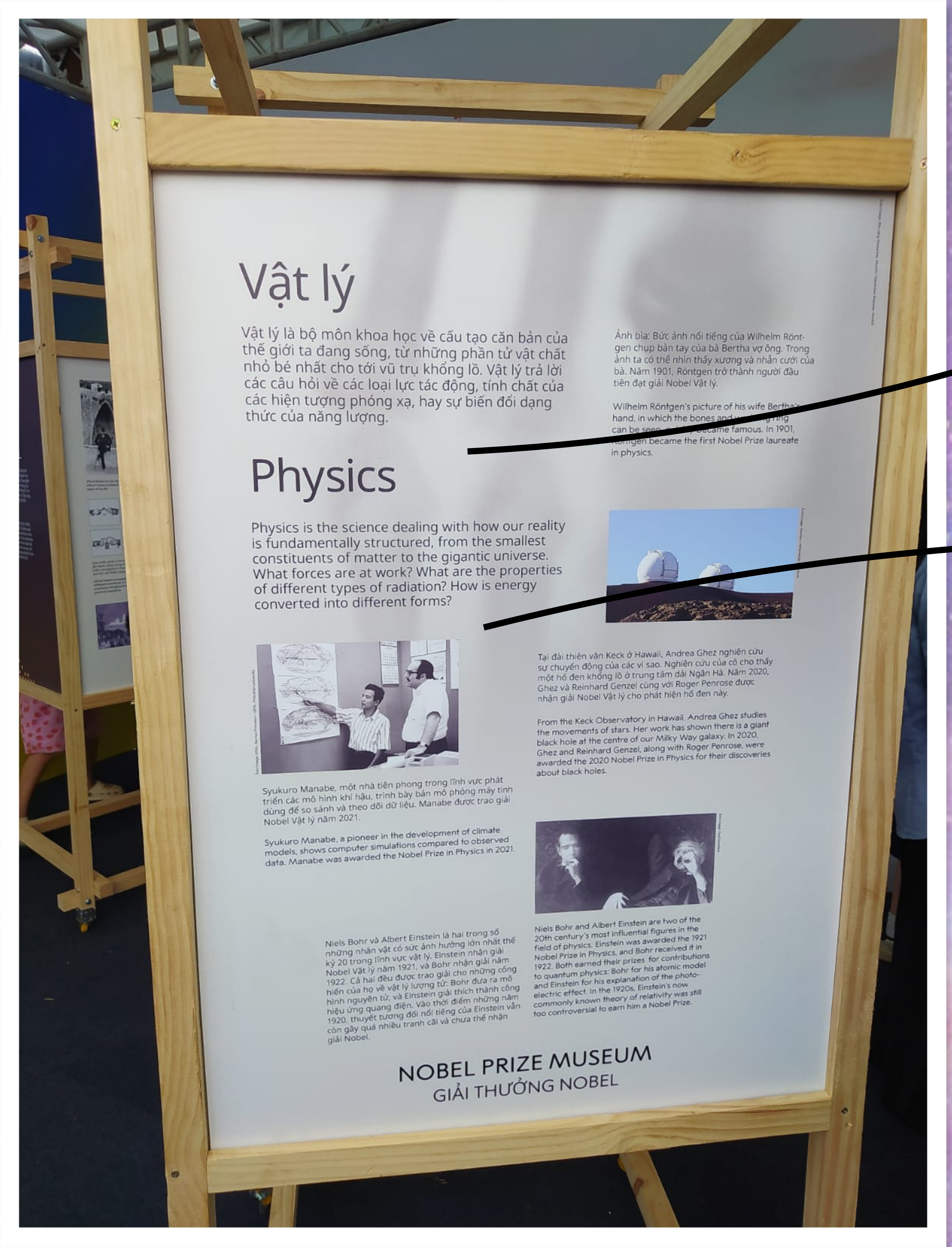
High-Energy Physics from a Theoretical Perspective: Major Results, Recent Results & Future Projects

Milada Margarete Mühlleitner, KIT

Phenikaa International Physics
Conference 2025:
Celebrating 100 years of
quantum physics
13-15 October 2025

Outline



Vật lý

Vật lý là bộ môn khoa học về cấu tạo căn bản của thế giới ta đang sống, từ những phần tử vật chất nhỏ bé nhất cho tới vũ trụ khổng lồ. Vật lý trả lời các câu hỏi về các loại lực tác động, tính chất của các hiện tượng phóng xạ, hay sự biến đổi dạng thức của năng lượng.

Ảnh bìa: Bức ảnh nổi tiếng của Wilhelm Röntgen chụp bàn tay của bà Bertha vợ ông. Trong ảnh ta có thể nhìn thấy xương và nhẫn cưới của bà. Năm 1901, Röntgen trở thành người đầu tiên đạt giải Nobel Vật lý.

Wilhelm Röntgen's picture of his wife Bertha's hand, in which the bones and wedding ring can be seen, [illegible] became famous. In 1901, Röntgen became the first Nobel Prize laureate in physics.

Physics

Physics is the science dealing with how our reality is fundamentally structured, from the smallest constituents of matter to the gigantic universe. What forces are at work? What are the properties of different types of radiation? How is energy converted into different forms?

Tại đài thiên văn Keck ở Hawaii, Andrea Ghez nghiên cứu sự chuyển động của các vì sao. Nghiên cứu của cô cho thấy một hố đen khổng lồ ở trung tâm dải Ngân Hà. Năm 2020, Ghez và Reinhard Genzel cùng với Roger Penrose được nhận giải Nobel Vật lý cho phát hiện hố đen này.

From the Keck Observatory in Hawaii, Andrea Ghez studies the movements of stars. Her work has shown there is a giant black hole at the centre of our Milky Way galaxy. In 2020, Ghez and Reinhard Genzel, along with Roger Penrose, were awarded the 2020 Nobel Prize in Physics for their discoveries about black holes.

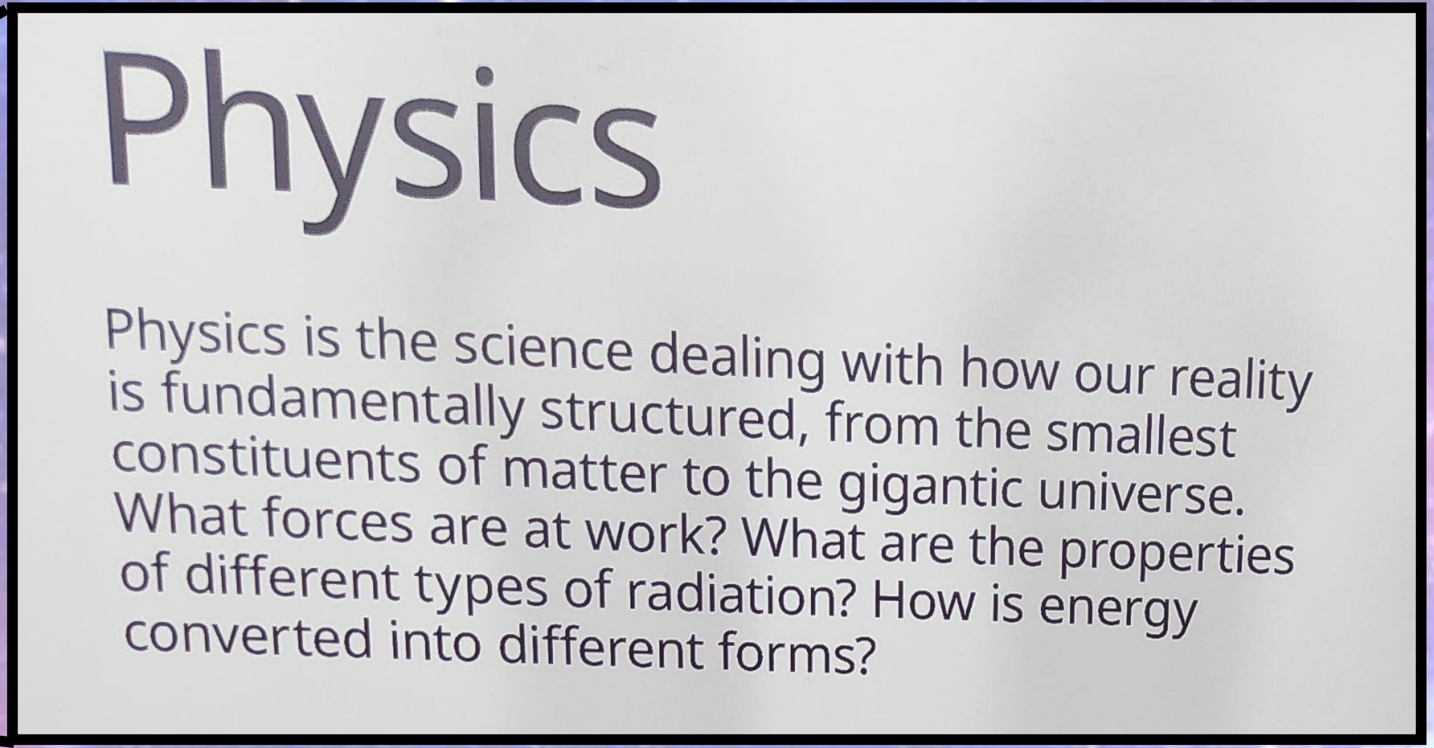
Syukuro Manabe, một nhà tiên phong trong lĩnh vực phát triển các mô hình khí hậu, trình bày bản mô phỏng máy tính dùng để so sánh và theo dõi dữ liệu. Manabe được trao giải Nobel Vật lý năm 2021.

Syukuro Manabe, a pioneer in the development of climate models, shows computer simulations compared to observed data. Manabe was awarded the Nobel Prize in Physics in 2021.

Niels Bohr và Albert Einstein là hai trong số những nhân vật có sức ảnh hưởng lớn nhất thế kỷ 20 trong lĩnh vực vật lý. Einstein nhận giải Nobel Vật lý năm 1921, và Bohr nhận giải năm 1922. Cả hai đều được trao giải cho những cống hiến của họ về vật lý lượng tử: Bohr đưa ra mô hình nguyên tử, và Einstein giải thích thành công hiệu ứng quang điện. Vào thời điểm những năm 1920, thuyết tương đối nổi tiếng của Einstein vẫn còn gây quá nhiều tranh cãi và chưa thể nhận giải Nobel.

Niels Bohr and Albert Einstein are two of the 20th century's most influential figures in the field of physics. Einstein was awarded the 1921 Nobel Prize in Physics, and Bohr received it in 1922. Both earned their prizes for contributions to quantum physics: Bohr for his atomic model and Einstein for his explanation of the photoelectric effect. In the 1920s, Einstein's now commonly known theory of relativity was still too controversial to earn him a Nobel Prize.

NOBEL PRIZE MUSEUM
GIẢI THƯỞNG NOBEL



Physics

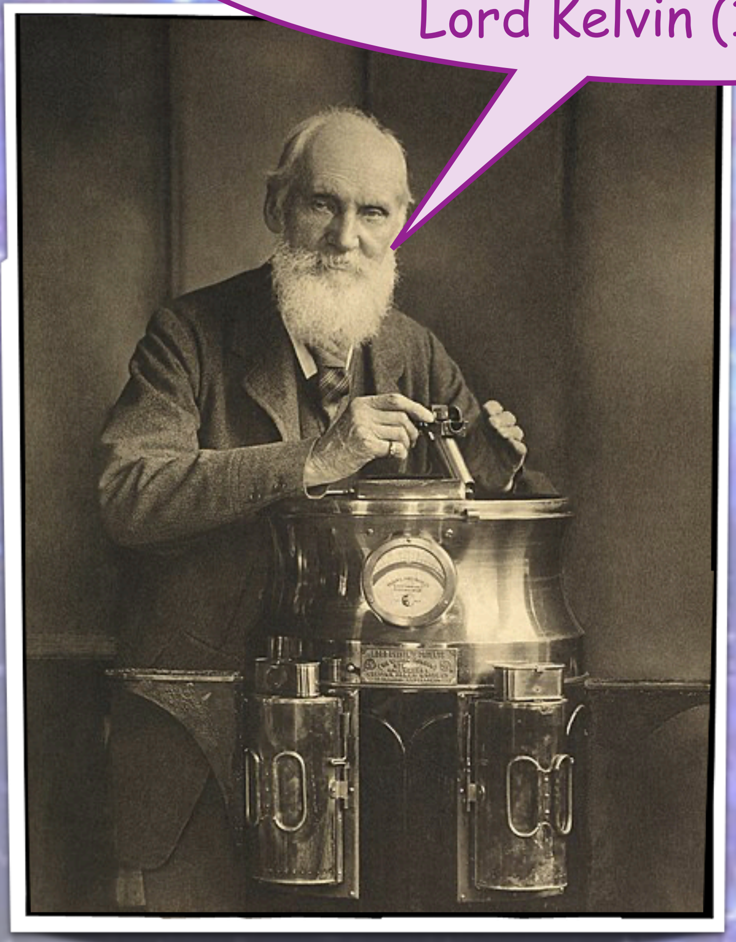
Physics is the science dealing with how our reality is fundamentally structured, from the smallest constituents of matter to the gigantic universe. What forces are at work? What are the properties of different types of radiation? How is energy converted into different forms?

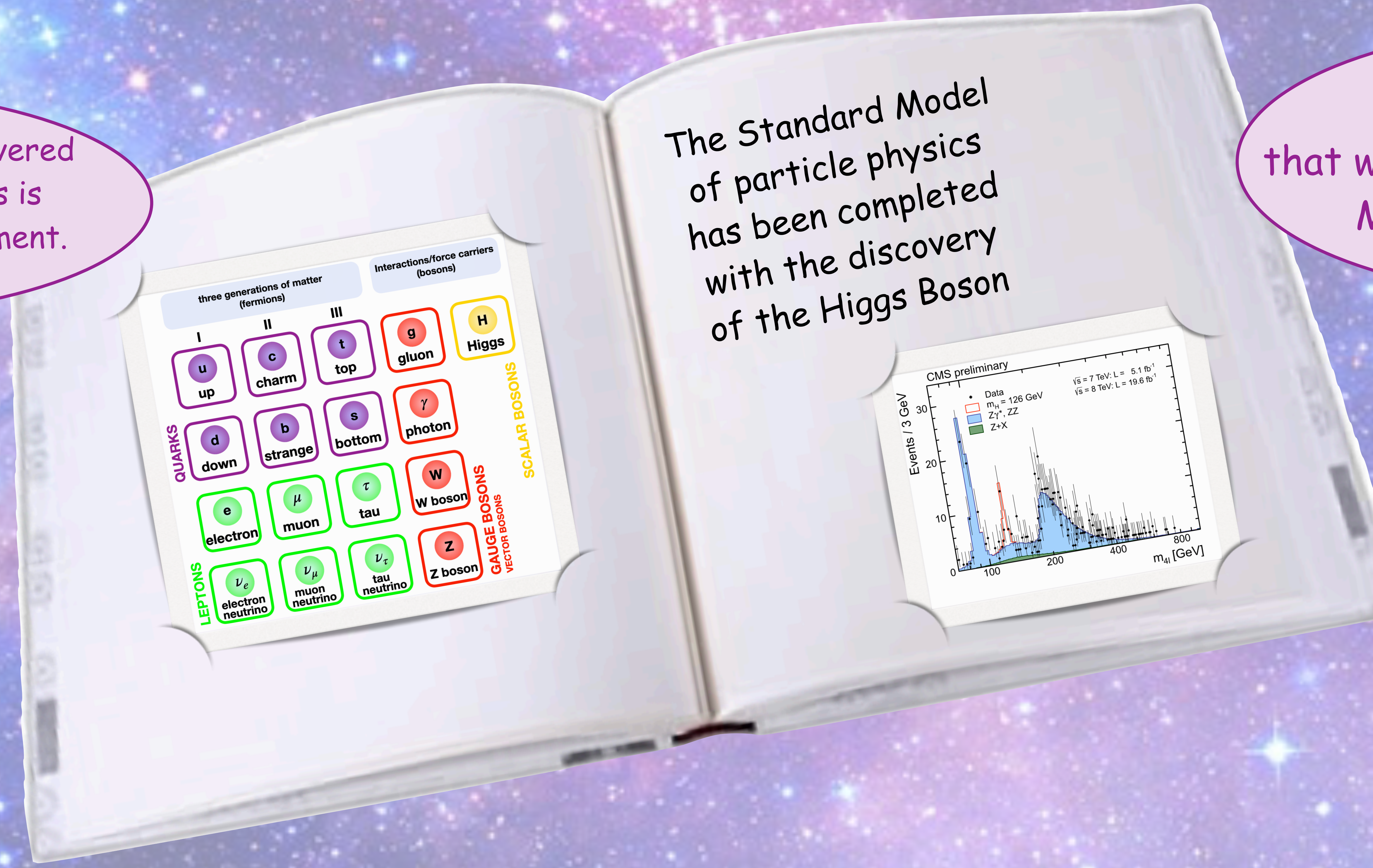
Photo taken at the
World Culture Festival 2025
in Hanoi, Vietnam

Outline

This talk is about the mankind's most fundamental questions:
How did the Universe start, how did it develop?
What is it made of? What are the building blocs of matter?
What are the forces to hold them together?

There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.
Lord Kelvin (1824-1907)





The Standard Model of particle physics has been completed with the discovery of the Higgs Boson

The most important is that we never stop asking questions.
Madame Curie, 1867-1934

The Quantum Legacy in Particle Physics

100 Years of Quantum Mechanics

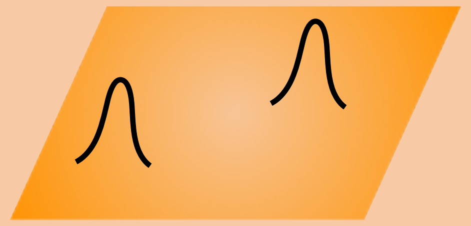
100 Years of Quantum Mechanics

Deep Connection of Quantum Mechanics & Particle Physics

Quantum Mechanics
delivers the framework
for the exploration of the
elementary particles and the
fundamental forces between them

Basics of modern particle physics:
Quantum Field Theory (QFT)

- **quantisation** of the **fields**
- particles: **quantum excitations** of the fields
- integrating special relativity

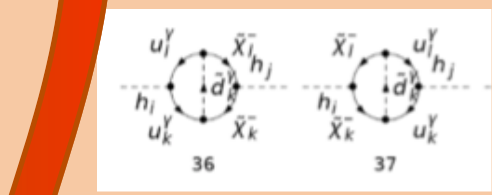


Manifestations of quantum physics

Quantum fluctuations omnipresent in the particle world and testable in high-precision experiments

Symmetries: guiding principle for the formulation of the QFT explaining nature

Symmetries must also hold at the **quantum level**: powerful tool for consistency tests



The Standard Model of Particle Physics

University of Glasgow | Particle Physics Theory

Have you asked any big questions today?

Where is all the antimatter?

What is our universe made of?

What happened in the Big Bang?

Is the universe supersymmetric?

Why are neutrinos so light?

What is Dark Matter?

Can we understand quark bound states?

What are the Higgs Boson's properties?

How is antimatter different from matter?

What will we find at the 14TeV Large Hadron Collider ?

What is Dark Energy?

Are there extra dimensions?

What is beyond the Standard Model?

What are the forces of nature?

What is the origin of mass?

Why are there three generations?

What are the symmetries of the universe?

Is gravity related to the other forces?

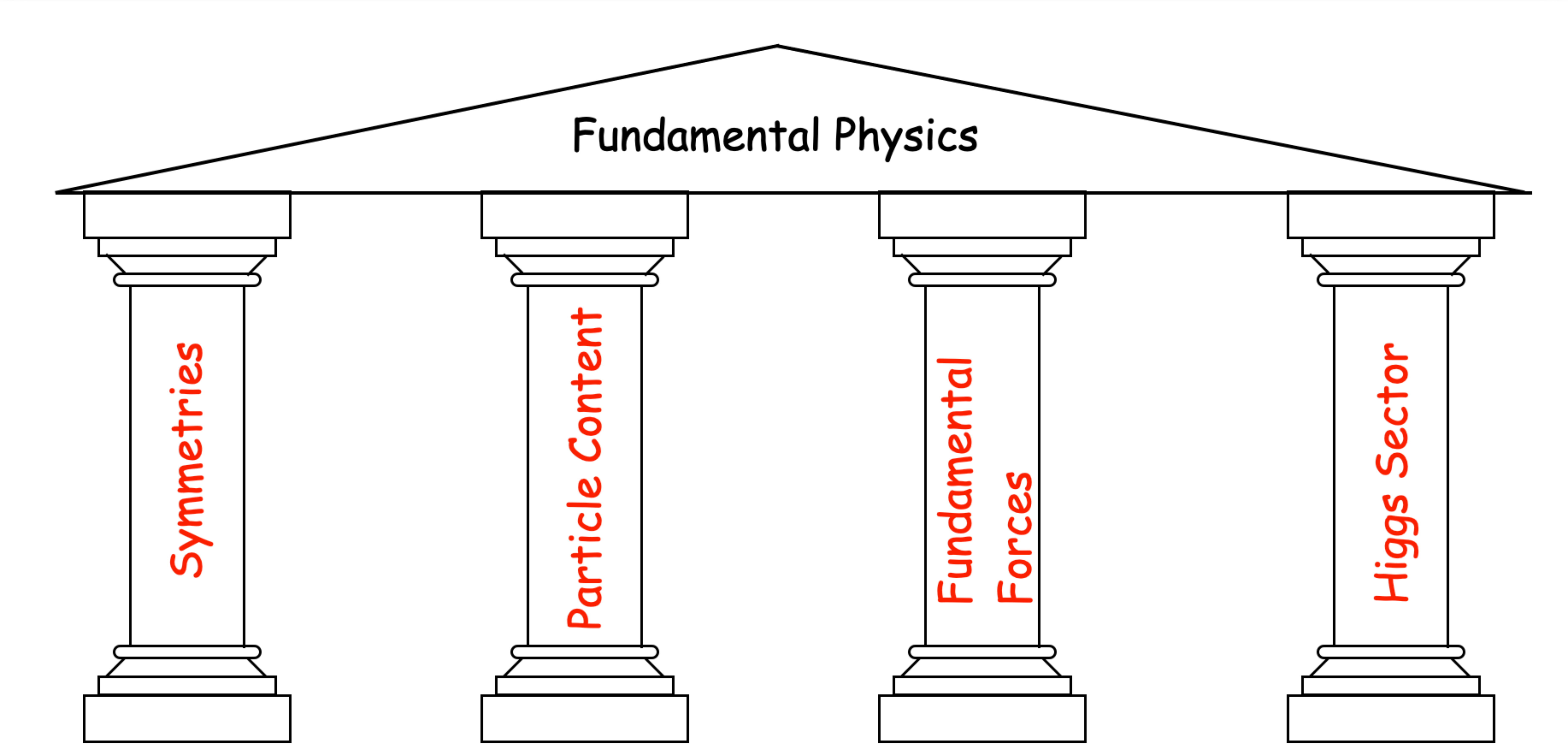
Are neutrinos their own antiparticle?

Why is the top quark so heavy?

It is a miracle that curiosity survives formal education.
Albert Einstein (1879-1955)

The Standard Model of Particle Physics in a Nutshell

Describes today known fundamental building blocs of matter
and the fundamental forces acting between them (except for gravity)



Particle Content

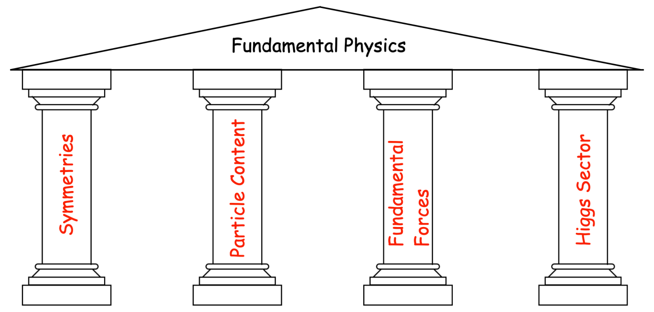
- Particle Content: Matter particles and interaction particles

Matter Particles

u	c	t	Quarks
d	s	b	
ν(e)	ν(μ)	ν(τ)	Leptons
e	μ	τ	
1	2	3	Families

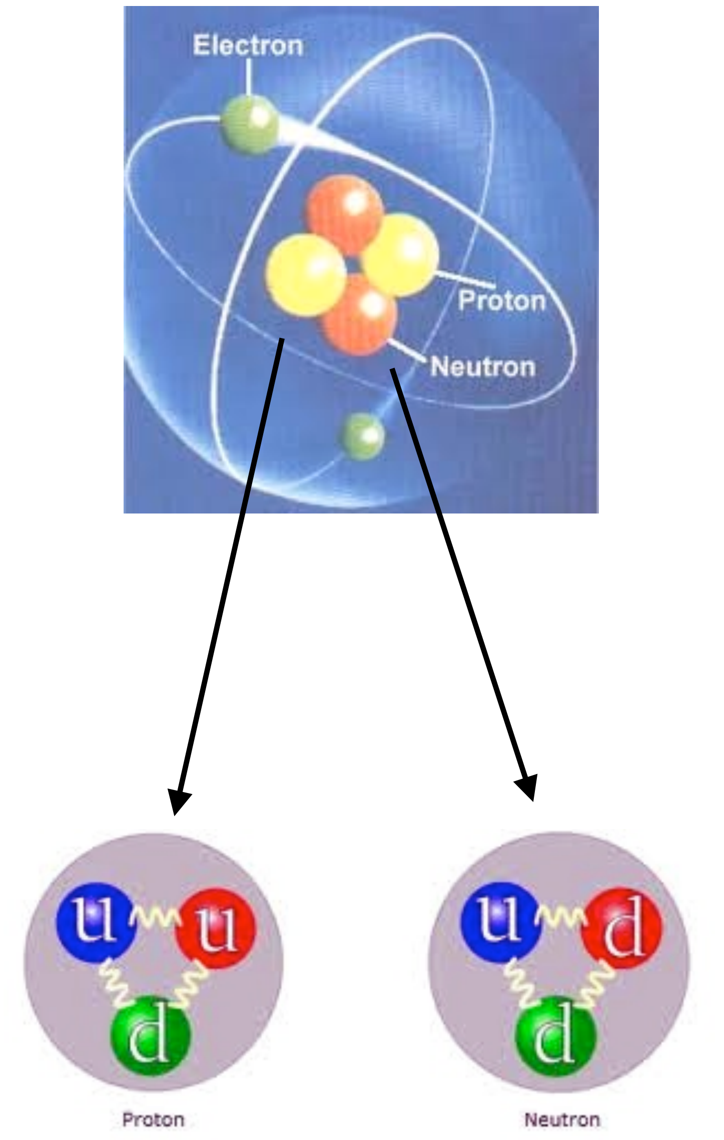
What is our Universe made of?

Why are the mass values as they are?



Particle Content

❖ Particle Content: Matter particles and interaction particles



Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

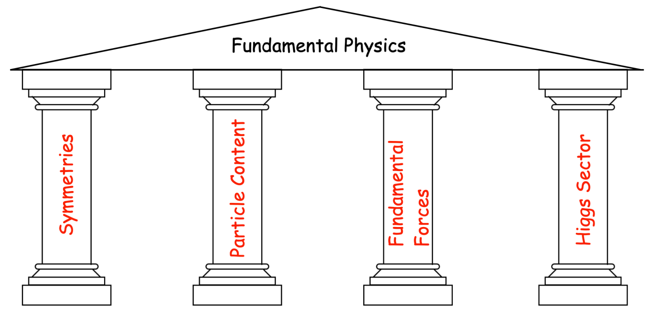
Ordinary Matter

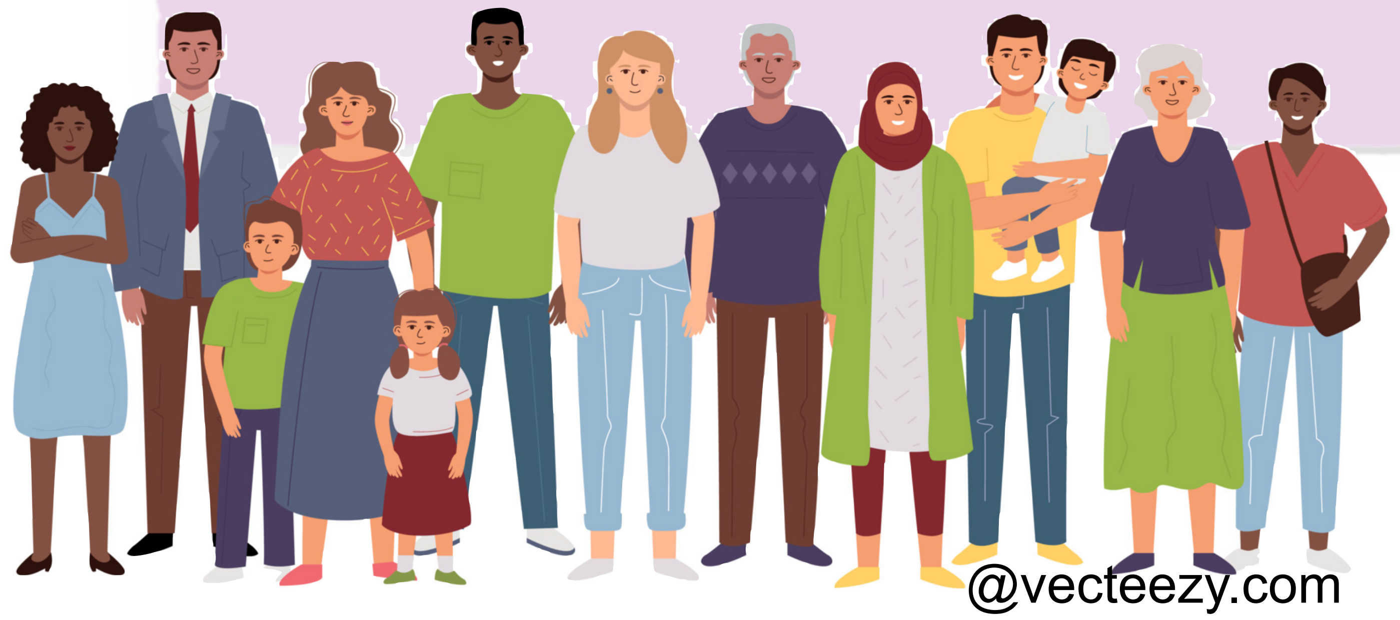
Matter Particles

u	c	t	Quarks
d	s	b	
ν(e)	ν(μ)	ν(τ)	Leptons
e	μ	τ	
1	2	3	Families

What is our Universe made of?

Why are the mass values as they are?

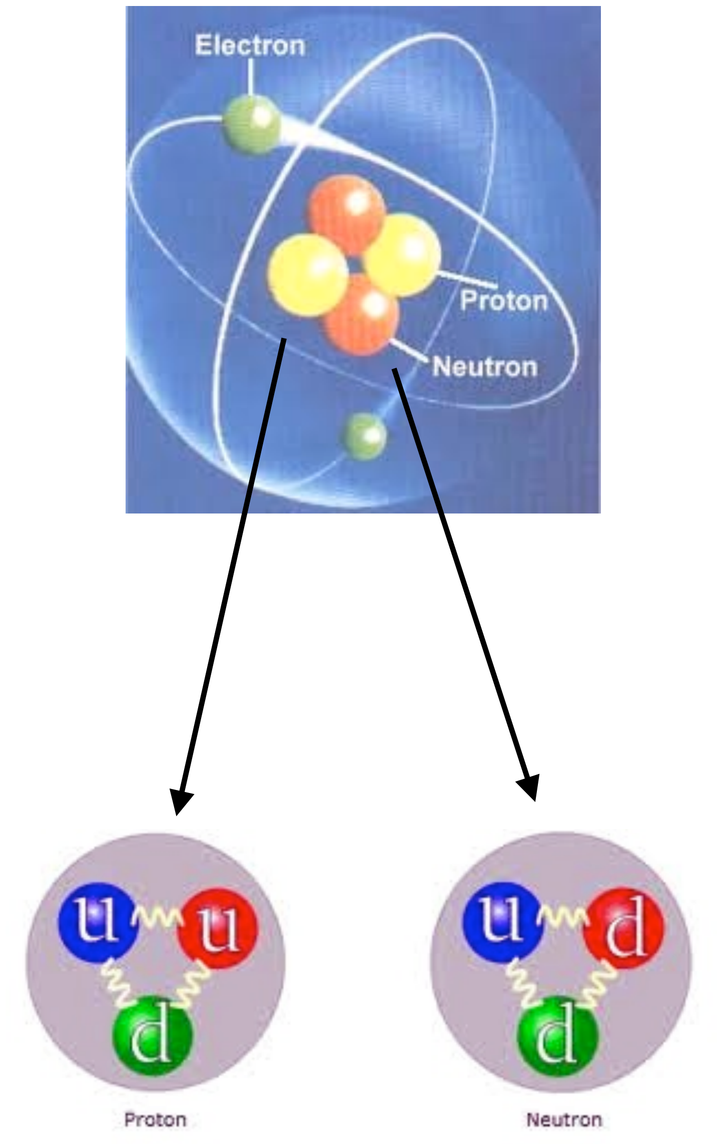




@vecteezy.com

Particle Content

❖ Particle Content: Matter partic

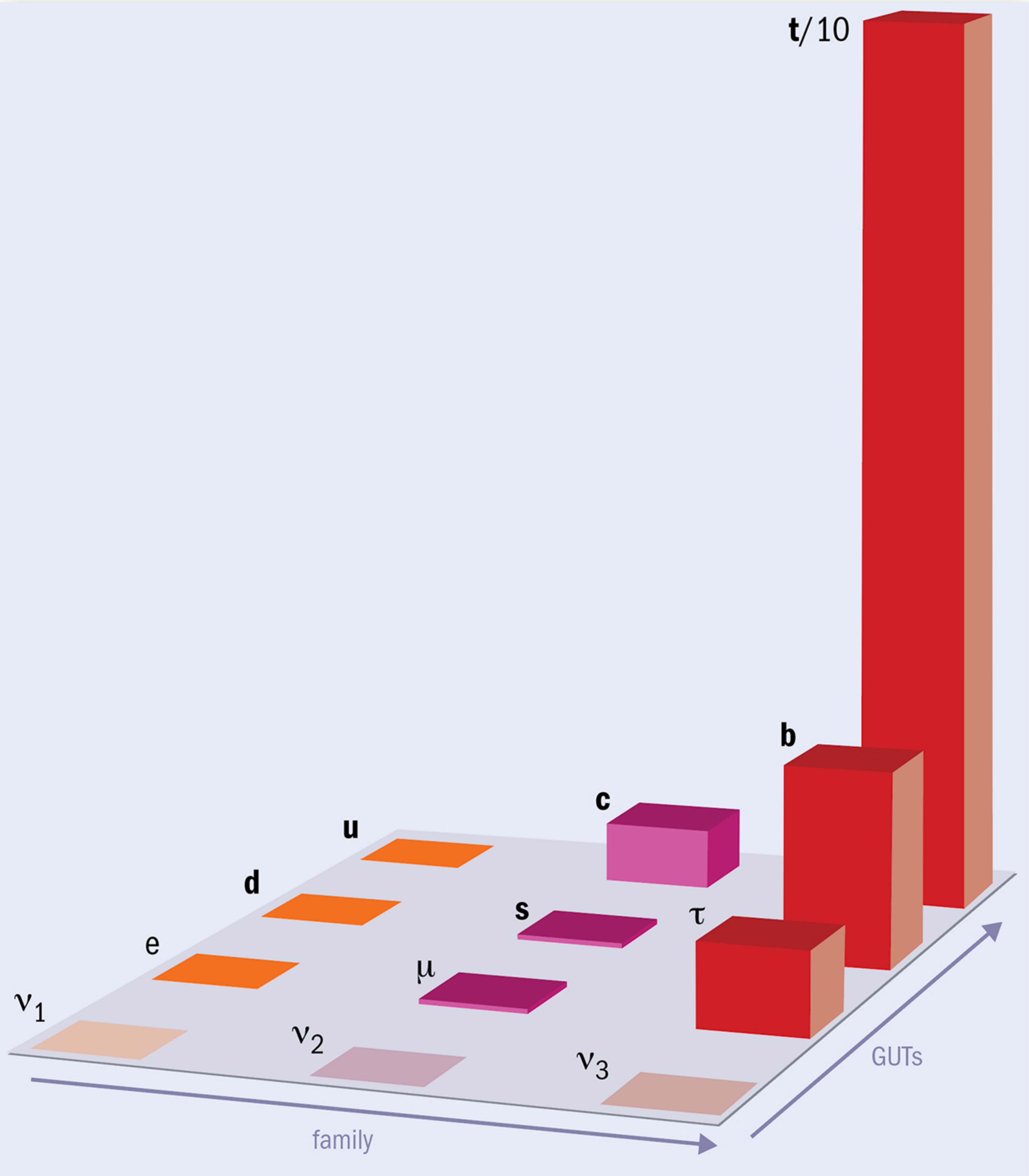


Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

rks

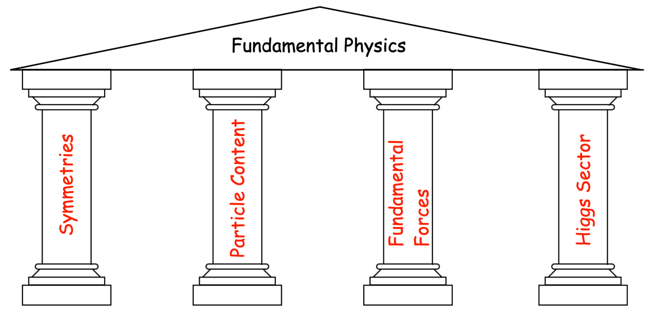
tons

ilies



What is our Universe made of?

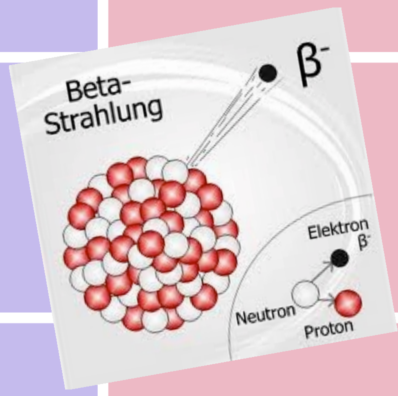
Why are the mass values as they are?

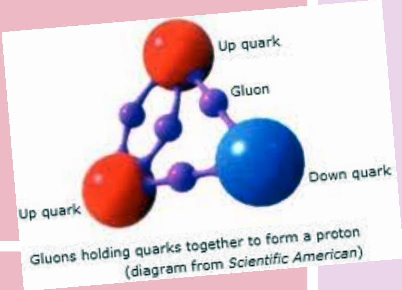


Fundamental Forces and Interaction Particles

❖ Fundamental Forces and interaction particles:

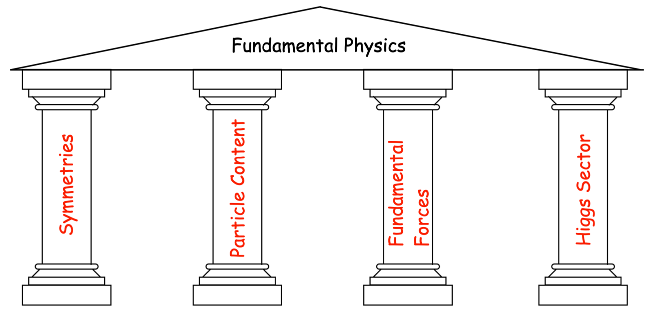
Fundamental Force	Mediator/Interaction Particle
Electromagnetic Force	Photon γ
Weak Force	W and Z Bosons
Strong Force	Gluons g
Not in the Standard Model:	
Gravity	Graviton





What are the forces of Nature?

How can we include gravity?



The Power of Symmetries

Symmetries are everywhere in Nature.

The Power of Symmetries

Symmetries are everywhere in Nature.

Noether's theorem:
Every continuous symmetry of a physical system has a conservation law

Experimentally observed interactions governed by charge conservation
~> continuous symmetry via Noether's law
~> construct symmetry-(gauge-)invariant Lagrangian
~> make predictions
~> check through experiment …

The Power of Symmetries

S

What is the logic behind all this?

What is the guiding principle?

Symmetries

⇓

Noether Theorem

⇓

Conserved Currents

ure

conservation law

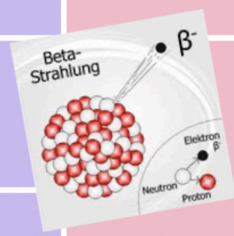
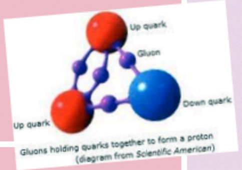
nservation

Gauge Symmetries

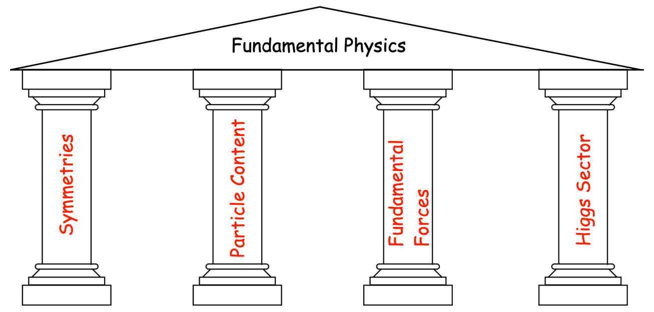
- **Construction principle:** requirement of local gauge invariance (internal symmetry)

- **Gauge symmetries of the Standard Model:**

$$\underbrace{U(1)_Y \times SU(2)_L}_{\text{electroweak}} \times \underbrace{SU(3)_C}_{\text{strong}} \quad \text{interaction}$$

Fundamental Force	Mediator/Interaction Particle
Electromagnetic Force	Photon γ 
Weak Force	 W and Z Bosons
Strong Force	Gluons g 
Not in the Standard Model:	
Gravity	 Graviton

What is the guiding principle?



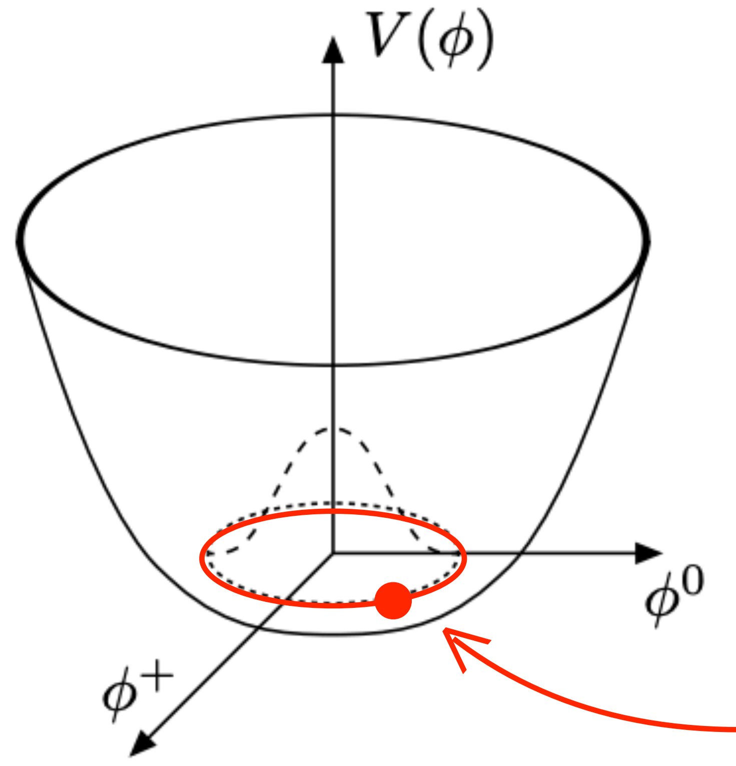
Higgs Mechanism

❖ The problem with the masses:

- ✏ Matter and interaction particles $W^{\pm}$, Z are massive
- ✏ Lagrangian describing Standard Model with mass terms violates gauge symmetries ⚡

❖ Solution - Higgs Mechanism (proposed 1964):

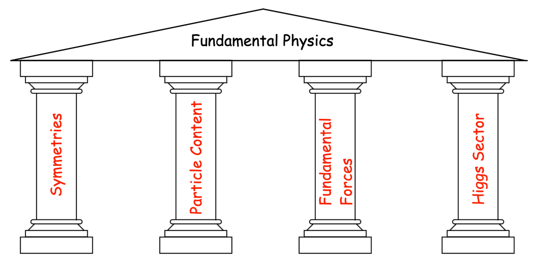
Generation of particle masses through spontaneous symmetry breaking (SSB)



❖ SSB: Lagrangian preserves the gauge symmetry, but the ground state breaks it

❖ Generation of particle masses: through particle interactions with Higgs in the ground state

What is the origin of mass?



