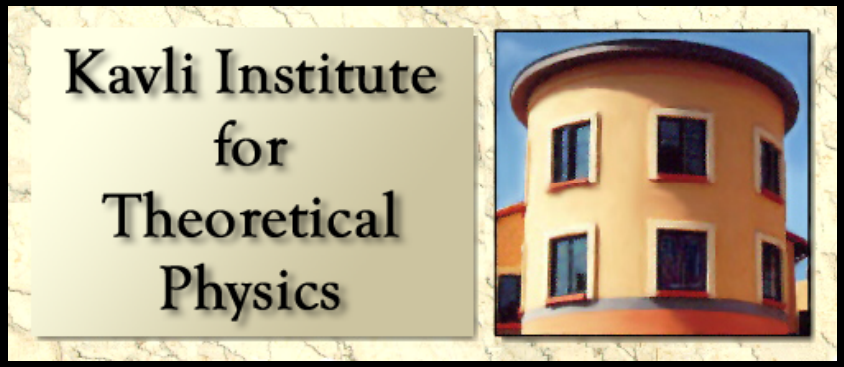
FRONTIERS OF Fundamental Physics

DAVID GROSS



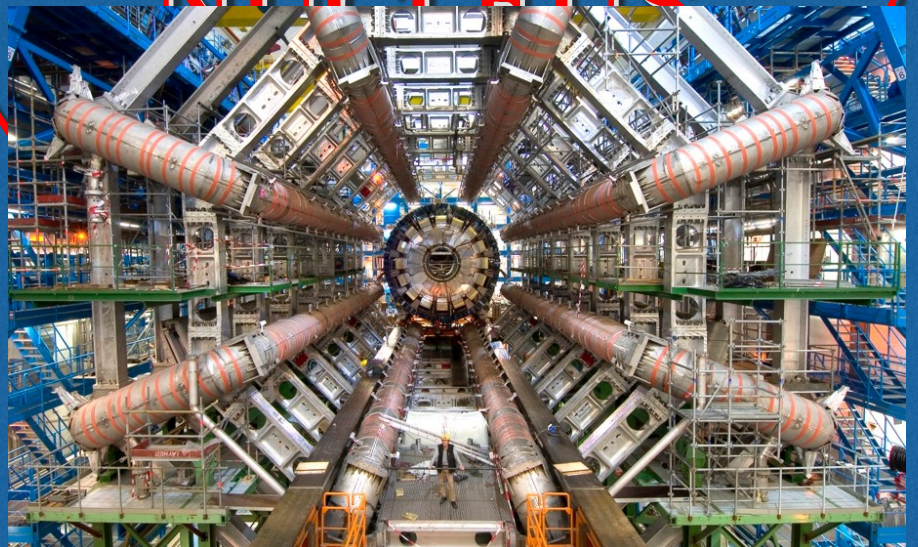
COLOQUIOS PACO YNDURAIN

APRIL 13, 2016

Elementary Particle Physics

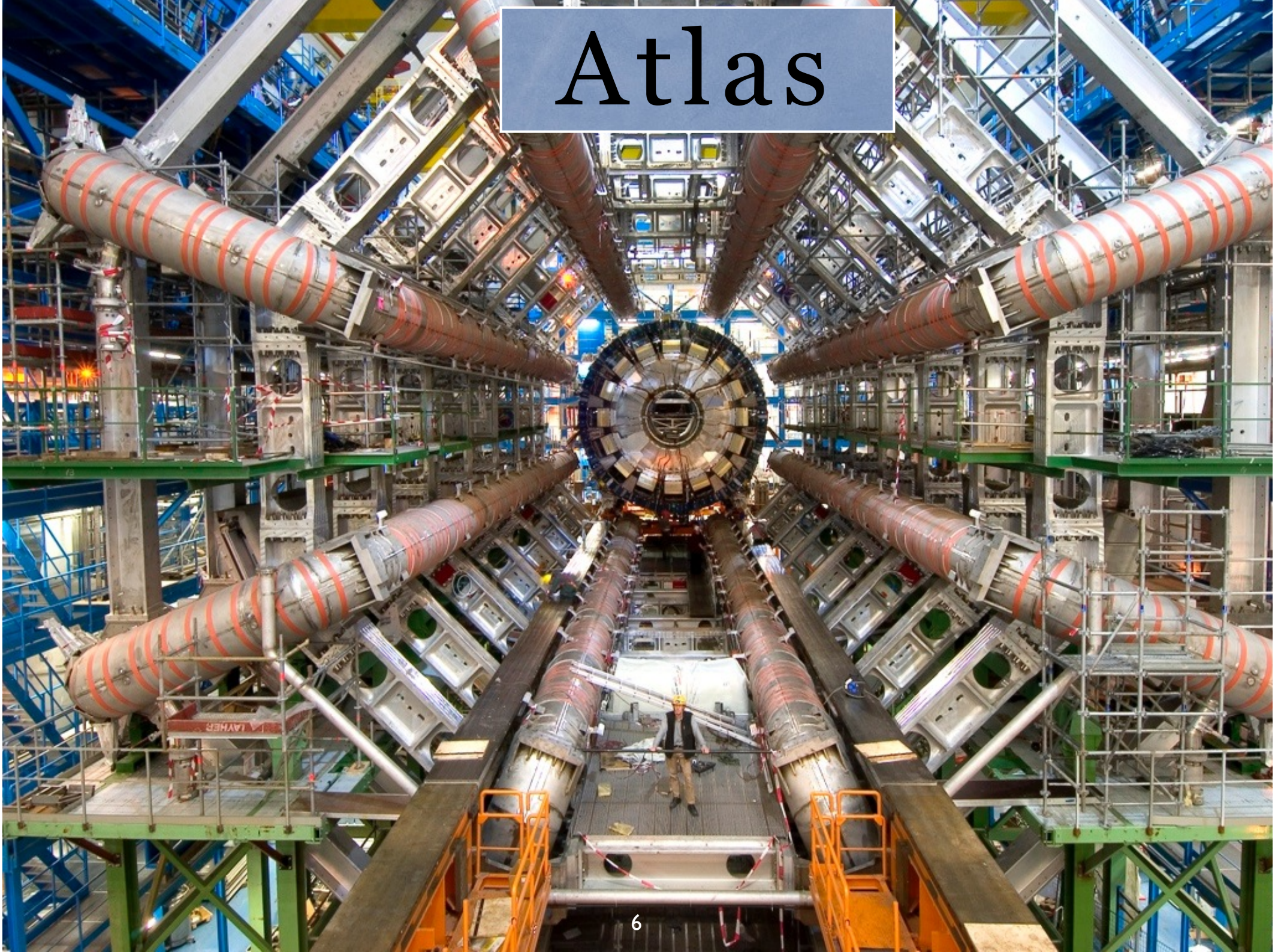
The discovery and understanding of the basic building blocks of all matter and the forces that act on them.

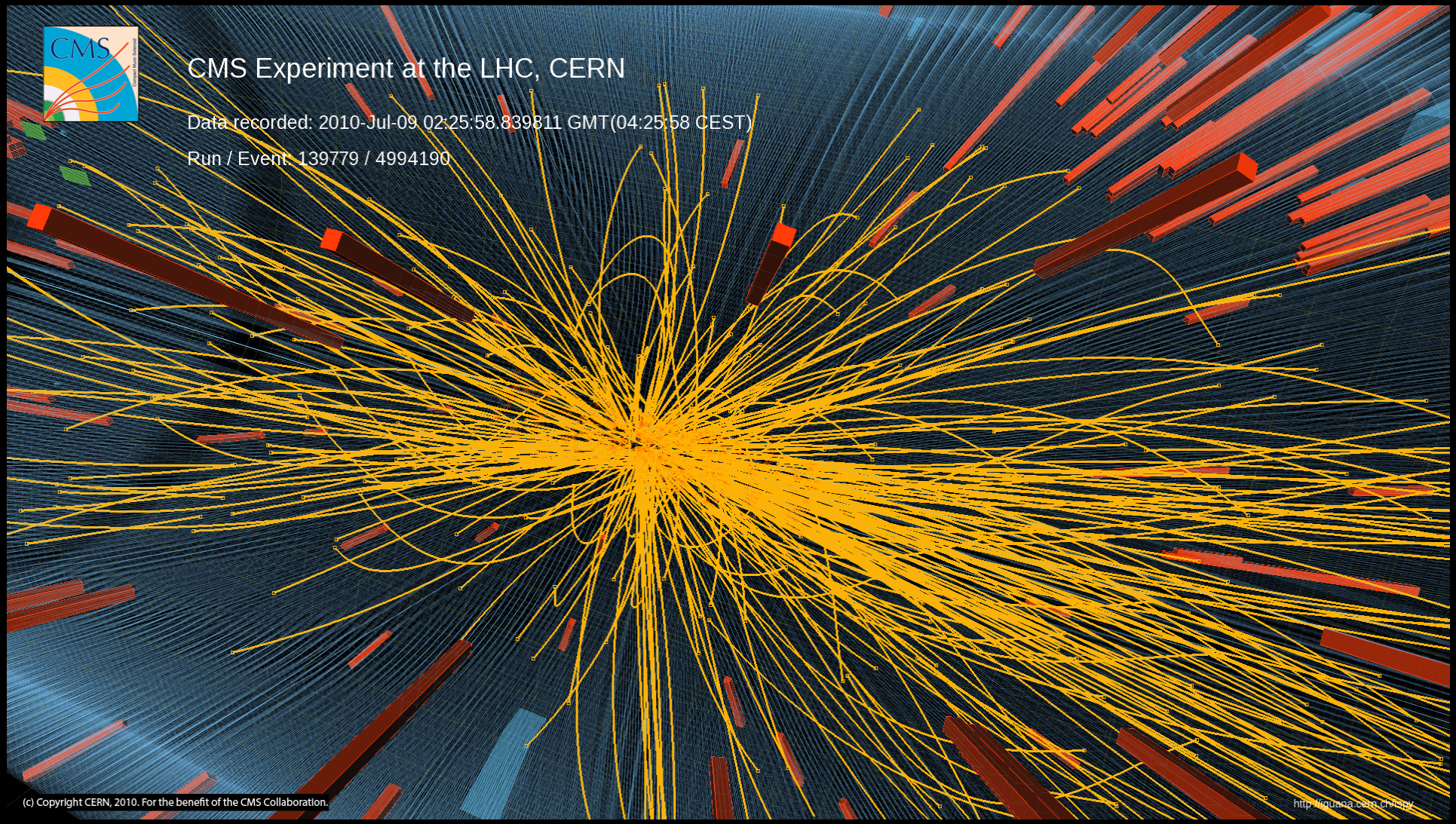
Rutherford's Discovery of the Nucleus 1911



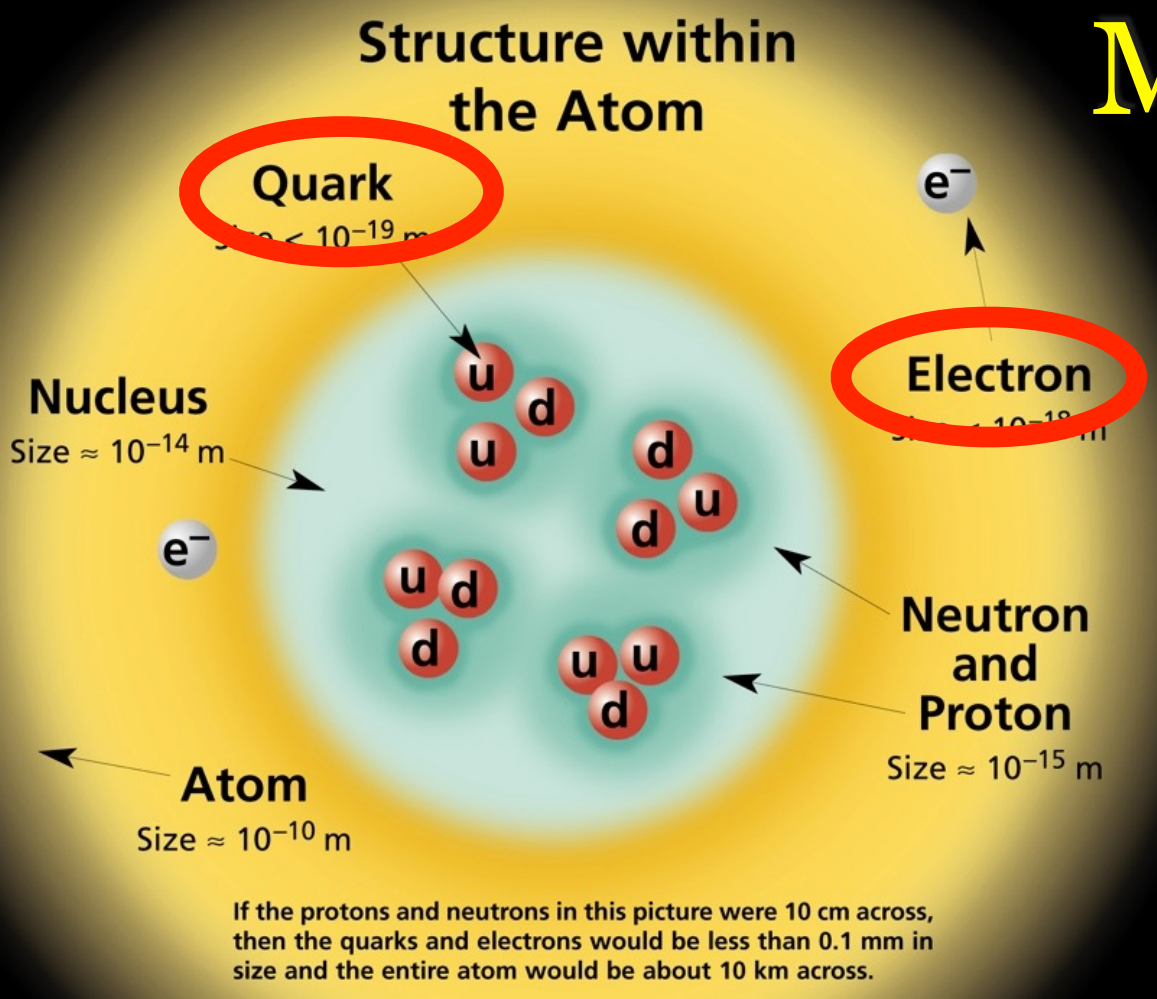

Large Hadron Collider
SWITZERLAND
FRANCE

Atlas




CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
(c) Copyright CERN, 2010. For the benefit of the CMS Collaboration.
http://iguana.cern.ch/ispy

