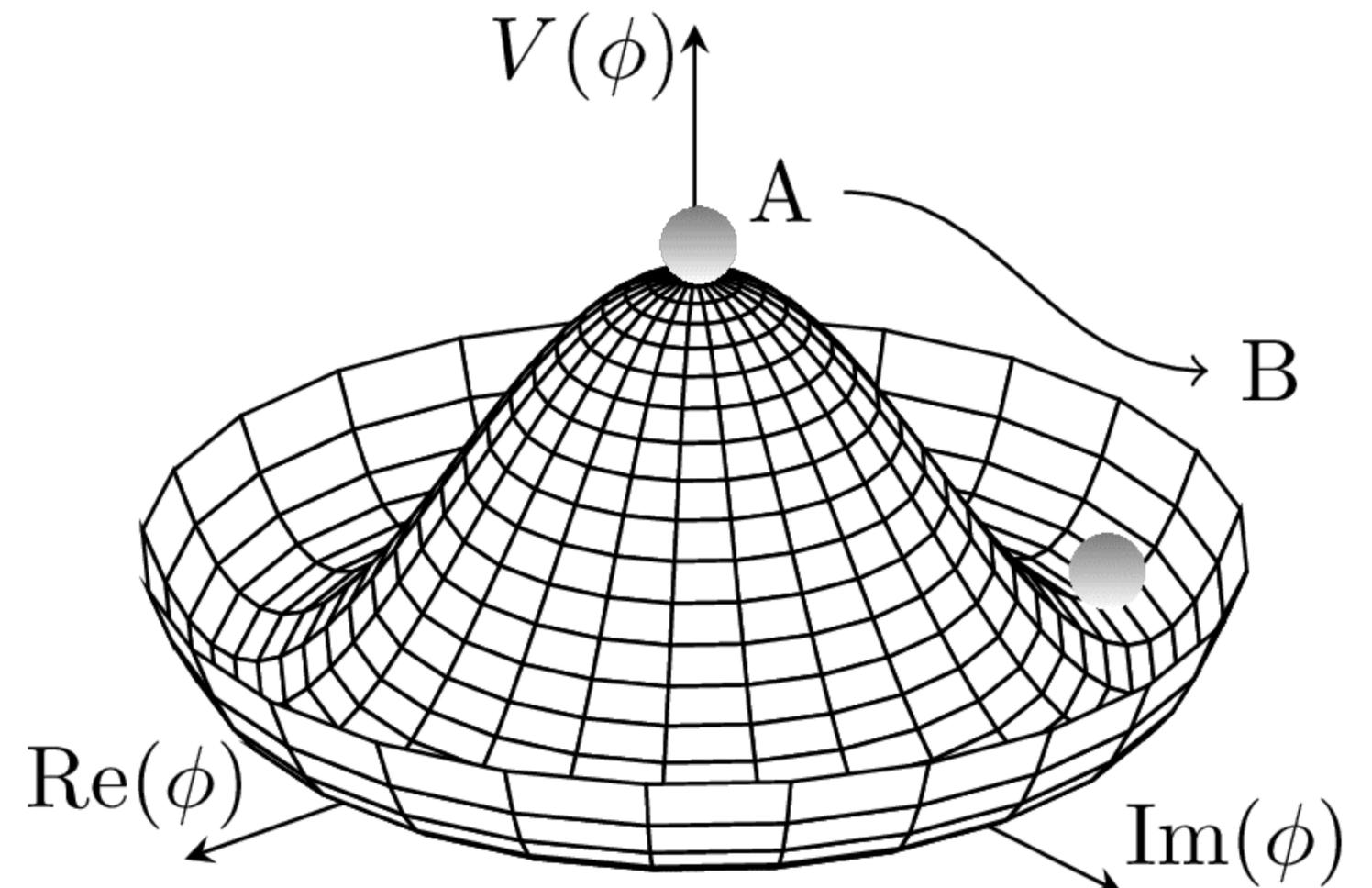


STRONG FORCE (QCD)

Things we know about the strong force from data:

2. **Spontaneous symmetry breaking**: symmetry of bound states different than that of physical laws.

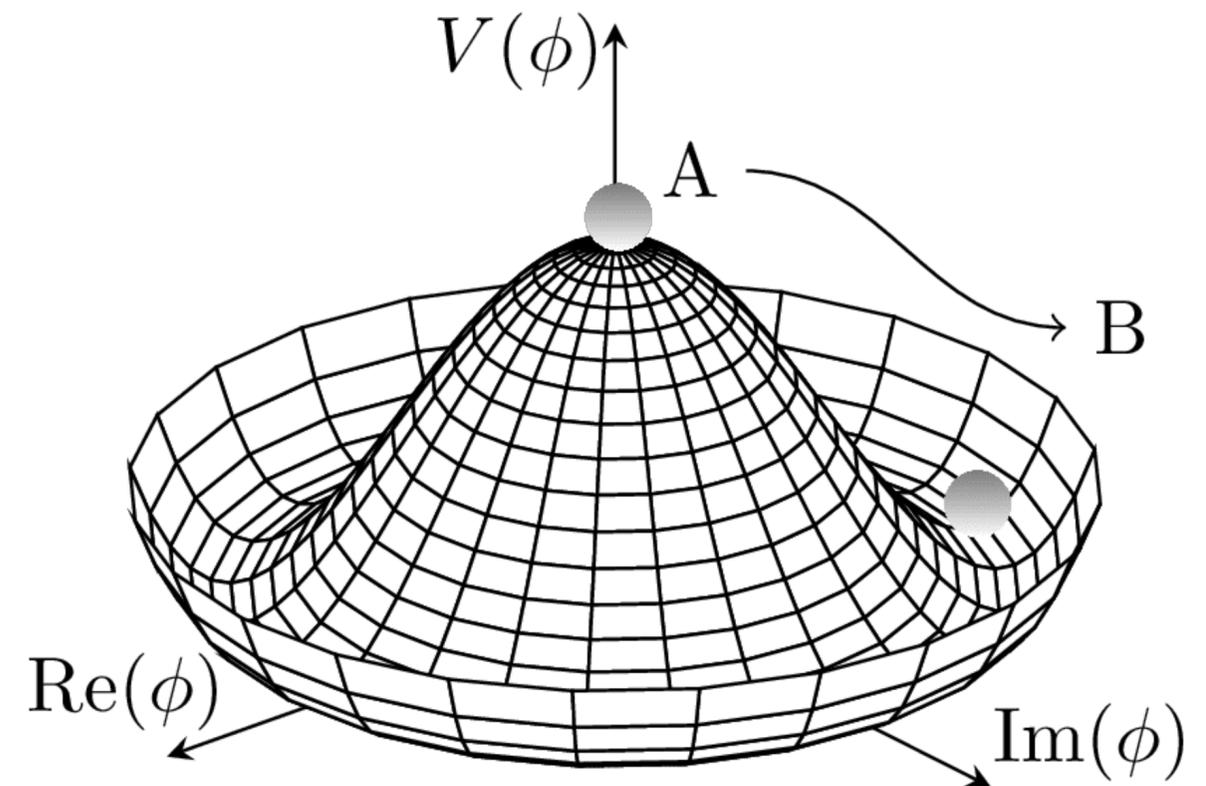
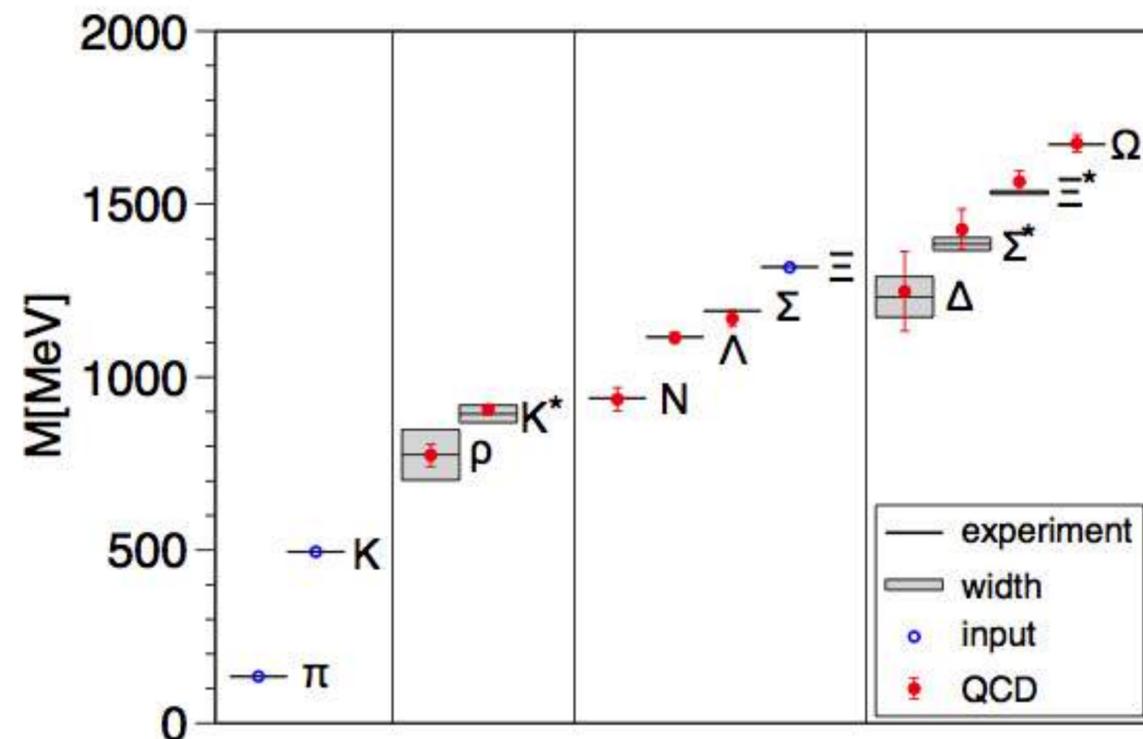
$$V(\phi) = -m^2 |\phi|^2 + \lambda |\phi|^4$$



STRONG FORCE (QCD)

Two things are actually deeply connected.

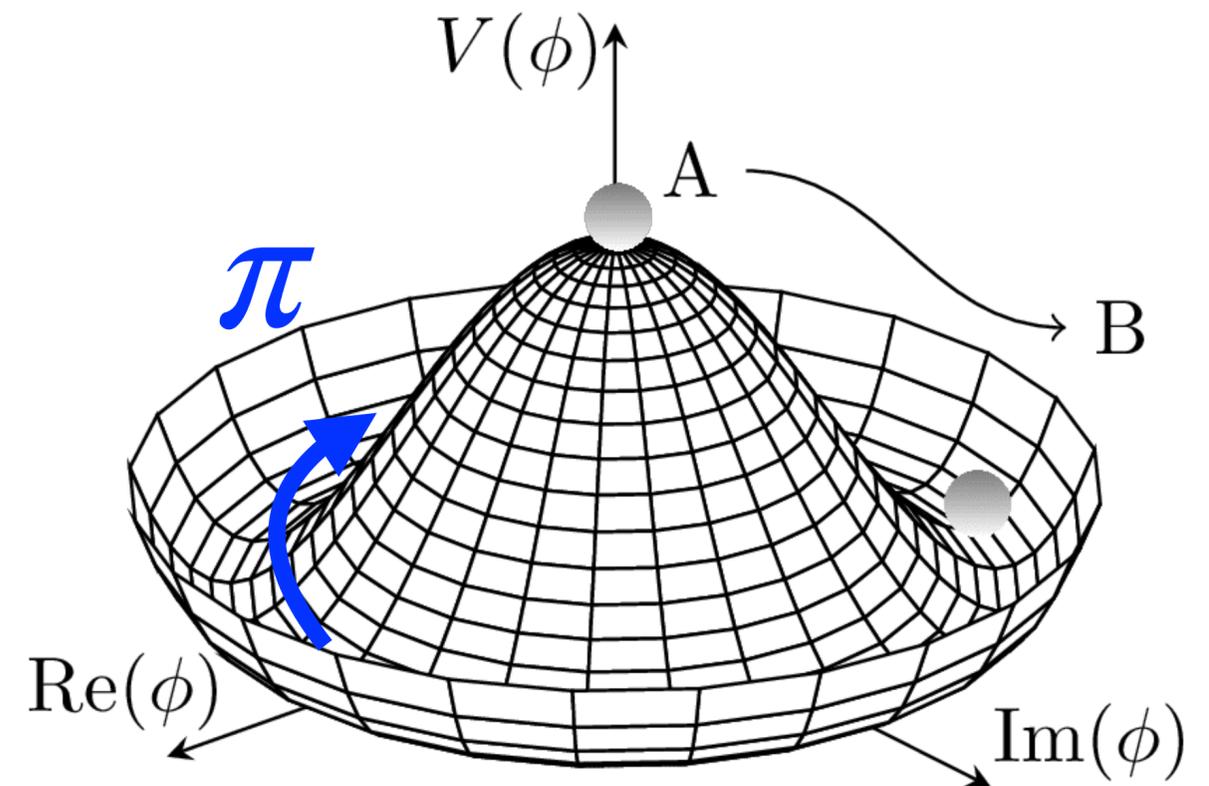
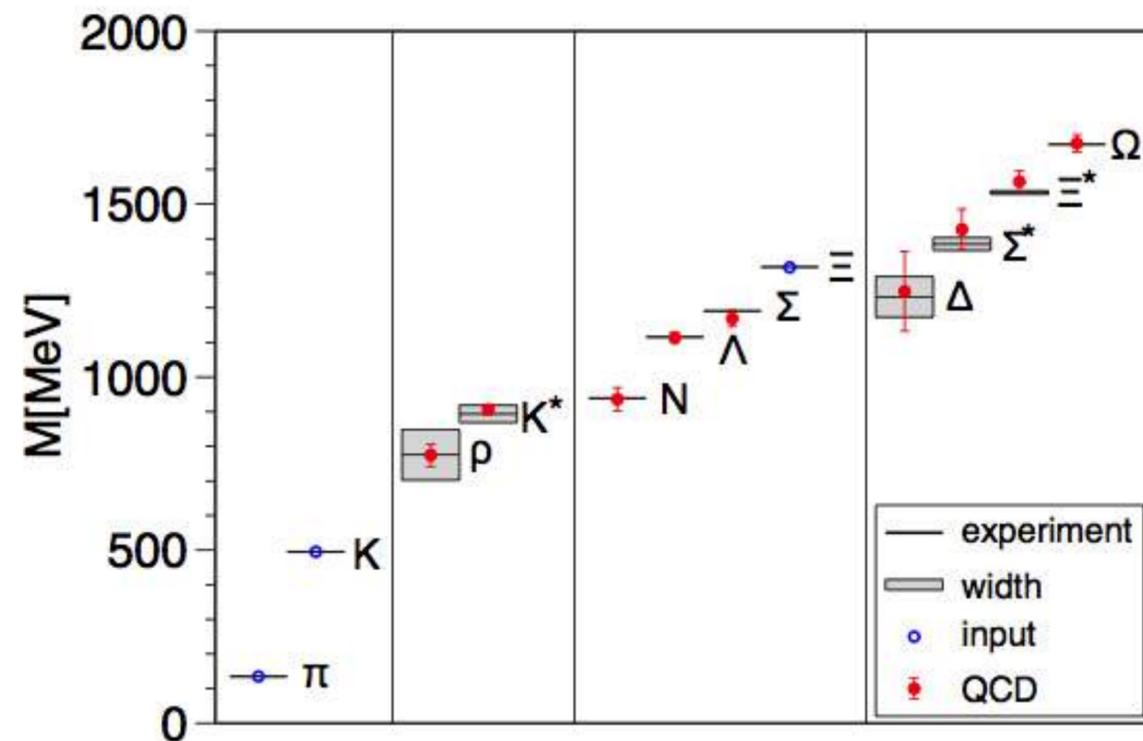
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RUNNING STRONG COUPLING

Like electromagnetism, strong coupling α_s changes with energy.

