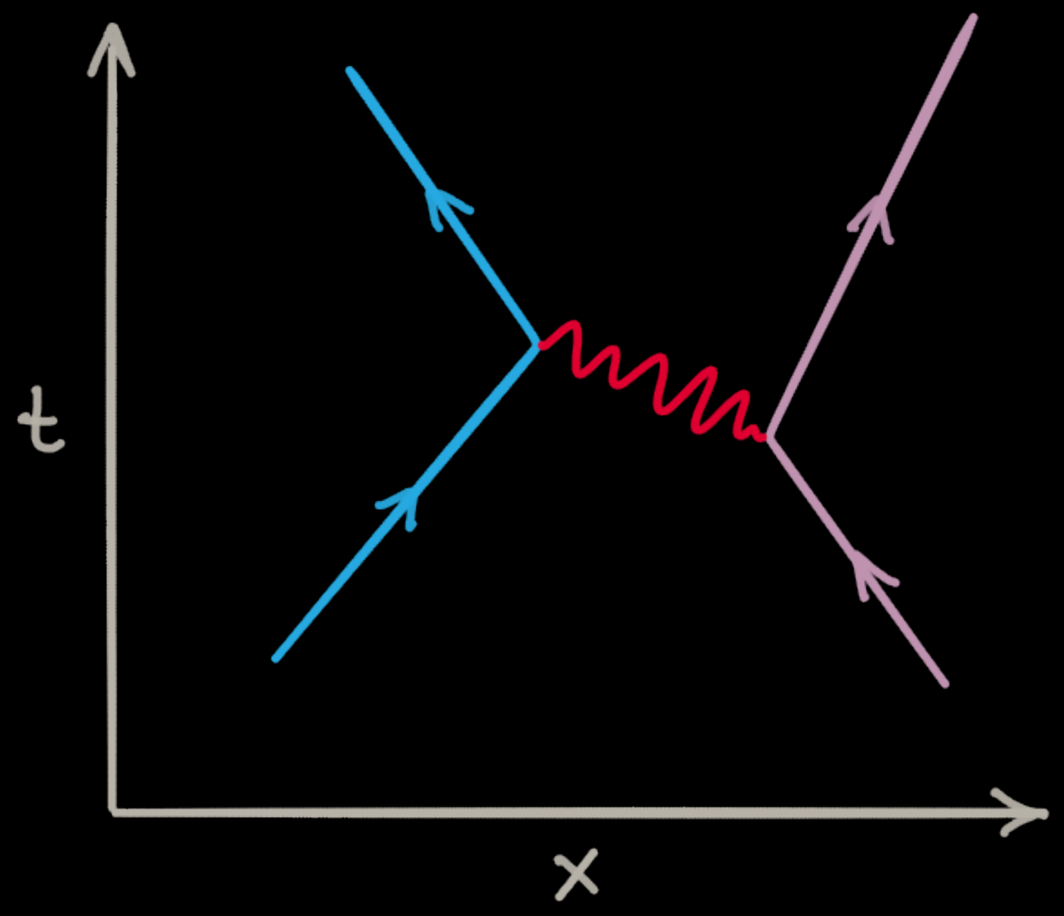
The Quantum Frontiers of Particle Physics

