Overview of dark matter

Anne Green
University of Nottingham

Why?

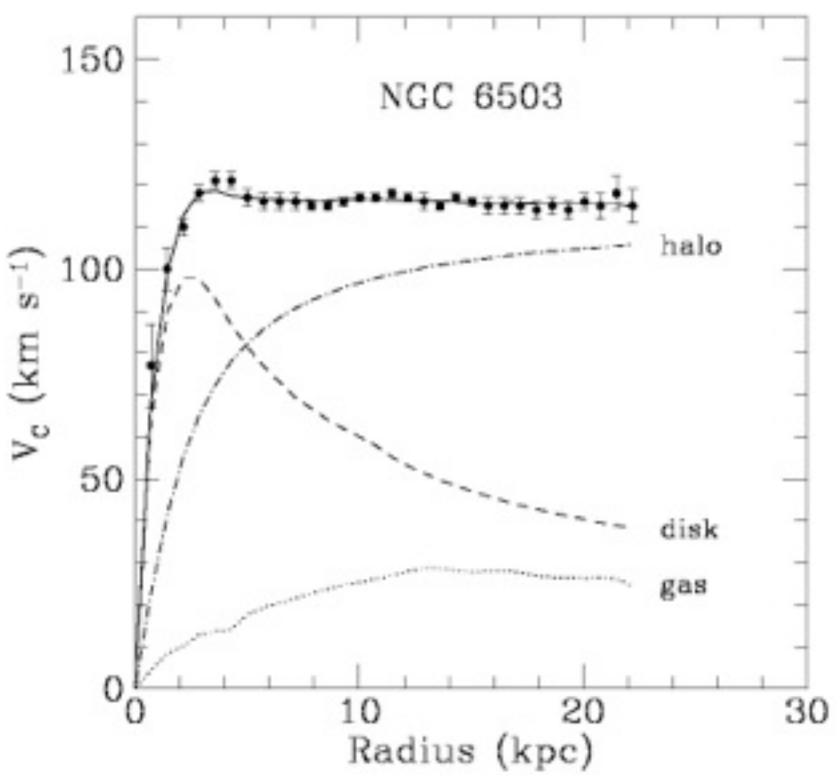
What?

How?

Why?

Galaxies

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



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

$$v_{\rm rot} \sim {\rm const}$$

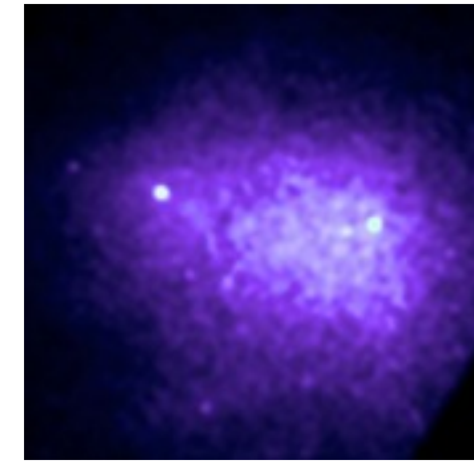
$$M(<r) \propto r$$

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

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

Galaxy clusters and large scale structure

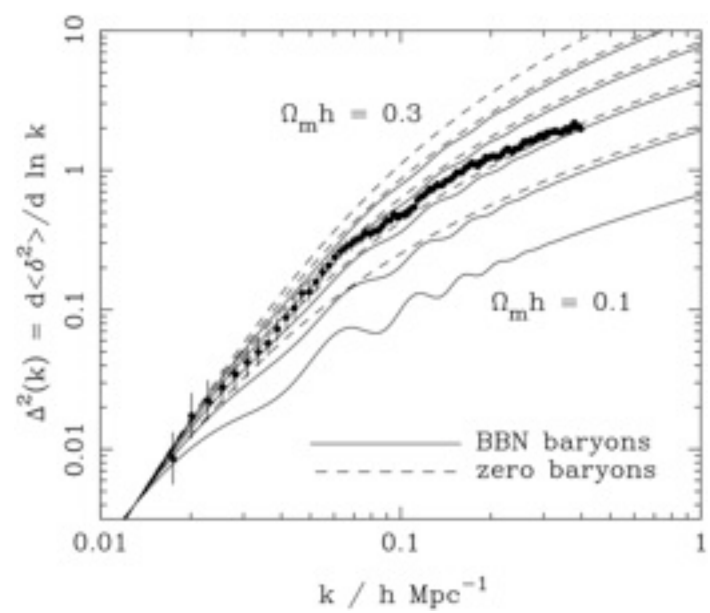
Total mass of galaxy cluster ~4+ times visible mass in order to confine galaxies and hot gas.



Galaxy clustering depends on the matter & baryon densities:

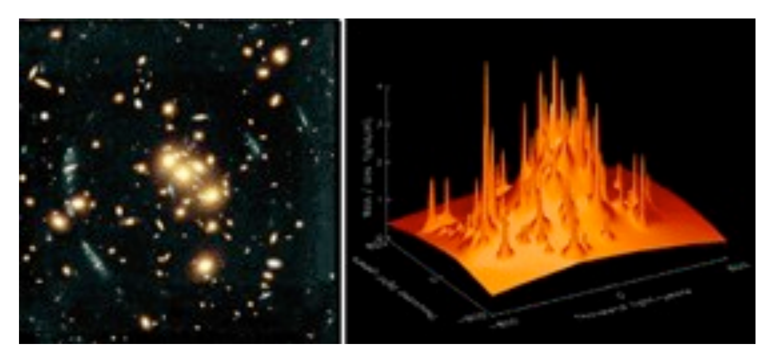
$$\Omega_{\rm m} h = 0.168 \pm 0.016$$

$$\frac{\Omega_{\rm b}}{\Omega_{\rm m}} = 0.185 \pm 0.046$$



[2dFGRS]

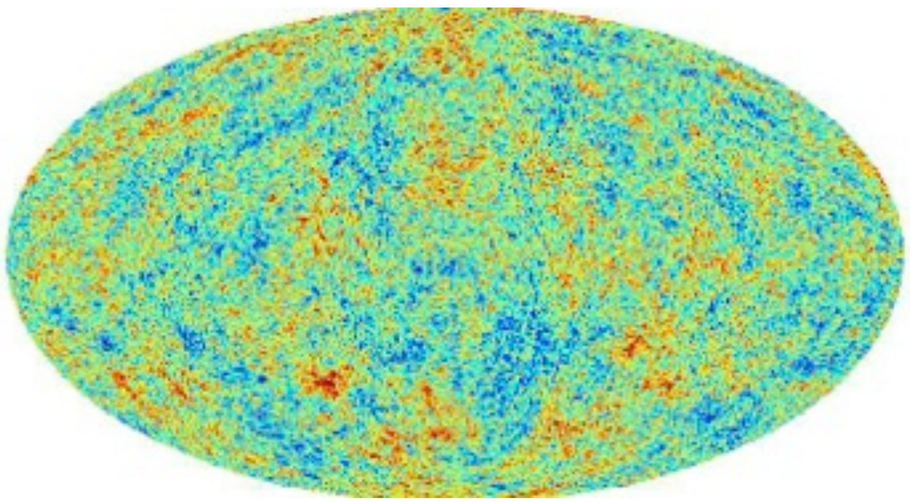
Can map the total matter distribution by measuring deflection of light by gravitational lensing.

