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Cosmology Short Course for Planetarians

September 27th, 2012

THE PARTICLE NATURE OF DARK MATTER (WHAT IS THIS STUFF MADE OF?)

What is the Dark Matter?

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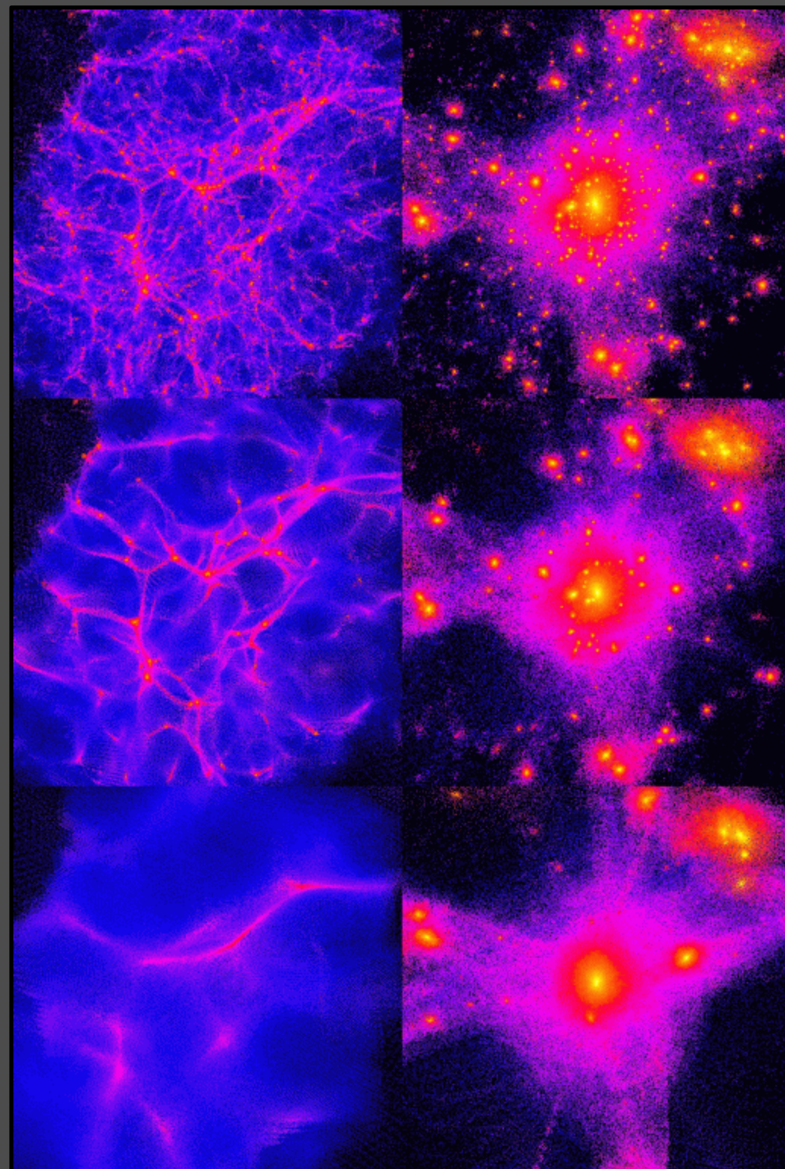
Cold

Warm

Hot



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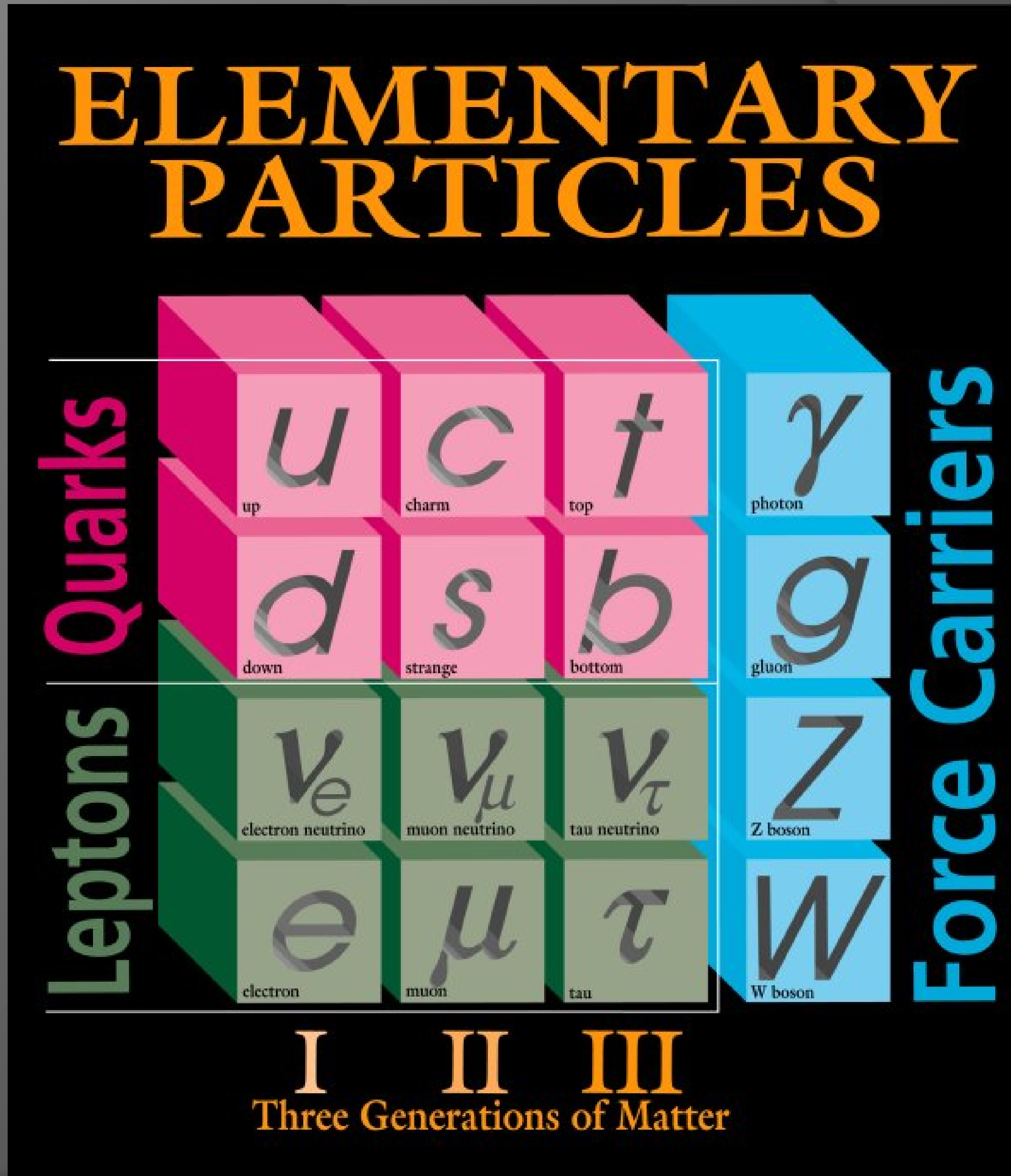
  - Stable
  - Dark (do not significantly emit, reflect or absorb light)
  - Collisionless (do not significantly scatter with atoms or themselves)

The Four Known Forces

- Physicists know of four forces that act in our universe:

Force	Range	Carrier	Acts on
Strong	nuclear distances	gluon	quarks, gluons, particles made of quarks
Electromagnetic	all distances	photon	electrically charged particles
Weak	subnuclear distances	W^+, W^-, Z^0	quarks, leptons, particles made of quarks
Gravity	all distances	graviton (not yet observed)	all particles

- In order for dark matter particles to be "dark" and "collisionless", they must not possess electric charge or feel the strong force


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I II III
Three Generations of Matter

The Dark Matter Candidate Zoo

- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie*. “WIMPzillas”)
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, mirror matter, and many, many, many others…

WIMPs
(Weakly Interacting Massive Particles)

- Of these many proposed possibilities for the particles that make up dark matter, a class of hypothetical particles called WIMPs are particularly interesting
- Currently, most particle physicists believe that new (yet undiscovered) particles exist with masses in the ~10-1000 GeV range (~10-1000 times the mass of the proton; for comparison, the recently discovered Higgs boson has a mass of about 125 GeV) – the Large Hadron Collider was designed and built to discover these particles
- In many well motivated and popular particle physics theories, some of the new particles interact only through the weak force, and can only be destroyed or created in pairs – this makes an isolated particle stable
- Such particles are called WIMPs, and could very well make up our universe's dark matter

How Many WIMPs Were Created In (and survived) The Big Bang?

- $T >> M_X$ ($t < 10^{-12}$ sec.), WIMPs are about as abundant in the universe as other types of particles (electrons, neutrinos, etc.)
- $T < M_X$, no longer enough energy present to easily create WIMPs, but WIMPs continue to be destroyed – number of WIMPs becomes exponentially suppressed
- But the universe is expanding and getting bigger very quickly – before you know it, there are too few WIMPs left for them to encounter each other
- In typical models, the abundance of WIMPs that survives this process is roughly equal to the measured density of dark matter in our universe – in other words, if particles like WIMPs exist, then one should expect them to make up most of the mass in the universe

But what are the WIMPs?

