The search for dark matter

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Why?

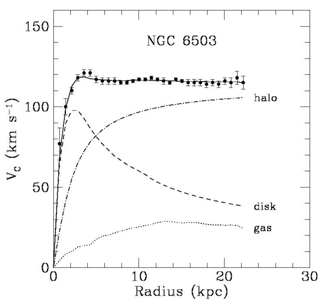
How? (in general)

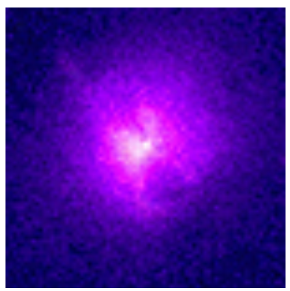
How? (gamma-rays specifically)

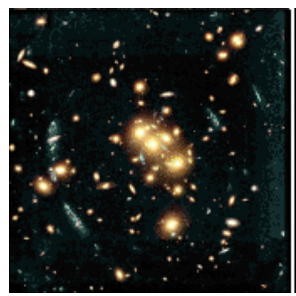
Why?

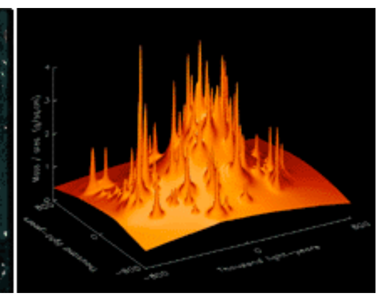
Lots of evidence for (non-baryonic cold) dark matter from diverse astronomical and cosmological observations

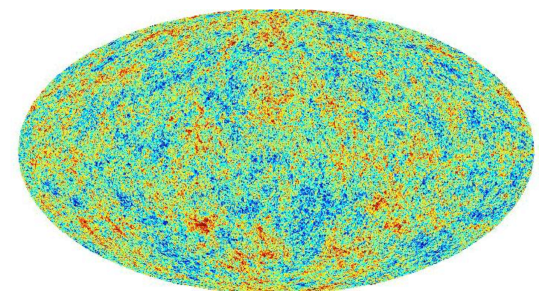
[galaxy rotation curves, galaxy clusters (galaxy velocities, X-ray gas, lensing), galaxy red-shift surveys, Cosmic Microwave Background]











