計算科学と天体物理学

森正夫
筑波大学計算科学研究センター

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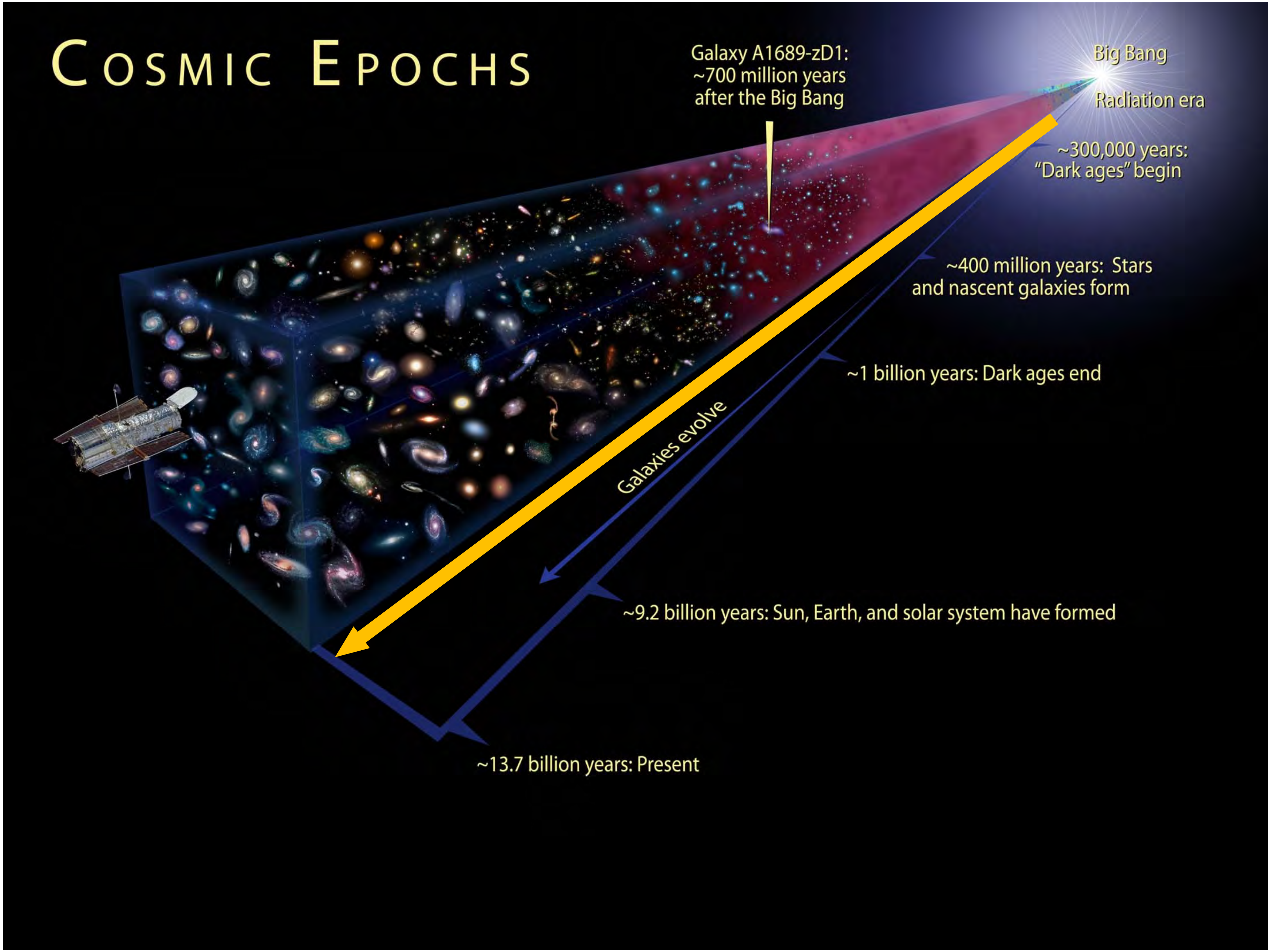
2016年10月18日　学際計算科学による新たな知の発見・統合・創出

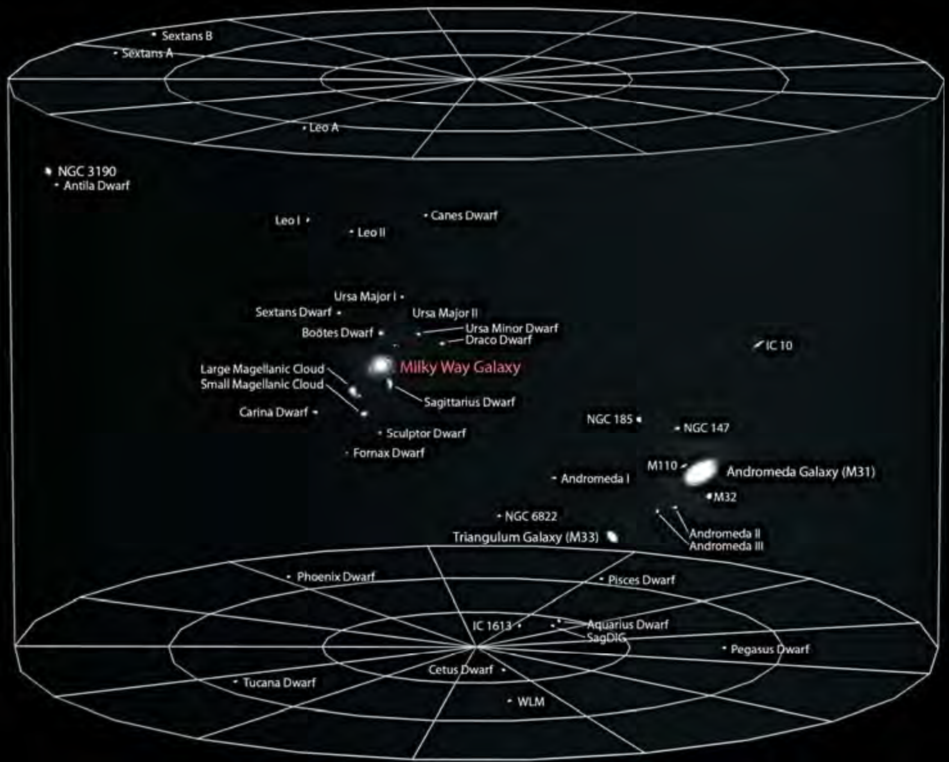
内容

- はじめに
  - 宇宙の構造形成：階層的構造形成理論と諸問題
- 重力多体問題とその計算手法
- 近傍宇宙における階層的構造形成論の検証
  - ✓ アンドロメダ銀河と矮小銀河の衝突
  - ✓ 暗黒物質の分布に関する理論と観測の不一致
- まとめ


Cosmic Epochs
Galaxy A1689-zD1:
~700 million years
after the Big Bang
Big Bang
Radiation era
~300,000 years:
"Dark ages" begin
~400 million years: Stars
and nascent galaxies form
~1 billion years: Dark ages end
Galaxies evolve
~9.2 billion years: Sun, Earth, and solar system have formed
~13.7 billion years: Present

