Indirect detection of Dark Matter

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Table of Contents

Table of Contents

Dark matter

- Current cosmological model: ΛCDM
  - Λ: cosmological constant (i.e. dark energy)
  - CDM: cold dark matter (i.e. non relativistic, non baryonic matter)

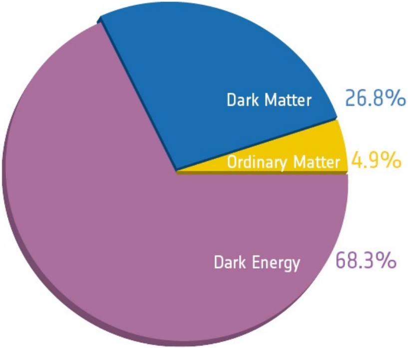

Figure : Results Planck satellite, Copyright: ESA

Indications for dark matter

- Velocity dispersion galaxies in clusters
- Rotation curves galaxies

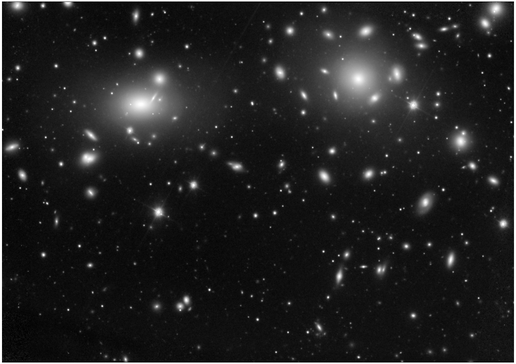

Figure : Copyright S. Moore 2005

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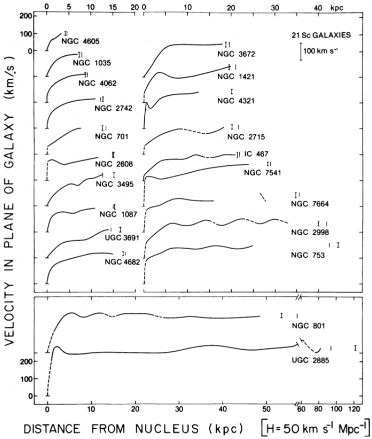

Figure : V. C. Rubin et al. 1979

Indications for dark matter II

- Weak/strong lensing
- Hot gas in clusters
- Bullet Cluster

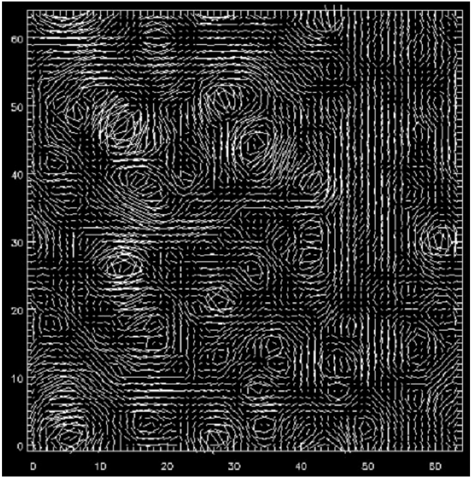

Figure : A. Refregier 2003

Indications for dark matter II

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Figure : Copyright NASA

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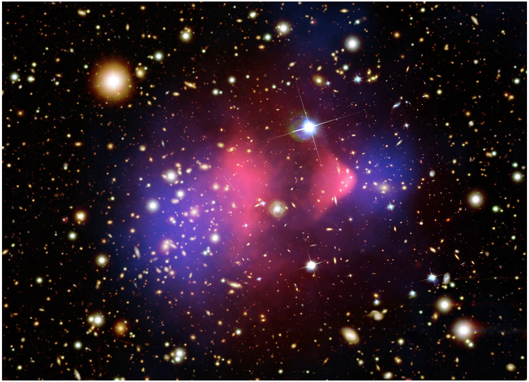

Figure : Copyright NASA

Indications for dark matter III

- Big Bang Nucleosynthesis
- Distant supernovae
- CMB
- Large scale structure

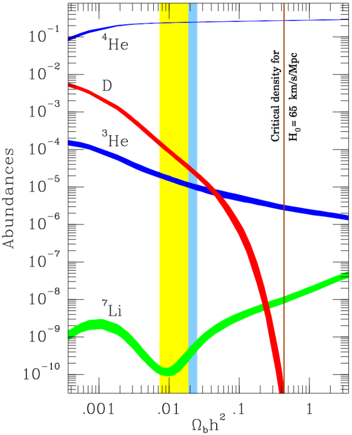

Figure : Schramm & Turner 1998

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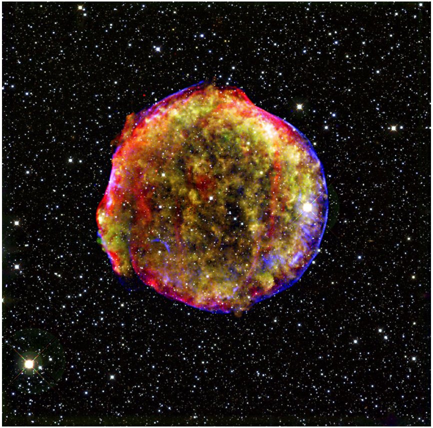

Figure : Copyright Max-Planck-Institut für Astronomie

Indications for dark matter III

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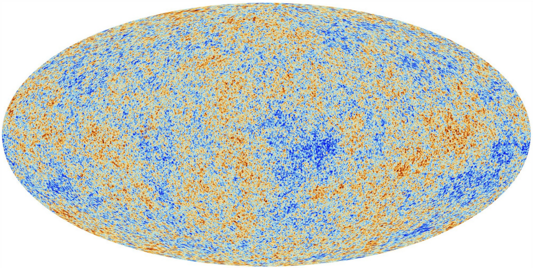


Figure : Copyright ESA and the Planck Collaboration

Indications for dark matter III

- Big Bang Nucleosynthesis
- Distant supernovae
- CMB
- **Large scale structure**

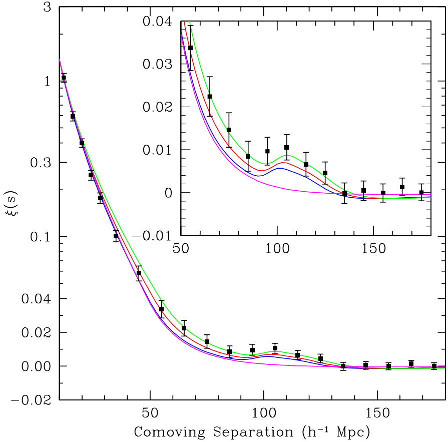


Figure : D. J. Eisenstein et al. 2005

Hot or cold dark matter?