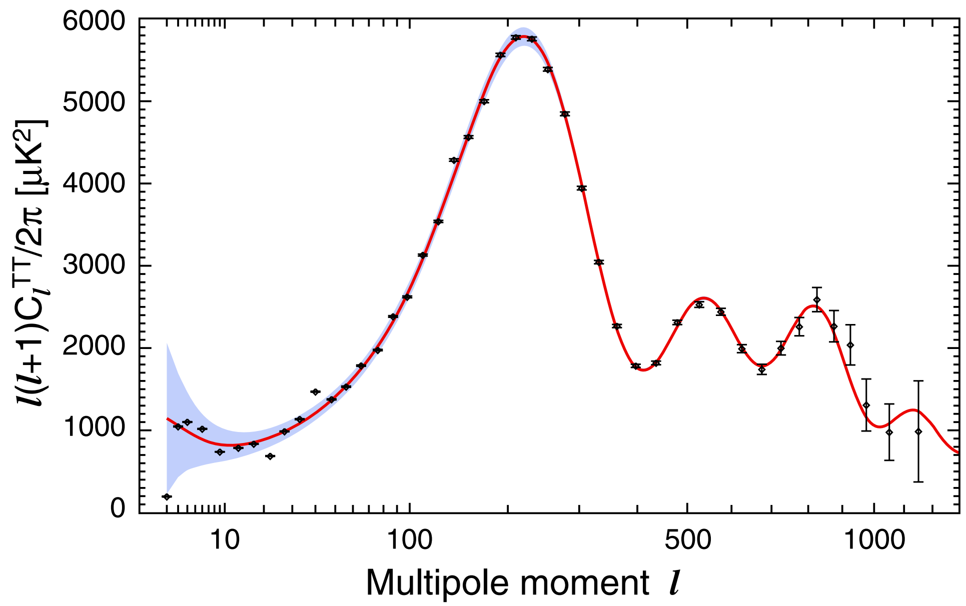


[Tyson et al.]

Cosmic microwave background radiation

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





[WMAP]

Characteristic scale: total energy density close to critical

$$-0.0133 < \Omega_k < 0.0084$$

WMAP + BAO + H_0

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

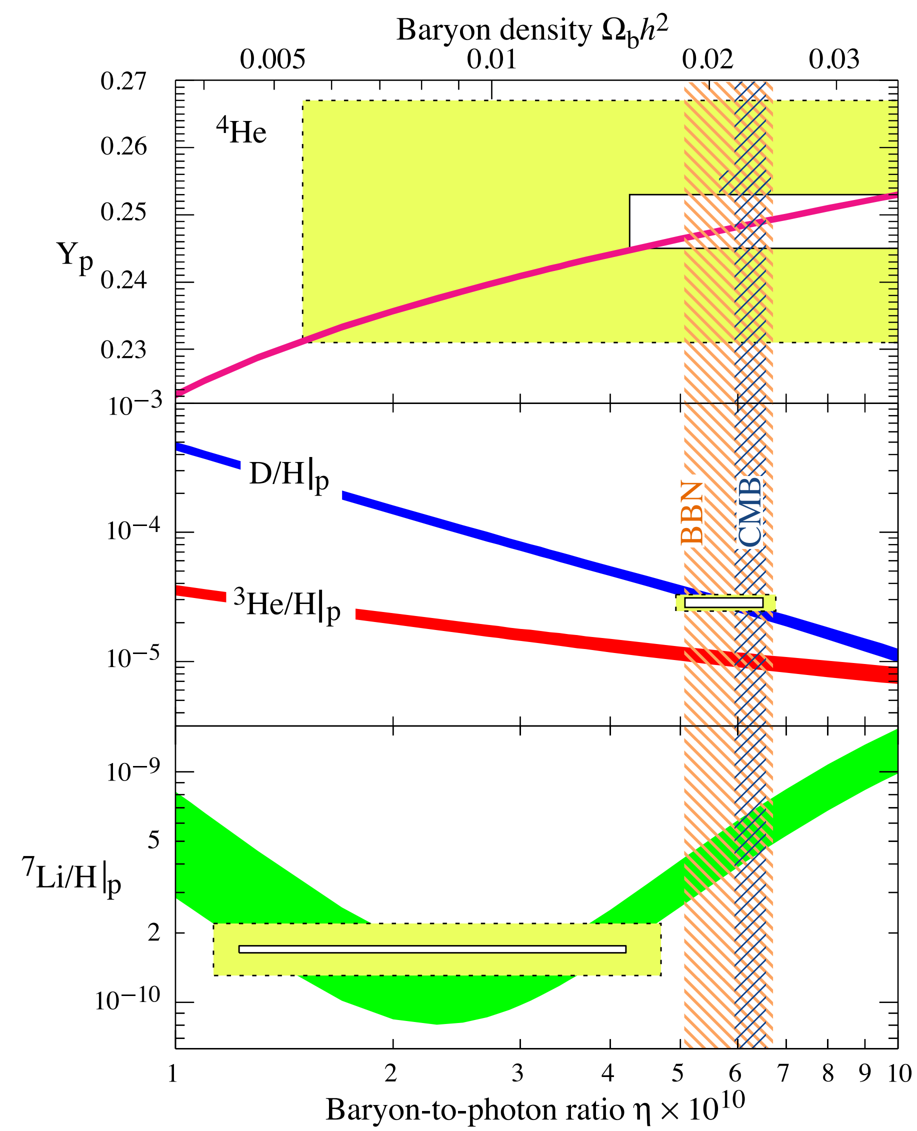
$$\Omega_{\rm cdm} h^2 = 0.1126 \pm 0.003$$

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.

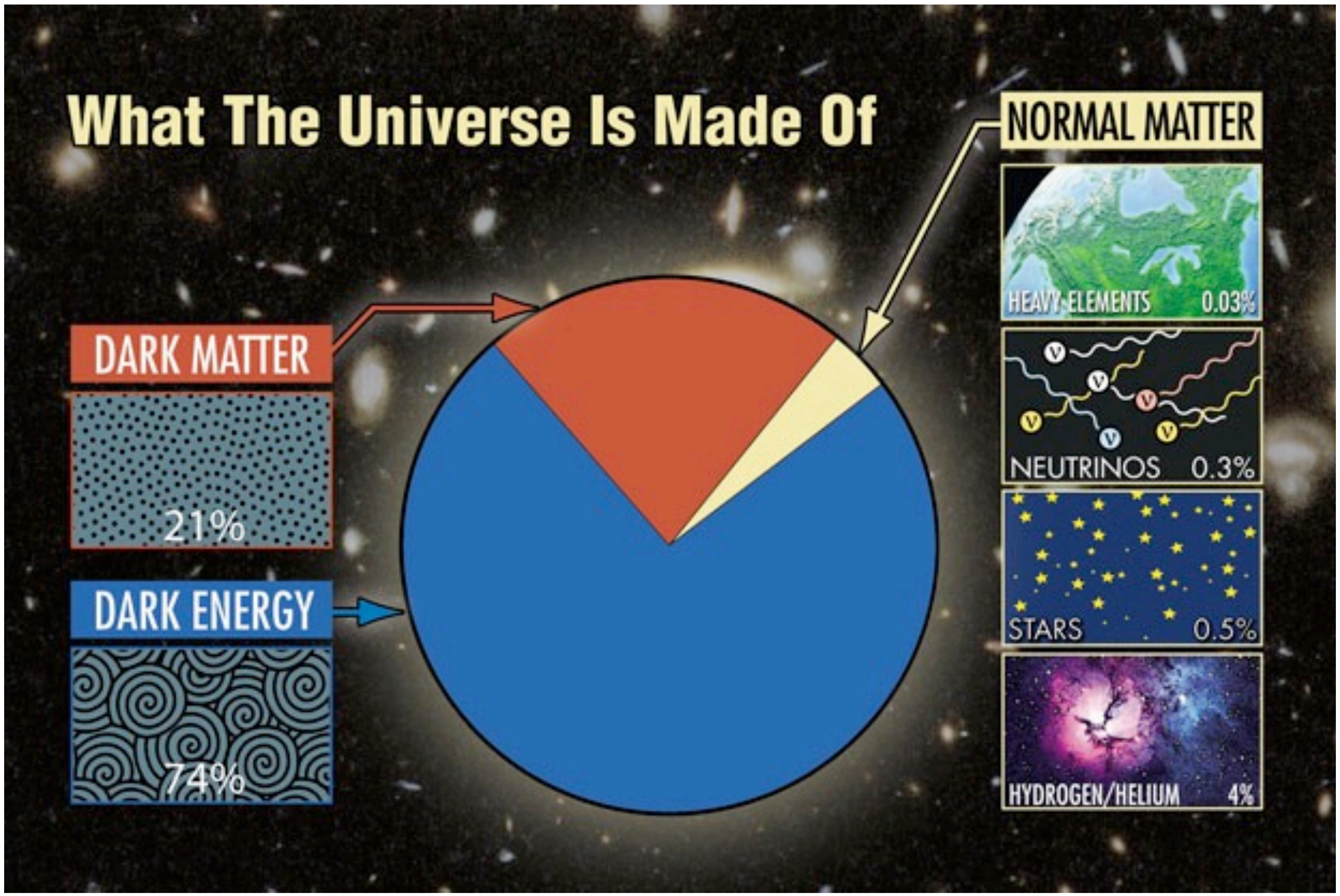
Can measure baryon density by comparing theoretical calculations with observed high redshift (~primordial) abundances.



