Connecting the Standard Models of Particle Physics and Cosmology

Andrei Gritsan

Johns Hopkins University

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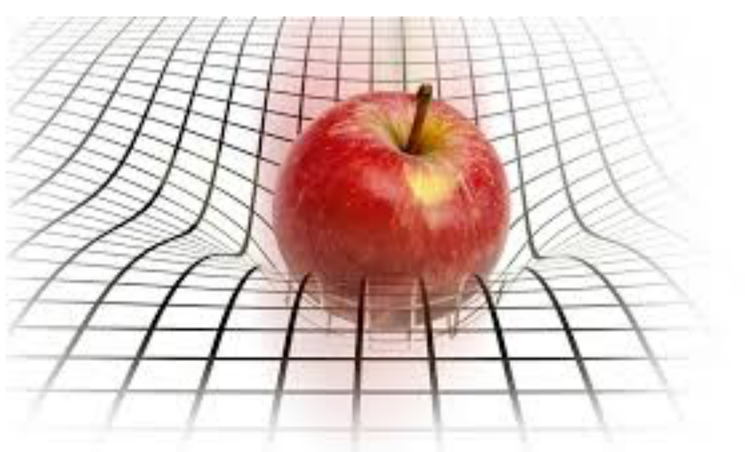
Johns Hopkins University QuarkNet Physics Workshop

Vision of the World by an Exp. Particle Physicist

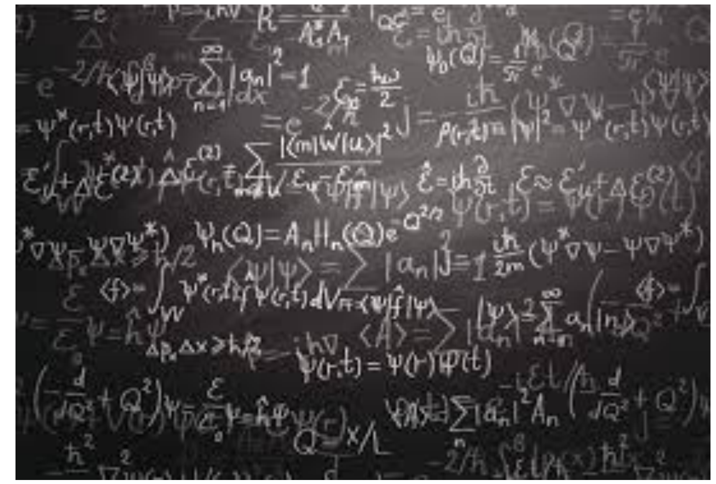


Gravity

Electricity

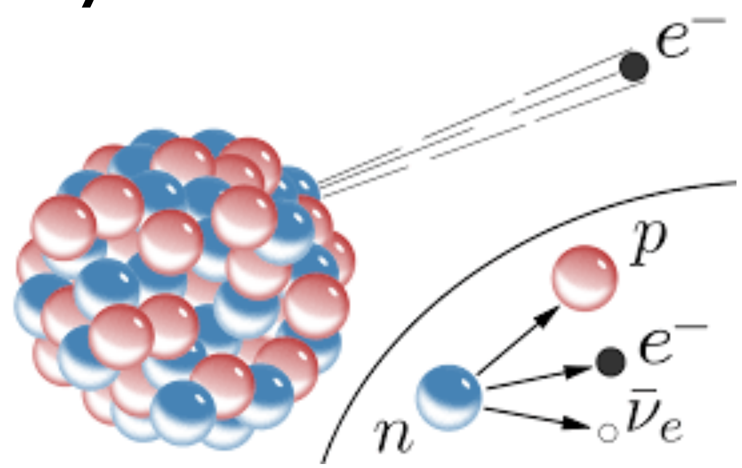
Magnetism

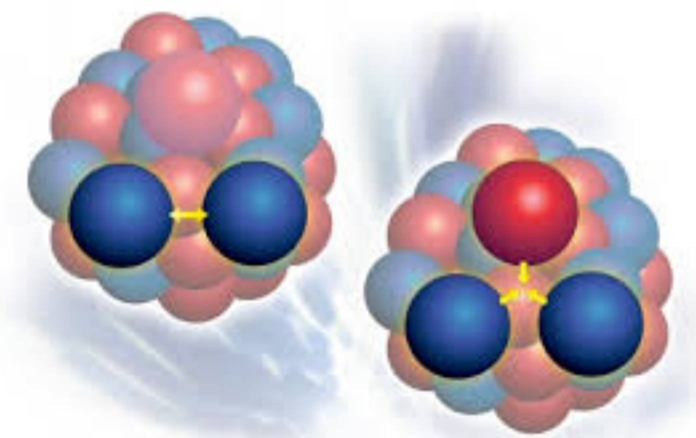
Vision of the World by an Exp. Particle Physicist

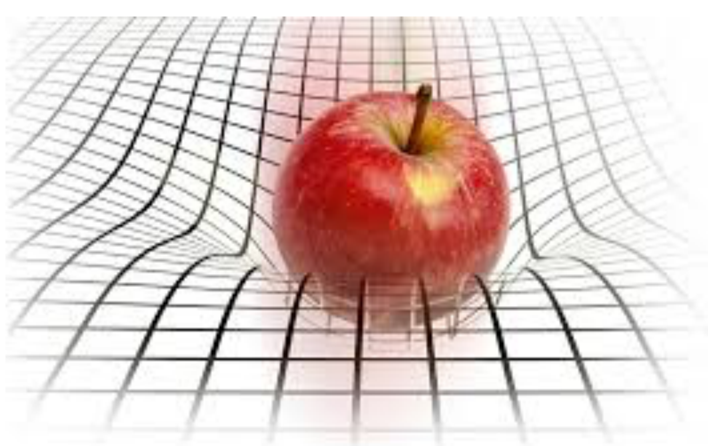


Quantum Field Theory

Quantum Mechanics
+ Special Relativity







Gravity

Weak

E&M

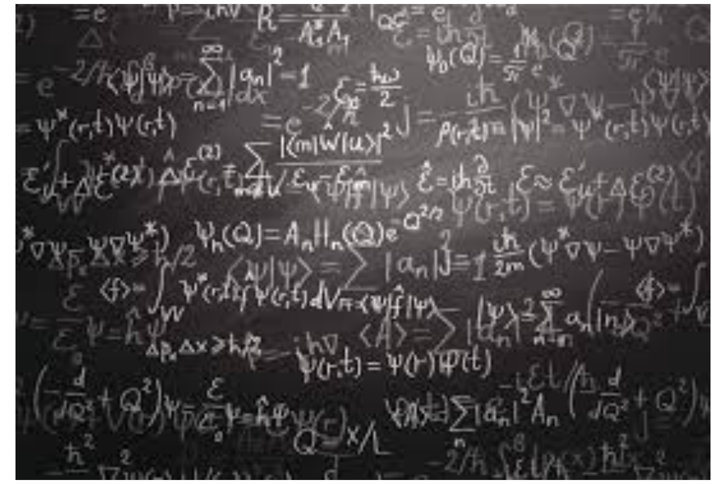
Strong

Electricity

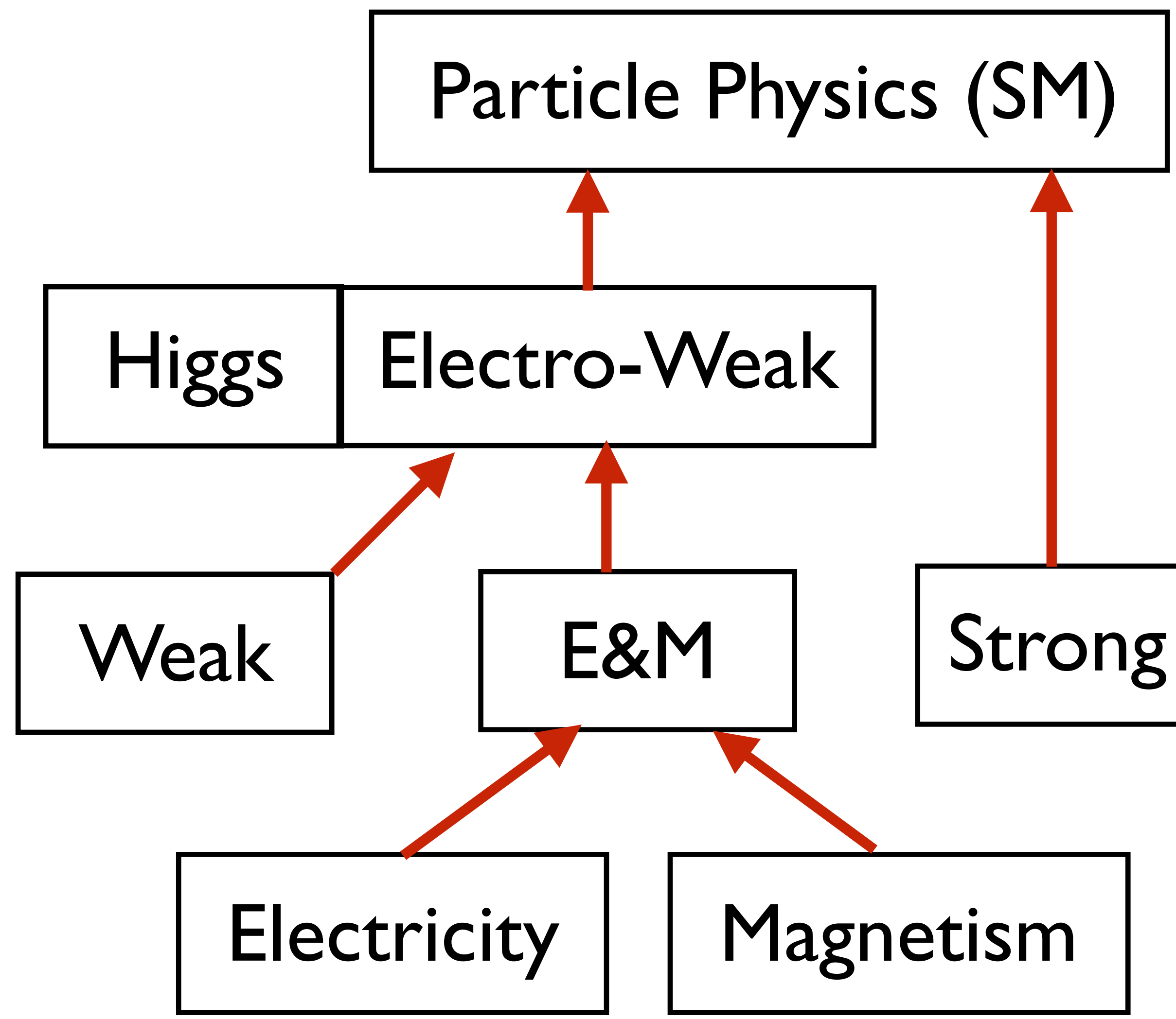
Magnetism

Vision of the World by an Exp. Particle Physicist

Quantum Field Theory



Quantum Mechanics
+ Special Relativity



Gravity

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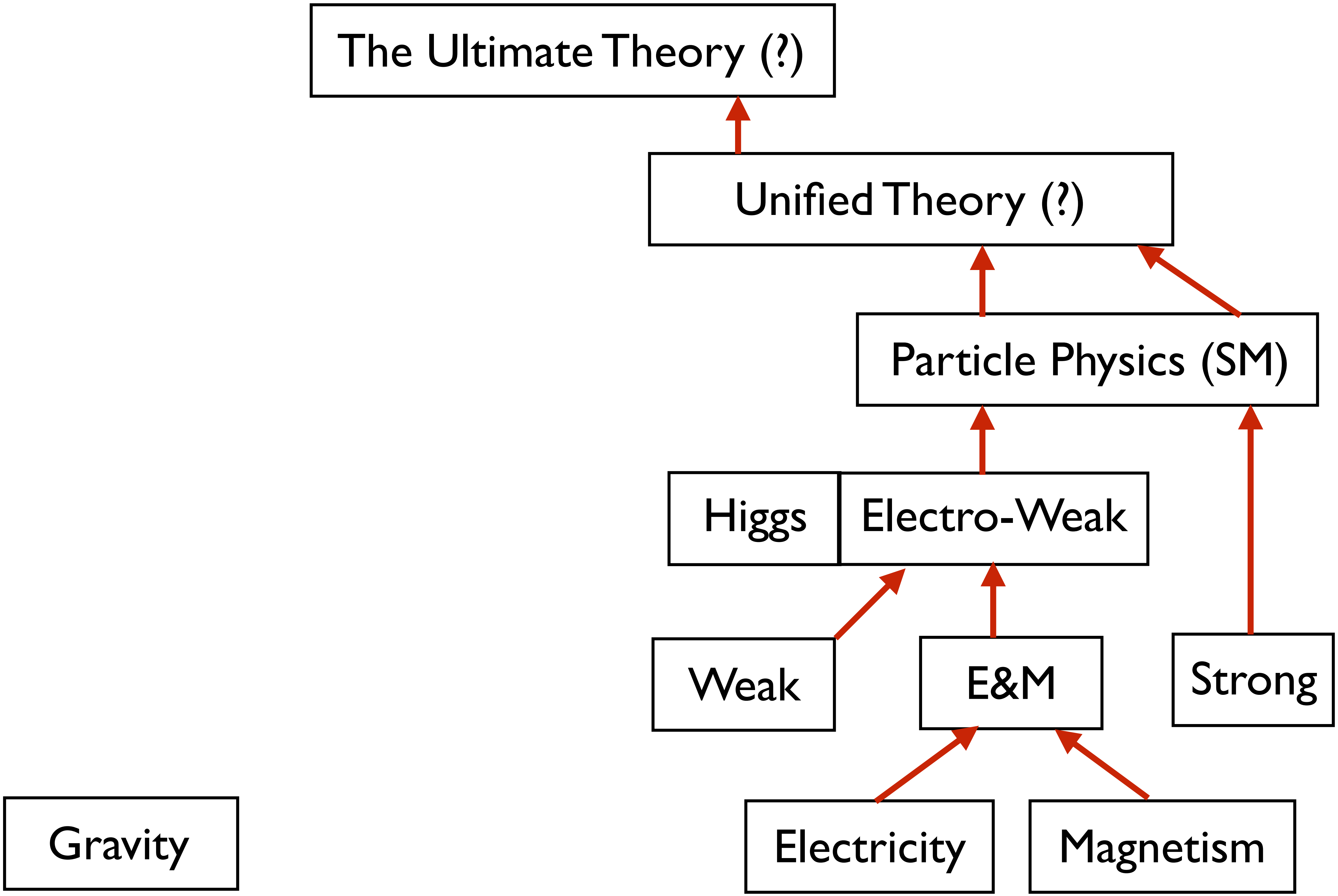

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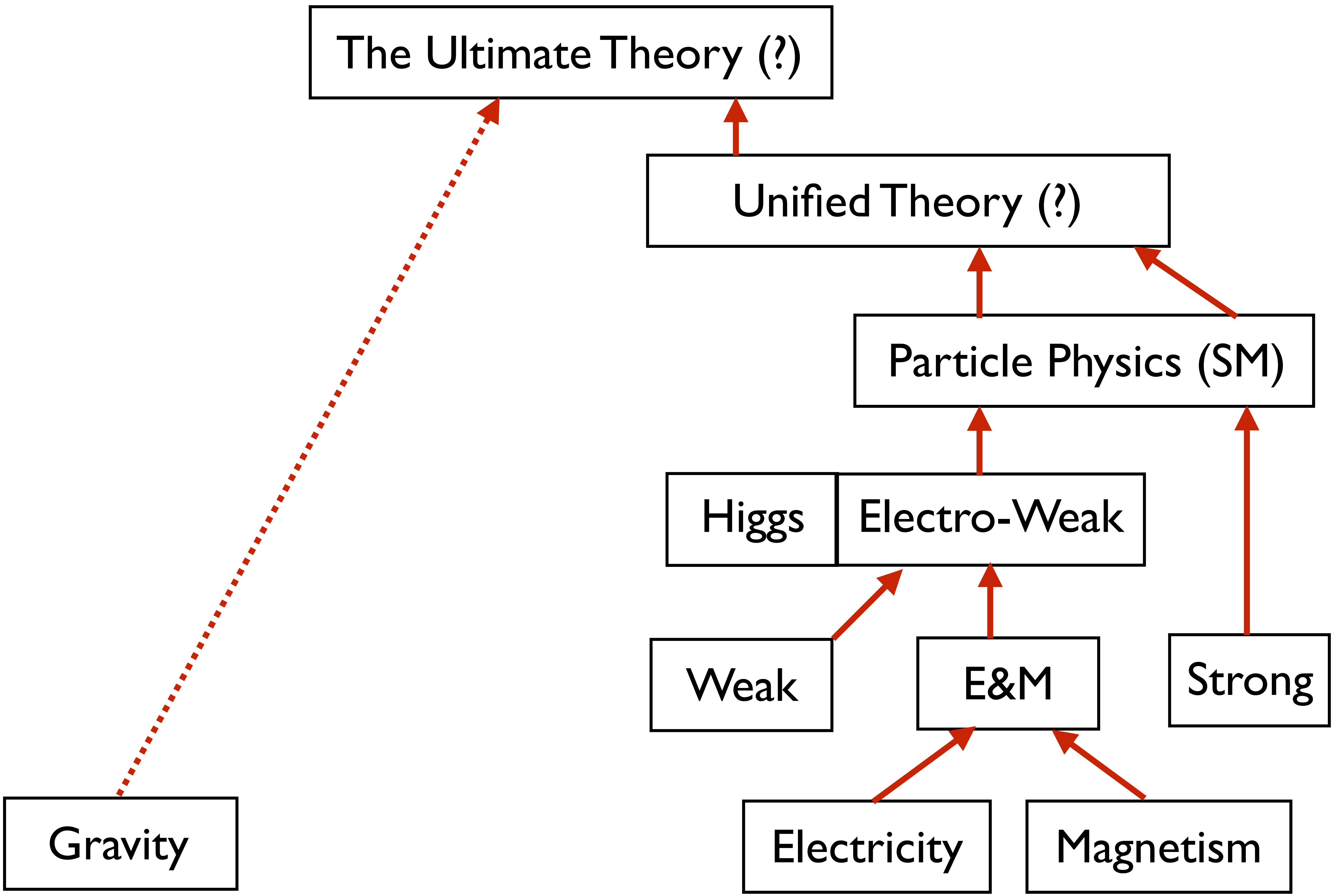

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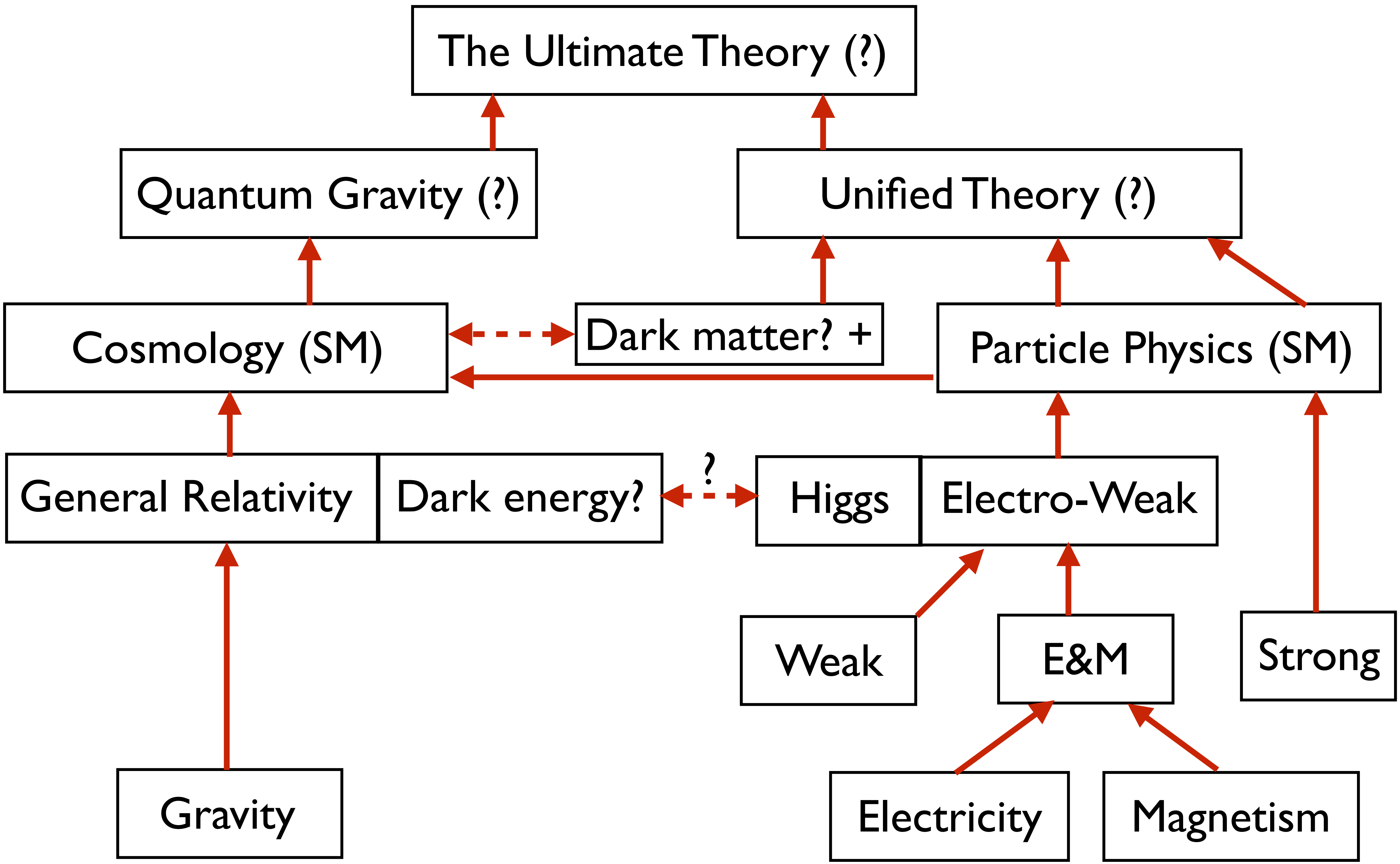

