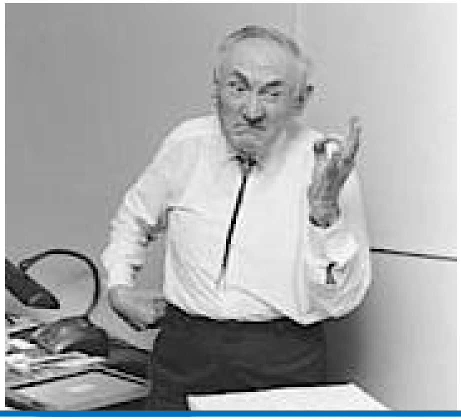
Chapter 5. 銀河の暗黒物質

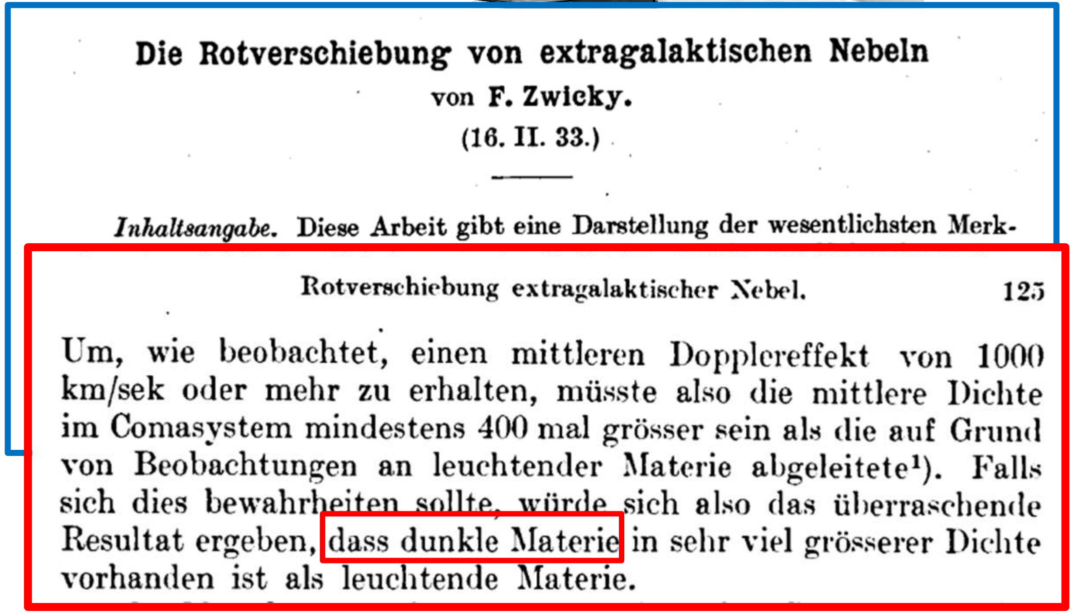
5.1 ダークマターの発見

ダークマターの証拠 (1)
銀河団内の銀河の運動

Fritz Zwicky 1933



Coma Cluster of galaxies



Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merk-

Rotverschiebung extragalaktischer Nebel. 125

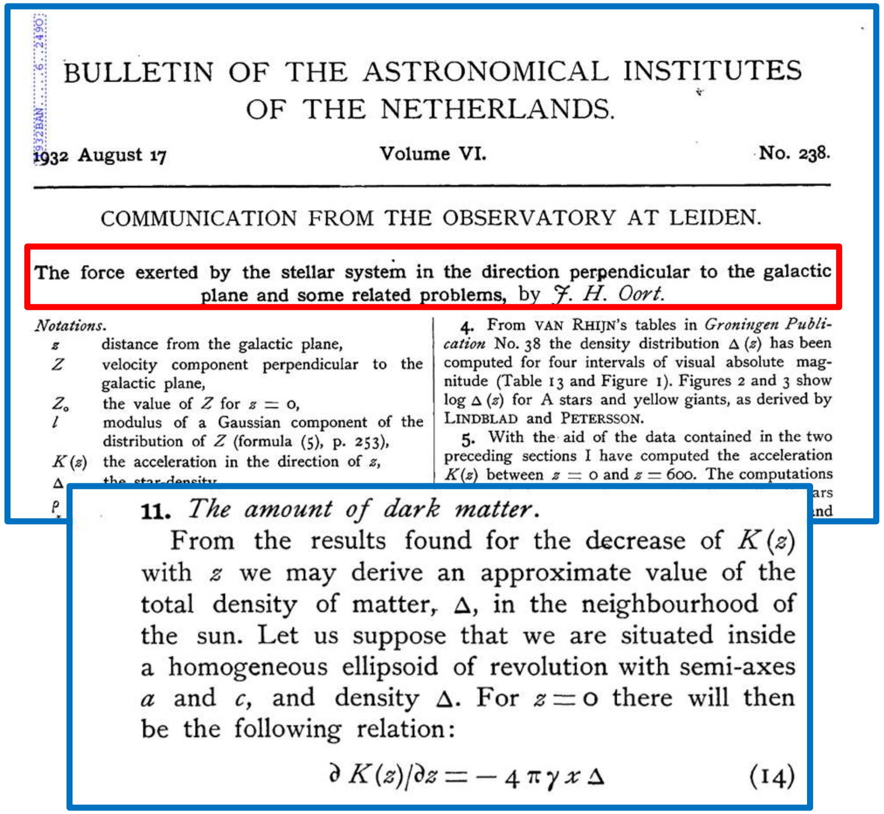
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Spatial motions of galaxies in the cluster
(velocity dispersion): $<V^2>^{1/2}$ ~ 1000 km/s
Radius of the cluster: R ~ 4 Mpc
Virial theorem: $<V^2>$ ~ GM/2R
⇒ Total (dynamical) mass M_{dyn} ~ 2 x 10^{15} M_{sun}
whereas total luminous mass M_{lum} ~ $10^{13}M_{sun}$
⇒ dark matter between galaxies

ダークマターの証拠 (2)
太陽近傍の恒星の運動

Jan 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.

z distance from the galactic plane,
Z velocity component perpendicular to the galactic plane,
Z_o the value of Z for $z = 0$,
l modulus of a Gaussian component of the distribution of Z (formula (5), p. 253),
$K(z)$ the acceleration in the direction of z,
Δ the star-density

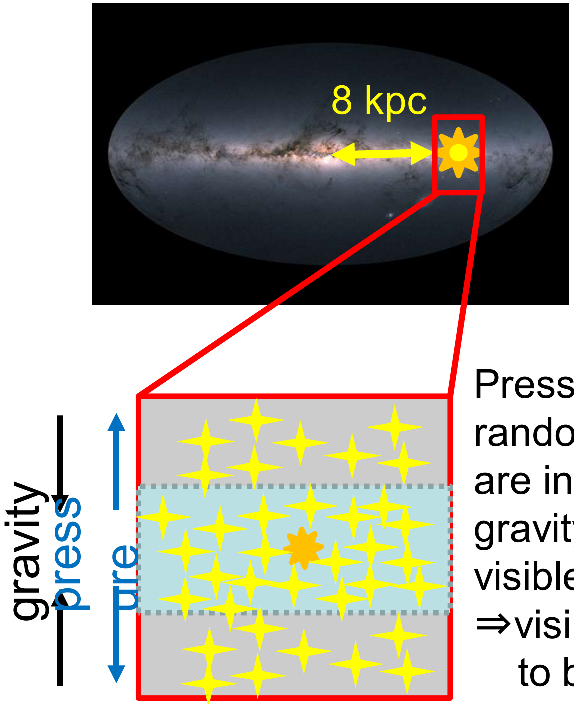
4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figure 1). Figures 2 and 3 show $\log \Delta(z)$ for A stars and yellow giants, as derived by LINDBLAD and PETERSSON.

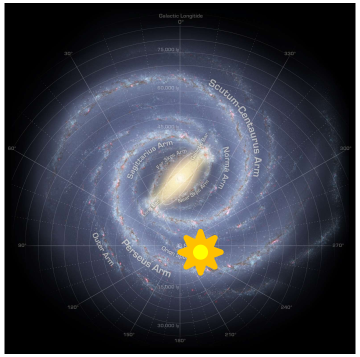
5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations

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:

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

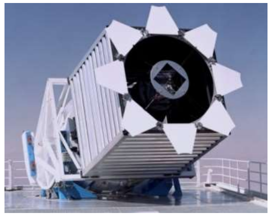




Pressure force due to the random motions of stars are in balance with gravity exerted from both visible and invisible matter
⇒visible mass is found to be insufficient
⇒missing mass, dark matter

太陽近傍のダークマター密度

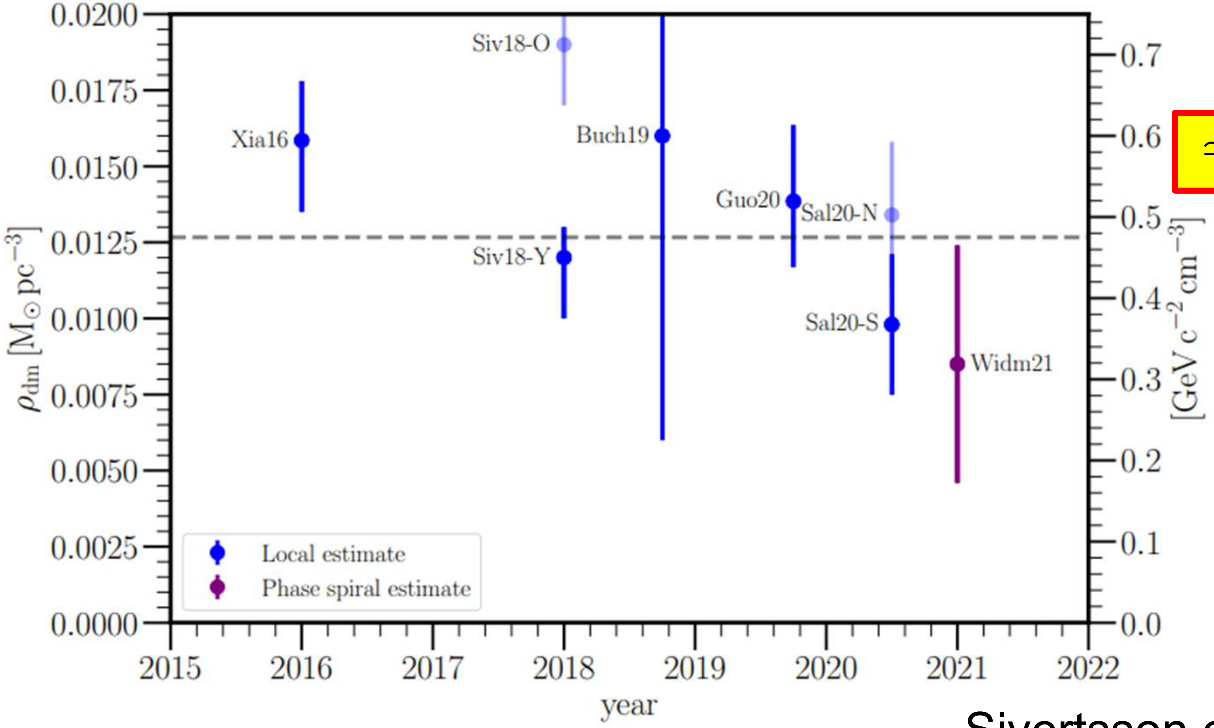
SDSS



LAMOST

Gaia

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



$\simeq 0.5$ GeV/cm^3

Sivertsson et al. 2022

ダークマターの証拠 (3)
銀河の回転曲線

Vera C. Rubin

Rubin et al. (1980)
Rotation curves for 21 Sc galaxies
(optical spectra)

RUBIN, FORD, AND THONNARD

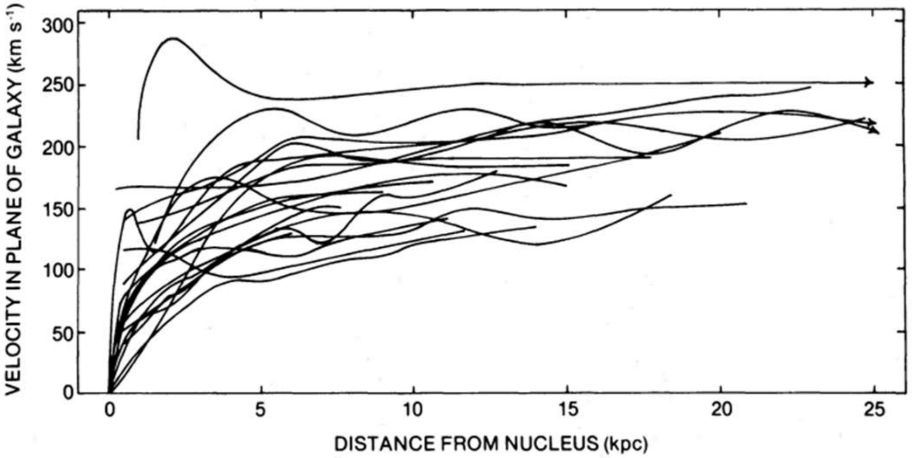


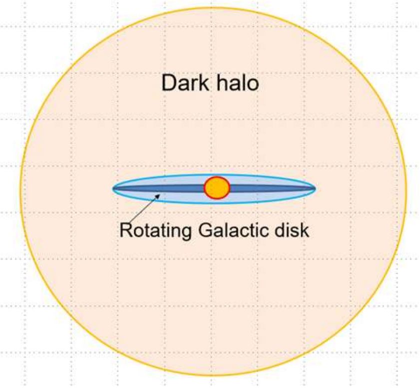
FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter at any R.

If spherically symmetric,

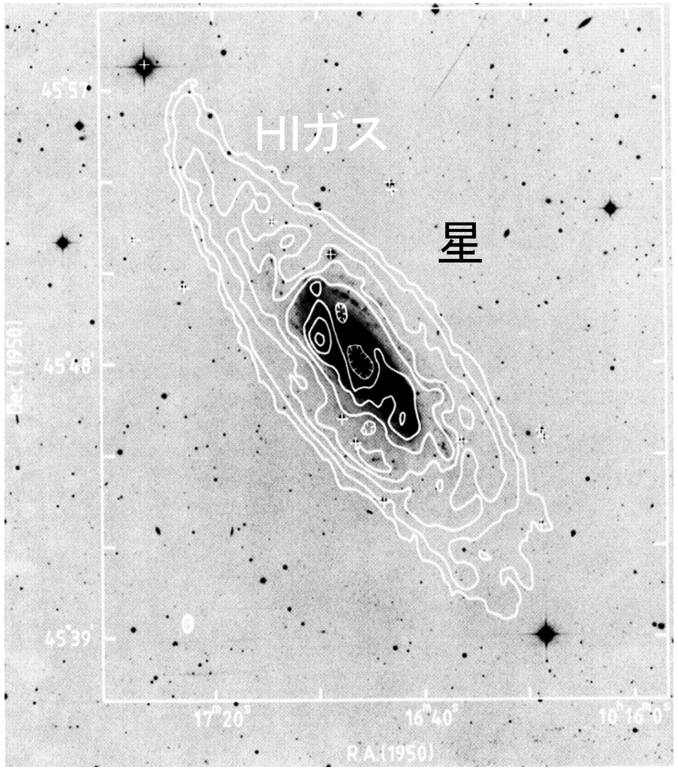
$$\frac{V_{rot}^2}{r} = \frac{GM(<r)}{r^2}$$

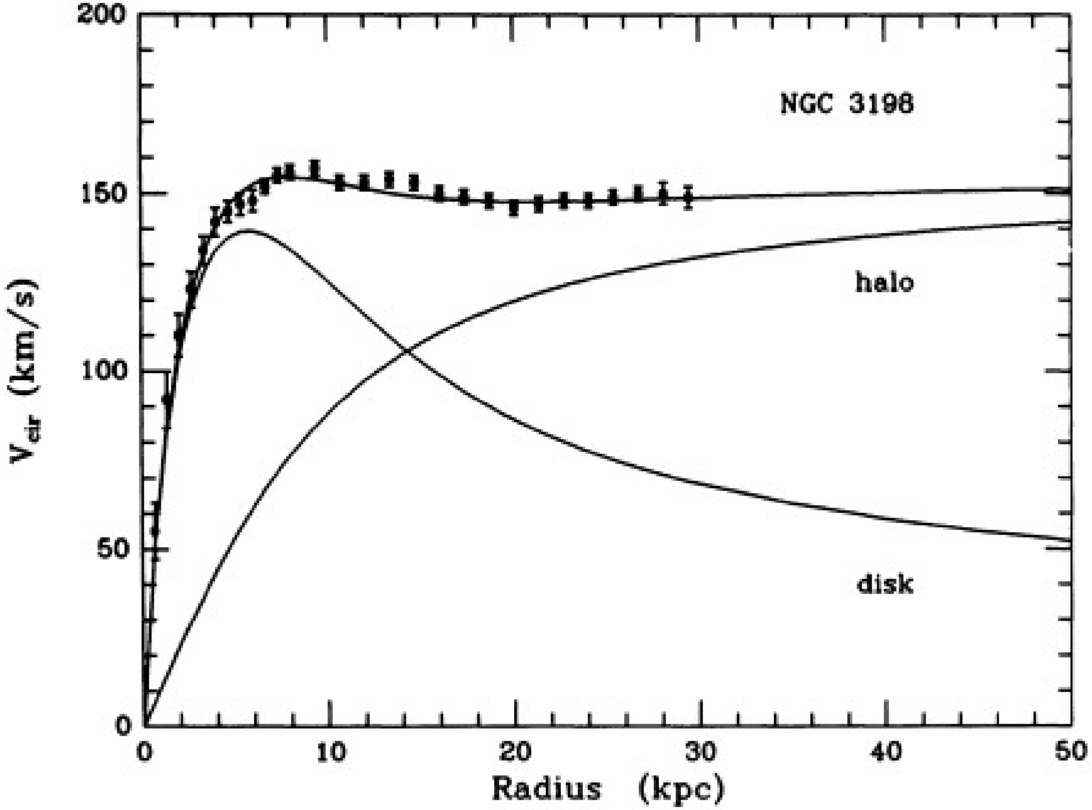
$$V_{rot} = const. \Rightarrow M(<r) \propto r$$

Presence of a dark matter halo



銀河の回転曲線の内訳





もし密度分布ρ(r)が球対称であったら

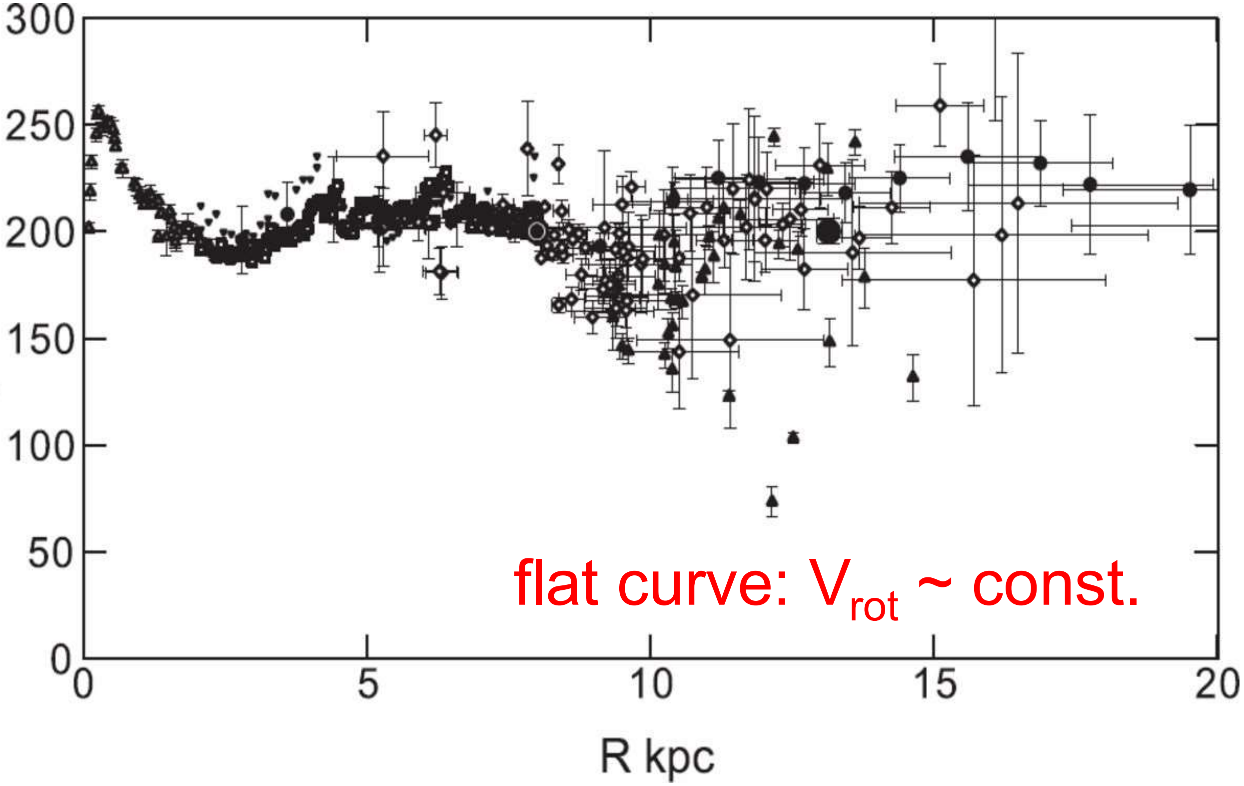
ここで $M(<r) = \int^r 4\pi\rho r^2 dr$

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

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

Rotation curve of the Milky Way

(Sofue et al. 2009)



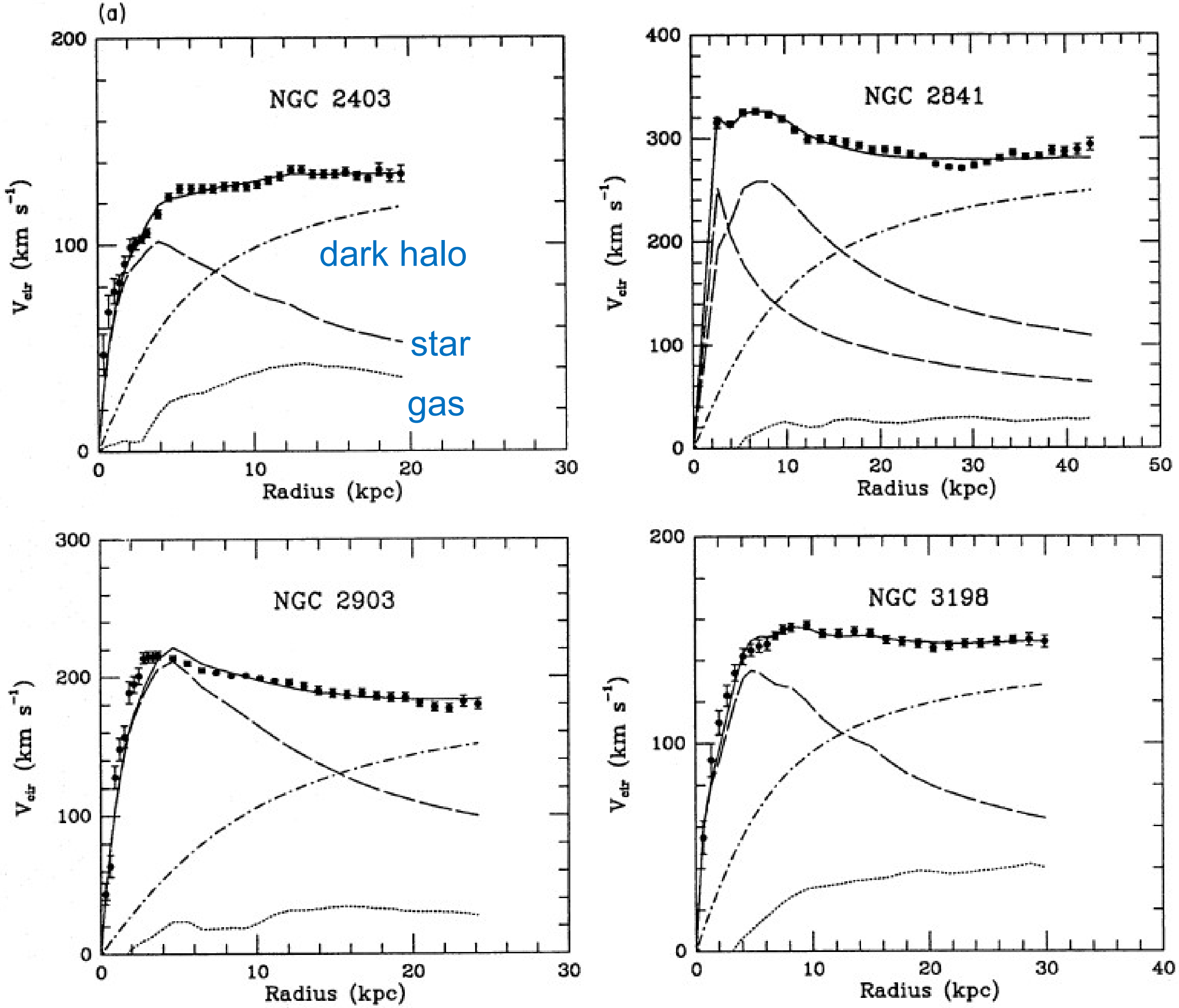
If spherically symmetric, $\frac{V_{rot}^2}{r} = \frac{GM(<r)}{r^2}$