Higgs Mechanism

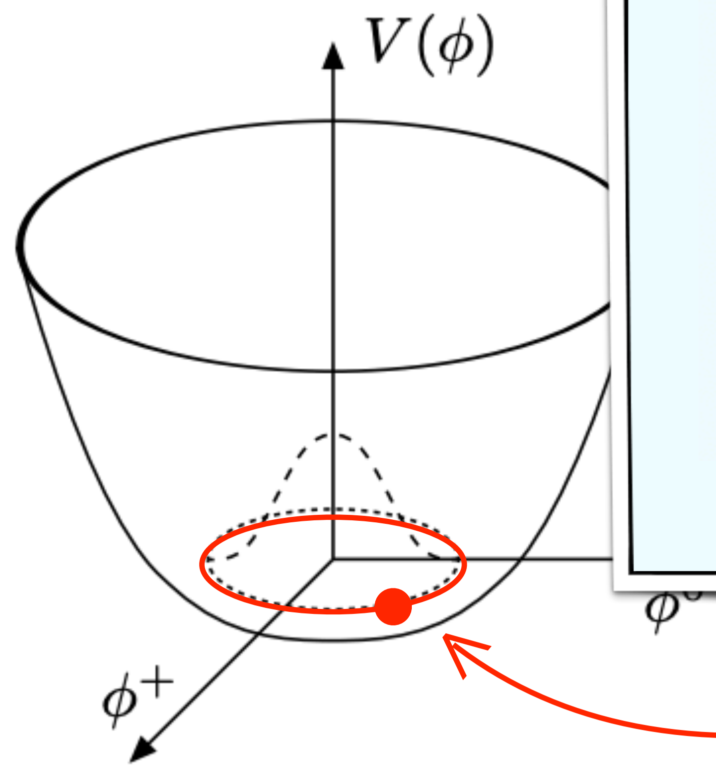
❖ The problem with the masses:

✏ Matter and interaction particles W$^\pm$, Z are massive

✏ Lagrangian describing Standard Model with ma

❖ Solution - Higgs Mechanism (proposed 1964):

Generation of particle masses through spontaneous symm



Examples of SSB

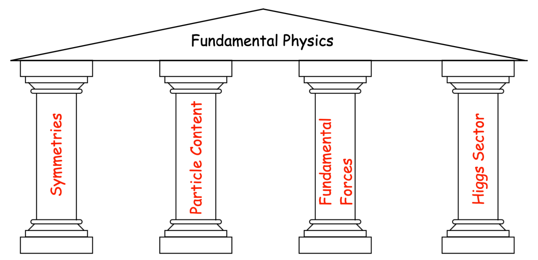
- Ferromagnet

$T > T_C : \langle M \rangle = 0$ $T < T_C : \langle M \rangle \neq 0$

- Cooper pairs in superconductor

❖ Generation of particle masses: through particle interactions with Higgs in the ground state

What is the origin of mass?

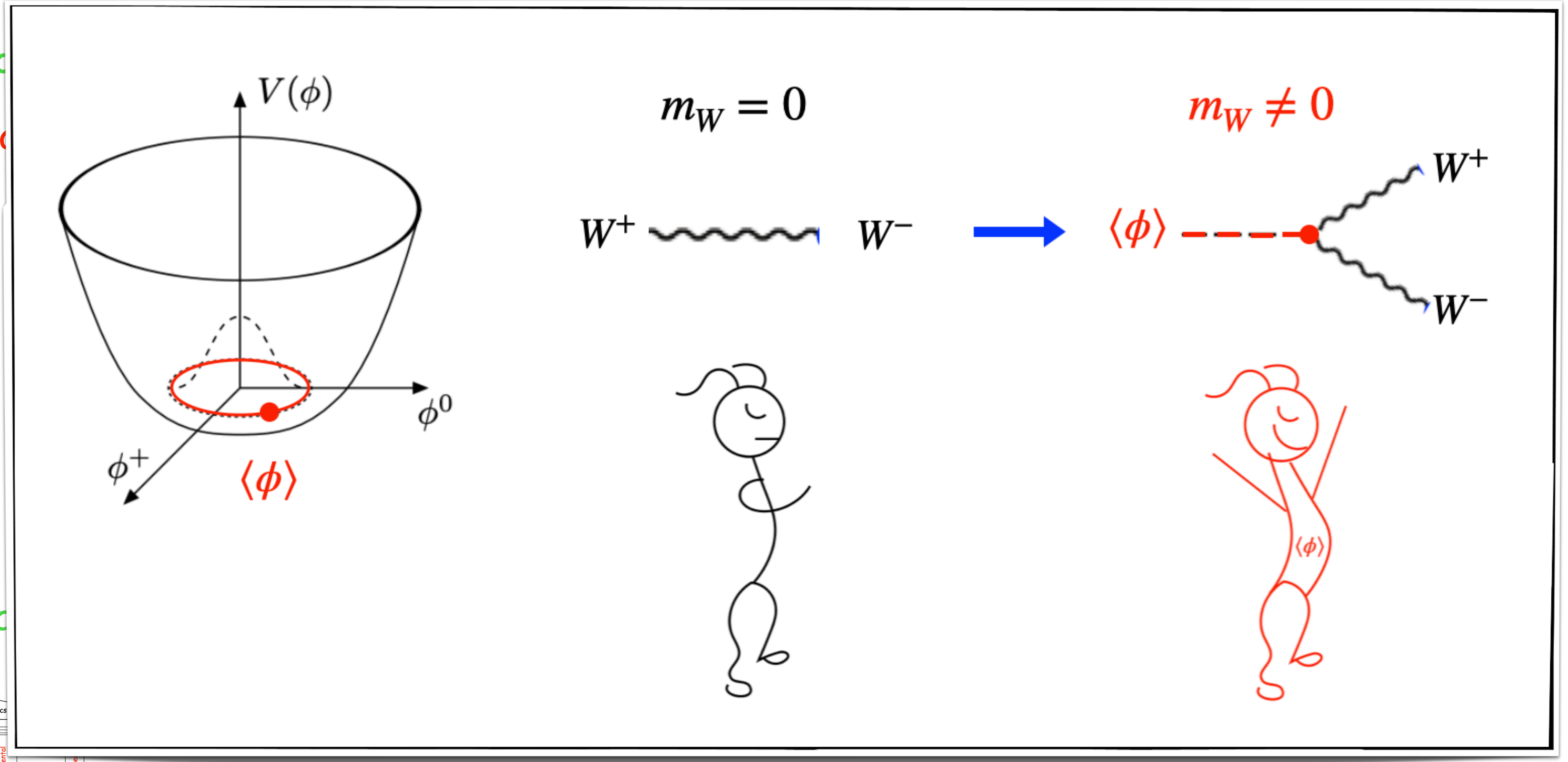


Higgs Mechanism

- The problem with the masses:
  - ✏ Matter and interaction particles $W^{\pm}$, Z are massive
  - ✏ Lagrangian describing Standard Model with mass terms violates gauge symmetries ϟ

- Solutio

  Genera

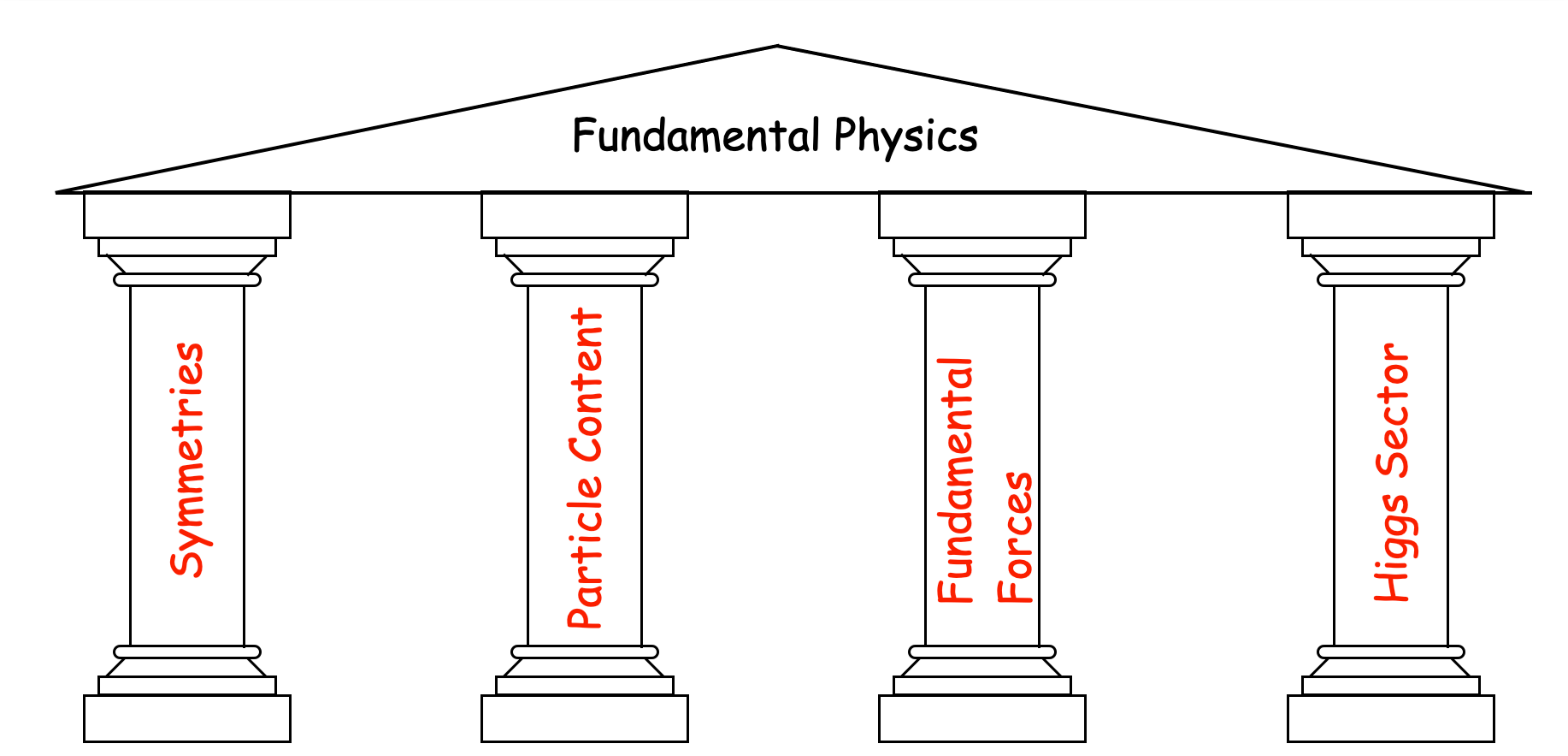


- Genera

What is the origin of mass?

The Standard Model of Particle Physics in a Nutshell

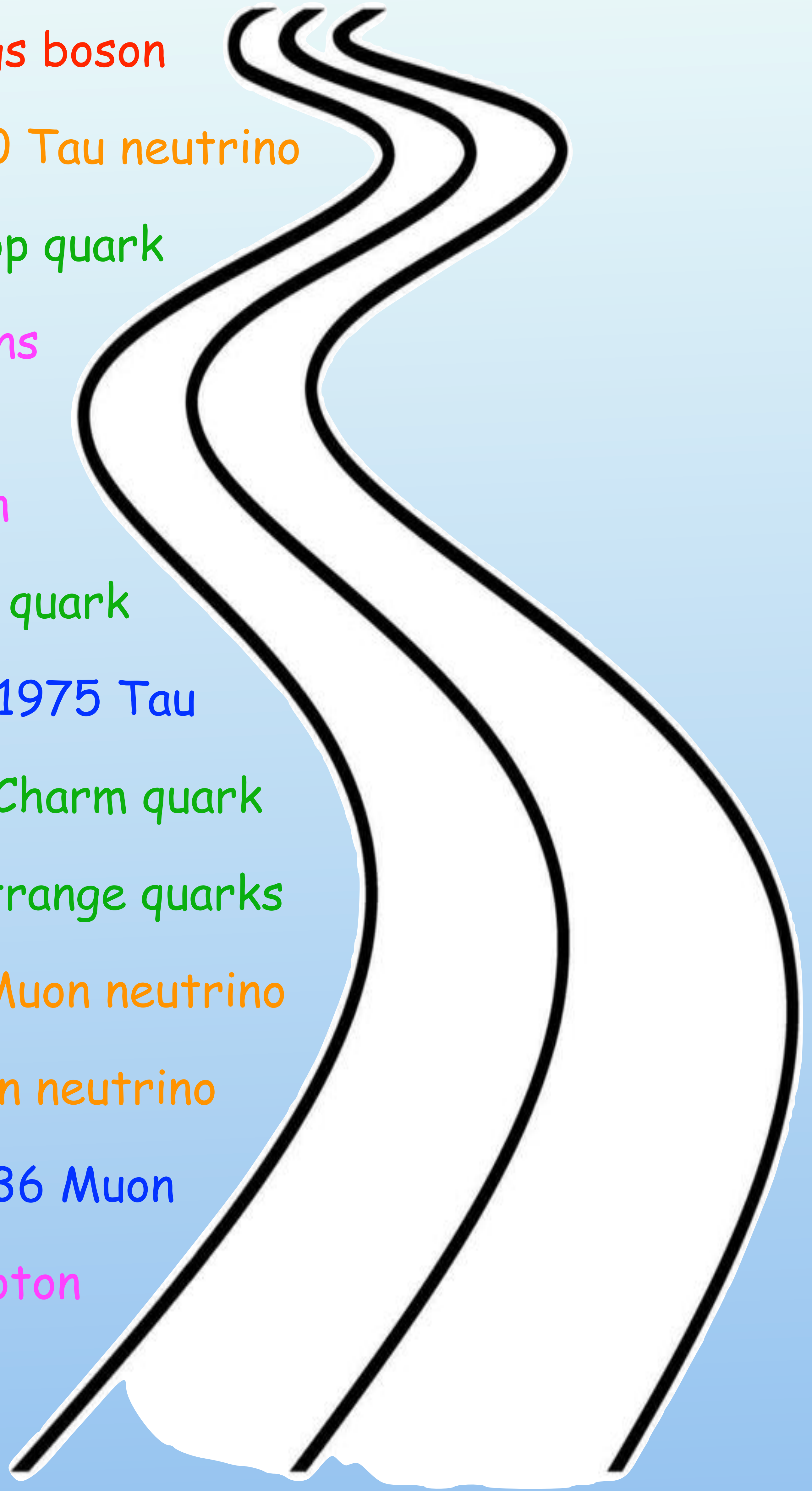
Describes today known fundamental building blocs of matter
and the fundamental forces acting between them (except for gravity)



The Success Story of Particle Physics

Visualization of the Big Bang in the Science Parc in Hanoi, Vietnam

Particle Road



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

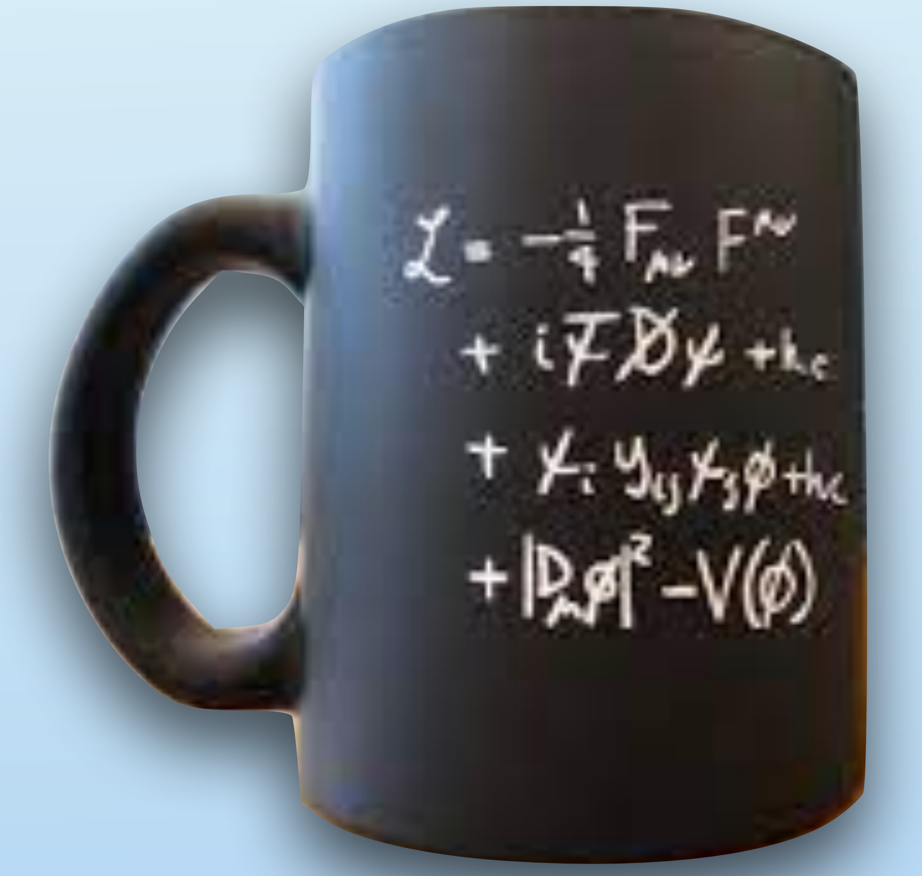
1956 Electron neutrino

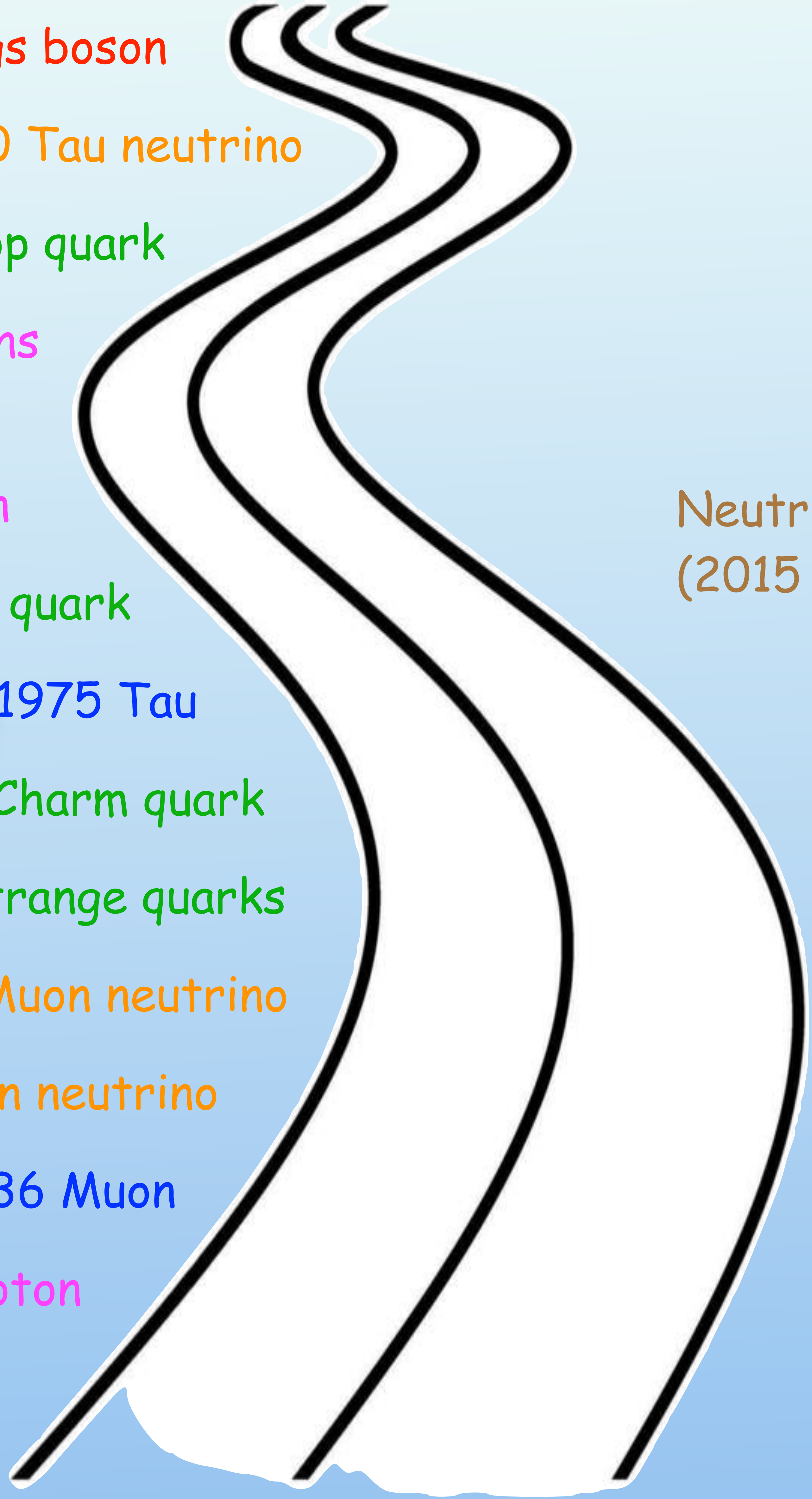
1936 Muon

1905 Photon

1897 Electron

Particle Road





2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

1956 Electron neutrino

1936 Muon

1905 Photon

1897 Electron

Coherent
Picture

Neutrino oscillations
(2015 Kajita, McDonald)

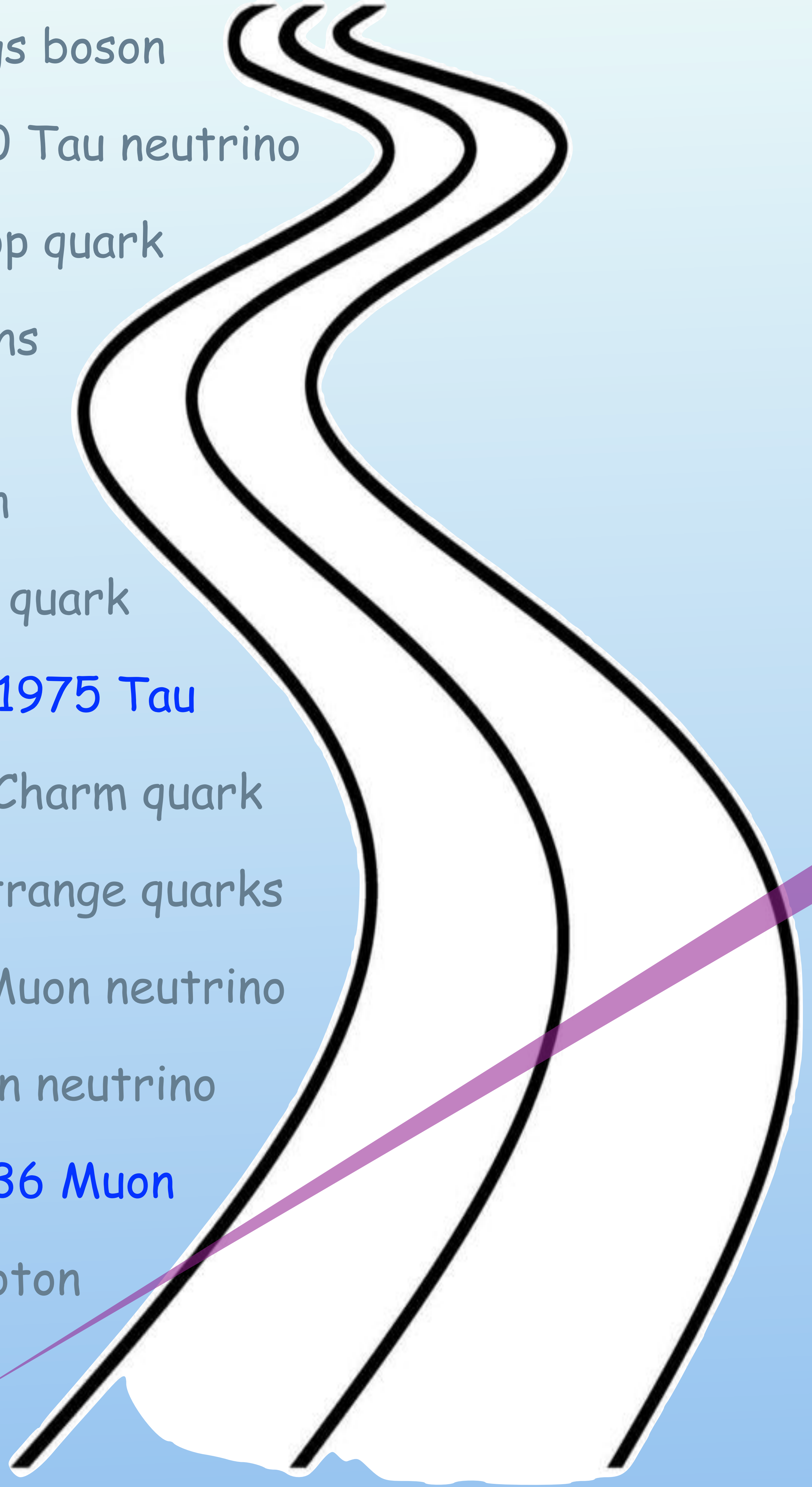
Asymptotic freedom
(2004, Gross, Politzer,Wilczek)

Renormalizability
(1999, 't Hooft, Veltman)

Parton model (1969 Gell-Mann)

CP violation (1964, Cronin, Fitch)

Particle Road



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

1956 Electron neutrino

1936 Muon

1905 Photon

1897 Electron

First discovered elementary particle

Particle Road

2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

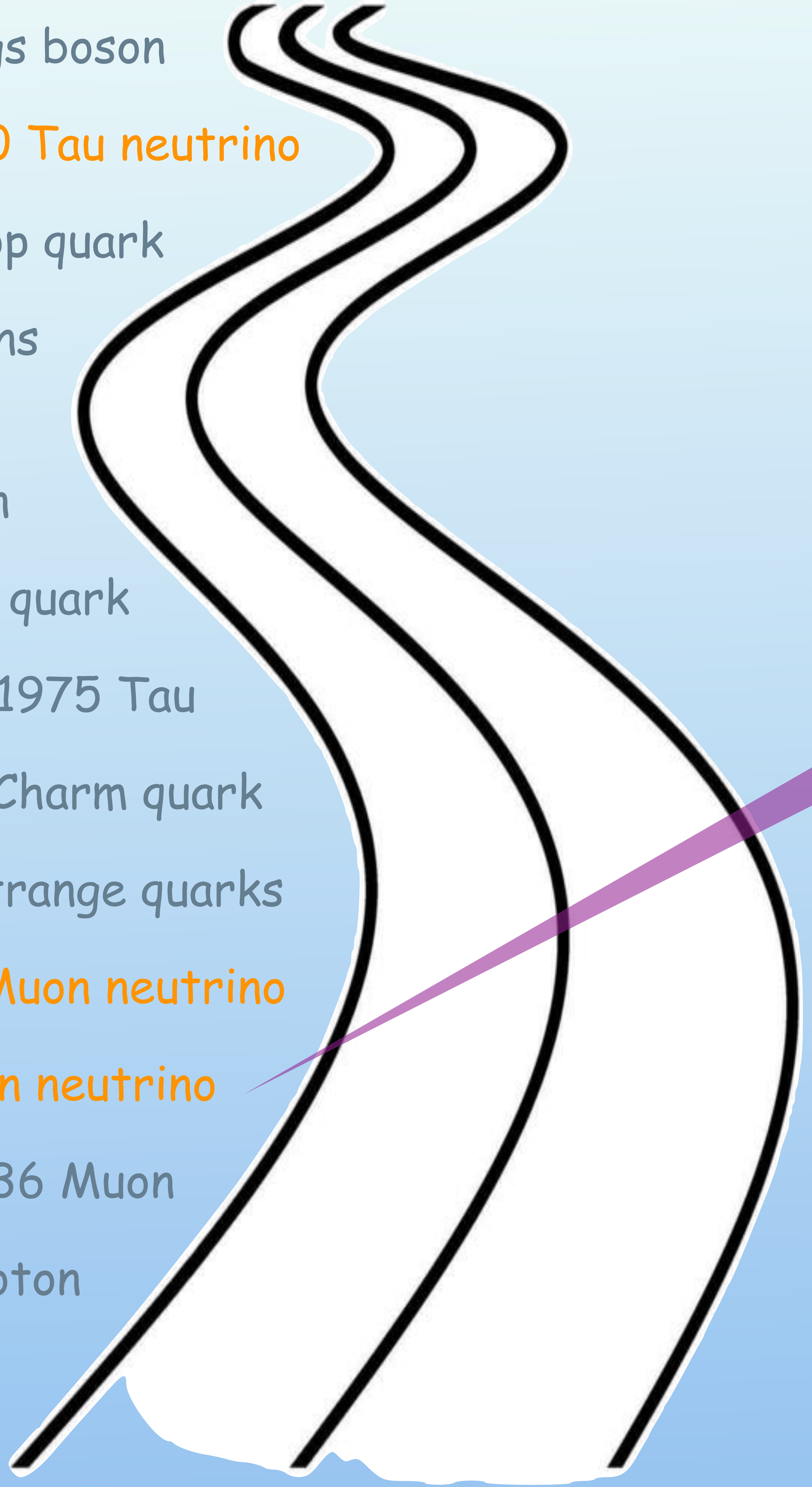
1962 Muon neutrino

1956 Electron neutrino

1936 Muon

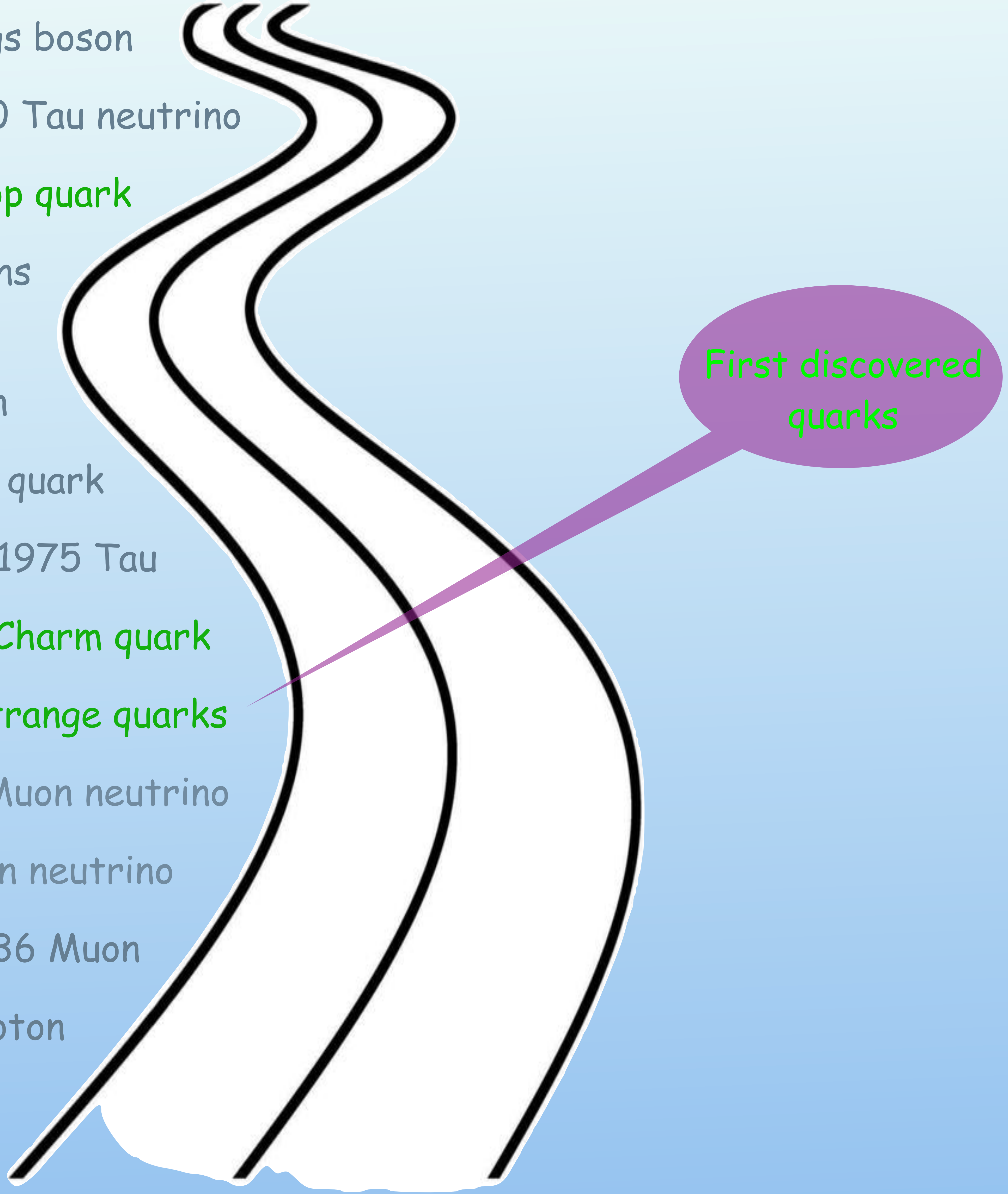
1905 Photon

1897 Electron



First species of weakly interacting neutrinos

Particle Road



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

1956 Electron neutrino

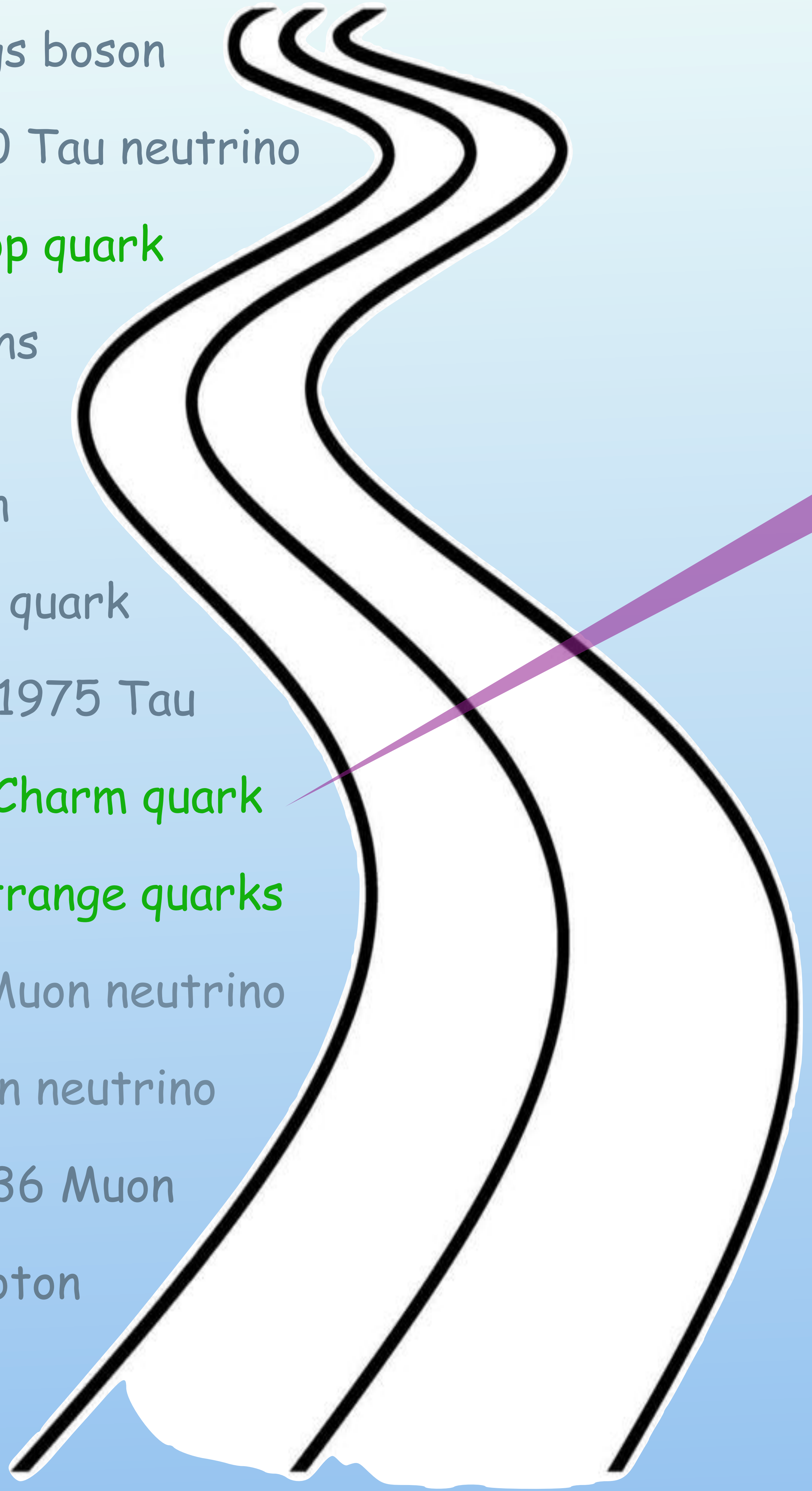
1936 Muon

1905 Photon

1897 Electron

First discovered quarks

Particle Road



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

1956 Electron neutrino

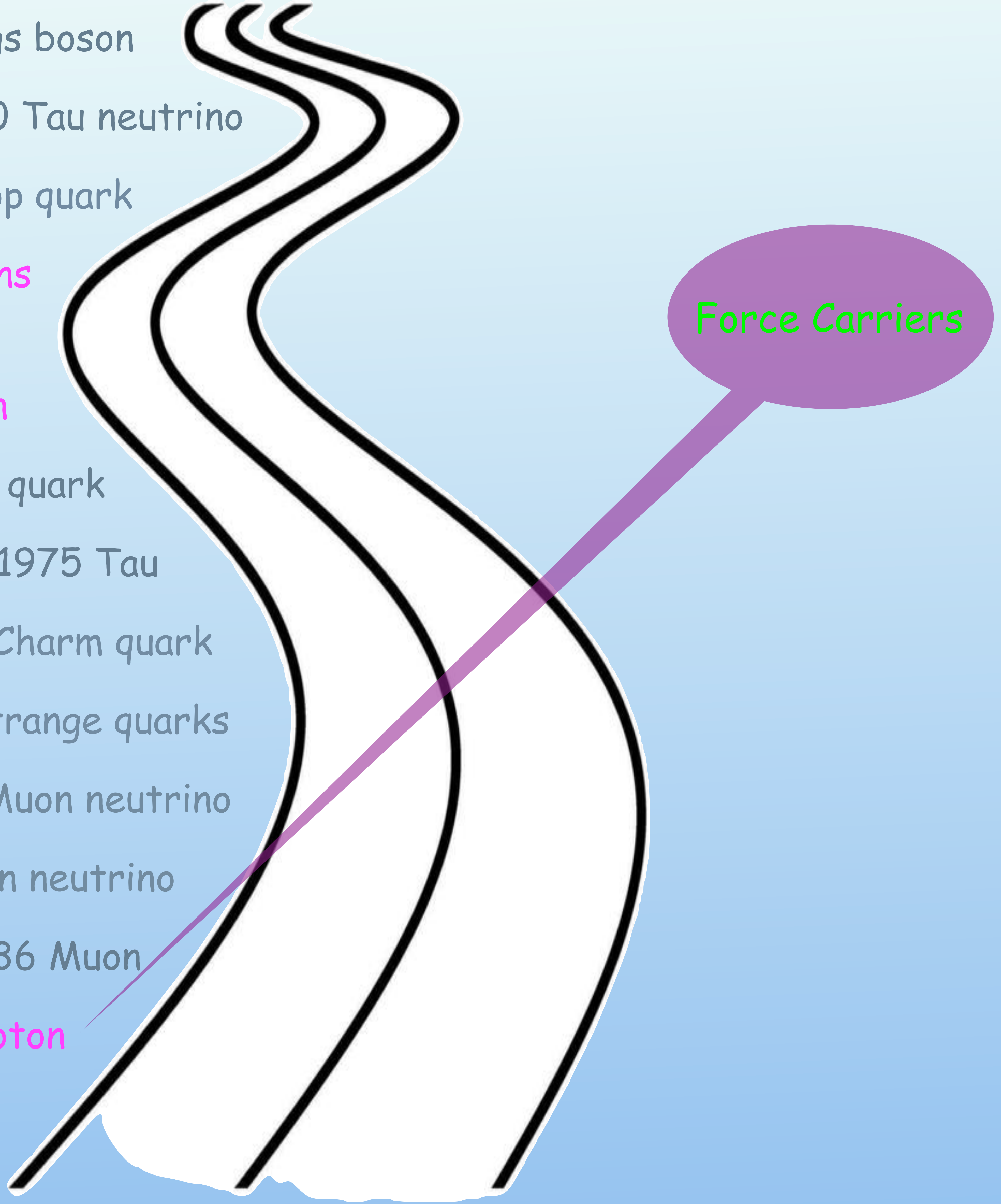
1936 Muon

1905 Photon

1897 Electron

The November Revolution!

Particle Road



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

1956 Electron neutrino

1936 Muon

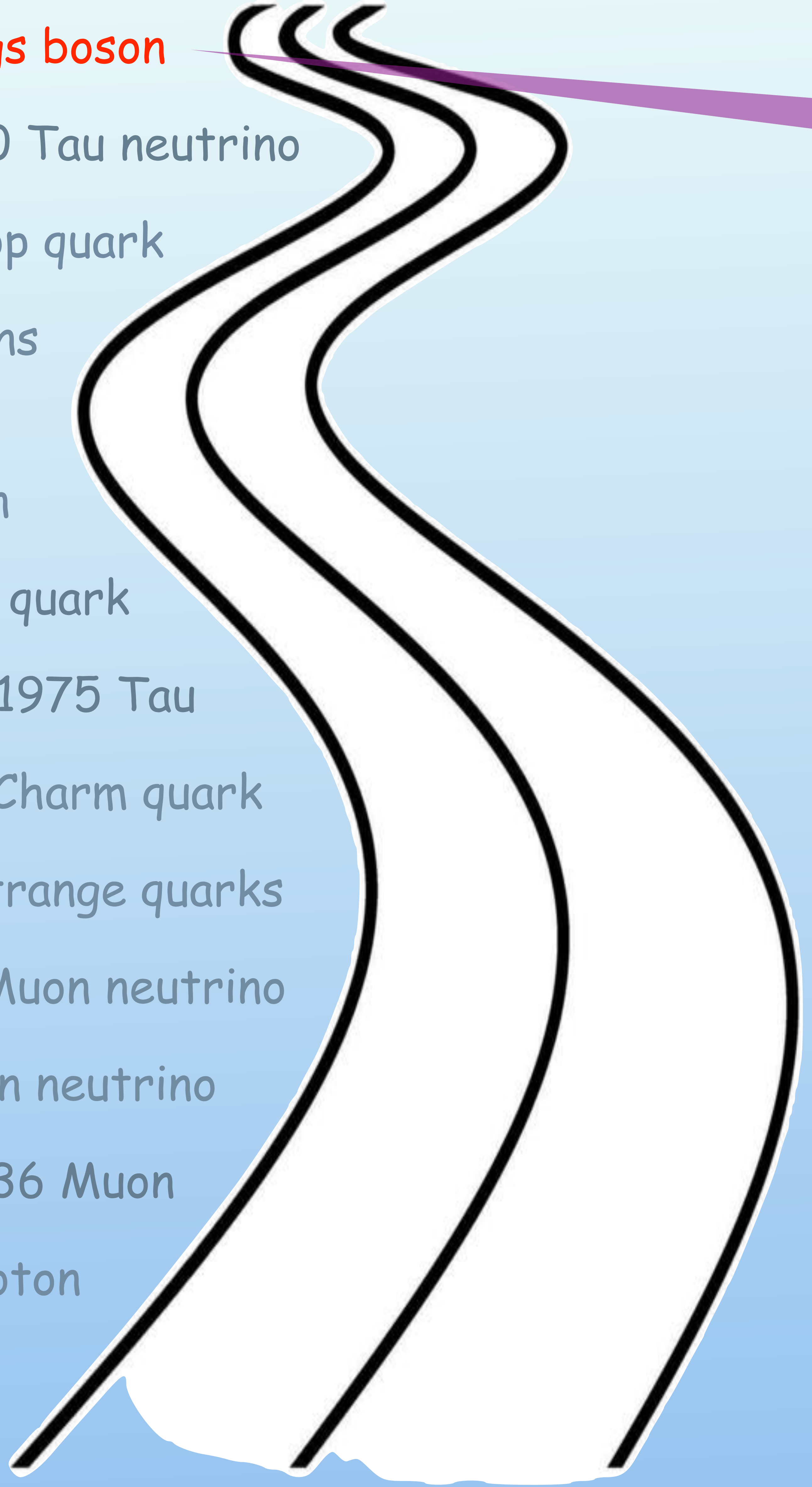
1905 Photon

1897 Electron

Force Carriers

Particle Road


Science
21 December 2012 | $10
BREAKTHROUGH of the YEAR
The HIGGS BOSON
AAAS



2012 Higgs boson

2000 Tau neutrino

1995 Top quark

1983 W- and Z-bosons
(1973 indir.)

1979 Gluon

1977 Bottom quark

1975 Tau

1974 Charm quark

1968 Up, down, strange quarks

1962 Muon neutrino

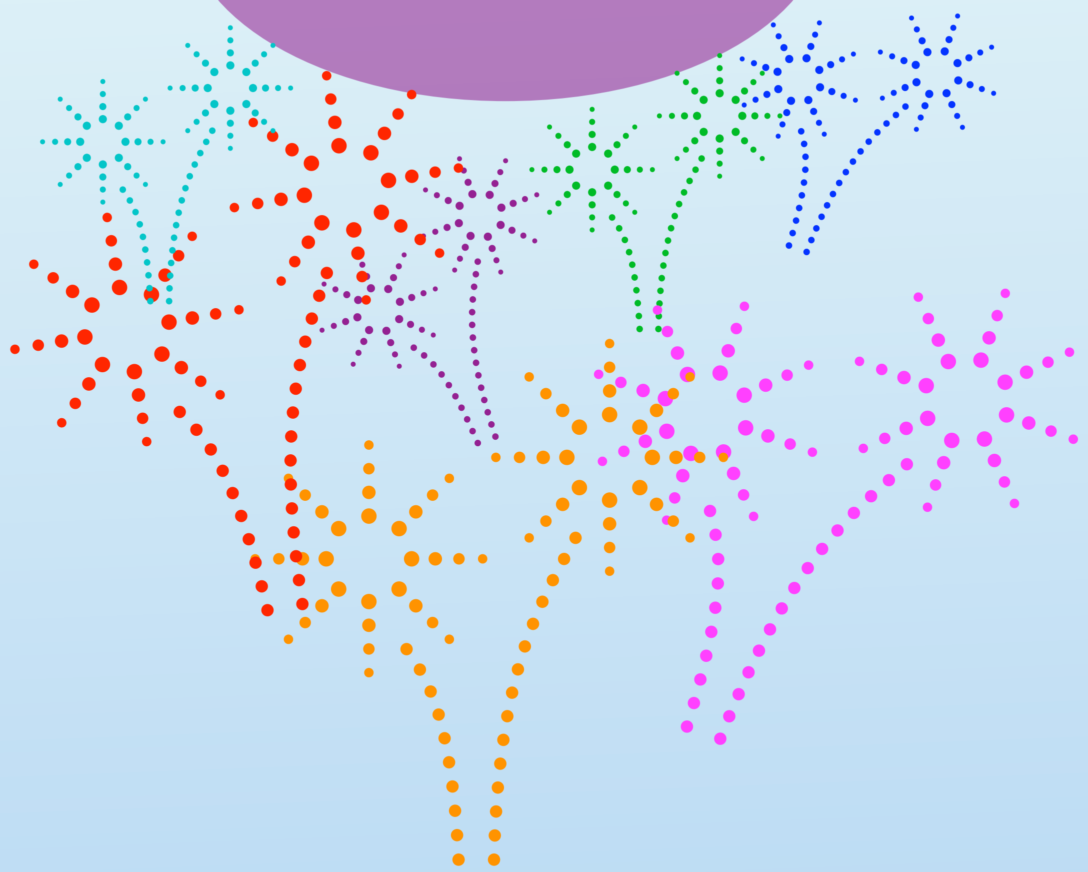
1956 Electron neutrino

1936 Muon

1905 Photon

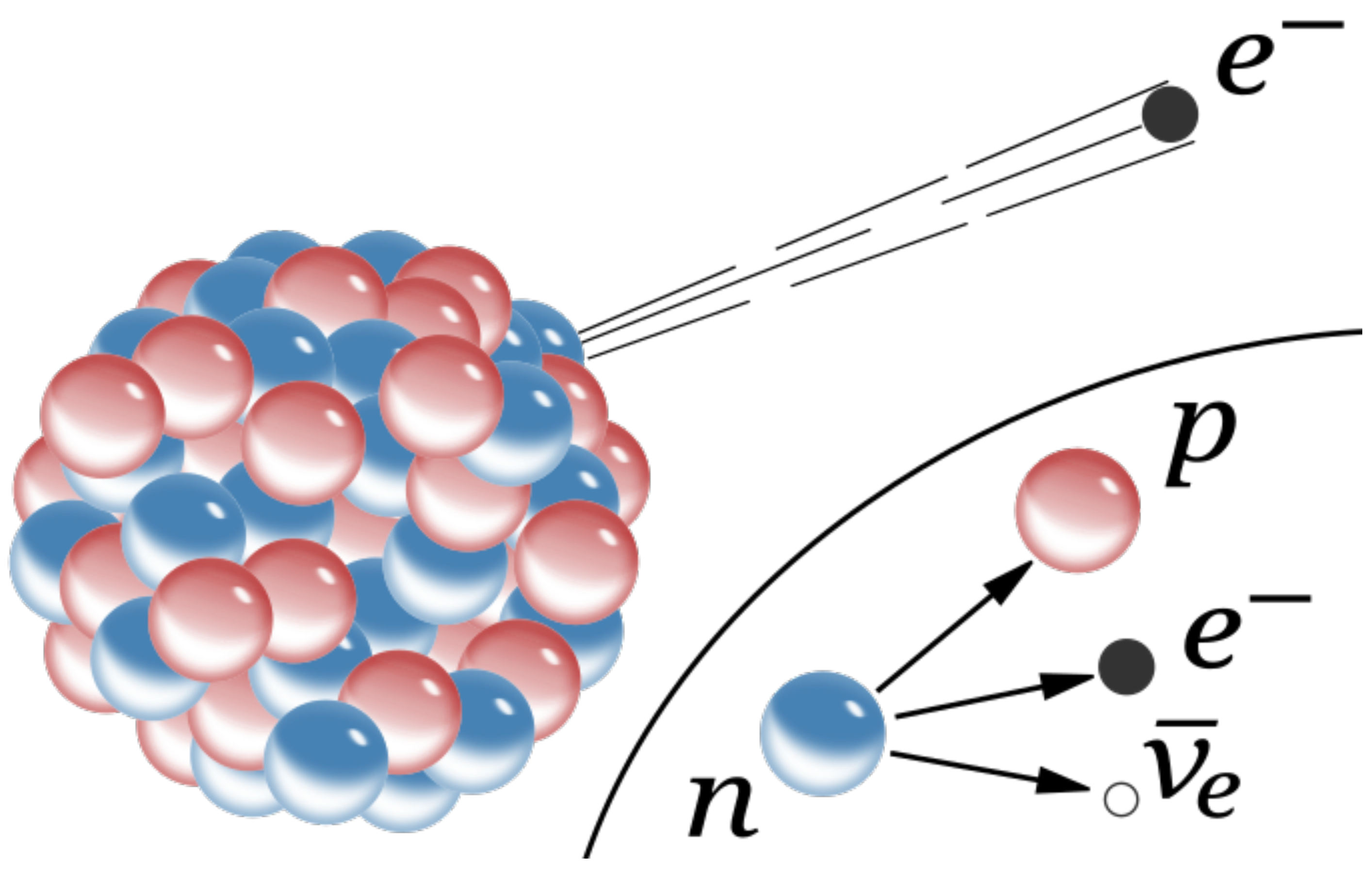
1897 Electron

The completion!