[Fields and Sarkar]

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

Precision cosmology: (some) cosmological parameters measured to several significant figures.



BUT 95% of the Universe is exotic and unknown....

Detecting dark matter would:

★ answer a major fundamental question ('what is the Universe made of?').

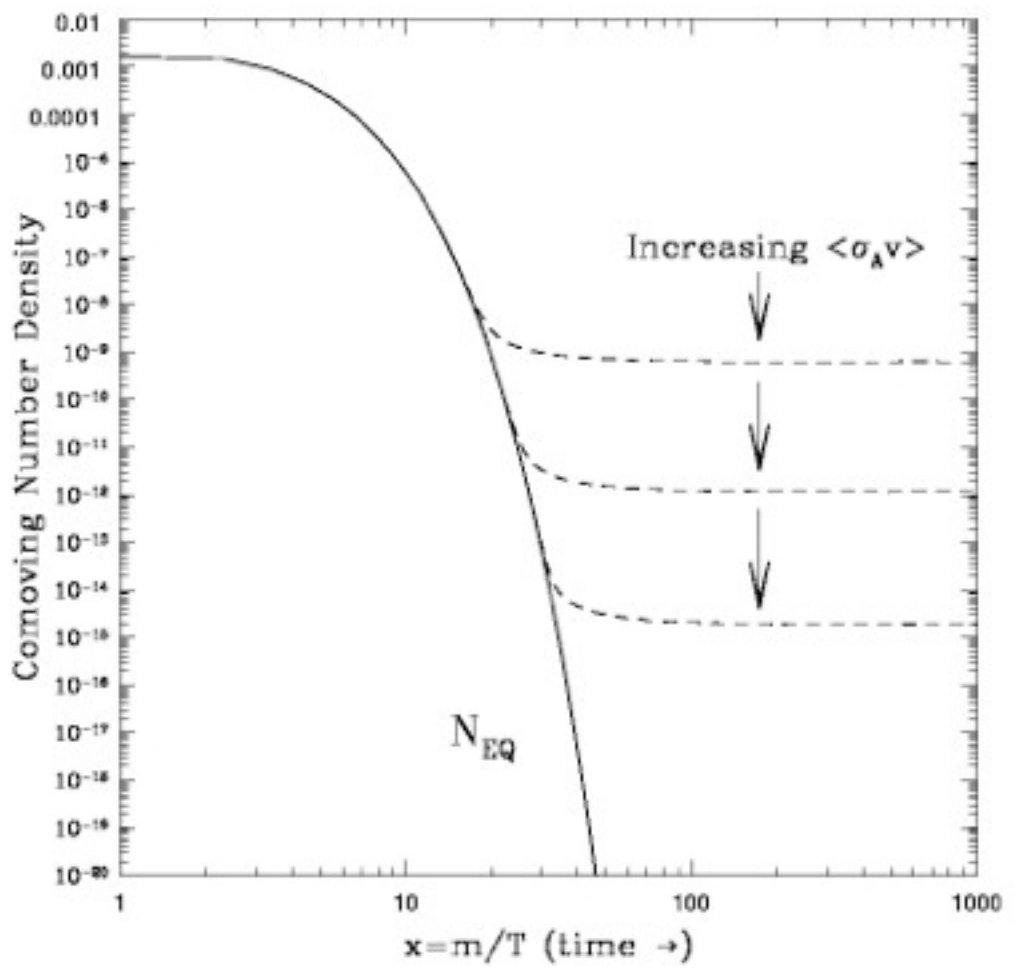
★ provide confirmation of the standard cosmological model (and rule out modified gravity e.g. MOND, TeVeS [Skordis]).

★ probe physics beyond the standard model.

What?

WIMPs: generic motivation

A stable, **W**eakly **I**nteracting **M**assive **P**article in thermal equilibrium in the early Universe will have an interesting density today.



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

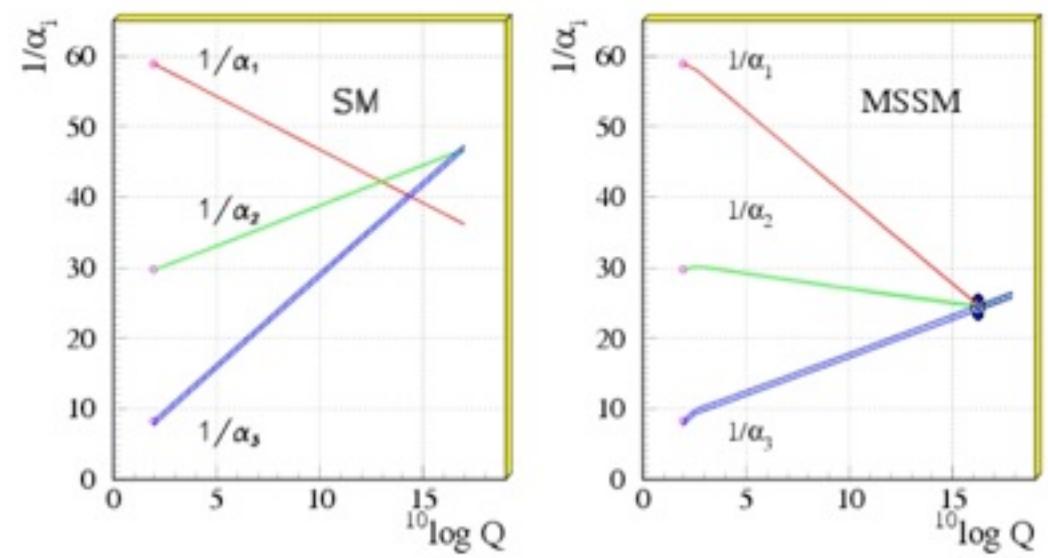
$$\chi + \chi \longleftrightarrow X + \bar{X}$$

Supersymmetry

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

Motivations:

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



[Kazakov]

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.

BUT

WIMPs are not the only cold dark matter candidate

[Cirelli; Frandsen; Jedamzik]

and

neutralinos are not the only WIMP candidate.

[Schmidt-Hoberg; Belyaev; Pilaftsis,]

How?

