The Hunt for the Identity of Dark Matter

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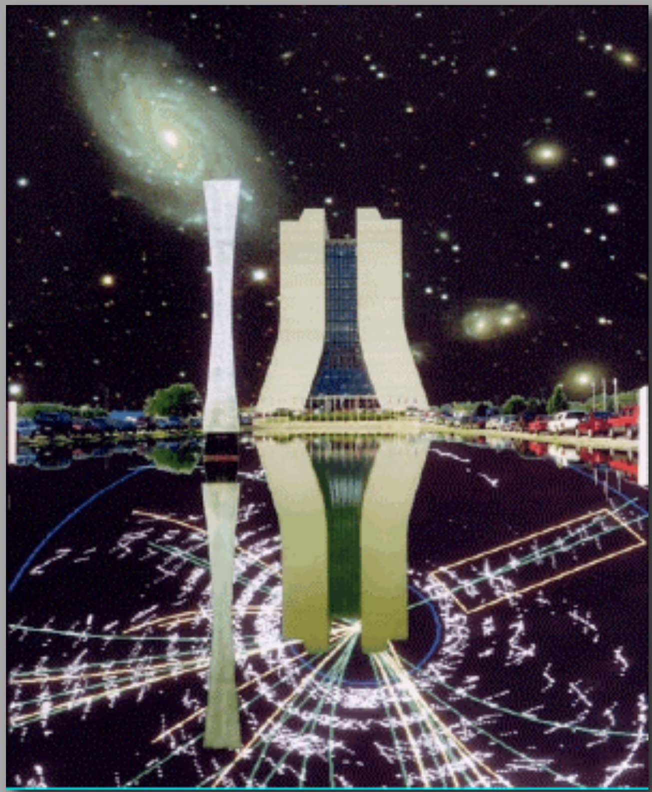


Fermilab User's Meeting

June 7, 2007

Dark Matter

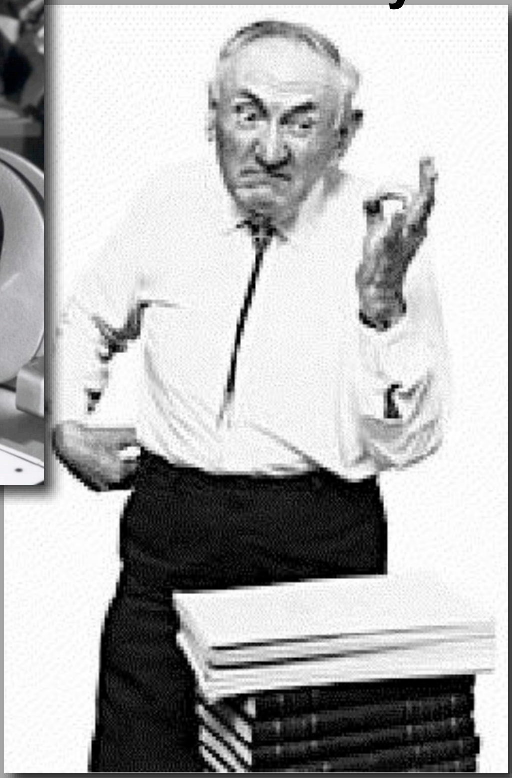
•It has been known that there was too little luminous matter in galaxies and clusters of galaxies for many decades

•This evidence has become increasingly compelling

•By the end of the 1970s, the existence of dark matter was accepted by much of the scientific community

Vera Rubin

Fritz Zwicky



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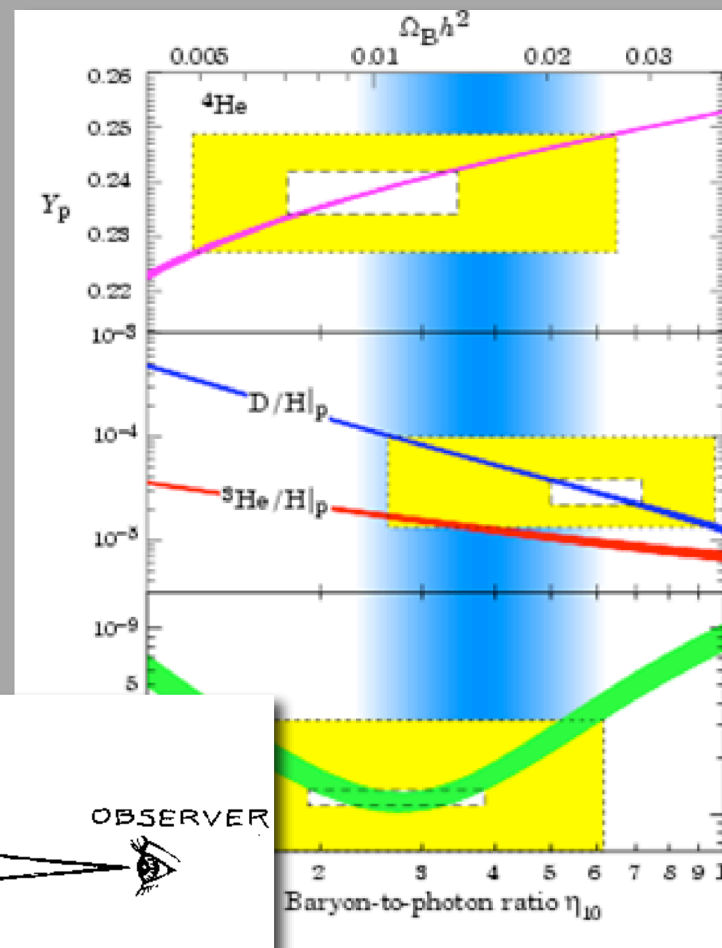
Dark Matter - MACHOs?

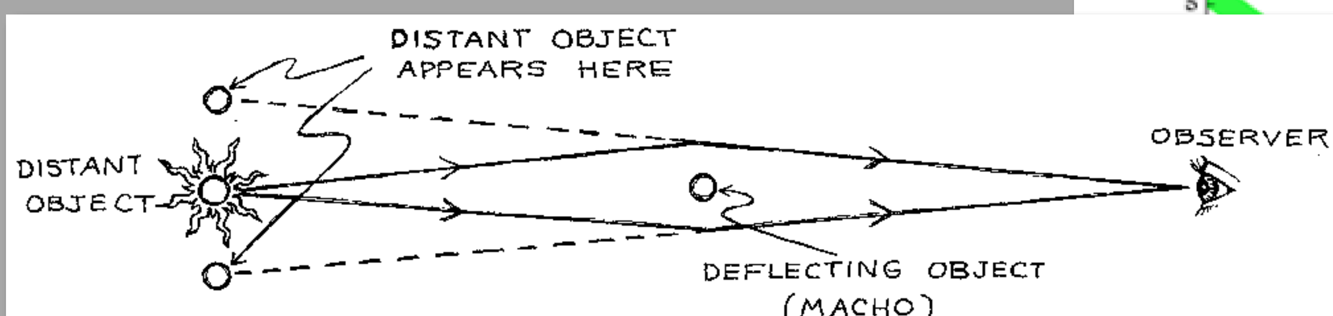
First popular candidates for dark matter were MACHOs:
Massive Compact Halo Objects

MACHOs face a number of serious problems, however:

1) Big Bang Nucleosynthesis, $\Omega_B h^2 \sim 0.02$, $\Omega_M h^2 \sim 0.13$

2) Negative results of microlensing searches





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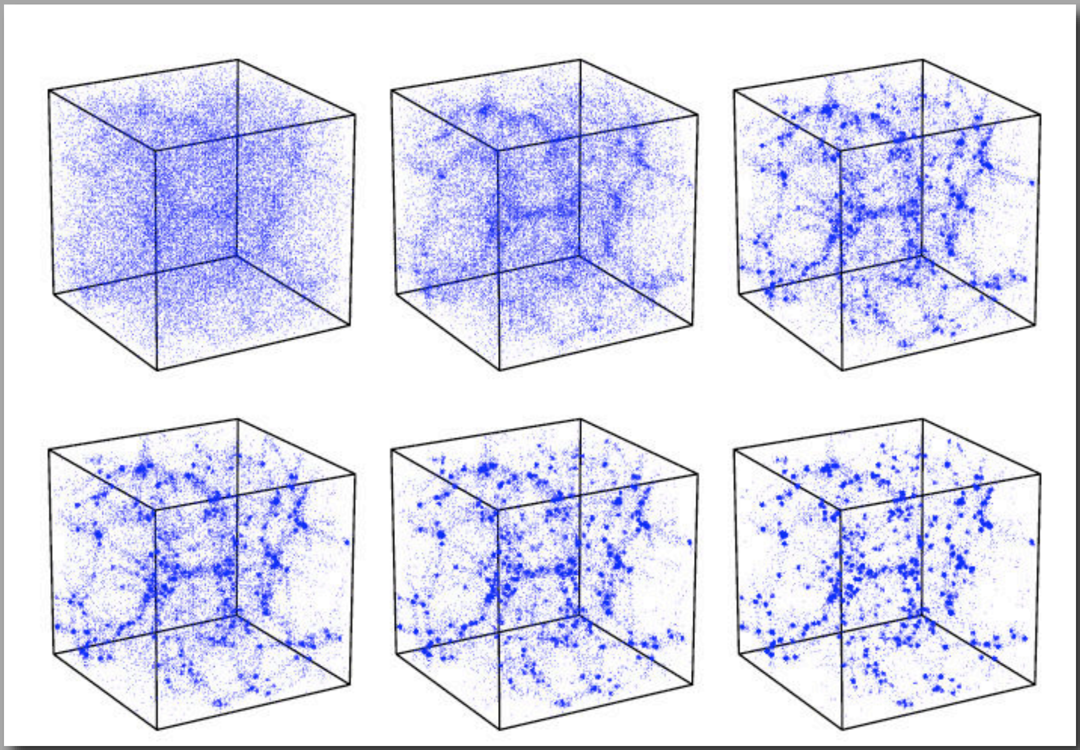
Dark Matter - WIMPs

•In light of these problems with MACHOs, ***WIMPs*** - Weakly Interacting, Massive Particles - have become the leading class of dark matter candidates

•One of the most impressive successes of the WIMP hypothesis is that the large scale structure of our universe matches that predicted for ***cold***, ***collisionless*** dark matter

•WIMPs act as the seeds for the growth of structure



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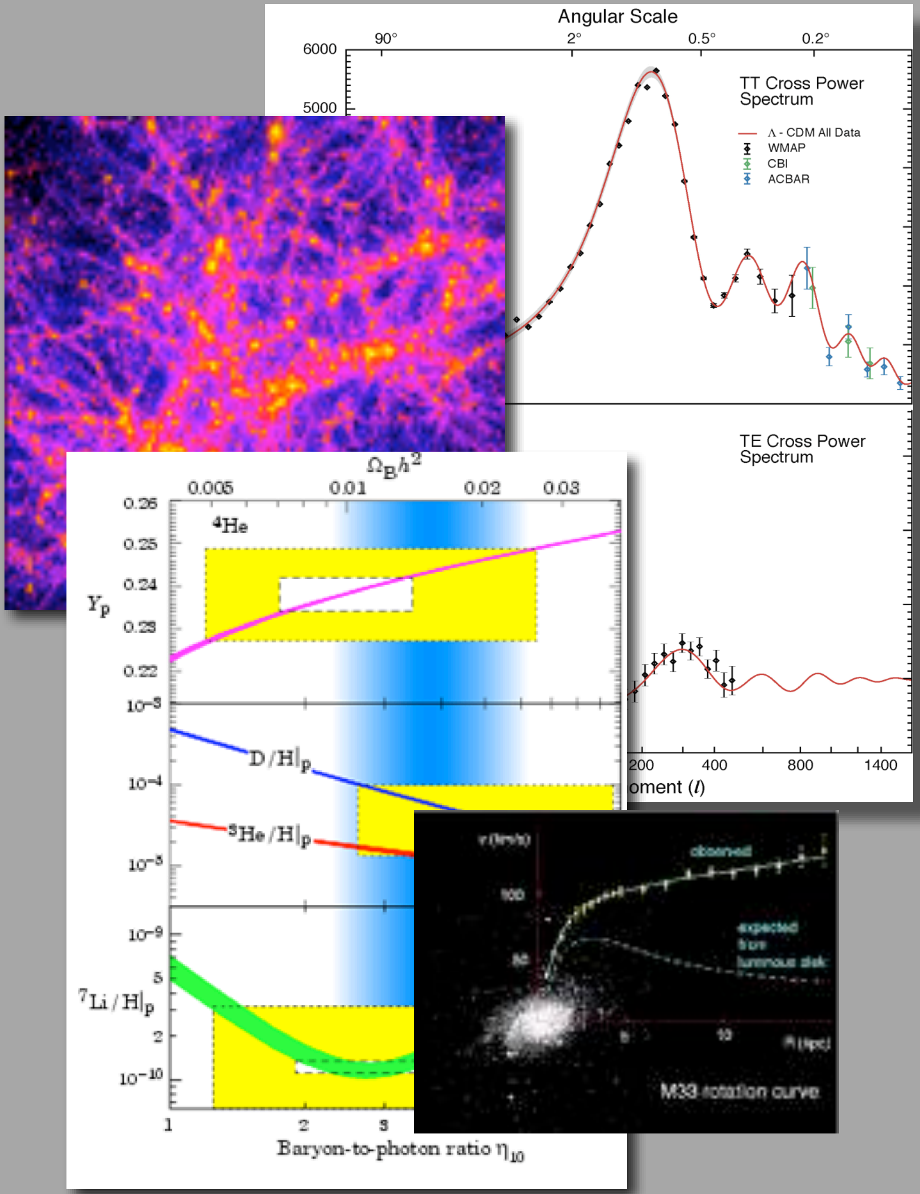
Dark Matter