Nathaniel Craig
UCSB

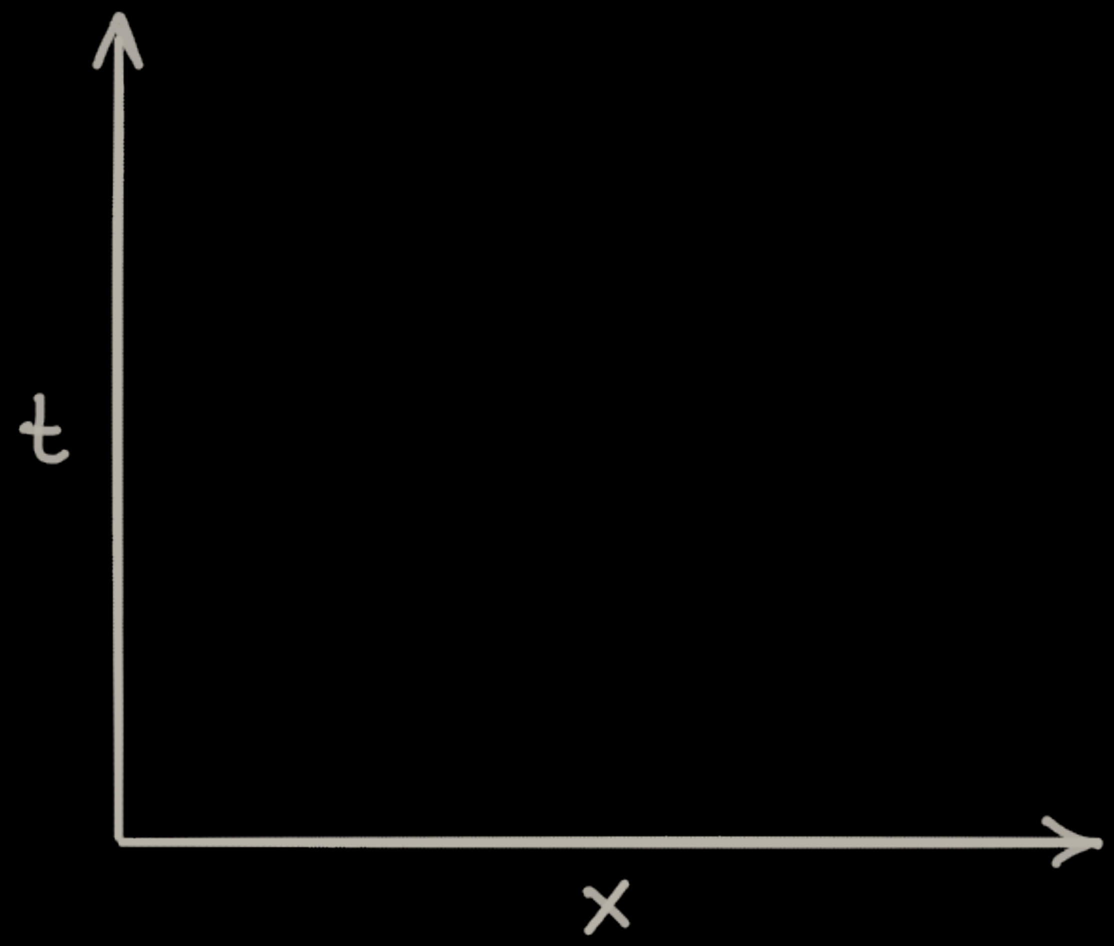
A Hundred Years of Quantum Mechanics

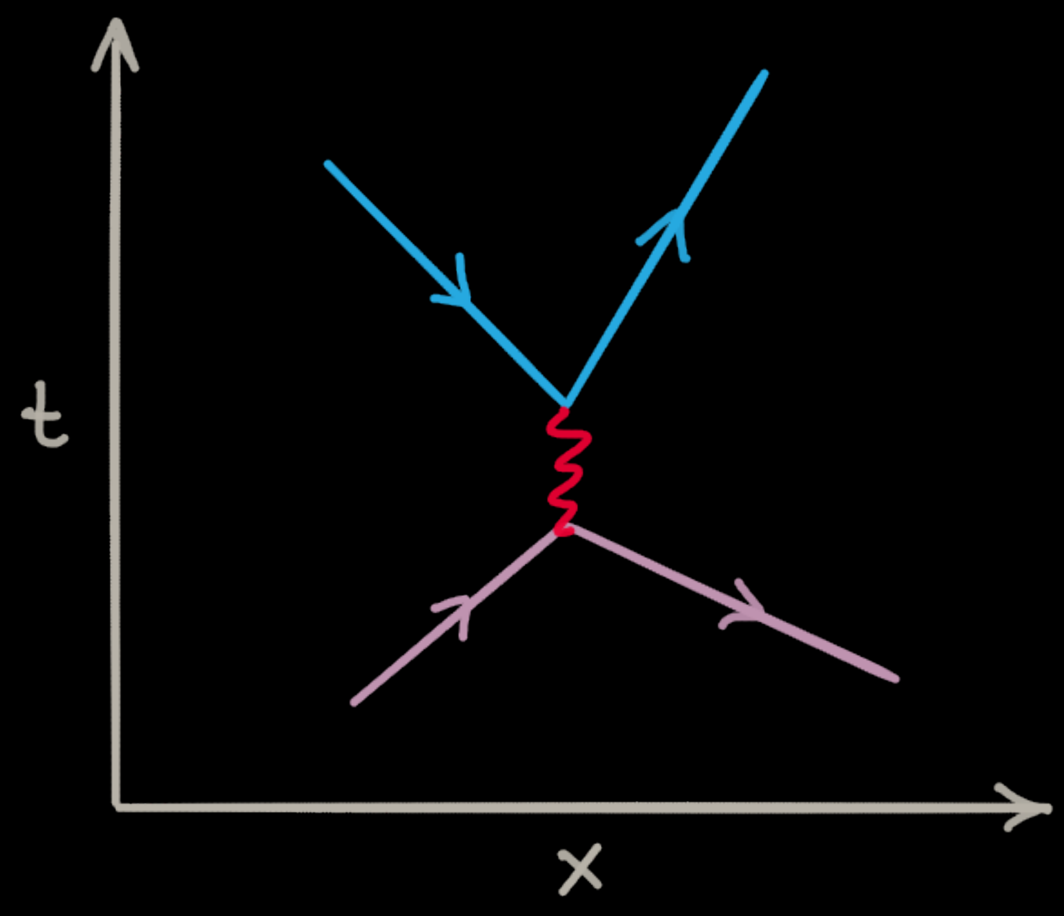
TIFR, 01/13/25

Particle Physics: SR+QM

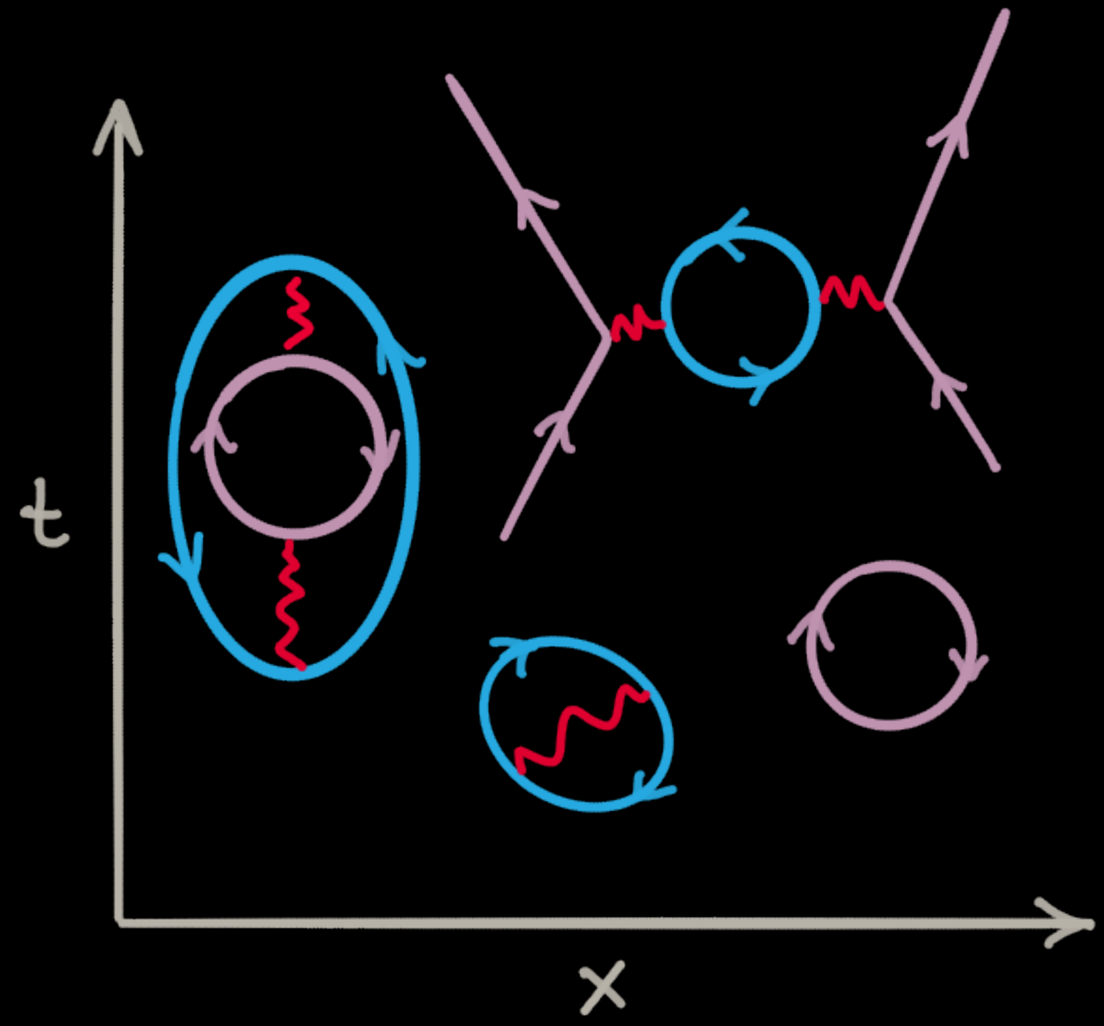


$(\hbar = 0)$

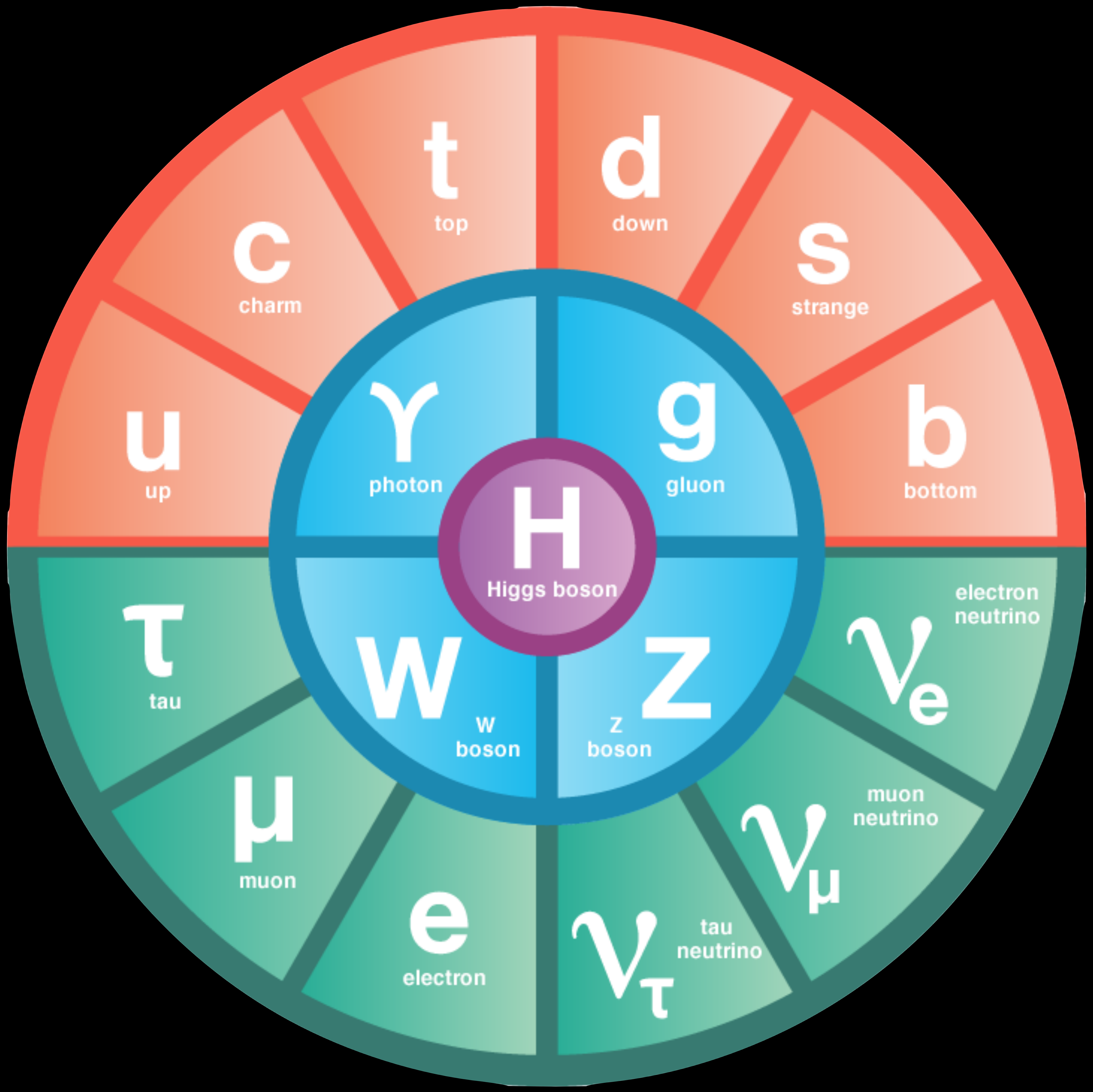




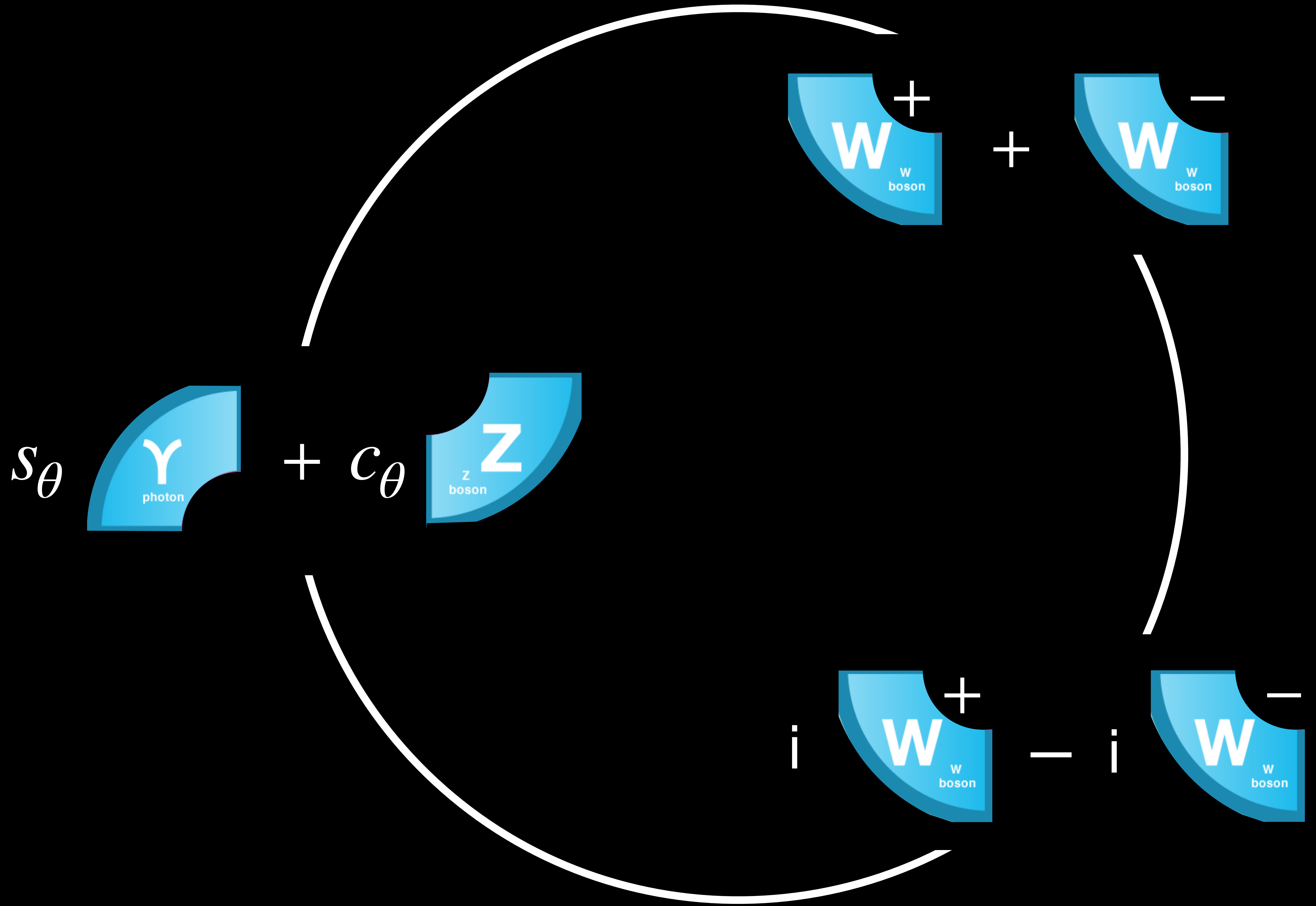
$(\hbar \neq 0)$



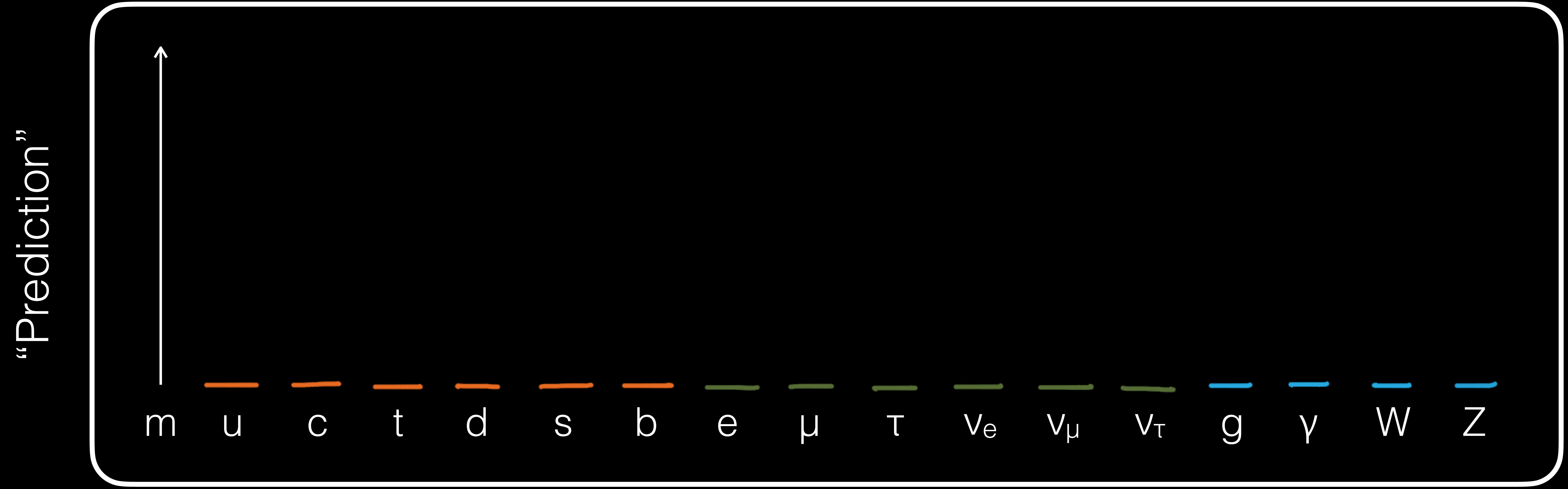
The Standard Model



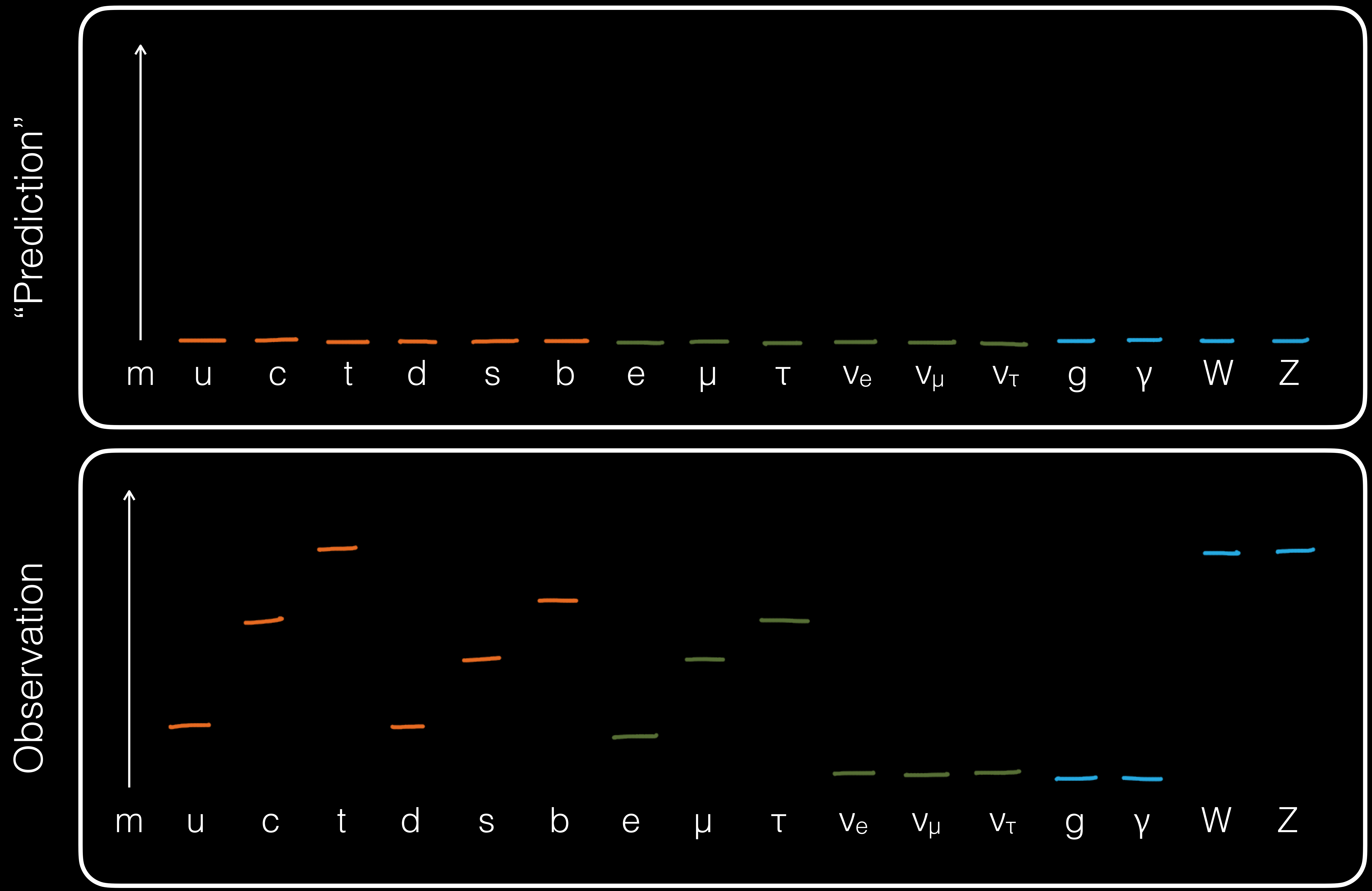
Electroweak Unification



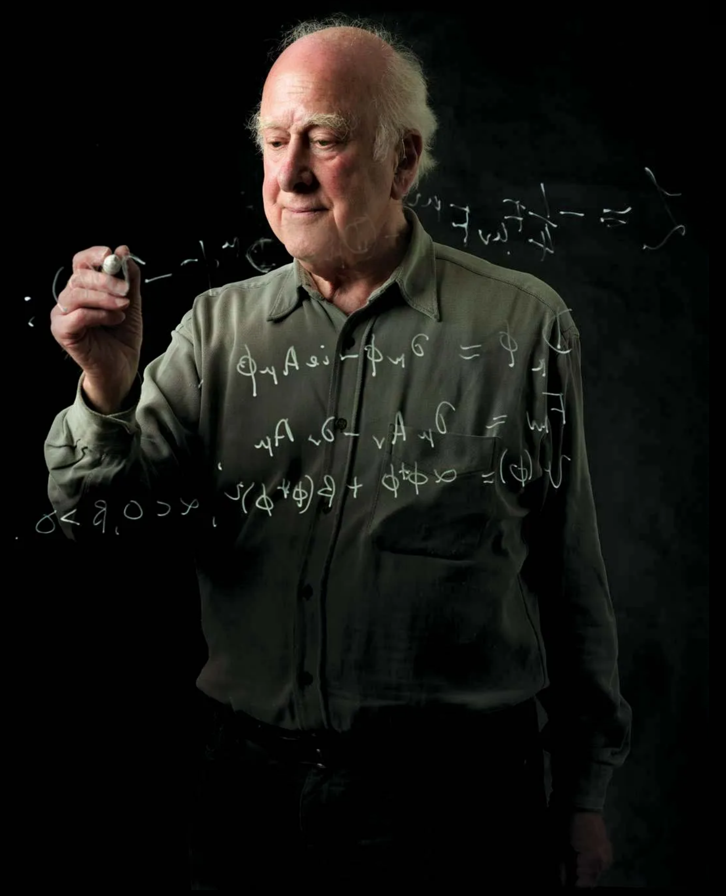
The Mystery of Mass

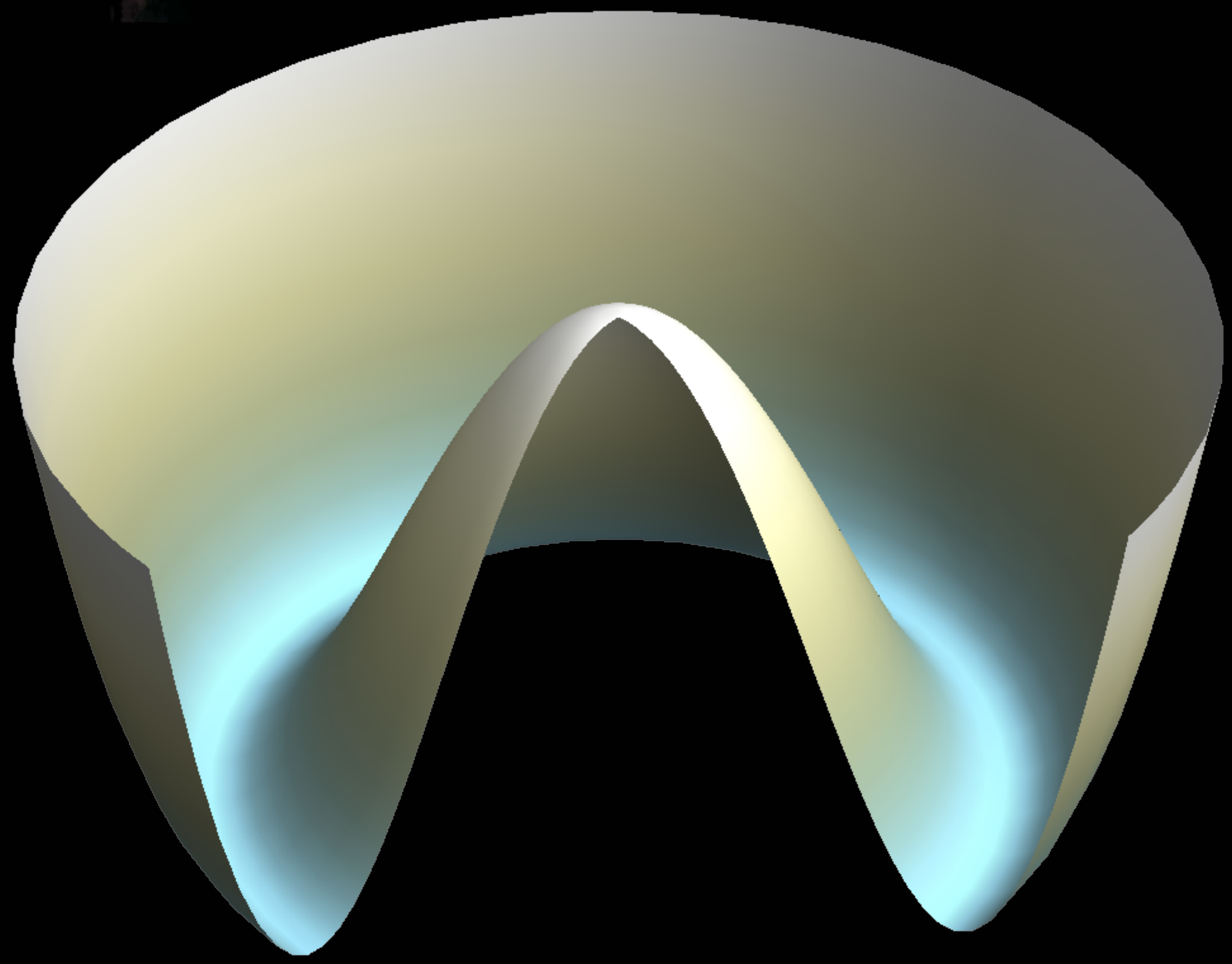


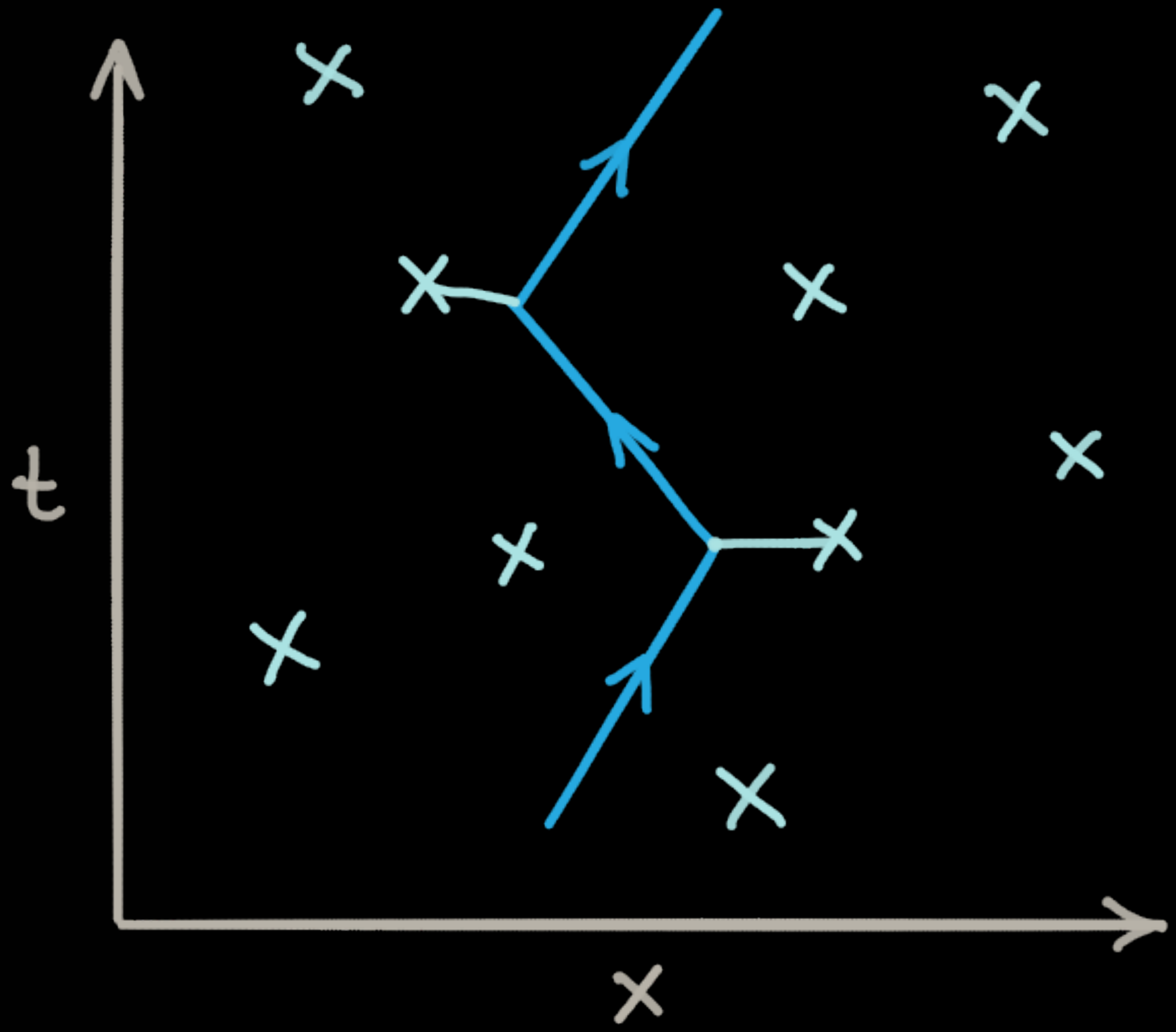
The Mystery of Mass



The Higgs







The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had discovered a new subatomic particle that looks for all the world like the Higgs boson, a key to understanding why there is diversity and life in the universe.

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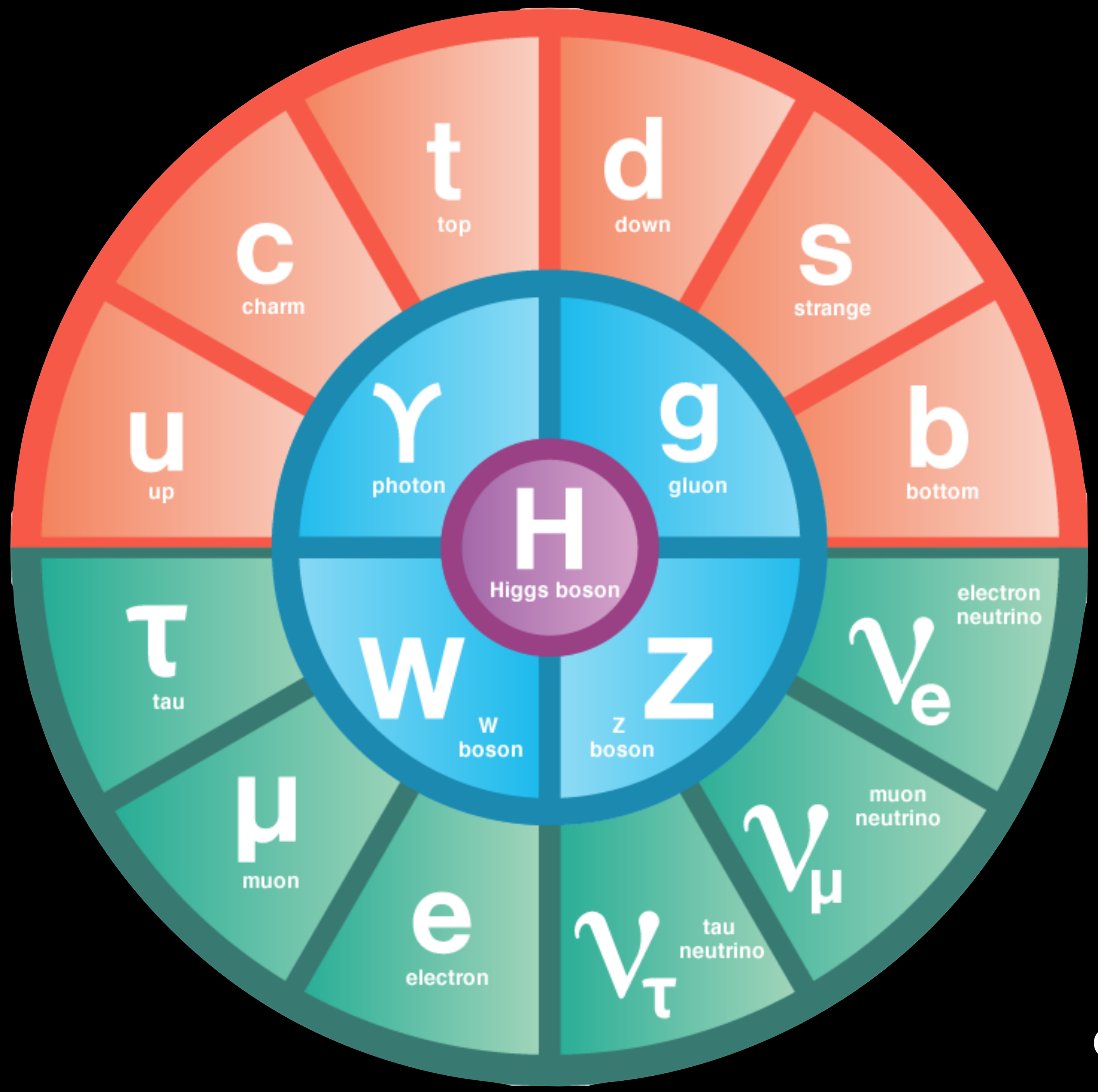
While it is never safe to affirm that the future of Physical Science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.

