The Future of High Energy Physics From Quark to the Cosmos

https://arxiv.org/abs/1707.03711

Ian Shipsey
Oxford

XIV ICFA SCHOOL ON INSTRUMENTATION IN ELEMENTARY PARTICLE PHYSICS

LA HABANA, 27 November - 8 December, 2017

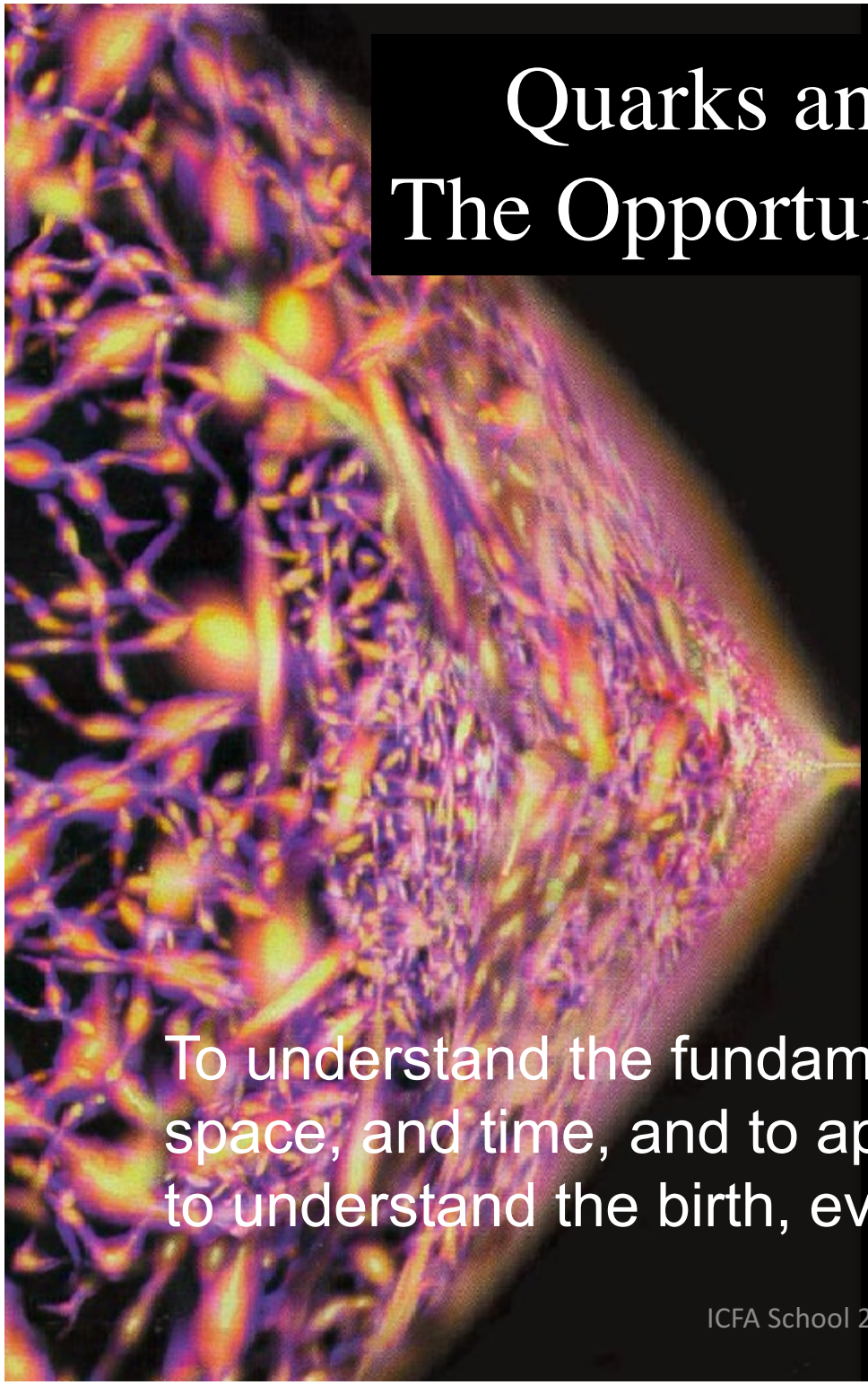
OUTLINE

The status of the field circa 2017

Opportunities for achieving “transformational or paradigm-altering” scientific advances: *great discoveries*.

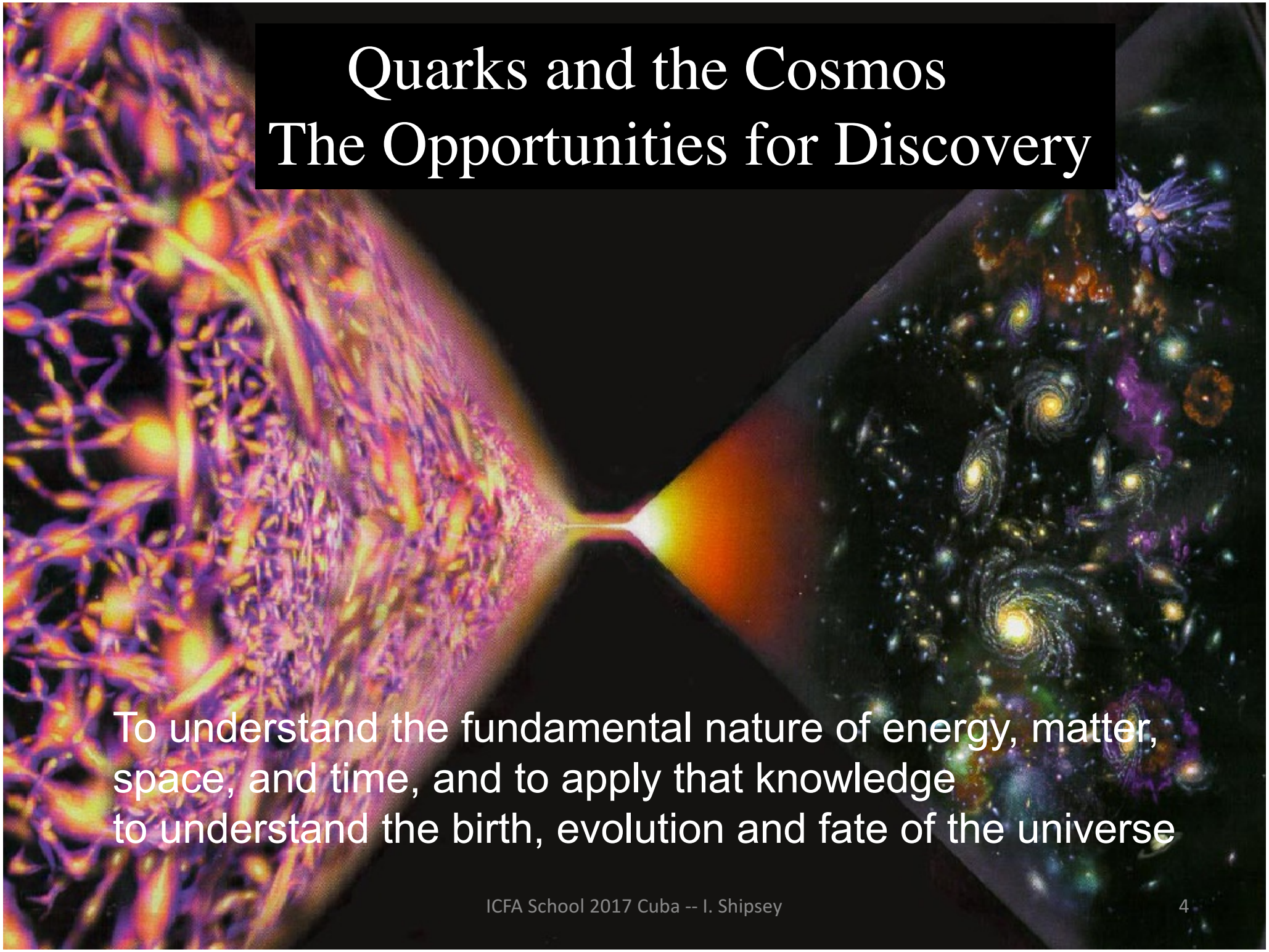
One field, one voice, one world

Note there are many more slides uploaded on the web than I will show in this talk (they serve as a reference)



Quarks and the Cosmos
The Opportunities for Discovery

To understand the fundamental nature of energy, matter, space, and time, and to apply that knowledge to understand the birth, evolution and fate of the universe



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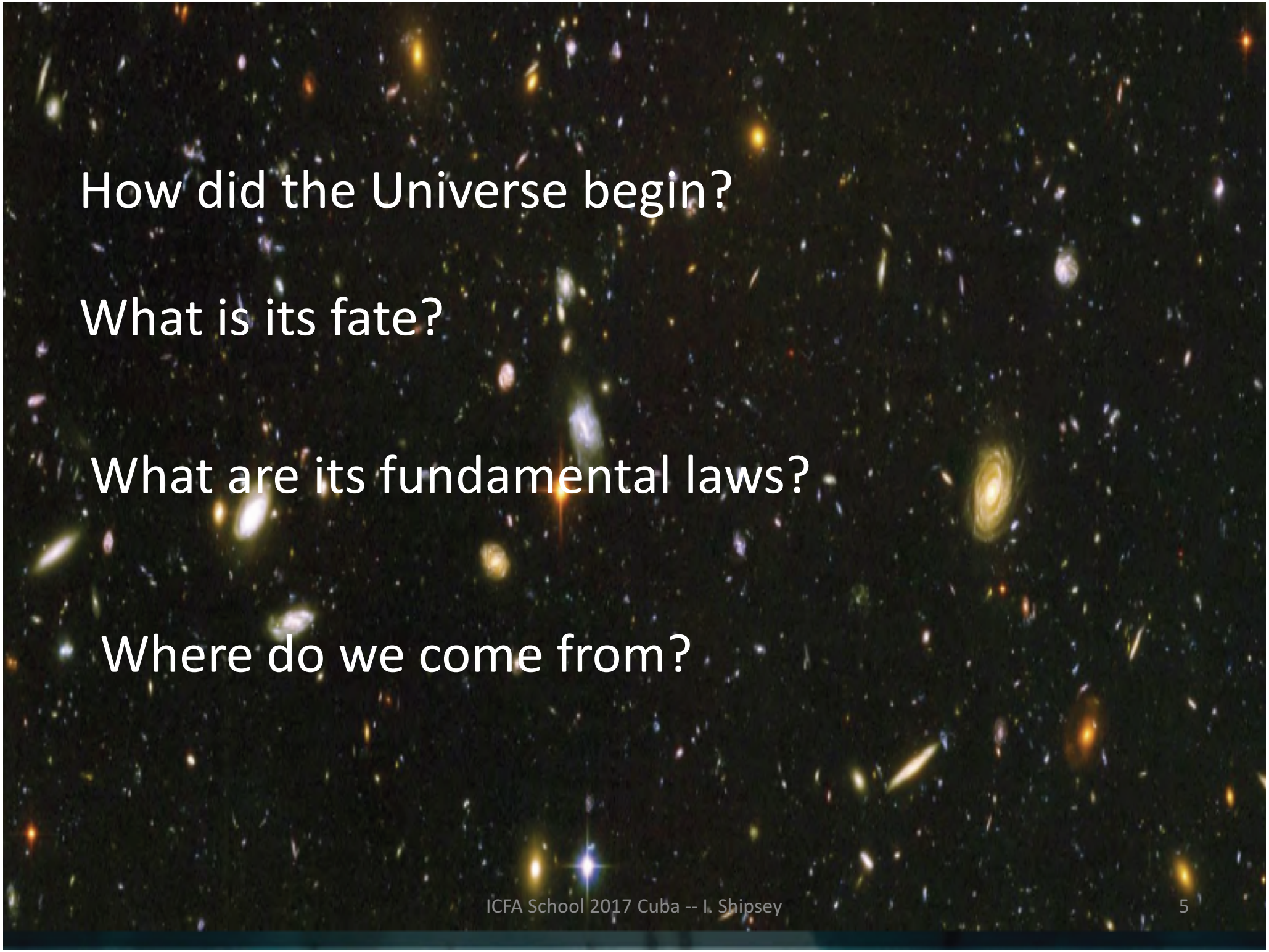

How did the Universe begin?
What is its fate?
What are its fundamental laws?
Where do we come from?

Quarks and the Cosmos

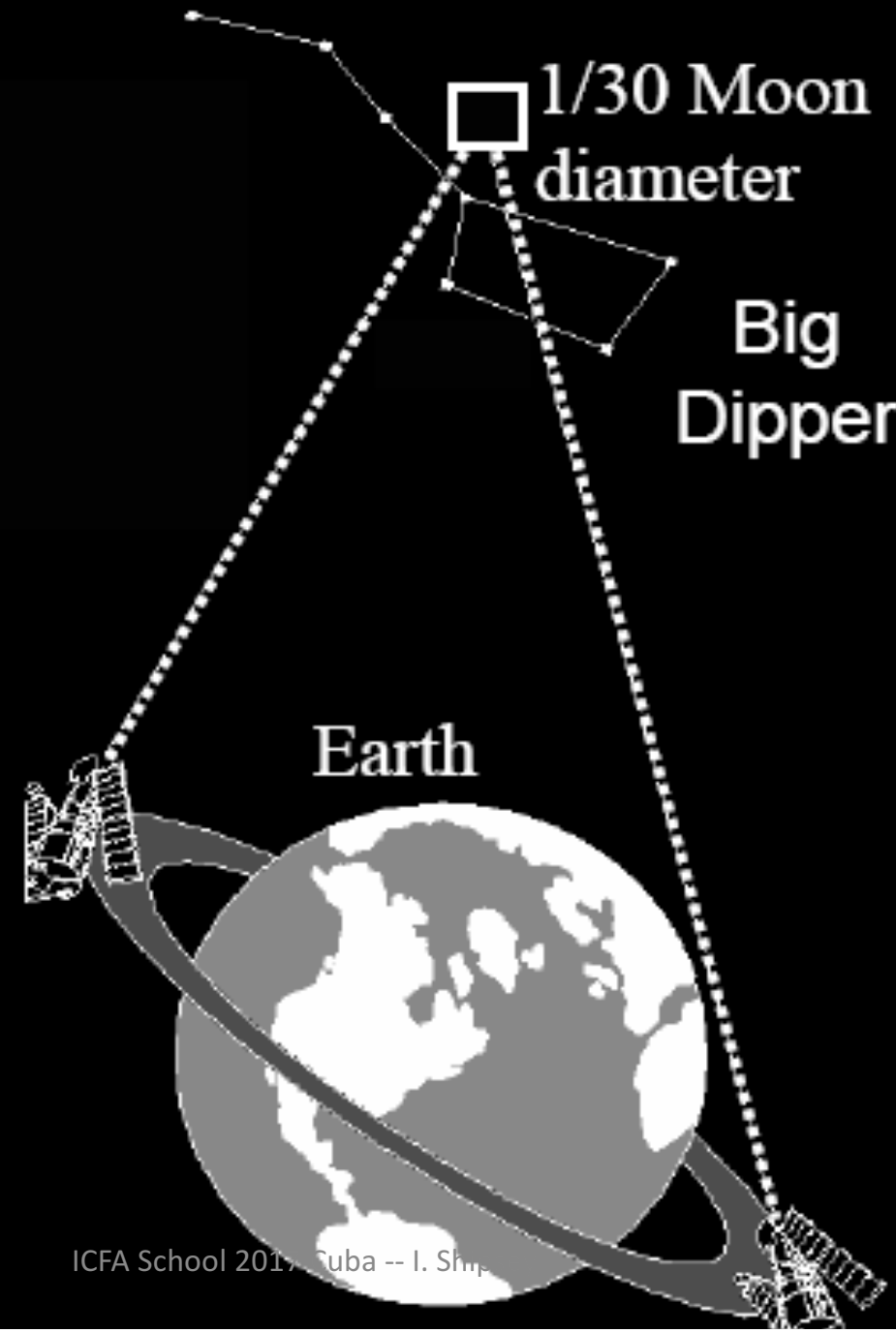
Particle Physics & Cosmology

Deeply connected & highly complementary

Instrumentation the Great Enabler

Our scope is broad and we use many tools: accelerator, non-accelerator & cosmological observations all have a critical role to play

