Introduction to High Energy Physics

QuarkNet 2020

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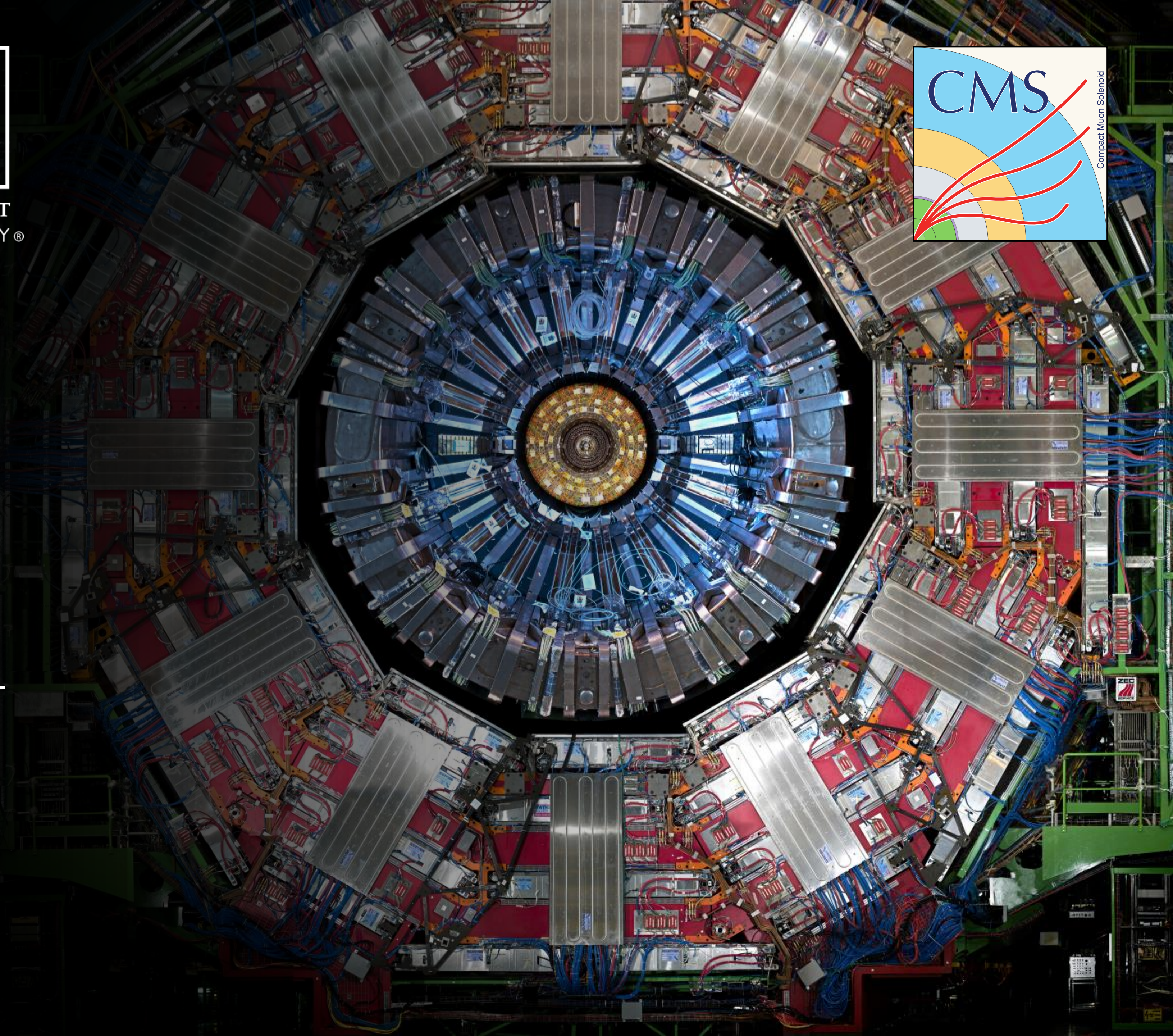


Outline

What do we know? – The Standard Model of Particle Physics

The unknown – Dark matter

Conclusions

My experience becoming a particle physicist

Resources for high school teachers and students.

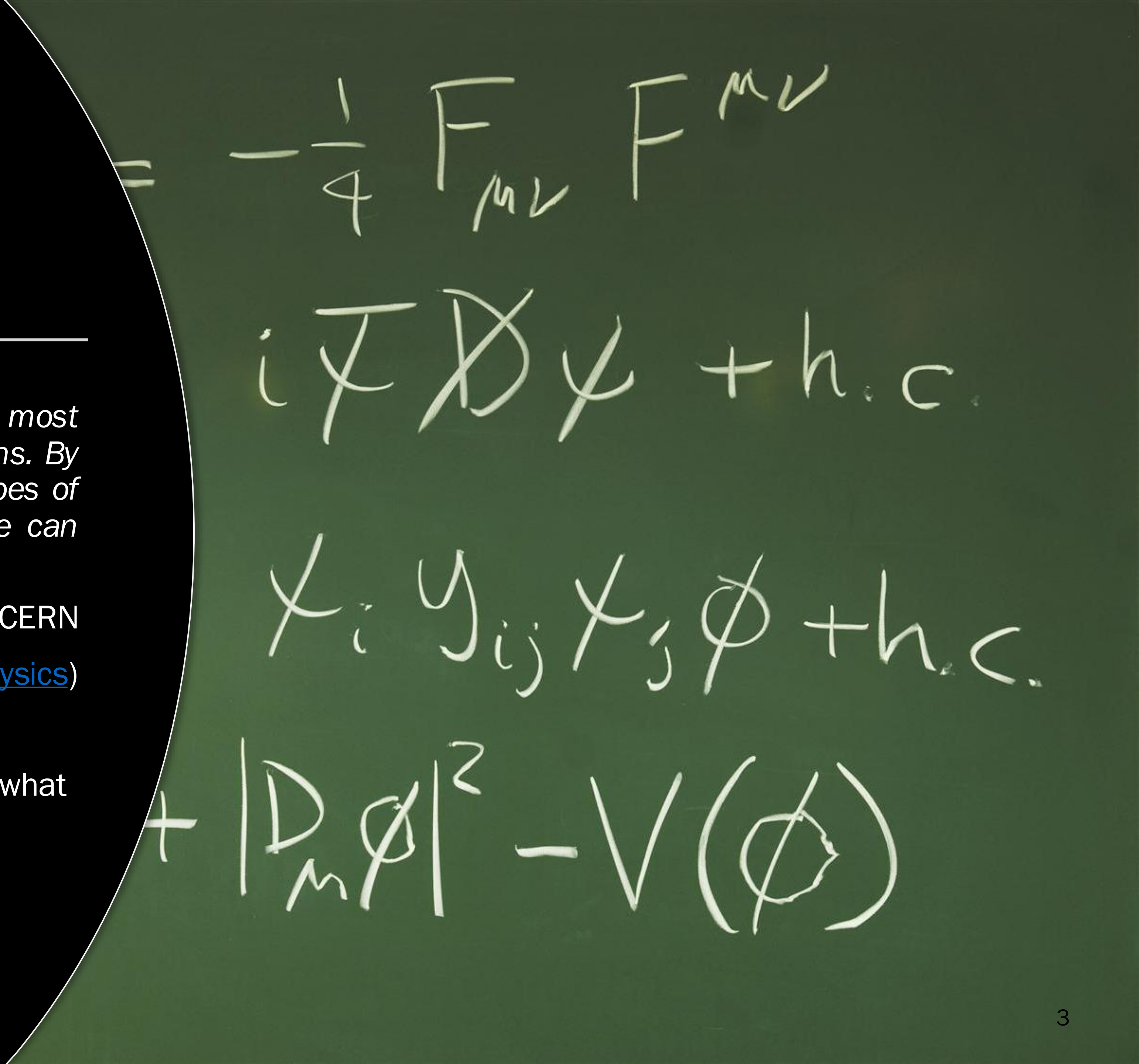
Introduction

*"Particle physicists study Nature at its most fundamental level by observing particle collisions. By understanding the properties of the various types of **particles** and the **forces** that govern them, we can learn about the origins of the Universe itself."*

Physics. The CMS experiment at CERN

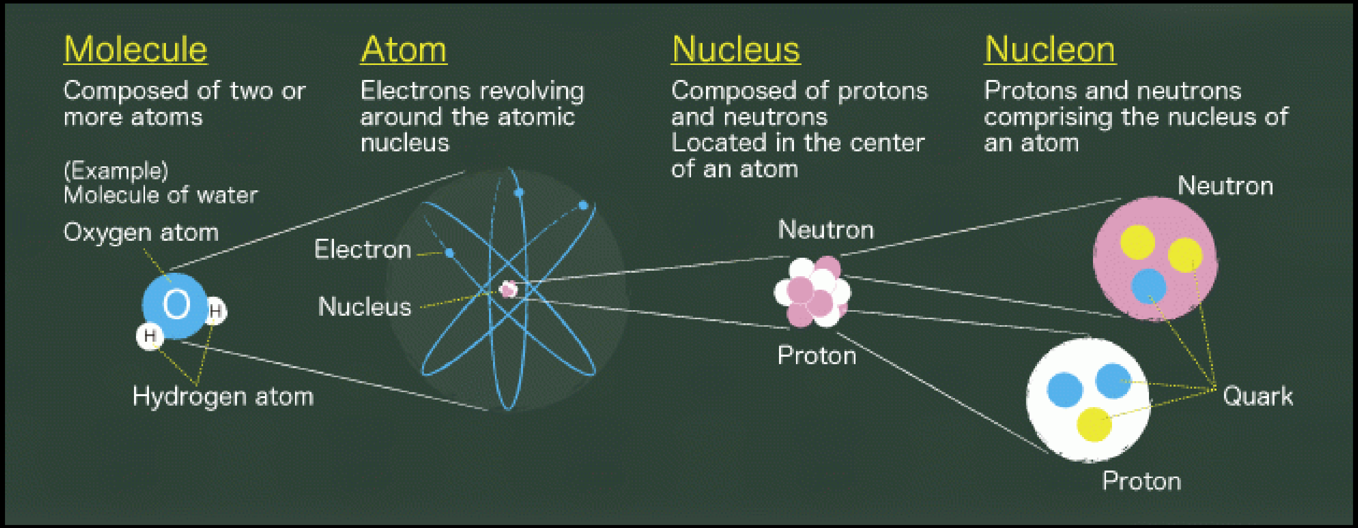
(https://cms.cern/physics)

The **standard model of particle physics** explains what the world is made of (matter) and what holds it together (interactions) through particles.



What is a particle?

- Particles are physical things that we can count.
- A fundamental particle is such that it does not have internal structure.
- Fundamental particles have properties like mass, but they are thought to be “point-like” or ”size-less”.



Shinji Ohsuka, Intro to the story of Particle Physics [*].

Fundamental blocks of matter

Less mass → More mass

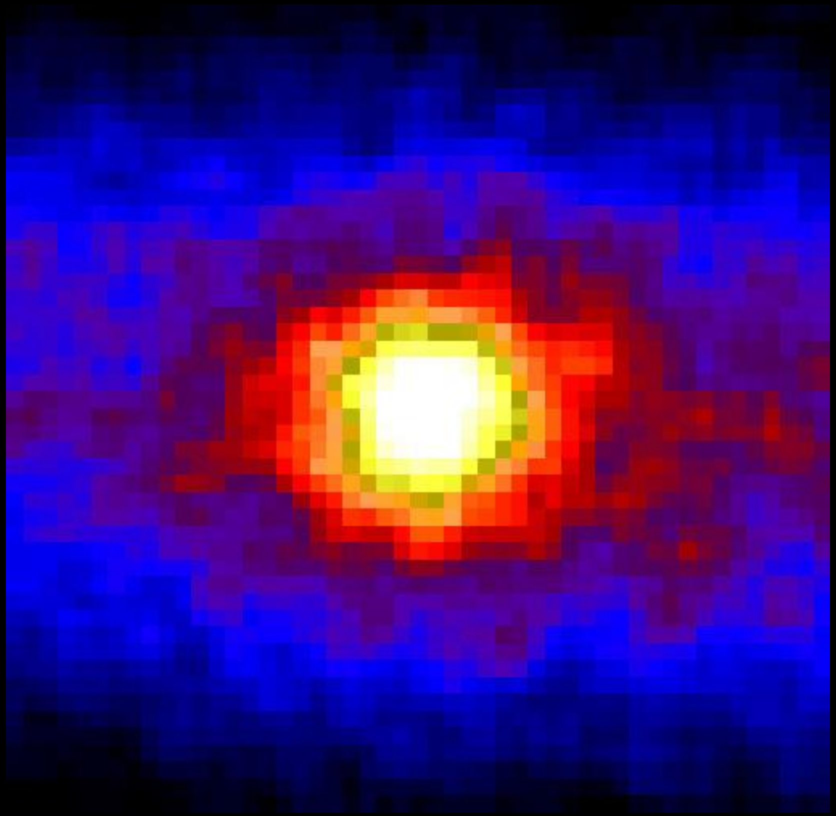
	First generation	Second generation	Third generation	Electric charge
Quarks	u up quark	c charm quark	t top quark	+2/3 e
	d down quark	s strange quark	b bottom quark	-1/3 e
Leptons	e electron	μ muon	τ tau	- e
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	0

All stable matter in the Universe is made of these particles!

Stable ← Unstable

Leptons

- Three of them have (integer) electric charge and have different flavors: electron, muon and tau.
- The rest are neutral and are called neutrinos, since they have very little mass.
- Neutrinos are hard to detect.