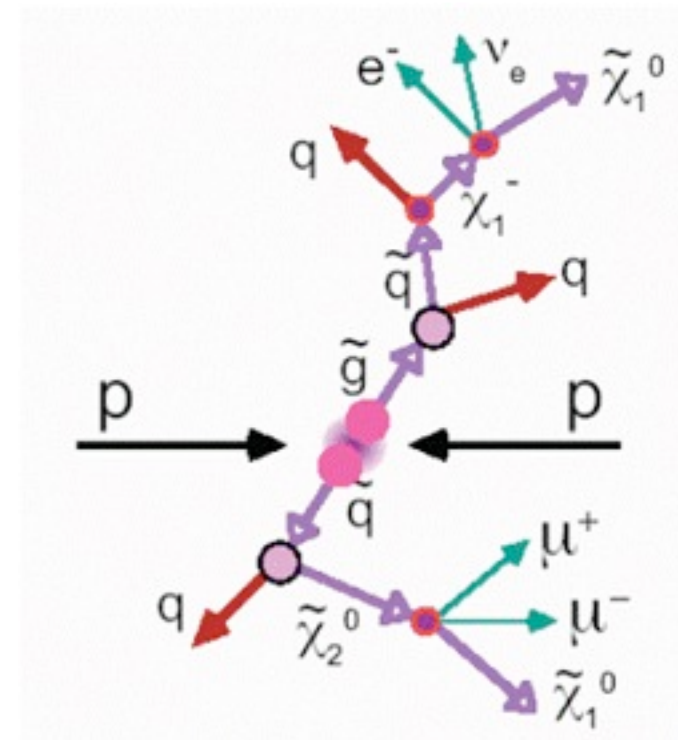
Collider production

Classic signal:

missing transverse energy + jets.

(but many model-dependent SUSY searches).

[Ellis; Barr; Worm]



Collider production and detection of a WIMP-like particle would be very exciting, but wouldn't on it's own solve the dark matter problem.

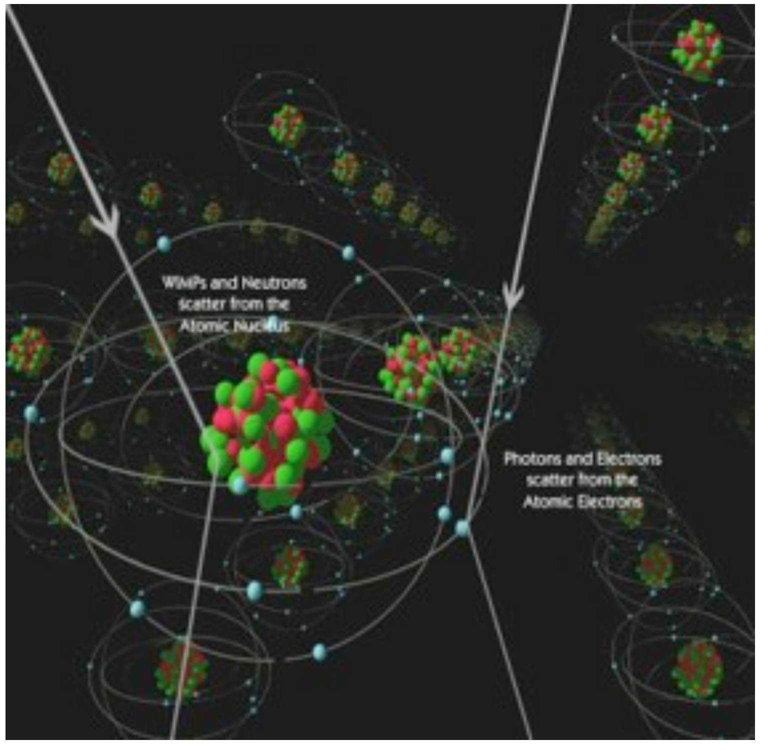
(Do they have lifetime greater than the age of the Universe?
What is their cosmological abundance?)

What could the LHC tell us about the properties of a DM candidate?

If the LHC doesn't see any signs of SUSY (or other BSM physics) what would that tell us?

Direct detection

Detect nuclear recoils induced when WIMPs elastic scatter off detector nuclei, via energy deposited in detector (ionisation, scintillation, phonons).



Interaction between WIMP and nucleus can be spin-independent (scalar) or spin-dependent (axial-vector). Most, but not all, current (and planned future) experiments use heavy targets for which spin-independent coupling dominates.

Differential event rate: (assuming elastic scattering & equal couplings to p and n)

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

n.b. depends on (ultra-) local DM distribution [Fairbairn]

For a convincing detection will need to demonstrate that events are due to WIMPs and not backgrounds.

electron recoils due to βs and γs:

look at multiple energy deposition channels (but beware surface events)

nuclear recoils due to neutrons from cosmic rays or local radioactivity:

indistinguishable on an event by event basis

[Kraus; Sumner; Nikkel; Araujo; Henry]

[Boulby mine]

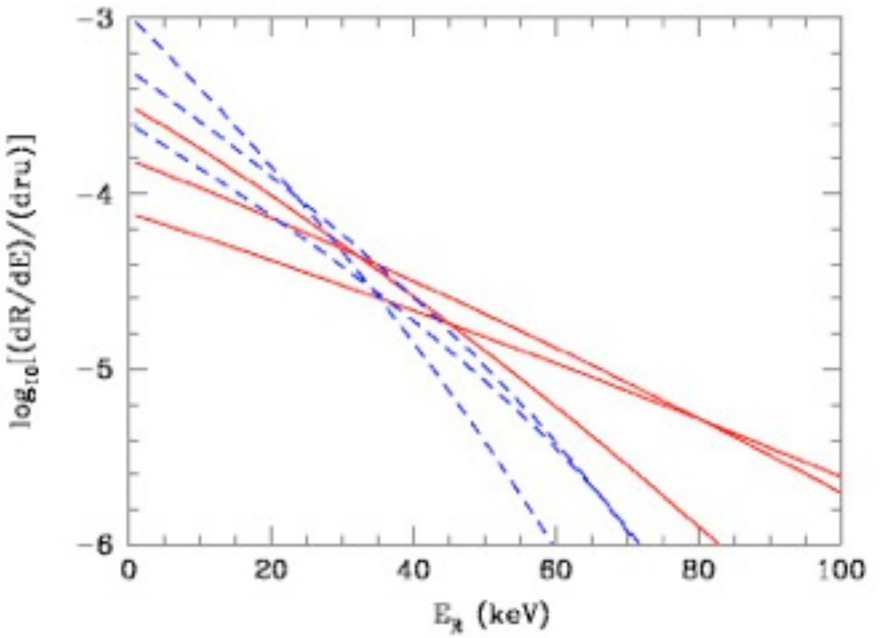
[Zeplin III]

Signals:

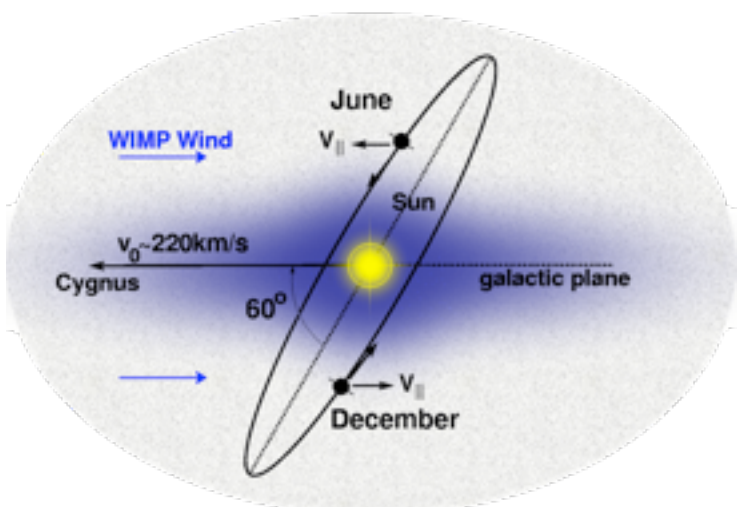
i) Materials signal

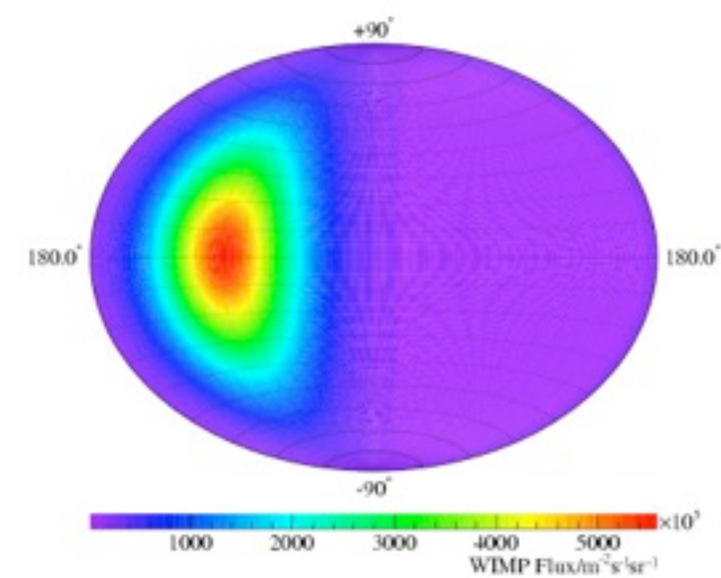
Differential event rate depends on WIMP and target nuclei masses.

Ge and Xe m_χ = 50, 100, 200 GeV



ii) Direction dependence [Spergel]

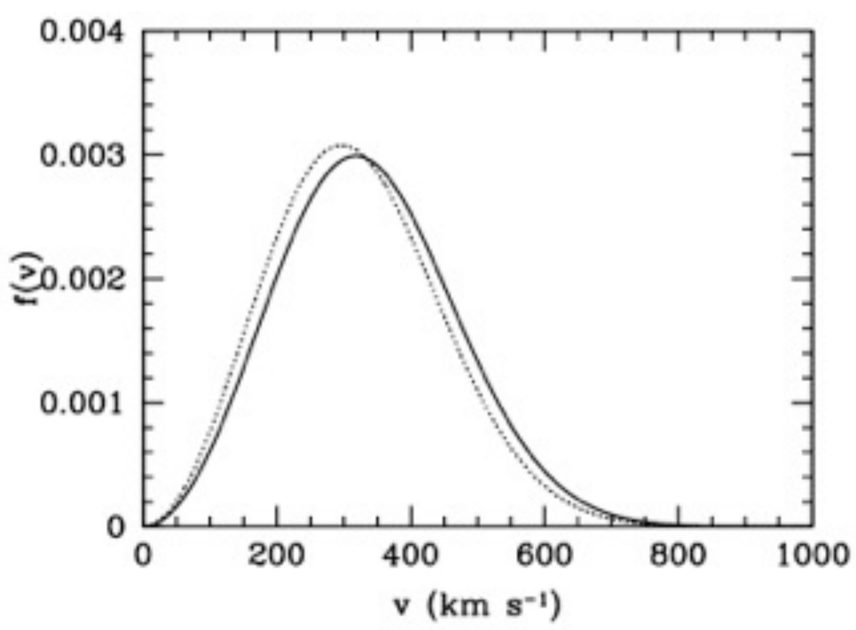




Large signal (potentially only O(10) events required to detect anisotropy [Morgan, Green & Spooner] and O(30) to confirm peak direction [Green & Morgan].) [Morgan]

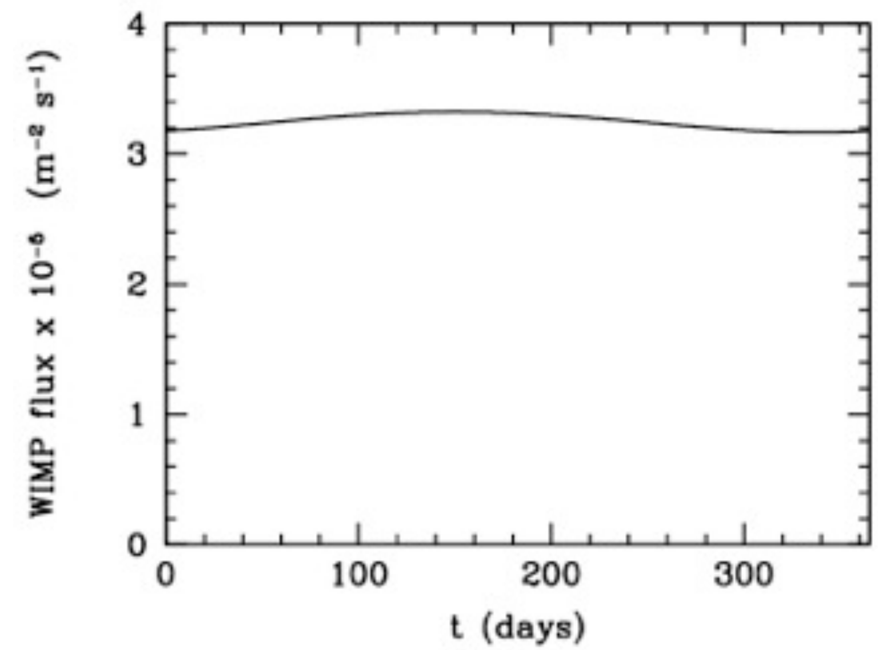
But need a detector (e.g. DMTPC, DRIFT, MIMAC, NEWAGE) which can measure recoil directions. [Sadler]

iii) Annual modulation [Drukier, Freese & Spergel]

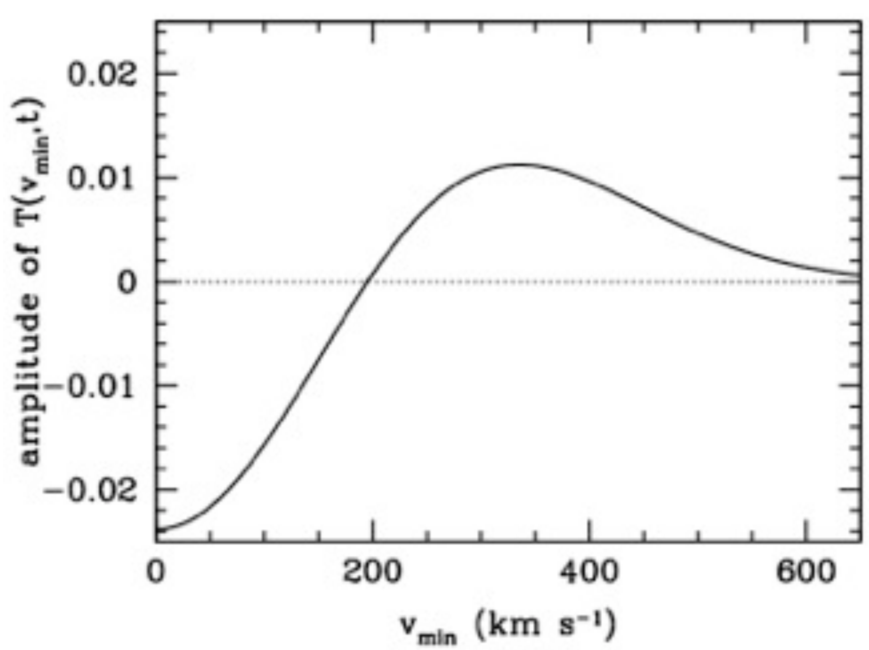


WIMP ‘standard’ (Maxwellian) speed dist.