Outer Space - The Cosmos



The Hubble Deep Field

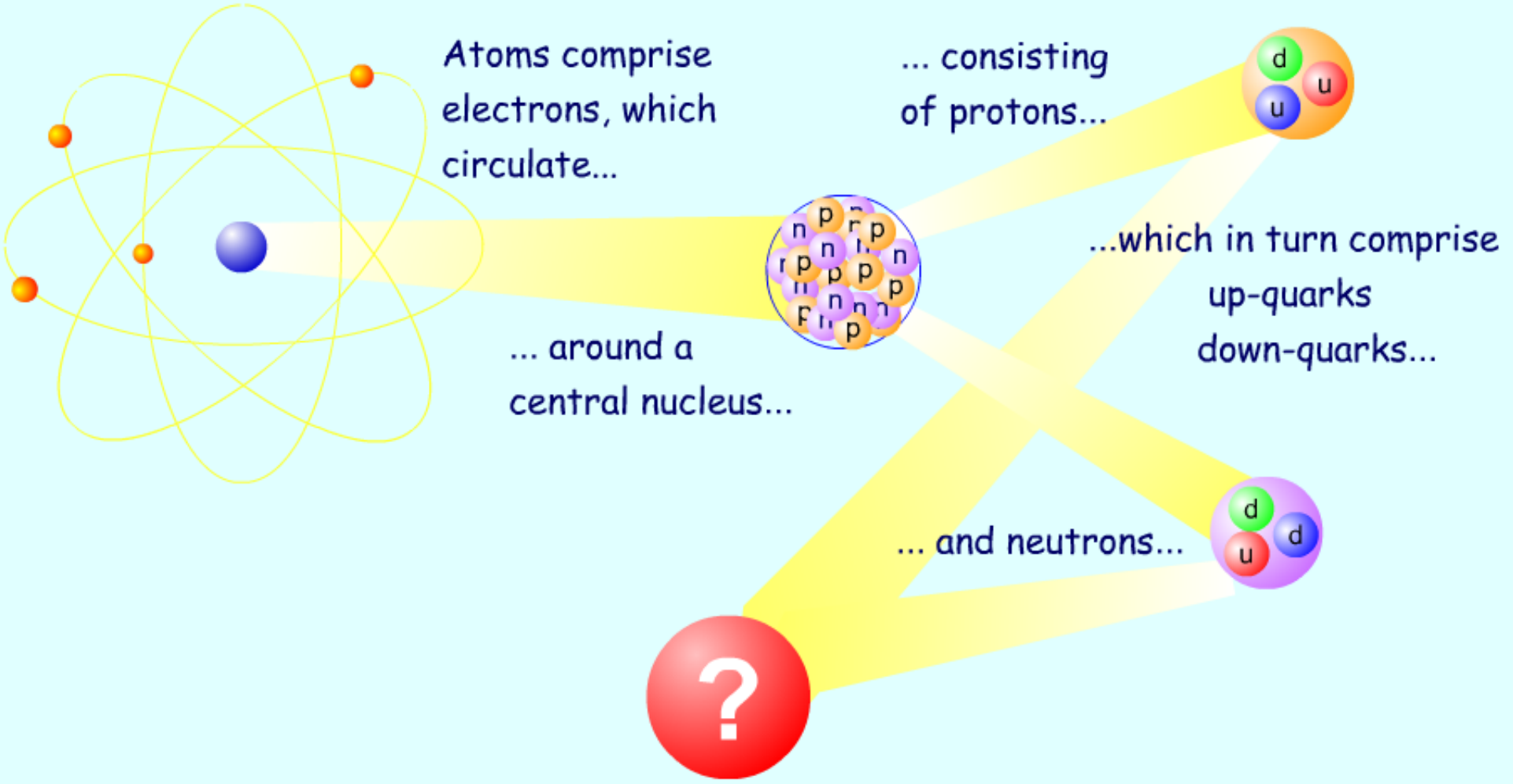
Hubble deep field

UNIVERSE OF GALAXIES

3000 here →

100 billion over entire sky

Inner Space: atoms quarks & electrons

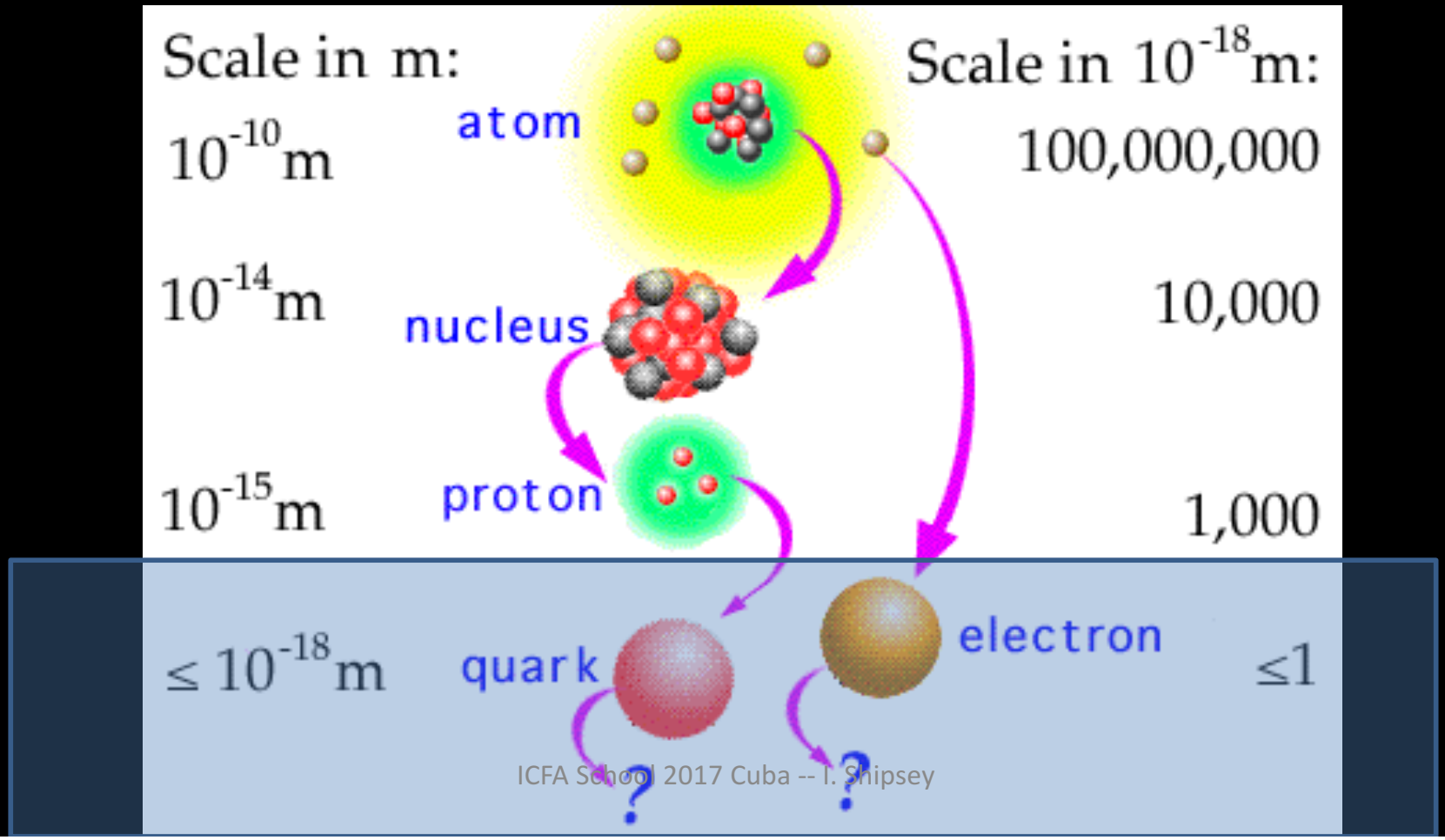


...and that is the frontier of our present understanding on the nature of matter

Animation: *Elena Symeonidou*

The size of atoms, quarks and electrons

- Atom: 0.1 nm



The size of atoms, quarks and electrons

- Atom: 0.1 nm

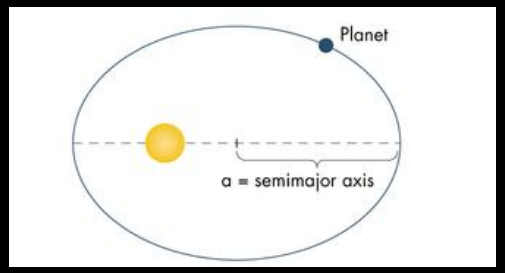
The size of an atom compared to an apple is like:

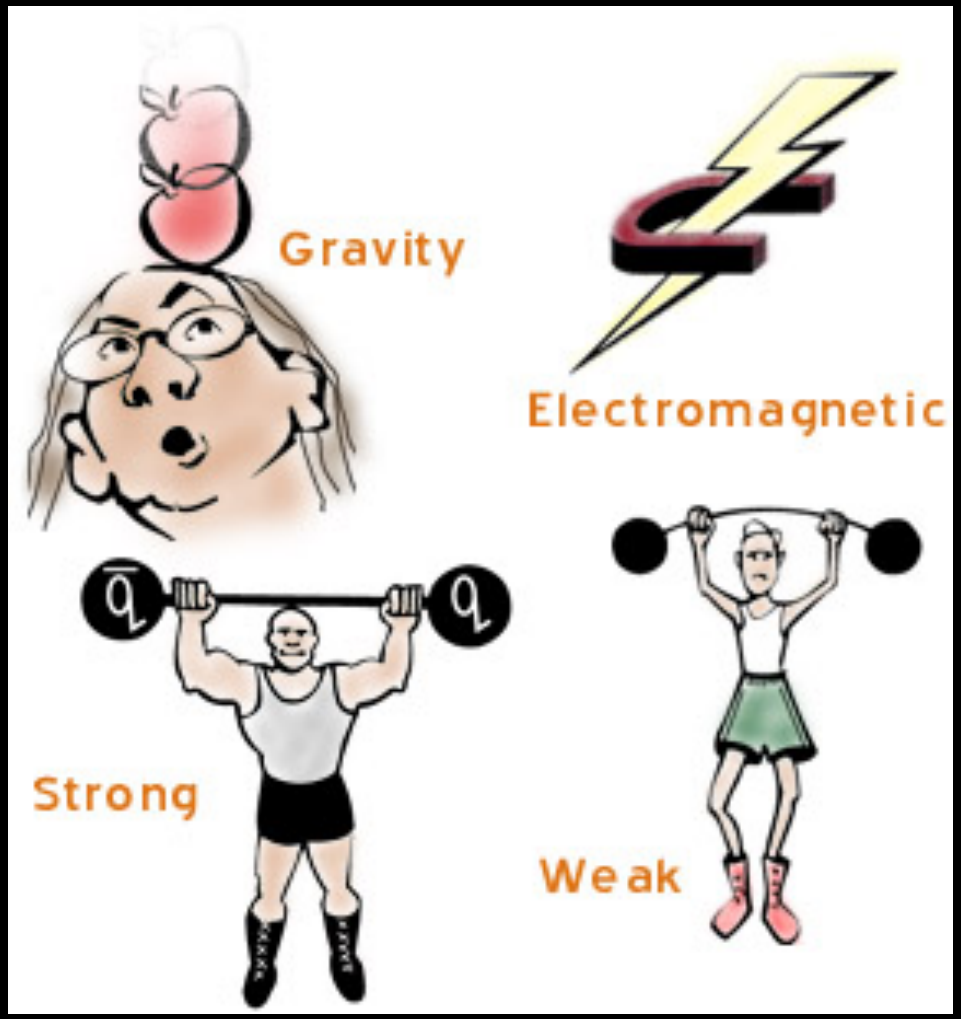
The proton compared to an atom is like a raisin in the middle of a football field

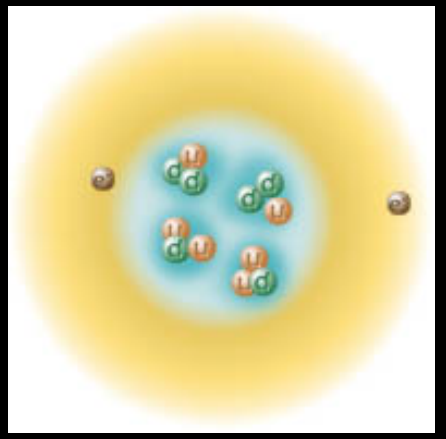
A quark has a volume less than one billionth of a proton

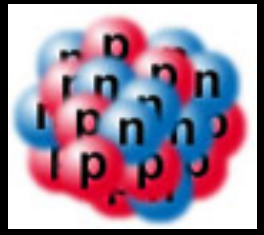
The LHC can see a volume one trillionth the size of a proton

Inner space: The four forces







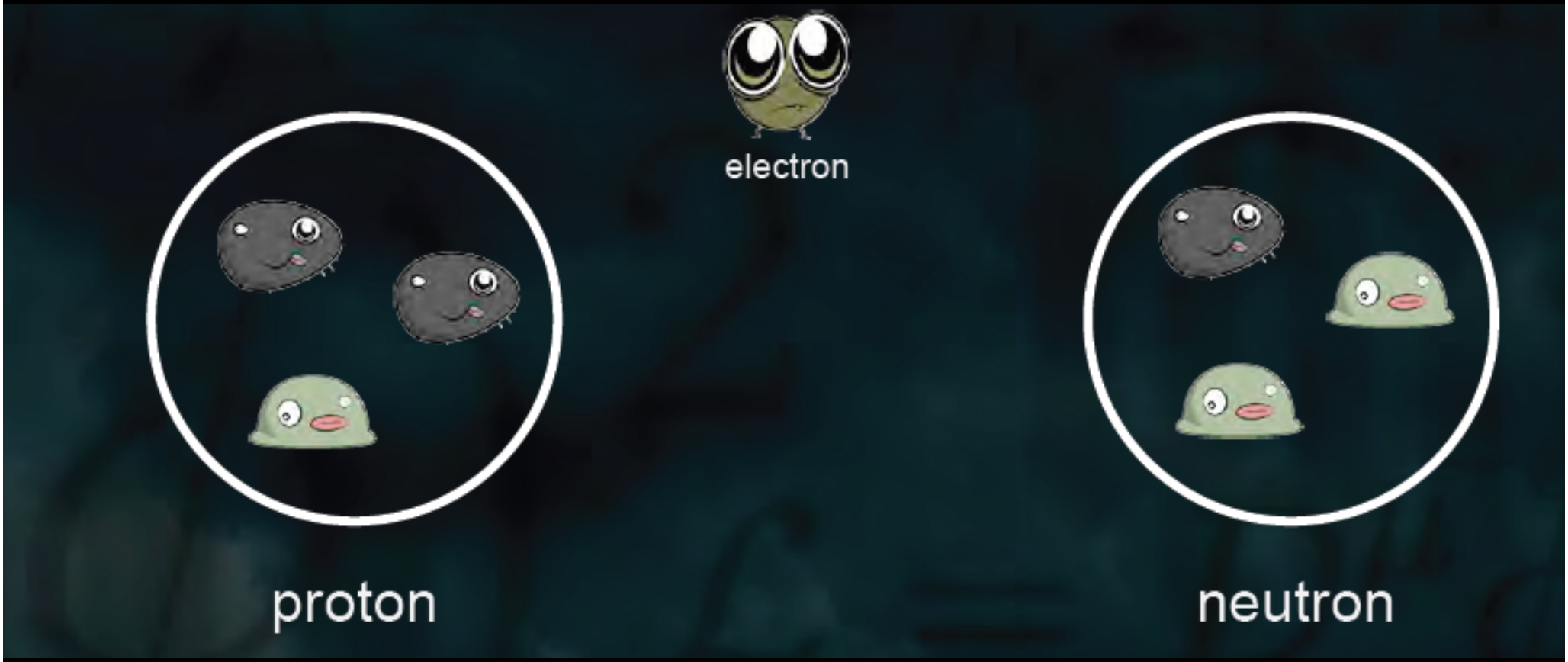


lets quarks change identity example: down→up producing natural radioactivity

Ordinary matter

Everything is made of electrons, up & down quarks

BUILDING A UNIVERSE

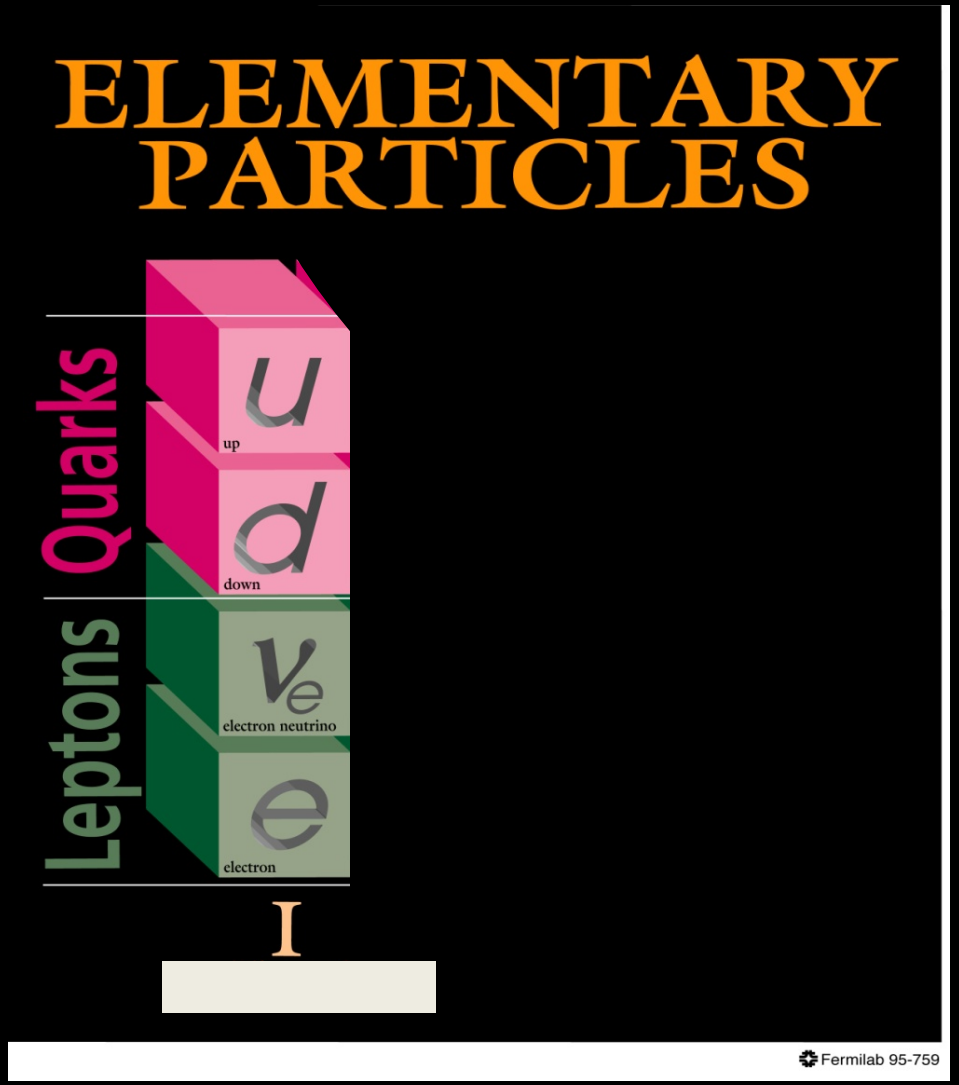


Multiply by billions and billions and billions (there are 10^{78} atoms in the universe)

