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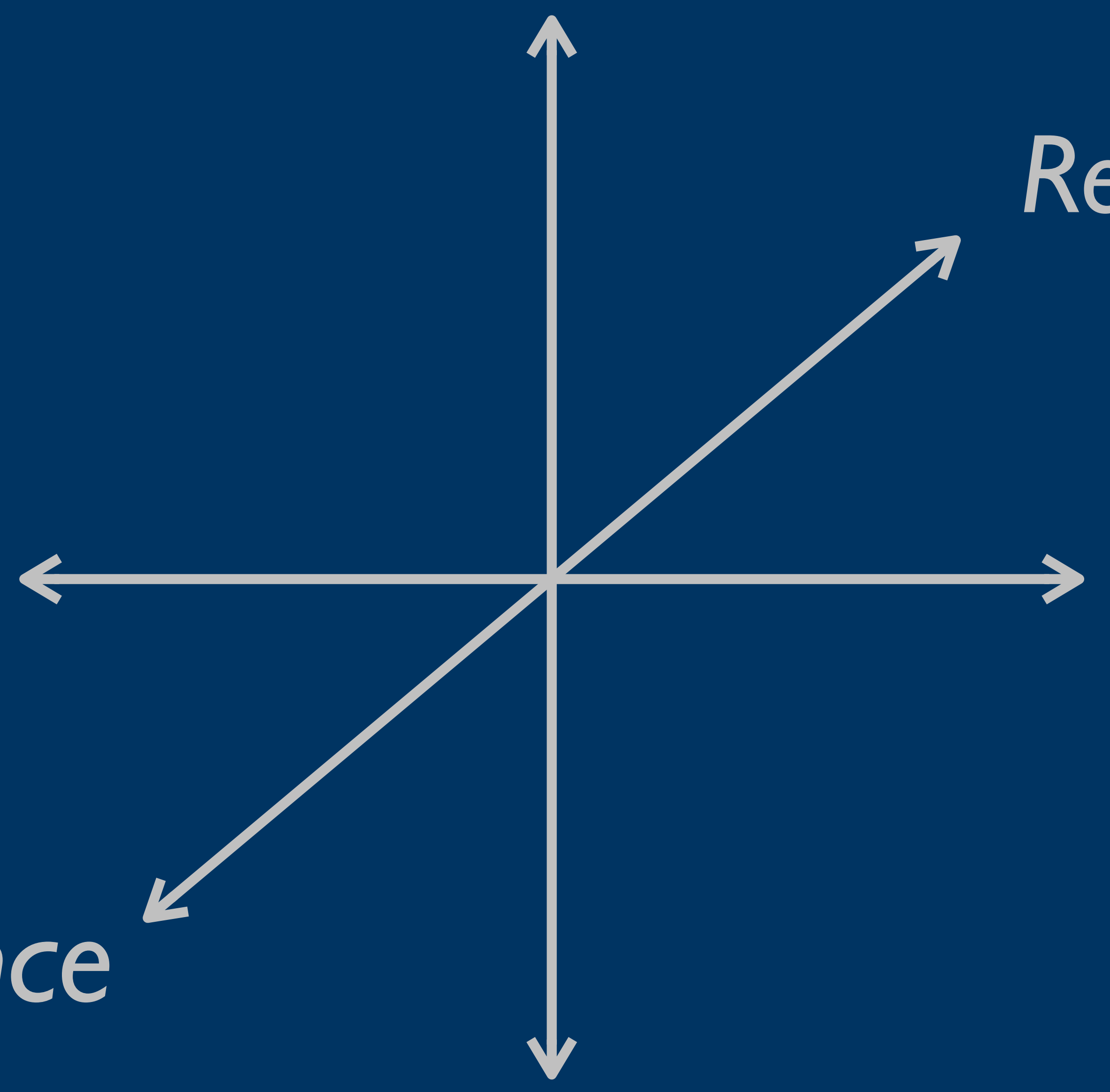
Chris Quigg · *Big Questions* · 7 March 2022