History of the SM - Highlights & Milestones

The Unitarity Path to the Higgs Boson



@Wikipedia

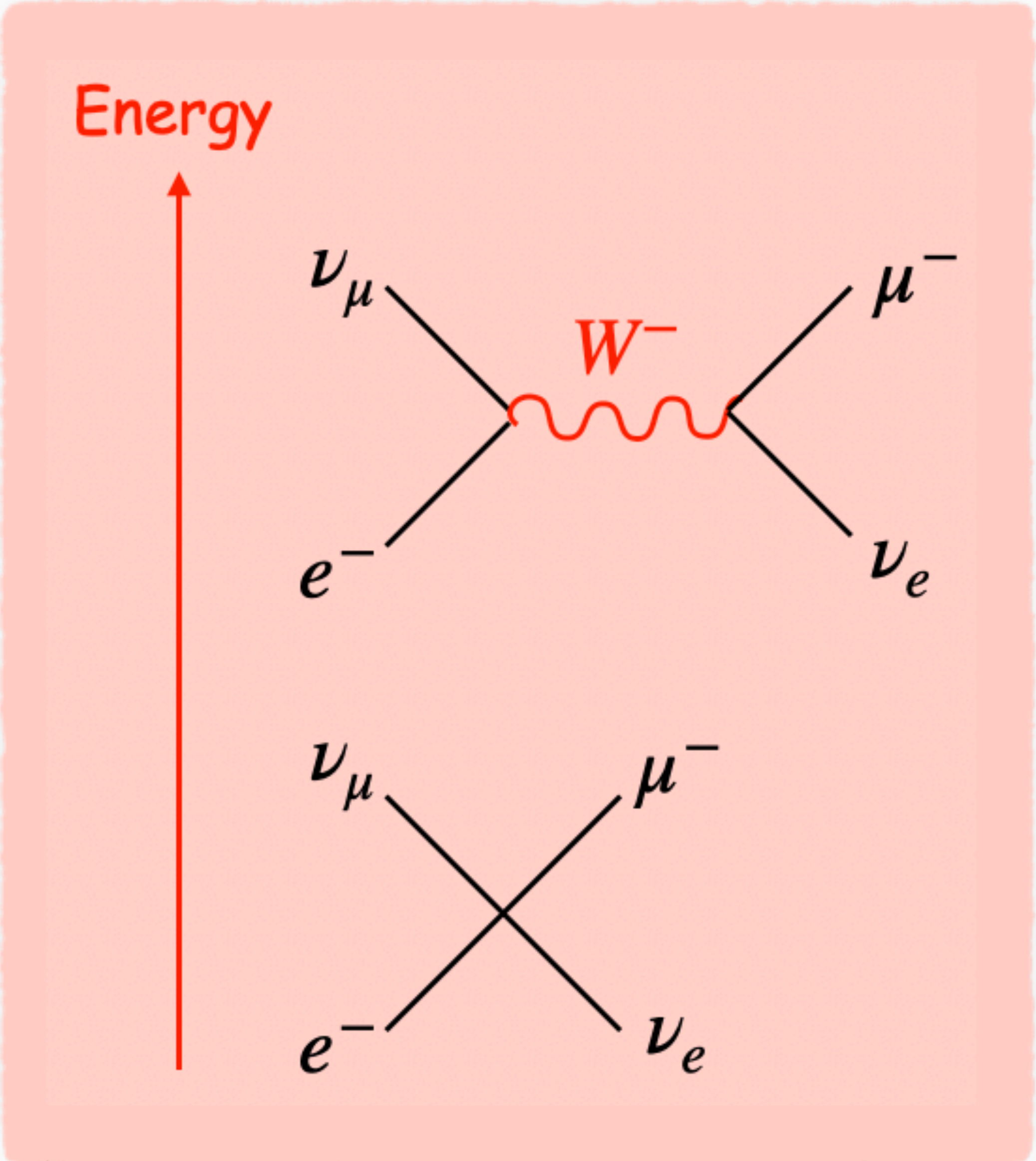
✦ Radioactive beta decay:
- consequence of the weak force
- described by Fermi theory of weak interaction with four fermions interacting directly

✦ Problem:

scattering probability of $\nu_\mu e^- \to \mu^- \nu_e$ rises with squared energy

=> Fermi theory: effective low-energy theory

✦ Solution: Introduction of the W boson

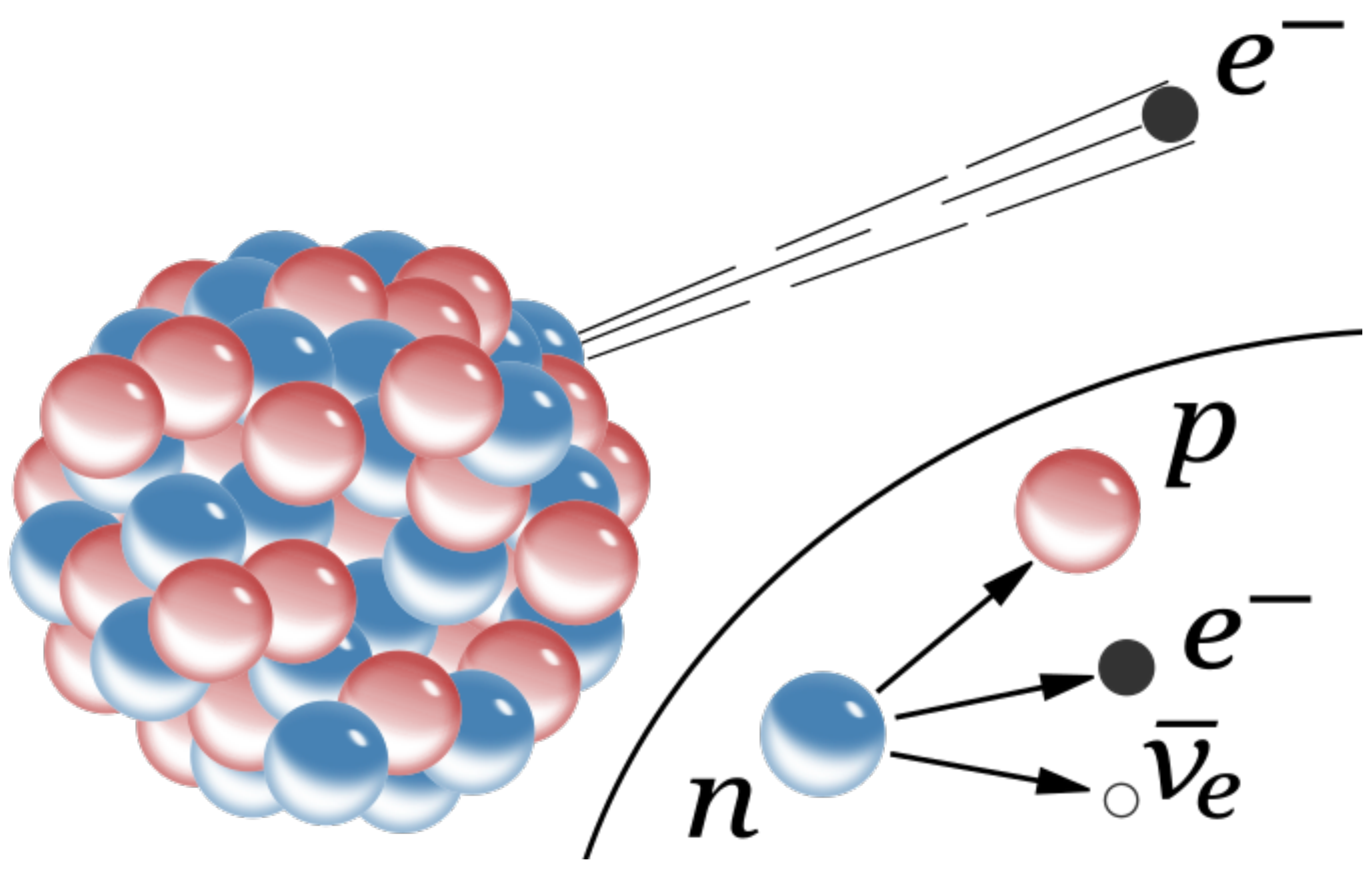


Discovery of the W boson in 1983 at CERN

What is the origin of mass?

MILESTONE

The Unitarity Path to the Higgs Boson



@Wikipedia

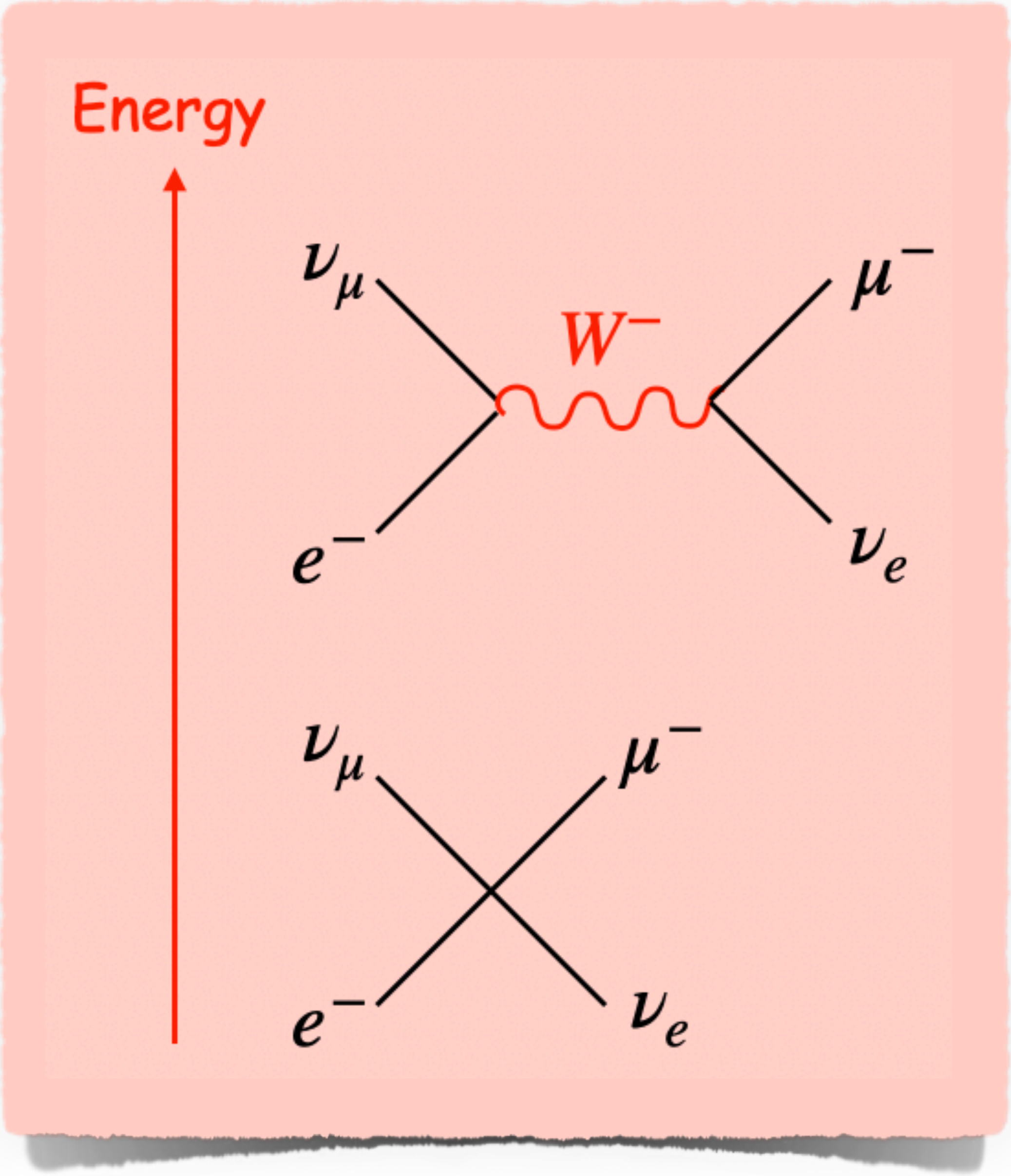
- Radioactive beta decay:
  - consequence of the weak force
  - described by Fermi theory of weak int
    with four fermions interacting dire
- Problem:

  scattering probability of $\nu_\mu e^- \to \mu^-$

  squared energy

  => Fermi theory: effective low-energy theory

- Solution: Introduction of the W boson

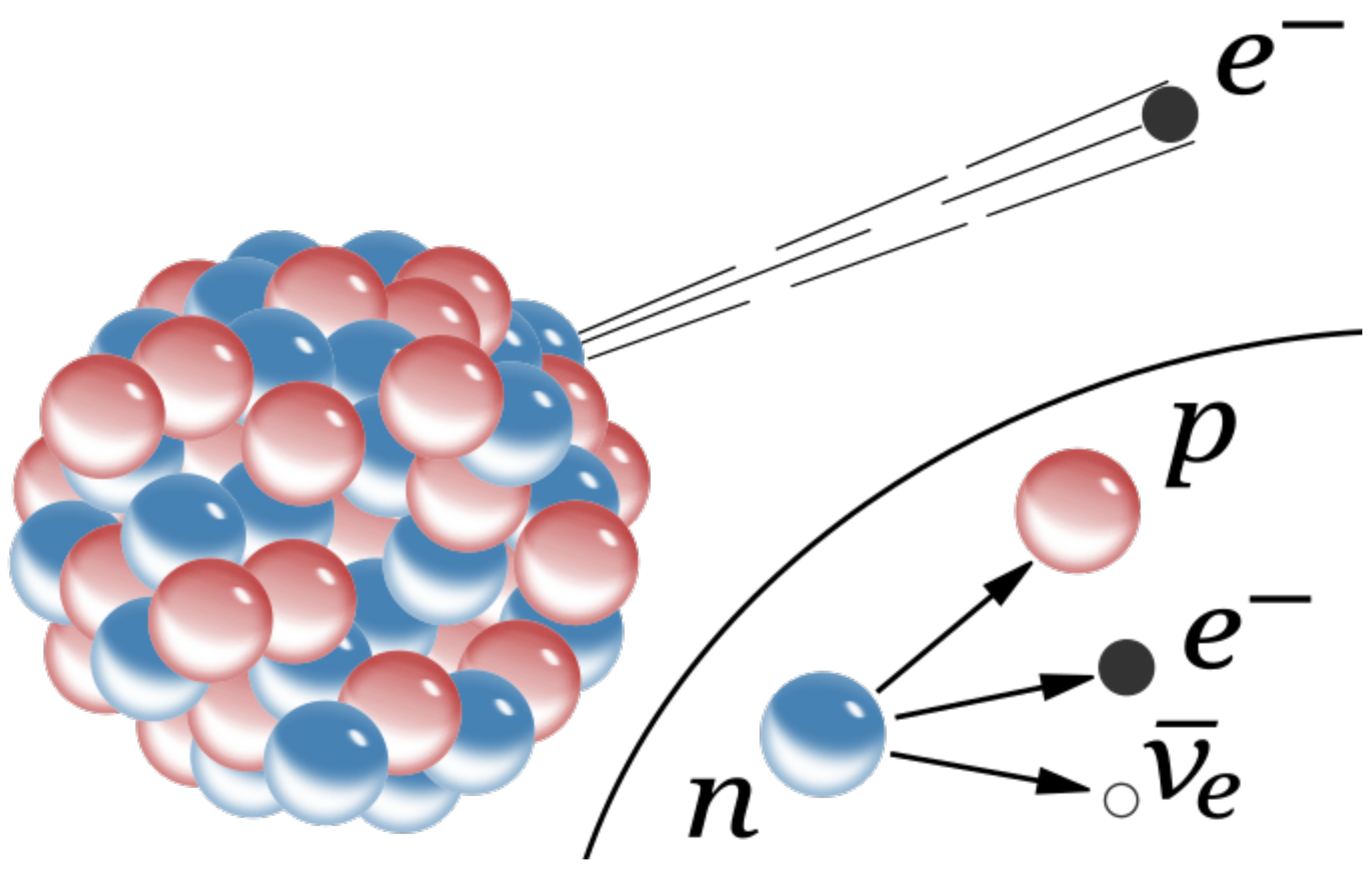


Discovery of the W boson in 1983 at CERN

What is the origin of mass?

MILESTONE

The Unitarity Path to the Higgs Boson



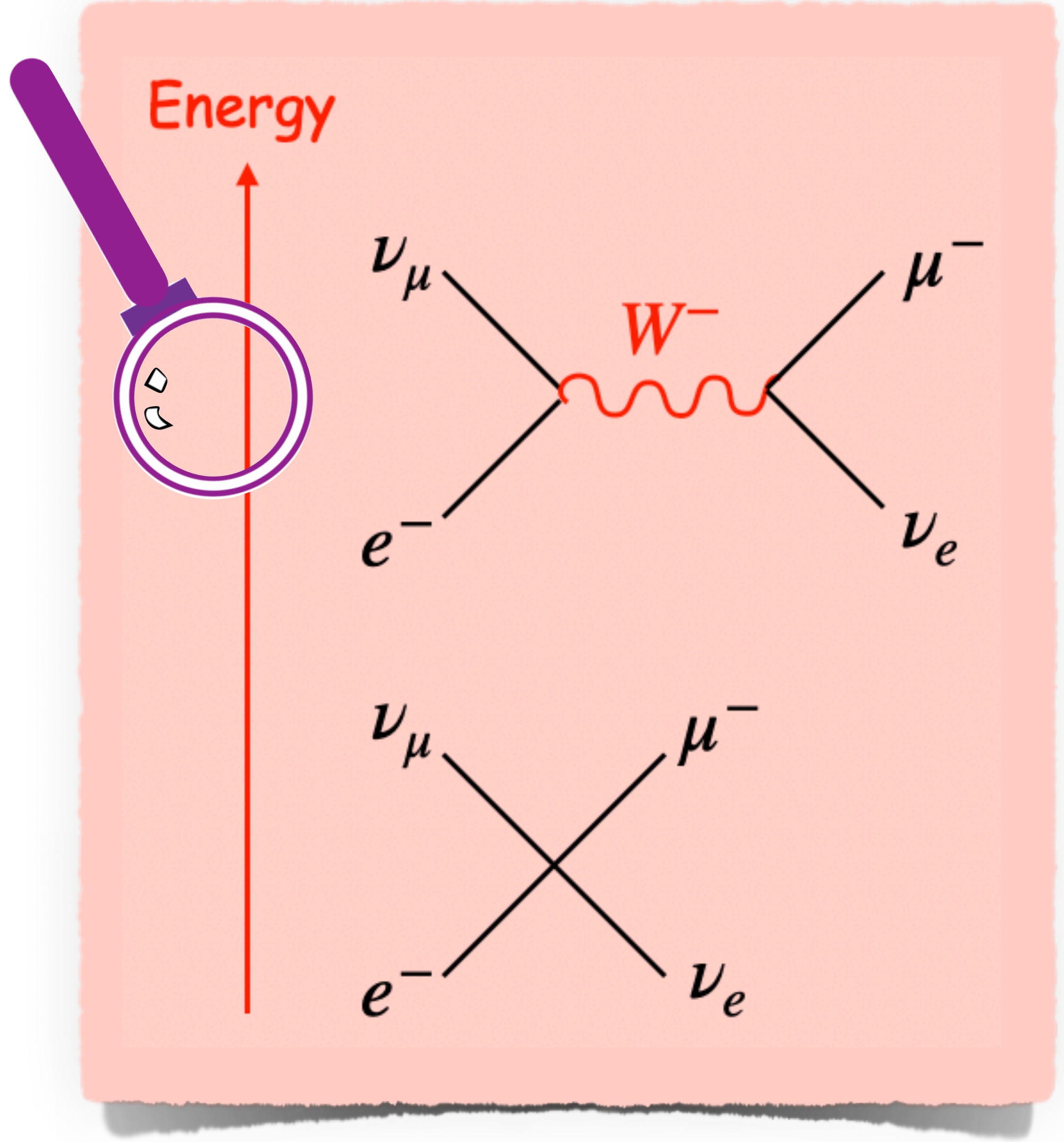
@Wikipedia

- **Radioactive beta decay:**
  - consequence of the weak force
  - described by Fermi theory of weak interaction with four fermions interacting directly
- **Problem:**

  scattering probability of $\nu_\mu e^- \rightarrow \mu^- \nu_e$ rises with squared energy ϟ

  => Fermi theory: effective low-energy theory

- **Solution:** Introduction of the W boson

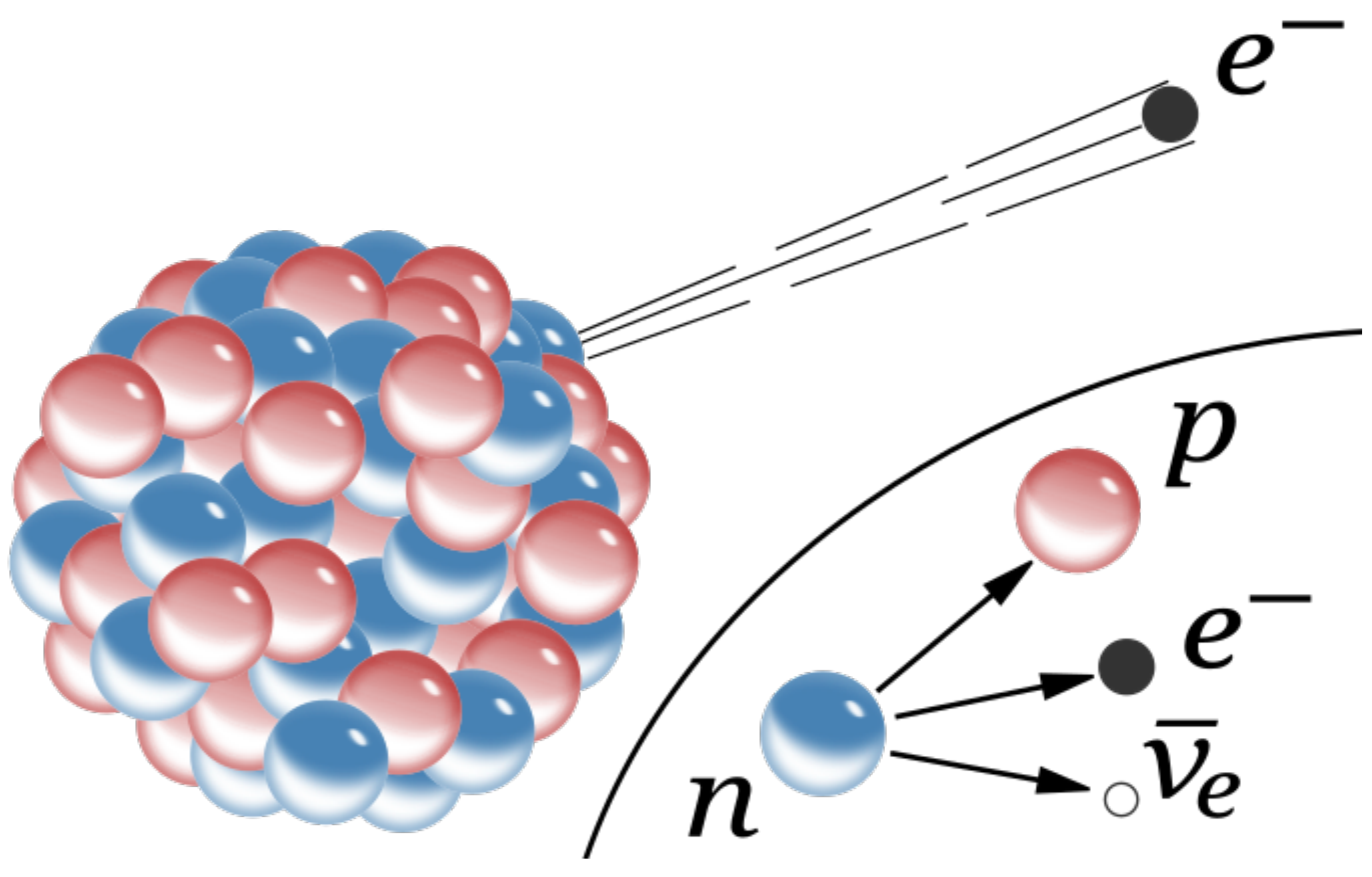


Discovery of the W boson in 1983 at CERN

What is the origin of mass?

MILESTONE

The Unitarity Path to the Higgs Boson



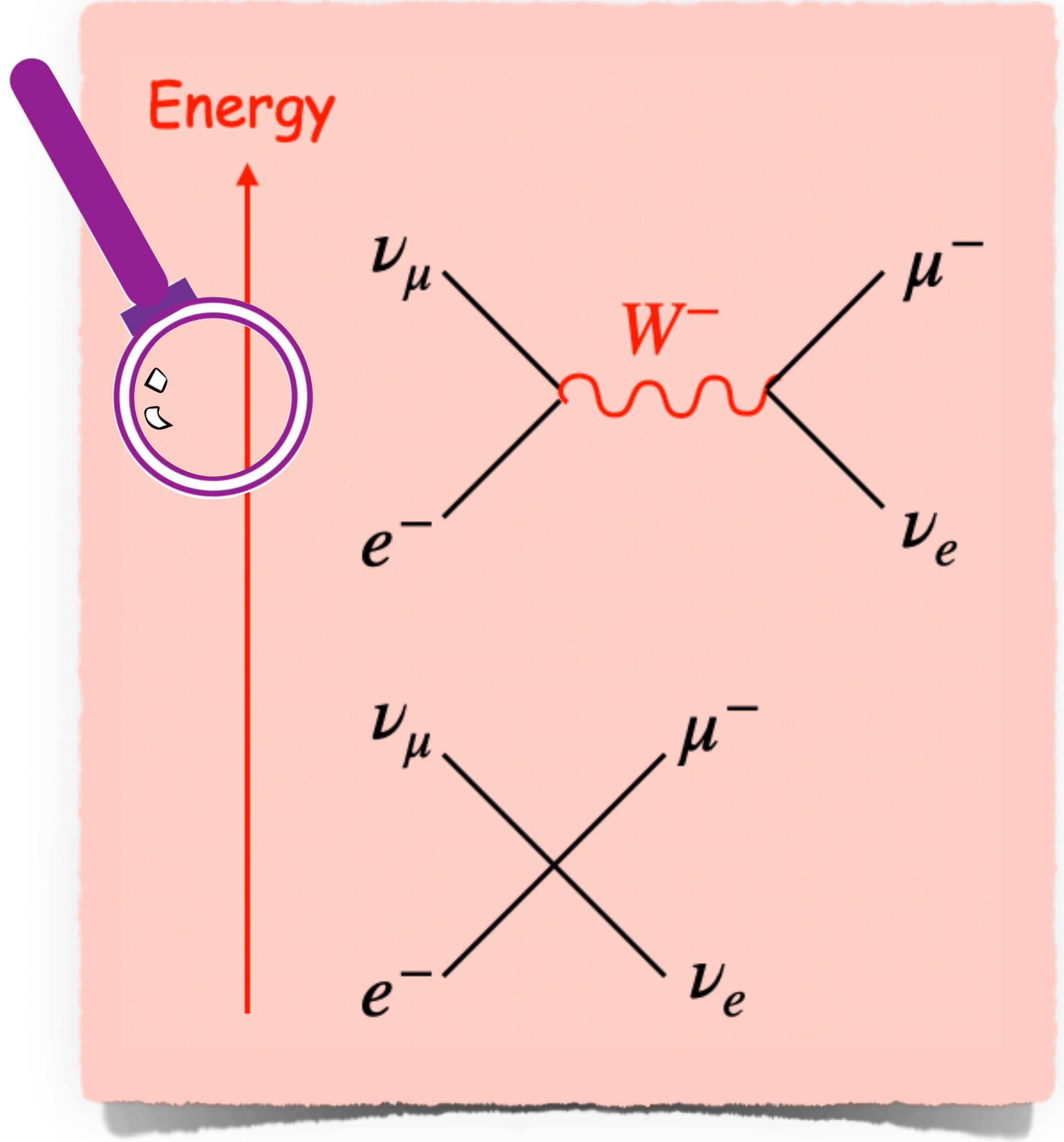
@Wikipedia

- **Radioactive beta decay:**
  - consequence of the weak force
  - described by Fermi theory of weak interaction with four fermions interacting directly
- **Problem:**

  scattering probability of $\nu_\mu e^- \to \mu^- \nu_e$ rises with squared energy ↯

  => Fermi theory: effective low-energy theory

- **Solution:** Introduction of the W boson



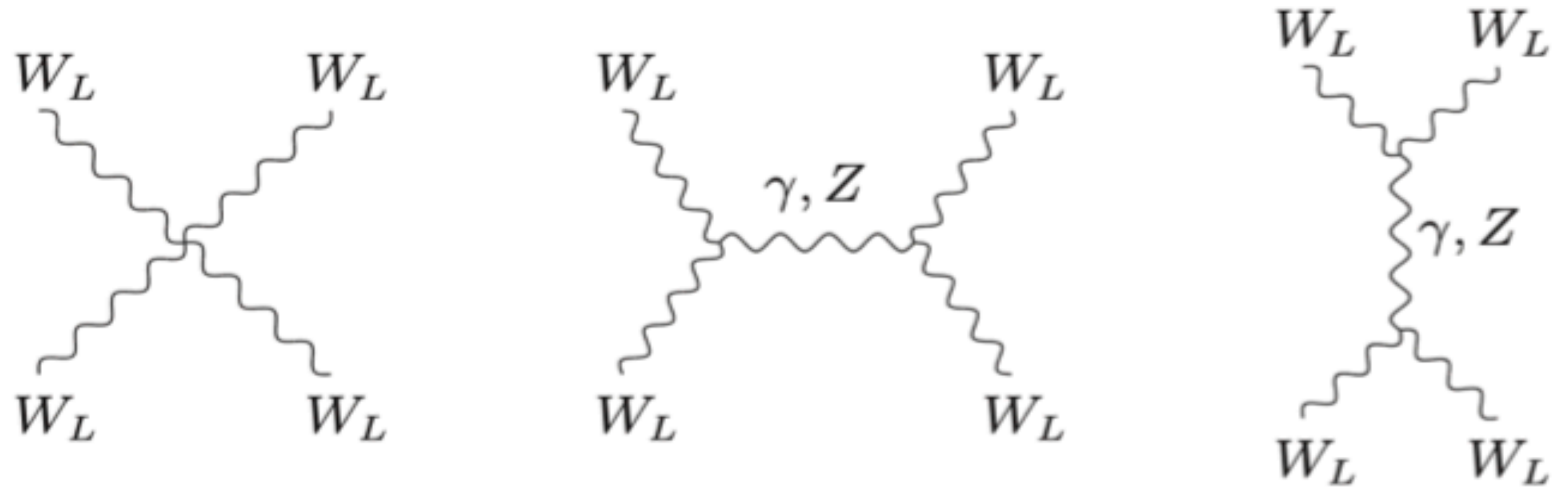
Discovery of the W boson in 1983 at CERN

Nobel Prize 1984 to Carlo Rubbia and Simon van der Meer

What is the origin of mass?

The Unitarity Path to the Higgs Boson

- Longitudinal W boson scattering: production amplitude diverges ϟ with the energy

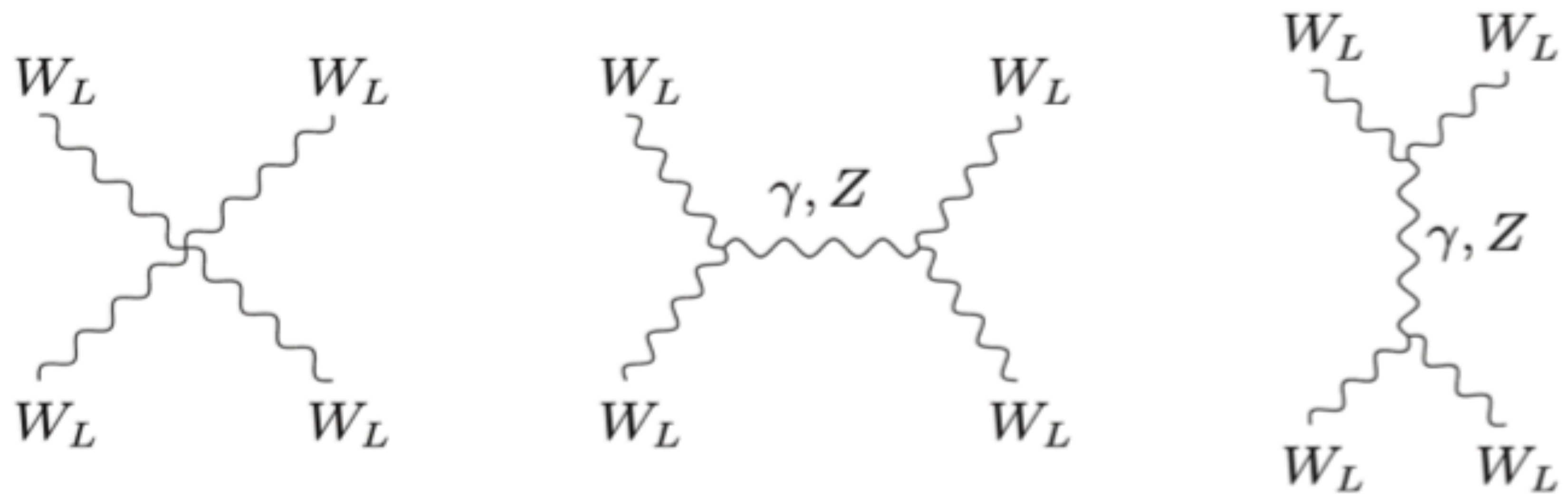


Violates unitarity (probability conservation)!

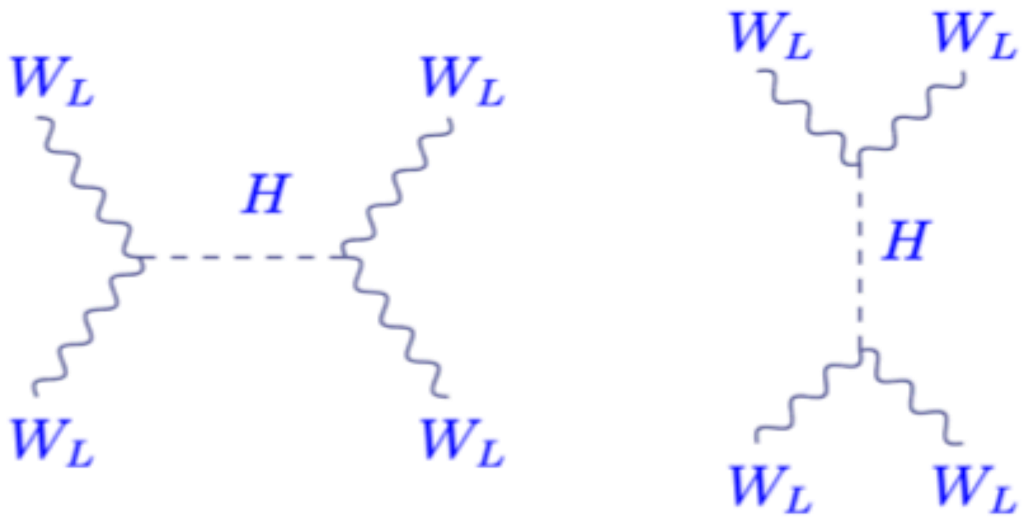
What is the origin of mass?

The Unitarity Path to the Higgs Boson

- Longitudinal W boson scattering:
  production amplitude diverges ↯
  with the energy



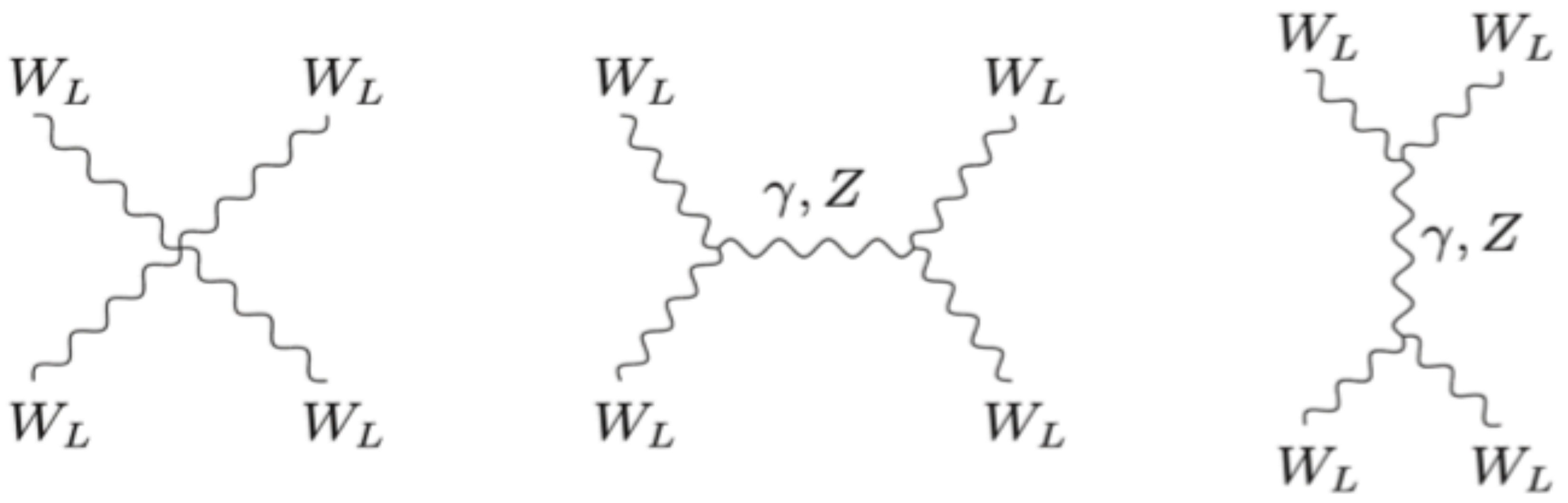
- Solution:
  introduction of scalar (spin-0) particle
  coupling strength ~ squared W boson mass



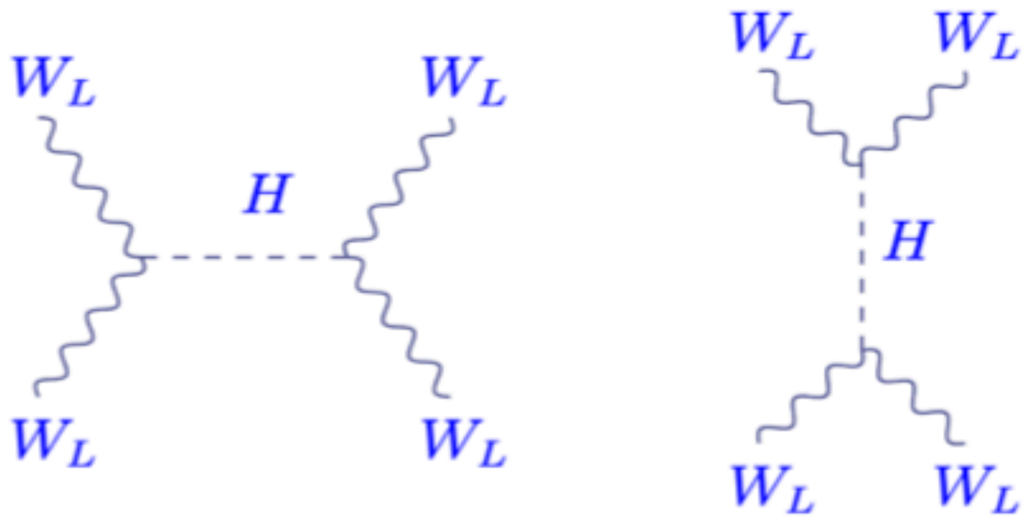
What is the origin of mass?

