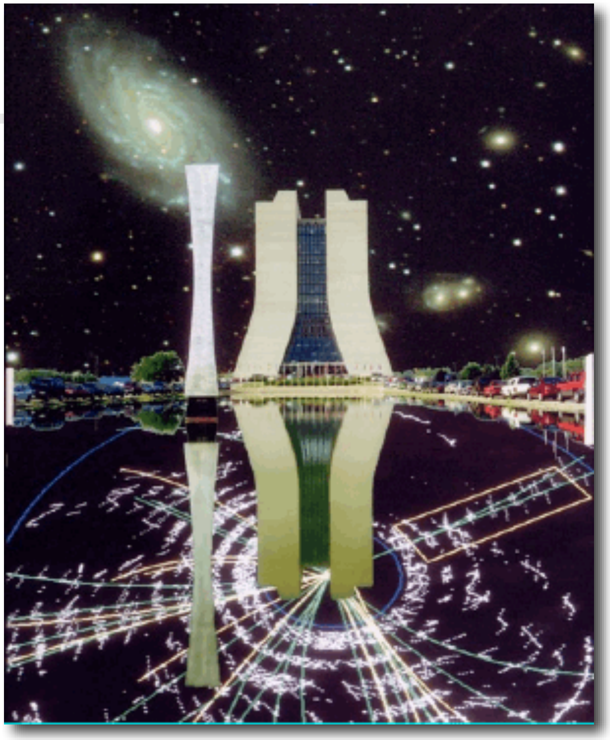
Cosmology For Particle Physicists

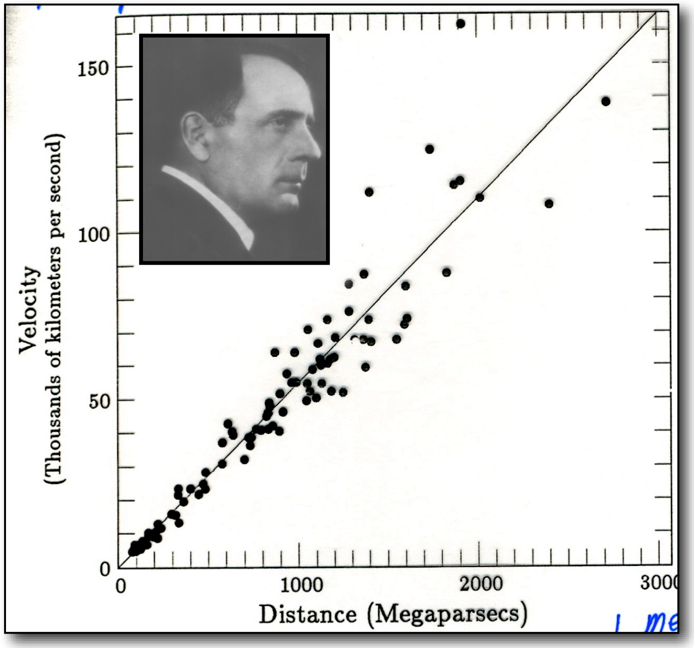
Dan Hooper
Fermilab/University of Chicago



Hadron Collider Physics Summer School
Fermilab
August 23, 2010

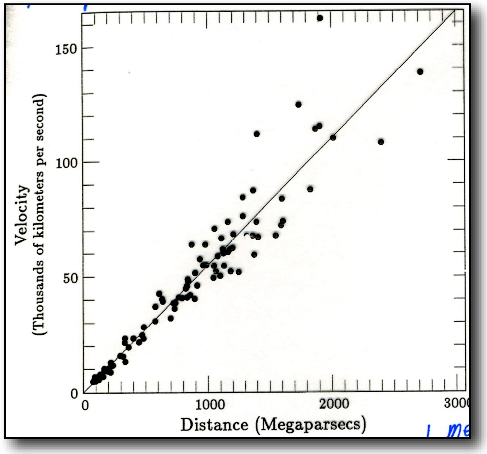
The Pillars Of Physical Cosmology

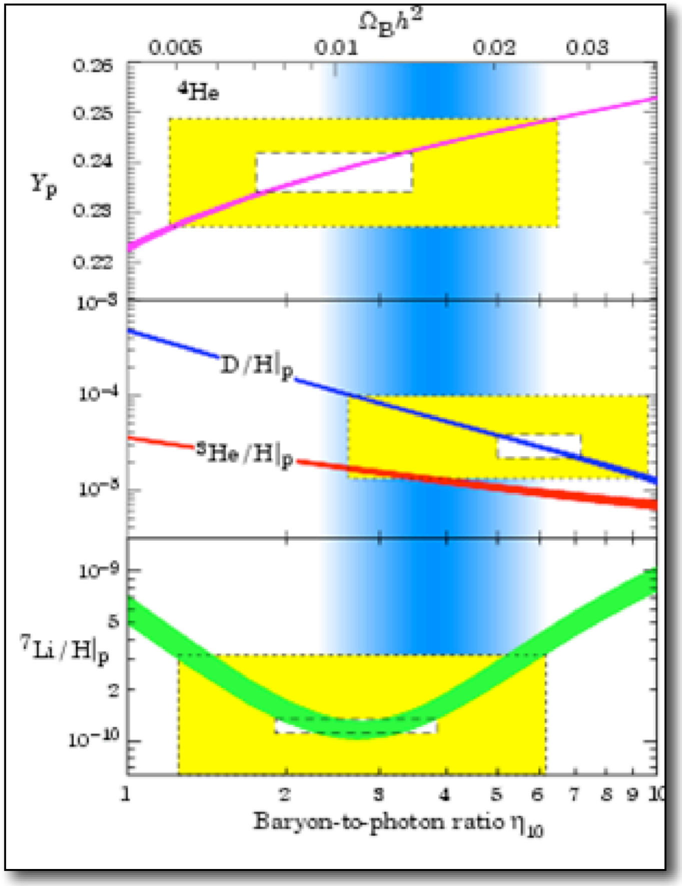
- Hubble Expansion

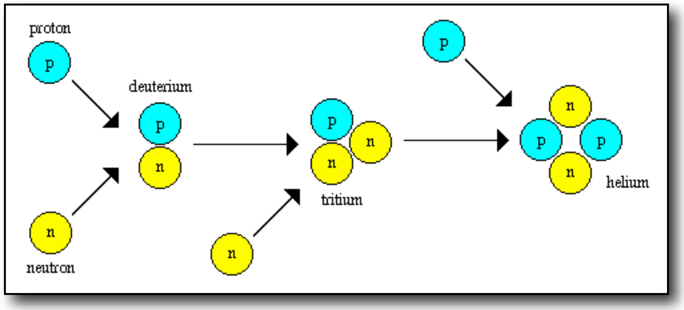


The Pillars Of Physical Cosmology

- Hubble Expansion
- The Light Element Abundances

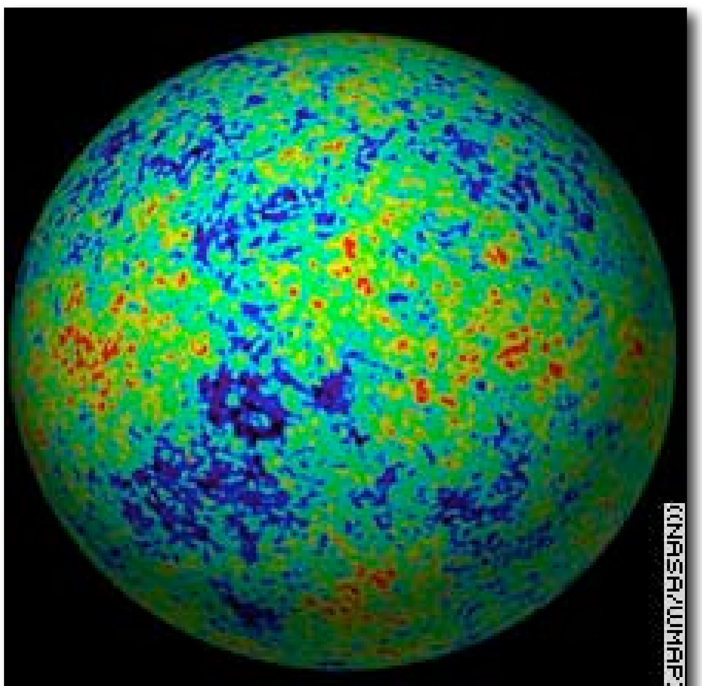


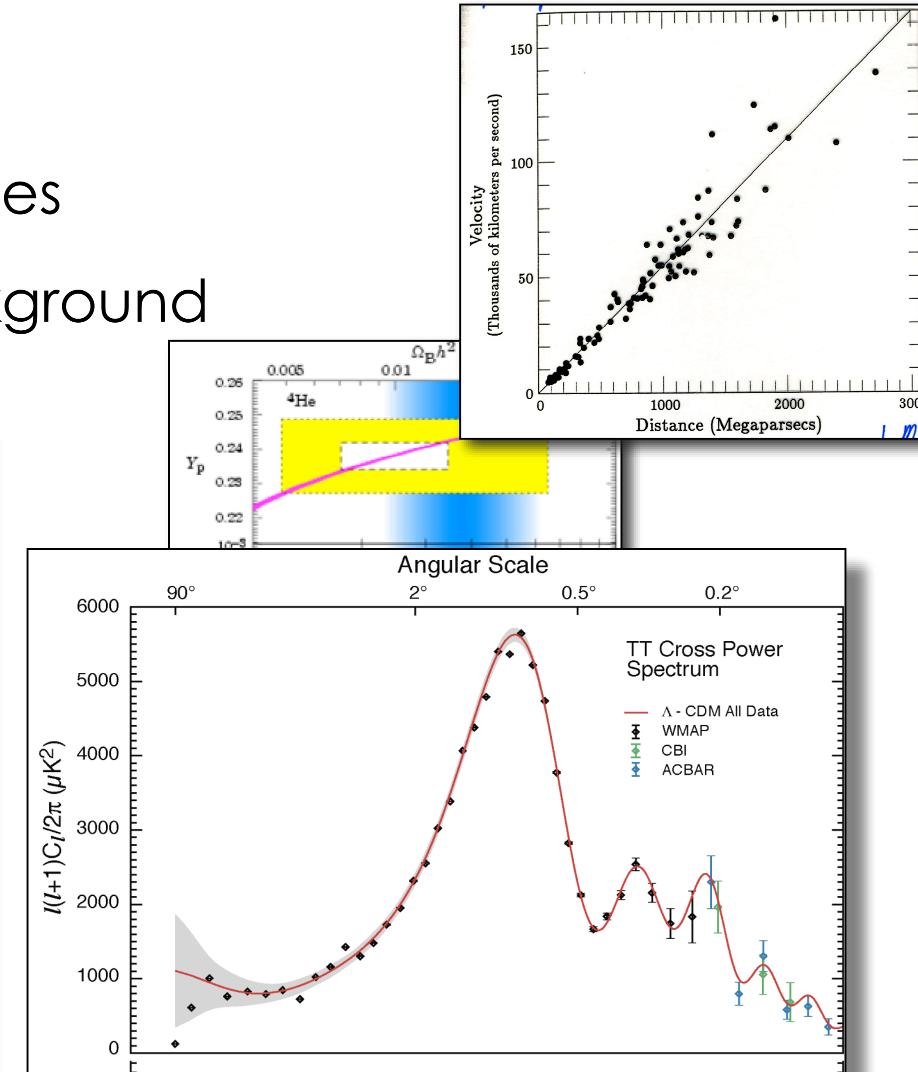




The Pillars Of Physical Cosmology

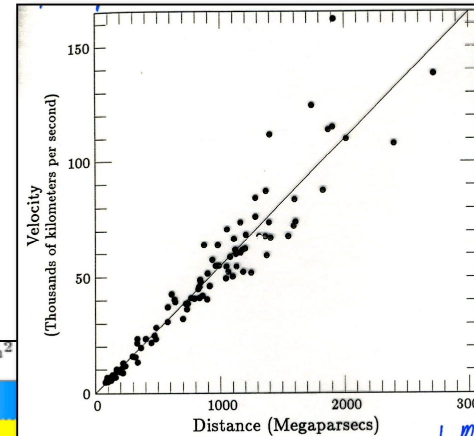
- Hubble Expansion
- The Light Element Abundances
- The Cosmic Microwave Background

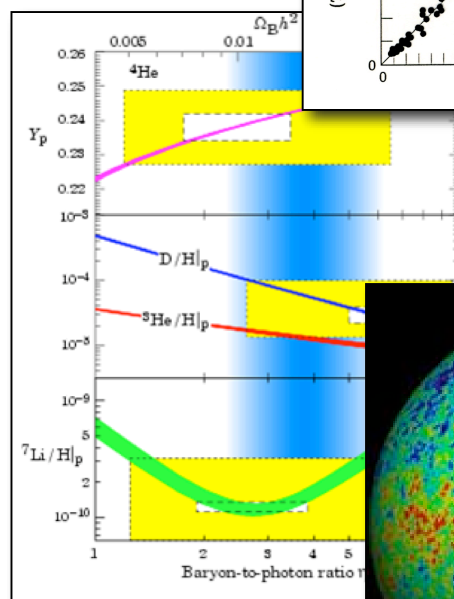


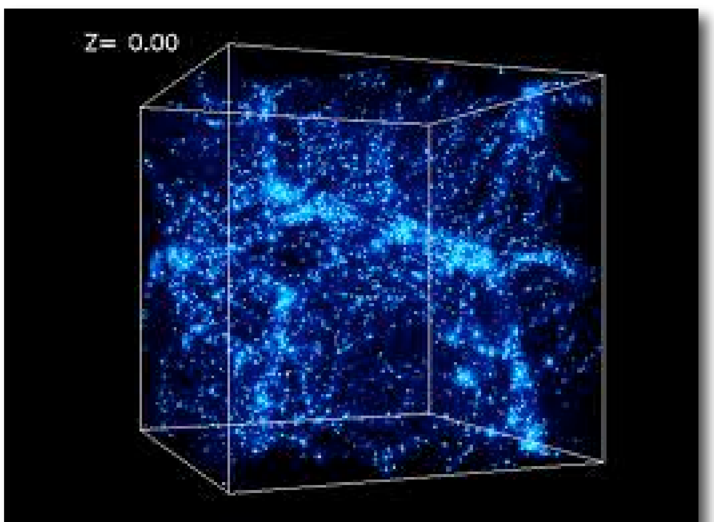


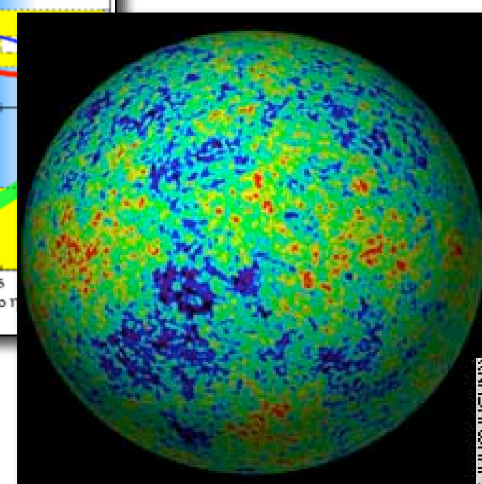
The Pillars Of Physical Cosmology

- Hubble Expansion
- The Light Element Abundances
- The Cosmic Microwave Background
- Large Scale Structure









The Pillars Of Physical Cosmology

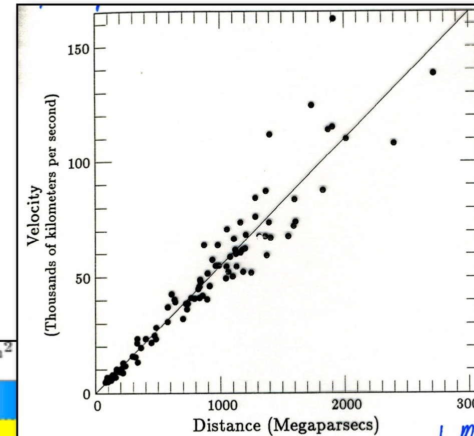
- Hubble Expansion
- The Light Element Abundances
- The Cosmic Microwave Background
- Large Scale Structure

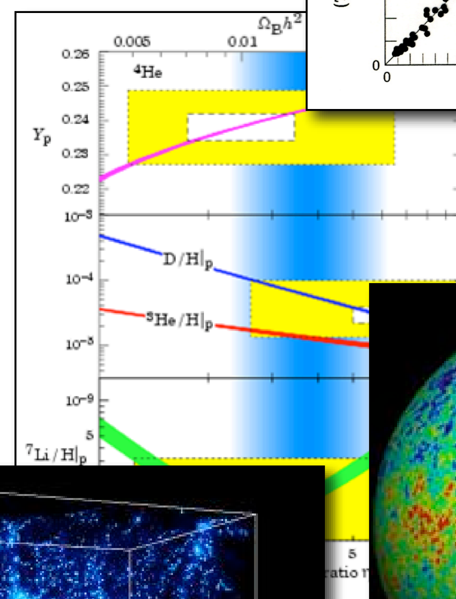
The Big Bang Theory, although remarkably successful, requires us to introduce:

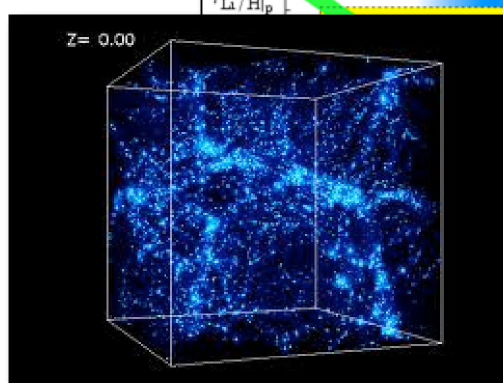
1) something that drives accelerated expansion in the early universe (inflation)

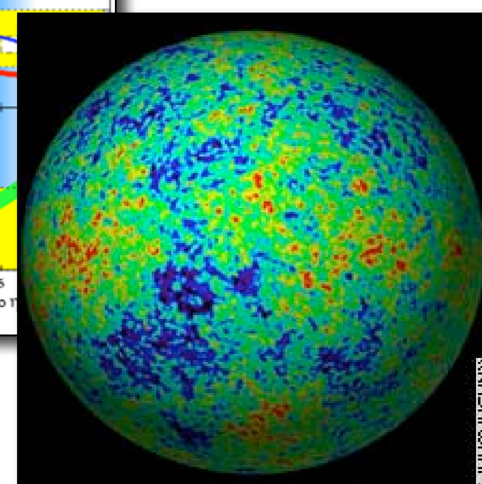
2) dark matter

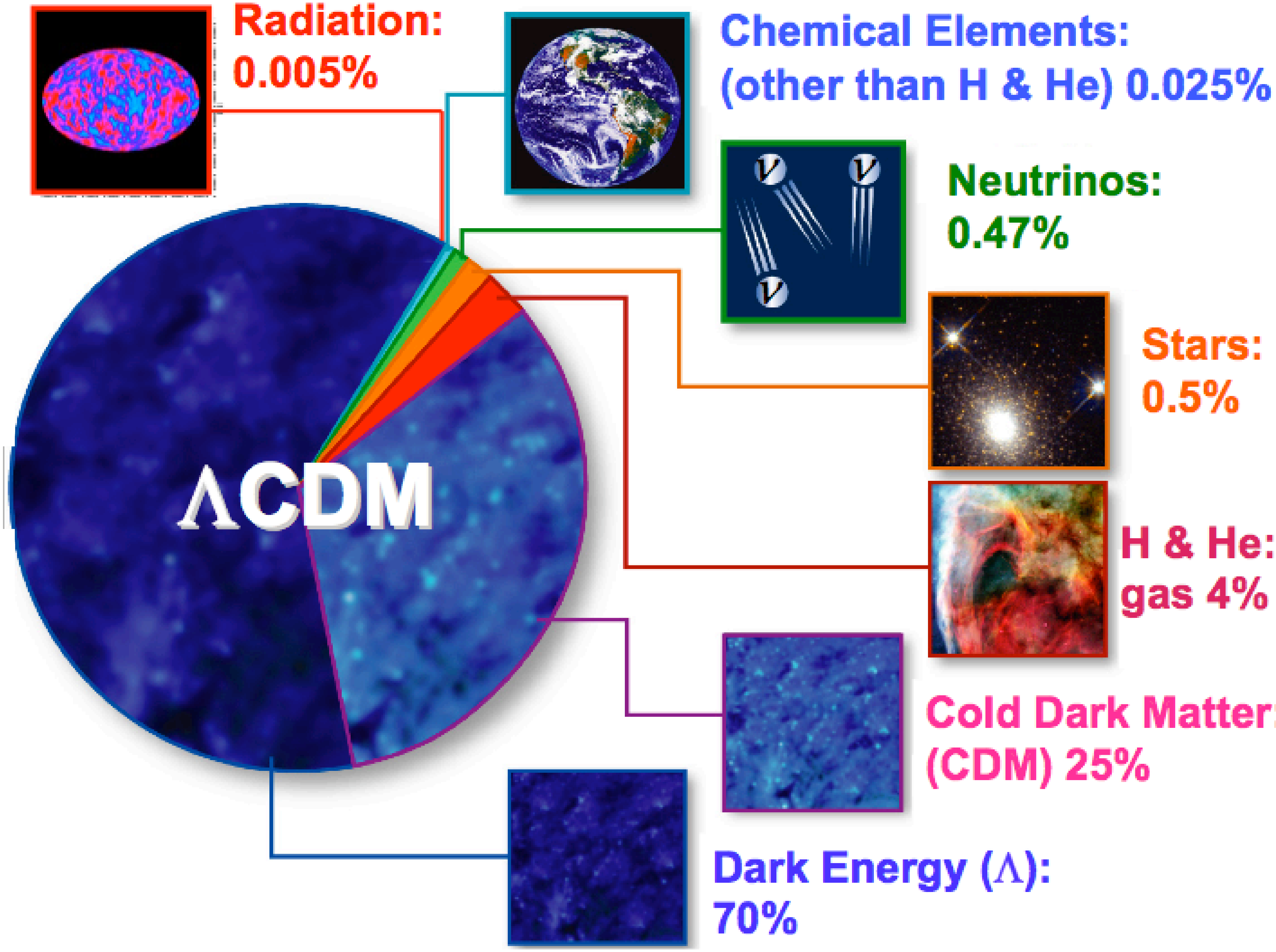
3) something that drives accelerated expansion in the current era (dark energy)





