Detecting Dark Matter

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Why?

What?

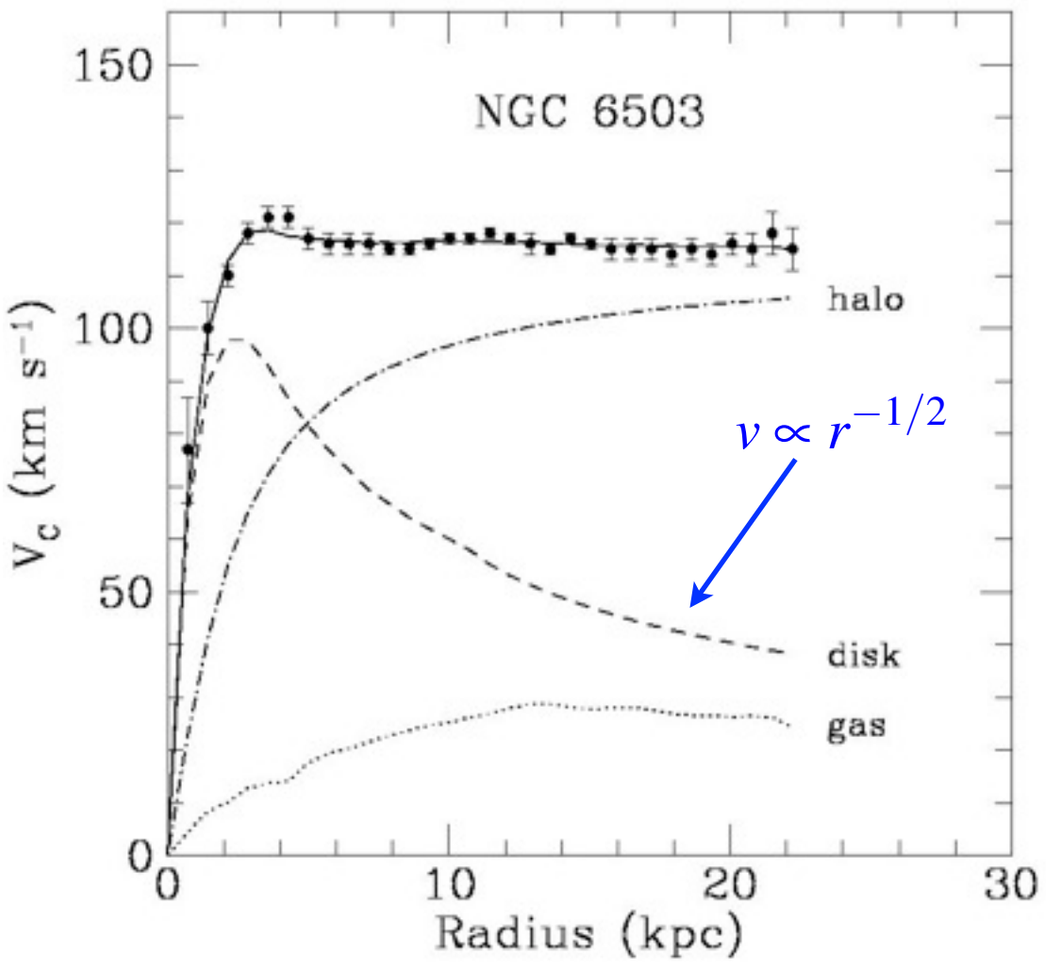
How?

Why? : Observational evidence for dark matter

Galaxy rotation curves

Velocities of stars and clouds of neutral hydrogen measured using doppler effect.

Speeds are (roughly) constant at large radii.



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

$$v_{rot} \sim const$$

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

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

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

Galaxy Clusters

Kitt Peak

In 1933 Zwicky measured velocities of galaxies in Coma cluster.

Far larger than expected, concluded that if cluster is gravitational bound it must contain significant amounts of non-luminous (dark) matter.

Virial theorem

$$2K + V = 0$$

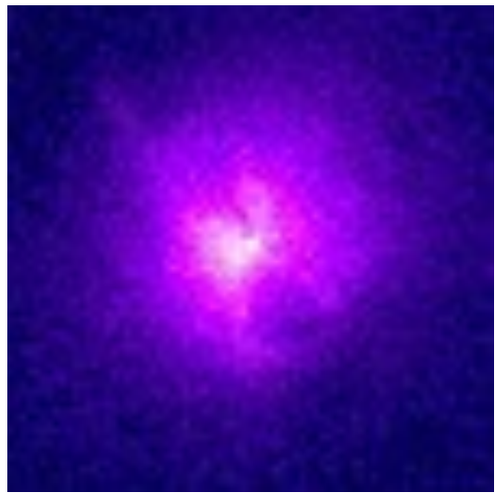
For a self-gravitating system in equilibrium.

$$K = \frac{1}{2}\Sigma_i m_i v_i^2 \qquad V = -\frac{1}{2}\Sigma_i \Sigma_{j\neq i} \frac{G m_i m_j}{r_{ij}} \qquad < v^2 > \equiv \frac{\Sigma_i m_i v_i^2}{\Sigma_i m_i} \qquad R_G \equiv 2\,(\Sigma m_i))^2 \left(\Sigma_i \Sigma_j \frac{m_i m_j}{r_{ij}}\right)^{-1}$$

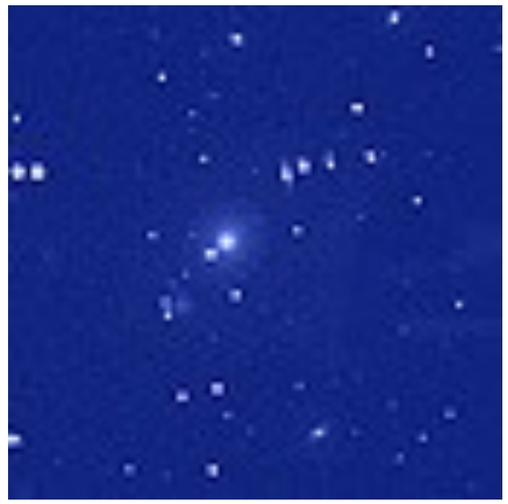
from projected positions → $M \equiv \Sigma_i m_i = \frac{R_G \langle v^2 \rangle}{G}$ ← from galaxy speeds

$$\frac{M}{L} \sim 400 \frac{M_\odot}{L_\odot} \qquad \rightarrow \qquad \Omega_m \sim 0.4$$

Galaxy clusters contain hot X-ray emitting gas.



Chandra X-ray image of Coma



optical image of Coma

Assuming the gas is in hydrostatic equilibrium (and spherically symmetric) can measure the baryon fraction, $f_b = \frac{M_b}{M_{tot}}$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM(<r)}{r^2} \quad \xrightarrow{\text{using ideal gas law}} \quad \frac{kT}{\mu m_p}\left(\frac{d\ln T}{d\ln r} + \frac{d\ln \rho}{d\ln r}\right) = -\frac{GM(<r)}{r}$$

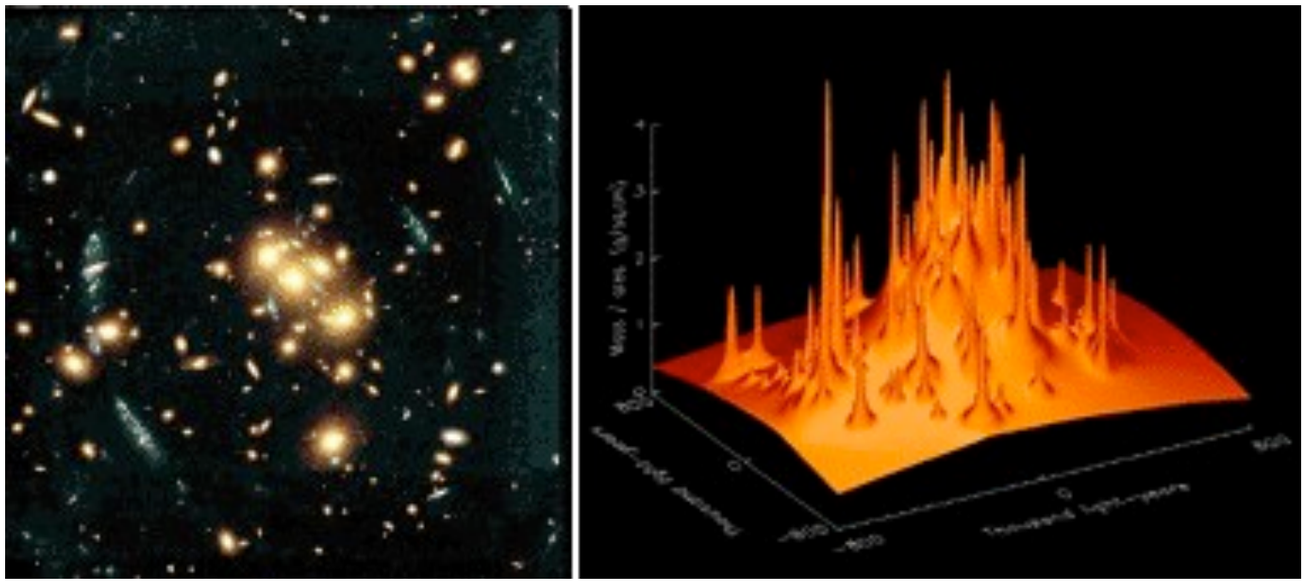
from X-ray spectra — from X-ray surface brightness

$f_b \approx 0.13$ e.g. Gonzalez et al.

Galaxy clusters are largest gravitational bound structures in Universe, therefore assume are "fair sample" of global baryon fraction.
BUT systematic errors not necessarily non-negligible [many cluster undergoing mergers (therefore not in equilibrium....) and some uncertainties in cluster physics e.g. temperature-mass relation].

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

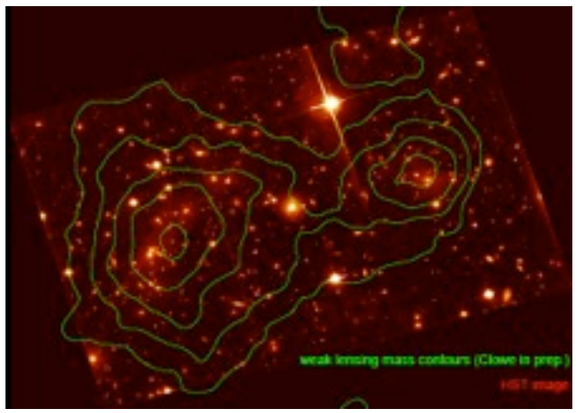
Strong lensing of galaxy (fortuitously) aligned behind galaxy cluster CL0024+1654:

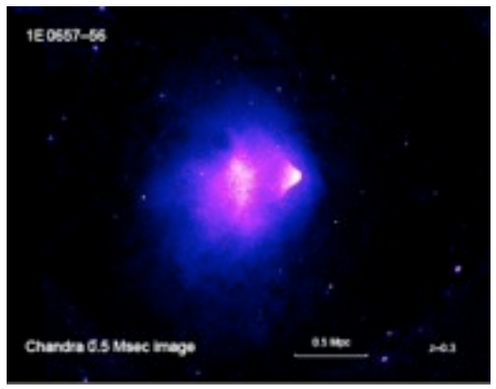


Tyson et al.

The Bullet Cluster

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





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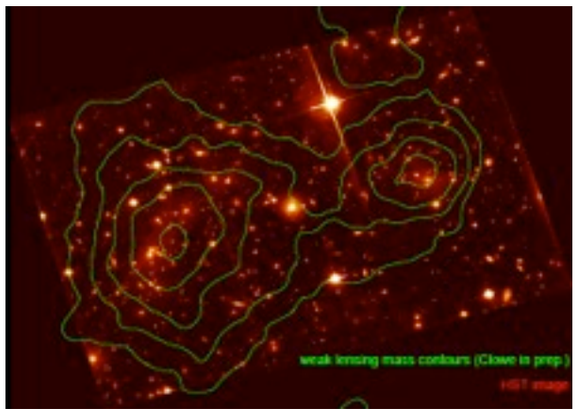
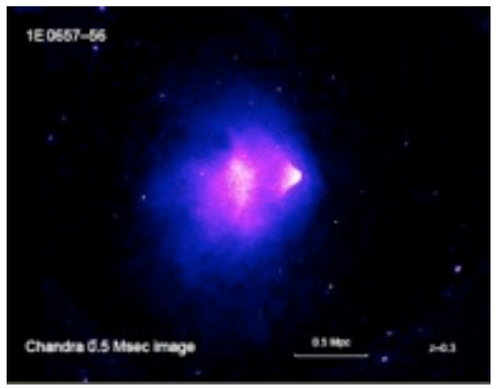




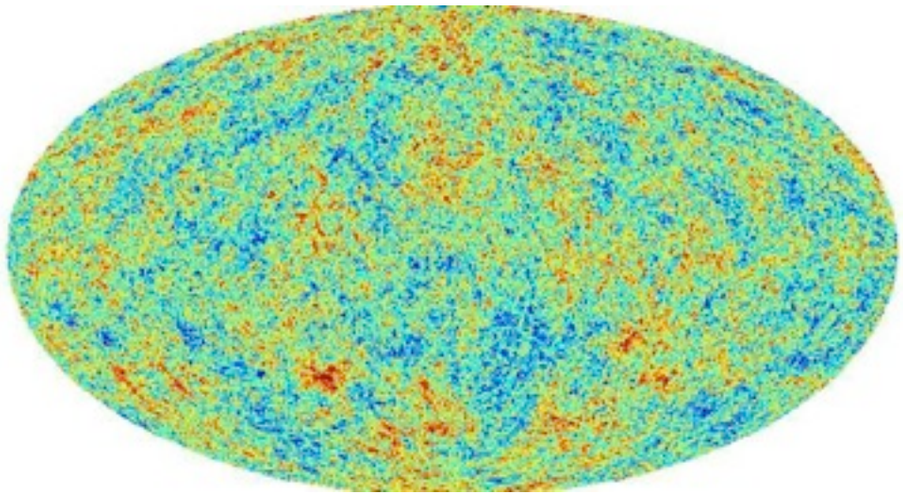
Separation of gravitational potential (reconstructed from lensing obs.) and dominant baryonic mass component (hot gas, X-ray emission detected by Chandra)

→ dark matter

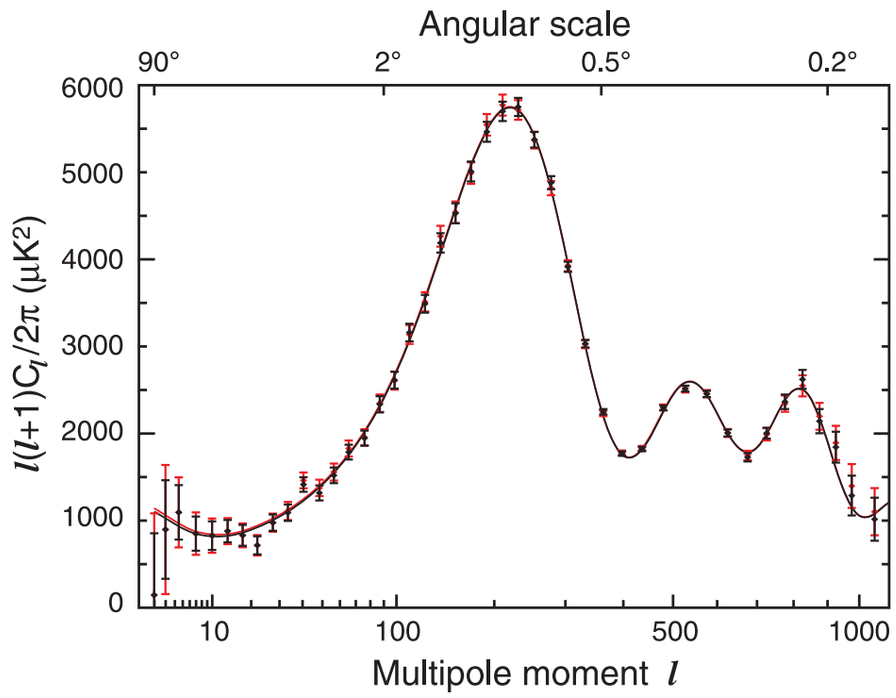
n.b. lensing analysis assumes GR, however explaining these observations is a big challenge for modified gravity theories.

Cosmic Microwave Background anisotropies

Fluctuation distribution depends on contents of Universe (because of growth of fluctuations and also projection of length scales onto sky) and also primordial perturbations (usually assumed to be adiabatic and close to scale-invariant).



WMAP [Komatsu et al.]



total energy density (matter + cosmological constant):

$$\Omega_{\rm tot} - 1 = 0.001 \pm 0.012$$ from CMB data alone

$$\Omega_{\rm tot} - 1 = 0.0027^{+0.0038}_{-0.0039}$$ + other data sets

$$\Omega_i \equiv \frac{\rho_i}{\rho_{\rm c}}$$

$\rho_{\rm c}$ critical density for which geometry of universe is flat

baryons: $\Omega_{\rm b} h^2 = 0.002230 \pm 0.00037$

cold dark matter: $\Omega_{\rm cdm} h^2 = 0.1127 \pm 0.0037$

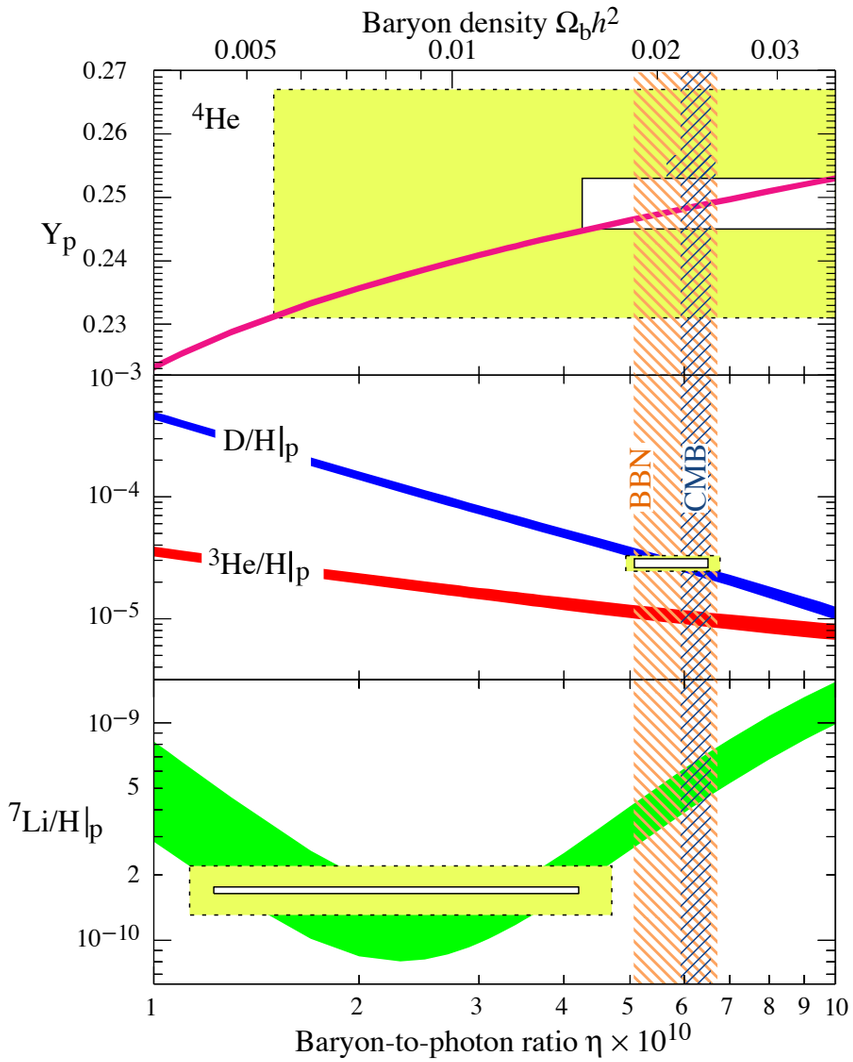
$$H_0 = 100\, h\, {\rm km\, s^{-1}\, Mpc^{-1}}$$

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.



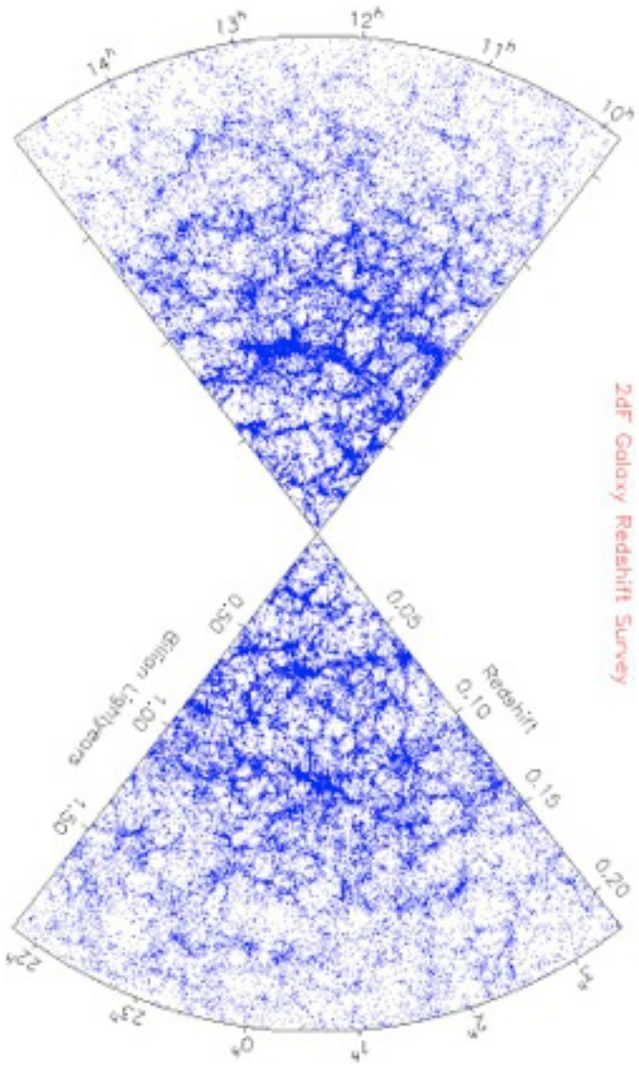
[Fields and Sarkar]

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

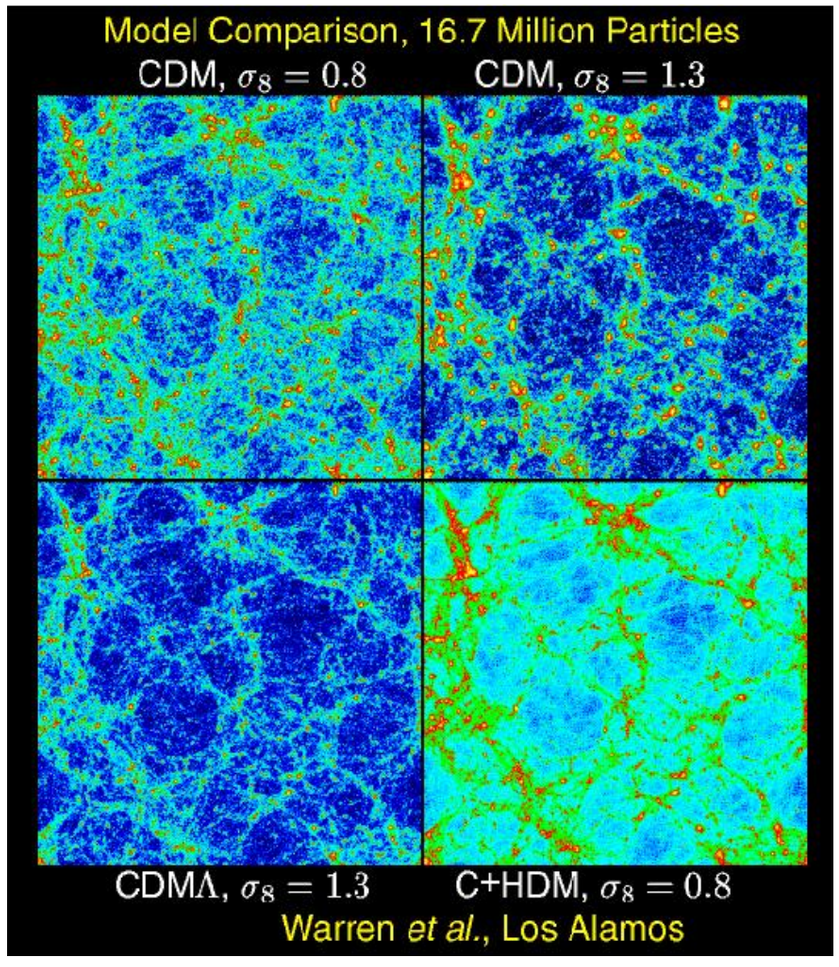
Large scale structure

Depends on late time density perturbation power spectrum

(which depends on primordial perturbation spectrum and growth of fluctuations, which depends on composition of Universe).