Styles of investigation

Observation · Experiment · Phenomenology · Formal Theory



Search for Microscopic Laws

Reduction

Inspiration from natural phenomena

Imagination

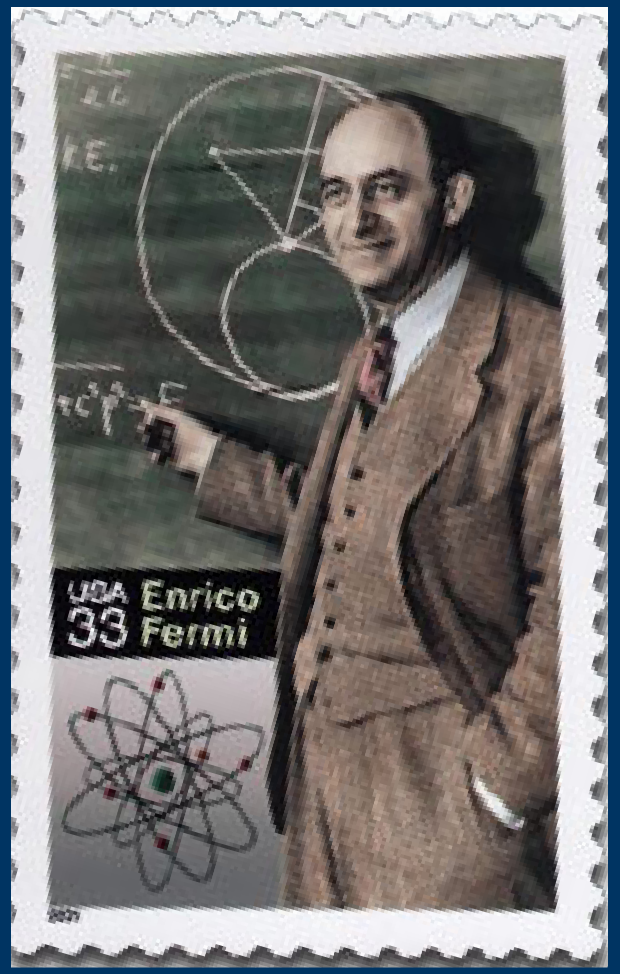
Emergence

Fascination with Phenomena

Where is your home base? How far do you roam?

A plan for 70 years … (or 50)?

E_p = 5000 TeV, \$$1.7 \times 10^{11}$



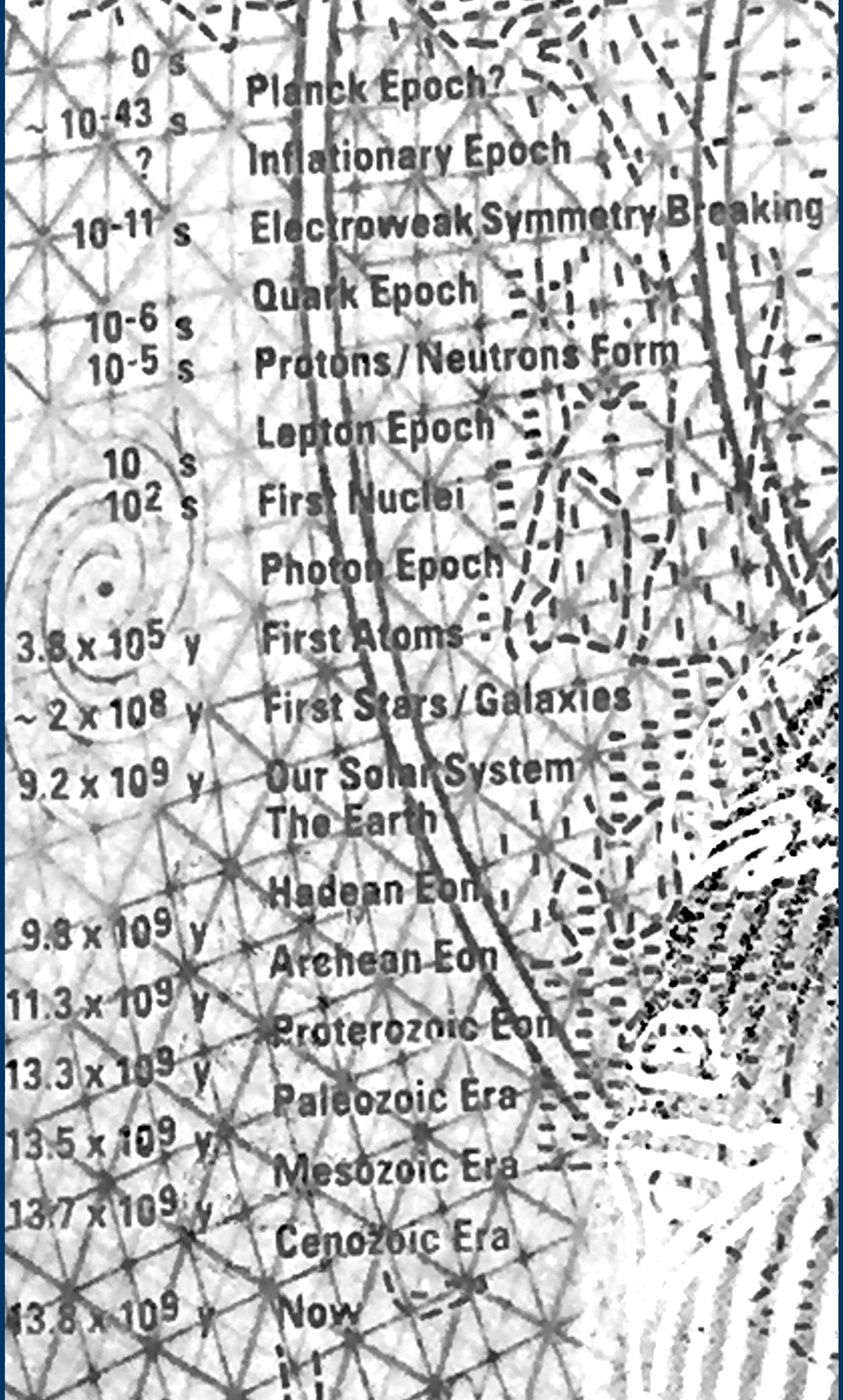
A program for several generations must be flexible as well as visionary and must not foreclose other promising initiatives.
Scientific imperatives evolve; technology advances.

The great lesson of 20th-century science

The human scale of space and time is not privileged
for understanding Nature, and may even be disadvantaged.

