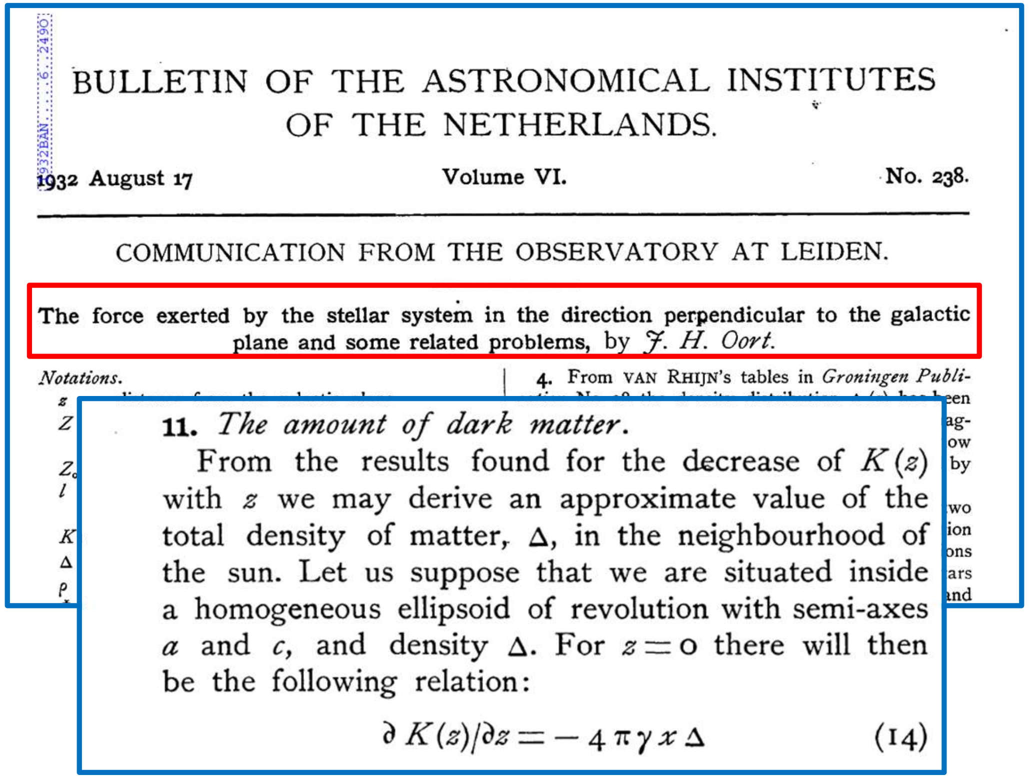
Chap.4　Dark matter in galaxy scales

- Evidence for dark matter in the Galaxy
- Properties of a dark matter halo
  - Total mass, global shape, density profile, substructures
- Crisis in CDM: problems in small scales
  - Missing satellites problem, Core/cusp problem, TBTF problem
- Probing dark matter substructures
  - Stellar streams, gravitational lensing
- New limits from stellar systems in the Galaxy
  - Search for new MW satellites, Limits on DM profiles in dSphs

1. Evidence for dark matter in the Galaxy

Jan Hendrik Oort

In 1932, Jan Oort suggested the presence of dark matter near the Sun ("missing mass") from the dynamical analysis of stellar motions



BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 — Volume VI. — No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

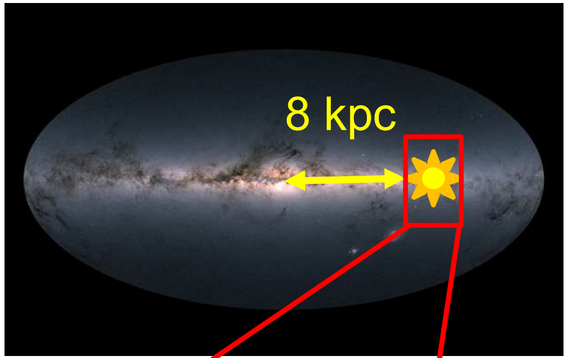
Notations.

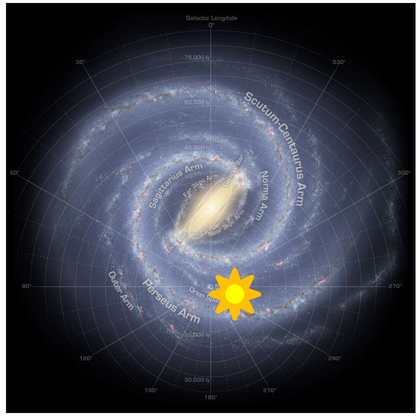
4. From VAN RHIJN's tables in *Groningen Publi-*

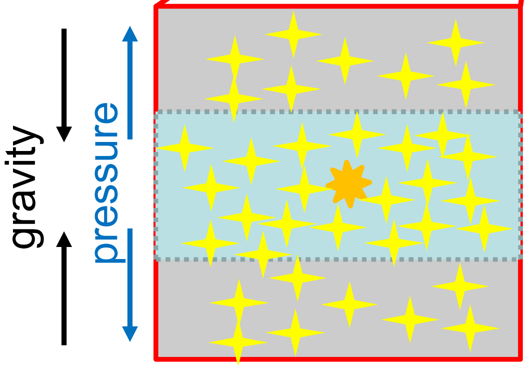
11. *The amount of dark matter.*

From the results found for the decrease of $K(z)$ with z we may derive an approximate value of the total density of matter, Δ, in the neighbourhood of the sun. Let us suppose that we are situated inside a homogeneous ellipsoid of revolution with semi-axes a and c, and density Δ. For $z=0$ there will then be the following relation:

$$\partial K(z)/\partial z = -4\pi\gamma x \Delta \qquad (14)$$

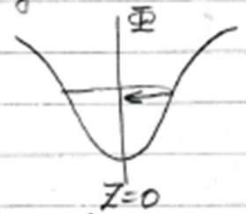






Pressure force due to the random motions of stars are in balance with gravity exerted from both visible and invisible matter
⇒visible mass is found to be insufficient
⇒missing mass, dark matter

- mass density in the solar neighborhood



ある星の密度 ν (e.g. K giants) test particle

外場 Φ ⟷ 質量密度 ρ

Jeans eq. $\quad \frac{1}{\nu}\frac{\partial(\nu \overline{v_z^2})}{\partial z} = -\frac{\partial \Phi}{\partial z}, \quad \frac{\partial^2 \Phi}{\partial z^2} = 4\pi G \rho$ Poisson eq.

$$\rightarrow \frac{\partial}{\partial z}\left[\frac{1}{\nu}\frac{\partial(\nu \overline{v_z^2})}{\partial z}\right] = -4\pi G \rho$$

obs. $\nu(z)$, $\overline{v_z^2}$ ⟶ ρ mass density

2階微分で不定性大: $\rho_0 \equiv \rho(R_\odot, z=0) = 0.15 \sim 0.18\ M_\odot\,pc^{-3}$

Oort limit.

Luminous mass
$\rho_{lum} = 0.114$ Msun/pc^3

or $\Sigma(z) = \int_{-z}^{z} \rho(z')dz' = -\frac{1}{2\pi G \nu}\frac{\partial(\nu \overline{v_z^2})}{\partial z}$ ← 1階微分.

面密度

$\Sigma(z \le 1.1\,kpc) \simeq 70\ M_\odot\,pc^{-2}$

Kuijken & Gilmore 1991, ApJ, 367, L9

Bahcall et al. 1992, ApJ, 389, 234

一方

$\Sigma_{gas+stars} \simeq 48\ M_\odot\,pc^{-2}$

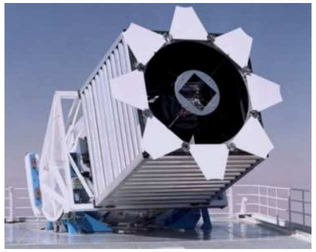
Local dark matter

Missing mass (1/3 mass is missing)

Dark matter density near the Sun

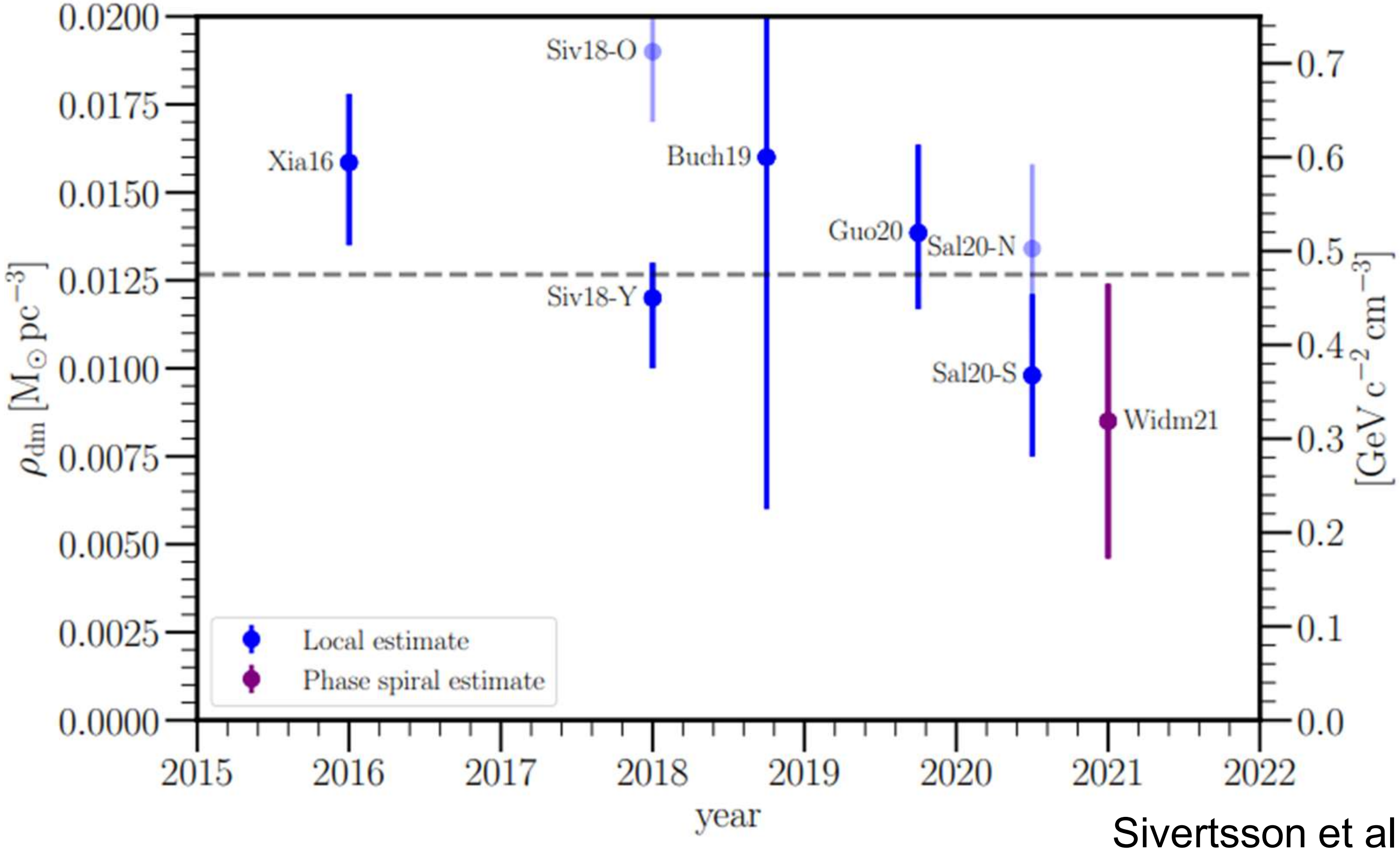
Measured from the dynamical analysis of
the large number of nearby star sample

SDSS



LAMOST

Gaia

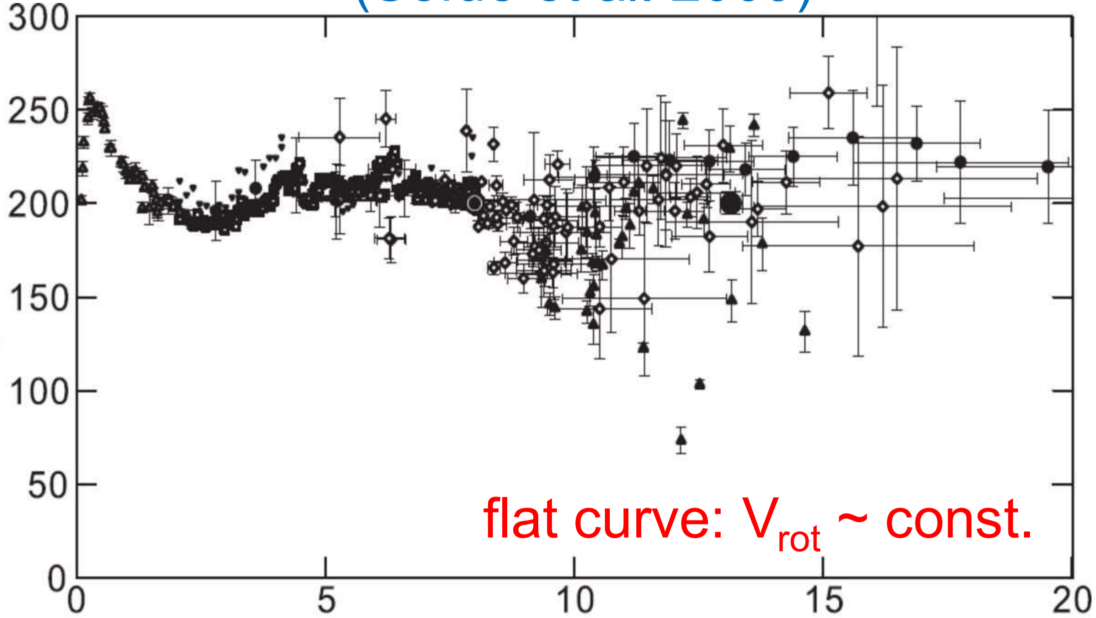


$\simeq$ 0.5 GeV/cm^3

Sivertsson et al. 2022

Evidence for dark matter from rotation curves

Rotation curve of the Milky Way
(Sofue et al. 2009)



If spherically symmetric,

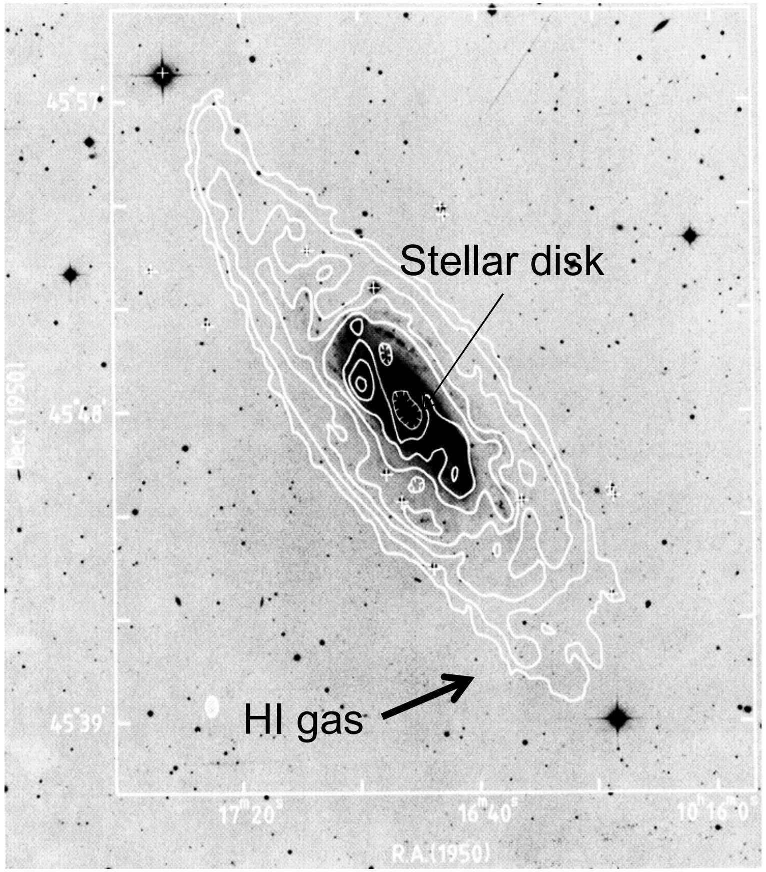
$$\frac{V_{rot}^2}{r} = \frac{GM(<r)}{r^2}$$

$$V_{rot} = const. \Rightarrow M(<r) \propto r$$

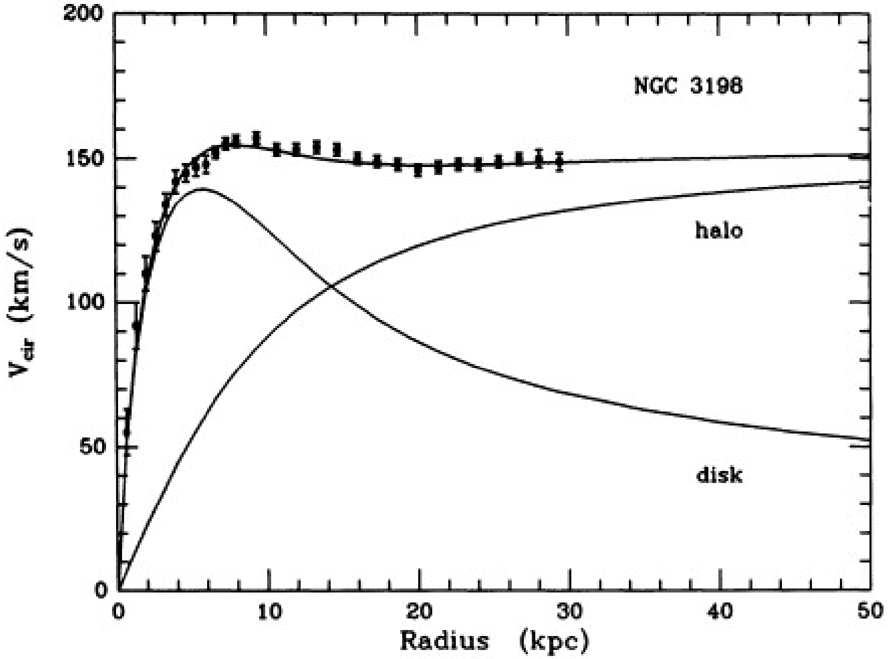
Presence of a dark matter halo

Dark matter in an external spiral galaxy

NGC3198



van Albada et al. 1985



If $\rho(r)$ is spherically symmetric

$V_{rot}(r) = (GM(<r)/r)^{1/2}$

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

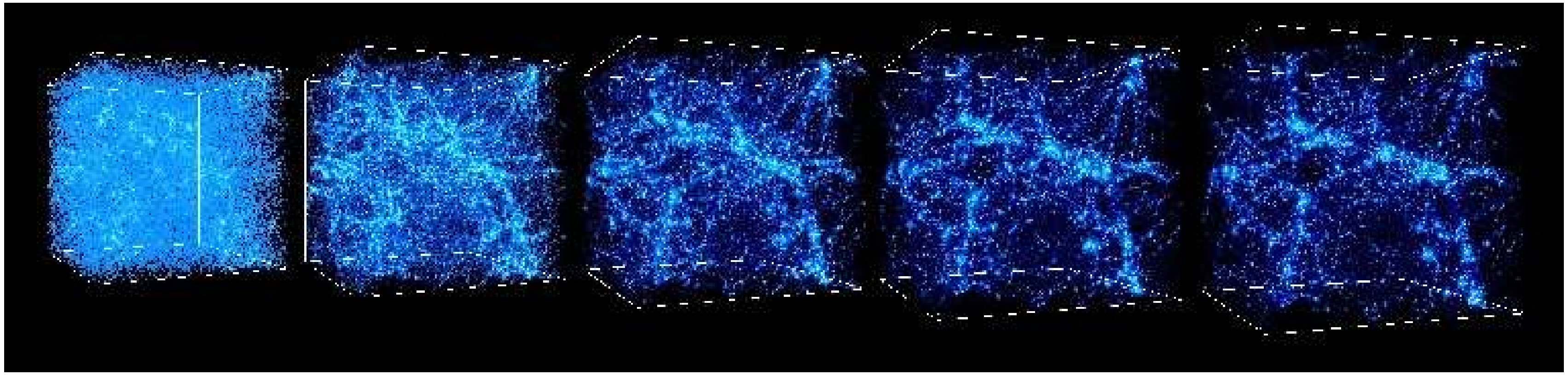
Dark matter candidates

- Faint compact objects
  - Brown dwarfs, white dwarfs, neutron stars, stellar BHs
  - Primordial BHs
  - MACHOs（Massive Compact Halo Objects ）
- Elementary particles （non-baryonic matter）
  - Neutrino, neutralino, axion…
  - Cold Dark Matter: CDM
    - Massive particles (10~1000 Gev) with small streaming motions
      WIMPs（Weakly Interacting Massive Particles）
      e.g. neutralino
    - Axions

CDM-based structure formation

Distribution of CDM particles

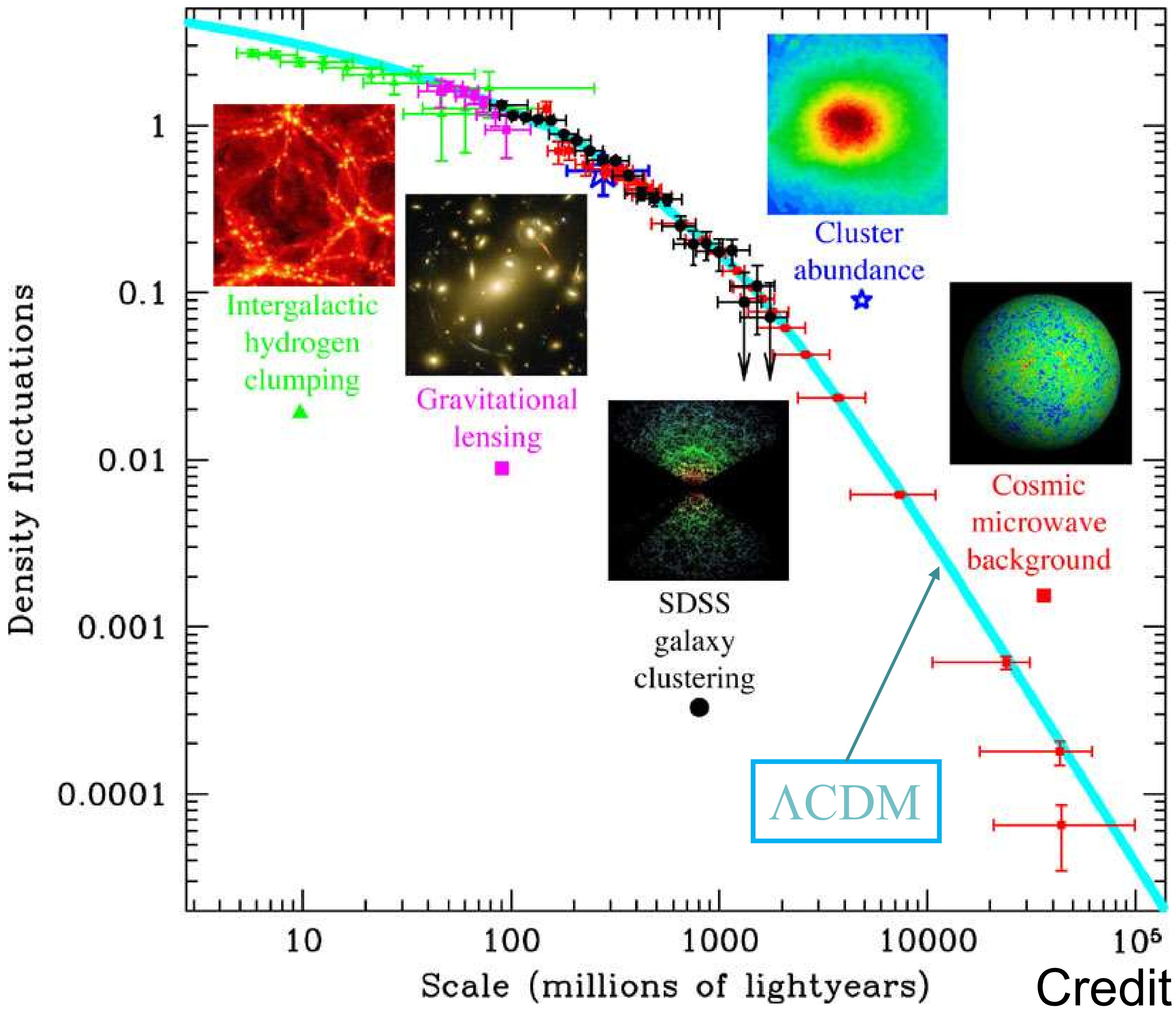
time



Cold Dark Matter (CDM): WIMP, Axion

Small-scale halos form first, then larger-scale structures form subsequently through merging and accretion
⇒ successful for reproducing observed structures