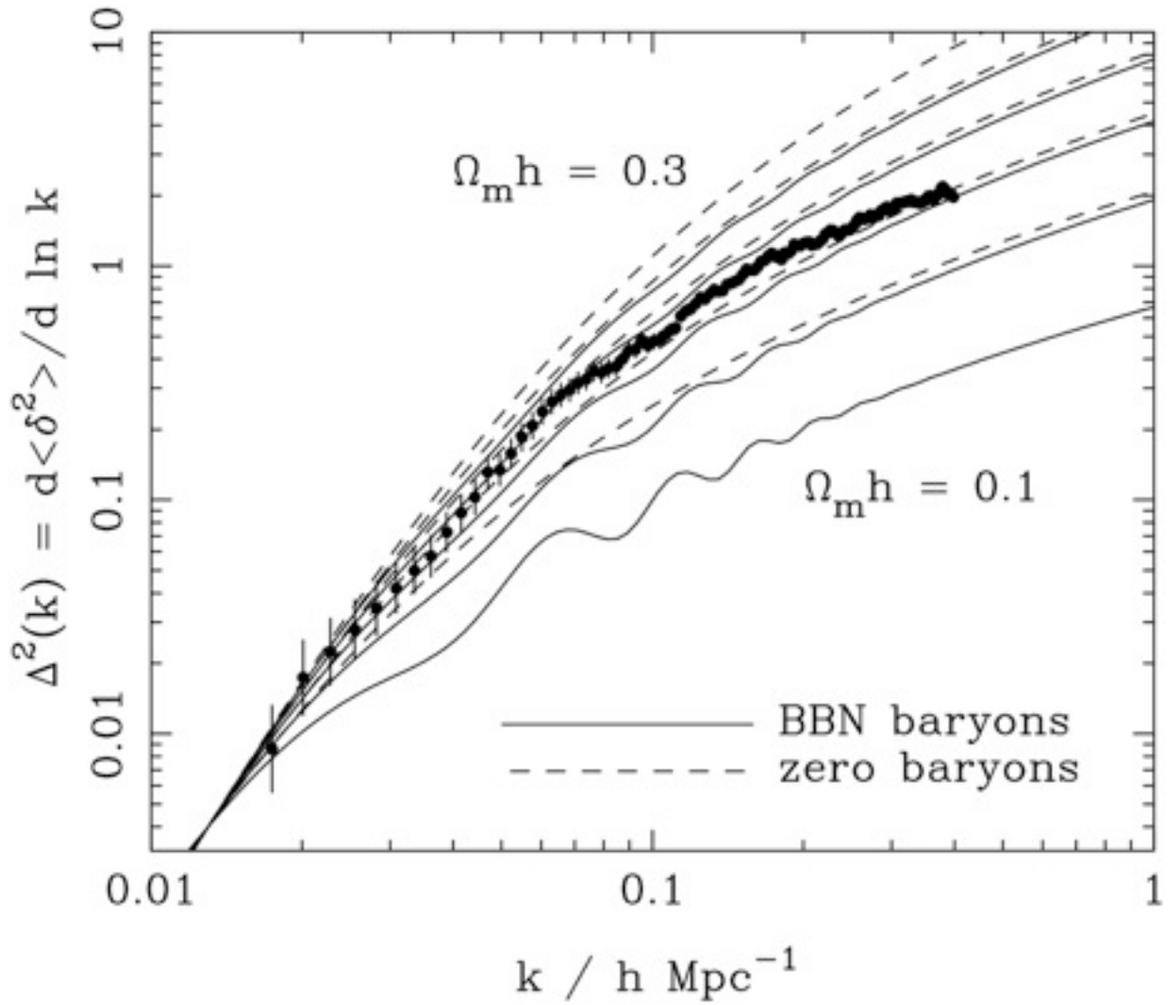
2dF galaxy red-shift survey



Simulations

n.b. current state of the art simulations have better resolution (more particles) but are only carried out for one fixed cosmology

Power spectrum:



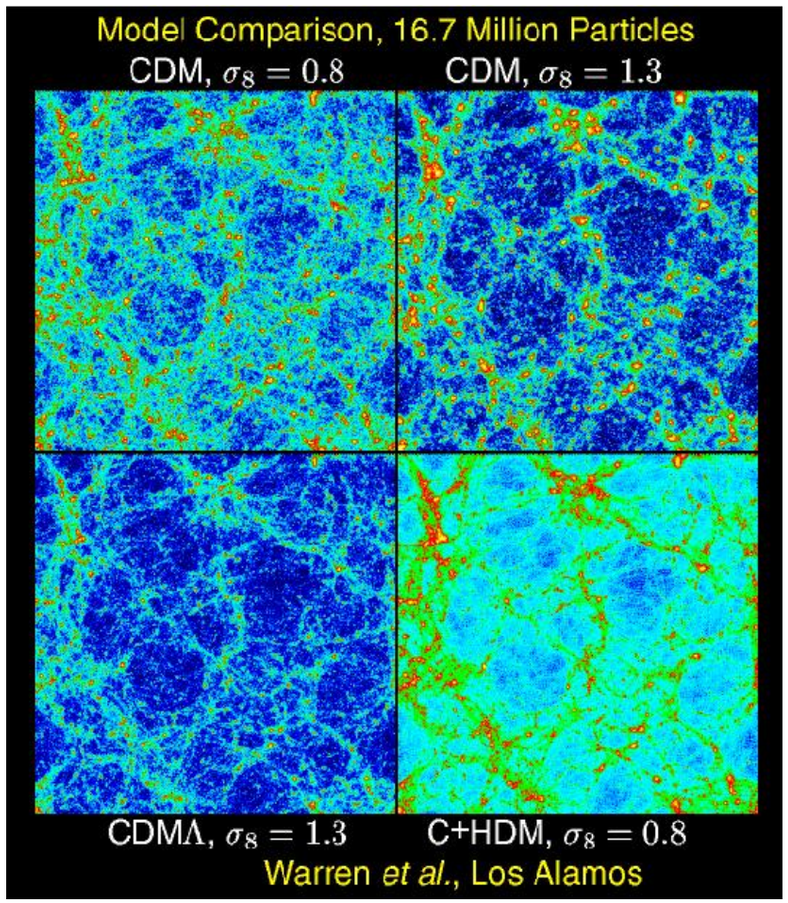
2dFGRS [Cole et al.]

$$\Omega_m h = 0.168 \pm 0.016 \qquad \frac{\Omega_b}{\Omega_m} = 0.185 \pm 0.046$$

Sloan Digital Sky Survey (SDSS) finds similar results.

Limits on Hot Dark Matter

Hot dark matter (e.g. light neutrinos) is relativistic and free-streams over cosmological scales erasing structure.



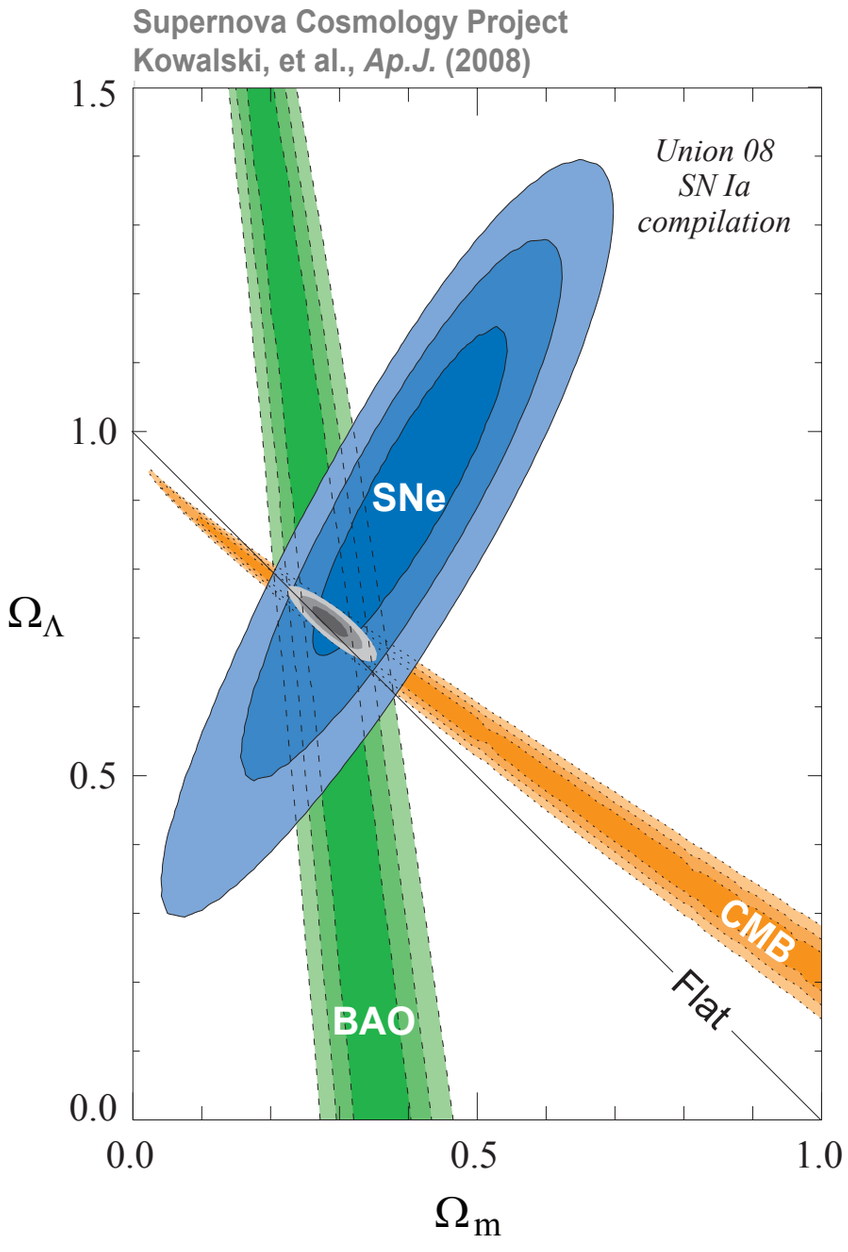
$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{94\,\mathrm{eV}}$$

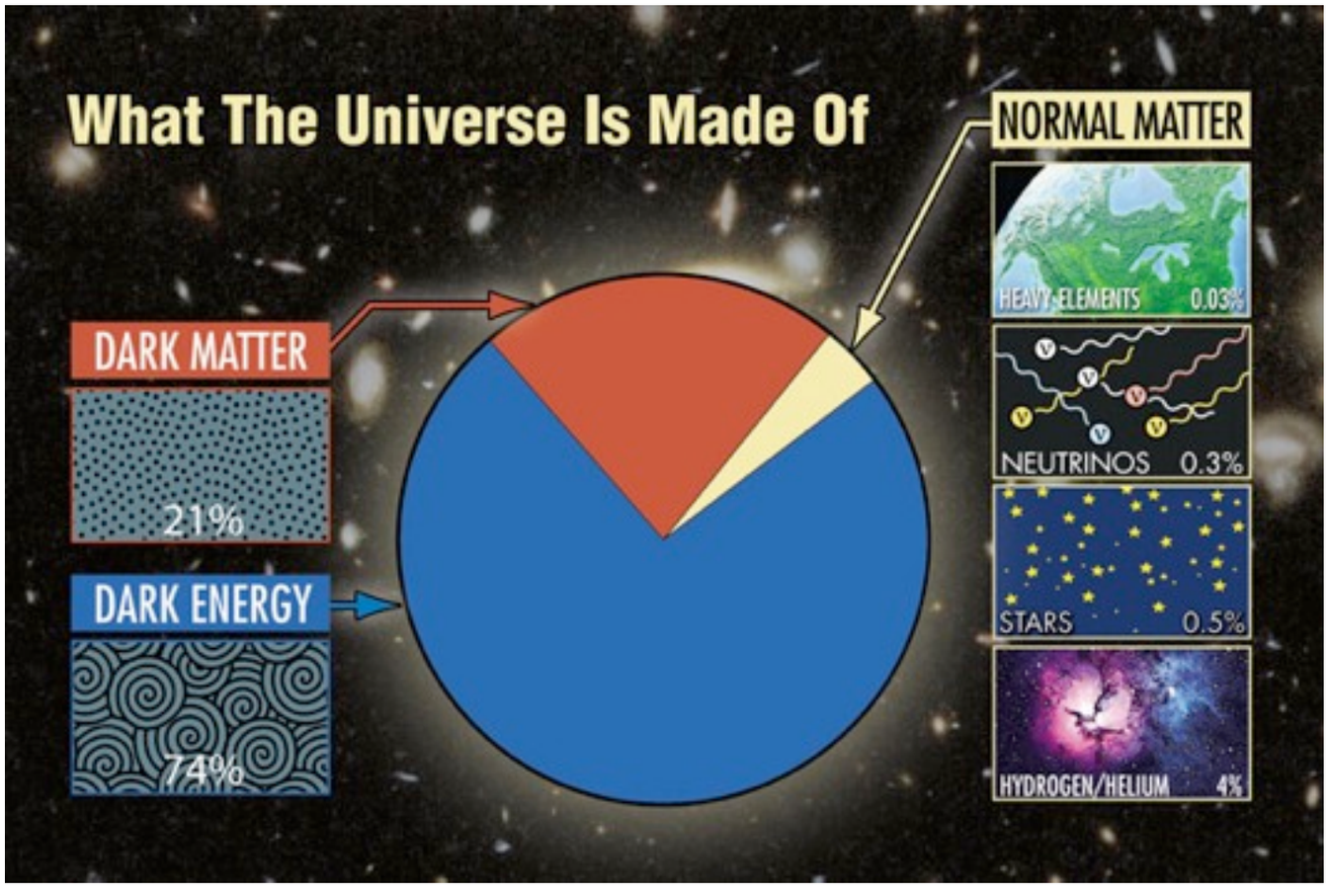
Cosmological constraints: $\sum m_\nu < (0.3 - 1.1)\,\mathrm{eV} \quad \equiv \quad \Omega_\nu h^2 < (0.003 - 0.012)$

(n.b. significant dependence on priors, data sets used)

Direct limits on neutrino mass: $m_{\nu_e} < 2\,\mathrm{eV}$

Cosmological energy budget





Should we be worried that 95% of the energy density of the Universe is apparently in exotic (and as yet undetected...) forms?

All the evidence for dark matter comes from its gravitational effects.....

Could the observations be explained by modifying gravity instead?

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

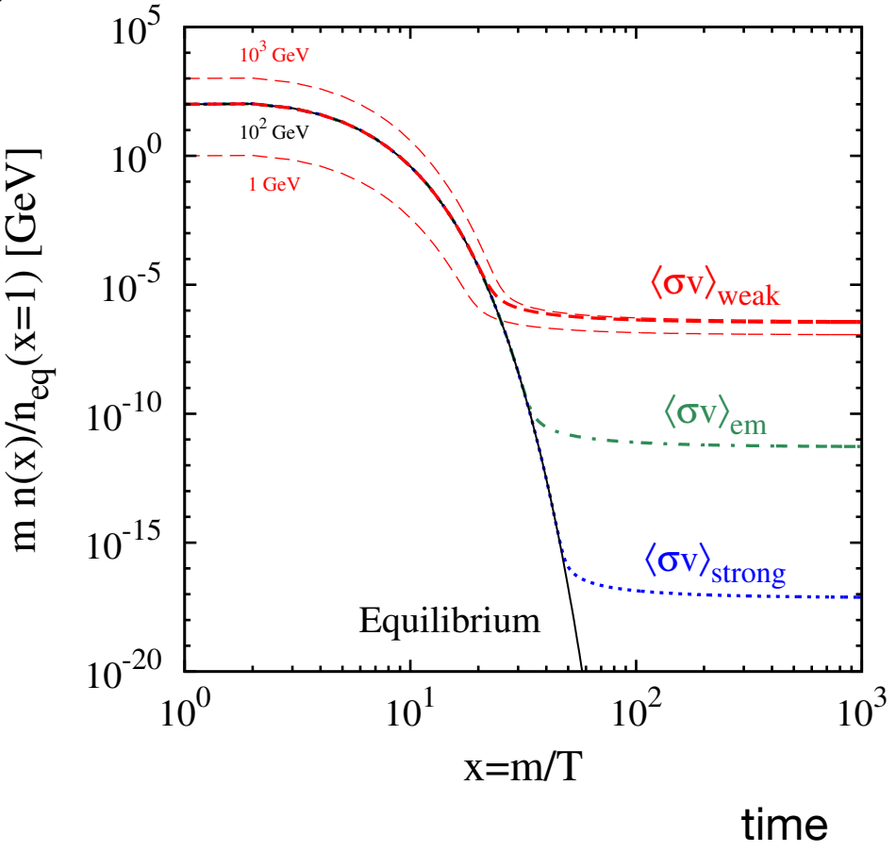
What? : WIMPs

Generic motivation

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

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

comoving number density



[Steigman, Dasgupta & Beacom]

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

Simple argument:

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

If g~0.01 and m_w~100 GeV:

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

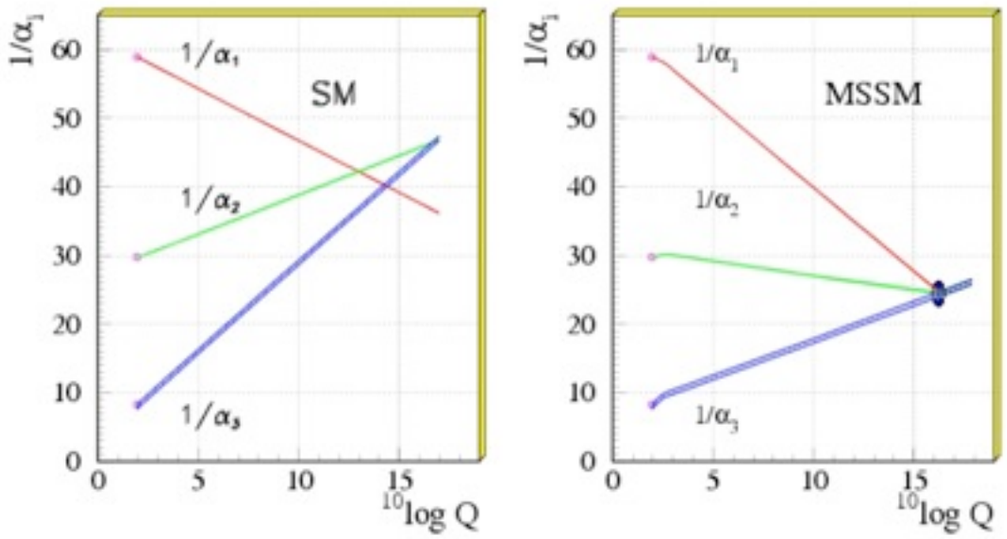
n.b. note link between WIMP density and annihilation cross-section.

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 (LSP) (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.

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, **c**(onstrained) **MSSM**)

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

Other models drop/modify some of these assumptions e.g. Non-Universal Higgs Model (NUHM).

