Vanderbilt QuarkNet Workshop 2023

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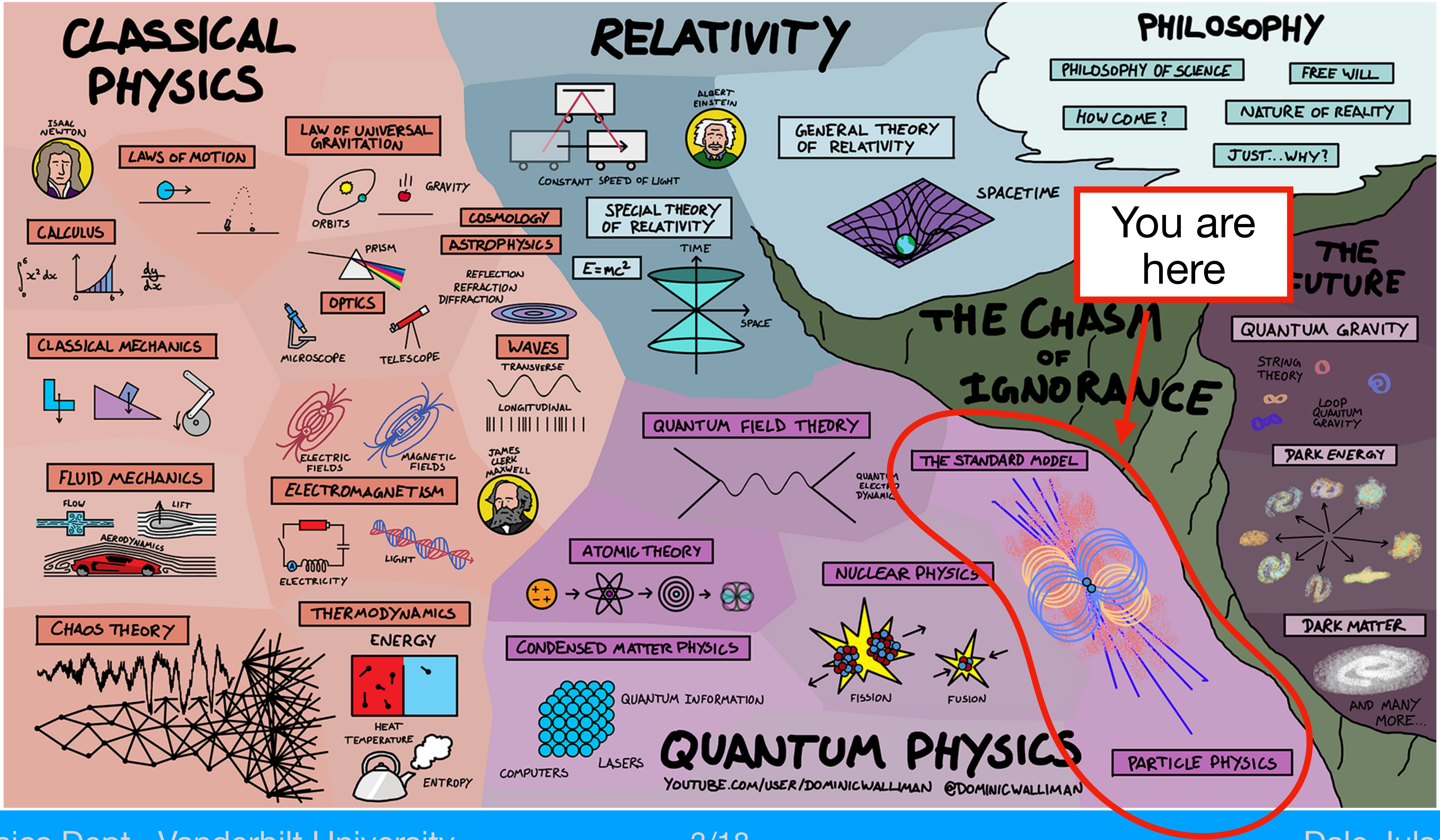
Overview

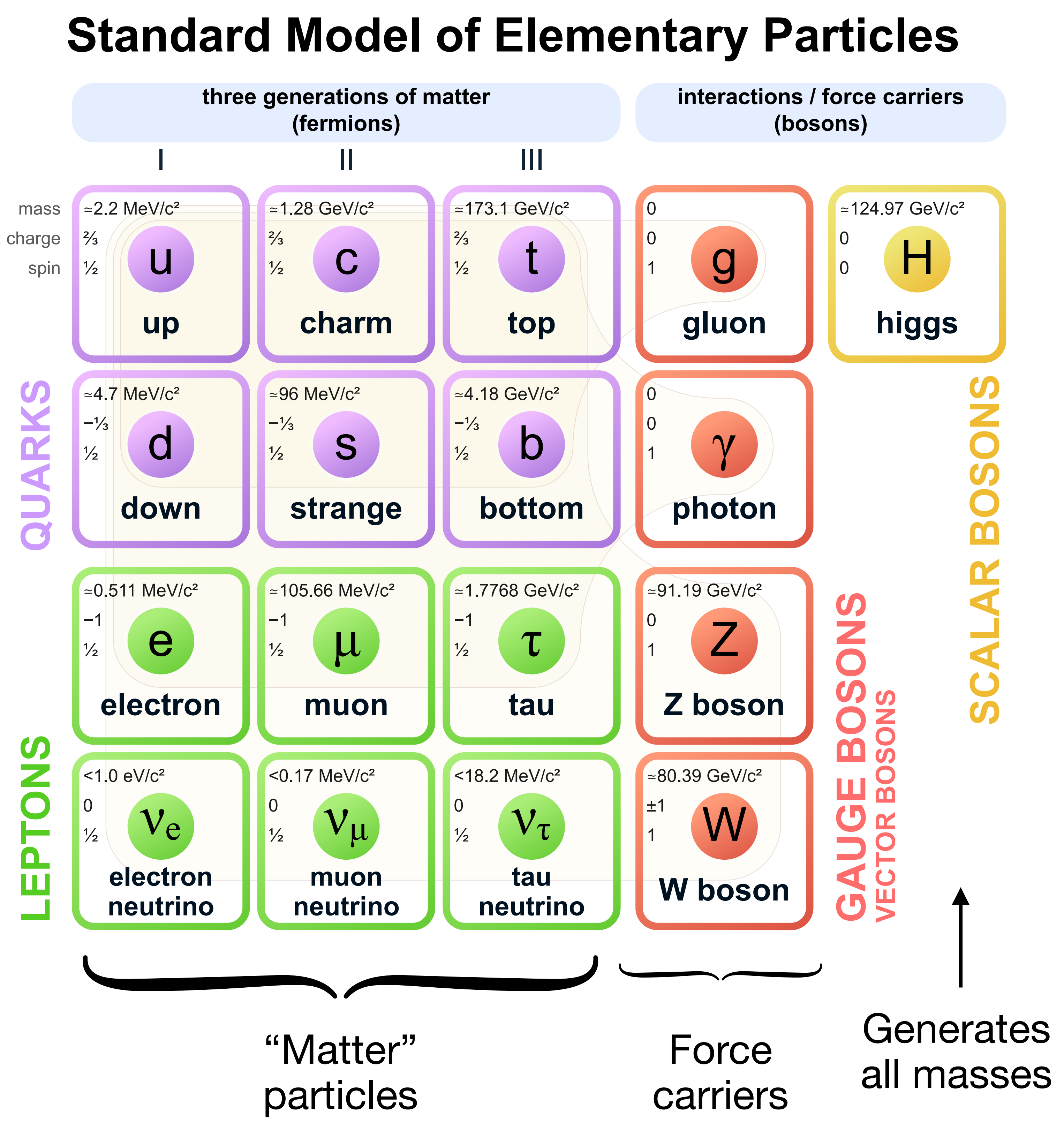
- Introduction
- Particle Physics & The Standard Model
- Dark Matter (DM)
- SuperSymmetry (SUSY)
- Compressed Mass Spectra & Co-annihilation scenarios.
- Compact Muon Solenoid (CMS) Experiment and the Large Hadron Collider (LHC)
- How to search for new physics at the LHC
- Probing SUSY at the LHC
- Vector boson fusion (VBF) interactions
- Conclusion

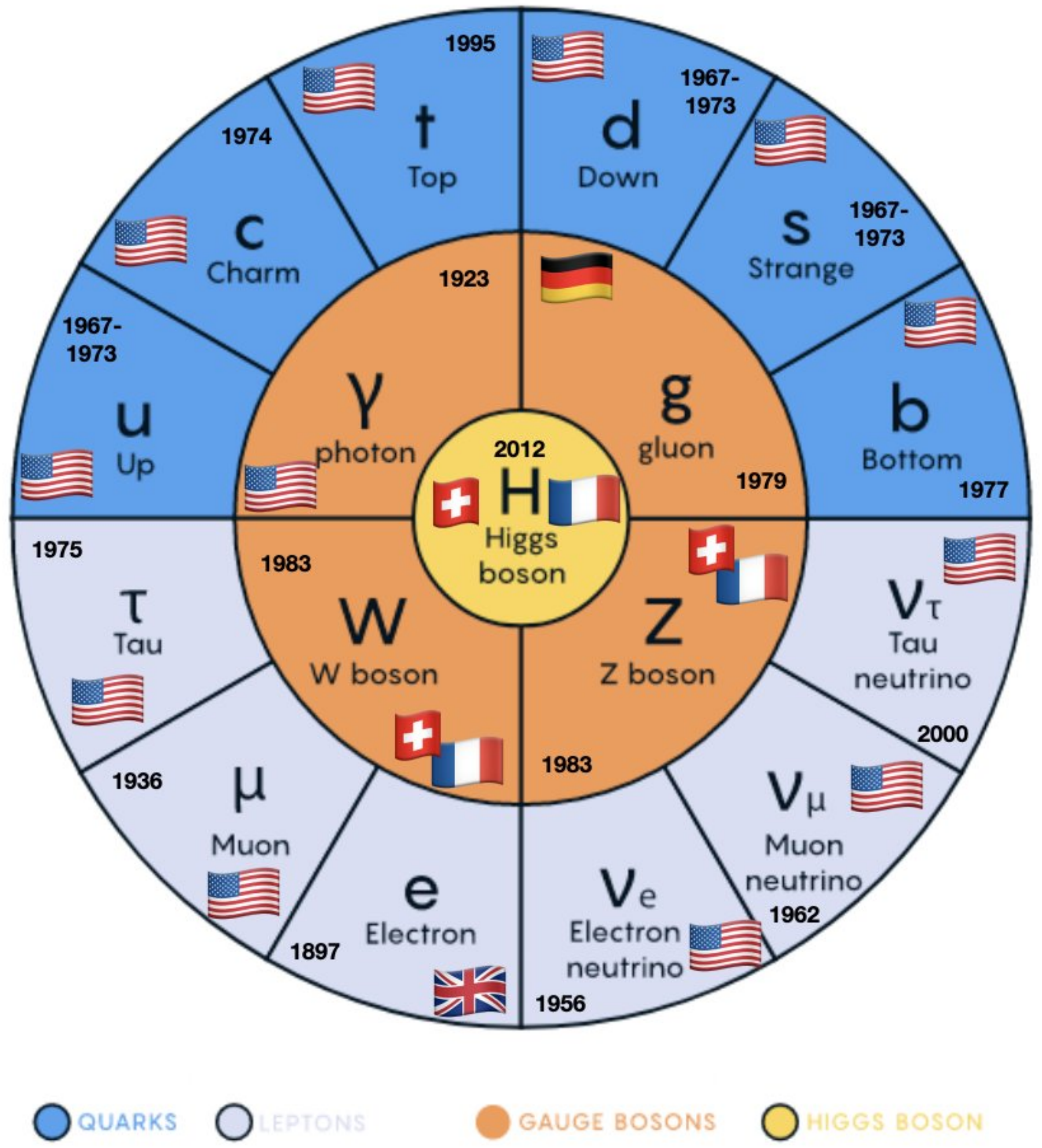
Overview of Physics:



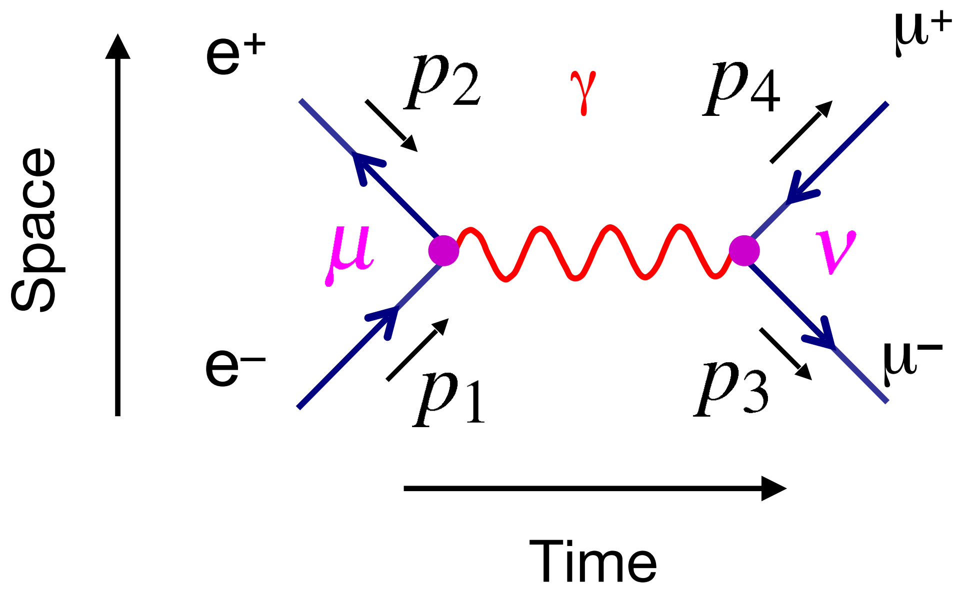
The Standard Model of Particle Physics (as an experimentalist)

- The Standard Model (SM) represents our current understanding of particle physics.
- The theory was completed in the mid 1970's, however the final predicted particle (the Higgs Boson) was not discovered until 2012 — 50 years later!