- Power spectrum density perturbations after inflation: $P(k) \propto k^n$
  - $n \sim 1$: Harrison-Zel'dovich spectrum

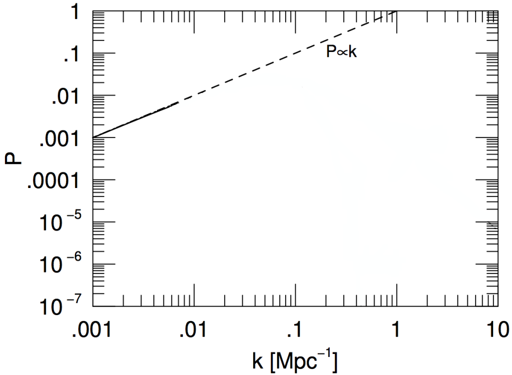


Figure : B. Ryden 2003

Hot or cold dark matter? II

Power spectrum will be changed between inflation and radiation-matter equality ⇒ depends on hot or cold DM

- Consider Hot DM
- Relativistic particles will wipe out any density fluctuation they meet ⇒ *free streaming*
- Particles stay relativistic until t_h
- No fluctuations on scales smaller than $ct_h \Rightarrow \sim 60$ Mpc
- **Mass inside sphere with $r = ct_h$: supercluster mass for particle with $\sim$ eV mass**

Hot or cold dark matter? III

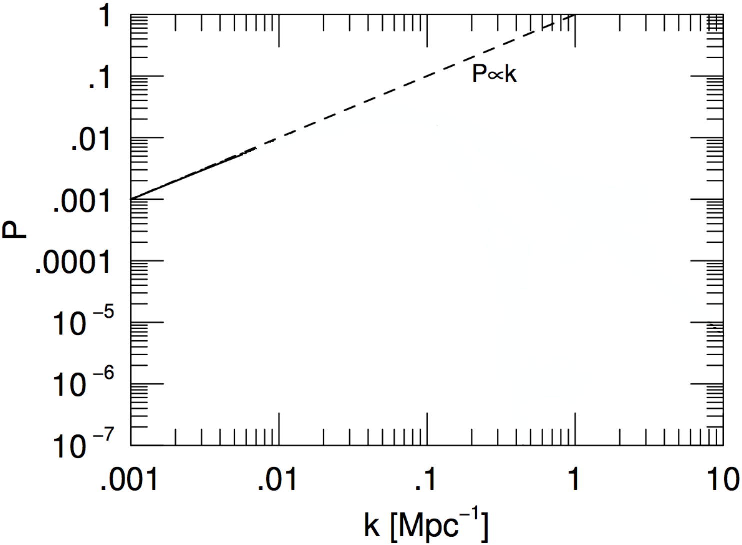
Hot dark matter ⇒ large scale structure formed first

- Fragmentation ⇒ small scale structure
- *Top-down* scenario

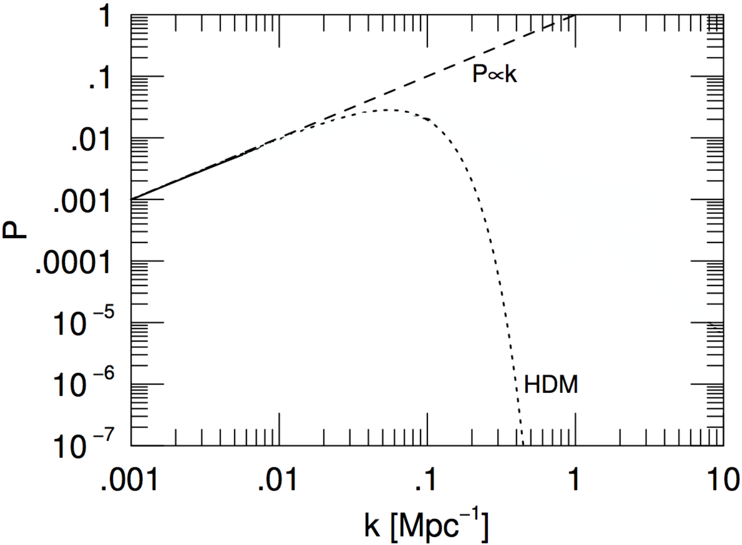
No free streaming with cold dark matter

- **Cold DM ⇒ small scale structures form first**
- *Bottom-up* scenario
- **Consistent with observations**

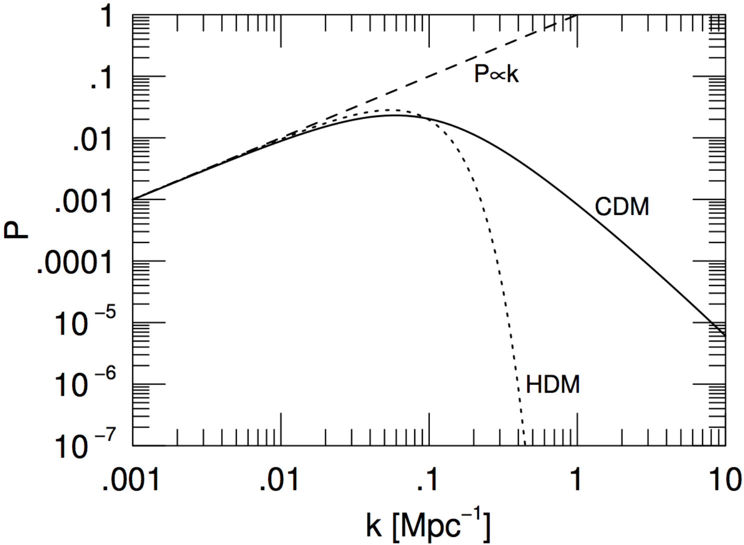
Hot or cold dark matter? IV



Hot or cold dark matter? IV

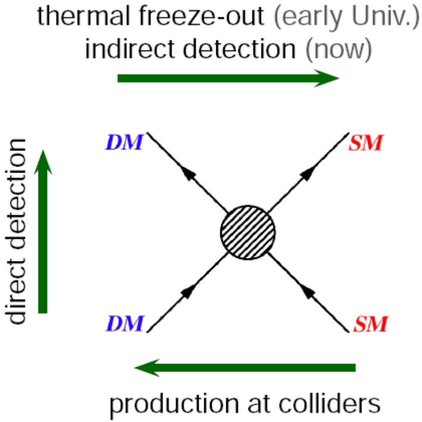


Hot or cold dark matter? IV



Principle of indirect detection

- Indirect detection requires DM self-annihilation
- Try to detect SM particles produced in DM annihilation



Indirect detection methods

Main indirect detection methods:

- Neutrino detection
- Gamma-ray observations
- Radio observations (synchrotron radiation)
- Positron/anti-proton detection

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Hierarchy problem & WIMP miracle

- Gauge hierarchy problem motivates new particles at weak scale
- Needed: stable, weakly interacting massive particle ⇒ WIMP
- **If stable WIMP exists, it is naturally produced with a relic density needed to explain DM ⇒ WIMP miracle**

Hierarchy problem & WIMP miracle

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Boltzmann equation

Early universe → all particles in thermal equilibrium

- Generic WIMP scenario: $X\ X \leftrightarrow \ell\ \ell$
- Governed by Boltzmann equation:

$$\frac{1}{a^3}\frac{d(n_X a^3)}{dt} = n_{X,0}^2 < \sigma v > \left(\frac{n_\ell^2}{n_{\ell,0}^2} - \frac{n_X^2}{n_{X,0}^2}\right)$$

($n_{X,0}$, $n_{\ell,0}$: equilibrium densities)

- Reaction rate large compared to expansion
  $\Rightarrow$ Abundance $X \propto e^{-m/T}$

Boltzmann equation II

If $X\ X \leftrightarrow \ell\ \ell$ stays in equilibrium:

- WIMP abundance suppressed by $e^{-m/T}$
- No WIMPs left today

However, as universe expands:

- Probability of WIMPs finding each other to annihilate drops
- Reaction freezes out
- Relic abundance of WIMPs

Boltzmann equation III

Assume:

- ℓ tightly coupled to cosmic plasma ($n_{\ell,0}=n_\ell$)

$$\frac{1}{a^3}\frac{d(n_X a^3)}{dt} = < \sigma v > \left(n_{X,0}^2 - n_X^2\right)$$

- Radiation dominated universe ($T \propto a^{-1}$)

Differential equation can be numerically solved

Boltzmann equation IV

$$\lambda = \frac{m^3 <\sigma v>}{H(m)}$$

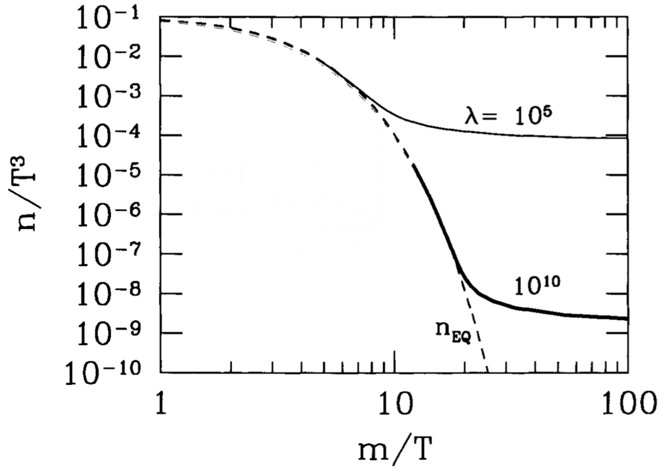


Figure : S. Dodelson 2003

Boltzmann equation V

- Larger cross section ⇒ in equilibrium longer ⇒ lower relic density
- X and ℓ fell out of equilibrium at $T \sim m_X$
  - Use this as boundary condition to obtain current relic density
- Relic density insensitive to WIMP mass
- Relic density known from experiments ⇒ cross section can be determined

Crossection

$$\Omega_X = 0.3h^{-2}\left(\frac{x_f}{10}\right)\left(\frac{g_*(m)}{100}\right)^{1/2}\frac{10^{-39}\mathrm{cm}^2}{<\sigma v>}$$

- x_f: m/T at freeze-out
- Both x_f and $g_*(m)$, insensitive to m
- $<\sigma x>$ is of order $10^{-39}\ \mathrm{cm}^2$
- Weak scale

Mass + WIMP miracle

WIMP miracle

- Weak scale particles make excellent dark matter candidates

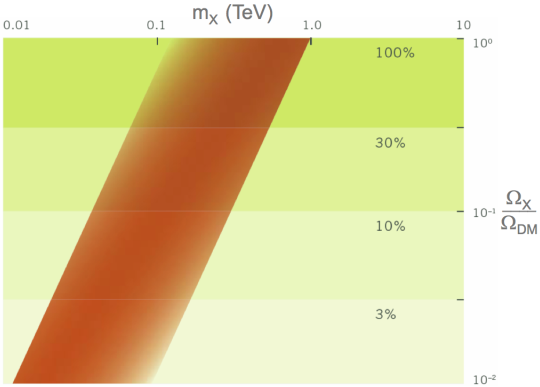
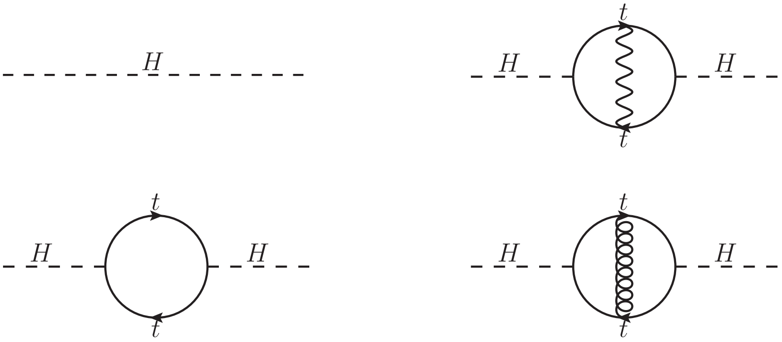


Figure : J. L. Feng 2010

Table of Contents

Gauge hierarchy problem

- Higgs mass has radiative corrections

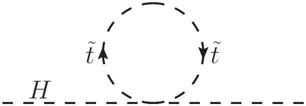


- Radiative corrections are very large compared to bare mass

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2}\int^{\Lambda}\frac{d^4p}{p^2} \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

Fermion boson pairs

- Solve gauge hierarchy problem by introducing supersymmetric partners to Standard Model particles



- Bosonic and fermionic loops compensate each other when particles have equal mass
- SUSY is broken, so still some fine tuning needed:

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2}\left(\int^{\Lambda}\frac{d^4p}{p^2}\bigg|_{\mathrm{SM}} - \int^{\Lambda}\frac{d^4p}{p^2}\bigg|_{\mathrm{SUSY}}\right) \quad (1)$$

$$\sim \frac{\lambda^2}{16\pi^2}\left(m_{\mathrm{SUSY}}^2 - m_{\mathrm{SM}}^2 \,\mathrm{Ln}\frac{\Lambda}{m_{\mathrm{SUSY}}^2}\right) \quad (2)$$

SUSY fields

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{Q}$	3	2	$\frac{1}{6}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{2}{3}$	$\overline{u}_R$, $\tilde{u}^*_R$
$\hat{D}^c$	$\overline{3}$	1	$\frac{1}{3}$	$\overline{d}_R$, $\tilde{d}^*_R$
$\hat{L}$	1	2	$-\frac{1}{2}$	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	1	$\overline{e}_R$, $\tilde{e}^*_R$
$\hat{H}_1$	1	2	$-\frac{1}{2}$	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	$\frac{1}{2}$	$(H_2, \tilde{h}_2)$

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{G}^a$	8	1	0	g, $\tilde{g}$
$\hat{W}^i$	1	3	0	W_i, $\tilde{\omega}_i$
$\hat{B}$	1	1	0	B, $\tilde{b}$

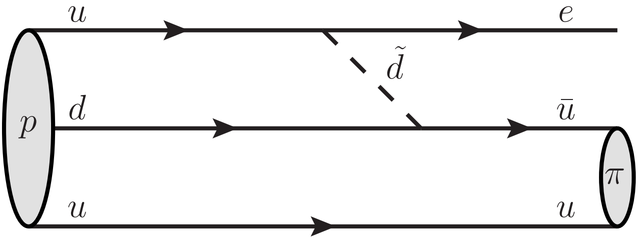
SUSY particles

- 4 charginos: $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$
- 4 neutralinos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$
- In most models $\tilde{\chi}_1^0$ is the lightest supersymetric particle

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	(same) (same) $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \ \widetilde{W}^0\ \ \widetilde{H}_u^0\ \ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \ \widetilde{H}_u^+\ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Proton decay

- SUSY particles do have the same interactions as their SM counterparts
- Superpotential contains lepton and baryon number violating couplings
- $p \rightarrow e^- + \pi^0$
- Proton decay has never been observed