The Unitarity Path to the Higgs Boson

- Longitudinal W boson scattering:
  production amplitude diverges ↯
  with the energy



- Solution:
  introduction of scalar (spin-0) particle
  coupling strength ~ squared W boson mass



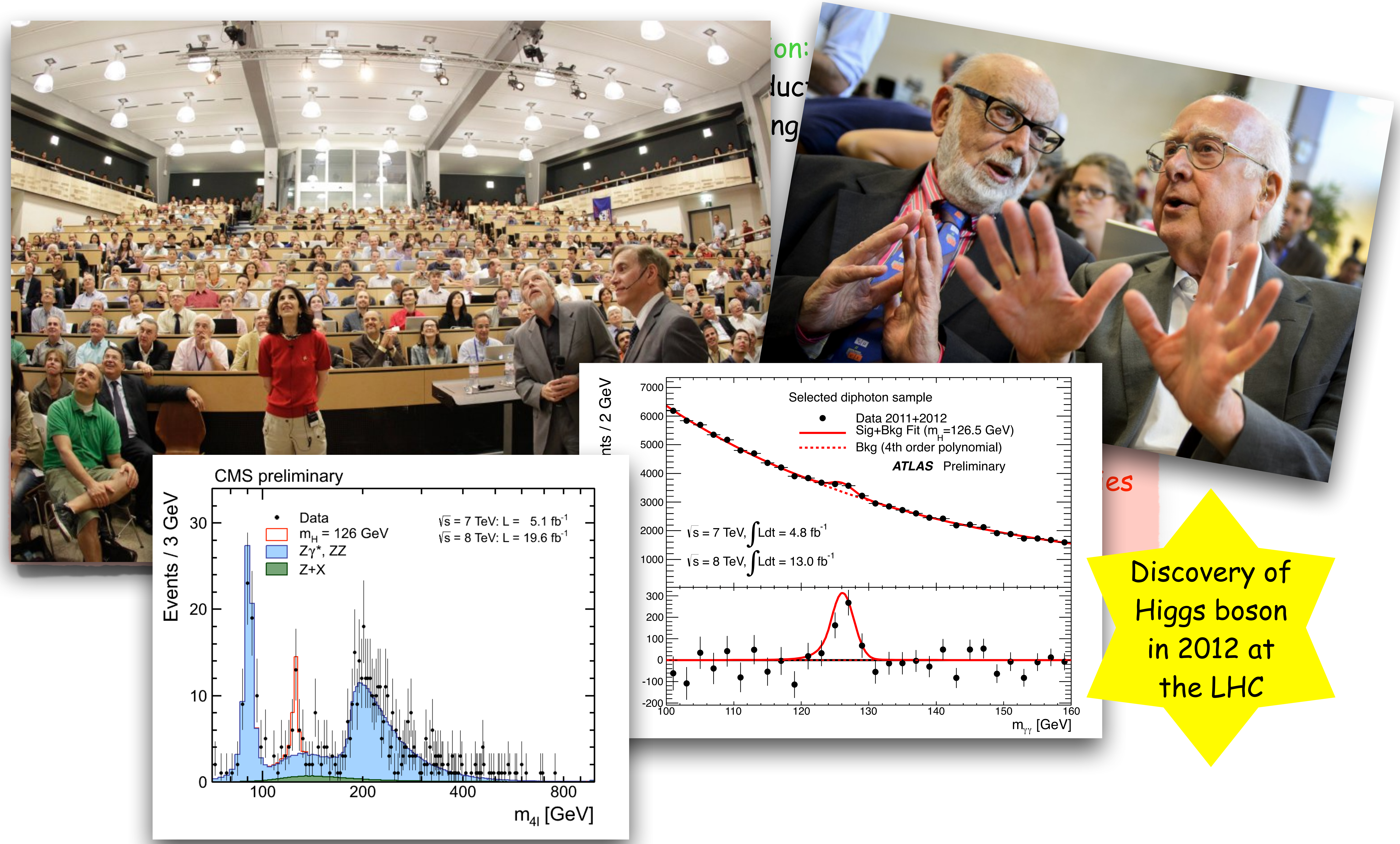
- Solution: Higgs mechanism - also provides mass generation compatible w/ symmetries
  developed 1964 by Higgs, Englert, Brout and Guralnik, Hagen, Kibble

Discovery of Higgs boson in 2012 at the LHC

What is the origin of mass?

MILESTONE

The Unitarity Path to the Higgs Boson



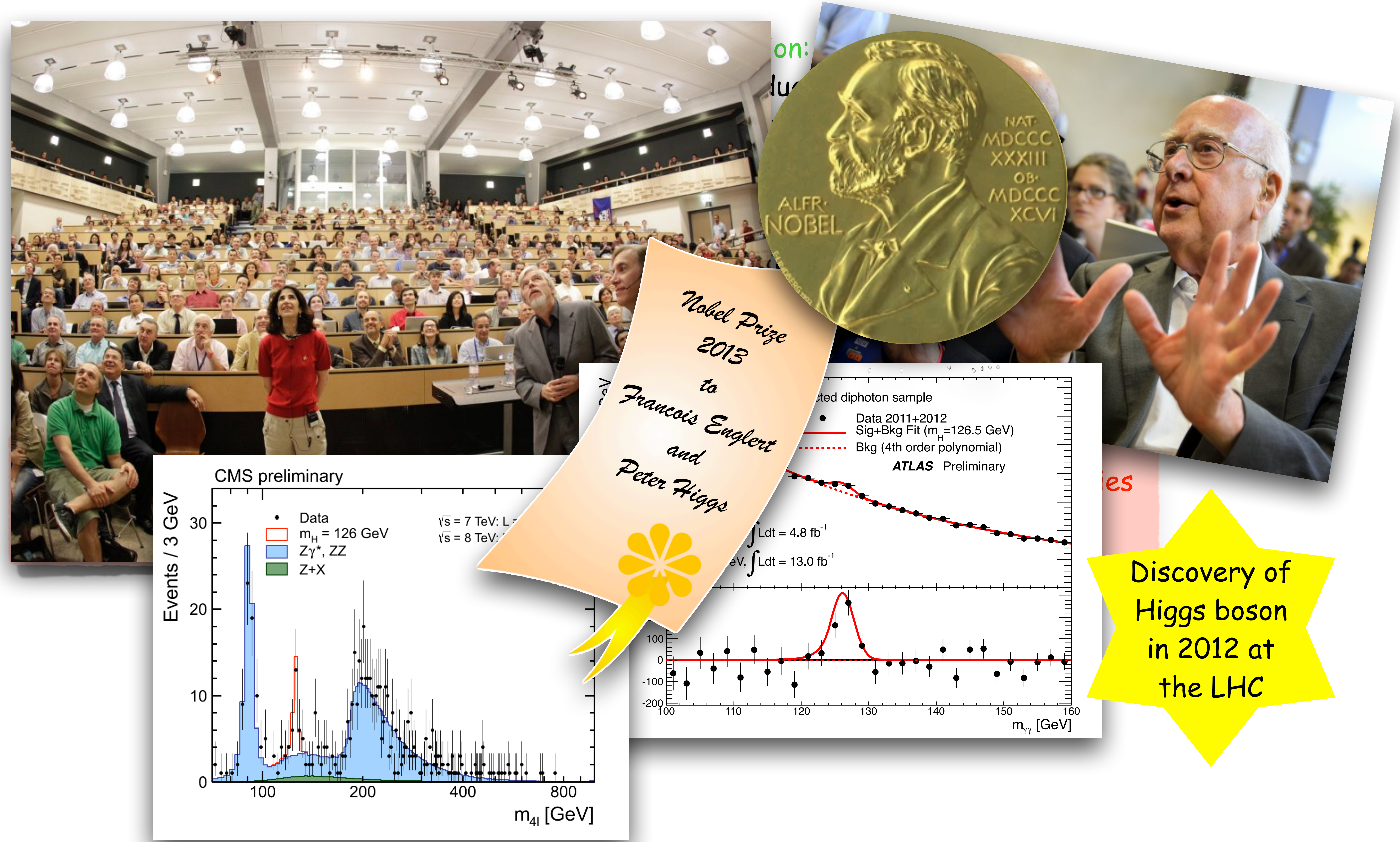
Discovery of Higgs boson in 2012 at the LHC

What is the origin of mass?

MILESTONE

The Unitarity Path to the Higgs Boson

What is the origin of mass?



Nobel Prize 2013 to Francois Englert and Peter Higgs

Discovery of Higgs boson in 2012 at the LHC

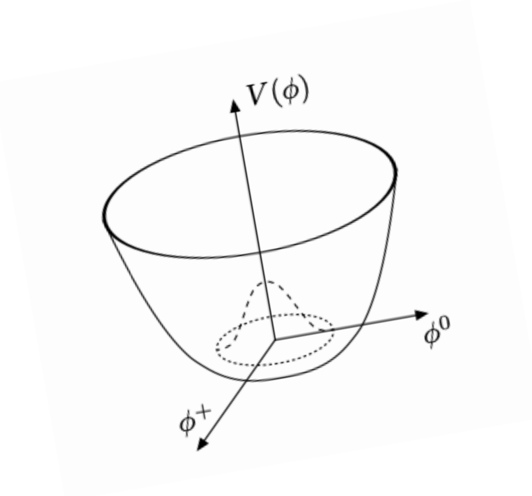
MILESTONE

The Power of Symmetries

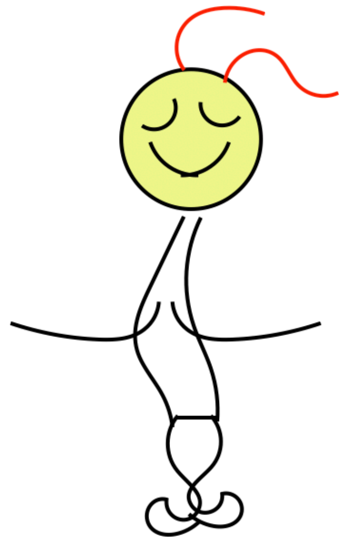
S ure

MILESTONE

Symmetry requirement:
Raison d'être for the Higgs boson



Higgs mechanism was introduced 1964 to provide masses to the gauge bosons without violating the SM gauge symmetries!



ı conservation law

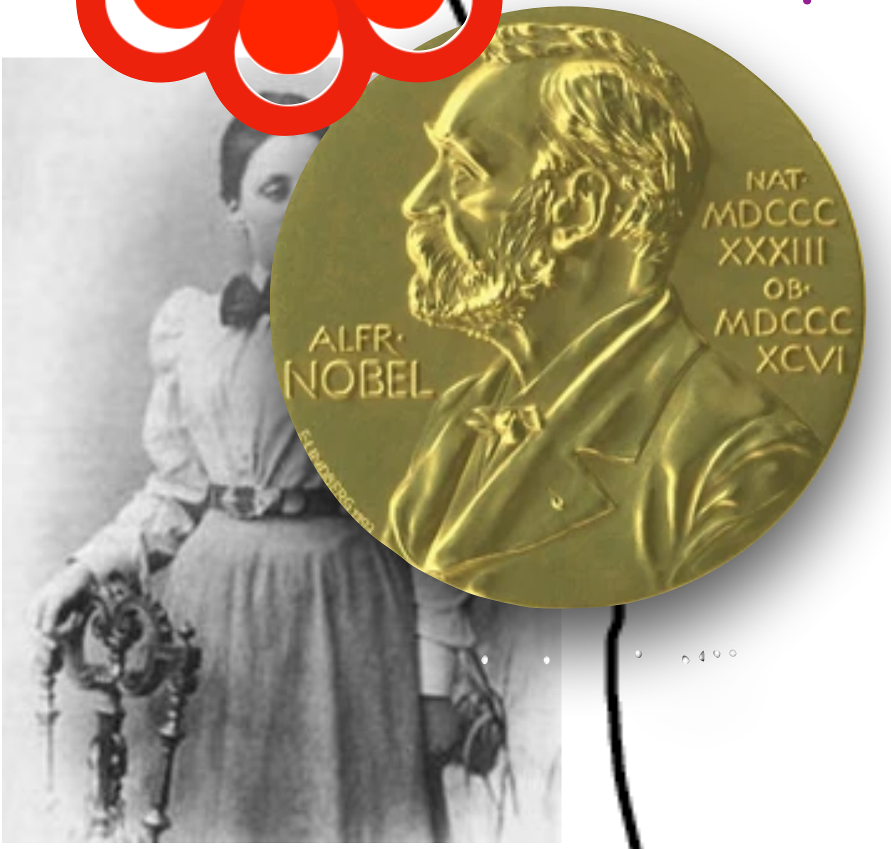
nservation

The Power of Symmetries

S

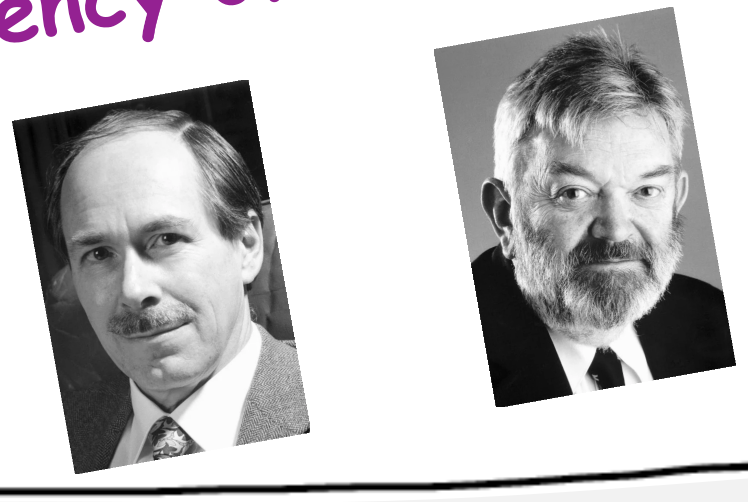
ure

MILESTONE



Nobel Prize 1999 for 't Hooft and Veltman "for elucidating the **quantum structure** of electroweak interactions in physics"

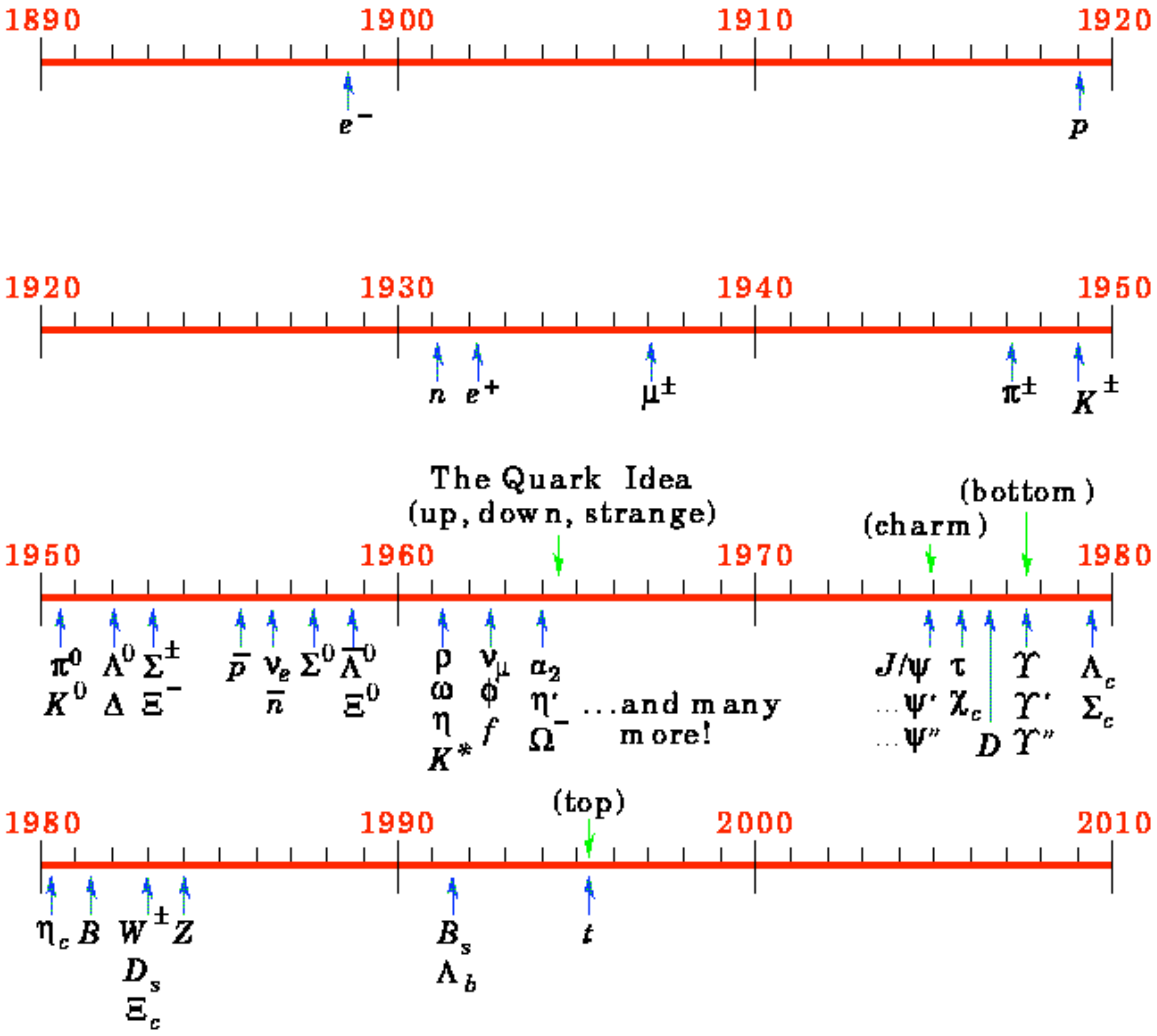
Showed that electroweak gauge theory also holds at the quantum level => **Consistency of the theory**



ı conservation law

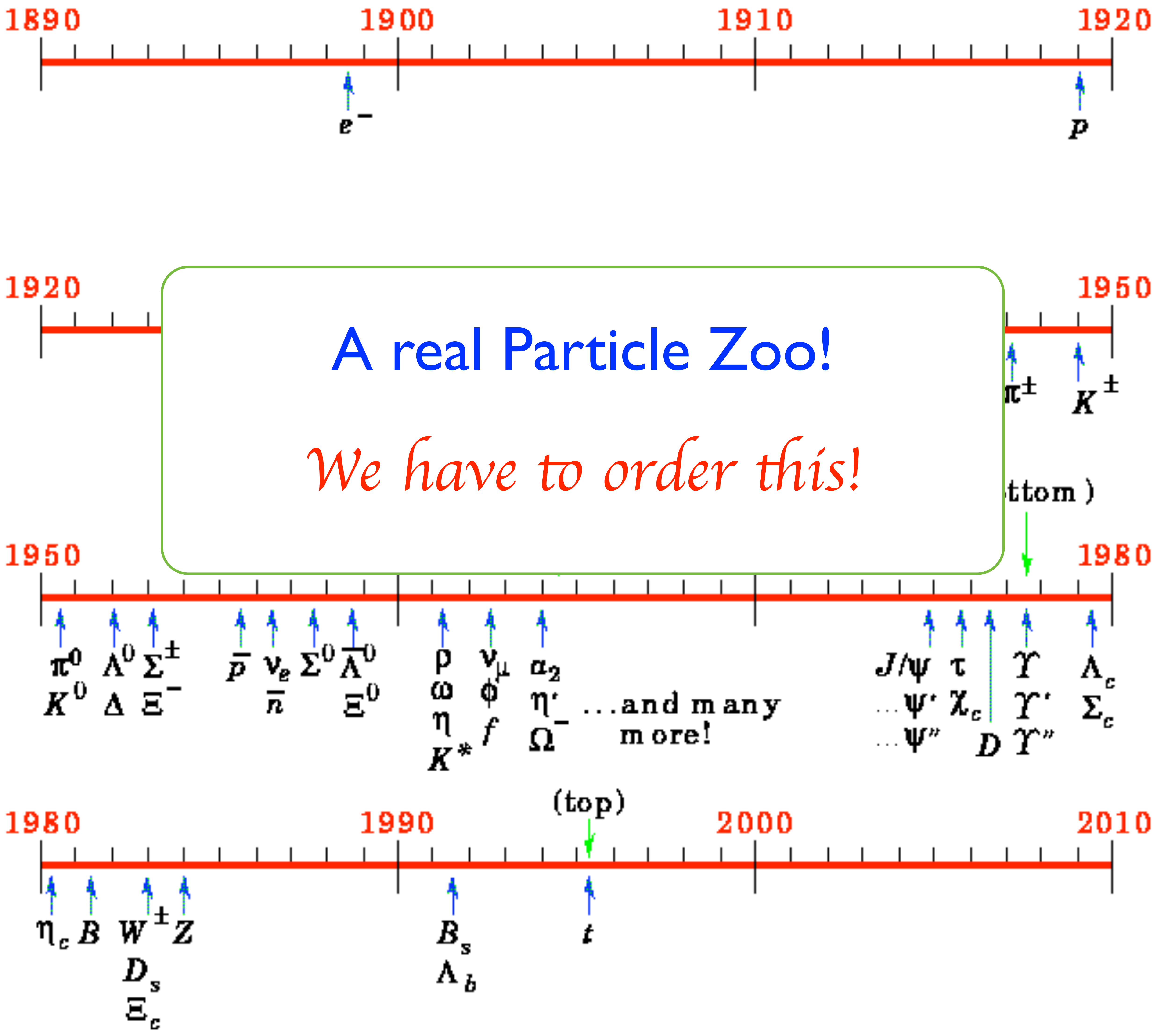
nservation

Partons – the Constituents of Quantum Chromo Dynamics (QCD)



Can we get order in the particle zoo?

Partons – the Constituents of Quantum Chromo Dynamics (QCD)

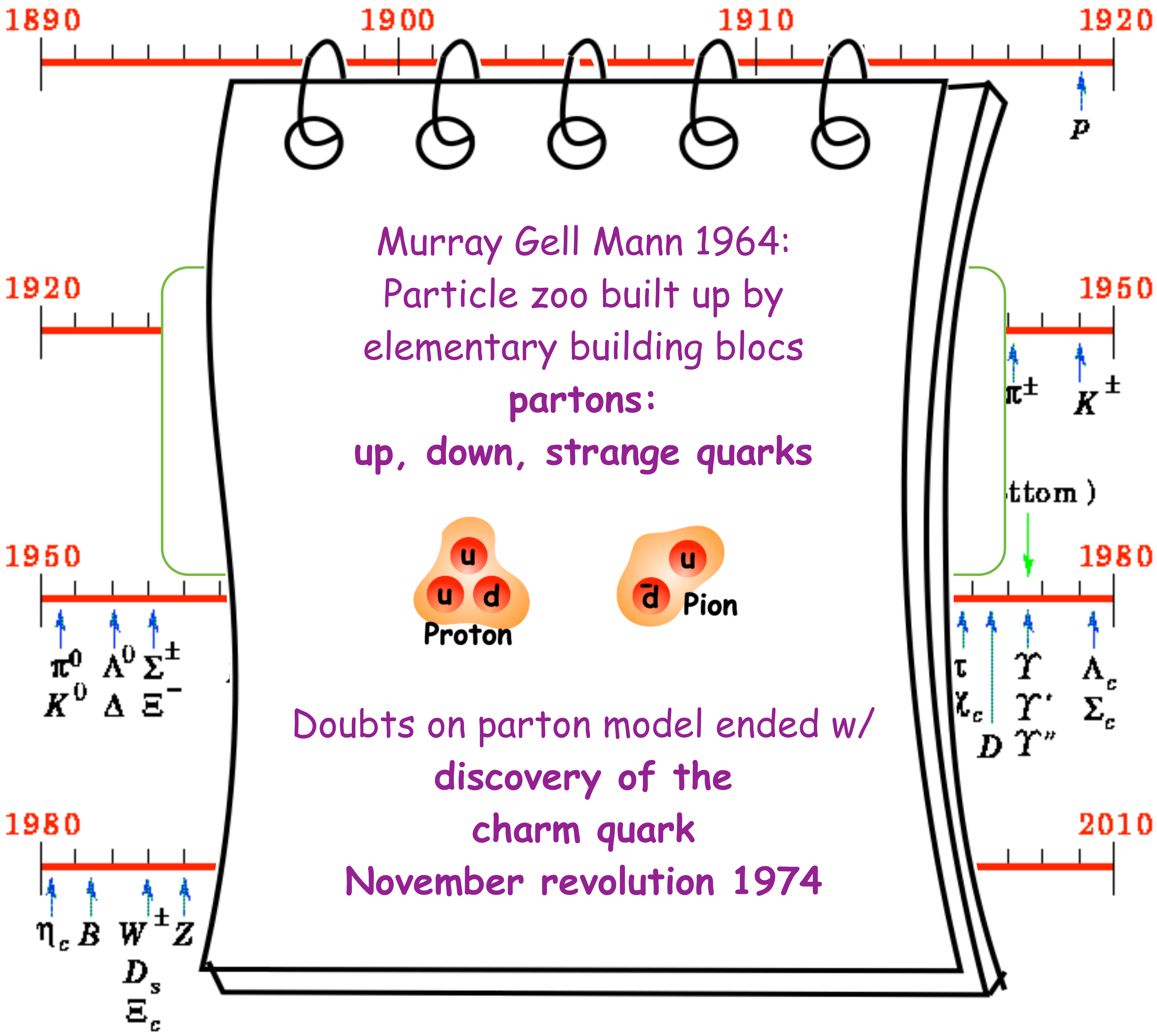


A real Particle Zoo!

We have to order this!

Can we get order in the particle zoo?

Partons – the Constituents of Quantum Chromo Dynamics (QCD)



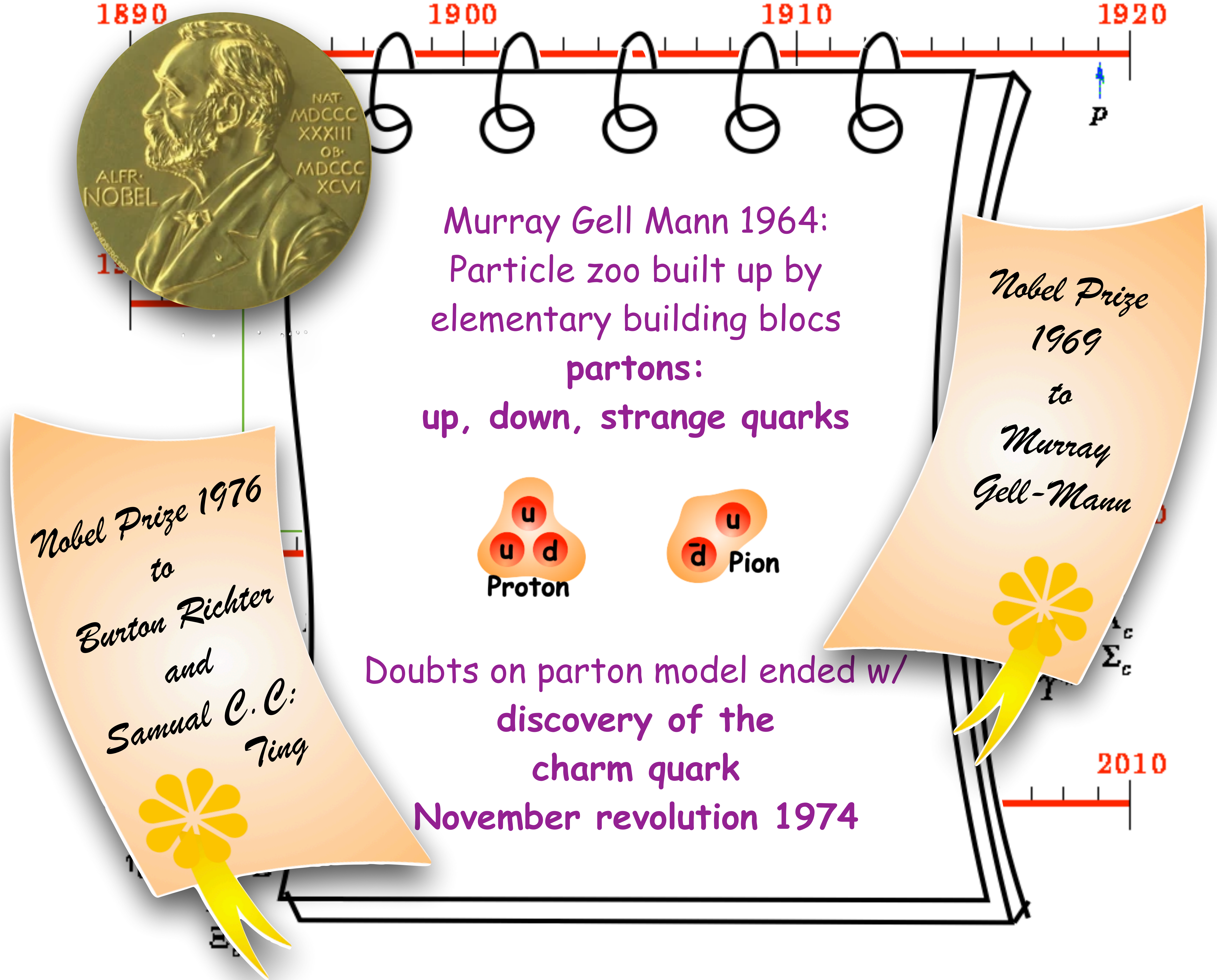
Murray Gell Mann 1964:
Particle zoo built up by
elementary building blocs
partons:
up, down, strange quarks

Doubts on parton model ended w/
discovery of the
charm quark
November revolution 1974

Can we get order in the particle zoo?

HIGHLIGHT

Partons - the Constituents of Quantum Chromo Dynamics (QCD)



Murray Gell Mann 1964:
Particle zoo built up by
elementary building blocs
partons:
up, down, strange quarks

Doubts on parton model ended w/
discovery of the
charm quark
November revolution 1974

Nobel Prize 1969 to Murray Gell-Mann

Nobel Prize 1976 to Burton Richter and Samual C.C. Ting

Can we get order in the particle zoo?

HIGHLIGHT

Quantum Chromodynamics (QCD)

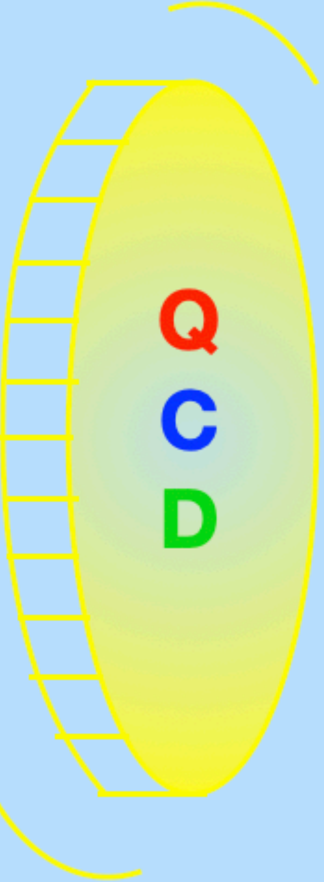
- QCD: quantum field theory of the strong interaction

Two sides of a coin

Confinement:

Quarks cannot be separated ~> no free quarks

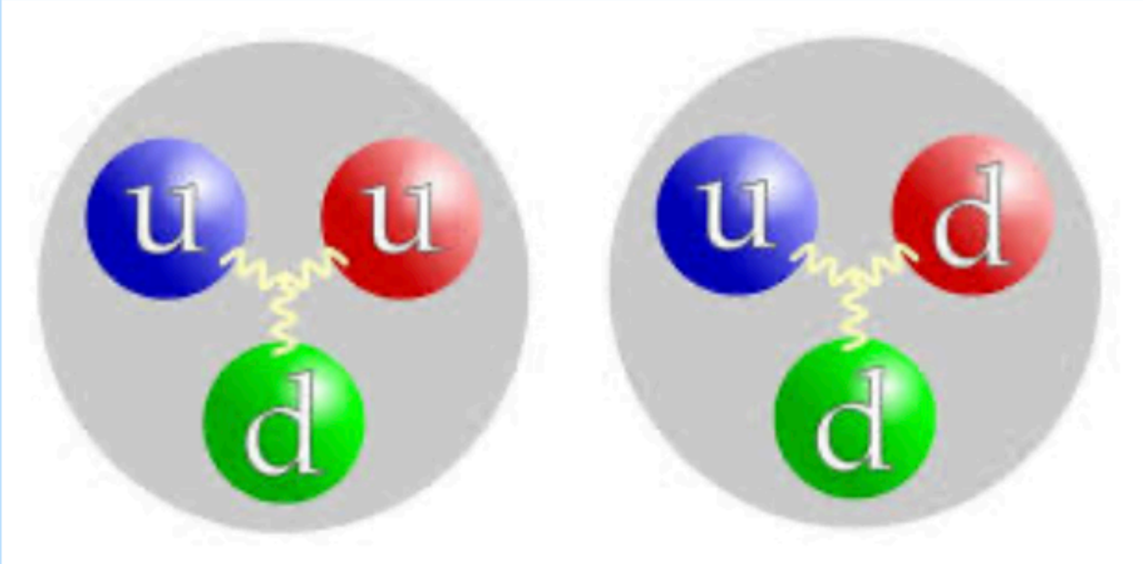
=> stability of nucleons

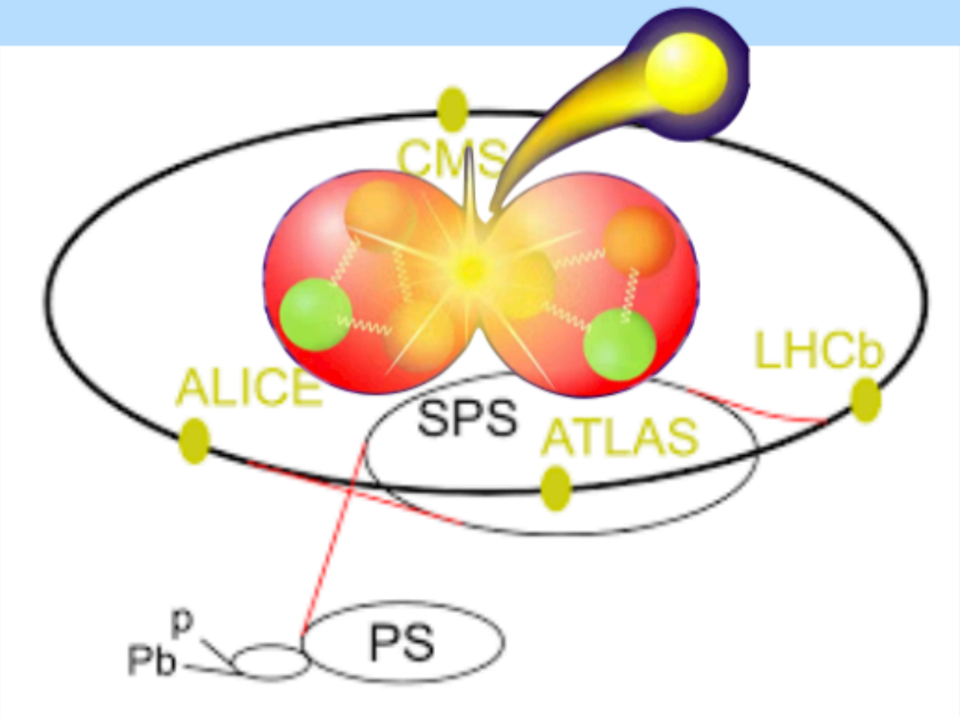


Asymptotic freedom:

Quarks are asymptotic free at high-energies

=> collider physics





Can we understand quark bound states?

MILESTONE

Quantum Chromodynamics (QCD)

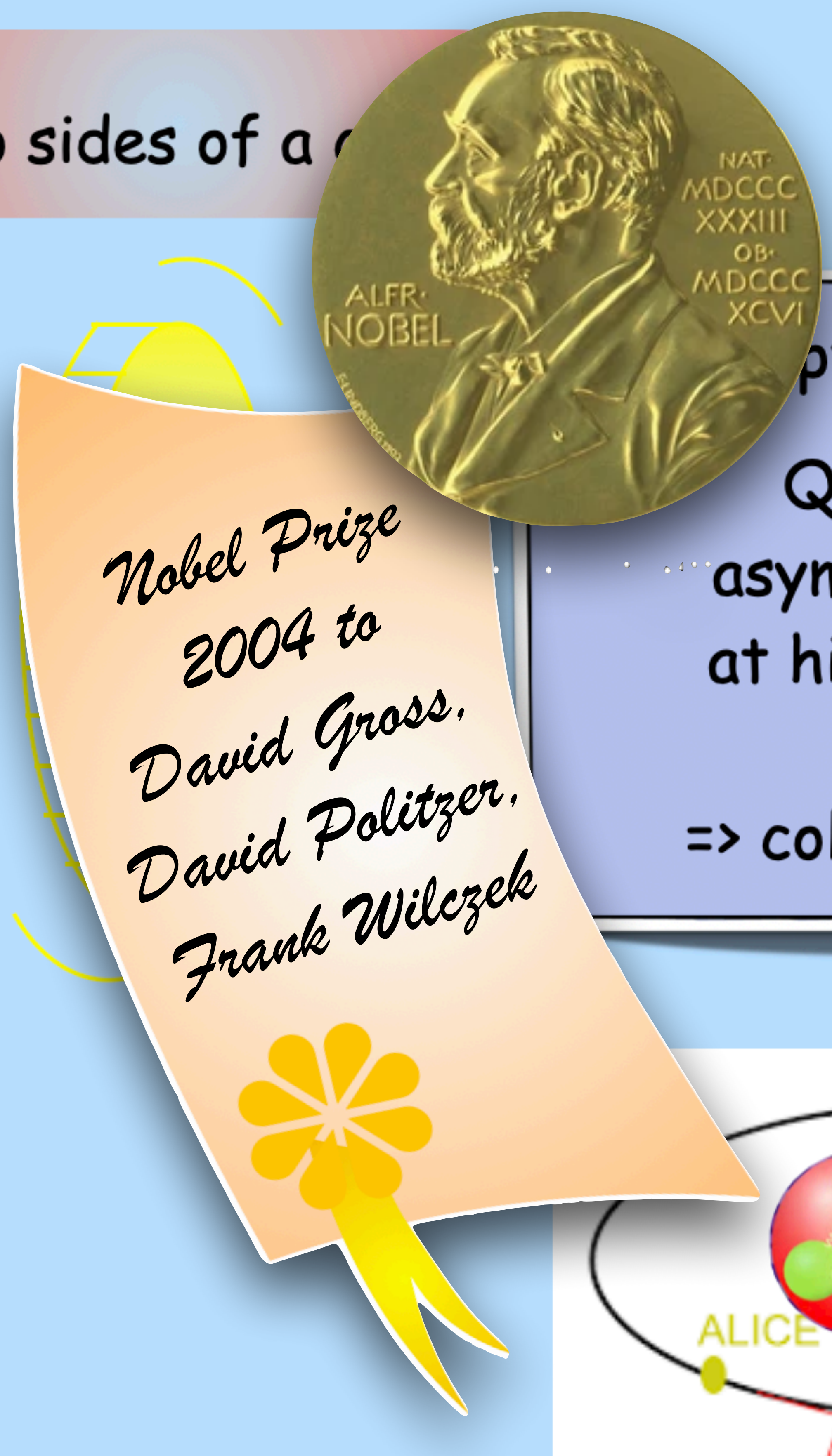
- QCD: quantum field theory of the strong interaction

Two sides of a c

Confinement:

Quarks cannot be separated ~> no free quarks

=> stability of nucleons

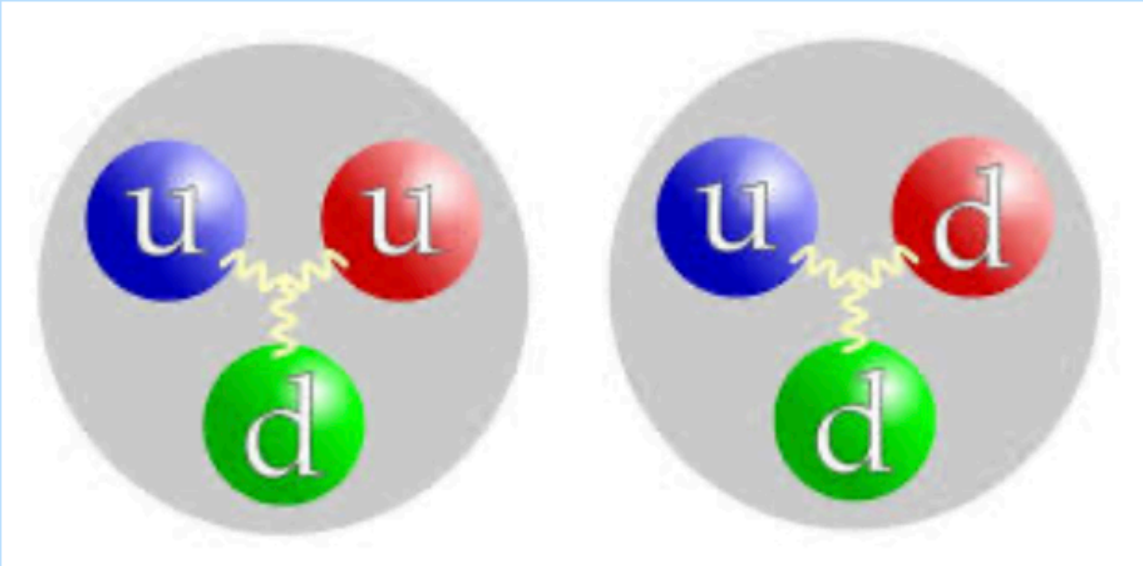


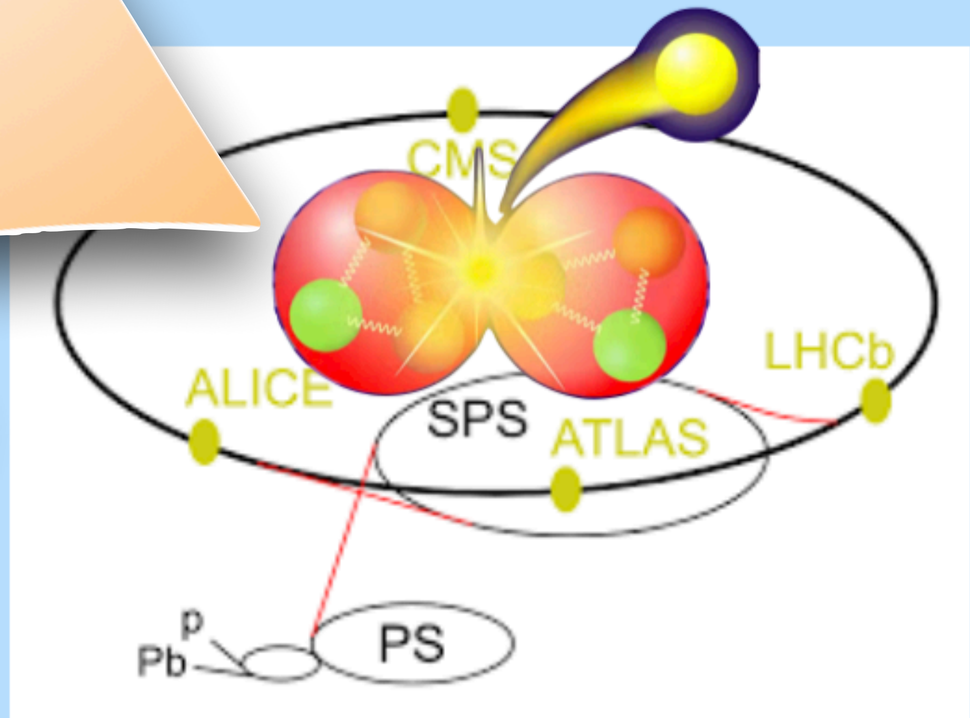
Nobel Prize 2004 to David Gross, David Politzer, Frank Wilczek

ptotic freedom:

Quarks are asymptotic free at high-energies

=> collider physics





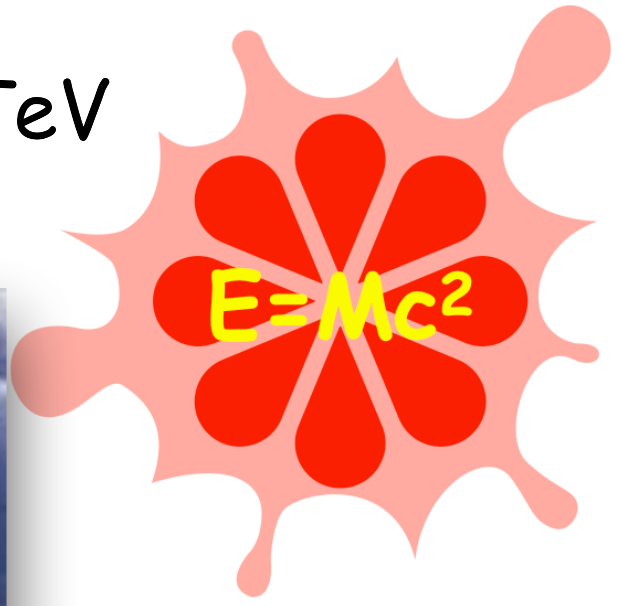
Can we understand quark bound states?