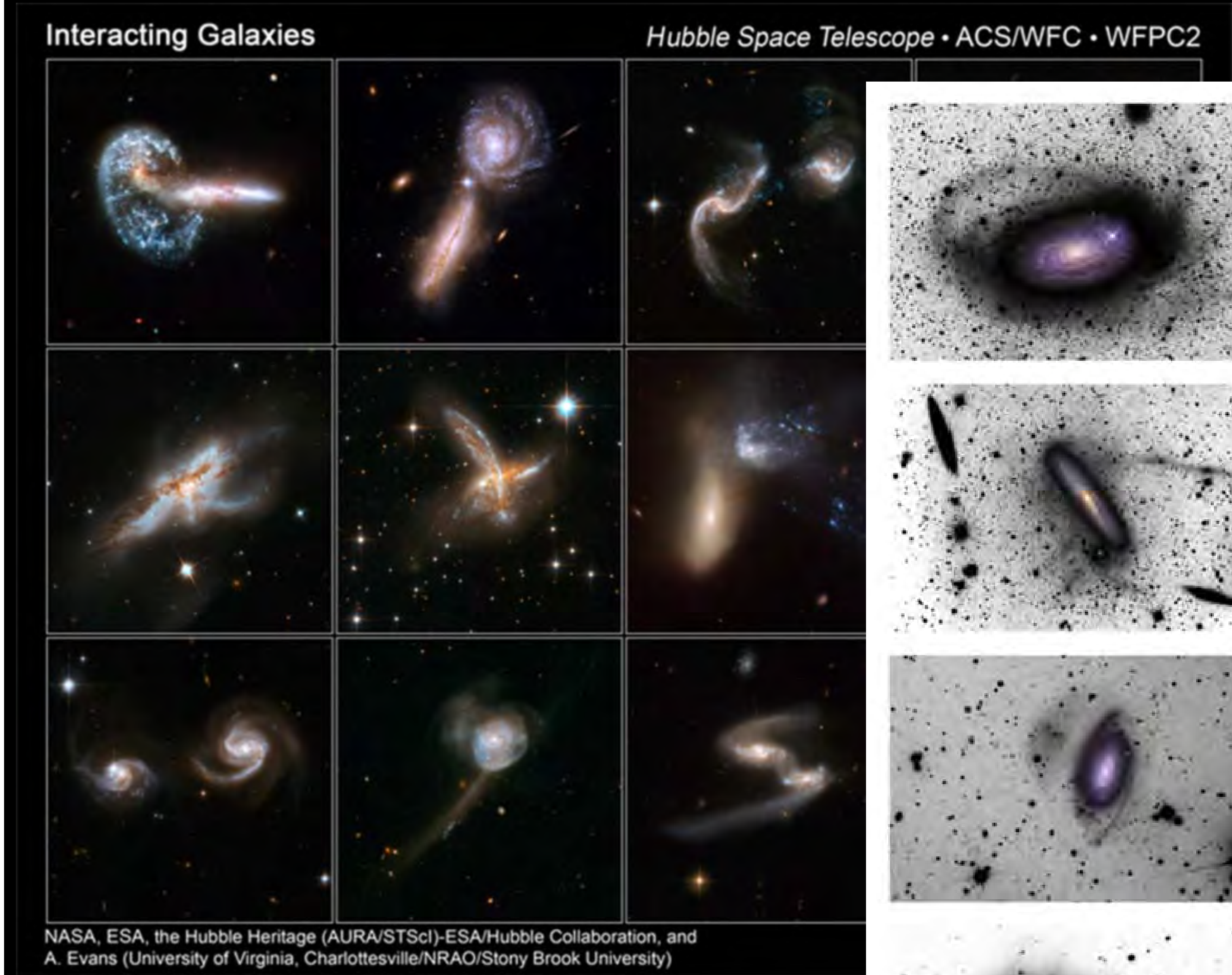

z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

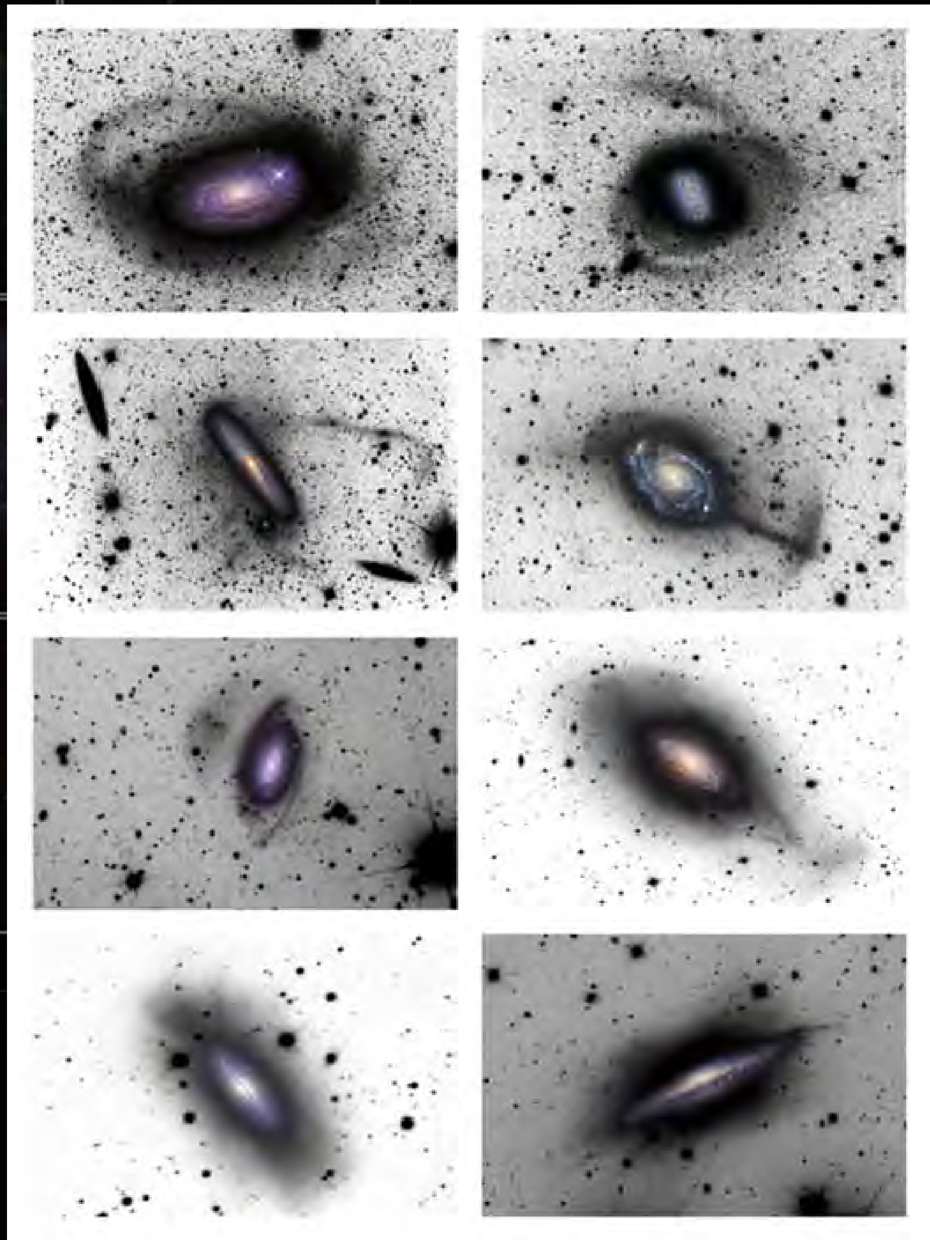
Local Galactic Group



Virgo Supercluster

Credit: Andrew Z. Colvin

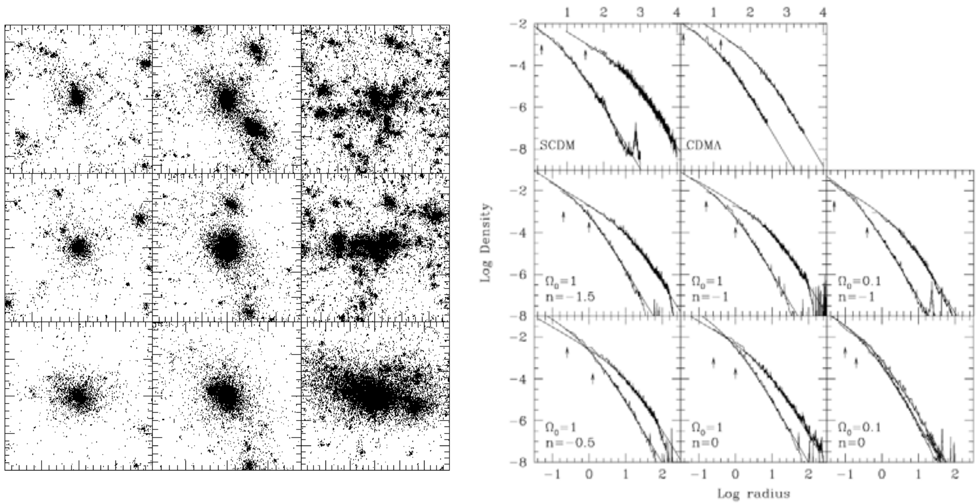




銀河衝突・合体の現場

Martinez-Delgado et al. 2010

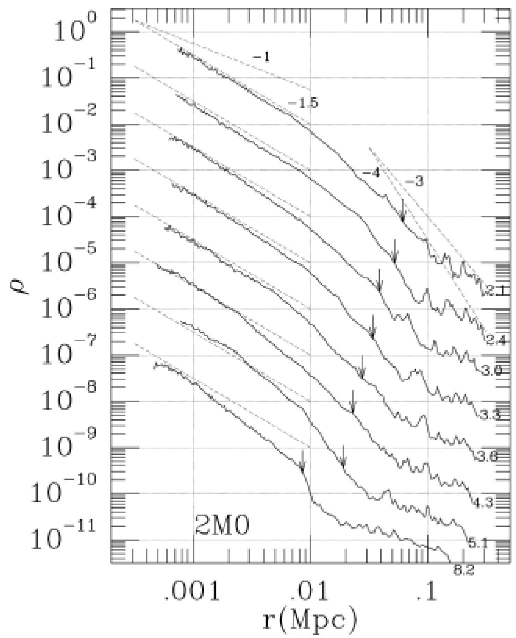
Universal density profile from hierarchical clustering



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

NFW profile $$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

中心付近の密度は、$\rho \propto r^{-1}$



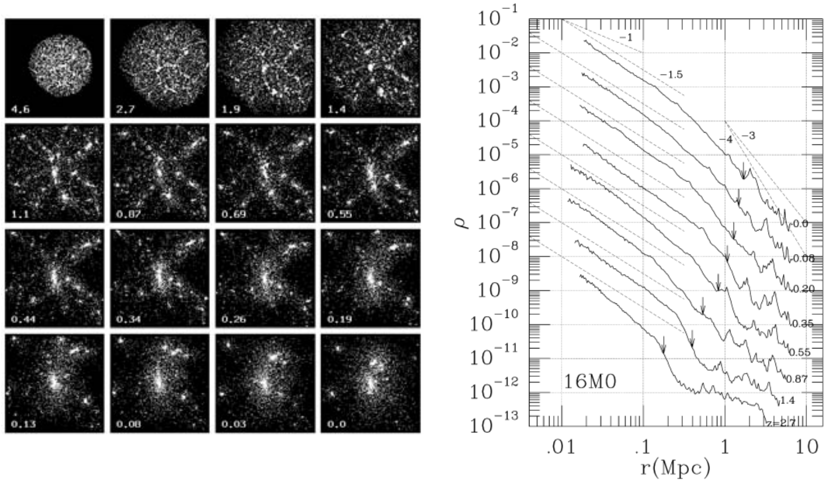
計算分解能をあげると、中心付近の
密度は、$\rho \propto r^{-1.5}$

Fukushige & Makino, ApJ, 477, L9 (1997)
Moore et al., ApJ, 499, L5 (1998) 他

Central density profile of dark matter halo

Theory- cusp: $\rho \sim r^{\alpha}$

- α=-1 : Navarro, Frenk & White (1997)…
- α=-1.5 : Fukushige & Makino (1997), Moore et al. (1998)…

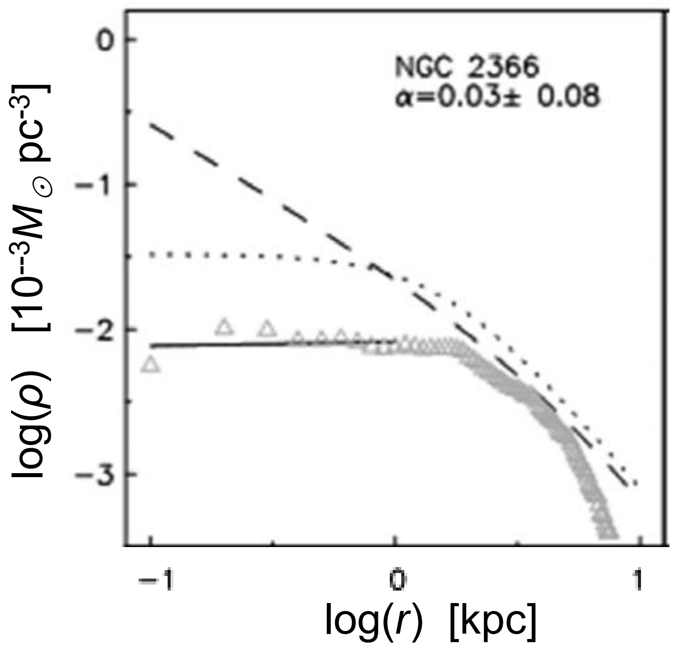


Fukushige & Makino (2001)

Observation- core

– Burkert (1995)

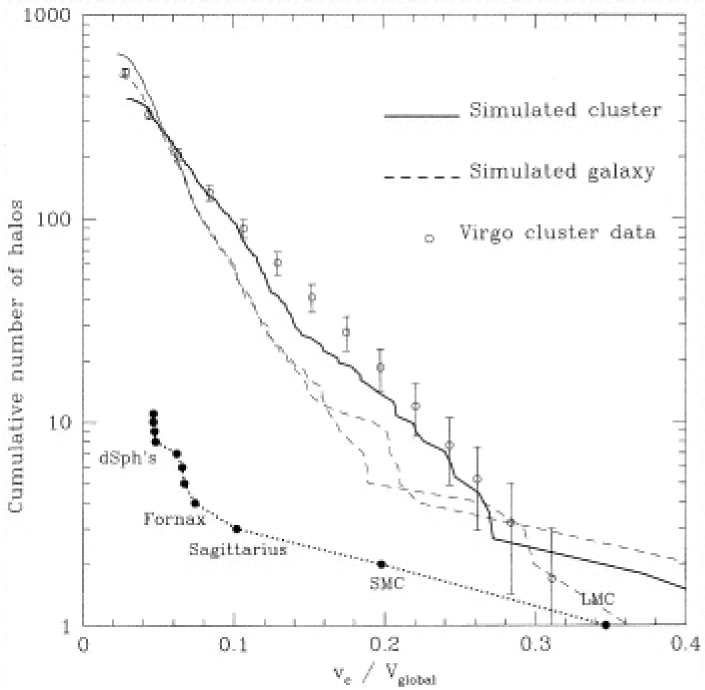
$$\rho_{\rm DM}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)},$$



van Eymeren *et al.* 2009

Substructure problem

Moore et al, ApJ, 524, L19 (1999)



Missing satellite

メンバー銀河の数が、銀河団サイズでは観測とシミュレーションはよく一致するが、銀河サイズでは、全く合わない。

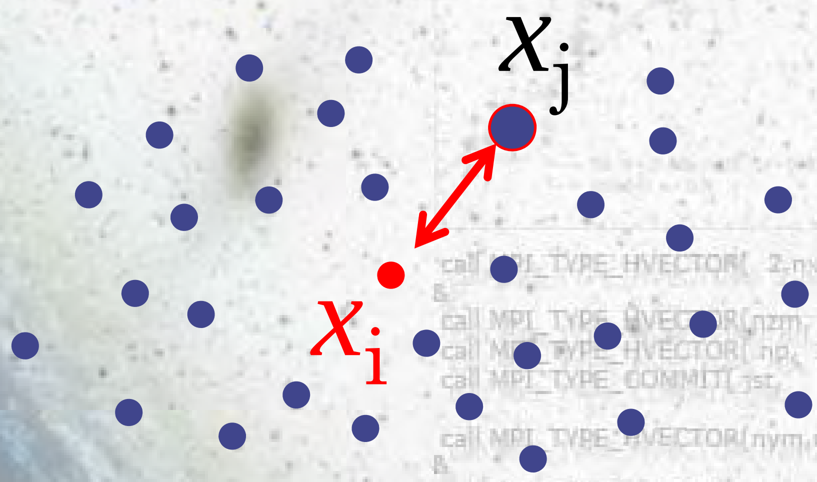
see Ishiyama, Fukushige & Makino PASJ, 60, L13 (2008)