•Evidence from a wide range of astrophysical observations including rotation curves, CMB, lensing, clusters, BBN, SN1a, large scale structure

•Each observes dark matter through its gravitational influence

•Still no conclusive observations of dark matter’s electroweak interactions (or other non-gravitational interactions)



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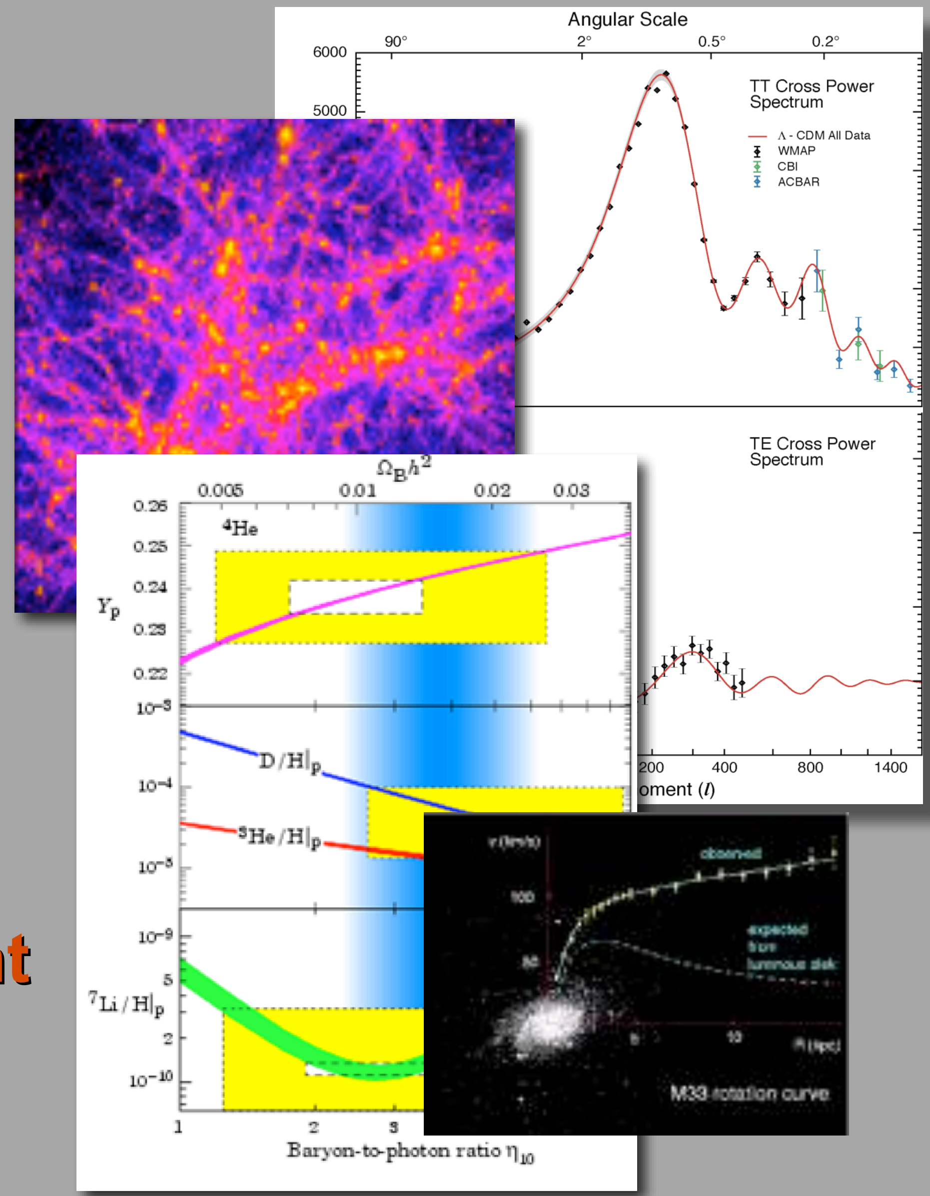

Instead of dark matter, might we not understand gravity?

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NASA/Chandra Press Release,
August 21, 2006

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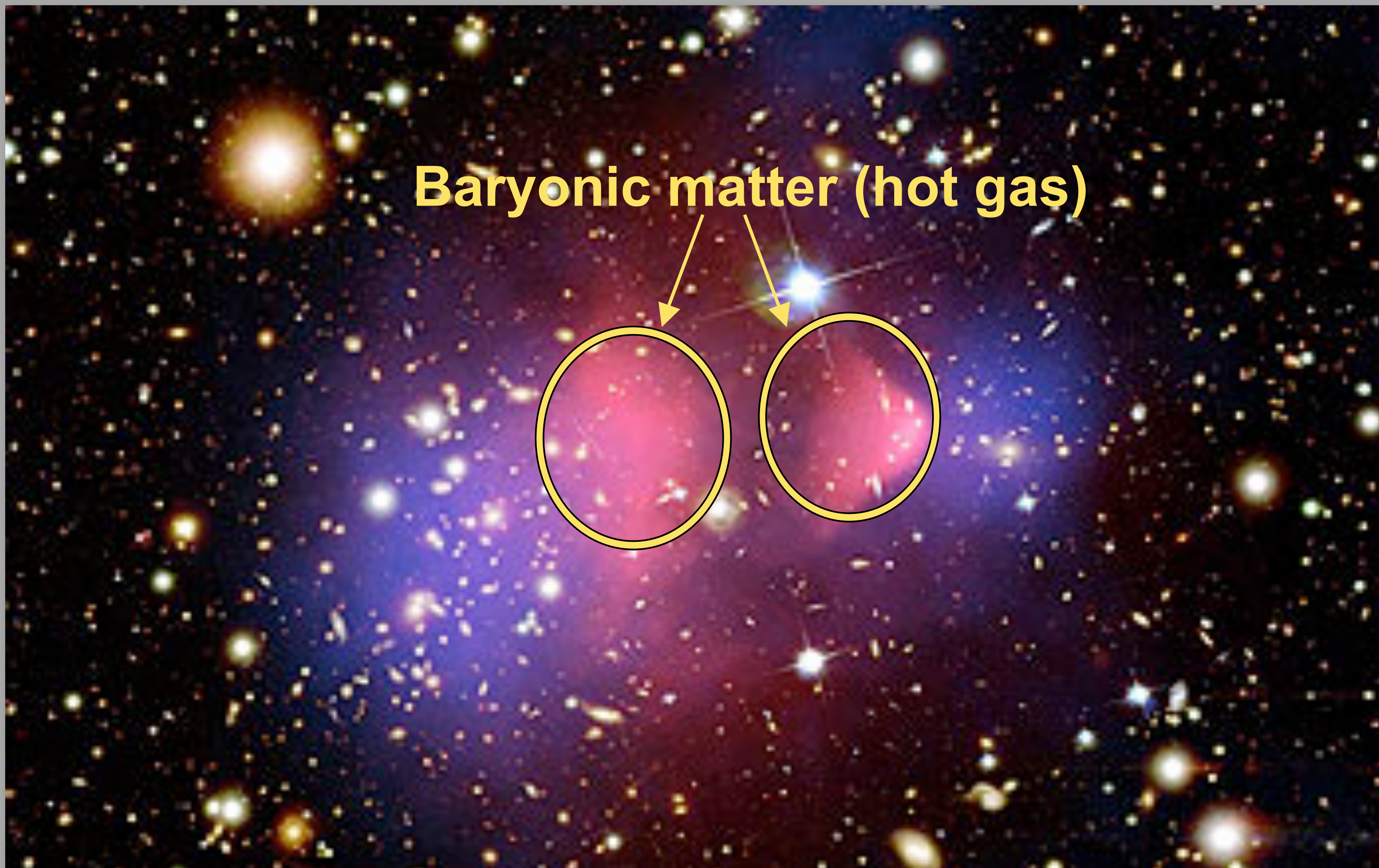

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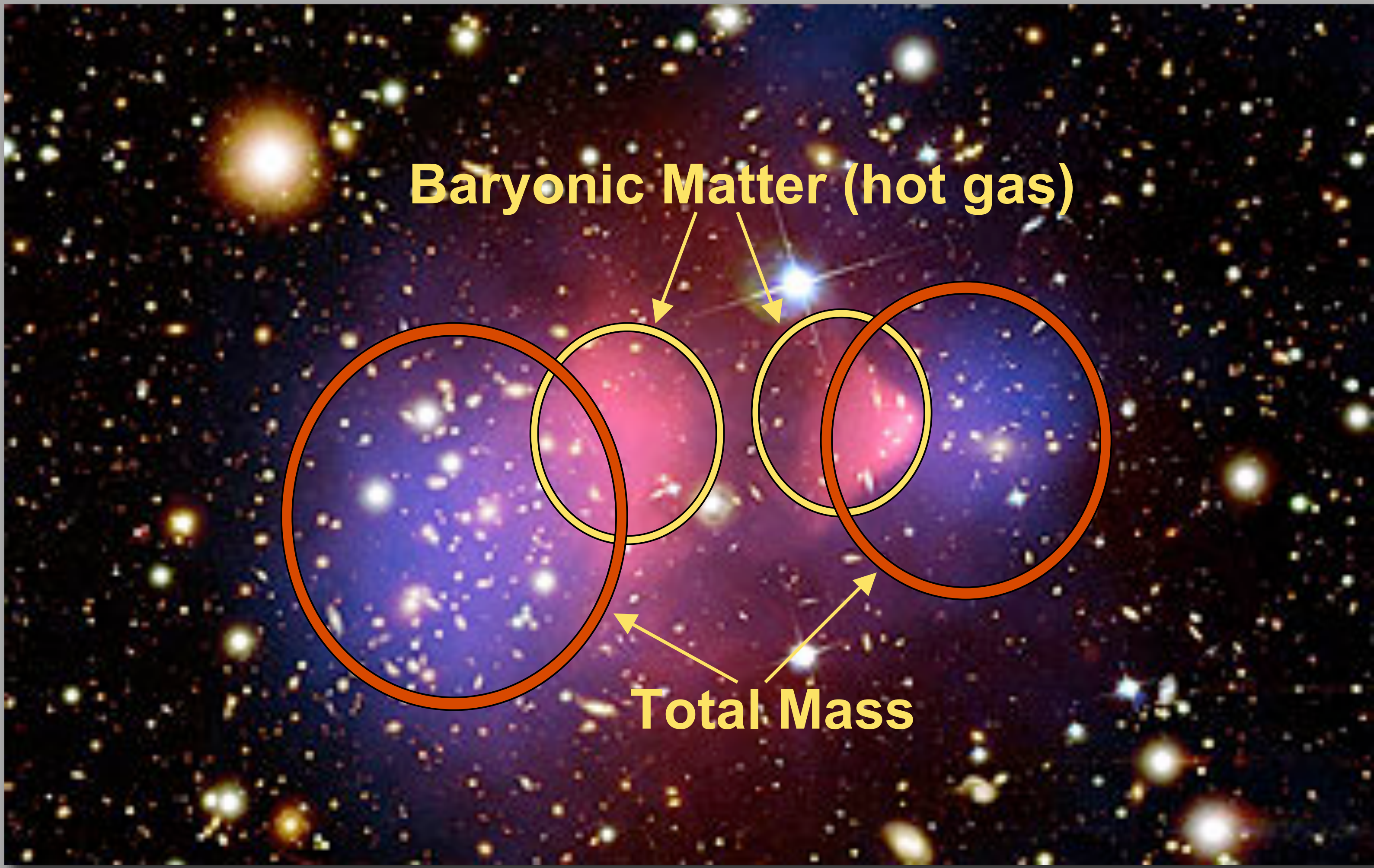