Renormalization group analysis · effective field theories
Resolution and extent in time and distance
Diversity and scale diversity in experimental undertakings

The discovery that the human scale is not preferred
is as important as the discoveries that
the human location is not privileged (Copernicus)
and that there is no preferred inertial frame (Einstein)
and will prove as influential.



CHF200 security stripe

Scales …

Recent history: *H* or something new on TeV scale

Where is the next important scale?

(Higher energies needed to measure *HHH*,
verify that *H* regulates $W_L W_L$.)

Unification scale: $10^{15–16}$ GeV,
Planck scale: 10^{19} GeV out of direct reach.

At what scale are
charged-fermion masses set? neutrino masses set?
New physics at 1×, 10×, 100×, … EW scale?
New phenomena at macroscopic scales?

The standard model did not always exist.

What do we know that is not true?
(or for which evidence is lacking)

Parity conservation

Planck scale

How to progress?

Explore the regions of the unknown, the unanswered questions.

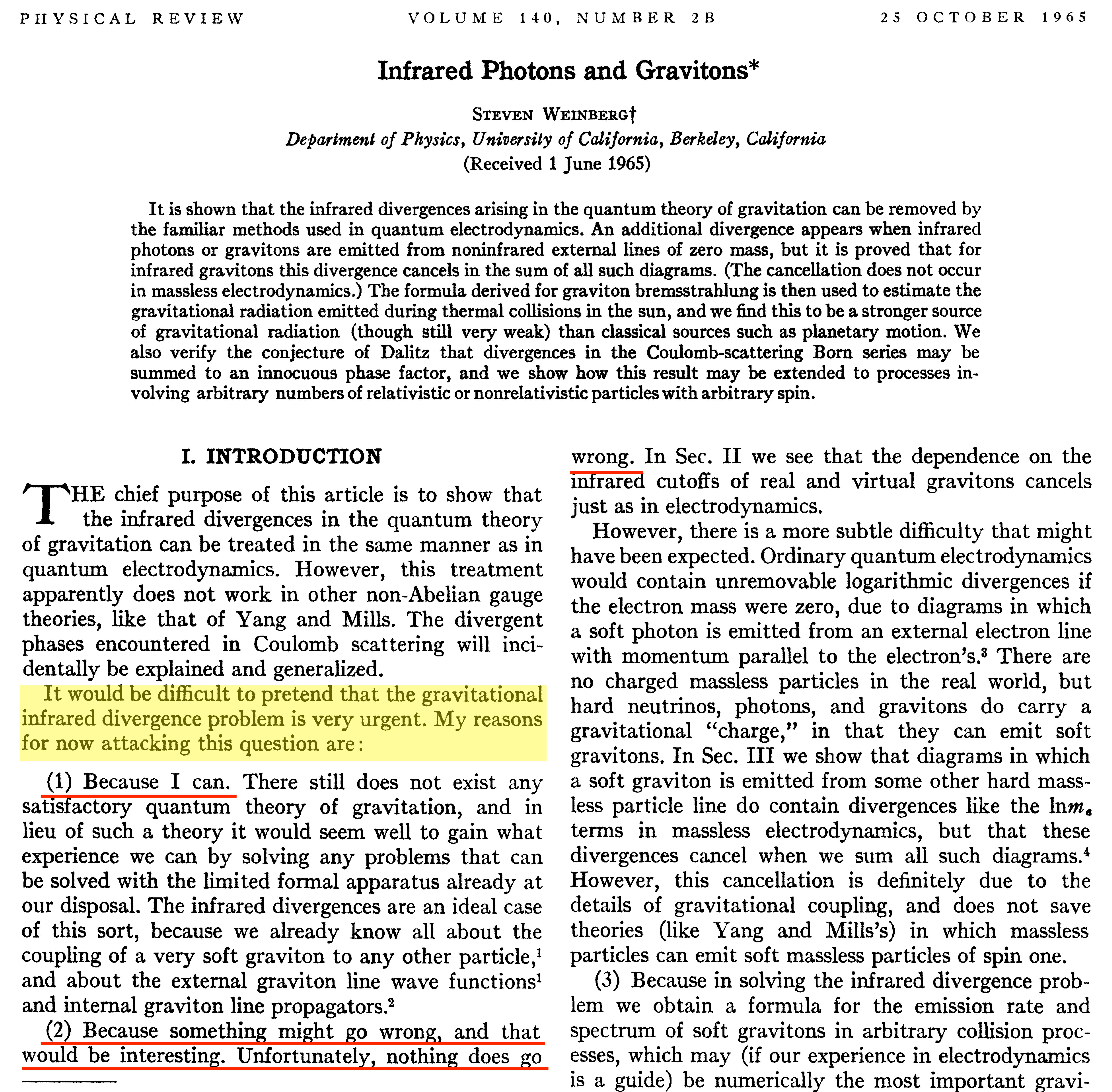
Try to divine where the secrets are hidden.

Seek out soft spots in our current understanding,
especially where the stories we tell are
unprincipled ≡ not founded on sound principles.