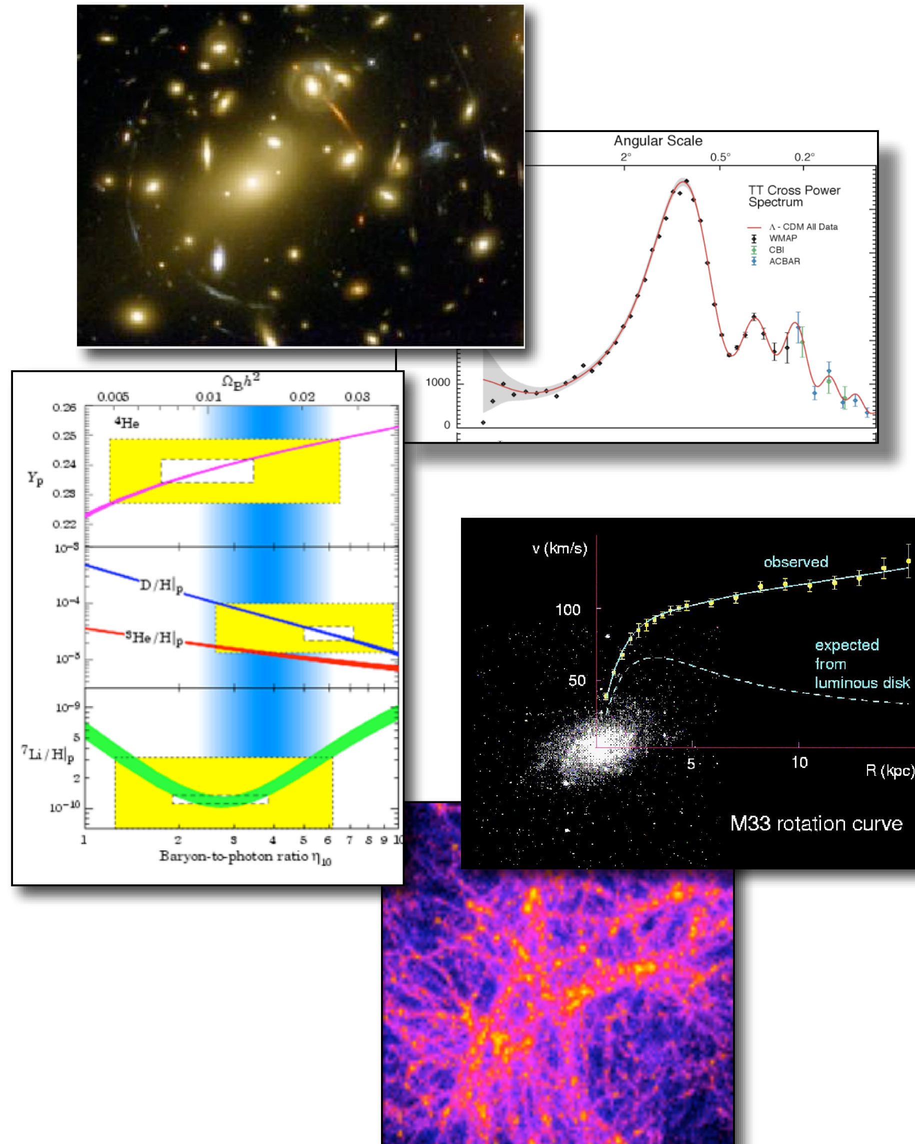





Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM

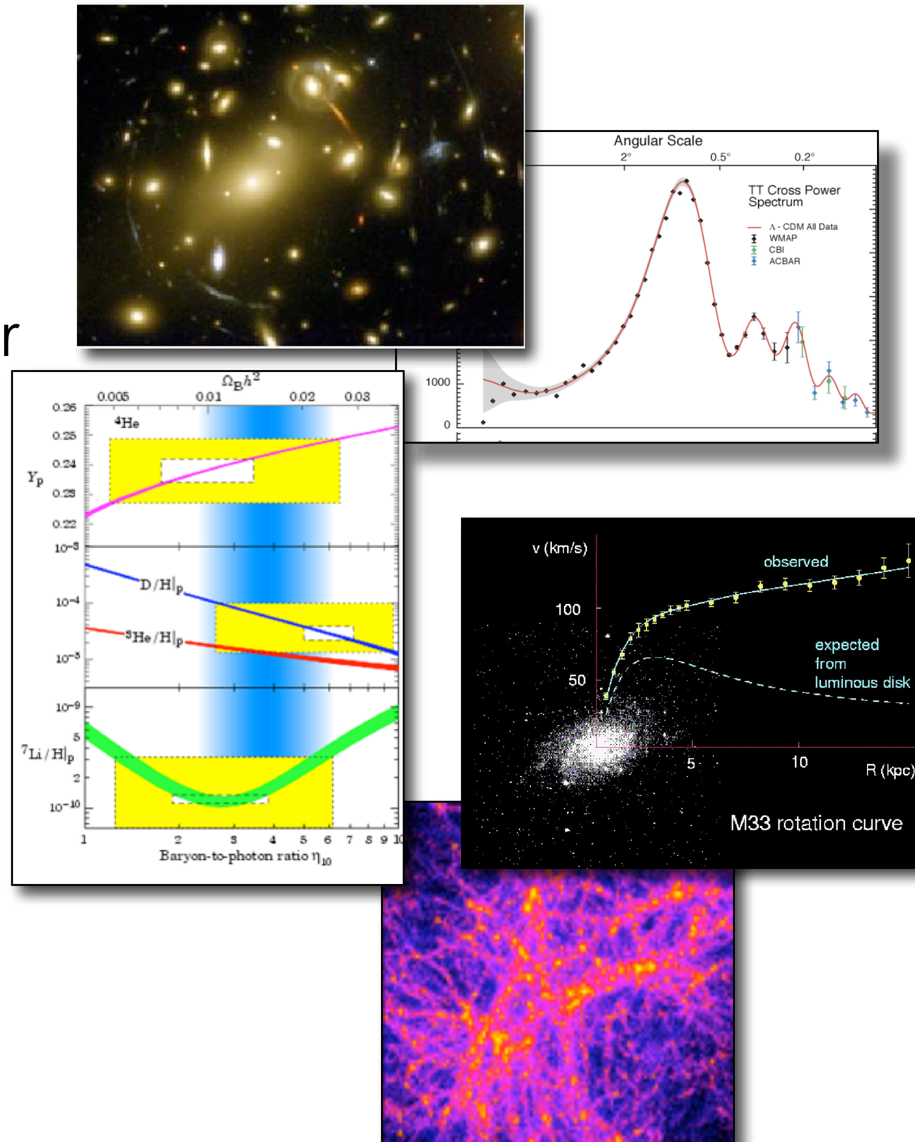
Evidence For Dark Matter

- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- Cosmic microwave background anisotropies
- Large scale structure



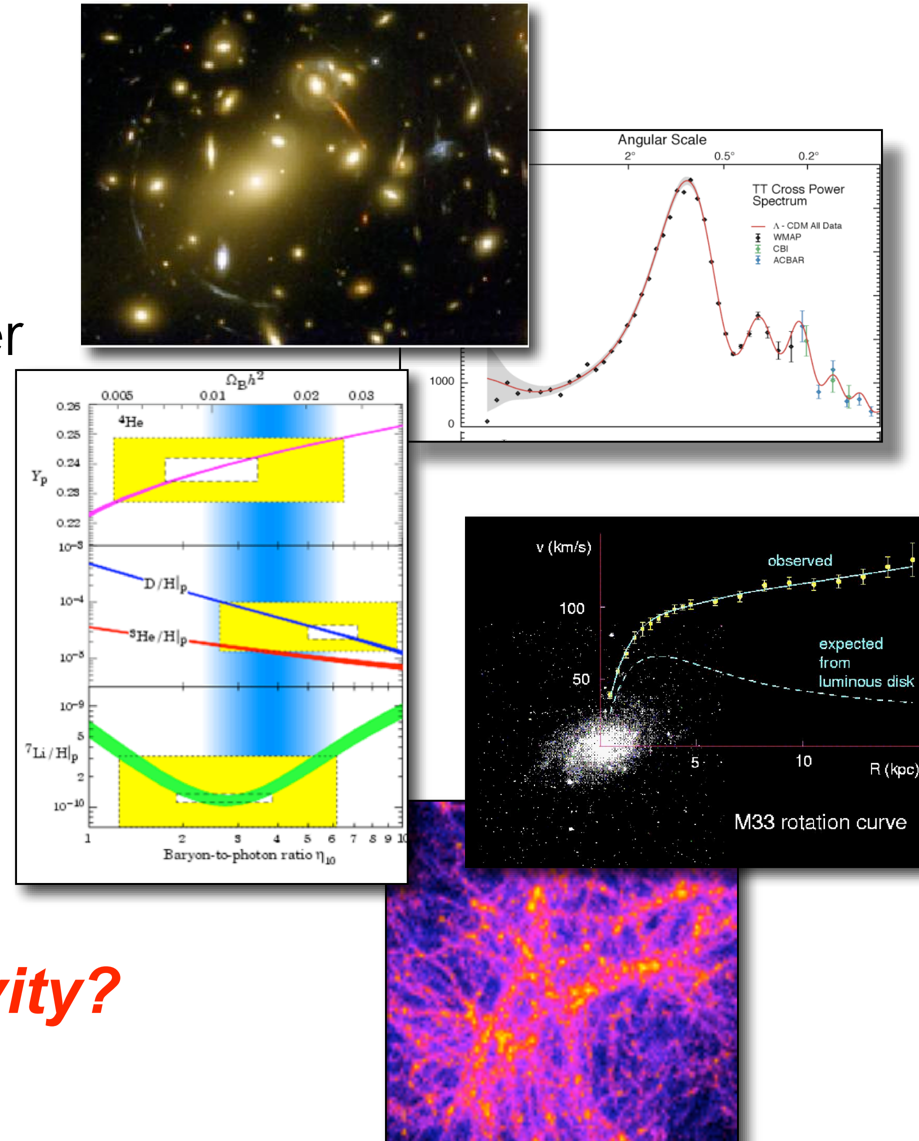
Evidence For Dark Matter

- There exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter's presence through its gravitational influence
- Still no observations of dark matter's electroweak interactions (or other non-gravitational interactions)



Evidence For Dark Matter

- There exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter's presence through its gravitational influence
- Still no observations of dark matter's electroweak interactions (or other non-gravitational interactions)



Instead of dark matter,
might we not understand gravity?

Modified Newtonian Dynamics (MOND)

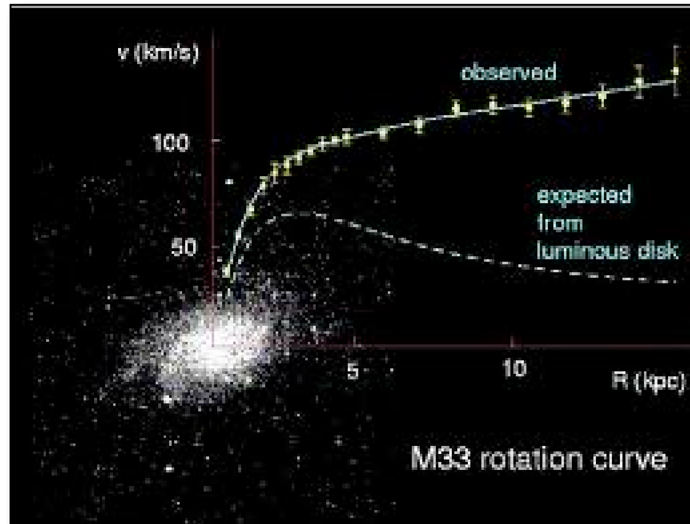
- Begin by modifying Newtonian dynamics as follows:

$$F = ma \longrightarrow F = ma \times \mu(a)$$

where $\mu \approx 1$, except at small accelerations, at which $\mu = a/a_0$

- For a circular orbit,

$$F = \frac{GMm}{r^2} = ma\mu$$



Which in the low-acceleration limit yields:

$$a = \frac{\sqrt{GMa_0}}{r} = \frac{v^2}{r} \quad \Longrightarrow \quad v = (GMa_0)^{1/4}$$

Rotational velocity independent of galactic radius (flat rotation curve)

Modified Newtonian Dynamics (MOND)

•MOND has been quite successful in explaining galactic dynamics of galaxies, and provides an explanation for the Tully-Fisher relationship

•Galaxy clusters have been less well described by MOND

•MOND cannot by applied to questions of cosmology
(toy theory – modifies Newton, not Einstein)

MONDs and Dark Matters Throughout History

- Case 1: Astronomical tables of Uranus' orbit deviated from observations. It was suggested that either another planet was perturbing Uranus' orbit (Dark Matter) or that Newton's laws had broken down (MOND).

MONDs and Dark Matters Throughout History

- Case 1: Astronomical tables of Uranus' orbit deviated from observations. It was suggested that either another planet was perturbing Uranus' orbit (Dark Matter) or that Newton's laws had broken down (MOND).

-One Point For Dark Matter

MONDs and Dark Matters Throughout History

•Case 1: Astronomical tables of Uranus' orbit deviated from observations. It was suggested that either another planet was perturbing Uranus' orbit (Dark Matter) or that Newton's laws had broken down (MOND).

-One Point For Dark Matter

•Case 2: Precession of perihelion of Mercury did not match the prediction of Newtonian gravity. Another planet (Vulcan)? Einstein solved with general relativity.

MONDs and Dark Matters Throughout History

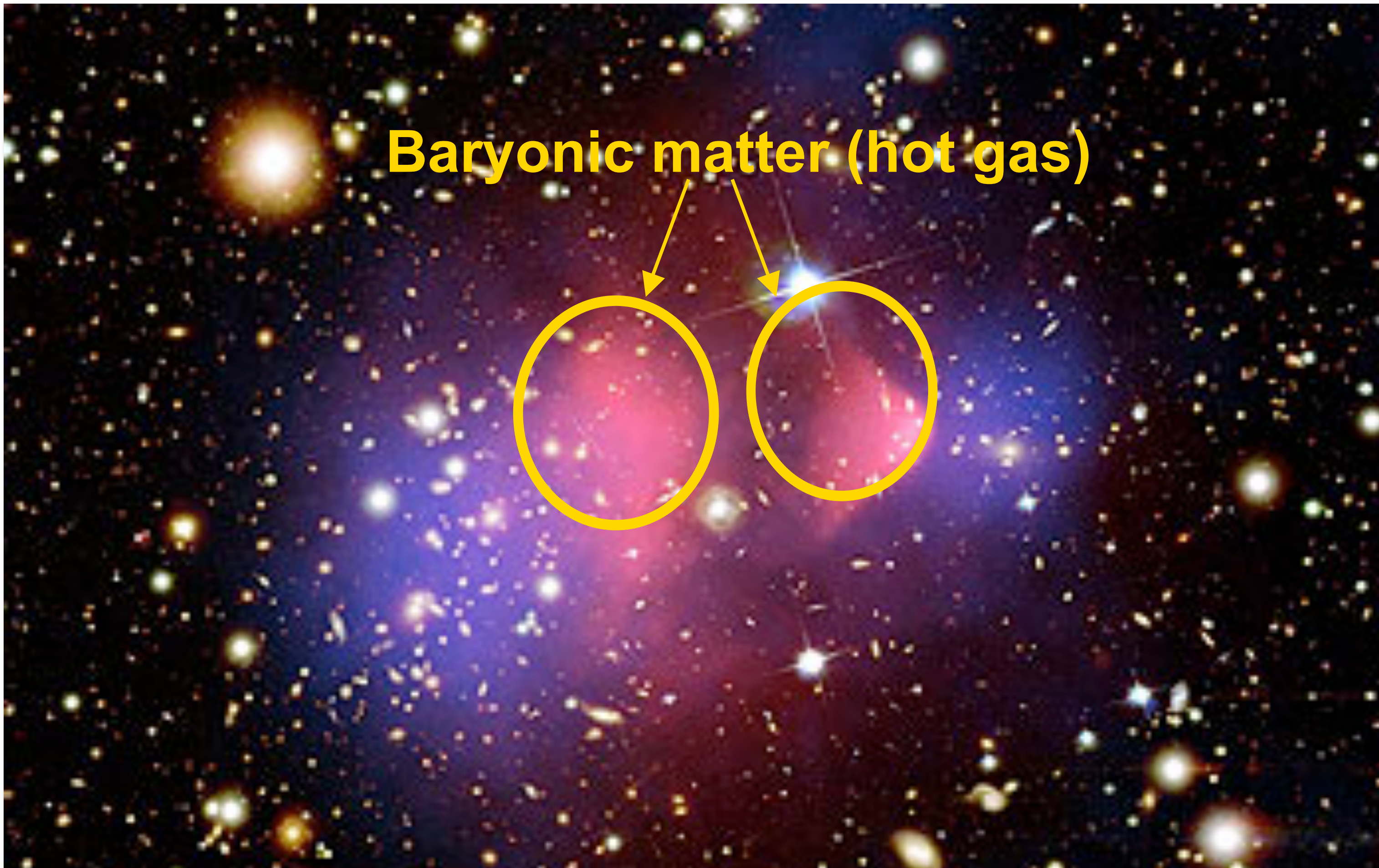
•Case 1: Astronomical tables of Uranus' orbit deviated from observations. It was suggested that either another planet was perturbing Uranus' orbit (Dark Matter) or that Newton's laws had broken down (MOND).

-One Point For Dark Matter

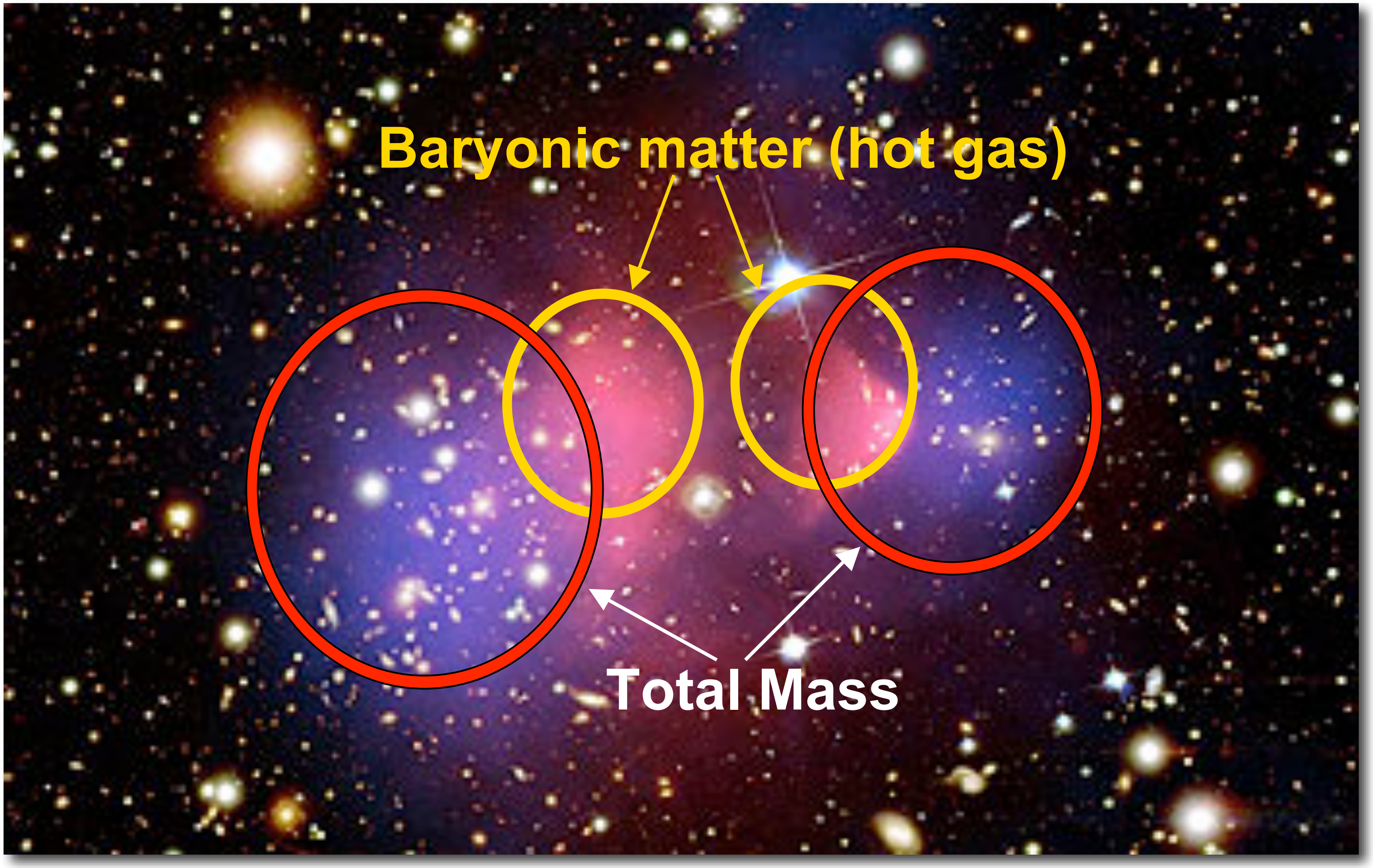
•Case 2: Precession of perihelion of Mercury did not match the prediction of Newtonian gravity. Another planet (Vulcan)? Einstein solved with general relativity.

-One Point For MOND

NASA/Chandra Press Release,
August 21, 2006



NASA/Chandra Press Release,
August 21, 2006



NASA/Chandra Press Release,
August 21, 2006

MOND Takes Another Bullet

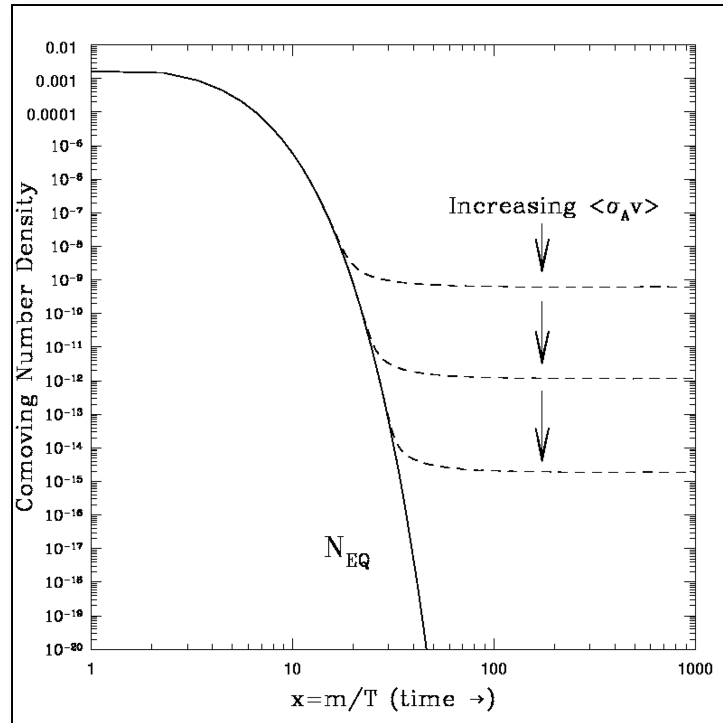
MACS J0025.4-1222,
R. Massey et al, August 27, 2008

Why WIMPs?

The thermal abundance of a WIMP

- T >> M_X, WIMPs in thermal equilibrium
- T < M_X, number density becomes Boltzmann suppressed

$$n_{X,\,\mathrm{eq}} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$



Why WIMPs?

<u>The thermal abundance of a WIMP</u>

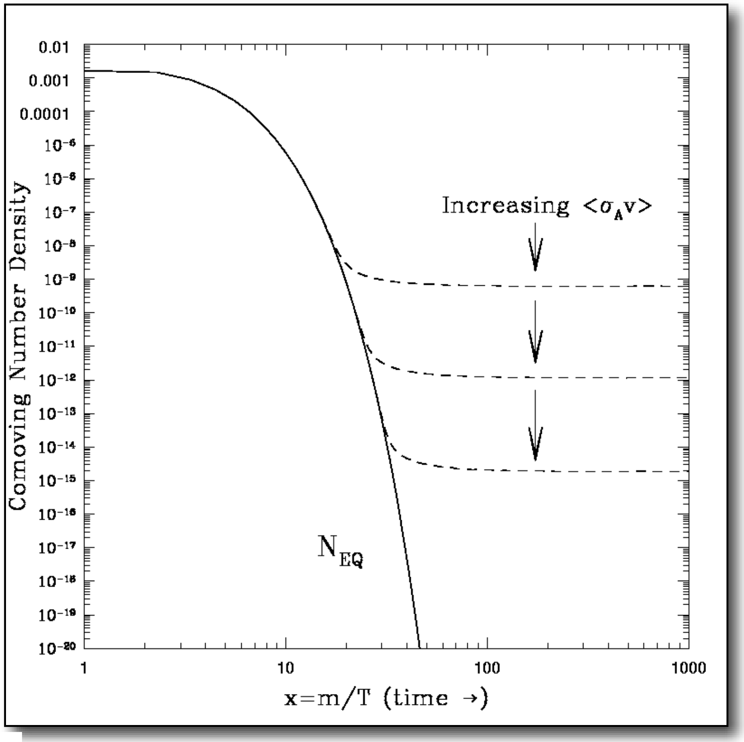
- T >> M_X, WIMPs in thermal equilibrium
- T < M_X, number density becomes Boltzmann suppressed

$$n_{X,\,\mathrm{eq}} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

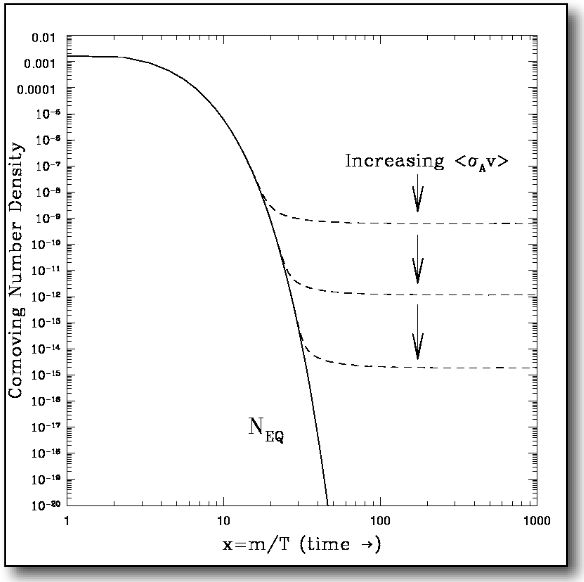
- Including the effects of expansion pulls the density away from its equilibrium value:

$$\frac{dn_X}{dt} + 3Hn_X = - < \sigma_{X\bar{X}}|v| > (n_X^2 - n_{X,\,\mathrm{eq}}^2)$$

$$H \equiv \dot{R}/R = (8\pi^3\rho/3M_{\mathrm{Pl}})^{1/2}$$



Why WIMPs?