THE STRUCTURE OF MATTER



ELECTRO-MAGNETISM

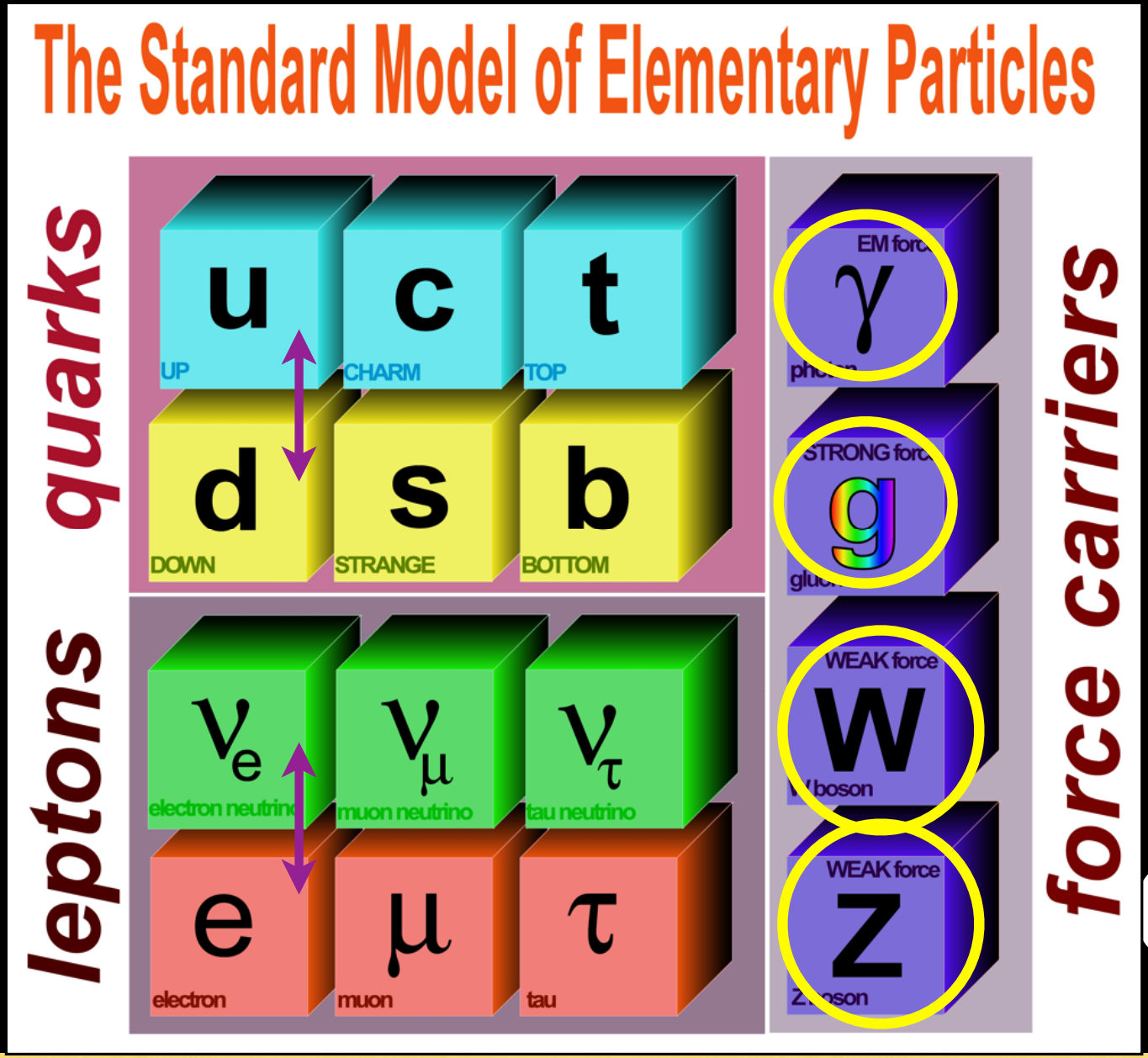
STRONG NUCLEAR FORCE

WEAK NUCLEAR FORCE

THE STANDARD THEORY

$$\mathcal{L} =$$
$$-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i$$
$$+(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + c.c.)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

UNBELIEVABLY SUCCESSFUL



E & M

STRONG

WEAK

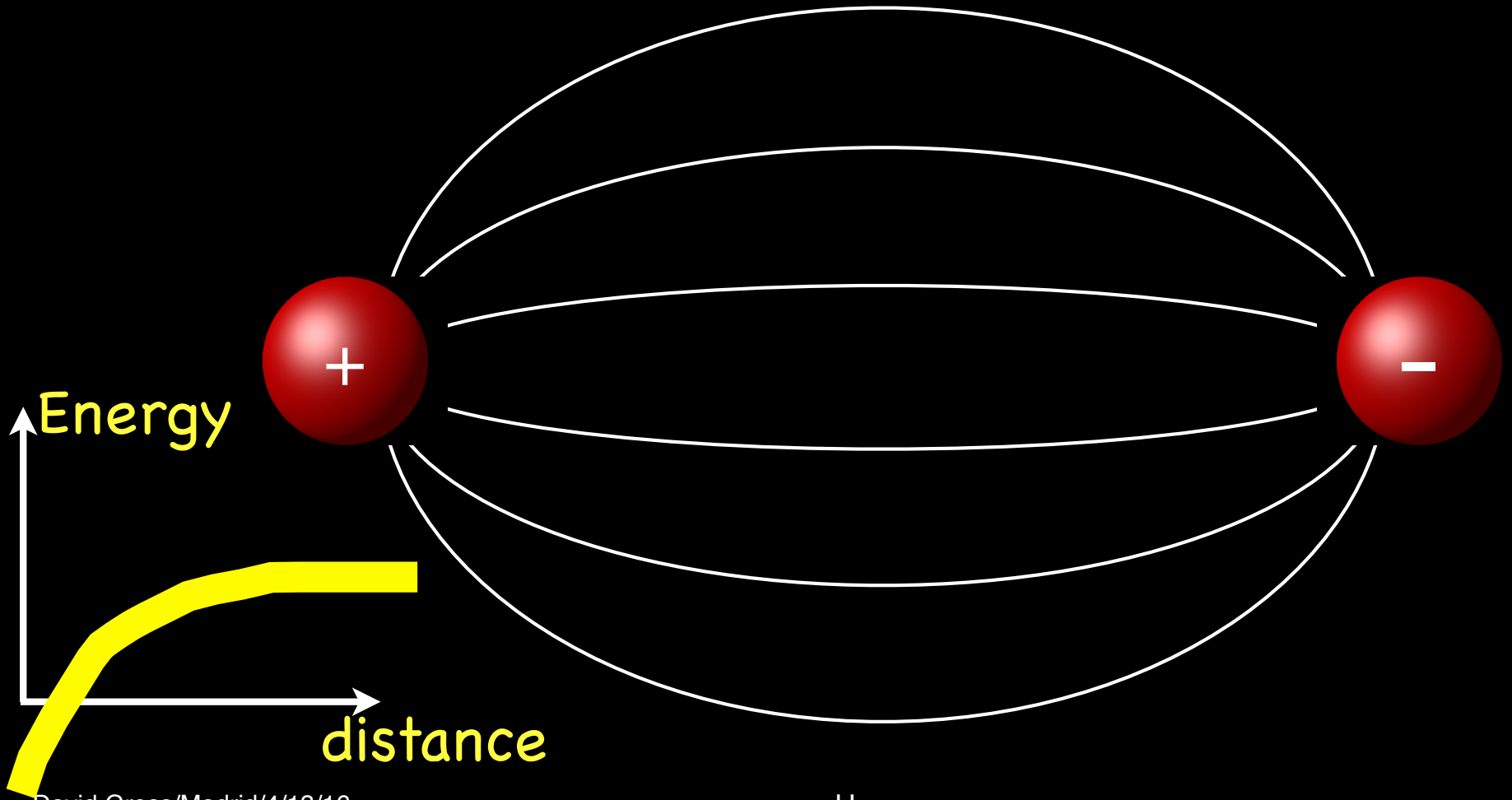
HIGGS

IT WORKS FROM THE PLANCK LENGTH TO THE EDGE OF THE UNIVERSE

60 ORDERS OF MAGNITUDE

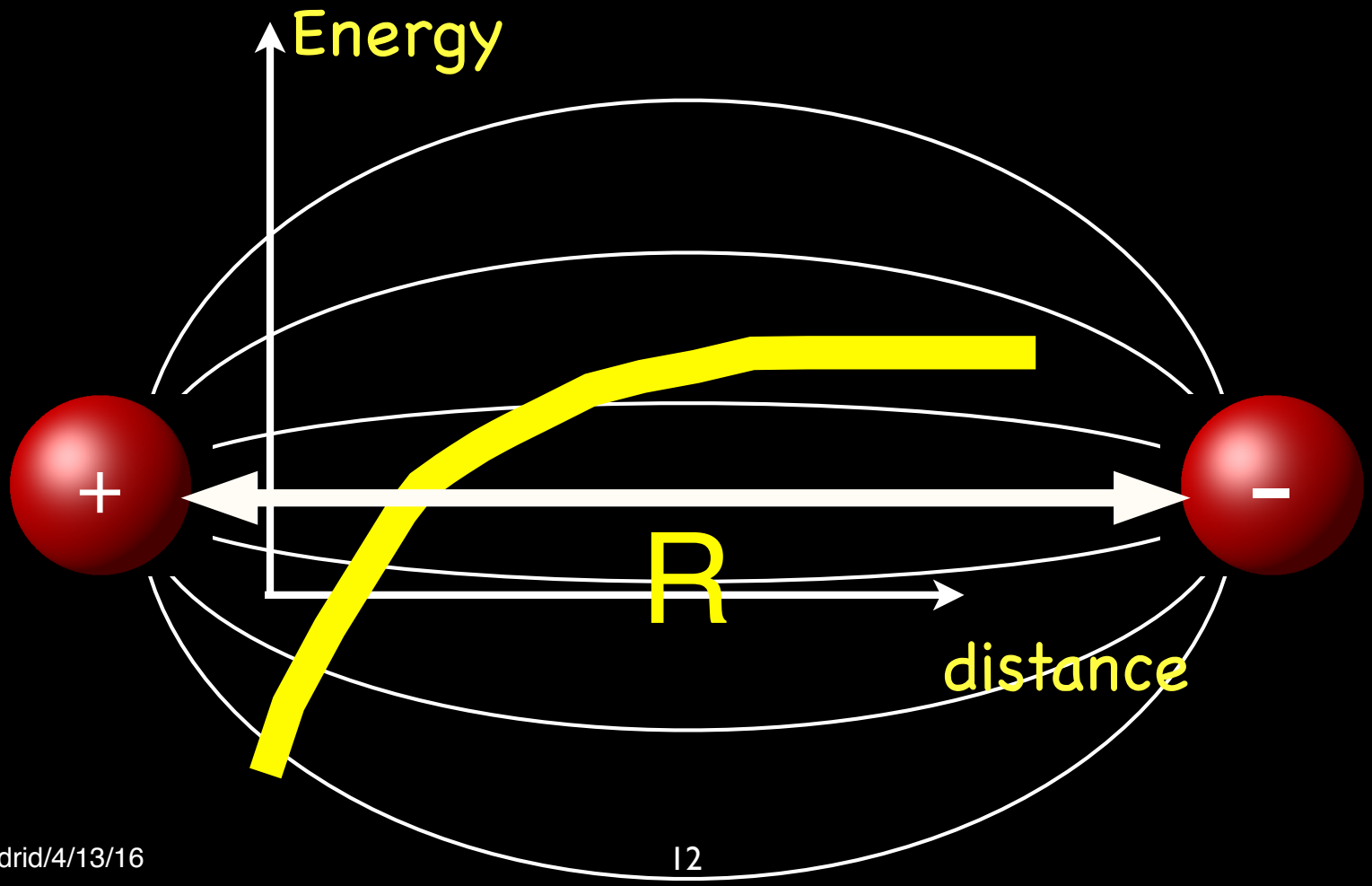
ELECTROMAGNETISM FORCE MEDIATED BY THE ELECTROMAGNETIC FIELD

ONE CHARGE

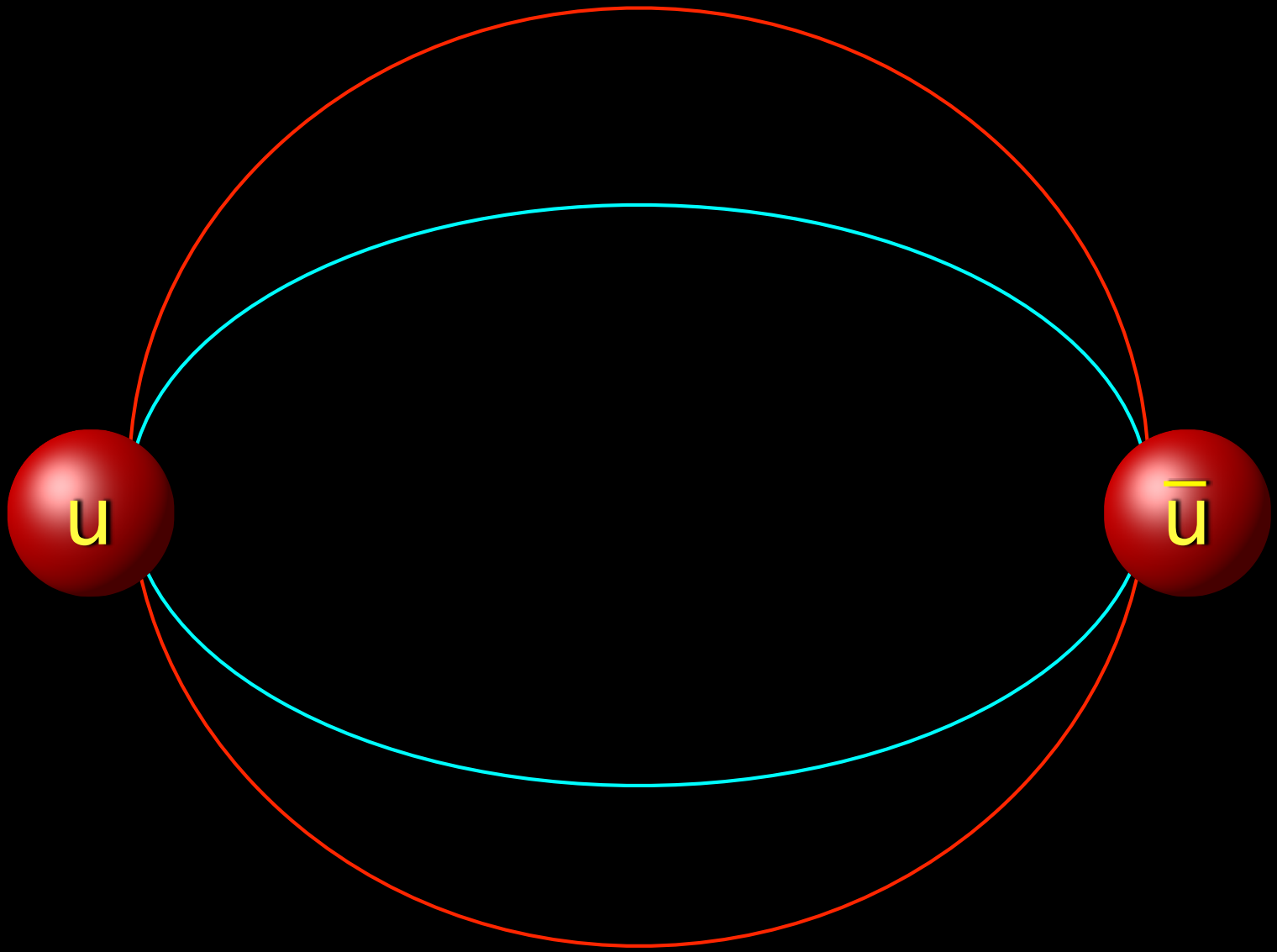


$$\mathbf{E}R^2 = Q$$

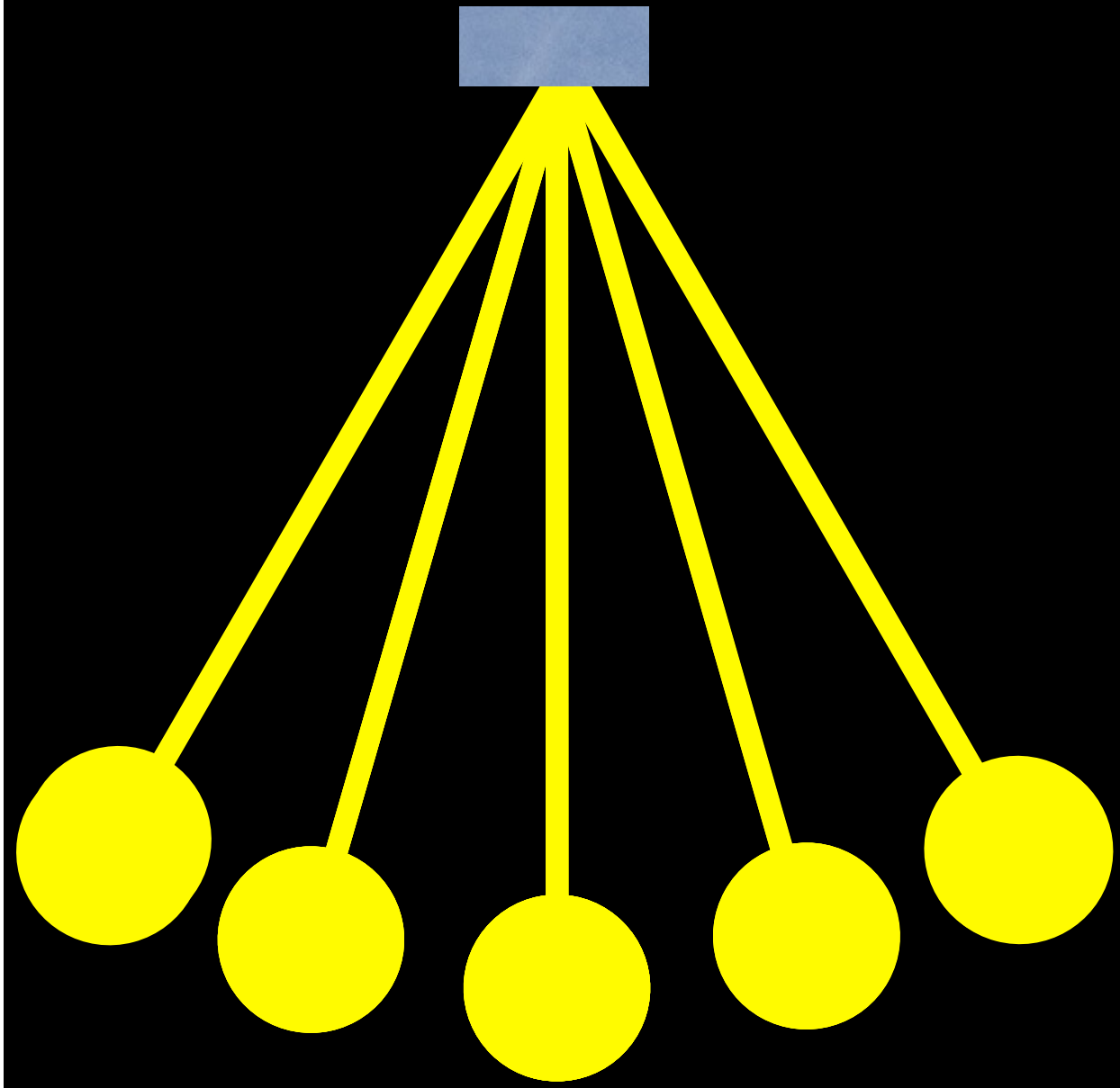
$$dW = Q\mathbf{E}\cdot d\mathbf{R} \quad \rightarrow \quad \text{ENERGY} \sim I - \frac{Q^2}{R}$$



