Dark matter particles in our Galactic halo

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- ☆ Why is the dark matter distribution important?
- ☆ Dark matter detection (very briefly).
- ☆ The simplest halo model: the isothermal sphere
- ☆ 'Observational' constraints on the Milky Way halo.
- ☆ Analytic halo modeling.

- ☆ Numerical simulations.
- ☆ (very) Small scales.
- ☆ Implications for direct & indirect detection experiments.

Why is the dark matter distribution important?

All the observational evidence for dark matter arises from it's gravitational effects.

If we want to confirm the existence of dark matter (and the standard cosmological model) and understand it's nature we need to detect it.

The event rates, and signals, in dark matter detection experiments depend on the dark matter density (and in some cases velocity) distribution.

Dark matter detection

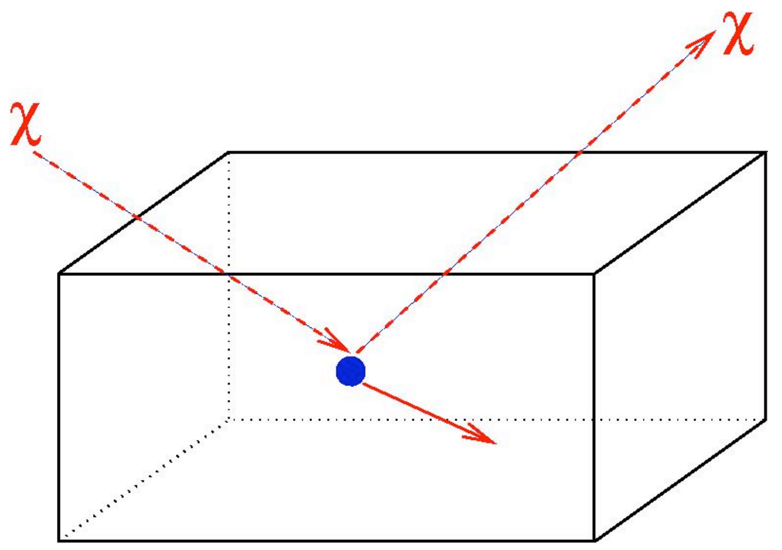
Weakly Interacting Massive Particles

i) Direct detection

See talks by Elena Aprile and Gabriel Chardin tomorrow.

Via elastic scattering on detector nuclei in the lab.

$$\chi + N \to \chi + N$$



Differential event rate (for spin-independent coupling):

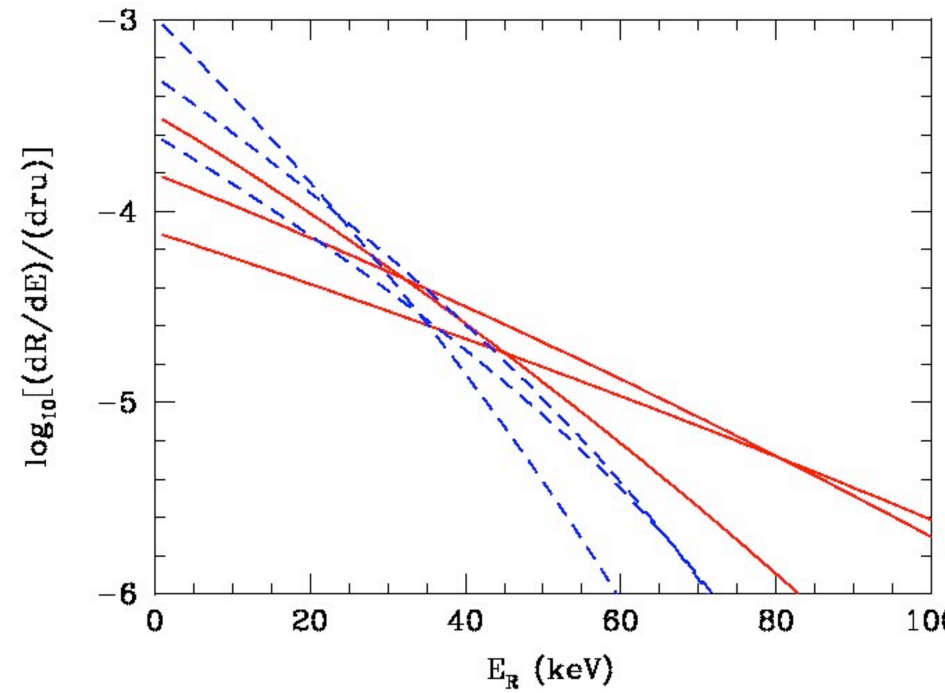
$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_p \rho_\chi A^2 F^2(E) \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v} \mathrm{d}v$$

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

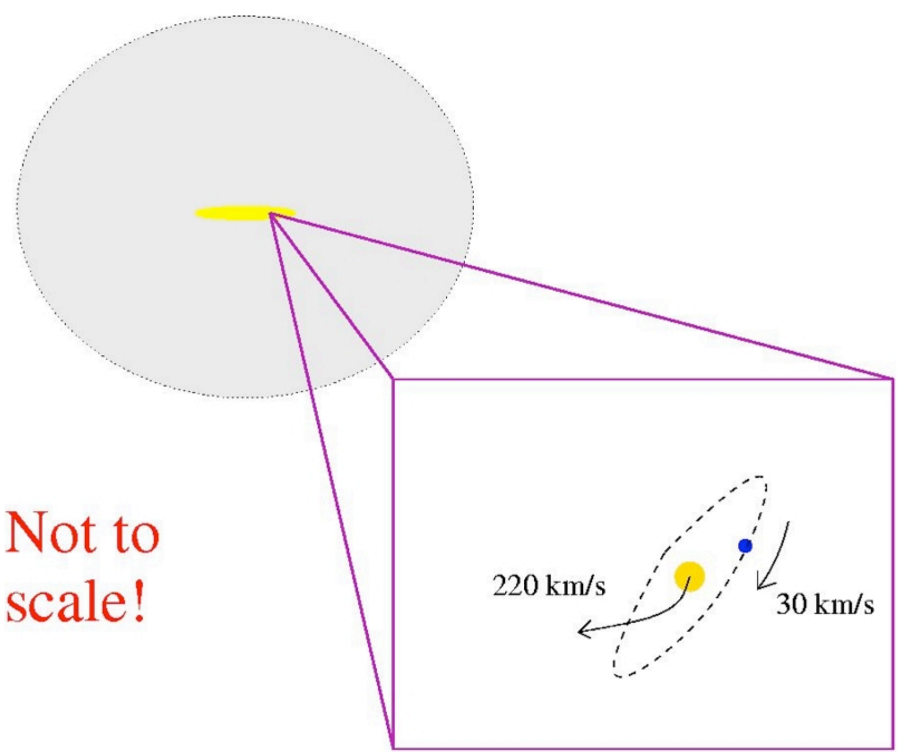
Signals (here all calculated assuming the simplest halo model where the speed distribution is gaussian):

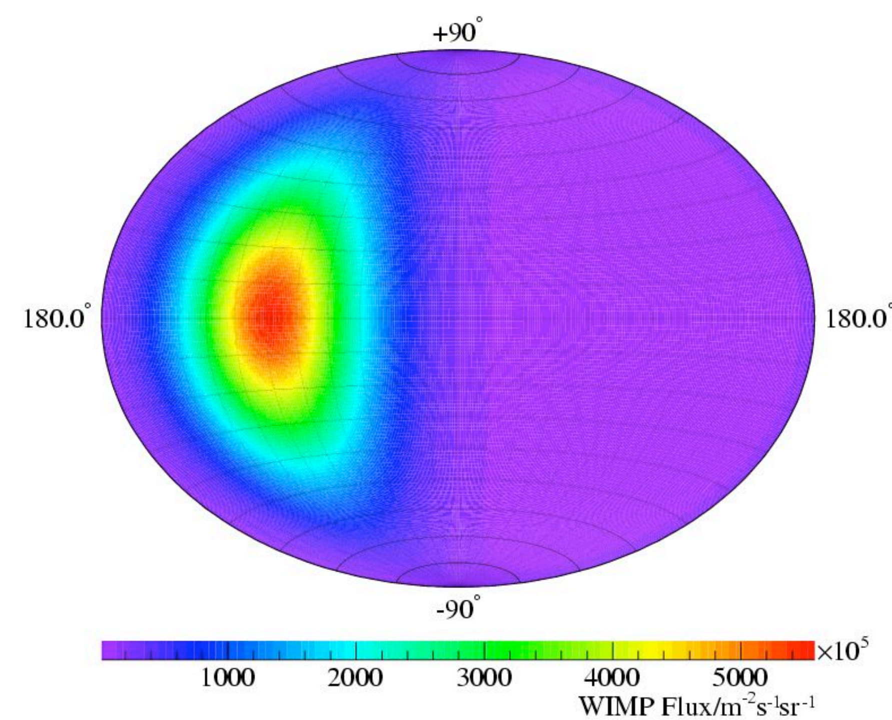
a) material signal Lewin & Smith

Energy spectrum for
Ge and Xe m_χ = 50, 100, 200 GeV



b) directional dependence of event rate Spergel

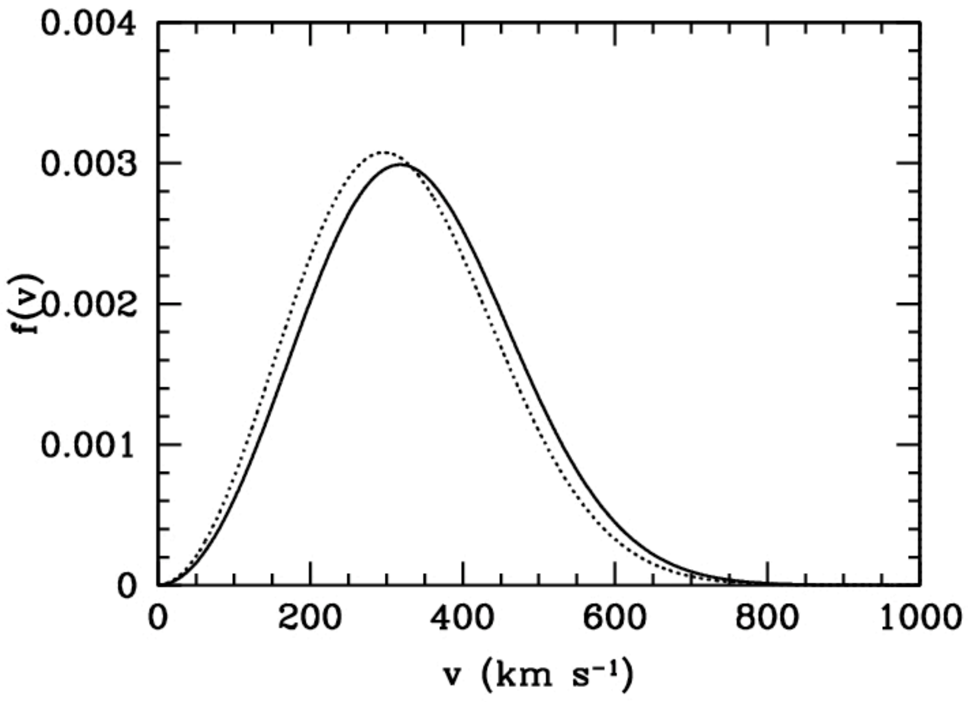




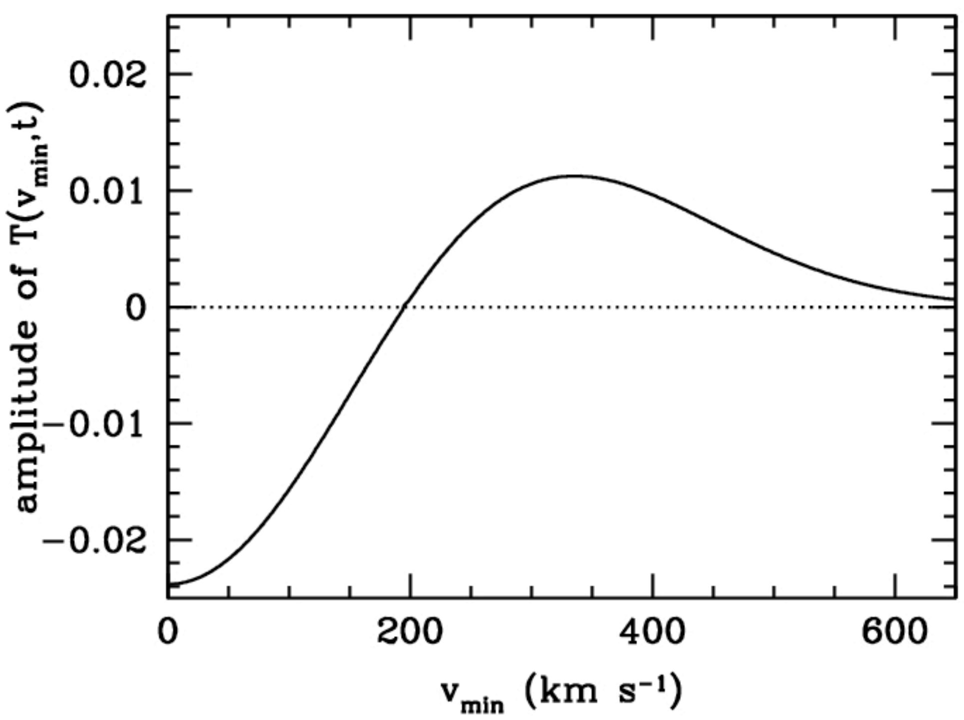
WIMP flux

c) annual modulation of event rate

Drukier, Freese & Spergel



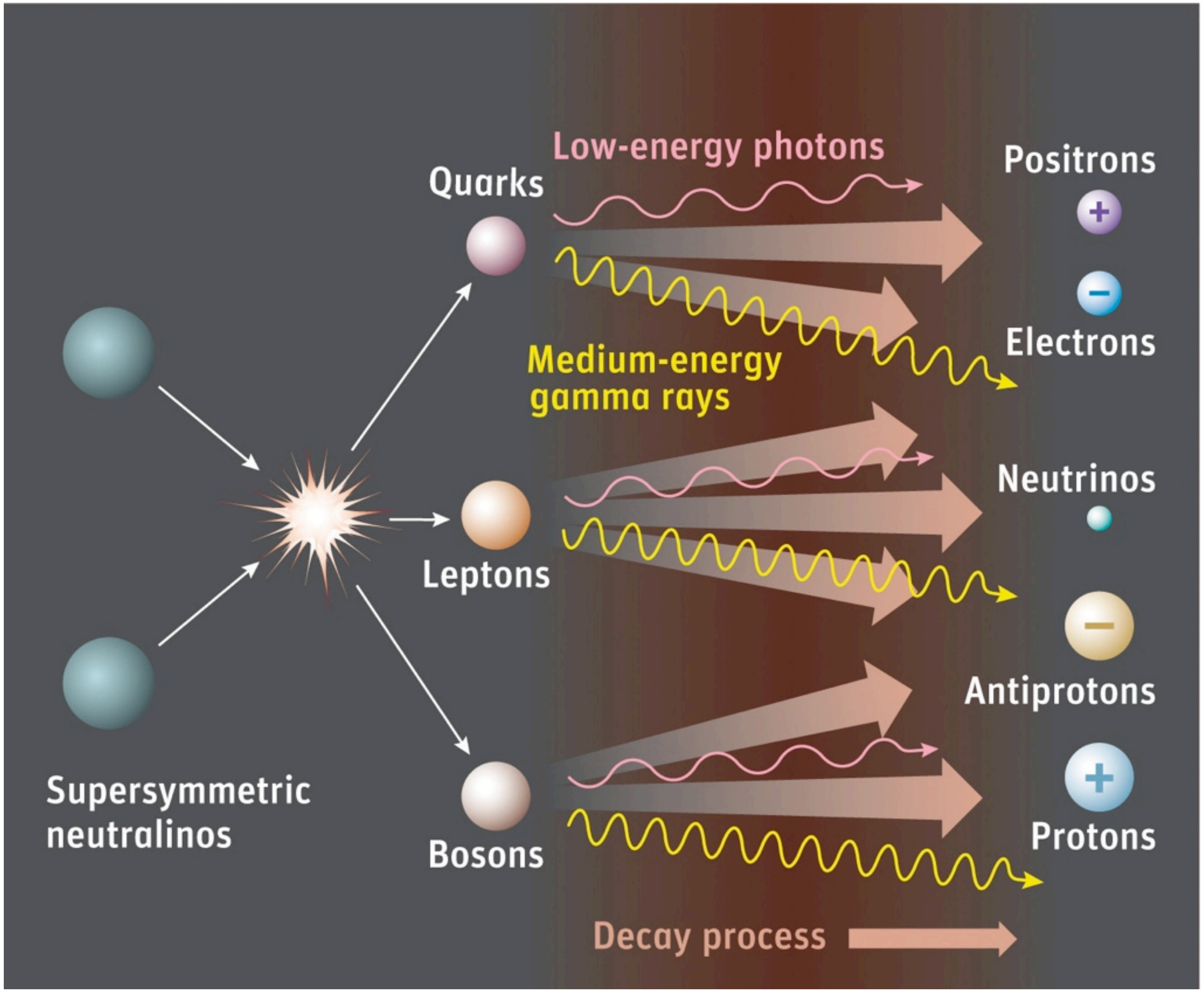
‘standard’ WIMP speed distribution (summer and winter)



amplitude of annual modulation

ii) Indirect detection

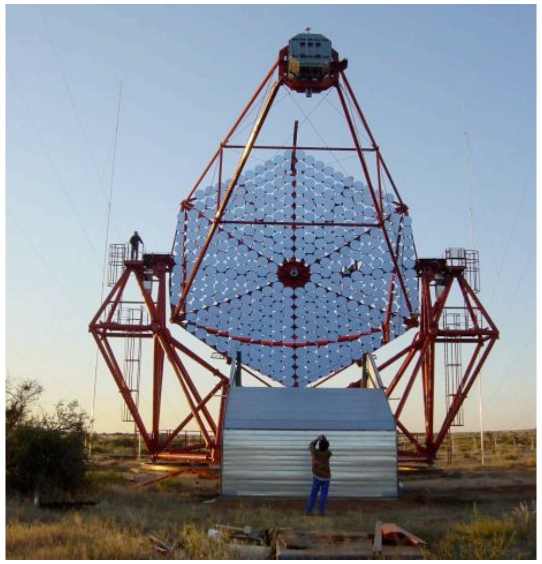
See talk by Piergiorgio Picozza on Thursday.