- The SM can successfully describe particle interactions over an energy range of 12 orders of magnitude.
- The SM is believed to be incomplete, as it cannot explain dark matter, dark energy, neutrino masses, matter-antimatter asymmetry, gravity, etc.



The Standard Model of Particle Physics (as a theoretician)

- For the theorists, the SM looks a little bit different:
  - The SM Lagrangian (shown below) allows for the calculation of the dynamics of a system.
  - These equations are VERY hard to solve.

1

$$-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu$$

2

$$-\partial_\nu W^+_\mu\partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$-\bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] +$$

4

$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

5

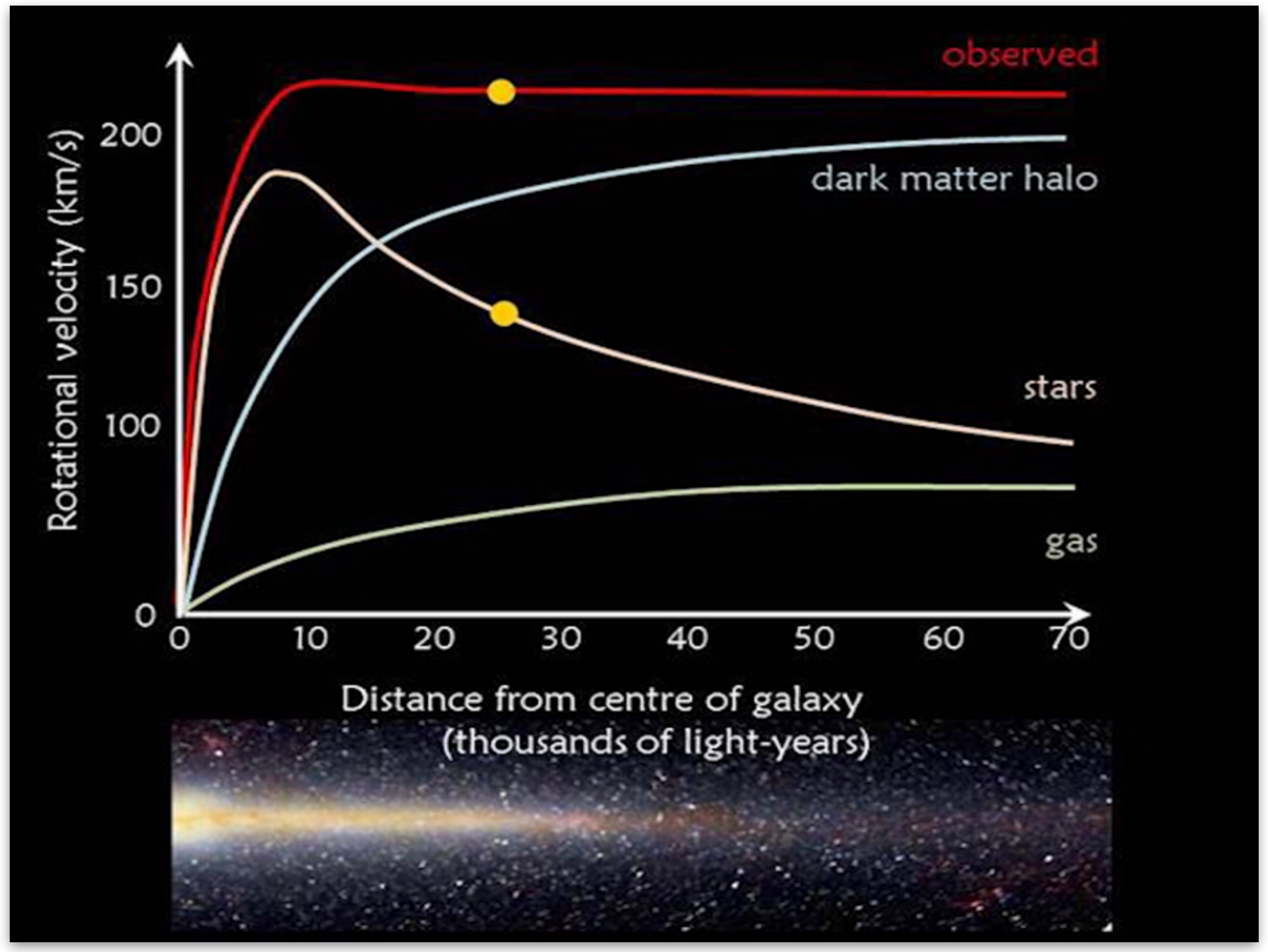
$$\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

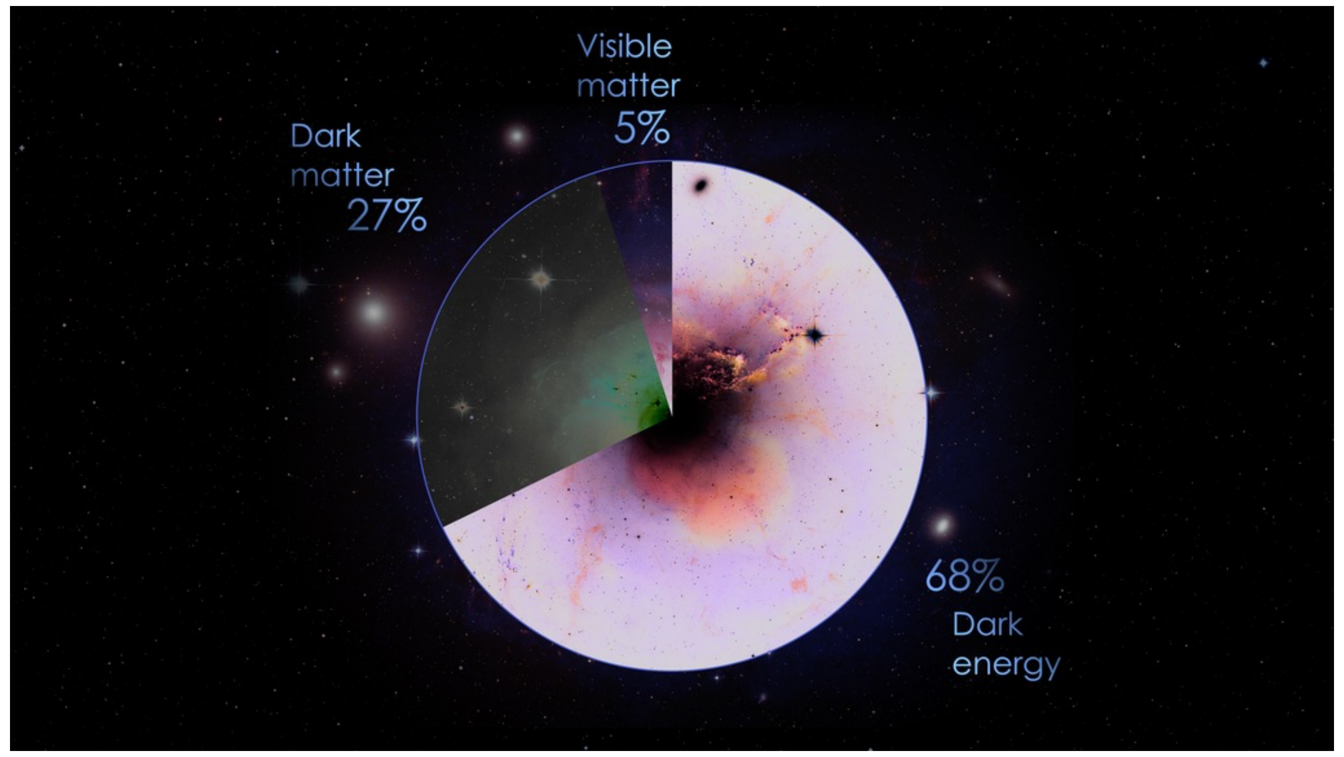
Problems of the SM: Dark Matter

- The rotational velocity per distance of an object goes as:

$$G\frac{Mm}{r^2} = \frac{mv^2}{r} \rightarrow v(r) = \sqrt{\frac{GM}{r}}$$

- When observing actual galaxy velocity curves however, the visible matter does not follow the trend, implying invisible mass!
- Strongest current day evidence comes from surveys of the cosmic microwave background. This looks at pressure waves in the very early universe to determine early universe composition.
- Our research group is very interested in dark matter! We primarily perform searches for theories which can postulate a “dark matter candidate particle”.