STRONG FORCE

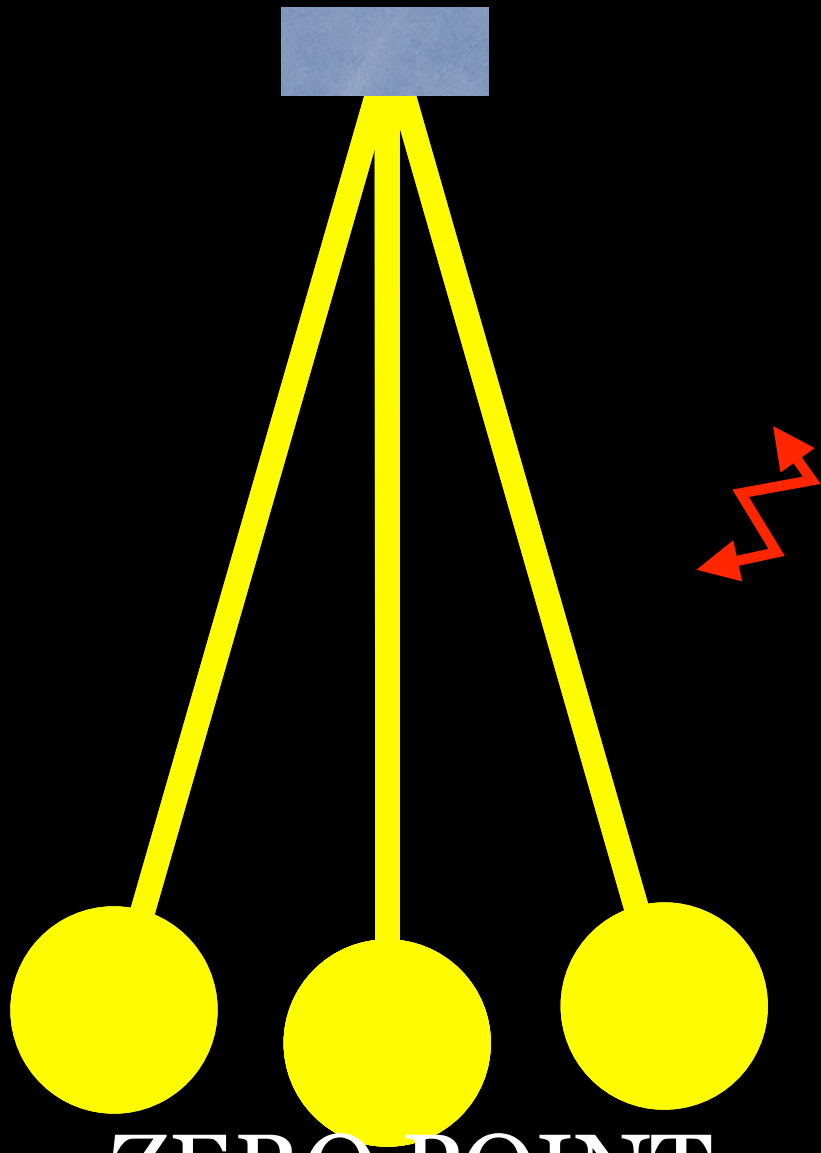


Classical Oscillator



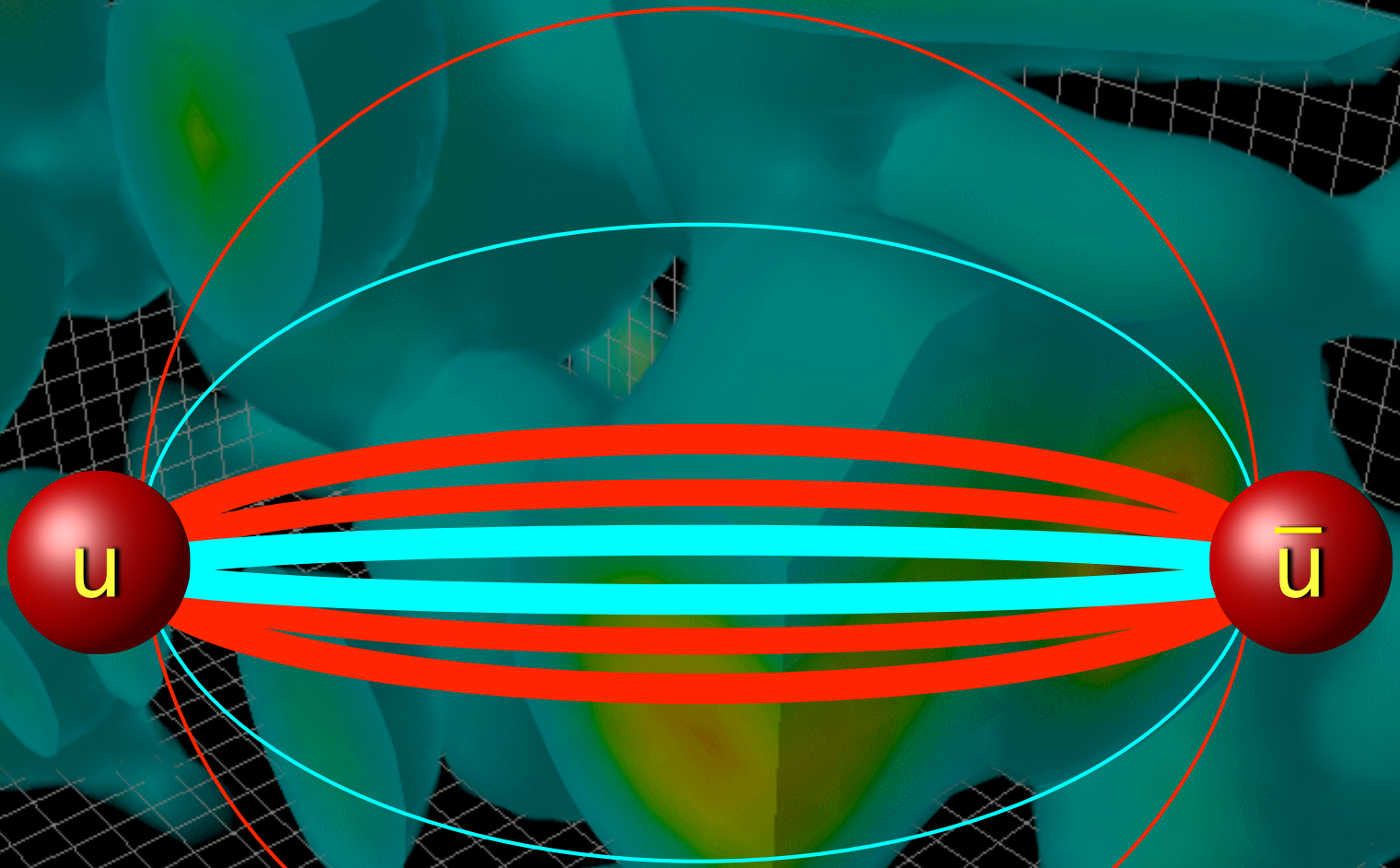
GROUND STATE

Quantum Oscillator



ZERO POINT OSCILLATION

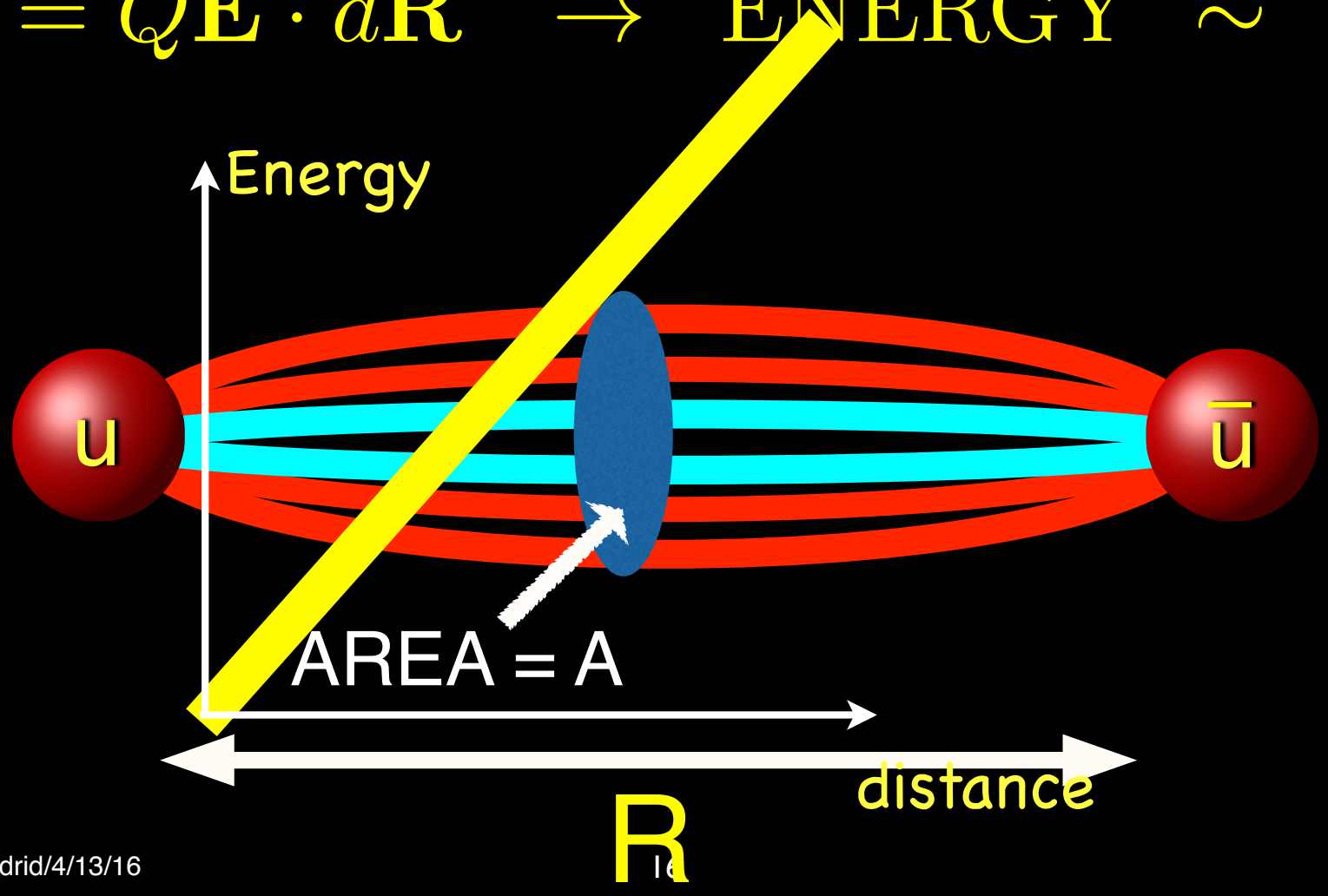
STRONG FORCE MEDIATED BY THE CHROMODYNAMIC FIELD



ASYMPTOTIC FREEDOM

$$\mathbf{E}A = Q$$

$$dW = Q\mathbf{E}\cdot d\mathbf{R} \quad \rightarrow \quad \text{ENERGY} \sim \frac{Q^2}{A^2}R$$

