New Directions for Discovering Physics Beyond the Standard Model

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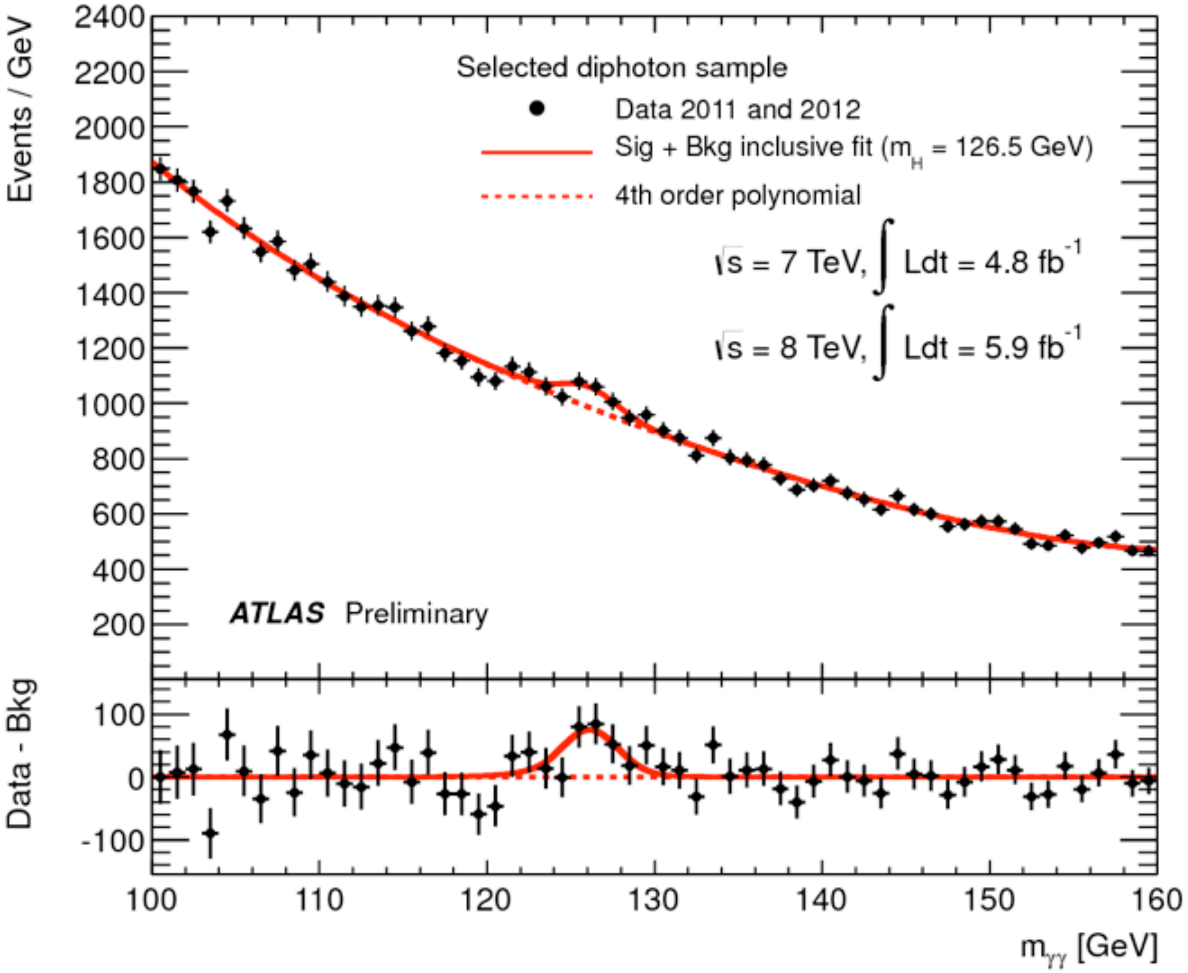
19 July 2022

UCIrvine

4 July 2022 was a special date in particle physics

Marked **10 year anniversary** of announcement that **Higgs Boson** was **discovered** at large hadron collider (LHC)



ATLAS collaboration :https://cds.cern.ch/record/2627611

4 July 2012, Higgs discovery announcement in packed auditorium at CERN (credit: https://home.cern/fr/node/76)

Higgs discovery had many important implications

One of the biggest being the completion of the standard model (SM)

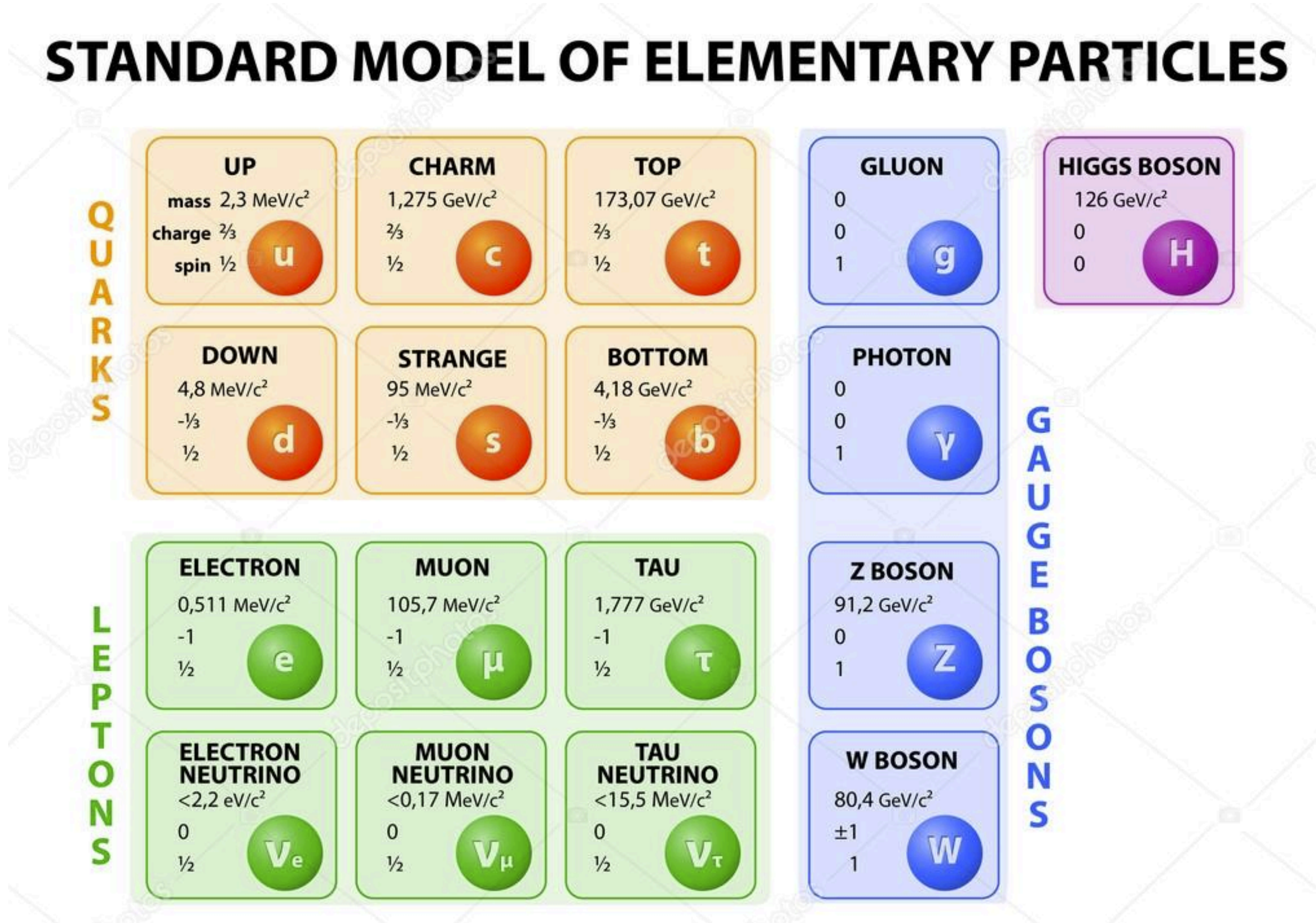


Image: quantumdiaries.org

All particles theorized in SM have been **experimentally verified**

Been very successful in explaining much of observed phenomena

Higgs discovery had many important implications

One of the biggest being the completion of the standard model (SM)