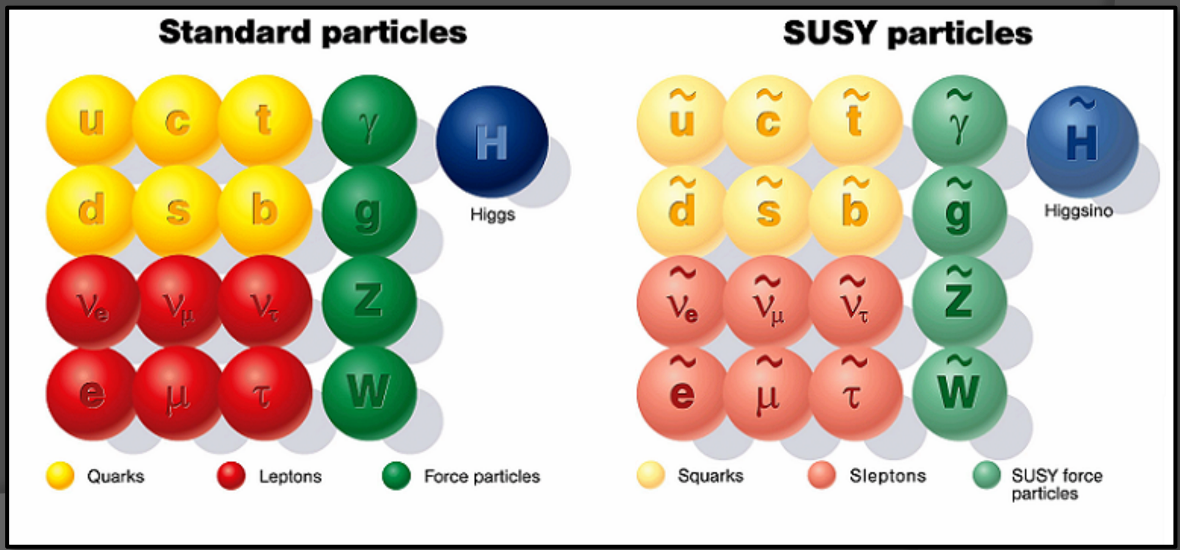
Beyond Known Particles - Supersymmetry!

-In the 1970s, a new theory known as supersymmetry was invented
-According to this theory, matter and force cannot exist without each other
-If supersymmetry is manifest in nature, a number of theoretical problems can be solved

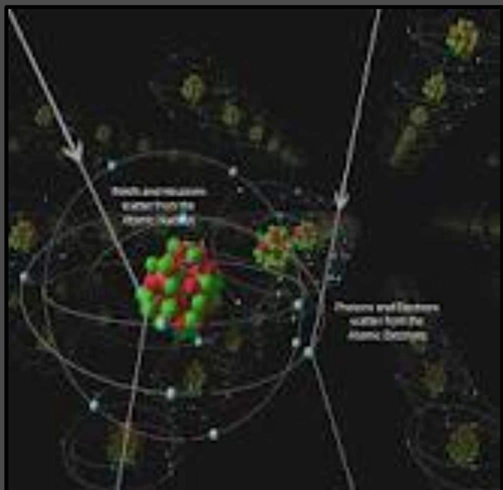
Matter ⟷ Force
(fermion particles) (boson particles)

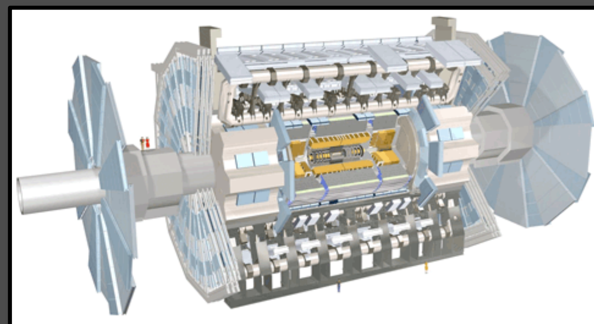
Beyond Known Particles - Supersymmetry!

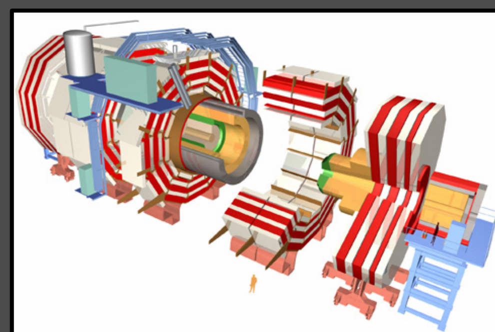
photon ⟷ photino
selectron ⟷ electron
squark ⟷ quark
graviton ⟷ gravitino
W ⟷ wino

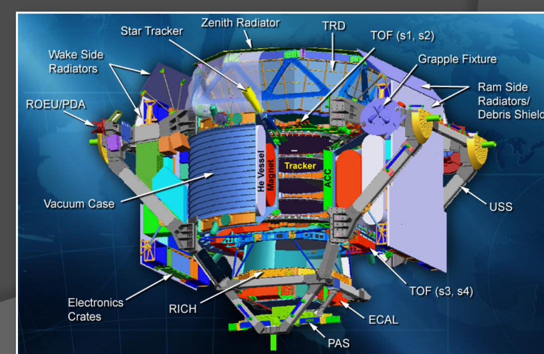


Putting the WIMP Hypothesis to the Test



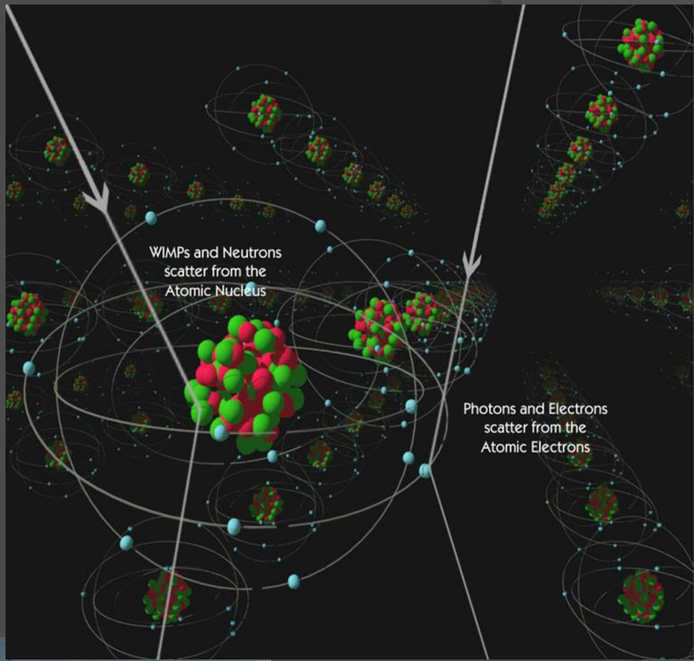






Direct Detection

- A WIMP moving a typical halo velocities (~300 km/s) striking a nucleus imparts a modest recoil
- Numerous technologies have been developed and deployed in an effort to observe these collisions
  – scintillation, ionization, phonons



The Soudan Mine

Direct Detection

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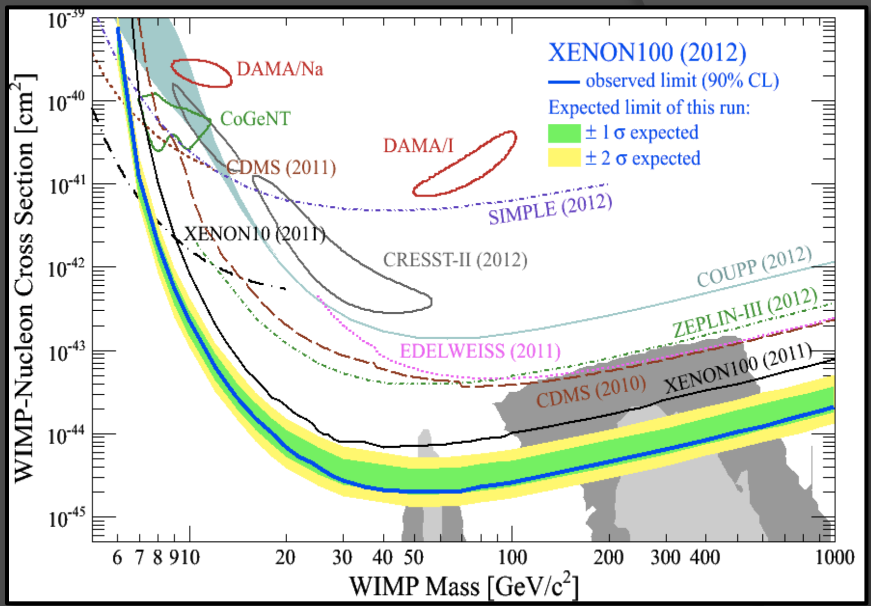
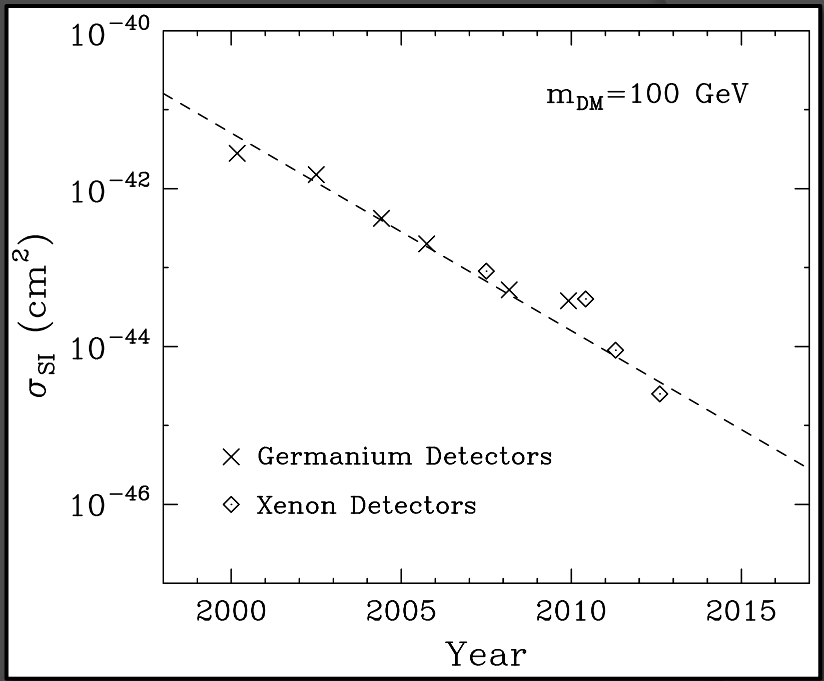
- Numerous technologies have been developed and deployed in an effort to observe these collisions – scintillation, ionization, phonons
- Current state-of-the-art experiments make use of 10-100 kg heavy nuclei targets (Ge, Xe), instrumented and located deep underground to minimize backgrounds