Supersymmetry: + R-parity + μ problem + tame FCNC
Big-bang cosmology: + inflation + dark matter + dark energy

Particle content, gauge symmetries of the standard model

We often answer *Big Questions*
by posing and resolving small questions



PHYSICAL REVIEW VOLUME 140, NUMBER 2B 25 OCTOBER 1965

Infrared Photons and Gravitons*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California

(Received 1 June 1965)

It is shown that the infrared divergences arising in the quantum theory of gravitation can be removed by the familiar methods used in quantum electrodynamics. An additional divergence appears when infrared photons or gravitons are emitted from noninfrared external lines of zero mass, but it is proved that for infrared gravitons this divergence cancels in the sum of all such diagrams. (The cancellation does not occur in massless electrodynamics.) The formula derived for graviton bremsstrahlung is then used to estimate the gravitational radiation emitted during thermal collisions in the sun, and we find this to be a stronger source of gravitational radiation (though still very weak) than classical sources such as planetary motion. We also verify the conjecture of Dalitz that divergences in the Coulomb-scattering Born series may be summed to an innocuous phase factor, and we show how this result may be extended to processes involving arbitrary numbers of relativistic or nonrelativistic particles with arbitrary spin.

I. INTRODUCTION

THE chief purpose of this article is to show that the infrared divergences in the quantum theory of gravitation can be treated in the same manner as in quantum electrodynamics. However, this treatment apparently does not work in other non-Abelian gauge theories, like that of Yang and Mills. The divergent phases encountered in Coulomb scattering will incidentally be explained and generalized.

It would be difficult to pretend that the gravitational infrared divergence problem is very urgent. My reasons for now attacking this question are:

(1) Because I can. There still does not exist any satisfactory quantum theory of gravitation, and in lieu of such a theory it would seem well to gain what experience we can by solving any problems that can be solved with the limited formal apparatus already at our disposal. The infrared divergences are an ideal case of this sort, because we already know all about the coupling of a very soft graviton to any other particle,[1] and about the external graviton line wave functions[1] and internal graviton line propagators.[2]

(2) Because something might go wrong, and that would be interesting. Unfortunately, nothing does go wrong. In Sec. II we see that the dependence on the infrared cutoffs of real and virtual gravitons cancels just as in electrodynamics.

However, there is a more subtle difficulty that might have been expected. Ordinary quantum electrodynamics would contain unremovable logarithmic divergences if the electron mass were zero, due to diagrams in which a soft photon is emitted from an external electron line with momentum parallel to the electron's.[3] There are no charged massless particles in the real world, but hard neutrinos, photons, and gravitons do carry a gravitational "charge," in that they can emit soft gravitons. In Sec. III we show that diagrams in which a soft graviton is emitted from some other hard massless particle line do contain divergences like the $\ln m_e$ terms in massless electrodynamics, but that these divergences cancel when we sum all such diagrams.[4] However, this cancellation is definitely due to the details of gravitational coupling, and does not save theories (like Yang and Mills's) in which massless particles can emit soft massless particles of spin one.

(3) Because in solving the infrared divergence problem we obtain a formula for the emission rate and spectrum of soft gravitons in arbitrary collision processes, which may (if our experience in electrodynamics is a guide) be numerically the most important gravi-

Learn about other approaches, other fields.

EWSB and superconductivity:

Ginzburg–Landau $\longleftrightarrow$ Higgs

BCS $\longleftrightarrow$ Technicolor, …

Go to seminars! Learn from colleagues!

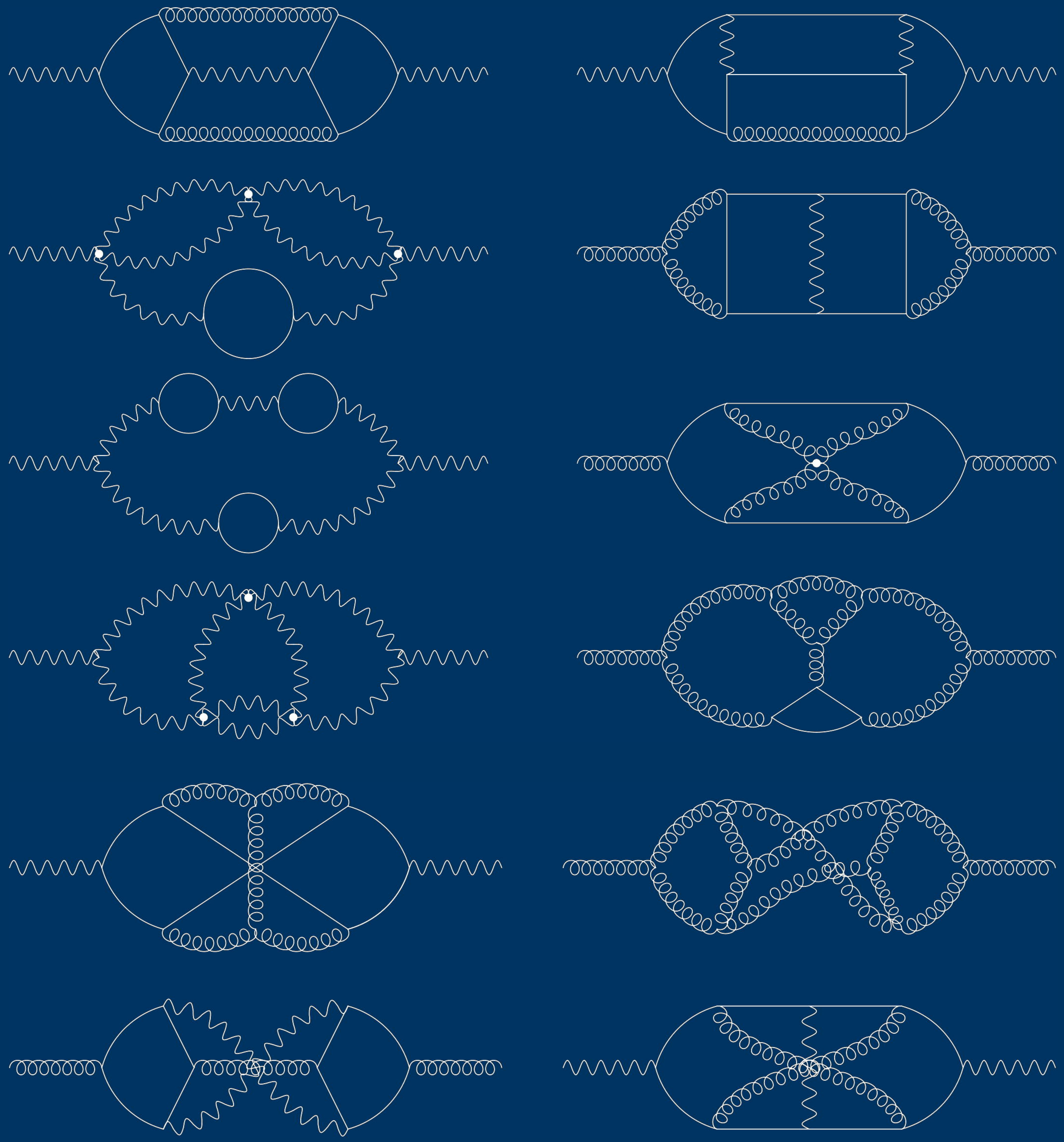
Mix with experimenters.