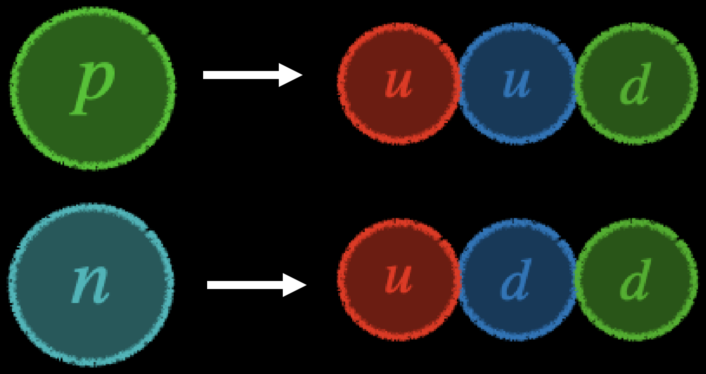


The sun seen through the Earth in ”neutrino” light.
© R. Svoboda, K. Gordan

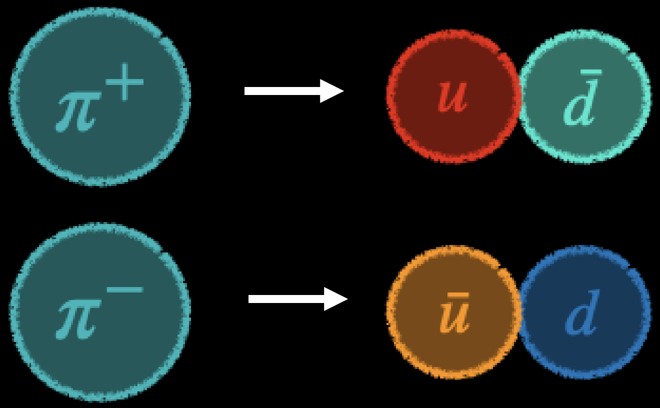
Quarks

- Quarks carry (fractional) electric charge and color charge. They come in six different flavors: up, down, charm, strange, top and bottom.
- They only exist in groups with other quarks, called hadrons.
- Hadrons have a net integer electric charge and zero color charge.

Baryons: 3 quarks

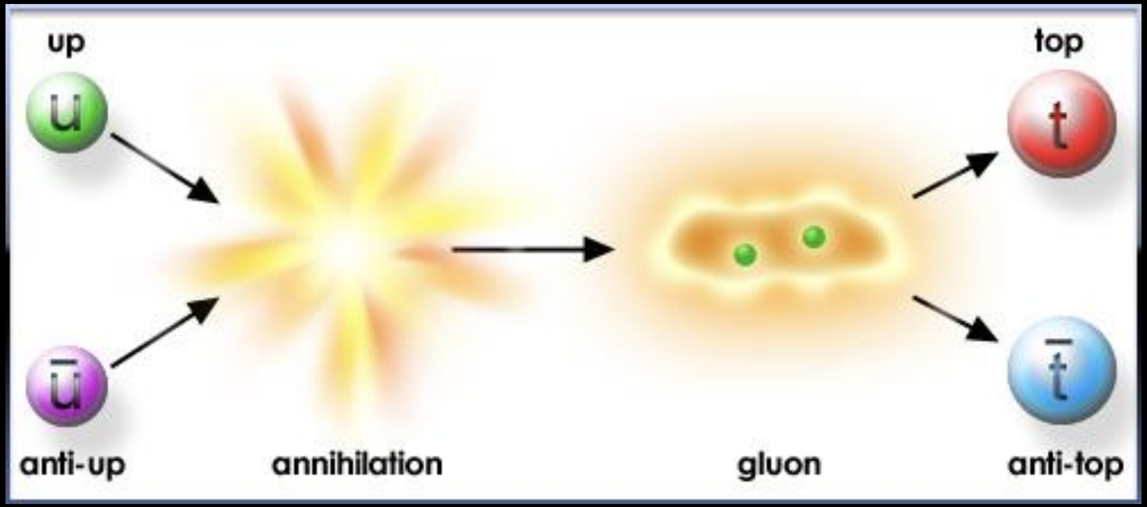


Mesons: quark + antiquark



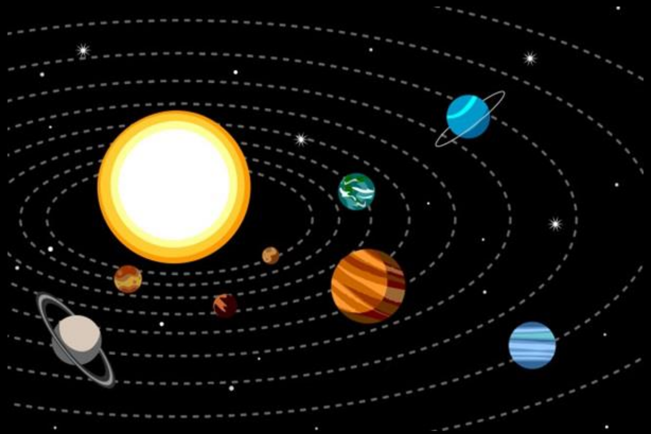
Matter and antimatter

- For each matter particle there is a corresponding antimatter particle.
- The only known difference between matter and antimatter particles is that they have opposite electric charge.
- When a particle and an antiparticle meet, they annihilate into pure energy.



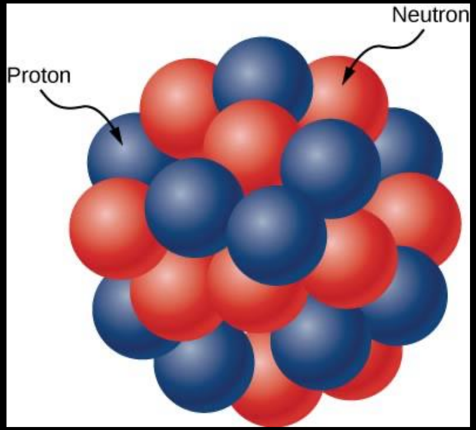
Matter and antimatter. The Particle Adventure.

Fundamental interactions

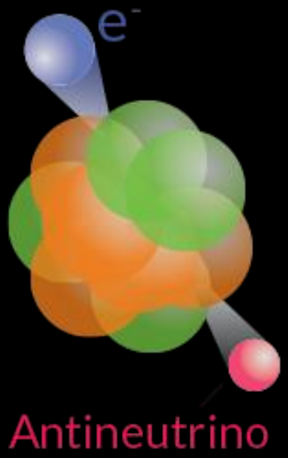


Gravity

Electromagnetism [*]



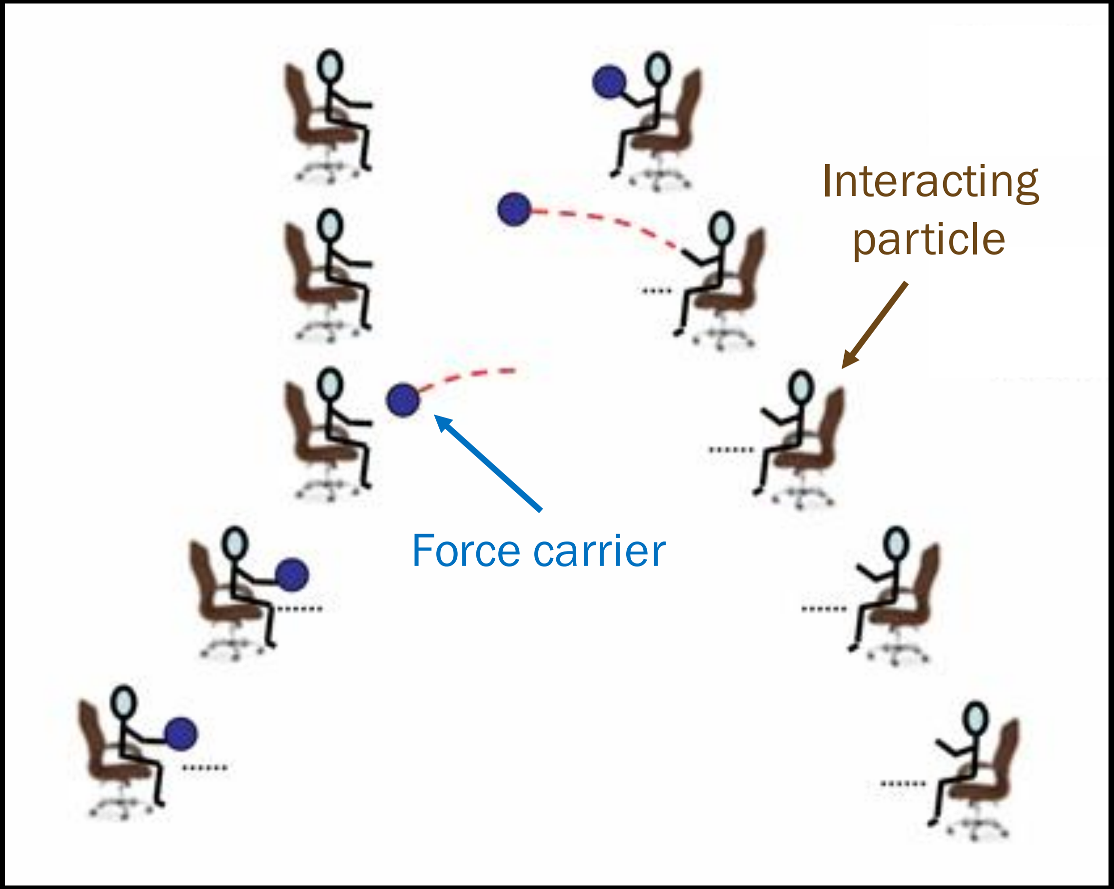
Strong

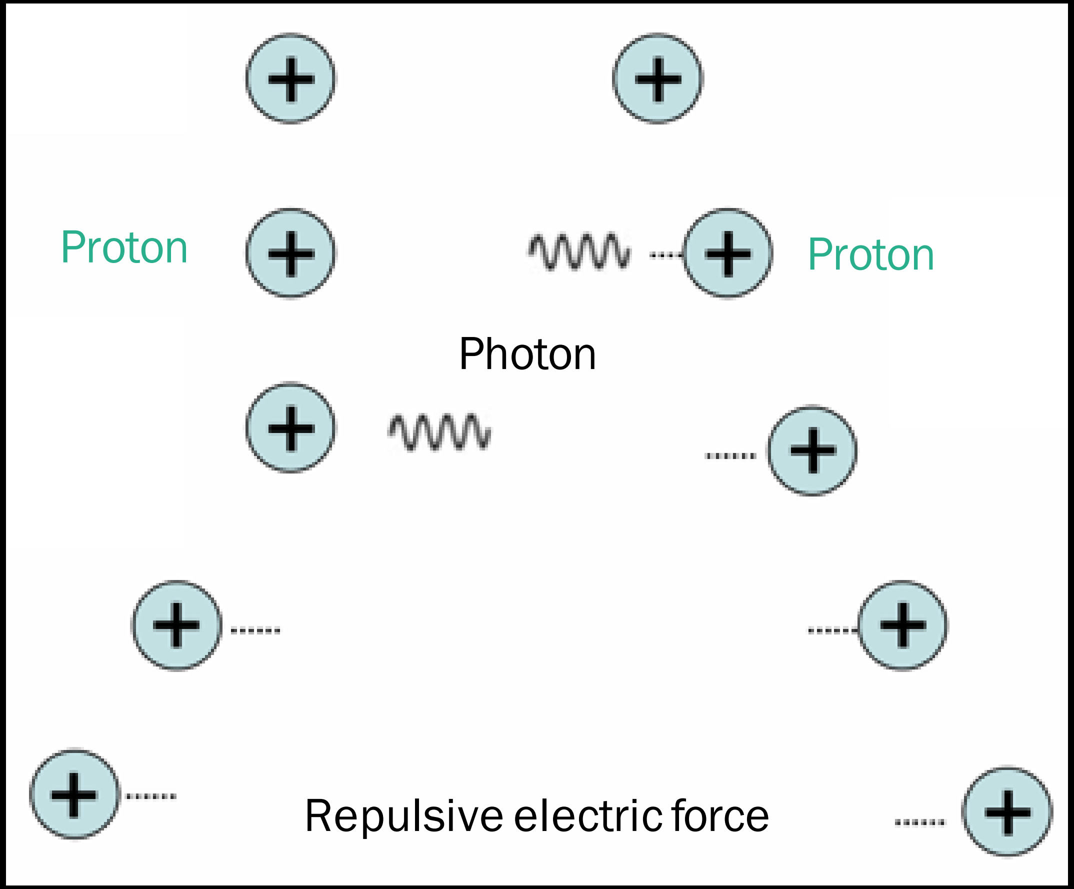


Weak

- At a fundamental level, a force is the exchange of particles called force carriers between two matter particles.

Fundamental interactions





Owen Long, [The Standard Model of Particle Physics](), 2014.

Fundamental interactions

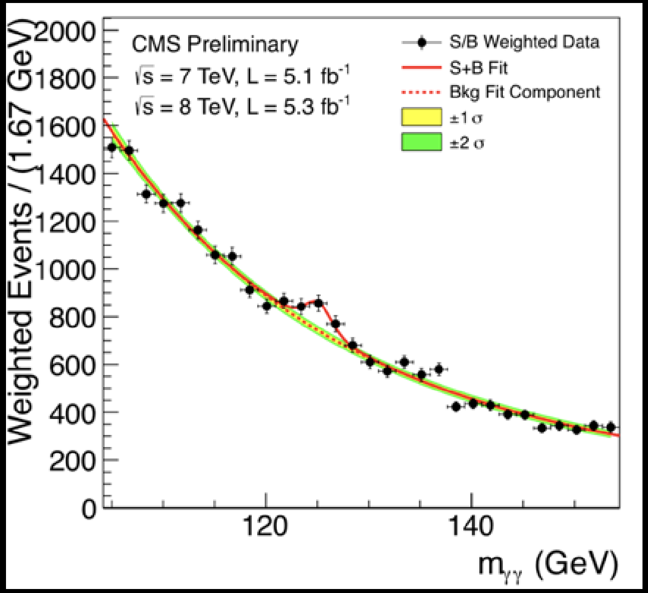
Interaction	Gravitational	Weak	Electromagnetic	Strong
Acts on:	Mass-energy	Flavor	Electric charge	Color charge
Particles experiencing: (fermions)	All	Quarks and leptons	Electrically charged particles	Quarks and gluons
Particles mediating: (bosons)	Graviton G (not observed yet)	W^+, W^-, Z bosons (massive)	Photon γ (massless)	Gluons g (massless)
Strength at (1) 10^{-18} m, (2) 3 x 10^{-17} m (proton diameter ~ 10^{-16} m)	(1) 10^{-41} (2) 10^{-42}	(1) 0.8 (2) 10^{-4}	(1) 1 (2) 1	(1) 25 (2) 60
Theory:	General relativity	Quantum flavordynamics	Quantum electrodynamics (QED)	Quantum chromodynamics (QCD)

Standard Model!

