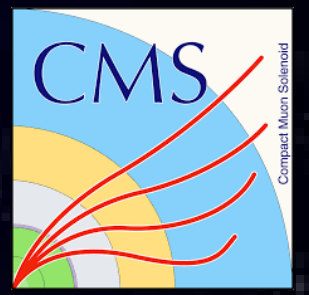
Why I Study Particle Physics

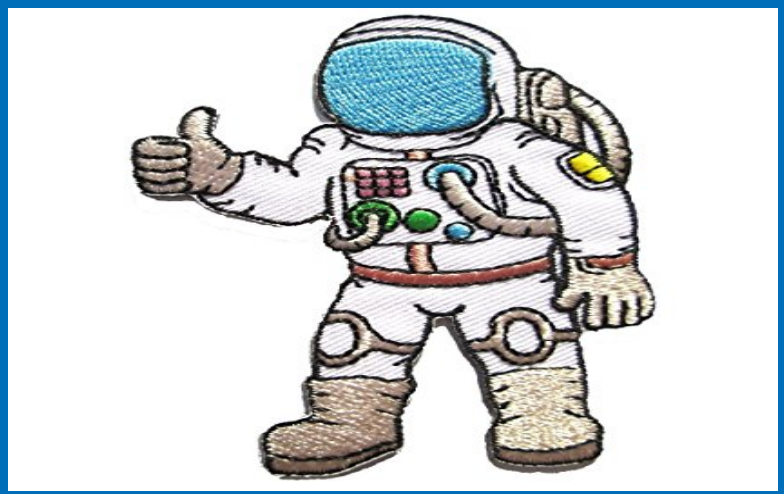
Savanna Rae Starko

June 25, 2018

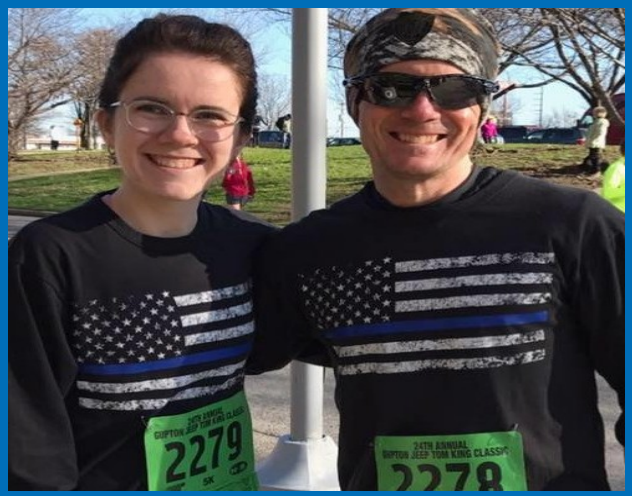
Vanderbilt University



Misconception 1∼"You must have known you wanted to be a physicist from a very early age."



Misconception 2∼ "A passion for science must originate somewhere in your family."

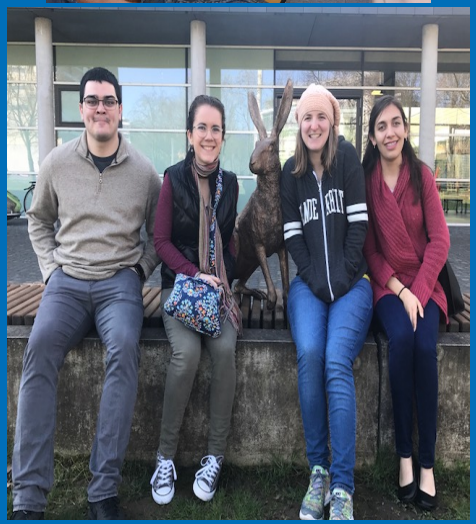


Misconception 3∼"As a scientist, I'm guessing you've followed a logic-driven path through life."

WASHINGTON & JEFFERSON COLLEGE

VANDERBILT

Misconception 4∼ "Physics is a very solitary field."



High Energy Physics at Vanderbilt University

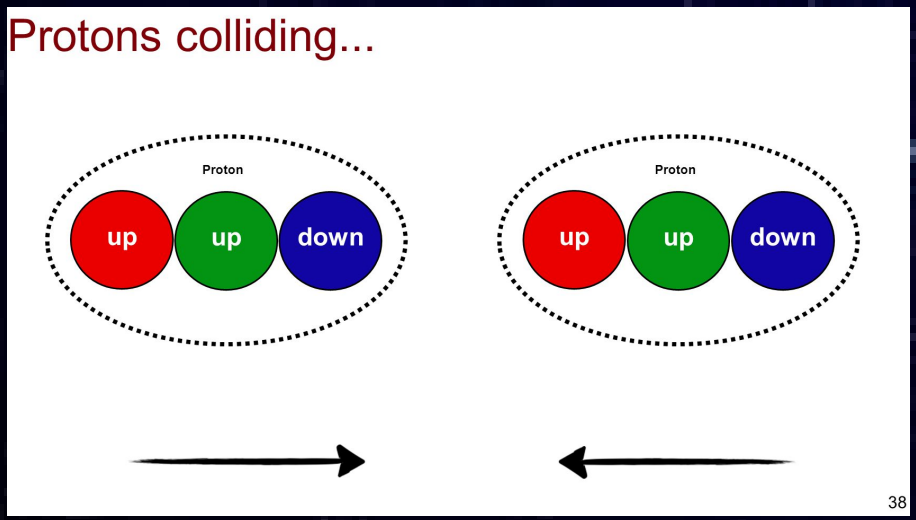
Vanderbilt Johns / Sheldon / Webster
Elementary Particle Physics Group

- Advisor: Dr. Alfredo Gurrola
  - Dark Matter Searches
  - Heavy Neutrino Physics
  - Vector Boson Fusion Studies

The Status of Particle Physics

Particle Physics...

- **...has relied on the Standard Model (SM) for the last several decades to describe particles and their interactions.**
- **...connects microscopic and macroscopic scales.**
- **...addresses questions of societal intrigue (ex. identity of dark matter).**