Channels:

a) high energy gamma-rays

Fermi



ACTs
(e.g. HESS, MAGIC, VERITAS)

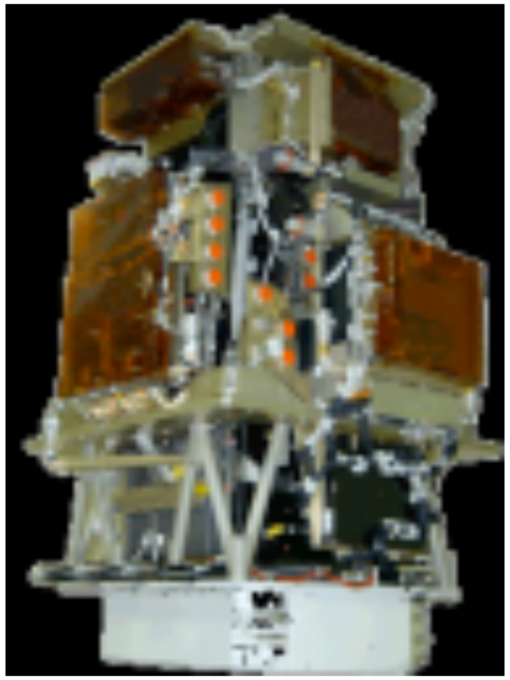
Dependence on dark matter distribution:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\int_{\mathrm{l.o.s}}\rho^2(l)\mathrm{d}l$$

Regions with high predicted dark matter density are potentially good targets:

(close to) Galactic centre,
substructures (e.g. dwarf galaxies)
....

b) anti-matter (e.g. positrons, anti-protons)



PAMELA

Charged particles propagate through Milky Way's magnetic field.

Dependence of signal on dark matter distribution:

local dark matter density distribution

positrons: diffusion length O(kpc), decreases with increasing energy

anti-protons: diffusion length O(kpc) increases sharply with increasing energy

c) neutrinos

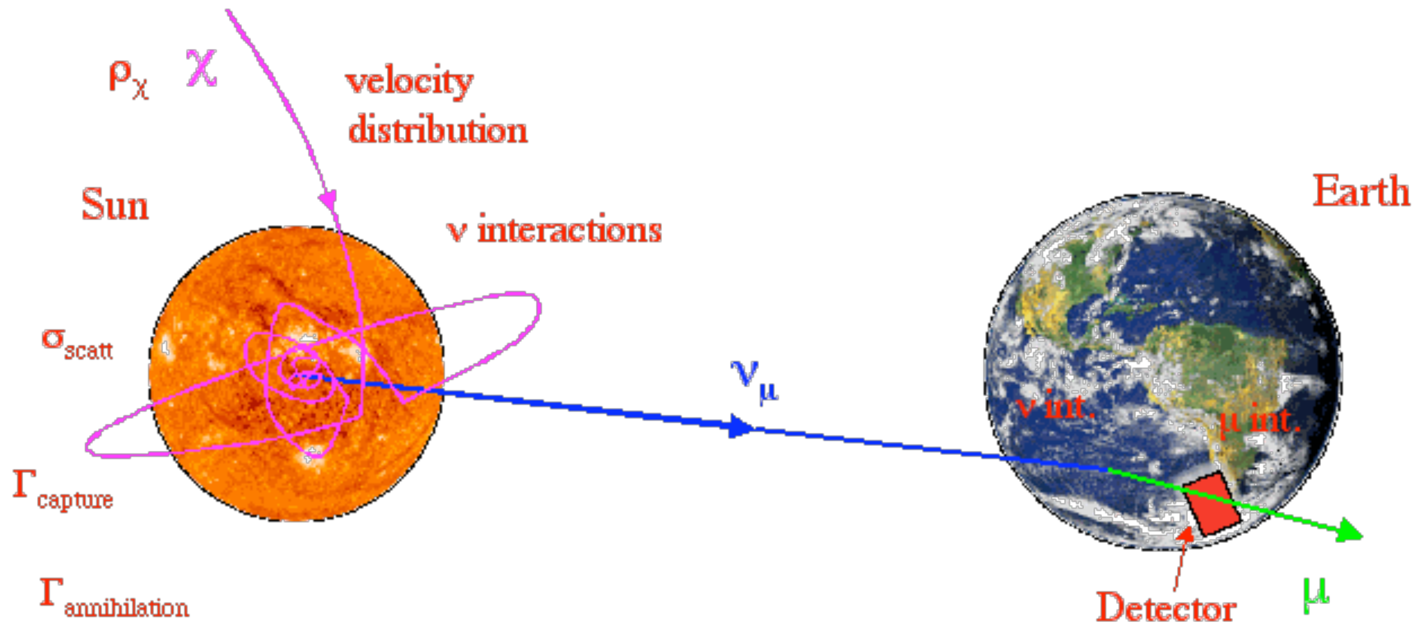
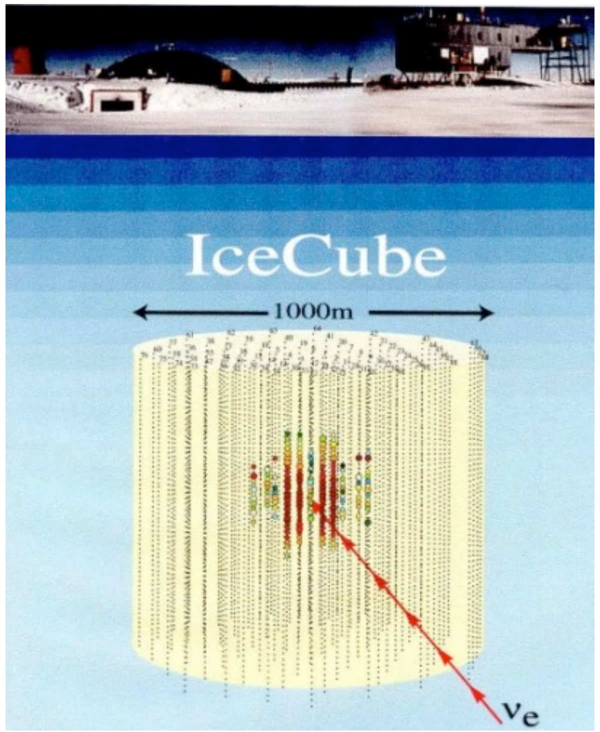


fig: AMANDA



Neutrino telescopes
(IceCube, ANTARES)

Dependence on dark matter distribution:

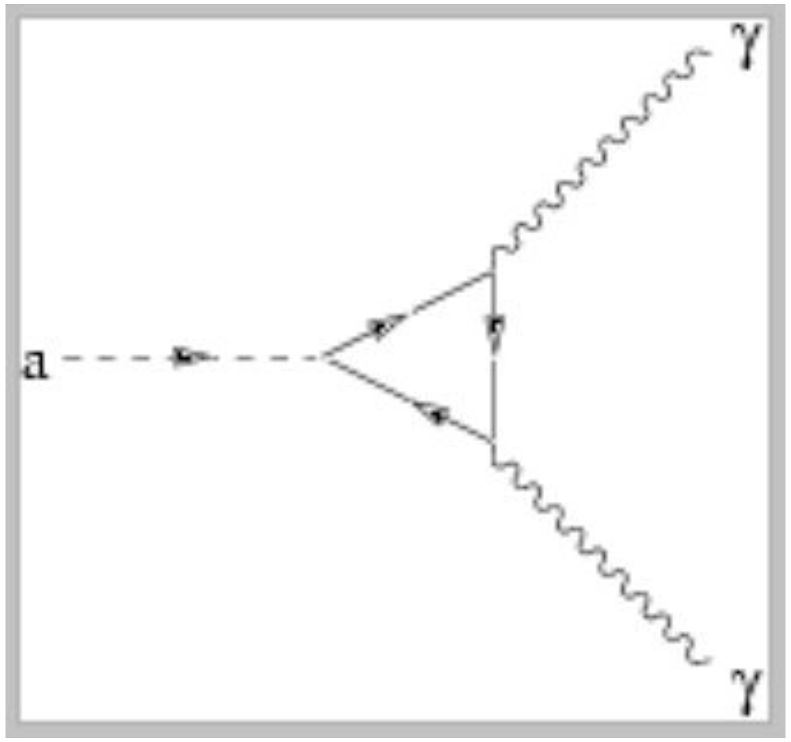
local dark matter density averaged over cosmological times
low v tail of speed distribution

Axions

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

Detection:

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



Dependence on dark matter distribution:

ultra-local dark matter density

Intro-summary

- To confirm the existence of dark matter and understand it's nature we need to detect it (other than through it's gravitational effects).

- WIMPs are generically a good dark matter candidate and SUSY provides us with a concrete well-motivated WIMP candidate.

  WIMPs can be detected:

  directly via elastic scattering in the lab

  signals depend on ultra-local dark matter density and speed distribution

  indirectly via annihilation products,

  signals depend on Milky Way density distribution in particular in high density regions (& for neutrinos low v tail of local speed distribution)

- Axions are also a possible dark matter candidate.

  Axions can be detected:

  in the lab via resonant conversion to photons

  depends on ultra-local dark matter density

The simplest halo model: the isothermal sphere

Theory

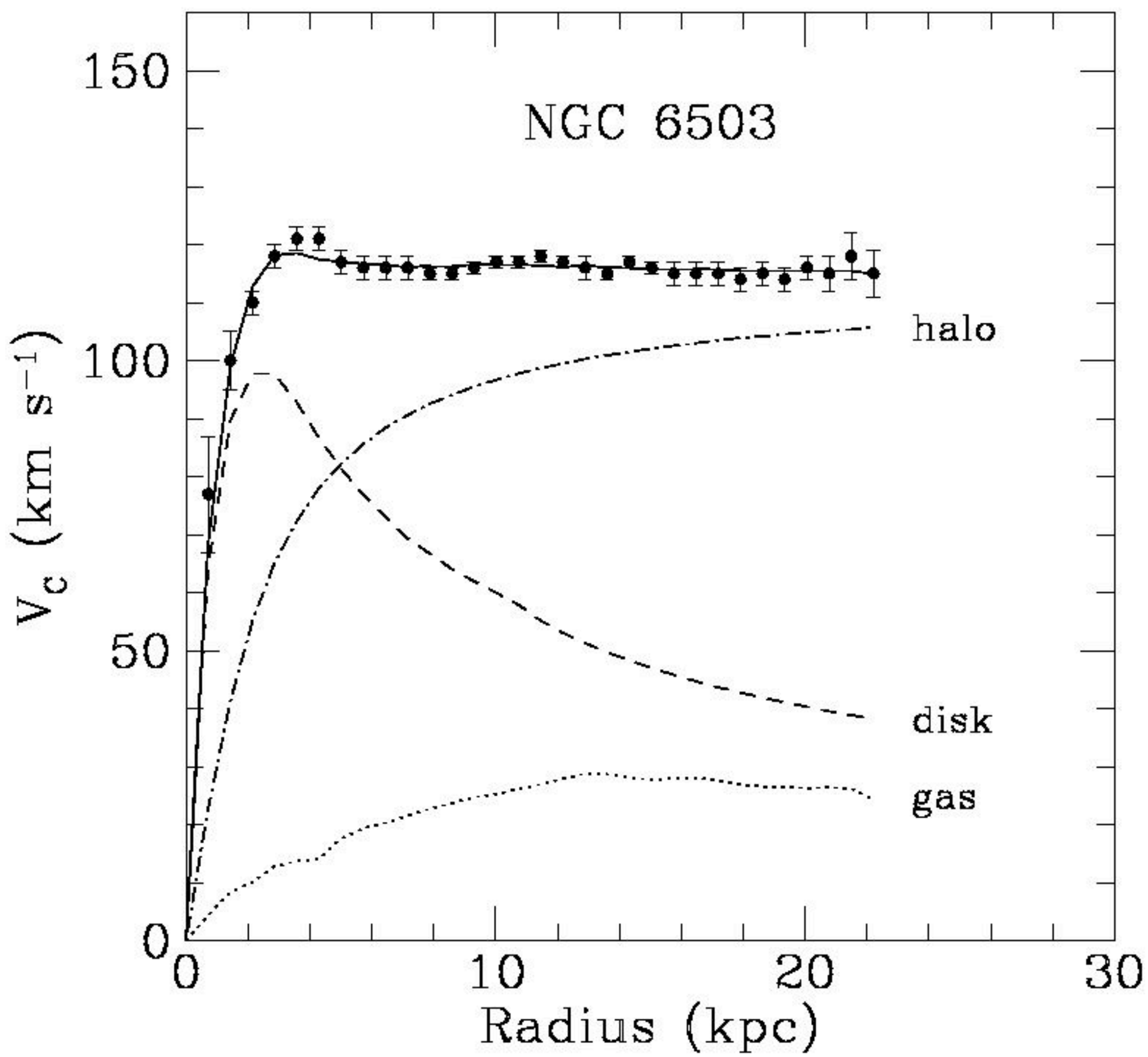
The equilibrium distribution of a gas of self-gravitating particles is an isothermal (velocity dispersion/temperature independent of position) sphere with a Maxwellian velocity distribution:

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

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

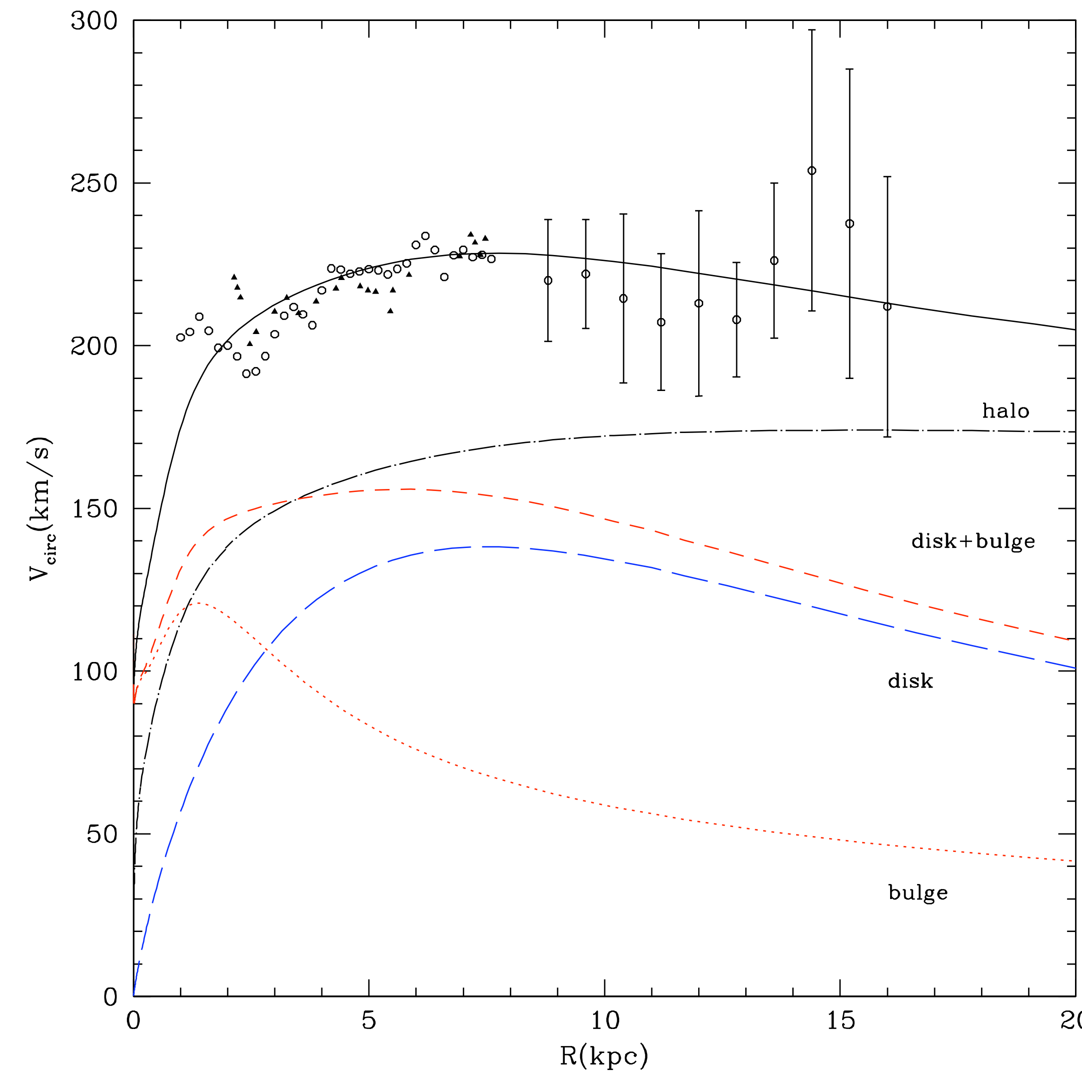
n.b. isothermal sphere is infinite in extent (particles with arbitrarily large speeds can reach any given radius) and mass diverges.

