Dark matter detection

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- WIMPs

  Motivation

  Detection — directly, indirectly, colliders } principals, current status, practicalities, future prospects

- Other DM candidates (briefly if time permits)

  axions

  sterile neutrinos

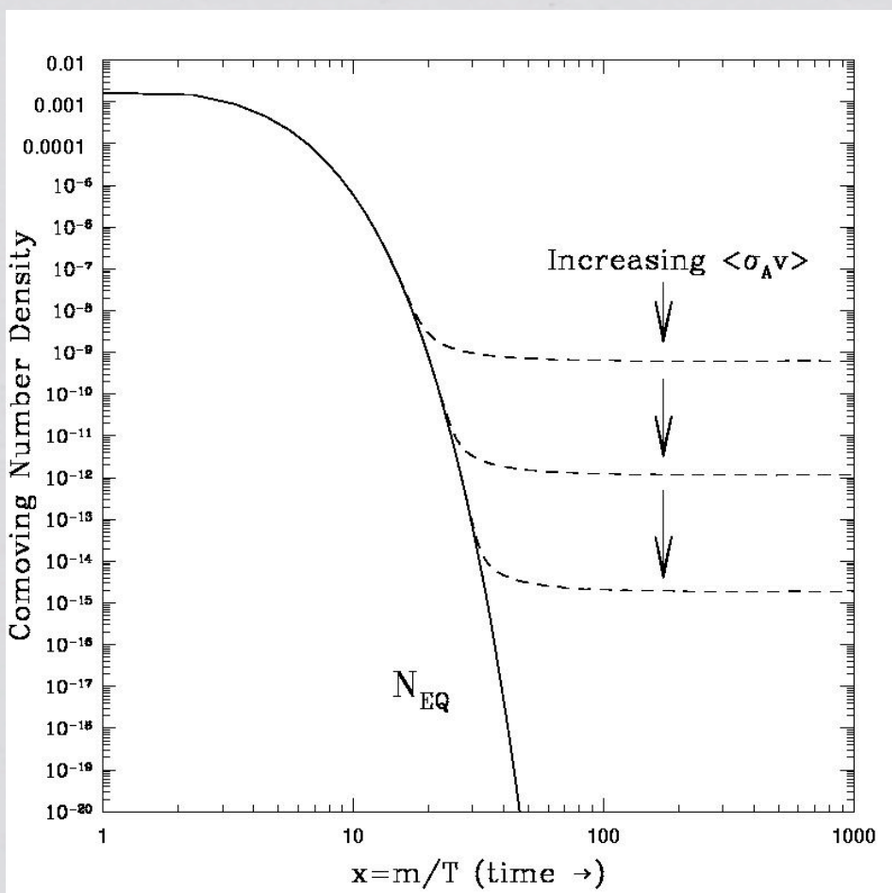
WIMPs: generic motivation

Lee & Weinberg; Gunn et al.; Steigman et al.; Eliis et al.; Kolb & Turner; Scherrer & Turner; Griest & Seckel

Any stable Weakly Interacting Massive Particle in thermal equilibrium in the early Universe will have an interesting present day density:

$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_c} \sim \mathcal{O}(1)$$

comoving number density v. time



$$\chi + \chi \leftrightarrow X + \bar{X}$$

'Freeze-out' (chemical decoupling) occurs when:

$$\Gamma = n_\chi \langle \sigma_A v \rangle \sim H$$

$$\Omega_\chi h^2 \approx 0.3 \left(\frac{10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle} \right)$$

Simple argument:

$$\langle \sigma_A v \rangle \sim \frac{g^2}{m_W^2}$$

If g~0.01 and m_W~100 GeV:

$$\langle \sigma_A v \rangle \sim 10^{-25} \mathrm{cm}^3 \mathrm{s}^{-1}$$

Need an extension to the Standard Model of particle physics which has a stable neutral particle with weak-scale couplings to SM particles.

WIMPs: concrete candidates

i) Supersymmetry (Susy)

e.g. Haber & Kane

Every standard model particle has a supersymmetric partner with mass < O(TeV).
(Bosons have a fermion spartner and vice versa, with suffix 'ino' or prefix 's')

Motivations:

- ✦ Gauge hierarchy problem
  (M_W ~100 GeV << M_{Pl} ~ 10^{19} GeV)
- ✦ Unification of coupling constants
- ✦ String theory

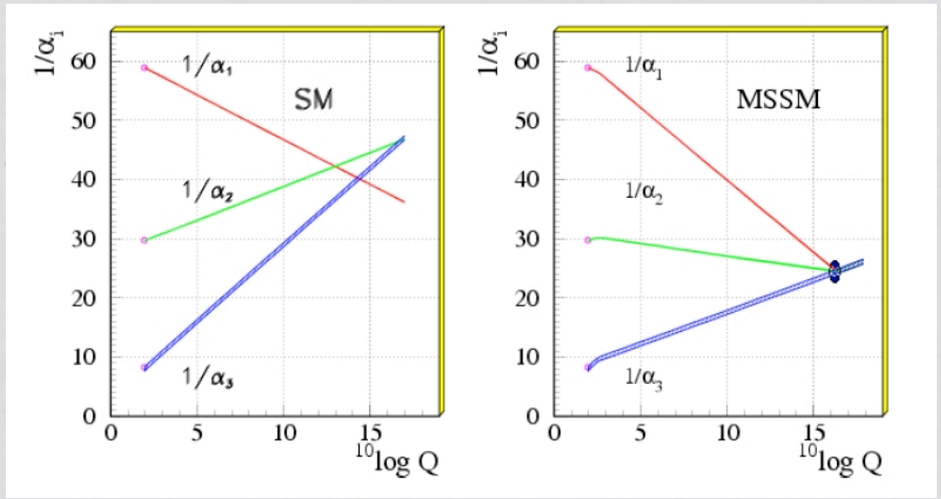


Fig: Kazakov

Conserved quantum number, R-parity (required to prevent decay of proton) renders the lightest supersymmetric particle (LSP) stable.

The LSP is usually (but not always....) the lightest neutralino (mixture of the supersymmetric partners of the photon, the Z and the Higgs). e.g. Ellis et al.

Minimal **S**upersymmetric **S**tandard **M**odel

Minimal supersymmetric extension of the SM.

More than 100 free parameters → for phenomenological studies of experimental signals need to make assumptions which reduce this number.

mSUGRA (constrained **MSSM**)

Assume parameters (couplings and masses) unify at the GUT scale → 5 free parameters.

+ many other models

Parameters constrained by: measured CDM density, collider searches (e.g. anomalous magnetic moment of the muon, b → s γ, flavour changing neutral currents, Higgs searches...)

Various approaches: select representative benchmarks points e.g. Ellis et al.
scan parameter space
Bayesian MCMC analysis e.g. Baltz & Gondolo, Trotta et al., Allanach et al.

ii) Universal Extra Dimensions (UED)

Applequist, Cheng & Dobrescu; Servant & Tait

Compactified extra dimensions and all fields can propagate in the extra dimensions.

Motivations:

- ✦ String theory
- ✦ Gauge hierarchy problem
  (M_W ~100 GeV << M_{Pl} ~ 10^{19} GeV)
- ✦ proton decay, electroweak symmetry breaking

Particles which propagate in the extra dimensions have their momentum quantised → `tower' of Kaluza-Klein states.

Conserved quantum number, KK-parity (to ensure momentum conservation), renders lightest Kaluza-Klein particle (LKP) stable.

The LKP is usually the first excitation of the photon.

How can we detect WIMPs?

Directly

Indirectly

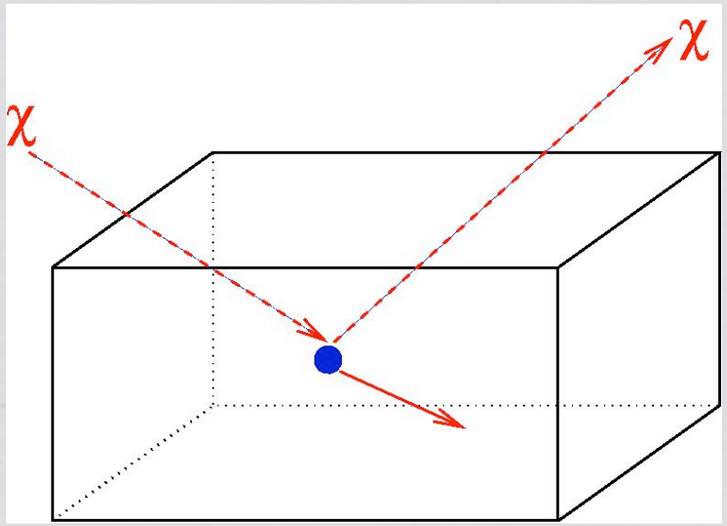
Colliders

WIMPs: direct detection

Goodman & Witten

i) principals

Via elastic scattering on detector nuclei in the lab.



$$\chi + N \rightarrow \chi + N$$

Interaction between WIMP and nucleus can be spin-independent (scalar) or spin-dependent (axial-vector). Most current (and planned future) experiments use heavy targets for which spin-independent coupling dominates.

Differential event rate: (per kg/day/keV)

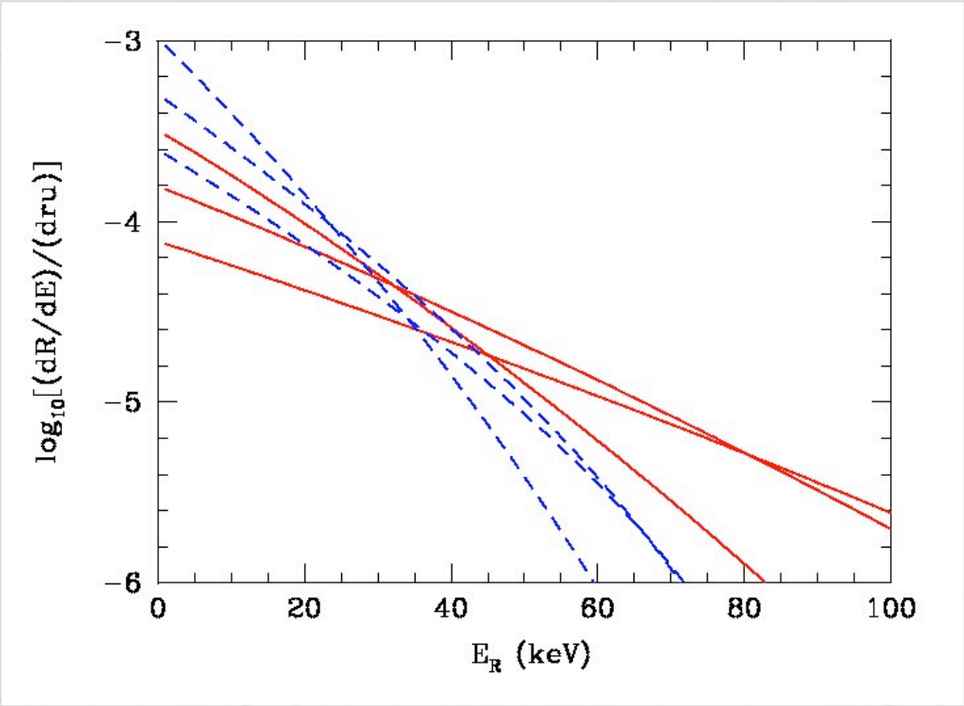
$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_p \rho_\chi A^2 F^2(E) \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v} \mathrm{d}v \qquad v_{min} = \left(\frac{E(m_A + m_\chi)^2}{m_A m_\chi^2} \right)^{1/2}$$

Multiply by exposure (detector mass x running time) to get energy spectrum.