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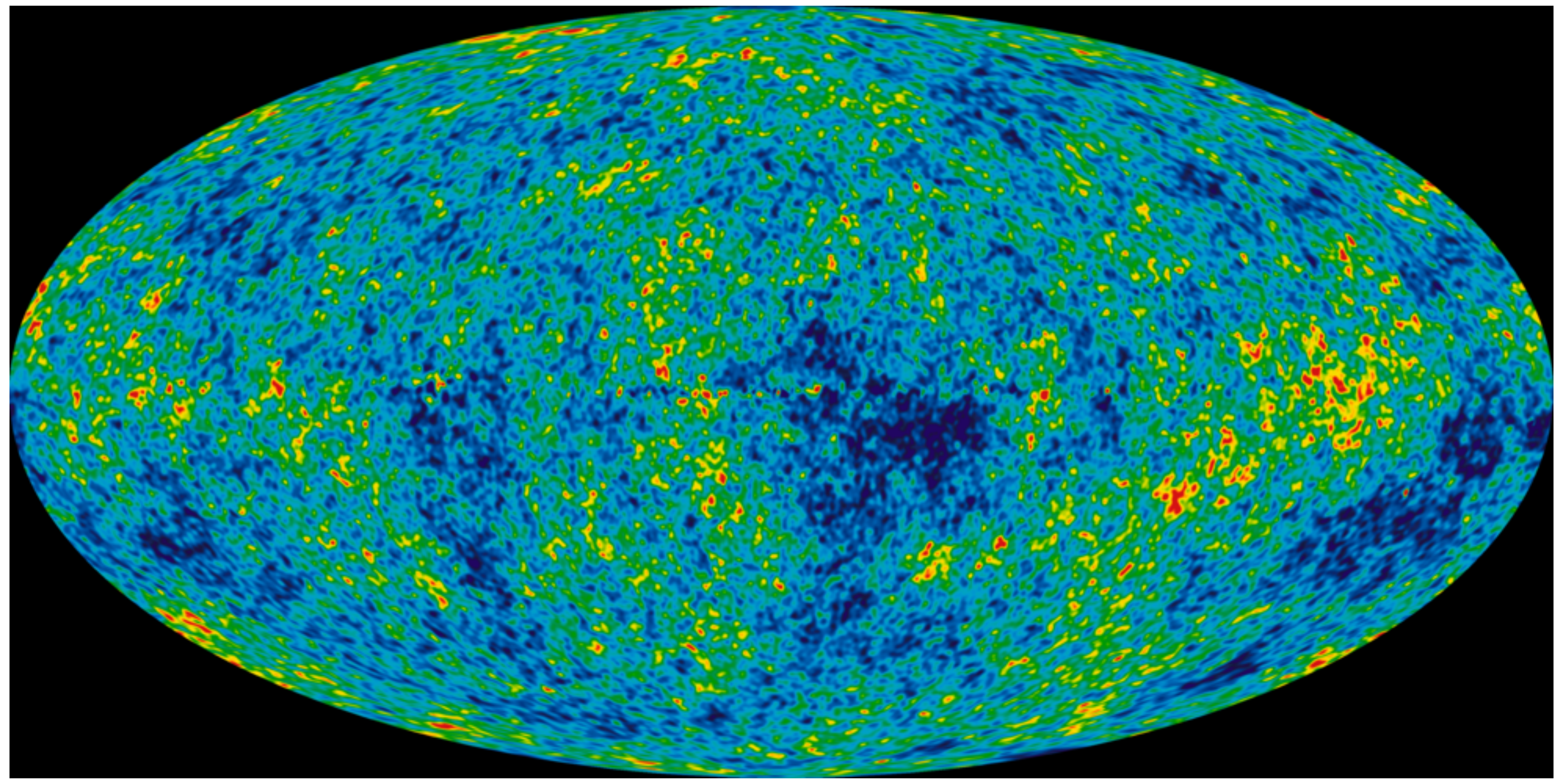
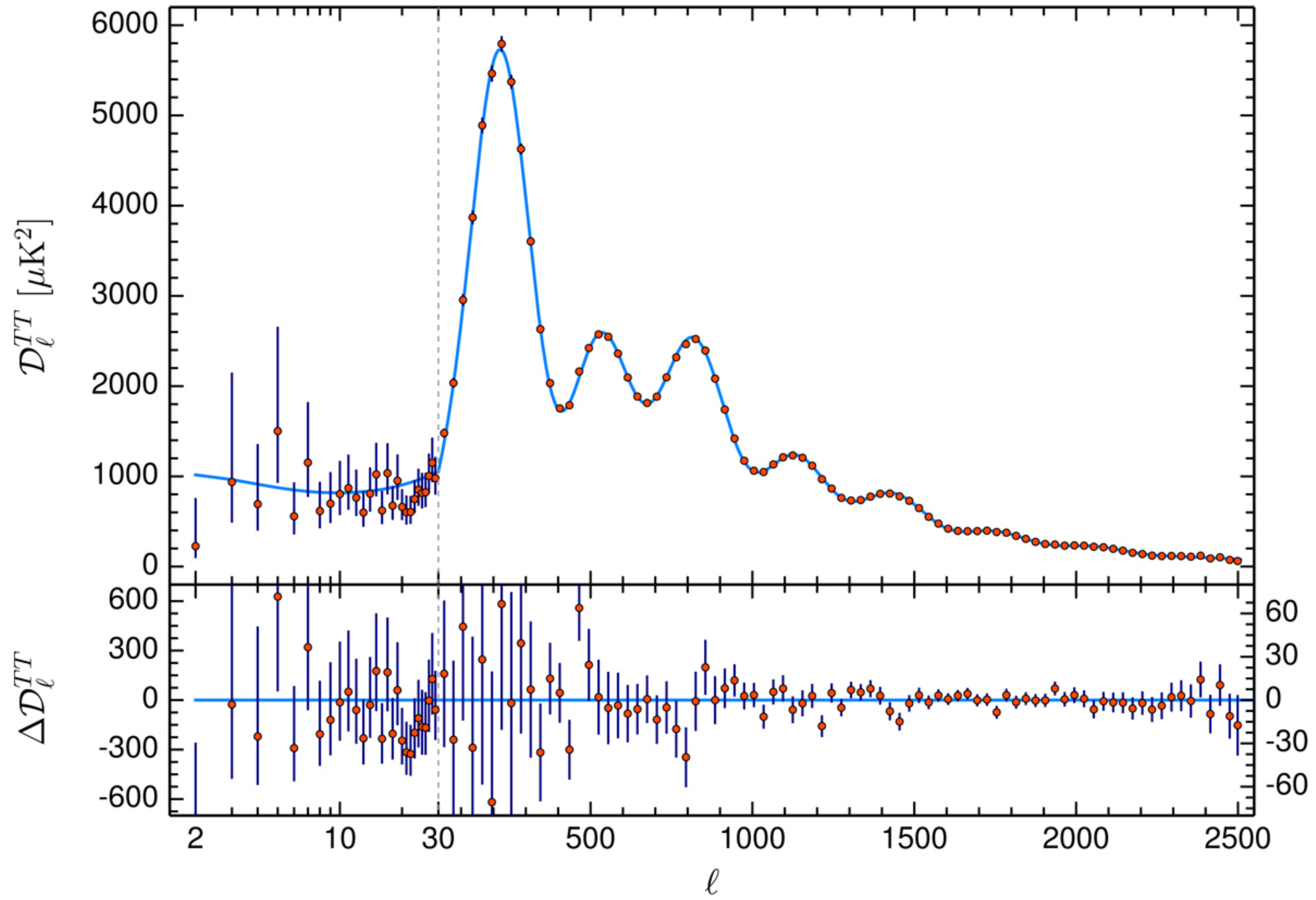
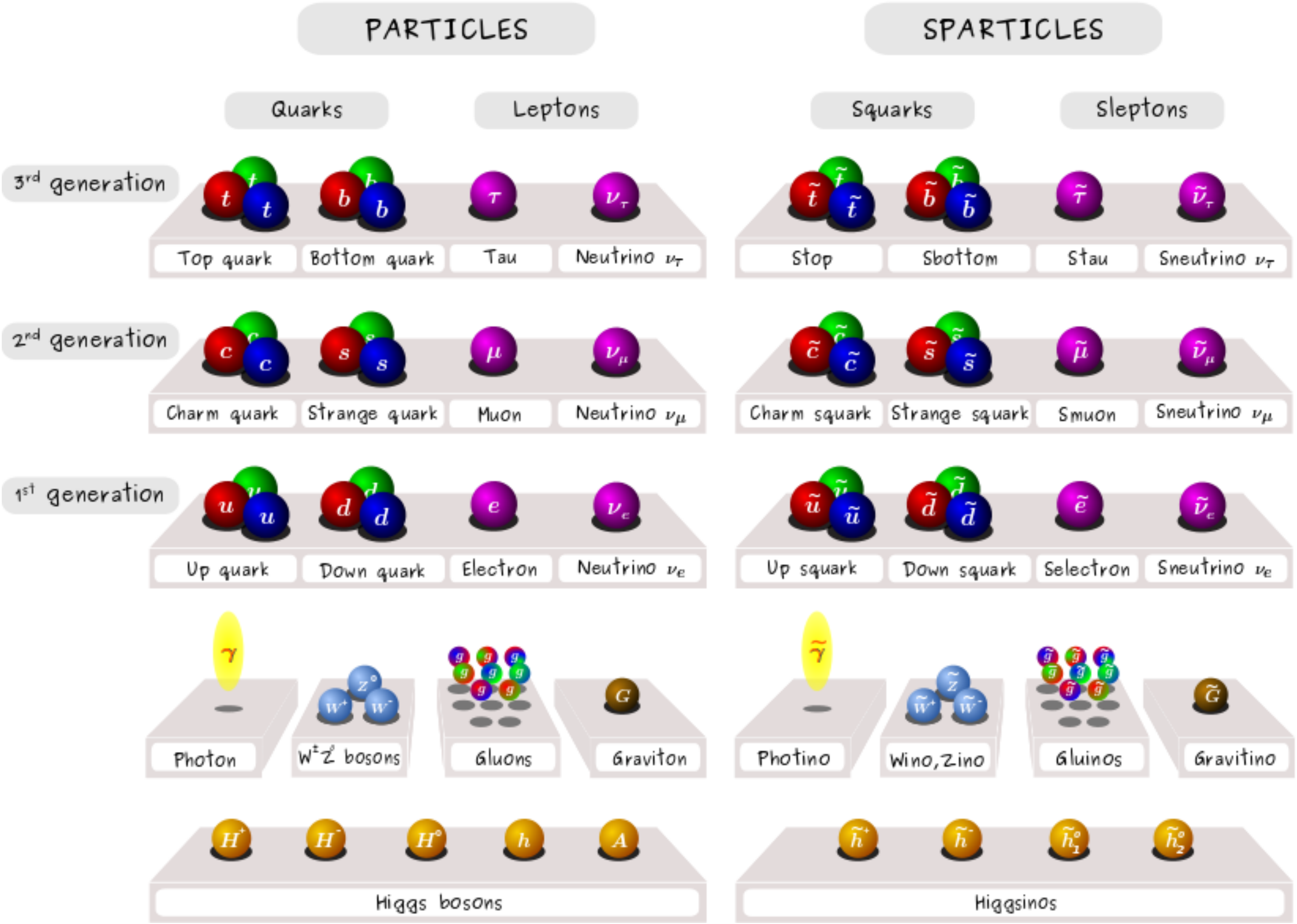




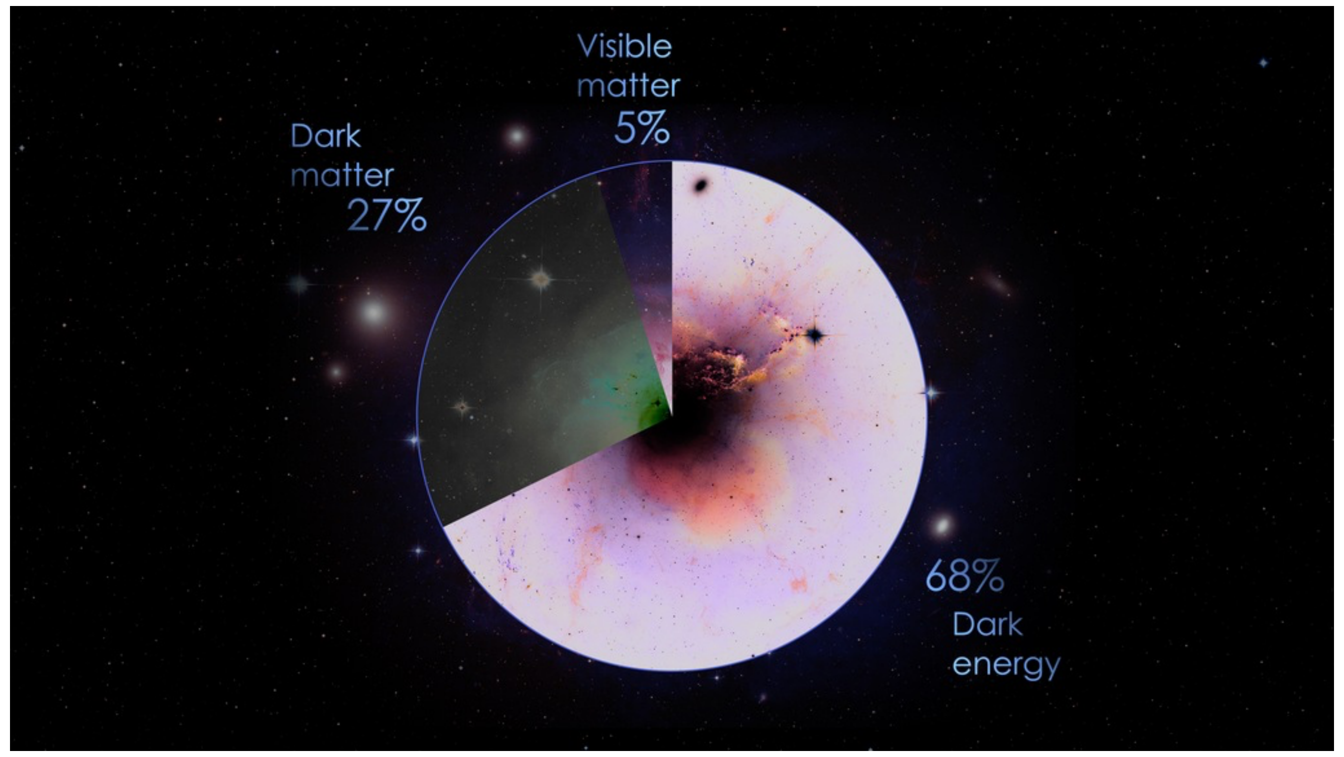
SuperSymmetry (SUSY)

- **Problem:** SM tells us the Higgs field generates the masses of all particles. As a result, its own mass (~125 GeV) should receive quantum corrections and be much much bigger
- **Solution**: Supersymmetry! (SUSY for short)
- SUSY predicts a new fundamental symmetry between all particles.
- The result is that the quantum corrections cancel exactly, leaving the Higgs boson a “natural” mass.
- Even better though, SUSY offers a **dark matter candidate particle**!!
- The photino, zino, wino, and higgsino “mix” to form new particles, the lightest of which is massive, stable, and weakly interacting (exactly what we expect DM to be).



Dark Matter & the Evolution of the Universe

- Current evidence suggests Dark matter (DM) constitutes 85% of the matter content of the universe (27% of the energy content).
- For thermal Big Bang Cosmological models, DM is created in thermal equilibrium with SM matter, permitting the interaction $DM + DM \rightleftarrows SM + SM$
- As the universe expands and cools, DM annihilation begins per $DM + DM \not\rightleftarrows SM + SM$.
- Eventually, DM becomes too diffuse to interact, leaving behind the "DM relic density" (freeze-out).
- When searching for DM, the DM relic density offers a benchmark test for identifying new particles as being the canonical DM particle (does it predict the experimentally observed value?).
- DM relic density depends on the cross section (σ) of the DM annihilation interaction. For scenarios that predict an overabundance, a "co-annihilation" (CA) partner is required for experimental consistency.



