Nature's Greatest Puzzles

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Fermilab

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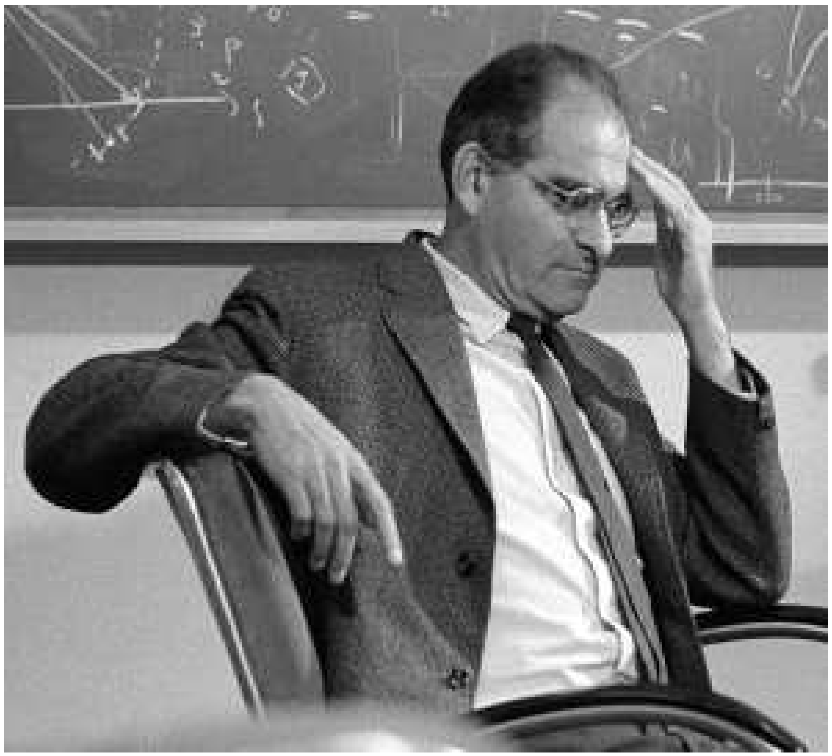


Viki Weisskopf

About 500 years ago man's curiosity took a special turn toward detailed experimentation with matter. It was the beginning of science as we know it today. Instead of reaching directly at the whole truth, at an explanation for the entire universe, its creation and present form, science tried to acquire partial truths in small measure, about some definable and reasonably separable groups of phenomena.

> Science developed only when men began to restrain themselves not to ask general questions, such as: What is matter made of? How was the Universe created? What is the essence of life? They asked limited questions, such as: How does an object fall? How does water flow in a tube? etc. Instead of asking general questions and receiving limited answers, they asked limited questions and found general answers.

VFW, *Physics in the Twentieth Century,* "The Significance of Science"

Io stimo più il trovar un vero, benchè di cosa leggiera, ch'l disputar lungamente delle massime questioni senza conseguir verità nissuna.

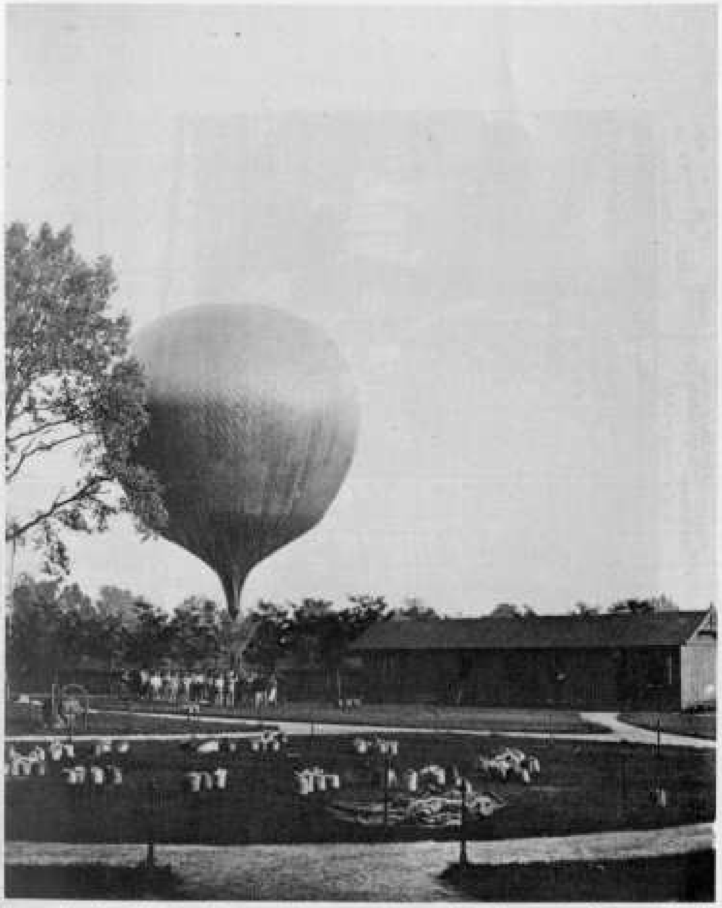
I attach more value to finding a fact, even about the slightest thing, than to lengthy disputations about the Greatest Questions that fail to lead to any truth whatever.