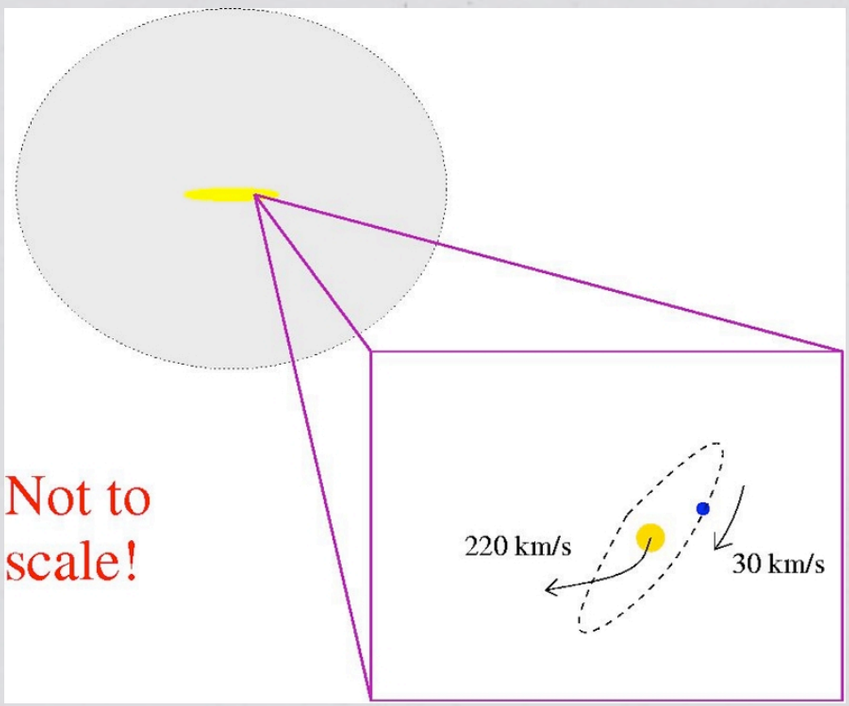
signals:

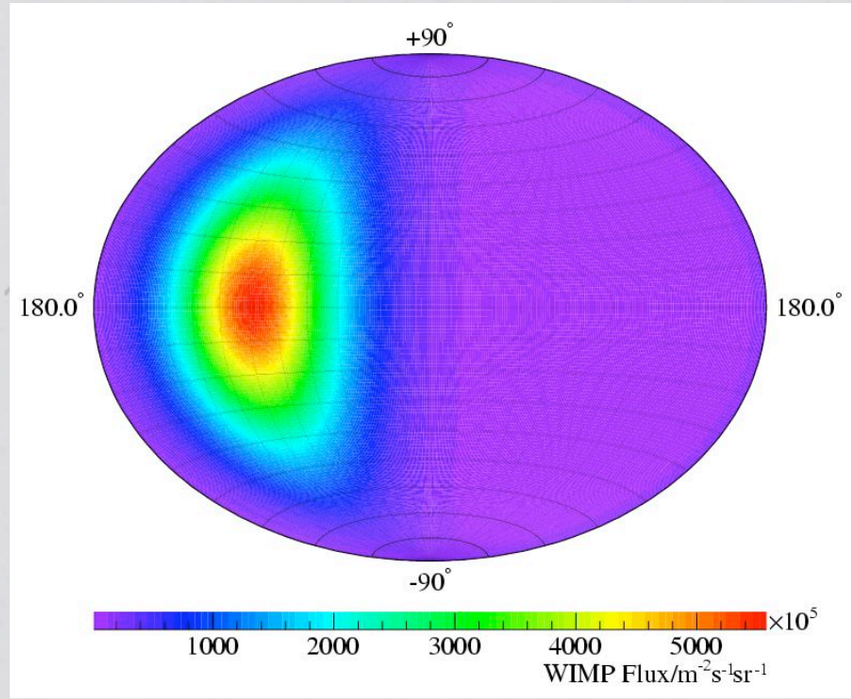
i) A^2 (mass of target nuclei) dependence of event rate Lewin & Smith

Ge and Xe m_χ = 50, 100, 200 GeV



ii) directional dependence of event rate Spergel

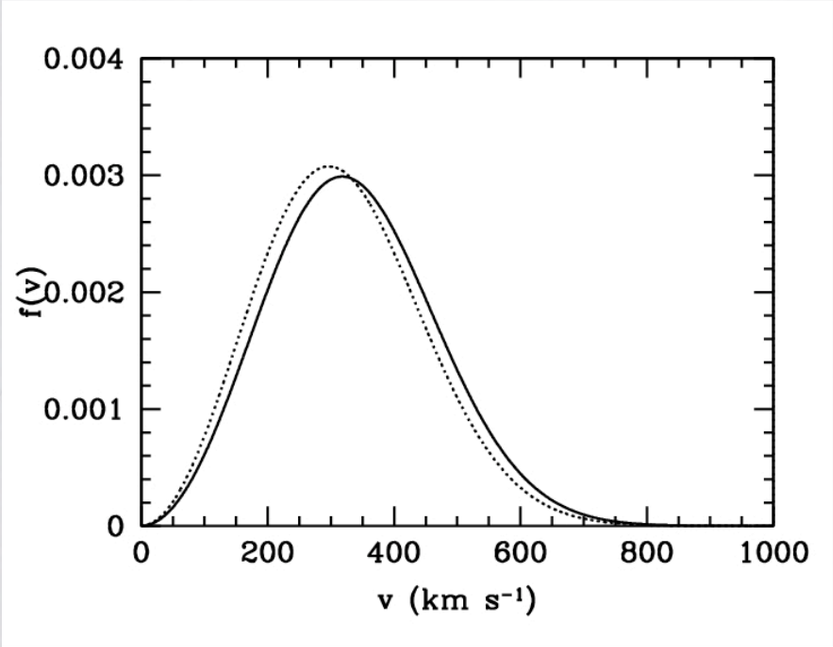




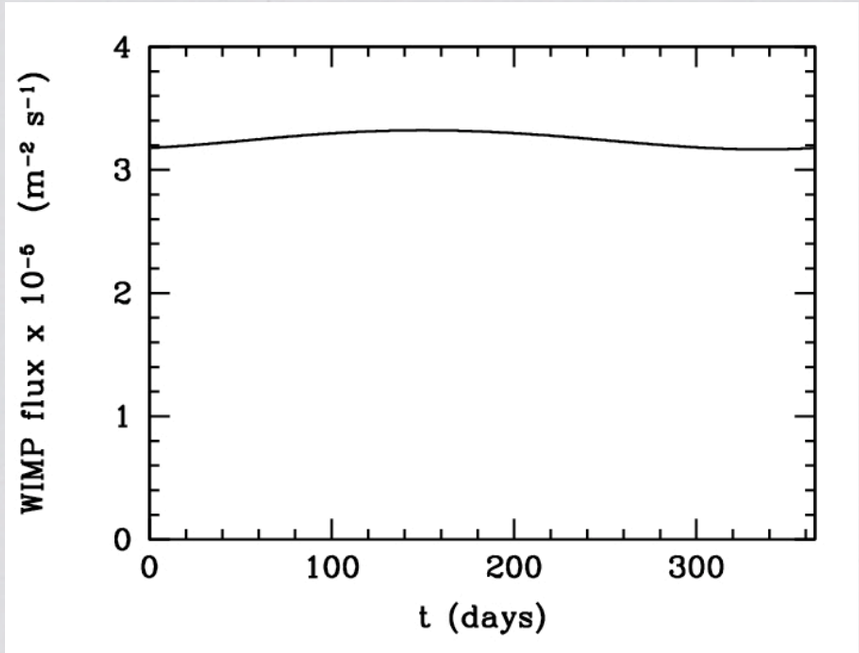
Large signal, but need detector sensitive to recoil directions

iii) annual modulation of event rate

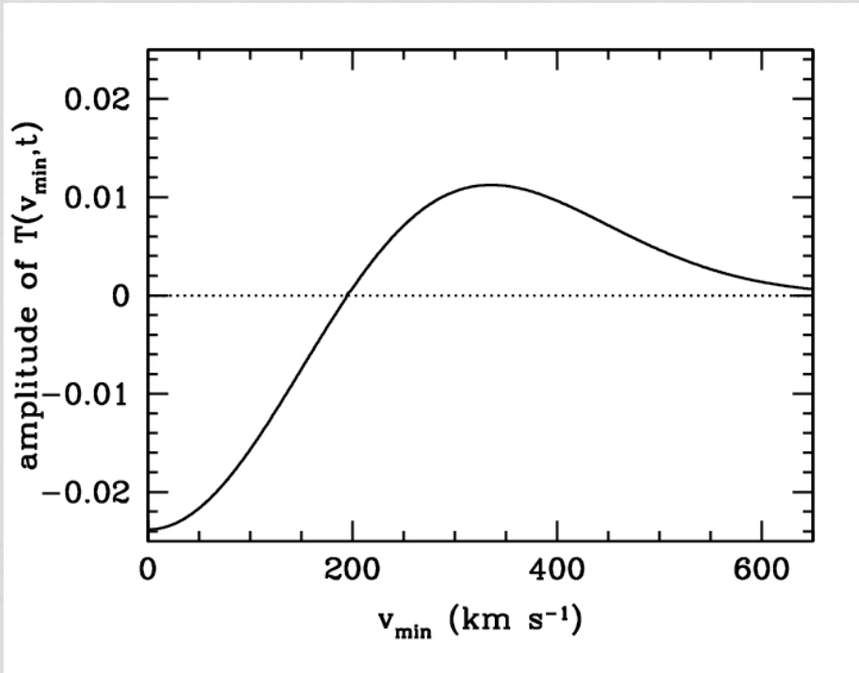
Drukier, Freese & Spergel



WIMP 'standard' (Maxwellian) speed dist.
detector rest frame (summer and winter)



total WIMP flux



modulation amplitude

Signal O(few per-cent),
therefore need large exposure.

ii) practicalities

Experimental issues:

event rate very small

recoil energy small (O(keV))

backgrounds

i) electron recoils due to αs and γs

ii) nuclear recoils due to neutrons from cosmic rays or local radioactivity

Solutions:

large detectors, low energy threshold

use multiple energy deposition `channels' (ionisation, scintillation, phonons) to distinguish electron and nuclear recoils

go underground, use shielding and radiopure detector components

ZEPLIN III
at Boulby mine

Theoretical issues:

Particle physics:

Elastic scattering cross-section on proton can vary by many orders of magnitude, depending on the parameters of the underlying model.