R-parity

- $R \equiv (-1)^{3(B-L)+2s}$
- Multiplicative quantum number, SM particles have R-parity 1, SUSY particles have R-parity -1

particle	B	L	s	$3(B-L)+2s$	R
u	$\frac{1}{3}$	0	$\frac{1}{2}$	2	1
d	$\frac{1}{3}$	0	$\frac{1}{2}$	2	1
$\tilde{d}$	$\frac{1}{3}$	0	0	1	-1
e	0	1	$\frac{1}{2}$	2	1

Extra dimensions

- UED derived from idea originally from Kaluza and Klein
- All SM fields propagate extra compact dimensions
- This leads to an infinite amount of modes for all fields
- At tree level KK-mode is conserved, due to momentum conservation
- Extra dimention must me moded out by an orbifold, leading to violation of KK-number
- All odd-level KK particles are charged under KK-parity
- Lightest KK-particle will be stable

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B^1

- WIMP must be neutral and non-baryonic
- Consider first KK-modes of gauge bosons
- Electroweak symmetry breaking

$$\begin{pmatrix} \frac{n}{R^2} + \frac{1}{4} g_1^2 v^2 + \delta M_1^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{n}{R^2} + \frac{1}{4} g_2^2 v^2 + \delta M_2^2 \end{pmatrix} \begin{pmatrix} B^{(1)} \\ W_3^{(1)} \end{pmatrix}$$

- δM_1^2 and δM_2^2 are small
- $\frac{n}{R}$ is modest
- $\delta M_2^2 > \delta M_1^2$
- $\delta M_2^2 - \delta M_1^2 \gg g_2 g_1 v^2$

- B^1 is lightest KK-particle

Neutralino

- WIMP's are weakly interacting, so final states of annihilation are too
- Neutralino annihilates at tree level to fermion anti fermion pairs and gauge bosons
- Cross section model dependent
- Cross section is expanded in non-relativistic limit:

$$\sigma v = a + b v^2 + \mathcal{O}(v^4)$$

Fermion final states

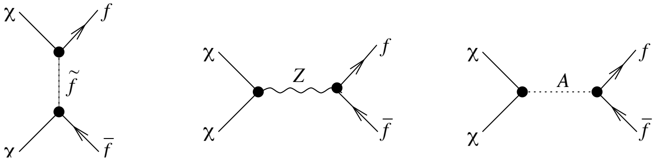


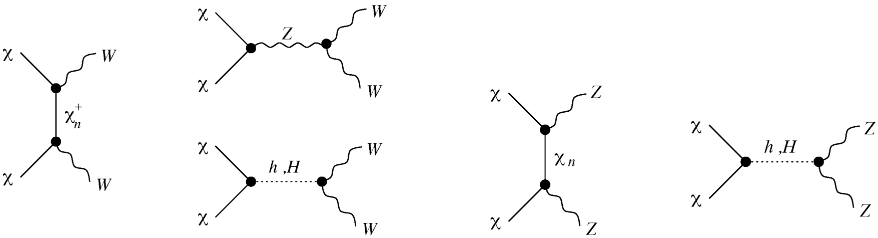
Figure : Jugman et al. 1995

$$\sigma v(\chi\chi \rightarrow \bar{f}_i f_1)_{v\rightarrow 0} = \frac{c_f}{128\pi m_\chi^2}\sqrt{1-\frac{m_f^2}{m_\chi^2}}|\mathcal{A}_A + \mathcal{A}_{\tilde{f}} + \mathcal{A}_Z|^2$$

- $\mathcal{A} \propto m_f$
- $b\bar{b}$ and $\tau^-\tau^+$ dominate
- No neutrinos

Gauge and Higgs boson final states

- $W^+ + W^-$
- $Z + Z$
- $Z + h^0$
- $Z + H^0$
- $W^- + H^+$
- $W^+ + H^-$
- $A + h^0$
- $A + H^0$



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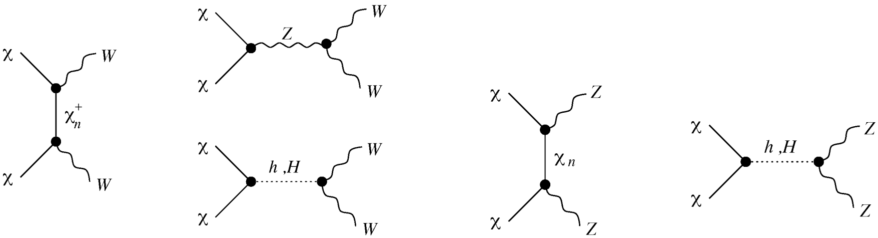

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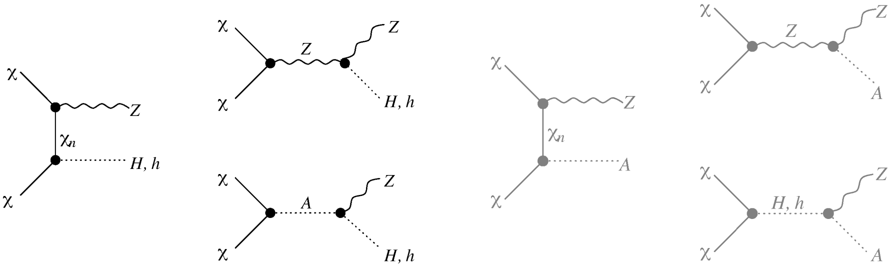

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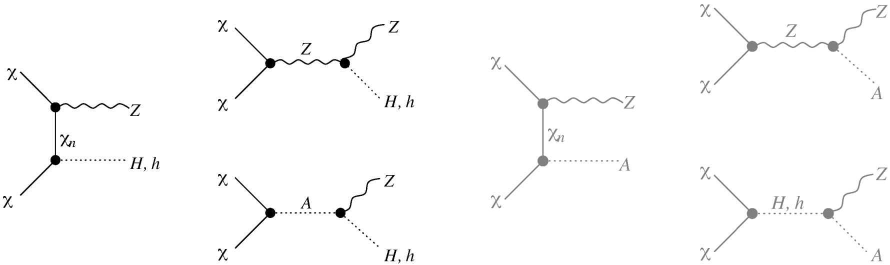

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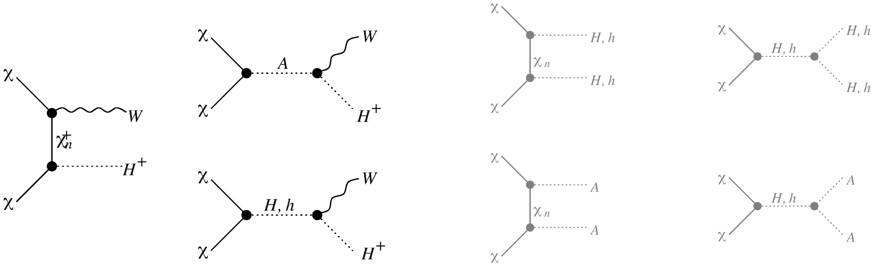

