Formation and evolution of CDM halos and their substructure

1) cold dark matter and structures on all scales
2) via lactea, z=0 results
3) subhalo evolution
4) DM annihilation and GLAST

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What is dark matter?

Evidence for DM:
Galaxy cluster dynamics (Fritz Zwicky, 1933)

Coma, Credit: Lopez-Cruz et al
What is dark matter?

Evidence for DM:
- Galaxy cluster dynamics (Fritz Zwicky, 1933)
- Spiral galaxy rotation curves
- X-rays from galaxy groups and clusters
- Kinematics of stellar halos and globular cluster systems
- Dwarf galaxy velocity dispersions
- Strong and weak lensing

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CMB, LSS, SN Ia, BBN  \rightarrow  LambdaCDM

WMAP-3yr (alone, flat prior):
Omega_m=0.238
of which Omega_b is only 0.042
with small errors (less than 10%)

DM is “cold”, or at least “cool”:
Lyman–alpha forest, early reionisation

83% of the clustering matter is some non-baryonic, very weakly interacting, “cold” dark matter
We don’t know yet what the DM is, but we can still simulate its clustering ...
Simulating structure formation

our approach:
collision-less ("pure N-body", "dark matter only") simulations

- treat all of Omega_m like dark matter, and sample it with \( N \) particles
- bad approximation near galaxies, OK for dwarf galaxies and smaller scales
- simple physics: just gravity
- allows high resolution
- no free parameters (ICs known thanks to CMB)

accurate solution of the idealized problem
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accurate solution of the idealized problem

complementary approach:
hydro-dynamical simulations
- computationally expensive, resolution relatively low
- hydro is not trivial (SPH and grid codes often disagree, e.g. Agertz etal 2006)
- important physical processes far below the resolved scales (star formation, SN, ... ?)
  implemented through uncertain functions and free parameters

approximate solution to the more realistic problem
Simulating structure formation

N-body models approximating CDM halos (about 1995 to 2000)

log density

log phase space density

from Ben Moore: www.nbody.net
CDM forms (sub)structures on many scales
CDM forms (sub)structures on many scales

M ~ 0.01 Msun microhalo
no baryons, dark DM structure, but relevant for DM annihilation signal: extragalactic background, M31, Draco ... nearby dark subhalos

M=6e14 Msun galaxy cluster
For a 100 GeV SUSY neutralino (a WIMP) there is a cutoff at about $10^{-6}$ Msun due to free streaming.

Small, “micro”-halos should forming around $z=40$ are the first and smallest CDM structures.
CDM microhalos seem to be cuspy like the larger halos that formed in mergers. They are very concentrated, with a concentration of $c \approx 3.3$ at $z=26$, evolving into $c \approx 90$ by $z=0$, consistent with the Bullock et al. model.

The image on the right shows a plot of $r(t)/\rho_{\text{crit}}(z=0)$ versus $r$ in units of parsecs, with different markers representing different masses and profiles. The plot includes a line for the $\alpha\beta\gamma$-profile with $c=1.6$ and markers for different masses.
CDM microhalos seem to be cuspy like the larger halos that formed in mergers they are very concentrated c~3.3 at z=26 evolves into c~90 by z=0 consistent with Bullock etal model

-> they are stable against tides caused by the MW potential if the live more than about 3 kpc form the galactic center i.e. a huge number ~ 5x10^{15} could be orbiting in the MW halo today JD, Moore,Stadel, astro-ph/0501589

some tidal mass loss and disruption due to encounters with stars (see Goerdt etal astro-ph/0608495)
since $P(k) \sim k^{-2.9}$
sigma(M) almost constant on microhalo scales

structures of different mass form almost simultaneous
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structures of different mass form almost simultaneous

only true for the average field halo

not true for subhalos, they form on top of a larger perturbation, and therefore earlier

is there enough time for them to virialize and survive accretion into a larger host?
almost simultaneous collapse of a 0.01 Msun halo at z=75

lower density contrast, but similar subhalo abundance as in a z=0 cluster

hierarchical formation of a z=0 cluster

same comoving DM density scale from 10 to $10^6$ times the critical density

in each panel the final $M_{\text{vir}} \sim 20$ million particles are shown

JD,Kuhlen,Madau astro-ph/0603250
2) \( z=0 \) results form “via lactea”

a Milky Way halo simulated with over 200 million particles

- JD, Kuhlen, Madau astro-ph/0611370

- largest DM simulation to date
  320,000 cpu-hours on NASA's Project Columbia supercomputer.

- 213 million high resolution particles, embedded in a periodic 90 Mpc box sampled at lower resolution to account for tidal field.