Density fluctuations in various scales

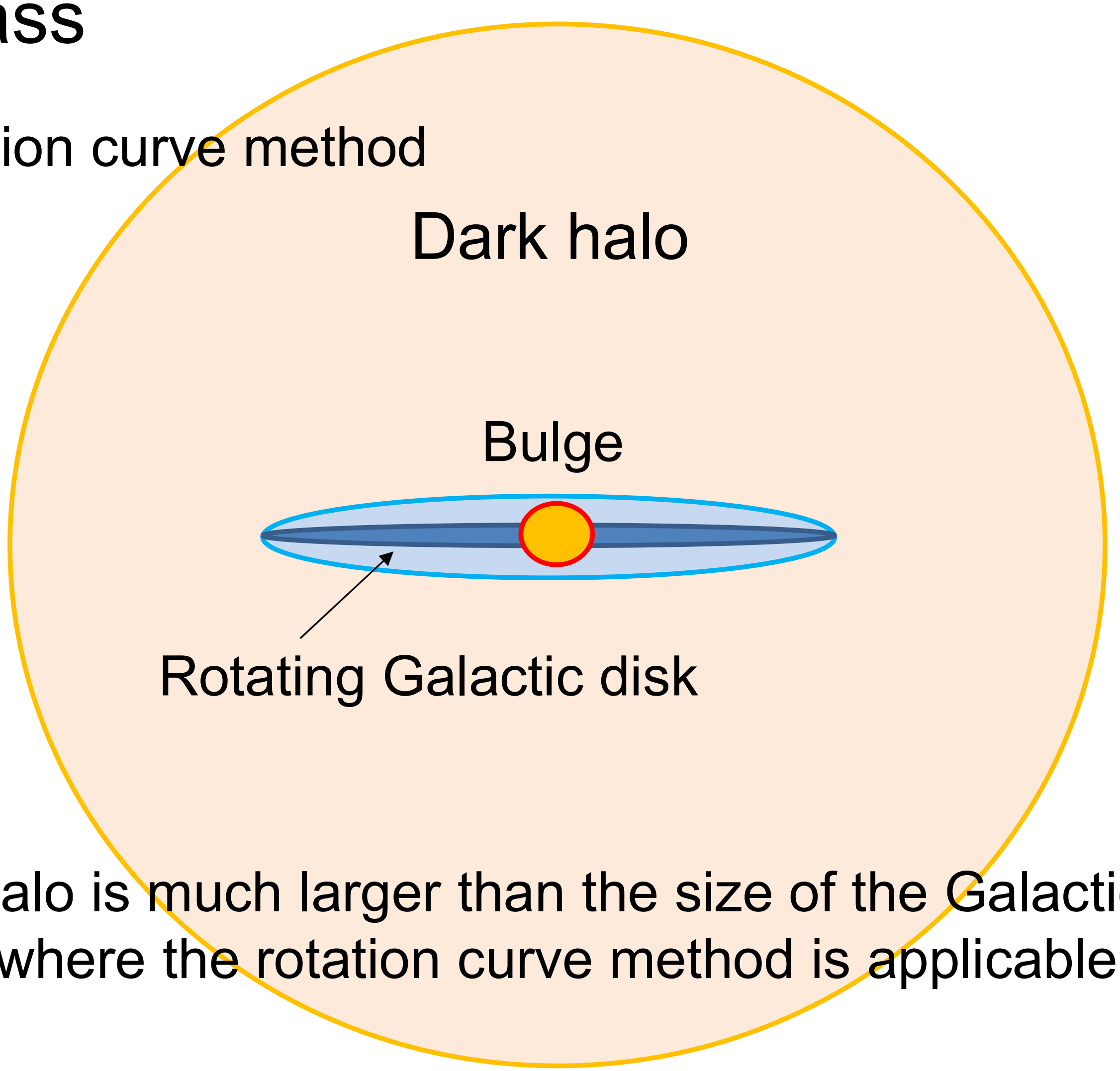


Credit: Tegmark

2. Properties of a dark matter halo

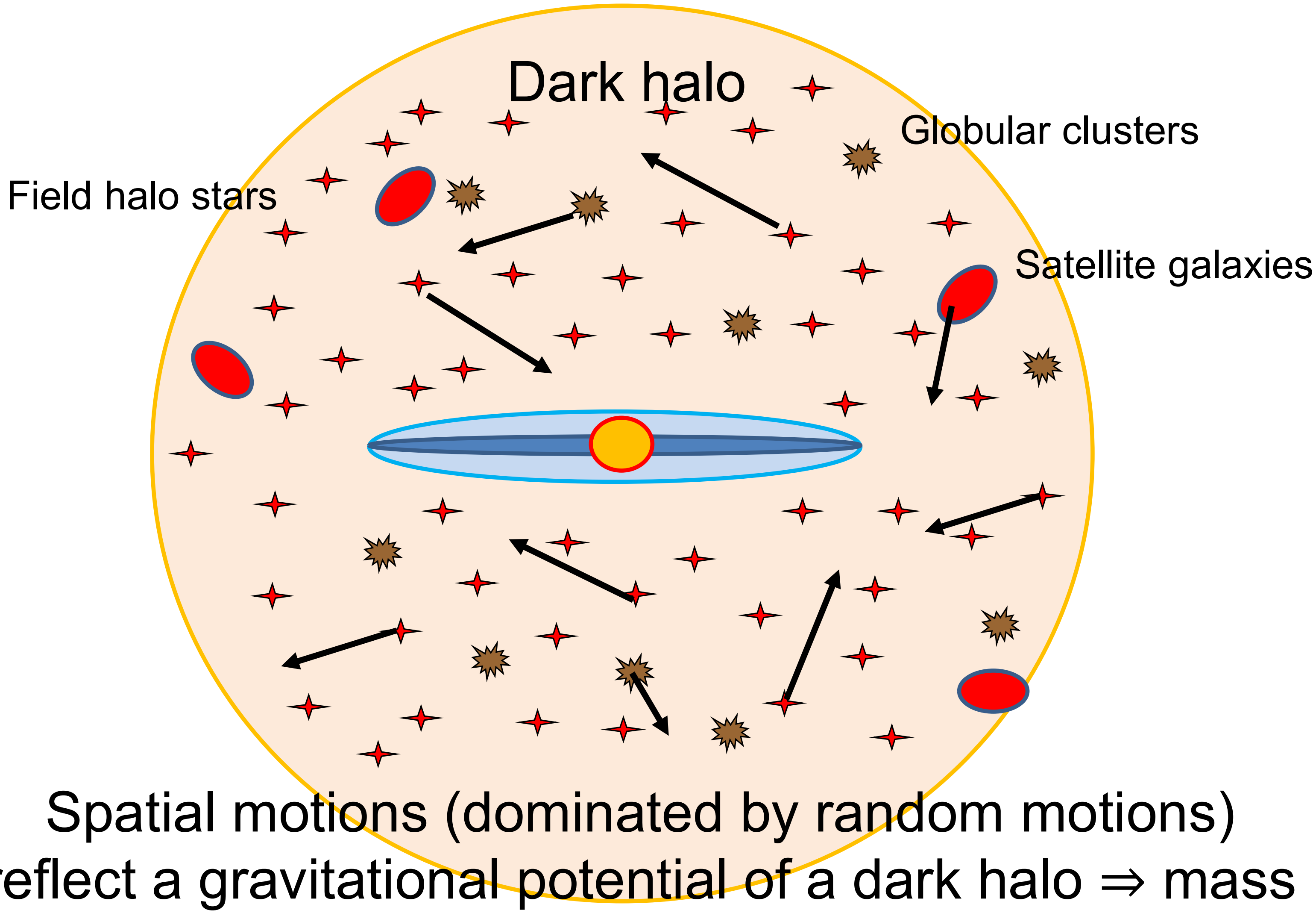
2.1 Total mass

Beyond the rotation curve method



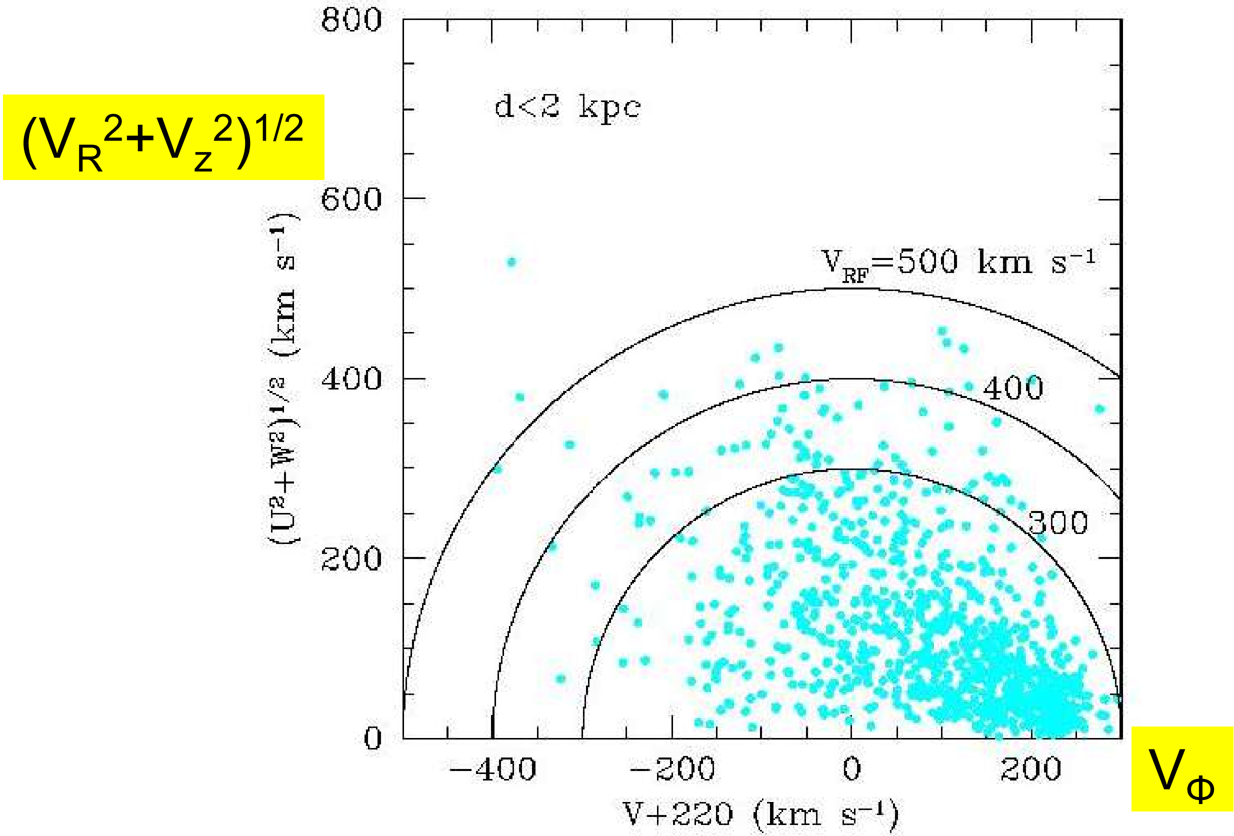
Dark halo is much larger than the size of the Galactic disk, where the rotation curve method is applicable

Halo objects as tracers of dark-halo mass



Spatial motions (dominated by random motions)
reflect a gravitational potential of a dark halo ⇒ mass

Velocity distribution of disk/halo stars near the Sun



Escape velocity near the Sun: V_{esc}=500~550km/s

⇒ Limits on a gravitational potential Φ at $R=R_{sun}$: $V_{esc}=(2\Phi(R_{sun}))^{1/2}$

Limits on Φ(r) at other radii based on rest-frame velocities of distant sample: $V_{RF} \leq V_{esc}(r)$

(Sakamoto, Chiba, Beers 2003)

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

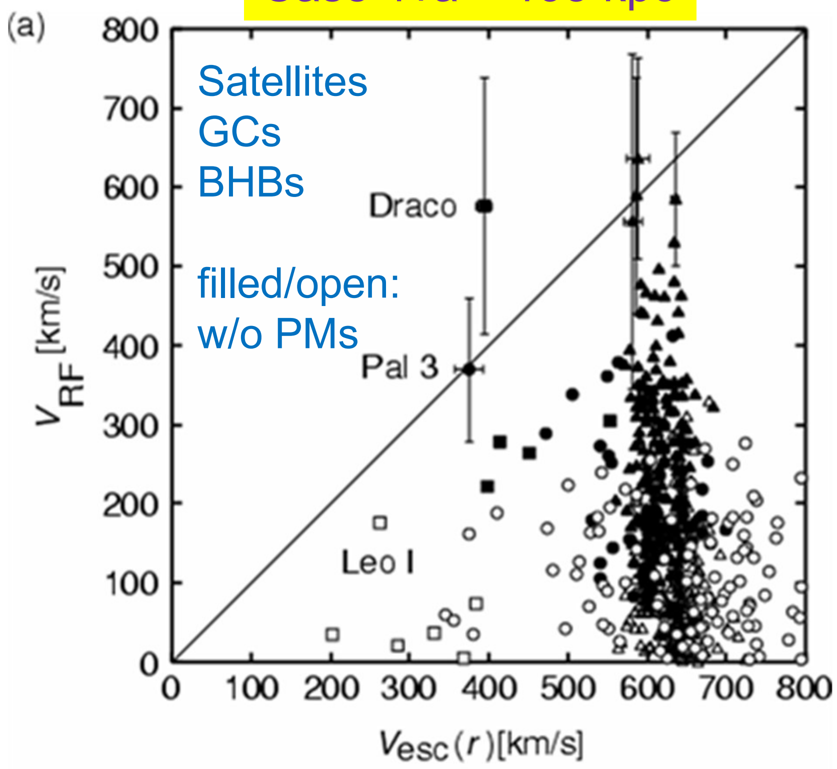
$$\rho(r) = \frac{M}{4\pi} \frac{a^2}{r^2 (r^2 + a^2)^{3/2}}$$

$\rho \propto r^{-5} at\ r \gg a$

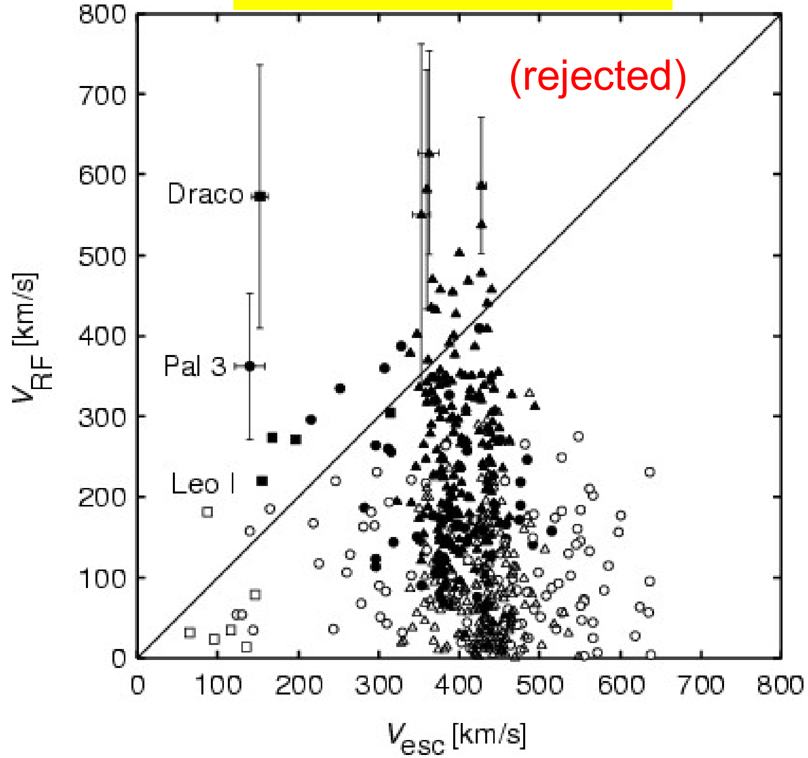
a: size of a halo

→ total mass M

Case 1 : a = 195 kpc

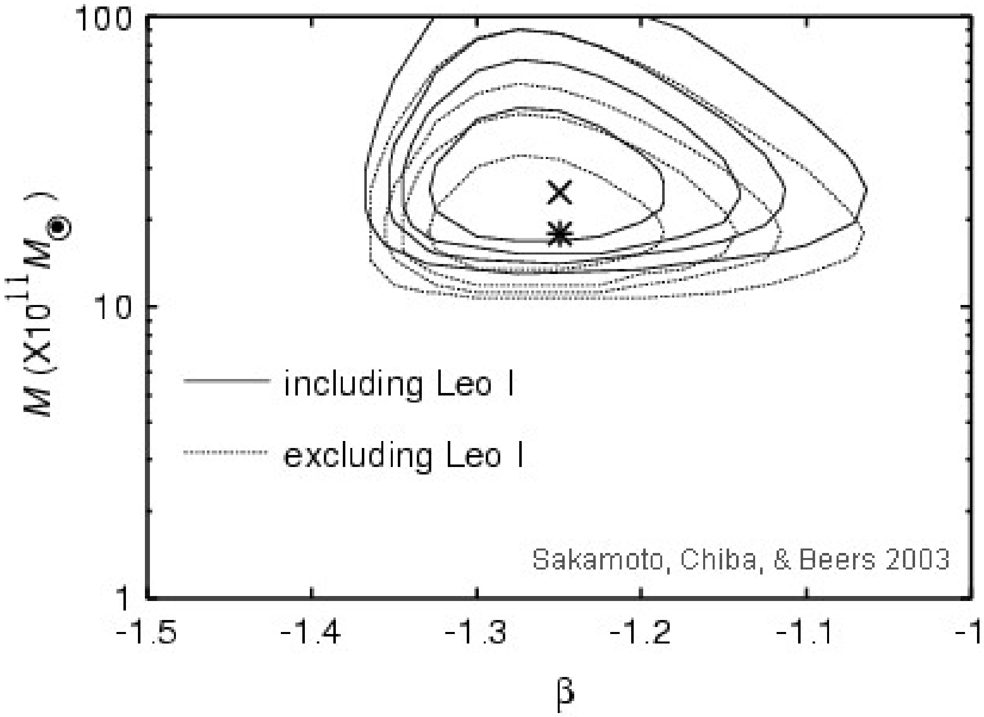


Case 2: a = 20 kpc



Maximum likelihood method to maximize the probability for getting the observed (r_i, v_i) i=1,N

assumption: stellar distribution function f(E,L)



$$\beta = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

Velocity anisotropy parameter

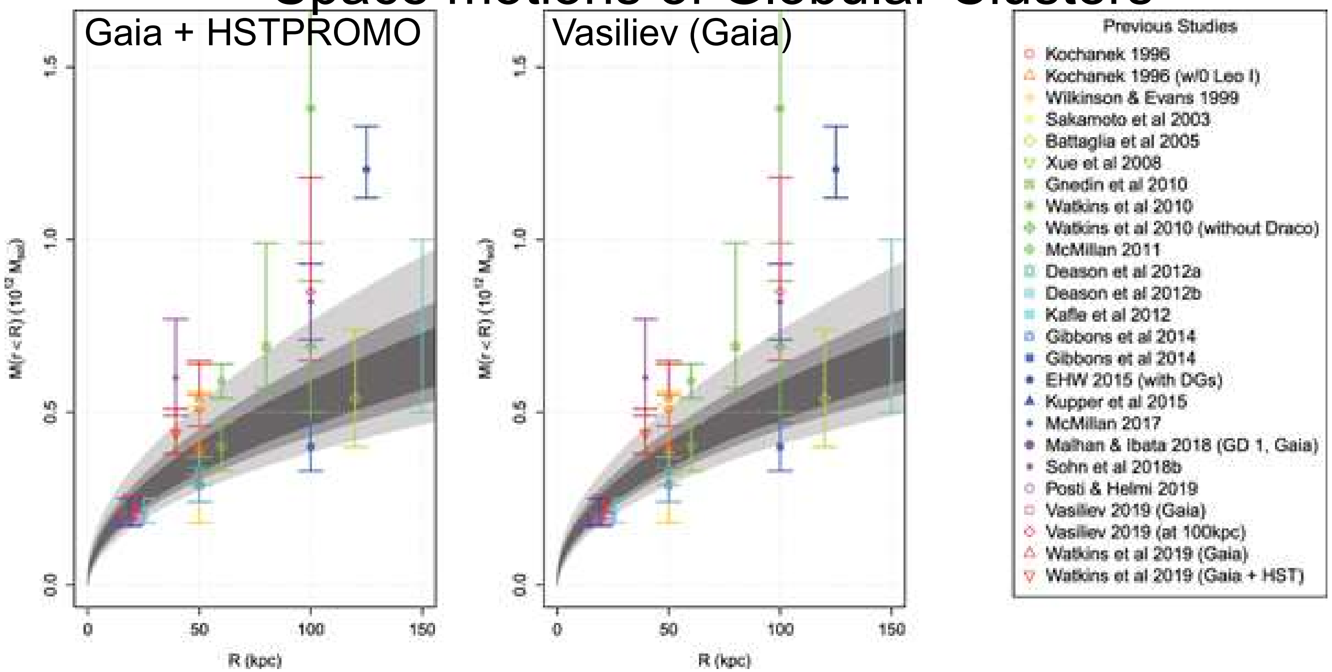
$$\frac{1}{\nu}\frac{d\left(\nu\overline{v_r^2}\right)}{dr} + 2\frac{\beta\overline{v_r^2}}{r} = -\frac{d\Phi}{dr} = -\frac{GM(r)}{r^2}$$

$$\beta = const. \Rightarrow \nu\overline{v_r^2} = r^{-2\beta}\int_r^\infty \frac{\nu GM(r)}{r^2} r^{2\beta} dr$$

Total mass = 2.5 × 10^{12} Msun over ~ 200 kpc
Visible mass = 10^{11} Msun over ~ 15 kpc
⇒ We see only 10 % of the total mass

More recent results using Gaia PMs

Space motions of Globular Clusters

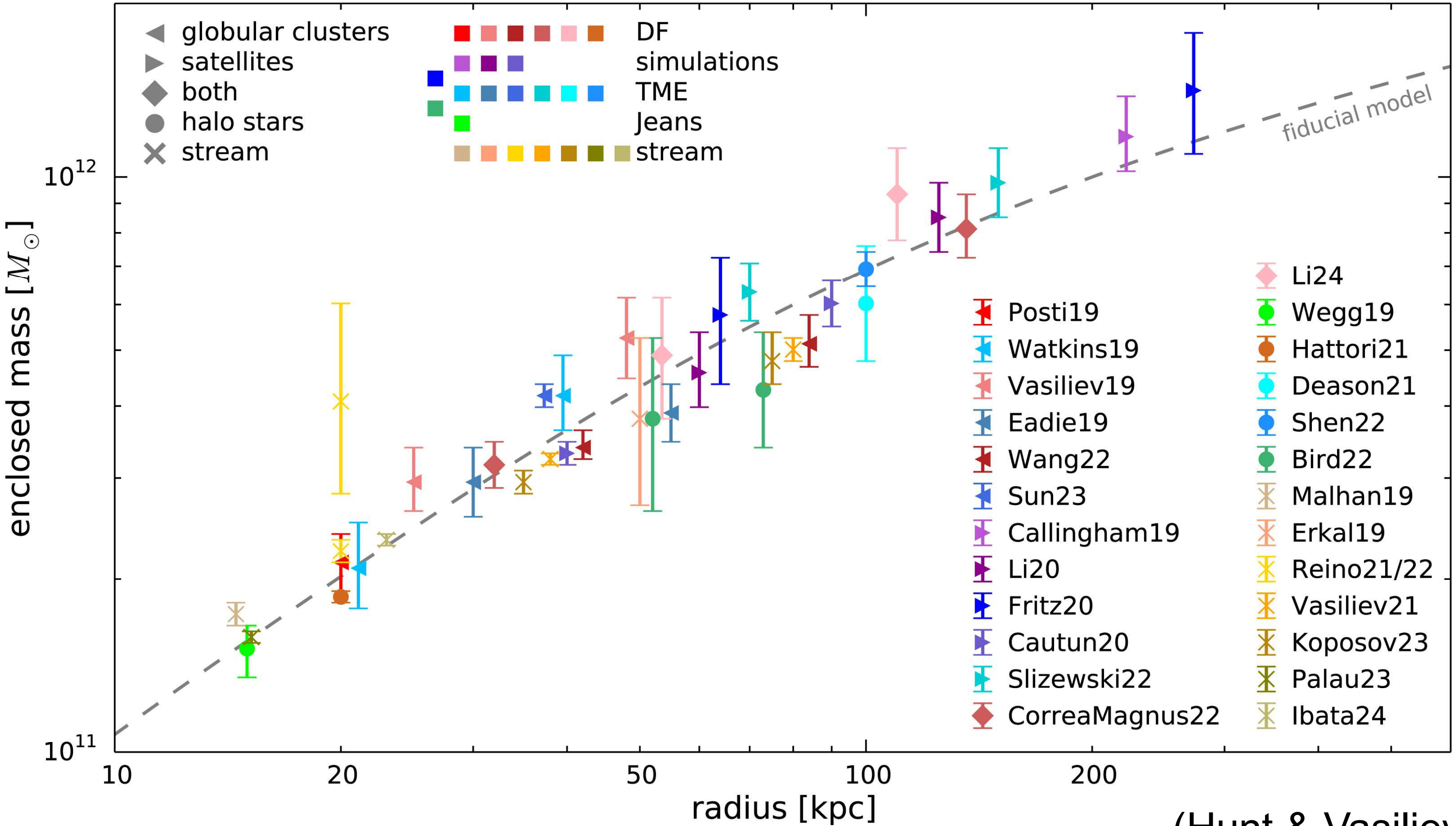


Eadie & Juric 2019 $M_{200} = 0.7^{+0.11}_{-0.08} \times 10^{12}$ Msun (r<200kpc)

Other recent results

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

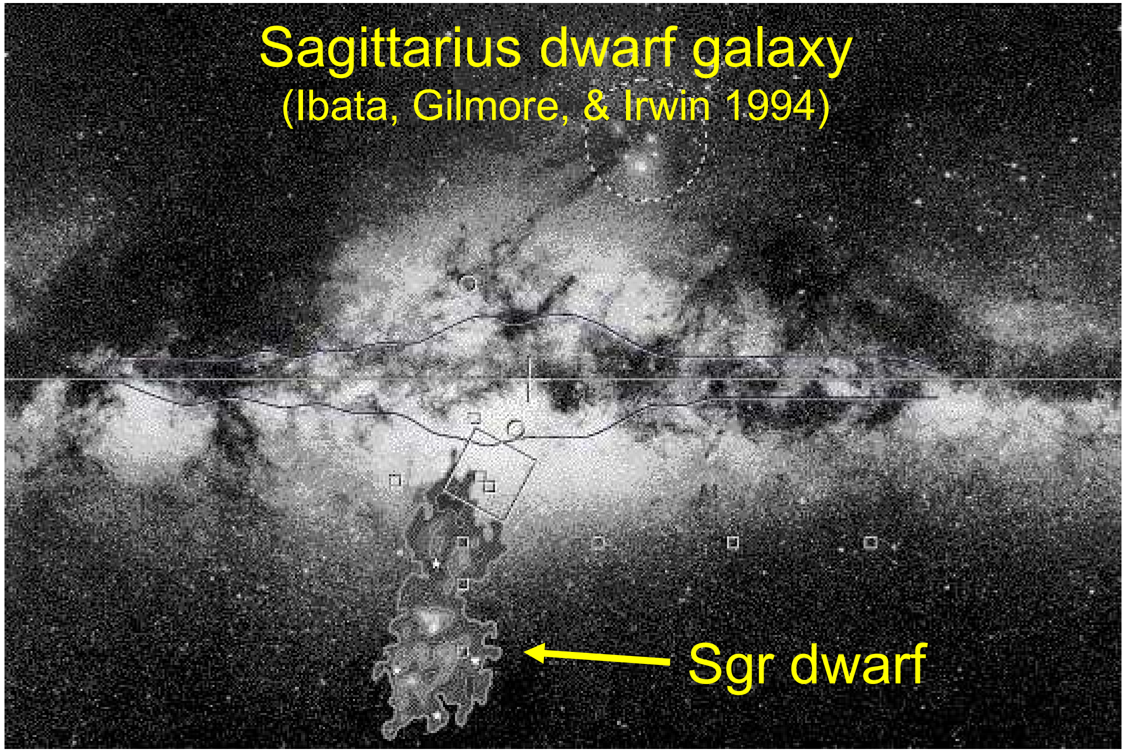
Enclosed mass profile

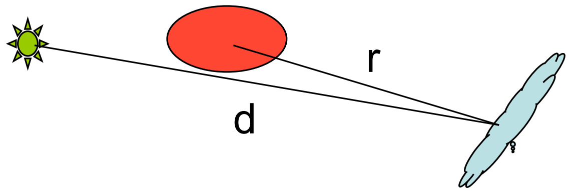


(Hunt & Vasiliev 2024)