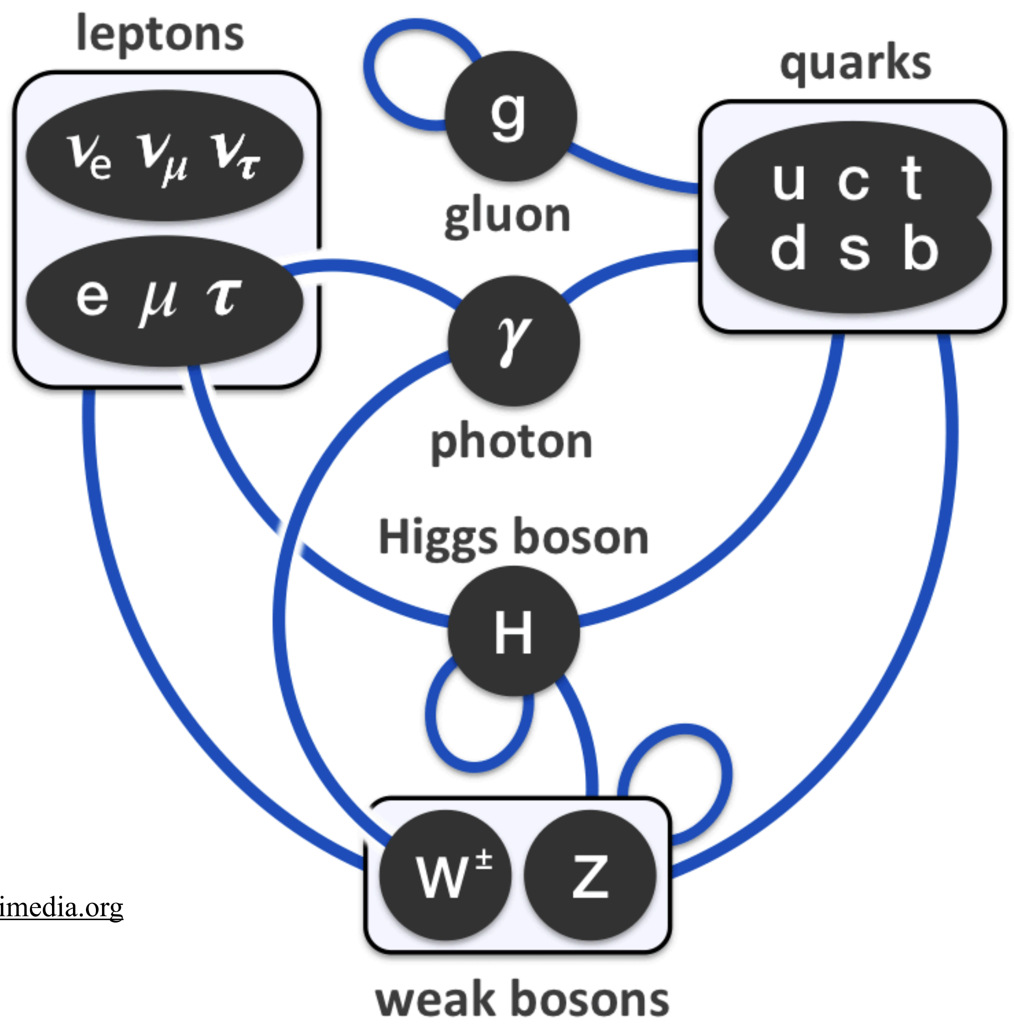


Image: wikimedia.org

All particles theorized in SM have been **experimentally verified**

Been very successful in explaining much of observed phenomena

SM one of the most successful theories created

1957 **T.S. Lee, C.N. Yang**: Parity Violation

1965 **R. Feynman, J. Schwinger, S. Tomonaga**: QED

1968 **L. Alvarez**: Meson Discovery

1969 **M. Gell-Mann**: Hadron classification

1976 **B. Richer, S. Ting**: Charm quark discovery

1979 S. **Weinberg, S. Glashow, A. Salam**: Electroweak unification

1980 **J. Cronin, V. Fitch**: CP violation

1982 **K. Wilson**: Renormalization group

1984 **C. Rubbia, S. Van der Meer**: W/Z boson discovery

1988 **L. Lederman, J. Steinberger, M. Schwartz**: Muon neutrino

1990 **H. Kendall, J. Friedman, R. Taylor**: Nuclear partons

1995 **M. Perl, F. Reines**: Tau lepton discovery

1999 **G. t'Hooft, M. Veltman**: Mathematical consistency of SM

2002 **R. Giacconi, R. Davis, M. Koshiba**: Cosmic Neutrinos

2004 **D. Gross, H. Politzer, F. Wilczek**: QCD

2008 **Y. Nambu, M. Kobayashi, T. Maskawa**: 3 Quark generations

2013 **P. Higgs, F. Englert**: Higgs & EW symmetry breaking

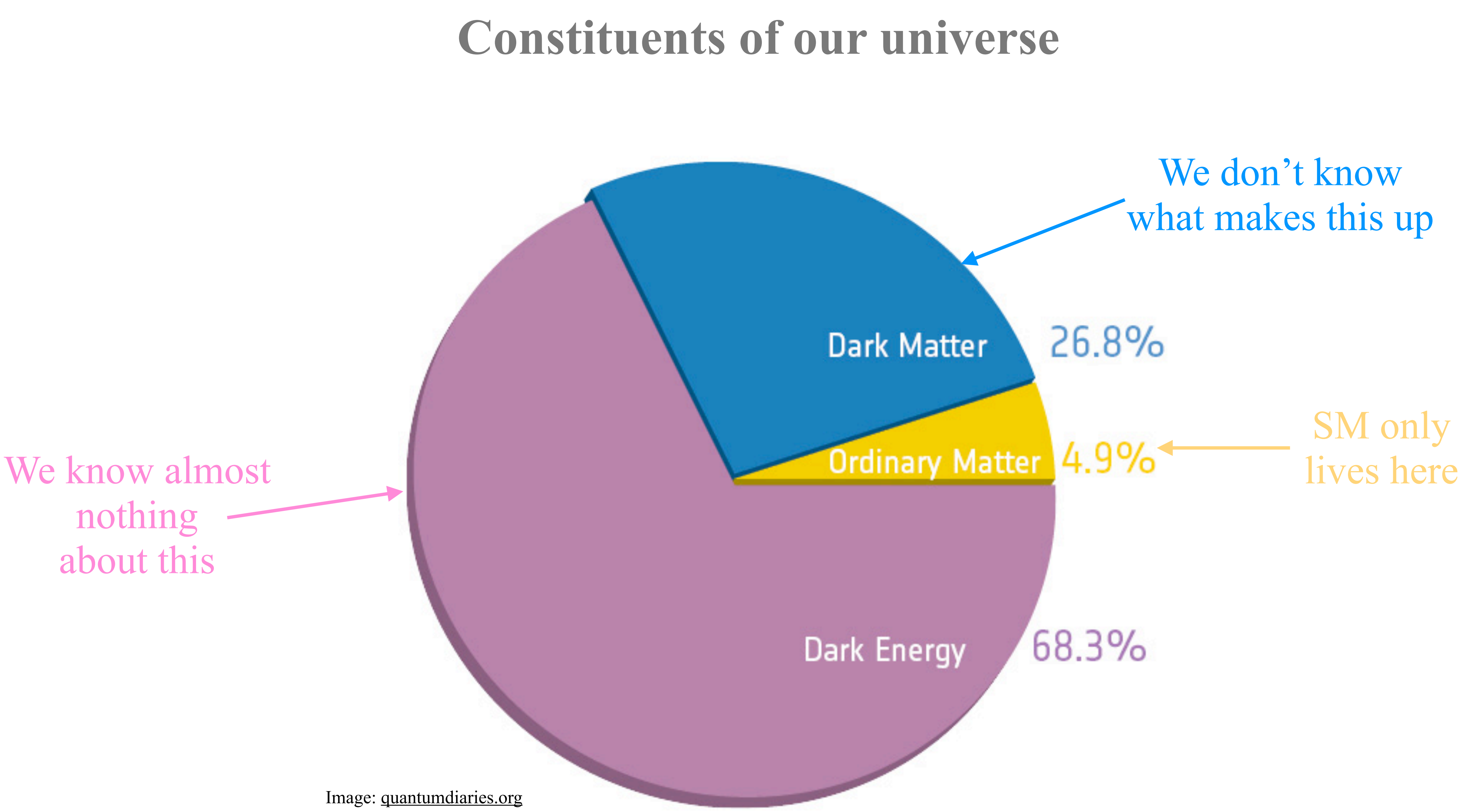
2015 T. **Kajita, A. McDonald**: Neutrino Oscillations

> 18 Nobel prizes

Yet SM does not tell complete story of Universe

Many puzzles SM cannot explain

1. SM cannot explain dark matter

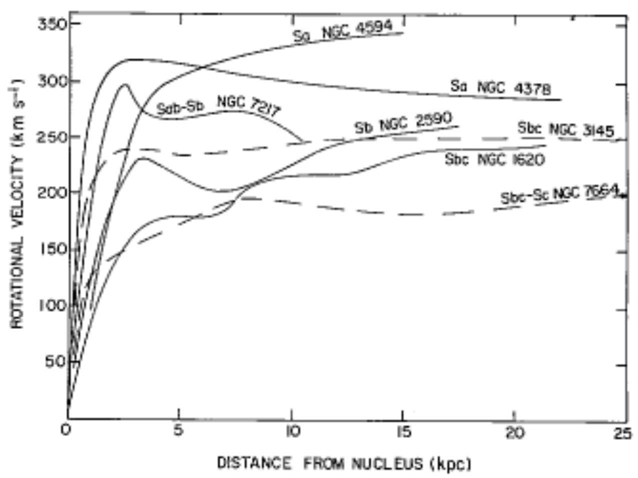


Particle physicists: fundamental physics that governs these sectors?