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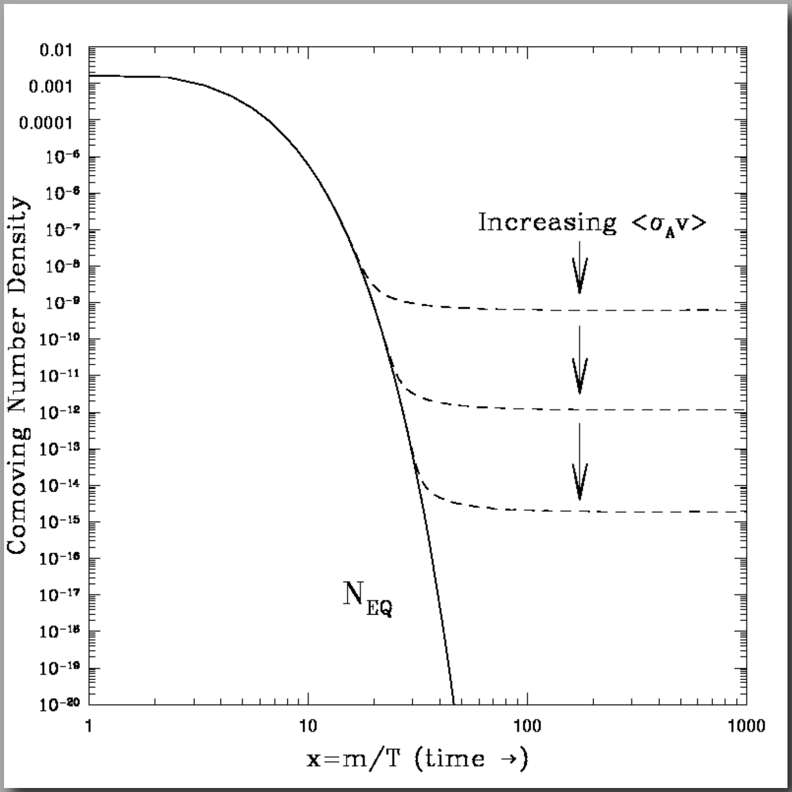
The Thermal Abundance of Weakly Interacting Massive Particles

- T >> m_χ, χ's in thermal equilibrium
- T < m_χ, number density of χ's become Boltzmann suppressed
- T ~ m_χ/20, Hubble expansion dominates over annihilations, freeze-out occurs
- Precise temperature at which freeze-out occurs, and the density which results depends on the WIMP's annihilation cross section



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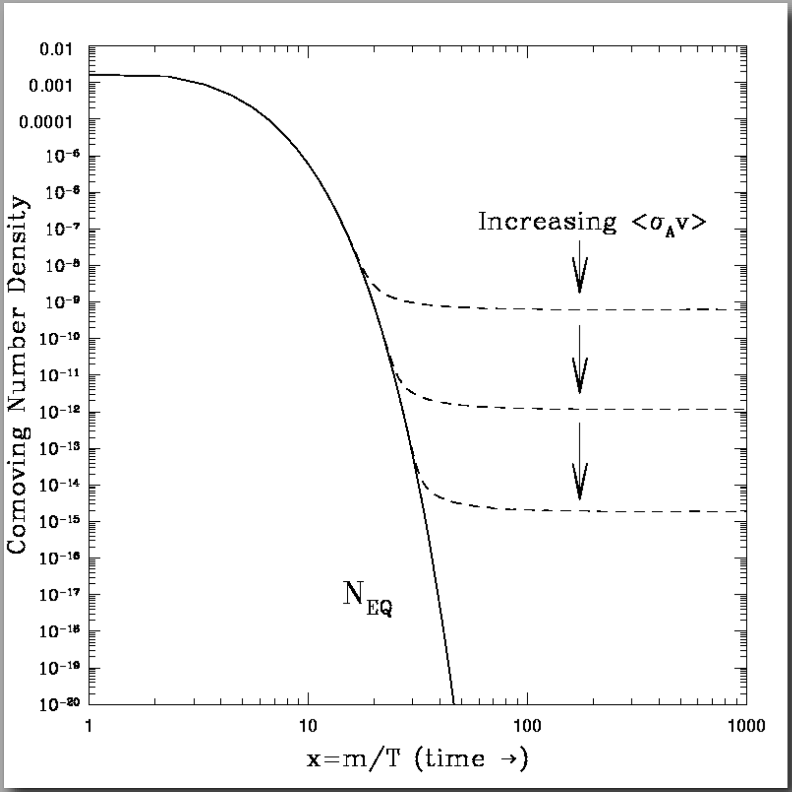
The Weak Scale and Weakly Interacting Massive Particles

- As a result of the thermal freeze-out process, a relic density of WIMPs is left behind: $\Omega h^2 \sim x_F / \langle \sigma v \rangle$

- For a particle with a GeV-TeV mass, to obtain a thermal abundance equal to the observed dark matter density, we need an annihilation cross section of $\langle \sigma v \rangle \sim$ pb

- Generic weak interaction yields:

$\langle \sigma v \rangle \sim \alpha^2 \, (100 \text{ GeV})^{-2} \sim$ pb



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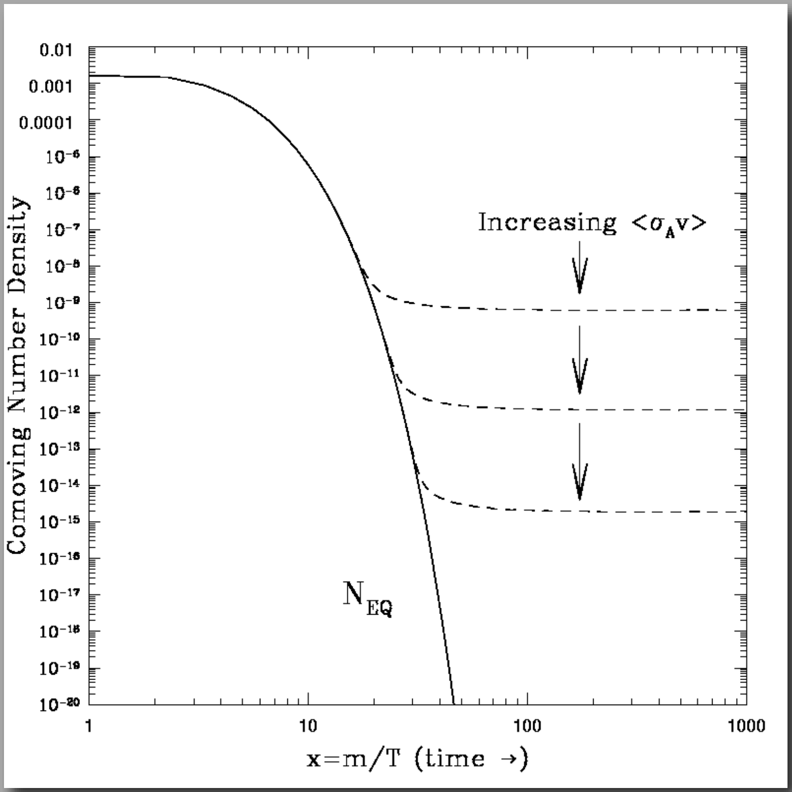

Numerical coincidence? Or an indication that dark matter originates from EW physics?

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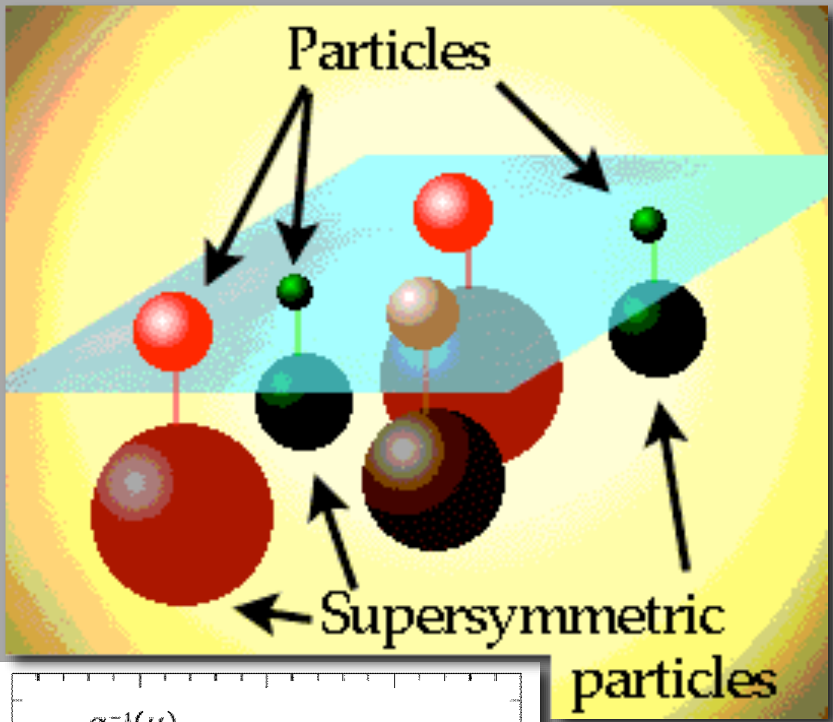
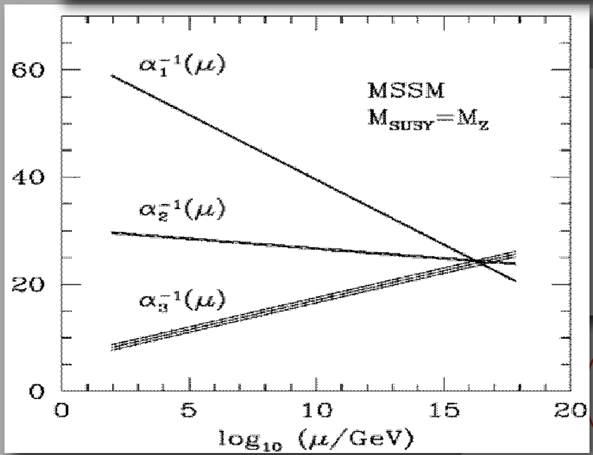
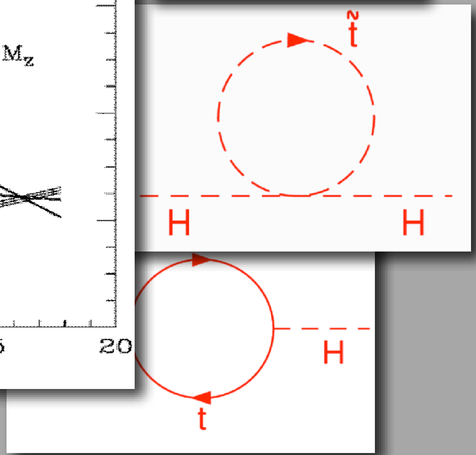
Supersymmetry

•Fundamental symmetry between bosons and fermions

•Perhaps the most theoretically appealing (certainly the most well studied) extension of the Standard Model