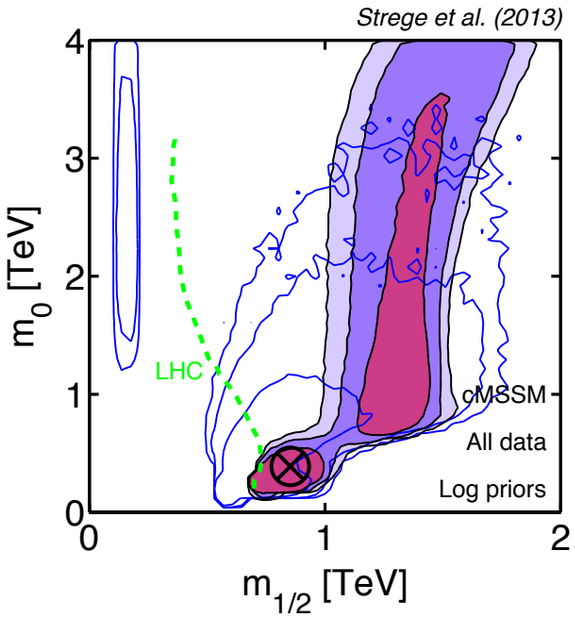
p(henomenological) **MSSM**:

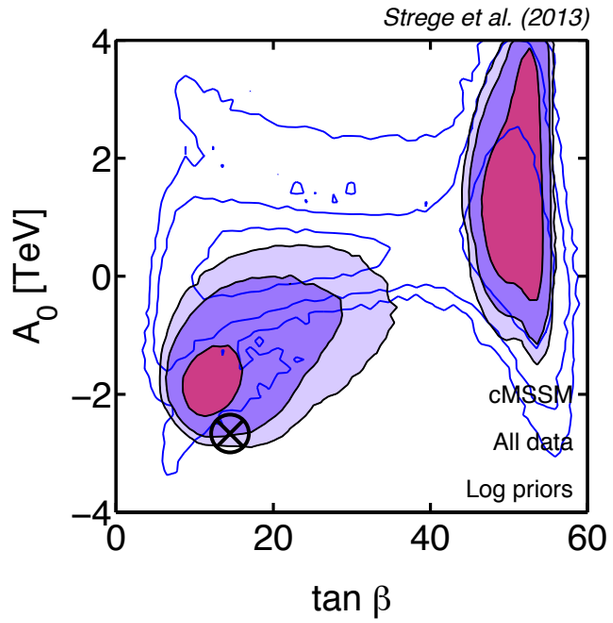
Use experimental considerations to reduce to 19 free parameters

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

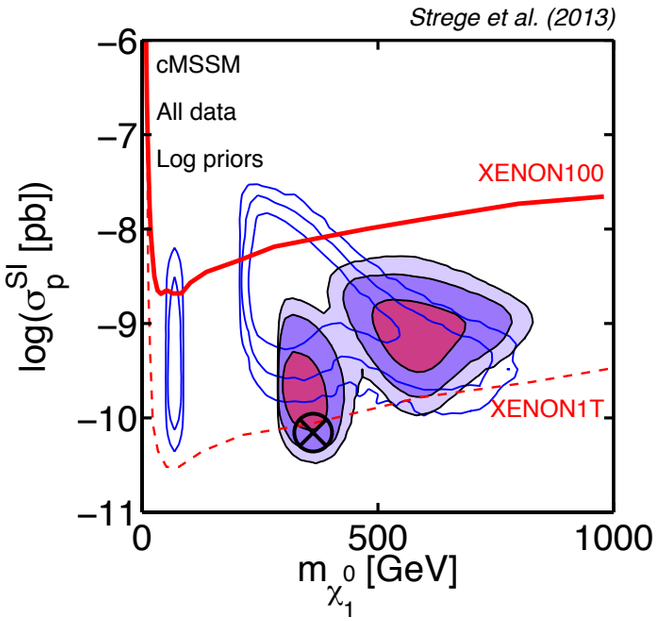
Select representative benchmarks points or use MCMC to explore parameter space.

e.g. Strege et al.





constraints on CMSSM parameters with log priors
(68%, 95% and 99% confidence)



cross-section & mass
of lightest neutralino

n.b. using flat priors or profile likelihood gives smaller confidence regions

n.b.

i) Other extensions of the standard model (e.g. Universal Extra Dimensions) also contain WIMP candidates (e.g. the Light Kaluza-Klein Particle).

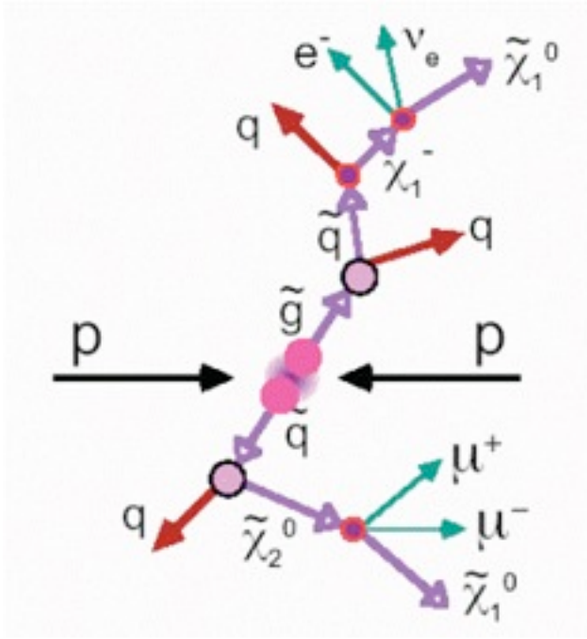
ii) WIMPs are not the only CDM candidate (other possibilities include axions and primordial black holes). Will be covered briefly in my talk in the DM session tomorrow.

Colliders

'generic' signal: missing energy/momentum

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.

Future prospects:

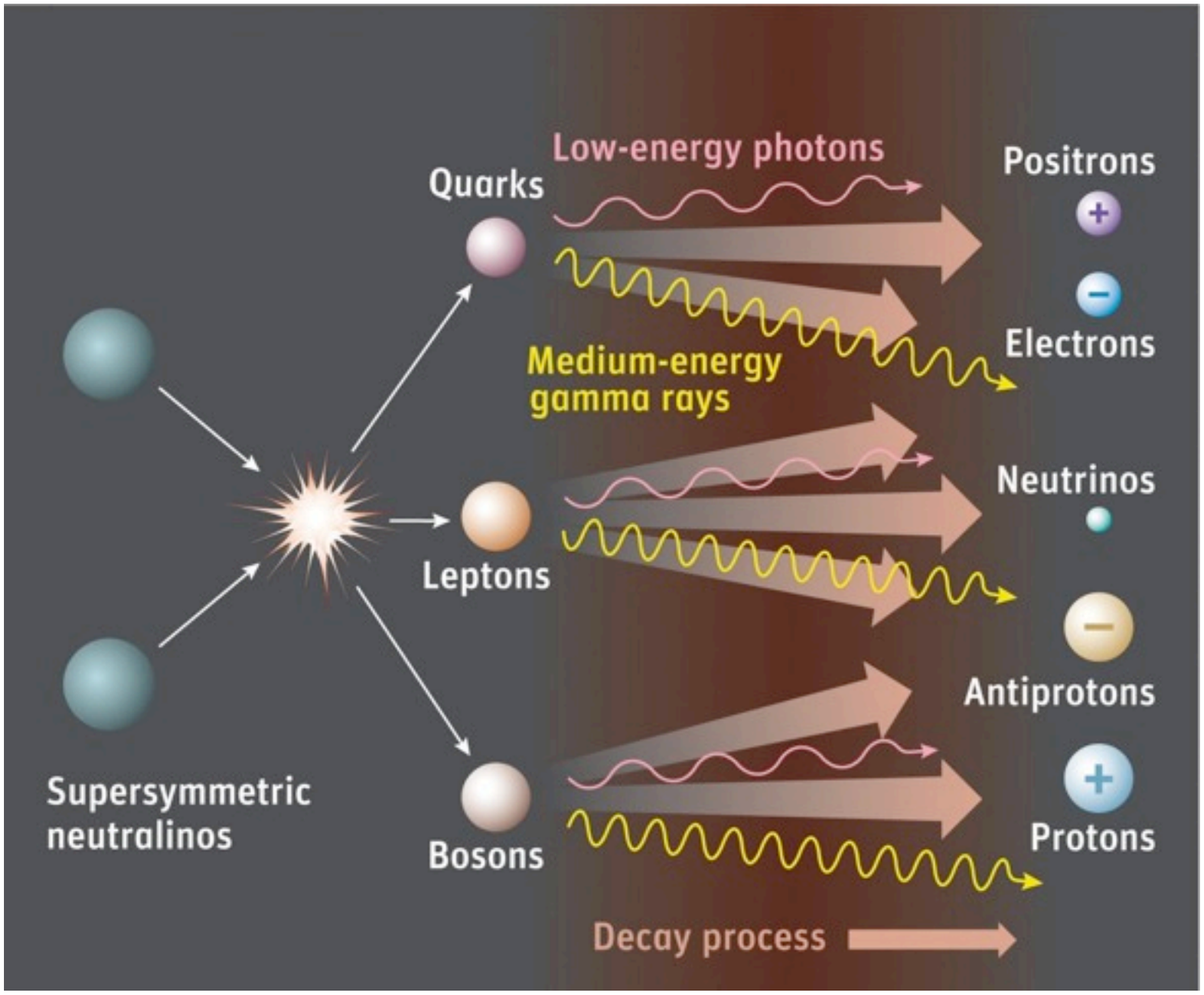
measure WIMP properties

mass: check consistency with other WIMP detection methods

interactions: calculate theoretical relic abundance

Indirect detection

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

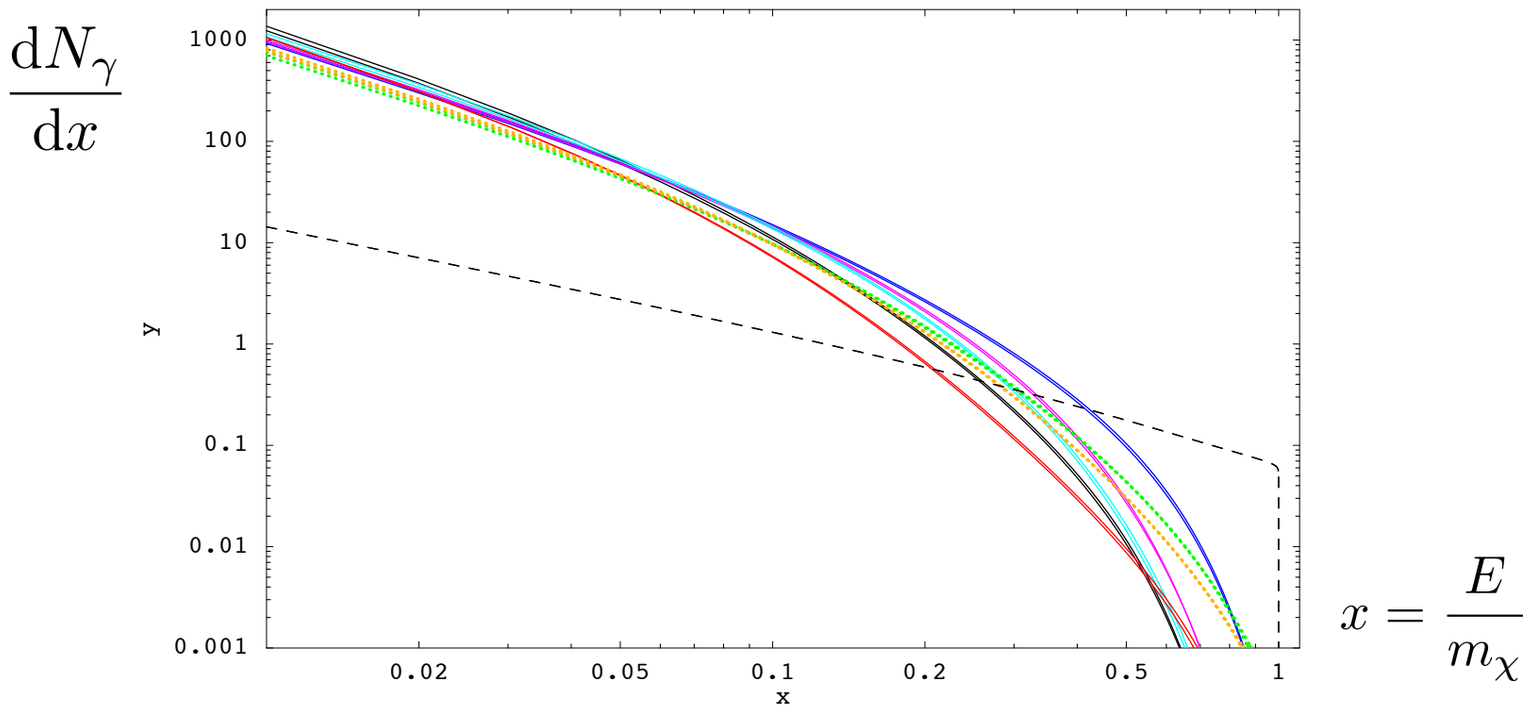


[Sky & Telescope]

Particle physics input

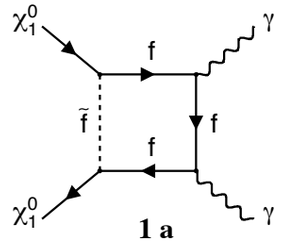
Fragmentation and hadronization (mainly through decay of π^0) produces a featureless spectrum of γs, which extends up to WIMP mass.

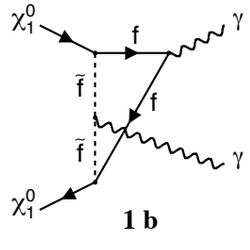
Depends relatively weakly on annihilation channel:

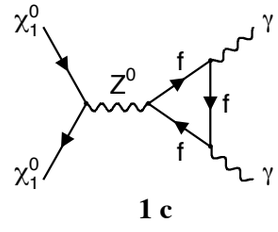


[Bertone et al. using PYTHIA]

Can also get mono-energetic gamma-rays from $\chi + \chi \to Z + \gamma$, $\chi + \chi \to \gamma + \gamma$ but rate typically small (loop suppressed).







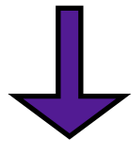
Particles produced in WIMP annihilations — Particle physics

+

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

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WIMP spatial (density) distribution — Astrophysics (with some particle input)

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(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 centre, dwarf galaxies,...)

Particles produced in WIMP annihilations — Particle physics

+

WIMP spatial (density) distribution — Astrophysics (with some particle input)

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(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 centre, dwarf galaxies,...)

Enhancement of rate w.r.t that produced by smooth halo, parameterised by boost factor.

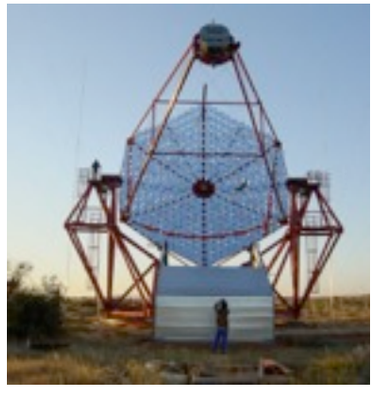
Different species probe different scales/regions (and often on scales far smaller than those directly resolved by numerical simulations). Boost factor species dependent and not accurately known.

Often need to distinguish WIMP annihilation from astrophysical backgrounds.

Current status:

Gamma-rays:

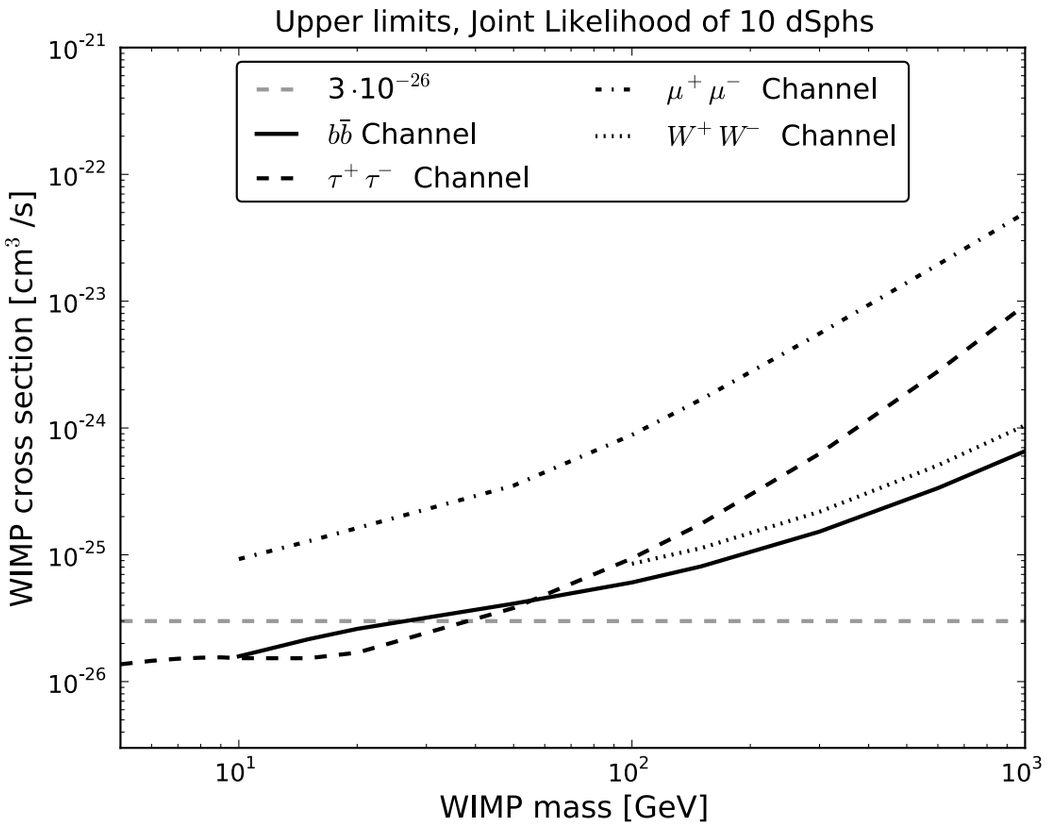
Fermi



Air Cherenkov Telescopes
(HESS, MAGIC, VERITAS)

Various claimed hints, but (IMHO) nothing convincing yet.

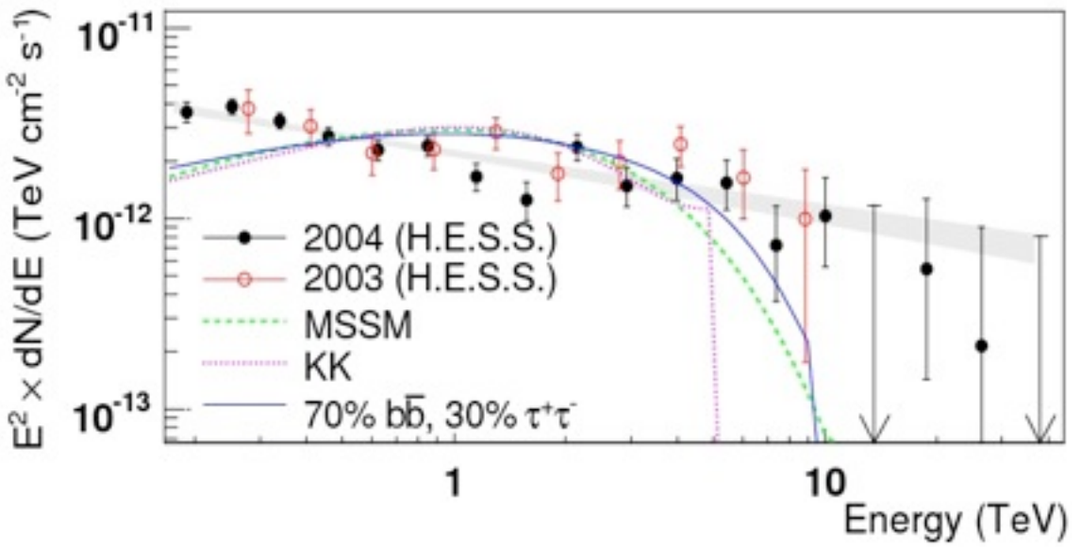
Constraints on WIMP annihilation cross-section from stacked Fermi observations of 10 Milky Way dwarf galaxies, beginning to exclude light WIMPs with canonical annihilation cross-section:



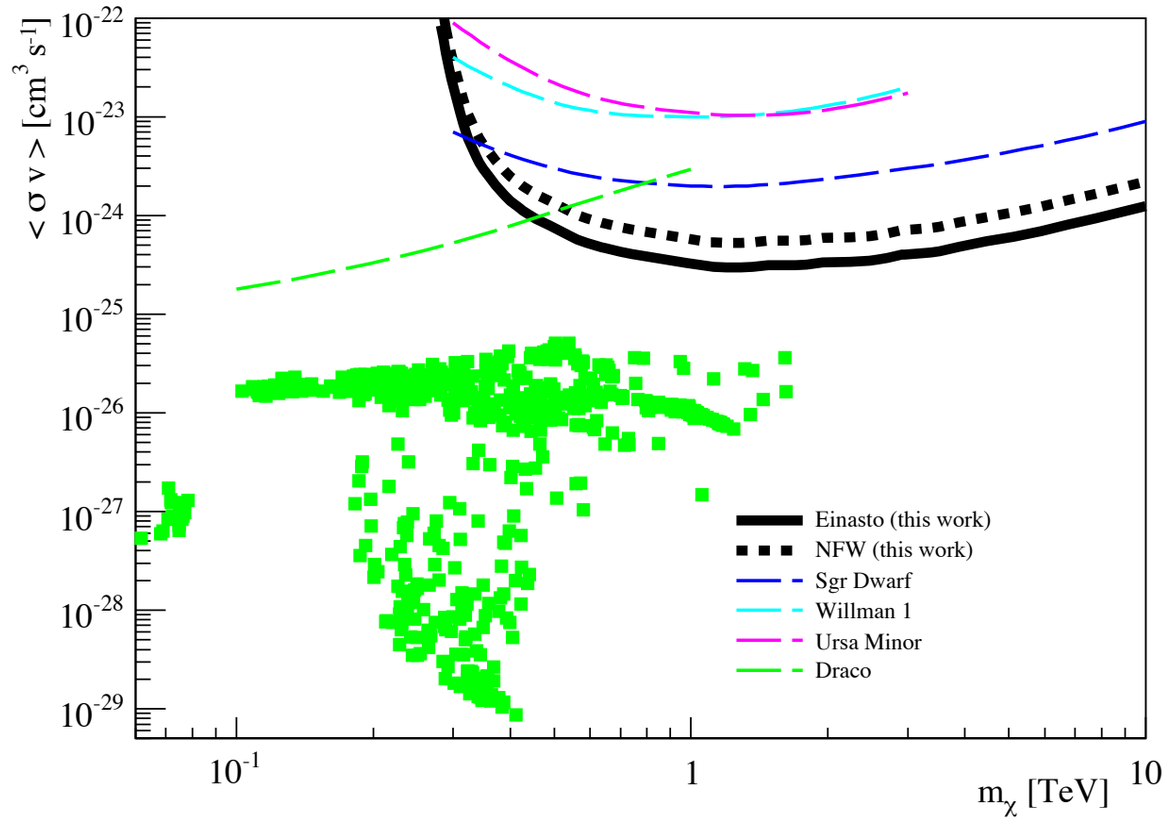
dependence on how WIMPs annihilate

value corresponding to observed CDM density

Spectrum of high energy source at Galactic centre observed by HESS extremely hard to reconcile with DM annihilation (extends to ~ 20 TeV) and hence is background for WIMP searches.