Observational support: Galaxy rotation curves



Milky Way

[Klypin, Zhao &Somerville]

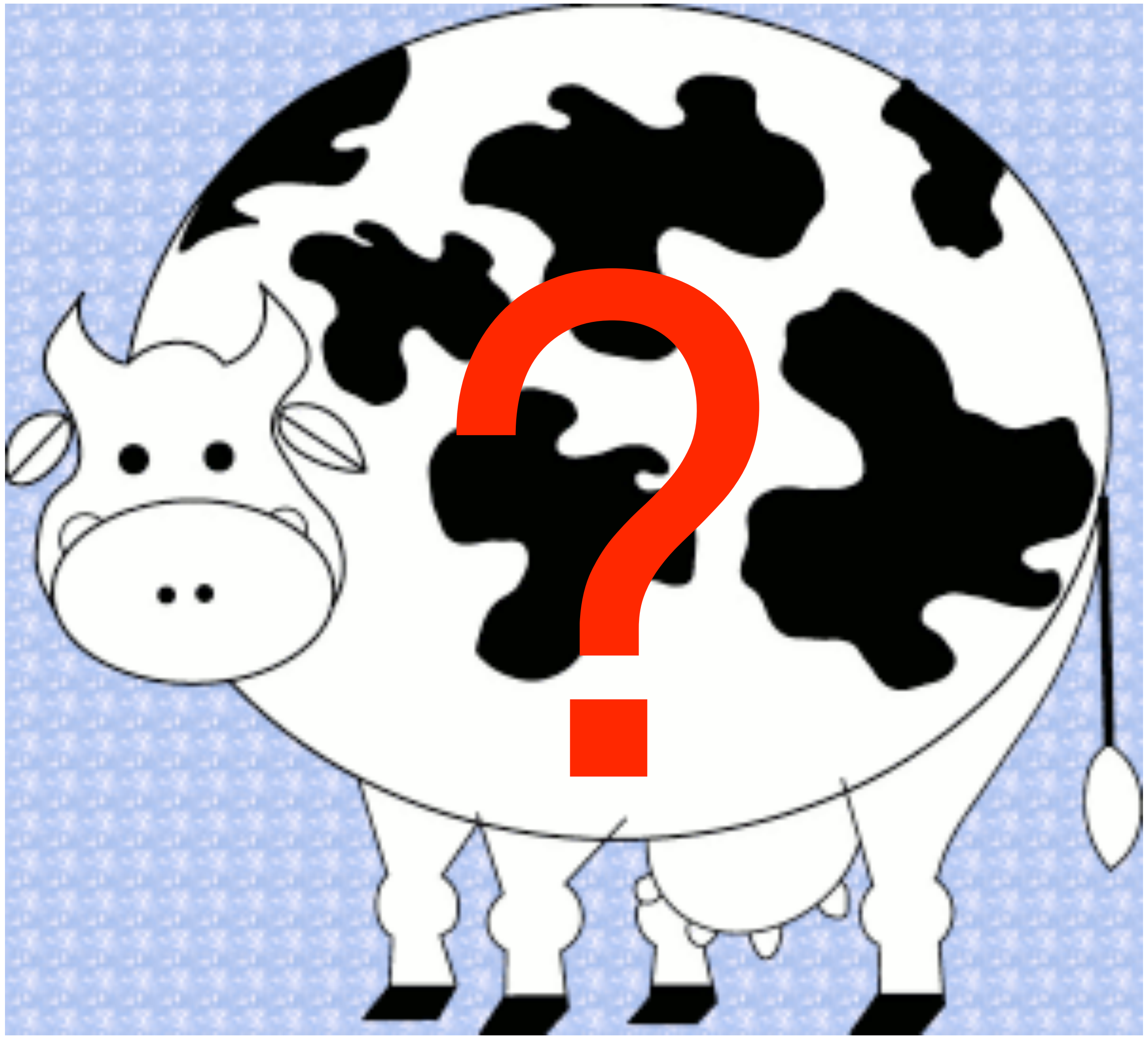


$$\frac{v_{rot}^2}{r} = \frac{GM(<r)}{r^2}$$

$$v_{rot} \sim const$$

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

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



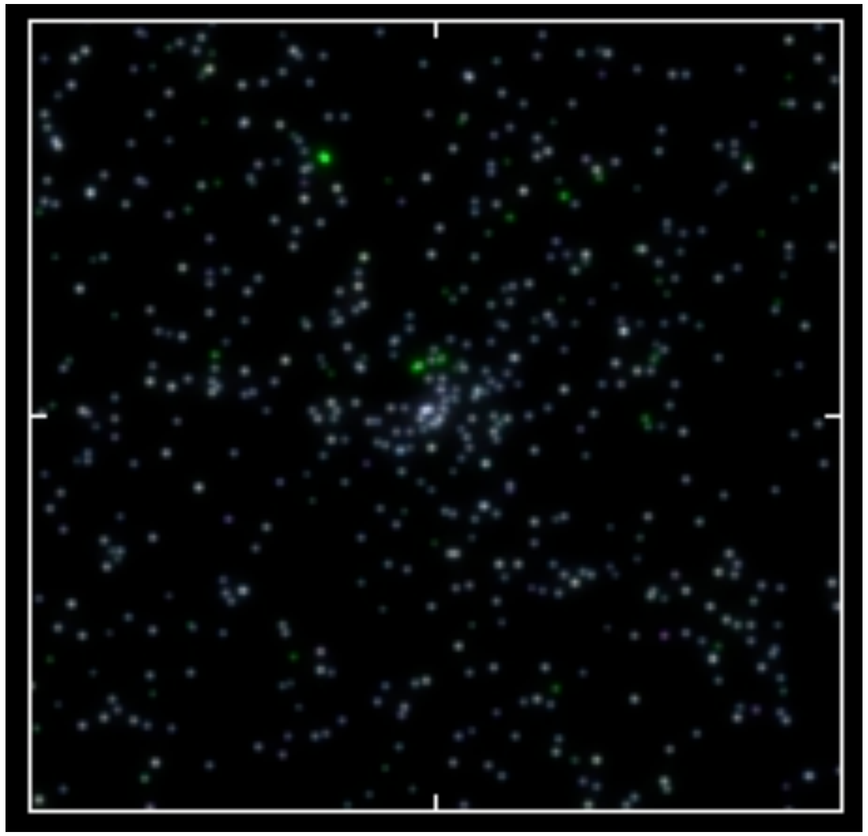
‘Observational’ constraints on the Milky Way halo

Substructure

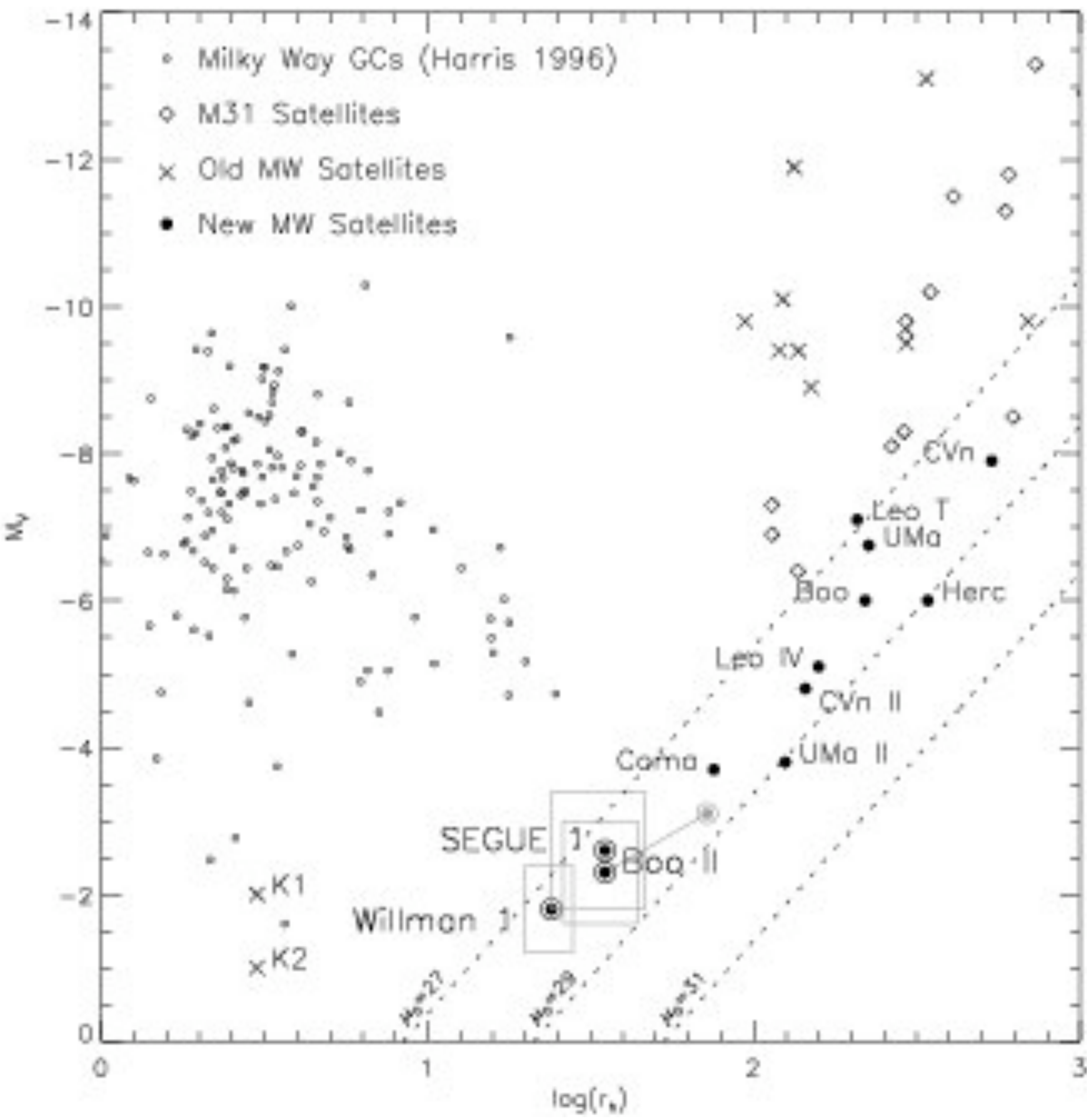
Prior to 2004, 11 known satellites of Milky Way (including LMC, SMC, Draco, Sagittarius).

Sloan Digital Sky Survey allowed discovery of >10 new low luminosity potential satellites (including Willman 1, Segue 1).

Ursa Minor
[WikiSky, DSS2]



Coma Berenices
[Belorukov]



Magnitude versus half light radii

- ◇ MW globular clusters
- x MW old satellites
- ● MW new satellites
- ◇ M31 satellites

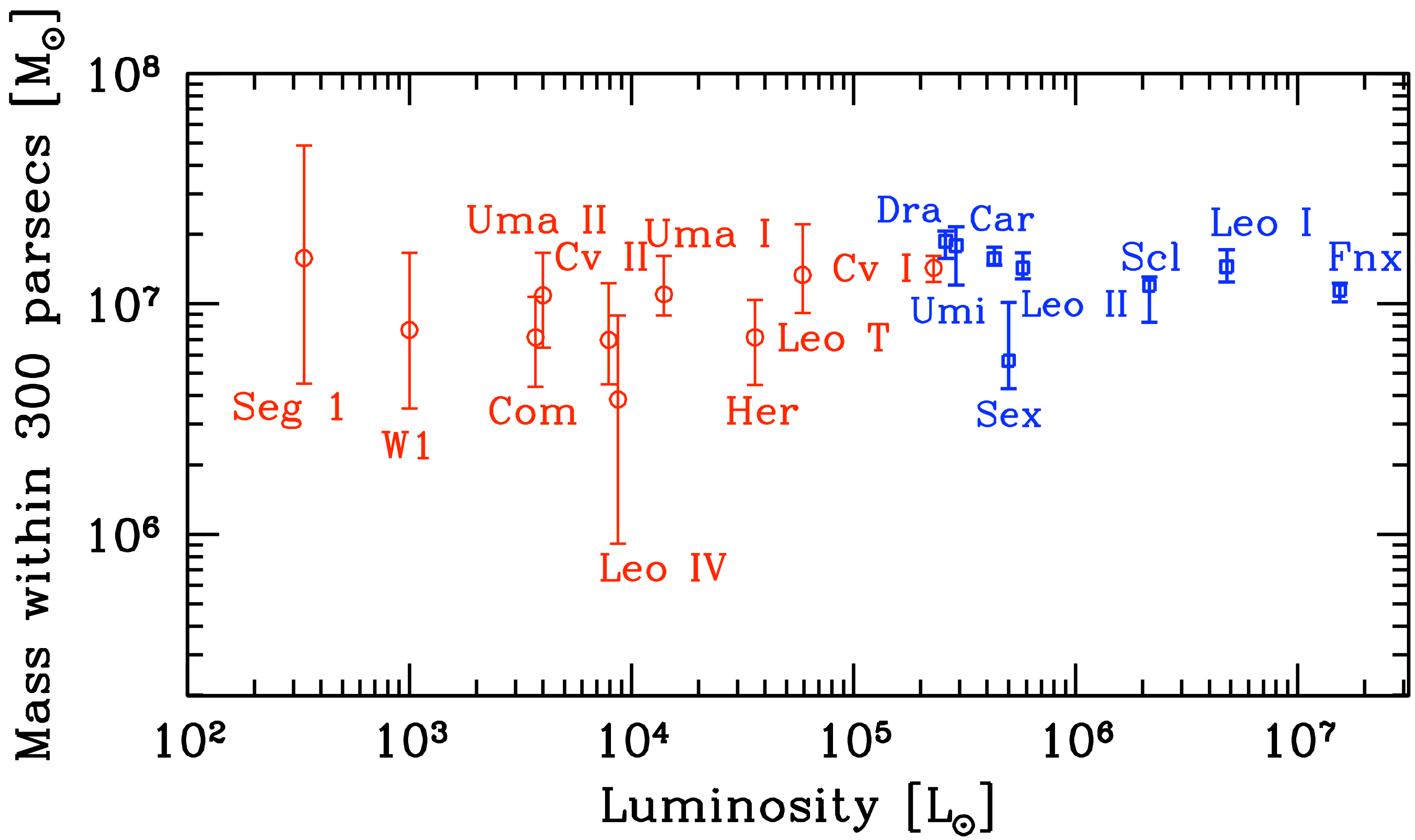
[Walsh from Bullock, Kaplinghat & Strigari]

Are ultra-faint satellites dwarf galaxies or star clusters?

If dwarf galaxies, Milky Way halo could contain ~200-1000 in total [Tollerud et al.]

Common mass [Mateo, Strigari et al.]

Using measurements of line-of-sight velocities of stars (and mass modeling) can measure dynamical masses of dwarfs.

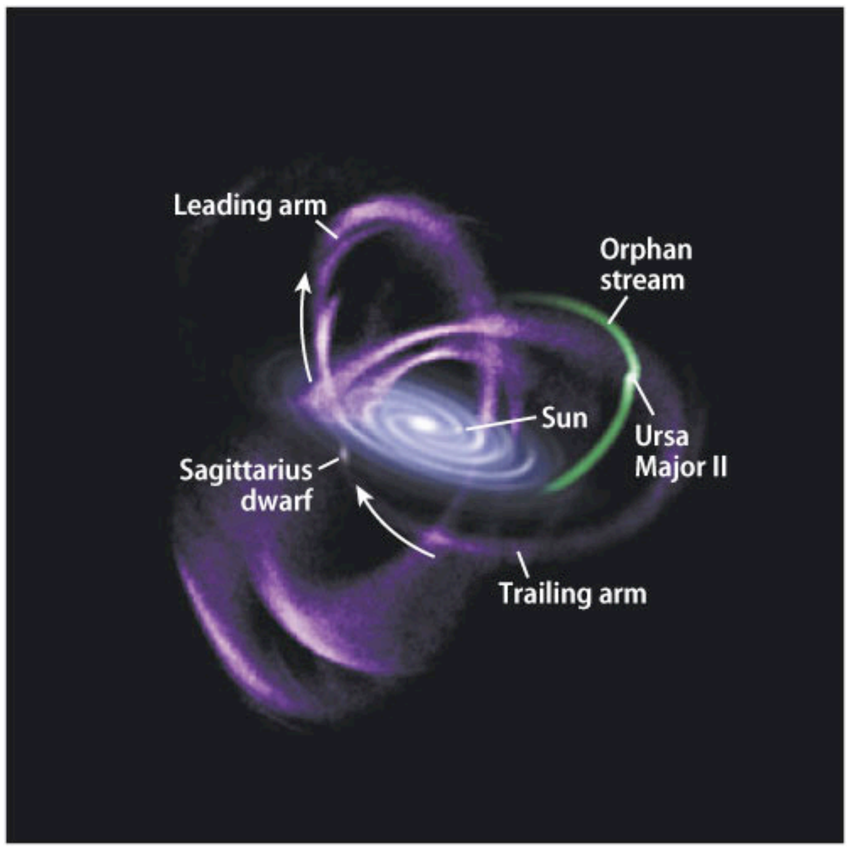


Minimum mass scale for galaxy formation or for dark matter halos?

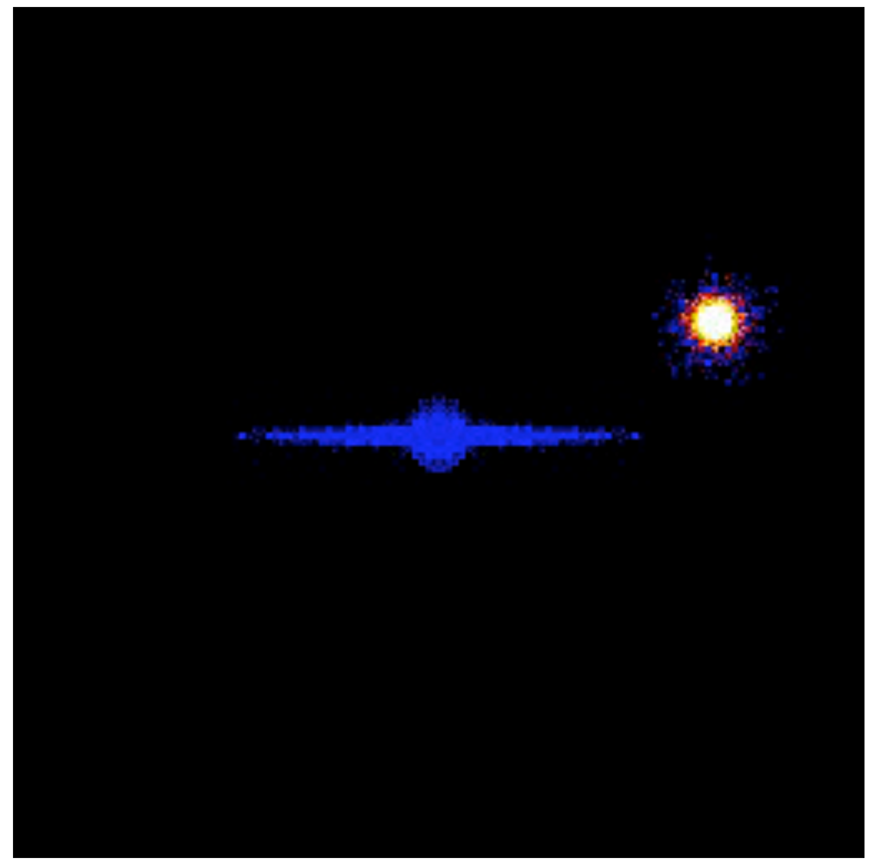
Shape usually in terms of density distribution

Flattening (polar to equatorial axis ratio of density distribution): q
Intermediate to long axis ratio: b/a Short to long: c/a

Sagittarius debris:



[Belokurov]



[Johnston]

Dynamics of streams depend on shape of potential.

from kinematics of leading stream: q~ 5/3 [Helmi, 04]

from bifurcation: ‘close to spherical’ [Fellhauer et al., 06]

Flaring of gas layer: $0.7 < q < 0.9$ [Merrifield & Olling]

Local density

[Caldwell & Ostriker; Bahcall, Schmidt & Soneira; Gate, Gyuk & Turner; Bergstrom, Ullio & Buckley
Widrow, Pym & Dubinski]

Local dark matter density calculated by applying observational constraints (including measurements of the rotation curve) to models of the Milky Way.
(flattening of halo enhances local DM density).