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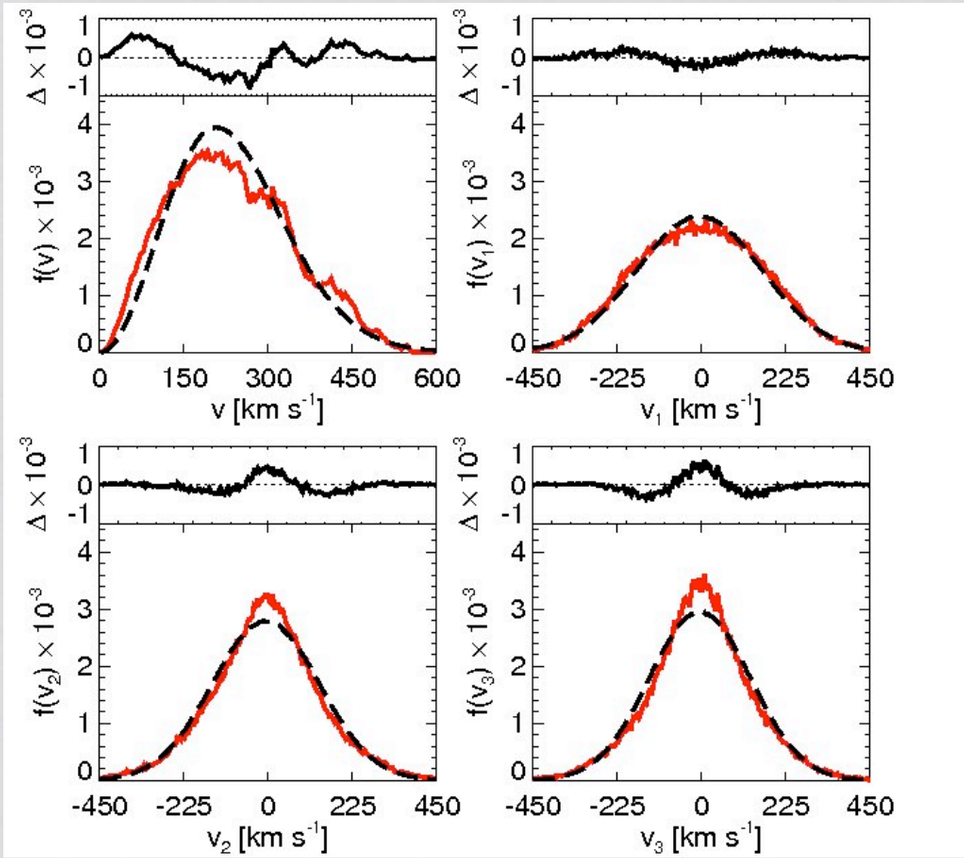
Astrophysics:

Event rate and signals depend on the ultra-local (i.e. sub-milli-pc) WIMP density and velocity distribution (in particular degeneracy between local density and cross-section).

High resolution simulations (e.g. Aquarius, Via Lactea) find velocity distributions which deviate significantly from 'standard' (or multi-variate) Maxwellian distribution:

CAVEAT: scales probed by simulations are many orders of magnitude larger than those probed by direct detection experiments.



Vogelsberger et al.

iii) current status

null-results

spin-independent coupling

- **CDMS**
  Ge, 150 kg-days,
  E_R=5/10 keV
  ionisation & heat

- **Xenon10**
  2-phase Xe, 140 kg-days,
  E_R = 4.5 keV
  scintillation & ionisation

- **Edelweiss**
  Ge, 60 kg-days,
  E_R=13 keV
  ionisation & heat

- **Zeplin III**
  liquid Xe, 847 kg-days,
  E_M = 5 keV
  scintillation & ionisation

- **WARP**
  Ar, 96.5 kg-days,
  E_R=55 keV
  scintillation & ionisation

- **CRESST**
  $CaWO_4$, 20 kg-days,
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- **CoGENT**
  Ge, 8.4 kg-days,
  E_M= 0.23 keV
  ionisation

- **TEXONO**
  Ge, 0.337 kg-days,
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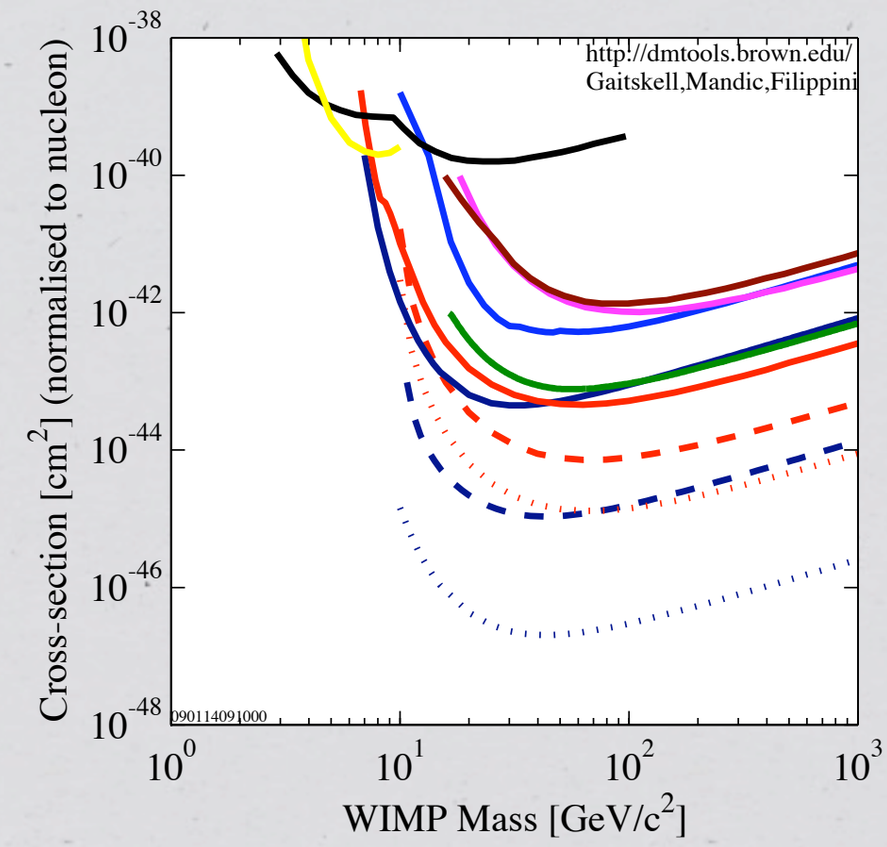
  ionisation



Assuming 'standard' halo model
(Maxwellian speed distribution
local density 0.3 GeV/cm^{-3})

Other experiments (e.g. KIMS, COUPP) sensitive to spin-dependent coupling, but haven't yet reached sensitivity to probe theoretically predicted cross-sections.

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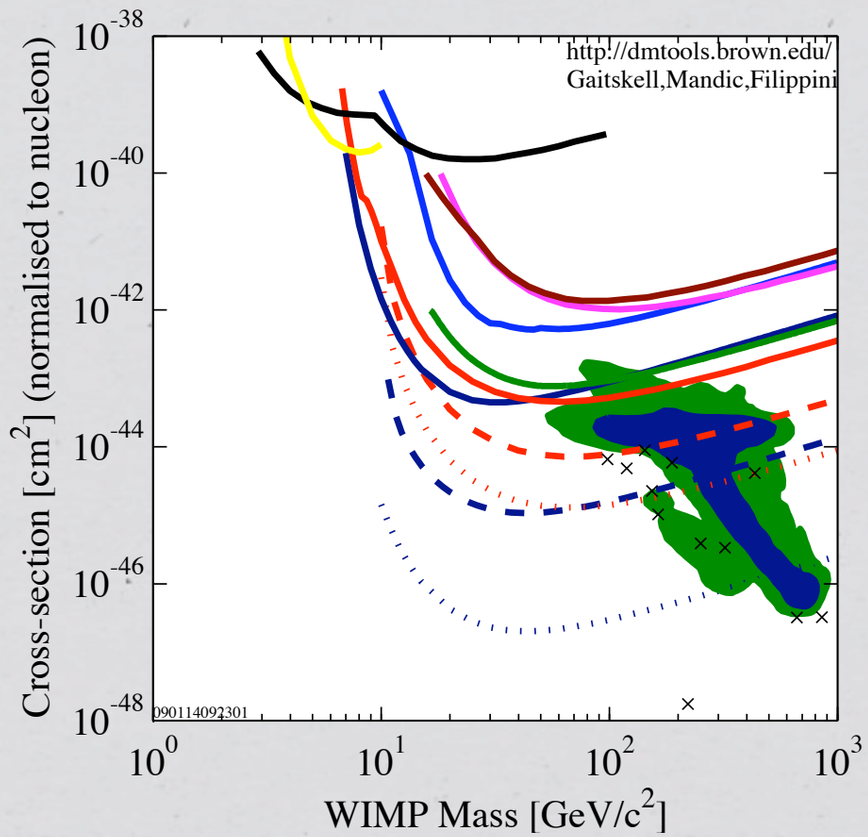


Theory expectations:

Trotta et al., MCMC analysis of CMSSM
Ellis et al., benchmark points

(n.b. other SUSY models can produce much smaller cross-sections)

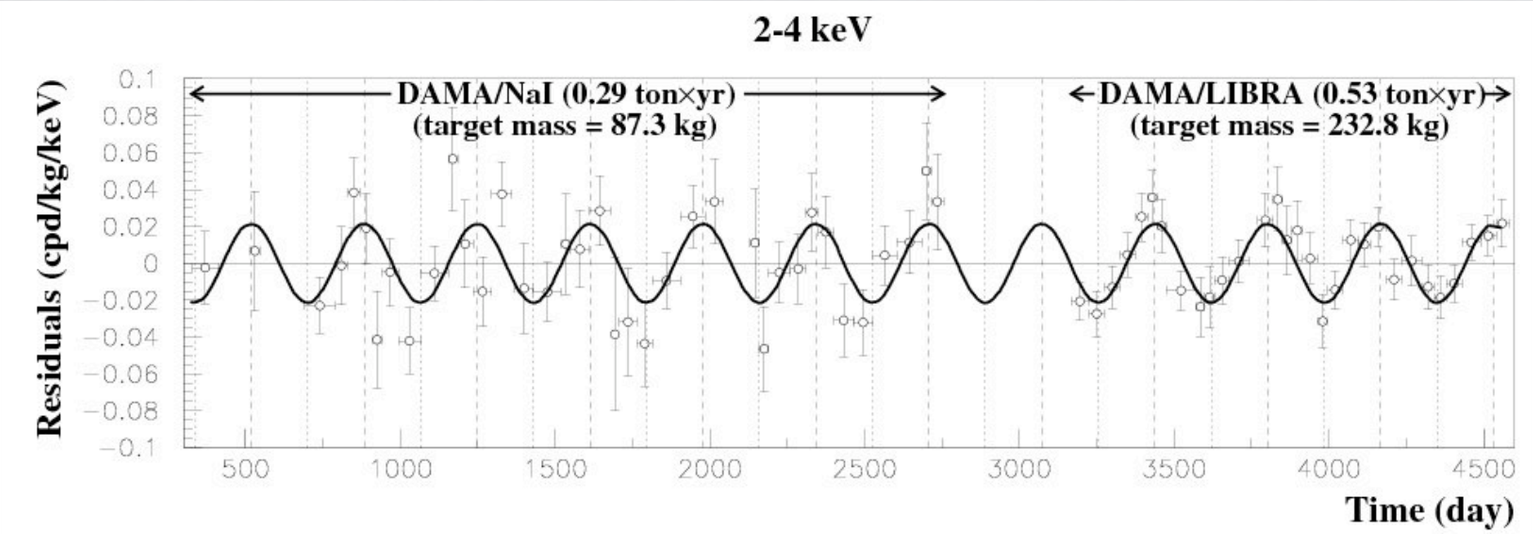
Other experiments (e.g. KIMS, COUPP) sensitive to spin-dependent coupling, but haven't yet reached sensitivity to probe theoretically predicted cross-sections.