MILESTONE

SM Tests at the Large Hadron Collider (LHC)

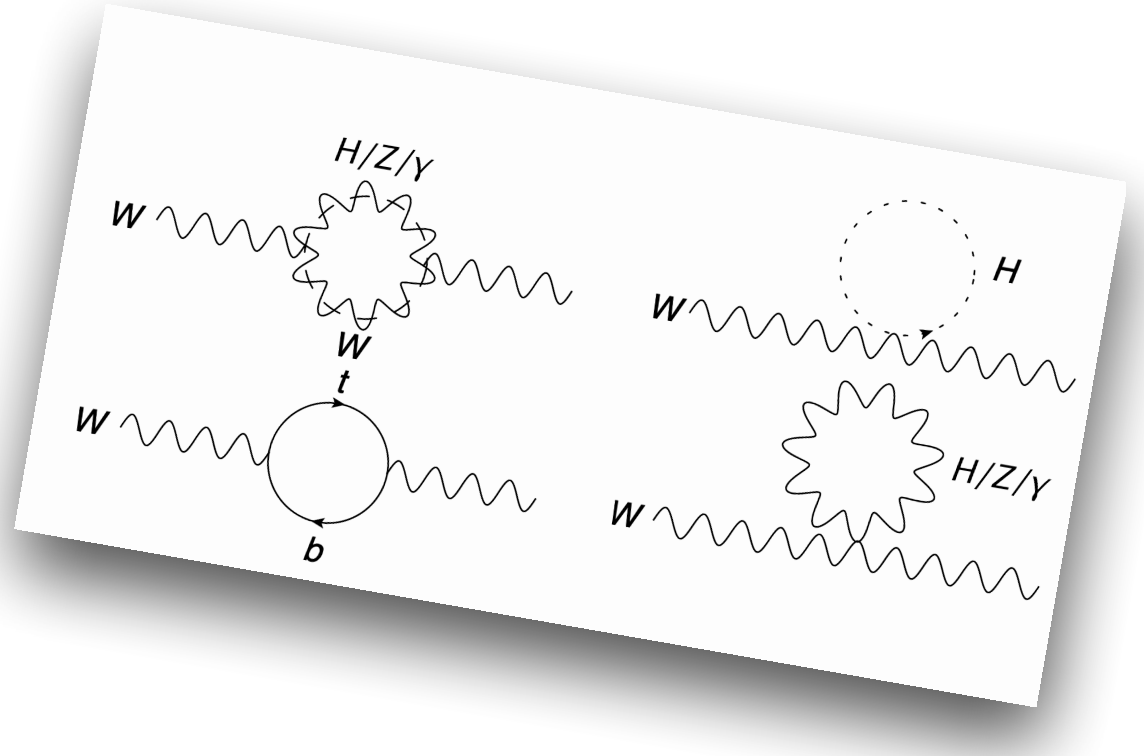
The Large Hadron Collider (LHC)

- Large Hadron Collider (LHC): collision of proton bunches at a center-or-mass energy of 14 TeV



- Machine of superlatives:
  total integrated luminosity 2024:
  196 fb^{-1} ~> precision measurements

- Standard Model test:
  at the quantum level

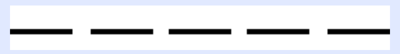


- Operation: since 2009, presently Run 3, until end 2026; long shutdown 2027-29; high-luminosity LHC 2030 w/ 3 ab^{-1} in 10 years

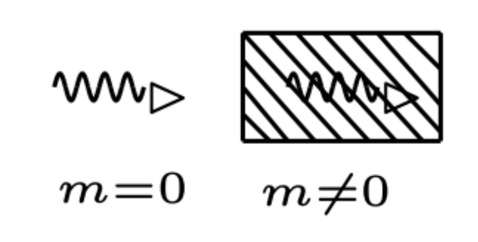
What we know about the Higgs Boson

Test of the Higgs Mechanism

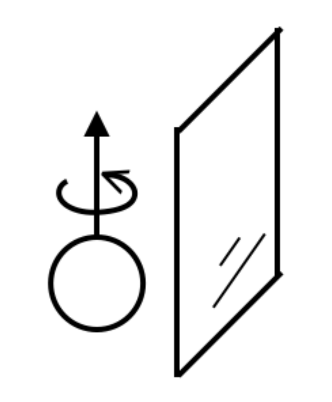
- ❖ Discovery M_H



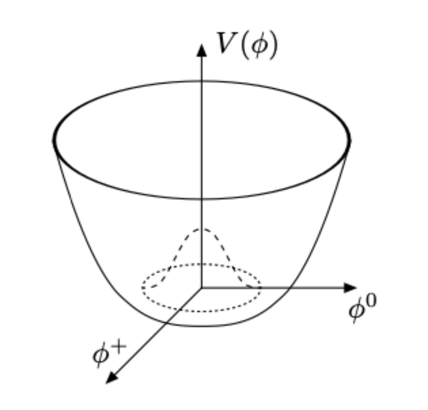
- ❖ Interactions $g^{\mathrm{H}}_{\mathrm{SMSM}} \sim m^{(2)}_{\mathrm{SM}}$



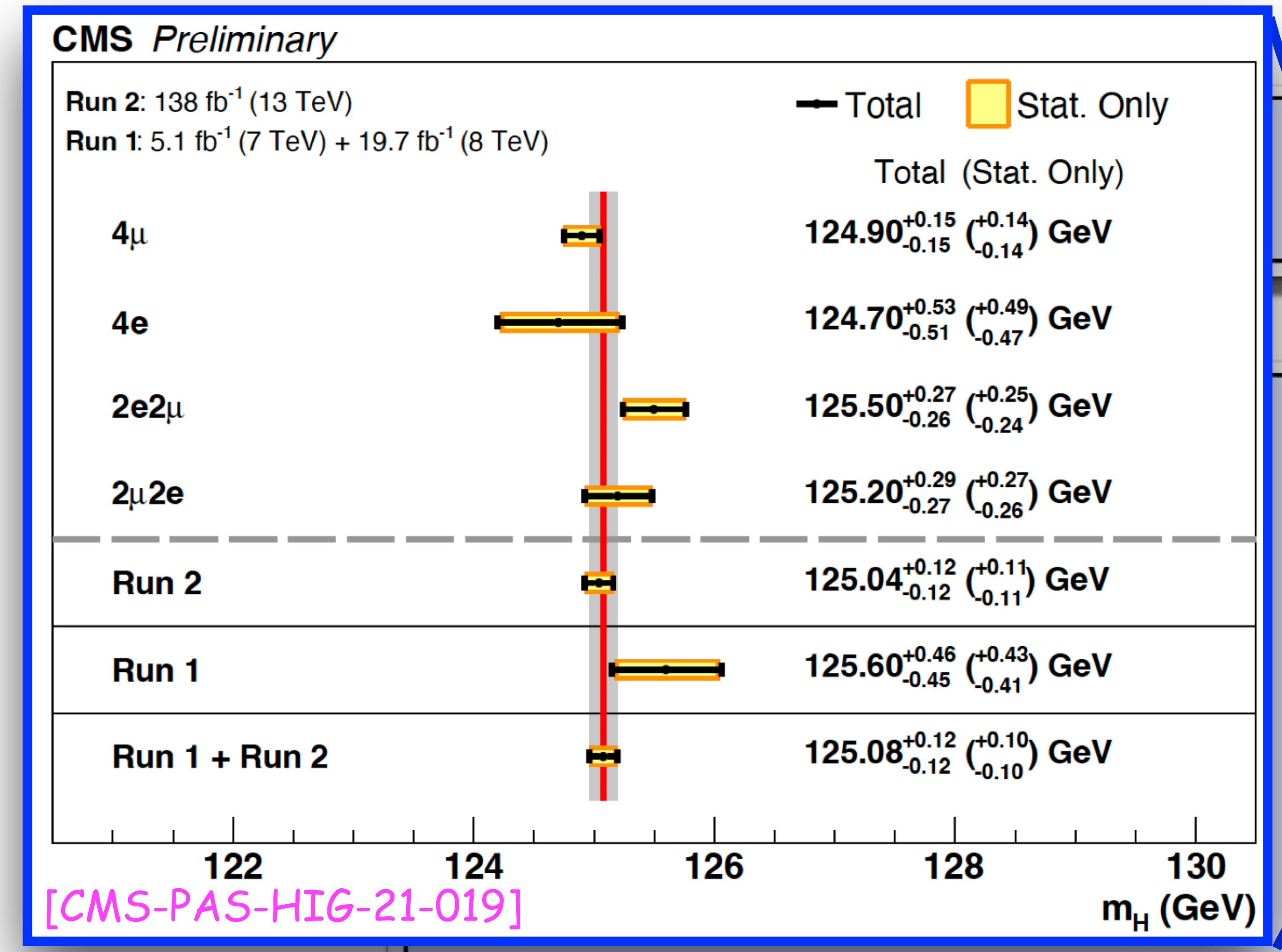
- ❖ Spin, parity quantum numbers J^{PC}



- ❖ EWSB Higgs potential $\lambda_{\mathrm{HHH}}, \lambda_{\mathrm{HHHH}}$



What we know about the Higgs Boson

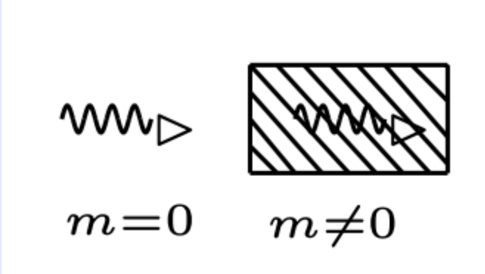


[CMS-PAS-HIG-21-019]

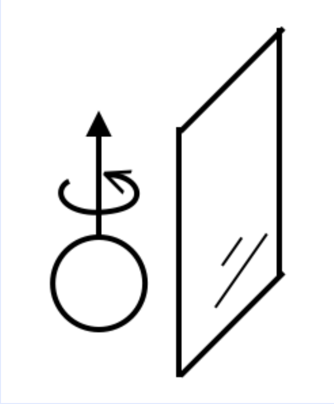
of the Higgs Mechanism

M_H

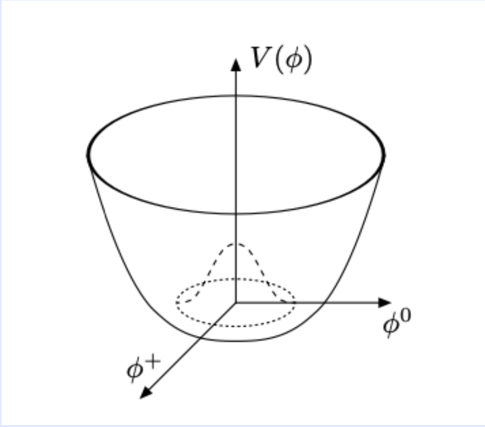
$g^{H}_{\mathrm{SMSM}} \sim m^{(2)}_{\mathrm{SM}}$



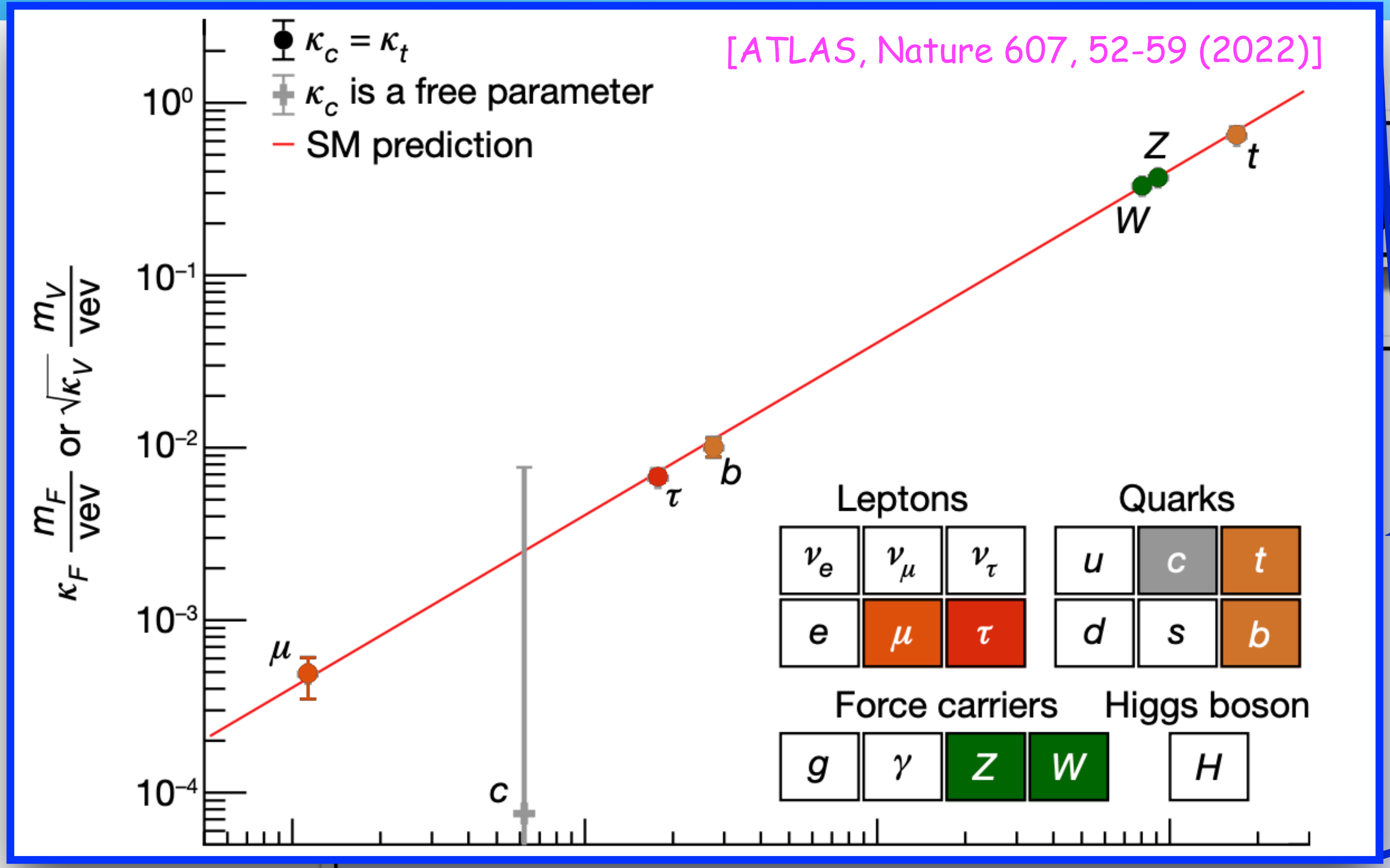
- ❖ Spin, parity quantum numbers J^{PC}



- ❖ EWSB Higgs potential $\lambda_{\mathrm{HHH}}, \lambda_{\mathrm{HHHH}}$



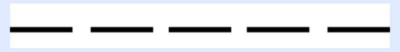
What we know about the Higgs Boson



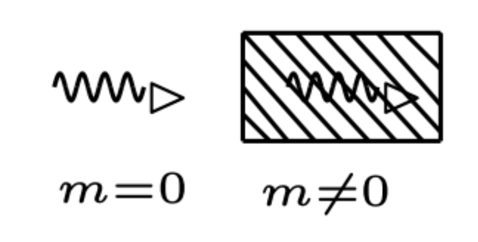
[ATLAS, Nature 607, 52-59 (2022)]

gs Mechanism

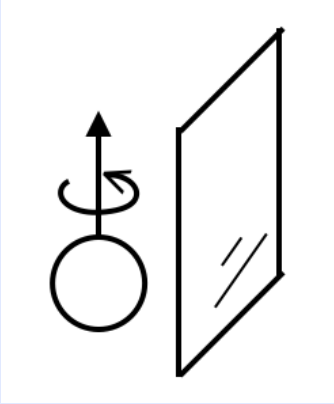
M_H



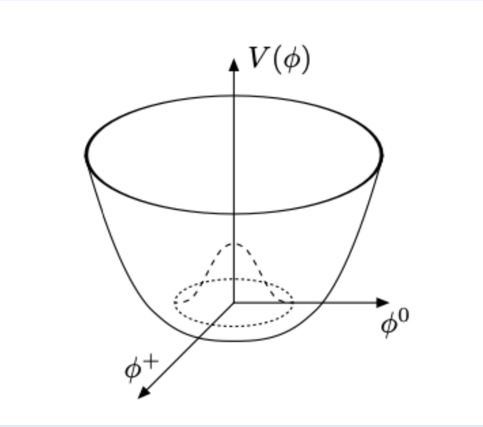
$g^{\text{H}}_{\text{SMSM}} \sim m^{(2)}_{\text{SM}}$



- Spin, parity quantum numbers J^{PC}

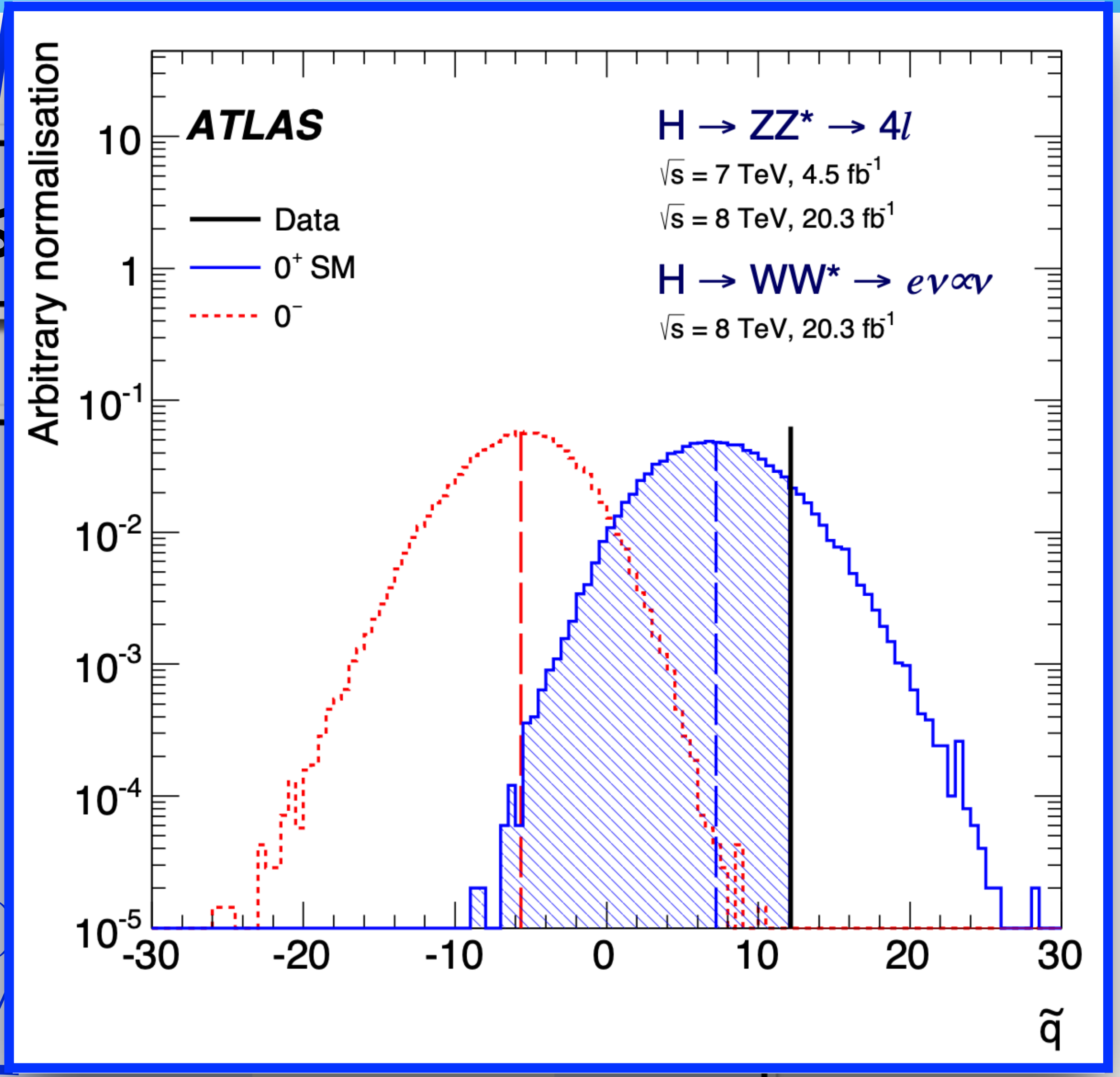


- EWSB Higgs potential $\lambda_{\text{HHH}}, \lambda_{\text{HHHH}}$

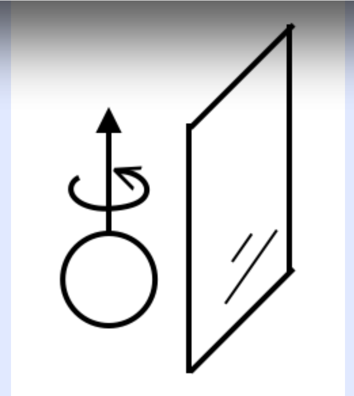


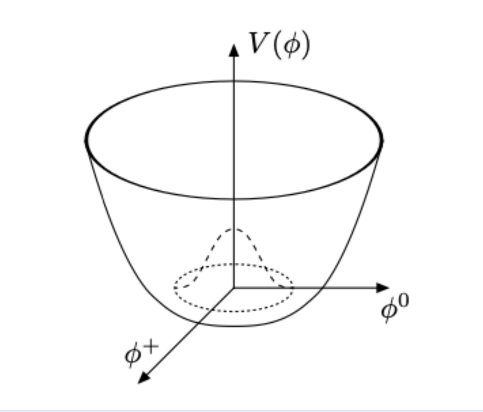
What we know about the Higgs Boson

Test of the Higgs Mechanis



- ❖ Discovery M_H
- ❖ Interactions $g^{\rm H}_{\rm SMSM} \sim m^{(2)}_{\rm SM}$
- ❖ Spin, parity quantum numbers $J^{\rm PC}$
- ❖ EWSB Higgs potential $\lambda_{\rm HHH}, \lambda_{\rm HHHH}$

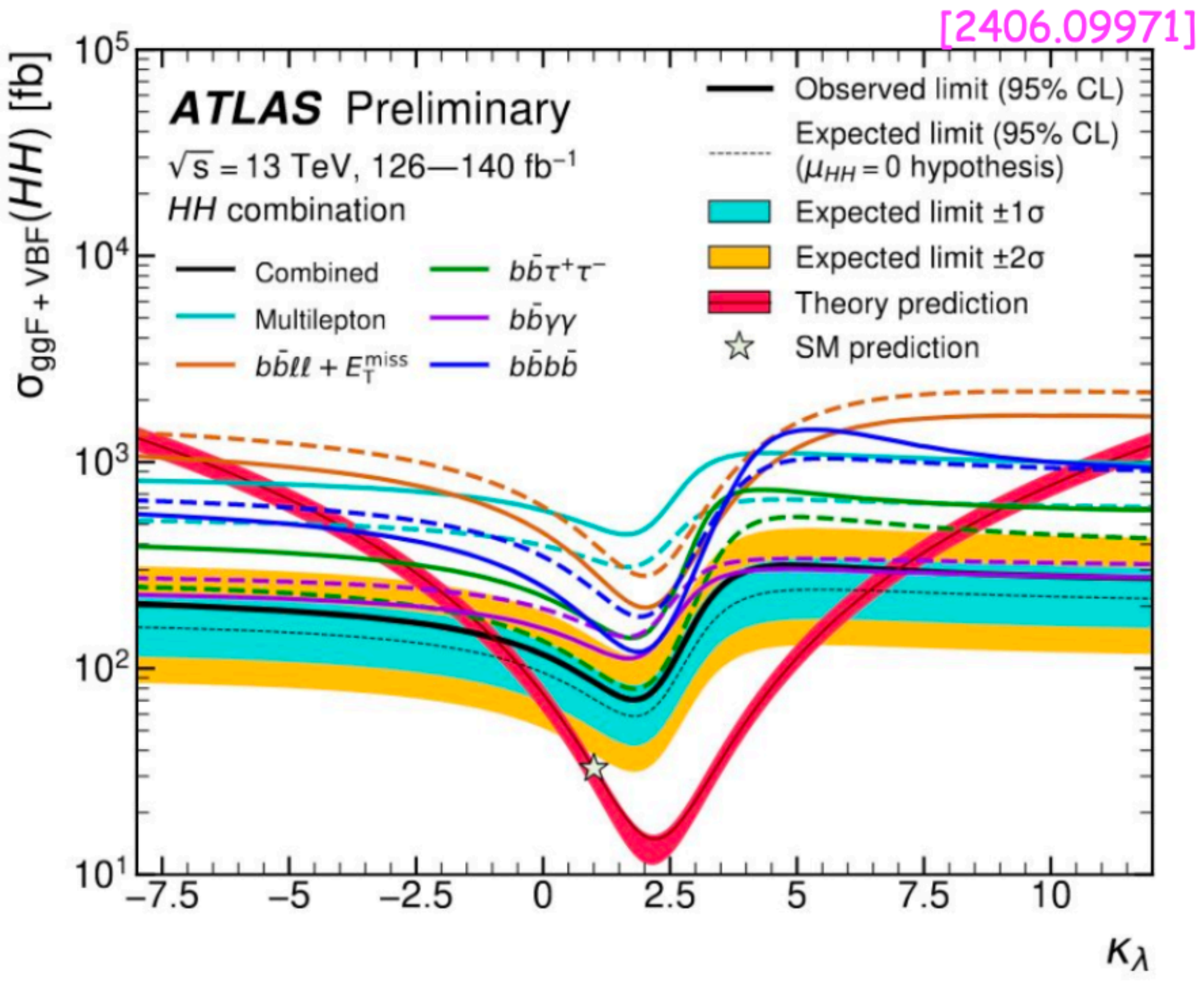


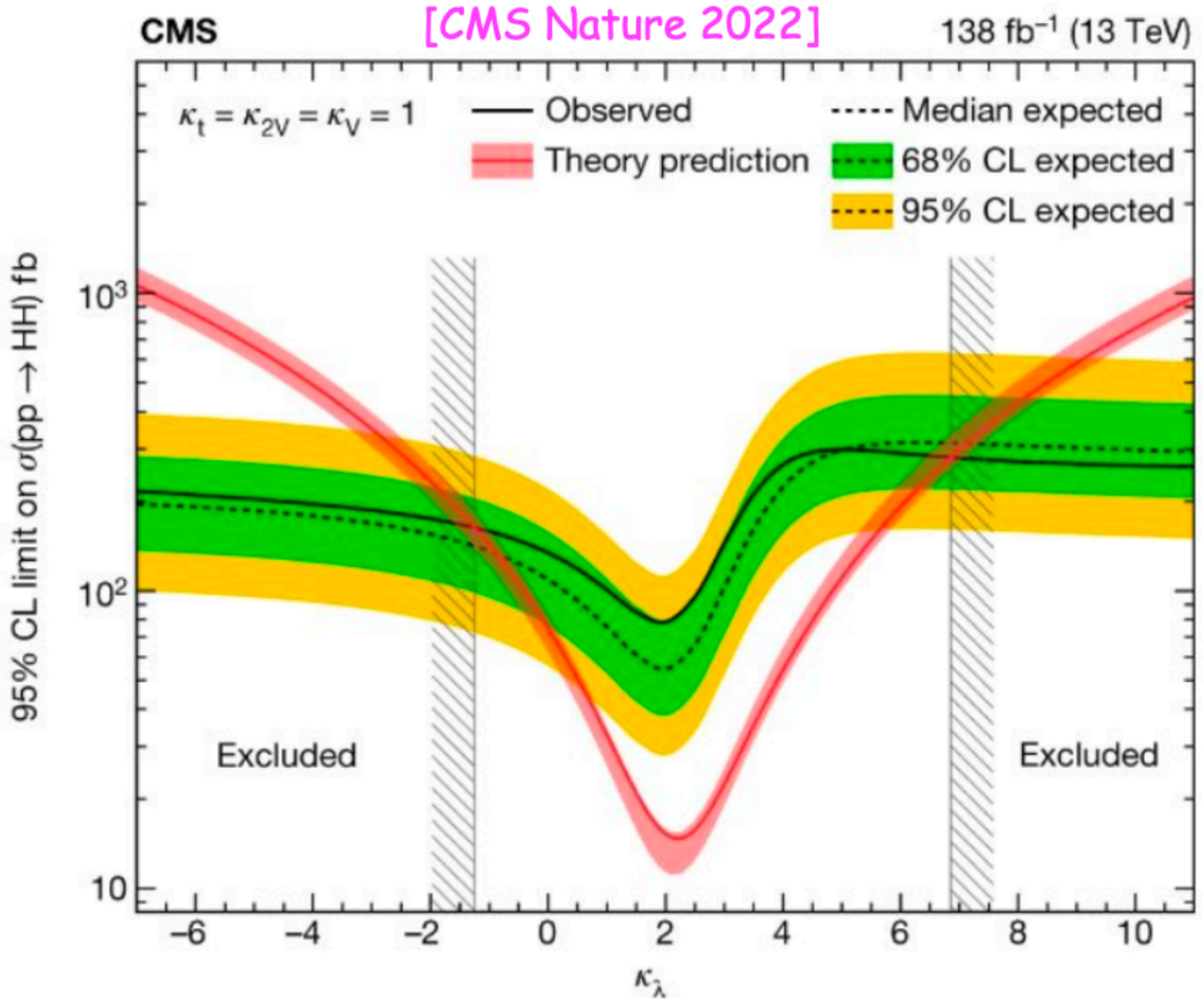


What we know about the Higgs Boson

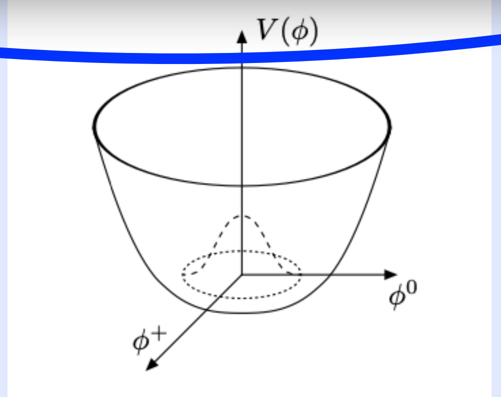
ATLAS: $-1.2 < \kappa_\lambda < 7.2$ at 95 % CL

CMS: $-1.24 < \kappa_\lambda < 6.49$ at 95 % CL





- ❖ EWSB Higgs potential $\lambda_{HHH}, \lambda_{HHHH}$

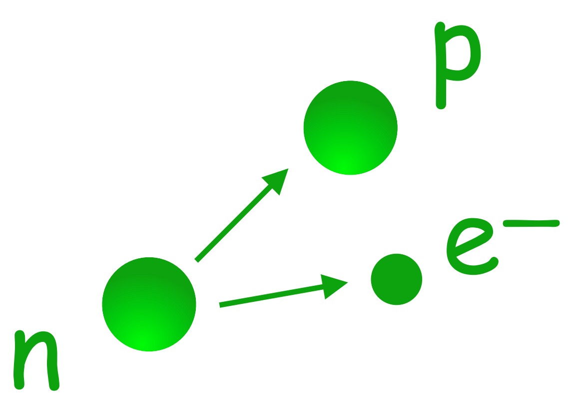


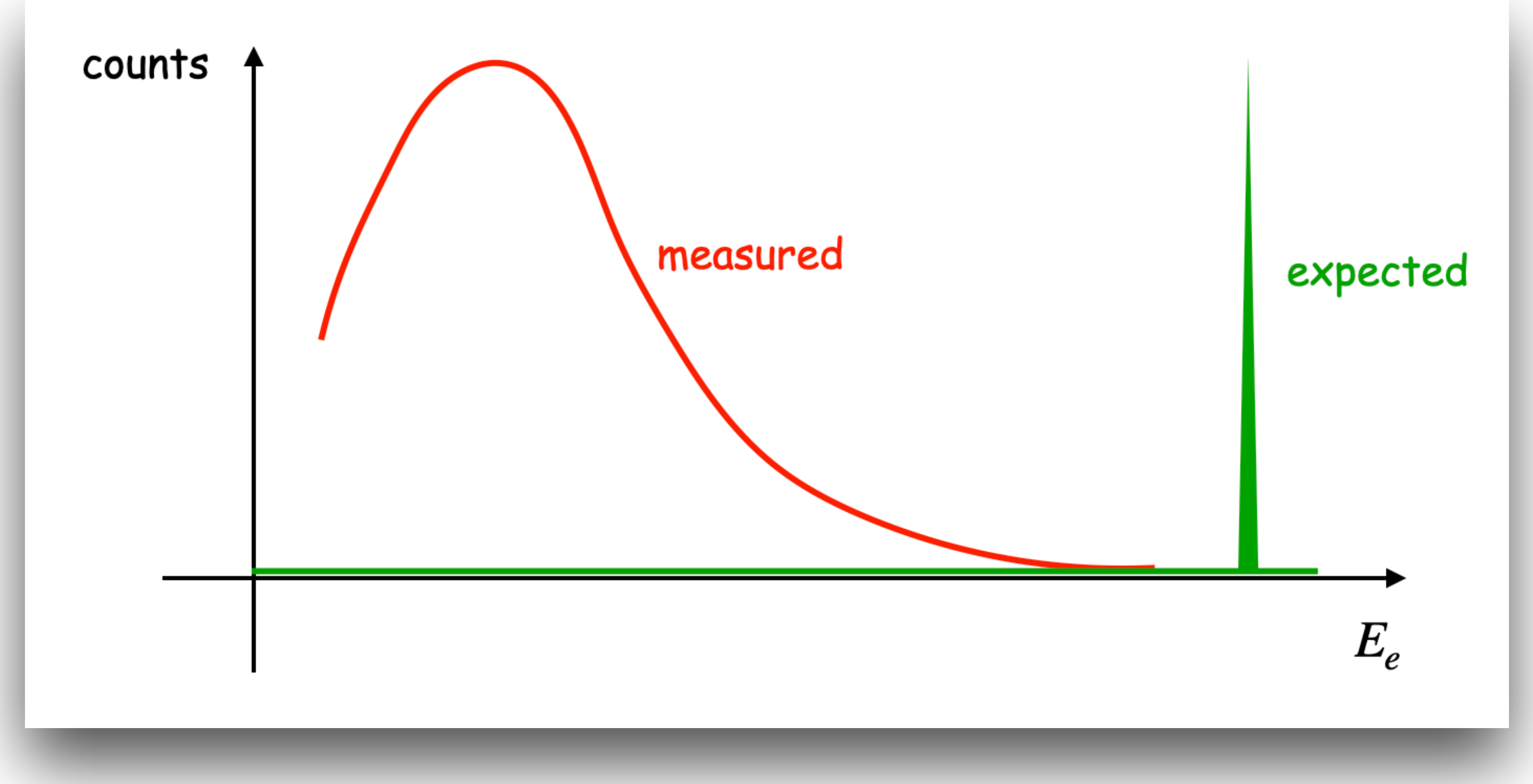
Neutrinos

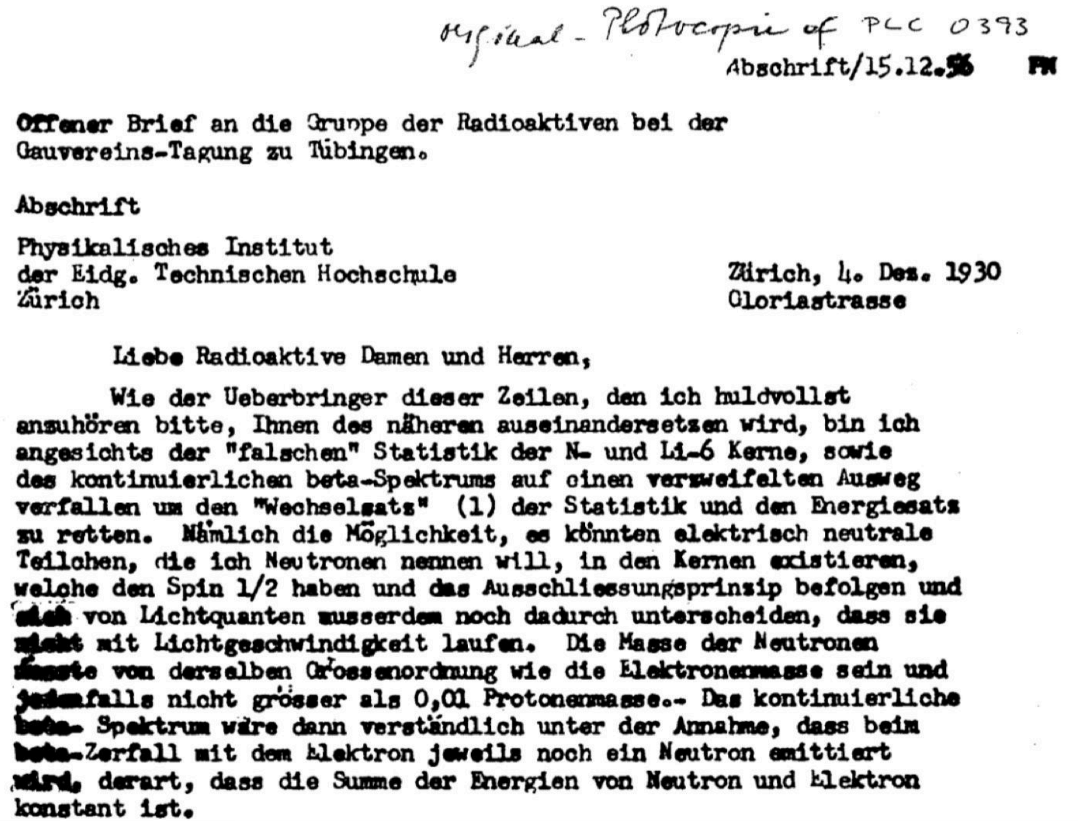
How light are neutrinos and why? Can neutrinos make up for Dark Matter?

Let's talk about Neutrinos

- **Neutrino:** suggested 1930 by Wolfgang Pauli for energy & momentum conservation in β decay







Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Grunpe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

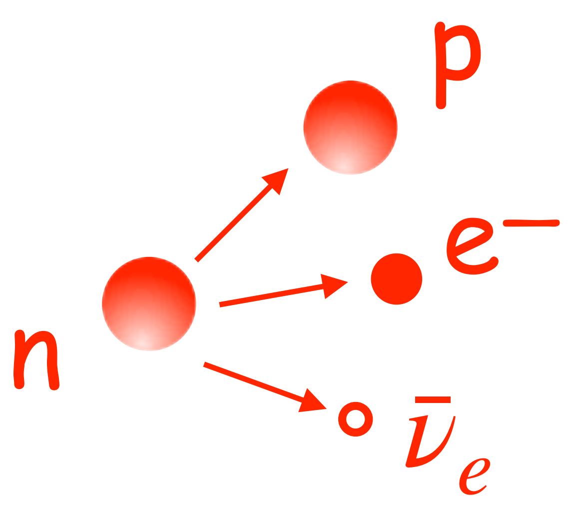
Zürich, 4. Des. 1930
Gloriastrasse

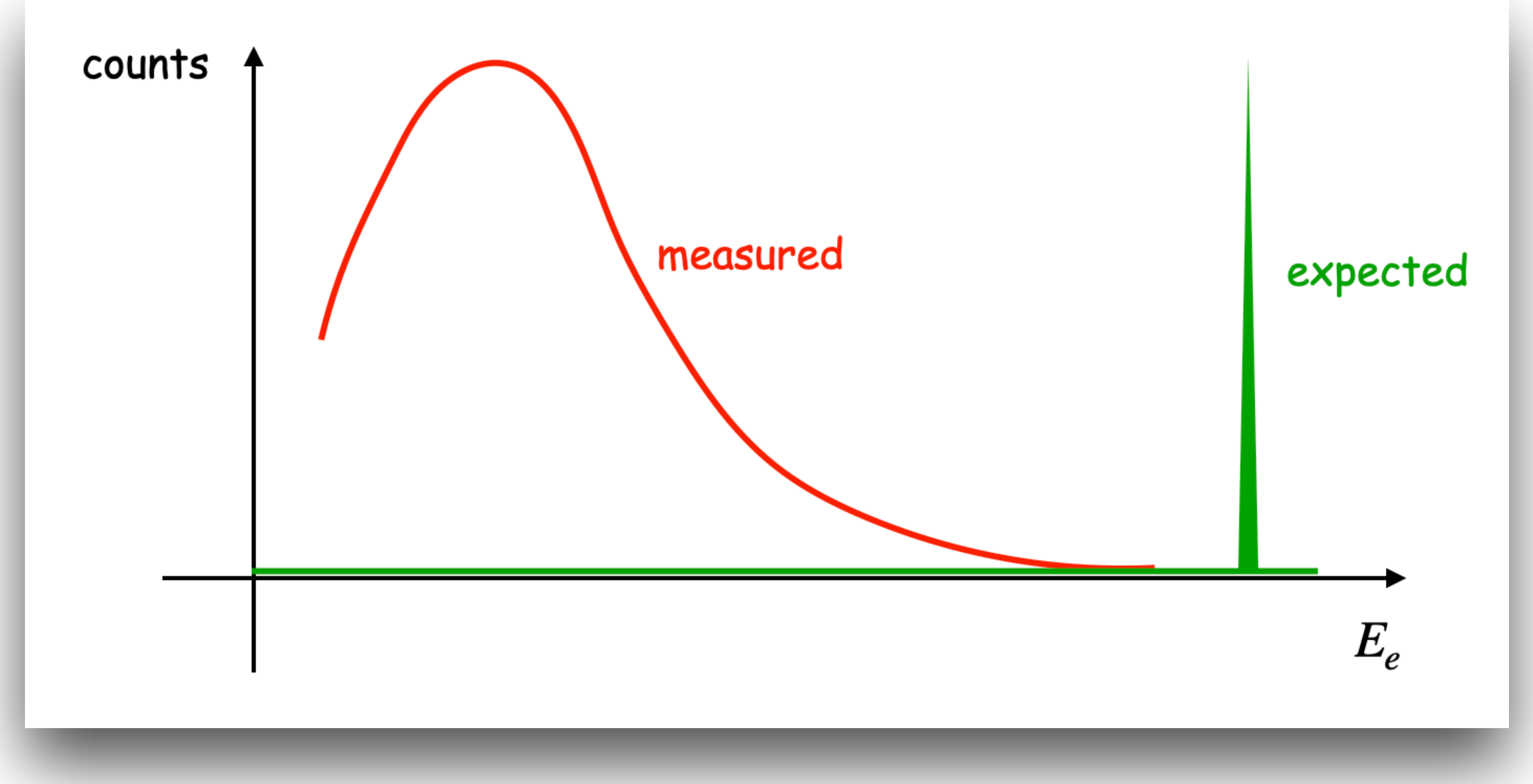
Liebe Radioaktive Damen und Herren,

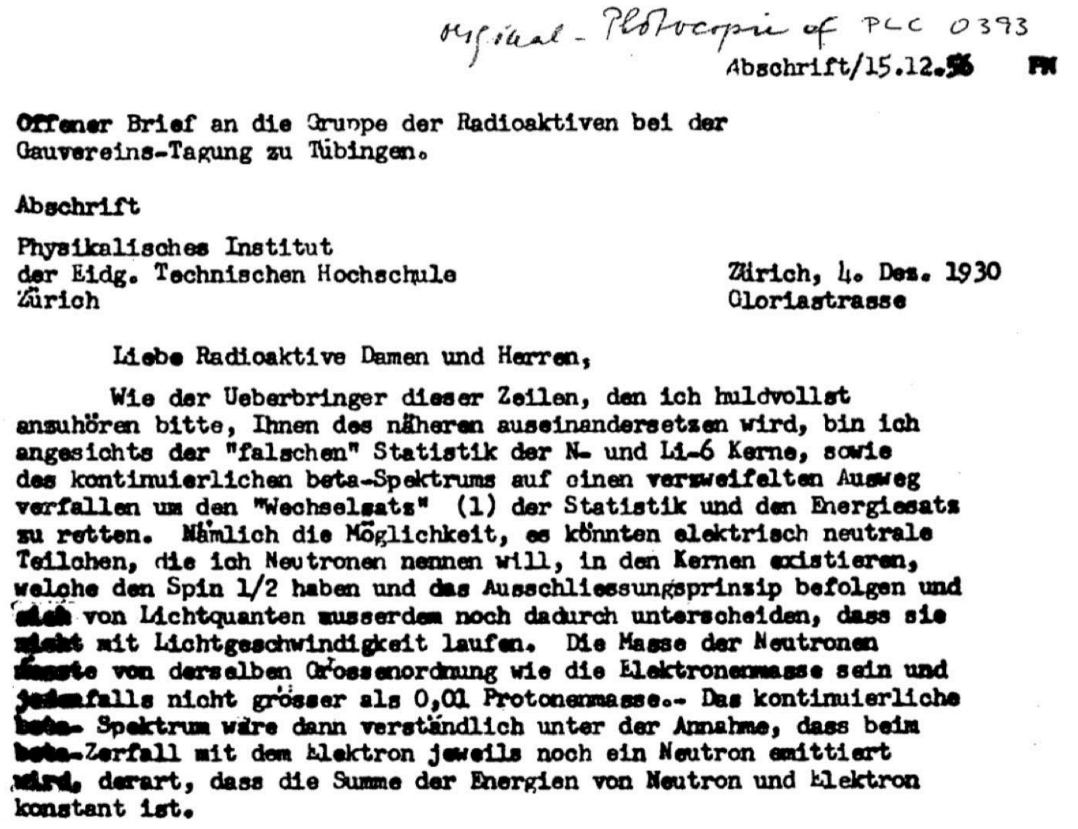
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Let's talk about Neutrinos

- **Neutrino:** suggested 1930 by Wolfgang Pauli for energy & momentum conservation in β decay







Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

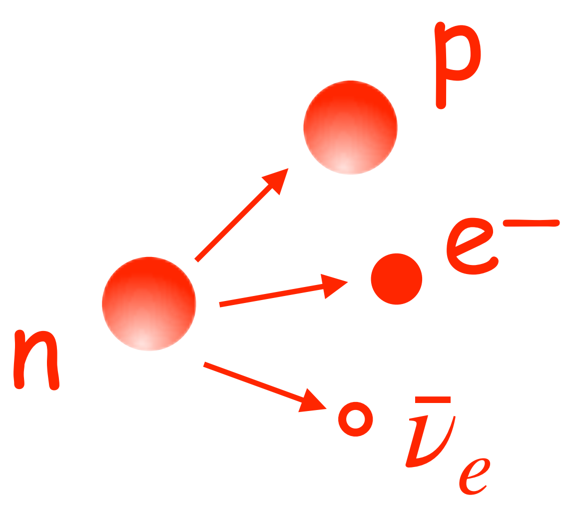
Zürich, 4. Dez. 1930
Gloriastrasse

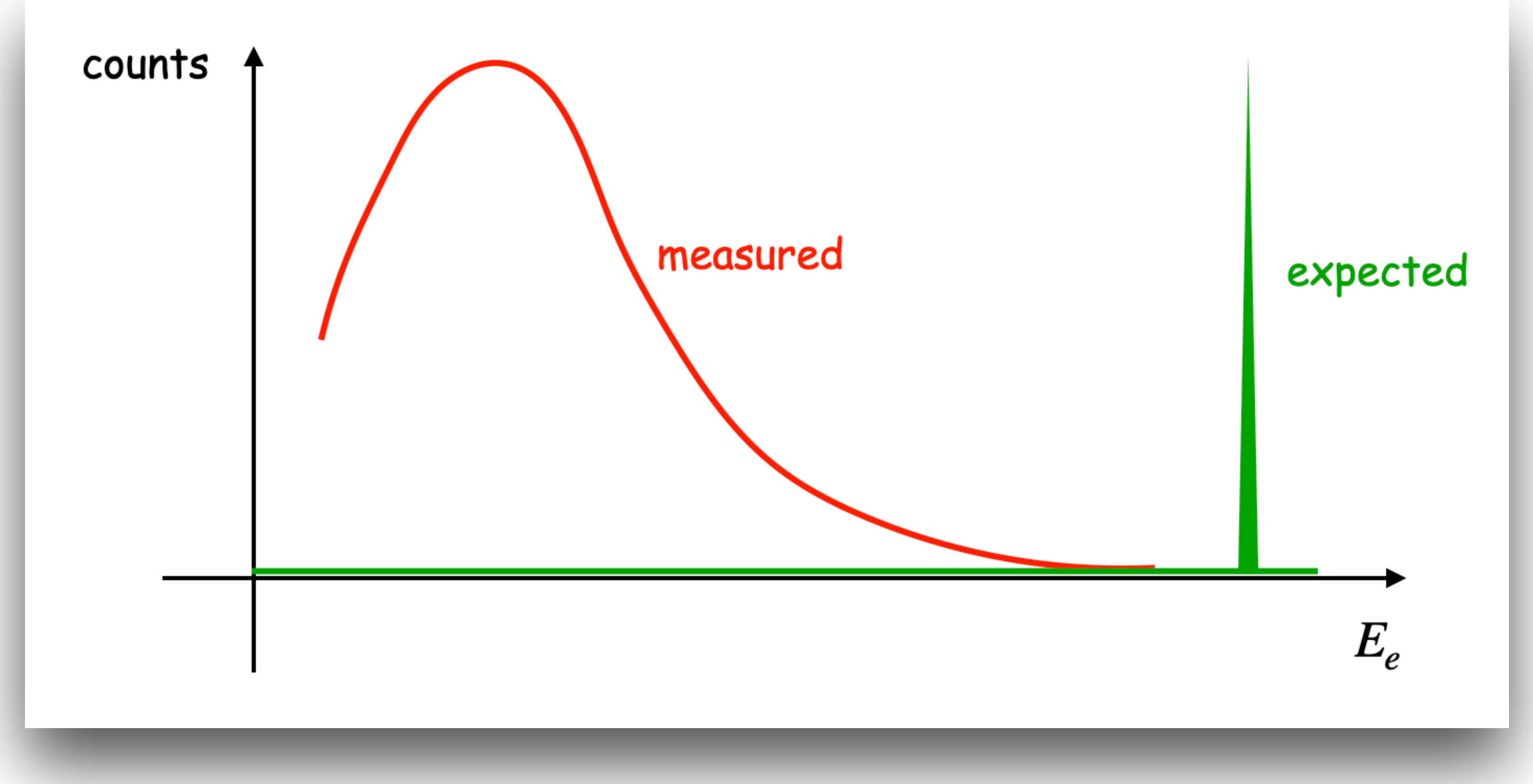
Liebe Radioaktive Damen und Herren,

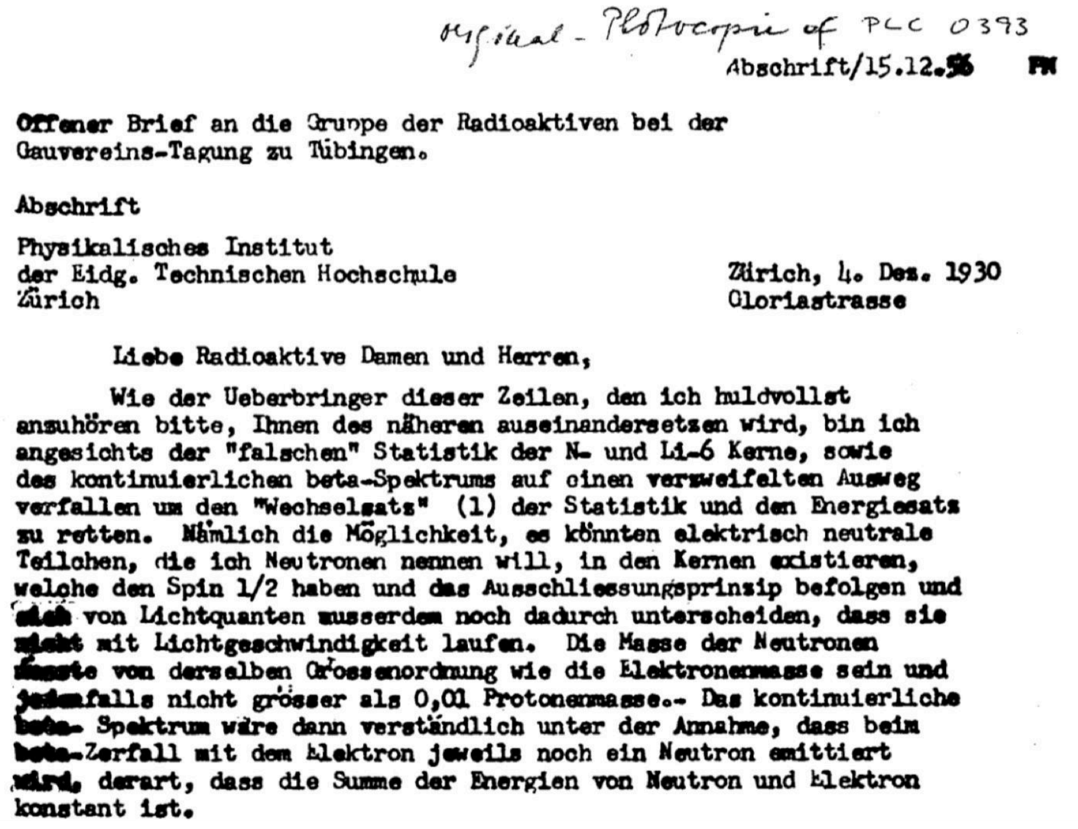
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Let's talk about Neutrinos

- **Neutrino:** suggested 1930 by Wolfgang Pauli for energy & momentum conservation in β decay







Original - Photocopie of PLC 0393
Abschrift/15.12.56 FM

Offener Brief an die Grunpe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

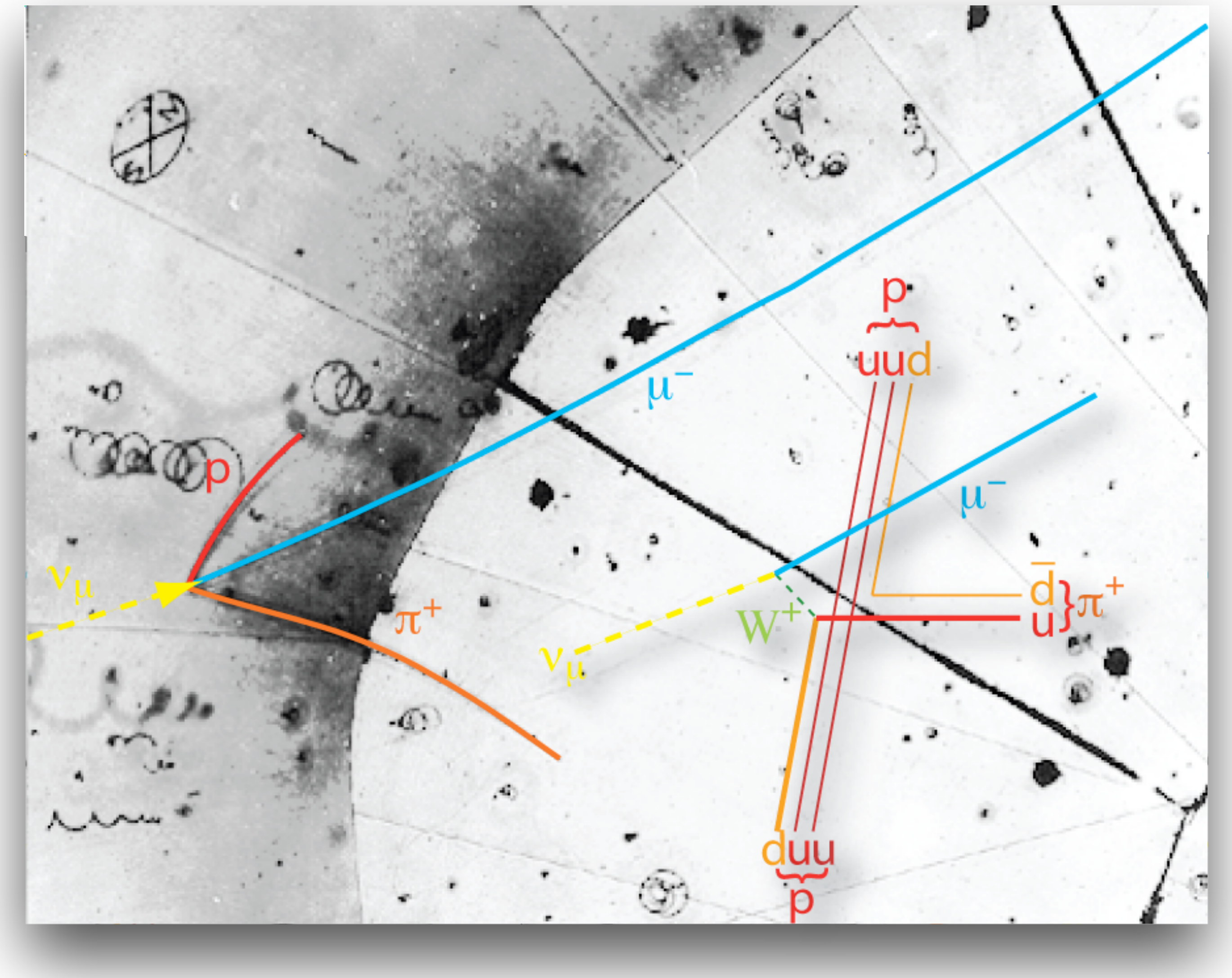
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats su retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

- **Neutrino discovery:**



First picture of a neutrino in a bubble chamber filled with liquid hydrogen at Argonne National Lab

- electron neutrino ν_e 1956 by Cowen & Reines at one of the first big nuclear reactors

to Reines 1995

- muon neutrino ν_μ 1962 by Steinberger, Schwartz, Lederman with the first neutrino beam generated by an accelerator

1988

- tau neutrino ν_τ 2002 at the DONUT experiment

HIGHLIGHT

Neutrino Oscillations

- Neutrino oscillations: considered by B. Pontecorvo in 1957 in case neutrinos are not massless.

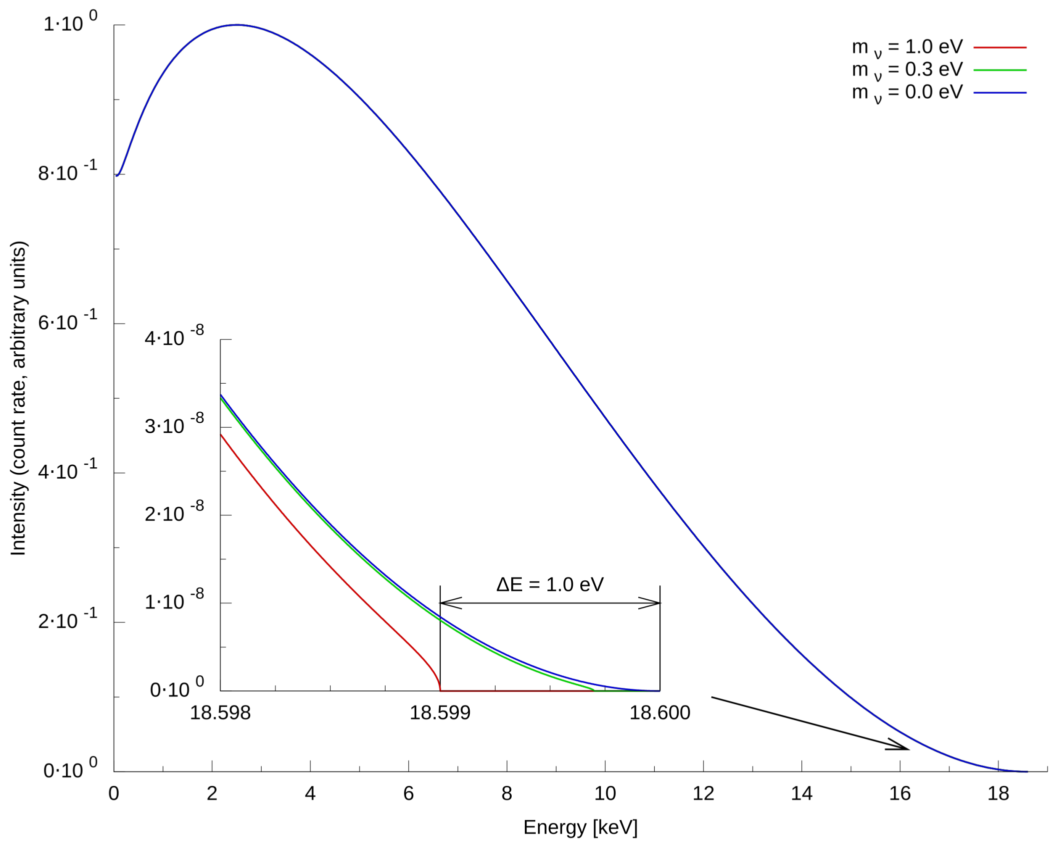
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta(0)|\nu_\alpha(L)\rangle|^2 \approx \sin^2\left(\frac{\Delta m^2 c^4}{4E}\,\frac{L}{\hbar c}\right)\cdot \sin^2(2\Theta_m)$$

HIGHLIGHT

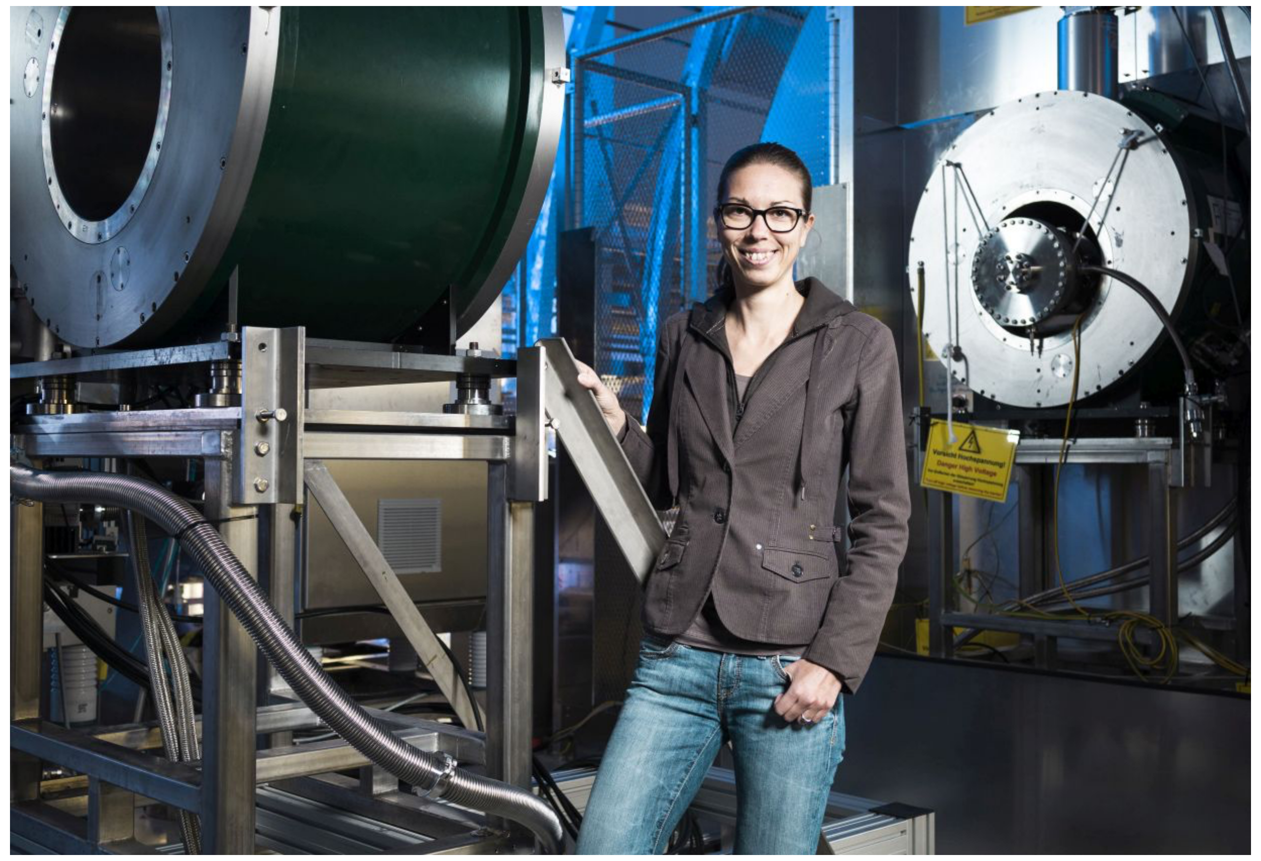
- first experimental hint: deficit of solar neutrinos (1960's, Homestake experiment)
- confirmation by Kamiokande II 1987
- numerous experiments with neutrinos from the sun, cosmic rays, nuclear reactors, colliders to determine ν parameters

2015 Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations as proof of neutrino masses

- World best limit on neutrino mass: 0.45 eV/c² via Tritium beta decay spectrum



@wikipedia



KATRIN spokesperson Prof. Kathrin Valerius, KIT @KIT

@KIT

Neutrino Oscillations

HIGHLIGHT

- Neutrino oscillations: considered by B. Pontecorvo in 1957 in case neutrinos are not massless.

$$P(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta \quad \Delta m^2 \quad 4 \quad L \quad) \cdot \sin^2(2\Theta_m)$$

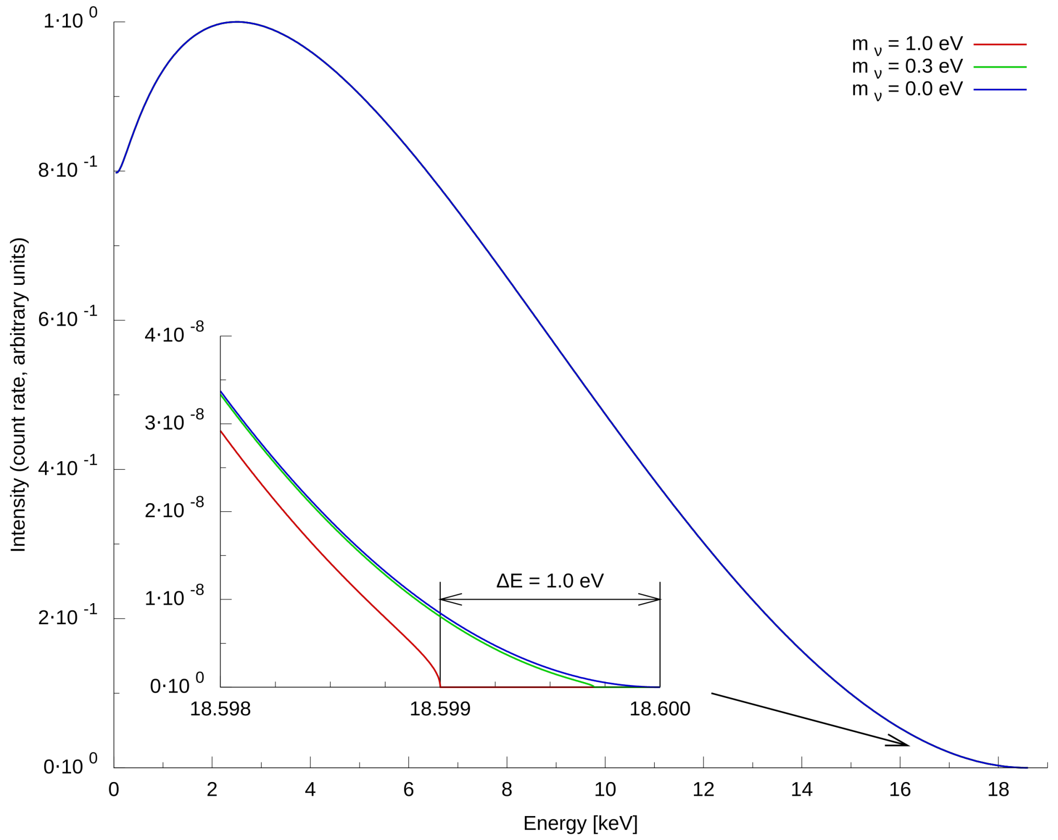
- first experimental hint: deficit of solar neutrinos (196
- confirmation by Kamiokande II 1987
- numerous experiments with neutrinos from the sun, cos
  nuclear reactors, colliders to determine ν parameters

Genius Ideas:

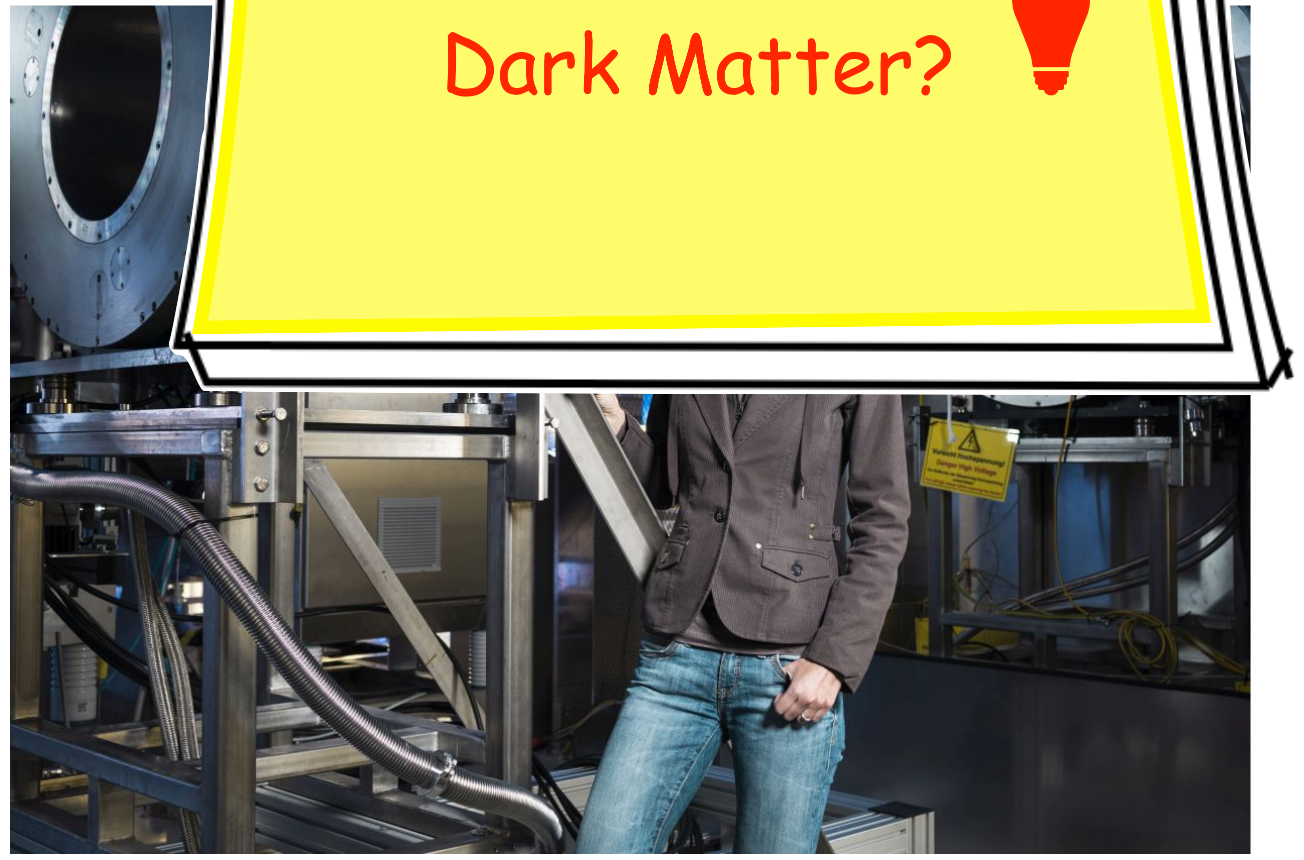
- ~~Dsjgöjrorn-fgs!~~
- ~~...üegg-kjs~~
- Could neutrinos account for Dark Matter?

2015 Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations as proof of neutrino masses

- World best limit on neutrino mass: 0.45 eV/c² via Trit



@wikipedia



KATRIN spokesperson Prof. Kathrin Valerius, KIT @KIT

@KIT

Open Questions of the Standard Model

What are the open questions of the SM and how can we solve them?

The Standard Model is not Perfect!

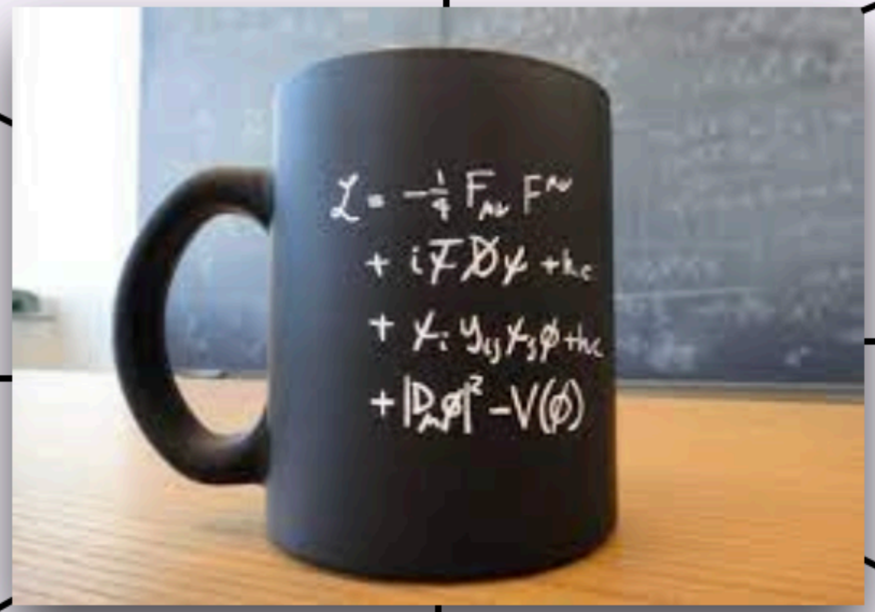
Open Questions of the SM

How include gravity?

Dark Matter

Matter Anti-Matter Asymmetry

Neutrino Mass



CP Violation

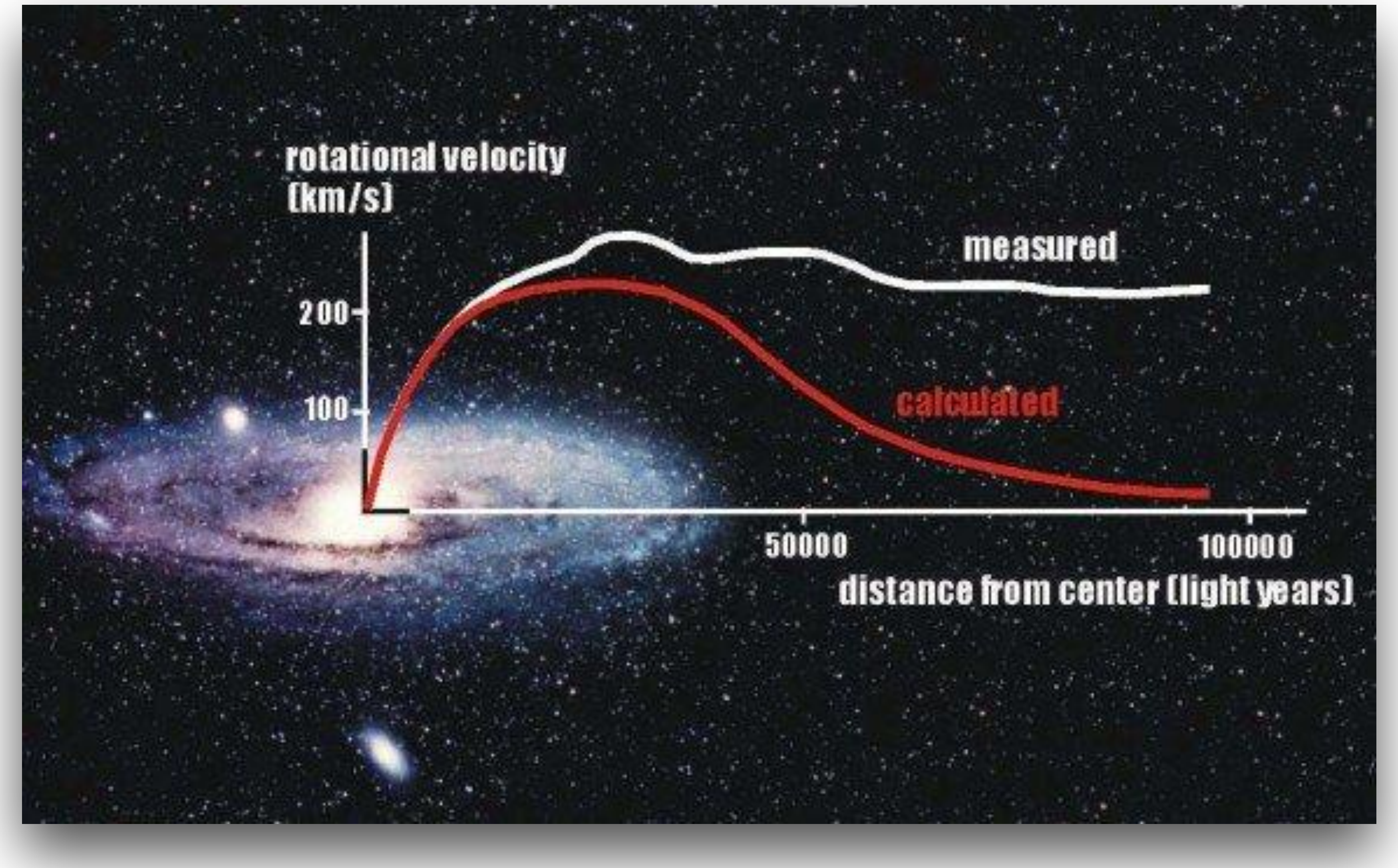
Why 3 generations?

...

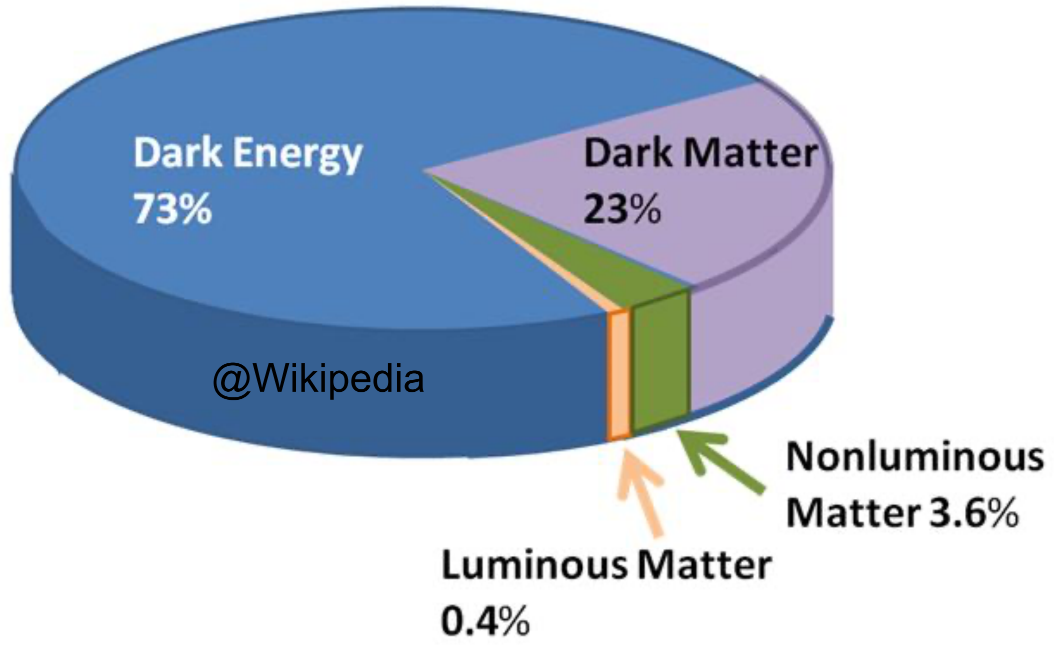
Unification Of Fundamental Forces

Mysterious Dark Matter (DM)

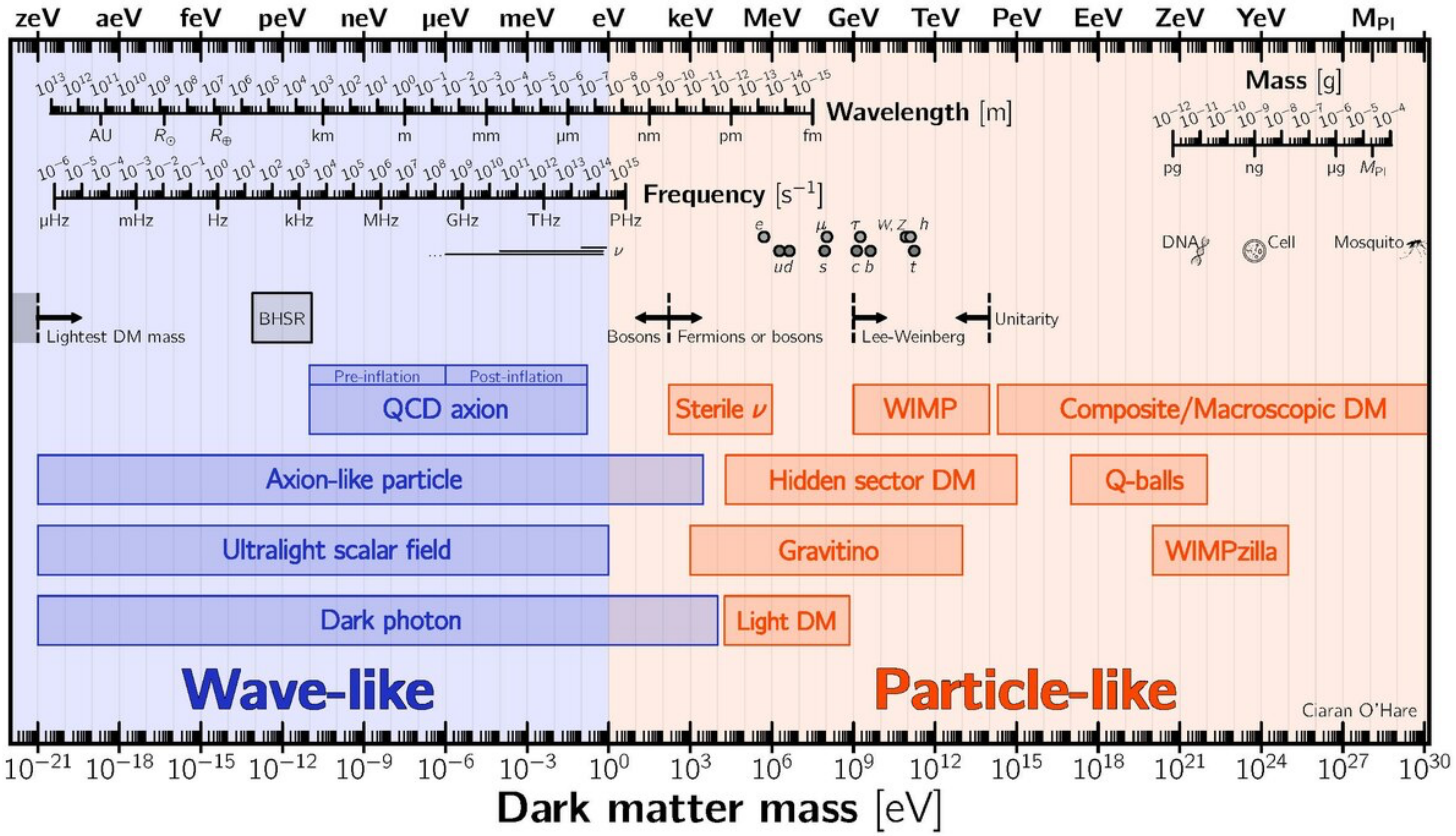
- Astrophysical and cosmological observations: Dark Matter



Vera Rubin
23.7.1928-25.12.2016



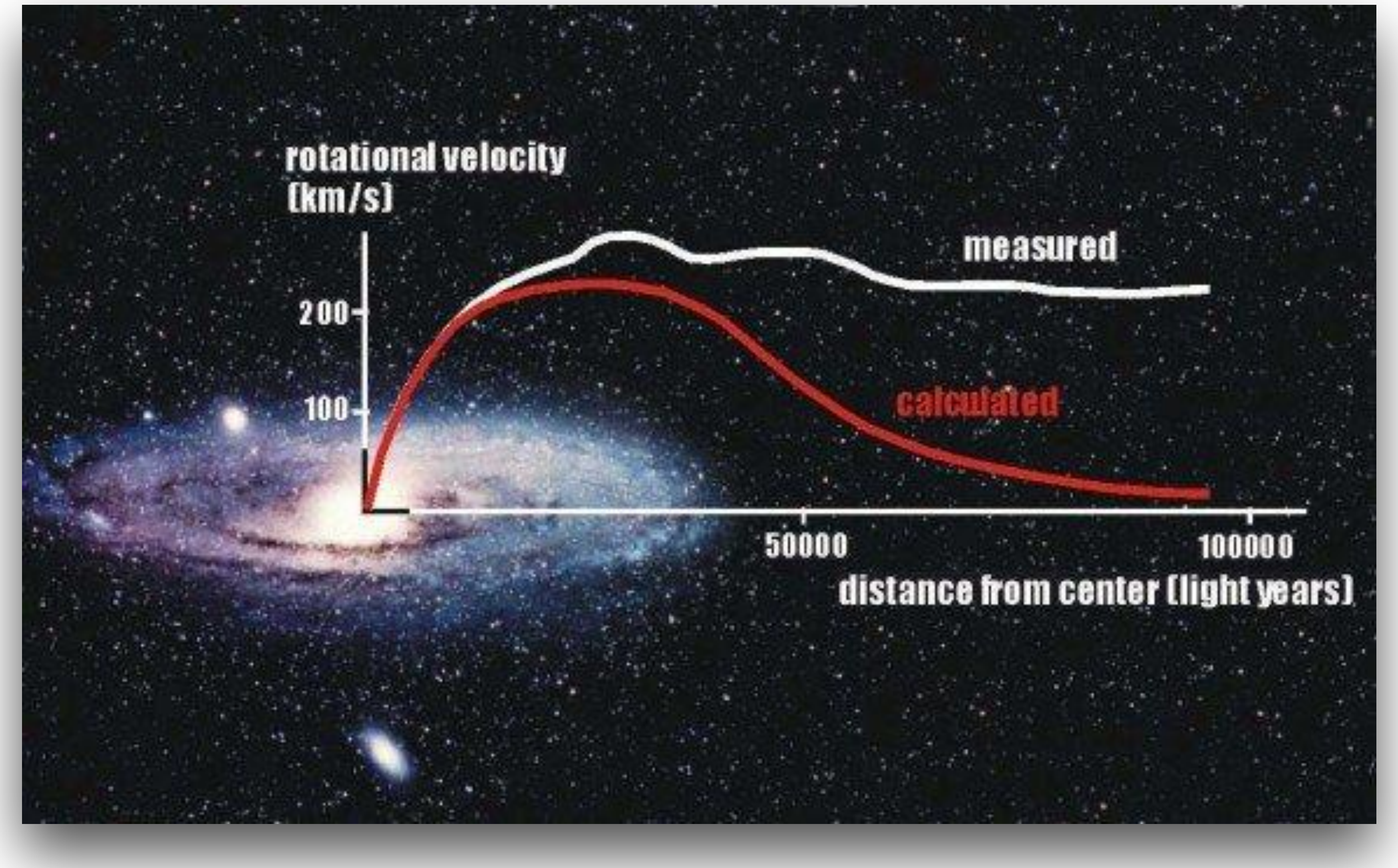
- Nature of Dark Matter: Unkown



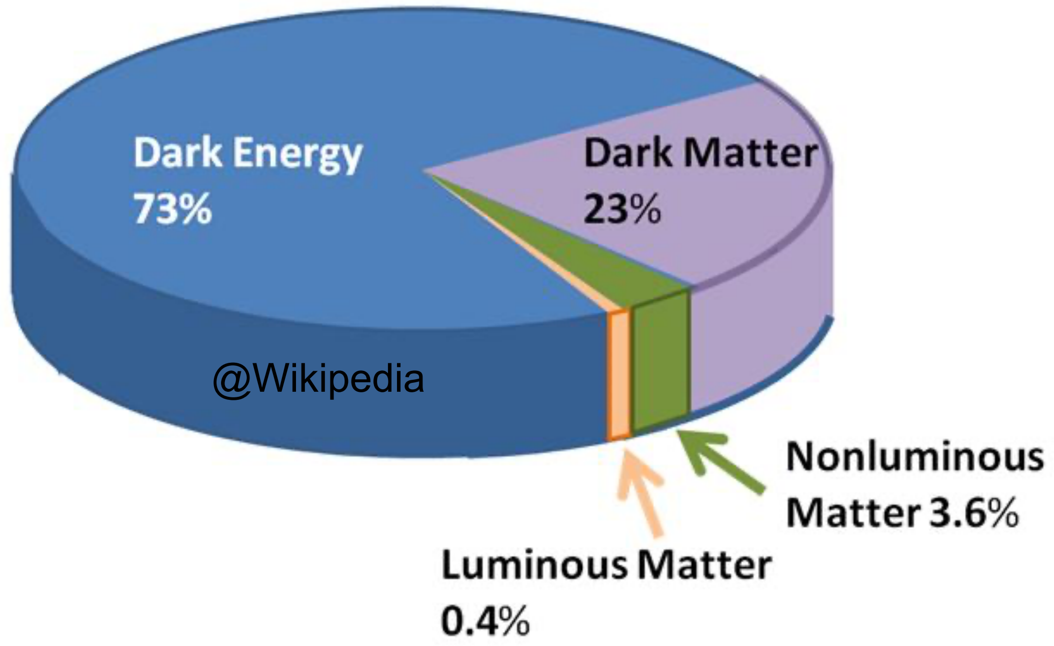
- If particle: must be **electrically neutral** and **weakly interacting**

Mysterious Dark Matter (DM)

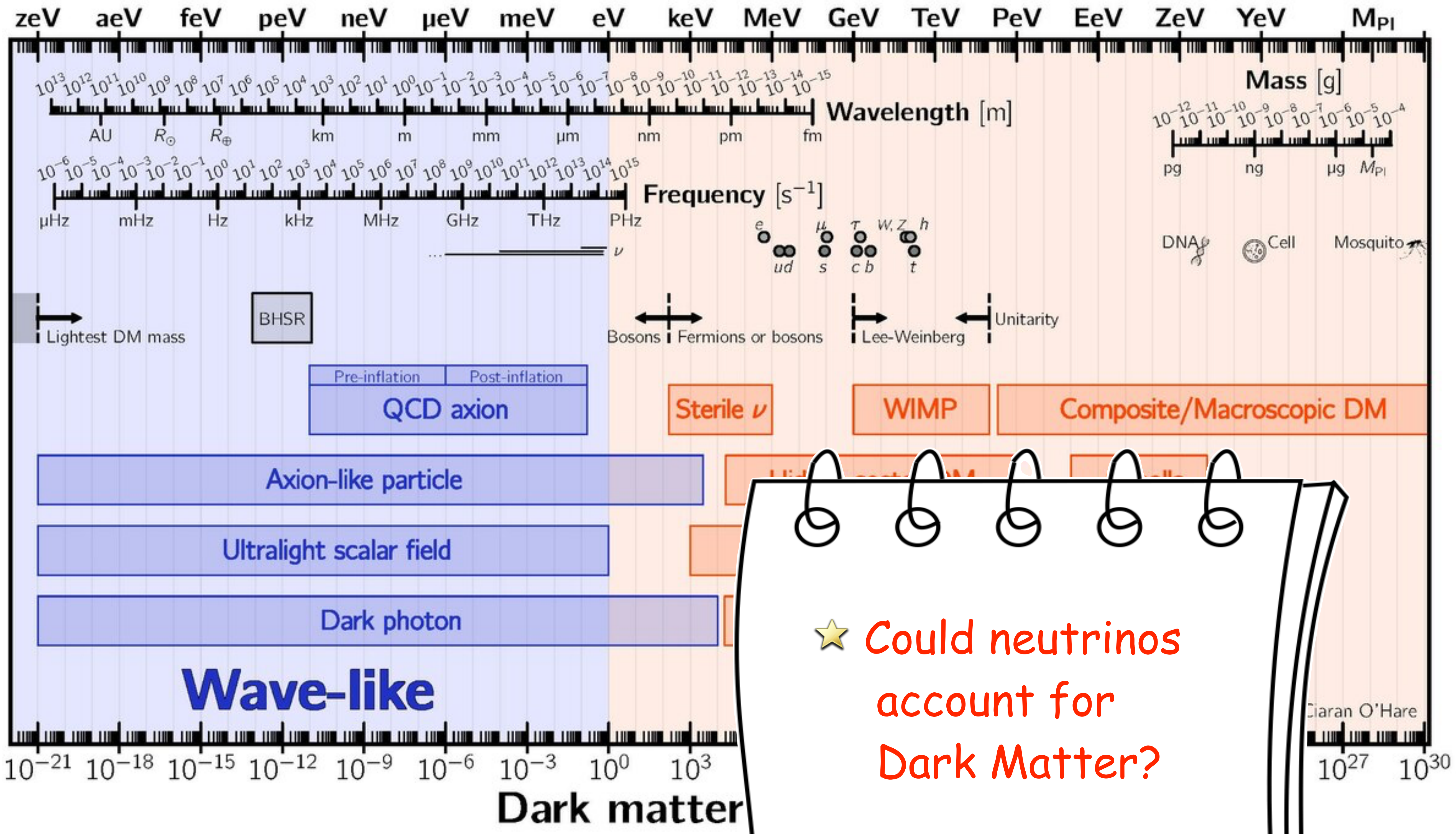
- Astrophysical and cosmological observations: Dark Matter



Vera Rubin
23.7.1928-25.12.2016



- Nature of Dark Matter: Unkown



- If particle: must be **electrically** **cting**

☆ Could neutrinos account for Dark Matter?