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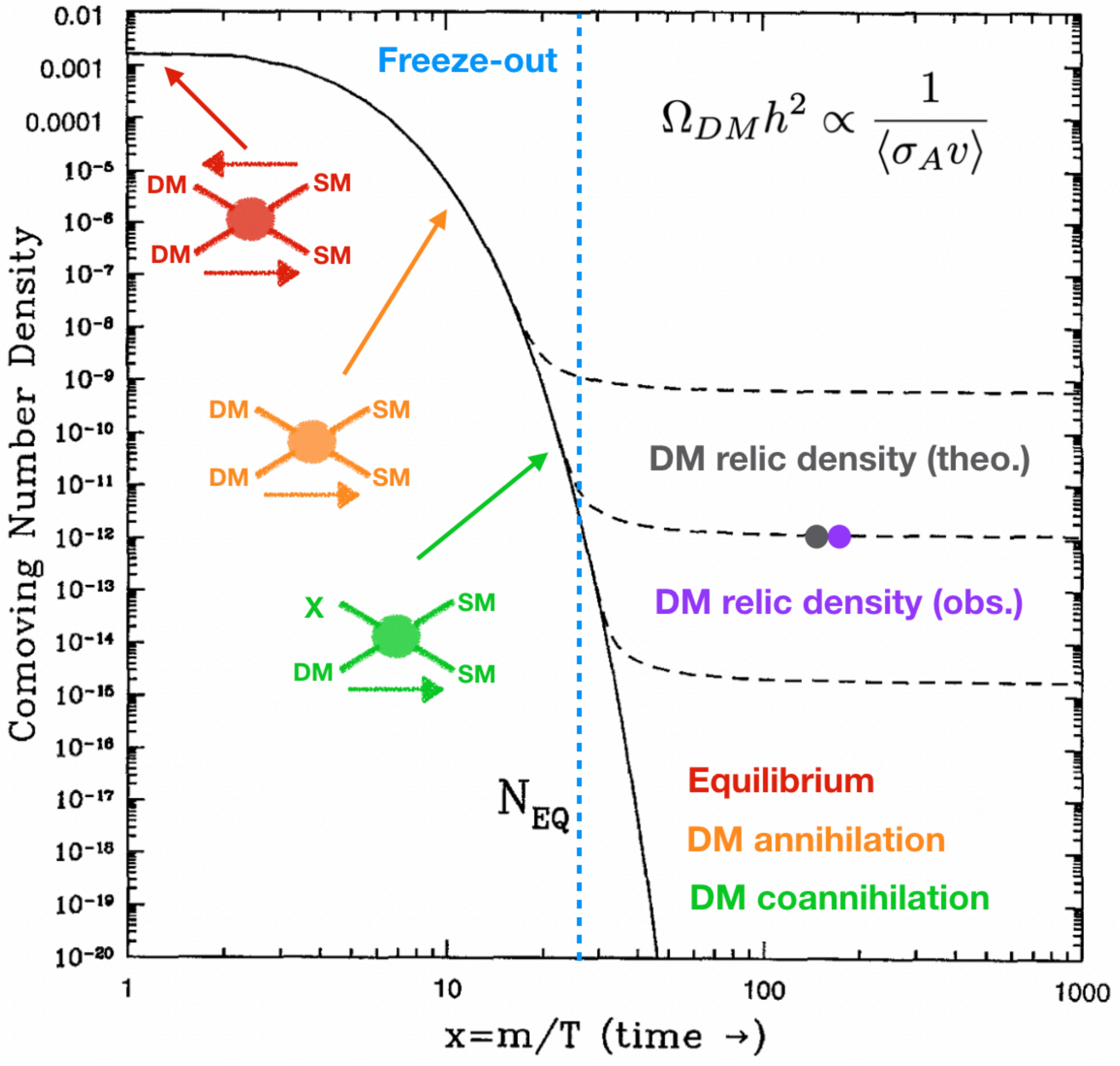
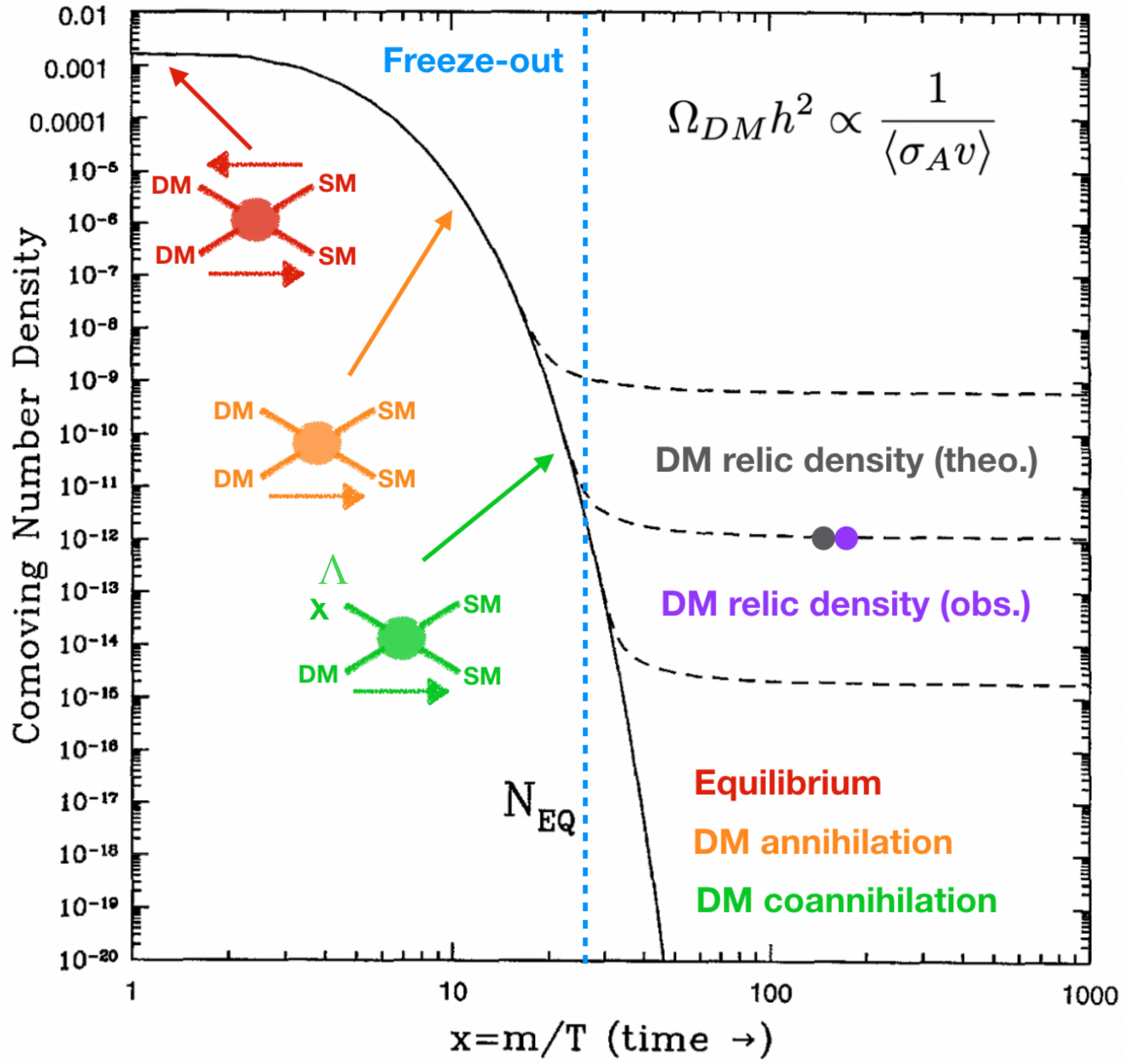


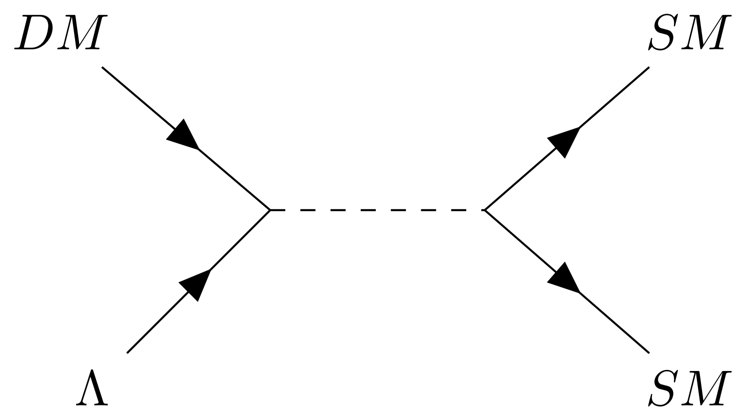
CA Partners & Compressed Mass Spectrum Scenarios

- For scenarios in which the DM is primarily bino, meaning the mass and flavor eigenstates are very close ($\tilde{\chi}_1^0 \approx \tilde{B}$), an overabundance of DM is predicted (DM does not reduce quickly enough).

- To remedy this, a CA partner (Λ) is introduced in order to increase the cross section ($\sigma_{eff} = \sigma_{DM} + \sigma_{\Lambda}$):

- The cross section of such an interaction is exponentially dependent on the mass gap (Δm) between DM & Λ:



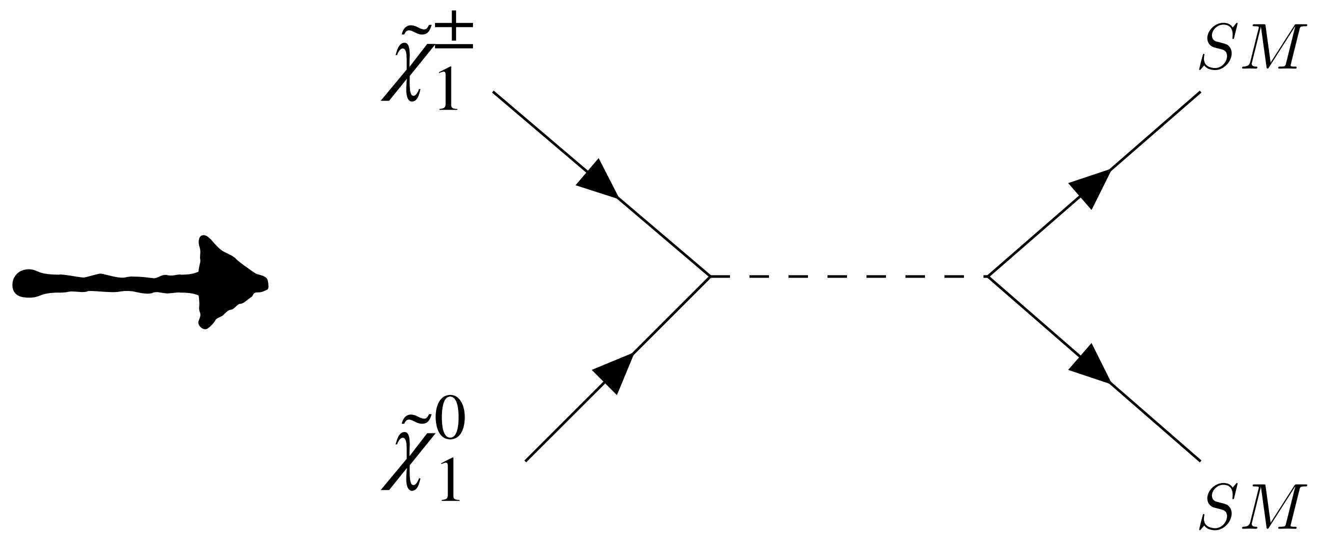


$$\sigma_{\Lambda} \propto e^{-\frac{\Delta m}{T}}$$

$$\Delta m \equiv m_{\Lambda} - m_{DM}$$

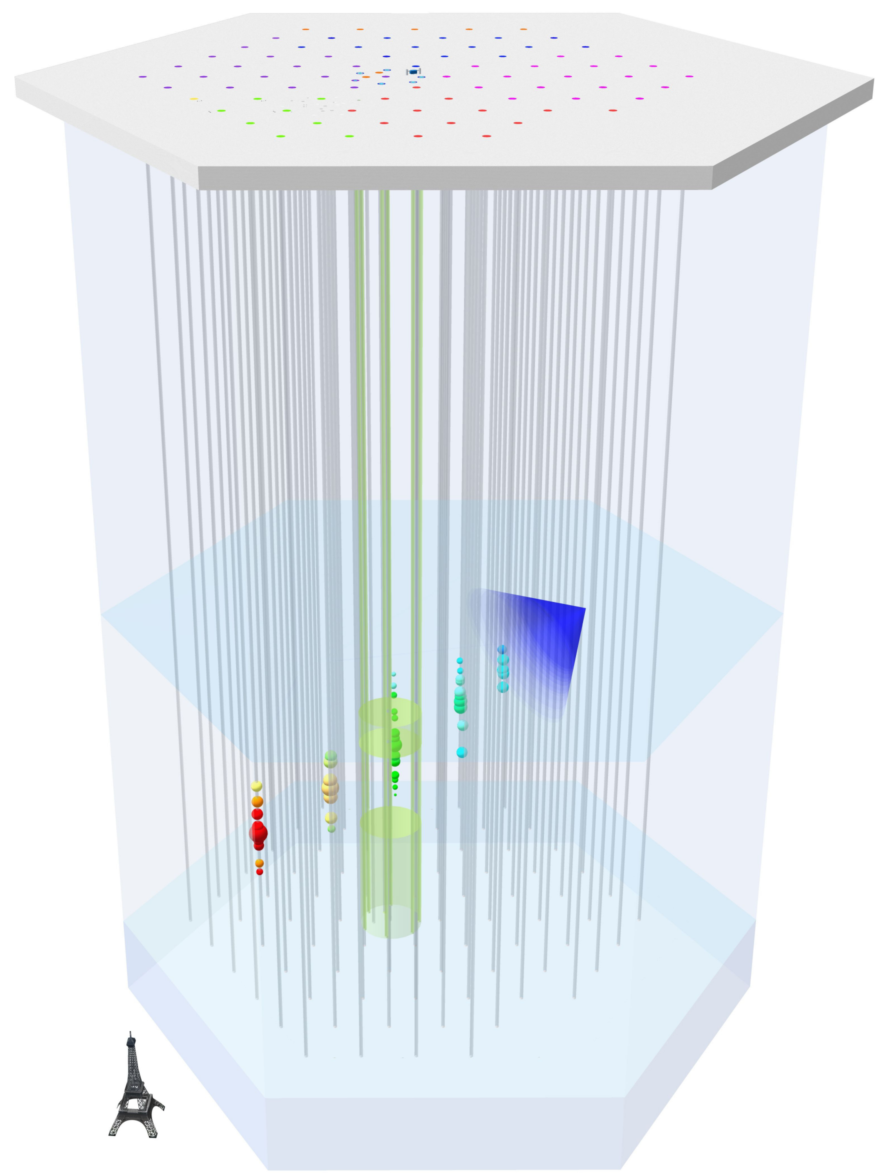
- For scenarios in which Δm is small, this interaction sufficiently reduces the DM relic density. These scenarios are referred to as “compressed mass spectrum”.

