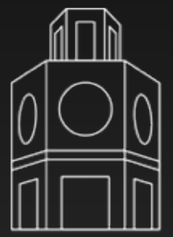
The Near Future of Physics Beyond the Standard Model

KITP Teacher's Conference
March 26th 2022



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Kavli Institute for
Theoretical Physics

Matheus Hostert
Post-Doctoral Researcher

Perimeter Institute
&
University of Minnesota

PERIMETER INSTITUTE
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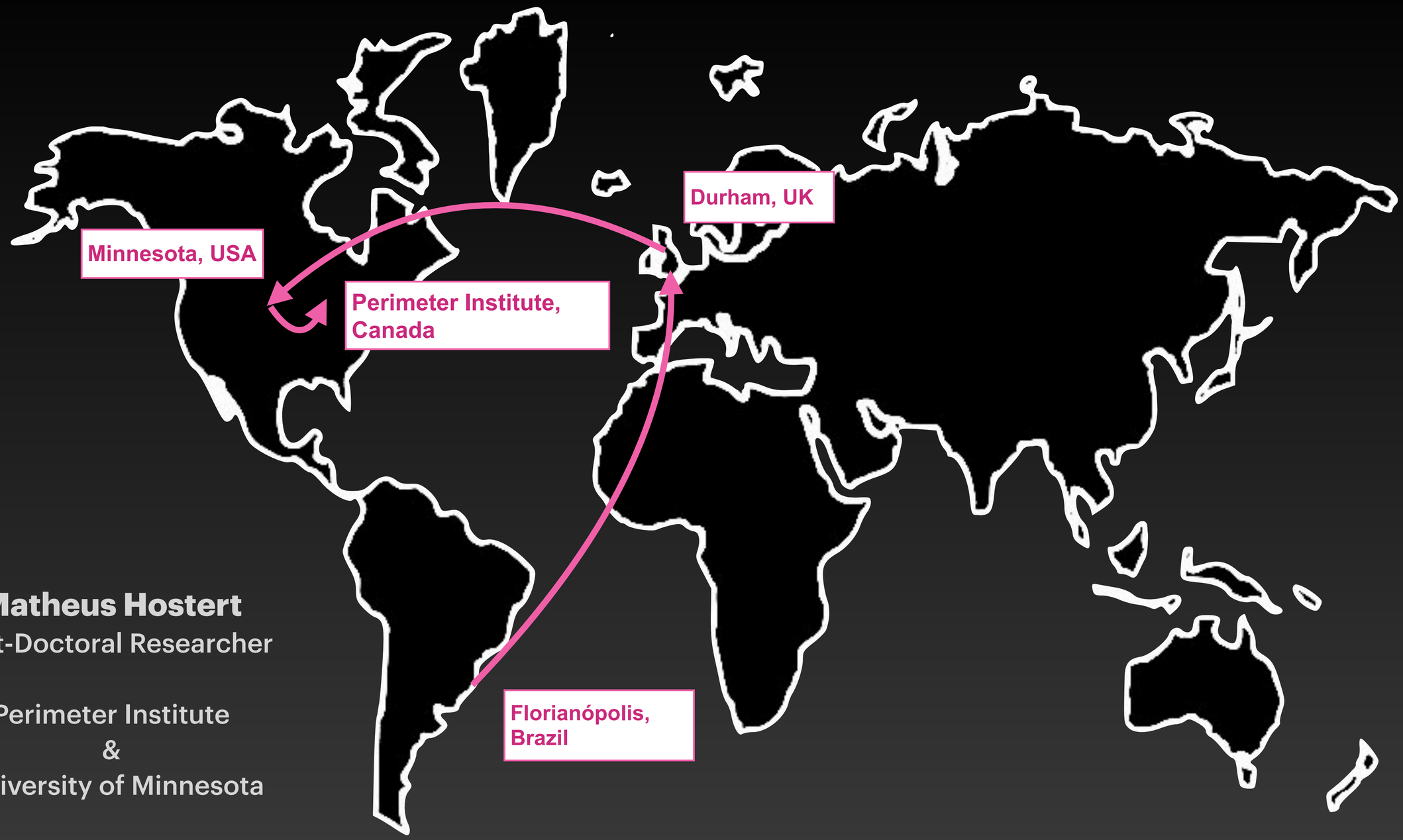

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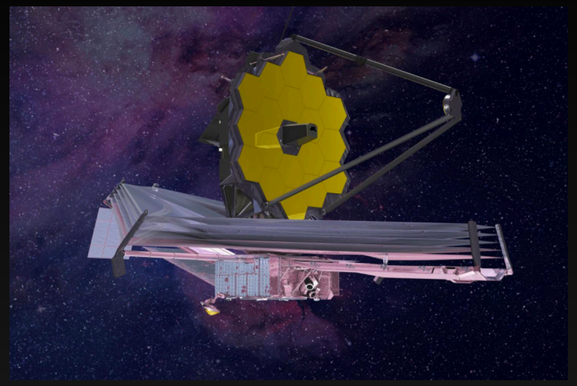
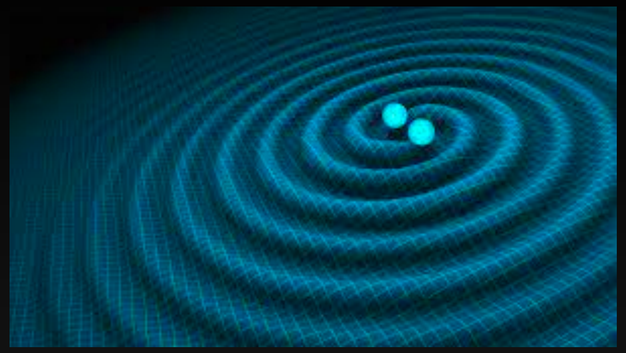
In this talk

Some ideas in the search for new fundamental particles and forces in Nature

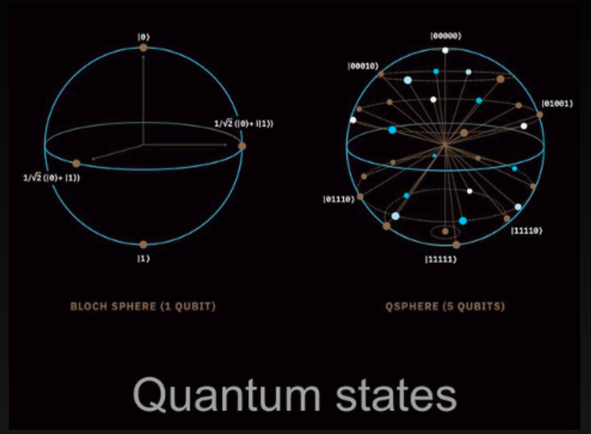
A few headlines that you can expect to hear **if we are successful**



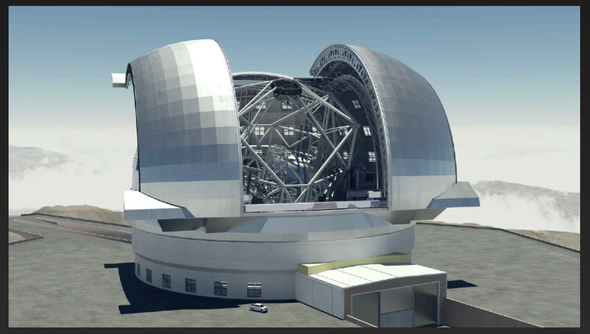
Astronomy — James Webb Telescope



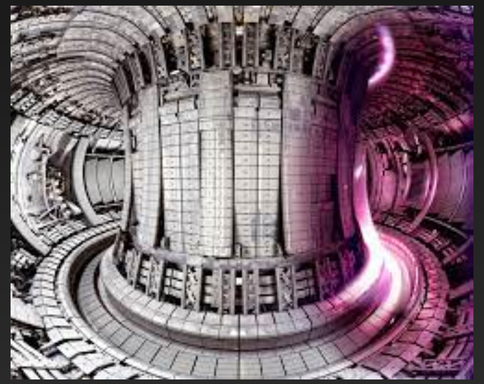
Gravitational Waves — LIGO/VIRGO



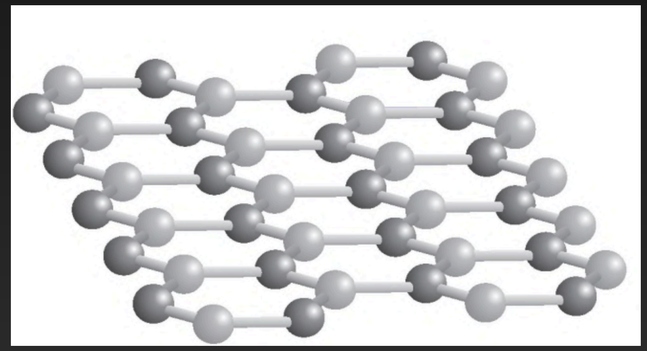
Quantum Computing



Astronomy — Extremely Large Telescope



ITER — Plasma Physics



Condensed Matter

Plethora of data and opportunities

Particle Physics

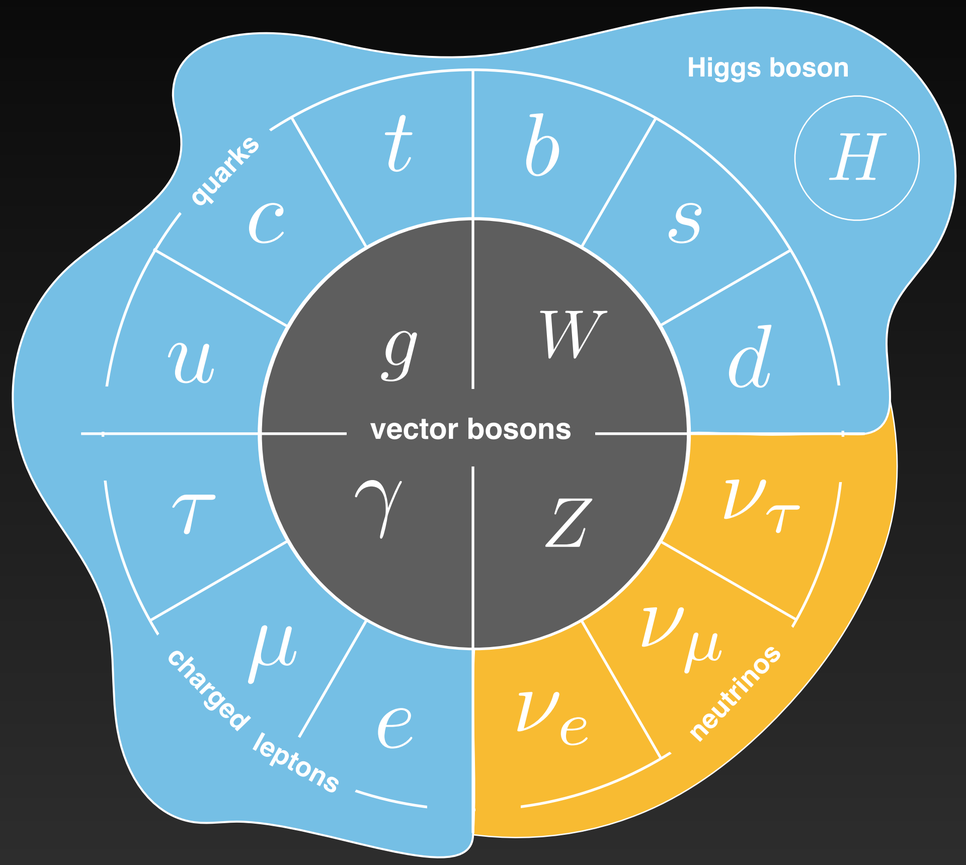
Using high energies to probe the building blocks of nature

$$E = \frac{h\,c}{\lambda}$$

The energy of a photon is inversely proportional to its wavelength.

High energy processes in particle physics probe small “things”.

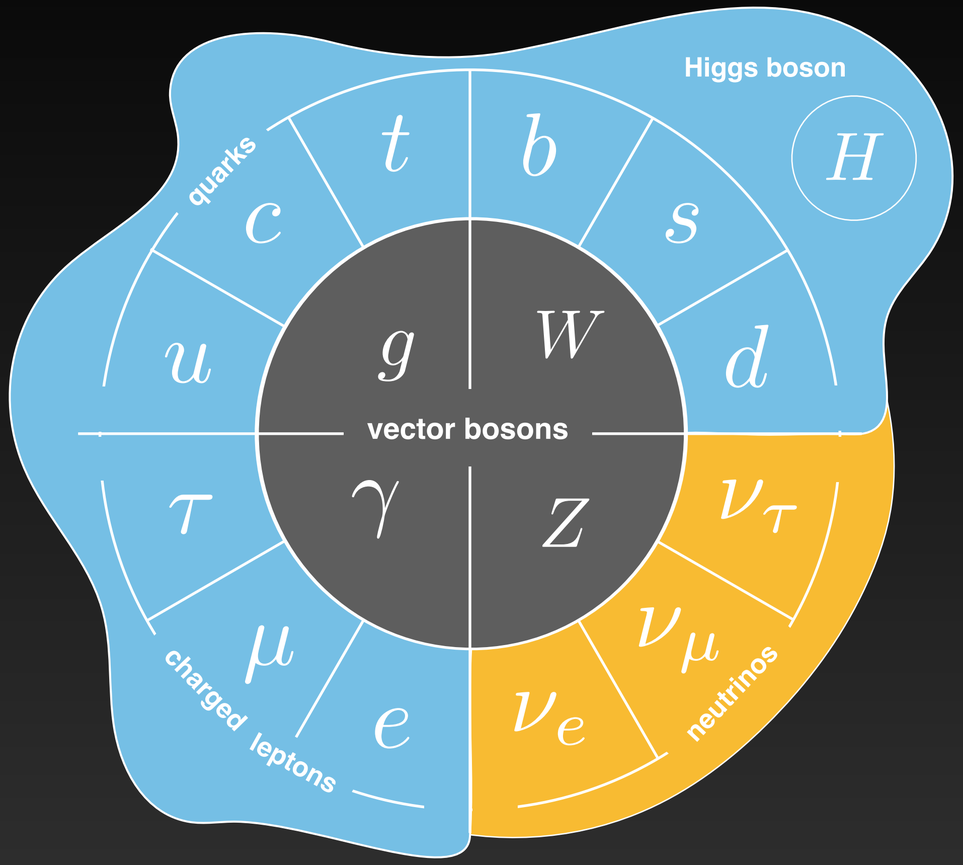
The Standard Model



"Of course our model has too many arbitrary features for these predictions to be taken seriously [...]"

