WIMP hunting: searching for dark matter

Anne Green

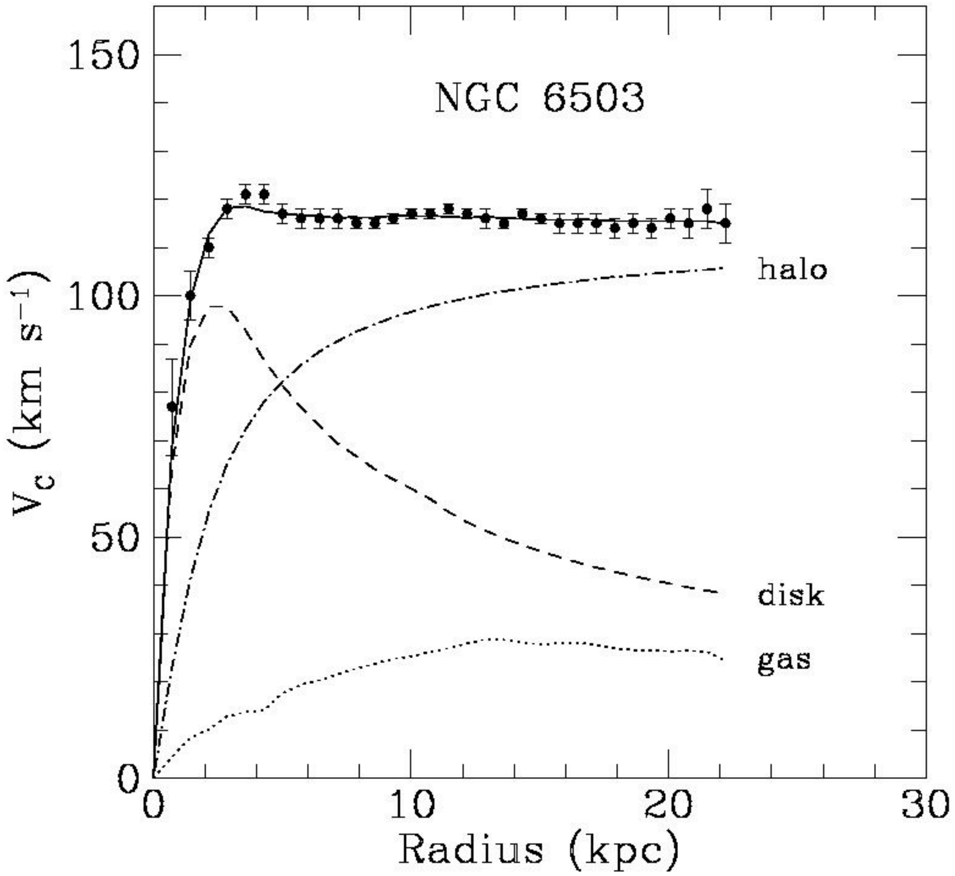
University of Nottingham

- Observational evidence
- Candidates
- WIMP detection
- Dependence on the dark matter distribution

Observational evidence for dark matter

Galaxies

Rotation curves of spiral galaxies are (roughly) flat at large radii.



$$\frac{v_{rot}^2}{r} = \frac{GM(<r)}{r^2}$$

$$v_{rot} \sim const$$

$$\Big\Downarrow$$

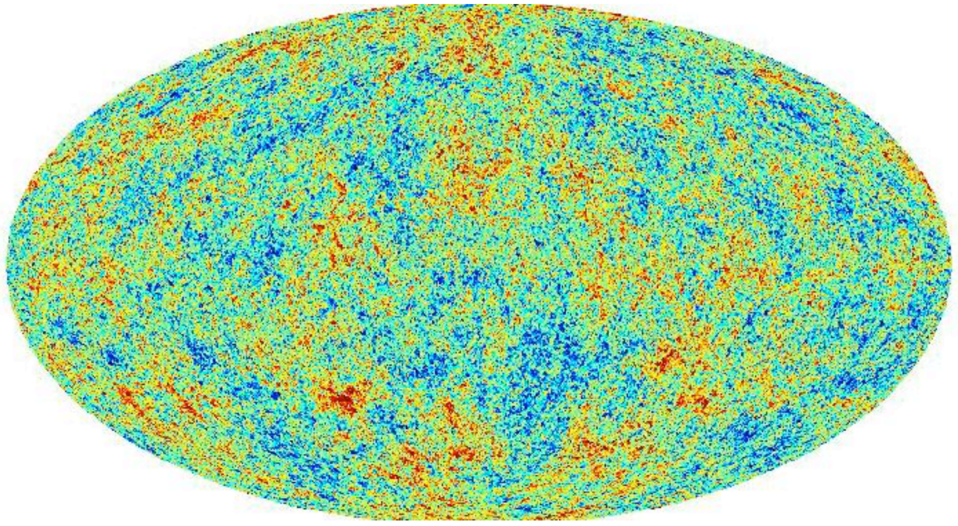
$$M(<r) \propto r$$

$$\rho(r) \propto \frac{1}{r^2}$$

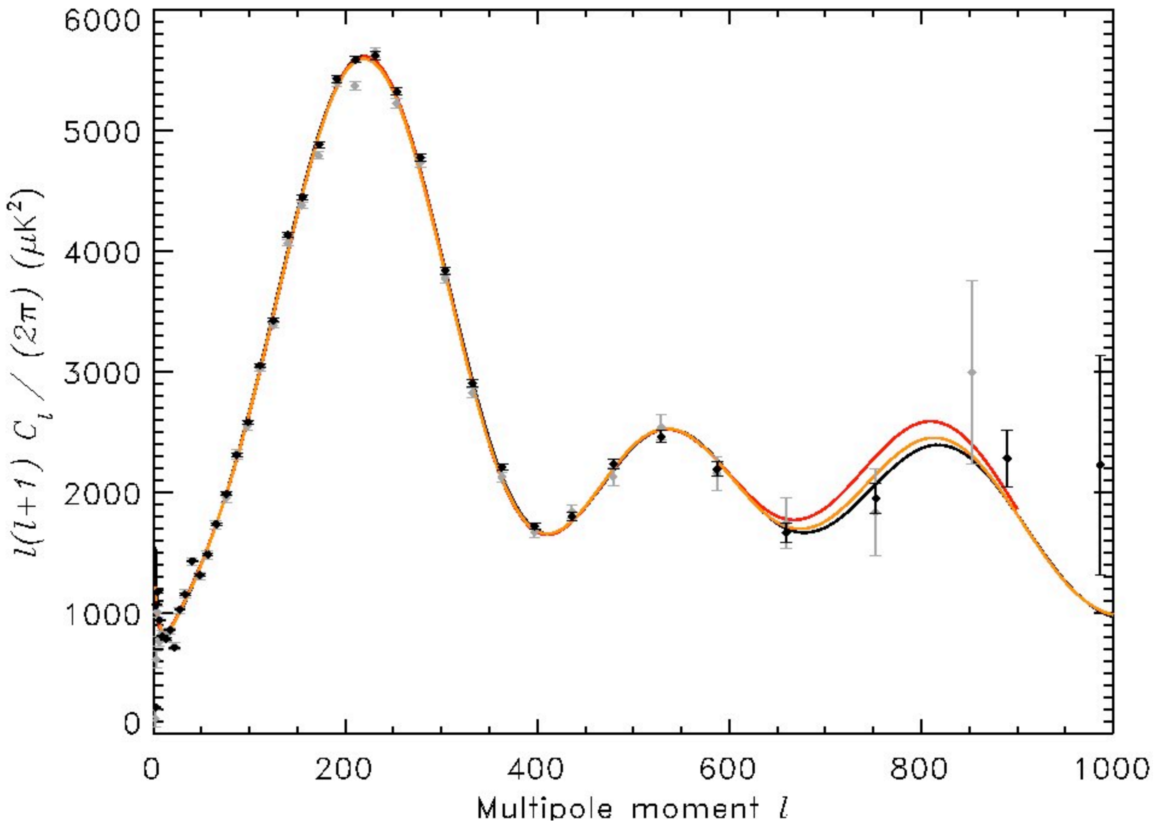
(Assuming Newtonian gravity is correct) galaxies are surrounded by halos of invisible matter.

Cosmic microwave background radiation

Fluctuation distribution depends on primordial perturbations and also contents of Universe.



WMAP



Characteristic scale: total energy density critical

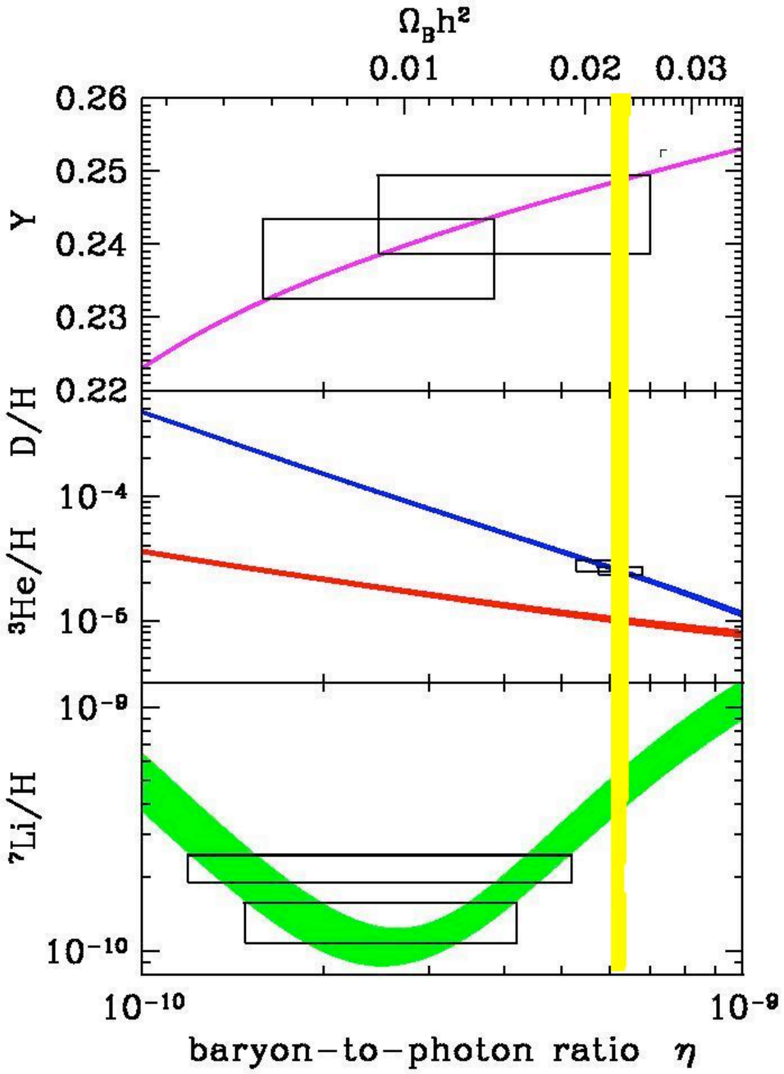
Scale dependence (and size): non-baryonic dark matter

Nucleosynthesis and the light element abundances

At t~1s the weak interactions which interconvert protons and neutrons cease and the light elements are synthesized.