It is here that the science of measurement shows its importance—where quantitative results are more to be desired than qualitative work. An eminent physicist has remarked that the future truths of Physical Science are to be looked for in the sixth place of decimals.[21]

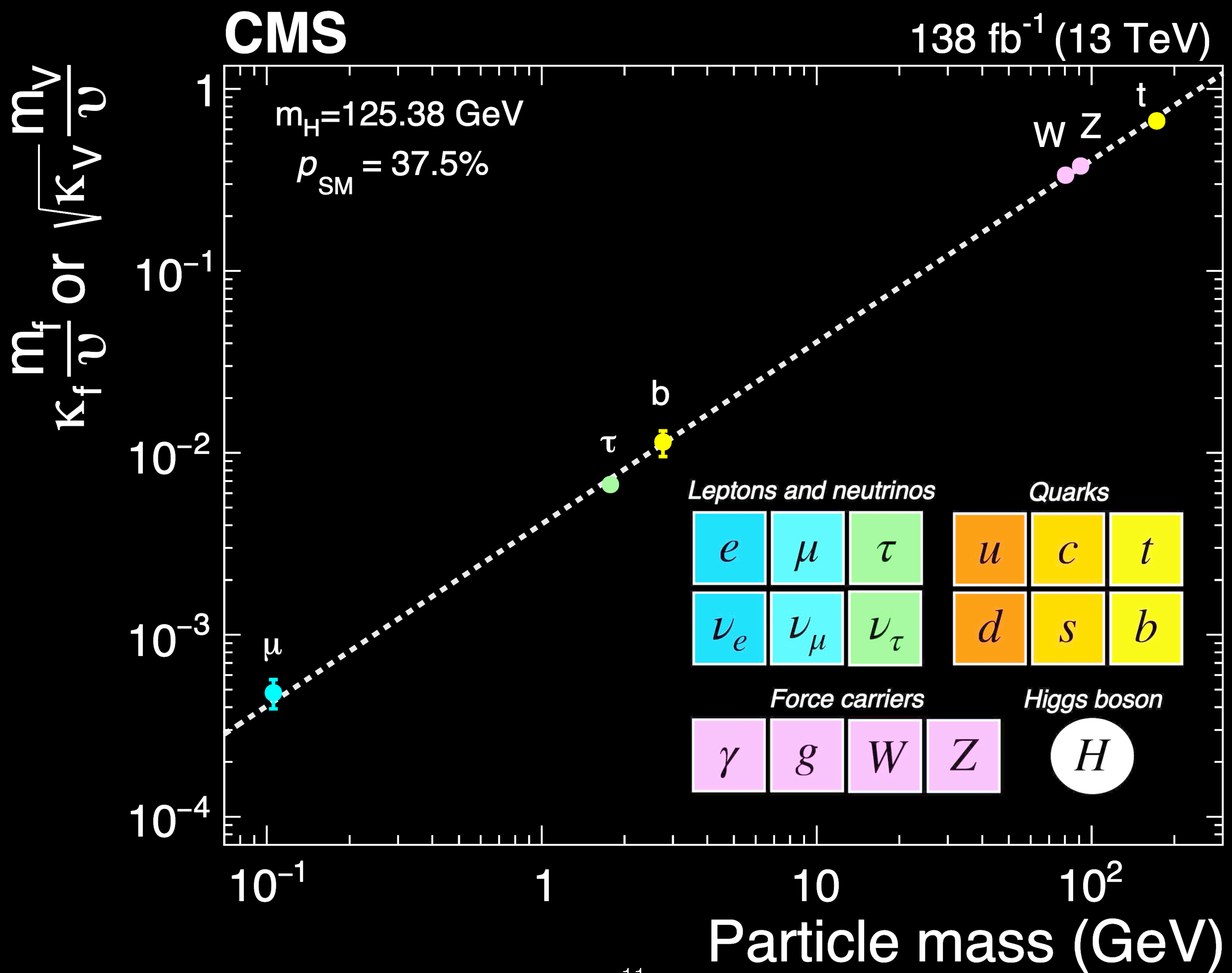
—A.A. Michelson, 1894

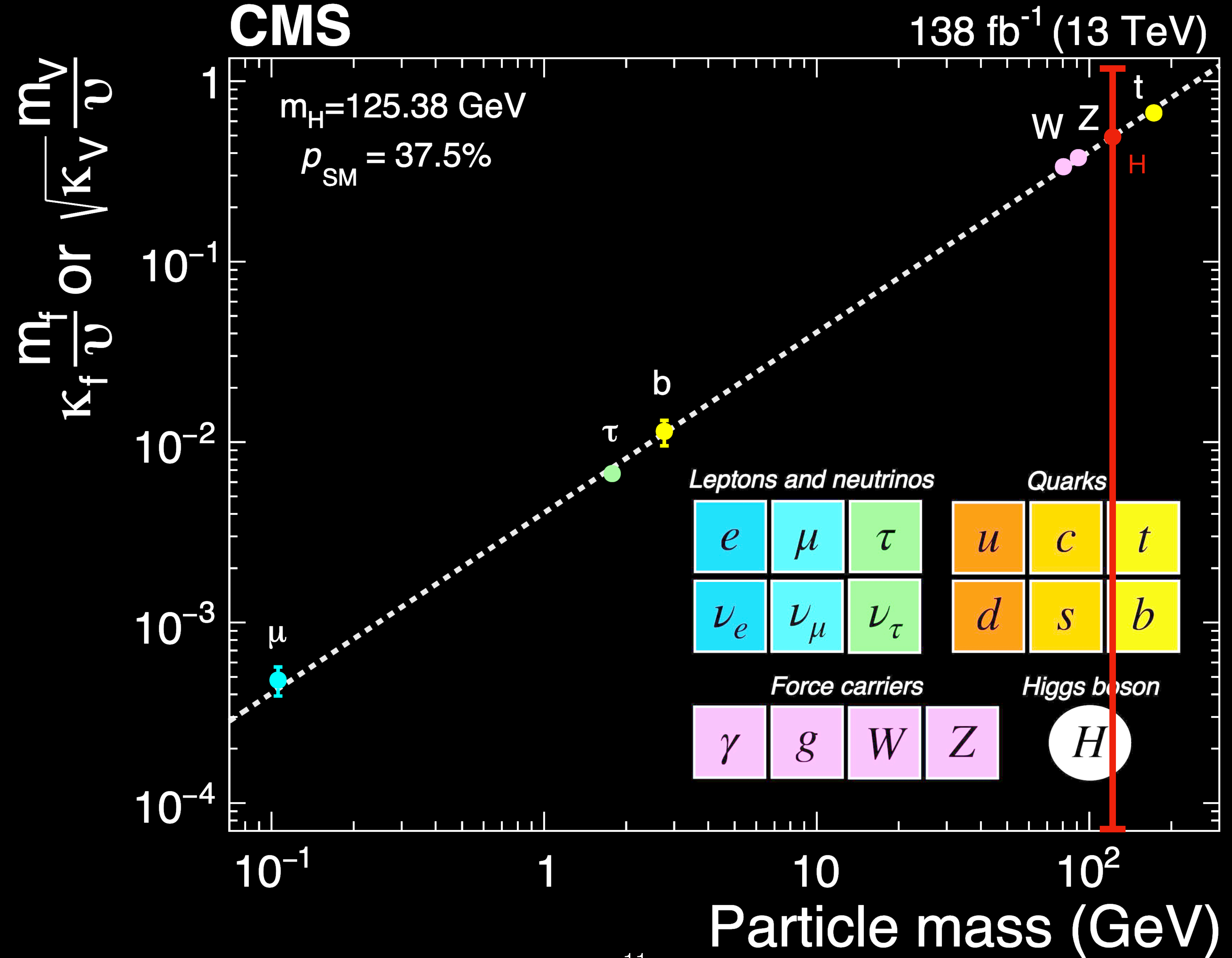
- The origin of mass?
- The nature of dark matter?
- Matter/antimatter asymmetry?
- The nature of dark energy?



- Strong CP?
- Neutrino mass?
- Cosmic inflation?
- Unification of forces?
- Generational structure of fermions?

The Origin of Mass


CMS
138 fb^{-1} (13 TeV)
m_H=125.38 GeV
p_{SM} = 37.5%
$\kappa_f \frac{m_f}{\upsilon}$ or $\sqrt{\kappa_V} \frac{m_V}{\upsilon}$
t
W Z
b
τ
μ
Leptons and neutrinos
Quarks
e μ τ
ν_e ν_μ ν_τ
u c t
d s b
Force carriers
Higgs boson
γ g W Z
H
Particle mass (GeV)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μ
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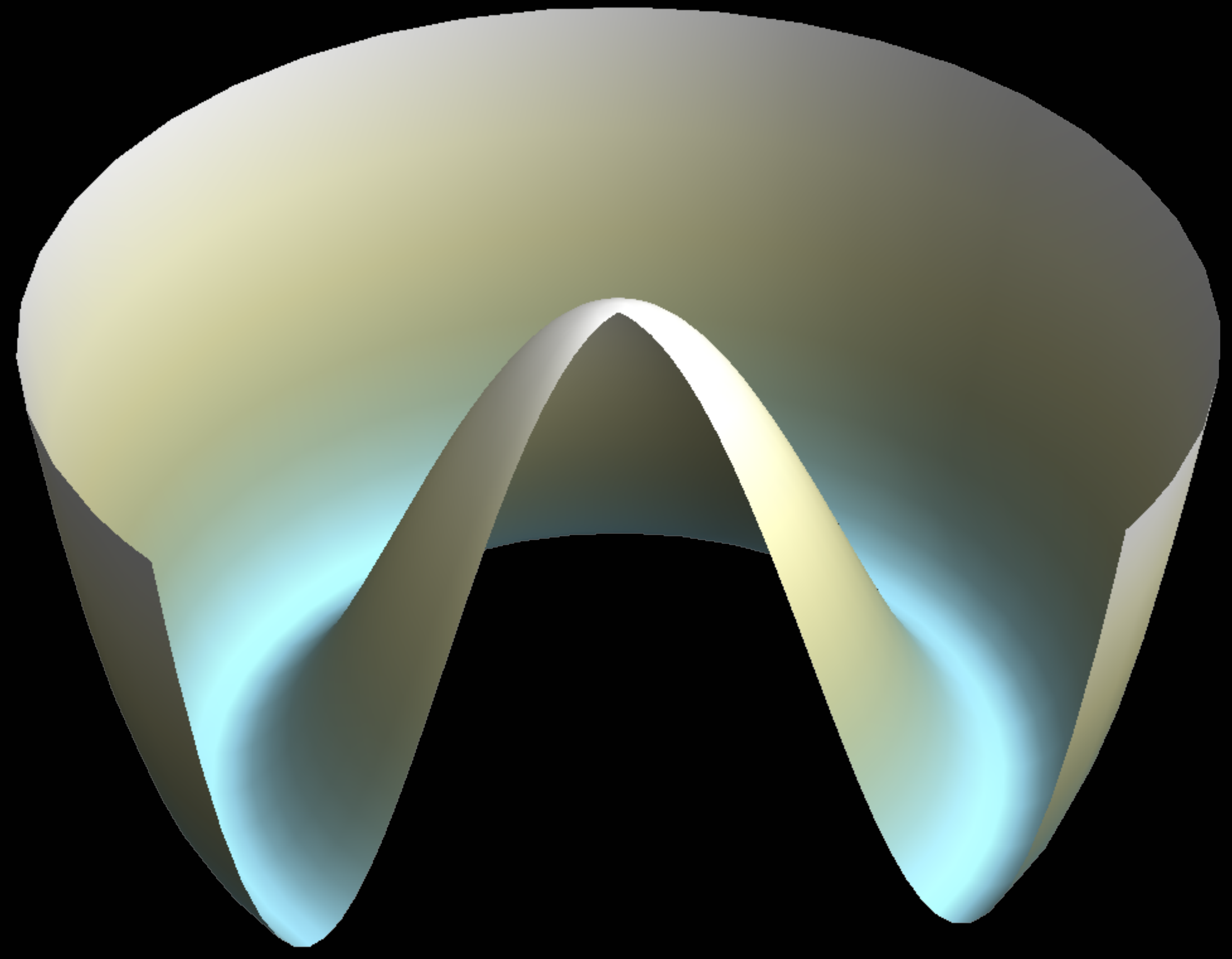
Leptons and neutrinos
Quarks
Force carriers
Higgs boson
Particle mass (GeV)

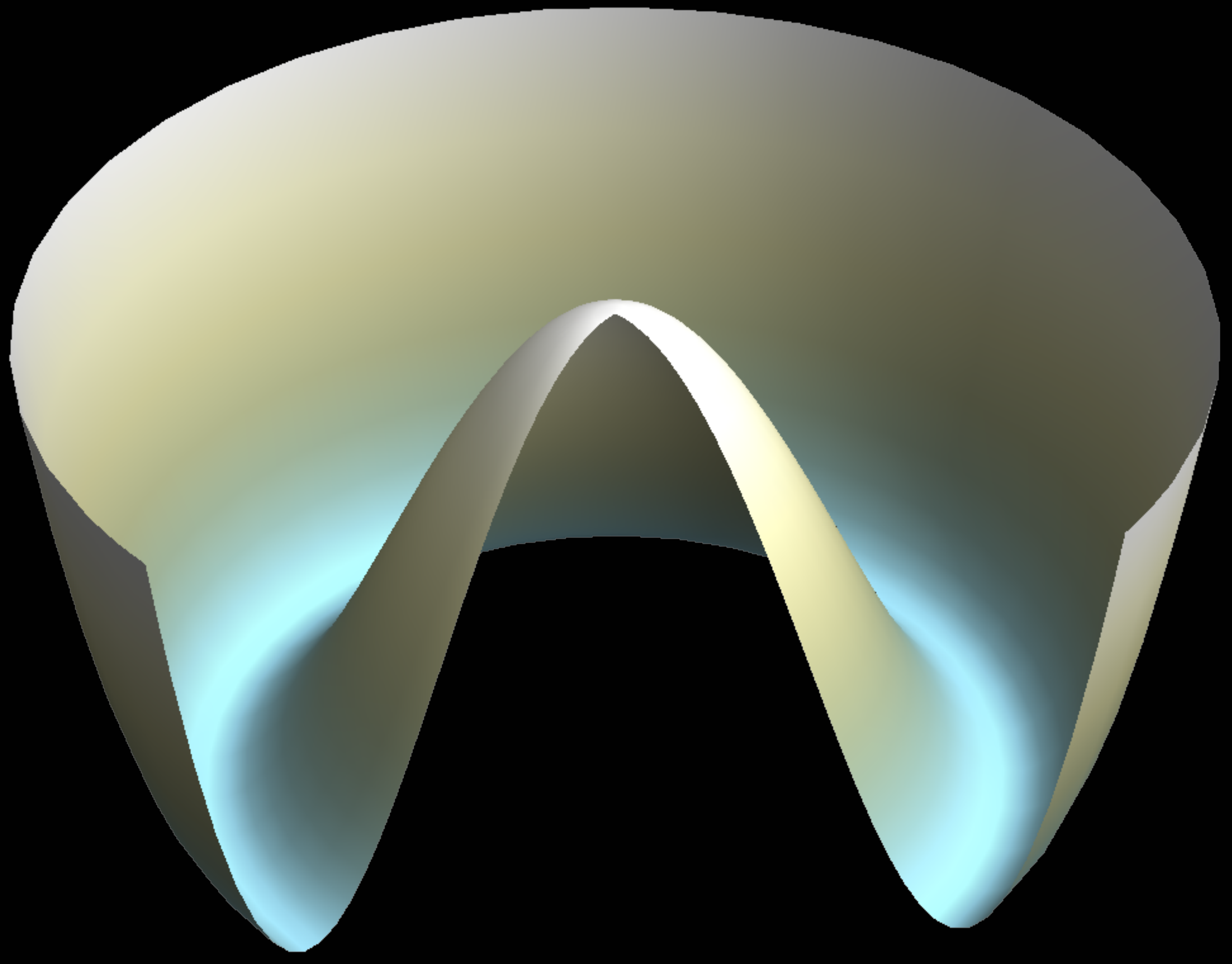
What is the origin of mass?

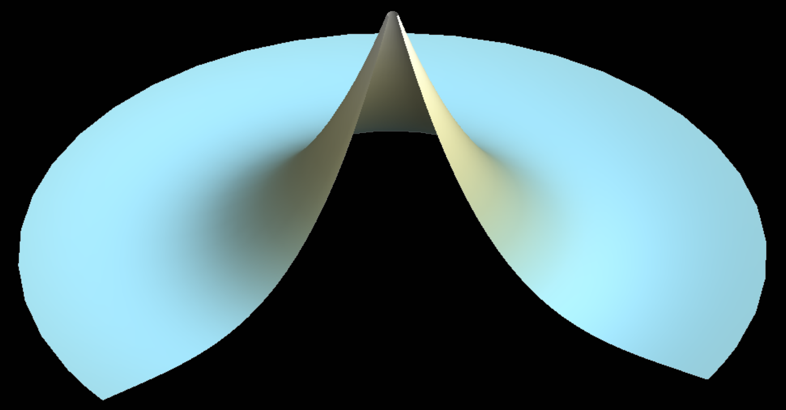


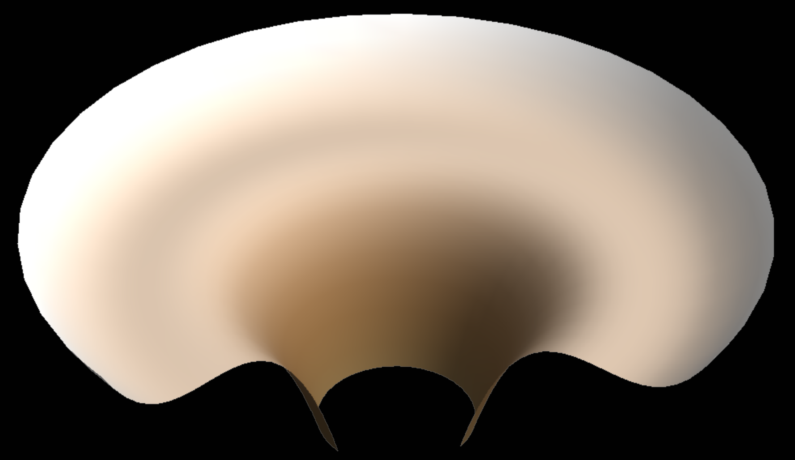
$$V(h) \sim c_2 h^2 + c_3 h^3 + c_4 h^4 + \dots$$

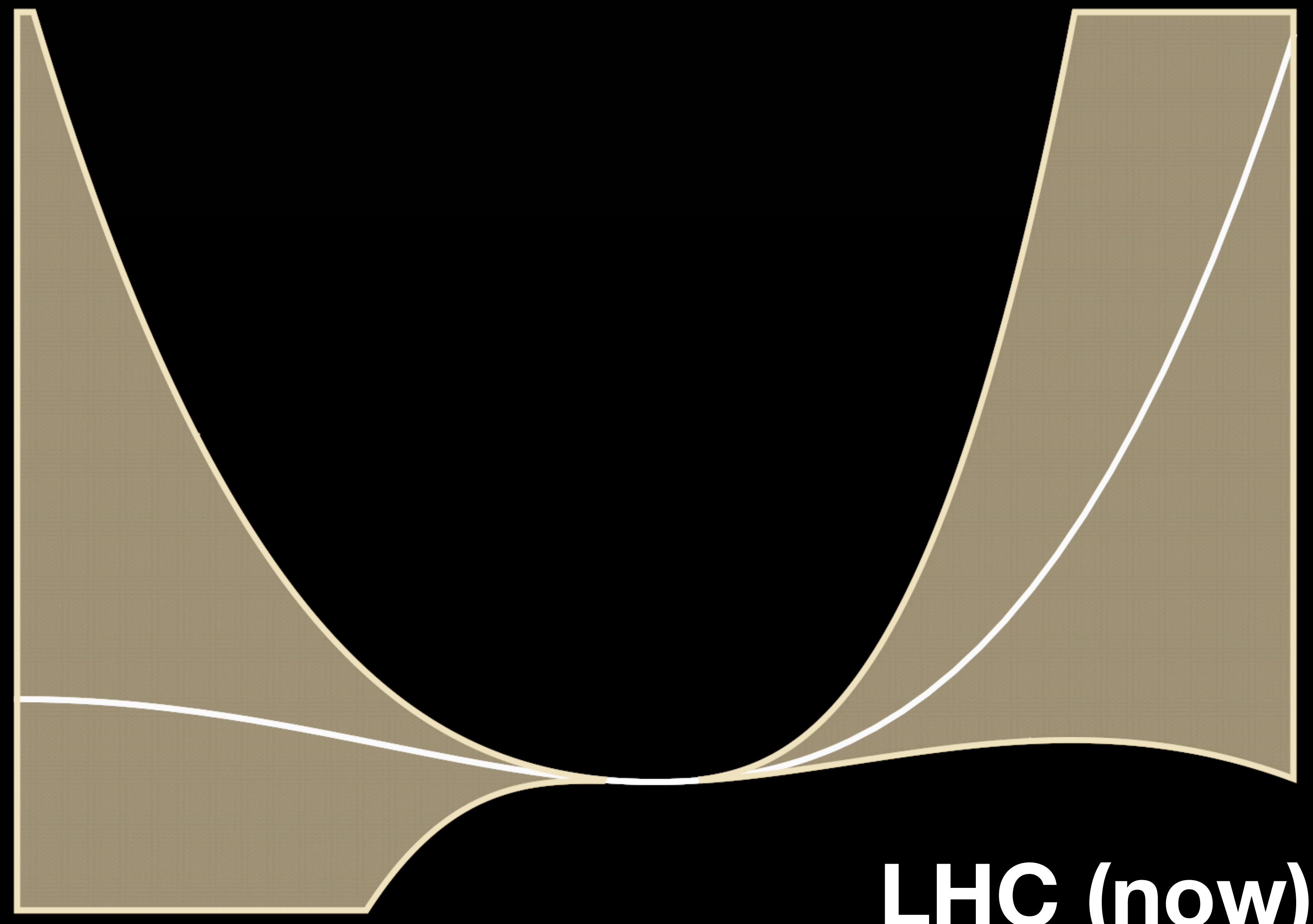
Mass (measured) Predicted by the Standard Model

What is the origin of mass?