Force computation and position update

$$\boldsymbol{a_i} = G \sum_{1 \le j \le N, j \ne i} \boldsymbol{m_j} \frac{\boldsymbol{x_i} - \boldsymbol{x_j}}{\left|\boldsymbol{x_i} - \boldsymbol{x_j}\right|^3}$$

$$v_{i+1/2} = v_{i-1/2} + a_i \, dt$$

$$x_{i+1} = x_i + v_{i+1/2} \, dt$$



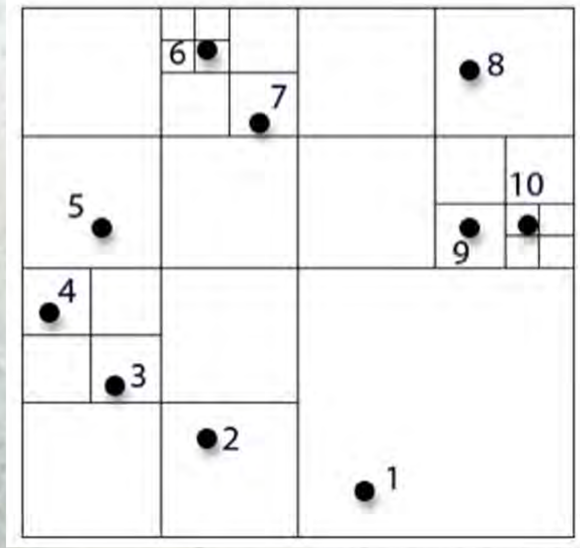
Number of particle: N

- The force between a body i and N other bodies is approximated as above by computing the interaction given their mass (m), the distance vector between them (r_{ij}).
- This is computed for all bodies with all other bodies.
- For each particle, a discrete time-step (dt) is used to approximate the continuous kinematic equation and update the position and velocity of each particles.

N-body simulation methods

- **Direct methods**
  Direct methods do not introduce approximations in the solution of the equations of motions and thus deliver the highest accuracy at the price of the longest computation time, of order $O(N^2)$ per timestep.

- **Tree methods**
  The tree method (Barnes & Hut 1986) provides a fast integrator for gravitational systems, when close encounters are not important and where the force contributions from very distant particles does not need to be computed at very high accuracy. In order to decrease the number of force calculations, one can begin to think about neglecting individual bodies that are far away from the body. The resulting computation time scales as O(N log(N)).

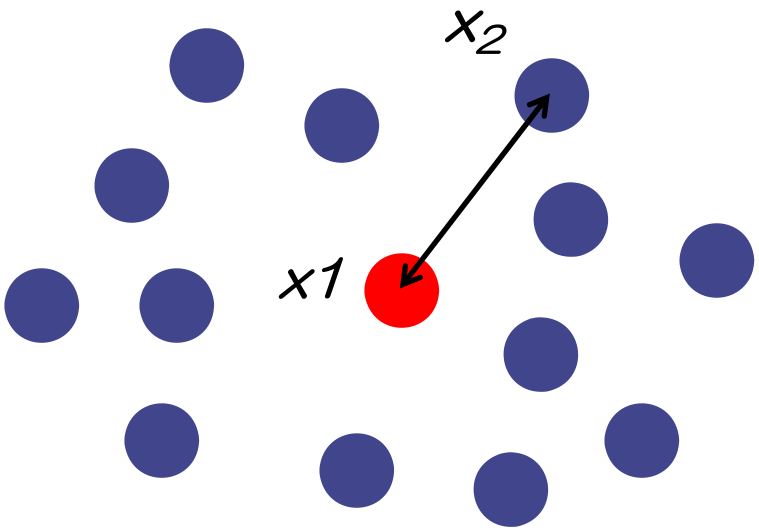


- **Particle-mesh codes**
  The particle mesh method represents another route to speed up direct force evaluation for collisionless systems. In this case the gravitational potential of the system is constructed over a grid starting from the density field and by solving the associated Poisson equation. The Poisson equation is typically solved using a Fast Fourier Transform. The method achieves a linear complexity in the number of particles and (O(Ng log(Ng)) in the number of grid.

重力多体問題

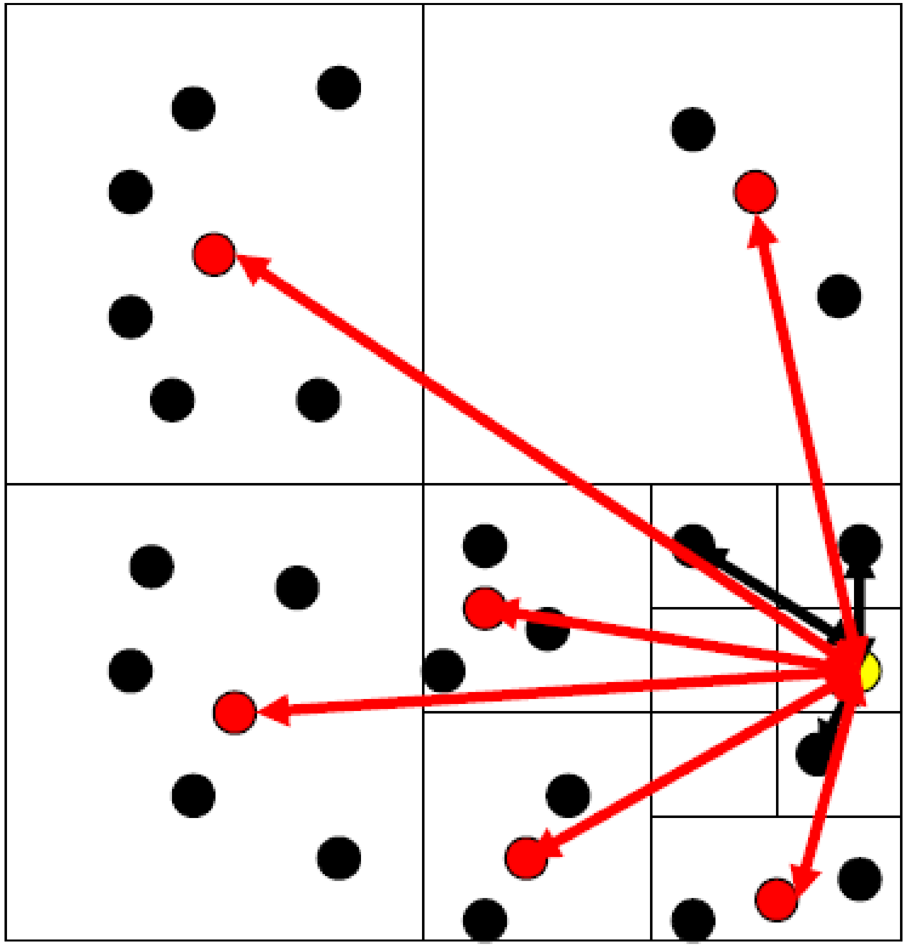
- 重力多体問題は沢山の質点がお互いに重力で引き合って運動重するというもので、星団、銀河等の基本的なモデルである。

$$F = G\frac{m_1\, m_2}{r^2} \quad + G\frac{m_1\, m_3}{r^2} + G\frac{m_1\, m_4}{r^2} + \cdots$$



粒子数：N
計算回数：$(N-1) \times N \sim N^2$
銀河の恒星：N〜数100億個

自己重力計算:Tree法



•粒子を再帰的に“セル”に分割する。
•ある粒子の加速度を計算するときは、
大きいセルから順番に

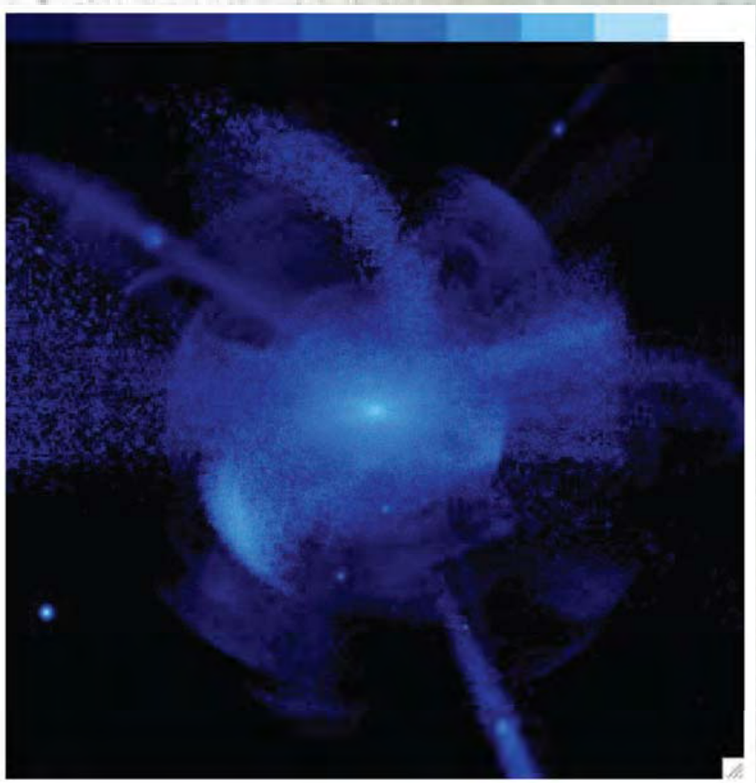
$$l/d < \theta$$

の関係を満たすかどうかを調べる。
ここで、 l はセルのサイズ、d は粒子からセルの重心までの距離、θ が計算精度を決めるパラメータ。通常は、
$0.5 < \theta < 0.7$ が使用される。

計算コストが粒子分布にあまり
左右されない。

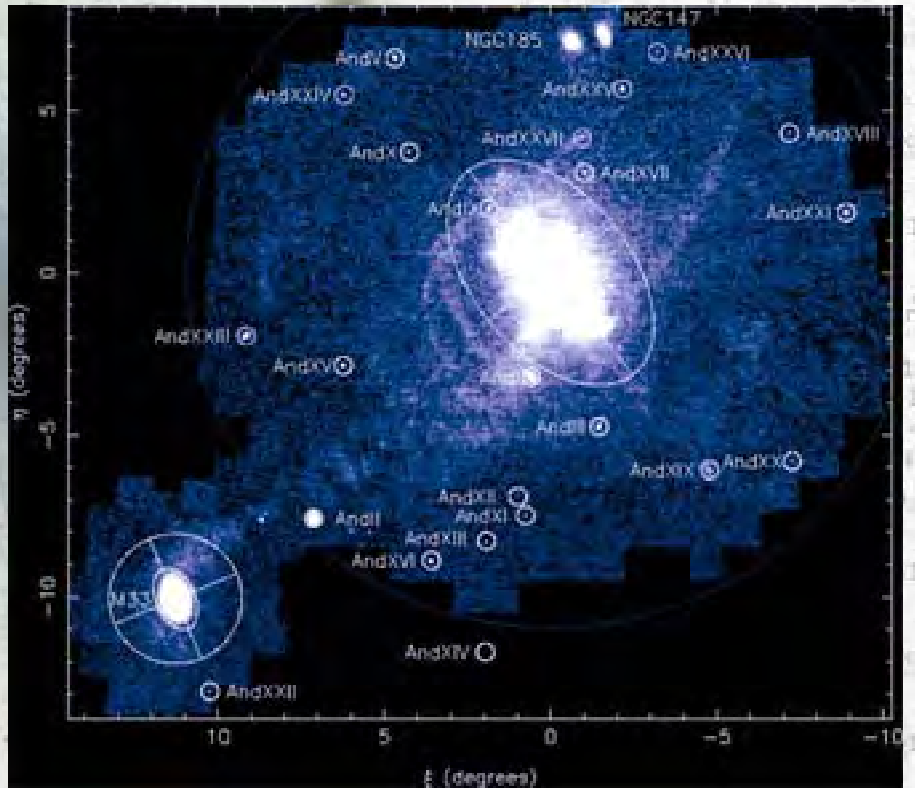
Hierarchical structure formation in the universe