detector rest frame (summer and winter)



total WIMP flux



modulation amplitude

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

Current status:

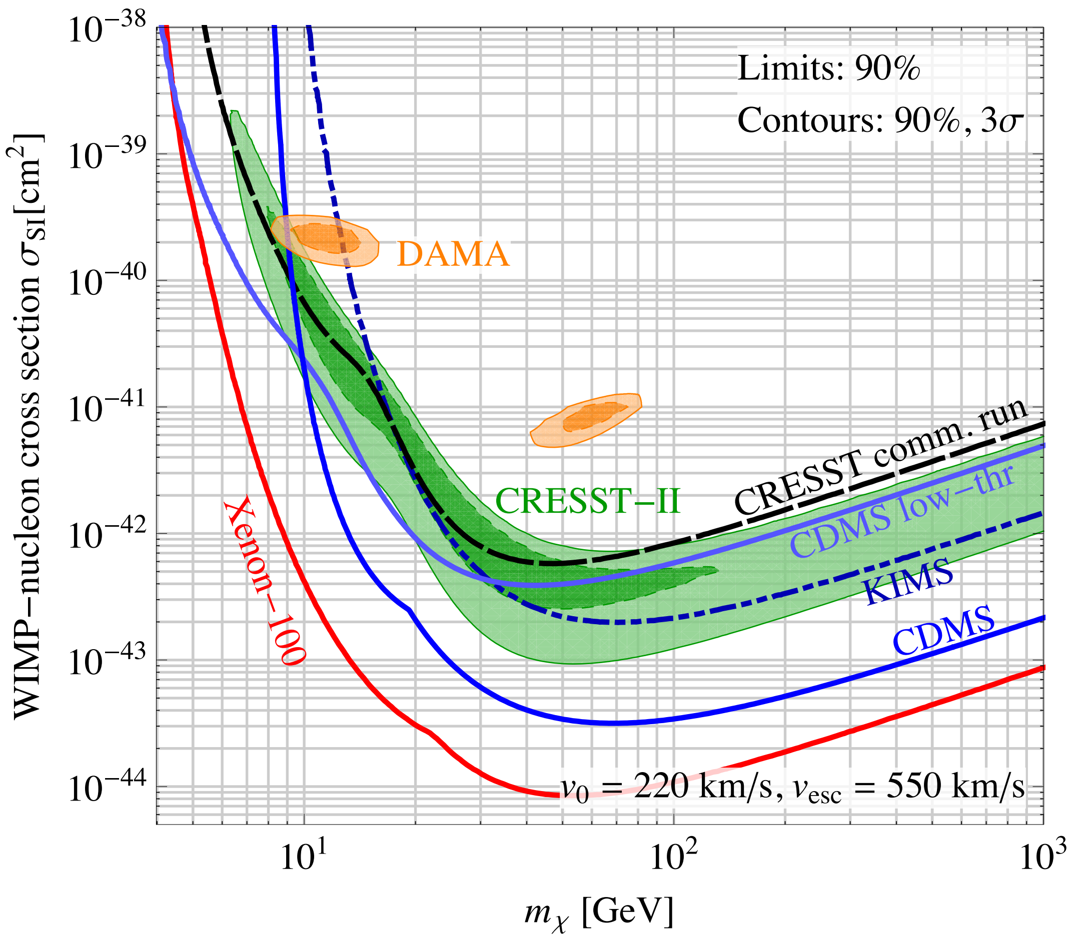
Exclusion limits: CDMS, Xenon-100, Zeplin III

'Hints':

excesses above expected backgrounds CoGeNT, CRESST

annual modulations CoGeNT, DAMA

which can individually be interpreted in terms of light (~10 GeV) WIMPS.



[Kopp, Schwetz & Zupan]

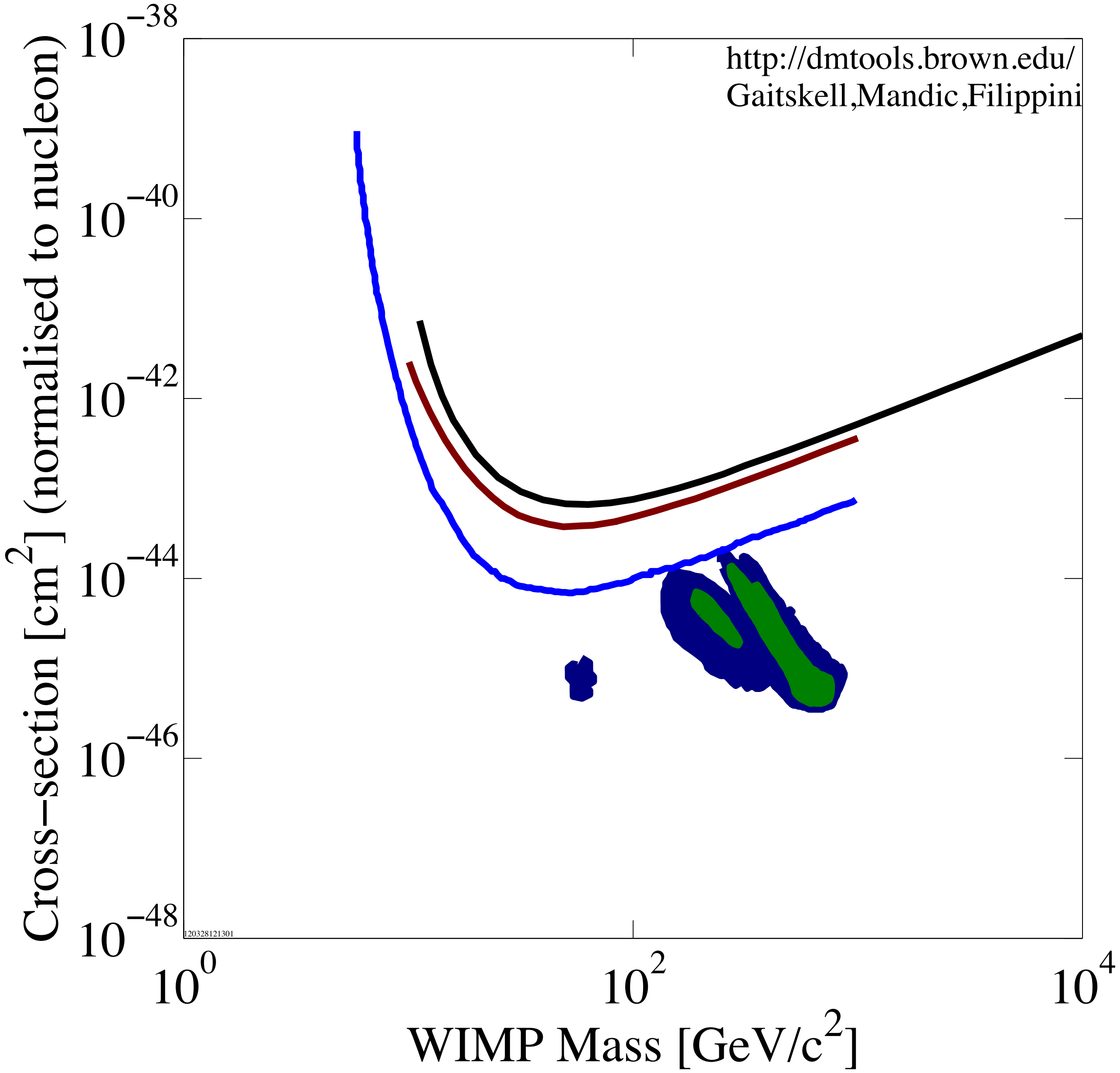
n.b.