BUILDING A UNIVERSE

The periodic table of the elementary particles

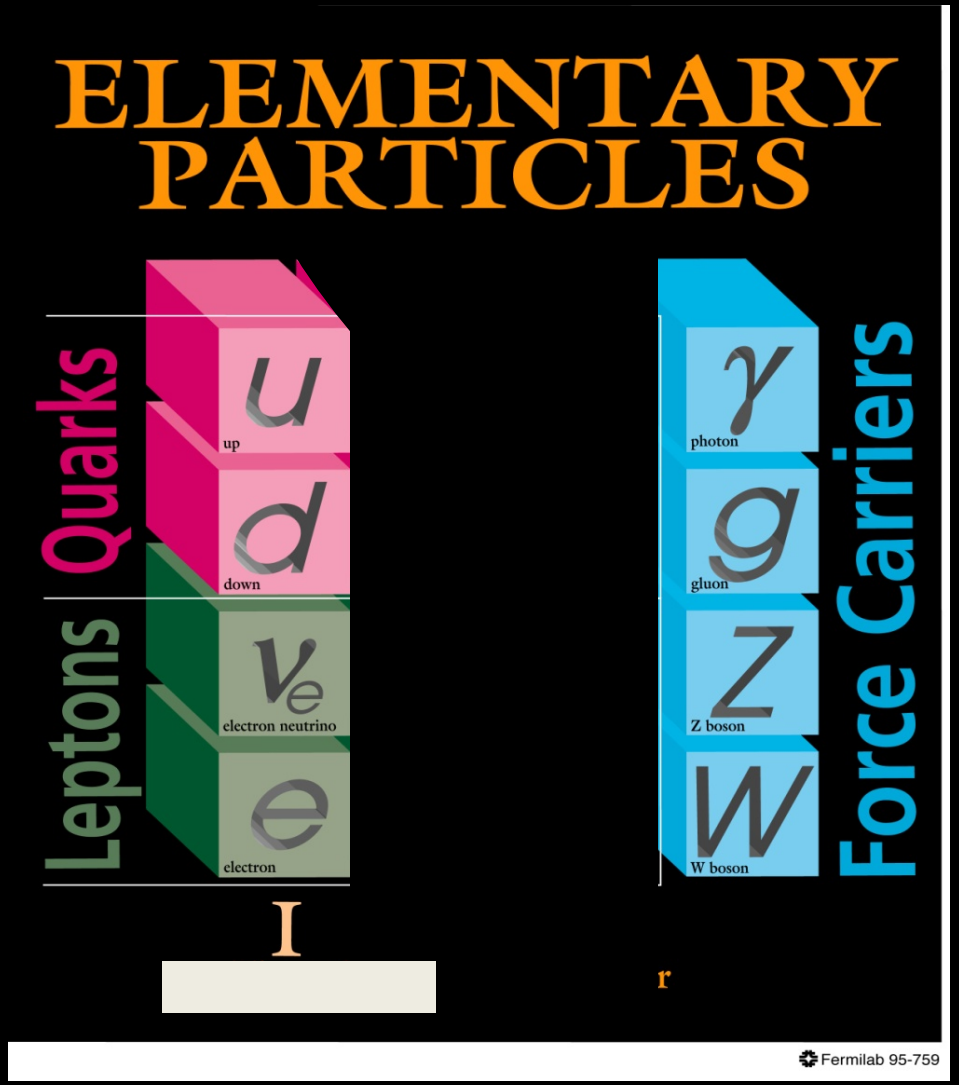
1897-2002



We are made of
u d e and there are
also neutrinos
produced
by radioactivity

The periodic table of the elementary particles

1897-2002



+ particles associated with force
Photon : EM
Gluon : strong
Z and W: weak

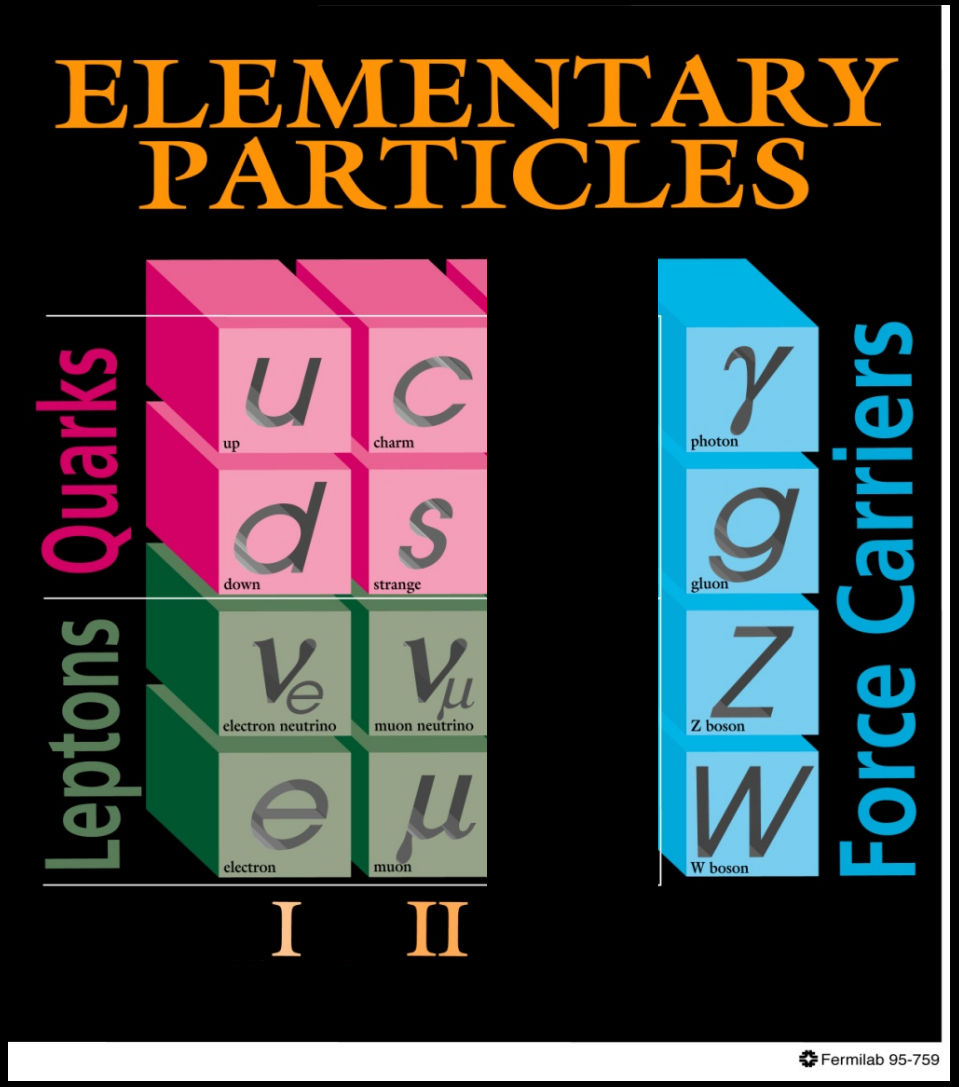
This, we thought, is enough to make a universe

Ordinary matter

Everything is made of electrons, up & down quarks

We discovered we could create additional heavier matter particles in accelerators

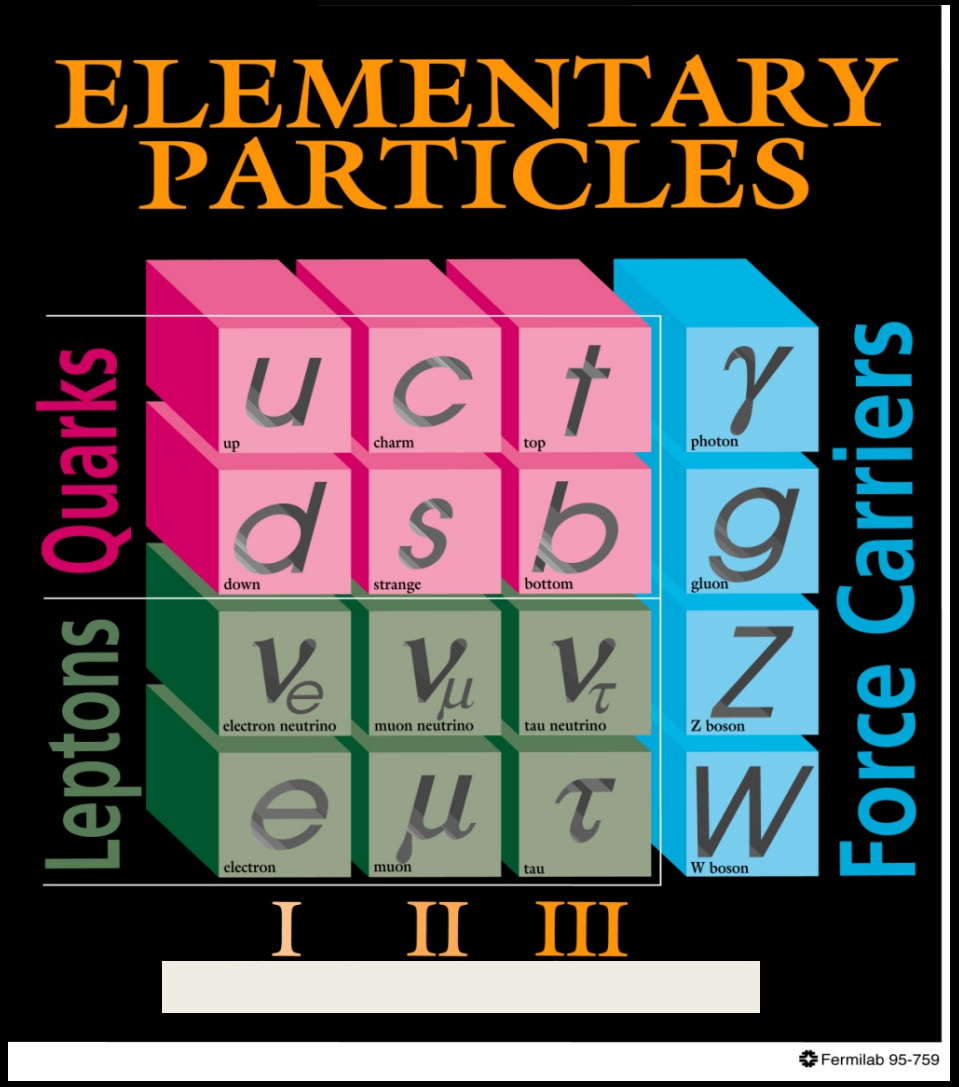
The periodic table of the elementary particles



1935-1974

the first group is replicated by a second group at greater mass

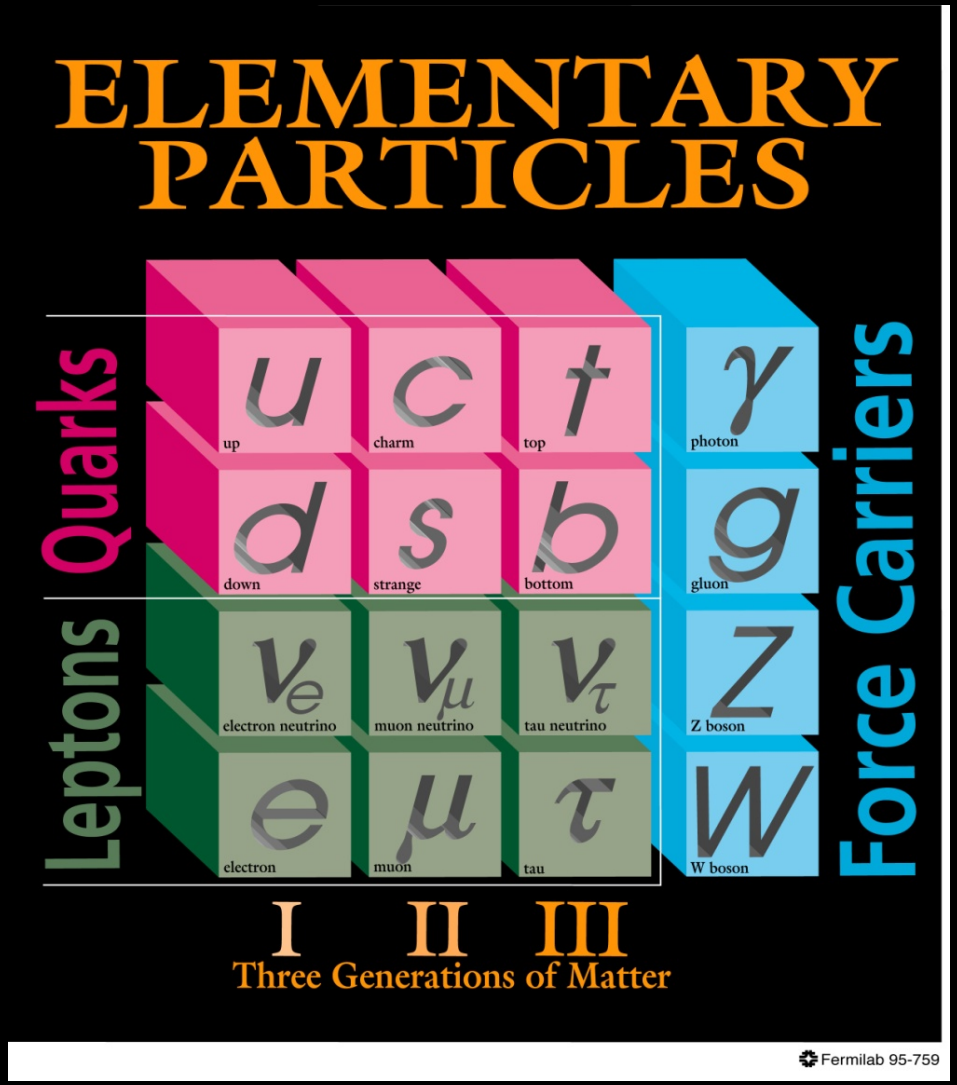
The periodic table of the elementary particles