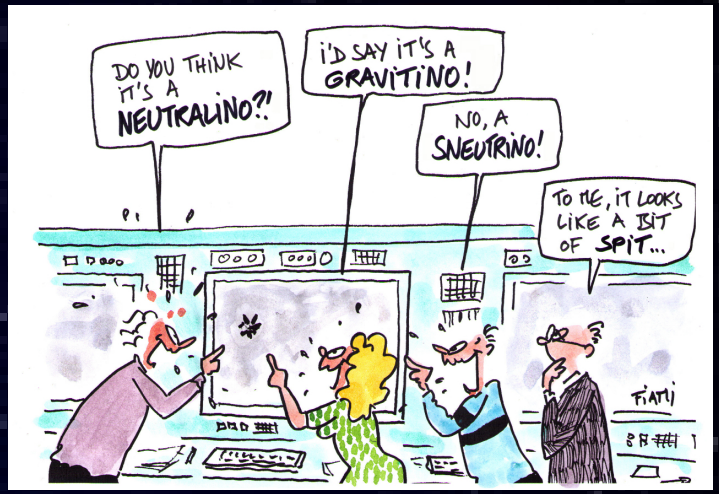
http://slideplayer.com/slide/2720427/

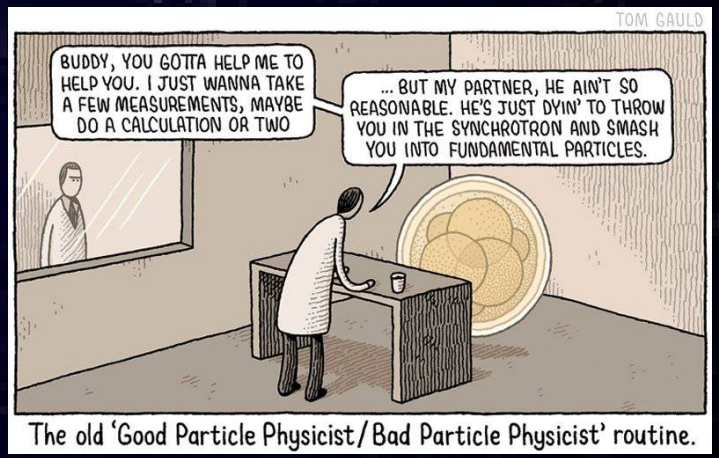
http://bigthink.com/dr-kakus-universe/andromeda-offers-clues-into-the-formation-of-galaxies-including-our-own

The Shortcomings of the SM

The unresolved problems of the SM suggest its incompleteness.

- **failure to provide a dark matter (DM) particle**
- **failure to explain...**
  - **...the matter-antimatter asymmetry in the universe**
  - **...the origins of dark energy**
  - **...the hierarchy problem (i.e. that gravity is so much weaker than the other forces)**

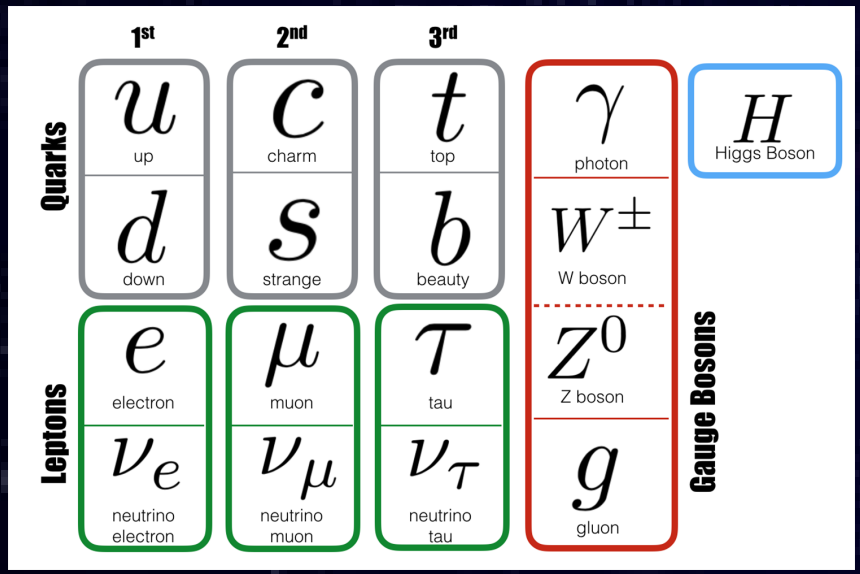




http://cds.cern.ch/record/1261775/files/postillonE_image.jpg

https://www.pinterest.com/pin/436215913894409290/?lp=true

The Standard Model



http://www.physik.uzh.ch/en/researcharea/lhcb/outreach/StandardModel.html

- Four fundamental forces: strong, weak, electromagnetism, gravity
- Fermions: the spin-$\frac{1}{2}$ particles
  - Quarks: electric charge and color charge, electromagnetic force, and strong force
  - Leptons: electric charge (e, μ, τ) and chargeless neutrinos, electromagnetic force, and weak force
- Bosons: the integer-spin particles
  - Gauge Bosons: mediators of particle interactions
  - Higgs: origins of mass

- We look at collisions at energies typical of the early universe in order to attempt to understand particles and interactions.

The Standard Model Lagrangian

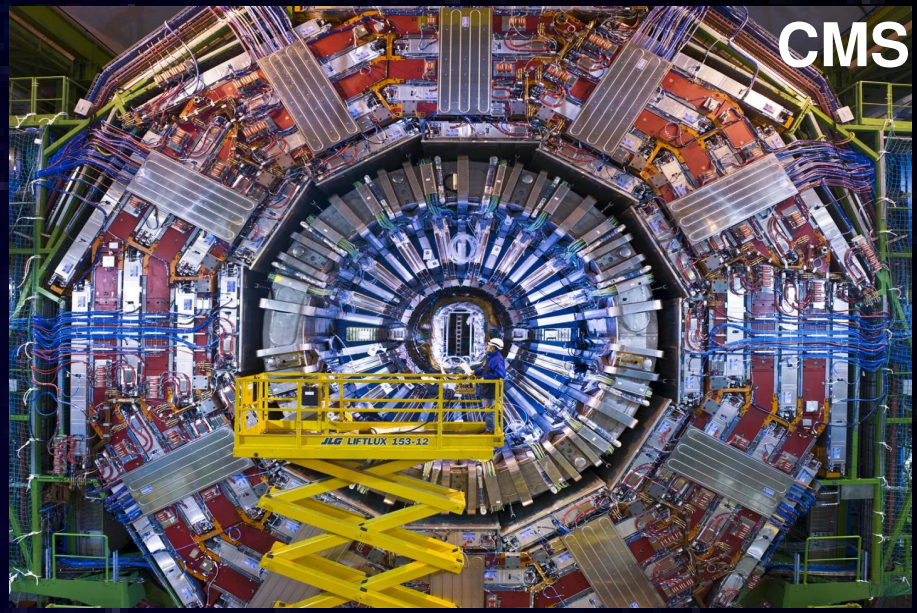
$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

1. the first line of the formula describes the **force carriers**
2. the second line describes **quarks** and **leptons** as well as their interactions
3. the third line describes the **Higgs particle**
4. the last line makes quarks and leptons massive

https://www.modellinginvisible.org/standard-model/

The Large Hadron Collider (LHC)