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

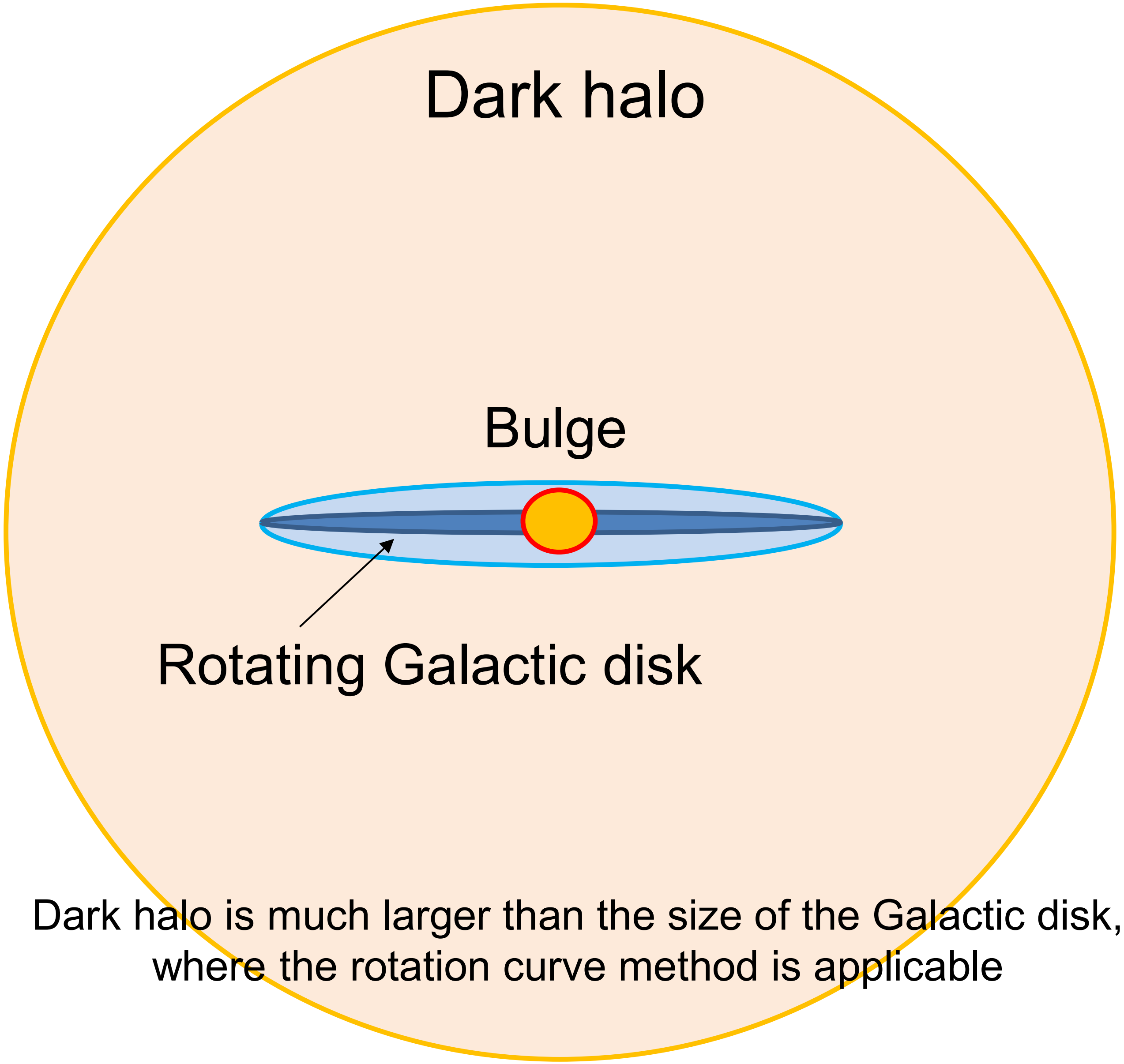
Presence of a dark matter halo

Rotation curves in various spiral galaxies

Begeman et al. 1991

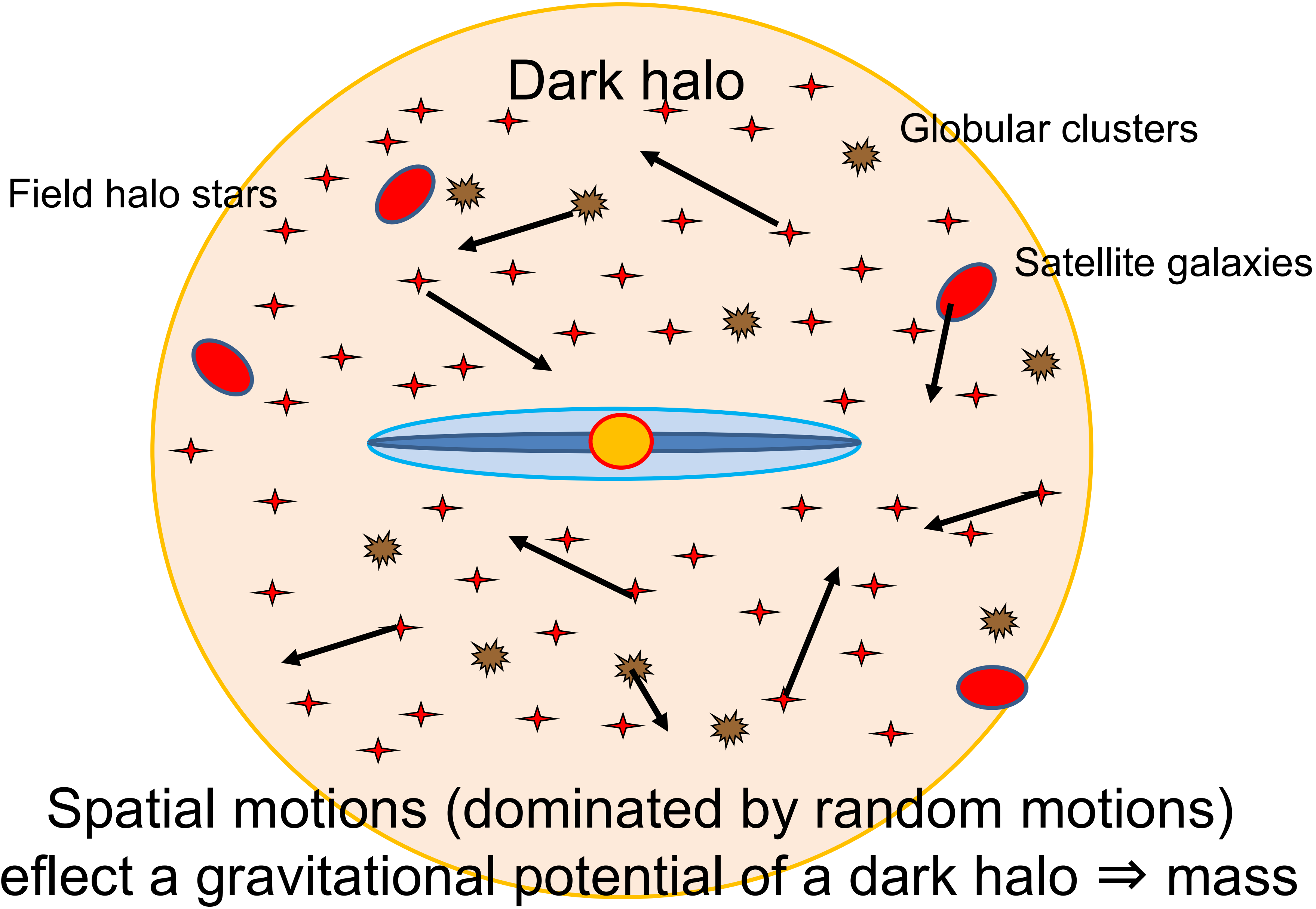


Limitation of the rotation curve method



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

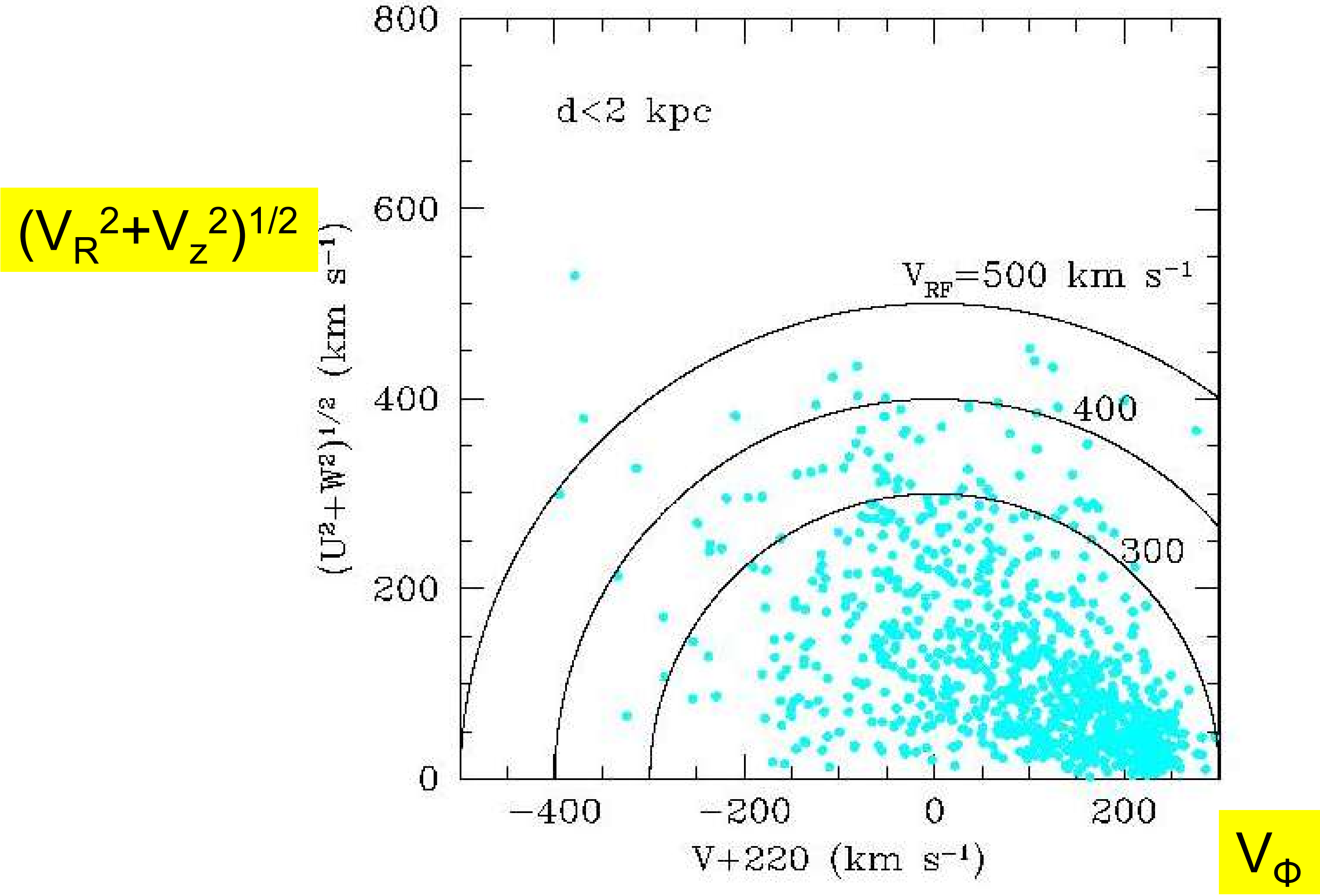
Halo objects as tracers of dark-halo mass



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

5.2 Total mass

太陽近傍における脱出速度



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

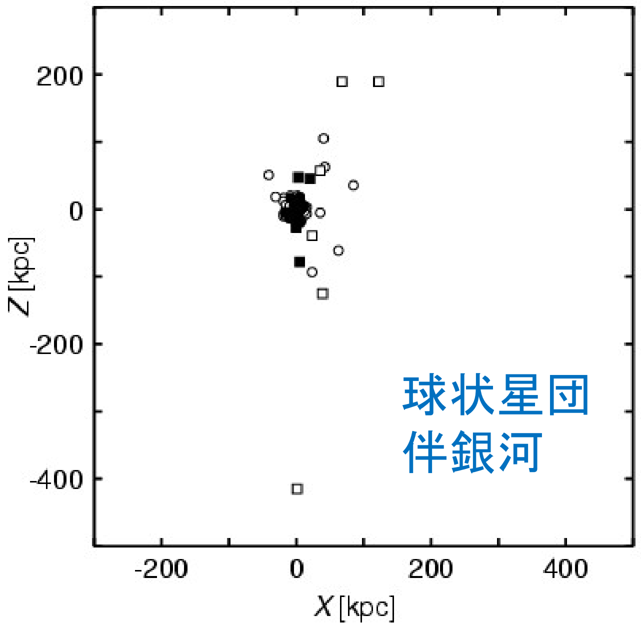
⇒ Limits on a gravitational potential Φ at $R=R_{sun}$: $V_{esc}=(2\Phi(R_{sun}))^{1/2}$

別の距離にある天体にてΦ(r)を制限

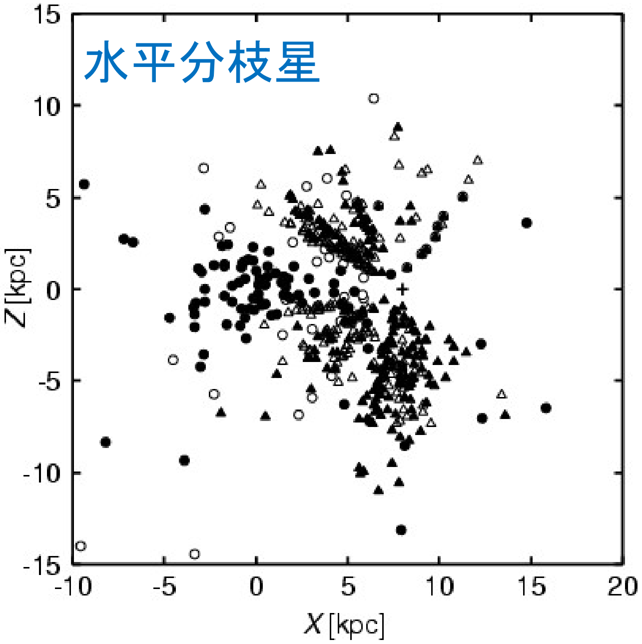
- 水平分枝星、球状星団、伴銀河

Sakamoto, Chiba, Beers 2003, A&A, 397, 899

(a)



(b)



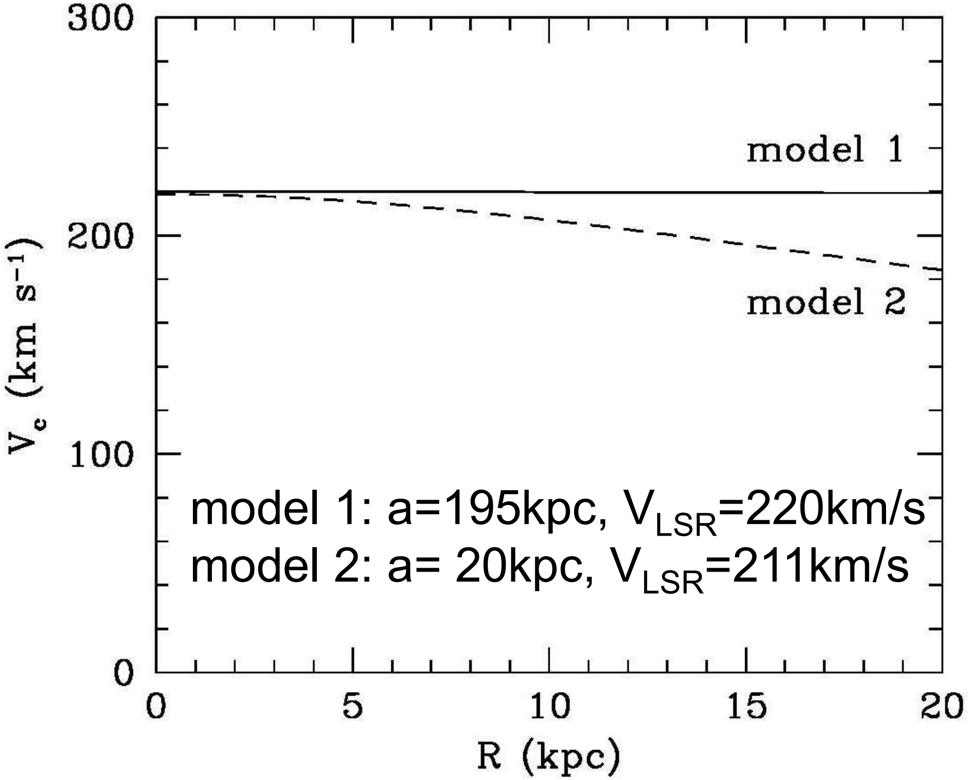
$$\Phi(r)=\frac{GM}{a}\log\left(\frac{\sqrt{r^2+a^2}+a}{r}\right)$$

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

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

a: size of a halo

→ total mass M

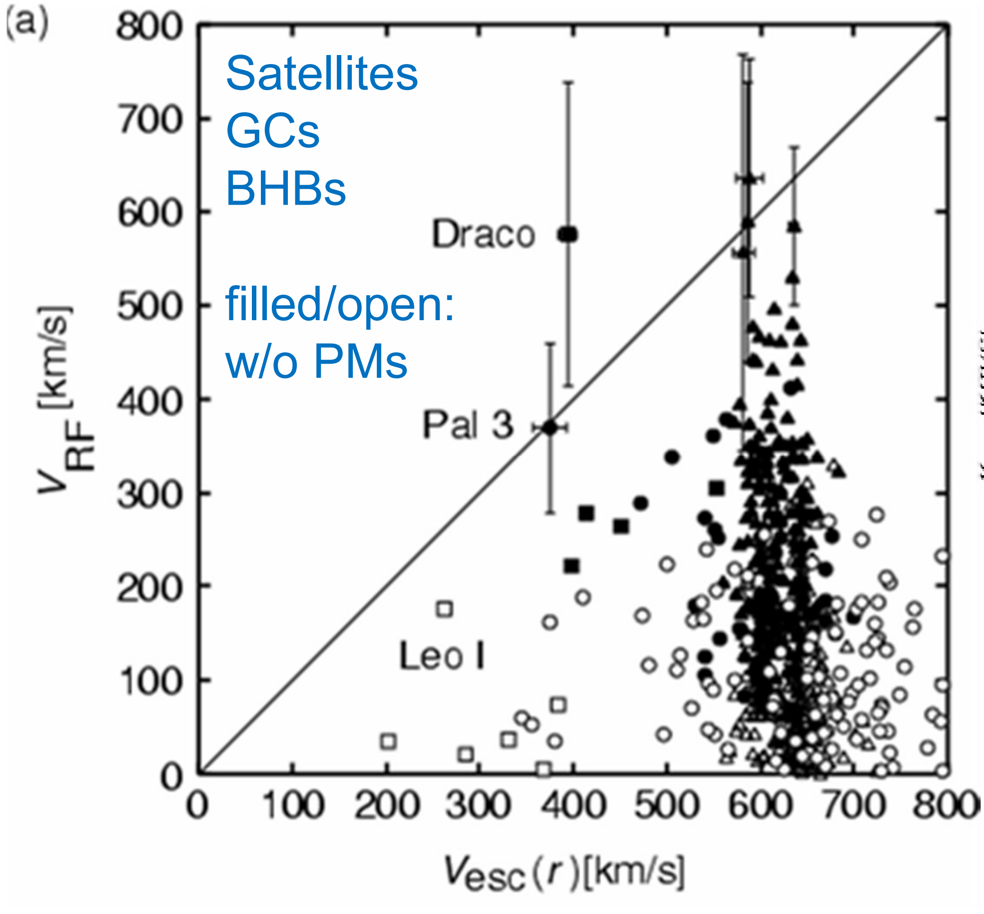


model 1: a=195kpc, V_{LSR}=220km/s

model 2: a= 20kpc, V_{LSR}=211km/s

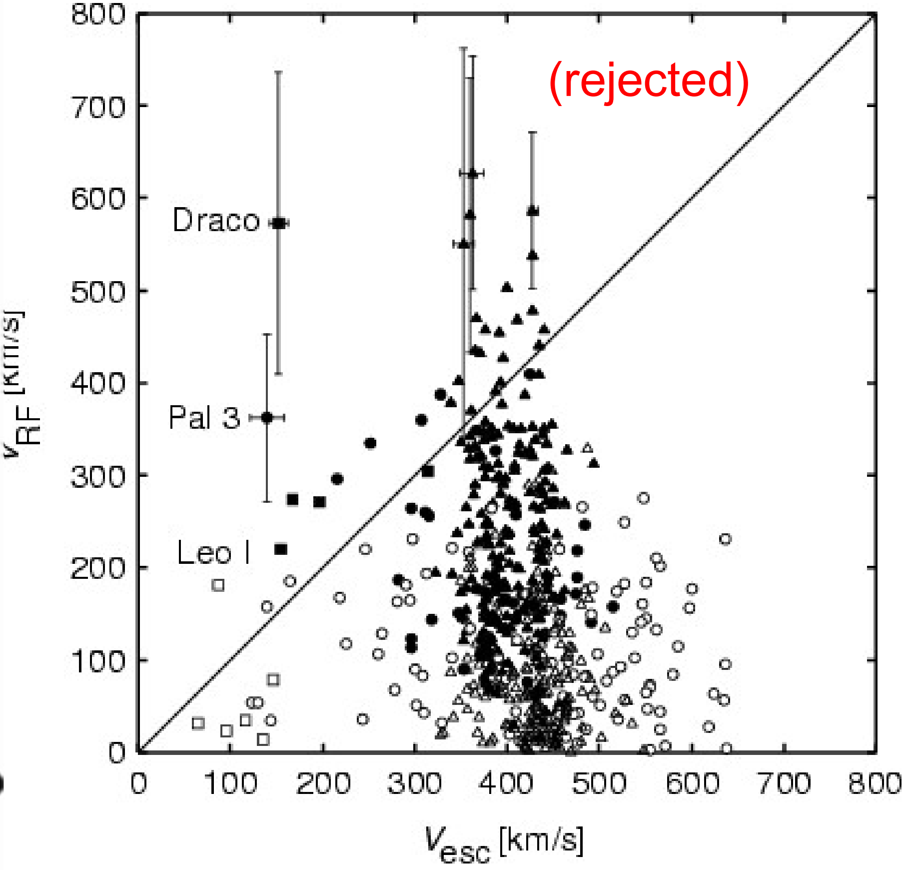
恒星・星団の3次元速度: $V_{RF} \le V_{esc}(r) = (2\,\Phi(r))^{1/2}$

Model 1: a = 195 kpc


Satellites
GCs
BHBs

filled/open:
w/o PMs

Model 2: a = 20 kpc
(Rとともに減少する回転曲線)

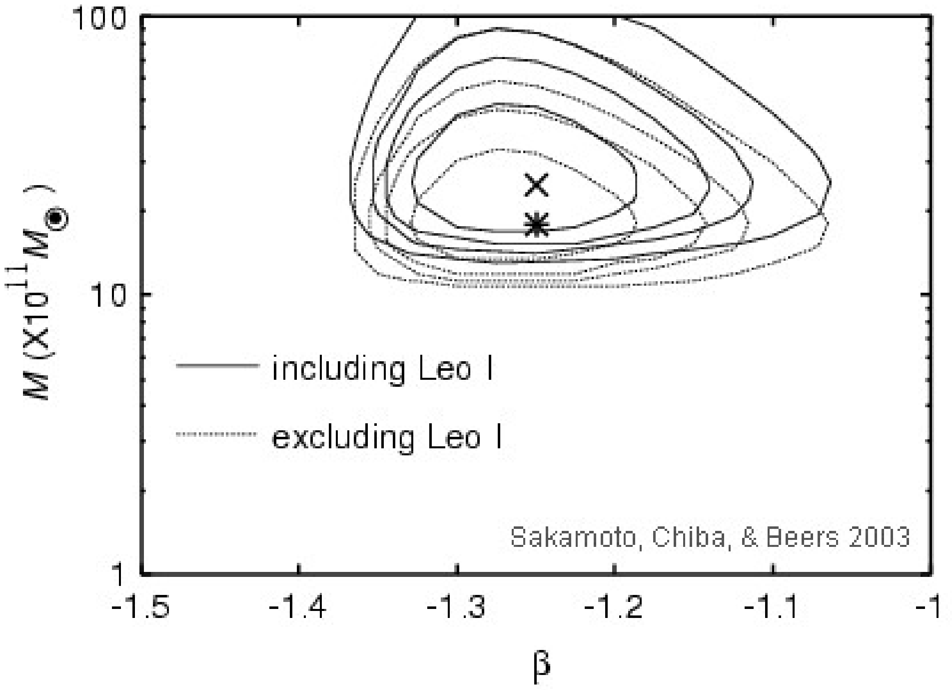

(rejected)

最尤法による銀河系質量決定

恒星系の分布関数 f(E,L) (速度非等方性 β)

重力を与える質量分布のscale length a → 全質量 M

観測される $(r_i, v_{r,i})$ i=1…N を最大にするような質量 M を求める



Sakamoto, Chiba, & Beers 2003

$$\boxed{\beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}}$$

Velocity anisotropy parameter

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

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

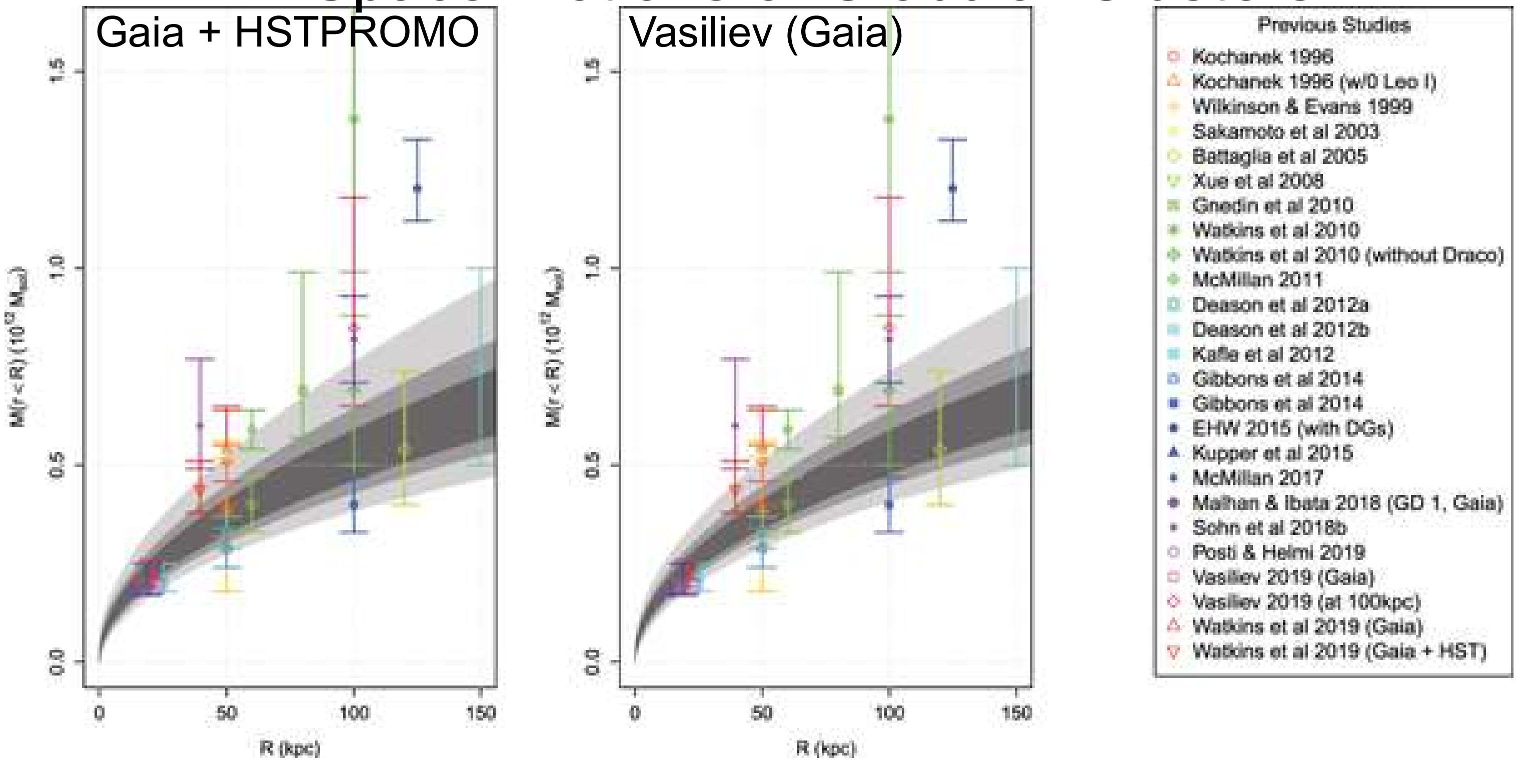
全質量 = 2.5 × 10^{12} M_{sun} at r <~ 200 kpc

可視質量 = 10^{11} M_{sun} at r <~ 15 kpc

⇒ 全質量の10 %しか見ていない

Gaia PMsを用いた最近の結果

Space motions of Globular Clusters



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

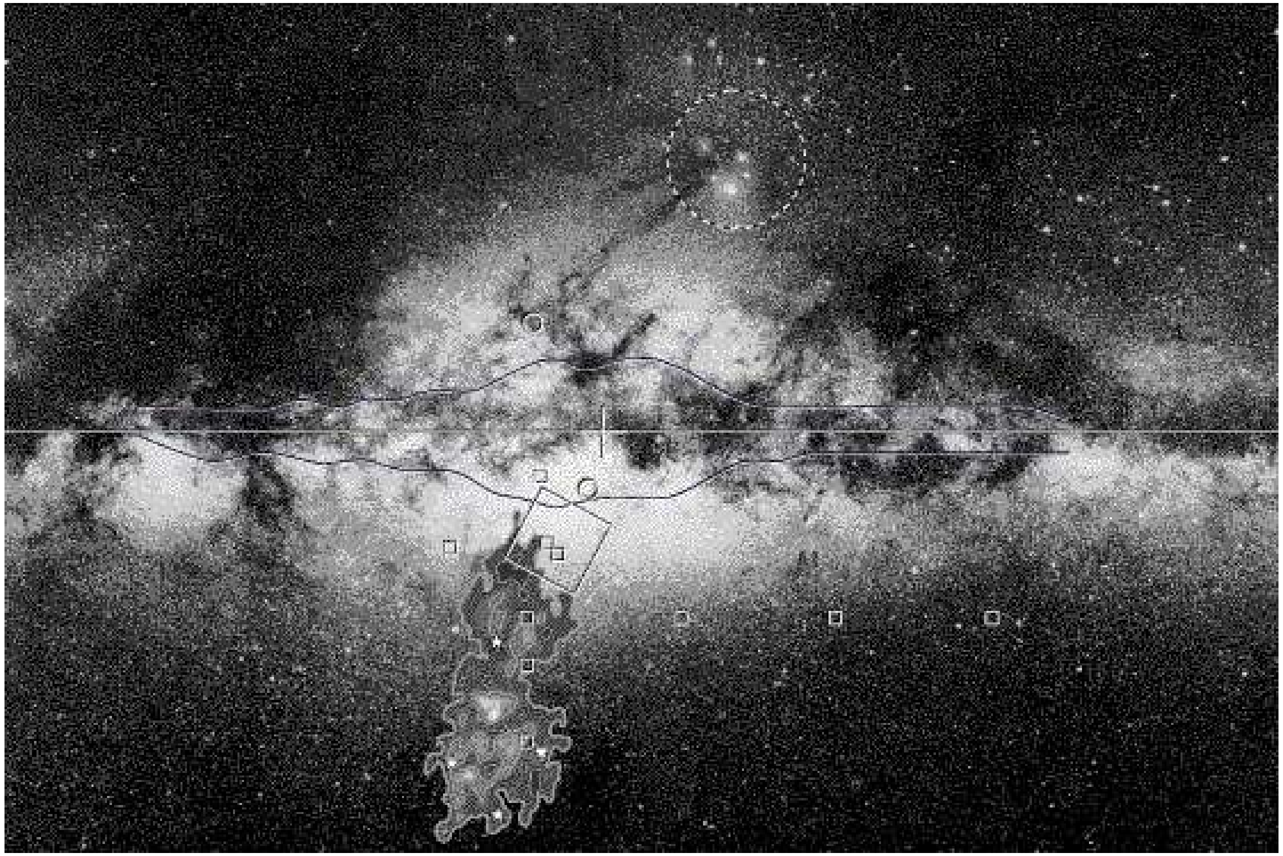
Other recent results

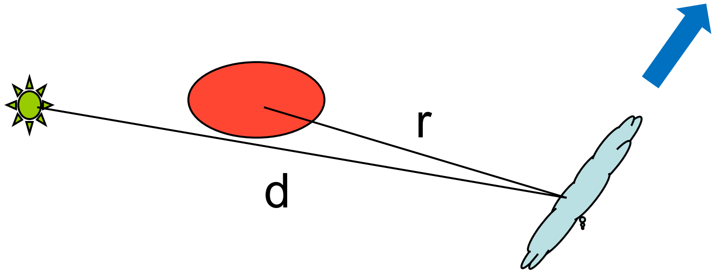
Sohn et al. 2018 $M_{vir} = 2.05^{+0.97}_{-0.79}$ x 10^{12} Msun
Watkins et al 2019 $M_{vir} = 1.41^{+0.99}_{-0.52}$ x 10^{12} Msun
Posti & Helmi 2019 $M_{vir} = 1.3 \pm 0.3$ x 10^{12} Msun