By focusing on "small things," with an eye to their larger implications, Galileo achieved far more than the philosophers and theologians whose authority asserted answers to the "greatest questions."

Our shame: Going through Galileo's motions, *without* an eye to their larger implications, too often constitutes freshman physics lab.

Balance grandeur and sweep
of the Great Questions
with our prospects
for answering them

Unimagined progress may flow from small questions



Aeronautisches Gelände im Wiener Prater, von dem aus V. F. Hess in den Jahren 1911/12 seine ersten Freiballon-Forschungsfahrten unternommen hatte. (Courtesy of Heeresgeschichtliche Museum, Vienna)

<Ed> Contributed by R. Steinmaurer. See p. 17.

Measuring conductivity of atmosphere, Hess discovered cosmic radiation

America's Best . . . a top ten list

The questions scientists are tackling now are a lot narrower than those that were being asked 100 years ago.

As John Horgan pointed out in his controversial 1997 best seller *The End of Science,*

we've already made

most of the fundamental discoveries:

that the blueprint for most living things is carried in a molecule called DNA; that the universe began with a Big Bang; that atoms are made of protons, electrons and neutrons; that evolution proceeds by natural selection.

Michael D. Lemonick, *Time,* September 10, 2001

List of "Greatest Puzzles" Changes with Time

"Metaphysical" questions become scientific . . .

▷ Why is proton mass 1836 $\times$ electron mass?

▷ What accounts for the different strengths of the strong, weak, and electromagnetic interactions?

Some questions remain so long, we might forget that they are questions . . .

Why are charged-current weak interactions left-handed?

Some questions are (now seem to us) the wrong questions . . .

> Kepler's Great Question: Why exactly six planets in the observed orbits?

L. Wolfenstein, *PNAS* **100**, 5001–5003 (2003)

Sometimes we answer a Great Question before it is recognized as a scientific question

What sets the mass of the proton?
What accounts for the visible mass of the universe?

Answered by QCD almost before most people realized that QCD had made the question answerable.

The Theory of Everything

Laughlin & Pines, *PNAS* **97**, 28–31 (2000) proclaim the end of reductionism ("the science of the past"), which they identify with particle physics, and the triumph of emergent behavior, the study of complex adaptive systems ("the physics of the next century").

> Emergent: not simply derived from $\mathcal{L}$; governed by "higher organizing principles" (perhaps universal), relatively independent of the fundamental theory

The Theory of Everything . . .

But emergence is ubiquitous in particle physics . . .

Example. As QCD $\rightsquigarrow$ strongly coupled, new phenomena emerge $\Rightarrow$ graceful description entails new degrees of freedom, new effective theory.

- $\triangleright$ Confinement and chiral symmetry breaking
- $\triangleright$ Goldstone Bosons . . . "Little Higgs"

. . . as is synthesis of principles through experiment

Is emergence a stage or an end?

Some Other Meta-Questions

- ▷ Is this the Best of All Possible Worlds?
- ▷ Is Nature simple or complex?
  Which aspects will have beautiful "simple" explanations and which will remain complicated?
- ▷ Are Nature's Laws the same at all times & places?
- ▷ Can one theoretical structure account for "everything," or should we be content with partial theories useful in different domains?

Exercise.

Explain in a paragraph or two how your current research project relates to Great Questions about Nature or is otherwise irresistibly fascinating.

Be prepared to present your answer to a science writer at a SSI social event.

A Decade of Discovery Past . . .

- ▷ Electroweak theory $\rightarrow$ law of nature $[Z,\, e^+e^-,\, \bar{p}p,\, \nu N,\, (g-2)_\mu,\, \ldots]$
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}, reactors]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, ions, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct $\mathcal{CP}$ violation in $K \rightarrow \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate $\mathcal{CP}$ [$e^+e^- \rightarrow B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Understanding the Everyday

- Why are there atoms?
- Why chemistry?
- Why stable structures?
- What makes life possible?