Traditionally: $\rho_0 \sim (0.2 - 0.8)\,\mathrm{GeV\,cm}^{-3}$

Recent study [Widrow et al.] using spherical halo models with a cusp ($\rho(r) \propto r^{-\alpha}\,, \ \mathrm{as}\ r \rightarrow 0$) found:

$$\rho_0 = (0.30 \pm 0.05)\,\mathrm{GeV\,cm}^{-3}$$

Local circular speed

Kerr and Lynden-Bell compilation:

$$v_{\rm c}(R_0) = (220 \pm 20)\,{\rm km\,s}^{-1}$$

Feast and Whitlock (HIPPARCOS measurement of proper motions of Cepheids):

$$v_{\rm c}(R_0) = (218 \pm 7)\left(\frac{R_0}{8\,{\rm kpc}}\right)\,{\rm km\,s}^{-1}$$

For the standard halo model (with Maxwellian speed distribution) dispersion related to circular speed by:

$$\sigma = \sqrt{3/2}\,v_{\rm c}$$

New value of v_c?

Reid talk on VLBA parallax observations of masers at AAS meeting in early January attracted lots of press attention:

Sun moving ~20% faster than previously thought (and hence MW ~50% more massive)

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

Needs increase in (v_c/R_0) from, standard value, of 26 km/s/Mpc to 30 km/s/Mpc.

Escape speed

A particle with $v \geq v_{\rm esc}(r) = \sqrt{\Phi(r)}$ has enough kinetic energy to escape the potential, therefore don't expect any (gravitationally bound) particles with speeds greater than this.

Can constrain local escape speed by measuring speed of local (high-velocity) halo stars.

Traditional 'standard' value: $v_{\rm esc}(R_0) \approx 650 \, {\rm km \, s}^{-1}$

Using data from the RAVE survey: $v_{\rm esc}(R_0) \approx 544 \pm 25 \, {\rm km \, s}^{-1}$ [Smith et al.]

n.b. assumes that high v tail of stellar velocity distribution is a power law

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 $\mathbf{x} \rightarrow \mathbf{x} + \mathrm{d}\mathbf{x}$, $\mathbf{v} \rightarrow \mathbf{v} + \mathrm{d}\mathbf{v}$ at time t: $f(\mathbf{x},\mathbf{v},t)\, \mathrm{d}^3\mathbf{x}\, \mathrm{d}^3\mathbf{v}$

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:

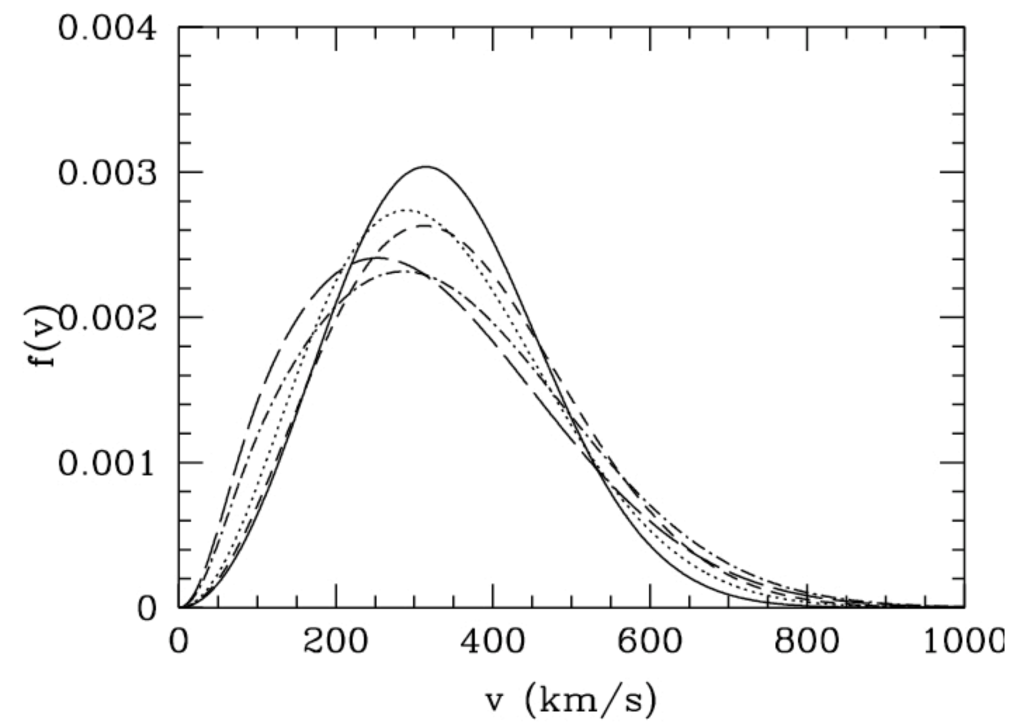
The logarithmic ellipsoidal model Evans, Carollo, de Zeeuw

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

Assumes that velocity ellipsoid aligned with conical co-ordinates.

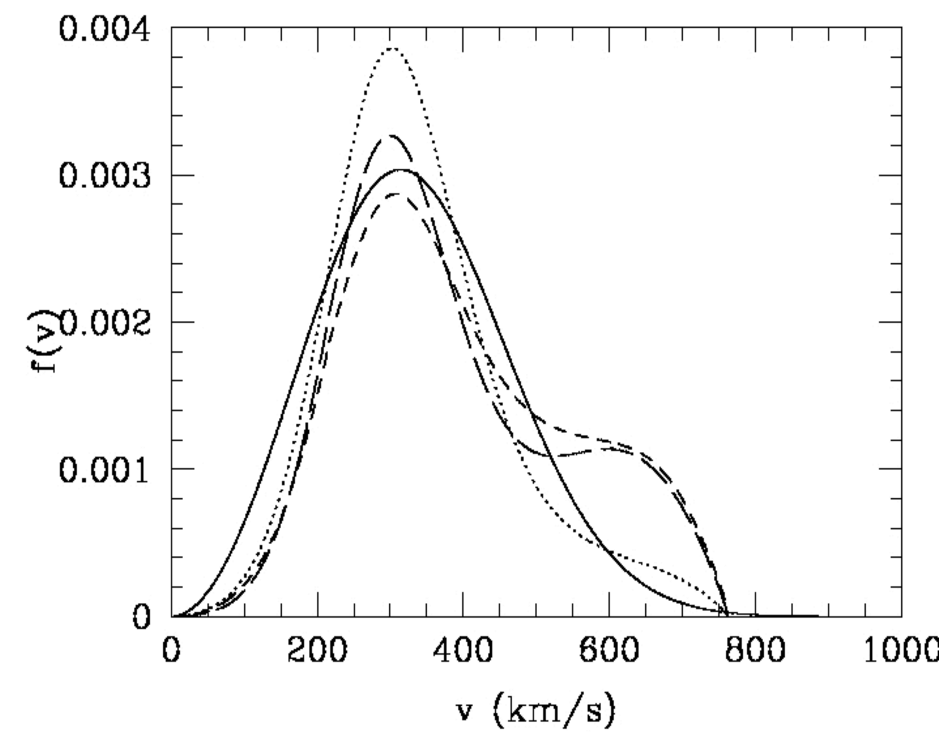
In planes of conical co-ordinates are locally equivalent to cyclindrical polars so f(v) is multi-variate gaussian in $(r,\, \phi,\, z)$.

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?

Numerical simulations

Background

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.

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

Simulating Milky Way like halos:

Chose input cosmological parameters (e.g. $h, \Omega_{\rm m}, \Omega_{\Lambda}, n_{\rm s}$). [n.b. relatively small differences in input parameters can lead to non-negligible changes in e.g. amount of substructure].

Calculate linear power spectrum.

Carry out large volume parent N-body simulation. [Sample gravitational field with massive particles, gravitational force softened to avoid spurious large forces for close interactions, tree and/or particle-mesh methods used to reduce number of interaction calculations required]

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

Resimulate using lower mass particles in region that forms halo of interest.

Carry out convergence tests (do results of interest change when you change the particle mass or gravitational softening?)

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Carry out convergence tests (do results of interest change when you change the particle mass or gravitational softening?)

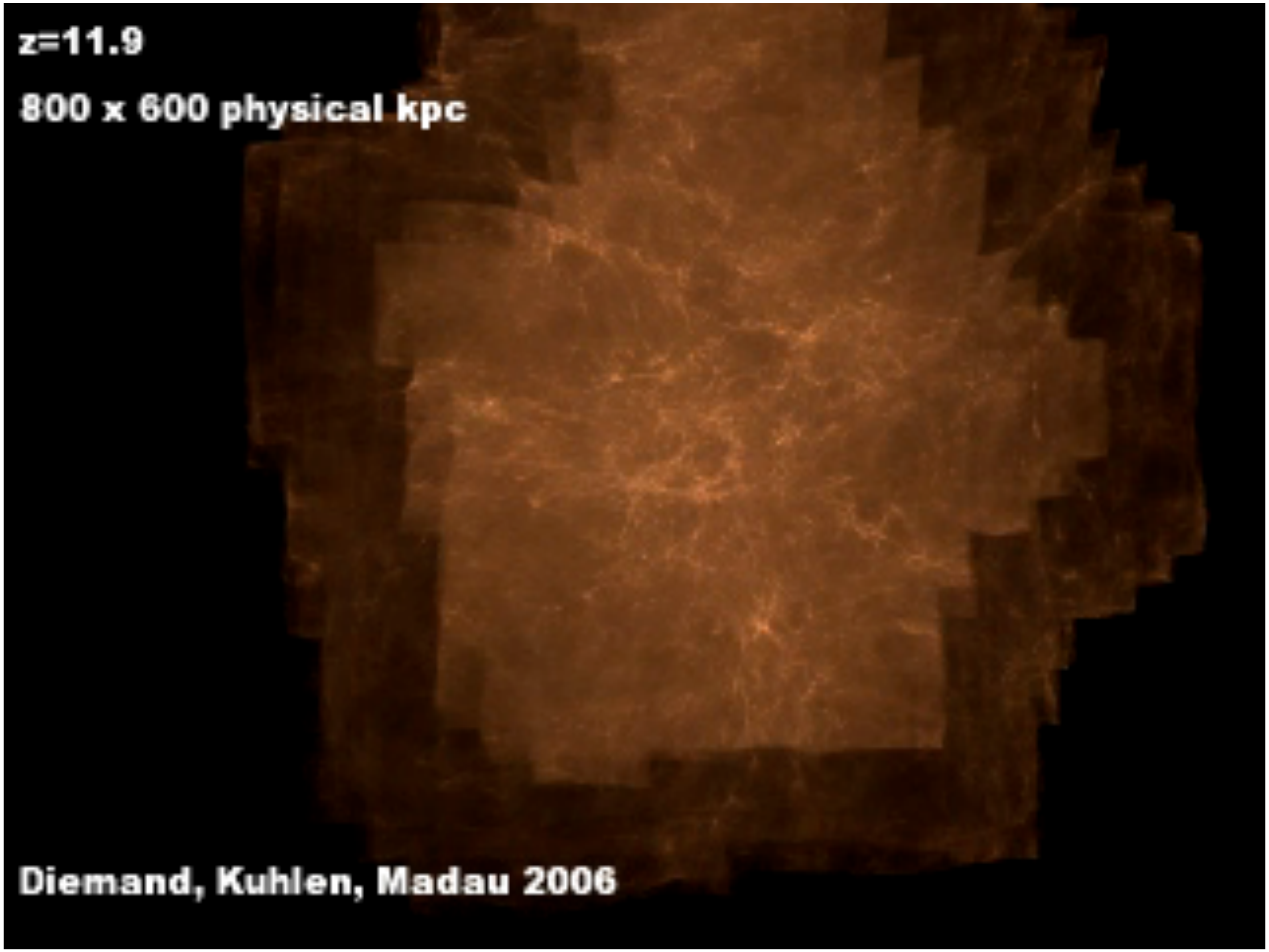
Health warning: codes are often publicly available, but carrying out (reliable) simulations is highly non-trivial.

Recent (2008+) simulations of Milky Way like halos:

Name	Authors	Code	(smallest) Particle mass (solar masses)	Softening (pc)	Number of halos simulated
Aquarius	Springel et al.	GADGET3 (TreePM)	1.7×10^3	21	6 (with 10^4 solar mass particles)
GHALO	Stadel et al.	PKDGRAV2	1.0×10^3	61	5 (at range of resolutions)
Via Lactea II	Diemand et al.	PKDGRAV2	4.0×10^3	40	1

Minimum mass and radius resolved are roughly one order of magnitude bigger than particle mass and softening respectively.

Results in broad agreement (but disagreement over implications for indirect detection experiments which result from extrapolations).



Via Lactea I, Diemand, Kuhlen & Madau

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.

Substructure

Since ~1998 simulations have been able to resolve large amounts of substructure (sub-halos) within galaxy halos [Klypin et al.; Moore et al.]

Can now (~2008) resolve sub-sub-halos.

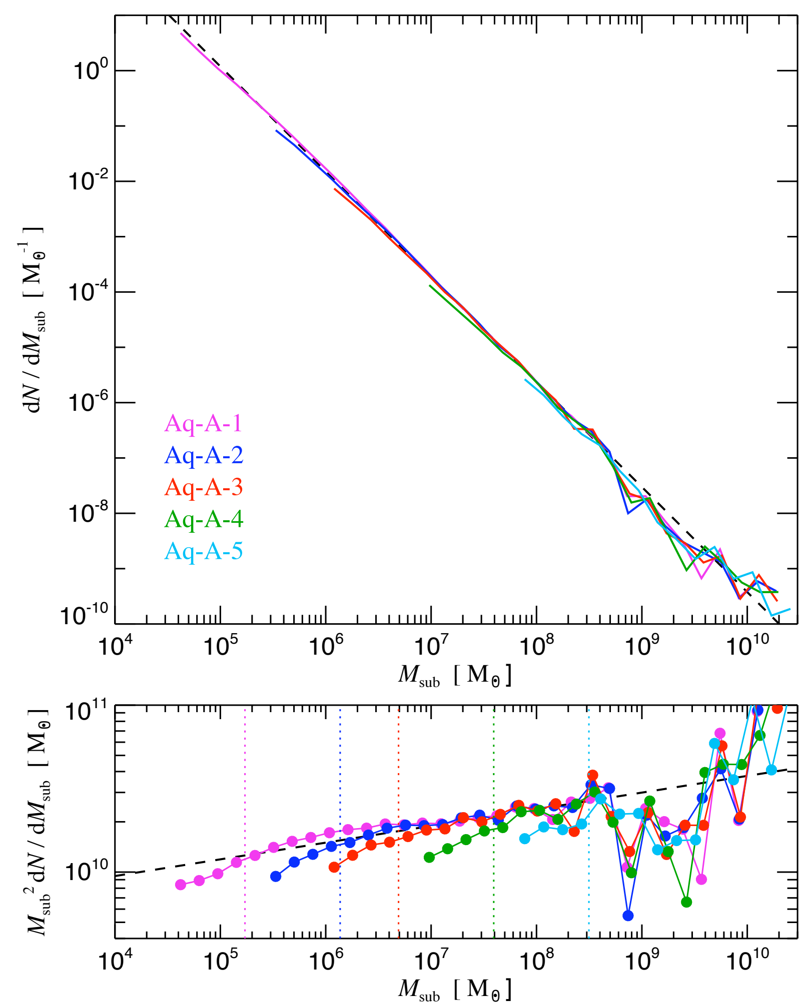
Aquarius:

$M/M_\odot$

10^4 10^{10}

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

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



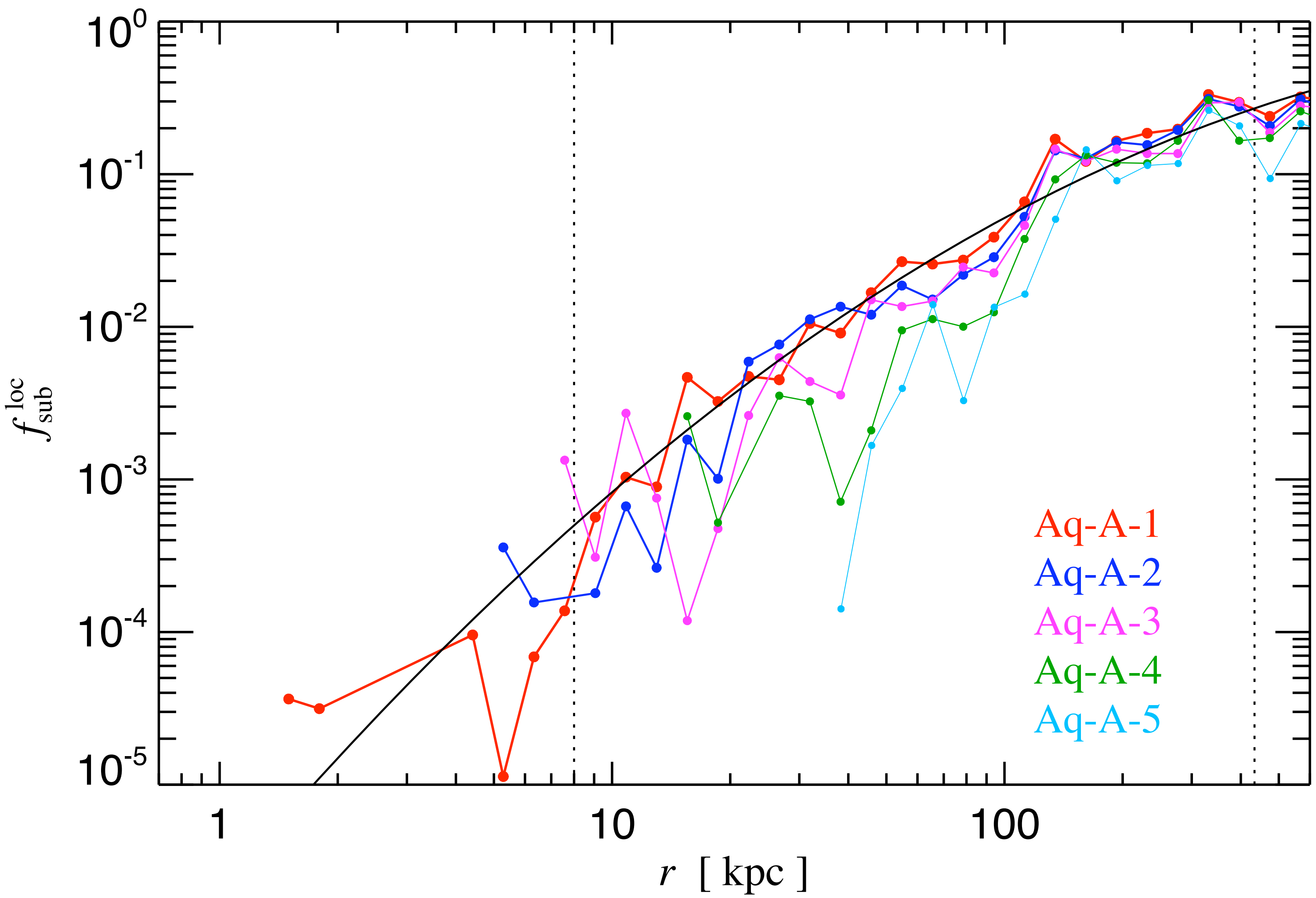
sub-halo mass function for 5 varying resolution simulations of same halo