5.3 Shape

射手座矮小銀河

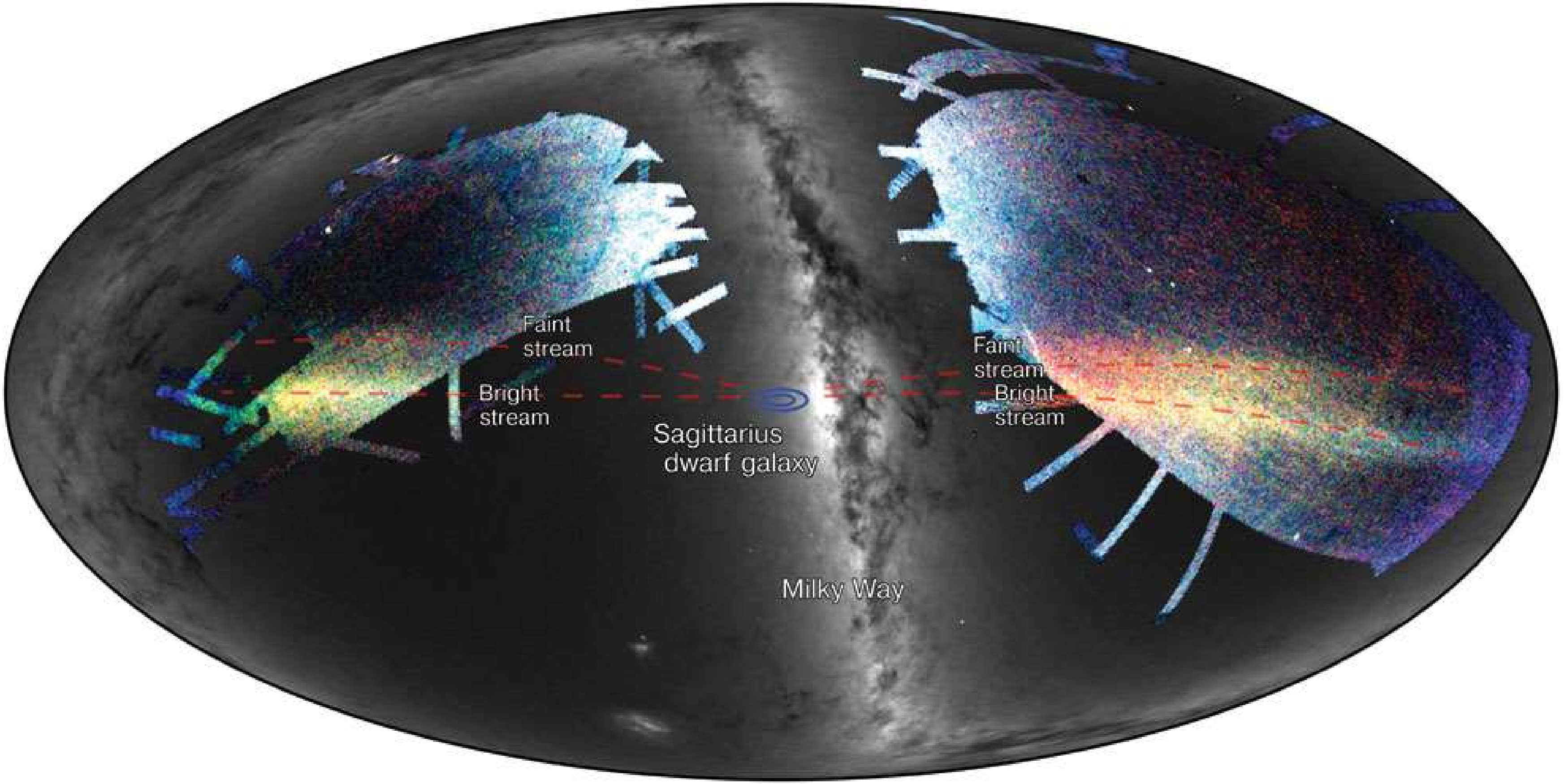
(Ibata, Gilmore, & Irwin 1994, Nature, 370, 194)





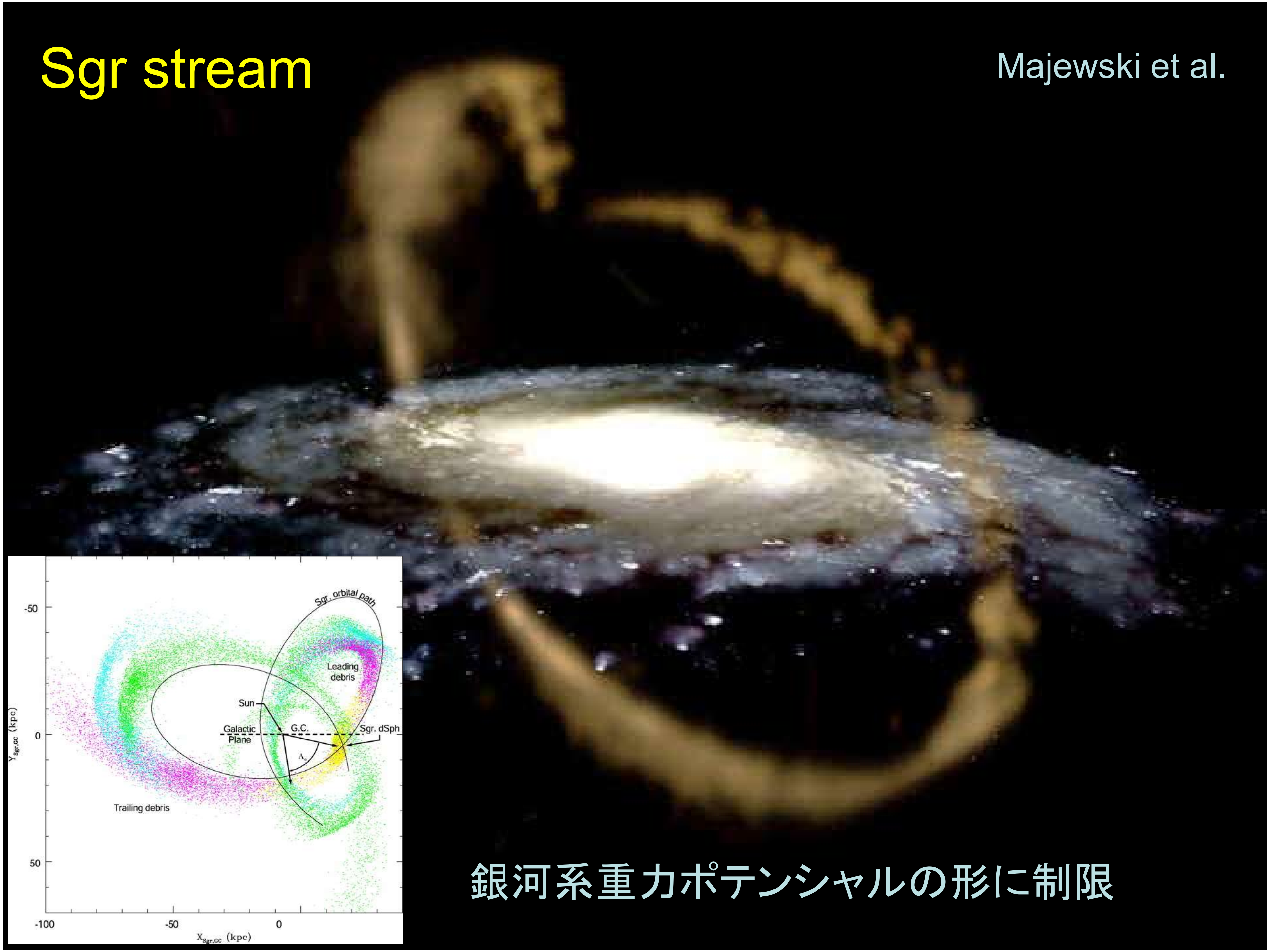
d ~ 24 kpc
r ~ 16 kpc

いて座ストリーム
Sagittarius stream

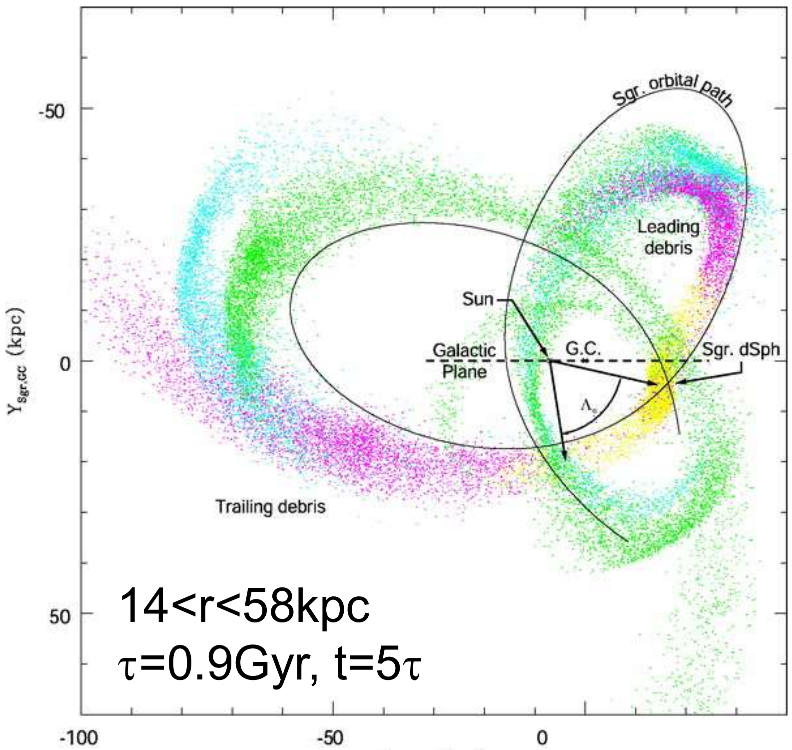


Sgr stream

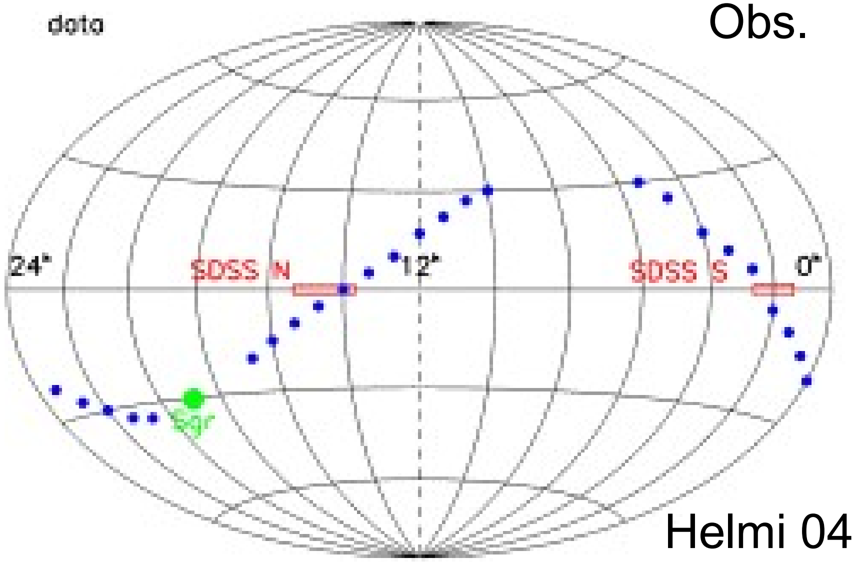
Majewski et al.



銀河系重力ポテンシャルの形に制限

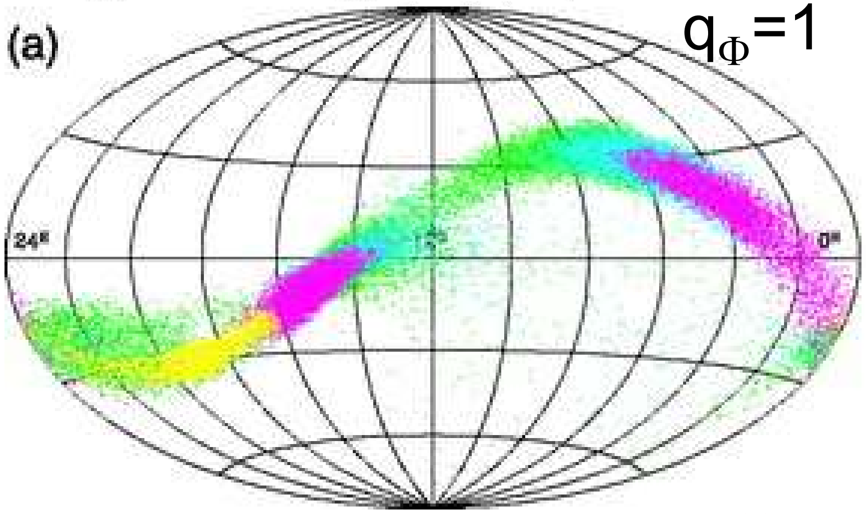


14<r<58kpc
τ=0.9Gyr, t=5τ

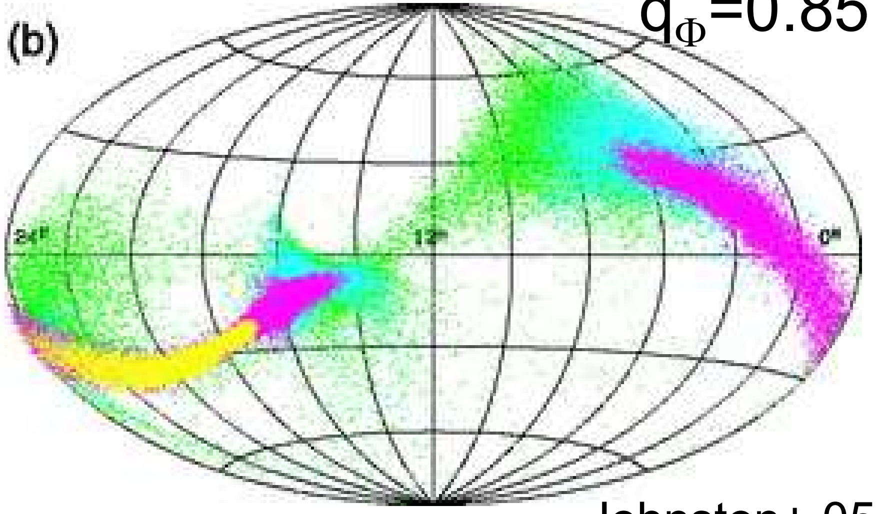


Obs.

Helmi 04



q_Φ=1

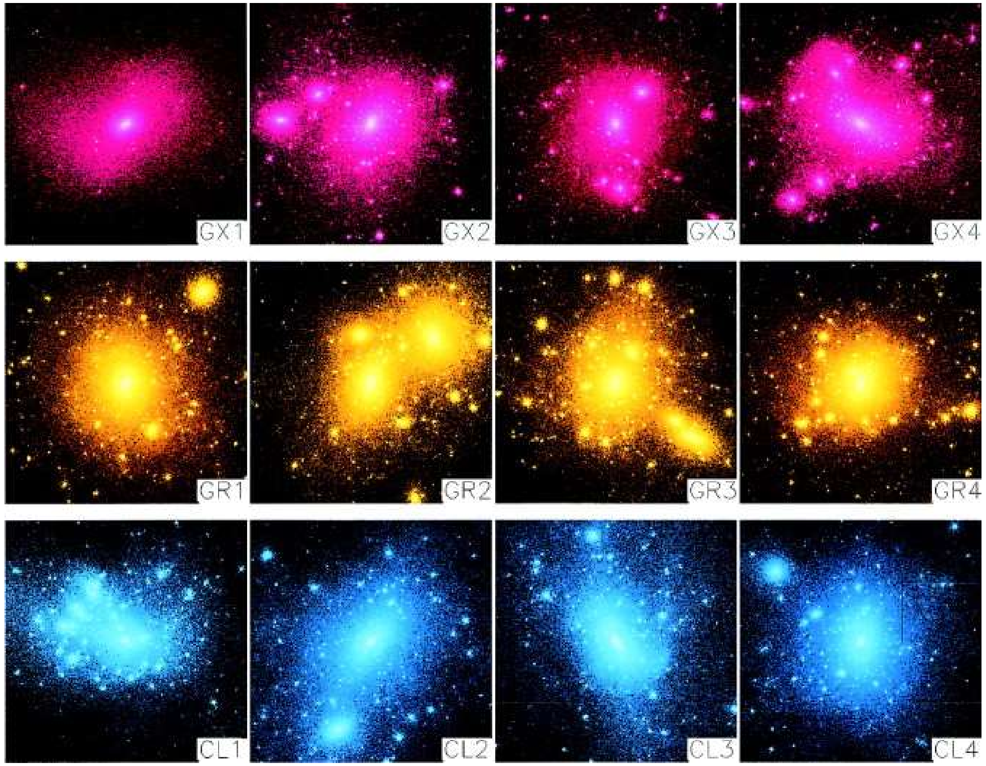


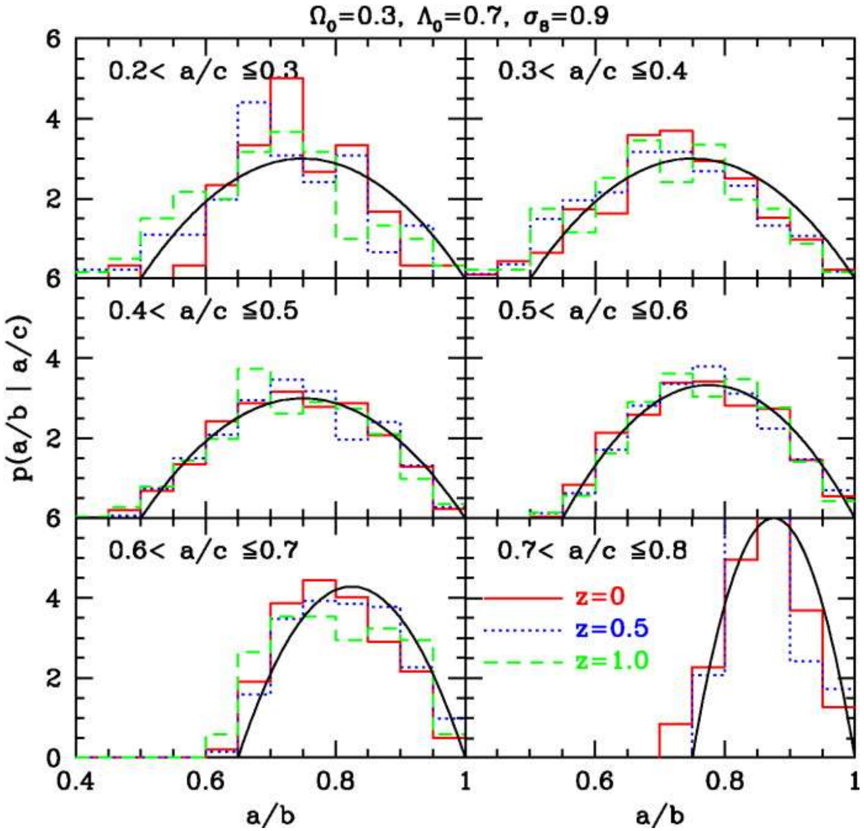
q_Φ=0.85

Johnston+ 05

可能な範囲0.90 < q_Φ < 0.95
(0.83<q_ρ<0.92)

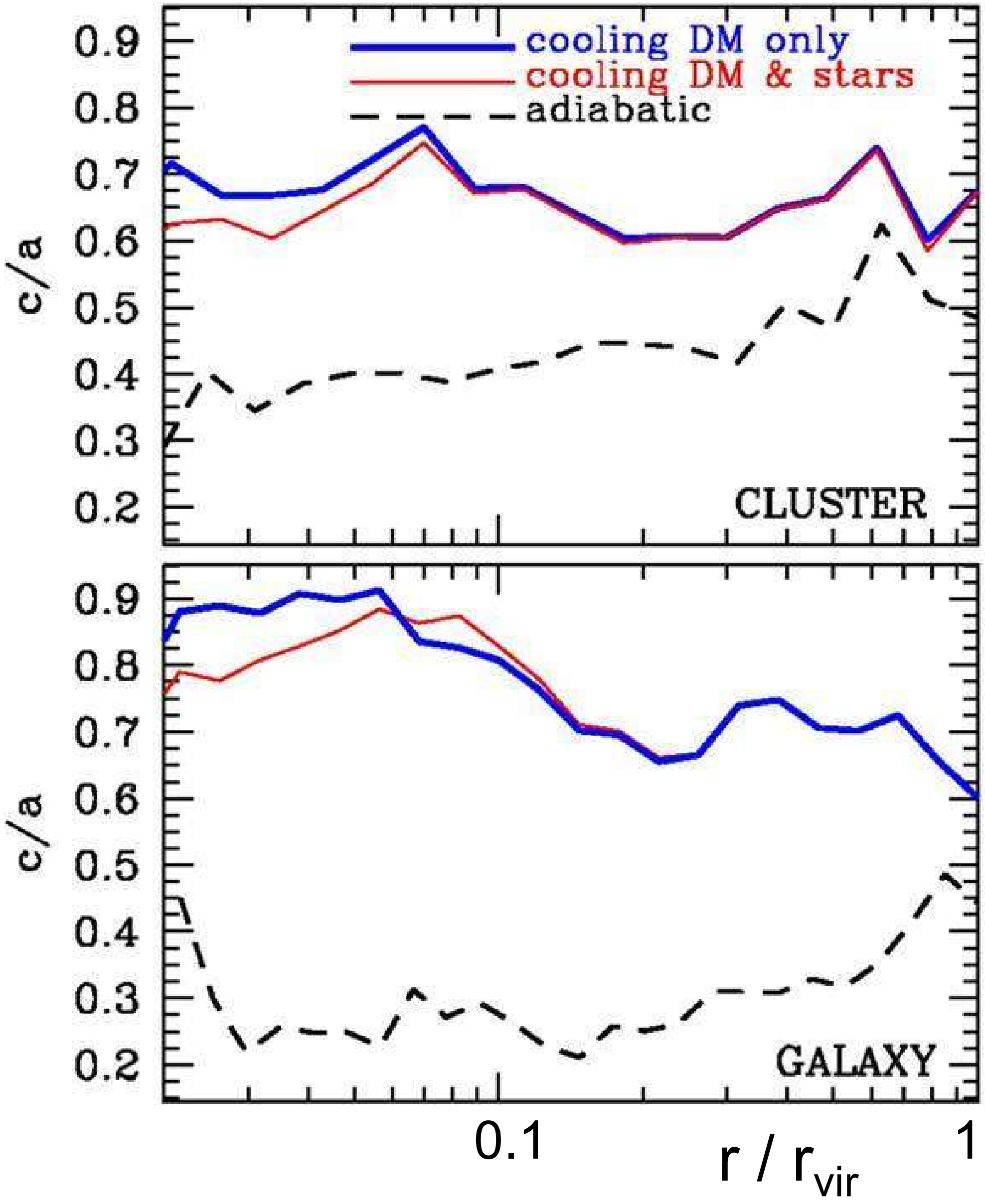
一方、CDM理論ではハローは一般に三軸非対称を予言
(Jing & Suto 2000, 2002)





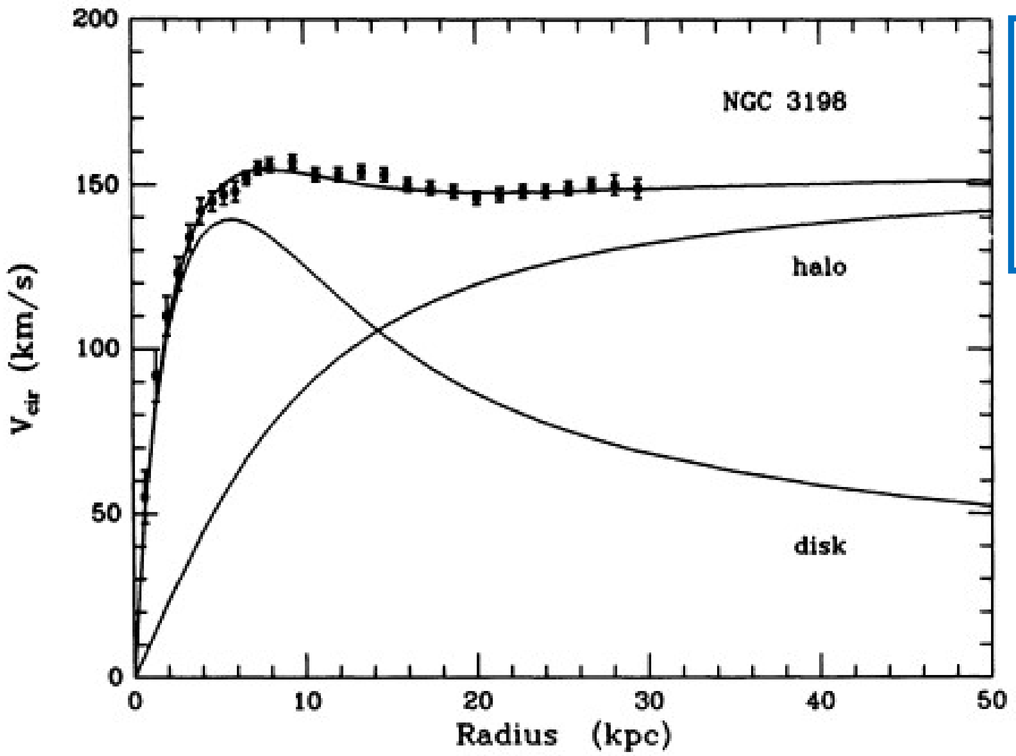
Hayashi et al.2007: $(c/a)_\Phi$ = 0.72, $(b/a)_\Phi$ = 0.78 in central parts

ガスの冷却・収縮がダークハローを丸くする方向
(Kazantzidis et al. 2004, ApJ, 611, L73)



5.3 Density profile
ダークハローの密度分布

van Albada et al. 1985



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

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

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

冷たい暗黒物質CDM理論によるダークハローの密度分布

(Navarro, Frenk, & White 1997, ApJ, 490, 493)

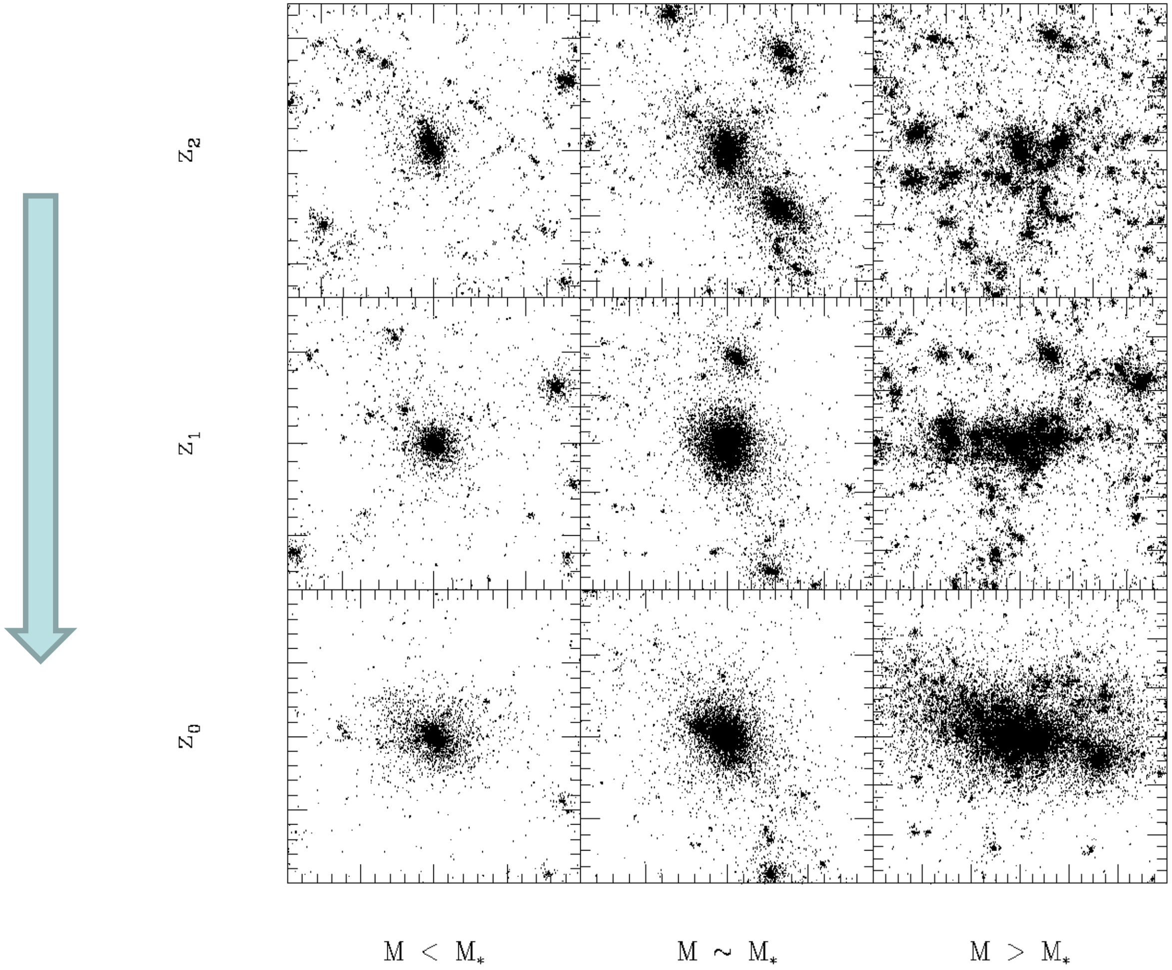


FIG. 1.—Particle plots illustrating the time evolution of halos of different mass in an $\Omega_0 = 1$, $\Lambda = 0$, and $n = -1$ cosmology. The box sizes of each column are chosen so as to include approximately the same number of particles. At $z_0 = 0$, the box size corresponds to about $6r_{200}$. 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.