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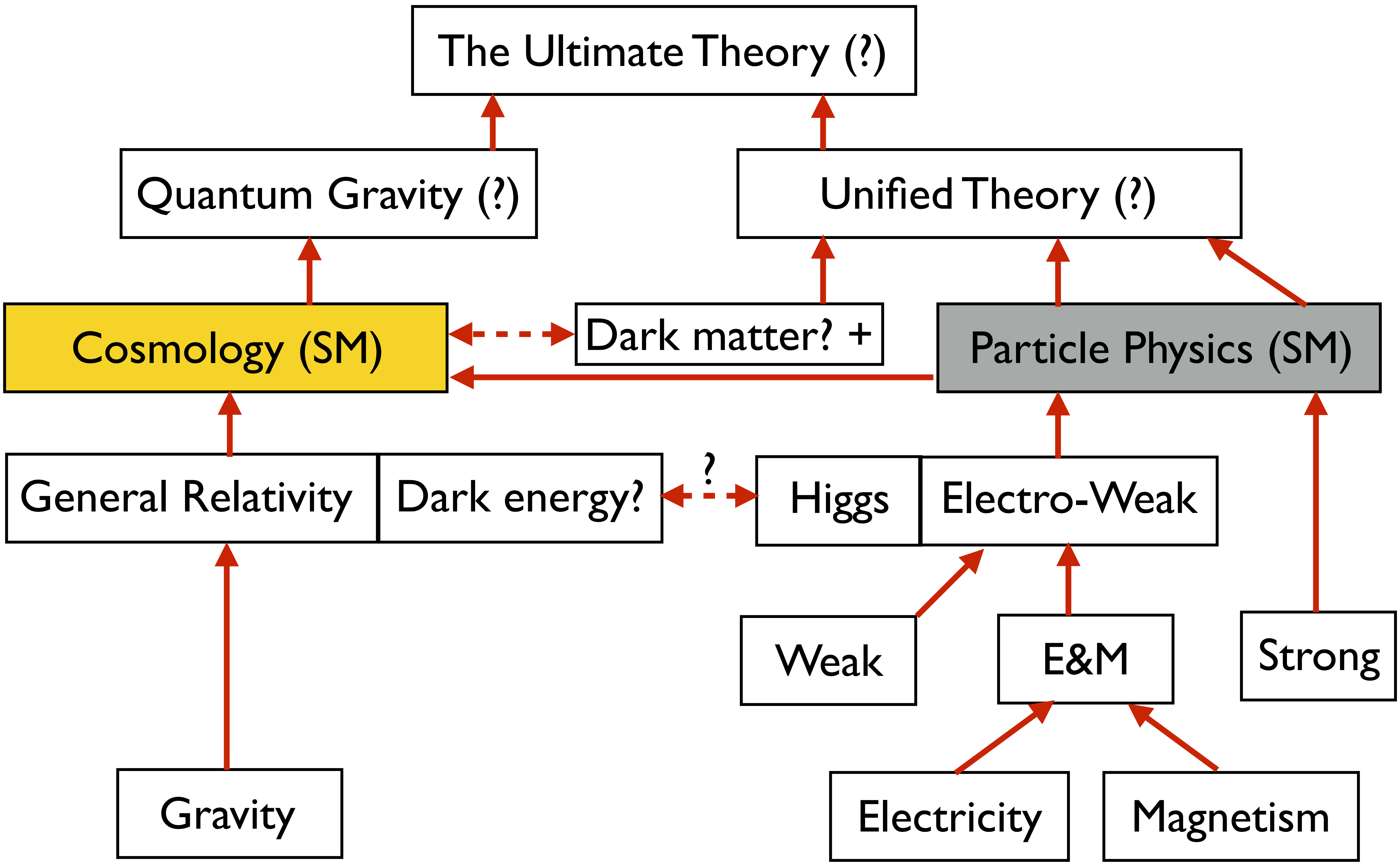

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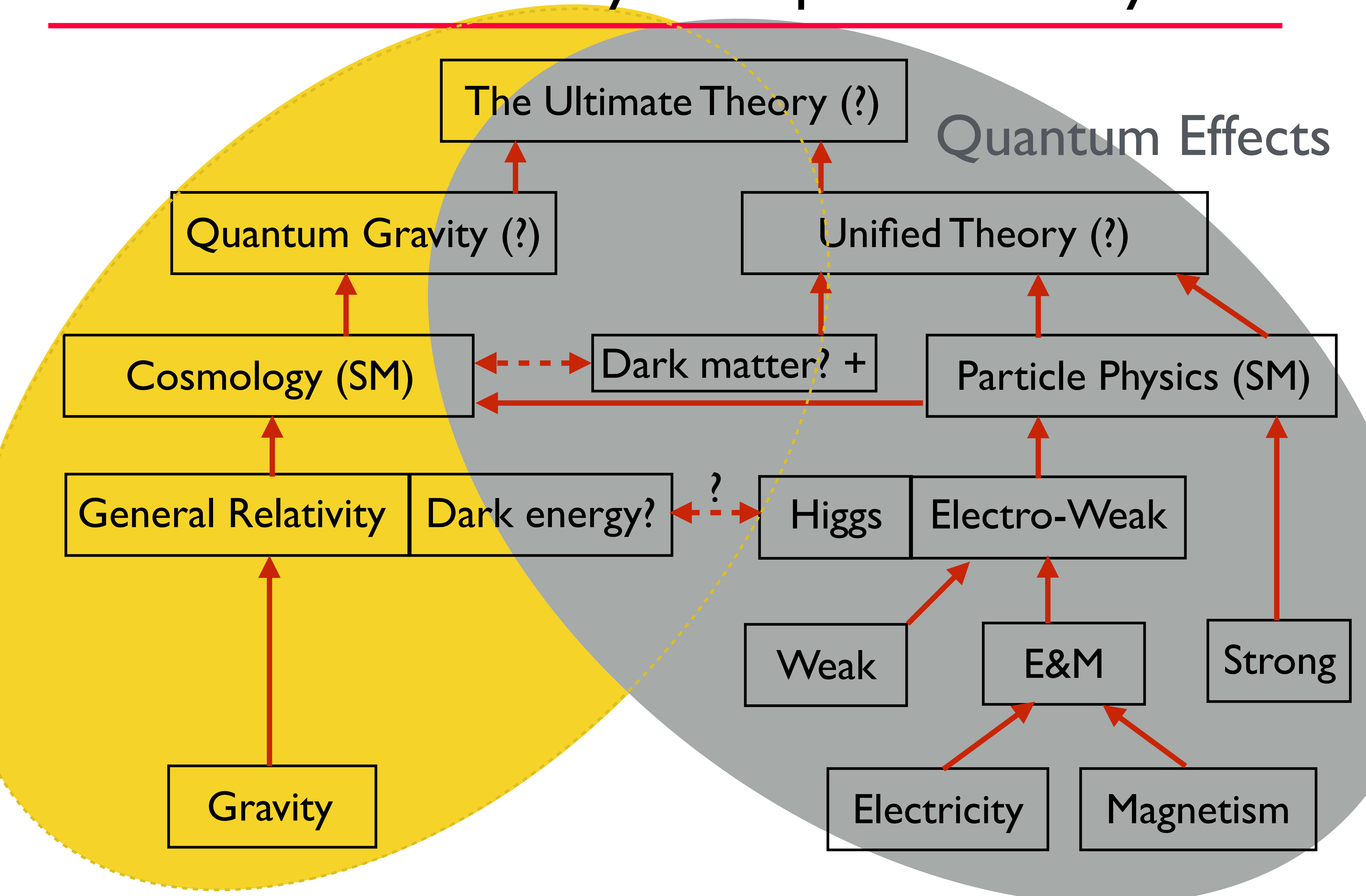

In the last 10 years…

Higgs

The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Electro-Weak

The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation
Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation
Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Electro-Weak

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

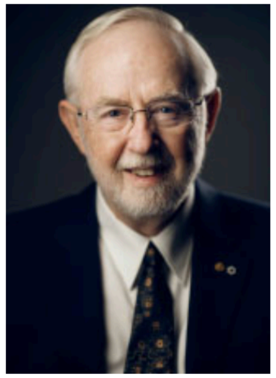

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

In the last 10 years…

General Relativity

Dark energy?

The Nobel Prize in Physics 2017

© Nobel Media. Ill. N. Elmehed
Rainer Weiss
Prize share: 1/2

© Nobel Media. Ill. N. Elmehed
Barry C. Barish
Prize share: 1/4

© Nobel Media. Ill. N. Elmehed
Kip S. Thorne
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

The Nobel Prize in Physics 2011

Photo: U. Montan
Saul Perlmutter
Prize share: 1/2

Photo: U. Montan
Brian P. Schmidt
Prize share: 1/4

Photo: U. Montan
Adam G. Riess
Prize share: 1/4

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Higgs

Electro-Weak

The Nobel Prize in Physics 2013

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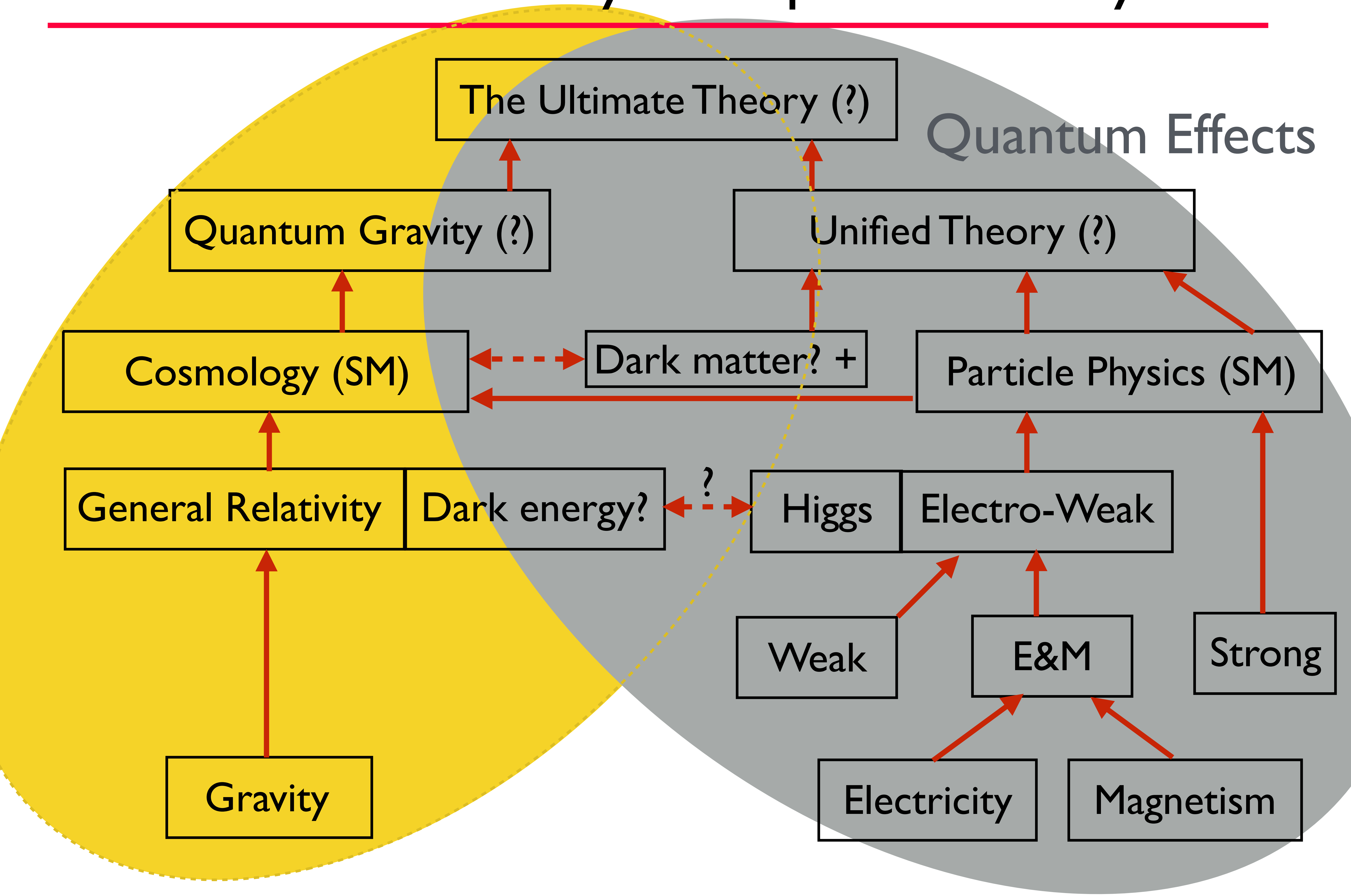

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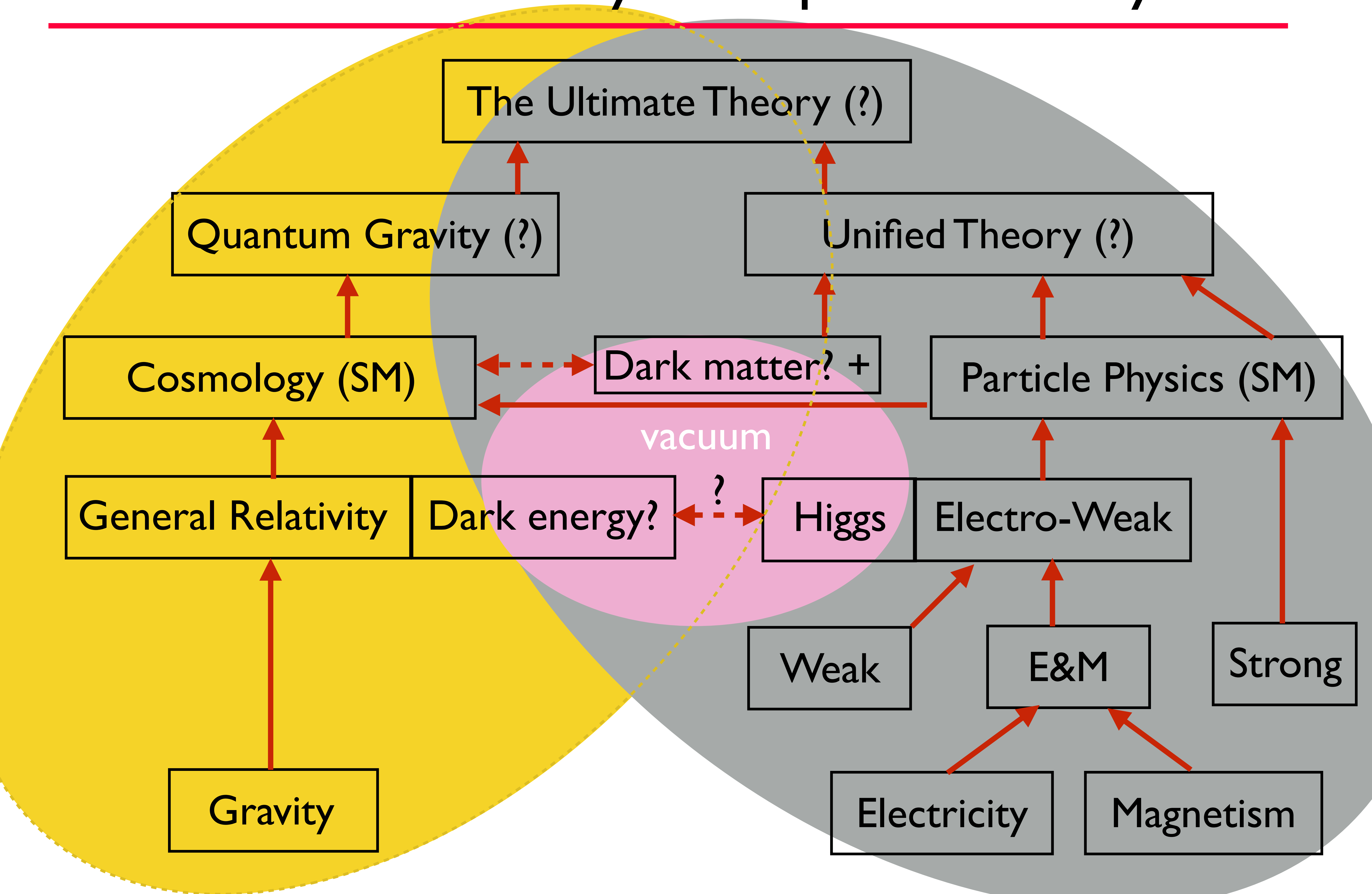

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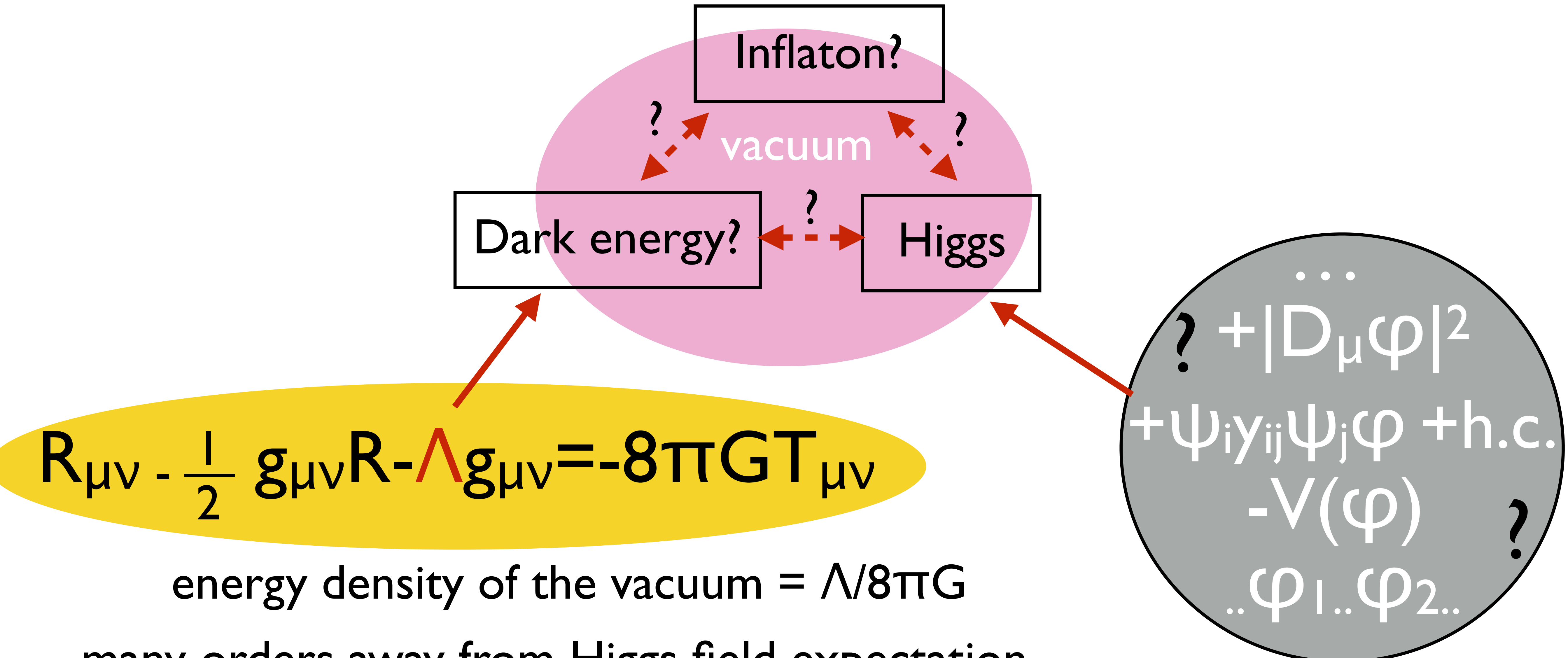


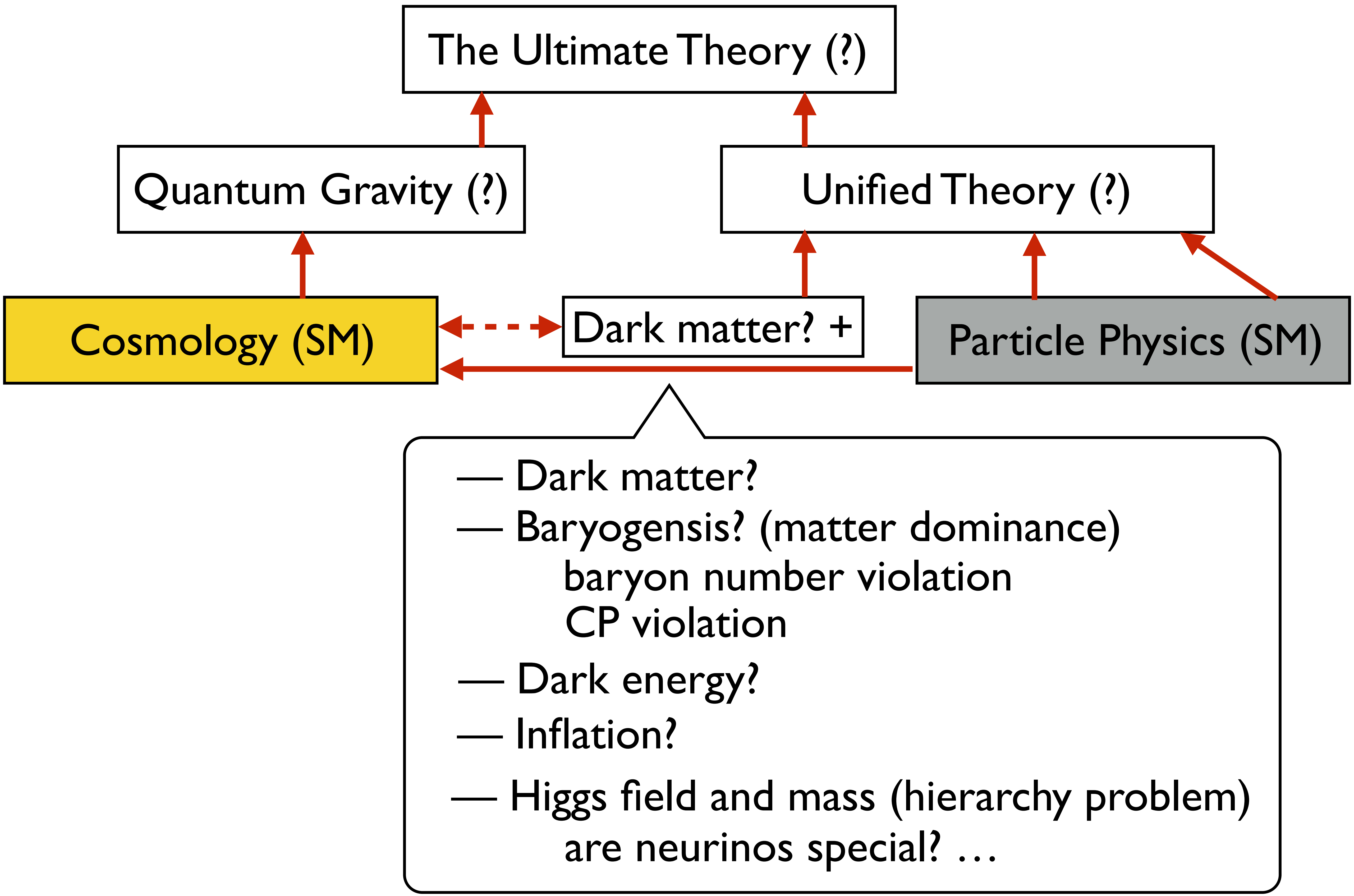
energy density of the vacuum = $\Lambda/8\pi G$

many orders away from Higgs field expectation

quantum numbers of the vacuum $J^{PC}=0^{++}$

- $H(125)^0$ boson is a completely new state of matter-energy
  — comes from a new scalar field of fundamental importance