Have we misconstrued naturalness and the hierarchy problem?

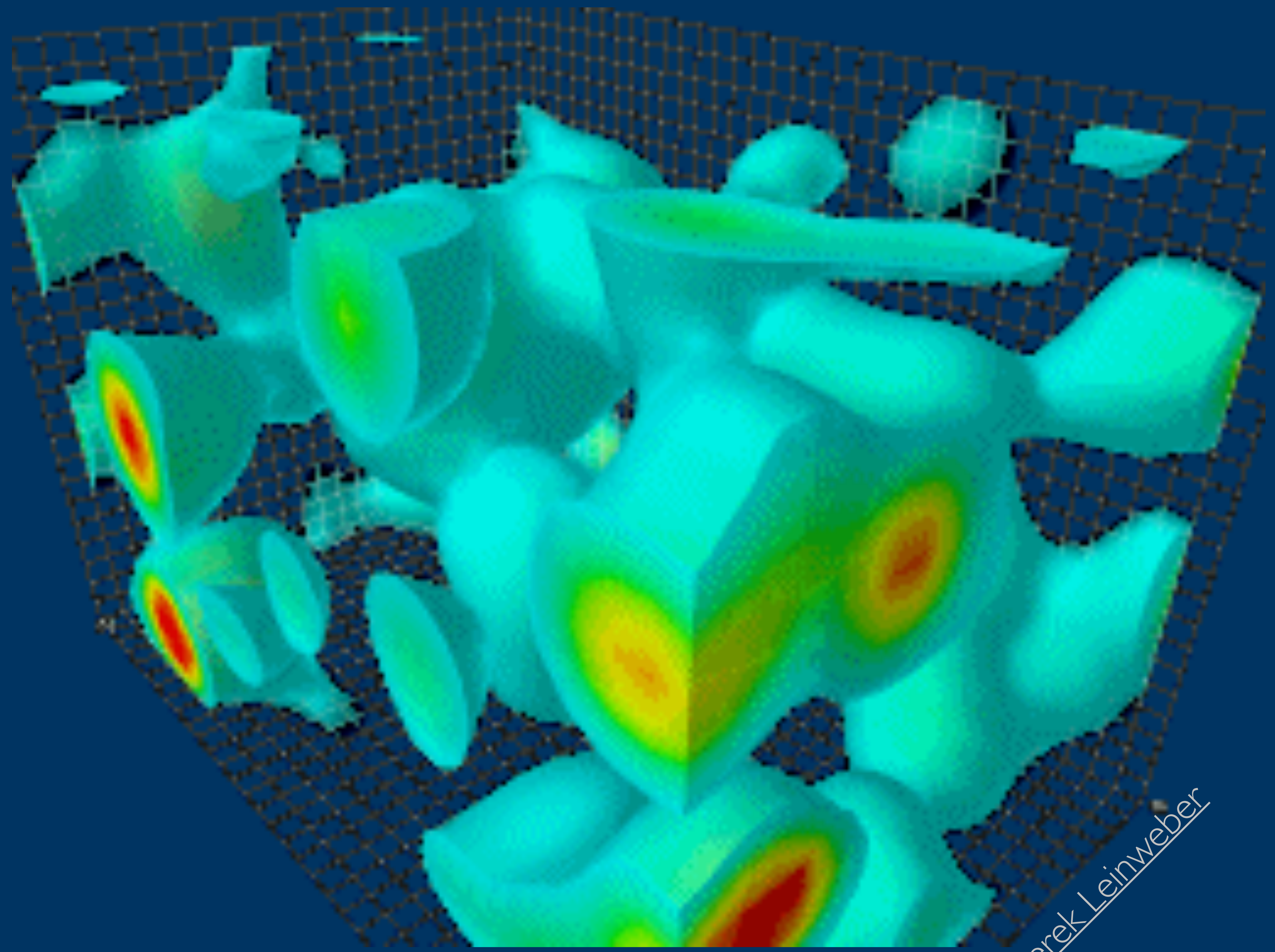
vacuum energy problem
quantum sensitivity of M_H
undesirability of elementary scalars
must small masses rely on symmetries?