— S. Weinberg

The Standard Model



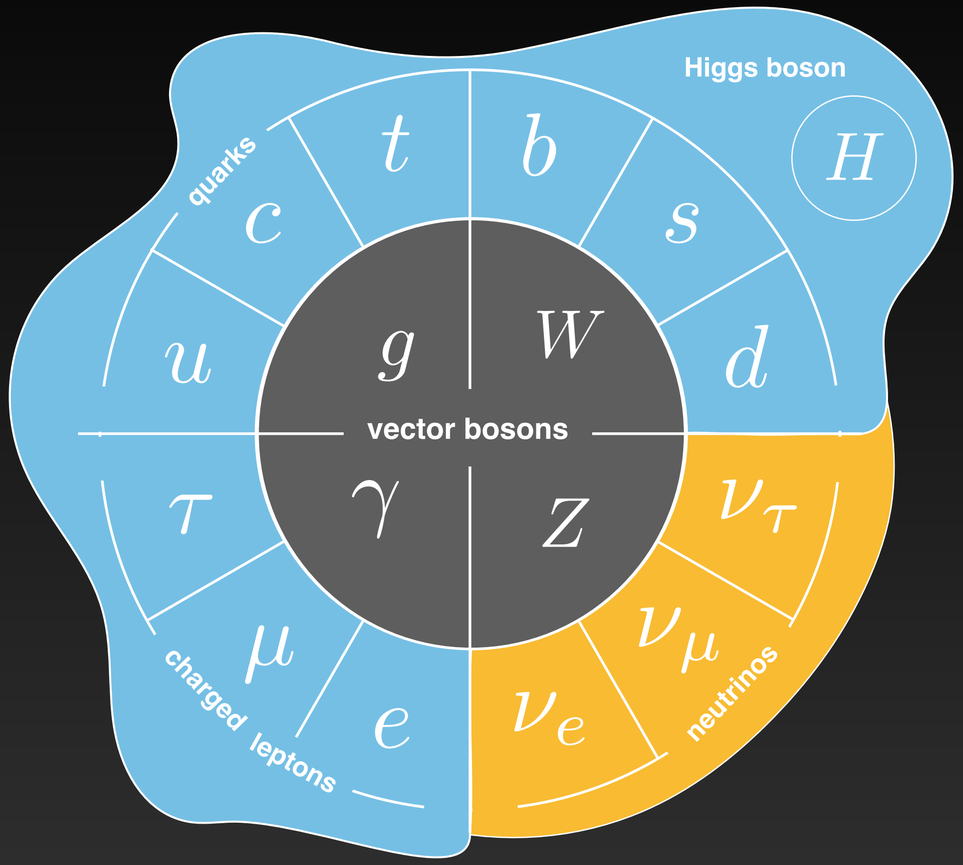
"Of course our model has too many arbitrary features for these predictions to be taken seriously [...]"

— S. Weinberg

We know it cannot be the end of the story.

- Cannot accommodate neutrino masses.
- Does not explain the existence of dark matter.
- Cannot explain the abundance of matter over antimatter in the Universe.

The Standard Model



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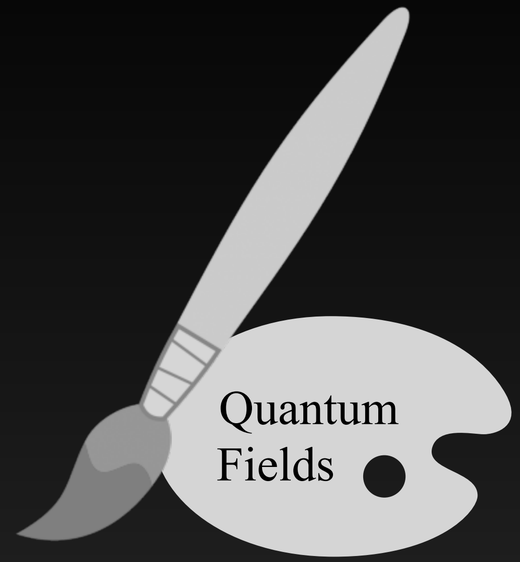
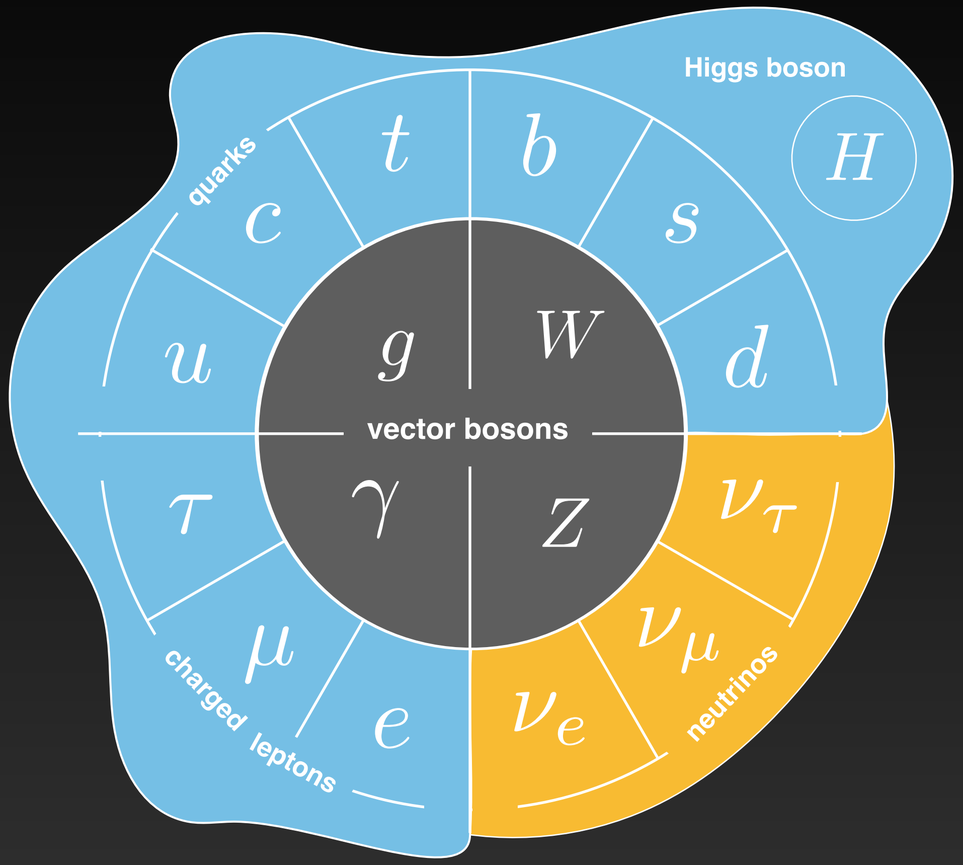


"Quantum field theory can arguably be regarded as the pinnacle of human thought."

— A. Zee

The Standard Model



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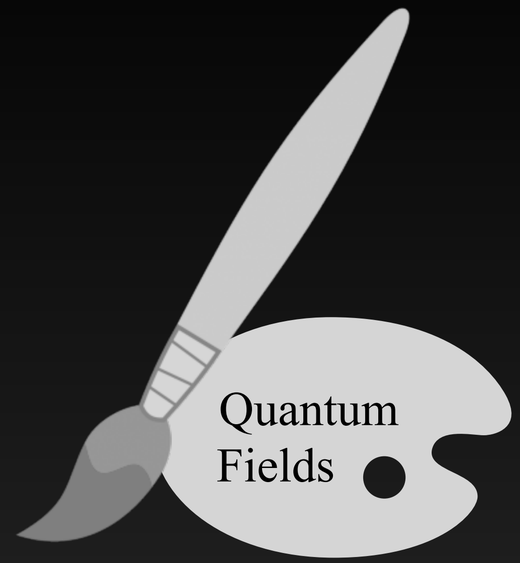


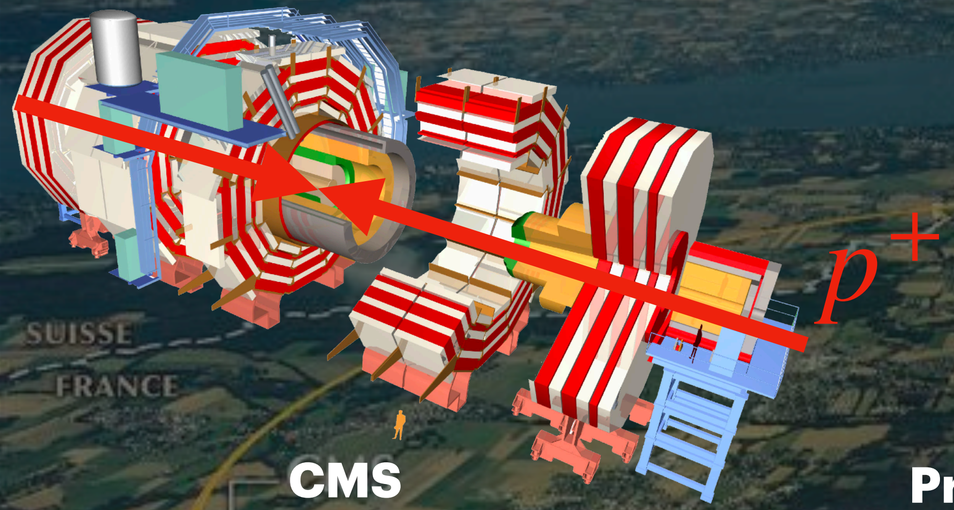
"Quantum field theory can arguably be regarded as the pinnacle of human thought."

— A. Zee

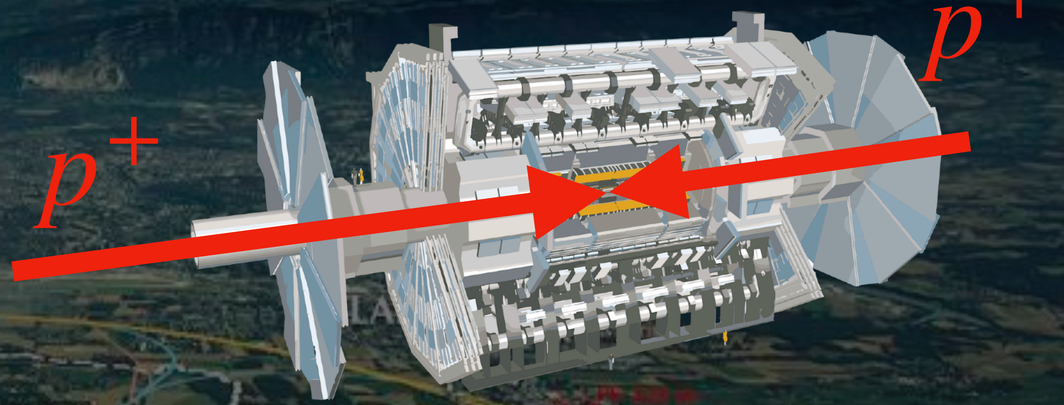
"[...] yet field theory is in my opinion still incomplete [...]"