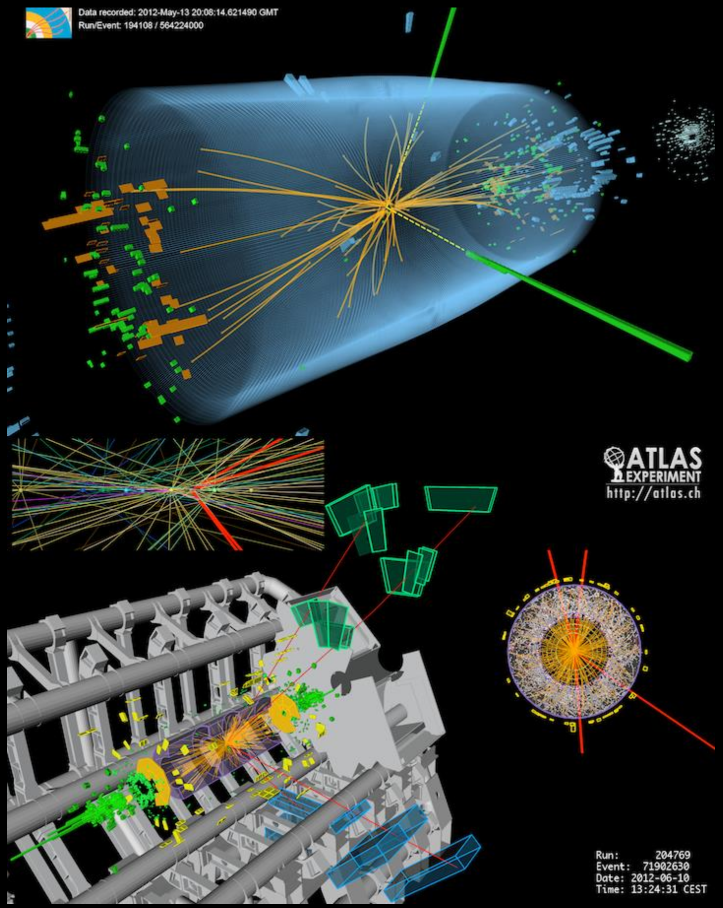
The Higgs boson

CERN by the ATLAS and CMS collaborations.

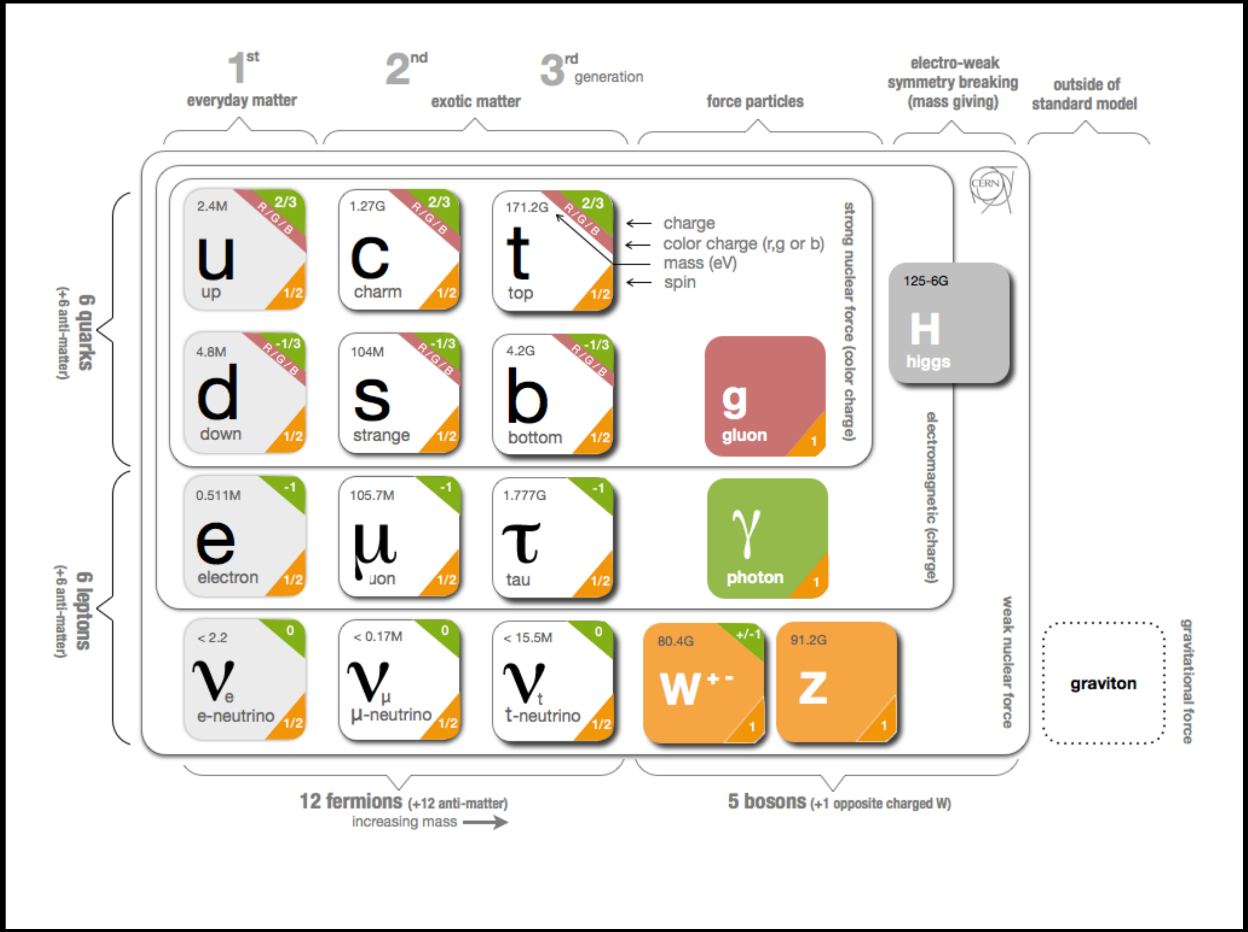
- The Higgs boson was predicted as a consequence of the Brout-Englert-Higgs mechanism, by which fundamental particles get mass.
- Its discovery was announced in July of 2012 by the ATLAS and CMS collaborations at the LHC.



CMS Higgs seminar (4 July 2012): plot from CMS statement.
CMS-PHO-EVENTS-2013-004



The Standard Model of Particle Physics



- The predictions of the Standard Model have been verified experimentally to incredible precision.
- However, it does not explain everything…

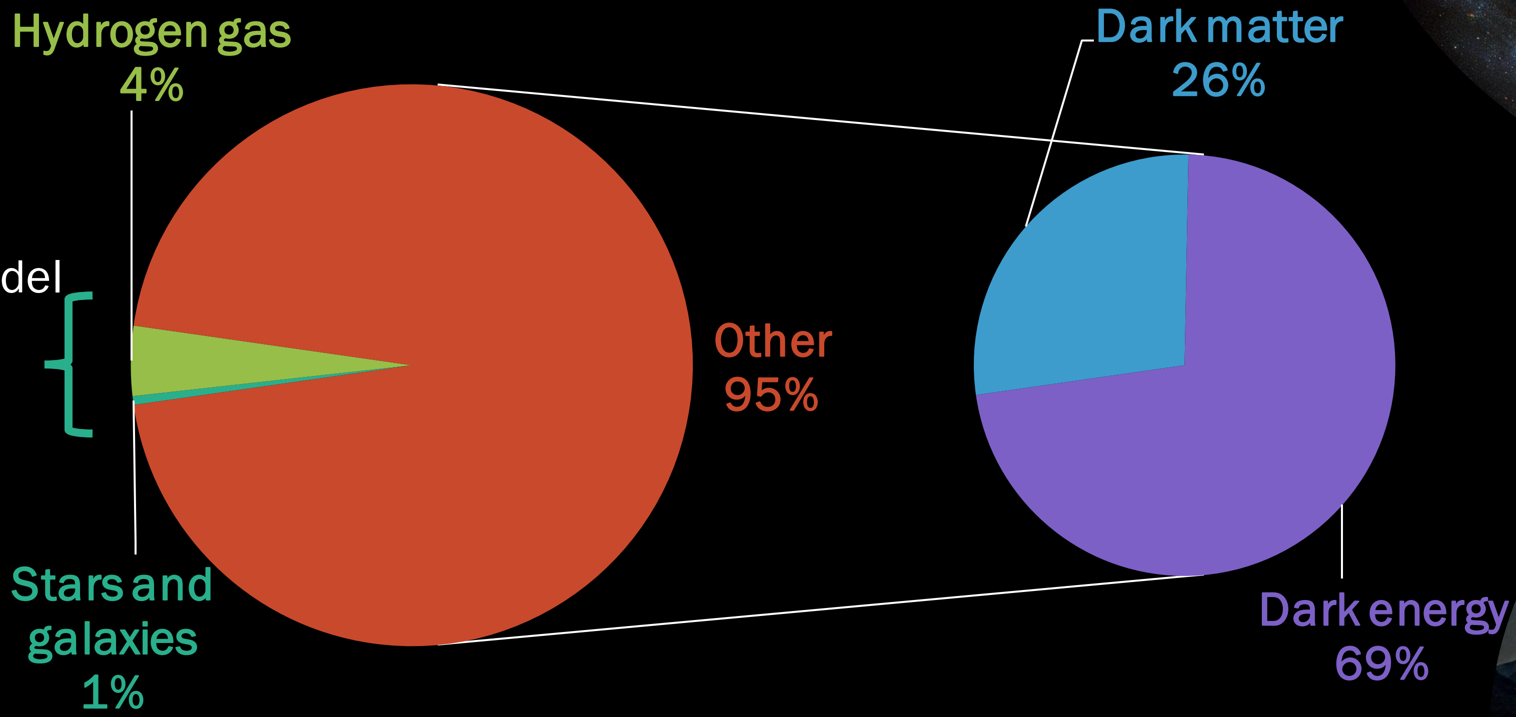
The unanswered questions

- There are many open questions that the standard model can't answer:
  - Matter-antimatter asymmetry,
  - Neutrino masses,
  - Higgs boson mass,
  - **Dark matter,**
  - Dark energy,
  - And more…

The Pinwheel Galaxy. ESA & NASA.

Composition of the Universe

The Standard Model describes this portion of the Universe.



… How do we know that there is **dark matter**?

Galaxy rotation curves and the dark matter hypothesis

$$F_c = m_{star}\frac{v_{star}^2}{R} \quad = \quad F_g = \frac{G m_{star} M_{galaxy}}{R^2}$$

(circular motion) (gravity)

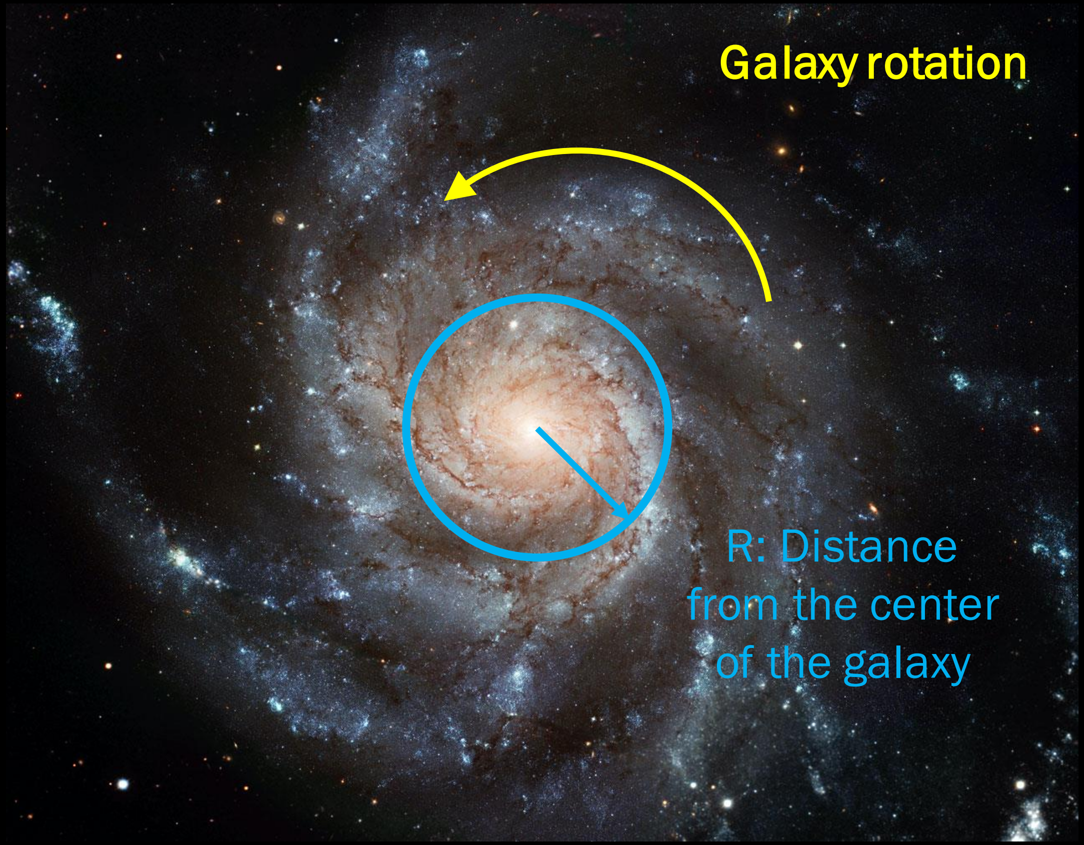
Star's velocity

Galaxy's mass = density · volume

$$M_{galaxy}(R) = \rho(R)\, V(R)$$

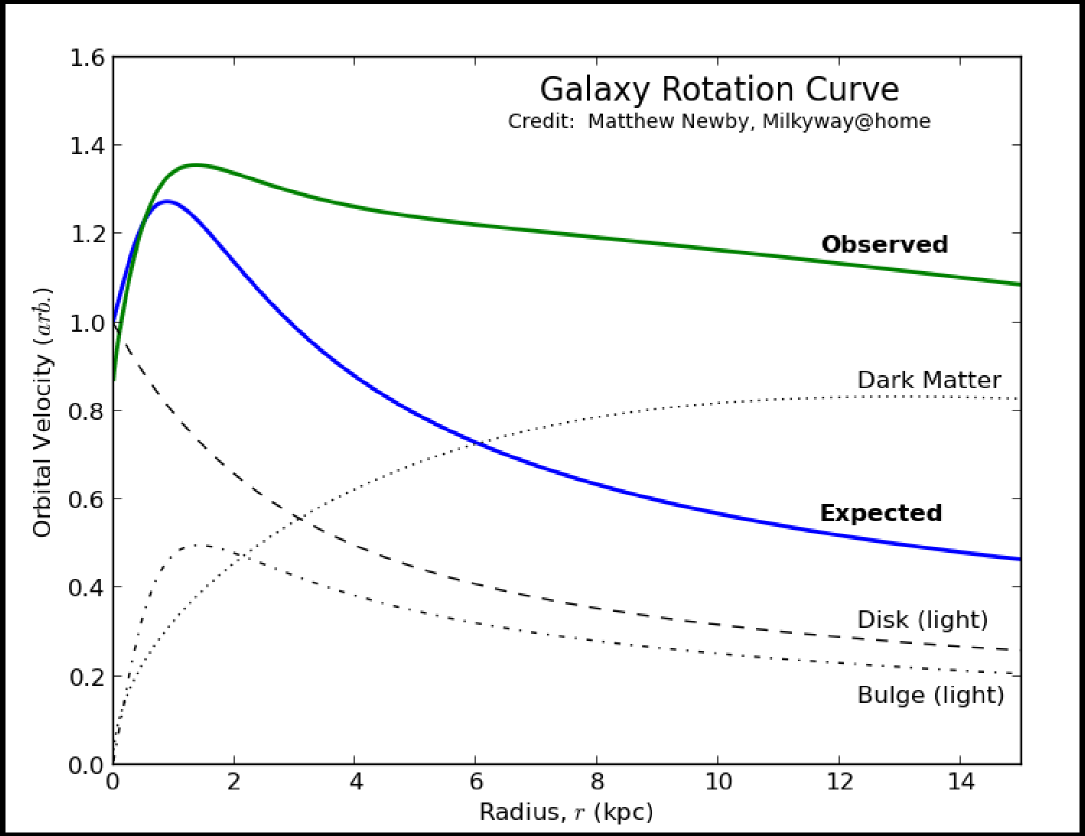
Galaxy rotation curve:

$$v_{star}(R) = \sqrt{\frac{G M_{galaxy}\,(R)}{R}}$$

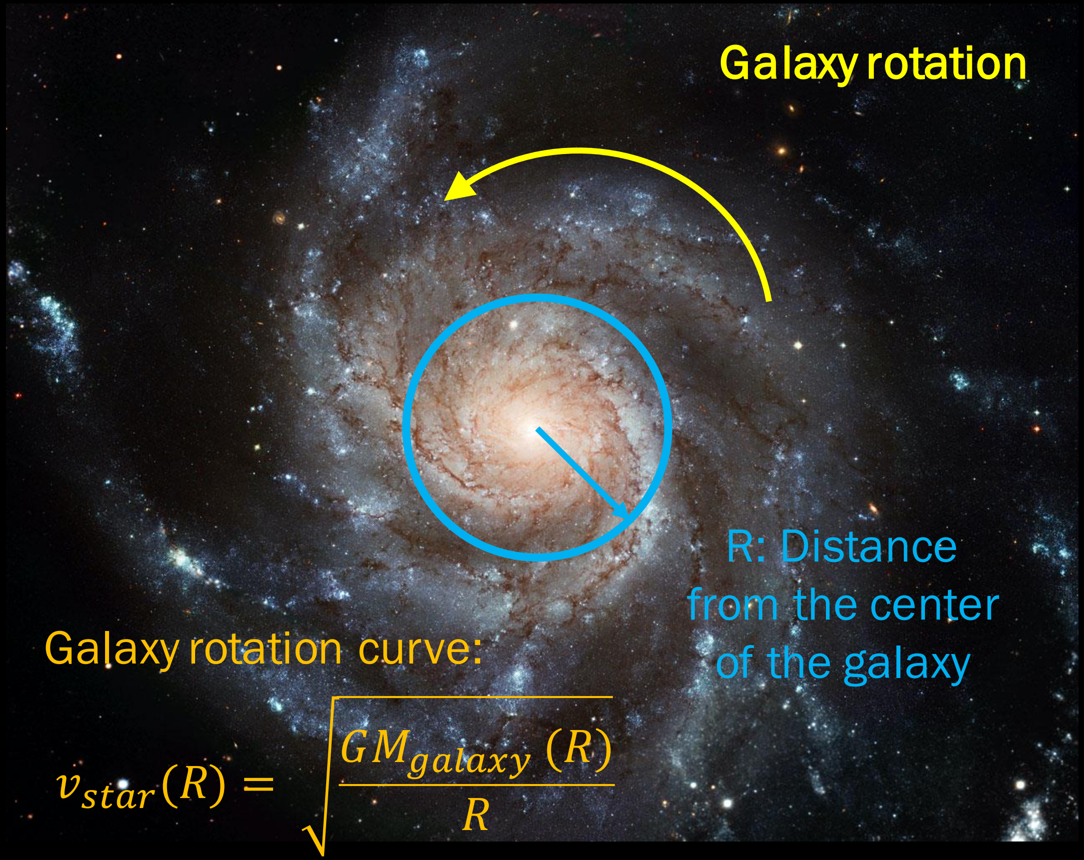


European Space Agency & NASA

Galaxy rotation curves and the dark matter hypothesis



Matthew Newby/Milkyway@home



European Space Agency & NASA

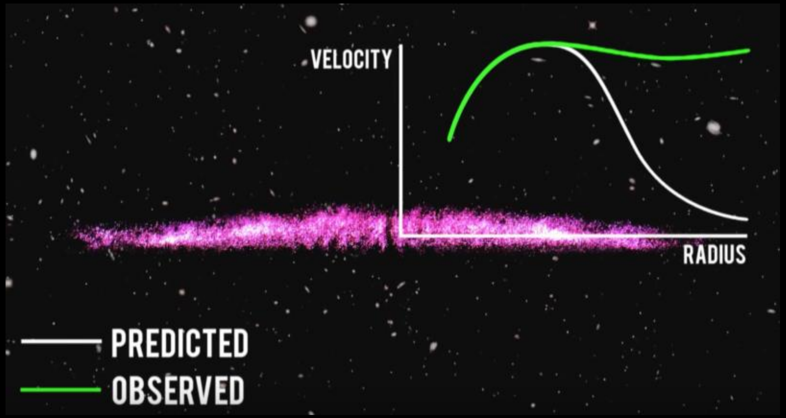
Galaxy rotation curves and the dark matter hypothesis

Two options:

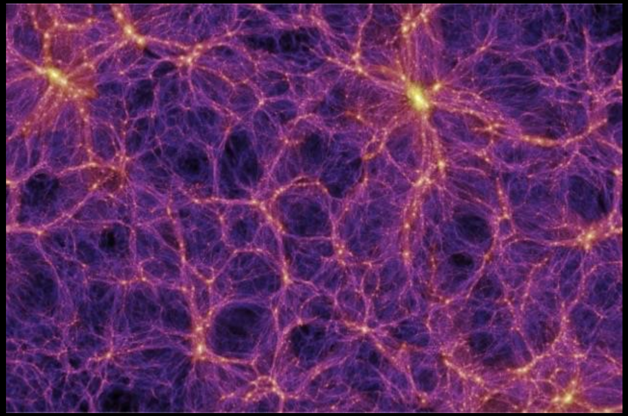
- Laws of circular motion and/or gravity are wrong.
- There must be some unknown mass that we cannot see: dark matter!

Do we have any other evidence for dark matter besides astronomical observations?

NO, we don't. The dark matter hypothesis is still unproven.



Galaxy rotation curves



Universe large scale structure

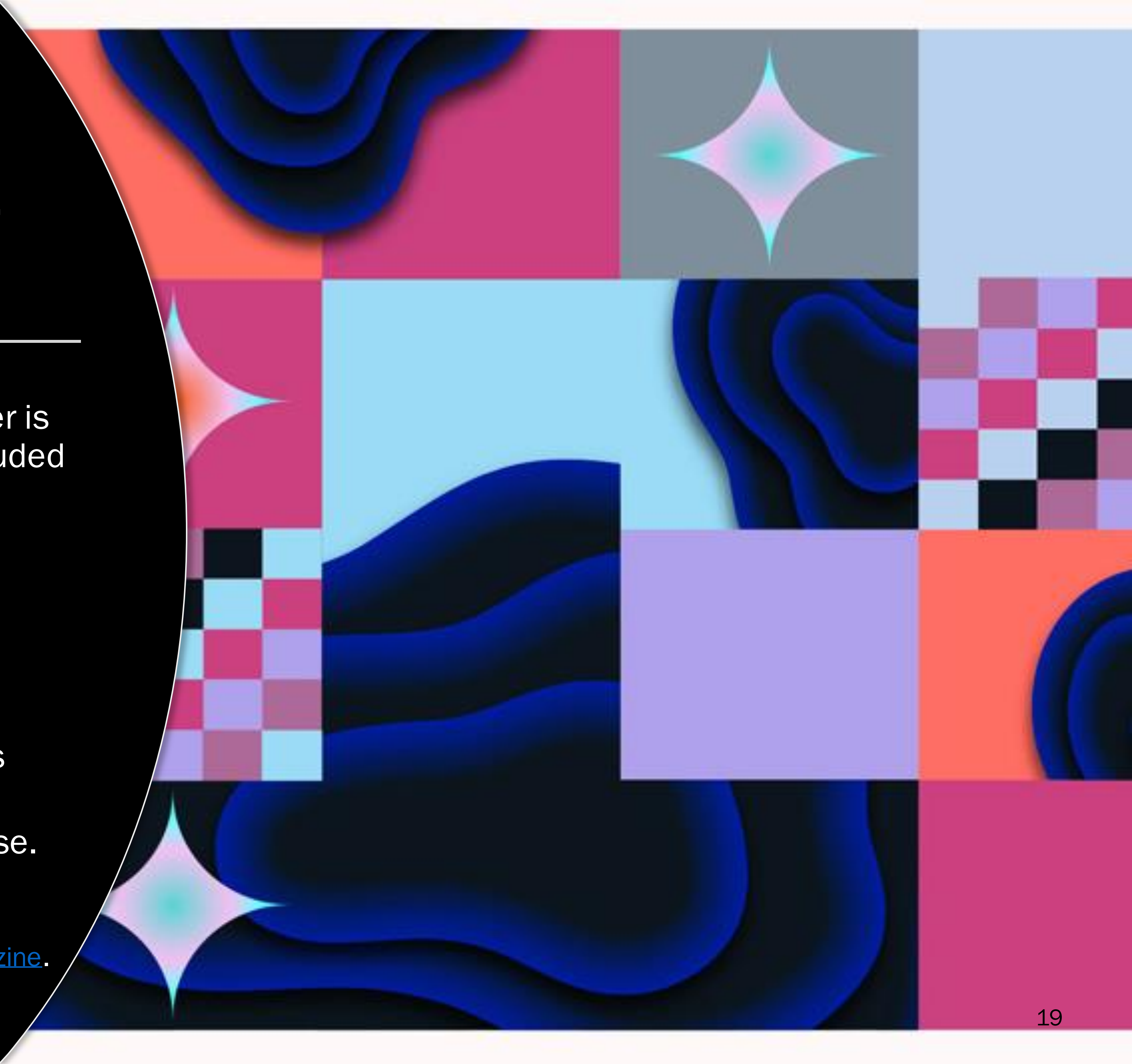
Galaxy cluster dynamics

What do we know about dark matter?

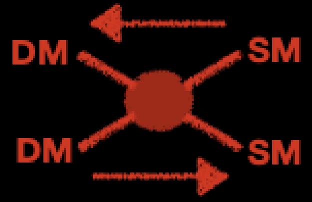
- As particle physicists, we believe dark matter is composed of a new kind of particle not included in the standard model.

- We do know that it is:
  - stable,
  - doesn’t interact through light,
  - main interaction with ordinary matter is through gravity,
  - determined the evolution of the Universe.

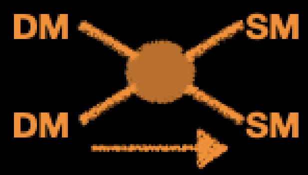
[What do we know about dark matter? Symmetry Magazine](#).



Evolution of the Universe



DM – SM and SM - DM annihilation

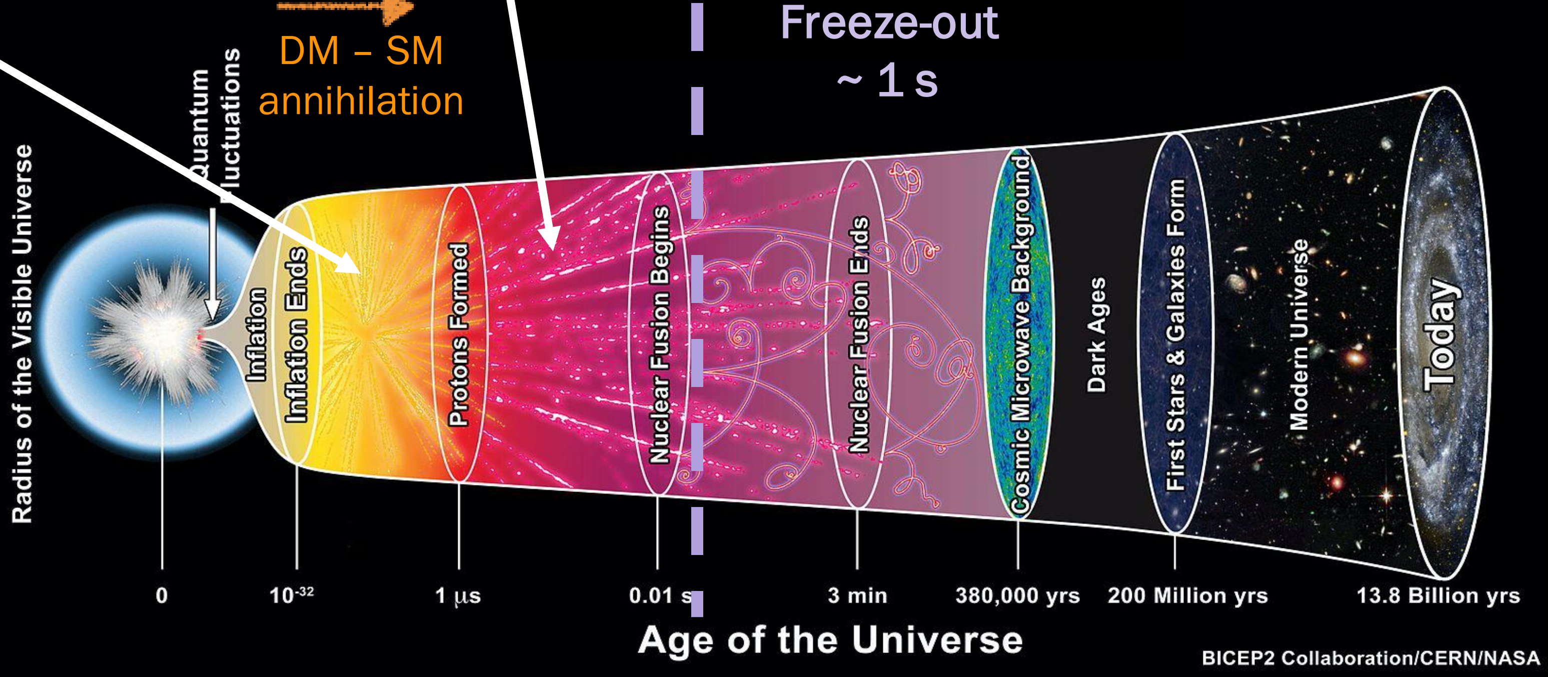


DM – SM annihilation

Freeze-out
~ 1 s

How can we experimentally detect and study dark matter?