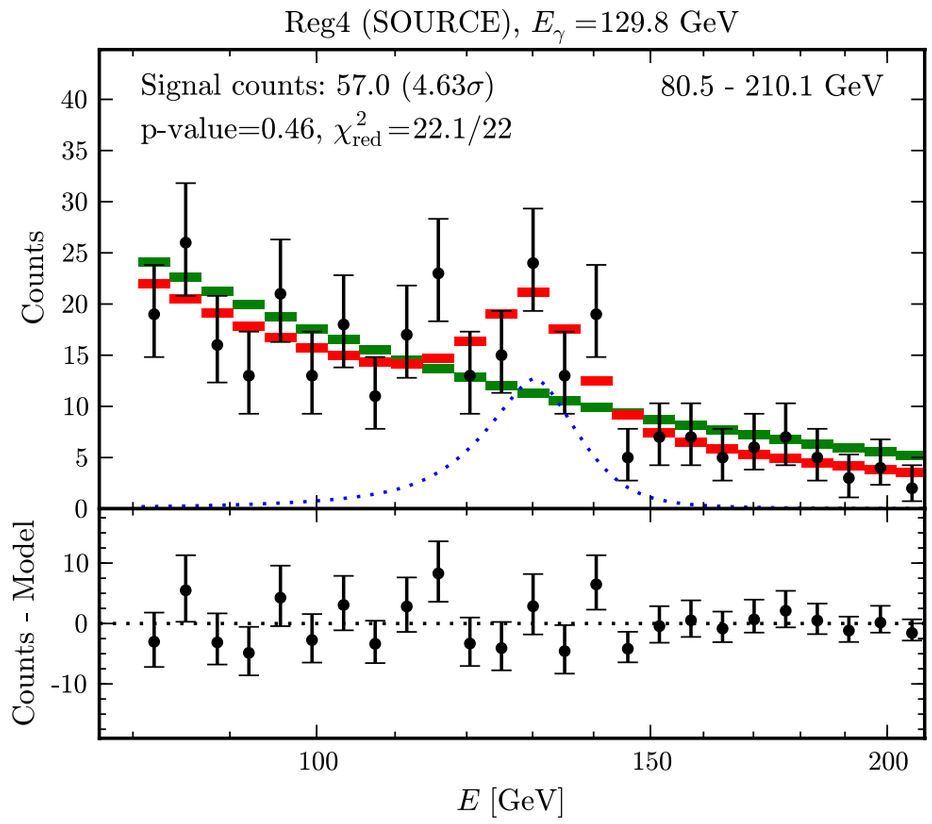
HESS constraints on WIMP annihilation cross-section from observations of region 0.3°-1° away from Galactic plane (backgrounds and uncertainty in ρ(r) relatively small).



gamma-ray line(s):

135 GeV line found in Fermi data with local (global) significance 3 (5) sigma by looking in regions where signal expected to be largest.
[Bringmann et al; Weniger; see also Tempel, Hecktor & Raidal; Su & Finkbeiner]

Possibly a 2nd line at 111 GeV. [Su & Finkbeiner]



Some evidence for line at same energy in direction of galaxy clusters. [Tempel, Hecktor & Raidal]

Published Fermi analysis [Ackermann et al.]: no evidence for lines (but uses smaller data set and different ROI).
Fermi symposium: no globally significant lines, but 135GeV feature from hot spots along GP.

Possible data issues: 'limb excess' (line in gamma-rays from cosmic-ray induced air showers in Earth's atmosphere).

No sign of associated continuum photons [Cohen et al.; Cholis, Tavakoil & Ullio]

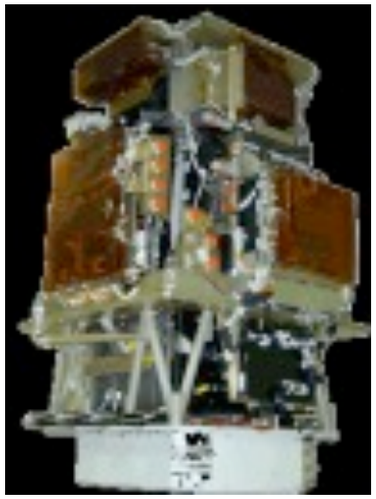
Anti-particles:

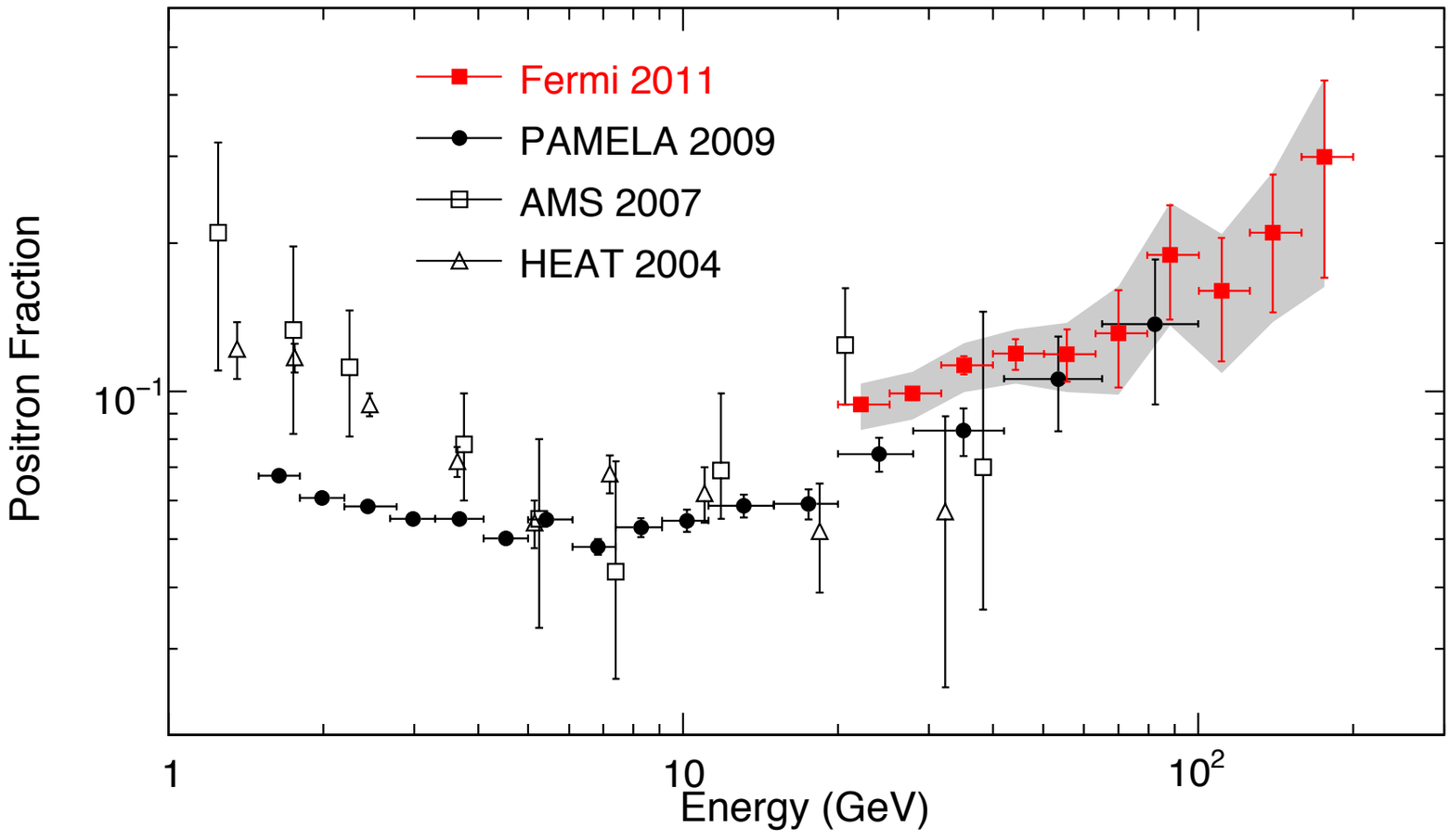
positrons: excess in positron fraction between 10 and 200 GeV

first observed by HEAT and AMS1

confirmed and improved by PAMELA

now confirmed and extended to higher E by Fermi





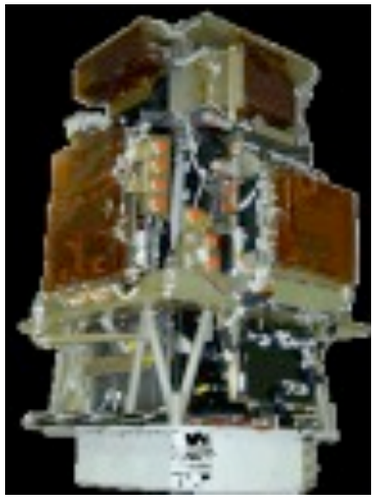
Anti-particles:

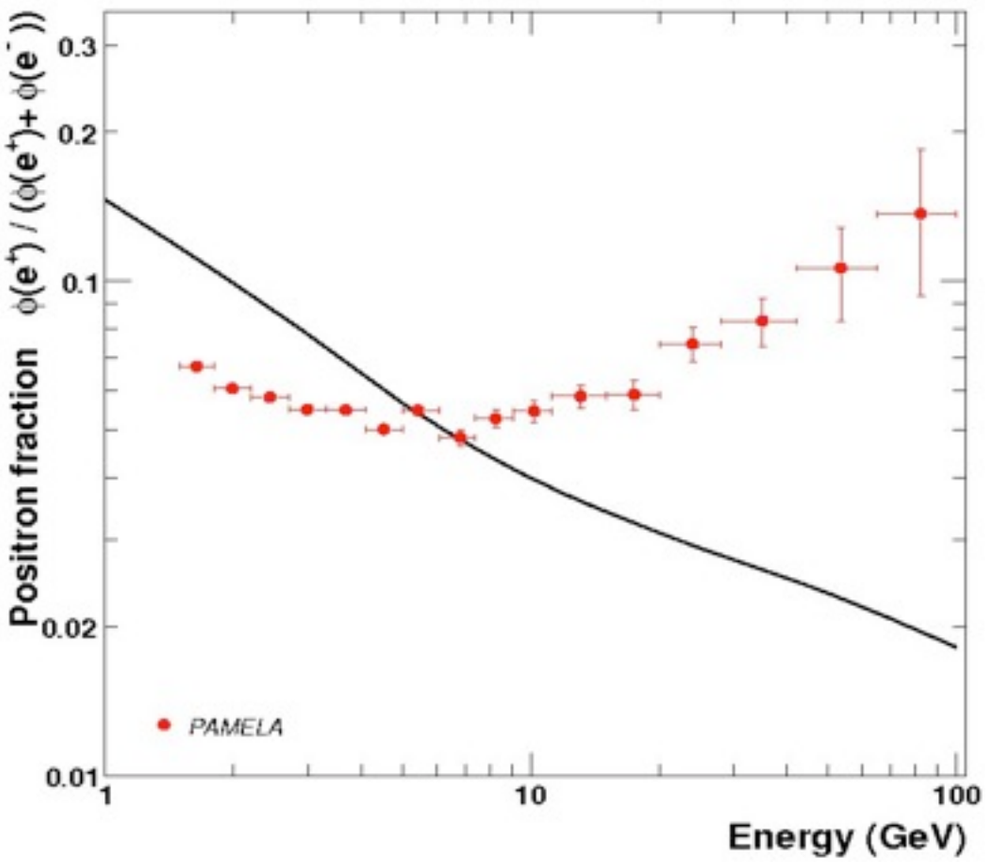
positrons: excess in positron fraction between 10 and 200 GeV

first observed by HEAT and AMS1

confirmed and improved by PAMELA

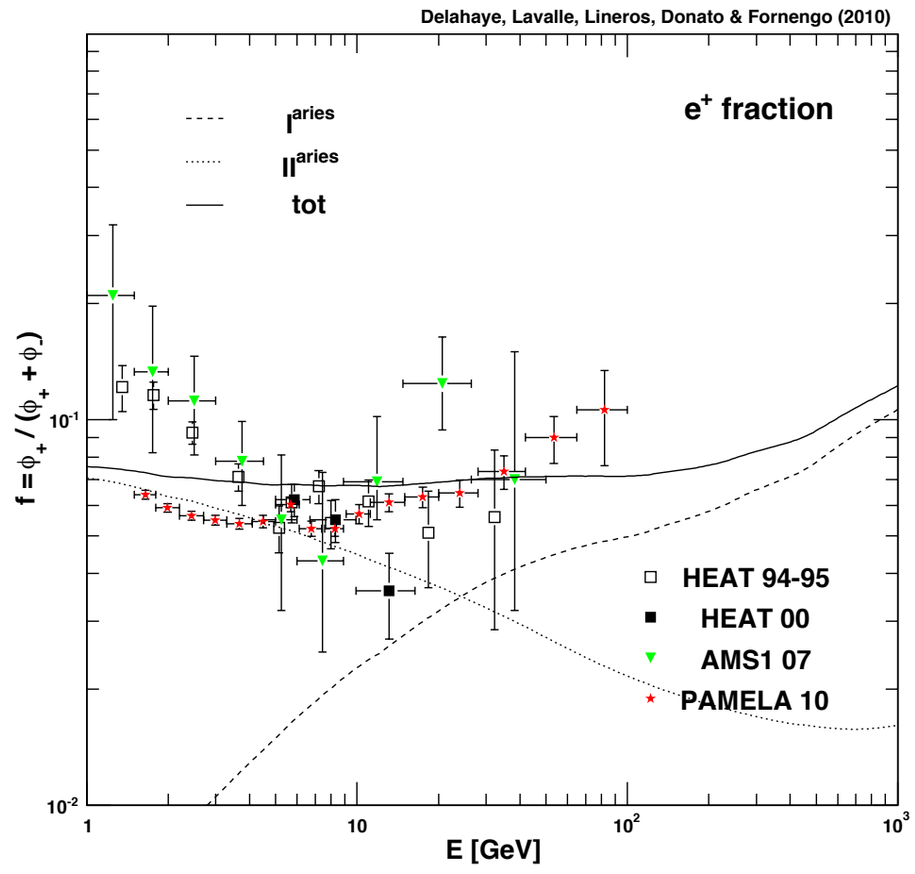
now confirmed and extended to higher E by Fermi





Interpretation?

Could be produced by astrophysical sources:



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

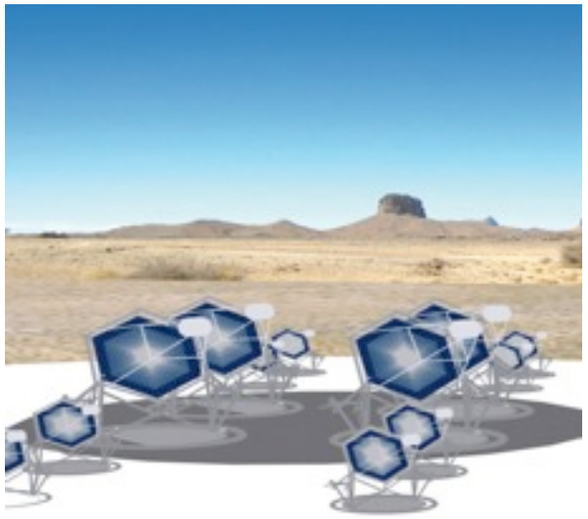
..... secondaries
produced by interactions between cosmic rays and interstellar gas

IF due to DM annihilation would need:

i) large enhancement in annihilation rate (clumpy DM 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...)

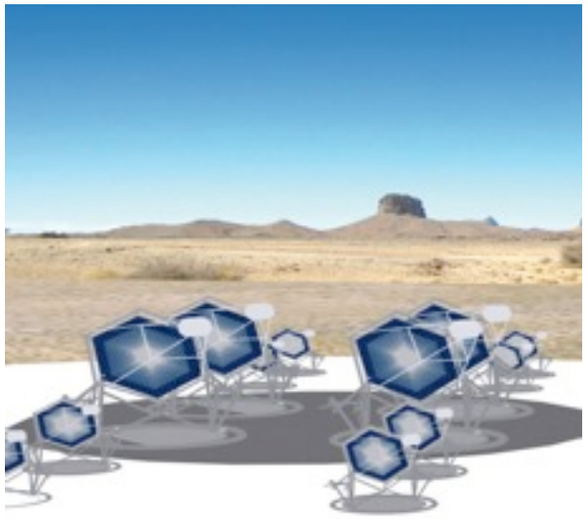
Future prospects:



CTA

AMS-02

Future prospects:

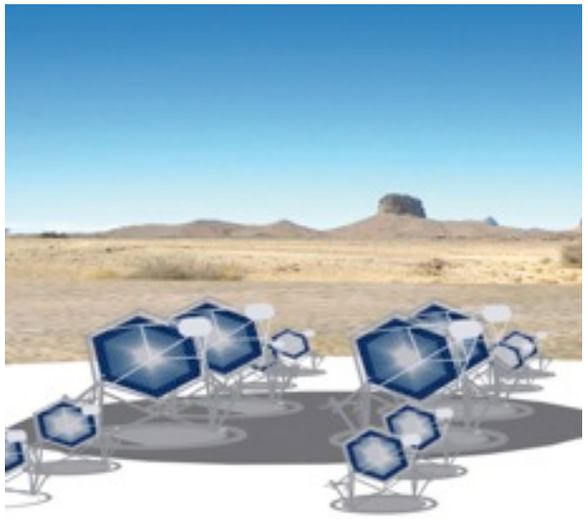


CTA

AMS-02

Warning: particle theorists can produce models to fit almost any astrophysical data!

Future prospects:



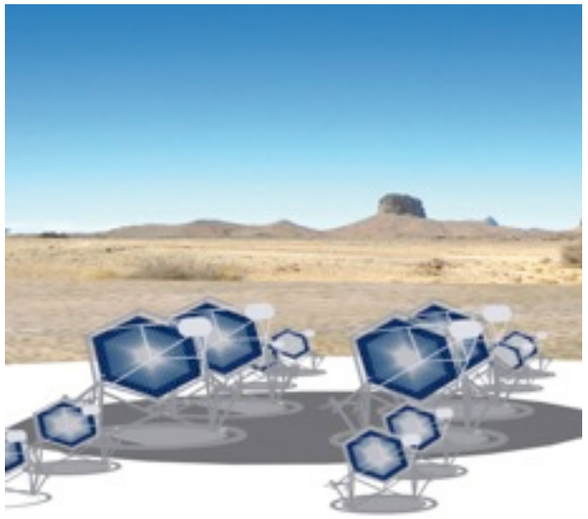
CTA

AMS-02

Warning: particle theorists can produce models to fit almost any astrophysical data!

Is it possible to convincingly detect WIMPs indirectly?

Future prospects:



CTA

AMS-02

Warning: particle theorists can produce models to fit almost any astrophysical data!

Is it possible to convincingly detect WIMPs indirectly?

Possibly...

e.g. look for features in gamma-ray spectrum: line at WIMP mass or high E feature (internal Bremsstrahlung)

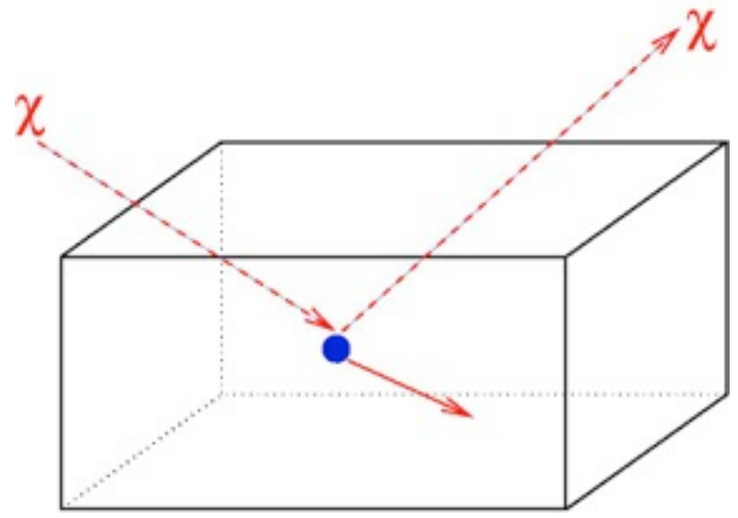
different sources with same energy spectrum

multi-wavelength signals

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). Majority experiments most sensitive to spin-independent.

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

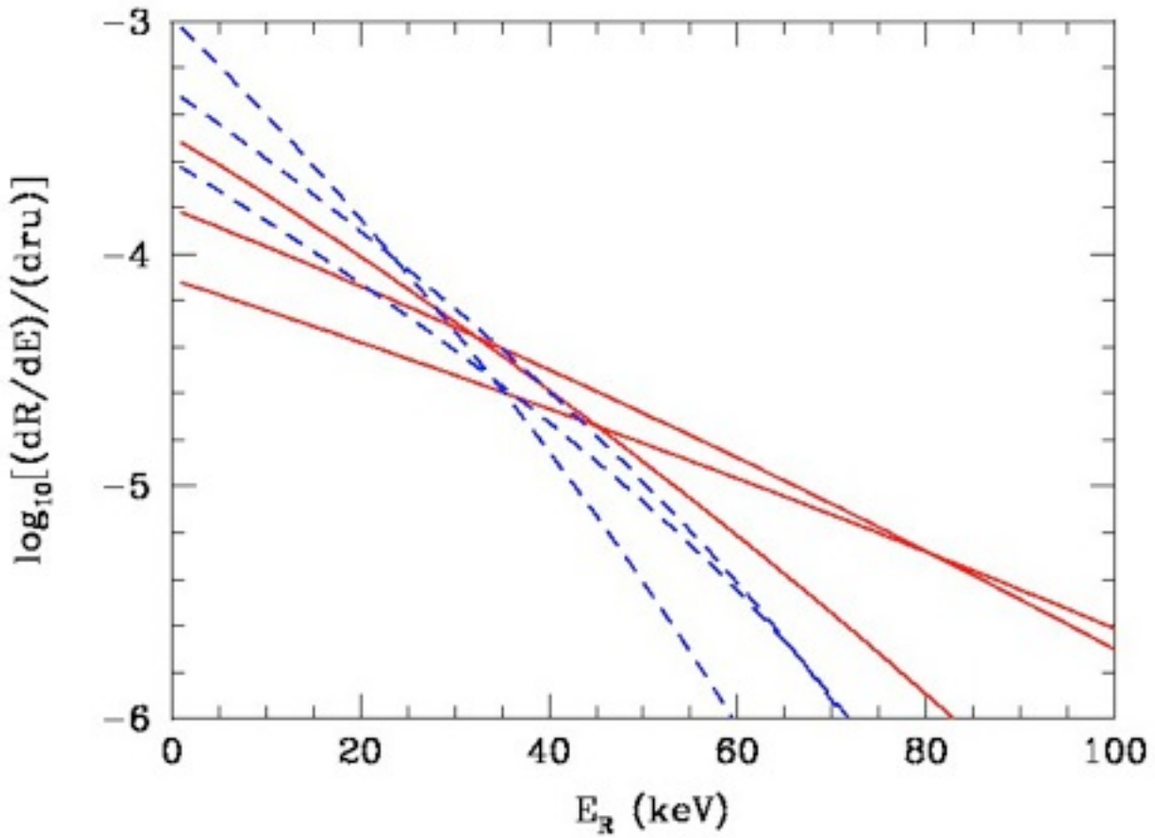
$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_p \rho_\chi A^2 F^2(E) \int_{v_{\min}}^{\infty} \frac{f(v)}{v} \mathrm{d}v$$

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

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

signals:

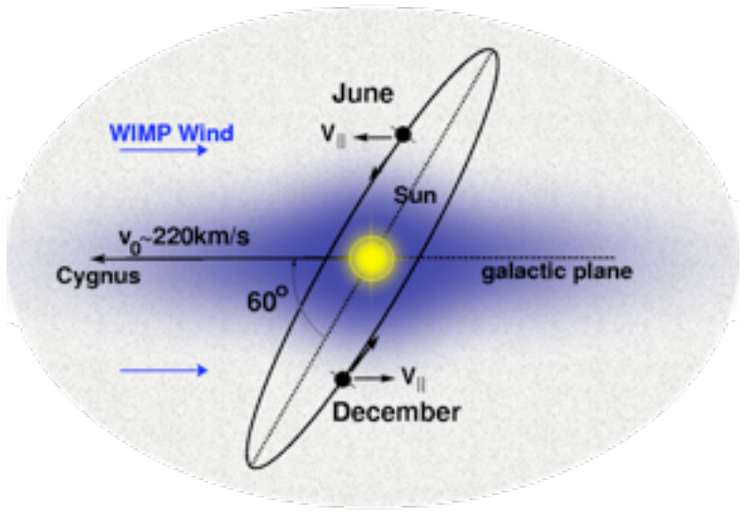
i) dependence of event rate on mass of target nuclei [Lewin & Smith]

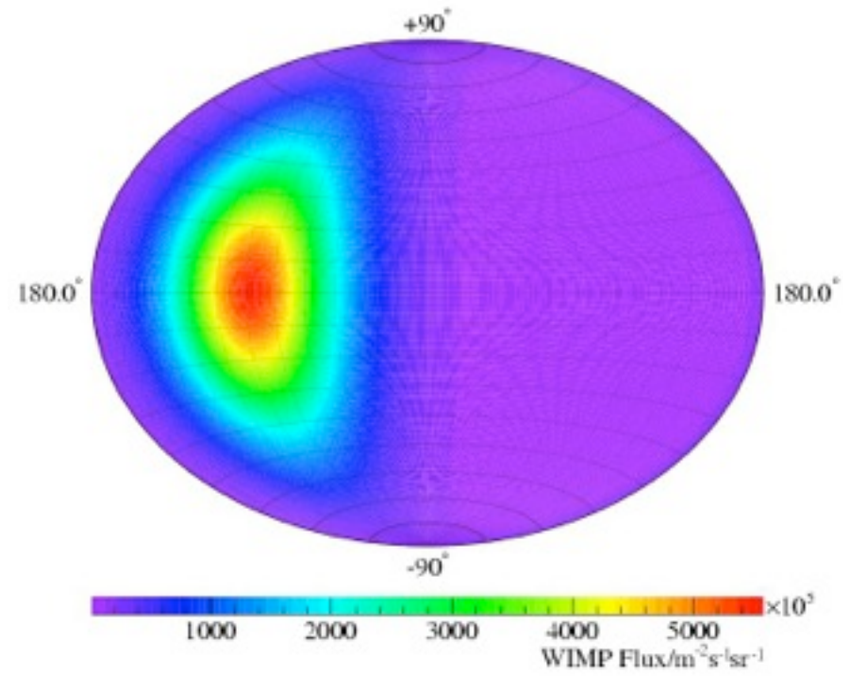


Ge and Xe m_χ = 50, 100, 200 GeV

i.e. measure consistent energy spectra using detectors made of different target nuclei.

ii) directional dependence of event rate [Spergel]





Large signal.