Mass function:

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

$$\alpha = -1.90 \pm 0.03$$

Radial distribution of sub-halos:



Fraction of local mass in (resolved) sub-halos as a function of radius

13% of the total mass is in resolved sub-halos

< 0.1 % of the mass at the solar radius is in resolved sub-halos

Density profiles

Navarro, Frenk & White (96): "A universal density profile from hierarchical clustering"

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

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

$r_{\rm s}$ scale radius $\quad$ $\rho_{\rm s}$ characteristic density $\quad$ $c = \frac{r_{\rm vir}}{r_{\rm s}}$ concentration

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

Several toy models/fitting functions for mass dependence of concentration [Bullock et al.; Eke, Navarro & Steinmetz]

Generalisations of NFW:

Assymptotic inner slope -γ

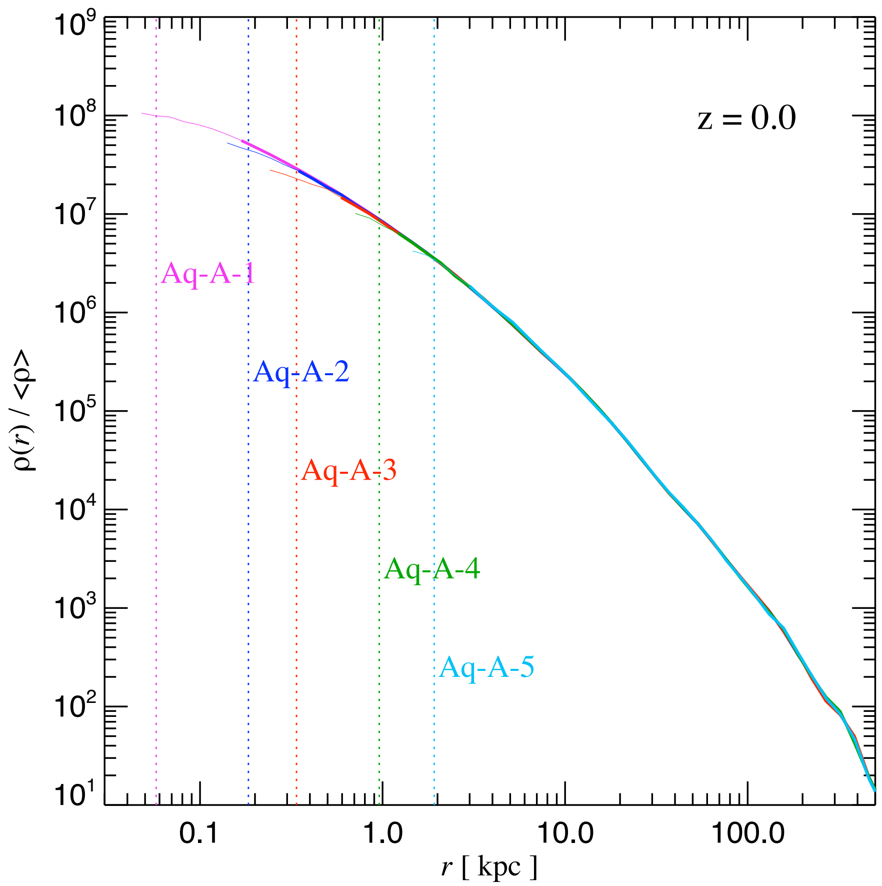
$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_s)^{\gamma}[1+(r/r_{\rm s})]^{3-\gamma}}$$

$\alpha\beta\gamma$

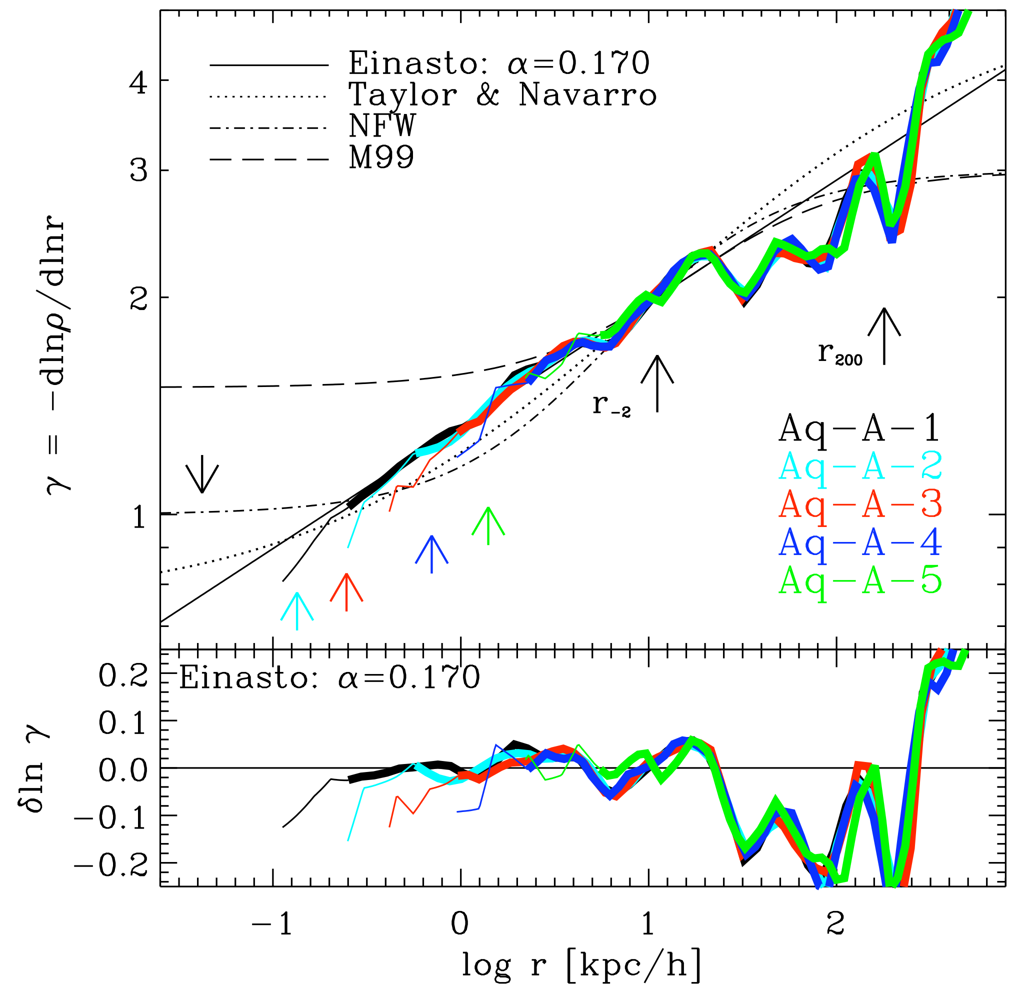
$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_s)^{\gamma}[1+(r/r_{\rm s})^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

Long standing controversy about density profiles in $r \to 0$ limit.

Aquarius:



density profiles of 5 varying resolution simulations of same halo



logarithmic slope of density profiles for same simulations

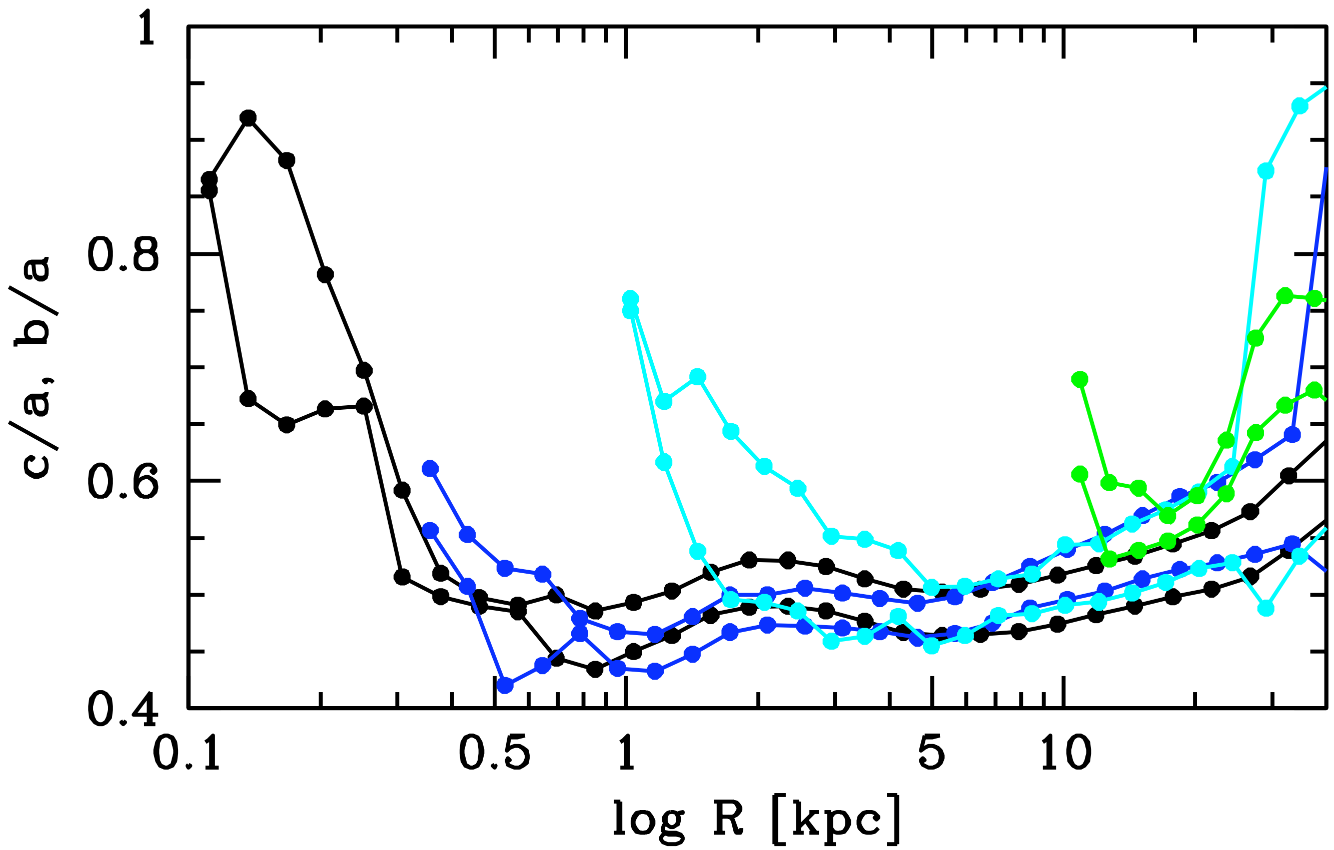
Einasto profile:

$$\rho(r) = \rho_s \exp\left\{-\frac{2}{\alpha}[(r/r_s)^\alpha - 1]\right\}$$

n.b. different halos have different best fit parameters
scatter between different halos similar to differences between profiles

<u>Shape</u>

GHALO:



Shape (axis ratio) for different resolution simulations

(in resolved regions): b/a ~ c/a ~ 0.5

Velocity distribution

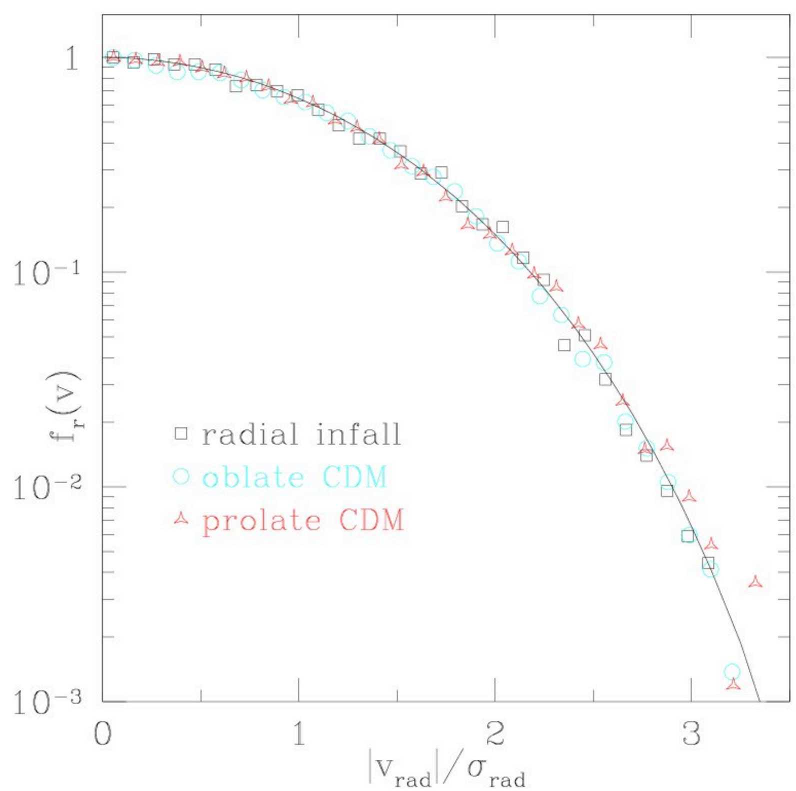
Hansen et al.

Found that halos formed in a variety of situations (head-on collisions, radial infall, cosmological simulations) have Tsallis velocity distribution functions (from non-extensive statistical mechanics):

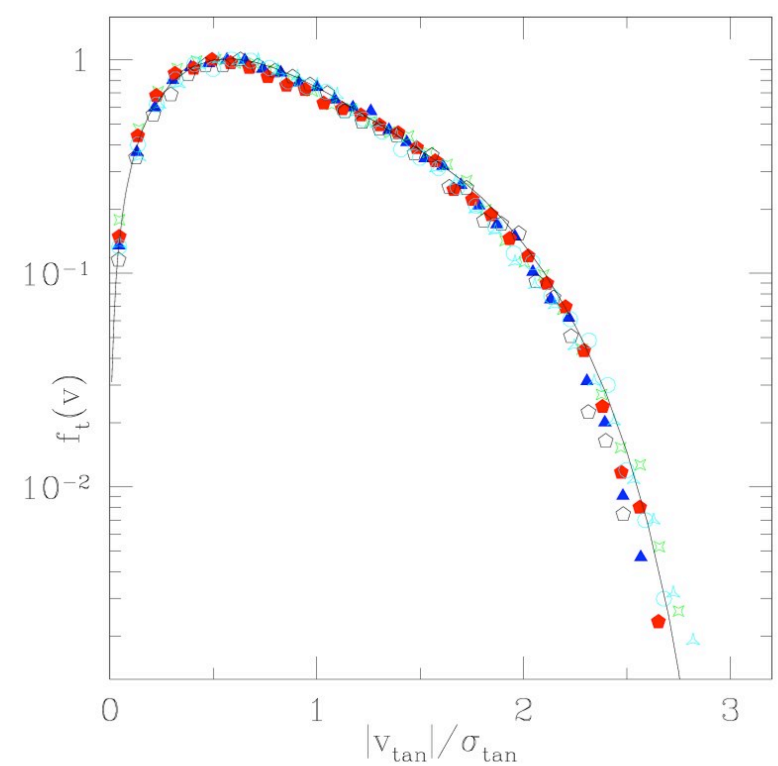
radial distribution: $$f(v_{\rm r}) = \left[1 - (1-q)\left(\frac{v_{\rm r}}{\kappa_1 \sigma_{\rm r}}\right)^2\right]^{\frac{q}{1-q}}$$ with similar form for tangential distribution

q = entropic index [q = 1 → Gaussian]

Value of q depends on slope of density profile $\alpha = \frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}$ for $\alpha = -2\,,\quad q = 0.9$.