$M_{tot} \simeq 1 \times 10^{12}$ Msun

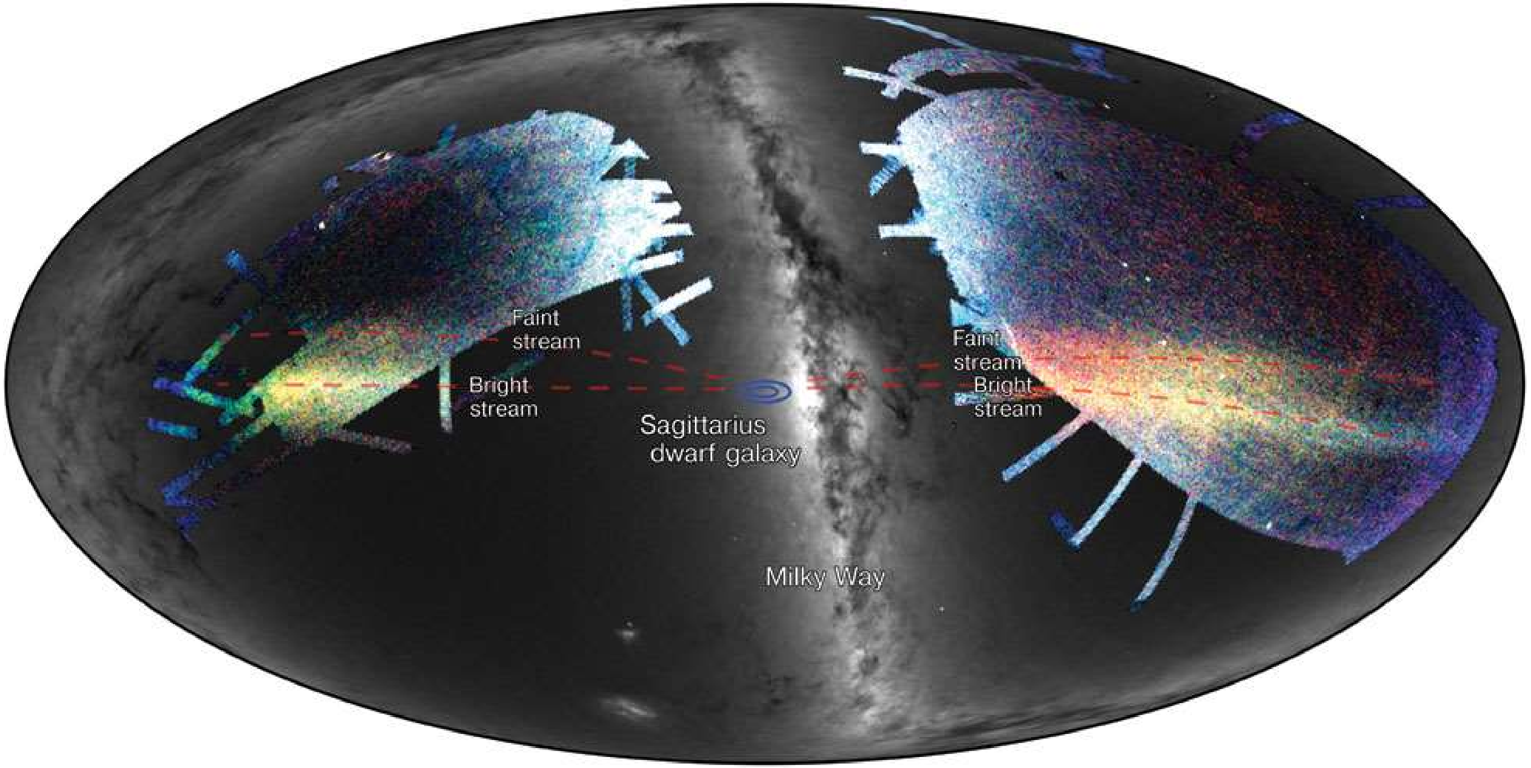
2.2 Global shape

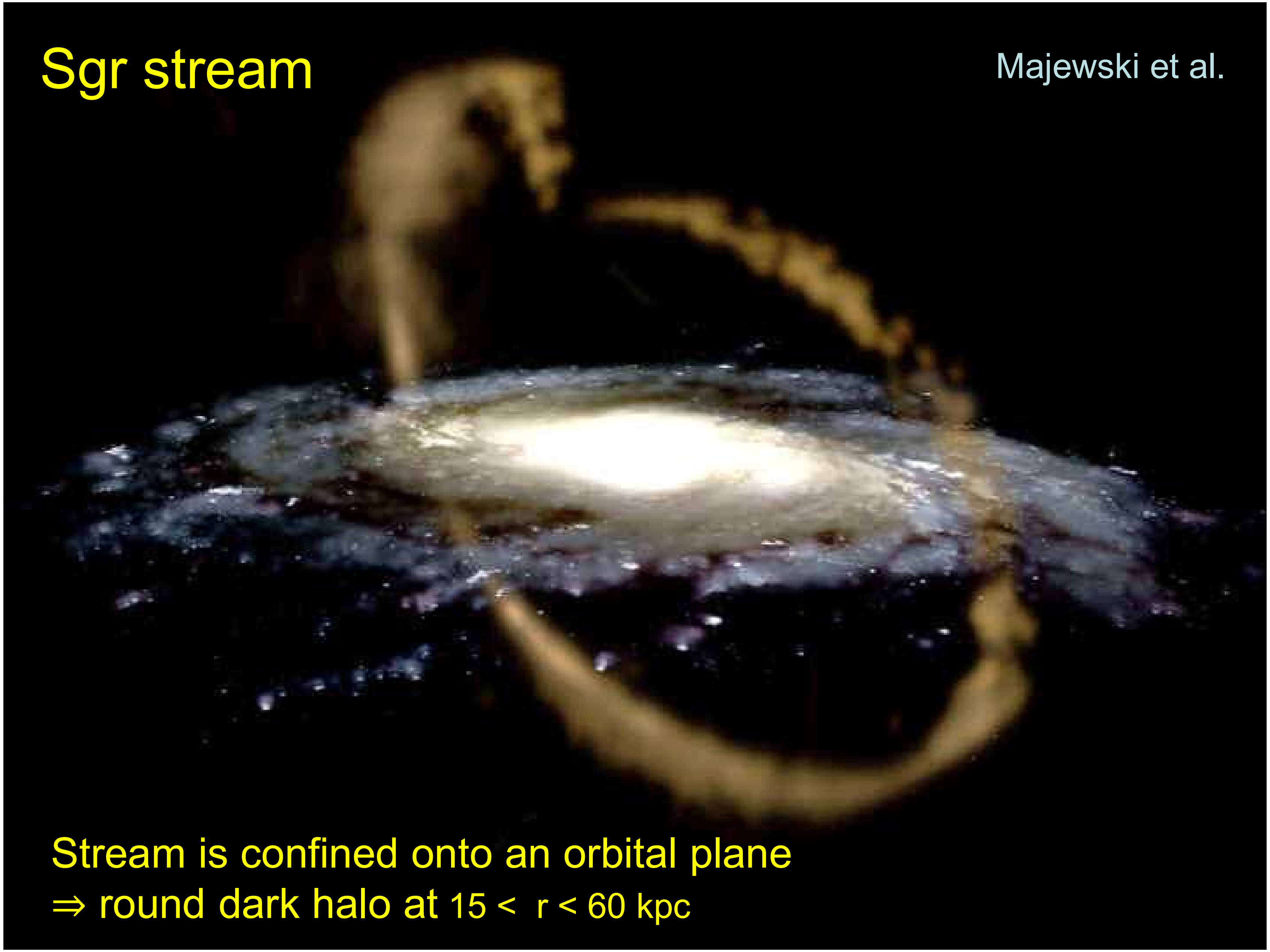




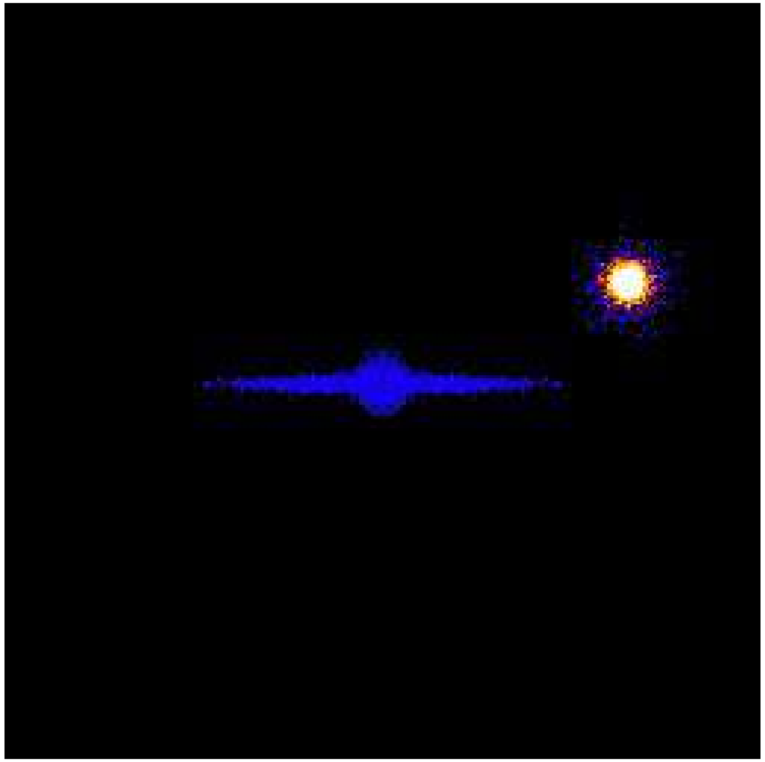
d ~ 24 kpc
r ~ 16 kpc

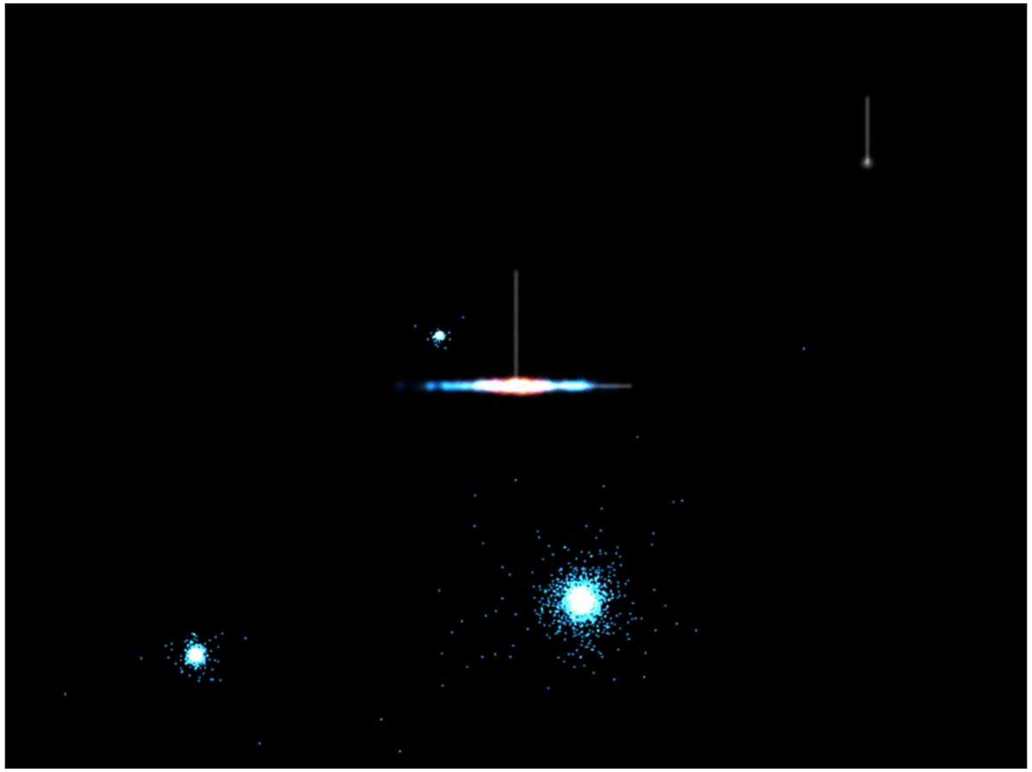
Sgr stream:
tracer of the MW dark halo

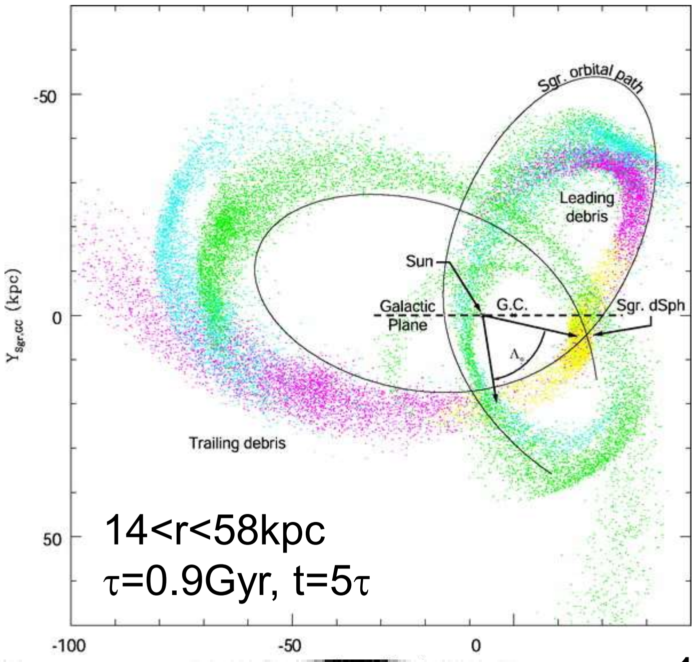


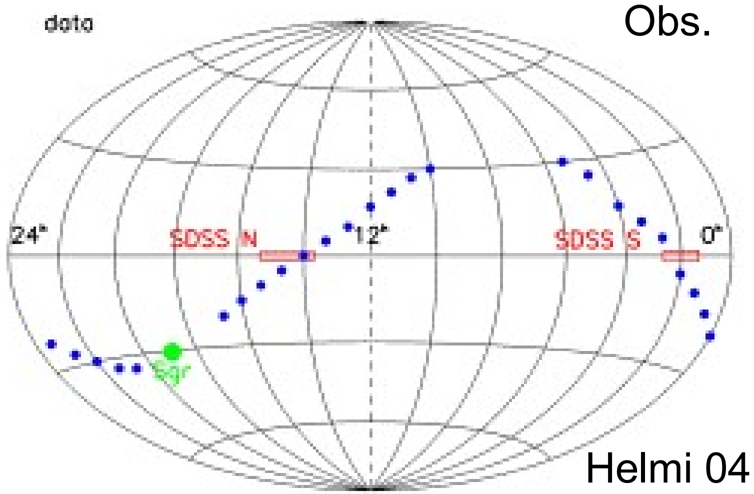

Sgr stream
Majewski et al.
Stream is confined onto an orbital plane
⇒ round dark halo at 15 < r < 60 kpc

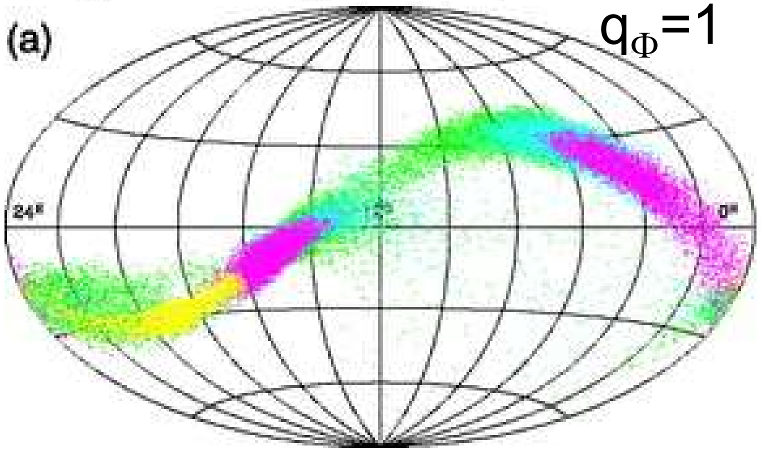
Formation of stellar streams (by tidal force)

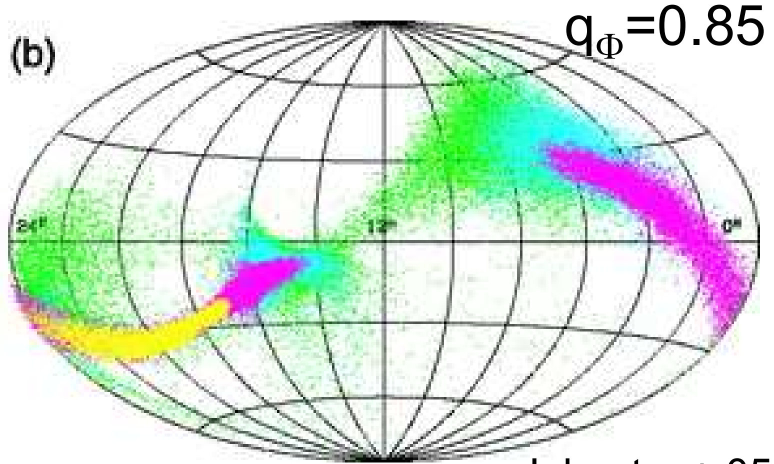








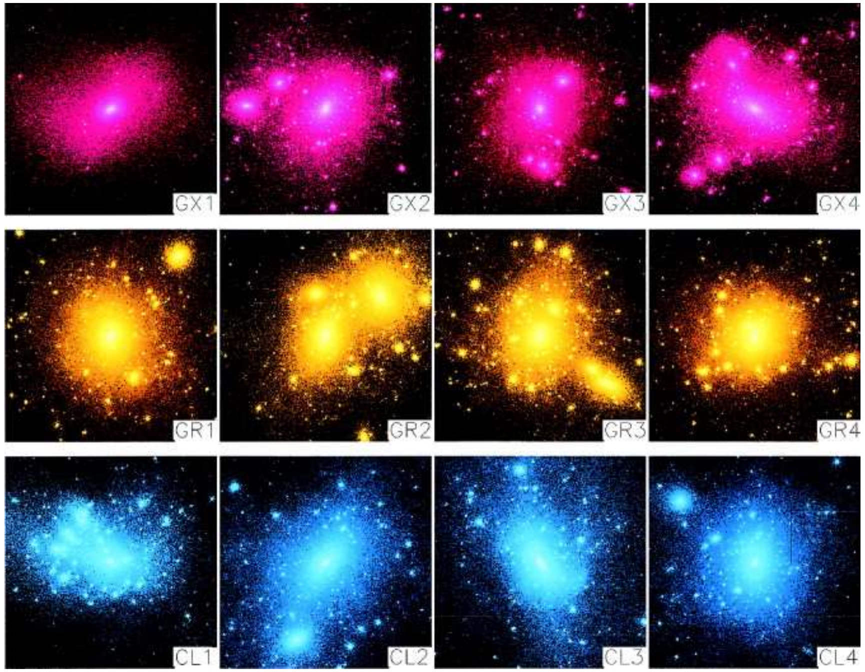


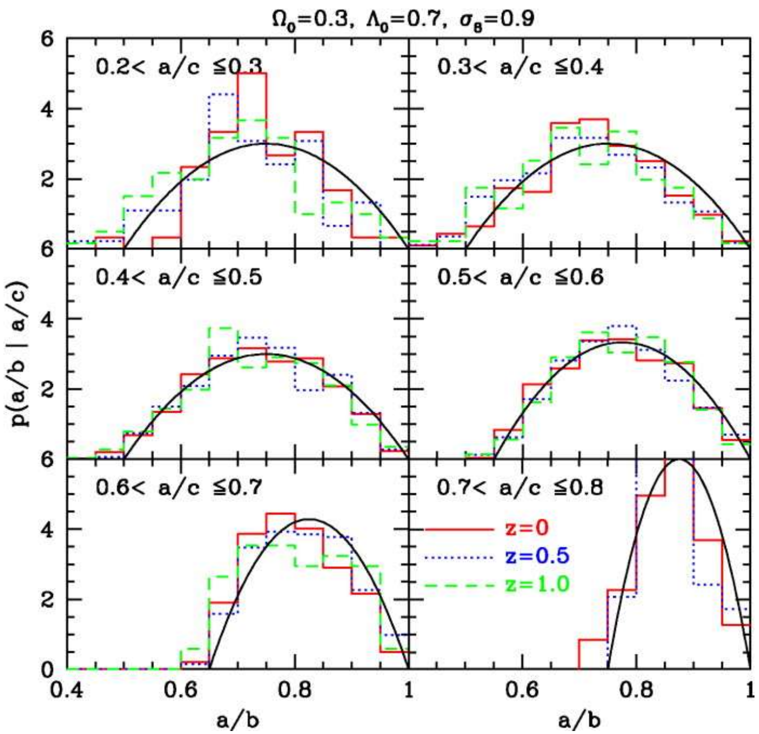


Johnston+ 05

$0.90 < q_{\Phi} < 0.95$ is most likely
($0.83<q_{\rho}<0.92$)

However, CDM halos are generally triaxial / prolate.
(Jing & Suto 2000, 2002)

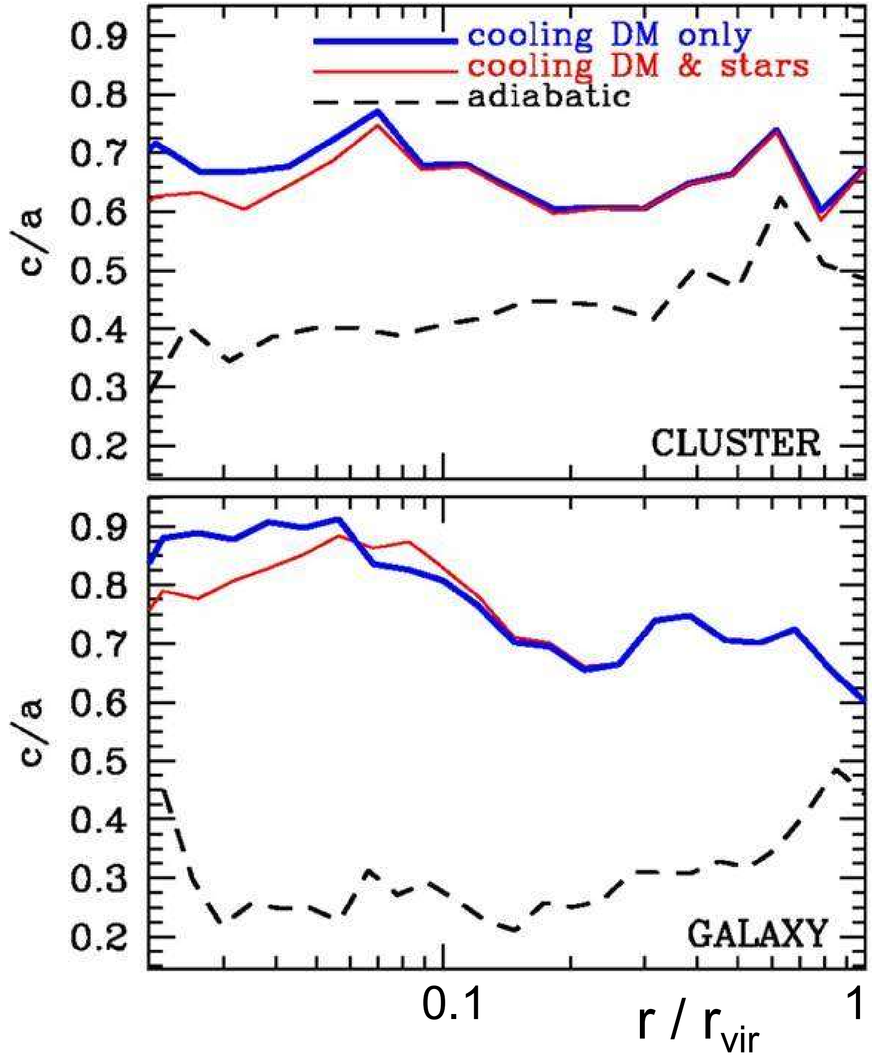




Hayashi+07: $(c/a)_\Phi$ = 0.72, $(b/a)_\Phi$ = 0.78 in central parts

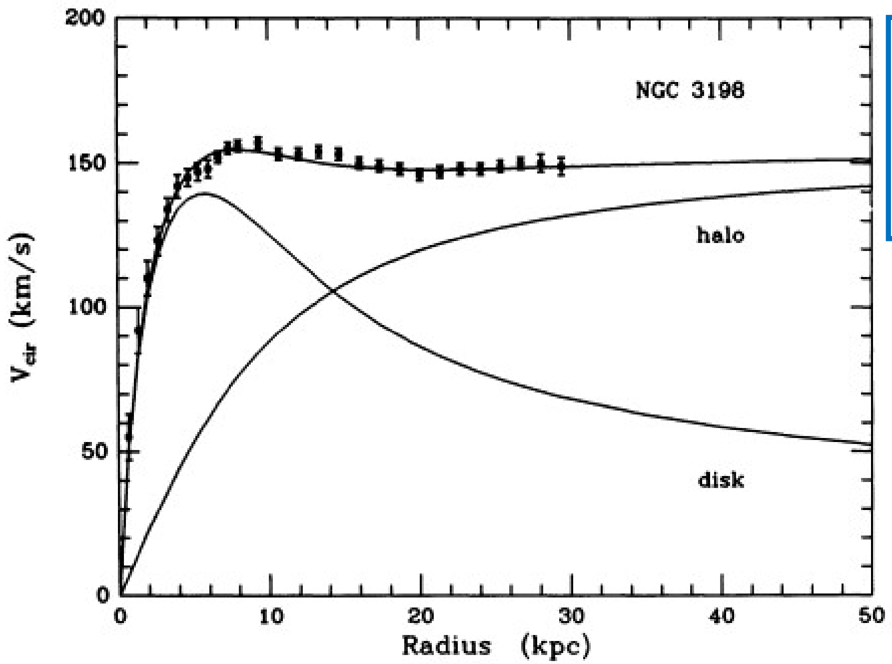
Gas cooling makes CDM halos rounder

(Kazantzidis et al. 2004)



2.3 Density profile

van Albada et al. 1985



If $\rho(r)$ is spherically symmetric
$V_{rot}(r) = (GM(<r)/r)^{1/2}$
where $M(<r) = \int^r 4\pi\rho r^2 dr$

$V_{rot}(r)$ = const.

$\rho(r) \propto 1 / r^2$
(Singular) isothermal sphere

Prediction of CDM models

Virialized dark halos and their density profiles
(Navarro, Frenk, & White 1997)

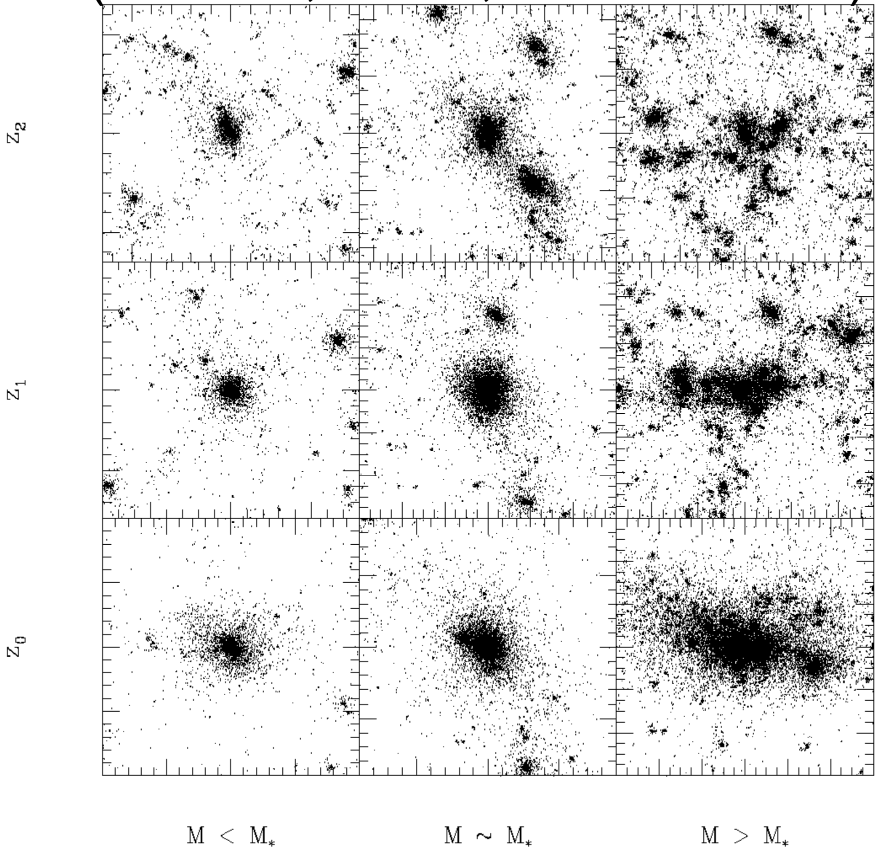


FIG. 1.—Particle plots illustrating the time evolution of halos of different mass in an $\Omega_0 = 1$, $\Lambda = 0$, and $n = -1$ cosmology. The box sizes of each column are chosen so as to include approximately the same number of particles. At $z_0 = 0$, the box size corresponds to about $6r_{200}$. Time runs from top to bottom. Each snapshot is chosen so that M_* increases by a factor of 4 between each row. Low-mass halos assemble earlier than their more massive counterparts. This is true for every cosmological scenario in our series.

