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

PRISMA+ Colloquium, JGU Mainz April 30, 2025

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

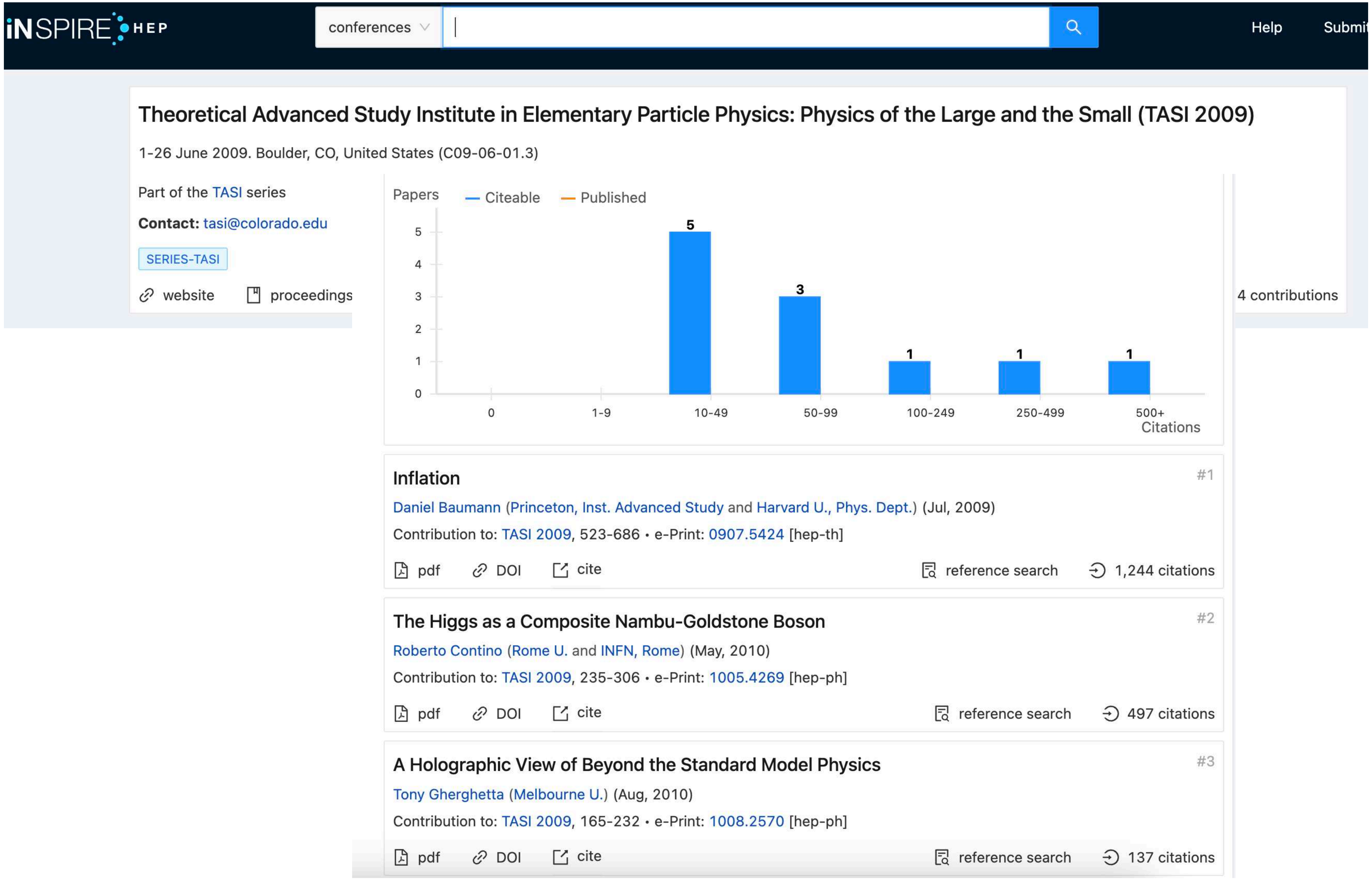
Undergrad research working on CMS for LHC.

Went to Berkeley wanting to do particle physics.

Experiment was hard, chose thoery.

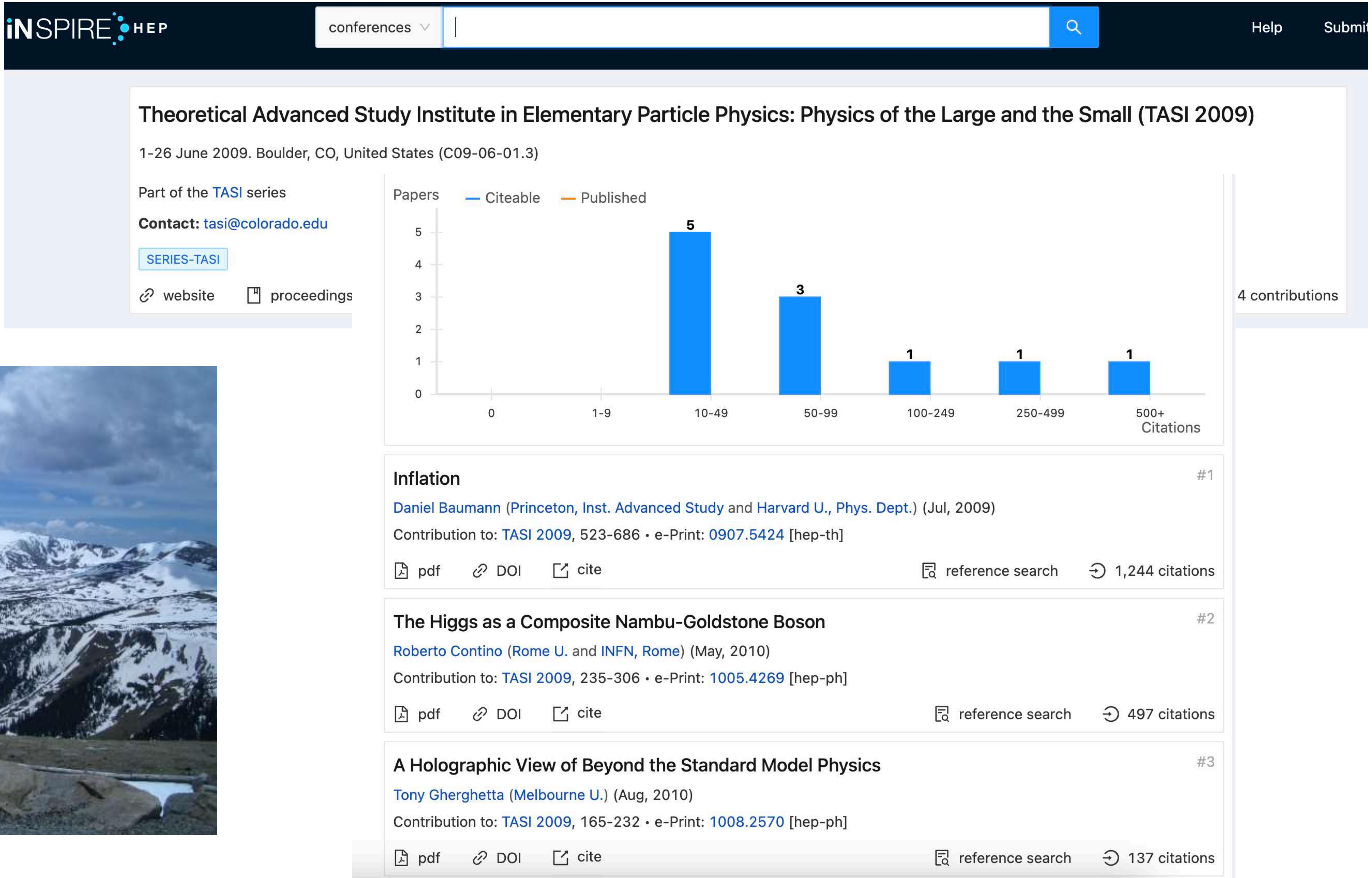
TASI 2009

Theoretical Advanced Study Institute was a great experience.



TASI 2009

Theoretical Advanced Study Institute was a great experience.


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

Contact: tasi@colorado.edu

SERIES-TASI

website proceedings

4 contributions

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

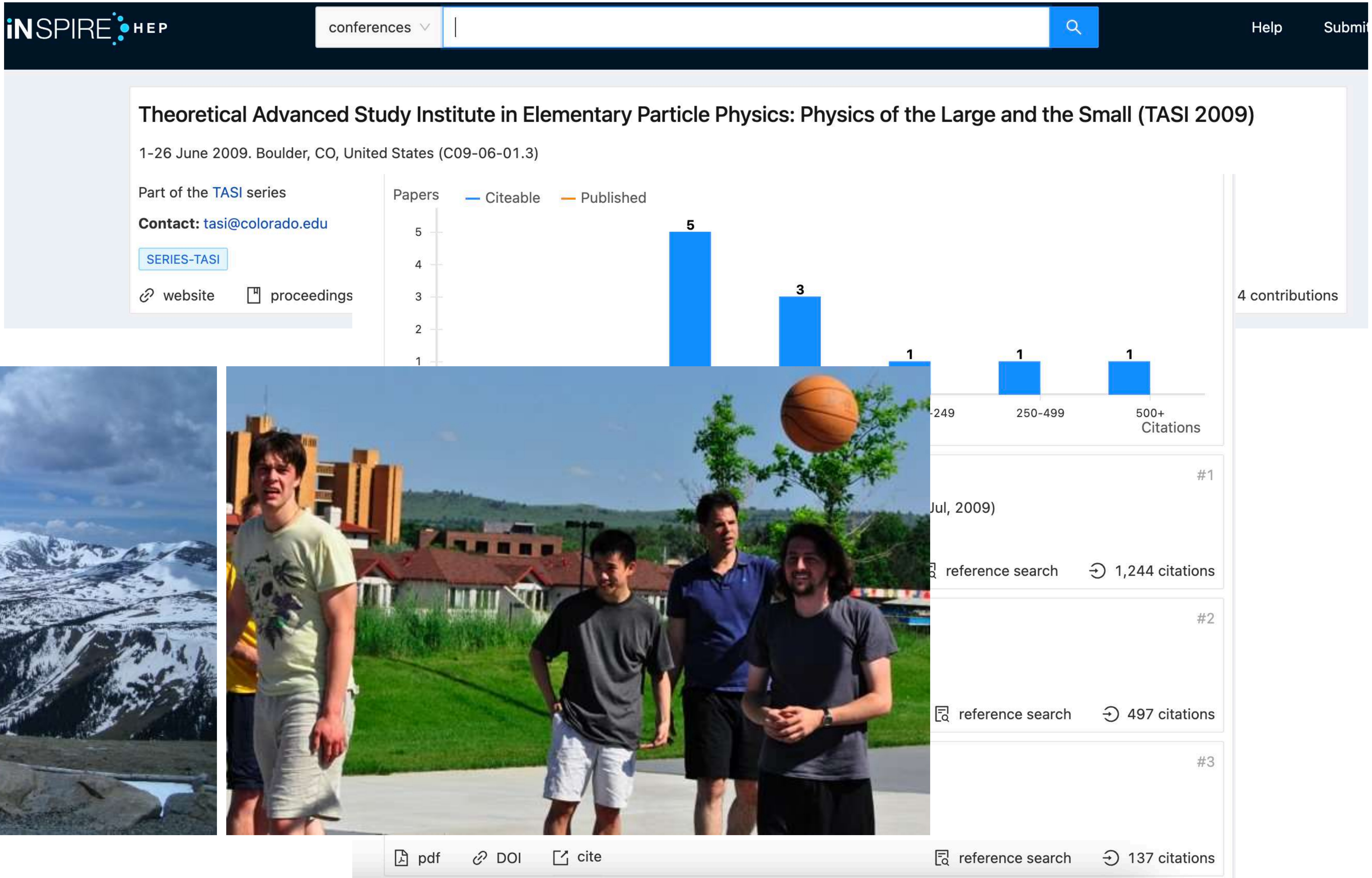
Tony Gherghetta (Melbourne U.) (Aug, 2010)

Contribution to: TASI 2009, 165-232 • e-Print: 1008.2570 [hep-ph]

pdf DOI cite reference search 137 citations

TASI 2009

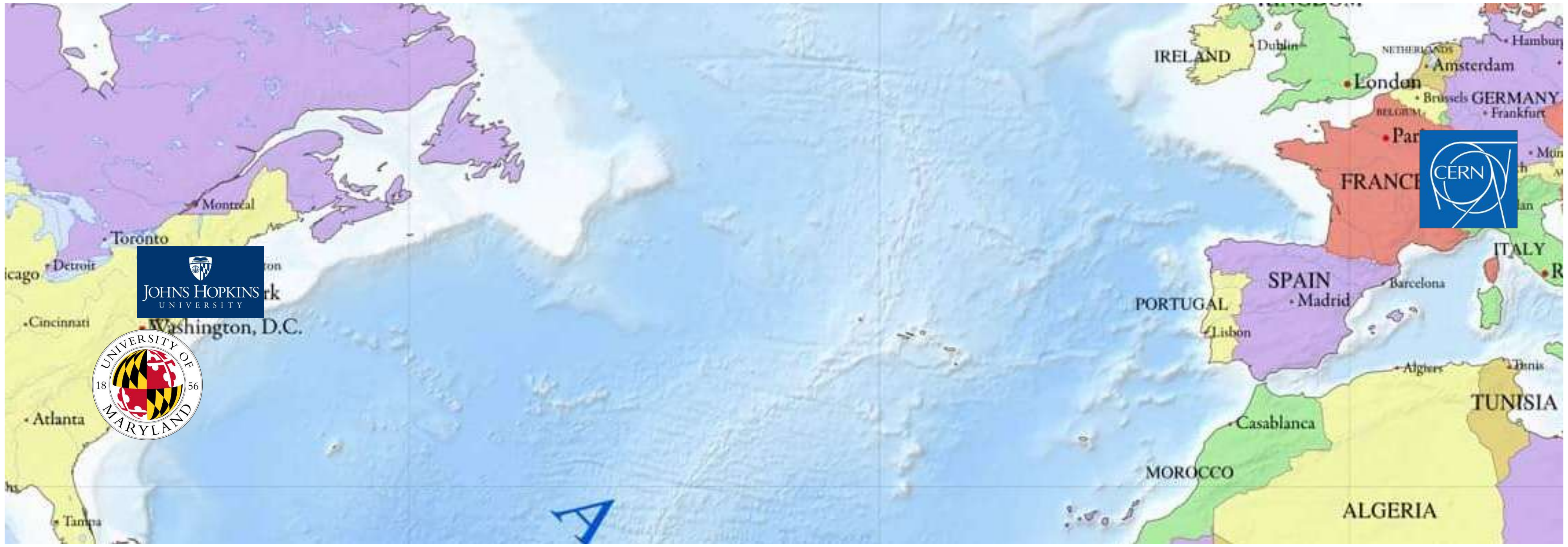
Theoretical Advanced Study Institute was a great experience.



POSTDOCS

First postdoc joint at University of Maryland and Johns Hopkins.

Second postdoc at CERN.



POSTDOCS

First postdoc joint at University of Maryland and Johns 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

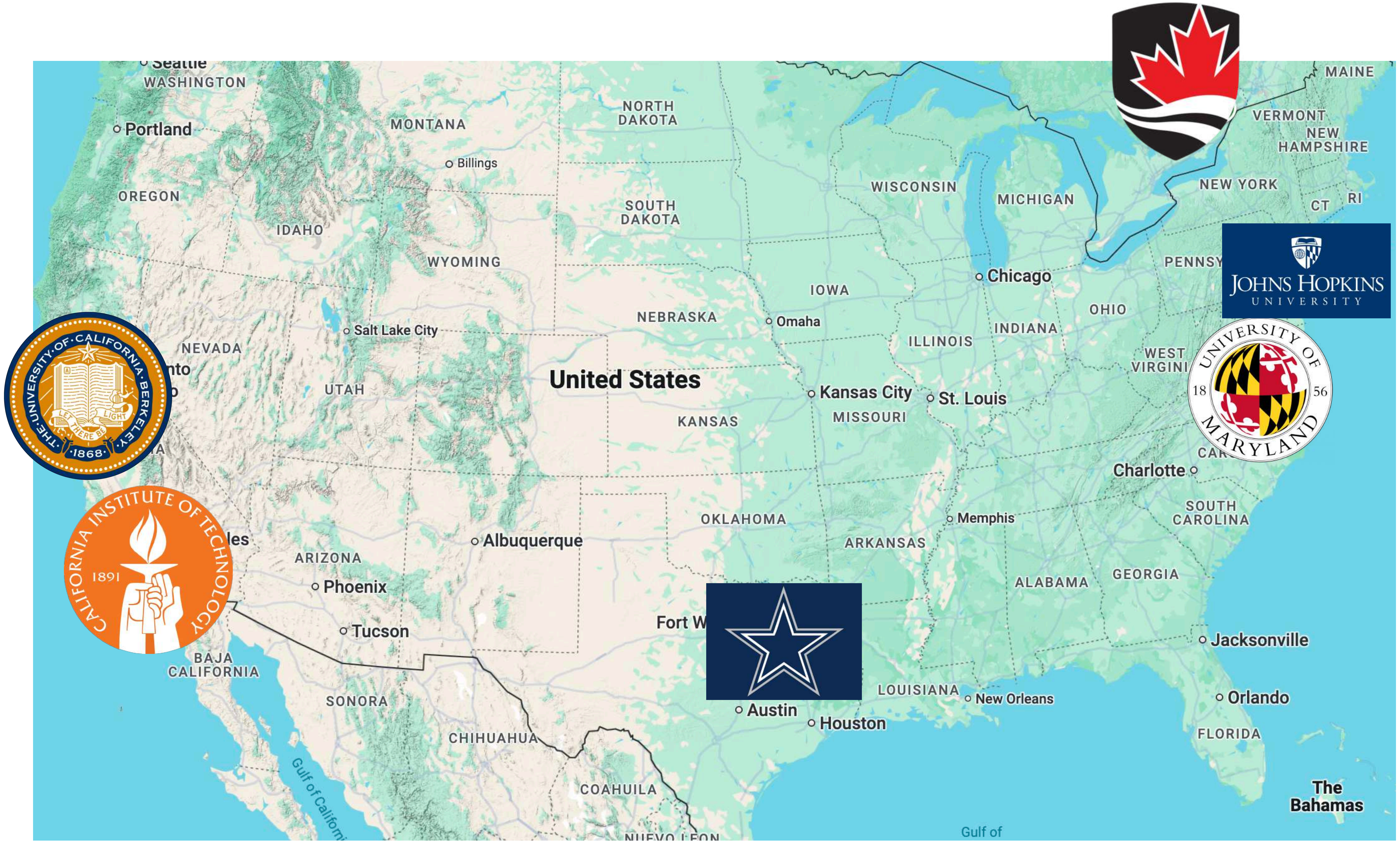
EMERGING JETS

DANIEL STOLARSKI
WITH PEDRO SCHWALLER
AND ANDREAS WEILER

To appear

Mainz   December 16, 2014

Faculty at Carleton University.



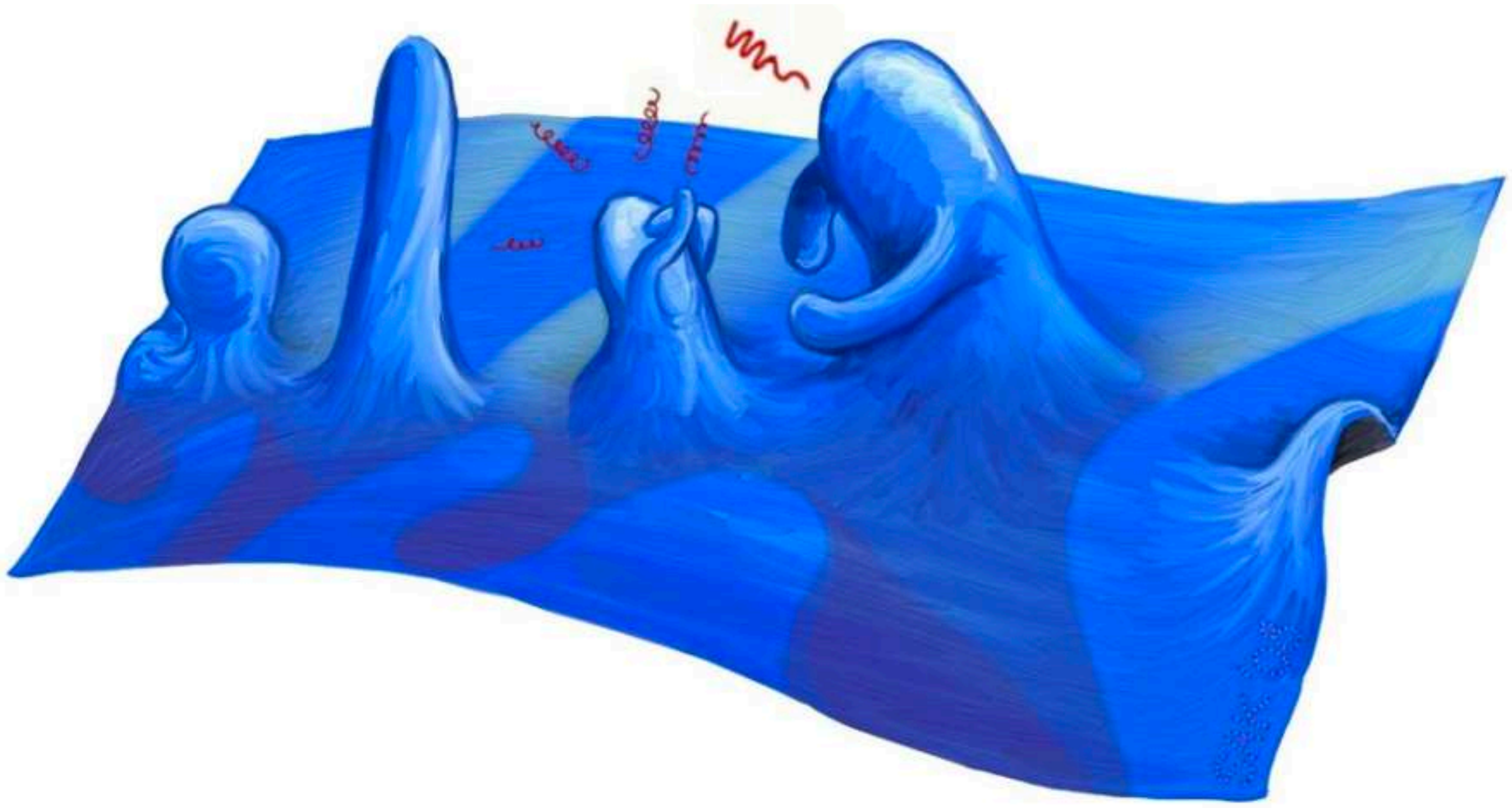
Faculty at Carleton University.

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.