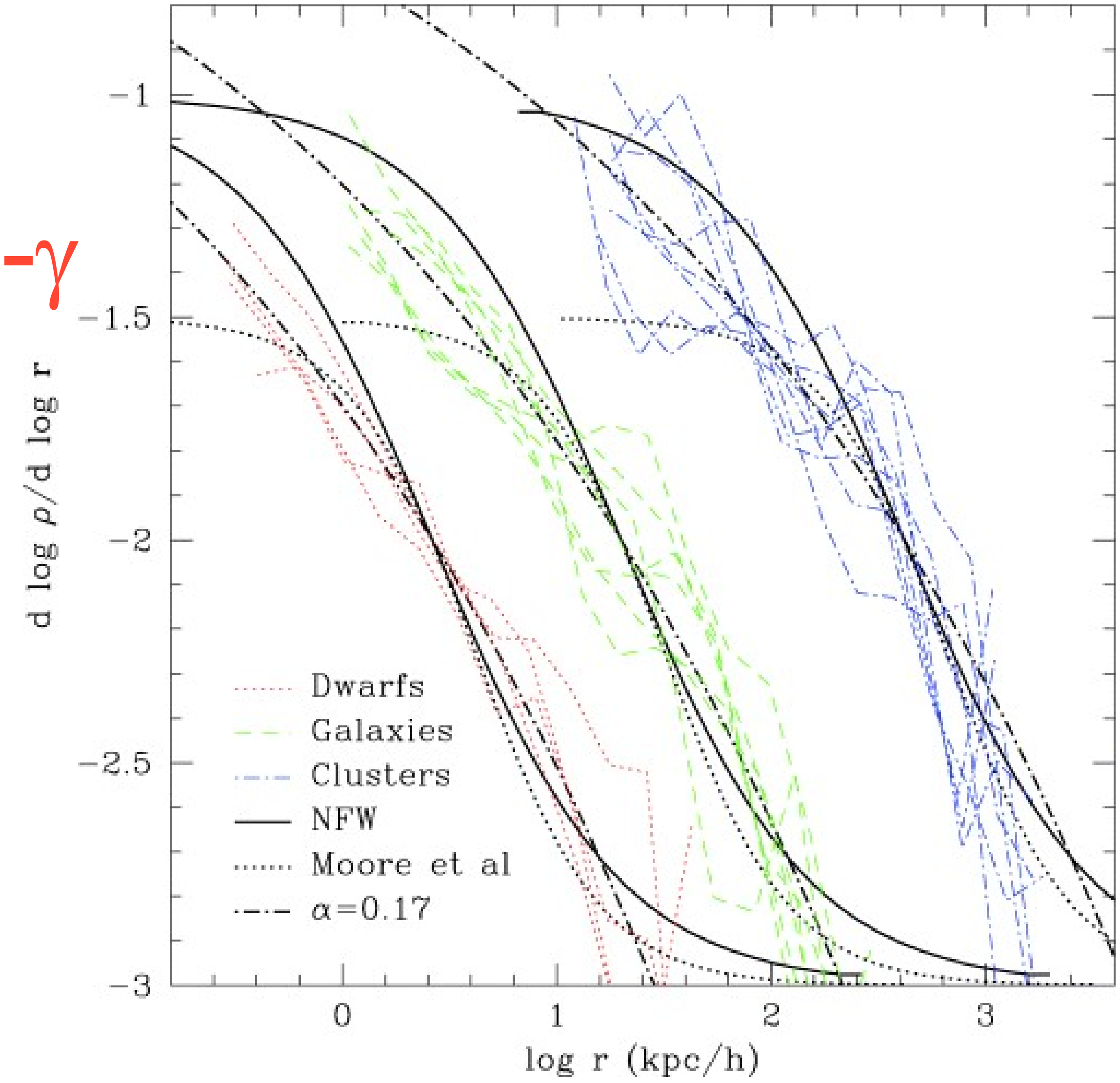
NFW profile

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

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

NFW or Moore et al. profile?

(Navarro et al. 2004)



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

at inner parts

γ= 1: NFW

γ= 1.5: Moore et al.

No universal γ

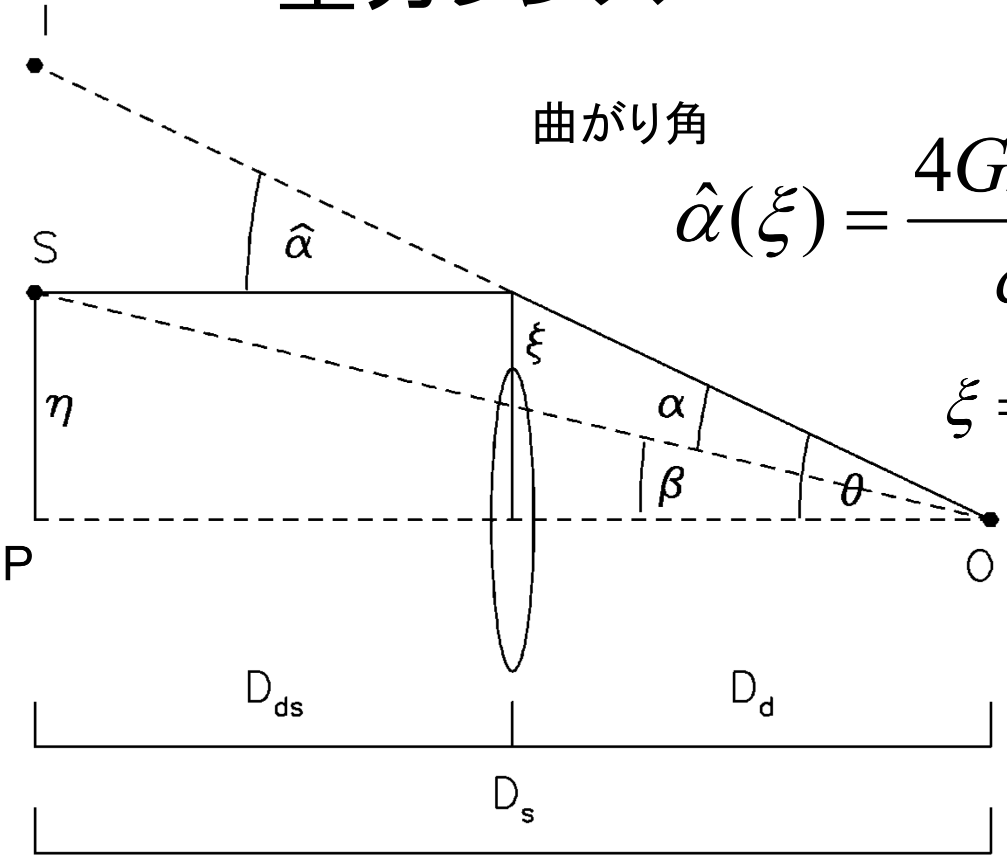
$1 < \gamma < 1.5$

Einasto profile:

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

5.4 重力マイクロレンズ

重力レンズ



曲がり角

$$\hat{\alpha}(\xi) = \frac{4GM(\xi)}{c^2 \xi}$$

$$\xi = D_d \theta$$

$$PI = PS + SI$$

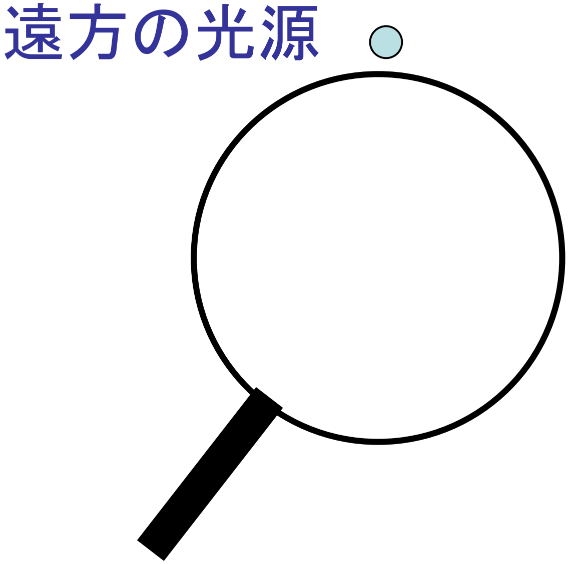
$$D_s \vec{\theta} = D_s \vec{\beta} + D_{ds} \vec{\hat{\alpha}} = D_s \vec{\beta} + D_s \vec{\alpha}$$

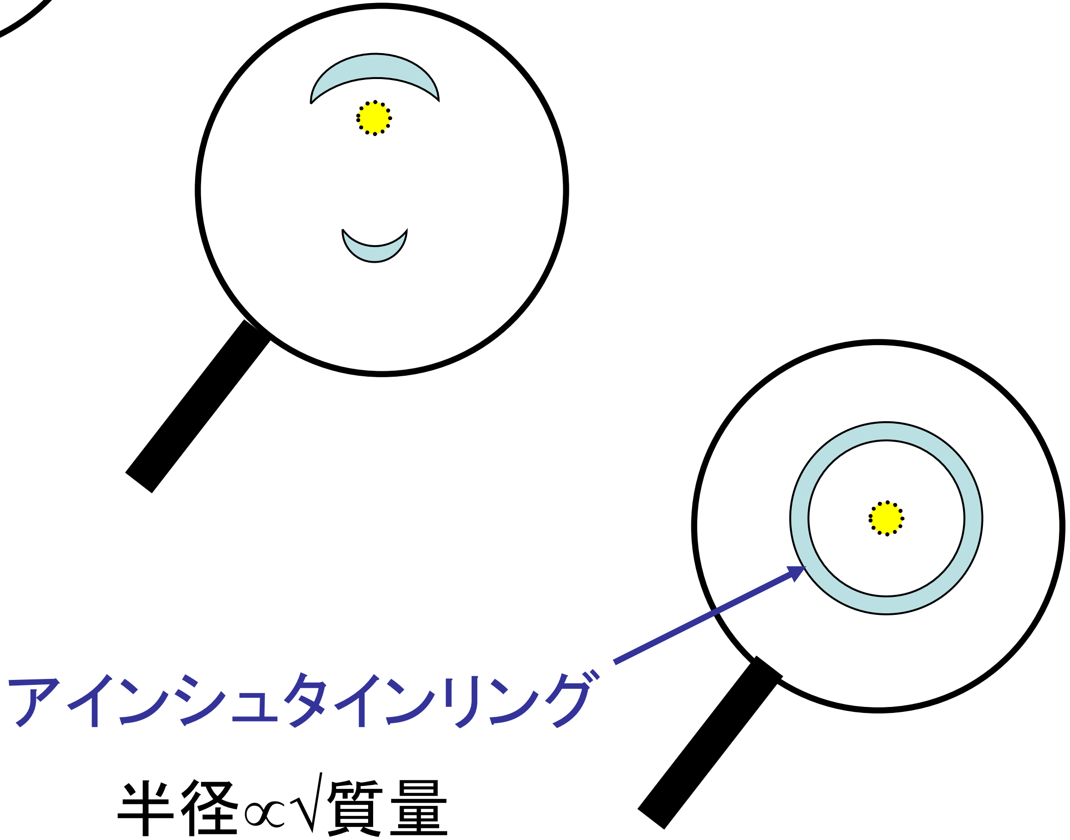
⇨

$$\boxed{\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})}$$

レンズ方程式

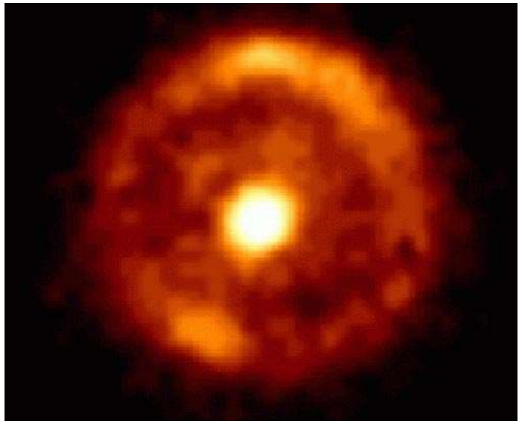
円対称な天体による重力レンズ



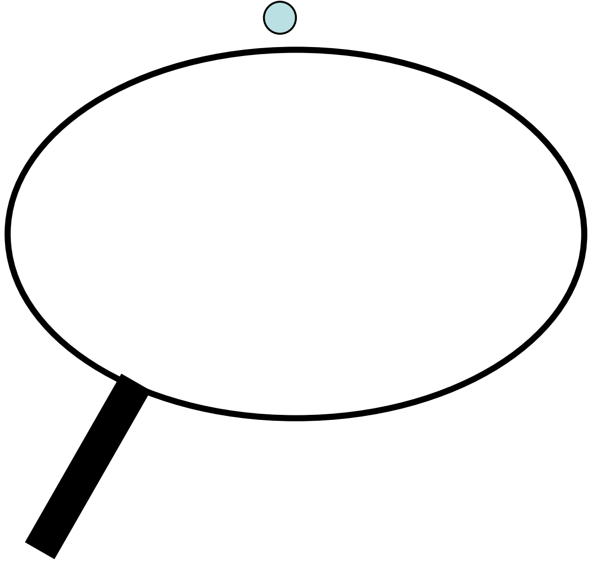


半径∝√質量

“Einstein Ring” B1938+666

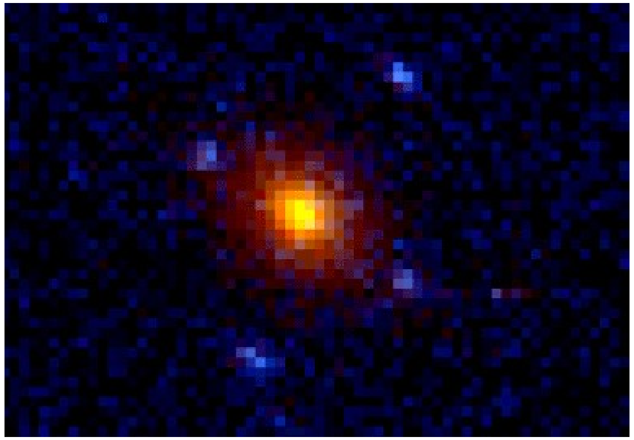


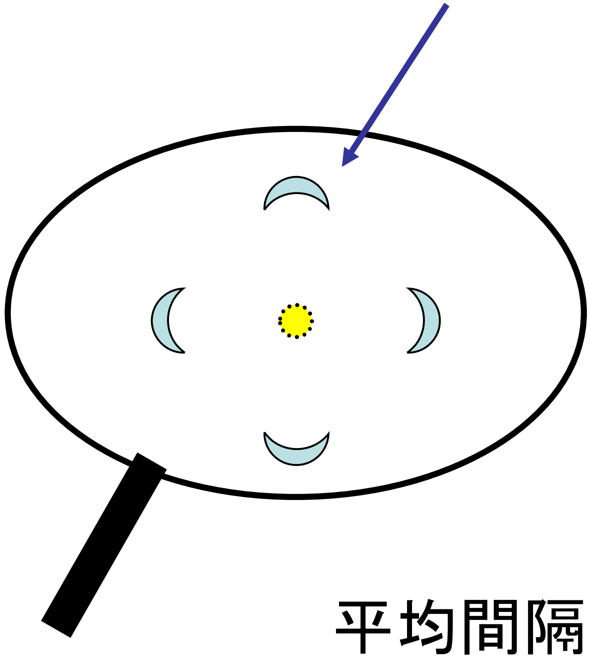
楕円形型天体による重力レンズ



遠方の光源

"Einstein Cross" HST14176+5226

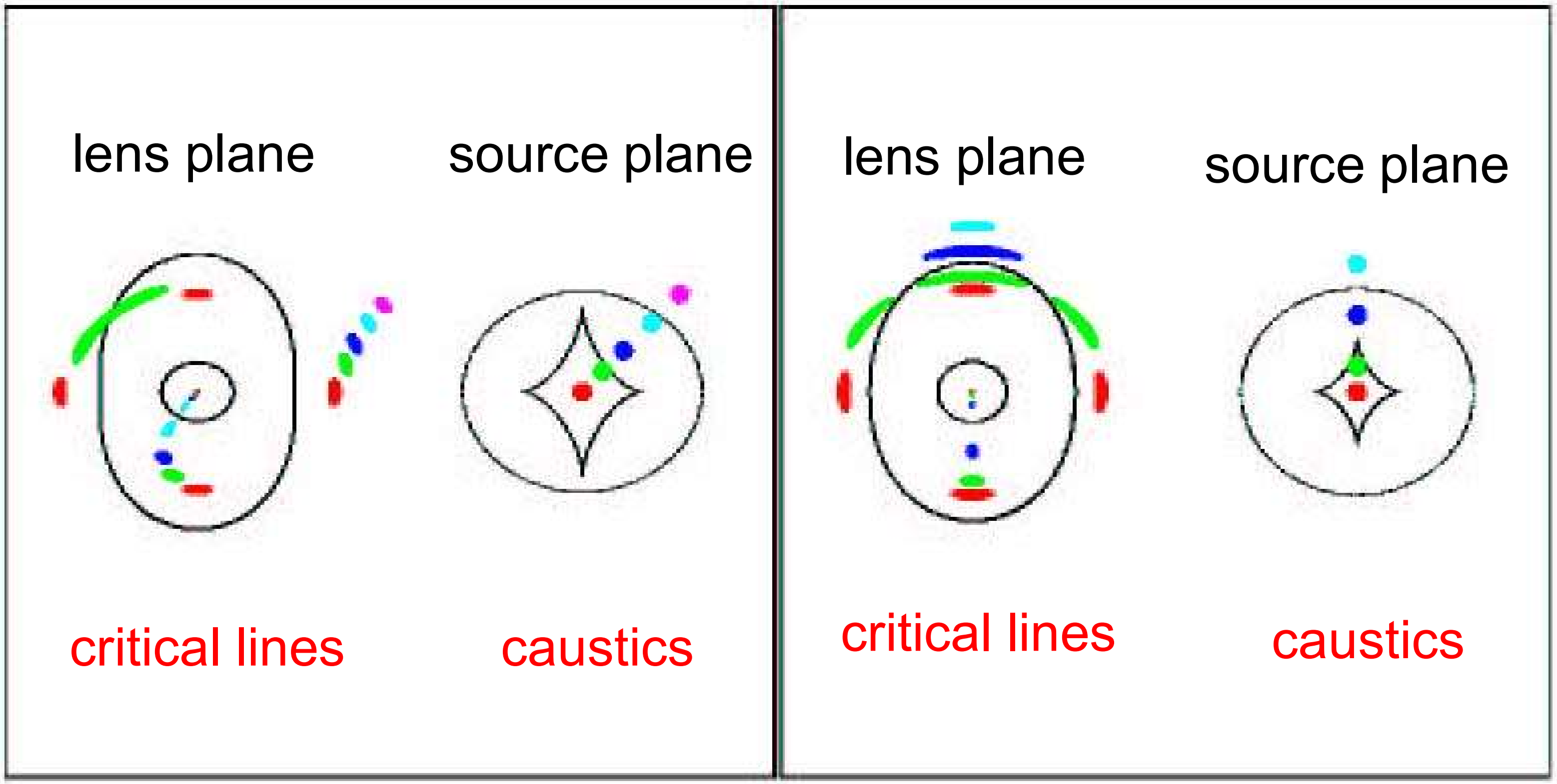




アインシュタインクロス

平均間隔∝√質量

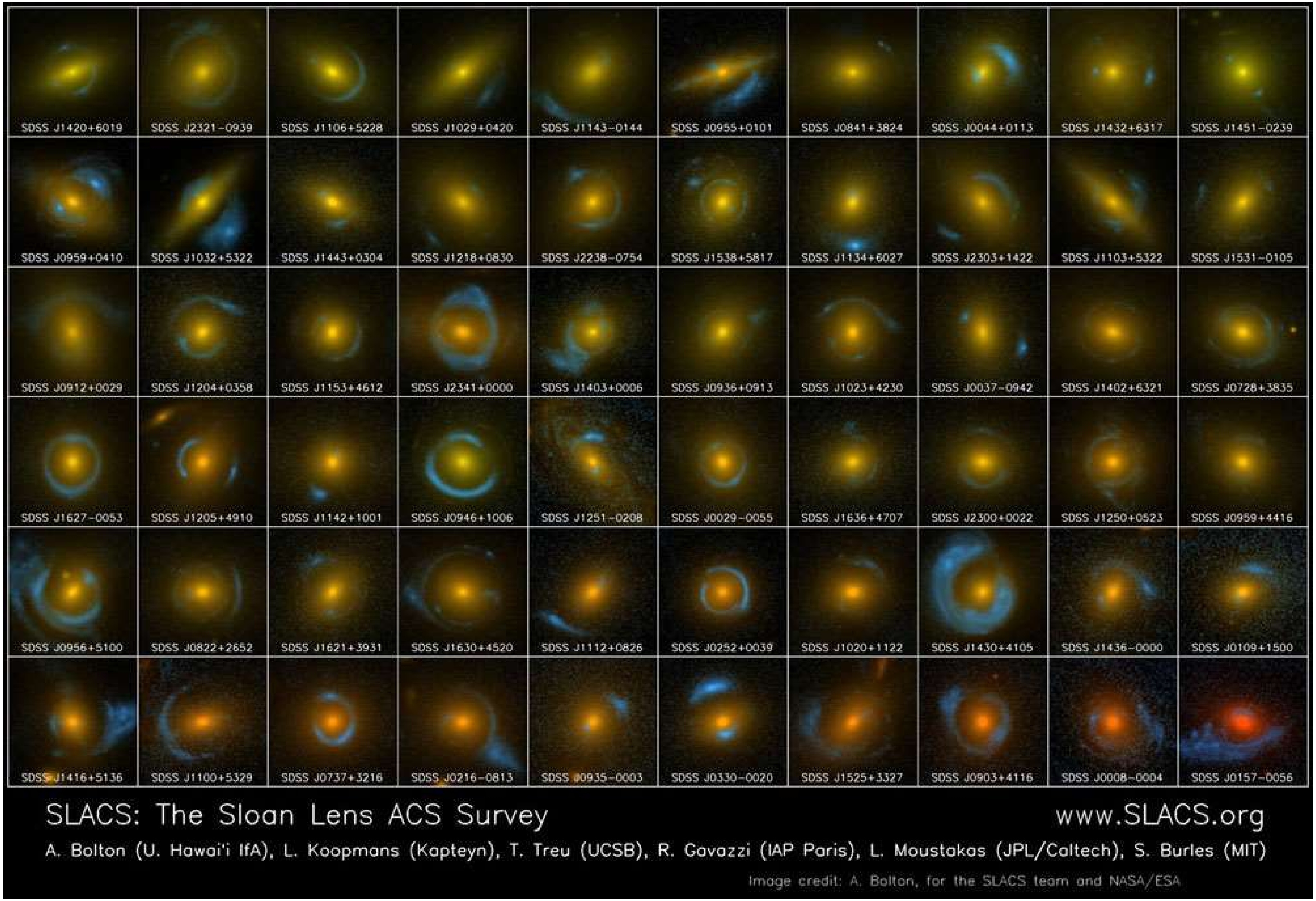
Elliptical Lens



lens plane source plane lens plane source plane

critical lines caustics critical lines caustics

● Fold singularity ● Cusp singularity



SLACS: The Sloan Lens ACS Survey

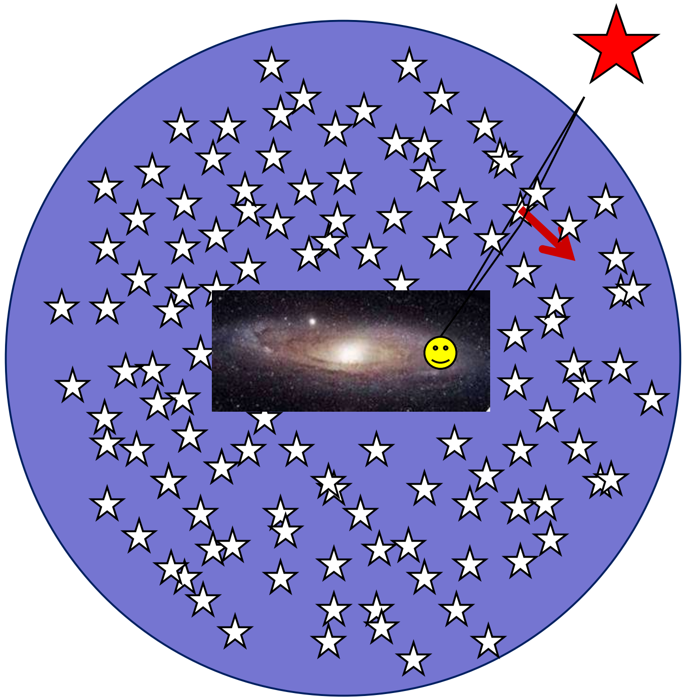
www.SLACS.org

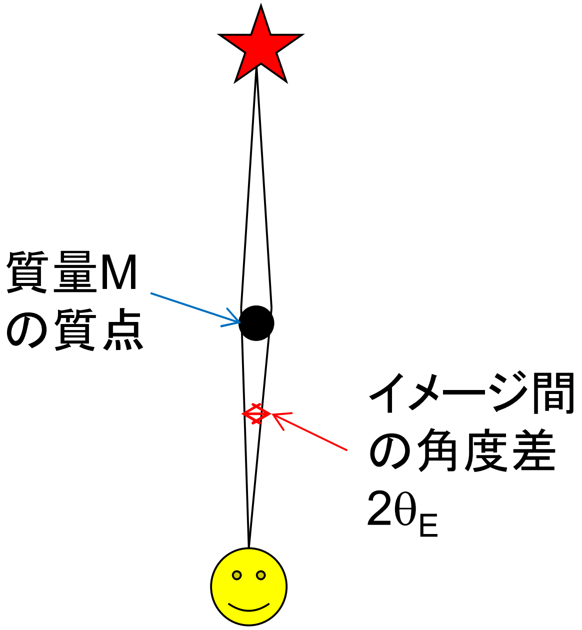
A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