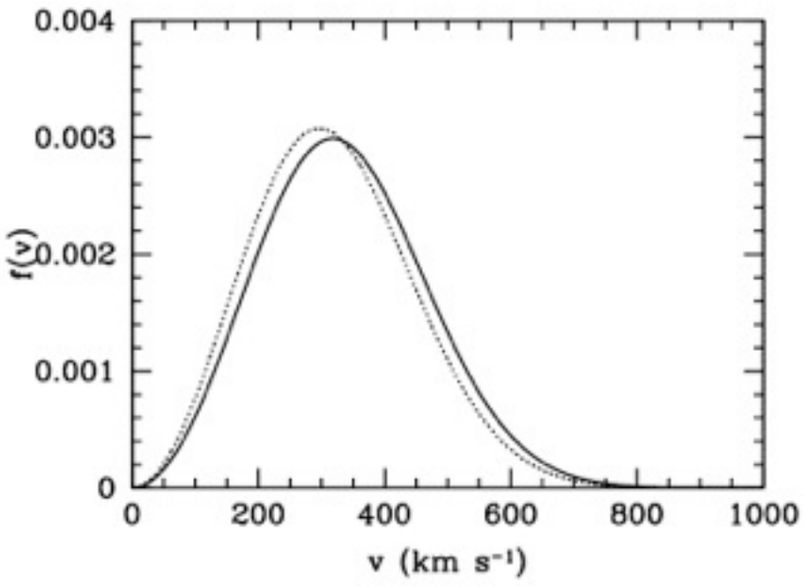
With an ideal detector:

~10 events required to reject isotropy of recoil directions [Morgan, Green & Spooner]

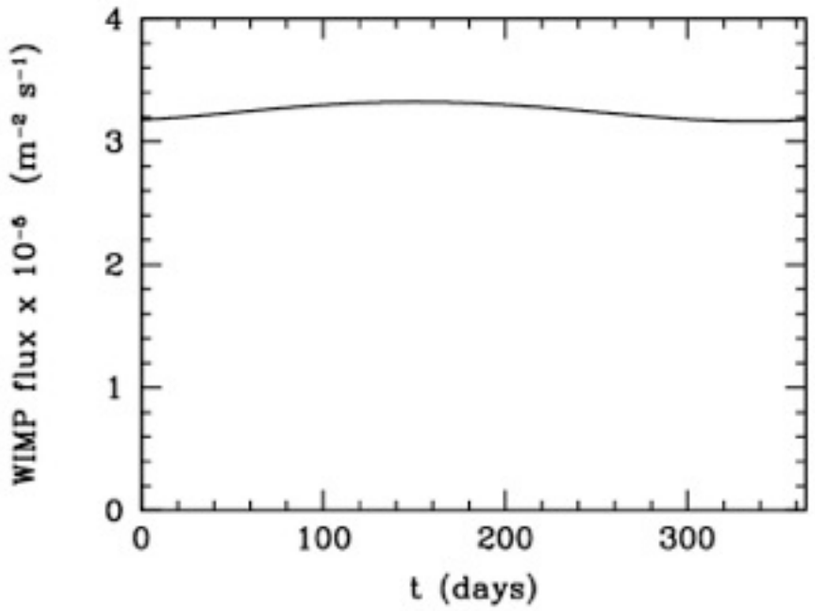
~30 events required to confirm peak direction coincides with direction of solar motion [Green & Morgan]

Need a detector which can measure recoil directions e.g. DMTPC, DRIFT, MIMAC, NEWAGE.

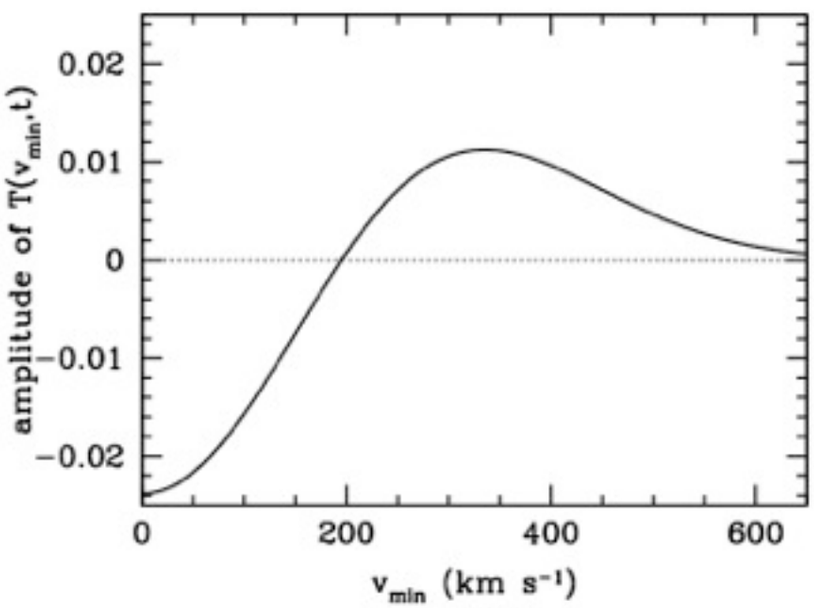
iii) annual modulation of event rate [Drukier, Freese & Spergel]



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



total WIMP flux



modulation amplitude

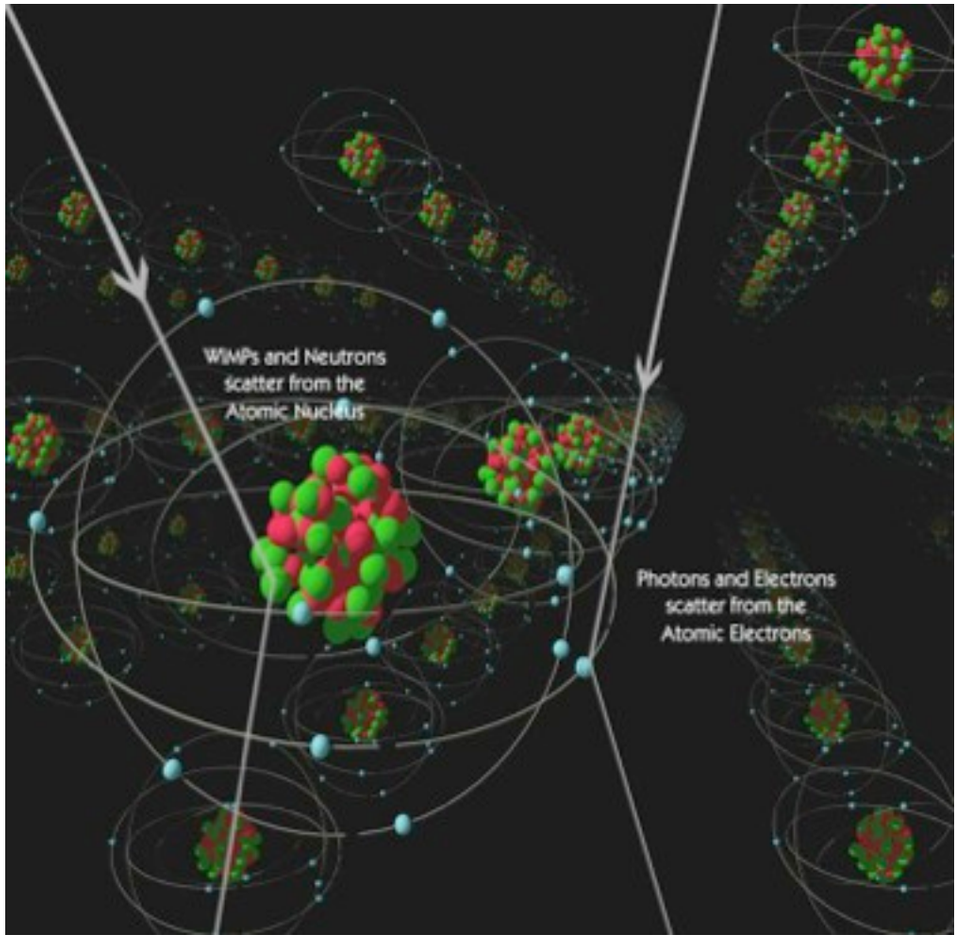
Signal fairly small, therefore need large detector running stably for a long time.

Depends on shape of f(v).

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

electron recoils due to βs and γs

nuclear recoils due to neutrons from cosmic rays or local radioactivity



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

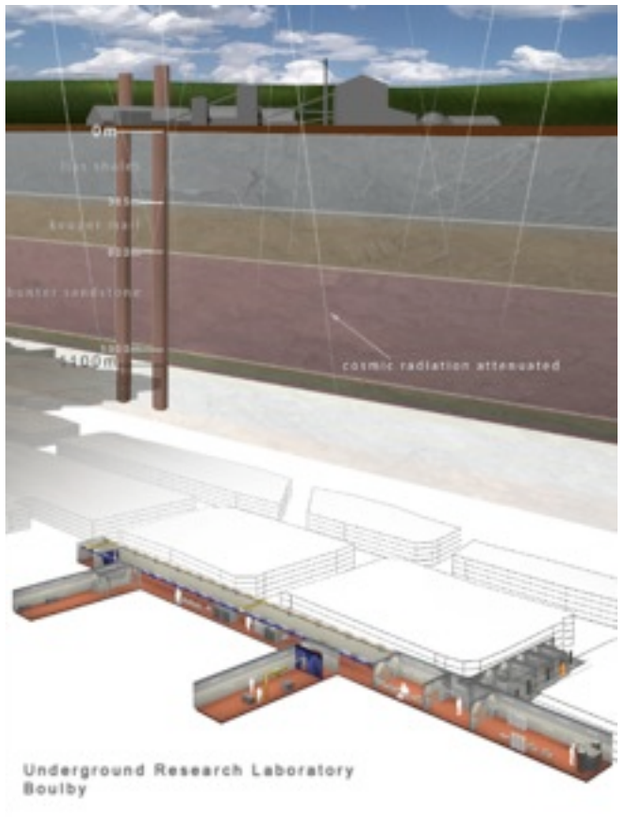
electron recoils due to βs and γs

look at multiple energy deposition channels (scintillation, ionisation, phonons)

nuclear recoils due to neutrons from cosmic rays or local radioactivity

indistinguishable on an event by event basis

operate detector deep underground, use shielding and radiopure components



[Boulby mine]

[Zeplin III]

Current status, i) null-results:

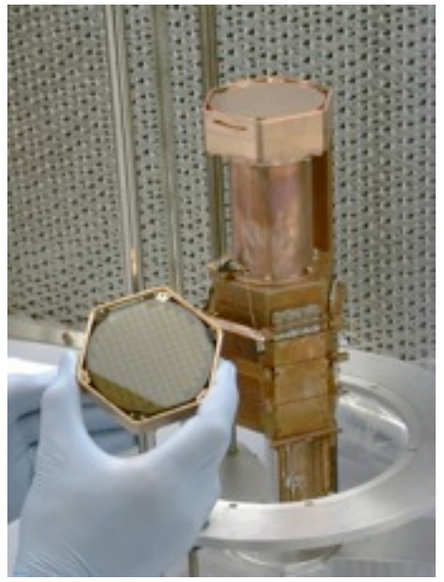
CDMS-II

cryogenic germanium (phonons and ionization)

612 kg days raw exposure, energy threshold 10 keV

2 events in signal region

0.8 background events expected
(surface events-electron recoils close to surface of detector)



Xenon100

two phase liquid/gas Xe (scintillation and ionisation)

48 kg fiducial volume, 101 days, energy threshold ~8.4 keV

3 events in signal region

1.8 ± 0.6 background events expected (mainly electron recoils)

ii) 'excesses'

CoGeNT

germanium (ionization)

330 g fiducial mass, 56 days, energy threshold ~2 keV

"excess" of low energy events after fitting for exponential + constant background consistent with ~10 GeV WIMPs

CRESST

$CaWO_4$ (phonons and ionization)

net exposure 730 kg days, energy threshold 10-20 keV

67 events in signal region

maximum likelihood analysis:
(including parameterizations of 4 backgrounds)
~20 events due to light (10-25 GeV) WIMPs

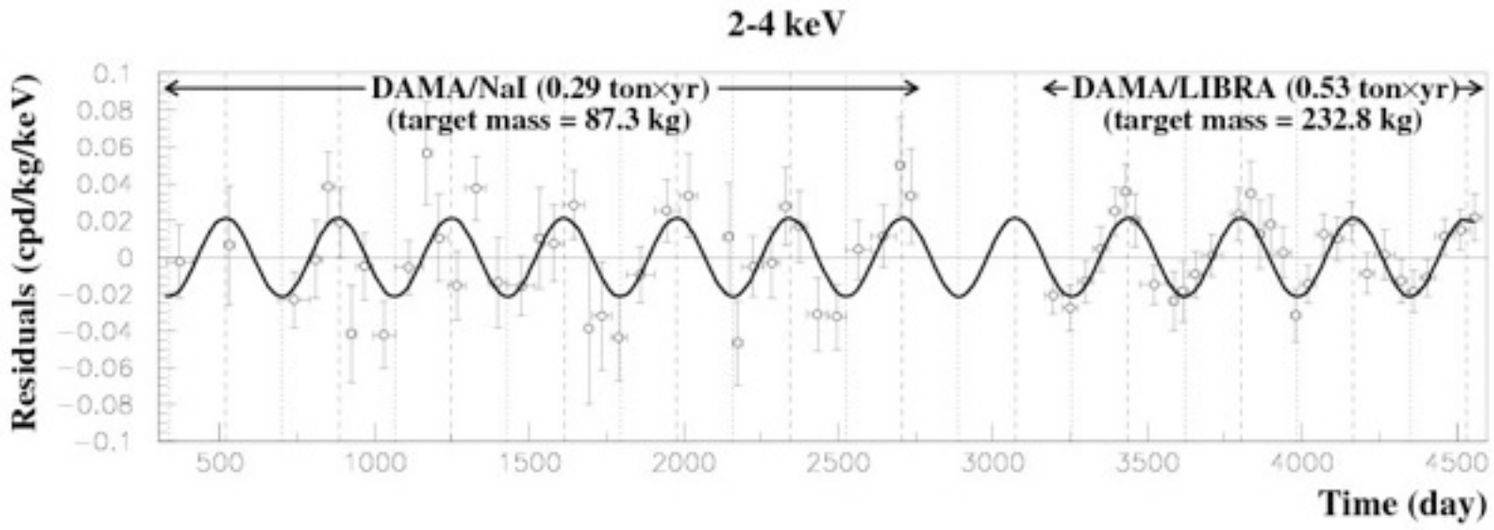
iii) annual modulations

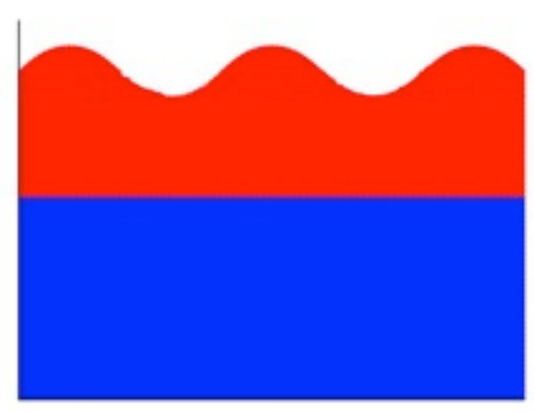
DAMA/LIBRA

NaI (scintillation)

exposure 1.2 ton years, energy threshold ~6 keV

8.4 σ annual modulation signal (over 12 years), phase compatible with WIMP expectations





CoGeNT

germanium (ionization)

145 kg days, energy threshold ~2 keV

2.8 σ annual modulation signal (roughly compatible with DAMA).

Summary of current status:

Various 'hints':

excesses above expected backgrounds (CoGeNT, CRESST)

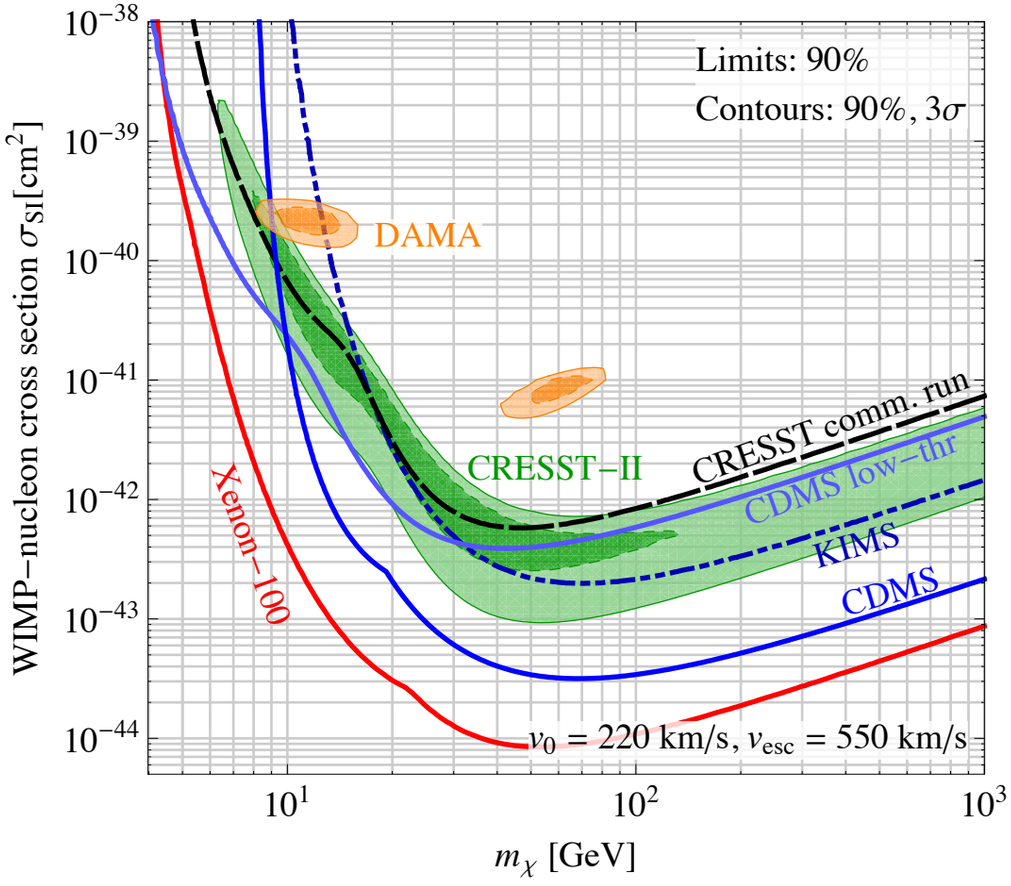
annual modulations (DAMA, CoGeNT)

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

BUT

Currently no consistent interpretation of all experimental data (including null results from e.g. CDMS & Xenon).