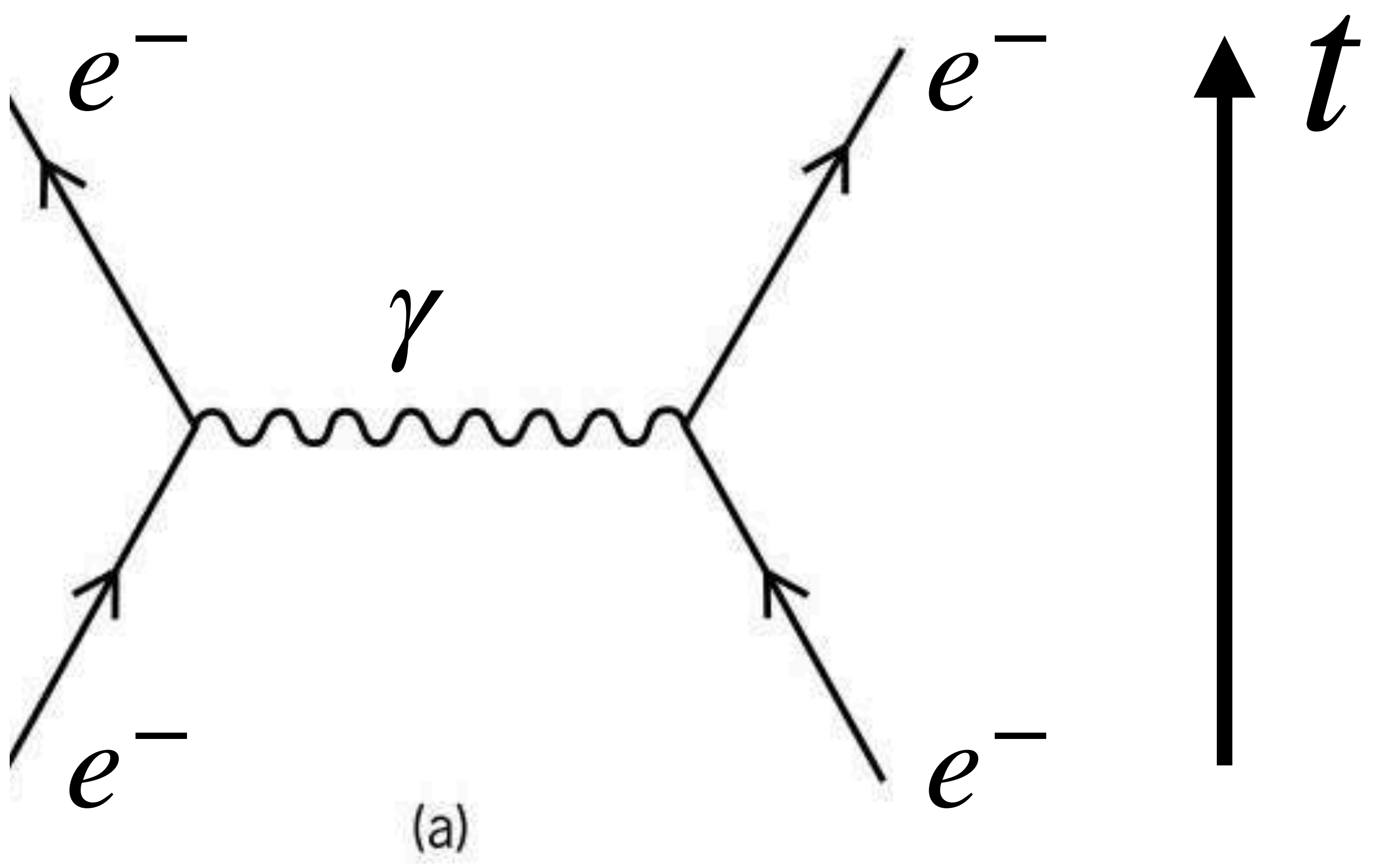
Most successful tool is perturbation theory.

Terms in series represented by Feynman diagrams.

Electron scattering:

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

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



PERTURBATIVE QFT

QFT is hard.

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

Most successful tool is perturbation theory.

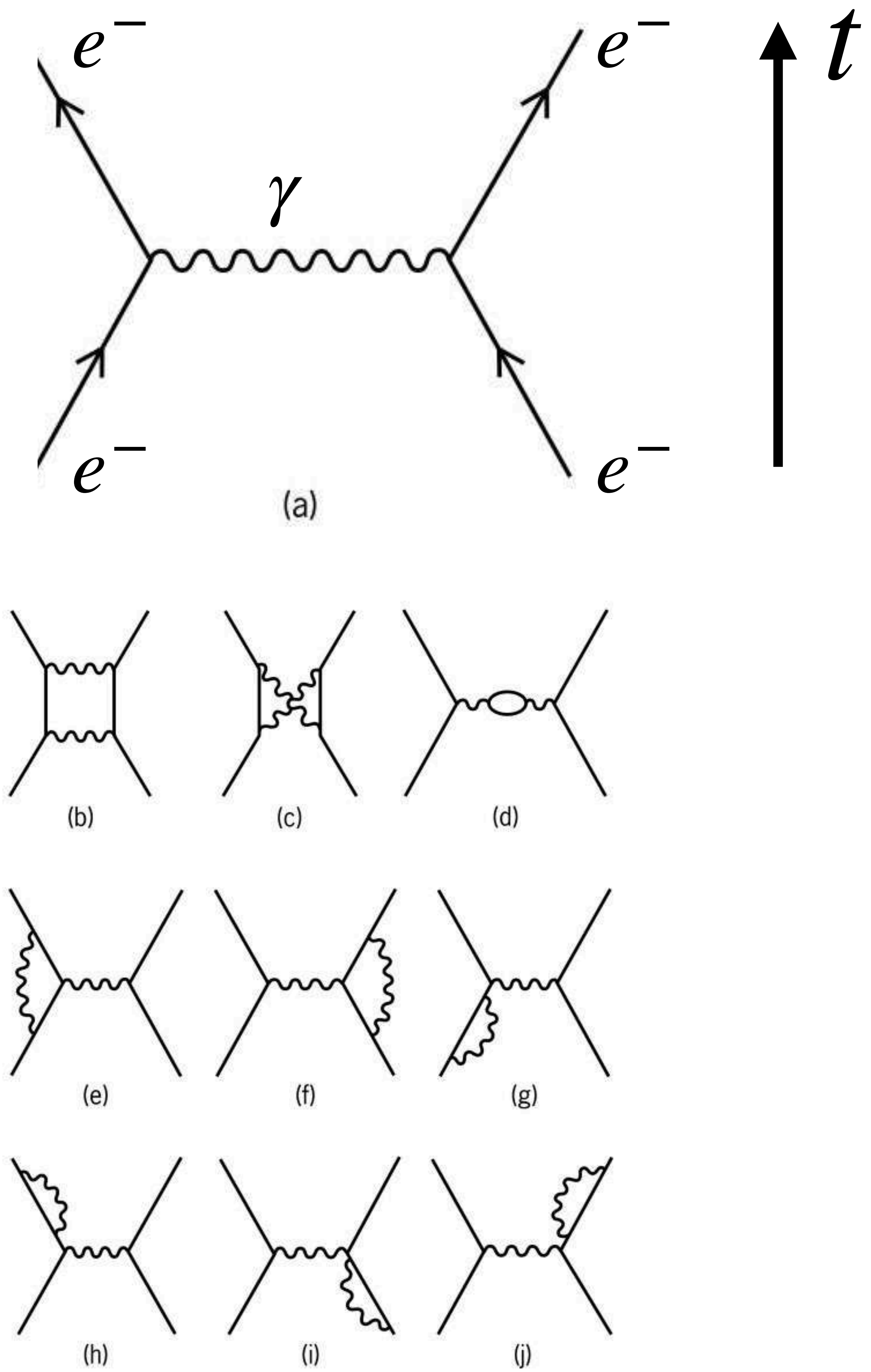
$$\sigma_{\text{Born}} \sim e^4$$

Terms in series represented by Feynman diagrams.

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

Electron scattering:

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



ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

$$g = 2$$

Dirac, 1928

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

ELECTRON MAGNETIC MOMENT

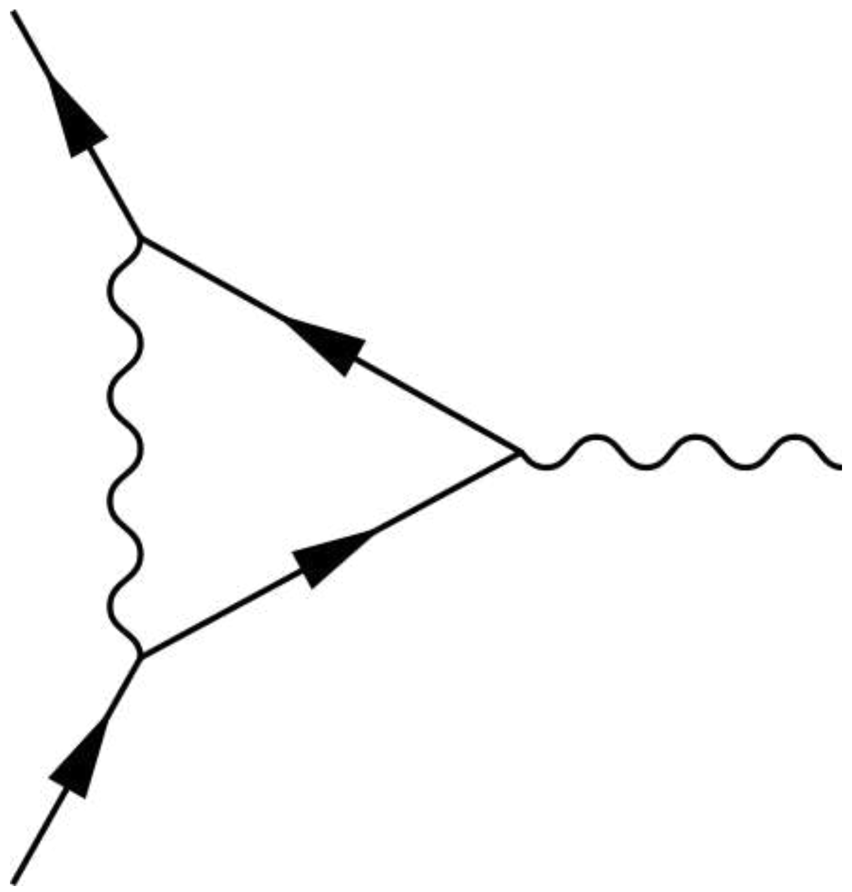
Electron magnetic moment:

$$g = 2$$

Dirac, 1928

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

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



Schwinger, 1948

ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

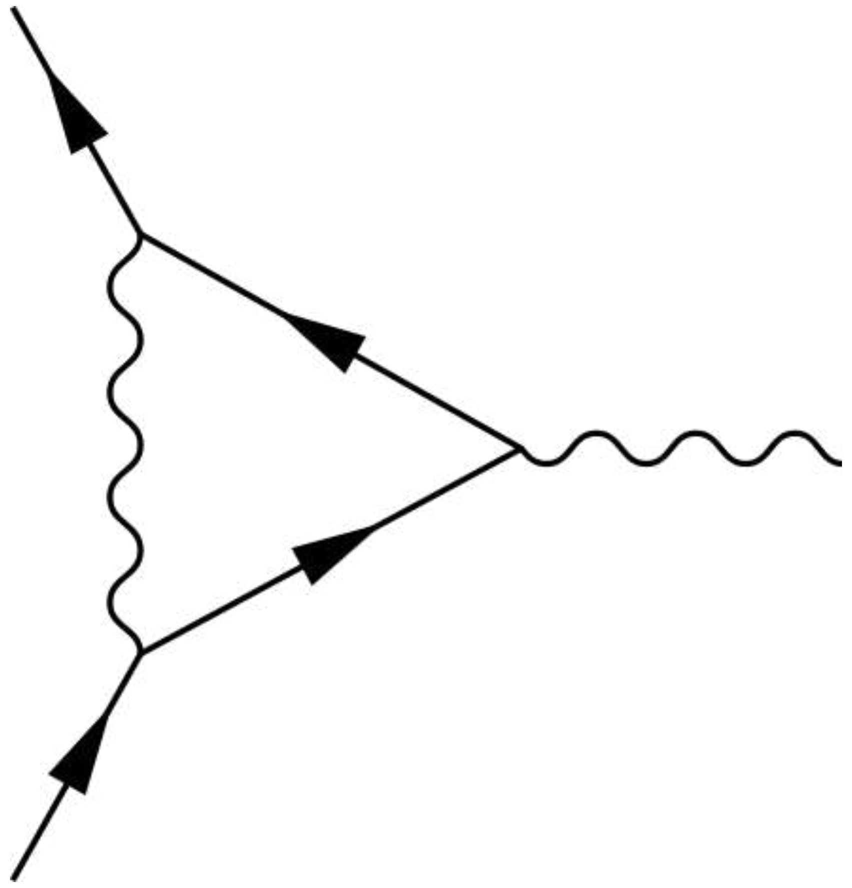
$$g = 2$$

Dirac, 1928

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

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

Schwinger, 1948



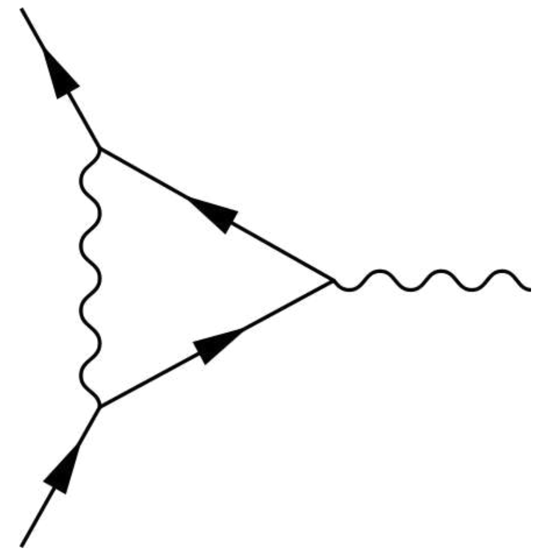
ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

$$g = 2$$ Dirac, 1928

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

$$g = 2\left(1 + \frac{\alpha}{2\pi}\right)$$ Schwinger, 1948



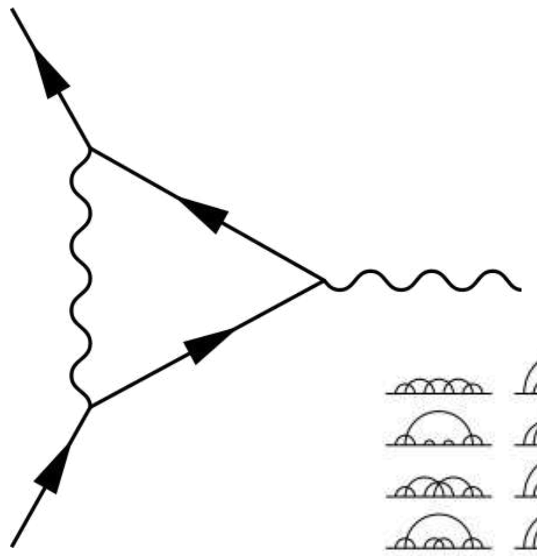
ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

$$g = 2$$ Dirac, 1928

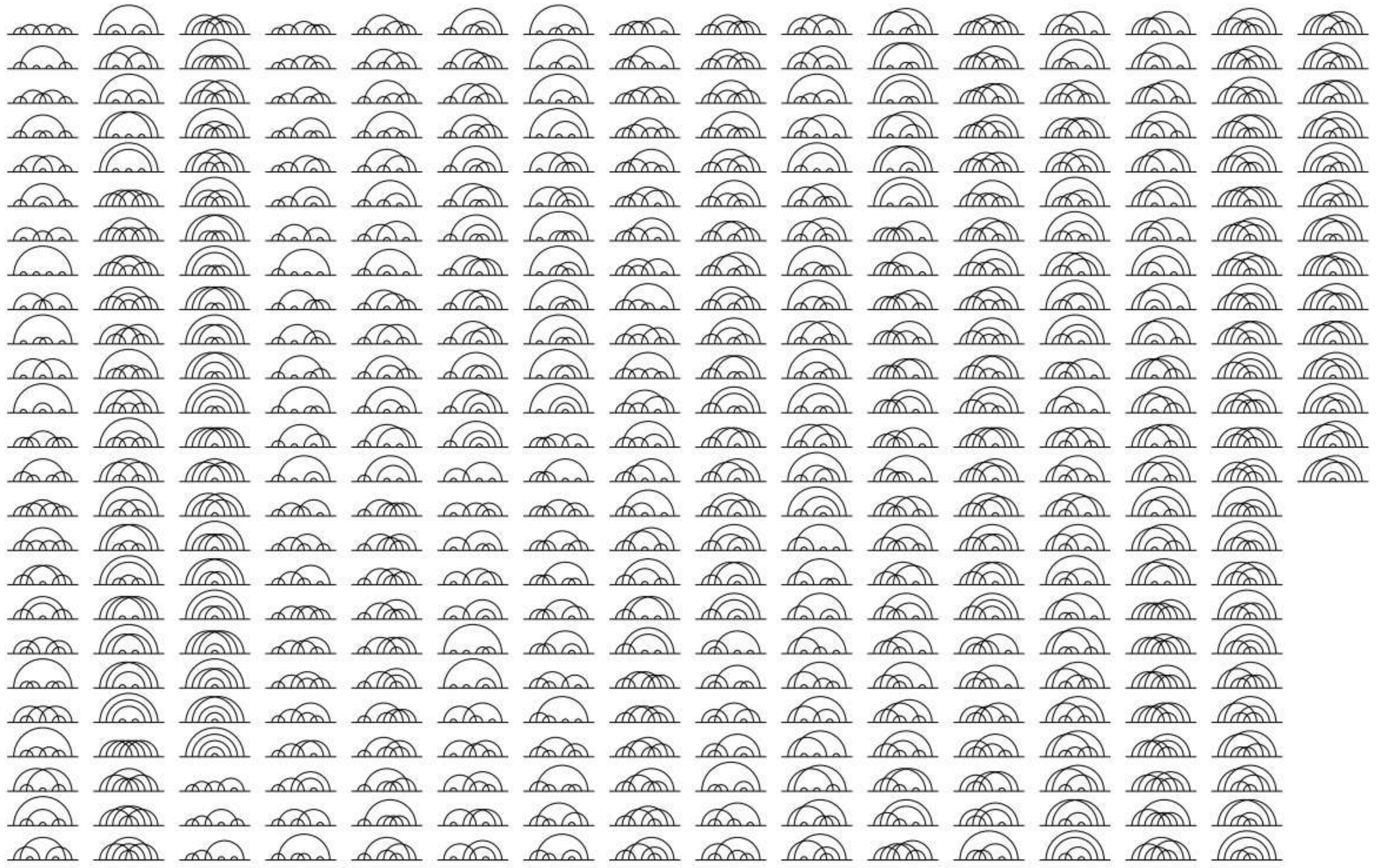
$$(i\gamma^\mu \partial_\mu - m)\psi(x) = 0$$

$$g = 2\left(1 + \frac{\alpha}{2\pi}\right)$$ Schwinger, 1948



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

Kinoshita et al, 2014



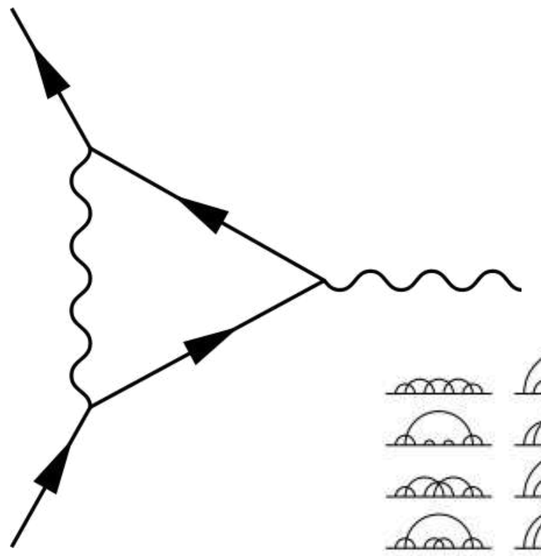
ELECTRON MAGNETIC MOMENT

Electron magnetic moment:

$$g = 2$$ Dirac, 1928

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

$$g = 2\left(1 + \frac{\alpha}{2\pi}\right)$$ Schwinger, 1948

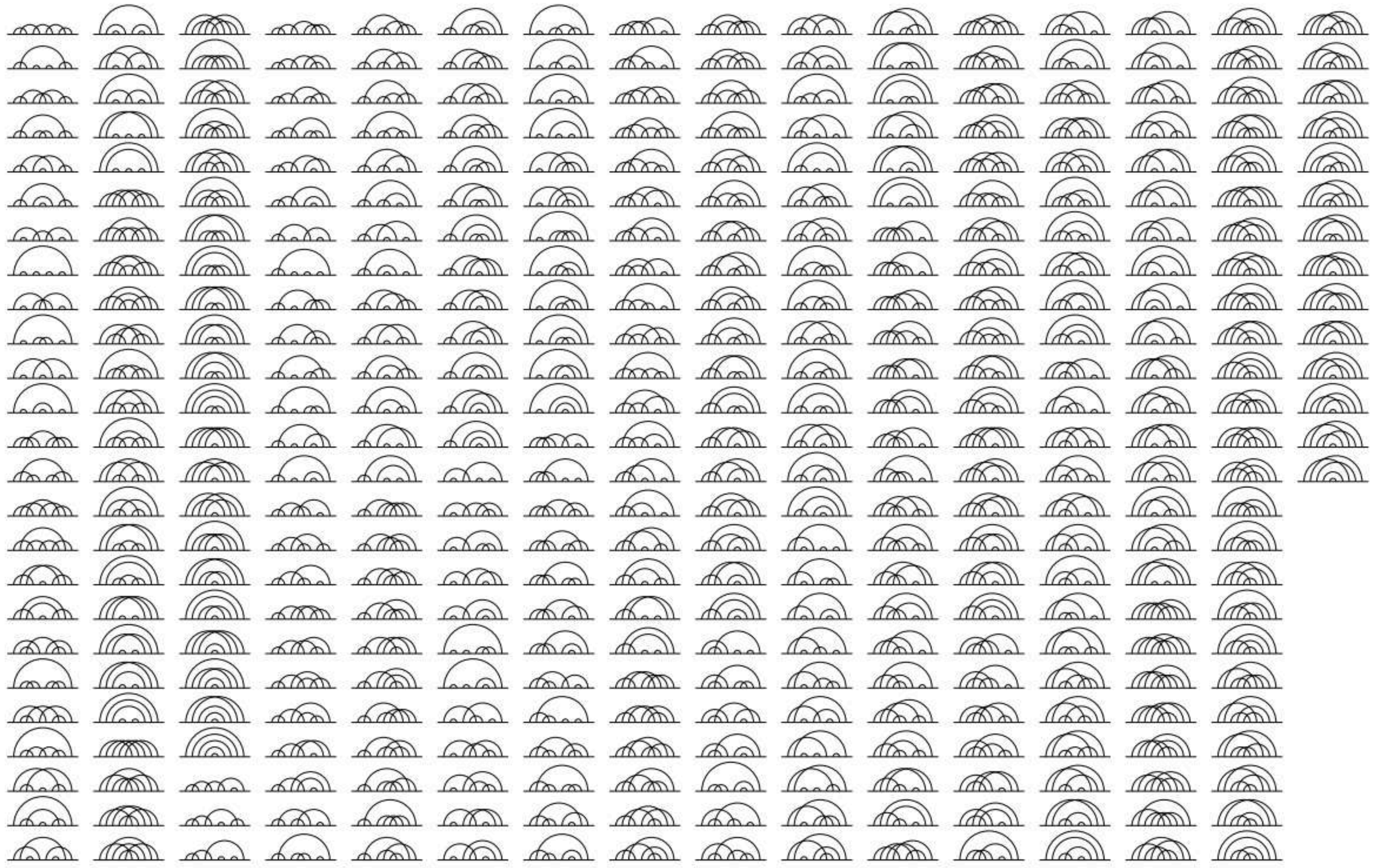


$$g_{\mathrm{th}} = 2(1 + 0.0011596521816)$$

Kinoshita et al, 2014

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

Fan et. al. 2023



RUNNING COUPLINGS

Quantum electrodynamics

characterized by charge of electron: e.

Often use dimensionless fine structure

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

RUNNING COUPLINGS

Quantum electrodynamics characterized by charge of electron: e.

$$E\frac{d\alpha}{dE} \approx \frac{2\alpha^2}{3\pi}$$

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

Fun fact: the fine structure constant is not a constant, it "runs" with energy.