Abundances depend on the photon to baryon ratio.

Can measure baryon density by comparing theoretical calculations with observed high redshift (~primordial) abundances.

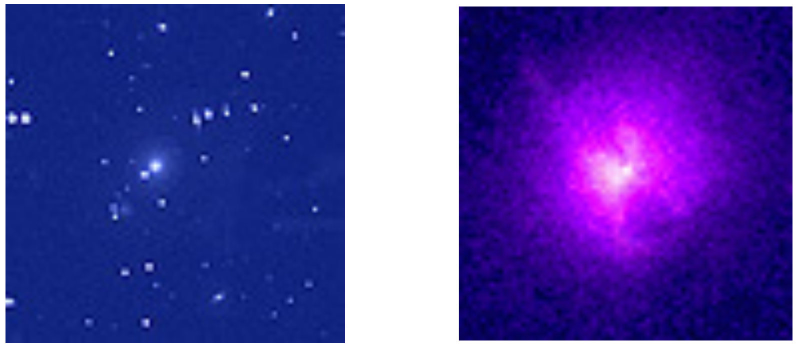


Cyburt

Consistent with (independent & much lower red-shift) measurement of baryon density from CMB temperature fluctuations.

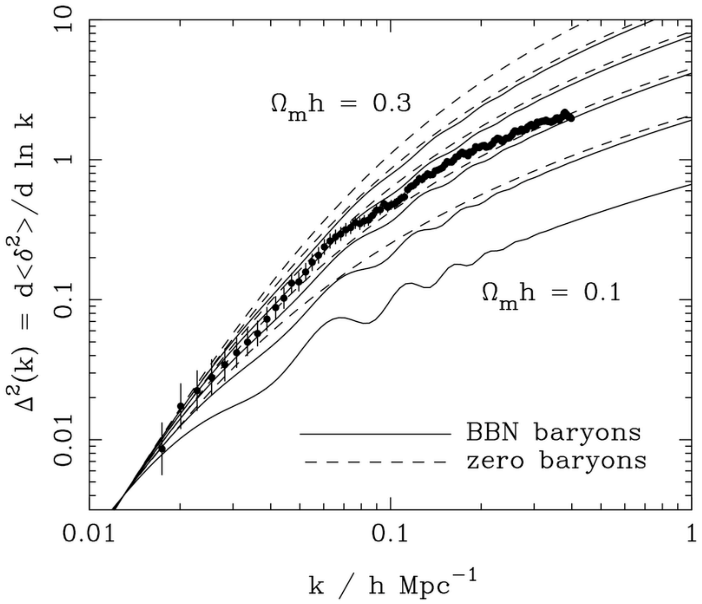
Galaxy clusters and large scale structure

Total mass of galaxy cluster ~4+ times the visible mass in order to confine galaxies and hot gas.



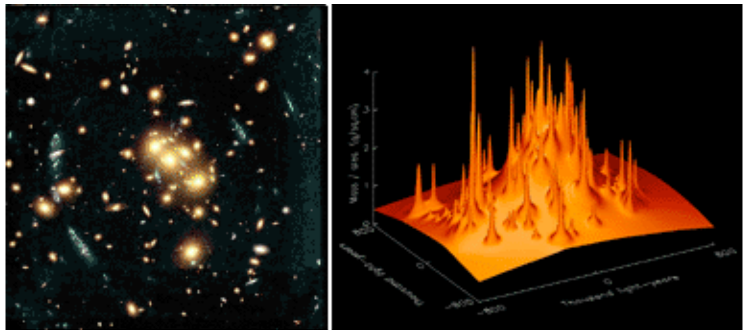
Chandra

Spatial distribution of galaxies depends on the matter & baryon densities.

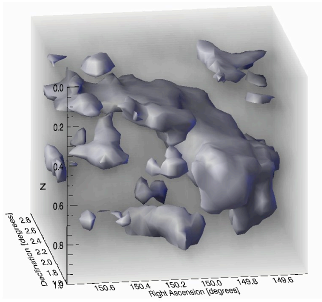


2dFGRS

Can map the total matter distribution by measuring deflection of light by gravitational lensing.



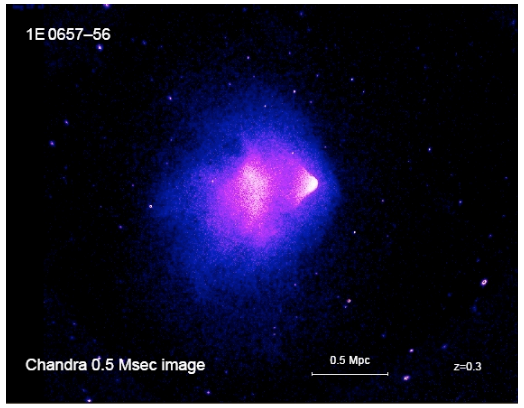
Tyson et al.

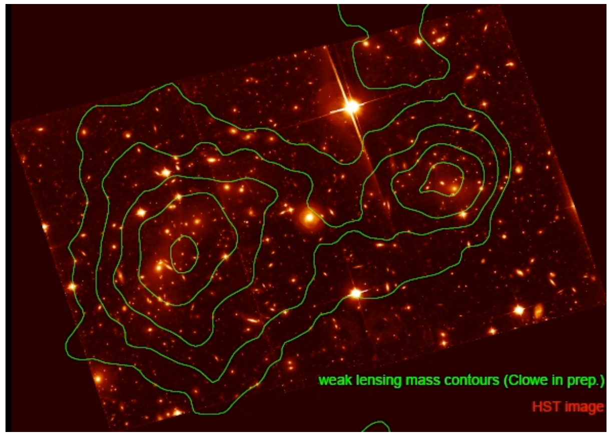


Massey et al.

A special case: the bullet cluster

"Direct empirical evidence for the existence of dark matter" (?....) Clowe et al.





Separation of gravitational potential (reconstructed from lensing obs.) and dominant baryonic mass component (hot gas, X-ray emission detected by Chandra)

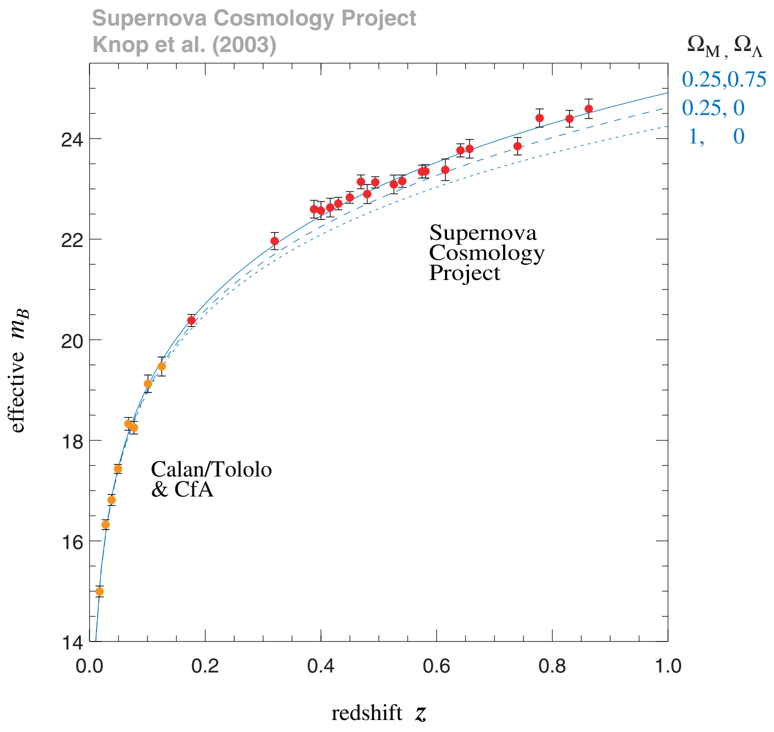
→ dark matter

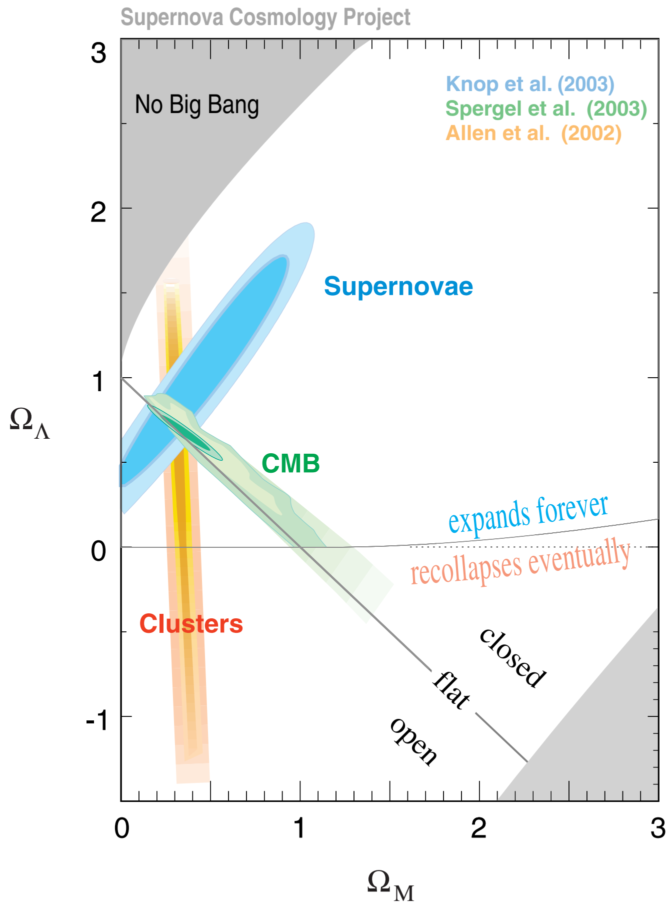
But lensing analysis assumes GR, modified gravity theories not definitely excluded, but these observations are a big challenge.

Dark energy in the Universe

type 1a supernovae High-z Supernova Search & Supernova Cosmology Project

Standardisable candles (correlation between timescale and peak magnitude).
Can use to measure expansion history of the Universe.