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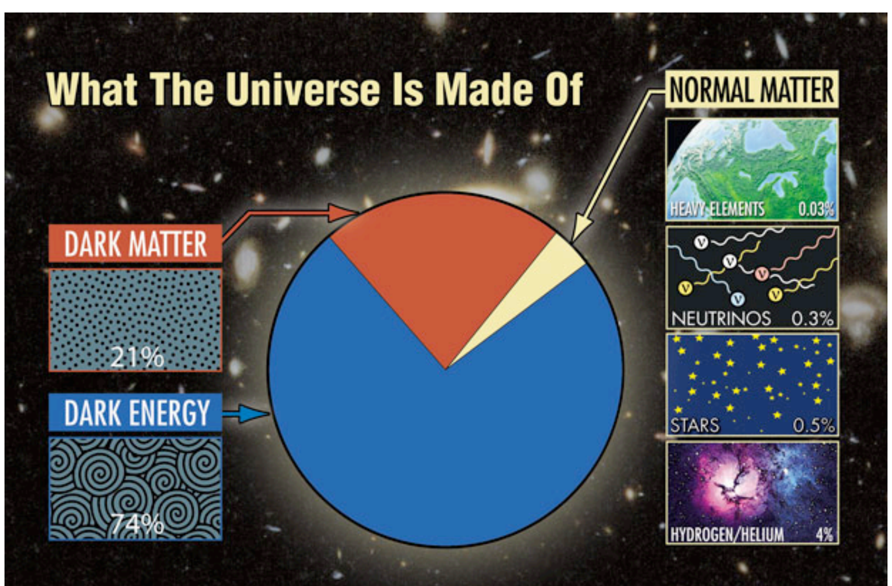
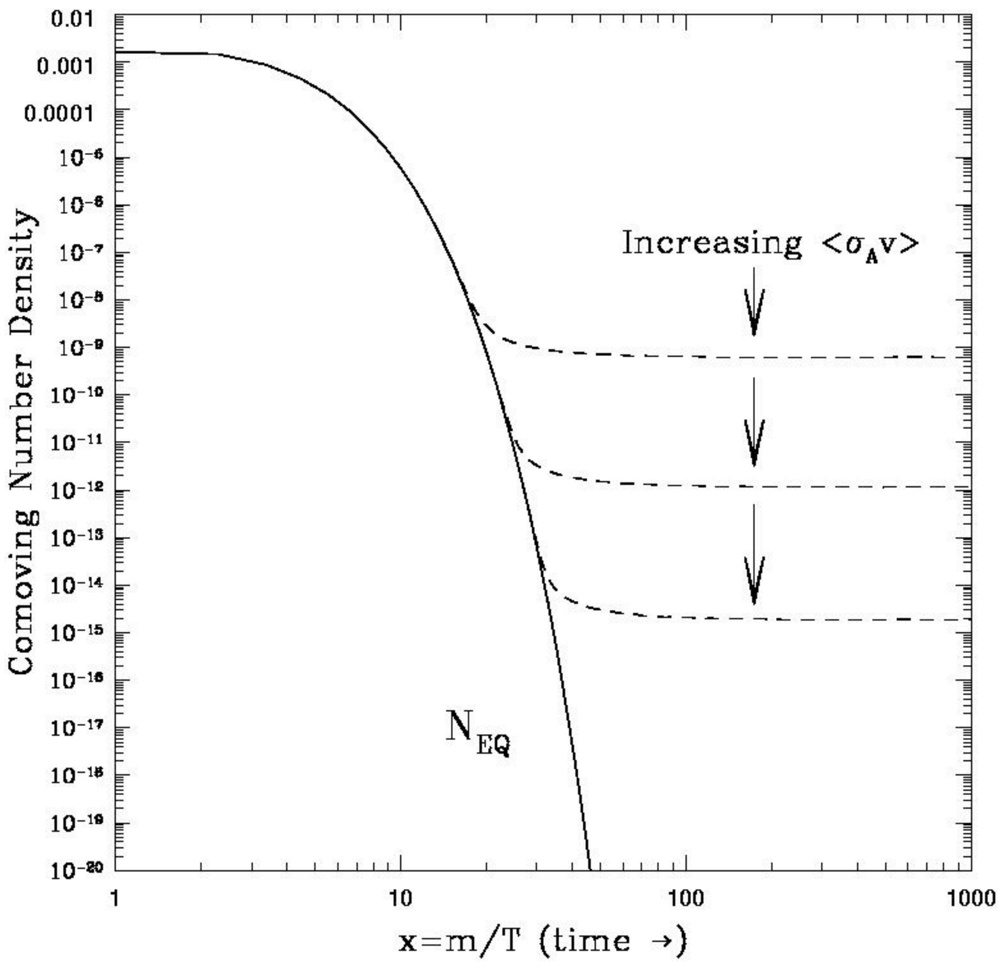


95% of the Universe is exotic and unknown

WIMPs: generic motivation

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



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

Simple argument:

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

If g~0.01 and m_W~100 GeV:

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

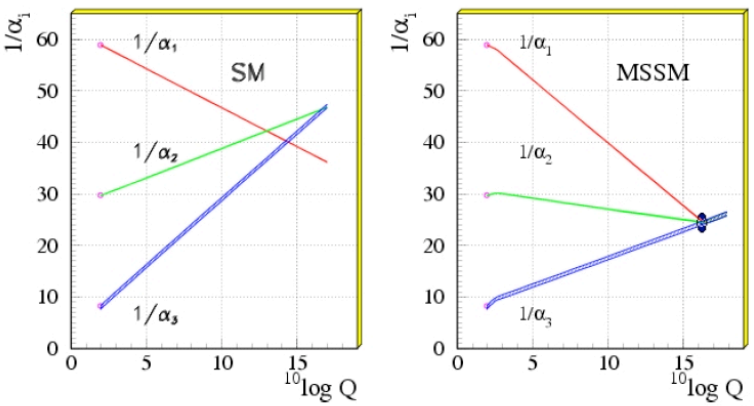
$$\chi + \chi \longleftrightarrow X + \bar{X}$$

Supersymmetry

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

Motivations:

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



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.

Detecting dark matter would:

★ answer a major fundamental question (‘what is the Universe made of?’)