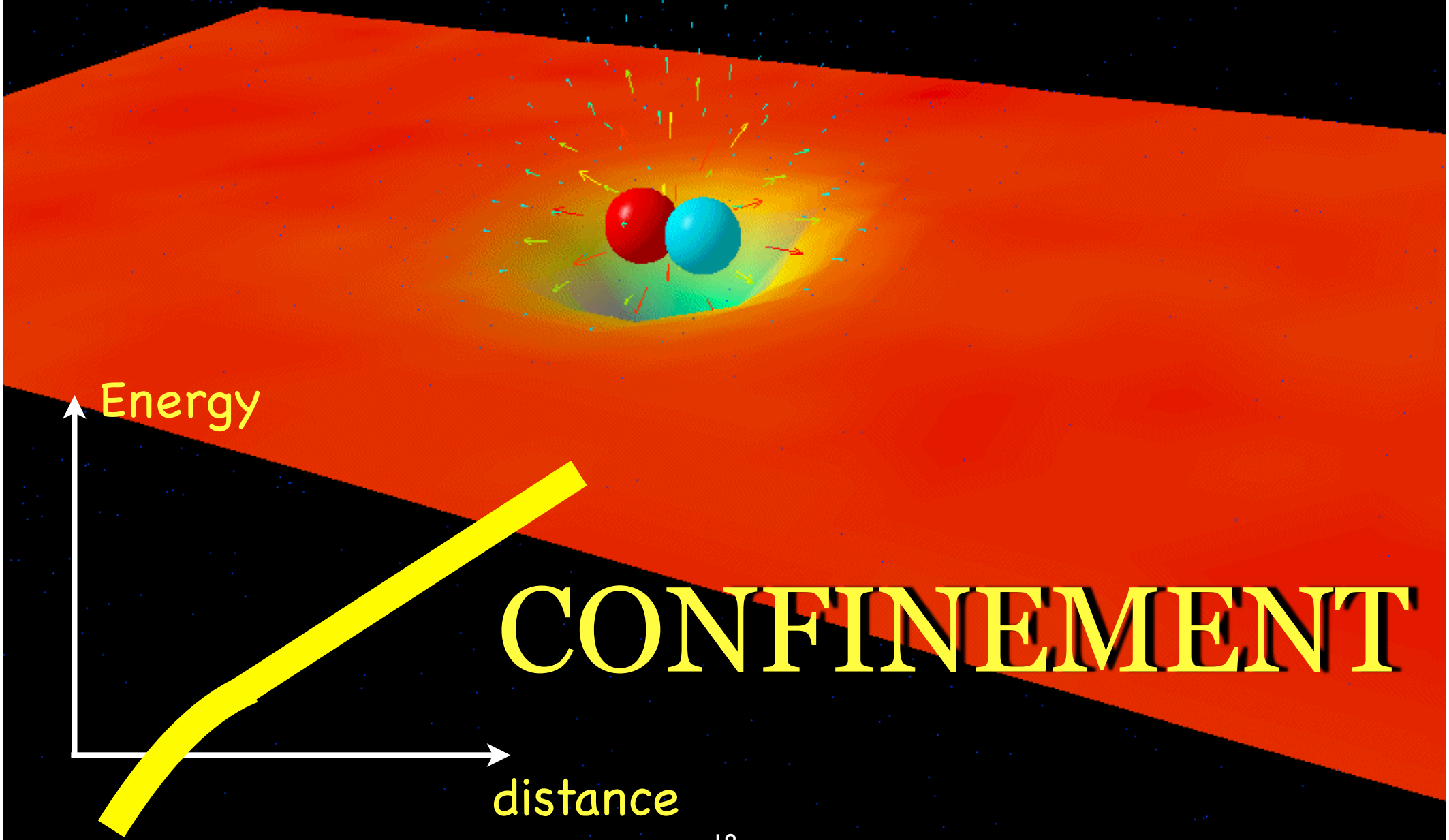


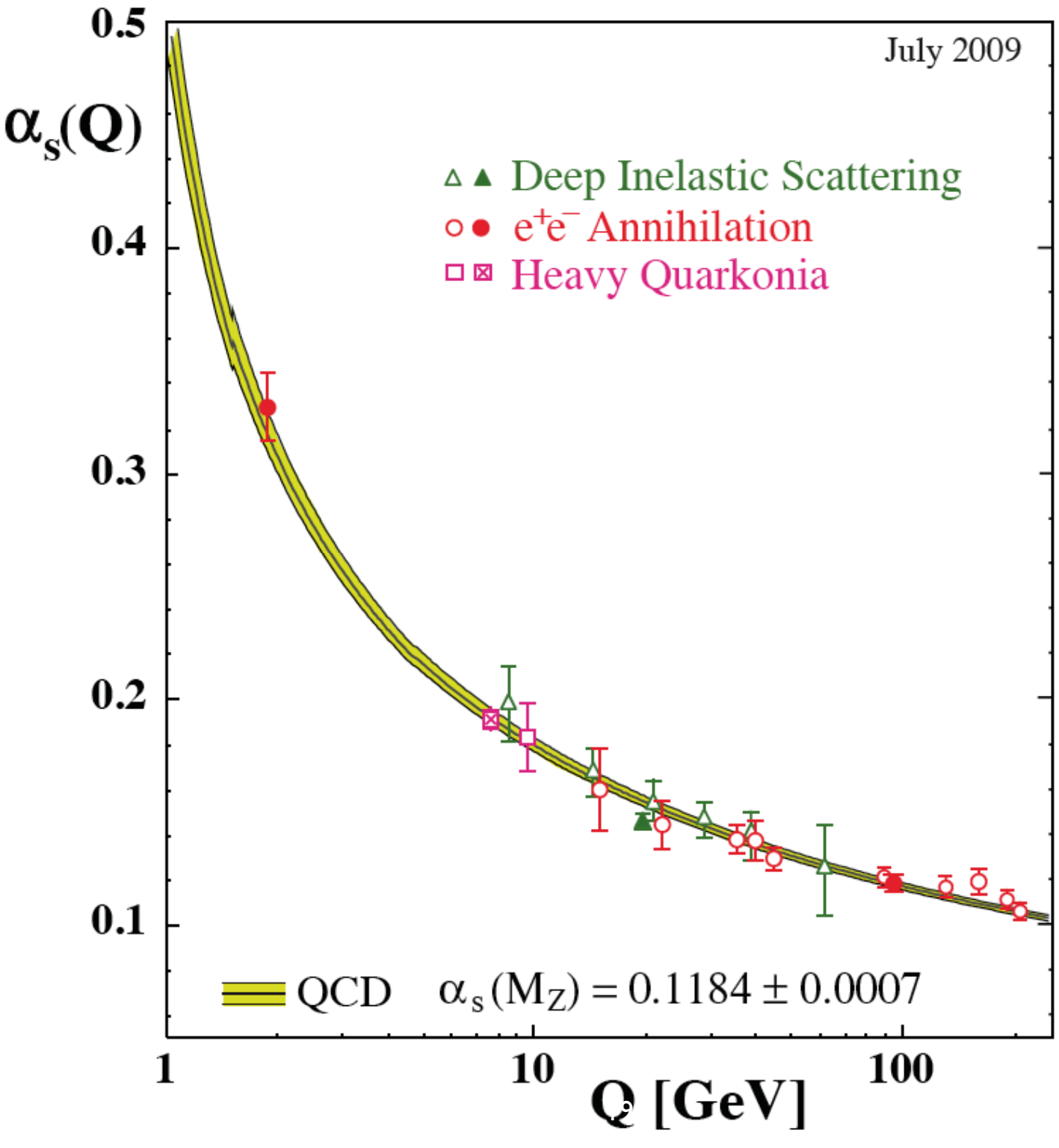
ASYMPTOTIC FREEDOM

QCD

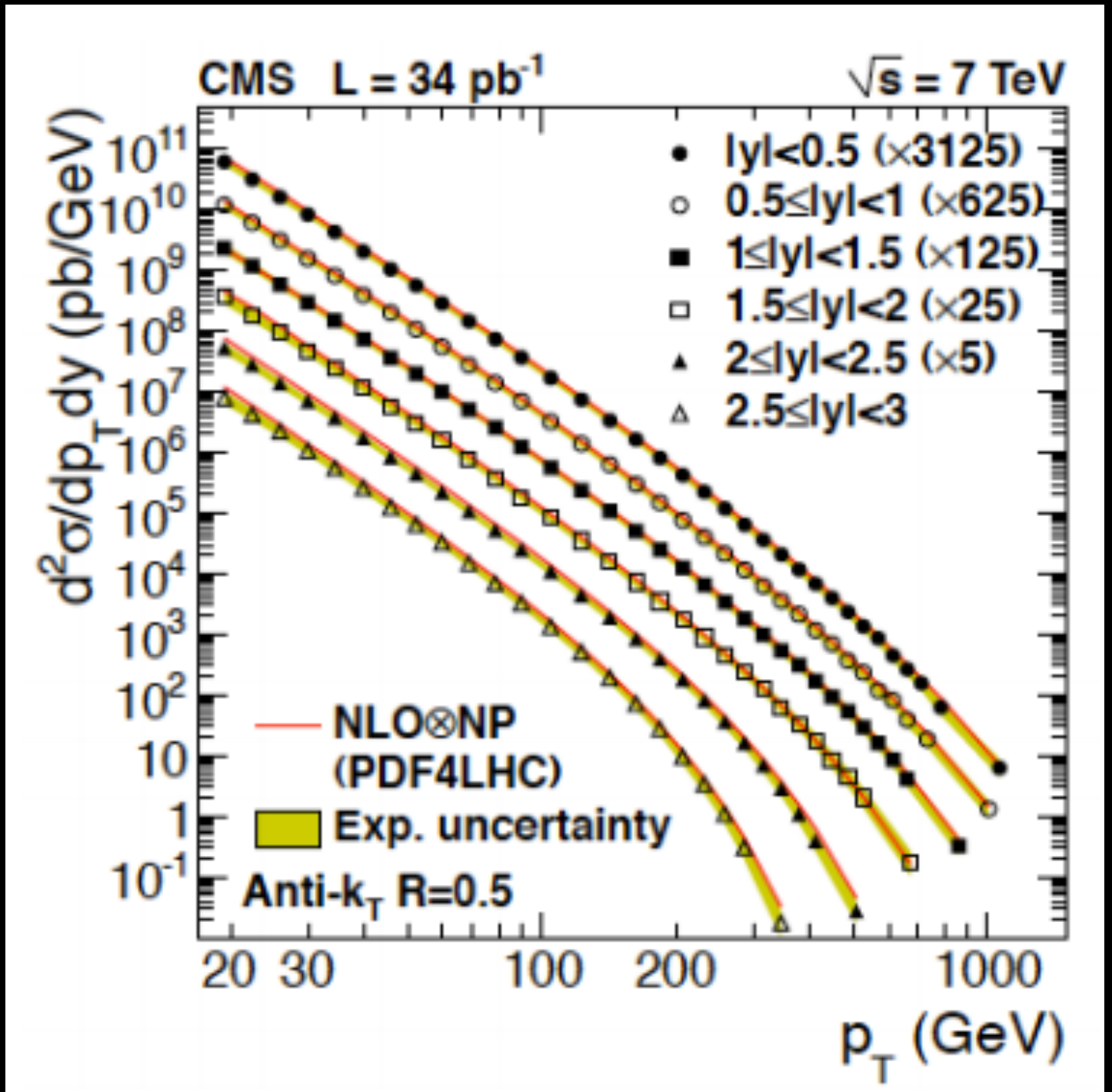
Quantum Chromodynamics

THE MESON IN QCD

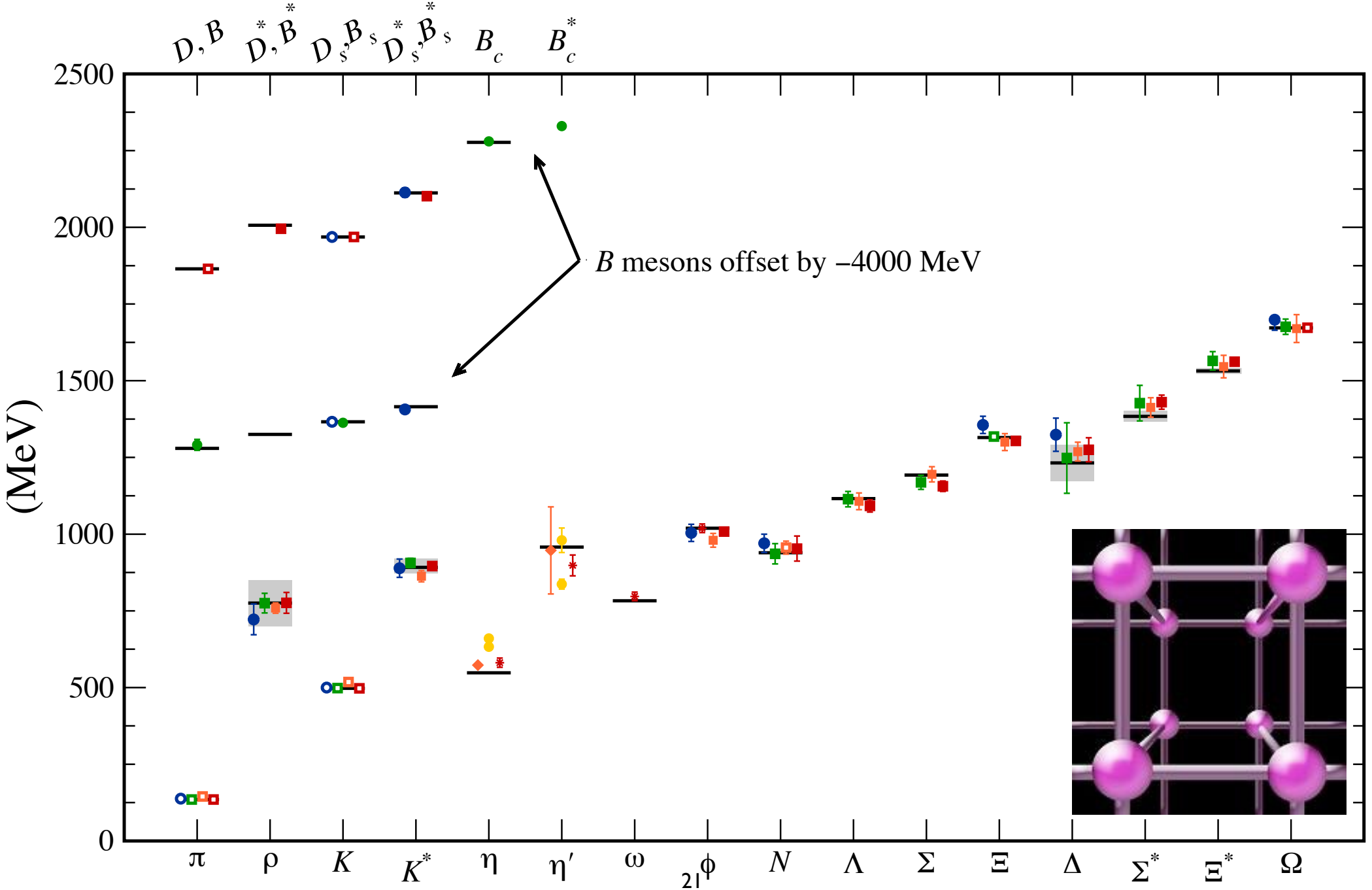



July 2009
$\alpha_s(Q)$
0.5
0.4
0.3
0.2
0.1
Deep Inelastic Scattering
e^+e^- Annihilation
Heavy Quarkonia
QCD
$\alpha_s(M_Z) = 0.1184 \pm 0.0007$
1
10
100
Q [GeV]

Impressive Tests



The Light Hadron Spectrum Of Qcd



BEYOND THE SM

- Dark Matter ✓
- Neutrino Masses
- Baryon Asymmetry
- Cosmic Acceleration …

Exp

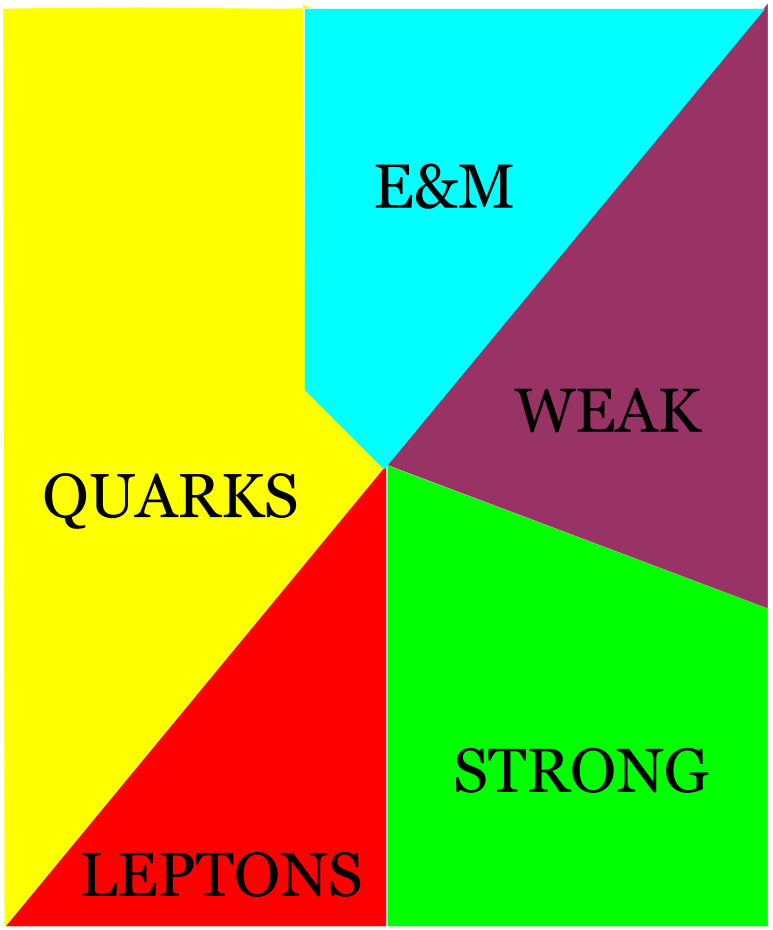
TEV

- Unification ✓
- Electroweak scale, "hierarchy" ✓
- Flavor masses, mixings, generations
- Cosmology, inflation, vacuum energy…

Th

SUSY= QUANTUM DIMENSIONS of SPACE TIME


THE SEARCH
FOR
UNIFICATION
E&M
QUARKS
WEAK
LEPTONS
STRONG

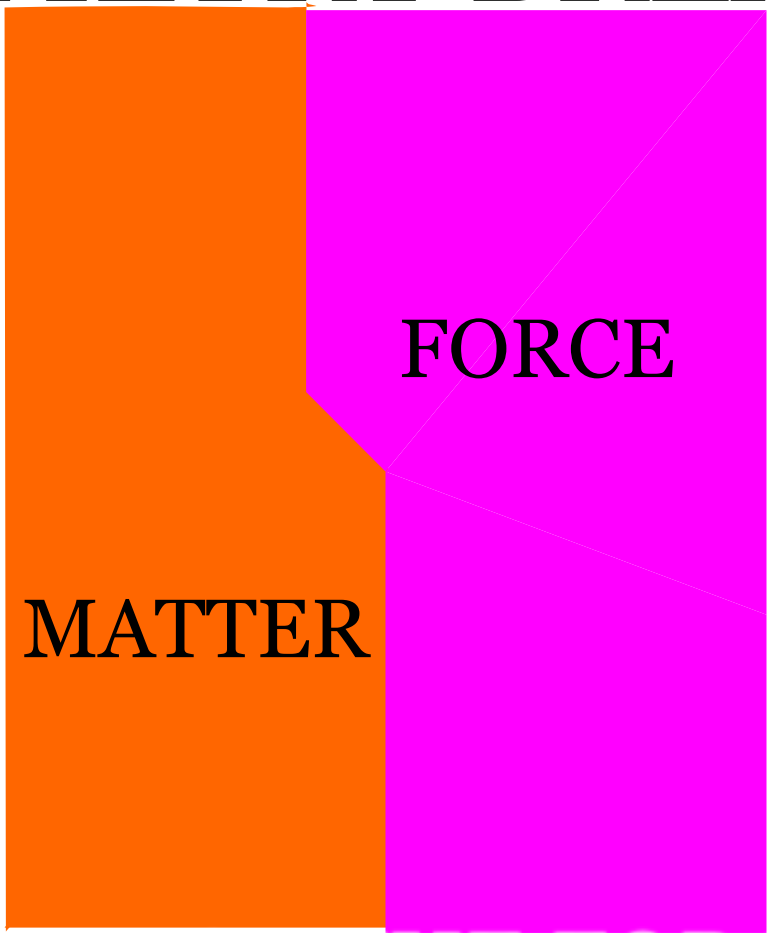

E&M
WEAK
QUARKS
STRONG
LEPTONS

BUT HOW CAN THE FORCES BE THE SAME IF THEY HAVE DIFFERENT STRENGTHS?