Vision of the World by an Exp. Particle Physicist



The Big Bang Theory: Fundamental Particles

THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

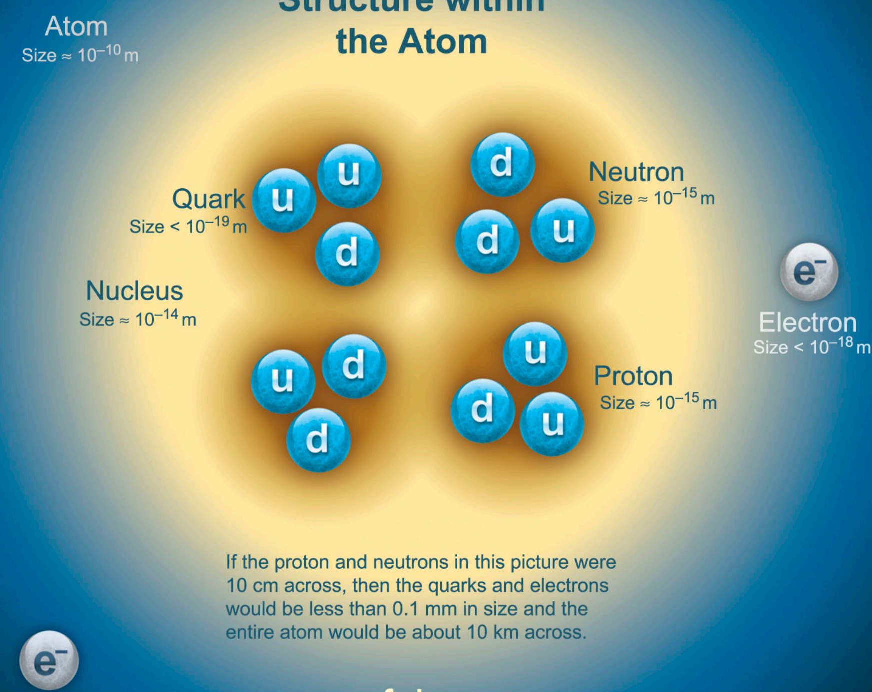
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

Properties of the Interactions

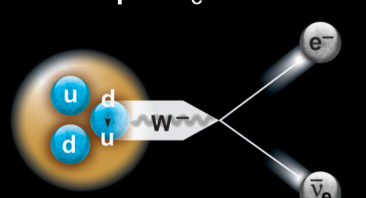
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

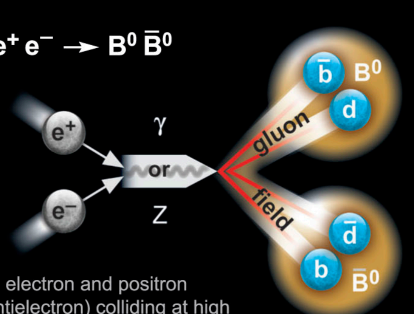
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

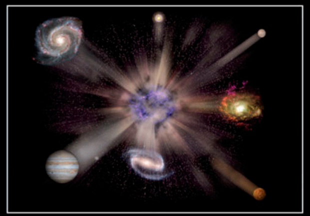


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

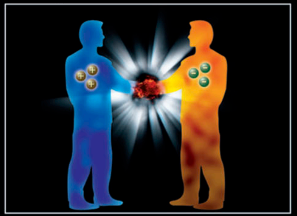
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

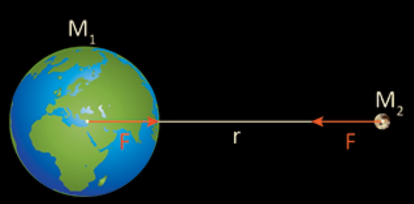
GRAVITATION:
FROM NEWTON TO EINSTEIN

The Newtonian View of Gravity

In 1687, Isaac Newton published his Law of Universal Gravitation. In this law, the gravitational force between two point-masses is proportional to the product of their masses divided by the square of their separation.

$$F = \frac{GM_1M_2}{r^2}$$

In this equation, the two objects have masses M_1 and M_2 and the distance between them is r. The proportionality constant G is called the *Universal Gravitational Constant*. An attractive force pulls the masses toward each other along a straight line that passes through them.



Newton's great insight was to realize that the same influence that makes objects fall toward the ground on Earth also keeps the planets and other celestial bodies in their orbits.

The Newtonian View of Black Holes

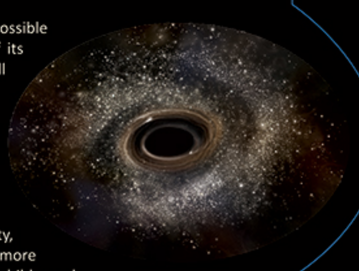
In 1783, the English philosopher John Michell first proposed the idea that there were such things as "dark stars," an idea which arose from Newtonian gravity. The escape velocity (v_{esc}) is the minimum speed required for a test particle to escape the gravitational pull of an object with mass M:

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

Notice that the escape velocity increases as the square root of the object's mass increases, and decreases if the test particle starts farther from the object's center (at a distance r).

If the escape velocity is set equal to the speed of light, c, then we can find the physical size (R_{Sch}) of Michell's dark star:

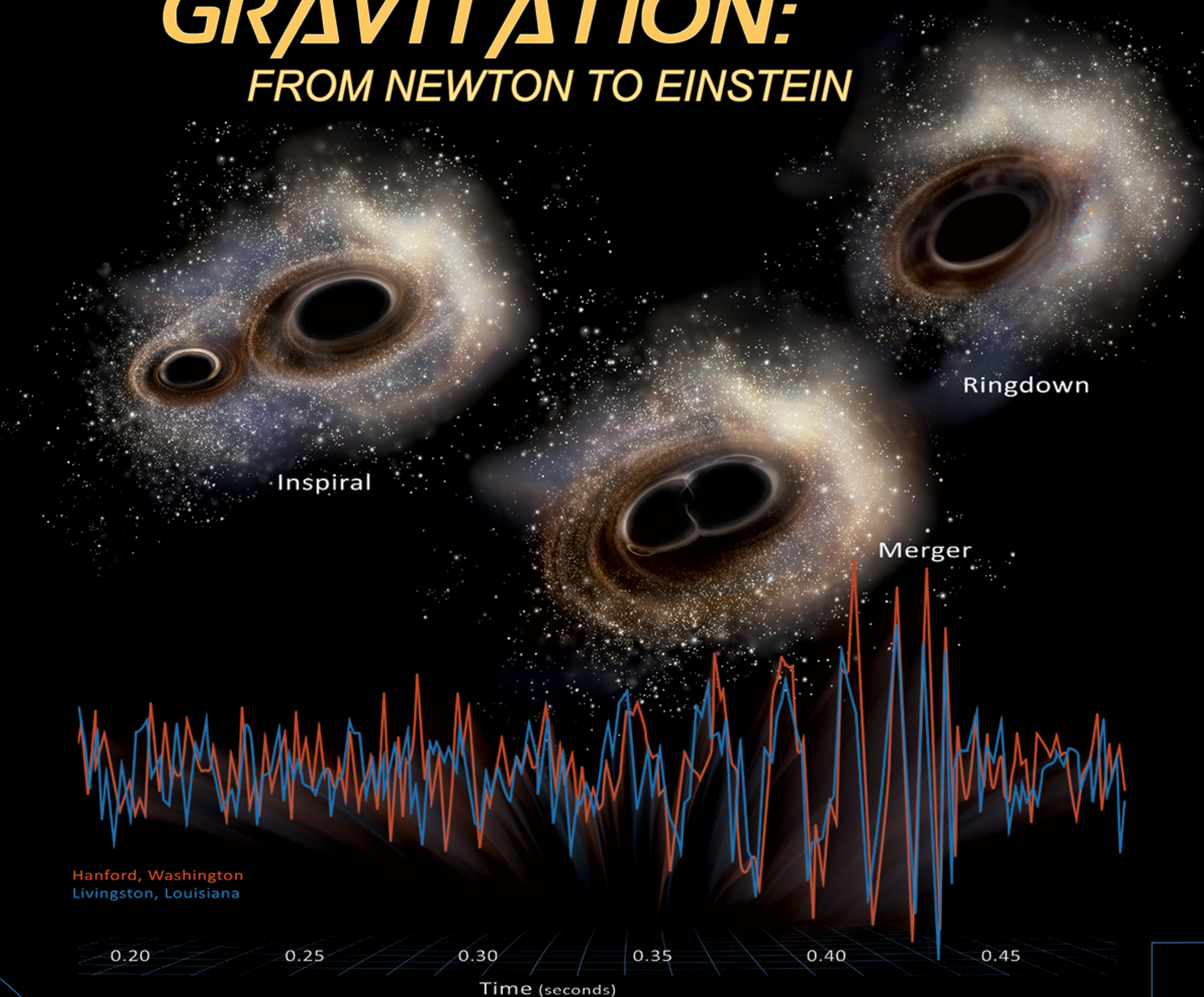
$$R_{Sch} = \frac{2GM}{c^2}$$



Since c is the maximum possible speed, an object with all of its mass within this radius will have such strong gravity that not even light can escape; it will thus be "black."

The same relation can be derived using Einstein's General Theory of Relativity, but the calculation is much more complicated. Karl Schwarzschild used General Relativity to solve for this "radius of no return" for non-spinning black holes: it is called the Schwarzschild radius, R_{Sch}, in his honor. It is just a coincidence that the size of black holes in Newtonian gravity and General Relativity are the same; at the point of forming a black hole, Newtonian gravitational theory is no longer valid, and General Relativity must be used.

We gratefully acknowledge support from the National Science Foundation for some of the work done to create this poster.



Direct Detection of Gravitational Waves

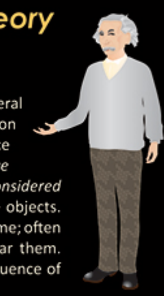
Gravitational waves were directly detected for the first time on September 14, 2015 by the LIGO (Laser Interferometer Gravitational-wave Observatory) scientific collaboration and the Virgo collaboration. The illustration above depicts the signals detected by the twin LIGO detectors from a system with two in-spiraling black holes. The red and blue lines show the amplitude of the gravitational wave signals received at the LIGO detectors in Hanford, Washington and Livingston, Louisiana, respectively. After traveling for billions of years, the signal arrived first at Livingston, and then 7 ms later, at Hanford.

Note the correspondence between the two signals. Both match closely to the theoretical model computed using General Relativity for an inspiralling black hole binary system. In this system, the black holes weigh in at 36 and 29 times the mass of our Sun, respectively. At the point of merger, the gravitational wave emission abruptly dies away, in an event called the ringdown, as the newly formed 62 solar mass black hole settles into its equilibrium state. The merger process emits the equivalent of 3 solar masses of energy as gravitational waves.

The artwork above the waveform shows a visualization of the binary black hole system at various times during the event. The inspiral phase lasts for millions to billions of years prior to the merger. The data show about the last 0.15 seconds of the inspiral phase, prior to the merger. The strongest gravitational waves are emitted during the black hole merger, which occurs from around t = 0.35 to t=0.44 seconds on this plot. The final, brief, ringdown phase starts at about t = 0.44 seconds.

Due to the small value of the Universal Gravitational Constant, gravity is considered the weakest of the four fundamental forces of physics. However, because extremely massive objects are usually involved, gravitational forces can generate considerable amounts of energy. The peak gravitational-wave power radiated during the final moments of this black hole merger was more than ten times greater than the power from the light emitted by all the stars and galaxies in the observable Universe.

Einstein's General Theory of Relativity



In 1915, Albert Einstein published his General Theory of Relativity. In this theory, gravitation is not a force at all, but a property of space and time (*spacetime – a union of space and time in which the two cannot be considered independently*) in the presence of massive objects. Such objects distort and stretch the spacetime; often we say that they *curve* the spacetime near them. What we experience as gravity is a consequence of objects moving in that curved spacetime.

Einstein expressed the gravitational effects of spacetime through an equation, called the Einstein Equation.

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

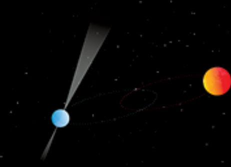
The Einstein Equation can be explained using the famous quote by John Archibald Wheeler:

"Spacetime tells matter how to move; matter tells spacetime how to curve."

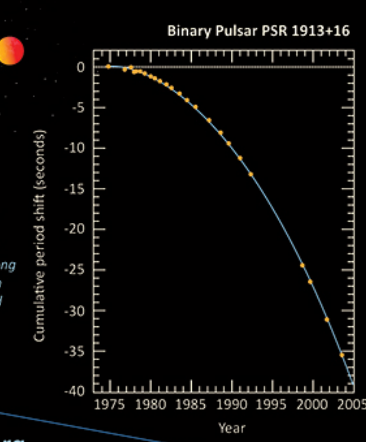
In Einstein's equation, $G_{\mu\nu}$ describes the curvature of spacetime while $T_{\mu\nu}$ describes the distribution and form of mass and energy. These two four-dimensional mathematical quantities are related through constants including the speed of light, c, and the Universal Gravitational Constant, G. Einstein's equation simplifies to Newton's Law of Gravitation in most cases.

Gravitational Waves

Einstein's General Theory of Relativity predicts that two stars in a binary orbit will generate gravitational waves as the stars orbit each other. These waves carry away energy. As a result, the two stars will slowly spiral in toward one another and will eventually merge. If one of the stars emits regular pulses (like a pulsar), the pulse period will appear to shift as the orbit shrinks. This phenomenon was first confirmed in a binary system discovered in 1974 by Russell Hulse and Joseph Taylor. In this system (known as the Hulse-Taylor binary pulsar or PSR 1913+16), both of the stars are collapsed objects called neutron stars. One of them is a pulsar that emits regular pulses which are used to measure the period shift of the shrinking orbit. The diagrams below shows an artist's illustration of the binary pulsar system and a plot of the changing period with time.



The figure to the right shows almost 30 years of data illustrating the changing orbit of the Hulse-Taylor binary pulsar. The measured points (orange dots) are plotted along with the theoretical prediction from Einstein's theory (blue line). Derived by J. M. Weisberg and J. H. Taylor.



CPEPphysics.org

THE HISTORY AND FATE OF THE UNIVERSE

Ancient light from sources billions of light-years away, such as galaxies and the cosmic background radiation, show us events occurring billions of years ago. These events map out the history of the universe and even predict its fate. The scales in this figure are often greater by many orders of magnitude than can be shown here (especially for inflation).

The Big Bang, Inflation & the Expanding Universe

The universe has been expanding since an initial moment called the Big Bang that occurred 13.8 billion (13.8×10^9) years ago. The earliest expansion – called "inflation" – was extraordinarily rapid and smoothed out any wrinkles or imperfections, just as we can stretch out a wrinkled fabric. After inflation ended in a tiny fraction of a second, the universe continued to expand, becoming cooler and less dense. The expansion causes the distance between distant galaxies to increase, and thus the distance from us to them.

A Relic from the Early Universe

For the first 380,000 years the universe was so hot that hydrogen atoms had not yet formed, but were separate electrons and protons. Photons, the particles of light, bounced back and forth from collisions with the electrons. With further cooling, the electrons and protons stuck together in neutral atoms, nearly invisible to the photons, which then escaped. We can see these very same photons today. After traveling for 13.8 billion years they arrive, but with their wavelength stretched by a factor of 1100, since the universe itself has stretched by this factor during that time.

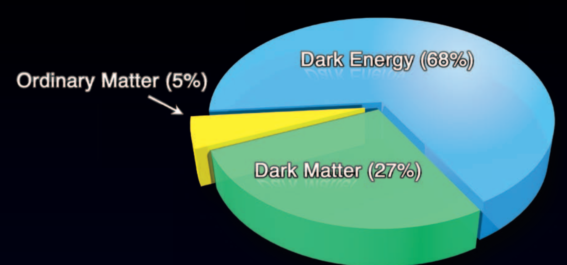
This Cosmic Microwave Background (labeled in the central figure) is nearly the same viewed in every direction. The very small variations – a part in 100,000 – are evidence of the small variations, which grew through gravitational attraction, to make the much larger variations we see today, things such as galaxies and solar systems.

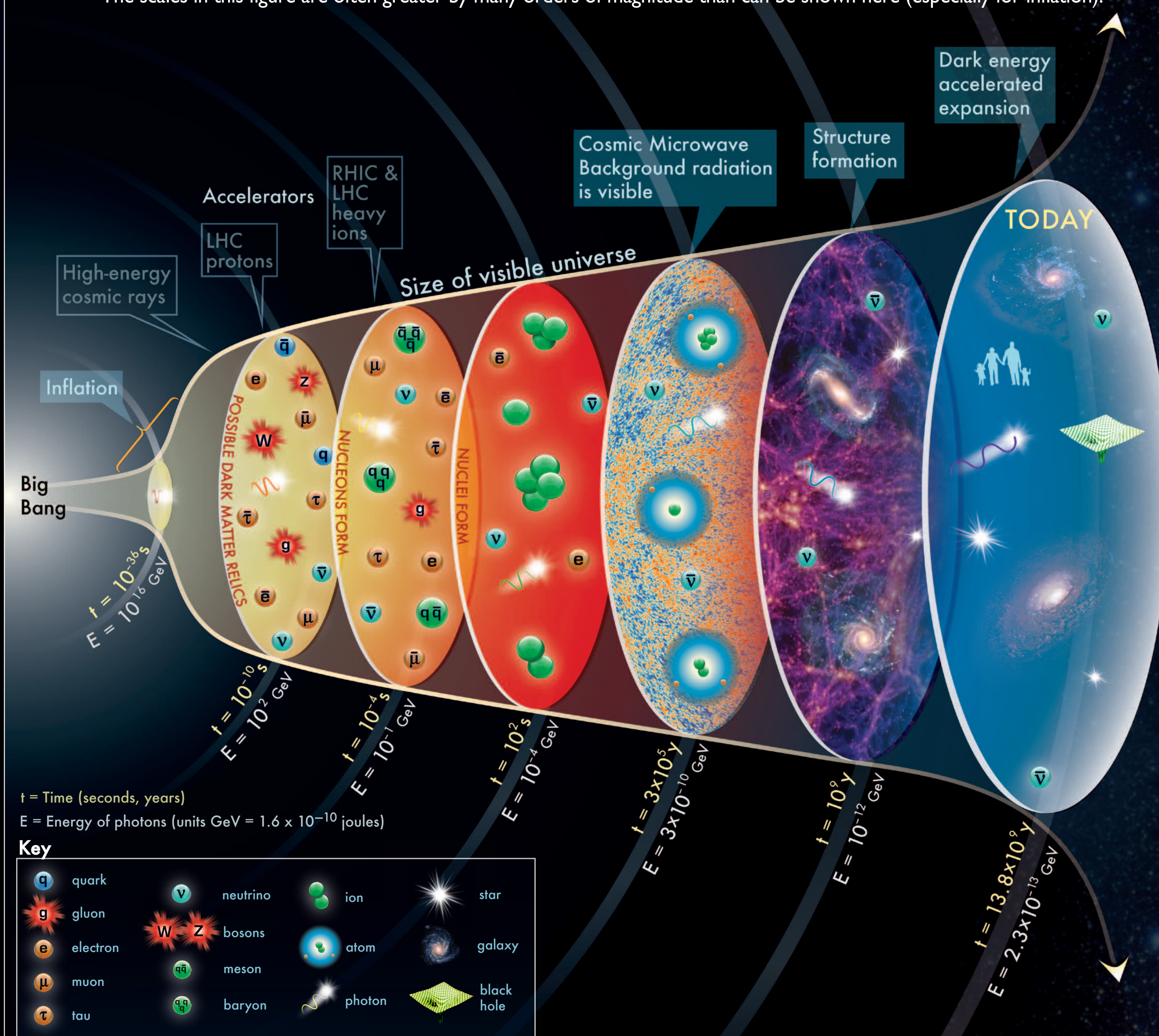
Dark Matter

Astronomers discovered that stars far out in a rotating galaxy move just as fast as those nearer the center. This is completely unlike our solar system where the innermost planets move the fastest. This couldn't happen if the matter in the galaxy is concentrated where we see stars; there must be much more unseen matter in the galaxy. This matter doesn't emit light or reflect it, so we call it dark matter. Since dark matter doesn't clump together with ordinary matter, we believe it interacts only feebly with the matter that makes up stars, planets, and people.

We have observed the results of a collision of two clusters of galaxies where the dark matter from the two clusters seems to have passed right through the other cluster, leaving behind the debris from the collision of the ordinary gas in the two clusters. Detailed measurements show that there is about six times more dark matter than ordinary matter in our universe.

Composition of the Universe





The concept for the above figure originated in a 1986 paper by Michael Turner.

Our Cosmic Address

Our sun is one of 400 billion stars in the Milky Way galaxy, which is one of more than 100 billion galaxies in the visible universe.

Invisible Skeleton of our Universe

Dark matter played a crucial role in the early universe creating all the structures we see today. Gravity caused the dark matter to coalesce into strands forming an invisible skeleton, as shown in the central figure (indicated by "Structure formation"). The gravity from the dark matter pulled ordinary matter to it. Then galaxies grew at the intersections of these filaments.