Allowed regions and exclusion limits depend on assumptions about WIMP interactions and velocity distribution.
[Kahlhoefer; Fairbairn; McCabe]

But

Currently no consistent WIMP interpretation of all experimental data. [Frandsen et al.; Kopp, Schwetz & Zupan]

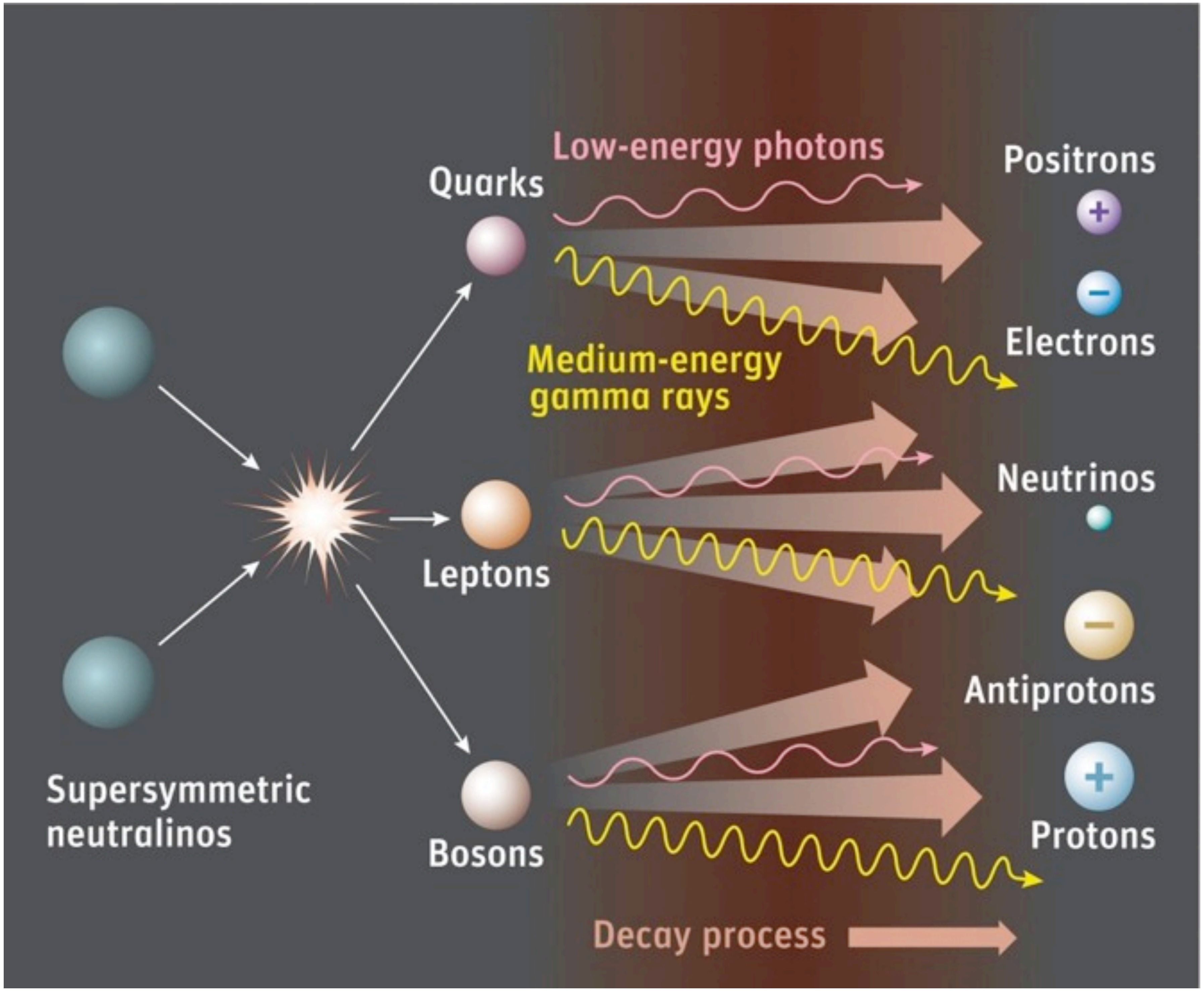
Comparison of current direct detection constraints on the WIMP mass and cross-section with global fits of constrainedMSSM:



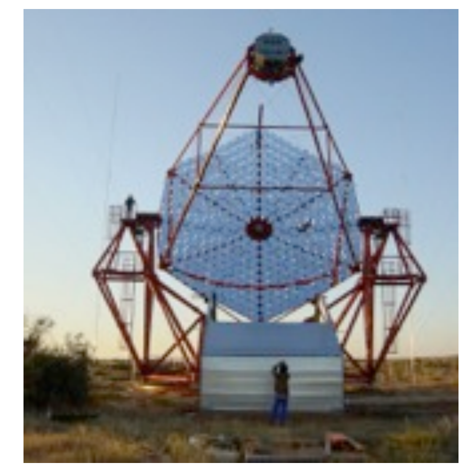
CDMS II
Xenon 100
Zeplin III, 2nd science run

Bertone et al., global fits of CMSSM
(flat priors, including Xenon100 & first LHC data)

Indirect detection



[Fermi]



[ACTs]

[PAMELA]

Astrophysical input

- Gamma-ray flux proportional to integral of ρ^2 along line of sight.

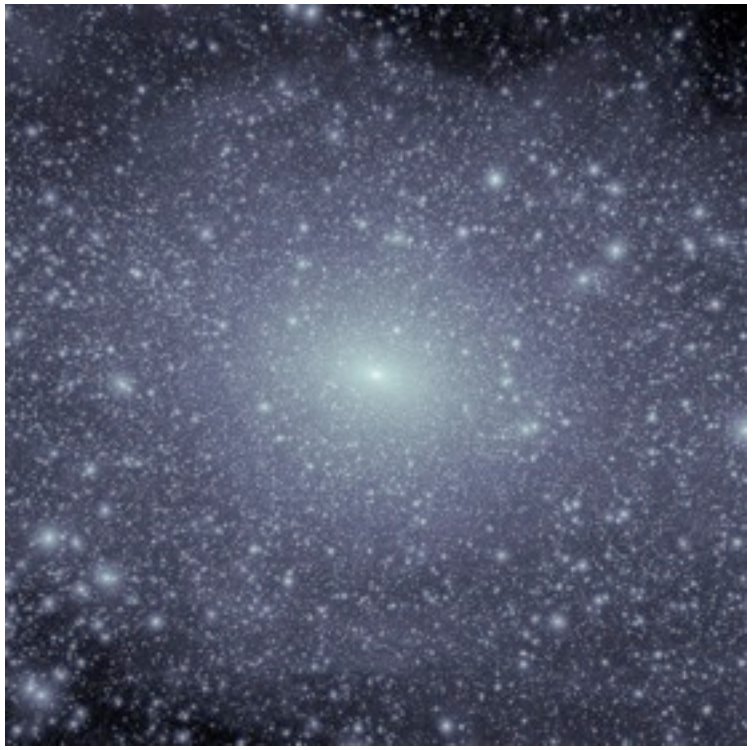
Largest signals expected from high density regions (e.g. Galactic centre, dwarf galaxies,...)

- Positrons propagate through MW magnetic field and reach Earth from ~kpc region, antiprotons from ~5-10 kpc.