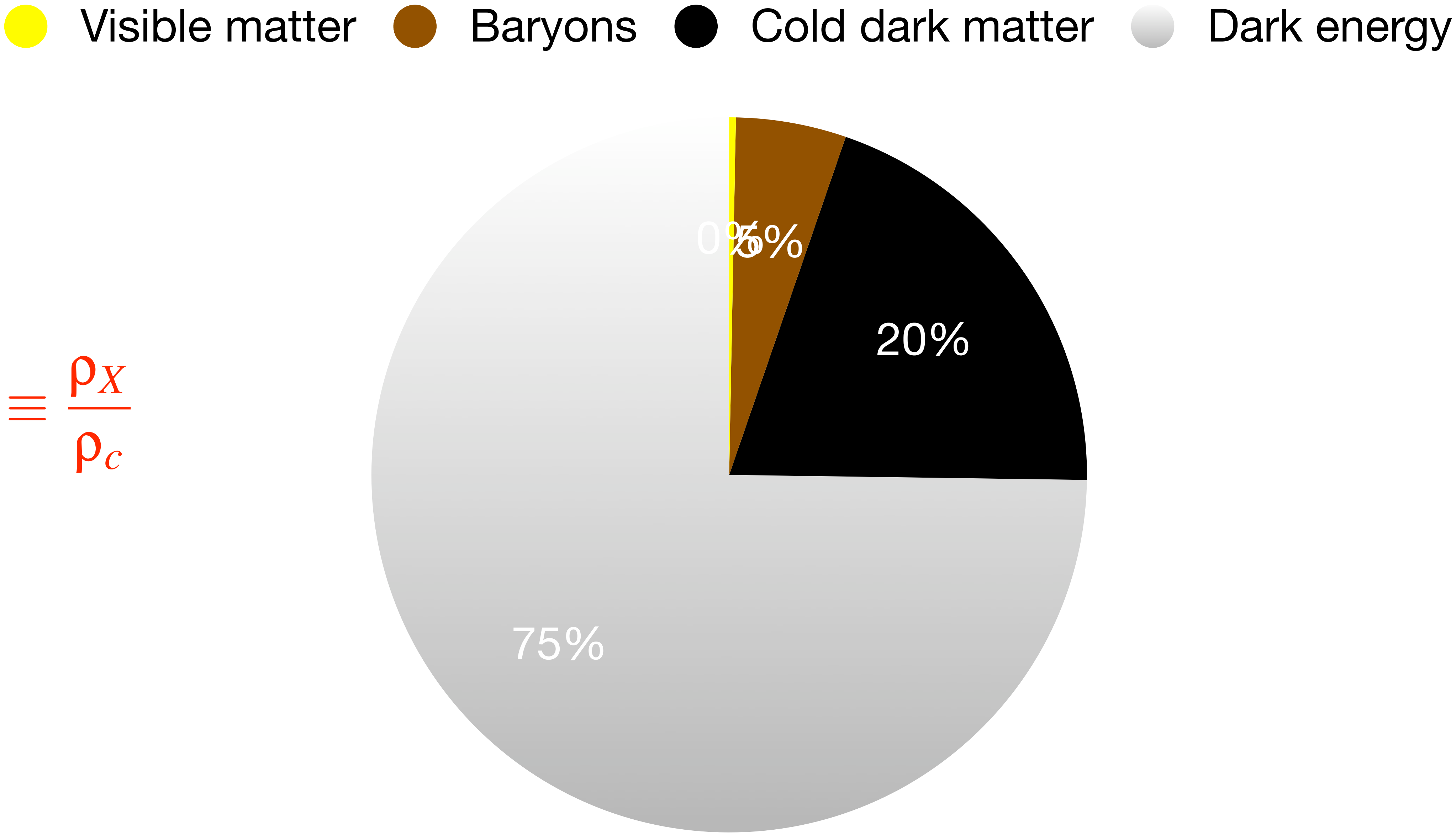


Other (low-ish sigma) evidence for dark energy:

from correlation of large scale structure & the CMB,
position of baryon acoustic oscillations

Putting it all together:

the standard cosmological model



$$\Omega_X \equiv \frac{\rho_X}{\rho_c}$$

There aren’t enough baryons for the Galactic dark matter to be entirely baryonic.

Dark matter candidates

Weakly Interacting Massive Particles

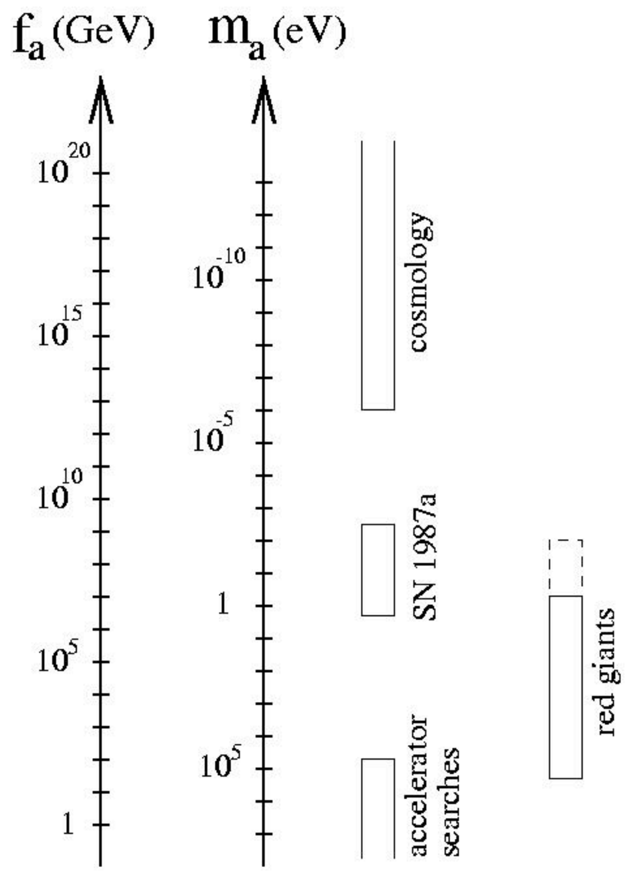
More later

Axions

✧ consequence of Pecci-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 (never in thermal equilibrium in the early Universe, microphysics very different from WIMPs).

✧ constraints on mass from cosmology, lab searches and from cooling of stars and supernovae.



Sikivie

Neutrinos

They exist, and have mass (neutrino oscillations) but can’t have high enough phase space density to be galactic dark matter (Pauli exclusion principle) and are relativistic and hence wash out structure on small scales.

Primordial Black Holes

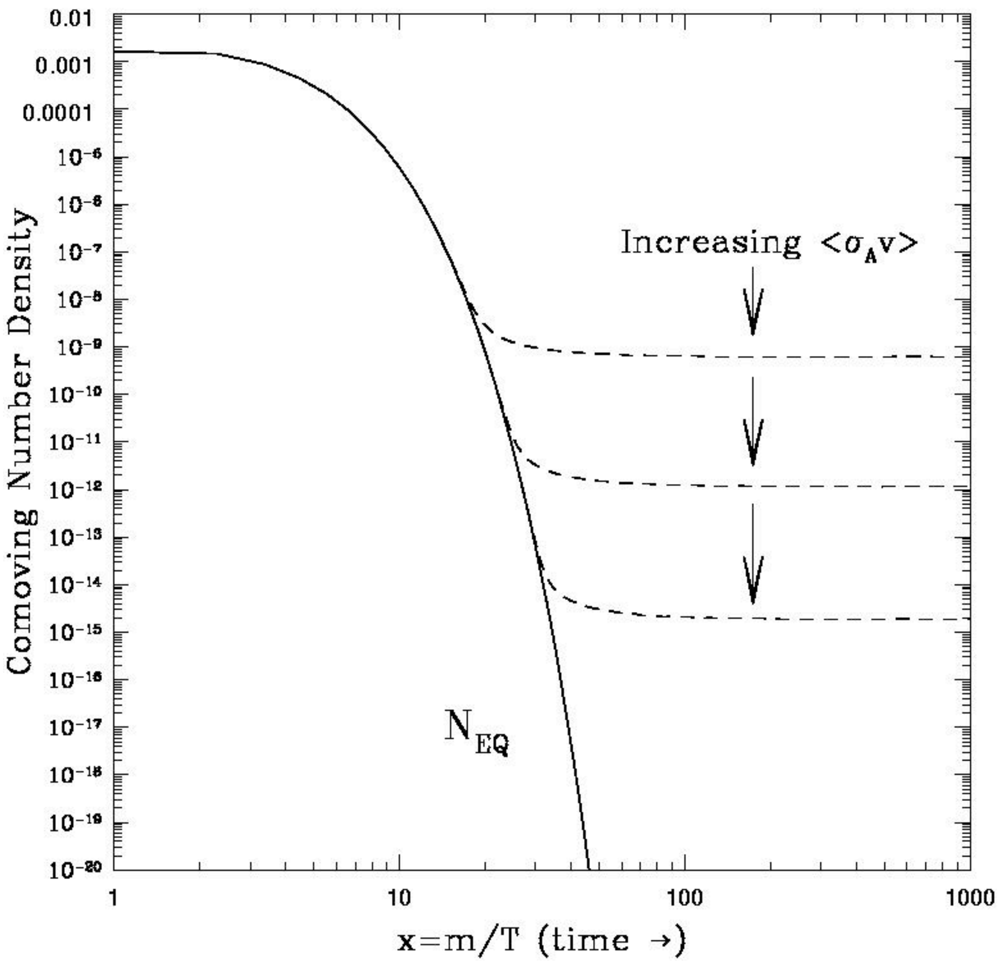
May be formed in the early Universe from large overdensities, but fine tuning required to produce interesting abundance?

‘Exotica’

Wimpzillas, solitons (Q-balls, B-balls),

WIMPs

Any Weakly Interacting Massive Particle in thermal equilibrium in the early Universe will have an interesting density today.