Theory



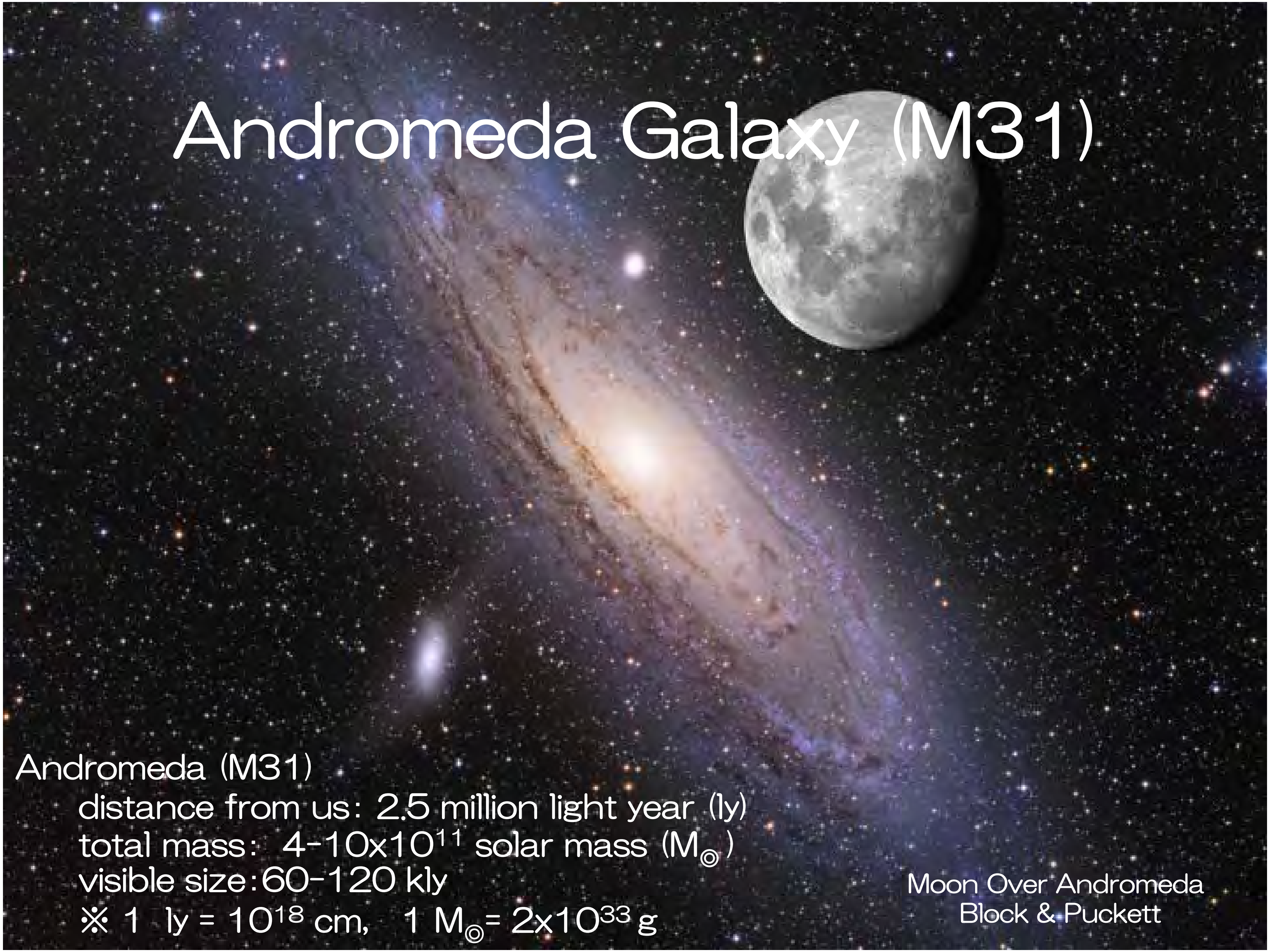
Bullock & Johnston 2005

Observation (Andromeda galaxy)



Richardson et al. (2011)

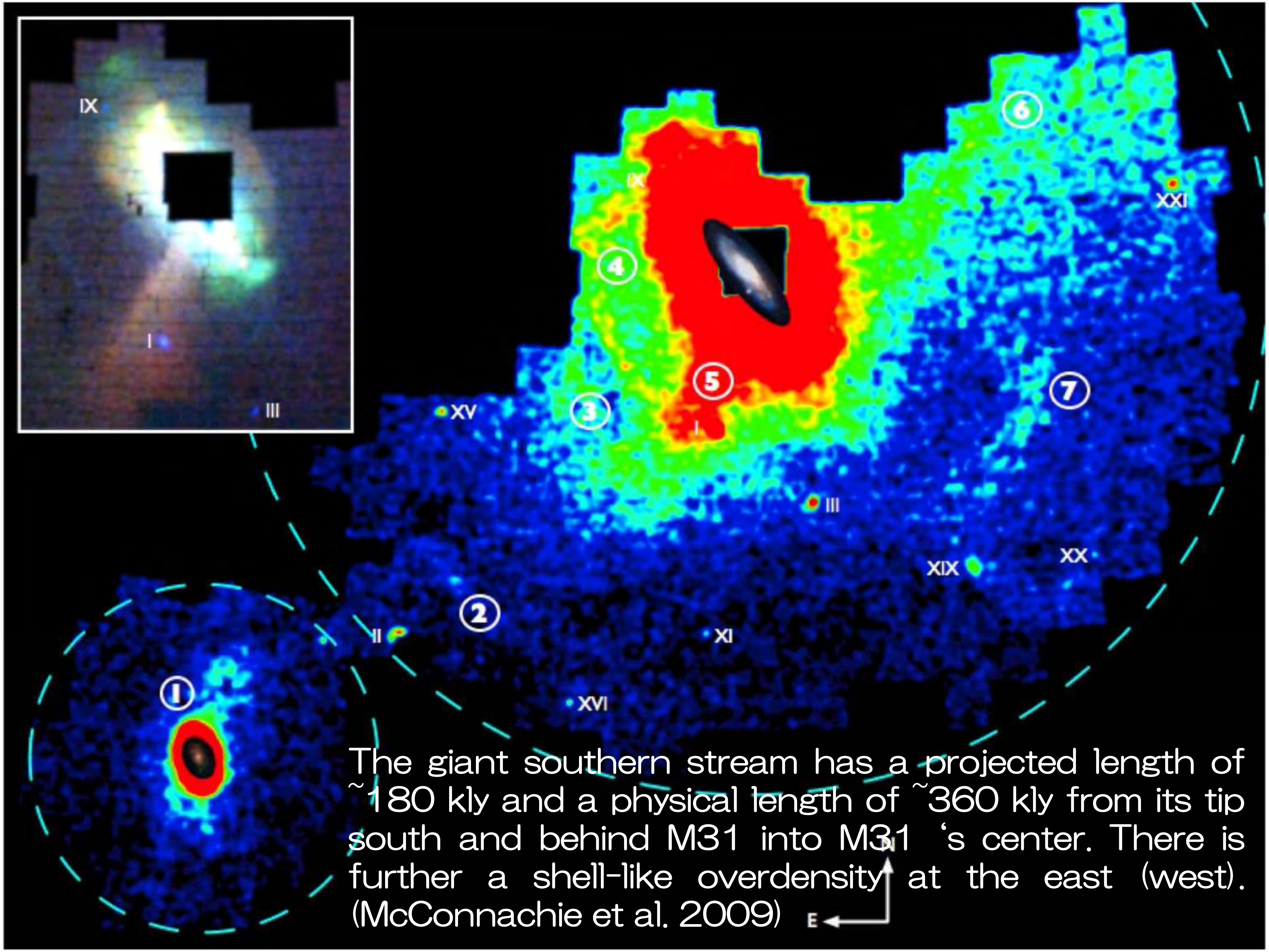
Andromeda Galaxy (M31)



Andromeda (M31)

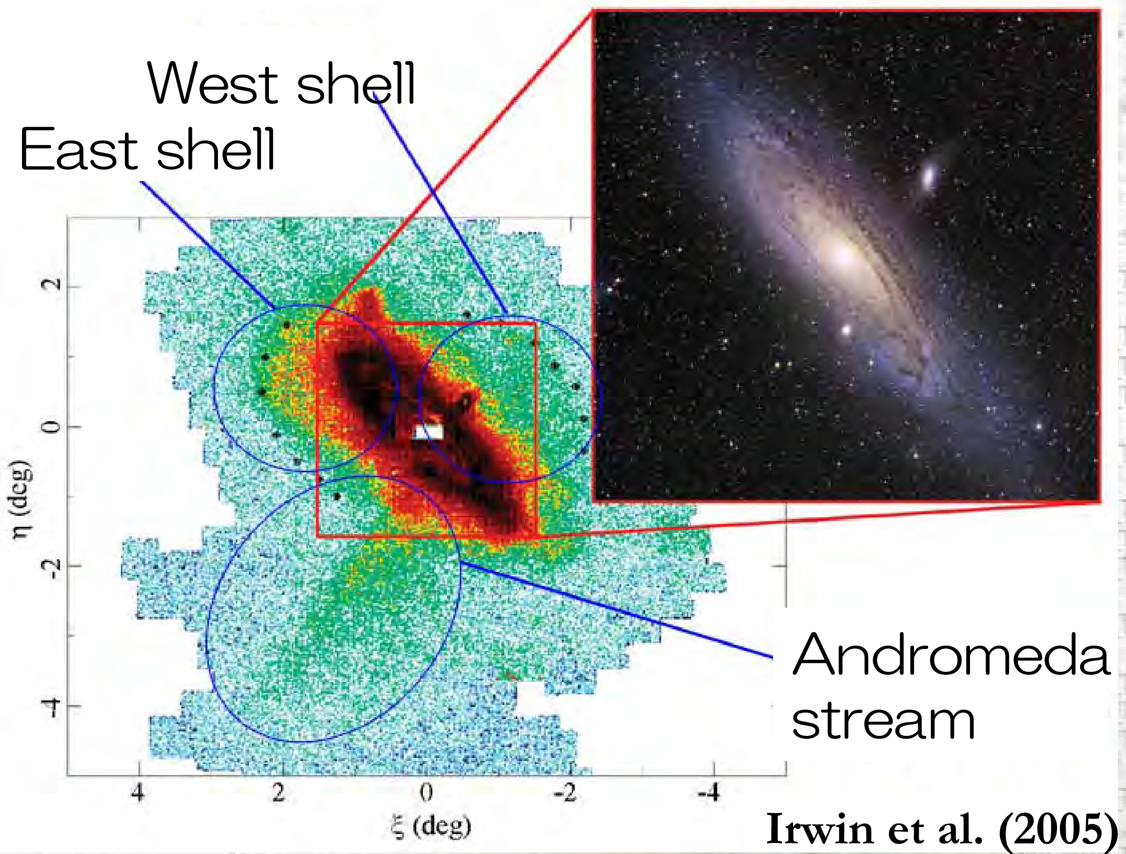
- distance from us: 2.5 million light year (ly)
- total mass: 4-10x10^{11} solar mass ($M_{\odot}$)
- visible size: 60-120 kly
- ※ 1 ly = 10^{18} cm, 1 $M_{\odot}$ = 2x10^{33} g