1977-2002

a third copy at still higher mass was discovered

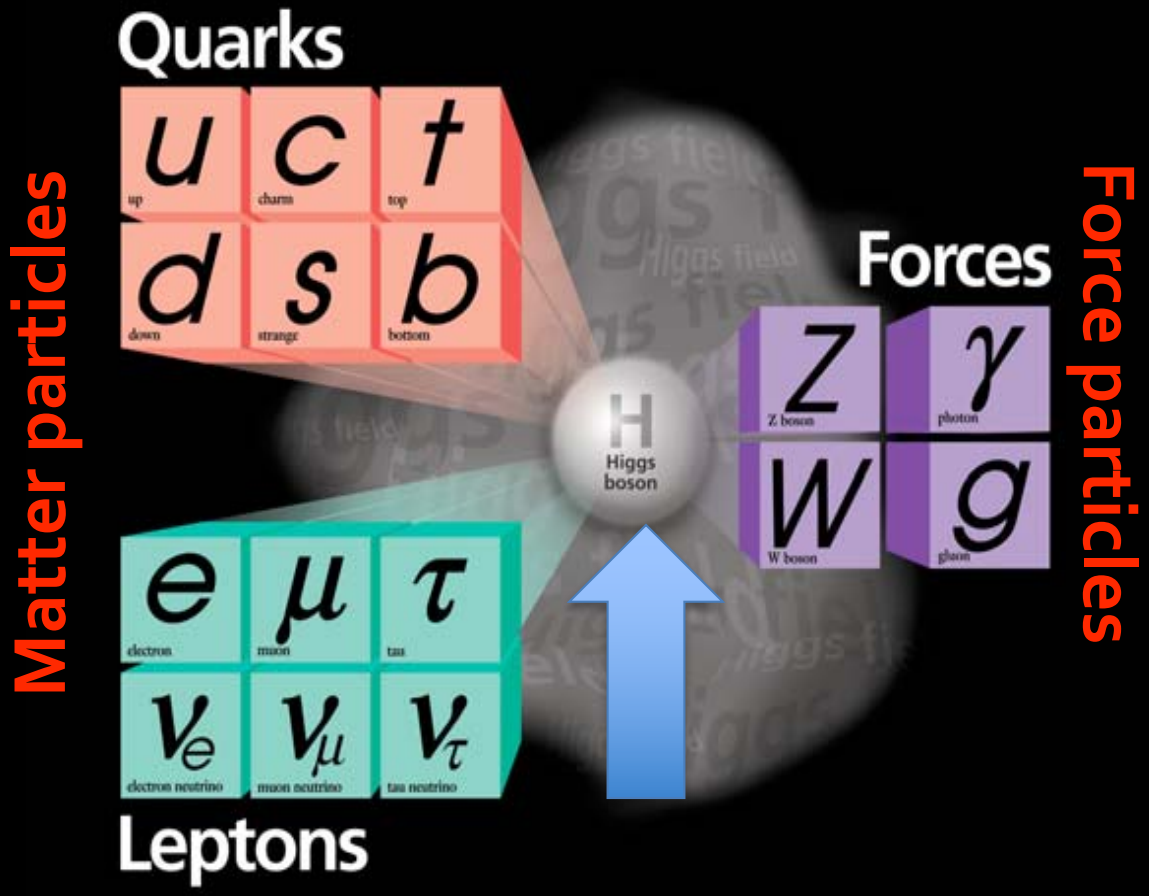
1897-2002



+ anti-matter (antiparticles for each quark & lepton

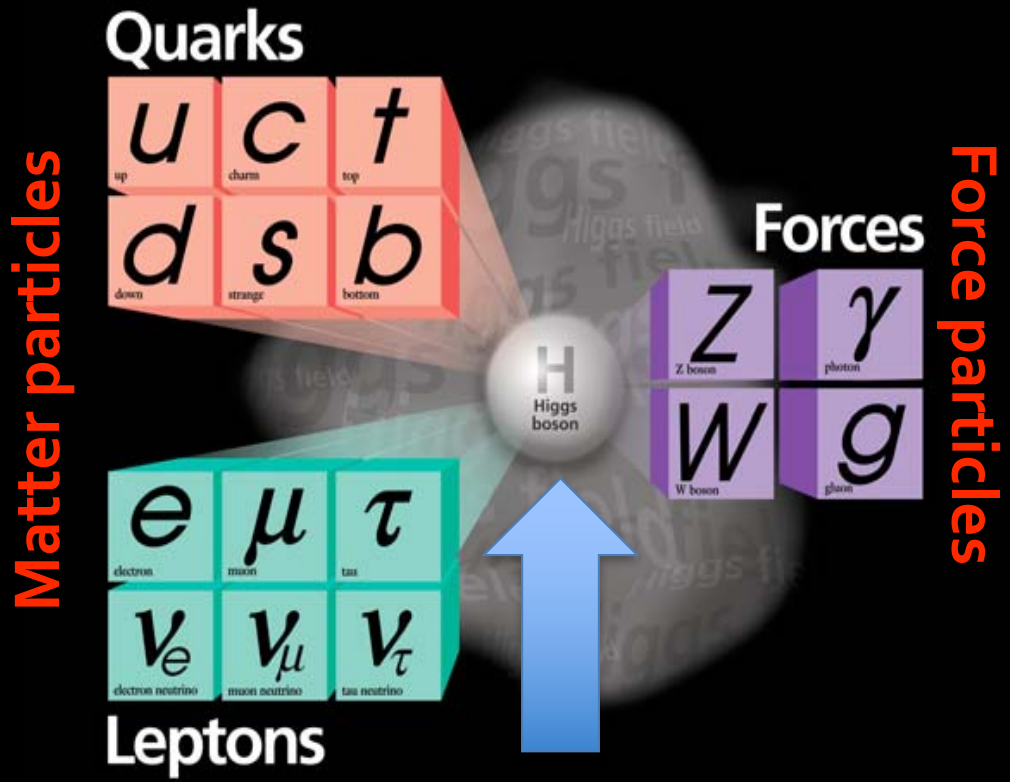
- The prevailing theory (the standard model) is a remarkable intellectual construction
- Particle experiments confirm the theory with exquisite precision to one part in 10 billion

But there are many mysteries



Mystery: One missing element was the Higgs
It gives mass to the particles of the standard model

The Standard Model



The discovery of the Higgs completed the Standard Model

The Standard Model: A work a century in the making

Highly predictive, it has been rigorously tested in some cases to 1 part in 10 billion

It has revolutionized our understanding of the subatomic world

The Higgs

Searching for the Higgs we seek to understand why the world is the way it is

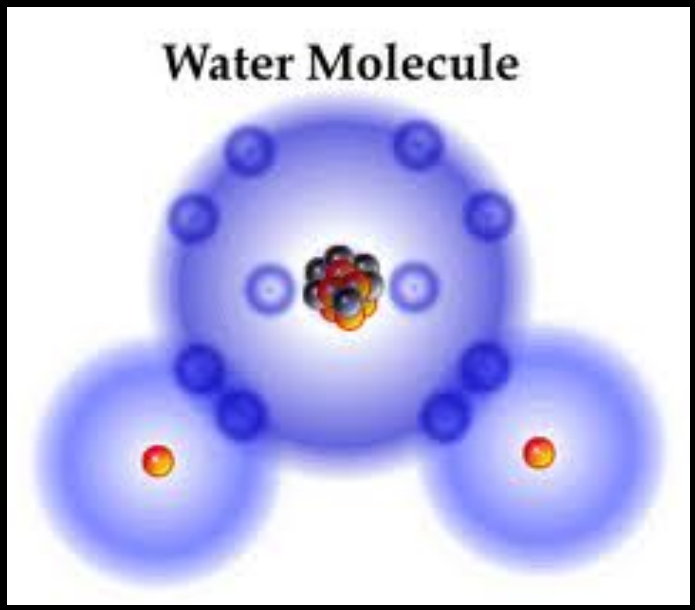
It is one of deepest questions humans have ever pursued

Higgs field analogy to an ocean

Barracuda supremely streamlined passes through water effortlessly (there is a low interaction with the water)
The Barracuda represents a low mass particle: electron

People wading through deep water do so with great effort. (There is a large interaction with the water) These people represent high mass particles: top quark

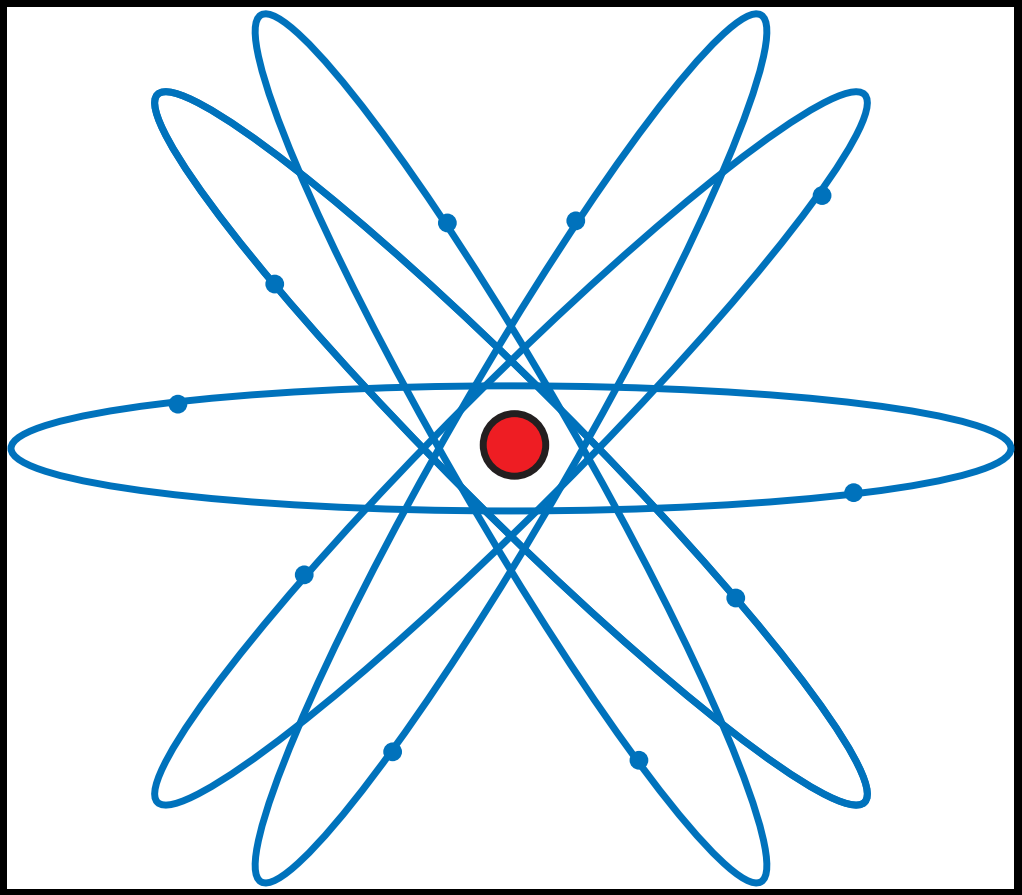
HIGGS FIELD, but what about HIGGS PARTICLE?



Just as the photon is the particle of the electromagnetic field

HIGGS

If electrons did not have mass they would move at the speed of light preventing the formation of atoms: no chemistry, no biology, no life