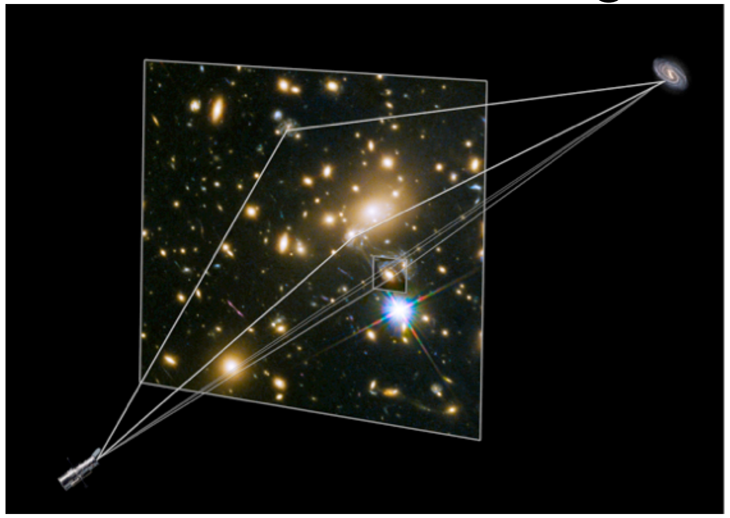
We know dark matter exists

Astronomy & Cosmology tell us

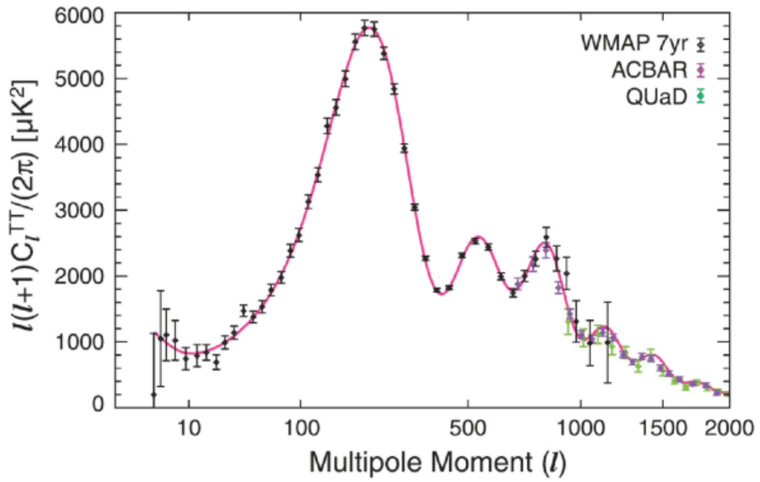
1. Rotation Curves



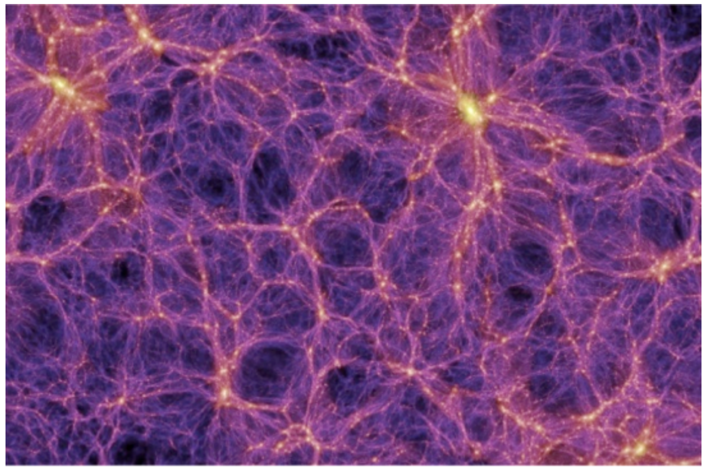
2. Gravitational Lensing



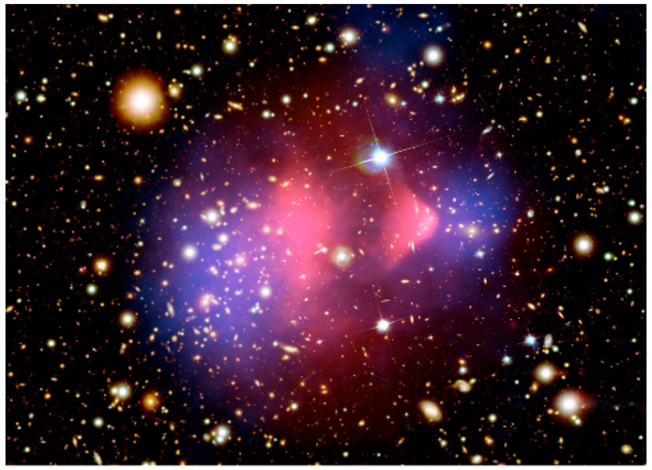
3. CMB Acoustic Peaks



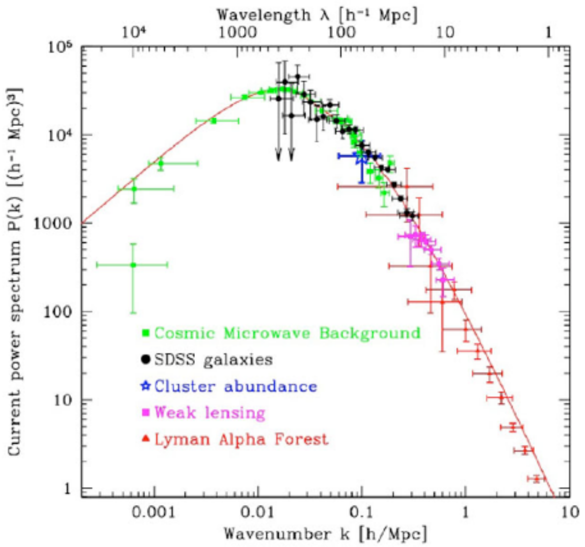
4. Large Scale Structure



5. Galaxy/Cluster Collisions



6. Matter Power Spectrum



Images: adapted from K. Mack

Inconvenient truth: We don't know what its made of

2. Cannot explain where neutrino masses come from

In 1998, Super-K announced neutrino oscillations

1998 presentation by Takaaki Kajita

Image: twitter.com/annalisavarri