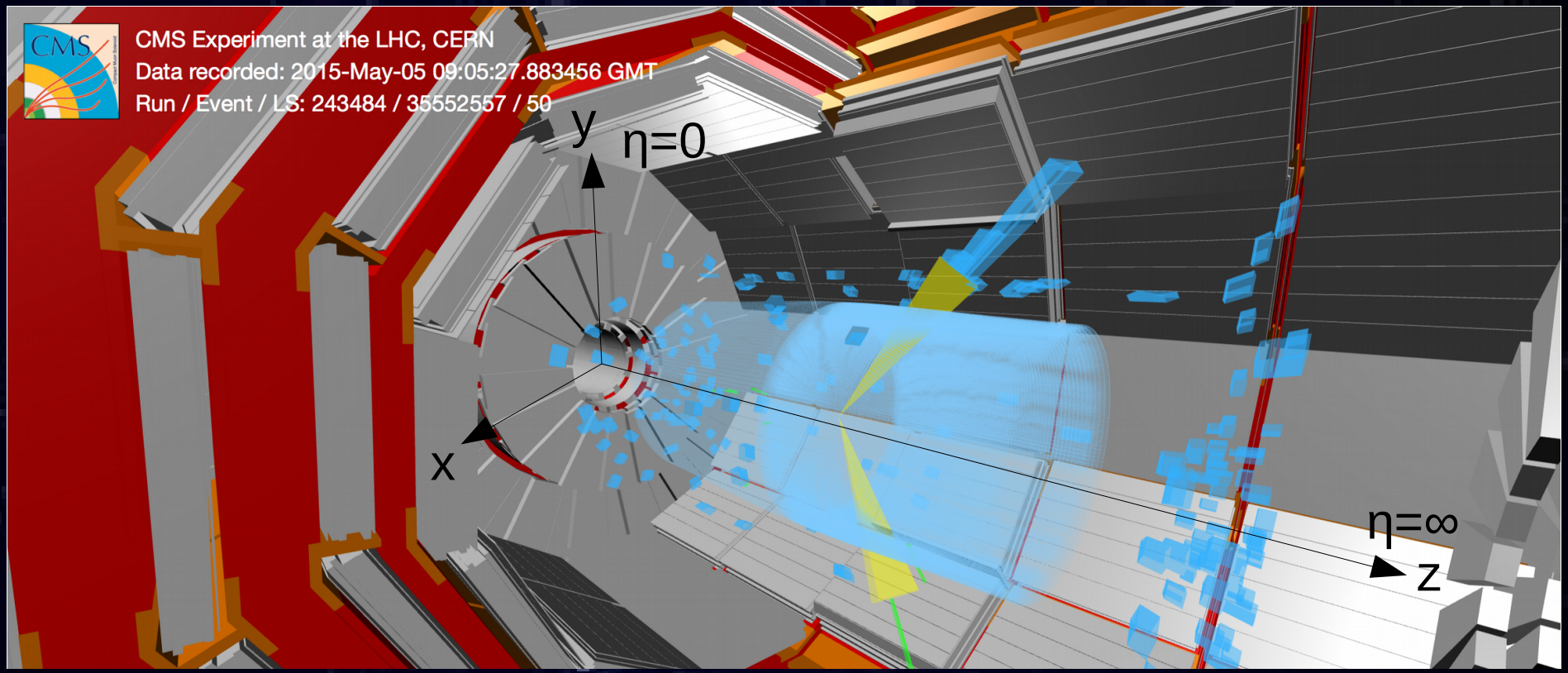
https://sureshemre.wordpress.com/2017/06/05/updated-links-lhc-large-hadron-collider-operation/



http://www.extremetech.com/extreme/152326-cern-begins-lhc-upgrade-to-hopefully-change-our-understanding-of-the-universe

- **The LHC is a 27-km ring straddling France and Switzerland that accelerates protons to nearly the velocity of light prior to colliding them.**
- **Each proton beam has 6.5 TeV of energy.**
- **The beams are collided at four different locations along the ring, one of which is CMS.**

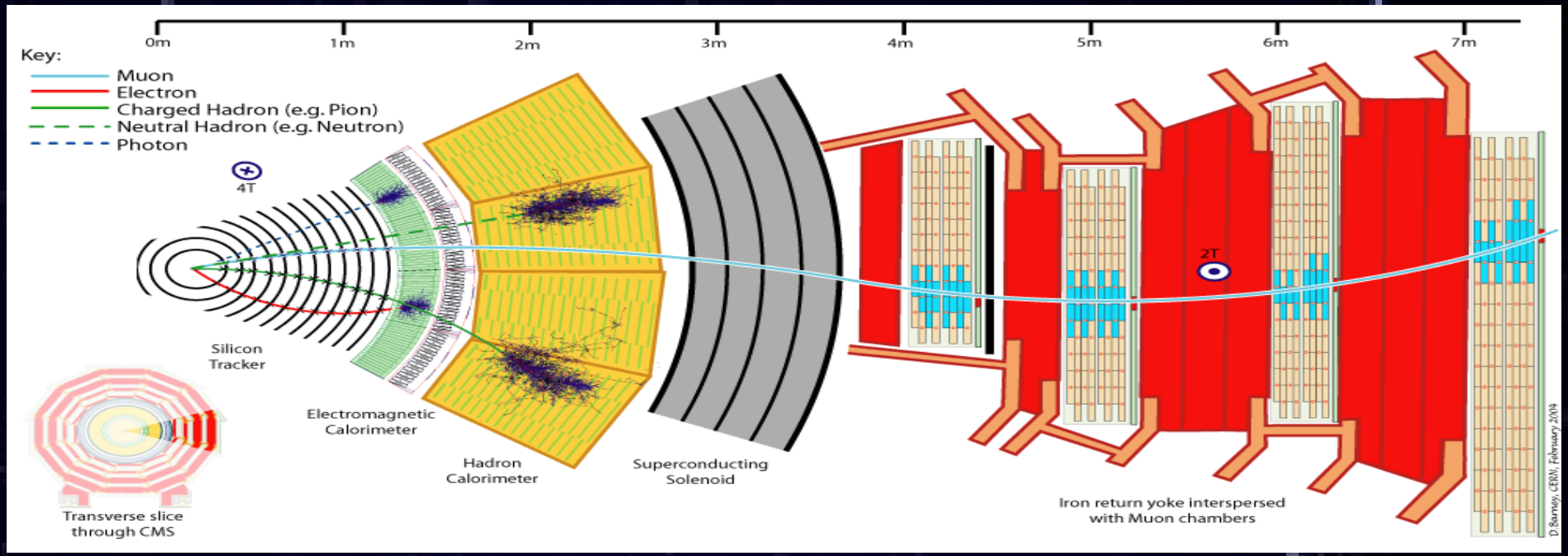
The CMS Experiment



http://cms.web.cern.ch/news/lhc-delivers-low-energy-collisions-cms-and-other-experiments

- **Two circulating beams of protons collide along *z*-axis; *xy*-plane is the transverse plane.**
- **The relativistic energy of the collision can be transferred to mass.**
- **CMS measures positions, momenta, and energies of resulting heavier particles.**