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

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

Simple argument:

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

If g~0.01 and m_W~100 GeV:

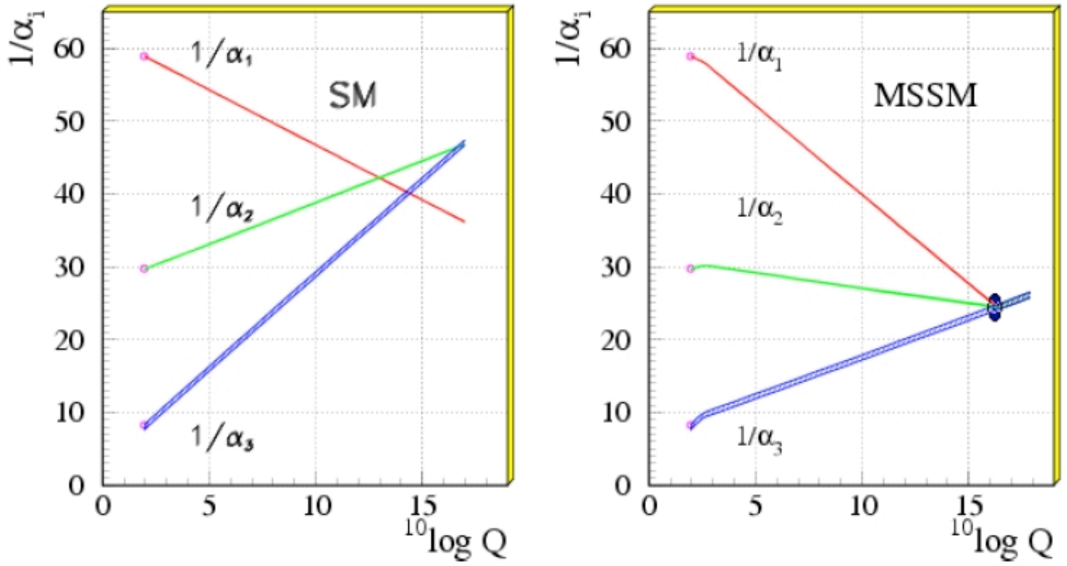
$$\langle \sigma_A v \rangle \sim 10^{-25}\mathrm{cm}^3\mathrm{s}^{-1}$$

Supersymmetry

Every standard model particle has a supersymmetric partner. (Bosons have a fermion spartner and vice versa)

Motivations:

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



Kazakov

In most models the Lightest Supersymmetric Particle (which is usually the lightest neutralino, a mixture of the susy partners of the photon, the Z and the Higgs) is stable (R parity is conserved) and is a good CDM candidate.

How to detect WIMPs?

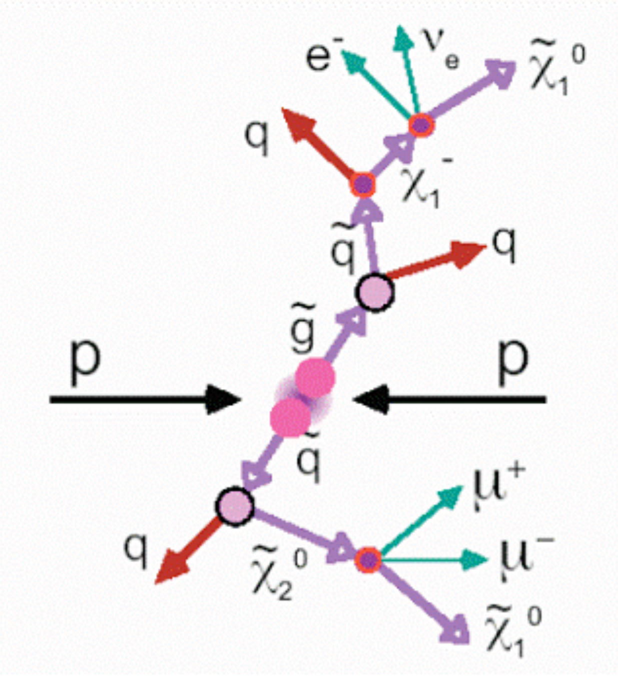
Particle Colliders (LHC)

In theory 'generic' signal: missing energy/momentum.

In practice not quite that simple.....

In SUSY models characteristic event:

decay of gluinos and squarks into energetic quarks and leptons and invisible WIMPs

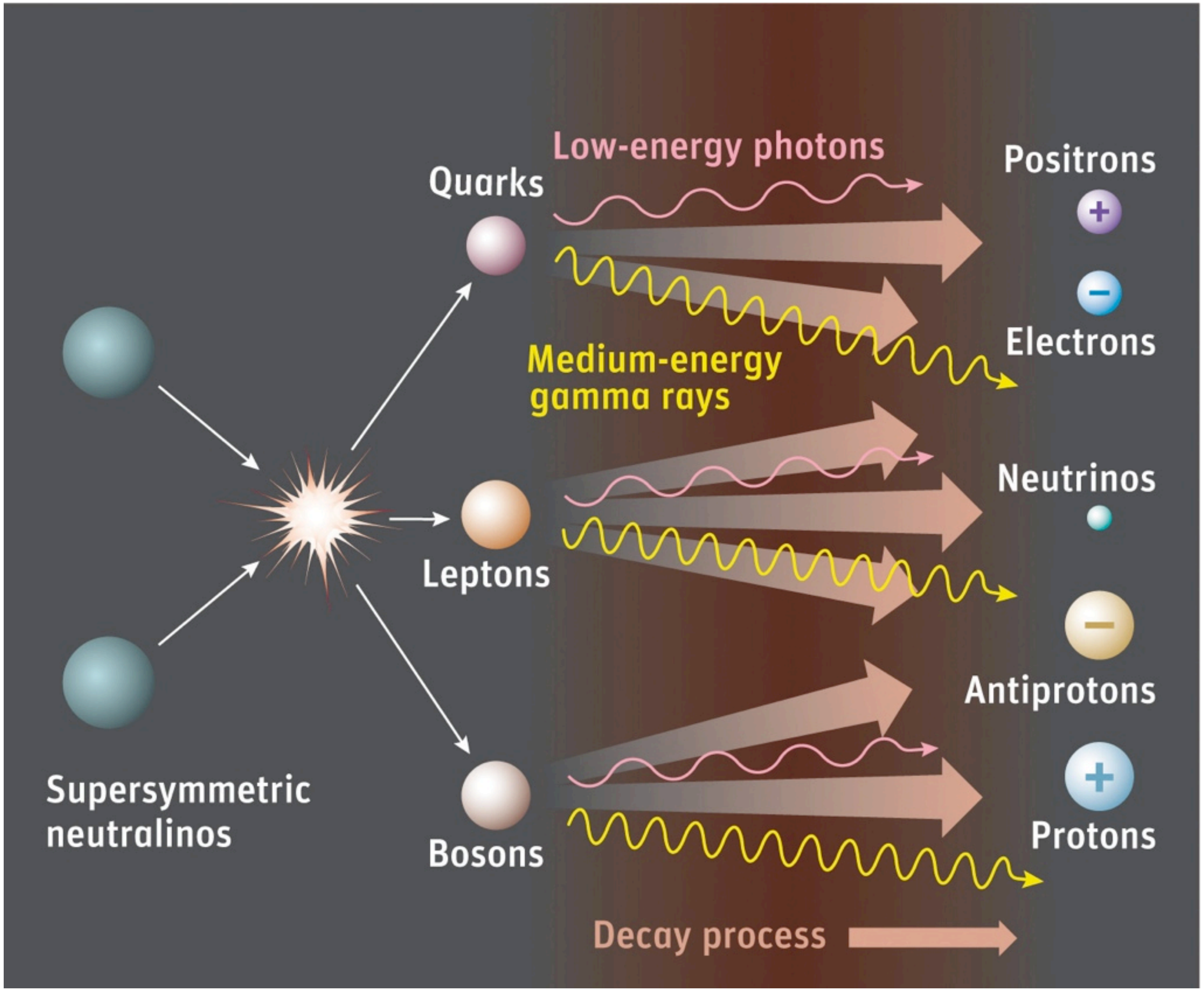


Collider production and detection of a WIMP-like particle would be very exciting, but wouldn't demonstrate that the particles produced have lifetime greater than the age of the Universe and are the dark matter.

Current status: waiting......

Indirect detection

Via products of annihilations, gamma-rays, positrons and anti-protons



Particles produced in WIMP annihilations

Particle physics

+

WIMP spatial (density) distribution

Astrophysics
(with some particle input)

+

(for charged particles) propagation of annihilation products

⇩

predicted signals

Particles produced in WIMP annihilations

Particle
physics

+

WIMP spatial (density) distribution

Astrophysics
(with some particle input)

+

(for charged particles) propagation of annihilation products

↓

predicted signals

Event rates depend on WIMP distribution $\propto \rho^2$. Enhancement of rate w.r.t that produced by smooth halo, parameterised by boost factor.

Different species probe different scales/regions (and often on scales far smaller than those directly resolved by numerical simulations). Boost factor species dependent and not accurately known.

Often need to distinguish WIMP annihilation from astrophysical backgrounds.

Current status:

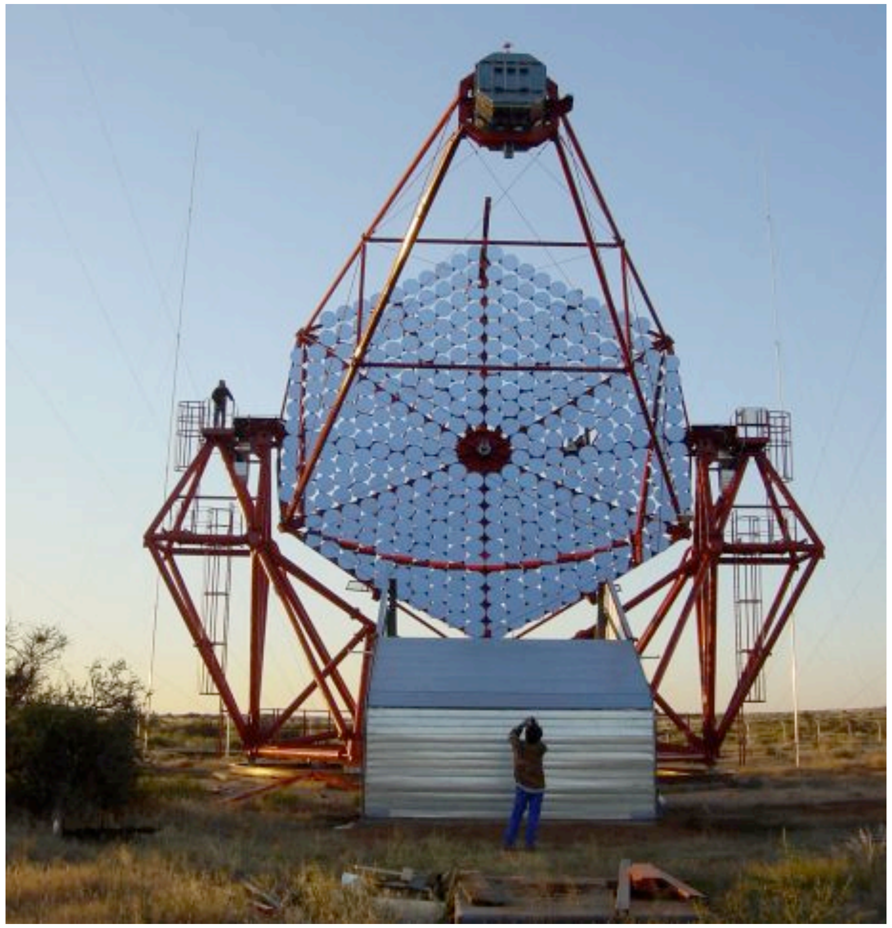
Gamma-rays:

Fermi (aka GLAST):

launched June 08, data taking underway

Air Cherenkov Telescopes (HESS, MAGIC, VERITAS):

have observed Galactic centre and several dwarf galaxies, (weak) constraints on annihilation cross-section



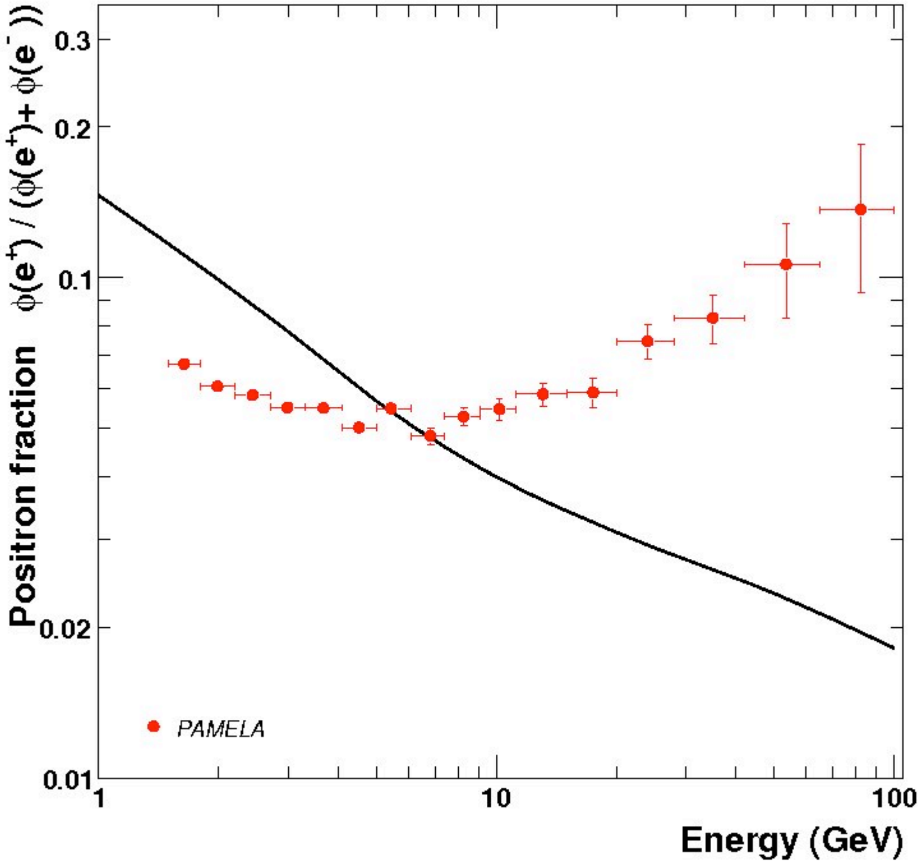
Anti-particles:

PAMELA:

excess in positron fraction between 10 and 100 GeV

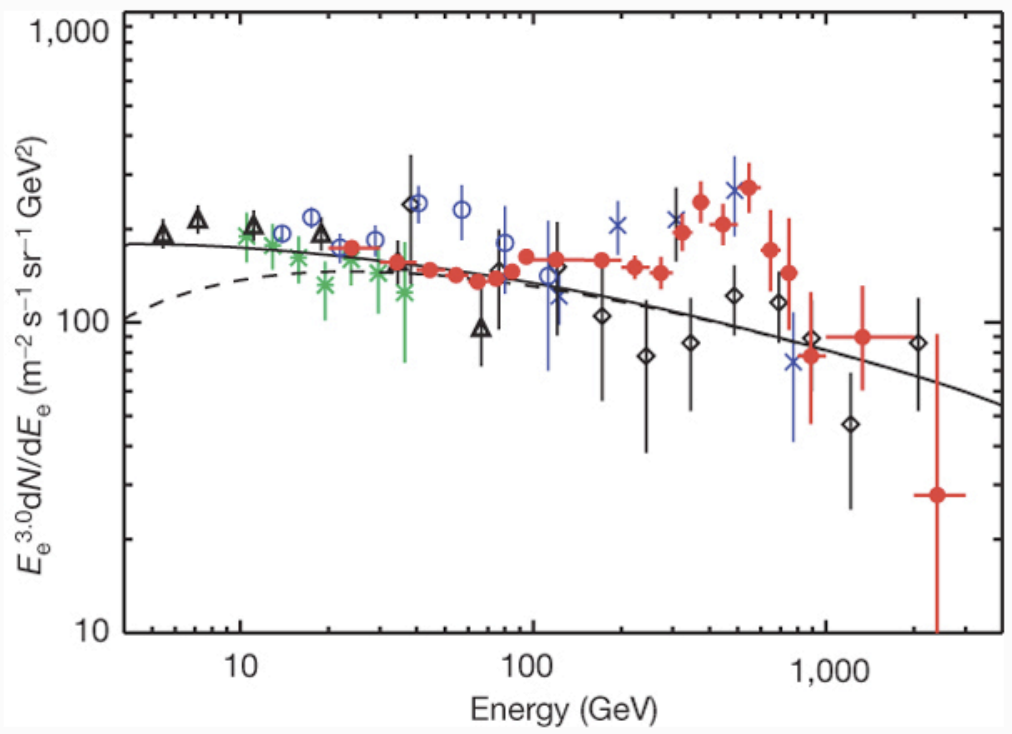
(confirming and improving earlier observations by HEAT, AMS1)

no excess in anti-protons



ATIC:

excess in electrons + positrons at 300-800 GeV



PAMELA/ATIC interpretation?

Could be produced by nearby pulsars.

Significant uncertainties in flux of secondary positrons (produced by interactions between cosmic rays and interstellar gas).

IF due to DM annihilation need:

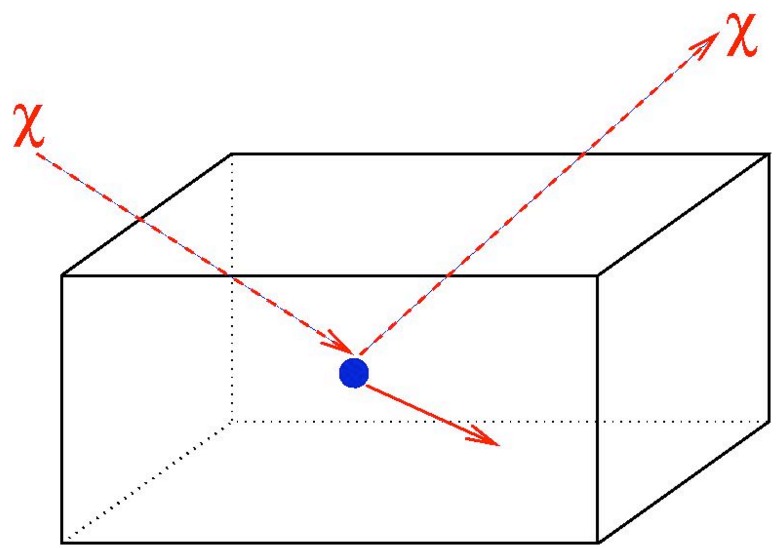
i) large enhancement in annihilation rate (clumpy DM within ~kpc, or enhancement of annihilation cross-section)

ii) to not overproduce anti-protons

Direct detection

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)

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_p \rho_\chi A^2 F^2(E) \int_{v_{\min}}^{\infty} \frac{f(v)}{v} \mathrm{d}v$$

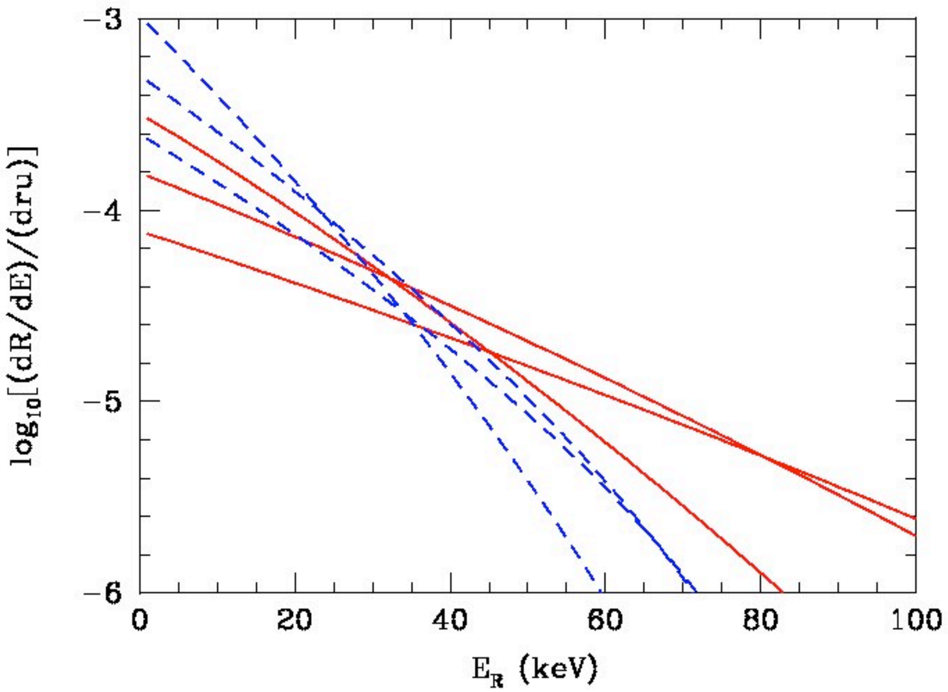
$$v_{min} = \left(\frac{E(m_A + m_\chi)^2}{m_A m_\chi^2} \right)^{1/2}$$