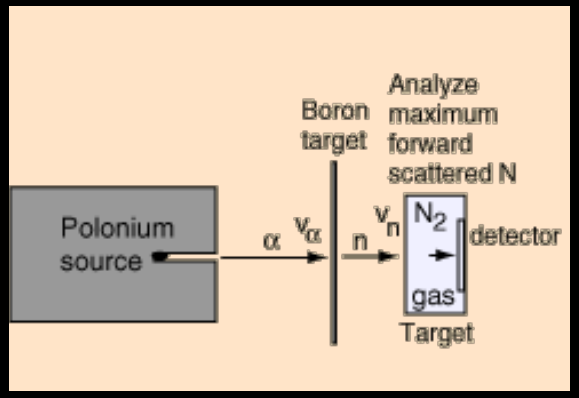


Without a Higgs field we would evaporate

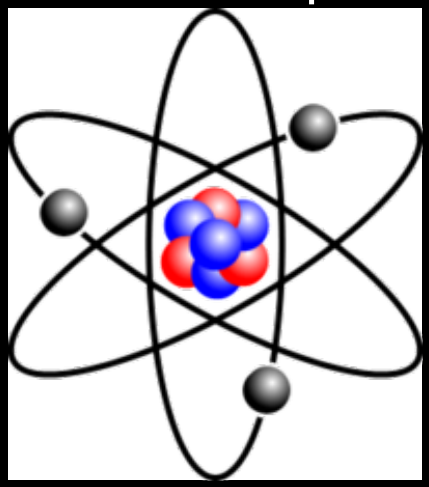
A work a century in the making

From the discovery of the electron in 1896, the nucleus in 1911 to

the neutron in 1932

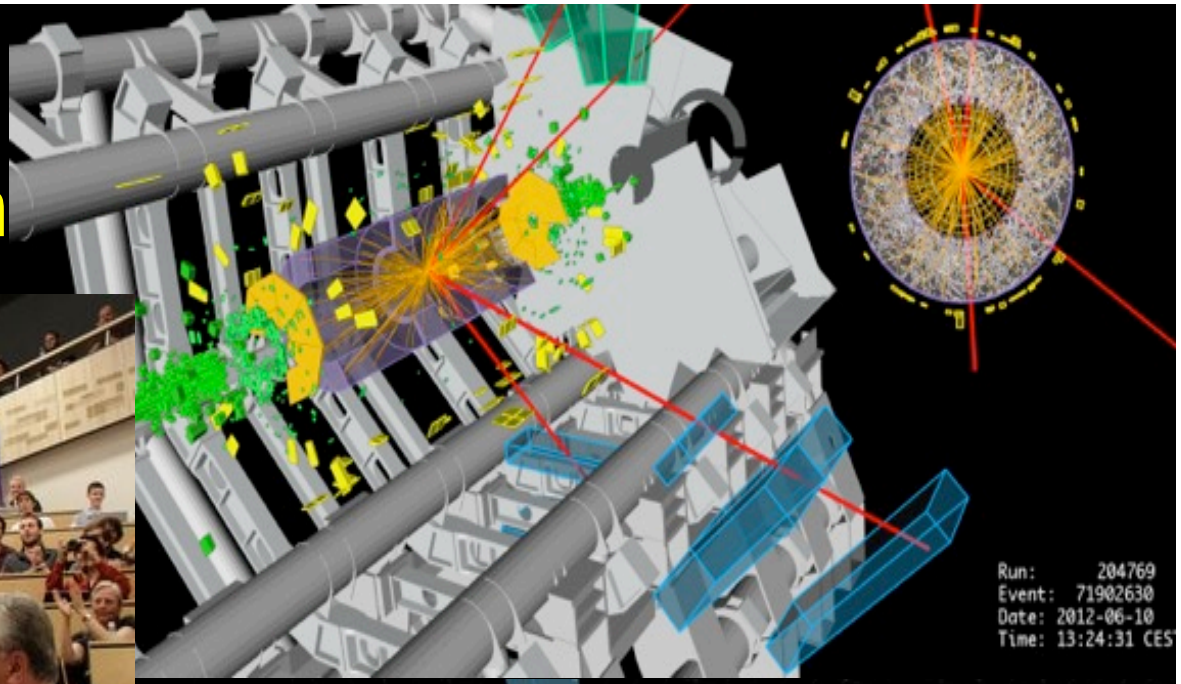


the particles that compose an atom



2012.7.4

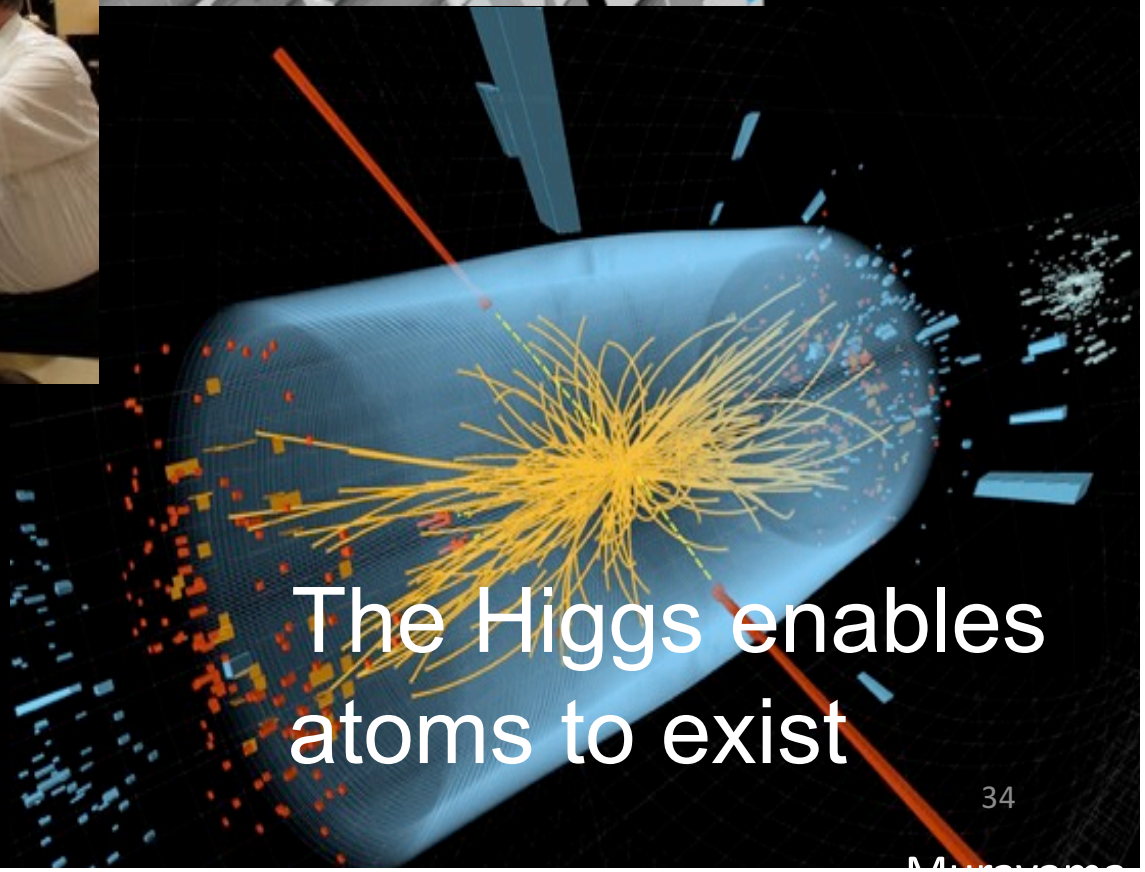
discovery of Higgs boson



theory：1964

design：1984

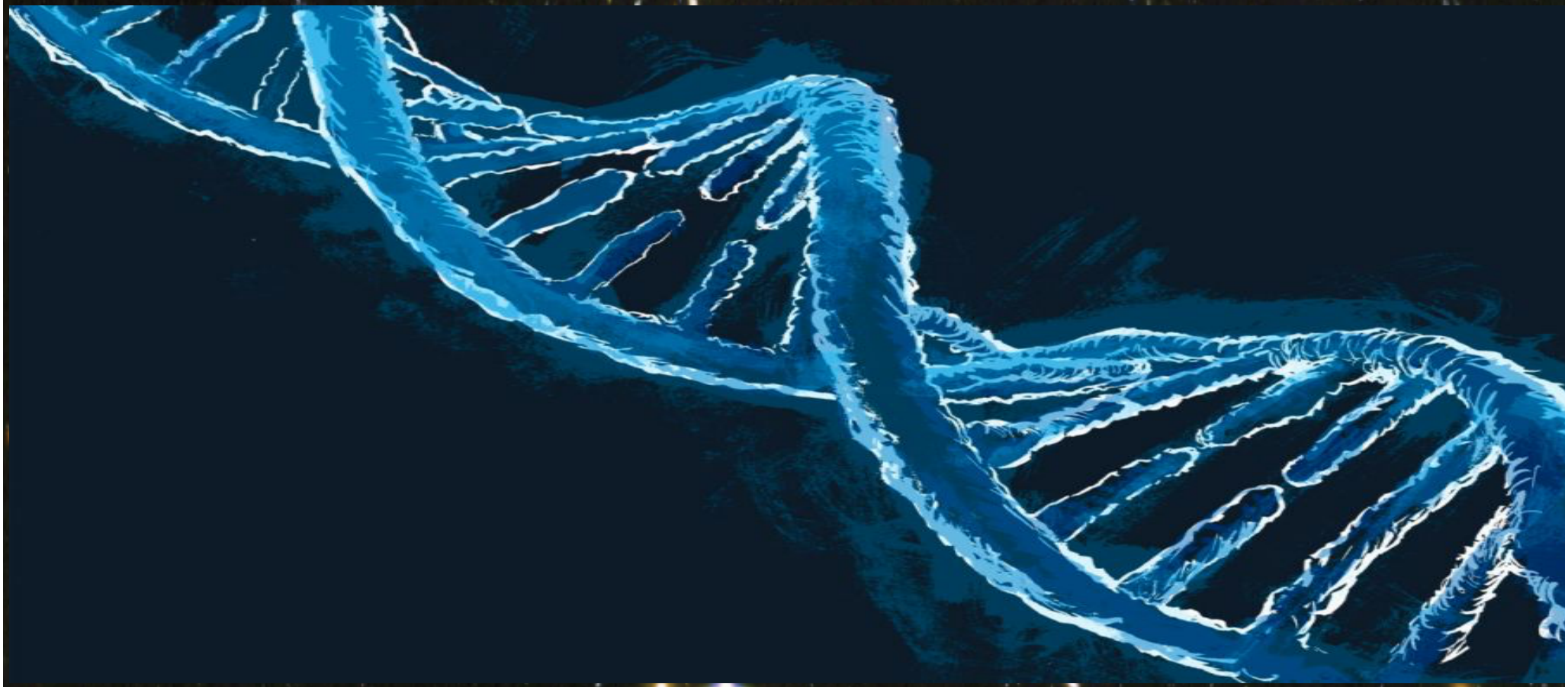
construction：1998



The Higgs enables atoms to exist

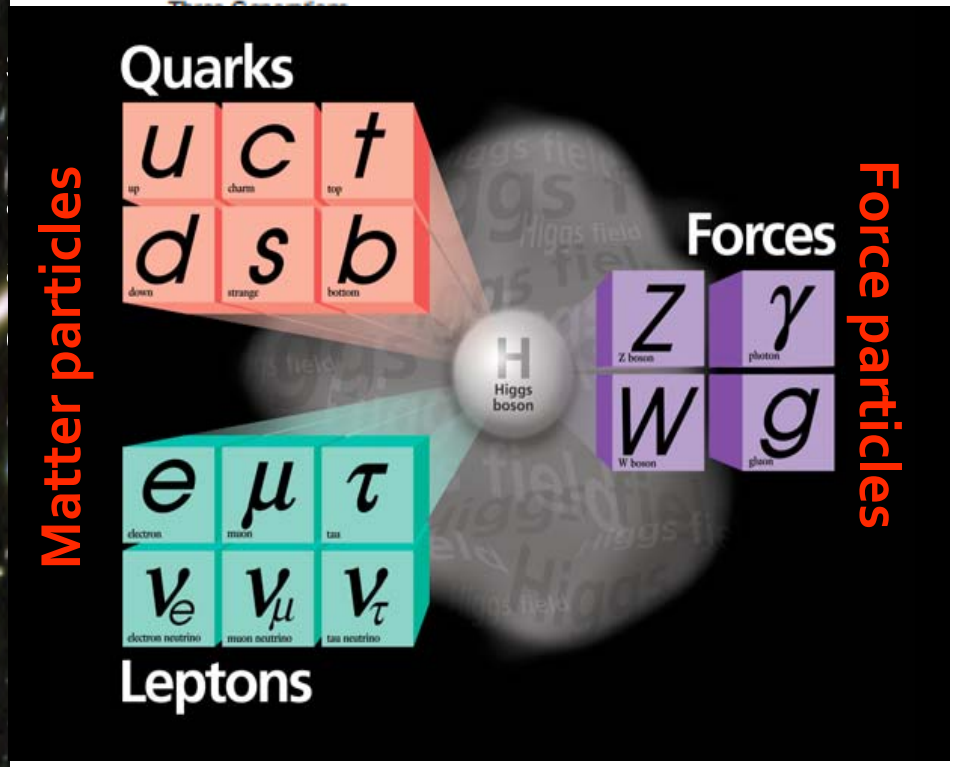
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our community has revolutionized human understanding of the Universe – its underlying code, structure and evolution

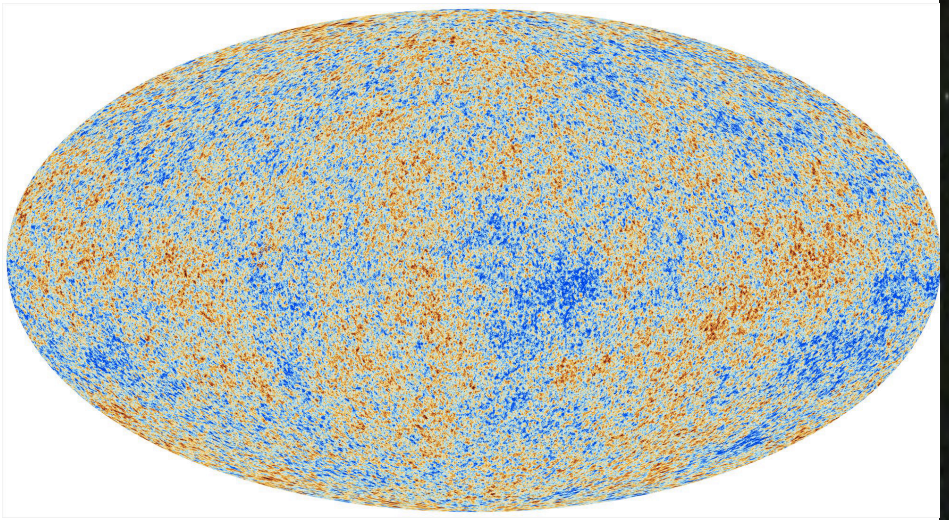


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

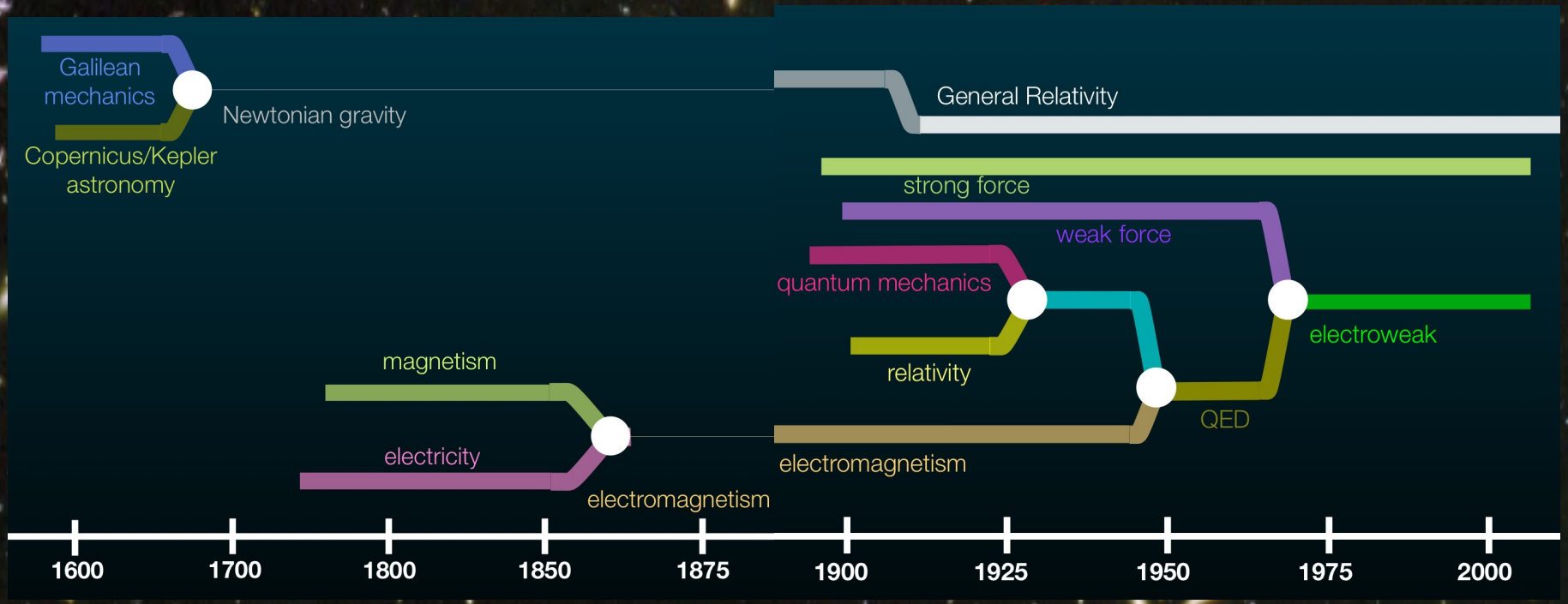
…..that are highly predictive and have been rigorously tested in some cases to 1 part in 10 billion

Quantity	Value	Standard Model	Pull	Dev.
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4961 ± 0.0010	−0.4	−0.2
Γ(had) [GeV]	1.7444 ± 0.0020	1.7426 ± 0.0010	—	—
Γ(inv) [MeV]	499.0 ± 1.5	501.69 ± 0.06	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	84.005 ± 0.015	—	—
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	41.477 ± 0.009	1.7	1.7
R_e	20.804 ± 0.050	20.744 ± 0.011	1.2	1.3
R_μ	20.785 ± 0.033	20.744 ± 0.011	1.2	1.3
R_τ	20.764 ± 0.045	20.789 ± 0.011	−0.6	−0.5
R_b	0.21629 ± 0.00066	0.21576 ± 0.00004	0.8	0.8
R_c	0.1721 ± 0.0030	0.17227 ± 0.00004	−0.1	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01633 ± 0.00021	−0.7	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.4	0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1034 ± 0.0007	−2.6	−2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0739 ± 0.0005	−0.9	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1035 ± 0.0007	−0.5	−0.5
$\bar{s}^2_\ell(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23146 ± 0.00012	0.8	0.7
	0.23200 ± 0.00076		0.7	0.6
	0.2287 ± 0.0032		−0.9	−0.9
A_e	0.15138 ± 0.00216	0.1475 ± 0.0010	1.8	2.1
	0.1544 ± 0.0060		1.1	1.3
	0.1498 ± 0.0049		0.5	0.6
A_μ	0.142 ± 0.015		−0.4	−0.3
A_τ	0.136 ± 0.015		−0.8	−0.7
	0.1439 ± 0.0043		−0.8	−0.7
A_b	0.923 ± 0.020	0.9348 ± 0.0001	−0.6	−0.6
A_c	0.670 ± 0.027	0.6680 ± 0.0004	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	−0.4	− 0.4

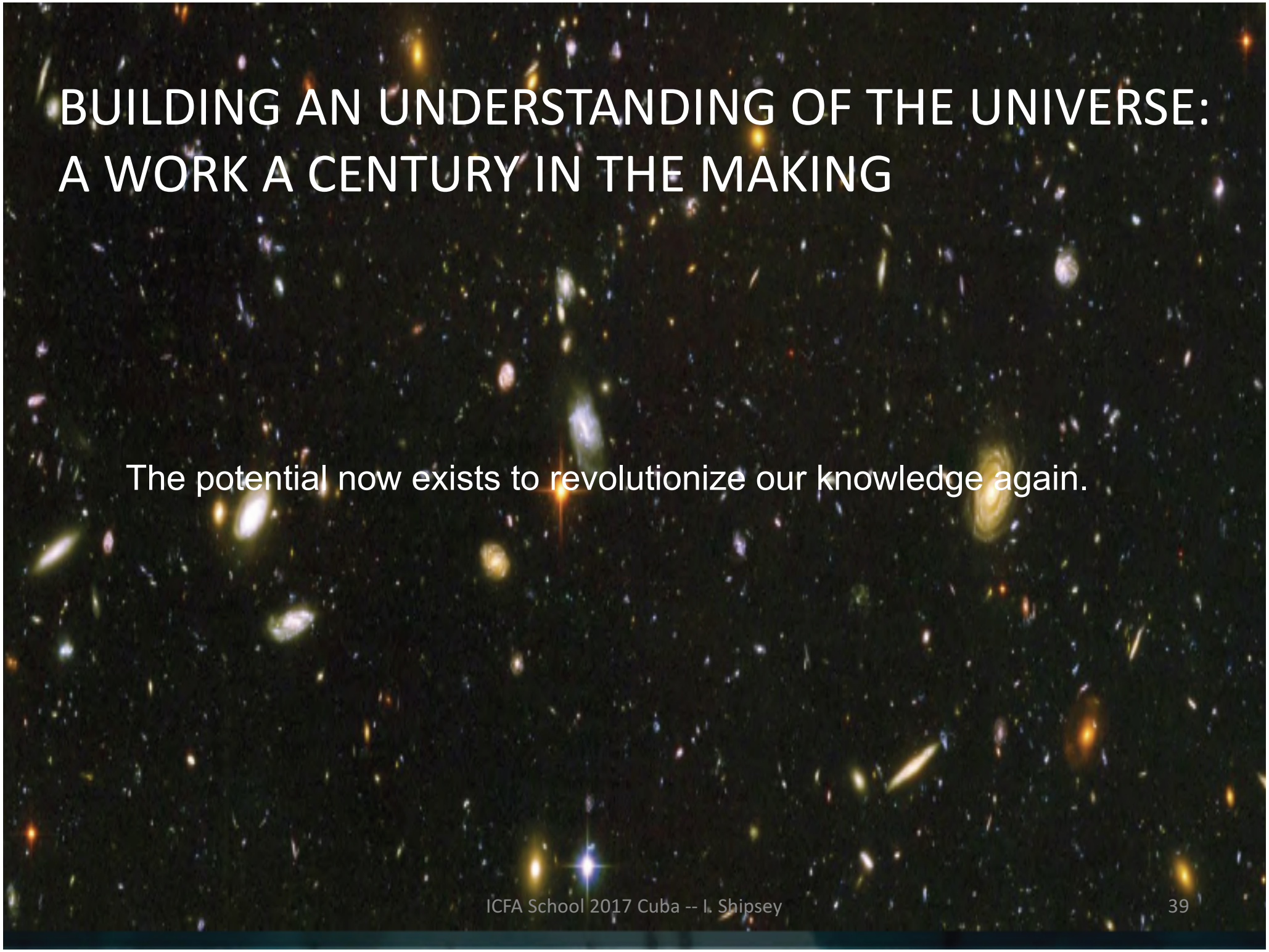
Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	−0.1	−0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		−0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
Q_W(Cs)	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
Q_W(Tl)	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

These are among the highest intellectual achievements in the history of our species, they will be part of our legacy to future generations for eternity



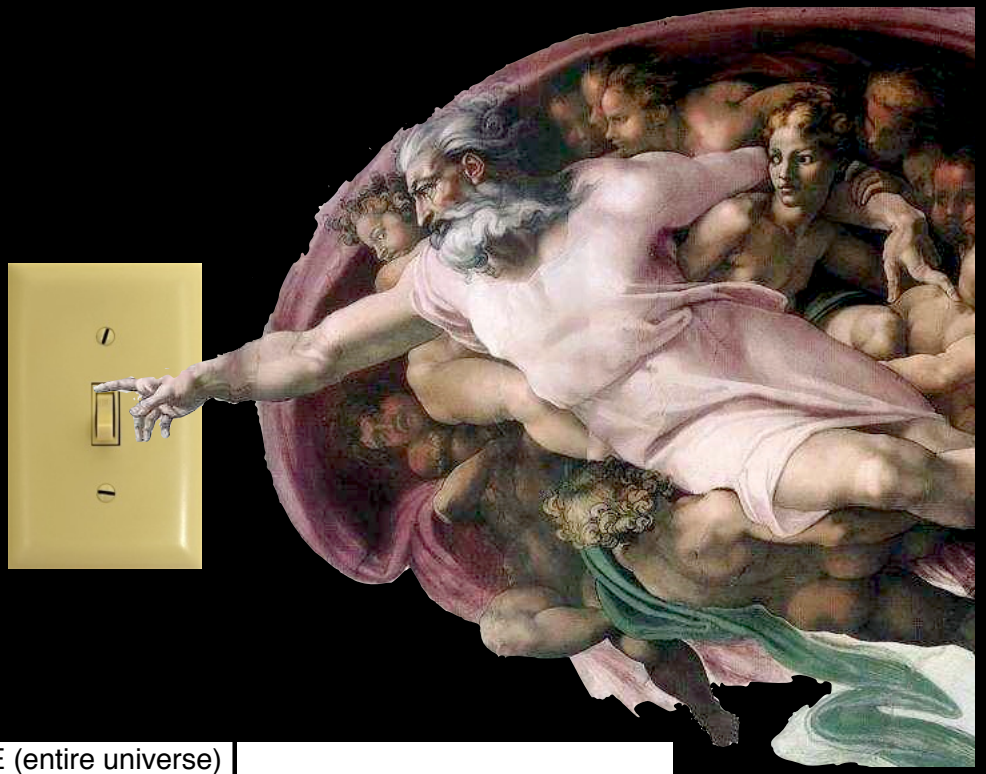
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

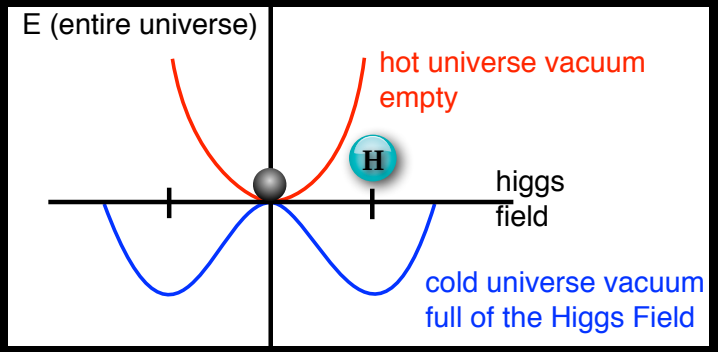


The potential now exists to revolutionize our knowledge again.