If electroweak symmetry were not hidden . . .

▷ Quarks and leptons would remain massless

▷ QCD would confine them into color-singlet hadrons

▷ *Nucleon mass would be little changed,* but proton outweighs neutron

▷ QCD breaks EW symmetry, gives $(1/2500\times$observed) masses to W, Z, so weak-isospin force doesn't confine

▷ Rapid! β-decay $\Rightarrow$ lightest nucleus is one neutron; no hydrogen atom

▷ Probably some light elements in BBN, but ∞ Bohr radius

▷ No atoms (as we know them) means no chemistry, no stable composite structures like the solids and liquids we know

. . . the character of the physical world would be profoundly changed

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV.

We do not know the nature of the new force.

What is the nature of the mysterious new force that hides electroweak symmetry?

- ▷ A fundamental force of a new character, based on interactions of an elementary scalar
- ▷ A new gauge force, perhaps acting on undiscovered constituents
- ▷ A residual force that emerges from strong dynamics among the weak gauge bosons
- ▷ An echo of extra spacetime dimensions

Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:

Find the Higgs boson and explore its properties.

- ▷ Is it there? How many?
- ▷ Verify $J^{PC} = 0^{++}$
- ▷ Does H generate mass for gauge bosons, fermions?
- ▷ How does H interact with itself?

Finding the Higgs boson starts a new adventure!

The Meaning of Identity

Varieties of Matter

▷ What sets masses & mixings of quarks & leptons?

▷ What is $\mathcal{CP}$ violation trying to tell us?

▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the universe.

All fermion masses and mixings mean new physics

▷ Will new kinds of matter help us see the pattern?
sterile neutrinos, superpartners, dark matter . . .

Many extensions to EW theory entail dark matter candidates.

Supersymmetry is highly developed, and has several important consequences:

- ▷ Predicts that the Higgs field condenses (breaking EW symmetry), if the top quark is heavy
- ▷ Predicts a light Higgs mass
- ▷ Predicts cosmological cold dark matter
- ▷ In a unified theory, explains the values of the standard-model coupling constants

The Unity of Quarks & Leptons

$\triangleright$ What do quarks and leptons have in common?

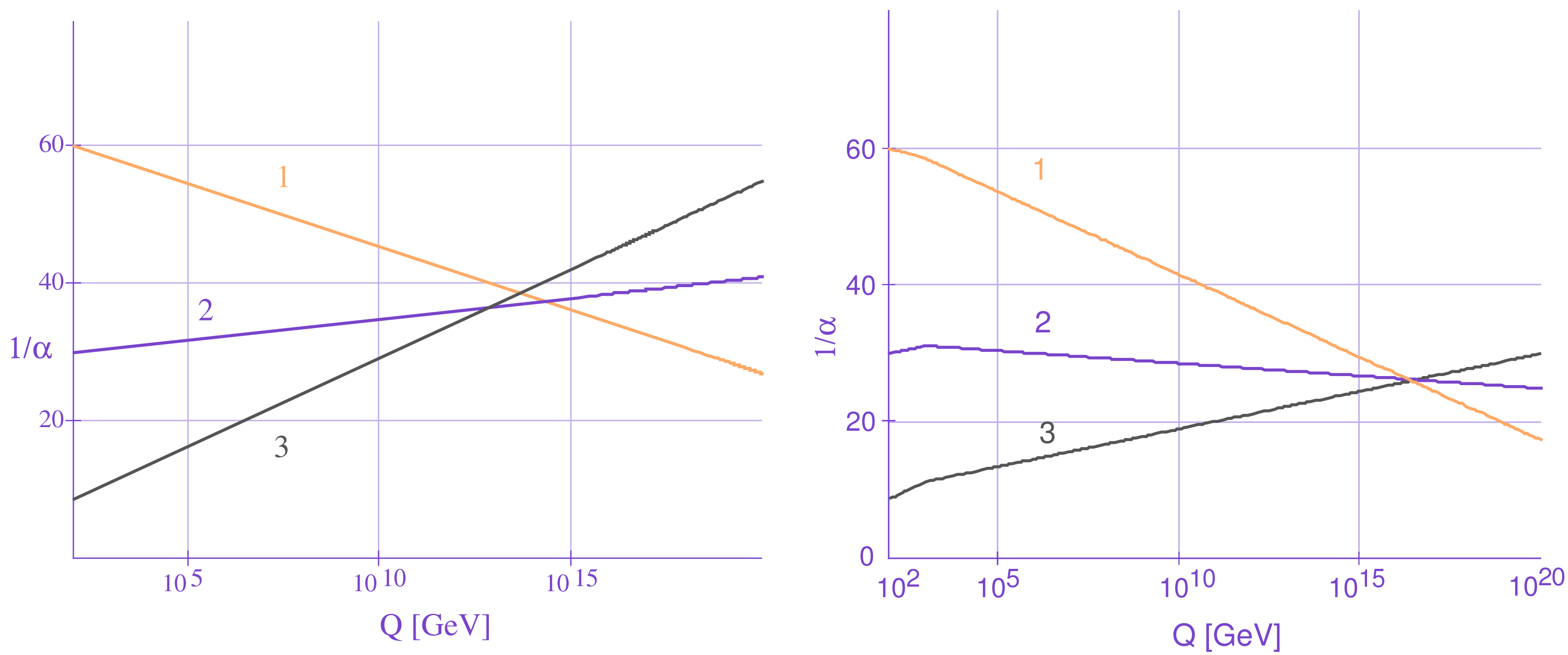
$\triangleright$ Why are atoms so remarkably neutral?