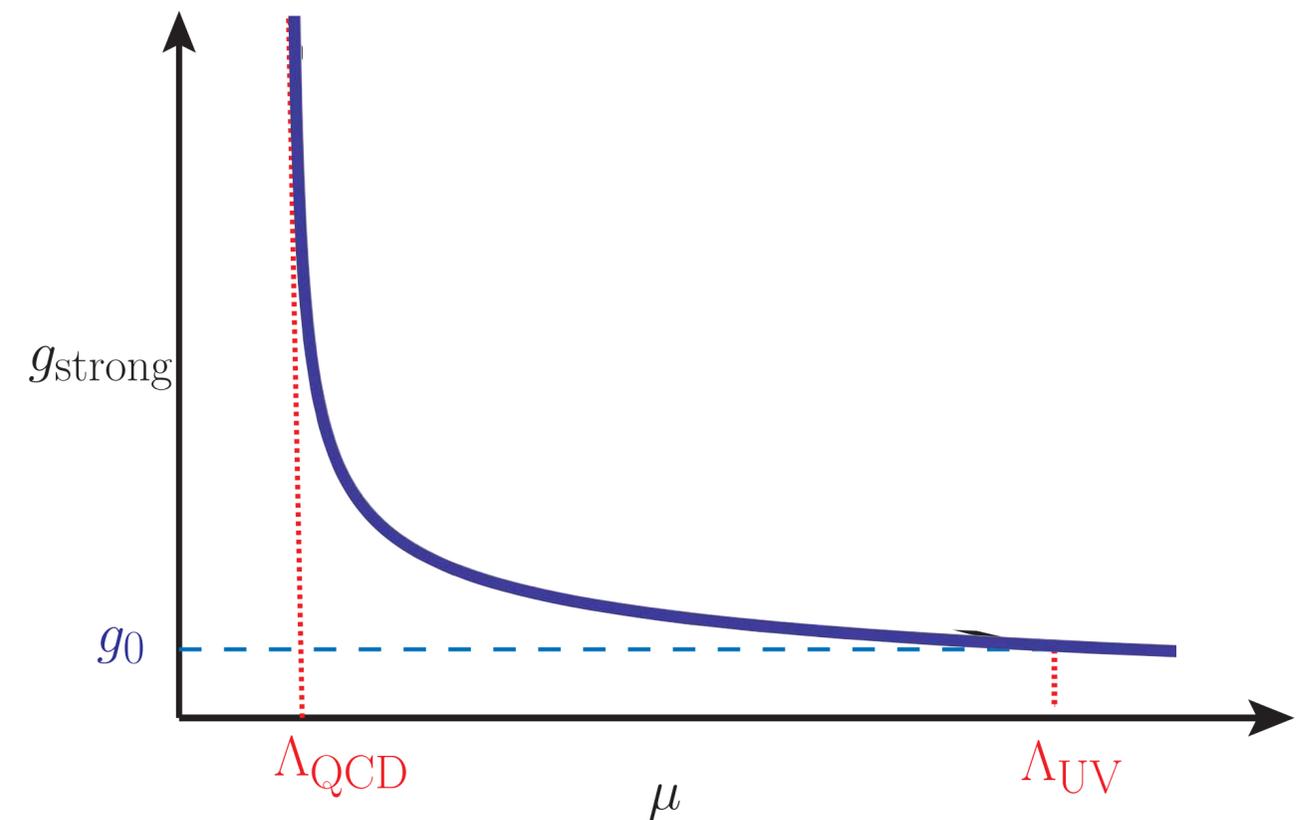
$$E \frac{d\alpha_s}{dE} \approx - \frac{7\alpha_s^2}{2\pi}$$

RUNNING STRONG COUPLING

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$$E \frac{d\alpha_s}{dE} \approx \ominus \frac{7\alpha_s^2}{2\pi}$$

Coupling gets weaker at high energy:
asymptotic freedom.



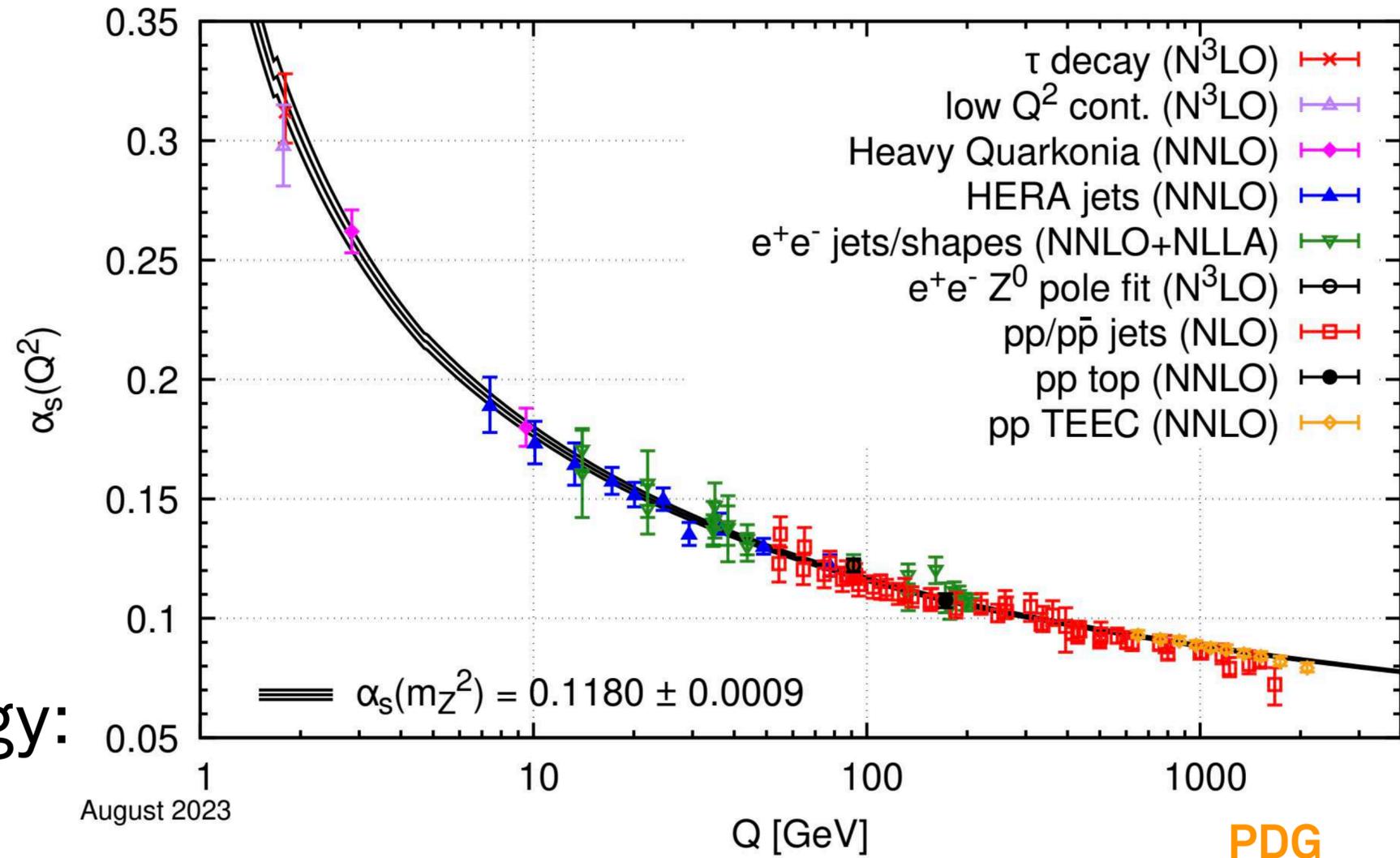
Politzer PRL '73. Gross & Wilczek PRL '73.

VERIFIED BY DATA

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TRIP TO STOCKHOLM

THE NOBEL PRIZE IN PHYSICS 2004





David J. Gross
Kavli Institute for Theoretical Physics,
University of California, Santa Barbara, USA



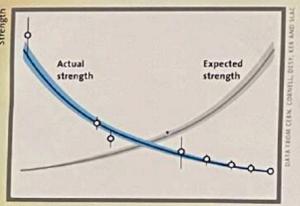
H. David Politzer
California Institute of Technology
(Caltech), Pasadena, USA



Frank Wilczek
Massachusetts Institute of Technology
(MIT), Cambridge, USA

A good start ...
Frank Wilczek and David Politzer were barely 20 years old and still PhD students when their discovery of asymptotic freedom was published. These were their very first scientific publications!

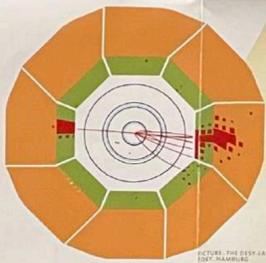
Many tried, but failed, to find a theory in which the strength of the strong force decreases as the energy increases. This year's Nobel laureates found a theory with the required minus sign. When the quarks are very close to each other, i.e. when the distance between them is asymptotically approaching zero, the force is so weak that they behave almost as free particles.

$$\beta(g) = -\frac{g^3}{16\pi^2} \left(\frac{11}{3} N_c - \frac{4}{3} N_f \right)$$


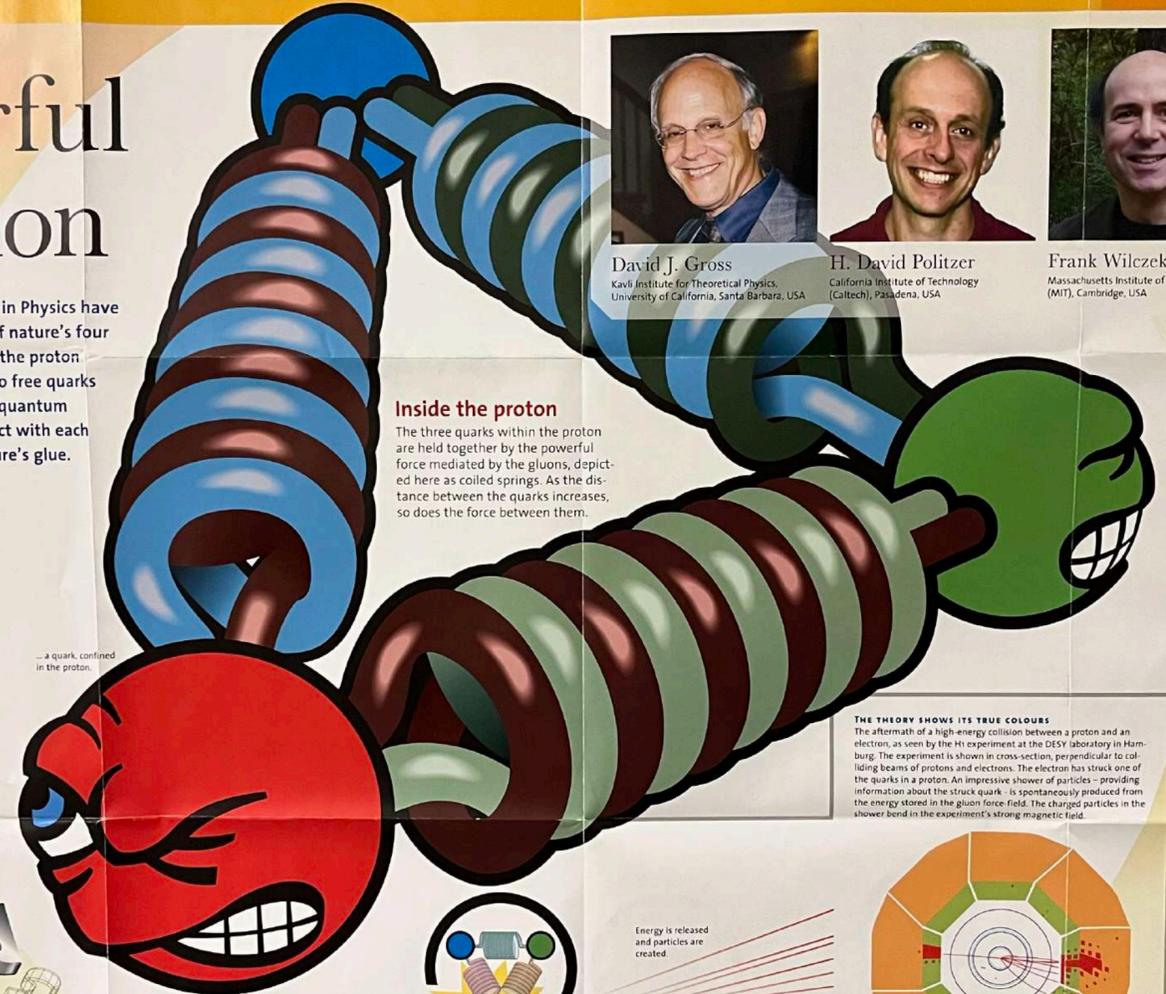
Low energy – large distances High energy – small distances

A unified theory for all forces?
This year's prize paves the way for a more fundamental future description of the forces in nature. The electromagnetic, weak and strong forces have much in common and are perhaps different aspects of a single force. They also appear to have the same strength at very high energies, especially if 'supersymmetric' particles exist. It may even be possible to include gravity if theories which treat matter as small vibrating strings are correct.

THE THEORY SHOWS ITS TRUE COLOURS
The aftermath of a high-energy collision between a proton and an electron, as seen by the H1 experiment at the DESY laboratory in Hamburg. The experiment is shown in cross-section, perpendicular to colliding beams of protons and electrons. The electron has struck one of the quarks in a proton. An impressive shower of particles – providing information about the struck quark – is spontaneously produced from the energy stored in the gluon force field. The charged particles in the shower bend in the experiment's strong magnetic field.



Inside the proton
The three quarks within the proton are held together by the powerful force mediated by the gluons, depicted here as coiled springs. As the distance between the quarks increases, so does the force between them.



