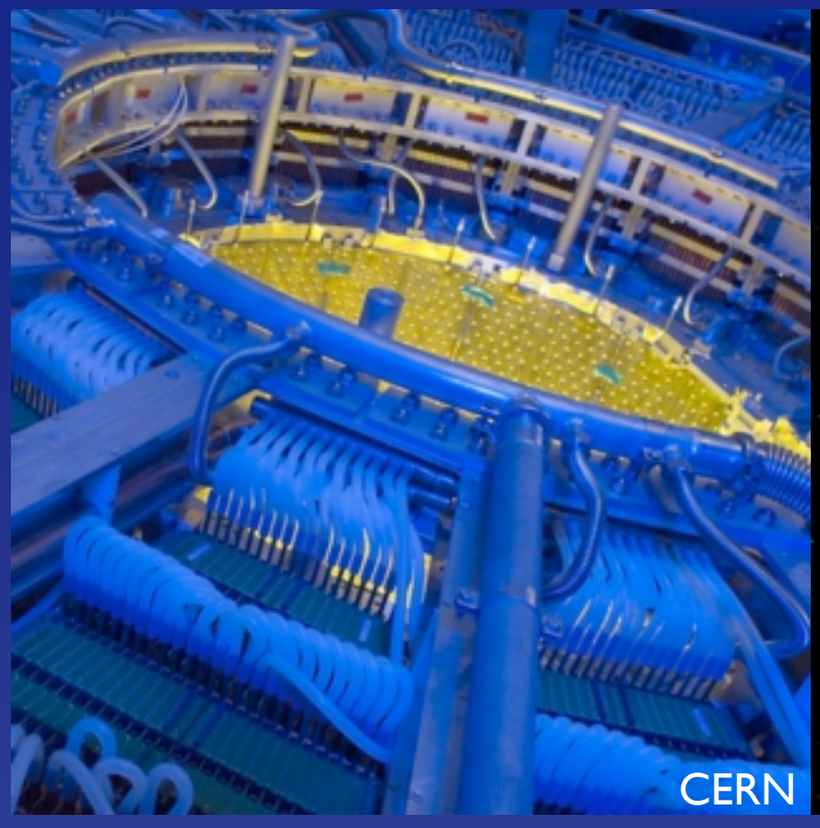
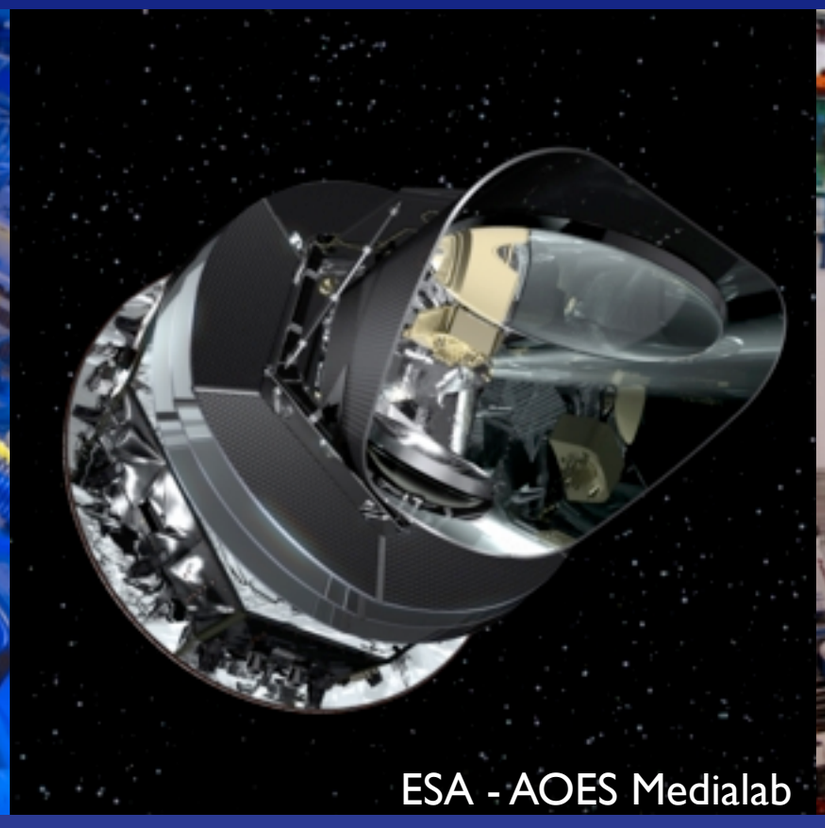
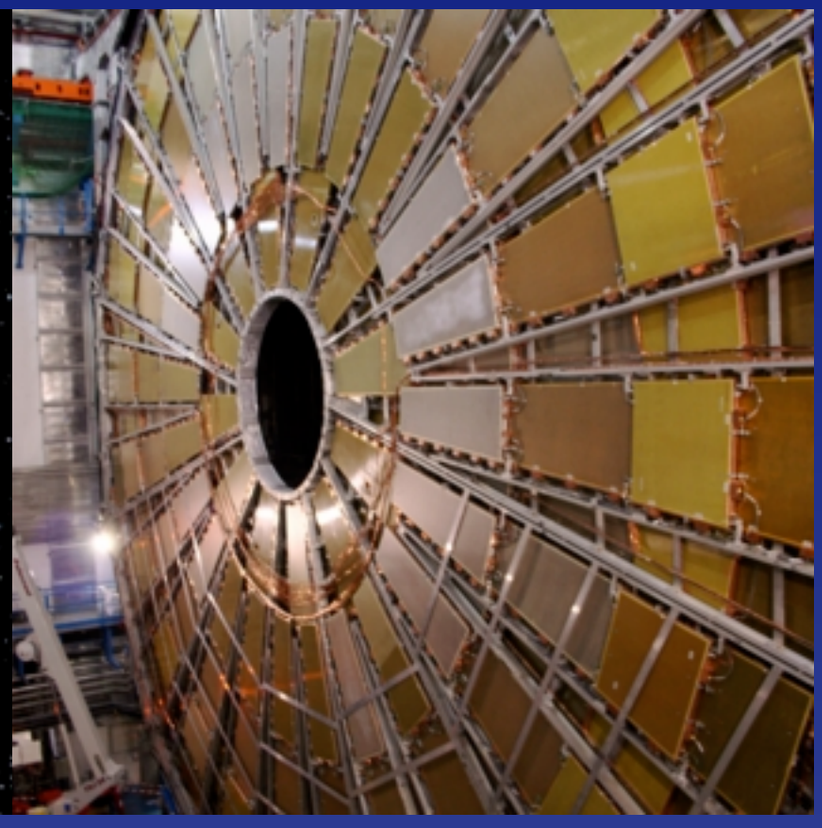
A New World of Particle Physics

Chris Quigg
Fermi National Accelerator Laboratory


CERN


ESA - AOES Medialab

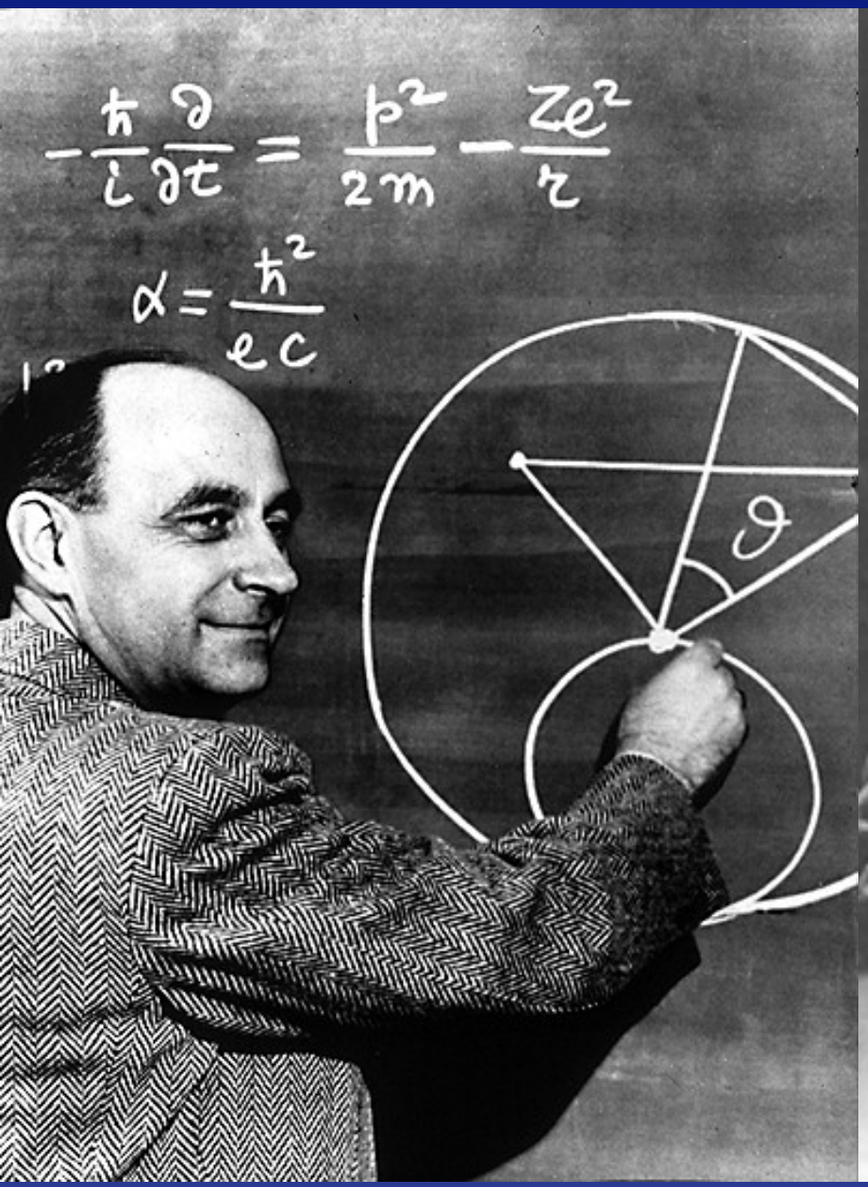


Discovery Center Inauguration · 21 January 2010

Thank you!