マイクロレンズ

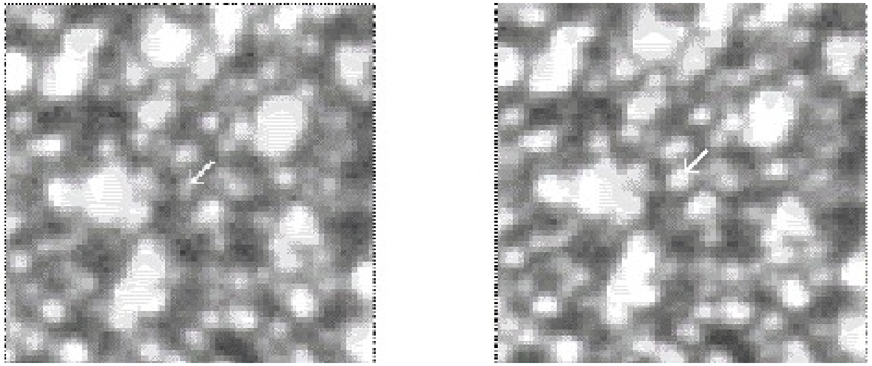
$$\theta_E \sim (M / M_{sun})^{1/2} \text{ mas}$$



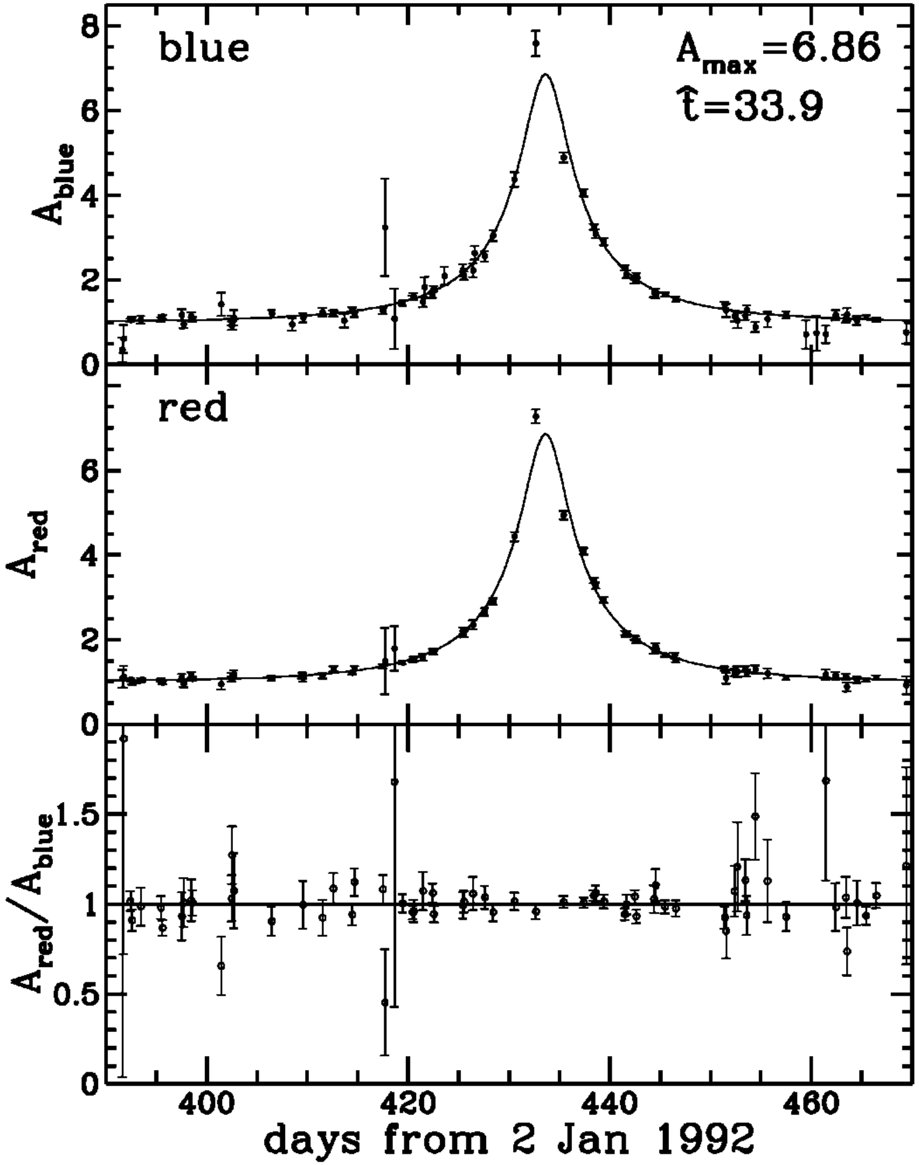


大マゼラン雲

銀河系中心からの距離～16万光年



大マゼラン雲におけるマイクロレンズイベントの発見



青い光の強度

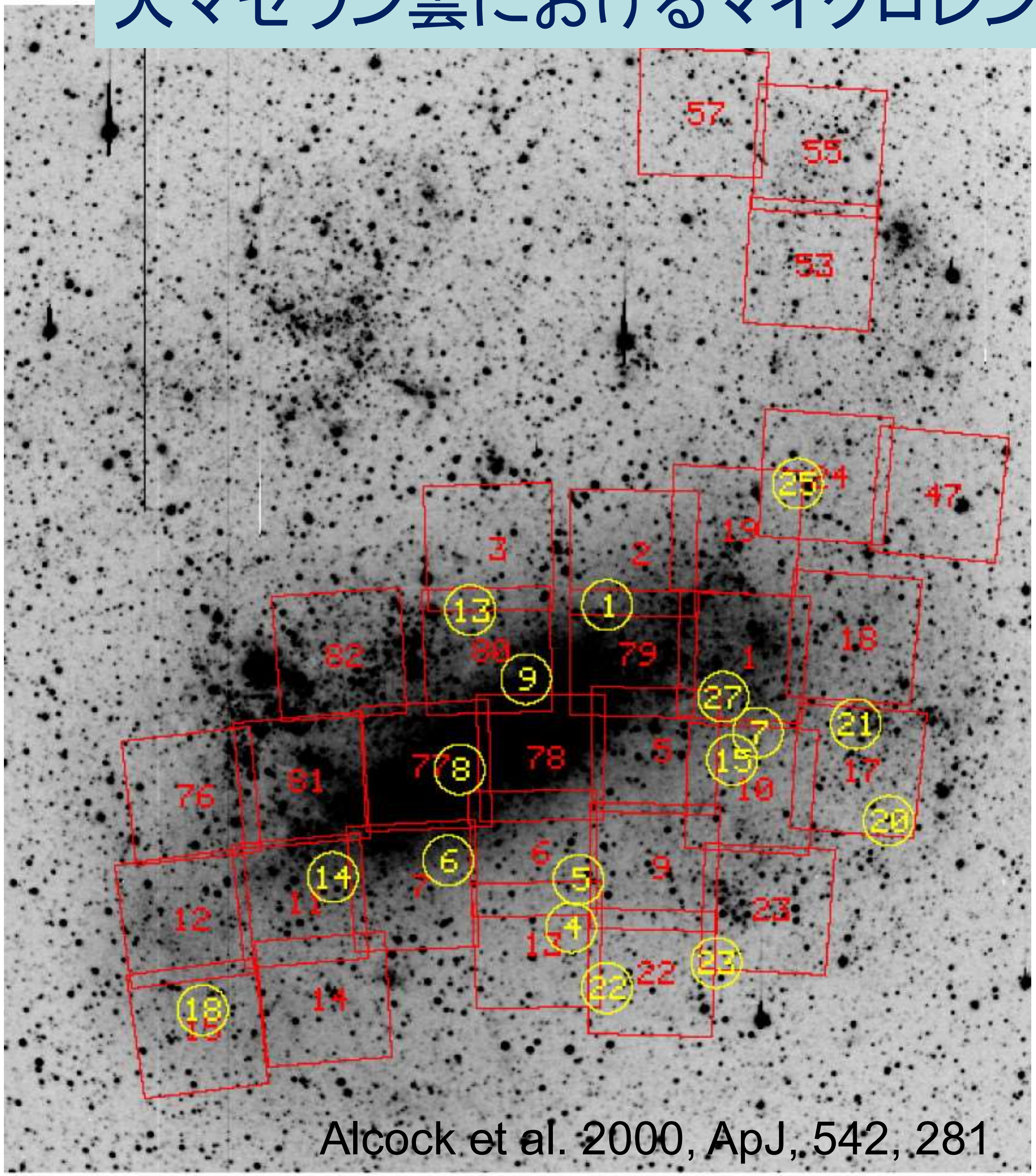
赤い光の強度

強度比

時間（日）

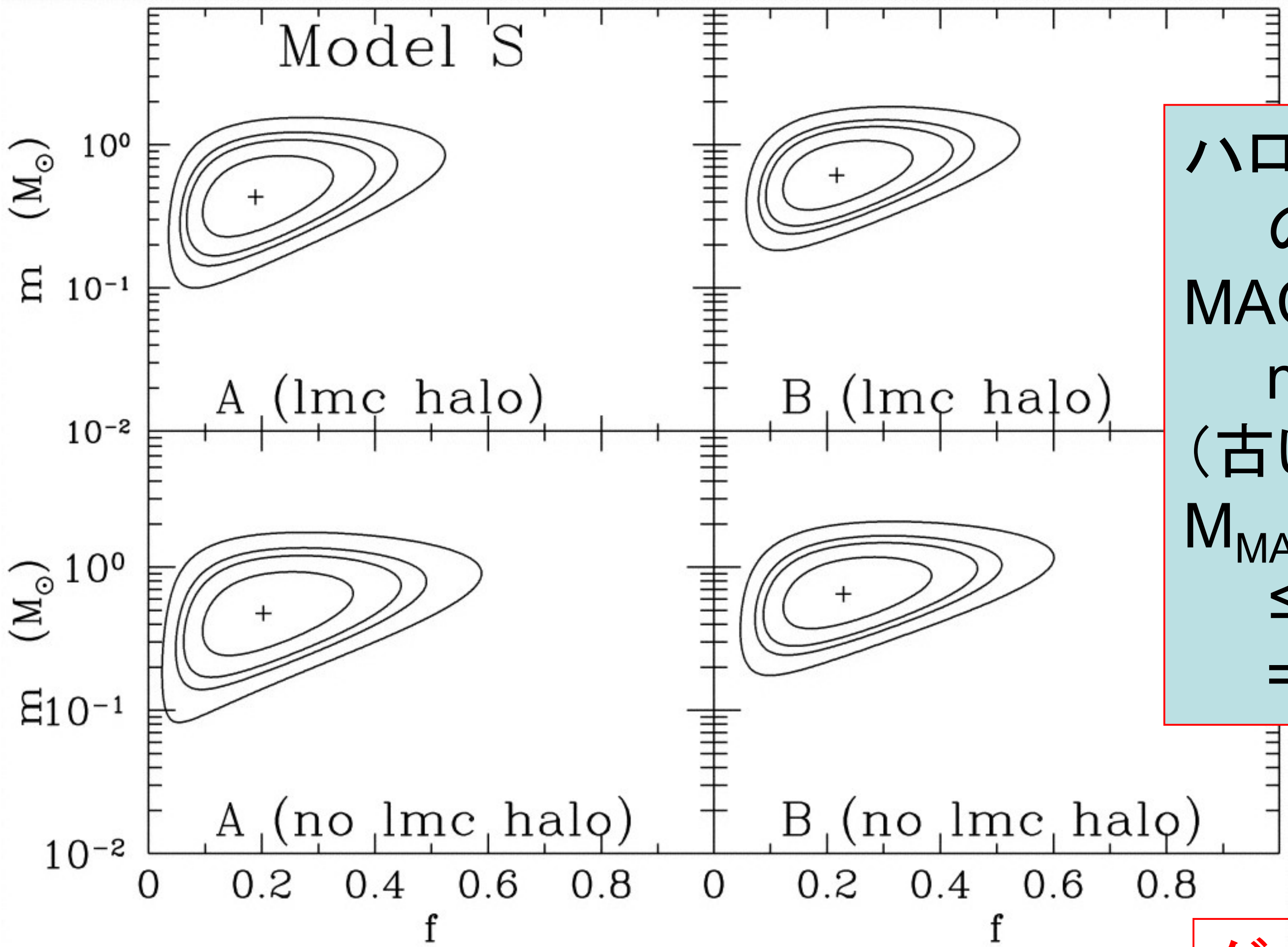
Alcock et al. 1993

大マゼラン雲におけるマイクロレンズイベントの場所



Alcock et al. 2000, ApJ, 542, 281

30 フィールド
11.9 x 10^6 個の星
5.7 年の観測
→13~17 イベント



ハローにおけるMACHO
　の割合 f ~ 20 %

MACHO1個の質量
　m =0.15~0.9 Msun

（古い白色矮星？）

M_{MACHO}(LMCまで
　≤50kpc)
　= 9 x 10^{10} Msun

ダークマターの大部分が説明できない

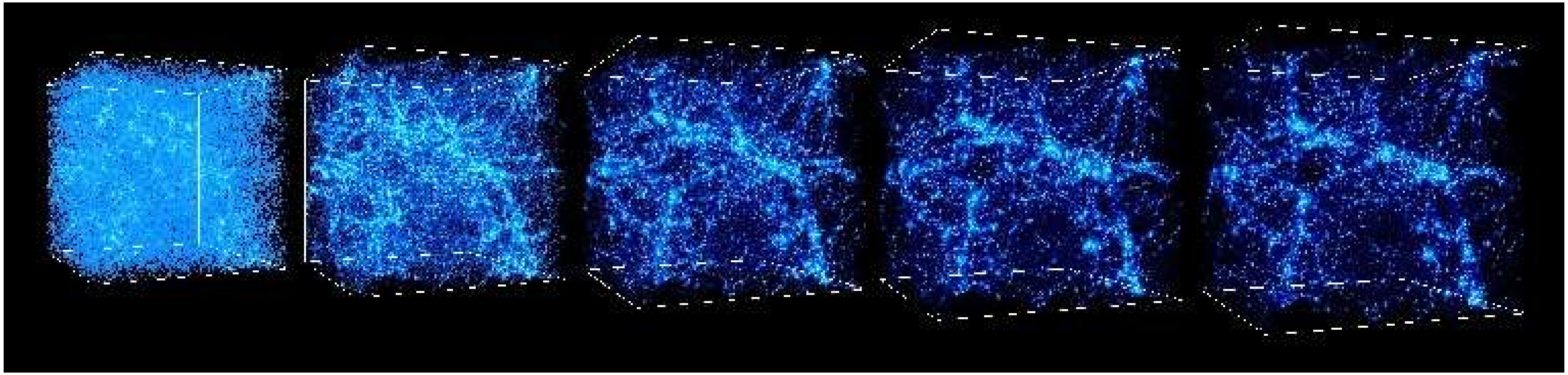
Dark matter の候補

- 暗くコンパクトな天体
  - Baryonic matter（陽子・中性子でできた通常の物質：バリオン）
    - 恒星になり損ねた星、白色矮星、中性子星、ブラックホール
  - 原始ブラックホール
  - MACHOs（Massive Compact Halo Objects ）
- Non-baryonic matter（バリオンではない物質）
  - 電磁波と相互作用しない素粒子
    - neutralino, massive neutrino, axion, ….
  - WIMPs（Weakly Interacting Massive Particles）
    - 特に重い素粒子でランダム速度小のものが重要
    - 冷たい暗黒物質（Cold Dark Matter）

冷たい暗黒物質による構造形成

暗黒物質の分布の時間発展

時間

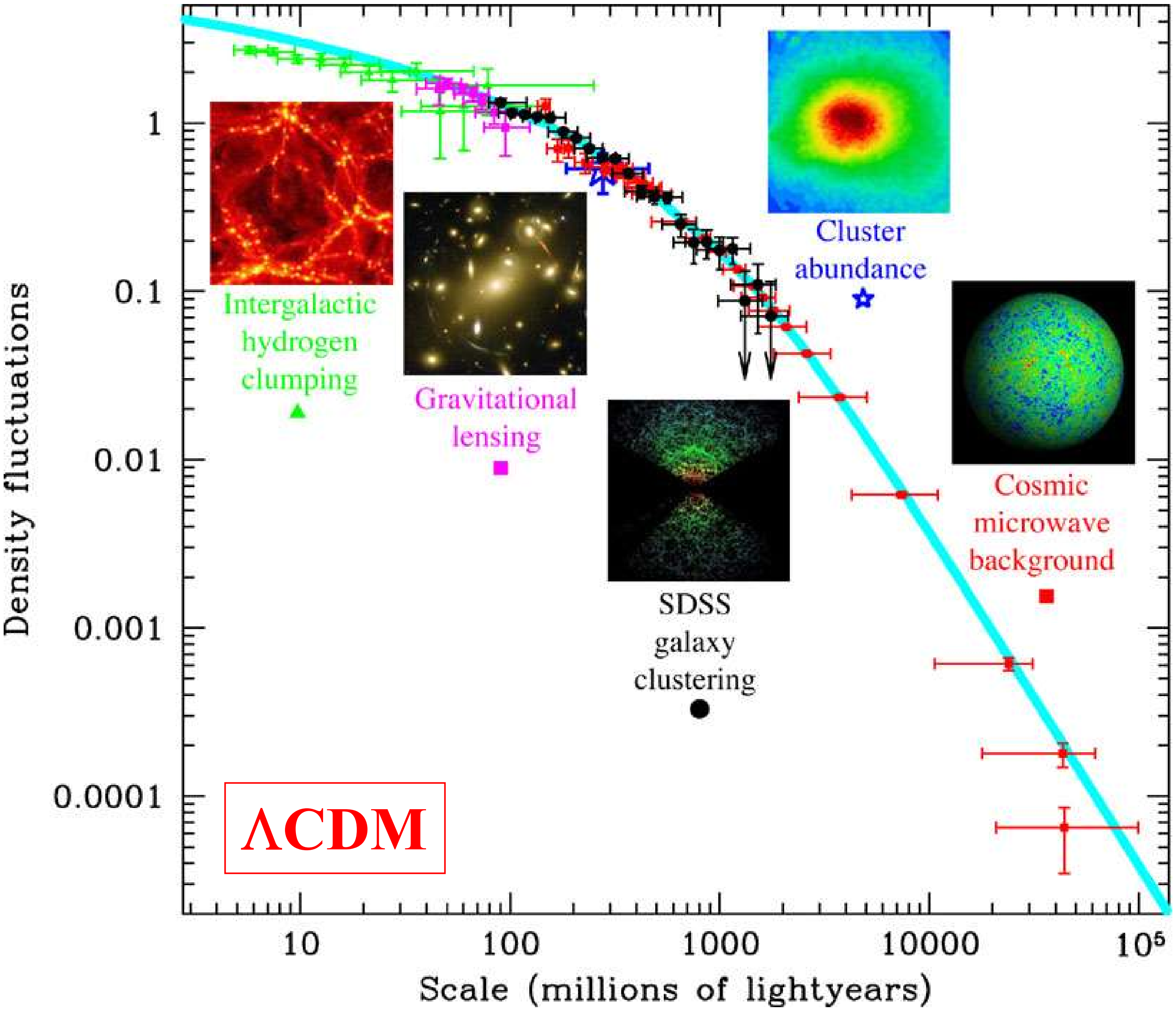


冷たい暗黒物質 Cold Dark Matter (CDM)　例:ニュートラリーノ

小さなかたまりが最初にできて、合体・降着を経てより大きなスケールの構造が形成。様々なスケールの宇宙構造を再現。

CDMによる宇宙の構造形成

宇宙の大規模構造のスケール依存性

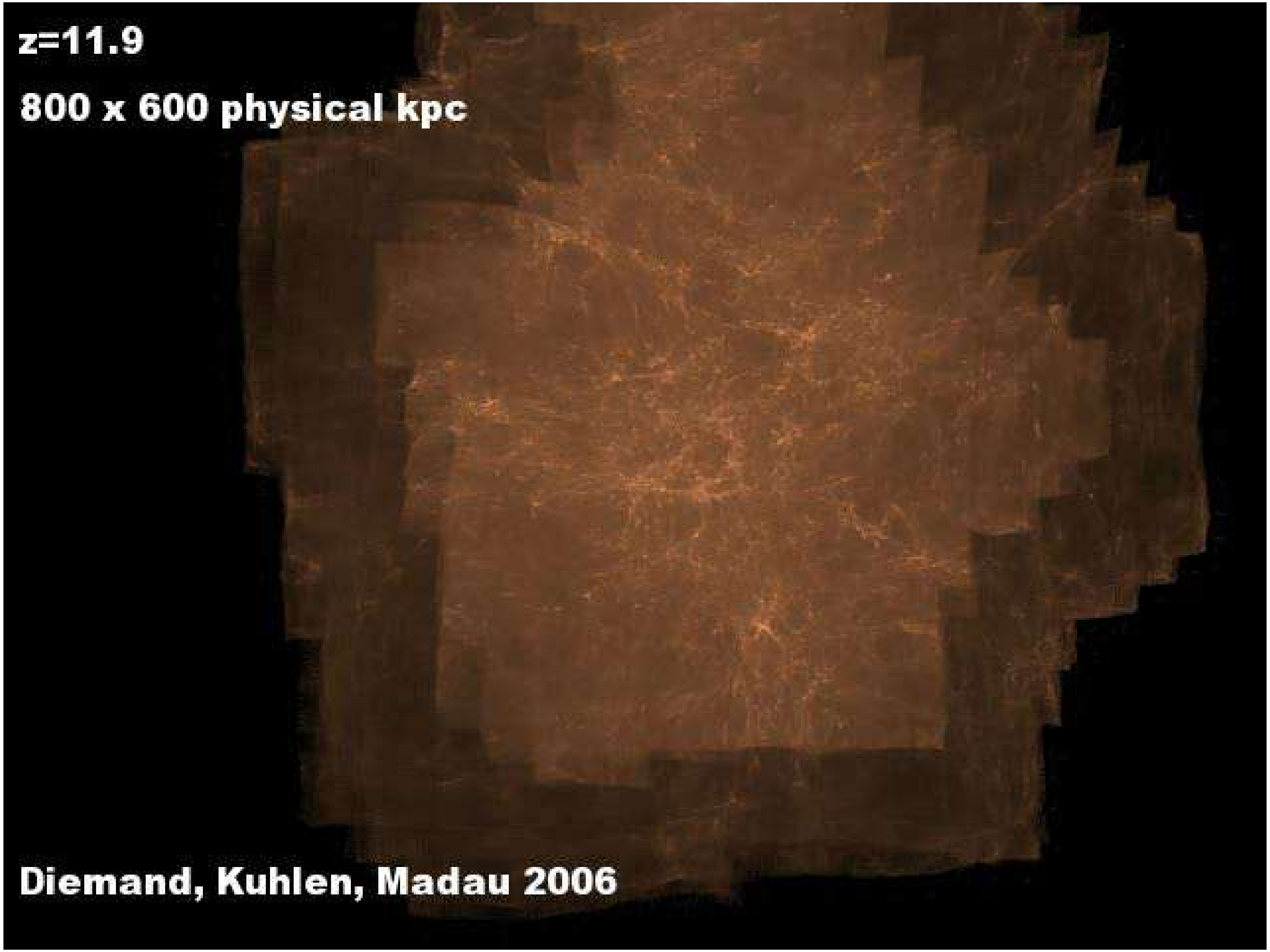


CDM subhalos

宇宙最初の天体を
作るゆらぎ
銀河の形態の決定

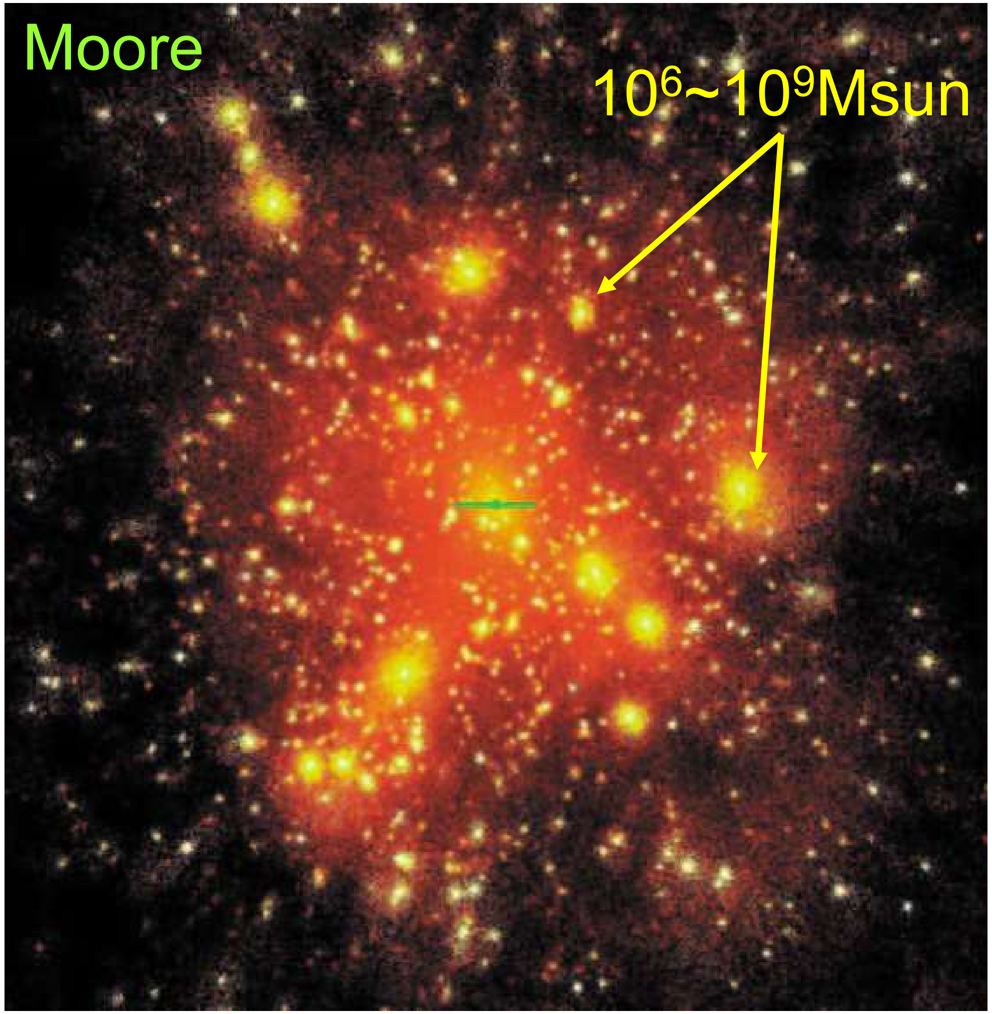
ダークマターの階層的合体のシミュレーション
（冷たい暗黒物質：Cold Dark Matter）

銀河スケール



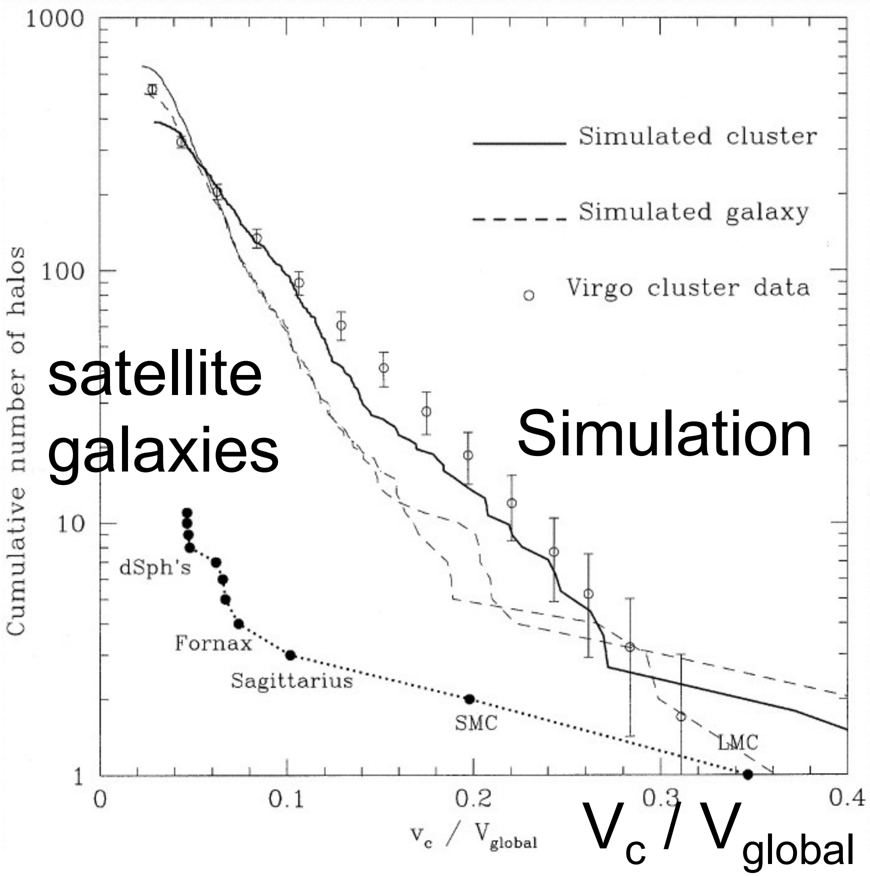
Dark matter substructure
Missing satellites problem