The thermal abundance of a WIMP

$$\frac{dn_X}{dt} + 3Hn_X = - < \sigma_{X\bar{X}}|v| > (n_X^2 - n_{X,\,\mathrm{eq}}^2)$$

- The departure from equilibrium occurs at a temperature given by:

$$x_{\mathrm{FO}} \equiv \frac{m_X}{T_{\mathrm{FO}}} \approx \ln\left[c(c+2)\sqrt{\frac{45}{8}}\frac{g_X}{2\pi^3}\frac{m_X M_{\mathrm{Pl}}(a+6b/x_{\mathrm{FO}})}{g_\star^{1/2}\, x_{\mathrm{FO}}^{1/2}}\right]$$

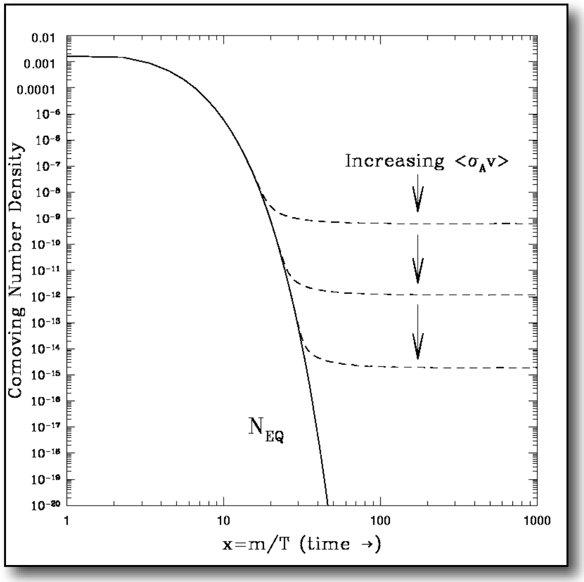
order one factor

# of external degrees of freedom

$$< \sigma_{X\bar{X}}|v| >= a + b < v^2 > + \mathcal{O}(v^4)$$

- For a weak-scale mass and cross section, T_{FO}~$M_X/20$

Why WIMPs?



<u>The thermal abundance of a WIMP</u>

- Numerically, this yield a thermal relic abundance given by:

$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{a+3b/x_{\rm FO}}{3\times 10^{-26}{\rm cm}^3/{\rm s}}\right)^{-1}$$

Approximately ~1 pb

- For comparison,

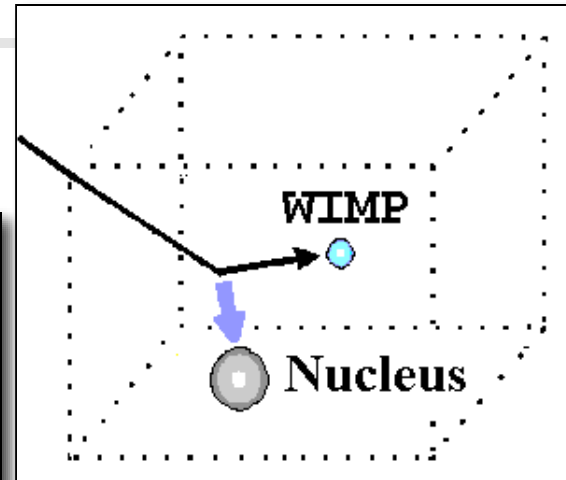
$$\alpha^2/(100\,{\rm GeV})^2 \sim 3\times 10^{-26}\,{\rm cm}^3/{\rm s}.$$

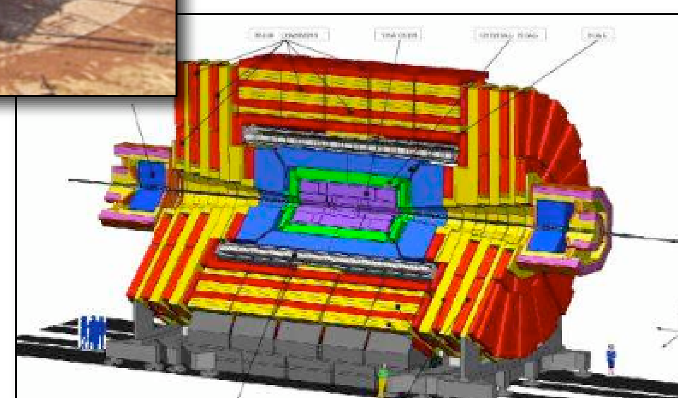
⇒Weak scale interaction yields approximately the Observed dark matter abundance

$$<\sigma_{X\bar{X}}|v|>= a + b < v^2 > +\mathcal{O}(v^4)$$

WIMP Hunting

- Direct Detection
- Indirect Detection
- Collider Searches



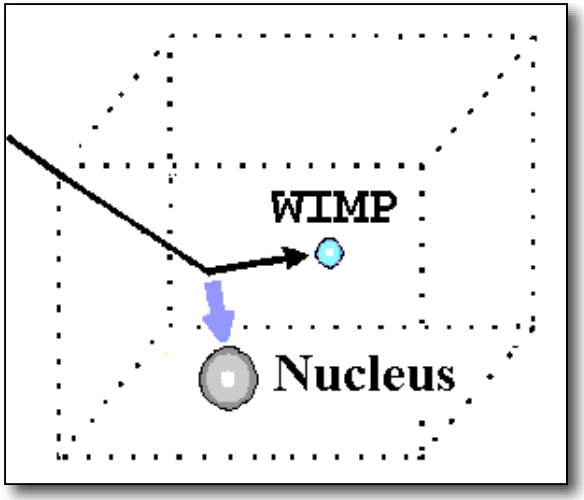


Direct Detection

- A WIMP striking a nucleus will impact a recoil of energy:

$$E_{\rm recoil} = \frac{|\vec{q}|^2}{2M_{\rm nucleus}} = \frac{2\mu^2 v^2 (1-\cos\theta)}{2M_{\rm nucleus}} = \frac{m_X^2 M_{\rm nucleus}\, v^2 (1-\cos\theta)}{(m_X + M_{\rm nucleus})^2}$$

- For $m_X >> M_{nucleus}$ and v~300 km/s, this corresponds to E_{recoil}~1-100 keV

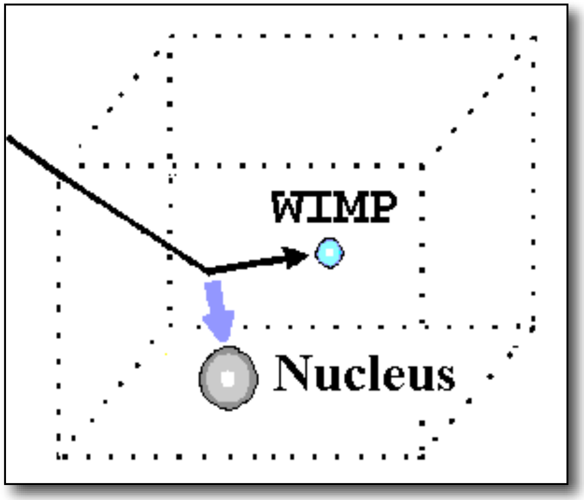


Direct Detection

- A WIMP striking a nucleus will impact a recoil of energy:

$$E_{\mathrm{recoil}} = \frac{|\vec{q}|^2}{2M_{\mathrm{nucleus}}} = \frac{2\mu^2 v^2 (1-\cos\theta)}{2M_{\mathrm{nucleus}}} = \frac{m_X^2 M_{\mathrm{nucleus}}\, v^2 (1-\cos\theta)}{(m_X + M_{\mathrm{nucleus}})^2}$$

- For $m_X >> M_{nucleus}$ and v~300 km/s, this corresponds to E_{recoil}~1-100 keV



- The rate of WIMP-nucleus scattering is given by:

$$R \approx \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \int_{v_{\mathrm{min}}}^{v_{\mathrm{max}}} \frac{2\rho}{m_X} \frac{d\sigma}{d|\vec{q}|}\, v\, f(v)\, dv\, dE_{\mathrm{recoil}}$$

DM velocity distribution

Direct Detection

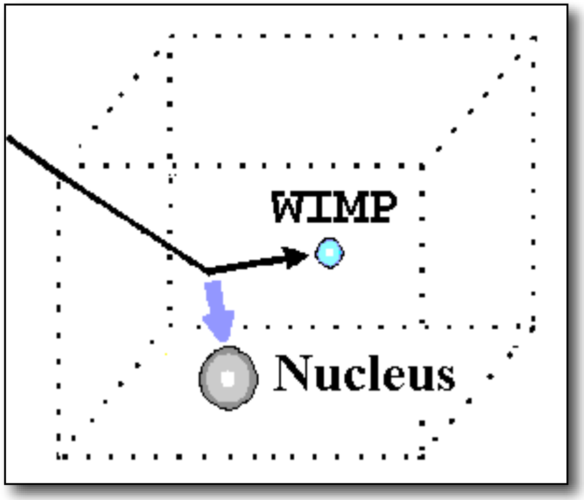
- In the non-relativistic limit, all interaction forms can be described as spin-independent (coherent) scattering or spin-dependent scattering

- For spin-independent scattering:

$$\sigma \approx \frac{4m_{\chi^0}^2 m_{\text{nucleus}}^2}{\pi(m_{\chi^0}+m_{\text{nucleus}})^2}[Zf_p+(A-Z)f_n]^2$$

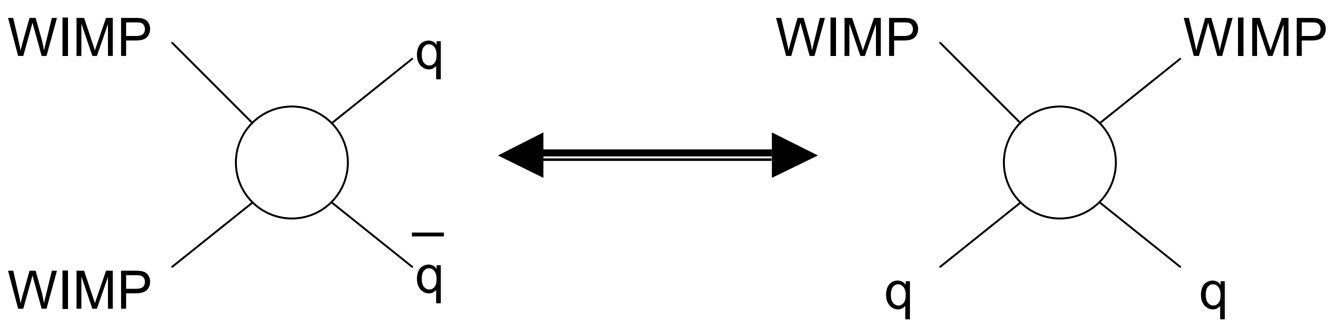
where

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}$$



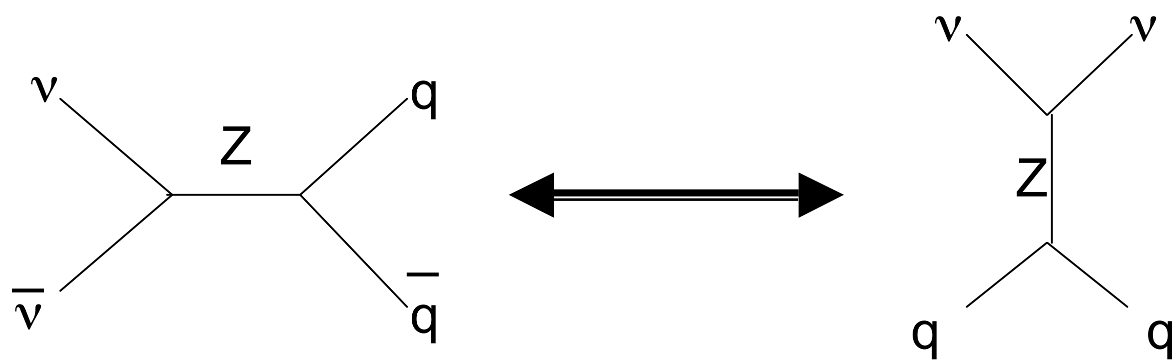
WIMP Annihilation and Elastic Scattering

- From the observed density of dark matter, we can estimate the couplings of the WIMP (in lieu of resonances, coannihilations, etc.)
- Annihilation rate to quarks can be used to estimate the elastic scattering cross section with nuclei



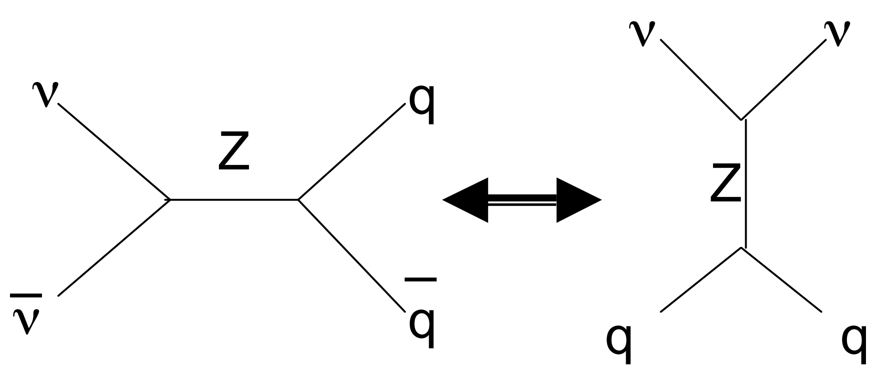
WIMP Annihilation and Elastic Scattering

- Case Example: Dirac Fermion or Scalar WIMP with vector-like interactions (such as a heavy 4th generation neutrino, or a sneutrino)

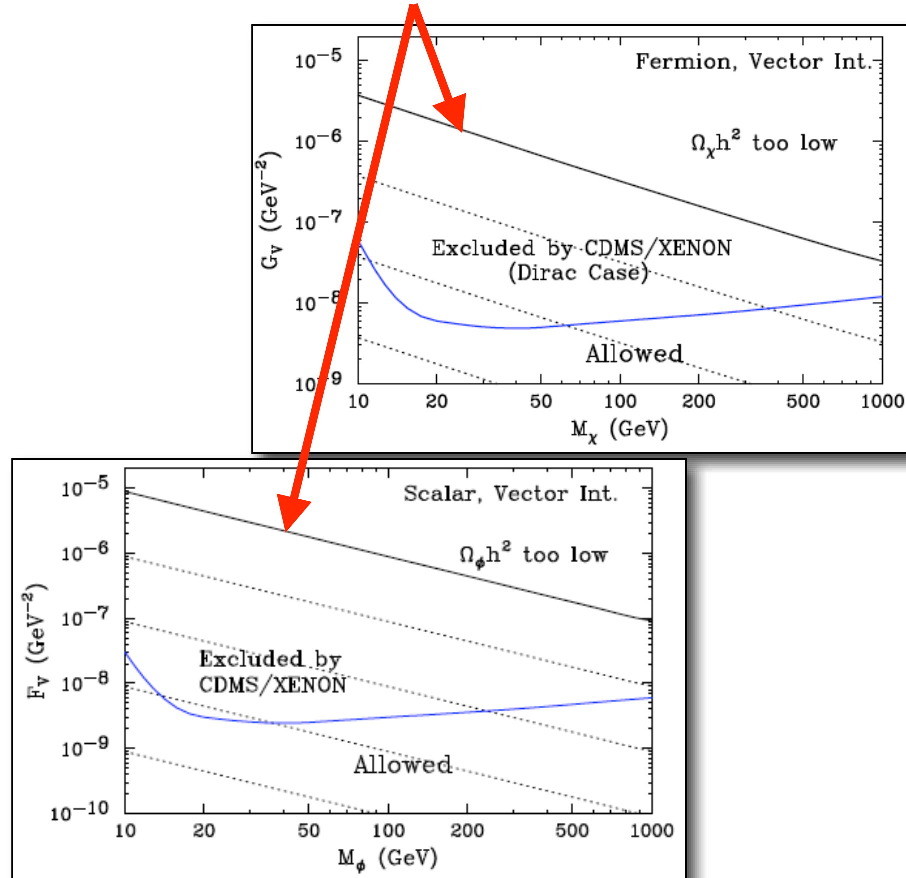


WIMP Annihilation and Elastic Scattering

- Case Example: Dirac Fermion or Scalar WIMP with vector-like interactions (such as a heavy 4th generation neutrino, or a sneutrino)



Coupling Needed To Acquire Measured Abundance



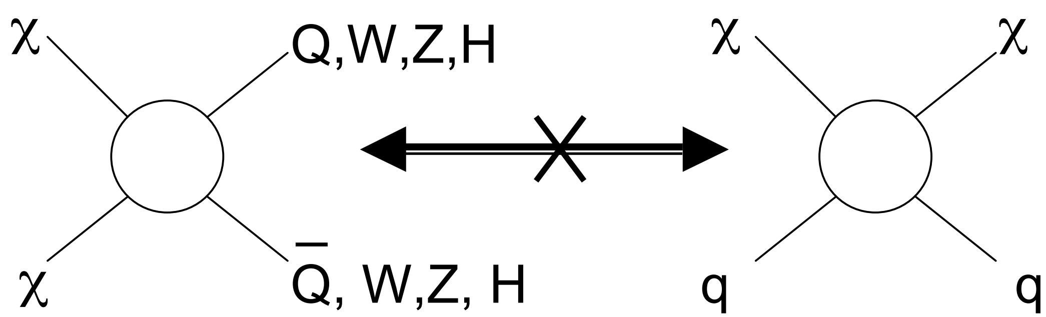
This candidate and many others are already excluded by the null results of CDMS and XENON!

Beltran, Hooper, Kolb, Krusberg, arXiv:0808.3384

WIMP Annihilation and Elastic Scattering

- Another Case Example: Majorana Fermion WIMP (such as a neutralino)

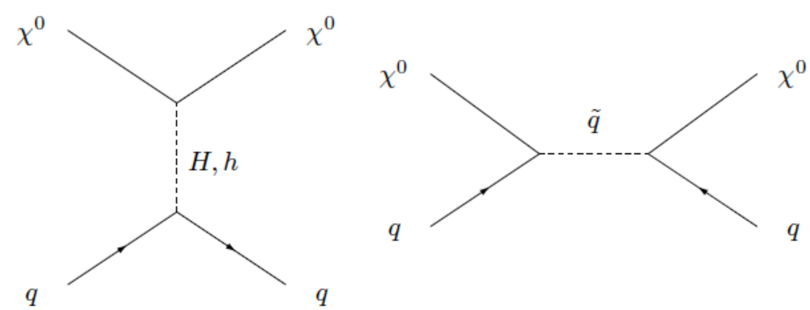
- Neutralino elastic scattering is suppressed by the fact that they annihilate to *heavy* quarks (and leptons) and gauge/higgs bosons, none of which are present in nuclei



- Elastic scattering is further suppressed if coannihilations or resonances play an important role in the early universe

The Direct Detection of Neutralino Dark Matter

- Neutralinos can coherently scatter with nuclei through scalar higgs and squark exchange



- Benchmark examples:

1) Dominated by relatively light “heavy” higgs:

m_H~200 GeV, μ~200 GeV $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-5} to 10^{-7} pb

m_H~200 GeV, μ~1 TeV $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-7} to 10^{-9} pb

2) Dominated by light (SM-like) higgs:

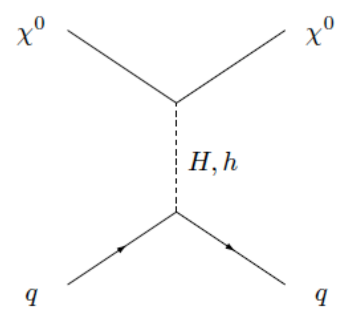
$m_H \gtrsim 500$ GeV, μ~200 GeV (1 TeV) $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-8} pb (10^{-10} pb)

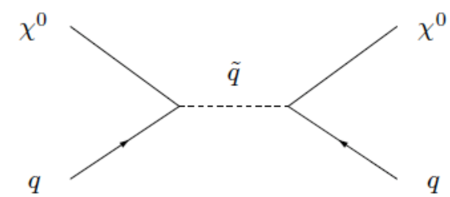
3) Dominated by light (sub-TeV) squarks:

Potentially competative with contributions from higgs exchange

The Direct Detection of Neutralino Dark Matter

- Neutralinos can coherently scatter with nuclei through scalar higgs and squark exchange





- Benchmark examples:

1) Dominated by relatively light "heavy" higgs:

m_H~200 GeV, μ~200 GeV $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-5} to 10^{-7} pb

~0.1-10 events per kg-day (Ge,Xe)

m_H~200 GeV, μ~1 TeV $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-7} to 10^{-9} pb

~0.1 events per ton-day (Ge,Xe)

2) Dominated by light (SM-like) higgs:

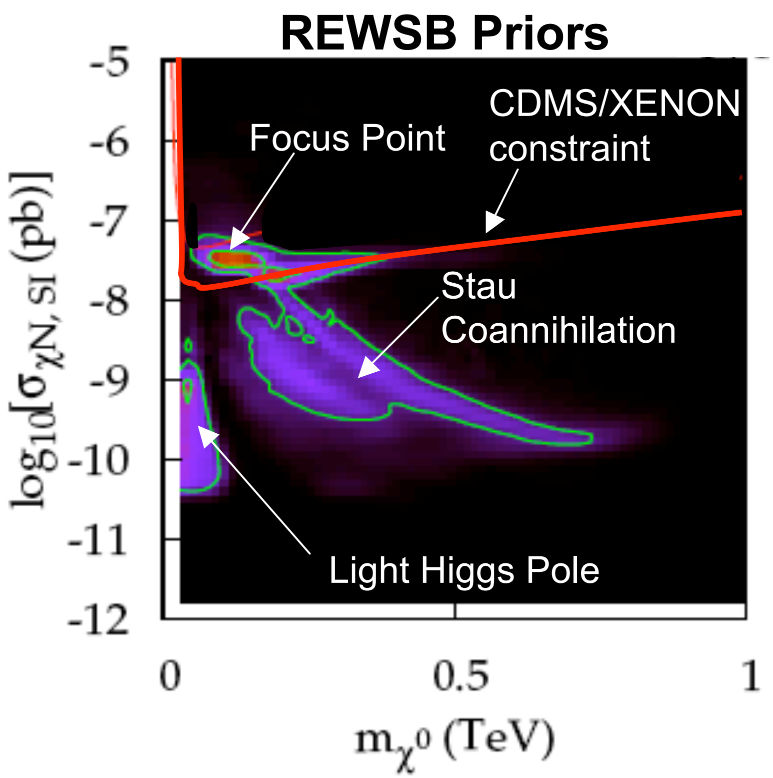
$m_H \gtrsim$500 GeV, μ~200 GeV (1 TeV) $\Rightarrow$ $\sigma_{\chi p}$~ 10^{-8} pb (10^{-10} pb)