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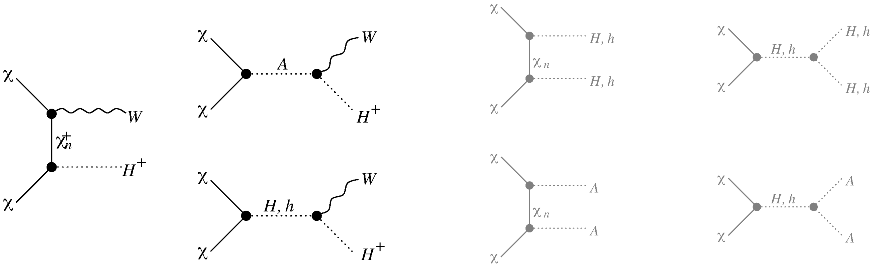

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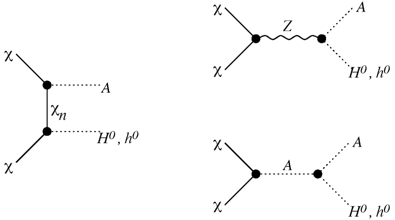

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- $A + H^0$

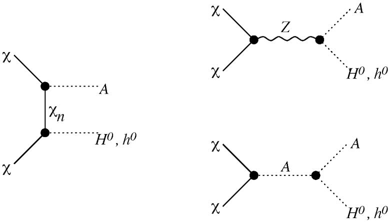

Figure : Jugman et al. 1995

Photon final states

- Neutralino does not react electromagnetically
- No tree level diagrams for photon final states
- Loop diagrams are highly suppressed
- Photon final states are interesting because they can give lines
- Both $\gamma + Z$ and $\gamma + \gamma$ final states of importance
- Cross section highly dependent on SUSY parameters

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γ γ loops

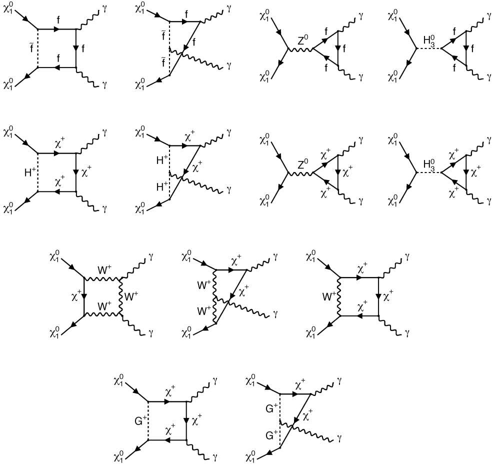


Figure : L. Bergstrom, P. Ullio, 1997

γ Z loops

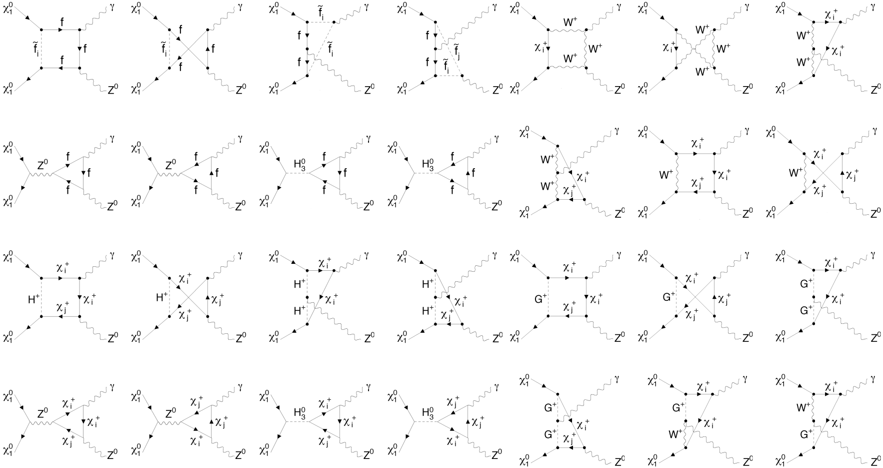


Figure : L. Bergstrom, P. Ullio, 1997

Kaluza-Klein

- Branching ratios at tree level independent of mass
  - 35% quark pairs
  - 59% charged lepton pairs
  - 4% neutrino pairs
  - 2% Higgs bosons
- Much less model dependent
- Photons also appear in loops
- B^1 has more mass, so photons are more energetic

Summary first half

- There are a lot of indications for Dark Matter
- Dark matter needs to be "cold" and stable
- WIMPS with a mass between 100 GeV and 1 TeV lead to good Dark matter density
- Supersymmetry and UED lead to stable weakly interacting dark matter candidates
- Annihilation of $\tilde{\chi}_1^0$ and B^1 differs
- No direct annihilation to photons

Table of Contents

Amplifiers

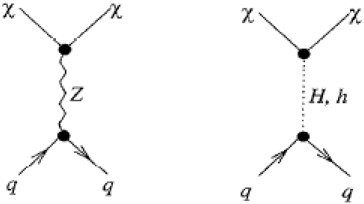
- Increased DM density
- Galactic Center, Sun, Earth...
- Strength depends on mass and particle density
- Sun appears to be ideal, Earth not so much

Capture

- WIMPs pass through the Sun
- Very small, but finite possibility of scattering on SM-particle
- If $v_{after} < v_{esc}$, WIMP is captured

Capture

- $C_{SD}^{\odot} \simeq 3,35 \cdot 10^{20} \rho_{local} v_{local}^{-3} m_{DM}^{-2} \sigma_{H,SD}$
- $C_{SI}^{\odot} \simeq 1,24 \cdot 10^{20} \rho_{local} v_{local}^{-3} m_{DM}^{-2} \left(\sigma_{H,SI} + \sigma_{He,SI}\right)$
- Appear to be comparable, but for most models σ_{SD} is a couple orders of magnitude larger than σ_{SI}



Left: Spin-dependent scattering through Z-boson exchange.
Right: Spin-independent scattering through Higgs-boson exchange

Annihilation

- If ρ_{WIMP} becomes high enough → amplifier
- WIMP annihilation becomes significant, producing SM particles
- What is the annihilation rate?

Annihilation

- If there are $N(t)$ WIMPs in the Sun, we get $\frac{dN}{dt} = C^{\odot} - A^{\odot} N^2$
- $A^{\odot} = \frac{<\sigma v>}{V_{eff}}$, averaged cross-section times velocity of WIMPs
- Annihilation rate $\Gamma = \frac{1}{2} A^{\odot} N^2$, because at annihilation two particles disappear
- Solving the differential equation for N, we get

$$\Gamma = \frac{C}{2} tanh^2 \left(\frac{t}{\tau} \right)$$

where $\tau = \frac{1}{\sqrt{AC}}$

Neutrinos

- Neutrinos are well known: neutral leptons with very small (but nonzero) mass
- Abundantly produced in nuclear reactions in the Solar core
- Sun is opaque to photons, but transparent to neutrinos
- Earth transparent as well

Neutrino vs. Neutrino

- We already receive lots of neutrinos from the solar nuclear fusion
- Energies
- Solar neutrinos have $E \sim MeV$, DM neutrinos have $E \sim GeV$