WHY ARE THEY DIFFERENT AT LOW ENERGY ?

SYMMETRY BREAKING

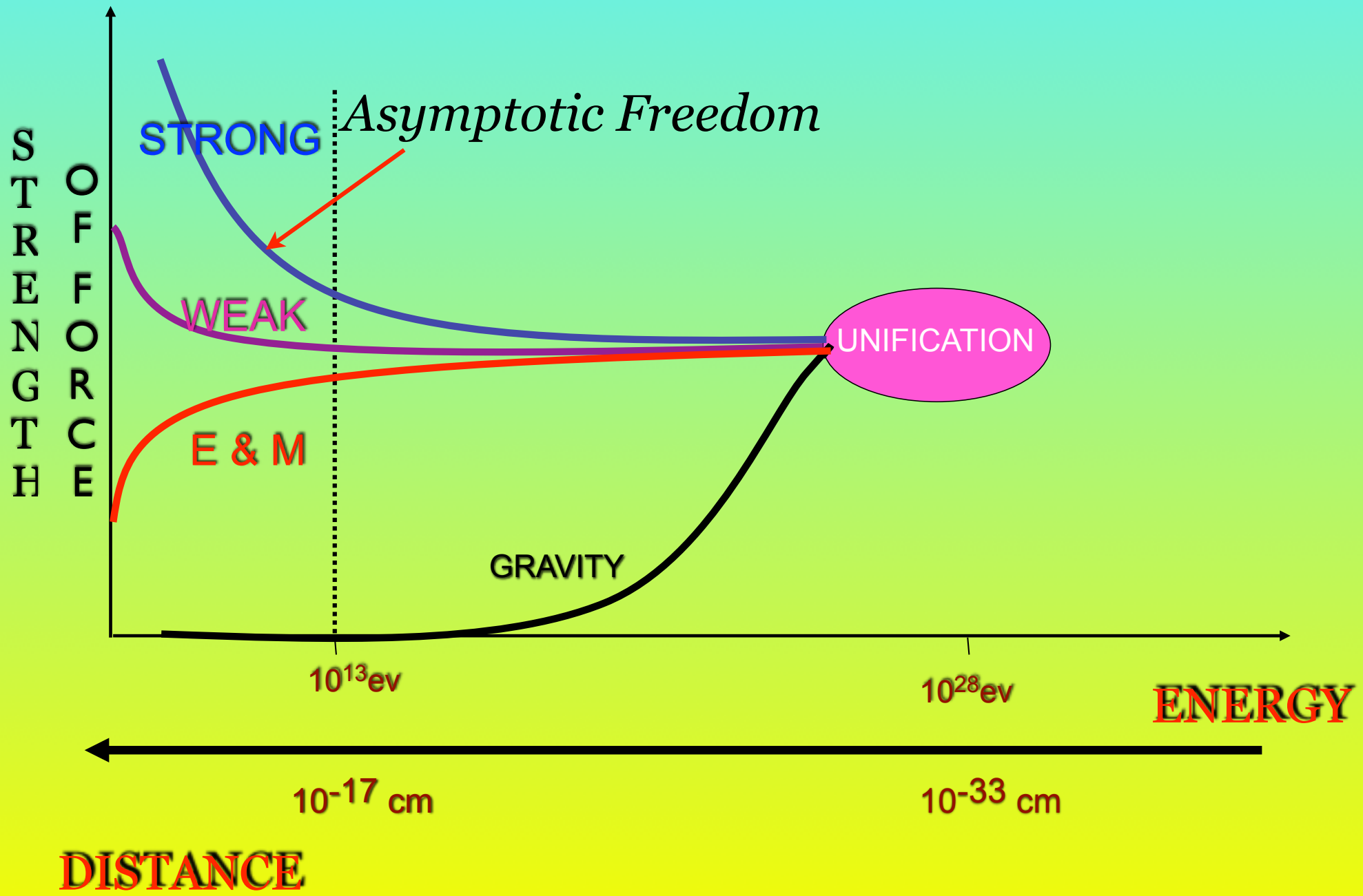
16



SO(10)

THE STRENGTH OF THE FORCES COULD BE THE SAME AT HIGH ENERGY

HOW DO THE FORCES UNIFY?

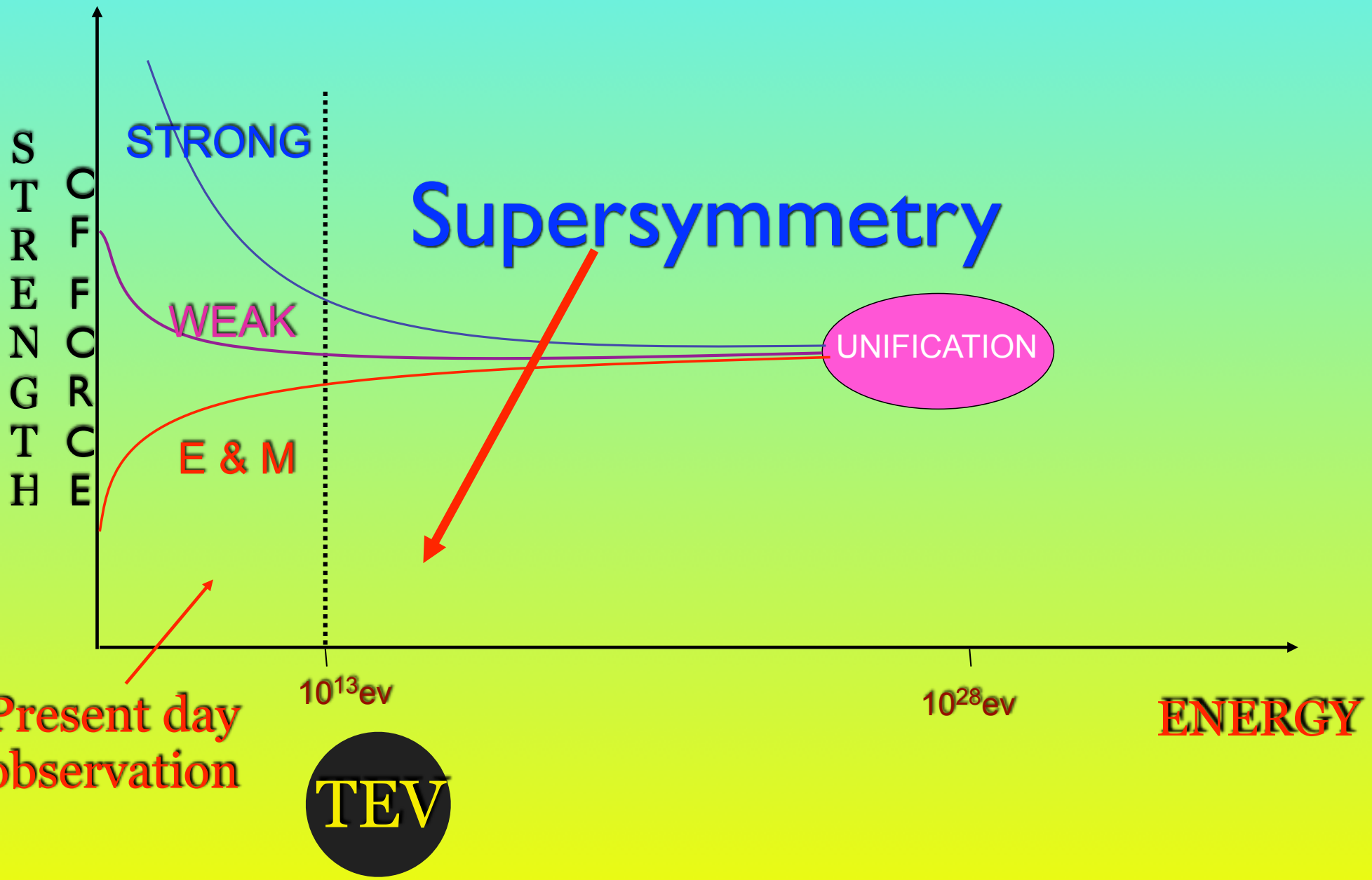


An important clue for unification of all the forces with gravity at $\sim 10^{19}$ TeV, 10^{-33} cm

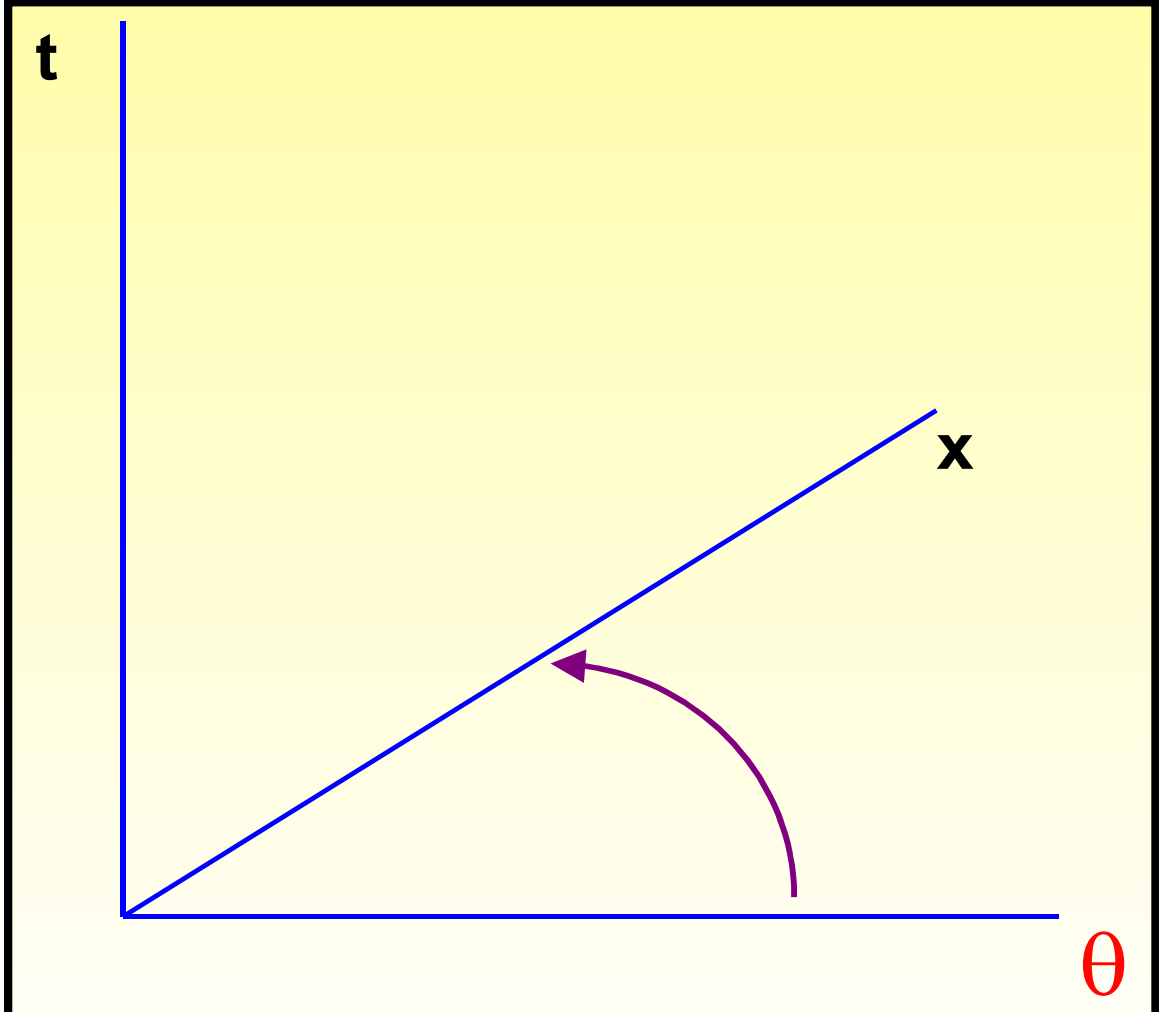
OR

A Coincidence

HOW DO THE FORCES UNIFY?



SUPERSYMMETRY



$$\theta_1 \theta_2 = -\theta_2 \theta_1$$

ROTATIONS IN SUPERSPACE

CLUES:

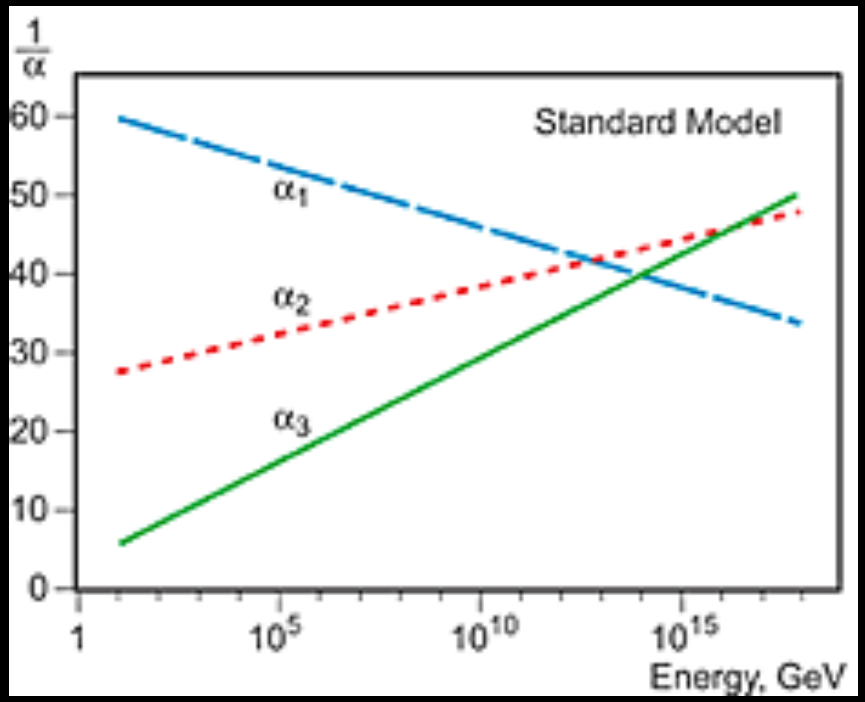
SCALE HIERARCHY

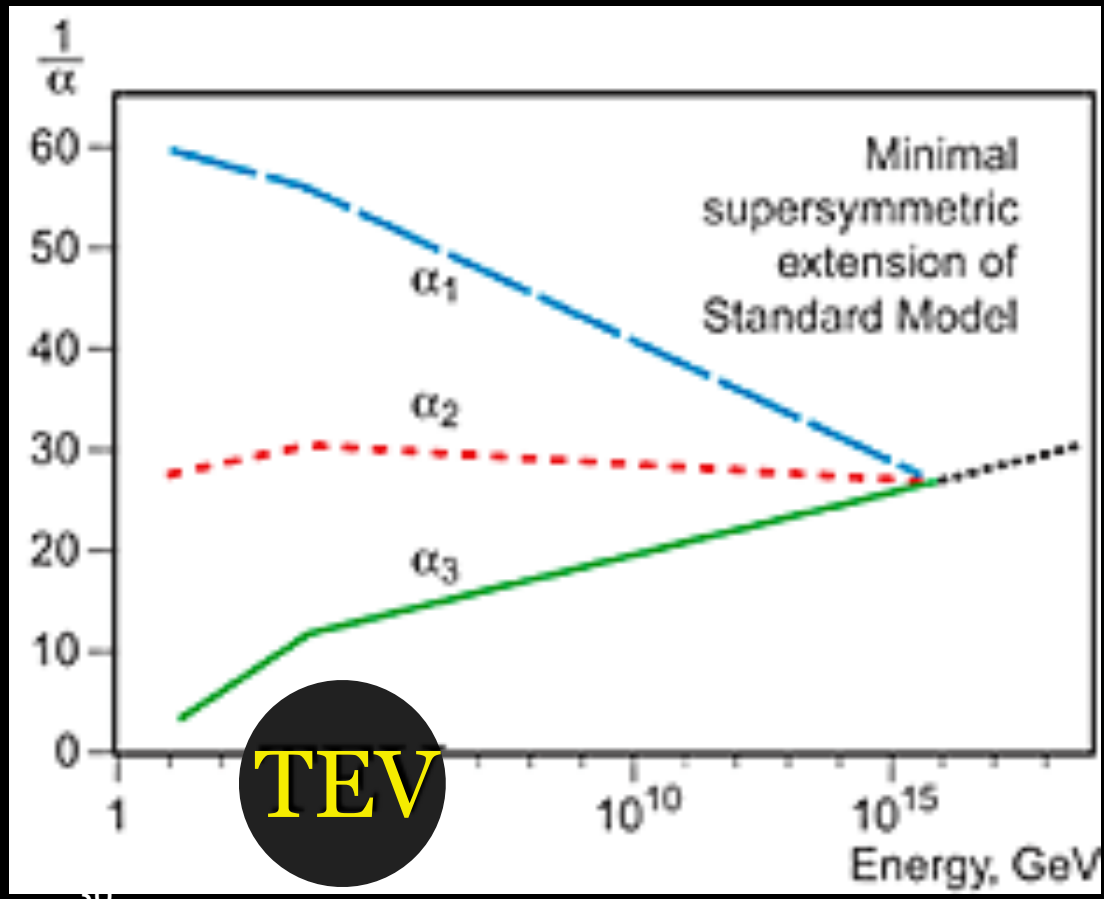
UNIFICATION

DARK MATTER

SUPERSYMMETRY

Helps unify the forces



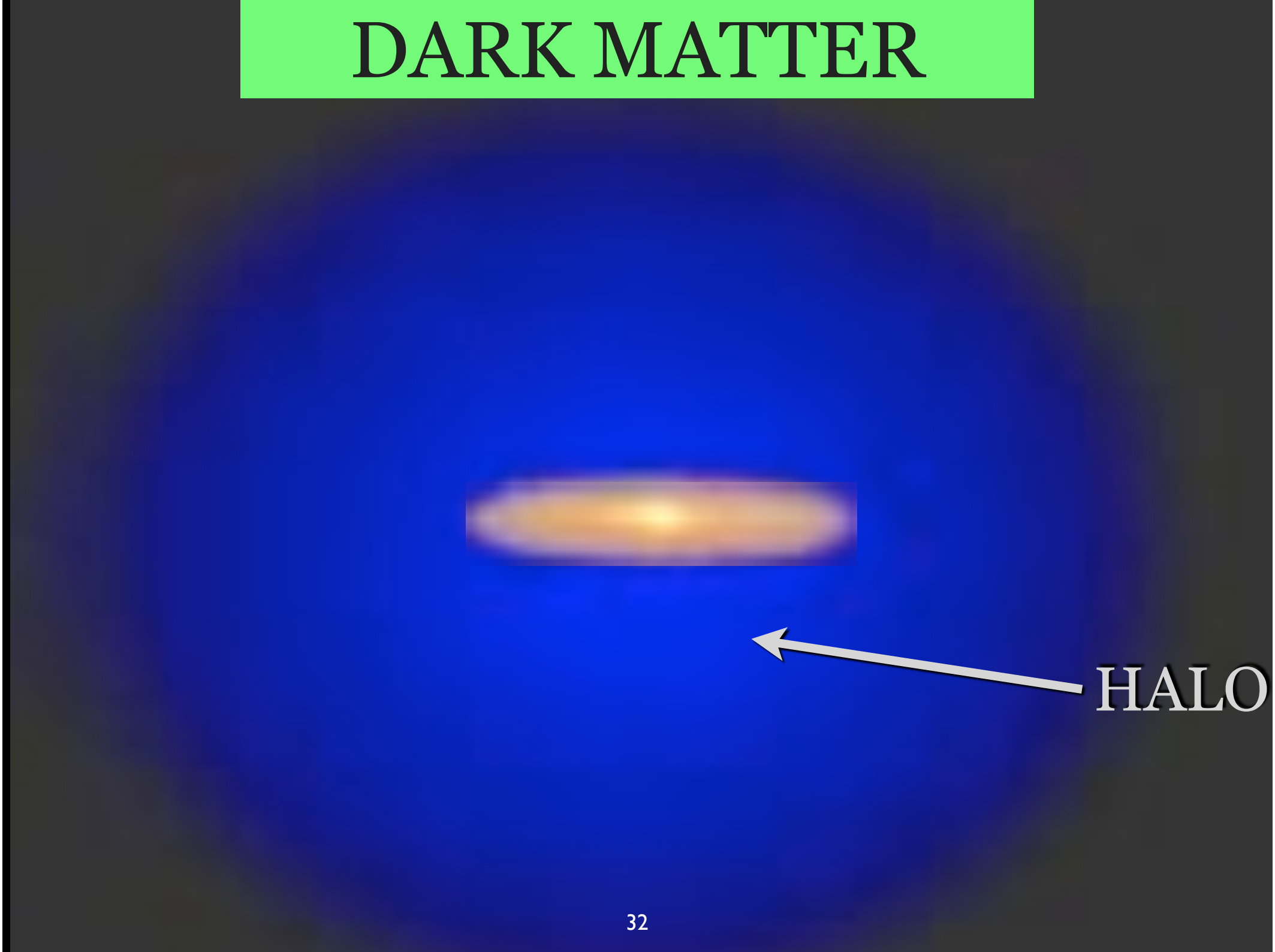


An important clue for Susy at ~ Tev
(and unification)

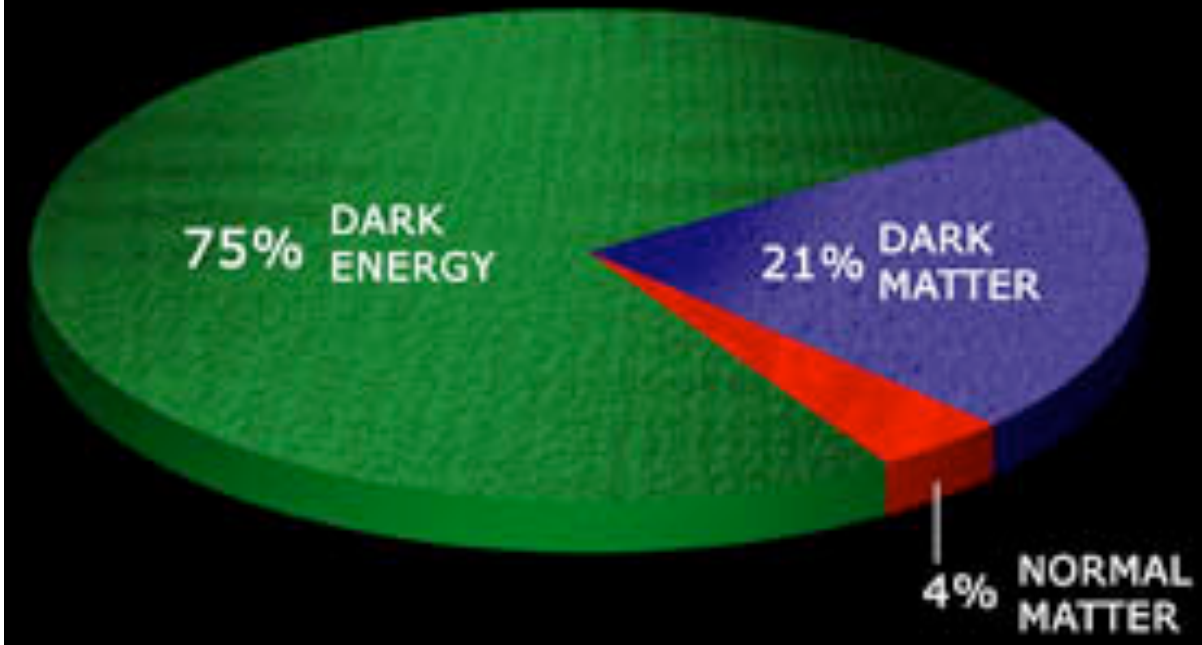
OR

A Coincidence

DARK MATTER



90% of Matter is DARK



Astrophysicists tell us that, most likely, dark matter =

Weakly
Interacting
Massive
Particle

WHAT ARE WIMPS ?

SUPERSYMMETRY
predicts a candidate for

DARK MATTER

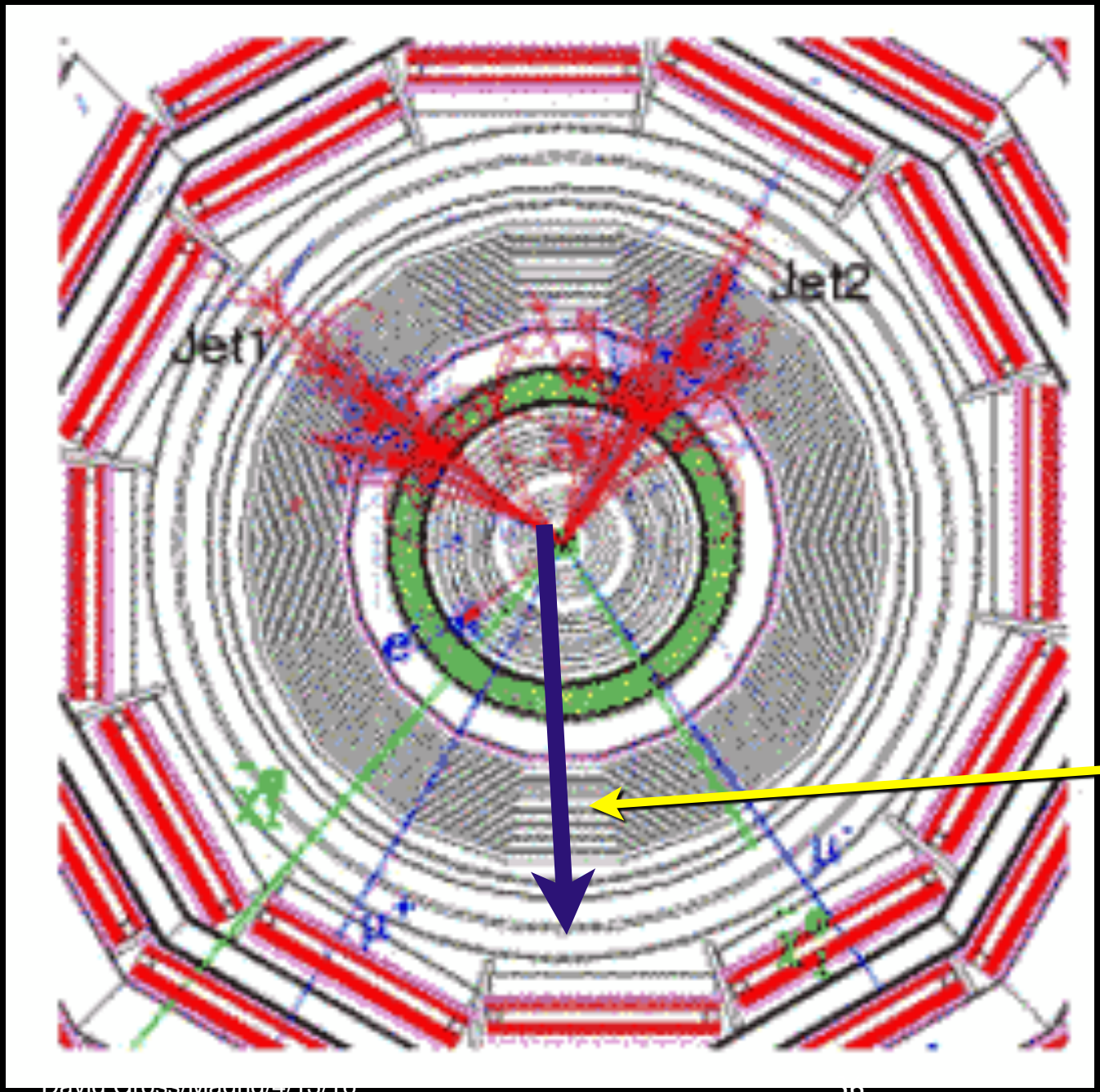
$$\text{IF } M_{\text{SUSY}} \sim 1\,\text{TEV}$$
$$\Rightarrow \text{DM} \sim 90\%$$

An important clue for Susy at ~ Tev

or

A Coincidence

'TYPICAL' SUSY EVENT



MISSING ENERGY = ? DARK MATTER

The discovery of SUPERSYMMETRY is the discovery of quantum dimensions of space-time