Neutrinos change flavor as they propagate

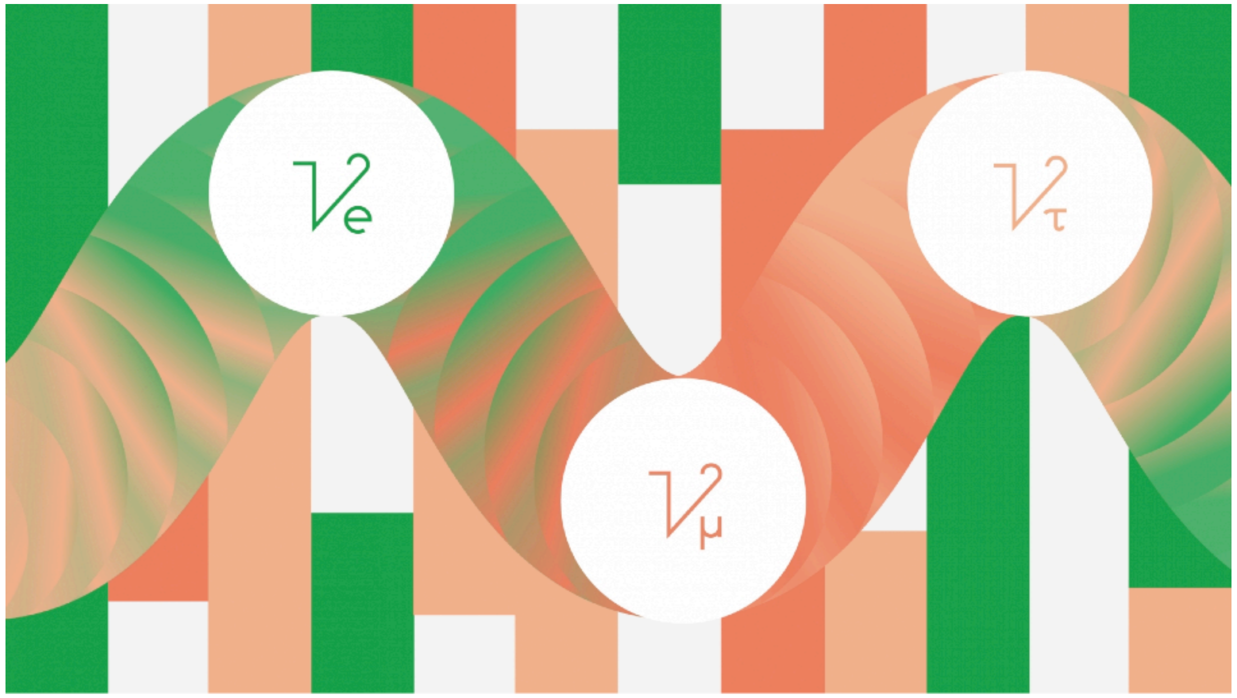


Image: sanfordlab.org

- As neutrinos propagate they change flavor
- Oscillations only true if **neutrinos have mass**
- For this result the 2015 Nobel Prize was awarded to T. Kajita & A. McDonald

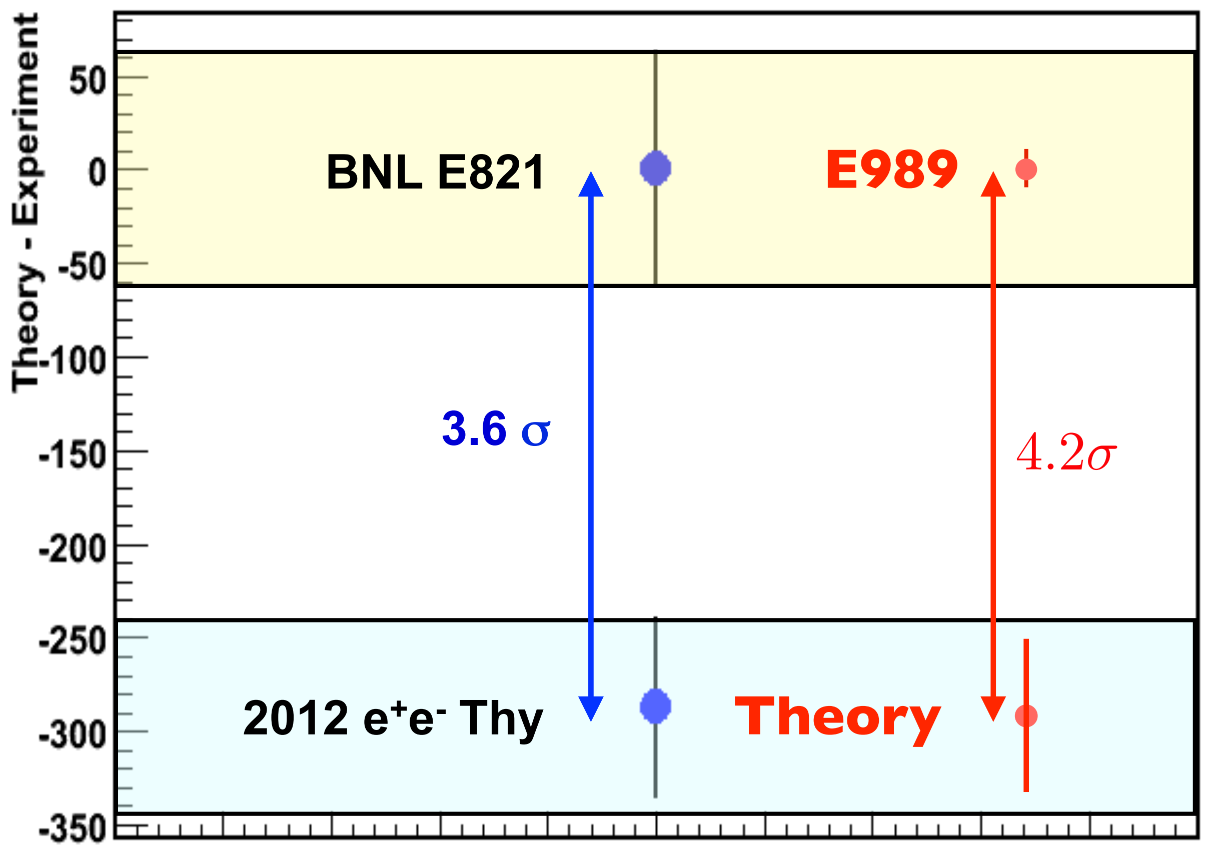
Where do neutrino masses come from? We don’t know

Yet SM is not complete theory of Universe

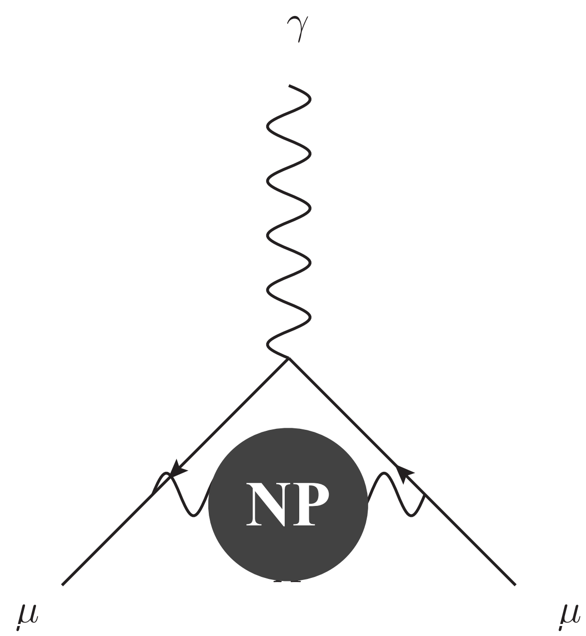
3. Doesn't seem to explain some recent experimental anomalies

A particularly long-standing anomaly > 2 decades

Muon g-2 anomaly: discrepancy between exp and theory in muon anomalous magnetic moment