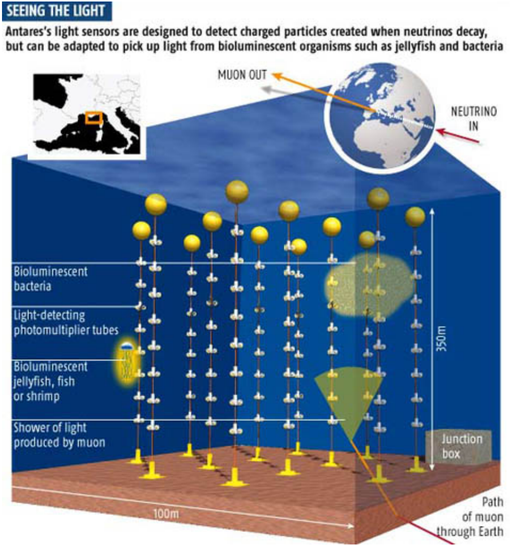
Detection

- Decay into charged leptons
- Cherenkov effect → detection
- Background from cosmic rays (directly), atmospheric neutrinos (induced by cosmic rays) and bioluminosity
- Partial solution: only measure upward flux

Experiments

- ANTARES
- ICECUBE
- Super Kamiokande
- All based on Cherenkov, so different set-up, identical principle

Experiments



Results

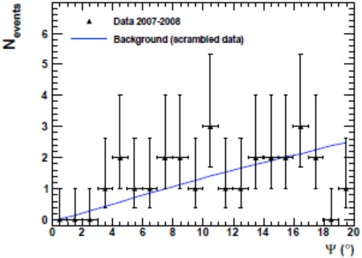


Figure 4. Differential distribution of the angular separation Ψ of the event tracks with respect to the Sun's direction for the expected background (solid blue line) compared to the data (black triangles). A 1σ Poisson uncertainty is shown for each data point.

Figure : arXiv: 1302.6516v1

Results

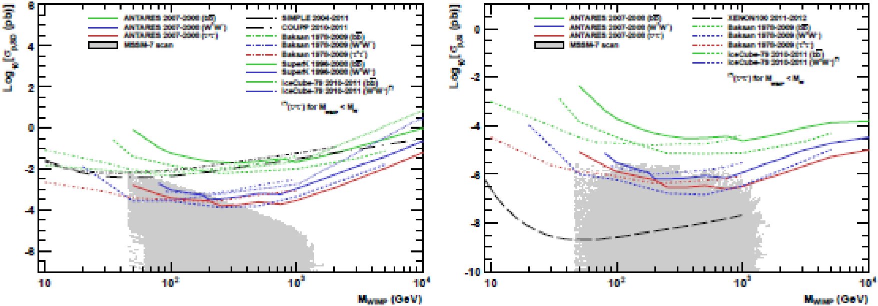


Figure : arXiv: 1302.6516v1

Conclusions

- Until now, exclusively null results
- Constraints on model parameters
- Further research may lead to stronger constraints, discoveries or rejection?

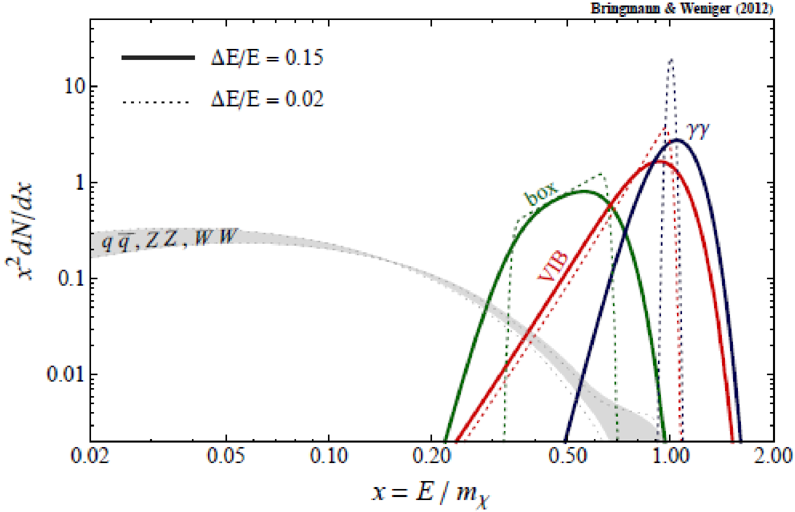
Table of Contents

Production of Gamma Rays

Production mechanisms:

- $\chi + \chi \to X + \gamma$
  - Produces a line at $E_\gamma = m_\chi(1 - \frac{m_X^2}{4m_\chi^2})$
- $\chi + \chi \to \gamma + \gamma$
  - Produces a line at $E_\gamma = m_\chi$.
- $\chi + \chi \to q\bar{q}, W^+W^-, ... \to \gamma + X$
  - Produces a broad spectrum of photons
- Internal Bremsstrahlung

Spectrum


Bringmann & Weniger (2012)
ΔE/E = 0.15
ΔE/E = 0.02
10
1
0.1
0.01
$x^2 dN/dx$
$q\,\bar{q}$, ZZ, WW
box
VIB
γγ
0.02
0.05
0.10
0.20
0.50
1.00
2.00
$x = E / m_\chi$

Production of Gamma Rays

- **Direct production**
  Occurs only through higher order loops, branching fraction $10^{-4} - 10^{-1}$
- **Indirect production**
  Occurs more often, difficult to distinguish from background/cosmic rays.

Line observation would be 'smoking gun' for WIMP DM!

Observed Flux

Flux from annihilation:

$$\Phi_\gamma^{DM} = \frac{1}{4\pi}\frac{\langle\sigma\nu\rangle}{m_\chi^2}\frac{dN_\gamma}{dE}\int_{los}\rho^2 ds$$

Depends on:

- WIMP mass and cross section
- DM distribution along line of sight
- Energy distribution $\frac{dN_\gamma}{dE}$, related to production mechanism

Expectations

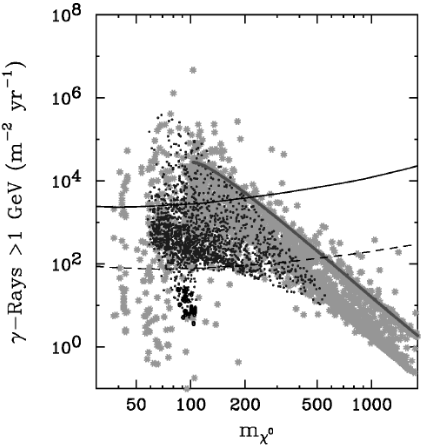


Figure : G. Bertone, 2004

Where to look?

