Chap.4 Galactic Dark Matter

• Total mass of a dark halo in a galactic scale
• Shape of a dark halo
• Density profile of a dark halo
• Dark matter substructure
Evidence for dark matter

If $\rho(r)$ is spherically symmetric

$$V_{\text{circ}}(r) = (GM(<r)/r)^{1/2}$$

where $M(<r) = \int r 4\pi \rho r^2 dr$
Dark matter candidates

- Faint compact stars (baryonic matter: normal matter made of protons and neutrons)
  - brown dwarfs, white dwarfs, neutron stars, BHs
  - MACHOs (Massive Compact Halo Objects)

- Elementary particles (non-baryonic matter)
  - neutrino, neutralino, photino, axion, ...
  - WIMPs (Weakly Interacting Massive Particles)
    - Massive particles having small random motions are playing important roles

Cold Dark Matter: CDM
  e.g. neutrino
CDM-based structure formation

Cold Dark Matter (CDM) e.g. neutralino
Small-scale halos form first, then larger-scale structures form subsequently through merging and accretion ⇒ successful for reproducing observed structures
CDM-based structure formation
Current Power Spectrum

Tegmark et al. 2004
4.1 Total mass

⇒ Escape velocity near the Sun: $V_{\text{esc}} = 500\sim550 \text{ km/s}$

⇒ Limits on a gravitational potential $\Phi$ at $R=R_{\text{sun}}$
More distant halo tracers

- HB stars (211 w. pm / 413)
- Globular clusters (41/137)
- Satellite galaxies (5/11)

confined in a model potential

\[
\Phi(r) = \frac{GM}{a} \log\left( \frac{\sqrt{r^2 + a^2} + a}{r} \right)
\]

Satellites

GCs

HBs

GCs

model 1: a=195kpc, \(V_{\text{LSR}}=220\text{km/s}\)
model 2: a=20kpc, \(V_{\text{LSR}}=211\text{km/s}\)
Rest-frame velocity: $V_{RF} \leq V_{esc} = (2\Phi)^{1/2}$

model 1: $a = 195$ kpc

model 2: $a = 20$ kpc

(rejected for a declining rotation curve)
Milky Way mass from maximum likelihood

Stellar distribution function $f(E,L)$ (velocity anisotropy $\beta$) inside a gravitational potential (scale length $a \rightarrow$ total mass $M$)

Max. probability for getting the observed $(r_i, v_i)$ i=1,N

\[
\int_0^\infty \frac{1}{v} \frac{d}{dr} \left( v v_r^2 \right) + 2 \frac{\beta v_r^2}{r} = - \frac{d\Phi}{dr} = - \frac{GM(r)}{r^2}
\]

$\beta = \text{const.} \Rightarrow v v_r^2 = r^{-2\beta} \int_r^\infty \frac{vGM(r)}{r^2} r^{2\beta} dr$

Total mass $= 2.5 \times 10^{12}$ Msun over $\sim 200$ kpc

Visible mass $= 10^{11}$ Msun over $\sim 15$ kpc

$\Rightarrow$ We see only 10% of the total mass
Recent results using Gaia

Space motions of Globular Clusters

Eadie & Juric 2019 \( M_{200} = 0.7^{+0.11}_{-0.08} \times 10^{12} \) Msun \((r<200\text{kpc})\)

Other recent results

Sohn et al. 2018 \( M_{\text{vir}} = 2.05^{+0.97}_{-0.79} \times 10^{12} \) Msun
Watkins et al 2019 \( M_{\text{vir}} = 1.41^{+0.99}_{-0.52} \times 10^{12} \) Msun
Posti & Helmi 2019 \( M_{\text{vir}} = 1.3 \pm 0.3 \times 10^{12} \) Msun
4.2 Shape  

Sagittarius dwarf galaxy  
(Ibata, Gilmore, & Irwin 1994, Nat, 370, 194)

$\text{d} \sim 24 \text{ kpc}$  
$\text{r} \sim 16 \text{ kpc}$

![Image of Sagittarius dwarf galaxy with annotations]
Stream is confined onto an orbital plane
⇒ round dark halo at $15 < r < 60$ kpc
$q_\Phi = 1$

$14 < r < 58 \text{kpc}$

$\tau = 0.9 \text{ Gyr}, t = 5 \tau$

$0.90 < q_\Phi < 0.95$ is most likely

$(0.83 < q_\rho < 0.92)$
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
Virialized CDM halos

\[ \rho = \rho_s \left[ \frac{r}{r_s} \right]^{2} \left( 1 + \frac{r}{r_s} \right)^{-2} \]

\[ \rho \propto r^{-1} \text{ at } r << r_s \]
\[ \rho \propto r^{-3} \text{ at } r >> r_s \]
NFW or Moore et al. 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:
\[
\ln \frac{\rho(r)}{\rho_{-2}} = \left(\frac{-2}{\alpha}\right) \left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]
\]
Core/cusp problem