A colourful connection
The scientists awarded this year's Nobel Prize in Physics have solved a mystery surrounding the strongest of nature's four fundamental forces. The three quarks within the proton can sometimes appear to be free, although no free quarks have ever been observed. The quarks have a quantum mechanical property called colour and interact with each other through the exchange of gluons – nature's glue.



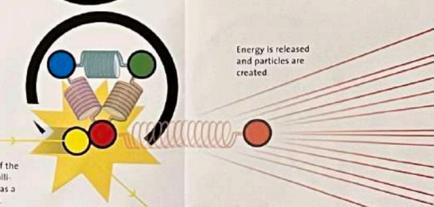
A high energy electron on collision course with ...

... a quark, confined in the proton.

The Standard Model and the four forces
The quarks and gluons of the strong (or colour) force are the third piece in the puzzle of nature's four forces. The first piece, the electromagnetic force, is similar to the strong force but instead of gluons, particles of light, photons, are the force carriers. The gluons carry colour charge while the photons are electrically neutral. The second piece in the puzzle is the weak force, which controls some radioactive decays and energy production in the sun. This force differs from the other two because the force-carrying particles are very heavy. The fourth force, gravity, is the least understood even though it is experienced by us all. Gravitons are thought to be the force-carrying particles, but they have yet to be discovered. The Standard Model provides a description of all the forces apart from gravity.



IF A QUARK IS KNOCKED OUT OF THE PROTON IN A HIGH-ENERGY COLLISION, IT APPEARS TO BEHAVE AS A FREE PARTICLE FOR AN INSTANT.



Energy is released and particles are created

EARLIER NOBEL LAUREATES WHOSE WORK WAS OF GREAT CONSEQUENCE FOR THIS YEAR'S AWARD:

<p>1949 HIDEKI YUKAWA, The theory of nuclear forces</p>	<p>1957 CHEN NING YANG AND TSUNG-DAO LEE, Parity violation in particle physics</p>	<p>1965 SHIN-ICHI TOMONAGA, JULIAN SCHWINGER AND RICHARD P. FEYNMAN, QED – the quantum theory of electromagnetic interactions</p>	<p>1969 MURRAY GELL-MANN, Symmetry properties of elementary particles</p>	<p>1979 SHELDON LE GLASHOW, ABDUS SALAM AND STEVEN WEINBERG, The theory of electroweak interactions</p>	<p>1982 KENNETH G WILSON, The theory of phase transformations</p>	<p>1990 JEROME I. FRIEDMAN, HENRY W. KENDALL AND RICHARD E. TAYLOR, The discovery of quarks through electron-scattering experiments</p>	<p>1999 GEORGIOS 'T. HOOFD AND MARTINUS J.G. VELTMAN, The quantum structure of the electro-weak interaction</p>
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FURTHER READING Information on the Nobel Prize in Physics 2004: www.nobelprize.org • CERN: www.cern.ch • Hands-on-CERN: <http://hands-on-cern.physta.se/> • DESY: www.desy.de • The particle adventure: <http://particleadventure.org/particleadventure/> • strongforce, by C. Davies, CERN Courier June 2004, p. 23 • The W and Z at LEP, by C. Sutton and Age, by C. De Tar and S. Gottlieb, Physics Today February 2004, p. 45 • In search of the ultimate building blocks, by G. 't Hooft, Cambridge University Press 1997

VOLVO

www.kva.se

Editors: Lars Bergström and Per Carlzon, Secretary and Member of the Nobel Committee for Physics, Mark Pearce, The Royal Institute of Technology, Stockholm, Jonas Fjöræ, Anna Lindqvist and Eva Krutmejer, The Royal Swedish Academy of Sciences.

Layout and illustrations: Typofarm, Printing: Billies Tryckeri 2005

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KUNGLIGA VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

TRIP TO STOCKHOLM

THE ROYAL SWEDISH ACADEMY OF SCIENCES HAS DECIDED TO AWARD THE NOBEL PRIZE IN PHYSICS FOR 2004 "FOR THE DISCOVERY OF ASYMPTOTIC FREEDOM IN THE THEORY OF THE STRONG INTERACTION" JOINTLY TO DAVID J. GROSS, H. DAVID POLITZER AND FRANK WILCZEK

A colourful connection

The scientists awarded this year's Nobel Prize in Physics have solved a mystery surrounding the strongest of nature's four fundamental forces. The three quarks within the proton can sometimes appear to be free, although no free quarks have ever been observed. The quarks have a quantum mechanical property called colour and interact with each other through the exchange of gluons – nature's glue.

Inside the proton
The three quarks within the proton are held together by the powerful force mediated by the gluons, depicted here as coiled springs. As the distance between the quarks increases, so does the force between them.

The Standard Model and the four forces
The quarks and gluons of the strong (or colour) force are the third piece in the puzzle of nature's four forces. The first piece, the electromagnetic force, is similar to the strong force but instead of gluons, particles of light, photons, are the force carriers. The gluons carry colour charge while the photons are electrically neutral. The second piece in the puzzle is the weak force, which controls some radioactive decays and energy production in the sun. This force differs from the other two because the force-carrying particles are very heavy. The fourth force, gravity, is the least understood even though it is experienced by us all. Gravitons are thought to be the force-carrying particles, but they have yet to be discovered. The Standard Model provides a description of all the forces apart from gravity.

A good start ...
Frank Wilczek and David Politzer were barely 20 years old and still PhD students when their discovery of asymptotic freedom was published. These were their very first scientific publications!

A unified theory for all forces?
This year's prize paves the way for a more fundamental future description of the forces in nature. The electromagnetic, weak and strong forces have much in common and are perhaps different aspects of a single force. They also appear to have the same strength at very high energies, especially if 'supersymmetric' particles exist. It may even be possible to include gravity if theories which treat matter as small vibrating strings are correct.

THE THEORY SHOWS ITS TRUE COLOURS
The aftermath of a high-energy collision between a proton and an electron, as seen by the H_e experiment at the DESY laboratory in Hamburg. The experiment is shown in cross-section, perpendicular to colliding beams of protons and electrons. The electron has struck one of the quarks in a proton. An impressive shower of particles – providing information about the struck quark – is spontaneously produced from the energy stored in the gluon force field. The charged particles in the shower bend in the experiment's strong magnetic field.

Energy is released and particles are created

Actual strength vs Expected strength
A graph showing the strength of the strong force as a function of distance. The x-axis is labeled 'Distance' and the y-axis is 'Strength'. The 'Expected strength' curve shows a force that increases as distance increases. The 'Actual strength' curve shows a force that remains constant at large distances but decreases as distance decreases, approaching zero at very small distances.

Equation:
$$\beta(g) = -\frac{g^3}{16\pi^2} \left(\frac{11}{3} N_c - \frac{4}{3} N_f \right)$$

Earlier Nobel Laureates whose work was of great consequence for this year's award:

- 1949 HIDEKI YUKAWA, The theory of nuclear forces
- 1957 CHEN NING YANG AND TSUNG-DAO LEE, Parity violation in particle physics
- 1965 SHIN-ICHIRO TOMONAGA, JULIAN SCHWINGER AND RICHARD P. FENMANN, QED – the quantum theory of electromagnetic interactions
- 1969 MURRAY GELL-MANN, Symmetry properties of elementary particles
- 1979 SHELDON LEE GLASHOW, ABDUS SALAM AND STEVEN WEINBERG, The theory of electroweak interactions
- 1982 KENNETH G. WILSON, The theory of phase transformations
- 1990 JEROME I. FRIEDMAN, HENRY W. KENDALL AND RICHARD E. TAYLOR, The discovery of quarks through electron-scattering experiments
- 1999 GEORGIOS 'T. HOOFD AND MARTINUS J.G. VELTMAN, The quantum structure of the electro-weak interaction

Further Reading:
 Information on the Nobel Prize in Physics 2004: www.nobelprize.org • CERN: www.cern.ch • Hands-on-CERN: <http://hands-on-cern.physta.se/>
 DESY: www.desy.de • The particle adventure: <http://particleadventure.org/particleadventure/>
 strong force, by C. Davies, CERN Courier June 2004, p. 23 • The W and Z at LEP, by C. Sutton and Age, by C. De Tar and S. Gottlieb, Physics Today February 2004, p. 45 • In search of the ultimate building blocks, by G. 't Hooft, Cambridge University Press 1997

Volvo and **Kungliga Vetenskapsakademien** logos are also present.



SUPERSYMMETRY

SPHERICAL COW

Supersymmetric theories are the spherical cows of quantum field theory.

Double number of particles.

SUSY version of many QFTs can be solved. **Seiberg, mostly.**

Deform away from SUSY.



Keenan Crane, Wikipedia.

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SYMMETRY AND ENERGY

Does a spin up electron have the same energy as a spin down electron?

$$\langle \uparrow | H | \uparrow \rangle \stackrel{?}{=} \langle \downarrow | H | \downarrow \rangle$$

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Laws of physics are invariant under rotation.

Can separate the energy with a magnetic field, but that would be an explicit breaking of rotational symmetry.

SUPERSYMMETRY AND ENERGY

Supersymmetry relates bosons to fermions.

$$Q | \text{fermion} \rangle = | \text{boson} \rangle$$

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In supersymmetric theories, for every fermion, there is a boson with the exact same mass (energy) and charge.

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Supersymmetric electromagnetism:

	spin	mass
e	1/2	511 keV
se	0	511 keV
γ	1	0
γ ino	1/2	0

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Supersymmetric electromagnetism:

Not our universe!

	spin	mass
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BREAKING SUPERSYMMETRY

To break supersymmetry, give mass to some spins and not others.

Electromagnetism with broken supersymmetry.

	spin	mass
e	1/2	511 keV
se	0	1 TeV?
γ	1	0
γino	1/2	1 TeV?

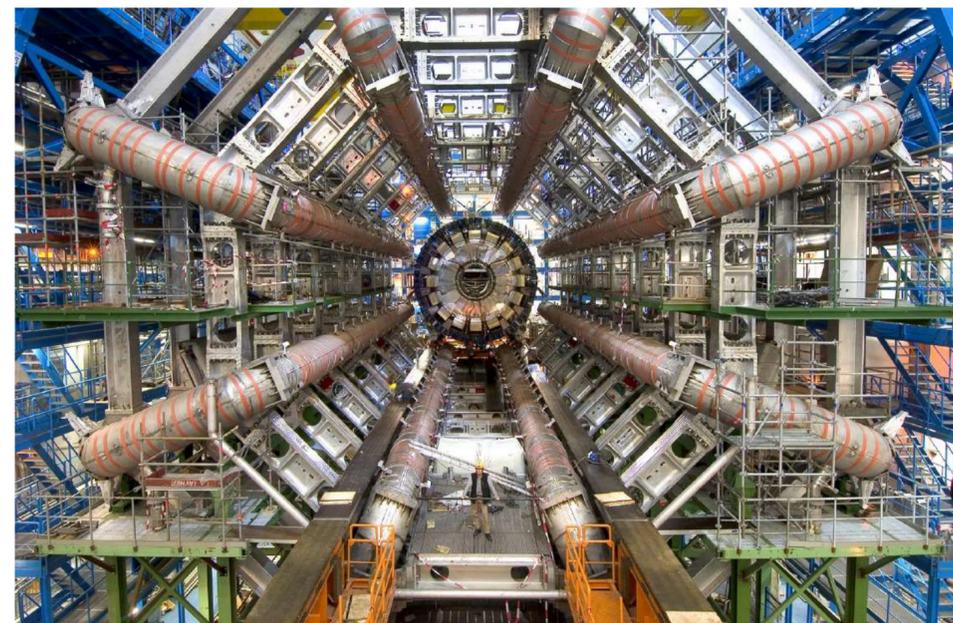
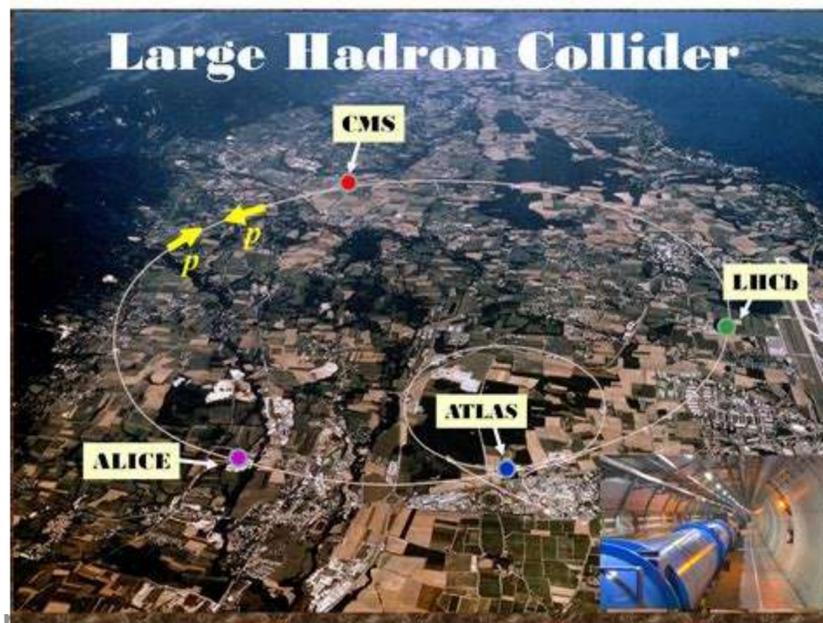
BREAKING SUPERSYMMETRY

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Electromagnetism with broken supersymmetry.

Could be our universe!

	spin	mass
e	1/2	511 keV
se	0	1 TeV?
γ	1	0
$\tilde{\gamma}$	1/2	1 TeV?



ANOMALY MEDIATED SUSY BREAKING

In general, new mass parameter for every particle.

A simple mechanism to break SUSY is called anomaly mediation (AMSB).

Randall, Sundrum, hep-th/9810155.

Giudice, Luty, Murayama, Rattazzi, hep-ph/9810442.

All new masses controlled by **one parameter**: $m_{3/2}$.