- **Galactic center**
    - High concentration of DM expected
    - Lot of other gamma ray sources
- **Dwarf Galaxies**
    - Low background and high DM concentration
    - Weak signal
- **Galactic Halo**

Experiments

For example:

- EGRET
    - Excess above 1 GeV
- Cherenkov telescopes
- Fermi-LAT
    - Line around 130 GeV detected

Fermi-LAT

- Launched in 2008
- Gamma ray detector (pair conversion)
- Covers energy range from 20 MeV up to 300 GeV

Figure : http://www-conf.slac.stanford.edu/fermiLAT

130 GeV line

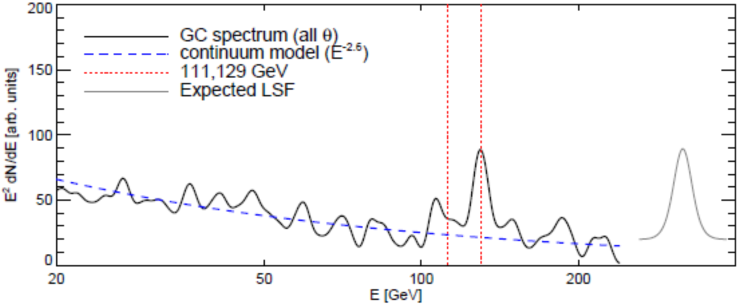


Figure : Su,Finkbeiner, 2012

- Significance $4.5 - 6.5\sigma$
- 1.5° left of Galactic Center
- correspond with $\langle \sigma\nu \rangle = 1.27 \pm 0.32 \cdot 10^{-27} cm^3 s^-$ and $m_\chi = 129.8 \pm 2.4\text{GeV}$

130 GeV line

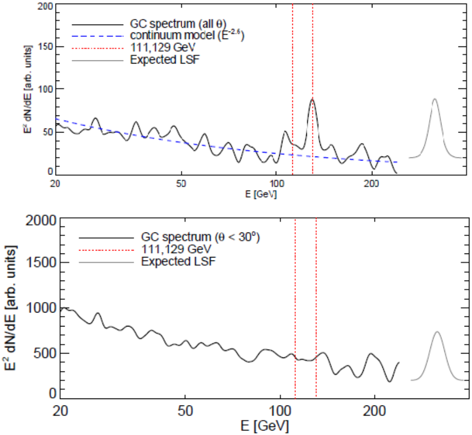


Figure : Su, Finkbeiner, 2012

New Data

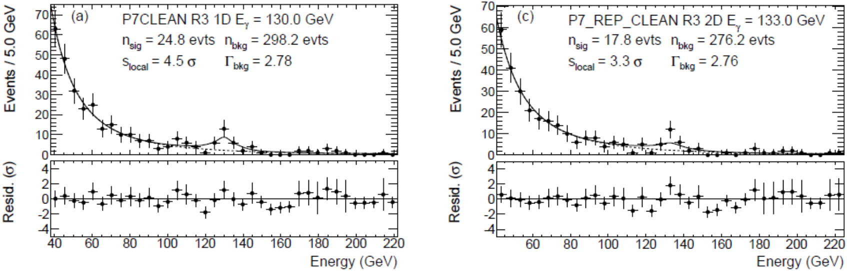


Figure : arXiv:1305.5597v2

- new data and analysis caused significance to drop to 3.3σ

New Data

- Line also observed in control region near earth
- But not in other control regions

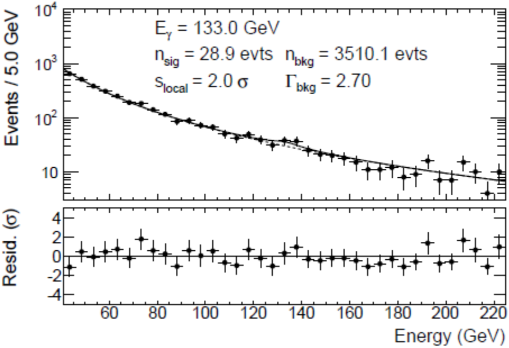


Figure : arXiv:1305.5597v2

Fermi bubbles

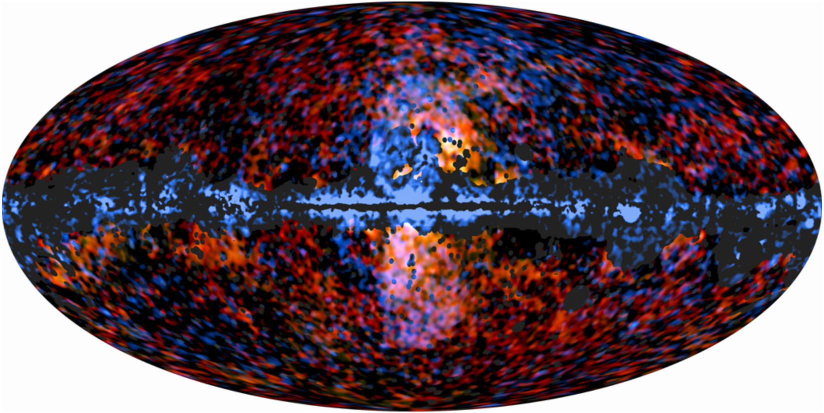


Figure : http://planck.cf.ac.uk/

Summary

- Gamma rays could carry a lot of spectral and spatial information about DM.
- Few interesting observations made.
- No clear DM signal so far.

Table of Contents

Indirect detection using charged particles

- Dark matter annihilations produce matter and antimatter
- Stable particles: $e^{\pm}$, p^{+}, $\bar{p}^{-}$
- Charged
- Detection:
  - Synchrotron radiation
  - Cosmic rays

Detection using synchrotron radiation

- Annihilation to charged particles in high magnetic field
- Need high magnetic field and high DM concentration
  - Galactic Center, dwarf galaxies
- Observations at radio wavelengths

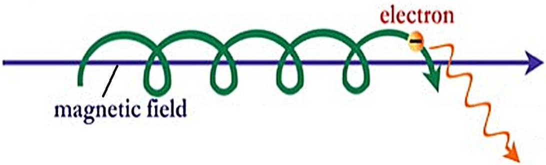


Figure : www.astro.wisc.edu

Detection using synchrotron radiation

- Depends on assumptions of mass profile and magnetic field
- Very low background
    - Example: M31

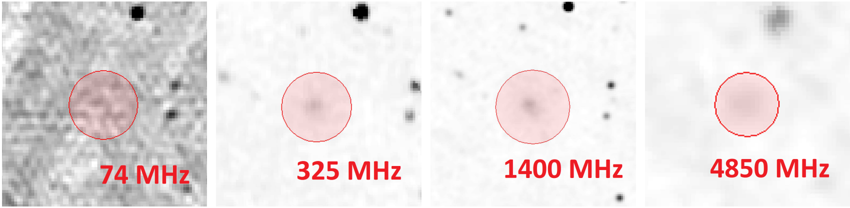


Figure : A. E. Egorov and E. Pierpaoli, 2013

Synchrotron constraints

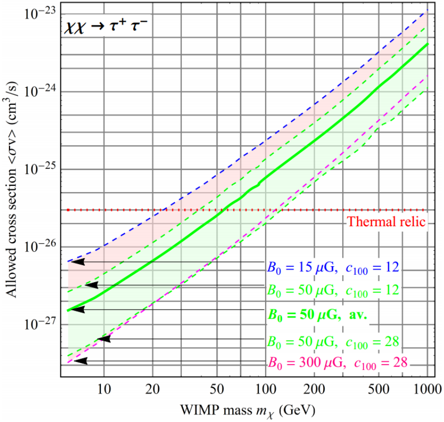


Figure : A. E. Egorov and E. Pierpaoli, 2013

Detection of charged cosmic rays

What to look for?

- DM annihilations produce matter and antimatter
- Ordinary matter: lot of background
- Excess in antiparticle flux or antiparticle ratio
  - $\eta_{\bar{p}}(E) \equiv \phi_{\bar{p}}/(\phi_p + \phi_{\bar{p}})$

Detection of charged cosmic rays

What are the complications?