Anomalous part of dipole moment



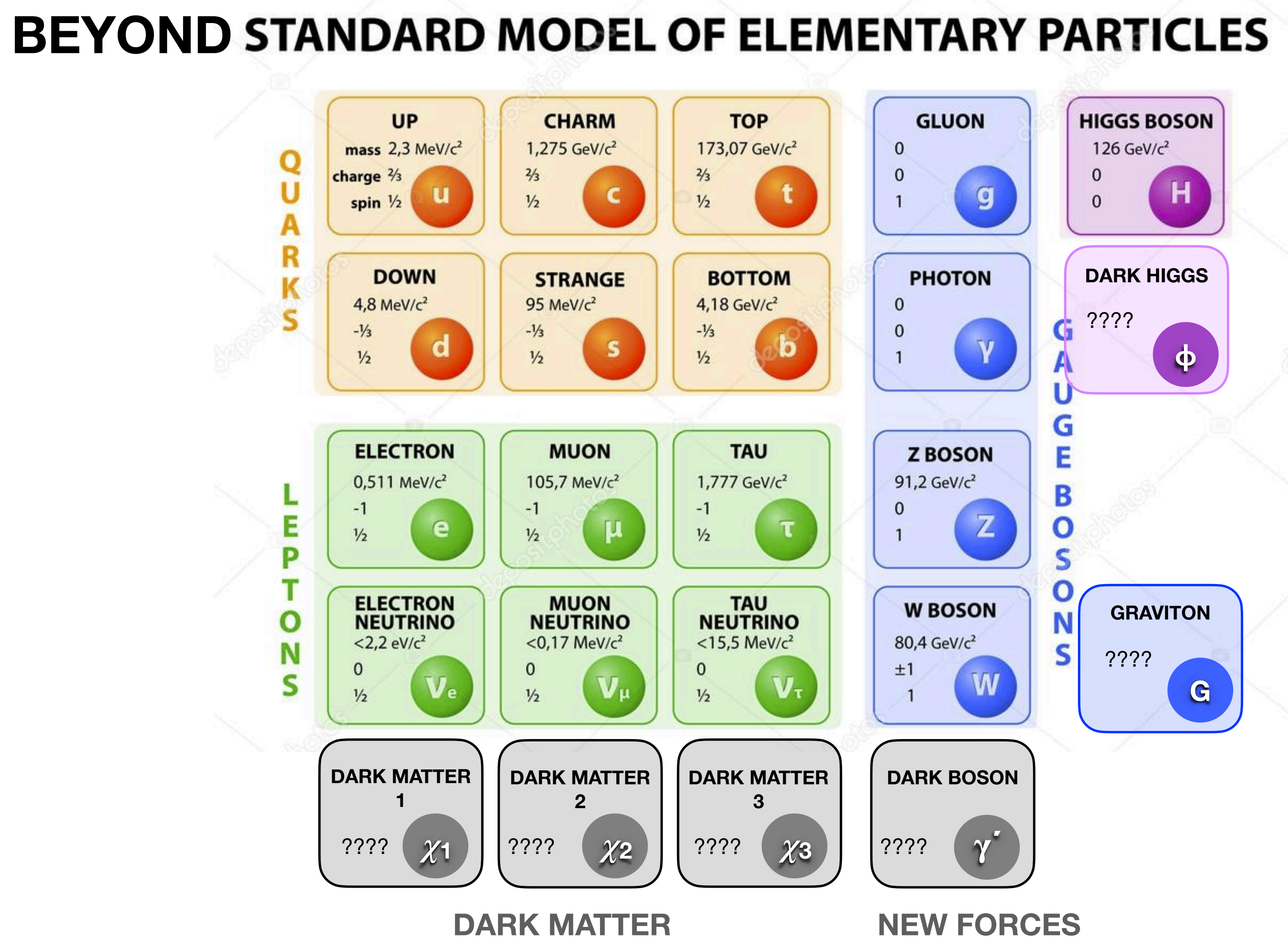
$$a_\mu = \frac{g_\mu - 2}{2}$$

Recent FNAL E989 results move closer to **new physics explanation**

SM does not tell complete story of Universe

- Dark matter
- neutrino mass origin
- explaining experimental anomalies
- Matter - antimatter asymmetry
- Gravity

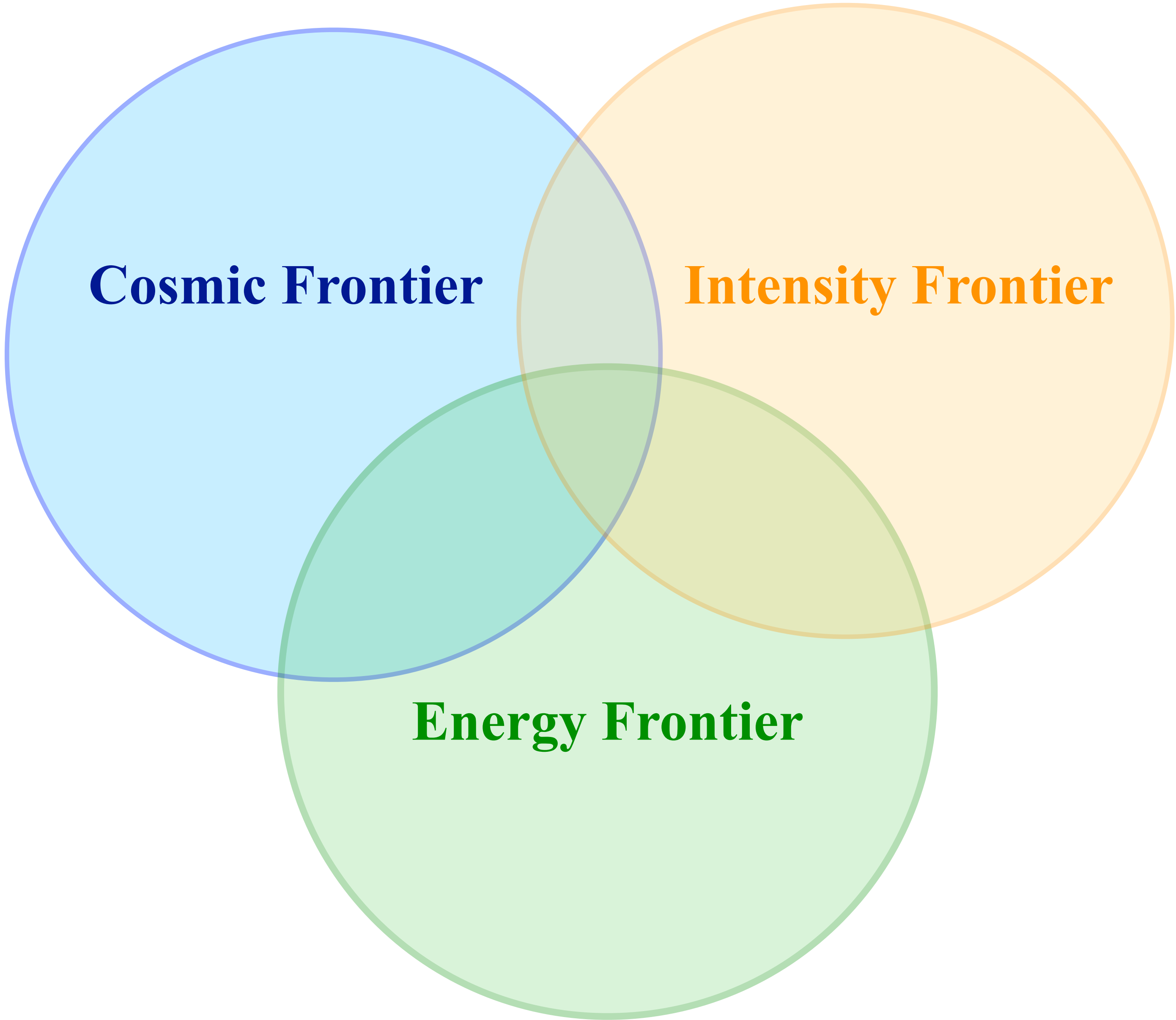
\+ Many Others



Need **New Theories Beyond the Standard Model**

Theorists & experimentalists are working hard to find BSM physics

Search for new physics separated into 3 complementary frontiers



All have new experiments & techniques for discovering BSM physics

Cosmic Frontier

Search for new physics from astrophysics & cosmology

e.g. DM particles can scatter with SM particles in underground experiments

DM direct detection

XENON1T & XENONnT
LUX-ZEPLIN
SENSEI
Super-CDMS
DEAP-3600
DarkSide-20k
…

Housed at SNOLAB & significant contributions from TRIUMF (Super-CDMS, DEAP-3600, DarkSide-20k)