Breaking mechanism is extremely predictive!

$$\mathcal{X} = -\frac{1}{3!} (\gamma_i + \gamma_j + \gamma_k) y^{ijk} \phi_i \phi_j \phi_k,$$
$$\gamma_i^j = -\frac{1}{32\pi^2} [y_{ikl}^* y^{jkl} - 4g^2 \delta_i^j C_A(\phi_i)],$$

$$A_{ijk} = -(\gamma_i + \gamma_j + \gamma_k) y^{ijk} m_{3/2}.$$

$$L = -\frac{1}{2} \dot{\gamma}_i^i \phi_i^+ \phi_i,$$

$$\dot{\gamma}_i^j = \frac{\partial \gamma_i^j}{\partial \ln \mu}.$$

$$m_i^2 = \frac{1}{4} \dot{\gamma}_i^i m_{3/2}^2.$$

ASIDE: AMSB FOR SQED

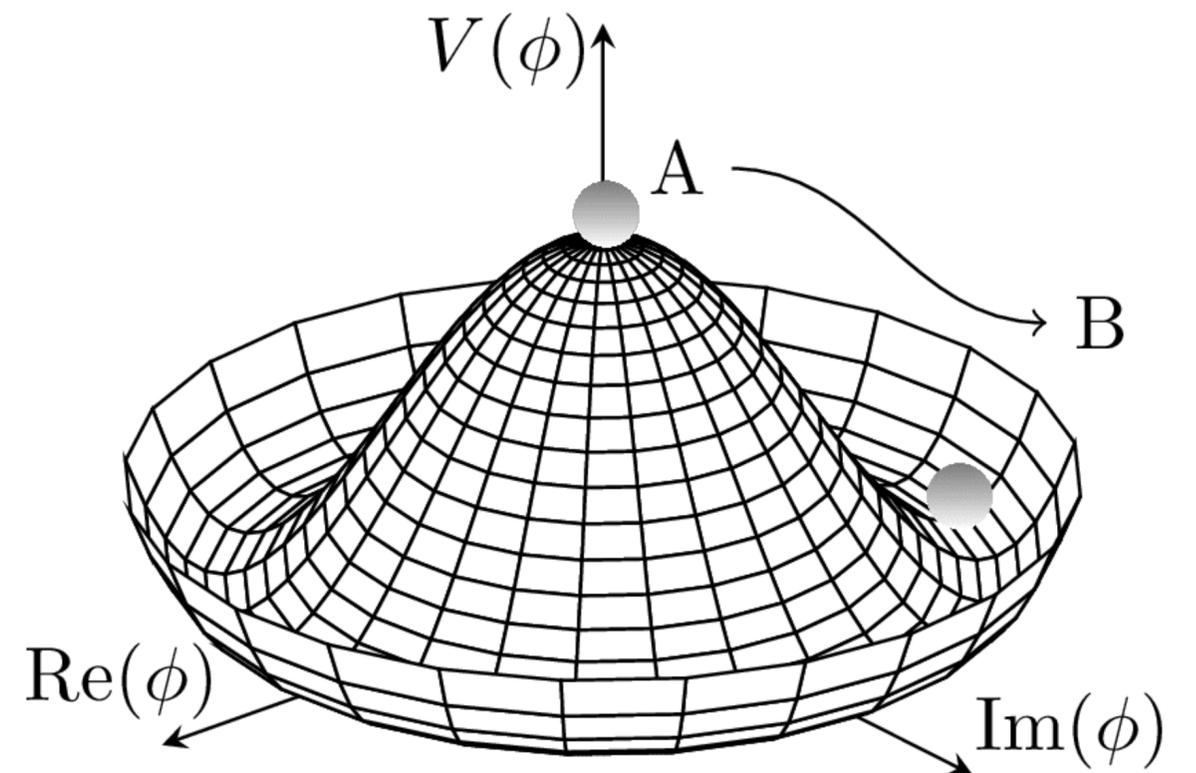
Consider supersymmetric electromagnetism coupled to AMSB:

$$m_{se}^2 \propto - \frac{d\alpha}{dE}$$

$\frac{d\alpha}{dE} > 0$ for electromagnetism.

Partner of the electron becomes a tachyon and gives mass to the photon!

SSM + AMSB does **not** describe our universe.



AMSB + NON-PERTURBATIVE QFT

arXiv > hep-th > arXiv:2104.01179

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High Energy Physics – Theory

[Submitted on 2 Apr 2021 (v1), last revised 19 Jun 2021 (this version, v3)]

Some Exact Results in QCD-like Theories

[Hitoshi Murayama](#)

I propose a controlled approximation to QCD-like theories with massless quarks by employing supersymmetric QCD perturbed by anomaly-mediated supersymmetry breaking. They have identical massless particle contents. Thanks to the ultraviolet-insensitivity of anomaly mediation, dynamics can be worked out exactly when $m \ll \Lambda$, where m is the size of supersymmetry breaking and Λ the dynamical scale of the gauge theory. I demonstrate that chiral symmetry is dynamically broken for $N_f \leq \frac{3}{2}N_c$ while the theories lead to non-trivial infrared fixed points for larger number of flavors. While there may be a phase transition as m is increased beyond Λ , qualitative agreements with expectations in QCD are encouraging and suggest that two limits $m \ll \Lambda$ and $m \gg \Lambda$ may be in the same universality class.

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arXiv > hep-th > arXiv:2104.01179

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High Energy Physics – Theory

[Submitted on 20 Apr 2021 (v1), last revised 13 May 2021 (this version, v2)]

Some Exact Results in Chiral Gauge Theories

Csaba Csáki, Hitoshi Murayama, Ofri Telem

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arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

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High Energy Physics – Theory

[Submitted on 7 May 2021]

More Exact Results on Chiral Gauge Theories: the Case of the Symmetric Tensor

Csaba Csáki, Hitoshi Murayama, Ofri Telem

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arXiv > hep-th > arXiv:2104.10171
arXiv > hep-th > arXiv:2105.03444
arXiv > hep-th > arXiv:2106.10288

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High Energy Physics – Theory

[Submitted on 18 Jun 2021 (v1), last revised 9 Sep 2021 (this version, v2)]

Demonstration of Confinement and Chiral Symmetry Breaking in $SO(N_c)$ Gauge Theories

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri Telem

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arXiv > hep-th > arXiv:2104.01179

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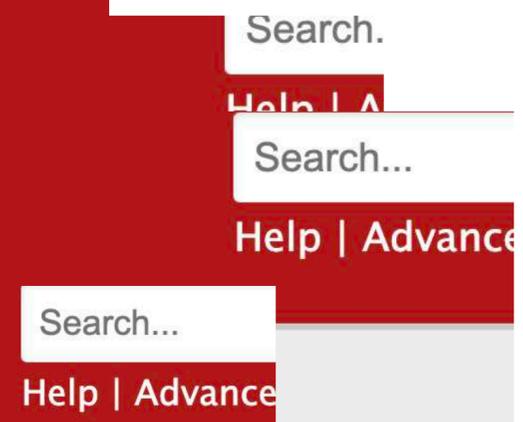
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High Energy Physics – Theory

[Submitted on 6 Jul 2021 (v1), last revised 9 Sep 2021 (this version, v2)]

The Phases of Non-supersymmetric Gauge Theories: the $SO(N_c)$ Case Study

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arXiv > hep-th > arXiv:2107.02813

arXiv > hep-th > arXiv:2111.09690

High Energy Physics – Theory

[Submitted on 18 Nov 2021]

Broken Conformal Window

Hitoshi Murayama, Bea Noether, Digvijay Roy Varier

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High Energy Physics – Theory

[Submitted on 19 Sep 2022]

Dynamics of Simplest Chiral Gauge Theories

Dan Kondo, Hitoshi Murayama, Cameron Sylber

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High Energy Physics – Theory

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[Submitted on 6 Dec 2022]

A Guide to AMSB QCD

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Bea Noether, Digvijay Roy Varier, Ofri Telem

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arXiv > hep-ph > arXiv:2407.06252

High Energy Physics - Phenomenology

[Submitted on 8 Jul 2024 (v1), last revised 16 Dec 2024 (this version, v2)]

Spontaneous CP Breaking in a QCD-like Theory

Csaba Csáki, Maximilian Ruhdorfer, Taewook Youn

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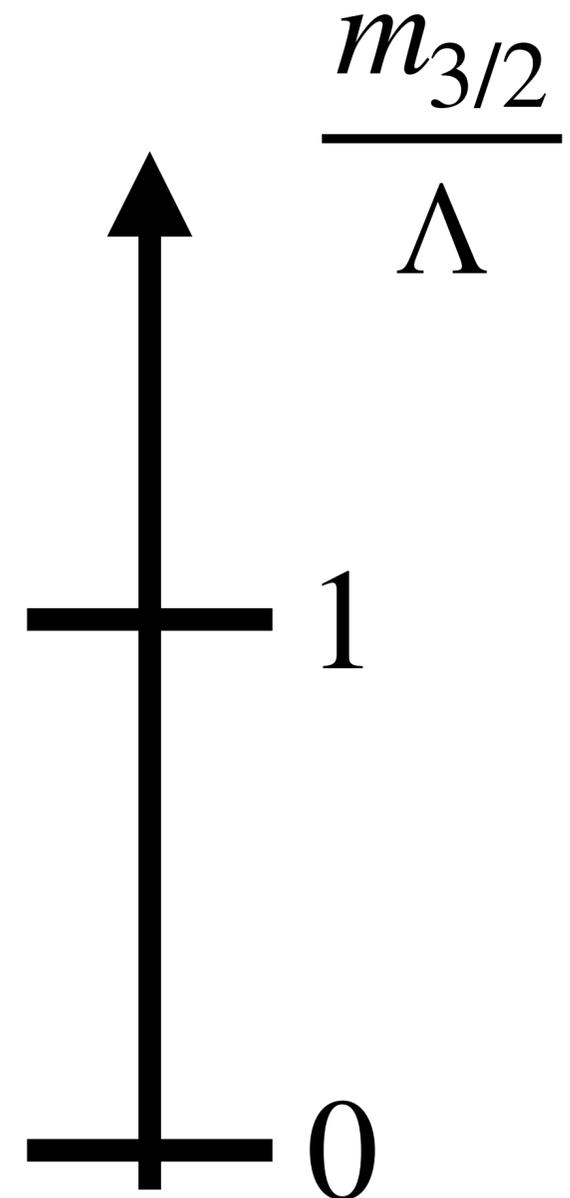
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SMALL VS. LARGE SUSY BREAKING

Two dimensionful parameters:

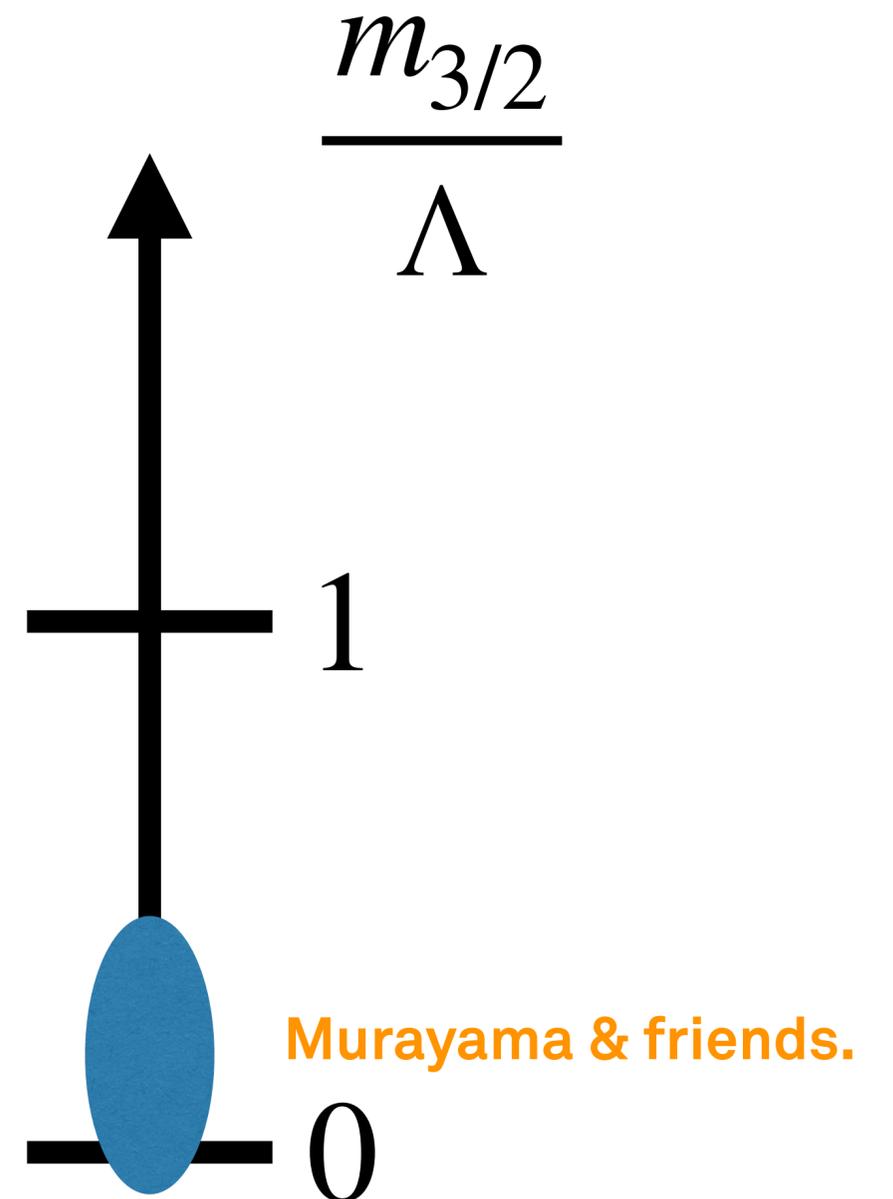
- Λ - mass of bound states
- $m_{3/2}$ - size of SUSY breaking