(even taking into account experimental and astrophysical uncertainties [Frandsen et al.], & 'non-standard' WIMP interactions e.g. isospin dependent couplings, inelastic DM [Kopp, Schwetz & Zupan])

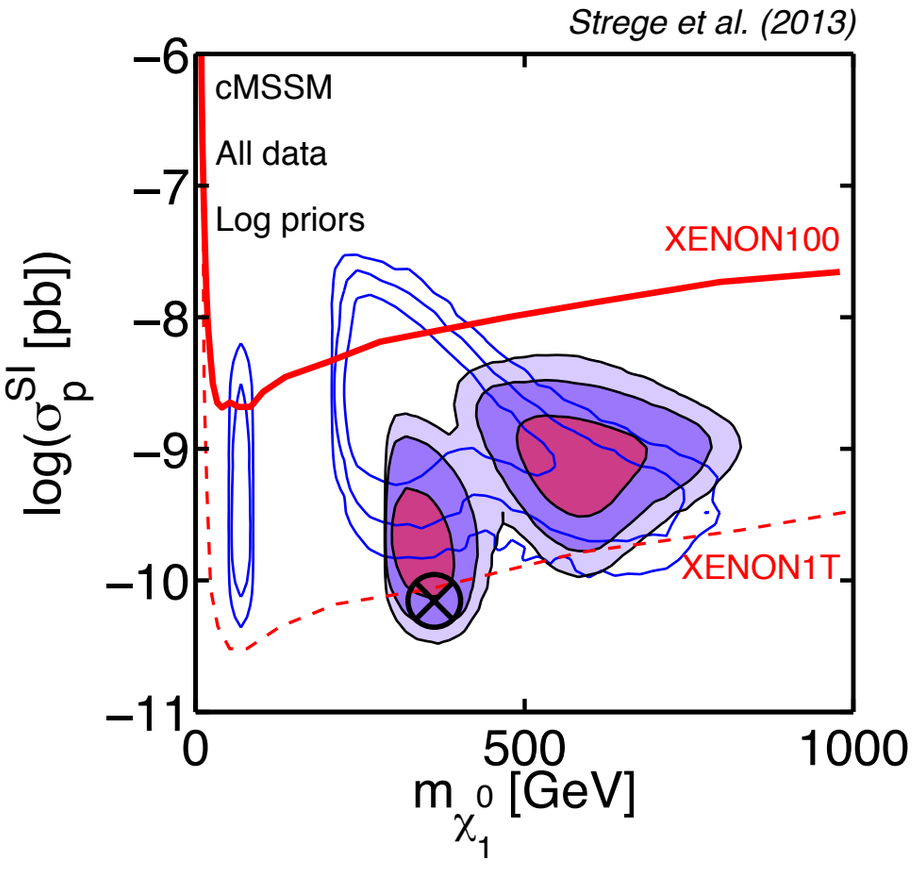


[Kopp, Schwetz & Zupan]

Future prospects:

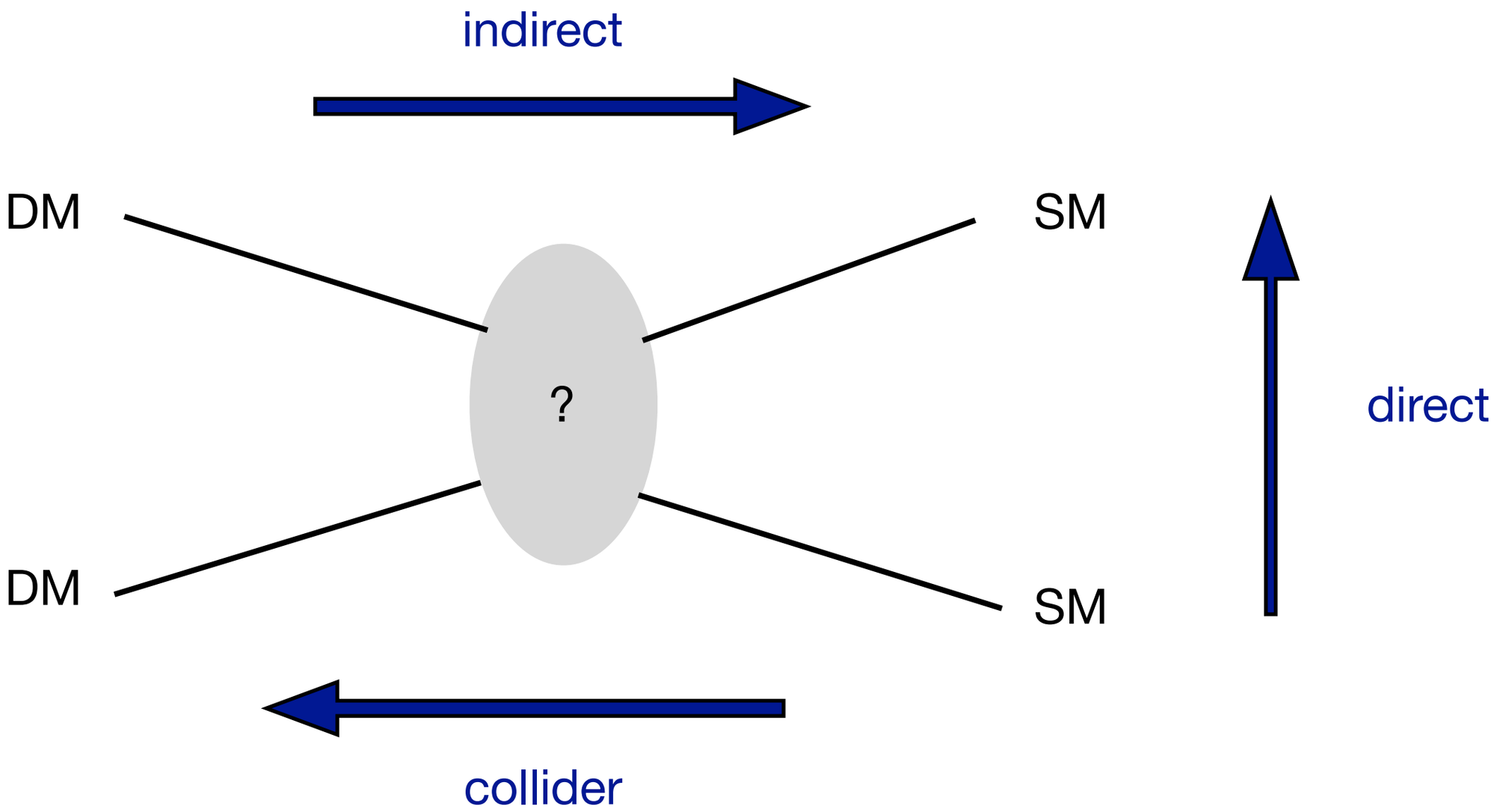
Upgrades of current experiments to the multi-tonne scale, improving sensitivity by up to 3 orders of magnitude.
(e.g. DARWIN, EURECA, LUX-Zeplin, SuperCDMS/GEO)

Strege et al.: cMSSM, constraints from CDM density, anomalous magnetic moment of the muon, b → s γ, flavour changing neutral currents, Higgs mass.



So how can we (convincingly....) detect WIMPs?

Consistent measurements of WIMP properties (e.g. mass) from different direct, indirect and collider experiments.



Summary

★ Lots of cosmological and astronomical evidence for non-baryonic cold dark matter
(imho modified gravity hasn't been completely ruled out yet, but has some tough observational tests to pass).

★ WIMPs are generically a good CDM of particle physics and supersymmetry provides us with a well motivated WIMP candidate in the form of the lightest neutralino (but there are many other dark matter candidates).

★ (convincingly) Detecting CDM (and measuring its properties) will probably require a mixture of lab, collider and astrophysical experiments/observations.

The simplest halo model: the isothermal sphere

Theory

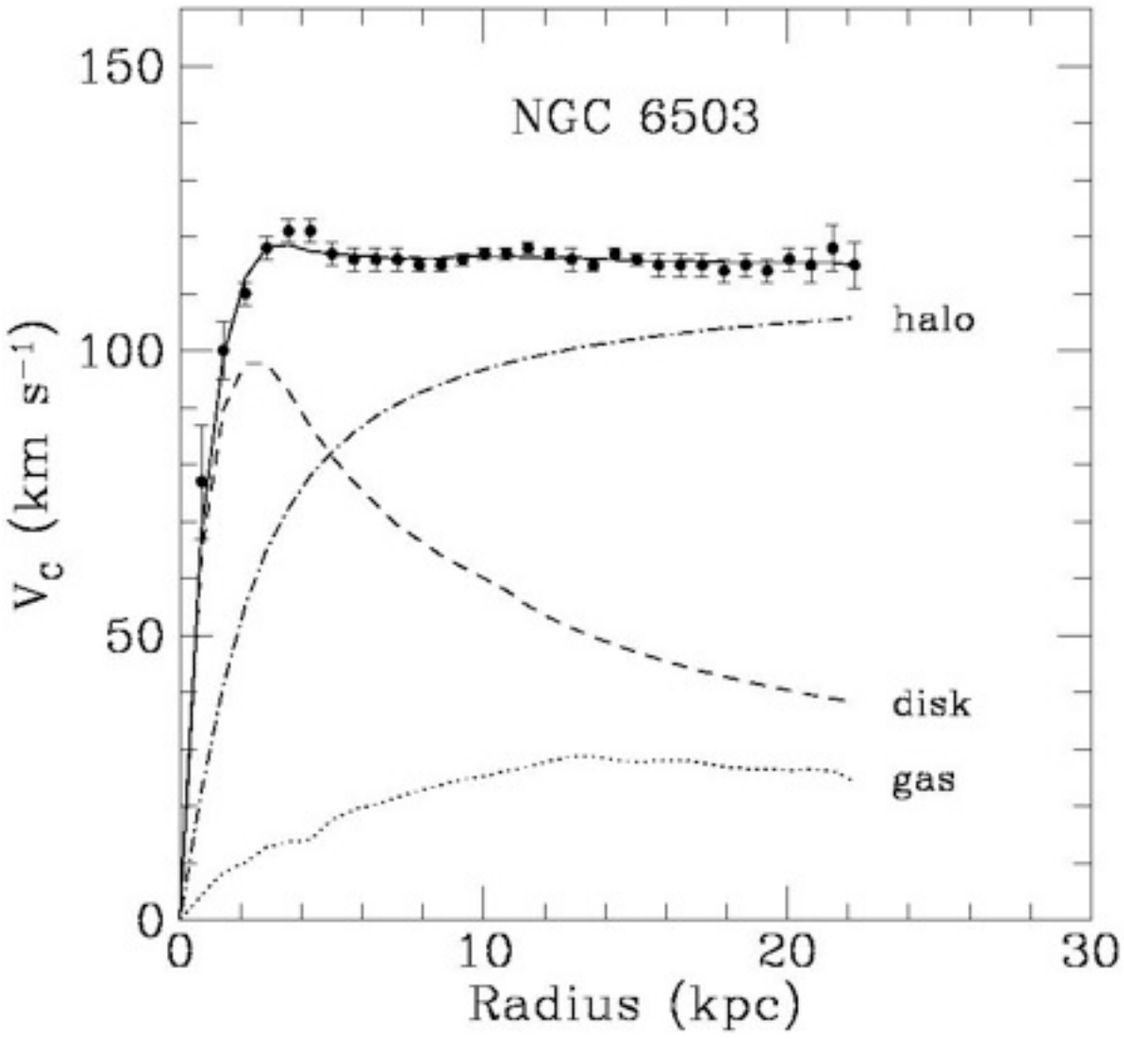
The equilibrium distribution of a gas of self-gravitating particles is an isothermal (velocity dispersion/temperature independent of position) sphere with a Maxwellian velocity distribution:

$$\rho(r) = \frac{\sigma_v^2}{2\pi G r^2} \qquad f(v) \propto \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma_v^2}\right) \qquad \sigma_v^2 = \frac{kT}{m}$$

Collisionless particles can change their energy if they experience a fluctuating gravitational potential and also reach this configuration (**violent relaxation**).

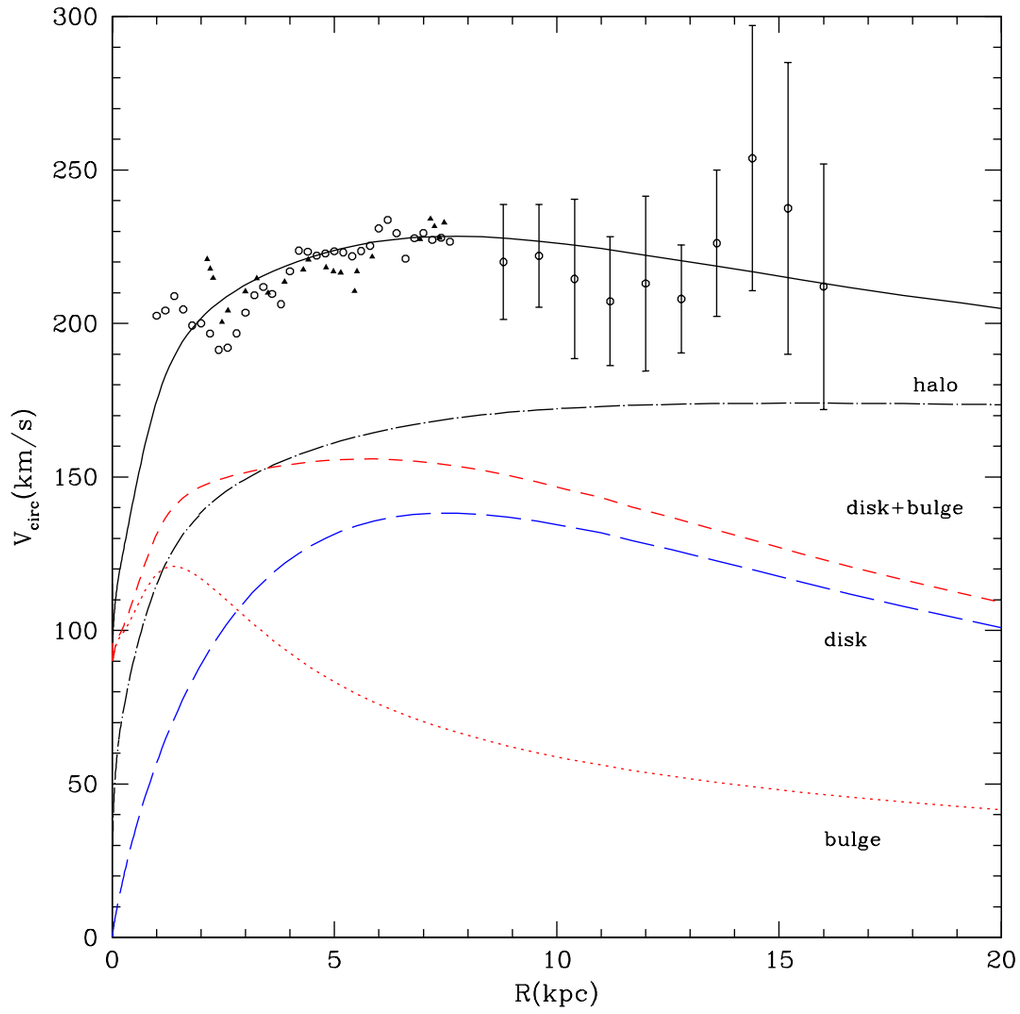
n.b. isothermal sphere is infinite in extent (particles with arbitrarily large speeds can reach any given radius) and mass diverges.

Observational support: Galaxy rotation curves



Milky Way

[Klypin, Zhao &Somerville]

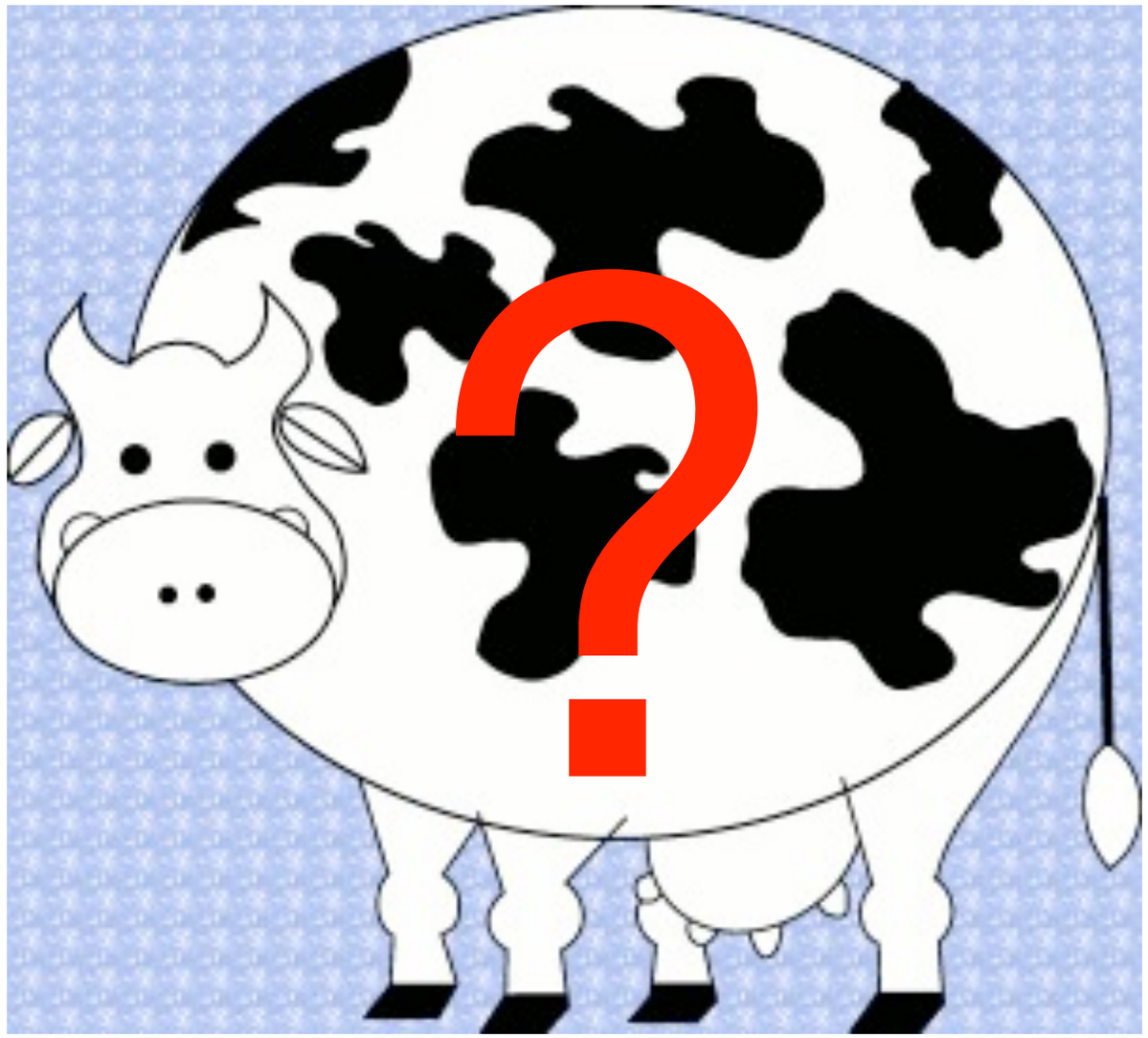


$$\frac{v_{rot}^2}{r} = \frac{GM(<r)}{r^2}$$

$$v_{rot} \sim const$$

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

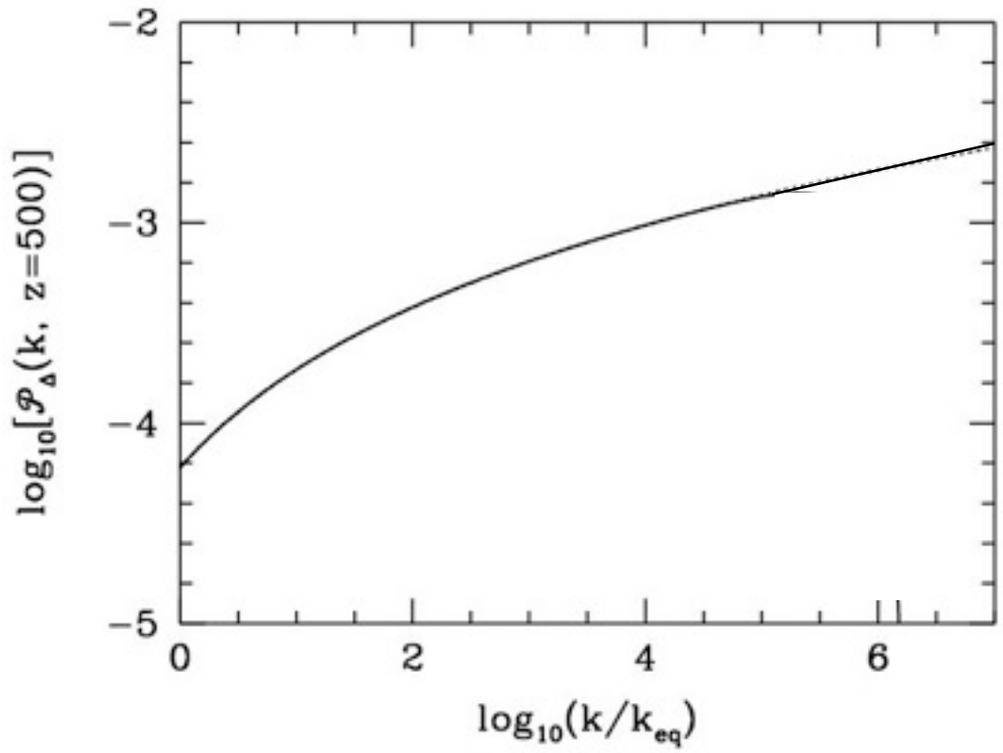
$$\rho(r) \propto \frac{1}{r^2}$$



Numerical simulations

In CDM cosmologies structure forms hierarchically: small halos (typically) form first and then larger halos form via mergers and accretion.

Small scales (re-)enter the horizon, and density perturbations can start growing, earliest.



$$\mathcal{P}_\delta(k) = \frac{k^3}{2\pi^2}\langle|\delta^2|\rangle$$

$$\delta = \frac{\delta\rho - \bar{\rho}}{\bar{\rho}}$$

Therefore if the initial power spectrum is (close to) scale-invariant small scales go non-linear and collapse first.

Simulating Milky Way like halos (a ‘non-expert’ summary):

Chose input cosmological parameters (e.g. $h,\ \Omega_{\rm m},\ \Omega_{\Lambda}, n_{\rm s}$).

Calculate linear power spectrum.