THE FUTURE

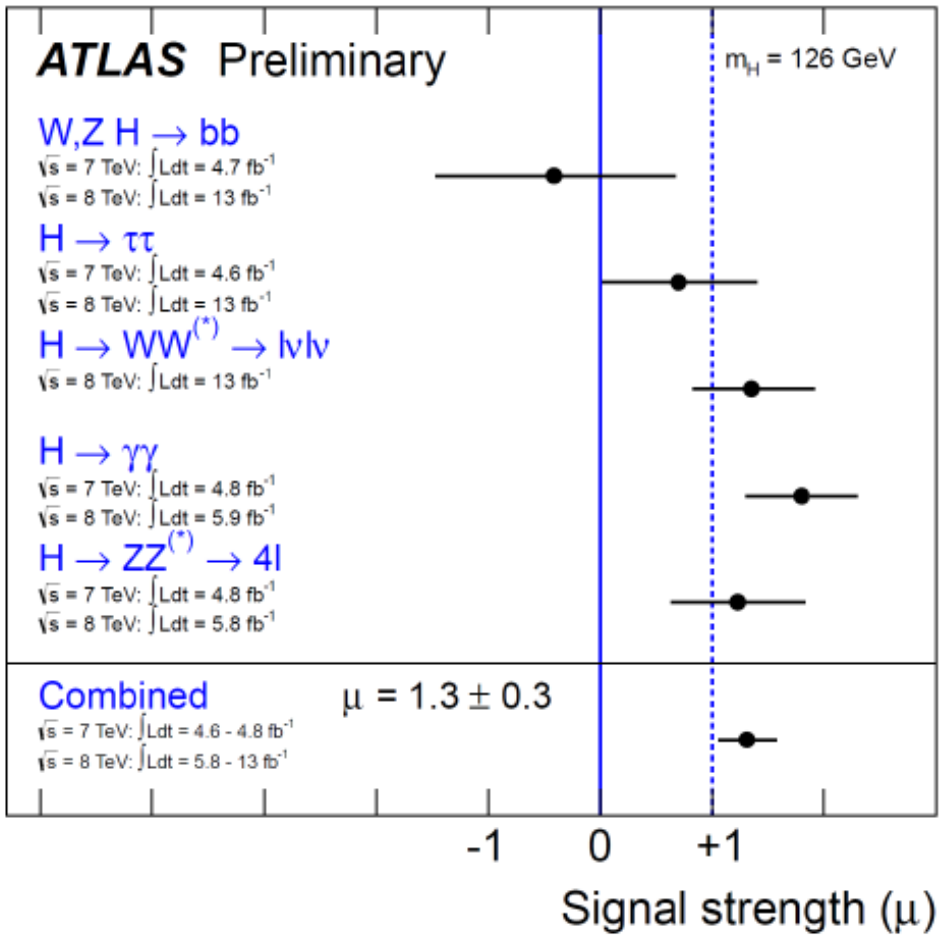
2 EXTREME SCENARIOS

OPTIMISM

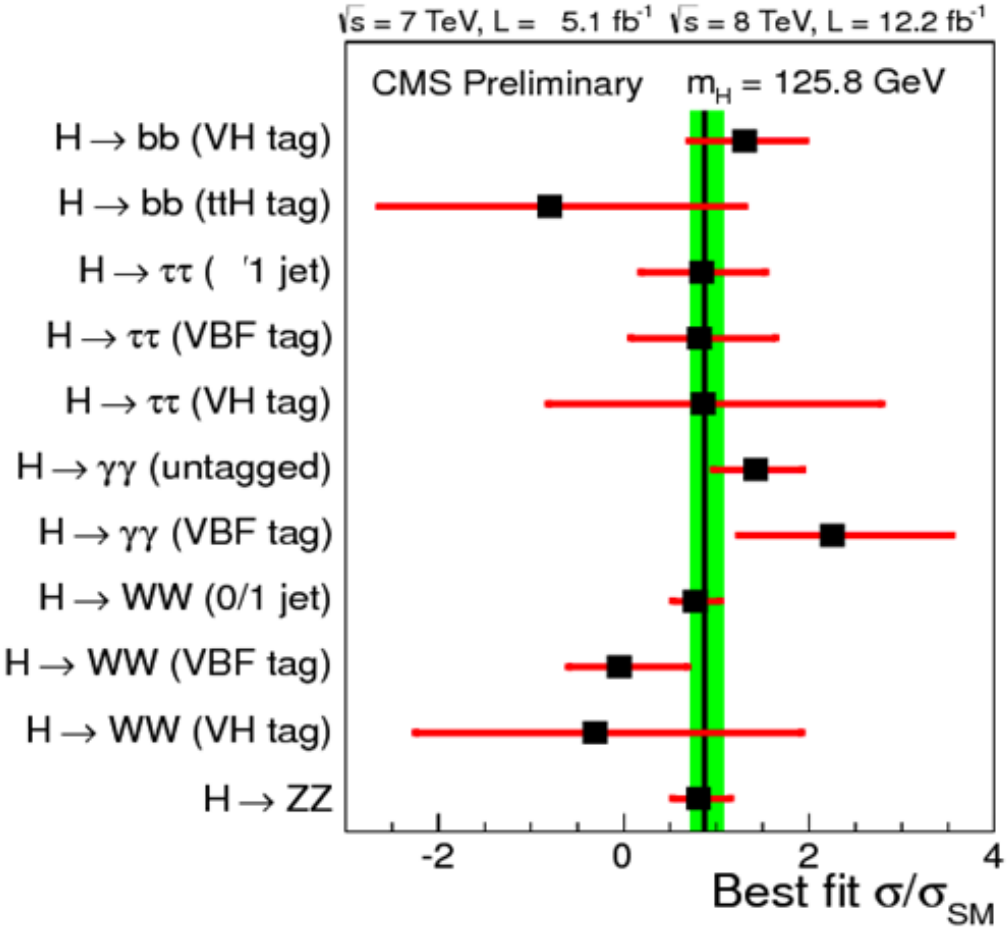
PESSIMISM

The Extreme Pessimistic Scenario

Best–fit Higgs mass m_H :
126.0 ± 0.4 (stat) ± 0.4 (syst) GeV



- M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV



- σ/σ_{SM}=0.88±0.21

- The Higgs(-like) boson = SM Higgs.
- No direct signal for SUSY (or anything else) .
- No detection of Dark Matter, in the sky, underground or at the LHC.
- No direct indication of the next threshold!

Maybe 10^{10}--10^{19} GeV

WHAT TO DO ?

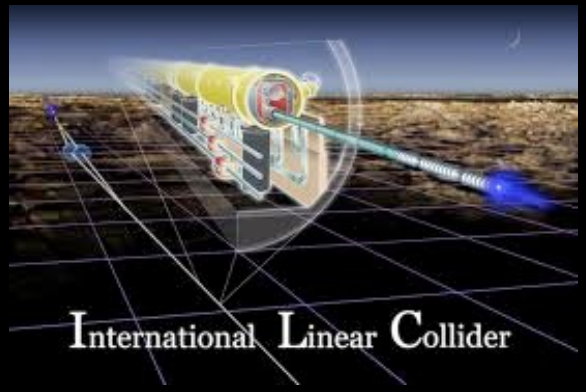
We Must Fully Explore the 10-100 TeV Energy Range

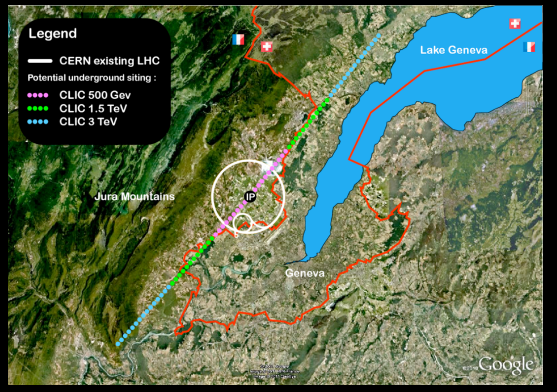
The Extreme Optimistic Scenario

- The Higgs(-like) boson ≠ SM Higgs
- Direct production of SUSY particles
- Detection of Dark Matter, in the sky, underground and at the LHC
- Strong guidance for the next steps!

ILC, CLIC, HL-LHC, VHE-LHC, HHC, …

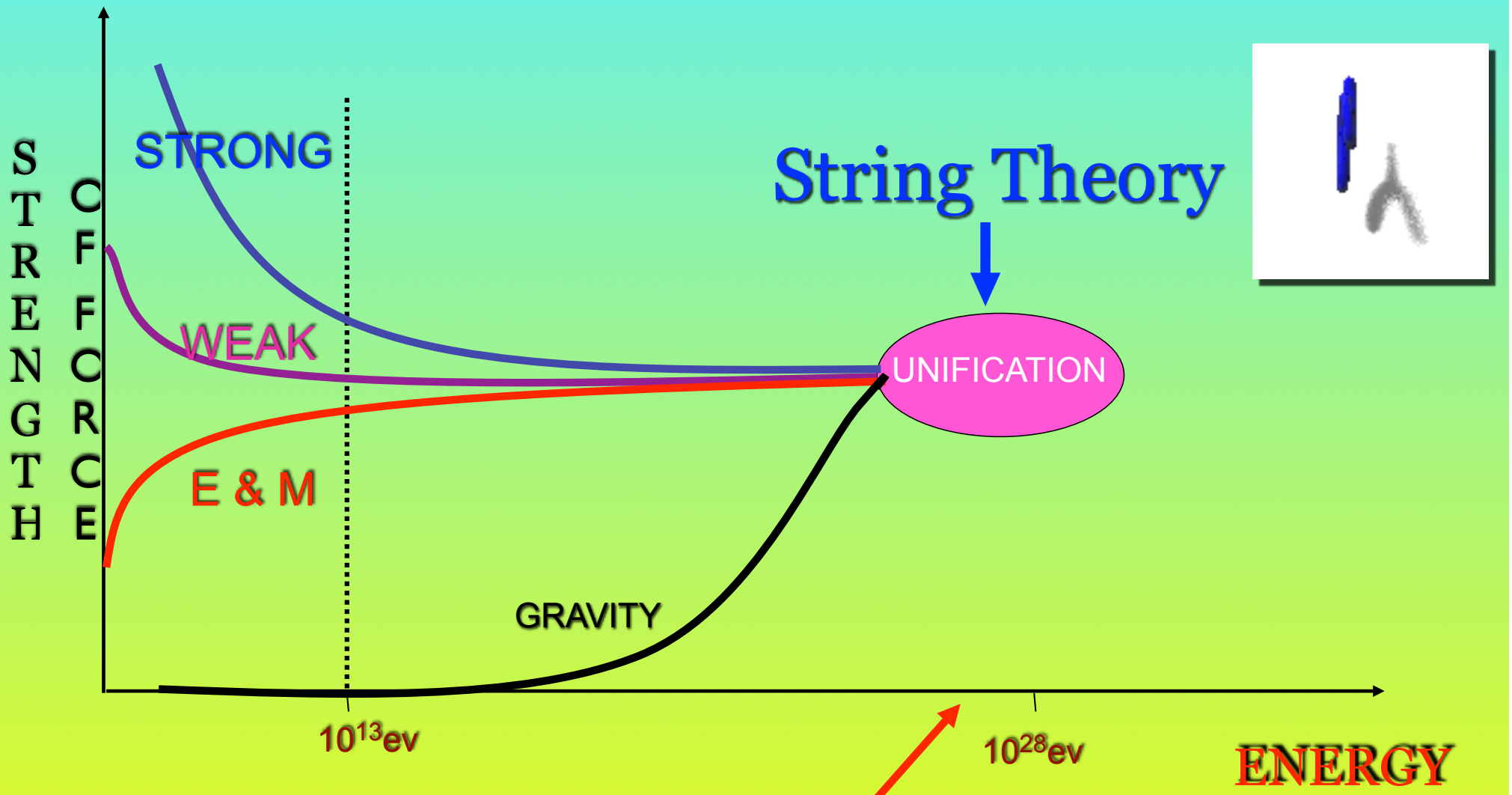
We Must Fully Explore the 10-100 TeV Energy Range





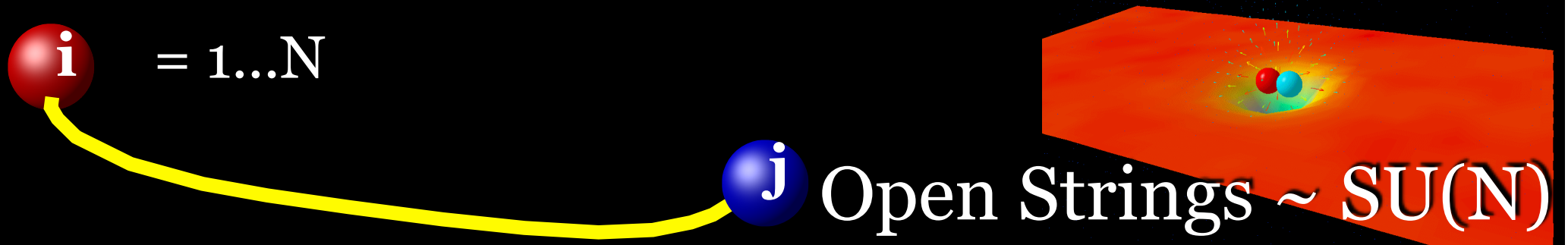
THE GREAT COLLIDER

HOW DO THE FORCES UNIFY?



$$F_{GRAVITY} \sim M^2 \sim E^2$$

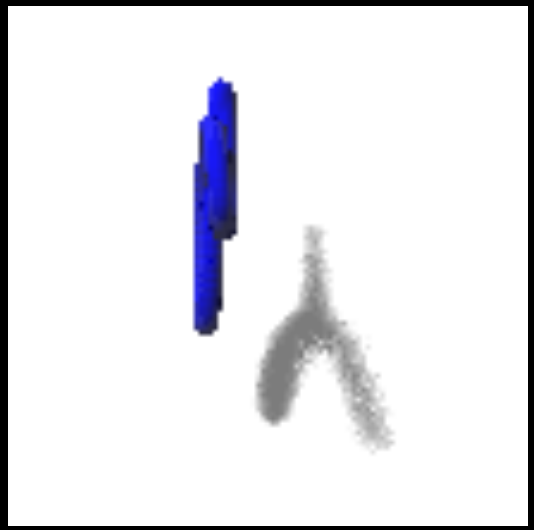
STRING THEORY



Open Strings ~ SU(N)
Gauge Mesons

GAUGE THEORY = STRING THEORY

Closed Strings ~ Gravitons

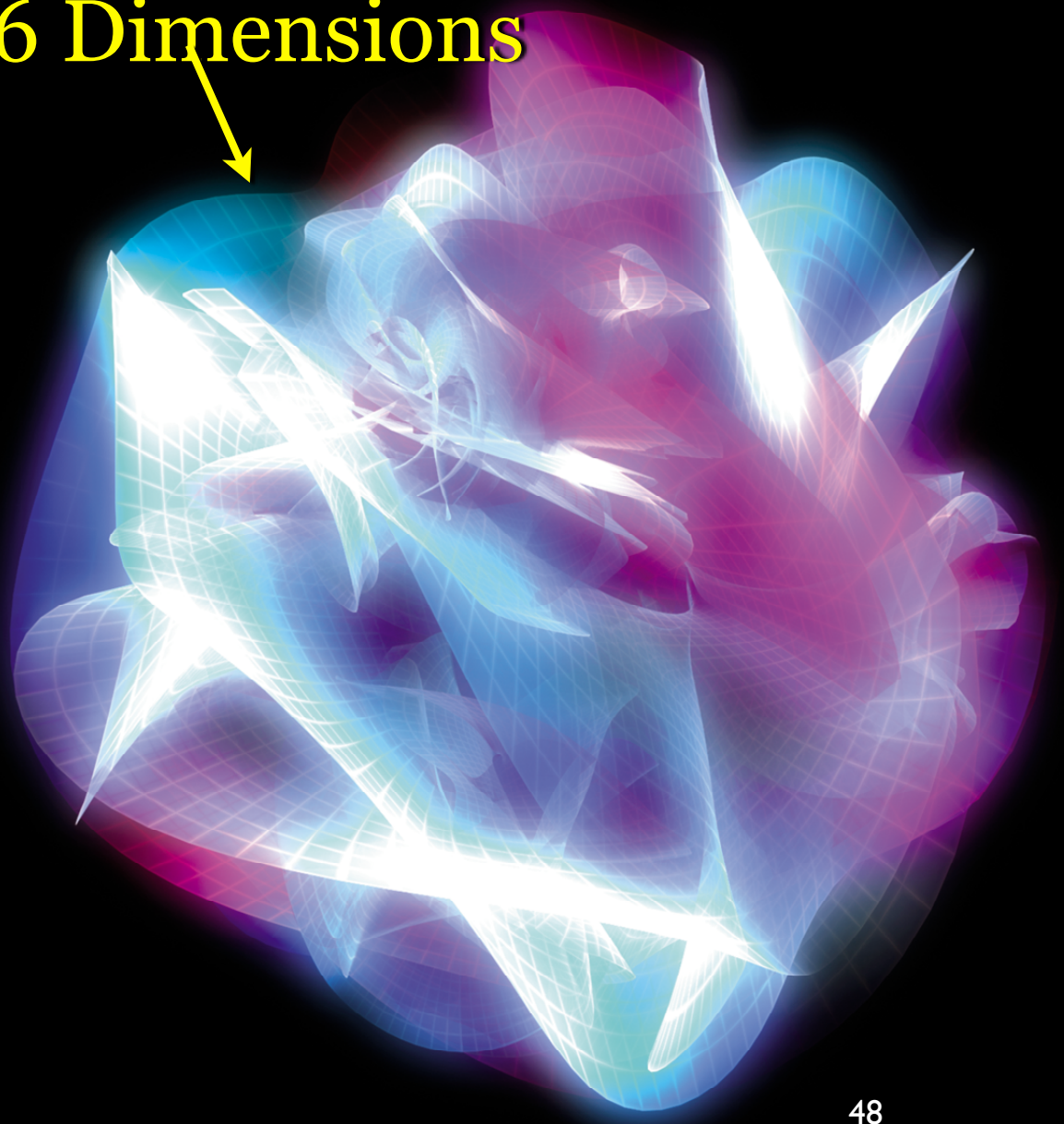


ARE ALL PARTICLES DIFFERENT VIBRATIONS OF A SUPERSTRING ?