$\triangleright$ Which quarks go with which leptons?

$\triangleright$ Quark-lepton extended family $\rightsquigarrow$ proton decay:
SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y

$\triangleright$ Unified theories $\rightsquigarrow$ coupling constant unification

$\triangleright$ Rational fermion mass pattern at high energy?
(Masses run, too)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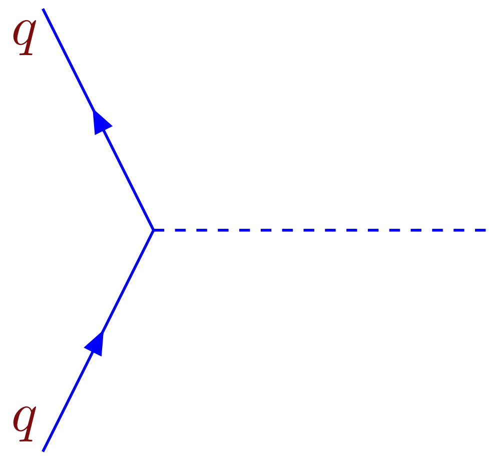
10^2
10^5
10^10
10^15
10^20
Q [GeV]

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

$$G_{\text{Newton}} \textit{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV } \textit{large}$$

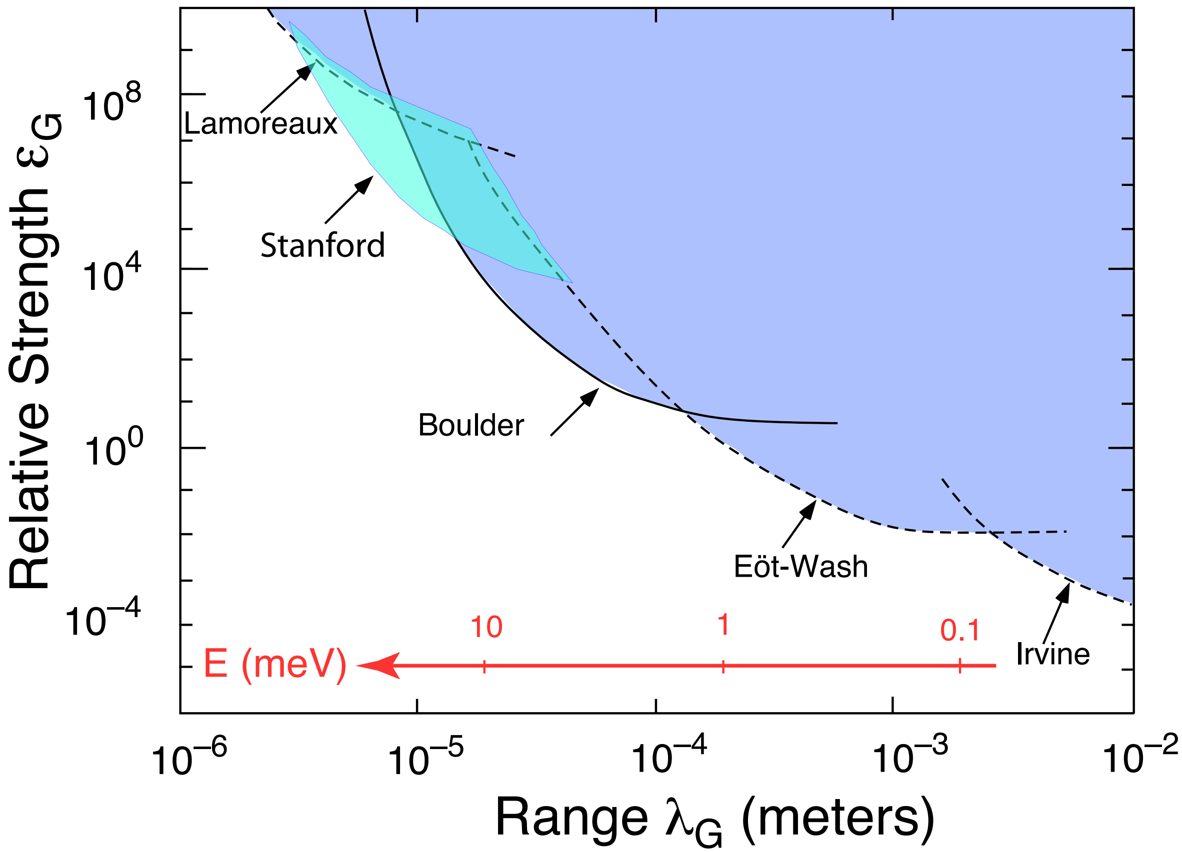


$$G \quad \sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

Gravity follows Newtonian force law down to $\lesssim 1$ mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_G \exp(-r_{12}/\lambda_G)\right]$$