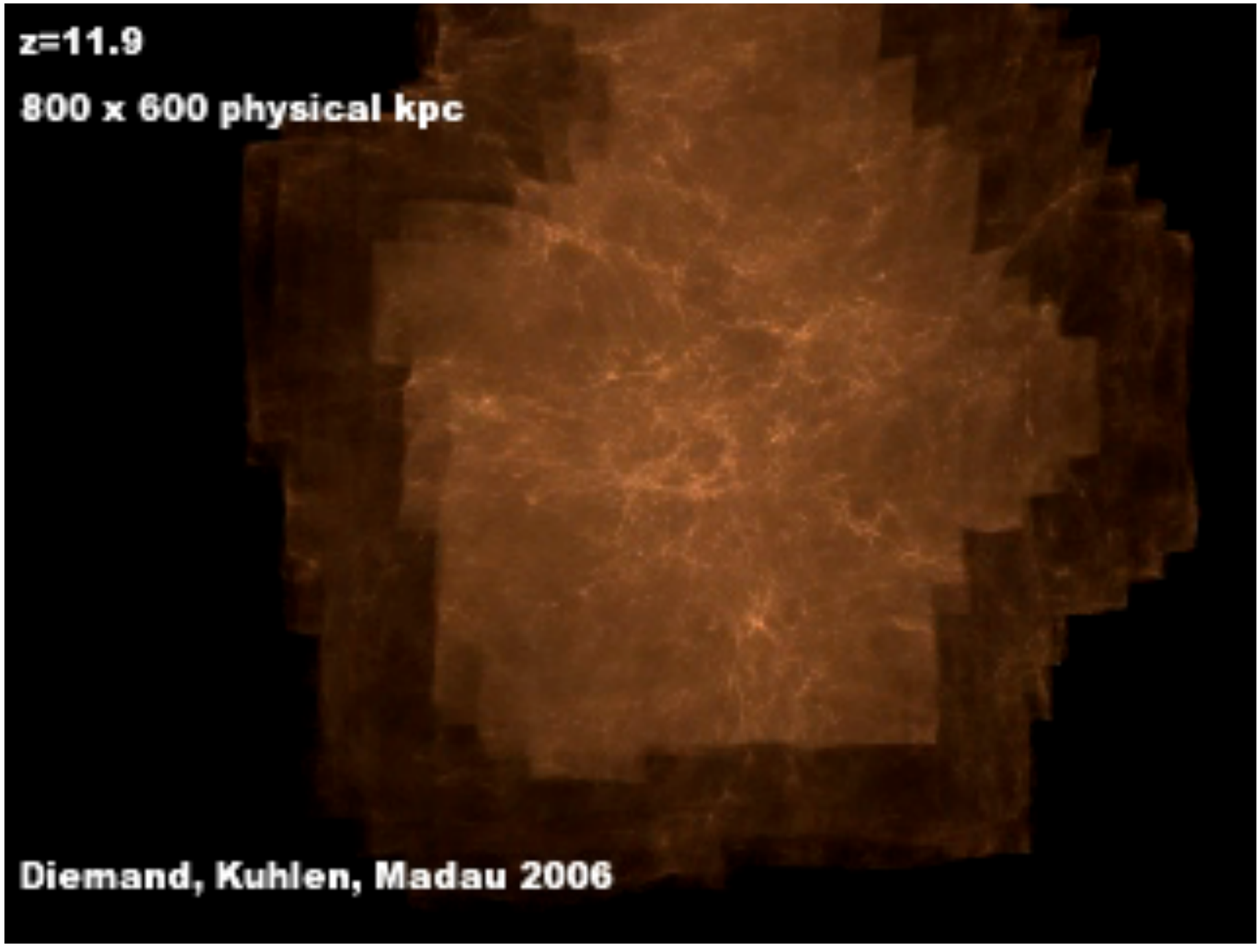
Carry out large volume simulation.

Select Milky Way like halo ($M \sim 10^{12} M_{\odot}$, no massive close neighbours or recent major mergers).

Resimulate, using lower mass particles in region that forms halo of interest (“zoom technique”).

Carry out convergence tests (do properties change when you change the particle mass or gravitational softening?) and study halo-to-halo scatter.

Recent high resolution ***dark matter only*** simulations (e.g. Aquarius, GHALO, Via Lactea II) can resolve scales $M \sim 10^{4} M_{\odot}$.



Via Lactea I, Diemand, Kuhlen & Madau

Not smooth, spherical and isotropic (a la isothermal sphere).

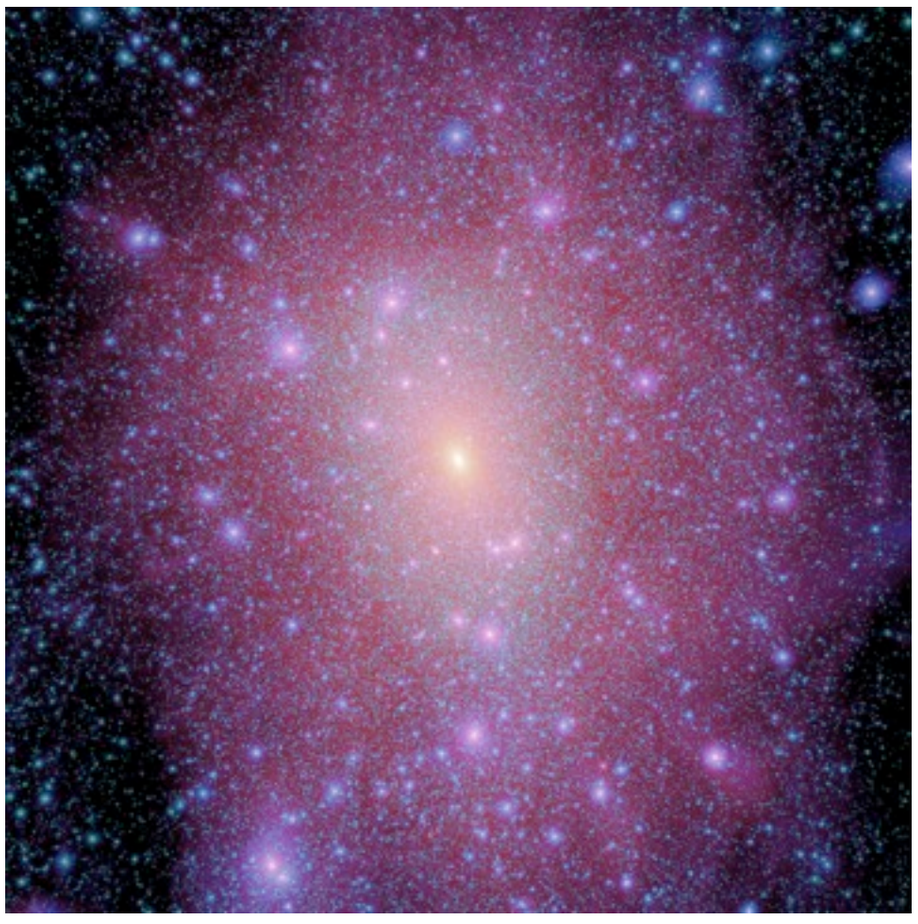
Radius (O(200 kpc)), much larger than Solar radius (8 kpc).

No well-defined edge.

Substructure

Since late 90s simulations have been able to resolve large amounts of substructure (sub-halos) within galaxy halos [Klypin et al.; Moore et al.]

Aquarius:

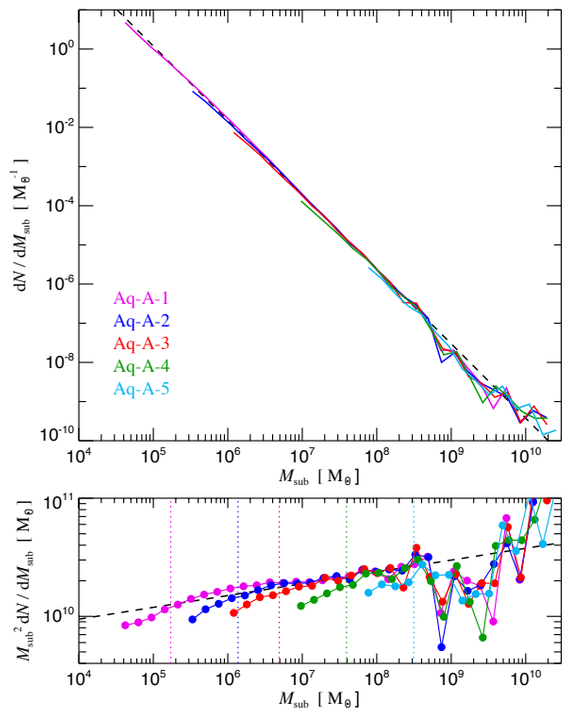


$$\frac{\mathrm{d}n}{\mathrm{d}M}$$

$$M^2 \frac{\mathrm{d}n}{\mathrm{d}M}$$

$M/M_\odot$

10^4 10^{10}



sub-halo mass function for 5 varying resolution simulations of same halo

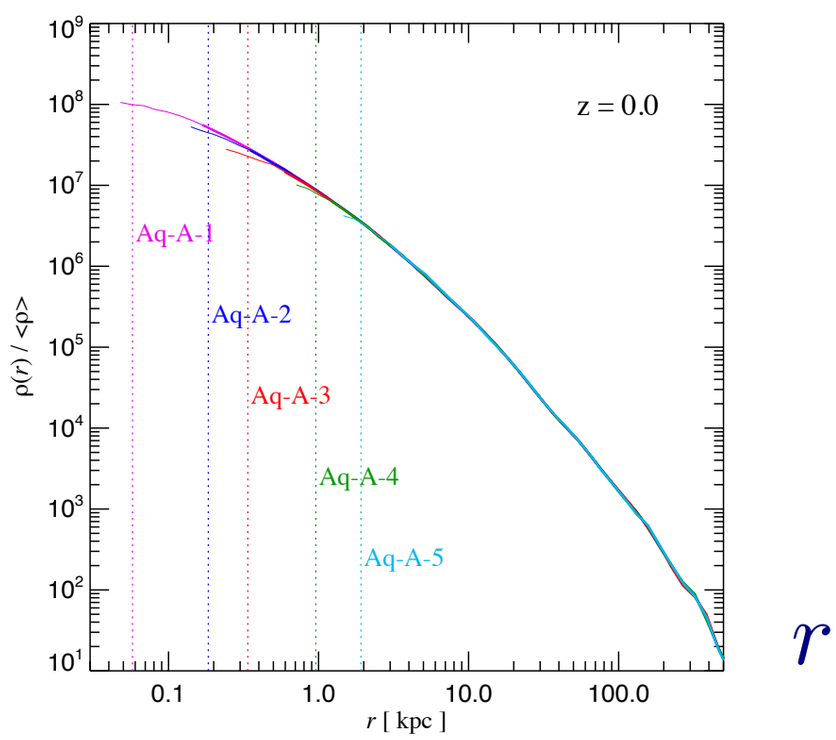
mass function:

$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \left(\frac{M}{M_\odot}\right)^{-\alpha}$$

$$\alpha = 1.90 \pm 0.03$$

Density profile

Aquarius:



Navarro, Frenk & White: "A universal density profile from hierarchical clustering"

$$\rho(r) = \rho_{\rm crit}\,\frac{\delta_{\rm char}}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2}$$

$r_{\rm s}$ scale radius $\left(\frac{{\rm d}\ln\rho}{{\rm d}\ln r}\right)_{r=r_{\rm s}} = -2$

$r_{\rm vir}$ virial radius, radius within which mean density is $\Delta\rho_{\rm m}$

Δ virial overdensity

$c = \frac{r_{\rm vir}}{r_{\rm s}}$ concentration

$\rho(r) \propto r^{-1}$, as $r \to 0$, $\rho(r) \propto r^{-3}$, for $r \gg r_{\rm s}$

c.f. (singular) isothermal sphere: $\rho(r) \propto r^{-2}$ for all r.

The physics behind the NFW profile and its parameters:

Smaller halos form earlier (when the density of the Universe is larger) and hence have higher characteristic densities.

Concentration depends on mass and red-shift. n.b. this is partly because virial radius, by definition, increases with time.
Empirical models [e.g. Navarro, Frenk & White; Bullock et al.; Eke, Navarro & Steinmetz; Zhao et al.] relate concentration to formation time of halo.

Formation history: early rapid merger phase (inner part of halo assembled) followed by slow accretion (increases mass and size of halo but doesn't affect inner regions).

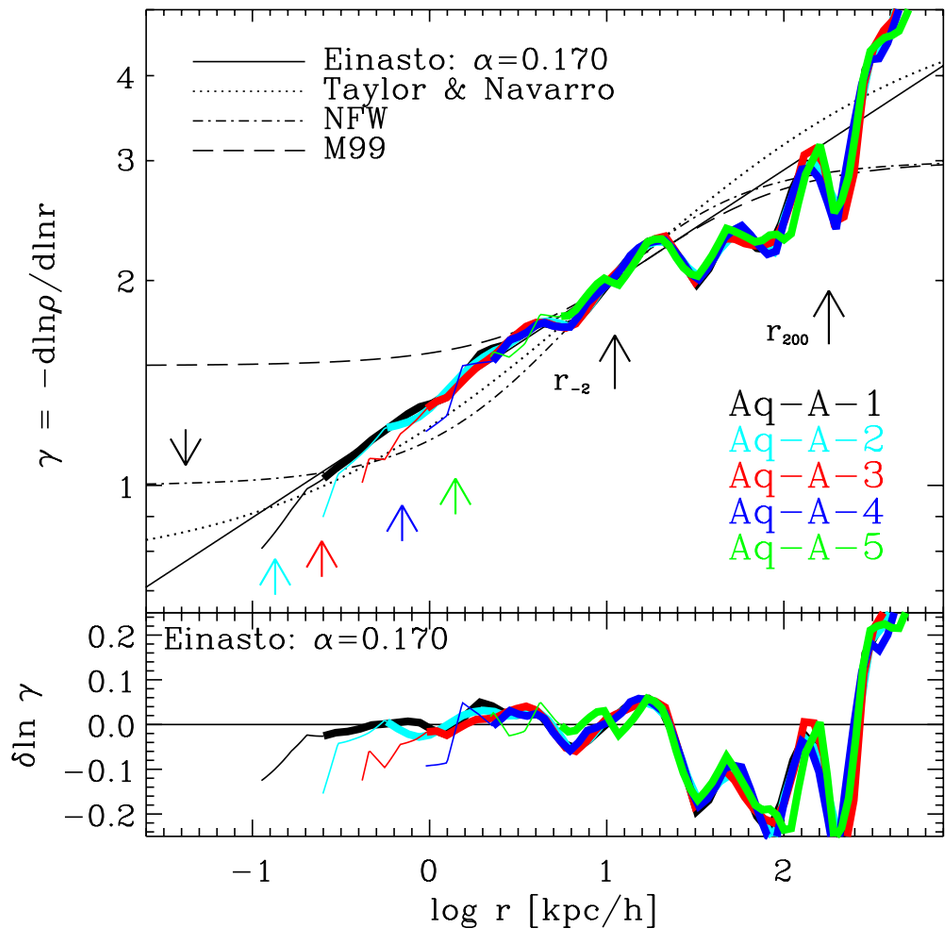
Various proposed explanations for uniformity of density profile [e.g. Syer & White; Dekel et al.; Lu et al.; Dalal, Lithwick & Kuhlen] in terms of, for instance, formation history but no generally accepted explanation.
(n.b. NFW-like profiles even arise in simulations of non-hierarchical structure formation e.g. monolithic collapse.)

How does the density profile behave in $r \to 0$ limit?

Aquarius:

logarithmic slope of density profile

$$\gamma = -\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}$$



Einasto profile: $$\rho(r) = \rho_{\rm s} \exp\left\{-\frac{2}{\alpha}[(r/r_{\rm s})^{\alpha} - 1]\right\}$$

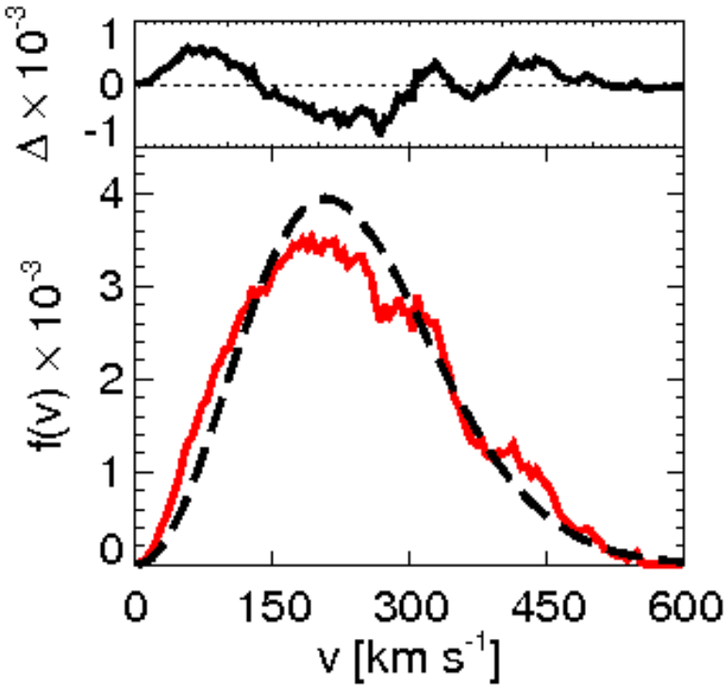
n.b. different halos have different best fit parameters

scatter between different halos similar to differences between profiles

Local velocity distribution

Systematic deviations from multi-variate gaussian: more low speed particles, peak of distribution lower/flatter.

Stocastic high v features. As well as cold tidal streams, tidal stripping produces spatially extended debris flows (shells, sheets & plumes) that aren't completely phase mixed. [Lisanti & Spergel; Kuhlen, Lisanti and Spergel]



Vogelsberger et al.

red lines: simulation data,
black lines: best fit multi-variate Gaussian

Hansen et al.; Fairbairn & Schwetz and Kuhlen et al. have found similar results.

f(v) fit fairly well by modified Maxwellian or Tsallis distribution
(arises from non-extensive statistical mechanics).

$$f(v_{\rm r}) = \frac{1}{N_{\rm r}} \exp\left[-\left(\frac{v_{\rm r}}{\bar{v}_{\rm r}}\right)^{\alpha_{\rm r}}\right] \qquad f(v_{\rm t}) = \frac{v_{\rm t}}{N_{\rm r}} \exp\left[-\left(\frac{v_{\rm t}}{\bar{v}_{\rm t}}\right)^{\alpha_{\rm t}}\right]$$

How is the dark matter distributed on scales smaller than those resolved by simulations?

Why is this important?

Direct detection

Experiments probe sub milli-pc scales (c.f. 100 pc resolution of simulations).

Is the ultra-local dark matter distribution the same as that found in simulations?

Is the dark matter distribution smooth on these scales? (could we be sat in a dark matter void??)

Indirect detection

Substructure on all scales contributes to the signals.

What is the (mass and spatial) distribution of subhalos with $M < 10^4 M_\odot$?

Need to understand the properties and fate of the first, smallest, dark matter microhalos to form.

How small are the smallest (WIMP) microhalos?

[Hofmann, Schwarz & Stocker; Berezinsky, Dokuchaev & Eroshenko; Green, Hofmann & Schwarz; Loeb & Zaldarriaga; Bertschinger; Profumo, Sigurdson & Kamionkowski; Bringmann & Hofmann; Martinez et al.; Bringmann]

After freeze-out (chemical decoupling) at T~O(1-10 GeV) WIMPS carry on interacting kinetically with radiation:

$$\chi + \chi \not\Leftrightarrow X + X \qquad\qquad \chi + X \Rightarrow \chi + X$$

At T~O(1-10 MeV) WIMPS kinetically decouple and free-stream, erasing perturbations on co-moving scales < O(1 pc). [Hofman, Schwarz & Stocker]

For a typical 100 GeV WIMP, first smallest halos to form have [Green, Hofmann & Schwarz]

$$R \sim 0.01\,\mathrm{pc} \qquad\qquad M \sim 10^{-6} M_\odot$$

but in MSSM minimum mass can vary by many orders of magnitude.

(most recent calculations

$10^{-11} M_\odot < M < 10^{-3} M_\odot$ [Bringmann]

$10^{-9} M_\odot < M < 10^{-6} M_\odot$ [Martinez et al.])

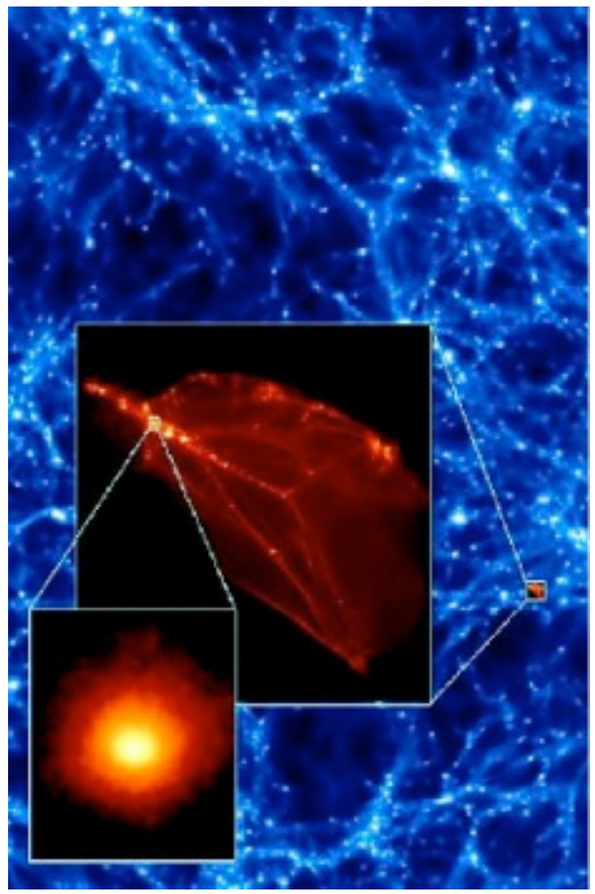
Simulations of microhalos formation Diemand, Moore and Stadel

Input power spectrum with cut-off at k~1pc.

Re-simulate a small 'typical' region starting at z=350 up until z=26 (when the high resolution region begins to merge with surrounding low resolution regions).

Smallest microhalos have, as expected, $M \sim 10^{-6} M_\odot$ and profiles similar to larger halos shortly after formation (NFW with low concentration).

Mass function: $\frac{\mathrm{d}n}{\mathrm{dln}M} \propto M^{-1}$ (same slope as on larger scales)



Initial box size (3 kpc)^3
both zooms are x100.

Subsequent dynamical evolution?

In addition to tidal stripping etc. microhalos on disc crossing orbits with be heated by encounters with stars and lose mass. [Diemand, Moore & Stadel; Zhao, Taylor, Silk & Hooper x2; Moore, Diemand, Stadel & Quinn; Berezinsky, Dokuchaev & Eroshenko; Angus & Zhao; Green & Goodwin; Goerdt et al; Schneider, Moore & Krauss]

Earth mass microhalos in the solar neighbourhood will typically lose most of their mass but may retain a dense central core.

Modelling the sub-halo distribution (down to the cut-off scale)

[e.g. Pieri, Branchini & Hofmann; Gioccoli, Pieri & Tormen; Kamionkowski, Koushiappas & Kuhlen; Lee, Ando & Kamionkowski]

Two main approaches

i) Use and extrapolate substructure properties (mass function, concentration) from simulations. Assume sub-halos trace mass (or are anti-biased as found in simulations).

ii) Use merger tree to calculate merger history. Combine with prescriptions for dynamical evolution of sub-halos.