- These cosmologically motivated compressed mass spectrum scenarios can be experimentally difficult to probe.



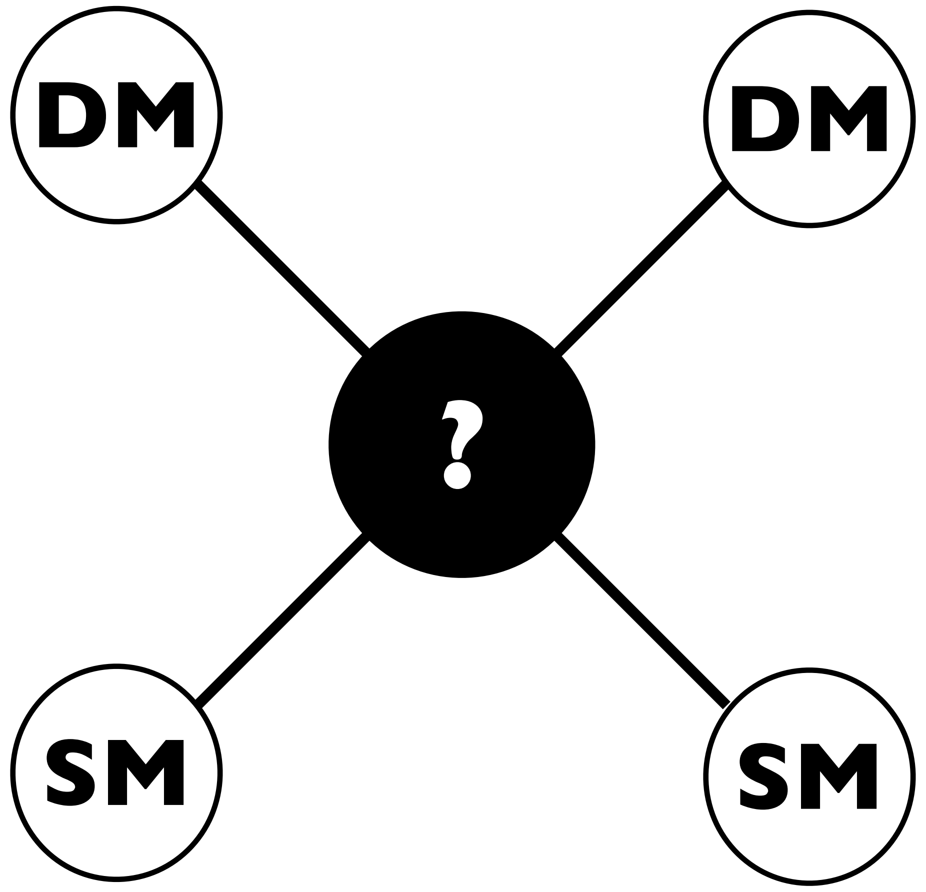
Searching for SUSY Dark Matter

How do we search for DM?

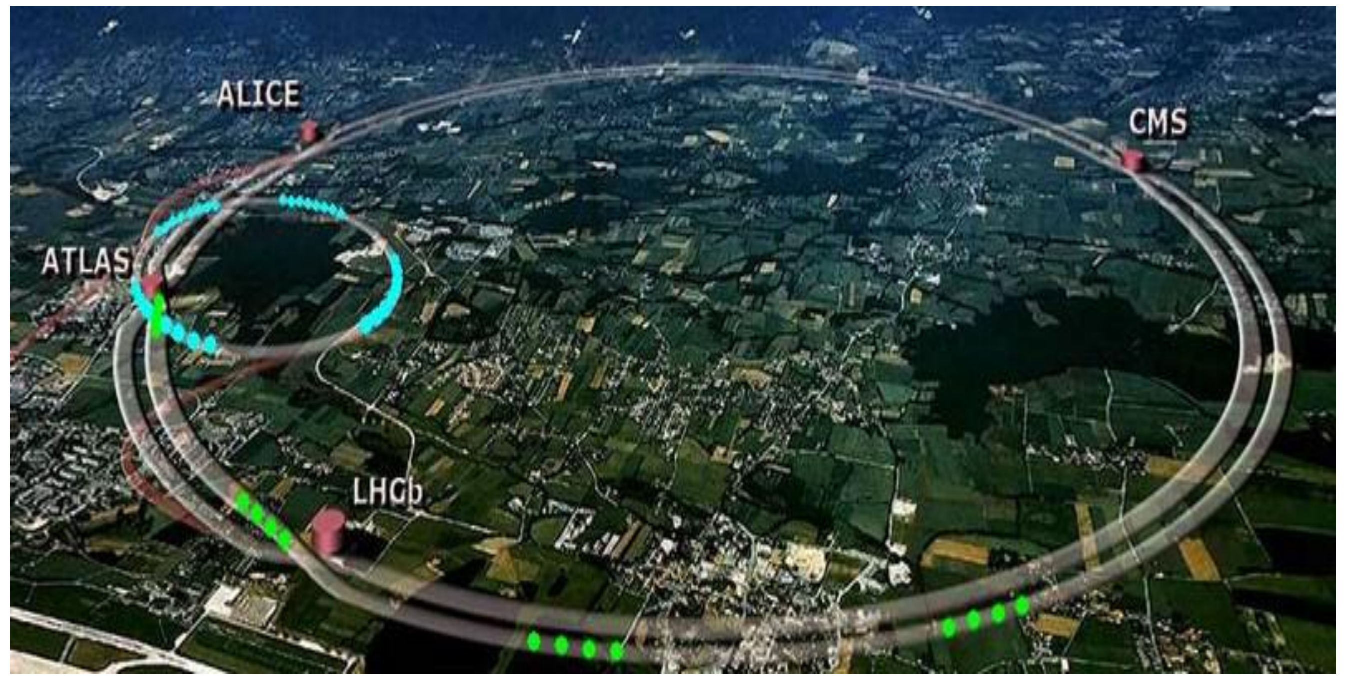


https://www.prisma.uni-mainz.de/files/2018/12/08_physik_etap_icecube_neutrinos_01.jpg

Indirect detection (ICECUBE)

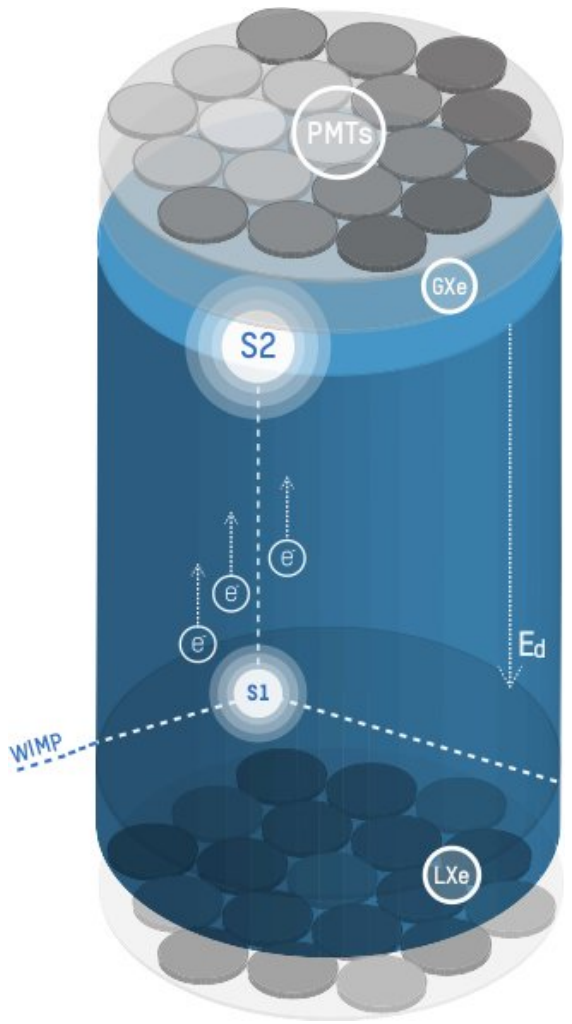


Particle production - direct detection (LHC)



https://www.forbes.com/sites/startswithabang/2016/03/11/could-the-lhc-make-an-earth-killing-black-hole/?sh=4efada152ed5

Scattering event - direct detection (XENON)



https://www.wikiwand.com/en/XENON

Can we measure DM at the LHC?

Yes! The DM Relic density can be parameterized via $m(\tilde{\chi}_1^{\pm})$, $m(\tilde{\chi}_1^{0})$, Δm, & μ, and **measured within 25% accuracy using 3000 fb^{-1}.**

Connecting particle physics and cosmology: Measuring the dark matter relic density in compressed supersymmetry models at the LHC

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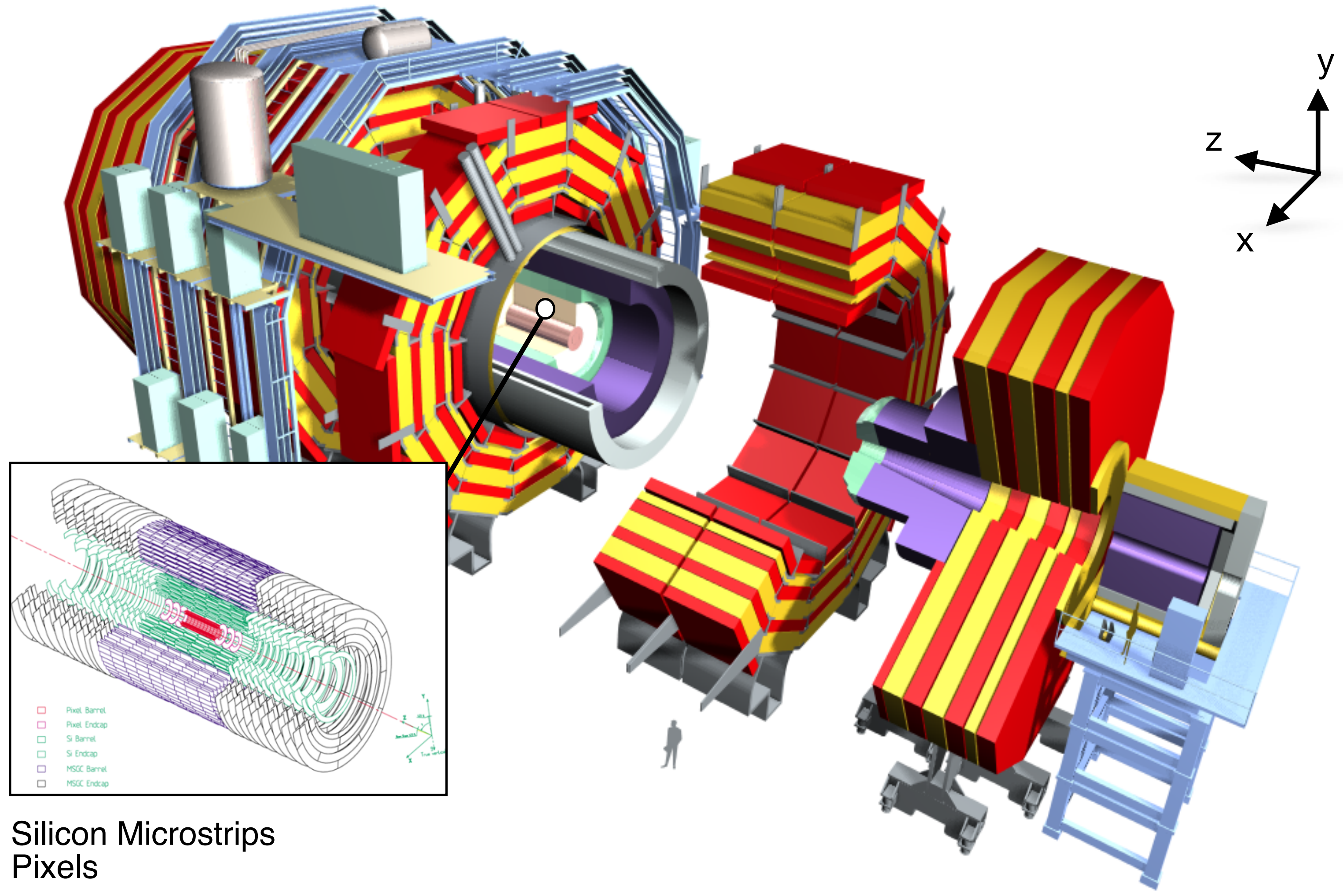
https://arxiv.org/pdf/1801.03966.pdf