*Did the existence of two once-and-done solutions
to the hierarchy problem (SUSY and Technicolor)
lead us to view the discipline of naturalness too simplistically?*

QCD



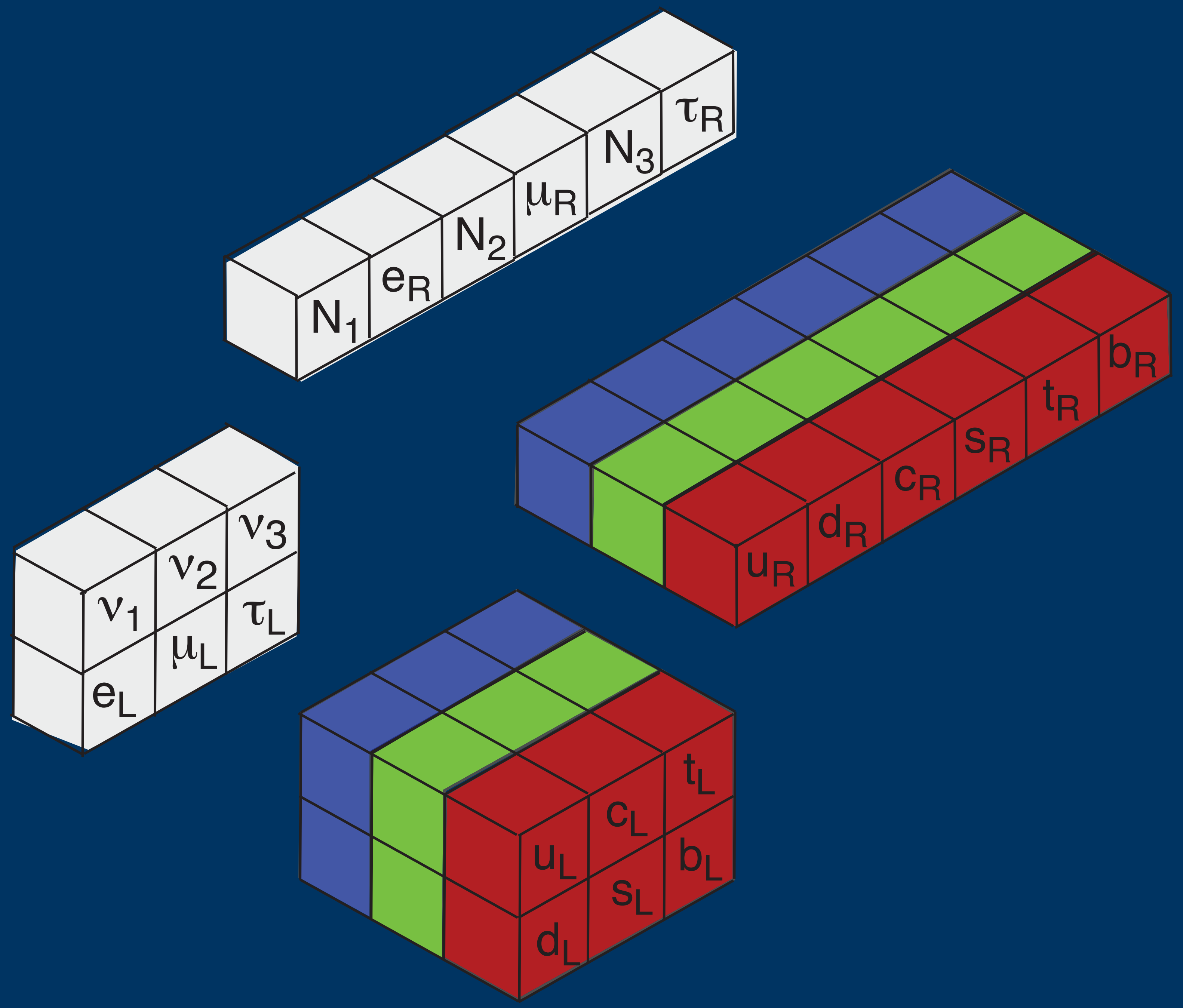
Florian Herren



Derek Leinweber

Flavor: the problem of identity

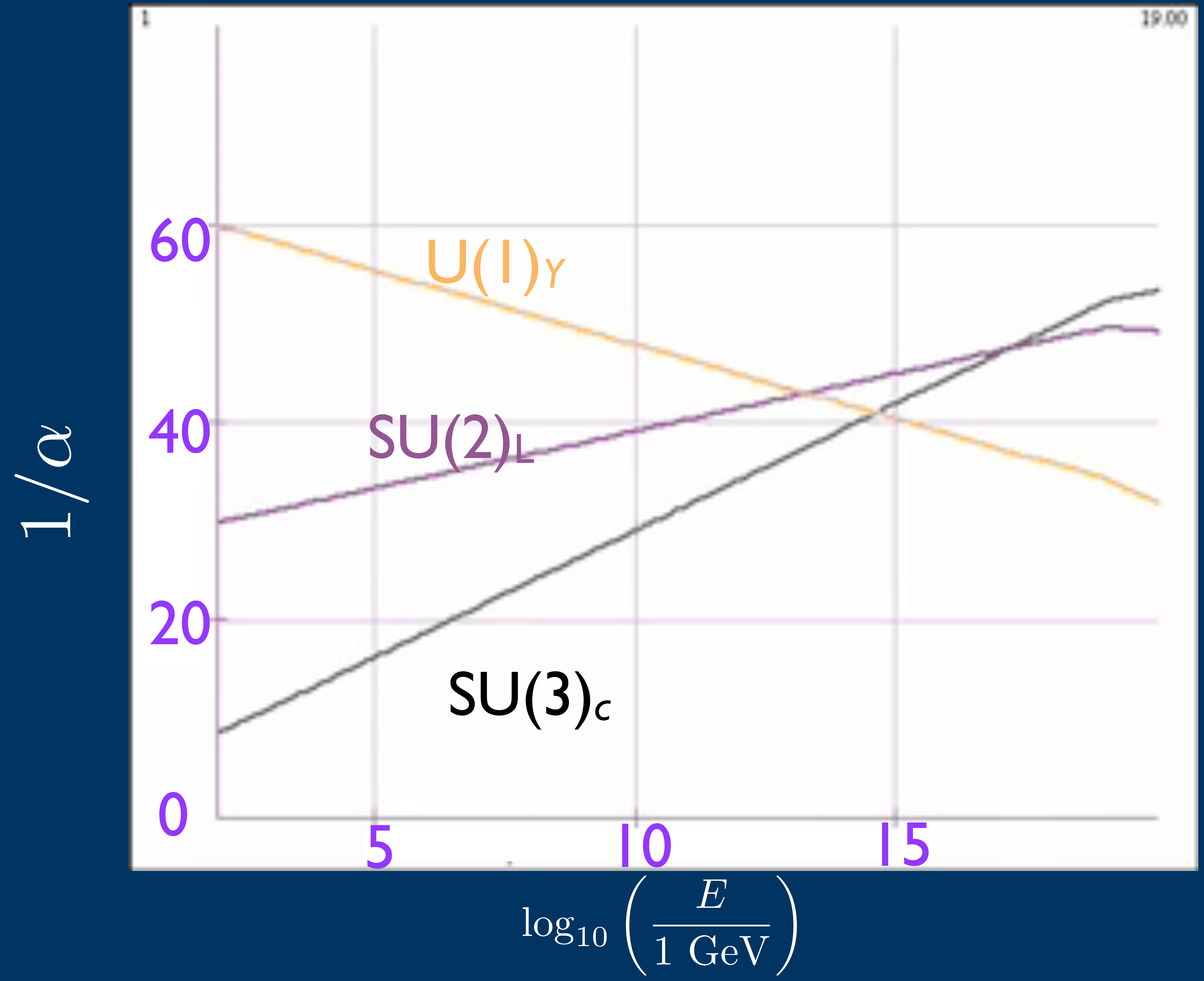
	Standard-model parameters
3	Coupling parameters α_s, α_{EM}, $\sin^2\theta_W$
2	Parameters of the Higgs potential
1	Vacuum phase (QCD)
6	Quark masses
3	Quark mixing angles
1	CP-violating phase
3	Charged-lepton masses
3	Neutrino masses
3	Leptonic mixing angles
1	Leptonic CP-violating phase (+ Majorana phases?)
26^+	Arbitrary parameters



Why no sign of flavor-changing neutral currents?

Unified Theory ⊃ SU(3)$_c$⊗SU(2)$_L$⊗U(1)$_Y$

Quark–lepton connection
Lepton number as 4th color?
New (leptoquark) gauge interactions?
Symmetry breaking mechanism?
Unstable proton?
n–$\bar{n}$ oscillations?
Coupling-constant unification?
$\sin^2\theta_W \equiv \alpha/\alpha_2$ evolution



Astro/Cosmo/Particle Physics

We do not know what the Universe at large is made of: subliminal (dark) matter?