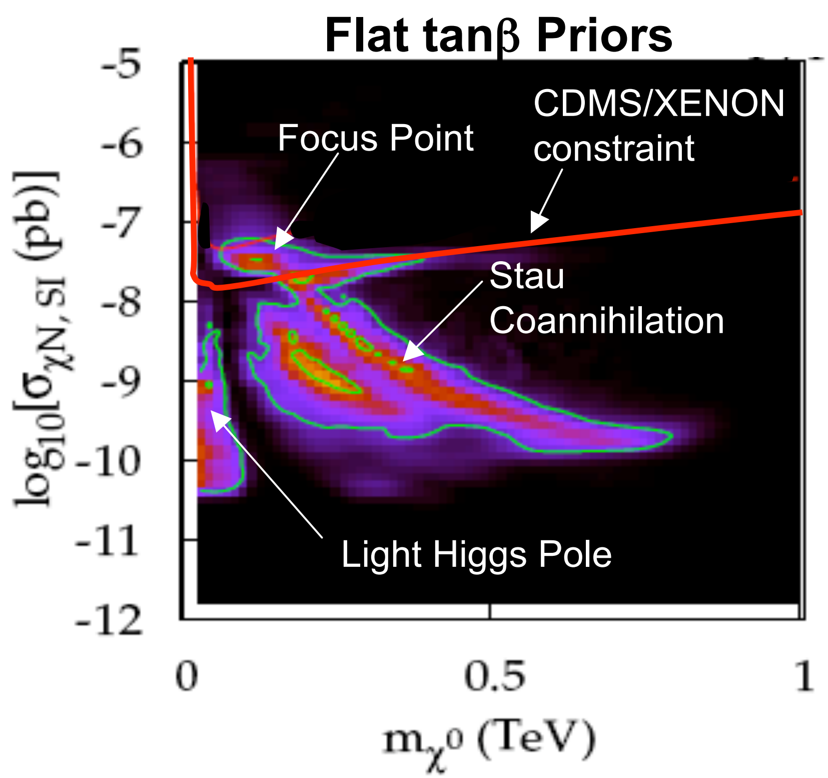
3) Dominated by light (sub-TeV) squarks:

Potentially competative with contributions from higgs exchange

The Case of Neutralino Dark Matter

- Current direct detection experiments are only beginning to constrain a significant fraction of the likely SUSY parameter space



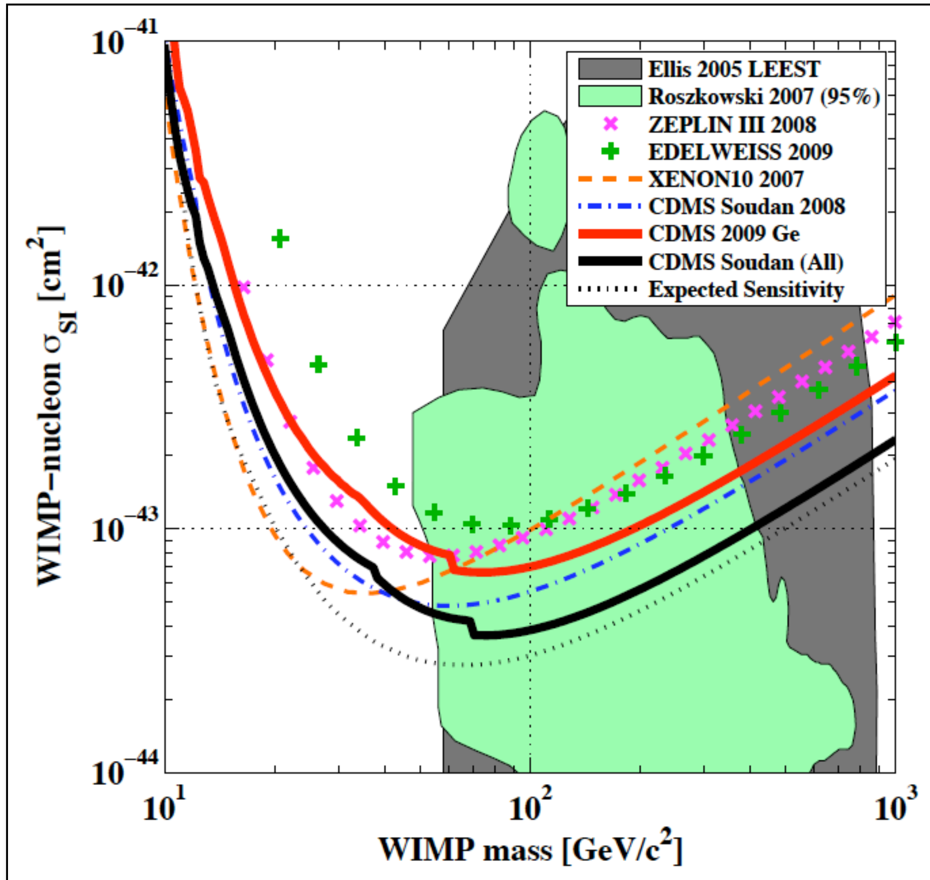


B. Allanach and D. Hooper, JCAP, arXiv:0806.1923

Direct Detection

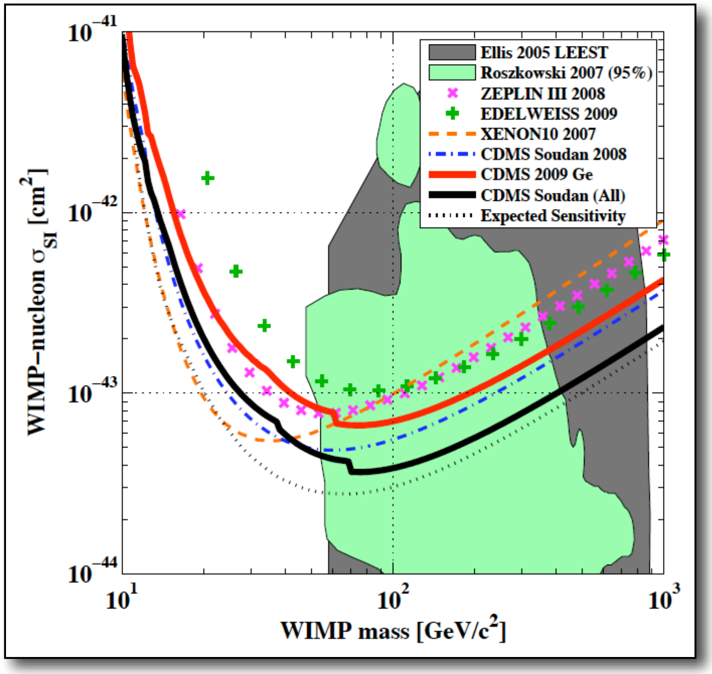
- Over the past decade, direct detection experiments have improved in sensitivity at a rate of about 1 order of magnitude every 2 years

Current Status



The Signals/Hints/Detections

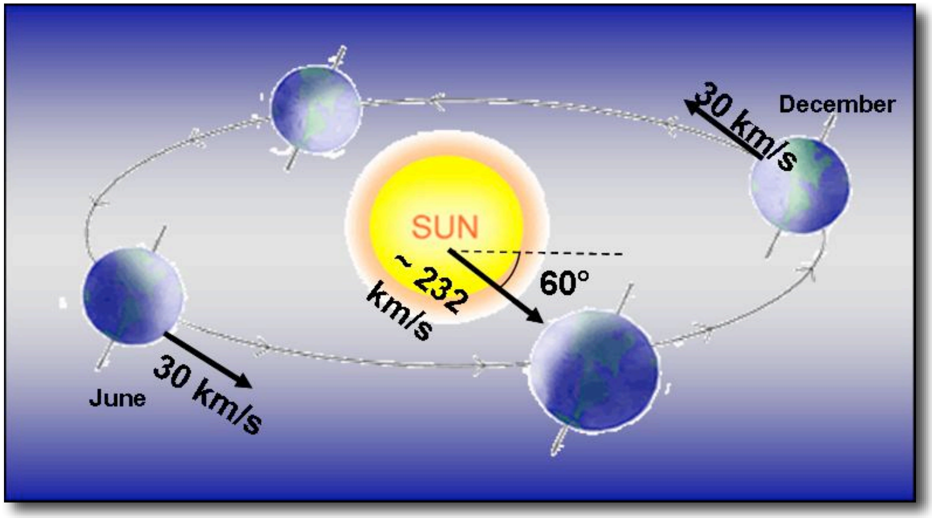
- But not all direct detection experiments have claimed null results
- For most of the past decade, DAMA has claimed to be observing dark matter scattering
- CoGeNT has recently reported a signal resembling dark matter
- CDMS recently reported 2 events



The Signals/Hints/Detections

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate

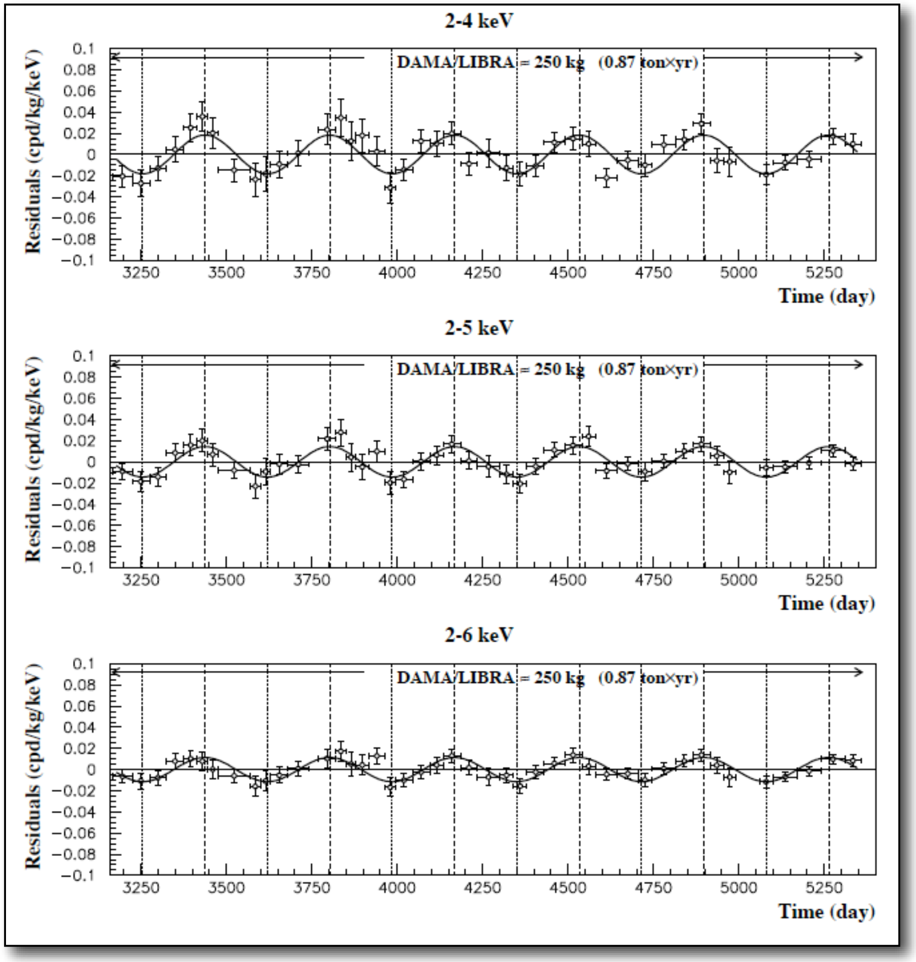


The Signals/Hints/Detections

DAMA/LIBRA

- Over the course of a year, the motion of the Earth around the Solar System is expected to induce a modulation in the dark matter scattering rate

- The DAMA collaboration reports a modulation with the right phase to be dark matter, and with high statistics (8.9σ)

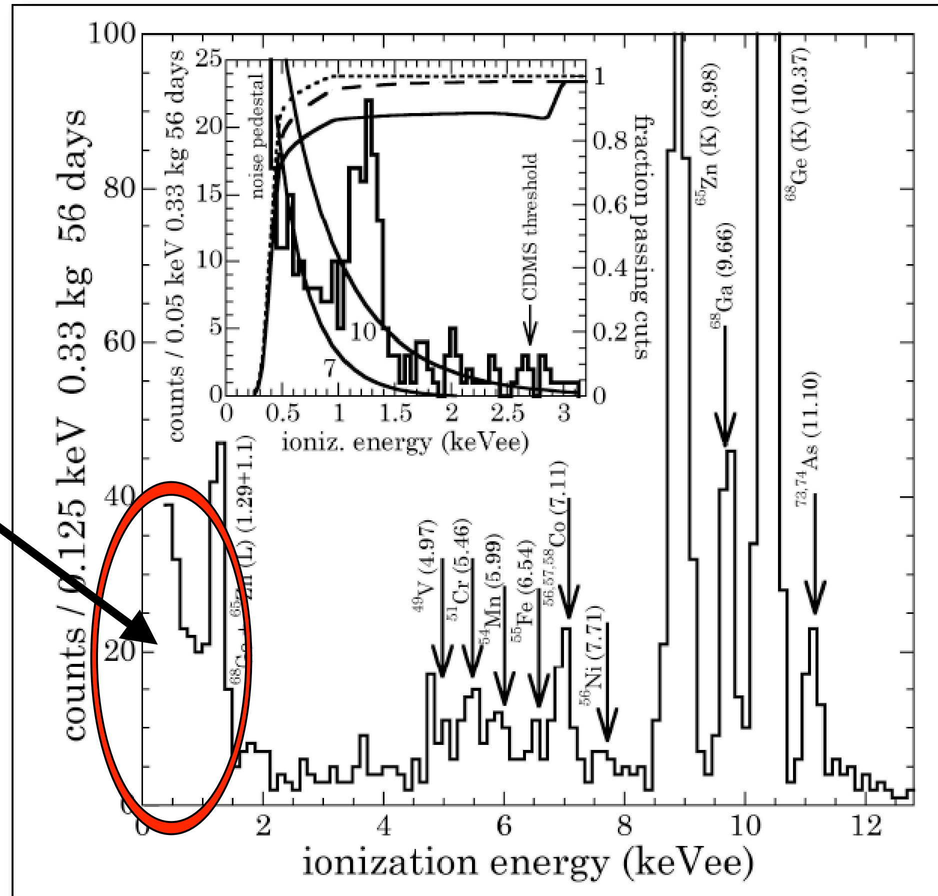


The Signals/Hints/Detections

CoGeNT

- The CoGeNT collaboration recently announced their observation of an excess of low energy events

- Although it has less exposure than other direct detection experiments, CoGeNT is particularly well suited to look for low energy events (low mass WIMPs)



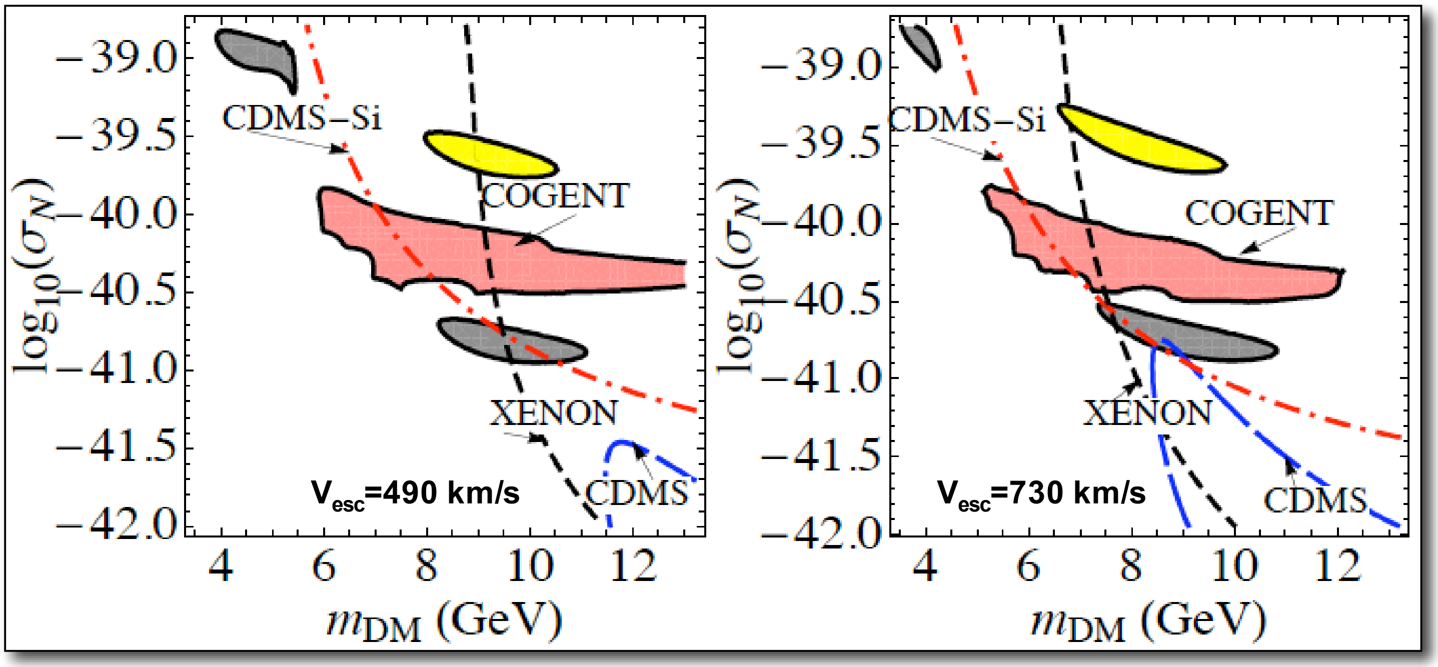
CoGeNT Collaboration, arXiv:1002.4703

The Signals/Hints/Detections

- Intriguingly, the CoGeNT and DAMA signals, if interpreted as dark matter, point to a similar region of parameter space

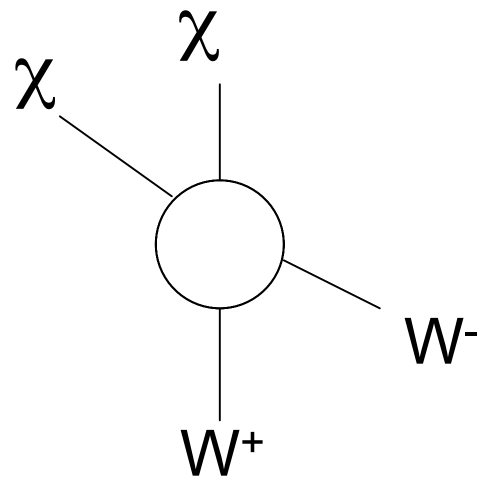
- Depending on the velocity distribution used, and on how one treats channeling, regions can be found in which both DAMA and CoGeNT can be explained by the same ~7 GeV dark matter particle

Fitzpatrick, Hooper, Zurek, arXiv:1003.0014



The Indirect Detection of Dark Matter

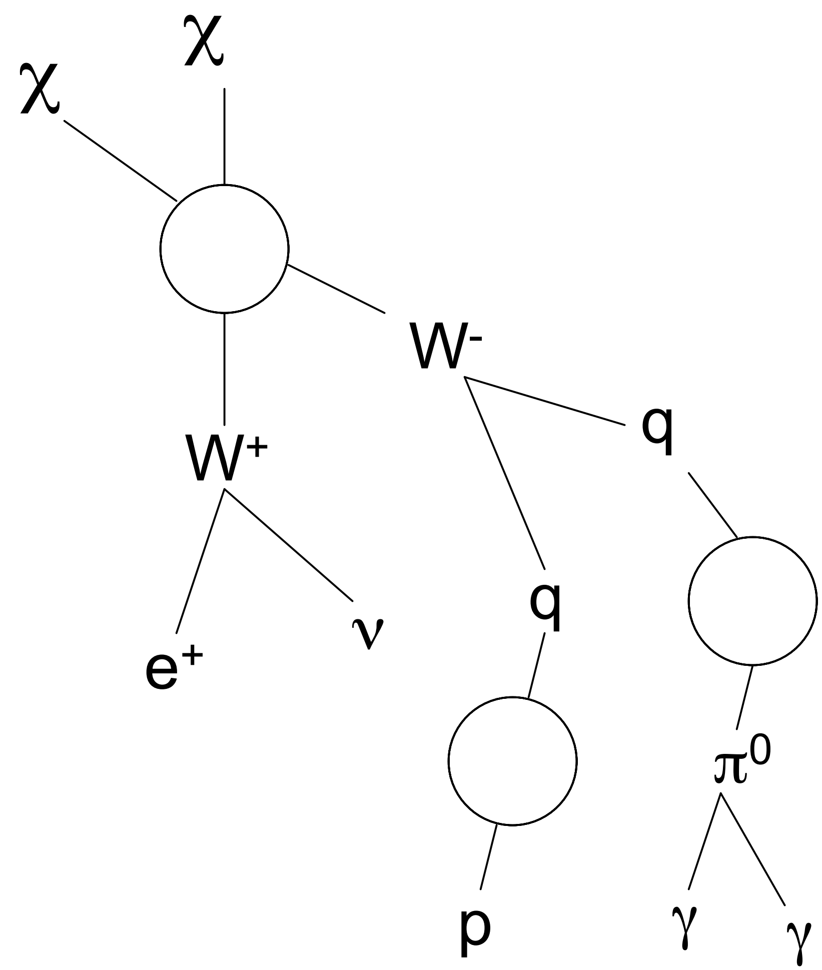
1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons



The Indirect Detection of Dark Matter

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

2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

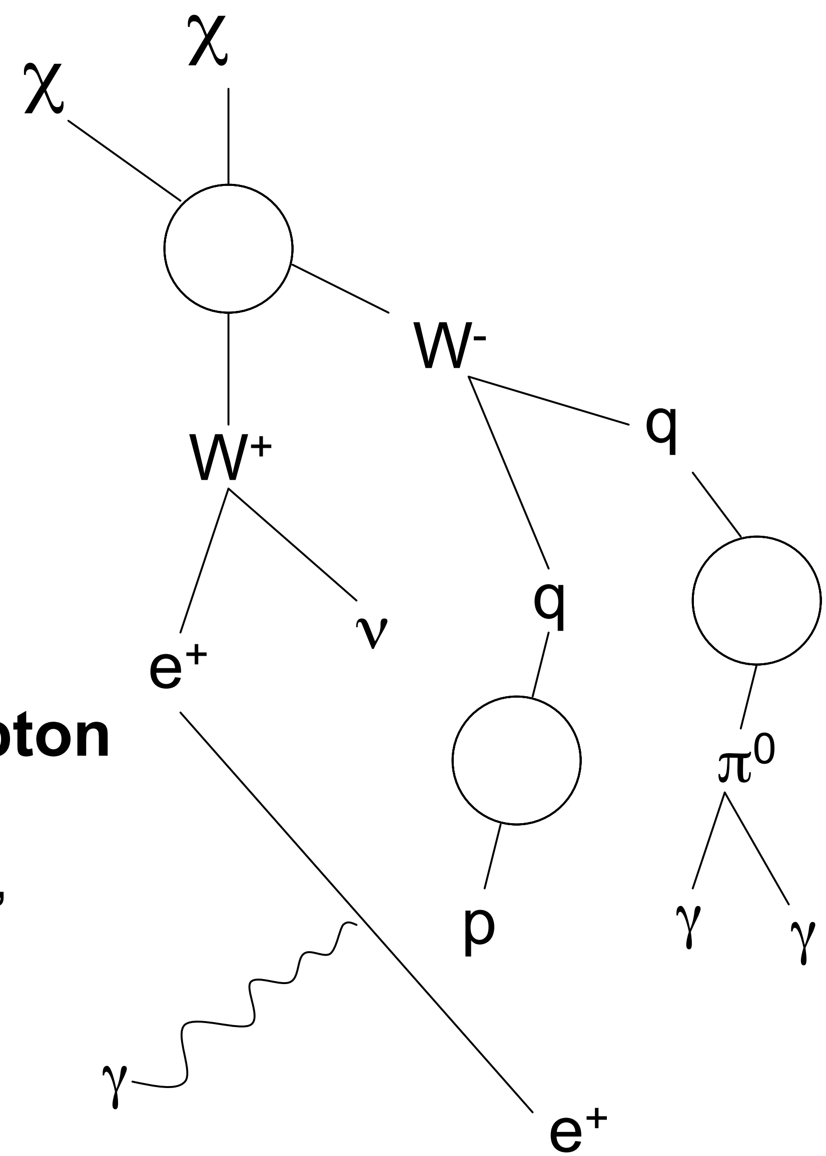


The Indirect Detection of Dark Matter

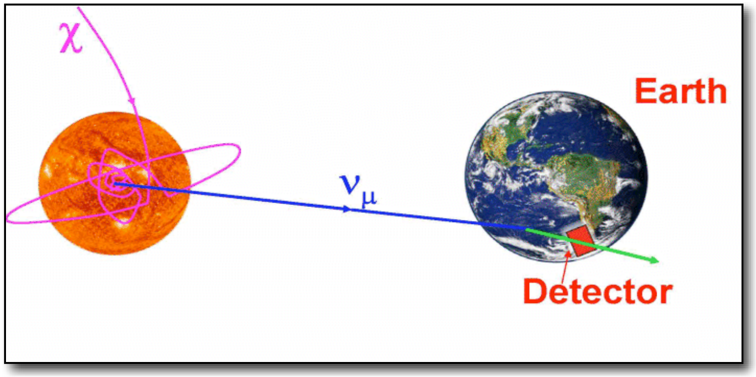
1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons