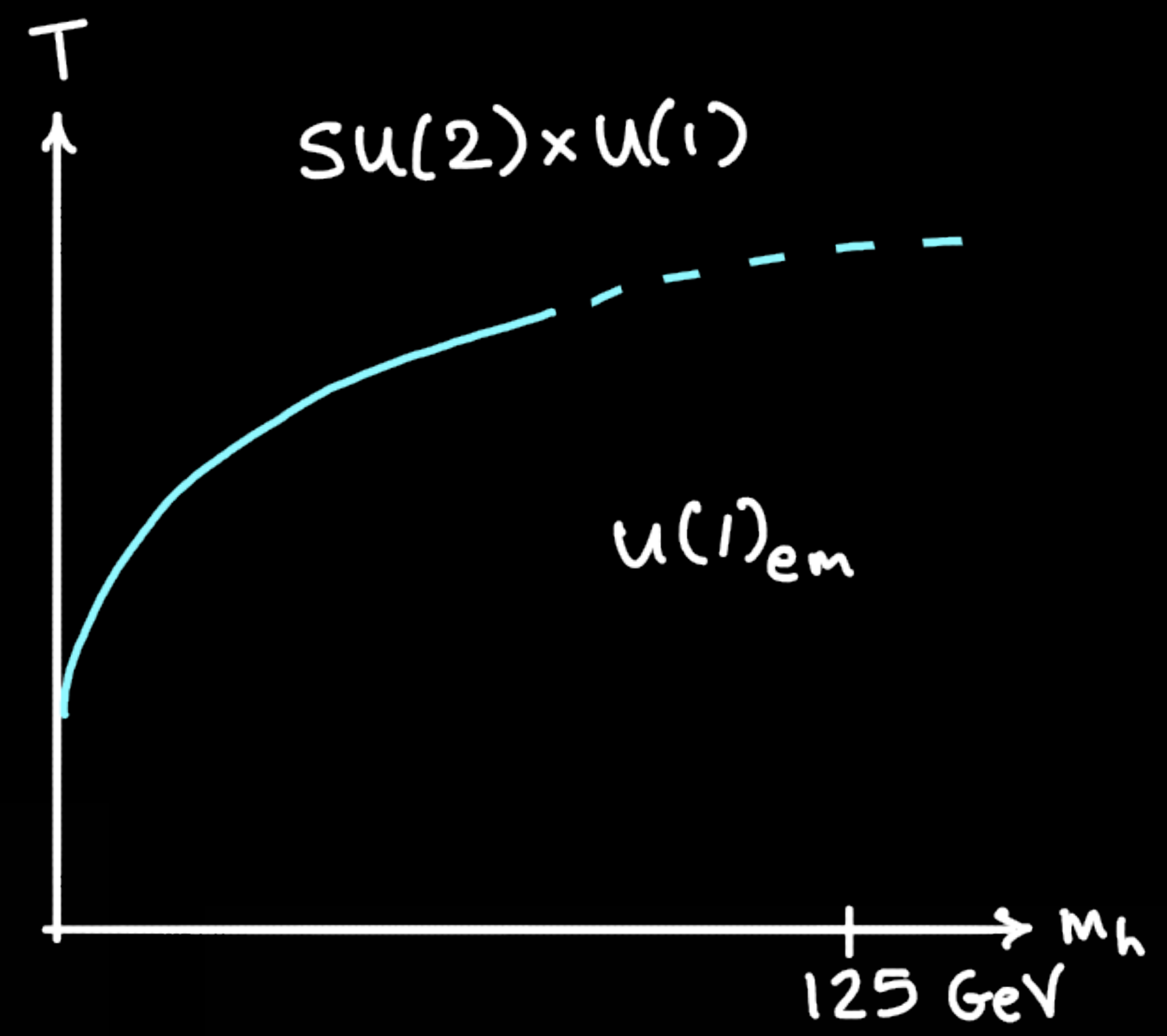
LHC (now)

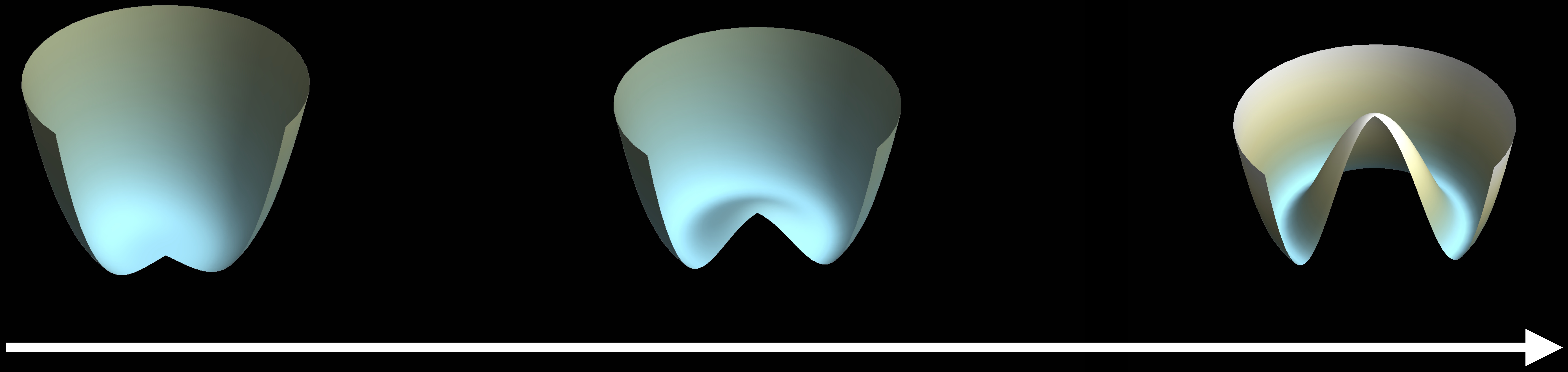
$$V(h) \sim c_2 h^2 + c_3 h^3 + c_4 h^4 + \ldots$$

Mass (measured)

Predicted by the Standard Model

The birth of the Universe?

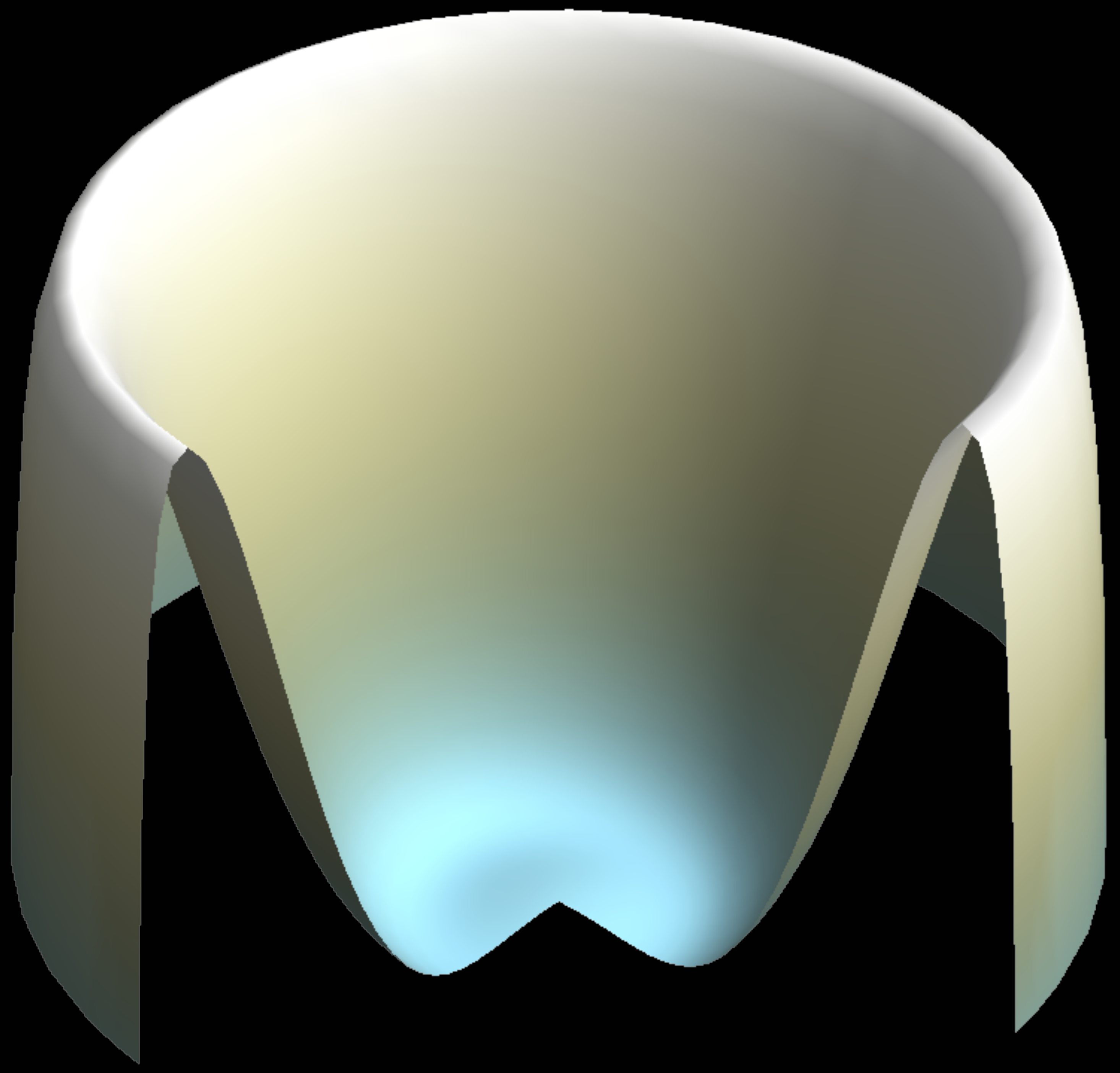




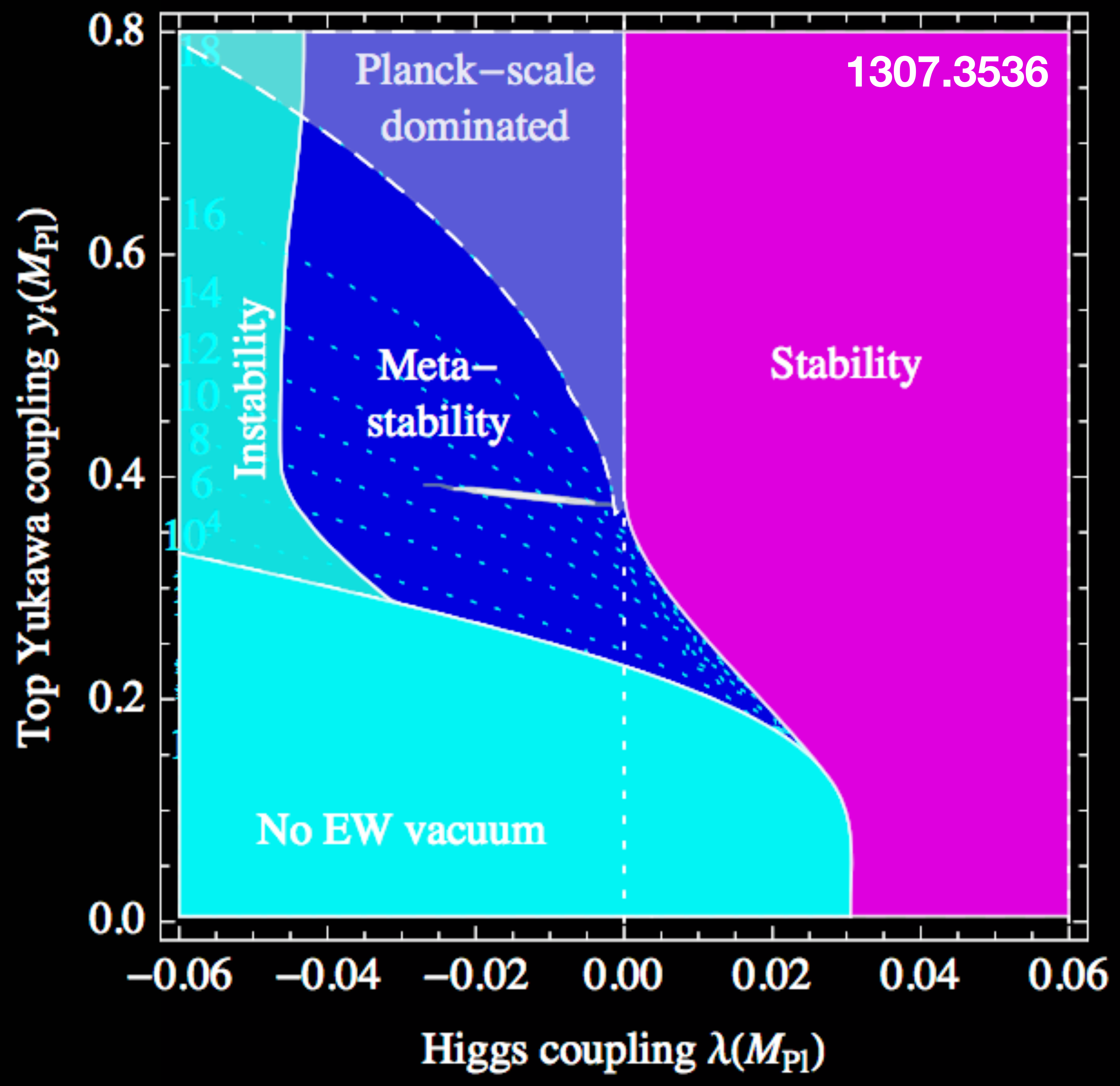
Time (~decreasing temperature)

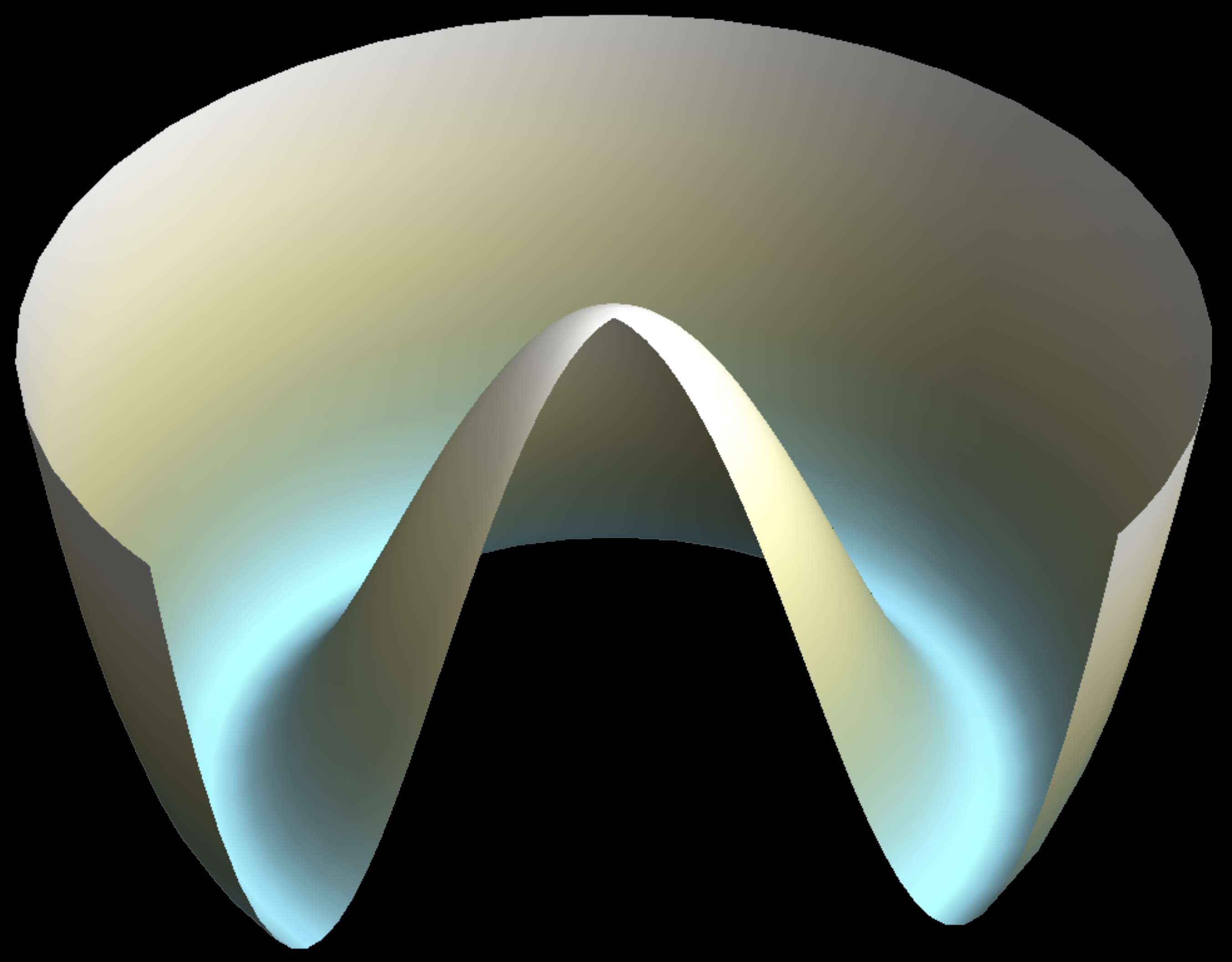
Image Credit: DWeir

The death of the Universe?



(Not to scale!)





The Scale Itself?

What sets the scale of the potential and hence particle masses?

Incalculable in the SM & profoundly sensitive to short-range physics.