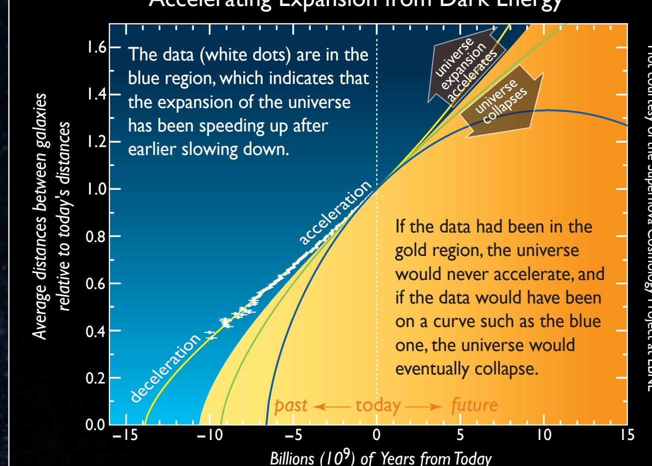
Dark Energy and the Accelerating Universe

By making detailed observations of distant supernovae, which are stars that exploded long ago, scientists discovered that the expansion of the universe is getting faster and faster instead of slowing down as would be expected from the effect of gravity pulling everything back together.

The plot shows data (white dots) from distant supernovae. From the brightness of a supernova we can infer how far away it is. By measuring the wavelengths of light from the supernova, we can determine how much the universe has expanded since the supernova explosion. Combining these gives the expansion history of the universe.

The yellow curve, with the best fit to the supernovae data, shows that about 6 billion years ago the expansion of the universe began to accelerate (the data curve upward slightly). This can only be explained by hypothesizing a new form of energy called "dark energy," which must be unlike any previously known source of energy.

Accelerating Expansion from Dark Energy



The Fate of the Universe

Whether the expansion of the universe will speed up, slow down, or even reverse into collapse depends on the types and amounts of matter and energy in it. Current observations imply that the universe will keep expanding forever, with galaxies becoming ever more distant from one another.

We have an excellent understanding of ordinary matter and all the particles discovered at accelerators, but these account for less than 5% of the energy and matter in the universe. The natures of dark energy (68% of the universe) and of dark matter (27%) are two of the greatest challenges scientists face today.

Learn more at
UniverseAdventure.org
and at CPEPphysics.org

This chart has been made possible by the generous support of: **U.S. Department of Energy and Lawrence Berkeley National Laboratory.** Photos courtesy of **NASA.**

Recently in the News

Adam Riess (JHU)

Hubble's constant

H_0= 73.5±1.7 km/s/Mpc

— For example, for a galaxy 10 Mpc away (32.6 million light years) radial velocity ~735 km/s (redshift)

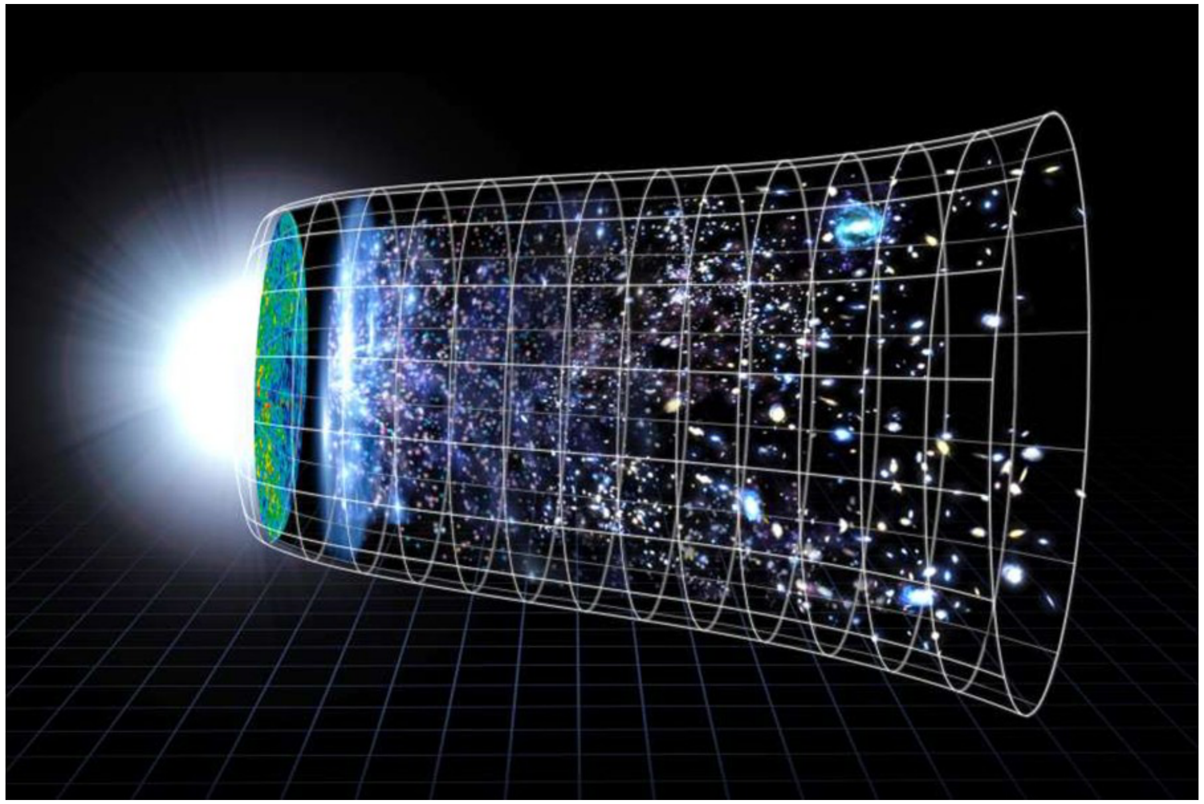
From cosmic microwave background:

H_0= 66.9±0.6 km/s/Mpc

Question

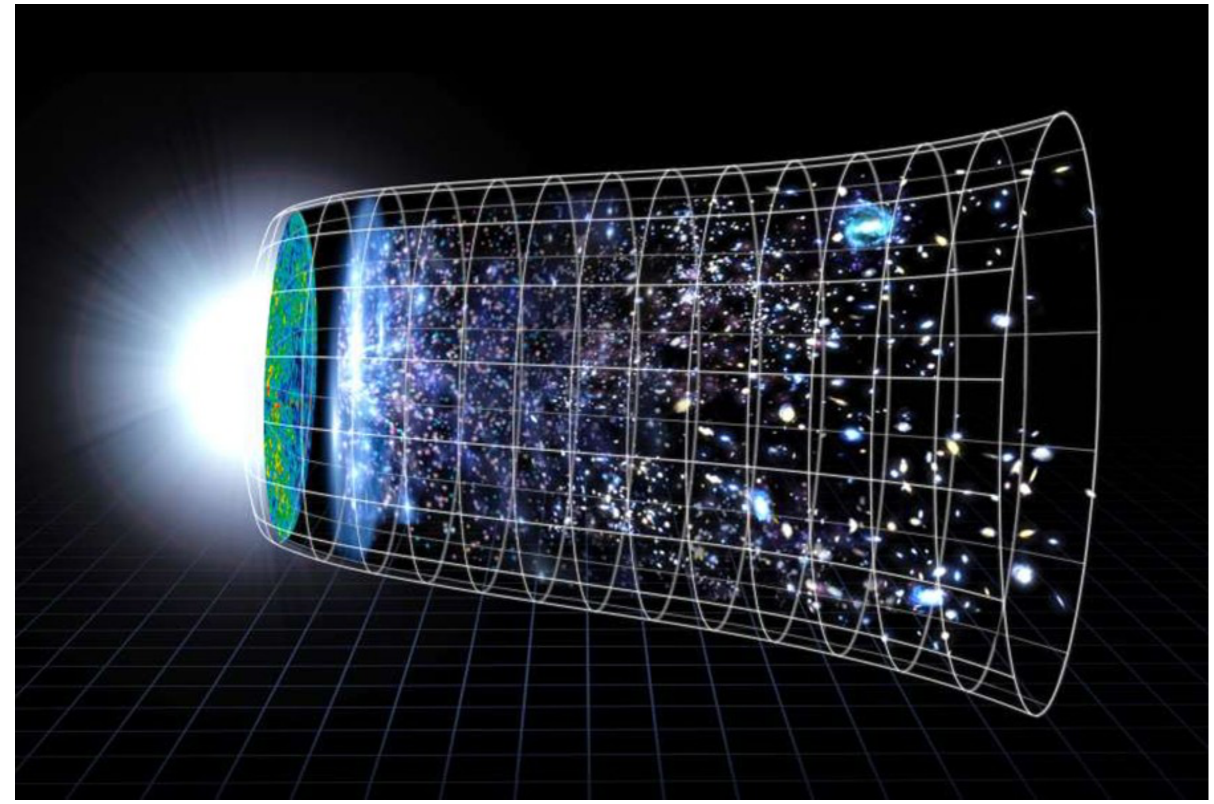
Cosmology (SM)

Particle Physics (SM)



Recently in the News

Adam Riess (JHU)



Hubble's constant

Question

Cosmology (SM)
Particle Physics (SM)

What could mismatch mean? Increase radiation density, expansion rate…

- existence of sterile neutrino? (not yet detected)
- stronger interaction of dark matter?
- dark energy more exotic?

Perhaps unaccounted systematic uncertainties?

Perhaps a third method based on gravitational wave detection could help?

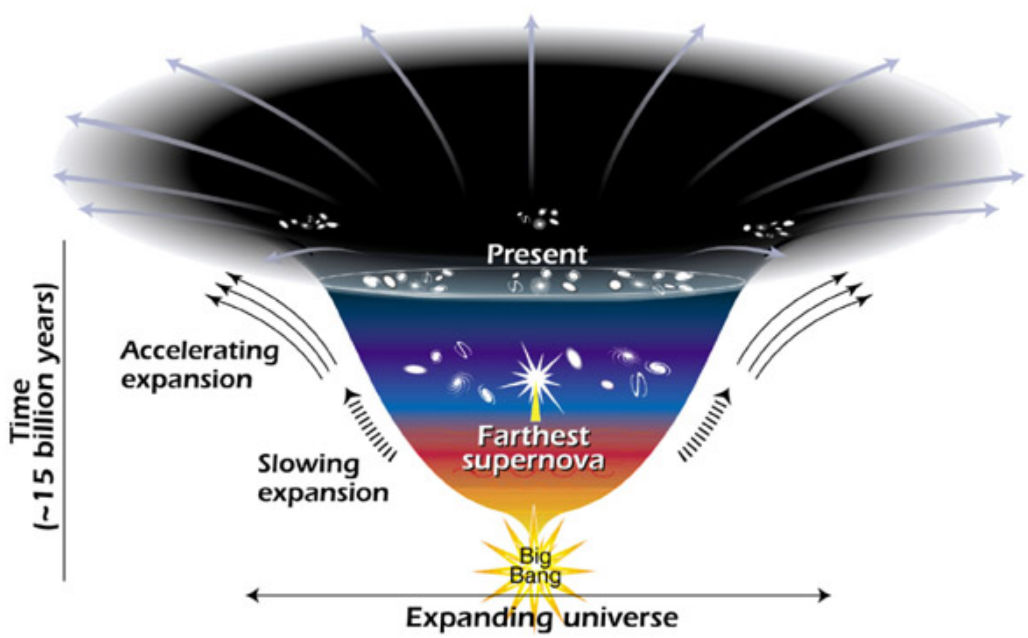
Quiz

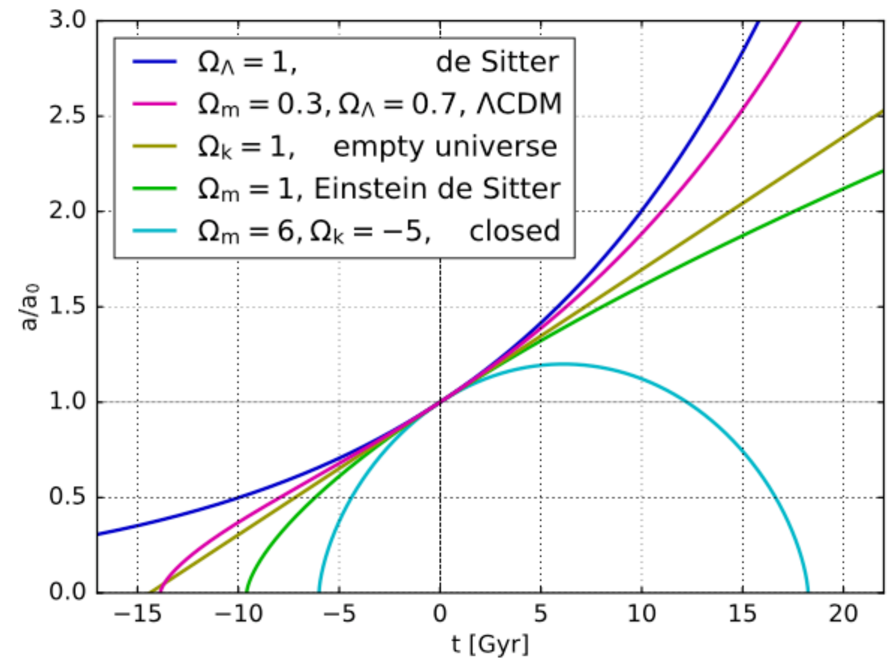
- What is the age of our Universe?

Quiz

- What is the age of our Universe?

  ~14 billion years, according to SM of Cosmology





Quiz

- What is the age of our Universe?

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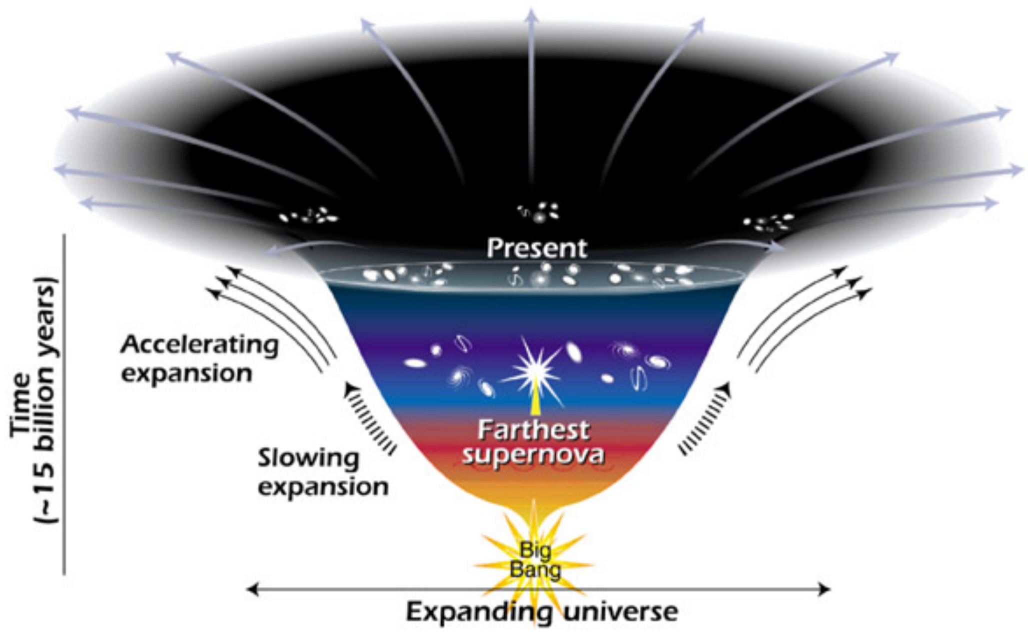
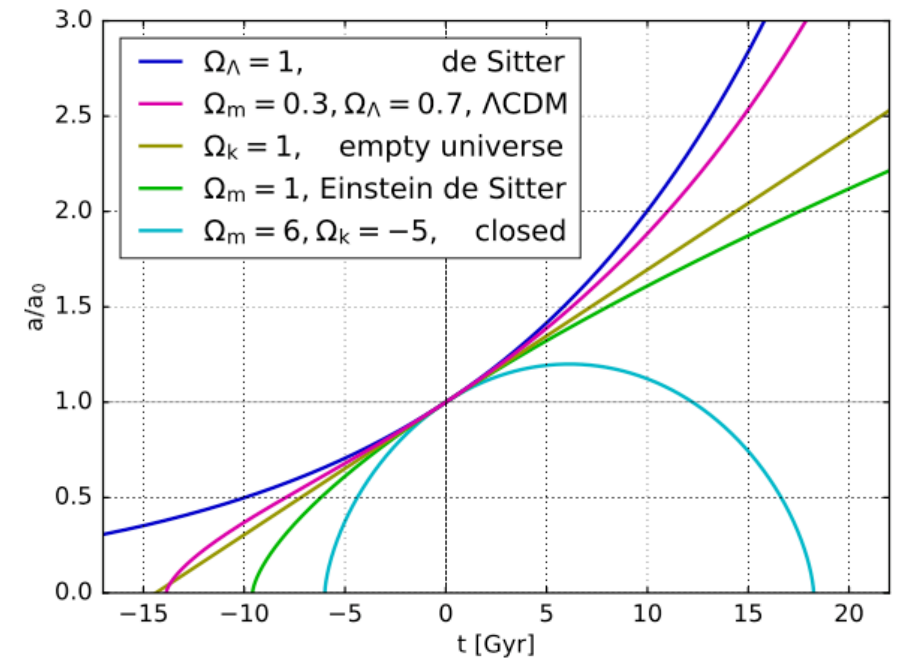


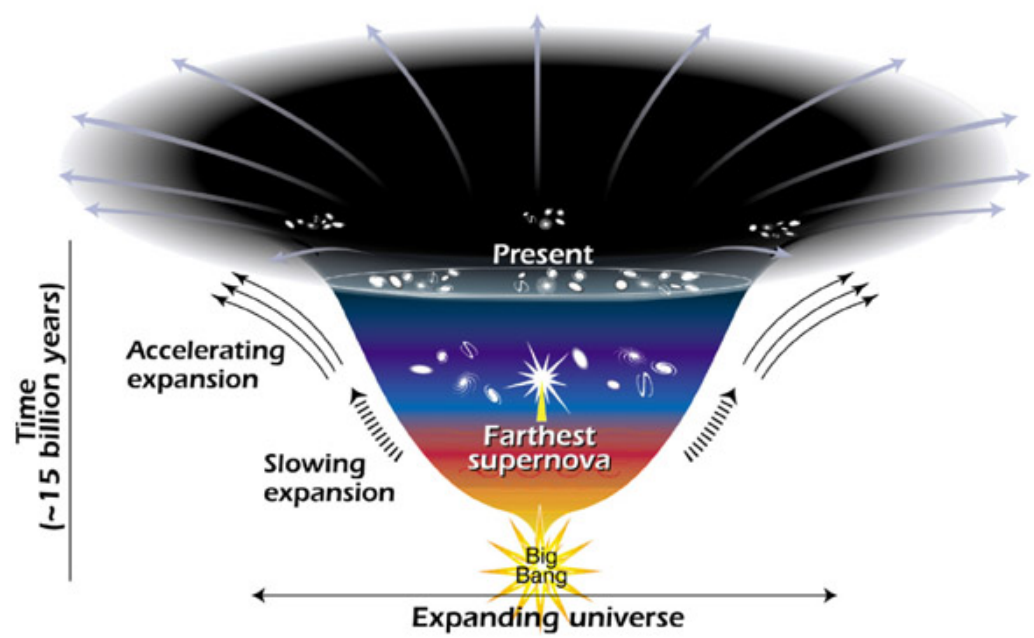


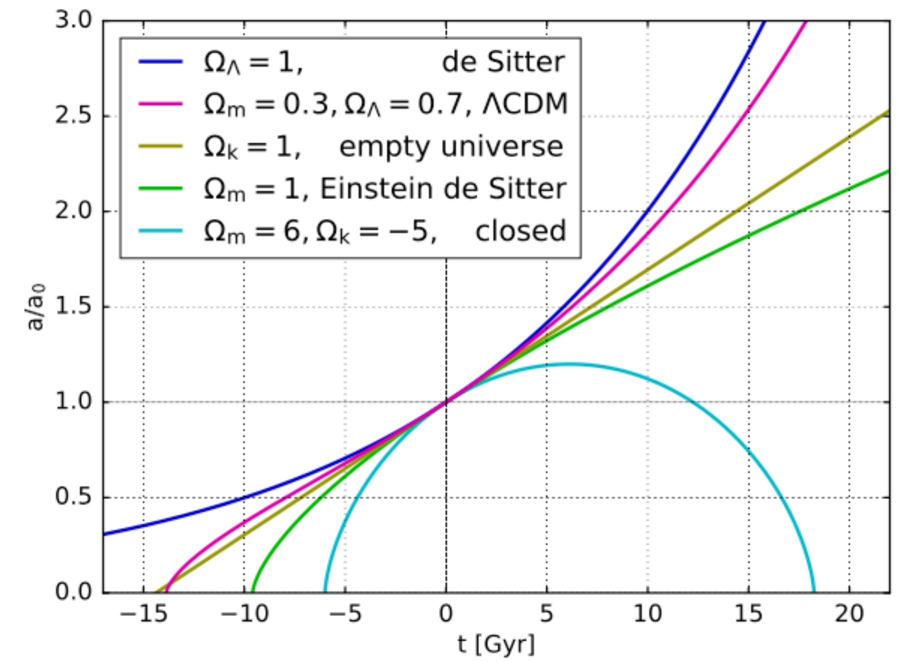
- Did it start from a single point at Big Bang?

Quiz

- What is the age of our Universe?

  ~14 billion years, according to SM of Cosmology





- Did it start from a single point at Big Bang?

  no, it started from a high-density, high-temperature state

  metric expanded R(t), but still not a point (infinite if flat k=0)

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

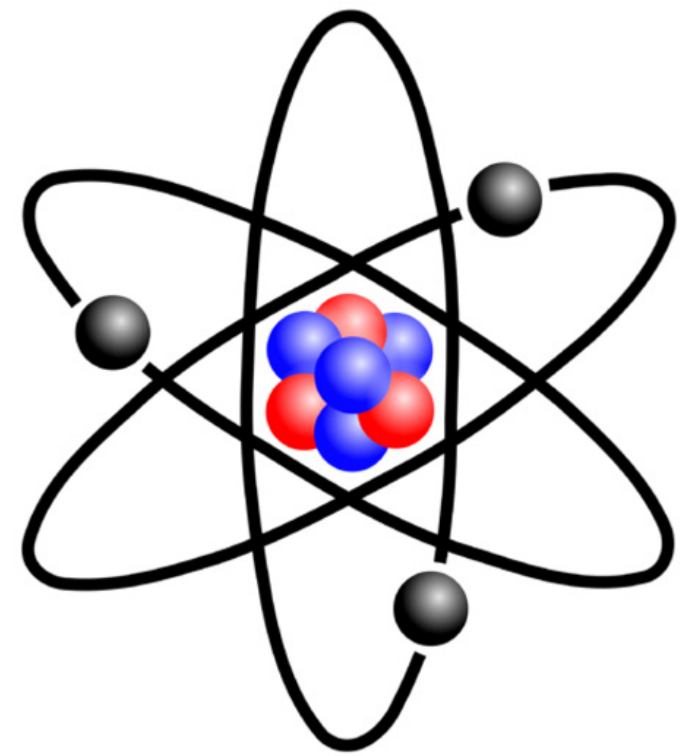
Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe?