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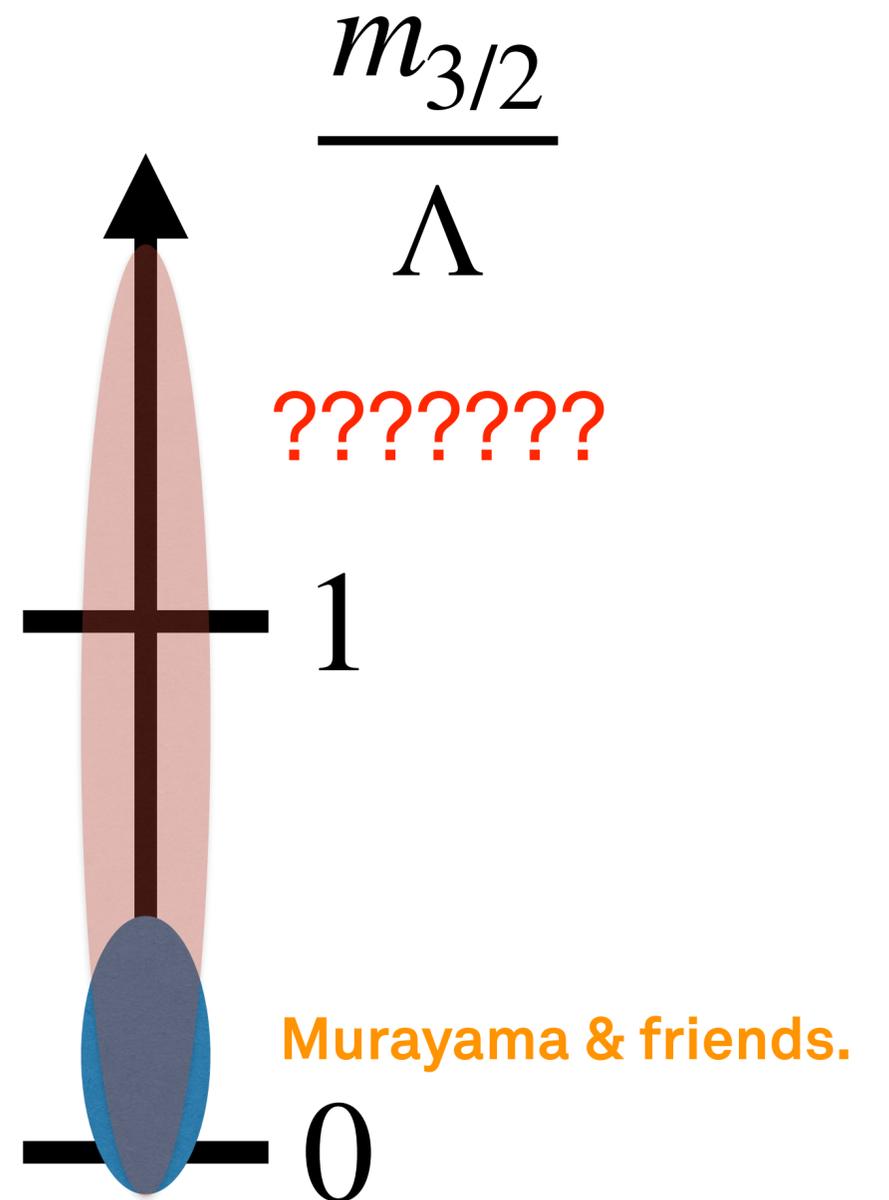
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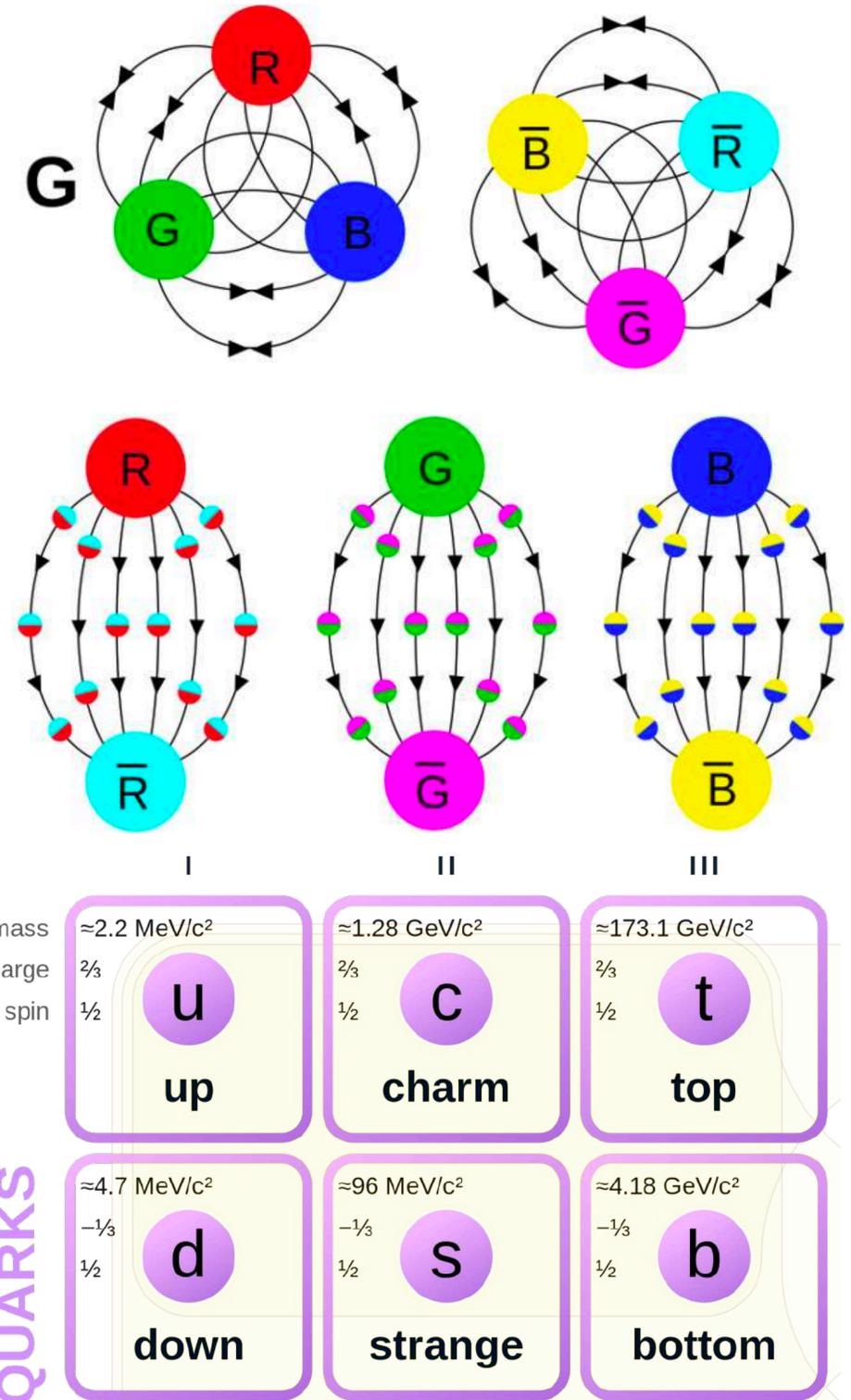


GENERALIZED QCD

Quantum Chromodynamics (QCD) described by $N_c = 3$ colours and $N_f = 3$ light flavours.

Promote N_c and N_f to variables.

$N_f = N_c + 1$ has a particularly nice SUSY description.



$$N_c = 2 \text{ AND } N_f = 3$$

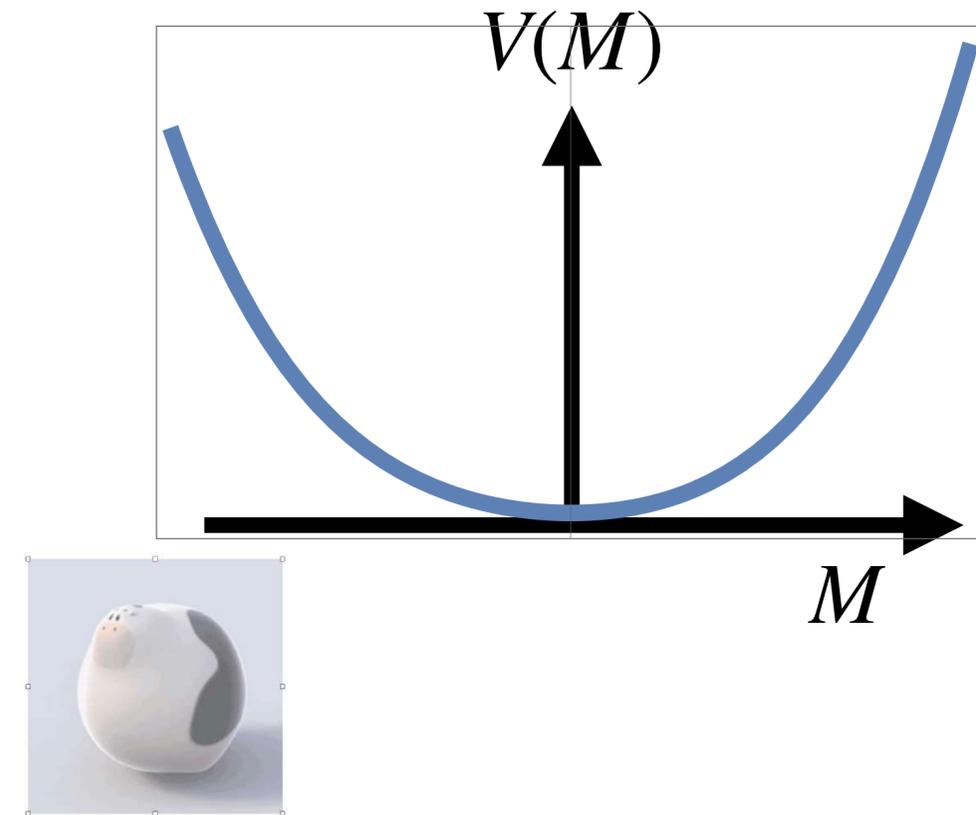
QCD with 2 colours is different. Can calculate potential for Meson field:

$$V = |M|^4 + \frac{27}{1024\pi^4} |M|^2 - \frac{9}{32\pi^2} M^3$$

This potential has a minimum at $M = 0$.

Theory does not have spontaneous symmetry breaking!

Non SUSY theory must have SSB.

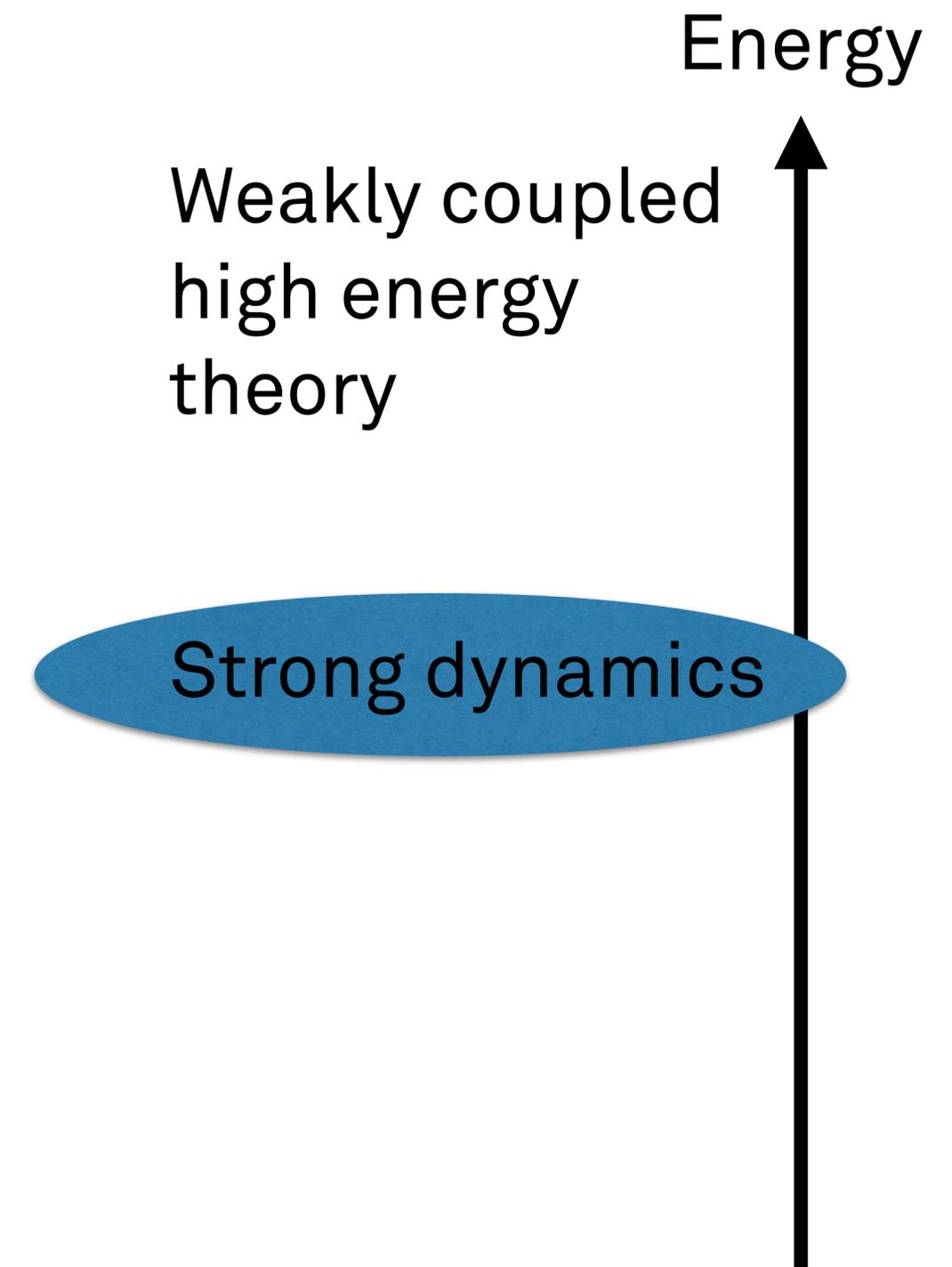


Hassan Easa PhD thesis,
Csaki et. al., arXiv:2212.03260.
de Lima, DS, arXiv:2307.13154.

'T HOOFT ANOMALY MATCHING

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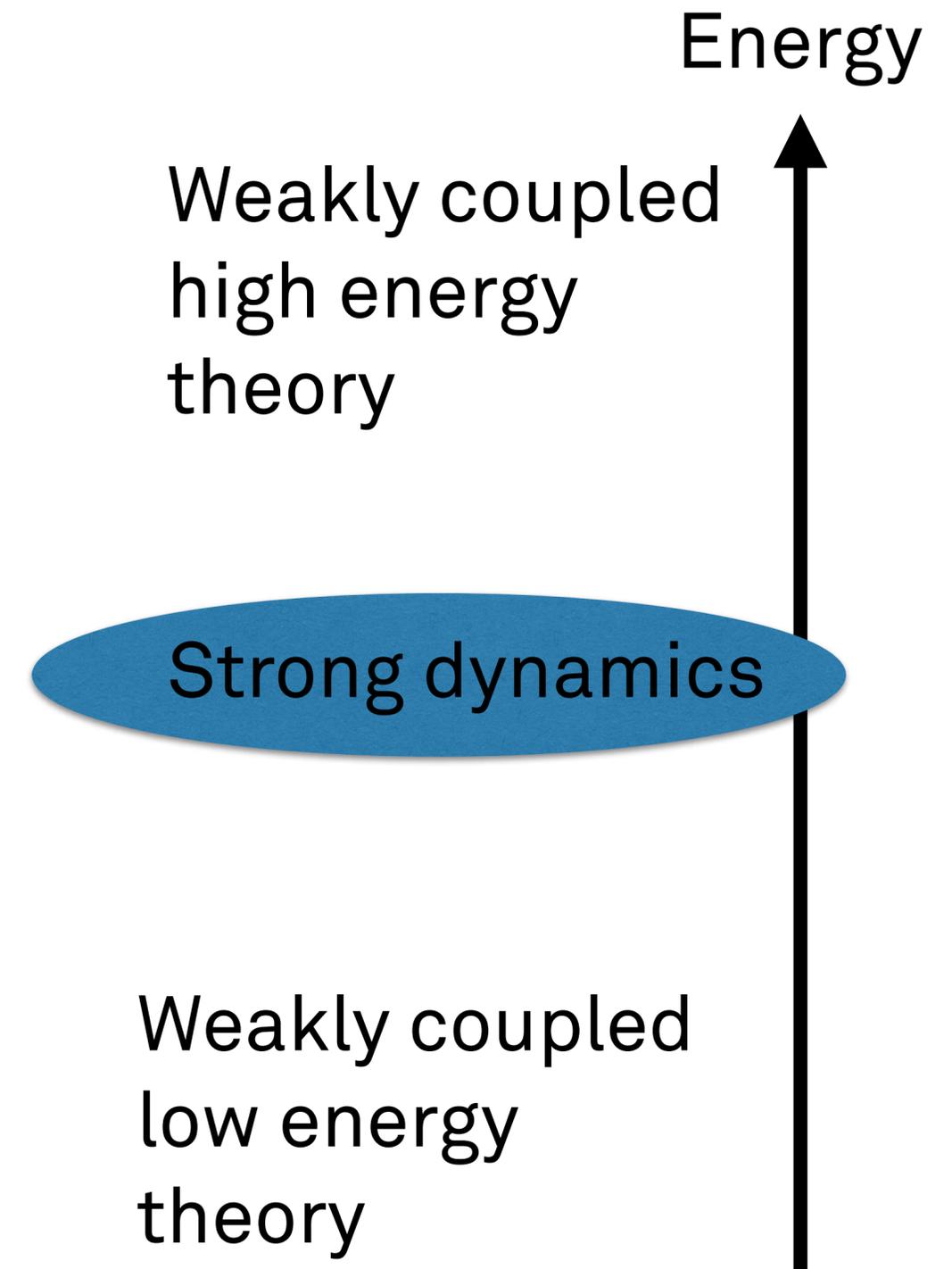
Most robust tool to analyze strong interactions is 't Hooft anomaly matching. 't Hooft '80.