Direct Detection

- Over the past dozen years, constraints from direct detection experiments have improved with a Moore's-law like behavior
(a factor of 2 every 15 months)



Direct Detection

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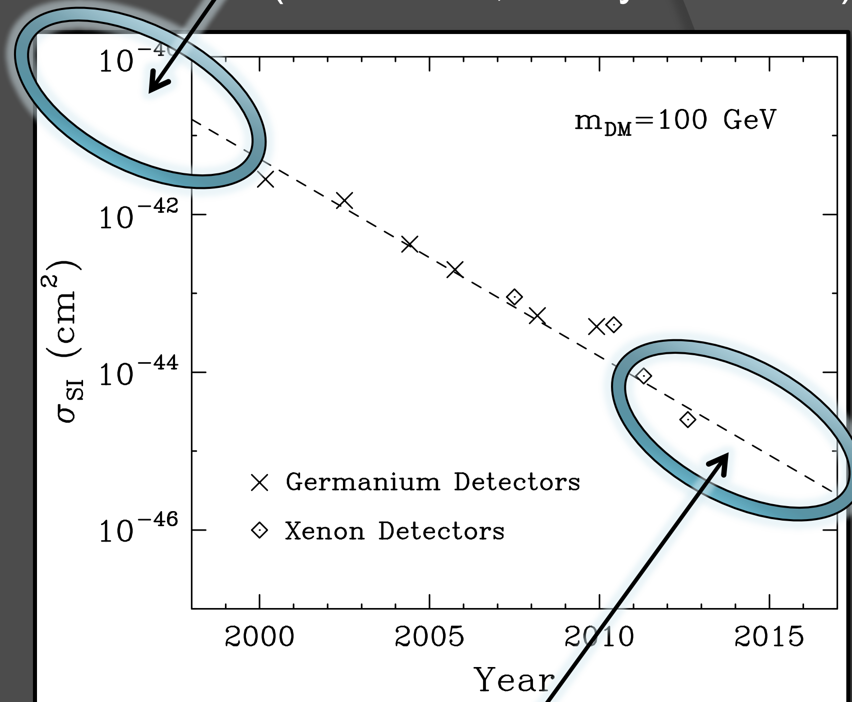
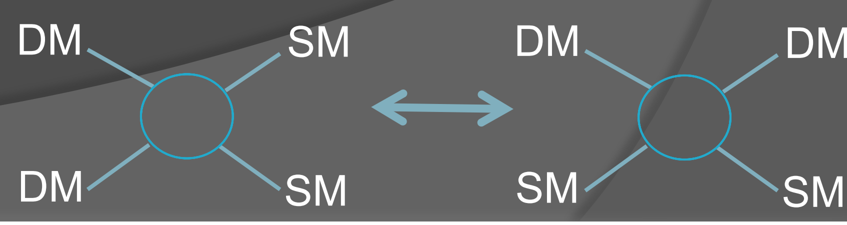
- Some important benchmarks exist along this line:
  - Mid-late 90s: Experiments (Heidelberg-Moscow, etc.) excluded the cross sections predicted for a WIMP which scatters and annihilates through Z-exchange
  - Now!: Current experiments are beginning to test WIMPs which interact through Higgs exchange (including many SUSY models)

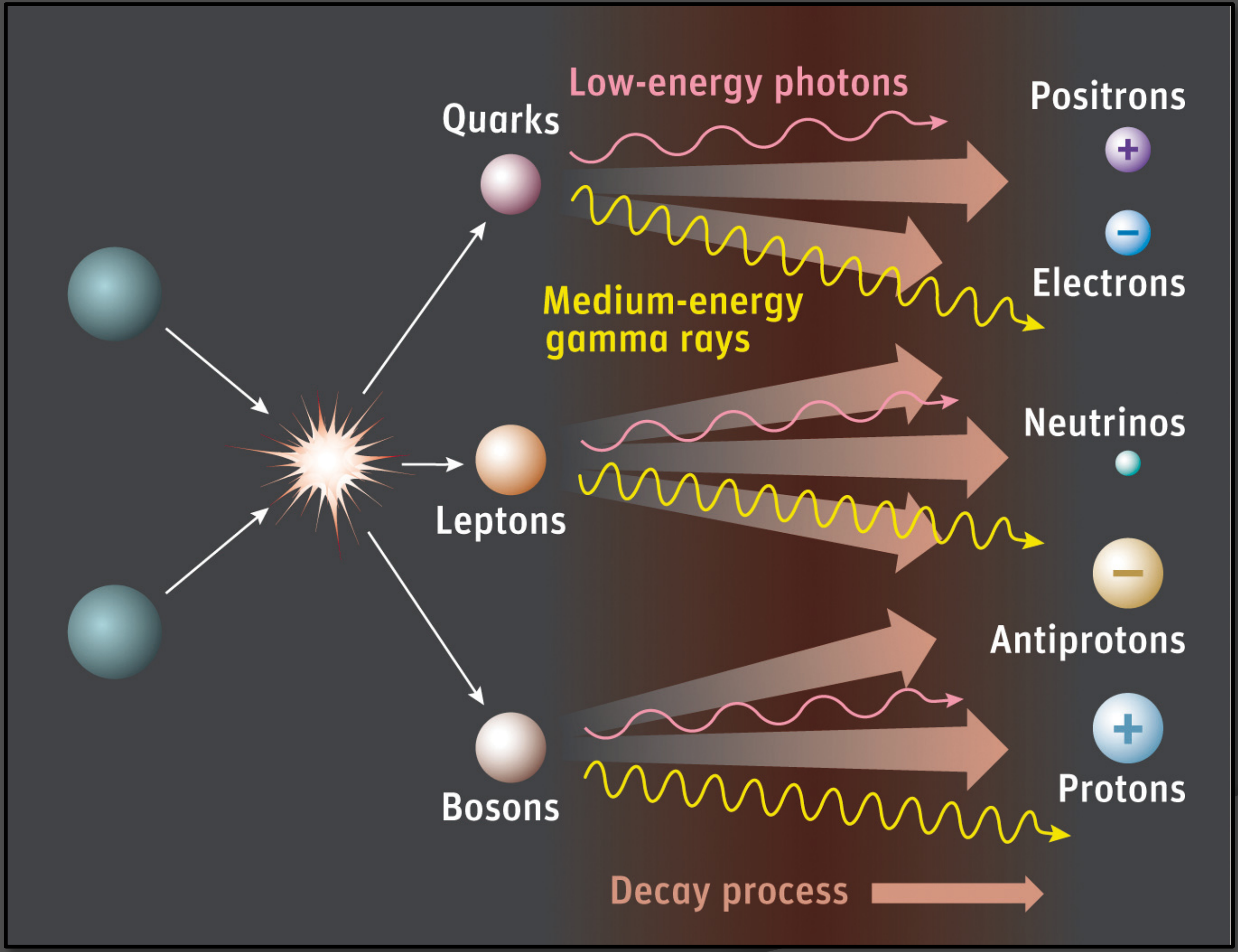
Z-mediated scattering
(sneutrinos, heavy neutrinos)



Higgs-mediated scattering
(A-funnel, focus point neutralinos)