- Substructure enhances rates [Bergstrom, Ullio & Buckley], enhancement relative to smooth halo parameterised by boost factor, B.

Different species probe different scales/regions (and often on scales far smaller than those directly resolved by numerical simulations).

Boost factor species/energy/direction dependent and not accurately known.

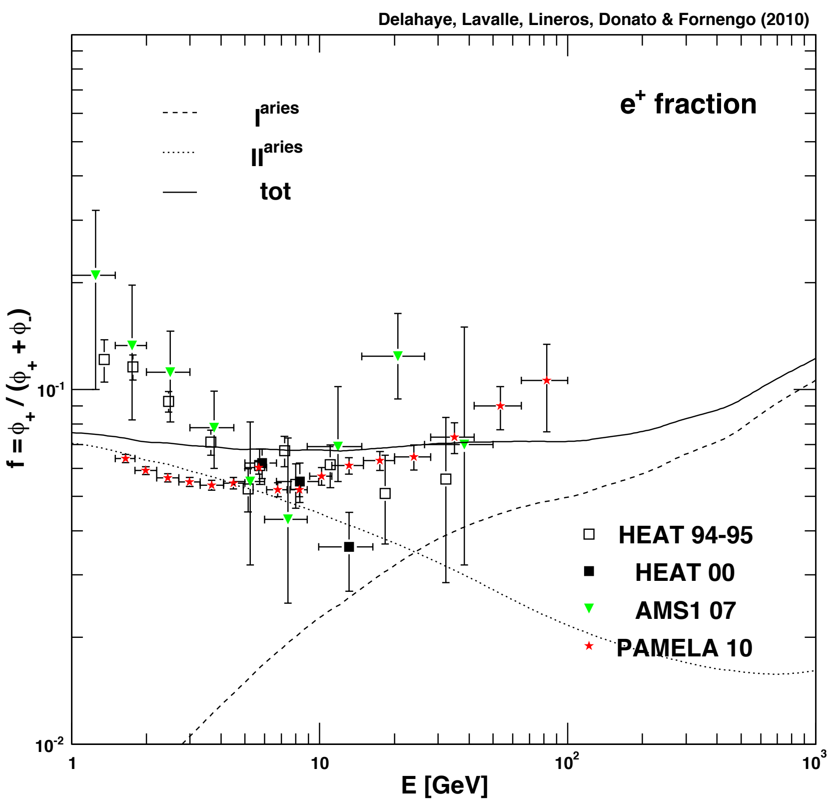


[Via Lactea]

- Often need to distinguish WIMP annihilation products from astrophysical ‘backgrounds’.

Current status:

Positrons: excess in positron fraction between 10 and 200 GeV



- - - - - primaries
produced by astrophysical sources, supernovae remnants and pulsars

.... secondaries
produced by interactions between cosmic rays and interstellar gas

Could be produced by astrophysical sources.

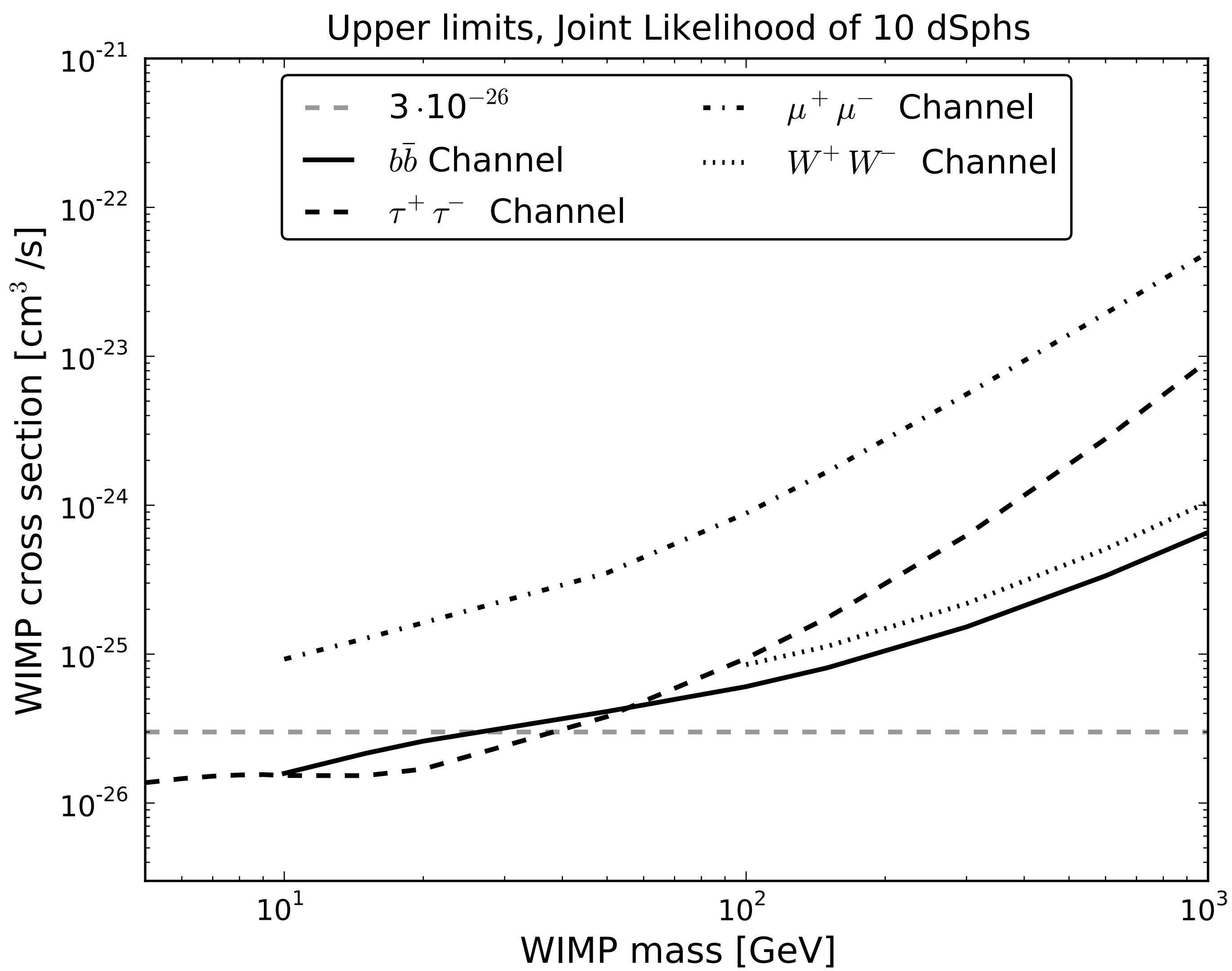
IF due to DM annihilation would need:

i) large enhancement in annihilation rate (big DM clump within ~kpc, or enhancement of annihilation cross-section, or non-thermal WIMP production)

ii) to not overproduce anti-protons (or gamma-rays or affect the CMB...)

Gamma-rays: just reaching sensitivity required to detect gamma-rays from WIMP annihilation.

e.g. constraints on WIMP annihilation cross-section from stacked Fermi observations of 10 Milky Way dwarf galaxies, beginning to exclude light WIMPs with canonical annihilation cross-section [see also Geringer-Sameth & Koushiappas; Cholis & Salucci]



dependence on how WIMPs annihilate

value corresponding to observed CDM density

Summary

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

★ WIMPs are generically a good (but not unique) dark matter candidate, and supersymmetry provides us with a concrete (but not unique) candidate, the lightest neutralino.

★ WIMPs can be produced at colliders, or detected directly or indirectly.

★ Very good prospects for detection in the next few years, but will probably need consistent signals in different channels to be convincing (c.f. ‘cosmic complementarity’).