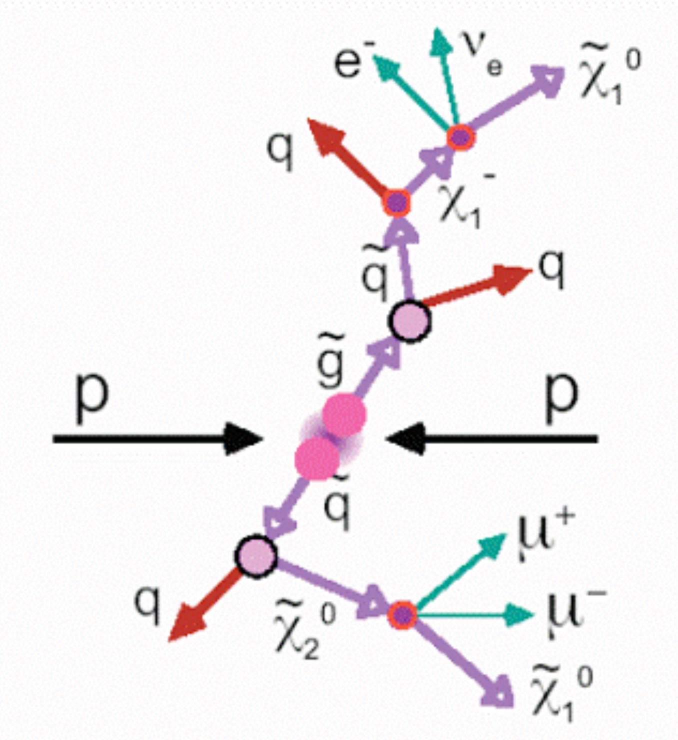
★ provide confirmation of the standard cosmological model (and rule out modified gravity e.g. MOND, TeVeS)

★ probe physics beyond the standard model

How?

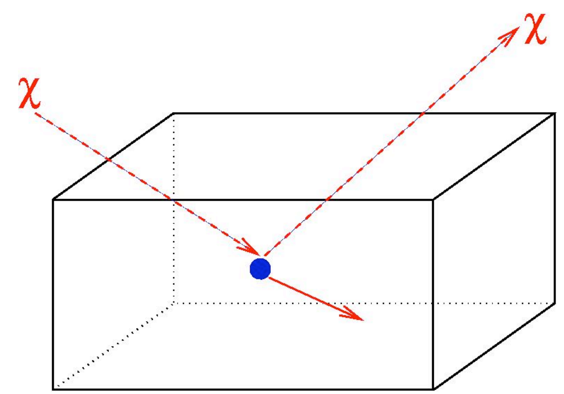
Collider production

Signal: missing energy and transverse momentum + jets.

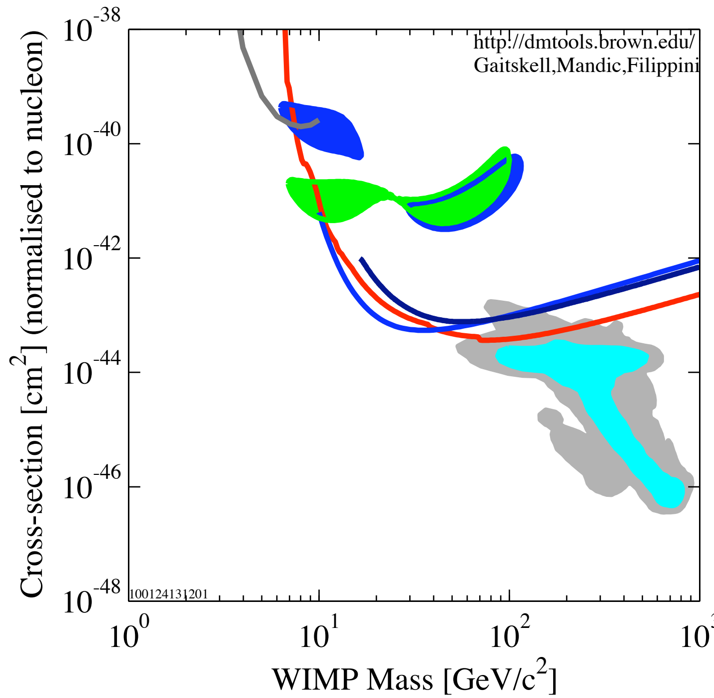


Collider production and detection of a WIMP-like particle would be very exciting, but wouldn't demonstrate that the particles produced have lifetime greater than the age of the Universe and are the dark matter.

Direct detection



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



Currently exclusion limits
(from e.g. CDMS, Xenon10, Zeplin)
probe parameter space of SUSY models.

DAMA annual modulation signal: controversial and hard to reconcile with null results from other experiments (need non-standard WIMP properties).

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 c.f. CDMS surface events)
- nuclear recoils due to neutrons from cosmic rays or local radioactivity:
  - indistinguishable on an event by event basis.