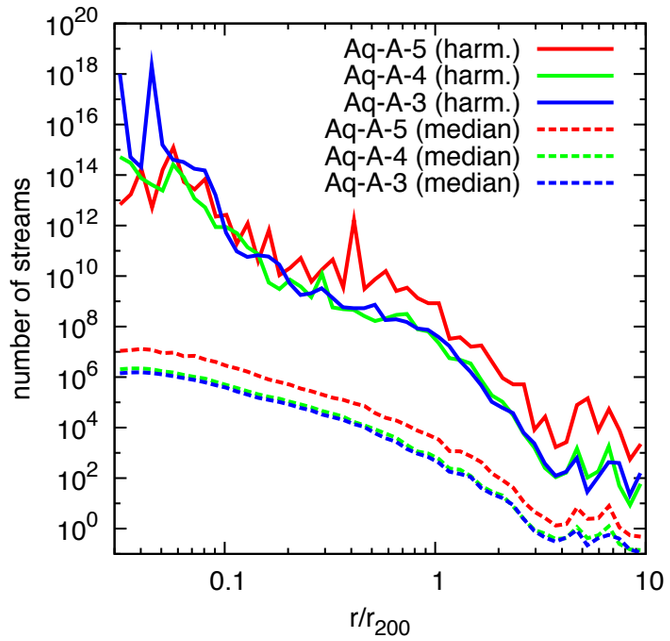
Extremely tricky problem, have to make extrapolations/assumptions.

Ultra-fine structure in the velocity distribution?

Vogelsberger & White:

Follow the fine-grained phase-space distribution, in Aquarius simulations of Milky Way like halos.

From evolution of density find ultra-local DM distribution consists of a huge number of streams.



number of streams as a function of radius
calculated using harmonic mean/median stream density

Schneider, Krauss & Moore: Simulate evolution of microhalos. Tidal disruption and heating from encounters with stars, produces 10^2-10^4 streams in solar neighbourhood.

But some features may be present. [Afshordi, Mohayee & Bertschinger; Fantin, Merrifield & Green]

How do baryons affect the dark matter distribution?

Central density profile

i) Adiabatic contraction due to cooling and contraction of baryons would steepen central density profile. [e.g. Blumental et al.; Gnedin et al.; Sellwood & McGaugh; Gustafsson, Fairbairn & Sommer-Larsen]

e.g. for a Milky Way like halo inner resolved slope can steepen by ~0.6.

ii) Supernovae feedback [e.g. Navarro et al.; Pontzen & Governato] or infall of baryon clump can weaken cusp. [e.g. El-Zant, Shlosman & Hoffman; Cole, Dehnen & Wilkinson]

iii) Supermassive black hole can change density profile in central ~pc. Nature and size of effect depends on how SMBH forms. [Gondolo & Silk; Ullio, Zhao & Kamionkowski; Bertone+Merritt +collaborators]

Substructure

[see Bullock 1009.4505 and Kravtsov 0906.3295 for overviews]

How do galaxies populate dark matter halos?
(in particular how do dwarf galaxies form in galactic sub-halos?)

Physical processes that affect (i.e. suppress) galaxy formation on small scales:

- supernovae feedback
- heating from photoionization
- ability of gas to cool

Galaxy formation is a very complicated process
(involving messy ‘sub grid’ physics).

Dark disc

Sub-halos merging at z<1 preferentially dragged towards disc, where they're destroyed leading to the formation of a co-rotating dark disc. [Read et al., Bruch et al., Ling et al.]

n.b. producing simulated halos which match the properties of the Milky Way is very challenging.

Detailed properties (& existence?) of dark disc are very uncertain.

Purcell, Bullock and Kaplinghat argue that to be consistent with the observed properties of thick disc, MW's merger history must be quiescent compared with typical ΛCDM merger histories, hence the DD density must be relatively low.

Bidin et al. measure surface density with 2-4 kpc of Galactic plane (using kinematics of thick disc stars), consistent with visible mass.

Observational probes of the density profile

the ‘core-cusp problem’

[see de Block for overview]

$$\text{as} \qquad r \to 0$$

core: $\rho \to \text{const}$ cusp: $\rho \propto r^{-\beta}$

NFW: $\beta = 1$

Rotation curves of low surface brightness (dark matter dominated) galaxies:
[THINGS, Oh et al.]

$$\beta = 0.29 \pm 0.07$$

Galaxy cluster Abell 383: strong & weak lensing data combined with stellar kinematics
[Newman et al.]

$$\beta = 0.59^{+0.30}_{-0.35}$$

Observational probes of substructure

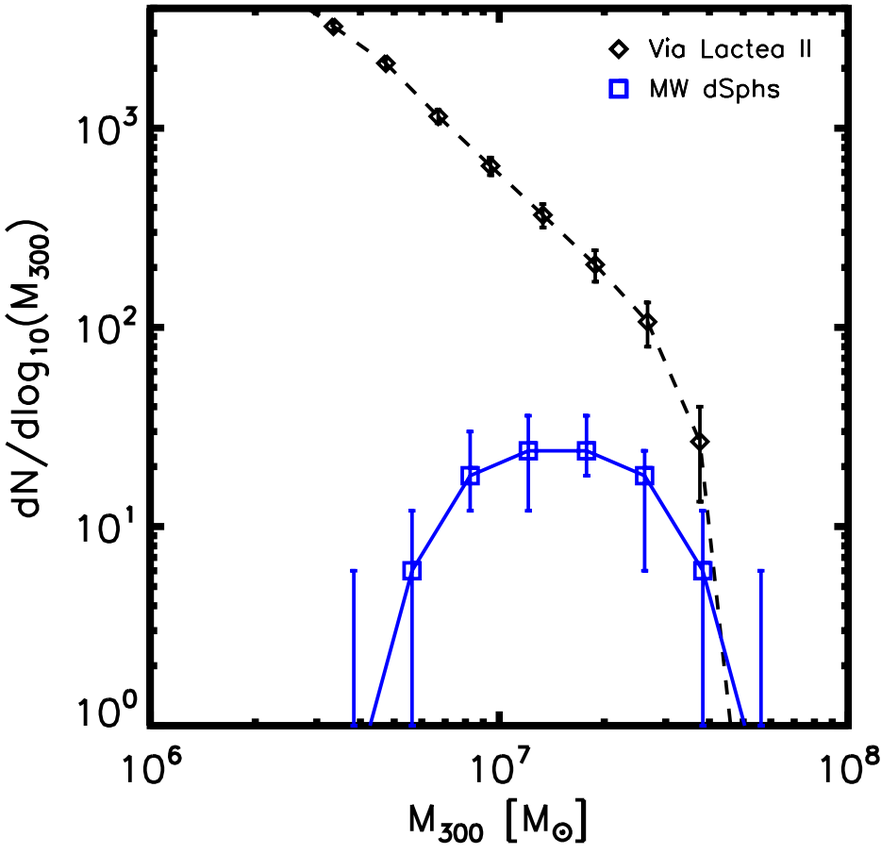
the ‘missing satellite problem’

[see Bullock 1009.4505 and Kravtsov 0906.3295 for overviews]

In the late 1990s:

MW had ~10 known satellite galaxies (‘classical dwarfs’ such as Draco & Fornax)

semi-analytic models and simulations find MW-like galaxies contain ~1000 sub-halos massive enough to host dwarf galaxies. [Kaufmann, White & Guiderdoni; Klypin et al.; Moore et al.]



[Bullock]

mass function in terms of M_{300}
(mass within central 300 pc, can be accurately determined for both observed and simulated satellites)

Via Lactea
observed MW dwarf Spheroidals

Since then:

~10 new dwarfs found (by searching for overdensities in SDSS and SEGUE data)
[e.g. Willman et al.]

majority less luminous and more dark matter dominated than previously known dwarfs (‘ultra-faint’)

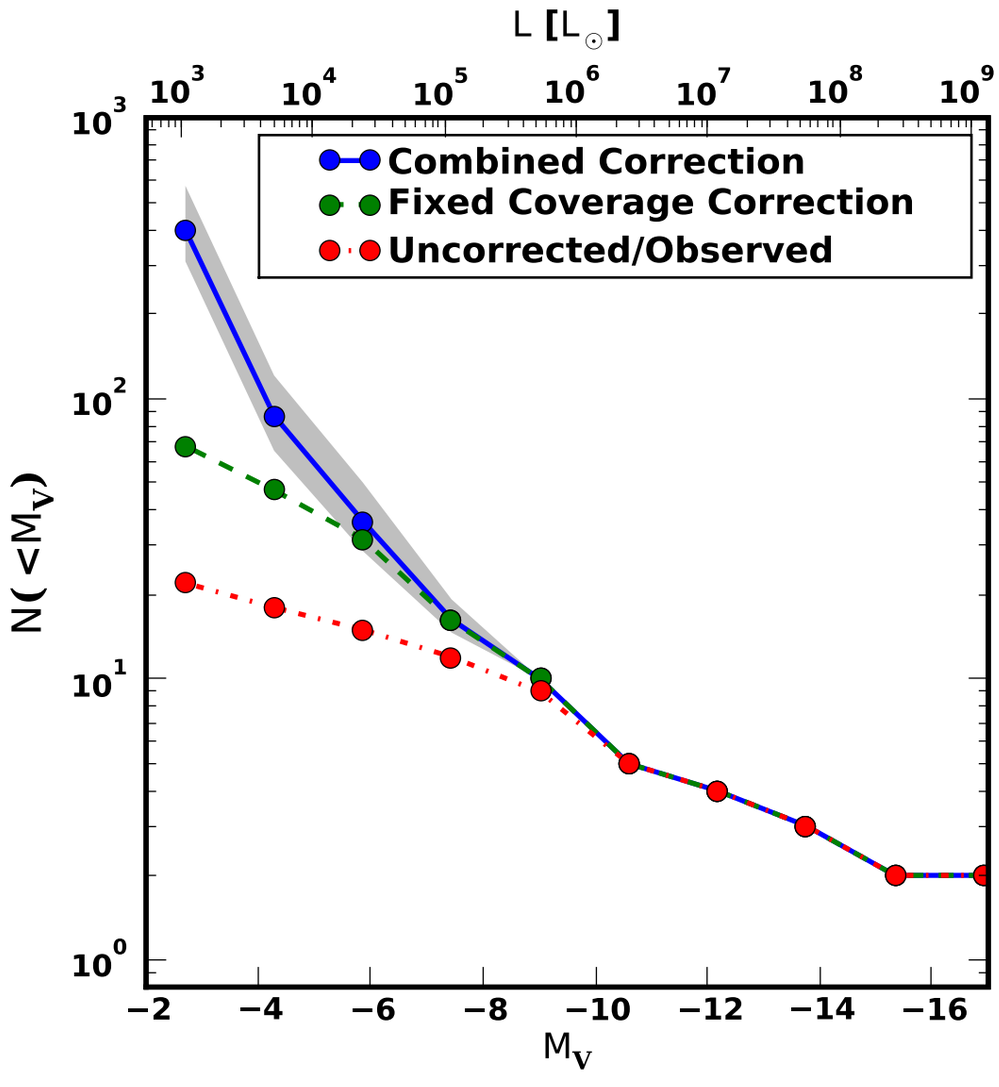
Segue 1
[Geha]

Since then:

~10 new dwarfs found (by searching for overdensities in SDSS and SEGUE data)
[e.g. Willman et al.]

majority less luminous and more dark matter dominated than previously known dwarfs ('ultra-faint')

taking into account limited sky coverage and detection limits MW could contain ~300-1000 of these ultra-faint dwarfs [Tollerud et al.]



[Tollerud et al.]

Luminosity of MW dSphs

observed
corrected for SDSS sky coverage
with luminosity correction

So is the ‘missing satellite problem’ solved?

Not really:

Simulated MW like halos contain huge numbers of subhalos massive enough to potentially host ‘ultra-faint’ dwarfs.

Also, MW satellite distribution more anisotropic [Kroupa et al.] and radially compact [e.g. Kravtsov, Gnedin & Klypin; Willman et al.; Taylor, Silk and Babul] than subhalos in simulations.

But not clear this is a ‘crisis for CDM’.

Need to understand galaxy formation on small scales.

Observational probes of local density

General approach: use multiple data sets (rotation curve, velocity dispersions of halo stars, local surface mass density, total mass...) and model for the MW (luminous components and halo).

Widrow et al. using spherical halo models with a cusp ($\rho \propto r^{-\alpha} \quad r \to 0$):

$$\rho_0 = (0.3 \pm 0.05)\,\mathrm{GeV\,cm^{-3}}$$

Catena & Ullio using NFW & Einasto profiles (motivated by simulations):

$$\rho_0 = (0.39 \pm 0.03)\,\mathrm{GeV\,cm^{-3}}$$

Weber and de Boer using range of halo density profiles:

$$\rho_0 = (0.2 - 0.4)\,\mathrm{GeV\,cm^{-3}}$$

Salucci et al. 'model independent' method:

$$\rho_0 = (0.43 \pm 0.11 \pm 0.10)\,\mathrm{GeV\,cm^{-3}}$$

Pato et al. DM density in stellar disc of simulated halos is ~ 20% larger than the shell average determined by observations.

Summary: recent determinations have ~10% statistical errors, but systematic uncertainties from modelling are still significantly larger.

Observational probes of local circular speed

IAU/Kerr & Linden-Bell compilation of measurements:

$$v_{\rm c} = (220 \pm 20)\,{\rm km\,s^{-1}}$$

Reid et al. trigonometric parallaxes and proper motions of masers, :

$$v_{\rm c} = (254 \pm 16)\,{\rm km\,s^{-1}}$$

Bovy et al. masers (including phase modelling), Galactic center analyses & GD-1 stellar stream, assuming flat rotation curve:

$$v_{\rm c} = (236 \pm 11)\,{\rm km\,s^{-1}}$$

McMillan & Binney. masers, revised value of component of Sun's proper motion in direction of rotation, and allowing non-flat rotation curve:

$$v_{\rm esc} = (200 - 280)\,{\rm km\,s^{-1}}$$

Modelling uncertainties, larger than statistical uncertainties here too.

n.b. while for the standard halo there's a one-to-one relationship between the circular speed and velocity dispersion, $\sqrt{2}\sigma = v_{\rm c}$, in general the relationship depends on the density profile and velocity anisotropy:

$$\frac{1}{\rho}\frac{{\rm d}(\rho\sigma_r^2)}{{\rm d}r} + 2\frac{\beta\sigma_r^2}{r} = -\frac{v_c^2}{r}$$

What are the observational/experimental consequences?

Direct detection

[e.g. McCabe; Kuhlen et al.; Green and many, many more]

(time and direction) averaged event rate

Depends on integral of WIMP speed distribution, f(v), therefore relatively insensitive to detailed shape of f(v) in general.

But event rate can change significantly if only the high speed tail of f(v) is probed i.e. light WIMP + experiment with large energy threshold.

Most important uncertainties: local density and circular speed (velocity dispersion).

annual modulation

Arises due to (small) shift in f(v) due to Earth's orbit, therefore far more sensitive to shape of f(v).

direction dependence

Rear-front asymmetry is robust, but peak/median recoil direction of high energy recoils may deviate somewhat from direction of solar motion.

Indirect detection

gamma-rays

Large uncertainties in DM density close to Galactic center (plus astrophysical source....), solution: observe region ~10 degrees away from GC. [Stoehr et al.]

Substructure boosts MW diffuse emission by factor B~2-10, [Aquarius; Via Lactea II] (depending on how you extrapolate subhalo mass function and concentration down to cut-off mass).

anti-matter

From modelling of sub-halo distribution, maxiumum boost factor (for both positrons and anti-protons): ~20 [Lavalle et al.]

Considering halos within ~1 kpc of Solar radius: typically B~1.4,
1% of locations (with nearby large subhalo) have B>10. [Via Lactea II]

Difficult to make definitive statements about which target [(close to) Galactic centre, classical dwarfs, 'ultra-faint' dwarfs, galaxy clusters, ...] is most promising.

A note on halo masses/radii:

Halos don't have sharp edges and well defined total masses.

Conventional to use viral radius/mass, motivated by spherical collapse.
[In a $\Omega_{\rm m} = 1$ Universe a spherical over density has, after virialisation, a density $\rho = 178\rho_{\rm c} \approx 200\rho_{\rm c}$]

But:

i) different people use different definitions of the virial overdensity.

ii) in a ΛCDM Universe the virial overdensity depends on red-shift

iii) the background density decreases with time, therefore the mass and radius of a halo increases with time, even if it doesn't change physically

For many purposes it's better to parameterise halos in terms of their peak circular velocity.

Analytic halo modelling (for velocity distribution)

Phase space distribution function: $f(\mathbf{x},\mathbf{v},t)$

Number of particles with phase space co-ordinates in range $\mathbf{x} \rightarrow \mathbf{x} + d\mathbf{x}$, $\mathbf{v} \rightarrow \mathbf{v} + d\mathbf{v}$ at time t: $f(\mathbf{x},\mathbf{v},t)\, d^3\mathbf{x}\, d^3\mathbf{v}$

Steady-state phase space distribution of a collection of collisionless particles is given by the solution of the collisionless Boltzmann equation:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0$$

In Cartesian co-ordinates:

$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{x}} + \frac{\partial \Phi}{\partial \mathbf{x}}.\frac{\partial f}{\partial \mathbf{v}} = 0$$

For a self-consistent system (where density distribution generates potential):

$$\nabla^2\Phi = 4\pi G \int f \mathrm{d}^3\mathbf{v}$$

For spherical isotropic systems there's a unique relationship between ρ(r) and f(v) (Eddington's equation).

Multiplying the collisionless Boltzmann equation by the velocity components and integrating produces the Jeans equations.

In Cartesian co-ordinates:

$$\frac{\partial(\rho\bar{v_j})}{\partial t} + \frac{\partial(\rho\overline{v_i v_j})}{\partial x_i} + \rho\frac{\partial\Phi}{\partial x_j} = 0$$

Get three equations for six unknowns: $\overline{v_1^2}, \overline{v_2^2}, \overline{v_3^2}, \overline{v_1 v_2}, \overline{v_2 v_3}, \overline{v_1 v_3}$

Therefore need to make assumptions about alignment of velocity ellipsoid (e.g. choose co-ordinates such that $\overline{v_i v_j} = 0 \quad \text{if} \quad \mathrm{i} \neq \mathrm{j}$).

Often then assume that velocity dispersion is a multivariate gaussian in these co-ordinates:

$$f(\mathbf{v}) \propto \exp\left(-\frac{v_1^2}{2\sigma_1^2} - \frac{v_2^2}{2\sigma_2^2} - \frac{v_3^2}{2\sigma_3^2}\right)$$

two examples:

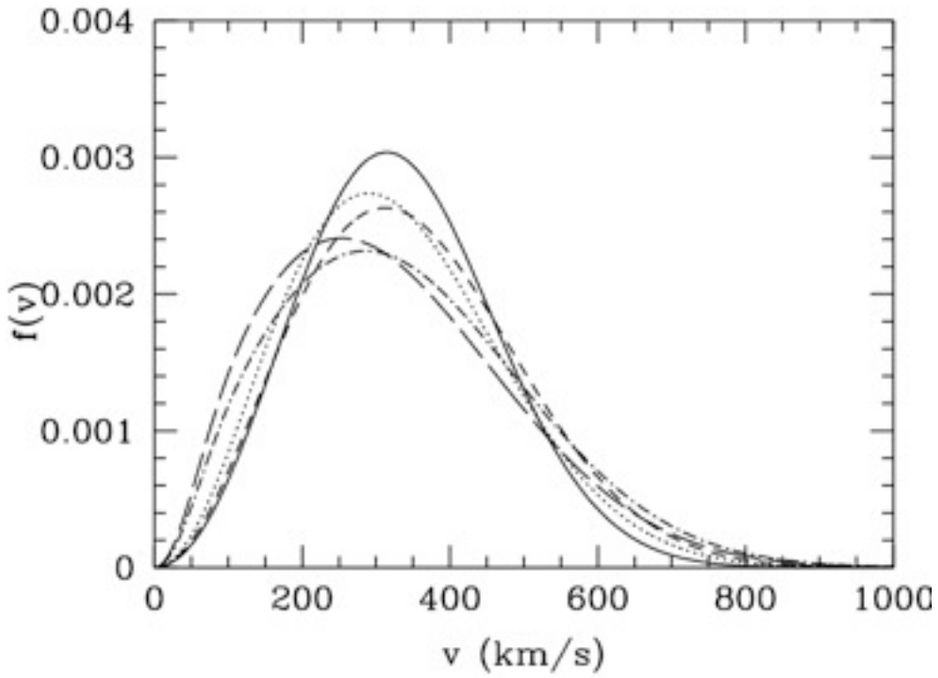
The logarithmic ellipsoidal model Evans, Carollo, de Zeeuw

The simplest triaxial generalisation of the isothermal sphere (axis ratios independent of position).

Assumes that velocity ellipsoid aligned with conical co-ordinates.

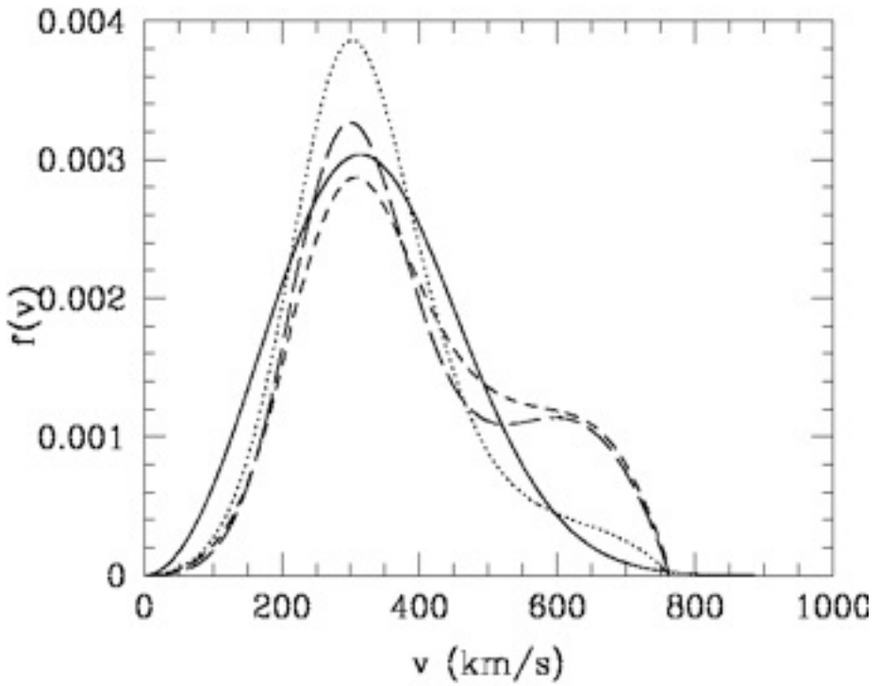
In planes of conical co-ordinates are locally equivalent to cyclindrical polars so f(v) is multi-variate gaussian in $(r,\ \phi,\ z)$.

Velocity dispersions depend on axis ratios of halo.



Osipkov-Merritt

Spherically symmetric, anisotropy increases with radius.



Speed distributions

Analytic halo models have been useful for assessing the changes in the direct detection signals which results from deviation of the velocity distribution from the Maxwellian of the standard halo model **BUT**

i) Have the (inner regions of the) Milky Way halo reached a steady state?

ii) Are the assumptions (e.g. alignment of velocity ellipsoidal) physically plausible?