radial velocity distribution



tangential velocity distribution

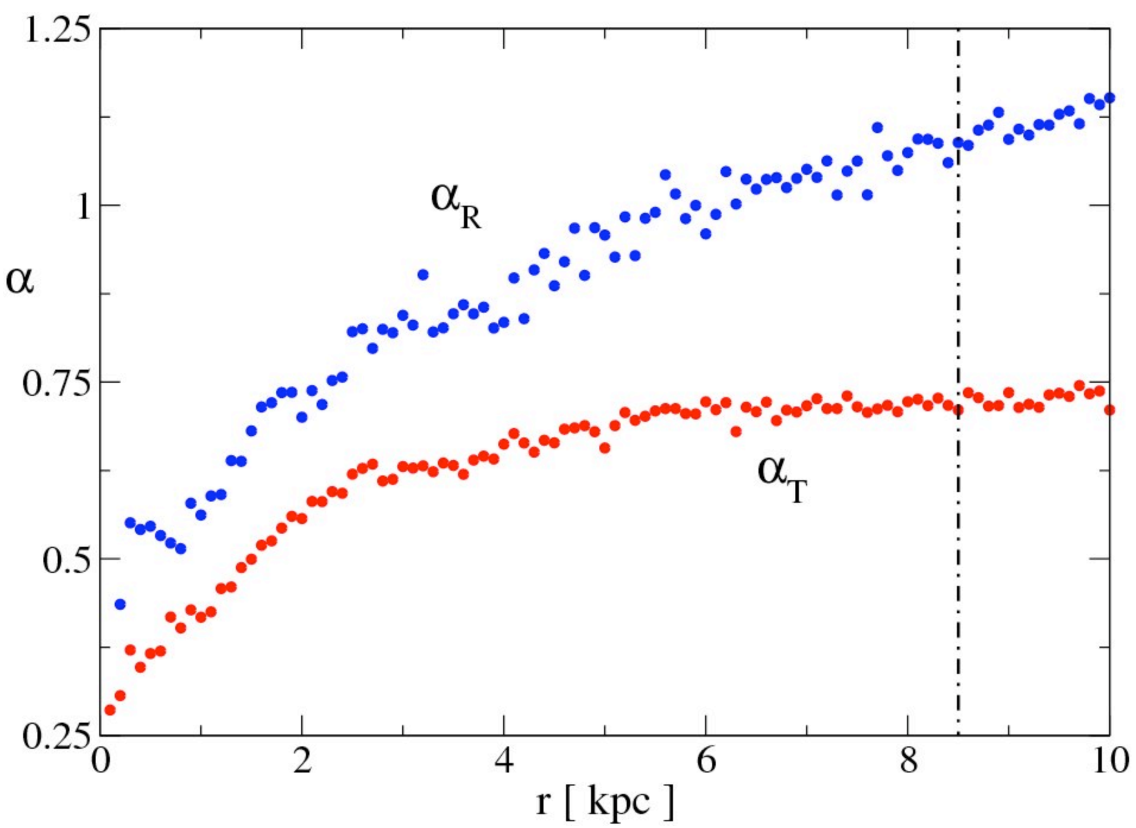
Fairbairn & Schwetz (using Via Lactea data)

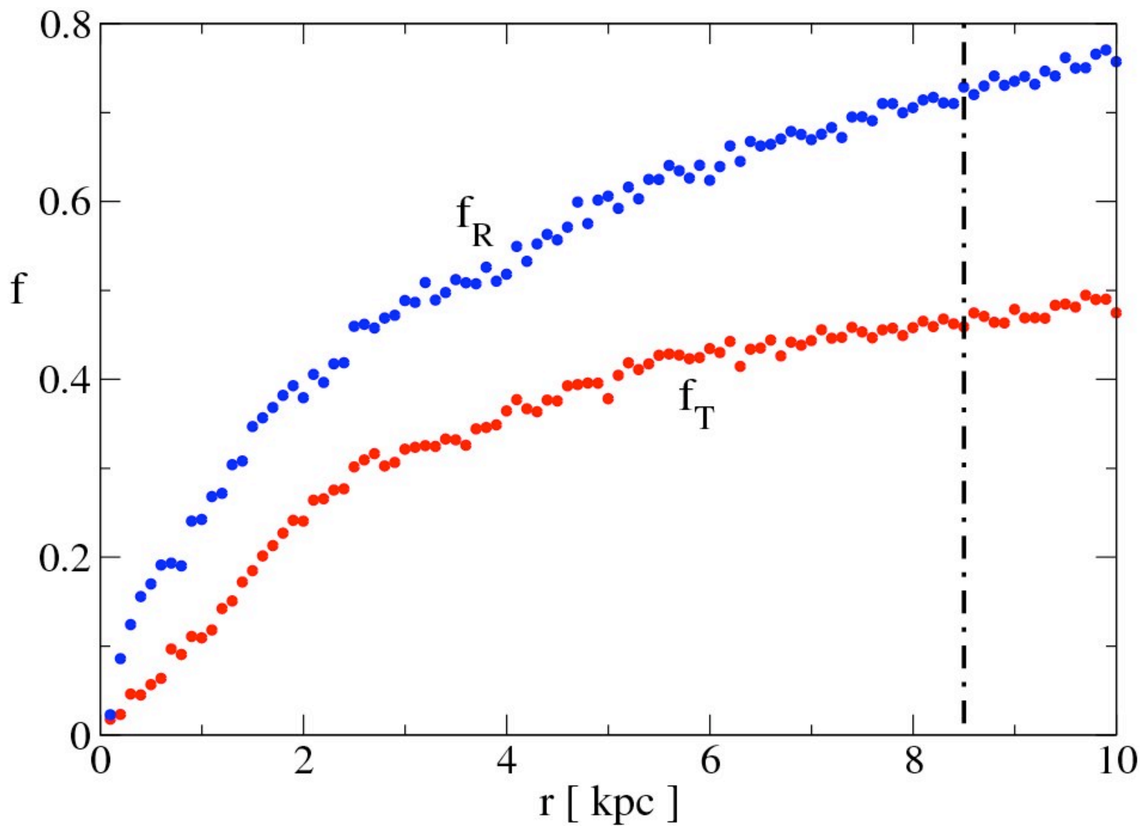
Find better fit, than Tsallis function, given by:

$$f(\tilde{v}_r) \propto \exp\left[-\left(\frac{\tilde{v}_{\mathrm{r}}^2}{f_{\mathrm{r}}^2}\right)^{\alpha_{\mathrm{r}}}\right] \qquad f(\tilde{v}_t) \propto \tilde{v}_{\mathrm{t}} \exp\left[-\left(\frac{\tilde{v}_{\mathrm{t}}^2}{f_{\mathrm{t}}^2}\right)^{\alpha_{\mathrm{t}}}\right]$$

$\tilde{v}$ are speeds normalised by square root of local gravitational potential

α encodes deviation from gaussianity





Distribution of parameters with radius

Aquarius

Examined distribution of particles (10^4-10^5) in 2 kpc boxes at solar radius in various simulated halos.

All halos have similar form for f(v):

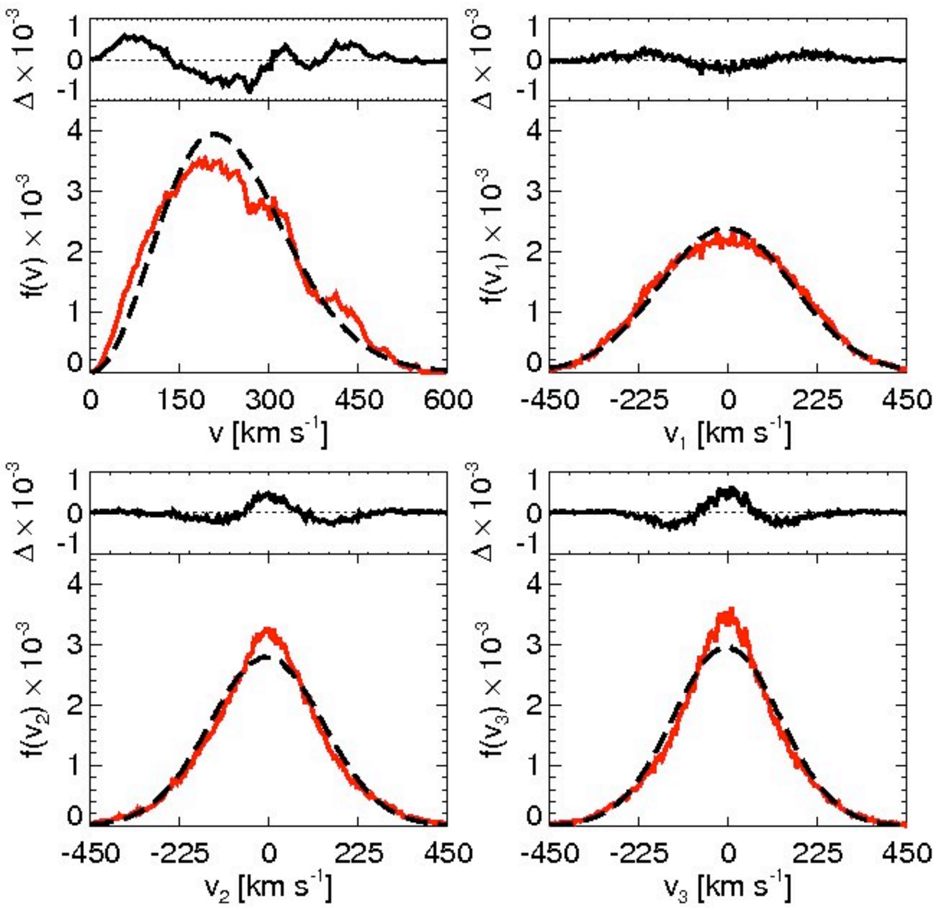
compared with multi-variate Gaussian
more low v particles, peak suppressed

features (bumps and dips) at high v

High v features reflect merger history of halo:

appear in different places for different halos, but are similar for different regions within a given halo.

[n.b. not streams, too broad]



Speed distribution (top left)
+ distribution of principle components
[red lines: simulation data,
black lines: best fit multi-variate Gaussian]

Caustics

Self-similar radial infall onto a spherical overdensity produces shells with high densities (caustics). [Filmore & Goldreich; Bertschinger; Sikivie]

Do caustics form in hierarchical structure formation simulations?

[Vogelsberger et al.; Diemand & Kuhlen; Afshordi, Moyahee & Bertschinger]

Yes, in the outer regions of halos, but they're broad and weak.

Effects of baryons

N-body simulations are dark matter only, 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. [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) 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]

Density spikes may form around IMBHs also [Bertone, Zenter & Silk].

Shape

Baryons make halos more spherical in inner regions (box orbits which support triaxial shape pass close to center and are scattered by baryons). [Katz & Gunn; Kazanzidis et al. Debattista et al.]

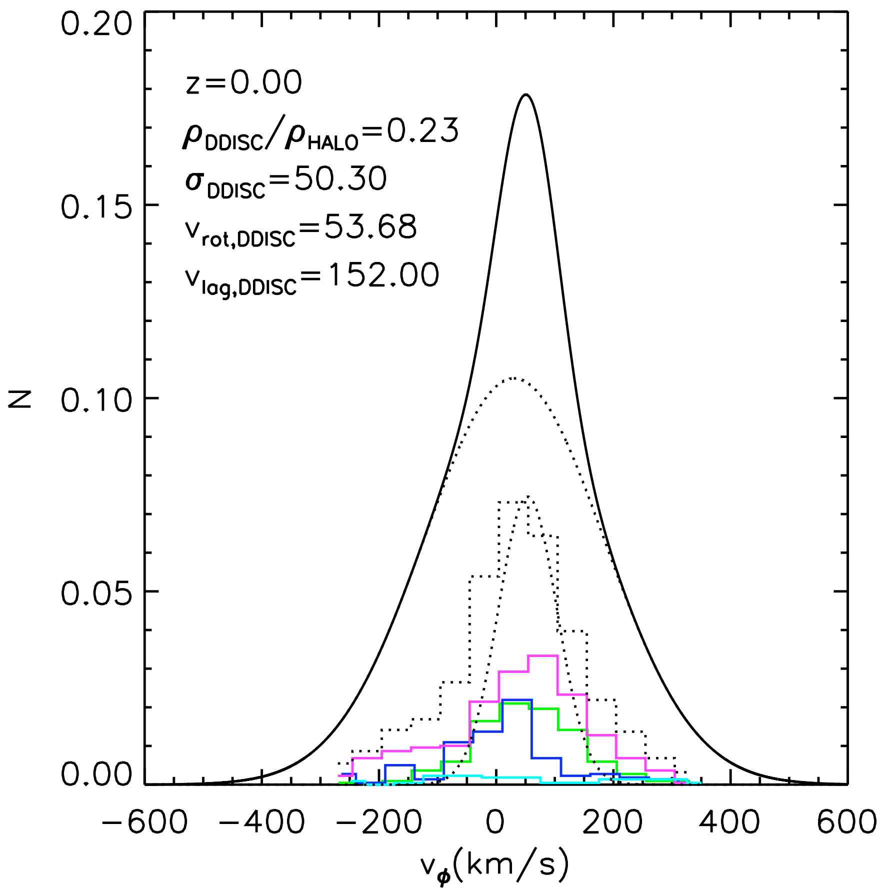
Dark disc

[Read et al.; Bruch et al.]

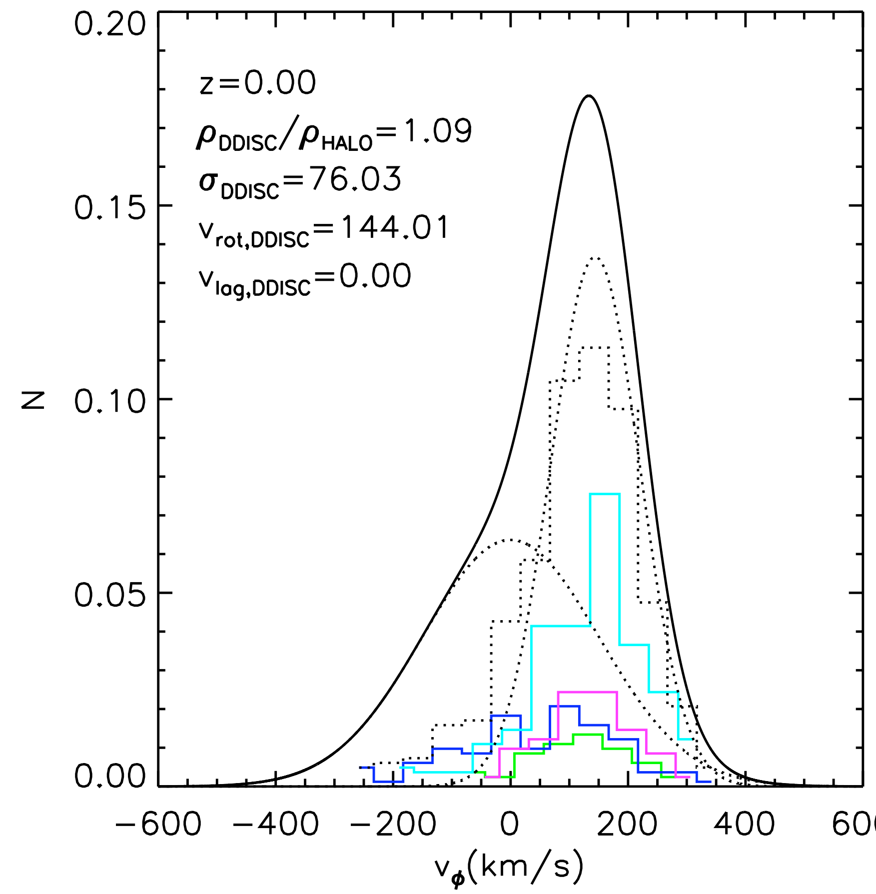
Sub-halos merging at z<1 preferentially dragged towards disc, where they're destroyed leading to the formation of a rotating dark disc (which lags the stellar disc).

Distribution of dark matter particle rotational speeds for galaxies from cosmological hydrodynamics simulations with:

no major mergers after z=2



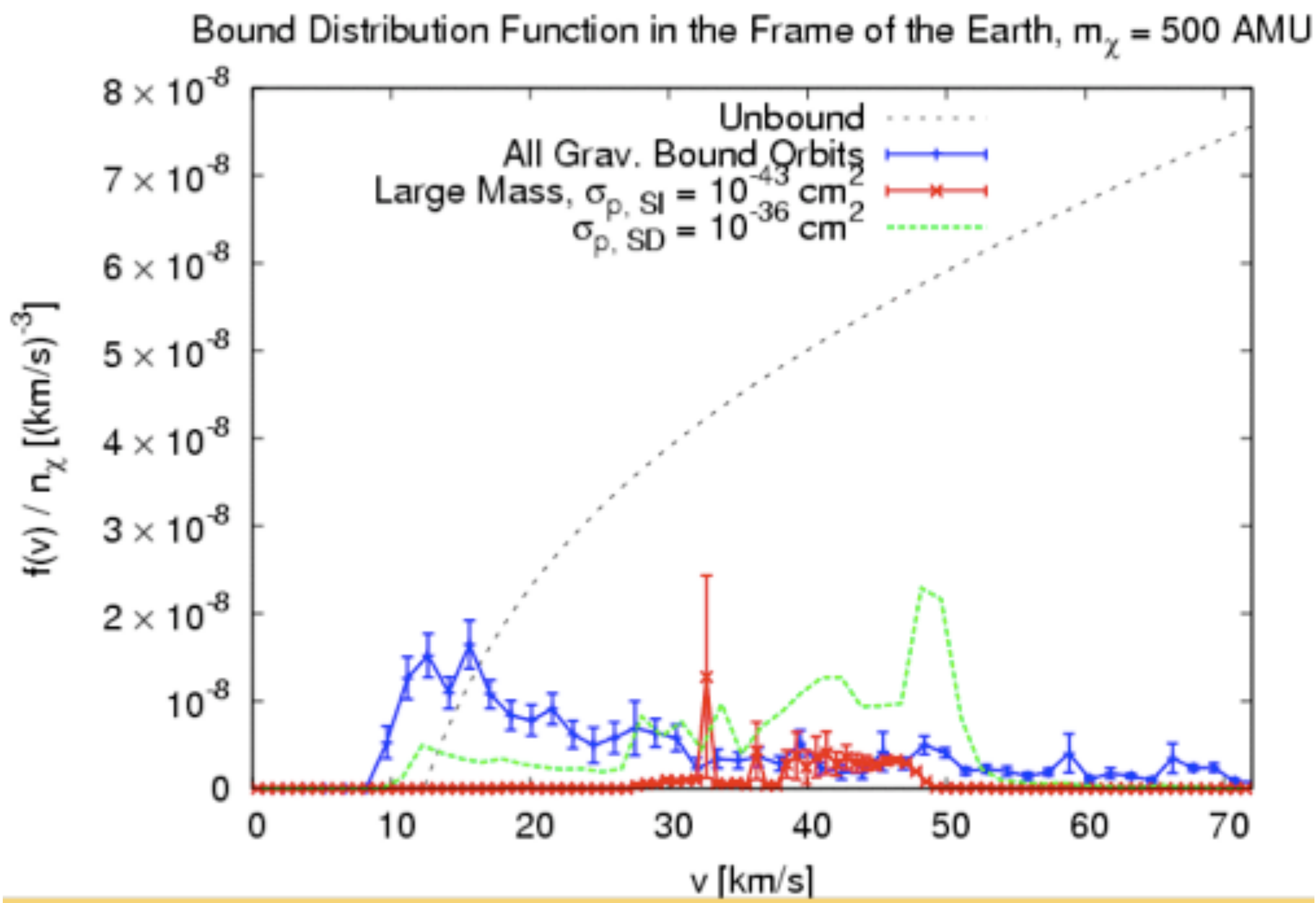
several massive mergers after z=1



Density at solar radius 0.25-1 times that of halo.