— A. Zee

The Large Hadron Collider



CMS



ATLAS

27 km of circumference

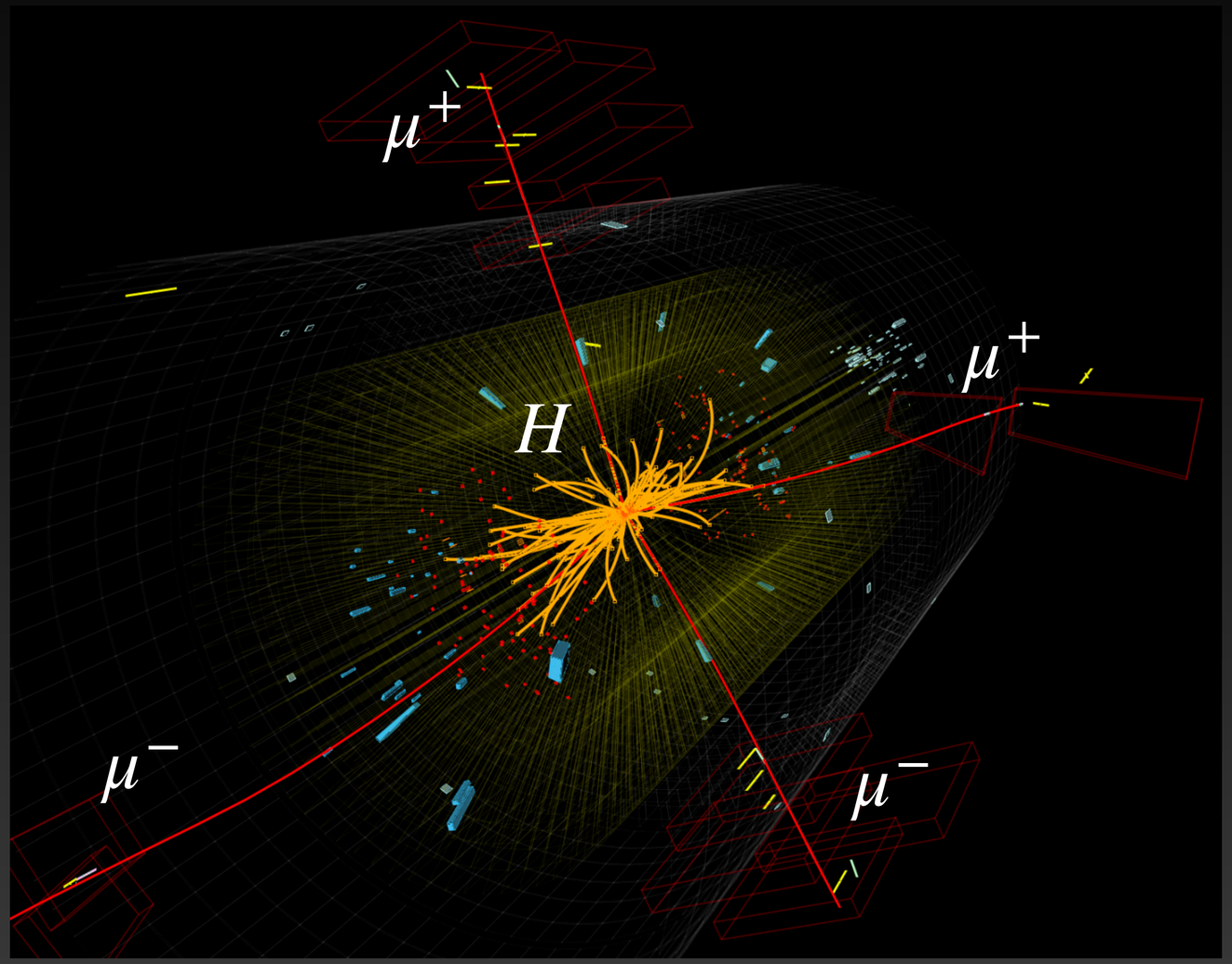
Protons accelerated to 13 TeV

The largest single-particle energy ever created in the laboratory.

Four collision points, each with a detector used by thousands of collaborators:

ATLAS (> 5500 members)
CMS (> 5000 members)
LHCb (> 1400 members)
ALICE (> 1000 members)

The most important development in the last decade



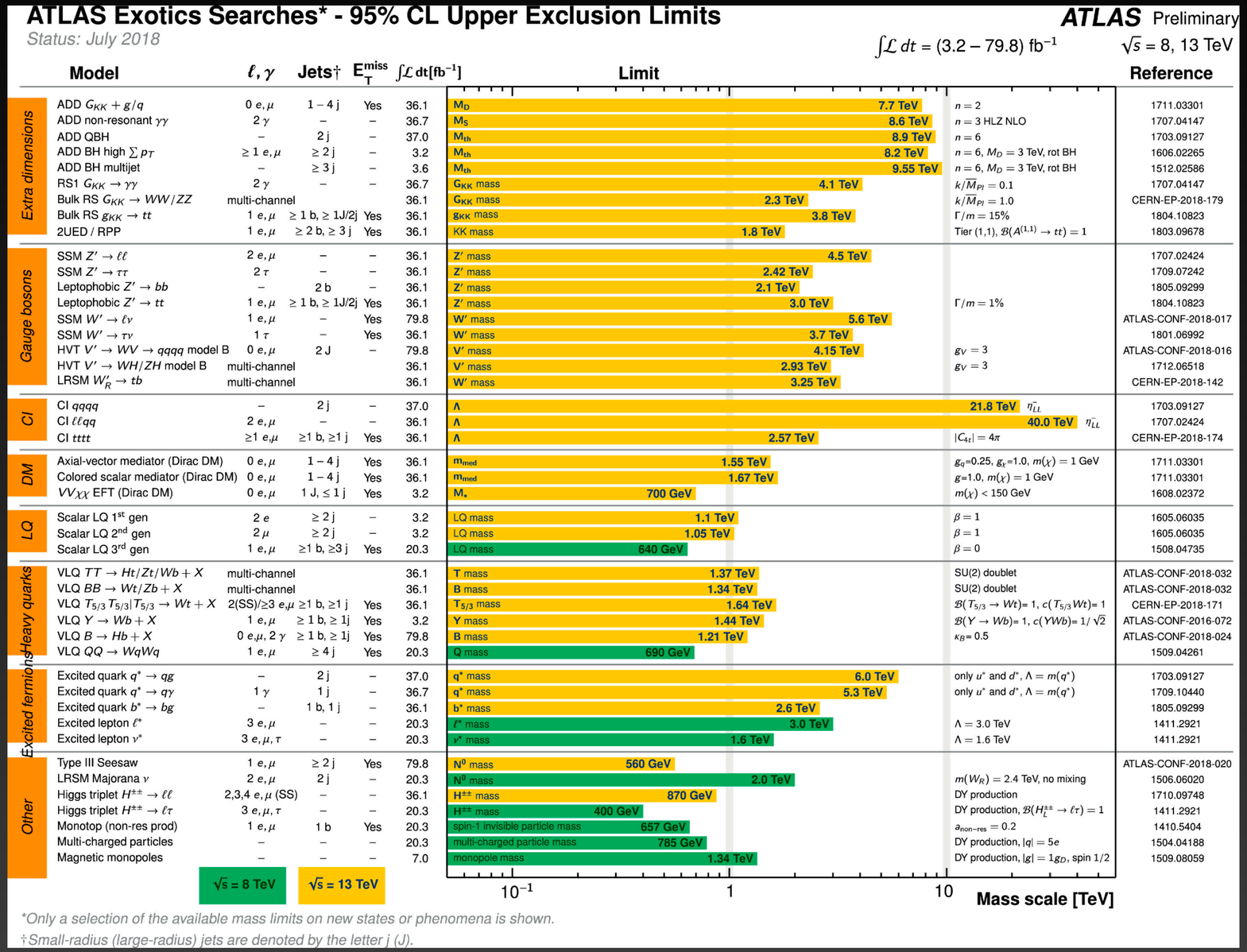
On July 4th, we will celebrate the 10th anniversary of the announcement of the discovery of the Higgs boson.

The last piece of the Standard Model.

Since then, we have been checking that it indeed looks like the Higgs.

And, *so far*, it does.

But did we find anything else?



Where else can we look?

We may have missed something on the way to the Higgs.

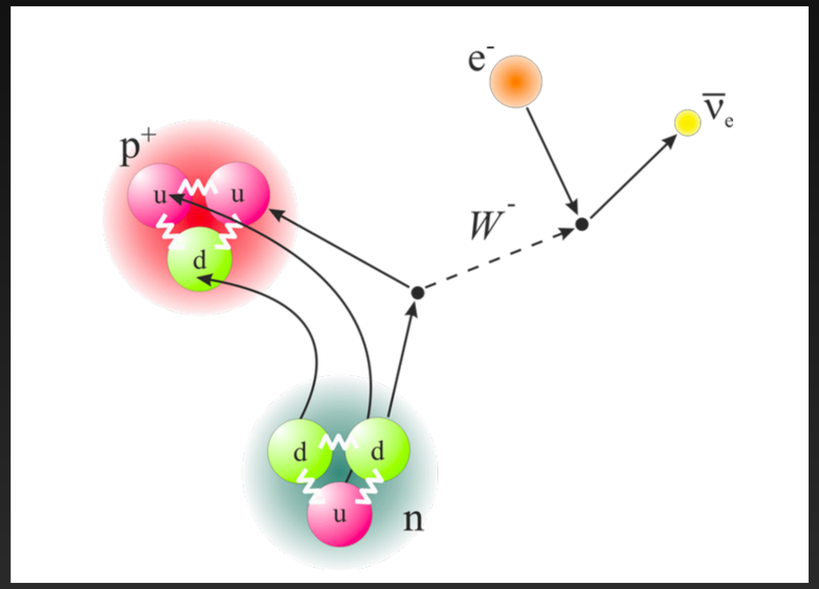
Fundamental forces in nature

Particles interact by exchanging force mediators.

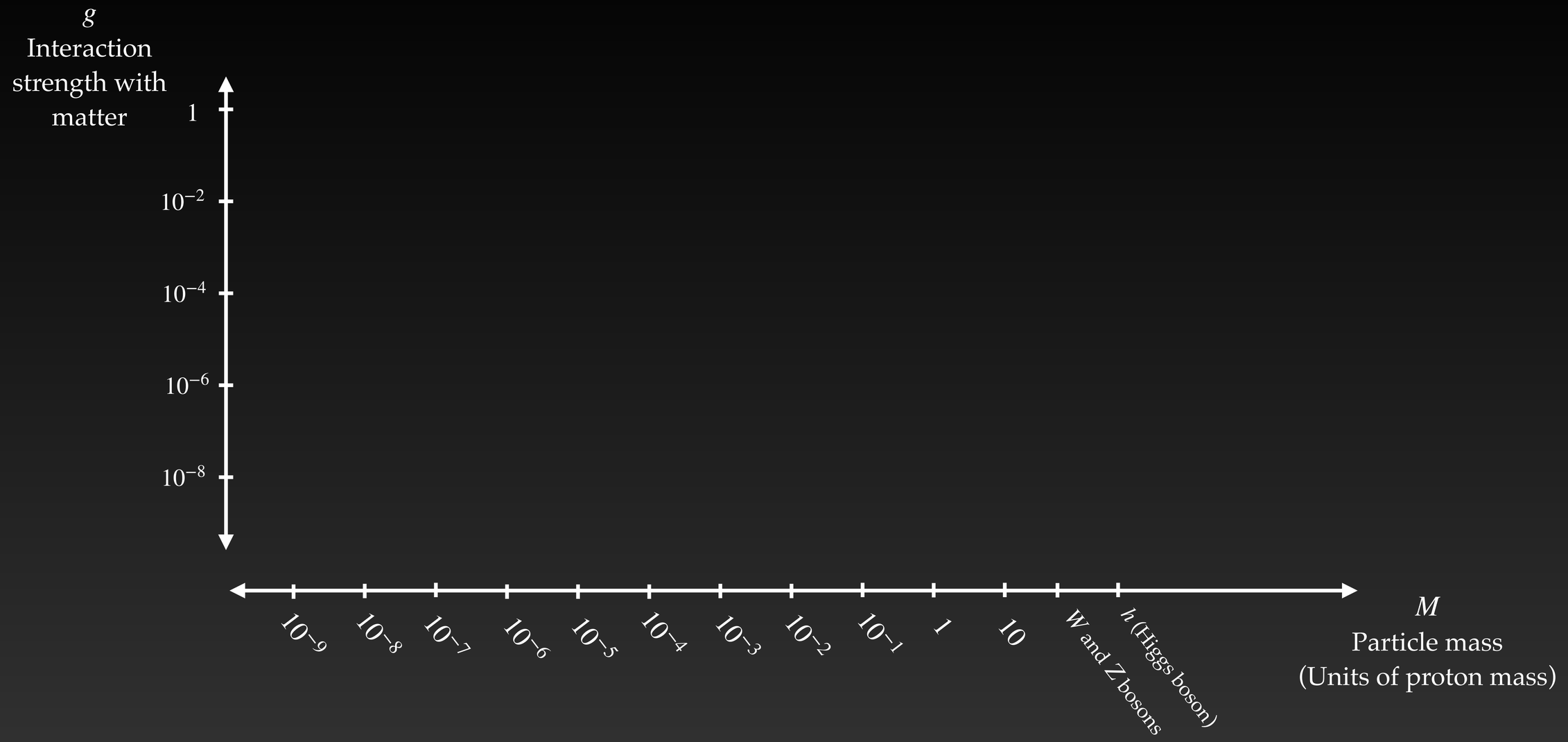
For massive mediators,
the interaction strength is proportional to