(long-distance alternatives to dark matter)

But gravity is not always negligible . . .

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|(\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

contributes field-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8}}$$

Adding vacuum energy density $\varrho_{\mathsf{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = \frac{8\pi G_{\mathsf{Newton}}}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_{\mathsf{Newton}}}{c^4} \varrho_{\mathsf{vac}}$$

Observed vacuum energy density $\varrho_{\text{vac}} \lesssim 10^{-46}$ GeV^4

≈ 10 MeV$/\ell$ or 10^{-29} g cm^{-3}

But $M_H \gtrsim 114$ GeV $\Rightarrow$

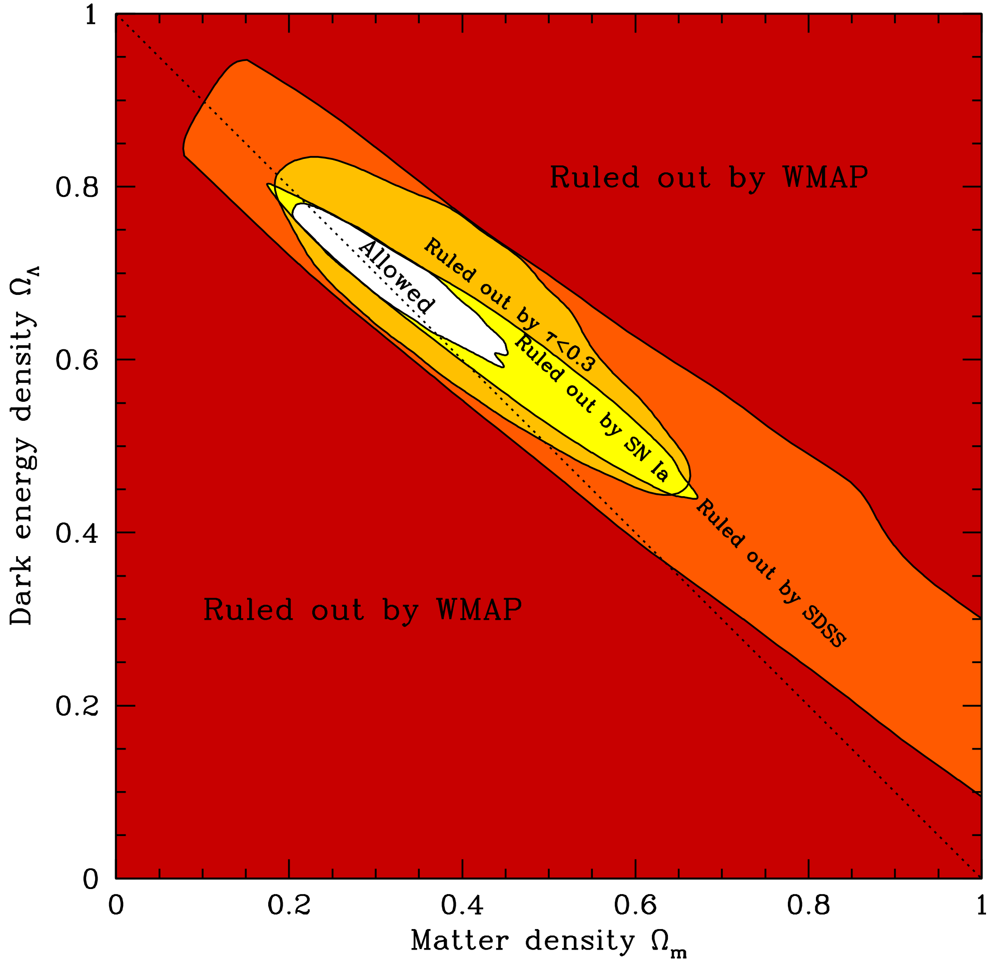
$$\varrho_H \gtrsim 10^8 \text{ GeV}^4$$

MISMATCH BY 54 ORDERS OR MAGNITUDE

A chronic dull headache for thirty years . . .

