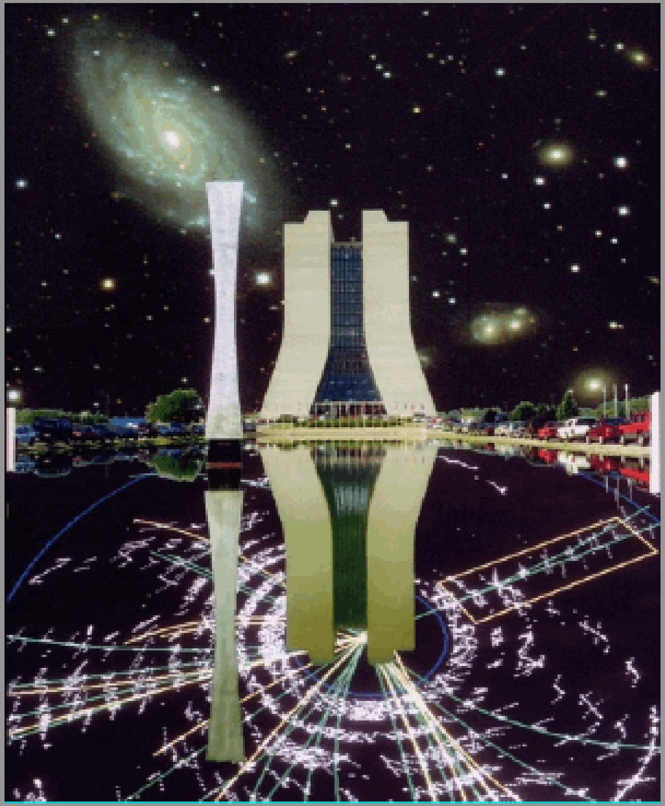
Indirect Signals of Particle Dark Matter

Dan Hooper
Particle Astrophysics Center
Fermi National Accelerator Laboratory
dhooper@fnal.gov



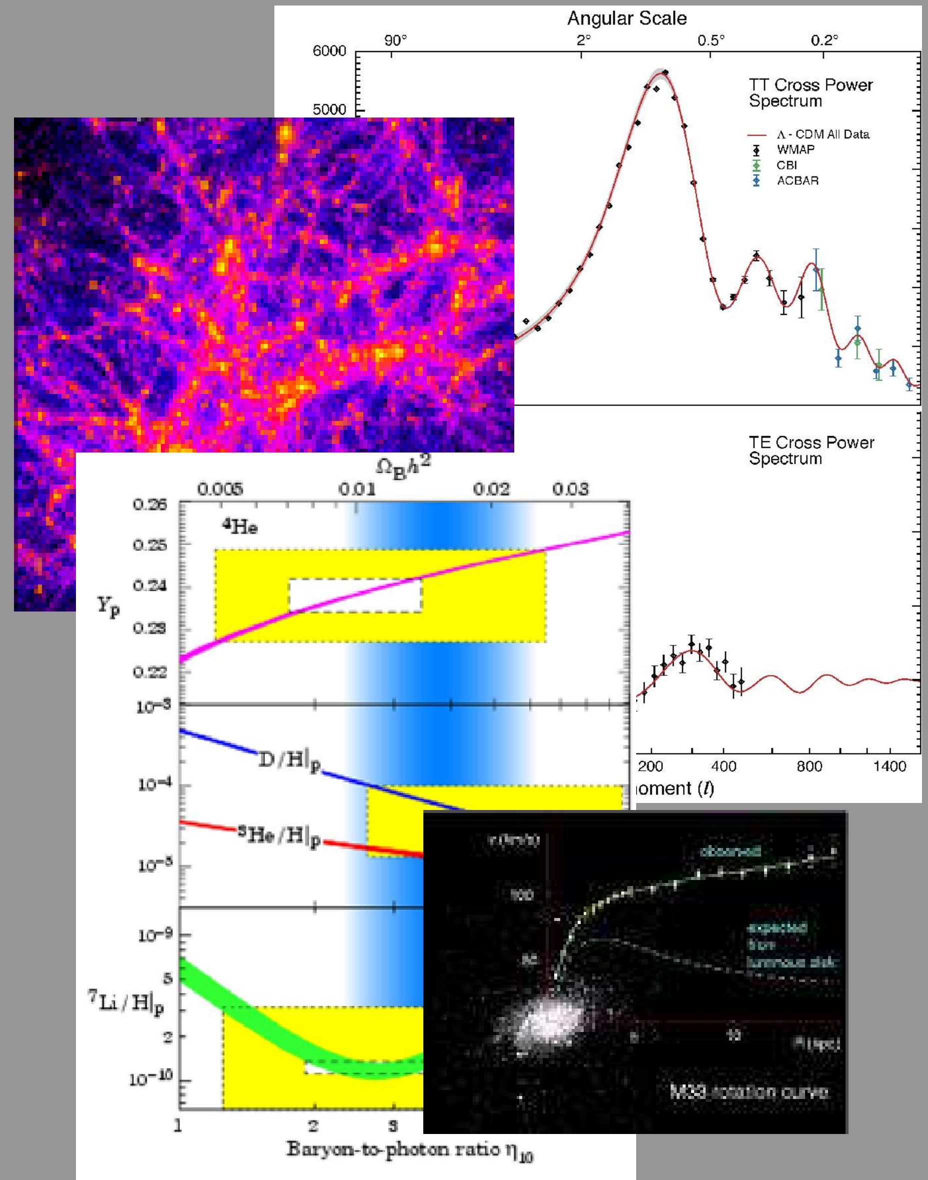
IOP/RAS Meeting, London
November 26, 2007

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 observations of dark matter's electroweak interactions (or other non-gravitational interactions)



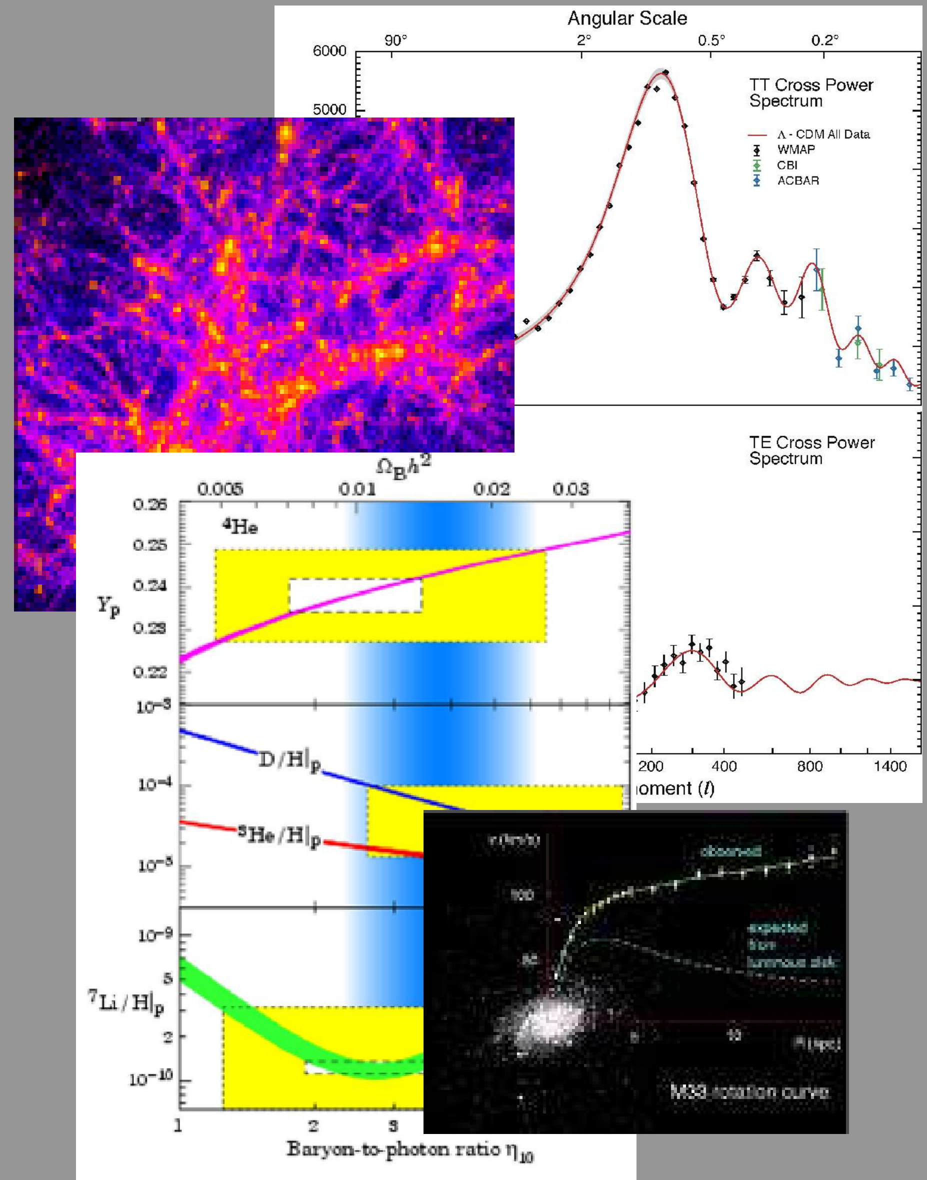
Dark Matter

- 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

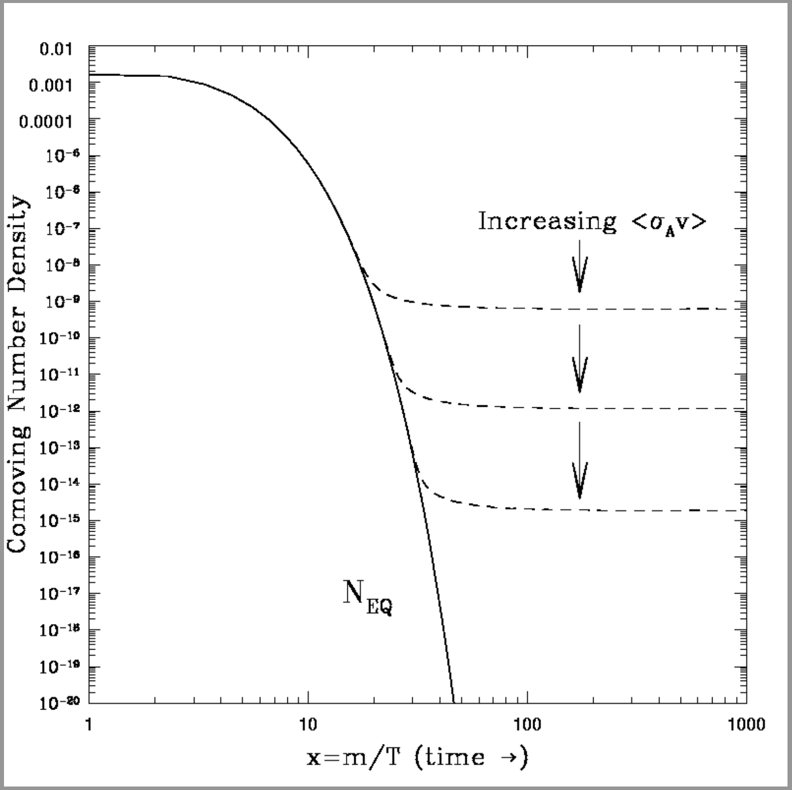
- Still no observations of dark matter's electroweak interactions (or other non-gravitational interactions)

- ***Dark matter's particle identity remains unknown!***



The Thermal Abundance of Weakly Interacting Massive Particles

- $T >> m_\chi$, χ's in thermal equilibrium
- $T < m_\chi$, number density of χ's become Boltzmann suppressed
- $T \sim m_\chi/20$, 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

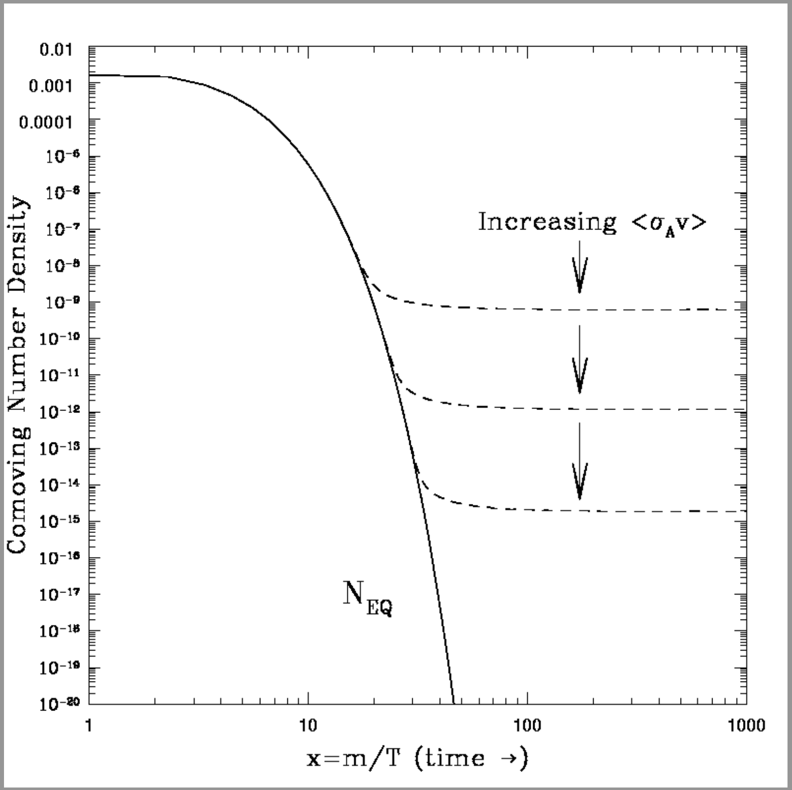


The Weak Scale and Weakly Interacting Massive Particles

- 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:

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

The Weak Scale and Weakly Interacting Massive Particles

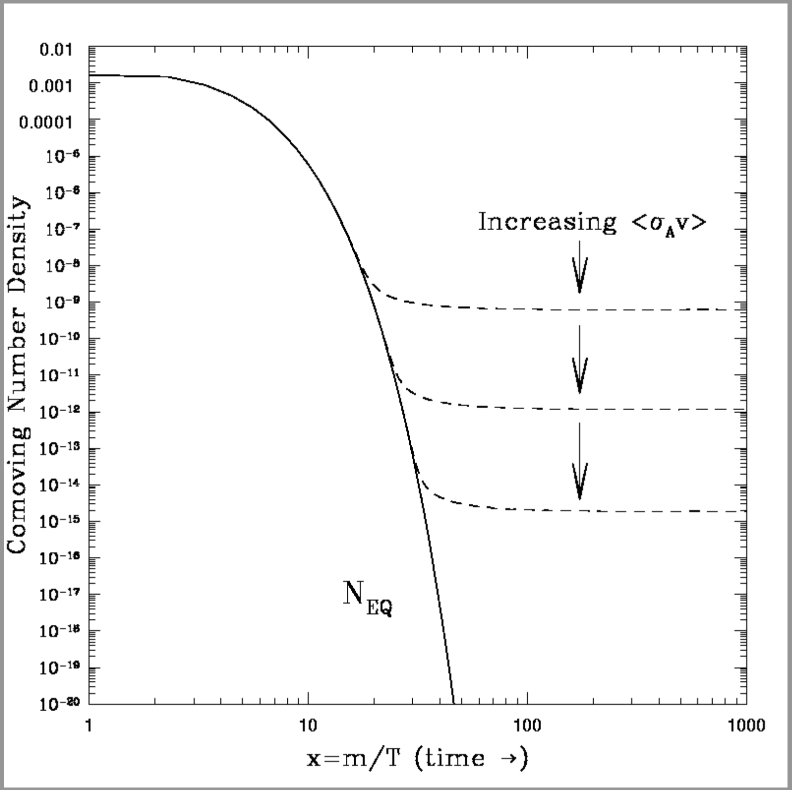
- As a result of the thermal freeze-out process, a relic density of WIMPs is left behind:

$$\Omega\, h^2 \sim x_F / \langle\sigma v\rangle$$

- 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:

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

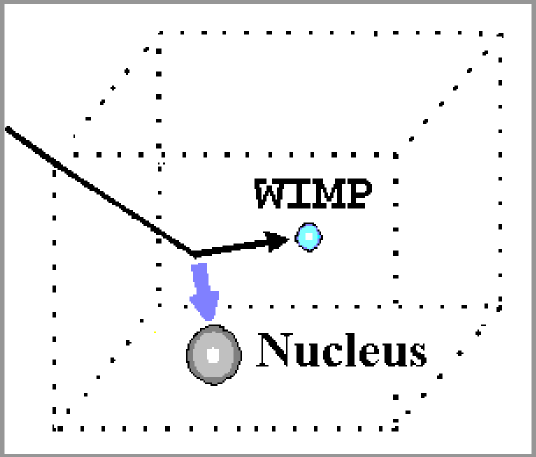


Numerical coincidence? Or an indication that dark matter originates from EW physics?

Astrophysical Probes of Particle Dark Matter

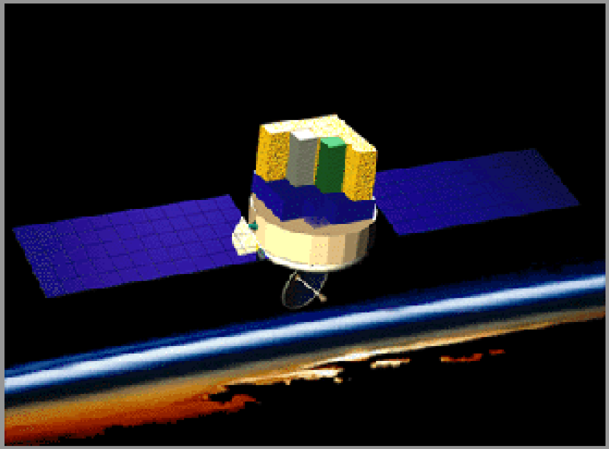
Direct Detection

-Momentum transfer to detector through elastic scattering



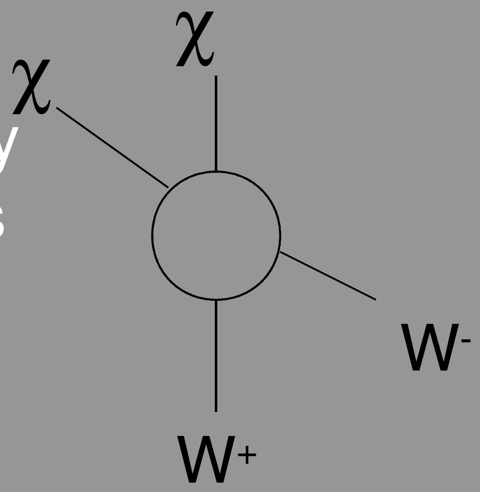
Indirect Detection

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



Indirect Detection of Dark Matter

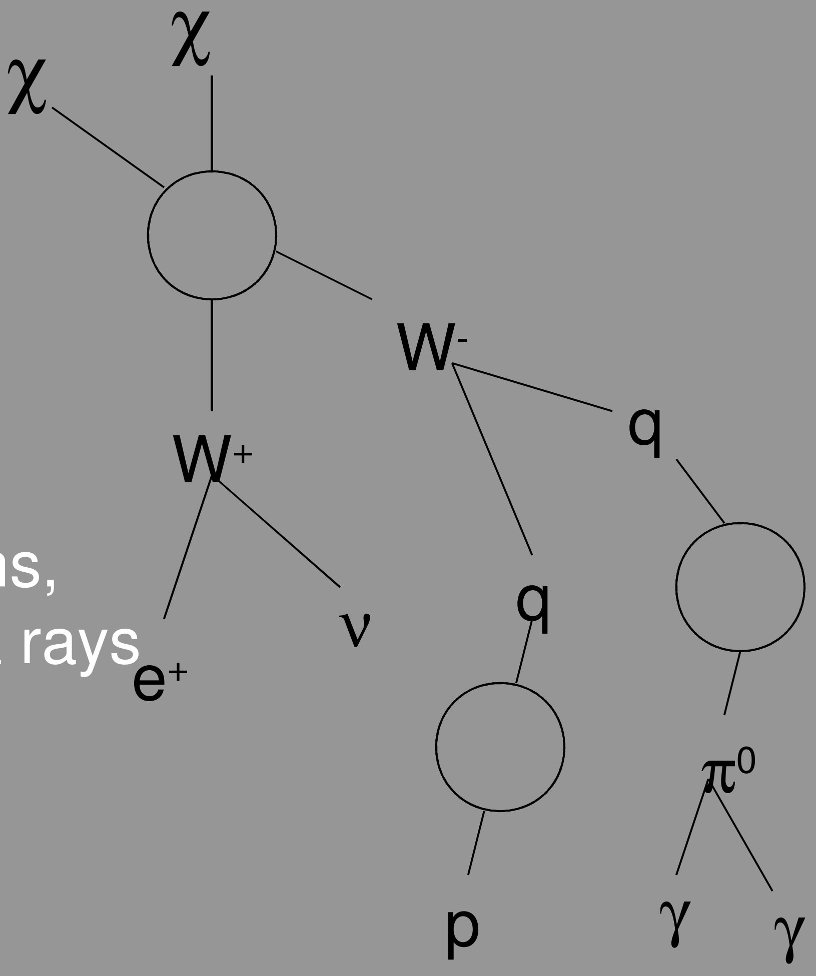
- **WIMP Annihilation**
  Typical final states include heavy fermions, gauge or Higgs bosons



Indirect Detection of Dark Matter

- **WIMP Annihilation**
  Typical final states include heavy fermions, gauge or Higgs bosons

2) Fragmentation/Decay
Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays

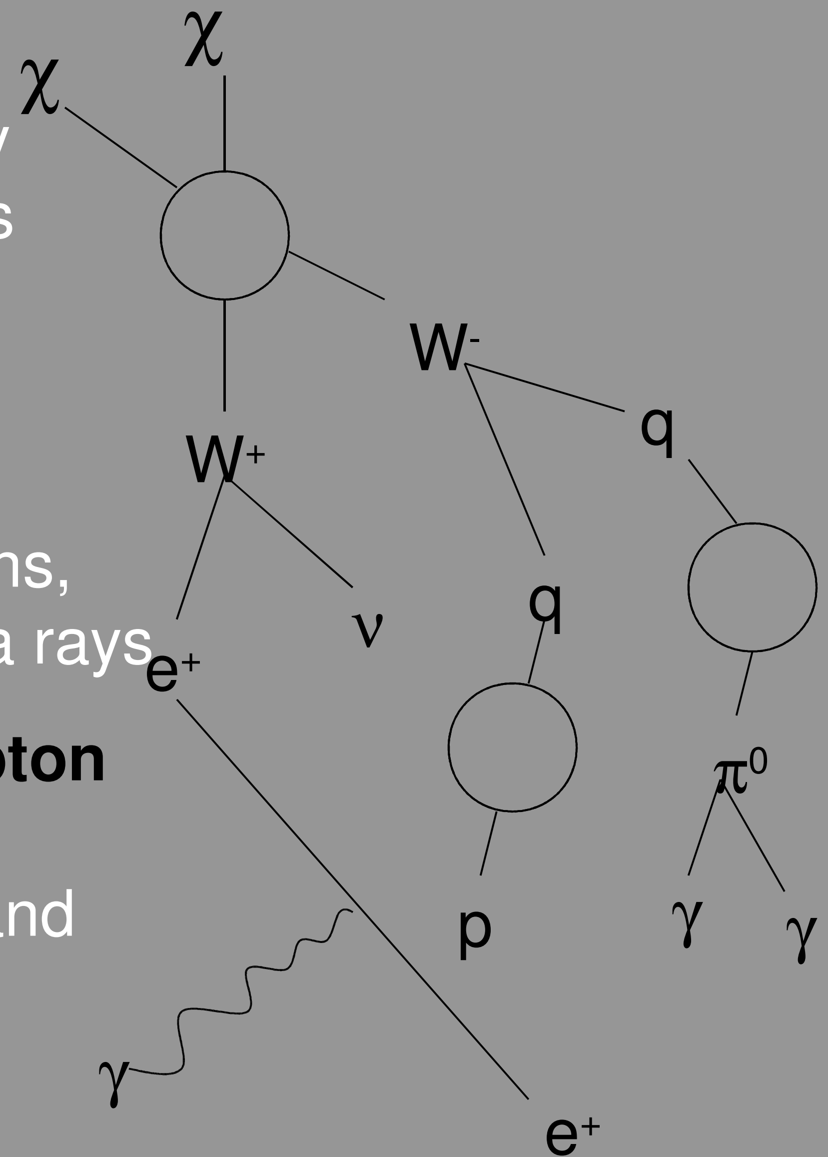


Indirect Detection of Dark Matter

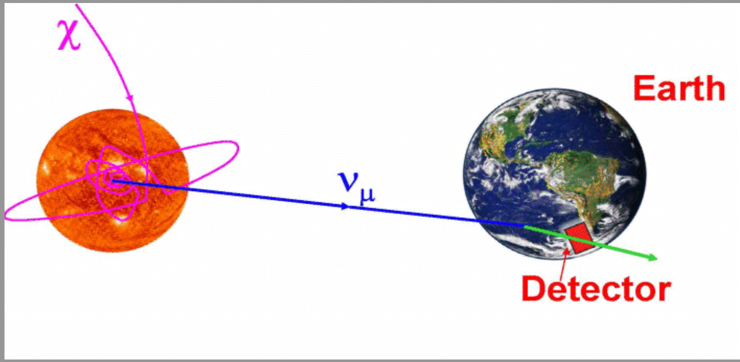
- **WIMP Annihilation**
  Typical final states include heavy fermions, gauge or Higgs bosons

2) Fragmentation/Decay
Annihilation products decay and/or fragment into some combination of electrons, protons, deuterium, neutrinos and gamma rays

3) Synchrotron and Inverse Compton
Relativistic electrons up-scatter starlight to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



Indirect Detection of Dark Matter

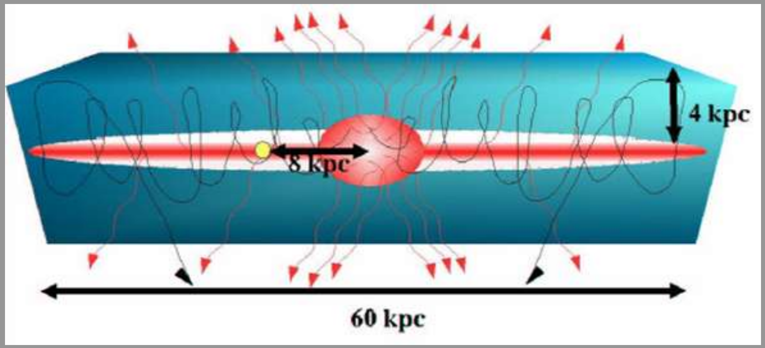


Neutrinos from annihilations
in the core of the Sun

Gamma Rays from annihilations
in the galactic halo, near the
galactic center, in dwarf galaxies, etc.

Positrons/Antiprotons from annihilations
throughout the galactic halo

Synchrotron Radiation from
electron/positron interactions
with the magnetic fields of the
inner galaxy



Indirect Detection With Gamma-Rays

<u>Advantages of Gamma-Rays</u>:

•Propagate undeflected (point sources possible)

•Propagate without energy loss (spectral information)

ACTs - HESS, MAGIC, VERITAS, and next generation experiments

GLAST - Launch scheduled for May 2008

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

•Evidence for dark matter, or other astrophysics?