An **analogy** from electromagnetism:

$$\Delta E_C = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e} \qquad \Rightarrow \qquad (m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_C$$

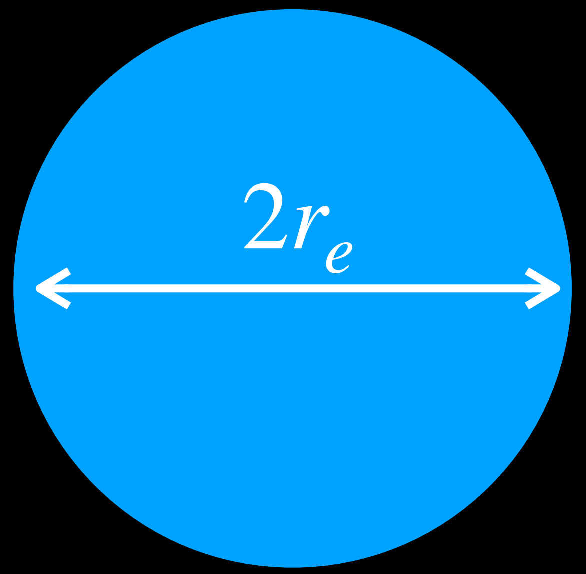
Experimentally $\quad r_e \lesssim 10^{-18}\,\mathrm{cm} \Rightarrow \Delta E_C \gtrsim 100\,\mathrm{GeV}$

If so, implies $\quad 0.511 = -99999.489 + 100000.000\,\mathrm{MeV}$

Alternately, the physical theory could change on much longer scales…

The Scale Itself?

Weisskopf: Naively, quantum mechanics only makes the problem worse.



Quantum fluctuations of the electric field within the “volume” $\sim r_e^3$ of the electron: $|\vec{E}|^2 \sim \dfrac{hc}{r_e^4}$ with mean frequency $\nu \sim \dfrac{c}{r_e}$

Induces electron to vibrate w/ amplitude $x \sim \dfrac{e|\vec{E}|}{m\nu^2}$ and energy $E \sim \dfrac{e^2|\vec{E}|^2}{m\nu^2} \sim \dfrac{e^2 h}{mcr_e^2}$

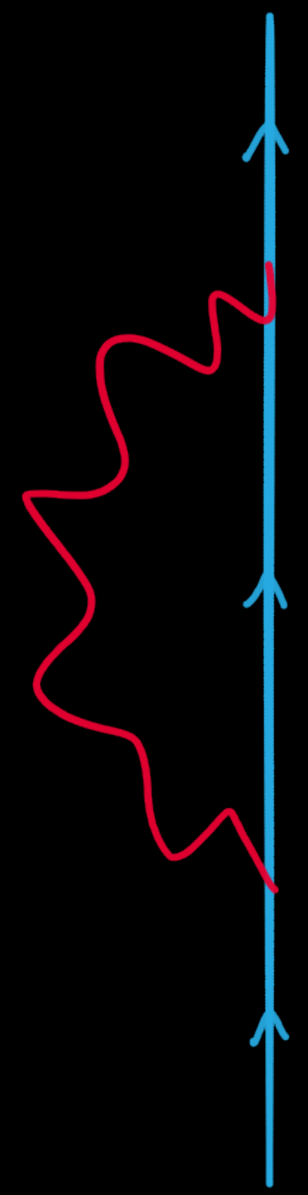
Seven orders of magnitude larger than the classical problem!

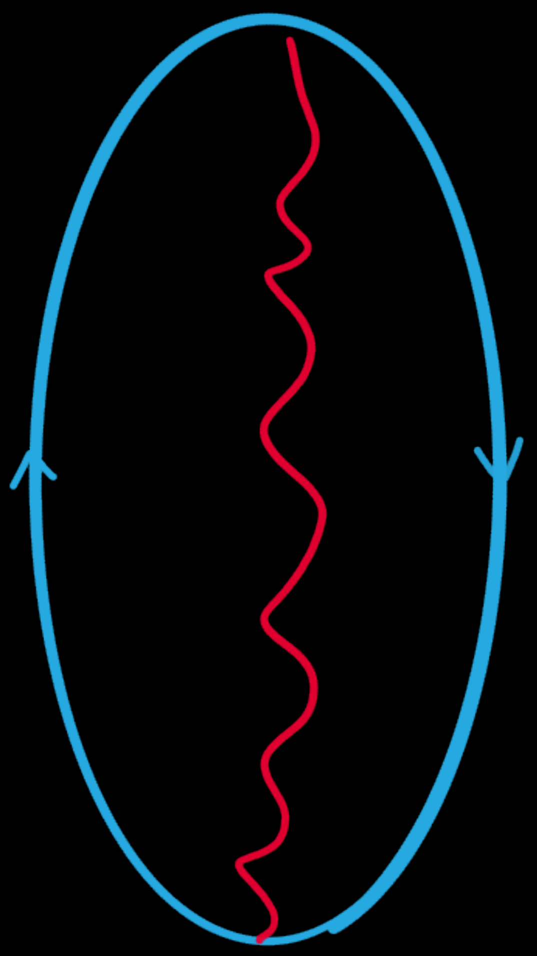
The Scale Itself?

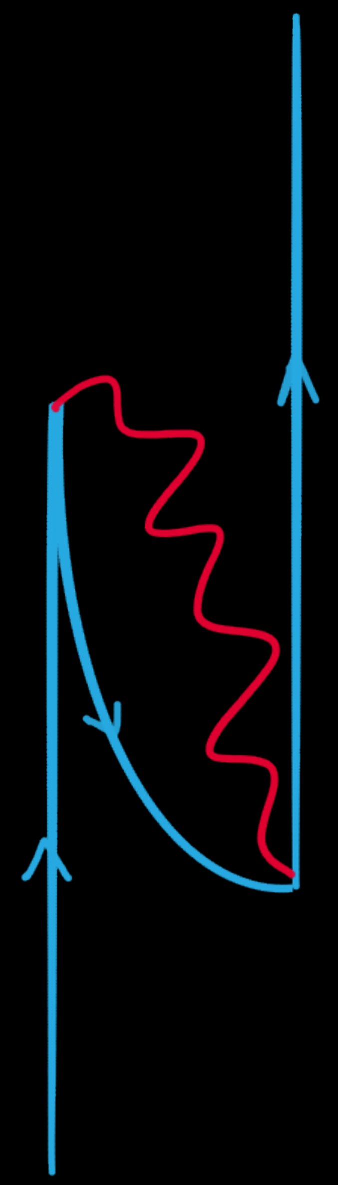
Dirac (1928/29): There is a new state in the relativistic quantum theory

Weisskopf (1939): Compute the self-energy including the positron

$$\Delta t \sim \hbar/\Delta E \sim \hbar/(2 m_e c^2)$$







$$\Delta E = \Delta E_C + \ldots$$

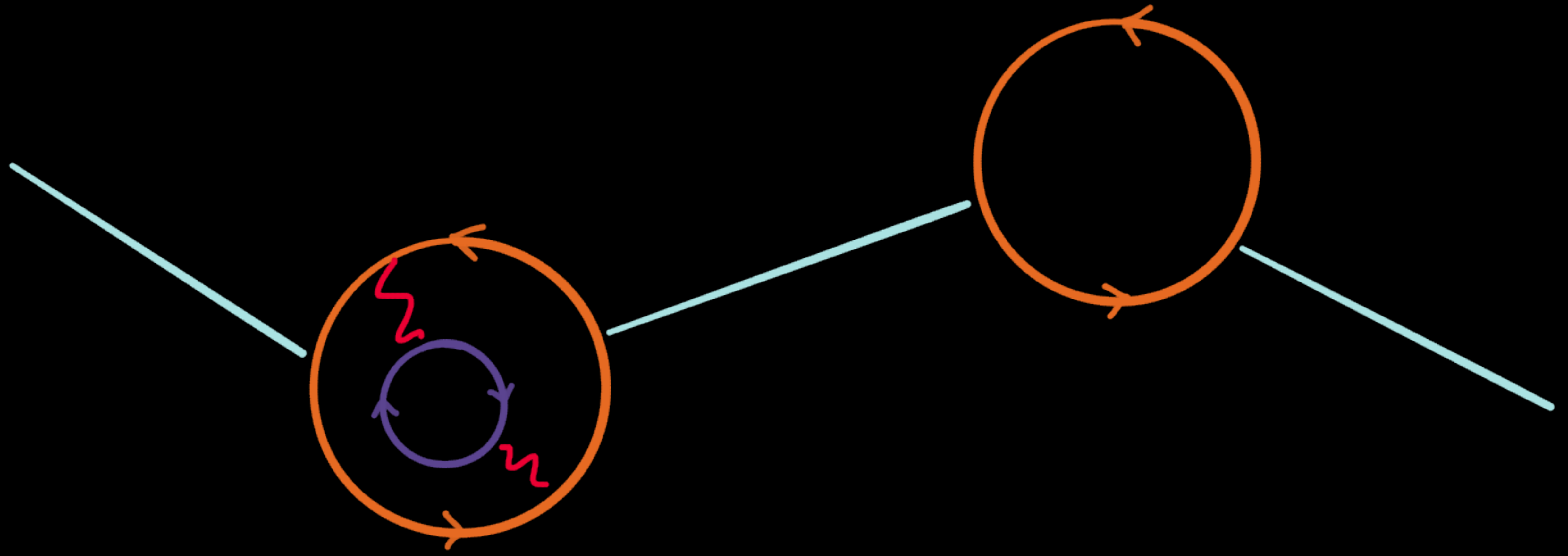
$$d \sim c\Delta t \sim 200 \times 10^{-13}\ \mathrm{cm}$$

$$\Delta E = -\Delta E_C + \ldots$$

$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

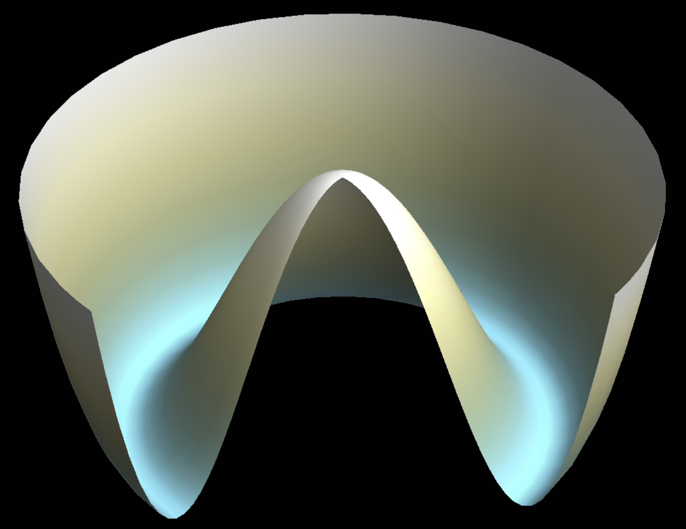
The Scale Itself?

The Higgs boson is an apparently elementary scalar w/ self-energy due to its couplings to Standard Model particles



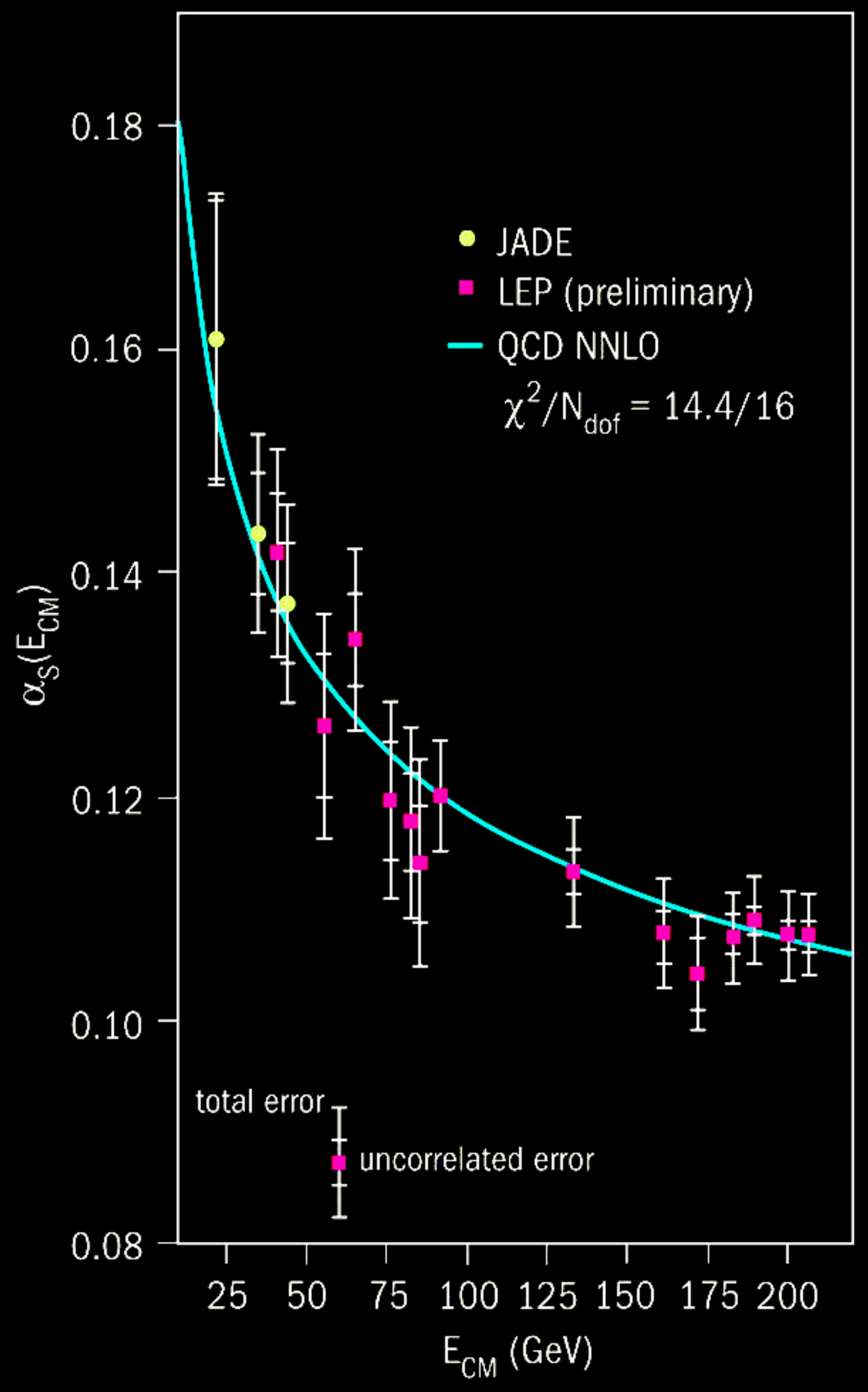
Assuming SM is valid down to some length scale $r_{\mathrm{new}} \equiv \frac{\hbar c}{\Lambda}$ then we have

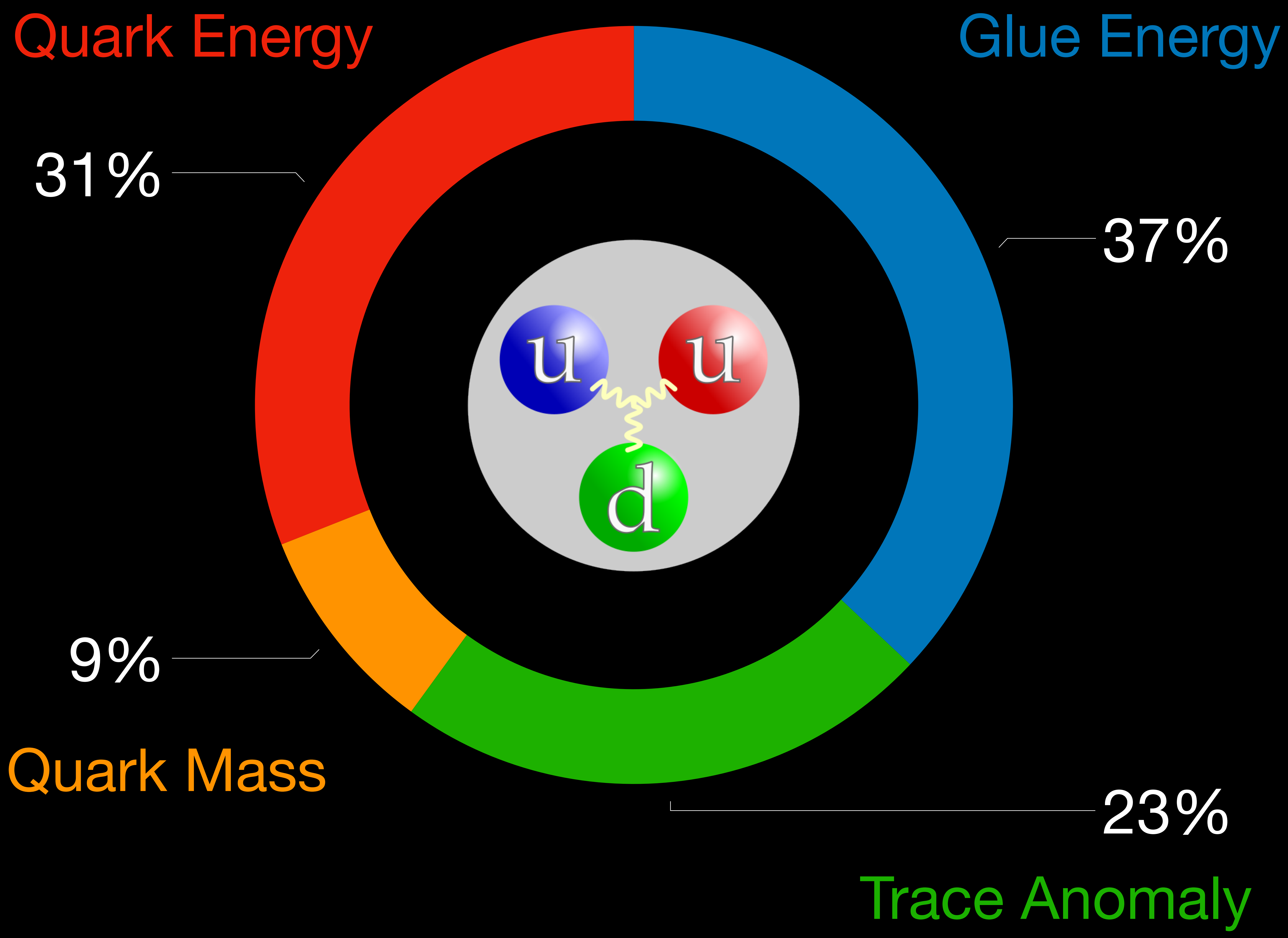
$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\left[-6y_t^2 + \frac{9}{4}g_2^2 + \frac{3}{4}g_Y^2 + 6\lambda + \ldots\right] \Rightarrow$$



Given the scale of the Higgs potential, *expect* new physics at TeV energies.

