Dark matter structure in galactic and sub-galactic scales

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What is a galactic scale?

Evidence for DM from rotation curve

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

HI gas

stars

~ 3 x $10^4$ light year

~ 10^5 ly

Evidence for DM from rotation curve
Stars are a good tracer of background gravitational field.
What is a sub-galactic scale?

Satellite galaxies of the Milky Way

Size < $3 \times 10^3$ ly
Cold Dark Matter (CDM) is successful for explaining large-scale structures galactic and sub-galactic scales?
DM in a galactic scale
Halo stars show velocity anisotropy \((\sigma_R, \sigma_\phi, \sigma_z) \approx (150, 100, 100)\) km/s
Velocities of stars near the Sun

⇒ Escape velocity near the Sun: \( V_{\text{esc}} = 500 \sim 550 \text{km/s} \)

⇒ Limits on a gravitational potential \( \Phi \) at \( R = R_{\text{sun}} \)

\[
(V_R^2 + V_z^2)^{1/2} \quad \text{(km/s)}
\]
With more distant stars

Rest-frame velocity: $V_{RF} \leq V_{esc} = (2 \Phi)^{1/2}$

Model A: $a = 195$ kpc

Model B: $a = 20$ kpc (to be rejected)

Total mass $= 2 \times 10^{12} M_{sun}$ over ~ 200 kpc

Visible mass $= 10^{11} M_{sun}$ over ~ 15 kpc

⇒ We see only 10% of the total mass
Shape

Stellar stream as tidally disrupted dwarf galaxy

‘Field of Streams’ seen in star distribution
Stream is confined onto an orbital plane
⇒ round dark halo at $15 < r < 60$ kpc
However, CDM halos are generally triaxial / prolate. (Jing & Suto 2000, 2002)

Hayashi+07: \((c/a)_\Phi = 0.72, (b/a)_\Phi = 0.78\) in central parts

Axial ratio of a dark halo
Density profile

CDM halos have cuspy central density profile

\[ \rho \propto r^{-\gamma} \]

at inner parts

\[ \gamma = 1: \text{ NFW} \]
\[ \gamma = 1.5: \text{ Moore et al.} \]

No universal \( \gamma \)

\( 1 < \gamma < 1.5 \)

Einasto profile:

\[ \ln \rho(r) / \rho_{-2} = (-2/\alpha) \left( \frac{r}{r_{-2}} \right)^\alpha - 1 \]

\[ V(r) = \frac{V_0}{(1 + x^{-\gamma})^{1/\gamma}} \]

\( x \equiv r / r_0 \)

Obs: \( 0 < \gamma < 5 \)

Fitting with \( \gamma \sim 1 \)

\~70\% sample galaxies are consistent with CDM
More on DM density profile: Stellar dynamics + lens analysis

HST14113+5211
$z_L = 0.47, \ z_S = 2.8$

Stars ($r^{1/4}$ profile) + DM with $\rho_{DM}(r) \propto r^{-\gamma}$
Total density profile $\rho_{tot}(r) \propto r^{-\gamma'}$

Velocity dispersion = $174 \pm 20$ km/s

Subaru FOCAS spectrum

Hamana+ 2005

Fischer et al. 1998
Stars \( r^{1/4} \) profile + DM with \( \rho_{DM}(r) \propto r^{-\gamma} \), \( \gamma < 1.5 \)

Total density profile \( \rho_{tot}(r) \propto r^{-\gamma'} \), \( \gamma' = 1.6 \text{~} 1.9 \)

Consistent with CDM prediction
DM in a sub-galactic scale
Satellite galaxies in the Milky Way

Dwarf spheroidal galaxies (dSph)

Images of various satellite galaxies:
- Scl
- Car
- For
- Leo II
- Leo I
- Phe
Deriving DM profiles from line-of-sight velocity dispersion profile of stars (Walker+2009)

(spherically-averaged) velocity dispersion profile

Much larger than expected from self-gravity of stellar system!
Mass enclosed within stellar extent ($\sim 4 \times 10^7 M_\odot$) in dSph galaxies

$\frac{M}{L} = 10^1 \sim 10^3$

dSphs are largely DM dominated!

dSphs are ideal sites for deriving DM properties

Gilmore+ 2007

(old data)
New mass limits on dSphs: Axisymmetric model
(Hayashi & Chiba 2012)

* Stellar component

Vol. density: \( \nu(R, z) = \frac{3L}{4\pi b_*^3} \left[ 1 + \frac{m_*^2}{b_*^2} \right]^{-5/2} \quad m_*^2 = R^2 + \frac{z^2}{q^2} \)