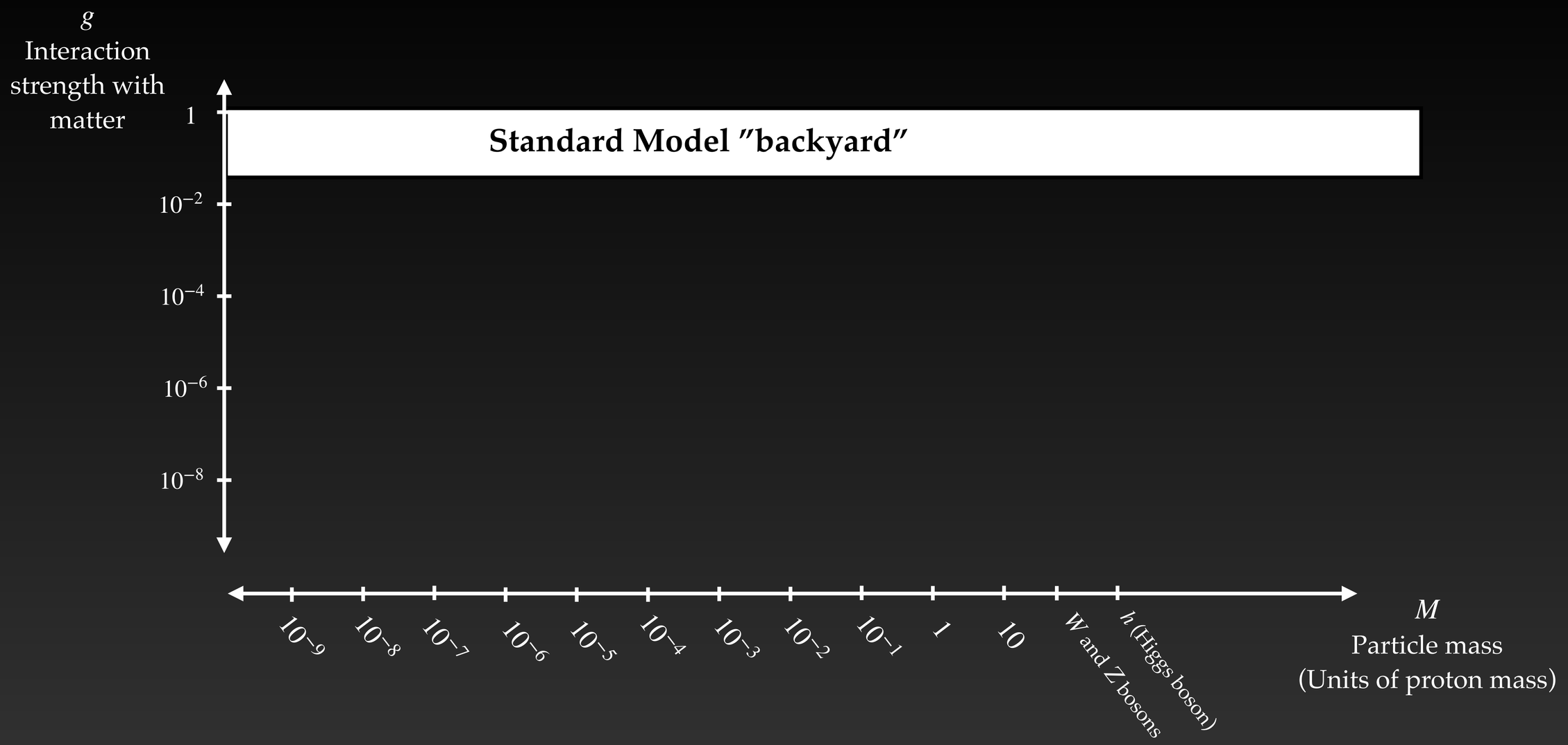
$$\frac{g}{M}$$

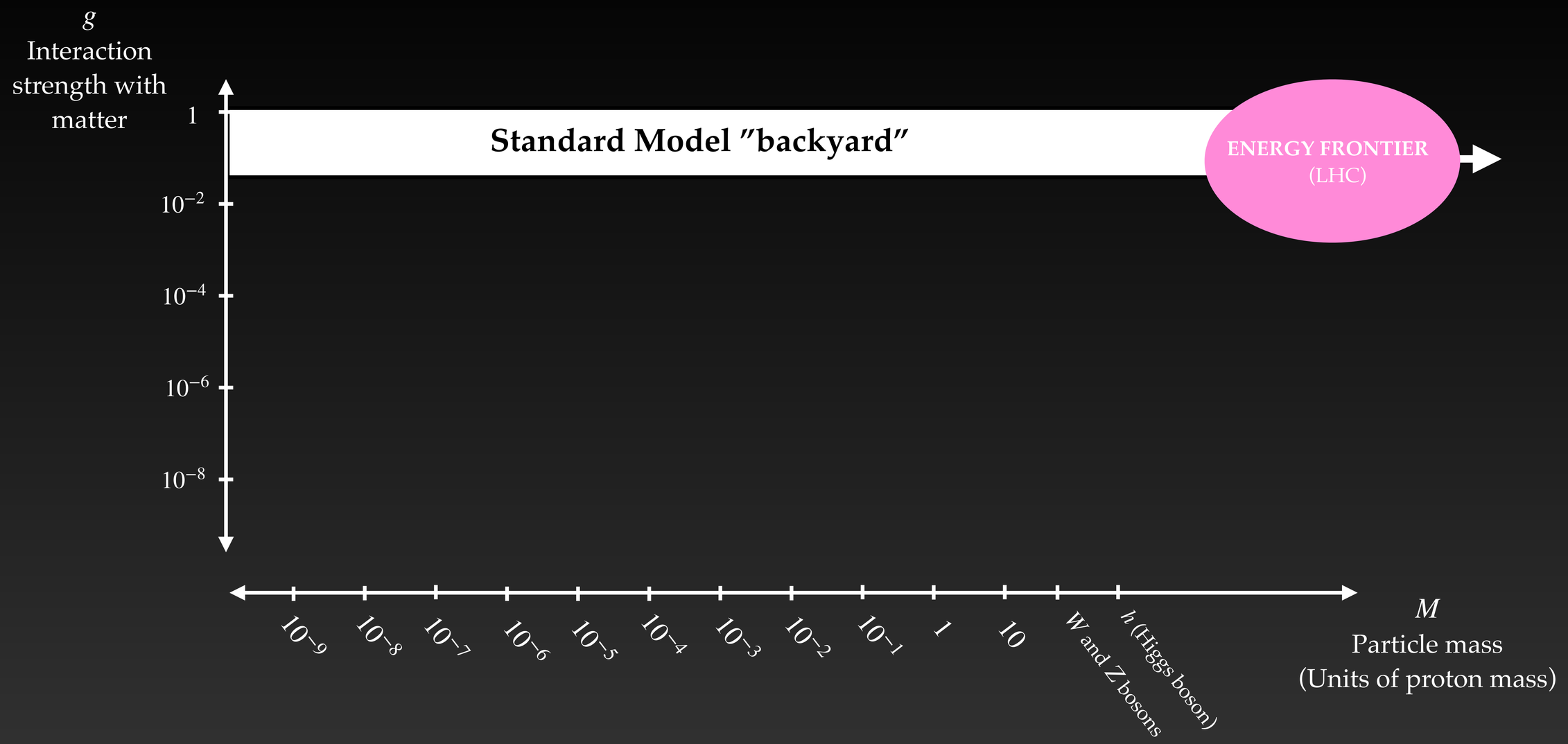
time

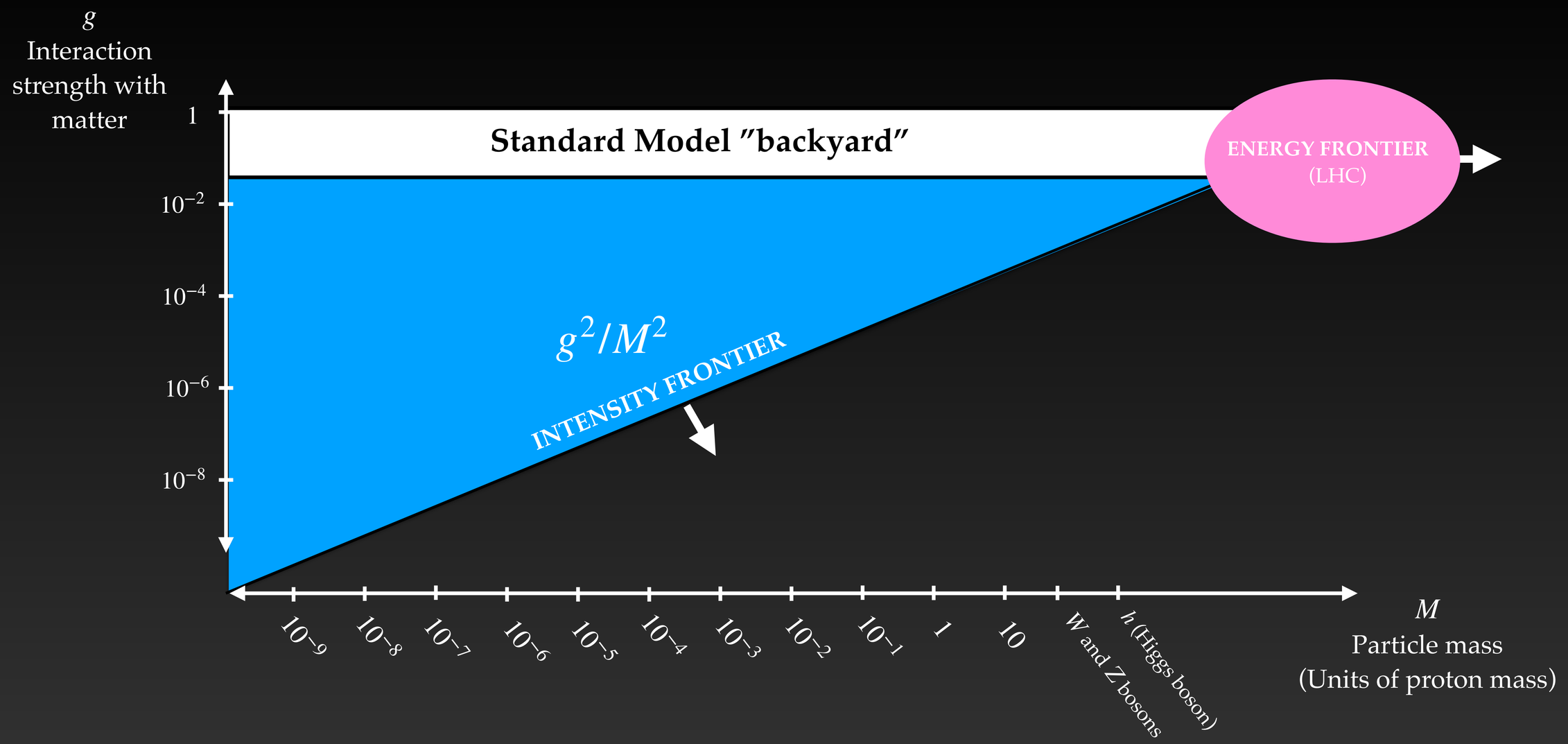


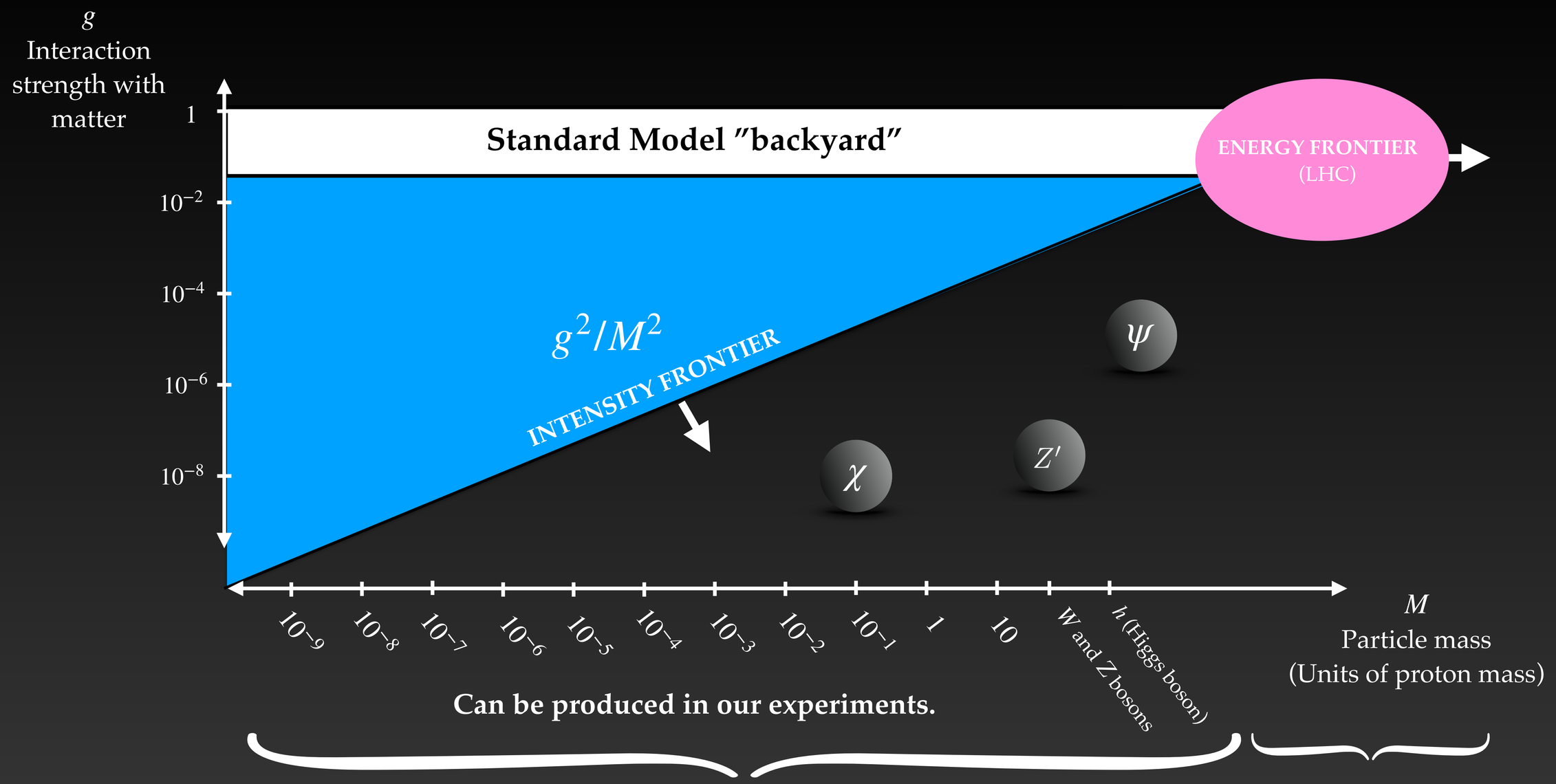
W boson in neutron decay.


g
Interaction strength with matter
1
10−2
10−4
10−6
10−8
10−9
10−8
10−7
10−6
10−5
10−4
10−3
10−2
10−1
1
10
W and Z bosons
h (Higgs boson)
M
Particle mass
(Units of proton mass)


g
Interaction strength with matter
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Standard Model "backyard"
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
W and Z bosons
h (Higgs boson)
M
Particle mass
(Units of proton mass)
ν
ν'
e
μ
τ
W
Z
H


g
Interaction strength with matter
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Standard Model "backyard"
ENERGY FRONTIER
(LHC)
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
W and Z bosons
h (Higgs boson)
M
Particle mass
(Units of proton mass)


g
Interaction strength with matter
1
10−2
10−4
10−6
10−8
Standard Model "backyard"
ENERGY FRONTIER
(LHC)
g2/M2
INTENSITY FRONTIER
10−9
10−8
10−7
10−6
10−5
10−4
10−3
10−2
10−1
1
10
W and Z bosons
h (Higgs boson)
M
Particle mass
(Units of proton mass)


g
Interaction strength with matter
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Standard Model "backyard"
ENERGY FRONTIER
(LHC)
g^2/M^2
INTENSITY FRONTIER
ψ
Z'
χ
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
W and Z bosons
h (Higgs boson)
M
Particle mass
(Units of proton mass)
Can be produced in our experiments.
We can only see its
Indirect effects.