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Look for dependence of event rate on:

time (annual modulation)
signal ~ few%, need large exposure and stable detector operation

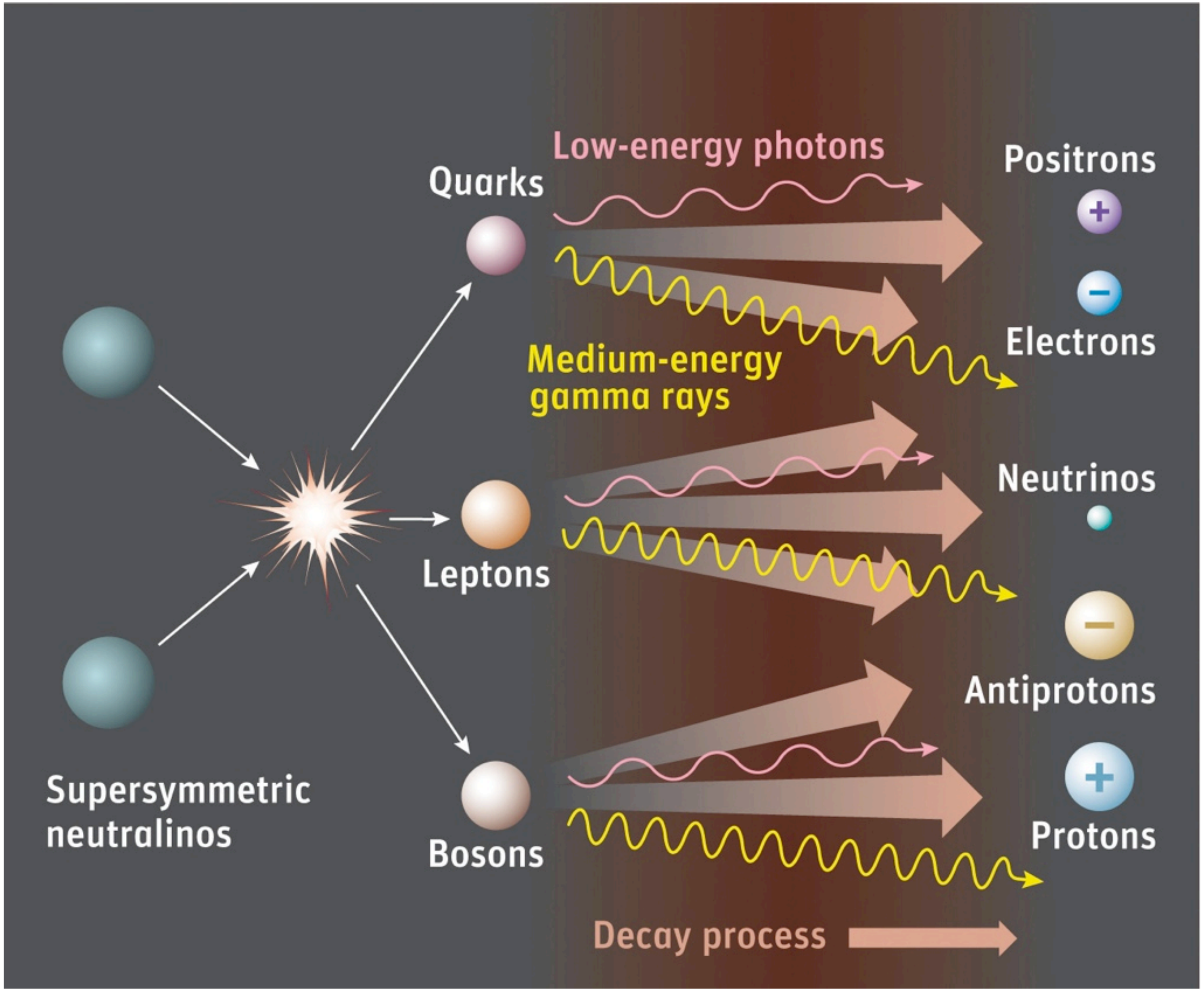
direction
large signal, but need directional detector

energy
check spectra measured with different target nuclei are consistent

n.b. some dependence on ultra-local WIMP density and velocity distribution (which can not be directly measured/probed by any other means).