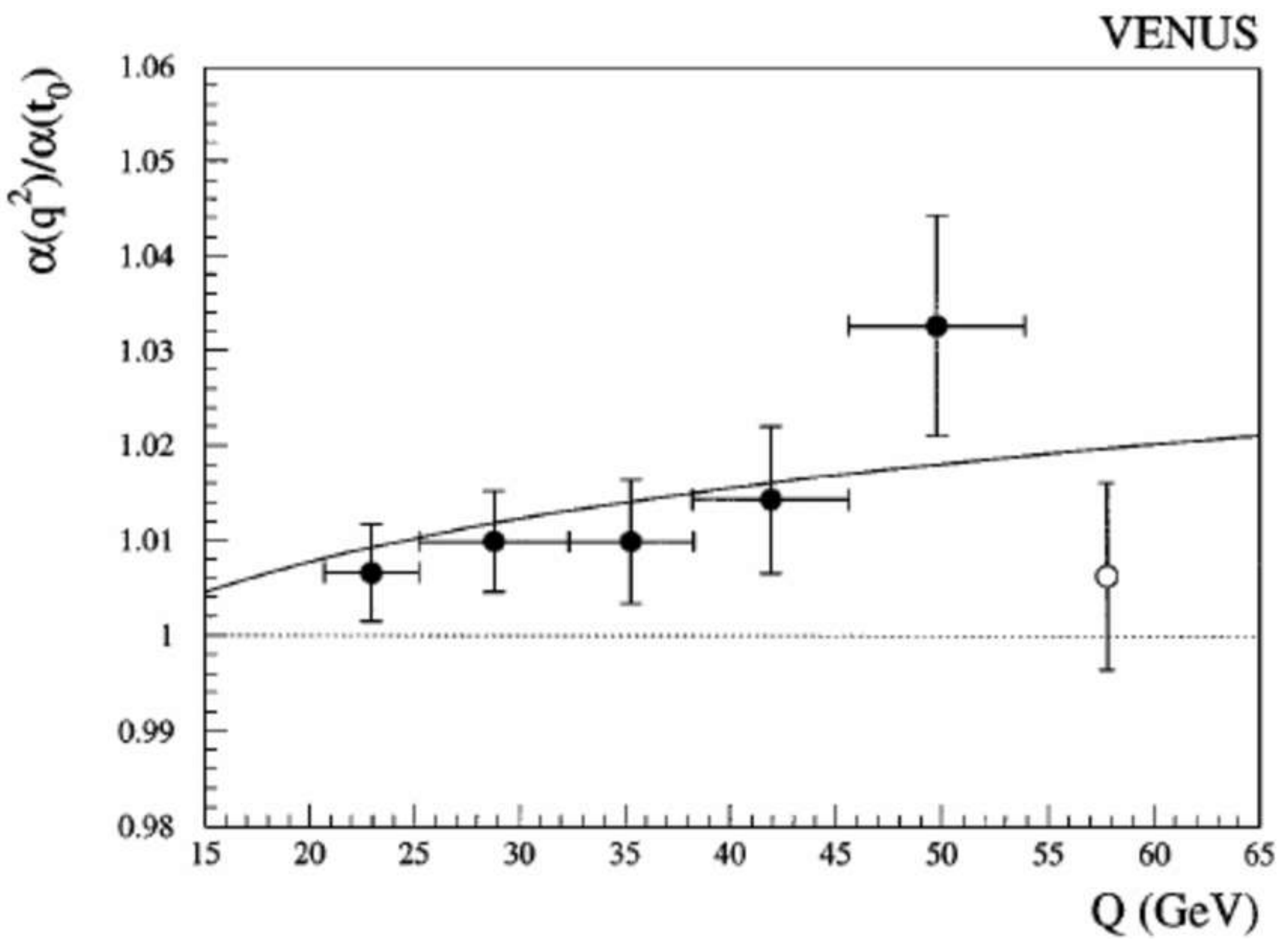
RUNNING COUPLINGS

Quantum electrodynamics characterized by charge of electron: e.

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

Fun fact: the fine structure constant is not a constant, it "runs" with energy.

$$E\frac{d\alpha}{dE} \approx \frac{2\alpha^2}{3\pi}$$



Venus Collaboration, 1998.

NON-PERTURBATIVE QFT

QED (electromangetic force)

expansion parameter is

$$\frac{e^2}{4\pi} \equiv \alpha \approx \frac{1}{137} \ll 1$$

What about theories where

expansion parameter is ~ 1?

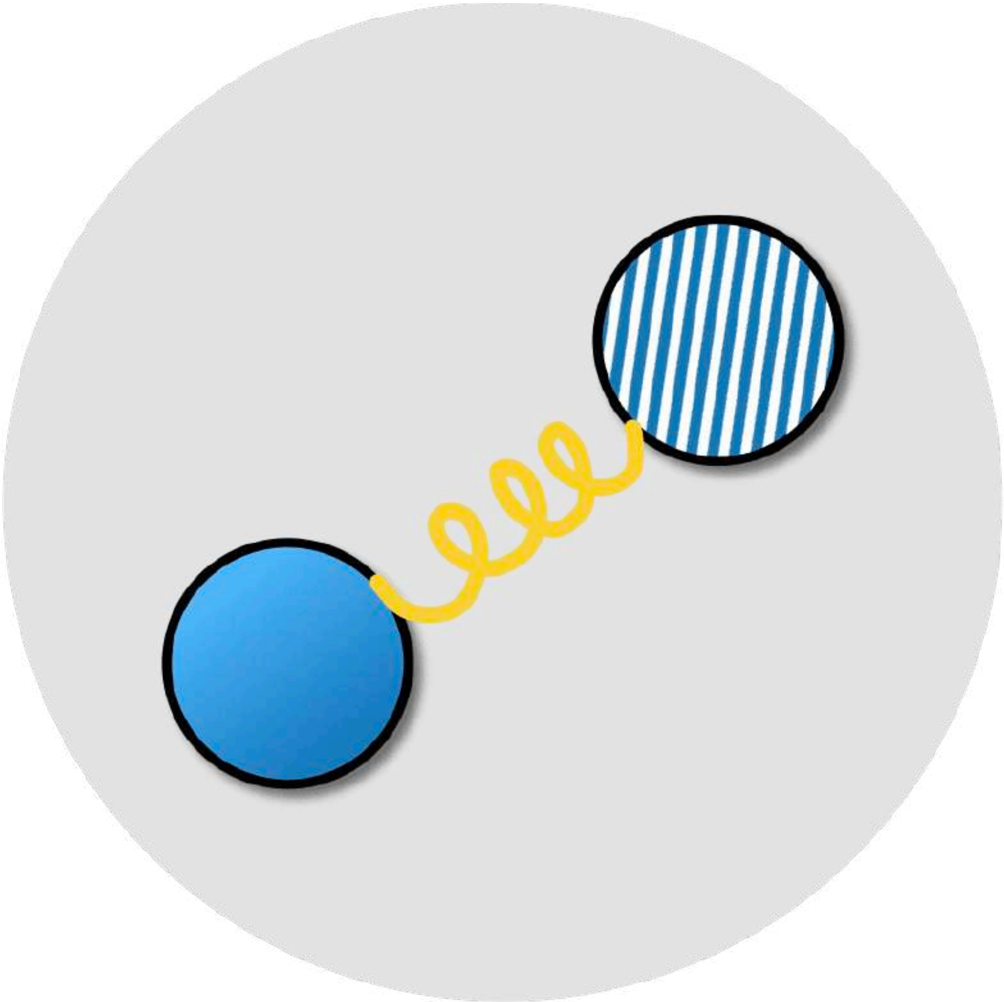
NON-PERTURBATIVE QFT

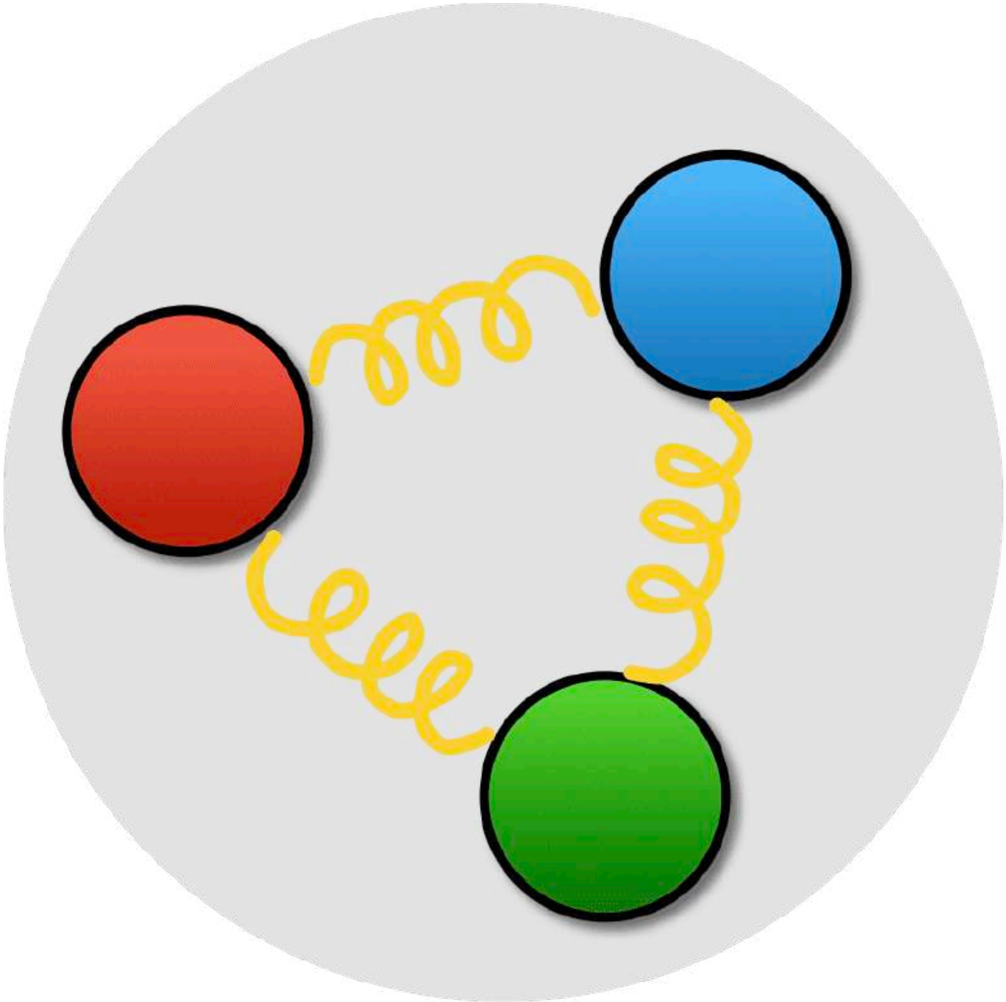
QED (electromangetic force) expansion parameter is

$$\frac{e^2}{4\pi} \equiv \alpha \approx \frac{1}{137} \ll 1$$

What about theories where expansion parameter is ~ 1?

Strong force (QCD) is such a theory!





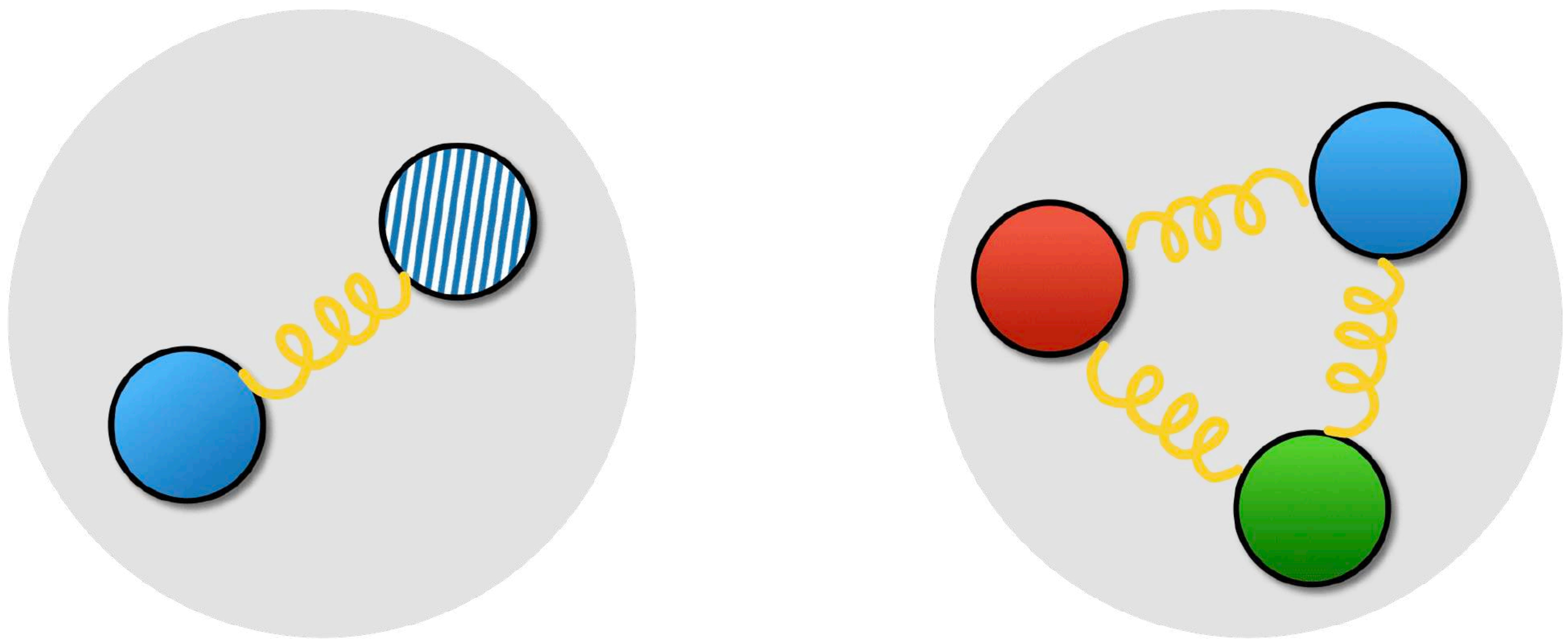
NON-PERTURBATIVE QFT

QED (electromangetic force) expansion parameter is

$$\frac{e^2}{4\pi} \equiv \alpha \approx \frac{1}{137} \ll 1$$

What about theories where expansion parameter is ~ 1?

Strong force (QCD) is such a theory!



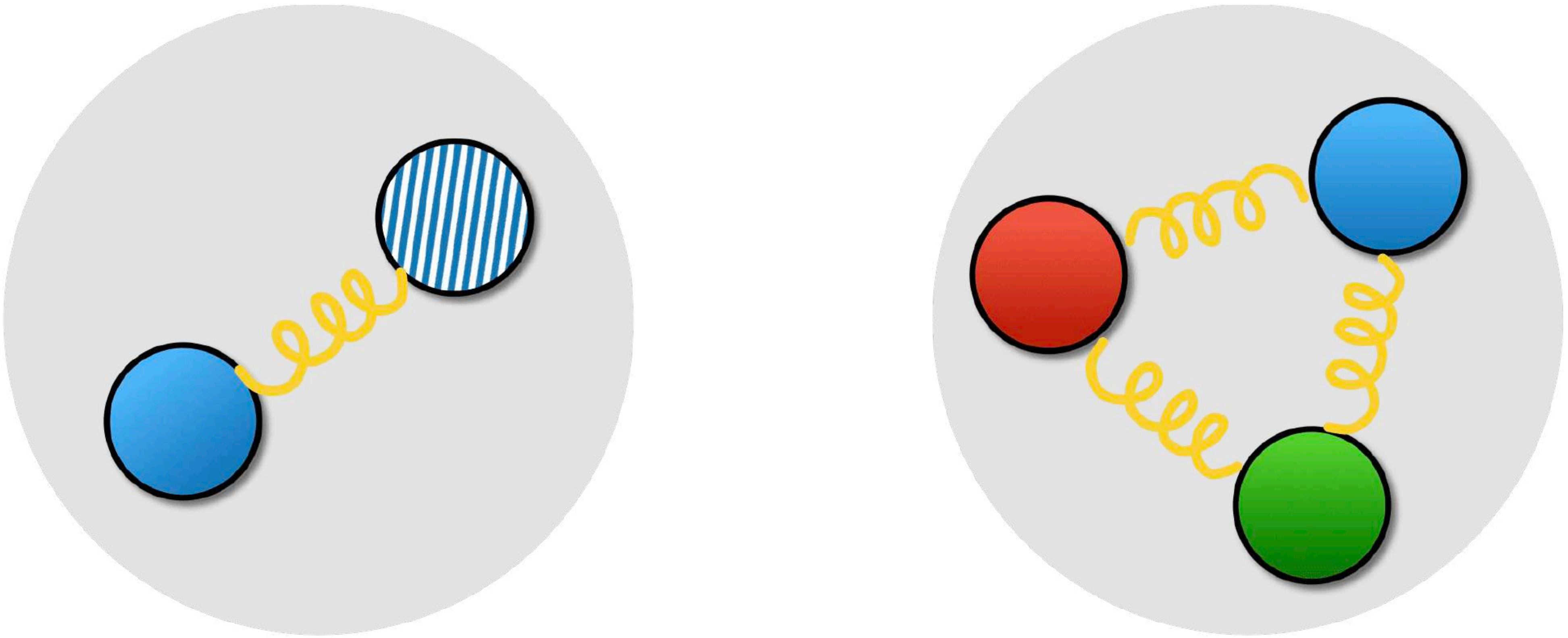
Feynman diagrams are unhelpful.

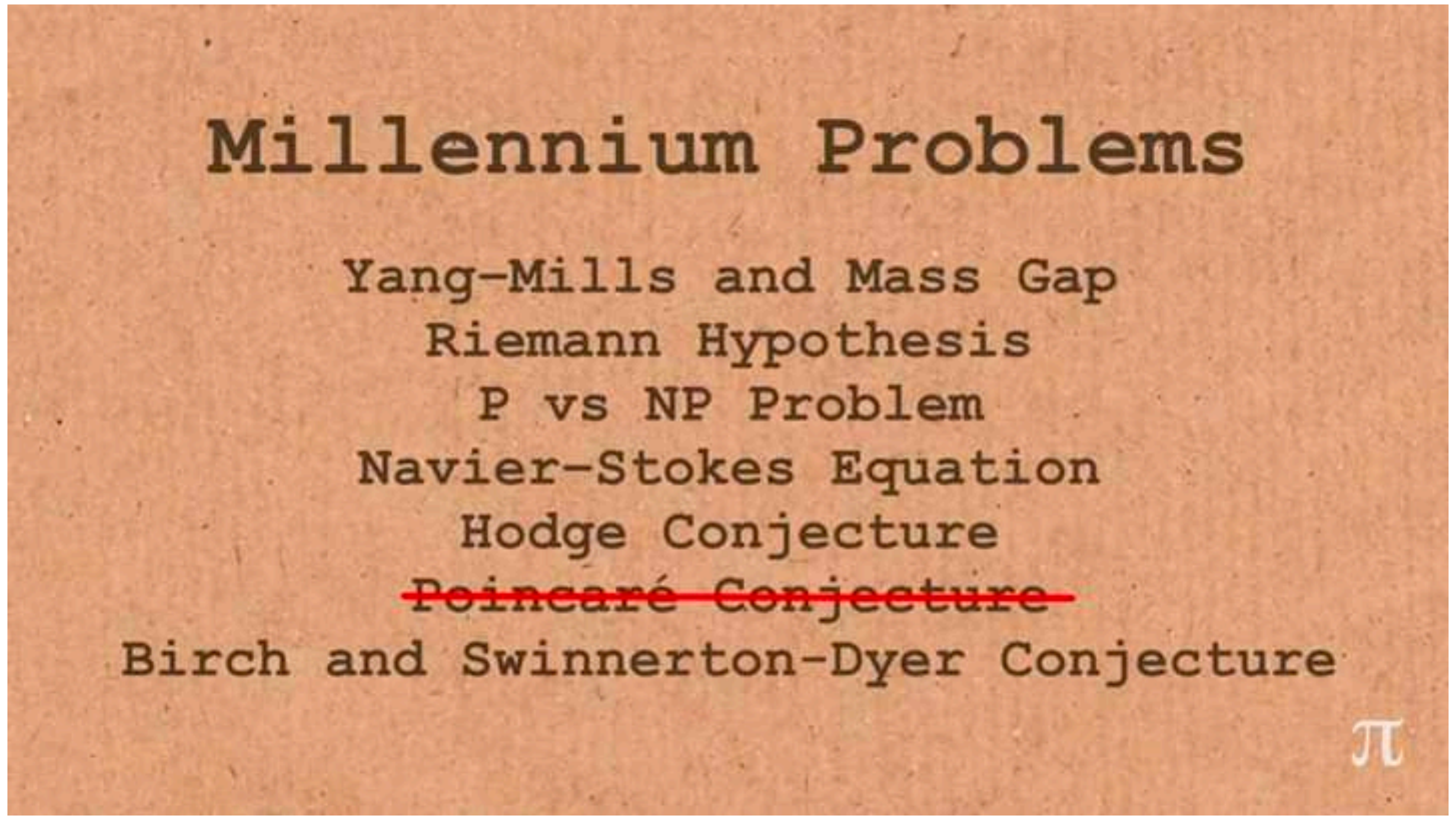
Most of our understanding of strong force is from data.

STRONG FORCE (QCD)

Things we know about the strong force from data:

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



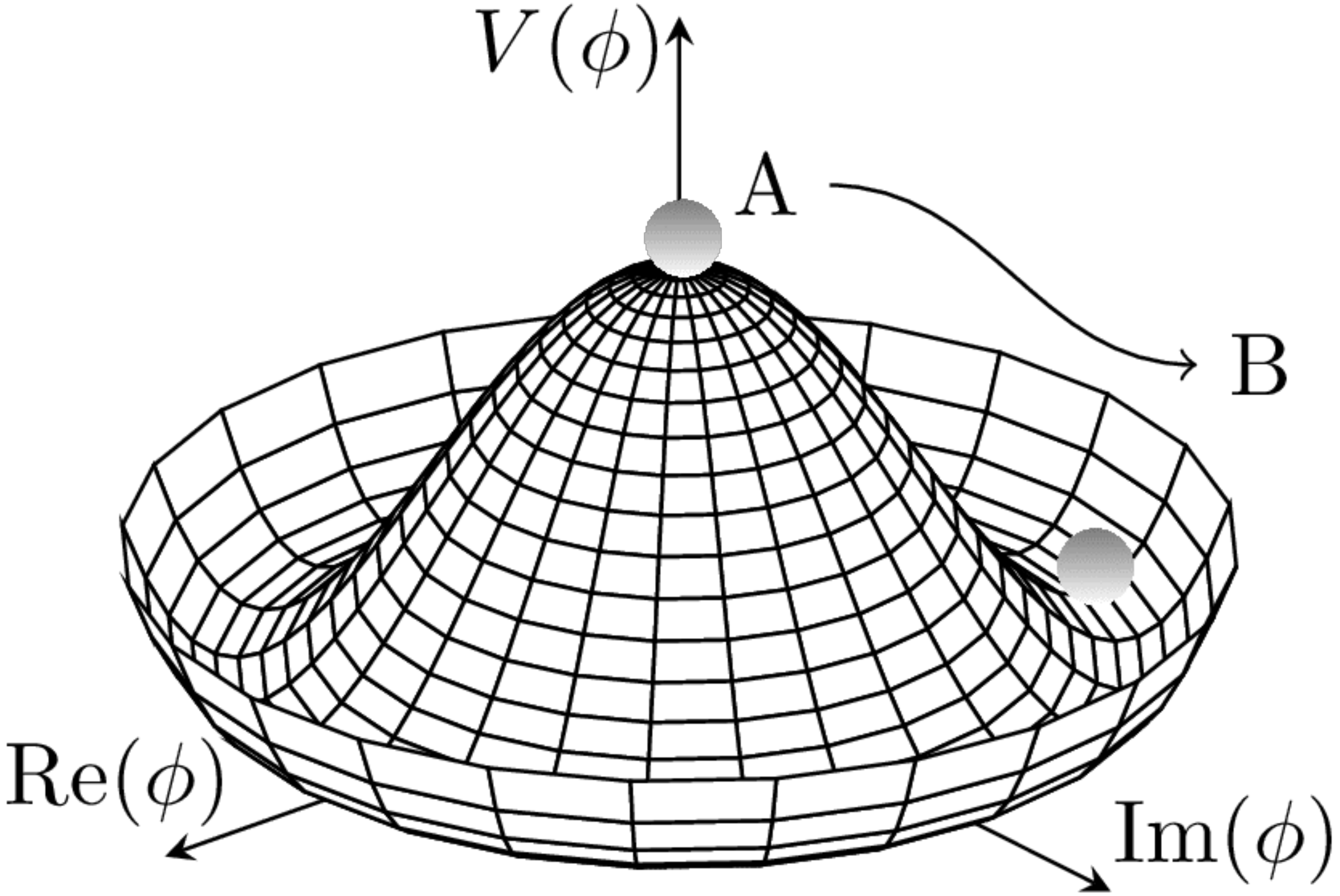


STRONG FORCE (QCD)

Things we know about the strong force from data:

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

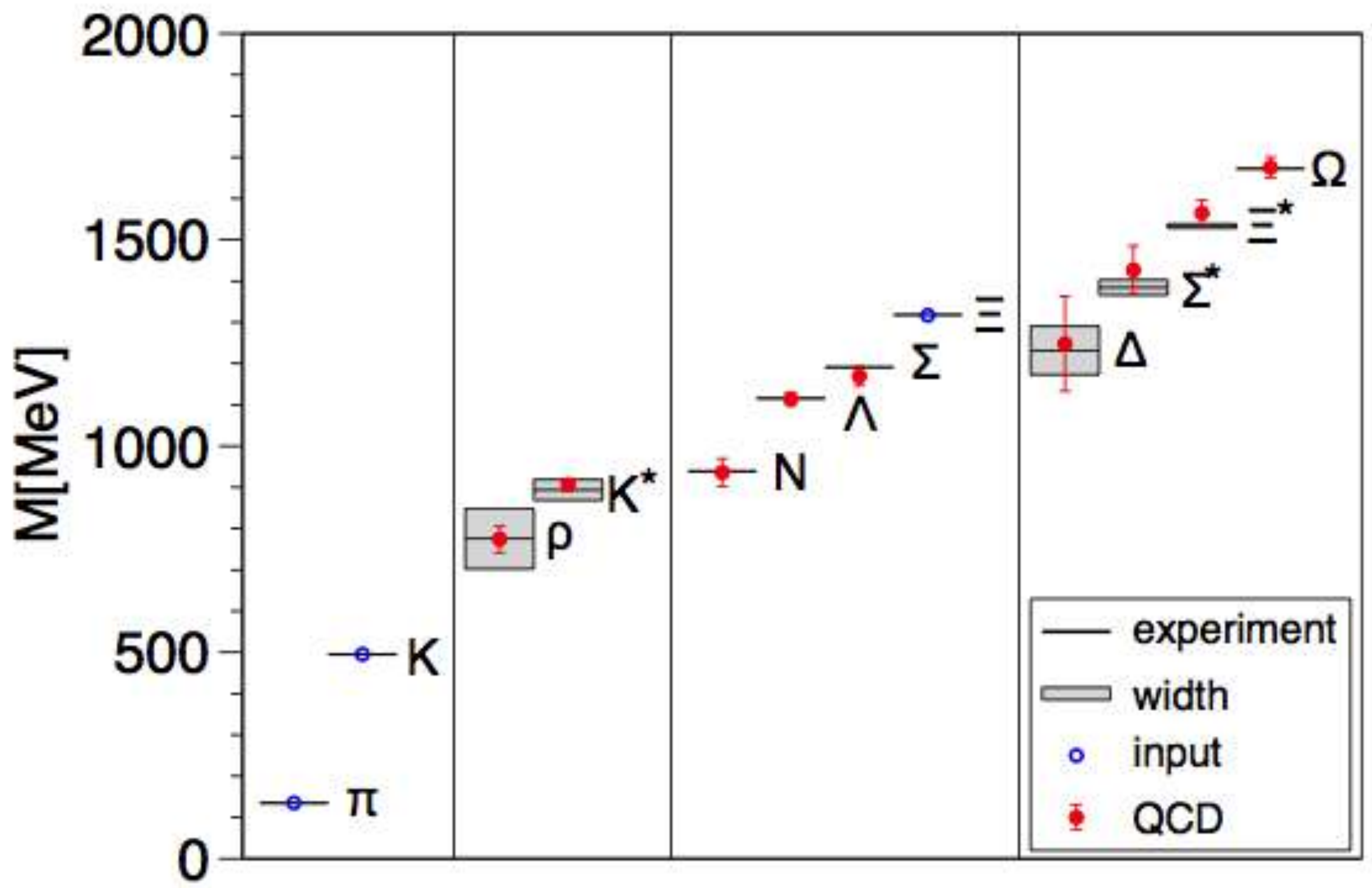
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$



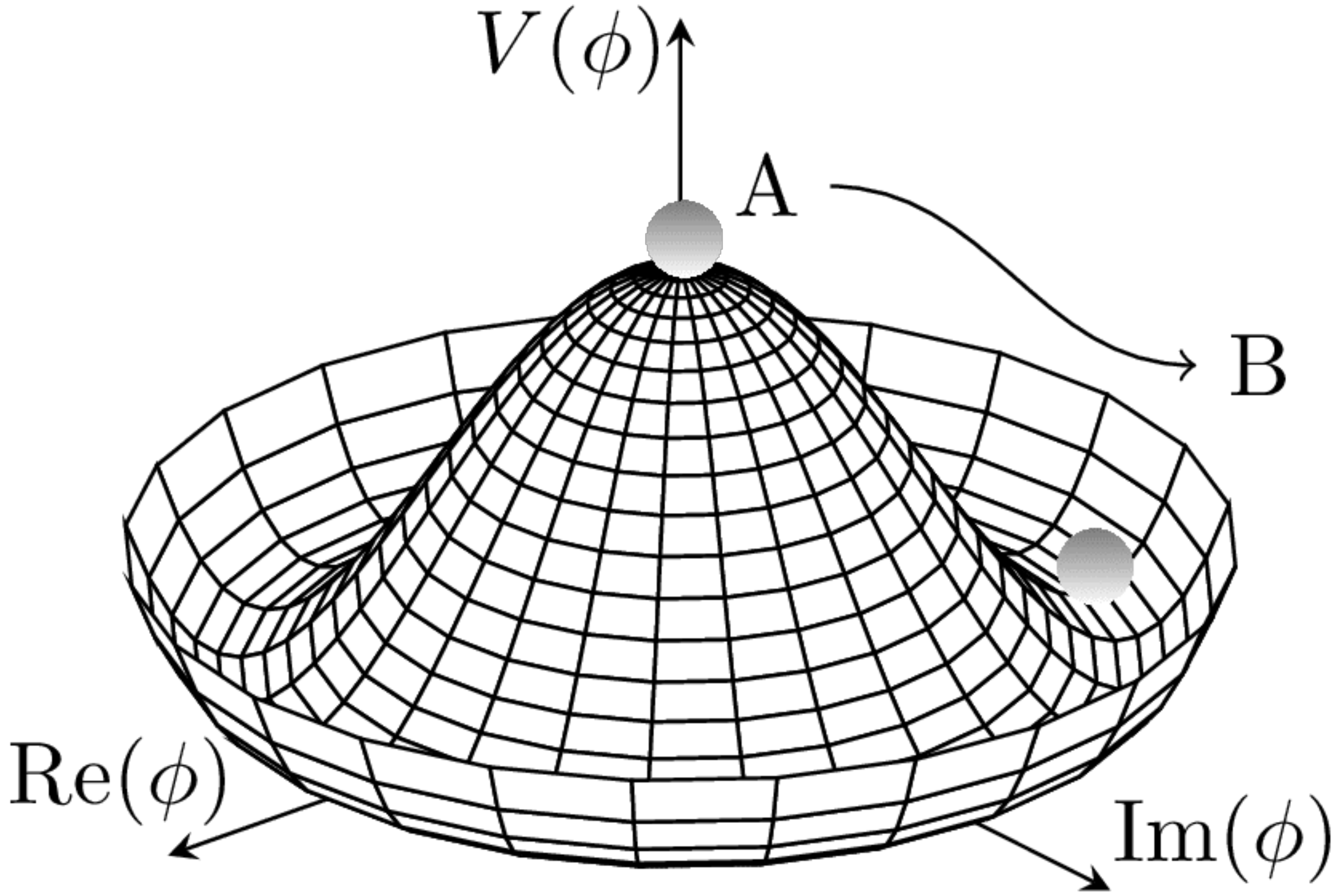
STRONG FORCE (QCD)

Two things are actually deeply connected.

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



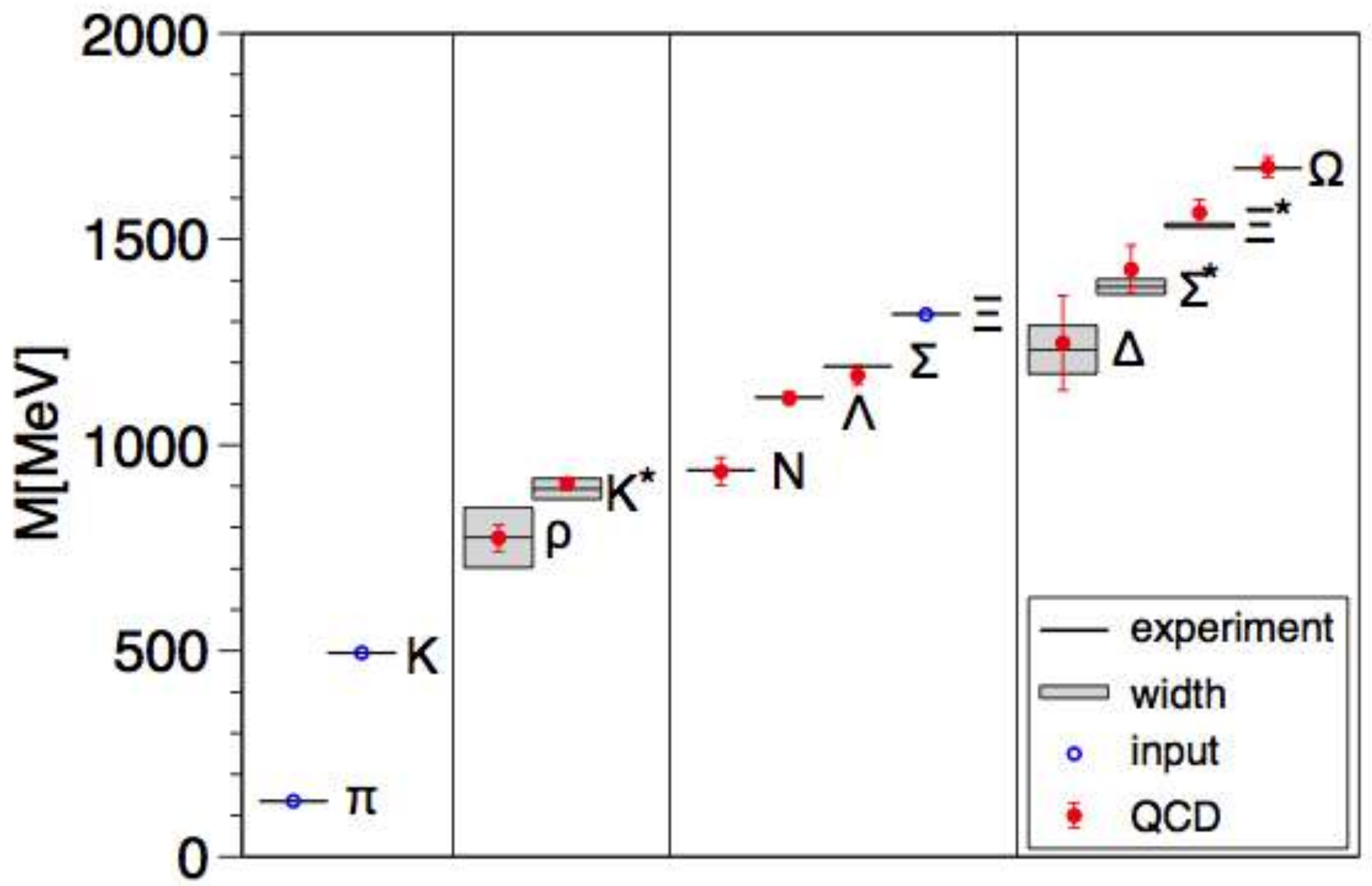
2. Spontaneous symmetry breaking



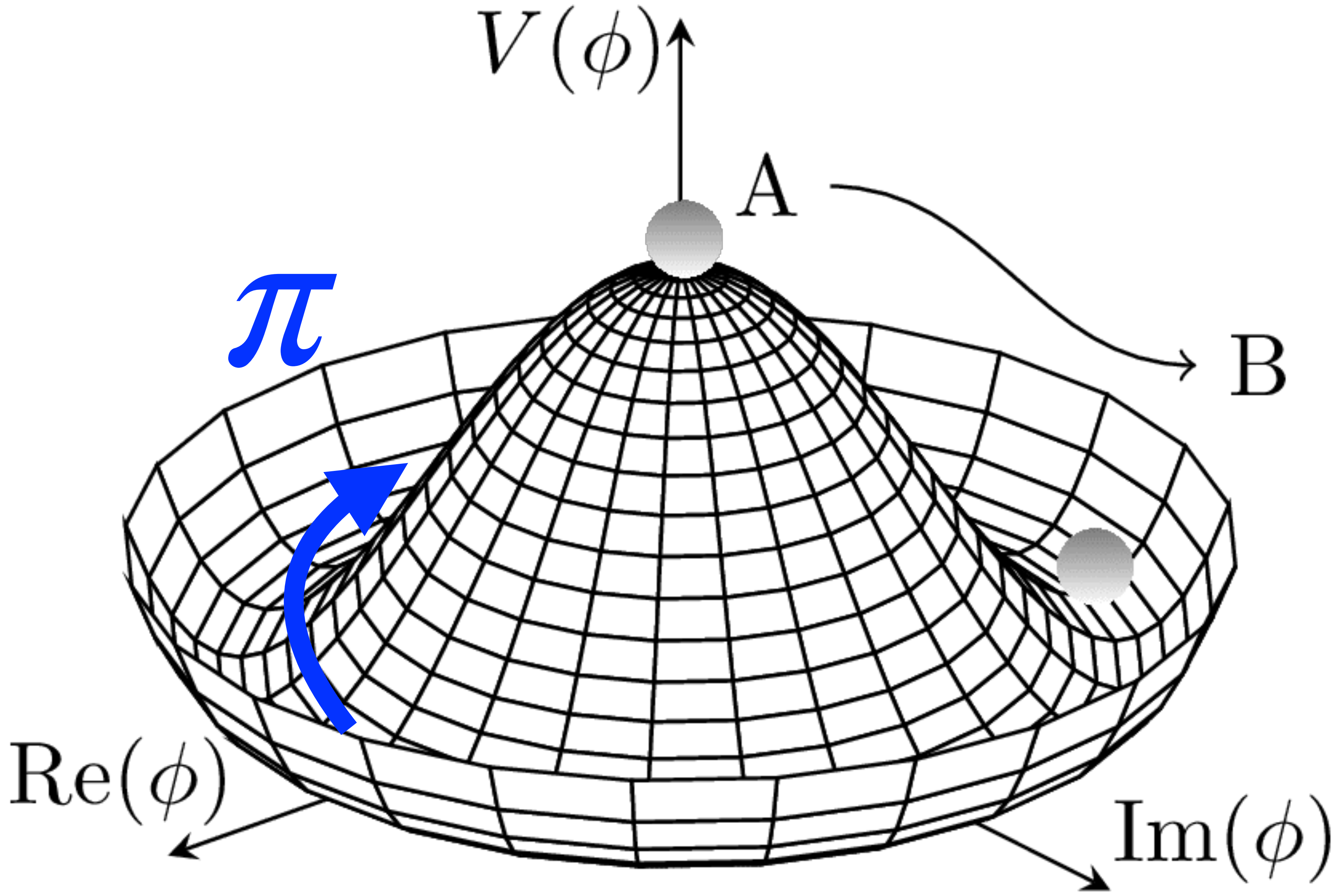
STRONG FORCE (QCD)

Two things are actually deeply connected.

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



2. Spontaneous symmetry breaking



RUNNING STRONG COUPLING

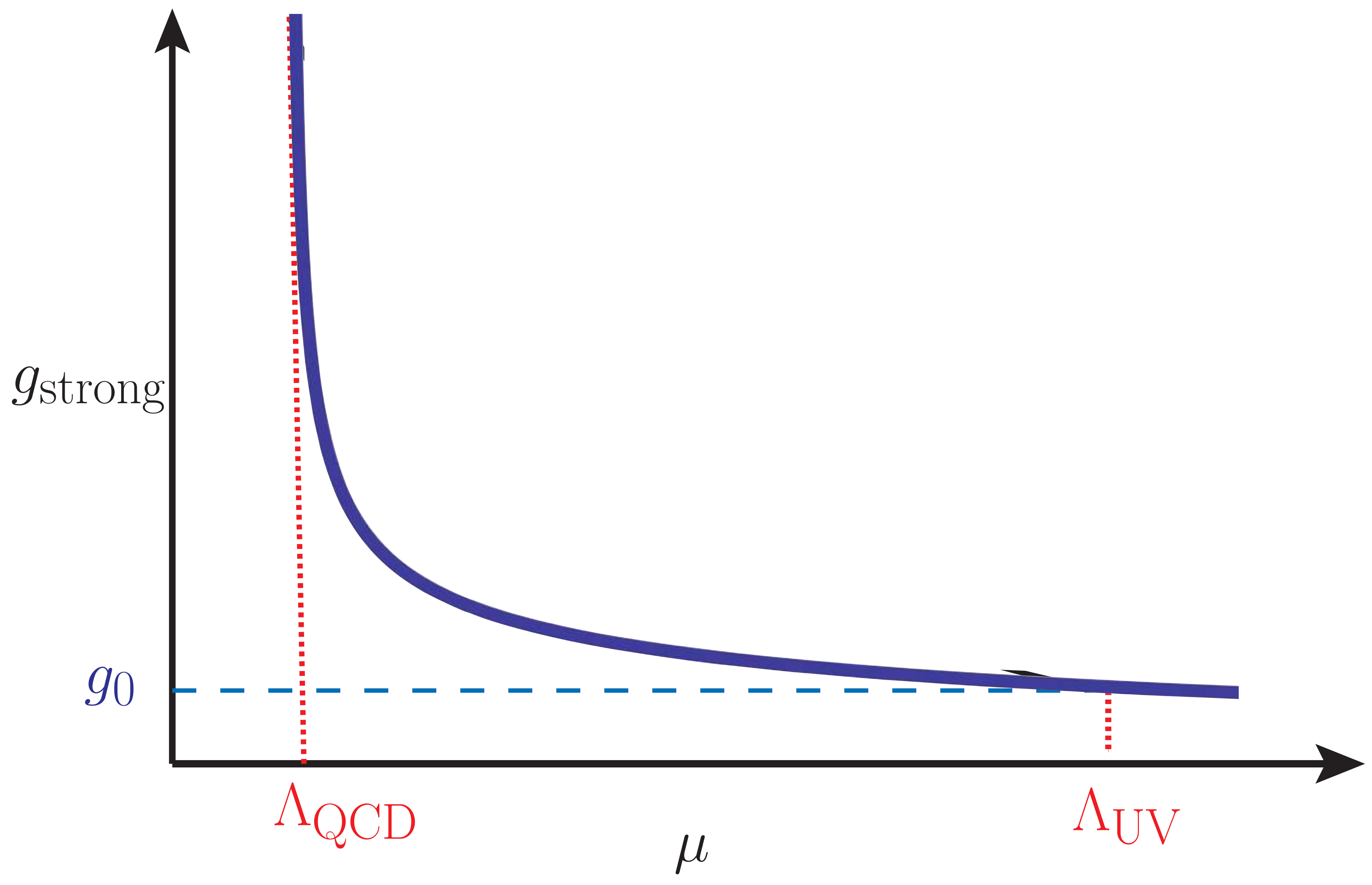
Like electromagnetism, strong coupling α_s changes with energy.

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

RUNNING STRONG COUPLING

Like electromagnetism, strong coupling α_s changes with energy.

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



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

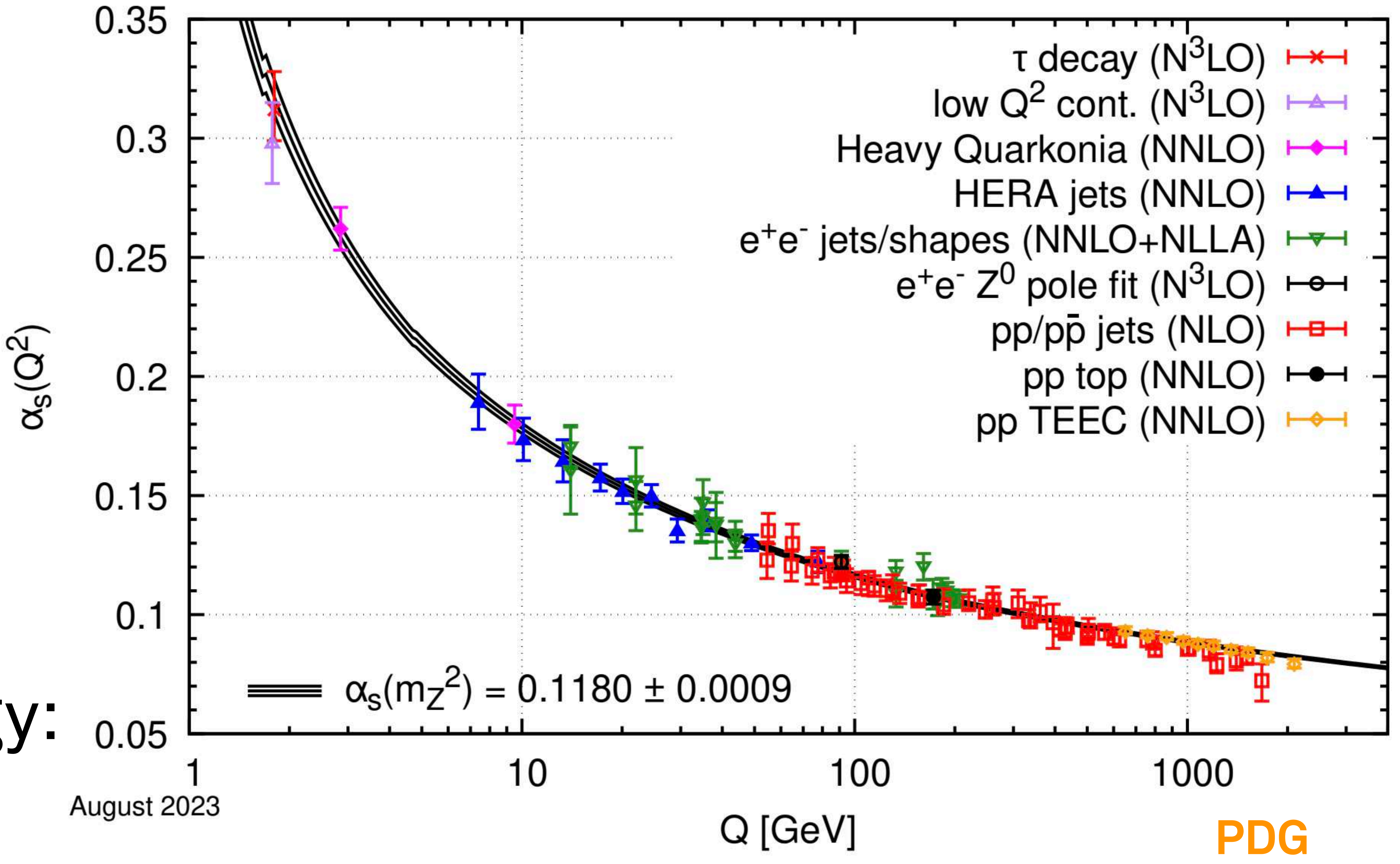
Coupling gets weaker at high energy: asymptotic freedom.