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If theory at very high energy is tractable (perturbative), get consistency condition for low energy spectrum.

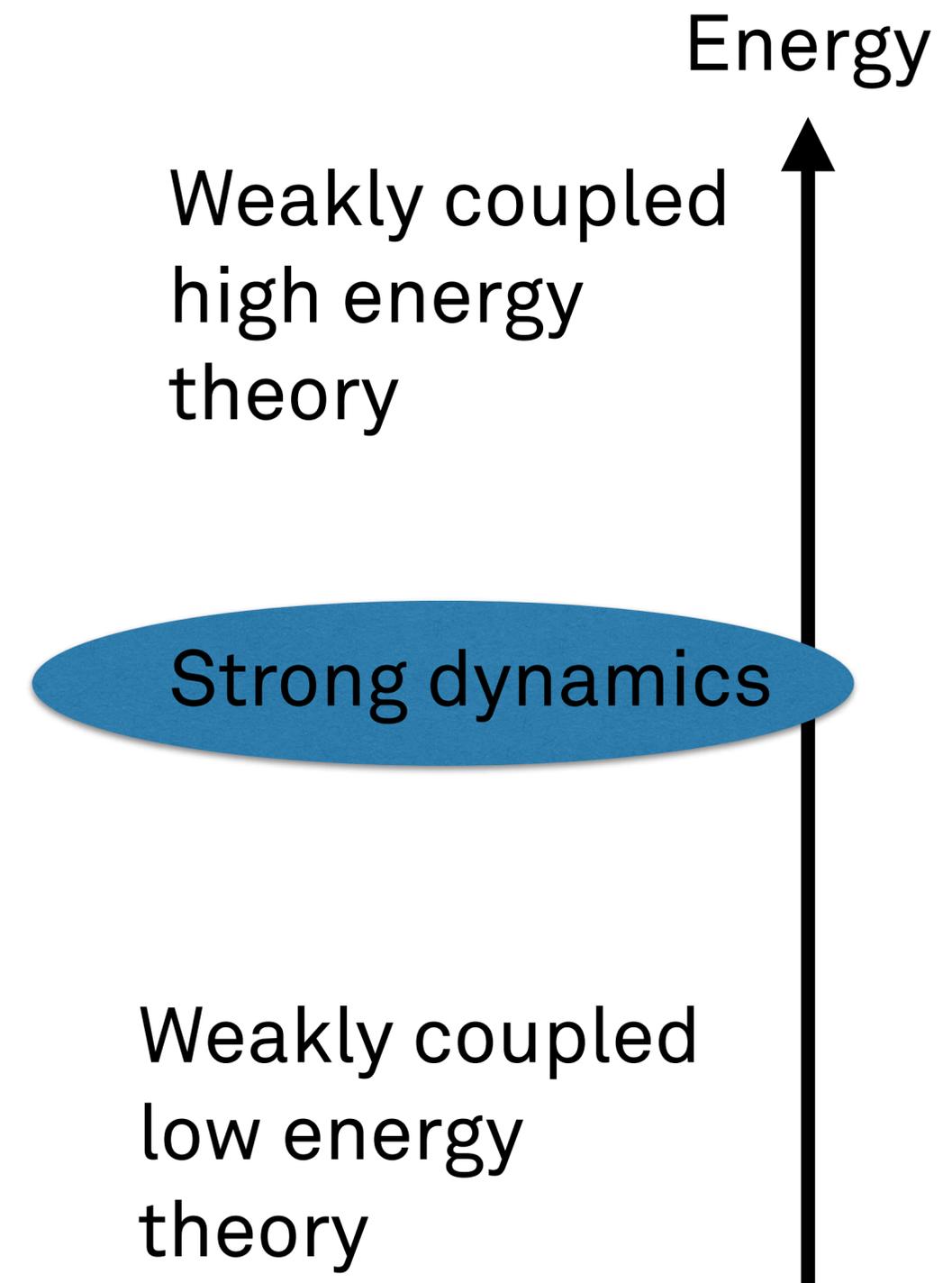


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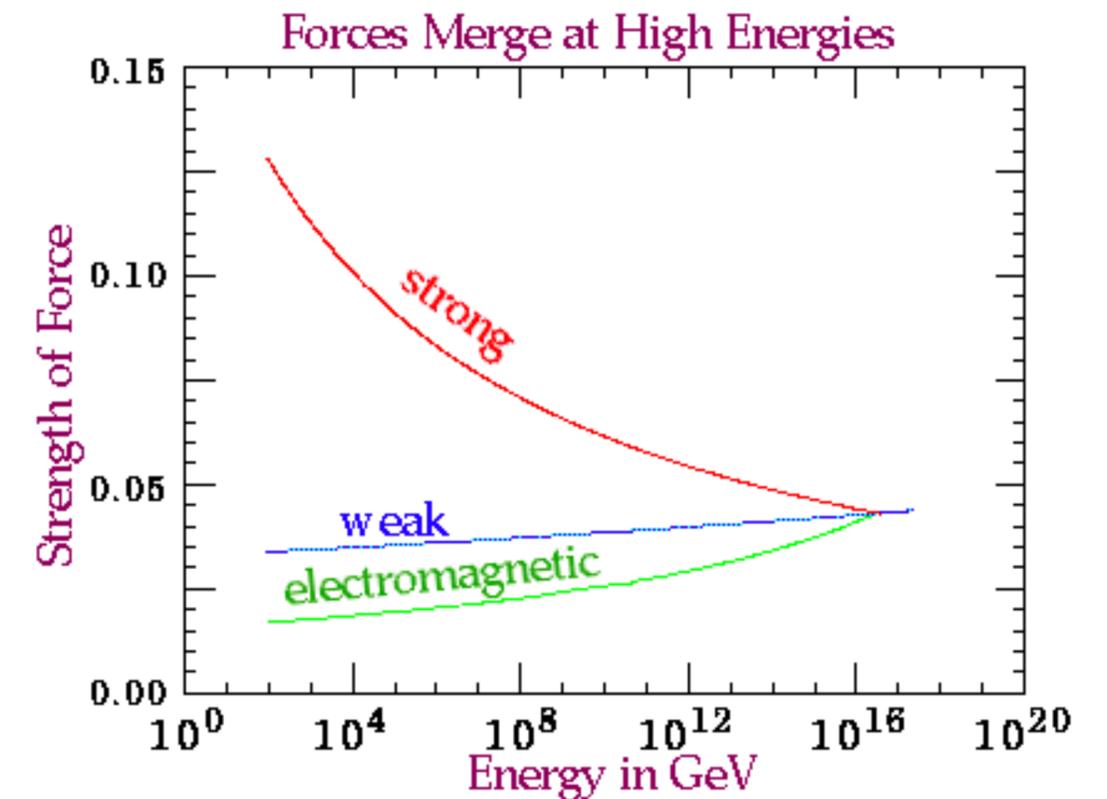
NB: 't Hooft **anomaly** matching \neq **anomaly** mediated SUSY breaking



ANOTHER THEORY

Simplest Grand Unified Theory of the SM is SU(5) GUT. **Georgi, Glashow, PRL '74.**

Can describe all (gauge) forces and all matter of SM.



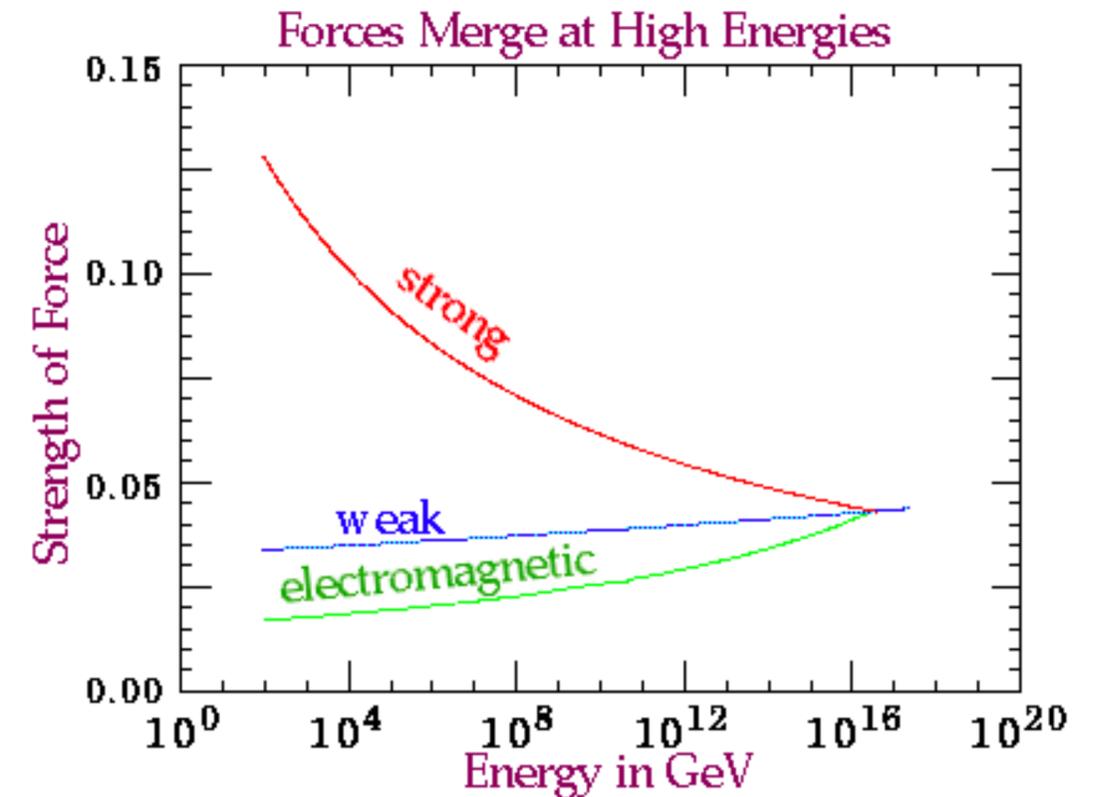
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$$E \frac{d\alpha}{dE} = -\frac{43}{3} \frac{\alpha^2}{2\pi} < 0$$



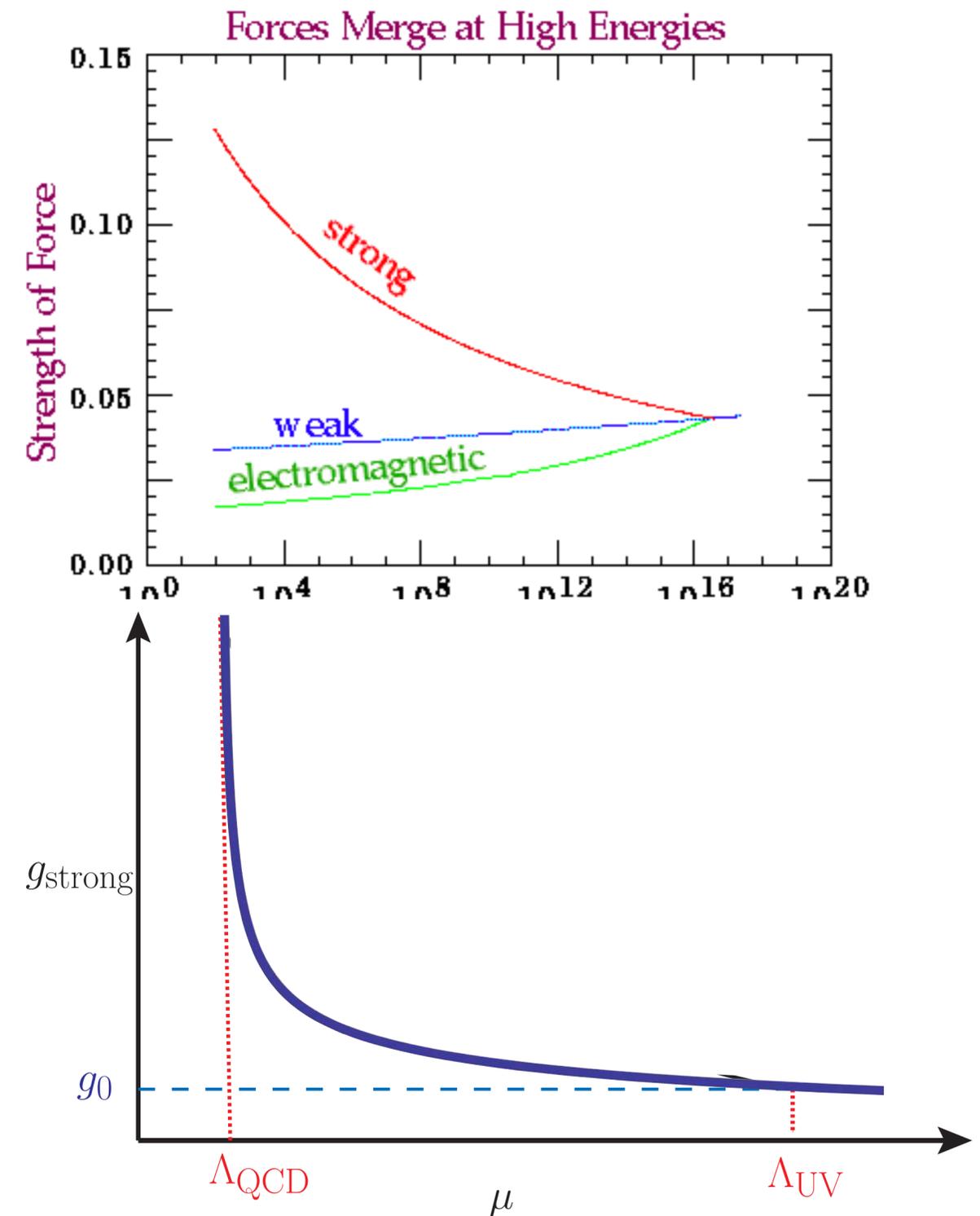
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'T HOOFT ANOMALY MATCHING

Compute anomalies at high energy.

$$A [SU(3)_A^3] = 10$$

$$A [SU(3)_{\bar{F}}^3] = 5$$

$$A [\text{grav}^2 \times U(1)_B] = -15$$

$$A [U(1)_B^3] = -375$$

$$A [SU(3)_A^2 \times U(1)_B] = 10$$

$$A [SU(3)_{\bar{F}}^2 \times U(1)_B] = -15$$

'T HOOFT ANOMALY MATCHING

Compute anomalies at high energy.