Indirect detection

i) gamma-rays & anti-matter



Particles produced in WIMP annihilations

+

WIMP spatial (density) distribution

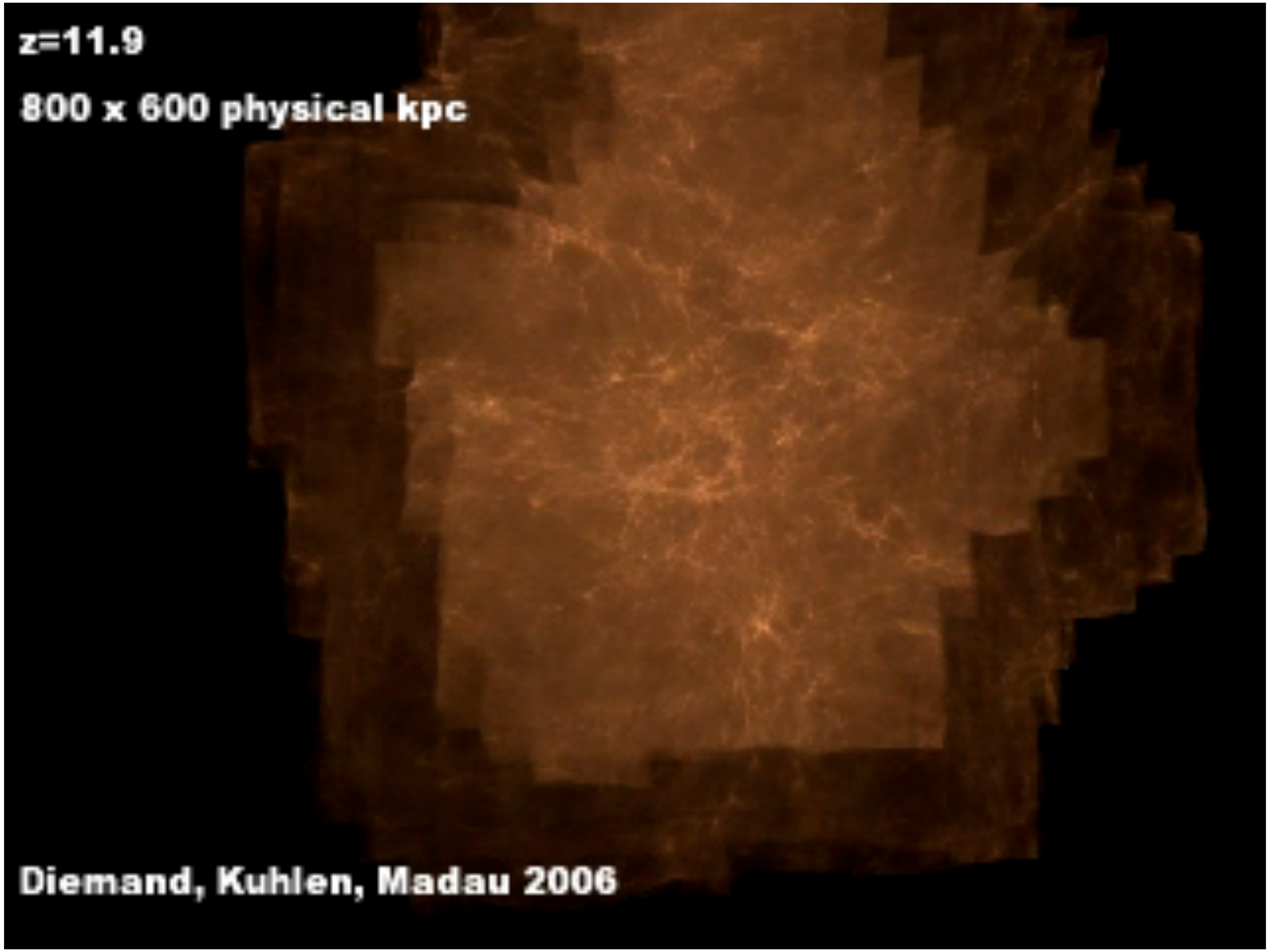
+

(for charged particles) propagation of annihilation products

⇩

predicted signals

Event rates depend on WIMP distribution $\propto \rho^2$. Largest signals expected from high-density regions (e.g. Galactic center, substructures)


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

Particles produced in WIMP annihilations

+

WIMP spatial (density) distribution

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⇓

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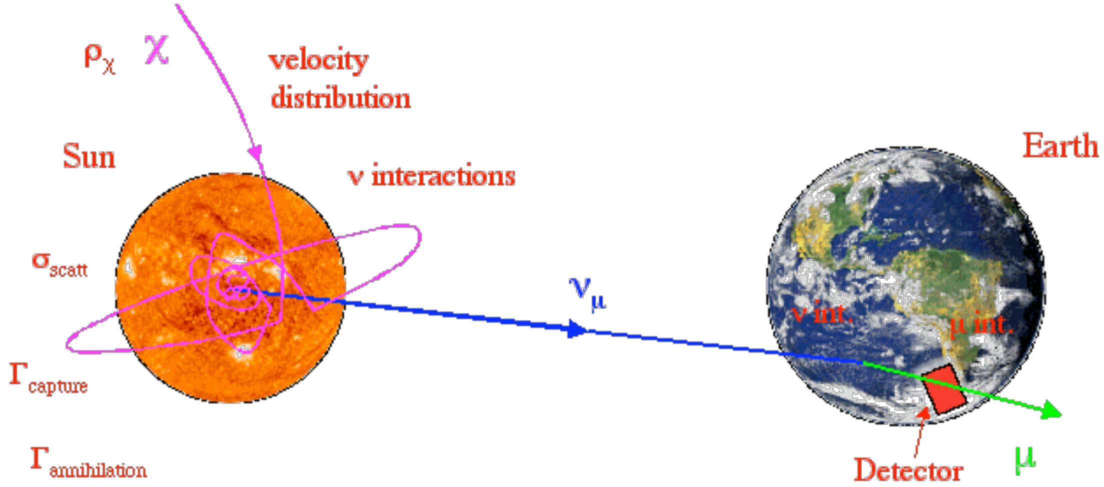
Different species probe different scales/regions (and often on scales far smaller than those directly resolved by numerical simulations).