Mystery: The Higgs

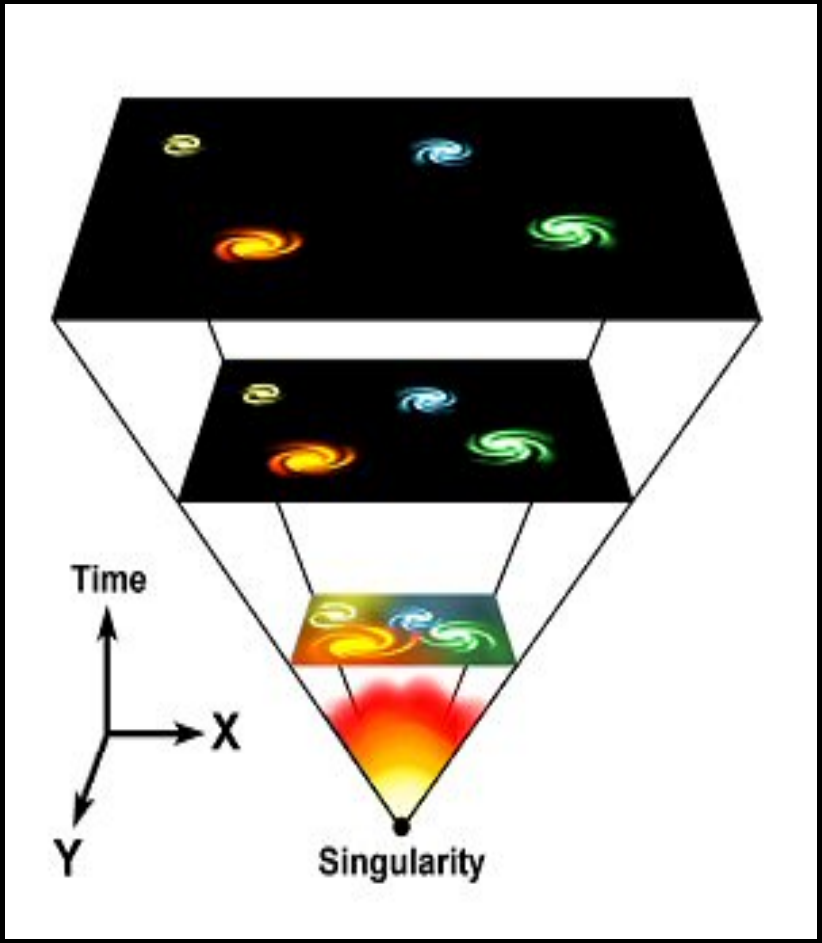
That Spin 0 Boson
Changes Everything



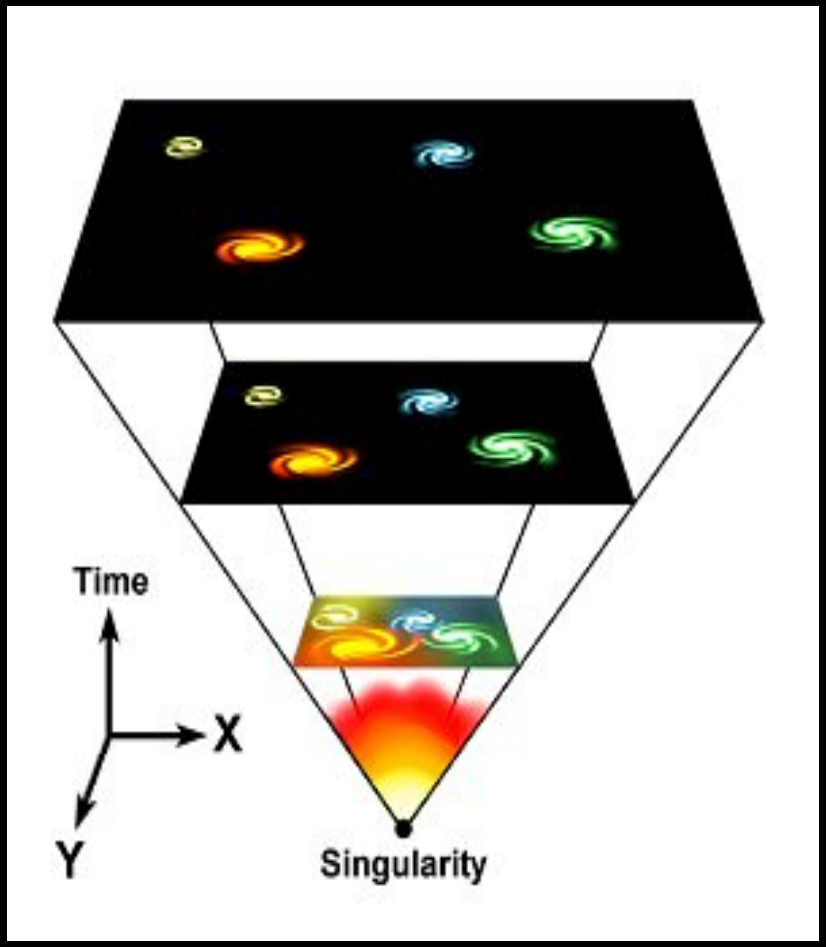


Mystery: Dark Matter

Mystery: Dark Energy

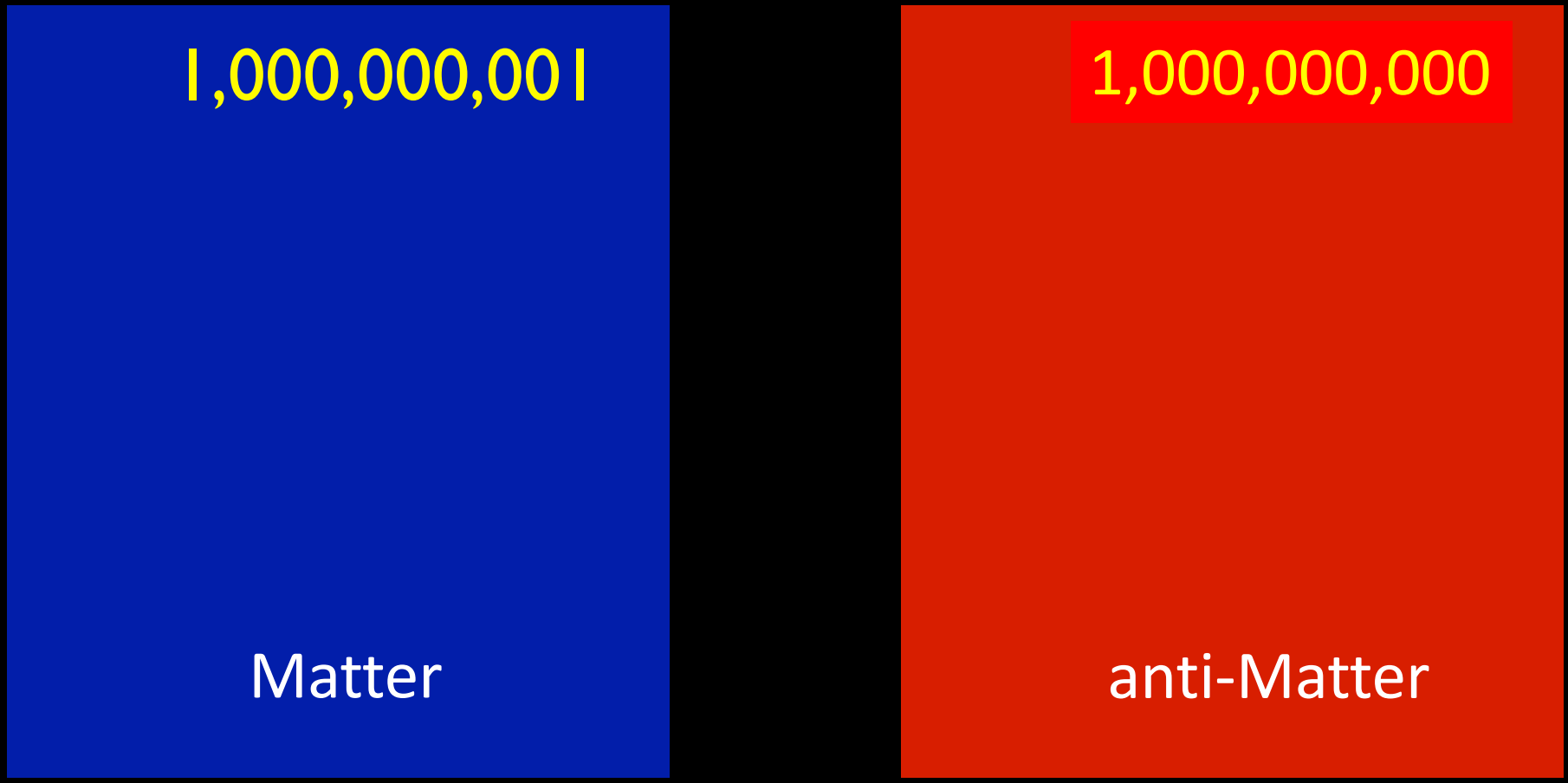


Mystery: Dark Energy



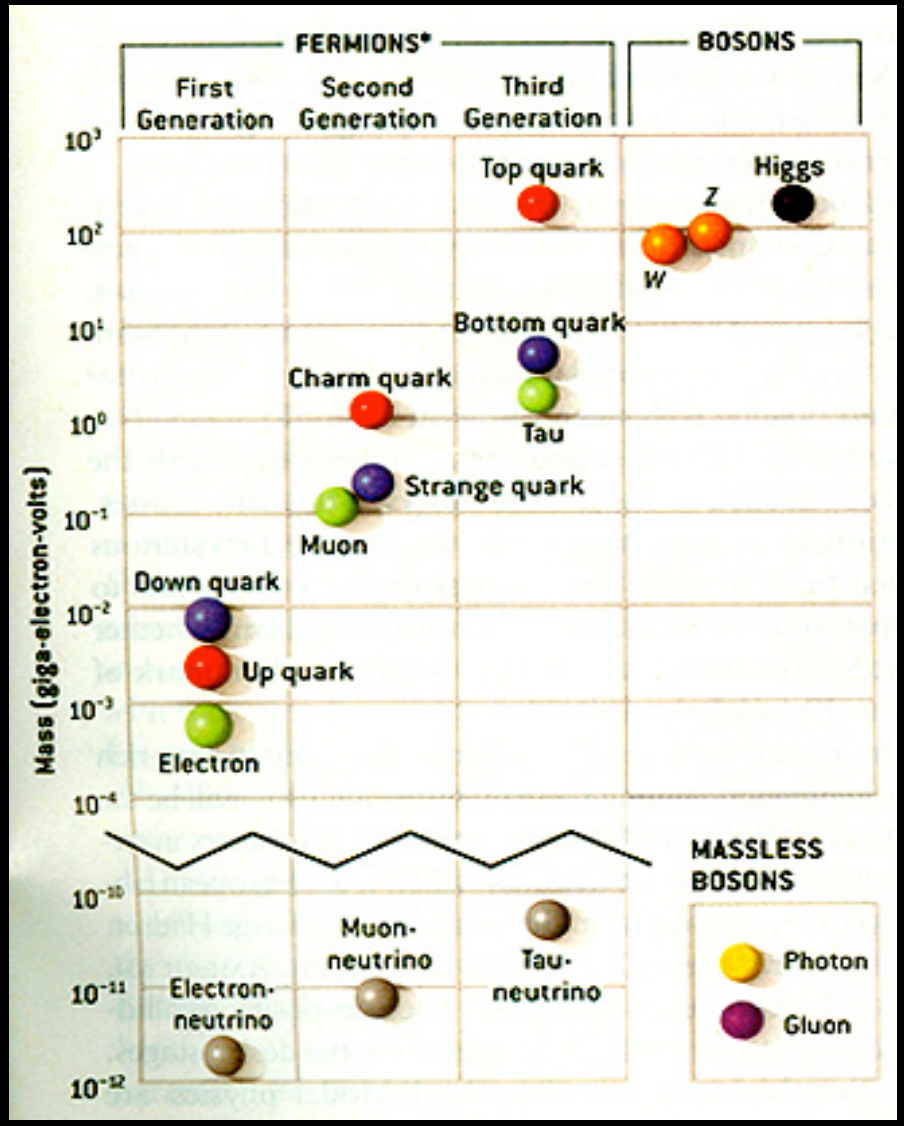
What we know: just the tip of the iceberg.

Mystery: how did matter survive the birth of the universe?



The baryon asymmetry of the Universe

Mystery: Why are there so many types of particles?

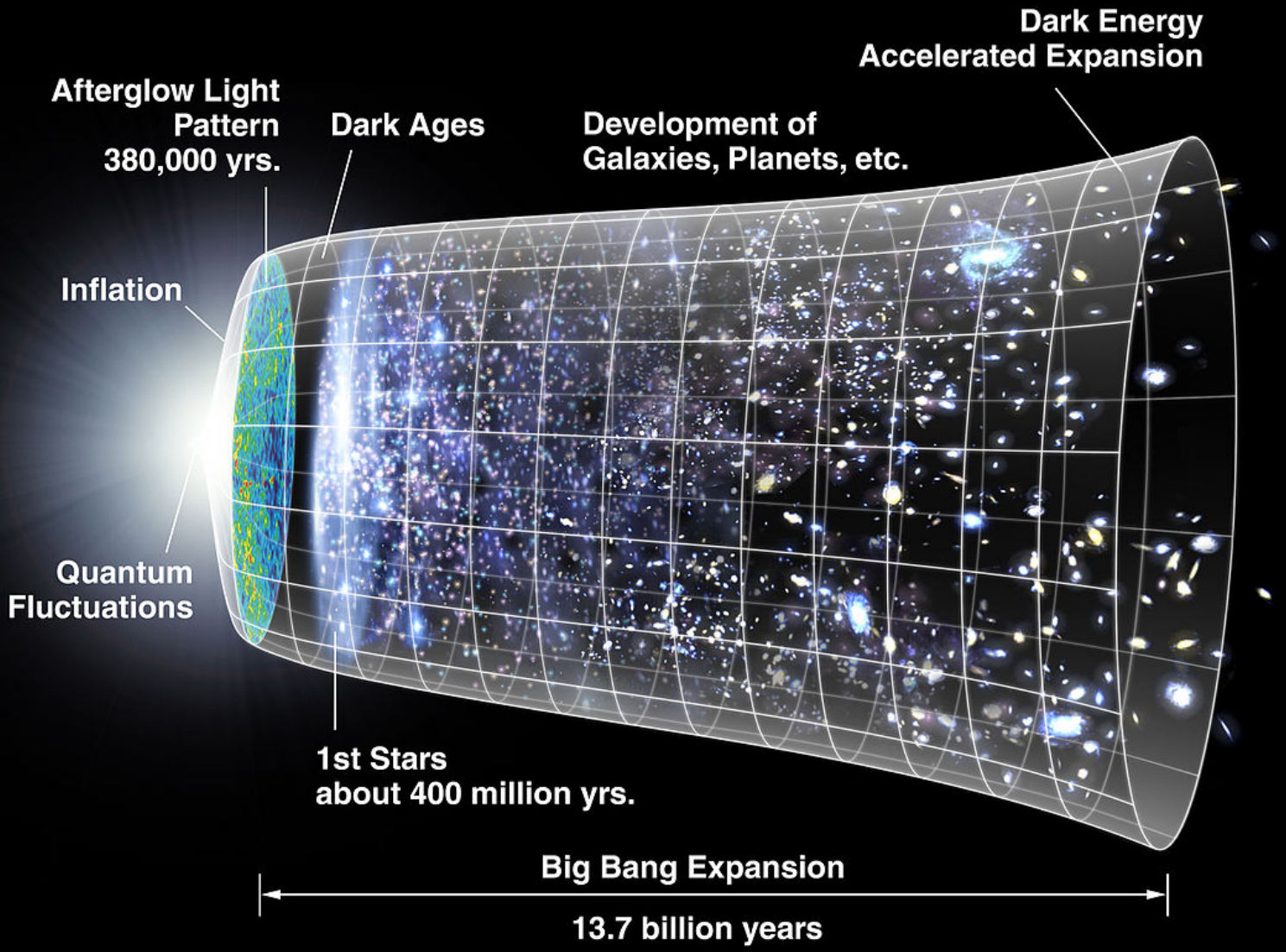


Why do the particles have such a large range of masses?

Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

Mystery: What powered cosmic inflation?



Outstanding Questions in Particle Physics *circa* 2011

EWSB
- ❑ Does the Higgs boson exist?

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2017

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent V_LV_L cross-section at high $M(V_LV_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

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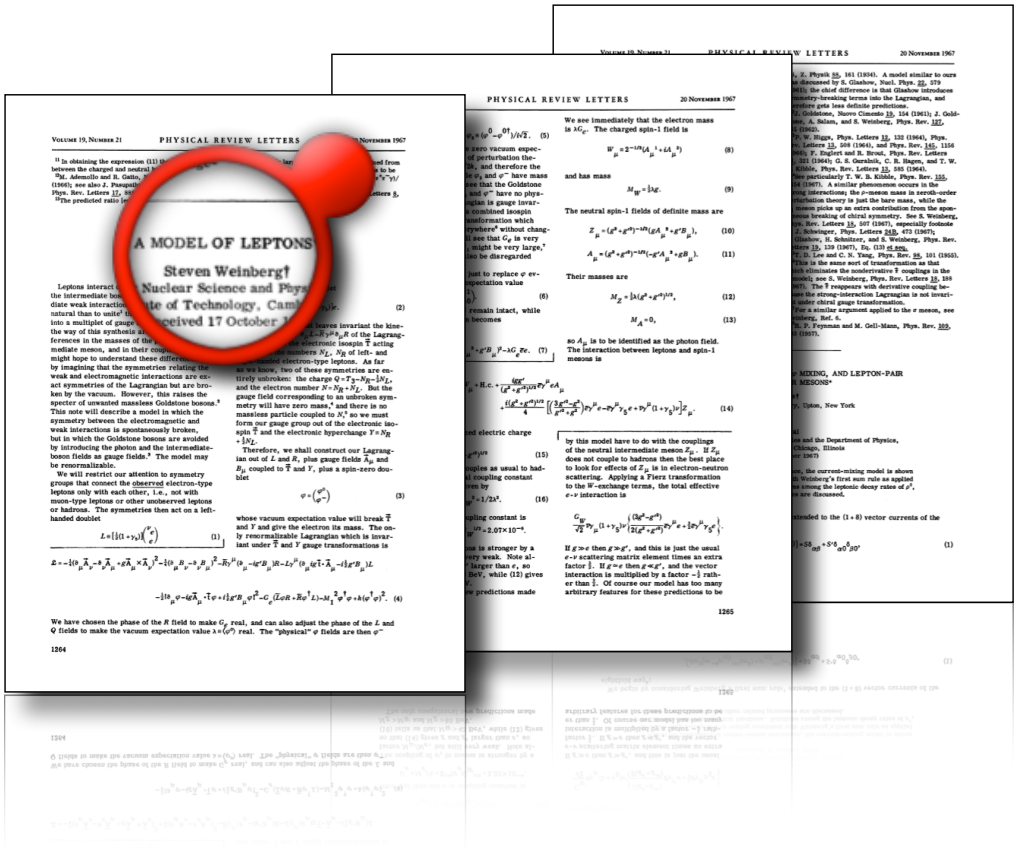
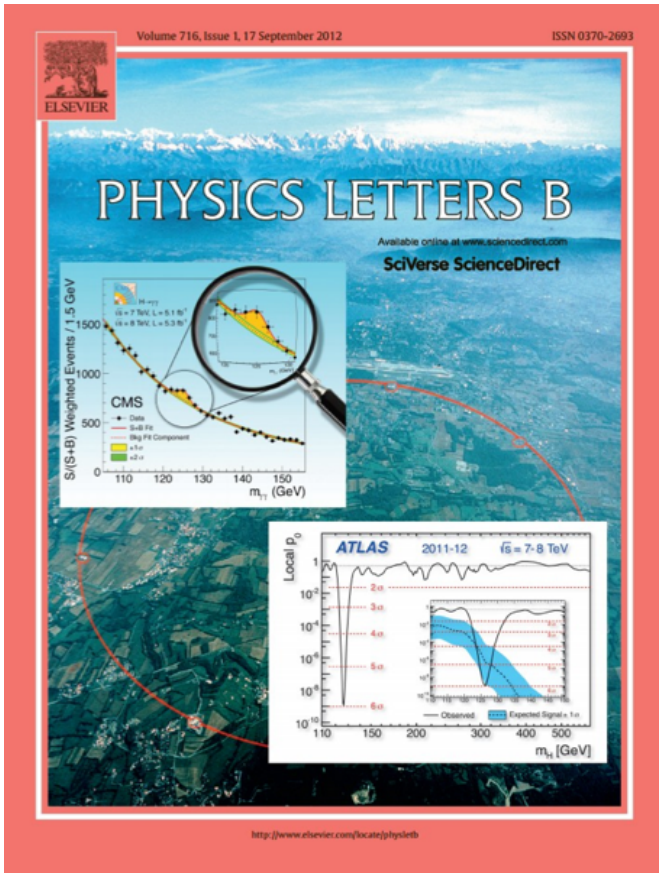
Neutrinos:
- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

between **1967 - 2012**





The Standard Model Guided Research

No-lose completion of the Standard Model

Guaranteed discoveries

W & Z CERN SppS (1983)
Top quark Tevatron (1995)
Higgs LHC (2012)

No-lose completion of the Standard Model

Now that the Standard Model is complete, there are no further no-lose theorems
In principle, the Standard Model could be valid to the Planck scale

No guaranteed discoveries

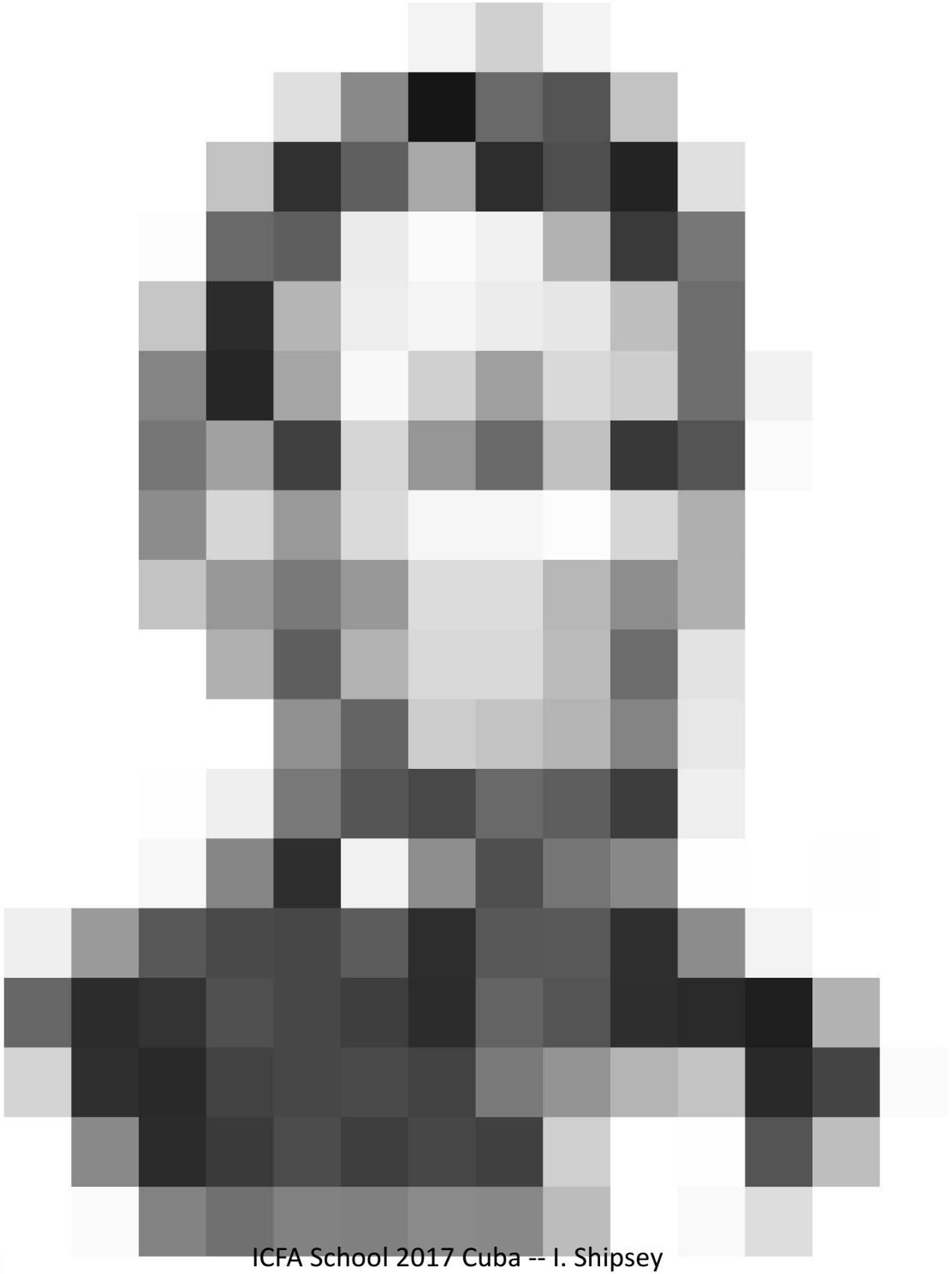
Perception & understanding *with a roadmap*

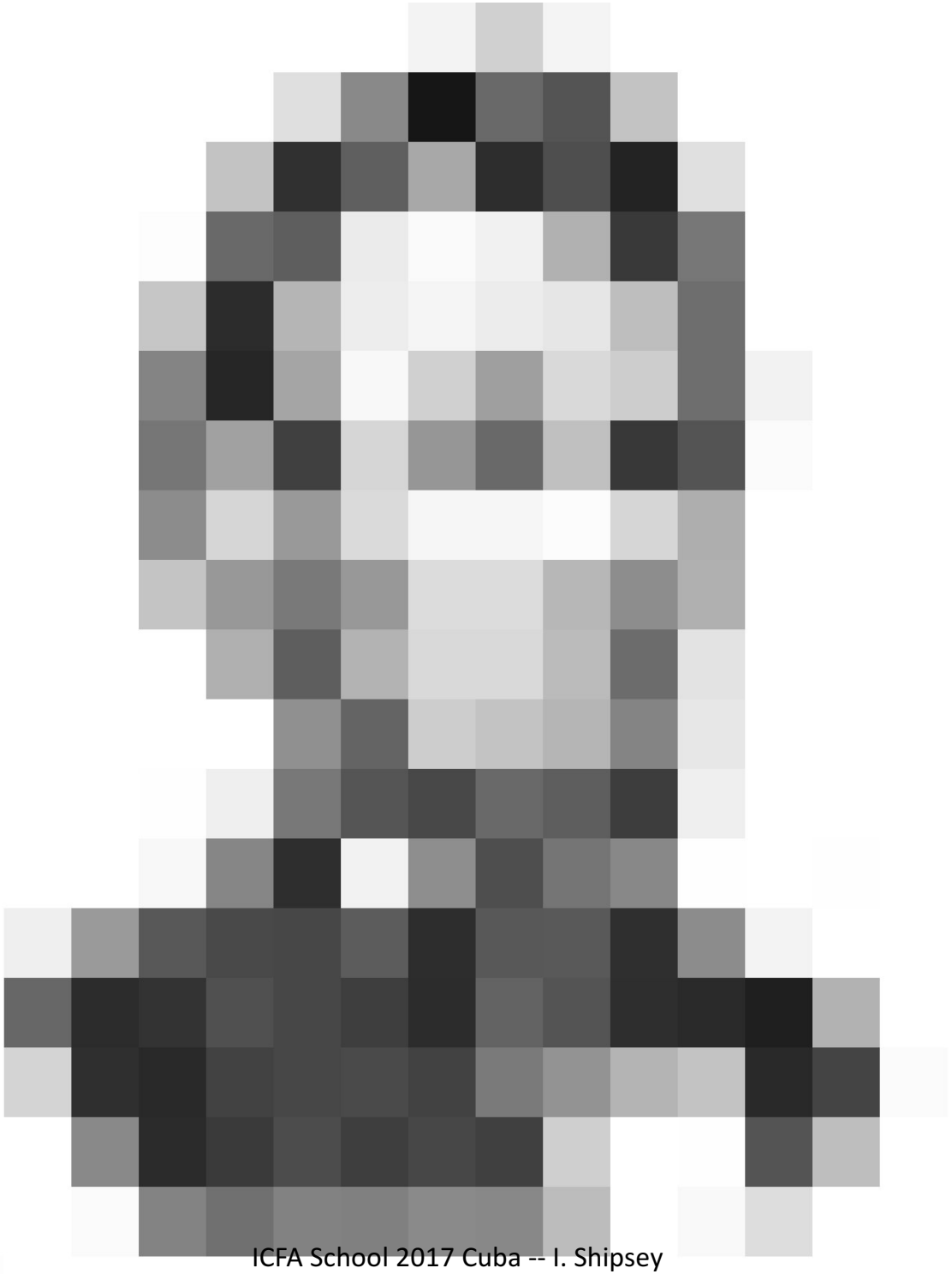
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

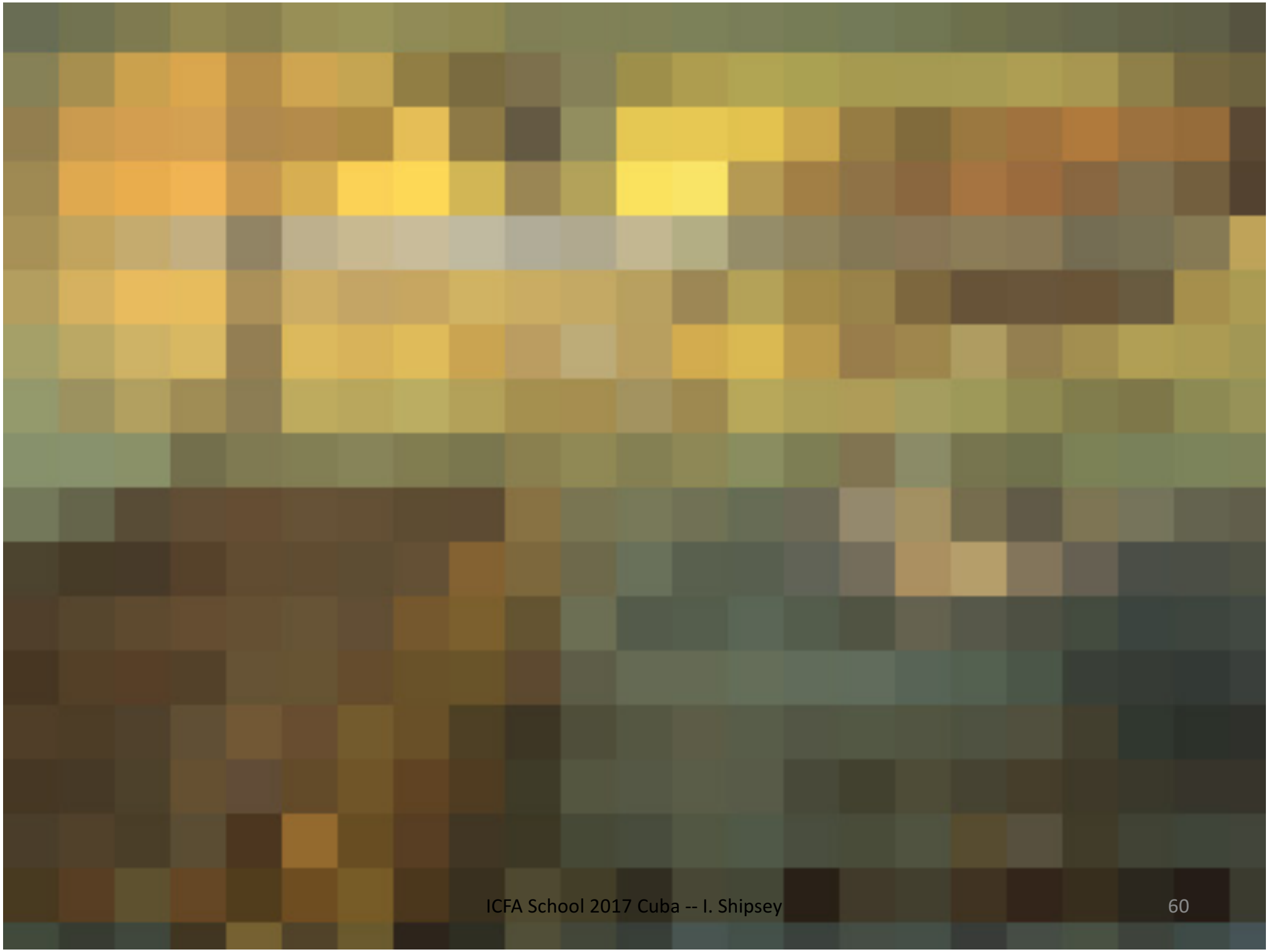
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