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

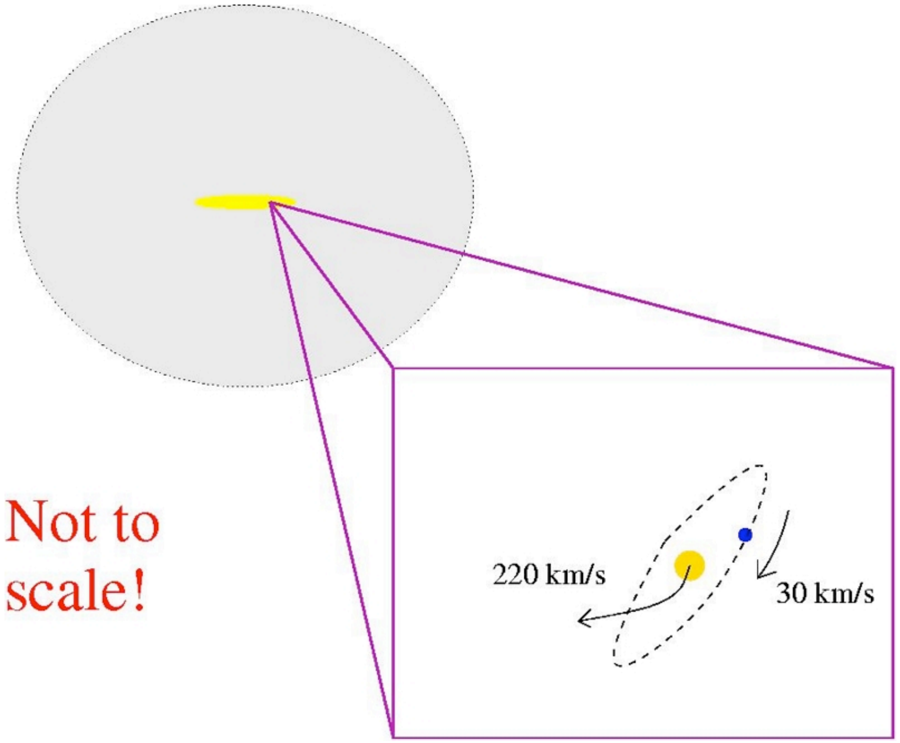
signals:

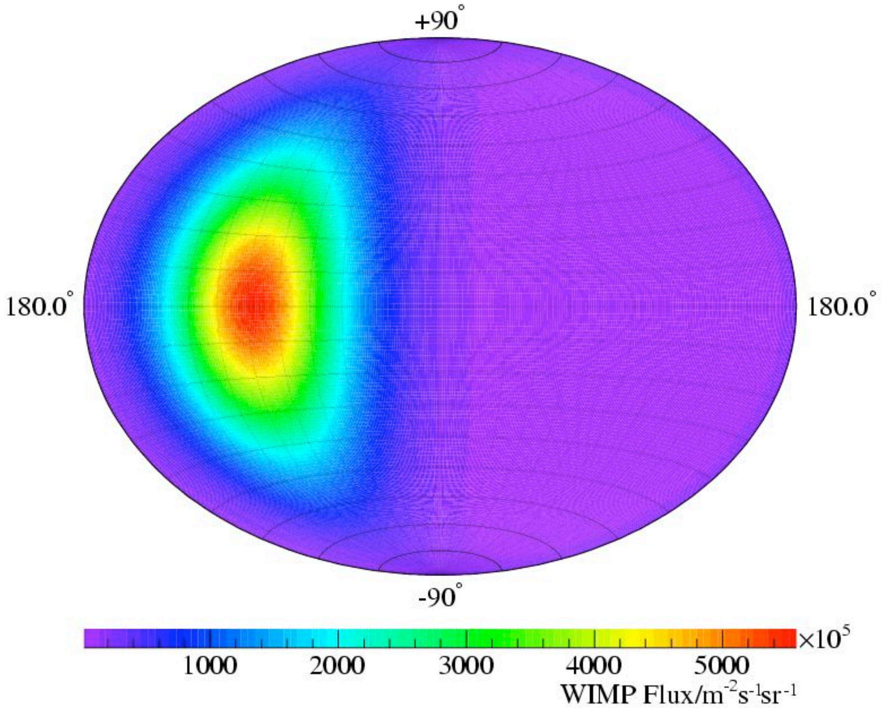
i) A^2 (mass of target nuclei) dependence of event rate Lewin & Smith

Ge and Xe m_χ = 50, 100, 200 GeV



ii) directional dependence of event rate Spergel

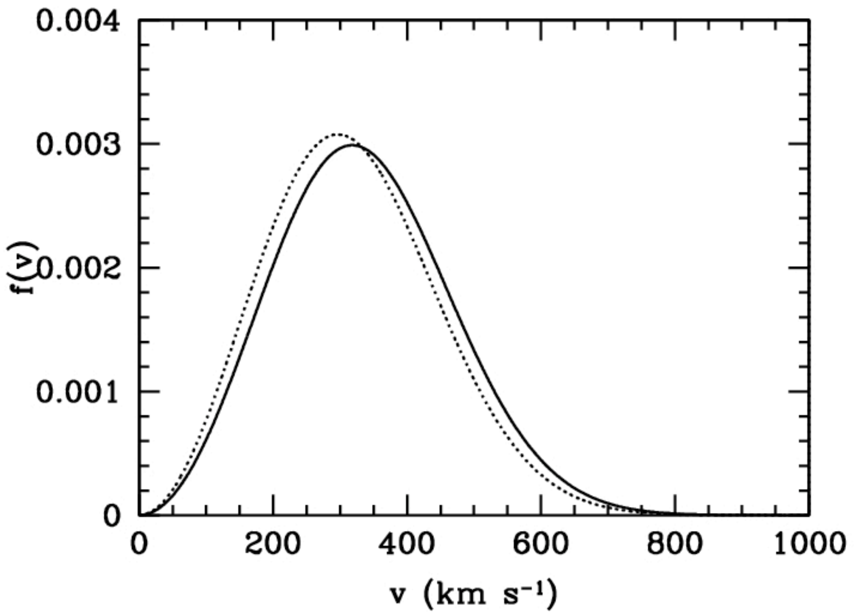




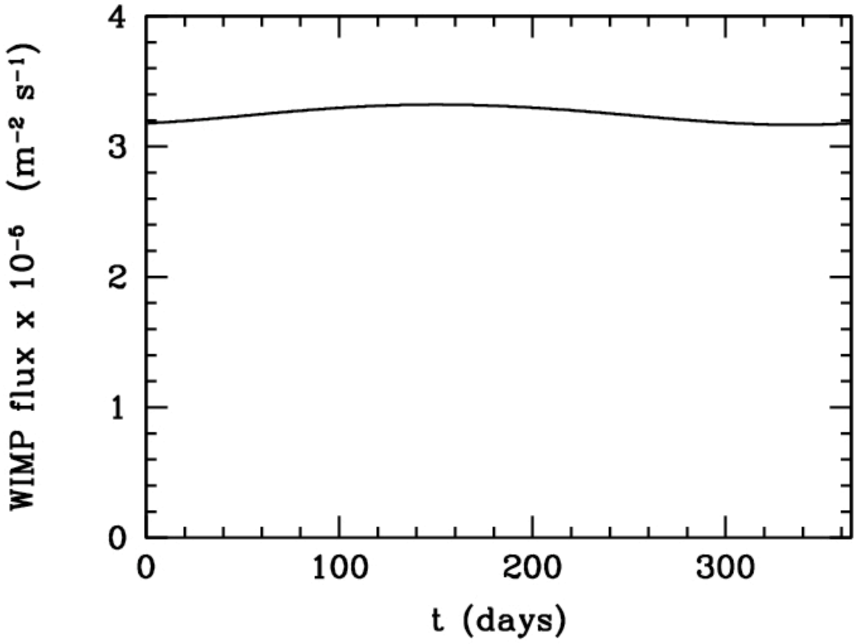
Large signal (potentially only O(10) events required [Morgan, Green & Spooner]) but need detector which can measure recoil directions.

iii) annual modulation of event rate

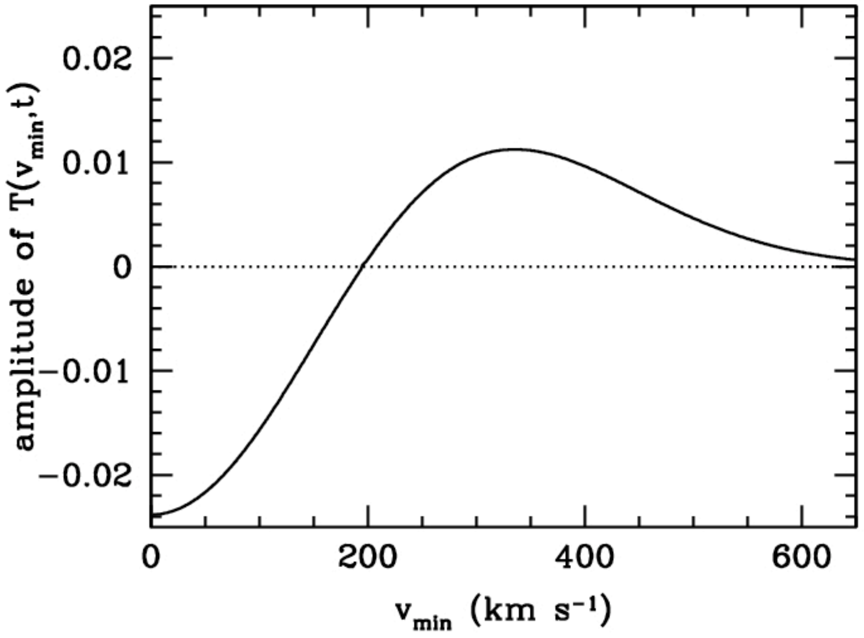
Drukier, Freese & Spergel



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.

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

current status

null-results

- **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,
  E_R=10 keV
  scintillation & heat

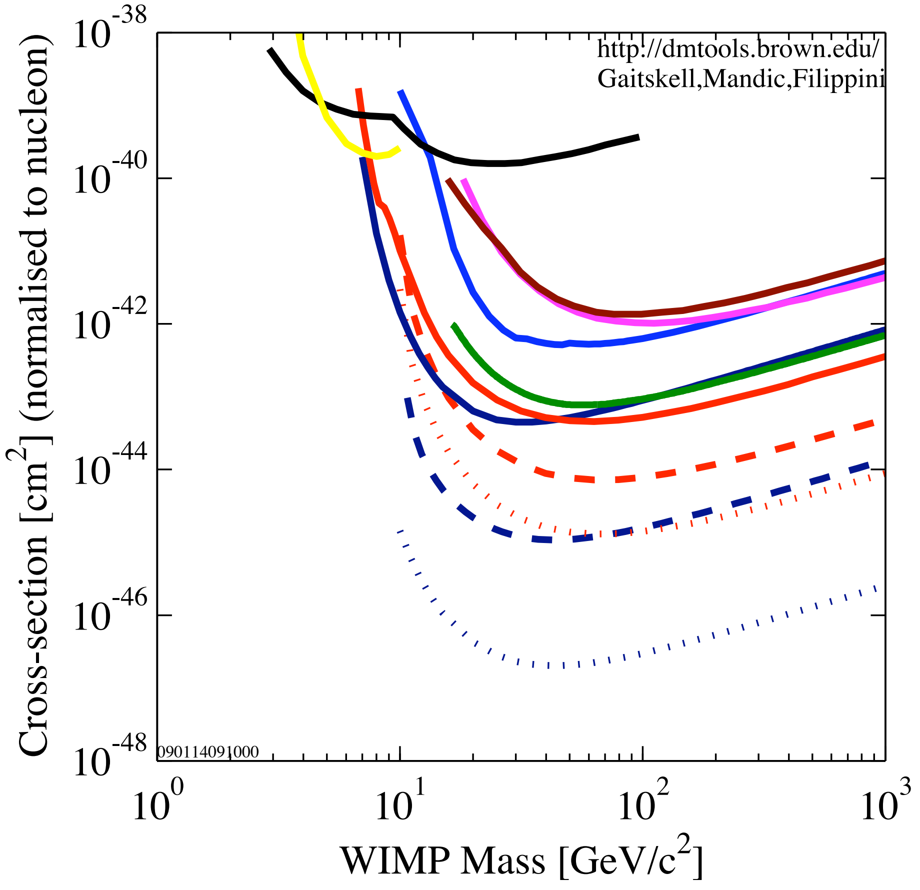
- **CoGENT**

  Ge, 8.4 kg-days,
  E_M= 0.23 keV
  ionisation

- **TEXONO**

  Ge, 0.337 kg-days,
  E_M=0.23 keV
  ionisation

spin-independent coupling



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.