So what are we hoping to find in the next 10 to 20 years?

Some **biased** and **optimistic** ideas.

A Word of Caution

A Word of Caution

Life is hard.

A Word of Caution

Life is hard.

Any new discovery would have profound consequences
for our understanding of the Universe.

It is a good idea to apply the “ECREE” standard.

"Extraordinary claims require extraordinary evidence”

— Carl Sagan

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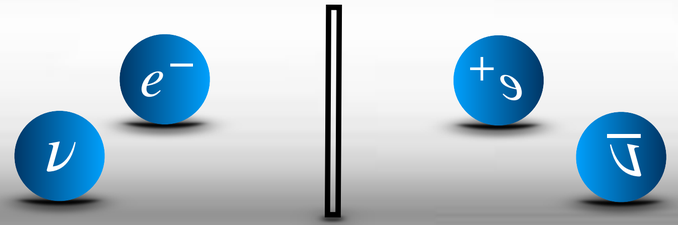
To be or not to be:

neutrinos had the answer all along



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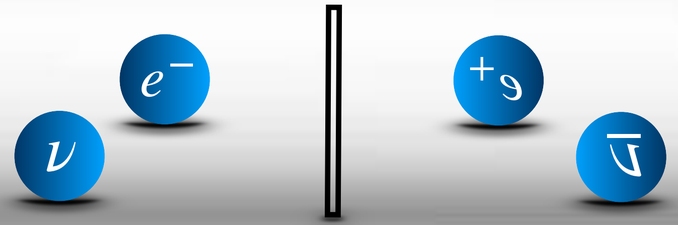
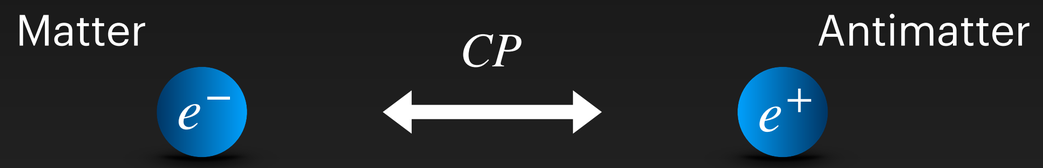


Around 2030 — 2035

The Matter-Antimatter Asymmetry



This symmetry is called Charge-Parity symmetry, or CP for short,
and **it should be broken in Nature**.

The Matter-Antimatter Asymmetry

This symmetry is CP for short,
a

The Matter-Antimatter Asymmetry

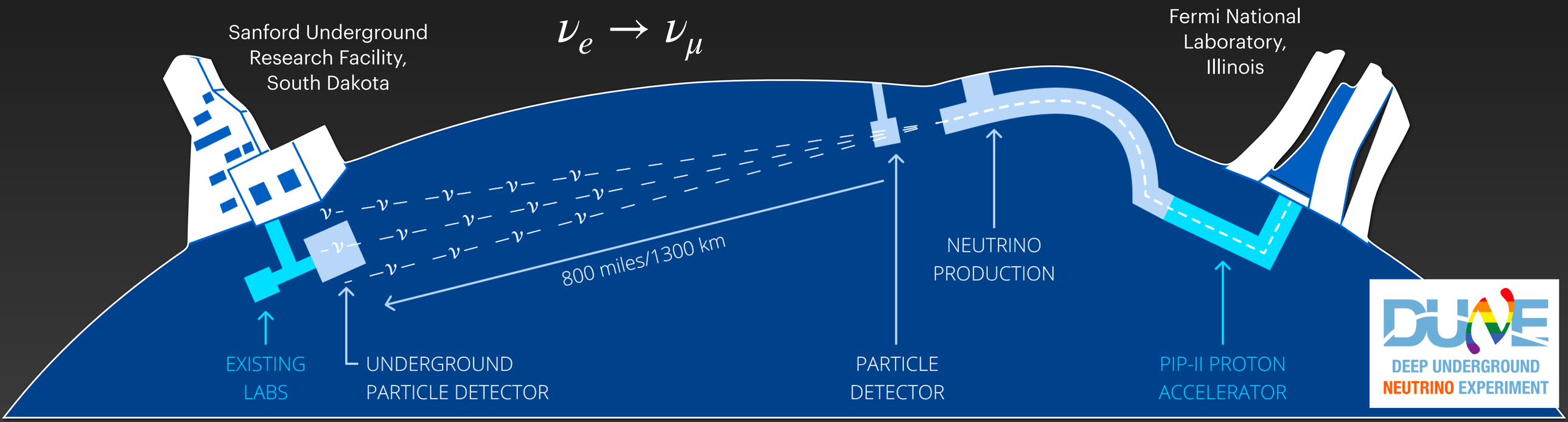
$$\nu_e \to \nu_\mu \quad \overset{\not{CP}}{\neq} \quad \bar{\nu}_e \to \bar{\nu}_\mu$$

Antineutrinos and neutrinos can mix among themselves differently.

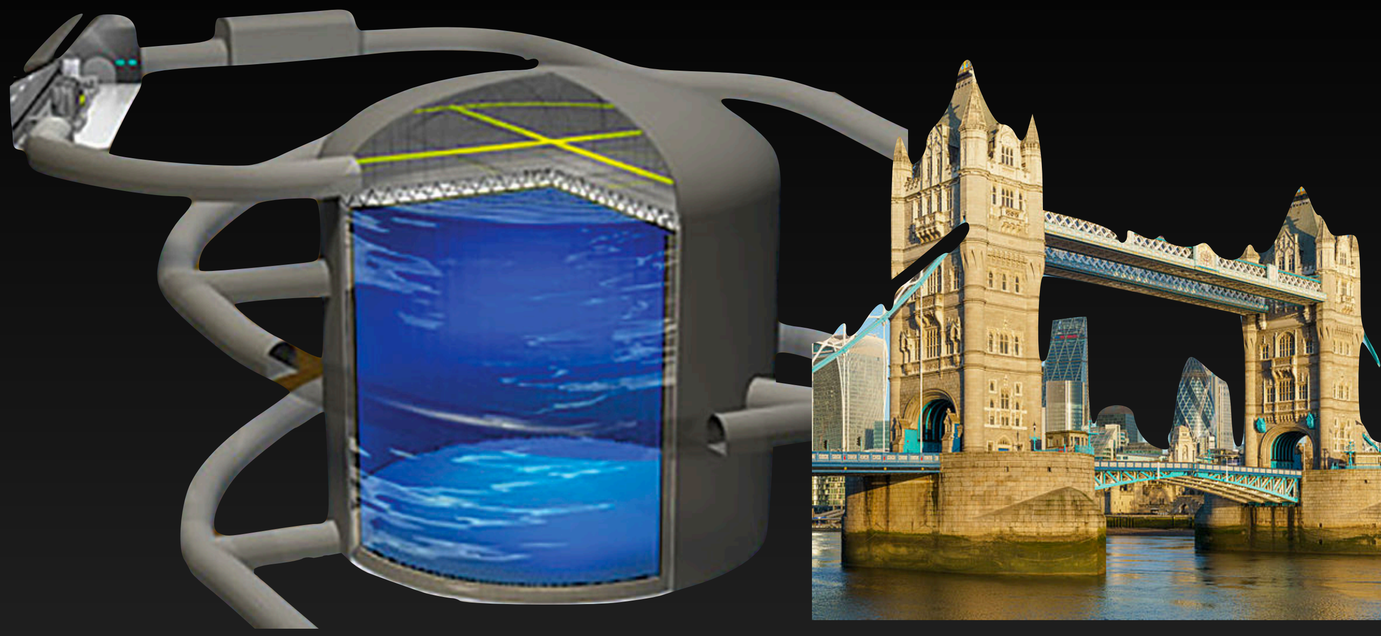
This difference can lead to a preferential treatment of the matter in the early Universe

DUNE

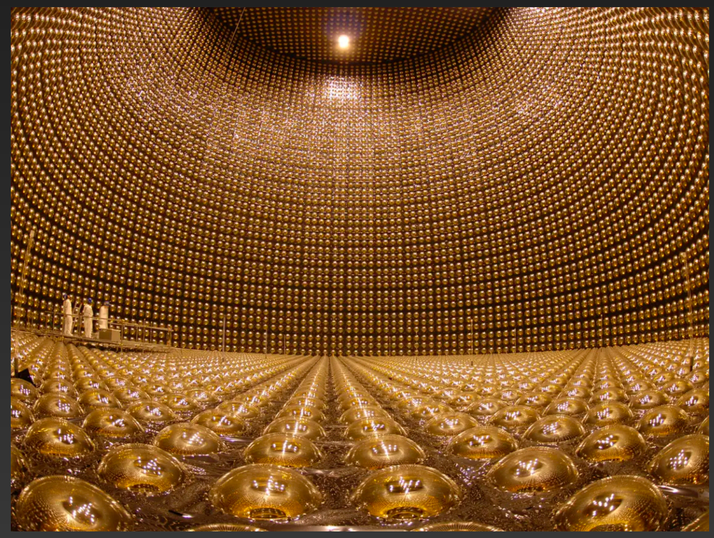
- Deep Underground Neutrino Experiment



Hyper-Kamiokande



- Water tank of 75 m diameter, 60 m tall.
- 295 km between Tokay and the Kamioka mine.
- 250 kilotonnes of water.



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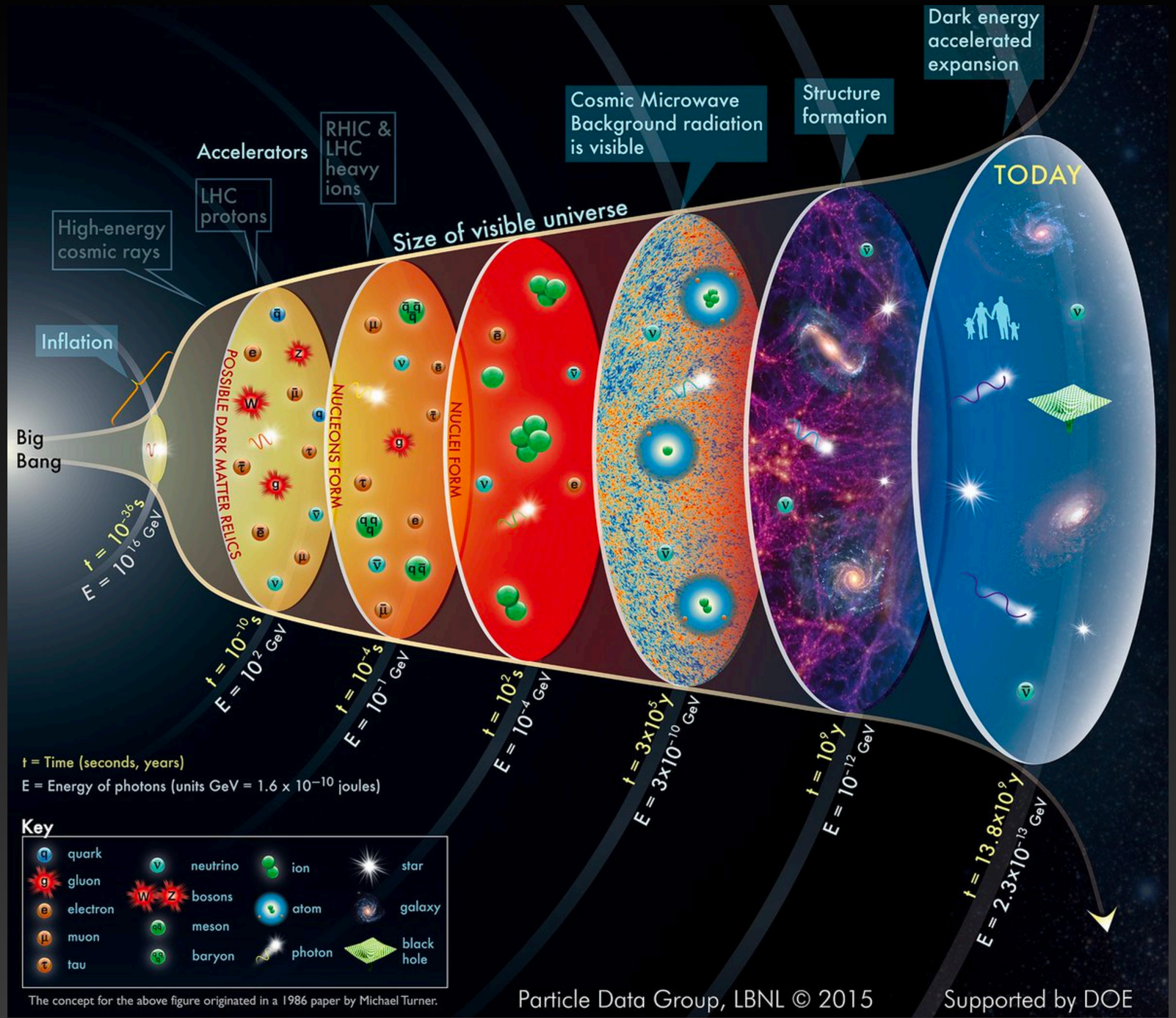
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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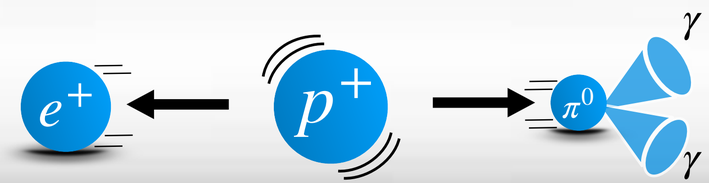
New evidence for the grand unification of all forces: physicists see a proton decay



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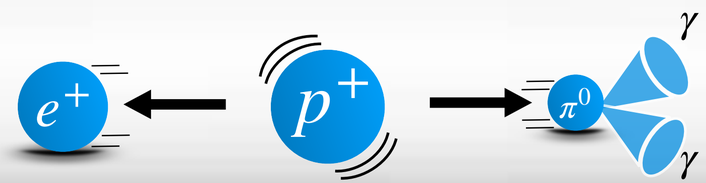


Later than 2030. But possibly never.