DAMA annual modulation signal

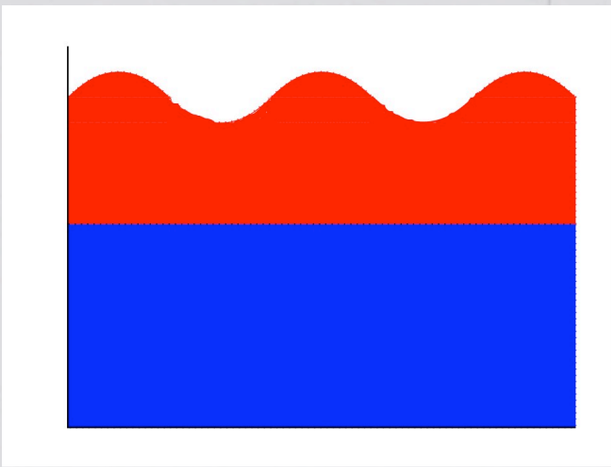
Bernabei et al.

Annual modulation in scintillation pulses in NaI crystals first reported by DAMA in 1998.

New experiment, by same collaboration, DAMA/LIBRA confirms observation of annual modulation at 8.2 sigma, total exposure: 299 000 kg-day.

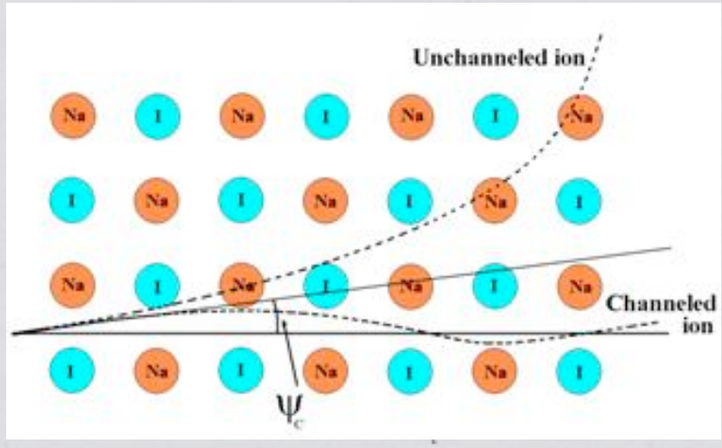


total rate



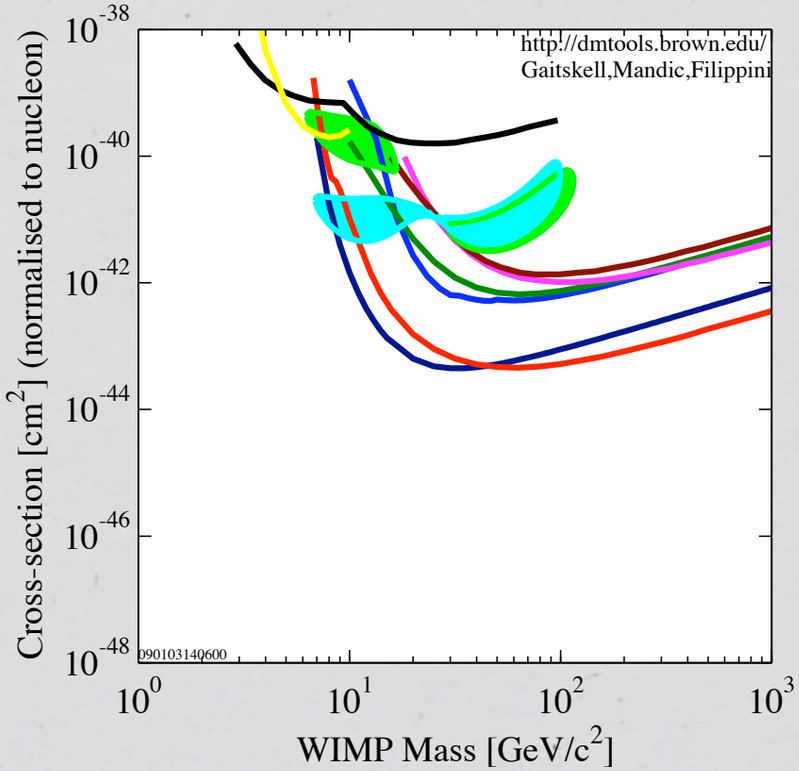
time

Channeling: recoils along crystal axes cause deposit larger fraction of energy to electrons (and recoil energy otherwise over estimated).



If channeling occurs, interpretation of DAMA signal in terms of very light (<10 GeV), but otherwise standard, WIMPs is just compatible with exclusion limits from other experiments.

Petriello & Zurek; Chang, Pierce & Wiener; Fairbairn & Schwetz; Savage, Gelmini, Gondolo & Freese



region of parameter space corresponding to DAMA data with/without channeling as calculated by Savage et al.

Alternative interpretations: inelastic DM

Tucker-Smith & Weiner & collaborators

iv) future prospects

Scale up of current experiments (e.g. SuperCDMS, Xenon) plus new experiments (e.g. EURECA, LUX).

tonne scale detectors, sensitive to large fraction of parameter space populated by theoretical models

with convincing detection(s) could measure the WIMP mass and cross-sections and potentially distinguish between WIMP candidates

Directional detectors (e.g. DRIFT, DM-TPC, NEWAGE)

demonstrate Galactic origin of signal

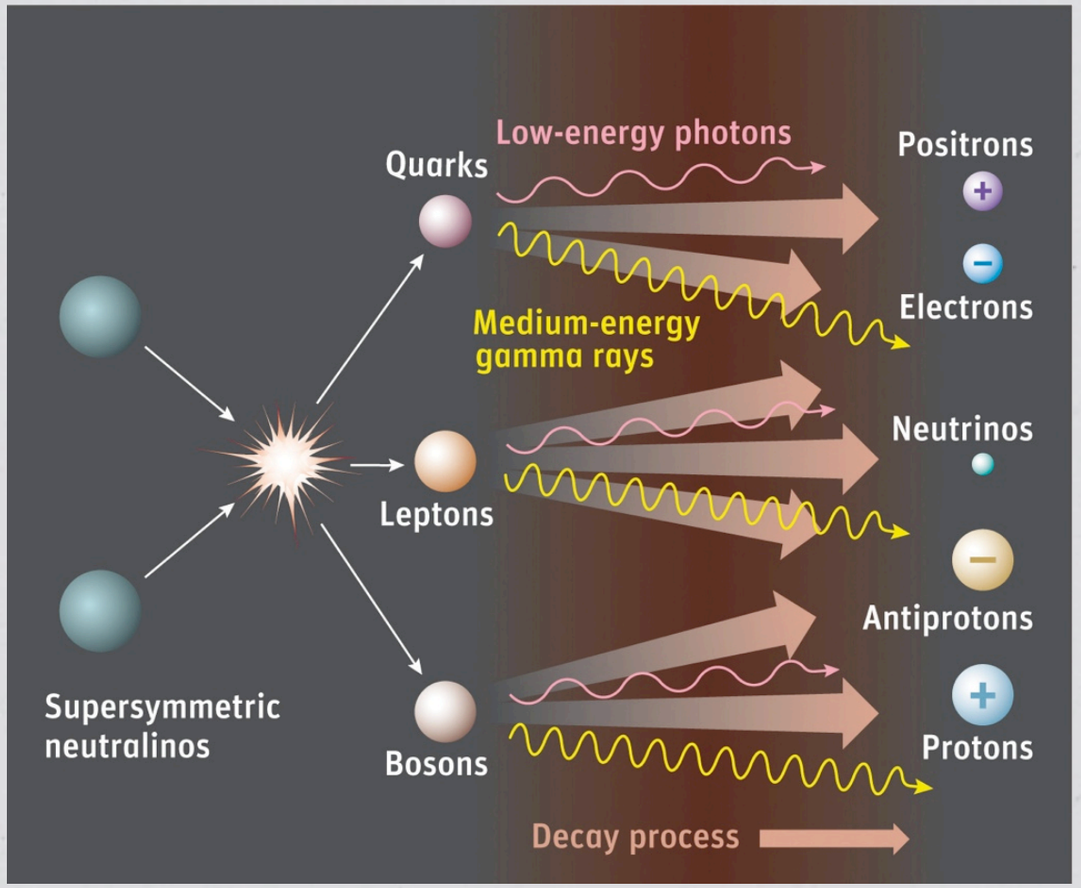
'WIMP astronomy'