- Particles are charged
    - Magnetic fields change direction
    - Interactions cause energy loss/gain
    - Particles travel finite distance ($e^{\pm}$: $\lesssim 1$ kpc)
- Background: cosmic ray interactions with interstellar medium
- Monte Carlo simulations
    - Magnetic fields
    - Known sources

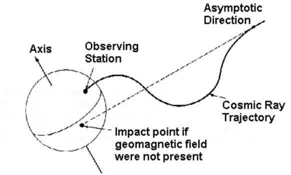


Figure : neutronm.bartol.udel.edu

Detection of charged cosmic rays

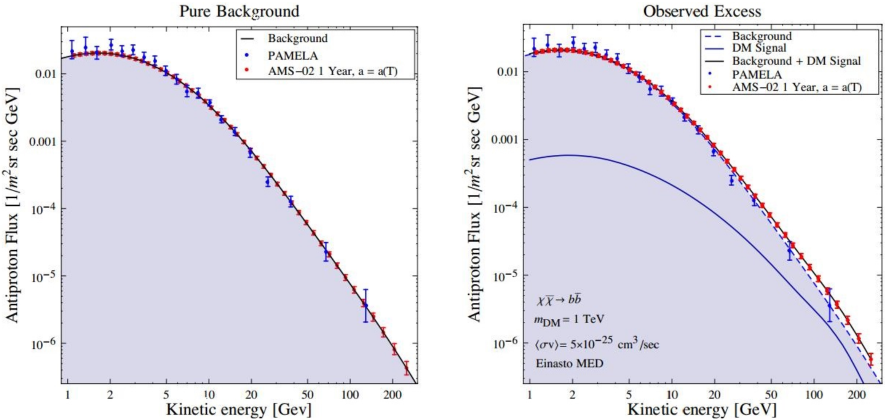
How do we measure them?

- Determine charge, mass, energy
  - Magnetic spectrometers
- Need spaceborne detectors (AMS-02, PAMELA, Fermi-LAT)
- AMS-02 will measure for 20 years

Figure : NASA

Antiprotons

- Anitproton flux measured using PAMELA and AMS-02
- No excess; constraints (blue line: example 95 % CL)



Positrons

- Positron ratio measured
- Excess at higher energies (‘second bump’)
- Is this DM detection?

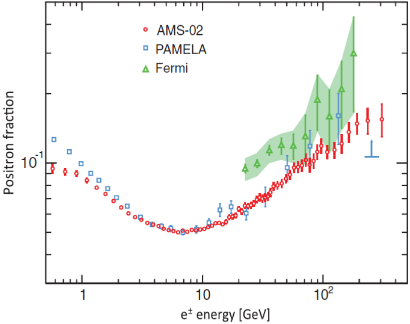


Figure : AMS Collaboration, 2013

Positrons

- Signal actually *too large*
- Need a boost for annihilation into leptons
  - Sommerfeld enhancement
  - Dark force-carrier ϕ
  - Boost cross-section $\sim$100-1000

Other sources

- Astrophysical sources suggested
- Calculated example: white dwarf pulsars
- ‘Less exotic’ then DM and dark force carrier
- Other experiments almost exclude DM source

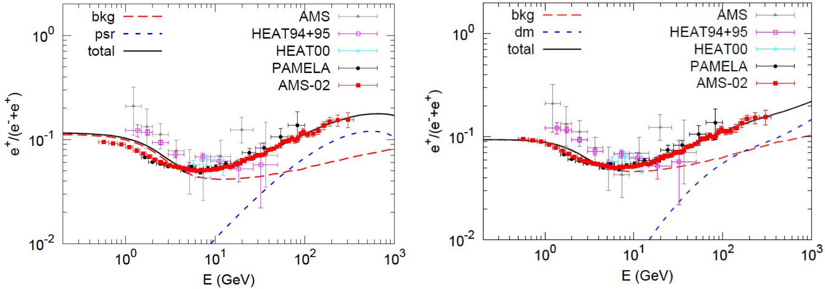
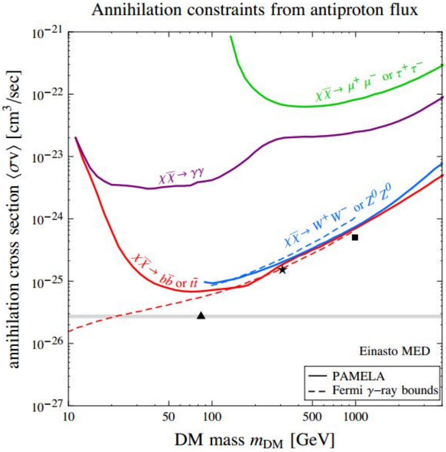


Figure : Q. Yuana et al., 2013

Conclusion

- Different experiments ongoing
    - Neutrinos: no signal
    - Gamma rays: signal, but probably nothing
    - Radio waves: no signal
    - Antiprotons: no signal
    - Positrons: signal, but probably something else
- No signal *yet*, all probing parameter space!

Antiproton constraints



Antiproton constraints

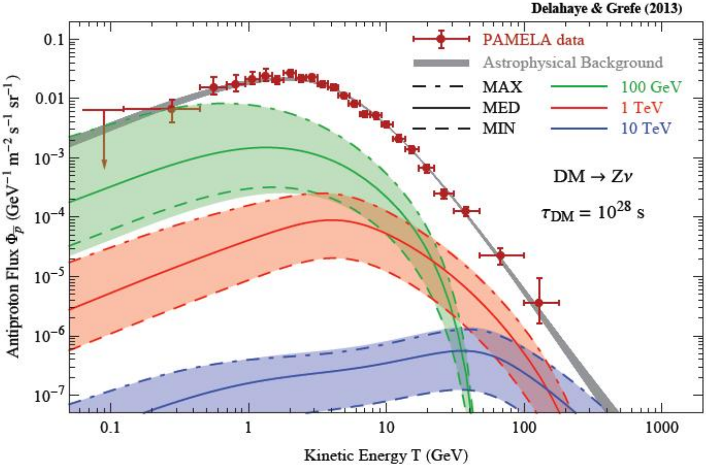
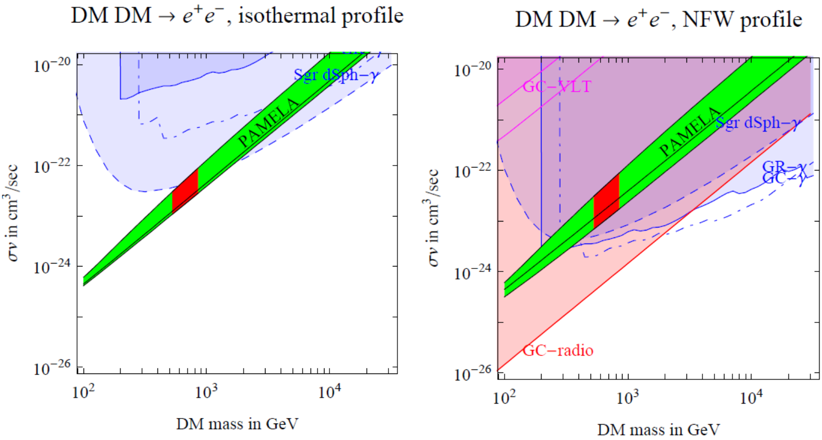


Figure : T. Delahaye and M. Grefe, 2013

Exclusions positron flux


DM DM → e^+e^-, isothermal profile

DM DM → e^+e^-, NFW profile

Figure : G. Bertone et al., 2009