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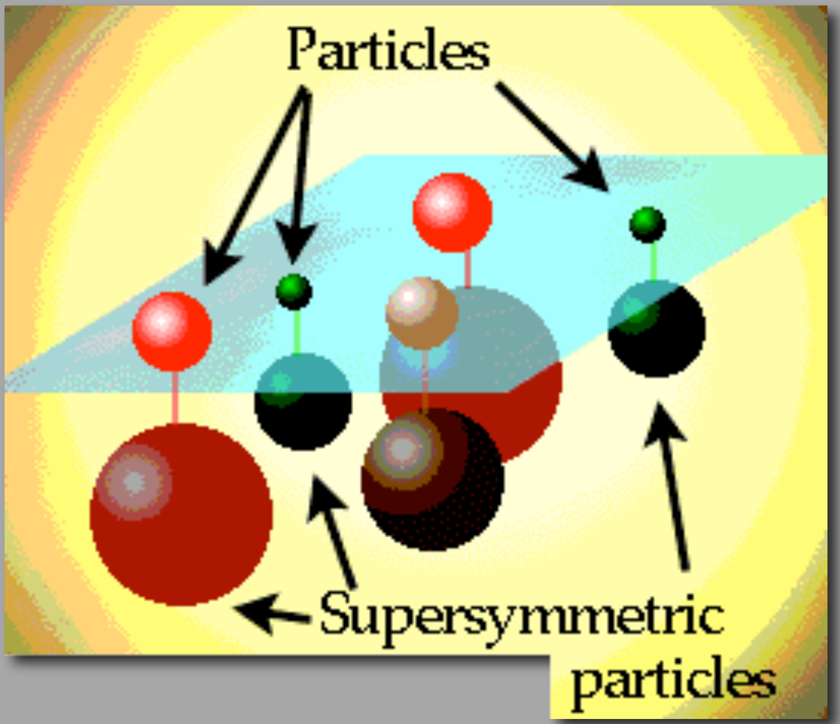
Supersymmetric Dark Matter

•R-parity must be introduced in supersymmetry to prevent rapid proton decay



•Another consequence of R-parity is that superpartners can only be created and destroyed in pairs, making the lightest supersymmetric particle (LSP) stable

•Possible WIMP candidates from supersymmetry include: $\tilde{\gamma}, \tilde{Z}, \tilde{h}, \tilde{H}$ ⟵ 4 Neutralinos

$\tilde{\nu}$ ⟵ 3 Sneutrinos

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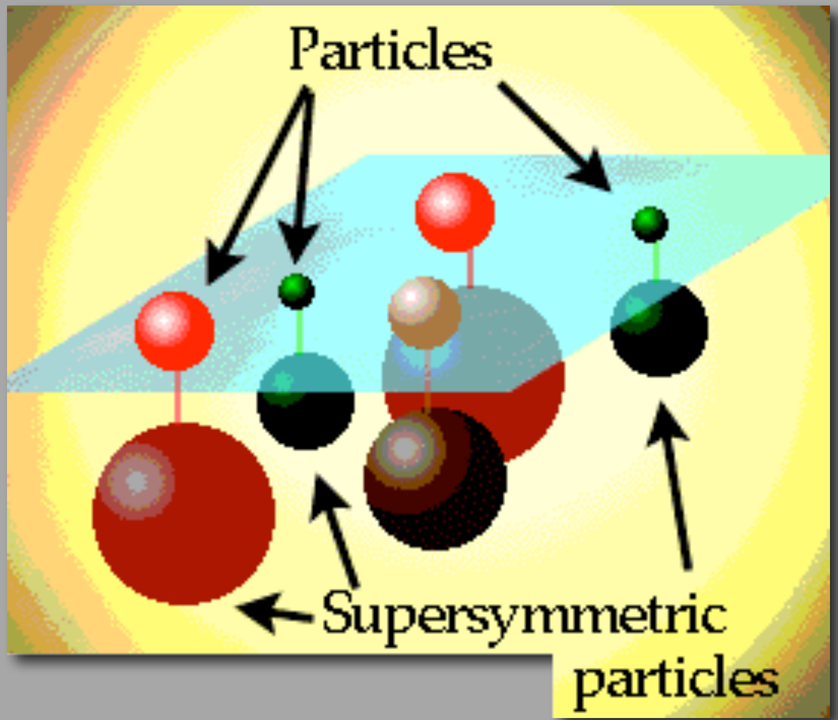

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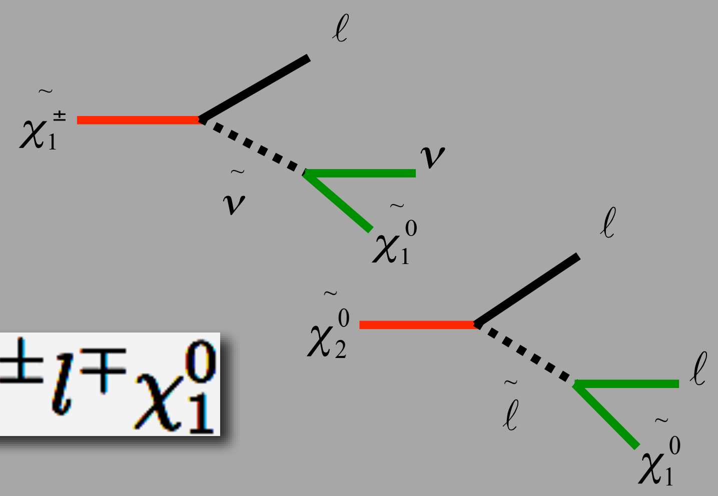
$\tilde{\nu}$ ← ~~3 Sneutrinos~~

Excluded by direct detection

Supersymmetry at the Tevatron

•Most promising channel is through neutralino-chargino production



For example:

$$\chi^{\pm}\chi_2^0 \to \tilde{\nu} l^{\pm} l^{\pm} \tilde{l}^{\mp} \to \nu \chi_1^0 l^{\pm} l^{\pm} l^{\mp} \chi_1^0$$

•Currently sensitive to charginos as heavy as ~140 GeV

•Tevatron searches for light squarks and gluinos are also very interesting

•For the case of light m_A and large $\tan\beta$, heavy MSSM higgs bosons (A/H) may be observable

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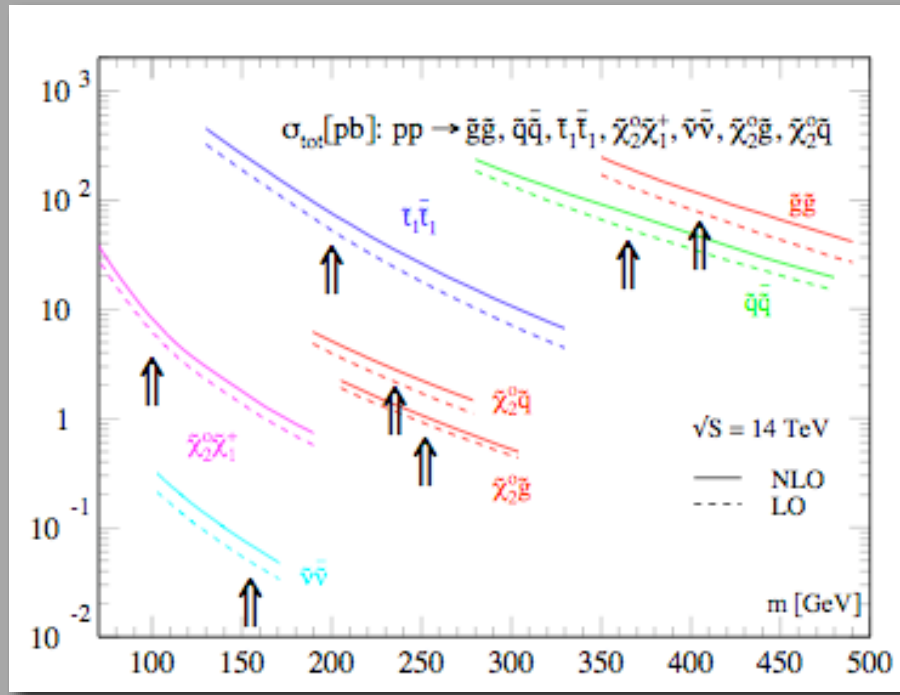
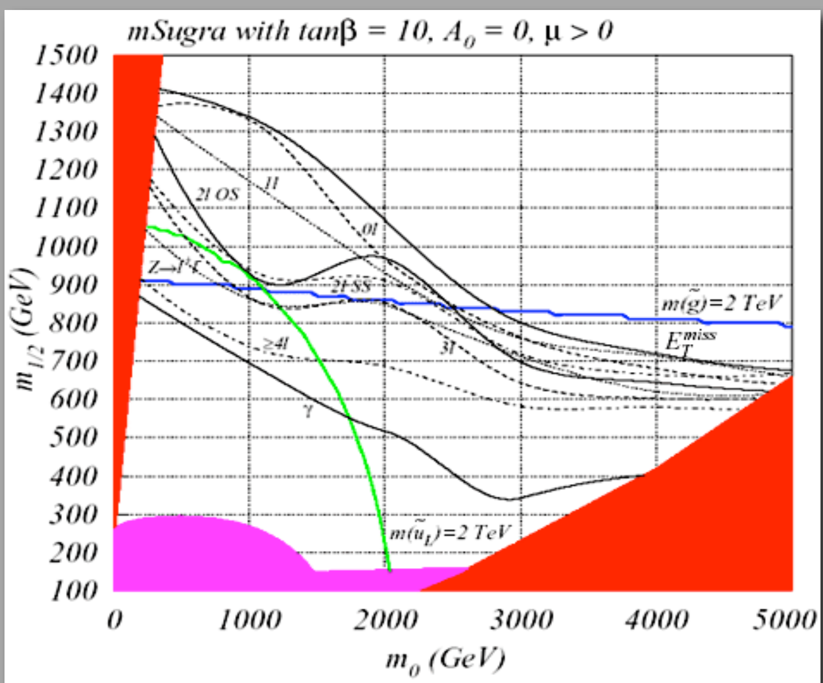
Supersymmetry at the LHC

- Squarks and gluinos produced prolifically at the LHC

- Subsequent decays result in distinctive combinations of leptons, jets and missing energy



T. Plehn, Prospino 2.0



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- Squarks and gluinos up to 1 TeV can be discovered with 1% of the first year design luminosity

- Ultimately, LHC can probe squarks and gluinos up to ~3 TeV

What Will The LHC Tell Us About Supersymmetry and Dark Matter?

The LHC Will ***NOT*** Tell Us:

- Whether the lightest neutralino is stable
- The couplings/interactions of the lightest neutralino
- Whether the lightest neutralino makes up all, some or none of the dark matter in our universe

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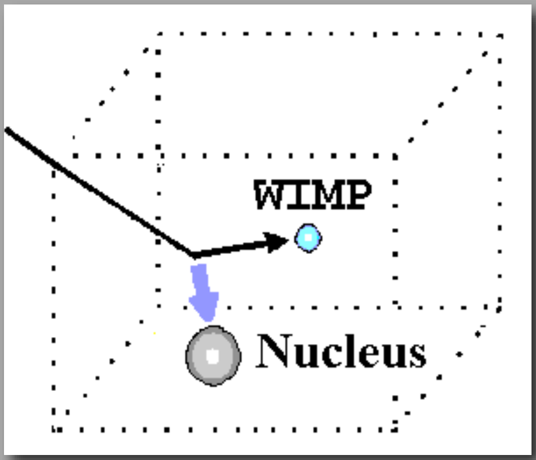
Astrophysical Dark Matter Experiments Provide a Complementary Probe into the Nature of Supersymmetry