WIMPs: indirect detection

i) principals

Via annihilation products e.g. gamma-rays, positrons, anti-protons, neutrinos

many refs., see classic Jungmann, Kamionkowski & Griest review



Sources:

gamma-rays: galactic center, substructures, diffuse emission

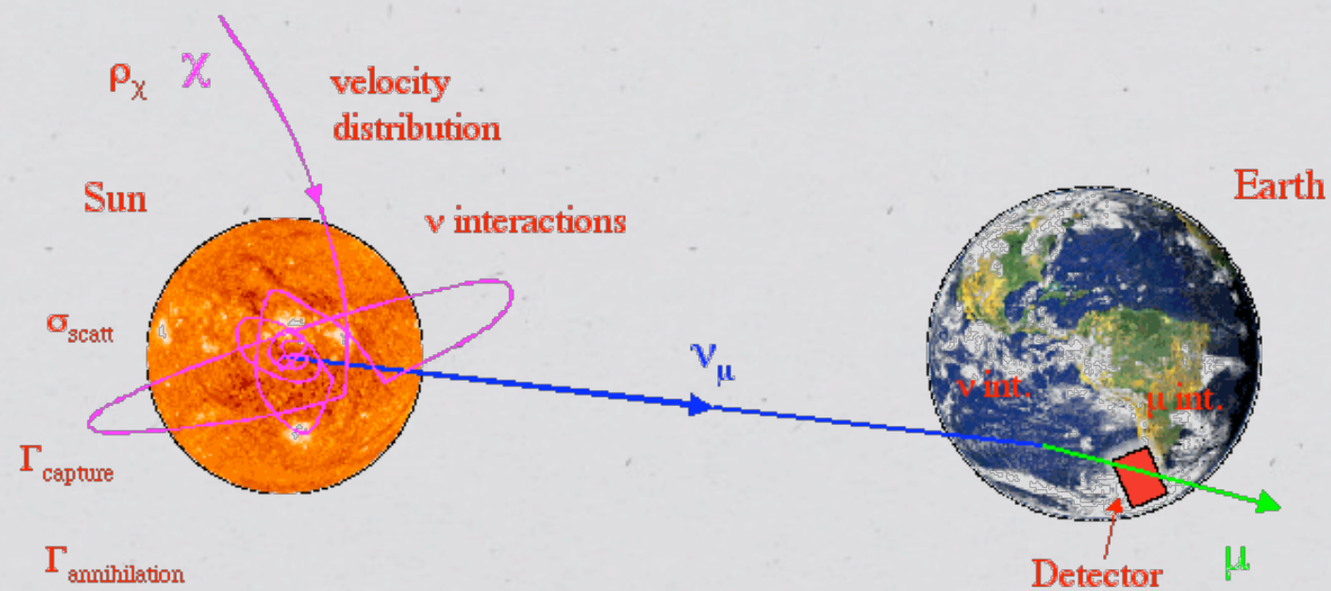
anti-matter: 'local' (~kpc) DM distribution

neutrinos:

Silk, Olive & Srednicki; Krauss et al.; Freese; Krauss, Srednicki & Wilczek

WIMPs gravitationally captured in Earth or Sun then annihilate producing energetic neutrinos which escape.

Muon neutrinos produce muons which can then be detected (via Cherenkov radiation) using neutrino telescopes.



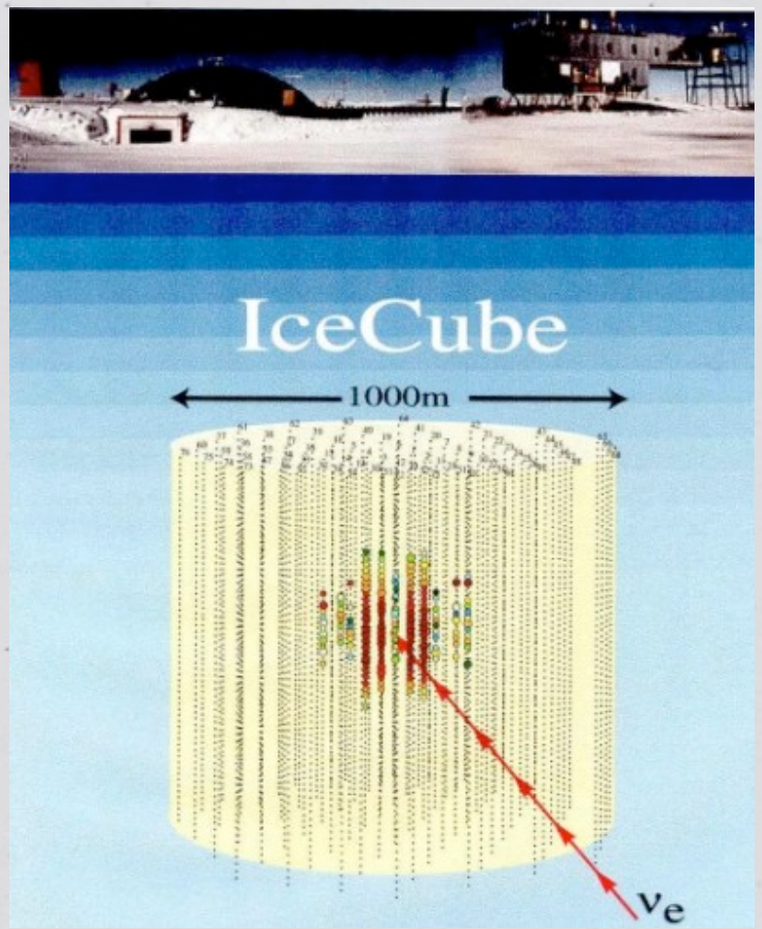


fig: AMANDA

ii) practicalities (for gamma-rays and anti-matter)

Particle physics

particles produced depend on nature of WIMP

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Astrophysics

dark matter distribution:

annihilation rate proportional to $\propto \rho^2$, depends on DM distribution of target (need to extract (parameters of) density profile from obs. of visible components, effect of baryons? density profile as r -> 0 ?)

enhancement due to substructure parameterised by *boost factor,* depends on species/target/energy

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charged particles affected by Milky Way's magnetic field

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backgrounds:

need to differentiate WIMP annihilation products from astrophysical backgrounds

possibilities: i) features in spectrum e.g. line from direct annihilation to photons (rate usually supressed) Bergstrom and collaborators

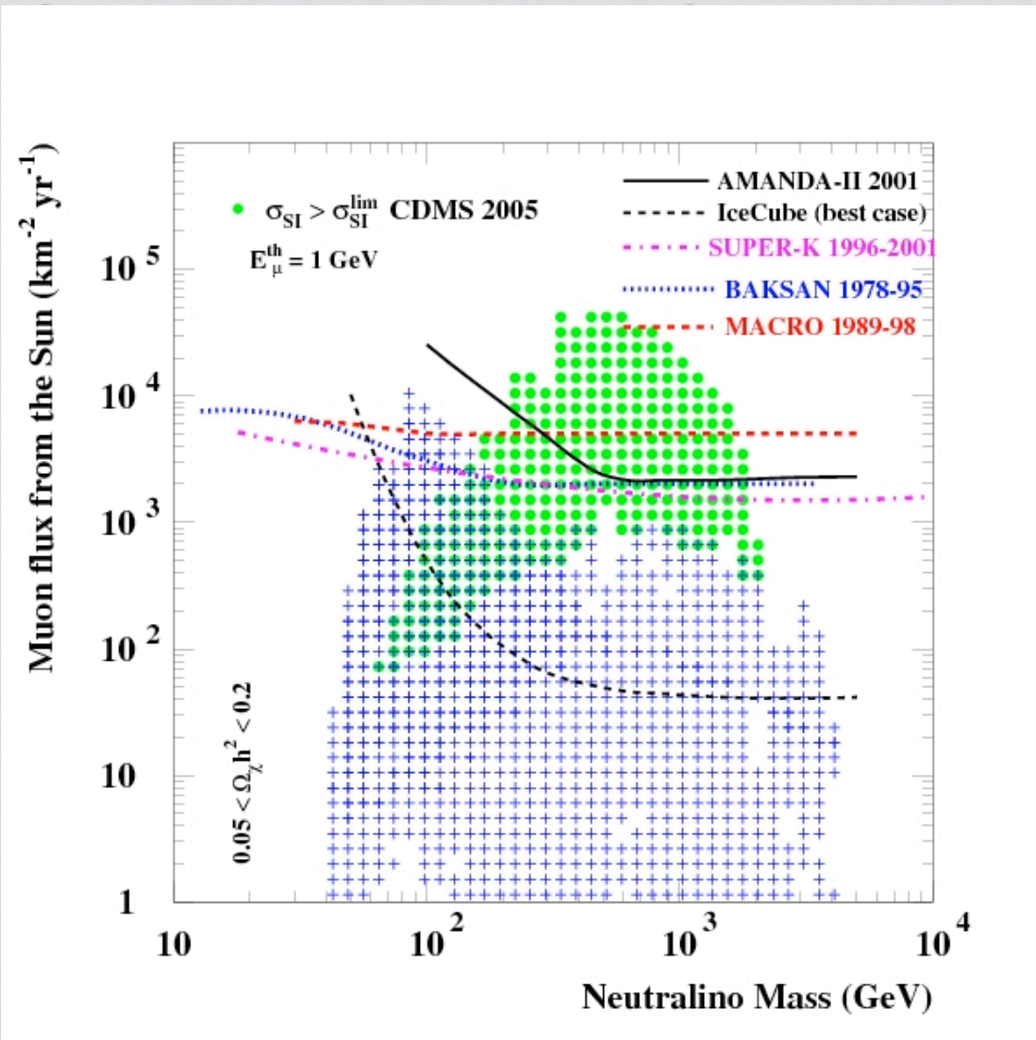
ii) (gamma-rays) same spectrum from different targets

iii) multi-wavelength signals e.g. Colafrancesco, Profumo & Ullio and collaborators