We do not know the complete thermal history of the universe

e.g., $H_0^{\text{local}} - H_0^{\text{Planck}} \approx (4\text{–}6)\sigma$

We have not accounted for the predominance
of matter over antimatter in the observed universe

We do not know what provoked inflation (if it happened)

We do not know why the expansion of the universe is accelerating

Learn to read new strata · Refine precision · Incorporate gravitational radiation

Neutrino physics

Accelerator-based NOvA, T2K, μBooNE

⟶ DUNE, Hyper-K, new short-baseline experiments

Tritium β-decay: KATRIN, …

$\beta\beta_{0\nu}$ searches

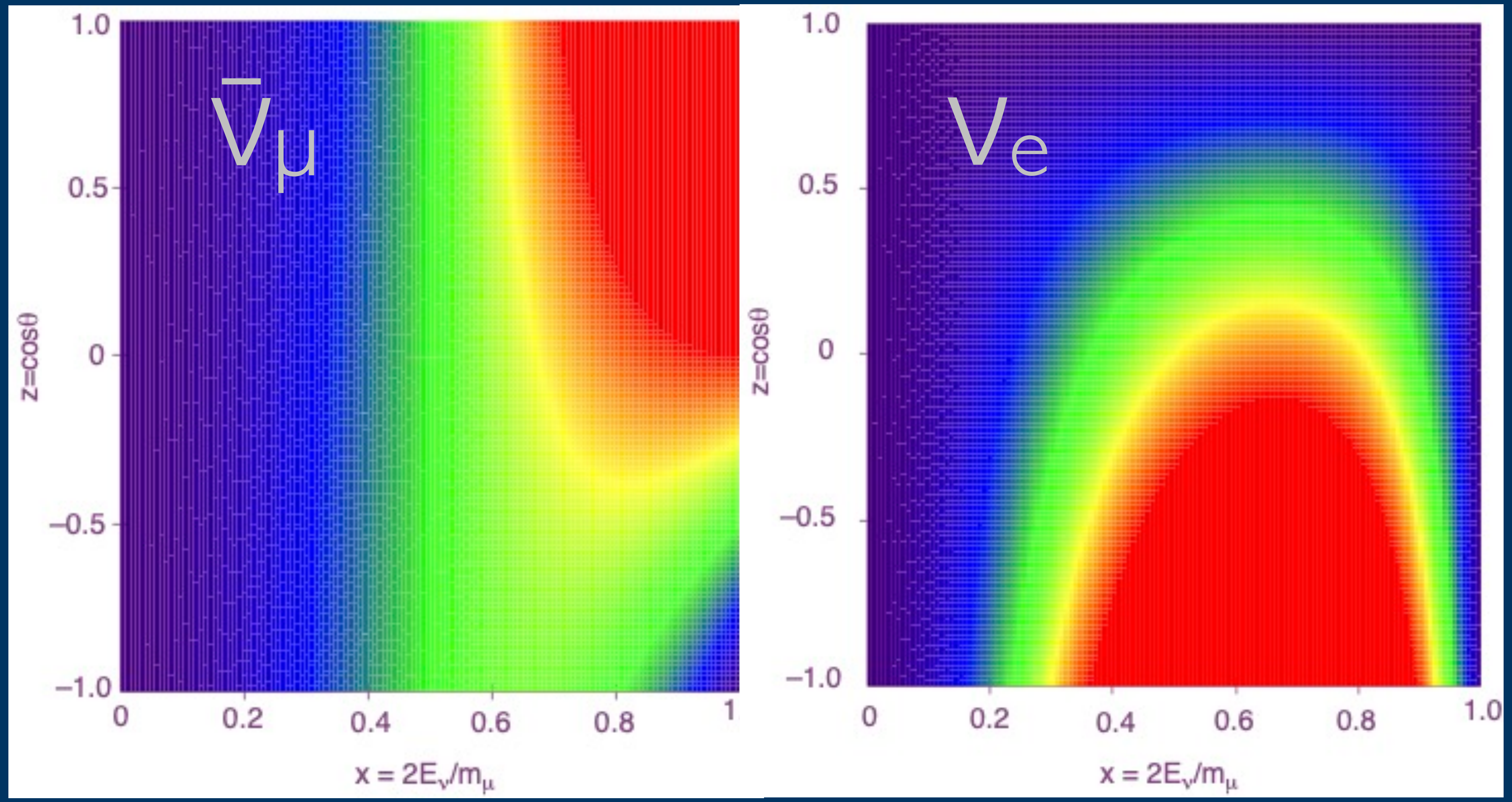
experiments that rely on reactors (JUNO)

or natural sources (IceCube, KM3Net)

cosmic neutrino background: each species, now: ≈ 56/cm^3, $T_\nu \approx$ 2K ≈ 1.7×10^{-4} eV

flavor mix of extraterrestrial ν at Earth: flavor mix at source, *stability* of ν species, …

Neutrino Factory



A muon storage ring could provide a very strong second act
for the coming generation of accelerator-based neutrino experiments.

Imagine on-campus experiments using 10^{20} ν / year:
thin targets, polarized targets, active targets to complement
nucleon-structure "femtoscopy" programs carried out in electron scattering
Gomez-Cadenas & Harris (2002)

“Tabletop” experiments

Electric dipole moments: e

Magnetic anomaly: e^-, e^+

Magnetic moments: p, $\bar{p}$

Charge/mass ratio: p, $\bar{p}$

Matter vs. antimatter (Eőtvős) comparison

Snowmass suggestion: tell your colleagues what you need.

"Learning to See at the Large Hadron Collider," [arXiv:1001.2025].

"Unanswered Questions in the Electroweak Theory," Ann. Rev. Nucl. Part. Sci. 59, 505–555 (2009) [arXiv:0905.3187].

"Electroweak Symmetry Breaking in Historical Perspective," Ann. Rev. Nucl. Part. Sci. 65, 25 (2015) [arXiv:1503.01756].

"Notes on Lepton Gyromagnetic Ratios," [arXiv:2105.07866].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