Often need to distinguish WIMP annihilation from astrophysical backgrounds.

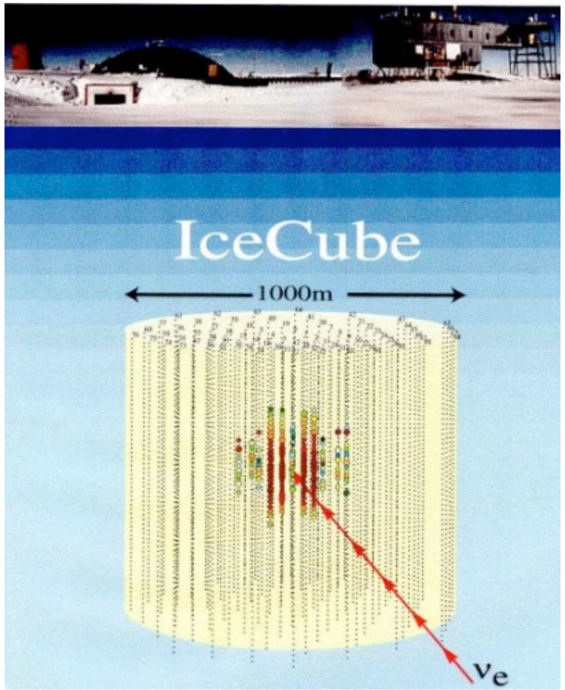
ii) neutrinos

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

muon neutrinos produce muons which can then be detected (via Cherenkov radiation) using neutrino telescopes (e.g. Baikal, NESTOR, AMANDA, ANTARES, IceCube).



AMANDA



Different search channels are complementary.

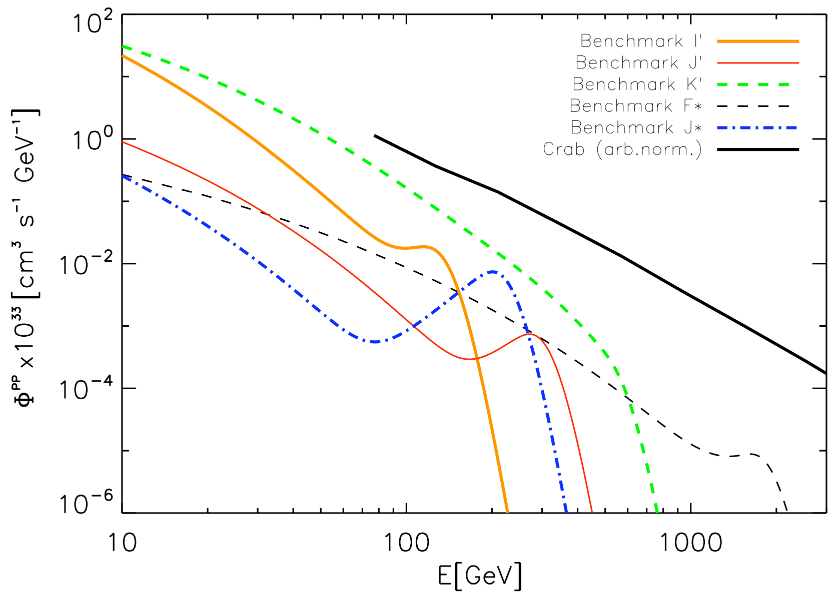
- A *convincing* detection of dark matter will probably require consistent (e.g. same WIMP mass) signals in several different channels.