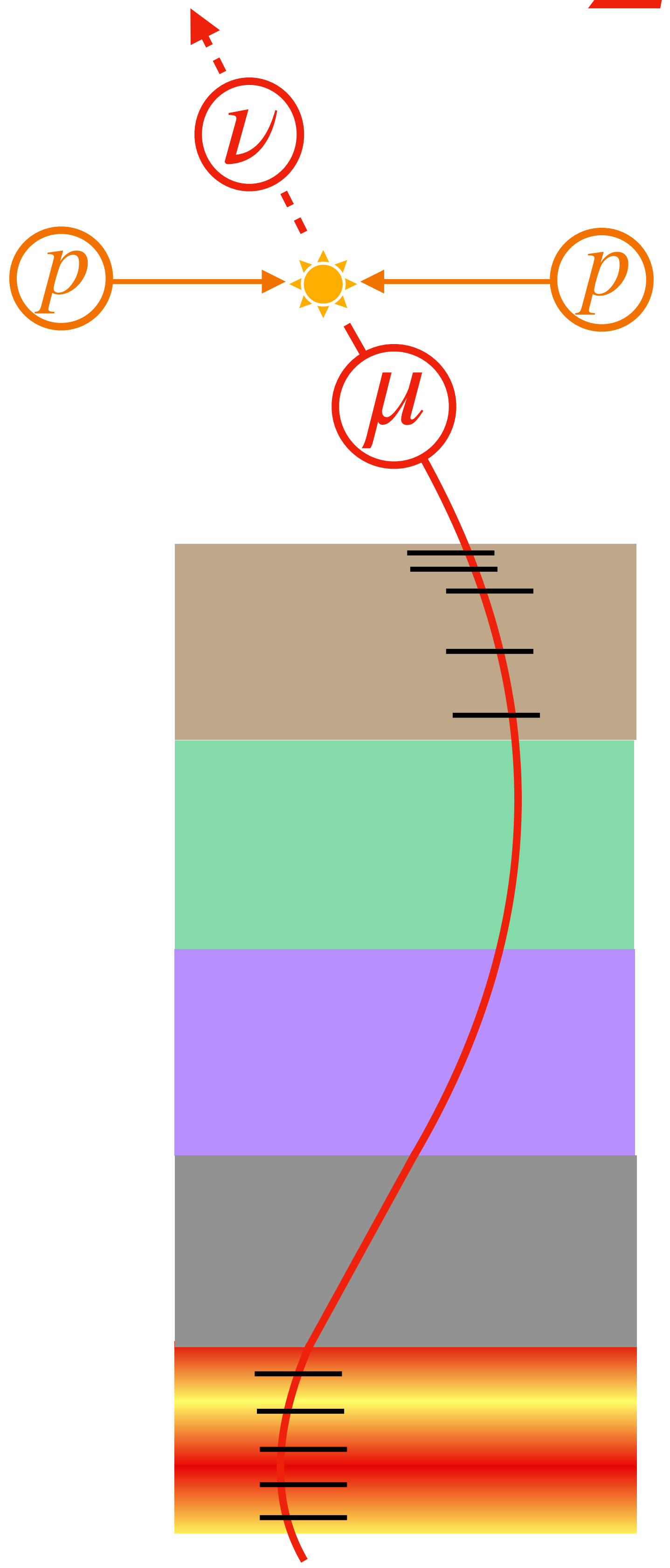
The Large Hadron Collider and Compact Muon Solenoid

https://www.symmetrymagazine.org/article/march-2015/the-lhc-does-a-dry-run



- The Large Hadron Collider (LHC) is (primarily) a proton-proton collider located at CERN, operating at $\sqrt{S} = 13$ TeV.
- The LHC consists of 2 all purpose detectors (**CMS** & ATLAS), and multiple smaller detectors.
- CMS consists of 4 detector layers + a 3.8T superconducting solenoid magnet:

$\vec{p}_{\mathrm{T}}^{miss} = -\sum \vec{p}_{\mathrm{T}}^{vis}$



Inner tracker (Pixel & Silicon Strip Tracker):

Records trajectories of charged particles, essential for reconstructing paths.

Electromagnetic calorimeter (ECAL):

Measures energy of electrons, positrons, and photons.

Hadronic calorimeter (HCAL):

Measures energy of hadronic material (protons, neutrons, pions, etc.)

3.8T solenoid magnet:

Bends charged particles to measure p, $\quad r = \dfrac{p}{qB}$

Muon Chamber:

Tracks muons, aids in muon particle identification.

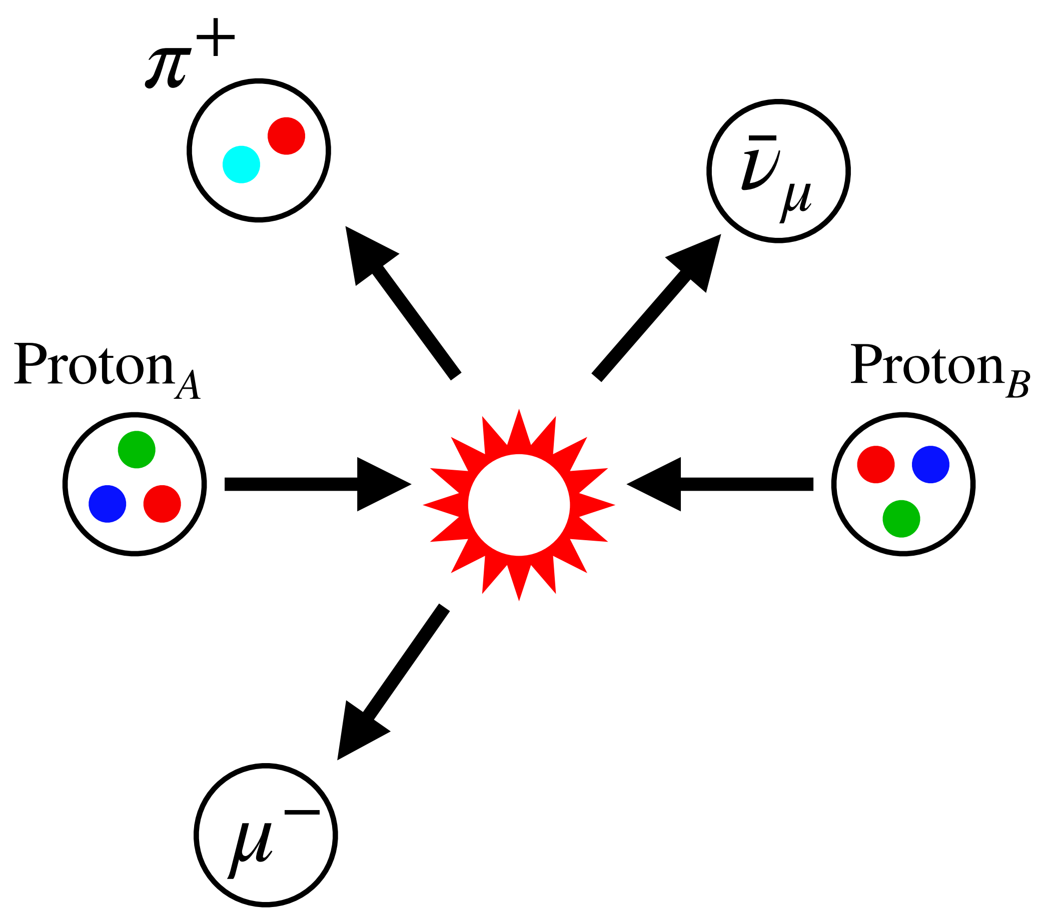
- Protons are collided in well defined momentum states. The total incoming momentum is zero (subject to a Parton Distribution Function), therefore outgoing momentum is zero, per conservation of momentum.
- CMS records tracks of charged particles, and deposits of energy in calorimeters. Not all particles interact with the detector (e.g. neutrinos, dark matter).
- We can infer undetected particles using “missing momentum”:

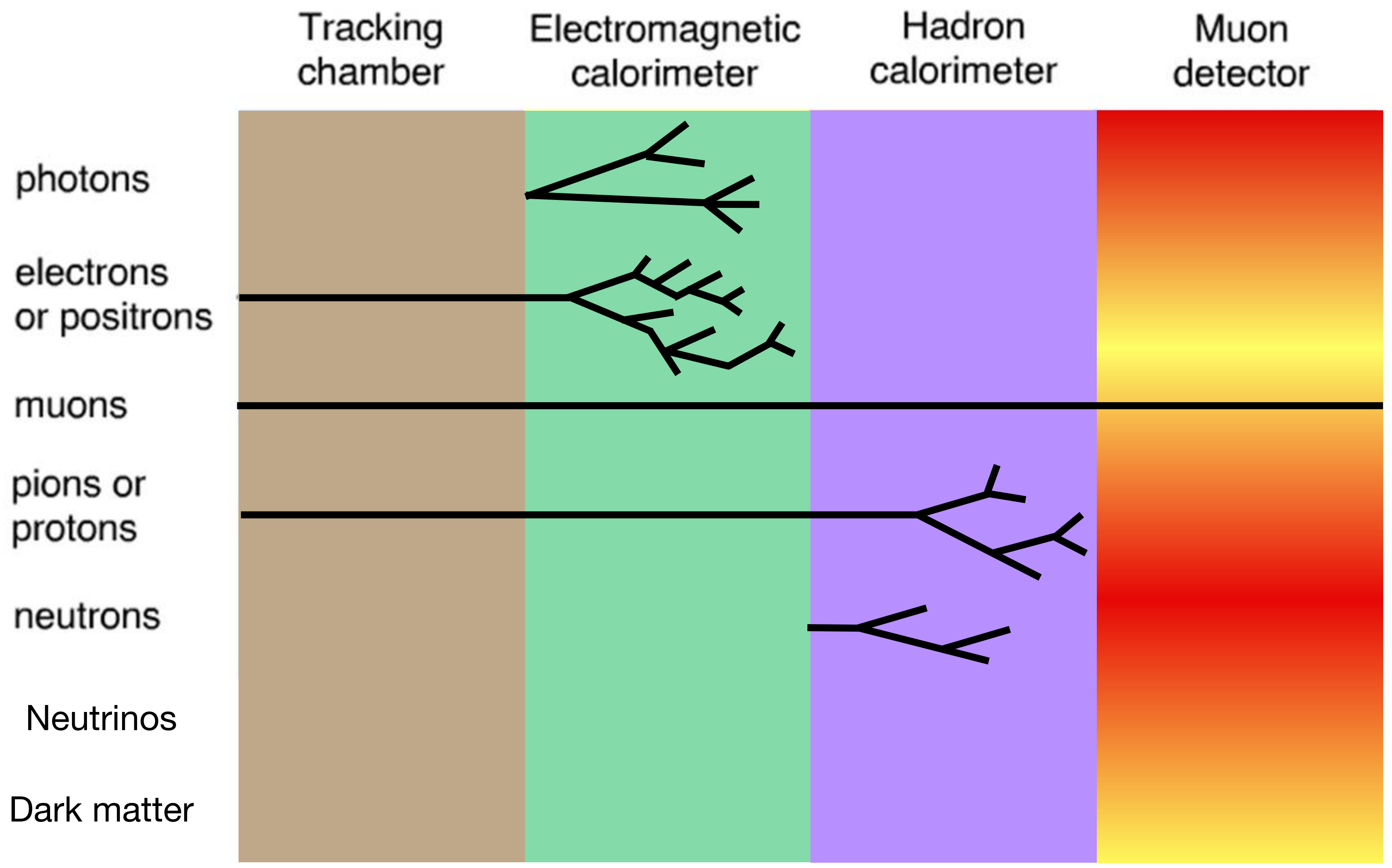
$$\sum \vec{p}_{(Total)} = \sum \vec{p}_{(visible)} + \sum \vec{p}_{(invisible)} = 0$$

- We can then define two common search quantities (working along the transverse plane offers the best resolution):

$$\vec{p}_T^{\,miss} = -\sum \vec{p}_{(T,visible)} \qquad E_T^{miss} = \left|\sum \vec{p}_{(T,visible)}\right|$$

- CMS records 4×10^7 proton bunch crossings every second, many containing multiple interactions (Pile-up). To reduce this number, triggers are employed to signal an event should be permanently recorded. These triggers reduce the data rate to $\approx 1\,kHz$.