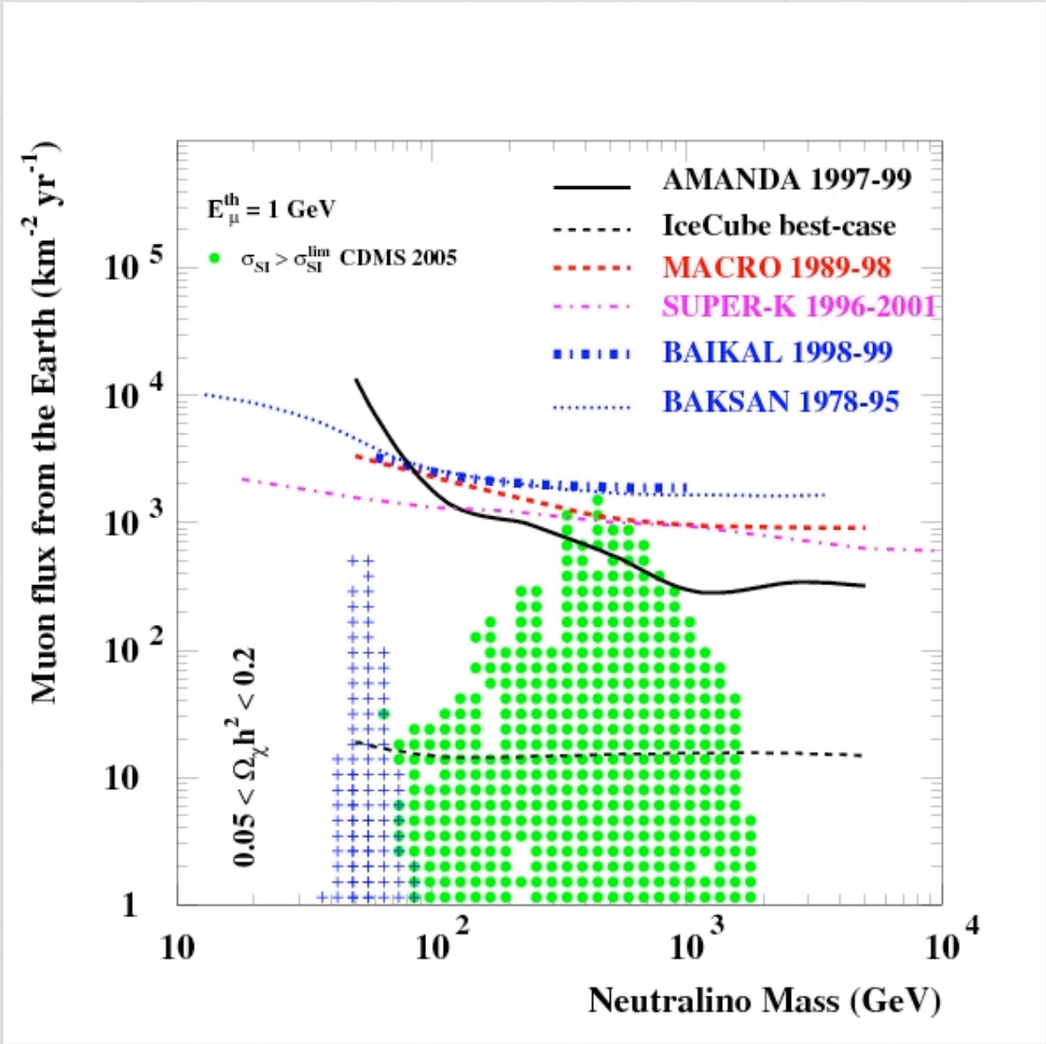
iii) current status

neutrinos

Sun



Earth

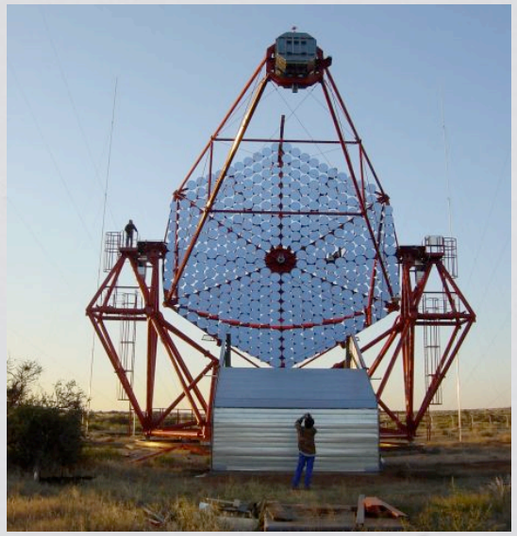


IceCube (DarkSUSY)

Some regions of parameter space of SUSY models excluded, but currently direct detection experiments are a more sensitive probe of elastic scattering cross-sections.

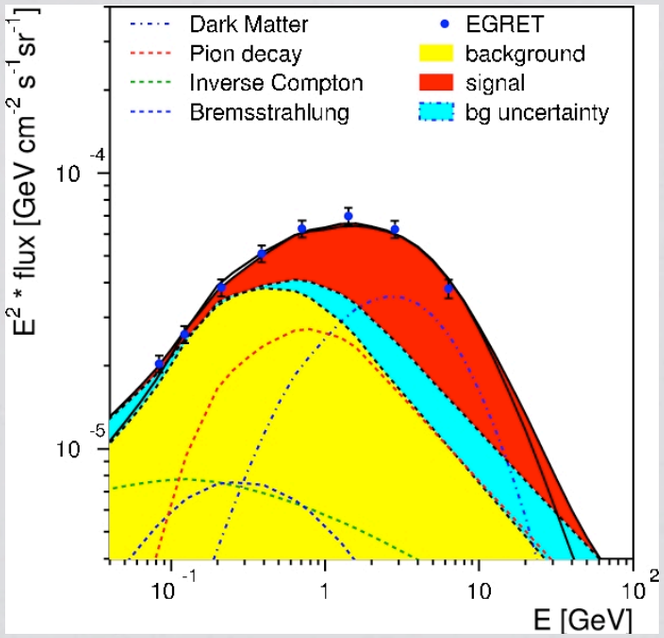
gamma-rays

Spectrum of high energy source at Galactic centre observed by HESS hard to reconcile with DM annihilation (extends to ~ 20 TeV).



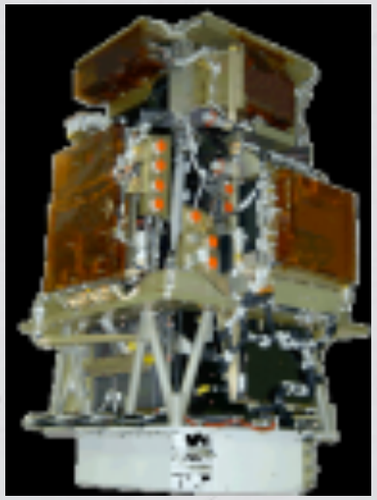
Null observations of dwarf satellite galaxies by HESS, MAGIC and Whipple place weak constraints on annihilation cross-section.

Excess over expected backgrounds at E > 1 GeV in Galactic gamma-ray emission detected by EGRET. Interpreted as from annihilation of 50-100 GeV WIMP by De Boer et al, but requires very unusual DM distribution (and in conflict with anti-proton observations).



De Boer et al

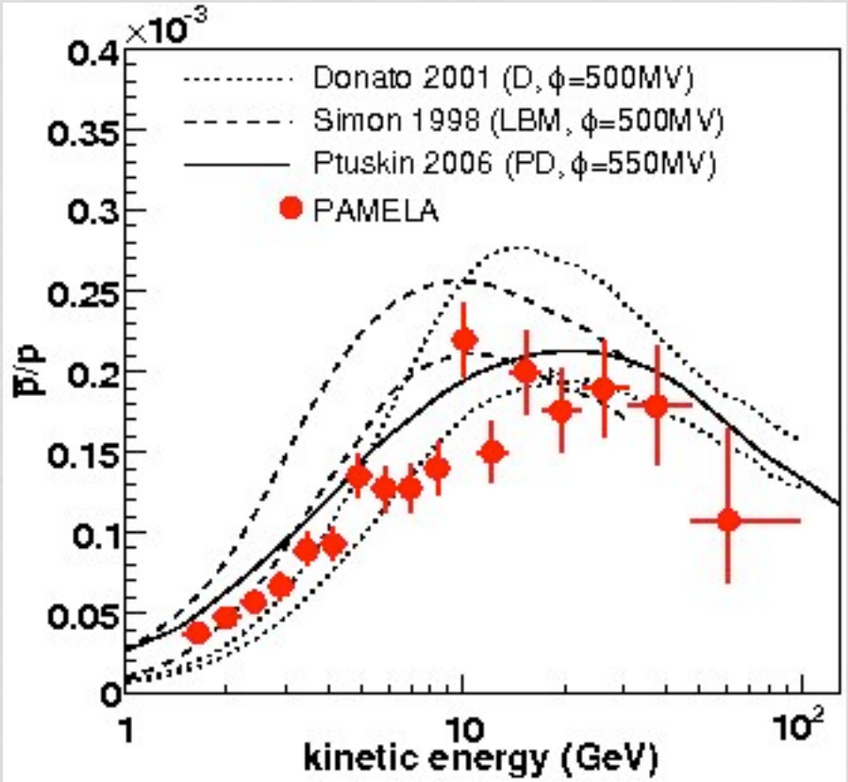
anti-protons



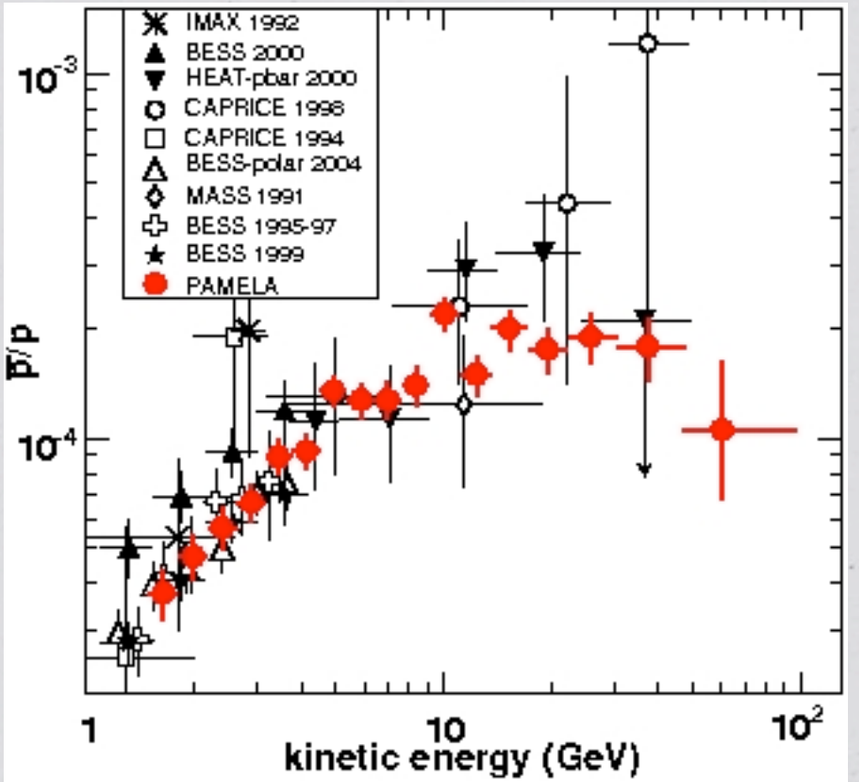
Recent data from PAMELA (launched 2006)

anti-proton to proton flux ratio, compared with:

theoretical predictions of secondary production from cosmic-rays propagating in MW



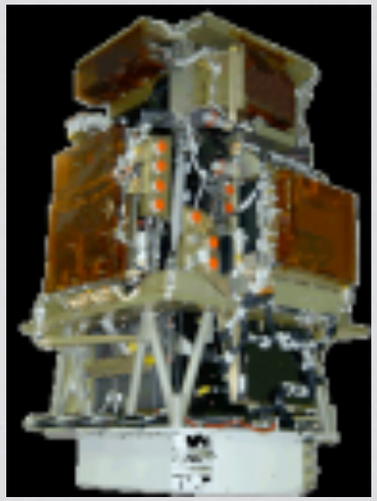
previous measurements



Limits on production of anti-protons by WIMP annihilation place important constraints on WIMP annihilation interpretation of gamma-ray Bergstrom et al. and positron Donato et al. excesses.