- Different channels
  - have different backgrounds/uncertainties
  - probe different aspects of WIMP properties (e.g. spin dependent v. spin independent coupling)

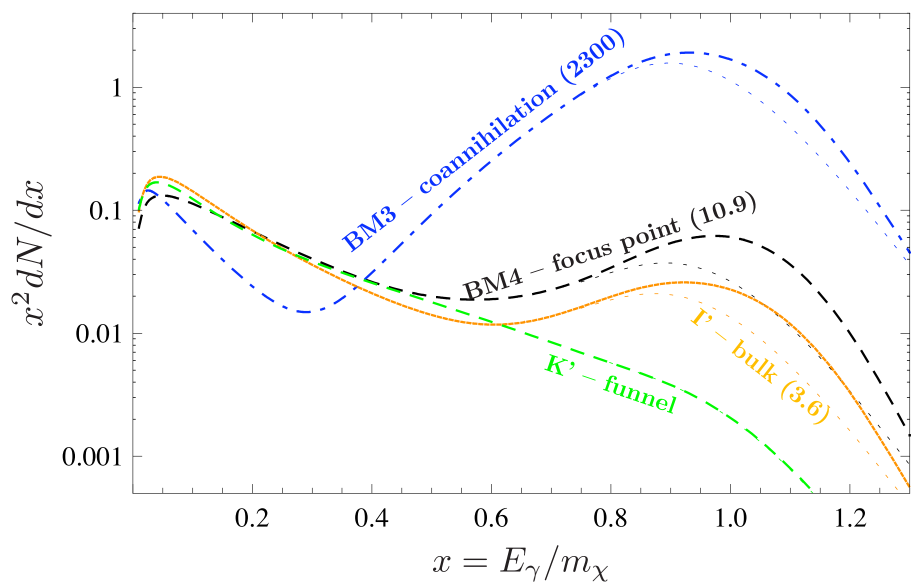
How? (gamma-rays)

Spectrum from fragmentation of fermion and gauge boson final states featureless, extends up to WIMP mass.

Loop induced annihilation ($\chi + \chi \to Z + \gamma$, $\chi + \chi \to \gamma + \gamma$) produce monoenergetic photons but rate typically small (features from internal Bremstrahlung more viable?)



line



internal Bremstrahlung

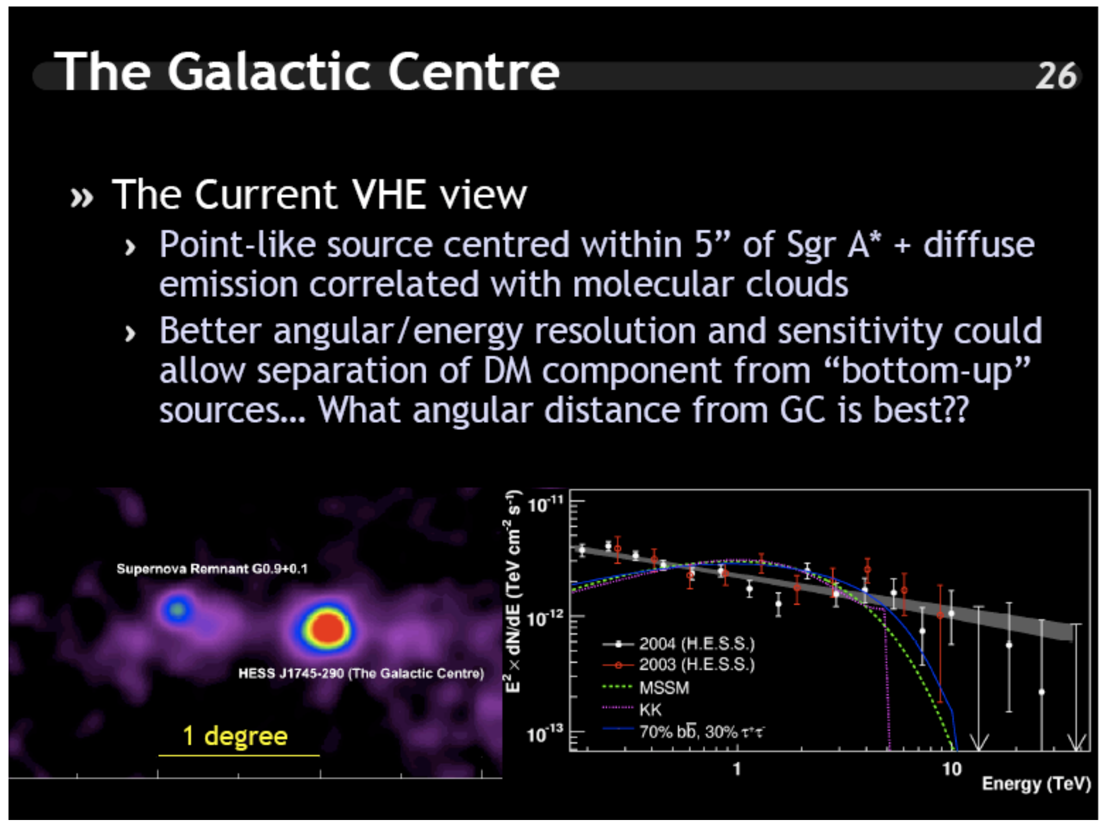
both as observed by a detector with ~10% energy resolution [Bringmann]

Galactic centre

Dark matter density expected to be large at Galactic centre, but how large is very uncertain: relevant scales far smaller than those resolved by simulations and baryonic physics (and the central massive black hole) will modify the DM distribution.