NFW profile

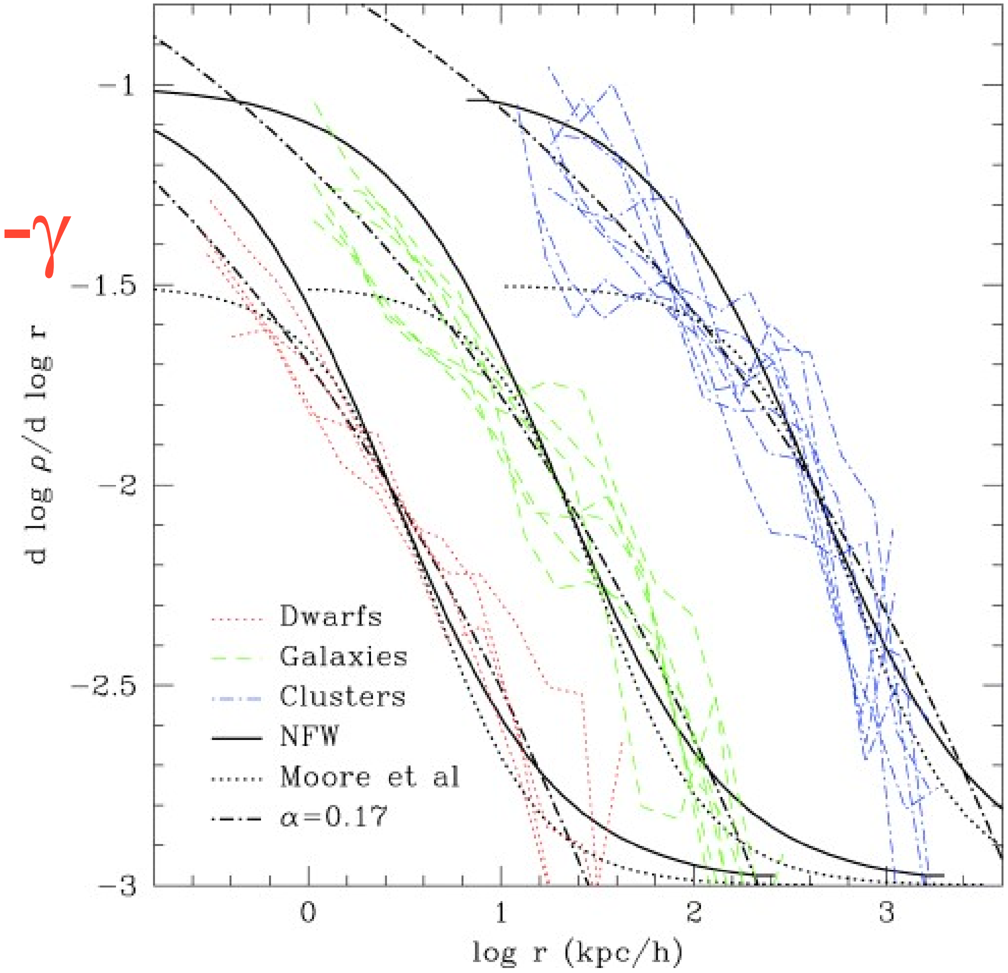
$$\rho = \frac{\rho_s}{\left(r/r_s\right)\left(1 + r/r_s\right)^2}$$

$\rho \propto r^{-1}$ at $r << r_s$
$\rho \propto r^{-3}$ at $r >> r_s$

NFW or Moore et al. profile?

(Navarro et al. 2004)

$-\gamma$



$\rho \propto r^{-\gamma}$
at inner parts
γ= 1: NFW
γ= 1.5: Moore et al.

No universal γ
$1 < \gamma < 1.5$

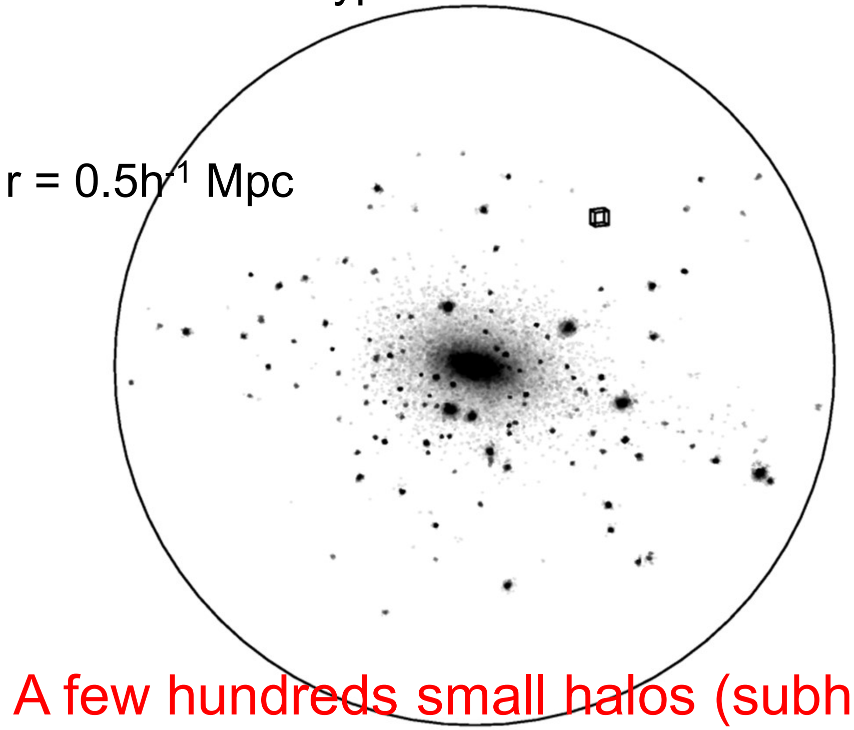
Einasto profile:

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

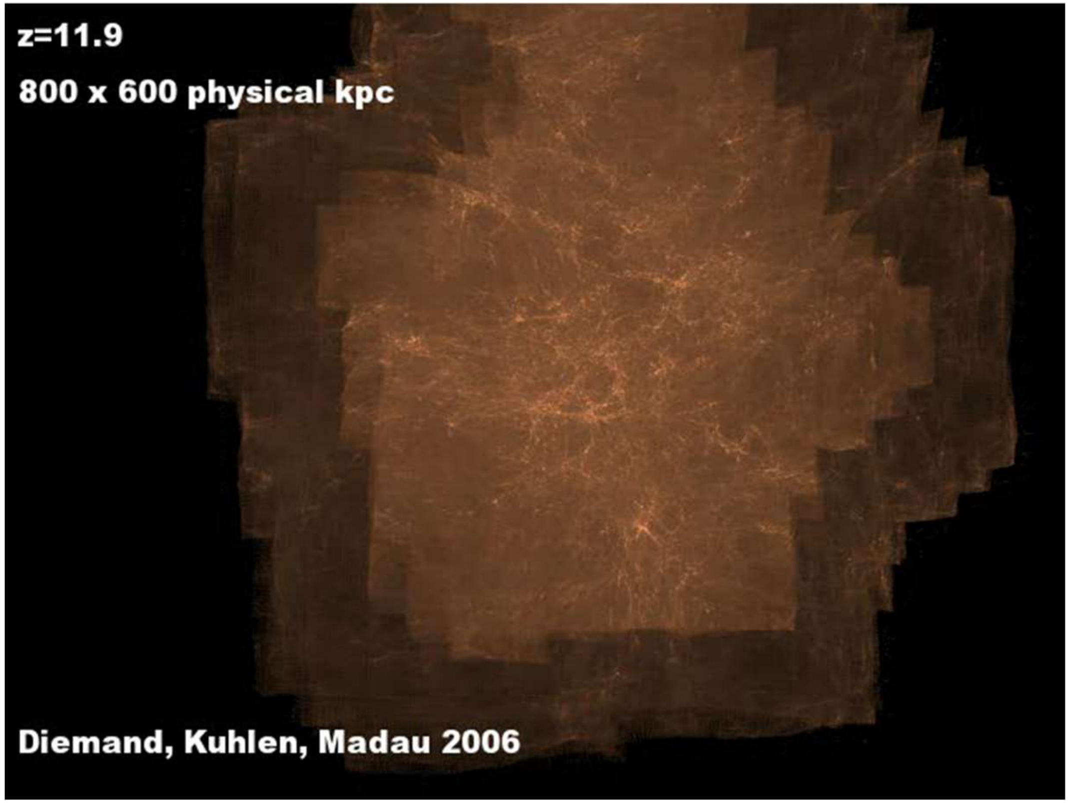
3. Crisis in CDM: problems in small scales

(1) Missing satellites problem
(2) Core/cusp problem
(3) Too big to fail problem

CDM distribution in the Milky Way scale
Klypin et al. 1999

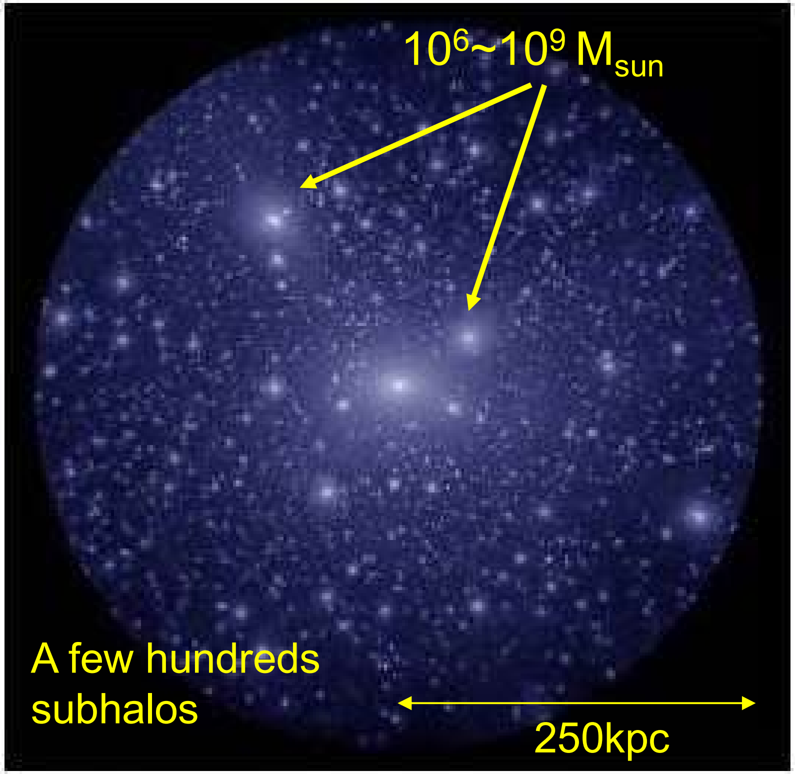


A few hundreds small halos (subhalos)

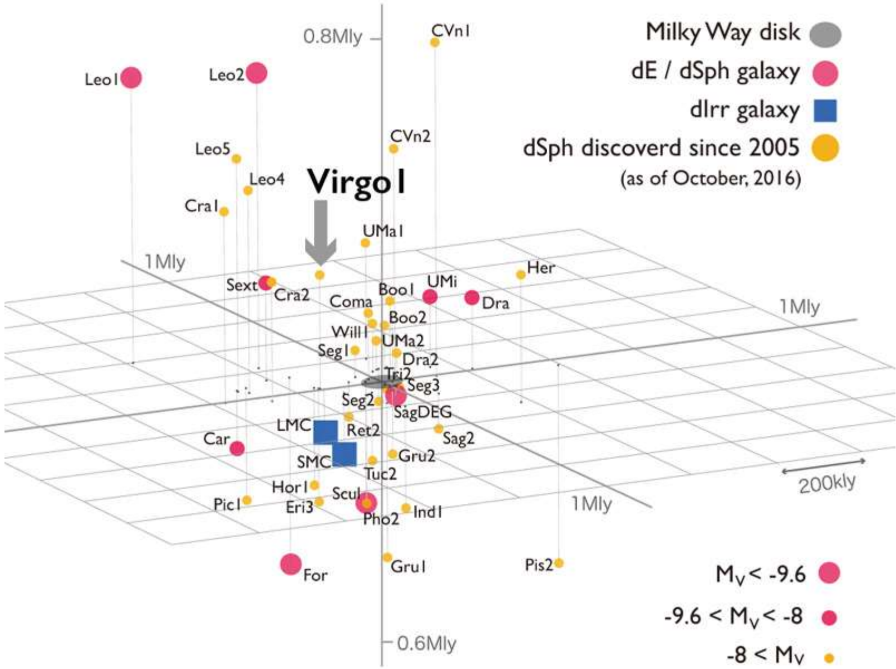


CDM crisis (1): Missing satellites problem

CDM distribution in
the Milky Way-sized halo
(Bullock & Boylan-Kolchin 2017)



Luminous satellites in the Galaxy

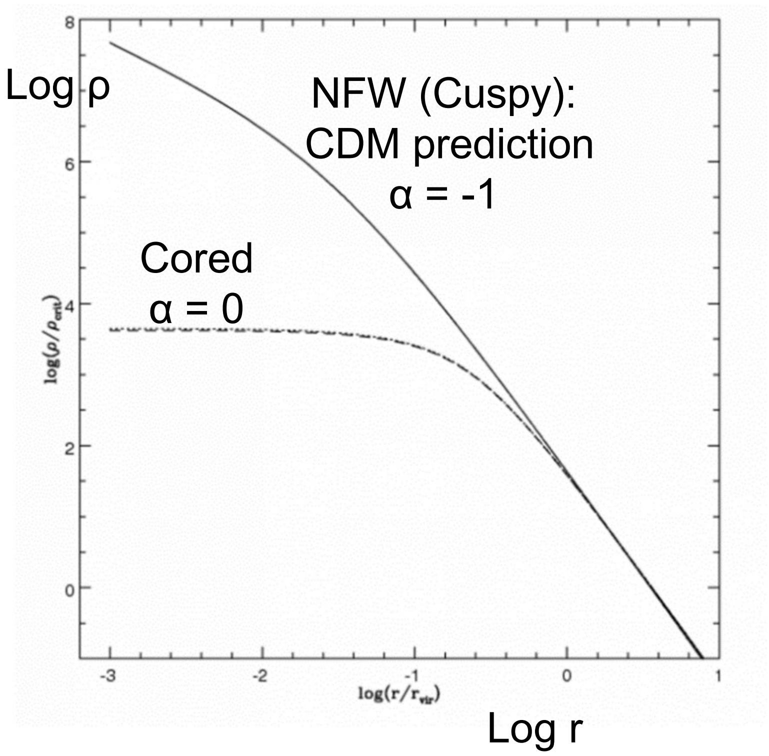


Only ~ 60 satellites are detected so far

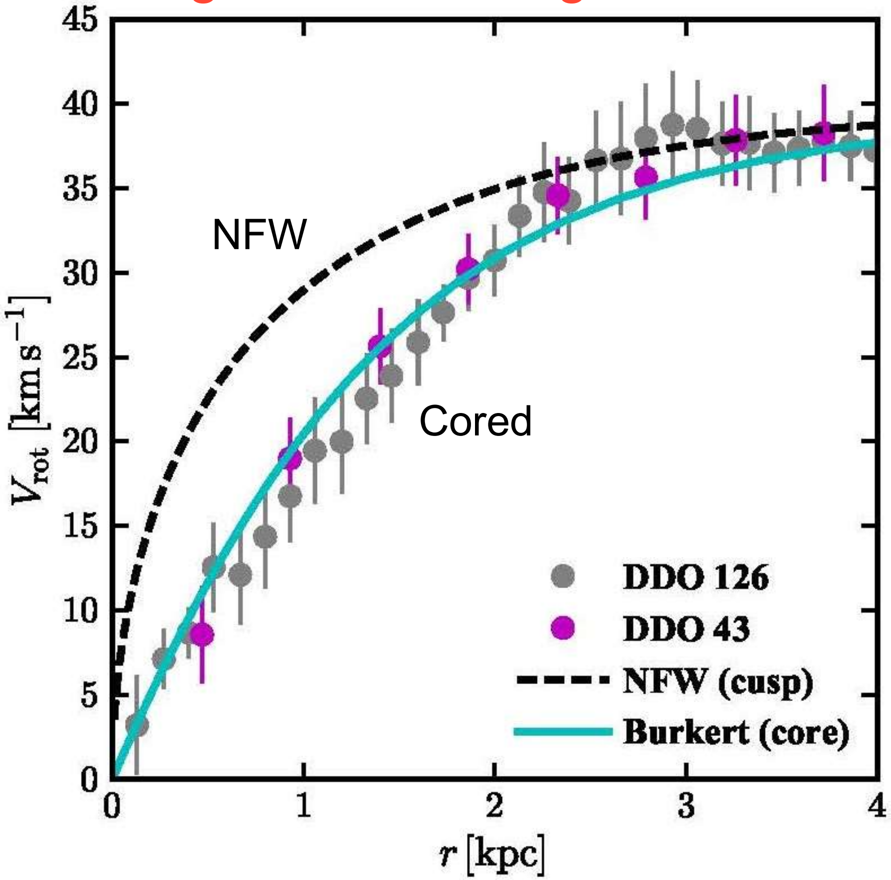
CDM crisis (2): Core/cusp problem

Density distribution of a dark halo

Inner profile: $\rho(r) \propto r^{\alpha}$



Rotation curves of (external) gas-rich dwarf galaxies



CDM crisis (2): Core/cusp problem

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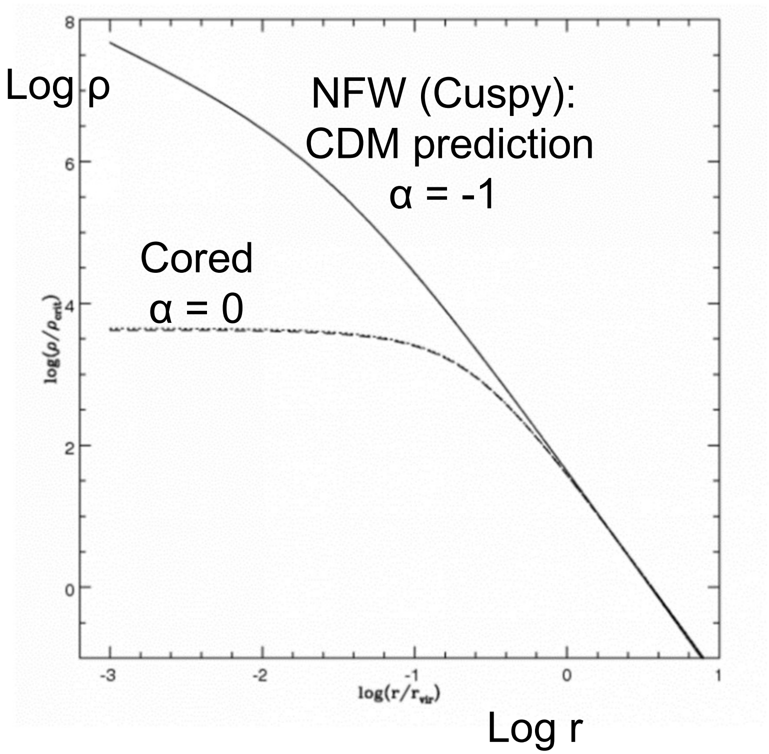
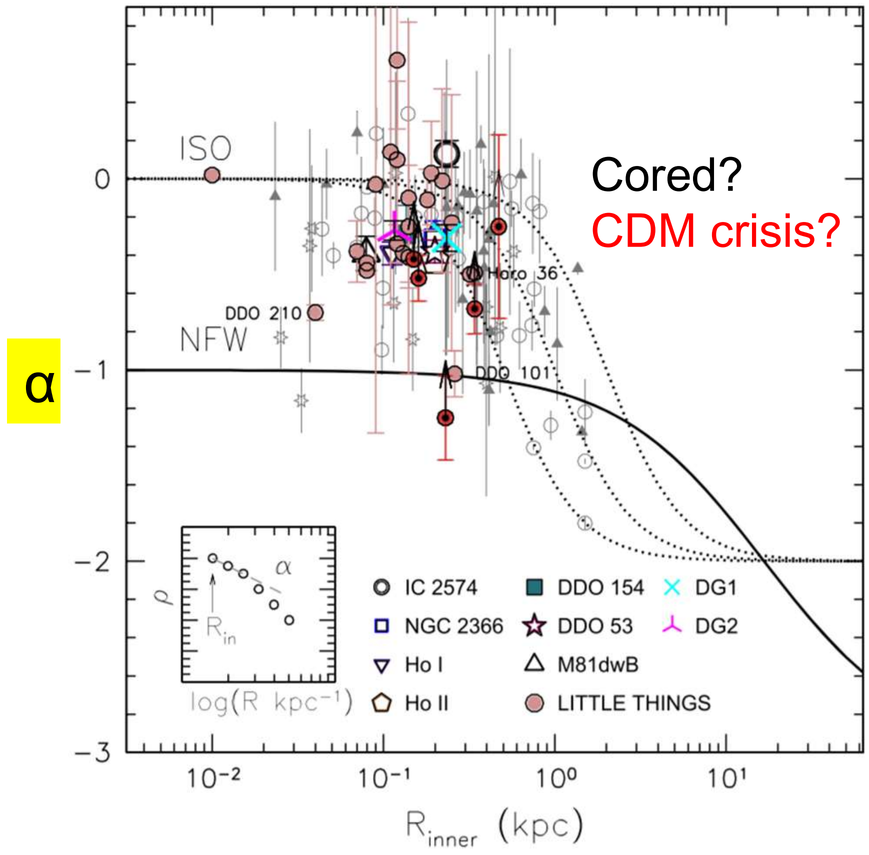


Oh et al. 2015

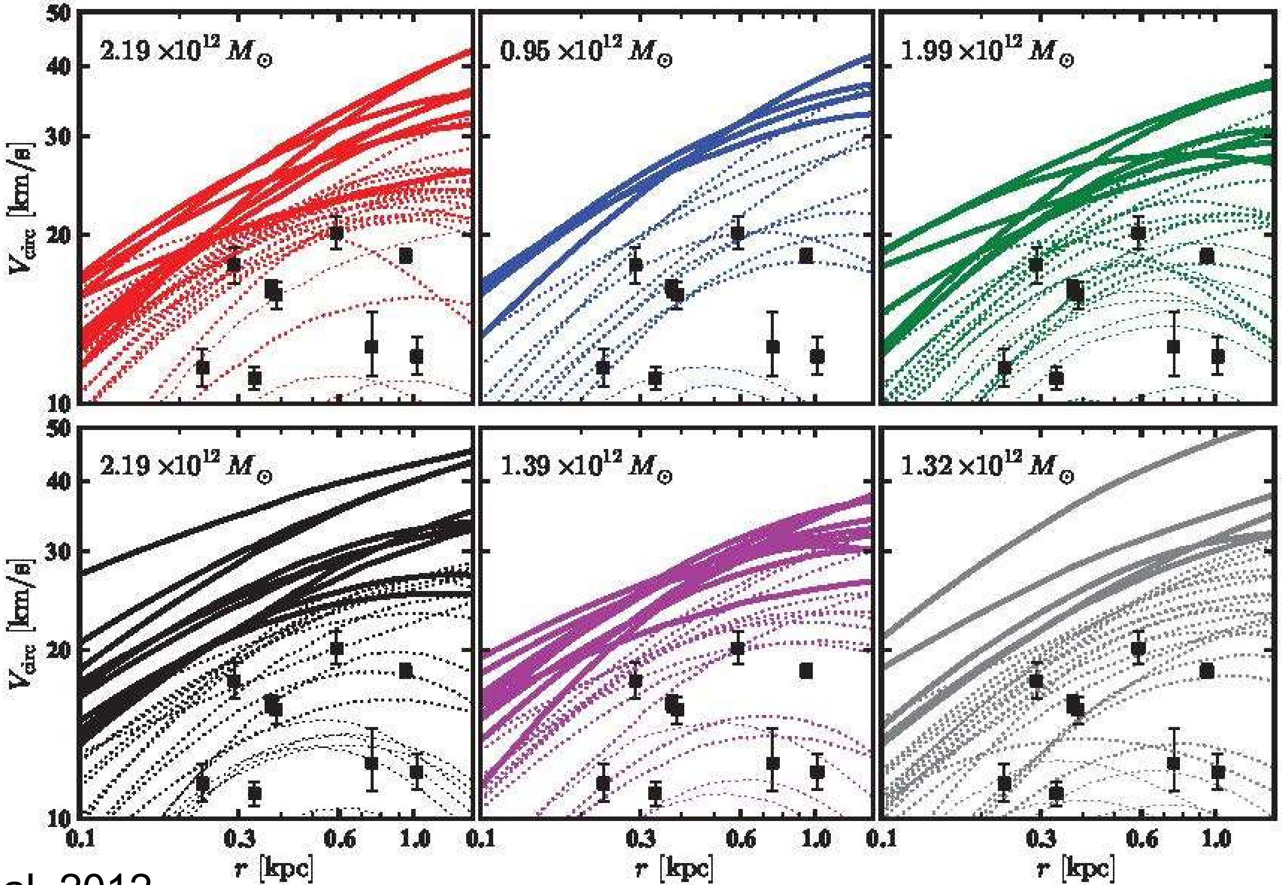


CDM crisis (3): Too big to fail problem

Most massive subhalos in ΛCDM simulation are denser than those in most luminous satellites.