Tak!

Theory · Experiment · Observation



Enrico Fermi

Harry Moseley

Vera Rubin

Discovery Center Science Targets

Electroweak Symmetry Breaking

Quantum Chromodynamics in new regimes

Cosmic Microwave Background

New Instruments

Large Hadron Collider + ATLAS & ALICE

Planck Satellite

Discovery Center Education Goals

Mentoring Postdoctoral Fellows

Educating Graduate Students

Engaging High School Students & Teachers

Shaping Tomorrow's Faculty and Research Groups

Increasing the Participation of Women

Make Copenhagen an essential stop for young physicists

8.B

Nuclear Physics **22** (1961) 579—588; © *North-Holland Publishing Co., Amsterdam*

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

Volume 11, number 3 PHYSICS LETTERS **1 August 1964**

ELEMENTARY PARTICLES AND SU(4) *

B. J. BJØRKEN ** and S. L. GLASHOW ***

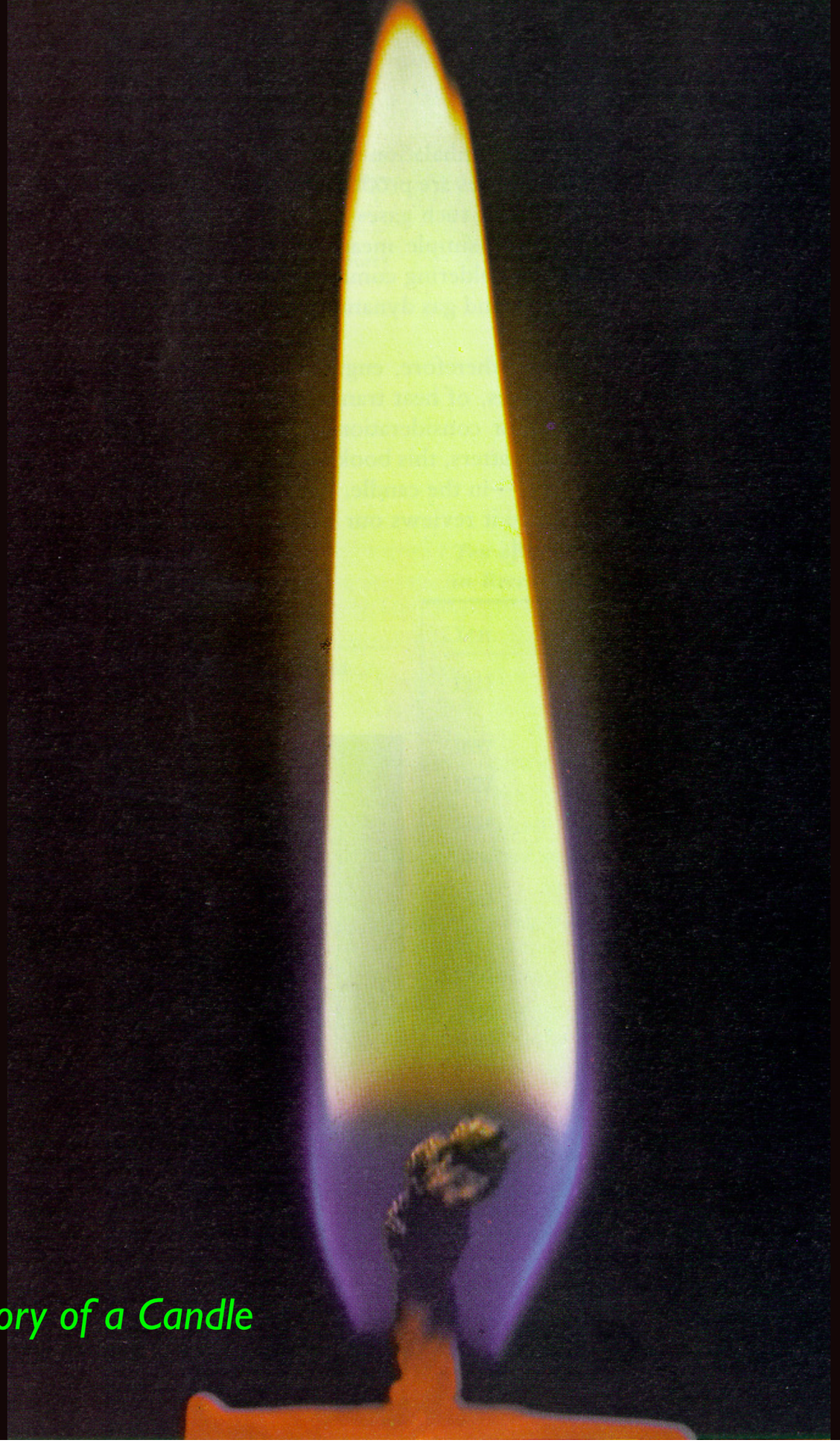
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 19 June 1964

Great Lesson of XXth Century Science

The human scale of space & time is not privileged for understanding Nature . . .

and may even be disadvantaged



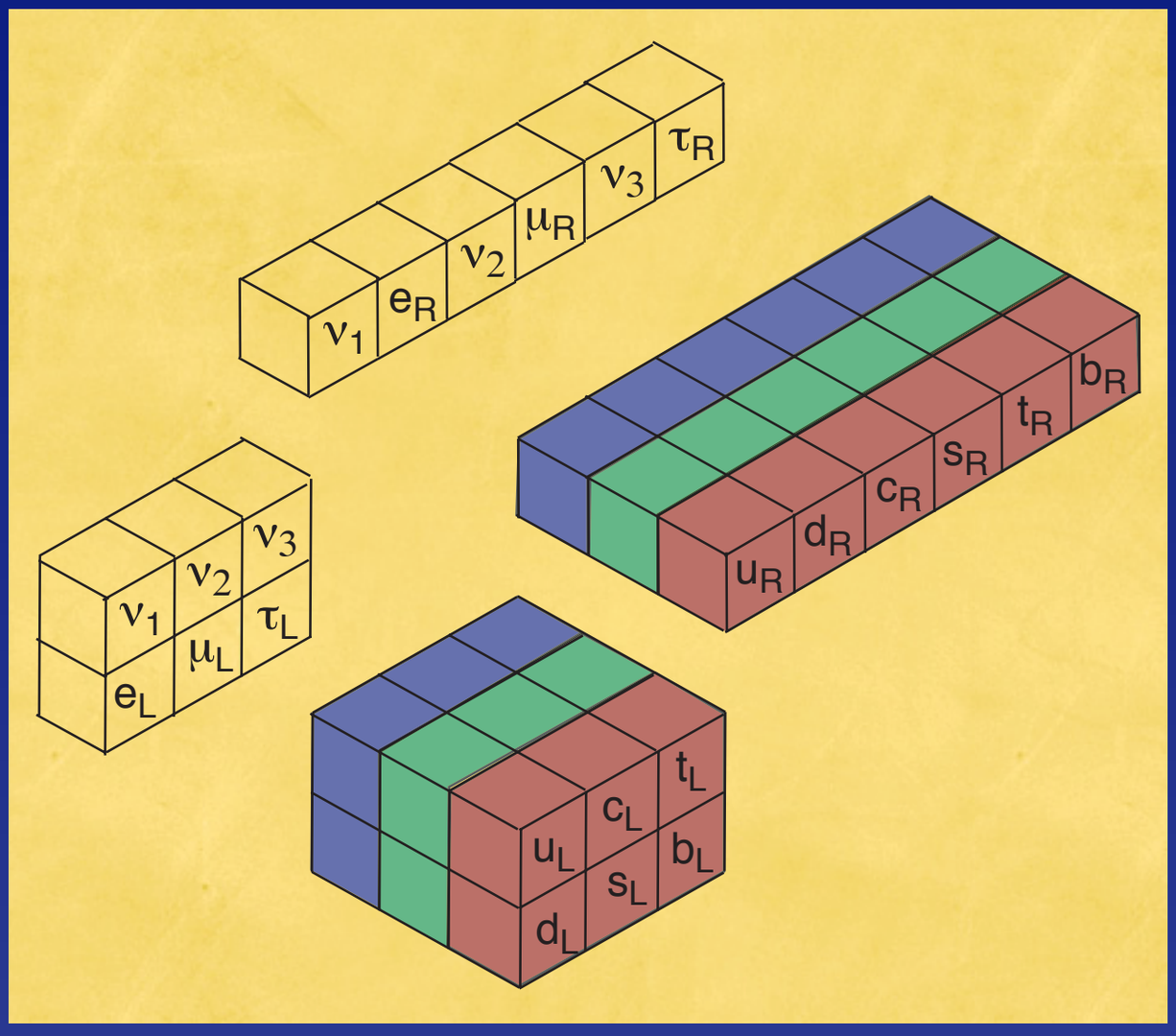
M. Faraday, *The Chemical History of a Candle*