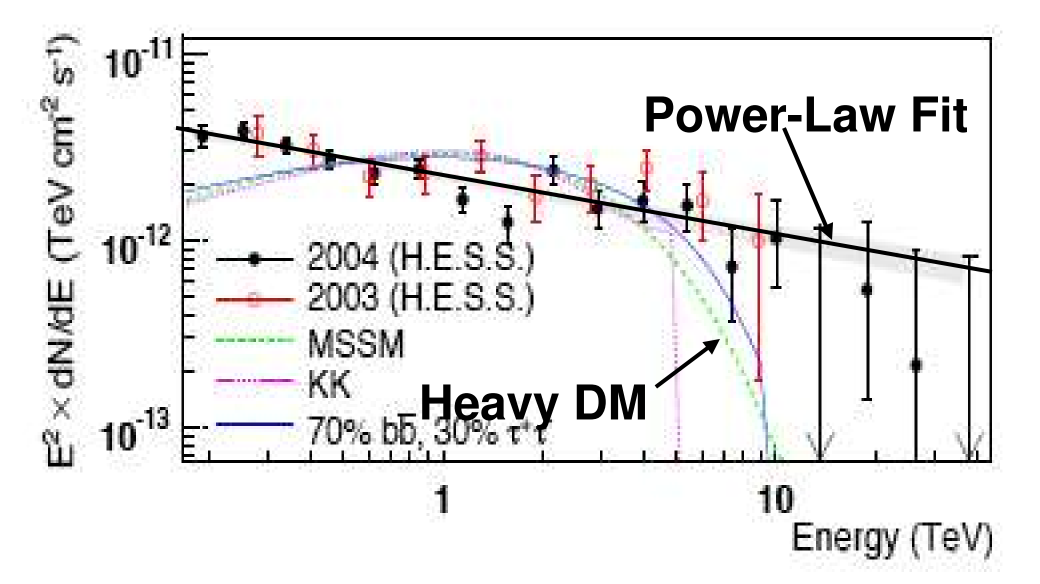
Gamma-Rays From The Galactic Center

•Spectrum as measured by HESS extends to at least ~10 TeV

•Consistent with a constant power-law spectrum

•Very poor match to the signal expected from dark matter

•Represents a daunting background for future dark matter searches to overcome

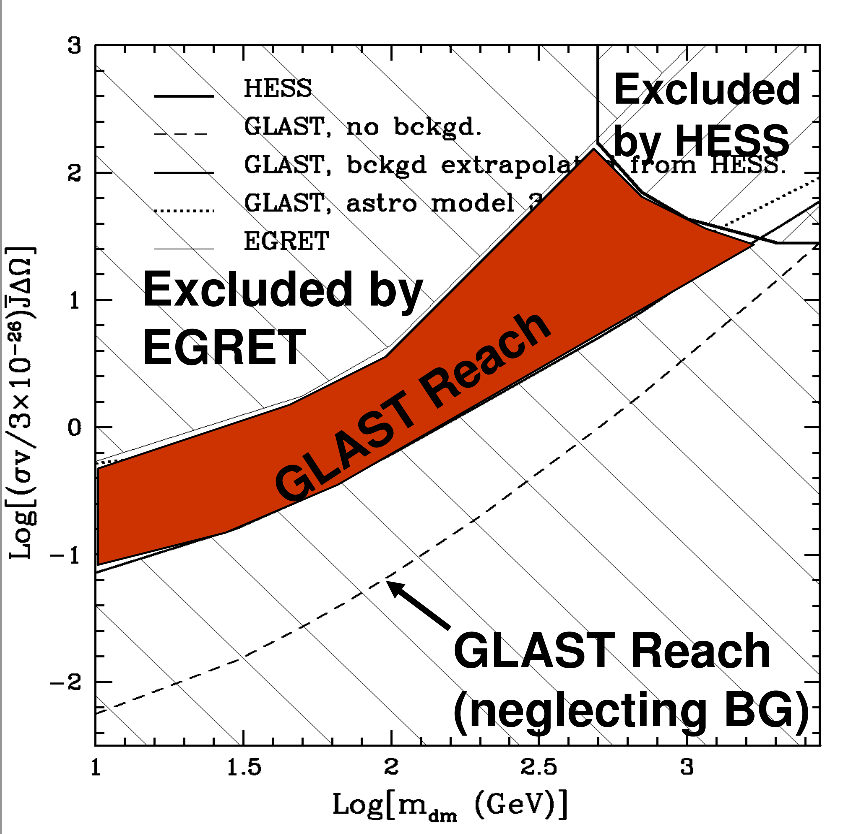


HESS Collaboration, PRL, astro-ph/0610509

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, but still about an order of magnitude improvement relative to EGRET



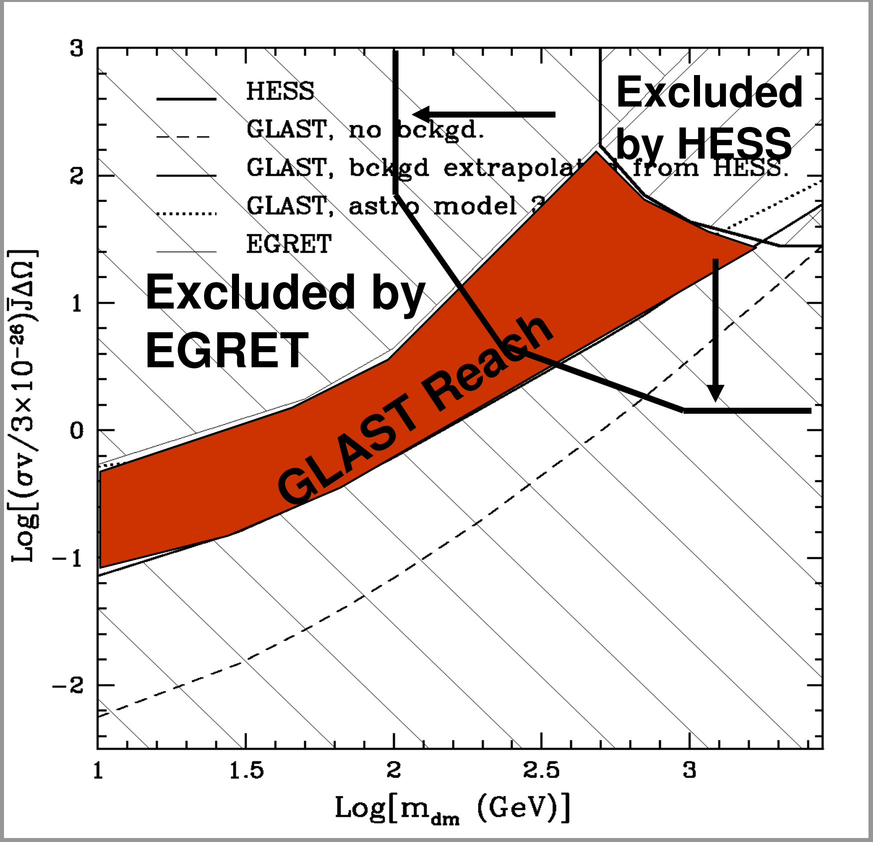
Hooper and G. Zaharijas, PRD, hep-ph/0603540

Next Generation ACTs

•Next generation ACTs will likely have greater collecting areas and lower energy thresholds than existing ground-based experiments

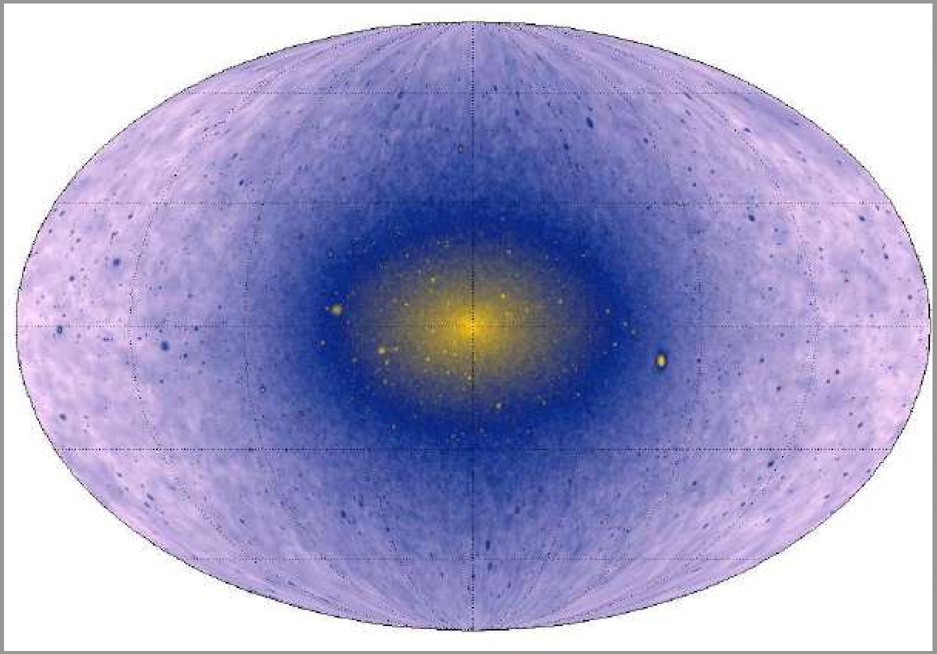
•Both lowering threshold *and* increasing sensitivity can dramatically improve discovery prospects

•Could plausibly outperform GLAST for WIMPs heavier than a few hundred GeV



Gamma-Rays From Galactic Substructure

- TeV-scale dark matter is expected to form structures down to very small (typically ~10^{-6} M) scales
- If substructures form with dense inner cusps (are survive), it may be possible to detect a number of point sources of dark matter annihilation radiation
- Such sources will require scrutiny with very sensitive telescopes to conclusively identify as dark matter
- Larger substructures (*ie*. dwarf galaxies) could also possibly generate an observable flux of dark matter annihilation radiation



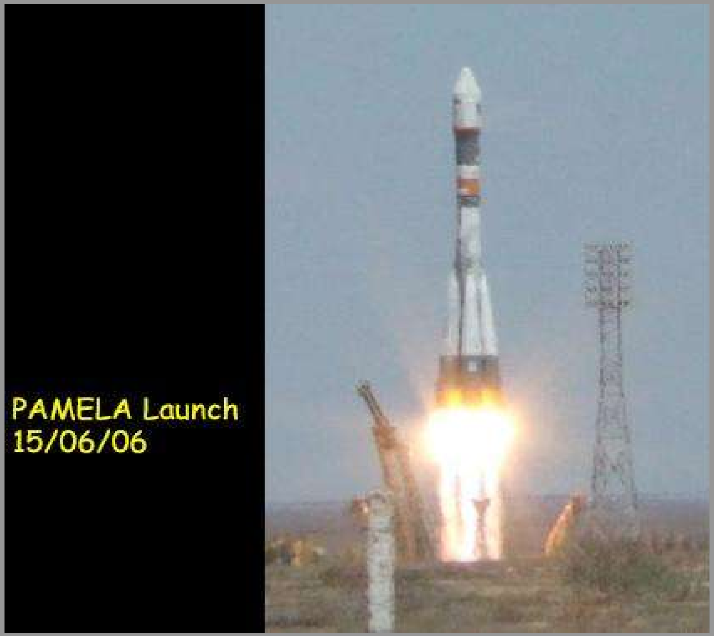
Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

Indirect Detection With Anti-Matter

•Matter and anti-matter 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 anti-matter spectrum with much greater precision, and at much higher energies



Indirect Detection With Anti-Matter

Anti-protons/anti-deuterons

•Energy loss lengths of tens of kpc (samples entire dark matter halo)

•Depends critically on understanding of halo profile, galactic magnetic fields and radiation backgrounds

Positrons

•Few kpc (or less) energy loss lengths (samples only the local volume)

•Less dependent on unknown astrophysics

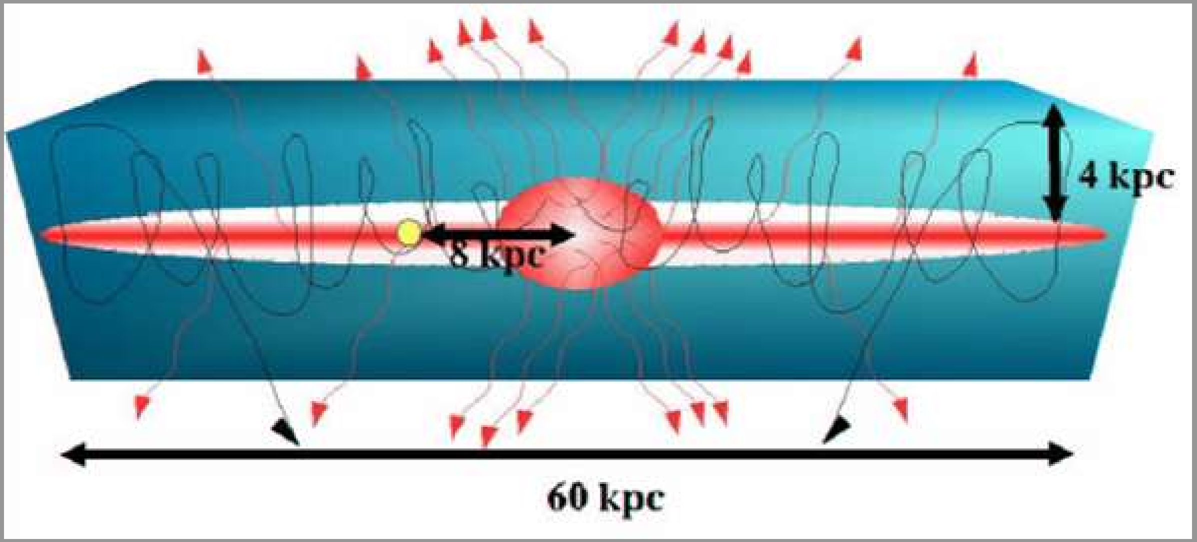
•Possible hints for dark matter present in existing data (?)

Indirect Detection With Positrons

•Positrons produced through a range of dark matter annihilation channels (decays of heavy quarks, gauge bosons, heavy leptons, etc.)