Astrophysical Probes of Particle Dark Matter

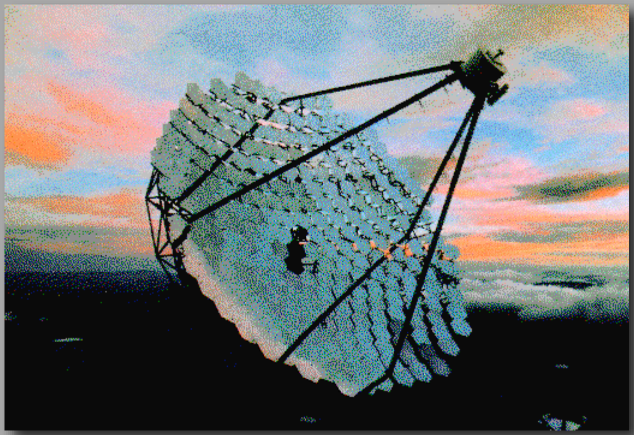
Direct Detection

-Momentum transfer to detector through elastic scattering



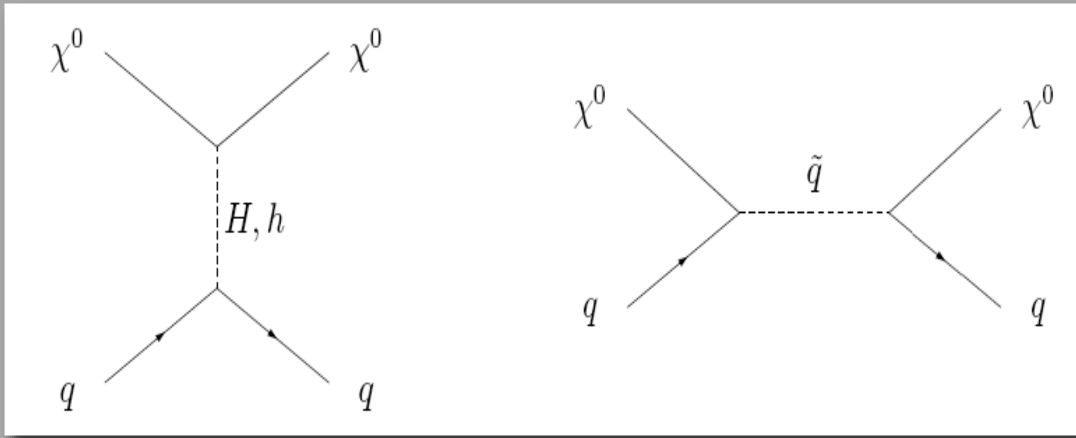
Indirect Detection

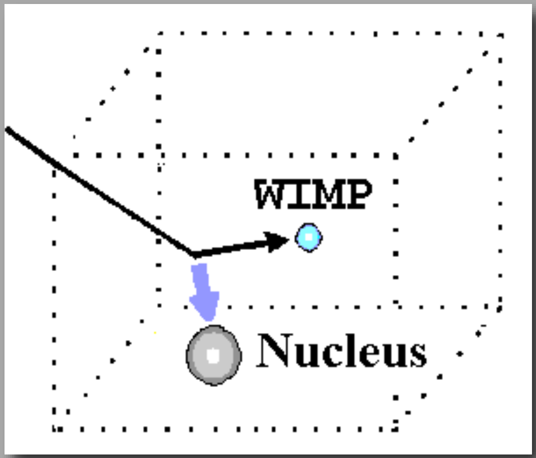
-Observation of annihilation products (γ, ν, e+, p, etc.)



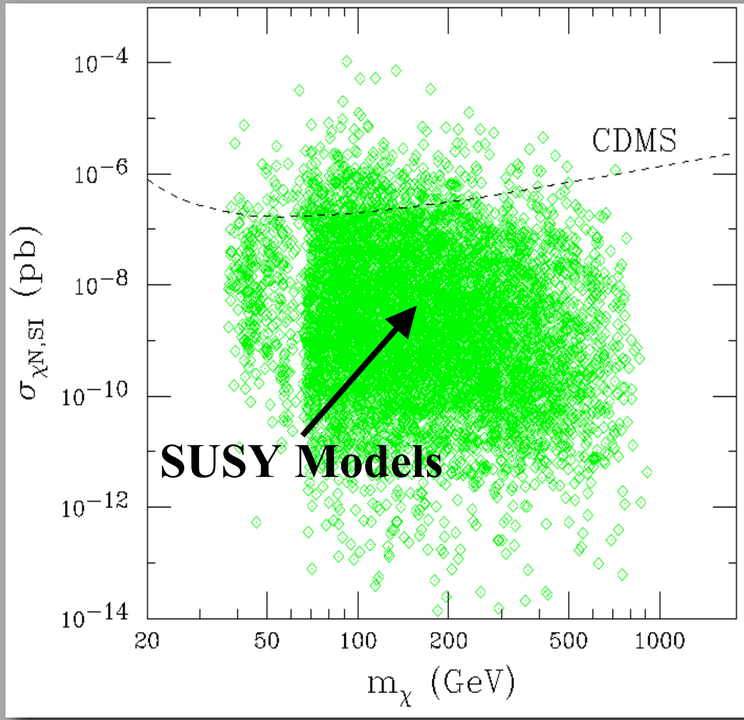
Direct Detection

- Neutralino-nuclei elastic scattering can occur through Higgs and squark exchange diagrams:





- Cross section depends on numerous SUSY parameters: neutralino mass and composition, tanβ, squark masses and mixings, Higgs masses and mixings



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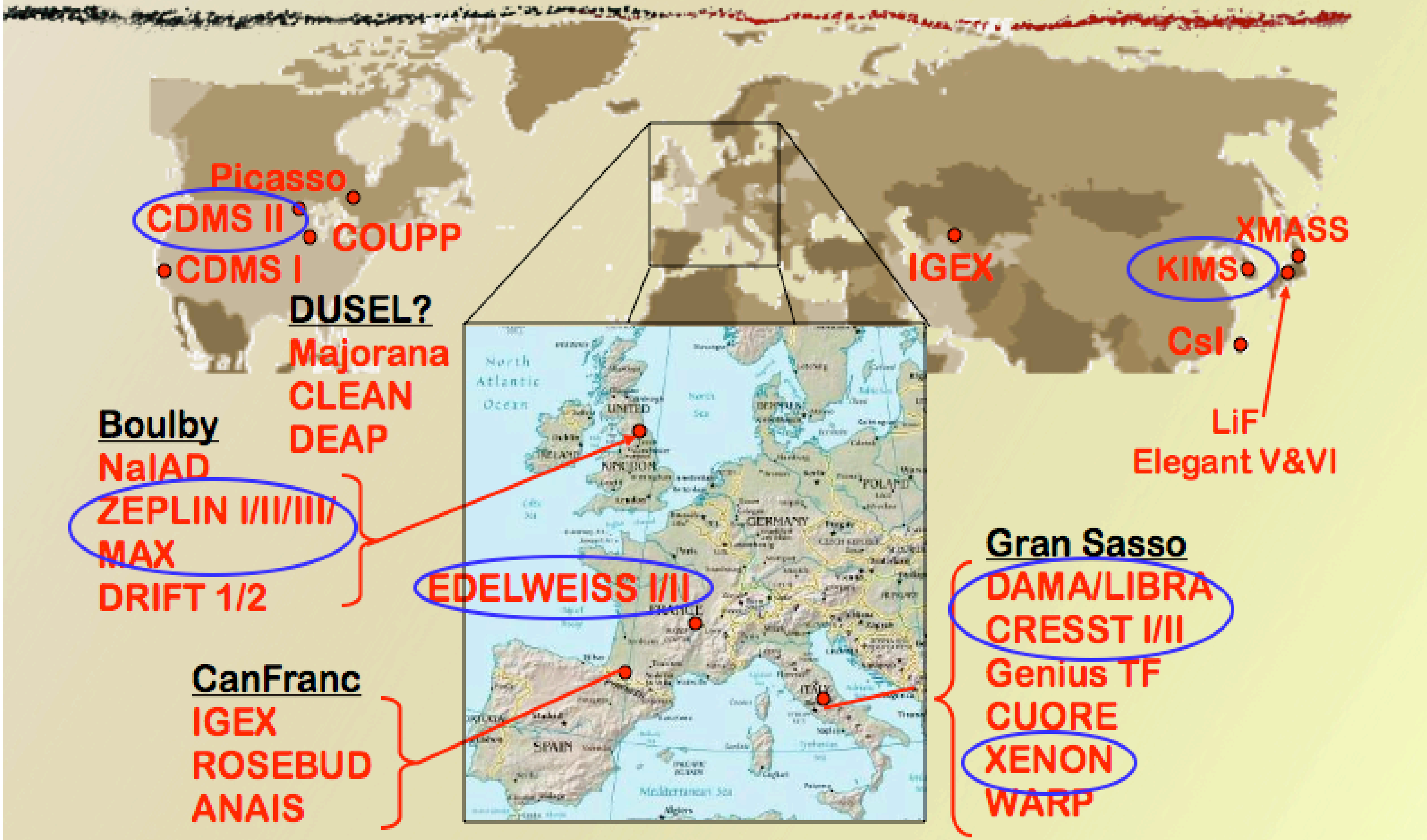
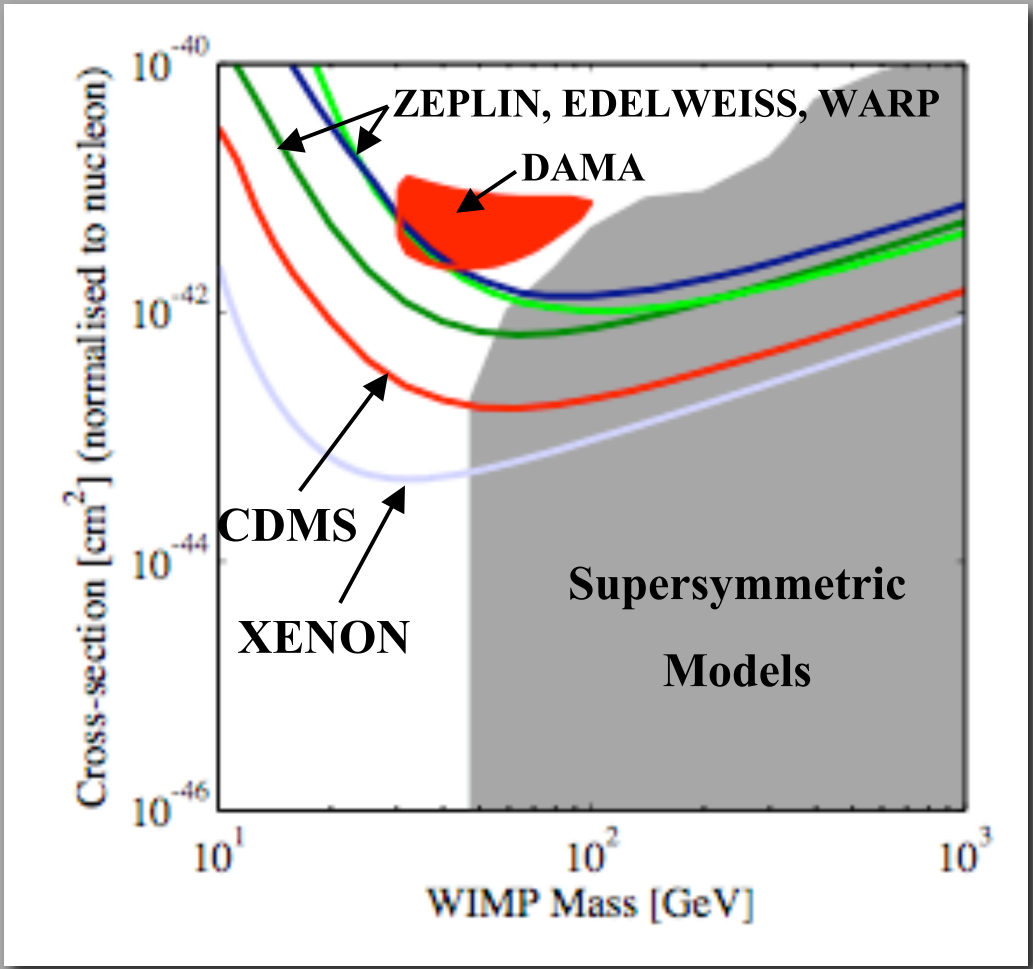
Direct Detection WIMP Experiments Worldwide