VERIFIED BY DATA

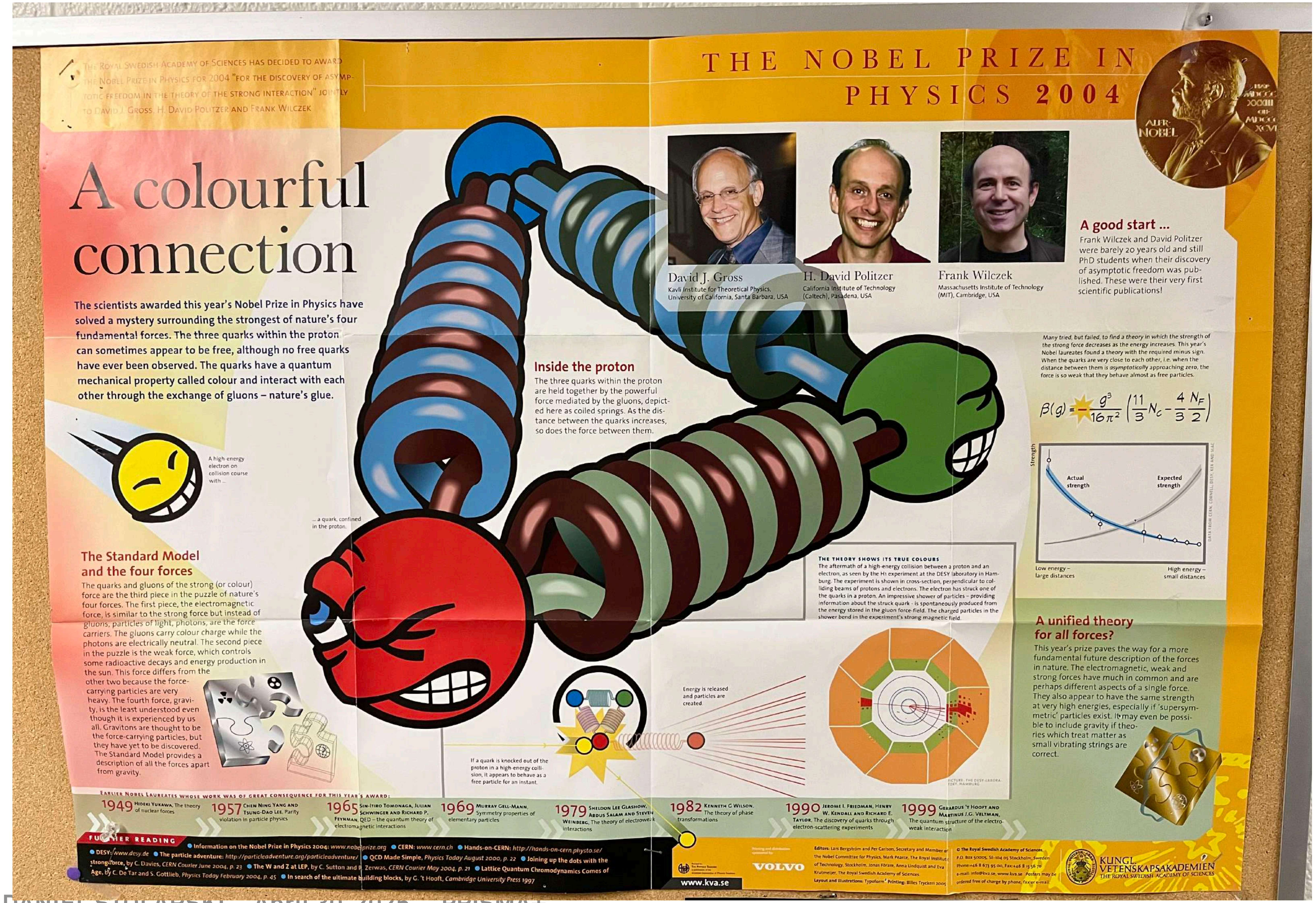
Like electromagnetism, strong coupling α_s changes with energy.

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

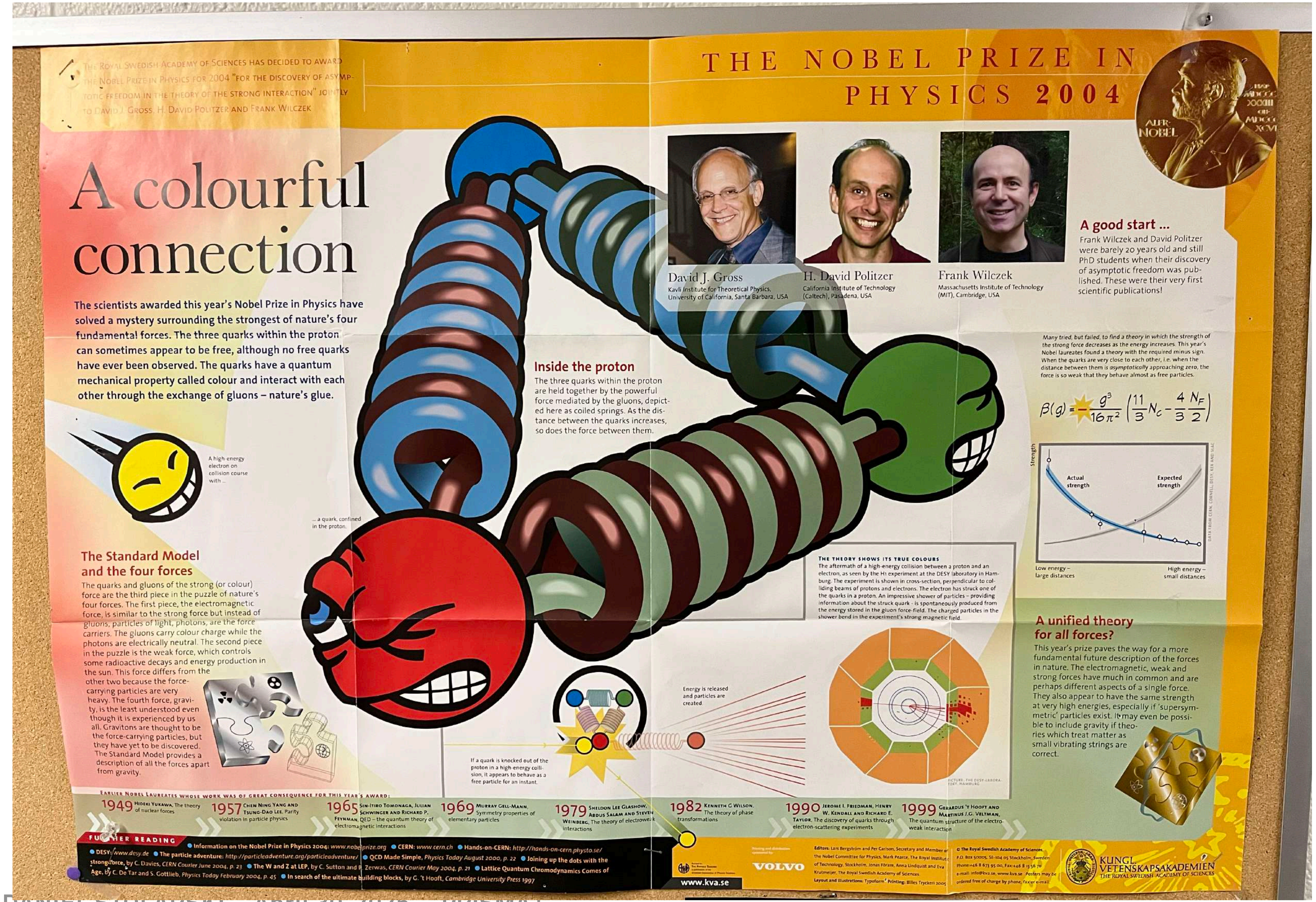
Coupling gets weaker at high energy: asymptotic freedom.



TRIP TO STOCKHOLM



TRIP TO STOCKHOLM



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.

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.

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.

SYMMETRY AND ENERGY

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

$$< \uparrow |H| \uparrow > \stackrel{?}{=} < \downarrow |H| \downarrow >$$

SYMMETRY AND ENERGY

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

$$< \uparrow |H| \uparrow > = < \downarrow |H| \downarrow >$$

Of course it does. If I just rotate the physicist, I turn $| \uparrow >$ into $| \downarrow >$.

SYMMETRY AND ENERGY

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

$$<\uparrow|H|\uparrow> = <\downarrow|H|\downarrow>$$

Of course it does. If I just rotate the physicist, I turn $|\uparrow>$ into $|\downarrow>$.

Laws of physics are invariant under rotation.

SYMMETRY AND ENERGY

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

$$<\uparrow|H|\uparrow> = <\downarrow|H|\downarrow>$$

Of course it does. If I just rotate the physicist, I turn $|\uparrow>$ into $|\downarrow>$.

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.

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

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

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

SUPERSYMMETRY AND ENERGY

Supersymmetry relates bosons to fermions.

$$Q\,|\,\text{fermion} > \;=\; |\,\text{boson} >$$

$$Q\,|\,\text{boson} > \;=\; |\,\text{fermion} >$$

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

Supersymmetric electromagnetism:

	spin	mass
e	1/2	511 keV
se	0	511 keV
ɣ	1	0
ɣino	1/2	0

SUPERSYMMETRY AND ENERGY

Supersymmetry relates bosons to fermions.

$$Q\,|\,\text{fermion} > \,=\, |\,\text{boson} >$$

$$Q\,|\,\text{boson} > \,=\, |\,\text{fermion} >$$

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

Supersymmetric electromagnetism:

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

Not our universe!

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?
ɣ	1	0
ɣino	1/2	1 TeV?

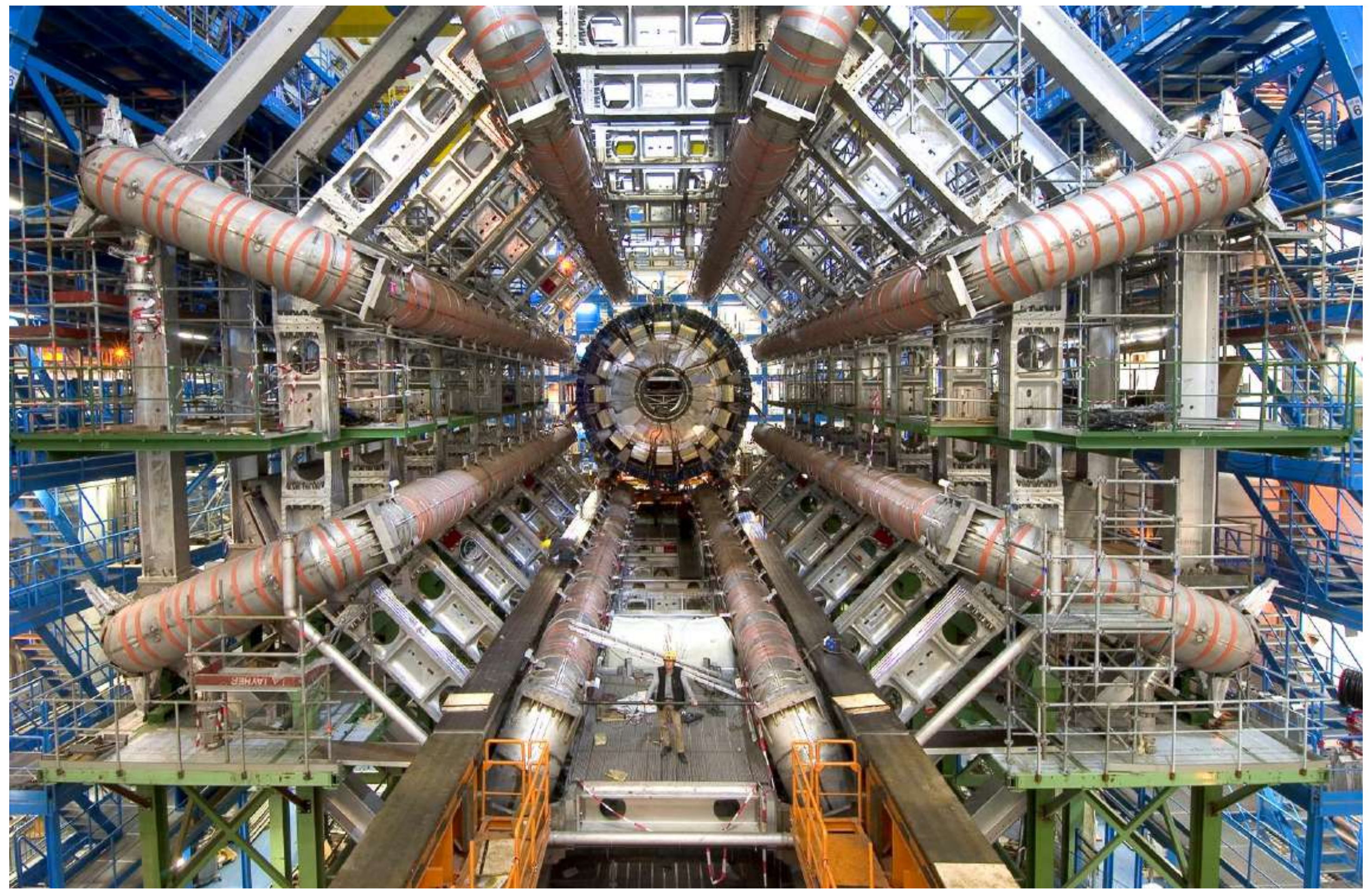
BREAKING SUPERSYMMETRY

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

Electromagnetism with broken supersymmetry.

Could be our universe!

	spin	mass
e	1/2	511 keV
se	0	1 TeV?
ɣ	1	0
ɣino	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!

$$\mathcal{X} = -\frac{1}{3!}\left(\gamma_i + \gamma_j + \gamma_k\right) y^{ijk} \phi_i \phi_j \phi_k,$$

$$\gamma_i^j = -\frac{1}{32\pi^2}[y_{ikl}^* y^{jkl} - 4g^2 \delta_i^j C_A(\phi_i)],$$

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

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

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

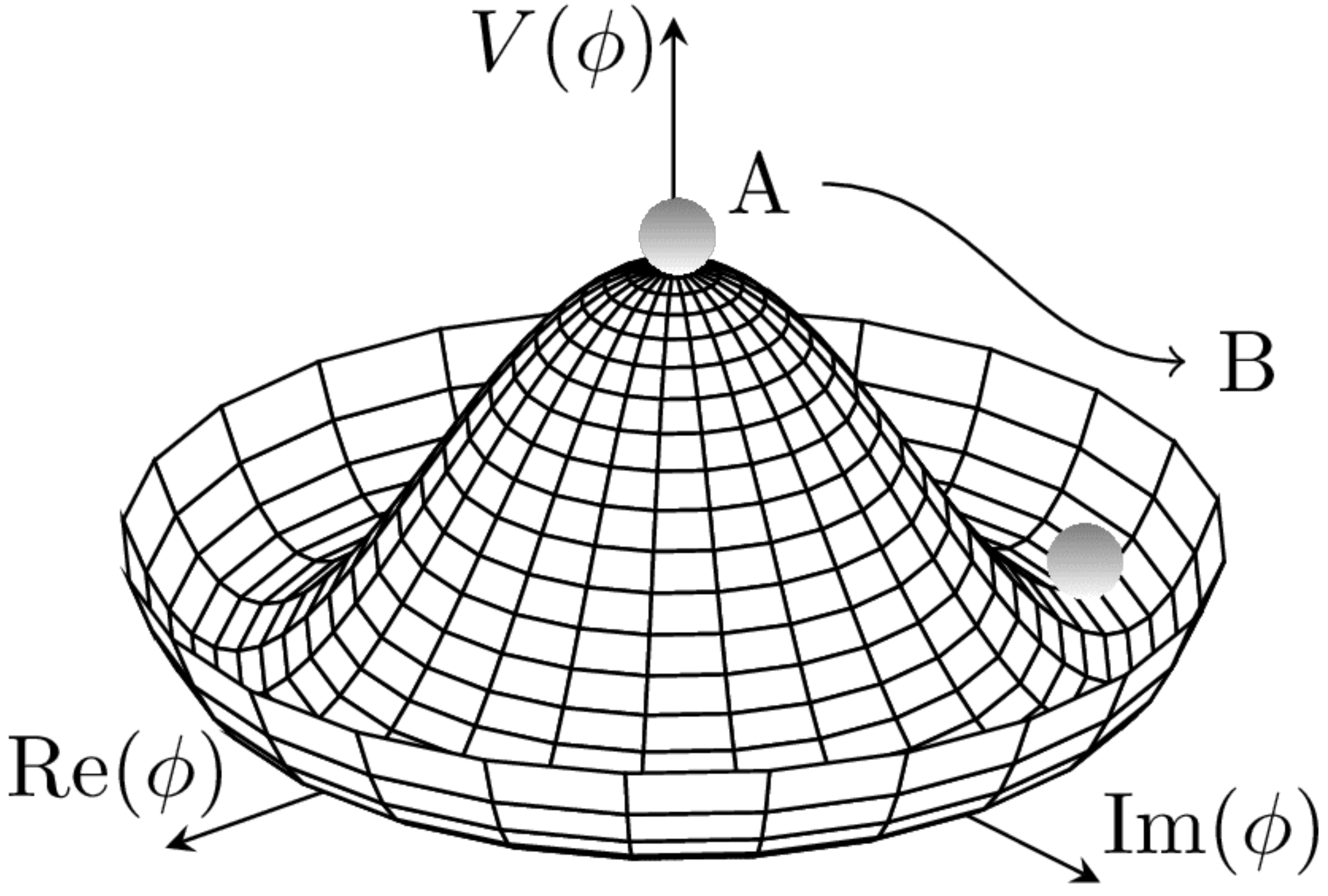
$$m_i^2 = \frac{1}{4}\dot{\gamma}_i^i \, m_{3/2}^2.$$

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

Search...

Help | Adv

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.

AMSB + NON-PERTURBATIVE QFT

arXiv > hep-th > arXiv:2104.01179

Search...

Help | Adv

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.

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

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

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

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

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

Search.

Help | A

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

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

Search...

Help | Advance

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

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

arXiv > hep-th > arXiv:2107.02813

Search...
Help | Advance

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

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri Telem

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

arXiv > hep-th > arXiv:2107.02813

Search...

Help | Advance

metry

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

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri Telem

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

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

arXiv > hep-th > arXiv:2107.02813

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

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri Telem

arXiv > hep-th > arXiv:2111.09690

metry

arXiv > hep-th > arXiv:2209.09287

Search

Help | A

High Energy Physics – Theory

[Submitted on 19 Sep 2022]

Dynamics of Simplest Chiral Gauge Theories

Dan Kondo, Hitoshi Murayama, Cameron Sylber

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

arXiv > hep-th > arXiv:2107.02813

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

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri Telem

arXiv > hep-th > arXiv:2111.09690

arXiv > hep-th > arXiv:2209.09287

Search

Help | A

arXiv > hep-th > arXiv:2212.03260

Search...

Help | Advanced

High Energy Physics – Theory

[Submitted on 6 Dec 2022]

A Guide to AMSB QCD

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

metry

AMSB + STRONG COUPLING

arXiv > hep-th > arXiv:2104.01179

arXiv > hep-th > arXiv:2104.10171

arXiv > hep-th > arXiv:2105.03444

arXiv > hep-th > arXiv:2106.10288

arXiv > hep-th > arXiv:2107.02813

High Energy Physics – Theory

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

The Phases of Non-supersymmetri[c ...] the $SO(N_c)$ Case Study

Csaba Csáki, Andrew Gomes, Hitoshi Murayama, Ofri T[...]

arXiv > hep-th > arXiv:2111.09690

arXiv > hep-th > arXiv:2209.09287

Search

Help | A[...]

arXiv > hep-th > arXiv:2212.03260

Search...

Help | Advance[d]

High Energy Physics – Theory

[Submitted on 6 Dec 2022]

A Guide to AMSB QCD

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

arXiv > hep-ph > arXiv:2407.06252

High Energy Physics – Phenomenology

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

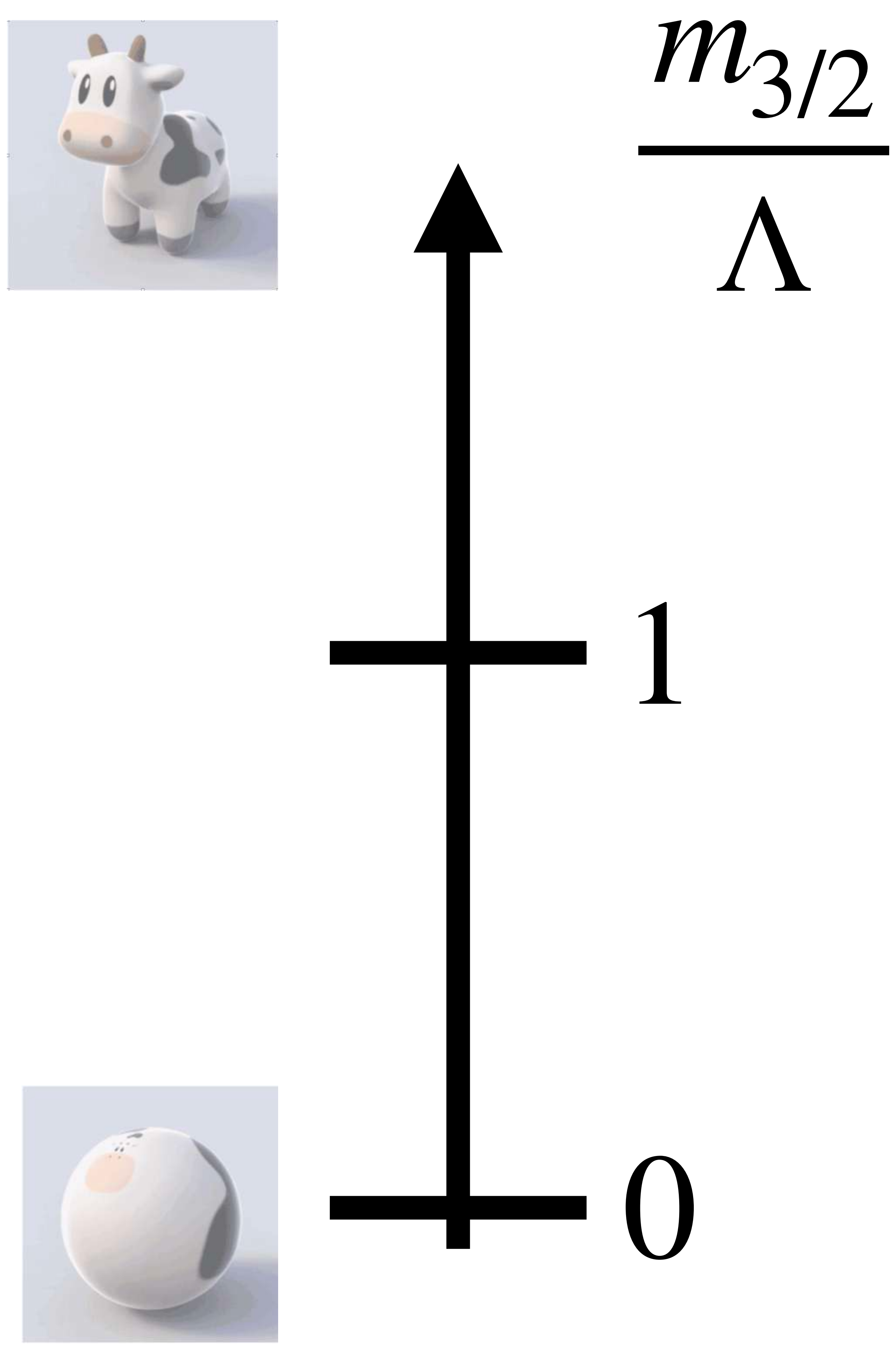
Spontaneous CP Breaking in a QCD-like Theory

Csaba Csáki, Maximilian Ruhdorfer, Taewook Youn

SMALL VS. LARGE SUSY BREAKING

Two dimensionful parameters:

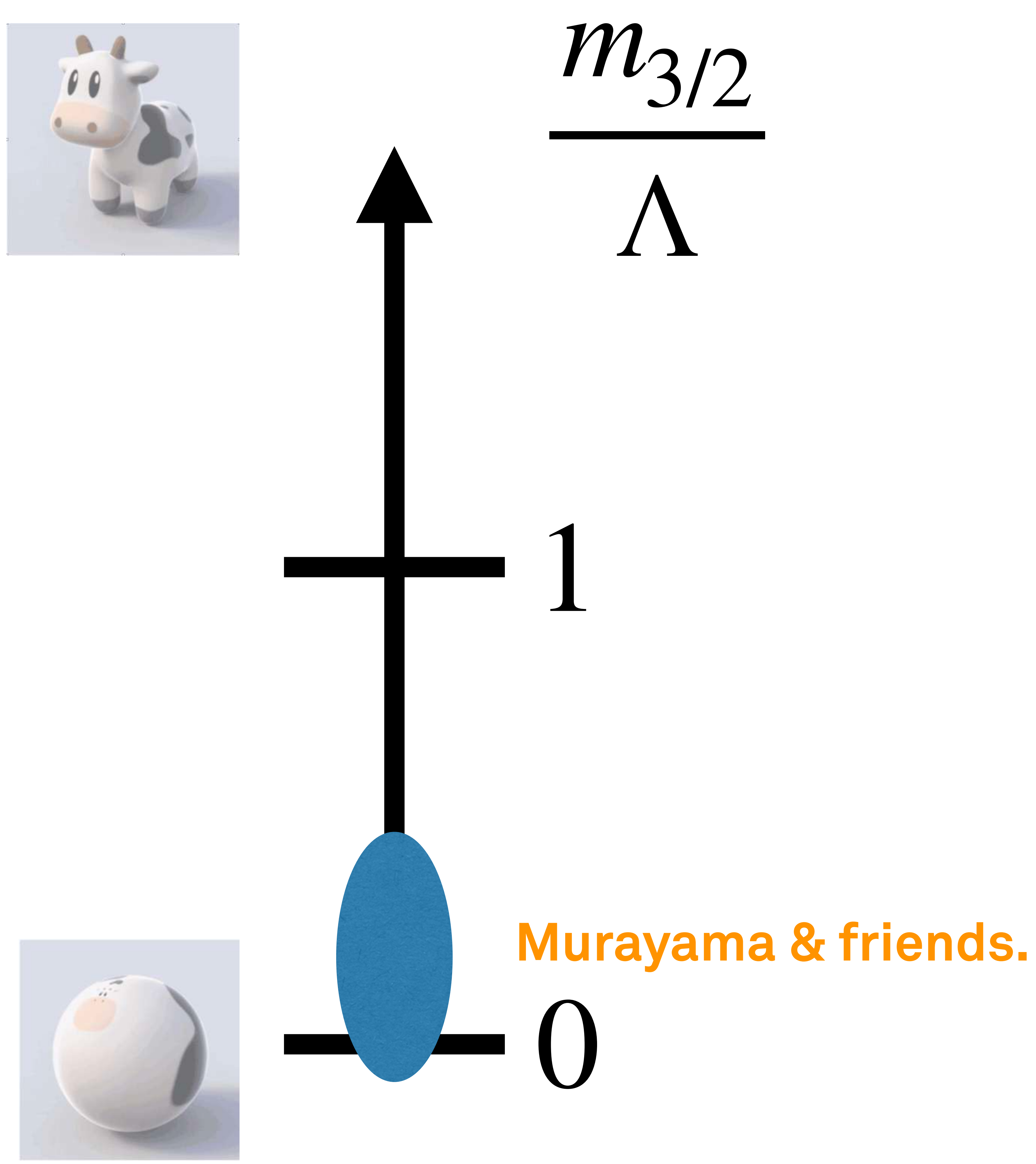
- Λ - mass of bound states
- $m_{3/2}$ - size of SUSY breaking



SMALL VS. LARGE SUSY BREAKING

Two dimensionful parameters:

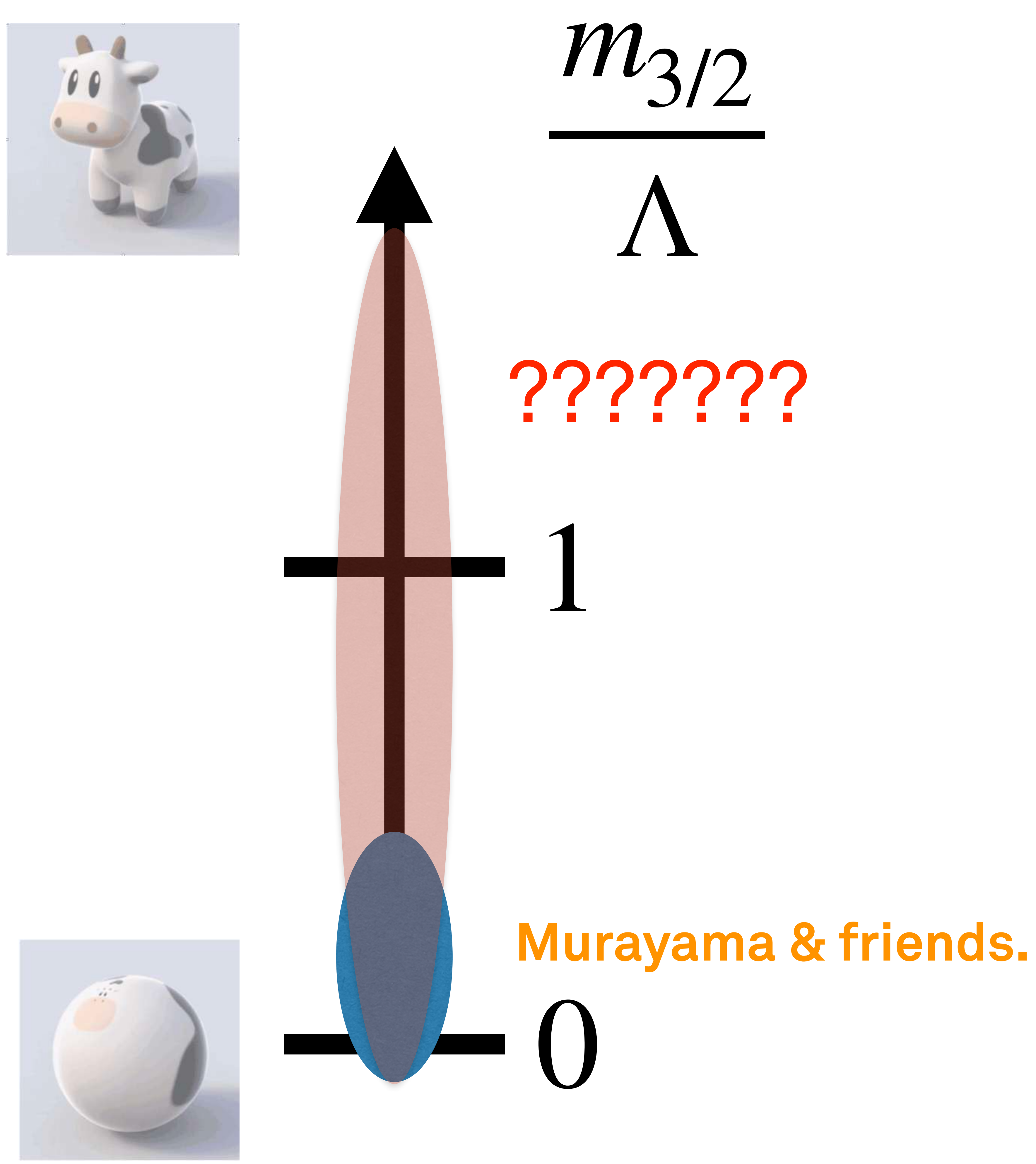
- Λ - mass of bound states
- $m_{3/2}$ - size of SUSY breaking



SMALL VS. LARGE SUSY BREAKING

Two dimensionful parameters:

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

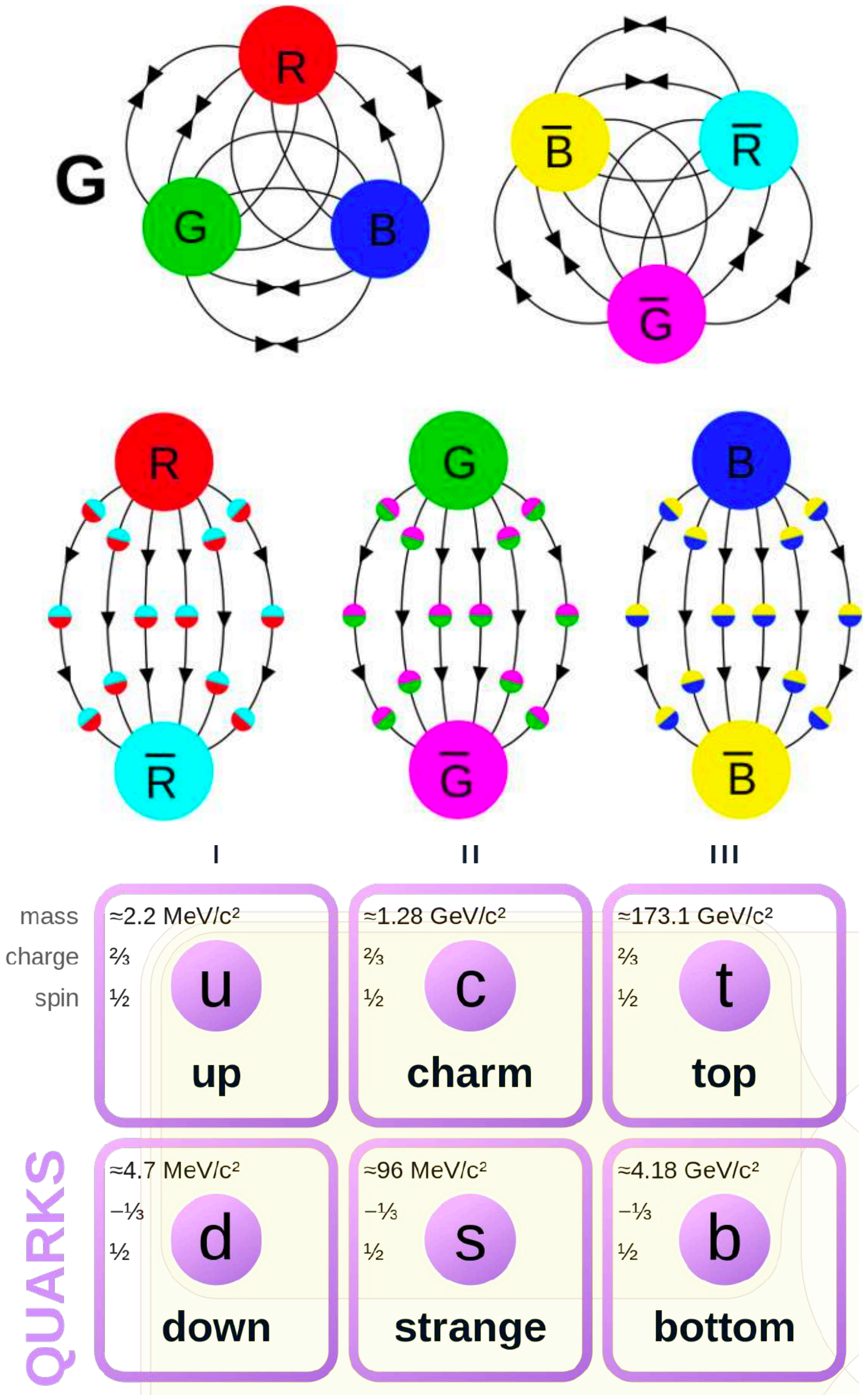


GENERALIZED QCD

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

Promote N_c and N_f to variables.

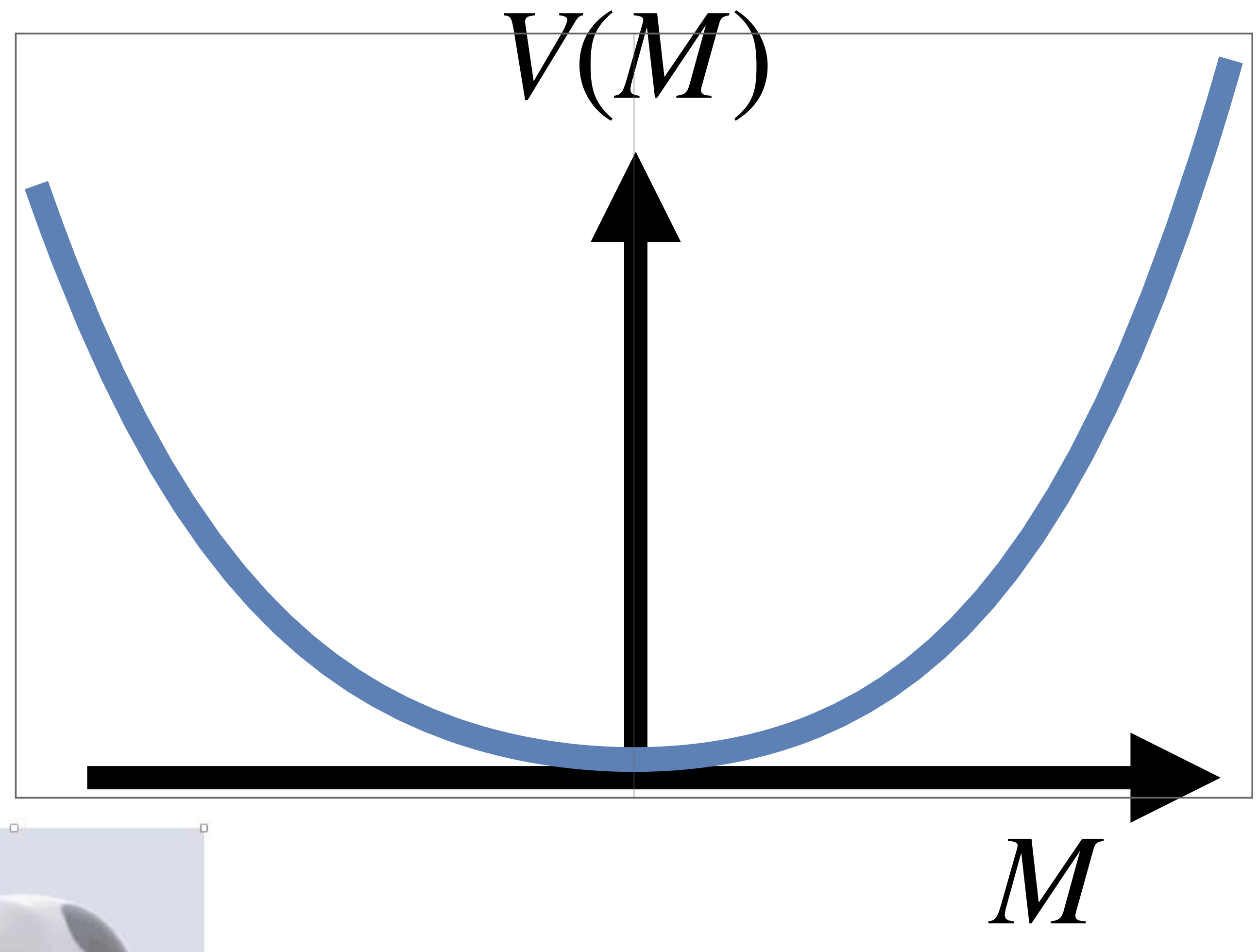
$N_f = N_c + 1$ has a particularly nice SUSY description.



$N_c = 2$ 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!

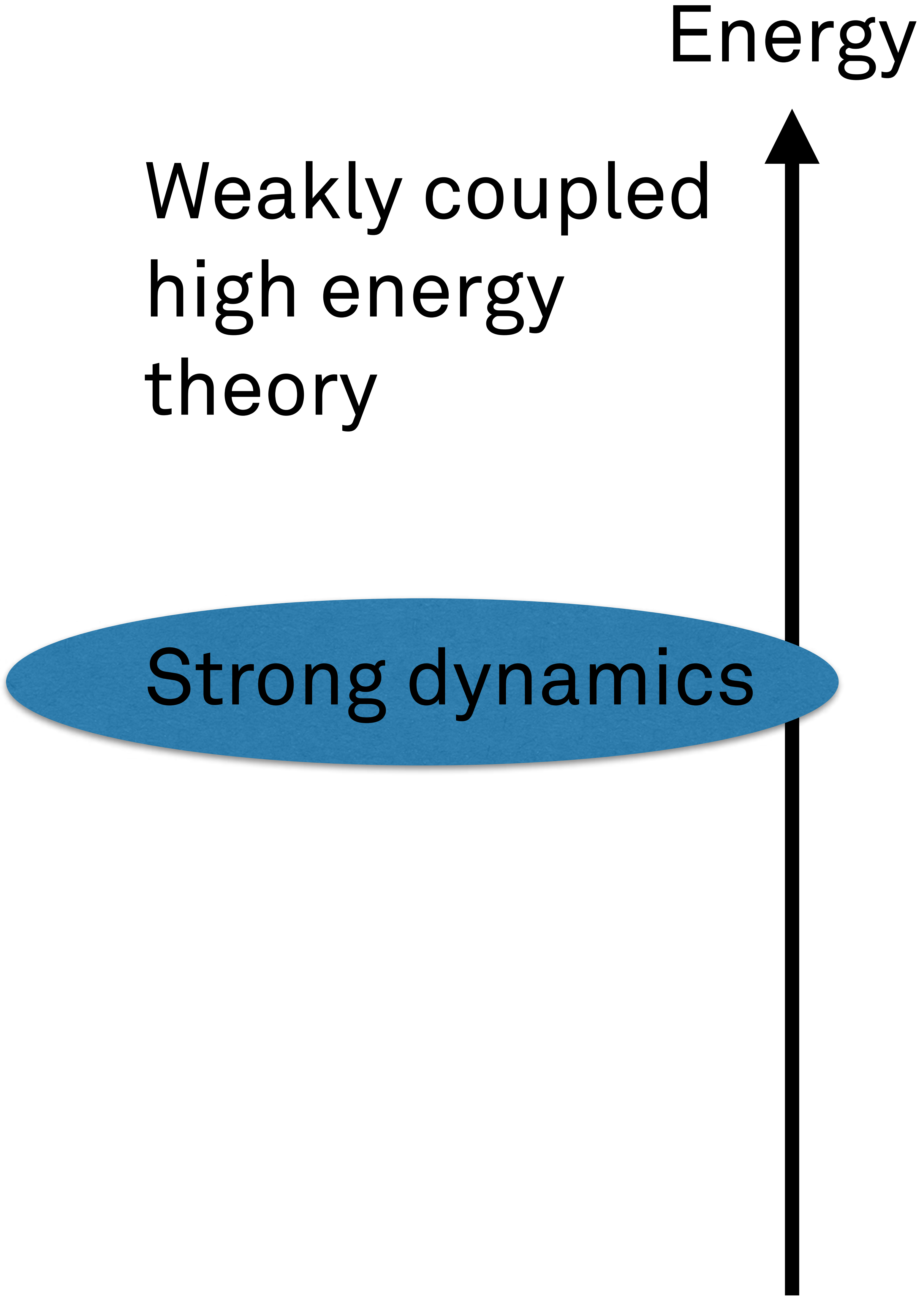
Non SUSY theory must have SSB.

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

’T HOOFT ANOMALY MATCHING

'T HOOFT ANOMALY MATCHING

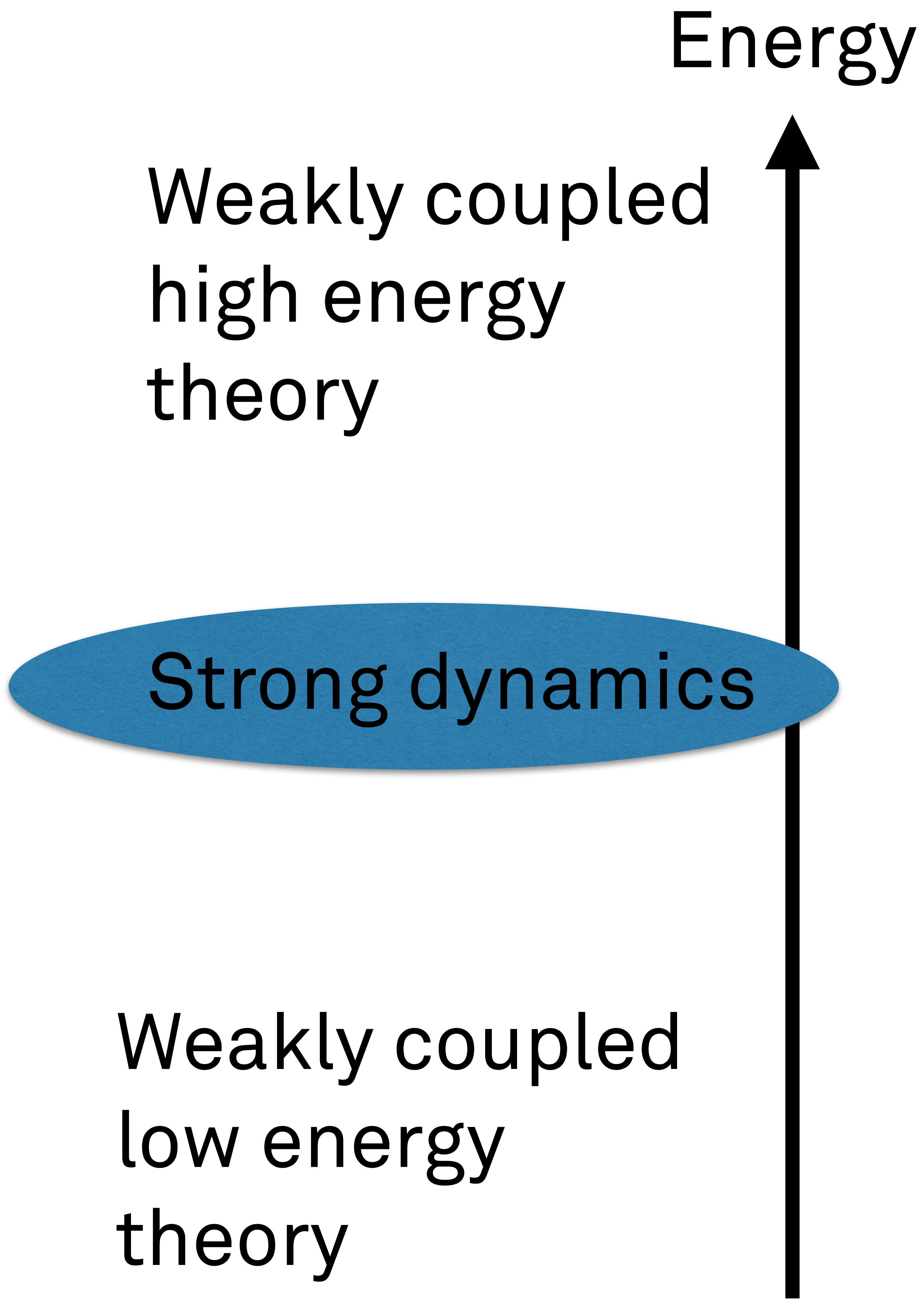
Most robust tool to analyze strong interactions is ’t Hooft anomaly matching. ’t Hooft ’80.