Dark matter interacted with ordinary matter other than gravitationally



Dark matter interacts with ordinary matter mostly gravitationally

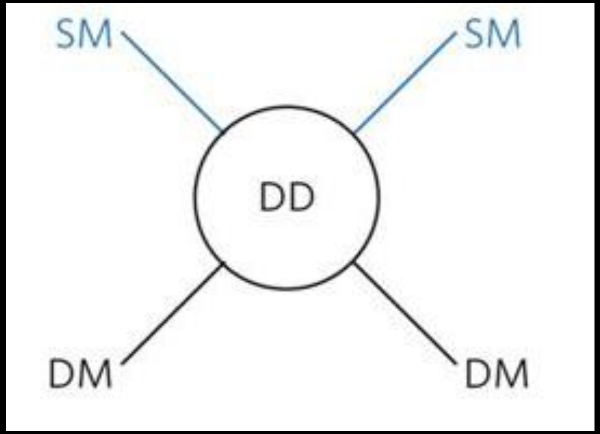
Small | Size | Large

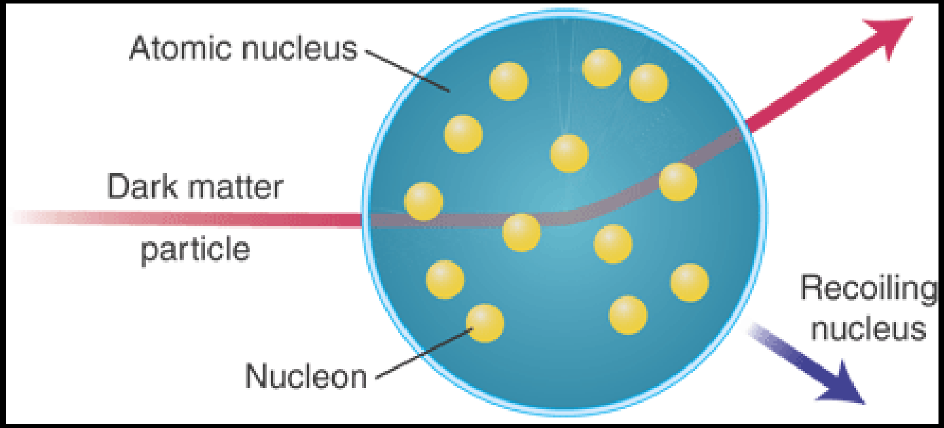
Hot | Temperature | Cold

How can we detect dark matter?

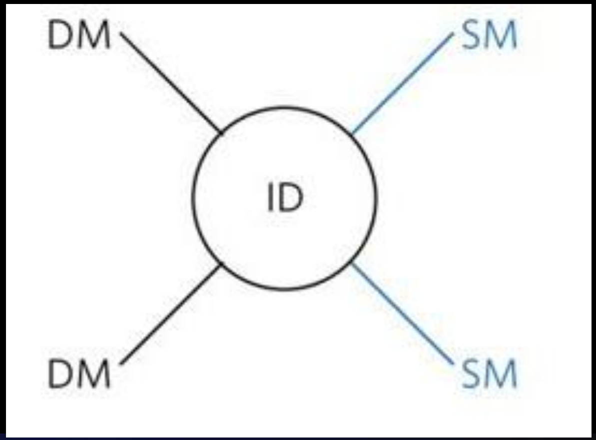
- Directly in underground experiments.

Underground water tank where LUX-ZEPLIN will eventually sit. (Image: © LBL)



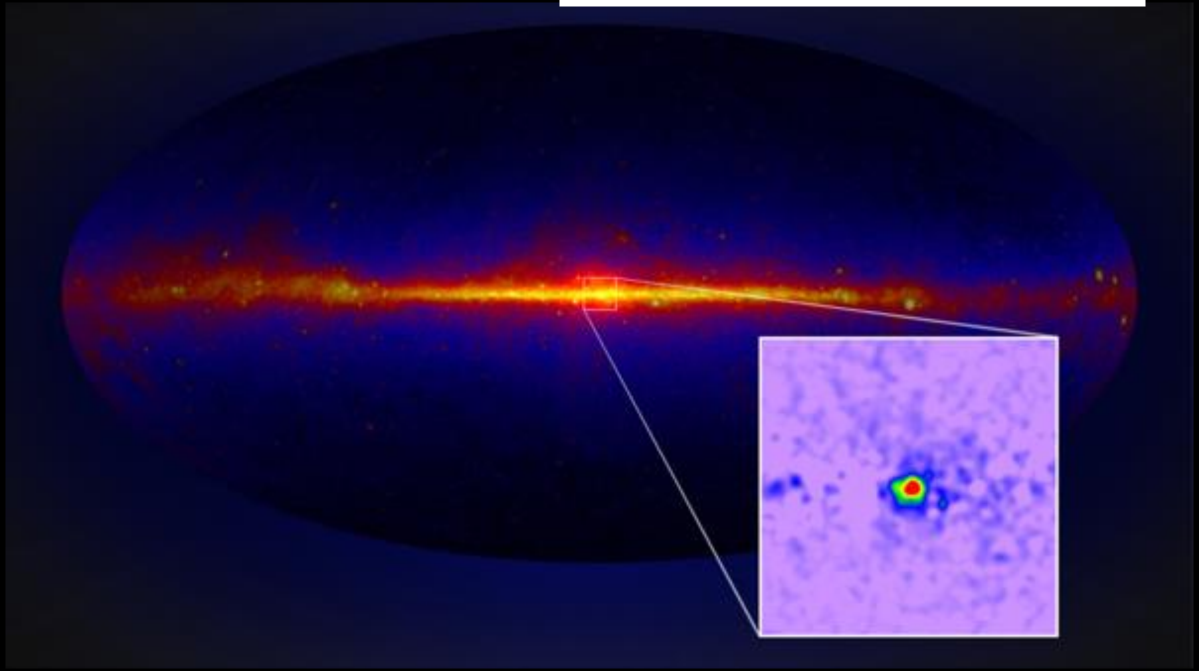


How can we detect dark matter?



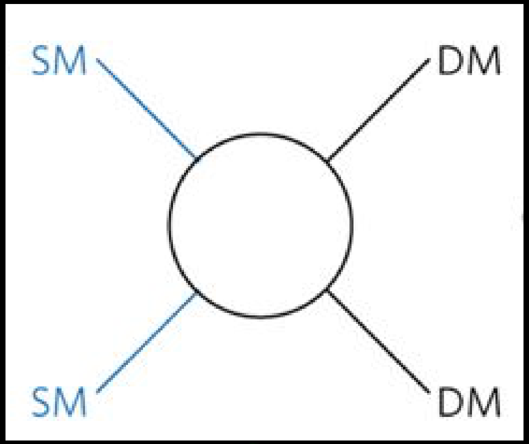
- Indirectly with satellites that probe the heavens.

Fermi Gamma Ray Space (Large Area) Telescope/NASA

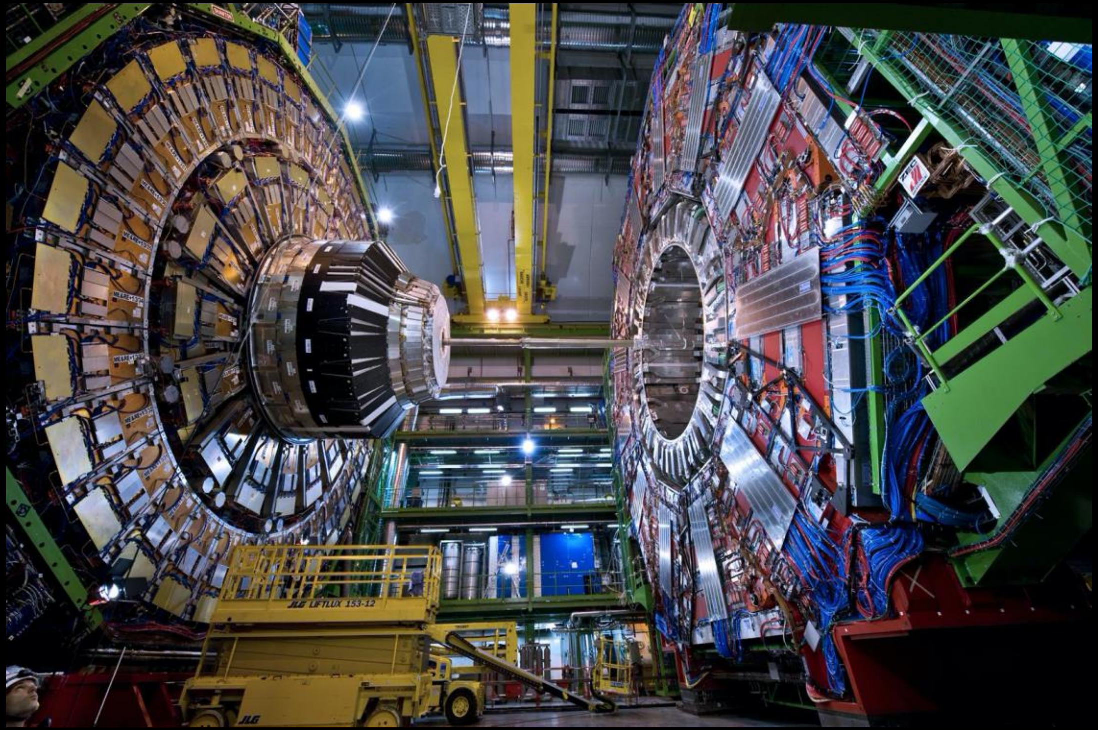


Fermi-LAT gamma-ray excess map showing the apparent energy excess surrounding the Galactic Center./NASA

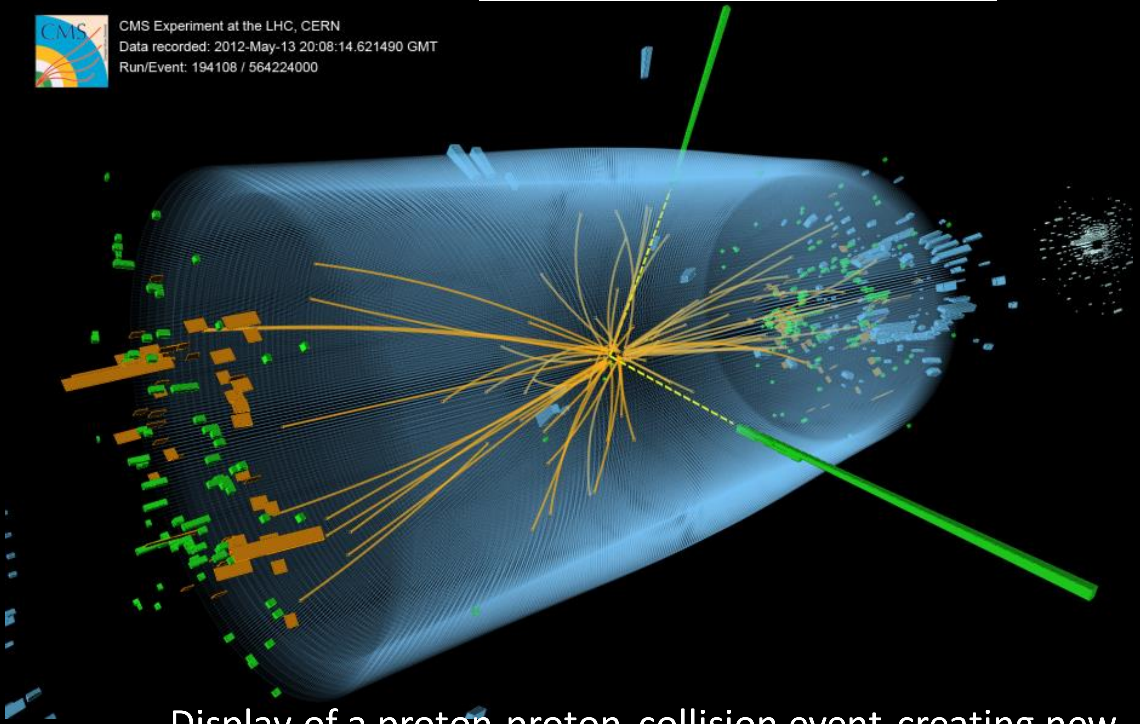
How can we detect dark matter?



- Creating it at particle colliders.



CMS detector at the Large Hadron Collider/CERN.