Moon Over Andromeda
Block & Puckett



The giant southern stream has a projected length of ~180 kly and a physical length of ~360 kly from its tip south and behind M31 into M31 's center. There is further a shell-like overdensity at the east (west). (McConnachie et al. 2009)

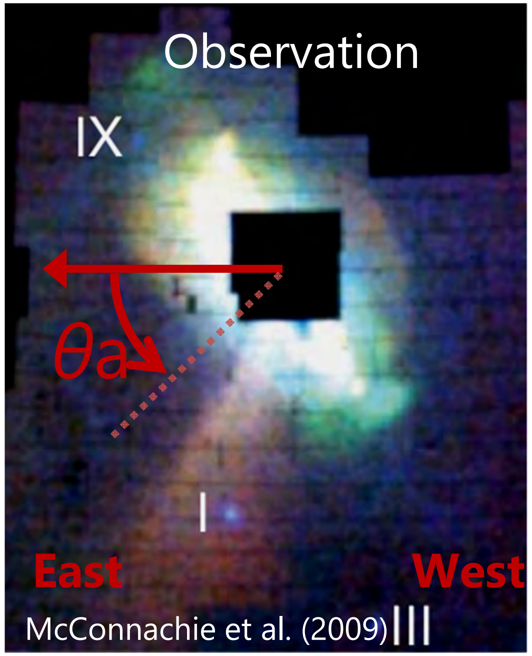
Andromeda giant stream and shells around M31



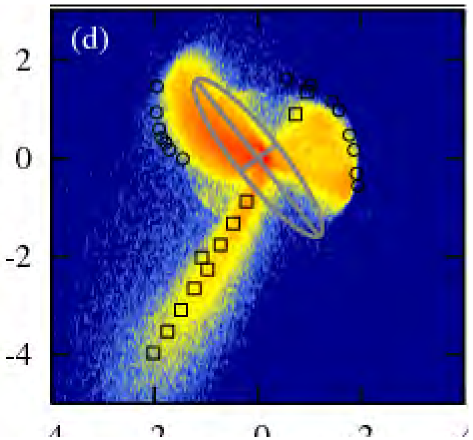
Irwin et al. (2005)

Starcount maps near the Andromeda galaxy exhibit a giant stellar stream to the south of this galaxy, as well as giant stellar shells to the east and the west of M31's center. (Ibata et al 2001; Ferguson et al 2002)

Asymmetric surface brightness profile of the Andromeda Giant Stream

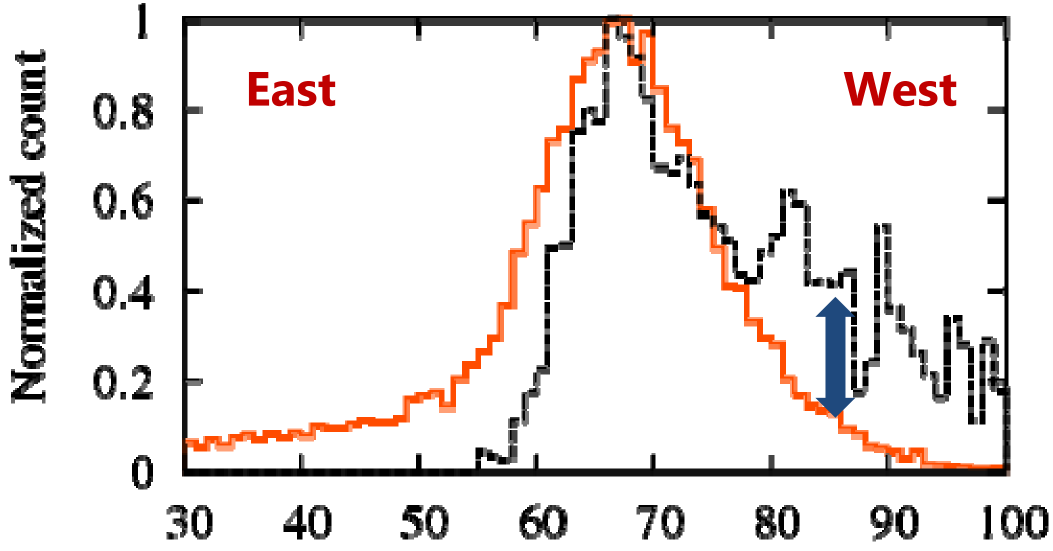


spherical dwarf galaxy



Kirihara et al., in press

Azimuthal surface brightness(SB) profile of the GSS



θa [°]

Irwin +05

(**Obs.**, **Sim.** **(spherical)**)

In observation …

Eastern side : sharp edge

Western side: smooth distribution

Numerical simulation

- Fixed potential for M31

  Hernquist bulge, Exponential disk, NFW DM halo

- Parameter space

  Scale height of disk (thin-thick-hot)

  Vrot of the disk (9 model of thick disk)

  • Initially inclined spin axis of the progenitor by θ, Φ （total ~2000model）

Properties of the progenitor：

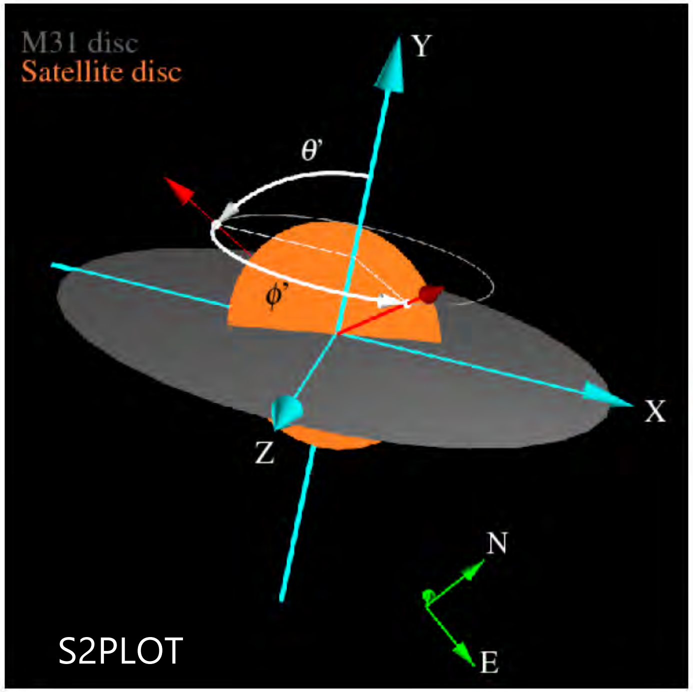
DM $4\times10^{9}M_{\odot}$

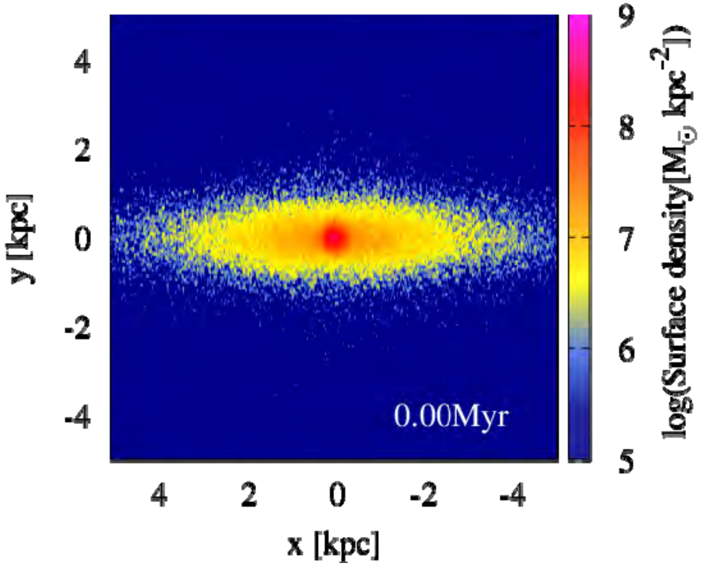
Disk $7\times10^{8}M_{\odot}$

Bulge $3\times10^{8}M_{\odot}$

N~ 2×10^{5}(stellar: N~ 5×10^{4})

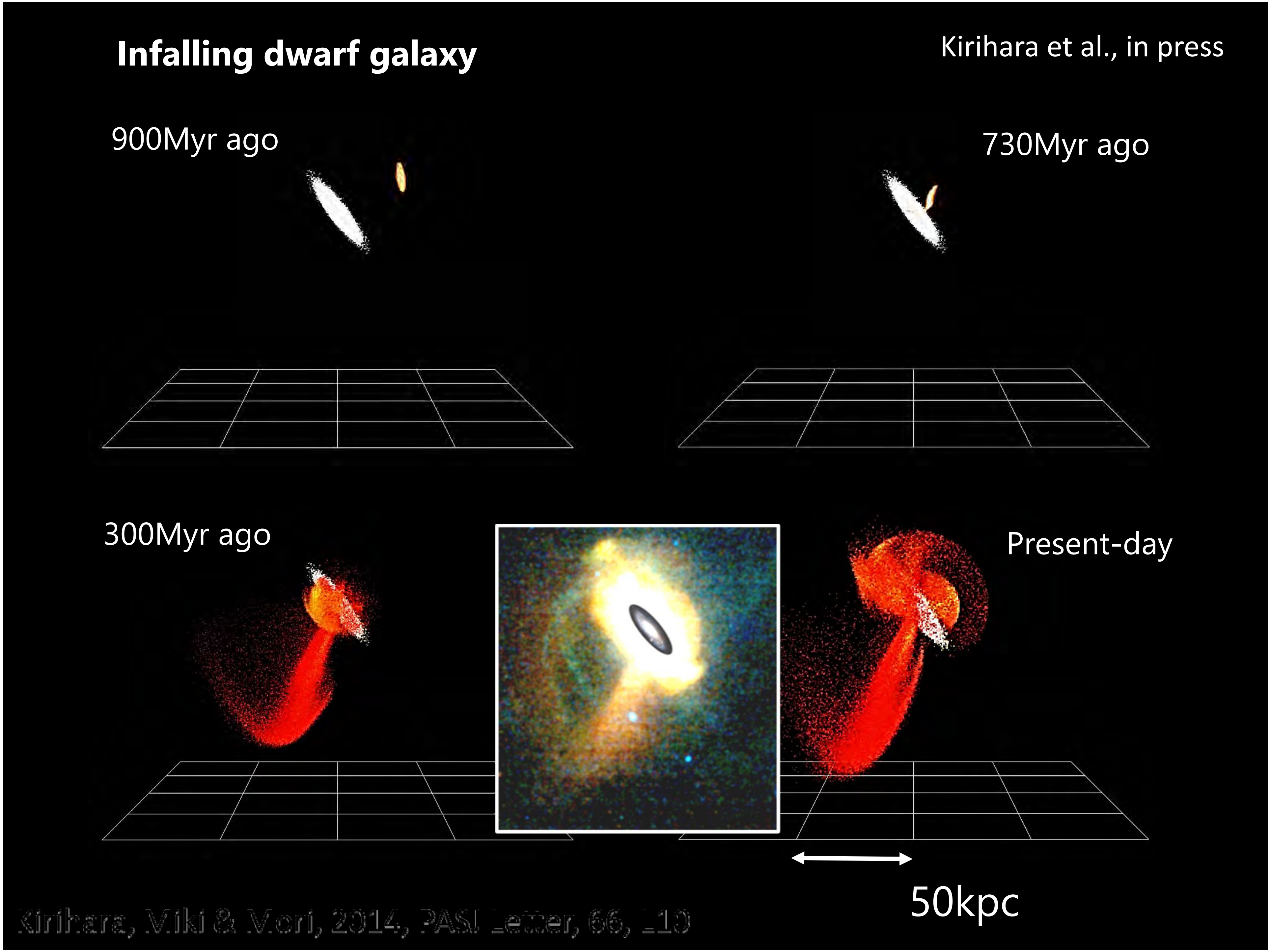
Kuijken & Dubinski 1995, Widrow et al. 2003