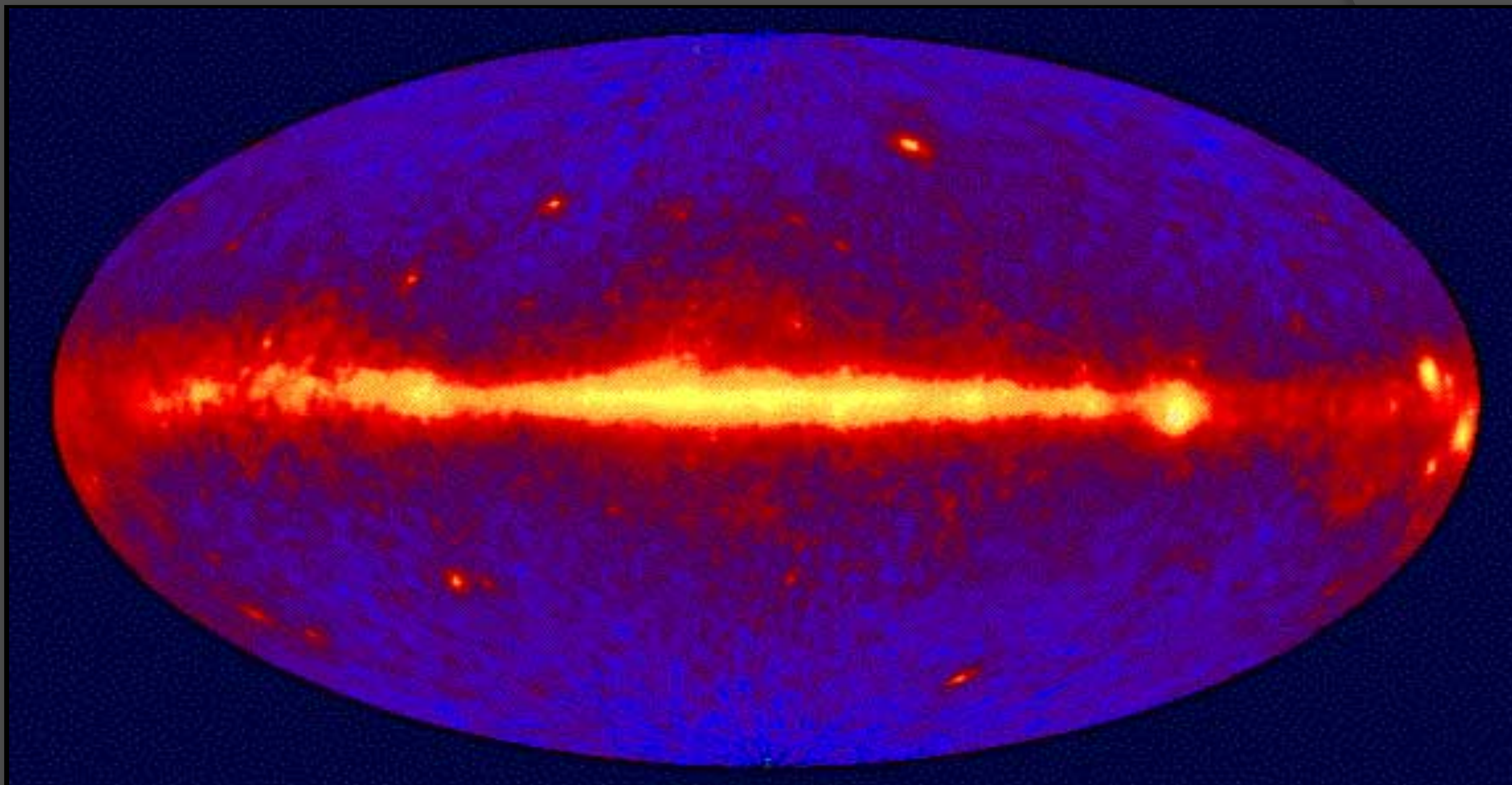


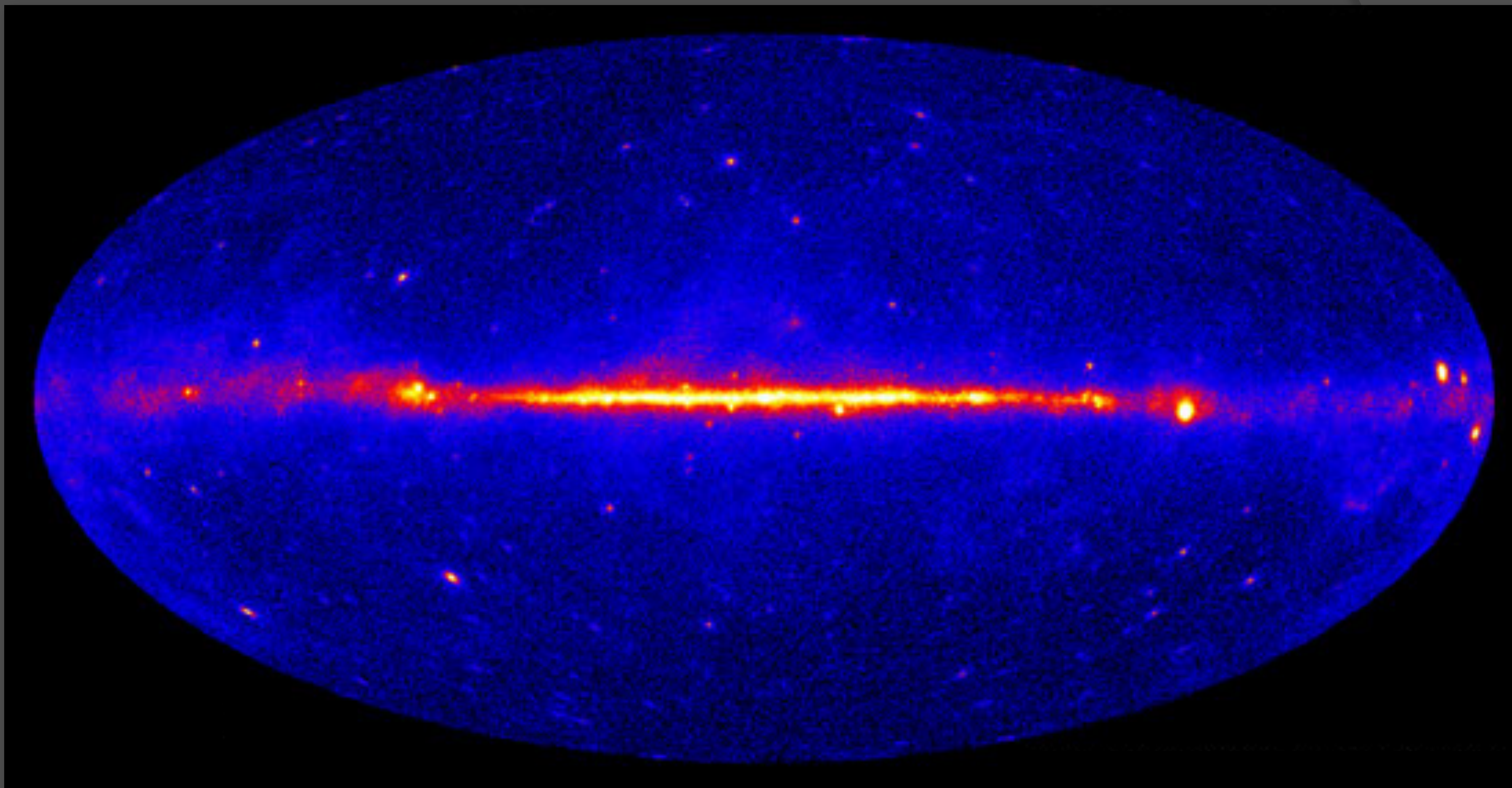
Indirect Detection



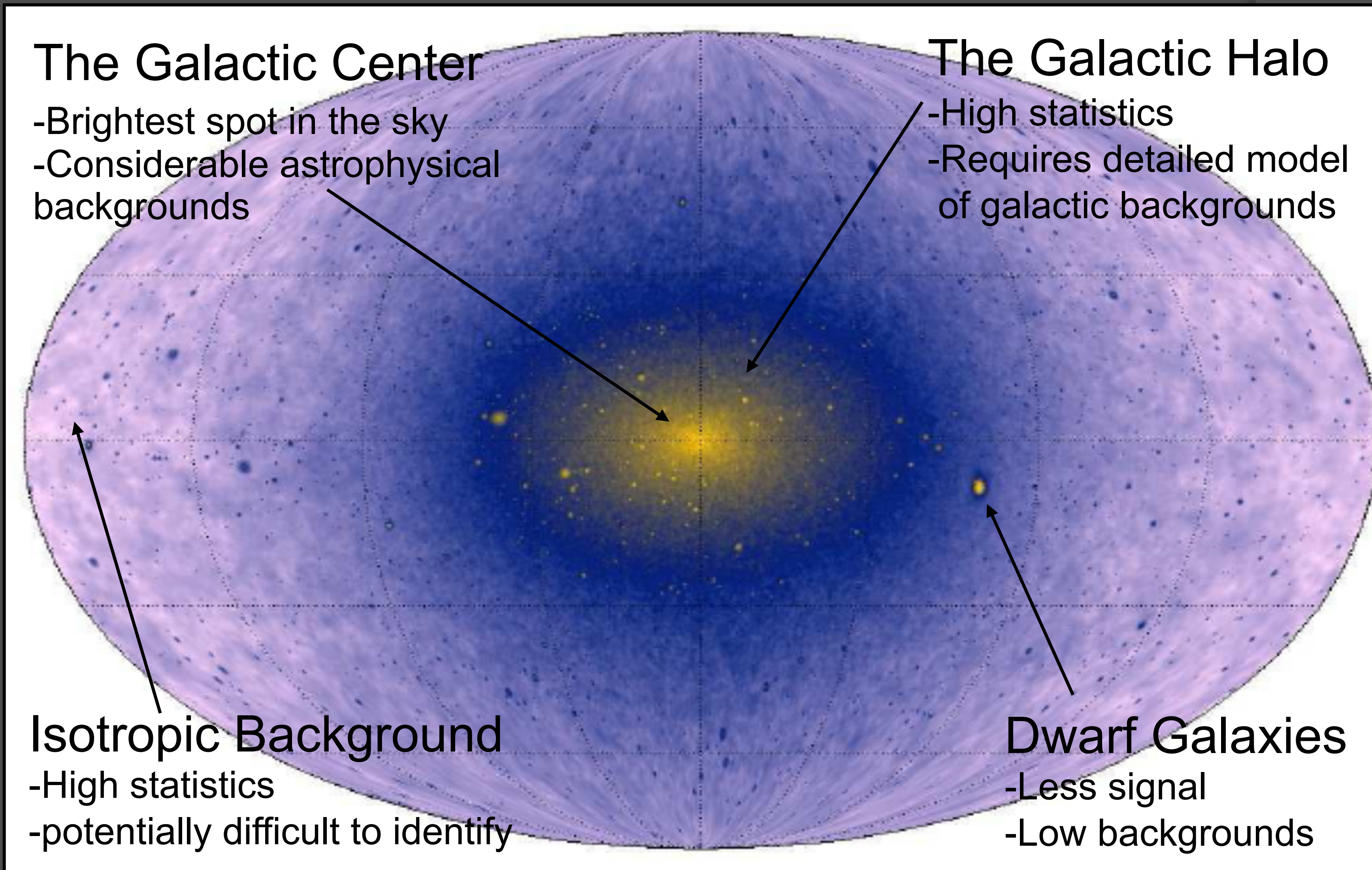
Indirect Detection With Fermi

- No indirect detection experiment has more potential to constrain or discover dark matter than the Fermi Gamma Ray Space Telescope (FGST)
- Fermi's Large Area Telescope (LAT) offers far more effective area (~8000 cm^2), better angular resolution (sub-degree), and energy resolution (~10%) that its predecessor, EGRET
- Unlike ground based telescopes, Fermi observes the entire sky and can study gamma rays down to ~100 MeV (ACTs are limited to ~100 GeV and up)





Where to look for Dark Matter with Fermi?