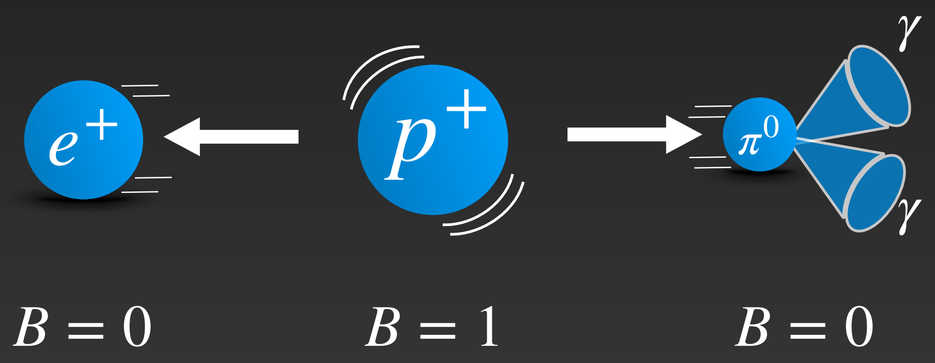
Proton decay

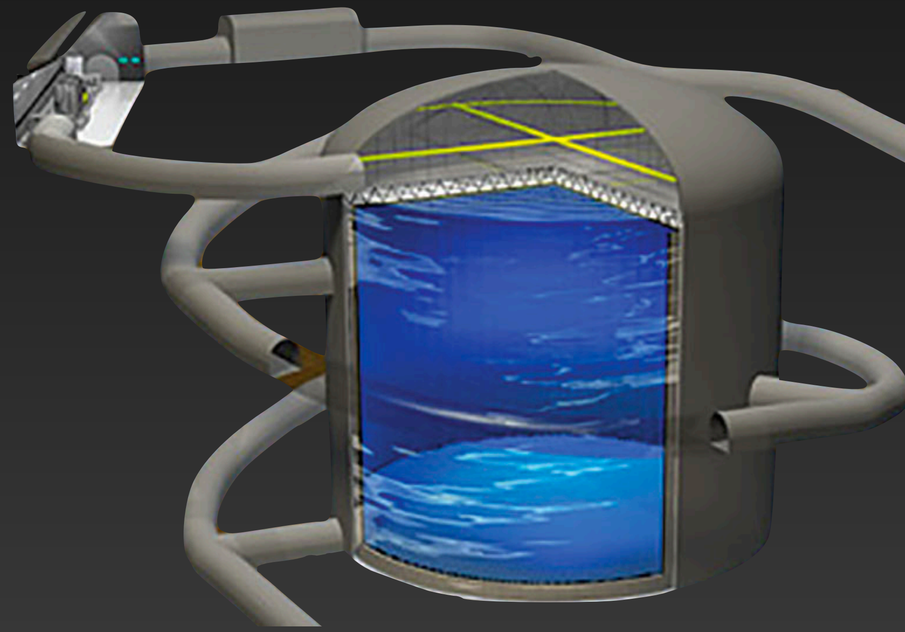
Heavier particles usually decay to less massive particles via one of the four fundamental forces of nature.

The proton is not even a fundamental particle, so why should it remain stable?

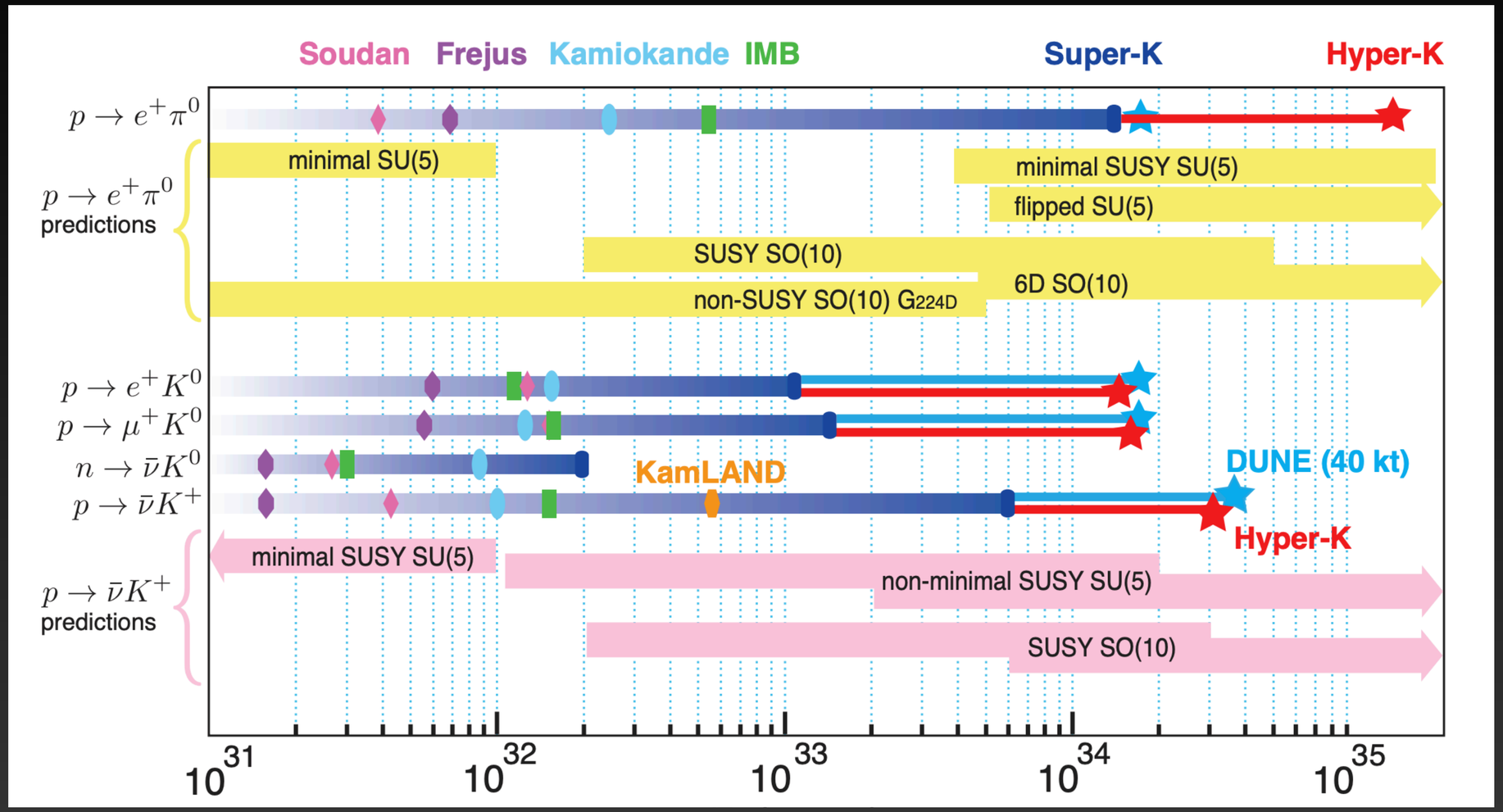
More than 10^{35} protons

Symmetry: **Conservation of Baryon Number**

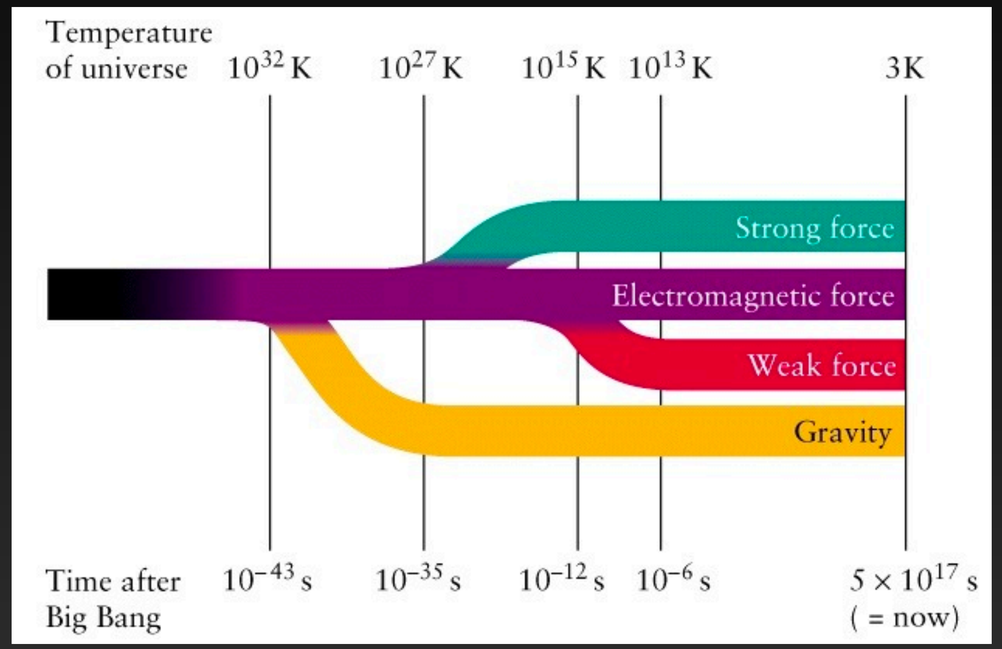




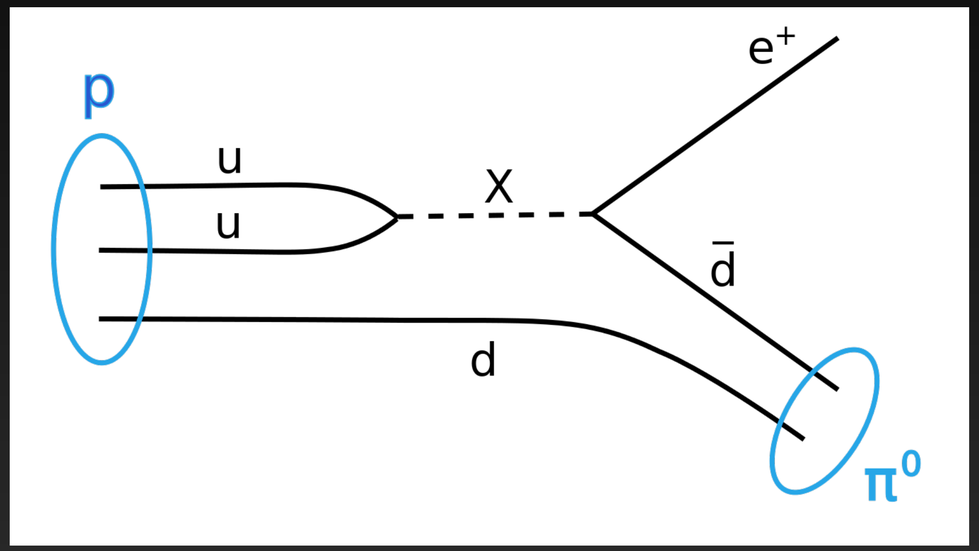
Proton decay



Proton decay



Fundamental forces could unify into a single force at very high energies.



The new force carriers can violate Baryon number conservation.

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This new particle could make up

85% of the matter in our Universe.