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

– Galileo Galilei

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $\mathsf{SU}(3)_c \otimes \mathsf{SU}(2)_L \otimes \mathsf{U}(1)_Y$ gauge symmetries

A Decade of Discovery Past

A new law of nature: electroweak theory

Neutrinos have mass: they morph

Top quark: very heavy, highly ephemeral

An imperfect mirror: matter/antimatter

Interactions of quarks and gluons

Universe filled with blackbody radiation

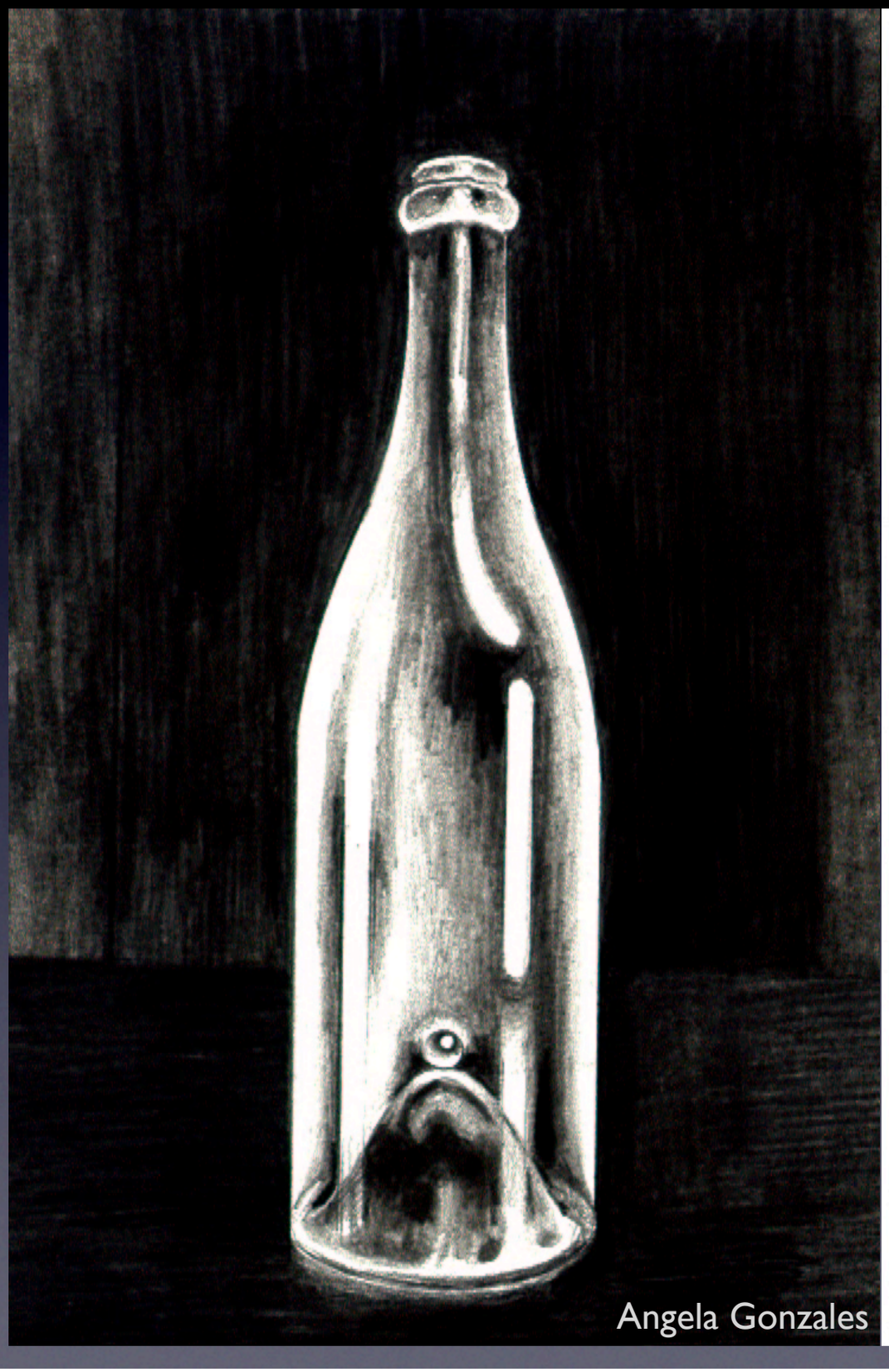
Novel forms of matter and energy (dark)

Weak interactions, electromagnetism seem so different …

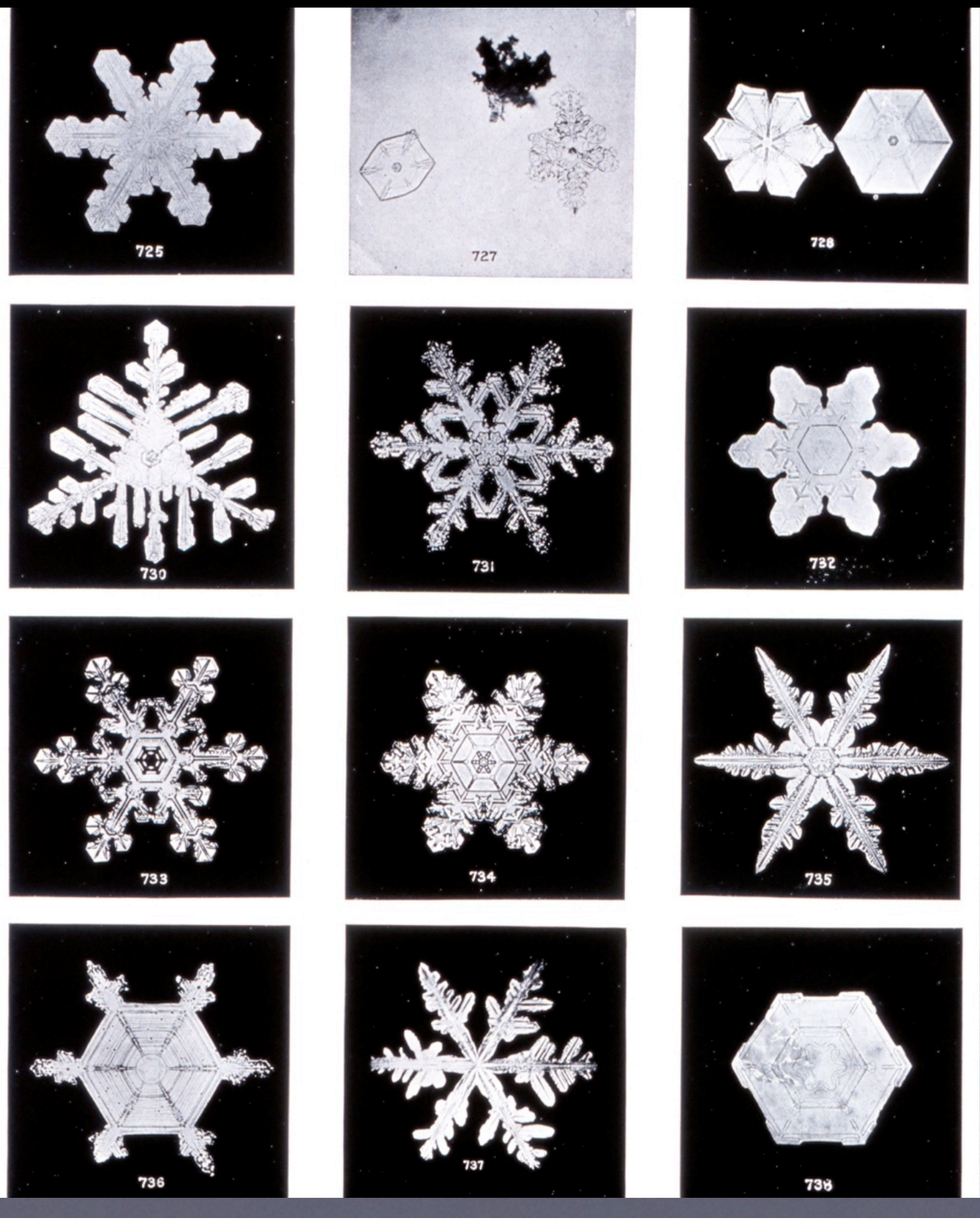
Weak	Electromagnetic
range: 1% proton size	infinite range
W: 100 × proton mass	massless photon

How can they share a common origin (symmetry)?