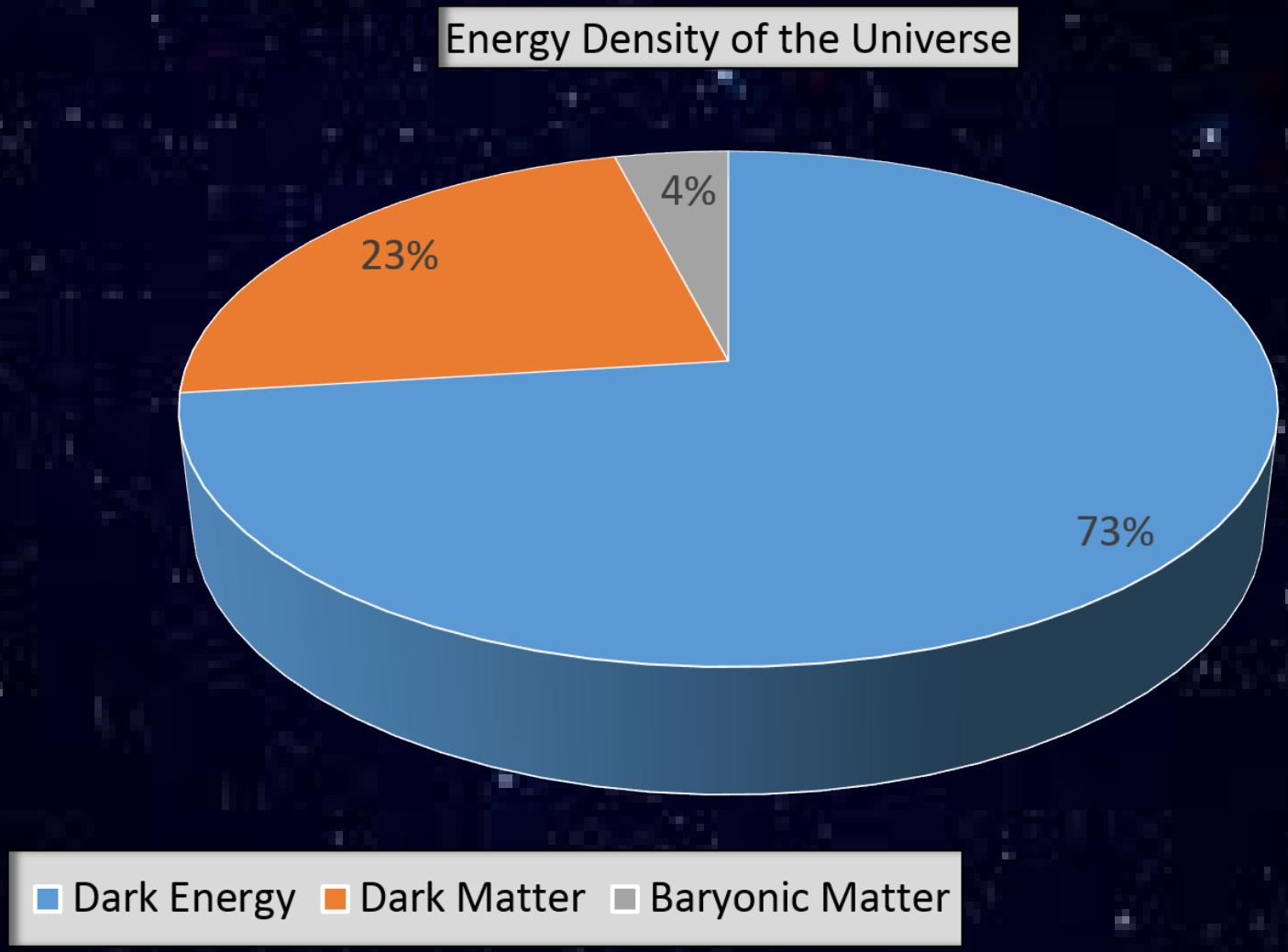
The CMS Detectors



https://cds.cern.ch/record/2205172

- Tracker: trajectories from position measurements.
- Electromagnetic Calorimeter (ECAL): energy deposits of charged particles like electrons and photons.
- Hadronic Calorimeter (HCAL): energy deposits of hadrons.
- Muon Chambers: signals from muons.

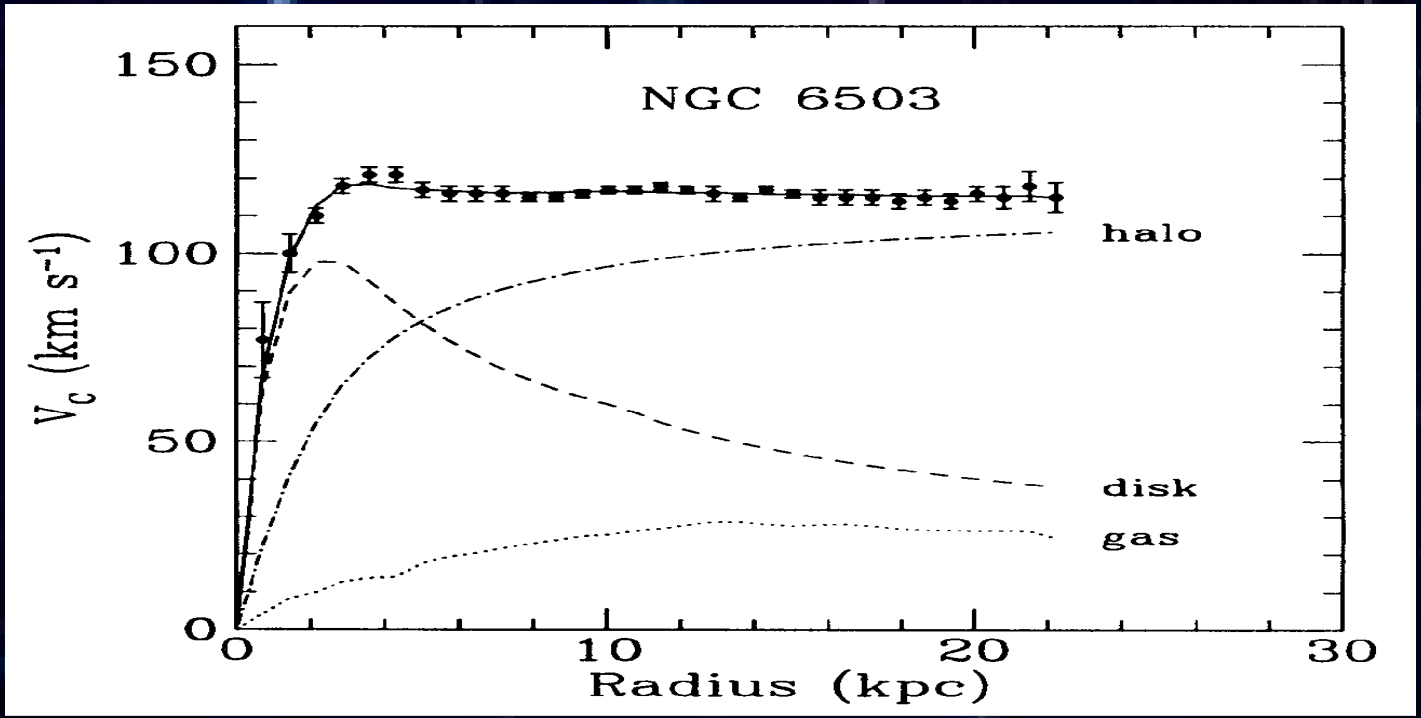
The Composition of the Universe



- **Baryonic matter comprises only a small fraction of our universe!**
- **Why don't we have a better understanding of dark matter & dark energy?**

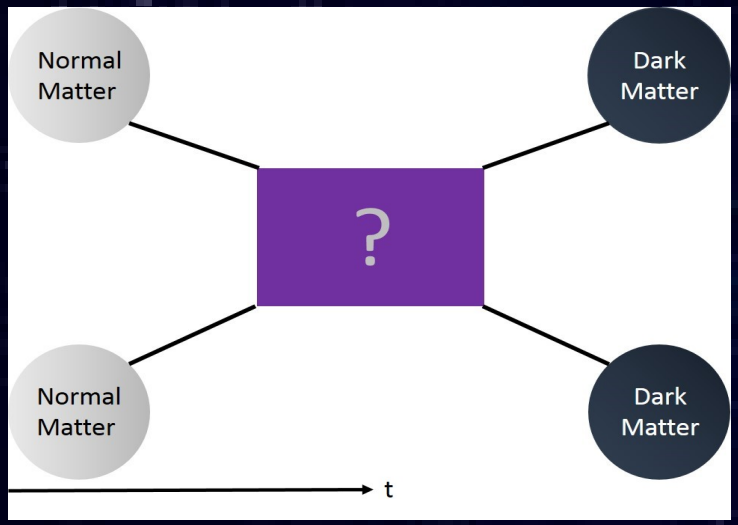
The Necessity of Dark Matter Searches

- DM binds the stars to the galaxies and the galaxies to the universe.
- DM is crucial to our understanding of the structure and evolution of the universe.
- DM is an essential part of Big Bang Cosmology.