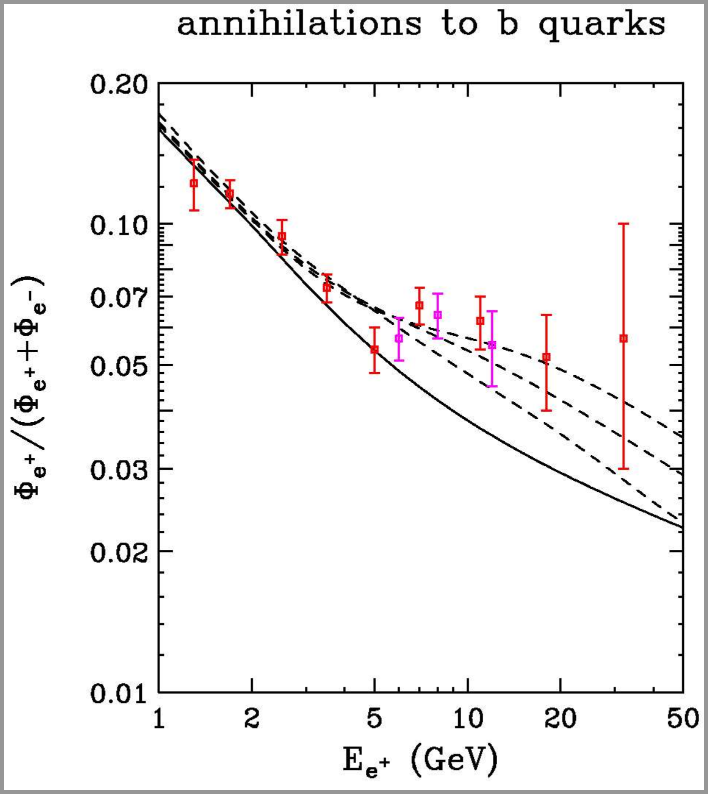
•Move as a random walk through galactic magnetic fields

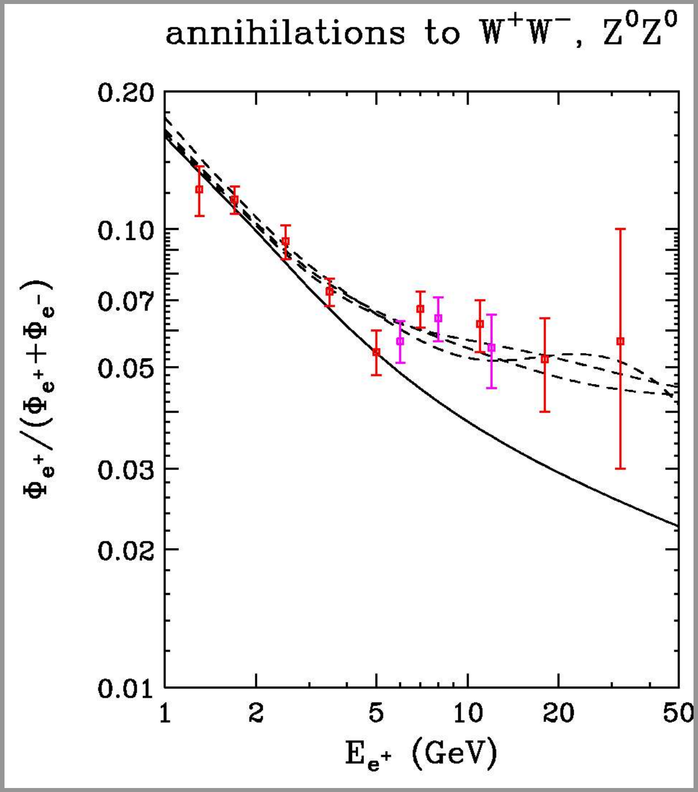
•Energy losses through inverse compton and synchotron scattering with starlight, CMB



Indirect Detection With Positrons

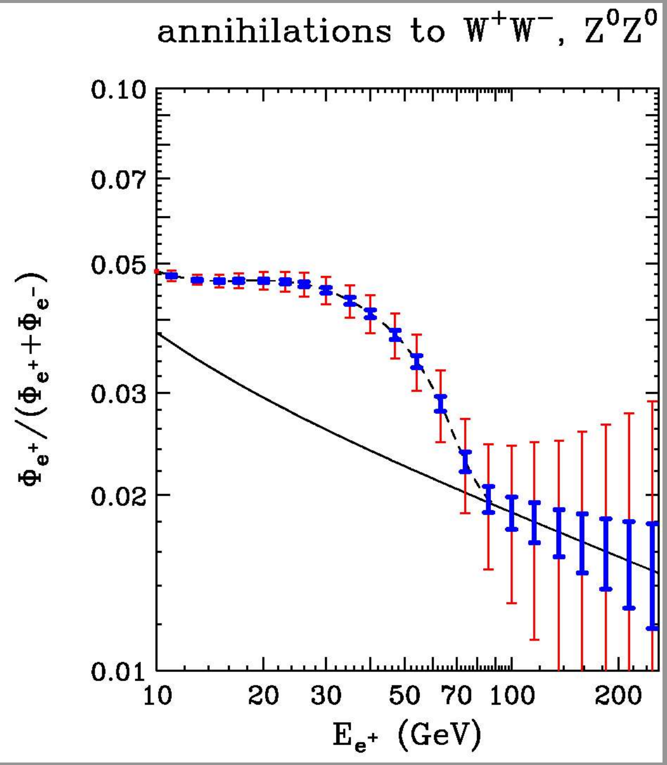
- HEAT experiment reported an excess of high-energy positrons in three balloon flights
- Neutralino annihilation can generate the signal, but only with unexpectedly high annihilation rates (by a factor of ~50)

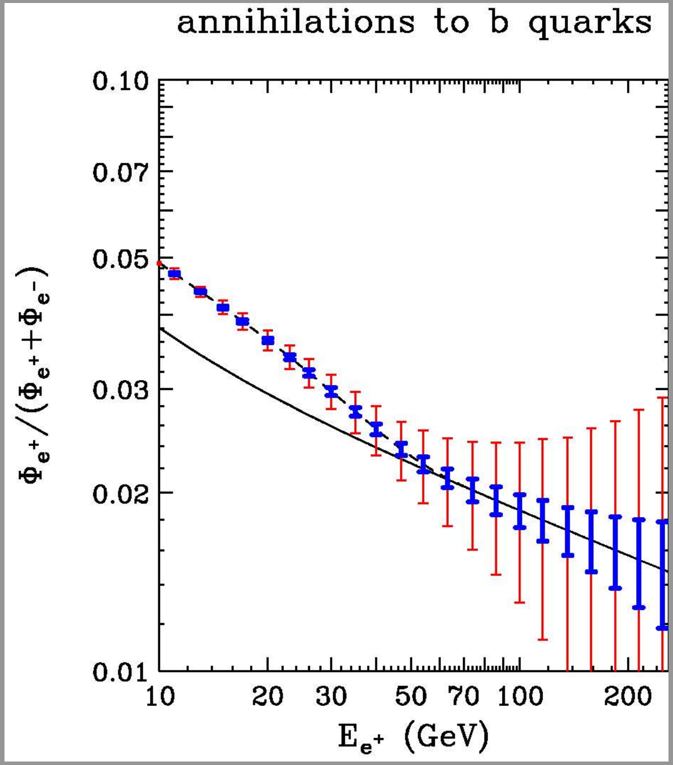




Indirect Detection With Positrons

With a HEAT-sized flux, dramatic signal in PAMELA and AMS

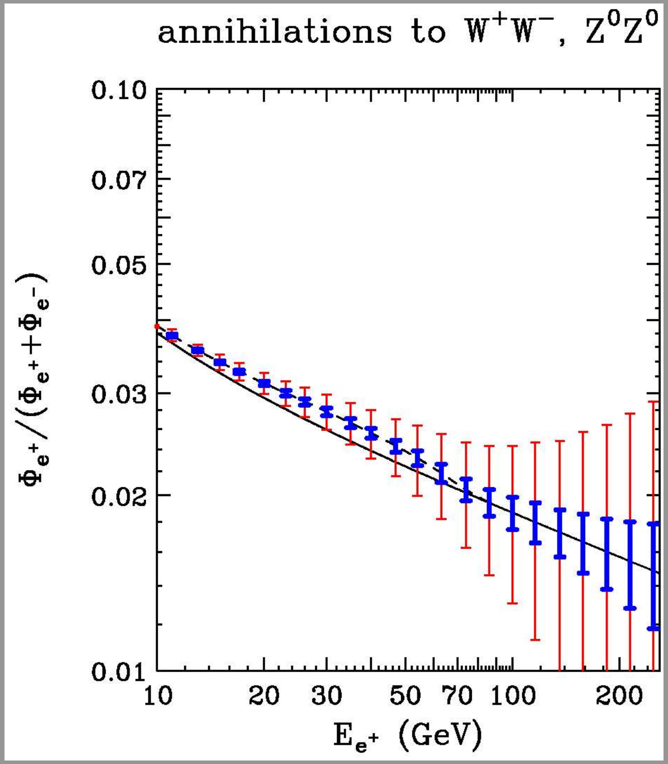


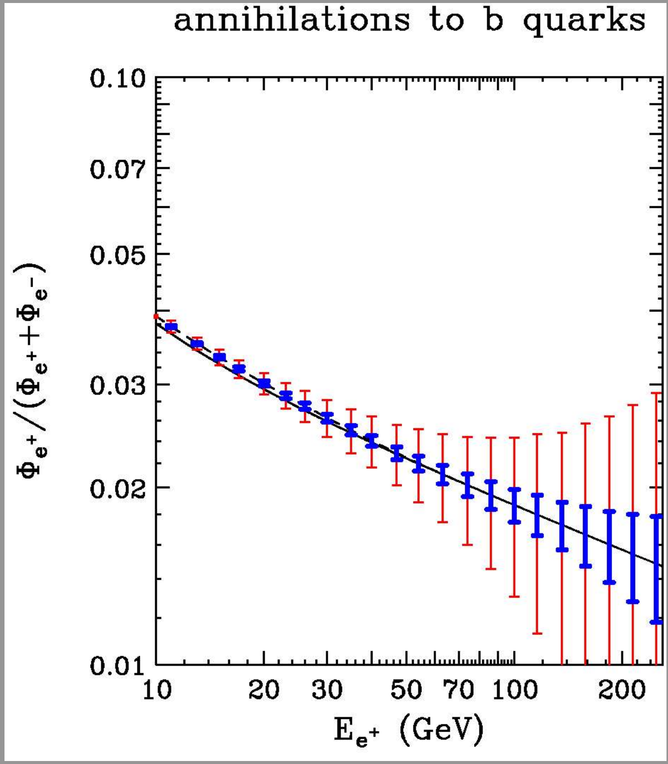


Hooper and J. Silk, PRD (hep-ph/0409104)

Indirect Detection With Positrons

With a smaller flux, more difficult, but potentially interesting

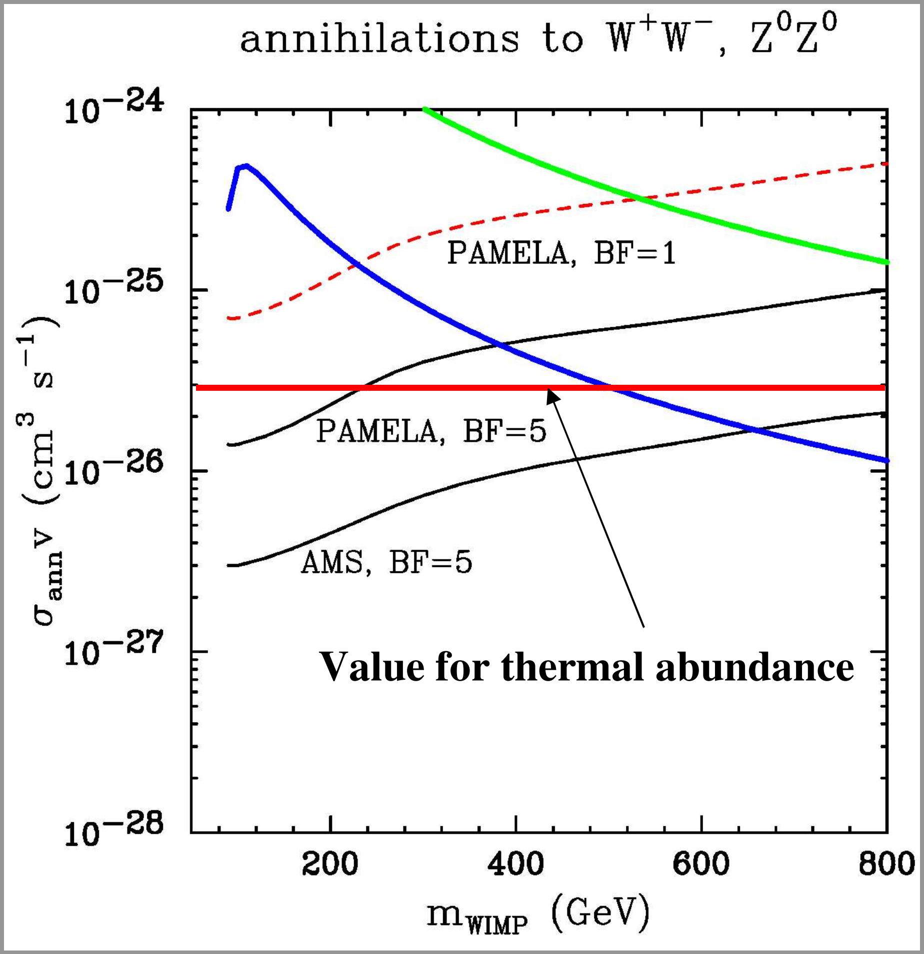




Hooper and J. Silk, PRD (hep-ph/0409104)