'T HOOFT ANOMALY MATCHING

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

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

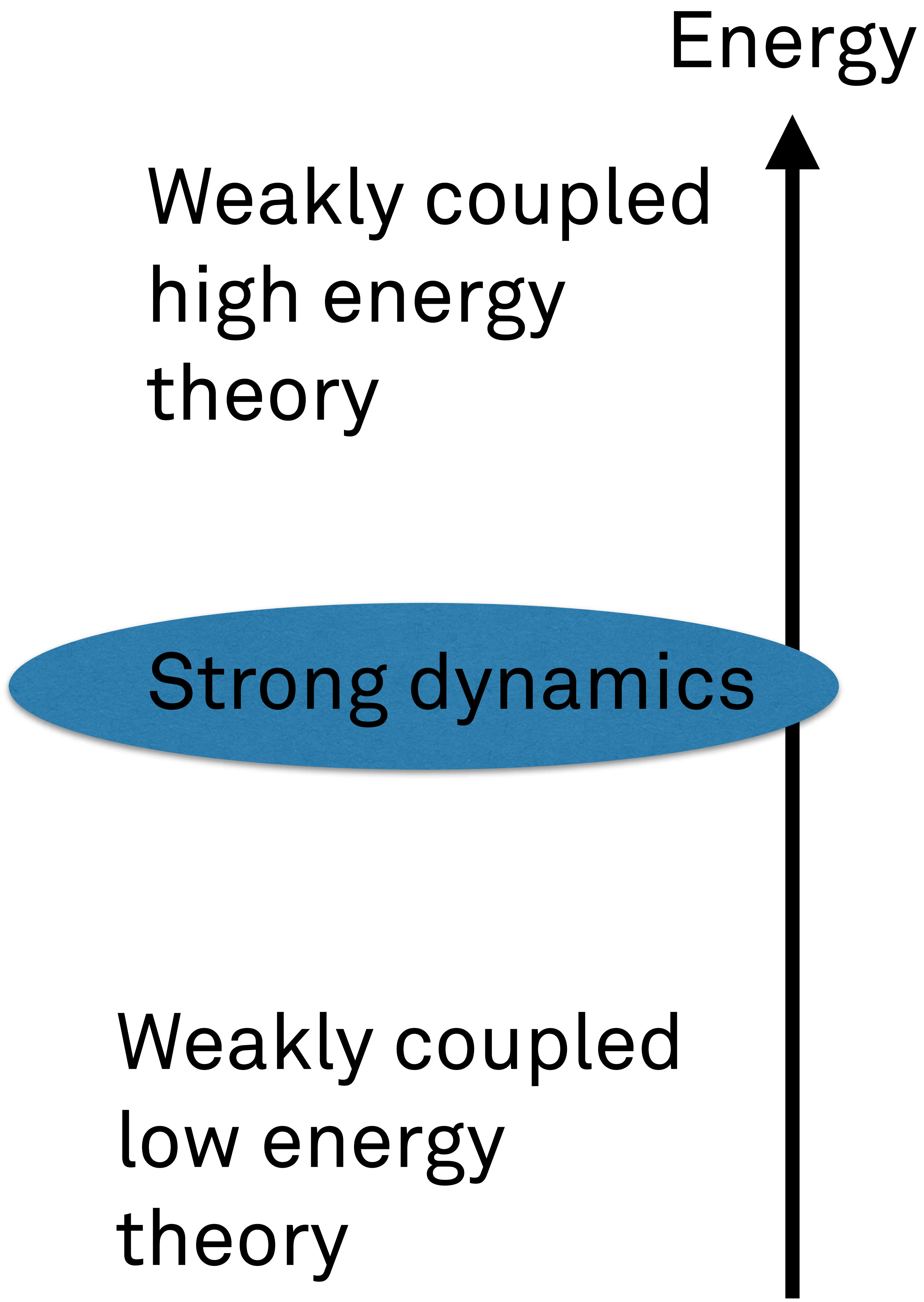


'T HOOFT ANOMALY MATCHING

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

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

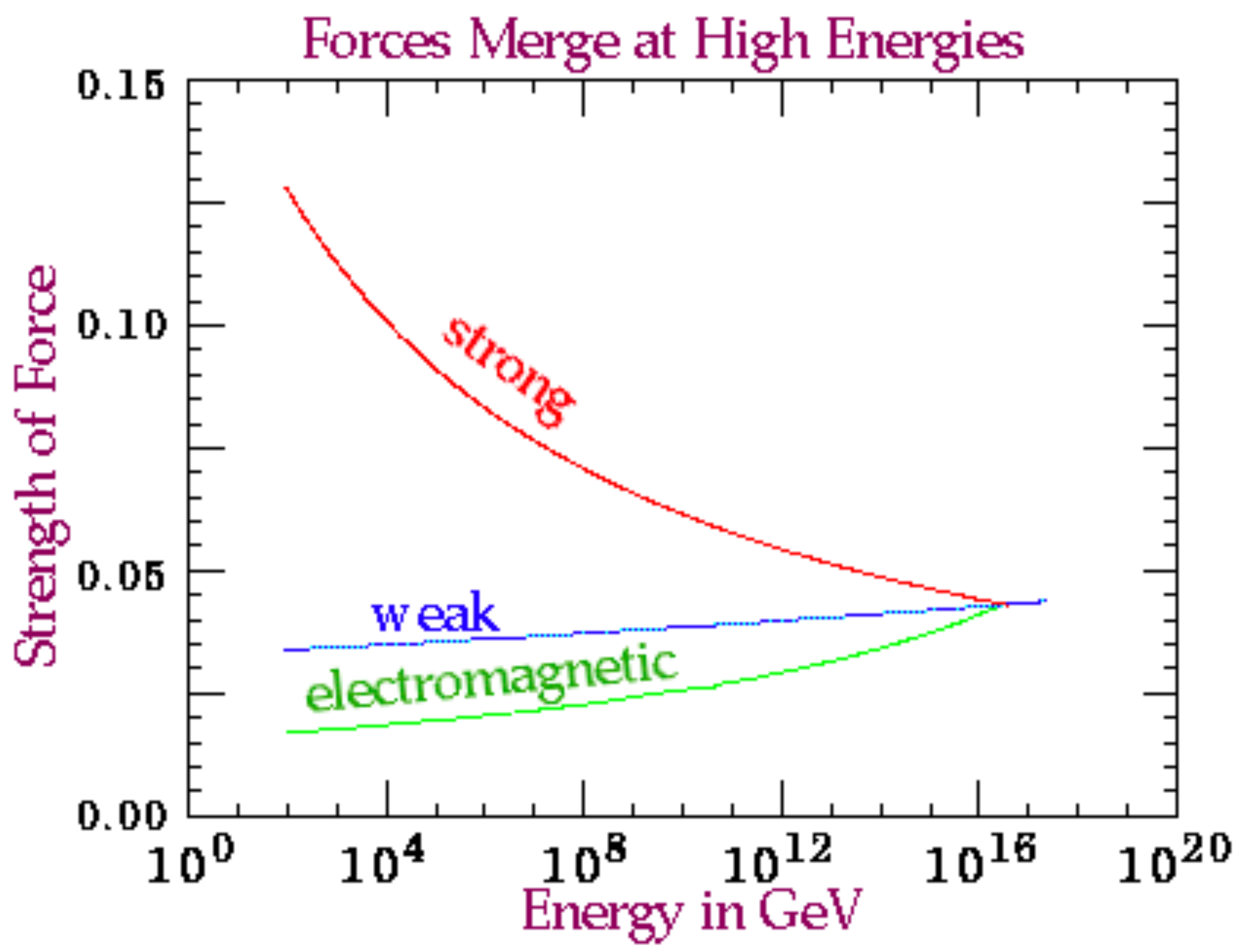
NB: 't Hooft anomaly matching $\neq$ anomaly mediated SUSY breaking



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.



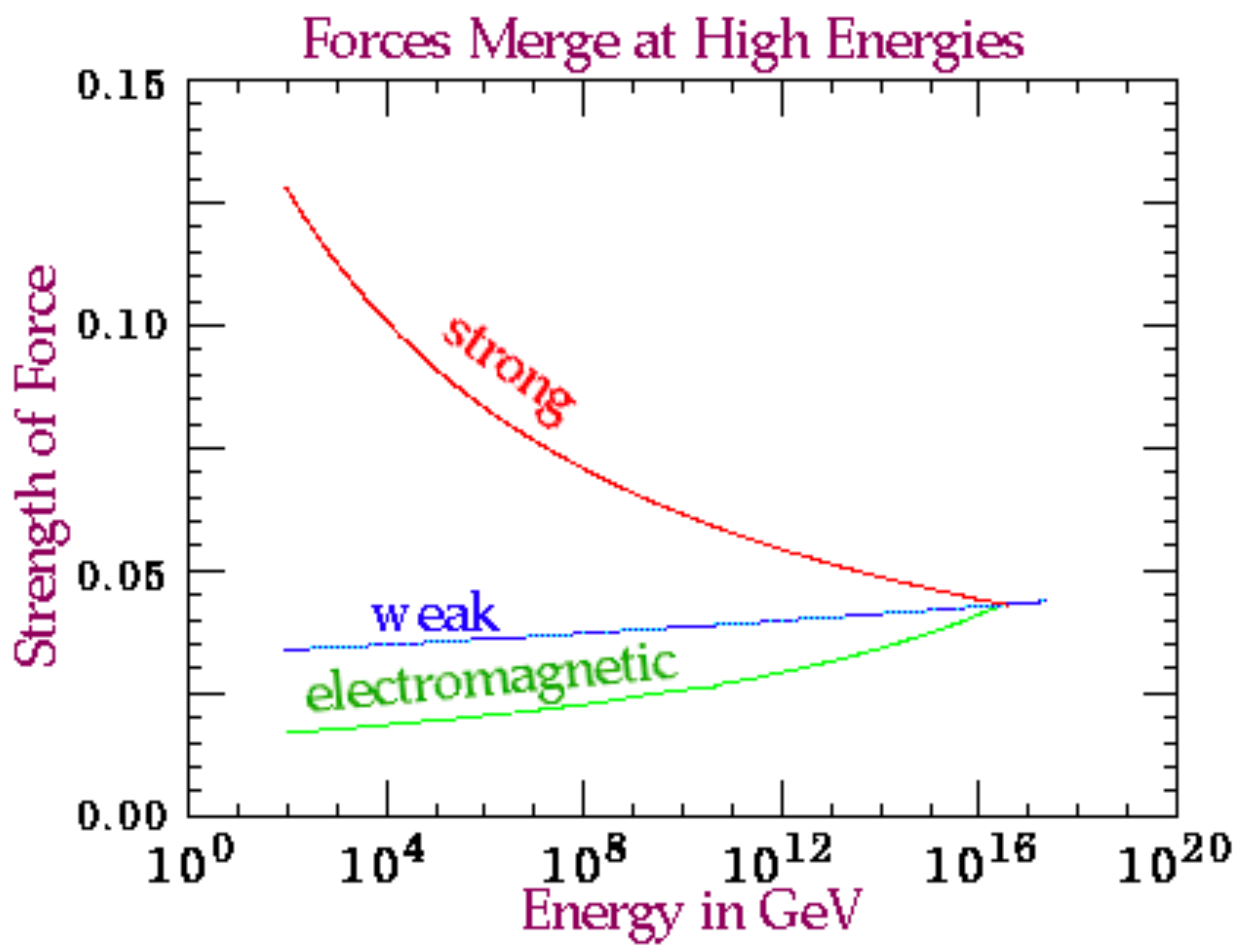
ANOTHER THEORY

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.

What if we do not break it to SM, and just let it evolve?

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



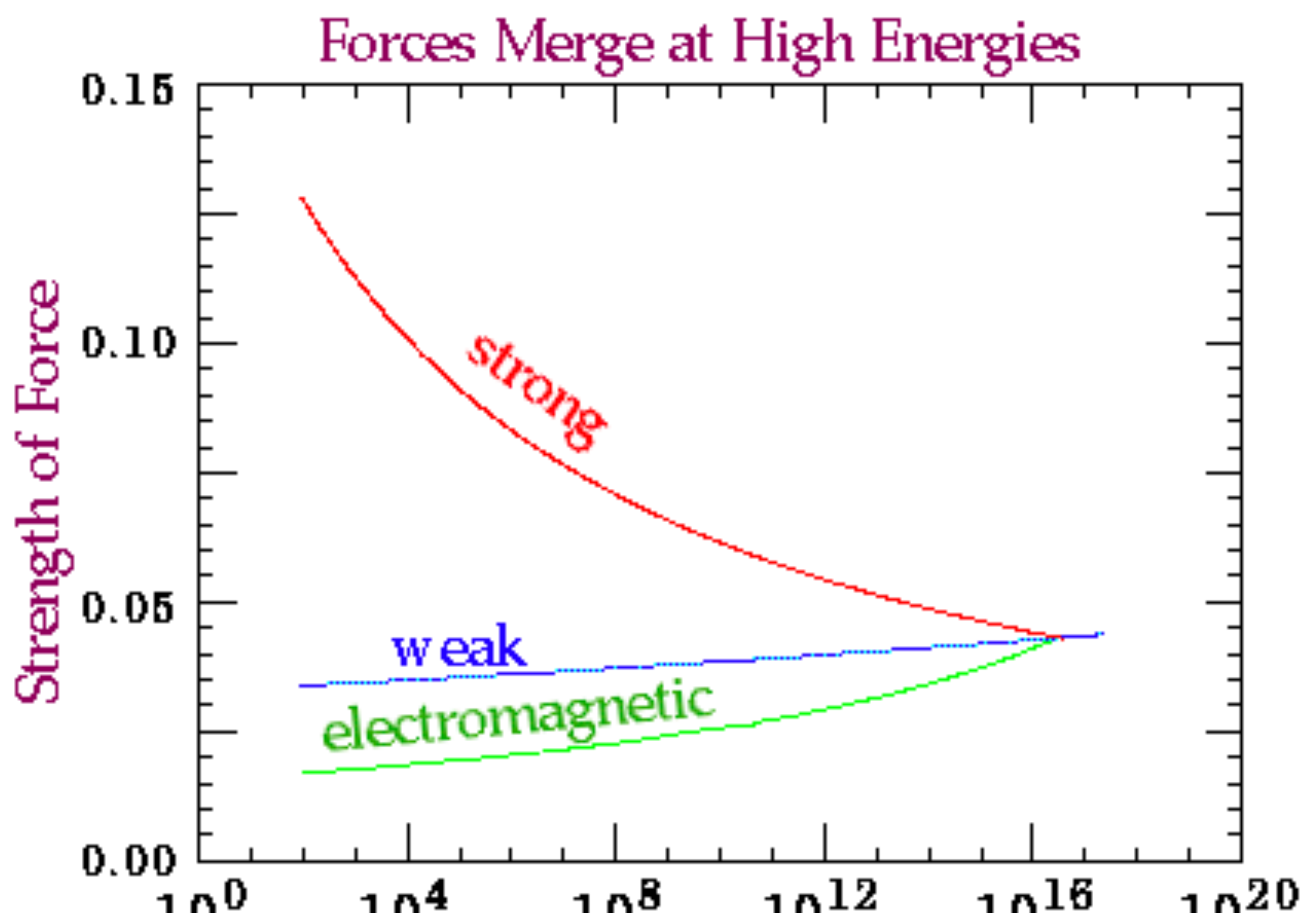
ANOTHER THEORY

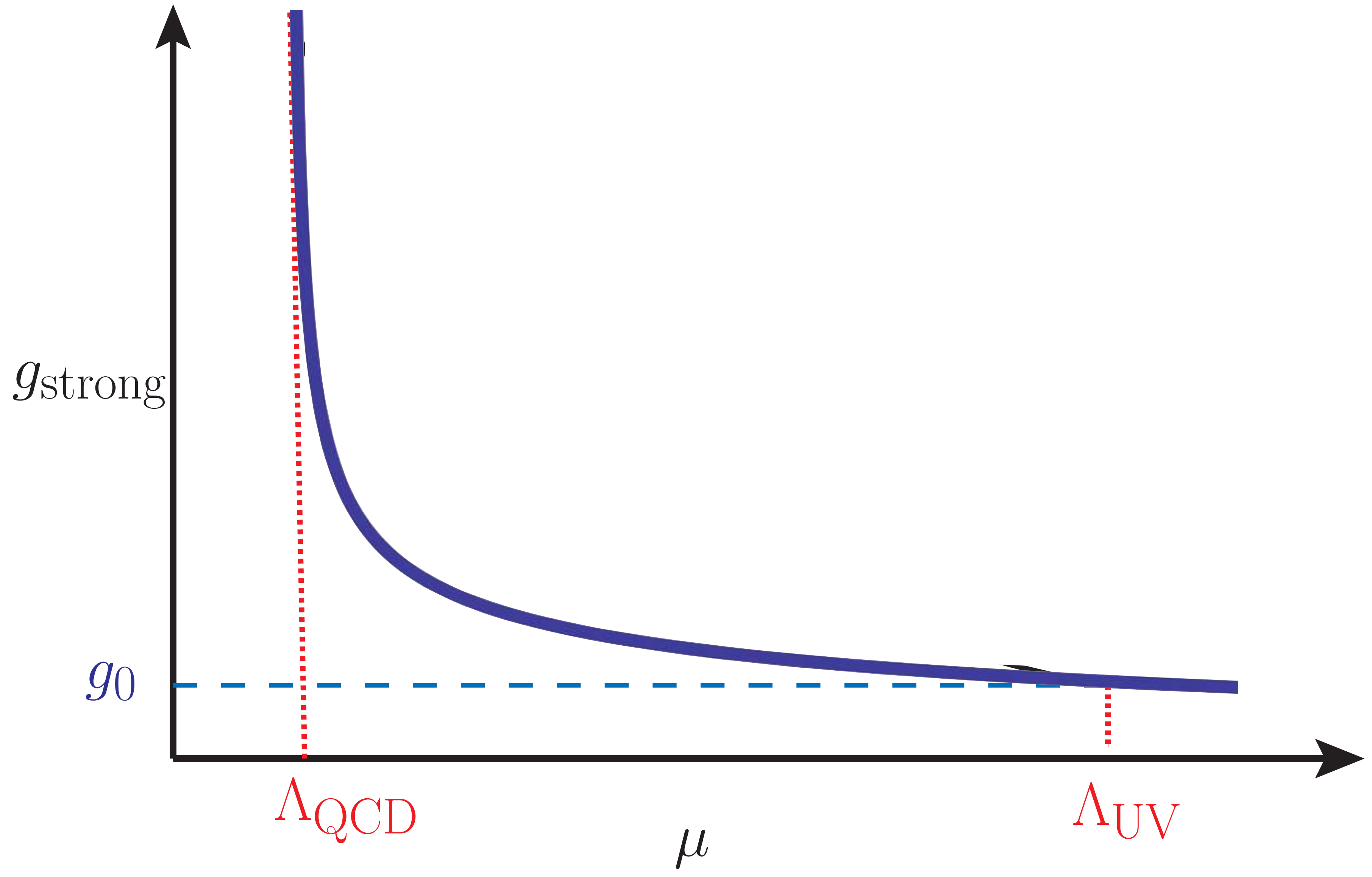
Simplest Grand Unified Theory of the SM is SU(5) GUT. Georgi, Glashow, PRL '74.

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

What if we do not break it to SM, and just let it evolve?

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





'T HOOFT ANOMALY MATCHING

Compute anomalies at high energy.

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

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

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

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

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

$$A\left[SU(3)_F^2 \times U(1)_B\right] = -15$$

'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.

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

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

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

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

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

$$A\left[SU(3)_F^2 \times U(1)_B\right] = -15$$

IR ANOMALY MATCHING

Solutions are quite complicated.

A relatively simple example:

quarks

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

Massless baryons

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

Bai, DS, arXiv:2111.11214.

IR ANOMALY MATCHING

Another example:

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

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

Bai, DS, arXiv:2111.11214.

IR ANOMALY MATCHING

Another example:

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

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

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

Bai, DS, arXiv:2111.11214.

IR ANOMALY MATCHING

Another example:

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

Color = anti-symmetric
Flavour = anti-symmetric
Spin = ?
Not enough states to satisfy Fermi statistics.

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

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

Bai, DS, arXiv:2111.11214.

IR ANOMALY MATCHING

Another example:

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

Color = anti-symmetric
Flavour = anti-symmetric
Spin = ?
Not enough states to satisfy Fermi statistics.

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

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

Can work with orbital angular momentum, but weird.

Bai, DS, arXiv:2111.11214.

WHAT HAPPENS?

If there are no solutions to anomaly matching conditions, theory **must** exhibit spontaneous symmetry breaking.

WHAT HAPPENS?

If there are no solutions to anomaly matching conditions, theory **must** exhibit spontaneous symmetry breaking.

This theory probably exhibits spontaneous symmetry breaking. Difficulty of ’t Hooft anomaly matching is one piece of evidence.

WHAT HAPPENS?

If there are no solutions to anomaly matching conditions, theory **must** exhibit spontaneous symmetry breaking.

This theory probably exhibits spontaneous symmetry breaking. Difficulty of ’t Hooft anomaly matching is one piece of evidence.

Breaking pattern:

$$SU(3)_L \times SU(3)_R \to SO(3)_V$$

WHAT HAPPENS?

If there are no solutions to anomaly matching conditions, theory **must** exhibit spontaneous symmetry breaking.

This theory probably exhibits spontaneous symmetry breaking.
Difficulty of 't Hooft anomaly matching is one piece of evidence.

Breaking pattern:

$$SU(3)_L \times SU(3)_R \to SO(3)_V$$

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

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:

$$V_{\text{susy}} + V_{\not{\text{susy}}} = \left|\frac{dW_\lambda}{dM^{ai}} + \frac{dW_\zeta}{dM^{ai}} + \frac{1}{3}A_1^* M^{ai*}\right|^2 + \left|\frac{dW_\zeta}{dB_2^{\beta\delta}} + (A_2^* - \frac{1}{3}A_1^*)B_2^{\beta\delta*}\right|^2 + \left|\frac{dW_\zeta}{dB_1^{\gamma i}}\right|^2$$

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

Bai, DS, arXiv:2111.11214.

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:

$$V_{\text{susy}} + V_{\text{su\not{s}y}} = \left| \frac{dW_\lambda}{dM^{ai}} + \frac{dW_\zeta}{dM^{ai}} + \frac{1}{3} A_1^* M^{ai*} \right|^2 + \left| \frac{dW_\zeta}{dB_2^{\beta\delta}} + (A_2^* - \frac{1}{3} A_1^*) B_2^{\beta\delta *} \right|^2 + \left| \frac{dW_\zeta}{dB_1^{\gamma i}} \right|^2$$
$$+ m_1^2 \sum_{\gamma i} |B^\gamma_{1\,i}|^2 + \left(m_2^2 - \left| A_2 - \frac{1}{3} A_1 \right|^2 \right) \sum_{\beta\delta} |B_2^{\beta\delta}|^2 + \left(m_3^2 - \left| \frac{1}{3} A_1 \right|^2 \right) \sum_{ai} |M^{ai}|^2$$

Sufficient condition for no symmetry breaking:

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

Bai, DS, arXiv:2111.11214.

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:

$$V_{\text{susy}} + V_{\text{su}\not{s}\text{y}} = \left|\frac{dW_\lambda}{dM^{ai}} + \frac{dW_\zeta}{dM^{ai}} + \frac{1}{3}A_1^* M^{ai*}\right|^2 + \left|\frac{dW_\zeta}{dB_2^{\beta\delta}} + (A_2^* - \frac{1}{3}A_1^*)B_2^{\beta\delta *}\right|^2 + \left|\frac{dW_\zeta}{dB_1^{\gamma i}}\right|^2$$

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

Sufficient condition for no symmetry breaking:

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

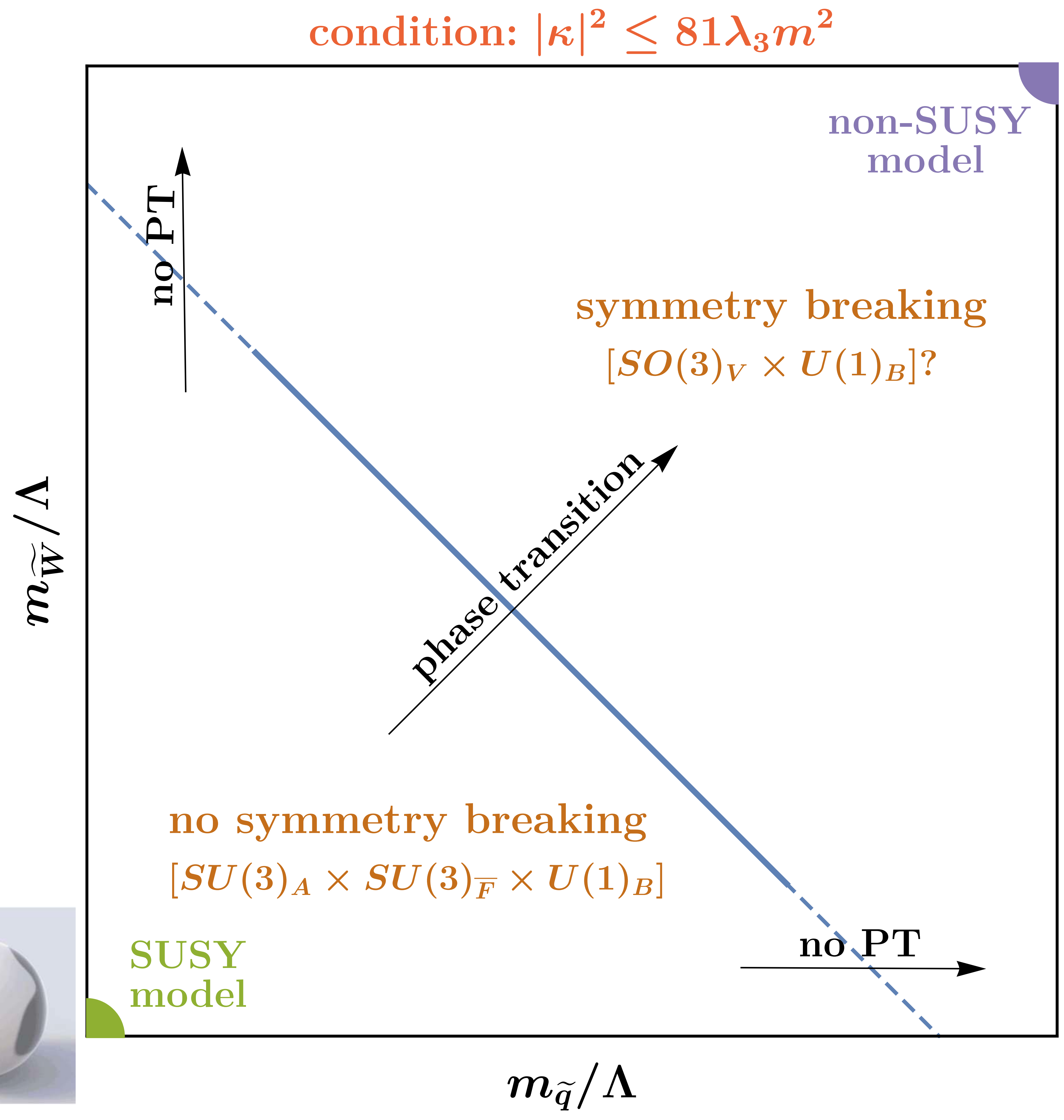
Bai, DS, arXiv:2111.11214.