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

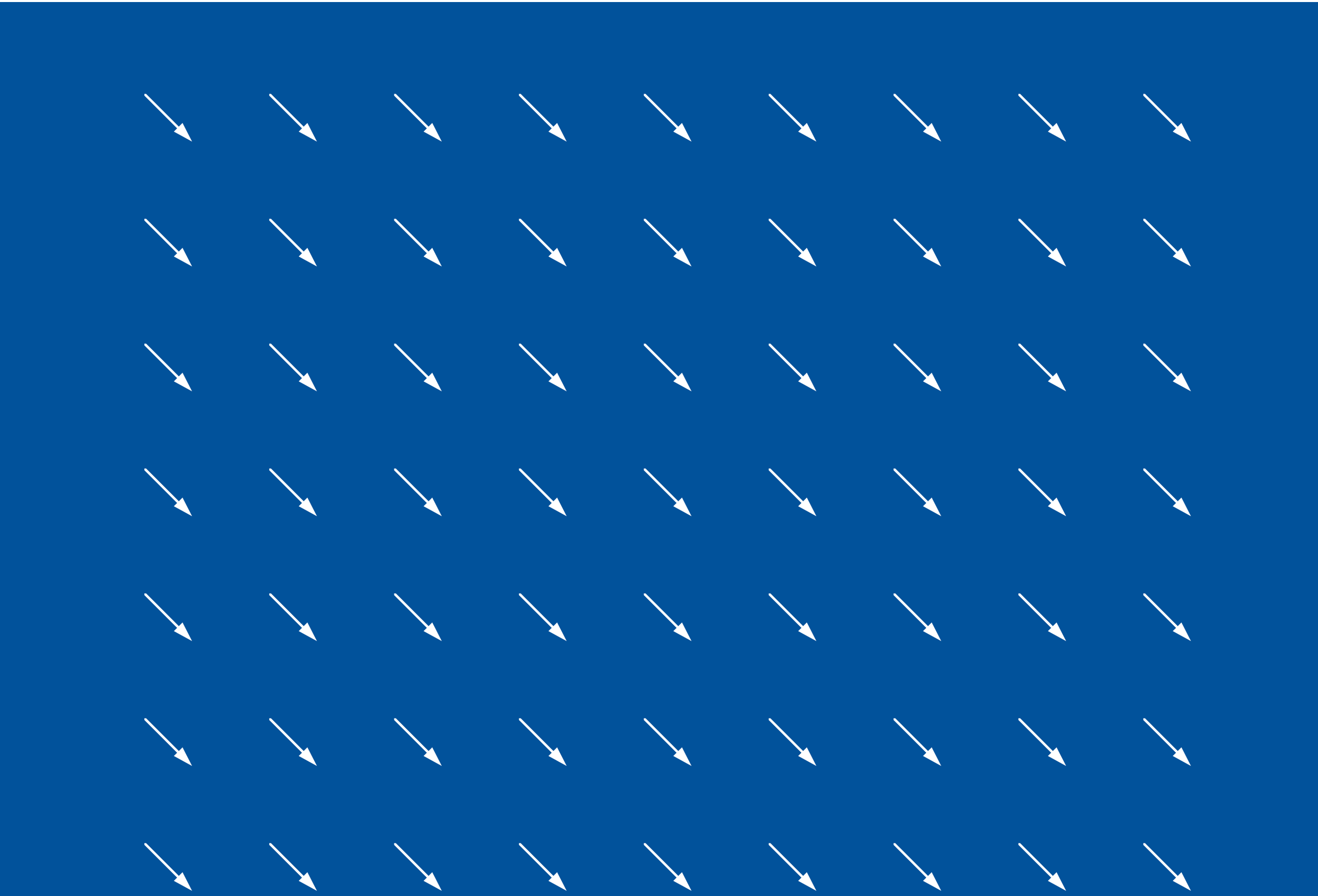


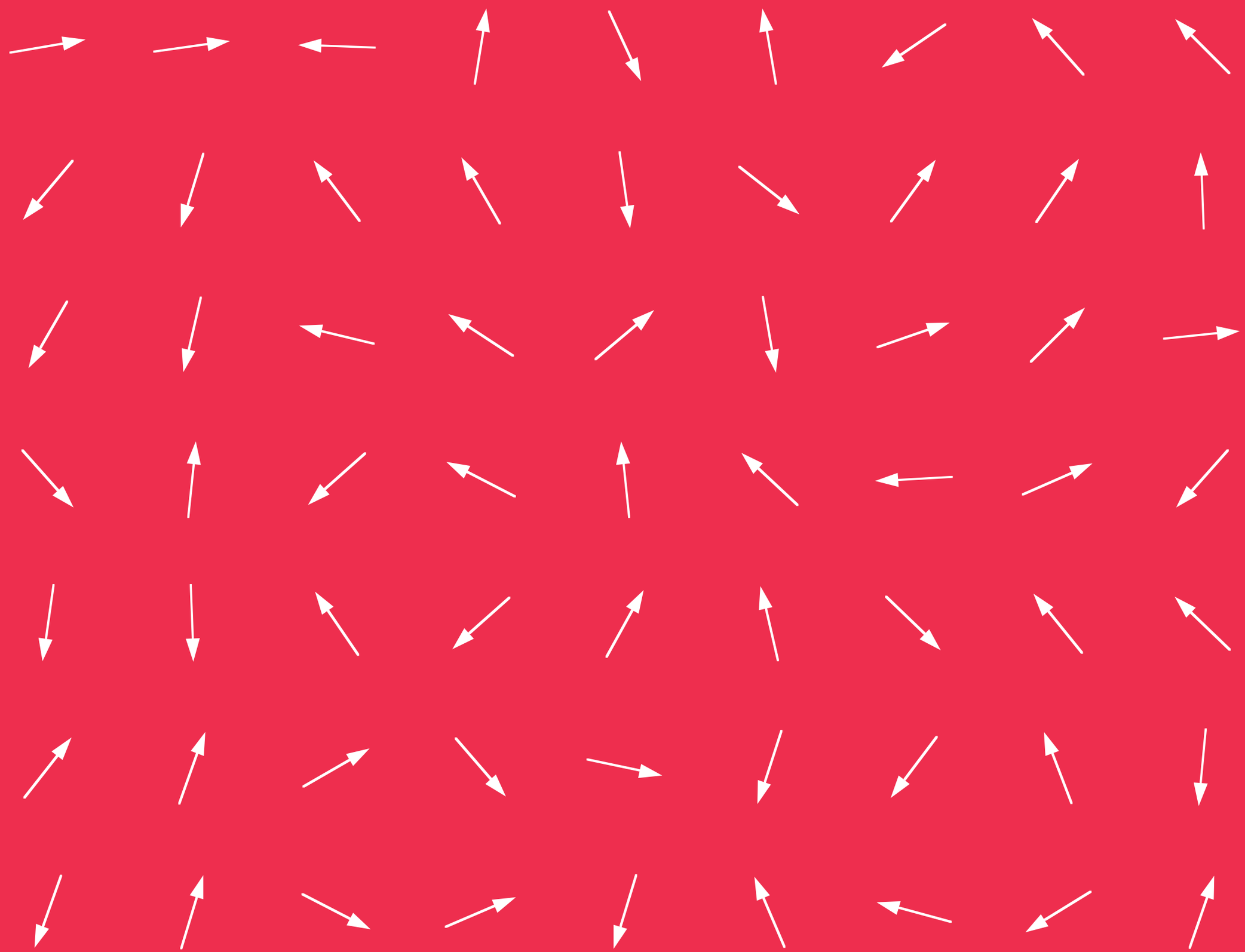
Angela Gonzales