Rotation curves of most massive subhalos in the MW-like halos

Filled circles: Galactic satellites rotation velocities at half-light radius

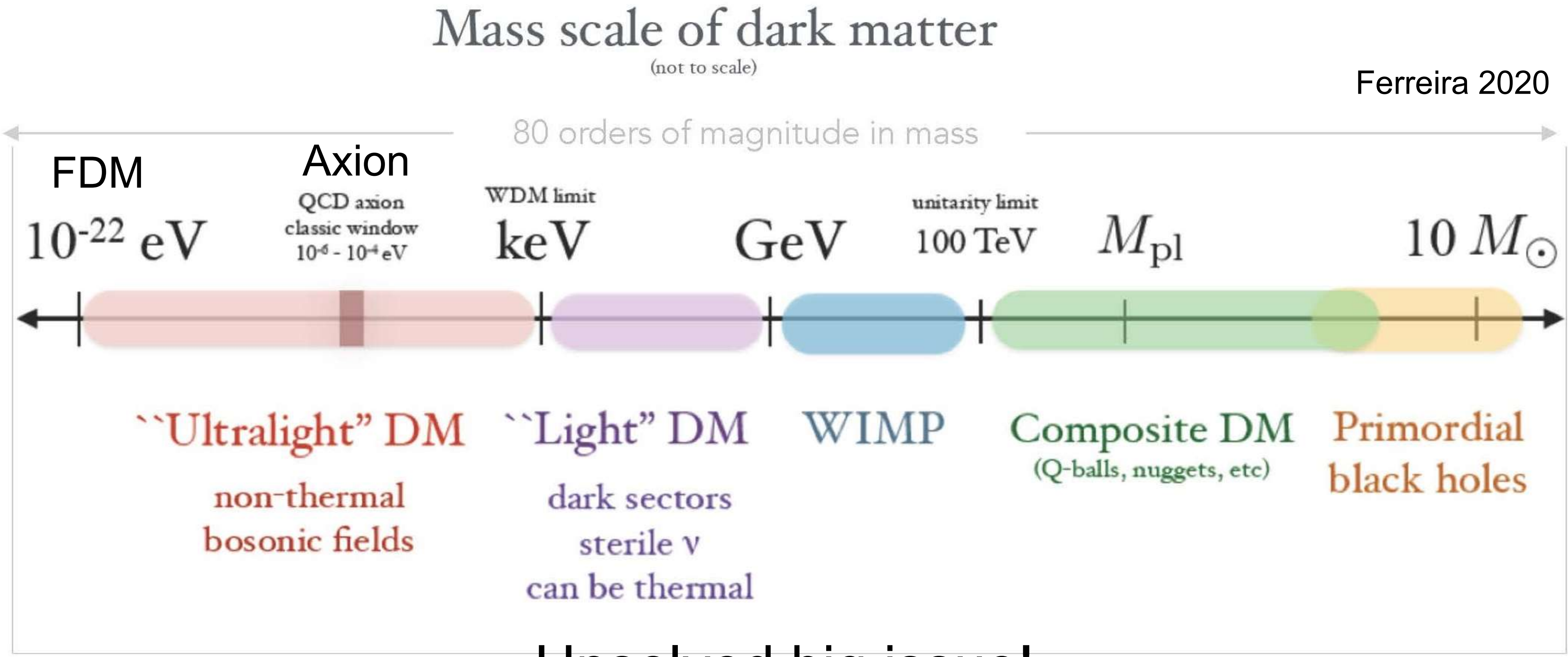


Bolyan-Kolchin et al. 2012

Solutions ?

- Alternative DM models
  - Suppression of small-scale powers: WDM, FDM (Hui et al. 2017)
  - Self-interacting DM producing a core (Spergel & Steinhardt 2000)

Various dark matter candidates



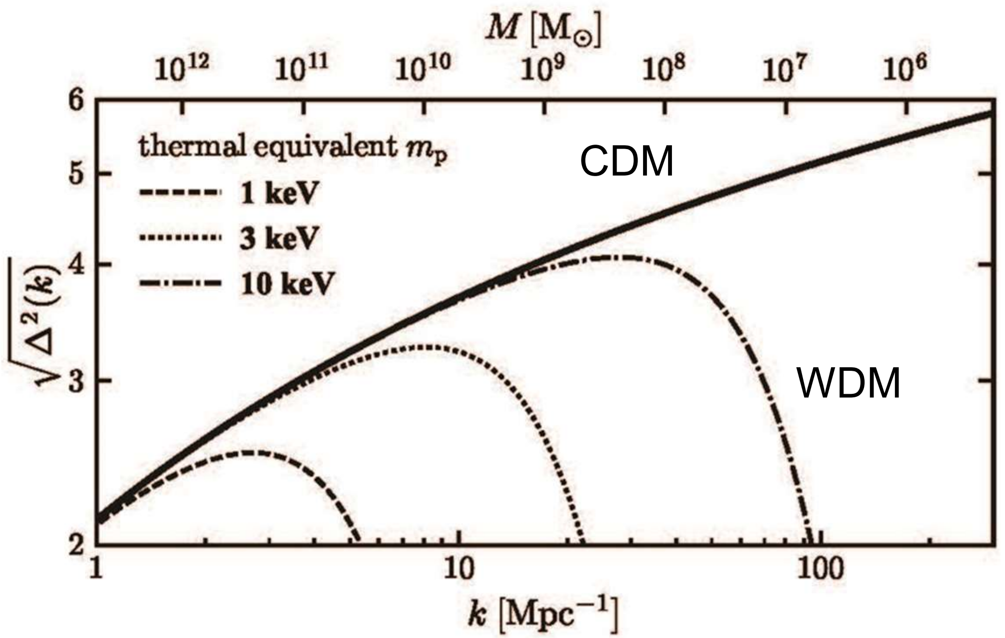
Unsolved big issue!

Power spectrum for DMs

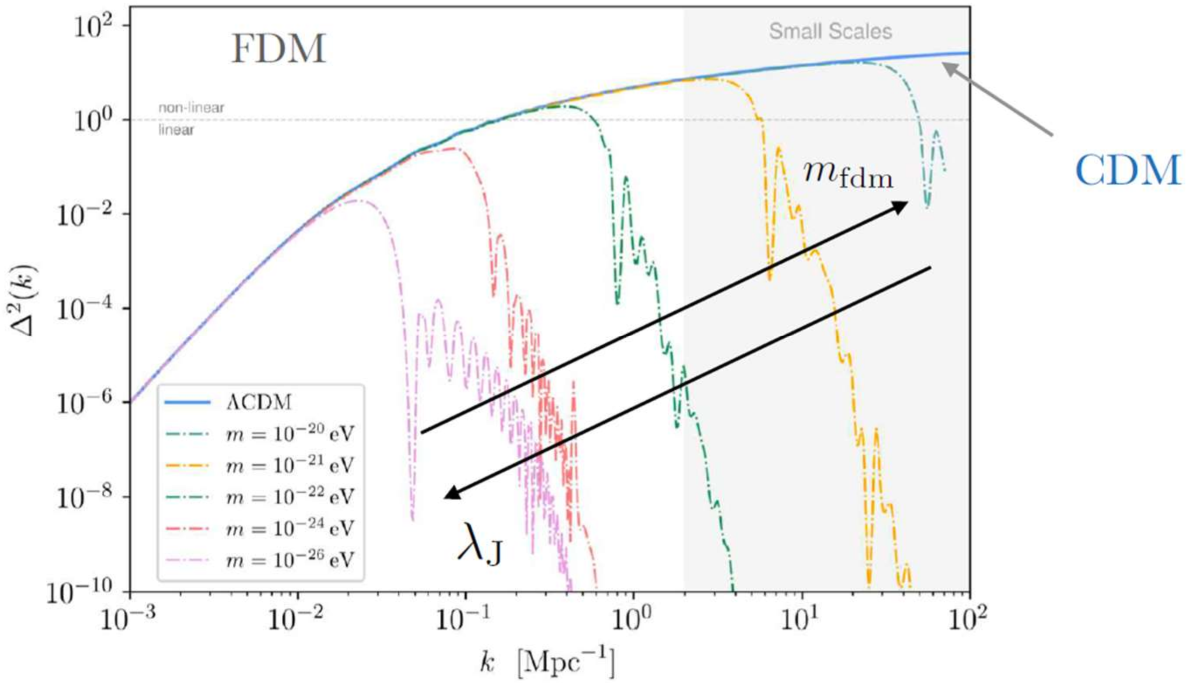
$$\Delta^2(k) \propto \frac{k^3}{2\pi} P(k)\, T^2(k)$$

Dark halos on scales of dwarf galaxies are most important keys

WDM



FDM

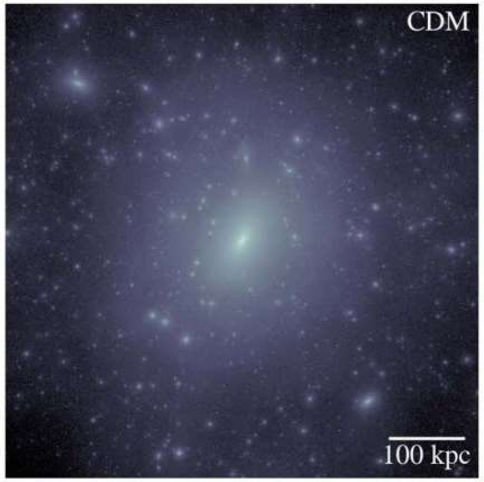


Bullock & Boylan-Kolchin 2017

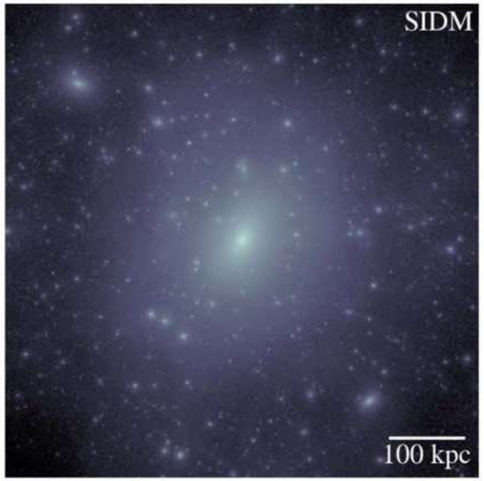
Ferreira 2022

Alternative dark matter models

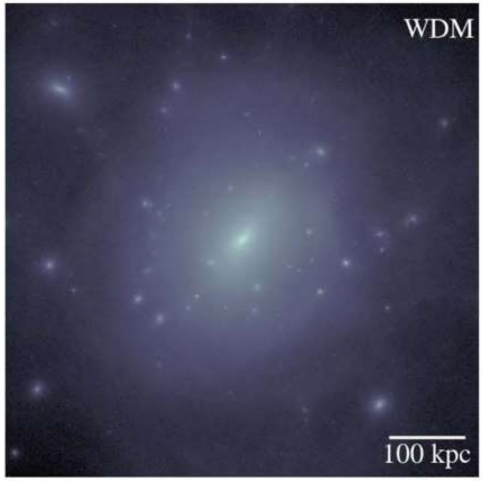
CDM



SIDM

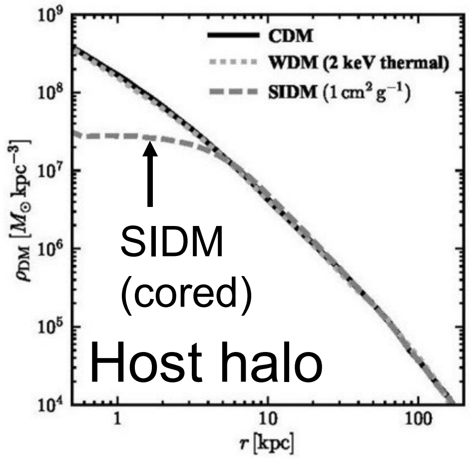


WDM

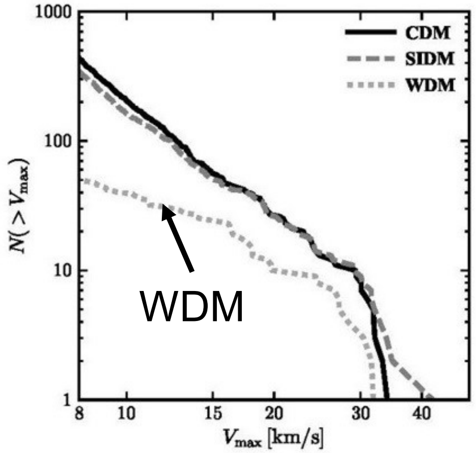


- Self-Interacting DM (SIDM)
  - Interaction among DM particles
    - cross section: σ/m
  - Cored profile is reproduced
- Warm Dark Matter (WDM)
  - m ~ O(keV) e.g. sterile neutrino
  - Number of subhalos is reduced

Density distribution



Number of subhalos



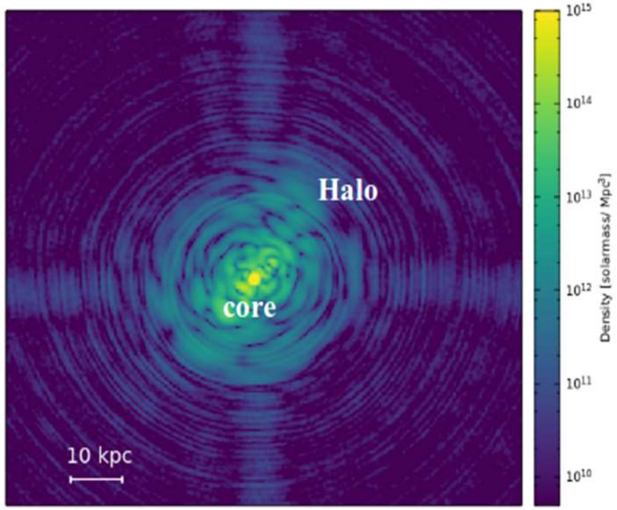
Ultralight DM：Fuzzy Dark Matter (FDM)

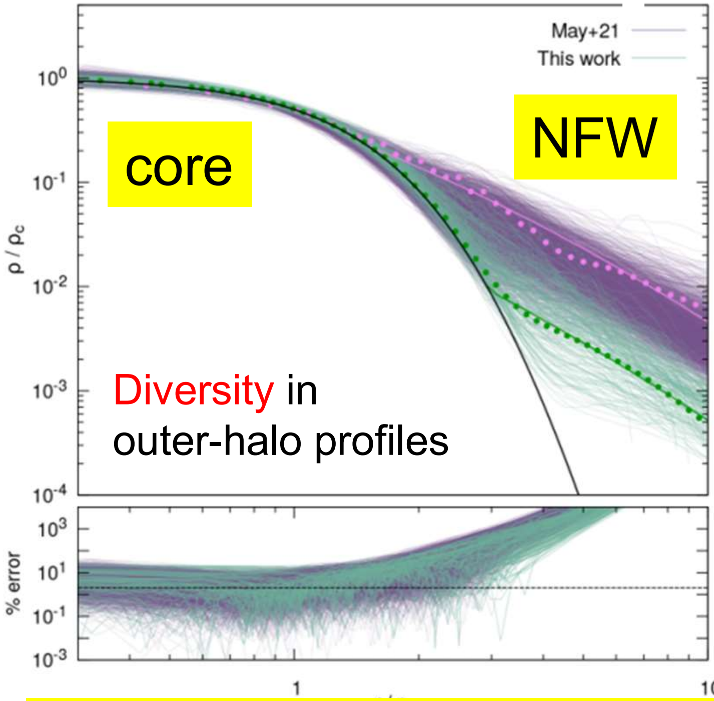
Hu, Barkana, Gruzinov (2000)

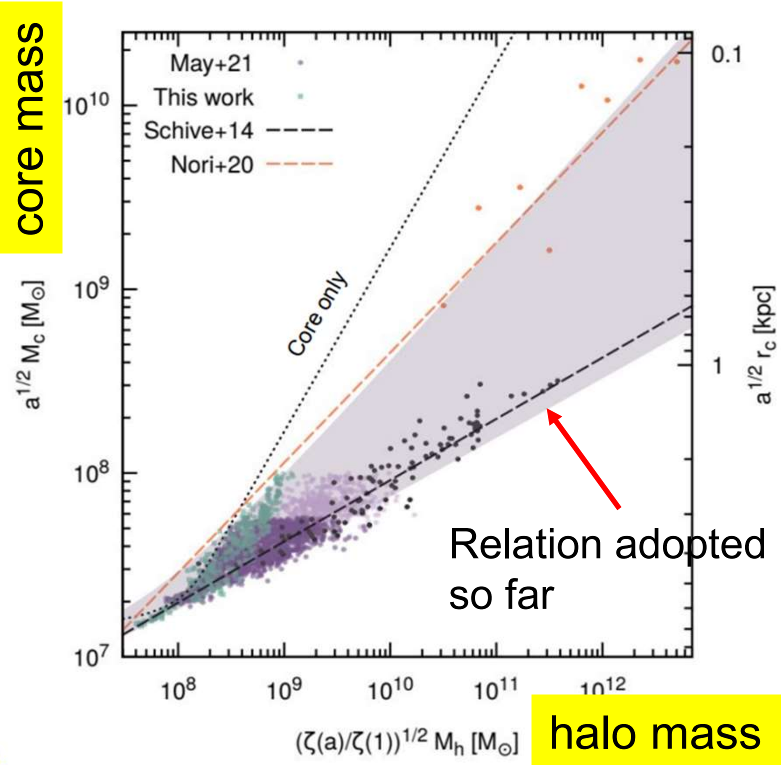
$m = 1 \times 10^{-22}$ eV

Jowett Chan

Chan, Ferreira, May, Hayashi, Chiba (2022)







Quantum pressure vs. gravity

$$\lambda_J = 55 \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h^2)^{-1/4} \ \mathrm{kpc}$$

A few kpc scales: dwarf galaxy sales

$$\rho_{\mathrm{soliton}}(r) = \frac{1.9 \times 10^{12} M_\odot \ \mathrm{pc}^{-3}}{[1 + 0.091 (r/r_c)^2]^8} \left(\frac{m_\psi}{10^{-22}\mathrm{eV}}\right)^{-2} \left(\frac{r_c}{\mathrm{pc}}\right)^{-4}$$

Diversity in core-halo mass relationship is discovered.

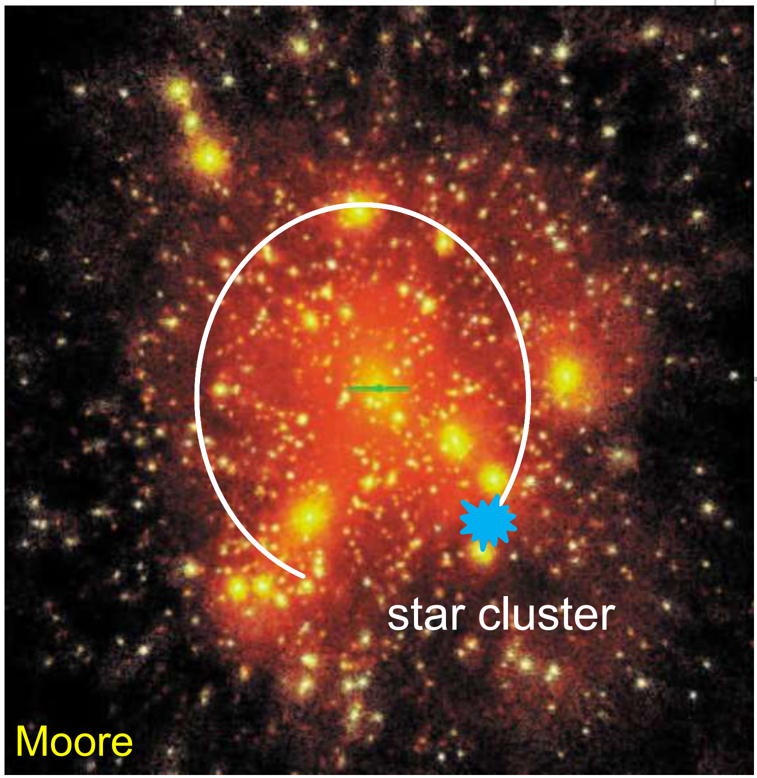
4. Probing dark matter substructures

- Dynamical effects on galactic structure
  - Star clusters and stellar streams
  - Stellar disks
- Effects on gravitational lensing
  - Anomalous flux ratios between lensed images
  - Effects on extended lensed images

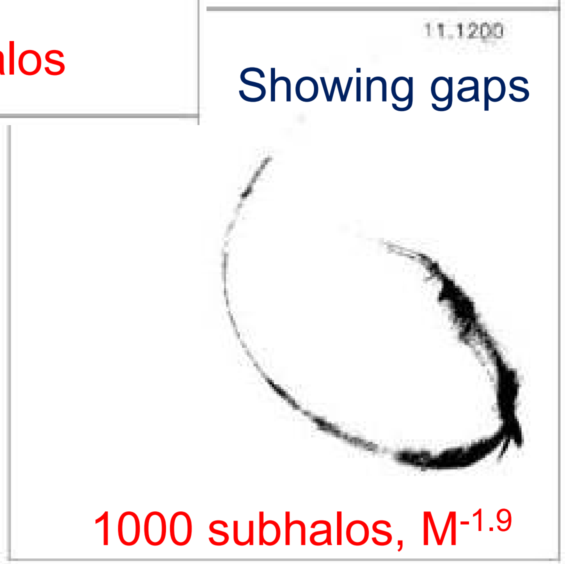
Probing evidence for CDM subhalos from their gravitational effects on a stellar stream

(Carlberg 2011)

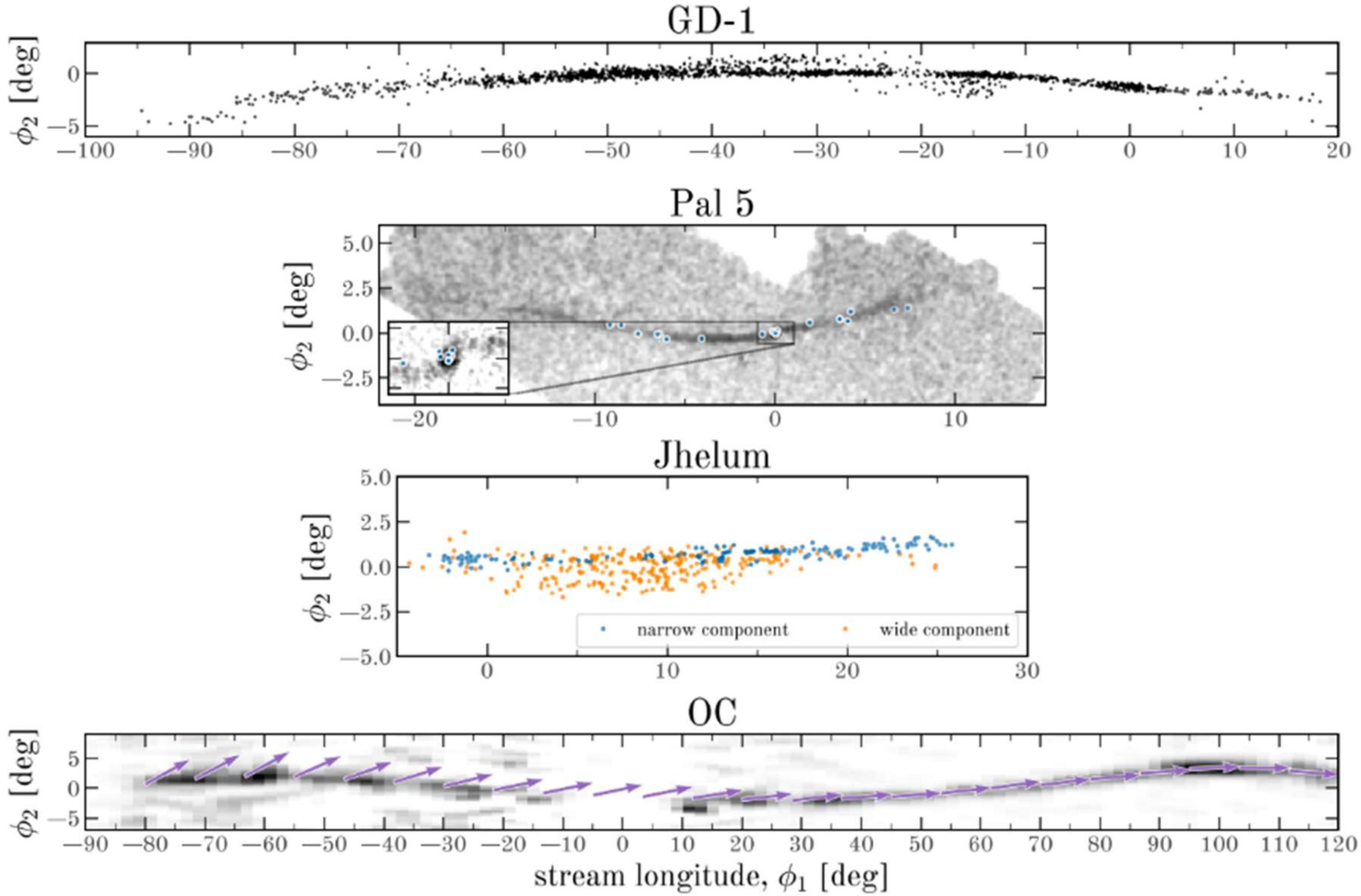
CDM halo in a galaxy



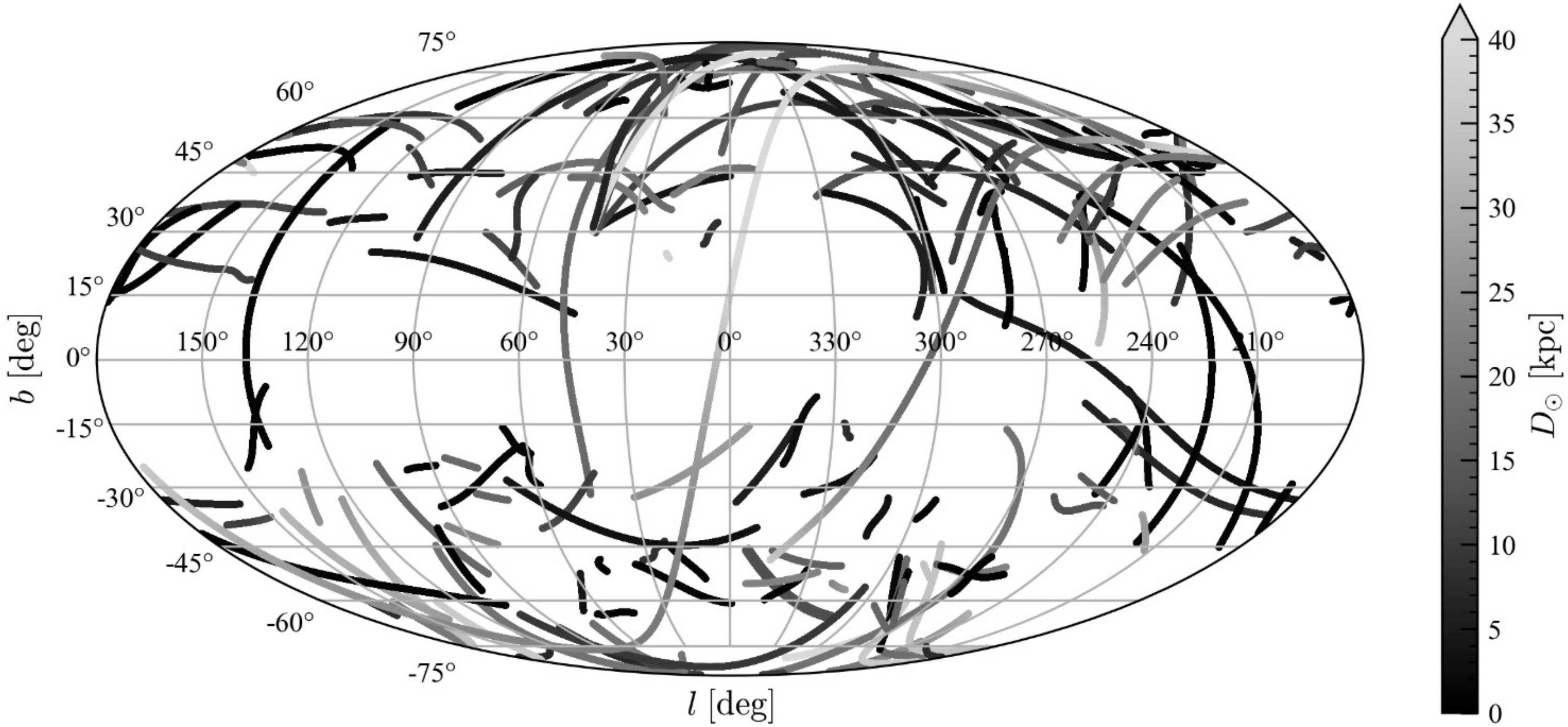
dynamical effects
on stellar stream
($M_{star}=10^6 M_{sun}$



Stellar stream in the Galaxy



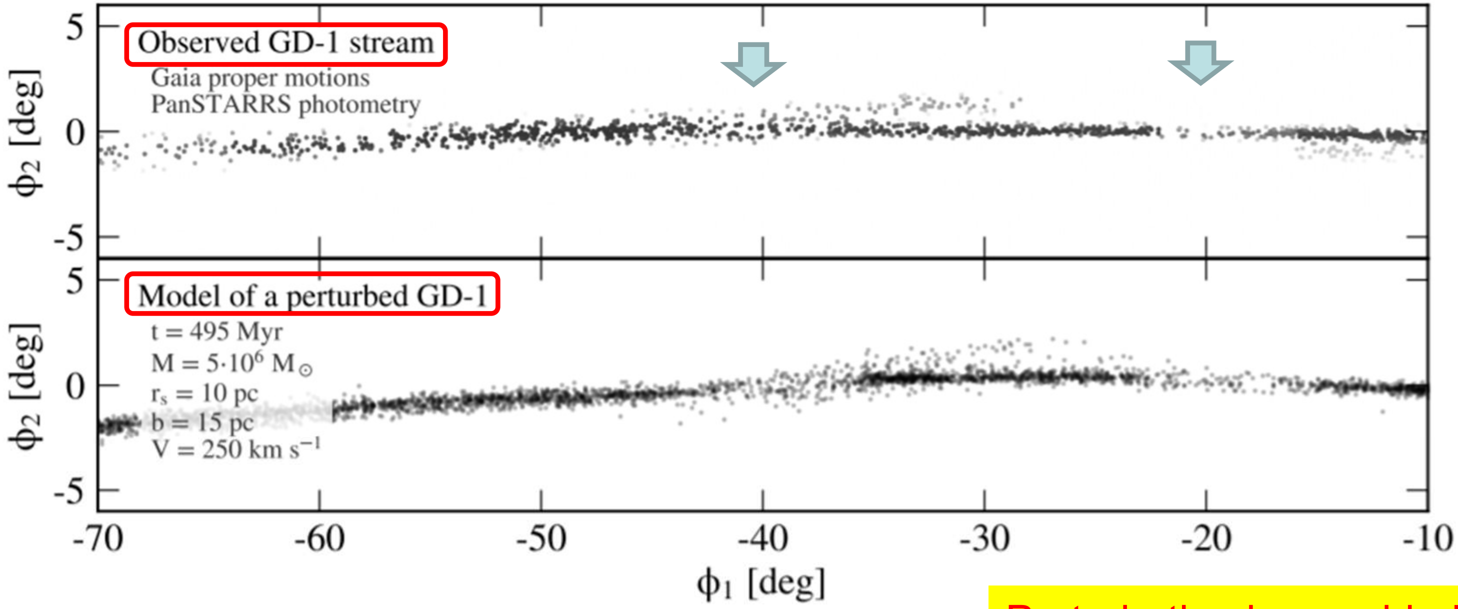
Stellar stream in the Galaxy



Credit: Y. Suzuki

Perturbation in the MW stream

Bonaca et al. 2019 GD-1 stream selected with Gaia PMs



Perturbation by a subhalo?