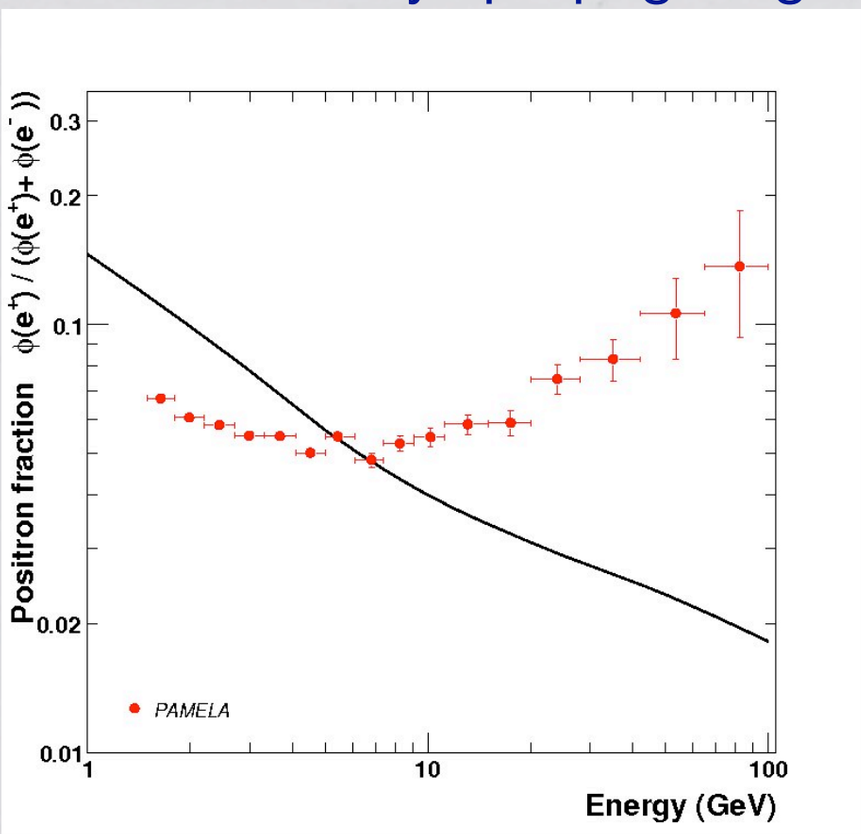
positrons

Long-standing excess recently confirmed by PAMELA and ATIC.



PAMELA positron fraction [positron flux/(positron + electron flux)] compared with:

theoretical predictions of secondary production from cosmic-rays propagating in MW



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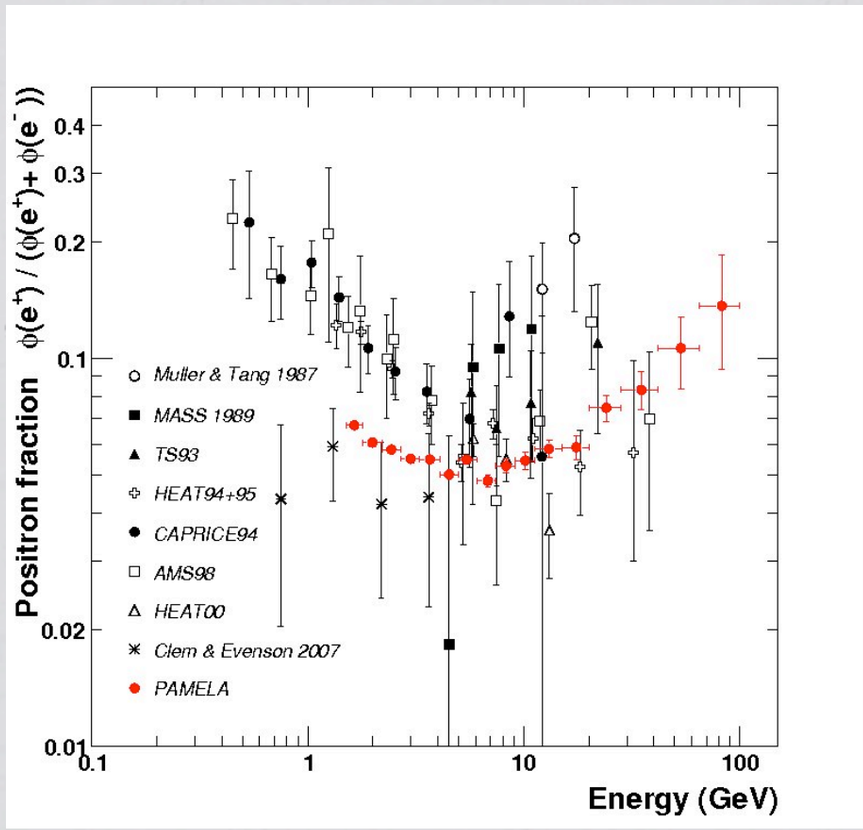
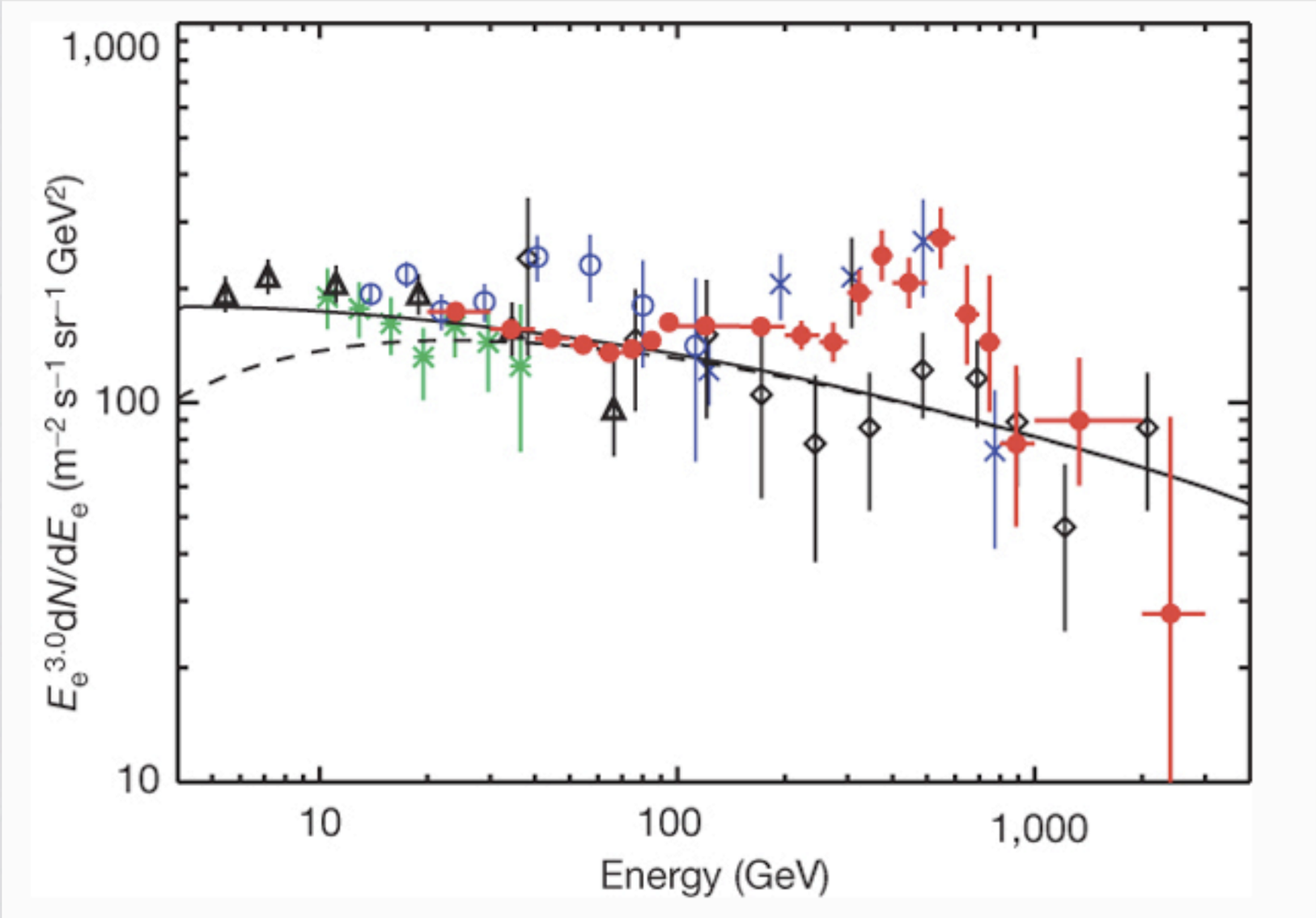


ATIC electron + positron differential energy spectrum



Lots of papers about WIMP annihilation interpretation.....

- Rate much larger than expected from a thermal relic (present day density -> annihilation cross-section) with a smooth density distribution.

Possible solutions: large boost factor e.g. large clump within a few kpc Hooper, Stebbins & Zurek, enhancement of annihilation cross-section at low velocities e.g. Sommerfeld effect due to new light boson Arkani-Hamed and collaborators, or formation of WIMPonium bound state. Pospelov & Ritz; March-Russell & West

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- Typically energy spectrum of leptons too hard and anti-protons and gamma-rays overproduced. Cirelli et al., Donato et. al., Bertone et al.

Possible solutions: DM candidates which predominately annihilate directly to leptons. e.g. Cholis et al., Zurek; Foz & Poppitz

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- Typically energy spectrum of leptons too hard and anti-protons and gamma-rays overproduced. Cirelli et al., Donato et. al., Bertone et al.

Possible solutions: DM candidates which predominately annihilate directly to leptons. e.g. Cholis et al., Zurek; Foz & Poppitz

- Nearby pulsars could plausibly produce the excesses. Hooper, Blasi, Serpico; Profumo

Lots of papers about WIMP annihilation interpretation.....

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- There are large uncertainties in the expected secondary positron flux from cosmic rays. Delahaye et al.

iv) future prospects

gamma-rays

Fermi (formerly known as GLAST), successfully launched in June 2008
(full-sky) data taking underway
will also be able to detect electrons

ACTs
more observations of dwarf galaxies planned
will be able to follow up any Fermi signal

Longer term: CTA

anti-matter

PAMELA
data taking ongoing, extending measurements to higher E

Longer term: AMS

neutrinos

ANTARES & IceCube
data taking, and construction [IceCube], ongoing

Longer term: KM3NeT

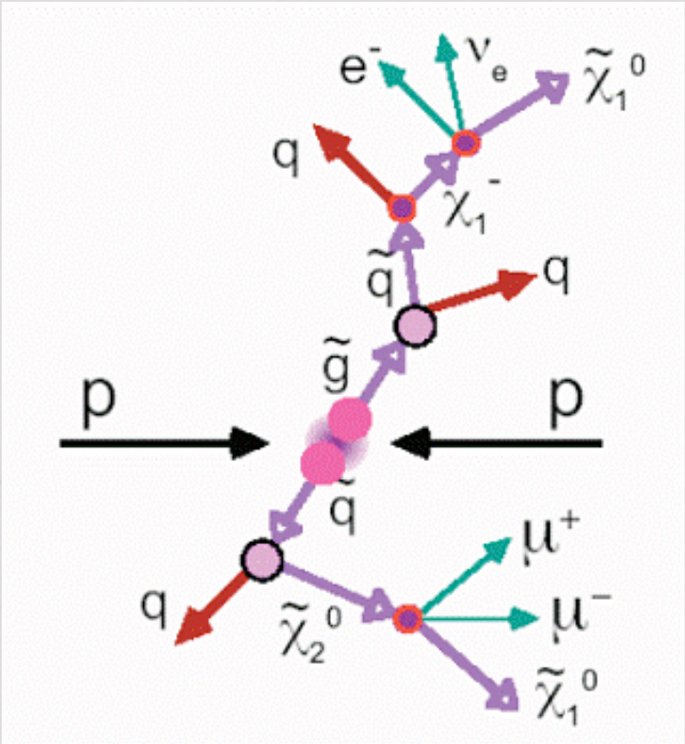
WIMPs: colliders

An extremely brief/rough overview.....