Can use 't Hooft anomaly matching to determine light bound states (baryons) of the theory.

Boils down to solving linear equations over integers.

$$A [SU(3)_A^3] = 10$$

$$A [SU(3)_{\bar{F}}^3] = 5$$

$$A [\text{grav}^2 \times U(1)_B] = -15$$

$$A [U(1)_B^3] = -375$$

$$A [SU(3)_A^2 \times U(1)_B] = 10$$

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IR ANOMALY MATCHING

Solutions are quite complicated.

A relatively simple example:

quarks

	$[SU(5)]$	$SU(3)_A$	$SU(3)_{\bar{F}}$	$U(1)_B$
A	10	3	1	1
\bar{F}	$\bar{5}$	1	3	-3

Massless baryons

	$[SU(5)]$	$SU(3)_A$	$SU(3)_{\bar{F}}$	$U(1)_B$
$(A\bar{F}\bar{F})^\dagger$	1	$\bar{3}$	3	5
$A\bar{F}\bar{F}$	1	3	6	-5
A^5	1	6	1	5
\bar{F}^5	1	1	$\bar{15}$	-15
$A^3\bar{F}^{\dagger 4}$	1	1	6	15
$A^3\bar{F}^{\dagger 4}$	1	1	$\bar{15}$	15
$2 \times (A^3\bar{F}^{\dagger 4})^\dagger$	1	1	3	-15

Bai, DS, arXiv:2111.11214.

IR ANOMALY MATCHING

Another example:

	$[SU(5)]$	$SU(3)_A$	$SU(3)_{\bar{F}}$	$U(1)_B$
A	10	3	1	1
\bar{F}	$\bar{5}$	1	3	-3

	$[SU(5)]$	$SU(3)_A$	$SU(3)_{\bar{F}}$	$U(1)_B$
$(\bar{F}^5)^\dagger$	1	1	3	15
A^5 or $(A^4\bar{F}^3)^\dagger$	1	6	1	5
$\bar{F}(A^2)^\dagger$	1	3	3	-5
$(A^3)^\dagger\bar{F}^4$	1	1	3	-15

IR ANOMALY MATCHING

Another example:

Looks simpler, but $(\bar{F}^5)^\dagger$ state is problematic.

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$(A^3)^\dagger\bar{F}^4$	1	1	3	-15

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Can work with **orbital** angular momentum, but weird.

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Different than QCD: $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$

SUPERSYMMETRIZE THE THEORY!

This theory also has a nice supersymmetric description.

Seiberg, [hep-th/9402044](#), [hep-th/9411149](#).

Csaki, Schmaltz, Skiba, [hep-th/9610139](#).

Can compute the scalar potential:

$$V_{\text{susy}} + V_{\text{susy}} = \left| \frac{dW_\lambda}{dM^{ai}} + \frac{dW_\zeta}{dM^{ai}} + \frac{1}{3} A_1^* M^{ai*} \right|^2 + \left| \frac{dW_\zeta}{dB_2^{\beta\delta}} + (A_2^* - \frac{1}{3} A_1^*) B_2^{\beta\delta*} \right|^2 + \left| \frac{dW_\zeta}{dB_1^{\gamma i}} \right|^2 \\ + m_1^2 \sum_{\gamma i} |B_1^{\gamma i}|^2 + \left(m_2^2 - \left| A_2 - \frac{1}{3} A_1 \right|^2 \right) \sum_{\beta\delta} |B_2^{\beta\delta}|^2 + \left(m_3^2 - \left| \frac{1}{3} A_1 \right|^2 \right) \sum_{ai} |M^{ai}|^2$$

Bai, DS, [arXiv:2111.11214](#).

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Sufficient condition for

no symmetry breaking:

$$\begin{aligned} m_1^2 &\geq 0 \\ m_2^2 - \left| A_2 - \frac{1}{3} A_1 \right|^2 &\geq 0 \\ m_3^2 - \left| \frac{1}{3} A_1 \right|^2 &\geq 0 \end{aligned}$$

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 &+ m_1^2 \sum_{\gamma i} |B_1^{\gamma i}|^2 + \left(m_2^2 - \left| A_2 - \frac{1}{3} A_1 \right|^2 \right) \sum_{\beta\delta} |B_2^{\beta\delta}|^2 + \left(m_3^2 - \left| \frac{1}{3} A_1 \right|^2 \right) \sum_{ai} |M^{ai}|^2
 \end{aligned}$$

Sufficient condition for
no symmetry breaking:

$$\begin{array}{ccc}
 m_1^2 \geq 0 & & 69|\zeta|^4 + 4|\zeta|^2|\lambda|^2 \geq 0 \\
 m_2^2 - \left| A_2 - \frac{1}{3} A_1 \right|^2 \geq 0 & \longleftrightarrow & 19|\zeta|^4 + 4|\zeta|^2|\lambda|^2 \geq 0 \\
 m_3^2 - \left| \frac{1}{3} A_1 \right|^2 \geq 0 & & 1161|\zeta|^4 + 216|\zeta|^2|\lambda|^2 + 80|\lambda|^4 \geq 0
 \end{array}$$

Bai, DS, arXiv:2111.11214.

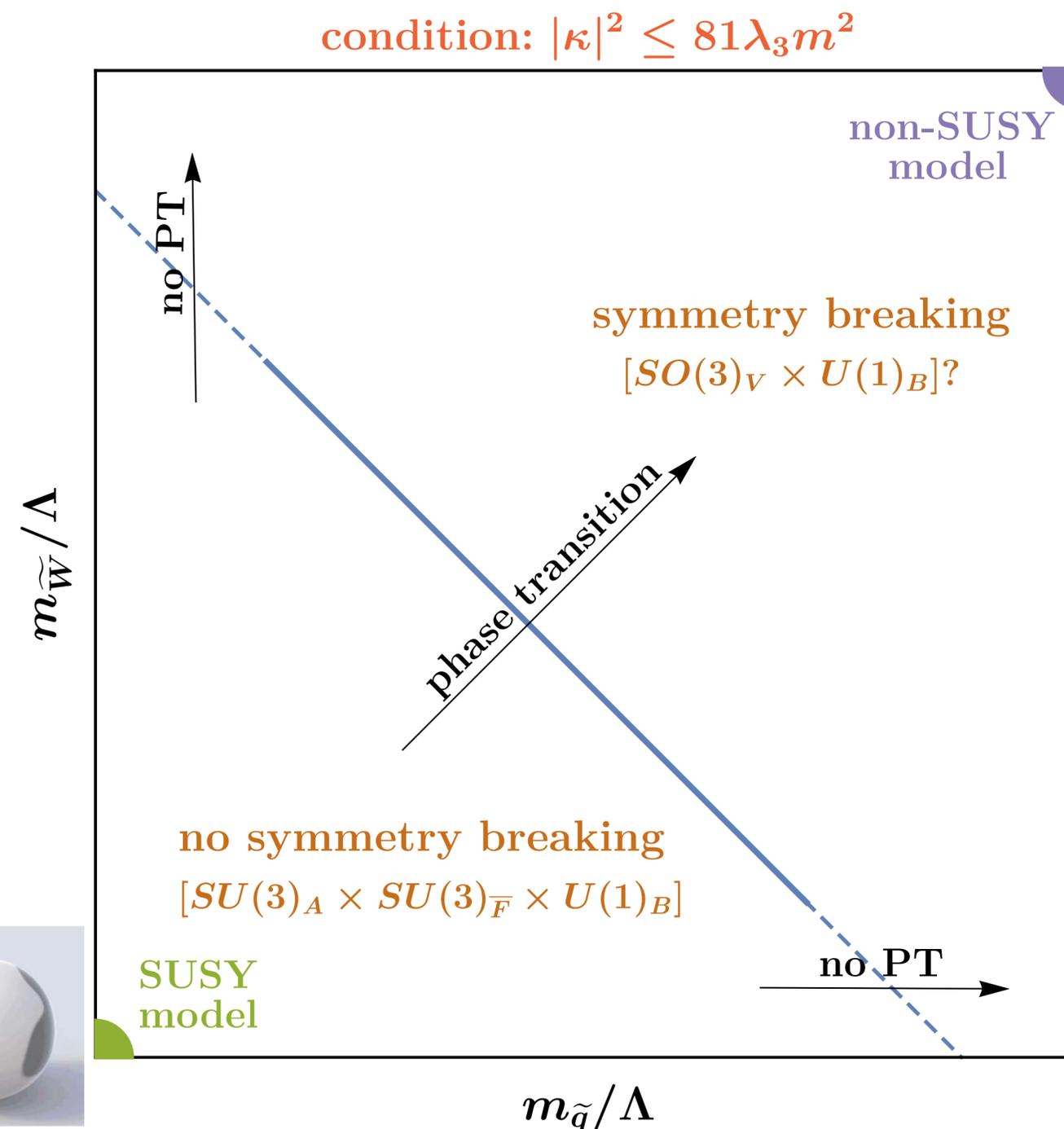
PHASE DIAGRAM

Can draw qualitative phase diagram in theory space.

Have some control at the corners.

Must have a phase transition in going to large SUSY breaking.

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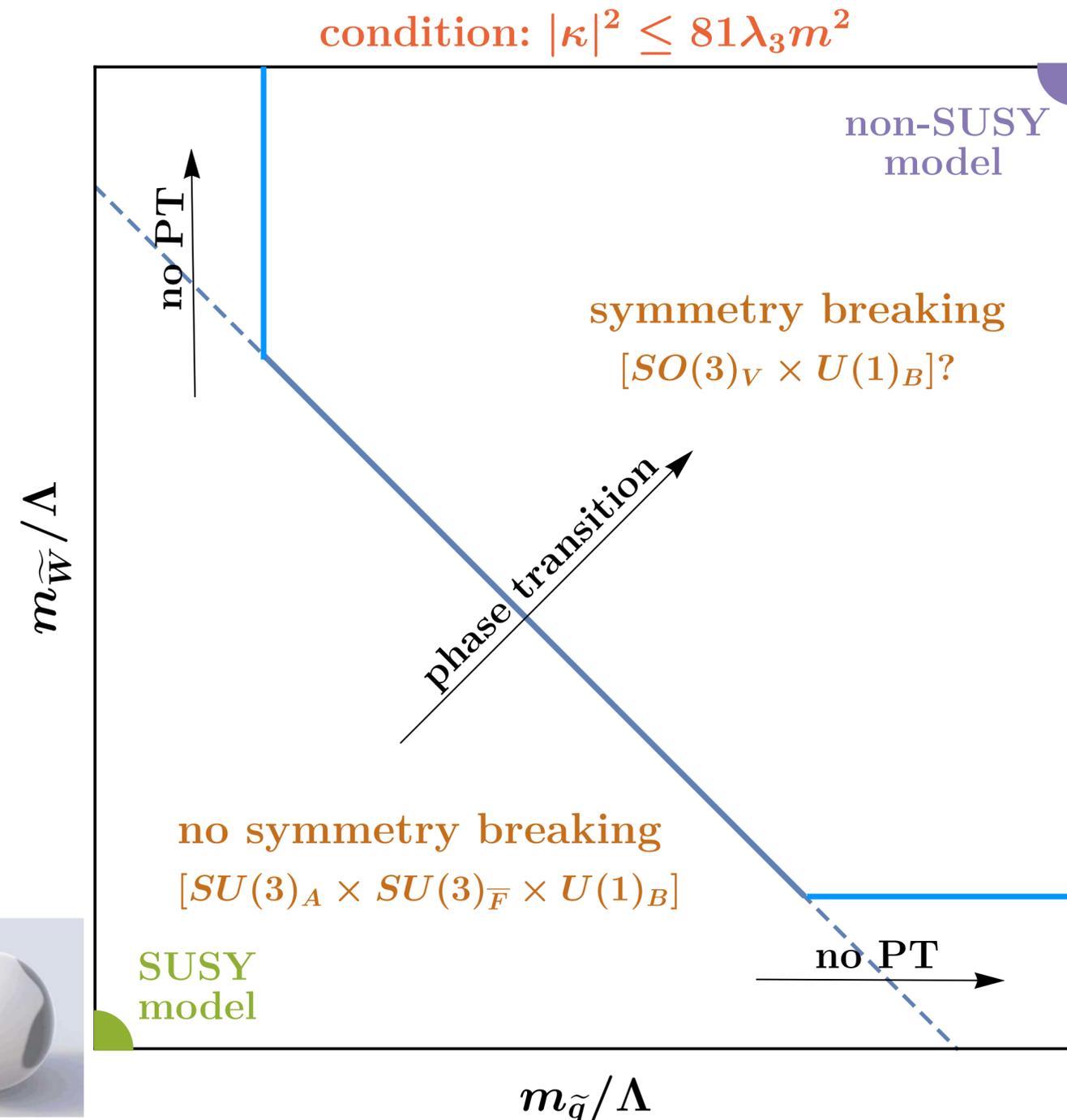
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LIGHTNING ROUND

DIFFERENT NUMBER OF FLAVOURS?

Analyzed SU(5) model with 3 flavours.

1 flavour dynamics are well known.

Dimopoulos, Raby, Susskind, NPB '80.

What about 2 flavours?