Multiple choice: (A) ~0%
(B) ~0.5%
(C) ~5%
(D) ~25%
(E) ~75%

Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe?



Multiple choice:

(A) ~0%

(B) ~0.5%

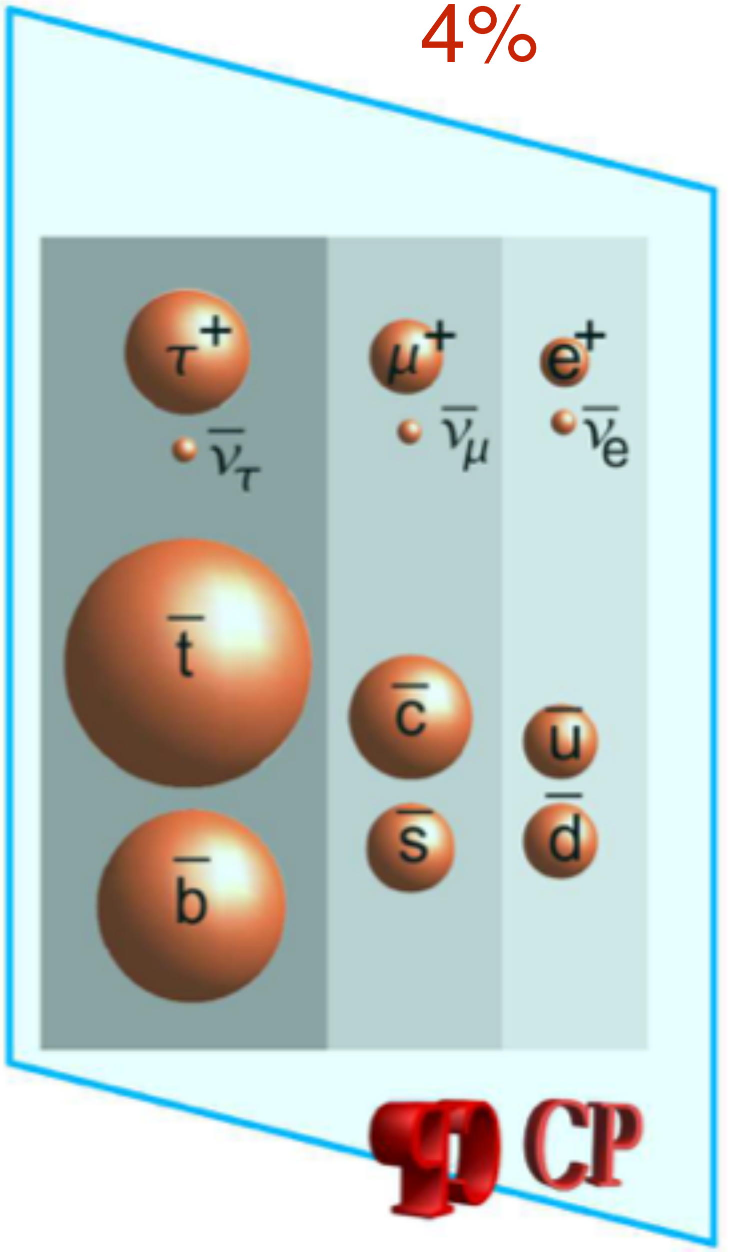
(C) ~5%

(D) ~25%

(E) ~75%

Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe 4%
- Fractions of antimatter in our Universe?



Multiple choice:

(A) ~0%

(B) ~0.5%

(C) ~5%

(D) ~25%

(E) ~75%

Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe 4%
- Fractions of antimatter in our Universe ~0%
- Fraction of dark matter in our Universe?

Multiple choice:

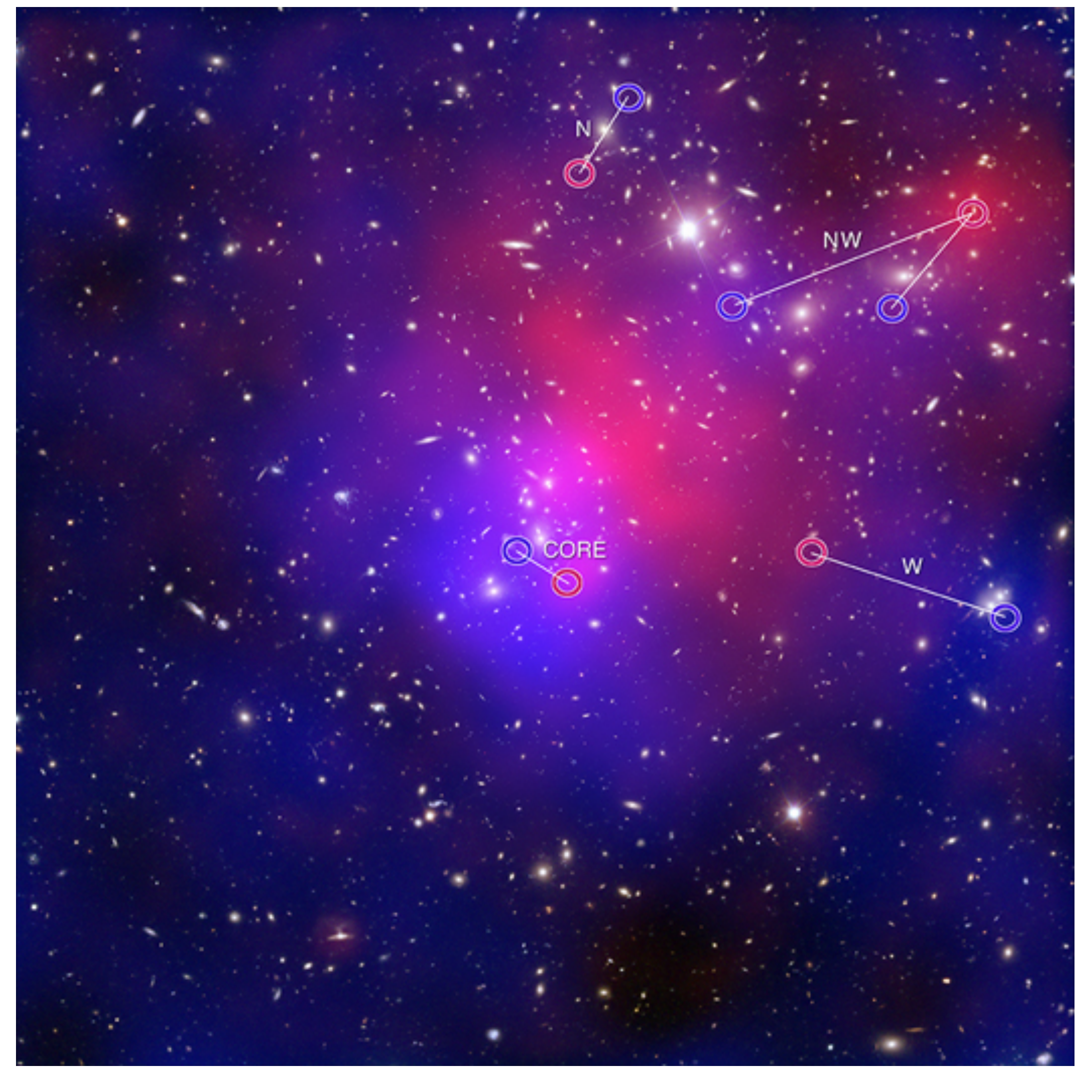
(A) ~0%

(B) ~0.5%

(C) ~5%

(D) ~25%

(E) ~75%



dark matter hot gas

Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe 4%
- Fractions of antimatter in our Universe ~0%
- Fraction of dark matter in our Universe?

Multiple choice:

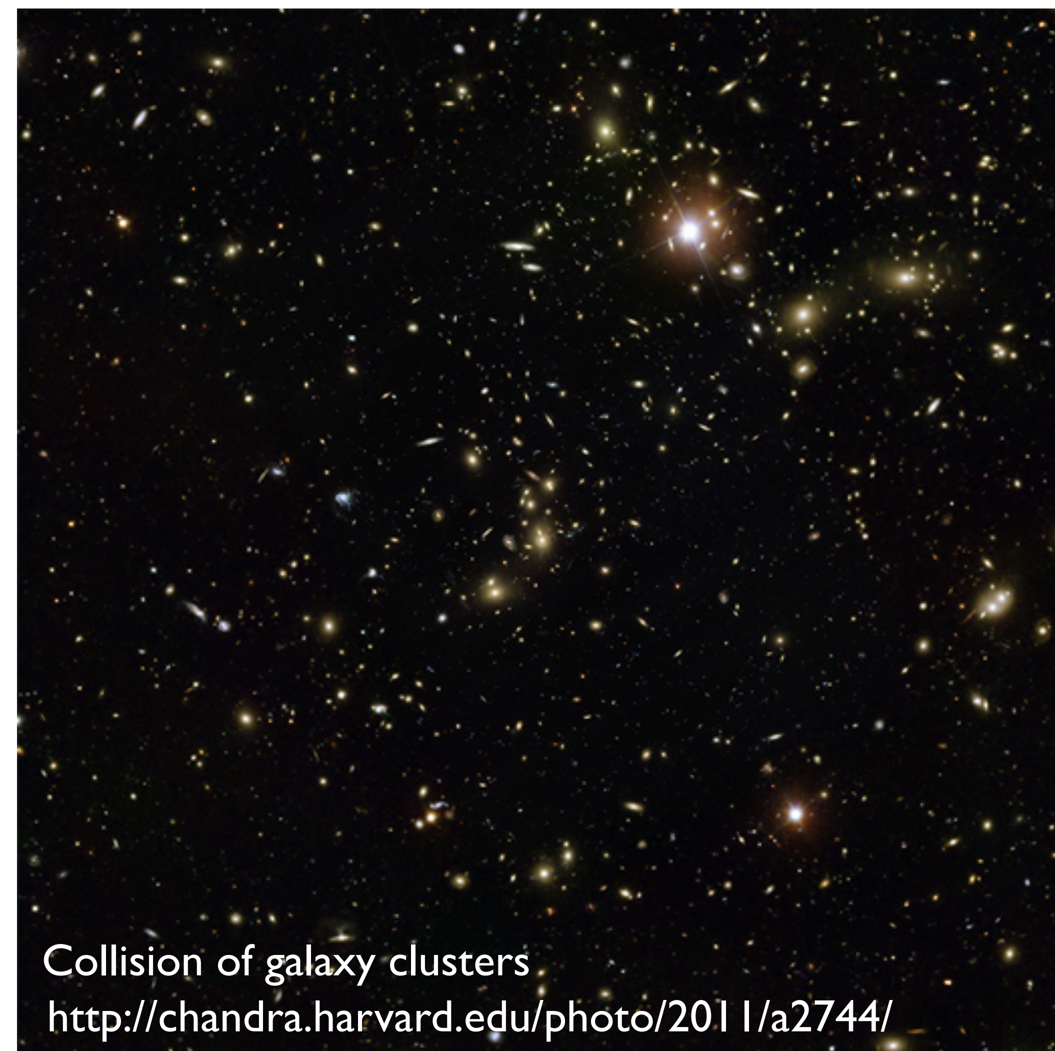
(A) ~0%

(B) ~0.5%

(C) ~5%

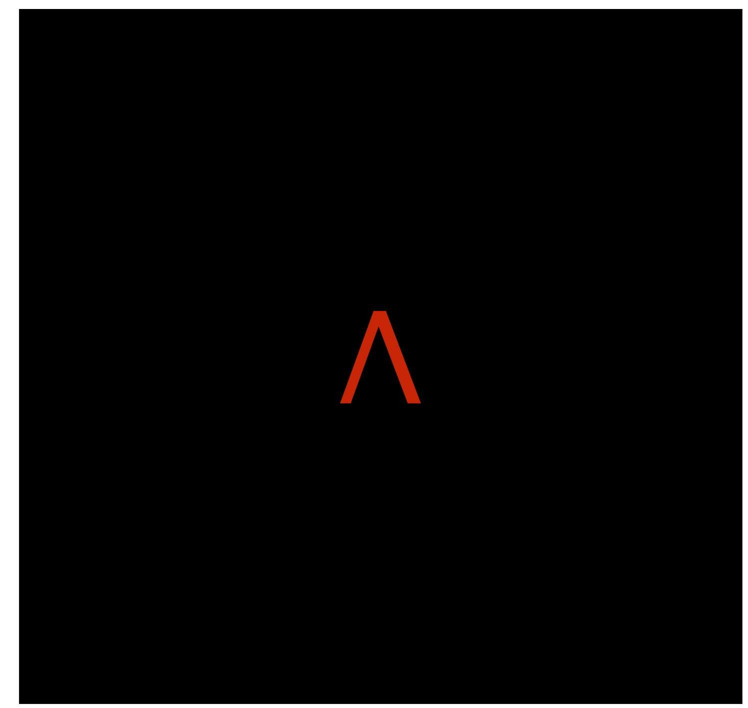
(D) ~25%

(E) ~75%



Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe 4%
- Fractions of antimatter in our Universe ~0%
- Fraction of dark matter in our Universe 23%
- Fraction of dark energy in our Universe?



Multiple choice:

(A) ~0%

(B) ~0.5%

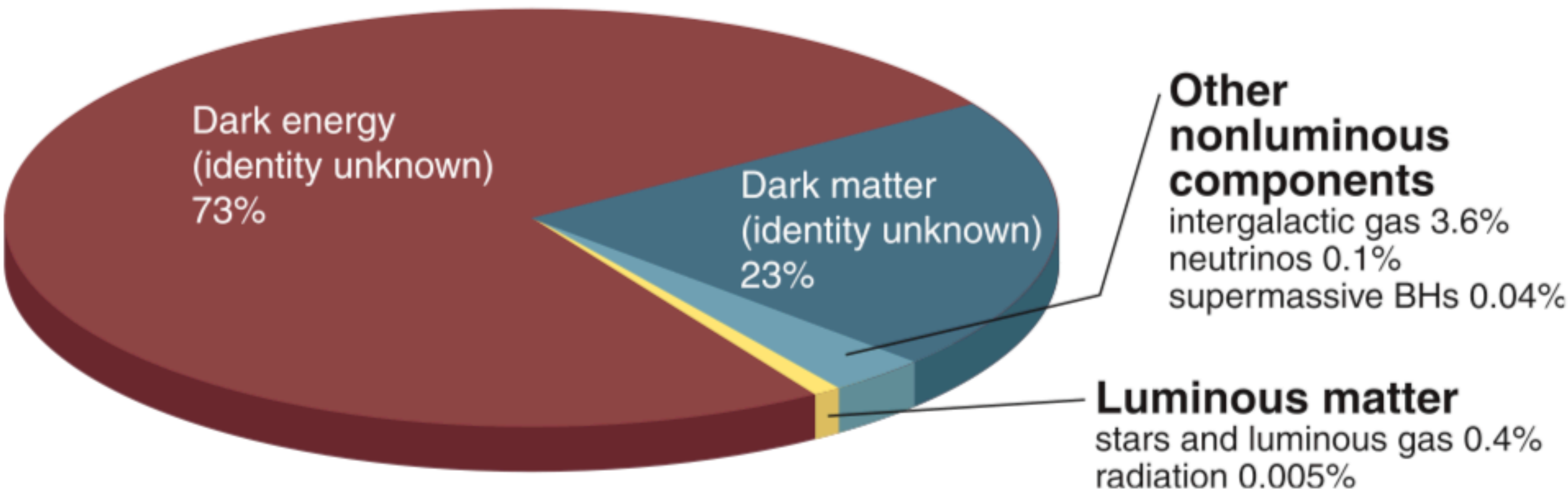
(C) ~5%

(D) ~25%

(E) ~75%

Quiz: relative to the total mass-energy balance

- Fraction of luminous matter in our Universe 0.4%
- Fraction of known matter in our Universe 4%
- Fractions of antimatter in our Universe ~0%
- Fraction of dark matter in our Universe 23%
- Fraction of dark energy in our Universe 73%



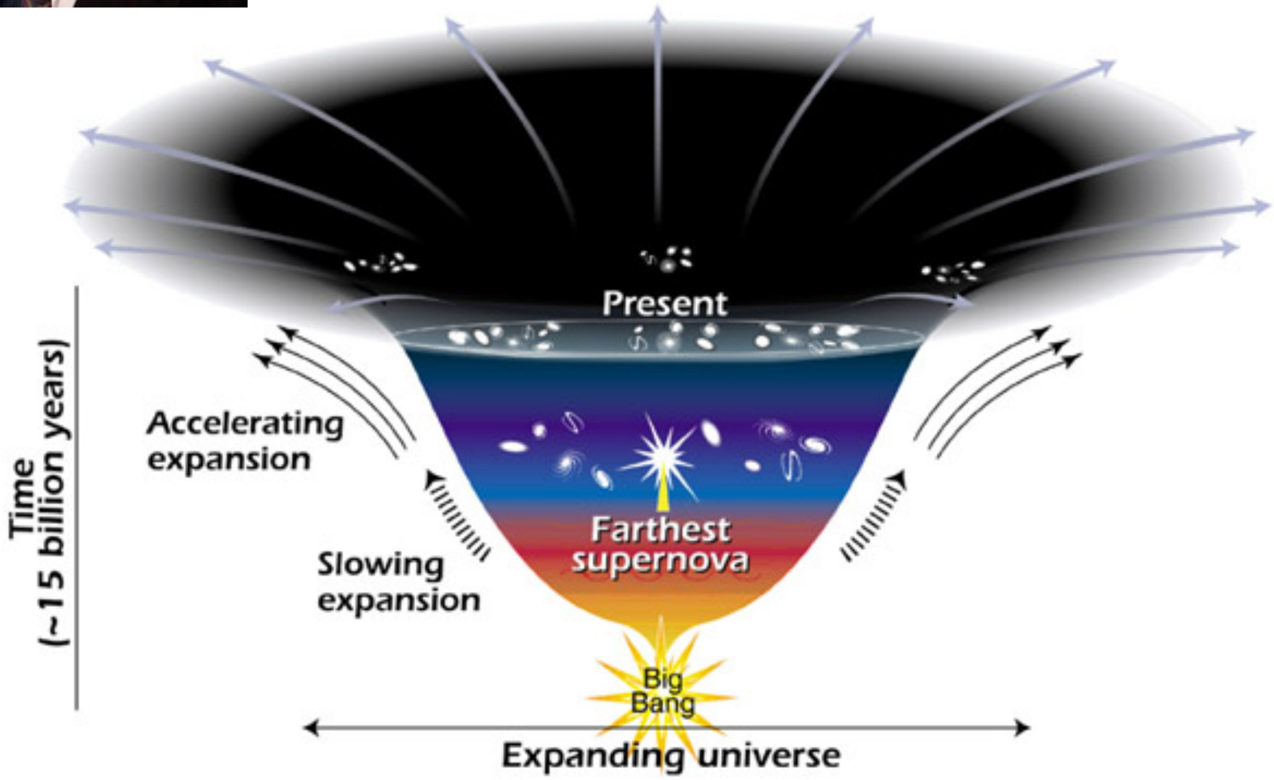
http://science.sciencemag.org/content/sci/300/5627/1909.full.pdf

WMAP Results

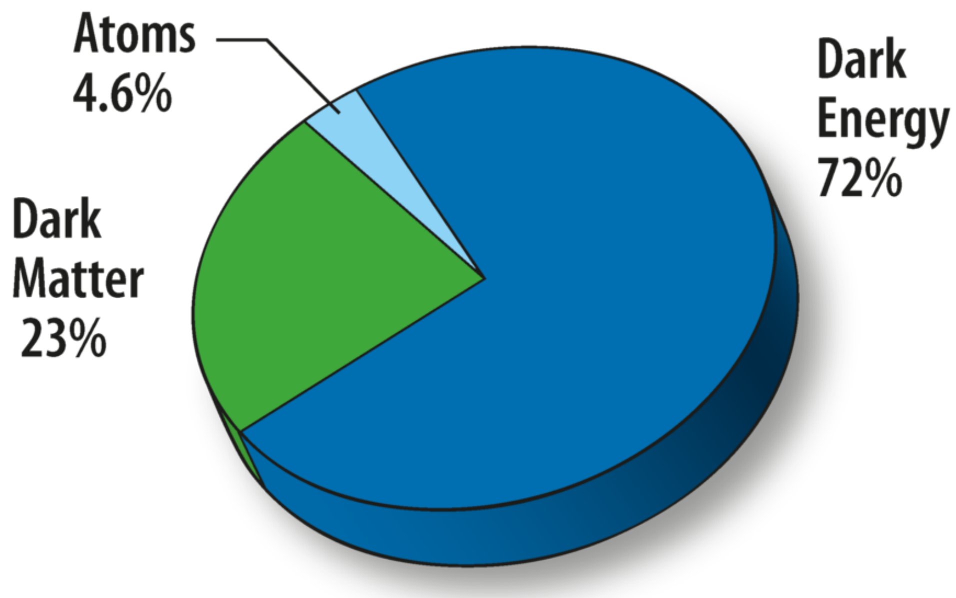
Charles Bennett (JHU)

WMAP study of CMB

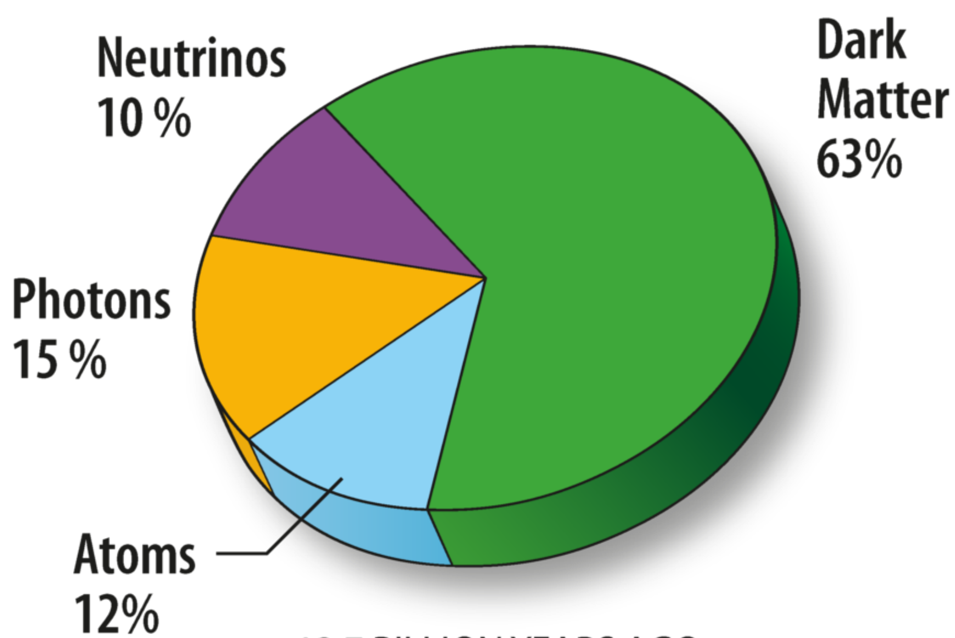
(Wilkinson Microwave Anisotropy Probe)



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.



TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

Recap: Current confusion in Standard Model(s)

Cosmology (SM) ⟵ Dark matter? + ⟵ Particle Physics (SM)

Not fully explained by either SM:

— Dark matter?

— Baryogensis? (matter dominance)
  baryon number violation
  CP violation
  lack of antimatter

— Dark energy?

— Inflation?

— Higgs field and mass (hierarchy problem)
  are neurinos special? …

Trying to approach from both directions

scalar field(s) may be at the core of solutions, Higgs field is the first observed

The Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013

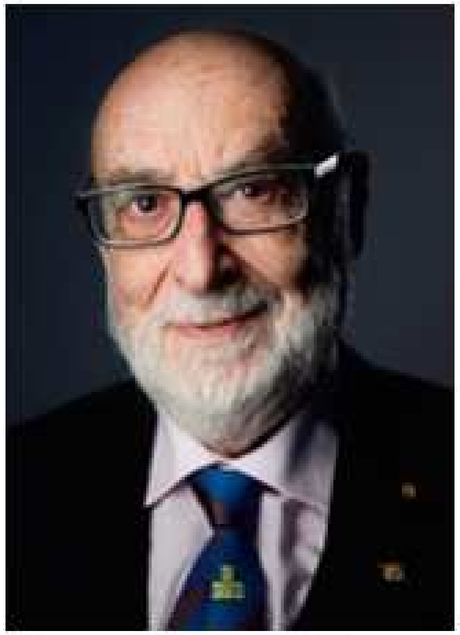


Photo: A. Mahmoud

François Englert

Prize share: 1/2

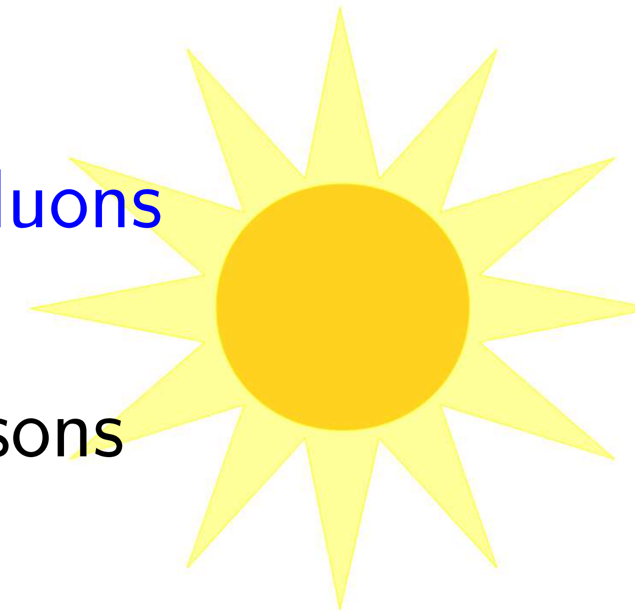
Photo: A. Mahmoud

Peter W. Higgs

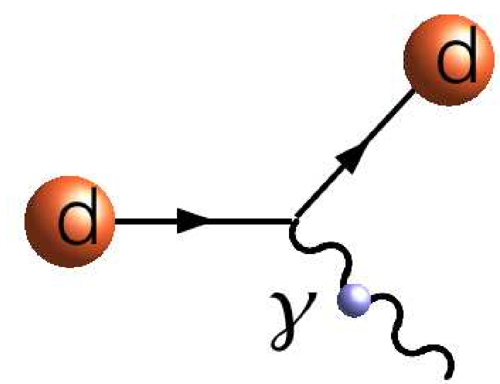
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

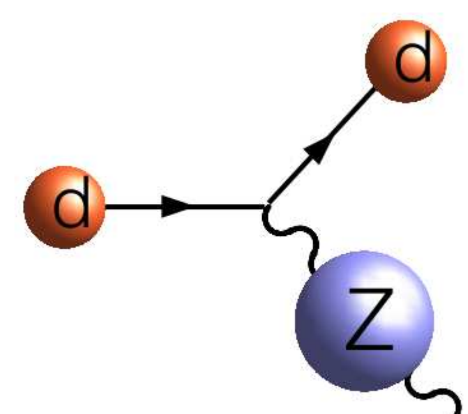
How many Bosons did we know in 2012?



- We knew 12 bosons: photon, Z^0, W^+, W^-, 8 gluons
- Photons (γ) are massless vector (spin=$\hbar$=1) bosons
- Z^0 and $W^\pm$ are heavy $\rightarrow$ weak force
- Gauge bosons in unified electro-weak theory
  after spontaneous symmetry breaking



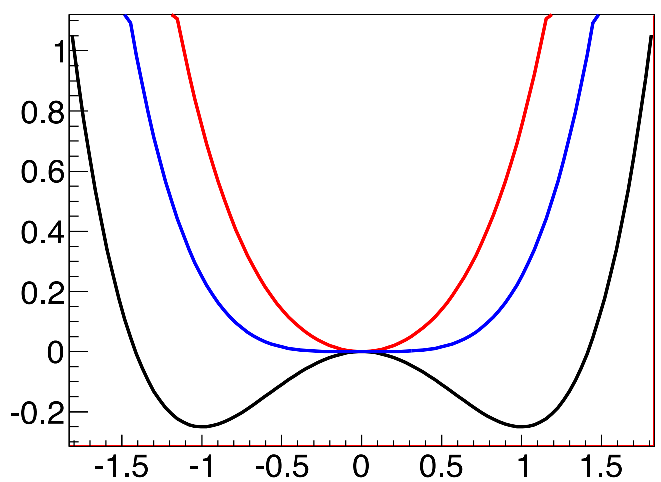
$$|\gamma\rangle \; = \cos\theta_W |B^0\rangle + \sin\theta_W |W^0\rangle \quad \text{light (massless)}$$
$$|Z^0\rangle = \sin\theta_W |B^0\rangle + \cos\theta_W |W^0\rangle \quad \text{heavy}$$

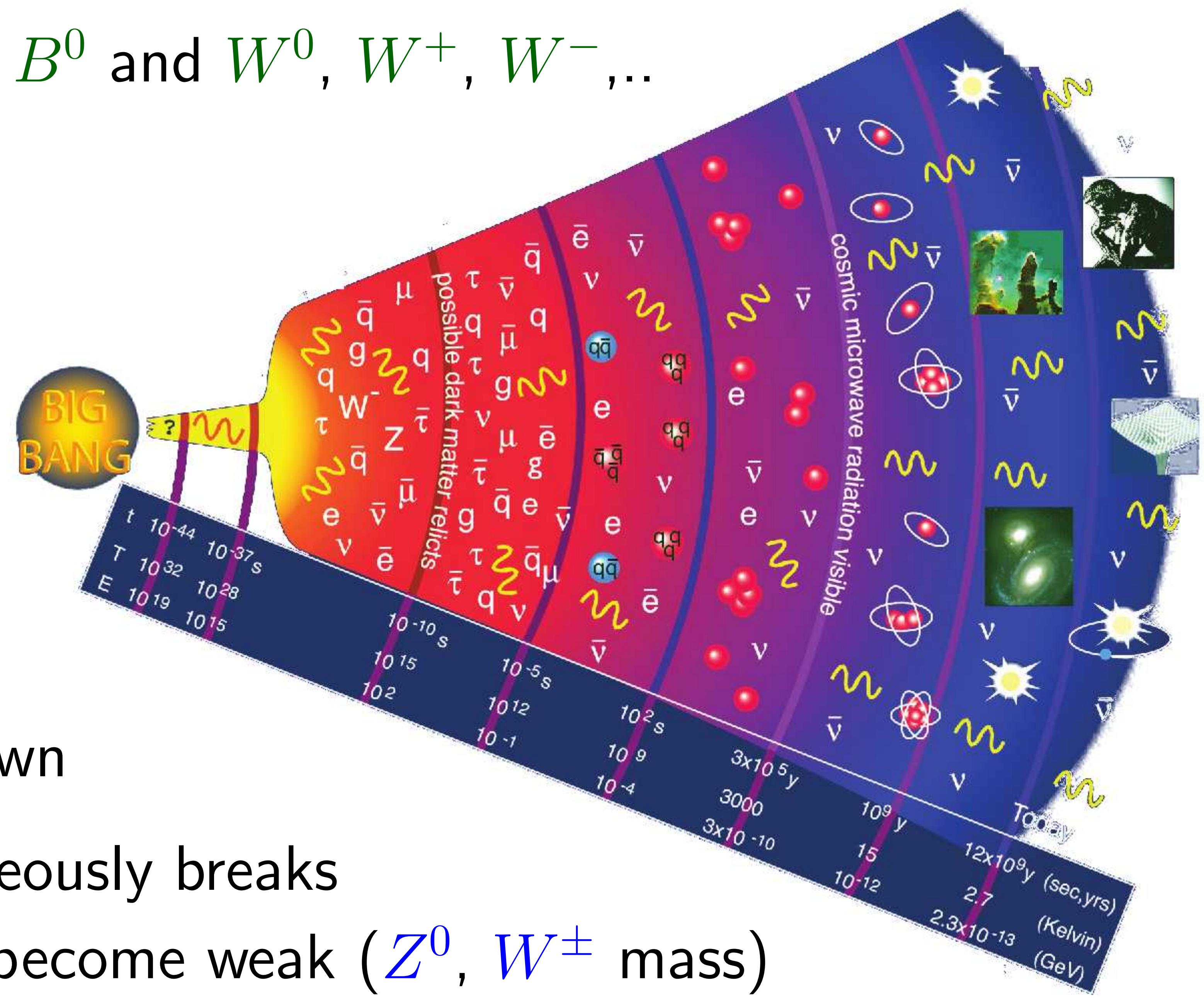


θ_W - Weak mixing (Weinberg) angle

Path from Light to Heavy

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify



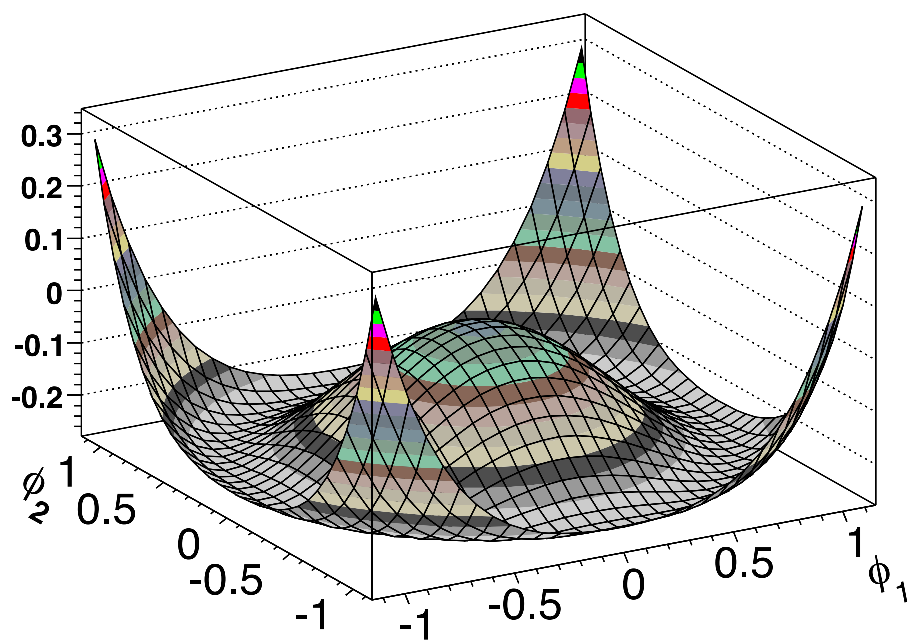


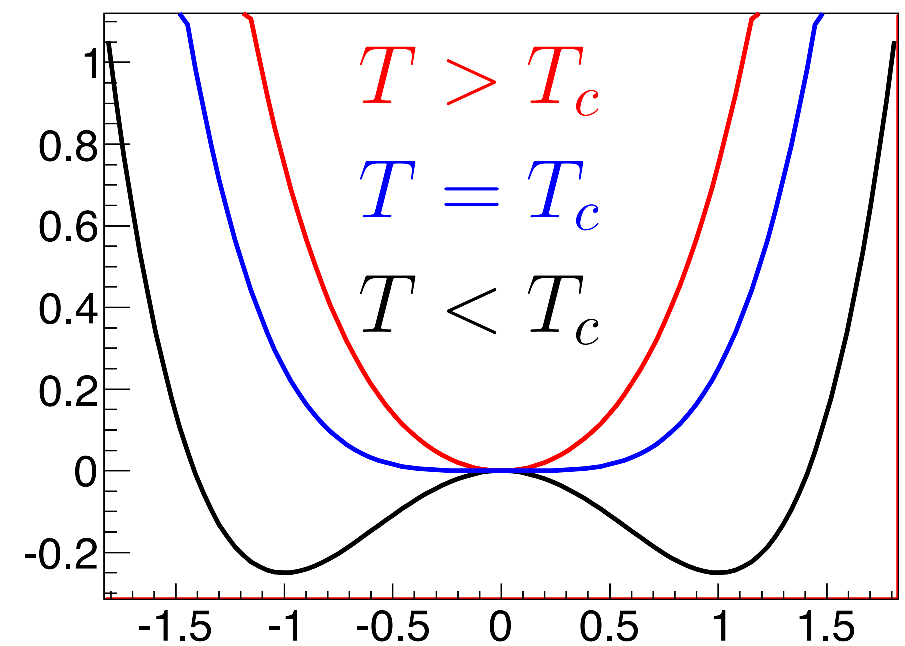
- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^{\pm}$ mass)
  - Higgs field – possible mechanism

The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V = \frac{1}{4}\lambda\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 + \frac{1}{2}\mu^2\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]$$





- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

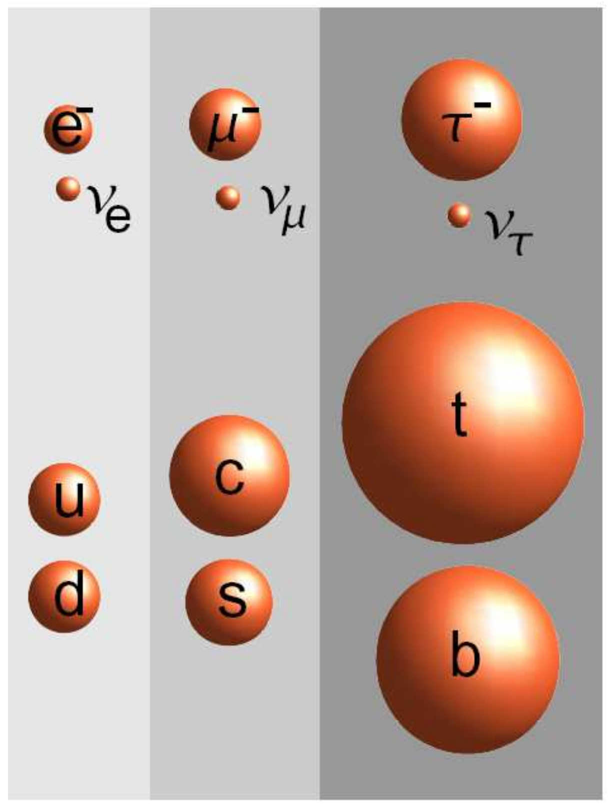
All Elementary Particles get Mass from Higgs Field

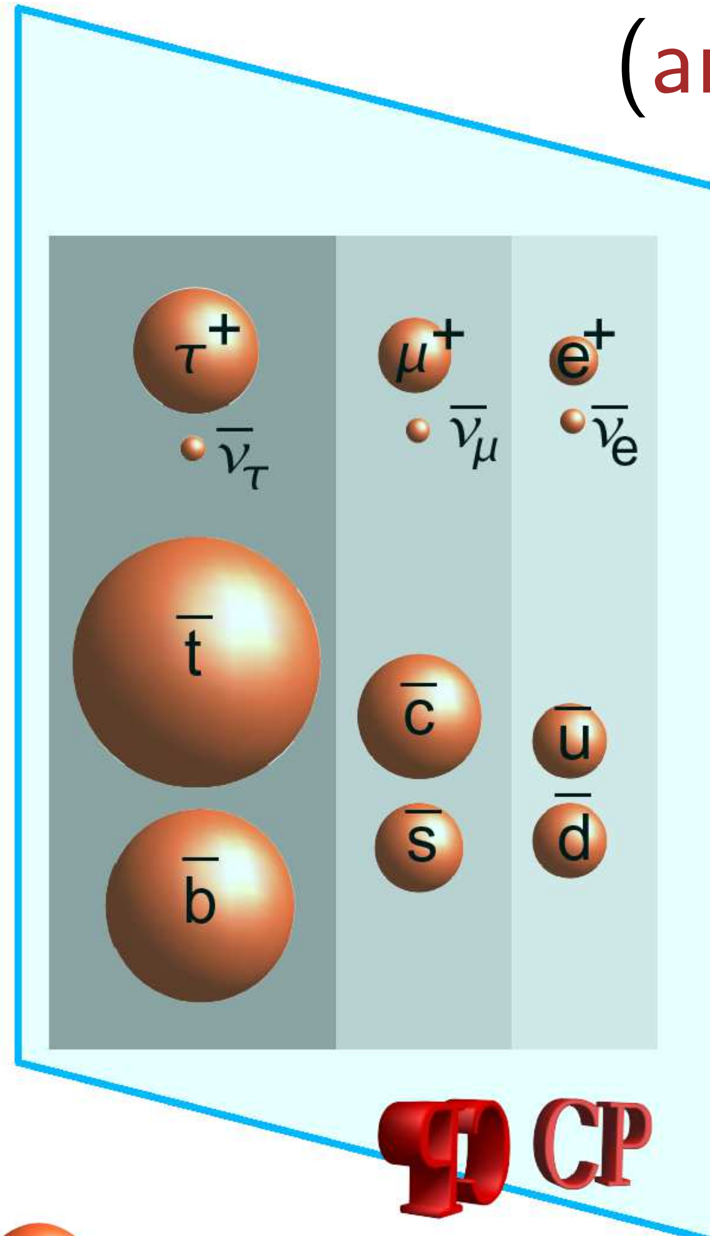
- Fermions $S = \frac{\hbar}{2}$ (matter)

(anti-matter)

leptons

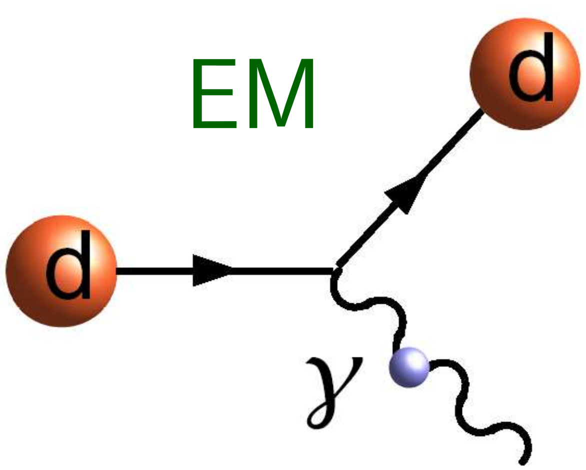
quarks



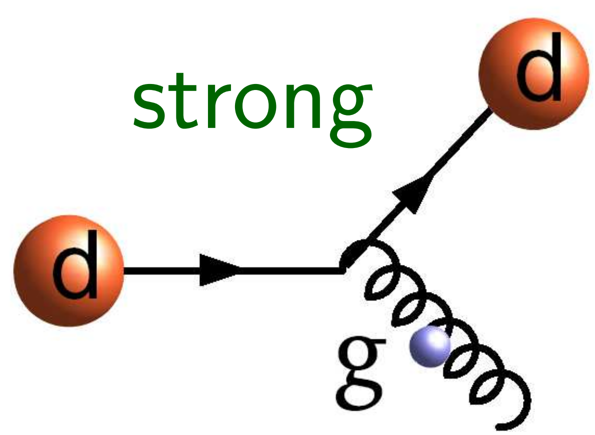


- Bosons $S = \hbar$ (force carries):