No

There is no DM candidate in the SM

The Matter-Antimatter Asymmetry

- There is more matter than antimatter in the Universe:

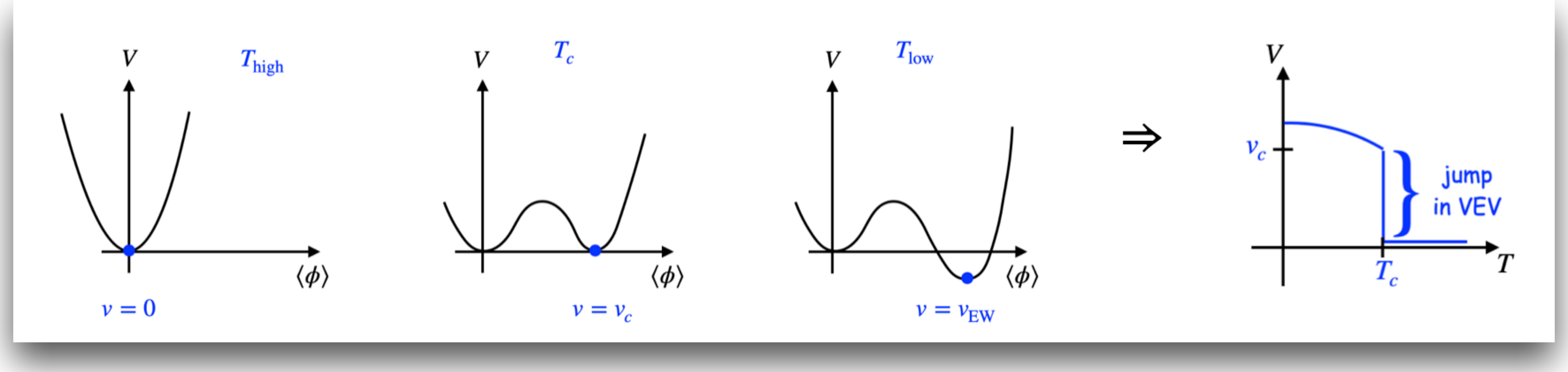
$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- Cannot be explained with standard cosmology (big bang)

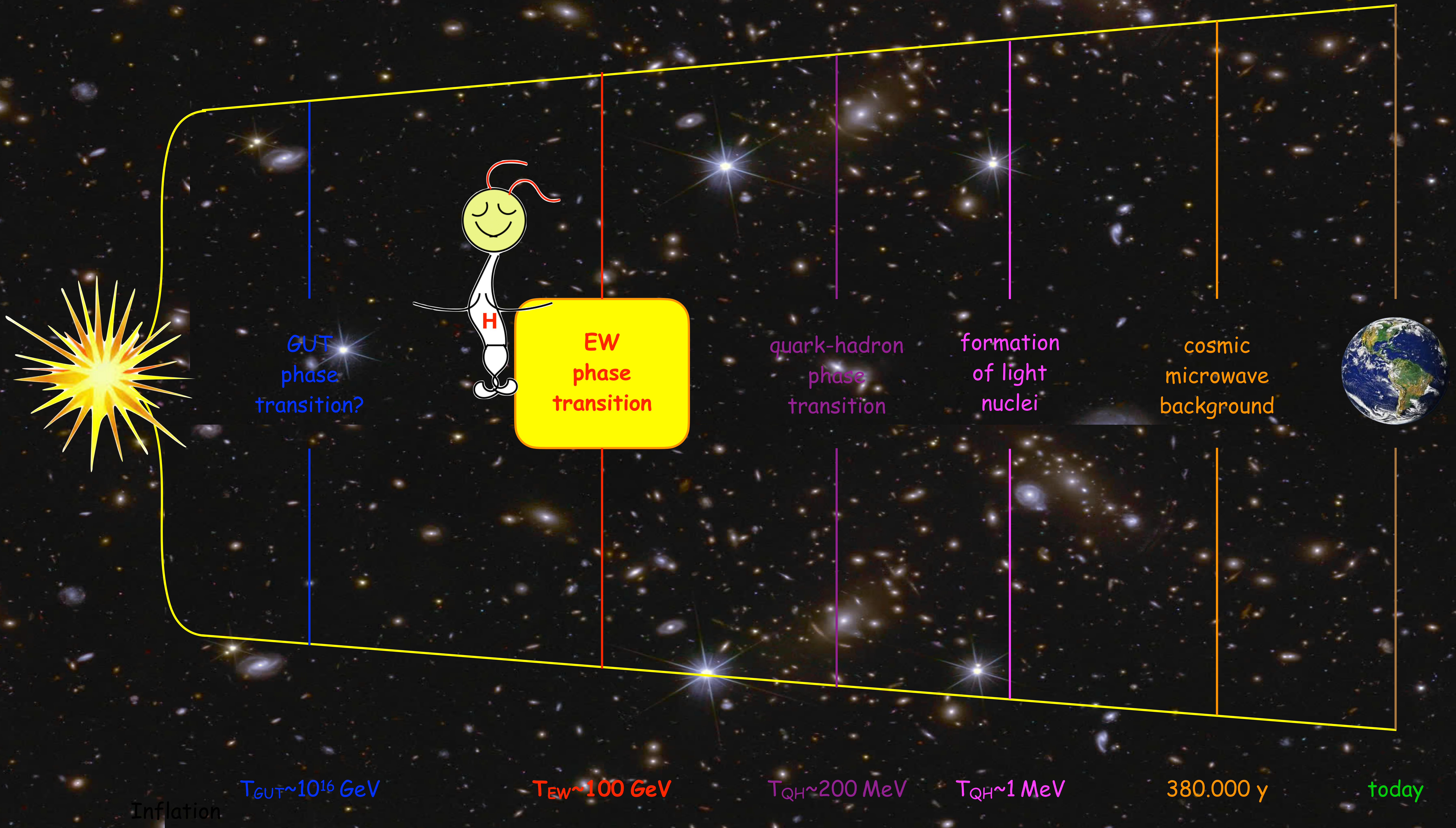
- Mechanism for dynamical generation: electroweak baryogenesis

  - ⋆Electroweak phase transition:
    order parameter is the vacuum expectation value (VEV): $v = 0 \;\Rightarrow\; v \neq 0$

  - ⋆Strong first-order electroweak phase transition (SFOEWPT):
    jump in the VEV at the phase transition



Higgs and the Evolution of the Universe



GUT phase transition?

EW phase transition

quark-hadron phase transition

formation of light nuclei

cosmic microwave background

Inflation

T_{GUT}~10^{16} GeV

T_{EW}~100 GeV

T_{QH}~200 MeV

T_{QH}~1 MeV

380.000 y

today

The Matter-Antimatter Asymmetry

- There is more matter than antimatter in the Universe:

$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

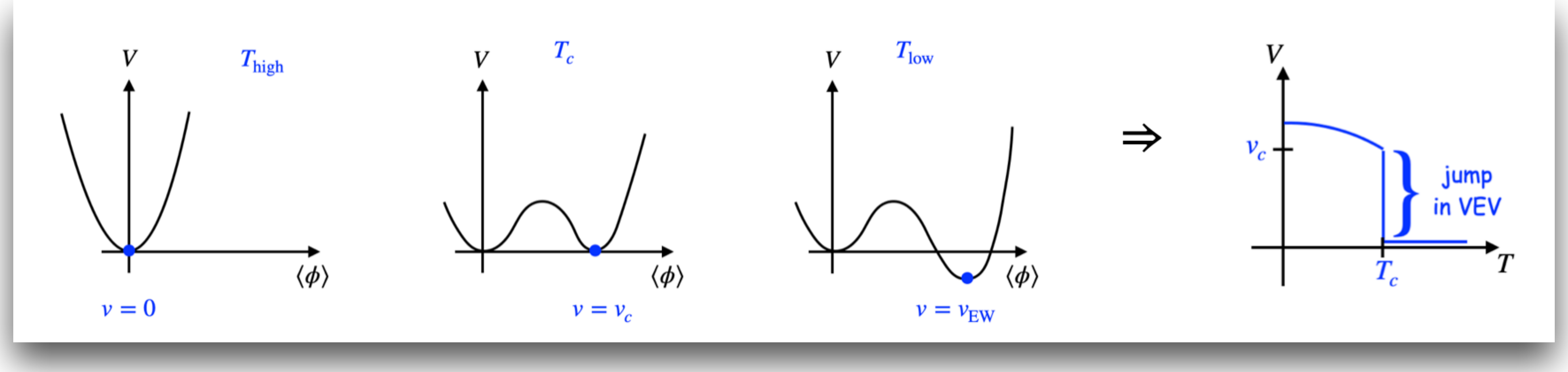
- Cannot be explained with standard cosmology (big bang)

- Mechanism for dynamical generation: electroweak baryogenesis

  ⋆Electroweak phase transition:
  order parameter is the vacuum expectation value (VEV): $v = 0 \;\Rightarrow\; v \neq 0$

  ⋆Strong first-order electroweak phase transition (SFOEWPT):
  jump in the VEV at the phase transition

Electroweak Baryogenesis is not possible in the SM



SFOEWPTS and Gravitational Waves

SFOEWPT
(for EWBG)

↓ can source

Gravitational Waves
(GW)

↑ sensitive to

Pulsar timing arrays, LISA
(space bound interferometer)

LIGO
Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT

Image credit: The SXS (Simulating eXtreme Spacetimes) Project

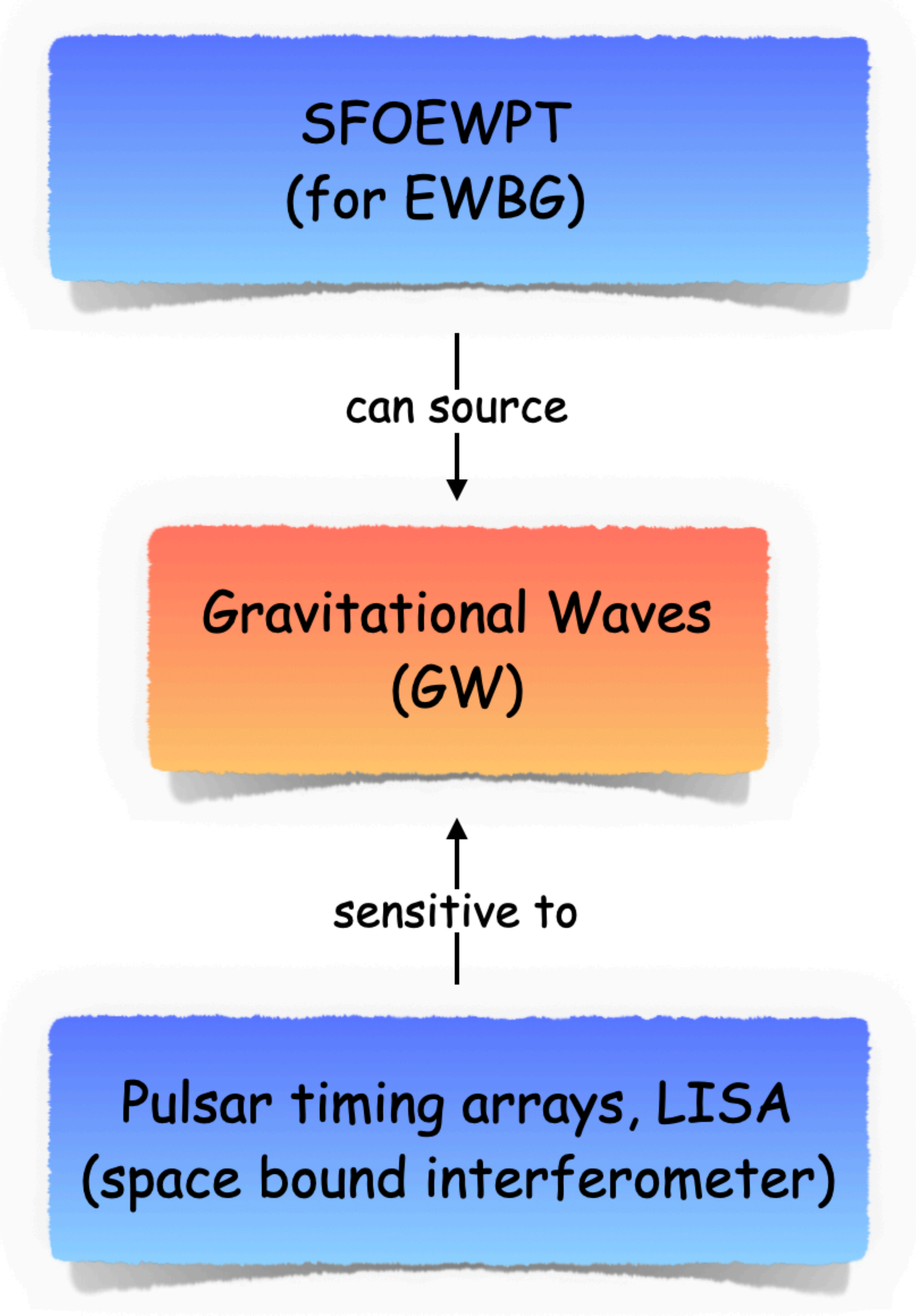
Gravitational Waves Detected 100 Years After Einstein's Prediction

News Release • February 11, 2016

SFOEWPTS and Gravitational Waves

Directly probe echo of Cosmological SFOPT

Discovery of Physics Beyond the SM



SFOEWPT
(for EWBG)

can source

Gravitational Waves
(GW)

sensitive to

Pulsar timing arrays, LISA
(space bound interferometer)

Image credit: The SXS (Simulating eXtreme Spacetimes) Project

Gravitational Waves Detected 100 Years After Einstein's Prediction

News Release • February 11, 2016

What is needed to solve our open questions?

What is needed to solve our open questions?

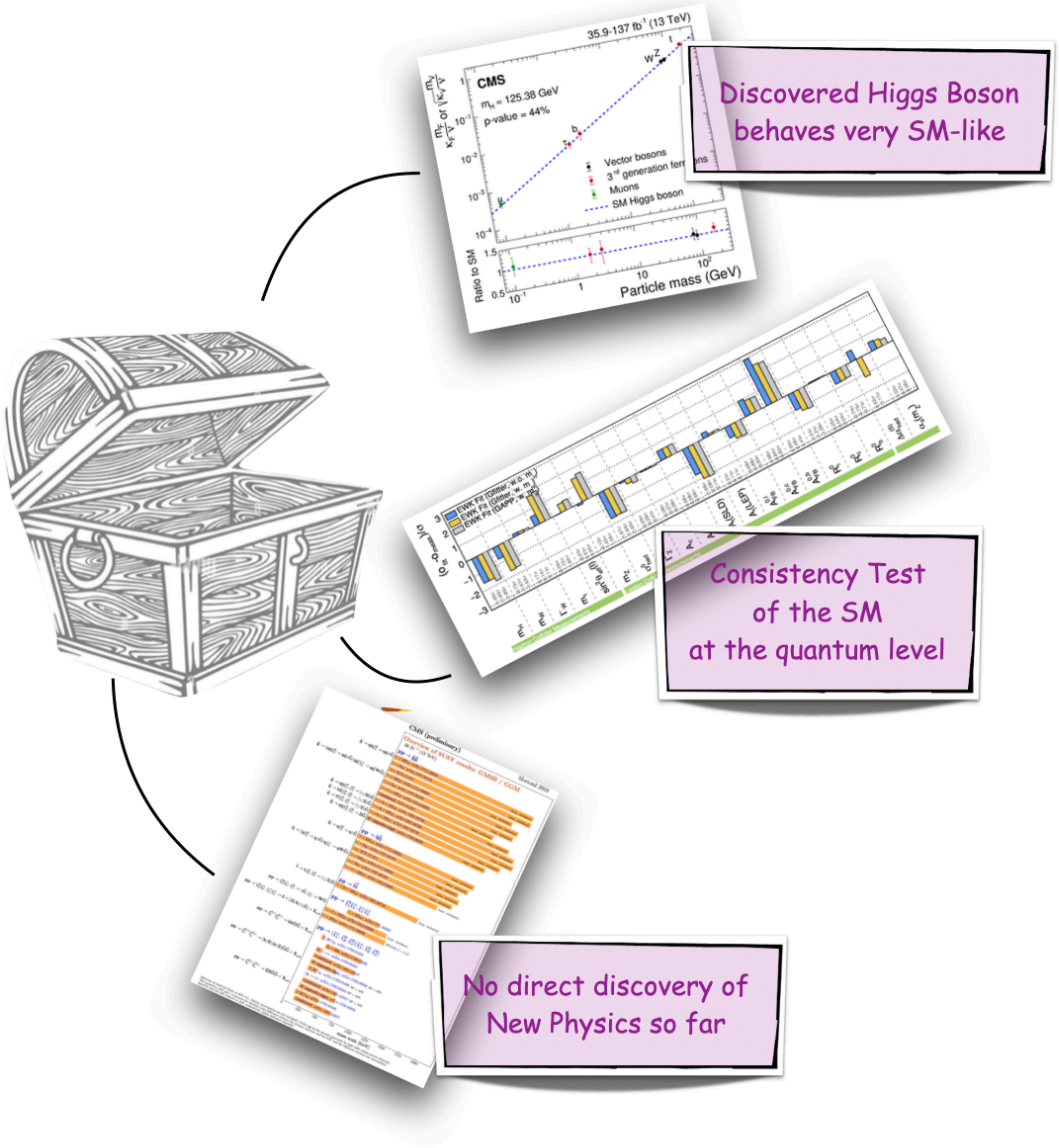
Special Offer: BSM Models

What is needed to solve our open questions?

Special Offer: BSM Models

Effective Field Theories: Parametrize beyond-SM-Physics in a model-independent way Applicable if new physicsi s heavy.

Status



Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

Did we find hints of beyond-SM physics?

If not should we be desperate?

Status

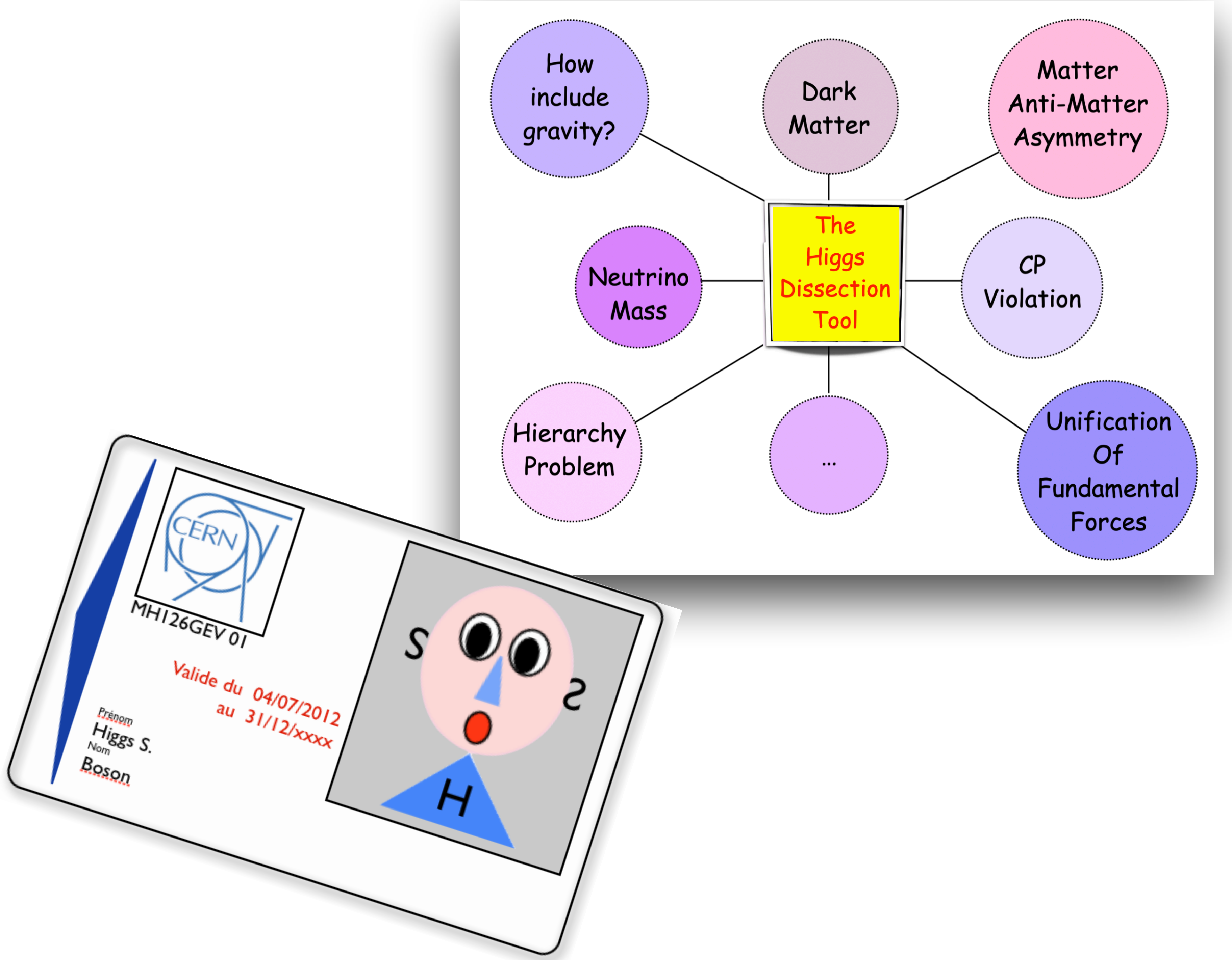
Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

We have the Higgs Boson

Higgs Laboratory for New Physics



How include gravity?

Dark Matter

Matter Anti-Matter Asymmetry

Neutrino Mass

The Higgs Dissection Tool

CP Violation

Hierarchy Problem

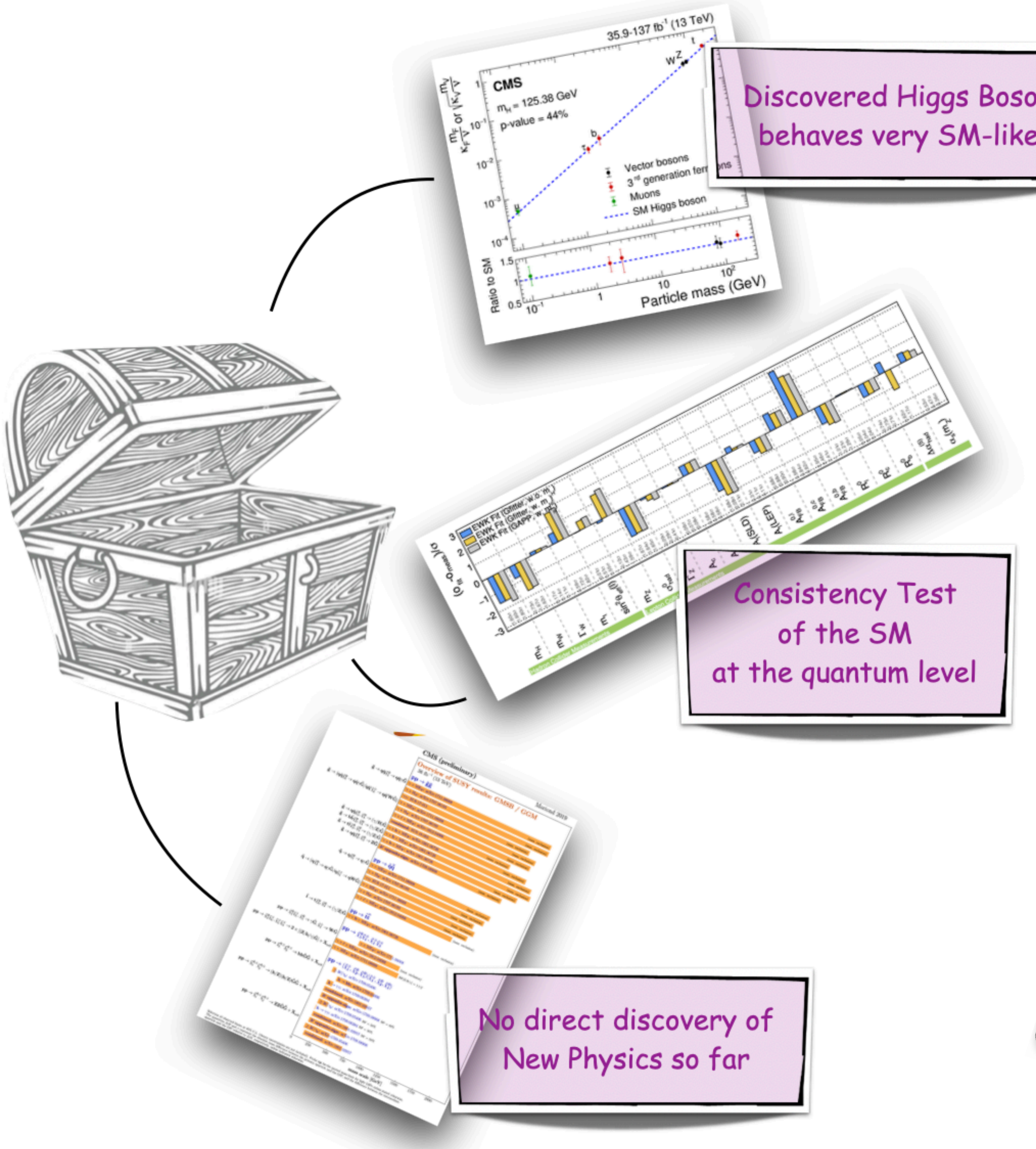
...

Unification Of Fundamental Forces

Did we find hints of beyond-SM physics?

If not should we be desperate?

Status



Discovered Higgs Boson behaves very SM-like

Consistency Test of the SM at the quantum level

No direct discovery of New Physics so far

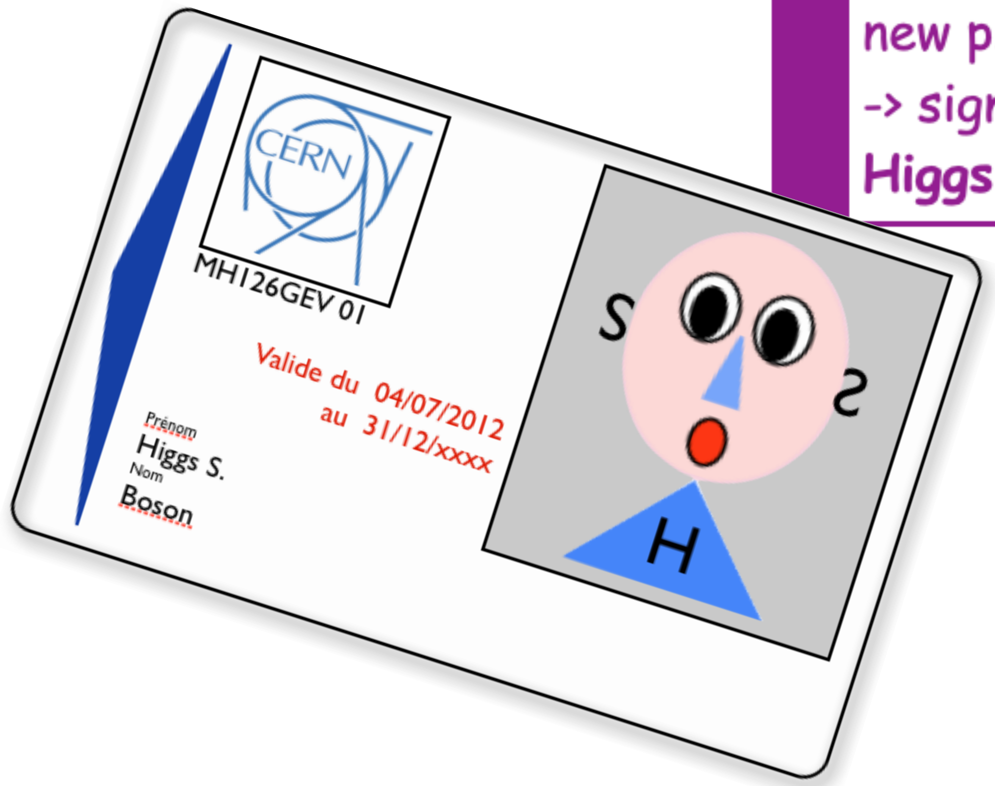
We have the Higgs Boson

Higgs Laboratory for New Physics

Direct search through Higgs couplings to new physics

Indirect search through new physics **quantum fluctuations** in Higgs observables

Direct & indirect sensitivity to new physics in **Higgs parameters** -> significant **BSM imprints** in **Higgs self-coupling** still possible



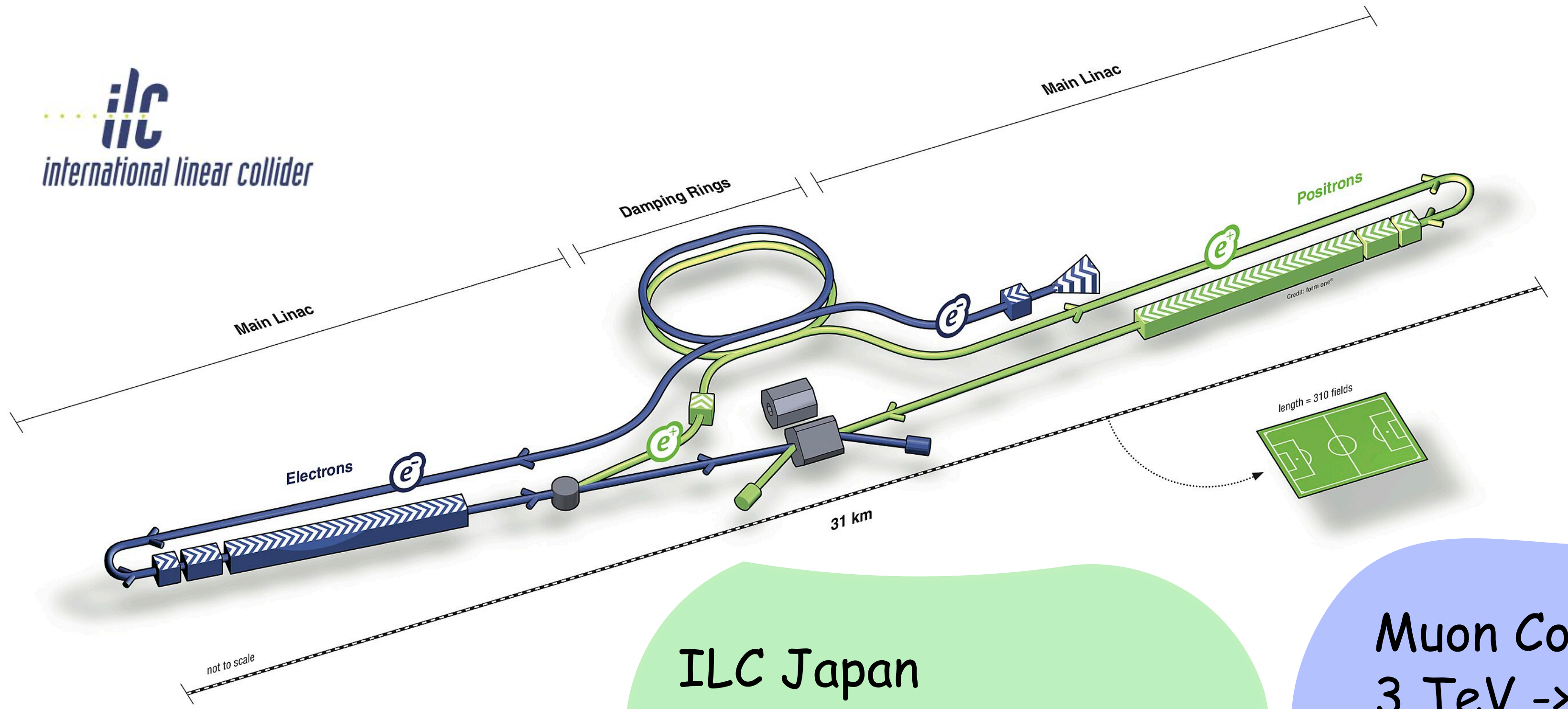
Did we find hints of beyond-SM physics?

If not should we be desperate?

The Future

Will we be able to solve the open questions?
What are future plans?

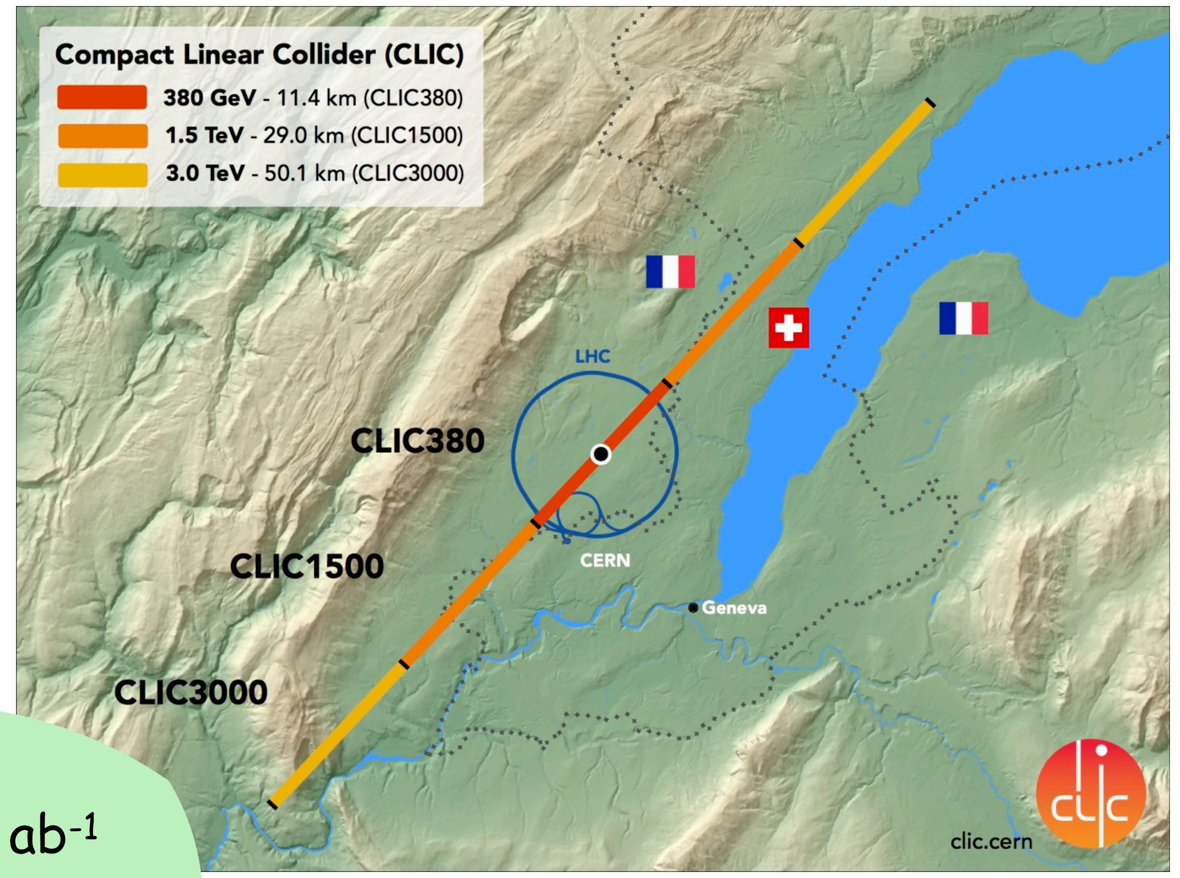
Future Colliders



ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

Cool Copper Collider
250 GeV -> 1.3x10^{34}/cm^{2}s
550 GeV -> 2.4x10^{34}/cm^{2}s

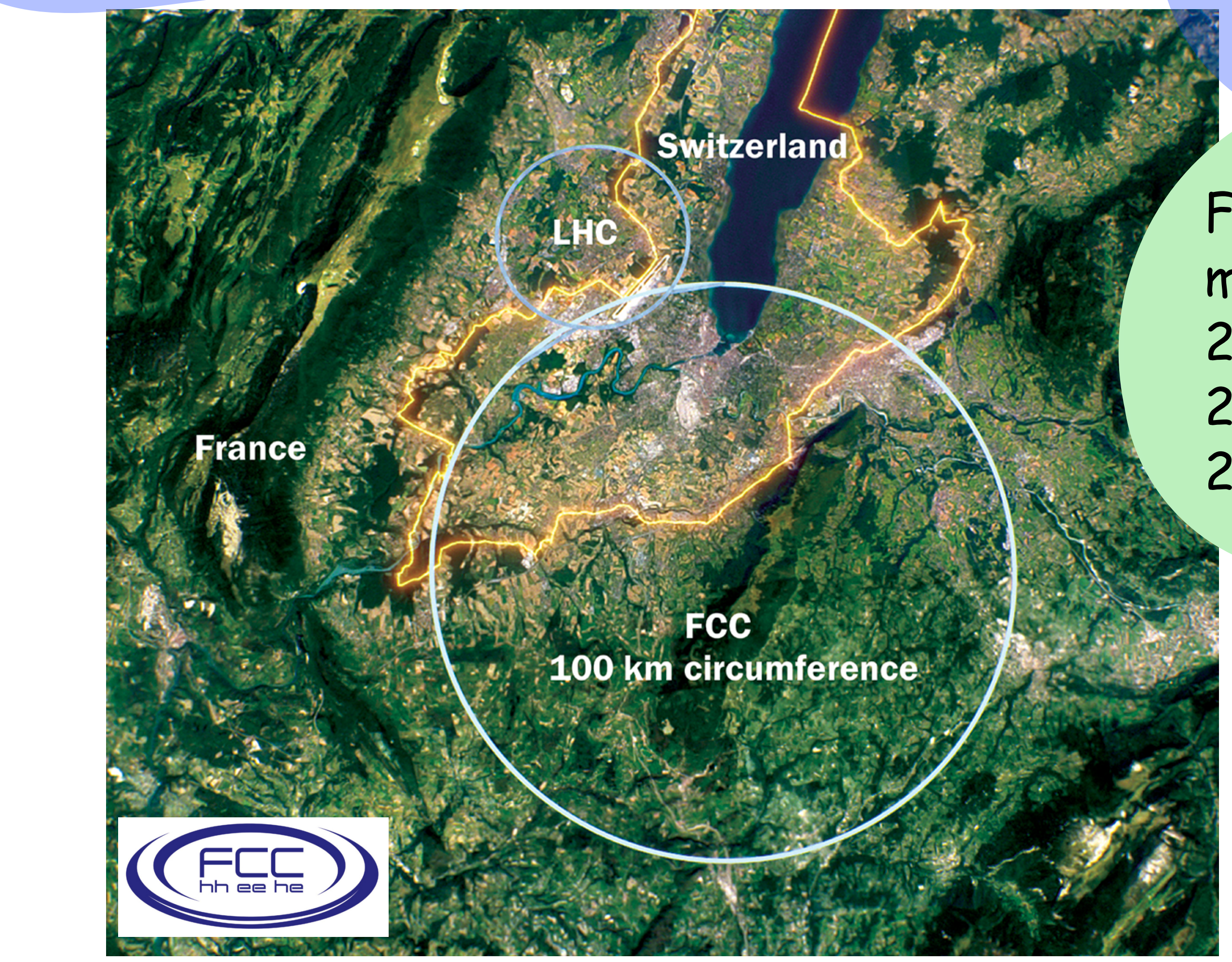
Muon Collider
3 TeV -> 1 ab^{-1}
10 TeV -> 10 ab^{-1}



CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}

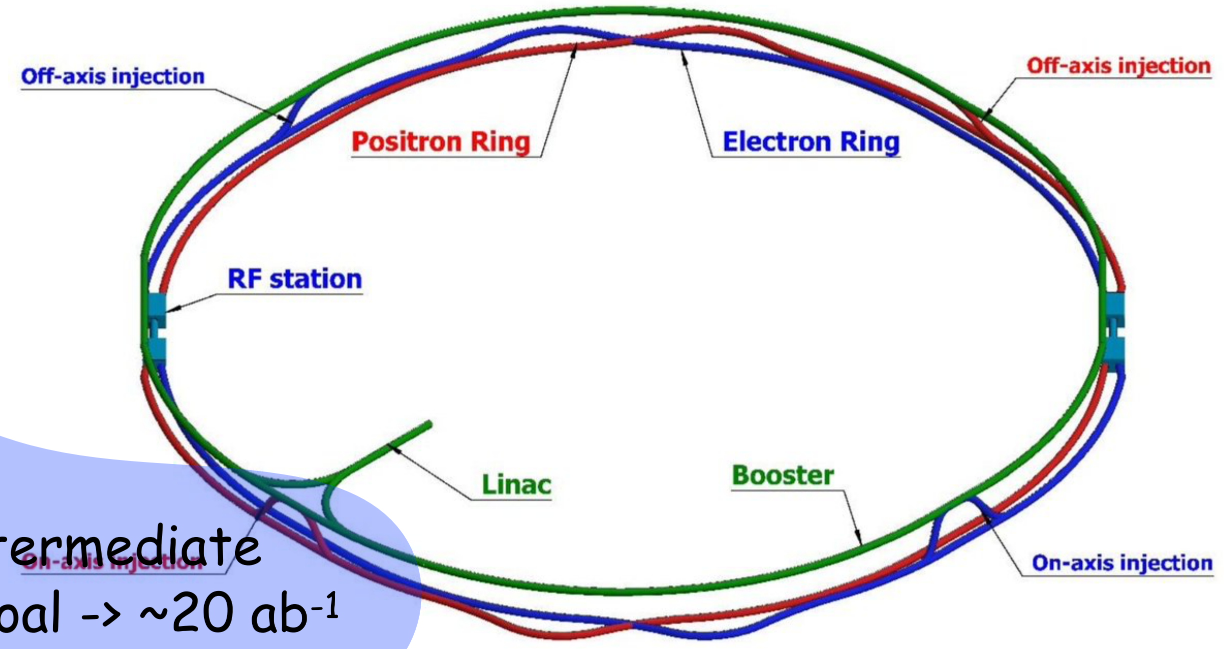
LHeC 0.2-1.3 TeV
run together w/ HL-LHC
($\gtrsim$ Run 5) -> 1 ab^{-1}

FCC-eh ($E_{e/p}$=60 GeV/50TeV)
3.5 TeV -> 2 ab^{-1}
run together w/ FCC-hh



FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}

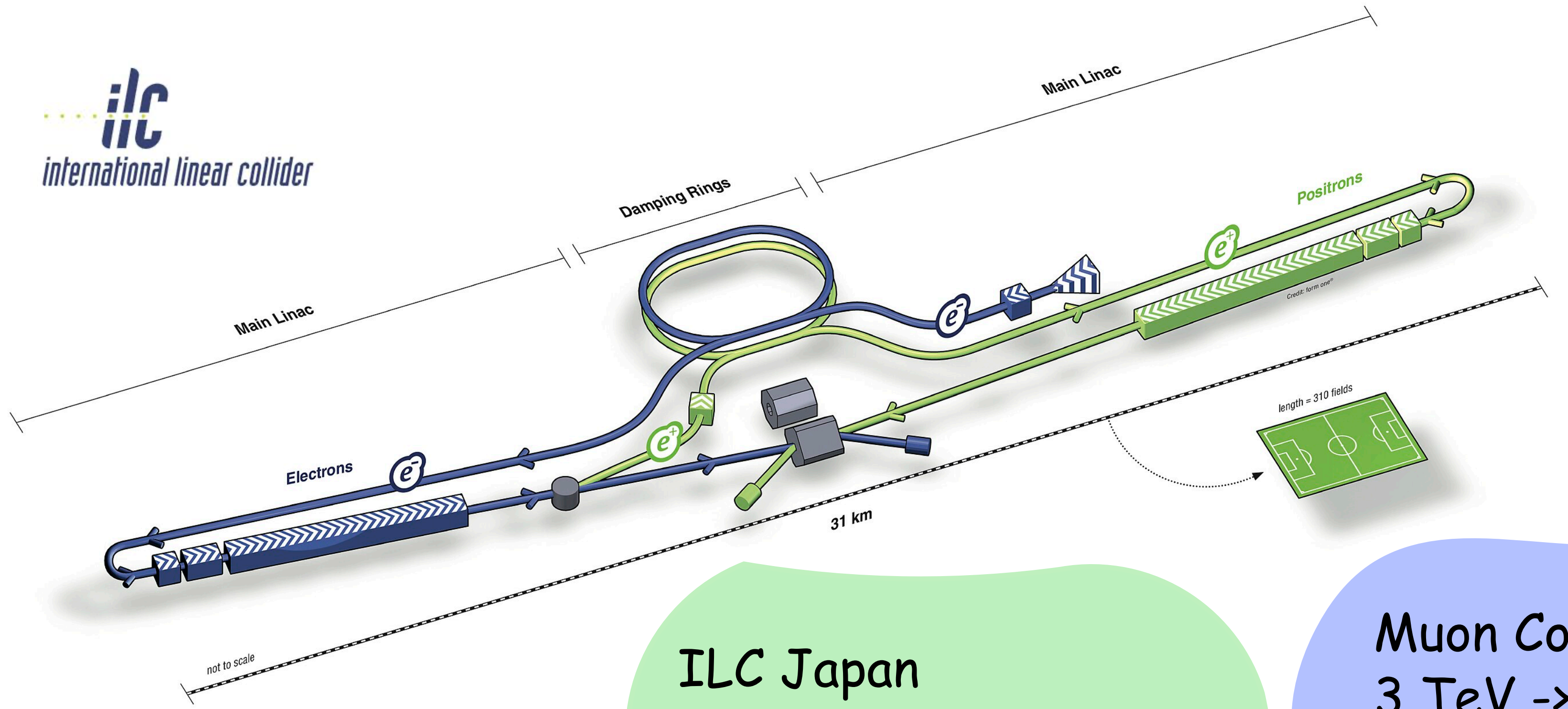
FCC-hh
100 TeV -> ~20-25 ab^{-1}
during 20-25y runtime



SPPC
75 TeV intermediate
125 TeV goal -> ~20 ab^{-1}

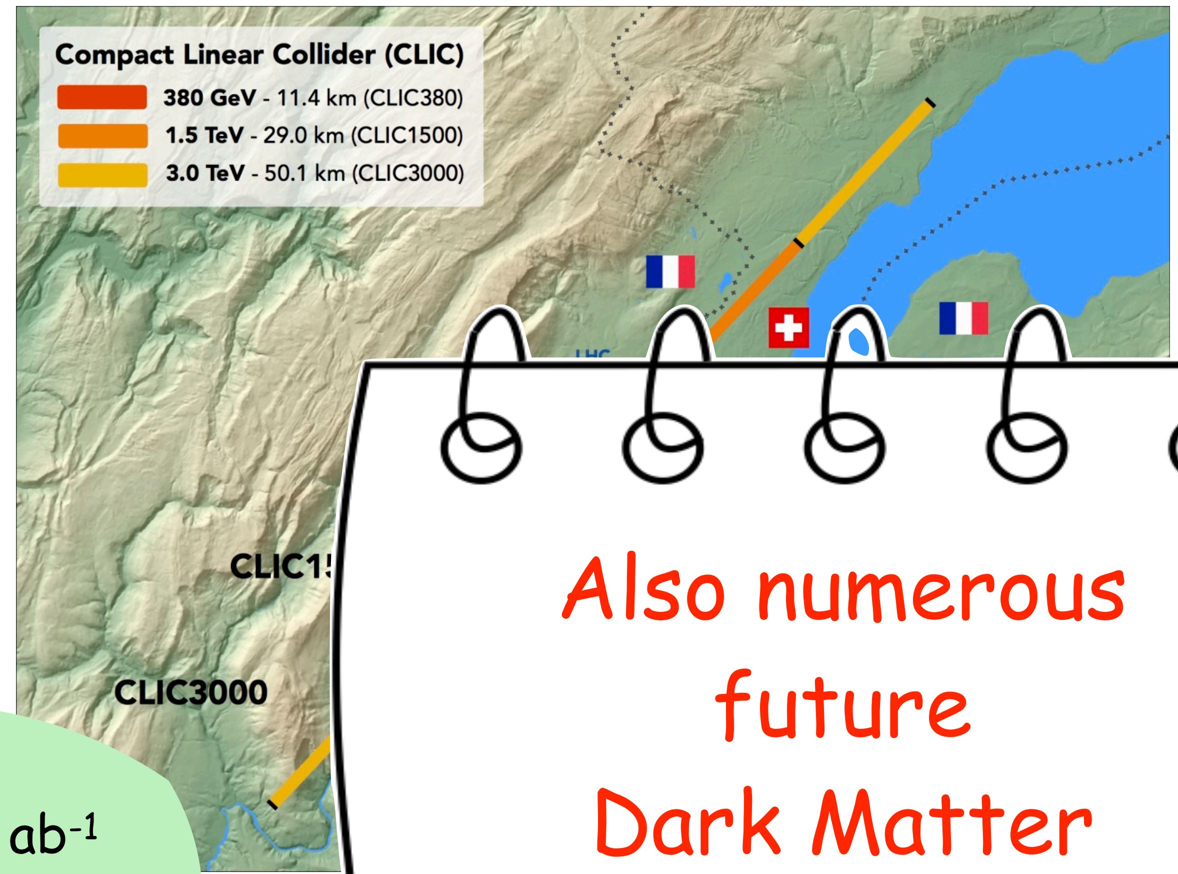
CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

Future Colliders



C^3

Cool Copper Collider
250 GeV -> 1.3x10^{34}/cm^{2}s
550 GeV -> 2.4x10^{34}/cm^{2}s



Also numerous
future
Dark Matter
Experiments
and
Gravitational Waves
Observatories
are planned.