- WMAP (year 3) cosmology:
  \( \Omega_m=0.238, \Omega_L=0.762, H_0=73 \text{ km/s/Mpc}, n_s=0.951, \sigma_8=0.74. \)

- force resolution: 90 parsec

- time resolution: adaptive time steps as small as 68,500 years

- mass resolution: 20,900 M\(_\odot\)
$z=11.9$

800 x 600 physical kpc

Diemand, Kuhlen, Madau 2006
a Milky Way dark matter halo simulated with 234 million particles on NASA’s Project Columbia supercomputer

movies

These animations show the projected dark matter density-square maps of the simulated Milky Way-size halo Via Lactea. The logarithmic color scale covers the same 20 decades in projected density-square in physical units in each frame. All movies are encoded in MPEG format and some are available in different quality versions.

the formation of the Via Lactea halo

- entire formation history (z=12 to 0): high quality (218MB) smaller frames, quality: high(55MB) medium(11MB) low(4.7MB)
- entire formation history, plus rotation and zoom at z=0: quality: high(433MB) medium(72MB)
- early, active phase of merging and mass assembly (z=12 to 1.3): (81MB)
- late, passive and stationary phase (z=1.3 to 0): (137MB)

rotation and zoom into the Via Lactea halo at z=0 (today)
subhalo properties: definitions

\[ V_c(r) = \sqrt{\frac{G \ M(<r)}{r}} \]

in spherical bins around a peak in phase space density fitted by a constant background density plus an NFW subhalo

\[ \rho(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2} \]
\[ r_{V_{\text{max}}} = 2.163 \ r_s \]

subhalo density (tidal radius) := 2 background density

subhalo tidal mass := total mass(< tidal radius) \(~<\) bound mass
subhalo mass functions

\[ N(>M) \sim M^{-a} \]

with \( a \) between 0.9 and 1.1, depending on mass range used

steeper at high \( M \) due to dynamical friction
subhalo mass functions

\[ N(M) \sim M^{-a} \]

with a between 0.9 and 1.1, depending on mass range used

steeper at high M
due to dynamical friction

shallower at low M
due to numerical limitations

Close to constant contribution
to mass in subhalos
per decade in subhalo mass
subhalo abundance vs Milky Way satellite galaxies

first direct comparison:
mass within 0.6 kpc is now well constrained from stellar kinematics

and this mass is now well resolved in Via Lactea
subhalo abundance vs Milky Way satellite galaxies

first direct comparison:

mass within 0.6 kpc is now well constrained from stellar kinematics

and this mass is now well resolved in Via Lactea

similar, but more accurate than the classic “missing satellites” figures in Moore et al 1999 and Klypin et al 1999 who assumed $\sqrt{3} \sigma^* = V_{\text{max}}$
sub–subhalos in all well resolved subhalos

$M_{\text{sub}} = 9.8 \times 10^9 \, M_\odot$
$r_{\text{tidal}} = 40.1 \, \text{kpc}$
$D_{\text{center}} = 345 \, \text{kpc}$

$M_{\text{sub}} = 3.7 \times 10^9 \, M_\odot$
$r_{\text{tidal}} = 33.4 \, \text{kpc}$
$D_{\text{center}} = 374 \, \text{kpc}$

$M_{\text{sub}} = 2.4 \times 10^9 \, M_\odot$
$r_{\text{tidal}} = 14.7 \, \text{kpc}$
$D_{\text{center}} = 185 \, \text{kpc}$

$M_{\text{sub}} = 3.0 \times 10^9 \, M_\odot$
$r_{\text{tidal}} = 28.0 \, \text{kpc}$
$D_{\text{center}} = 280 \, \text{kpc}$

JD, Kuhlen, Madau, astro-ph/0611370
3) subhalo evolution

**Total mass in spheres around subhalo center**

This subhalo has one pericenter passage at 56 kpc.

**Weak, long tidal shock**

**Duration:**

\[
\tau = \pi \left(\frac{56 \text{ kpc}}{423 \text{ km/s}}\right) = 406 \text{ Myr}
\]
evolution of subhalo density profiles

- total mass in spheres around subhalo center
- shock duration = internal subhalo orbital time
- weak, long tidal shock causes quick compression followed by expansion
- mass loss is larger further out
evolution of subhalo density profiles

- total mass in spheres around subhalo center
- tidal mass, smaller than the bound mass at pericenter
- "delayed" tidal mass
- shock duration = internal subhalo orbital time

\[
\Delta m = M(> r_t) \delta t / T_s
\]

with \( T_s = T_{\text{orbit}} / 6 \)

weak, long tidal shock causes quick compression followed by expansion

mass loss is larger further out
evolution of subhalo density profiles

total mass in spheres around subhalo center

this subhalo has its second of three pericenter passages at 7.0 kpc
evolution of subhalo density profiles