current status

null-results

- **CDMS**

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

- **Edelweiss**

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

- **WARP**

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

- **CoGENT**

  Ge, 8.4 kg-days,
  E_M= 0.23 keV
  ionisation

- **Xenon10**

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

- **Zeplin III**

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

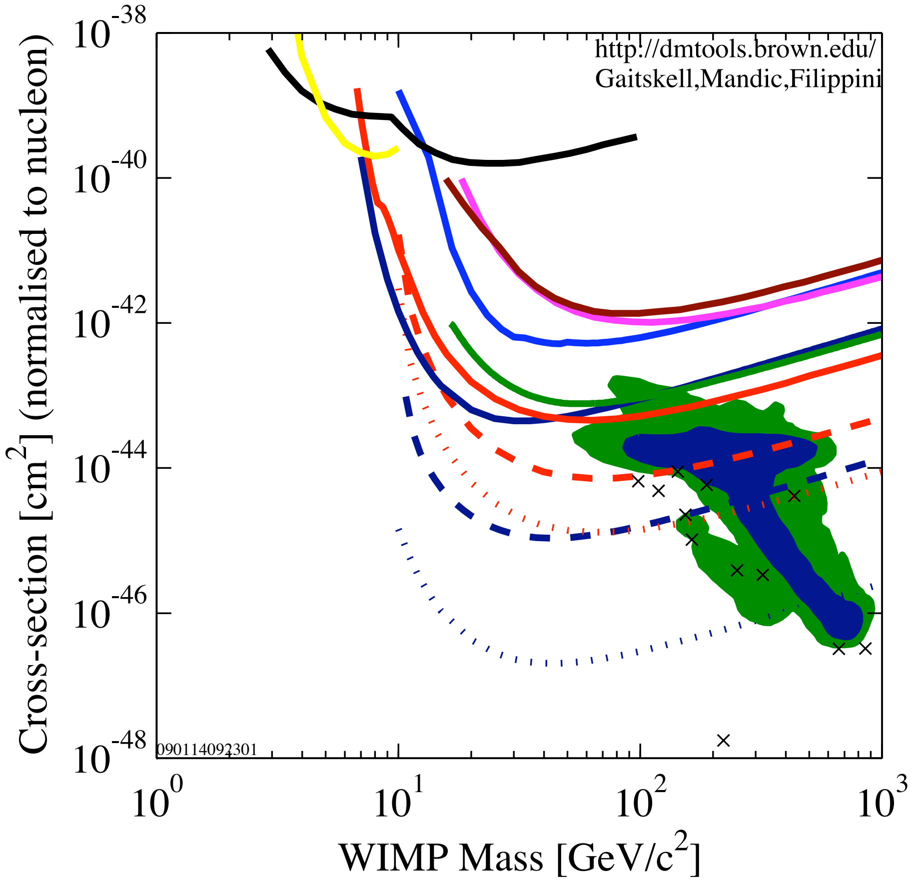
- **CRESST**

  CaWO$_4$, 20 kg-days,
  E_R=10 keV
  scintillation & heat

- **TEXONO**

  Ge, 0.337 kg-days,
  E_M=0.23 keV
  ionisation

spin-independent
coupling



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)

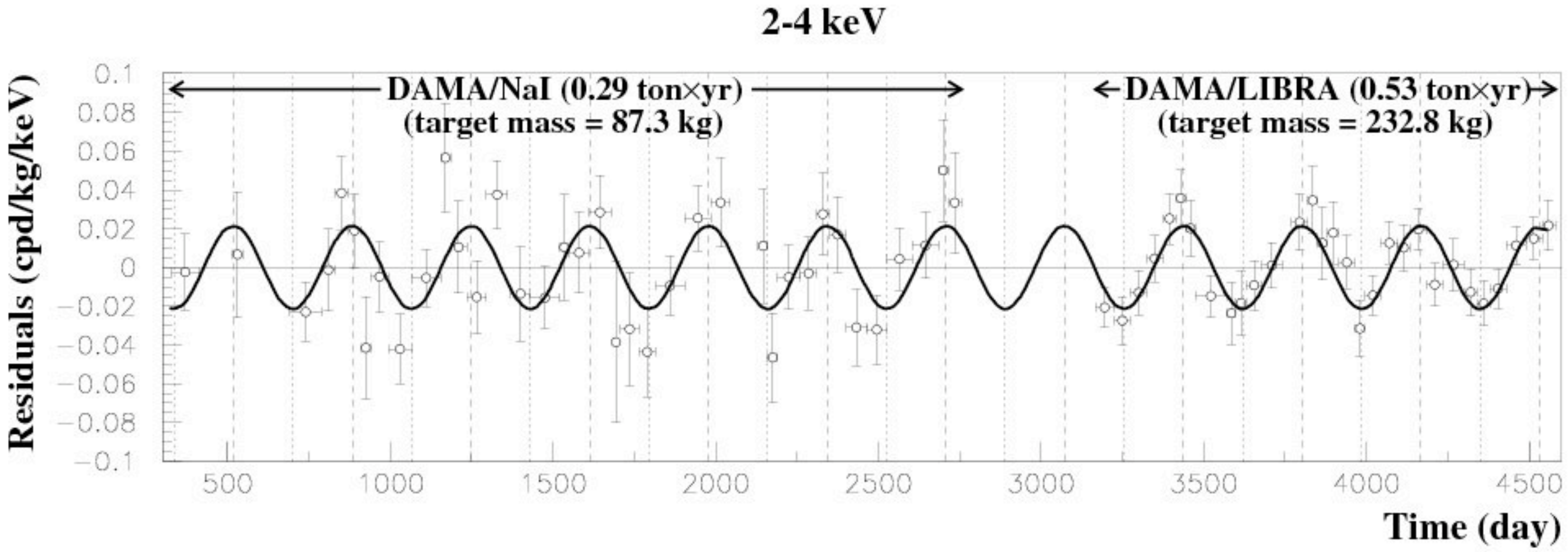
Other experiments (e.g. KIMS, COUPP) sensitive to spin-dependent coupling, but haven’t yet reached sensitivity to probe theoretically predicted cross-sections.

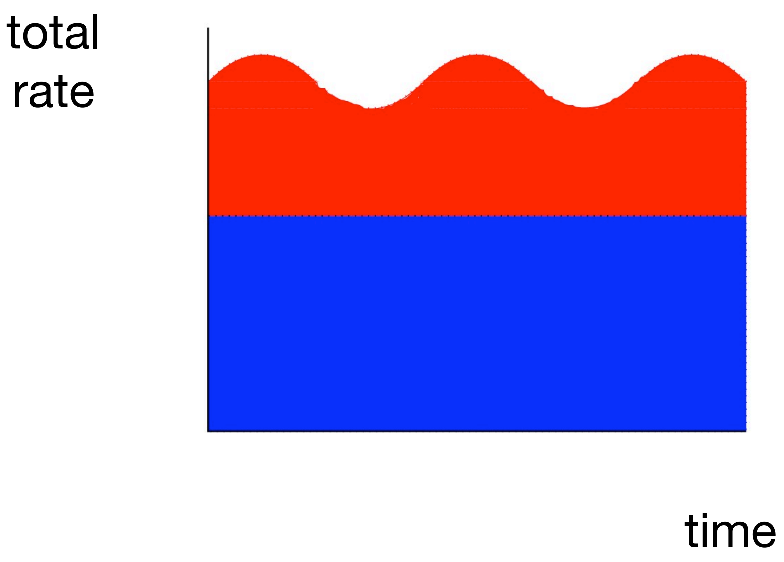
DAMA annual modulation signal

Bernabei et al.

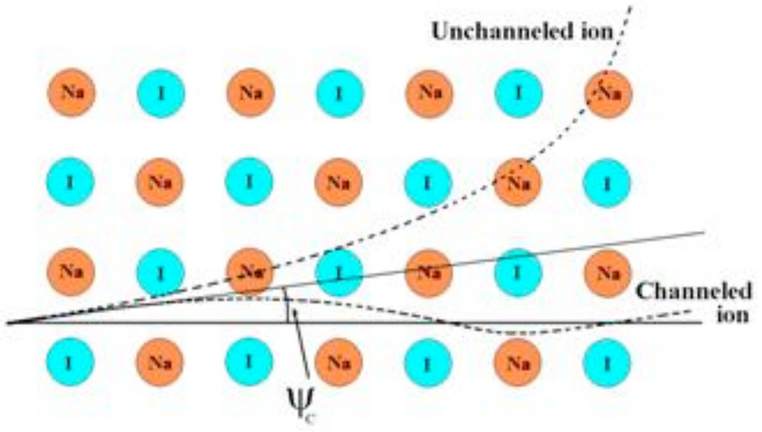
Annual modulation in scintillation pulses in NaI crystals first reported by DAMA in 1998.