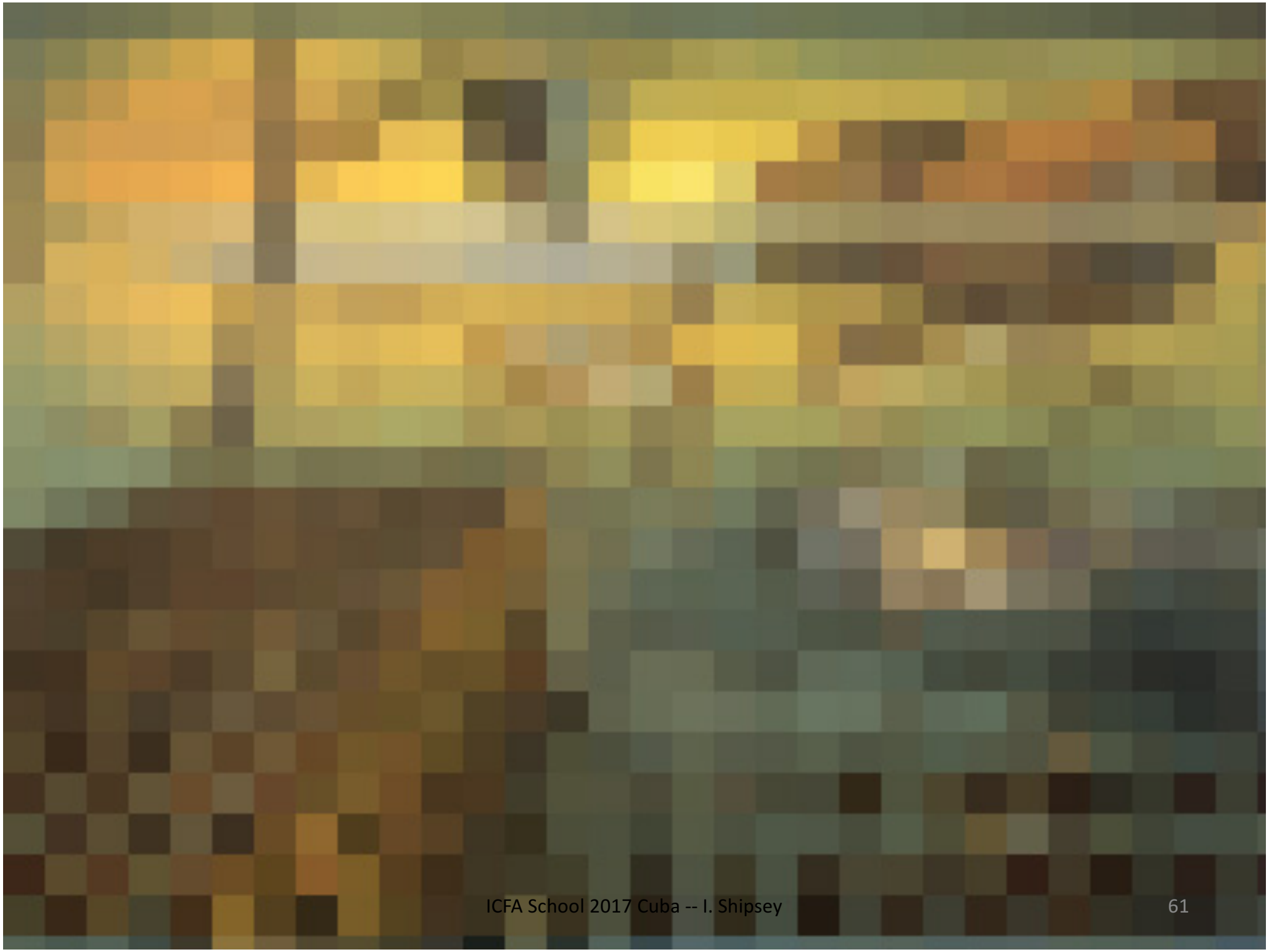
  When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)

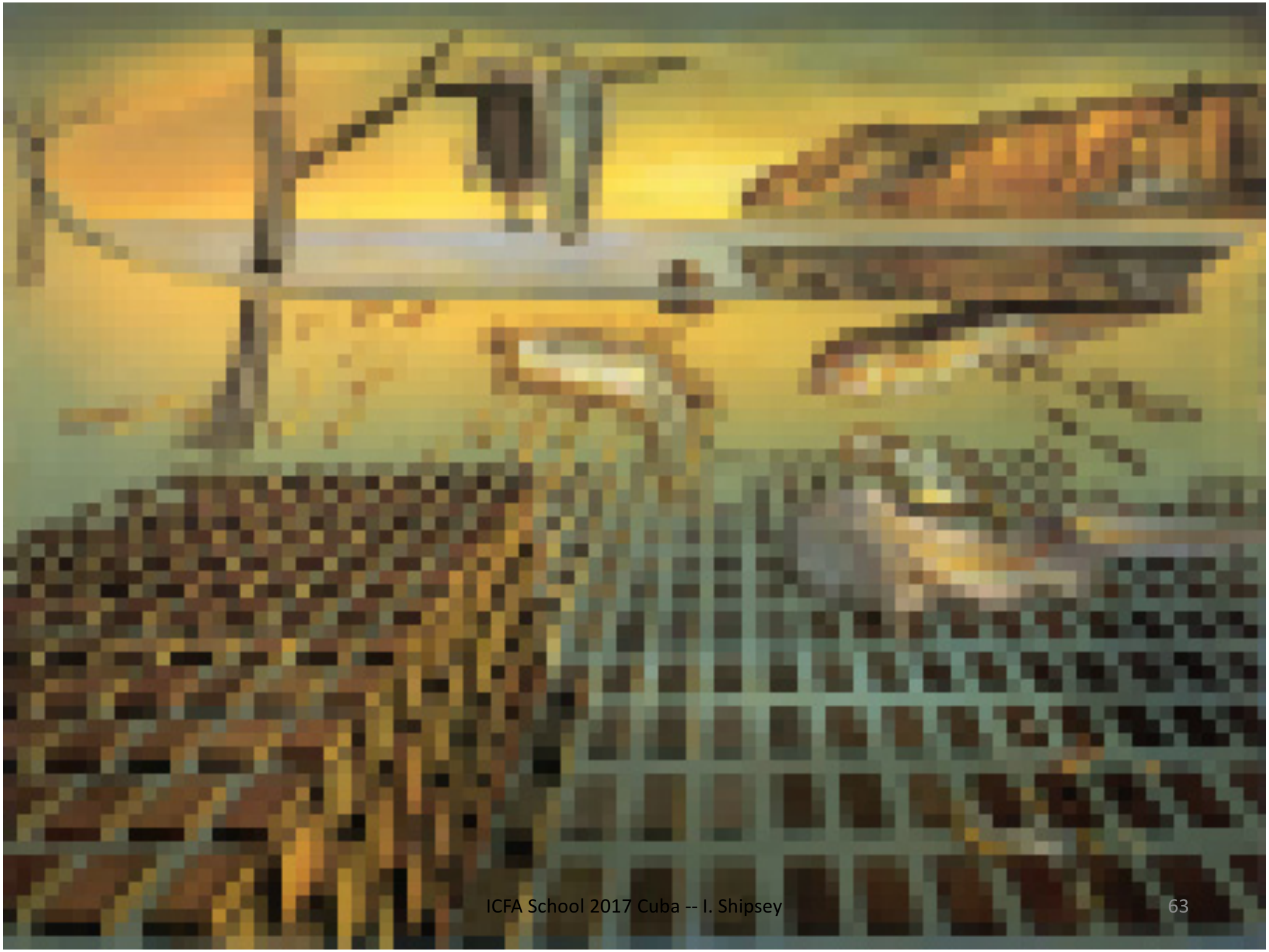
Visual examples…

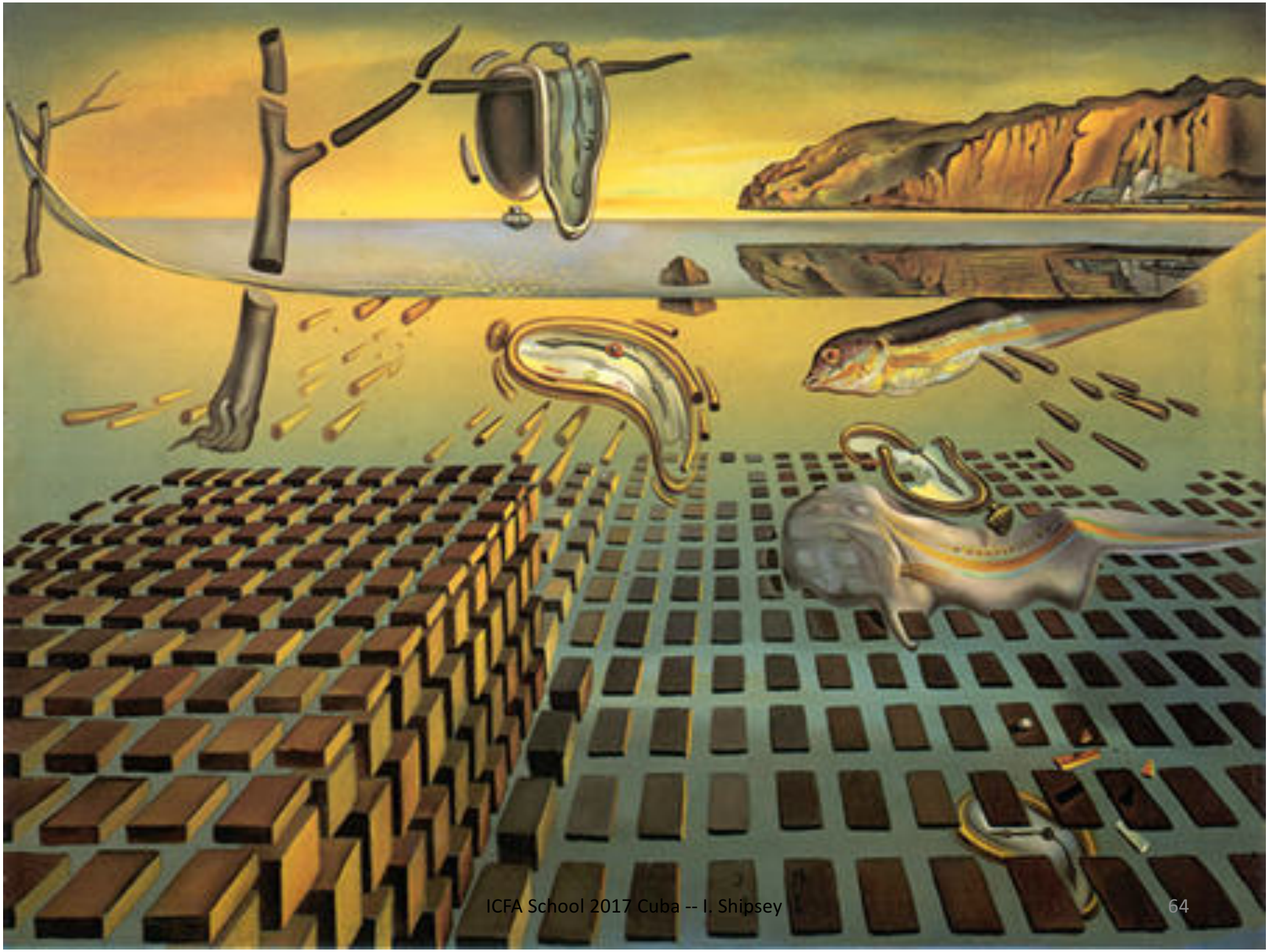






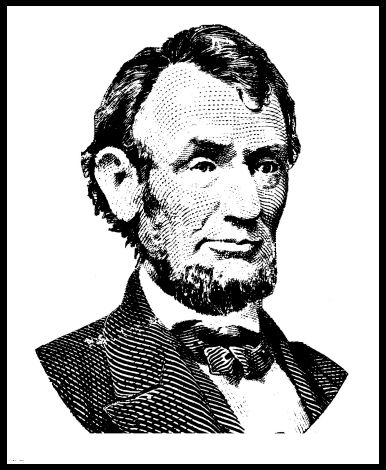






Perception & understanding

With a roadmap (theory)



(W,t,H) a little data goes a long way (top-down dominates)

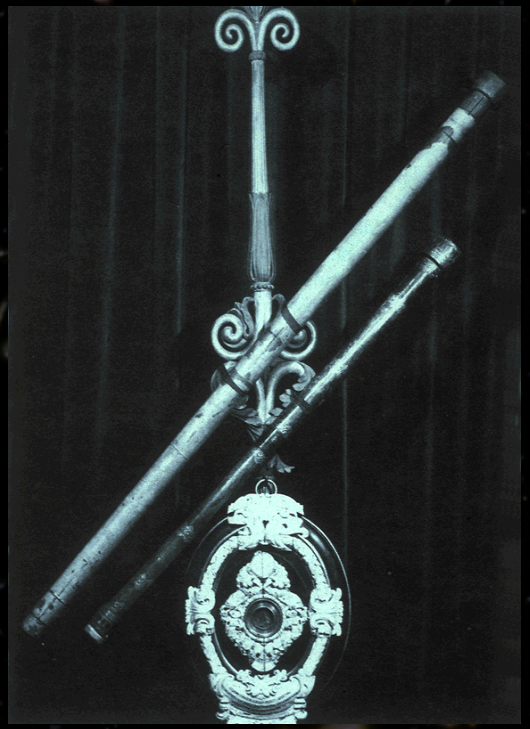
w/o a roadmap (data driven)

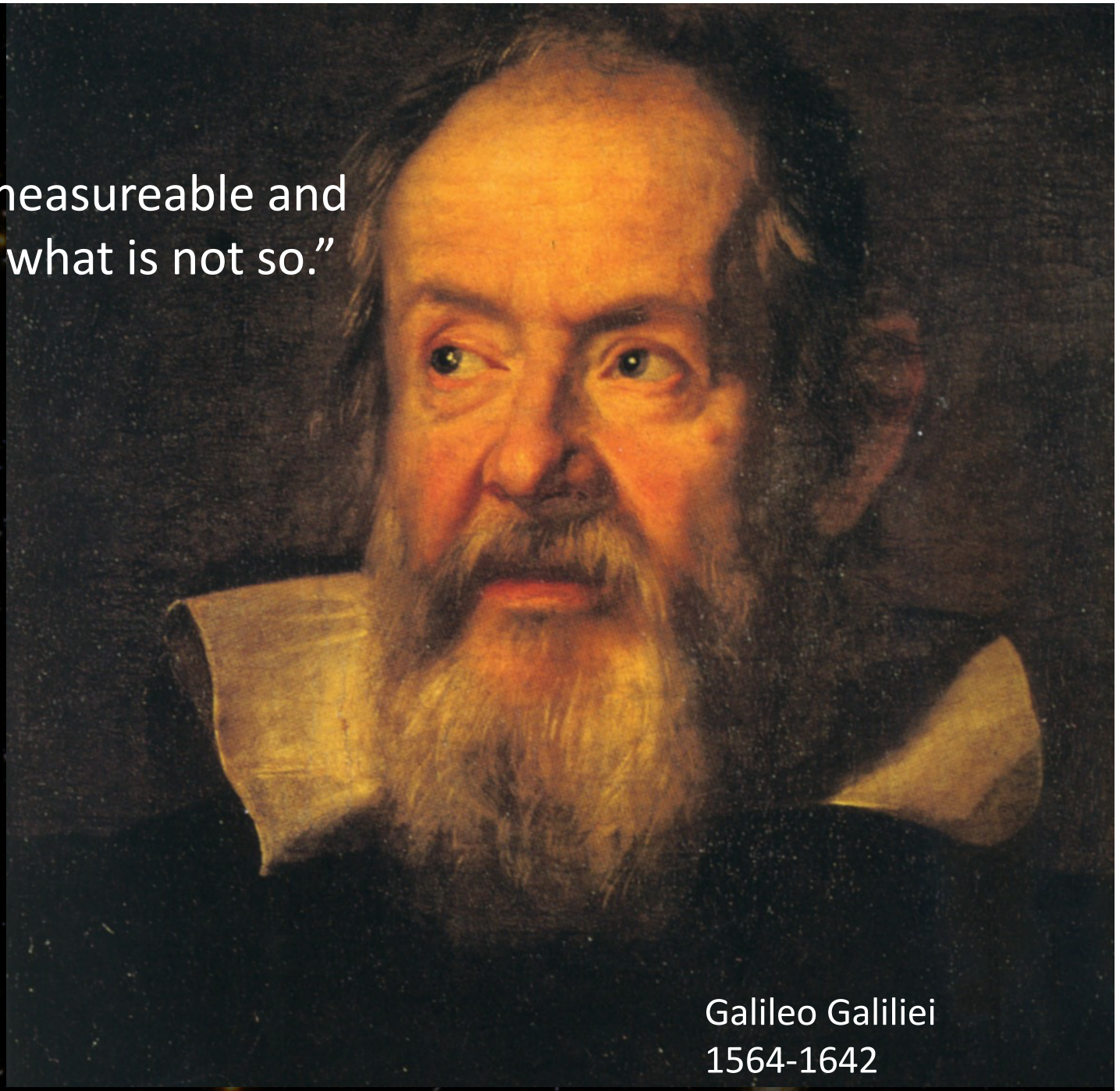
New physics need lots of data (bottom up dominates)


We are in a data driven era

#1 Context

"Measure what is measureable and make measureable what is not so."





Galileo Galiliei
1564-1642