Why is empty space so nearly massless?

Evidence that vacuum energy is present . . .



. . . recasts the old problem and gives us properties to measure

How to separate EW, higher scales?

Traditional: change electroweak theory to understand

why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve the hierarchy problem: *extend the standard model*

$$\mathrm{SU(3)_c \otimes SU(2)_L \otimes U(1)}_Y \begin{cases} \text{composite Higgs boson} \\ \text{technicolor / topcolor} \\ \text{supersymmetry} \\ \ldots \end{cases}$$

Newer approach: ask why gravity is so weak

why $M_{\text{Planck}} \gg$ electroweak scale

A New Conception of Spacetime

- Could there be more space dimensions than we have perceived?
- What is their size?
- What is their shape?
- How do they influence the world?
- How can we map them?

9 or 10 needed for consistency of string theory

Suppose at scale R ... Gravity propagates in $4+n$ dimensions

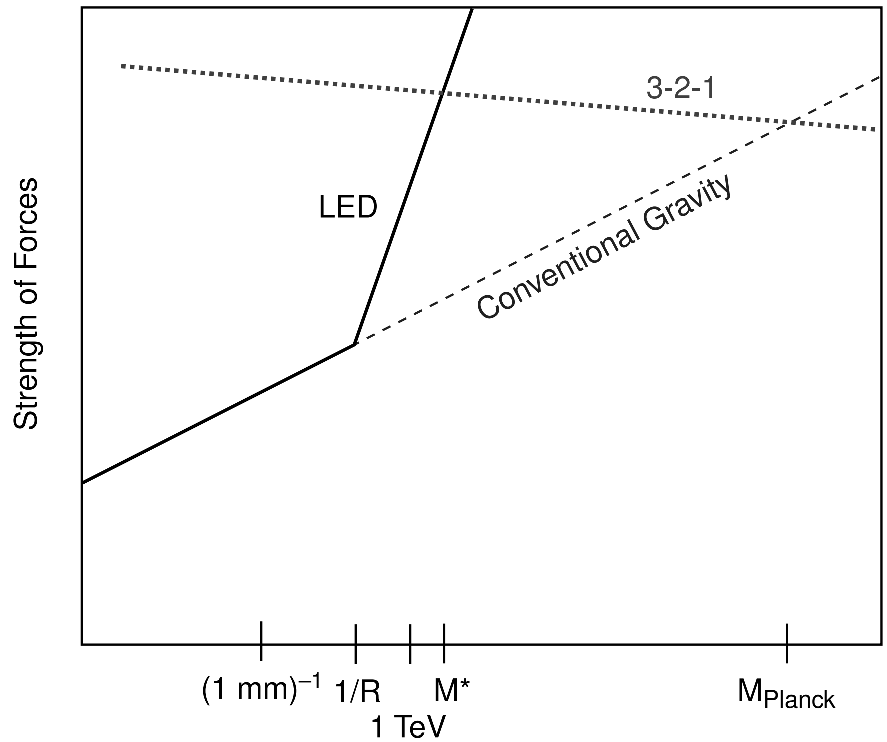
Force law changes:

Gauss's law $\Rightarrow$ $G_{\rm N} \sim M_{\rm Planck}^{-2} \sim M^{\star\,-n-2} R^{-n}$ $M^\star$: gravity's true scale