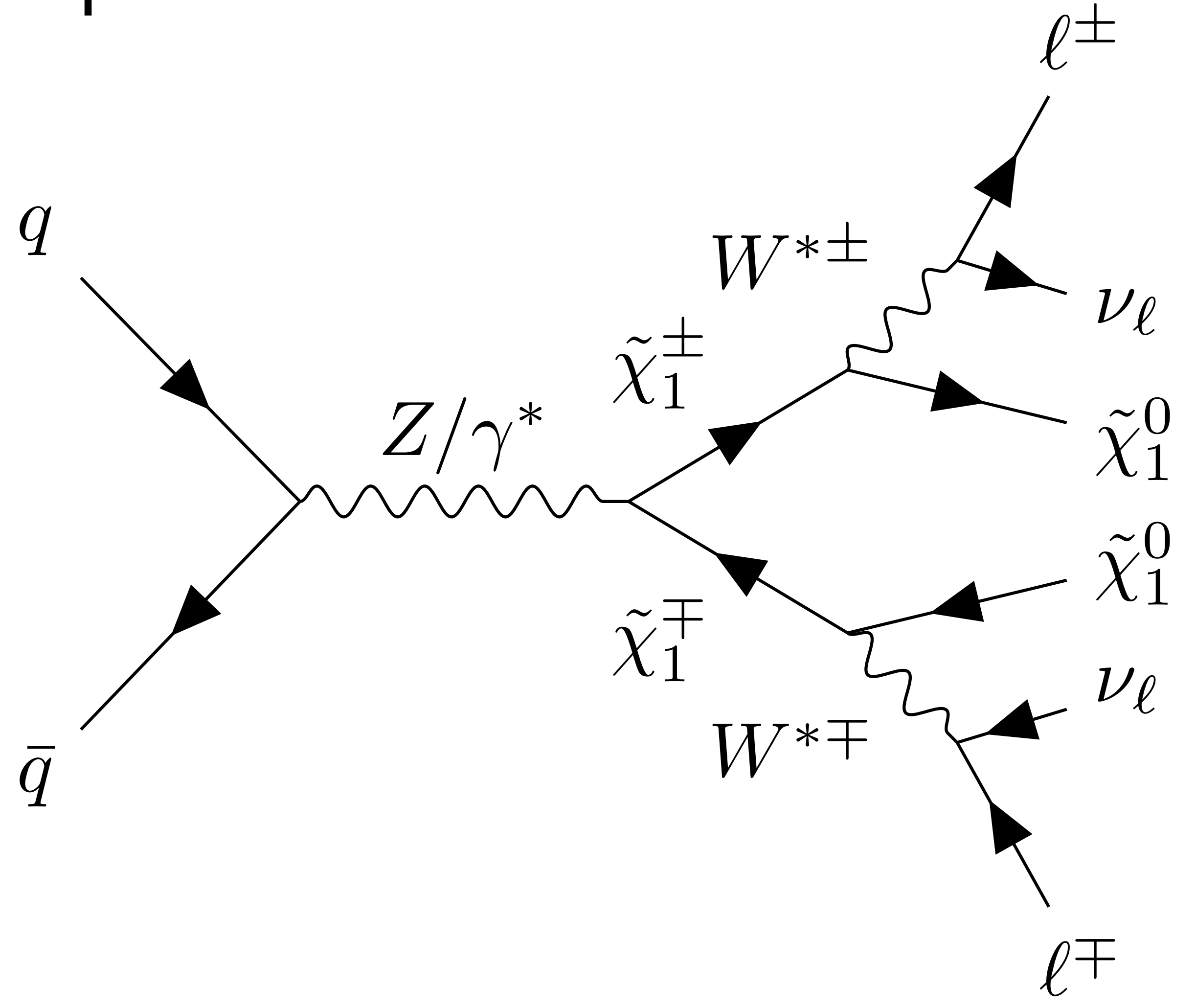


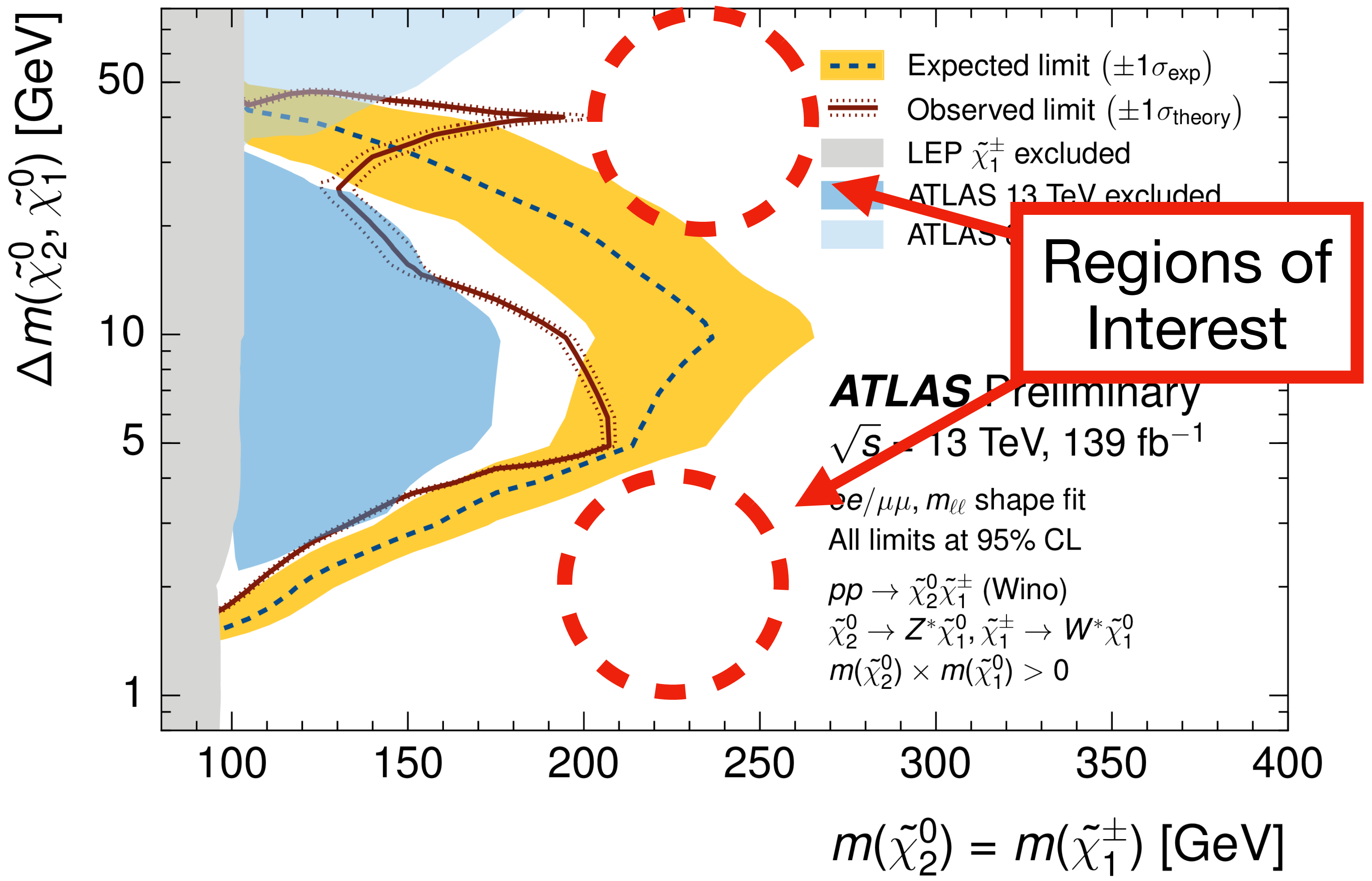


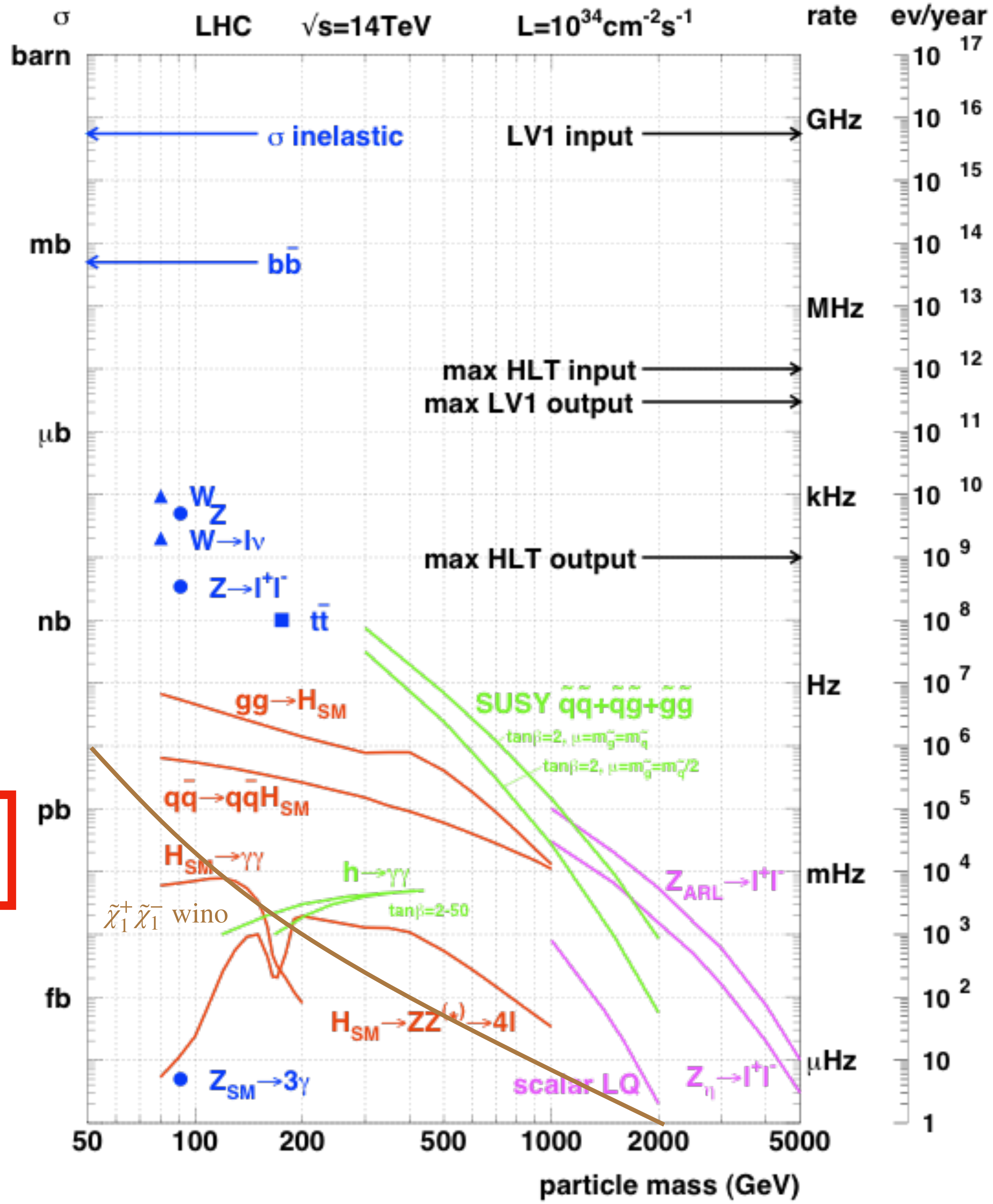
Particle interactions with specific detector layers.

Traditional SUSY Searches

- Traditional SUSY searches have targeted colored sparticles due to their significantly higher cross sections at hadron colliders.
- These searches have **excluded** 1st & 2nd generation squarks and gluinos out **~2 TeV**.
- Electroweakinos have similarly been excluded to **~1 TeV** for certain simplified models, assuming large Δm.
- **Such searches lose sensitivity for compressed mass spectrum scenarios** due to soft decay products ($p_{\mathrm{T}}(\ell)$ is typically $\approx \Delta m/3$).
- **We need a new interaction topology** in order to probe compressed mass spectrum scenarios.