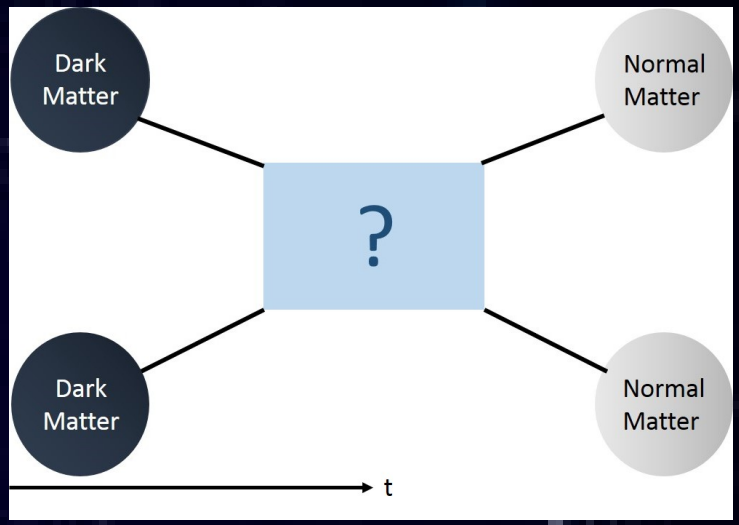


Source: [1]

Creation & Annihilation of DM in the Early Universe



Dark Matter Creation

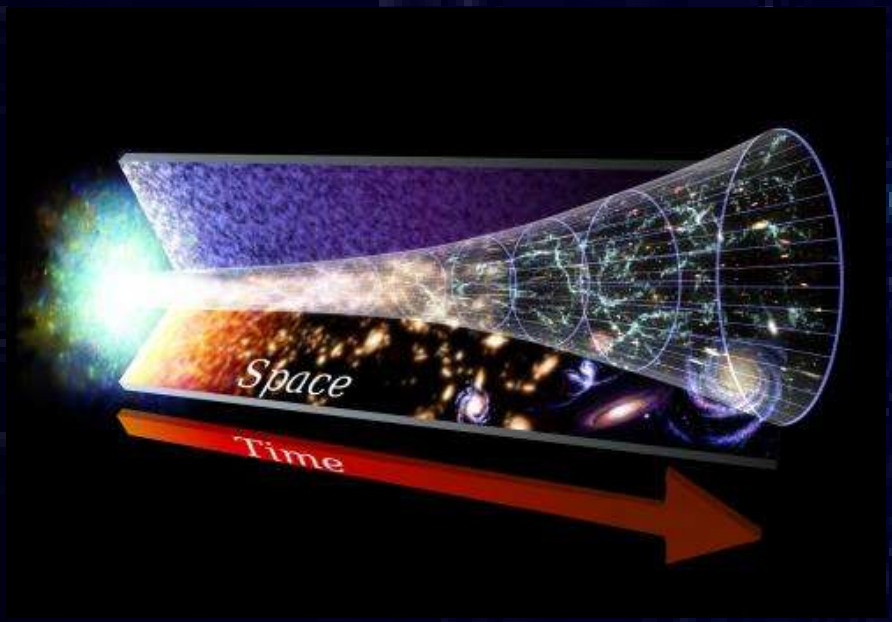


Dark Matter Annihilation

- A common theory dictates that in the early universe, dark matter could be both created and destroyed via processes above.
- Dark matter was both created and destroyed at equal rates. That is,

$$\Gamma_{\text{creation}} \approx \Gamma_{\text{reduction}}.$$

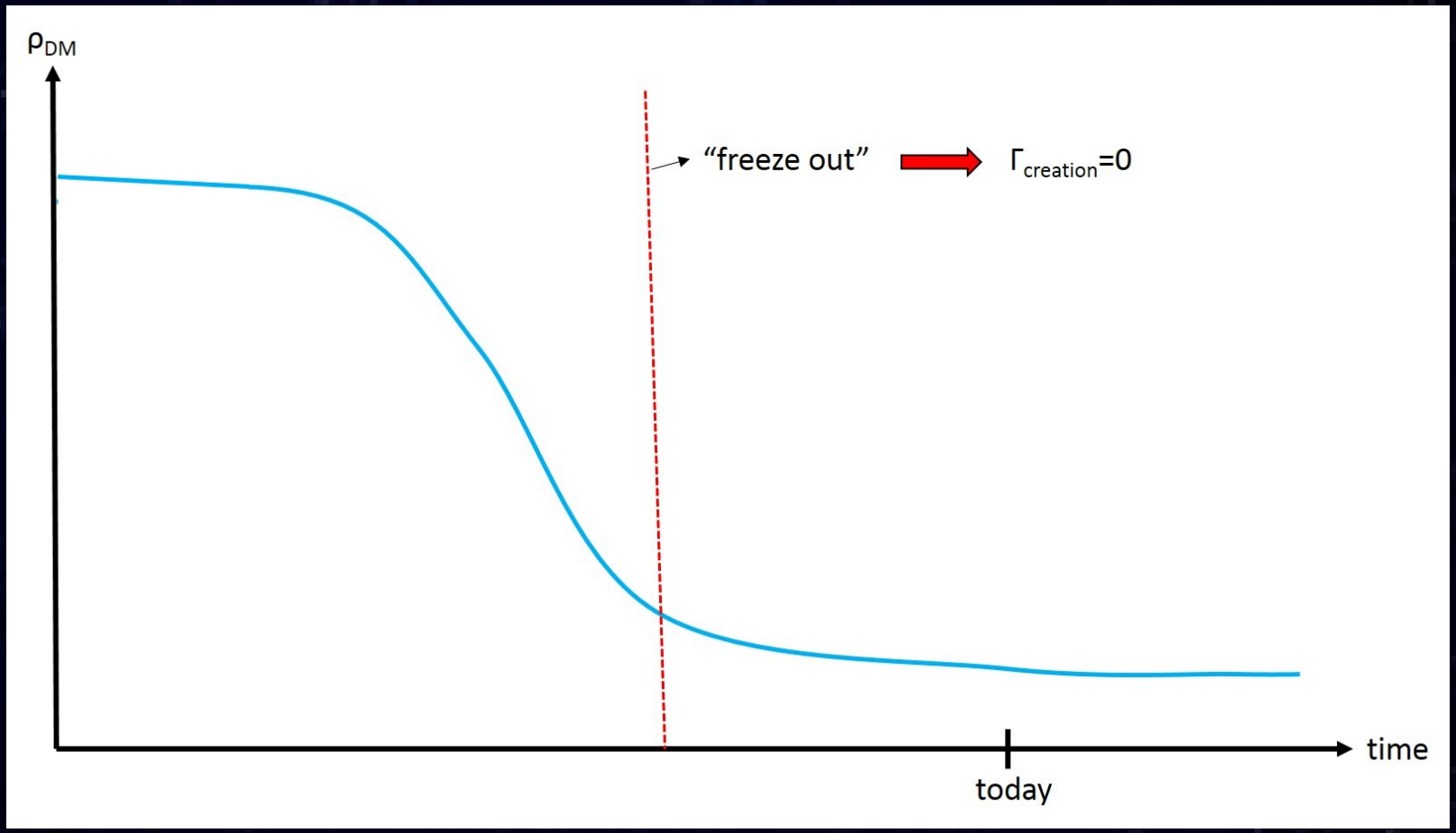
Expansion and Cooling of the Universe



Source: [2]