**total mass in spheres around subhalo center**

this subhalo has its second of three pericenter passages at 7.0 kpc

**strong, short tidal shock**

short duration: 43 Myr also affects inner halo, but mass loss still grows with radius

at pericenter $r_{\text{tidal}} = 0.2 r_{\text{Vmax}}$, but the subhalo survives this and even the next pericenter
subhalo survival and merging

out of 1542 well resolved (Vmax >5 km/s) z=1 subhalos:

97 % survive until z=0

(only 1.3% merge into a larger subhalo)
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affected by numerical limitations

stronger dynamical friction
possible hosts for Local Group dwarfs

early forming (EF) sample:

the 10 subhalos which had $V_{\text{max}} > 16$ km/s at $z=10$
motivated by reionisation, which might suppress further accretion of gas into
small halos (e.g. Bullock et al. 2000, Moore et al. 2006)
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largest before accretion (LBA) sample:

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if star formation is always inefficient in small halos

Kravtsov, Gendin & Klypin 2004 model lies in between these two selections
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EF and LBA have 6 common objects, out of 10

we show EF sample tracks and only LBA $z=0$ properties of the LBA sample ...
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diverse histories:
0 to 11 pericenters
inner subhalos tend to have more of them and starting earlier

none to very large mass loss

concentrations increase during tidal mass loss

field halo concentrations
larger mass loss at first pericenter

first

all

last
4) DM annihilation and GLAST
4) DM annihilation and GLAST

maybe we just need a different telescope???

glast.gsfc.nasa.gov
Q: Will GLAST detect $\gamma$-ray photons from dark matter annihilation?
(Bergström et al. 1999; Calcanéo-Roldán & Moore 2000; Stoehr et al. 2003; Taylor & Silk 2003; Tasitsiomi et al. 2004; Koushiappas et al. 2004; Baltz & Wai 2004; etc., etc.)

A: It depends. It depends on a lot of things:

1) DM particle properties: type, mass, cross section of particle

2) Backgrounds: extra-galactic and Galactic; how well can we subtract them?

3) DM distribution: how clumpy? subhalo spatial distribution? mass function?
   Internal density profile?

Numerical simulations of DM structure can help address 3).

- Run very high resolution simulation of a Milky Way scale DM halo.

- Run subhalo finder and determine subhalo abundance, distribution, and internal properties.

- Calculate annihilation fluxes and angular sizes, estimate boost factors.

- Pick a particular particle physics model, and create simulated GLAST allsky maps.
Particle Physics

DM (WIMP) annihilation signal

Many different DM candidates: axions, WIMPs (neutralino, Kaluza-Klein, ...), etc.

In the following: DM = lightest SUSY particle (neutralino)

γ's from neutralino annihilation:

a) $\chi \chi \rightarrow \gamma \gamma$

b) $\chi \chi \rightarrow \gamma Z^0$

c) $\chi \chi \rightarrow \{WW, Z^0Z^0, b\bar{b}, \tilde{t}, \tilde{u}\}$

a)+b) spectral line, lower $<\sigma v>$

c) photon continuum from $\pi^0$ decay, higher $<\sigma v>$, more ambiguous signal
DM annihilation signal from subhalos

Total signal from subhalos is constant per decade in subhalo mass.

The spherically averaged signal is about half of the total in Via Lactea, but the total signal has not converged yet.

Colafrancesco et al. (2005) analytical model

\[ S_i = \int_{V_i} \rho_{\text{sub}}^2 dV_i = \sum_{j \in \{P_i\}} \rho_j m_p \]
DM annihilation signal from subhalos

The spherically averaged signal is about half of the total in Via Lactea, but the total signal has not converged yet.

total boost factor from subhalos: between 3 (constant) and 8 (more from small subs)
total boost factor including sub-sub-...-halos: between 13 (constant) and about 80
## Detector properties