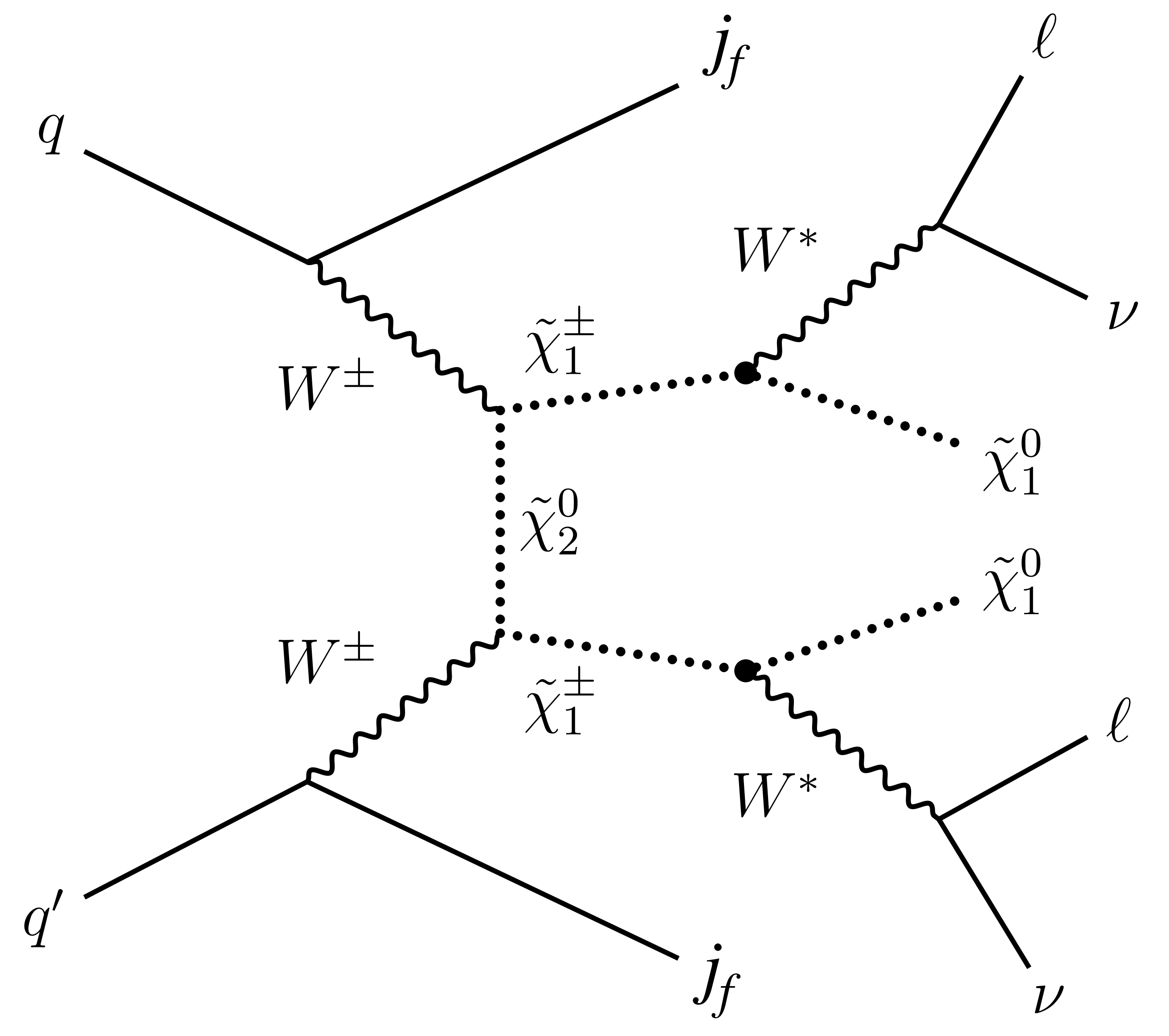




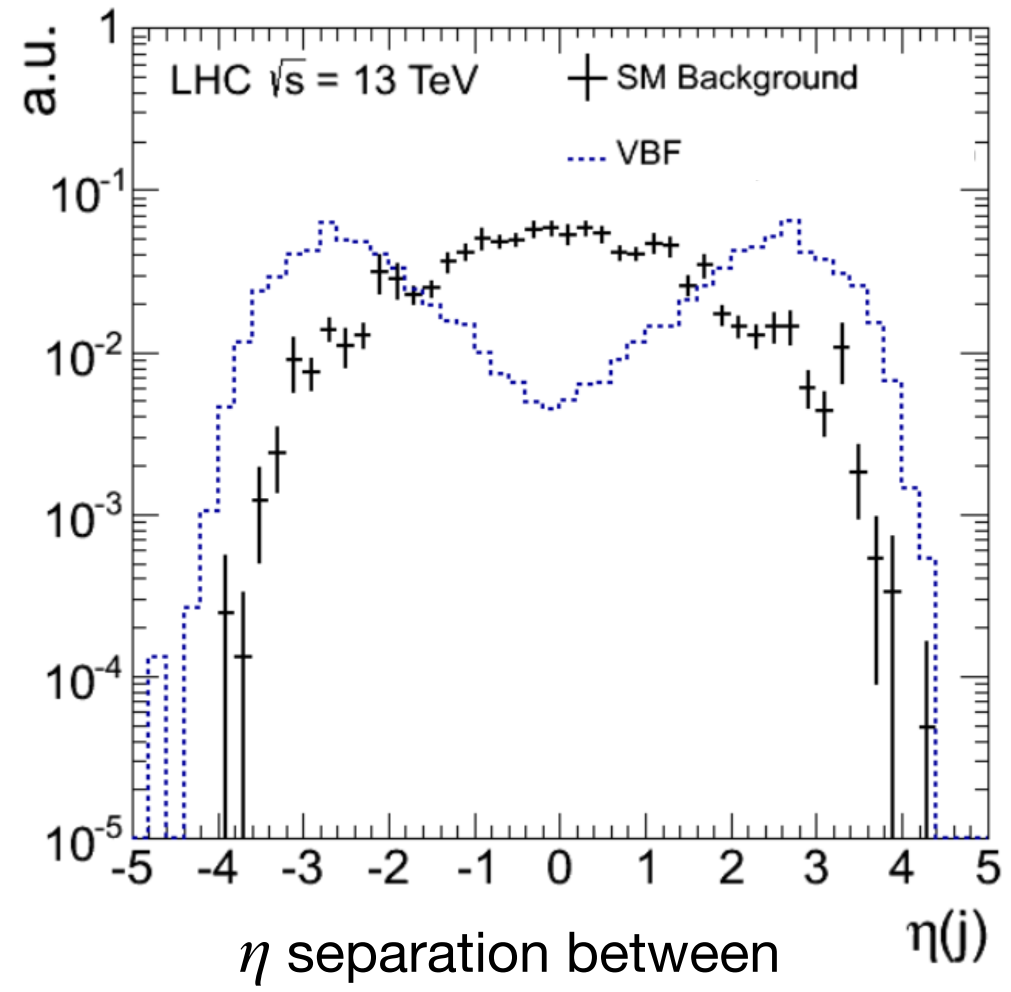


Vector Boson Fusion (VBF)

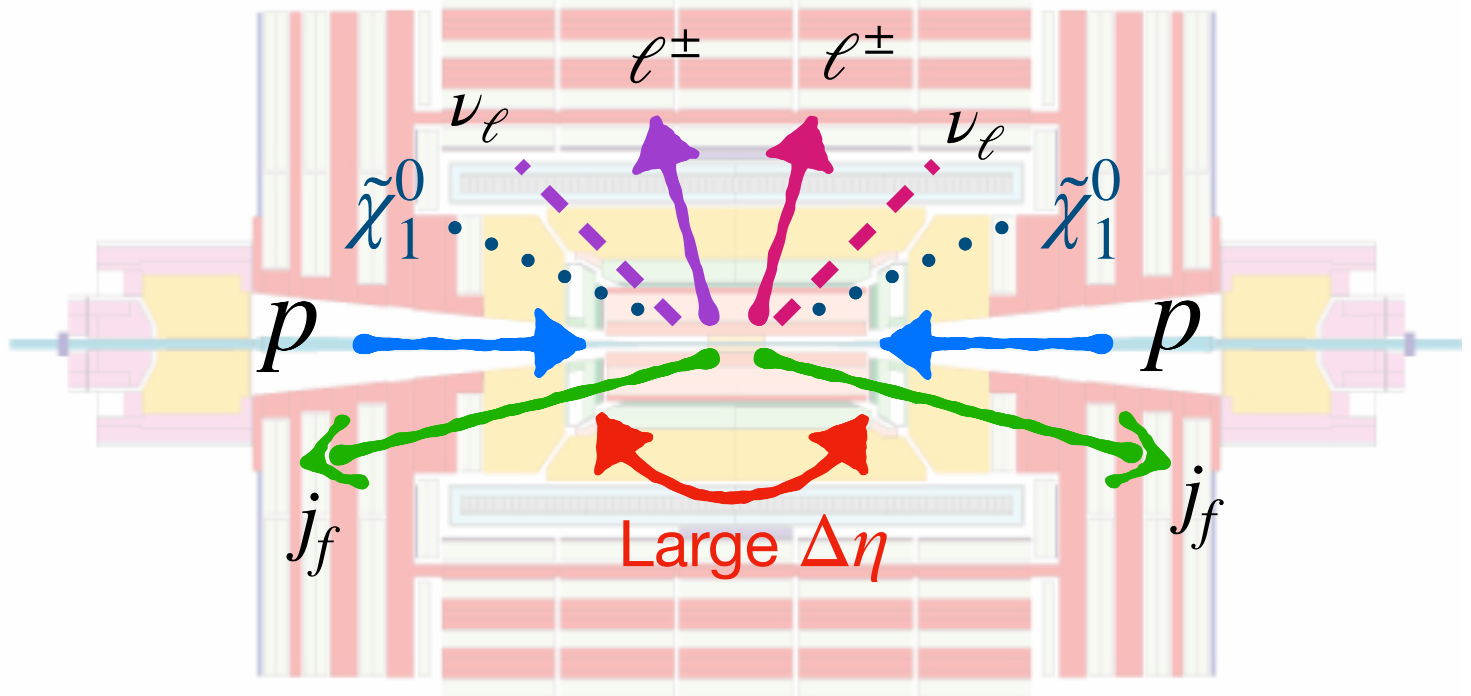
- Vector boson fusion (VBF) is a rare production mechanism, which provides a novel approach to probing compressed mass spectrum scenarios.
- VBF occurs when partons radiate weak vector bosons. These bosons “fuse”, producing a recoil effect which aids in the detection of E_T^{miss} and identification of soft decay products.
- VBF is characterized by two high-p_T jets, occurring in opposite hemispheres of the detector, with a large invariant dijet mass (m_{jj}) and large gap in pseudorapidity ($\Delta\eta > 5$).
- These unique interaction characteristics effectively suppress other SM background processes, which will produce decay products primarily along the transverse plane.
- The combination of the recoil effect from the heavy jets, with the SM BG suppression that allows for probing of small mass gap scenarios.



A VBF SUSY interaction resulting in 2 forward jets, 2 leptons, and E_T^{miss}.



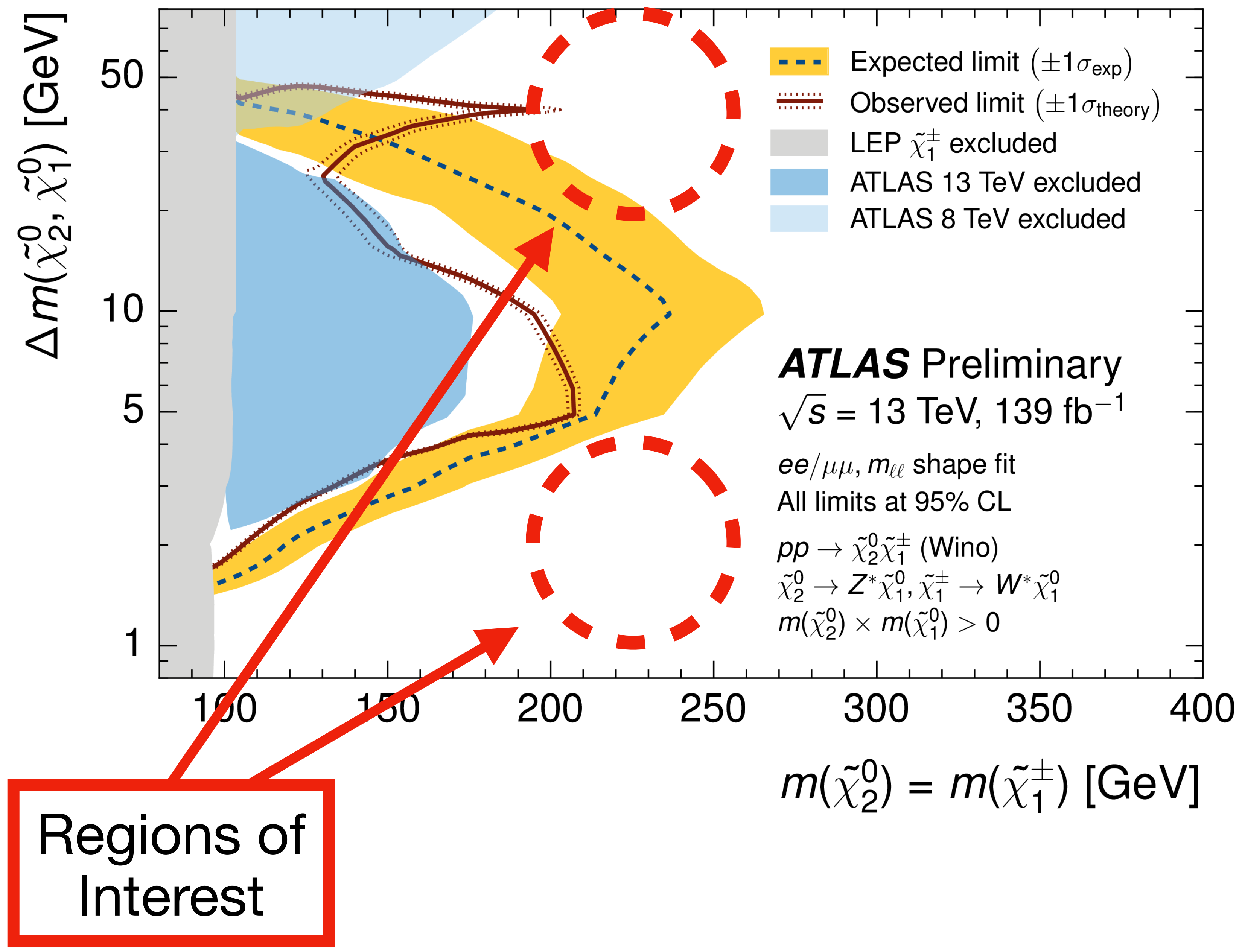
η separation between VBF & SM backgrounds.



A visualization of a VBF interaction, as seen in the detector.

Conclusion

- The standard model of particle physics represents one of the most accurate theories of physics ever created. It has predicted the existence of numerous particles which were eventually discovered, however there are known problems with the model.
- Dark matter is a mysterious substance we can infer gravitationally but currently have no firm understanding of what it might consist of.
- Supersymmetry postulates a symmetry which doubles the total number of particles in the universe and can solve multiple problems in modern physics.
- The Large Hadron Collider is a particle detector that searches for signs of new physics, including SUSY. To date, no new physics has been found outside the standard model, but searches are ongoing.
- Our group uses Vector Boson Fusion to search areas of phase space that are traditionally hard to probe. This will help us determine if SUSY is a correct theory, or just a fruitless endeavor.



Thank you! Questions?