Current observational situation:

from Jim Hinton's talk on 'Performance of CTA and relevance for dark matter studies' at 'Searching for dark matter-A multi-disciplinary approach' meeting in Leicester last week.



Solution: look close to, but away from, GC (where DM density will still be fairly large) and look at energy spectrum **and** angular variation.

Dwarf galaxies

Dark matter dominated, therefore effect of baryons on DM density profile smaller than for MW (but still uncertainty in density profile in central regions which dominate signal i.e. cusp versus core).

No (or low) astrophysical backgrounds.

Ursa Minor

Null observations of various dwarfs, place weak constraints on annihilation cross-section.

Which dwarf to look at? (new ultra faint v. classical)

Prior to 2004, 11 known satellites of Milky Way (including Draco, Fornax and Sagittarius).

SDSS allowed discovery of >10 new low luminosity potential satellites (including Wilman 1, Segue 1).

Very high M/L (and gamma-ray fluxes) have been claimed for the new dwarfs (in particular Wilman 1 and Segue 1) however:

properties very different from classical dwarfs-are they definitely dwarf galaxies rather than star clusters?

analysis based on very small data sets

Consensus of UK dynamics community: play it safe and look at one or two carefully chosen classical dwarfs.

Improved observations and modeling of several ‘classical’ dwarfs expected on O(year) timescale.

Substructures

Numerical simulations contain far more substructure than observed in Milky Way (even taking into account, and extrapolating, new potential dwarfs discovered by SDSS).

Milky Way halo could contain ‘non-luminous’ substructures with high gamma-ray fluxes (potentially discoverable by large FOV survey).

Other possibilities

Diffuse emission, galaxy clusters, DM spikes around Intermediate Mass Black holes, ...

Questions relevant for CTA

What energy resolution is required to detect features in energy spectrum (e.g. cut-off, lines, IB feature)?

What energy and spatial resolution are required to separate DM from astrophysical sources?

Where is the optimum place to look?

How heavy is the WIMP? (how low an energy threshold is needed?)

from Jim Hinton's talk on 'Performance of CTA and relevance for dark matter studies' at 'Searching for dark matter-A multi-disciplinary approach' meeting in Leicester last week.

PHYS WP Studies so far

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- Wide field searches for dark matter substructures
  - Pierre Brun, Jean-Francois Glicenstein, and Emmanuel Moulin, Aldee Charbonnier and David Maurin

  [exploits increased FoV for survey of ¼ of the sky]
- Spectral line features from Dark Matter annihilation
  - J. Conrad, L. Bergström, J. Edsjö, C. Meurer

  [exploits improved energy resolution, central ~1 kpc]
- Constraints on a Dark Matter annihilation signal from the observations of dwarf spheroidal galaxies
  - E. Moulin, P. Brun, J.-F. Glicenstein

Summary

★ There is lots of observational evidence for dark matter.

★ WIMPs are a well motivated dark matter candidate.

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

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

★ Various potential gamma-ray sources (dwarf galaxies, (close-to) Galactic centre, other substructures, diffuse emission).

★ Not obvious which is most promising (increasing interest from numerical simulation and galactic dynamics communities, expect progress, but maybe not a definitive answer, on this question).

Back-up slides

Some comments on the 'boost factor':

[Various definitions in use, the most general/accurate that I'm aware of is:]

Enhancement of rate w.r.t that expected if the density distribution is smooth (i.e. no substructure) and the annihilation cross-section is $\langle \sigma v \rangle = 3 \times 10^{-26} cm^{-3} s^{-1}$ (as deduced from the present day CDM density).

Not a fudge factor (we expect the DM distribution to be clumpy).

Not a single number, species dependent:

gamma-rays travel in straight line, integrate $\propto \rho^2$ along line of sight and over angular resolution, direction dependent

positrons reach earth from ~kpc region.
anti-protons reach earth from ~5-10 kpc region.
} and lose energy en-route

Not a completely free parameter: can estimate values from simulations, but need to make extrapolations regarding DM dist on sub-resolution scales.