Example: $M^\star = 1$ TeV $\Rightarrow R \lesssim 10^{-3}$ m for $n = 2$

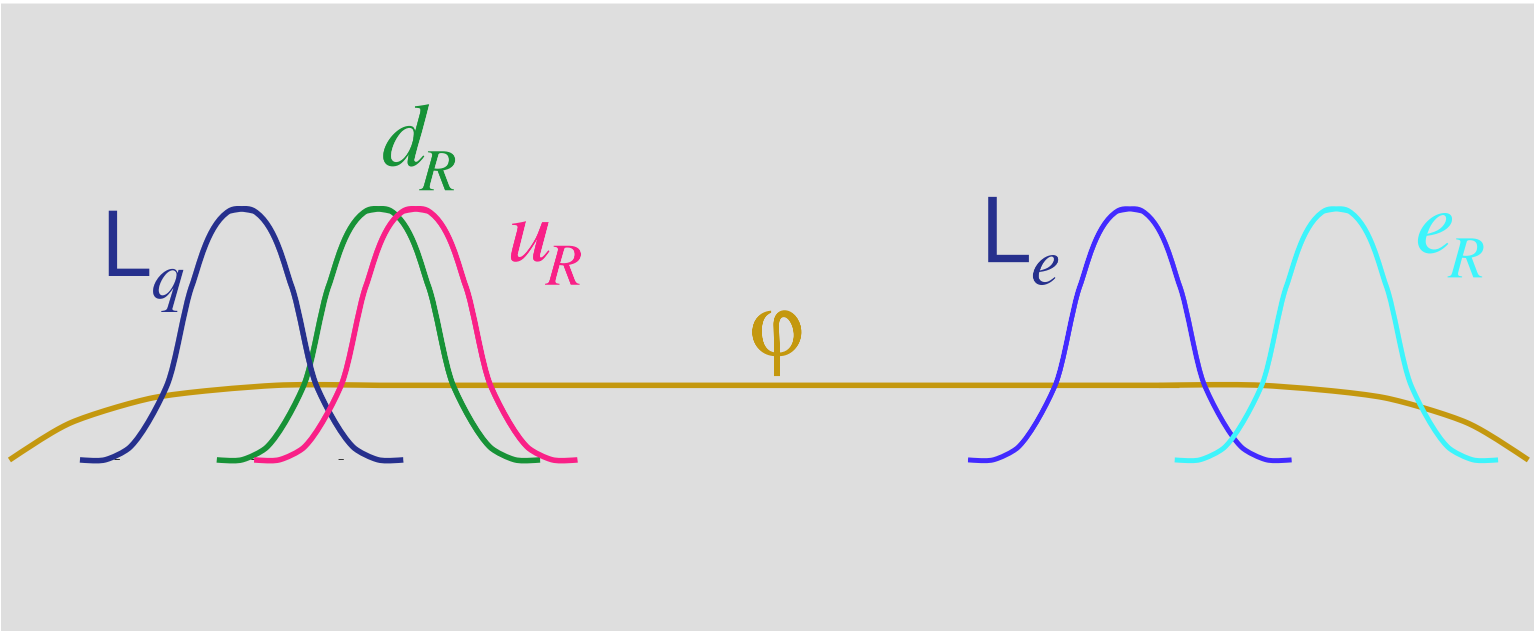
Traditional: Use 4-d force law to extrapolate gravity to higher energies; $M_{\rm Planck} \sim$ scale where Gravity, SM forces are of comparable strength

IF Gravity probes extra dimensions for $E \lesssim 1/R$, Gravity meets other forces at $E = M^\star \ll M_{\rm Planck}$



$M_{\rm Planck}$ is a mirage (false extrapolation)!

Might Extra Dimensions Explain the Range of Fermion Masses?



Different fermions ride different tracks in the fifth dimension

Small offsets in the new coordinate $\Rightarrow$ exponential differences in masses

Other extradimensional delights . . .