- Normal matter loses kinetic energy ($k_B T_{NM}$ decreases).
- The density of dark matter (ρ_{DM}) decreases since it is inversely proportional to $R^3_{universe}$.
- Eventually, the normal matter particles do not have enough total energy for dark matter creation; $\Gamma_{creation} \rightarrow 0$.
- The dark matter particles are too spread out for reduction to occur; $\Gamma_{reduction} \approx 0$.

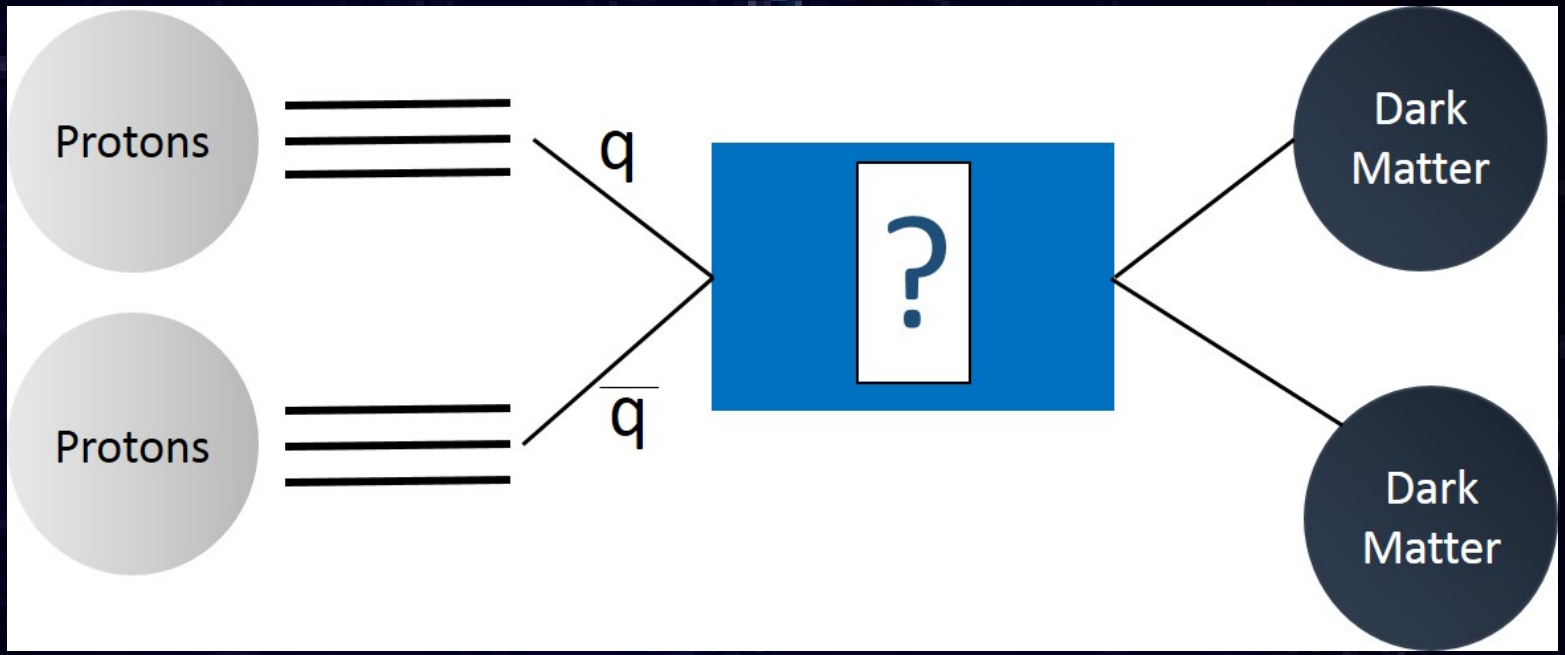
Dark Matter Relic Density



DM Density vs. Time

- **The number of dark matter particles in the universe is roughly constant.**

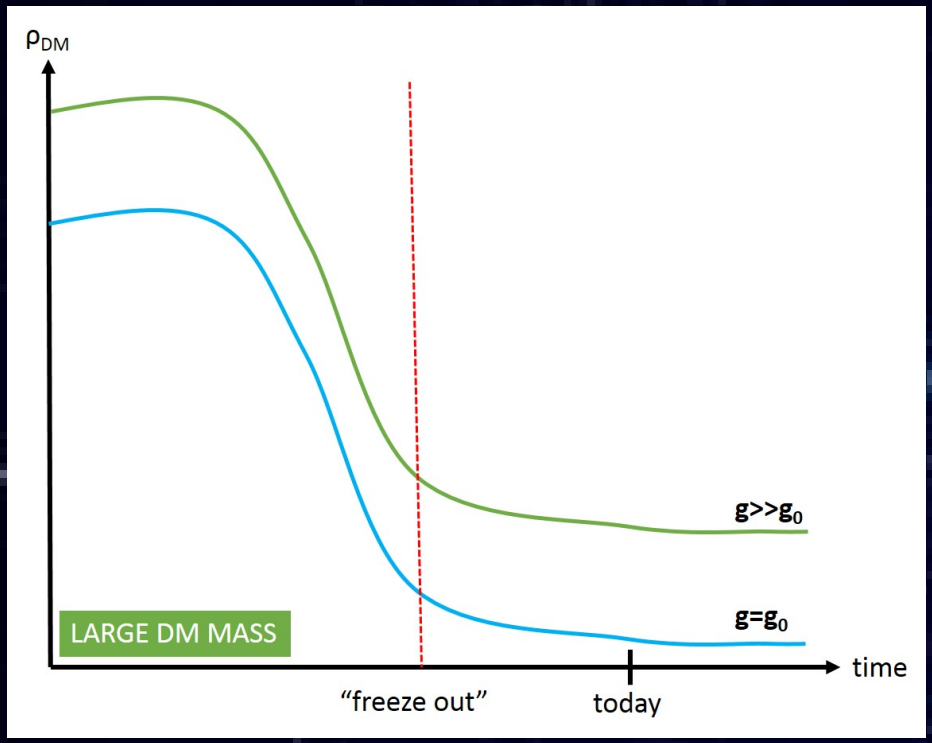
Dark Matter Searches at the LHC

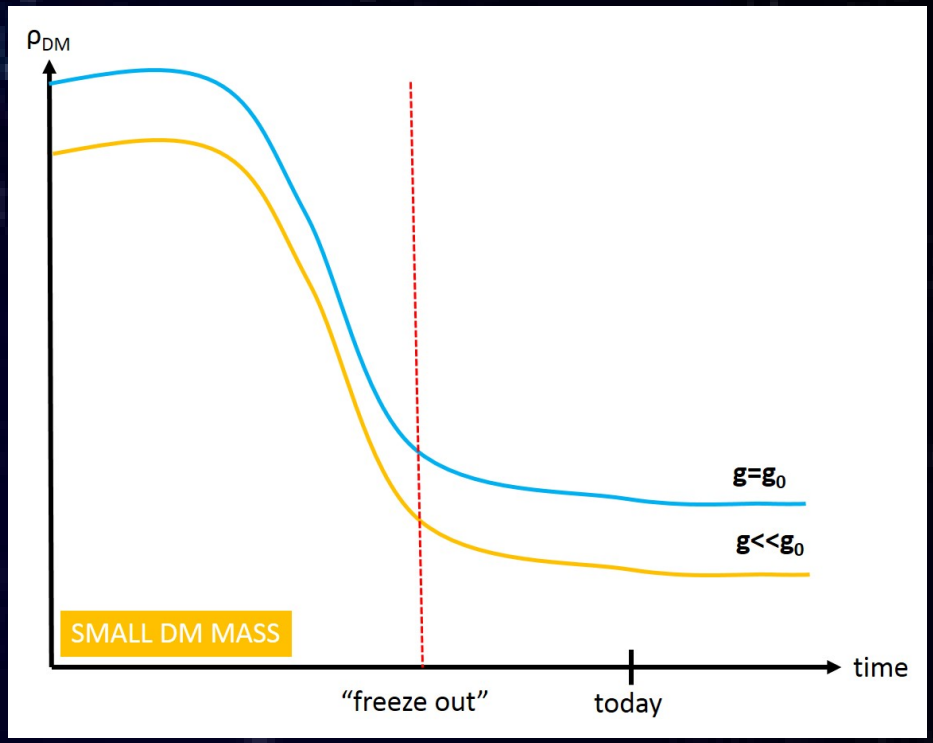


DM Production from Quark (q) and Antiquark ($\bar{q}$)

- **Advantage**: This collision will produce dark matter in high abundance.
- **Disadvantage**: There are high rates of background processes.

The Mediator of Dark Matter Interactions