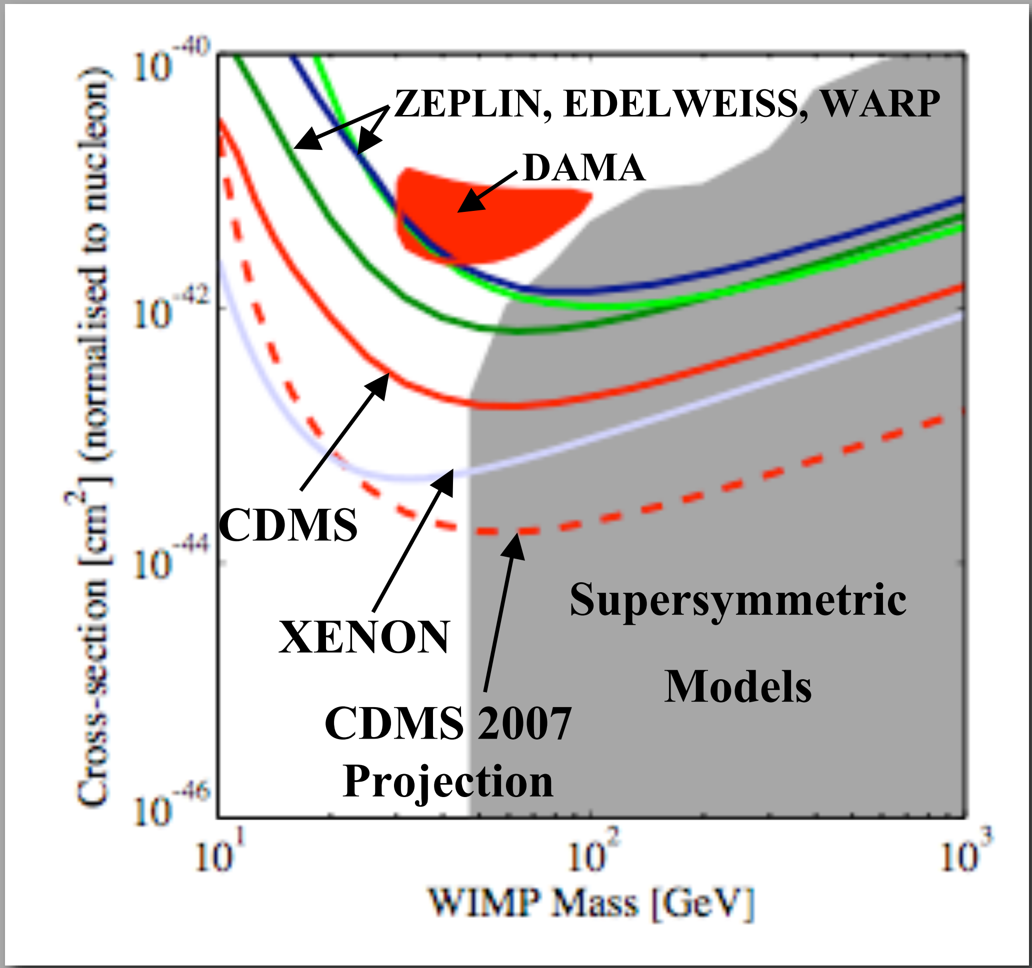
Direct Detection

•Current Status:



Direct Detection

- Near Future:



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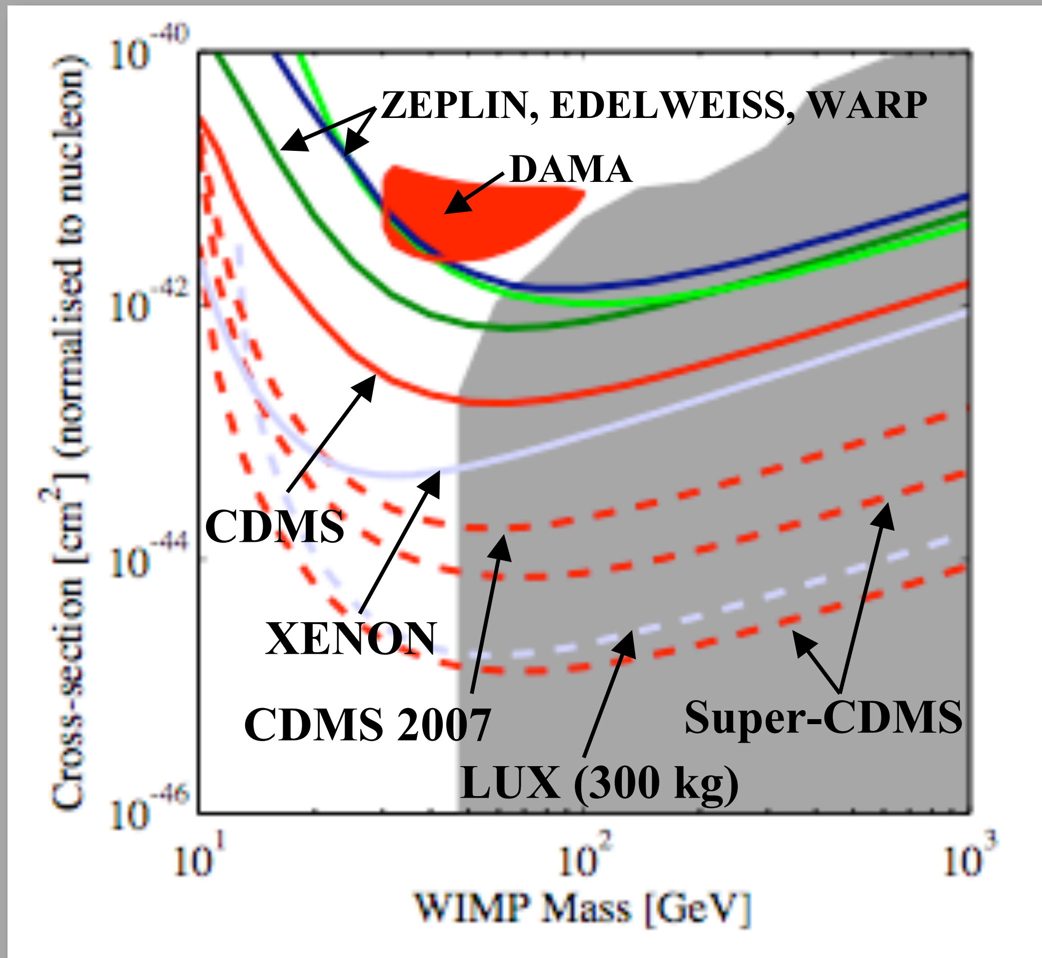
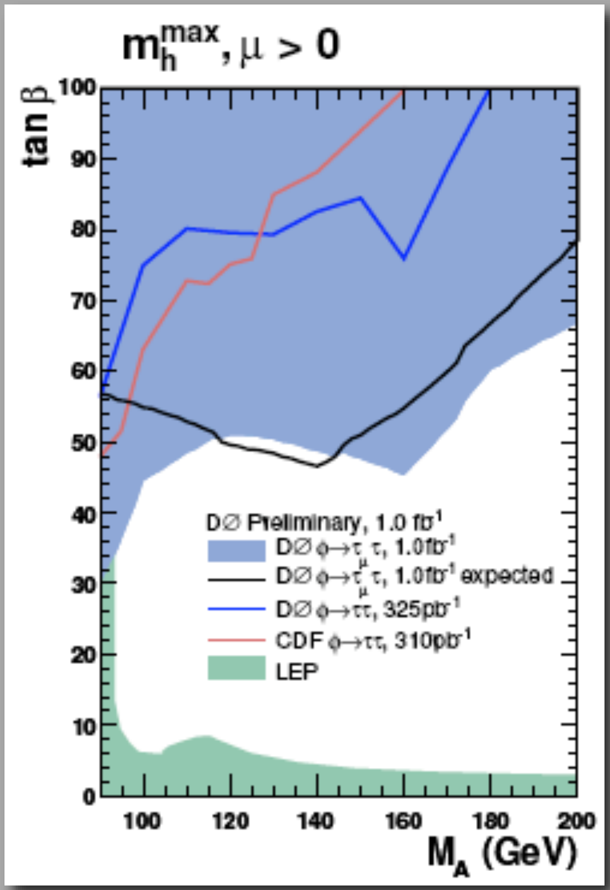
Direct Detection

•Long-Term Prospects:



Interplay Between Colliders and Direct Detection

•MSSM Higgs searches at the Tevatron are also most sensitive to models with large tanβ, small m_A (*ie.* $p\bar{p} \rightarrow A/H + X \rightarrow \tau^+\tau^- + X$)



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M. Carena, Hooper, P. Skands, PRL, hep-ph/0603180; M. Carena, Hooper, A. Vallinotto, PRD, hep-ph/0611065

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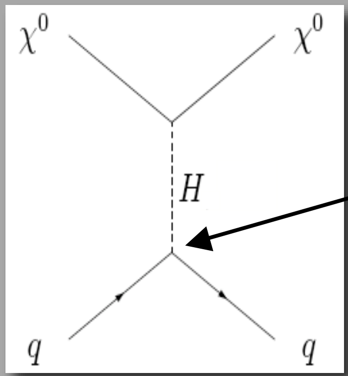
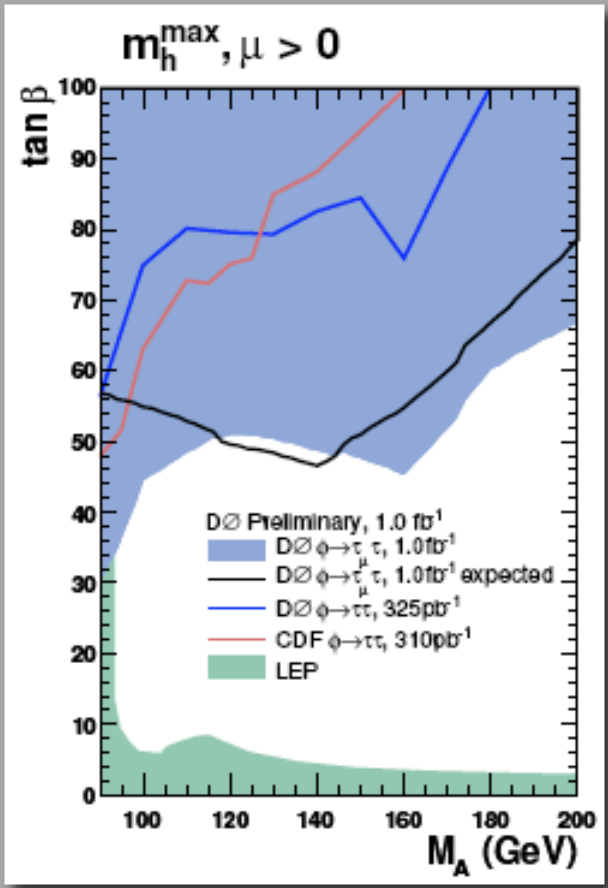
•Neutralino-nuclei elastic scattering cross section is also largest in the case of large tanβ, small m_A (m_H)



α tanβ



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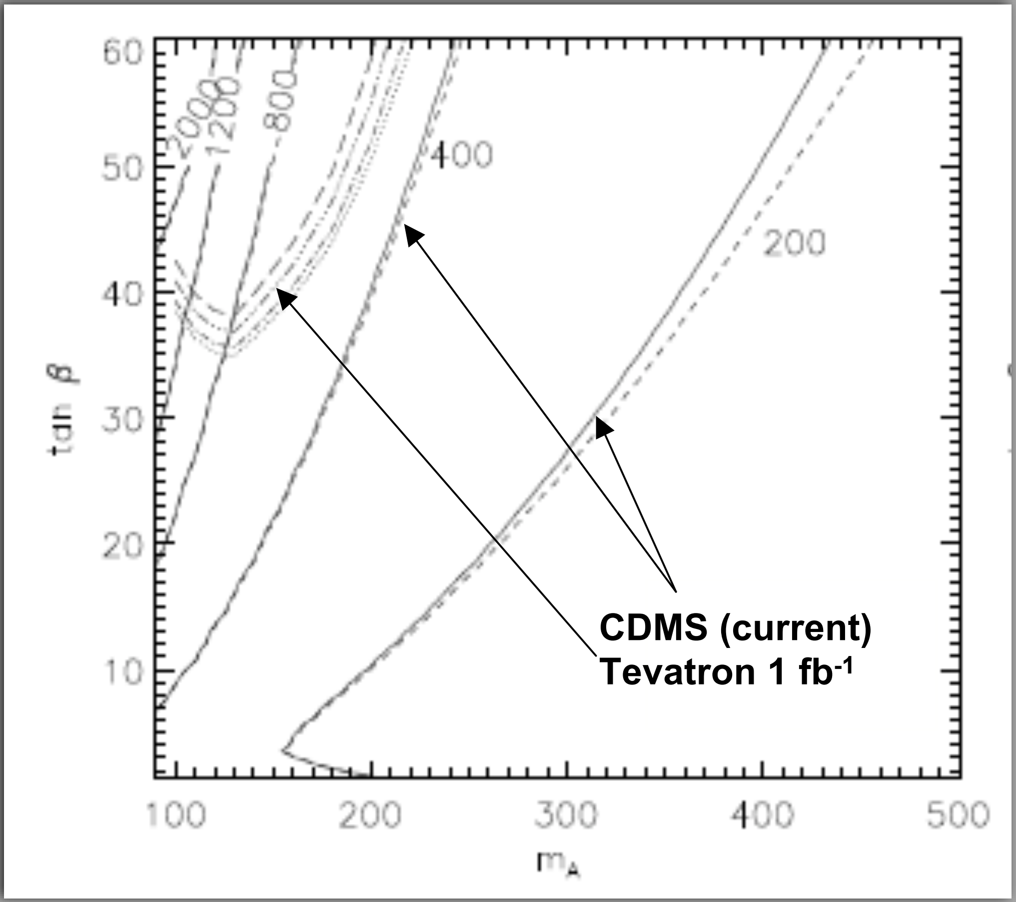
- Current CDMS limit suggests that the Tevatron should not have expected to detect heavy a Higgs boson, unless χ is a rather pure bino ($\mu > 600$ GeV)