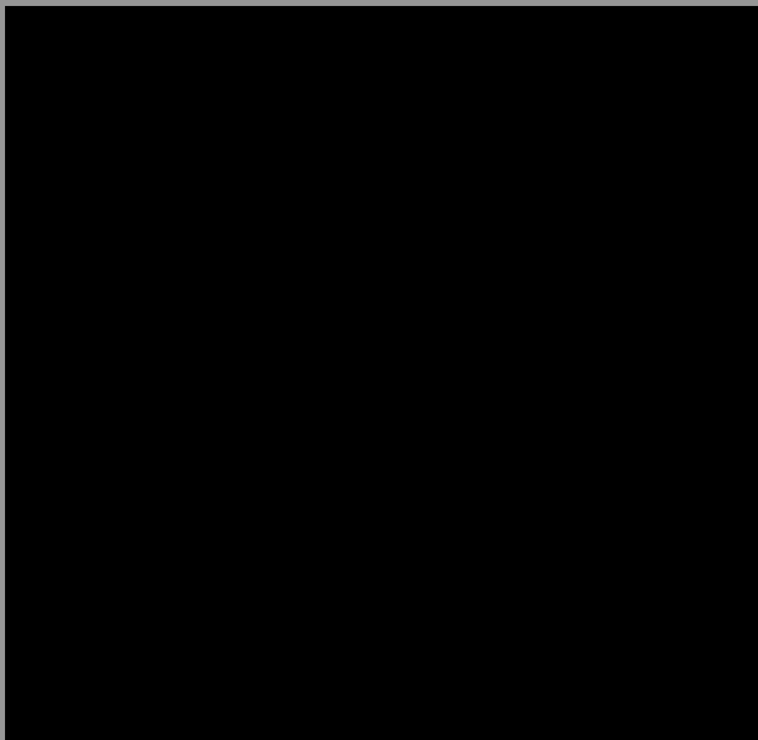
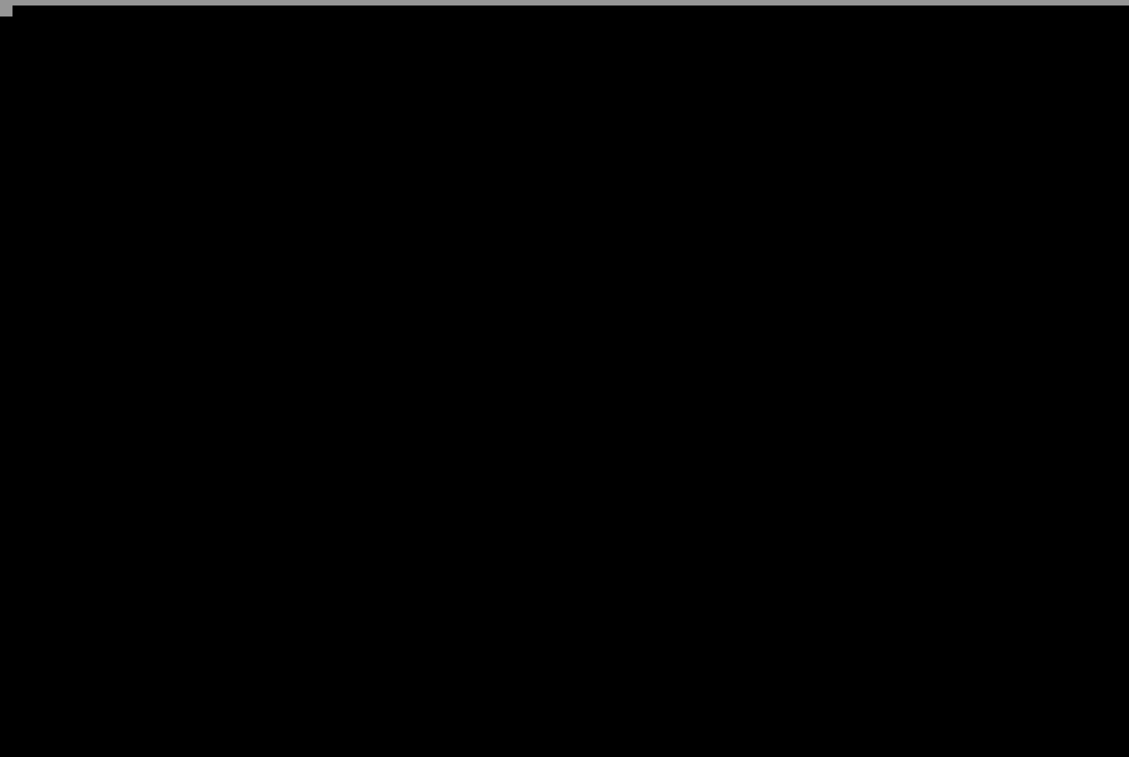
Indirect Detection With Positrons

- AMS-02 can detect most neutralinos up to ~200 GeV, for *any* boost factor, and all likely annihilation modes
- For modest boost factor of ~5, AMS-02 could detect dark matter as heavy as ~1 TeV
- PAMELA, with modest boost factors, can reach masses of ~250 GeV
- Non-thermal scenarios (AMSB, etc), can be easily tested



Hooper and J. Silk, PRD (hep-ph/0409104)

PAMELA's Launch - June 2006

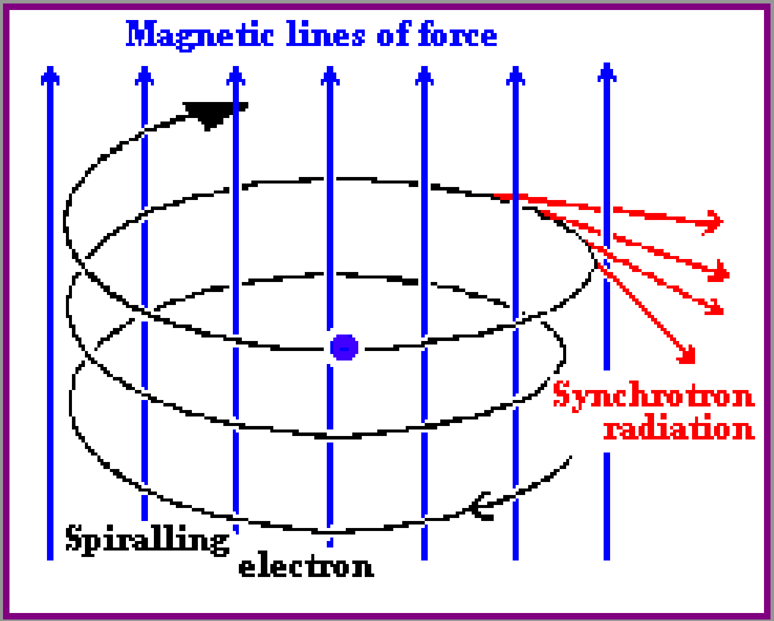



First data to be announced last summer… (?)

Will dramatically improve measurements of the galactic cosmic ray spectra, including positrons and antiprotons

Indirect Detection With Synchrotron

- Electrons/positrons produced in dark matter annihilations inverse Compton scatter with starlight and emit synchrotron photons as they propagate through the galactic magnetic fields



$$-\left(\frac{dE_e}{dt}\right) = \frac{4}{3}\sigma_T\, c \left(\frac{E_e}{m_e}\right)^2 (U_{\rm rad} + U_{\rm mag})$$

$$\approx 8 \times 10^{-16}\,{\rm GeV/s} \left(\frac{E_e}{1\,{\rm GeV}}\right)^2 \left[\left(\frac{U_{\rm rad}}{5\,{\rm eV/cm}^3}\right) + 0.4 \times \left(\frac{B}{10\,\mu{\rm G}}\right)^2\right]$$

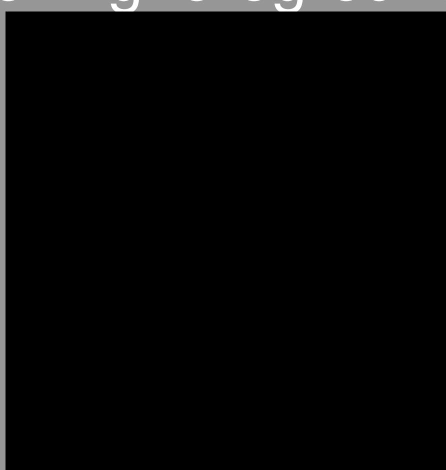
- For electroweak-scale dark matter, the resulting synchrotron radiation falls within the frequency range of WMAP

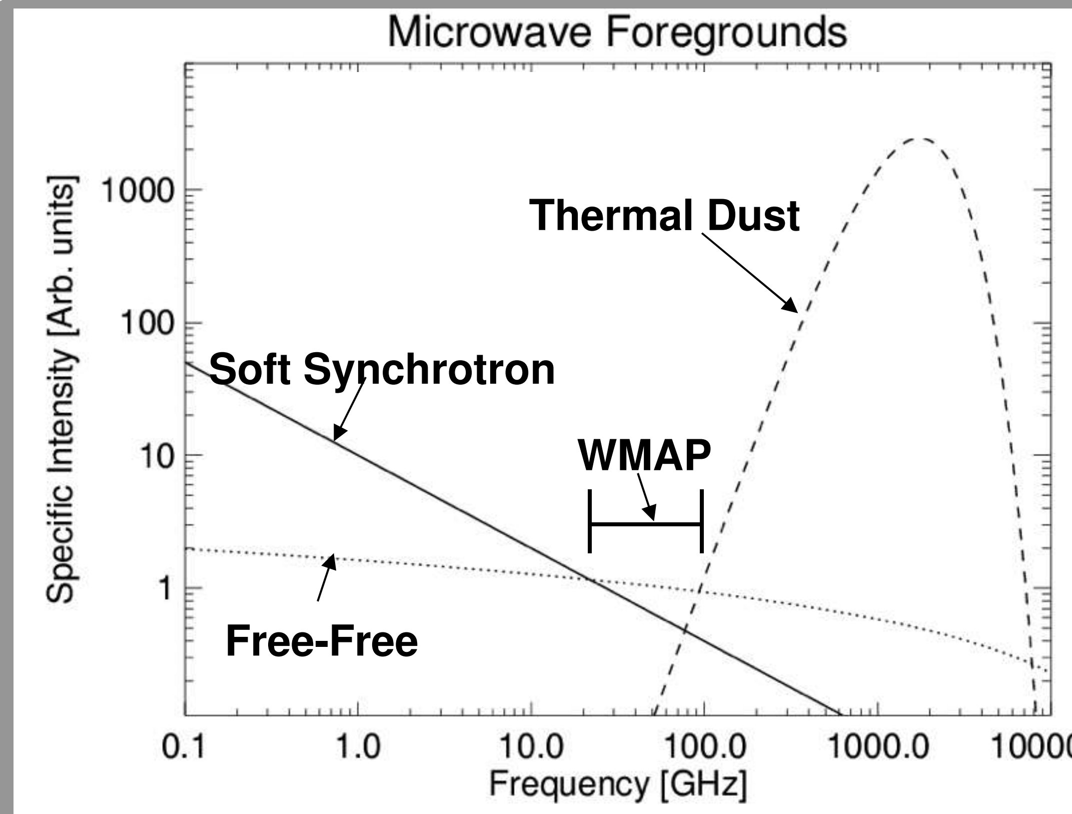
WMAP As A Synchrotron Telescope

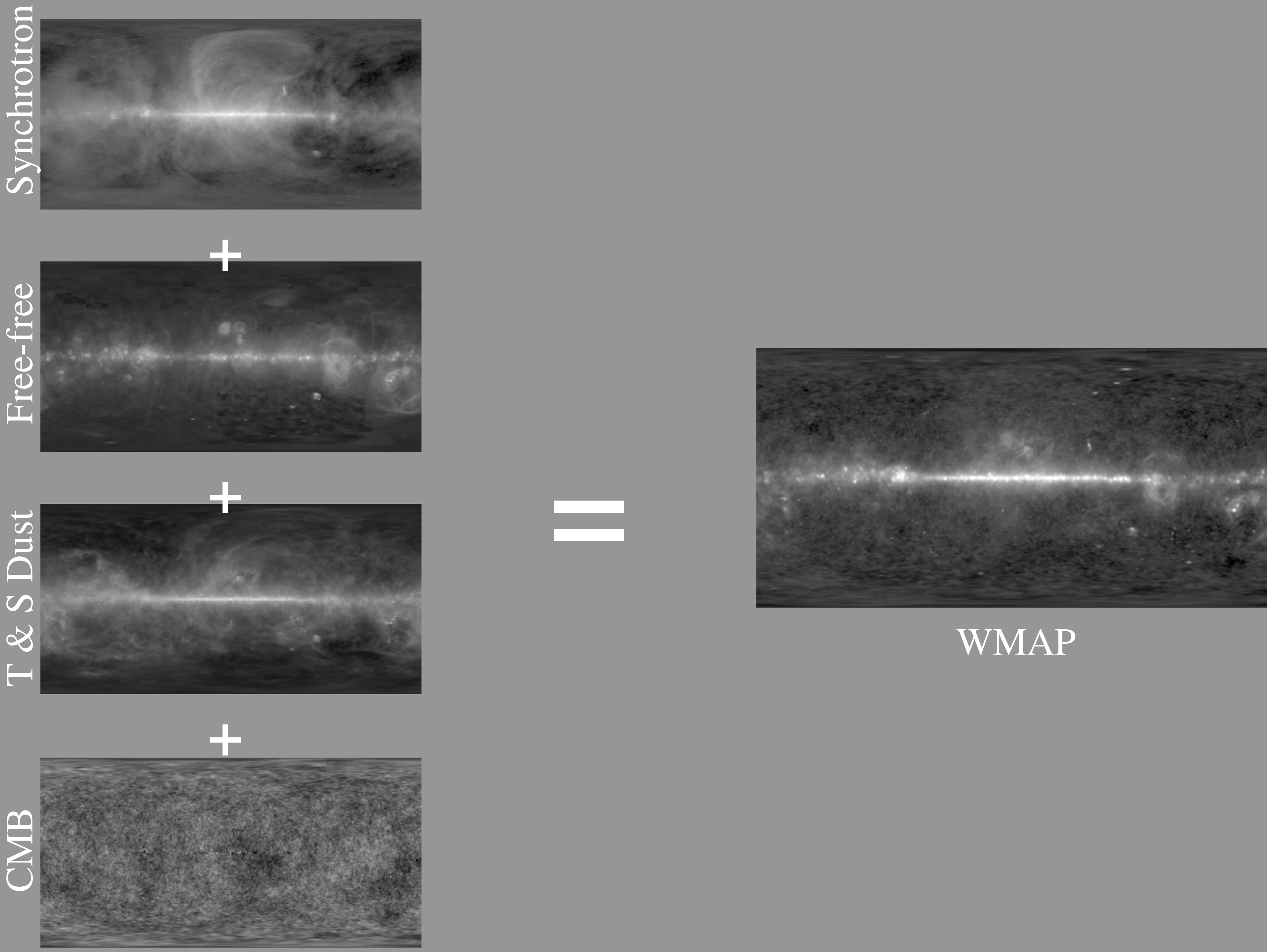
- In addition to CMB photons, WMAP data is "contaminated" by a number of galactic foregrounds that must be accurately subtracted