2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

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

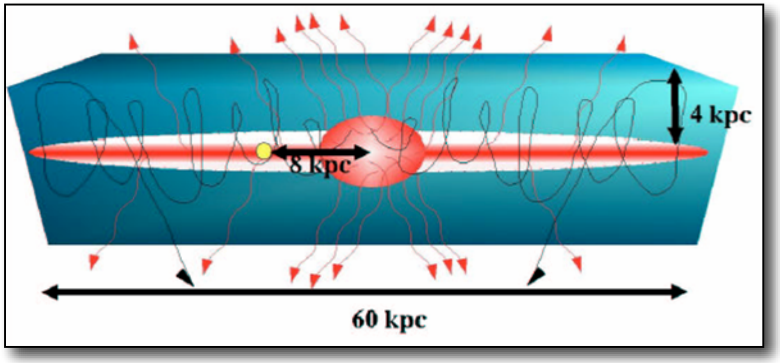


The Indirect Detection of Dark Matter



- **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 and Inverse Compton** from electron/positron interactions with the magnetic fields and radiation fields of the galaxy

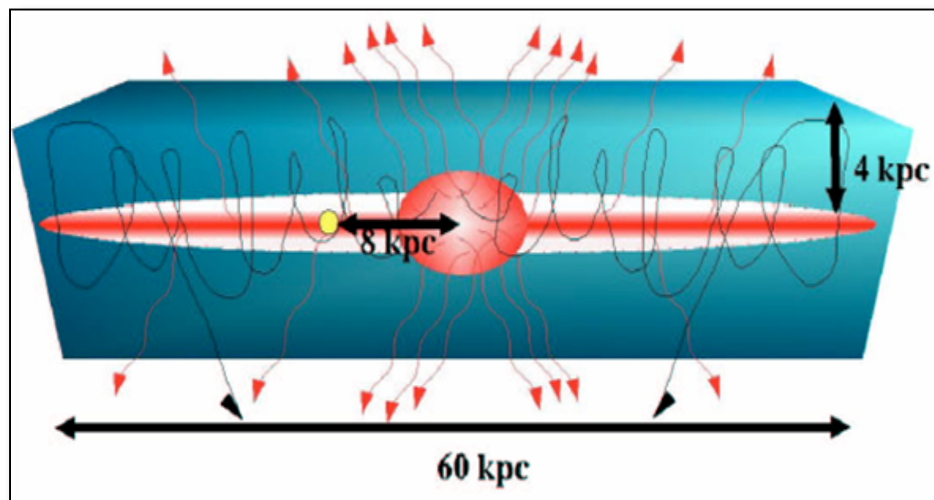


Dark Matter With Charged Cosmic Rays

- WIMP annihilation products fragment and decay, generating equal numbers of electrons and positrons, and of protons and antiprotons

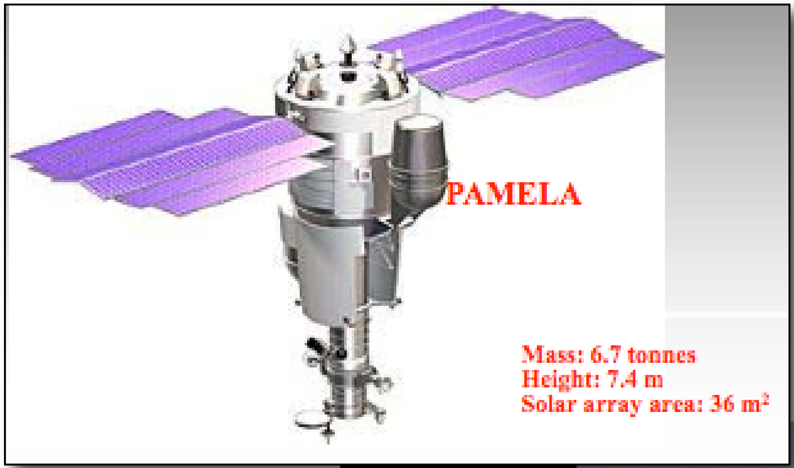
- Charged particles move under the influence of the Galactic Magnetic Field; Electrons/positrons lose energy via synchrotron and inverse Compton scattering

- Astrophysical sources are generally expected to produce far more matter than antimatter; large positron/antiproton content in the cosmic ray spectrum could provide evidence for dark matter

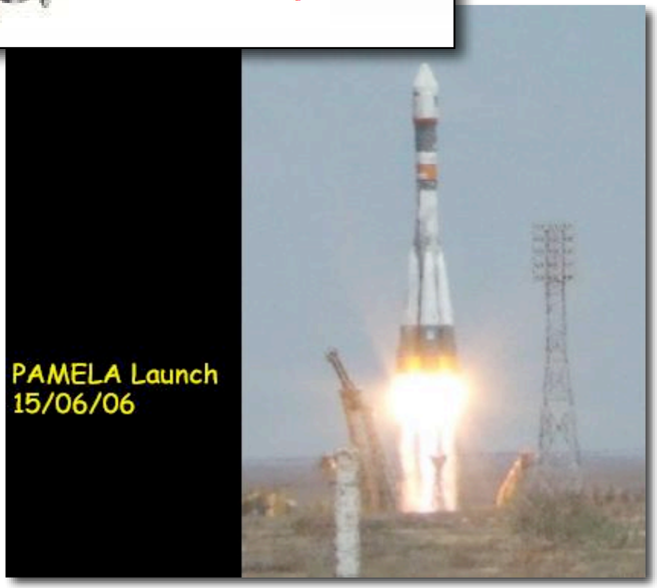


Charged Particle Astrophysics With Pamela

- Major step forward in sensitivity to GeV-TeV cosmic ray electrons, positrons, protons, antiprotons, and light nuclei



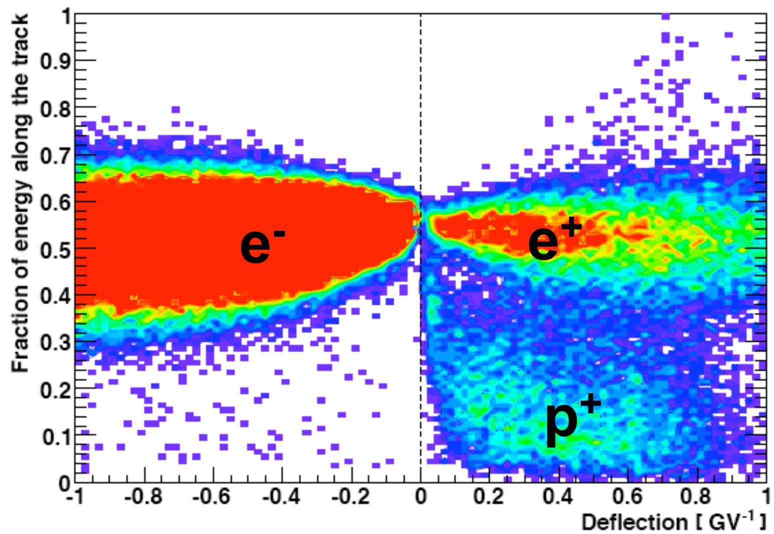
- Among other science goals, PAMELA hopes to identify or constrain dark matter annihilations in the Milky Way halo by measuring the cosmic positron and antiproton spectra

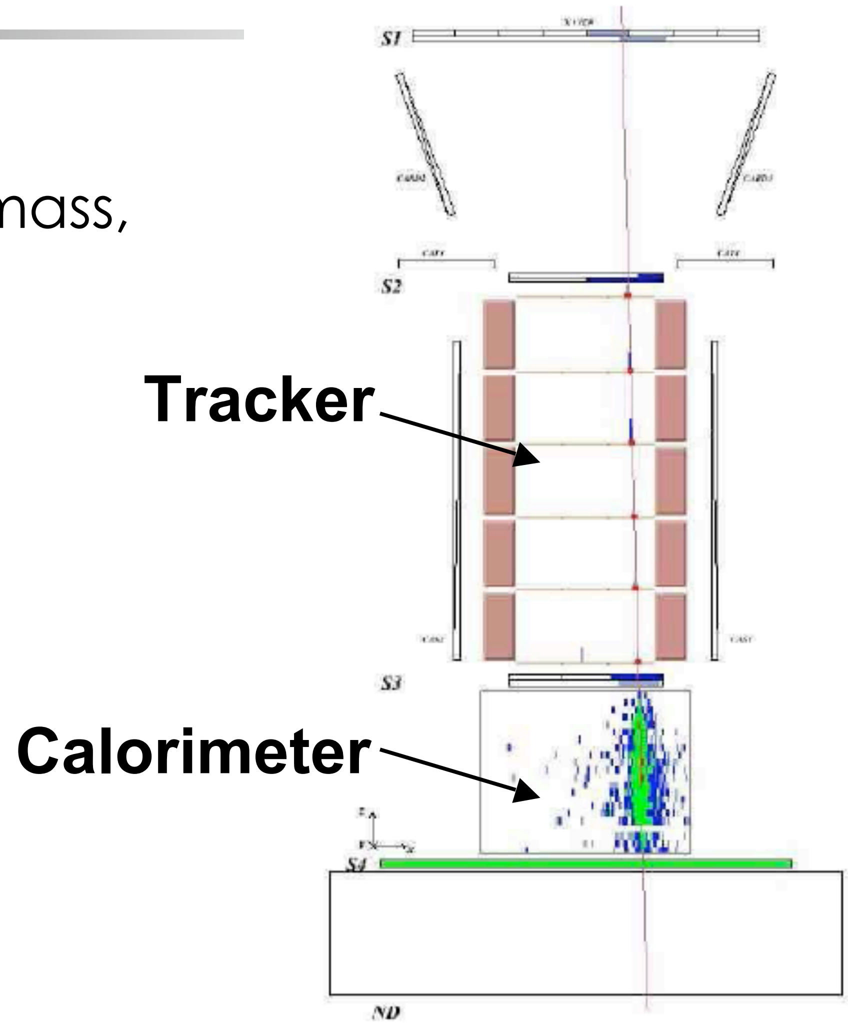


Charged Particle Astrophysics With Pamela

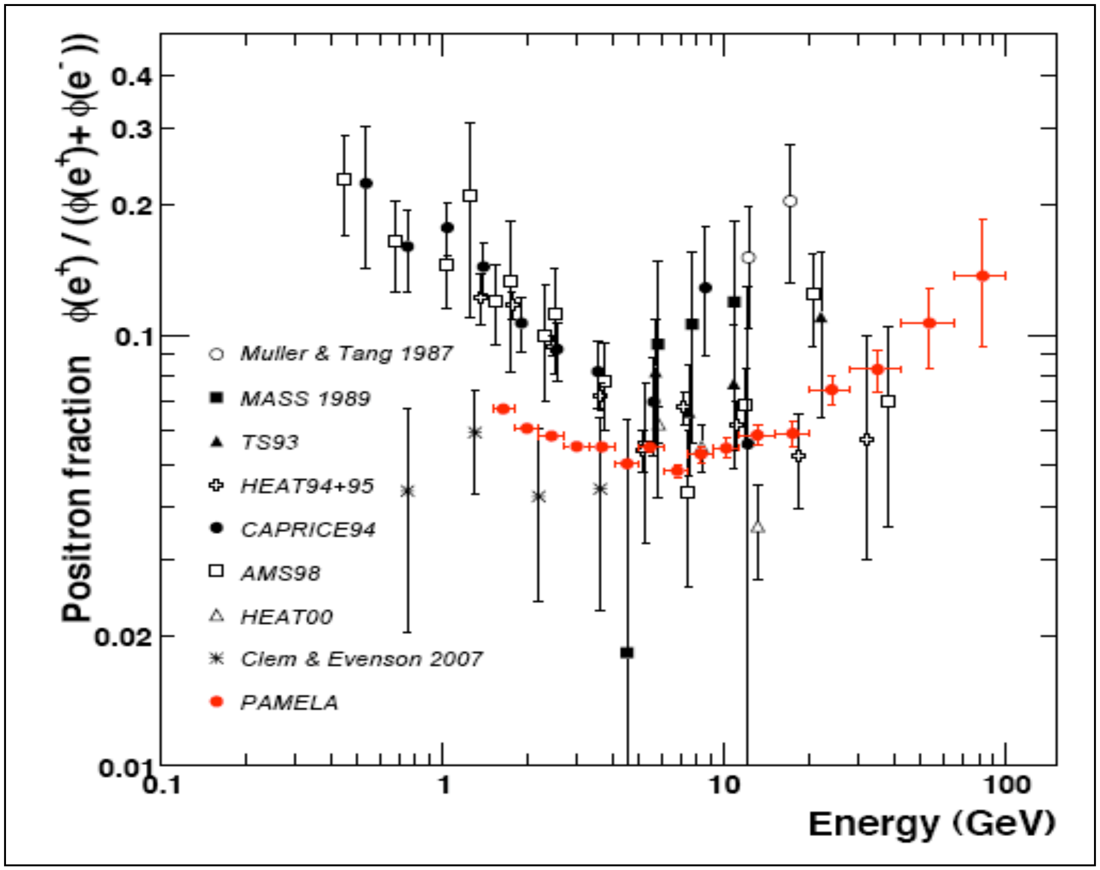
- Combination of tracker and calorimeter enable charge, mass, and energy determinations

- Very accurate particle ID





Pamela's New Positron Measurement



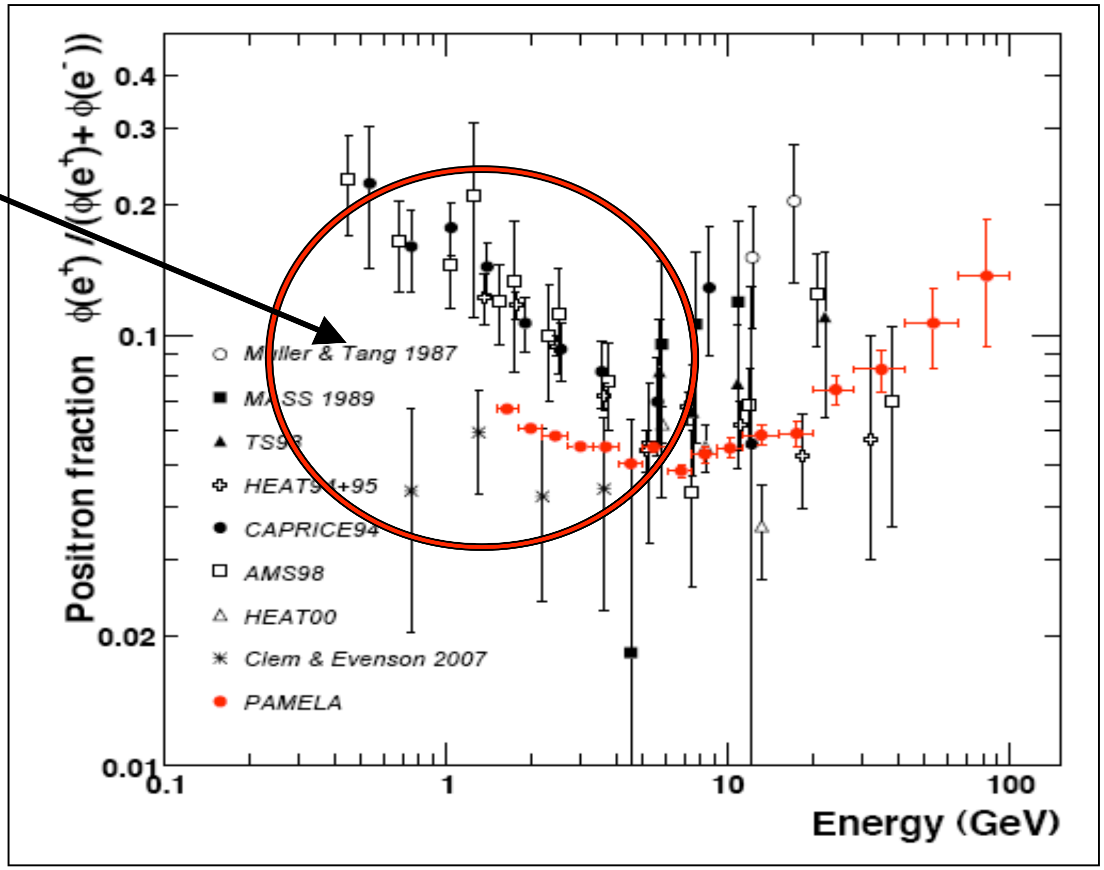
Pamela Collaboration, arXiv:0810.4995

Pamela's New Positron Measurement

First glance:
-Is this all screwed up?

Charge-dependent solar modulation important below 5-10 GeV!

(Pamela's sub-10 GeV positrons appear as they should!)



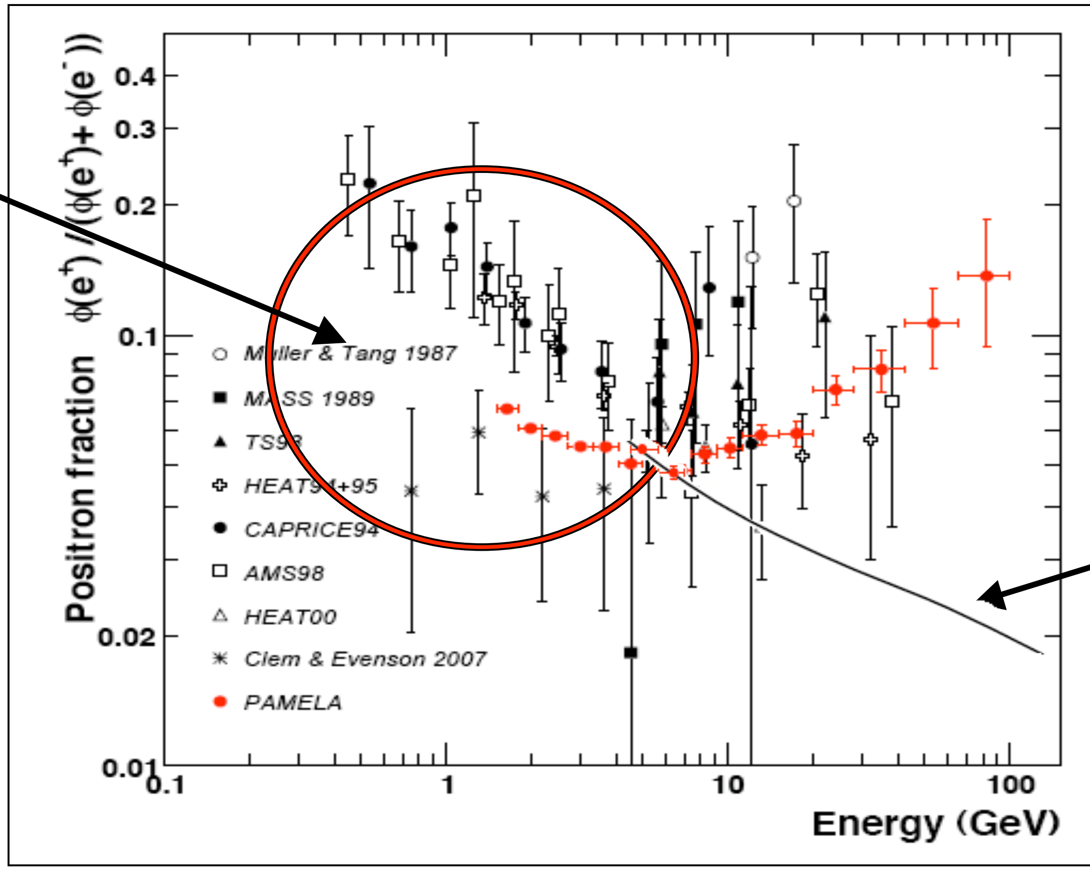
Pamela Collaboration, arXiv:0810.4995

Pamela's New Positron Measurement

First glance:
-Is this all screwed up?

Charge-dependent solar modulation important below 5-10 GeV!

(Pamela's sub-10 GeV positrons appear as they should!)



Astrophysical expectation (secondary production)

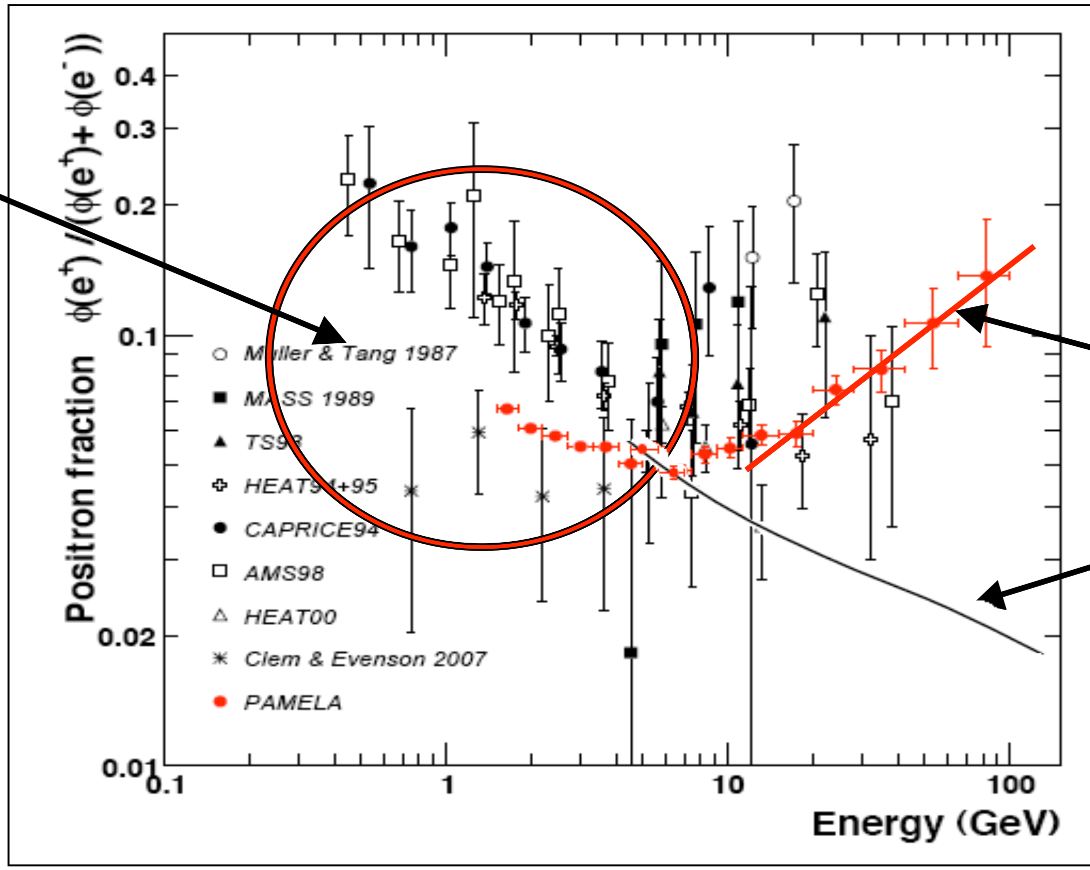
Pamela Collaboration, arXiv:0810.4995

Pamela's New Positron Measurement

First glance:
-Is this all screwed up?

Charge-dependent solar modulation important below 5-10 GeV!

(Pamela's sub-10 GeV positrons appear as they should!)