Surface density \( I(x, y) = \frac{L}{\pi b_*^2} \left[ 1 + \frac{m_*'^2}{b_*^2} \right]^{-2} \quad m_*'^2 = x^2 + \frac{q'^2}{q'^2} \quad q'^2 = \cos^2 i + q^2 \sin^2 i \)

* DM component

\( \rho(R, z) = \rho_0 \left( \frac{m}{b_{halo}} \right)^\alpha \left[ 1 + \left( \frac{m}{b_{halo}} \right)^2 \right]^{\delta} \quad m^2 = R^2 + \frac{z^2}{Q^2} \)

\( \alpha = -1, \delta = -1 \); NFW model
\( \alpha = 0, \delta = -1.5 \); with a core

Gravity can be calculated by 1D integral:

\[ g = -\nabla \Phi = -\pi G Q a_0 \int_0^\infty d\tau \frac{\rho(m^2) \nabla m^2}{(\tau + a_0^2) \sqrt{\tau + Q^2 a_0^2}} \]
New mass limits on dSphs: Axisymmetric model (Hayashi & Chiba 2012)

q: axis ratio of stellar system
Q: axis ratio of DM halo

Contours of l-o-s velocity dispersion

Solid: NFW
Dotted: Core

Q=1, q=0.8
Q=0.8, q=0.8
Q=1, q=1
New mass limits on dSphs (I)
Carina, Fornax, Sculptor

NFW

\[ \chi^2 = 1.90, \quad Q = 0.34 \]

Core

\[ \chi^2 = 0.88, \quad Q = 0.39 \]

\[ \chi^2 = 1.20, \quad Q = 0.42 \]

\[ \chi^2 = 0.62, \quad Q = 0.37 \]

\[ \chi^2 = 2.11, \quad Q = 0.82 \]

\[ \chi^2 = 1.08, \quad Q = 0.51 \]

Red: major axis
Green: minor axis
Blue: interm. axis
New mass limits on dSphs (II)
Sextans, Draco, Leo I

\[
\chi^2 = 1.81, Q = 0.31
\]

\[
\chi^2 = 1.14, Q = 0.40
\]

\[
\chi^2 = 0.49, Q = 0.41
\]
Comparison with N-body models

Via Lactea simulation (Kuhlen+ 2007)

Red line: axis ratio of a subhalo

This work: (axisymmetric model)

\[ Q = 0.4 \sim 0.5 \leq (b/a, c/a)_{\text{CDM}} \]

More flattened than CDM subhalos

Is CDM correct in a sub-galactic scale?
Missing satellites problem

Simulated CDM distribution

Moore

$10^6 \text{--} 10^9 \text{M}_{\odot}$

luminous parts

Cumulative number of halos

Is CDM correct in a sub-galactic scale?
Stellar halo in Andromeda

PAndAS survey: (g, i) 2-color imaging with CFHT

(Richardson+11) RGB with i<23.5

150kpc
Are there many CDM subhalos in a galaxy-sized halo? (Carlberg 2011)

CDM halo in a galaxy

dynamical effects on stellar stream
($M_{\text{star}} = 10^6 M_\text{sun}$)

No subhalos

Showing gaps

1000 subhalos, $M^{-1.9}$

globular cluster
Are there many CDM subhalos in a galaxy-sized halo? (Carlberg 2011)

NW stream in M31 (Richardson+ 2011)

Non-uniform density distribution (~12 gaps⇒consistent with CDM?)

Careful subtraction of foreground stars and more studies on a stream are needed!
Wide-field FoV is essential for mapping stars
Gravitational lensing as a probe of CDM subhalos

Flux–ratio distribution, especially in mid-infrared waveband, provides substructure of lens mass distribution (Chiba+2005; Minezaki+2008)

Signatures for CDM subhalos!
TMT
(Thirty Meter Telescope)

MIR observations of lensed QSOs with MICHI (みち)
"Mid-IR Camera, High-disperser, and Integral field unit"

ALMA

High-reso. sub-millimeter observations of lensed QSOs

Lens mapping of CDM substructures
$2 \times 10^8$ Msun subhalo at resolution 0.01 arcsec

$\sim 0.4$ mJy image contrast

$\Rightarrow$ a few 10min exposure@5σ (full operation)

3d position & mass

Inoue & Chiba 2005
when there’s no subhalo

Ohashi, Chiba, Inoue 08
Conclusion

• DM properties in a galactic scale can be understood in a framework of CDM models.
• DM properties in a sub-galactic scale are NOT well understood.
• Future observing program with Subaru/HSC, ALMA, and TMT/MICHI will provide DM substructures in detail.
End