Density distribution of a dark halo

Rotation curves of dwarf galaxies

Del Popolo 2009

![Graph showing rotation curves of dwarf galaxies with NFW and cored models.](image)
Subhalos have larger rotation curves ⇒ subhalos are more massive (denser)

Filled circles: Galactic satellites
Values of rotation curves at half-light radius

Too big to fail problem
Density profiles of Galactic dSph satellites
(Walker+09)

Dark halo model:
\[ \rho = \rho_0 \left( \frac{r}{r_0} \right)^{-\gamma} \left[ 1 + \left( \frac{r}{r_0} \right)^{\frac{\alpha}{\gamma-3}} \right]^{\frac{\gamma-3}{\alpha}} \]

NFW: \( \gamma = \alpha = 1 \)

Plummer for stars:
\[ \nu(r) \propto \left[ 1 + r^2 / r_h^2 \right]^{-5/2} \]

Jeans eq. (spherical sym.)

l-o-s velocity dispersion profile

Some dSphs have central cores
4.4 Dark matter substructure

Missing satellites problem

Moore

$10^6 \sim 10^9 \text{Msun}$

Virial radius $\sim 200 \text{kpc}$
Current Power Spectrum

Tegmark et al. 2004
Suppression of satellite formation

Extended Press-Schechter formalism + \textbf{UV feedback}

Formation of galaxies with $V_c < 30$ km/s is suppressed at $z < z_{\text{reionization}}$
Does baryonic feedback create a core?

Bullock & Boylan-Kolchin 2017

\[ \alpha \left[ 1.5\% \, R_{\text{vir}} \right] \]

\[ \log_{10}(M_{\ast}/M_{\text{halo}}) \]

NFW

Ultra-faint Dwarfs

Classical Dwarfs

Bright Dwarfs

\[ M_{\ast} = f_b M_{\text{halo}} \]
Modifying DM particles

CDM

SIDM

WDM

SIDM: cored
WDM: no missing satellites

Various DM theories are proposed

Density distribution

Number of subhalos
Probing dark matter substructure

- Dark matter (WIMP) annihilation
- Dynamical effects on visible galactic structure
  - Star clusters and stellar streams
  - Thin or thick disks
- Gravitational lensing
  - Anomalous flux ratios
  - Direct radio imaging
If dark matter is WIMP (Weakly Interacting Massive Particle), such as neutralino, it annihilates into visible photons.

WIMP mass is likely around Gev-Tev, so corresponding γ-ray photons may be detected by MAGIC, Fermi, etc.

γ-ray luminosity $\propto \int \rho^2 dV$, so subhalos (+ Galactic Center and dwarf spheroidal galaxies) may be detectable because these have high phase-space densities.
Probing evidence for CDM subhalos from their gravitational effects on a stellar stream (Carlberg 2011)

CDM halo in a galaxy

No subhalos

1000 subhalos, $M^{-1.9}$

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

star cluster
Lens mapping of CDM subhalos


These are hardly explained by smooth lens models.
**PG1115+080**
(radio quiet)

\( z_s = 1.72, \ z_L = 0.31 \)

Iwamuro et al. 2000

Model: \( A_2/A_1 \approx 1 \) (fold caustic)

Observed \( A_2/A_1 \) (near-IR): \( \approx 0.59 - 0.67 \) (anomalous)

Smooth lens model
(Singular Isothermal Ellipsoid + External Shear)
B1422+231 (radio loud)
$z_s = 3.62$, $z_L = 0.34$

Model: $(A+C)/B \approx 1$ (cusp caustic)

Observed $(A+C)/B$ (radio): $\approx 1.42 - 1.50$ (anomalous)
Elliptical Lens

- Critical lines
- Caustics
- Fold singularity
- Cusp singularity
Anomalous Flux Ratios

- Implausible by luminous GCs and satellites, CDM subhalos are most likely (Chiba 2002)
- Mass fraction of CDM subhalos ~ a few % (Dalal & Kochanek 2002)
- Flux anomaly depends on image parities, being consistent with substructure lensing (Kochanek & Dalal 2004)

⇒ Evidence for many CDM subhalos!?
Unsolved issues

• Other causes for anomalous flux ratios
  ✓ Differential dust extinction?
  ✓ Stellar microlensing?

• Limits on the mass of lens substructure
  ✓ Mass of a subhalo?
  ✓ How many subhalos?