EM



strong

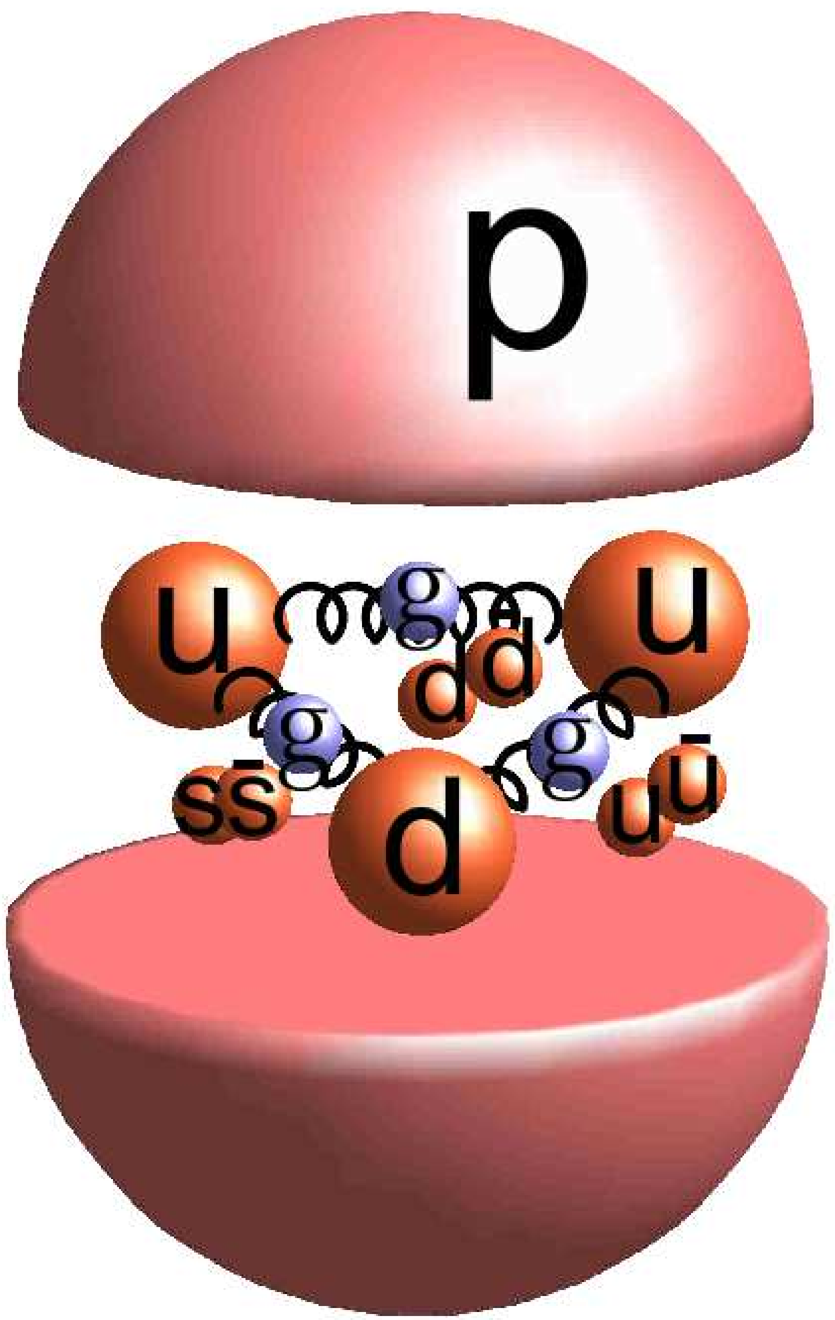


$\leftarrow$ massless

(weak force bosons mass)

Mass of Matter

- Most of our mass is protons and neutrons
  - most mass is energy of quark-gluon soup: $m_p c^2 = E$



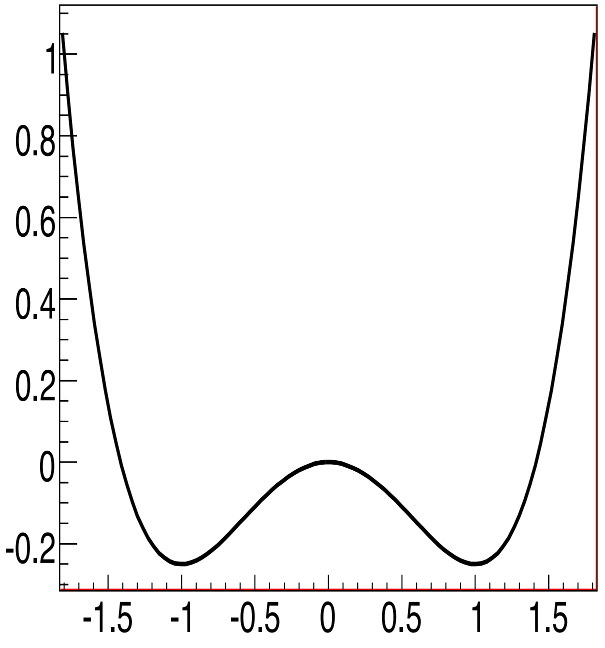
Mass from quark-glue soup energy:
$m_p c^2 = 938$ MeV $\simeq 1.7 \times 10^{-27}$ kg

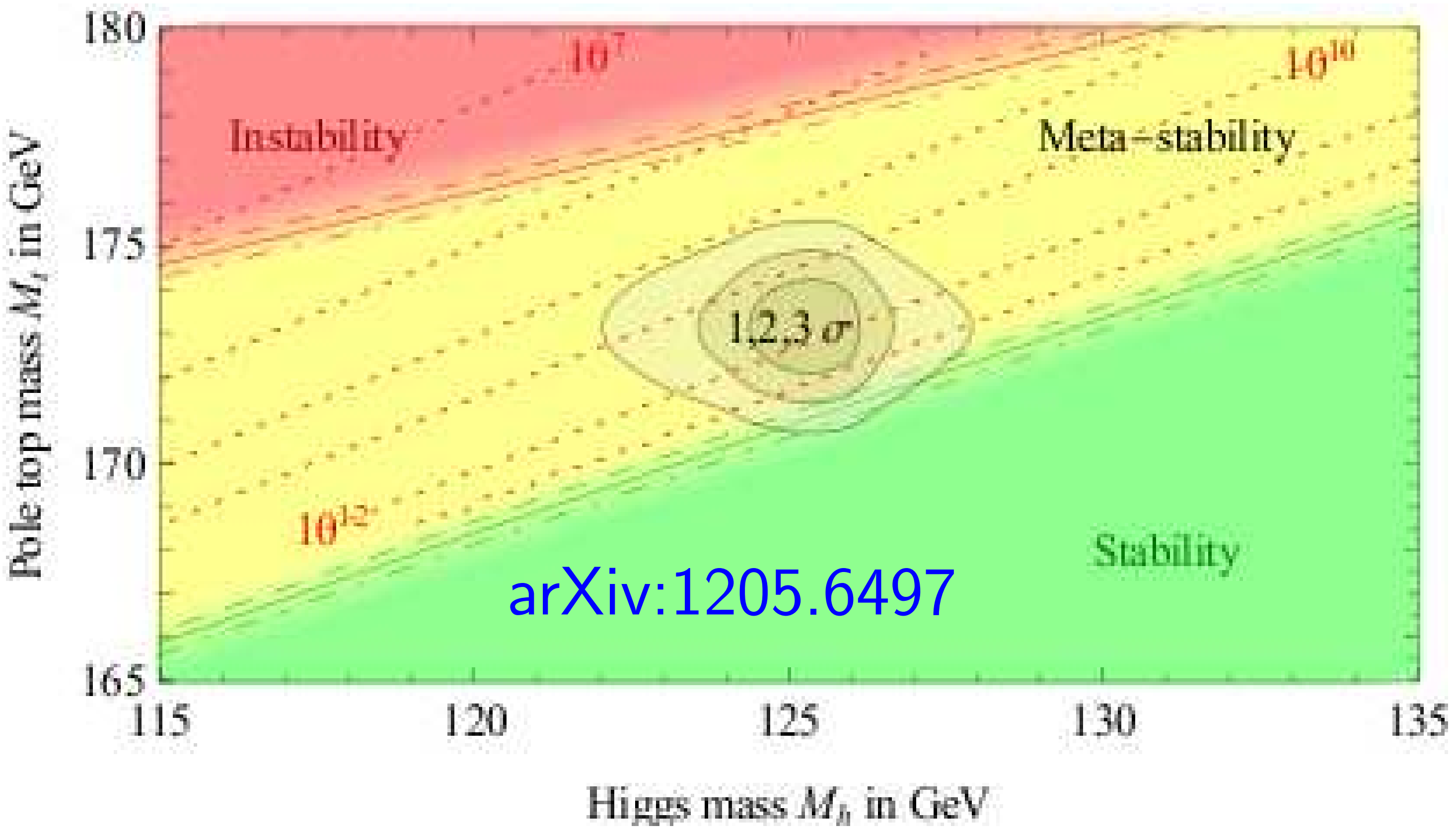
Mass from the Higgs field:
$m_u c^2 \sim 3$ MeV, $m_d c^2 \sim 5$ MeV

but Higgs field is very important

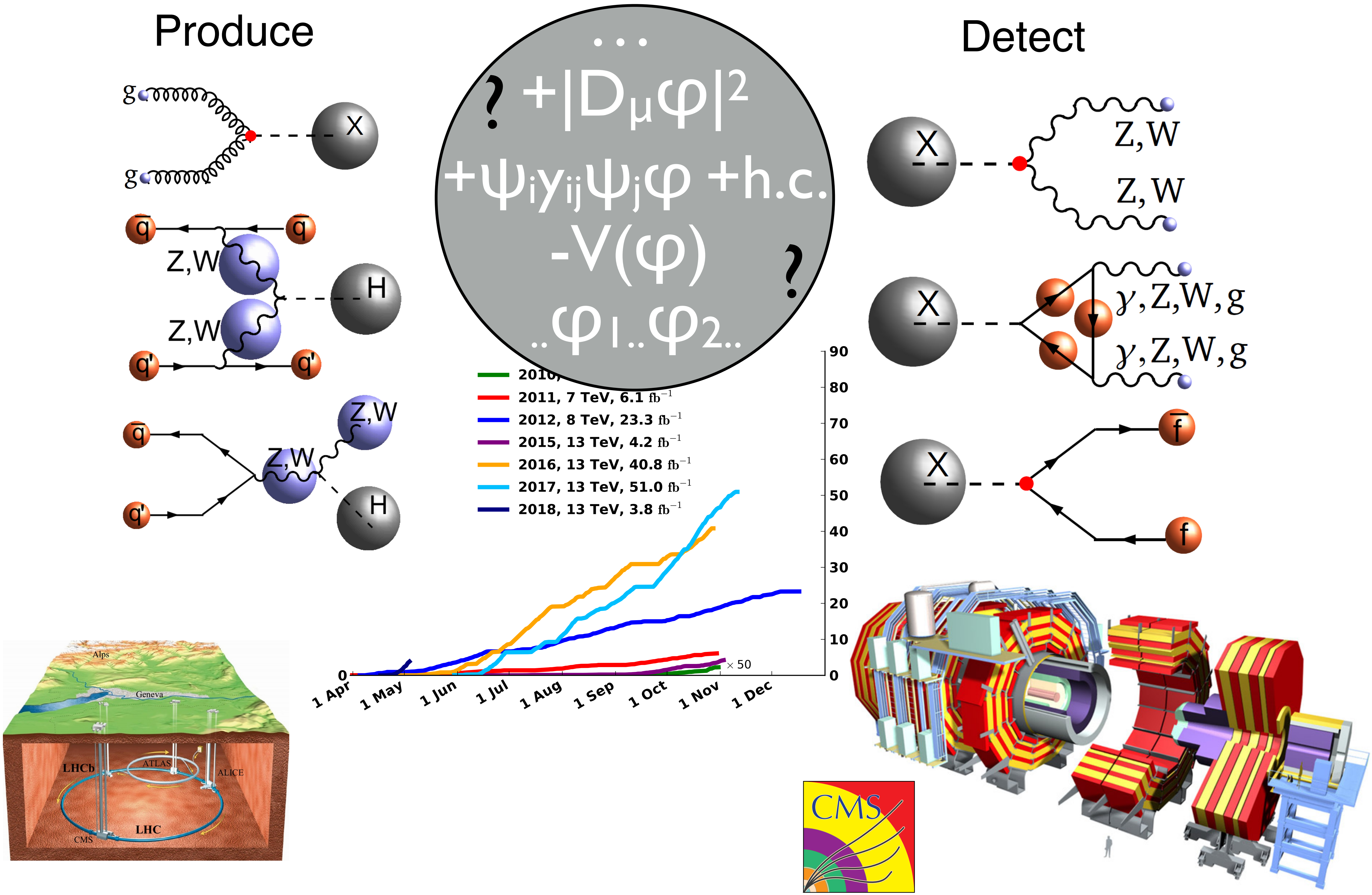
Stability of the Vacuum

- Higgs self-coupling $\lambda < 0$ at higher scale
  - may tunnel thru "potential barrier" $\Rightarrow$ unstable Universe
  - tunneling time $>$ Universe lifetime $\Rightarrow$ metastable Universe
  - for $m_H \sim 126$ GeV$/c^2$ and SM Higgs field $\Rightarrow$ metastable



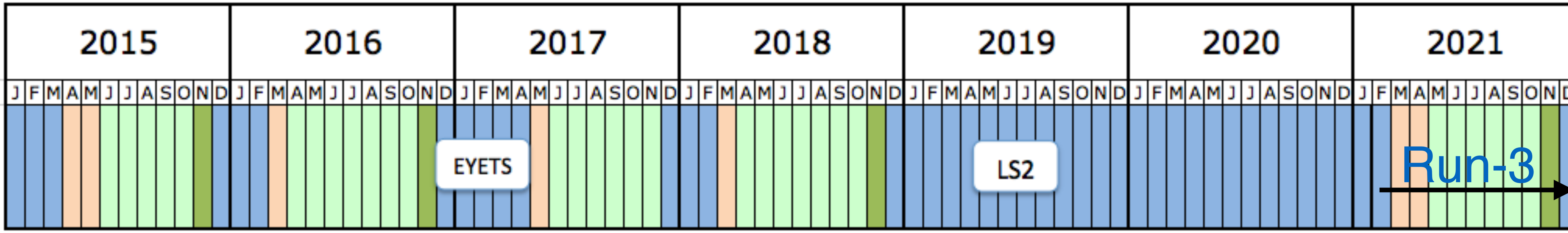


Study of the H^0 boson



LHC Run-2

- Run-1 (2010-2012) ~25 fb^{-1}



Run-2: 3 fb^{-1}

13 TeV

36 fb^{-1}

today

Some highlights at conferences this summer:

$t\bar{t}H^0, tH^0$

$H^0 \to \tau\tau$

$H^0 \to ZZ$

H^0H^0

…

$\psi_i y_{ij} \psi_j \varphi$

$|D_\mu \varphi|^2$

$V(\varphi)$

Study of the Higgs field φ

. . .

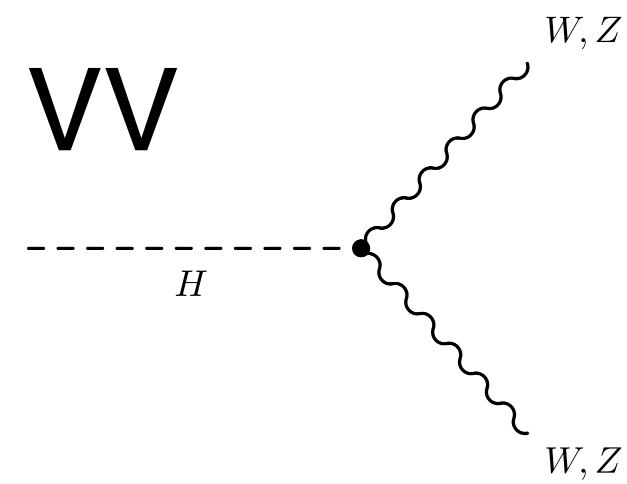
? $+|D_\mu\varphi|^2$

$+\psi_i y_{ij} \psi_j \varphi$ +h.c.

$-V(\varphi)$?

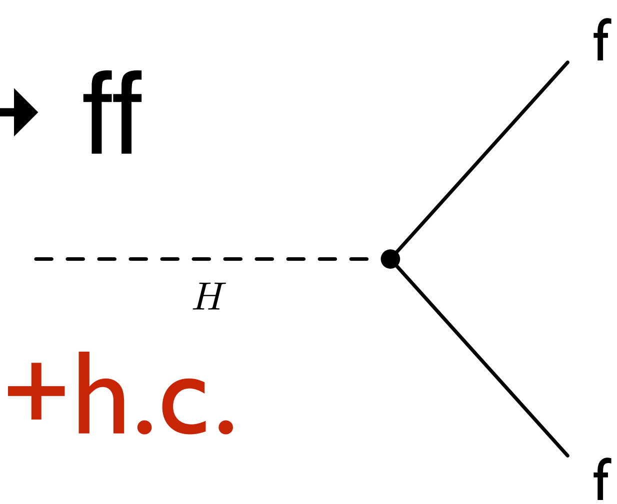
$..\varphi_1..\varphi_2..$

$H(125)^0 \to VV$



$|D_\mu\varphi|^2$

$H(125)^0 \to ff$



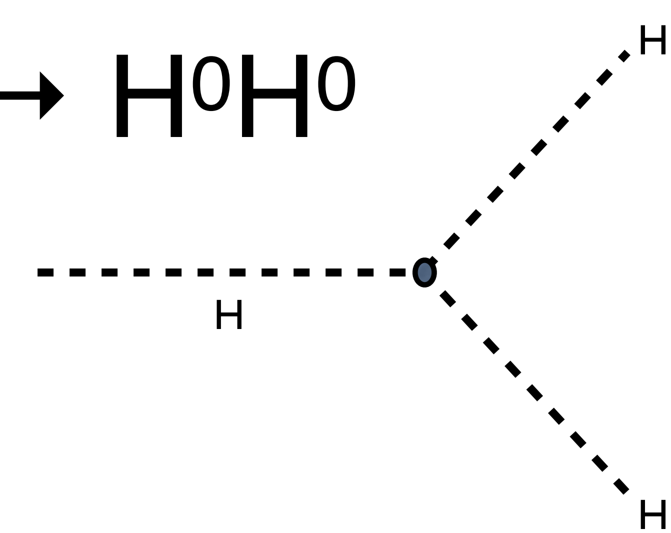
$\psi_i y_{ij} \psi_j \varphi$ +h.c.