e.g. Xenon1T detector

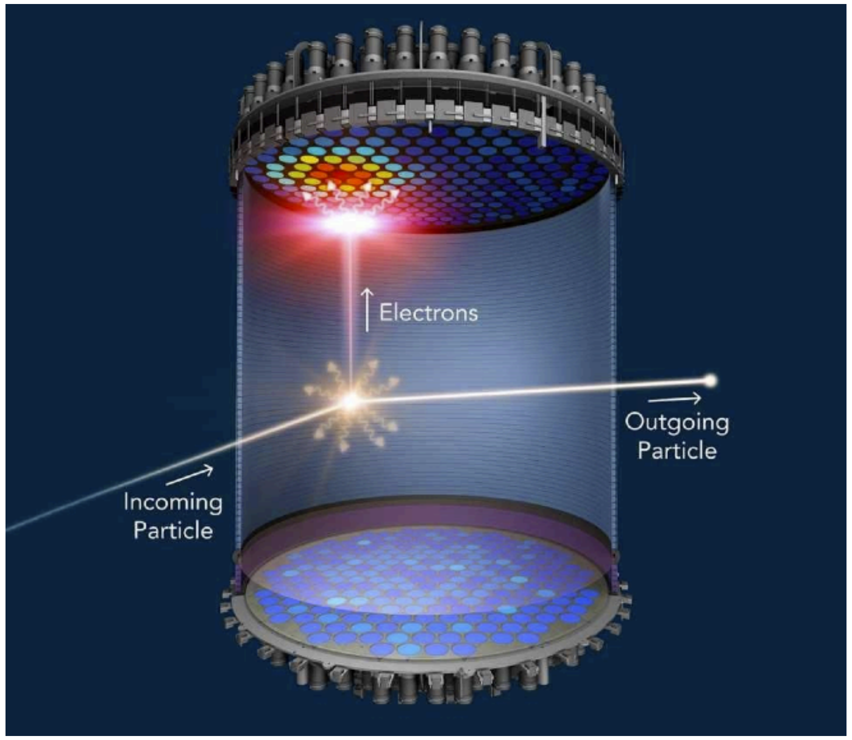


Image: symmetry magazine

DM particles can annihilate in astrophysical structures

indirect detection

Cherenkov Array Telescope
Hyper-Kamiokande
AMS-02

Hyper-Kamiokande

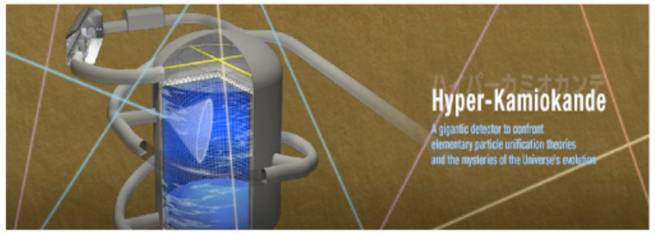


Image: vivierjapon.es

Search for new physics from astrophysics & cosmology

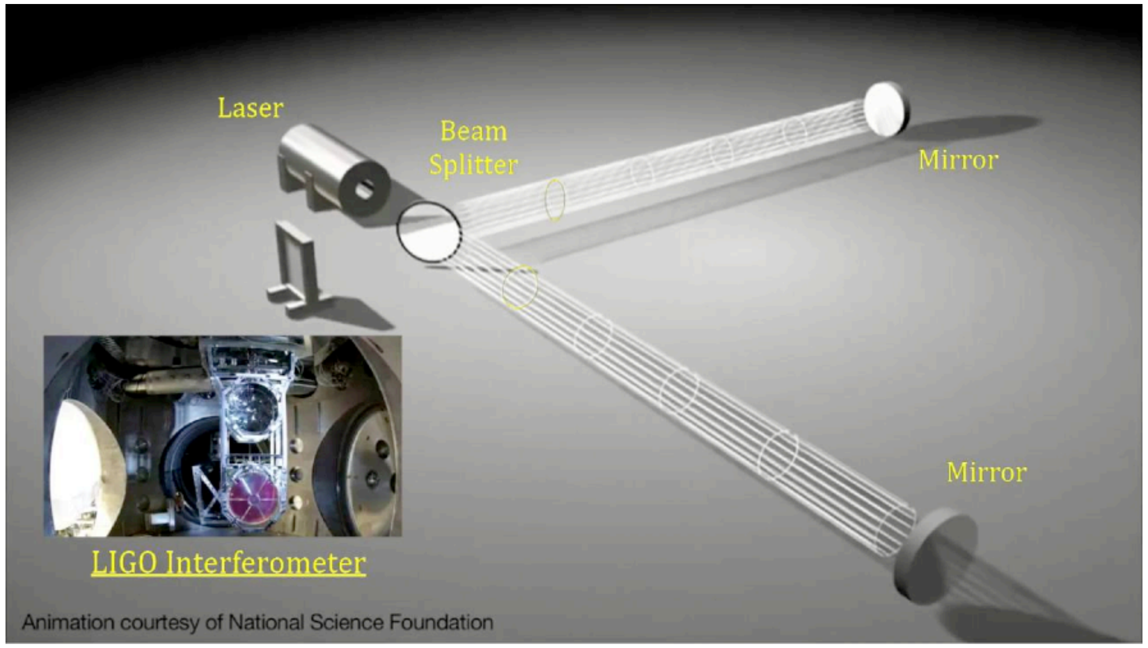
DM can also be primordial blackholes or composite objects

Search using gravitational waves:

LIGO, LISA

Gravitational lensing:

EROS-2 survey, CHIME, CMB -S4

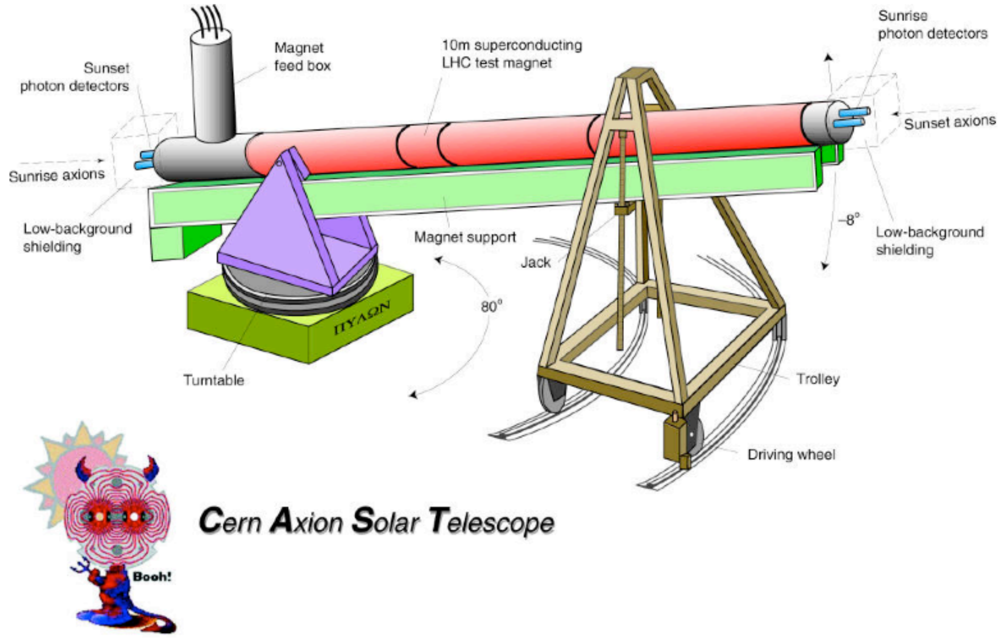


Ultralight particles called Axions

Light shining through wall: LSW, ALPS

Helioscopes: CAST, IAXO

Haloscopes: ADMX



Intensity Frontier

Usually lower energy/high intensity experiments

Search for light weakly coupled new particles

e.g. Fixed-target experiments

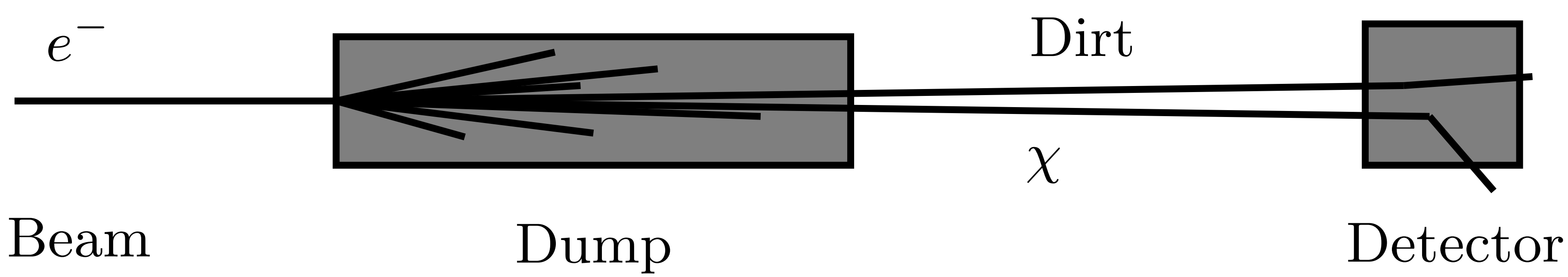


Image: G. Krnjaic

NA64 NA62 BDX MAMI ….