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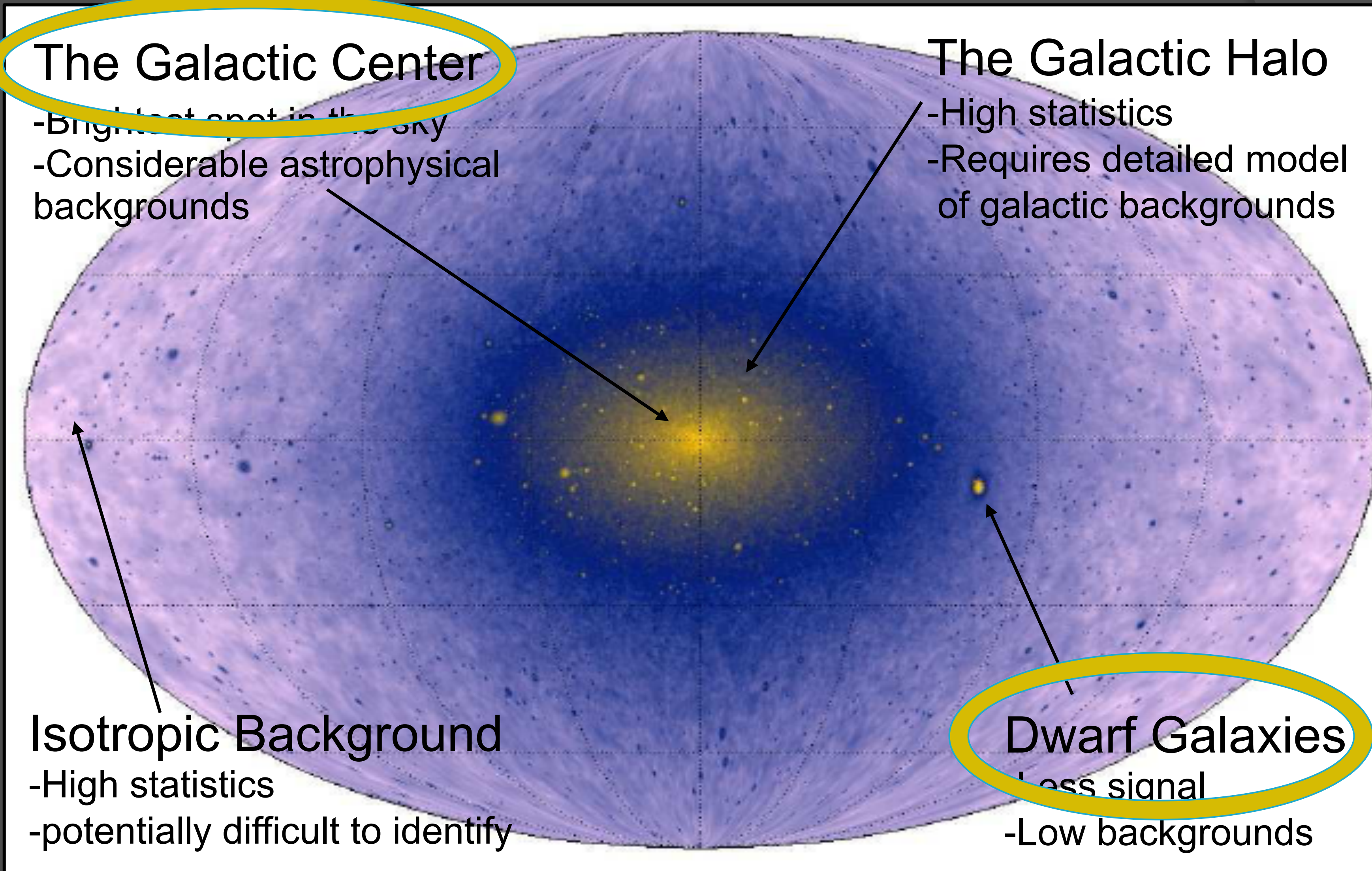
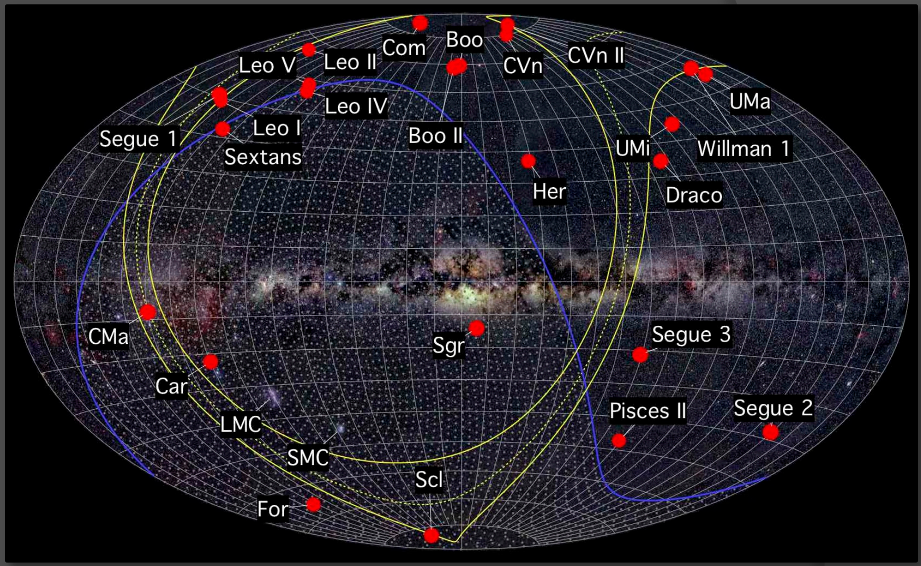


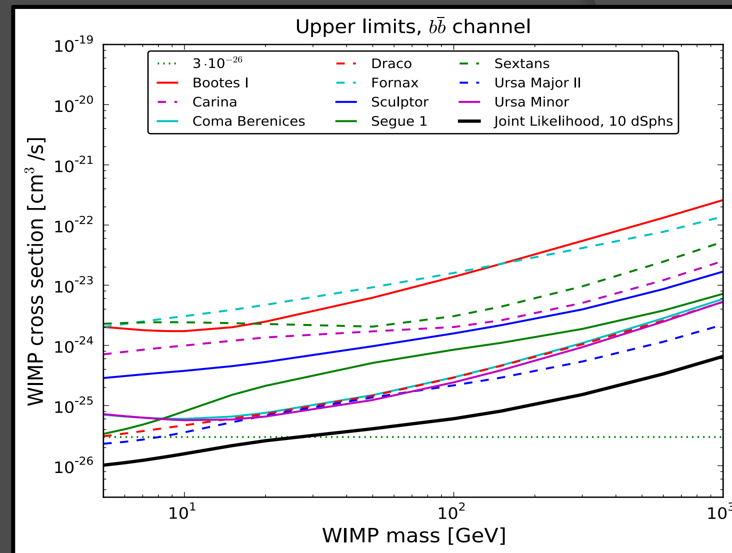
Dark Matter in Dwarf Galaxies

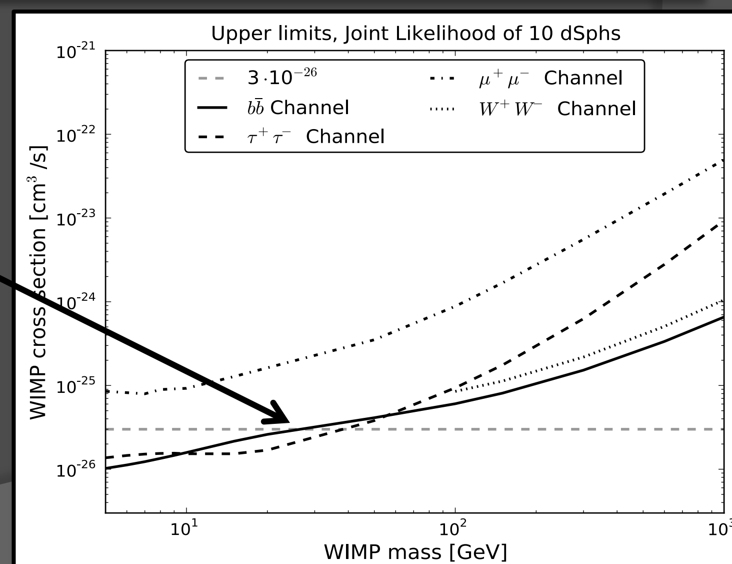
- The halo of the Milky Way contains numerous smaller halos, the largest of which are dwarf galaxies
- Dwarf galaxies are the most dark matter dominated known systems, with mass-to-light ratios as high as $\sim 10^3$
- These objects represent potentially bright sources of gamma rays from dark matter annihilations, with little in the way of astrophysical backgrounds