Solar system

Gravitational scattering of DM with the Sun or planets produces a (small) population of low speed WIMPs bound to the Solar System. [Damour & Krauss; Bergstrom et al.; Gould & Alam; Lundberg & Edsjo; Peter]



(very) Small scales

How is dark matter distributed on scales smaller than the resolution of numerical simulations?

Why is this important?

i) 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?

ii) Indirect detection

Substructure on all scales contributes to the signals.

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

Substructure

How small are the smallest (WIMP) substructures?

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

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).

For a typical 100 GeV WIMP, first smallest halos to form have

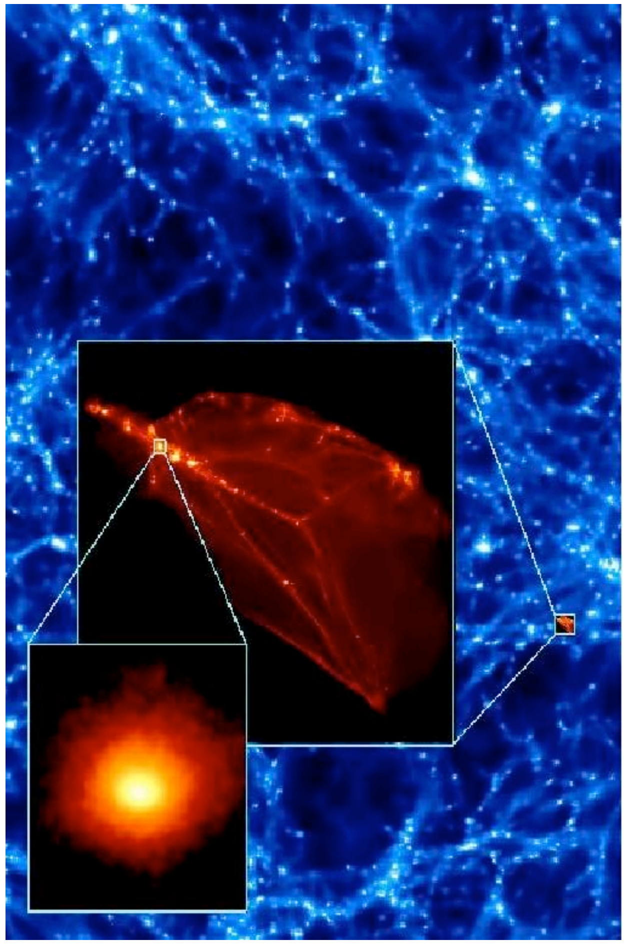
$$M \sim 10^{-6} M_{\odot} \qquad\qquad R \sim 0.01\,\mathrm{pc}$$

but in MSSM minimum mass can vary by many (~6) orders of magnitude.

Simulations by 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.]

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

Modelling the substructure distribution (down to the cut-off mass)

e.g. Pieri and collaborators

Broadly two approaches

i) Use and extrapolate substructure properties (mass function, concentration) from simulations. Assume sub-halos trace mass (or anti-biased as 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 assumptions/extrapolations (and results will only be as reliable as the input assumptions).

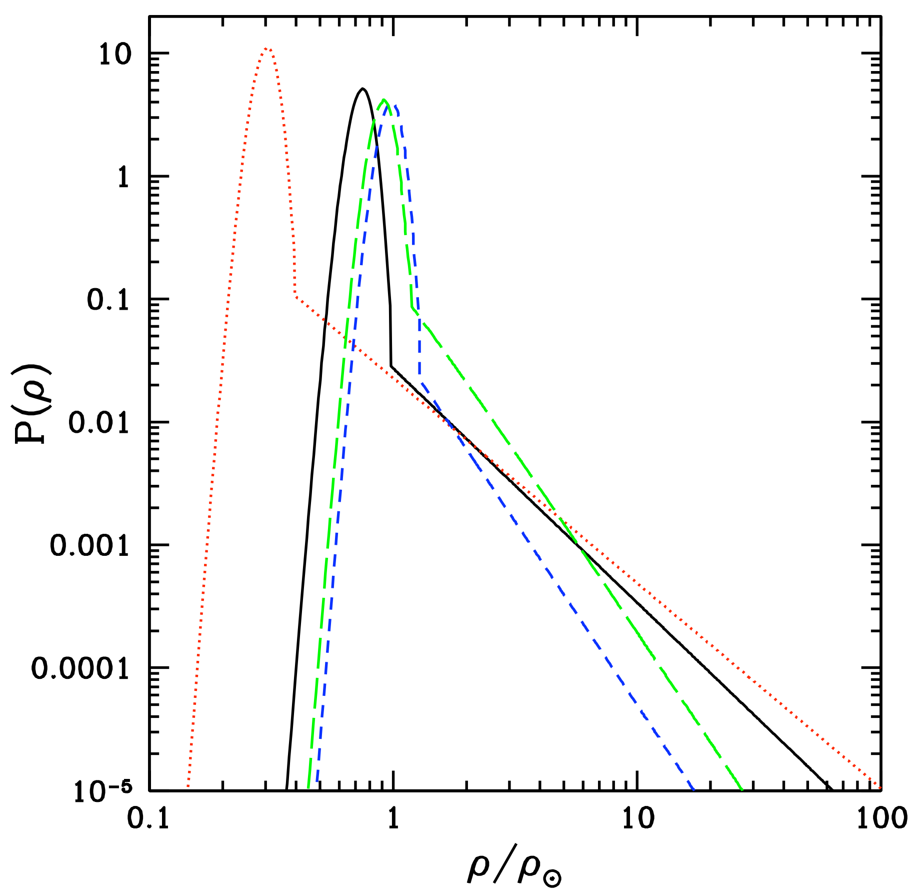
<u>(ultra-local) density</u> Kamionkowski and Koushiappas

Calculated probability density function of local density P() by

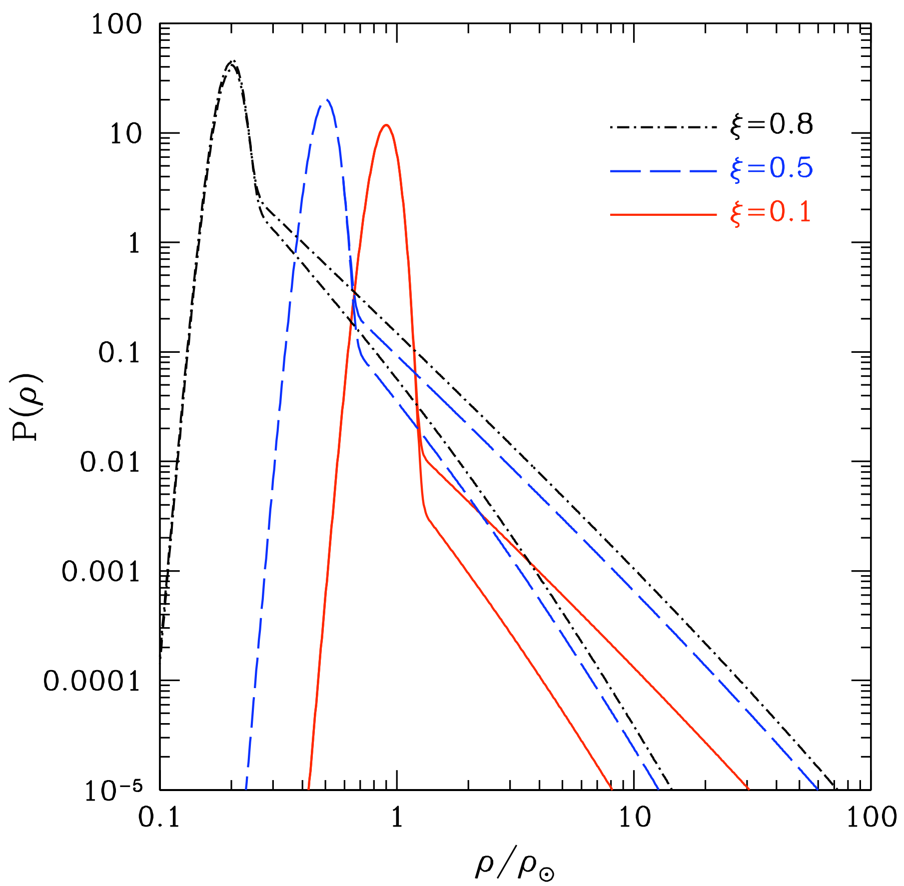
i) assuming early generations of subhalos survive with some probability (with functional form motivated by simulations).

ii) using (and extrapolating) subhalo mass function and concentration distribution found in simulations.

Probability distributions from approaches i) and ii)



varying the sub-halo survival probability



varying the fraction of the mean density in substructure

n.b. assume that material removed from sub-halos is smoothly distributed

(ultra-local) Velocity distribution

Stiff & Widrow

Run simulation, place grid of massless test particles at point of interest (c.f. terrestrial direct detection experiment).

Evolve simulation backwards to initial time, find where test particle distribution intersects initial DM dist, calculate distribution function at point of interest.

Find speed distribution consisting of a finite number of discrete peaks.

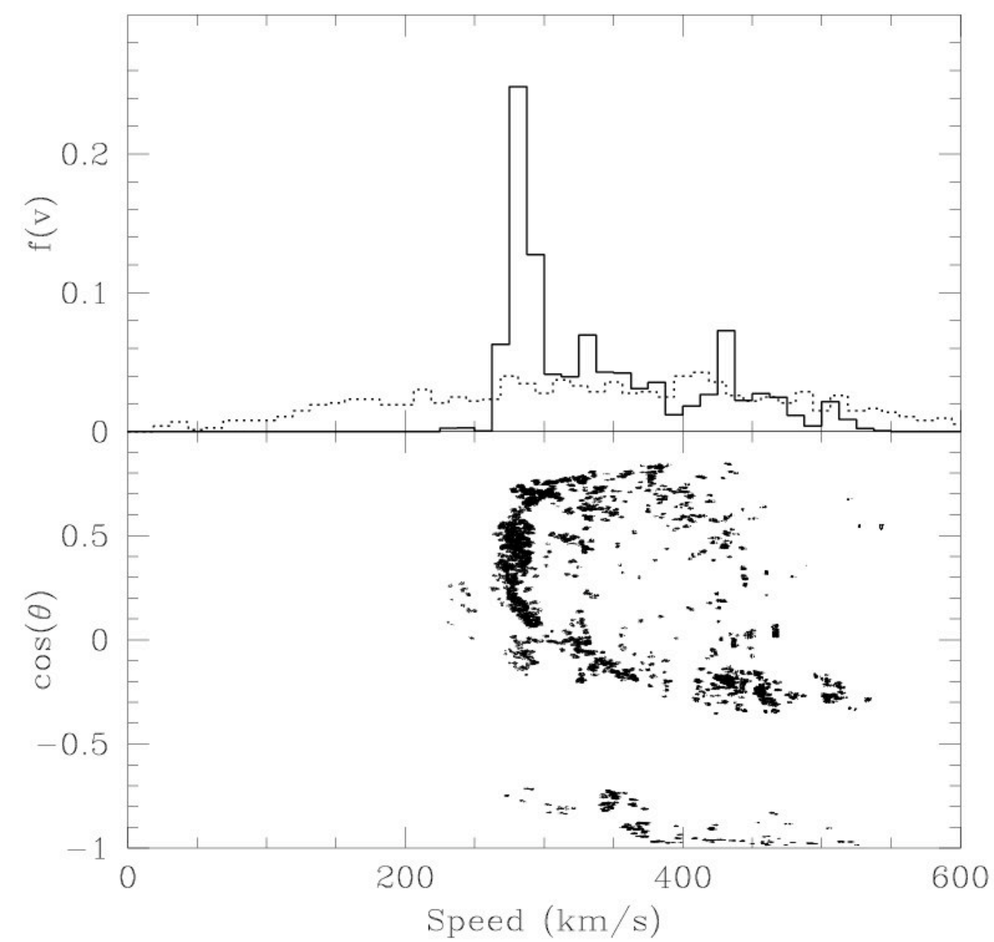
Caveats:

Large softening used for reverse simulations.

Not implemented in full cosmological simulation.

f(v)

cos()



v

Vogelsberger, White, Helmi & Springel

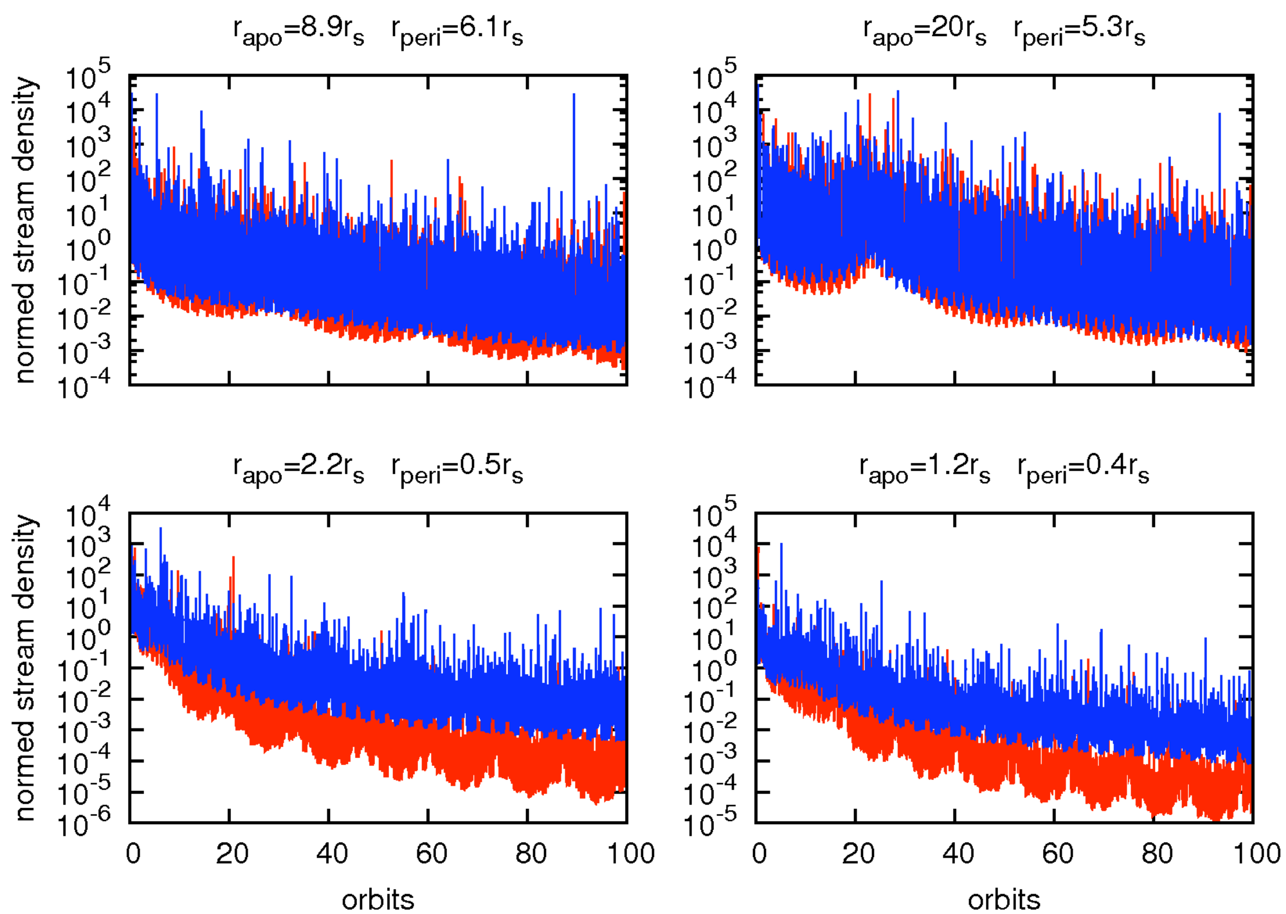
Argue that the local phase space distribution consists of a large number of streams (~10^5) and therefore the local velocity distribution is smooth.

Technique for calculating the phase space distribution function in the neighbourhood of a (simulation) particle.

Decrease in density of streams with time:

i) depends on number of independent orbital frequencies, n, as $(t/t_{orb})^{-n}$

ii) is more rapid in triaxial than spherical potentials



Variation of stream density with time for spherical NFW halo and triaxial halo (for four different orbits).

Estimate of local number of streams:

$$N = \frac{\rho_{\rm loc}}{\rho_{\rm str}(t_0)}$$

$$\rho_{\rm str}(t_0) \approx \rho_{\rm str}(t_{\rm i}) \left(\frac{t_0}{t_{\rm orb}}\right)^{-3}$$

$$\Downarrow$$

$$N \approx \frac{\rho_{\rm loc}}{\rho_{\rm str}(t_{\rm i})} \left(\frac{t_0}{t_{\rm orb}}\right)^{3} \sim 10^6 \frac{\rho_{\rm loc}}{\rho_{\rm str}(t_{\rm i})}$$

But [work in progress with Fantin & Merrifield] characteristic timescale of decrease in density should depend on parent halo mass.

(smaller mass ⟶ smaller velocity dispersion ⟶ longer timescale).

Implications for direct and indirect experiments

Direct detection

(Assuming ultra-local DM distribution is smooth:)

Order unity uncertainty in local density propagates directly into corresponding uncertainty in constraints on/measurements of the cross-section.

~10% uncertainty in circular speed affects slope of differential event rate (and WIMP mass inferred from signal) and properties of annual modulation.

Mean differential event rate (and hence exclusion limits) weakly sensitive to detailed shape of velocity distribution, but shape and phase of annual modulation can change significantly.

Dark disc may significantly affect signals?

Indirect detection:

Clumping of dark matter enhances event rates. [Bergstrom et al....]

Enhancement (relative to rate expected for a smooth halo) is usually parameterised in terms of the **boost factor**.