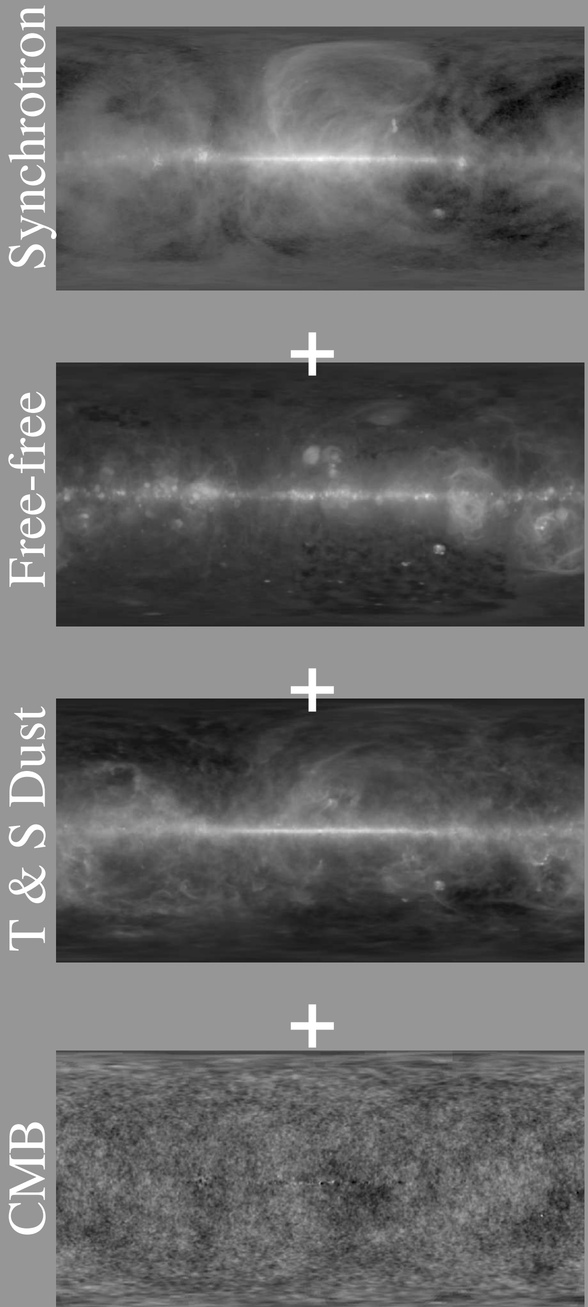
- The WMAP frequency range is well suited to minimize the impact of foregrounds

- Substantial challenges are involved in identifying and removing foregrounds

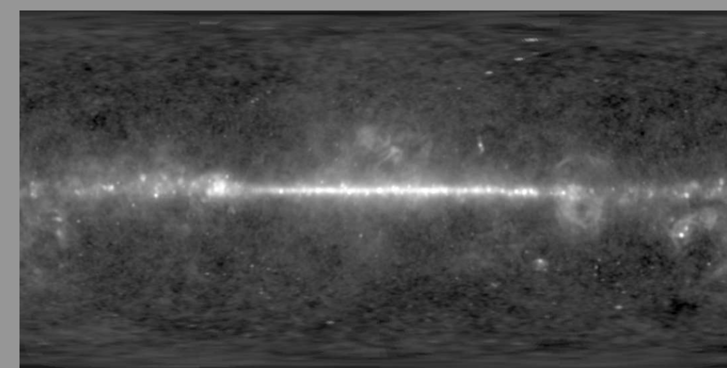





Synchrotron
+
Free-free
+
T & S Dust
+
CMB
=
WMAP

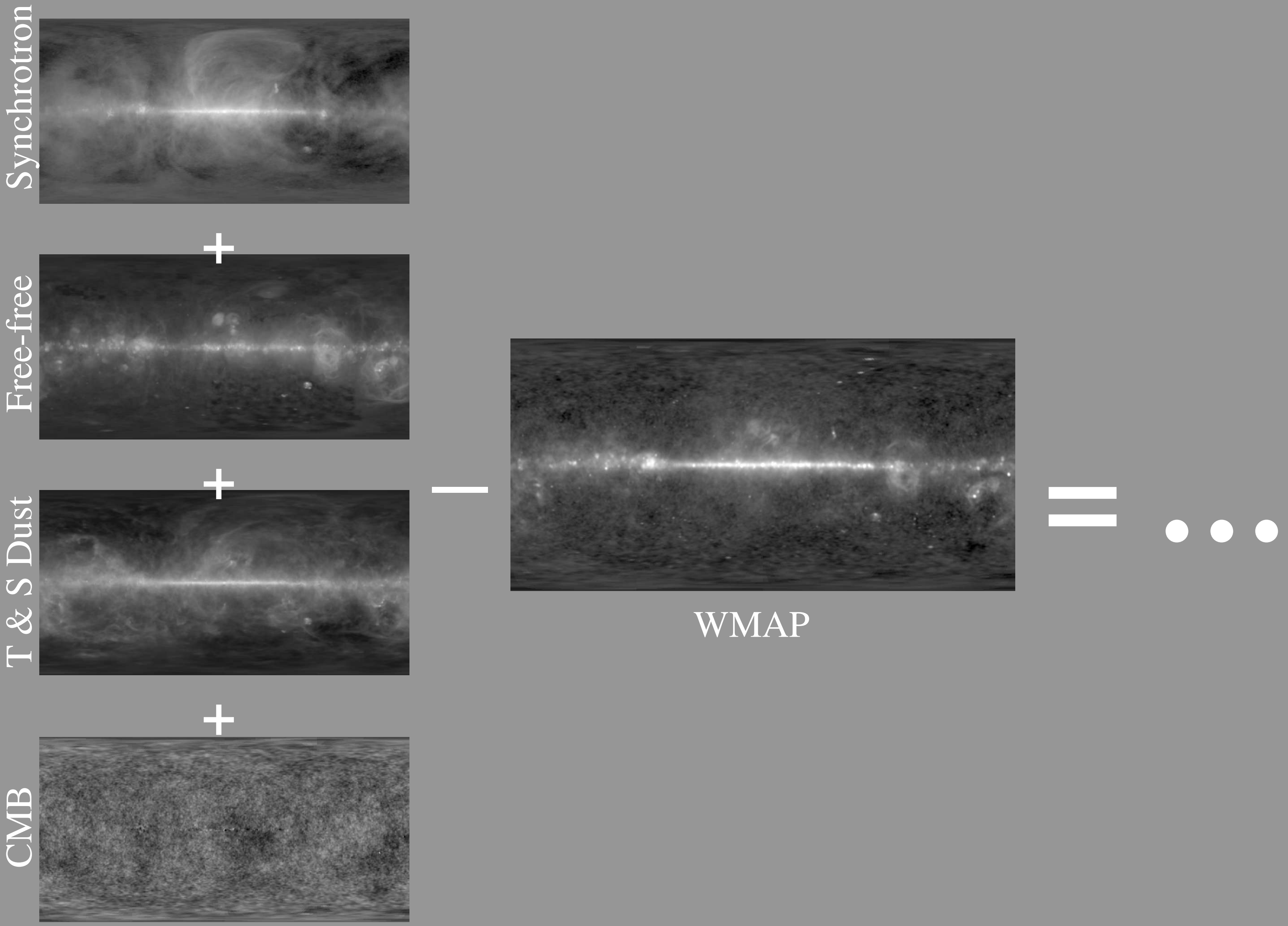


=

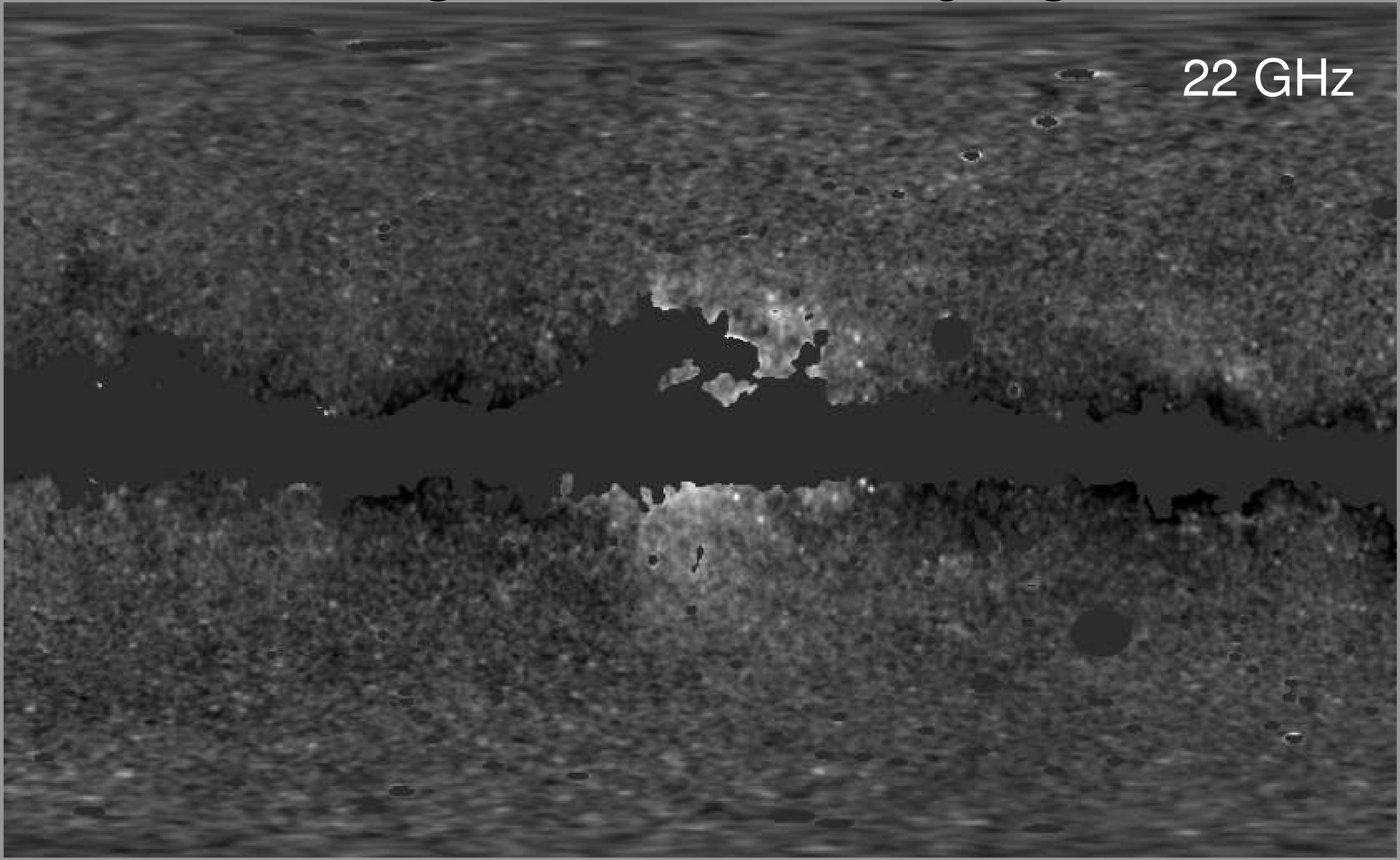


WMAP

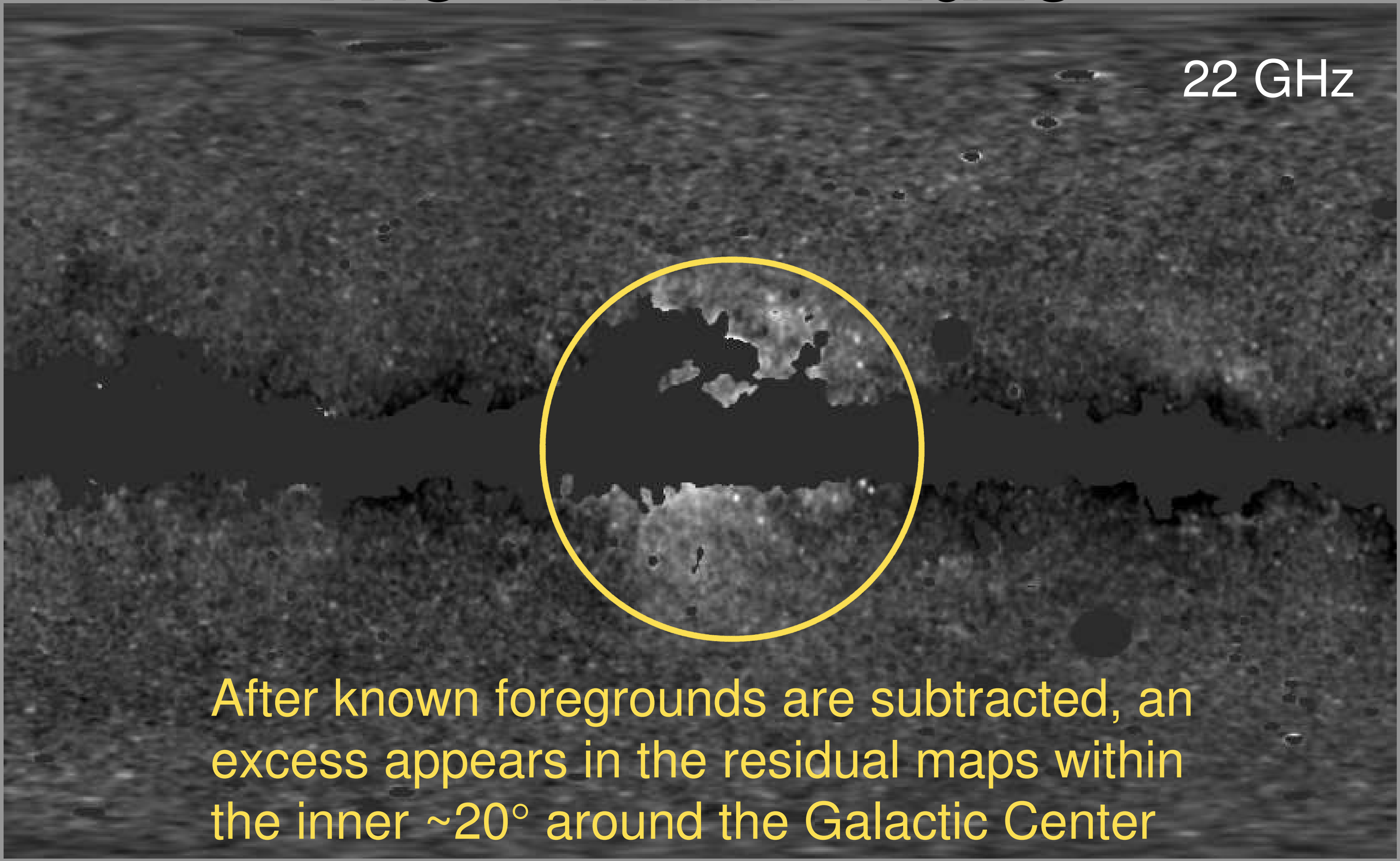
Well, actually… No


Synchrotron
+
Free-free
+
T & S Dust
+
CMB
−
WMAP
=
• • •

The "WMAP Haze"