シミュレーションによる銀河系サイズのダークハロー分布



Virial radius r_{vir}~ 200 kpc

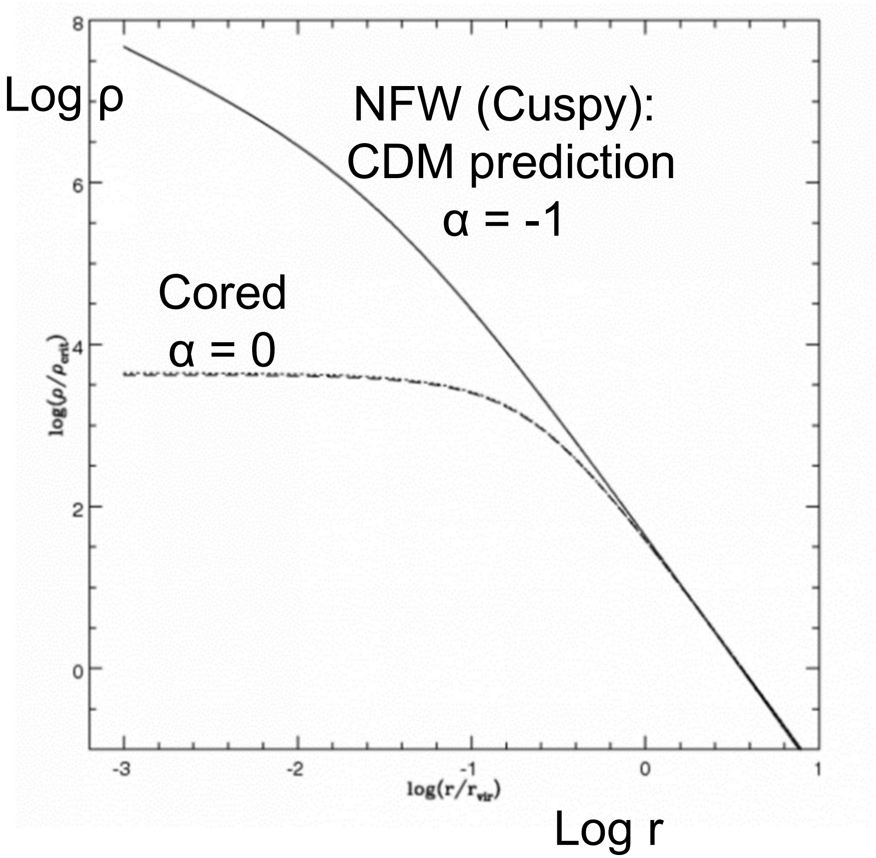
ハロー数の累積分布



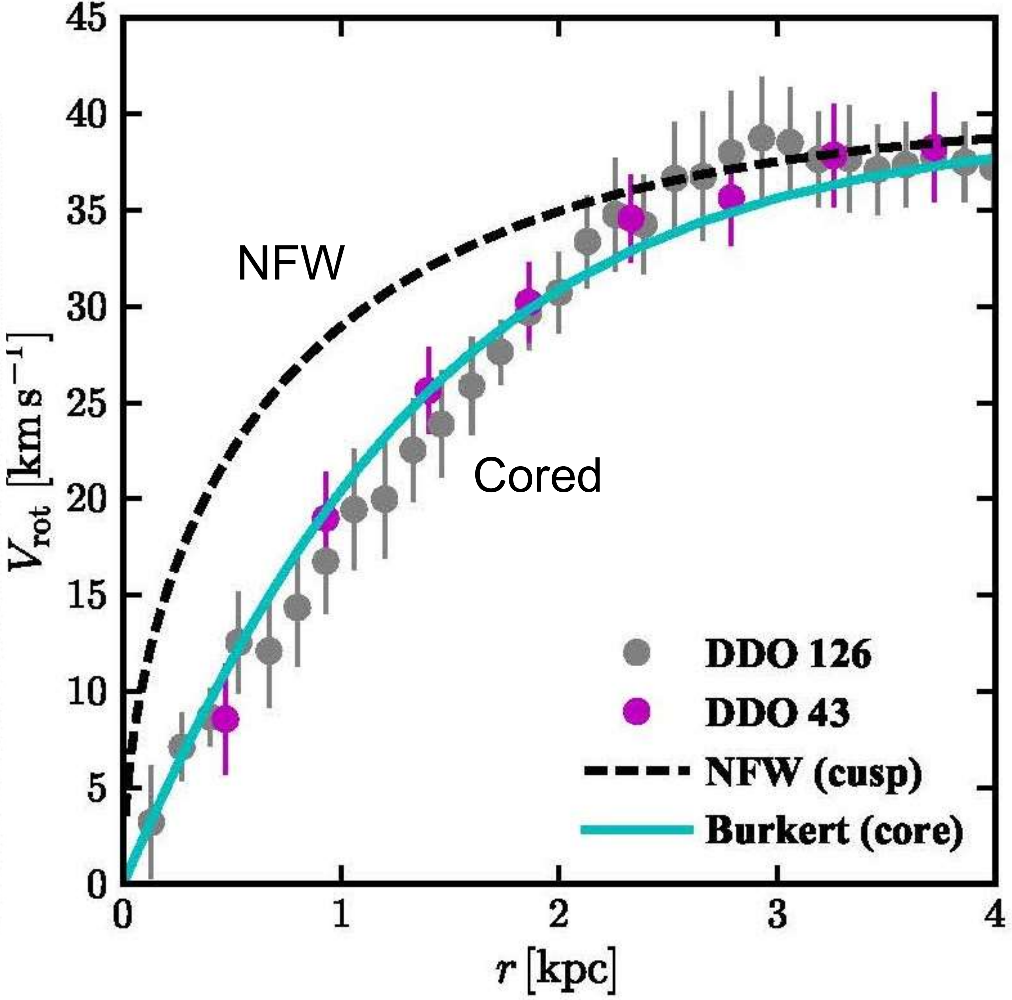
Core/cusp problem

Density distribution of a dark halo

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



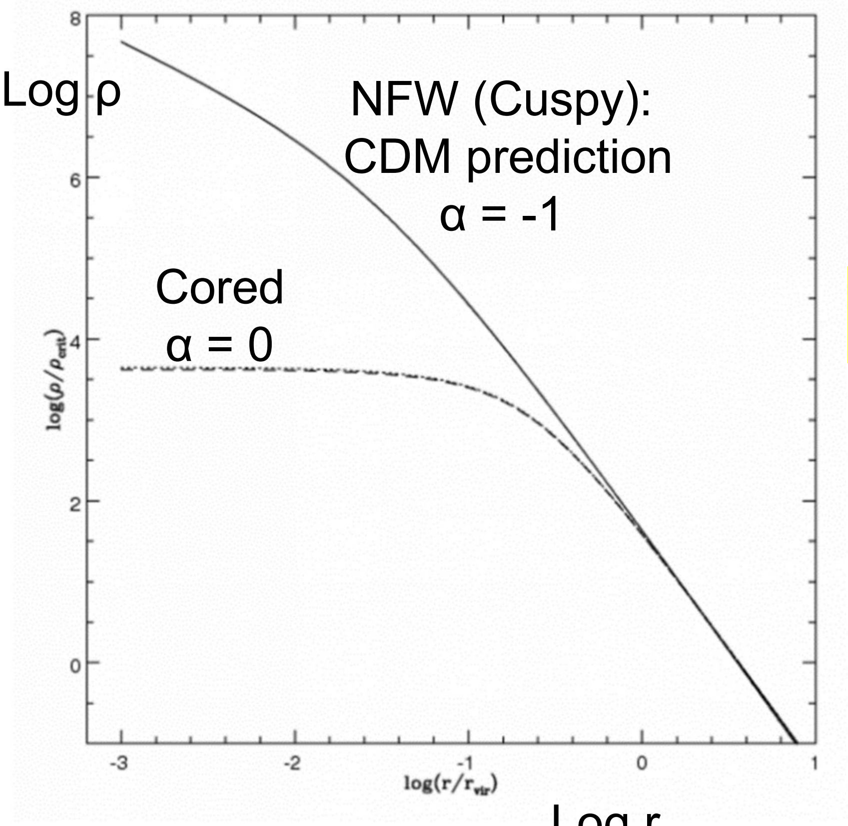
Rotation curves of (external) gas-rich dwarf galaxies



Core/cusp problem

Density distribution of a dark halo

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



Log ρ

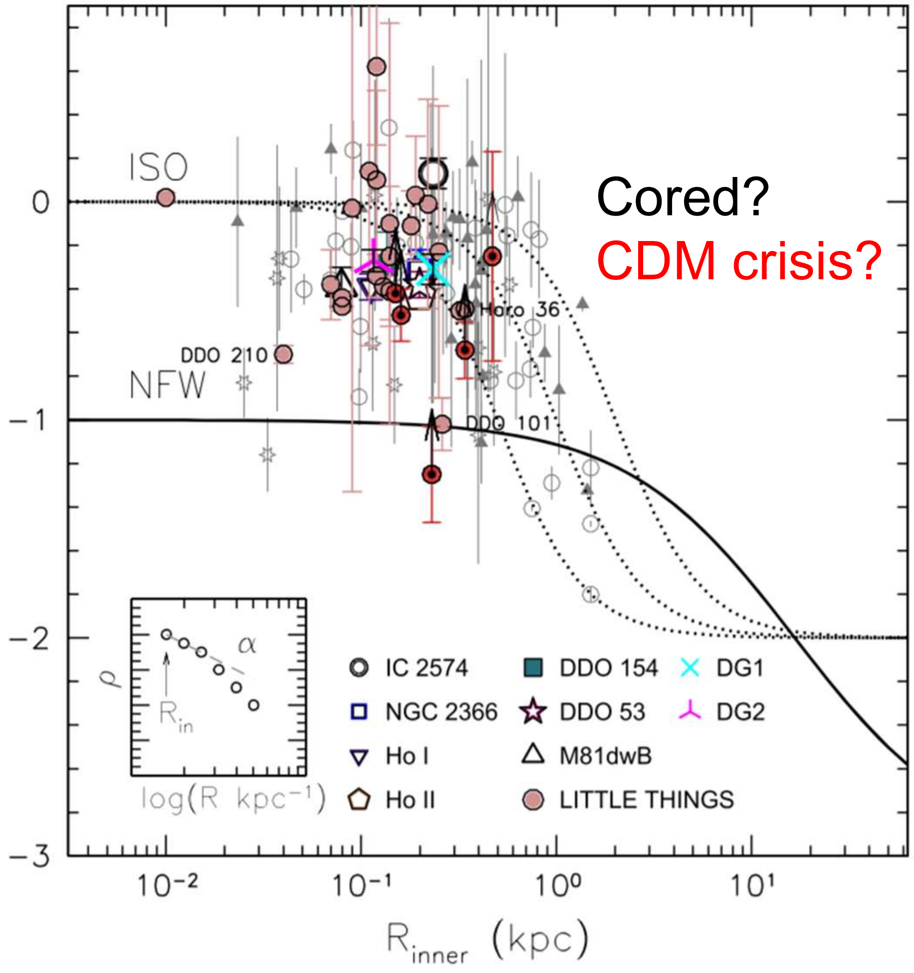
NFW (Cuspy):
CDM prediction
α = -1

Cored
α = 0

Log r

Oh et al. 2015

α

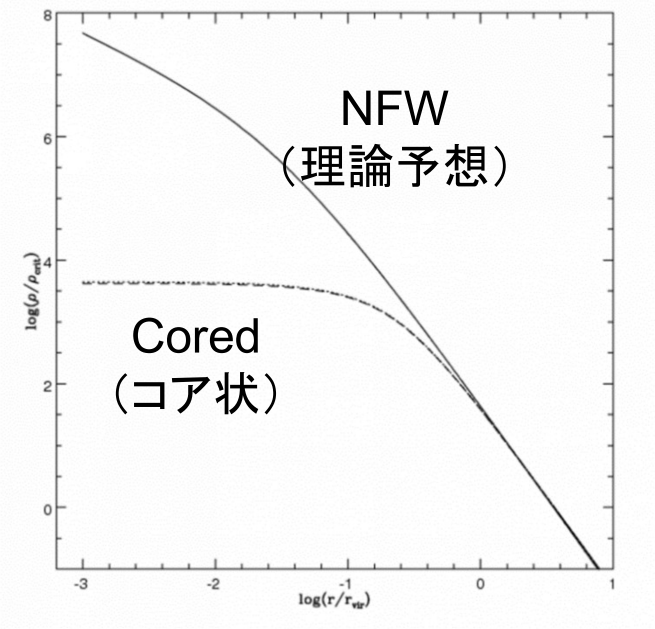


Cored?

CDM crisis?

Core/cusp problem

ダークハローの密度分布

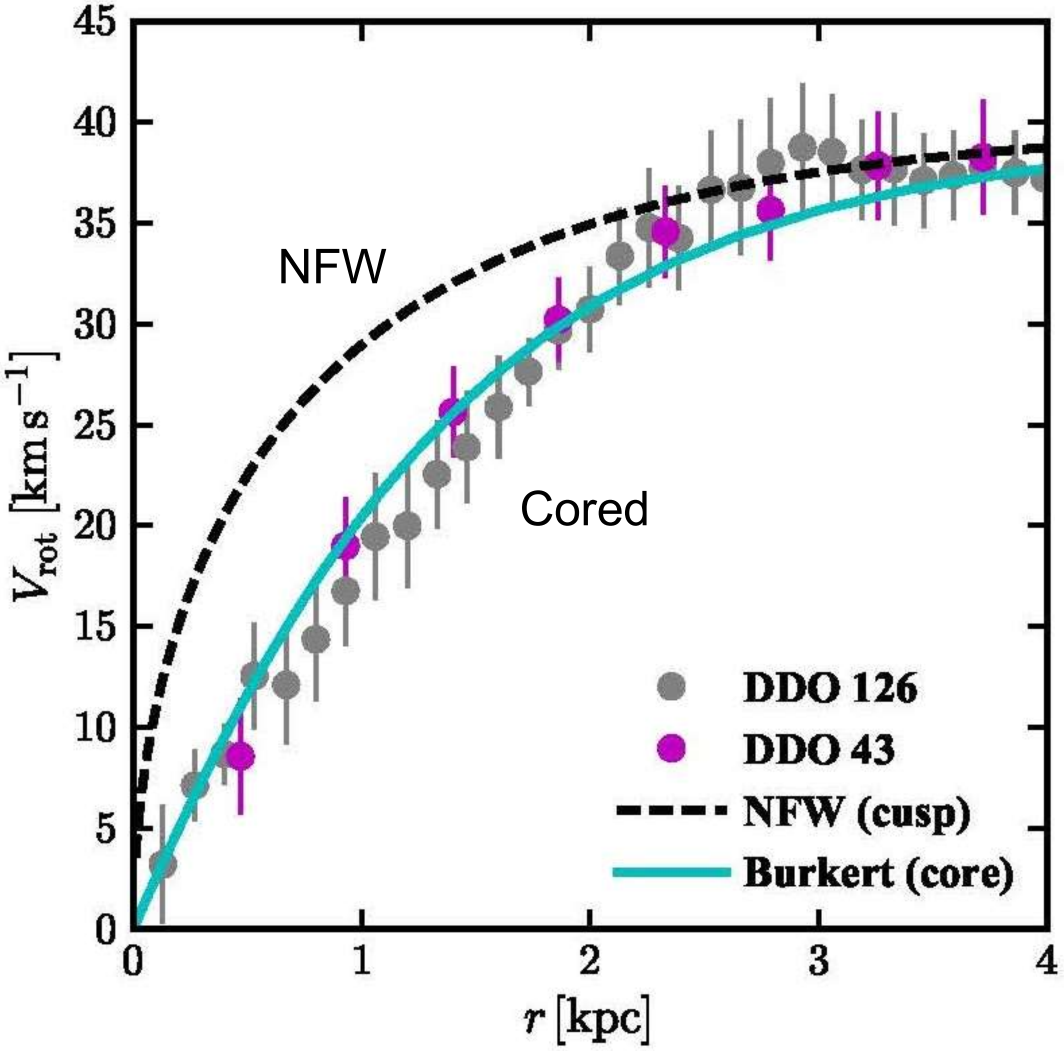


NFW
（理論予想）

Cored
（コア状）

Del Popolo 2009

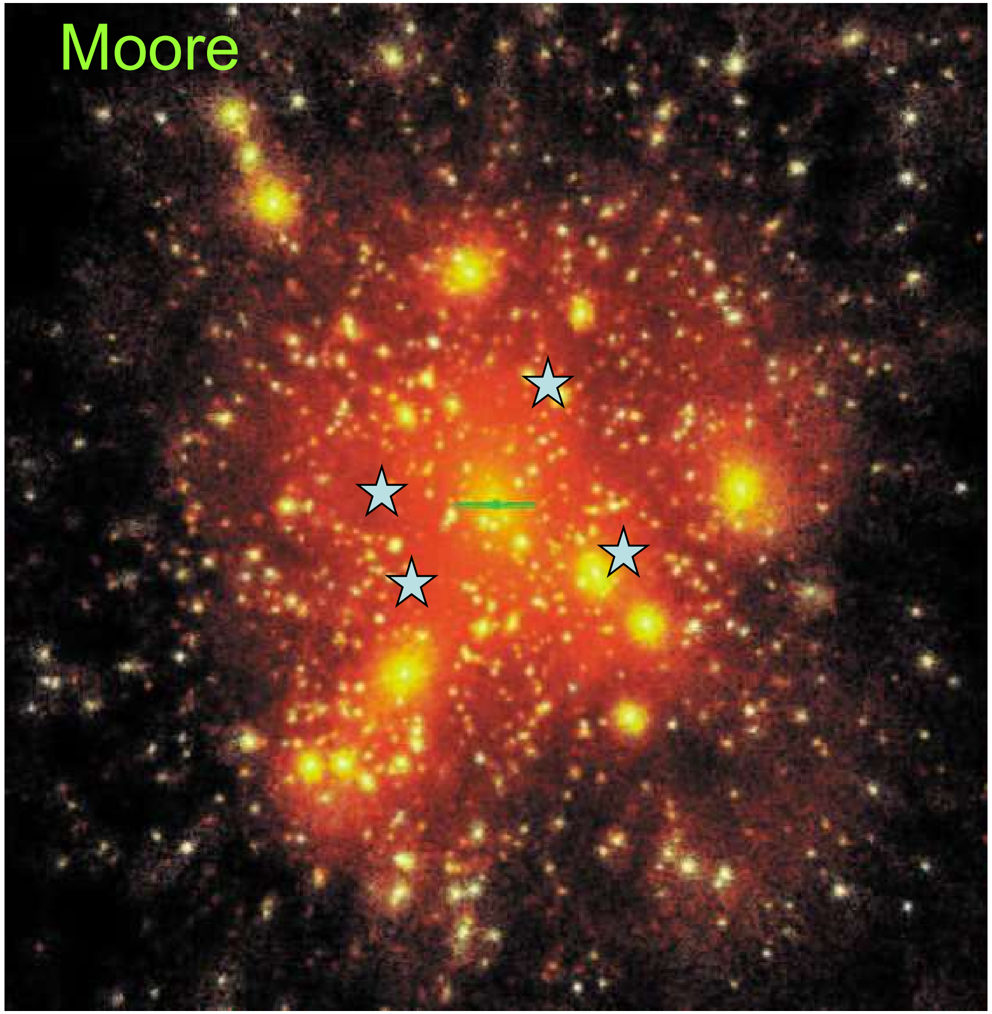
Rotation curves of dwarf galaxies



NFW

Cored

Lens mapping of CDM subhalos



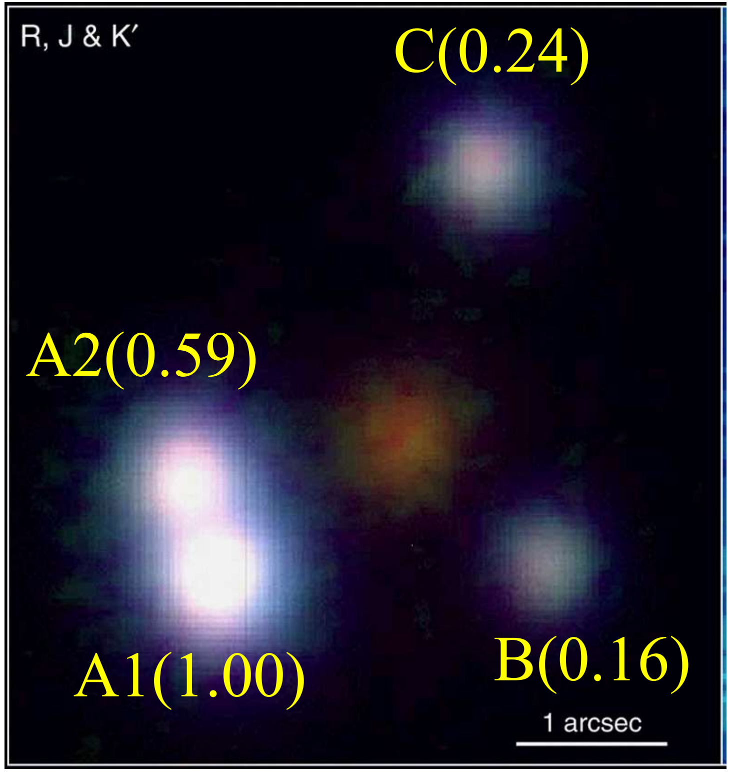
重力レンズ多重像間に見られる
“フラックス比異常”

(Metcalf & Madau 2001, Chiba 2002, Dalal & Kochanek 2002)

スムースダークハローでは
説明不能。
サブハロ―の効果による。

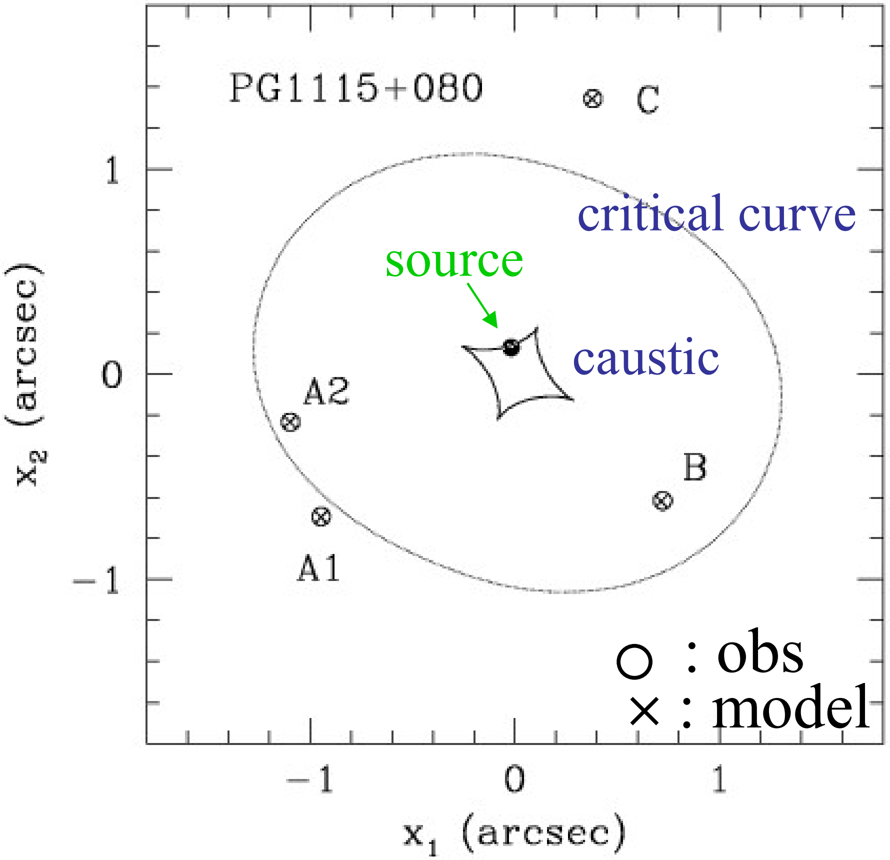
フラックス異常の例

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)

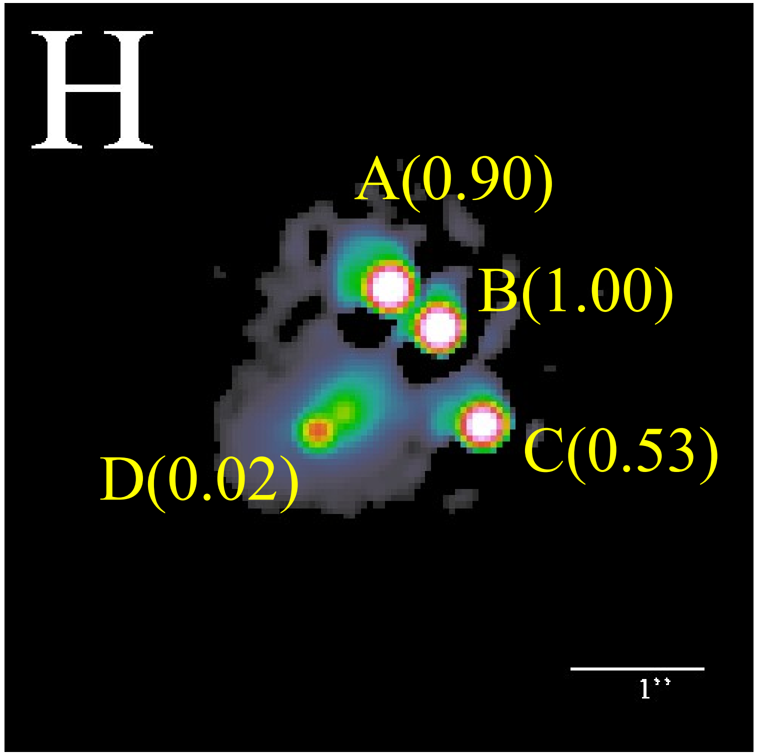


Model: A2/A1 ≈ 1 (fold caustic)

Observed A2/A1 (near-IR): ≈ 0.59 – 0.67 (anomalous)

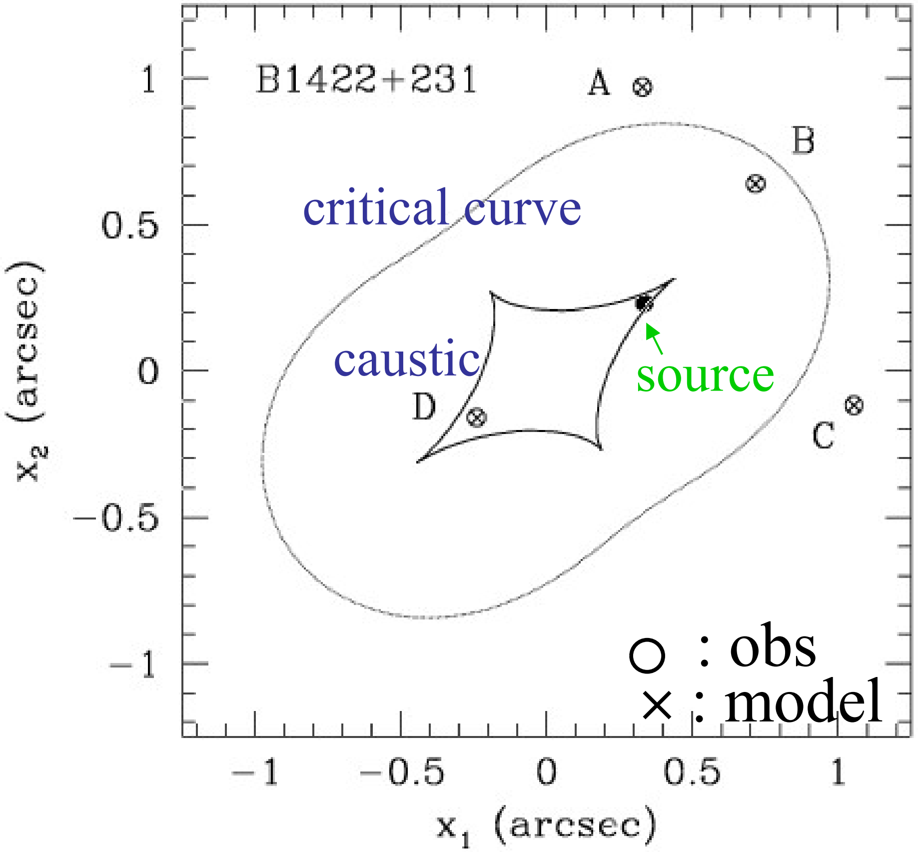
フラックス異常の例

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



CASTLES

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



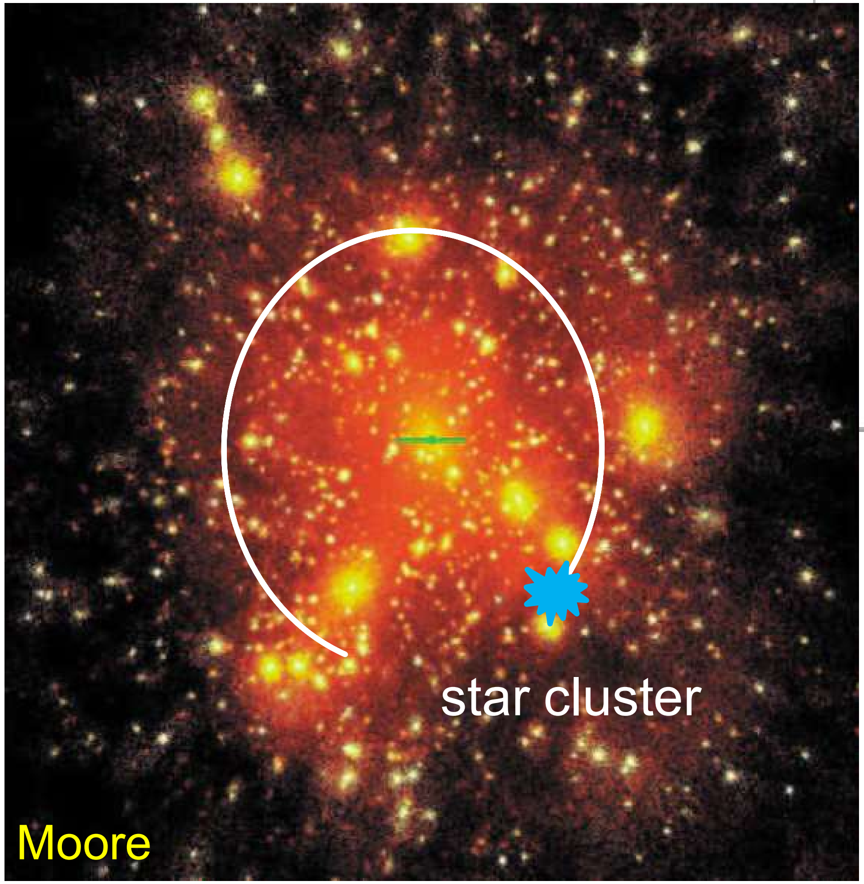
Model: (A+C)/B ≈ 1 (cusp caustic)