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Analysis of the 2 Flavour SU(5)

Georgi–Glashow Model

by

Jonathan Ponnudurai

A thesis submitted to the Faculty of Graduate and

Postdoctoral Affairs in partial fulfillment of the

requirements for the degree of

Master of Science

in

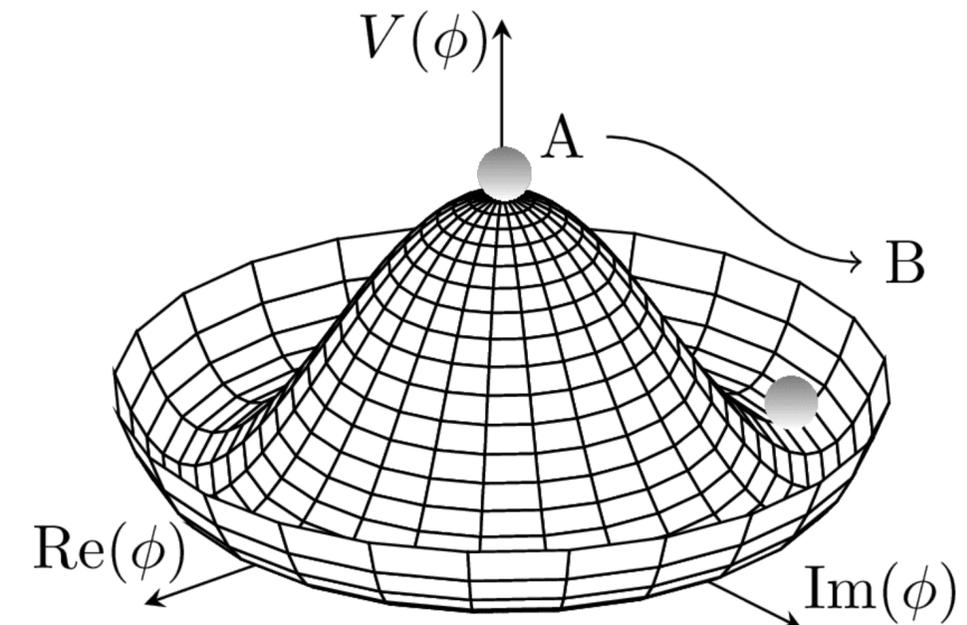
Physics

2 FLAVOUR RESULTS

Non-SUSY model:
anomaly matching solutions

Symmetries	UV Anomaly	$A_{4,1,5}^5$	$A^4 \bar{F}_{3,2,-5}^3$
$SU(2)_A^2 \otimes U(1)_B$	5	25	-20
$SU(2)_F^2 \otimes U(1)_B$	-15/2	0	-15/2
$U(1)_B^3$	-250	500	-750
$\text{grav.}^2 \otimes U(1)_B$	-10	20	-30
$SU(2)_A^3$	0	0	0
$SU(2)_F^3$	1	0	1

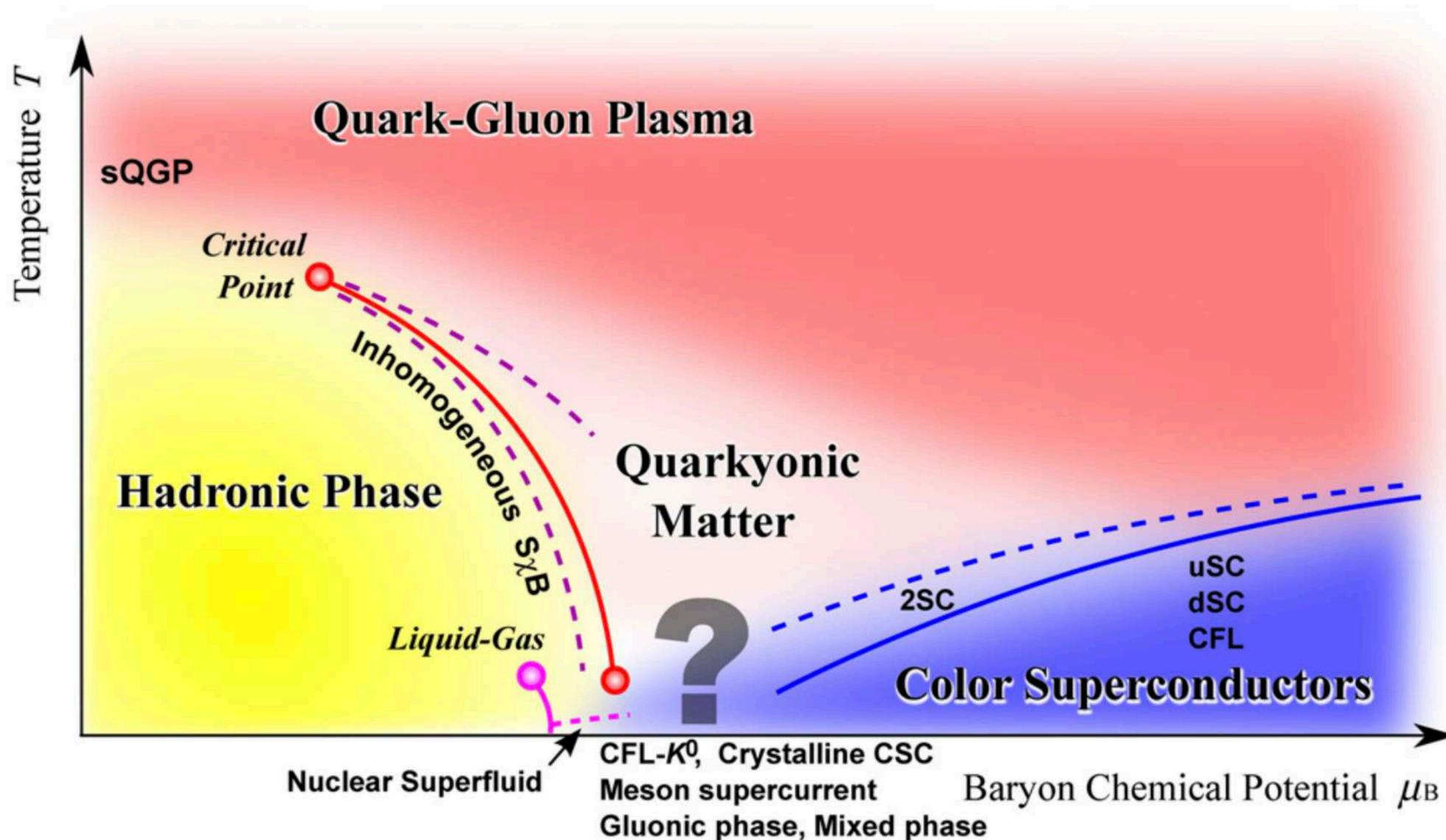
SUSY model: proof of spontaneous
symmetry breaking.



J. Ponnudurai MSc thesis.

PHASE DIAGRAM

What is the phase diagram of QCD?



Longstanding difficult problem with only partial results.

Focus on $T = 0$ for now.

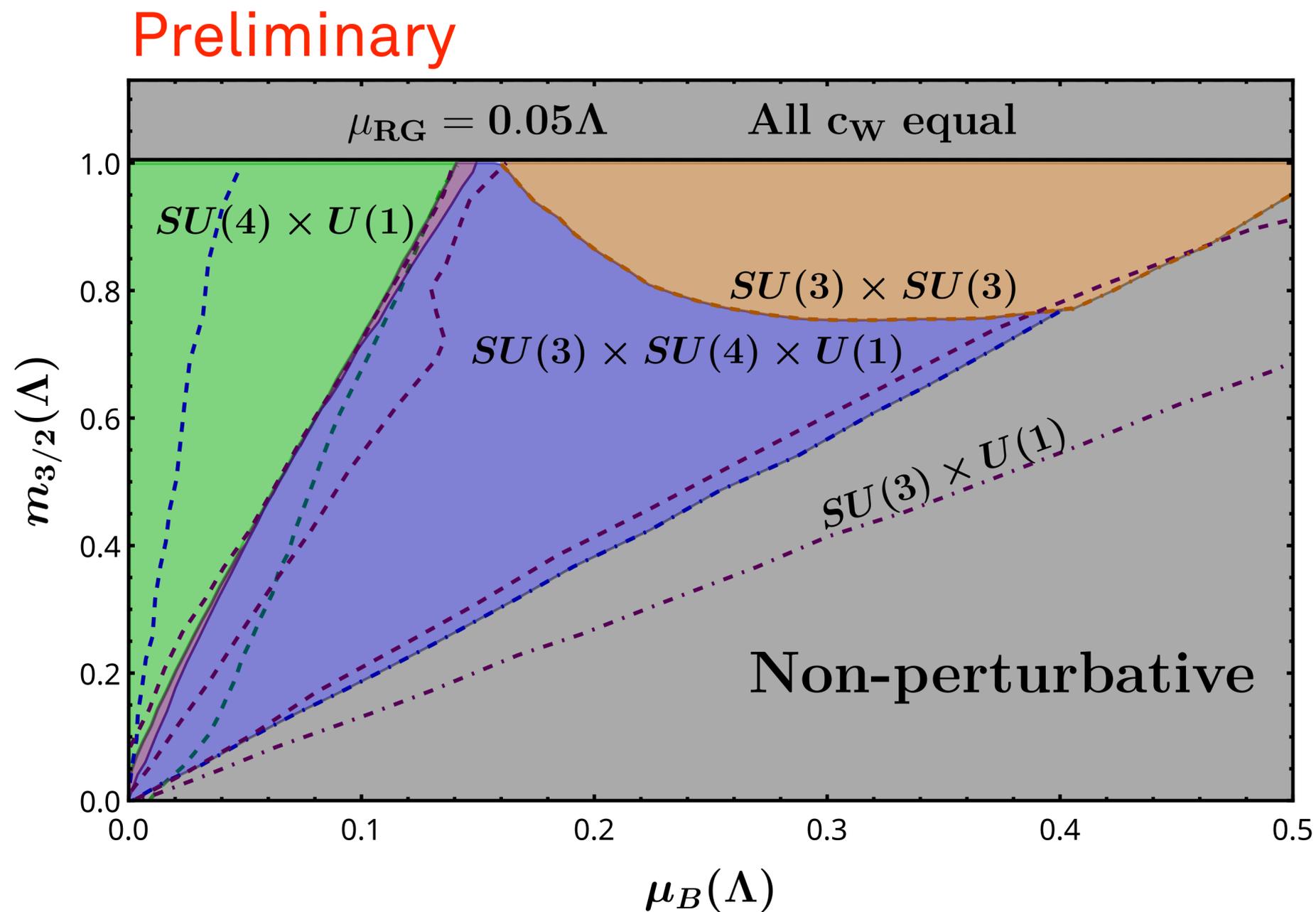
Fukushima and Hatsuda, '11.

PHASE DIAGRAM

Steps:

1. Supersymmetrize QCD
2. Break SUSY with AMSB
3. Turn on baryon density

Find some new phases that do not exist in the literature!



Work in progress with Bai and de Lima.

HOLOGRAPHY?

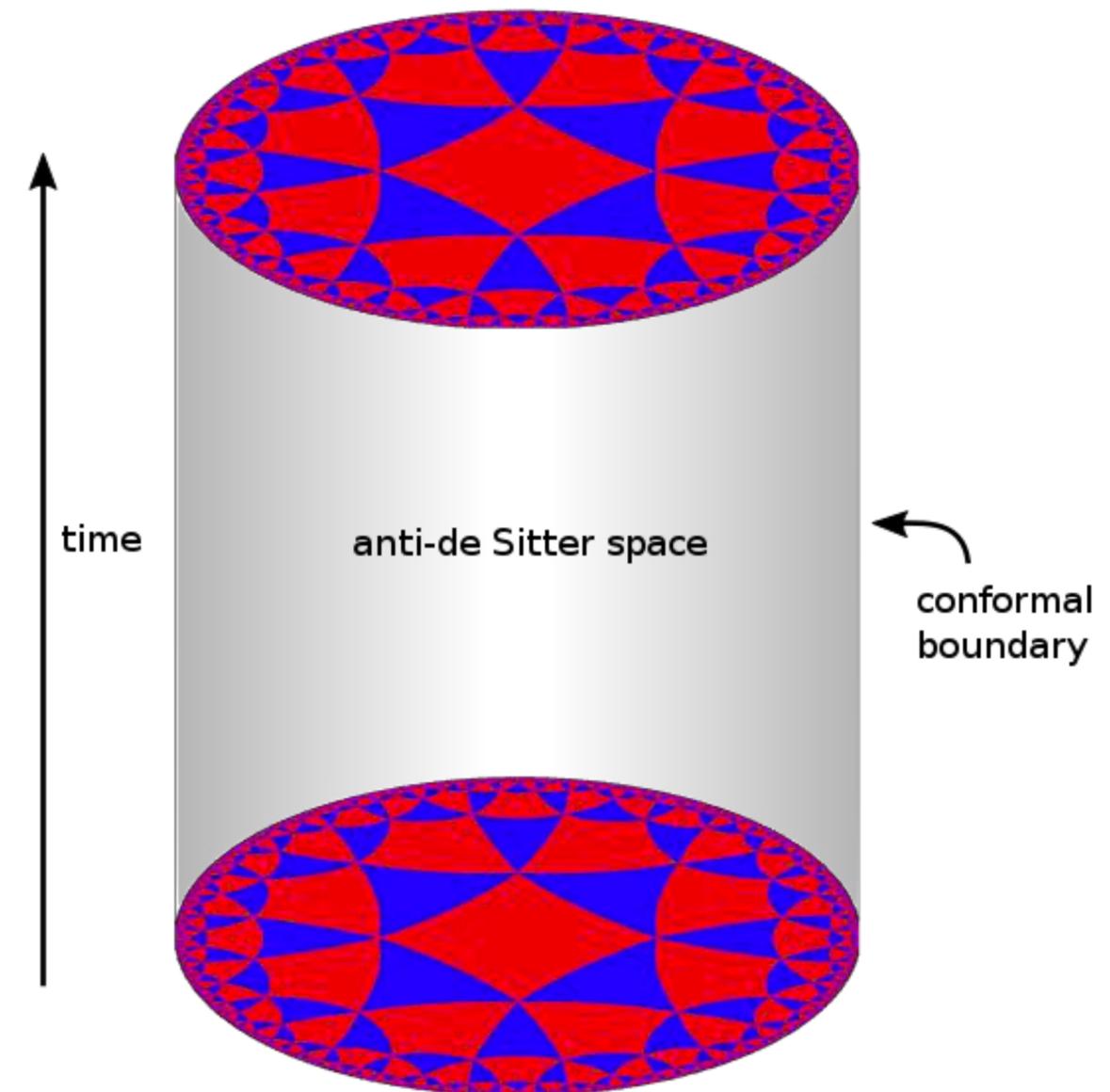
AdS/CFT correspondence says certain 4 dimensional theories are dual to 5 dimensional theories.

Maldacena, [hep-th/9711200](#). Witten, [hep-th/9802150](#).

Very supersymmetric theories fall in this category.

What is gravitational dual of Anomaly mediation?

Work in progress with Cyrus Robertson Orkish.



SUMMARY

Non-perturbative quantum field theories pose interesting and important open problems.

Supersymmetry + anomaly mediation gives useful new tool to analyze these theories.

Found two theories that violate conjecture that this tool can be used to analyze original theory.

Various ongoing directions of this research.

**THANK
YOU**