Figure 1. (Top) Likely members of the GD-1 stellar stream, cleanly selected using Gaia proper motions and PanSTARRS photometry, reveal two significant gaps located at $\phi_1 \approx -20°$ and $\phi_1 \approx -40°$, and dubbed G-20 and G-40, respectively. There is a long, thin spur extending for $\approx 10°$ from the G-40 gap. (Bottom) An idealized model of GD-1, whose progenitor disrupted at $\phi_1 \approx -20°$ to produce the G-20 gap, and which has been perturbed by a compact, massive object to produce the G-40 gap. The orbital structure of stars closest to the passing perturber is distorted into a loop of stars that after 0.5 Gyr appears as an underdensity coinciding with the observed gap, and extends out of the stream similar to the observed spur.

Limits on the abundance of DM subhalos from GD-1 and Pal 5 streams

Banik+2019
arXiv:1911.02663
Banik+2021
MN, 502, 2364

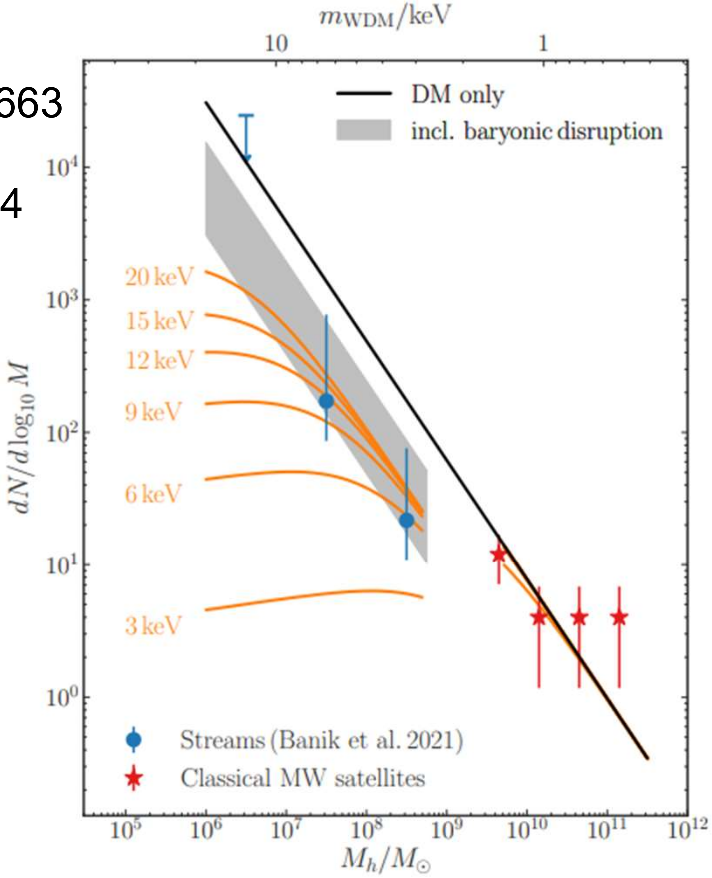


Figure 3. SHMF in the mass range $10^6 - 10^9 M_\odot$ reconstructed from the analysis of the perturbations induced on the GD-1 and Pal 5 streams. Red data points show the observed classical Milky Way satellites out to 300 kpc. The blue downward arrow and data points show the 68% upper bound, and the measurement and 68% error, respectively, in 3 mass bins below the scale of dwarfs, as obtained in B21 and extrapolated out to 300 kpc to place them on the same SHMF as the red points. The shaded area show the CDM mass function taking into account the baryonic disruption of the subhalos. The orange lines show the predicted mass function for thermal WDM candidates of different mass, taking into account the expected subhalo depletion due to baryonic disruption for the low-mass ($M < 10^9 M_\odot$) measurements from the inner Milky Way.

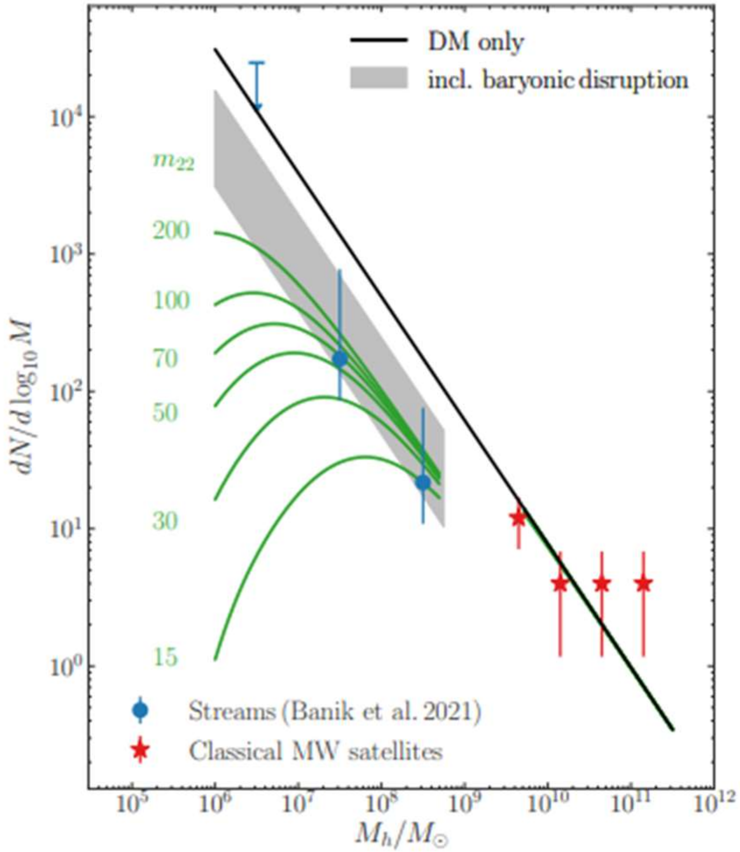
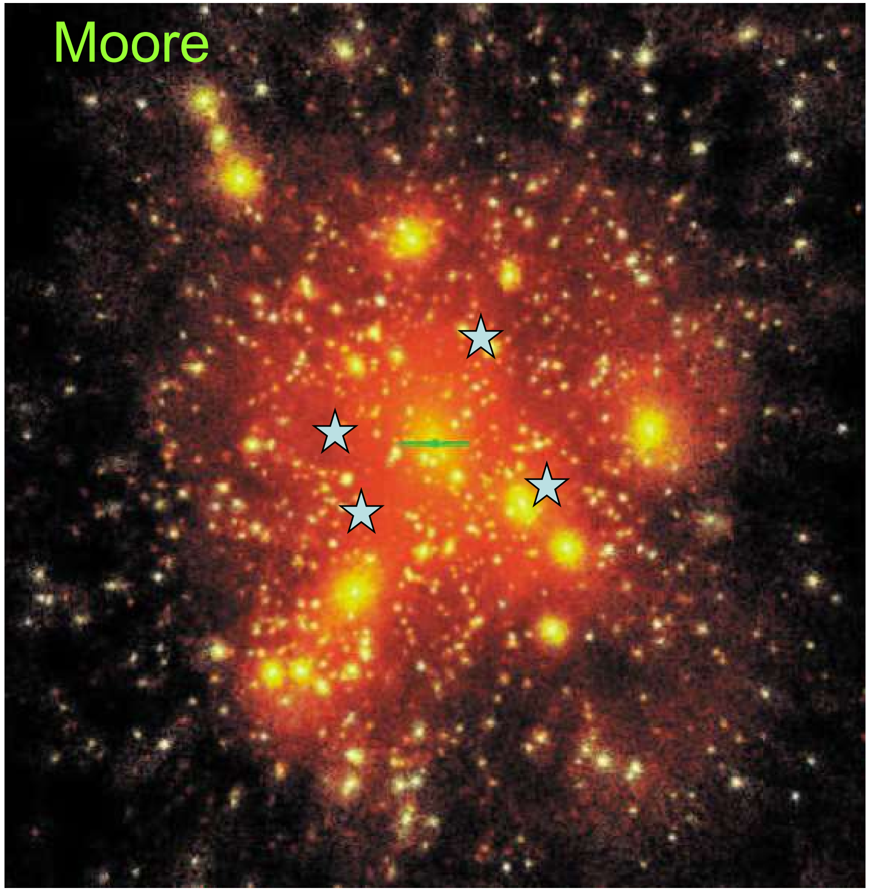


Figure 6. Milky Way SHMF compared with fuzzy DM models for different FDM masses. Data, black line, and gray band are as in Fig. 3, but green curves now show predicted SHMFs for fuzzy DM models with different FDM masses $m_{22} = m_{\rm FDM}/10^{-22}$ eV.

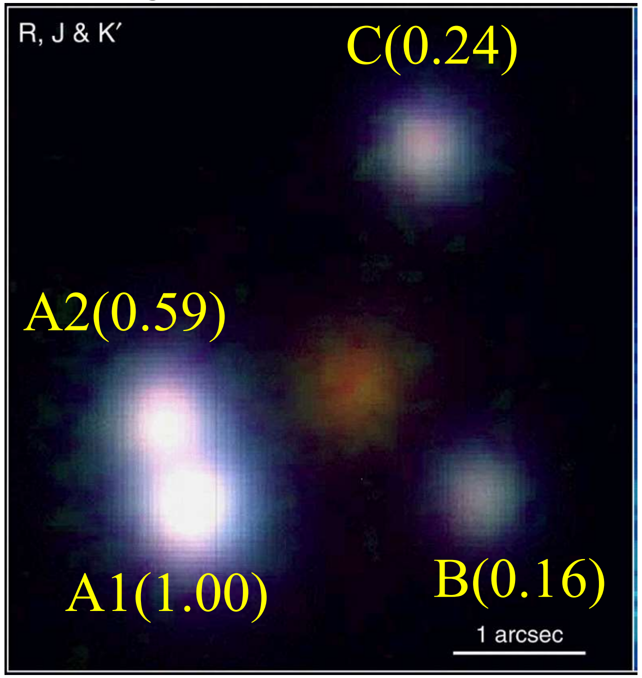
Lens mapping of CDM subhalos



"Anomalous Flux Ratios" for multiply lensed QSOs
(Metcalf & Madau 2001, Chiba 2002, Dalal & Kochanek 2002)

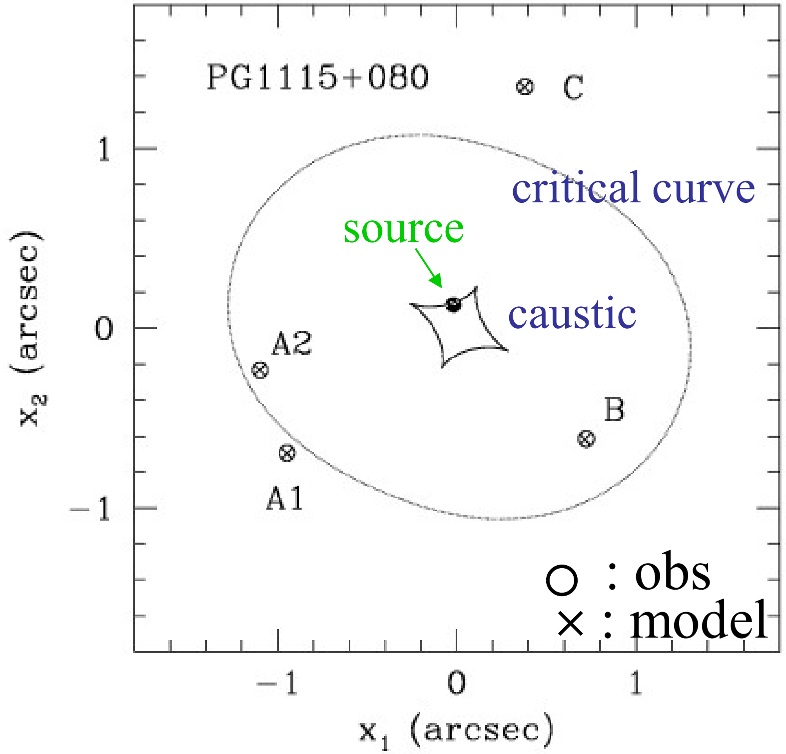
These are hardly explained by smooth lens models.

PG1115+080
(radio quiet)
z_S=1.72, z_L=0.31



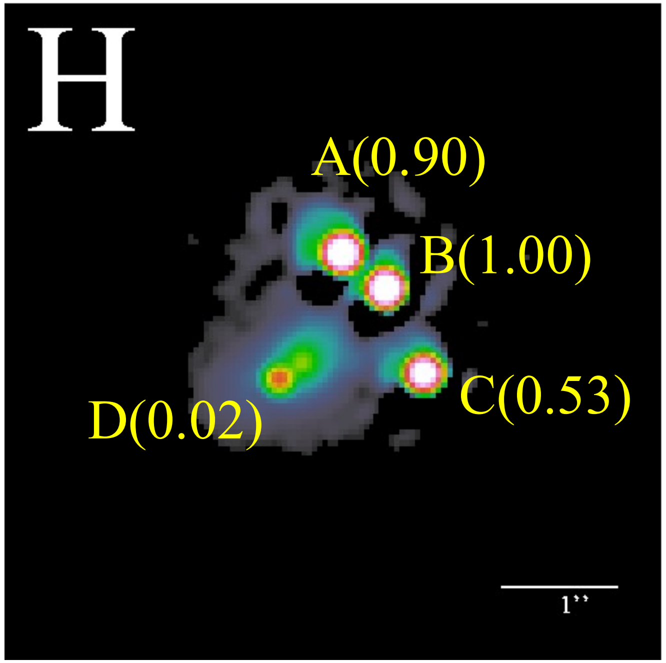
Iwamuro et al. 2000

Smooth lens model
(Singular Isothermal Ellipsoid
+ External Shear)
(Chiba 2002)



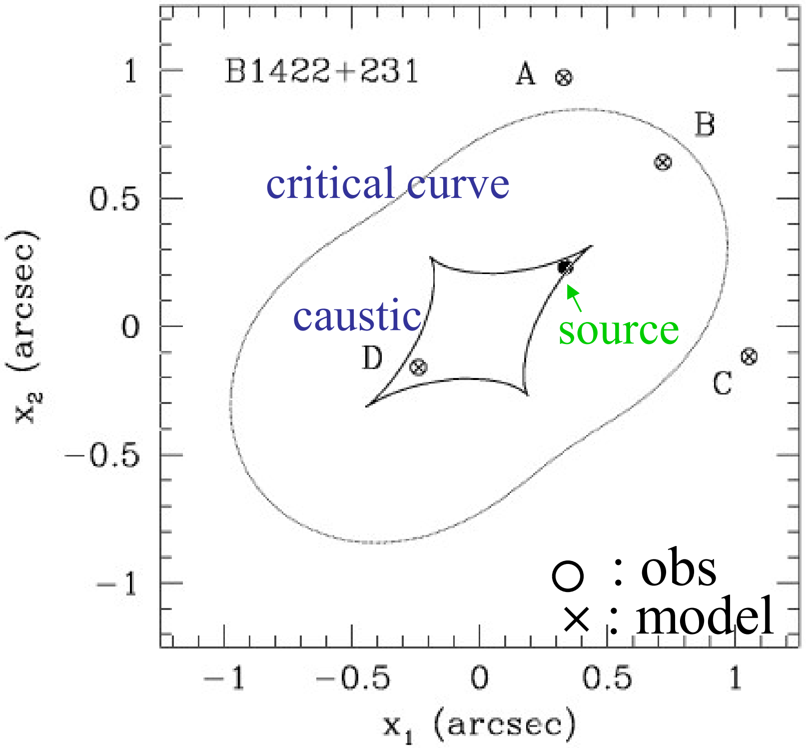
Model: A2/A1 ≈ 1 (fold caustic)
Observed A2/A1 (near-IR): ≈ 0.59 – 0.67 (anomalous)

B1422+231
(radio loud)
z_S=3.62, z_L=0.34



CASTLES

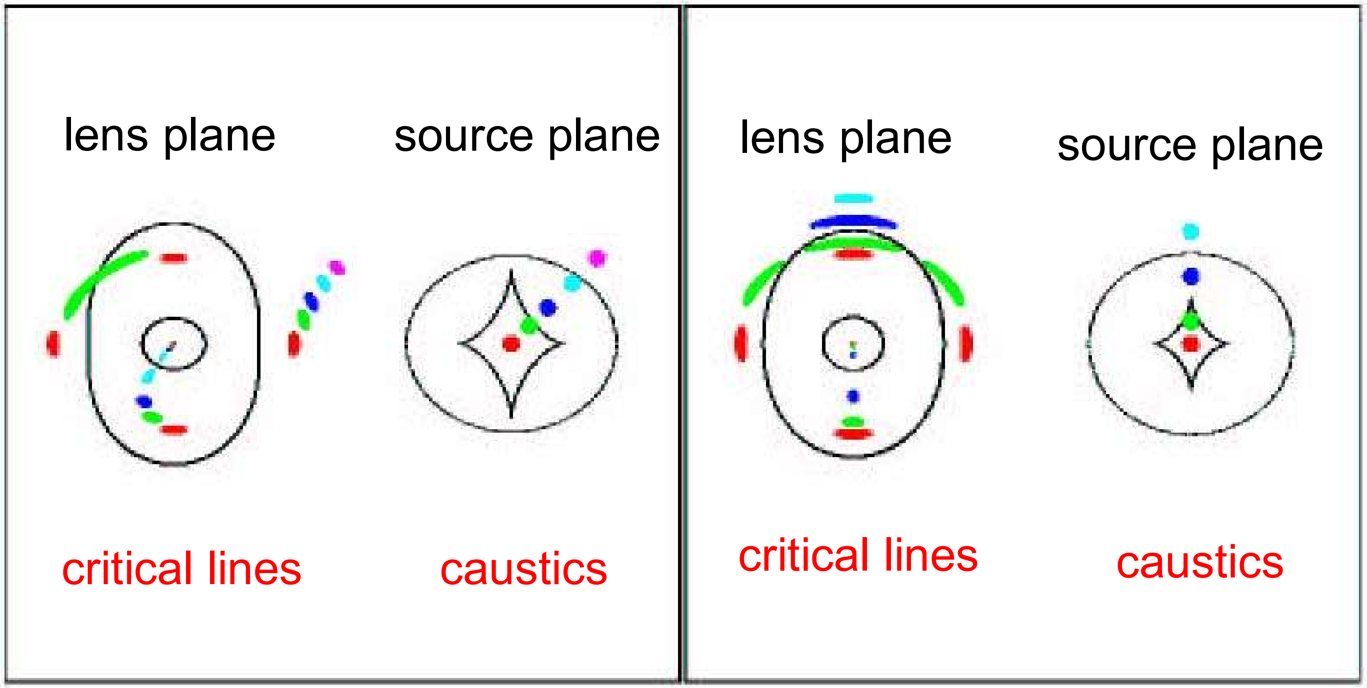
Smooth lens model
(Singular Isothermal Ellipsoid
+ External Shear)



Model: (A+C)/B ≈ 1 (cusp caustic)

Observed (A+C)/B (radio): ≈ 1.42 – 1.50 (anomalous)

Elliptical Lens



● 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!?

Limits on the abundance of WDM subhalos from lensing

Schutz 2021 (arXiv: 2001.05503)

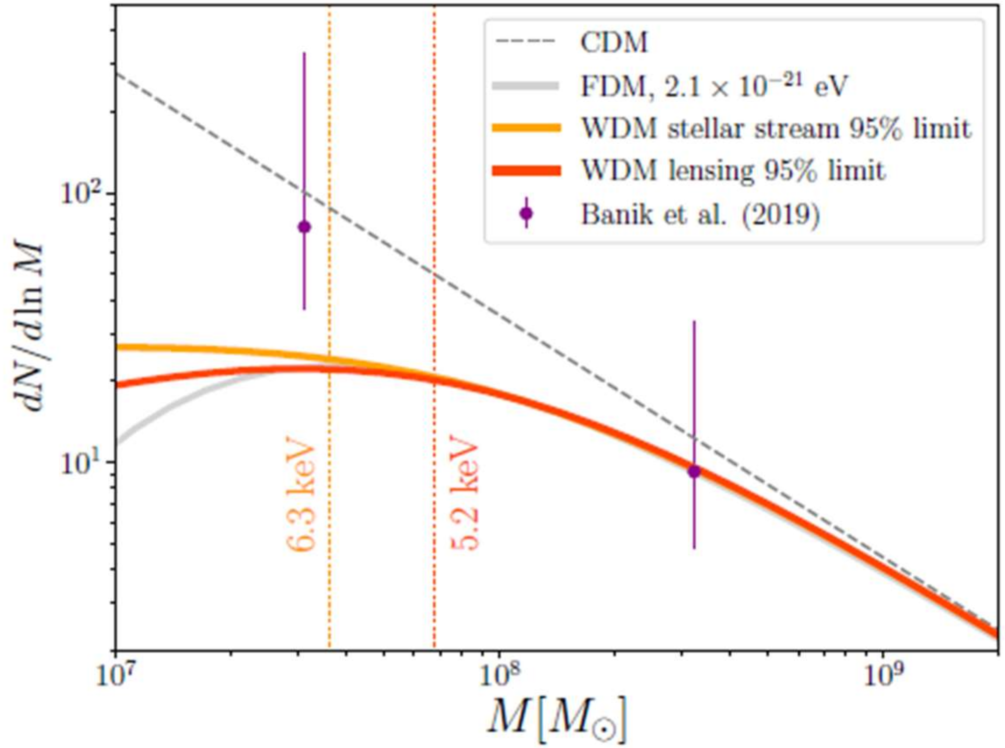
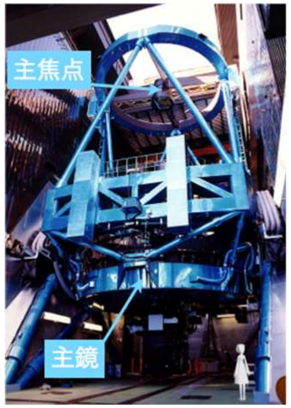


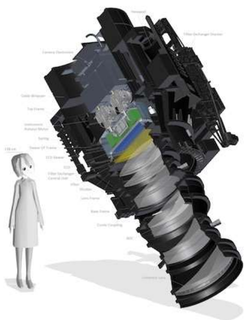
FIG. 1. The SHMF for our mass limit on FDM as compared with the SHMFs for WDM that are constrained by Ref. [7] from stellar streams and Ref. [6] from lensing. Vertical dotted lines show the half-mode mass $M_{\rm hm}$ for the values of m_χ that are excluded in those works. The value of m_{22} shown was chosen to be the maximum value of m_{22} where the predicted suppression of the FDM SHMF is more dramatic than for the excluded WDM cases at all subhalo masses. In this sense, the limits on WDM can be conservatively applied to FDM. Note that all SHMFs have been normalized to match Fig. 3 of Ref. [7] for subhalo masses below $\sim 10^9 M_\odot$, purely for the purposes of comparison of the SHMF shapes. Also note that Refs. [7] and [6] model the WDM SHMF slightly differently as a function of subhalo mass, which gives slightly different SHMF shapes for fixed m_χ.

Then, solutions under the CDM model?