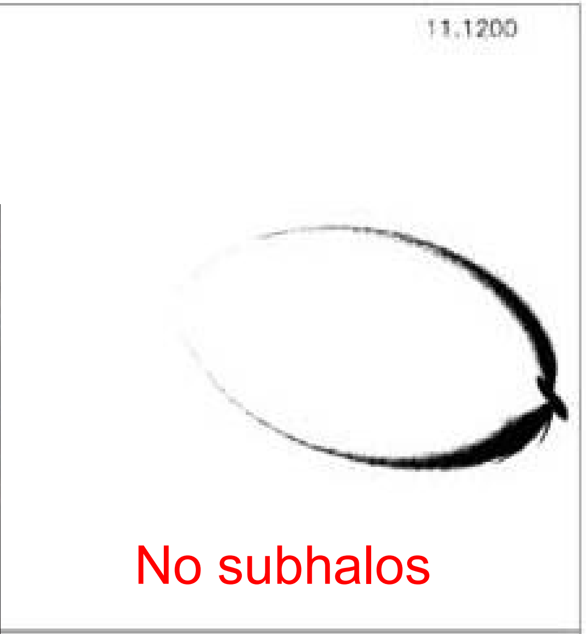
Observed (A+C)/B (radio): ≈ 1.42 – 1.50 (anomalous)

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

(Carlberg 2011)

CDM halo in a galaxy





No subhalos

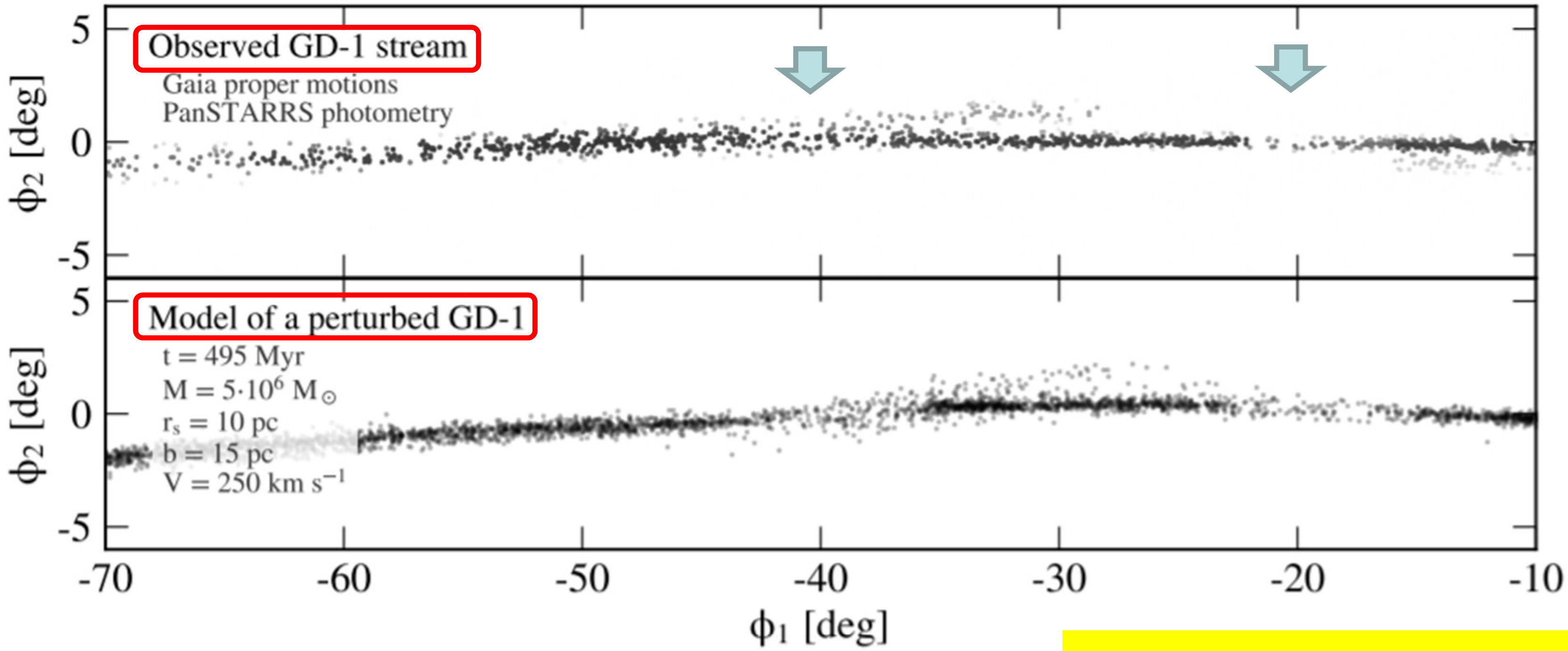
dynamical effects on stellar stream ($M_{star}=10^6 M_{sun}$

Showing gaps

1000 subhalos, $M^{-1.9}$

Perturbation in the MW stream

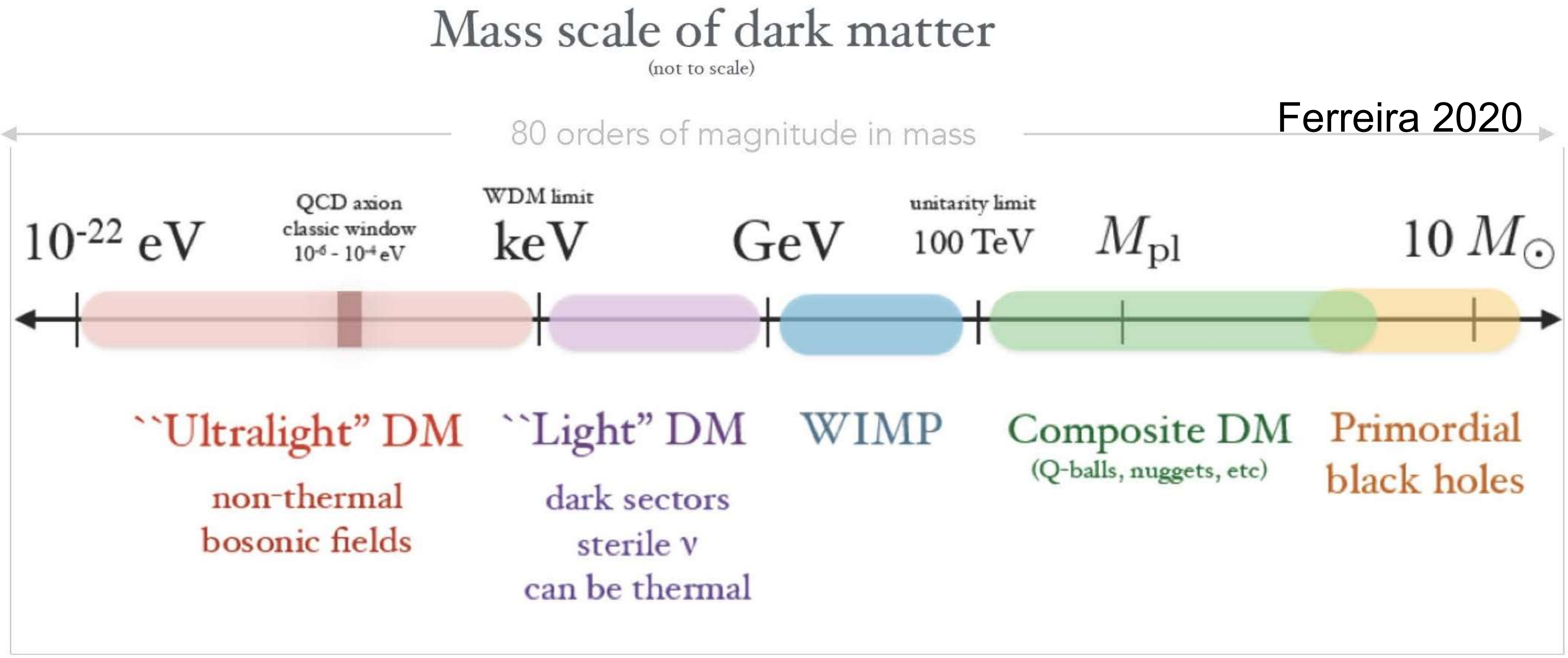
Bonaca et al. 2019 GD-1 stream selected with Gaia PMs



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.

Dark matter candidate



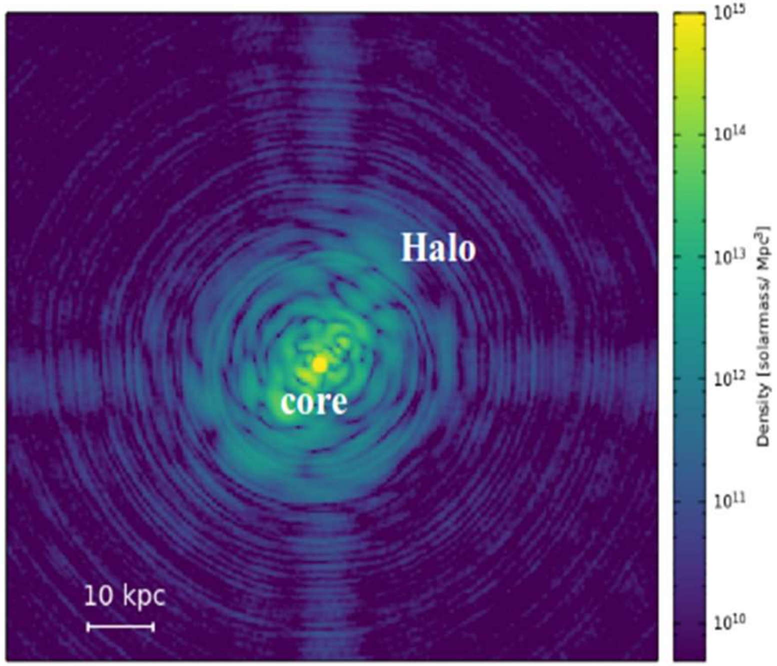
Ferreira 2020

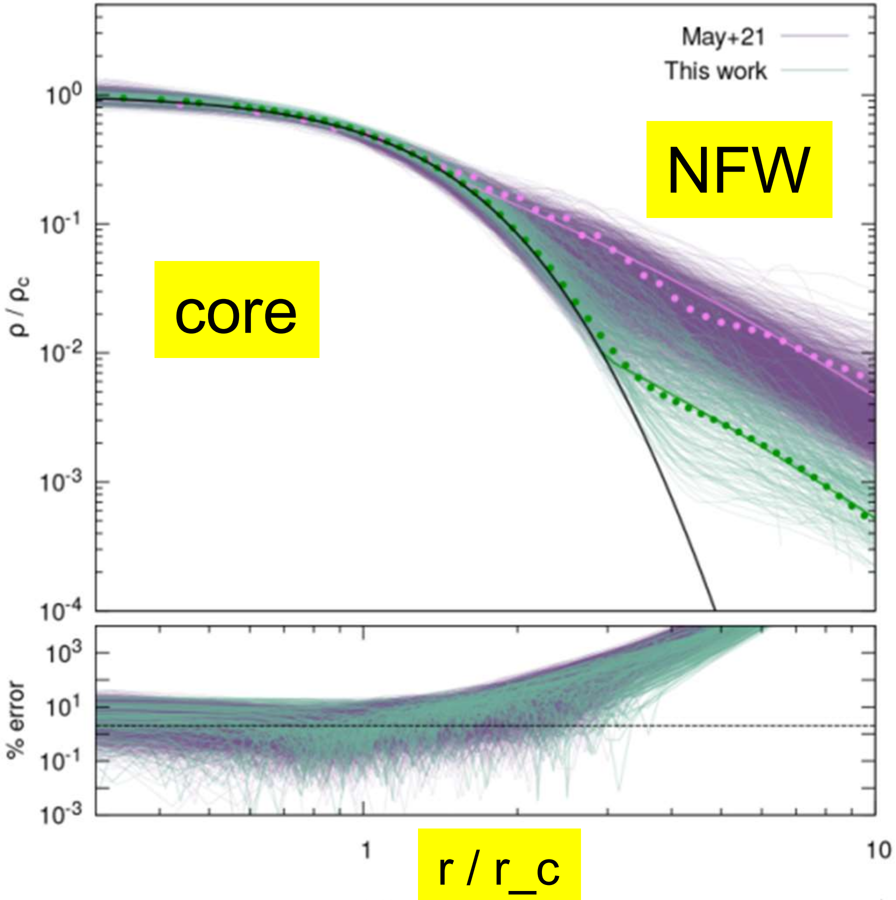
The case of ultra-light DM (FDM)

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

Simulated DM halo

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

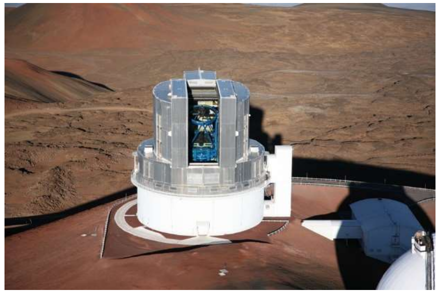




$$\rho_{\rm soliton}(r) = \frac{1.9 \times 10^{12} M_\odot \ {\rm pc}^{-3}}{[1 + 0.091 (r/r_c)^2]^8} \left(\frac{m_\psi}{10^{-22} {\rm eV}} \right)^{-2} \left(\frac{r_c}{\rm pc} \right)^{-4}$$

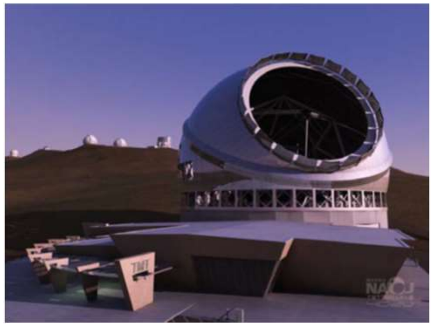
A few kpc scale ⇒ Dwarf galaxy scale is a key

5.6 今後の展望

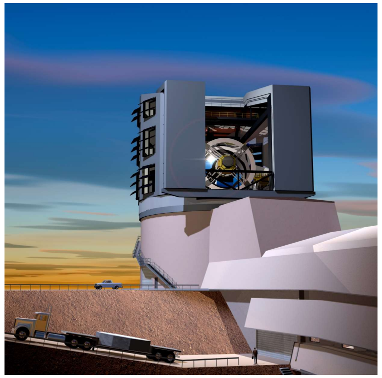


Subaru
HSC
PFS：2023-
Ultimate:

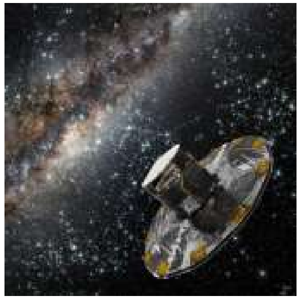
ALMA



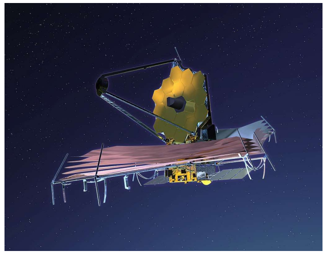
TMT
WFOS
HROS
NIRES
2028?



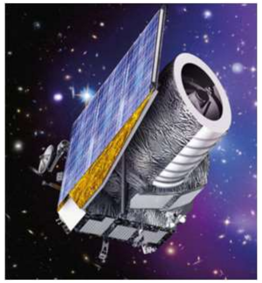
Vera C.
Rubin
(LSST)
2023-



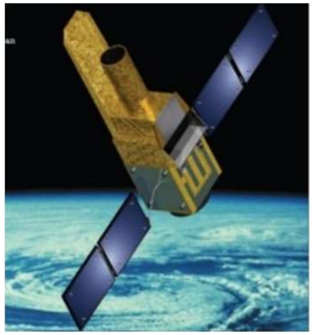
Gaia



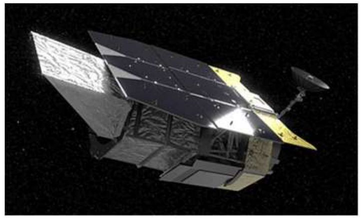
JWST
NIRCam
NIRSpec
MIRI
2021-



Euclid
YJH
2022-



JASMINE
NIR astrometry
Late 2020

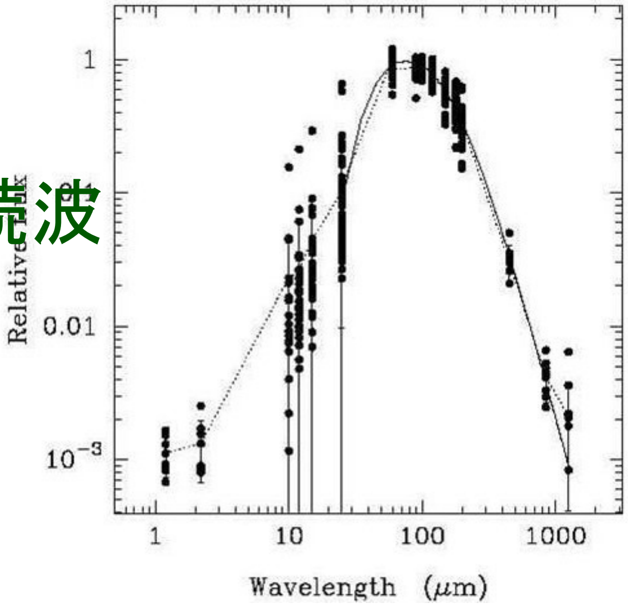


Nancy Grace
Roman Space
Telescope
(WFIRST)
2025-

銀河形成と暗黒物質の解明へ

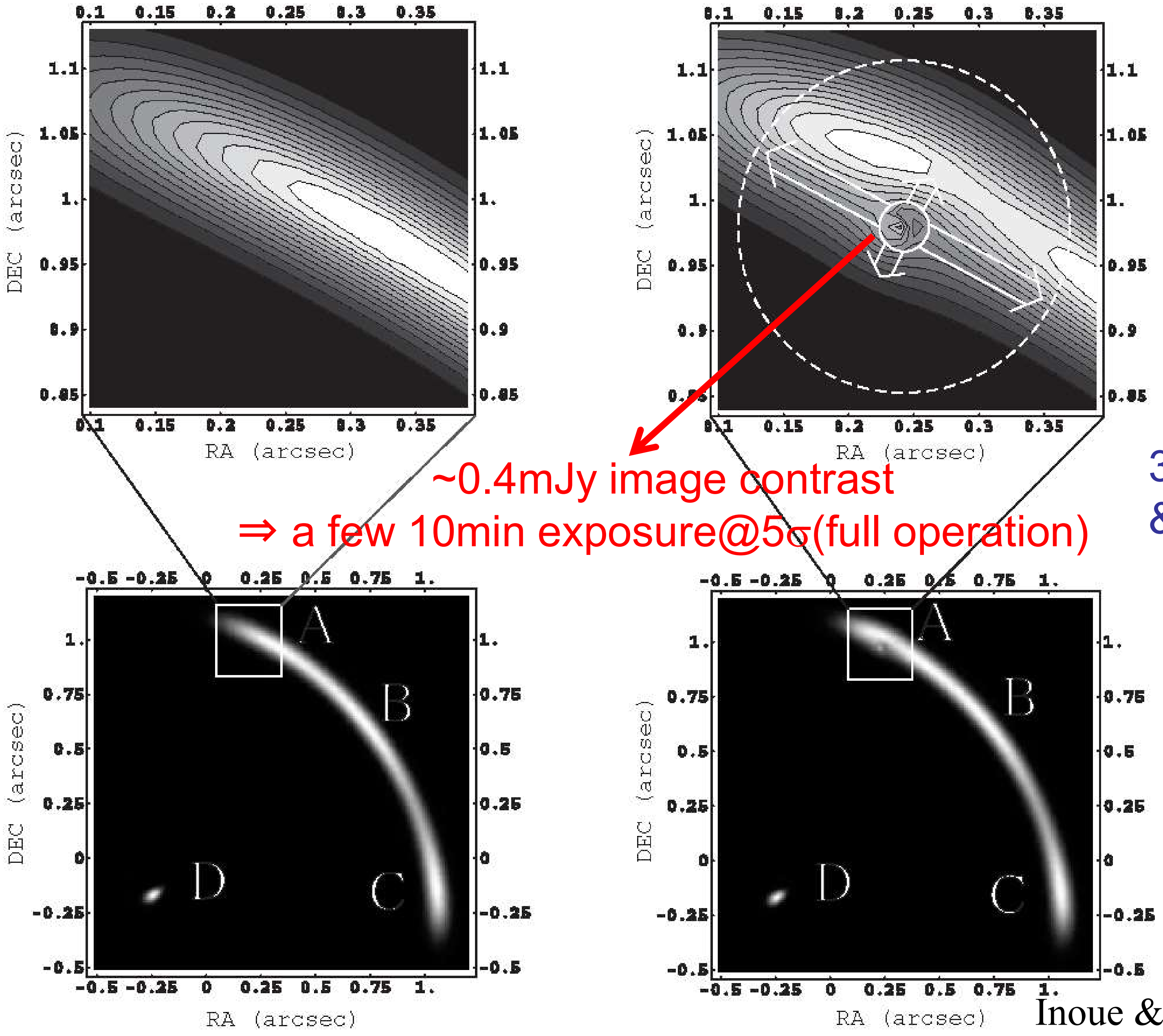
ALMA による
広がった光源の重力レンズ観測

- CDMサブハローによる重力レンズ効果の直接イメージング　(10mas)
  - ✓ Determination of subhalo masses
  - ✓ Spatial distribution of subhalos
- レンズ源: ダストからのサブミリ連続波
  - ✓ T=30~60 K, L=10^2~10^3 pc
  - ✓ S at 850μm=several tens mJy



CDM理論のテスト

2×10^8 Msun subhalo at resolution 0.01 arcsec



~0.4mJy image contrast

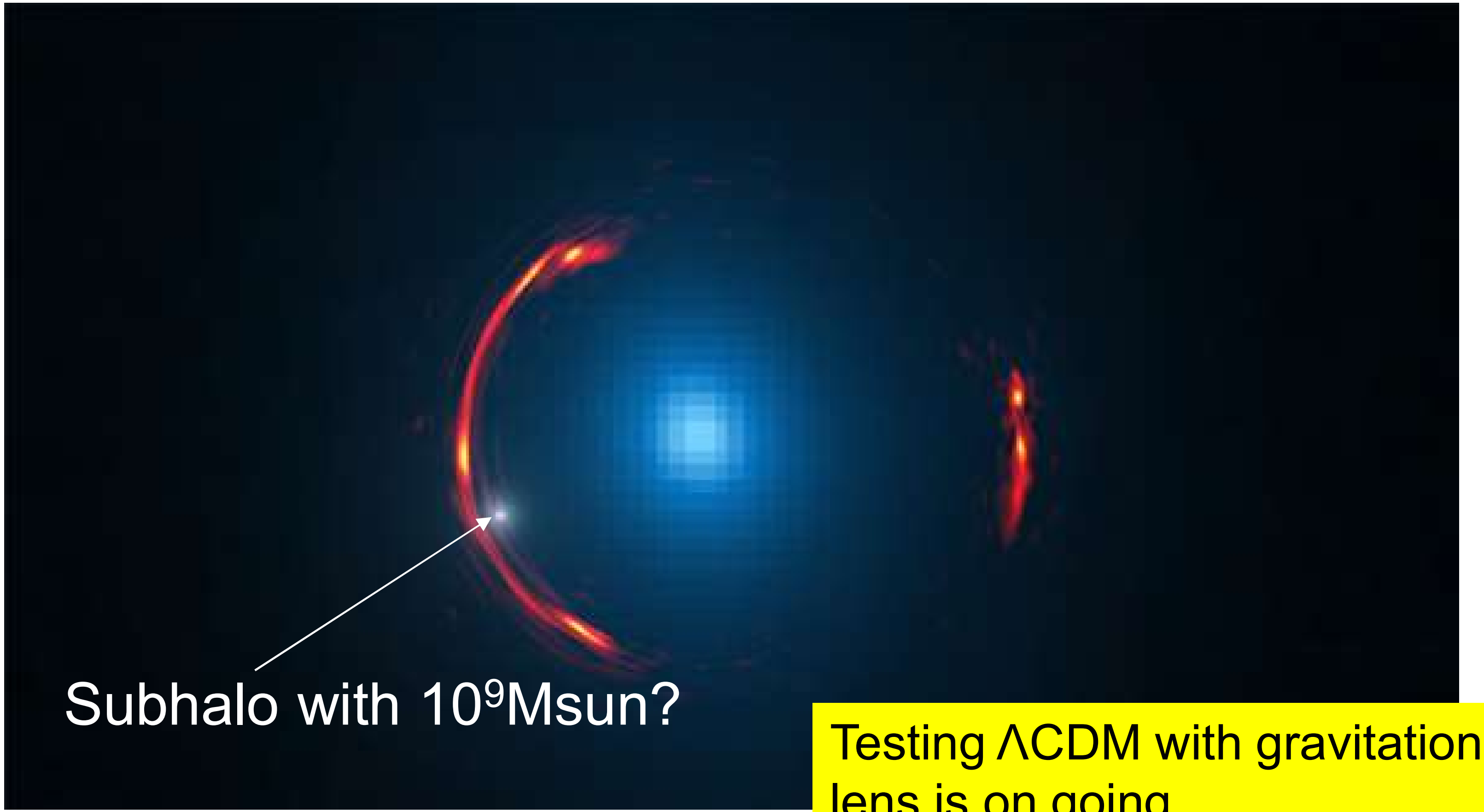
⇒ a few 10min exposure@5σ(full operation)

3d position
& mass

Inoue & Chiba 2005

ALMA: 重力レンズ銀河SDP.81

Hezaveh et al. 2016



Subhalo with 10^9Msun?