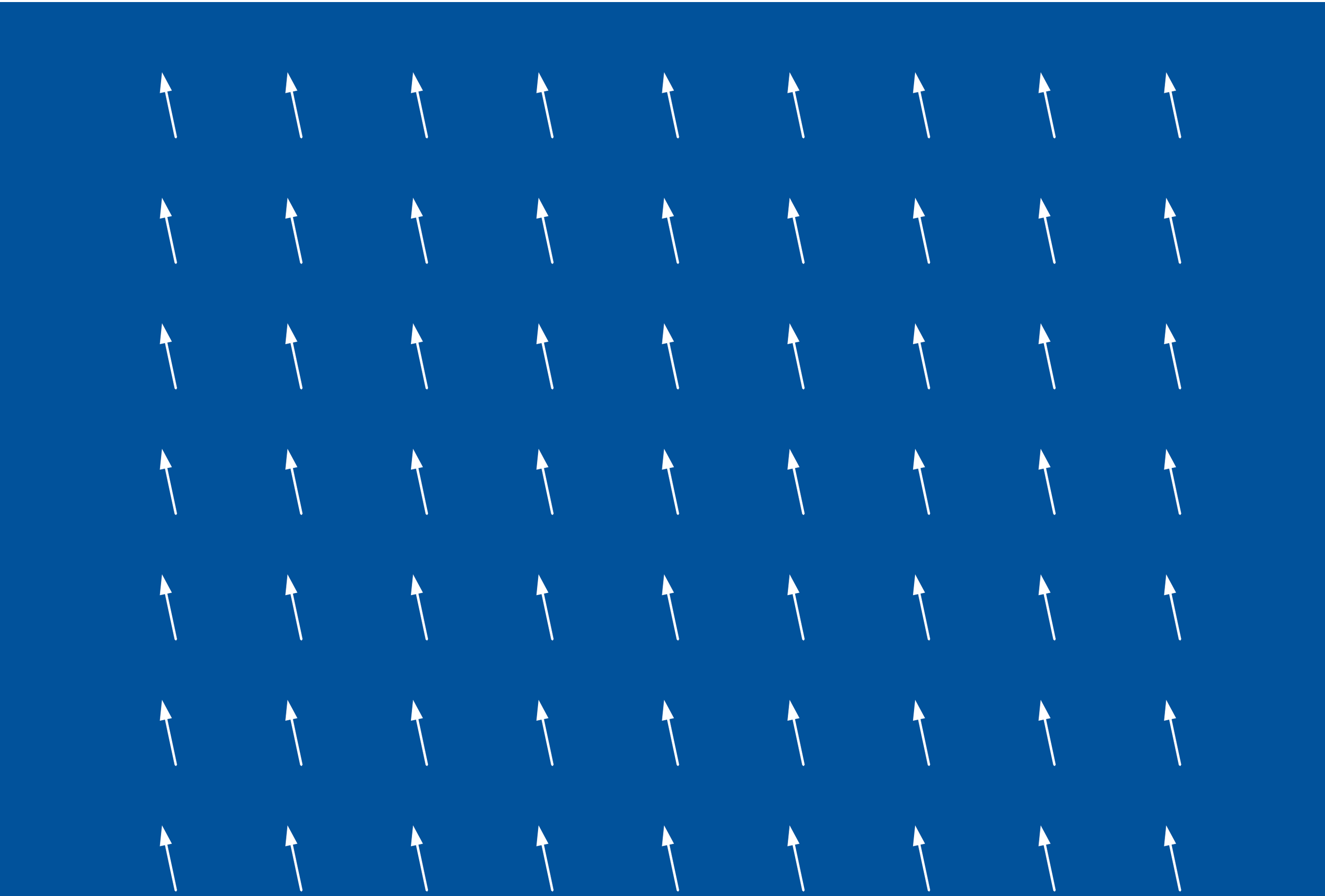


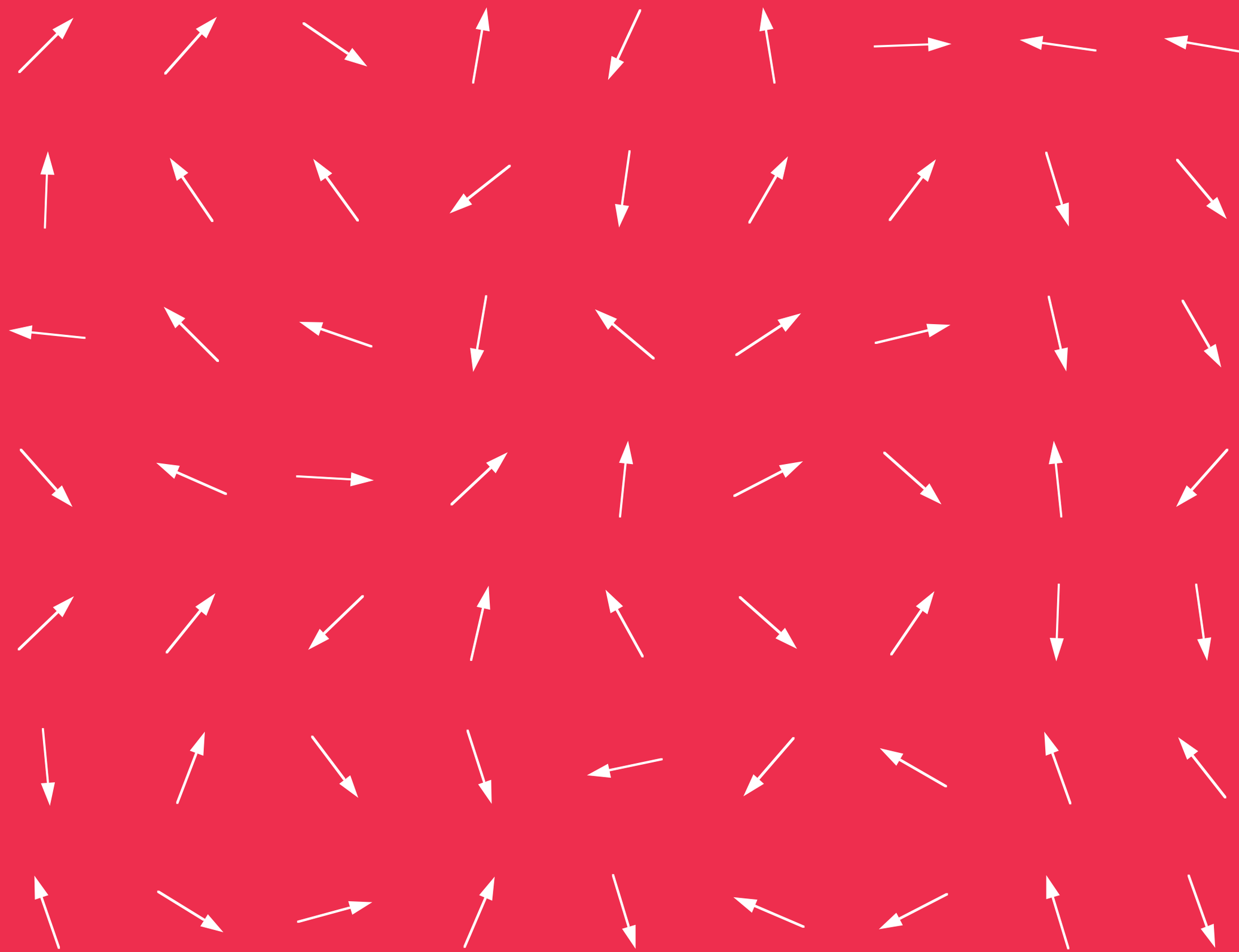
Studies among the Snow Crystals ... by Wilson Bentley, via NOAA Photo Library