Dark Matter in Dwarf Galaxies

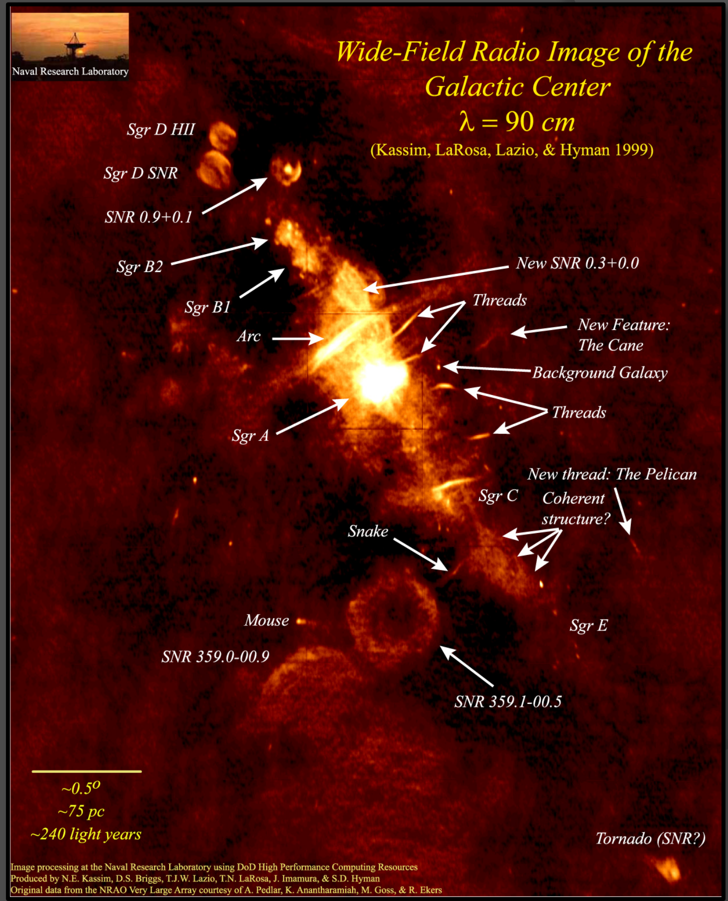
- In the summer of 2011, the results of two analyses of Fermi dwarfs were released (one by Geringer-Sameth & Koushiappas, and another by the Fermi Collaboration)
- Although no excess was reported, the lack of gamma rays can be used to derive a stringent constraint on the dark matter's annihilation cross section
- For the first time, Fermi is ruling out dark matter models with a cross section equal to the naïve estimate for a simple thermal relic ($\sigma v \sim 3\times10^{-26}$ cm^3/s) – reaching masses up to ~30-50 GeV
- With the full (10 yr.) Fermi data set and discoveries of southern hemisphere dwarfs by DES, Fermi should become sensitive to dark matter with masses as high as several hundred GeV





Dark Matter in The Galactic Center

- The volume surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood
- This does not, however, make searches for dark matter region intractable
- The flux of gamma rays predicted from dark matter annihilations around the Galactic Center is very large – tens of thousands of times brighter than that predicted from the brightest dwarf galaxies
- But to separate dark matter annihilation products from astrophysical backgrounds, one must take advantage of the distinct observational features of these components



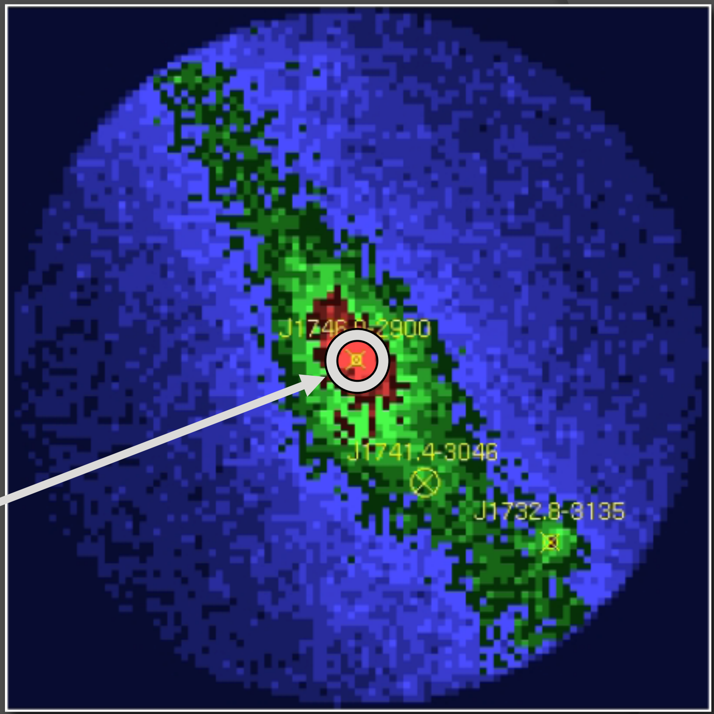
Dark Matter in The Galactic Center

The gamma ray signal from dark matter annihilations is described by:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\mathrm{los}} \rho^2(r) \mathrm{d}l$$

1) Distinctive "bump-like" spectral feature

2) Signal highly concentrated around the Galactic Center (but not entirely point-like); precise morphology determined by the dark matter distribution



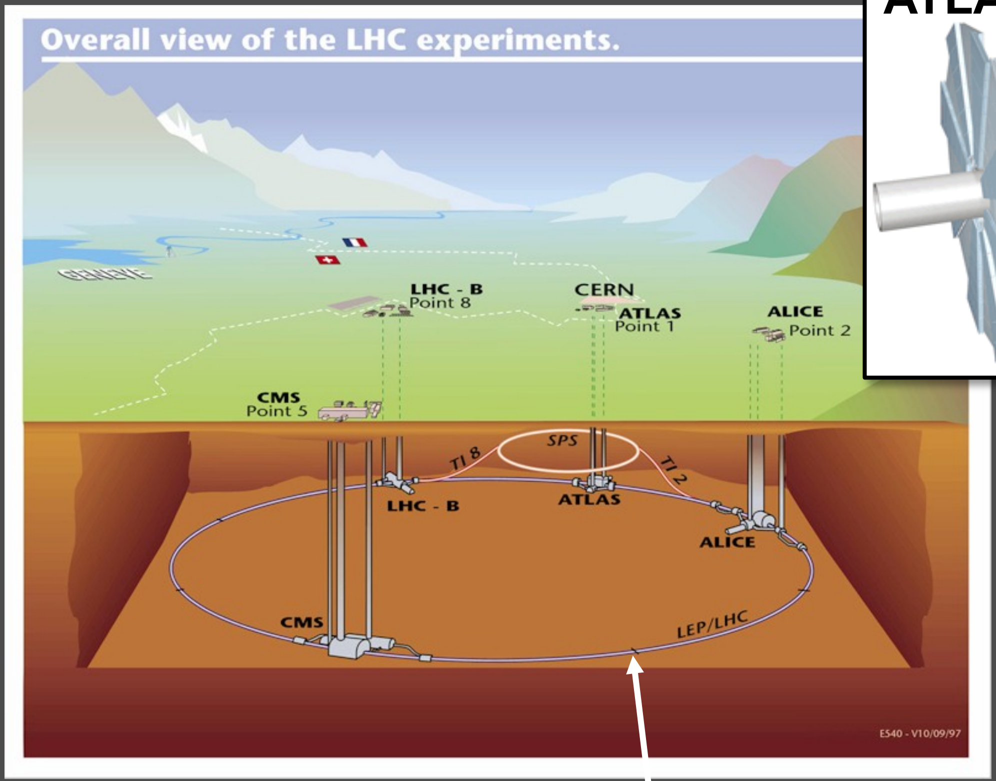
How to search for supersymmetric dark matter particles?

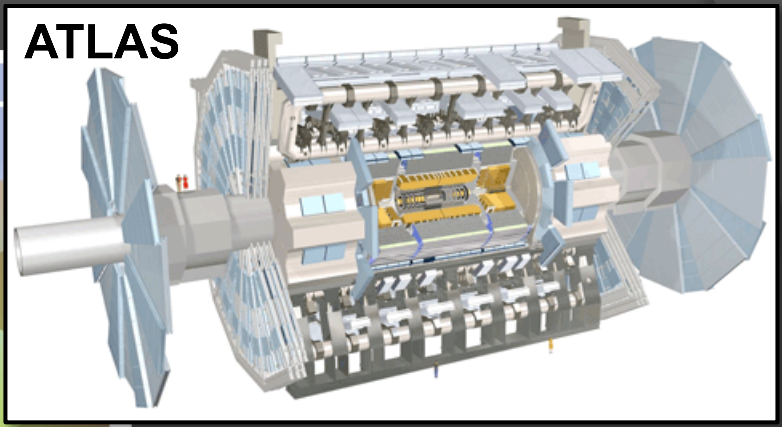
2) Create it using a particle accelerator

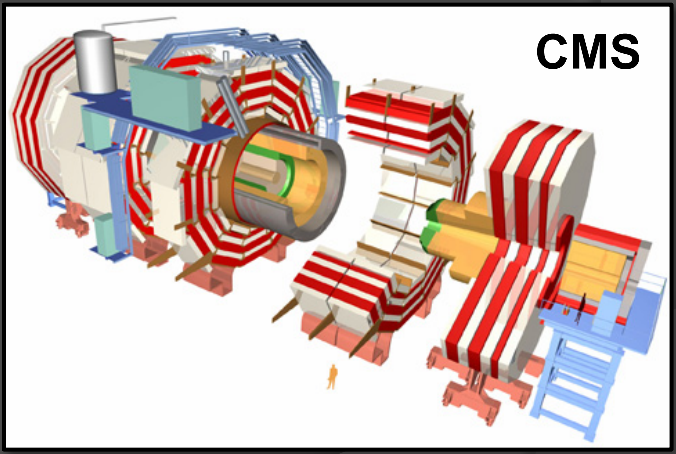
The Fermilab Tevatron

The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC)