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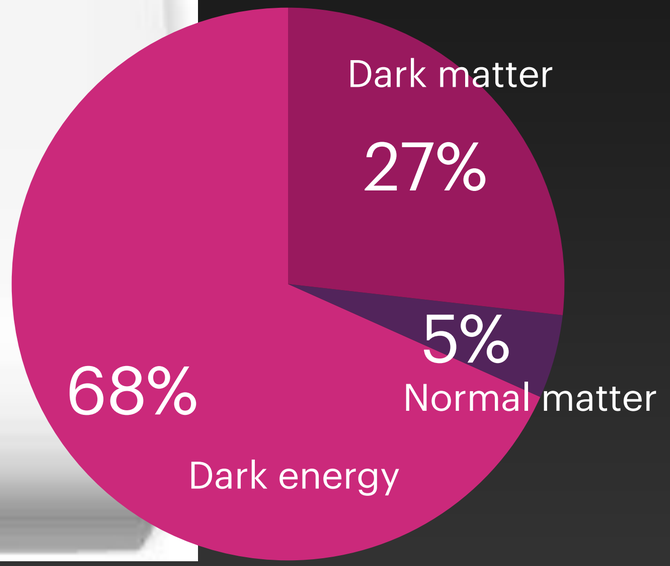
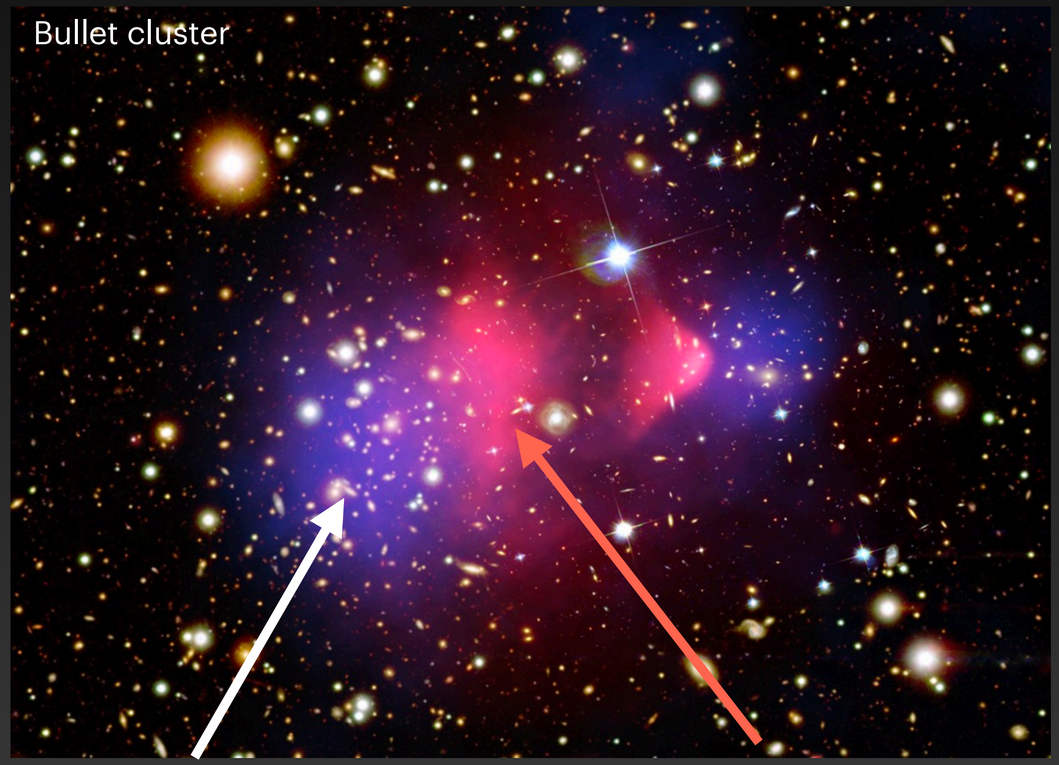


Likely to be found at some point, but we cannot rule out that it is truly **invisible**.

Dark Matter detection



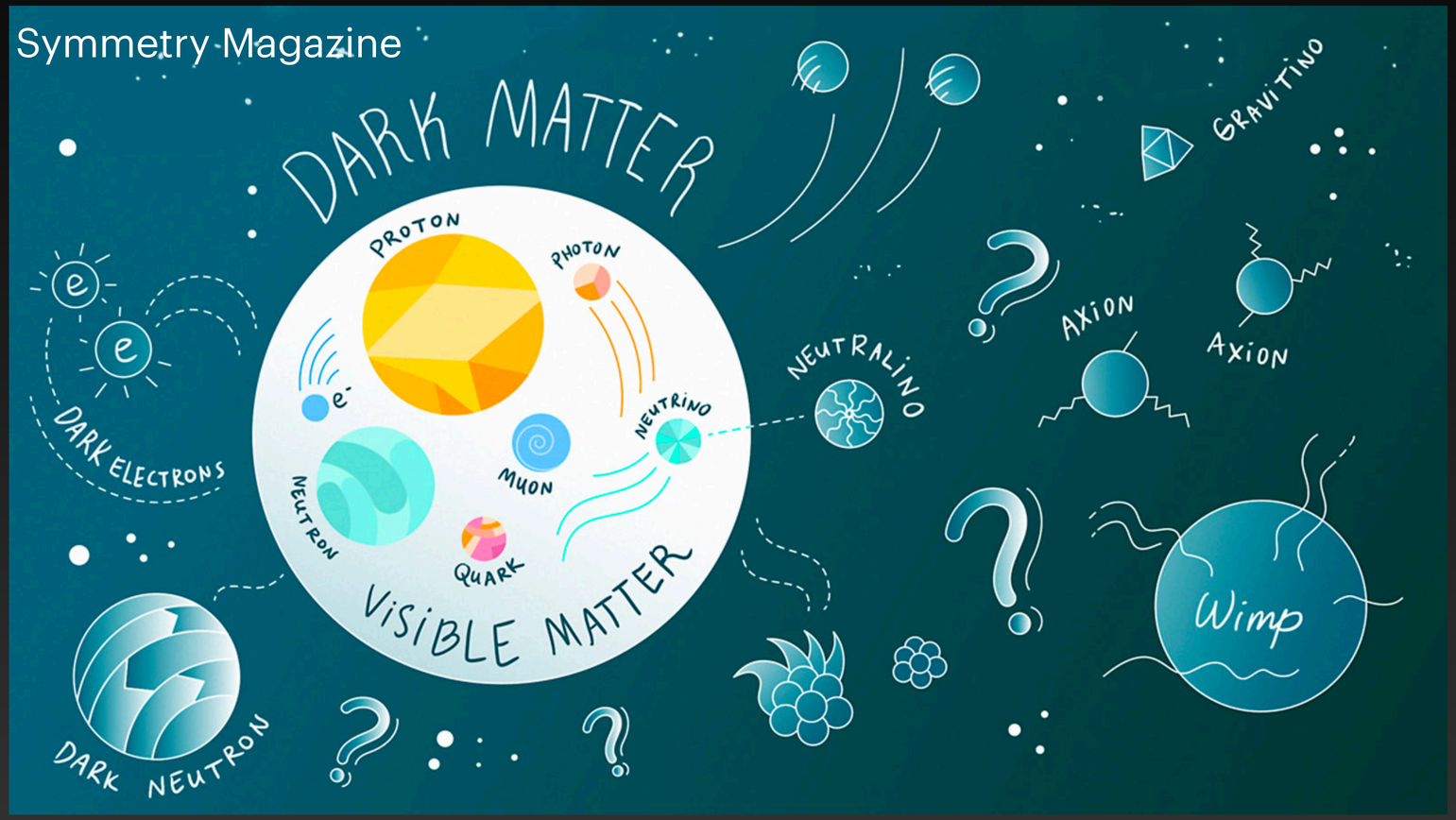
Dark (Inert) matter

Ordinary matter

We are (very noisy) guests

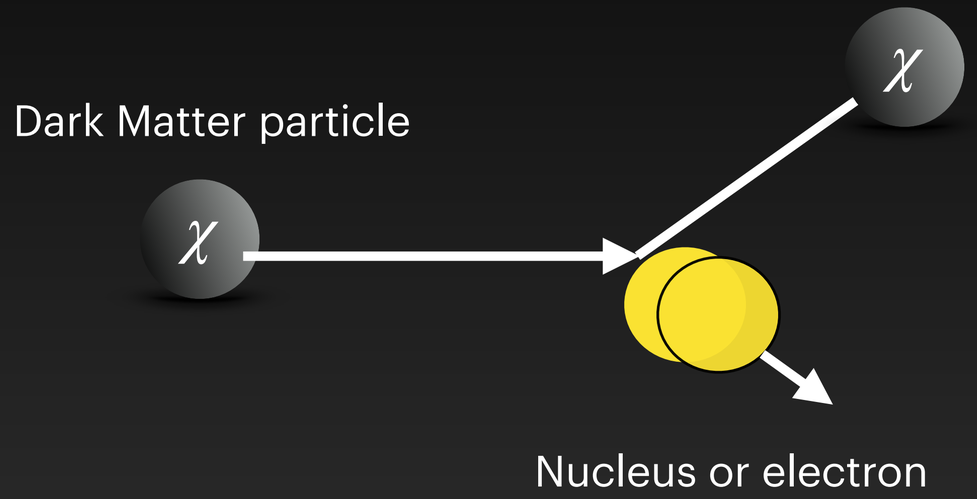
in a quiet dark matter halo

Dark Matter detection

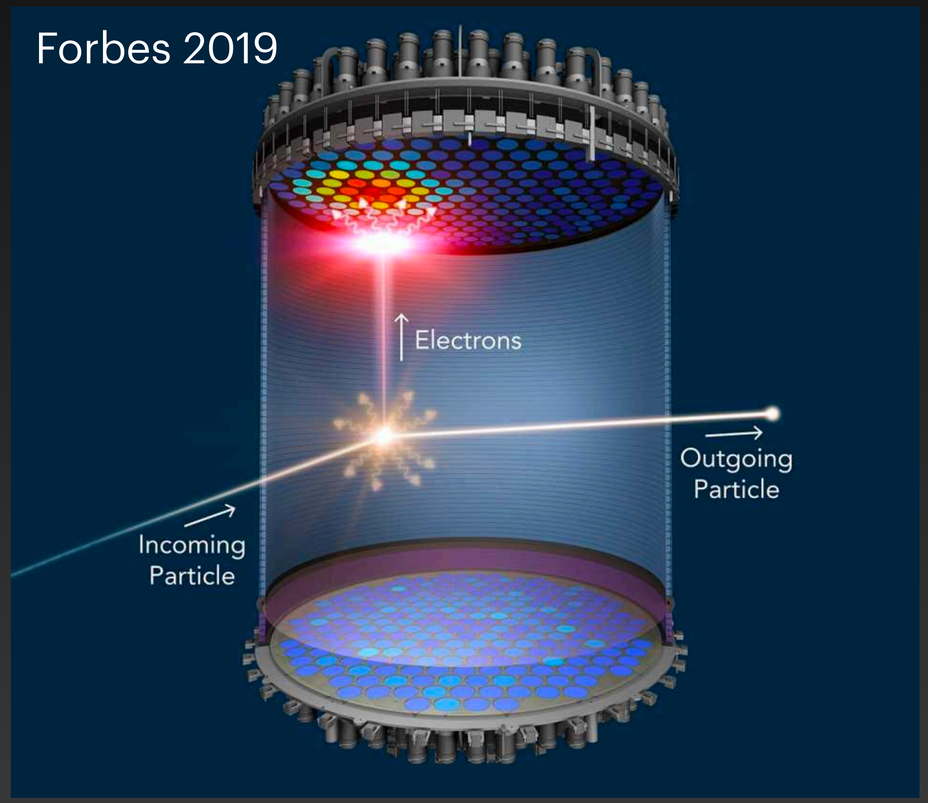


We have good reason to believe that it is made up of a new ”inert” type of particle. We just don’t know what it is.

Dark Matter detection



Very quiet detectors deep underground waiting for dark matter particles to create some kind of signal inside their volume.



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10.10.2023 № 7624177203

Physicists find a fifth force in Nature in the mysterious wiggle of the muon.

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Physicists find a fifth force in Nature
in the mysterious wiggle of the muon.

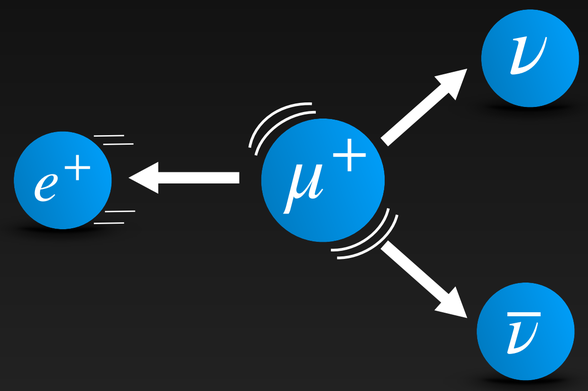
If we have done our calculations right, probably by the end of this decade.

The muon anomalous magnetic moment

Muons are a heavier version of the electron.