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.



Bai, DS, arXiv:2111.11214.

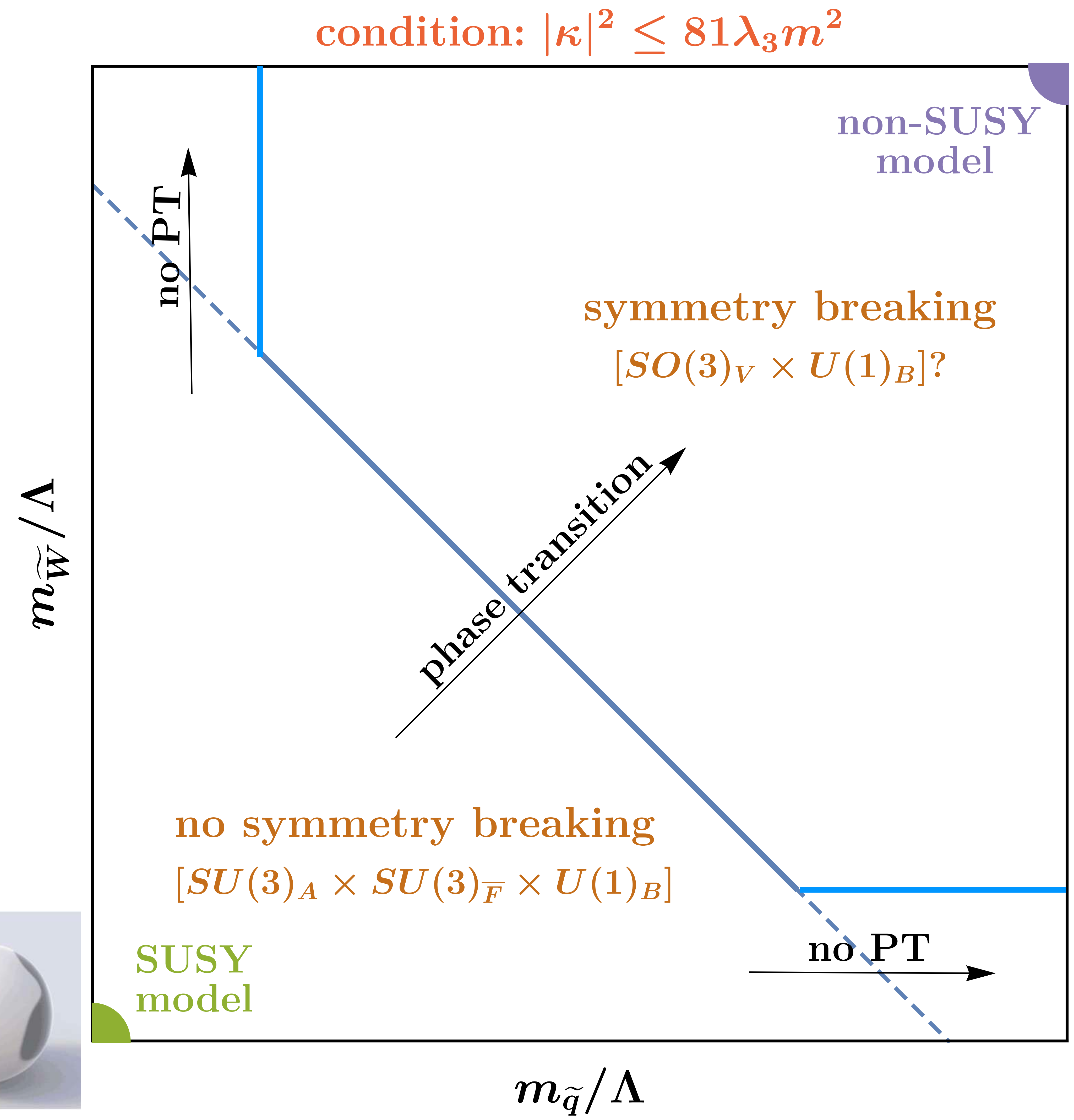
PHASE DIAGRAM

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.

Bai, DS, arXiv:2111.11214.



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?

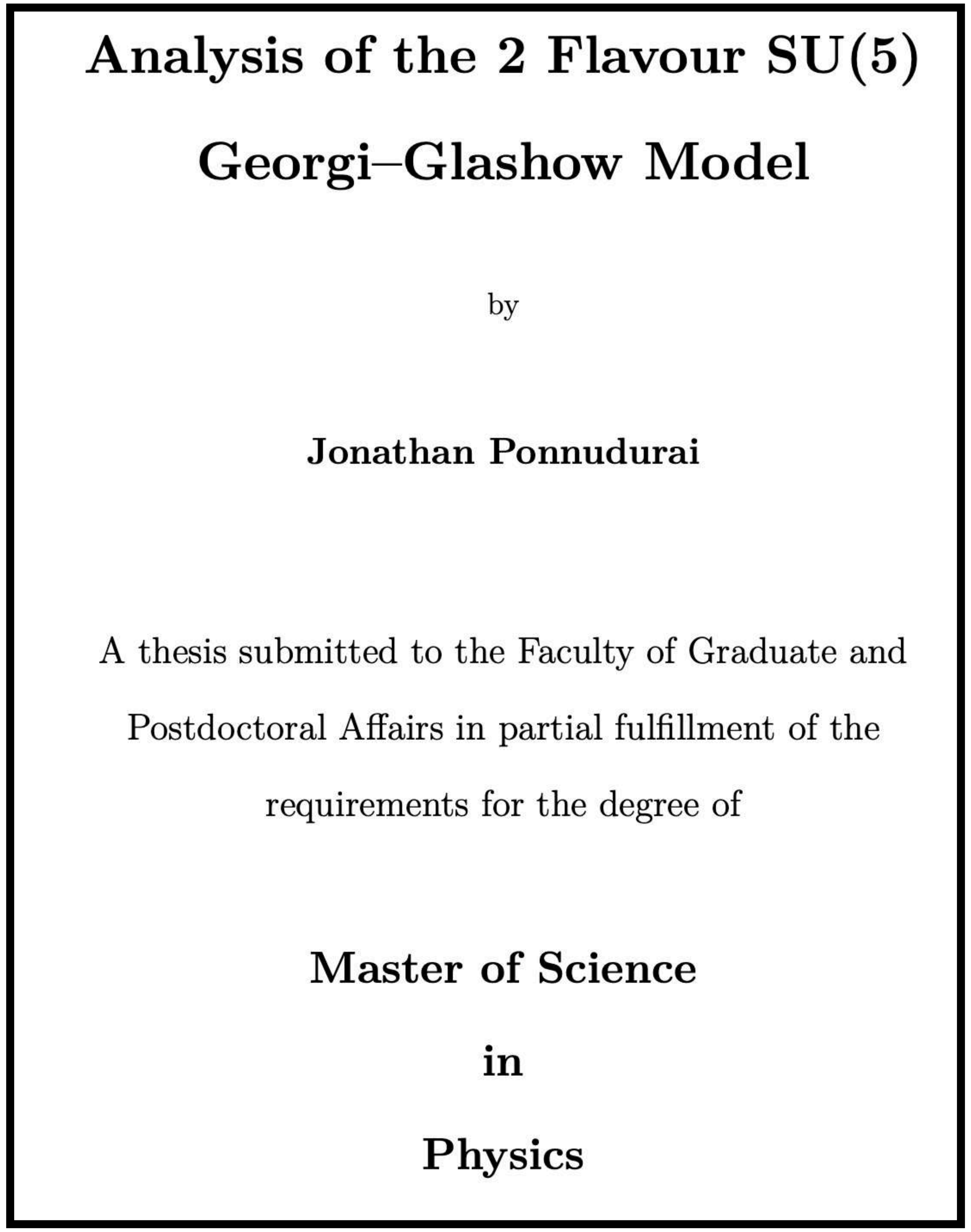
DIFFERENT NUMBER OF FLAVOURS?

Analyzed SU(5) model with 3 flavours.

1 flavour dynamics are well known.

Dimopoulos, Raby, Susskind, NPB '80.

What about 2 flavours?



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

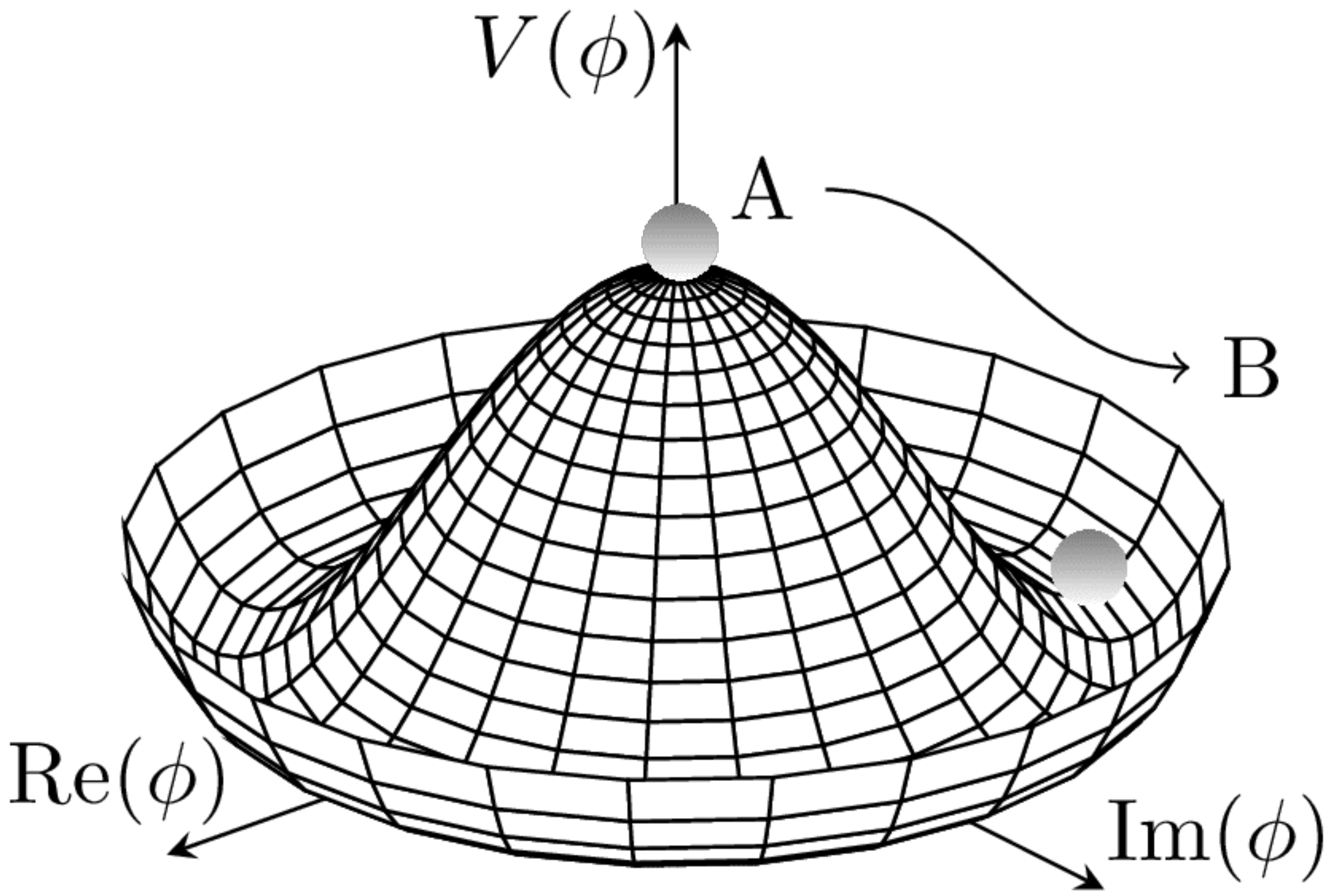
Physics

2 FLAVOUR RESULTS

Non-SUSY model:
anomaly matching solutions

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

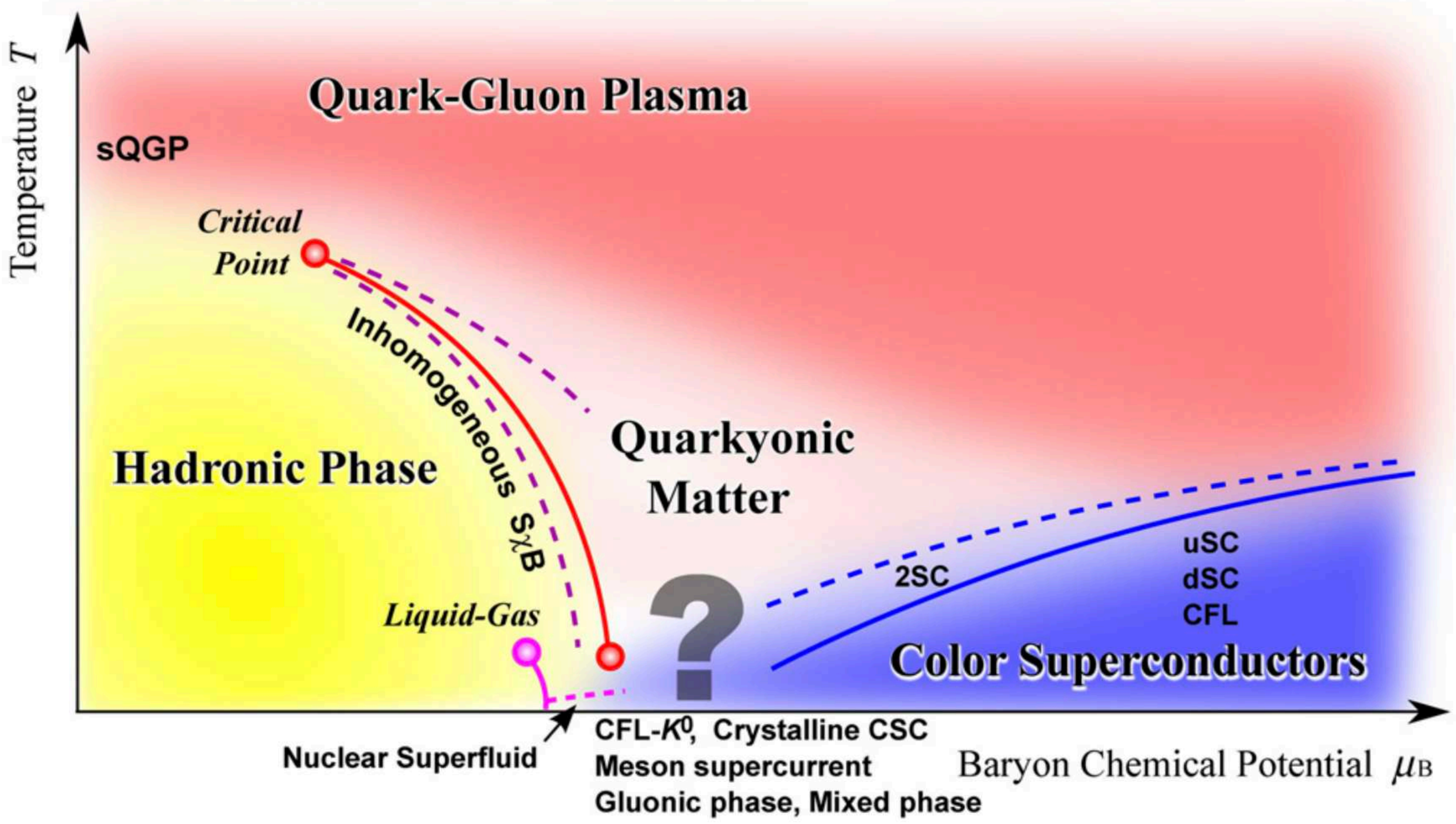
SUSY model: proof of spontaneous symmetry breaking.



J. Ponnudurai MSc thesis.

PHASE DIAGRAM

What is the phase diagram of QCD?



Conjectured QCD phase diagram with boundaries that define various states of QCD matter based on SχB patterns.

Longstanding difficult problem with only partial results.

Focus on $T = 0$ for now.

Fukushima and Hatsuda, '11.

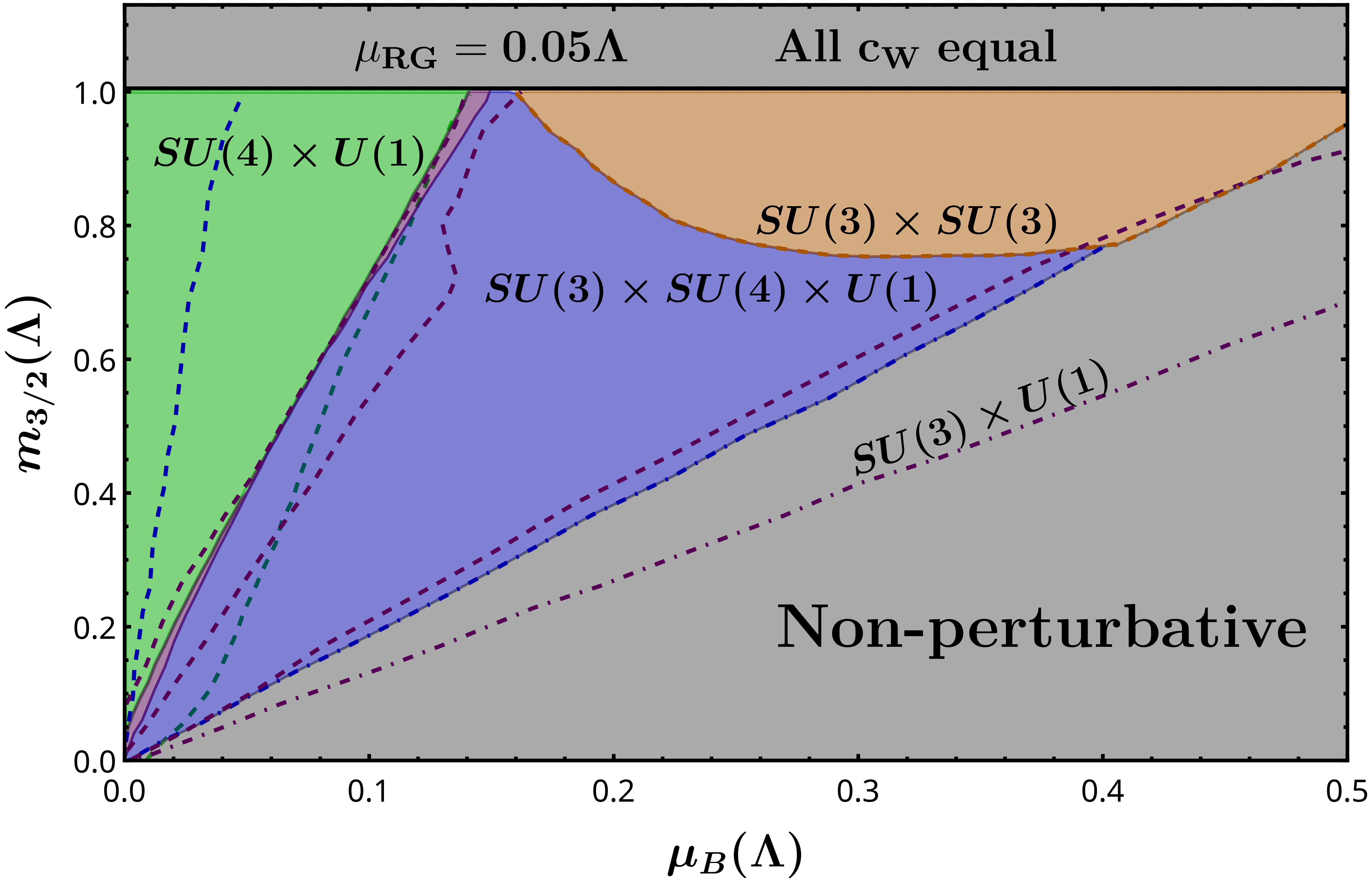
PHASE DIAGRAM

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!

Preliminary



Work in progress with Bai and de Lima.

HOLOGRAPHY?

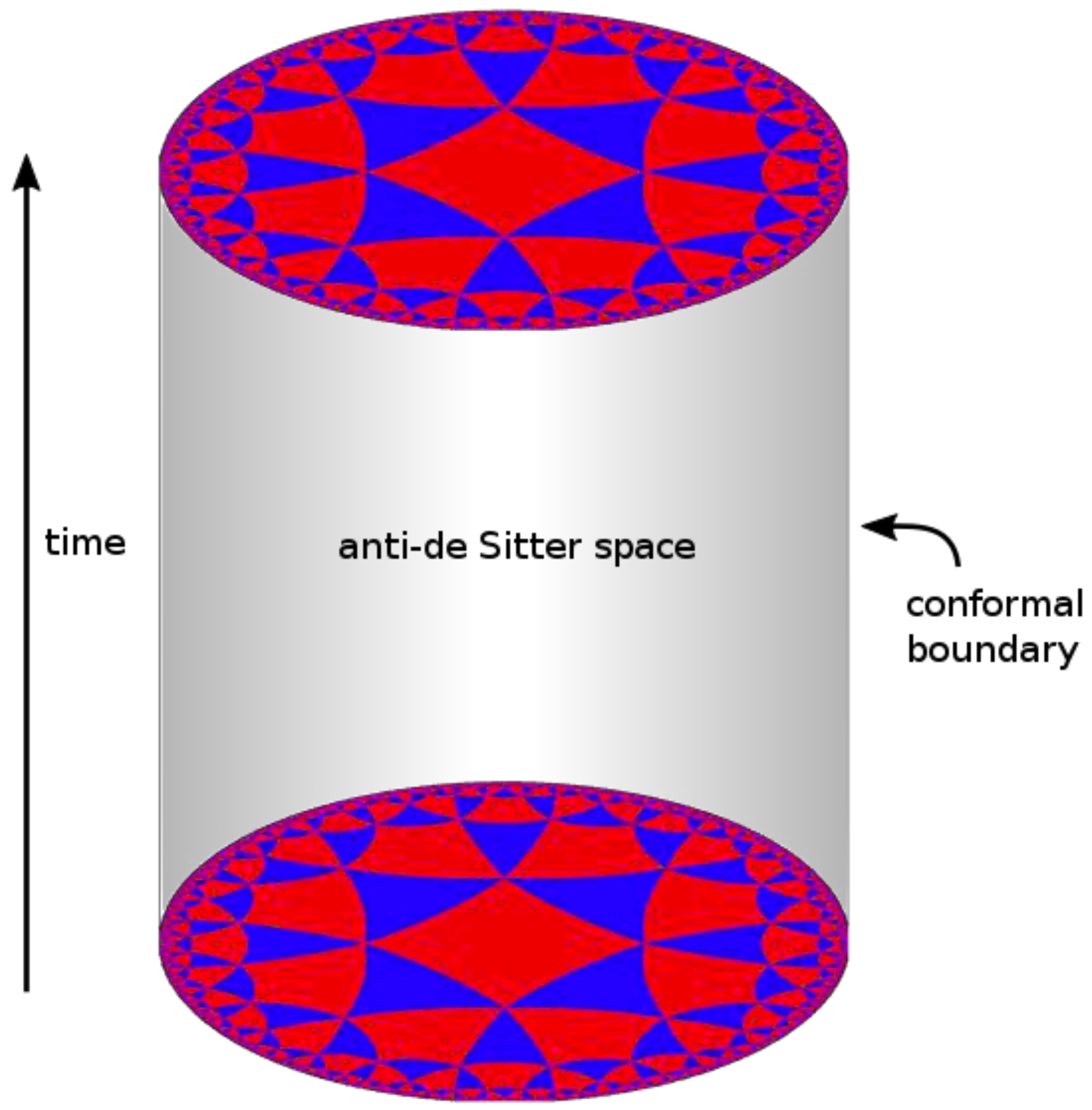
AdS/CFT correspondence says certain 4 dimensional theories are dual to 5 dimensional theories.

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