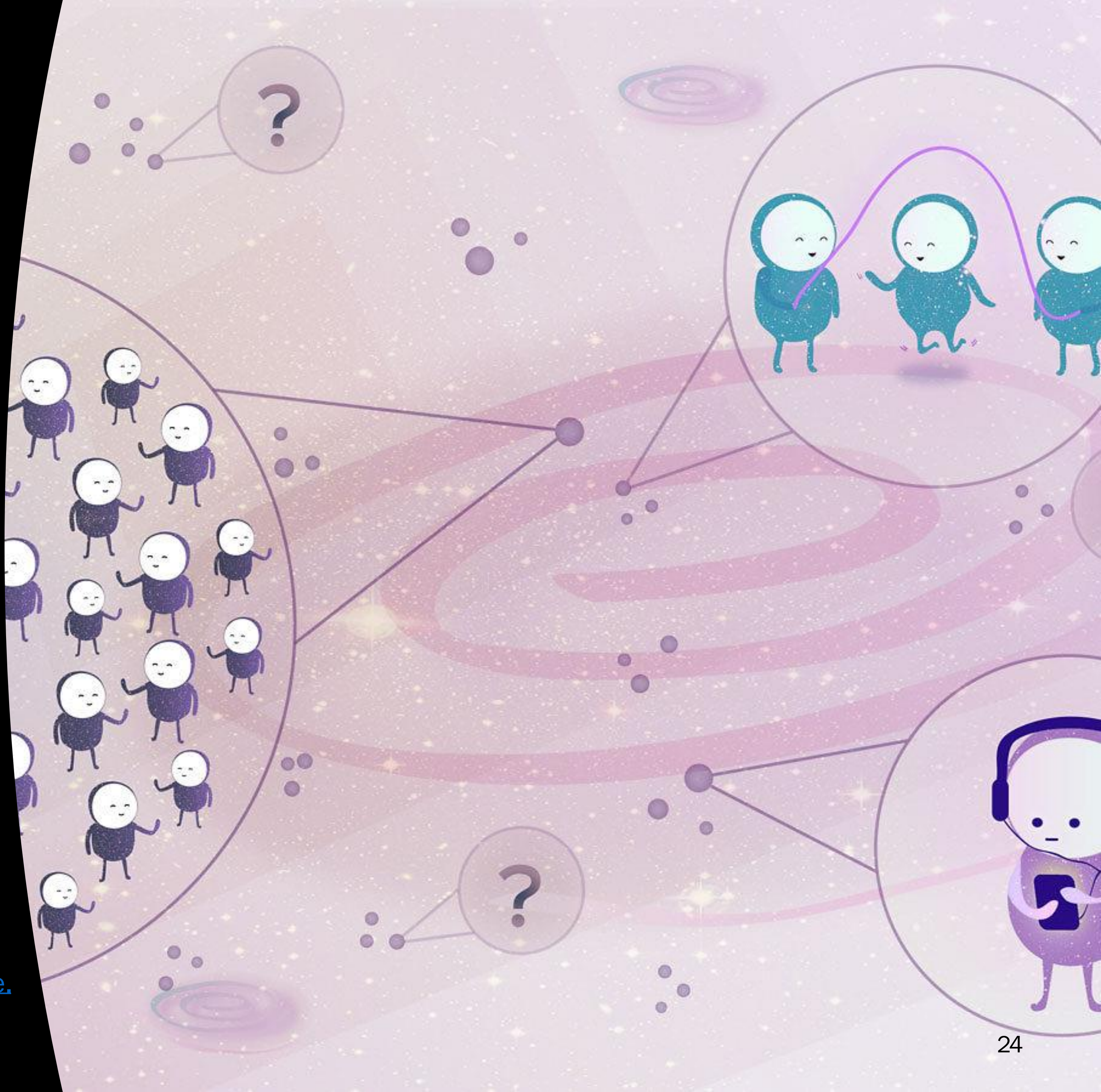


Display of a proton-proton collision event creating new particles. CMS/CERN.

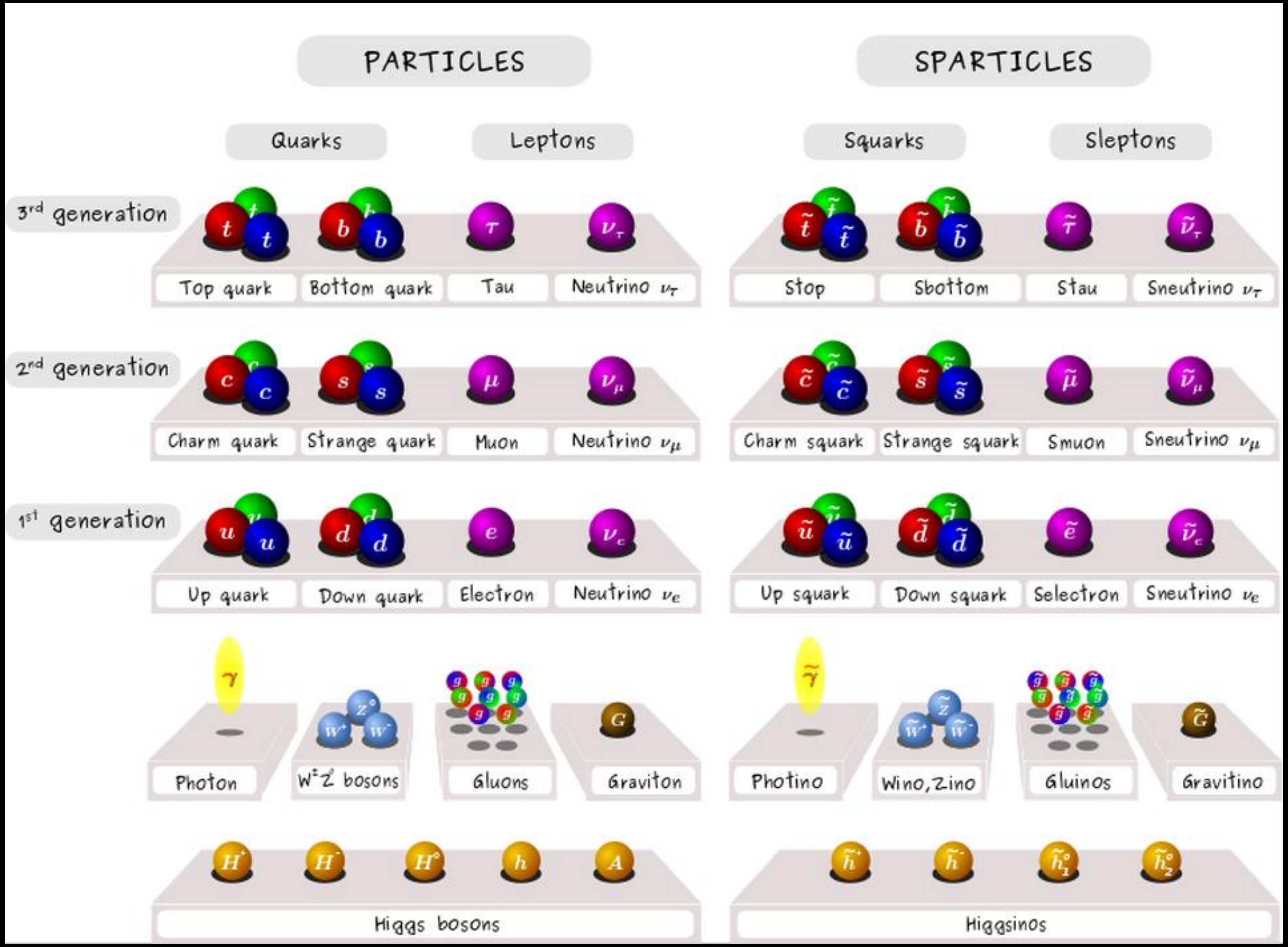
What could dark matter be?

- Main characteristics of a dark matter candidate:
  - Stable
  - Massive, heavier than any SM particle.
  - Electrically neutral.
  - It might be weakly interacting (weak interaction).
- Several candidates, some of them arose out of attempts to solve other problems in physics:
  - Neutralinos,
  - Sterile neutrinos,
  - Axions, etc.

[What could dark matter be? Symmetry magazine.]



Supersymmetry and dark matter

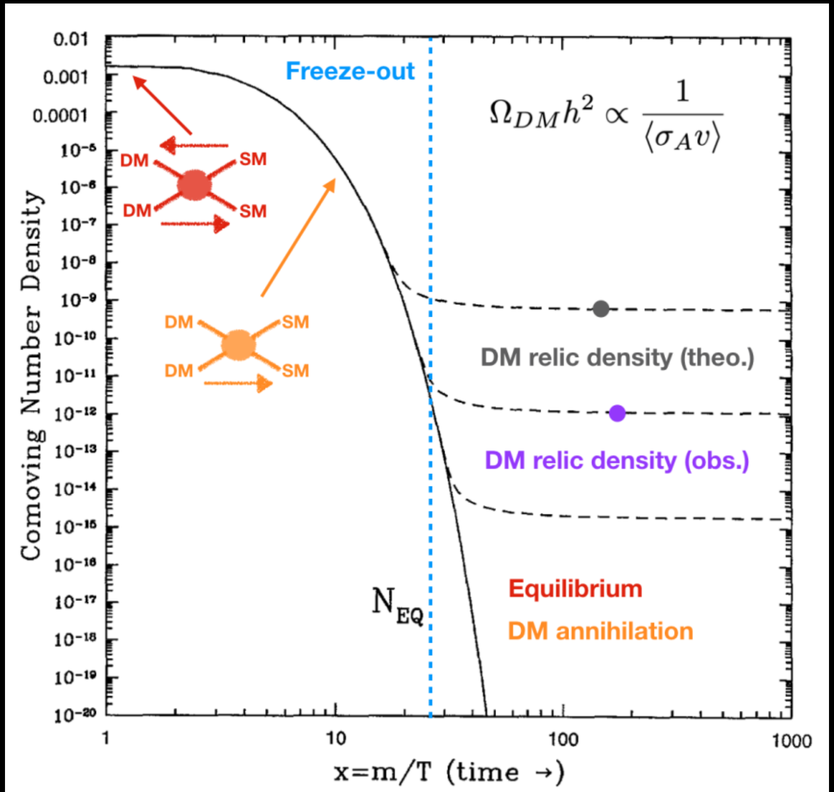


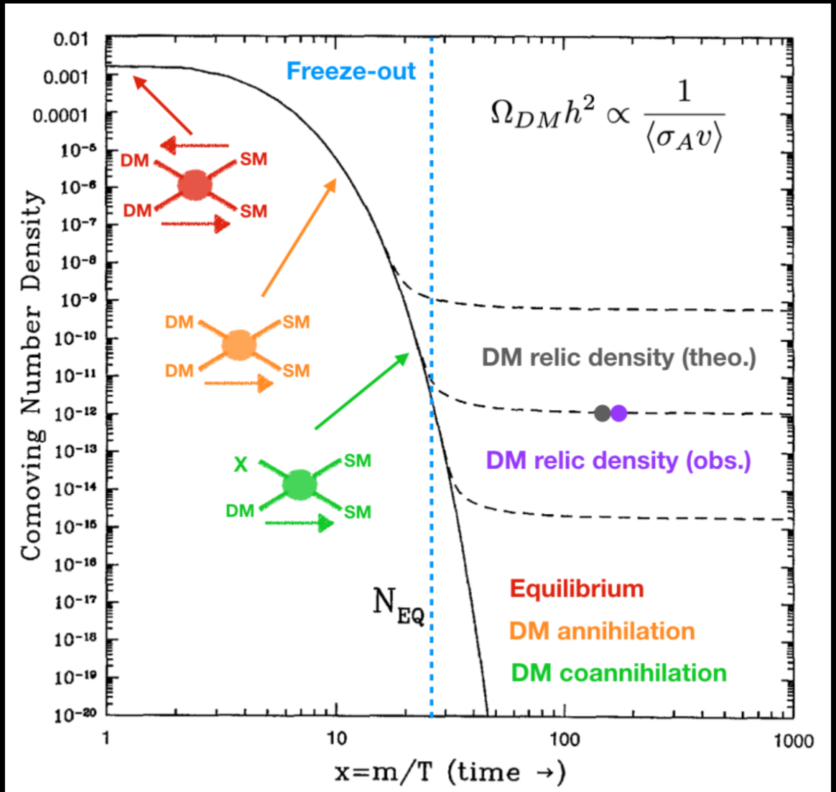
Claire David/CERN.

- In nature, exact supersymmetry does not exist.
- Neutralinos are a combination of the superpartners of the photon, Z and Higgs bosons of the SM.
- We get 4 neutralinos which are neutral, massive and weakly interacting.
- The lightest of them is the dark matter candidate.

Supersymmetry and dark matter

- To predict the right amount of dark matter relic density, the lightest neutralino needs to be close in mass with the next lightest particle (stau) and other neutralinos for coannihilation to be relevant.





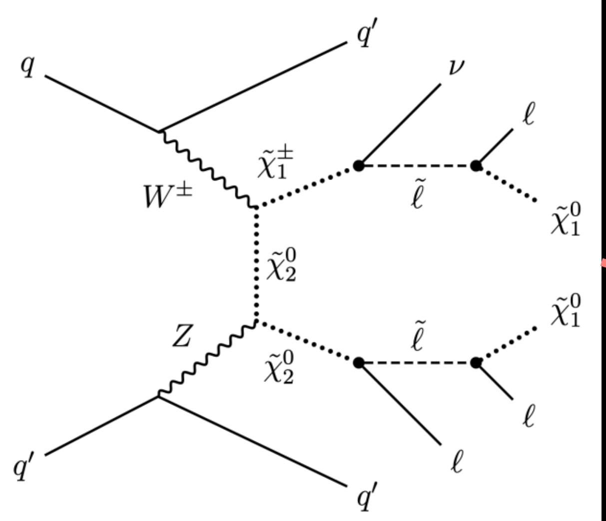
Comoving number density of a WIMP in the early Universe. Adapted from [arXiv:hep-ph/9506380](https://arxiv.org/abs/hep-ph/9506380).