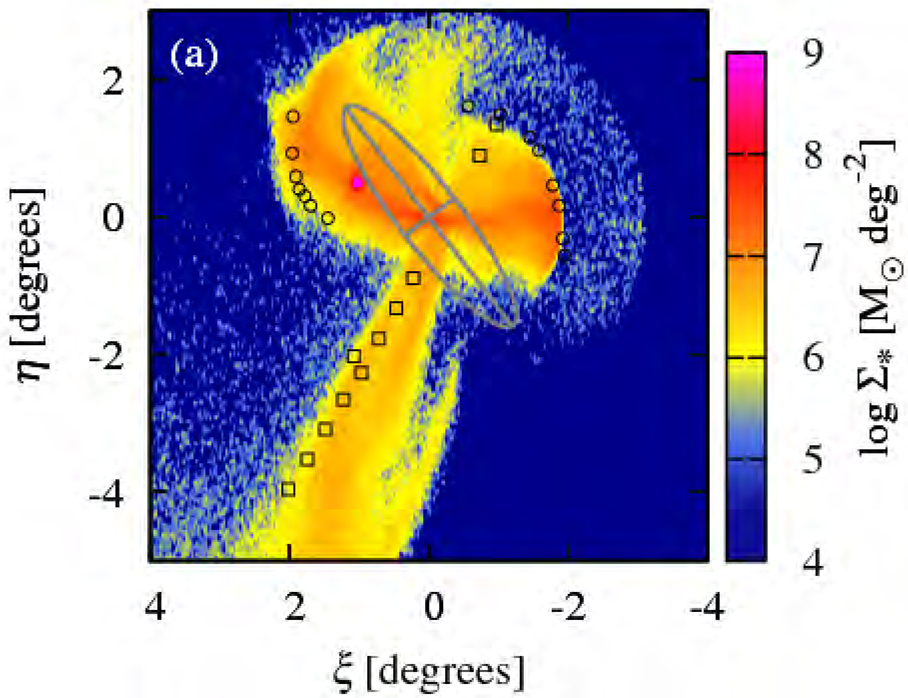
Orbit：Fardal et al. (2007)

Self-gravitation：Tree method（θ=0.6）on T2K-Tsukuba, HA-PACS, COMA

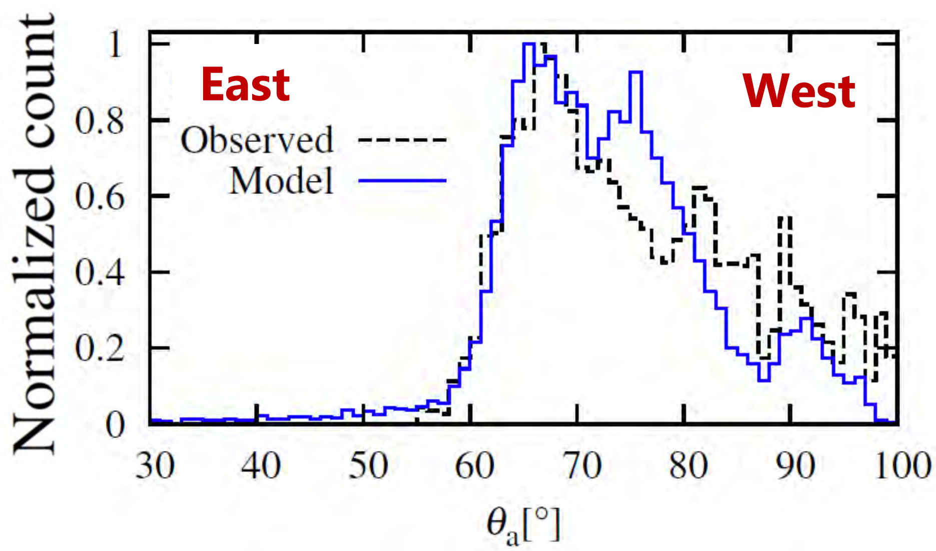

Infalling dwarf galaxy
Kirihara et al., in press
900Myr ago
730Myr ago
300Myr ago
Present-day
50kpc
Kirihara, Miki & Mori, 2014, PASJ Letter, 66, L10