### Science Performance Requirements Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SRD Value</th>
<th>Present Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Effective Area (in range 1-10 GeV)</td>
<td>&gt;8000 cm²</td>
<td>10,000 cm² at 10 GeV</td>
</tr>
<tr>
<td>Energy Resolution 100 MeV on-axis</td>
<td>&lt;10%</td>
<td>9%</td>
</tr>
<tr>
<td>Energy Resolution 10 GeV on-axis</td>
<td>&lt;10%</td>
<td>8%</td>
</tr>
<tr>
<td>Energy Resolution 10-300 GeV on-axis</td>
<td>&lt;20%</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Energy Resolution 10-300 GeV off-axis (&gt;60°)</td>
<td>&lt;6%</td>
<td>&lt;4.5%</td>
</tr>
<tr>
<td>PSF 68% 100 MeV on-axis</td>
<td>&lt;3.5°</td>
<td>3.37° (front), 4.64° (total)</td>
</tr>
<tr>
<td>PSF 68% 10 GeV on-axis</td>
<td>&lt;0.15°</td>
<td>0.086° (front), 0.115° (total)</td>
</tr>
<tr>
<td>PSF 95/68 ratio</td>
<td>&lt;3</td>
<td>2.1 front, 2.6 back (100 MeV)</td>
</tr>
<tr>
<td>PSF 55%/normal ratio</td>
<td>&lt;1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Field of View</td>
<td>&gt;2sr</td>
<td>2.4 sr</td>
</tr>
<tr>
<td>Background rejection (E&gt;100 MeV)</td>
<td>&lt;10% diffuse</td>
<td>6% diffuse (adjustable)</td>
</tr>
<tr>
<td>Point Source Sensitivity (&gt;100 MeV)</td>
<td>&lt;6×10⁻⁹ cm⁻² s⁻¹</td>
<td>3×10⁻⁹ cm⁻² s⁻¹</td>
</tr>
<tr>
<td>Source Location Determination</td>
<td>&lt;0.5 arcmin</td>
<td>&lt;0.4 arcmin (ignoring BACK info)</td>
</tr>
<tr>
<td>GRB localization</td>
<td>&lt;10 arcmin</td>
<td>5 arcmin (ignoring BACK info)</td>
</tr>
</tbody>
</table>
angular size vs. mass

\[ \Delta \theta = \text{angle subtended by twice the subhalo's scale radius } r_s. \]

For an NFW profile 90% of the flux originates from within \( r_s \).

the brightest subhalos would be extended sources for GLAST (PSF 9 arcmin at 10 GeV)
Simulated Maps

Observer along host halo's **intermediate** ellipsoidal axis

\[ \langle \sigma v \rangle = 5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

\[ M_\chi = 46 \text{ GeV} \]

9 arcmin pixels

2 year exposure

\[ \log N_\gamma \]

[Color scale from -1.5 to 2.0]
Simulated Maps

Anticenter

Most Massive Subhalo

$\gamma$
Simulated Maps

Observer along host halo's **major** ellipsoidal axis
Simulated Maps

Including a Poisson realization of the extra-galactic background.

\[
\frac{dN}{dE \, dA \, dt \, d\Omega} = 1.32 \times 10^{-5} \left( \frac{E}{1 \text{GeV}} \right)^{-2.1} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}
\]

From EGRET: Sreekumar et al. 1998 and Baltz et al. 1999
The Galactic background ($\propto N_{\text{HI}}$) dominates the annihilation signal.

Baltz et al. 1999; $N_{\text{HI}}$ from Dickey & Lockman 1990

$$\frac{dN}{dE \ dA \ dt \ d\Omega} = 3.10 \times 10^{-5} \left( \frac{N_{\text{HI}}}{10^{22}\text{cm}^{-2}} \right) \left( \frac{E}{1\text{GeV}} \right)^{-2.73} \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$
Simulated Maps

The detection significance exceeds 5 in the Galactic center and in one subhalo.
Simulated Maps

Signal with subhalo boost factor = 10 (strong boost)
Simulated Maps

Detection significance with subhalo boost factor = 10 (strong boost)

71 subhalos have $S > 5$. 
Simulated Maps

What if we happen to be sitting close to a dark halo?

mock $10^7 M_\odot$ NFW halo at 1 kpc
concentration = 30
CDM has structures and substructures on a wide range of scales.

Small subhalos contribute significantly to the mass fraction in subhalos and to the total DM annihilation signal. Therefore both quantities have not converged yet in current simulations.

Tides remove subhalo mass from the outside in and lead to higher concentrations for subhalos. Near the galactic center this effect is stronger.

Most (97%) subhalos survive from $z=1$ until today. Smaller ones lose less mass.

With an optimistic cross section and particle mass GLAST could detect the galactic center and some (massive and/or nearby) subhalos.
summary

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future work

higher resolution runs on INCITE (DOE), NASA and local (Plejades) supercomputers using improved time steps based on dynamical times (Zemp etal2006)

cosmological gamma ray background from DM annihilation (+ absorption by the EBL)

phase space distribution of DM in the solar neighborhood