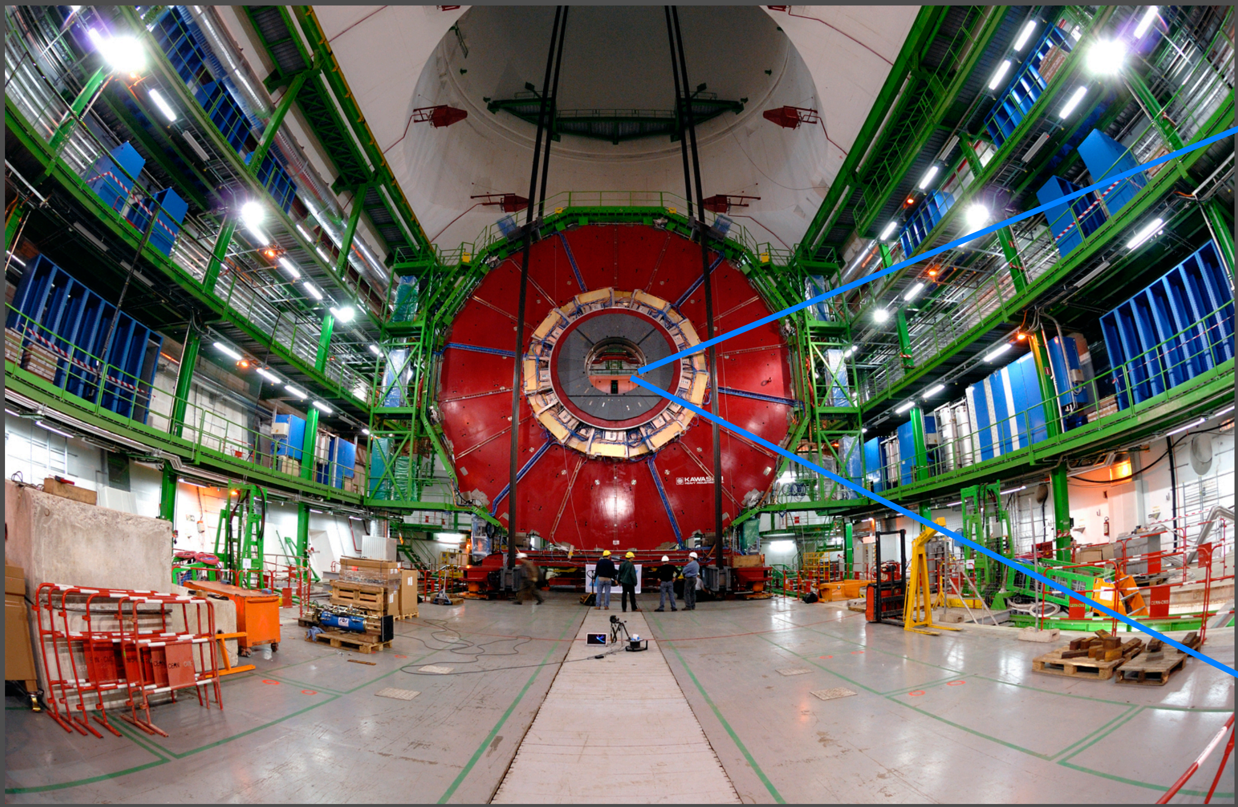




17 mile circular underground tunnel
Protons and antiprotons travel around the ring at 99.999999% of the speed of light, and then…

The Large Hadron Collider (LHC)

BLAMO! …They get smashed together!



Design Goal: 30 million bunches per second; 100 billion protons per bunch; 600 million collisions per second

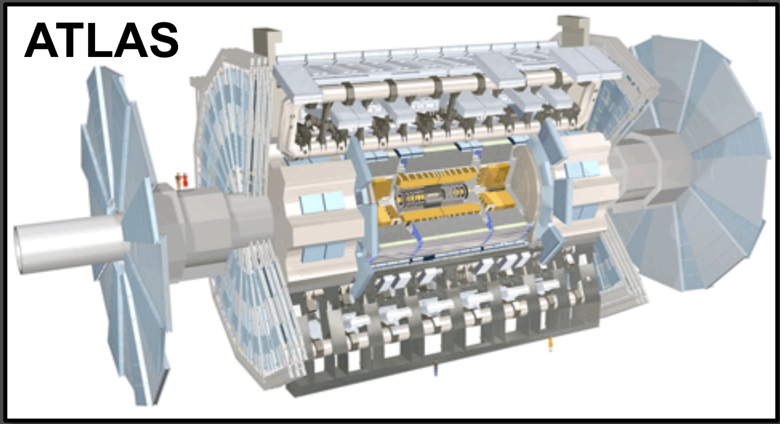
Achieved: About 10^{15} collisions so far

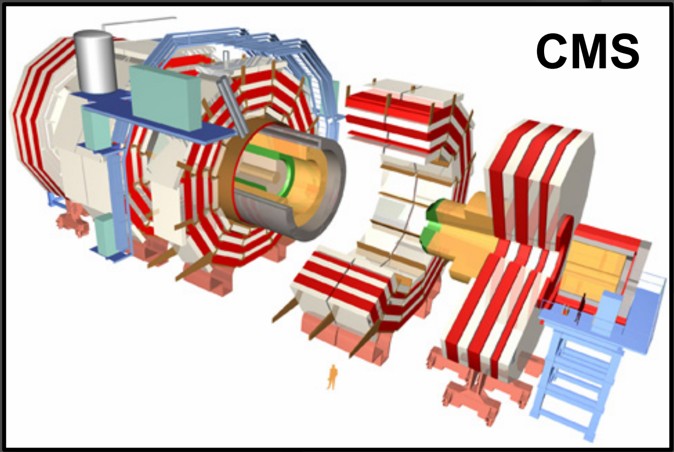
$$E = Mc^2$$

If supersymmetry exists, the LHC will almost certainly discover it!

Dark Matter at The LHC

- Machines such as the Large Hadron Collider (LHC) may be able to produce and observe dark matter particles
- The LHC collected data at a staggering rate last year, and is preparing to begin its 8 TeV run this spring
- The discovery of the/a Higgs boson with a mass of 125 GeV represents a major accomplishment for both ATLAS and CMS (and CDF, D0)
- A wide range of TeV-scale physics scenarios beyond the Standard Model are in the process of being put to the test by the LHC… including the WIMP hypothesis

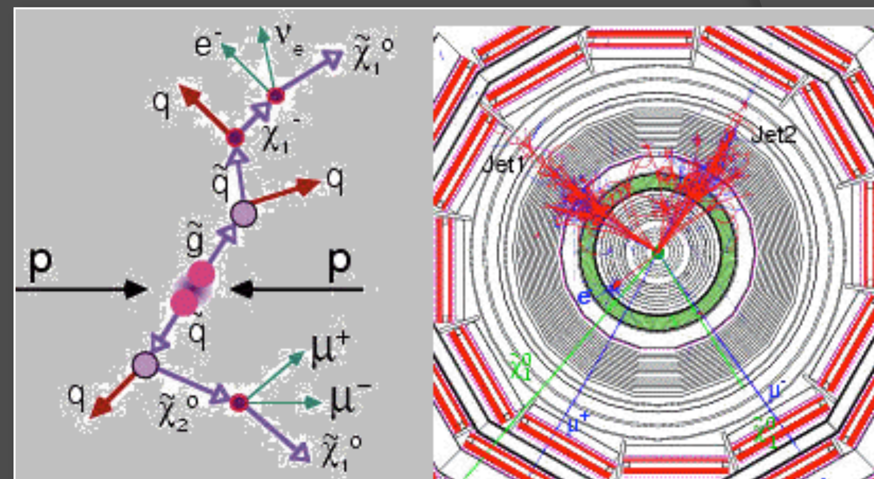




Dark Matter at The LHC

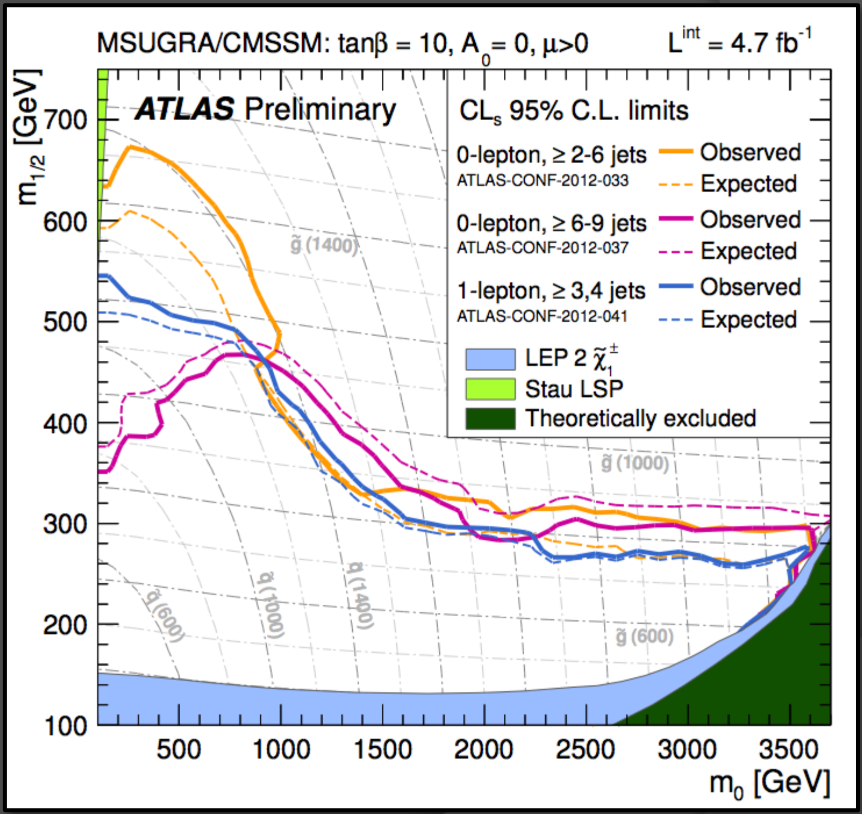
Two strategies for dark matter hunting at Hadron Colliders:

- **Strategy A (SUSY-like case):** Produce strongly interacting particles which, although not dark matter themselves, produce dark matter particles in their decays (study distributions of events with various combinations of jets, leptons, and missing energy)
- **Strategy B (Direct Production):** Produce the dark matter directly (in association with a jet or photon), leading to more model independent constraints

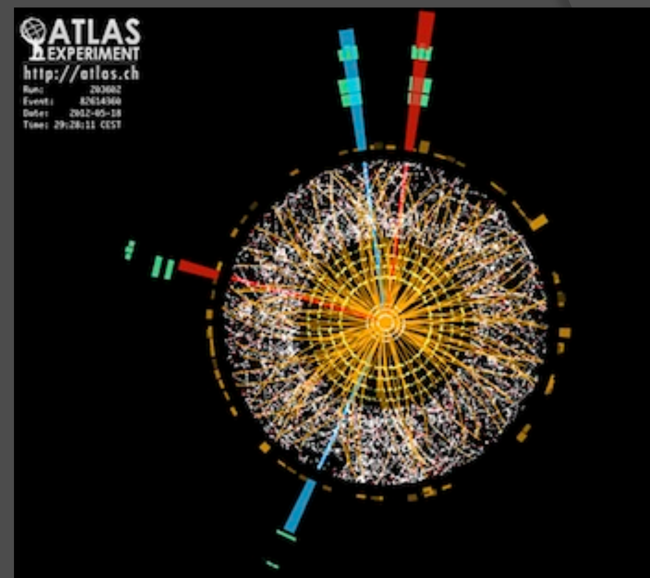


Dark Matter at The LHC

- Numerous searches for supersymmetry are being carried out by the ATLAS and CMS collaborations
- For typical patterns of superpartner masses, these results constrain squarks/gluinos to be heavier than ~1400/900 GeV (for comparison, the Tevatron probed up to ~450 GeV)
- Ultimately, the LHC will test models with squarks/gluinos as heavy as a few TeV
- Broadly speaking, models capable of addressing the electroweak hierarch problem (SUSY or otherwise) are likely to fall within the LHC's reach



The Discovery of the Higgs Boson

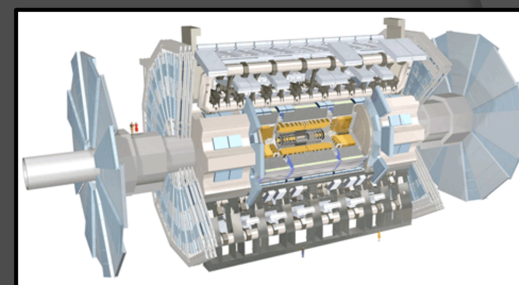


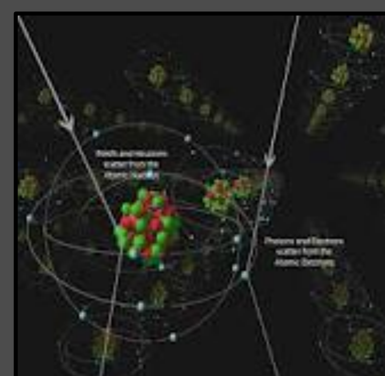
- In isolation, boson particles are required to be exactly massless in mathematically self-consistent theories (the photon and gluon are)
- But the weak force is communicated by two heavy bosons, the W and Z
- In the 1960s, it was postulated that the W and Z are massive only because of their interactions with a field of made up of particles now called Higgs Bosons, but until this year no Higgs bosons were directly observed
- It is probably the case that the other massive particles of the Standard Model (electrons, quarks, etc.) get their masses from the Higgs field as well
- The Higgs was the last particle in the Standard Model to be discovered

Putting This All Together

Various dark matter search strategies offer different advantages and disadvantages, and are potentially able to measure different quantities

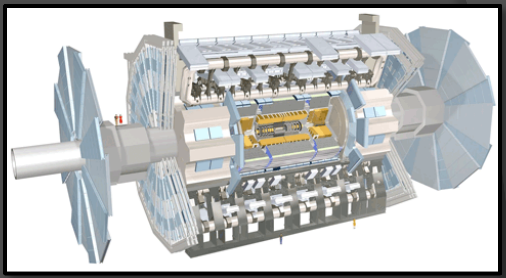
- Direct detection experiments measure a distribution of events connected to the WIMP's mass and scattering cross section with nuclei
- Indirect detection experiments measure a spectrum of annihilation products (gamma-rays, cosmic rays, etc.) determined by the WIMP's mass, annihilation cross section, and annihilation final states, along with the dark matter distribution
- The LHC measures a distribution of events with missing energy, but is the state stable? Or cosmologically relevant?

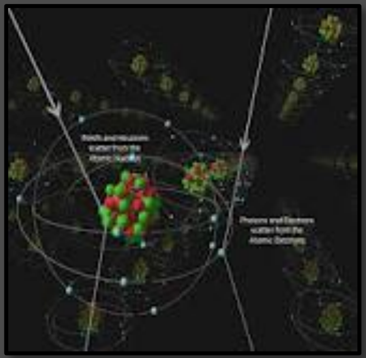


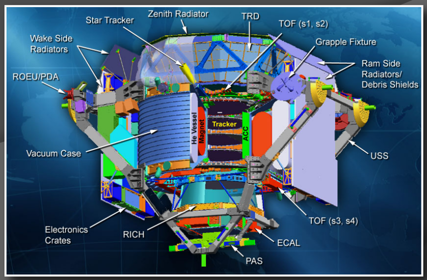


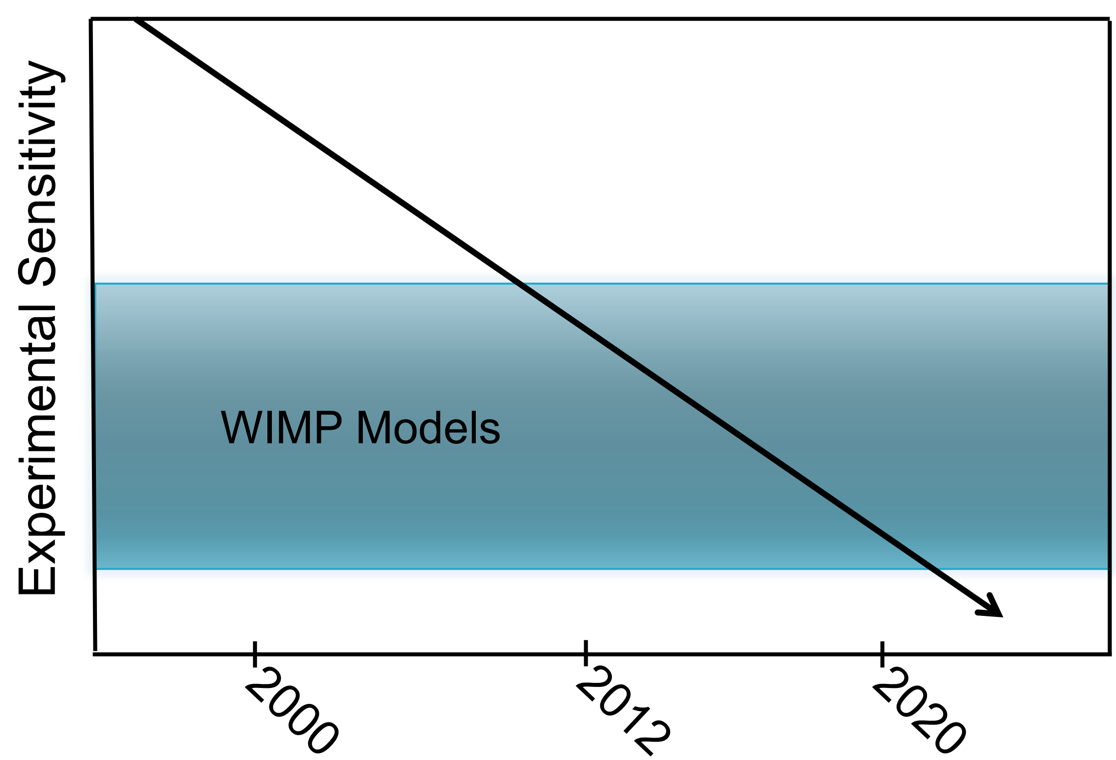
Summary

- Weakly interacting massive particles provide a natural class of candidates for dark matter, with a simple and compelling explanation for the observed dark matter abundance
- Searches for dark matter a the LHC, as well as direct and indirect astrophysical searches, are each approaching the sensitivity expected to be required to detect dark matter non-gravitationally








Experimental Sensitivity
WIMP Models
2000
2012
2020