Producing neutralinos in pp collisions

Quarks from colliding protons

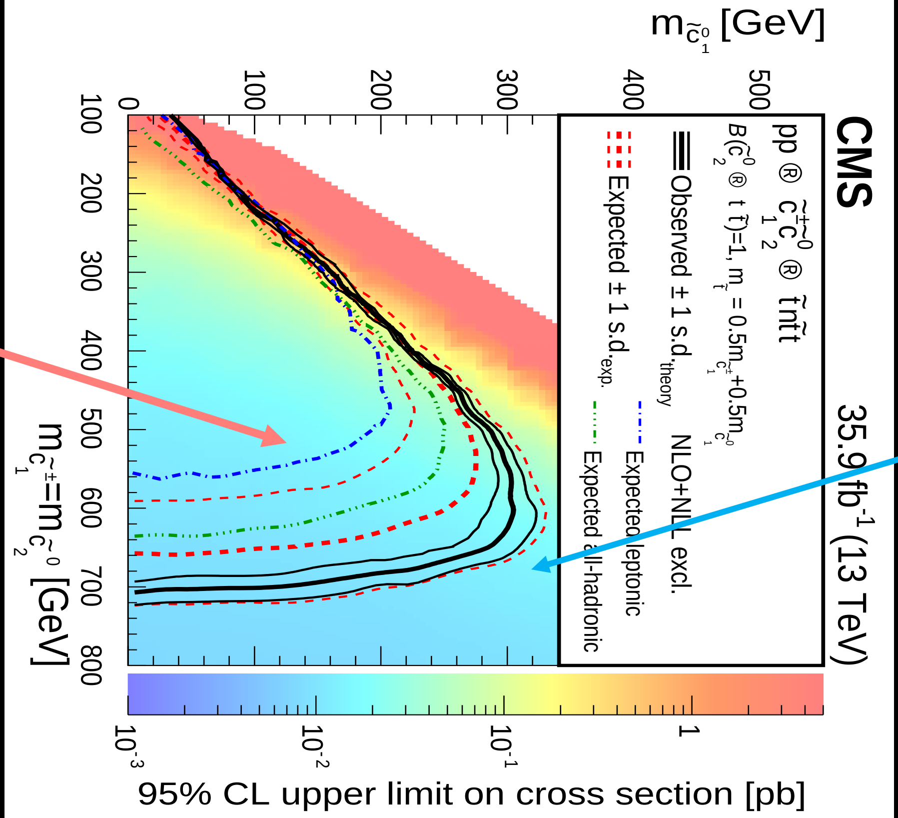
Weak bosons

Neutralino dark matter



CMS-SUS-17-007

Feynman diagram of electroweak “vector boson fusion” (VBF) neutralino production

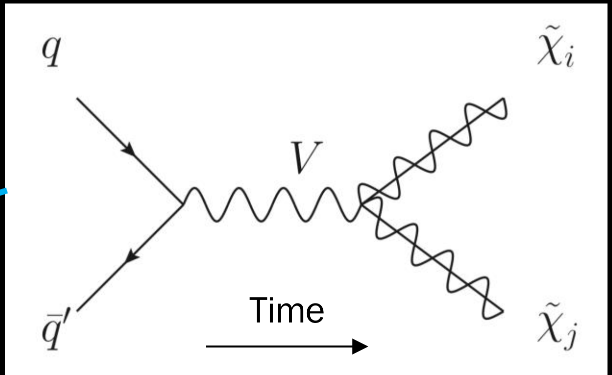


CMS-SUS-17-003

Quarks from colliding protons

Weak bosons

Neutralinos

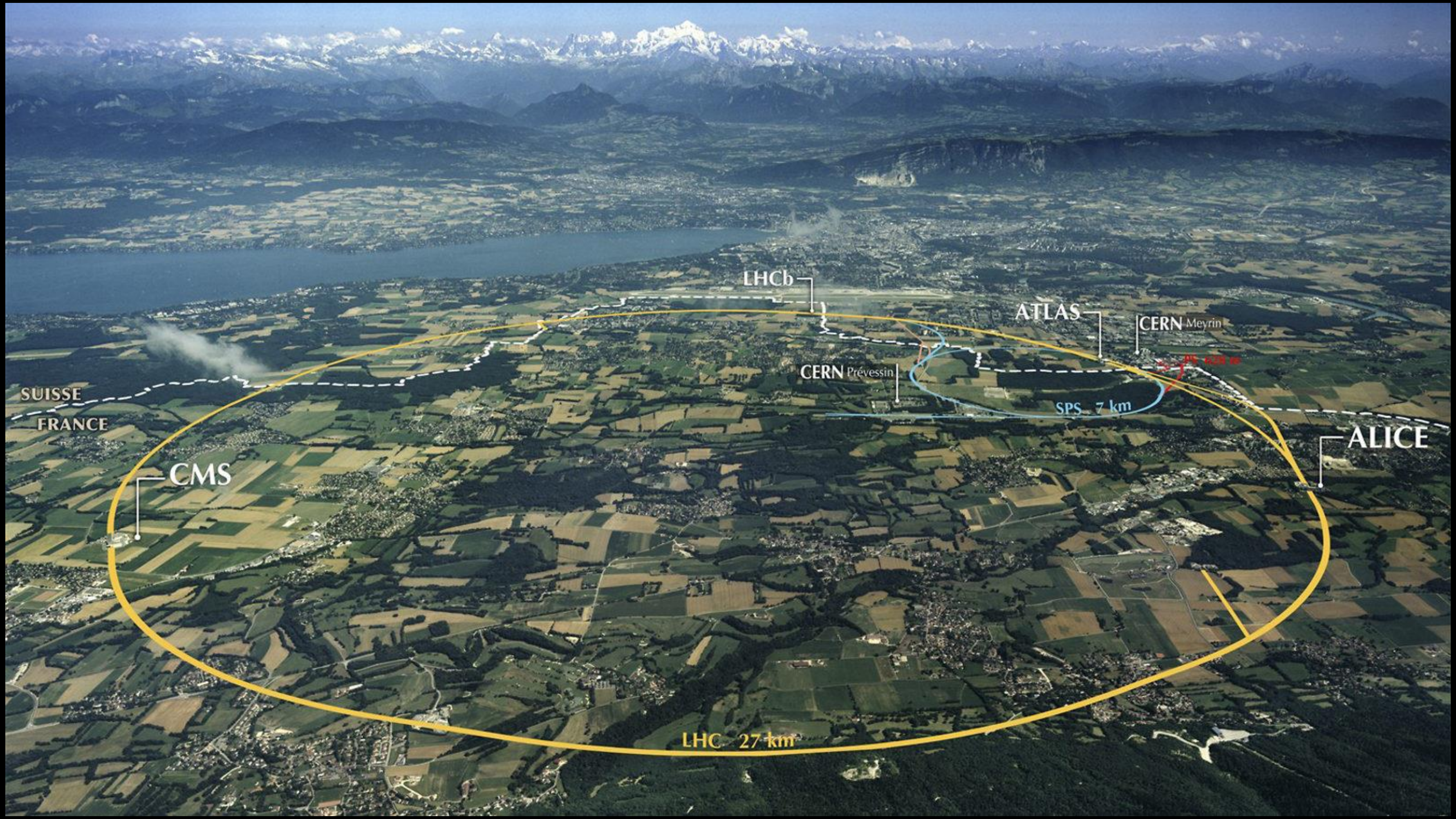


arXiv:1605.06509

Feynman diagram of "Drell-Yan” neutralino production

The Large Hadron Collider (LHC)

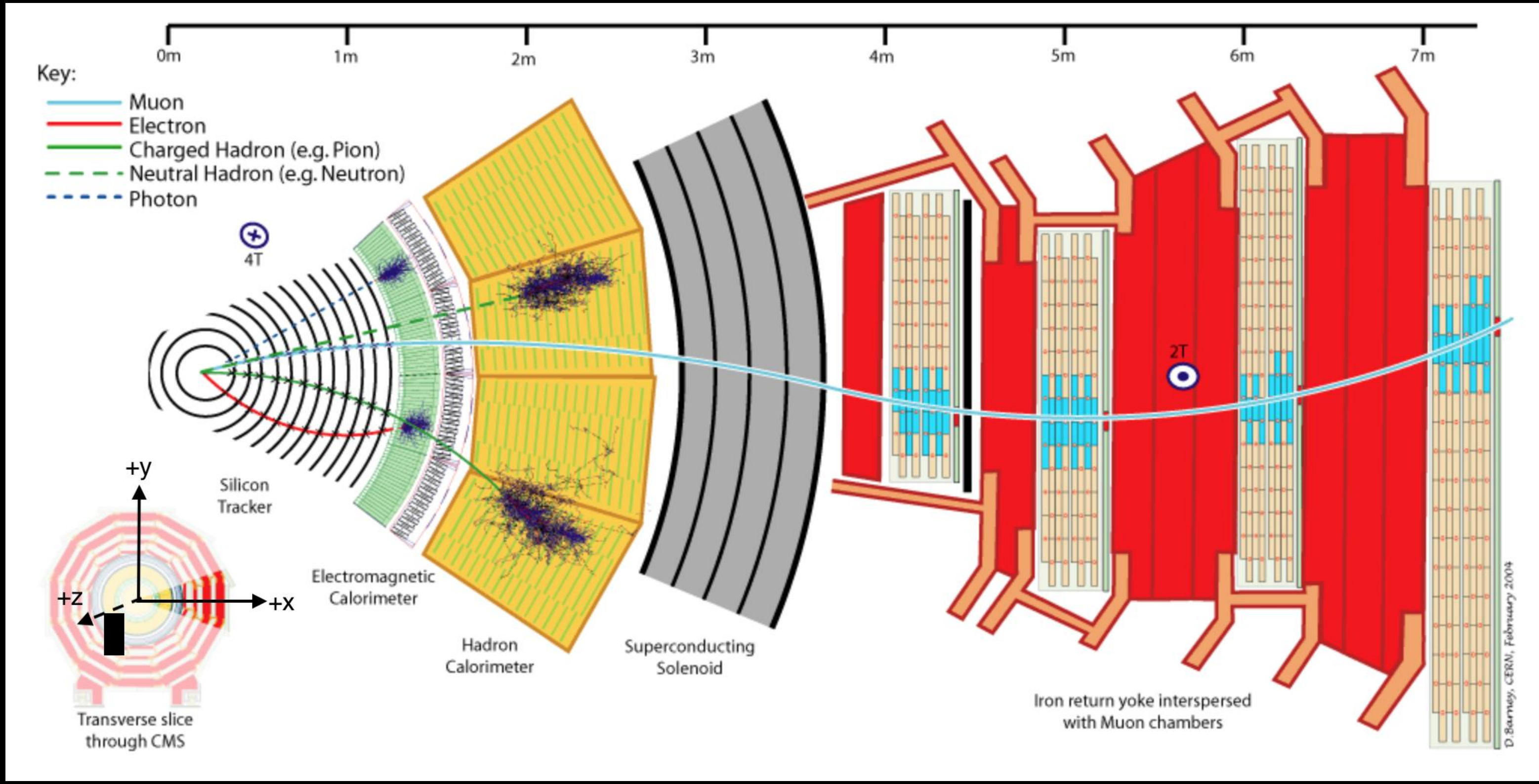
Large Hadron Collider (LHC): Two-ring superconducting hadron collider installed in the 26.7 km tunnel constructed for the Large Electron-Positron (LEP) collider at CERN.



Maximilien Brice, CERN.

Detecting particles at CMS

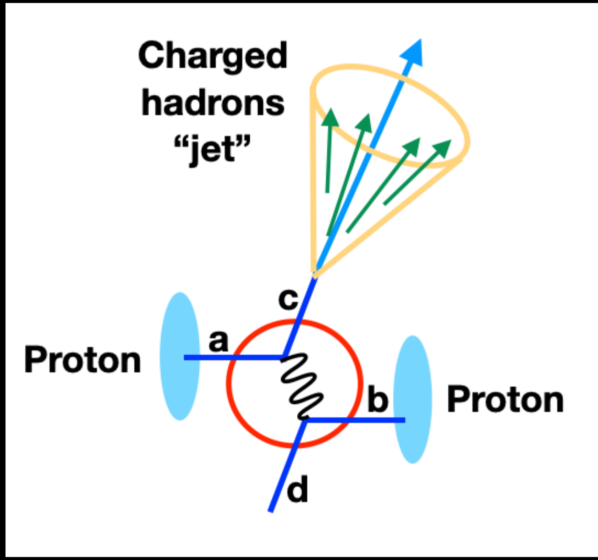
Compact Muon Solenoid (CMS): General purpose detector that hosts a 3.8 T superconducting solenoid. It consists of four main systems: tracking, electromagnetic and hadronic calorimeters and a muon system.

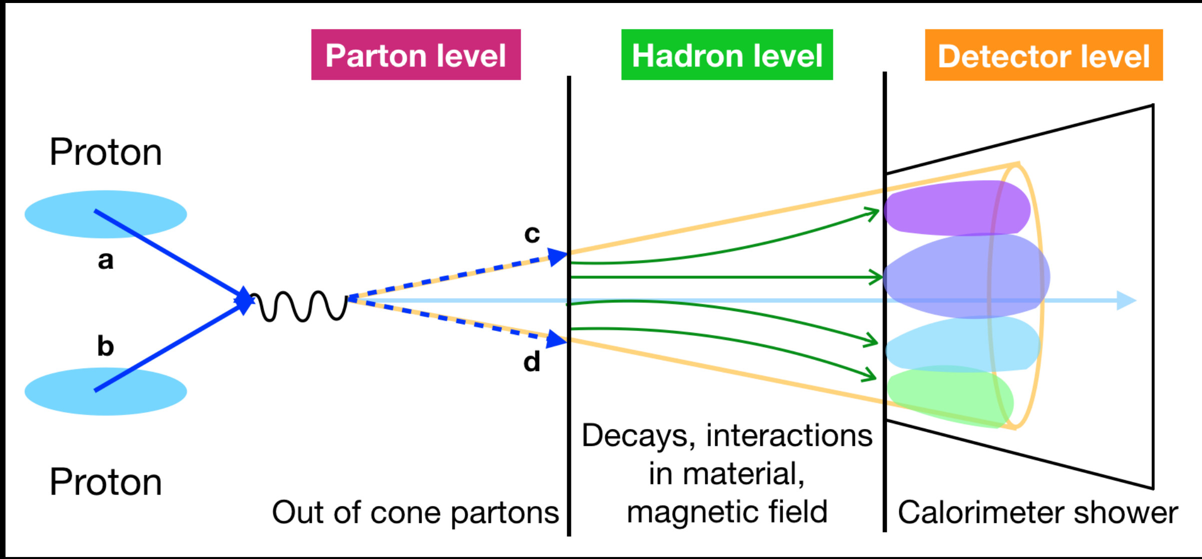


Transversal view of a CMS slice with all the subsystems labeled. CMS/CERN.

What is a jet?

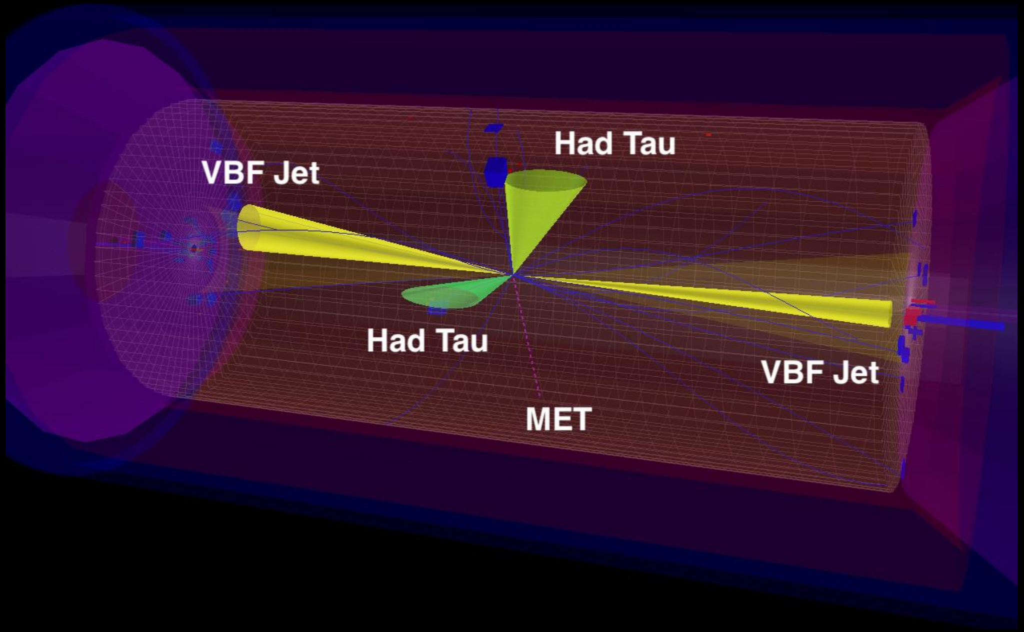
- Jets are experimental signatures of quarks and gluons and a predominant feature of energetic hadron collisions.
- In simple terms, we can think of a jet as a spray of hadrons that travel in the direction of the quark or gluon that originated it.