S

B



The muon anomalous magnetic moment

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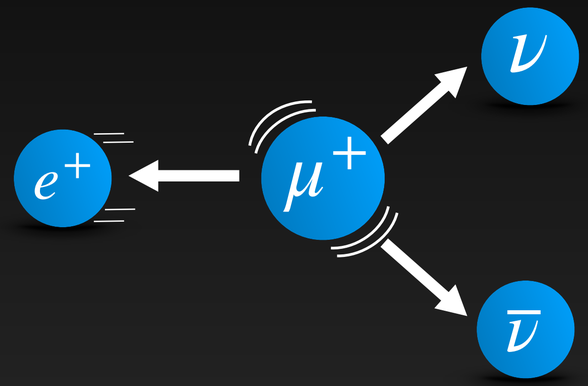
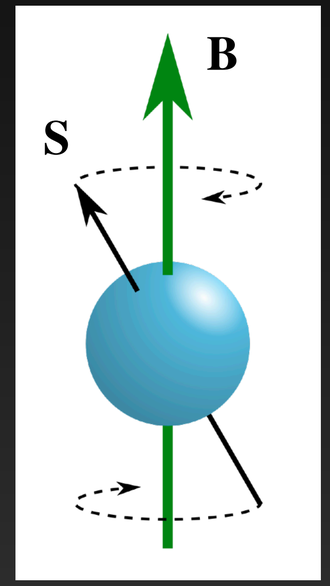


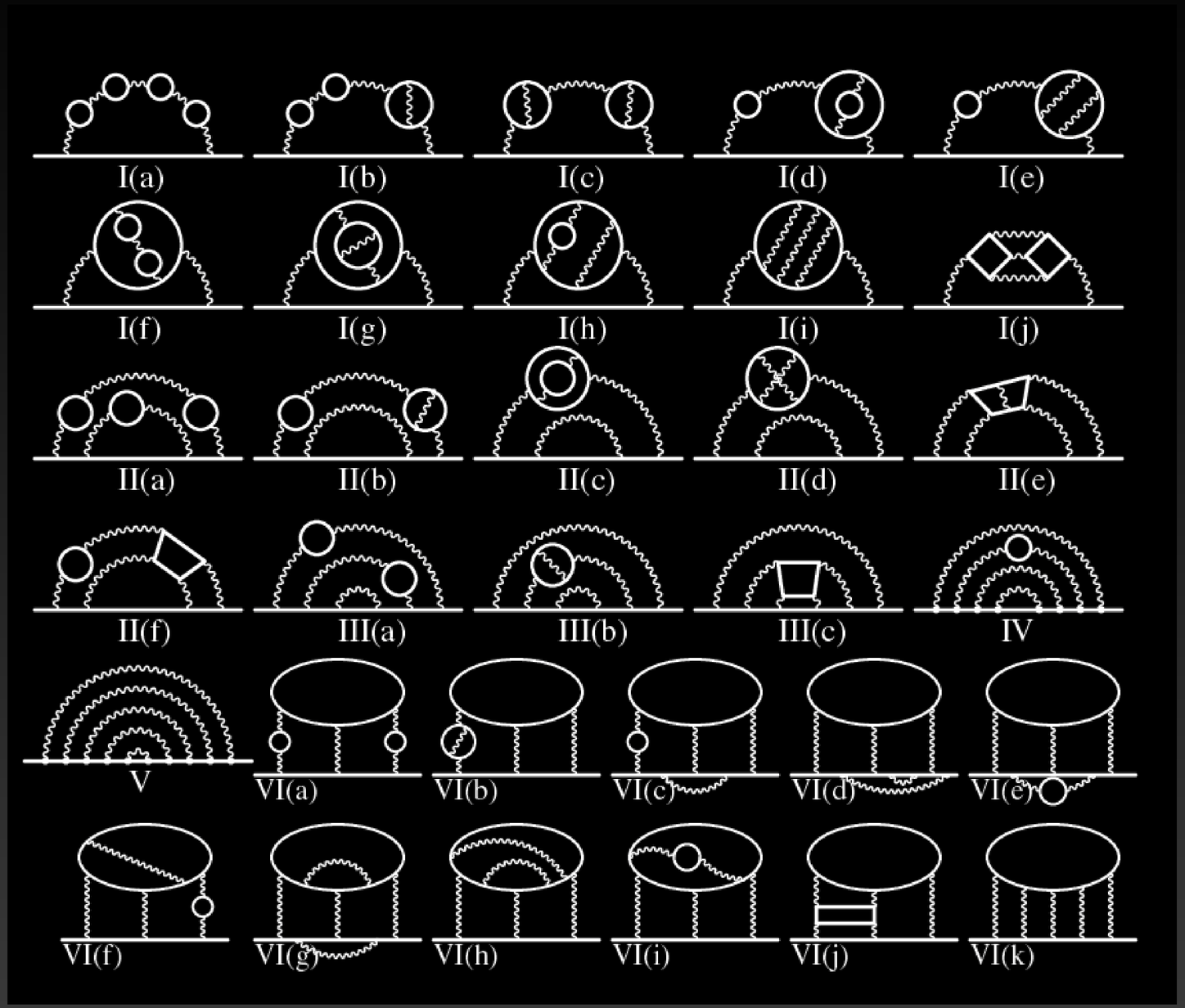


Just like any charged particle, they have (quantum) spin, and react to a magnetic field according to their **magnetic dipole moment**.

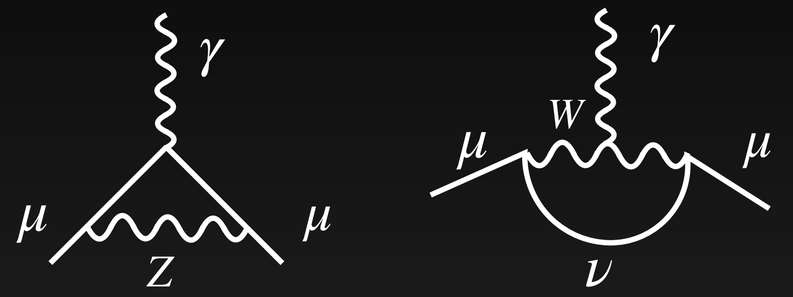
$$\mu_\mu = g\frac{q}{2m}\mathbf{S}$$

g is very close to 2 for leptons, except for very small quantum effects.

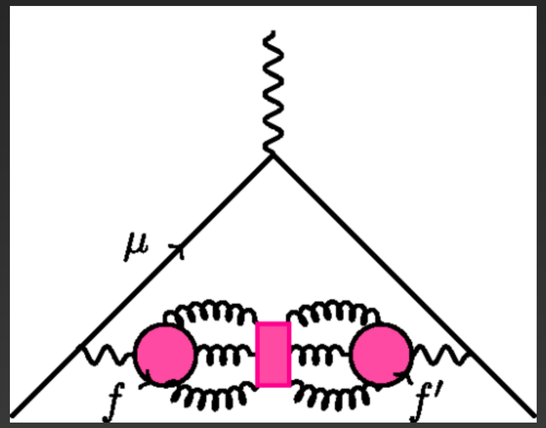
Quantum Electrodynamics
Electromagnetism (10th order)



Electroweak force



Quantum Chromodynamics (Strong force)



The muon anomalous magnetic moment

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP,\,LO}} + a_\mu^{\mathrm{HVP,\,NLO}} + a_\mu^{\mathrm{HVP,\,NNLO}} + a_\mu^{\mathrm{HLbL}} + a_\mu^{\mathrm{HLbL,\,NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

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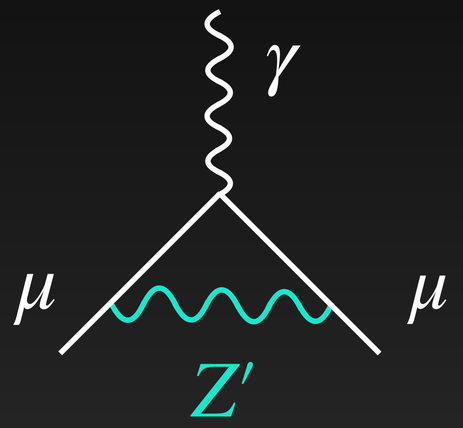
$$a_\mu^{\mathrm{EXP}} = 116592061(41) \times 10^{-11}$$

The disagreement happens at the 11th digit after the decimal point.

Are we missing a new quantum correction from new forces?

A fifth muonic force



$$\Delta a_\mu = \frac{g'^2}{16\pi}\frac{m_\mu^2}{M_{Z'}^2}$$

$$\frac{M_{Z'}}{g'} < 100\, m_p$$

We hope to observe it directly at LHC, DUNE, or HK.

This would mean that muons are fundamentally different from electrons.

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Death of a nearby star makes neutrino detectors light up around the world

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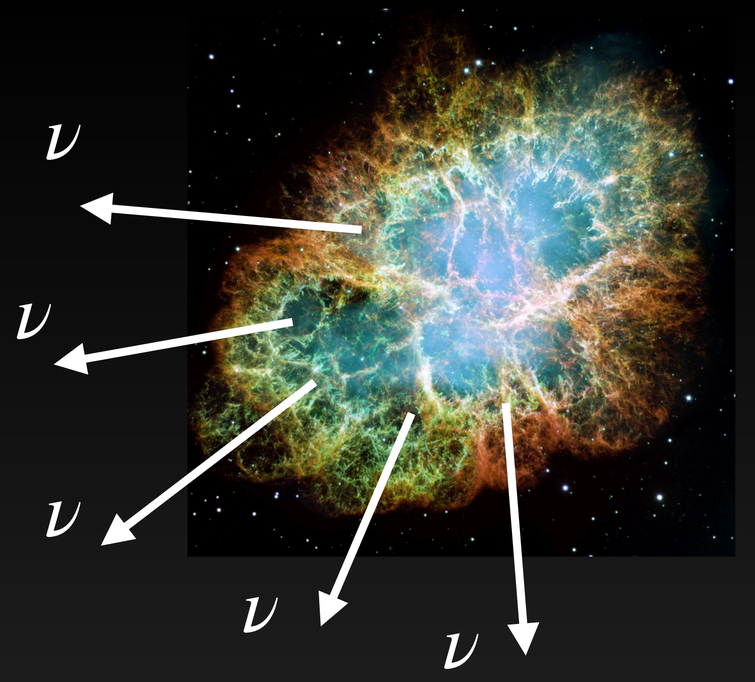
Death of a nearby star makes neutrino detectors light up around the world

Any day now.

Supernova neutrinos

- A nearby supernova explosion would emit a tremendous amount of neutrinos.

- Large-scale detectors would observe hundreds or thousands of these neutrinos, and tell us about the physics of stellar collapse as well as about fundamental properties of neutrinos, like their mass differences and potentially their decay.



See George Fuller’s talk.

Summary

1) To or not to be: neutrinos tell us the answer

    CP violation — matter-antimatter asymmetry

2) New evidence for the grand unification of all forces: physicists see a proton decay.

    The unification of all forces in Nature?

3) This new particle could make up 85% of the matter in our Universe.

    Origin of dark matter.

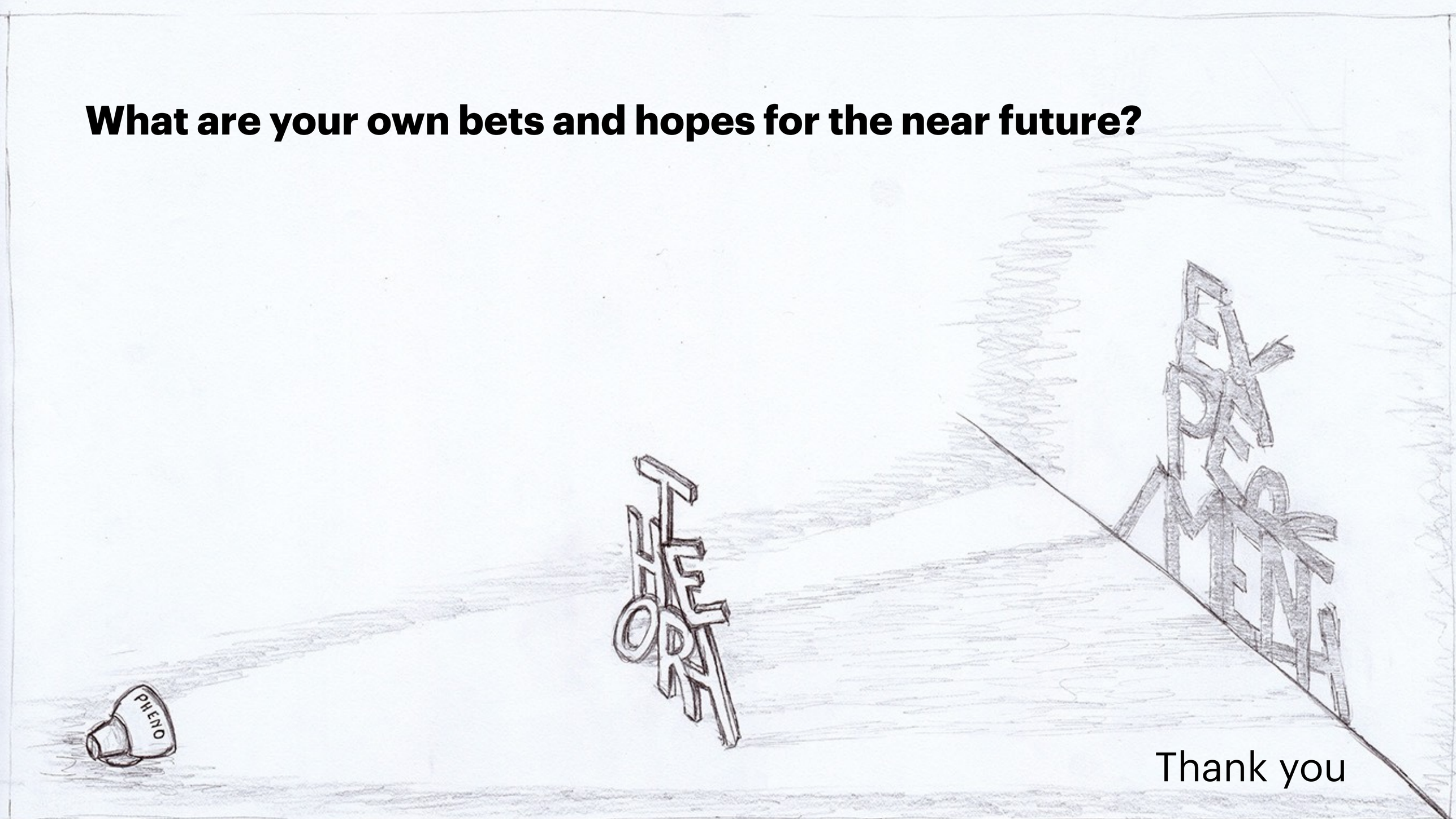
4) Physicists find a fifth force in Nature in the mysterious wiggle of the muon.

    Muons are different, for some reason.

5) Death of a nearby star makes neutrino detectors light up around the world.

    As exciting as it gets for neutrino astronomy.

What are your own bets and hopes for the near future?



Thank you