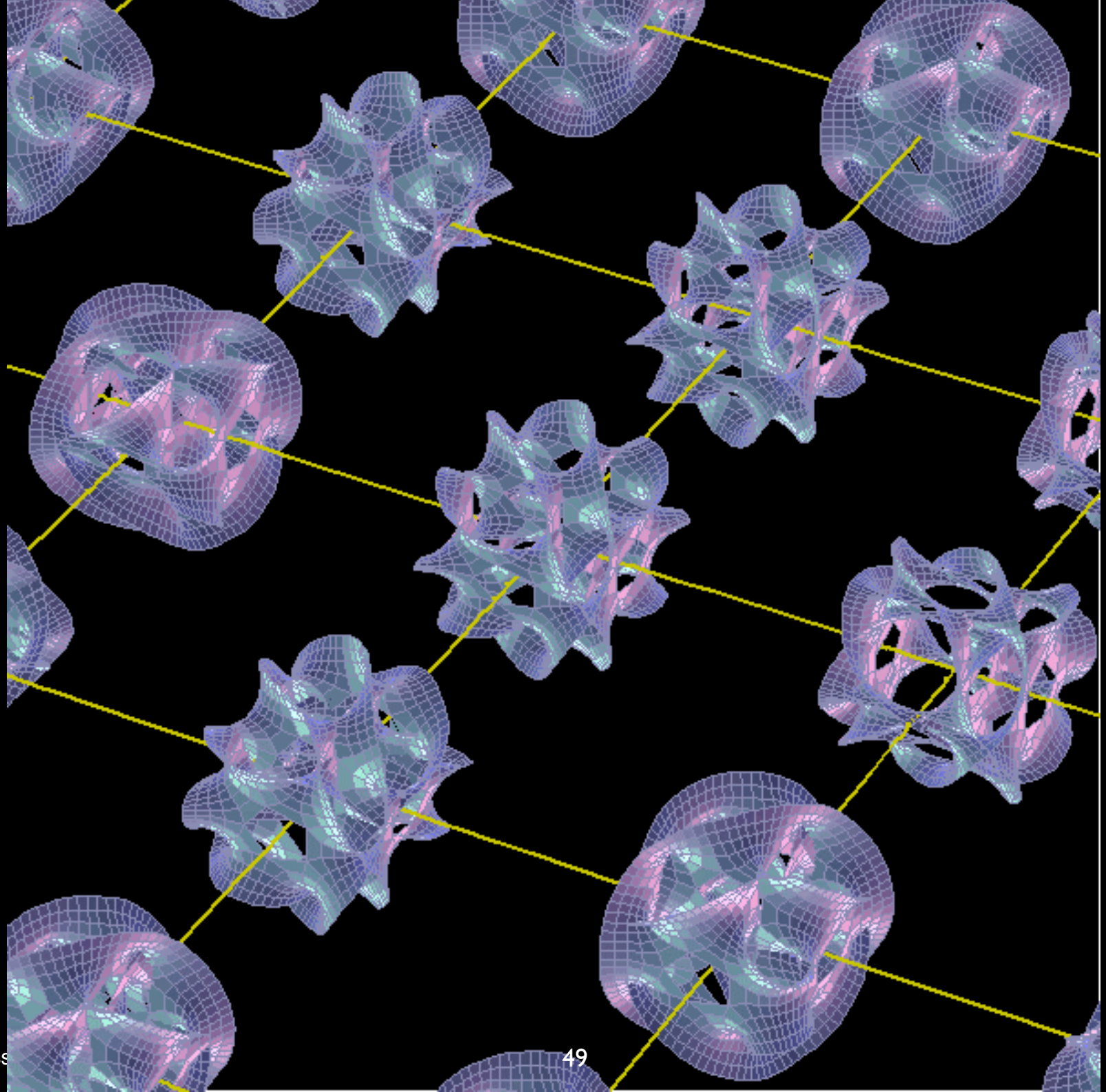
Are There More Than 3 Dimensions?

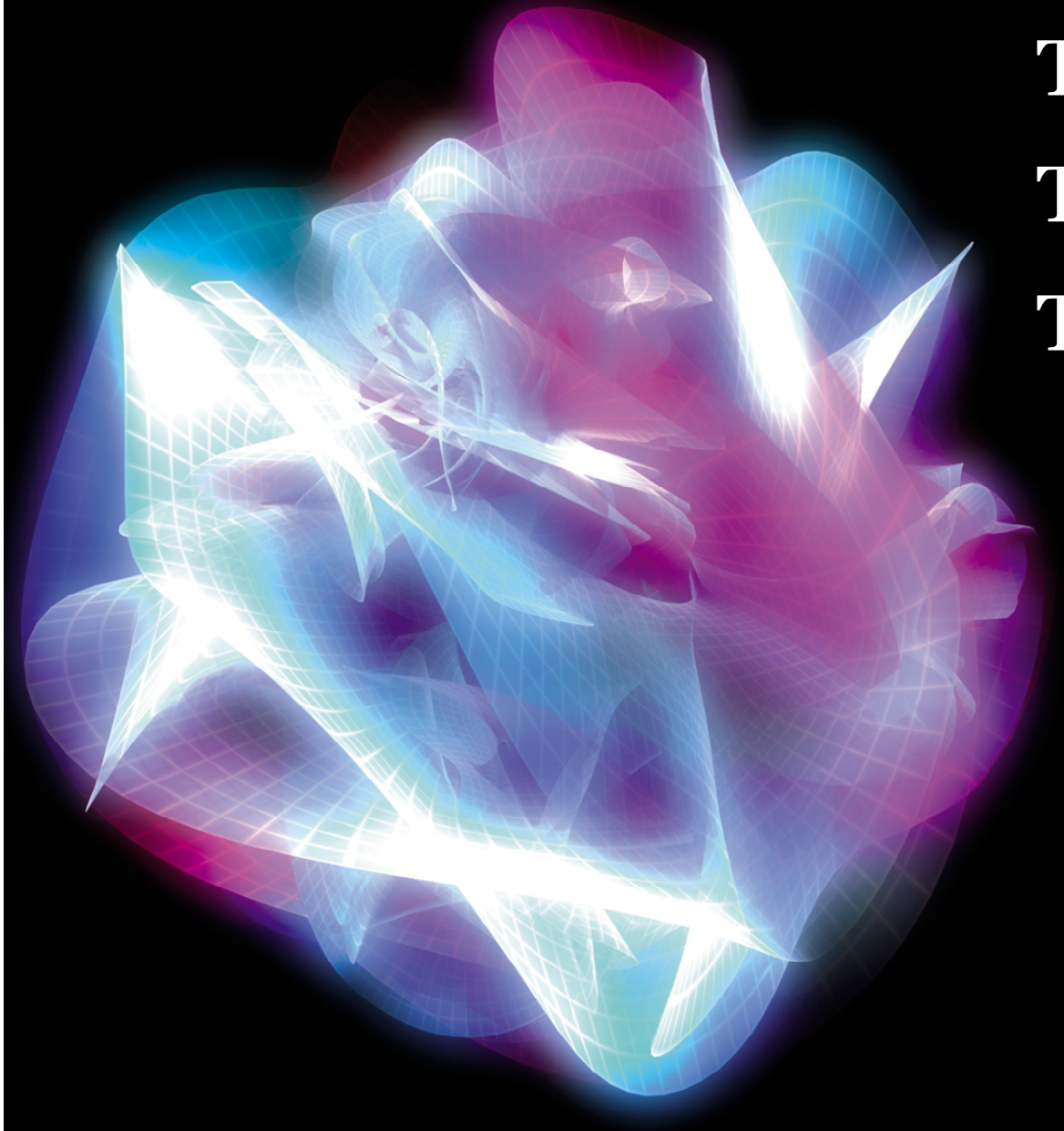
in string theory

6 Dimensions



A Calabi-Yau manifold





The nature of the forces

The form of matter

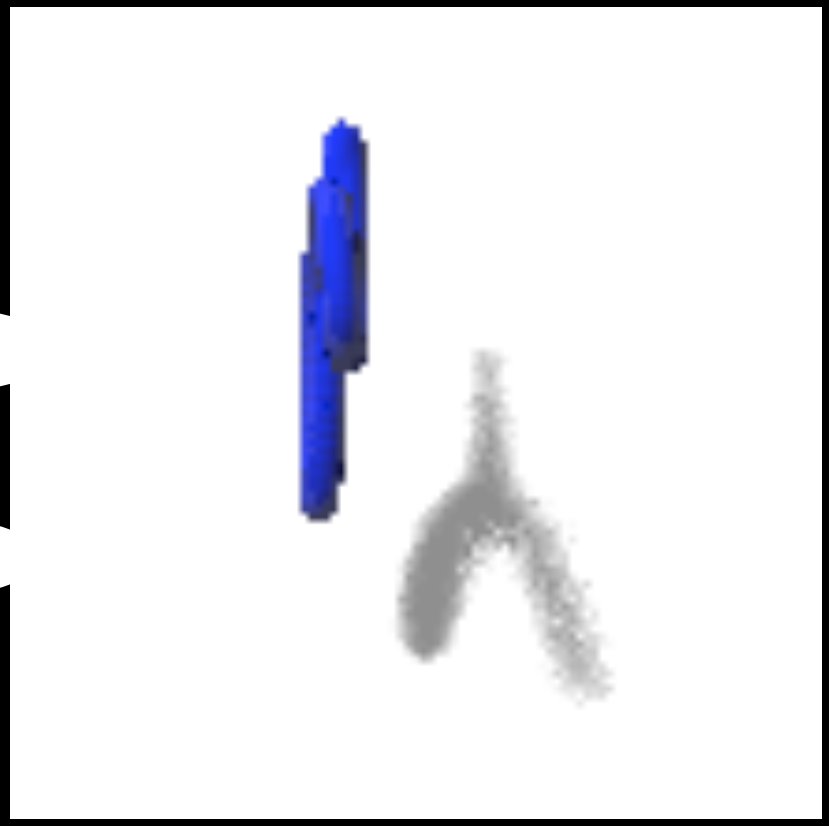
The values of the masses

are determined by the shape of the hidden dimensions

The Framework of Theoretical Physics

QUANTUM FIELD

FRAMEWORK



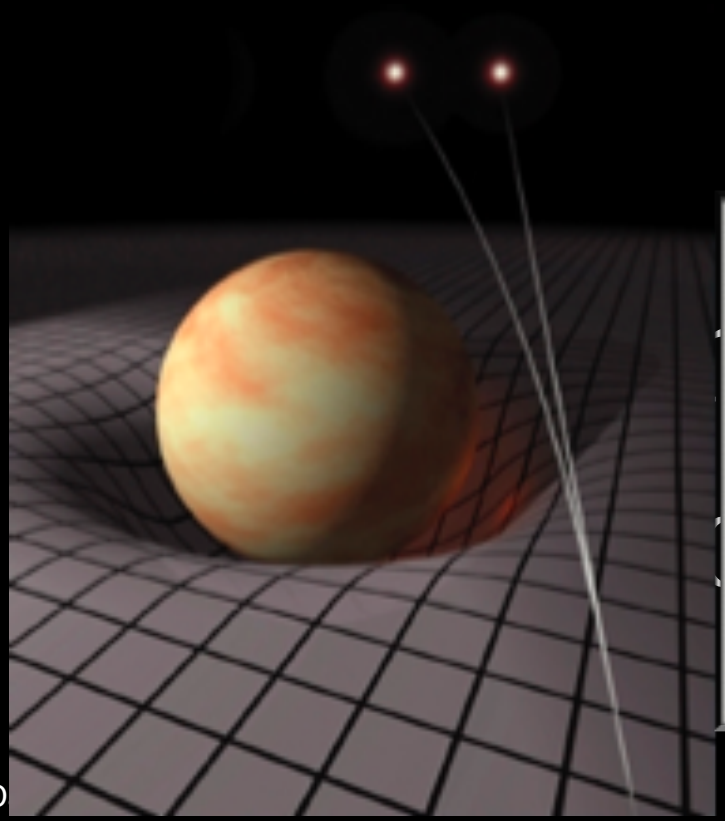
Standard Theory

The Framework of Theoretical Physics

An incredible
FRAMEWORK
that includes strings, branes, all consistent field theories and quantum gravity.

SPACETIME

IS ALL OF SPACETIME EMERGENT?

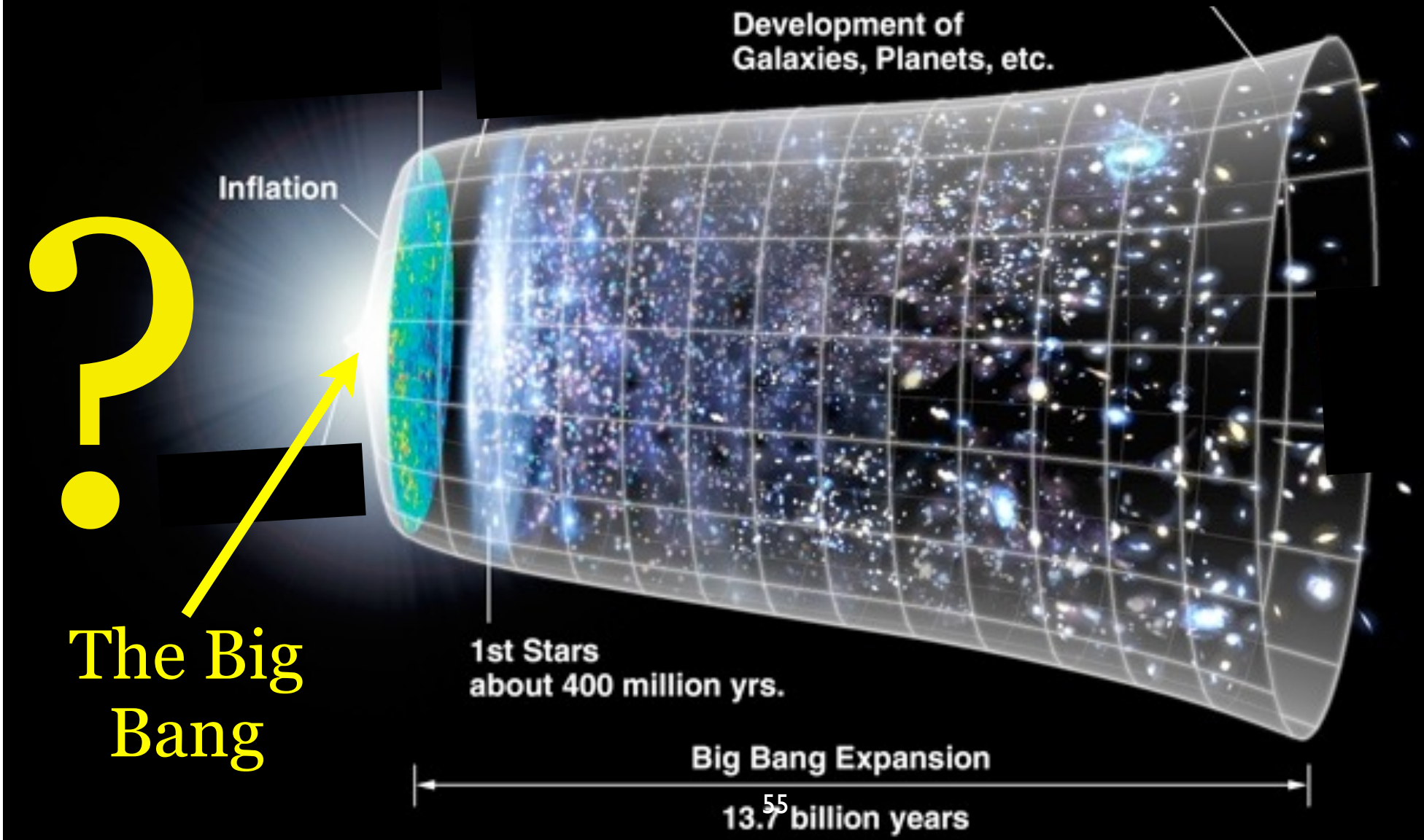


IS GRAVITY EMERGENT?

WHAT FIXES THE DYNAMICS?

WHAT FIXES THE INTIAL (FINAL) STATE ?

THE UNIVERSE



HOW DID THE UNIVERSE BEGIN?

Can we determine the initial condition?


THE END
Time
BOUNDARY
THE UNIVERSE
=
SPACETIME HISTORY
WHAT ARE THE RULES ?
Space
THE BEGINNING

WE HAVE A WONDERFUL THEORY OF ELEMENTARY PARTICLES

BUT THE MOST EXCITING QUESTIONS REMAIN TO BE ANSWERED

FANTASTIC INSTRUMENTS AND EXPERIMENTS

FANTASTIC SPECULATIONS

M

THE BEST IS YET TO COME

Thank You

THE END