Magnification of a source with radius $R_s$ compared with Einstein radius $R_E(\propto M^{1/2})$
1. Mid-IR imaging of a dust torus

(Near-IR at rest)

- Extinction free
- Microlensing free
- Radio quiet QSOs are available
- Source size is available
  - Hot dust torus at sublimation $T$ of $\sim 1800$K
  - Size (inner radius) $R_s$ ($\sim 1$pc) $\propto L^{1/2}$ from dust reverberation mapping
  - Einstein radius $R_E$ ($\propto M^{1/2}$) vs $R_s$ $\Rightarrow$ limits on $M$
Panoramic views of a QSO center

2. Spectroscopy of NLR and BLR

- NLR: microlensing free
- BLR: affected by microlensing

Selective magnification depending on $R_E$ vs $R_s$\[\Rightarrow\] limits on $M$
Subaru observations of quadruple lenses

- **Mid-IR imaging with COMICS**
  - (Chiba et al. 2005; Minezaki et al. 2009)
  - FOV=38" × 30", 0.”129/pix
  - N band, $\lambda=11.7\mu m$, continuum emission from dust torus

- **IFS observation with Kyoto 3DII**
  - (Sugai et al. 2007)
  - FOV=3” × 3”, 0.”096 lenslet$^{-1}$, $37 \times 37$ lenslets
  - $0.730 < \lambda < 0.915\mu m$, line emission from NLR and BLR
Chiba et al. 2005

Subaru image @ 11.7μm

PG1115+080

Total flux = 17.5 mJy
A2/A1 (Mid-IR) = 0.93±0.06 (model) ≈ 0.92 fold caustic (near-IR) = 0.59 ~ 0.67

B1422+231

Total flux = 19.2 mJy
(A+C)/B (Mid-IR) = 1.51±0.06 (model) ≈ 1.25 cusp caustic (radio) = 1.42 ~ 1.50
Subaru image @ 11.7μm

MG0414+0534

Total flux = 39.2 mJy
A2/A1 (Mid-IR) = 0.90±0.04
(model) ≈ 1.1 fold caustic
(near-IR) = 0.4 ~ 0.8

Q2237+030

Total flux = 22.2 mJy
B/A (Mid-IR) = 0.84±0.05,
C/A=0.46±0.02, D/A=0.87±0.05
B/A (model) = 0.87,
C/A=0.46, D/A=0.86

Minezaki et al. 2007
IFS data of RXJ1131-1231

Sugai et al. 2007

Model:
B ~ C
~ 0.5A

Selective Magnification!
Hβ line flux

[O III] line flux

\[ \frac{A}{B} = 1.74 \]
\[ \frac{C}{B} = 0.46 \]

\[ \frac{A}{B} = 1.63 \]
\[ \frac{C}{B} = 1.19 \]

Smooth model

\[ \frac{A}{B} \approx 1.7 \]
\[ \frac{C}{B} \approx 1.0 \]

- NLR([O III]) is OK
- BLR (Hβ) of Image C is microlensed

\[ [\text{O III}] \text{ line flux} \]
(point source subtracted)

\[ R_s (\text{NLR}) \approx 90 \text{pc} \]
Limits on substructure lensing

- **PG1115+080** *(A1, A2)*
  - $R_s \sim 1$ pc
  - Mid-IR flux ratio
  - $M_E < 16$ Msun

- **MG0414+0534** *(A1, A2)*
  - $R_s \sim 2$ pc
  - Mid-IR flux ratio
  - $M_E > 200$ Msun

- **B1422+231** *(A, B, C)*
  - $R_s \sim 3$ pc
  - Mid-IR flux ratio
  - $M_E > 200$ Msun

- **Q2237+030** *(A, B, C, D)*
  - $R_s \sim 2$ pc
  - Mid-IR flux ratio
  - $M_E < 10$ Msun

- **RXJ1131-1231**
  - $R_s$ (BLR) $\sim 0.01$ pc, $R_s$ (NLR) $\sim 100$ pc
  - $M_E < 10^5$ Msun for NLR

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ALMA observation of gravitationally-lensed, extended images

- Direct imaging of subhalo-lensed images with high resolution observation (10mas)
  - Determination of subhalo masses
  - Spatial distribution of subhalos

- Source image: sub-millimeter continuum radiation from dust
  - $T=30\sim60$ K, $L=10^2\sim10^3$ pc
  - $S$ at $850\mu$m=several tens mJy

Test for CDM models
Subhalo with $10^9$ Msun?

Testing $\Lambda$CDM with gravitational lens is on going

Inoue, K. T., Minezaki, Matsushita, Chiba 2016:
  showing the effect of under-dense large-scale structures on lensed image
This issue is yet unsettled.