SUUNTO
M3

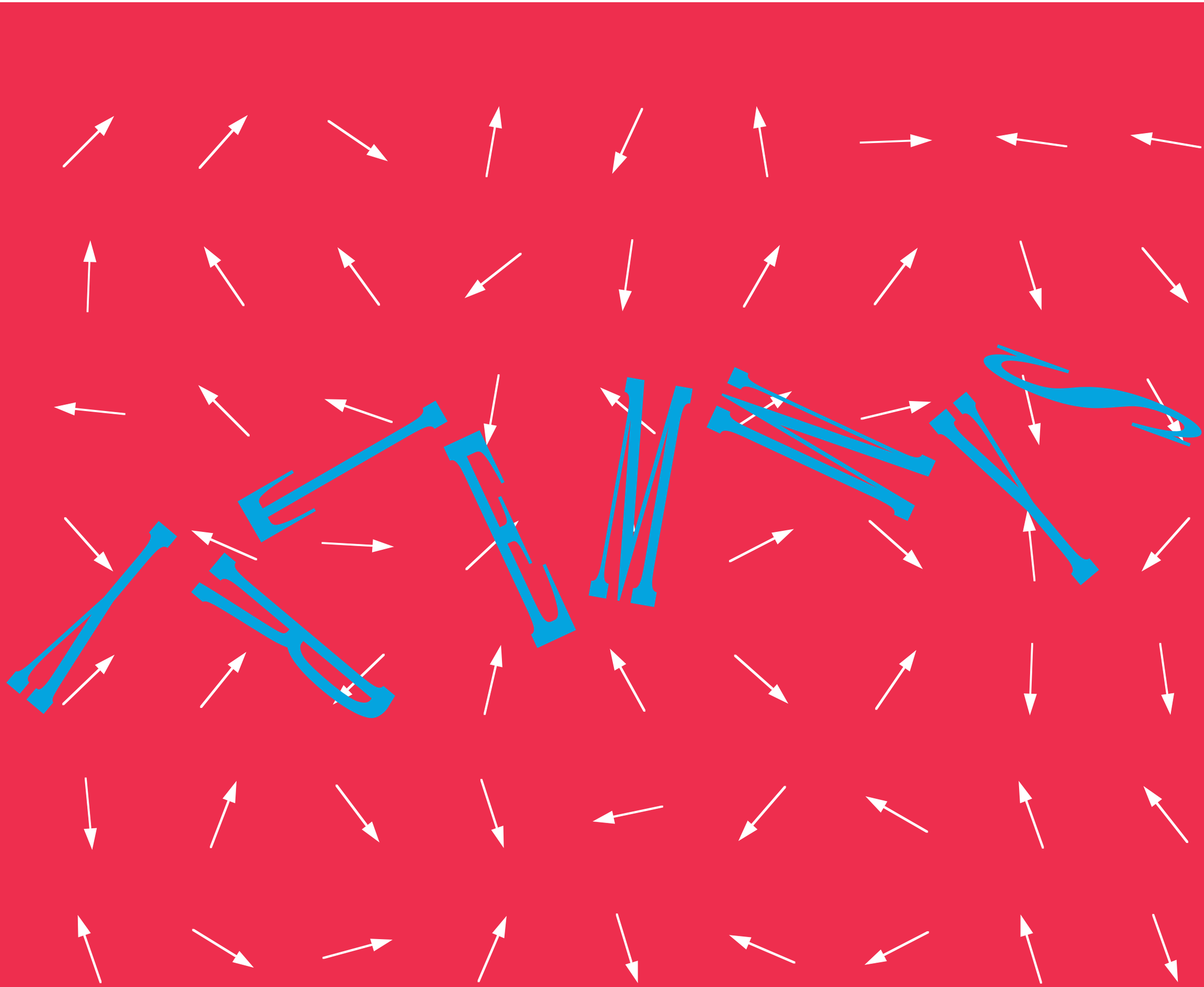






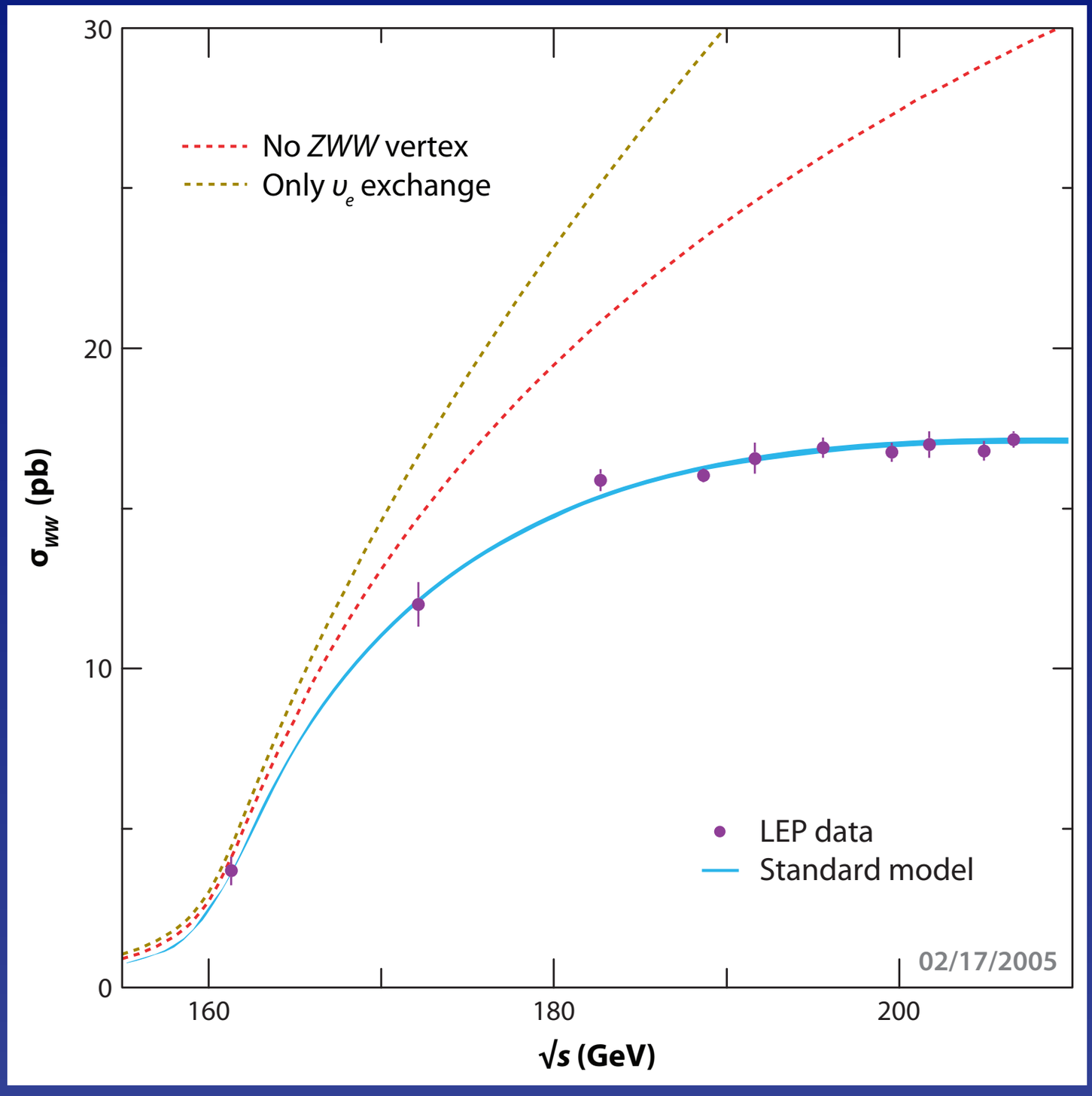


HIDDEN

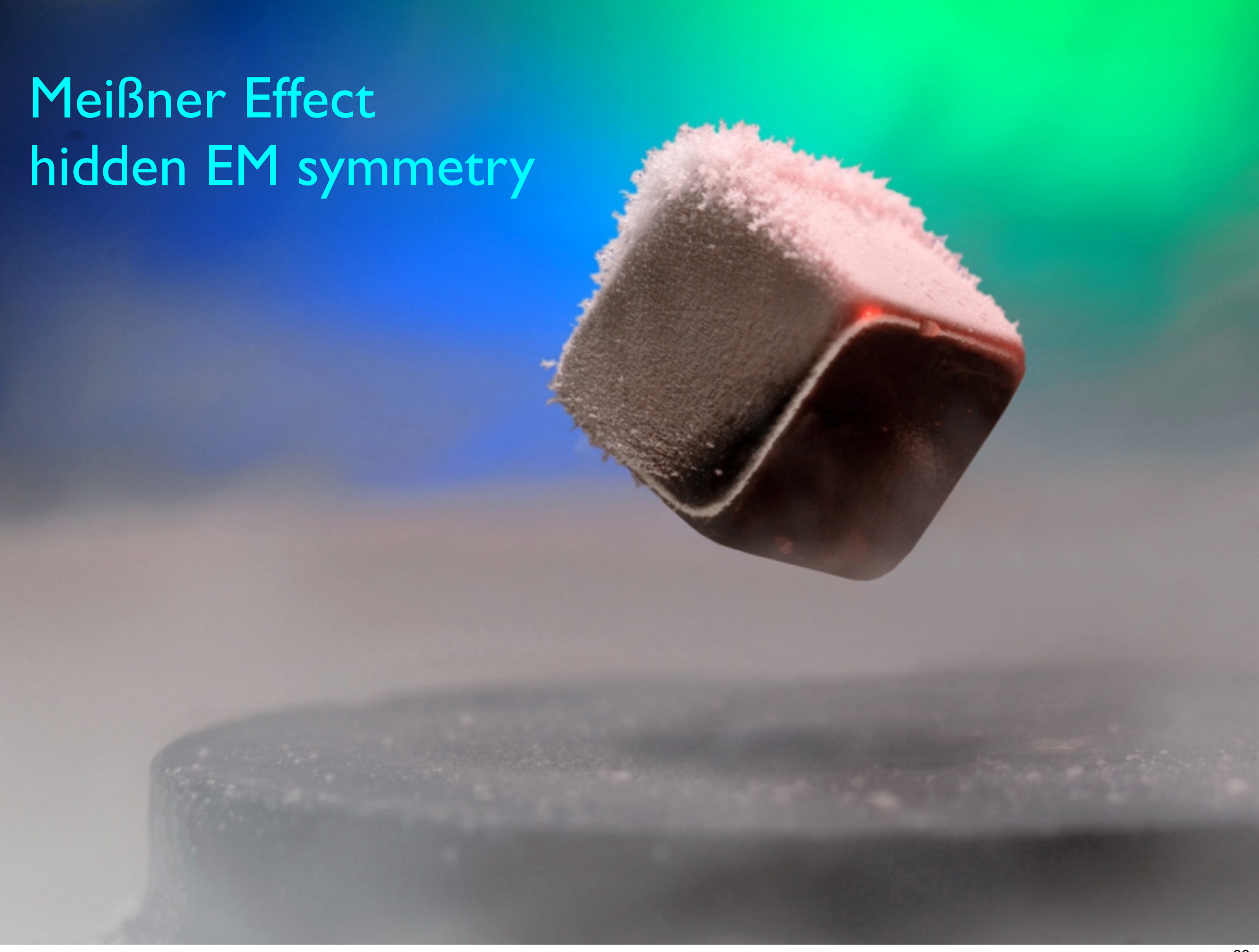


Gauge symmetry (group-theory structure) tested in

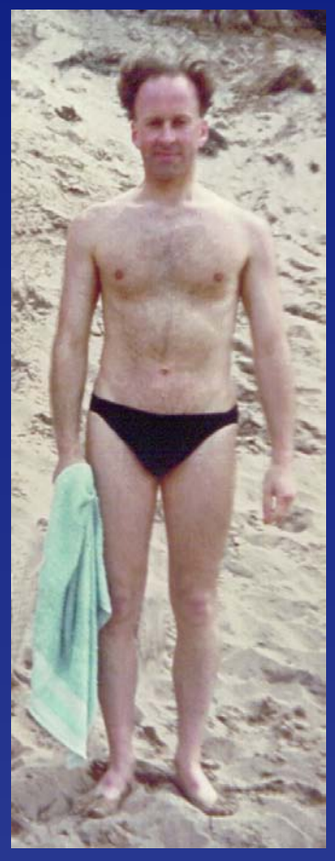
$$e^+e^- \longrightarrow W^+W^-$$



Meißner Effect
hidden EM symmetry



Superconductivity suggests
a field that permeates all of space
could hide electroweak symmetry



Peter Higgs
+ R. Brout, F. Englert, G. Guralnik, R. Hagen, T. Kibble

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

- ✳ A 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 electroweak gauge bosons
- ✳ An echo of extra spacetime dimensions

Which path has Nature taken?