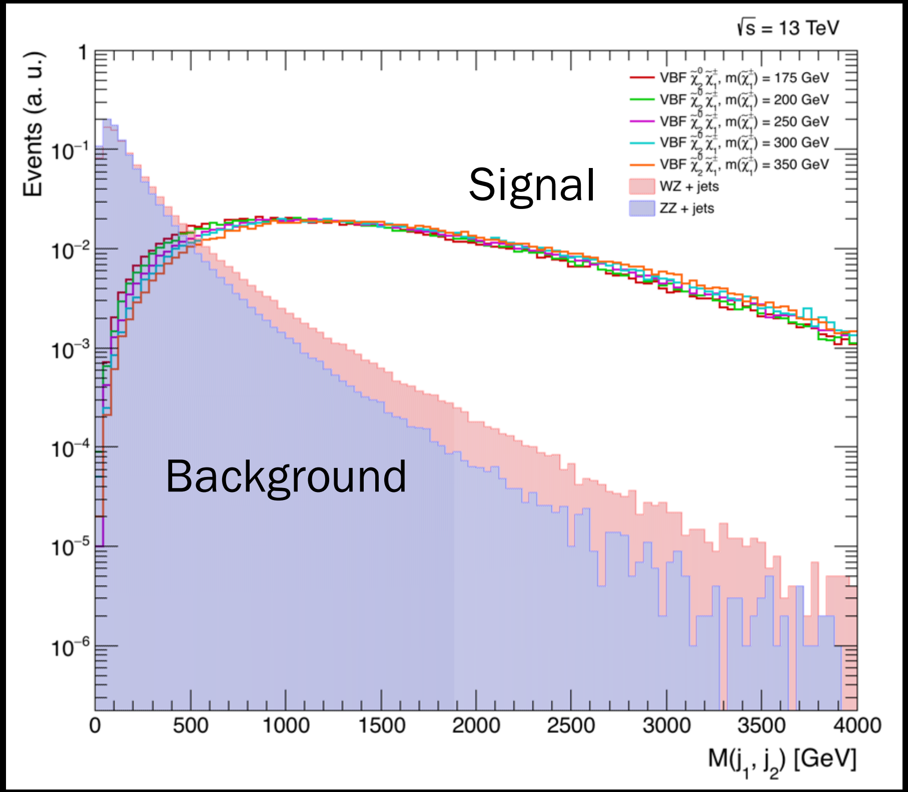
How does a neutralino look like?

In the detector



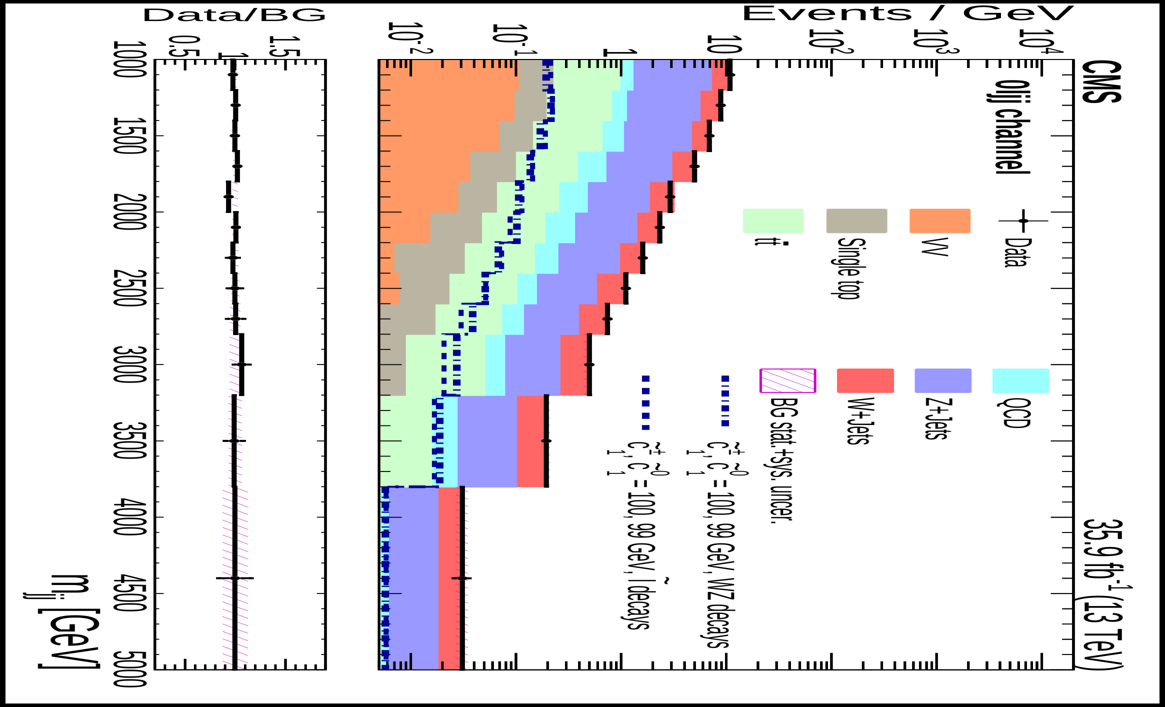
Event display of the production of neutralino dark matter in the CMS experiment via VBF.

In data analysis

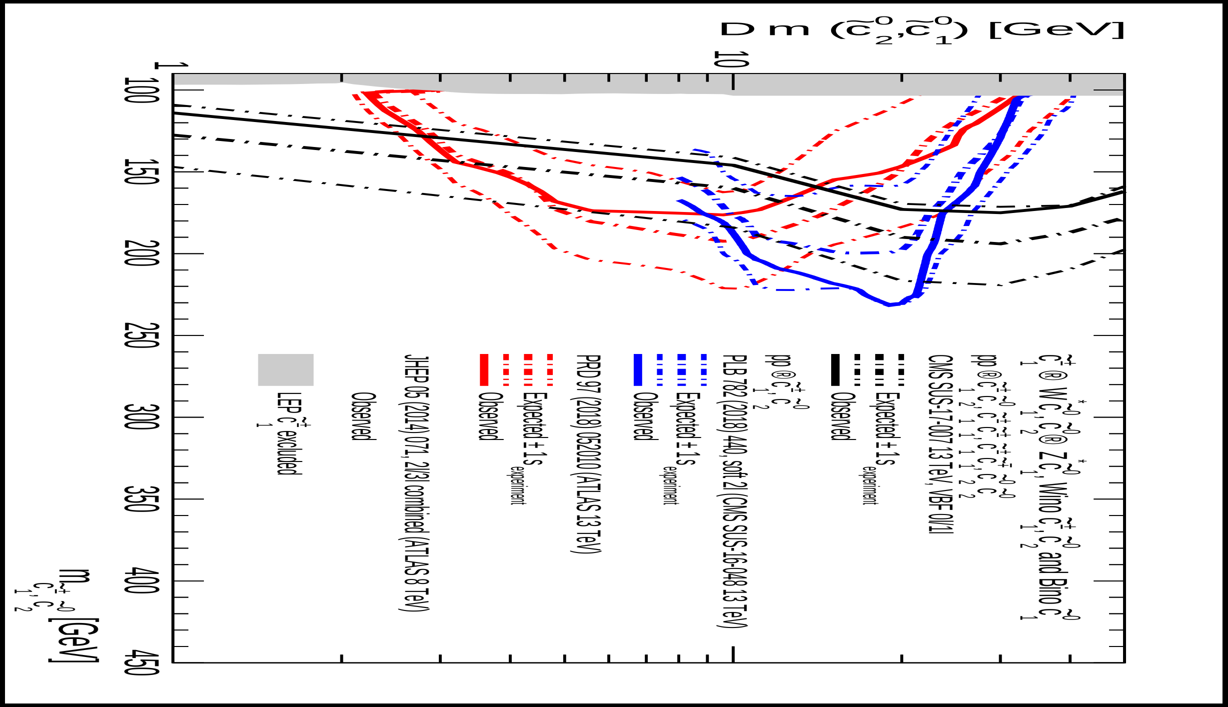


Invariant mass of the VBF dijet pair for signal (lines) and other SM processes (filled histograms) before any event selections.

Recent results of VBF SUSY searches at CMS



Observed mjj distribution for a 0-lepton VBF signal region where the expected signal distribution is overlaid.
[CMS-SUS-17-007]

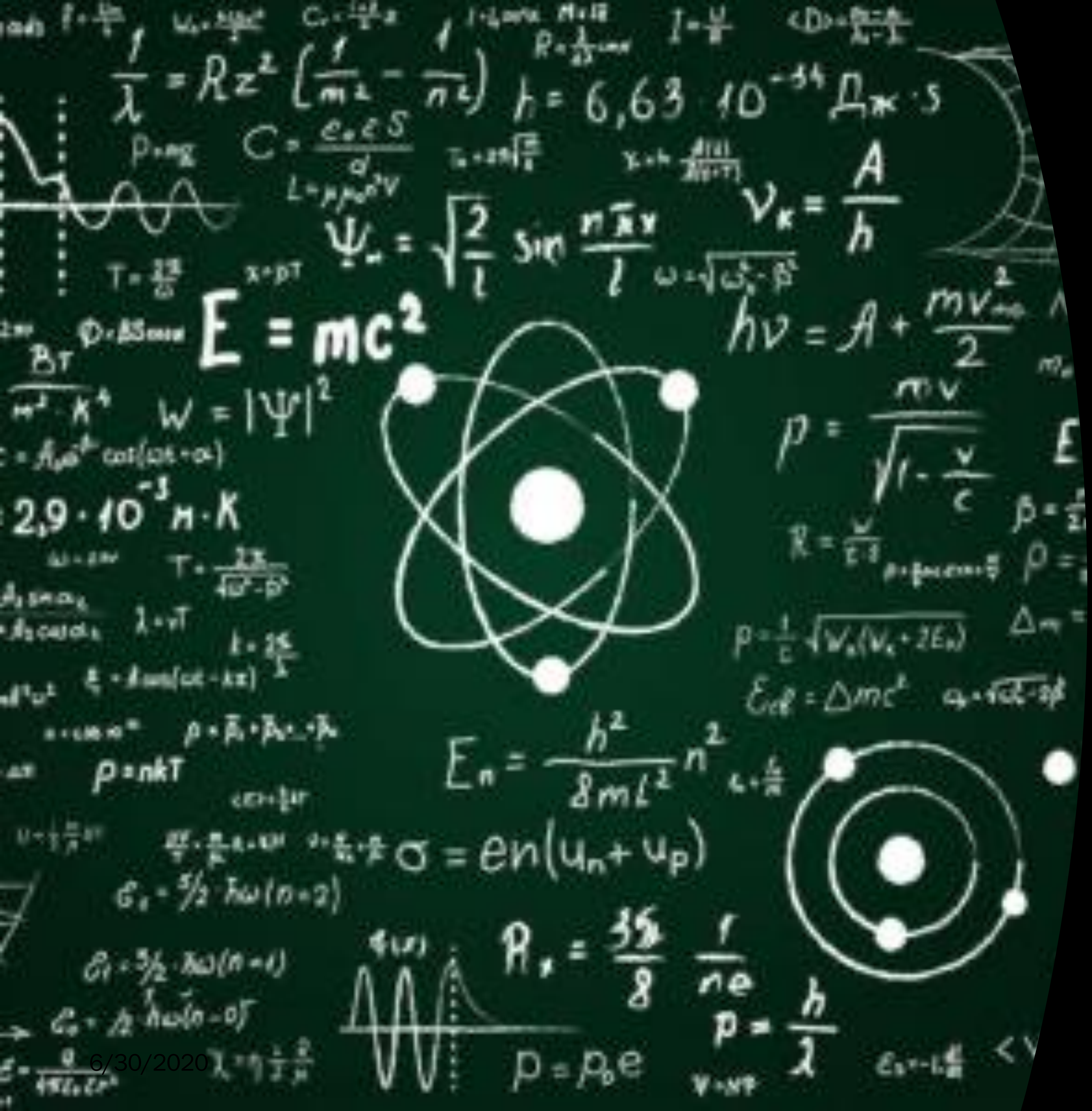


Summary of exclusion limits for chargino and neutralino searches at the LHC and LEP.

Conclusions

- The Standard Model describes the fundamental components of matter and their interactions through the electromagnetic, strong and weak forces.
- The SM does not explain everything, for example, the nature of dark matter.
- The search for dark matter creates an important link between particle physics and cosmology.
- One way to detect dark matter is by creating it in particle collisions.
- There are many models that describe the nature of dark matter but no one has been successful yet.
- New experimental techniques like VBF are needed to explore possibilities which haven't been accessible before.

My experience becoming a particle physicist



Links and resources for high school teachers and students

- Symmetry Magazine, FNAL: https://www.symmetrymagazine.org
- The Particle Adventure: https://particleadventure.org
- Quarked! University of Kansas: http://www.quarked.org
- Contemporary Physics Project: https://www.cpepphysics.org
- Videos by Don Lincoln (YouTube): https://www.youtube.com/playlist?list=PLCfRa7MXBEsoJuAM8s6D8oKDPyBepBosS
- Physics Girl (YouTube): https://www.youtube.com/user/physicswoman
- Ted-Ed Physics (YouTube): https://www.youtube.com/watch?v=7SWvDHvWXok&list=PLhDvDID3b85zmvERO_rSSUj3FVWScEA_X

Backup slides

Why “high energy physics”?

To study the most fundamental components of visible matter and their interactions, we need to accelerate particles at very high energies of about thousands of billions of electronvolts (eV) and collide them.