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Interplay Between Colliders and Direct Detection

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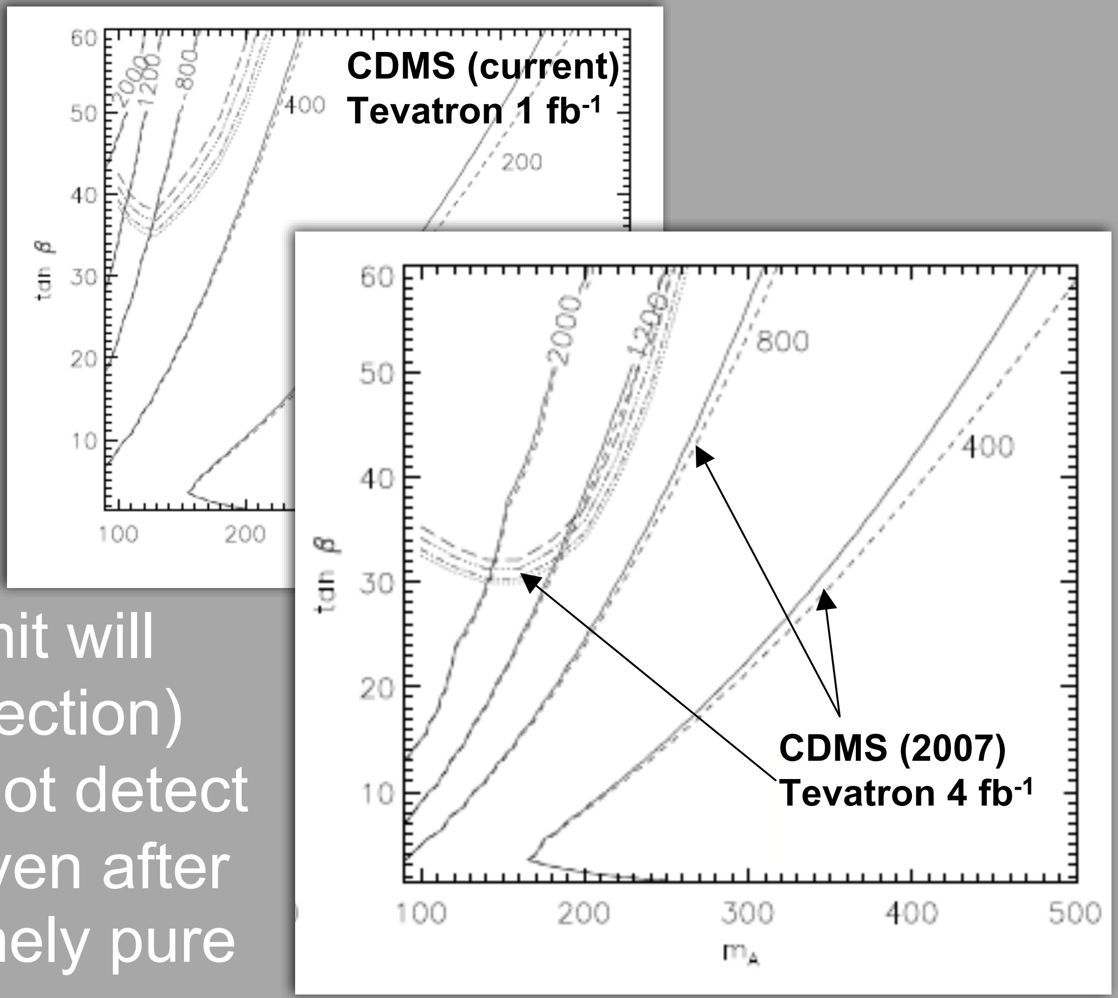
•Projected 2007 CDMS limit will suggest (assuming no detection) that the Tevatron should not detect the heavy Higgs boson, even after 4 fb^{-1}, unless χ is a extremely pure bino (μ > 1200 GeV)



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Indirect Detection

- **Gamma-rays** from the center of the Milky Way, dwarf galaxies, galactic halo, etc.

- **Neutrinos** from the core of the Sun

- **Positrons** and **Anti-Protons** from the Milky Way halo

Indirect Detection With Gamma-Rays

Advantages of Gamma-Rays:

•Propagate undeflected (point sources possible, angular information)

•Propagate without energy loss (spectral information)

•Rapid development in both space (GLAST) and ground-based (HESS, MAGIC, VERITAS) technologies

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Gamma-Rays From The Galactic Center

•Simulations predict that the GC contains very high densities of dark matter (and high annihilation rates)

•Long considered likely to be the brightest dark matter annihilation region in the sky

•HESS, MAGIC, WHIPPLE and CANGAROO each claim positive detection of ~TeV gamma-rays

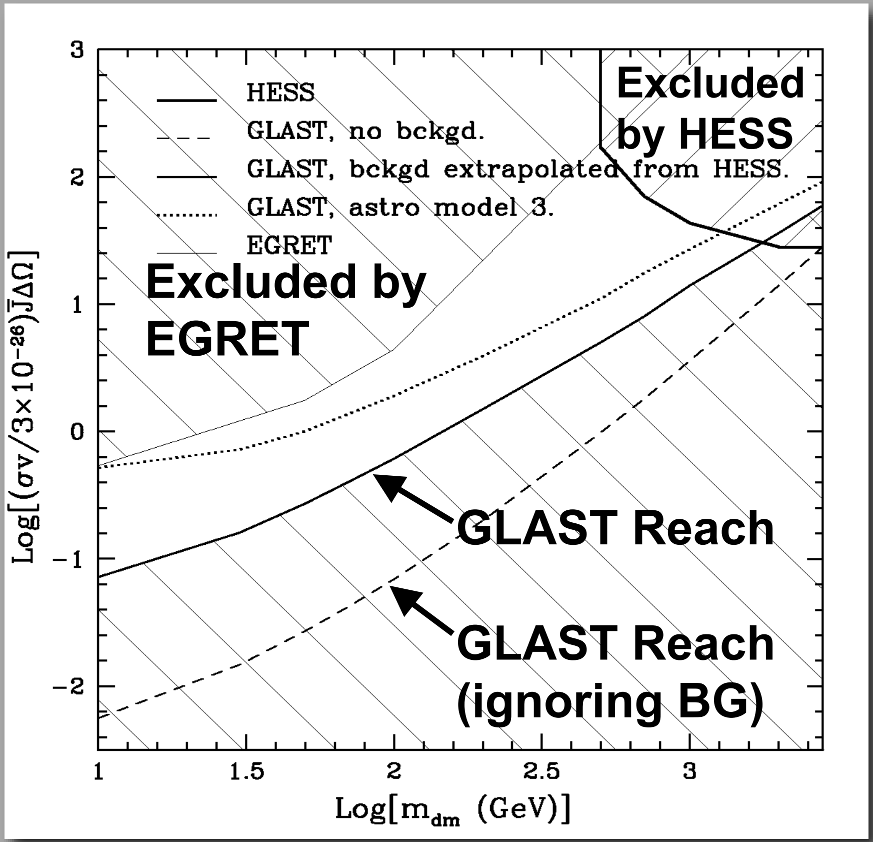
•Very likely not the production of dark matter annihilations, but rather evidence for other astrophysics

Gamma-Rays From The Galactic Center

•Prospects for GLAST and other future gamma-ray experiments are reduced as a result of this new background

•Range of annihilation rates observable with GLAST is reduced considerably

•Other sources become more interesting (*ie.* dwarf spheroidal galaxies, the diffuse background)

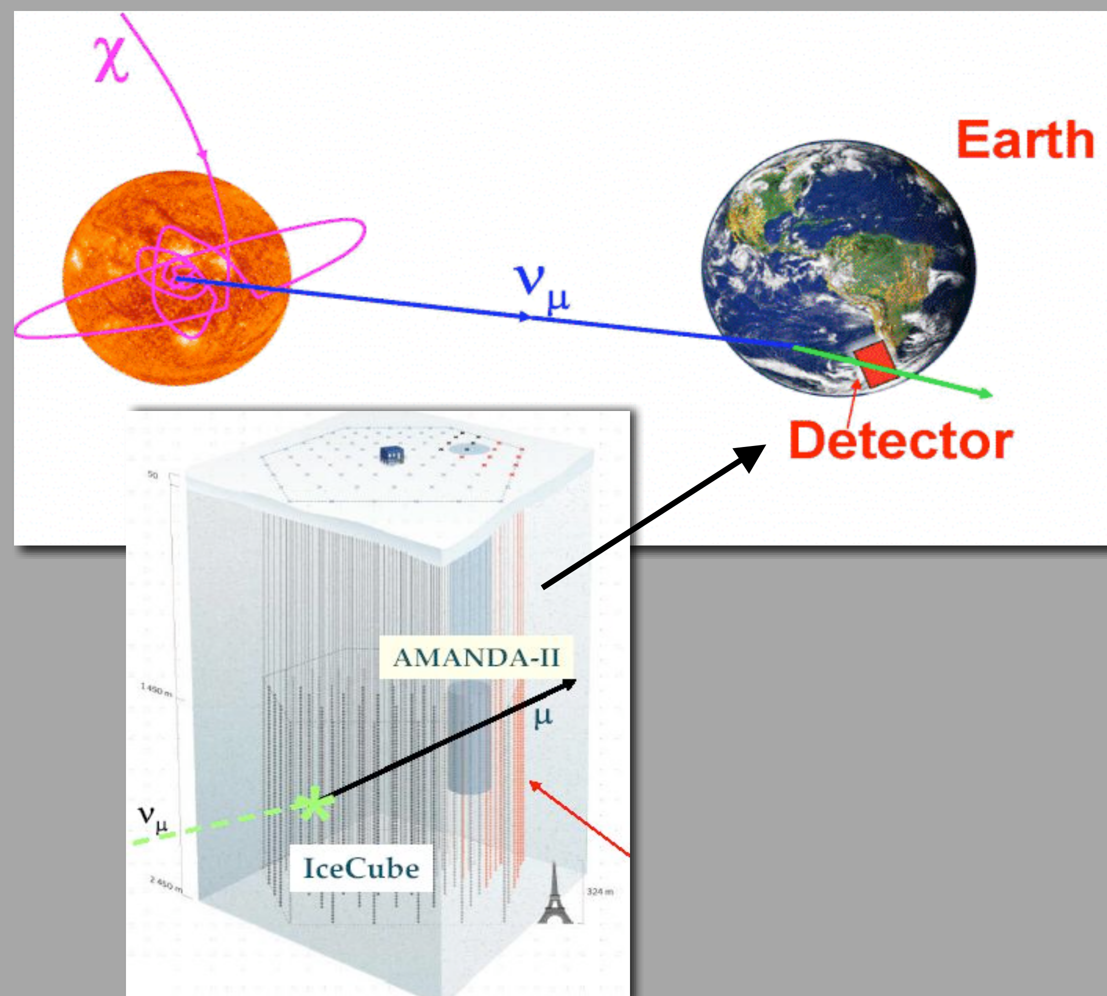


Hooper and G. Zaharijas, PRD, hep-ph/0603540

Indirect Detection With Neutrinos

•WIMPs elastically scatter with nuclei in the Sun, becoming gravitationally bound, and annihilate, producing high-energy neutrinos