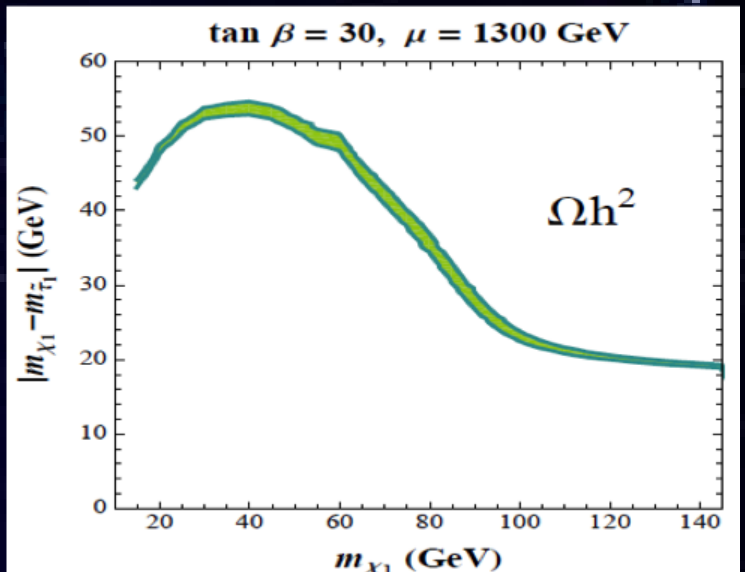


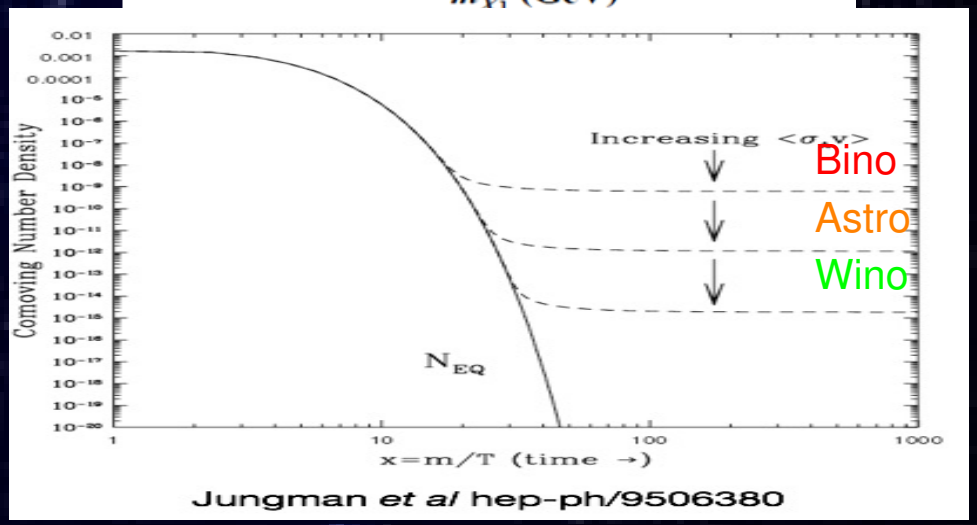


- If the mass of the DM particle is *large*, it must *couple strongly* to the mediator to match the relic density as measured by astronomers.
- If the mass of the DM particle is *small*, it must *couple more weakly* to the mediator to match the relic density as measured by astronomers.

Particle Physics, Cosmology, and Dark Matter

- Certain models provide a DM candidate in the form of a particle that is the lightest neutralino/gravitino.
- The composition of the dark matter is directly related to the amount of dark matter in the universe.
- For a relic DM density consistent with astronomy, *coannihilation* can be introduced.
- The DM relic density is extremely sensitive to the mass difference between the stau ($\tilde{\tau}$) and the $\tilde{\chi}_1^0 \rightarrow$ motivates a search for compressed spectra ($\Delta m < 50$ **GeV**).