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Why will it matter?

Understanding the everyday …

Why atoms?

Why chemistry?

Why stable structures?

Imagine a world without a Higgs mechanism

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

arXiv:0901.3958

Large Hadron Collider · CERN

proton-proton collisions at 7 TeV/beam

CMS

LHCb

ALICE

ATLAS

The world's most powerful microscopes
… home to *nanonanophysicists!*

Tevatron collider at Fermilab
protons on antiprotons at 1+1 TeV
speed of light: $c \approx 10^9$ km/h
speed of protons: c – 495 km/h

speed of protons in the LHC will be: c – 10 km/h

Learning to See at the LHC*

Many lessons from ISR, Fermilab bubble chambers:

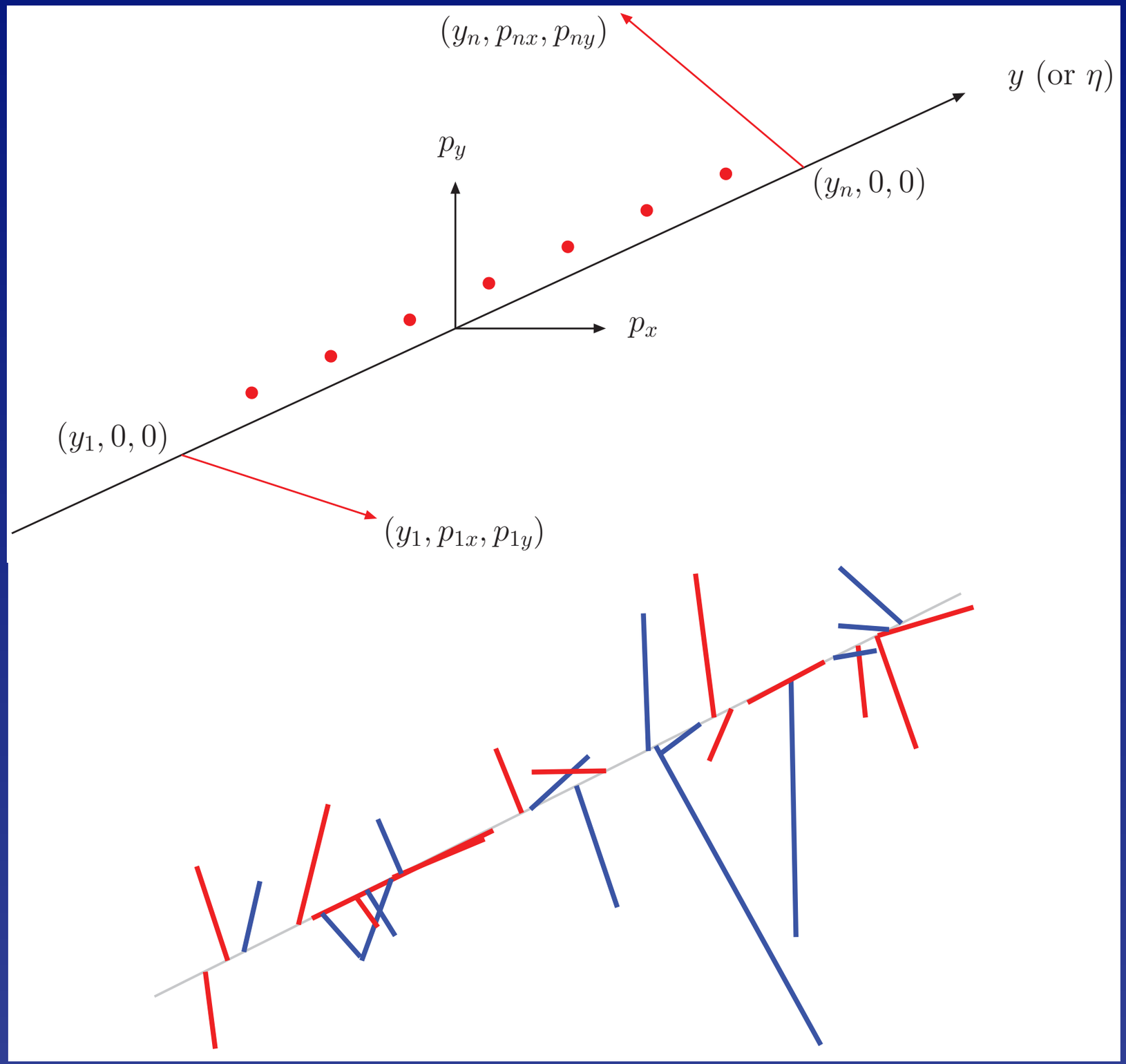
- two-component multiplicity distributions
- Feynman scaling
- approximately flat rapidity plateau, expanding as ln s
- short range order (multiperipheral)
- no evidence for hydrodynamic component

Not necessarily a full representation of what LHC will see

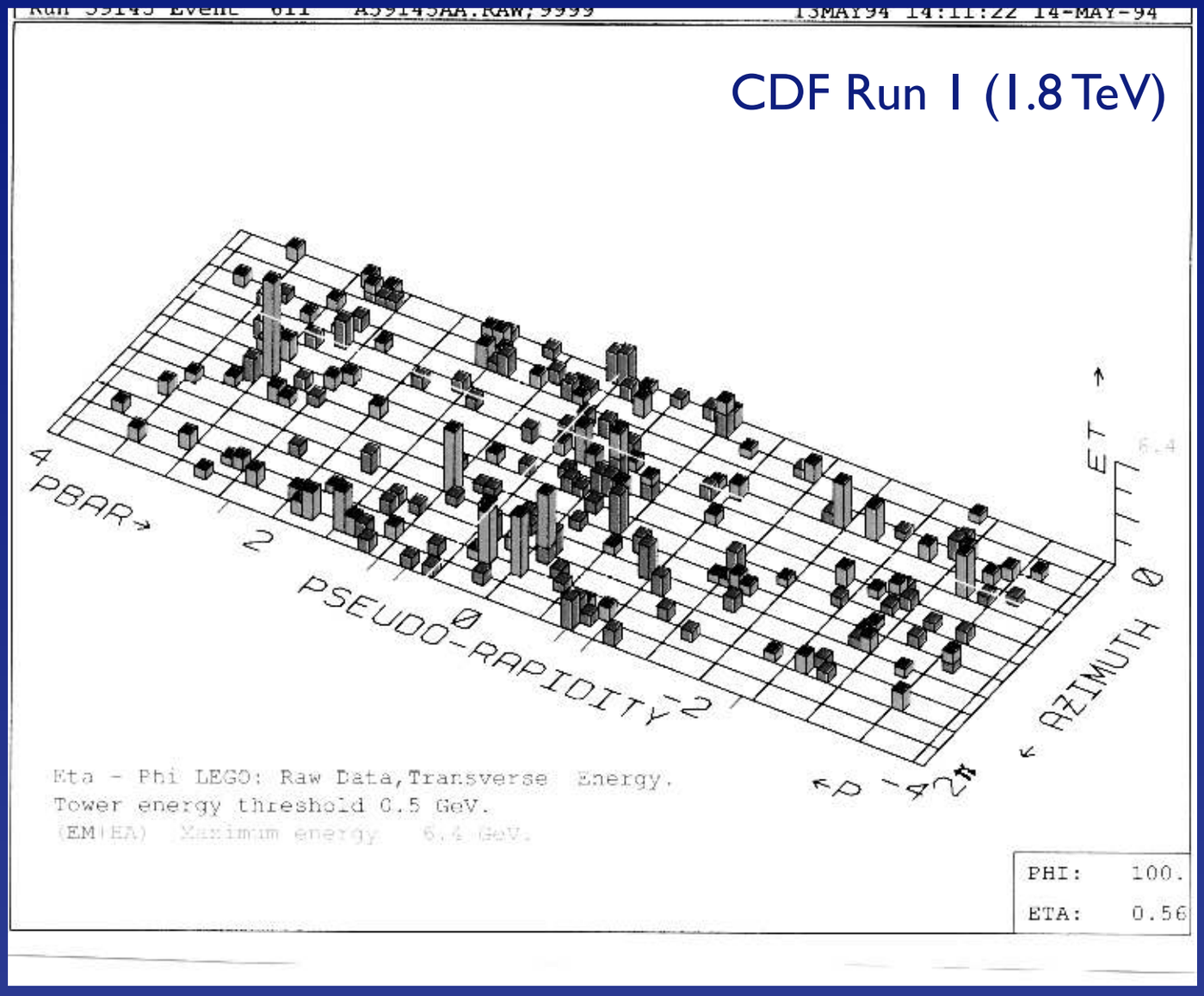
theoretical hints, vastly higher energy and statistics