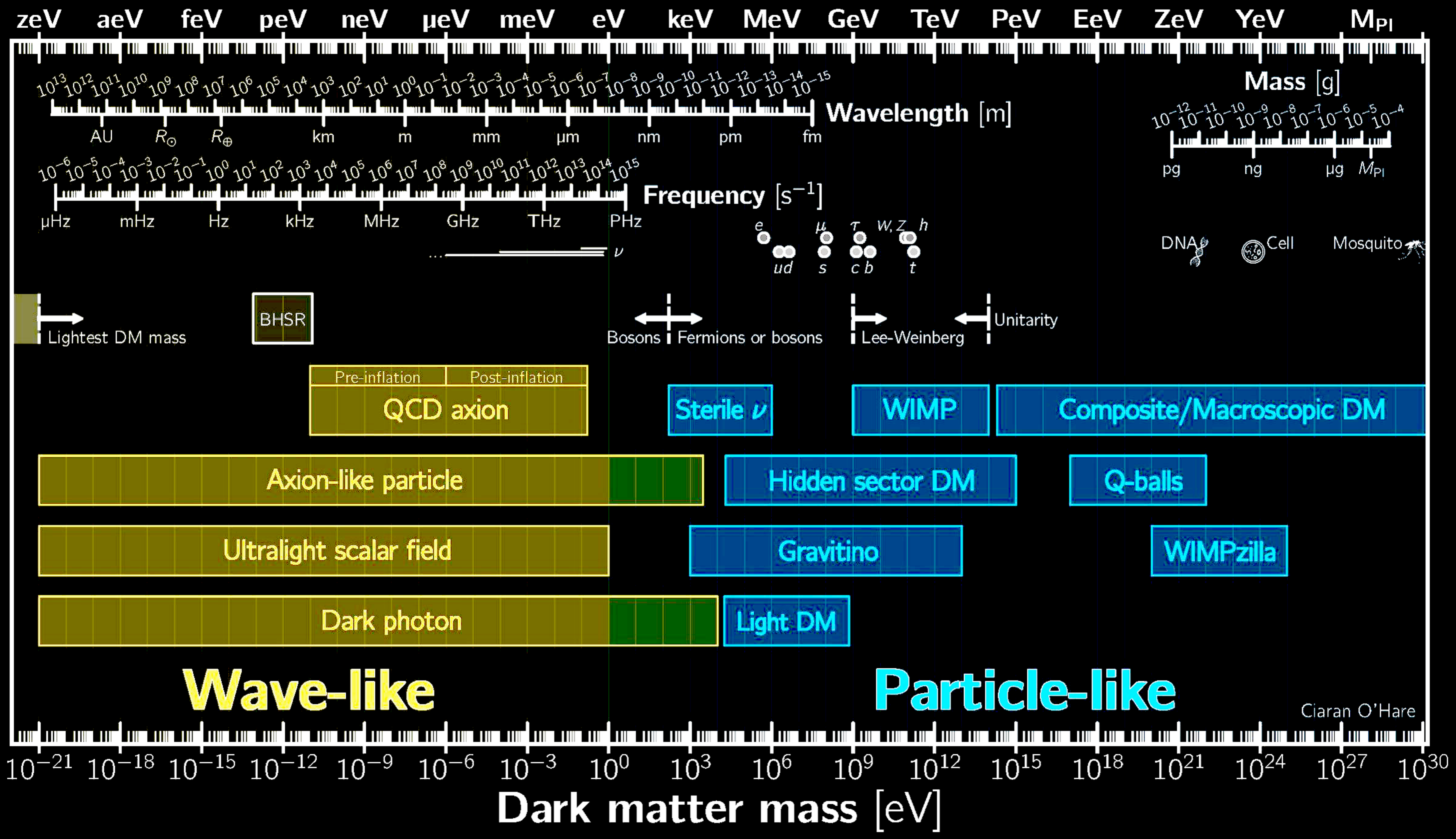
The Other Origin of Mass





The nature of dark matter?

Image Credit: NASA



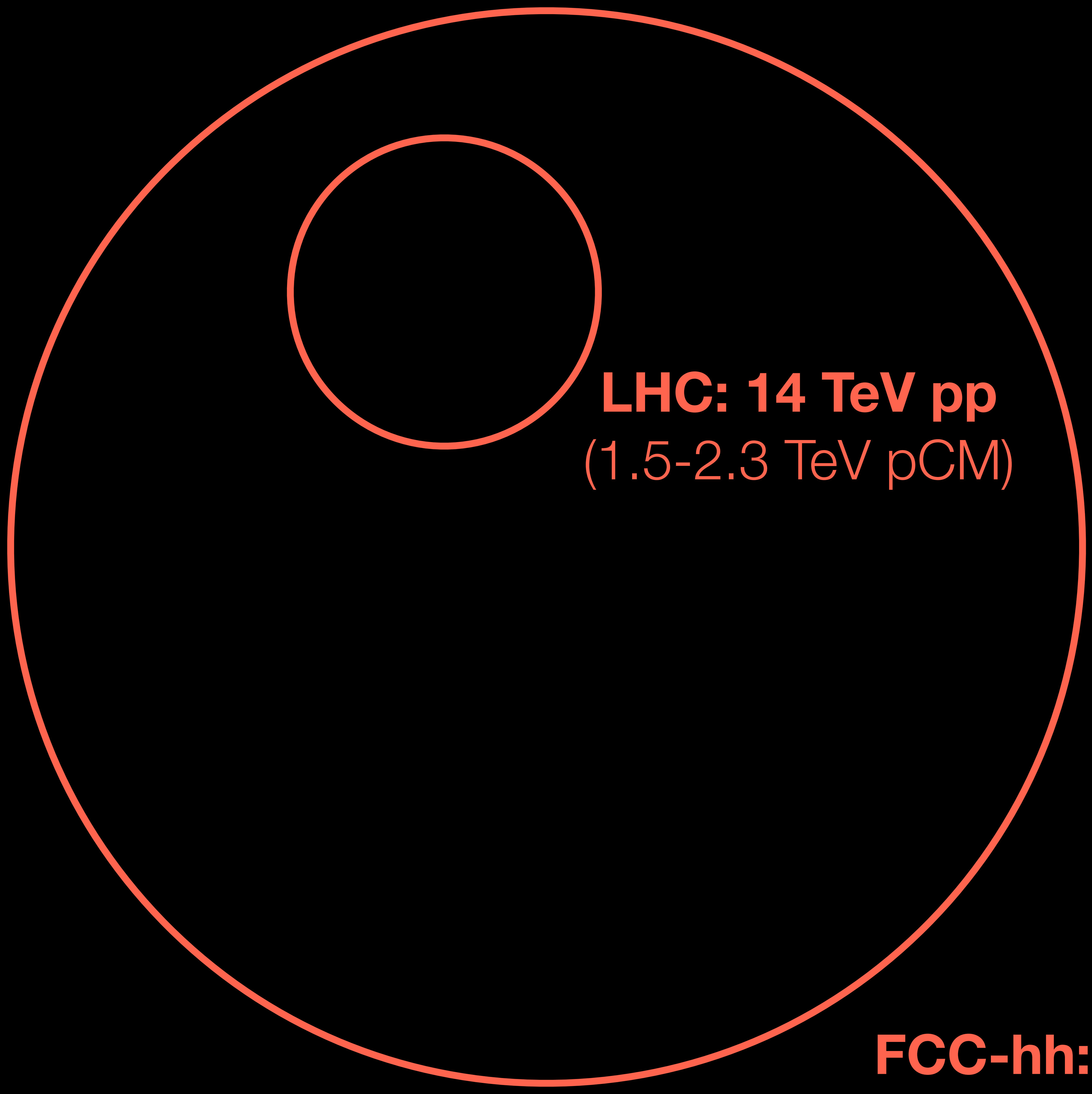
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV EeV ZeV YeV M_{Pl}
Wavelength [m]
AU $R_\odot$ $R_\oplus$ km m mm μm nm pm fm
Frequency [s^{-1}]
μHz mHz Hz kHz MHz GHz THz PHz
ν
e μ τ W, Z h
u d s c b t
Mass [g]
pg ng μg M_{Pl}
DNA Cell Mosquito
Lightest DM mass
BHSR
Bosons
Fermions or bosons
Lee-Weinberg
Unitarity
Pre-inflation
Post-inflation
QCD axion
Sterile ν
WIMP
Composite/Macroscopic DM
Axion-like particle
Hidden sector DM
Q-balls
Ultralight scalar field
Gravitino
WIMPzilla
Dark photon
Light DM
Wave-like
Particle-like
Ciaran O'Hare
10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} 10^{30}
Dark matter mass [eV]

The Quantum Tools for Discovery

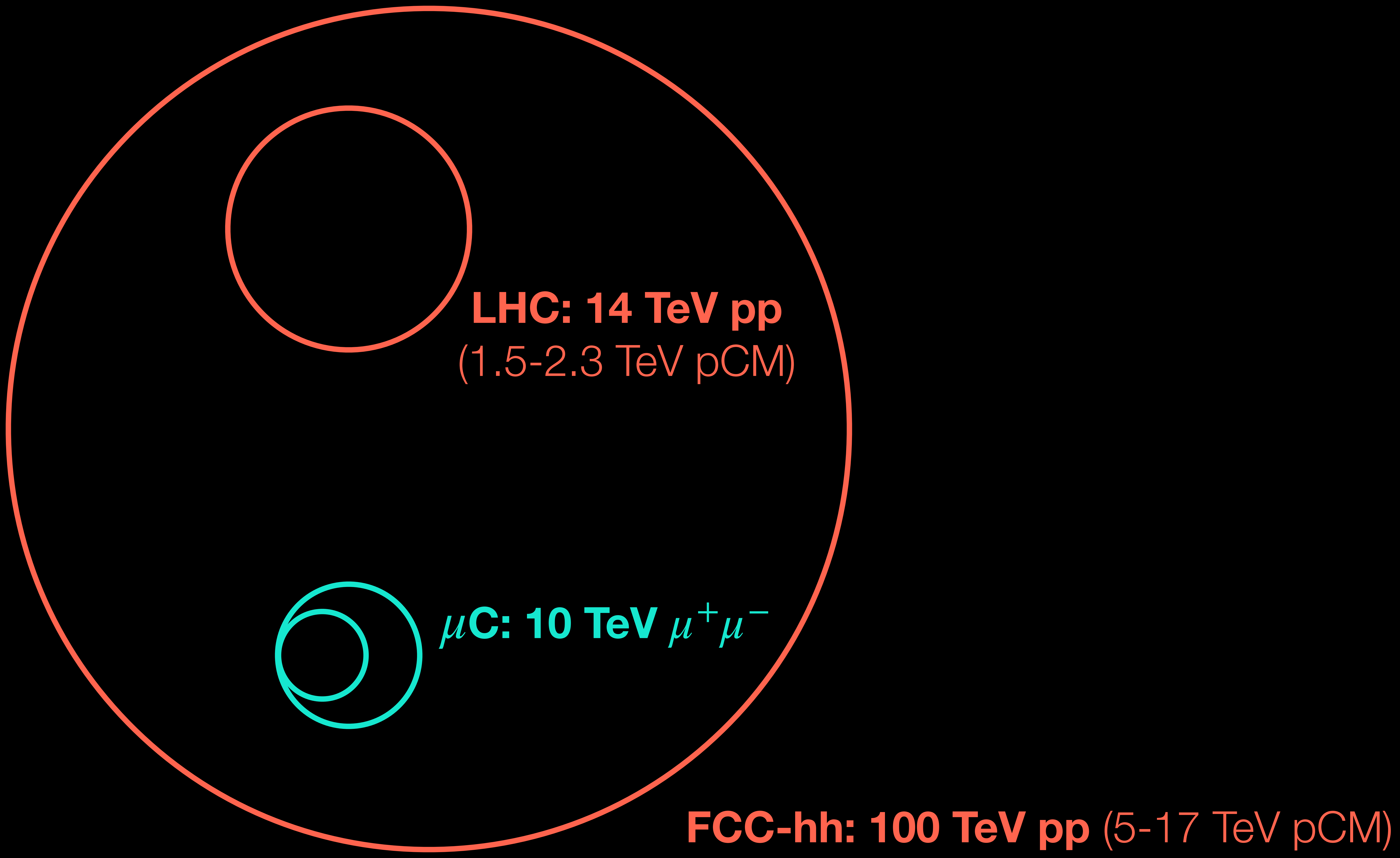
Colliders for Discovery

LHC: 14 TeV pp
(1.5-2.3 TeV pCM)