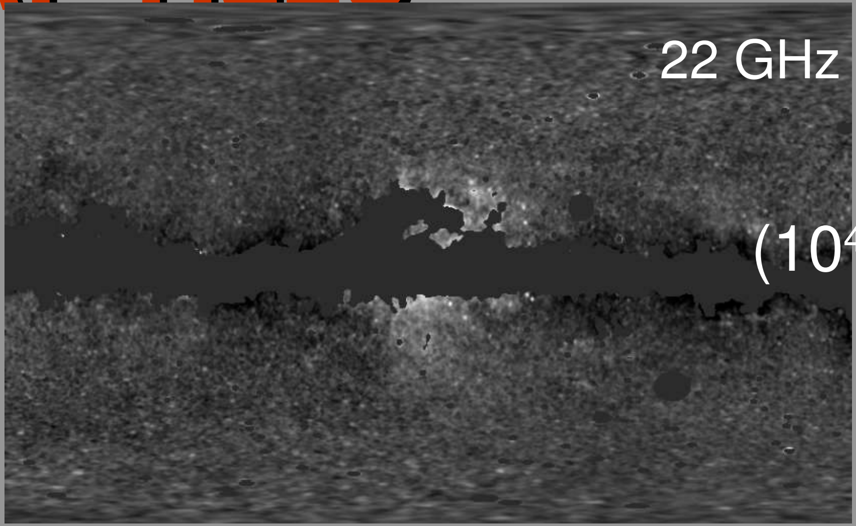


The “WMAP Haze”



After known foregrounds are subtracted, an excess appears in the residual maps within the inner ~20° around the Galactic Center

The "WMAP Haze"



•Initially interpreted as likely thermal bremsstrahlung (free-free emission) from hot gas (10^4-10^6 K)

•This interpretation has since been ruled out by the lack of a corresponding Hα recombination (x-ray) line

•Appears to be hard synchrotron emission from a new population of energetic electrons/positrons in the inner galaxy

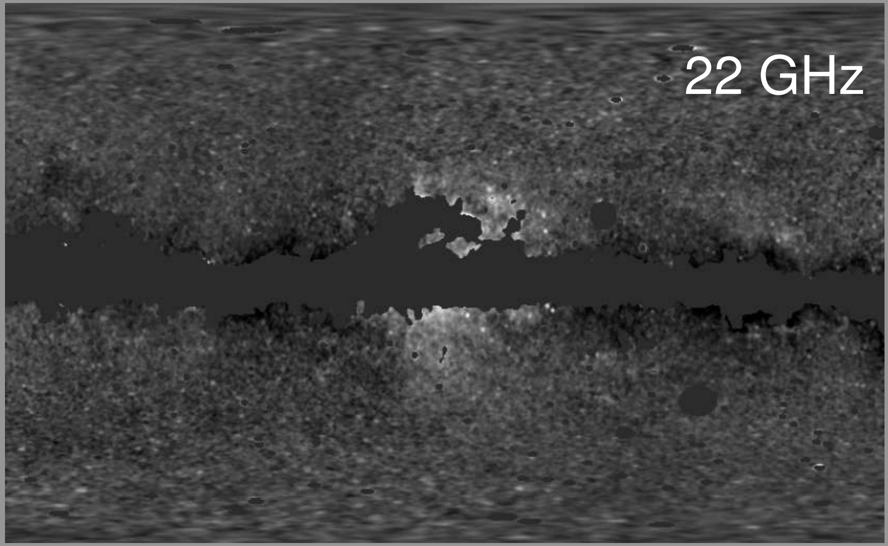
-Too hard to be supernovae shocks

-Too extended to be a singular event (GRB, etc.)

•Very Difficult to explain astrophysically

Dark Matter in the WMAP Sky

•In 2004, Doug Finkbeiner suggested that the WMAP Haze could be synchtrotron from electrons/positrons produced in dark matter annihilations in the inner galaxy (astro-ph/0409027)



•In particular, he noted that:

1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of 3×10^{-26} cm^3/s, the total power in dark matter annihilations in the inner 3 kpc of the Milky Way is

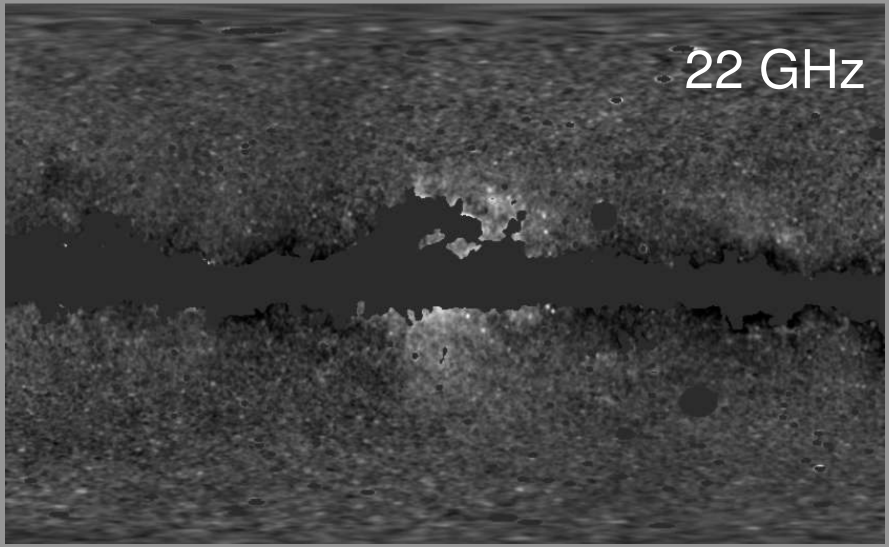
$\sim1.2\times10^{39}$ GeV/sec

2) The total power of the WMAP Haze is between

0.7×10^{39} and 3×10^{39} GeV/sec

Dark Matter in the WMAP Sky

•In 2004, Doug Finkbeiner suggested that the WMAP Haze could be synchtrotron from electrons/positrons produced in dark matter annihilations in the inner galaxy (astro-ph/0409027)



•In particular, he noted that:

1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of 3×10^{-26} cm^3/s, the total power in dark matter annihilations in the inner 2 kpc of the Milky Way is

$\sim 1.2 \times 10^{39}$ GeV/sec

Coincidence?

2) The total power of the WMAP Haze is between

0.7×10^{39} and 3×10^{39} GeV/sec

The Remarkable Match Of The WMAP Haze To The Signal Expected From Dark Matter

The Haze is consistent with dark matter annihilations with the following characteristics:

- A dark matter distribution with $\rho \propto R^{-1.2}$ in the inner kiloparsecs of our galaxy
- A dark matter particle with a ~100 GeV to several TeV mass, and that annihilates to typical channels (heavy fermions, gauge bosons, etc.)
- An annihilation cross section within a factor of a few of $3\text{x}10^{-26}$ cm^3/s (the value required of a thermal relic)

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

The Remarkable Match Of The WMAP Haze To The Signal Expected From Dark Matter

The Haze is consistent with dark matter annihilations with the following characteristics:

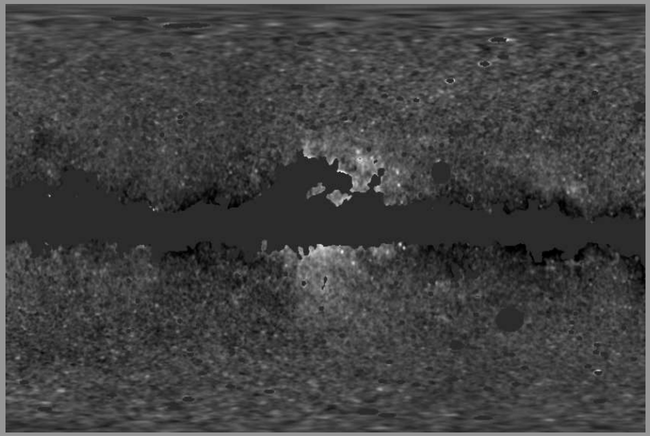
- A dark matter distribution with $\rho \propto R^{-1.2}$ in the inner kiloparsecs of our galaxy
- A dark matter particle with a ~100 GeV to several TeV mass, and that annihilates to typical channels (heavy fermions, gauge bosons, etc.)
- An annihilation cross section within a factor of a few of 3×10^{-26} cm^3/s (the value required of a thermal relic)

A completely vanilla dark matter scenario!

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

Summary

•Indirect searches for dark matter are developing rapidly
•GLAST and next-generation ACTs will open a new window into dark matter annihilation, especially in the Galactic Center
•HEAT may have already seen hints of dark matter in the positron spectrum. PAMELA will increase the sensitivity of this channel considerably
•Hard synchrotron emission from the inner galaxy observed by WMAP is a compelling signature of dark matter annihilations



Summary

•Searches for supersymmetry at colliders, direct and indirect dark matter experiments are each very exciting

•A few years from now, our understanding of dark matter will almost certainly be very different – either a discovery is on the way, or very new ideas will be needed

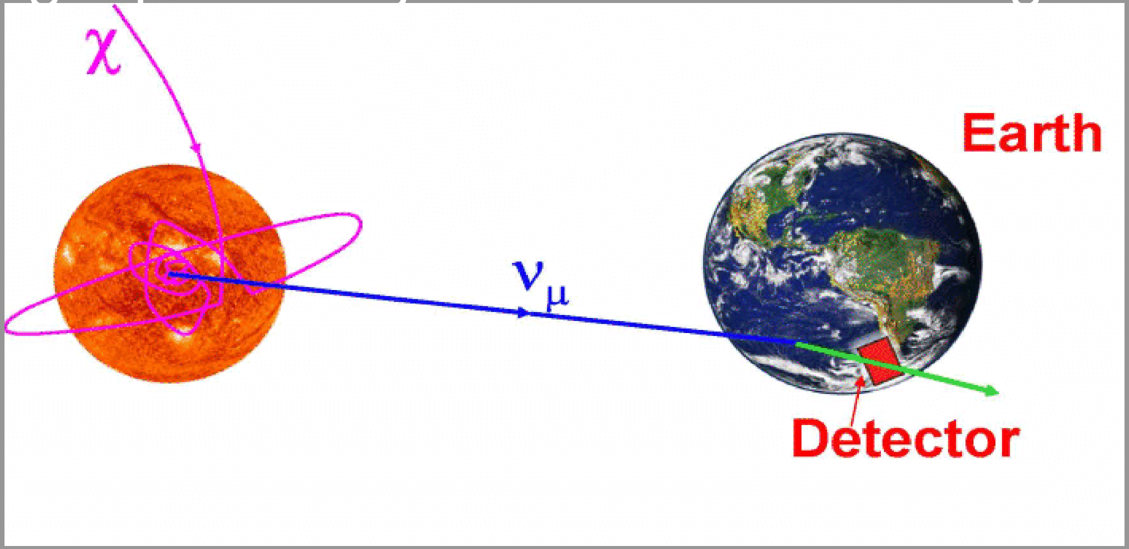
Let's use all of the tools we have to solve the puzzle of dark matter!

Indirect Detection With Neutrinos

•Neutralinos elastically scatter with nuclei in the Sun, becoming gravitationally bound

•As neutralinos accumulate in the Sun's core, they annihilate at an increasing rate

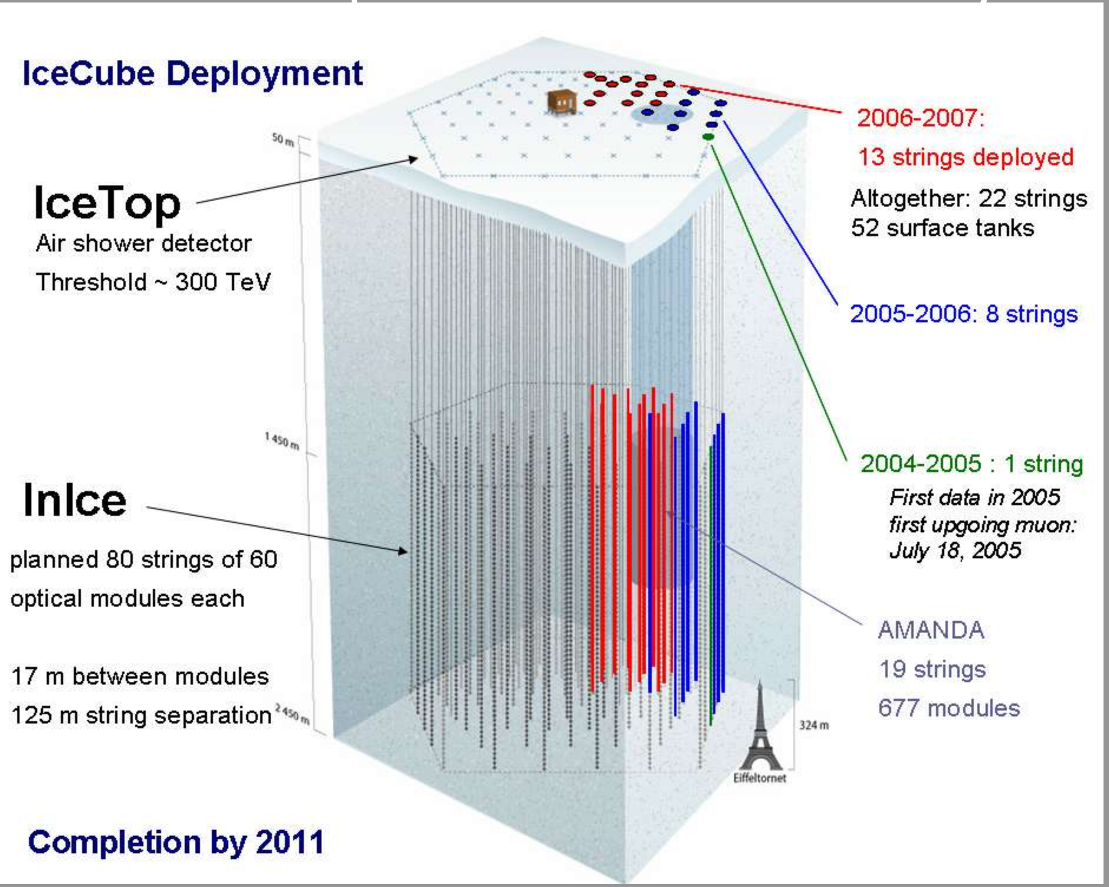
•After ~Gyr, annihilation rate typically reaches equilibrium with capture rate, generating a potentially observable flux of high-energy neutrinos