*arXiv:1001.2025

Event display for soft production



An atypical event: >100 towers over threshold



Shopping List (Short Form)

Revisit early studies:

topological cross sections

forward-backward multiplicity asymmetries

(semi)inclusive correlations

charge-transfer studies

Add collective variables explored at RHIC

elliptic flow

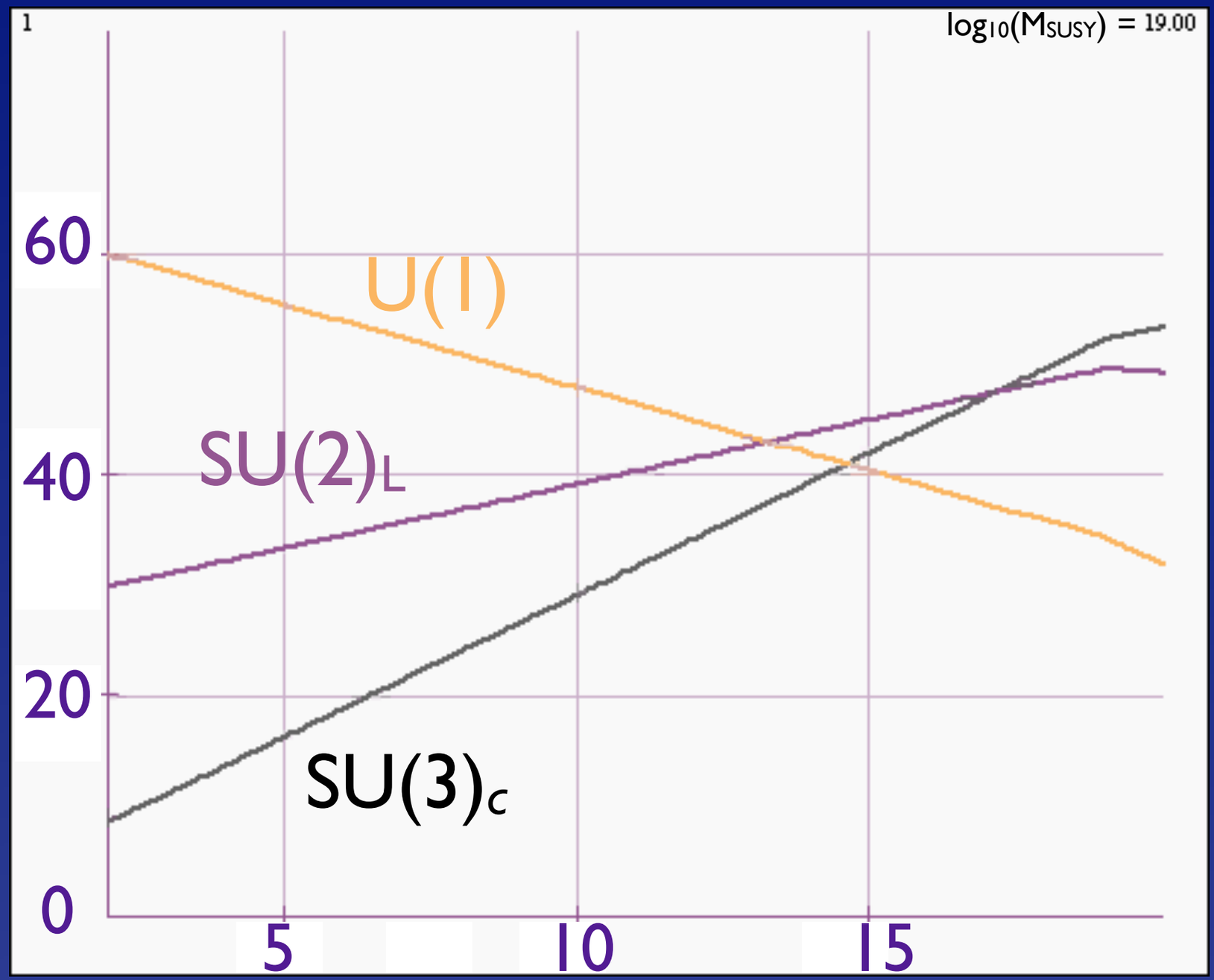
thermodynamic variables

…

The Unity of Quarks & Leptons

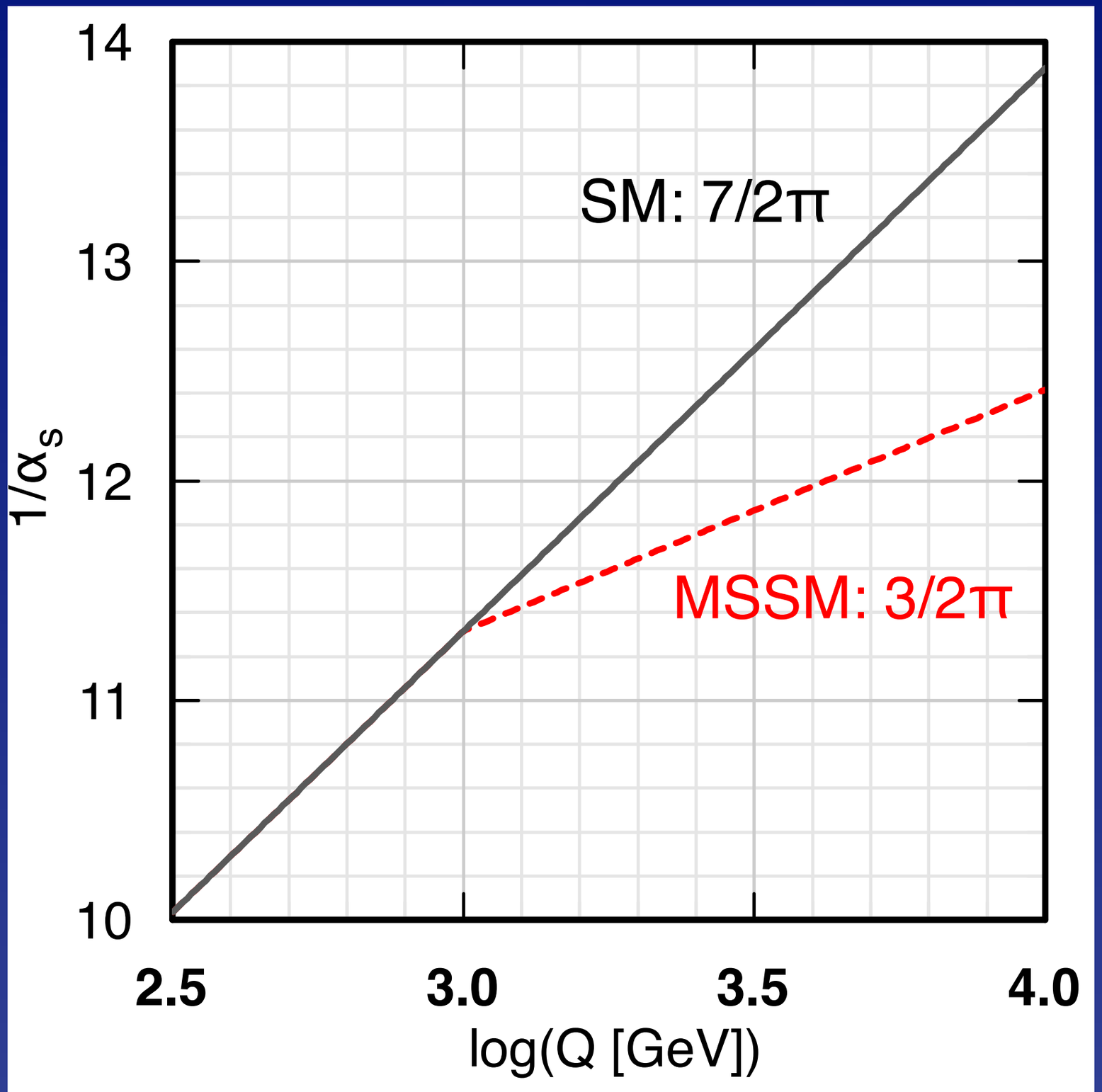
- What do quarks and leptons have in common?
- Why are atoms neutral?
- Which quarks with which leptons?
- Extended quark–lepton families: proton decay!

Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$ gives possibility of coupling constant unification



$$\alpha^{-1} = \tfrac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

Through QCD to New Physics?



Some of the issues before us …

Electroweak symmetry breaking:

Higgs or not?

Gives mass to gauge bosons *and fermions?*

Does M_H < 1 TeV make sense?

Supersymmetry

Dynamical symmetry breaking

Extra spacetime dimensions

New forces of nature?

Dark matter candidates

Connections …

arXiv:0905.3187

Scientific American, 2.2008

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 study CP violation in B decay
Exploit rare decays (K, D, . . .)
Observe n EDM, pursue e^- EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover QCD's full implications
Observe proton decay
Understand the baryon excess
Catalogue matter & energy of 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 origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate problem of identity
. . .

. . . learn the right questions to ask

. . . and rewrite the textbooks!