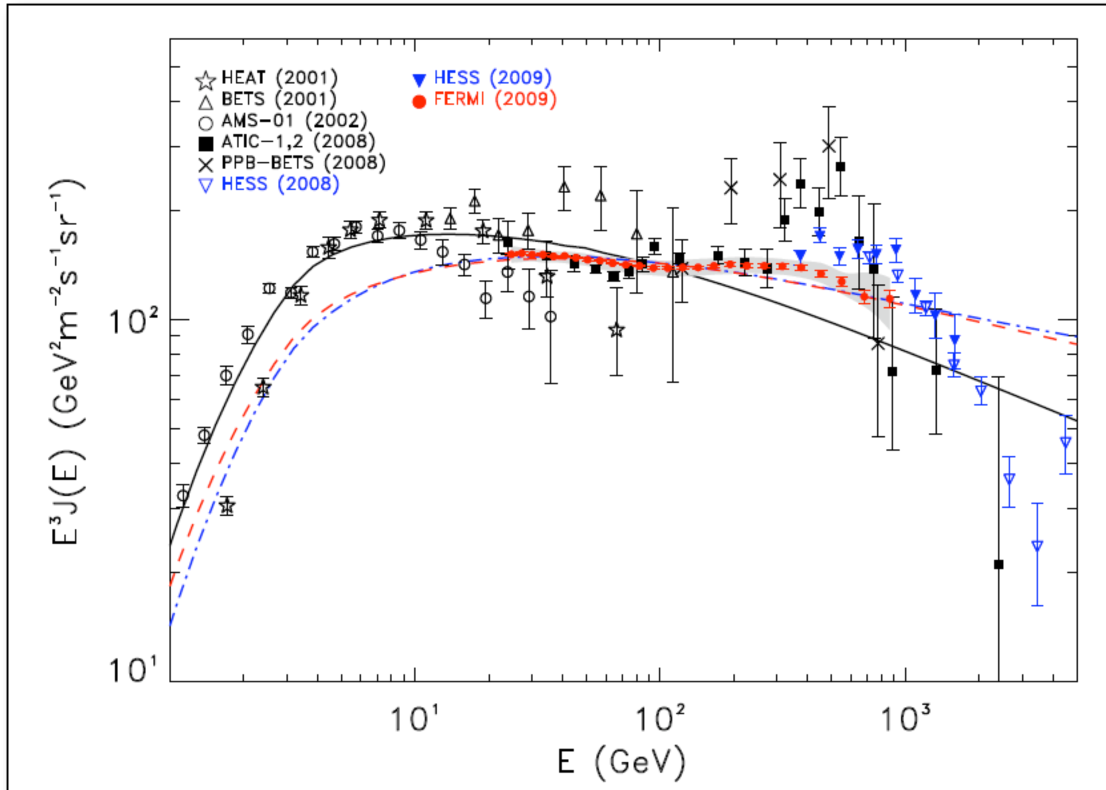
Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>

Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

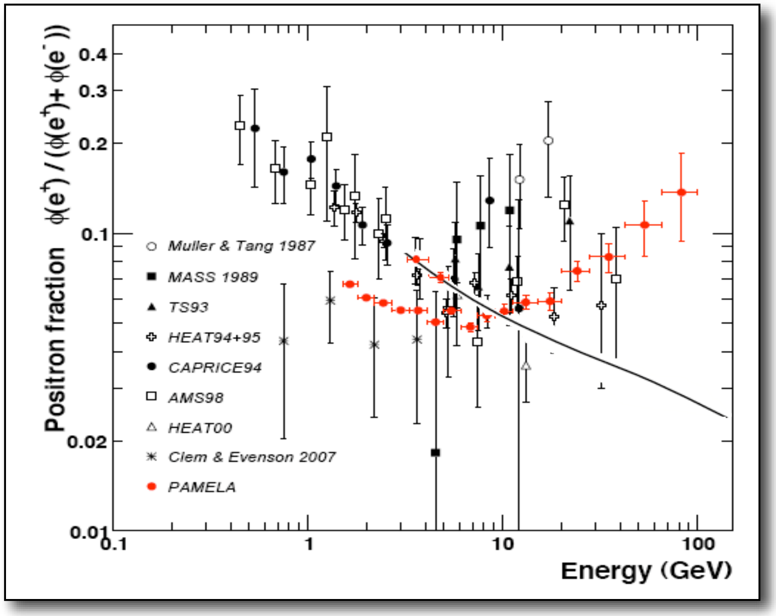
The Cosmic Ray Electron Spectrum

- Measurements from Fermi and HESS suggest a departure from simple homogeneous source models
- Not very surprising - At TeV energies, electrons sample only the surrounding ~1 kpc



Possible Origins of the PAMELA Positron Excess

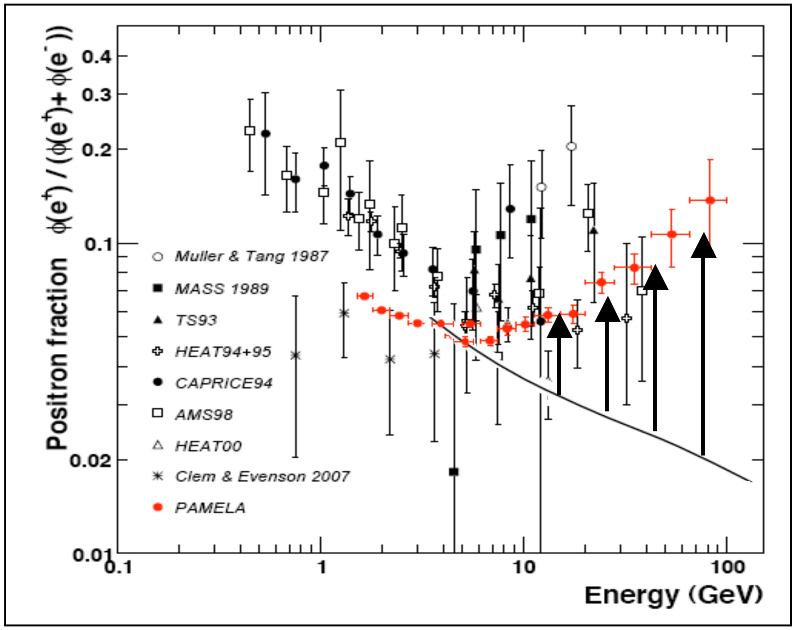
- Reacceleration of secondary positrons in or around supernova remnants
- Astrophysical primary positron sources (ie. pulsars)
- Dark matter annihilations or decays



Possible Origins of the PAMELA Positron Excess

- The standard prediction for secondary positron production is calculated by combining the spectrum of cosmic ray protons, the density of targets, and the spectrum of cosmic ray electrons; Unavoidably leading to the prediction of a steadily falling positron fraction

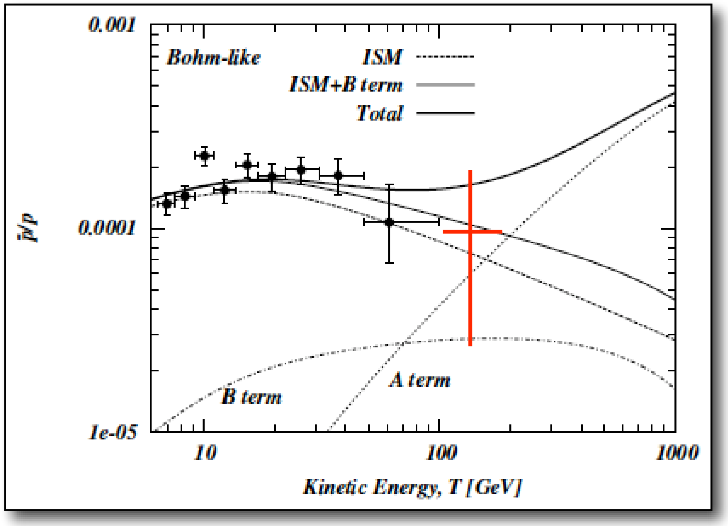
- It has been suggested that if secondary positrons are produced *inside of* cosmic ray acceleration regions, their spectrum may be hardened, potentially causing the positron fraction to rise



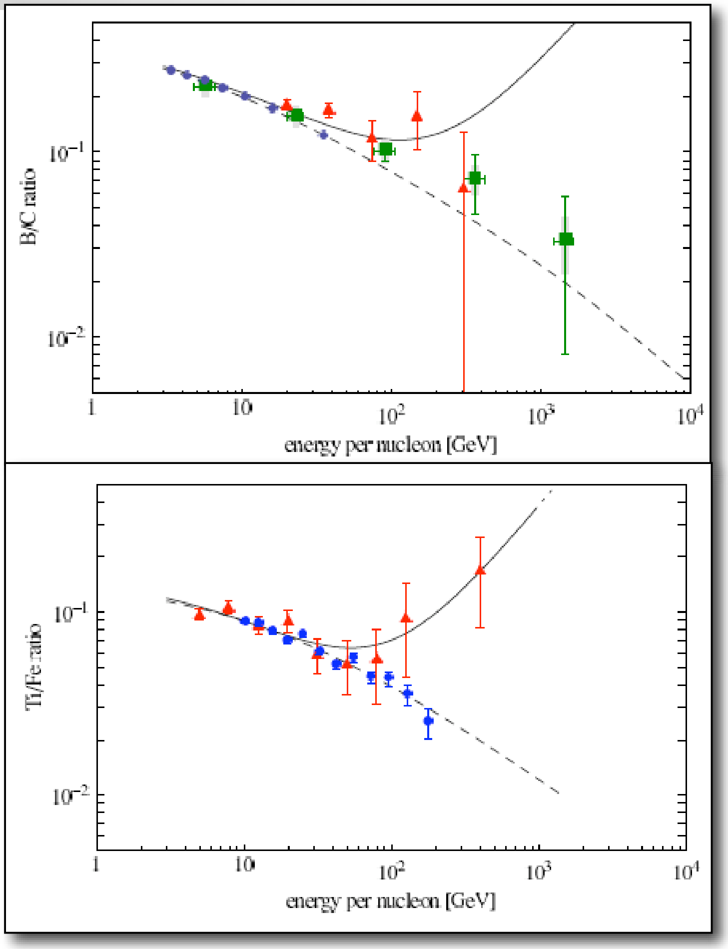
P. Blasi, arXiv:0903.2794

Possible Origins of the PAMELA Positron Excess

- The acceleration of positron secondaries, however, should be accompanied by the acceleration of antiproton, boron, and other secondary species
- This is not yet observed



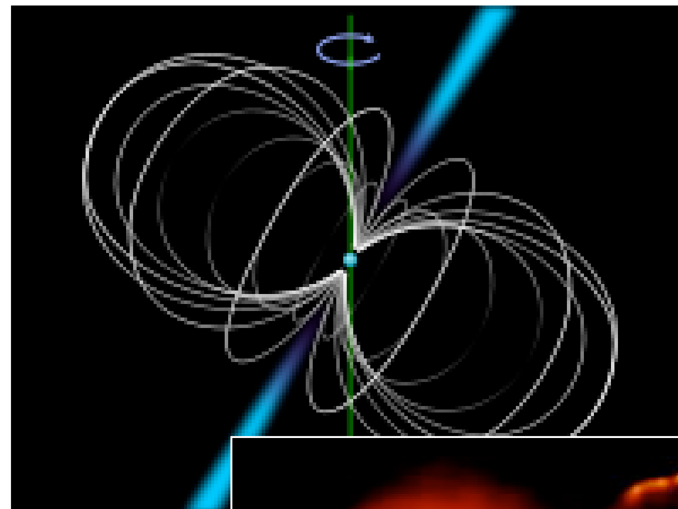
Blasi and Serpico, PRL, arXiv:0904.0871

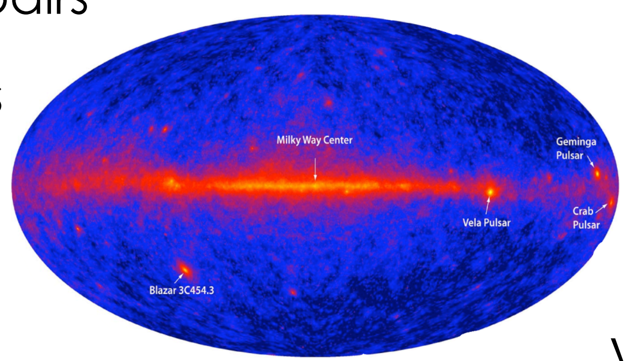


Sarkar, Mertsch, PRL, arXiv:0905.3152;
Ahlers, Mertsch, Sarkar, PRD, arXiv:0909.4060

High-Energy Positrons and Electrons From Nearby Pulsars

- Rapidly spinning (~msec period) neutron stars, accelerate electrons to very high energies (power from slowing rotation - spindown)
- Energies can exceed the pair production threshold
- Very young pulsars (≲10,000 years) are typically surrounded by a pulsar wind nebula, which can absorb energetic pairs
- Most of the spindown power is expended in first ~10^5 years



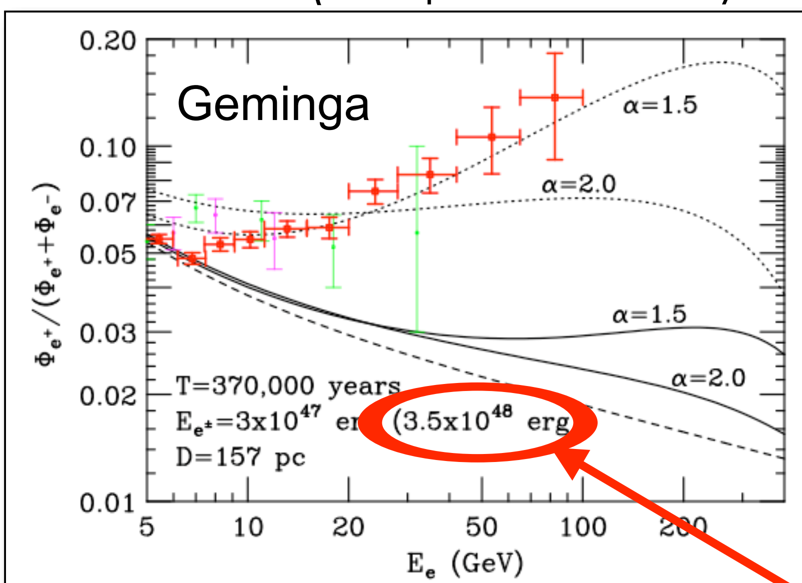


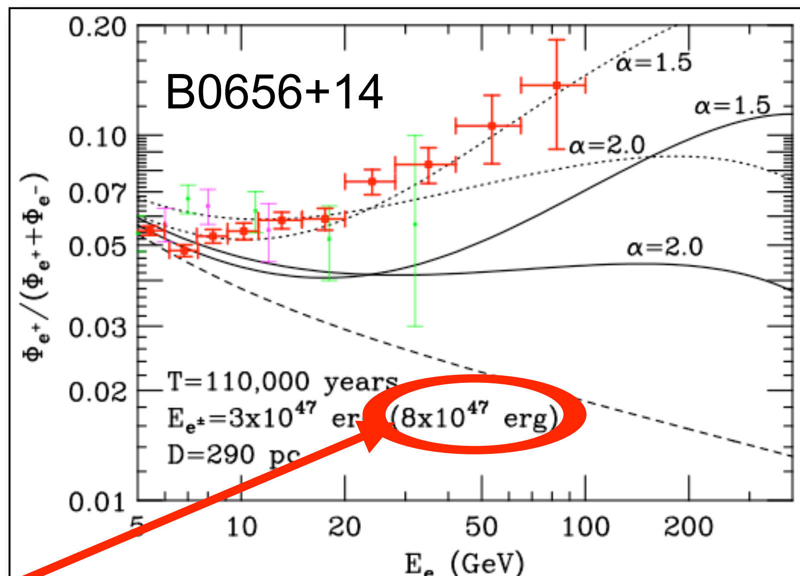
Vela Pulsar (12,000 yrs old)

High-Energy Positrons From Nearby Pulsars

Two promising candidates:

- Geminga (157 pc away, 370,000 years old)
- B0656+14 (290 pc, 110,000 years)





Tens of percent of the total spindown energy is needed in high energy e^+e^- pairs!

Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

Dark Matter and PAMELA

Dark matter annihilations in the halo of the Milky Way could explain the positron excess, although some obstacles exist

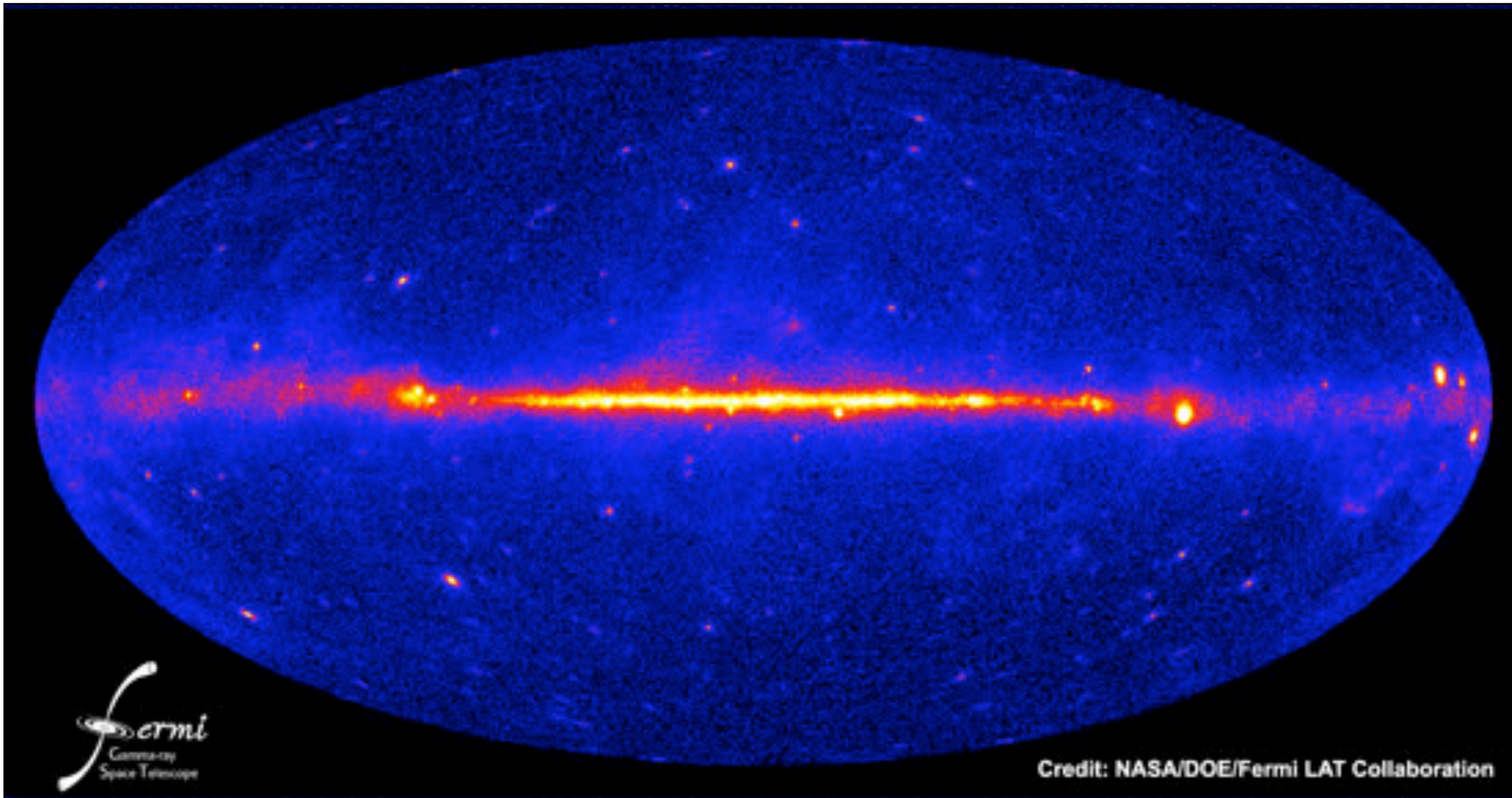
- **Hard positron spectrum** - Annihilation to leptons?
  Local overdensity/clump?
- **Lack of excess antiprotons** - Annihilation to leptons?
  Narrow diffusion region?
- **Large positron flux** - Non-thermal dark matter?
  Sommerfeld enhancements?
  Large degree of substructure?

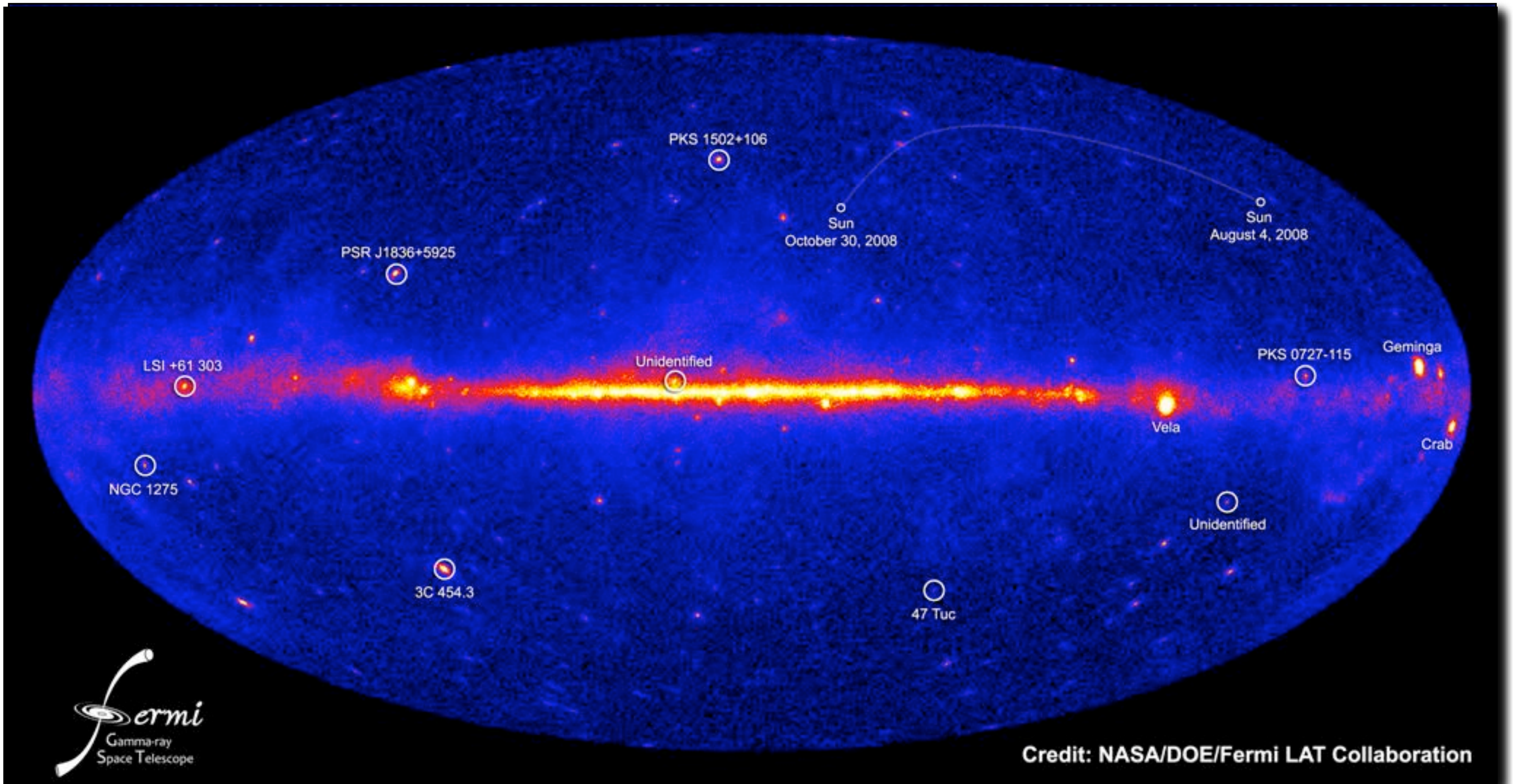
Pamela's positrons cannot be explained by Vanilla Dark Matter, but could be in more complex scenarios

An Essential Test:

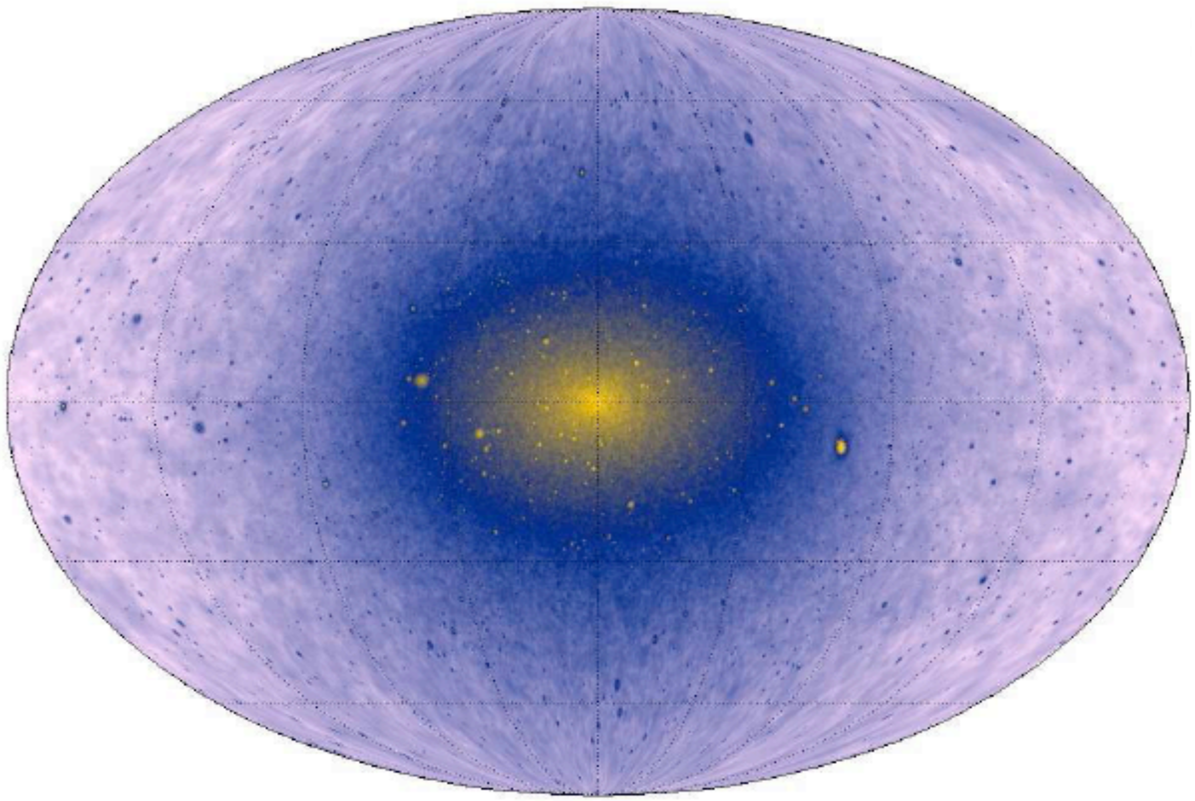
Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- Last year, the FERMI collaboration announced their first results!
- In August 2009, their first year data became publicly available
- Signatures of dark matter annihilation might appear clearly and quickly, or over years of exposure, or not at all, depending on the dark matter distribution, annihilation cross section, mass, and astrophysical backgrounds


fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration


PKS 1502+106
Sun
October 30, 2008
Sun
August 4, 2008
PSR J1836+5925
LSI +61 303
Unidentified
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

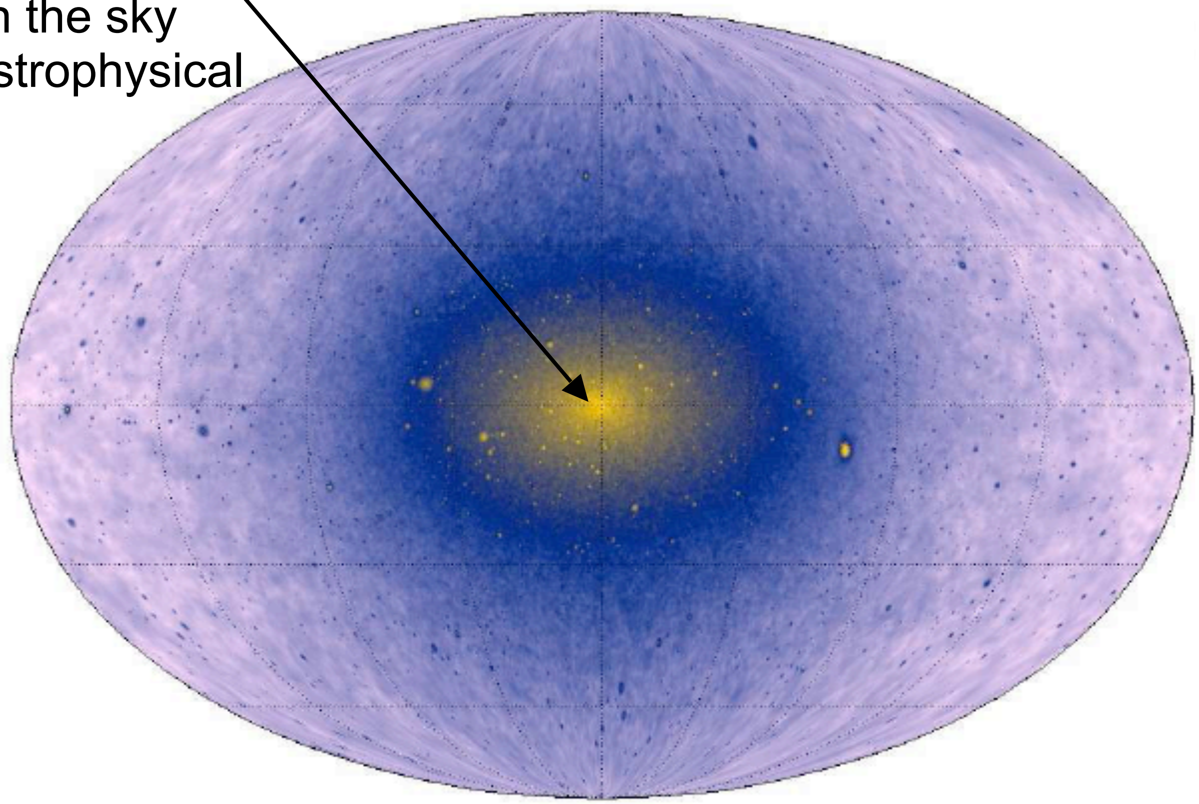
Where To Look For Dark Matter With Fermi?



Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds



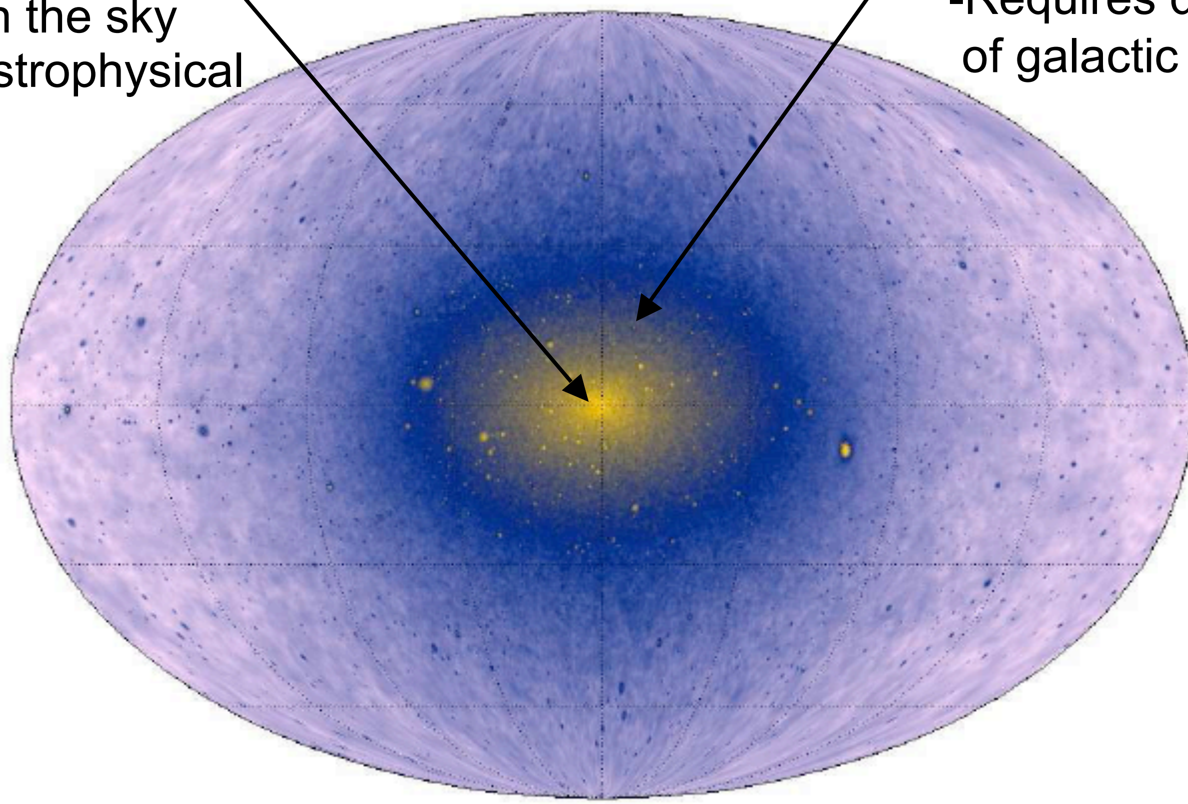
Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds

The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds



Where To Look For Dark Matter With Fermi?

The Galactic Halo

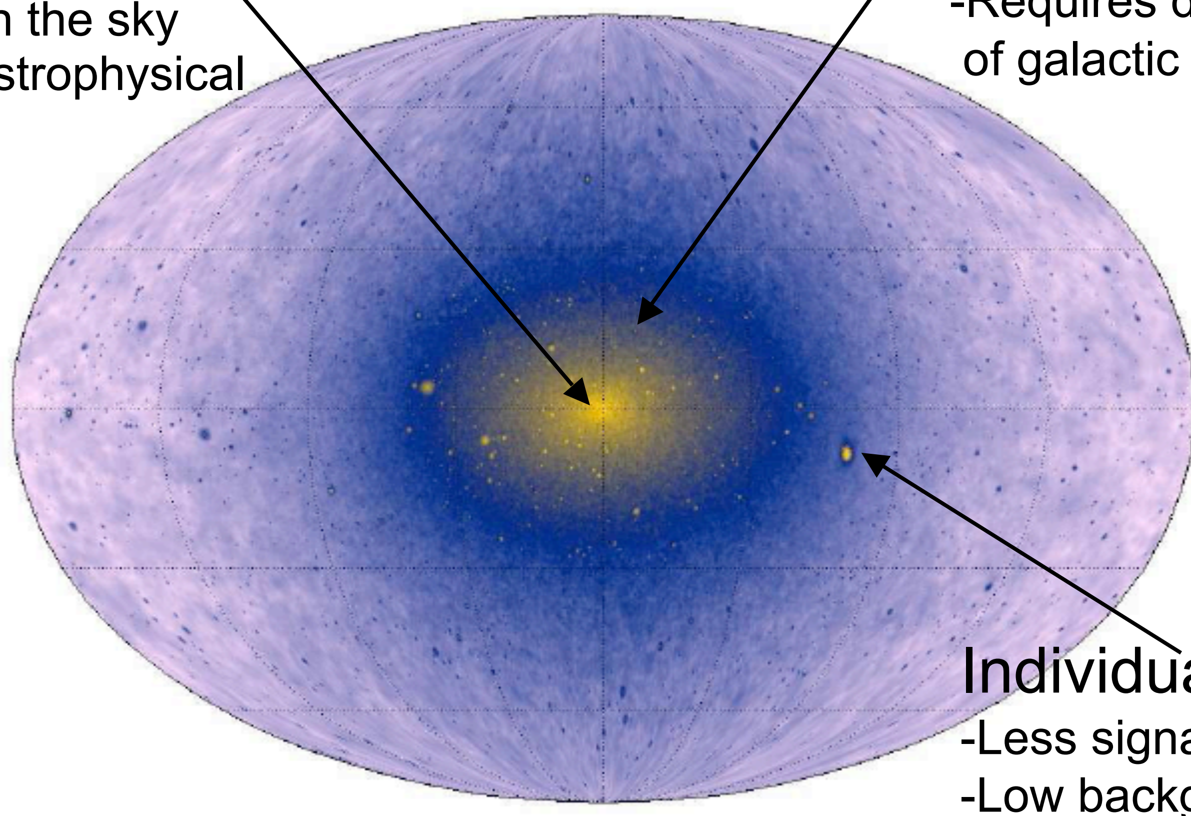
-High statistics

-Requires detailed model of galactic backgrounds

The Galactic Center

-Brightest spot in the sky

-Considerable astrophysical backgrounds



Individual Subhalos

-Less signal

-Low backgrounds

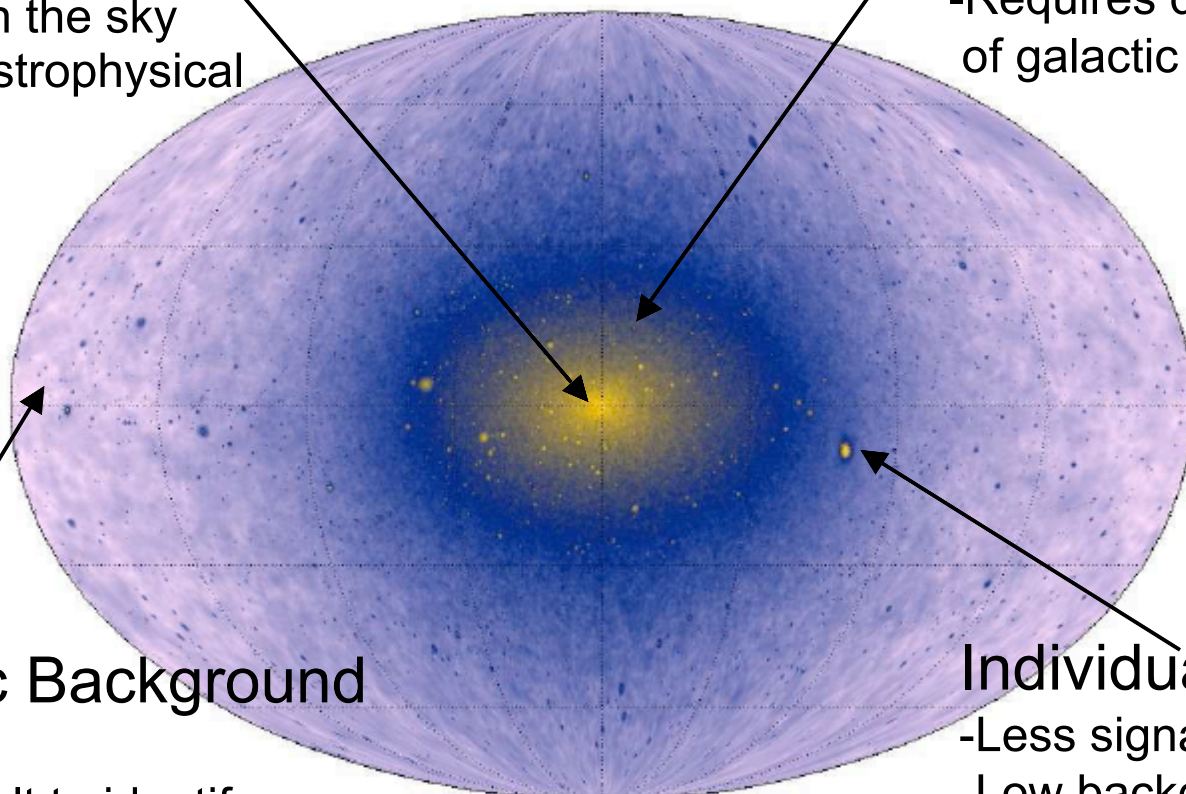
Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds

The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds



Extragalactic Background

-High statistics
-potentially difficult to identify

Individual Subhalos

-Less signal
-Low backgrounds

Some of the most interesting early dark matter results from Fermi

1) Galactic Diffuse Emission Measurement

2) The Galactic Center Region

3) Subhalos

4) Galaxy Clusters

5) Dwarf Spheriodal Galaxies

6) Line searches

7) Diffuse ICS (the “Fermi ~~Haze~~” Bubbles)

8) Isotropic Diffuse

Dwarf Spheroidal Galaxies

- The FGST collaboration has recently placed some relatively stringent limits on dark matter from observations of a number of satellite galaxies (dwarf spheroidals) of the Milky Way
- The most stringent limits come from those dwarfs which are 1) dense, 2) nearby, and 3) in low background regions of the sky

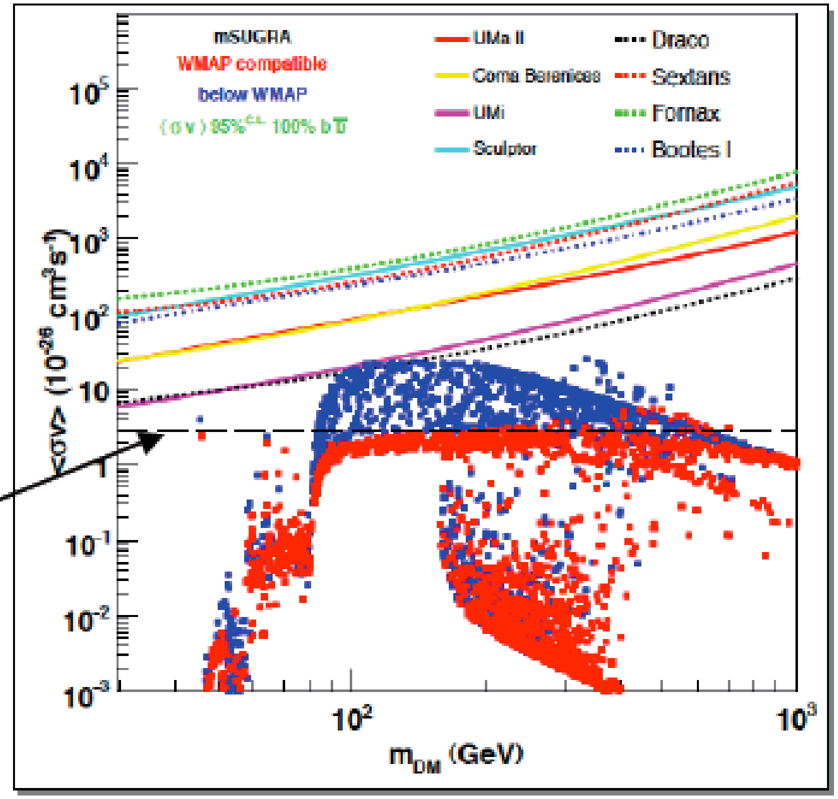
Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8	l	b	Ref.
Ursa Major II	30 ± 5	2006	4000^{+3700}_{-2100}	152.46	37.44	1,2
Segue 2	35	2009	650	149.4	-38.01	3
Willman 1	38 ± 7	2004	770^{+930}_{-440}	158.57	56.78	1
Coma Berenices	44 ± 4	2006	1100^{+800}_{-500}	241.9	83.6	1,2
Bootes II	46	2007	18000??	353.69	68.87	6,7
Bootes I	62 ± 3	2006	1700^{+1400}_{-700}	358.08	69.62	6
Ursa Minor	66 ± 3	1954	290^{+140}_{-90}	104.95	44.80	4,5
Sculptor	79 ± 4	1937	18^{+6}_{-5}	287.15	-83.16	4,5
Draco	76 ± 5	1954	200^{+80}_{-60}	86.37	34.72	4,5,9
Sextans	86 ± 4	1990	120^{+40}_{-35}	243.4	42.2	4,5
Ursa Major I	97 ± 4	2005	1800^{+1300}_{-700}	159.43	54.41	6
Hercules	132 ± 12	2006	1400^{+1200}_{-700}	28.73	36.87	6
Fornax	138 ± 8	1938	$8.7^{+2.8}_{-3.3}$	237.1	-65.7	4,5
Leo IV	160 ± 15	2006	260^{+1000}_{-200}	265.44	56.51	6

FGST Collaboration, arXiv:1001.4531

Dwarf Spheroidal Galaxies

- Analysis assumed an NFW profile form, with parameters constrained by stellar velocity measurements
- Ursa Minor and Draco provide the strongest constraints, with several others within a factor of ~3-10
- Constraints for M_{DM}~100 GeV or less are within a factor of a few of the value predicted for a simple thermal relic
- Based on only 11 months of data; given the low backgrounds, this curve will come down significantly with exposure

(stacked dwarf analysis in progress!)



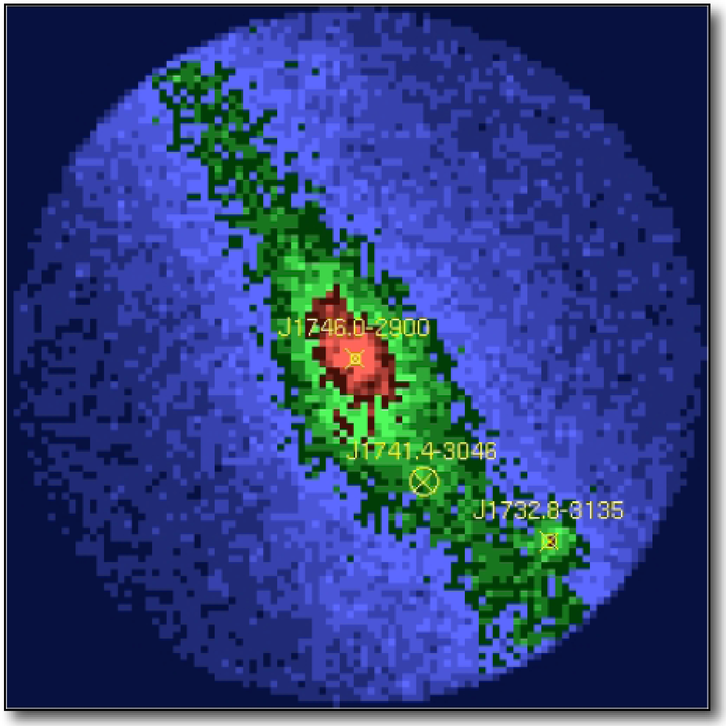
FGST Collaboration, arXiv:1001.4531

See also the analysis of Segue 1 by P. Scott *et al.*, arXiv:0909.3300

Dark Matter In The Galactic Center Region

- The region surrounding the Galactic Center is complex; backgrounds are poorly understood

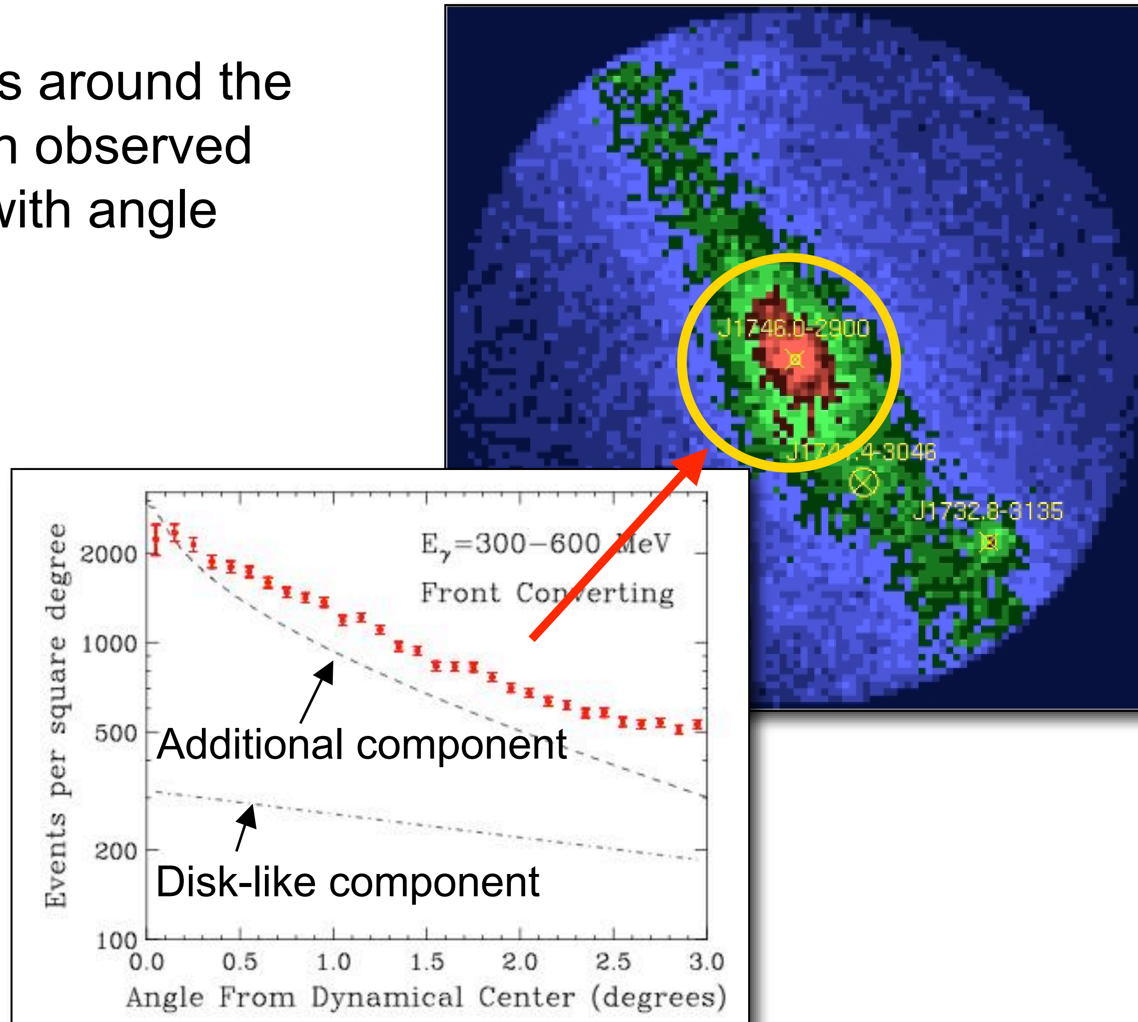
- This does not necessarily make searches for dark matter in this region intractable, however