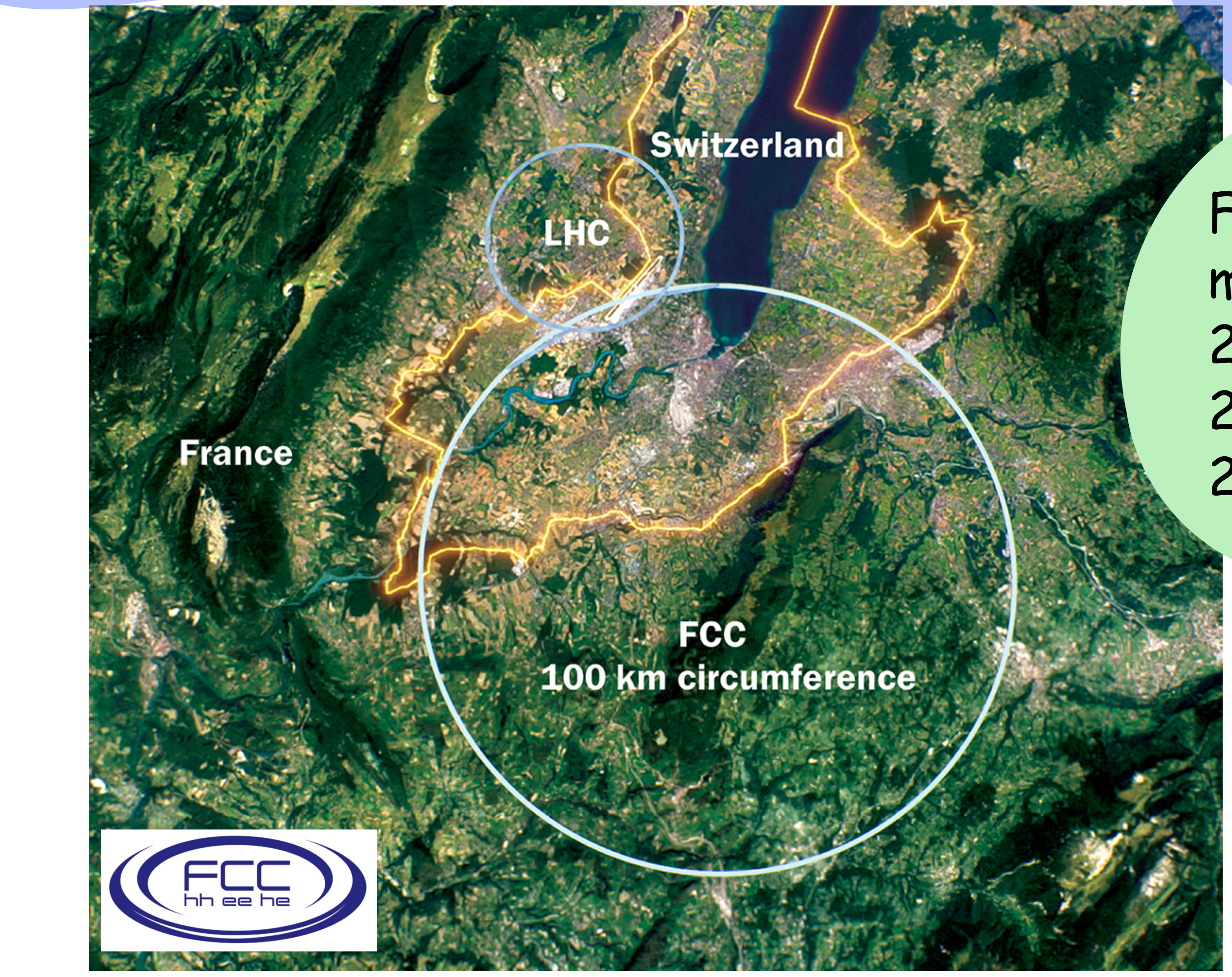
ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

Muon Collider
3 TeV -> 1 ab^{-1}
10 TeV -> 10 ab^{-1}

CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}

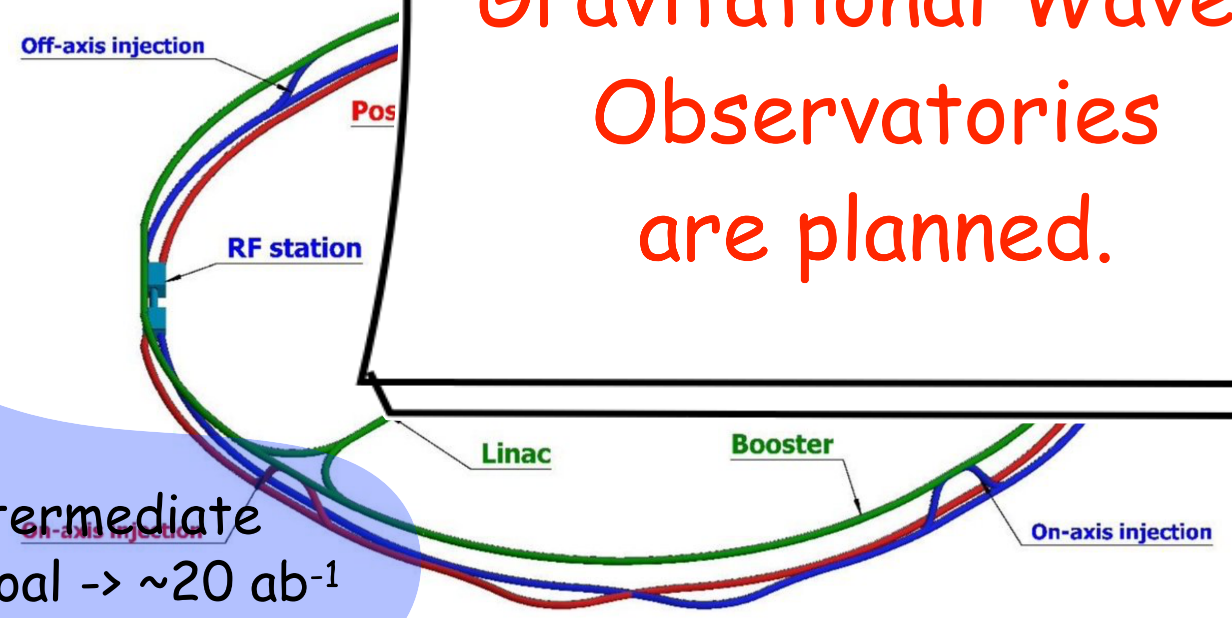
LHeC 0.2-1.3 TeV
run together w/ HL-LHC
($\gtrsim$ Run 5) -> 1 ab^{-1}

FCC-eh ($E_{e/p}$=60 GeV/50TeV)
3.5 TeV -> 2 ab^{-1}
run together w/ FCC-hh



FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}

FCC-hh
100 TeV -> ~20-25 ab^{-1}
during 20-25y runtime



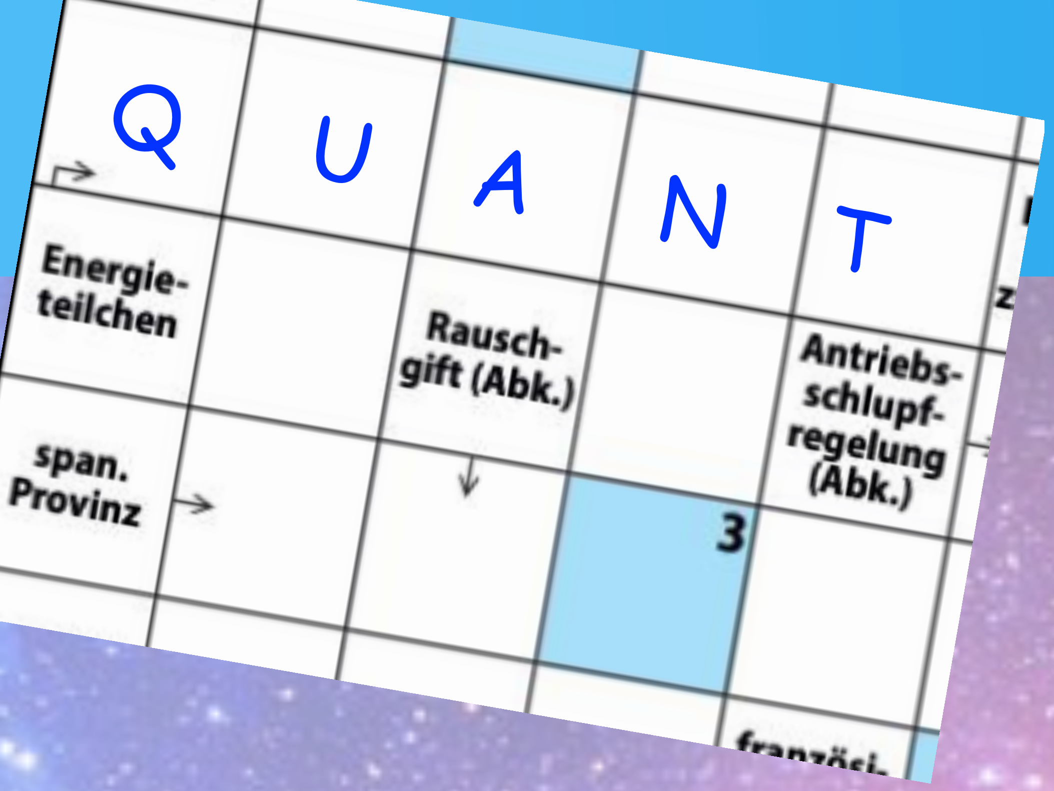
SPPC
75 TeV intermediate
125 TeV goal -> ~20 ab^{-1}

CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

CEPC

Exploit Synergies

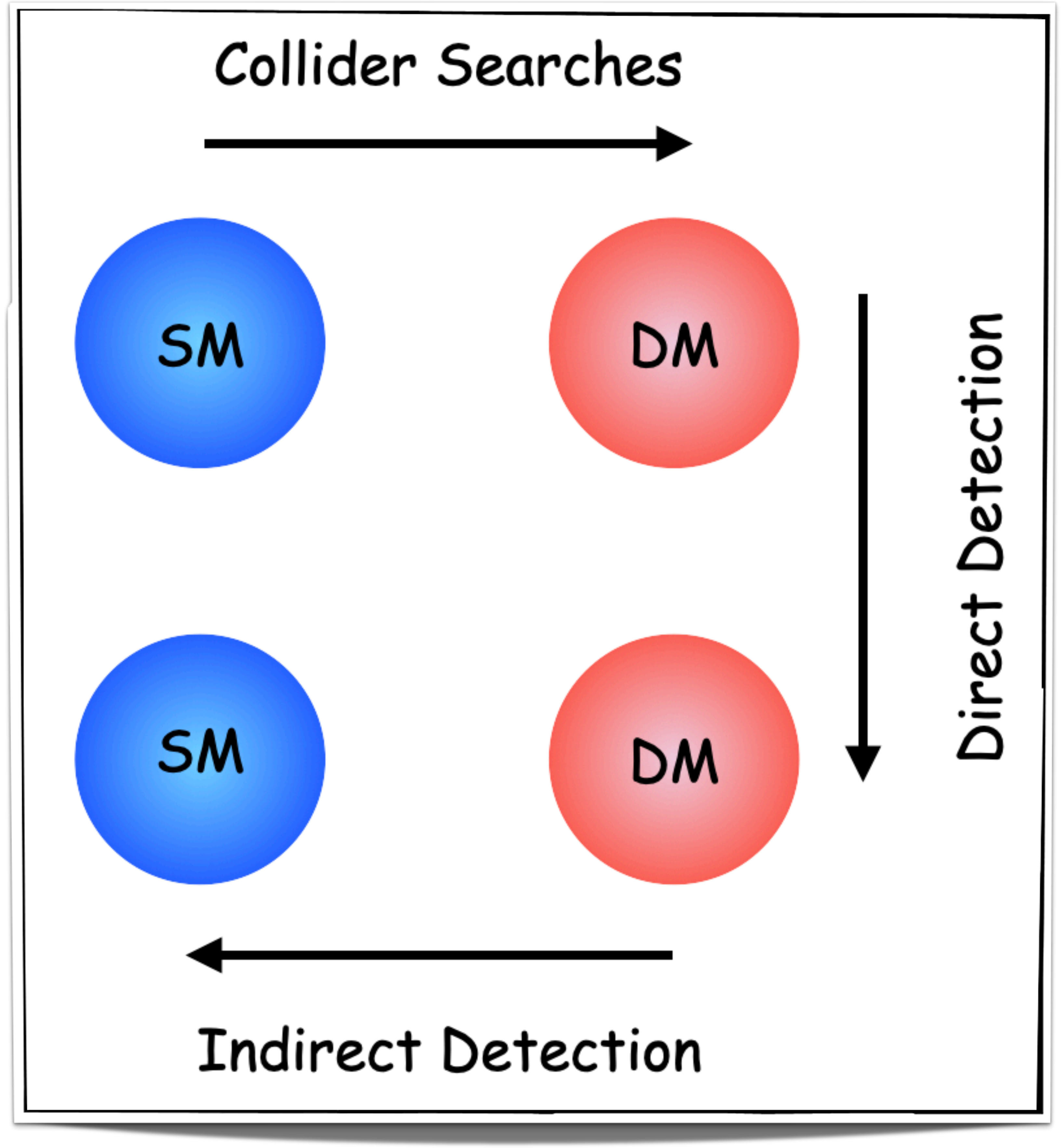
Conclusions



- Standard Model of particle physics
  - born out from our desire to understand nature at its fundamental level
  - by applying the principles quantum field theory and symmetry considerations
- Completed with the discovery of the Higgs Boson in 2012
- Many open questions still to be solved
- Their solution requires the synergies of particle physics, astroparticle physics and cosmology
  extraordinary experimental set-ups and analysis tools
  theoretical predictions at the highest precision
- Collider, DM, gravitation waves experiments running and planned

Thank you for your attention!

Pinning Down Dark Matter



Collider Searches

SM

DM

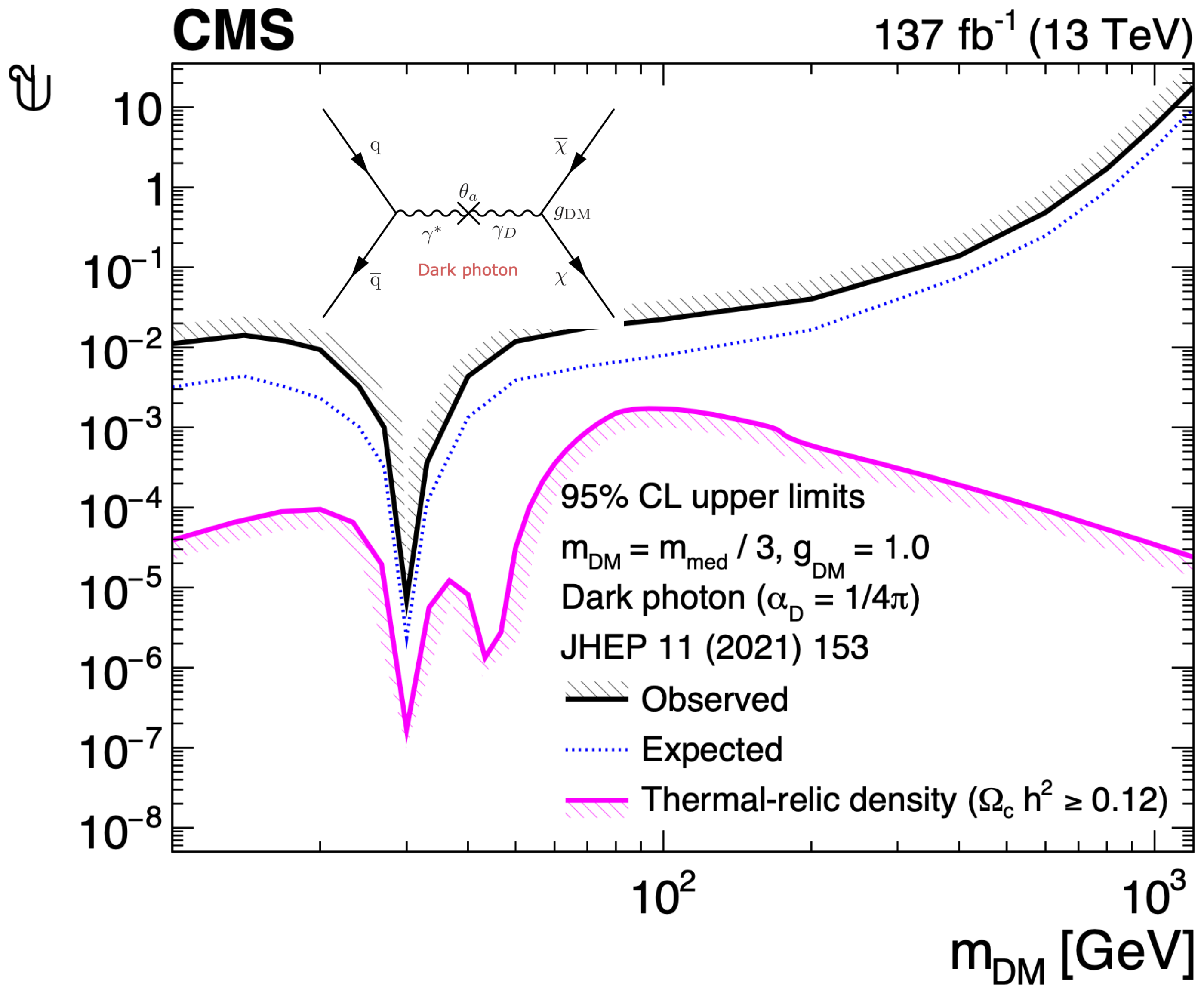
SM

DM

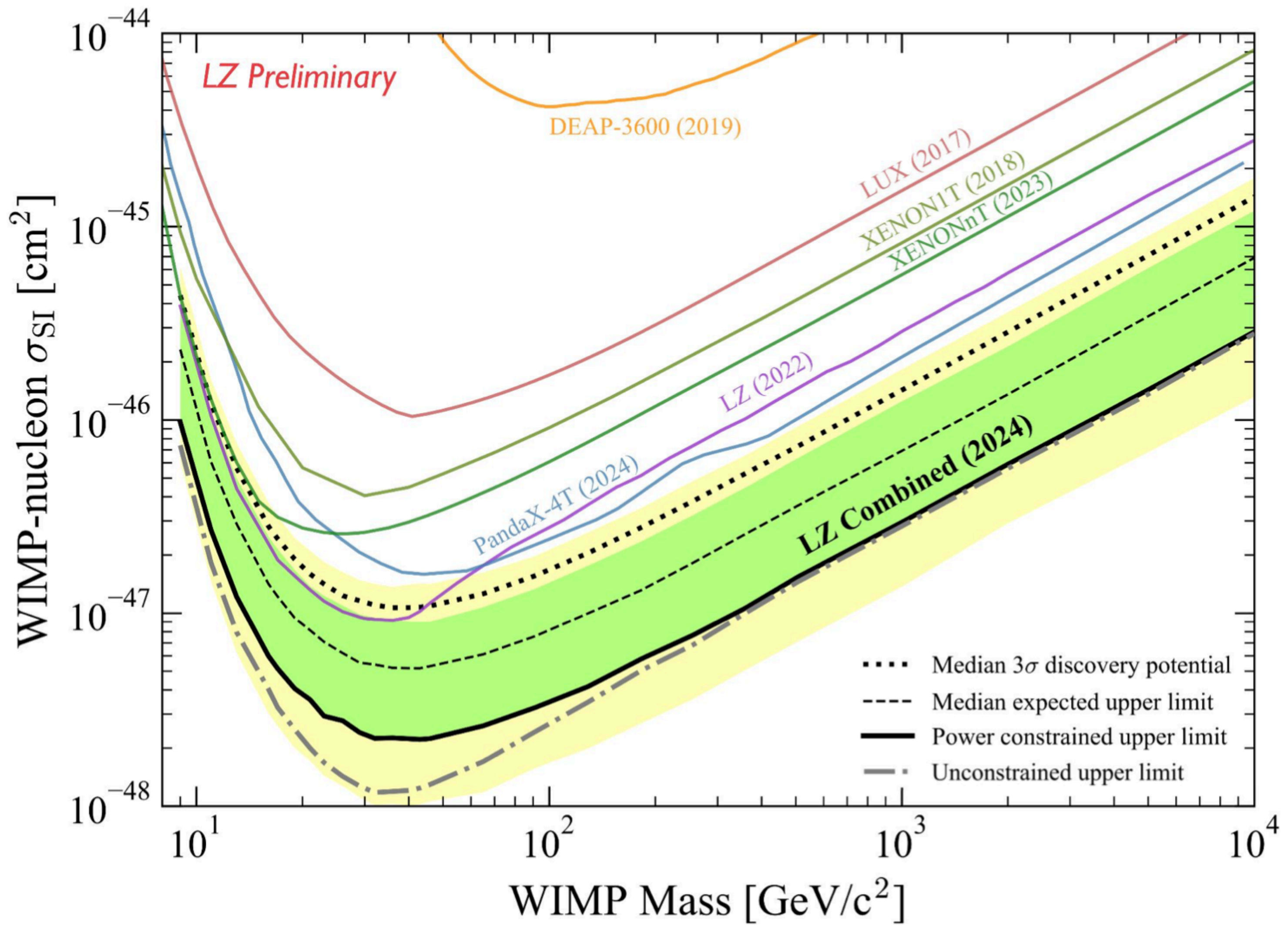
Direct Detection

Indirect Detection

Collider Search, taken from 2405.13778

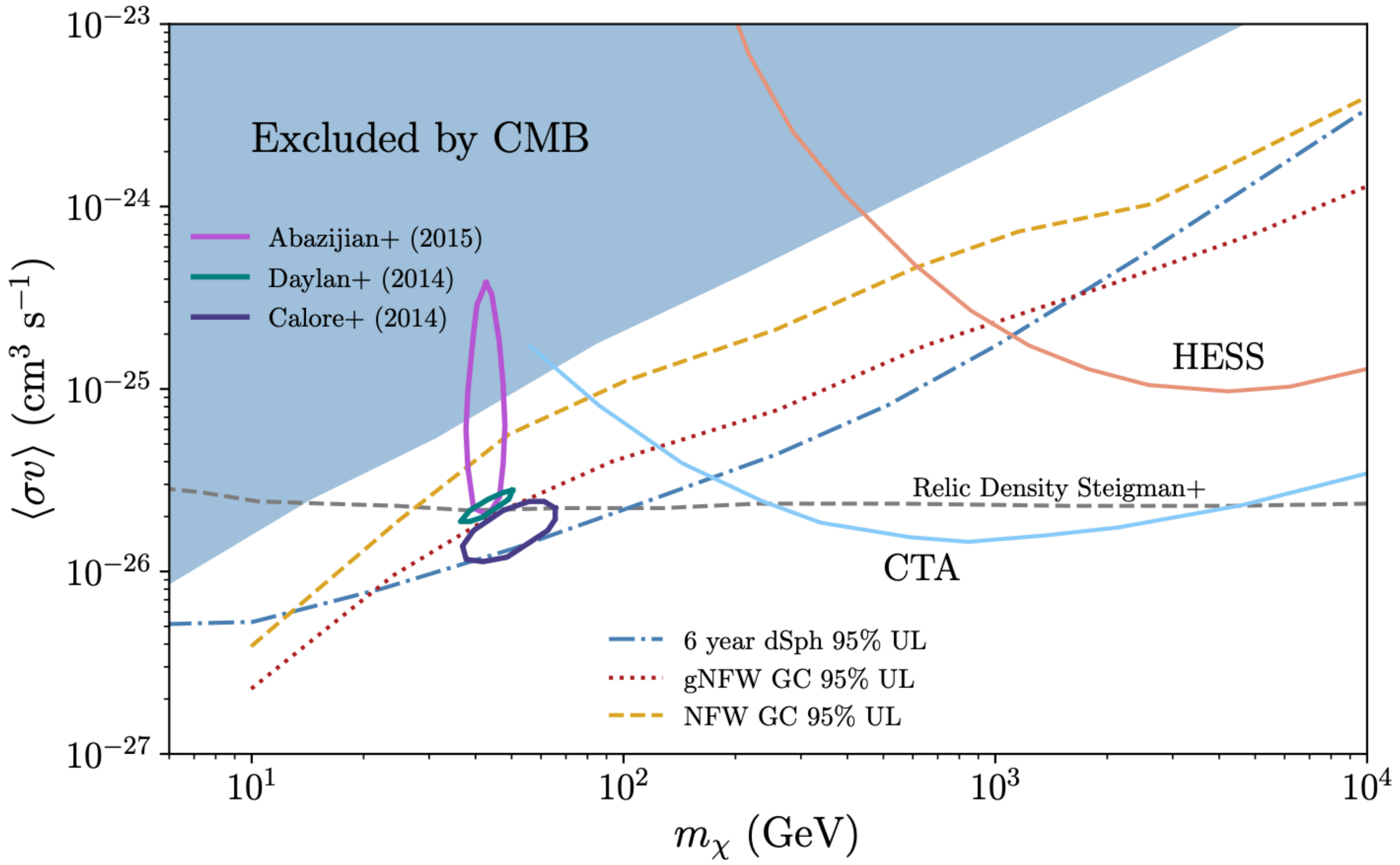


Direct Detection Limits



Taken from P. Bras, Jornadas Científicas do LIP 2024, Braga

Indirect Detection Limits



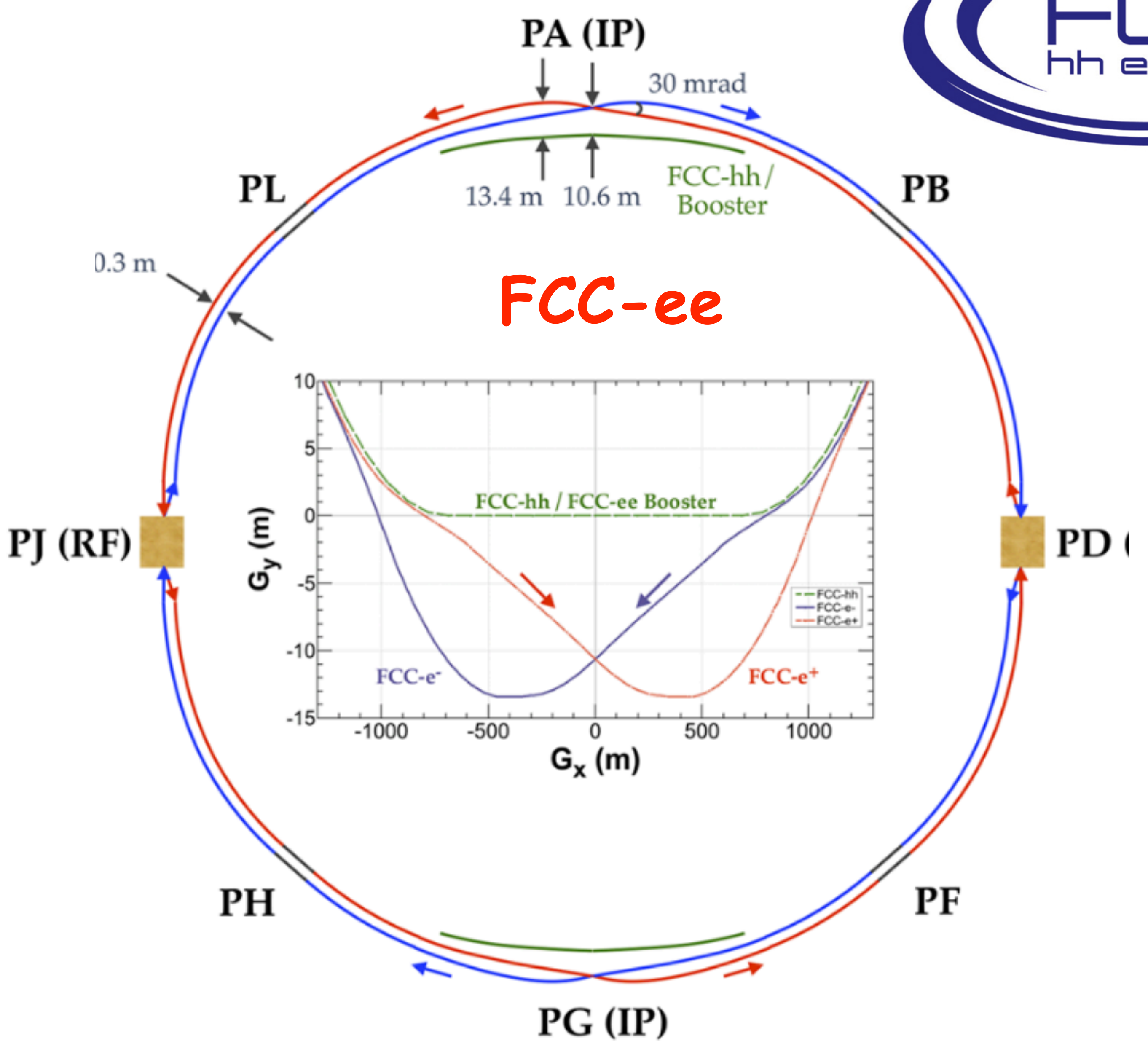
Taken from PDG 2025, fig. courtesy of Logan Morrison

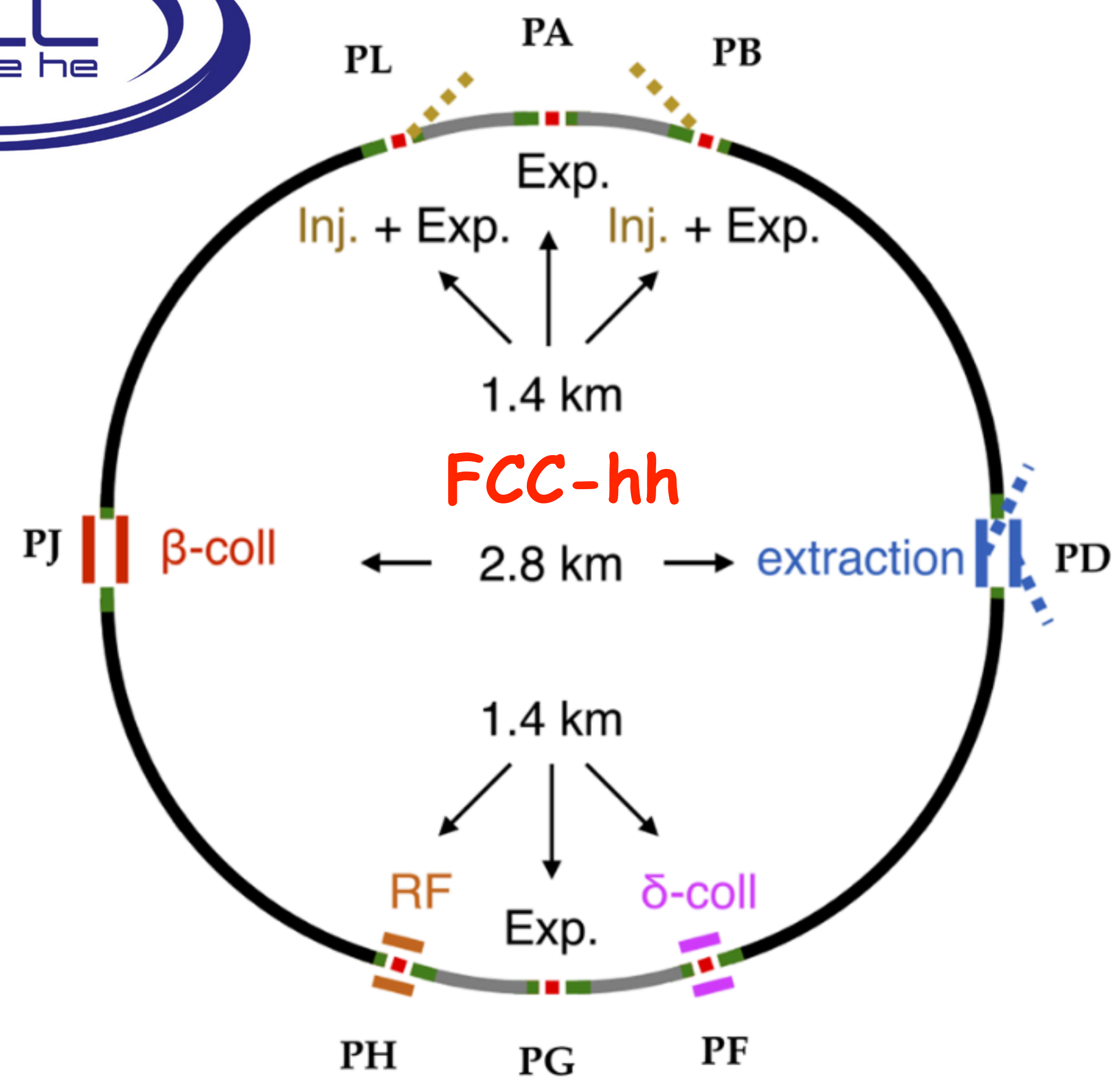
FCC Integrated Program

Stage1: Higgs,top,EW factory at highest luminosities (91->365 GeV)
Stage2: 100 TeV pp, energy frontier
(in addition eh and ion options)

Higgs, top, EW&QCD precision
model independence; flavor factory;
weakly coupled new physics;
prepare for hh

Higgs self-coupling
Higgs-top Yukawa coupling
Heavy new physics





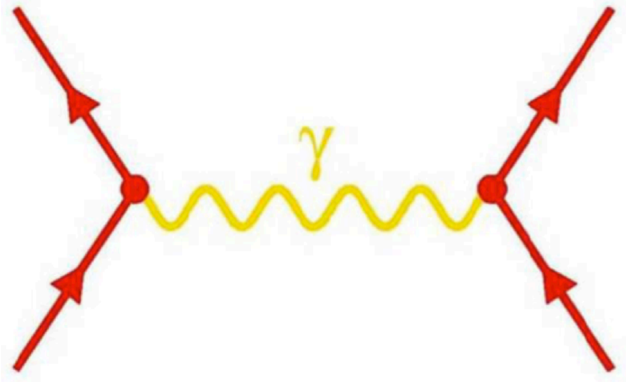
2029-2041

2048-2063

2074-

Gauge Symmetries

- Description of fundamental interactions: with quantum field theories
  fields are quantized, e.g. photon: electromagnetic field quantum



interaction: exchange
of field quanta

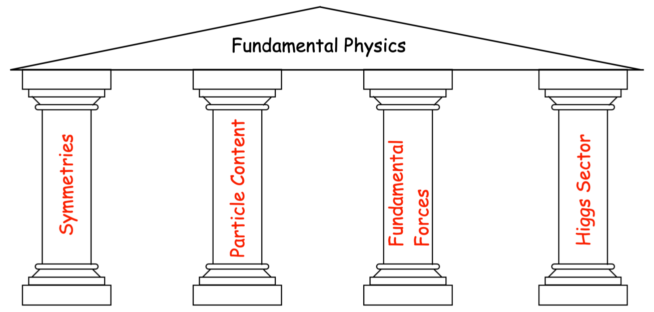
- Relativistic quantum field theories: invariant under space-time transformations:
  Lorentz transformations + space-time translations (Poincaré group)

- Construction principle: requirement of local gauge invariance (internal symmetry)

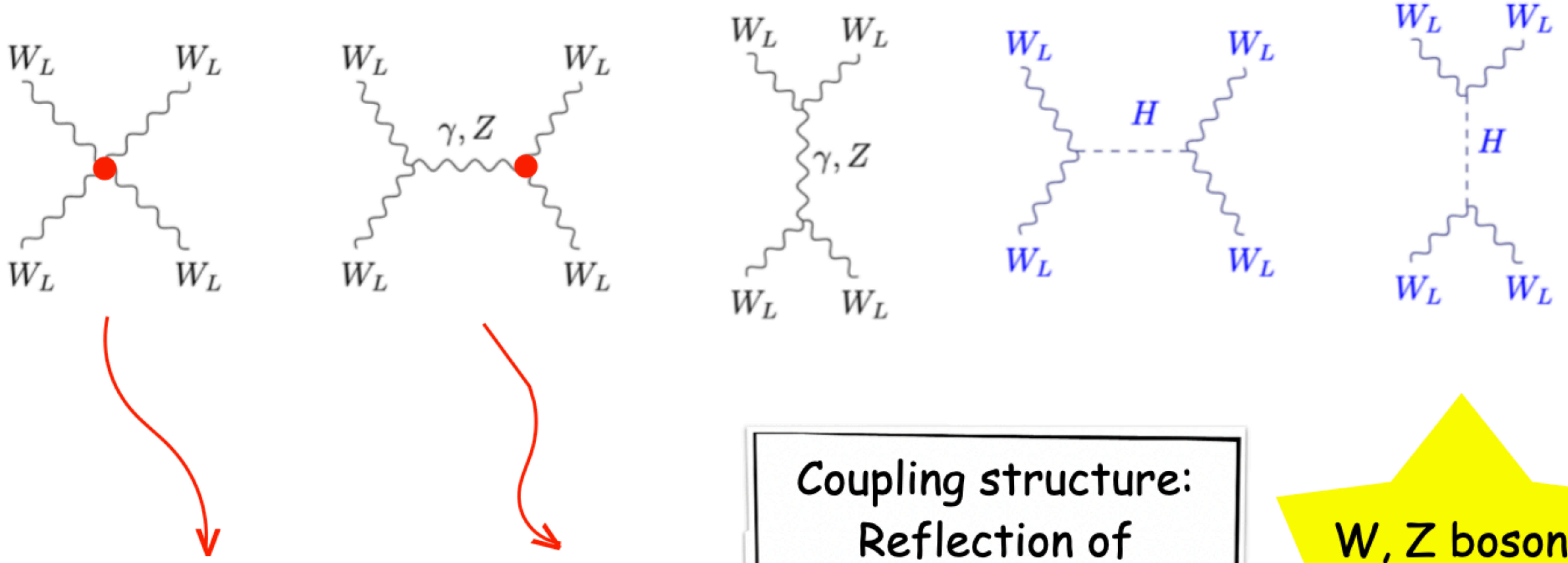
- Gauge symmetries of the Standard Model:

$$\underbrace{U(1)_Y \times SU(2)_L}_{\text{electroweak}} \times \underbrace{SU(3)_C}_{\text{strong}} \quad \text{interaction}$$

What is the
guiding
principle?



The Theoretical Base: Gauge Symmetries



Unitarity also Requires

Quartic W boson coupling

neutral Z exchange

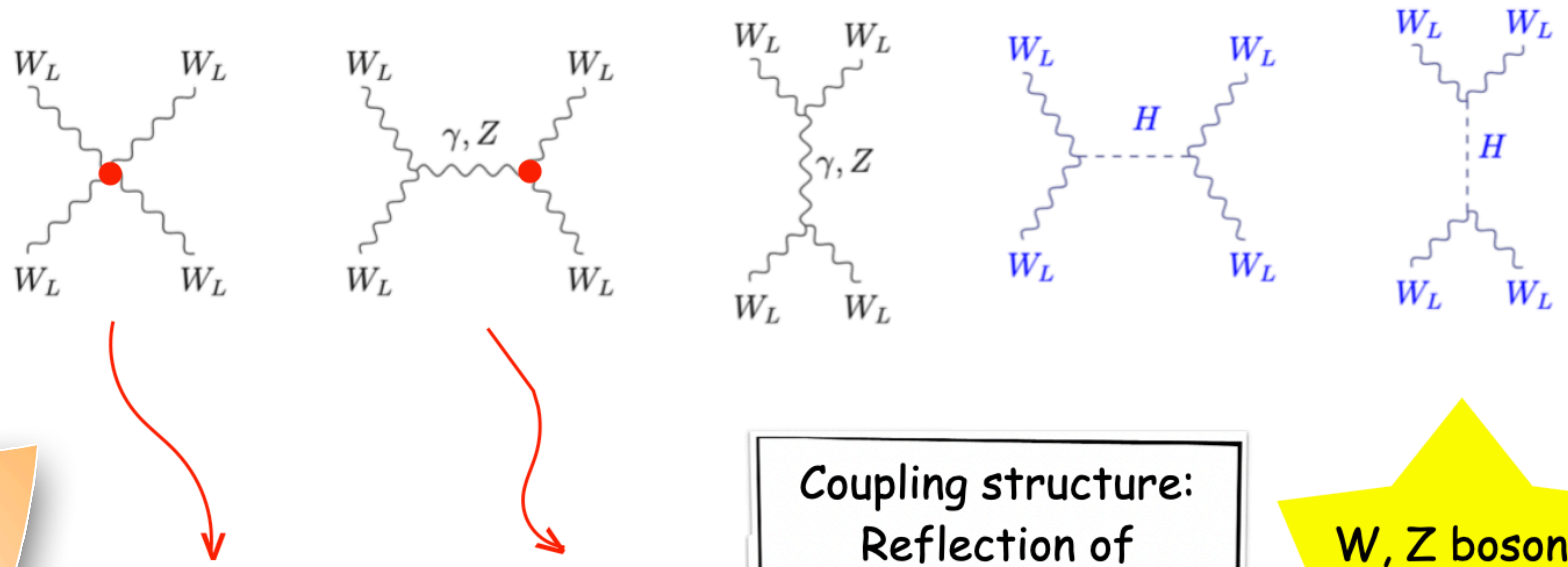
Coupling structure:
Reflection of
the structure of
the underlying
local gauge theory

W, Z bosons
discovered
1983

Gauge Theory

- Lagrangian and hence the dynamics of the system described by the Lagrangian is invariant under local (x-dependent) transformations.
- Ensured by the inclusion of gauge fields = force carriers: γ, W, Z, gluons
- Non-abelian gauge theories: 3- and 4-point interactions of gauge bosons.

The Theoretical Base: Gauge Symmetries



rity
so
quires

Quartic
W boson
coupling

neutral
Z
exchange

Coupling structure:
Reflection of
the structure of
the underlying
local gauge theory

W, Z bosons
discovered
1983

Nobel Prize
1984 to
Carlo Rubbia
and
Simon van der
Meer

MILESTONE

Gauge Theory

- Lagrangian and hence the dynamics of the system described by the Lagrangian is invariant under local (x-dependent) transformations.
- Ensured by the inclusion of gauge fields = force carriers: γ, W, Z, gluons
- Non-abelian gauge theories: 3- and 4-point interactions of gauge bosons.