'Generic' signal: missing transverse energy

Need to distinguish from backgrounds (standard model and instrumental).

Look for statistical excess of events with missing transverse energy + jets. (In SUSY models, gluinos and squarks decay producing energetic quarks and leptons and invisible WIMPs).



Collider production and detection of a WIMP-like particle would be very exciting, but wouldn't demonstrate that the particles produced have lifetime greater than the age of the Universe and are the dark matter.

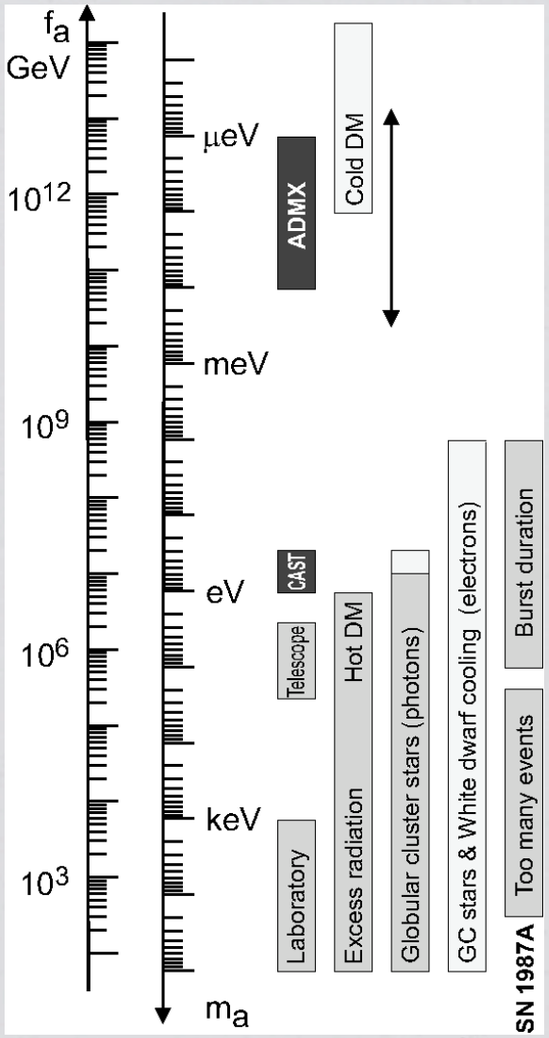
Axions

Weinberg, Wilczek

Consequence of Peccei-Quinn symmetry proposed to solve strong CP problem ("why is the electric dipole moment of the neutron so small?").

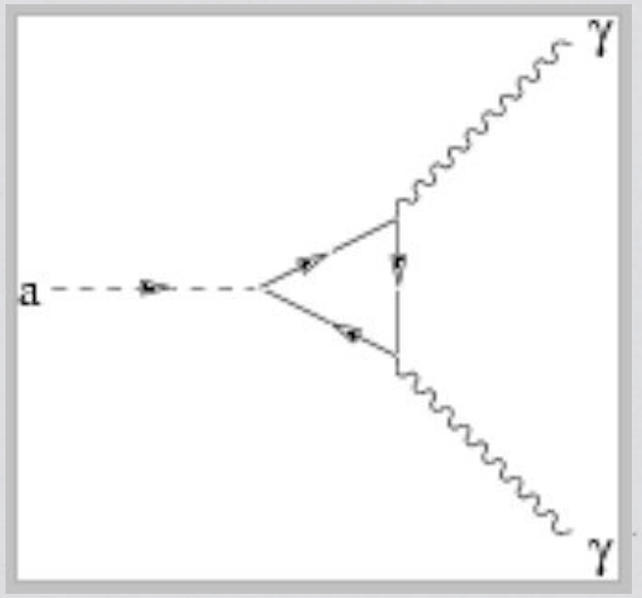
Very light and very weakly interacting, microphysics very different to WIMPs (if density is large enough to be dominant/sole CDM species, were never in thermal equilibrium in the early Universe produced via misalignment angle [coherent oscillations of scalar field] or, possibly, axionic strings)

Constraints on mass/coupling strength from cosmology, lab searches and from cooling of stars and supernovae.



Raffelt

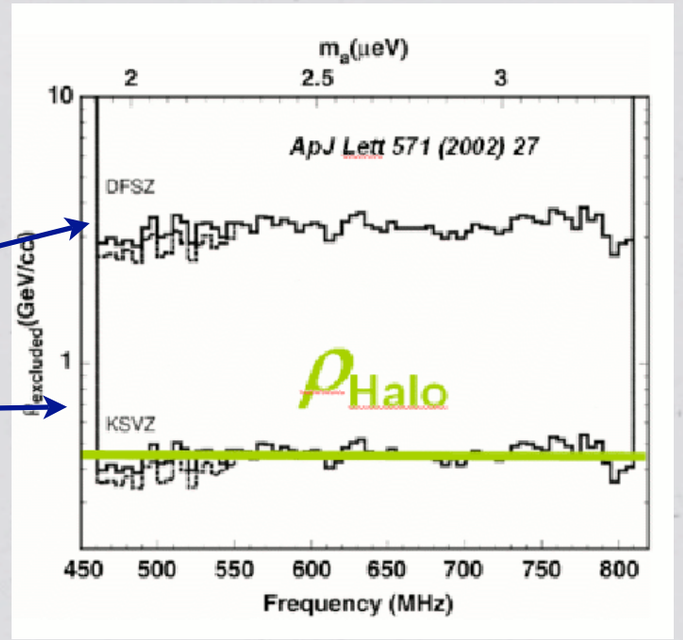
Coupling to two photons leads to resonant conversion of axions to photons in a strong magnetic field (Primakoff process).



ADMX (Axion Dark Matter eXperiment) has sensitivity to detect galactic halo axions

DFSZ: interact with electrons

KSVZ: no tree level coupling to electrons



AMDX

Sterile neutrinos

see recent review by Boyarsky, Ruchayskiy & Shaposhnikov

Fermions with no standard model couplings (other than to standard neutrinos through mass generation mechanism).

Arise in many extensions of standard model (grand unified models, string-inspired large extra dimensions).

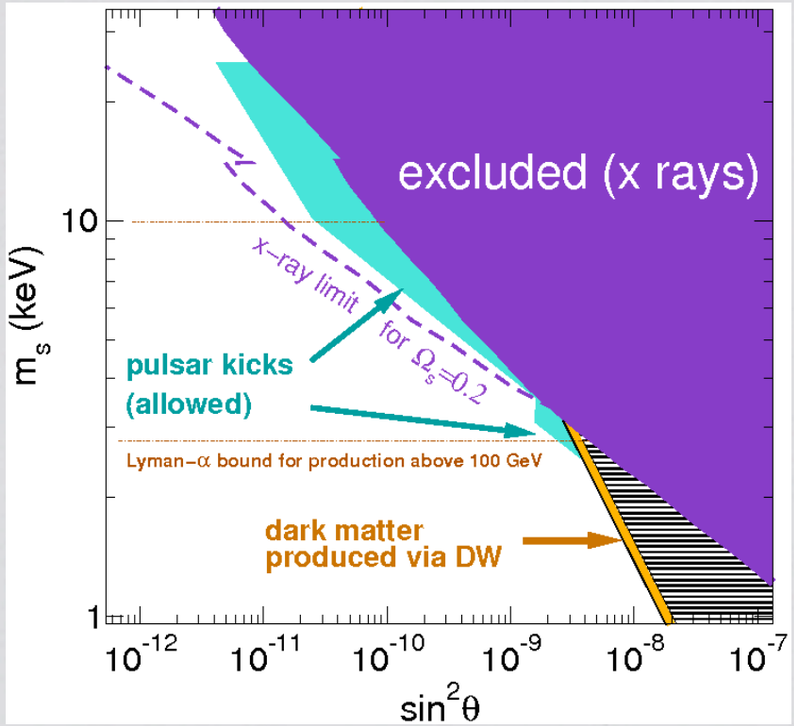
Can be produced with interesting density via oscillations with standard neutrinos (Dodelson-Widrow mechanism).

Other production methods possible.

Constraints from:

i) Large scale structure (e.g. CMB, galaxy clustering and Lyman-alpha forest) limits on suppression of density perturbations (warm dark matter, large free-streaming length).

ii) X-ray photons produced in decays



Kusenko

Dark matter detection: summary

- WIMPs are generically a good dark matter candidate and extensions of the standard model of particle physics provide us with concrete well-motivated WIMP candidates (in particular supersymmetry and the lightest neutralino).

- WIMPs can be detected:

  directly — via elastic scattering in the lab

  indirectly — via annihilation products

  at colliders — via missing transverse energy (+ jets)

- Prospects for (convincing) detection in the next few years are good, but consistent signals from different experiments/channels will probably be required.

- There are other plausible (and detectable) dark matter candidates (e.g. axions, sterile neutrinos.....)

Suggested reading

Classic reviews

`Non-baryonic dark matter: observational evidence and detection methods'
Bergström, hep-ph/0002126

`Particle dark matter: evidence, candidates and constraints'
Bertone, Hooper & Silk, hep-ph/0404175

`Non-baryonic dark matter: observational evidence and detection methods'
Jungmann, Kamionkowski & Griest, Phys. Rep. 267 195 (1996)

increasing complexity

n.b. significant improvements in observational evidence in recent years

Recent status overviews

`Indirect searches for dark matter: signals, hints and otherwise'
Hooper, arXiv/0710.2062

`Dark matter: a multidisciplinary approach'
Bertone, arXiv/0710.5603

`Direct detection of cold dark matter'
Baudis, arXiv/0711.3788

For an overview of PAMELA/ATIC and WIMP annihilation see e.g. the introductions of

'Dissecting Pamela (and ATIC) with Occam's Razor....' Profumo, arXiv:0812.4457

'The PAMELA and ATIC Excesses....' Hooper, Stebbins, & Zurek, arXiv:0812.0302