Dark Matter In The Galactic Center Region

- Within the inner few degrees around the Galactic Center, the emission observed by FGST steeply increases with angle

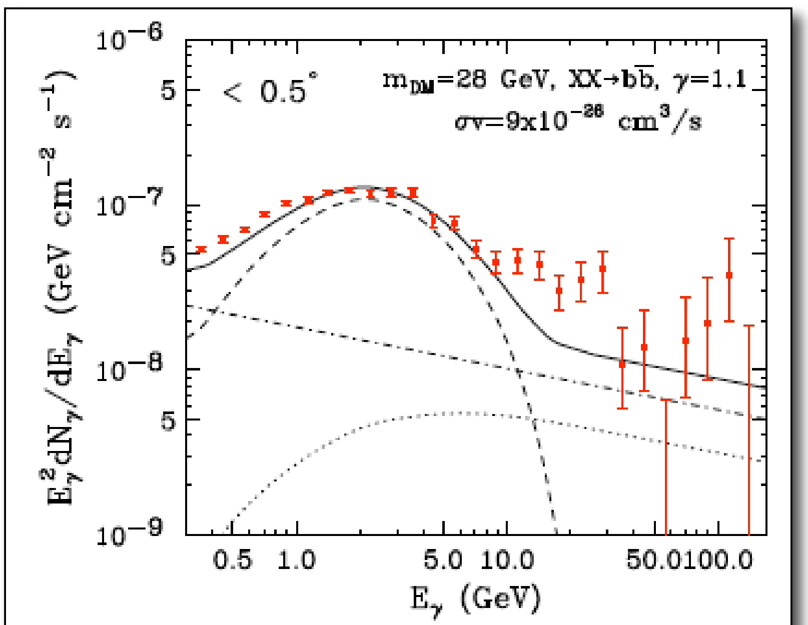
- If the diffuse background is modeled with the shape of the disk emission between 3° and 6°, another component is required that is more concentrated and spherically symmetric

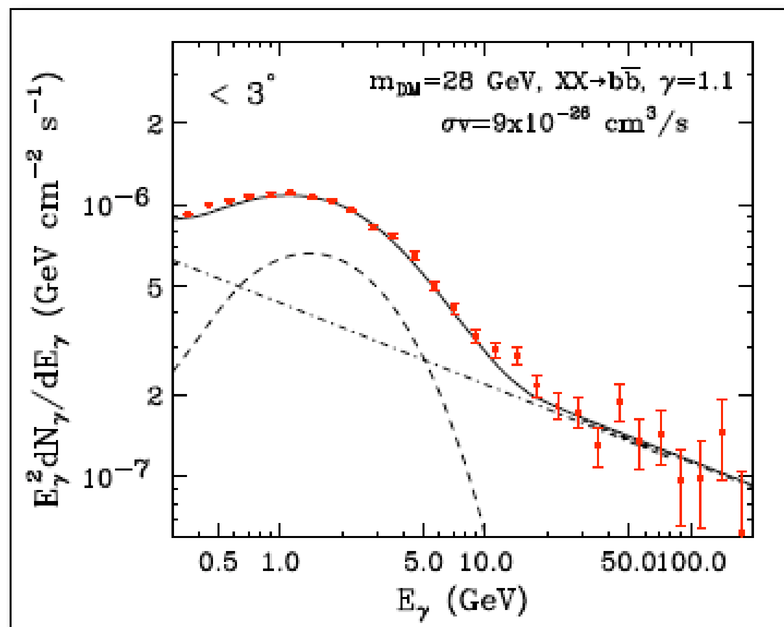


L. Goodenough, D. Hooper, arXiv:0910.2998

Dark Matter In The Galactic Center Region

- Intriguingly, the spectrum of the spherically symmetric component contains a “bump-like” feature at ~1-5 GeV
- Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to $b\bar{b}$ with σv ~ 9 x 10^{-26} cm^3/s

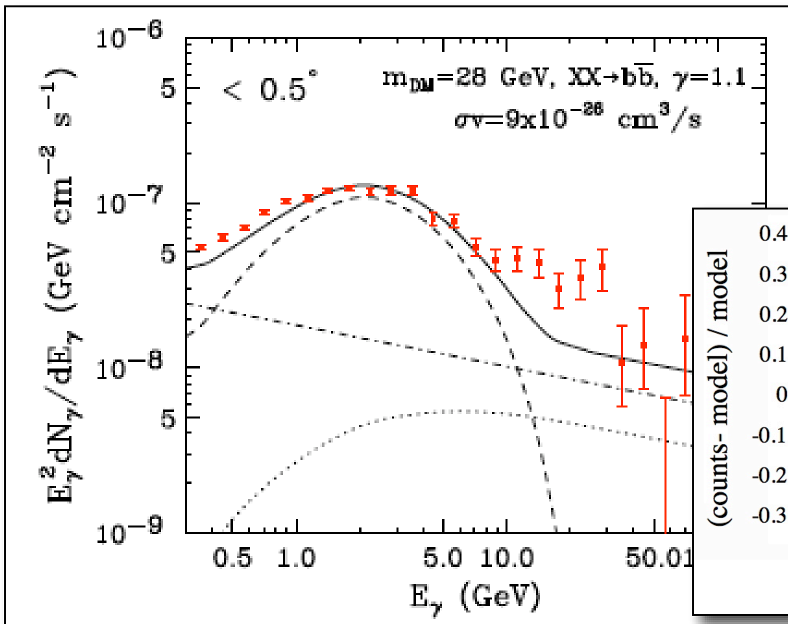




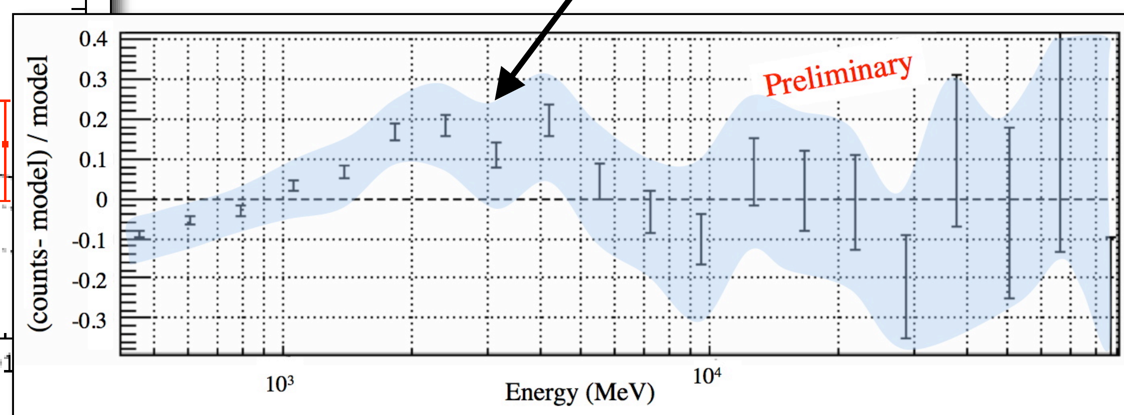
L. Goodenough, D. Hooper, arXiv:0910.2998

Dark Matter In The Galactic Center Region

- Intriguingly, the spectrum of the spherically symmetric component contains a “bump-like” feature at ~1-5 GeV
- Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to $b\bar{b}$ with $\sigma v \sim 9 \times 10^{-26}$ cm^3/s



- Recent presentations by the Fermi collaboration confirm the presence of this feature



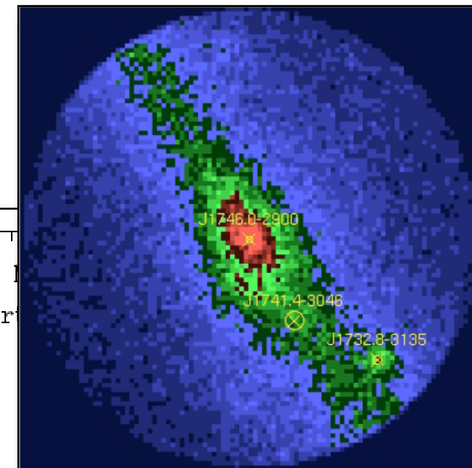
(Fermi Collaboration, Preliminary)

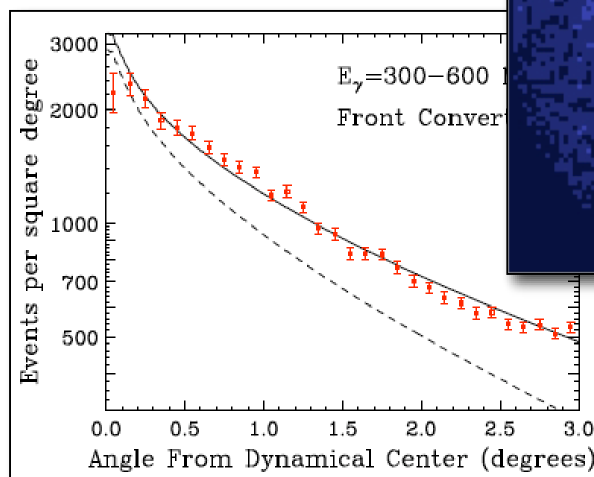
L. Goodenough, D. Hooper, arXiv:0910.2998

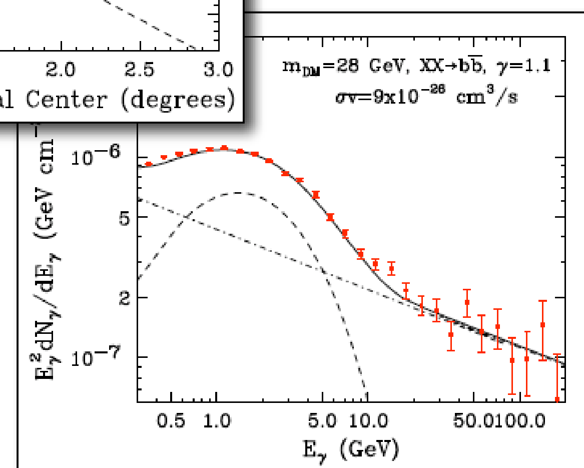
Dark Matter In The Galactic Center Region

Some words of caution:

- Although the angular distribution and spectrum observed from the inner Milky Way by FGST can be well fit by a simple annihilating dark matter scenario, an astrophysical background with a similar angular distribution and spectrum cannot be ruled out (π^0 decays have similar spectral shape, for example)
- The inner galaxy is a complex region, which must be scrutinized before any confident claims can be made
- Searches in other regions of the sky will be important to confirm or refute this interpretation



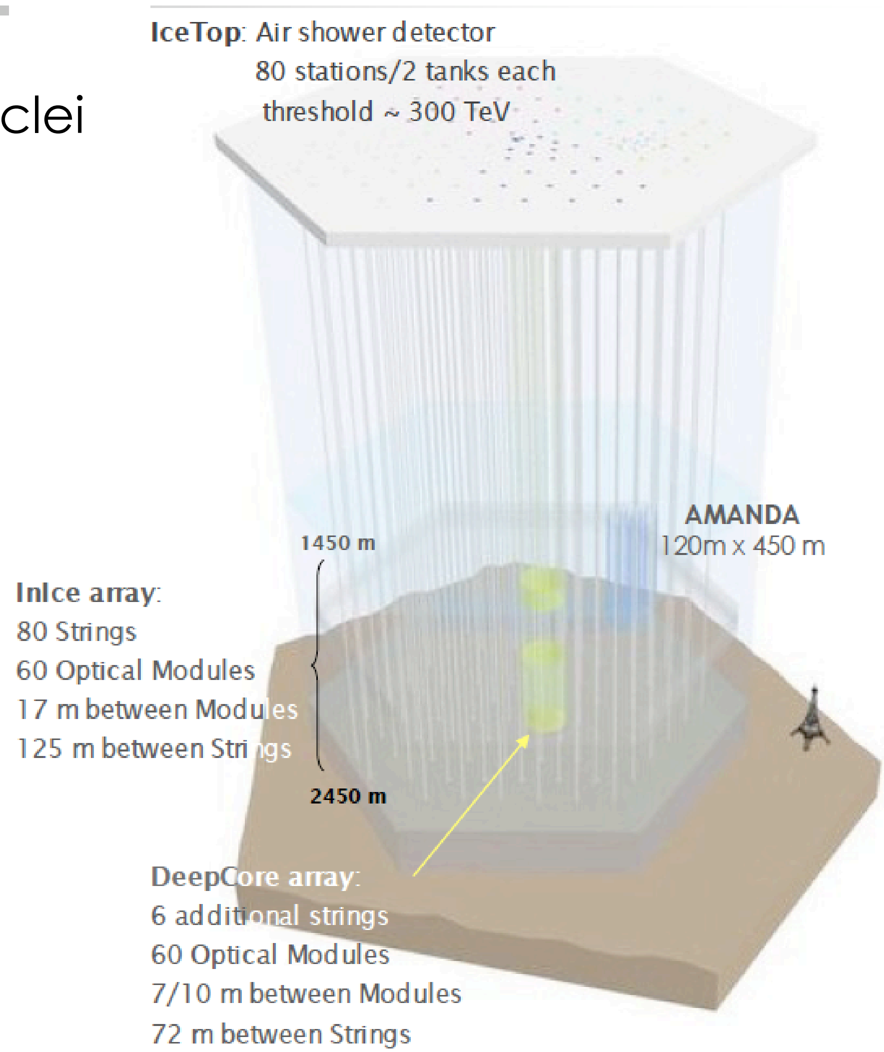




L. Goodenough, D. Hooper, arXiv:0910.2998

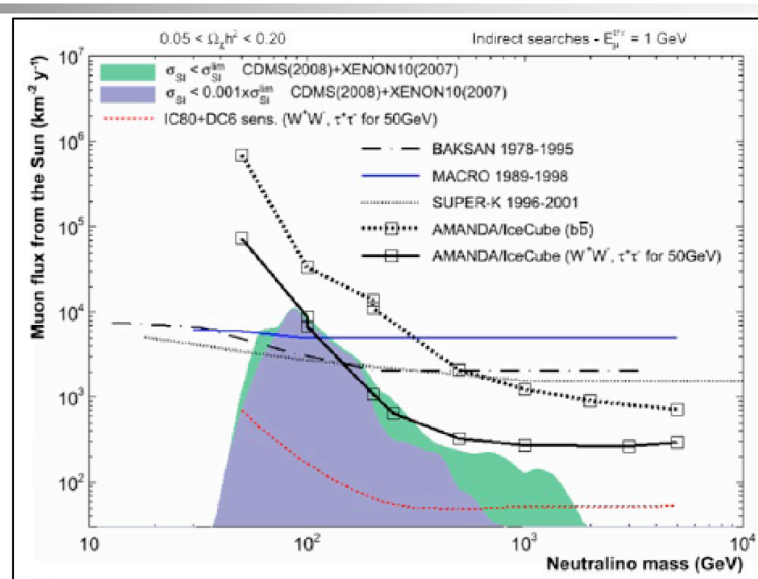
Dark Matter on Ice

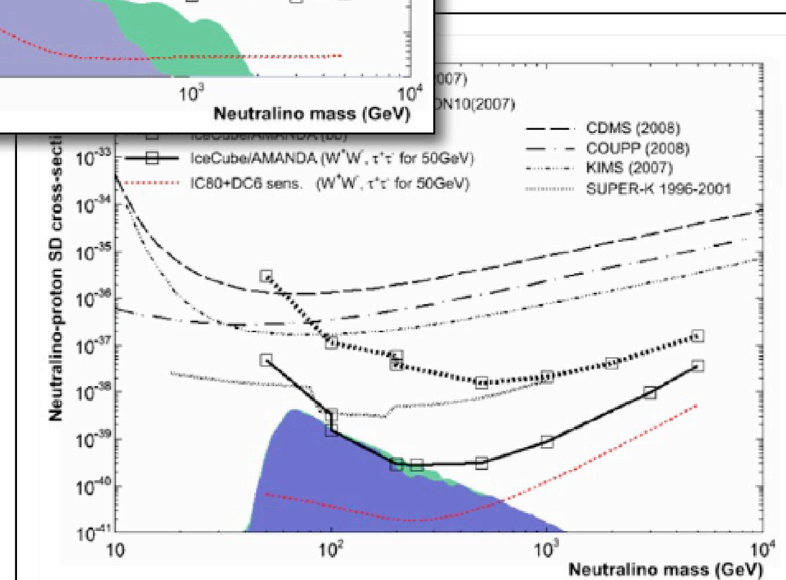
- WIMPs can elastically scattering with nuclei in the Sun, leading them to become gravitationally captured
- After millions/billions of years, the annihilation rate is (in many models) predicted to reach equilibrium with the capture rate
- Neutrino telescopes such as IceCube are sensitive to neutrinos from WIMP annihilations in the Sun



Dark Matter on Ice

- IceCube has placed constraints on the neutrino-induced muon flux from the Sun, and interpreted this in terms of a limit on the WIMP's spin-dependent elastic scattering cross section with protons
- These limits are competitive with or stronger than those from current direct detection experiments



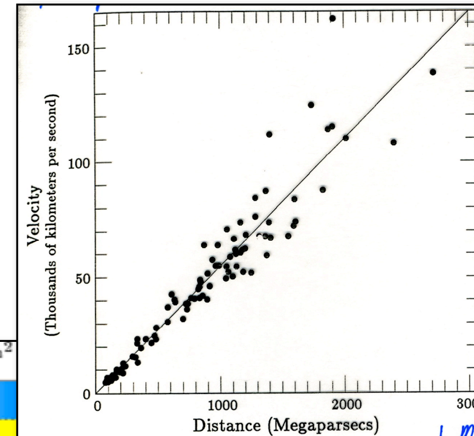


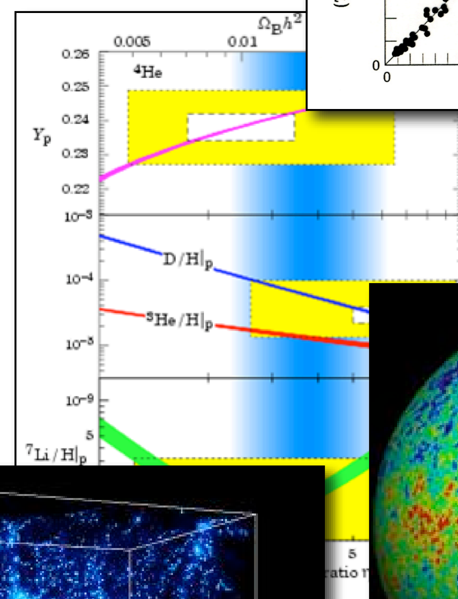
Summary

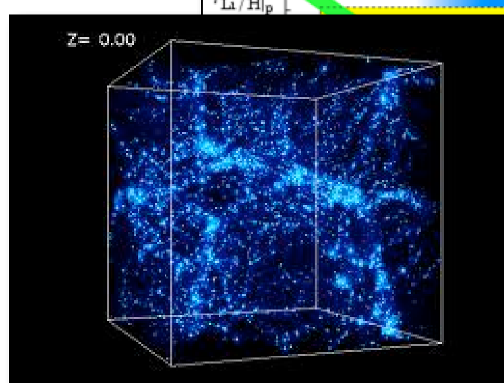
- Big Bang cosmology has been incredibly successful in explaining a wide range of observed phenomena

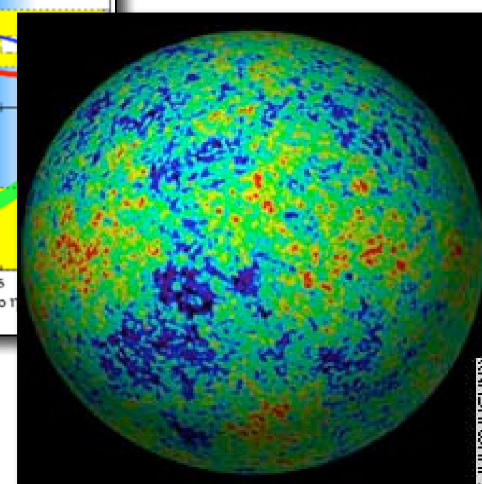
- Yet some aspects of our universe's history and composition remain poorly understood - dark matter, dark energy, inflation

- Weakly interacting massive particles provide a natural candidate for the dark matter, with a simple and compelling explanation for the observed dark matter abundance





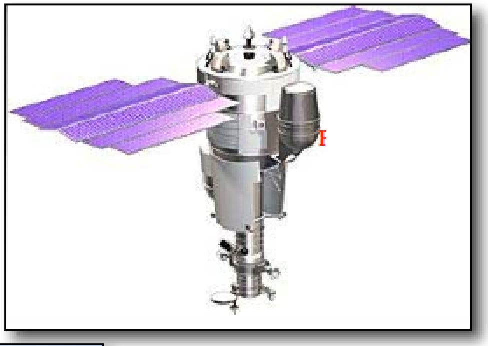


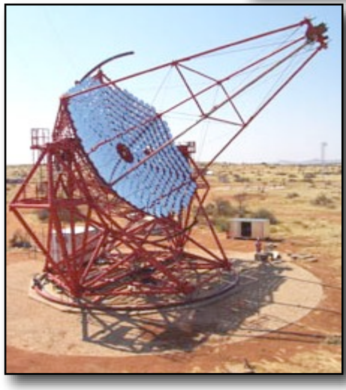


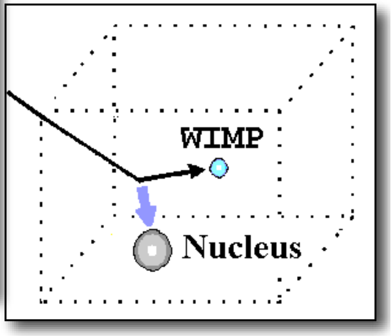
Summary

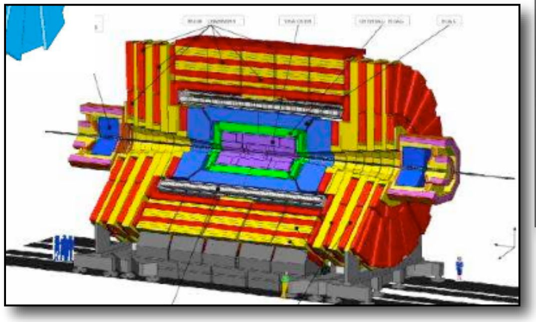
- In addition to searches for dark matter at the LHC, both direct and indirect astrophysical searches are approaching the sensitivities thought to be required to observe dark matter non-gravitationally

- A number of reported signals have been interpreted as possible detections of dark matter (CoGeNT, DAMA, Fermi, Pamela)









Summary

<u>One Year From Now</u>

- New direct detection results from XENON 100, COUPP, and others
- Pamela positron fraction up to 200 GeV? And first data from AMS-02
- More data from Fermi, and more analysis of Fermi data
- Further input from ground based gamma ray telescopes, and observations at other wavelengths