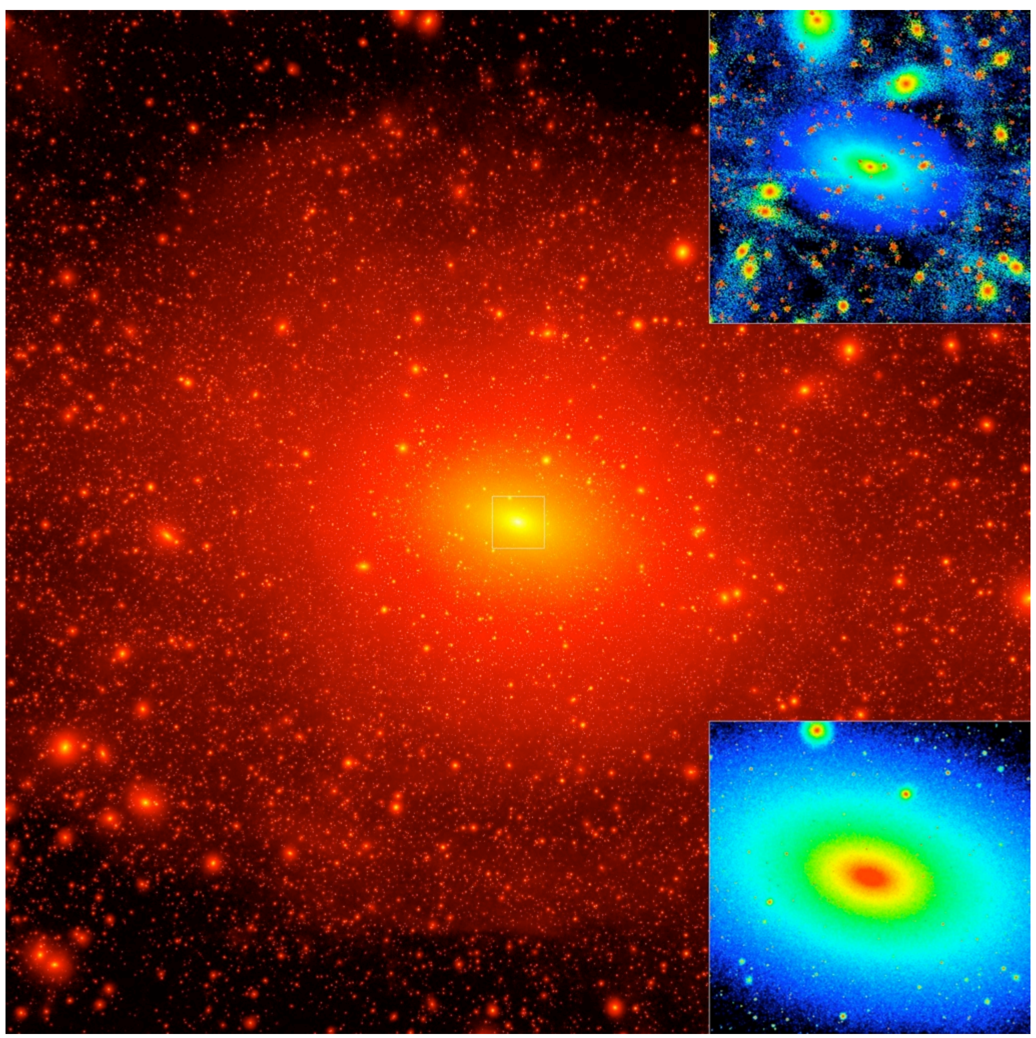
Boost factor is species, direction and sometimes energy dependent

gamma-rays

Large uncertainties in DM density close to Galactic center (plus astrophysical background....).

For an individual halo: $$\mathcal{L} \propto \int \rho^2(r)\mathrm{d}V \propto \rho_s^2 r_s^3 \propto \frac{V_{\max}^4}{r_{V_{\max}}}$$

Via Lactea II:



phase space density inner 40 kpc

density inner 40 kpc

projected ρ^2 (800 kpc cube)

Boost factor?

from resolved halos B~2

extrapolating down to cut-off B~10-15

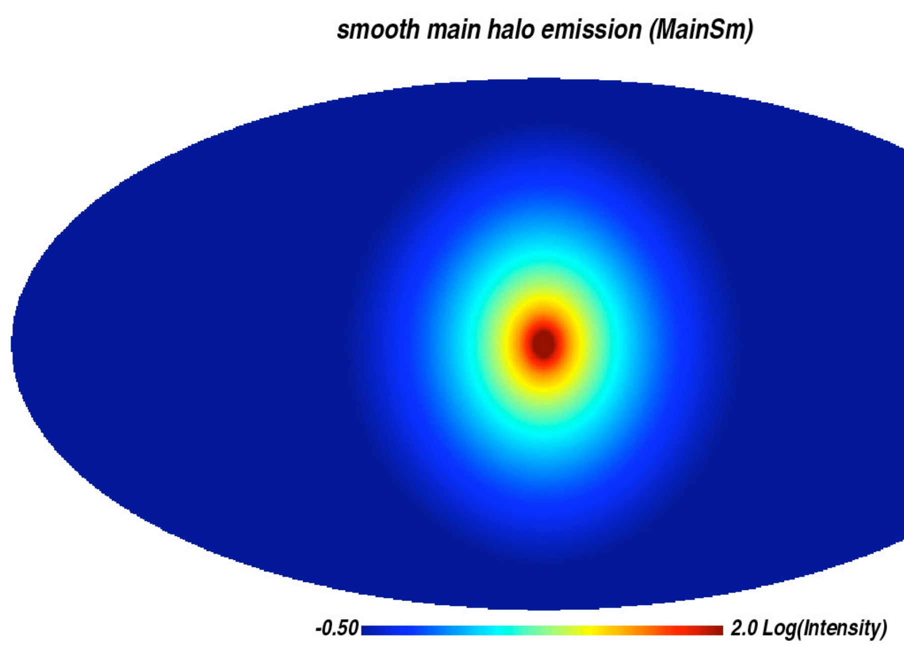
potentially ~10s of sub-halos detectable by Fermi

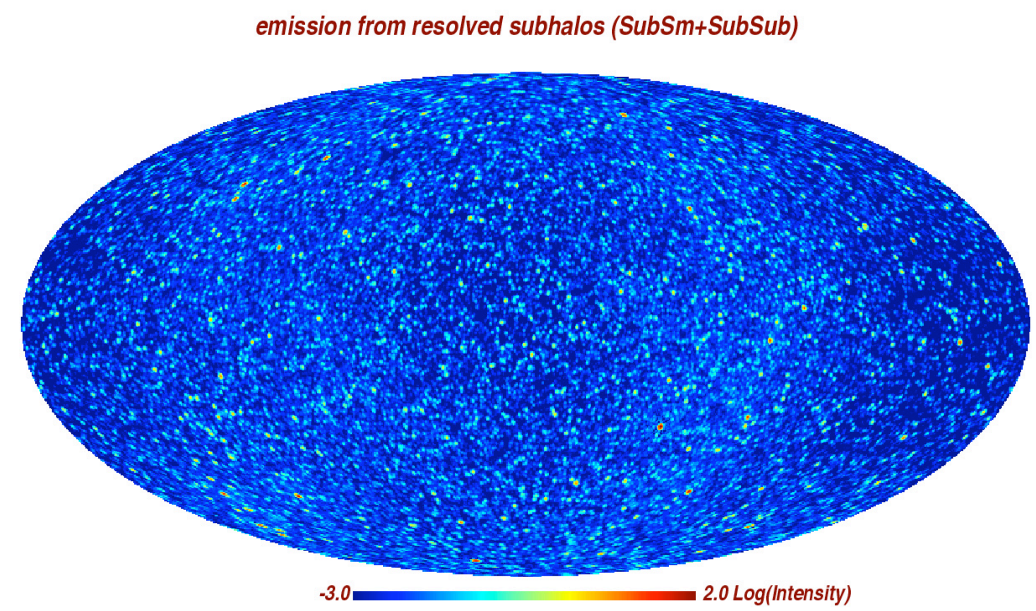
Aquarius:

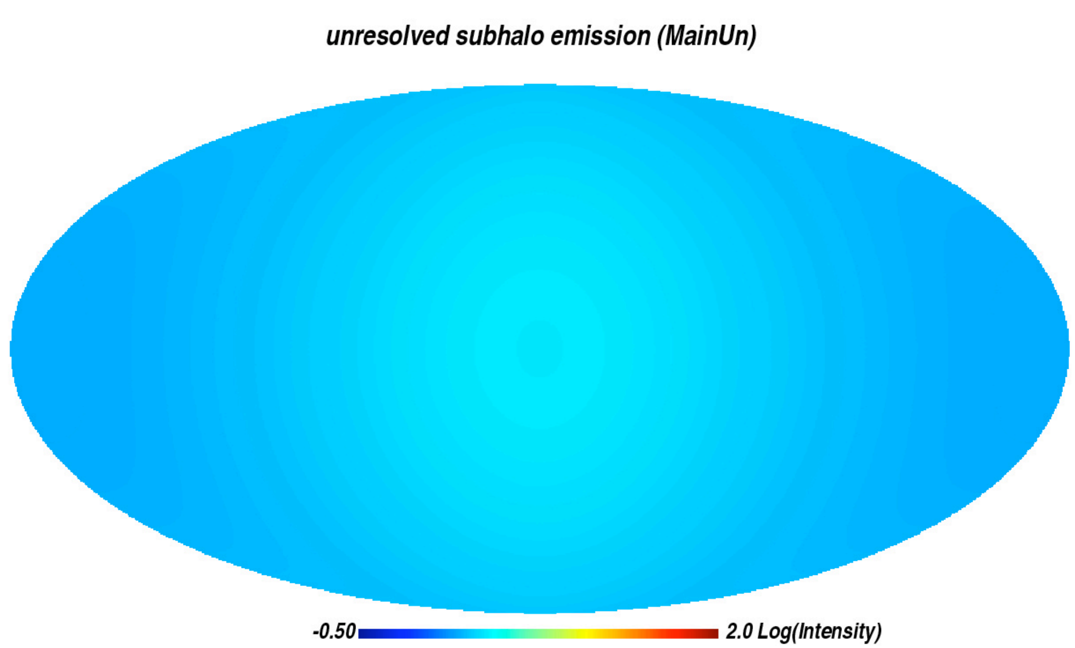
extrapolating down to cut-off B~2

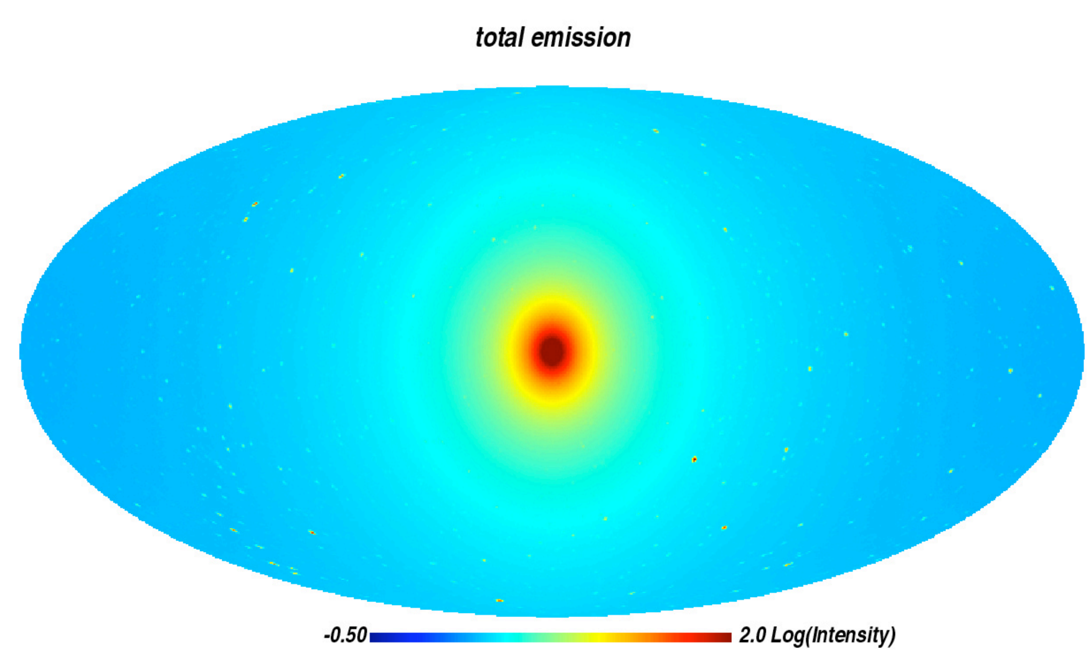
diffuse emission dominates

If annihilation cross-section sufficiently large may also be able to detect dark sub-halos.

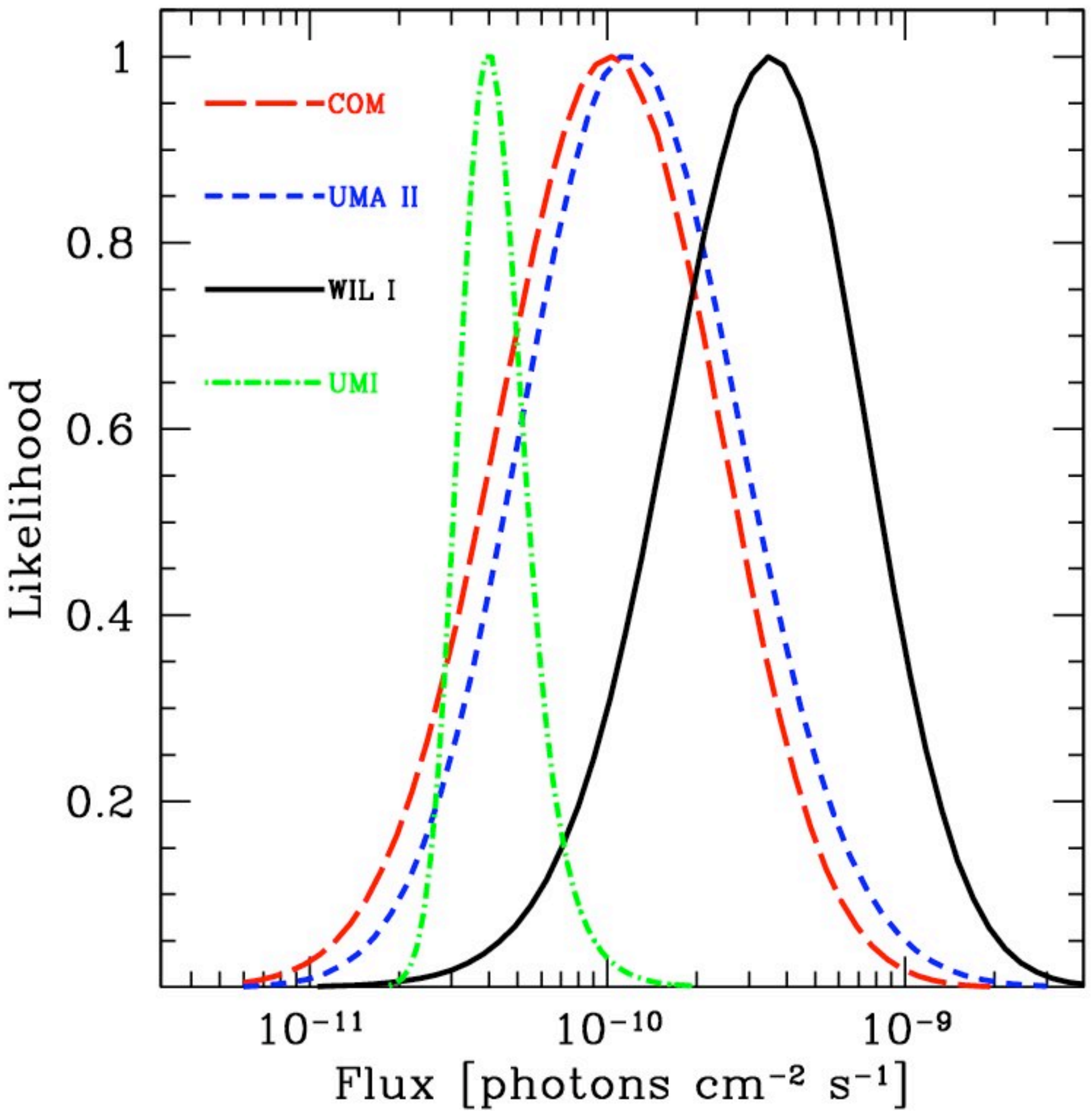








High (inferred) dark matter density, low baryon density and proximity make nearby dwarfs (e.g. Draco, Willman 1, Segue 1) potentially good indirect detection targets.



Predicted gamma-ray fluxes from new Milky Way satelites compared with Ursa Minor

Coma, Ursa Major II, Willman 1 and Ursa Minor [Strigari et al.]

Assuming:

most optimistic particle physics model
cuspy density profiles
smooth dark matter distribution (i.e. no boost factor)

Indirect detection: anti-matter

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

Via Lactea II:

considering halos within ~1 kpc of point at Solar radius:

typically B~1.4

1% of locations (with nearby large subhalo) have B>10

Summary

To confirm the existence of dark matter and understand it's nature we need to detect it. To do this we need to know how it's distributed.

Direct detection signals depend on ultra-local DM density and speed distribution.

Indirect detection signals depend on DM density distribution (enhanced by clumping).

Numerical simulations produce DM halos with non-gaussian velocity distributions, cuspy density profiles and large amounts of substructure **BUT**

i) how do baryons affect the DM distribution?

ii) how is the DM distributed on scales not resolved by simulations?

Direct detection:

uncertainties in local density and velocity dispersion (and for annual modulation, shape of velocity distribution) potentially signficant.

Indirect detection:

enhancement due to clumping (boost factor) species energy and direction dependent and somewhat uncertain

An advert:

Particle Dark Matter,

ed. G Bertone,

to be published (late 2009/early 2010) by CUP

28 chapters (by different authors) covering:

- DM in cosmology,
- Candidates,
- Collider searches,
- Direct searches
- Indirect searches & astrophysical constraints

Discussion session

Discussion session

Dealing with/reducing uncertainties

What are the most important uncertainties in the DM distribution?
(and how can we try and resolve them?)

How can/should we take uncertainties into account when comparing results from different experiments and/or deriving constraints on particle physics parameters (e.g. mass, cross-sections)?

Simulations

How much should we rely on the results of simulations?

How much should we worry about the effects of baryons?

Input to experimental strategies

What is/are the most promising targets for indirect detection?

Can astrophysics provide useful input into the design of direct detection experiments?