Indirect Detection With Neutrinos

•Muon neutrinos from the Sun interacting via charged current produce energetic muons

•The kilometer-scale neutrino telescope IceCube is currently under construction at the South Pole



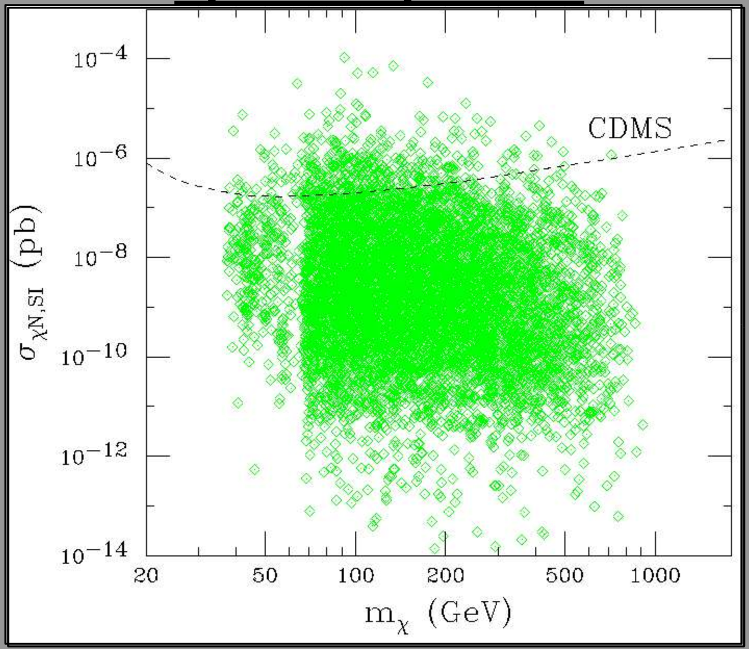
Indirect Detection With Neutrinos

- Rate observed at IceCube depends primarily on the neutralino capture rate in the Sun (the elastic scattering cross section)
- The reach of neutrino telescopes is, therefore, expected to be tied to that of direct detection experiments

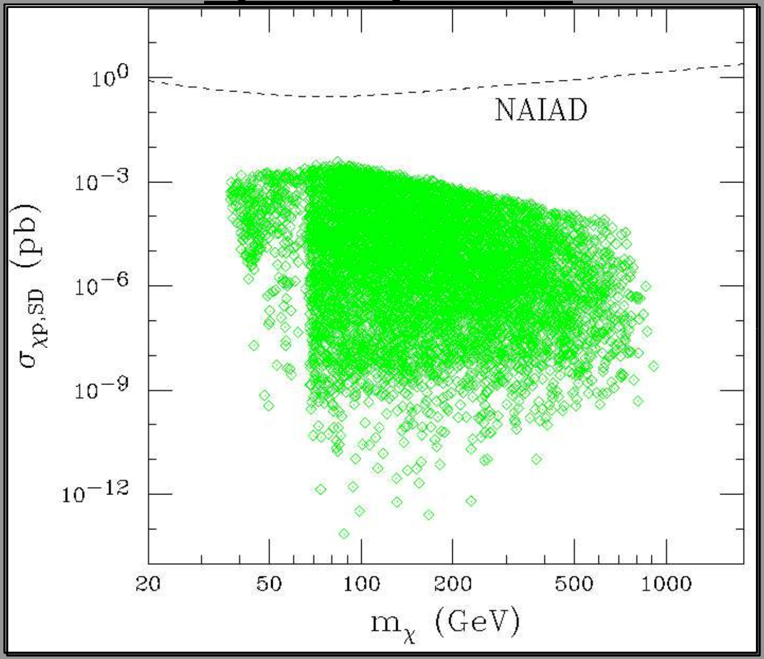
Indirect Detection With Neutrinos

- Important Caveat: WIMPs scatter with nuclei in the Sun through *both* spin-independent and spin-dependent scattering
- Sensitivity of direct detection to spin-dependent scattering is currently very weak

Spin-Independent



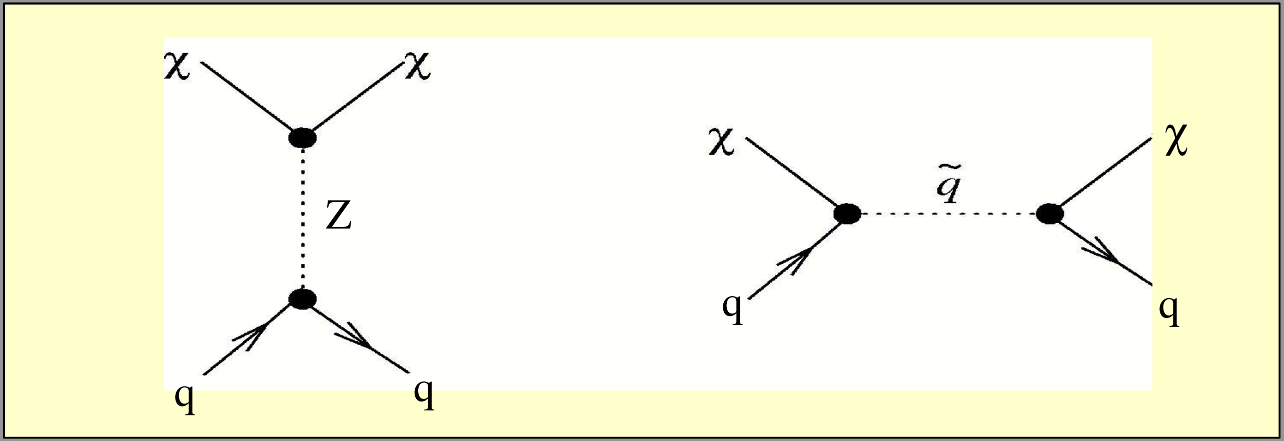
Spin-Dependent



F. Halzen and Hooper, PRD, hep-ph/0510048

Indirect Detection With Neutrinos

What kind of neutralino has large spin-dependent couplings?

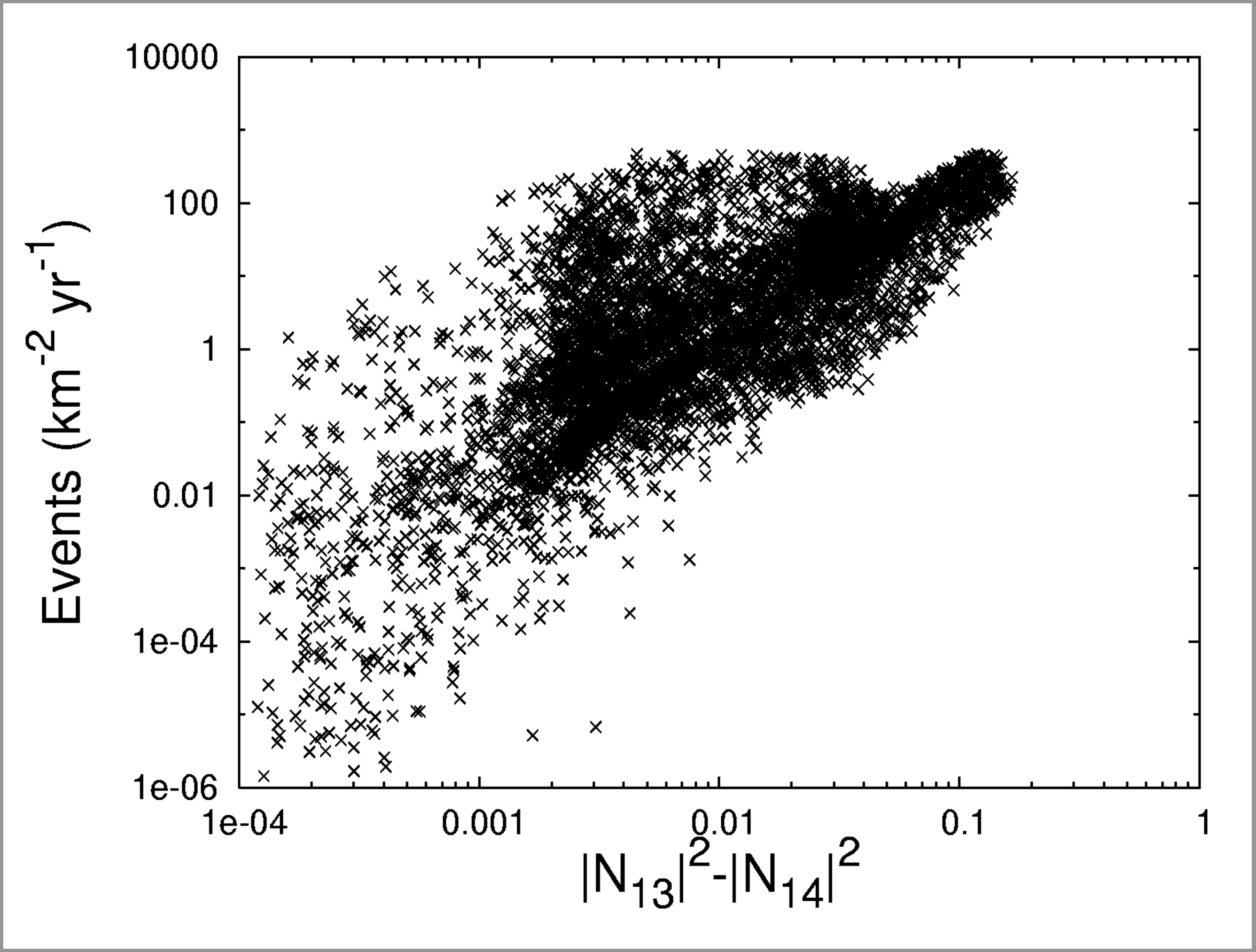


α $[\, |f_{H1}|^2 - |f_{H2}|^2 \,]^2$

Always Small

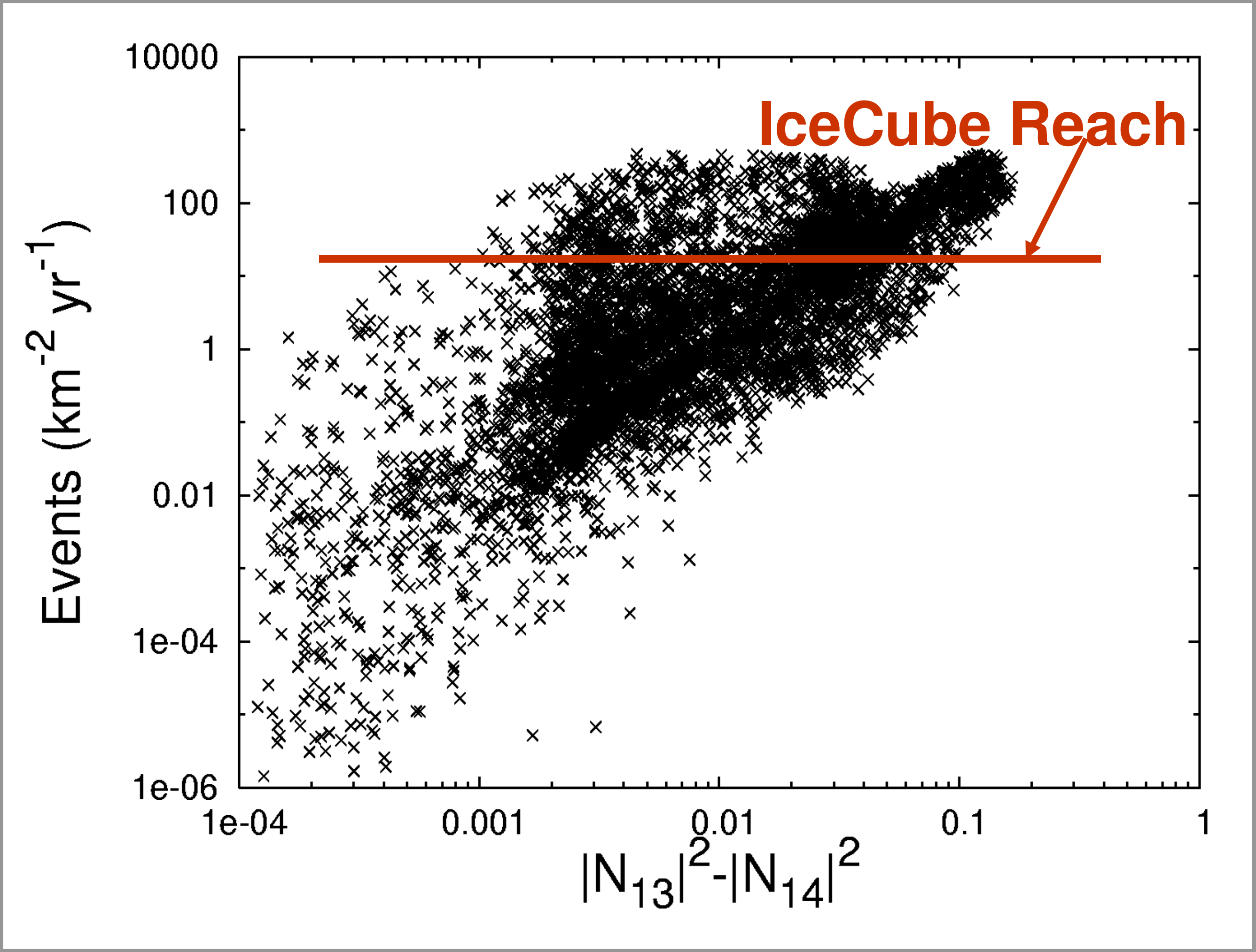
Substantial Higgsino Component Needed

Indirect Detection With Neutrinos



Hooper and A. Taylor, hep-ph/0607086;
F. Halzen and Hooper, PRD, hep-

Indirect Detection With Neutrinos



Hooper and A. Taylor, hep-ph/0607086;
F. Halzen and Hooper, PRD, hep-