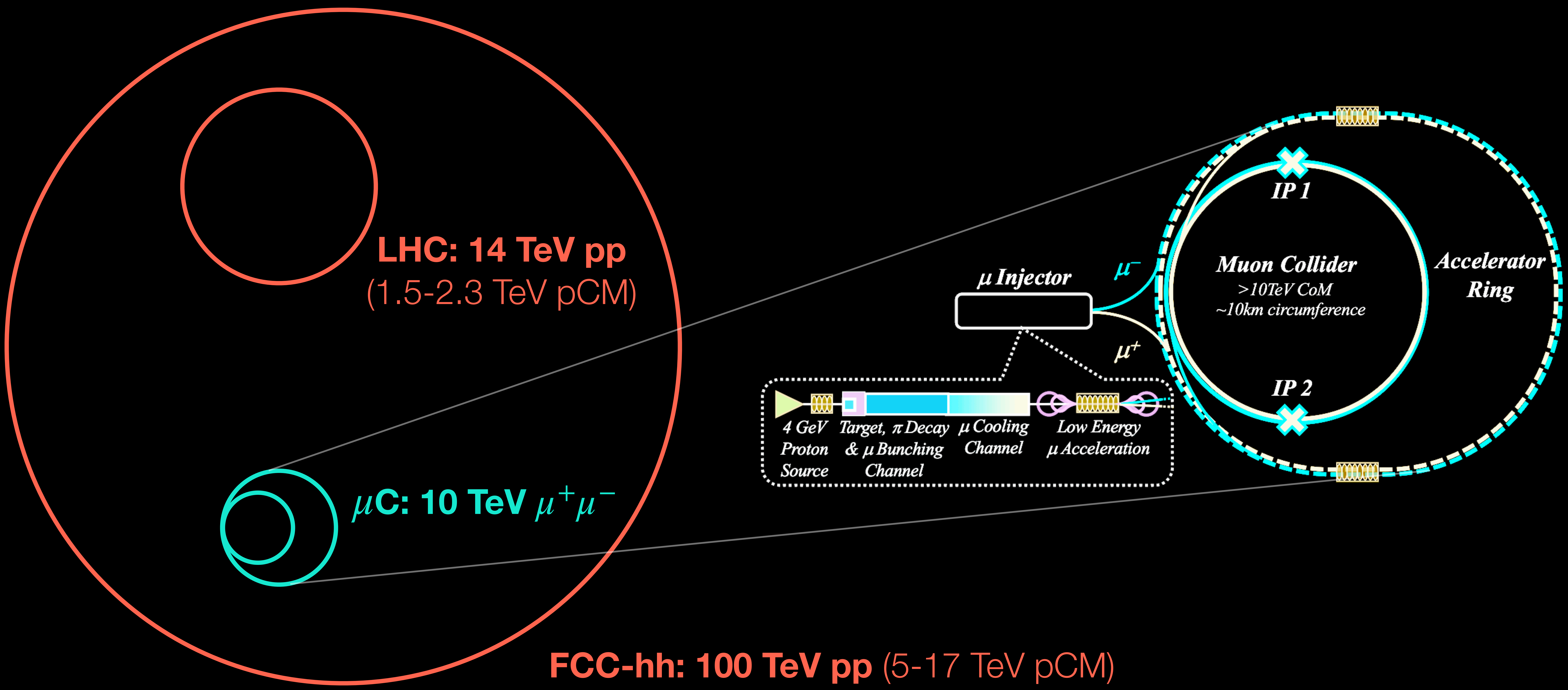
Colliders for Discovery



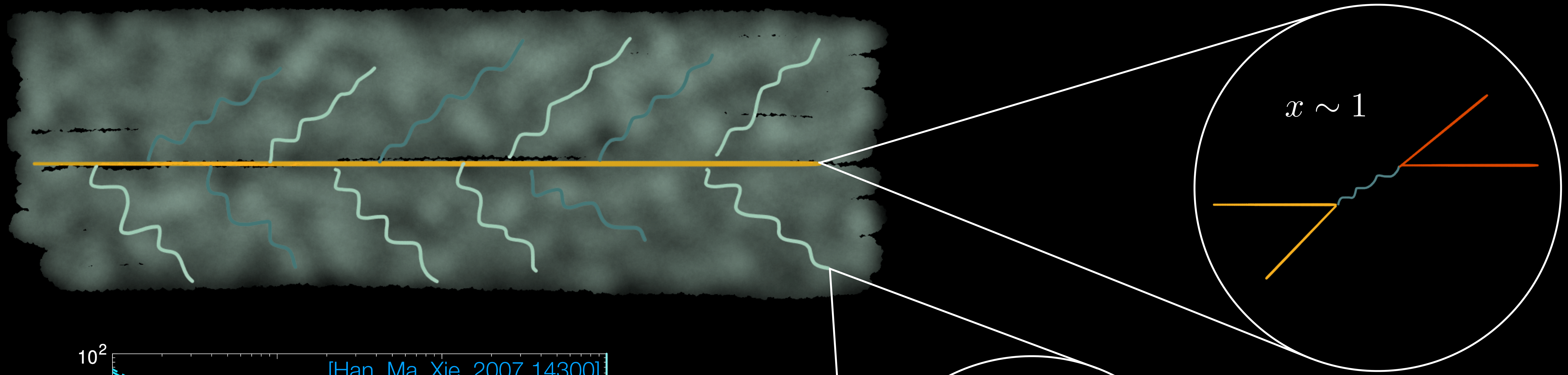
Colliders for Discovery

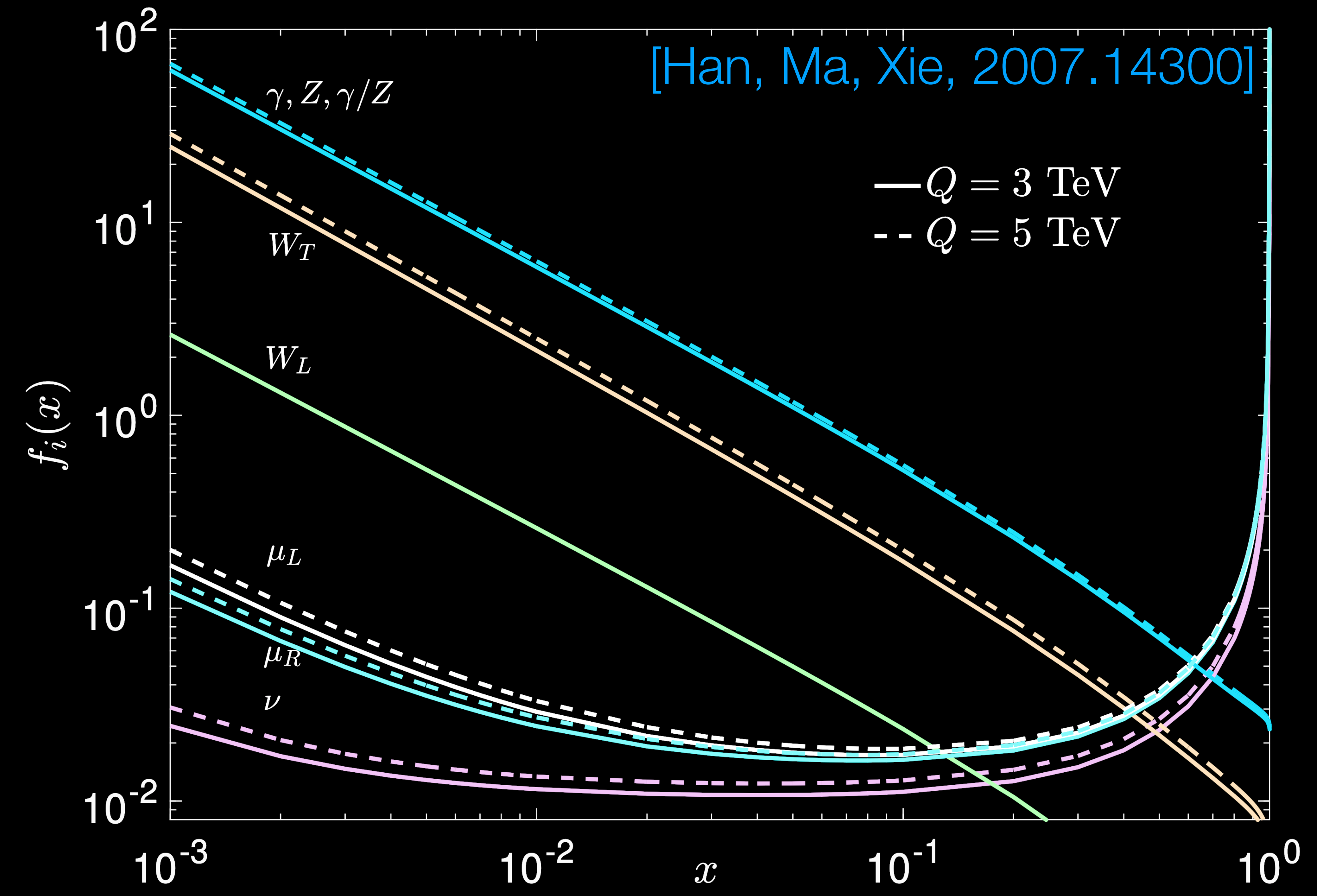


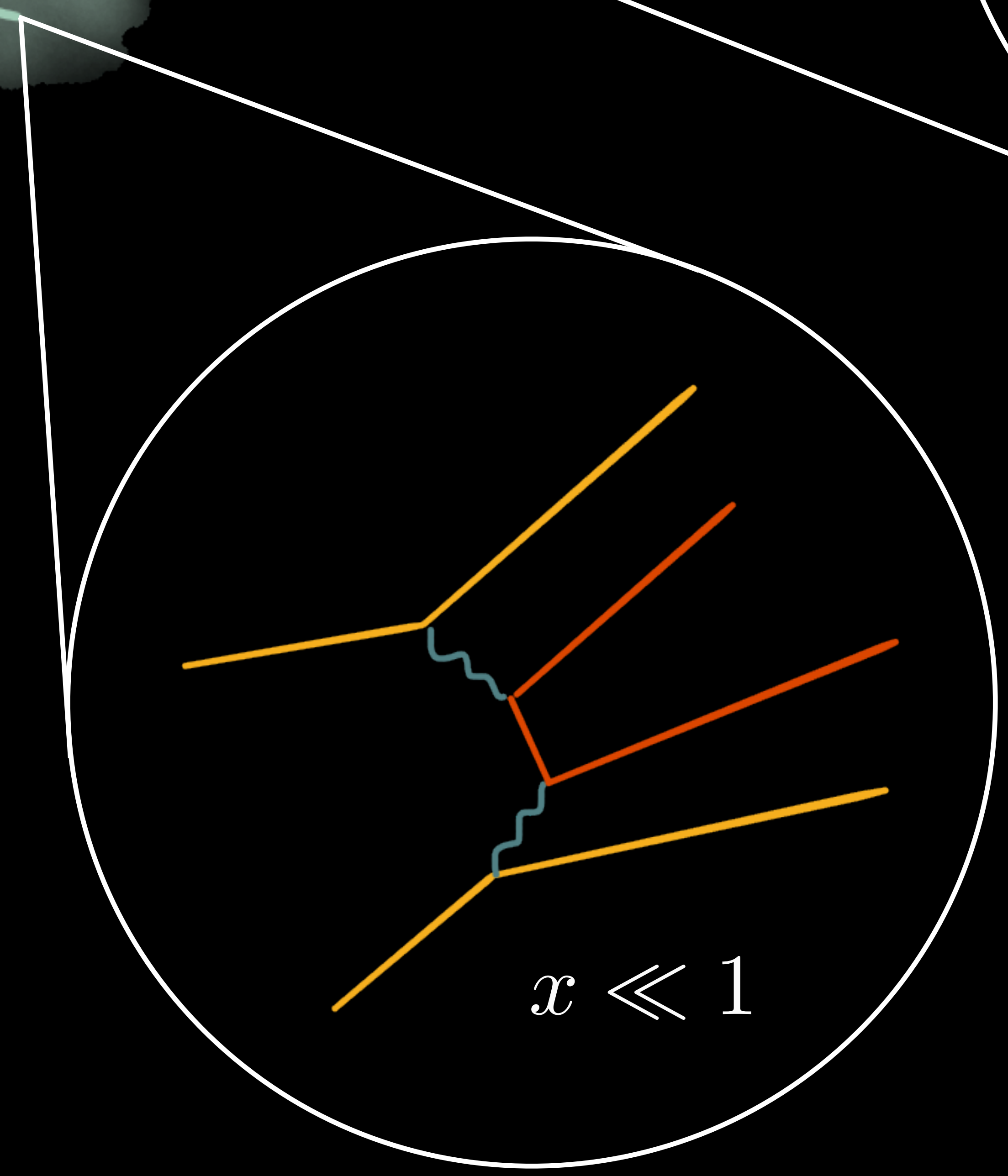
Colliders for Discovery



The Quantum Muon



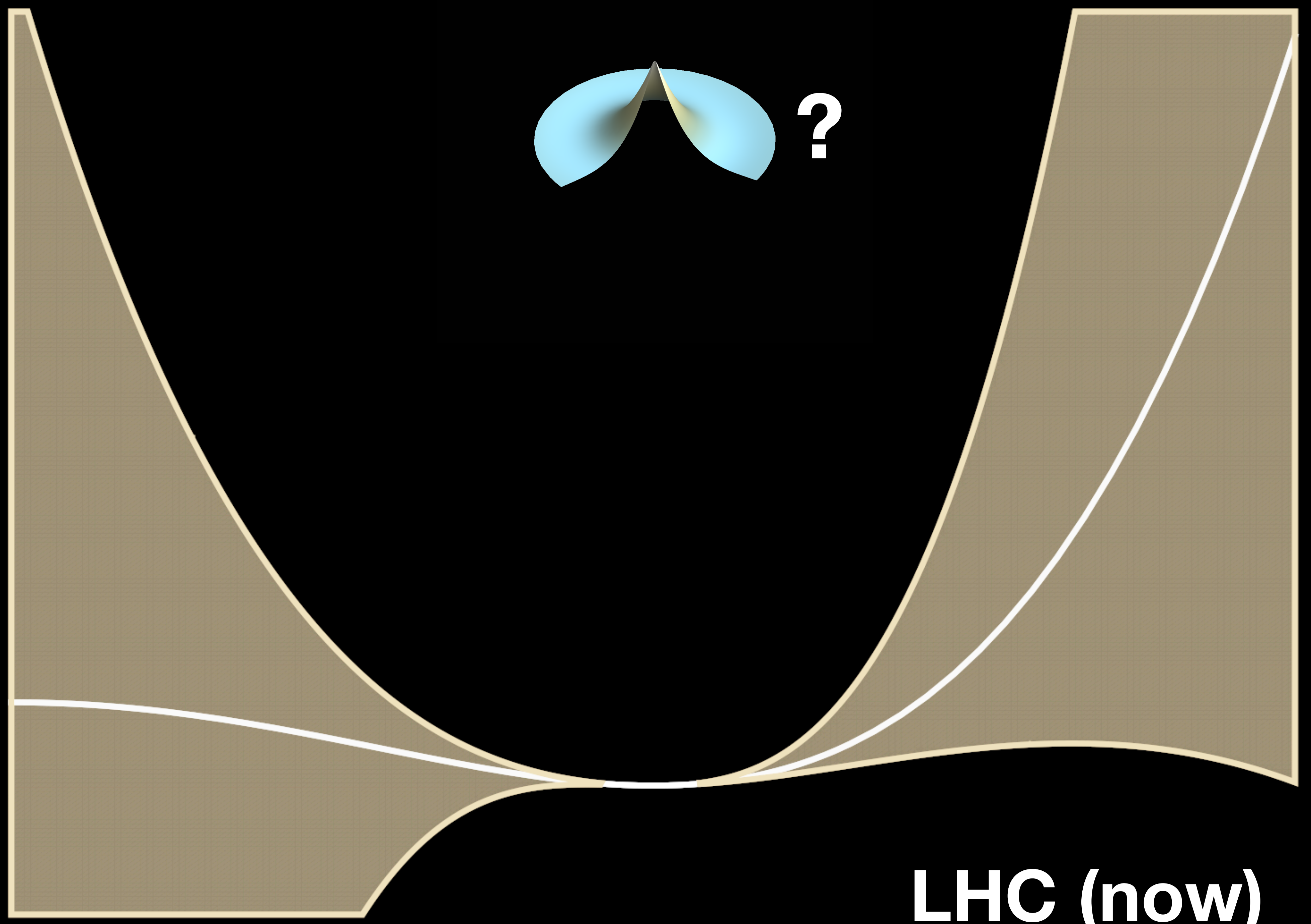




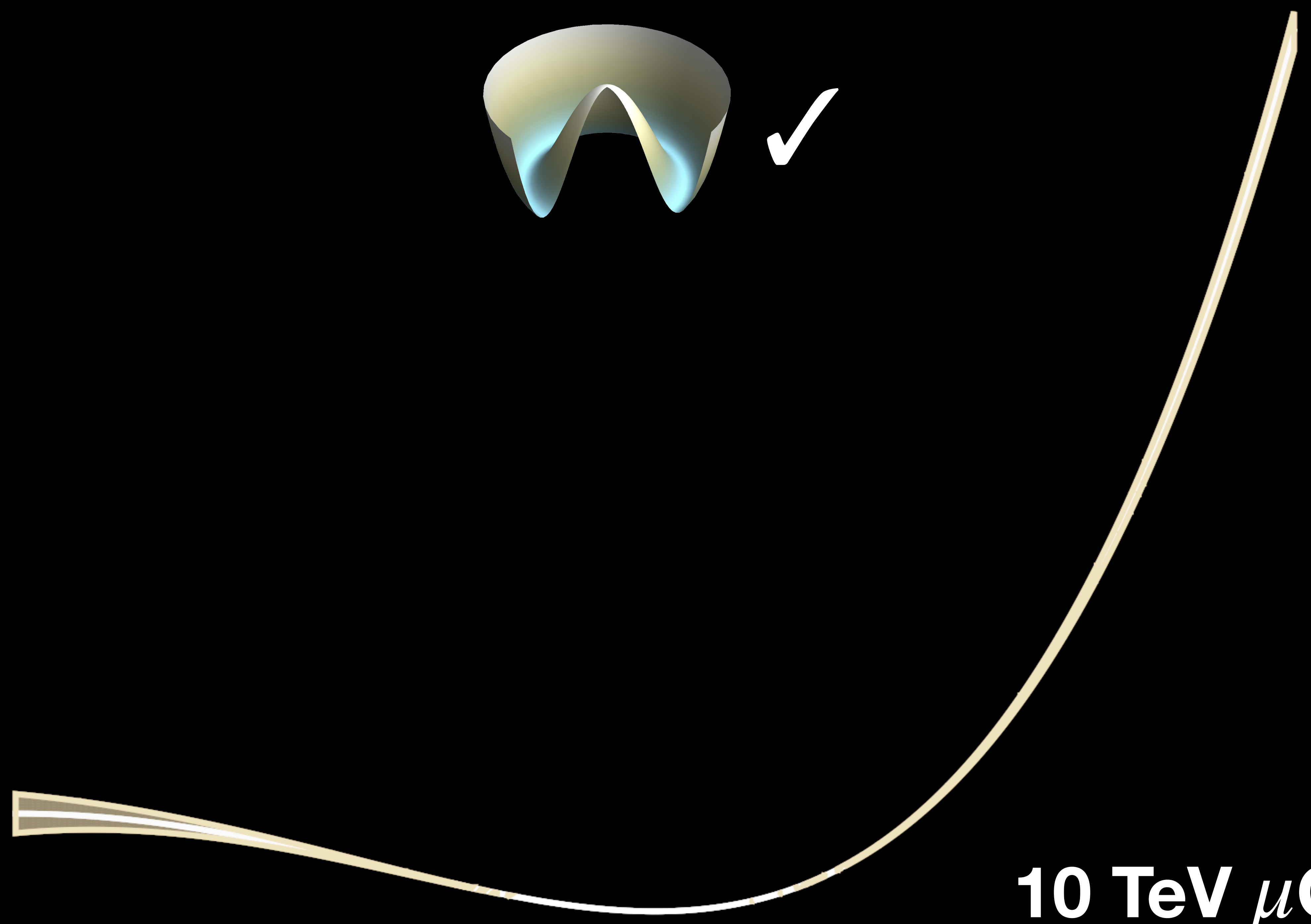
Muon annihilation
deploys the entire energy of the collider

Vector boson fusion
leverages the muon's virtual boson content

The Origin of Mass

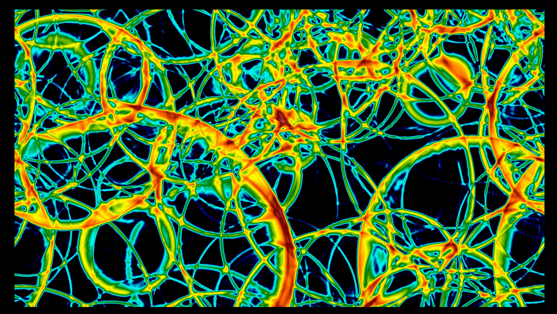


LHC (now)

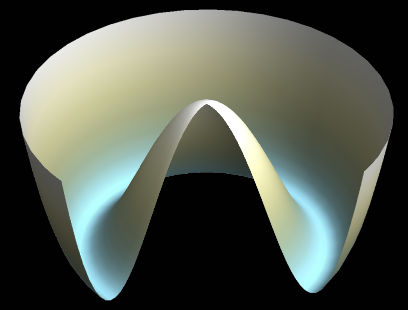


10 TeV μC

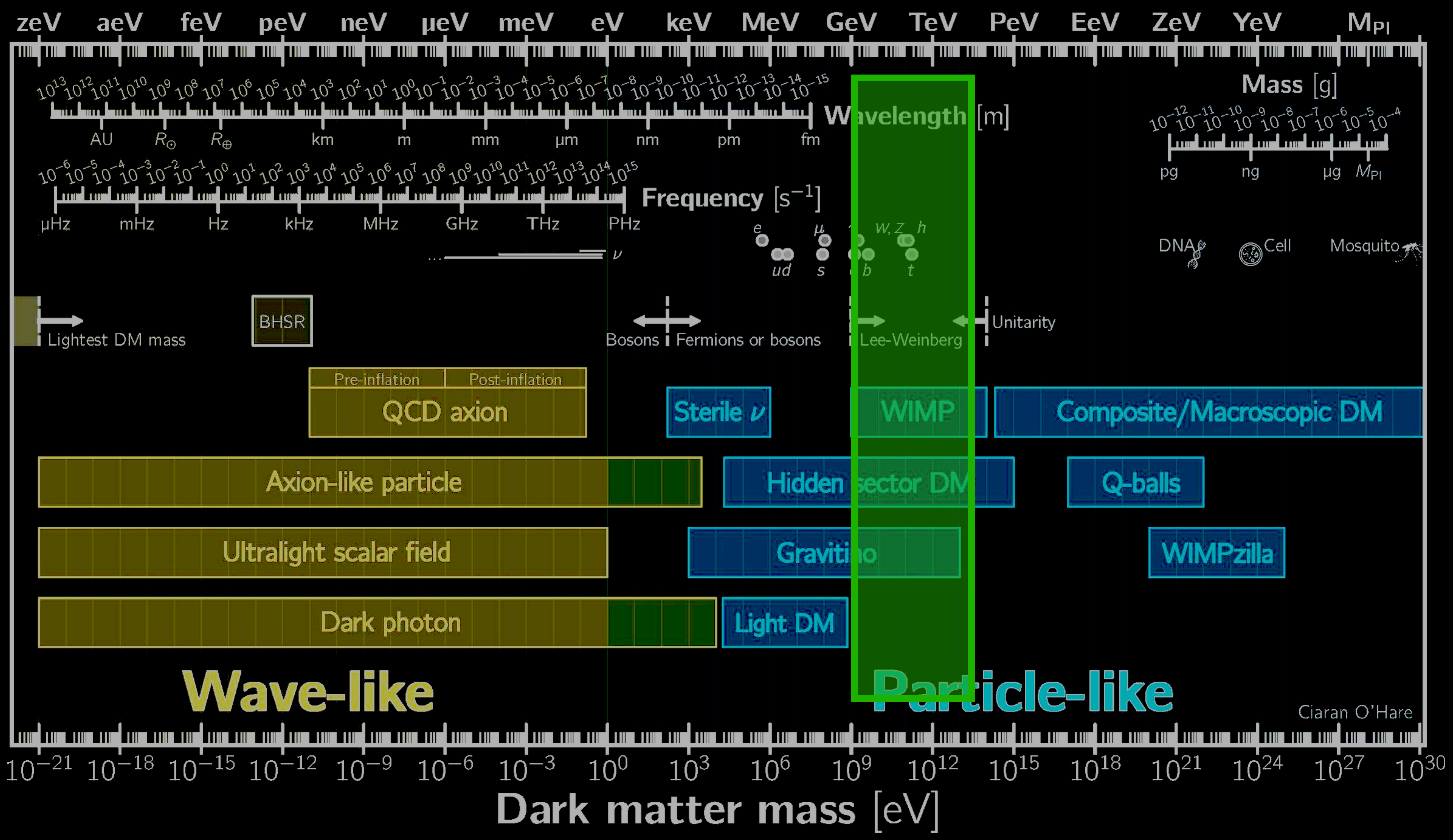
Sufficient to determine:



✓Whether this is how the universe began.
✓ Whether (if ever) this is how the universe will end.

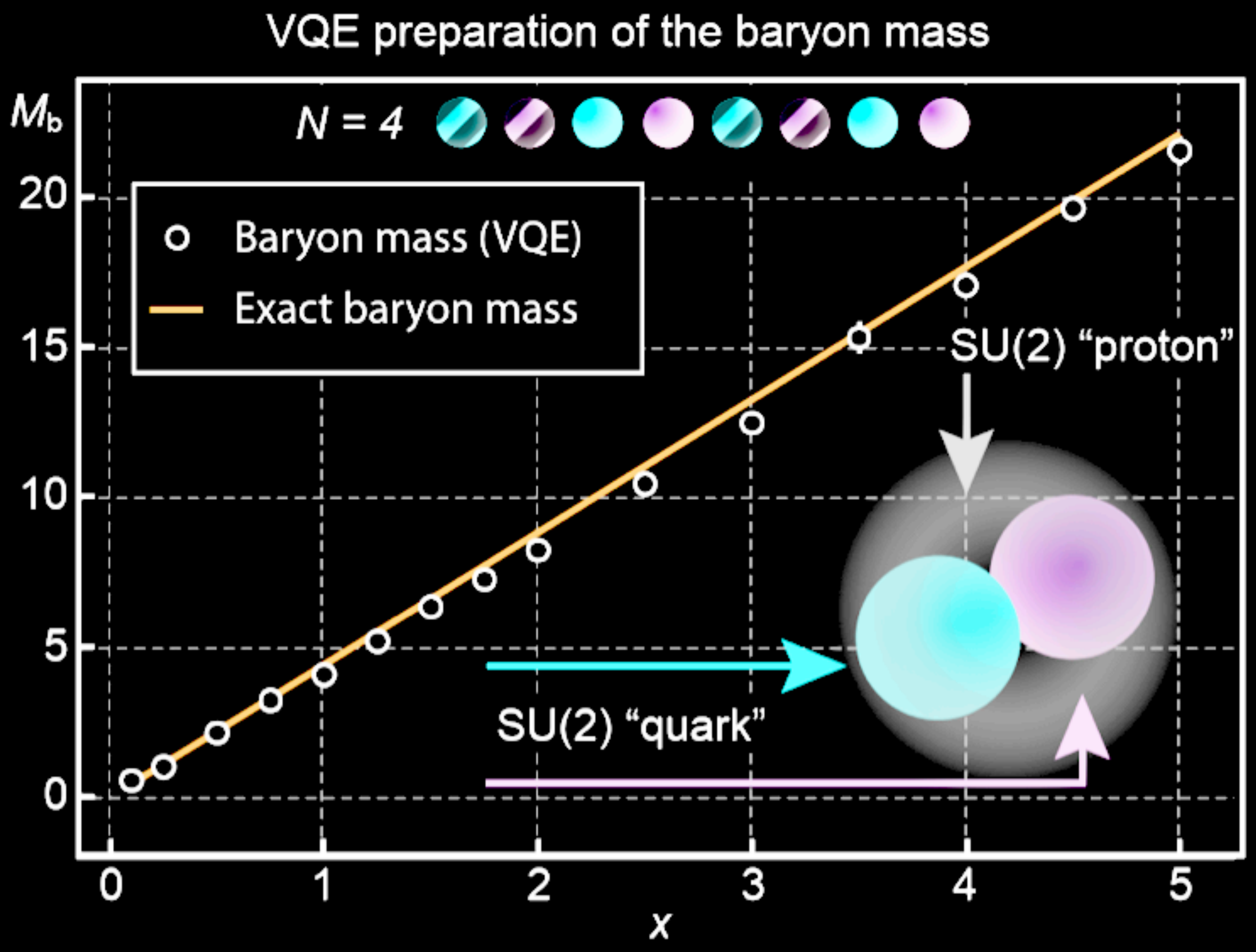


✓What sets the scale
(if generic)