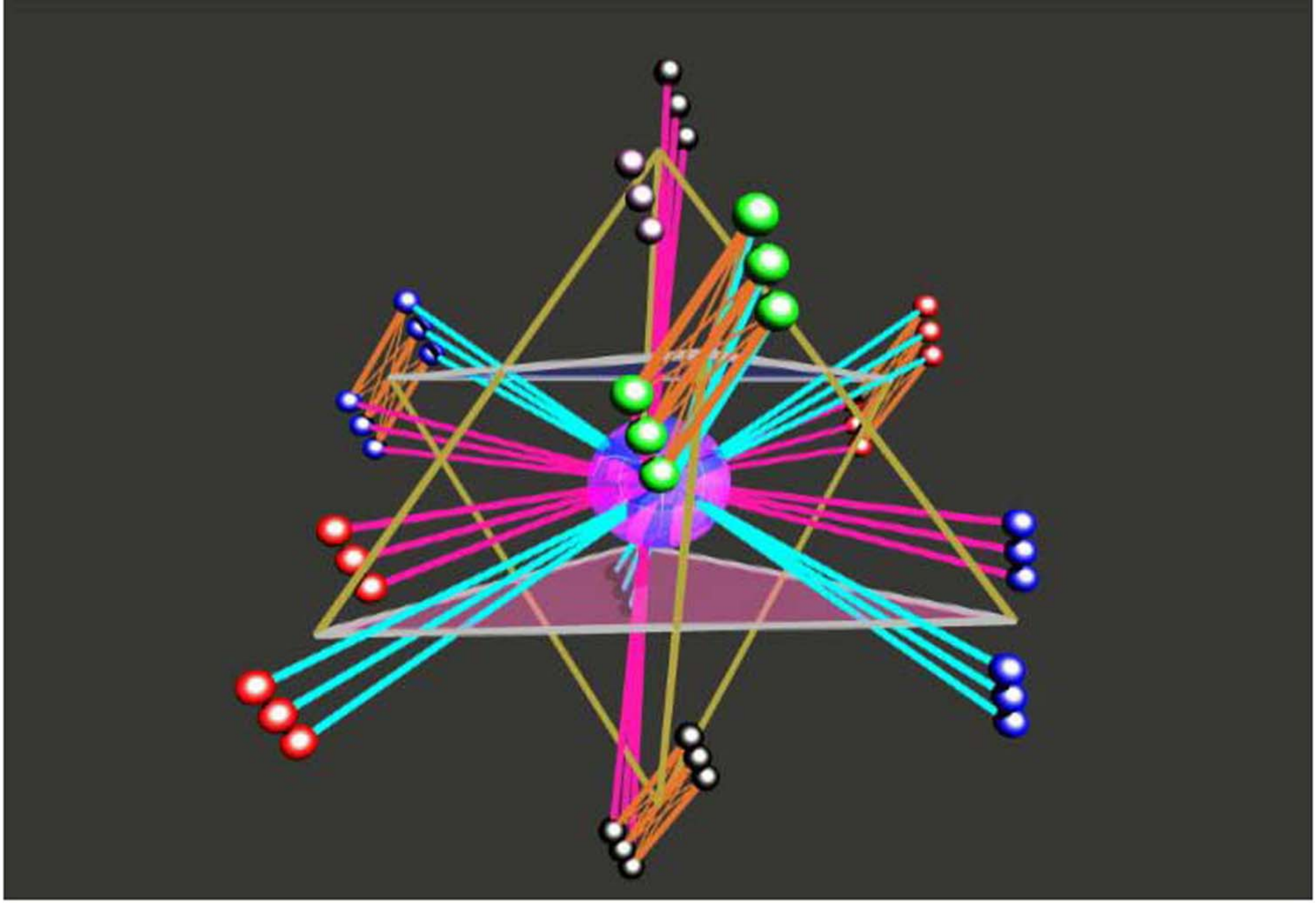
(provided gravity is intrinsically strong)

▷ If the size of extra dimensions is close to 10^{-19} m, tiny black holes might be formed in high-energy collisions: explosive evaporation ⇒ collider hedgehogs, spectacular UHECR showers

▷ Collider experiments can detect graviton radiation (missing-energy signatures) or graviton exchange (angular distributions)

(Cf. Dyson v. Greene, http://www.nybooks.com/articles/17094)

Gravity is here to stay!



Click on the Above Image to Download a Quicktime Video.

(Please note, this is a large file (12.9 MB) and it requires Quicktime to view.

A Decade of Discovery Ahead . . .

- ▷ Higgs search and study; EWSB / 1-TeV scale [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ CP violation (B); Rare decays (K, D, . . .) [e^+e^-, $p^{\pm}p$, fixed-target]
- ▷ Neutrino oscillations [$\nu_{\odot}$, ν_{atm}, reactors, ν beams]
- ▷ Top as a tool [$p^{\pm}p$ colliders; e^+e^- LC]
- ▷ New phases of matter; hadronic physics [heavy ions, ep, fixed-target]
- ▷ Exploration! [colliders, precision measurements, tabletop, . . .]
  Extra dimensions / new dynamics / SUSY / new forces & constituents
- ▷ Proton decay [underground]
- ▷ Composition of the universe [SN Ia, CMB, LSS, underground, colliders]

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, . . .)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

. . . learn the right questions to ask . . .

. . . and rewrite the textbooks!

Announcing a Competition:

Nature's Neglected Puzzles

The challenge: Propose a question not on the SSI2004 list, and explain *briefly* why it belongs in the pantheon of Nature's Greatest Puzzles.

The reward for the Best Eleventh Question: A bottle of California's finest sparkling wine and untold fame: an eleven-minute talk to present your question at the Wednesday, August 11, Discussion Session.

SSI Students may submit written entries until the close of the Monday, August 9, session.