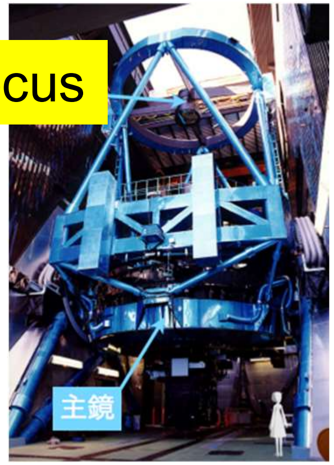
Testing ΛCDM with gravitational lens is on going

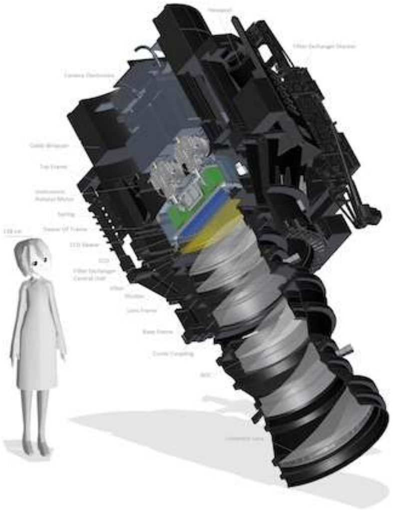
一方、Inoue, K. T., Minezaki, Matsushita, Chiba 2016:
銀河間空間にある負の密度摂動の効果とする主張
決着は付いていない。

Subaru/HSC

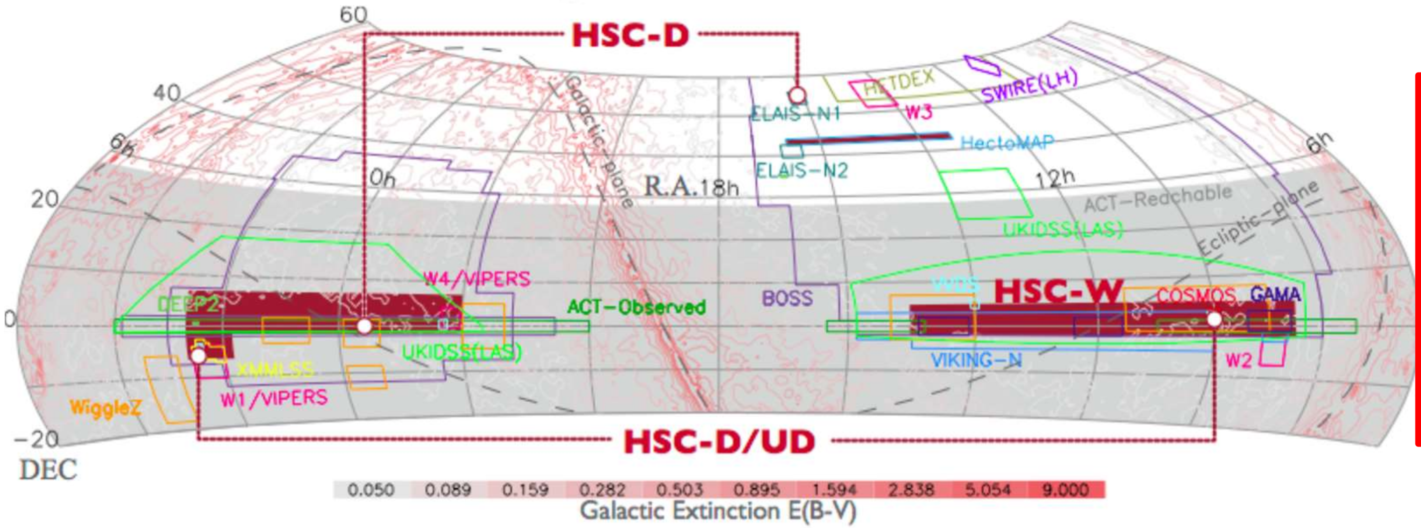
(Hyper Suprime Cam)

Prime focus





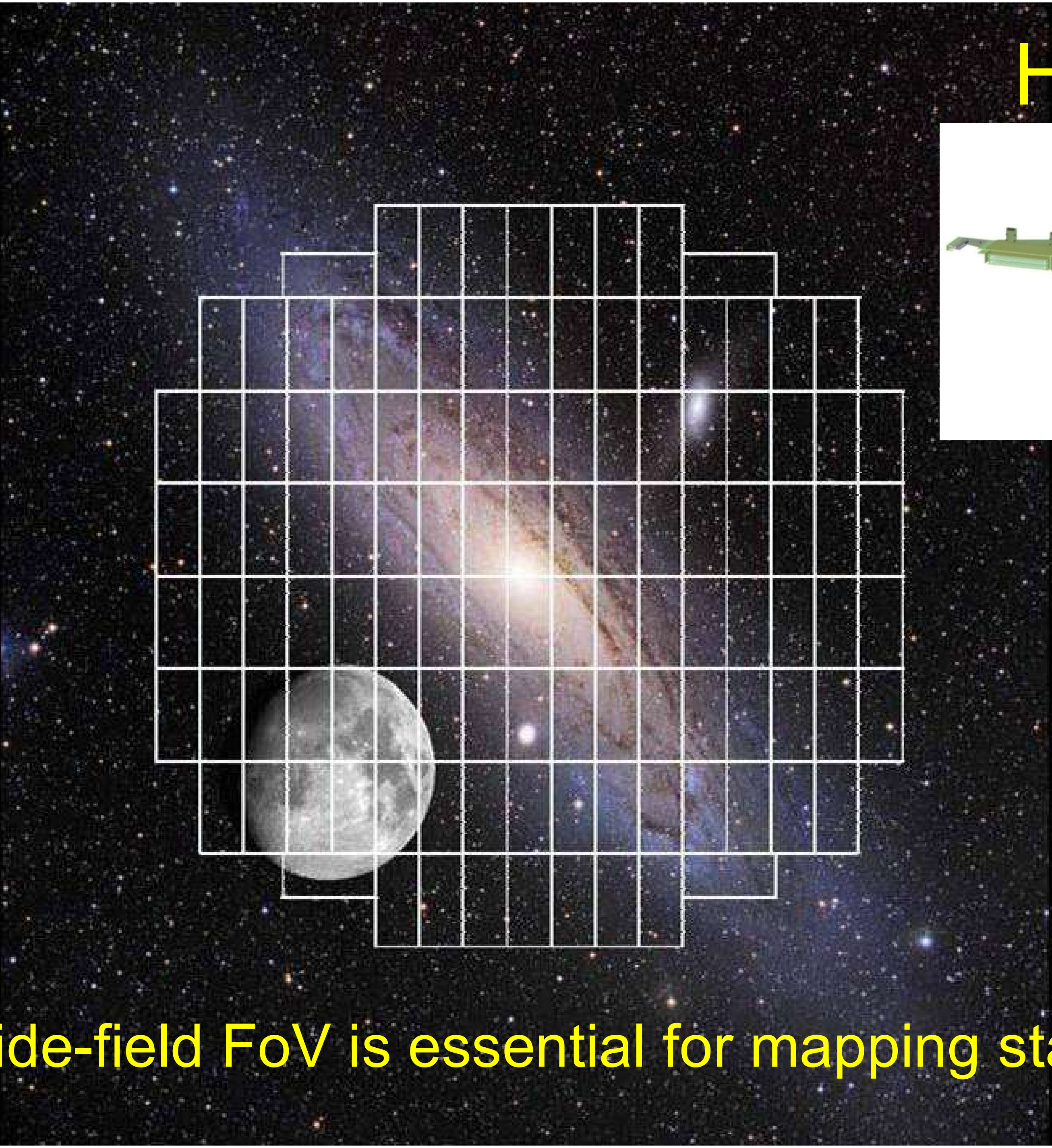
FOV: 1.77 sq deg
(1.5 deg diameter)
Pixel: 870 Mega pixels
Filters: grizy + many NB
Operation: 2013~

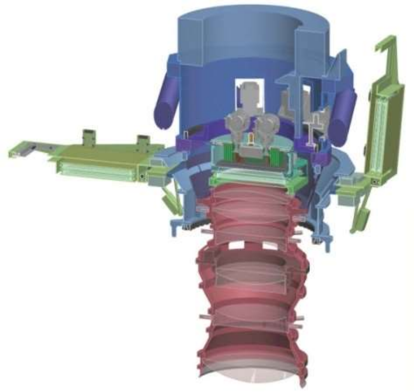


HSC-SSP

- Wide: 1100 deg^2, Deep, Ultra-deep
- 6 years
- 330 nights

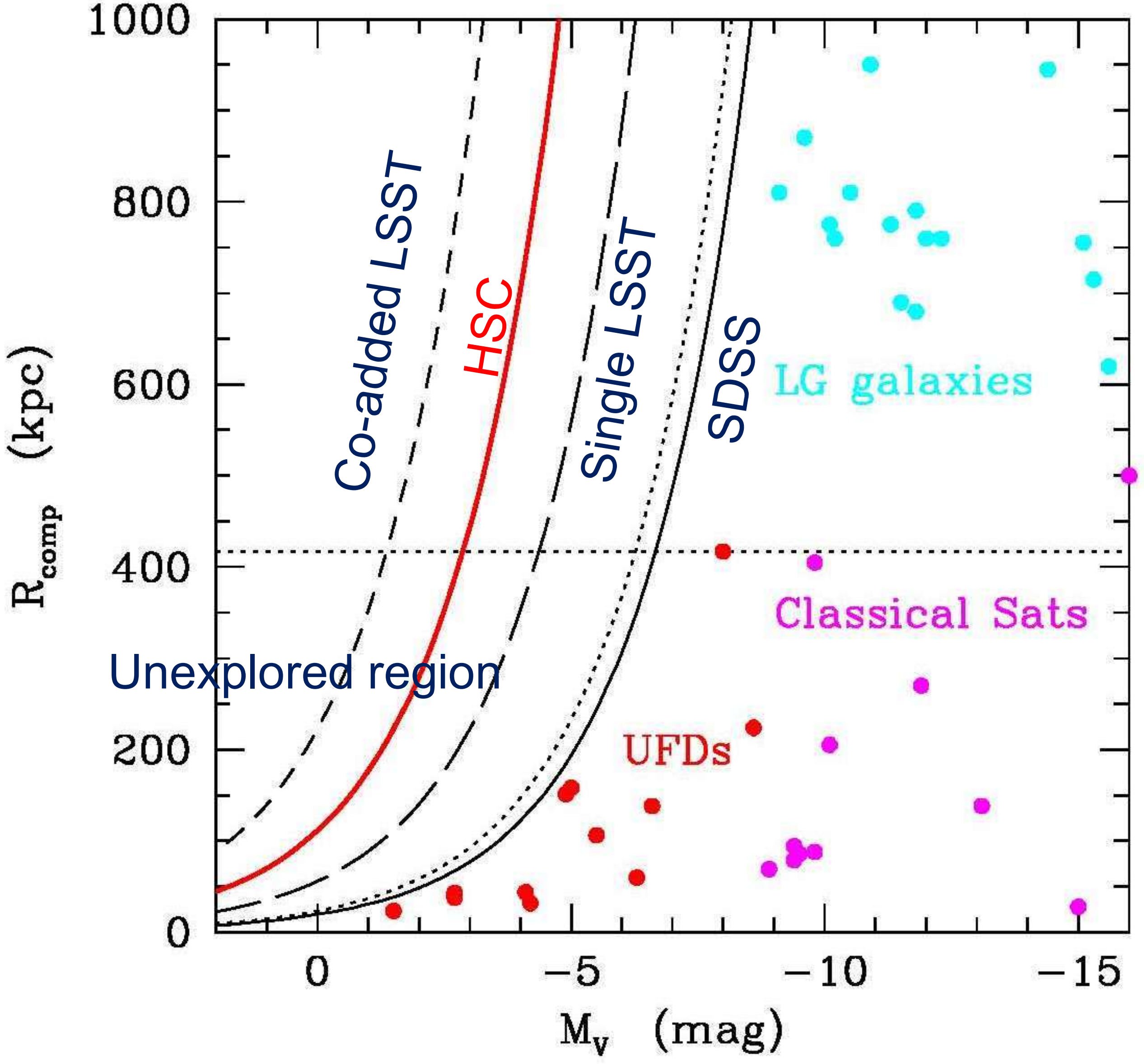
HSC





Wide-field FoV is essential for mapping stars

新しい銀河系矮小銀河の探査

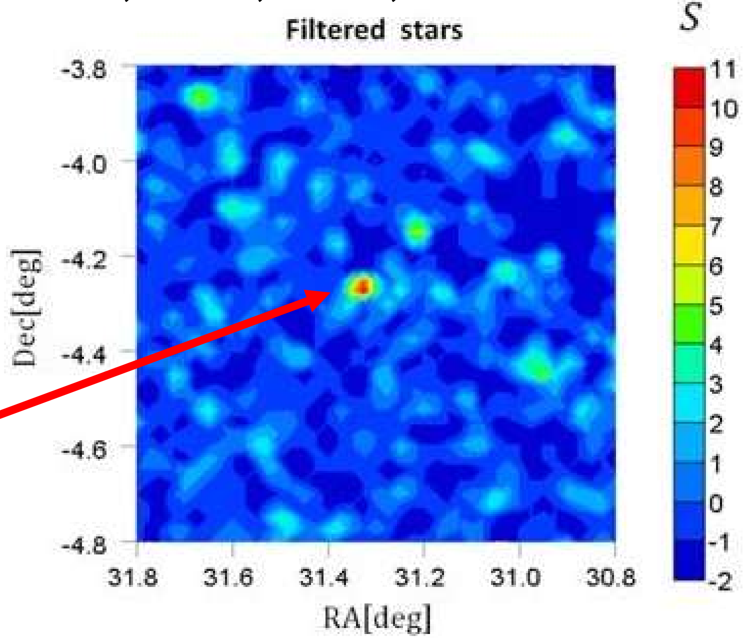


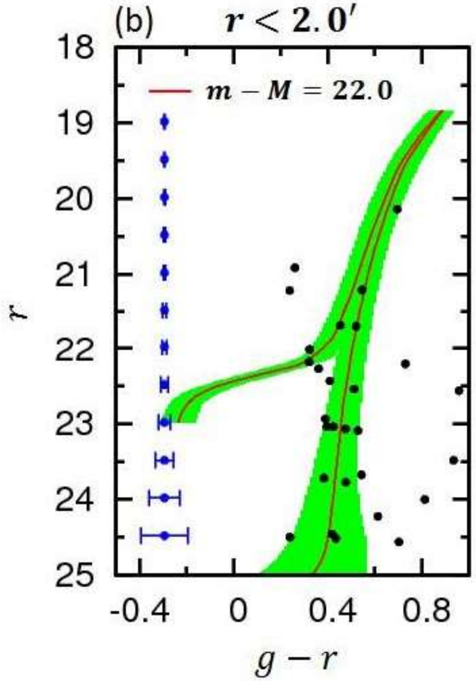
Single LSST:
r_{lim} = 24.5
Co-added LSST:
r_{lim} =27.5
Subaru/HSC
(wide-f. survey):
r_{lim}~26

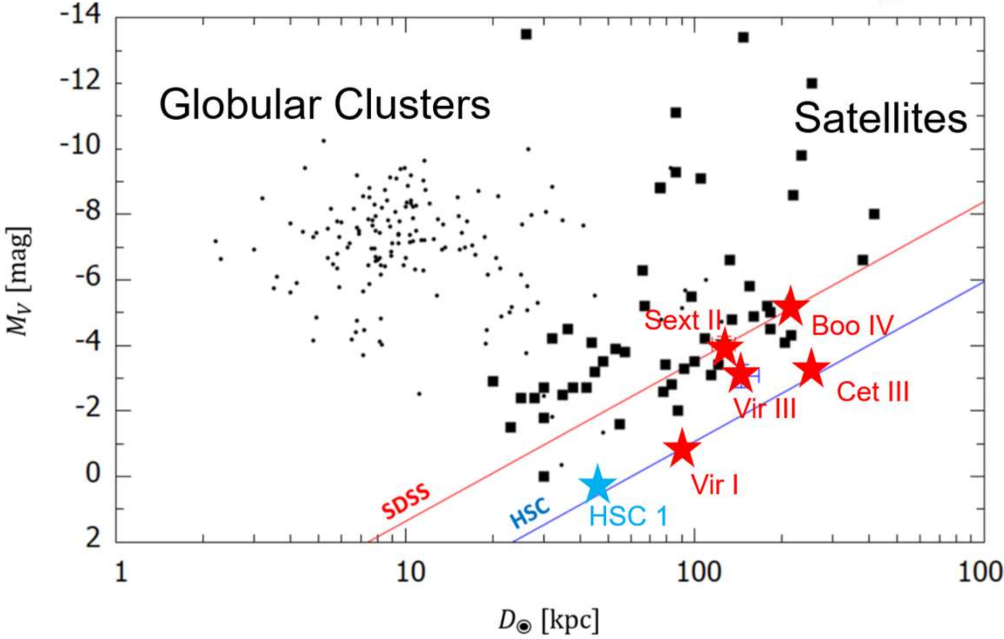
新しい矮小銀河の発見

Homma et al. 2016, 2017, 2019, 2023

Cetus III







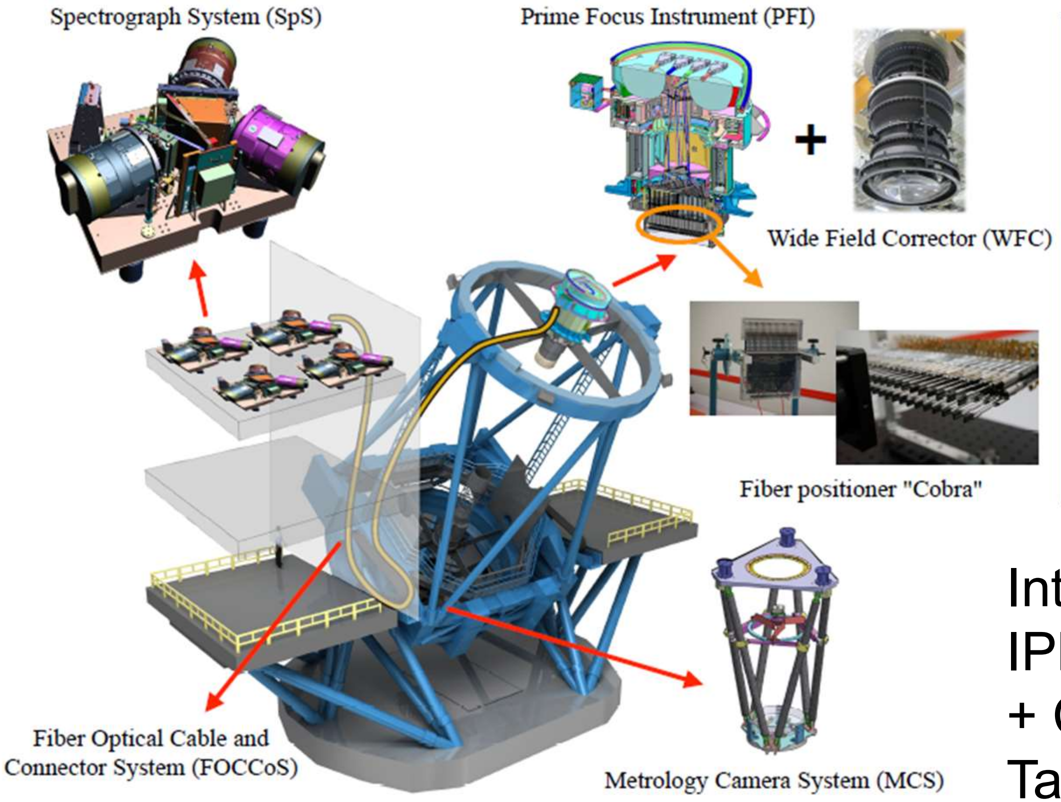
太陽からの距離

Vera C. Rubin Observatory
(LSST)

- Chile
- 8.4-meter
- 3.2 Gpix camera
- Operation: 2023~
- ~10 years operation
- Science in 4 main areas
  - the nature of Dark Matter and understanding Dark Energy, cataloging the Solar System, exploring the changing sky, Milky Way structure and formation

Subaru/PFS

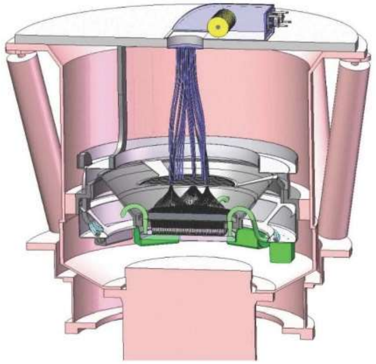
(Prime Focus Spectrograph)



FOV: 1.3 deg in diameter
2400 fiber positioners
λ: 380~1,300 nm
(3 channels: Blue, Red, IR)
R: ~3,000 (LR), 5,000 (MR)
Scientific run: 2024 ~

International collaboration:
IPMU (U. of Tokyo) & NAOJ/Subaru
+ Caltech/JPL, Princeton, JHU, LAM,
Taiwan, UK, Brazil, China

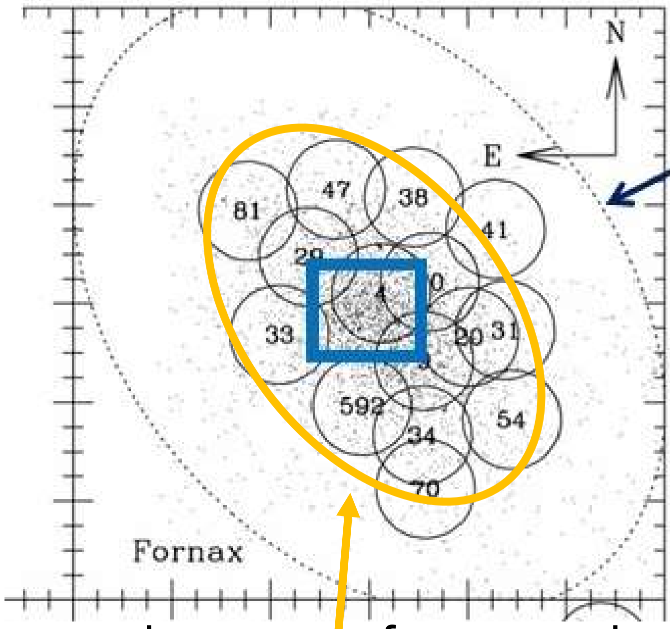
Science in 3 main areas
- Cosmology, Distant Galaxies, Galactic Archaeology



PFS

(Prime Focus Spectrograph)

Fornax dSph



Walker et al. 2009

tidal radius

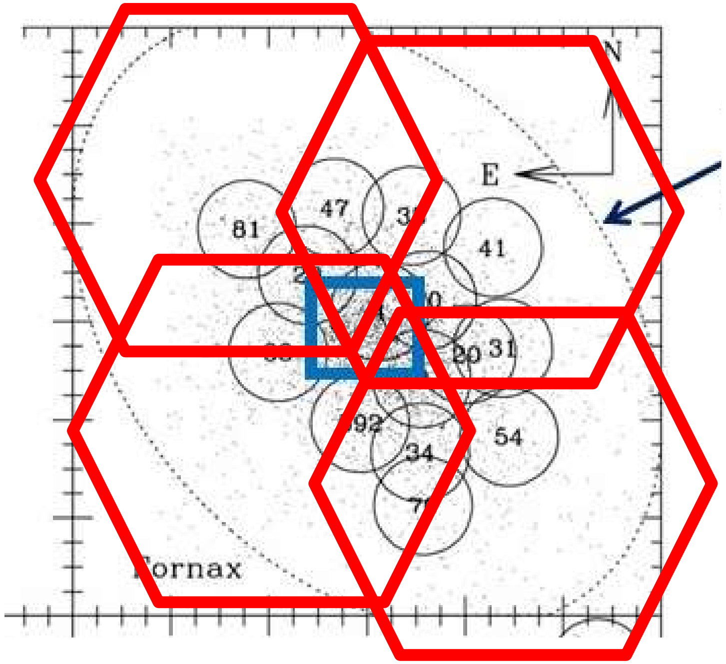
$r_t \sim 71'$

previous range for measuring dark halo profiles

🟦 Previous [α/Fe] measurements with DEIMOS (Kirby+)

○ Previous RV measurements with MMFS (Walker+)

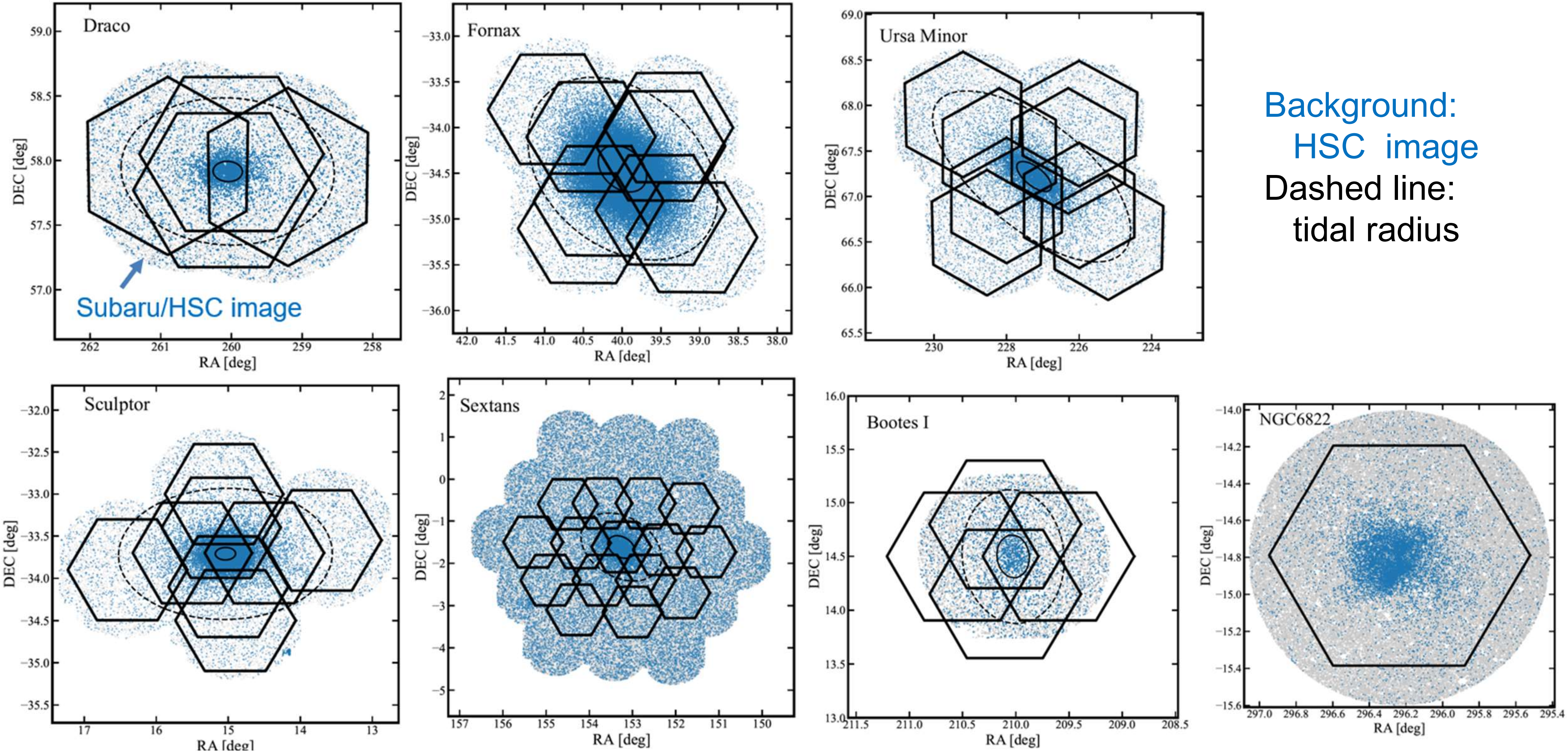
PFS pointings



Mapping dark matter

Nature of dark matter

PFS pointings for the 7 dwarf satellites

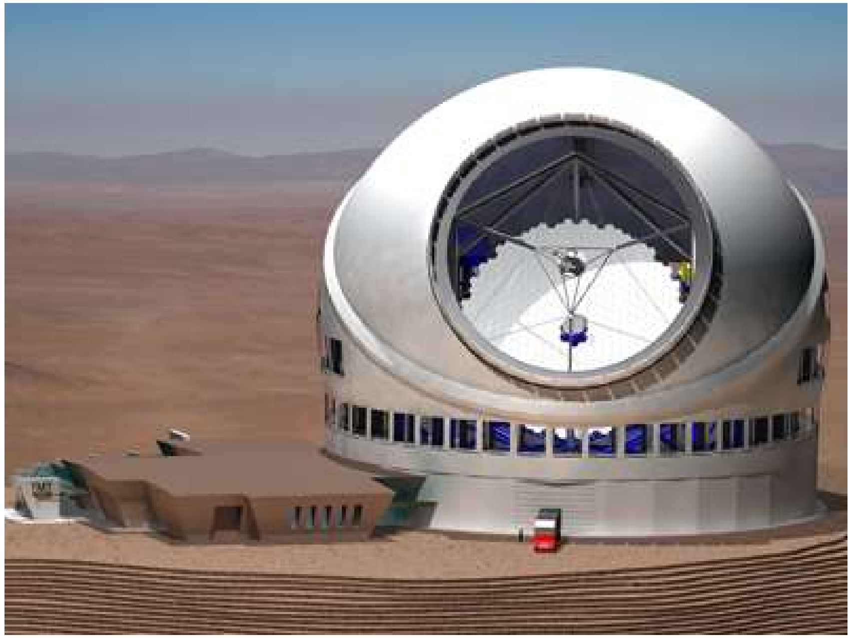


Background: HSC image

Dashed line: tidal radius

Chemodynamics + Dark matter over entire areas of each galaxy

TMT
(Thirty Meter Telescope)



WFOS, IRIS, IRMS,
HROS, NIRES etc.
R~5,000 for m_V<26 mag
R~50,000 for m_V<21 mag
First light: 2030?

膨張宇宙における銀河の形成と物質・生命の起源の解明