Successful model

A case with a thick disk progenitor



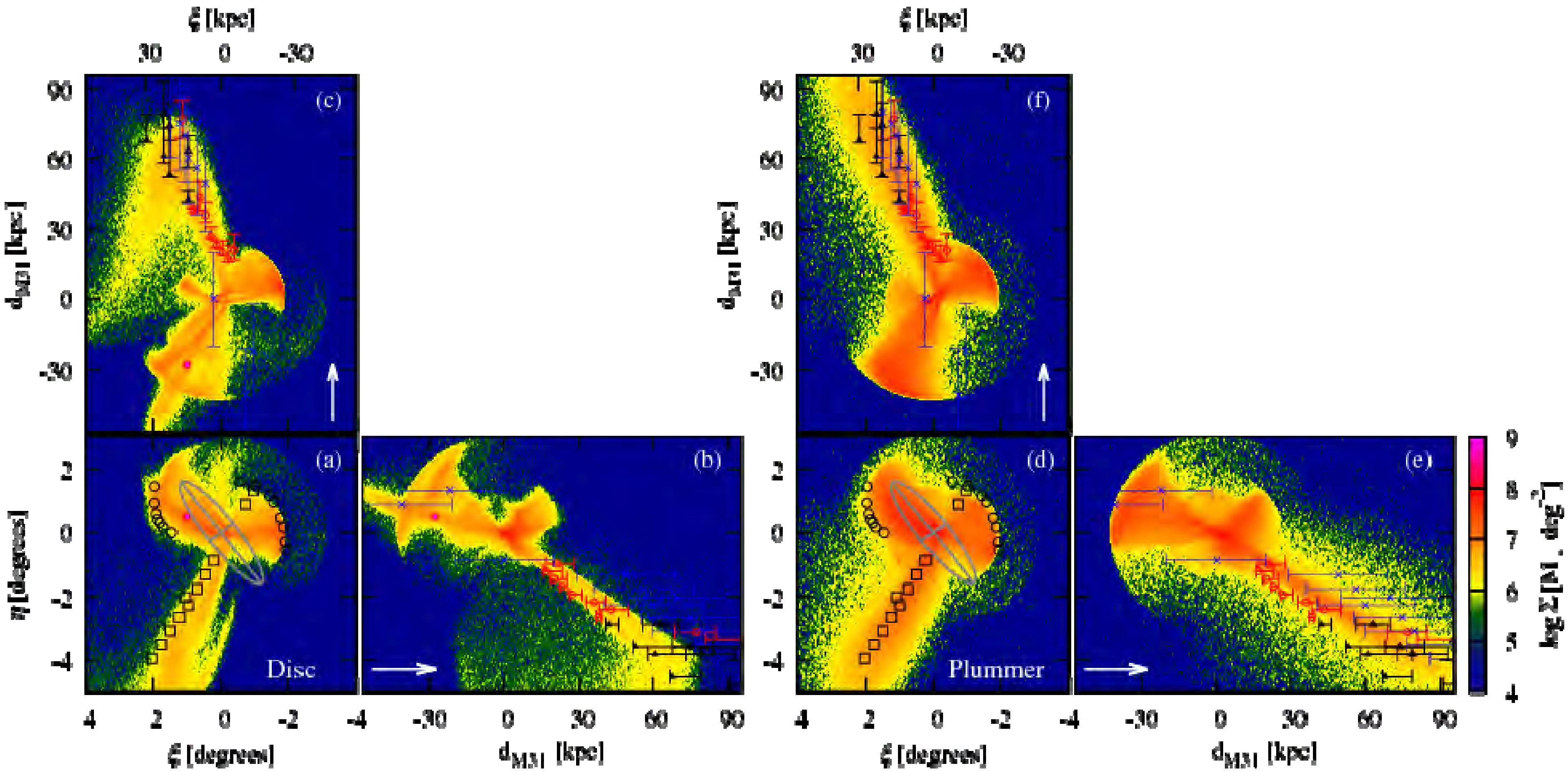
Azimuthal SB profile of the GSS



Observed data: Irwin +05

We reproduce the edge structure of the Andromeda giant stream

3D distribution of the merger remnant



Disk galaxy

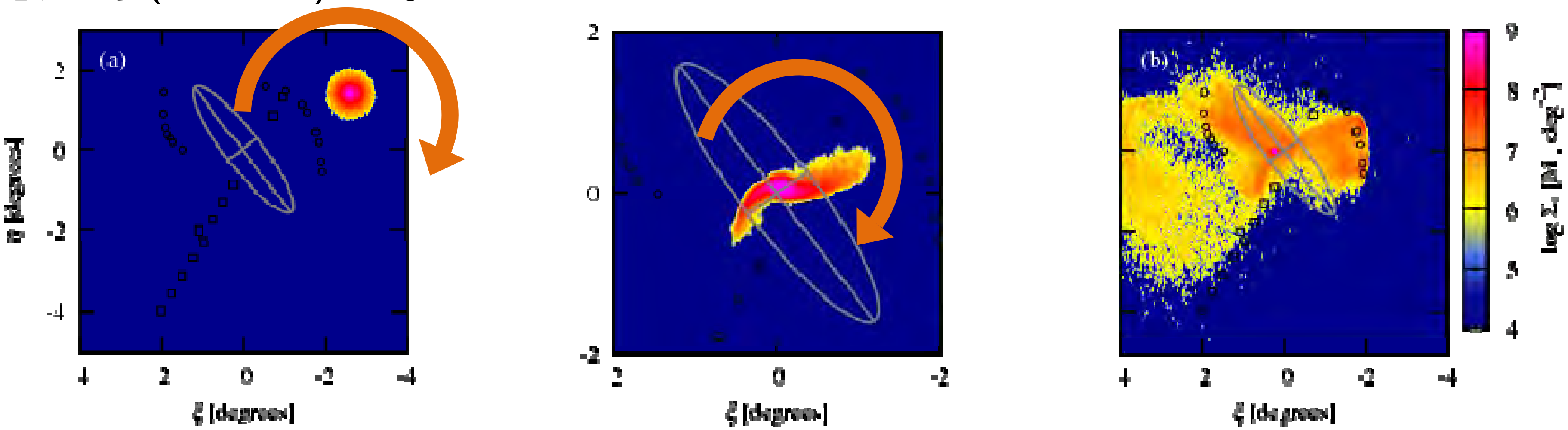
Spherical galaxy

Kirihara et al., in press

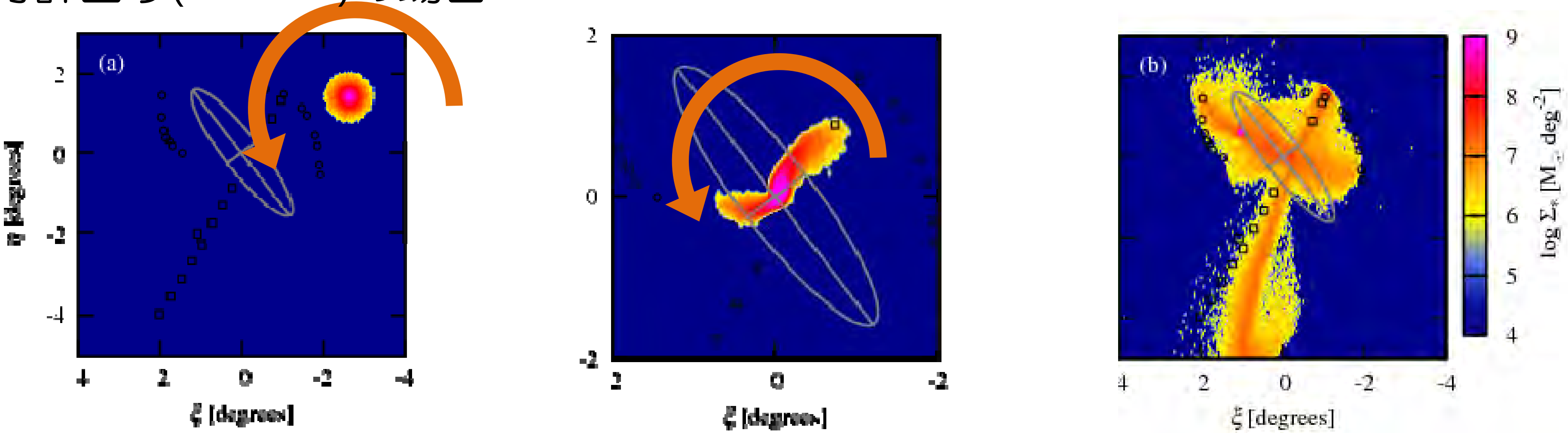
矮小銀河の円盤の傾け方の影響

時計回り(face-on)の場合

Kirihara et al., in press



反時計回り(face-on)の場合



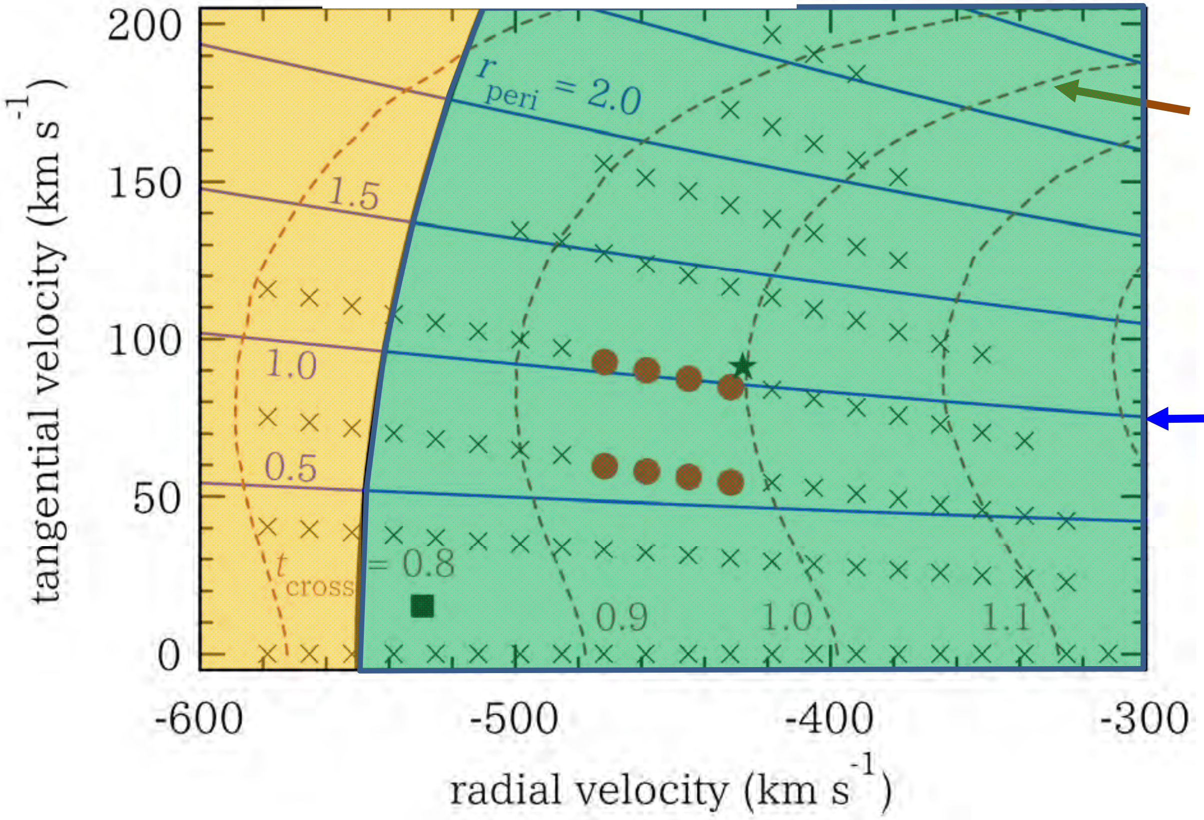
Edgeの再現には, M31中心の東を反時計回りの成分の通過が重要

Possible orbits of the progenitor

Miki, Mori, Kawaguchi & Saito, 2014, Astrophysical Journal, 783, 87

- 5,700,000 orbit models (～45,000 *N*-body runs)
  - **138** models reproduce the observed structures.