- Alternative DM models
  - Suppression of small-scale powers: WDM, FDM (Hui et al. 2017)
  - Self-interacting DM producing a core (Spergel & Steinhardt 2000)
- Astrophysical effects on CDM models
  - Reionized universe: suppression of galaxy formation in small halos
  - Core-induced baryonic feedback erasing a cusp
- Limitation of current observations
  - More satellites yet undetected in the distant halo
  - Uncertainties in determining DM profile from dwarf spirals
    - Non-circular motions, smearing effects from finite resolution …

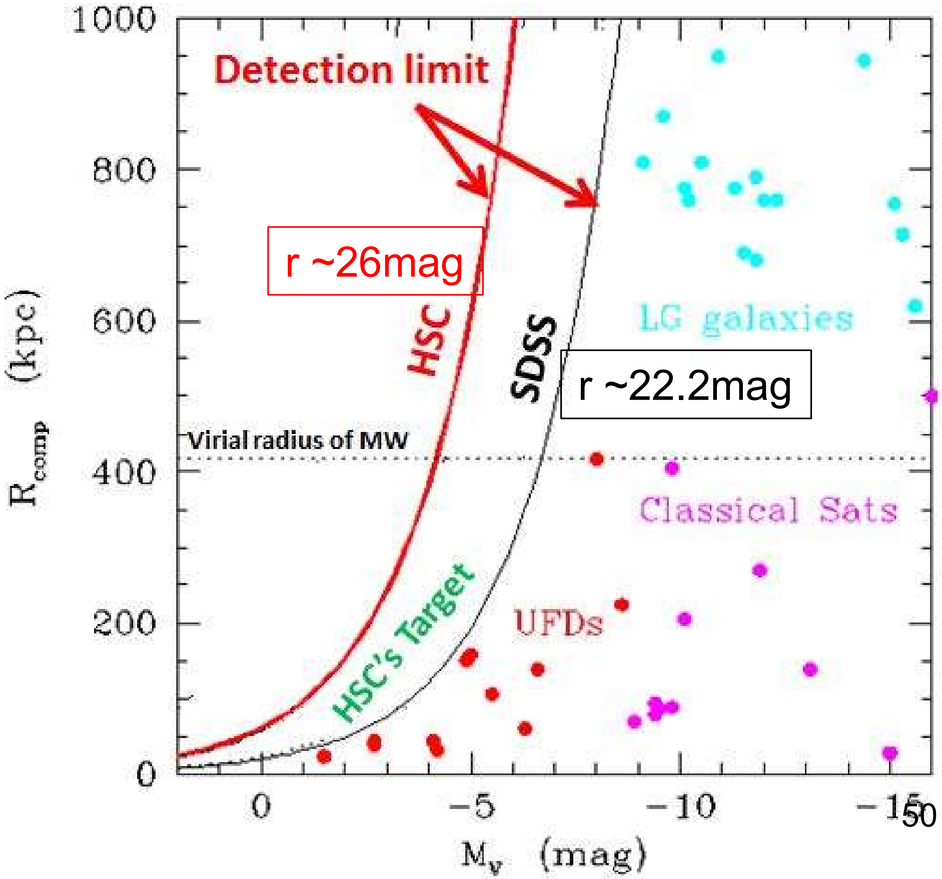
5. New limits from stellar systems in the Galaxy
5.1 Search for new MW satellites
UFDs: ultra-faint dwarfs (M_V > -8 mag)





Subaru Telescope
Hyper Suprime Cam (HSC)

FOV: 1.77 sq deg
(1.5 deg diameter)
Pixel scale: 0".17/pix
Filters: grizy + many NB
Operation: 2013~



HSC-Subaru Strategic Program (SSP)

330 nights over 6 years, Wide, Deep & Ultra-deep layers

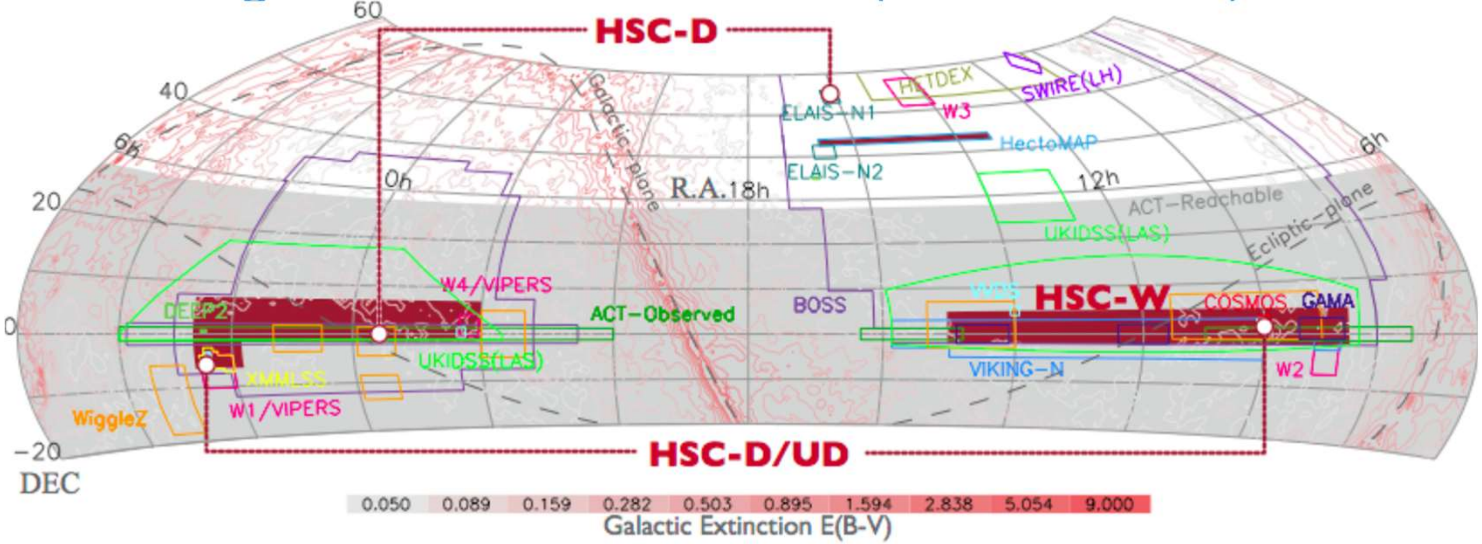
- MW science from the Wide-layer data

  Latest internal data release S21A: over ~1,200 deg^2

  (1) Searching for new MW satellites (e.g. Homma+2024)

  (2) Mapping Halo with Blue Horizontal-Branch stars (e.g. Fukushima+2024)

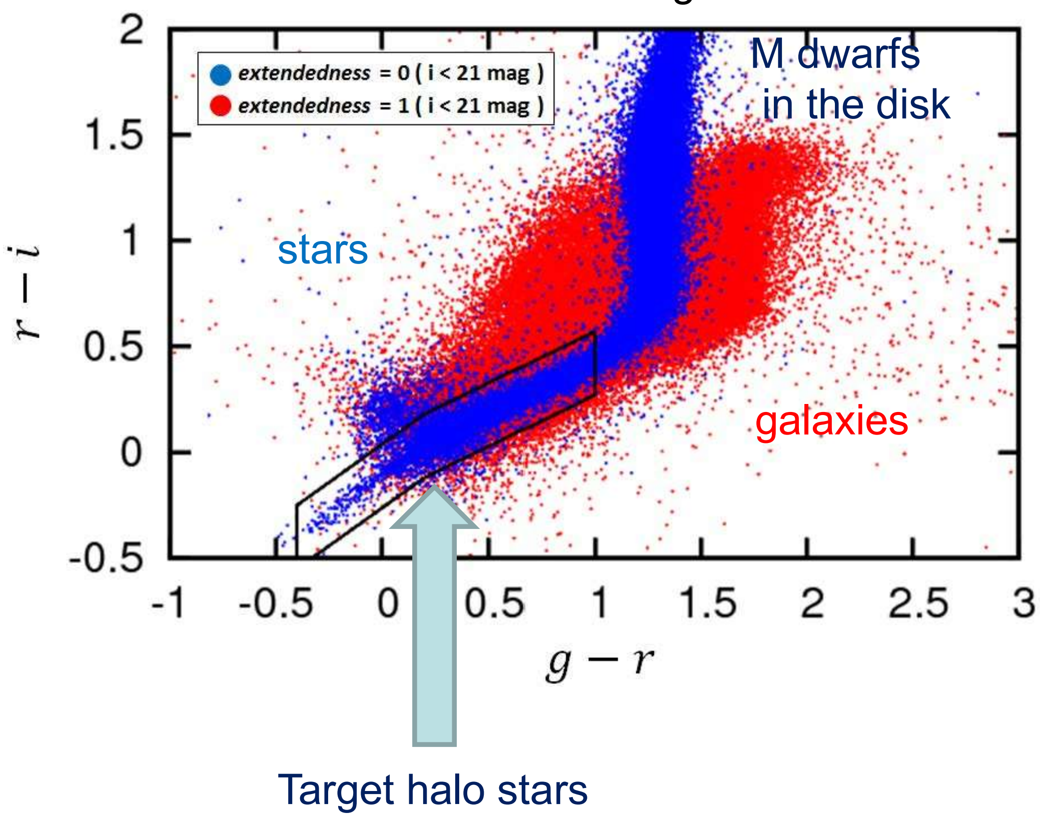
  (3) Searching for new stellar streams (Suzuki+ 2024)



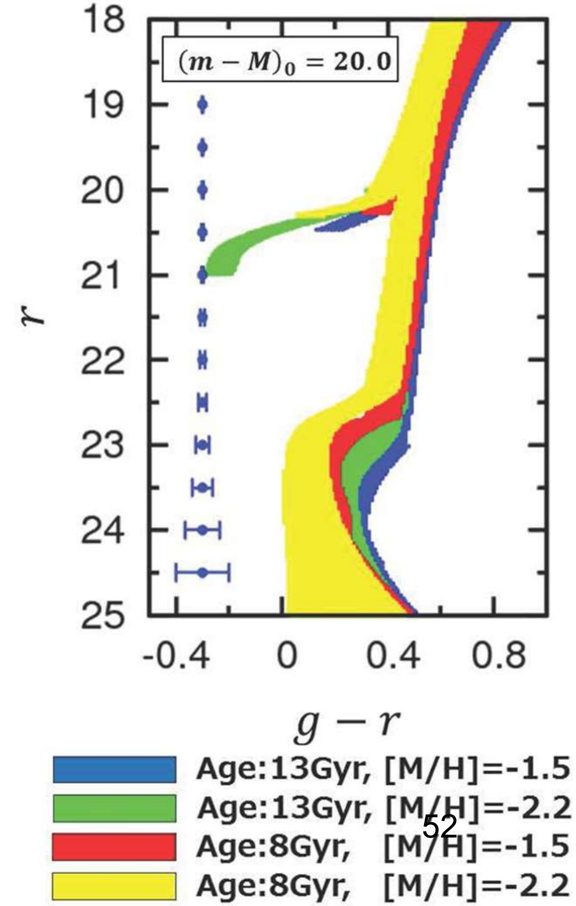
Search for new MW satellites from HSC-SSP

- Select point sources (stars)
- Remove remaining contaminants from color-color diagram
- Set isochrone filters and count stars in 0.05° x 0.05° bin (80 pc at D=90 kpc)
- Find overdensities with high statistical significance

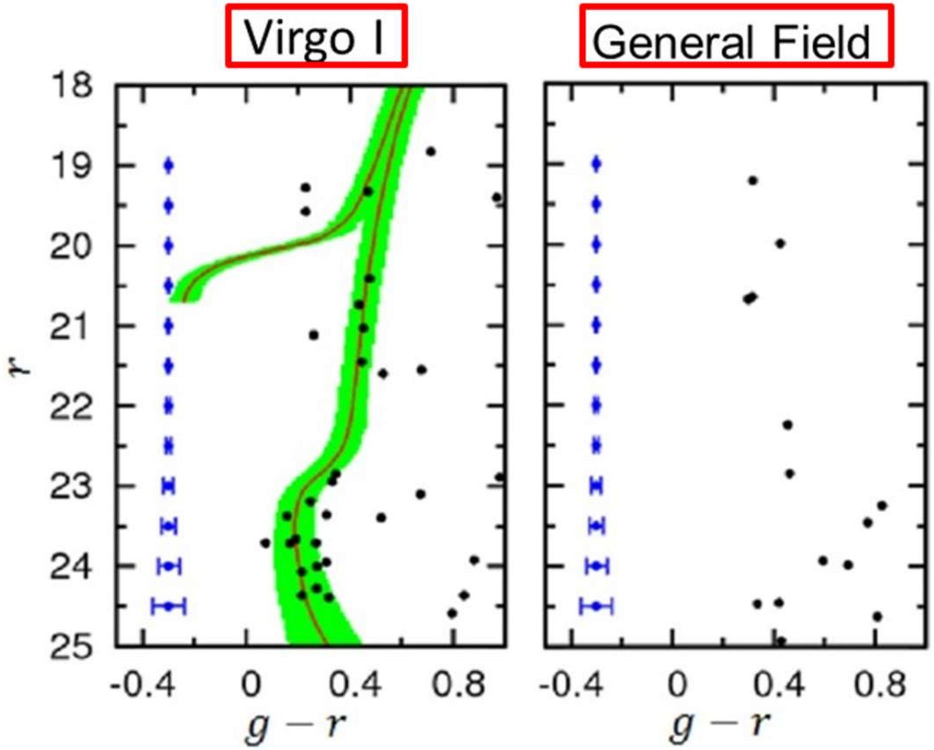
Color-color diagram



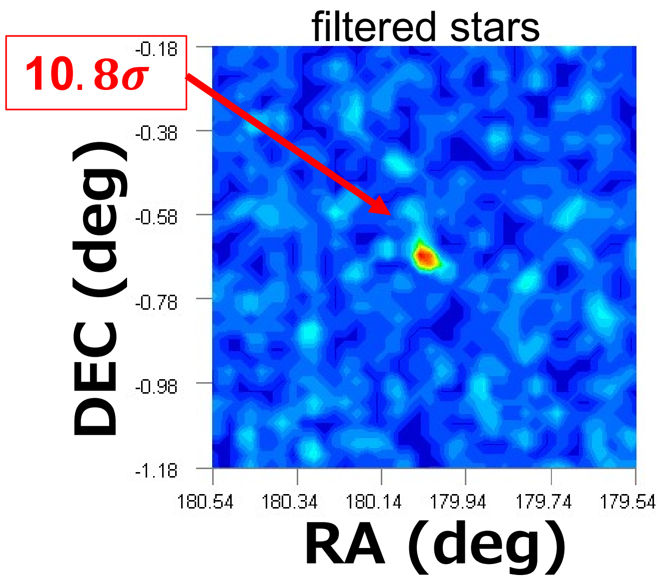
Isochrone filter
in the color-mag diagram



Stellar distribution
in the color-magnitude diagram



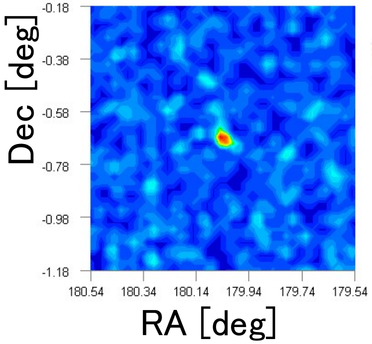
Stars passing the Isochrone filter
(green shaded envelope)

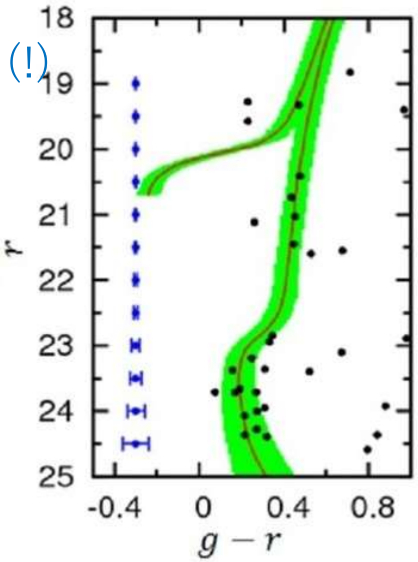


10.8σ overdensity
M_V = - 0.90 mag (faintest dSphs)

Virgo I

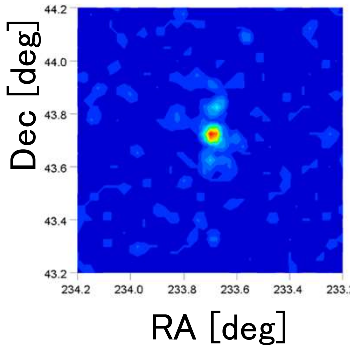
M_V = -0.90 mag (!)
D = 91 kpc
r_h = 47 pc

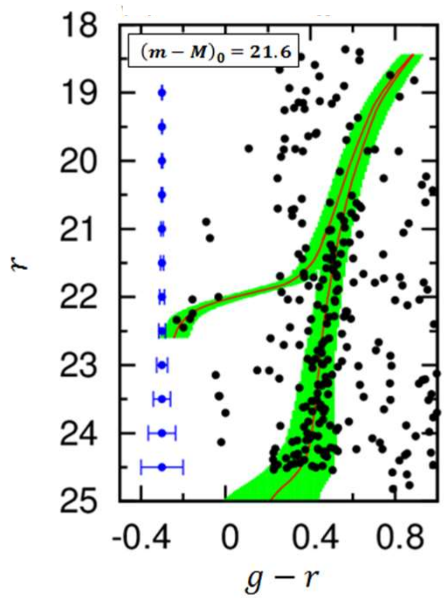




Bootes IV

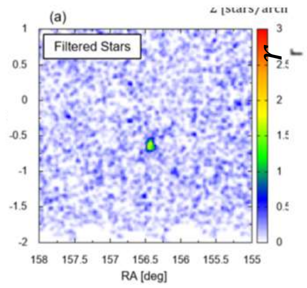
M_V = -5.34 mag
D = 209 kpc (!)
r_h = 462 pc

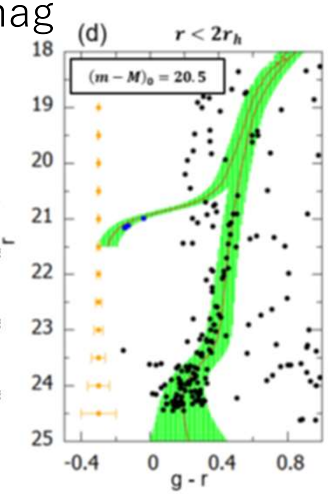




Sextans II

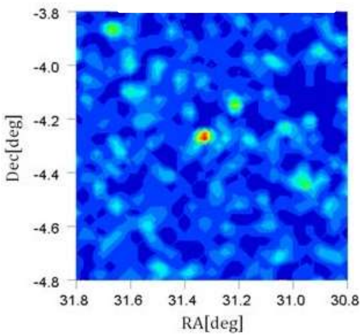
M_V = -3.91 mag
D = 126 kpc
r_h = 154 pc

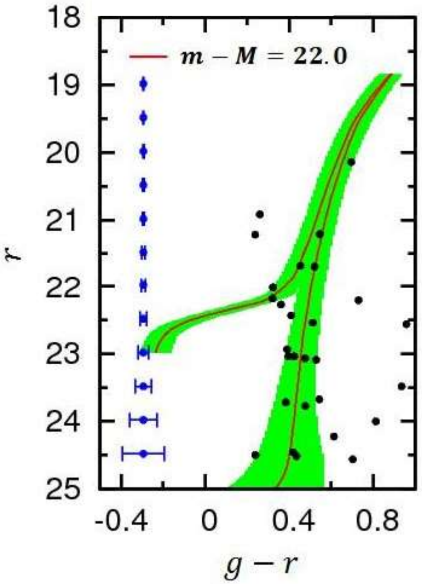




Cetus III

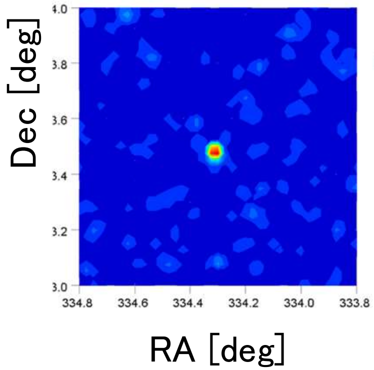
M_V = -3.45 mag
D = 251 kpc (!)
r_h = 90 pc