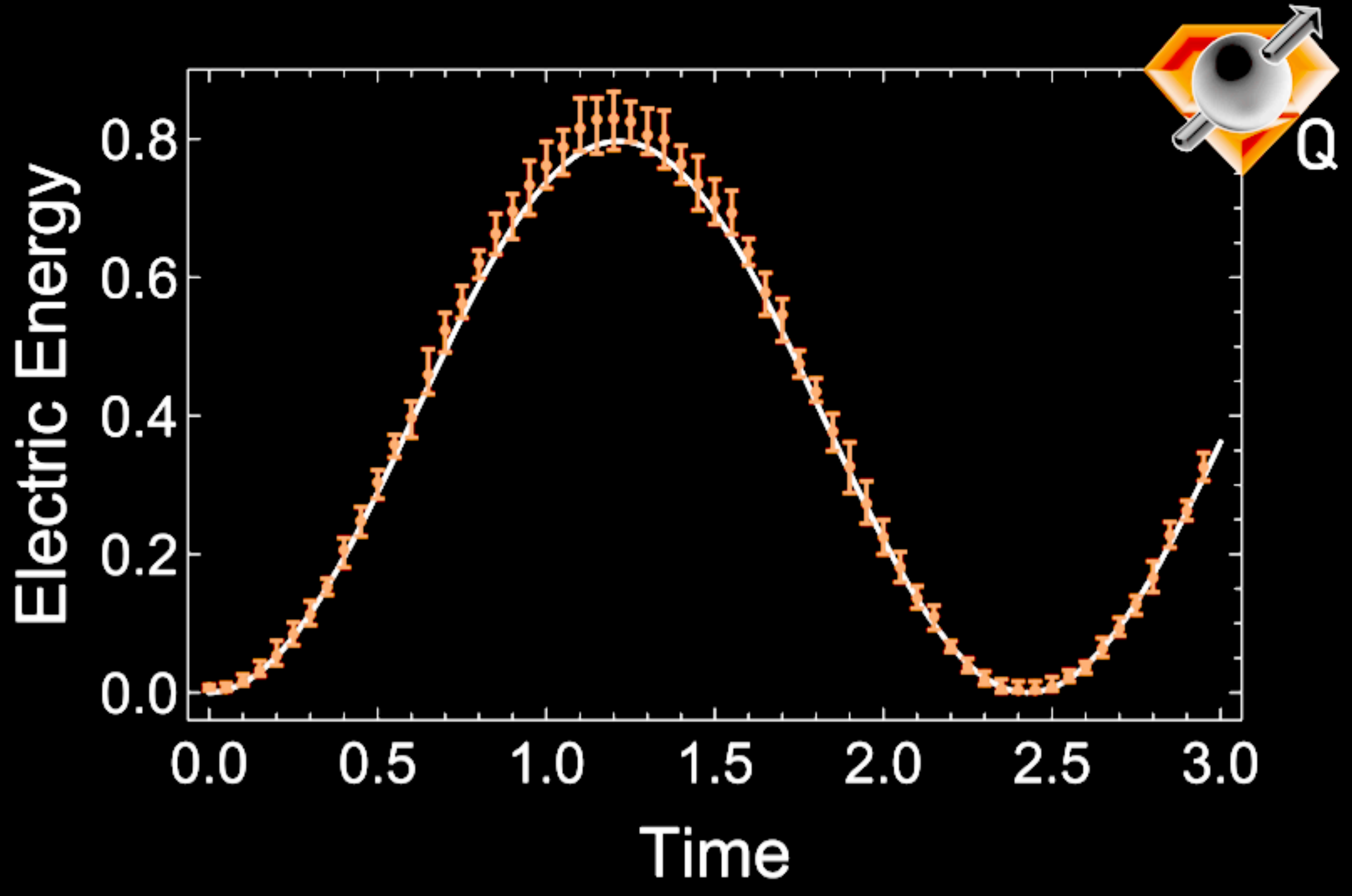


zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV EeV ZeV YeV M_Pl
Wavelength [m]
AU
km
m
mm
μm
nm
pm
fm
Frequency [s^-1]
μHz
mHz
Hz
kHz
MHz
GHz
THz
PHz
Mass [g]
pg
ng
μg
DNA
Cell
Mosquito
Lightest DM mass
BHSR
Bosons
Fermions or bosons
Lee-Weinberg
Unitarity
Pre-inflation
Post-inflation
QCD axion
Sterile ν
WIMP
Composite/Macroscopic DM
Axion-like particle
Hidden sector DM
Q-balls
Ultralight scalar field
Gravitino
WIMPzilla
Dark photon
Light DM
Wave-like
Particle-like
Ciaran O'Hare
Dark matter mass [eV]

Quantum Computation for QCD

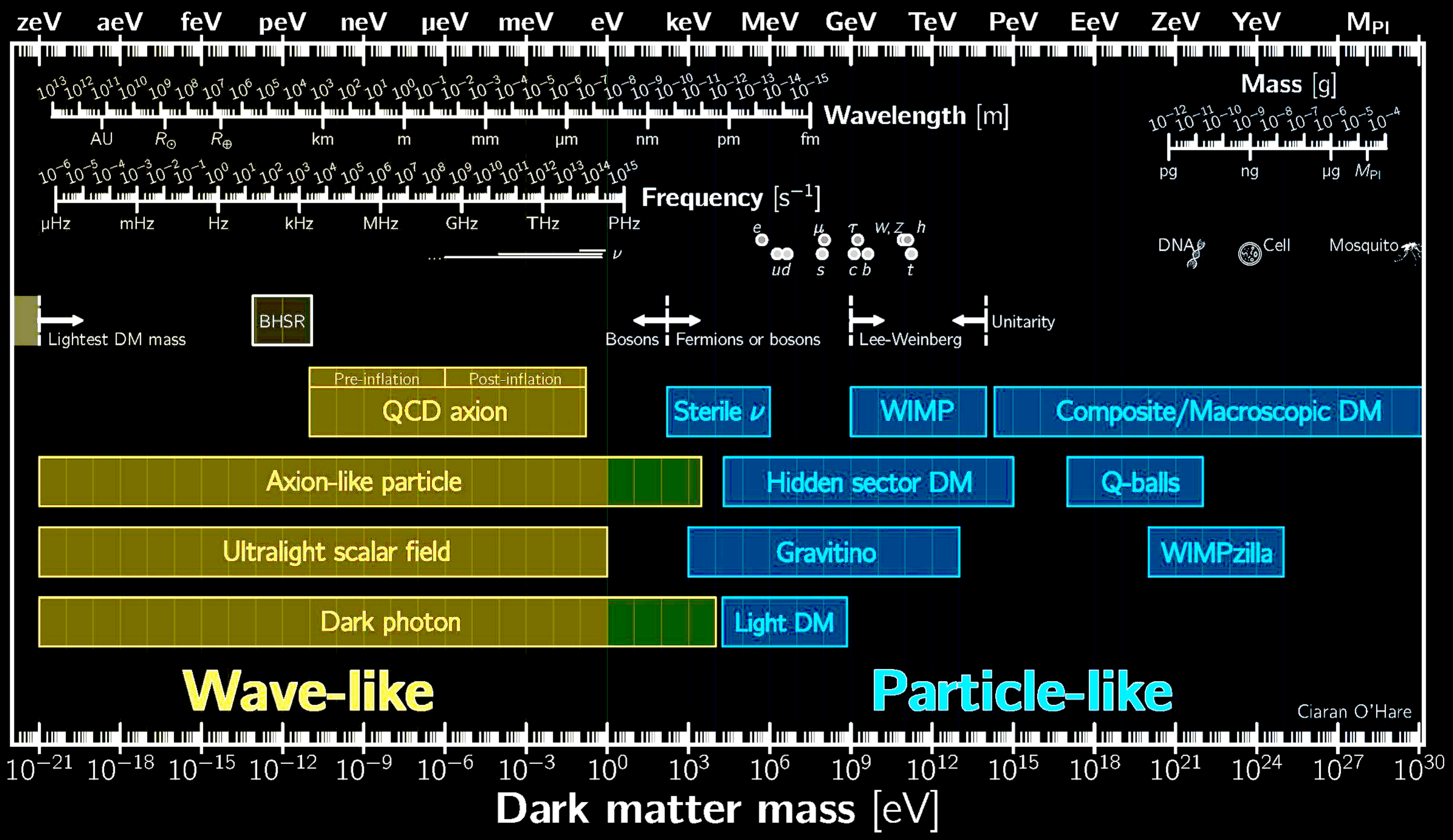


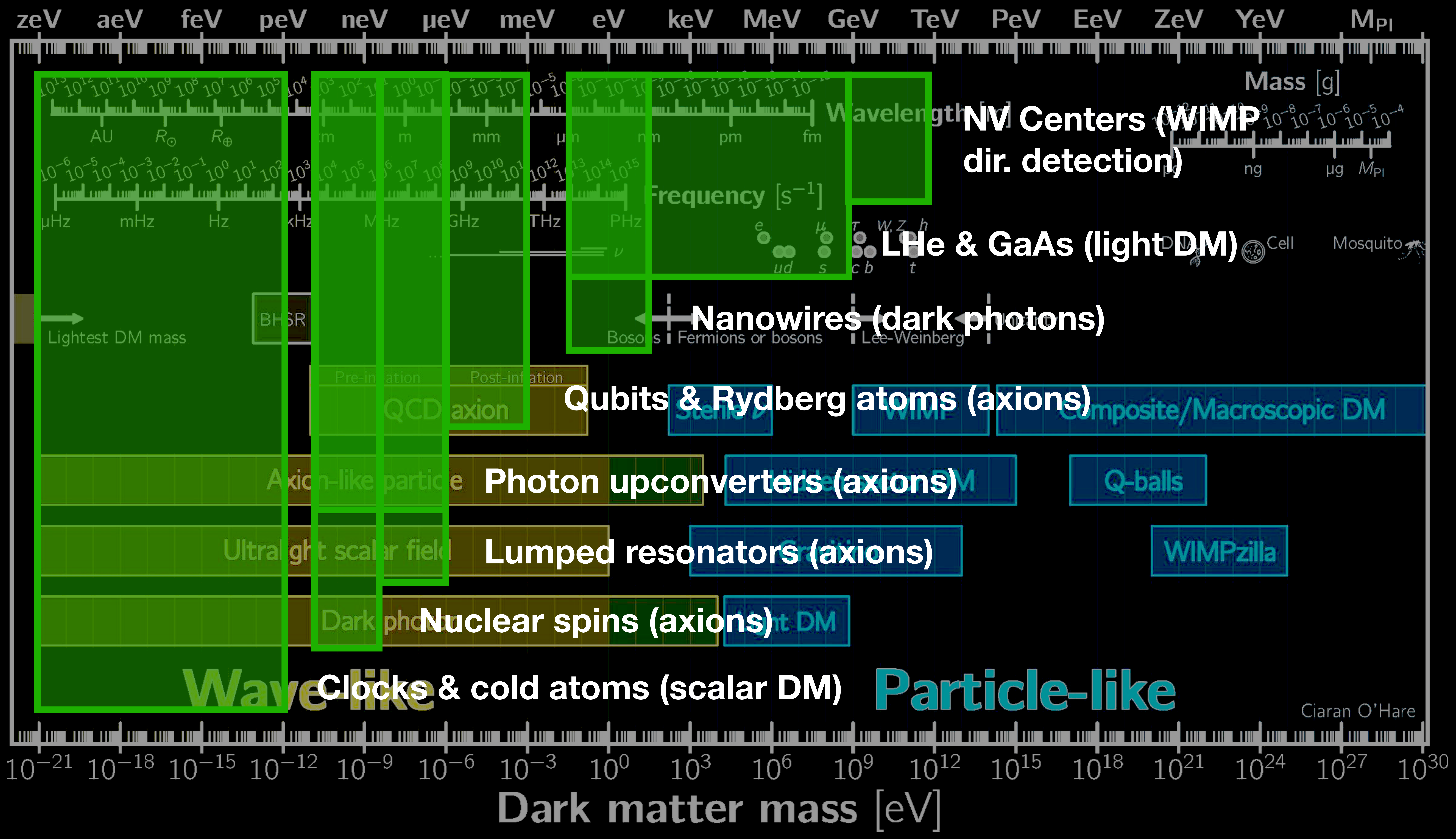
[Y. Y. Atas et al., Nat. Commun. 12, 6499 (2021)]



[A. Ciavarella, N. Klco, and M. J. Savage, Phys.Rev.D 103, 094501 (2021)]

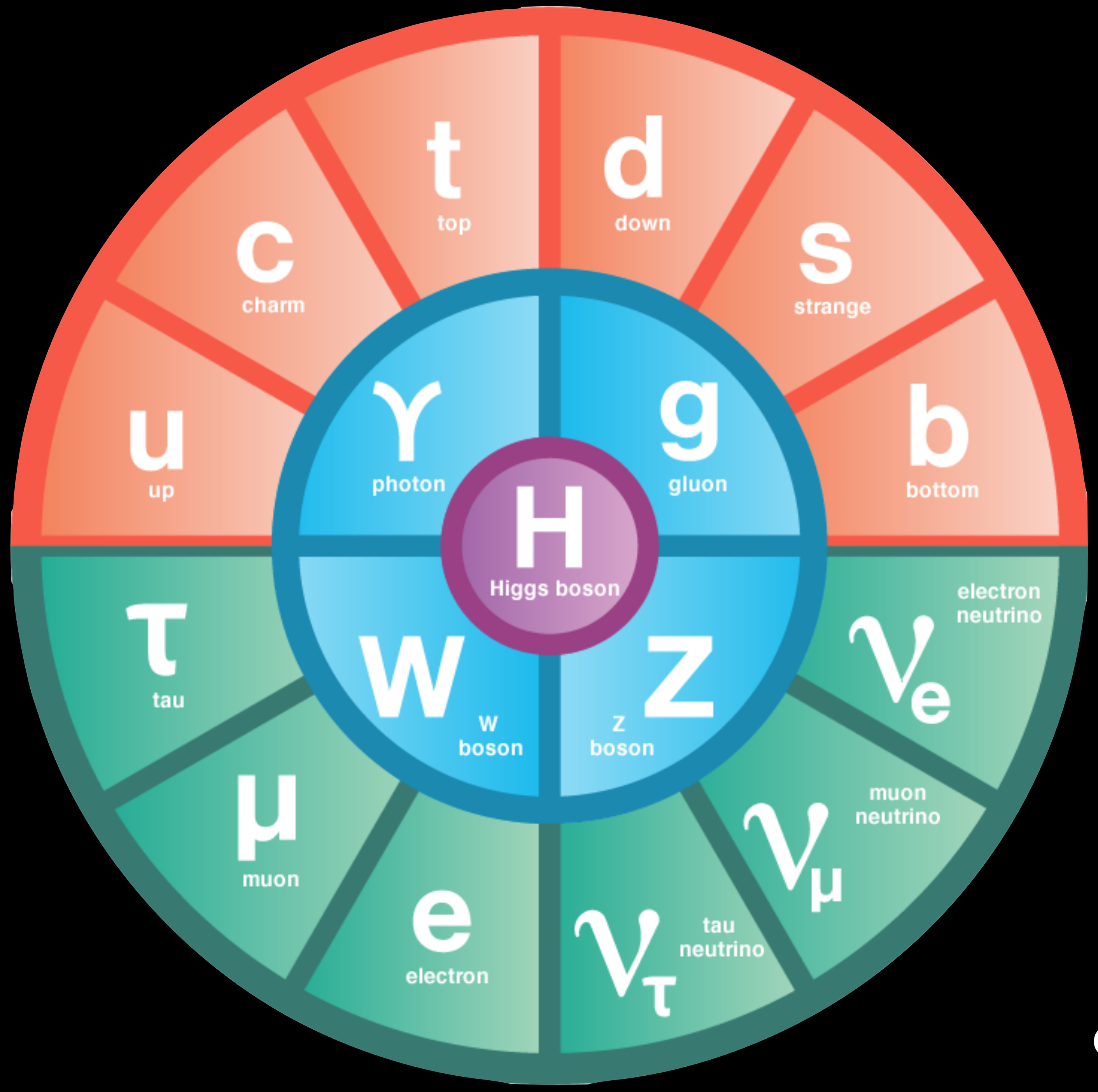
Quantum Sensing for DM





zeV aeV feV peV neV µeV meV eV keV MeV GeV TeV PeV EeV ZeV YeV M_{Pl}
NV Centers (WIMP dir. detection)
Mass [g]
LHe & GaAs (light DM)
Cell
Mosquito
Nanowires (dark photons)
Lightest DM mass
Fermions or bosons
Lee-Weinberg
Qubits & Rydberg atoms (axions)
QCD axion
Composite/Macroscopic DM
Photon upconverters (axions)
Q-balls
Lumped resonators (axions)
WIMPzilla
Nuclear spins (axions)
Clocks & cold atoms (scalar DM)
Particle-like
Ciaran O'Hare
10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} 10^{30}
Dark matter mass [eV]

- The origin of mass?
- The nature of dark matter?
- Matter/antimatter asymmetry?
- The nature of dark energy?



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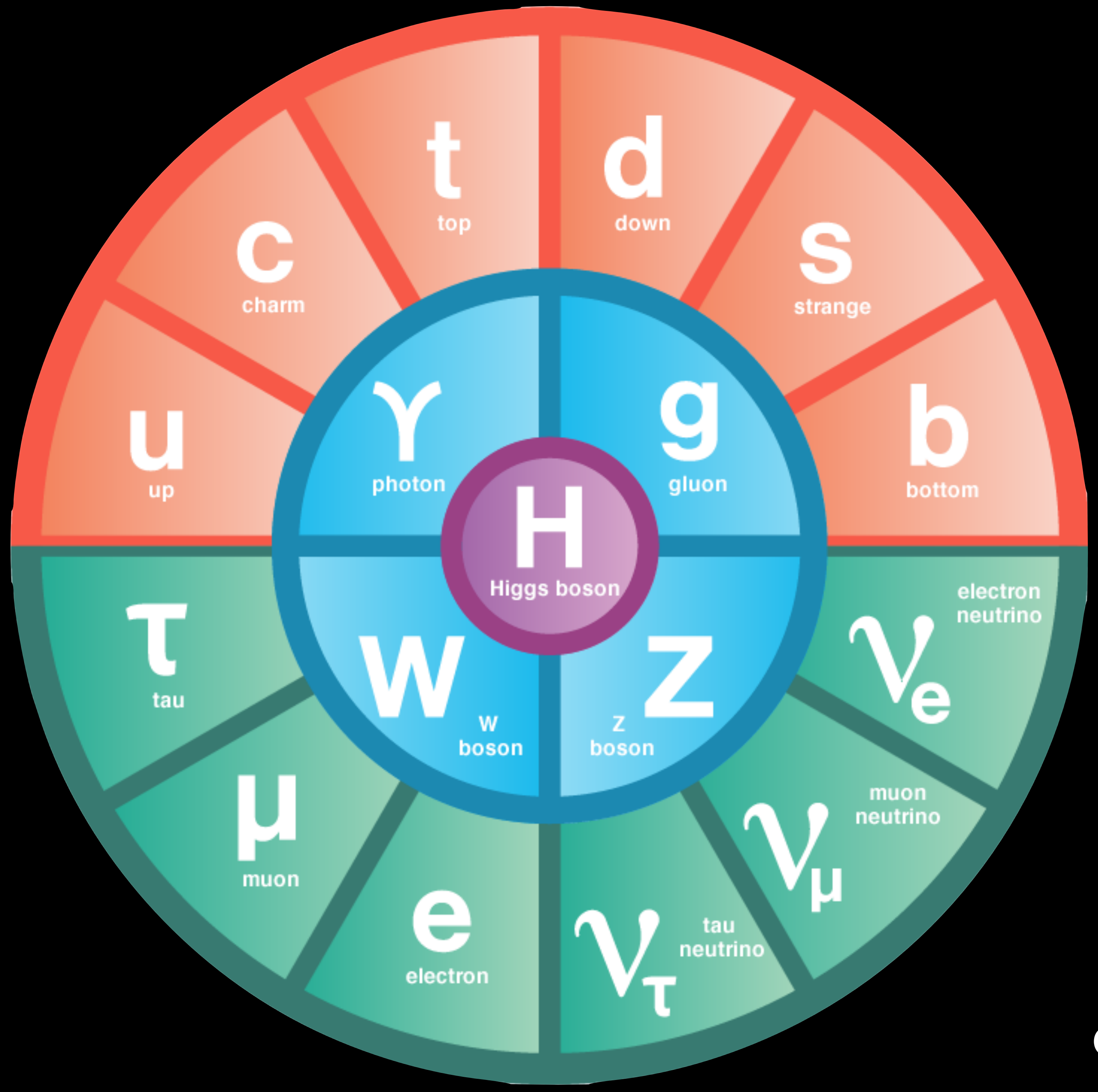

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Thank you!