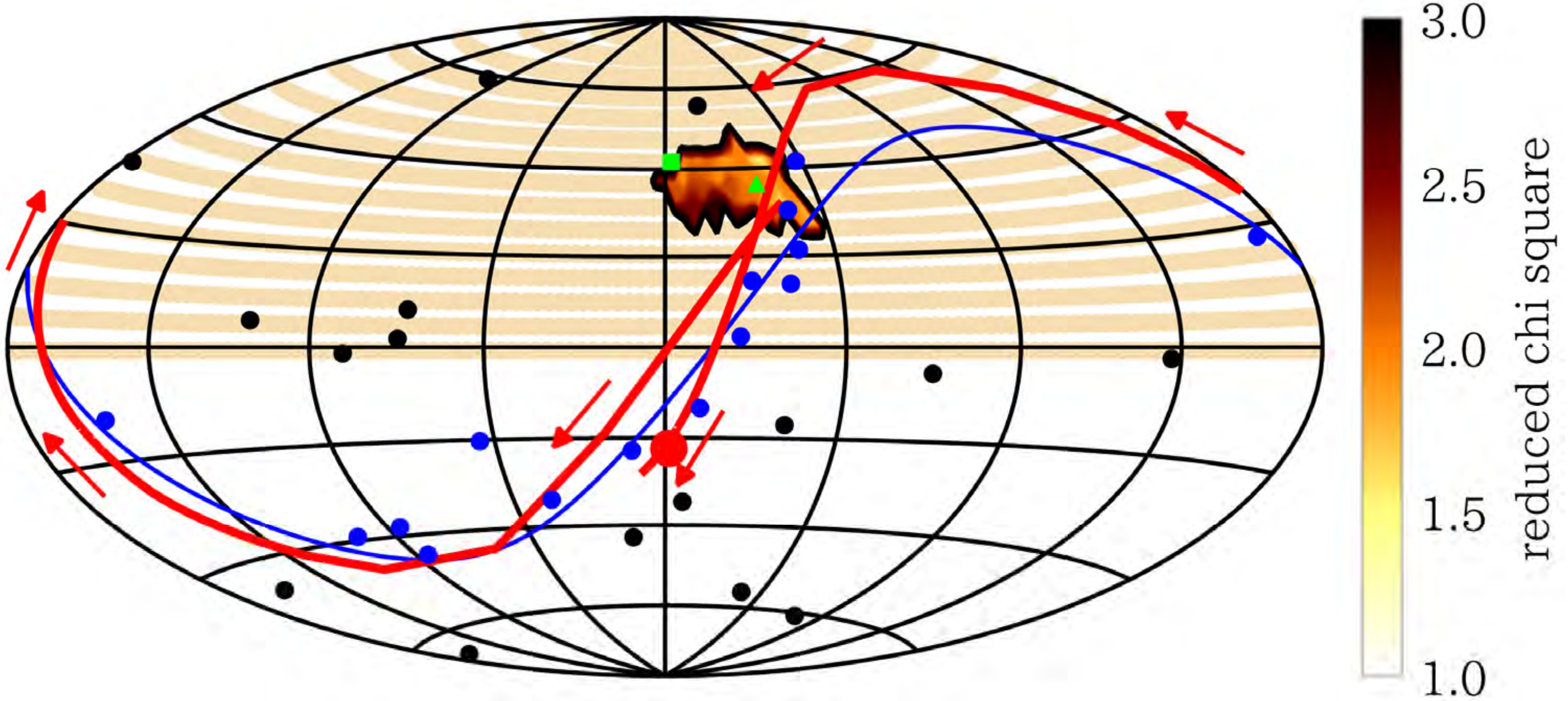
$v_{esc} = 550\mathrm{km/s}$



$t_{cross} = t_{ff}$

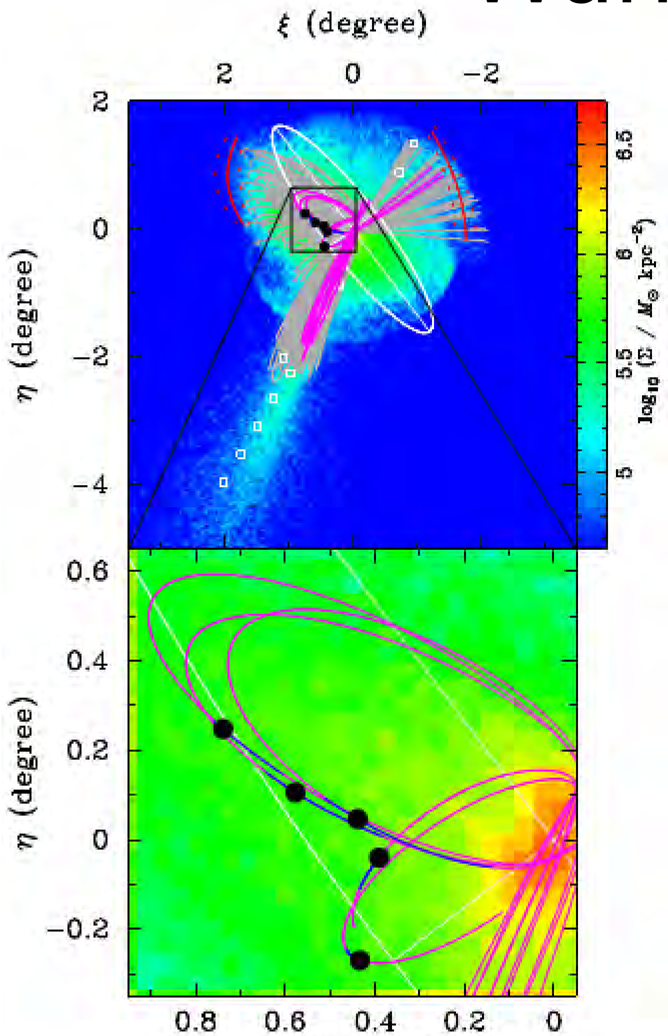
$r_{peri} = 1\ \mathrm{kpc}$

Sky map from M31



Miki, Mori, Kawaguchi & Saito, 2014, Astrophysical Journal, 783, 87

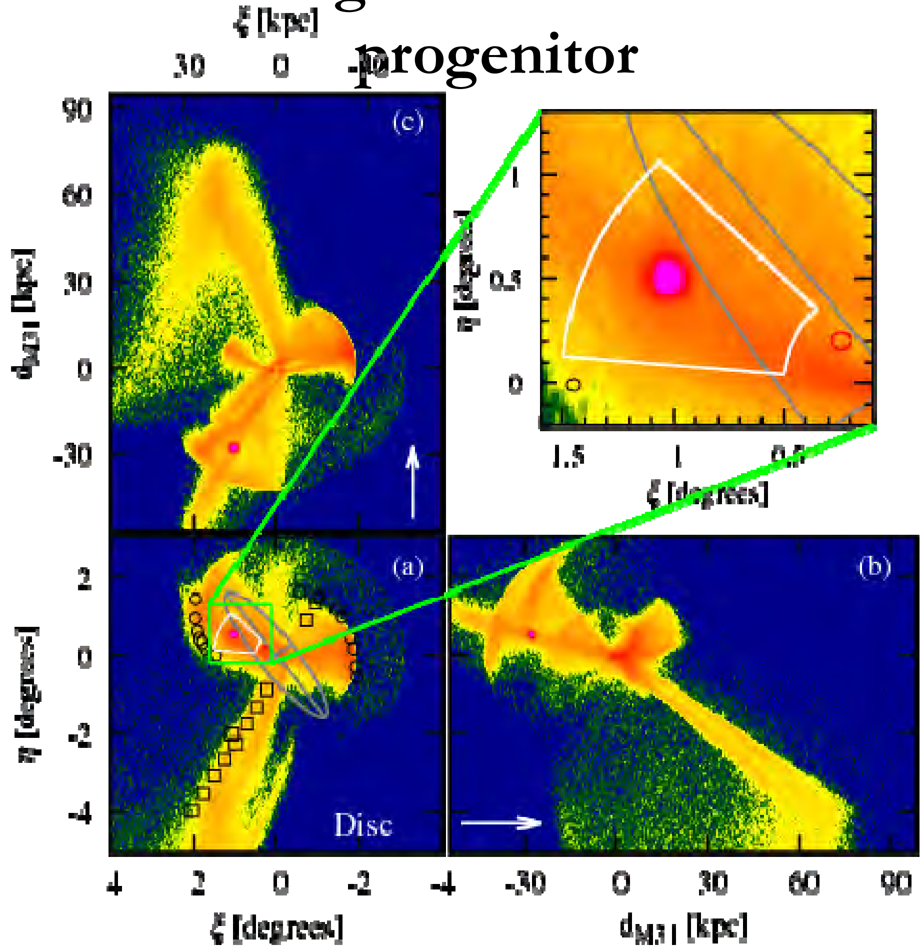
Wandering SMBH



Miki et al. 2014

See also Kawaguchi et al. 2014

Surviving central core of the progenitor

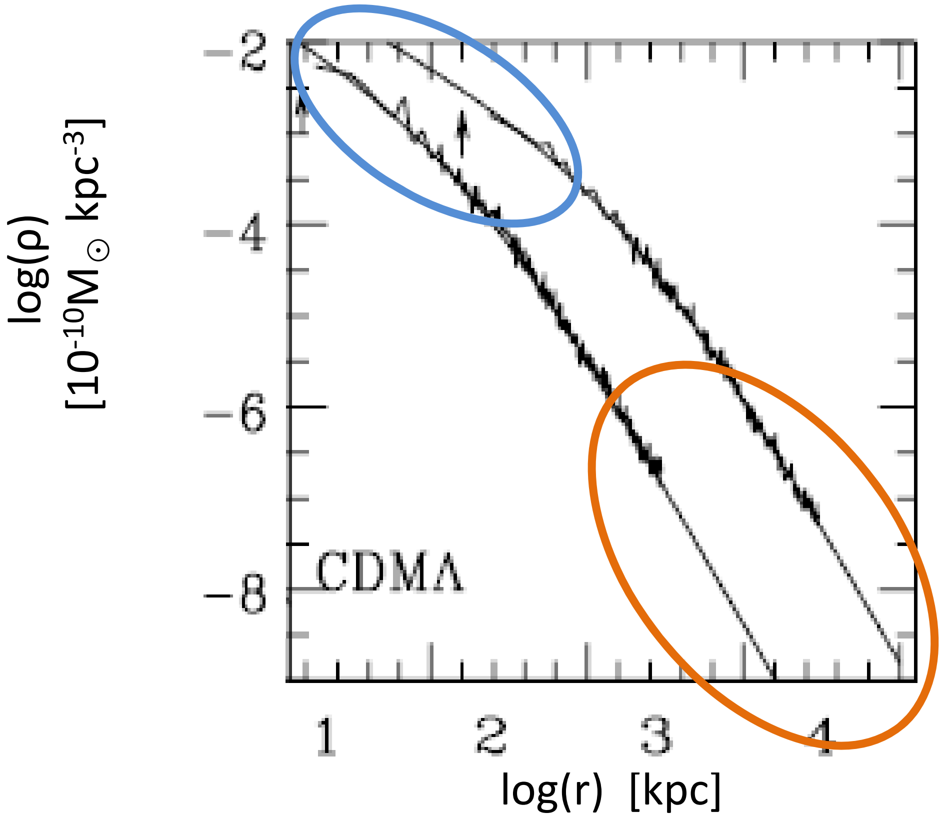


The position does not depend on the progenitor's morphology.

Miki, Mori, Kawaguchi & Saito, 2014, Astrophysical Journal, 783, 87

Outer density profile of the DM halo in M31

Kirihara et al. 2014



Navarro et al. 1996

コールドダークマターモデルは、小さな構造が先にでき、衝突・合体を繰り返して大きな構造ができることを予言。

そうしてできる銀河・銀河団スケールのダークマターハローの**密度分布がユニバーサル**であると予言

（Navarro et al. 1996; Fukushige & Makino 1997; Moore 1998等）

→内側は理論・観測面から活発に議論される

→外縁部の密度分布は、

$$\rho \propto r^{-3}$$

銀河外縁部の質量密度分布を観測することは容易ではなく理論の検証が進んでいない

方法

- 矮小銀河は、約25万体Plummer球　全質量 $2.2 \times 10^9 M_\odot$
- M31は、原点に固定されたfixed potential
  Exponential disk, Hernquist bulgeを仮定
- M31ダークマターハローの密度分布を次で定義

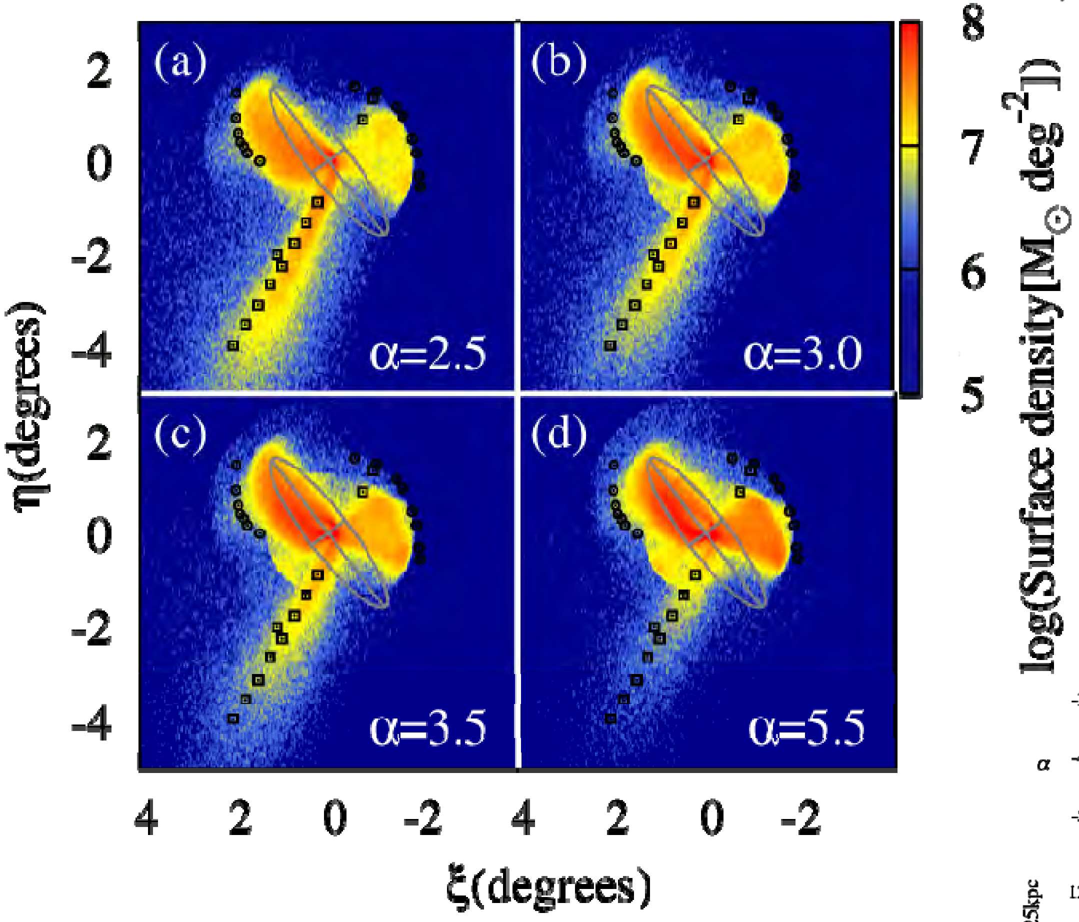
$$\rho_{\rm DMhalo}(r) = \frac{\rho_{s,\,\alpha}}{(r/r_{s,\,\alpha})(1+r/r_{s,\,\alpha})^{\alpha-1}}$$

αはダークマターハローの外側の密度を決める値
（α=3がCDM理論で予言される値）

αをパラメータにした銀河衝突シミュレーション(36model)
→ストリーム・シェルの構造を再現

Orbitは、Fardal et al. (2007)
重力計算部分はTree法（θ=0.5）、時間発展はleap-frog法

壊された矮小銀河の分布

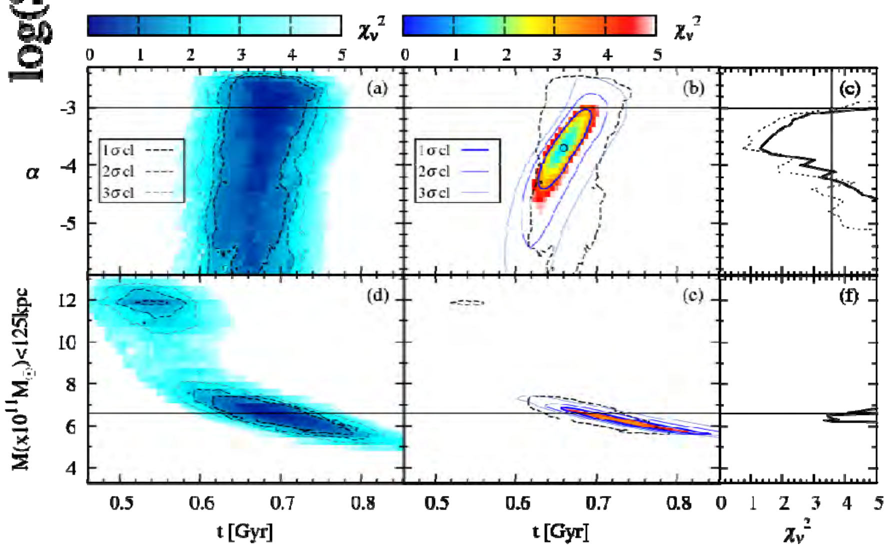


$$\rho_{\mathrm{DMhalo}}(r) = \frac{\rho_{s,\,\alpha}}{(r/r_{s,\,\alpha})(1 + r/r_{s,\,\alpha})^{\alpha - 1}}$$

ストリーム・シェルの面密度比についての解析

ストリーム / East シェル
West シェル/ East シェル

この2成分のシミュレーションと観測とのずれを χ_{υ}^{2} で評価



観測で得られる面密度比を再現するのは

$$3.2 < \alpha < 4.1$$

Kirihara et al. 2014

Summary

✓We study the interaction between an accreting satellite and the Andromeda galaxy (M31) analytically and numerically, using a high-resolution N-body simulation.

✓For the first time, we show the self-gravitating response of the disk, the bulge, and the dark matter halo of M31 to an accreting satellite.

✓We reproduce the stream and the shells at the east and west sides of M31 by following the evolution of the collision 4 Gyr into the future.

✓We calculate possible orbits of the progenitor dwarf galaxy using N-body simulations. Our results show that the MBH is within the halo, about 30 kpc away from the center of M31.

✓We examine the formation mechanism of the asymmetric surface brightness of the Andromeda giant stream. Minor merger of the progenitor with anticlockwise rotating disk can produce the eastern sharp edge of the Andromeda giant stream.