$..\varphi_1..\varphi_2..$

more Higgs bosons

$H(125)^0, H, A, H^+, H^-$

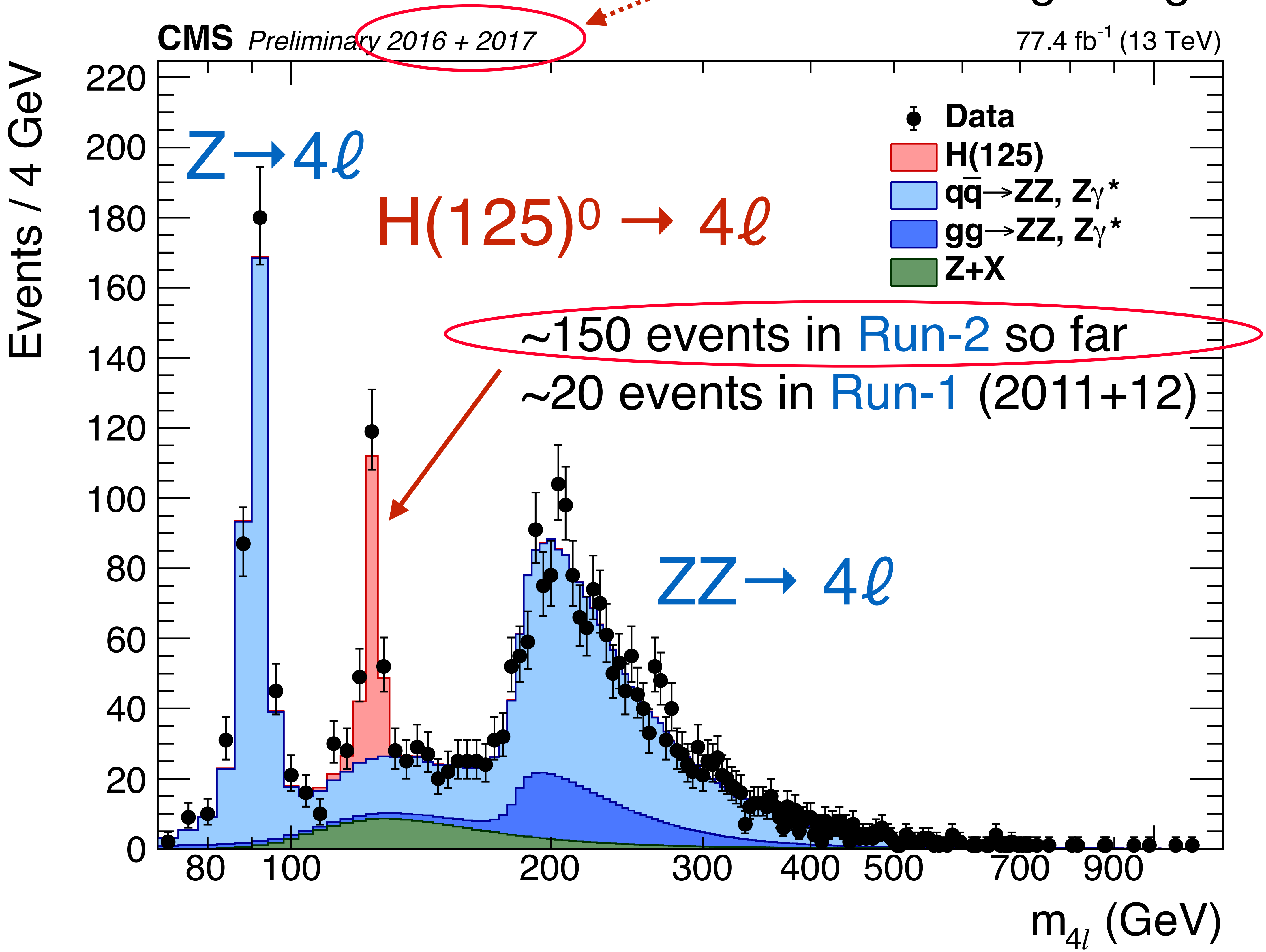
$H(125)^0 \to H^0 H^0$



$V(\varphi)$

Higgs→4ℓ boson yield

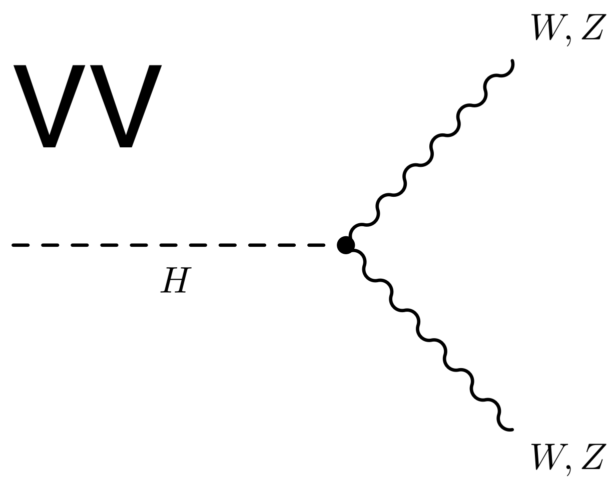
2018 data coming at high rate…



Study HVV or $|D_\mu \varphi|^2$

$H(125)^0 \rightarrow VV$

$|D_\mu \varphi|^2$

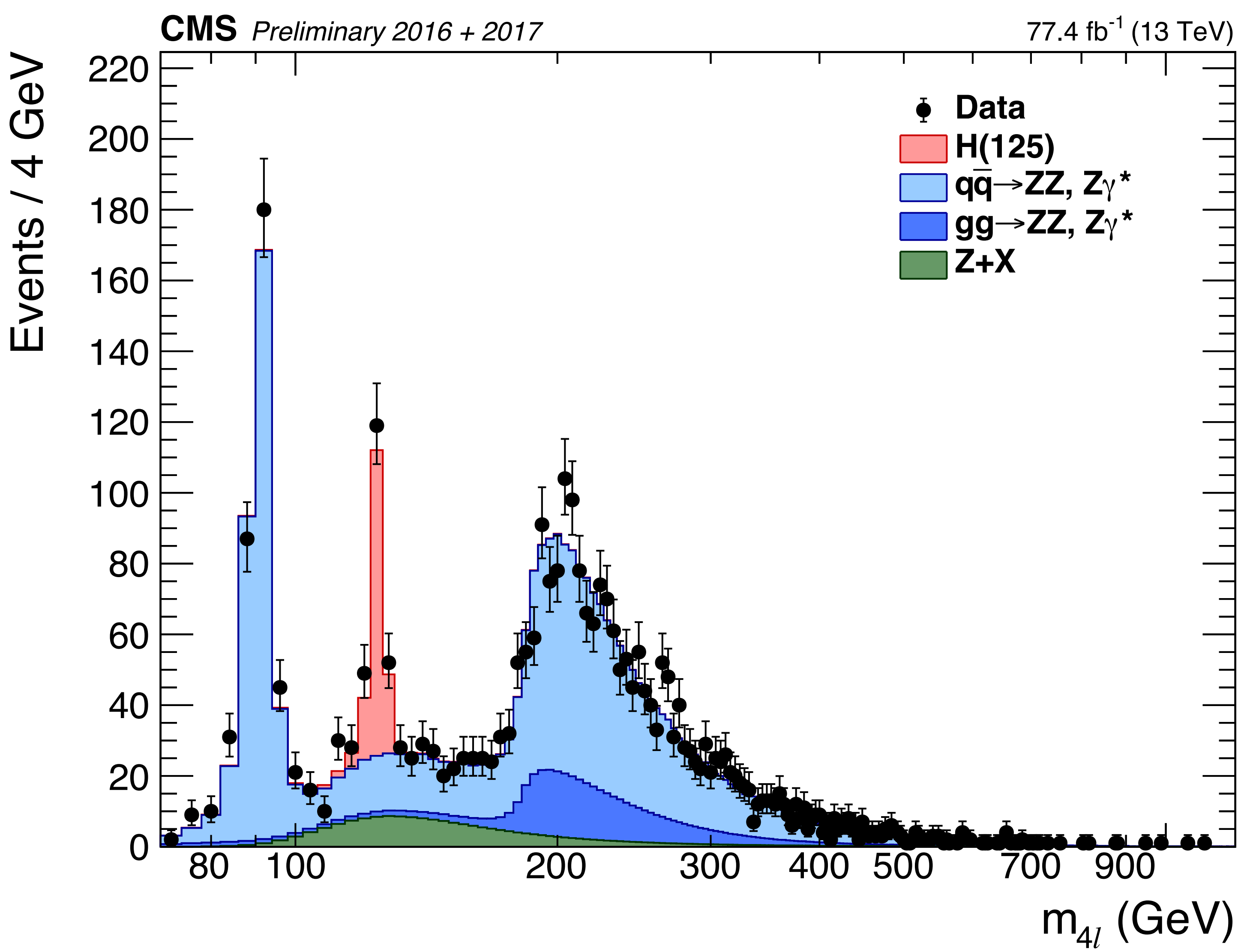


H^0 $J = 0$

pdg.lbl.gov
(LHC Run 1)

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

CMS (Run 2): $m_H = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst})$ GeV

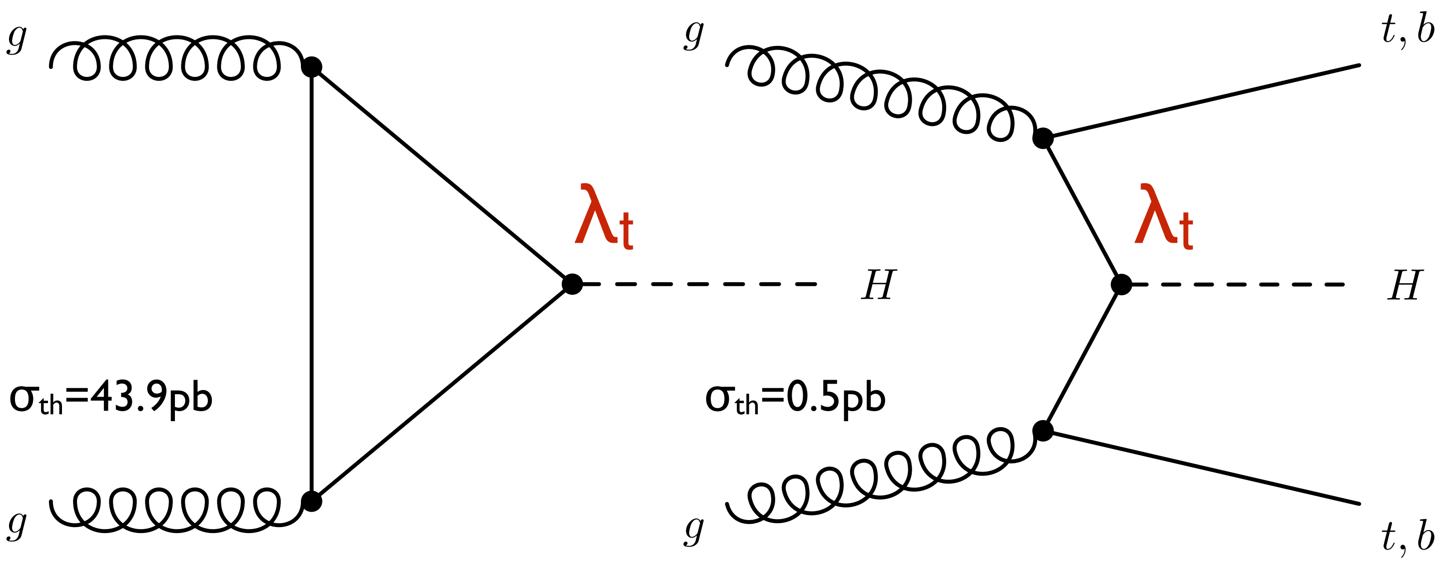


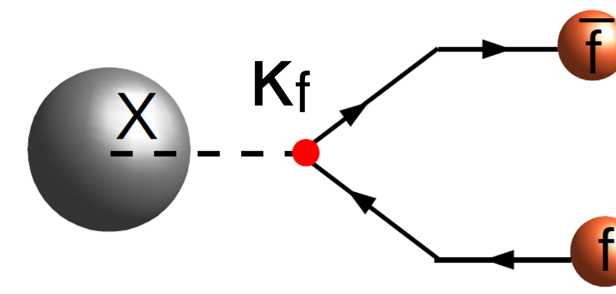
Follow PDG check-list

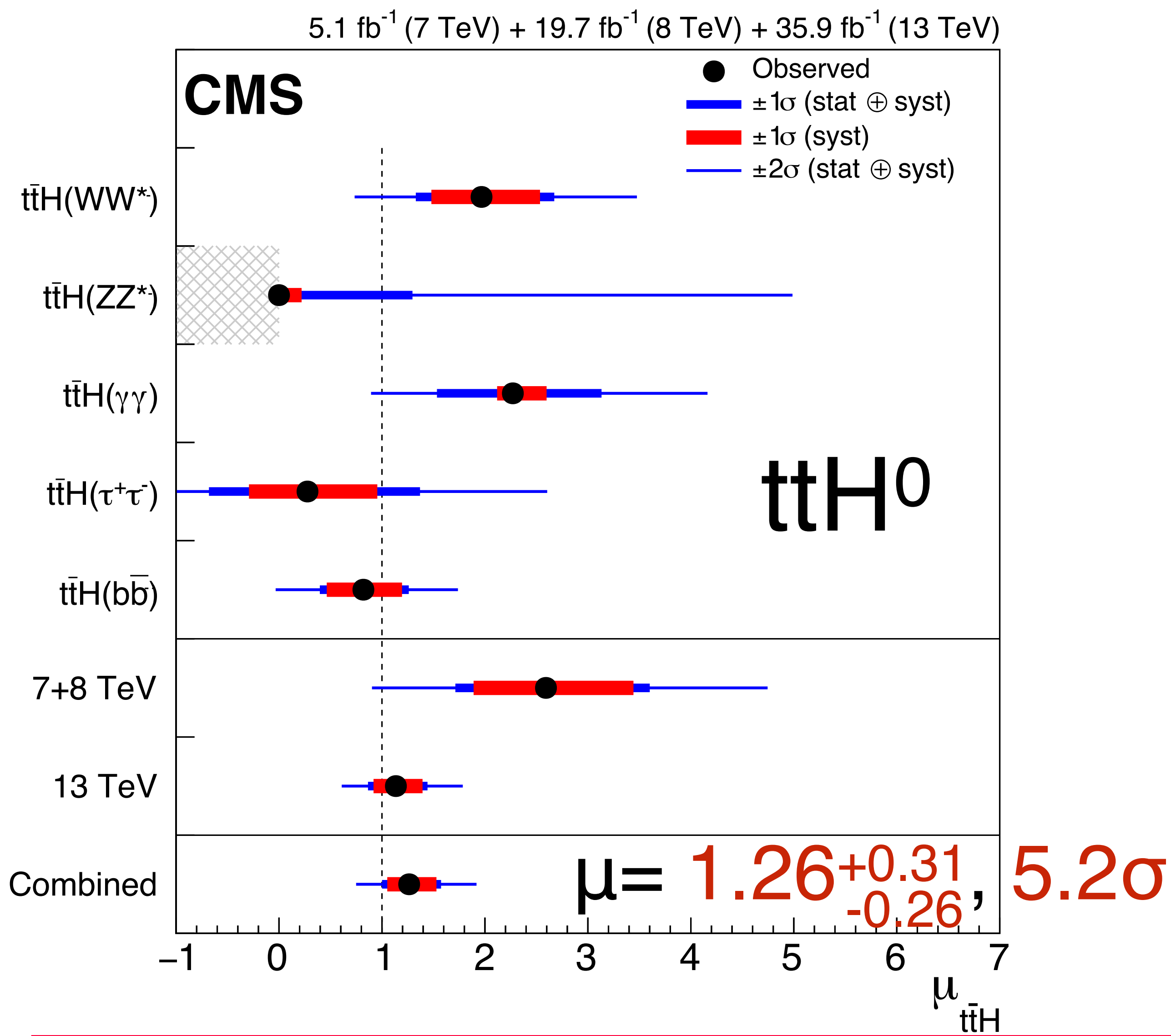
- mass
- lifetime
- width
- quantum numbers
- coupling strength

CMS combines Run1+2: ttH^0 and H$^0 \to \tau\tau$

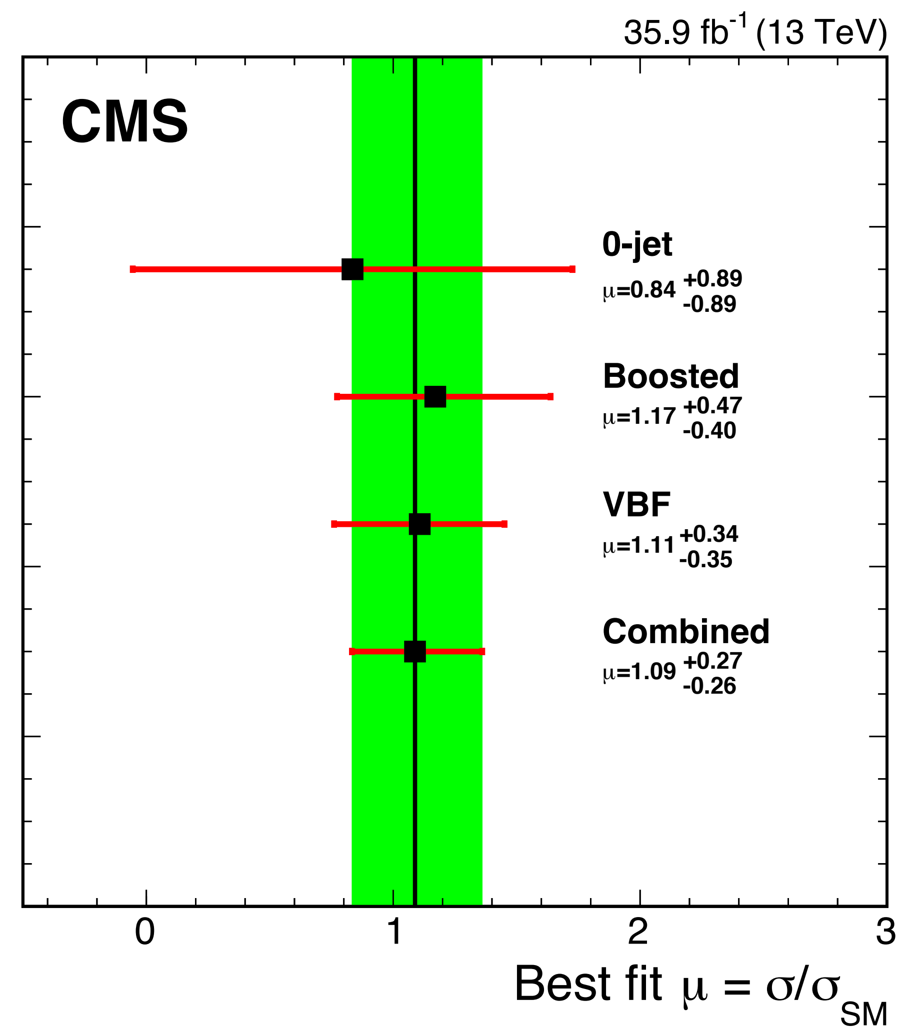
CMS-HIG-17-035
CMS-HIG-16-043







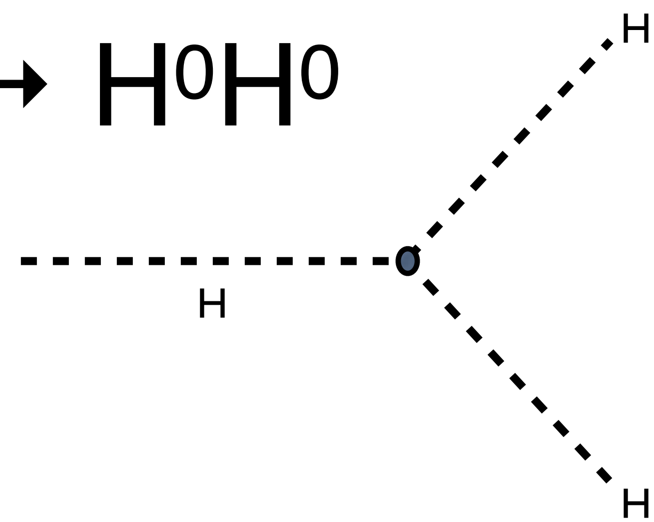
$H^0 \to \tau\tau$



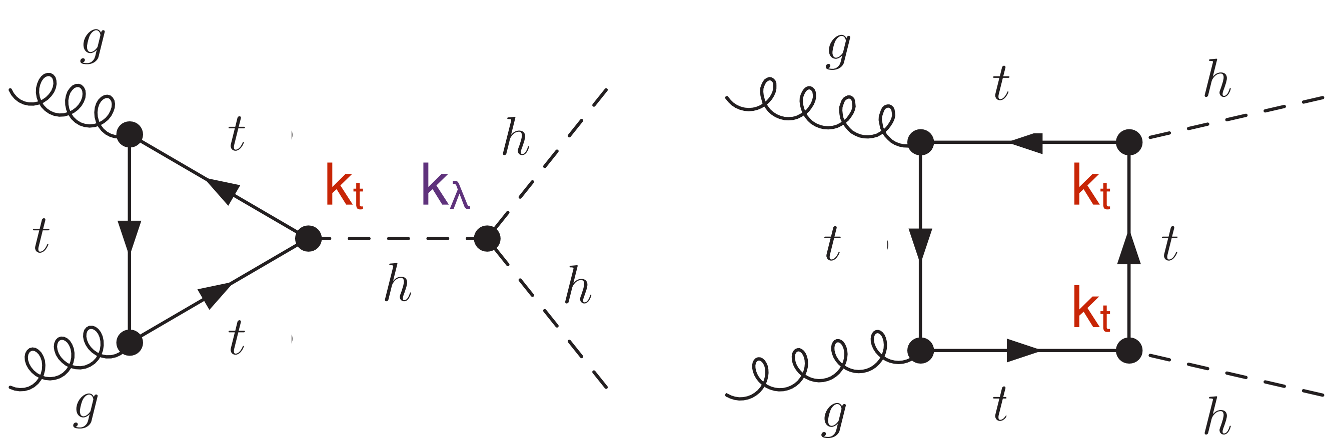
Run1+2: $\mu = 0.98 \pm 0.18$, 5.9σ

Study HHH or V(φ)

$H(125)^0 \rightarrow H^0H^0$



V(φ)

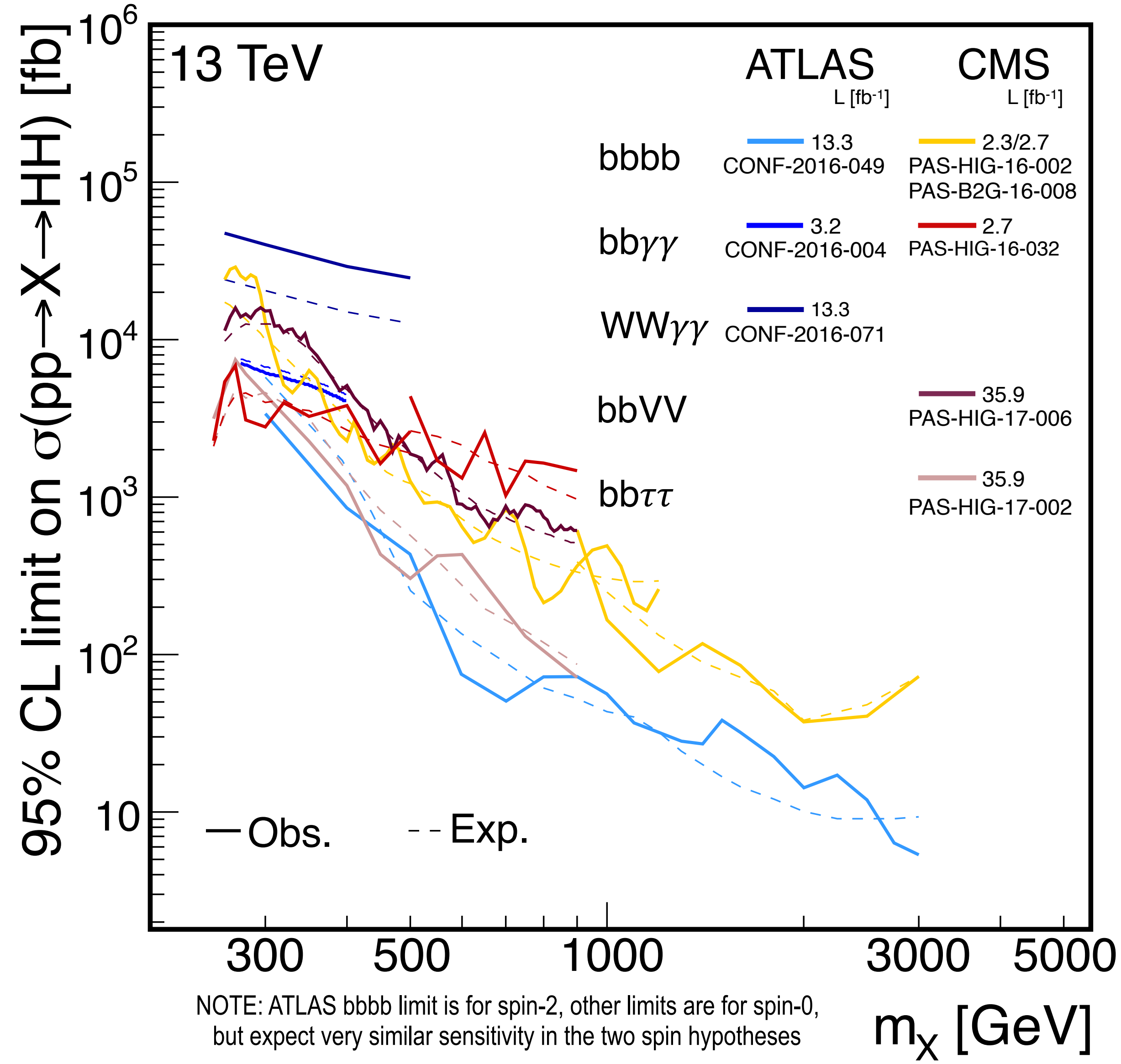


$HH \rightarrow (bb)+(bb/WW/ZZ/\tau\tau/\gamma\gamma)$

only limits so far

need HL-LHC (3000 fb^{-1})

to find SM H^0H^0 production



NOTE: ATLAS bbbb limit is for spin-2, other limits are for spin-0, but expect very similar sensitivity in the two spin hypotheses

Study of the Higgs field φ

- H(125)^0 is a completely new state of matter-energy

— the major LHC discovery so far

— yet it is just an extinct particle

— what remains in the Higgs field

— it is all around us

— gives mass to fermions, bosons

— its potential remains to be tested, implication for our existence

$$\ldots$$

$$? \; +|D_\mu \varphi|^2$$

$$+\psi_i y_{ij} \psi_j \varphi + h.c.$$

$$-V(\varphi) \quad ?$$

$$..\varphi_1..\varphi_2..$$