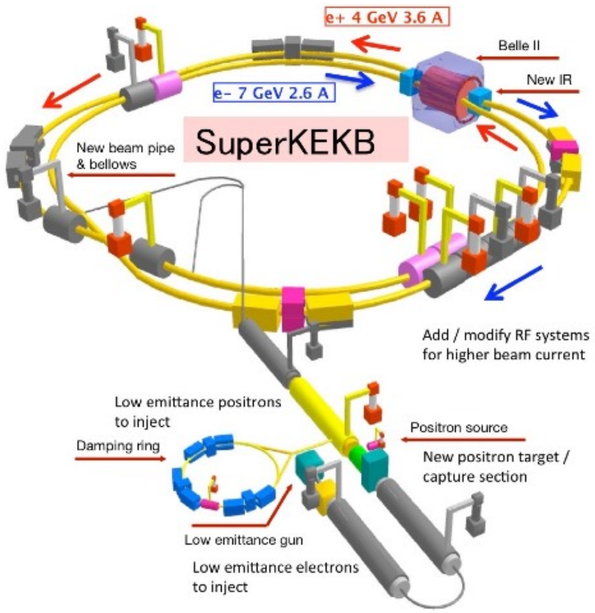
LDMX MiniBooNE DarkLight@ARIEL ⟵ See earlier talk by Katherine Pachal

Low energy colliders

BaBar

Belle II

KLOE



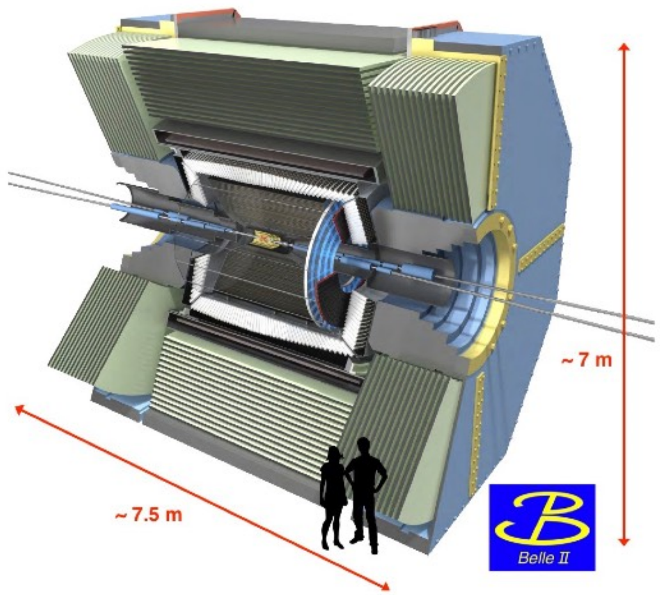
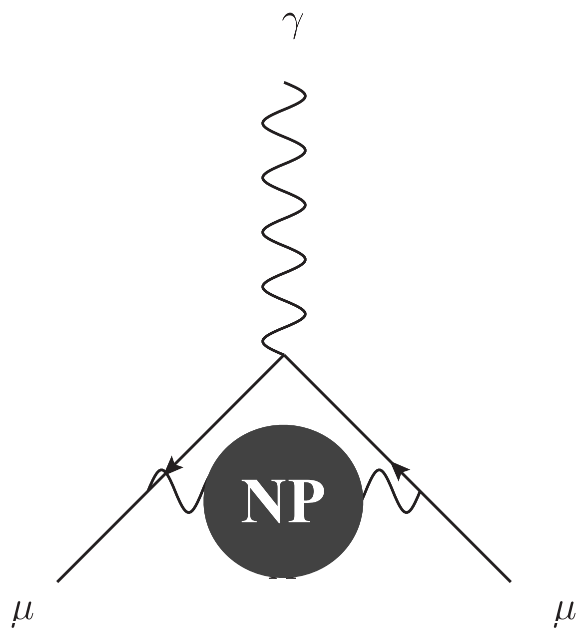


Image: belleII.org

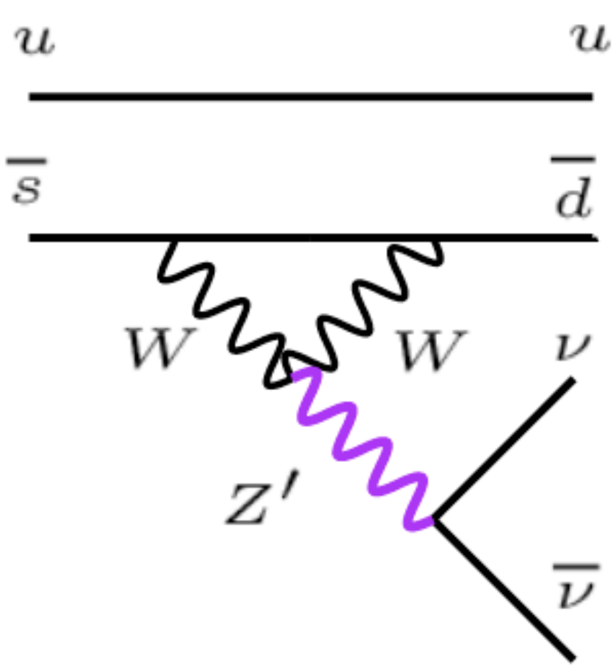
Usually lower energy/high intensity experiments

NP can show up in Precision measurements of SM

e.g. Muon g-2



Rare meson decays



Some experiments:

FNAL E989
J-PARC E34
→ g-2

TWIST
PIENu
NA62
GlueX
→ Meson decays

SNO+
nEXO
→ Neutrinoless ββ decay

MiniBooNE
T2K
DUNE
→ Precision Neutrino Oscillations

Usually high energy experiments directly produce new heavy particles

e.g. Bump/Resonance hunting

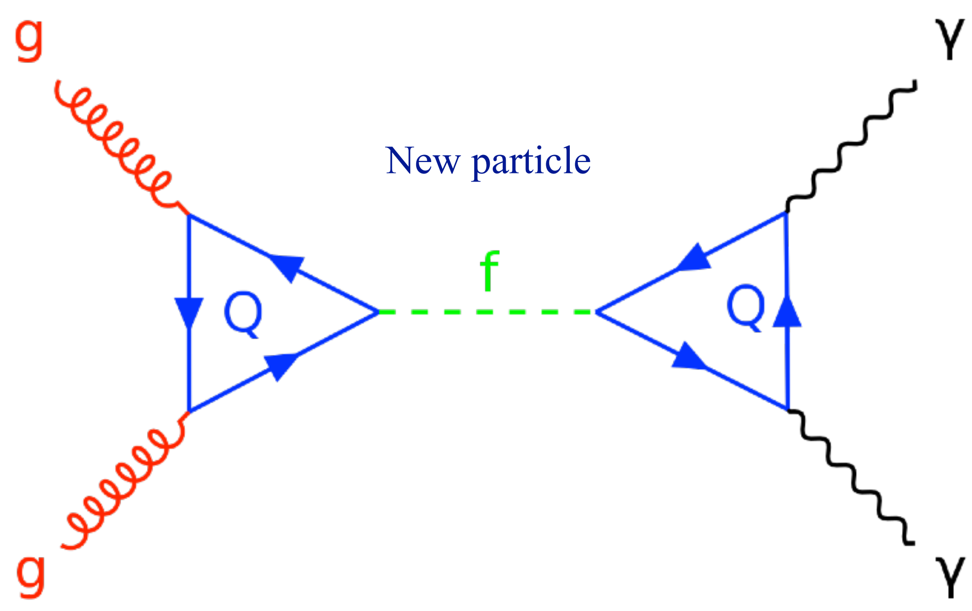


Image: Wikipedia

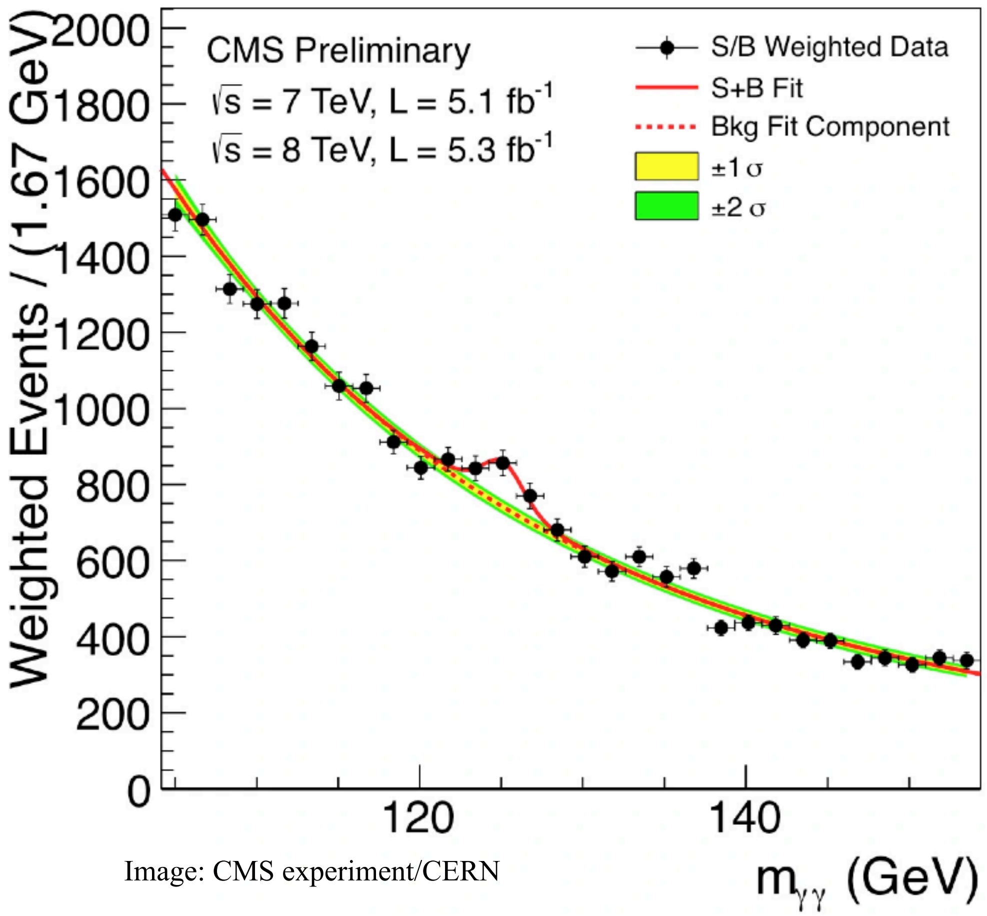


Image: CMS experiment/CERN

Some experiments:

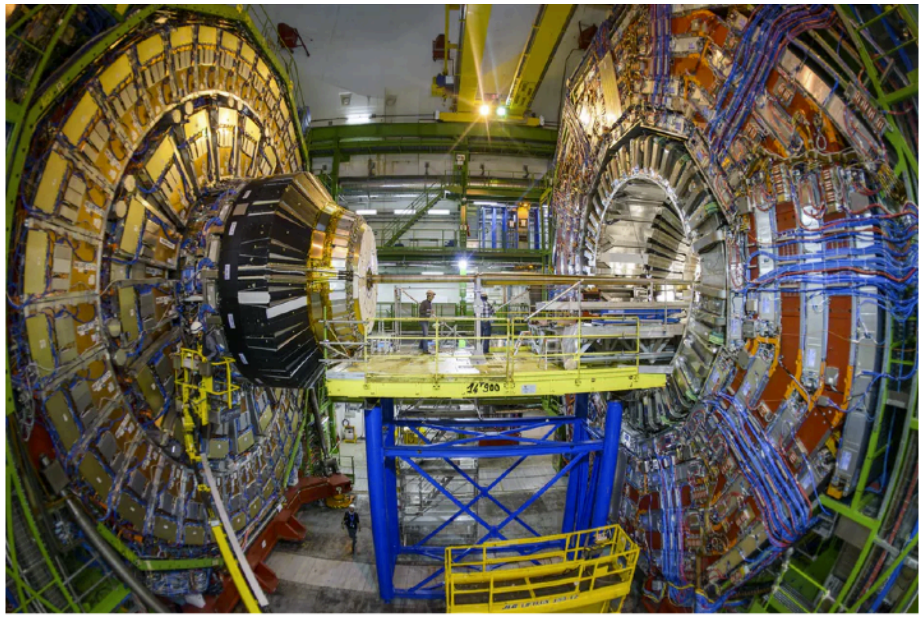
LHC: High Lumi, High Energy

International Linear collider (ILC)

Future Circular collider (ILC)

Cool Copper Collider (C^3)

ATLAS experiment at LHC



Energy Frontier

Usually high energy experiments directly produce new heavy particles

Long-lived particle searches

New particle decay in outer layers of detector or in another detector a few meters downstream

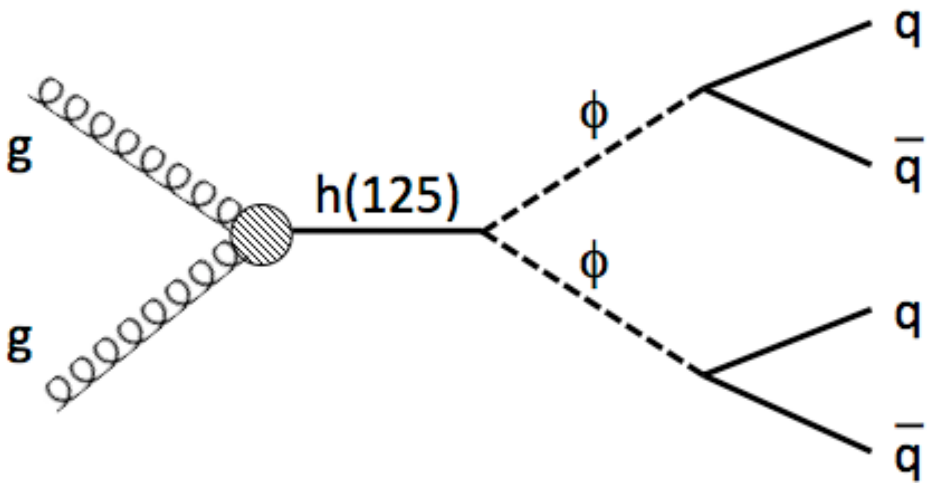


Image:cds.cern.ch/record/2641462/

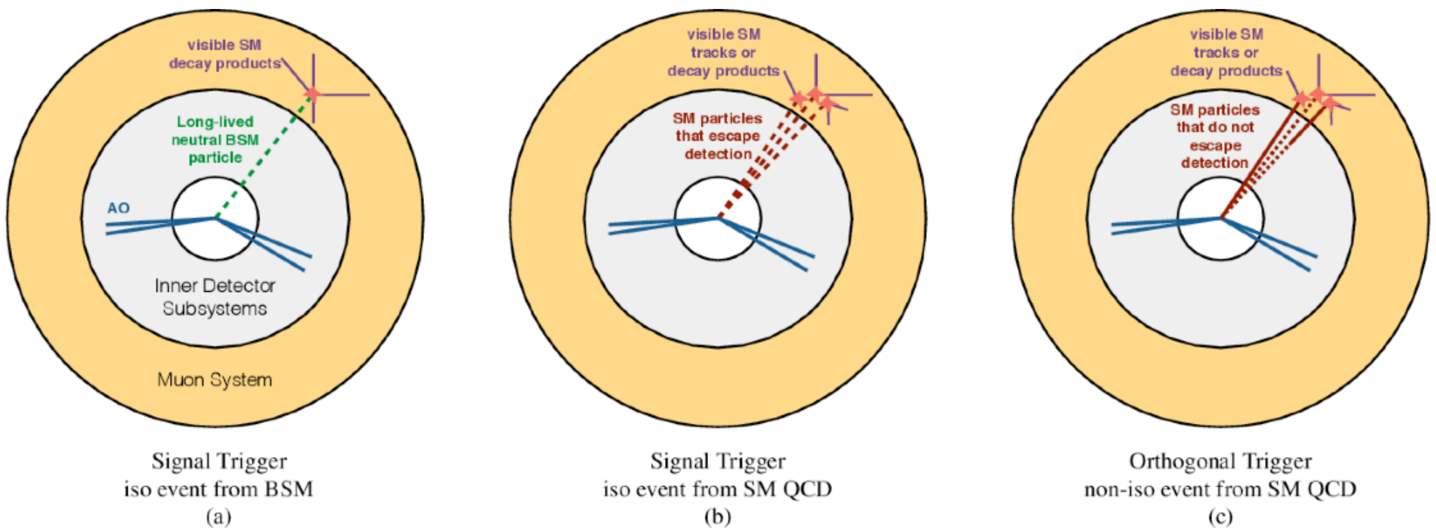


Image:semanticscholar.org

Some experiments:

ATLAS

CMS

FASER

SeaQuest/DarkQuest/LongQuest

MATHUSLA

CODEX-b

…

Looking Forward

Current era of multiple experimental probes present perfect opportunity to solve mysteries of the universe

Search for new particles at all frontiers are intensifying with

- New strategies & experiments for **detecting DM from laboratory to the cosmos** are developing at fast pace

- Accelerator experiments increasing energy & intensity to extend reach for production of new particles

- Neutrino program intensifying, building larger more sensitive detectors

Looking Forward cont'd

- Precision experiments are testing the SM to its limits, while trying to extract signals of new physics

- Theorists developing new and exciting ideas to maximally support experimental effort

We may be heading towards **golden age for particle physics**

TRIUMF & Canada will be at the cutting edge

Thank you