•Next generation km-scale experiments, such as IceCube, will be sensitive to mixed bino-higgsino neutralinos

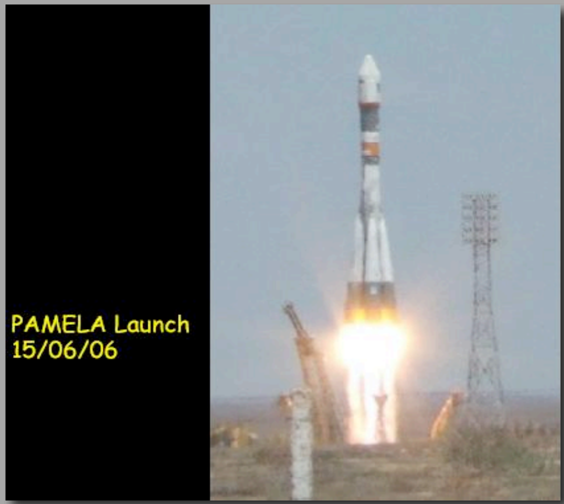


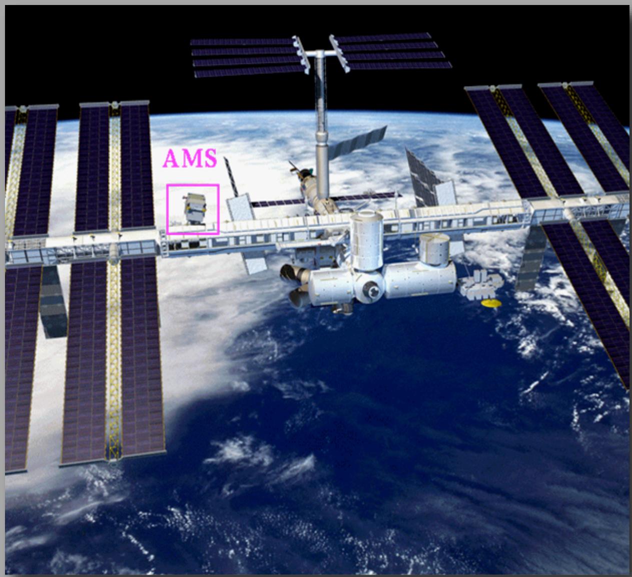
Indirect Detection With Antimatter

•Matter and antimatter generated equally in dark matter annihilations (unlike other astrophysical processes)

•Cosmic positron, anti-proton and anti-deuteron spectrum may contain signatures of particle dark matter

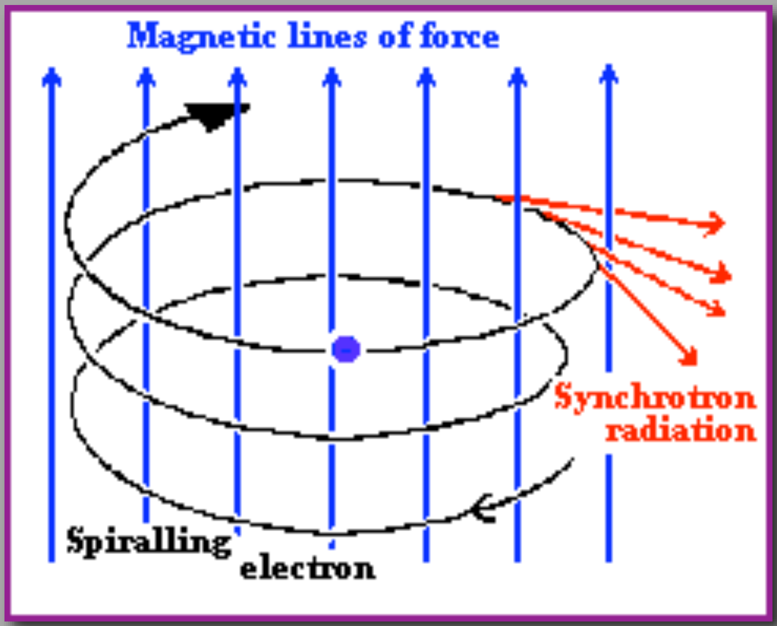
•Upcoming experiments (PAMELA, AMS-02) will measure the cosmic antimatter spectrum with much greater precision, and at much higher energies





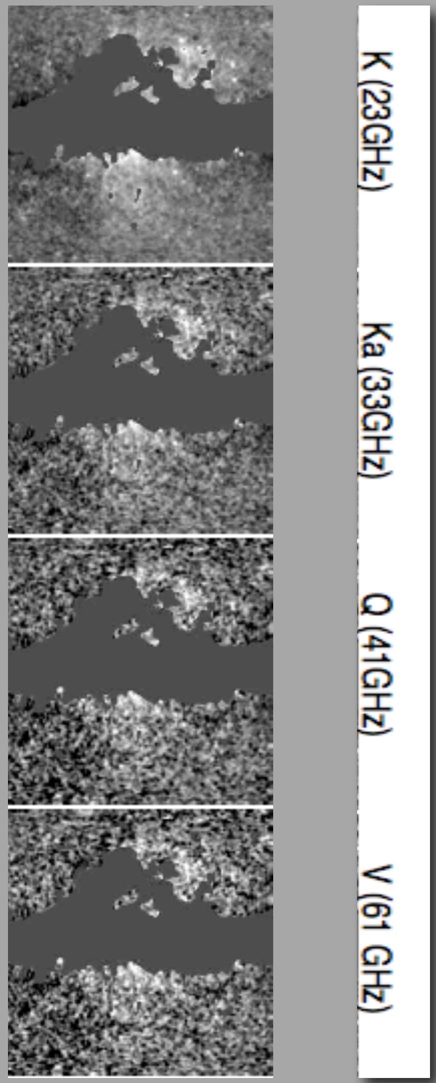
Indirect Detection With Synchotron Emission

- Electrons/positrons produced in dark matter annihilations will emit synchrotron photons as they propagate through the galactic magnetic fields
- For weak-scale dark matter, the synchrotron radiation falls within the frequency range of WMAP and other CMB experiments



Dark Matter and the WMAP Haze

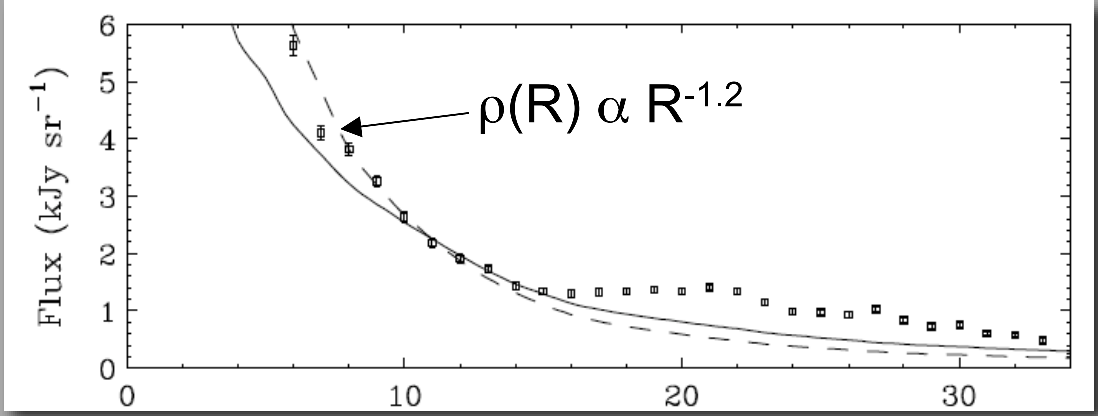
- When known foregrounds are subtracted from the WMAP data, a residual around the Galactic Center remains in all five frequency channels
- Approximate spherical symmetry
- 20-30° angular extension
- Initially interpreted as thermal bremstrahlung from hot gas, but now ruled out by the lack of corresponding X-ray line
- Possible synchrotron emission from dark matter annihilation products



Hooper and G. Dobler and D. Finkbeiner, arXiv:0705.3655

Three Reasons to Think the WMAP Haze is produced by Dark Matter

1) Angular distribution of the haze matches that found for a cusped halo profile, $\rho(R) \propto R^{-1.2}$



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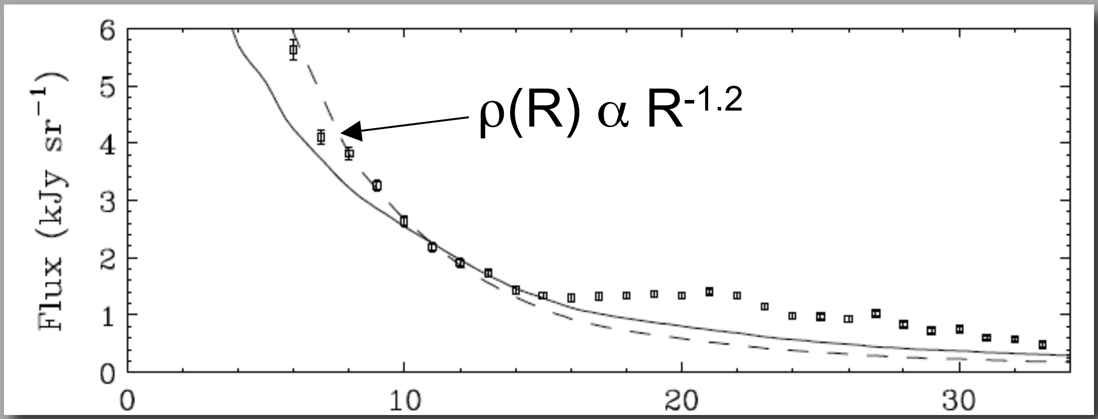

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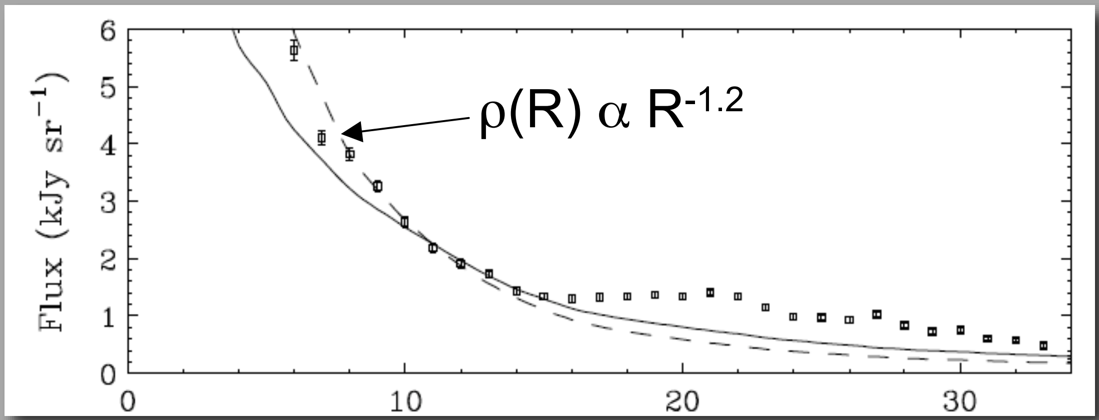

3) For 100-1000 GeV WIMP, the annihilation cross section required to produce the measured intensity of the haze is within a factor of 2-3 of the value needed to generate the density of dark matter thermally (~3x10^{-26} cm^3/s)

Hooper and G. Dobler and D. Finkbeiner, arXiv:0705.3655

Summary

•We are in the midst of a very exciting time for dark matter

•CDMS and XENON have already ruled out many SUSY models, and continue to push farther

•Searches with gamma-rays, antimatter and neutrinos are each developing rapidly

•We may have already seen WIMP annihilations in the form of the WMAP haze

Let's use all of the tools we have to solve the puzzles of dark matter and the TeV-scale!