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



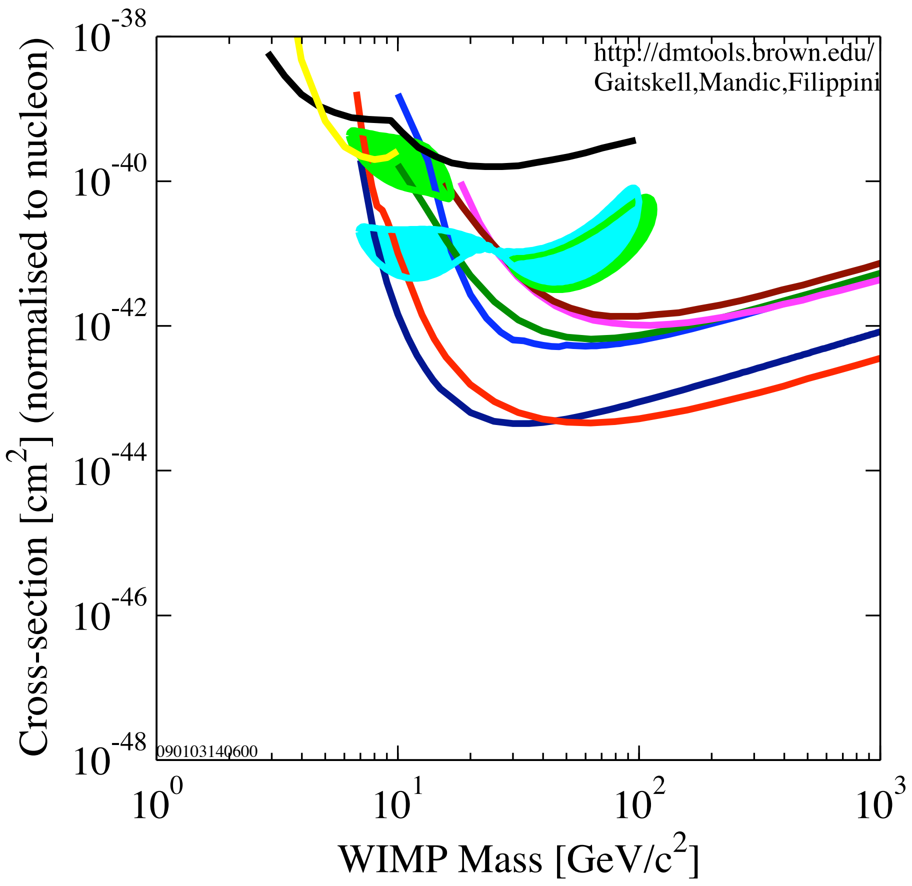


Channeling: recoils along crystal axes cause deposit larger fraction of energy to electrons (and recoil energy otherwise over estimated).



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



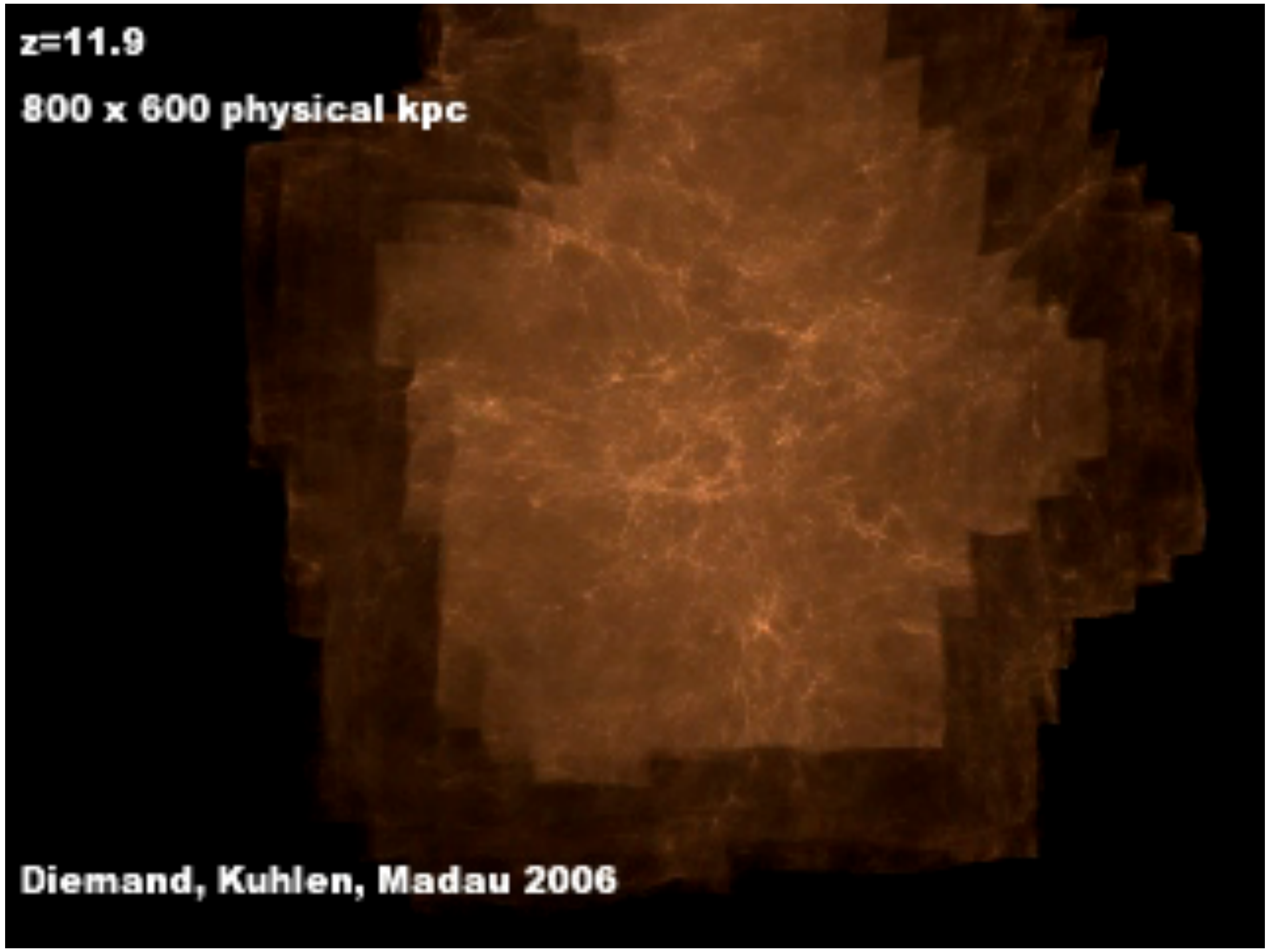
region of parameter space corresponding to DAMA data with/without channeling as calculated by Savage et al.

Dependence on the dark matter distribution

$$\frac{dR}{dE} \propto \sigma\rho \int_{v_{min}}^{\infty} \frac{f(v)}{v} dv$$

Standard halo model: isothermal sphere with isotropic Maxwellian velocity distribution

BUT structure forms hierarchically and "observed" and simulated halos are triaxial, anisotropic and contain substructure.



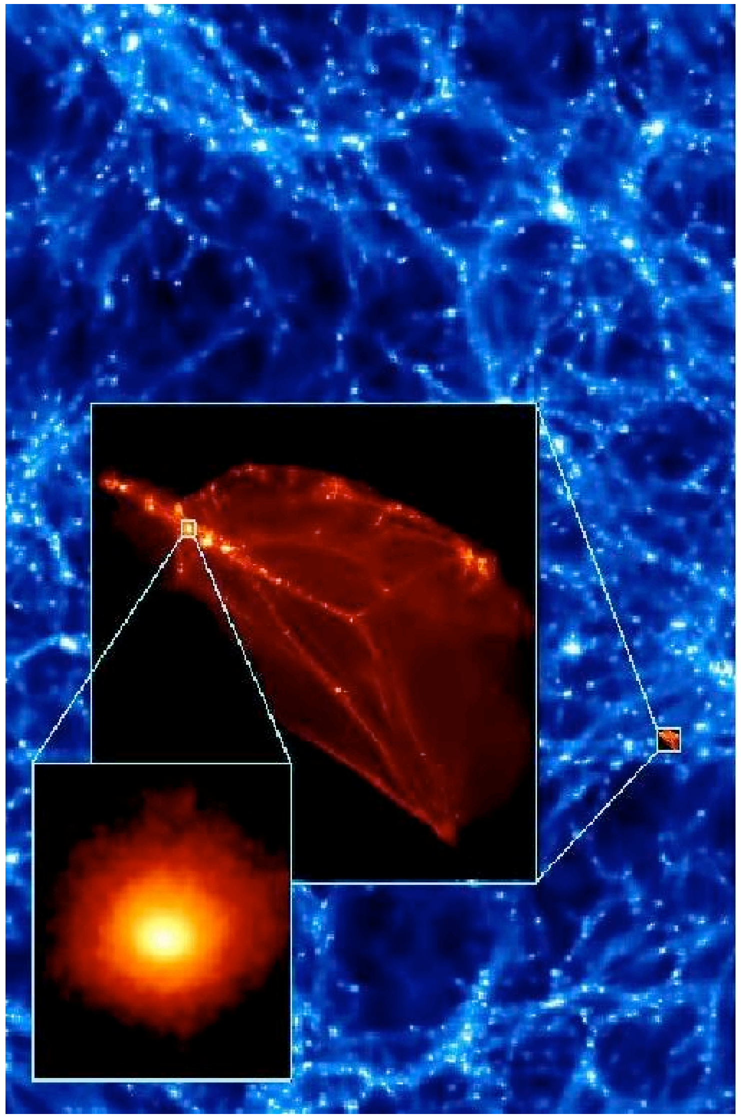
Diemand, Kuhlen, Madau 2006

WIMP direct detection probes the dark matter distribution on sub-mpc scales (c.f. ~100 pc resolution of Galaxy simulations, ~100 kpc radius of Milky Way)

Indirect detection rates enhance by clumping.

The best simulations of Milky Way like halos can’t resolve sub-halos smaller than $M \sim 10^5 M_\odot$.

The first WIMP microhalos to form have $M \sim 10^{-6} M_\odot$ (smaller density fluctuations erased by free-streaming Green, Hofmann & Schwarz)



simulation by
Diemand, Moore & Stadel

Open questions:

i) Do the microhalos survive to the present day (& significantly enhance the indirect detection signals)?

Lose mass due to interactions with stars and tidal stripping by gravitational field of parent halo.

Earth mass microhalos in the solar neighbourhood will typically have lost most of their but a high density central ‘cusp’ can survive.

Open questions:

i) Do the microhalos survive to the present day (& significantly enhance the indirect detection signals)?

Lose mass due to interactions with stars and tidal stripping by gravitational field of parent halo.

Earth mass microhalos in the solar neighbourhood will typically have lost most of their but a high density central ‘cusp’ can survive.

ii) What happens to the matter lost from the microhalos? (is the dark matter distribution smooth on the ultra-local scales probed by direct detection experiments?).

?

work in progress

Summary

- Galaxy halos (and the Universe as a whole....) contain significant amounts of non-baryonic dark matter (assuming Newtonian gravity/GR is correct).

- WIMPs generically have the right sort of present day density and supersymmetry provides us with a concrete candidate, the lightest neutralino.

- WIMPs can be detected indirectly (via their annihilation products) and and directly (via their elastic scattering from nuclei).

- Good prospects for detection in the next few years, but will probably need consistent signals from different experiments in different channels to be convincing.

- Detection signals depend on the small scale dark matter distribution (which depends on the fate of the first dark matter halos to form).