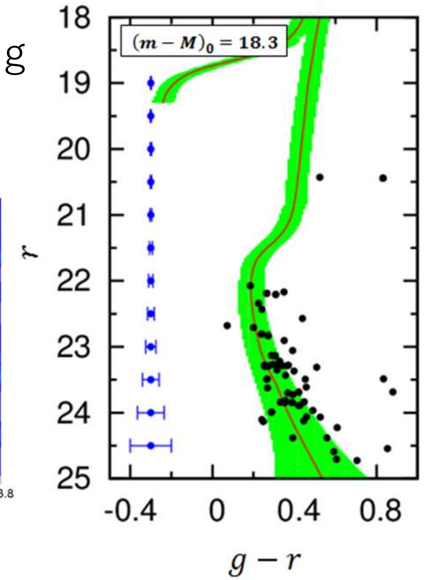




HSC 1

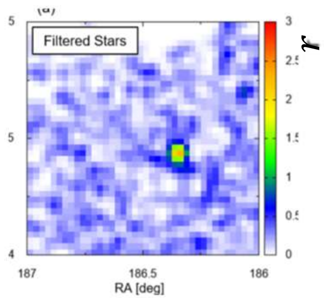
M_V = -0.20 mag
D = 46 kpc
r_h = 5.9 pc

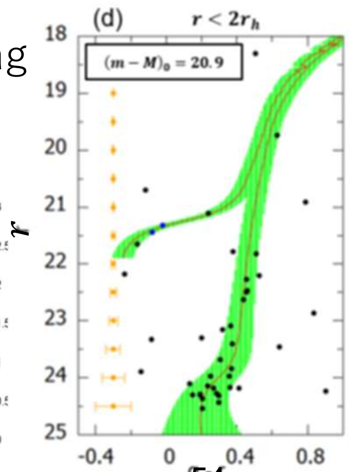




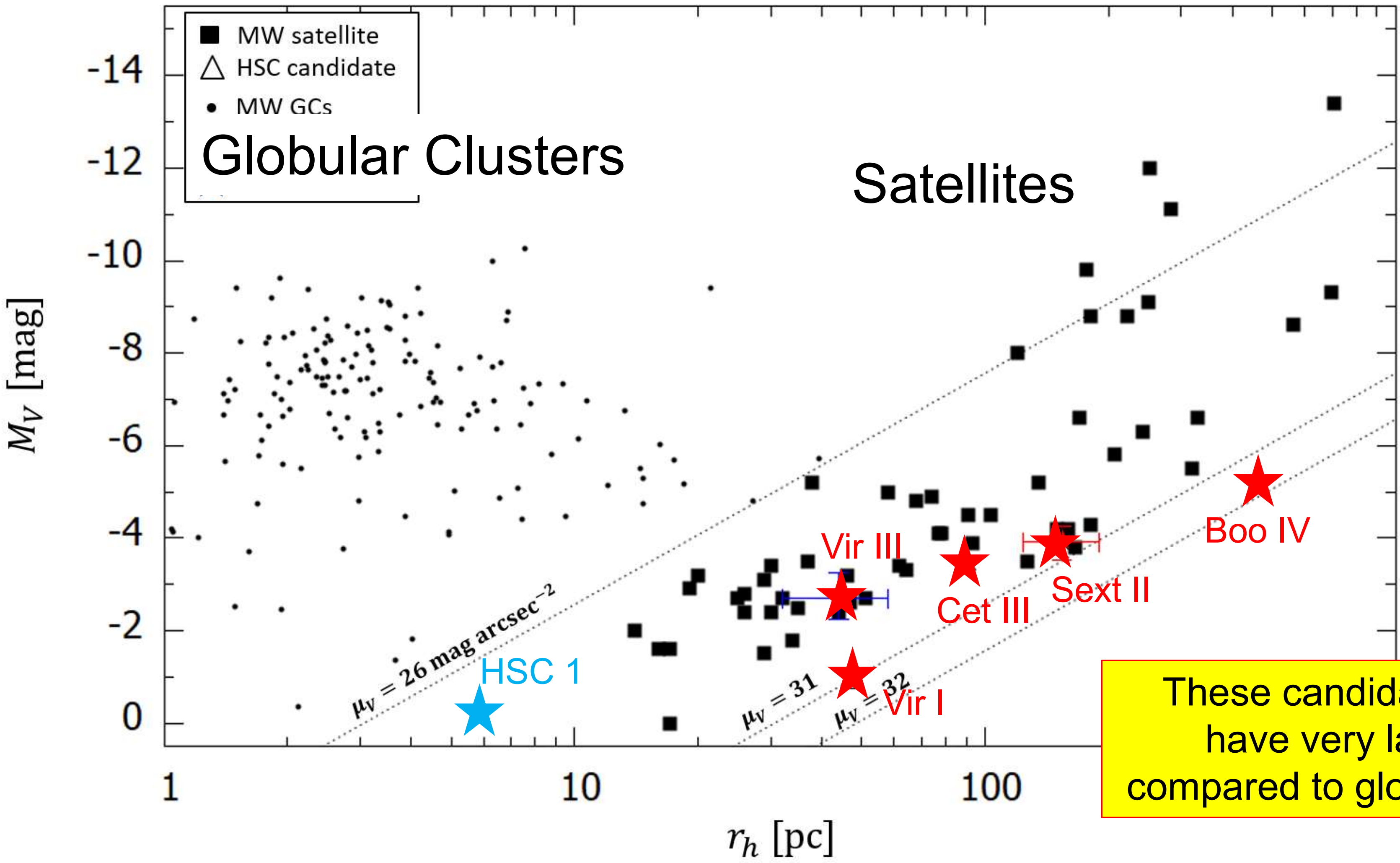
Virgo III

M_V = -2.69mag
D = 151 kpc
r_h = 44 pc



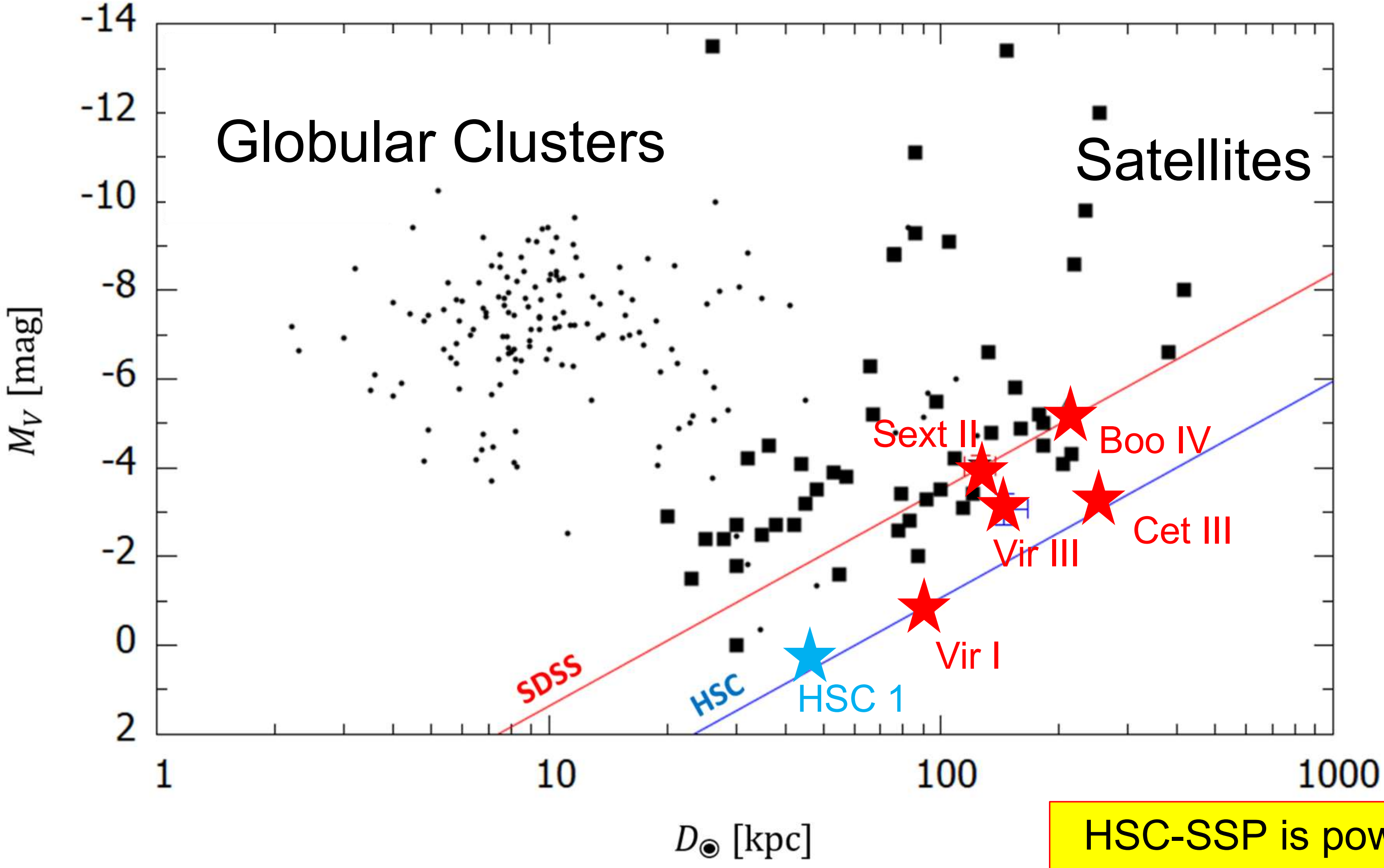


M_V vs half-light radius r_h



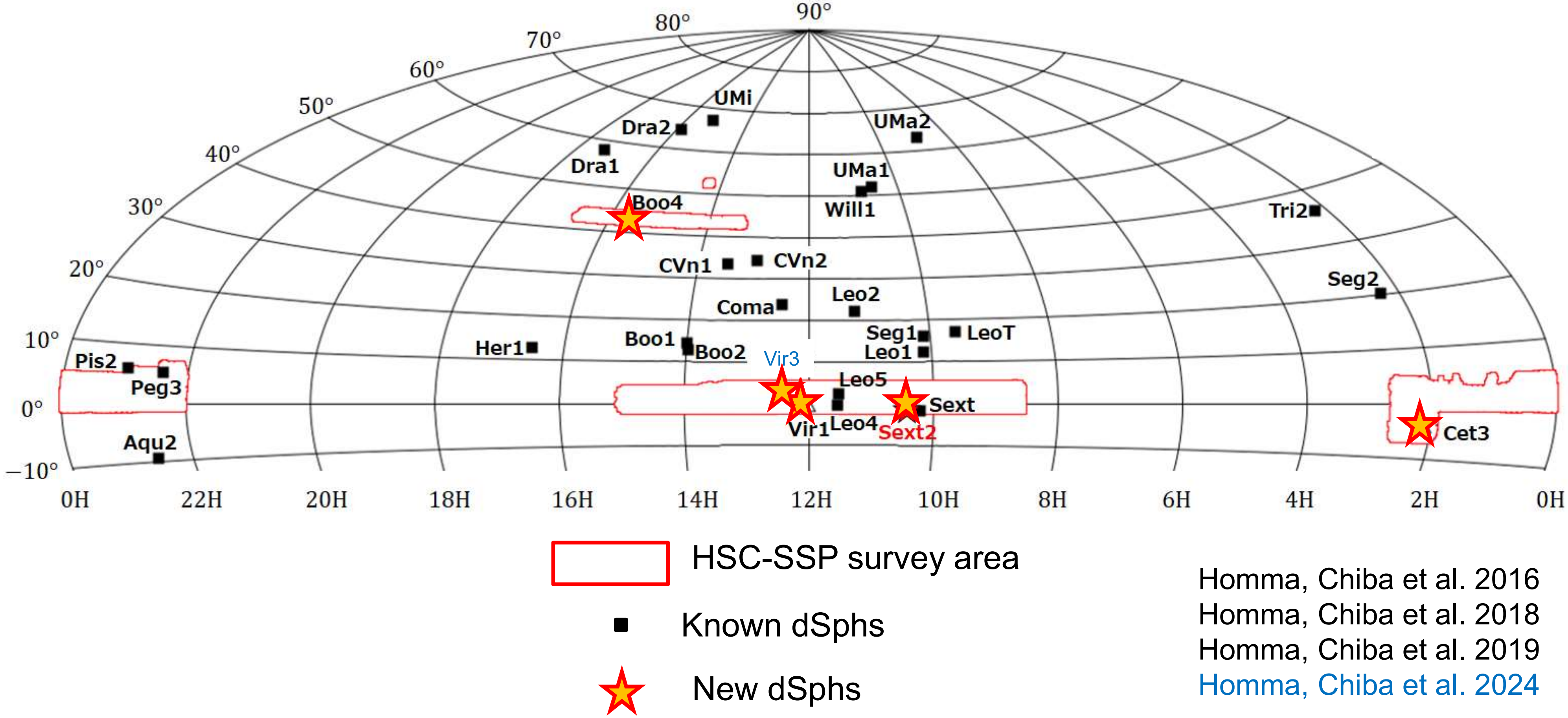
These candidate satellites have very large sizes compared to globular clusters.

M_V vs heliocentric distance



HSC-SSP is powerful to identify very distant stellar systems.

Implication for the missing satellites problem



Homma, Chiba et al. 2016
Homma, Chiba et al. 2018
Homma, Chiba et al. 2019
Homma, Chiba et al. 2024

9 satellites over ~ 1,200 deg^2: 5 new + 4 known satellites (Sext, Leo IV, Leo V, Peg III)

Implication for the missing satellites problem

- Nadler et al. (2020) satellite formation models in ΛCDM
  - DM-only simulation for MW-mass halos with LMC analog

    + galaxy-halo connection model (abundance matching),

    + marginalized over the satellites in the fields of DES+PS1 (r_{lim}=23.7, 22.5)

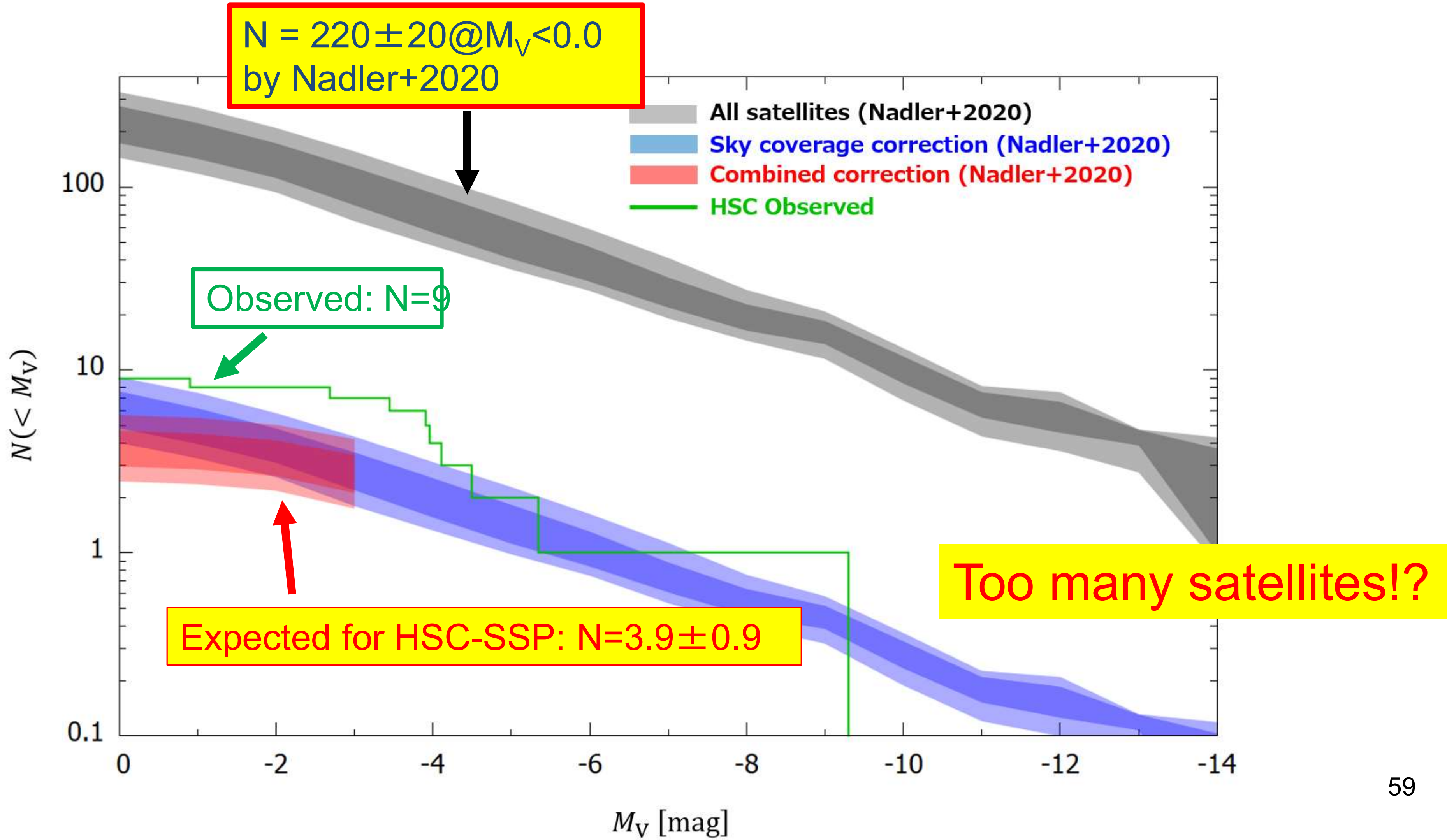
      (~ 15,000 deg^2, much wider but shallower than HSC-SSP)
  - Expected total number of luminous satellites $N_{tot} = 220 \pm 20$ at $M_V < 0$
  - HSC-SSP sky coverage correction: 6.2 ± 1.6 (if isotropically distributed)
  - HSC completeness correction: 3.9 ± 0.9

    compared to observed 9 in HSC-SSP footprint

    ⇒ Too many satellites!?

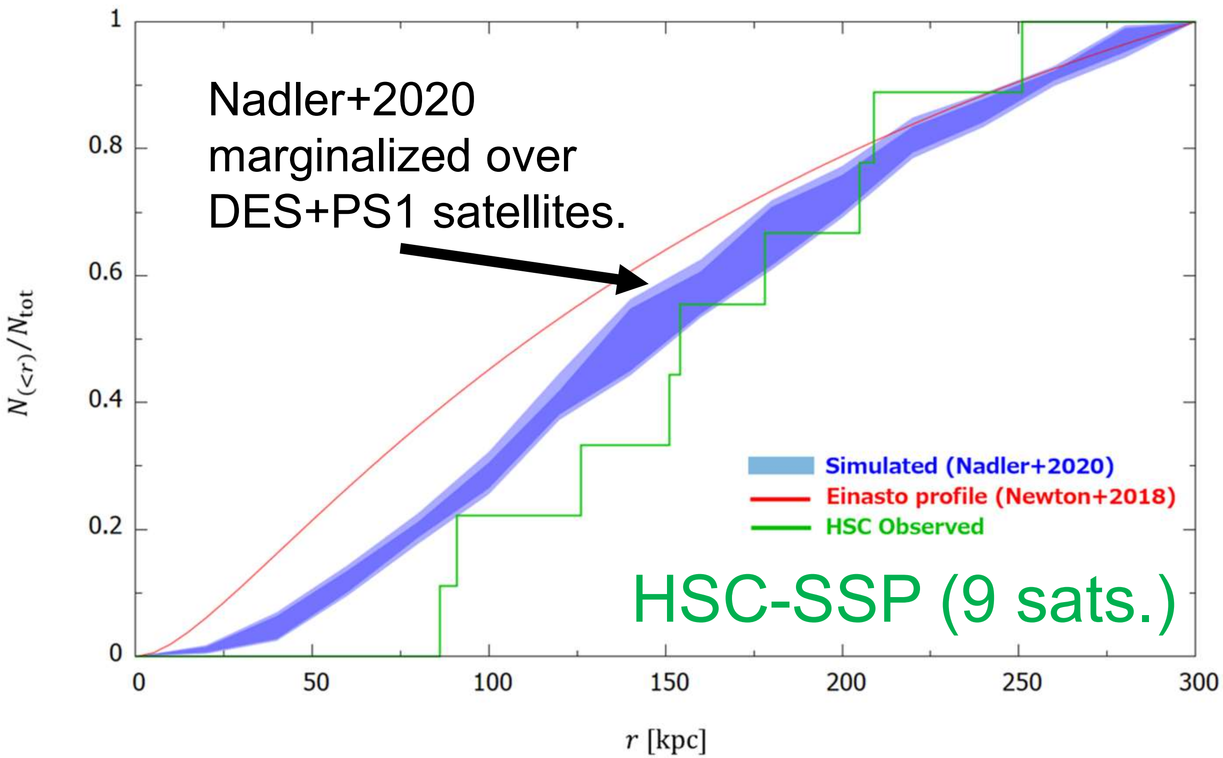
    N_{tot} (true) = 9/3.9 x 220 = 508 ?

Implication for the missing satellites problem



Implication for the missing satellites problem

~ Why too many satellites? ~



1. More satellites in the distant, outer halo ?

2. Revision of galaxy formation modeling
- anisotropic distribution?
- too much suppression?

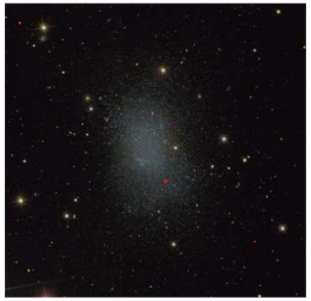
More refinement for CDM vs. galaxy formation

The missing satellites problem in CDM is not so serious!
WDM with light mass (<4kev), suggesting N_{tot} < 100, is ruled out

5.2 DM profiles in dwarf spheroidal galaxies (dSphs)

Fornax

Sextans



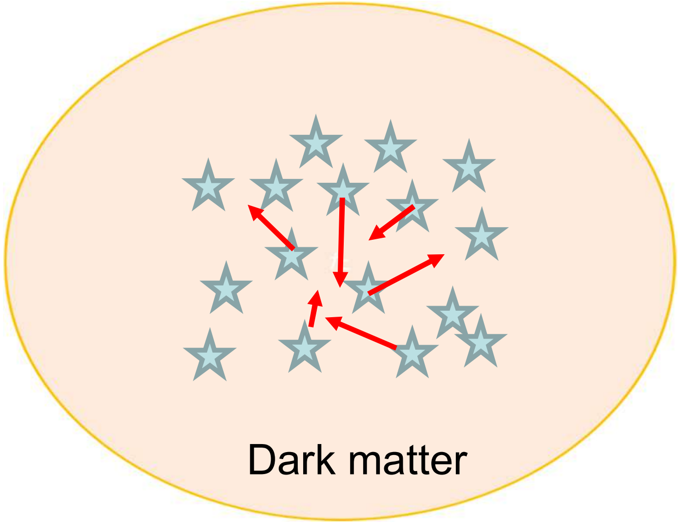
Dominant satellites in the Milky Way

no gas, diffuse and faint stellar systems

Dark matter is dominated significantly

(M/L)_tot = 10~1,000

Best site for studying DM!



Total stellar mass = 10^4~$10^6 M_{sun}$
Random motion ～10 km/s

↓

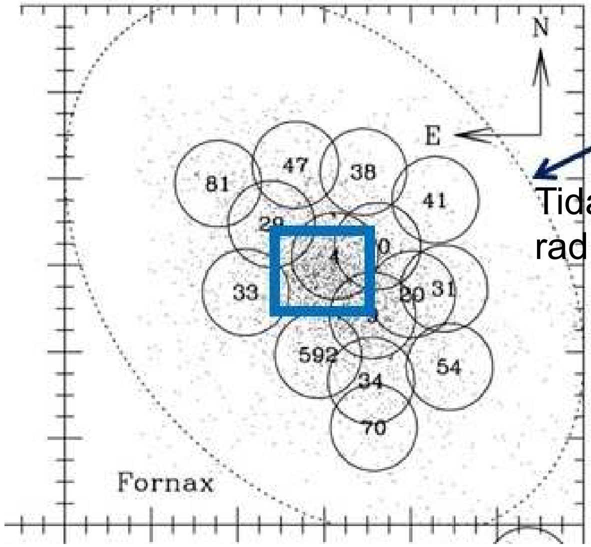
Self-gravity of the stellar system alone cannot bind member stars

↓

Massive dark matter needed

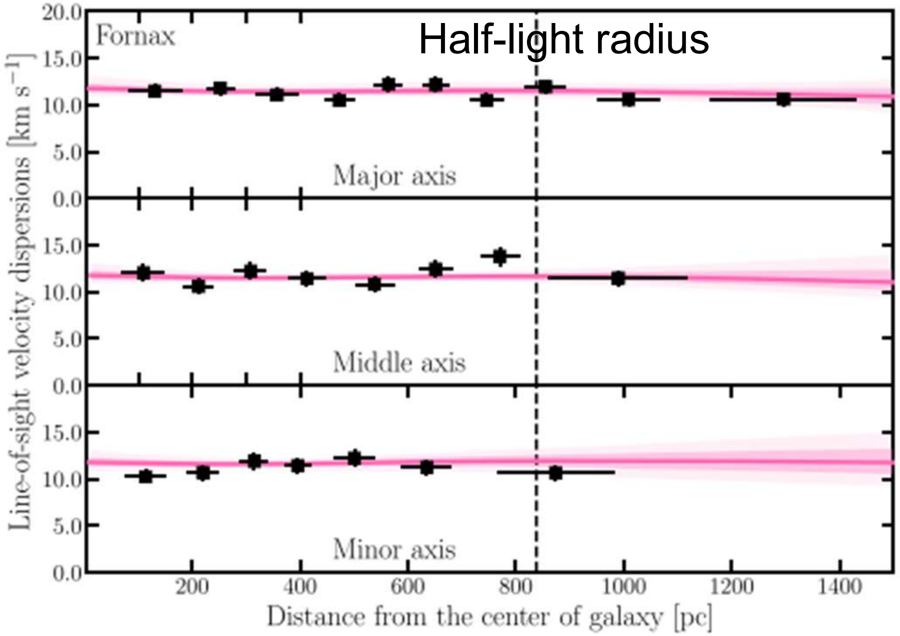
Deriving DM profiles in dSphs

Fornax



Radial velocity measurements with MMFS (Walker+2009) (Michigan/MIKE Fiber System at Magellan)

Velocity dispersion profile



Hayashi, Chiba, Ishiyama (2020)

LOS velocity dispersion profile of of member stars

↓

Dynamical analysis e.g. using Jeans equation

↓

Density distribution of dark matter ρ(r)

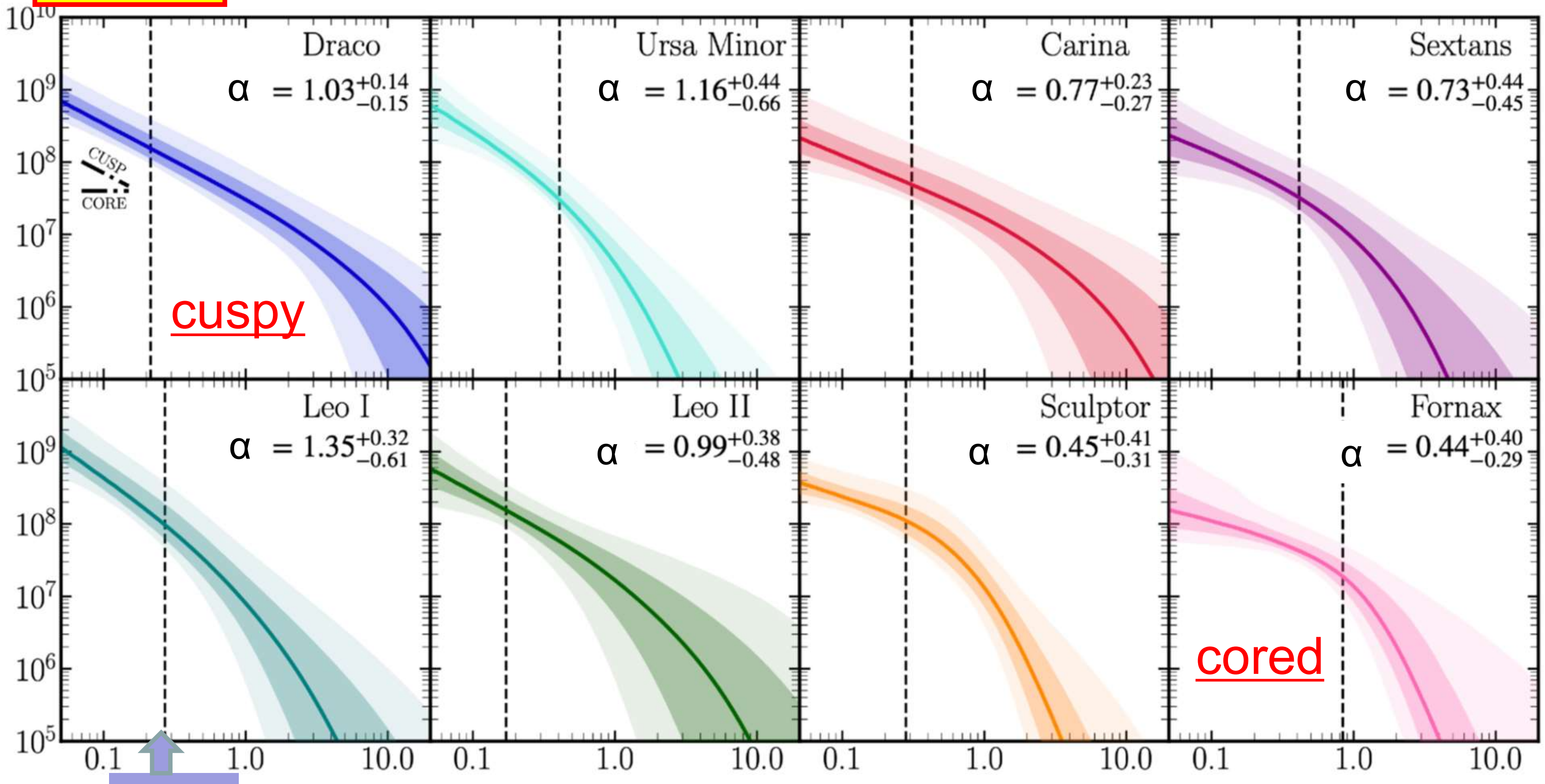
Diversity in the dark matter profiles of the Milky Way dSphs

(Hayashi, Chiba, Ishiyama 2020)

Hayashi

$\rho \propto r^{-\alpha}$

$\Delta\alpha \sim 0.45$



r_half

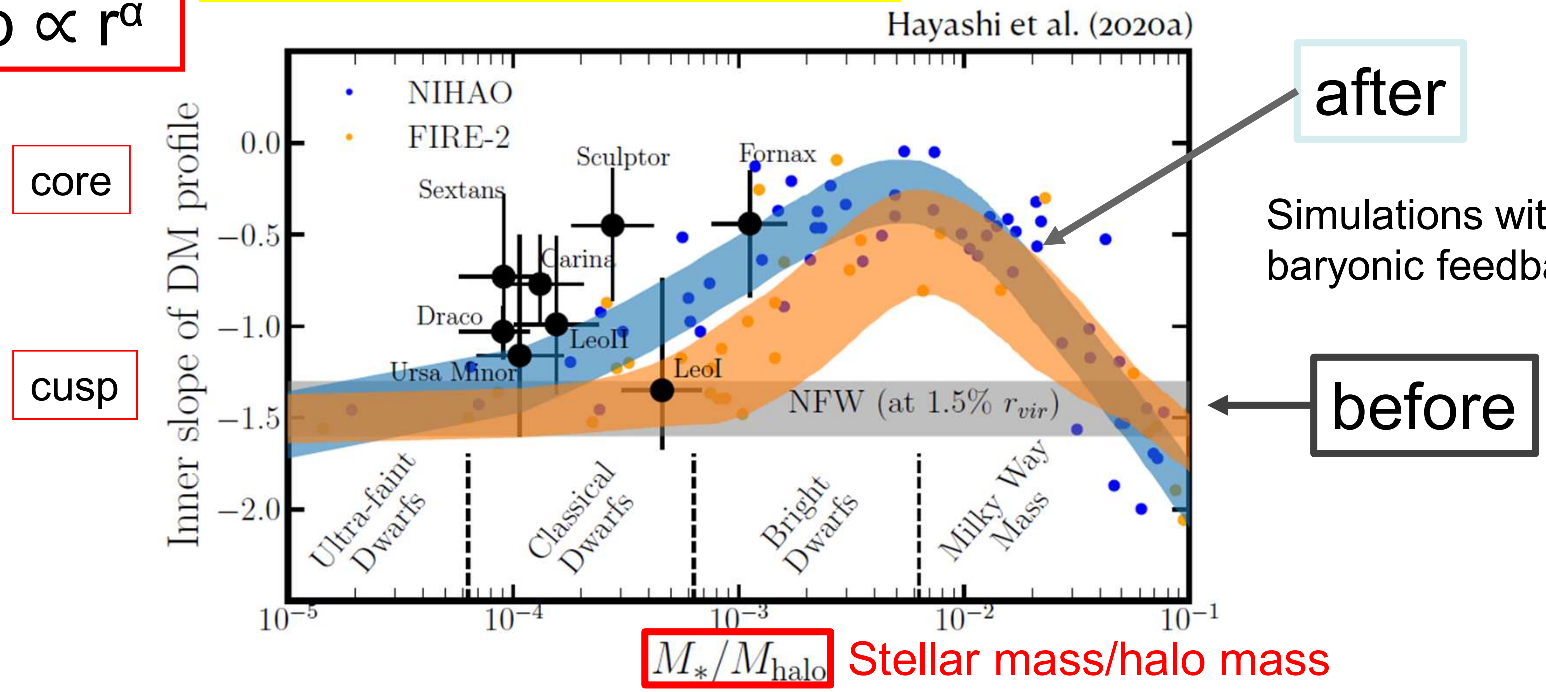
Major axis (kpc)

Why diversity?

- Baryonic feedback effects to erase a cusp in CDM

Change of inner density slope α

$\rho \propto r^{\alpha}$



- Yet small number of observed stars, small spatial coverage
  - Uncertainties in measuring DM profile

Summary

- The Milky Way is dominated by a dark halo
  - Halo tracers suggest M_{tot} (MW) =~ 1 x 10^{12} M_{sun}
  - Sgr stream suggests a nearly spherical shape at 15 < r < 60 kpc
  - Flat rotation curve suggests $\rho_{tot}(r) \propto r^{-2}$ in the inner part (where a disk dominates)
- Satellite galaxies and small-scale issues
  - Largely dark-matter dominated: (M/L) = 10 ~ 1000
  - Small-scale issues in CDM
    - Total number is small (Missing satellites problem)
    - Cored in some galaxies (Core/cusp problem)
    - Mean density is small (Too big to fail problem)