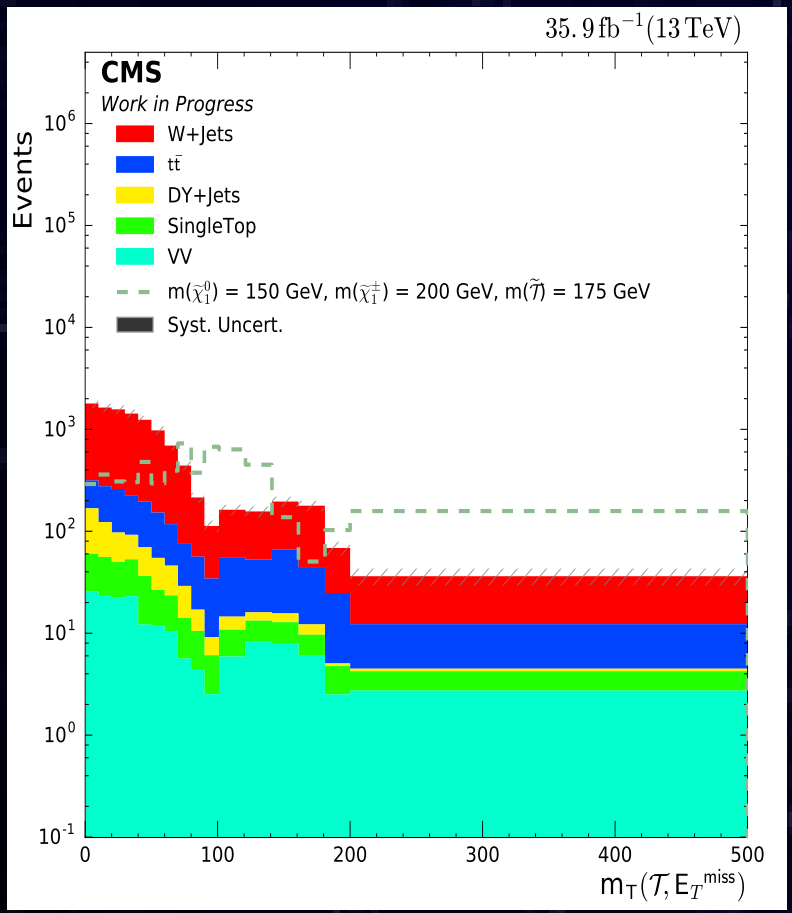


$$\Omega h^2 \propto \frac{1}{<\sigma v>_{\mathrm{A}} + <\sigma v>_{\mathrm{CA}}};$$

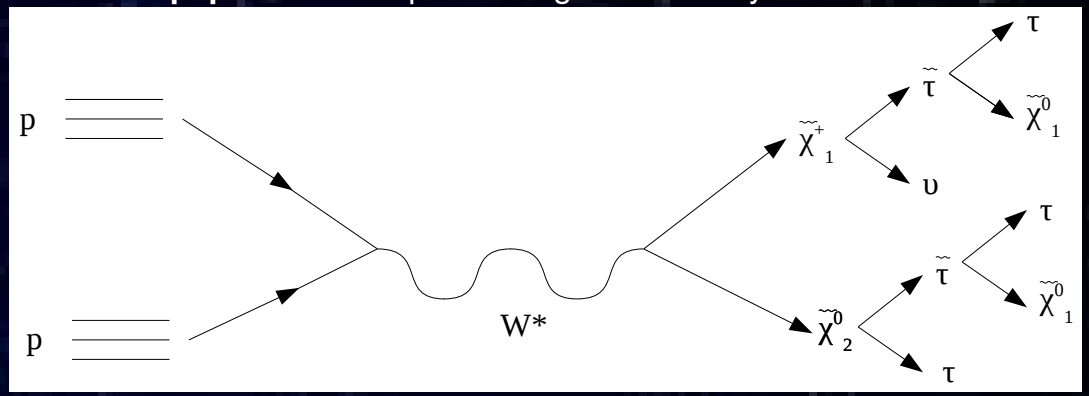
$$<\sigma v>_{\mathrm{CA}} \sim e^{-\Delta m}$$

Example Dark Matter Search

"ISR + stau"



Pheno. paper: *DOI:https://doi.org/10.1103/PhysRevD.94.073007



- We seek out a signal process and must differentiate it from background processes that mimic the outcome of signal.
- Primary backgrounds are from Z+Jets, W+Jets, and $t\bar{t}$.
- Signal cross-section is scaled by a factor of 10 for clarity.

Reason 1∼I've gotten opportunities to mentor and share my knowledge.

Reason 2∼I've had many chances to travel...

Reason 3∼I've acquired a wonderful extended family.

Reason 4∼I still have time to be me. :)

References (1)

A. Delannoy *et al.*, "Probing Dark Matter at the LHC using Vector Boson Fusion Processes," Phys. Rev. Lett. **111**, 061801 (2013) doi:10.1103/PhysRevLett.111.061801 [arXiv:1304.7779 [hep-ph]].

A. Florez *et al.*, "Searching for New Heavy Neutral Gauge Bosons using Vector Boson Fusion Processes at the LHC," Phys. Rev. Lett. B, **767**, (2017) doi:10.1016/j.physletb.2017.01.062 [arXiv:1609.09765 [hep-ph]].

B. Dutta, A. Gurrola, W. Johns, T. Kamon, P. Sheldon and K. Sinha, "Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC," Phys. Rev. D **87**, no. 3, 035029 (2013) doi:10.1103/PhysRevD.87.035029 [arXiv:1210.0964 [hep-ph]].

B. Dutta, T. Ghosh, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha and S. Wu, "Probing Compressed Sleptons at the LHC using Vector Boson Fusion Processes," Phys. Rev. D **91**, 055025 (2015) 10.1103/PhysRevD.91.055025 [arXiv:1411.6043 [hep-ph]].

B. Dutta, W. Flanagan, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, K. Wang and S. Wu, "Probing Compressed Top Squarks at the LHC at 14 TeV," Phys. Rev. D **90**, 095022 (2014) 10.1103/PhysRevD.90.095022 [arXiv:1312.1348 [hep-ph]].

"Big Bang Discovery: Physicists Hail Cosmic Holy Grail As Nobel Prize Beckons." HUFFPOST TECH, 17 Mar. 2014, huffingtonpost.co.uk. Accessed 09 Mar. 2017.

CERN [CERN Accelerating Science], "How an Accelerator Works," https://home.cern/about/how-accelerator-works, Web (2018).

CMS [CMS Collaboration], "CMS," https://home.cern/about/experiments/cms, Web (2018).

D. Griffiths, *Introduction to Elementary Particles; 2nd rev. version*, Wiley, New York, NY, Physics textbook (2008), https://cds.cern.ch/record/111880.

D. Pappadopulo *et al.*, "Heavy Vector Triplets: Bridging Theory and Data," JHEP **09**, 060 (2014) doi:10.1007/JHEP09(2014)060 [arXiv:1402.4431 [hep-ph]].

G. Aad *et al.* [ATLAS Collaboration], "The ATLAS Experiment at the CERN Large Hadron Collider," JINST **3**, S08003 (2008). doi:10.1088/1748-0221/3/08/S08003

References (2)

"How Does Dark Matter Solve the Galactic Motion Problem?" CosmoQuestX, 2017, forum.cosmoquest.org. Accessed 14 Mar. 2017.

Koberlein, Brian. "How Fast is the Universe Expanding?" PHYS.ORG, 10 Feb. 2015, phys.org. Accessed 08 Mar. 2017.

Romeyer, Alain. *Activity on CMS- Mons-Hainaut University*. UMH, cms.umh.ac.be. Accessed 08 Mar. 2017.

S. Chatrchyan *et al.* [CMS Collaboration], "The CMS experiment at the CERN LHC," JINST **3**, S08004 (2008). doi:10.1088/1748-0221/3/08/S08004

Stanley, Will. "LHC. Camera. Action! (Part 2)" Science Museum, 03 June 2013, blog.sciencemuseum.org.uk. Accessed 08 Mar. 2017.