Recent our study about galaxy formation and evolution

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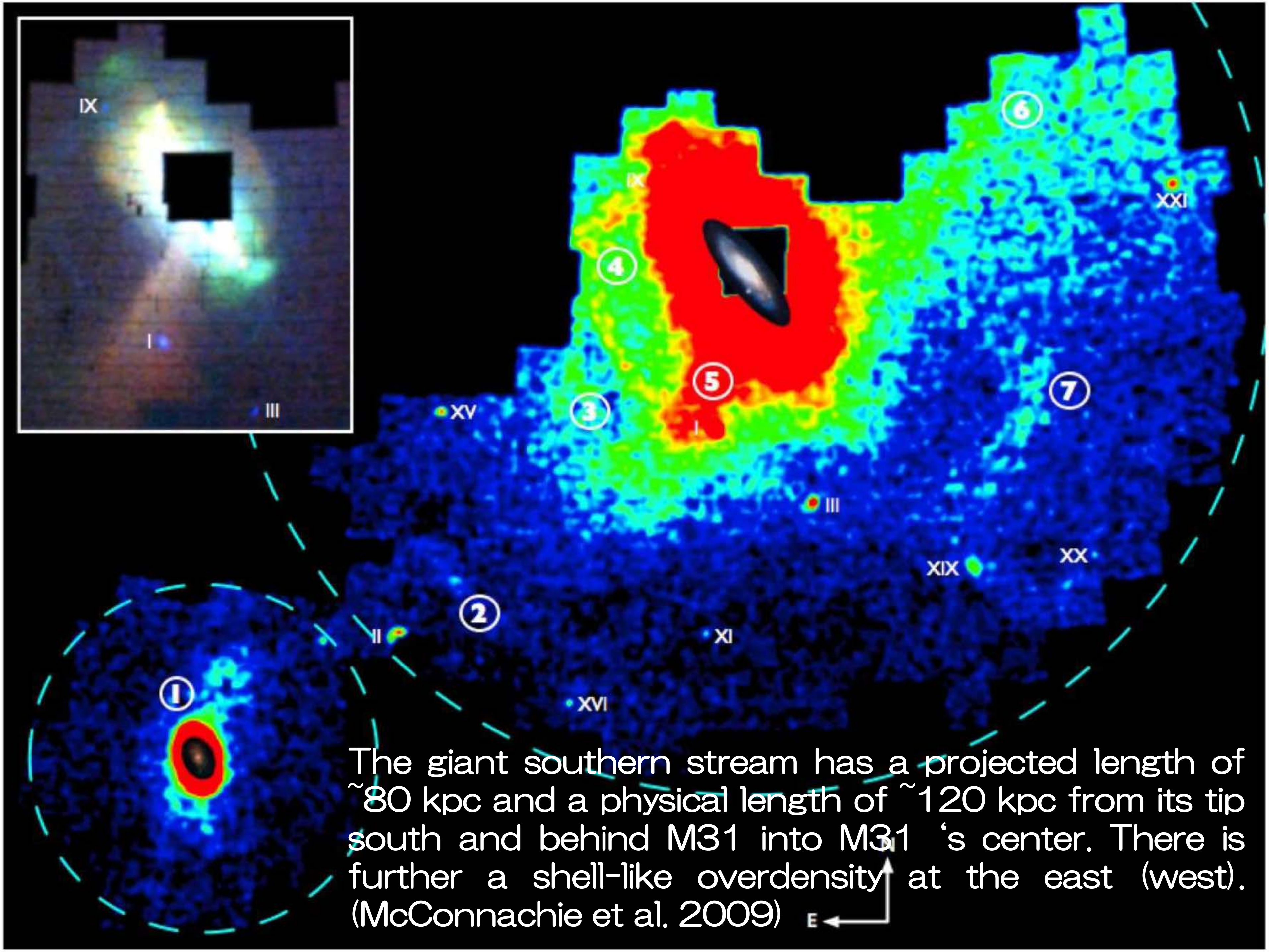
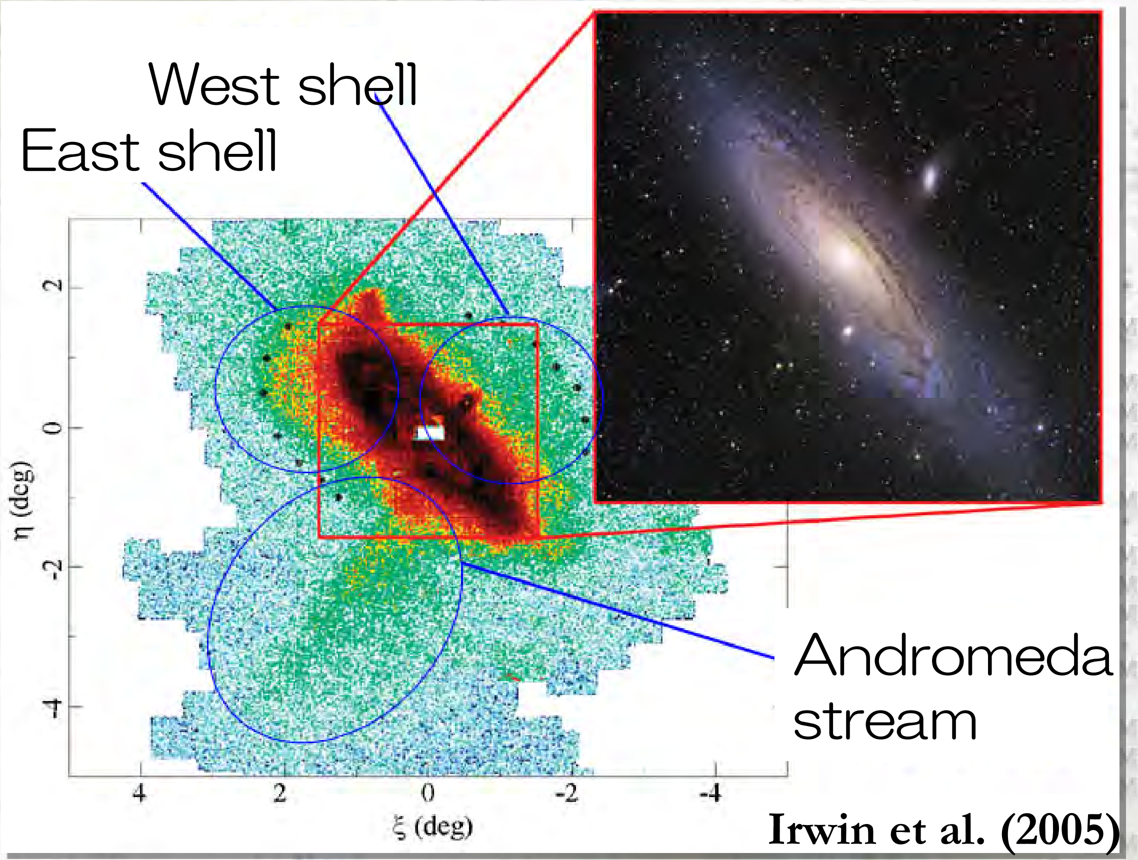
Outline

- Observational properties of faint features around Andromeda(M31).
- N-body simulations of Andromeda stream and shells
- Nature of the progenitor dwarf galaxy
- Wandering black hole in M31 halo
- Anomaly in the outer density profile of M31 dark matter halo
- Summary



The giant southern stream has a projected length of ˜80 kpc and a physical length of ˜120 kpc 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)

Giant stream and shells around M31



Irwin et al. (2005)

N-body simulations of the interaction between the progenitor of the giant stream and M31 suggest that these structures are the tidal debris formed in the last pericentric passage of a satellite on a radial orbit. (Fardal et al. 2006, 2007)

Motivations

So far, *N*-body simulations of the interaction between the progenitor of the giant stream and M31 suggest that the stream and shells are the tidal debris.

(Ibata et al. 2004; Font et al. 2006; Geehan et al. 2006; Fardal et al. 2006, 2007)

- However, these models have always assumed a fixed potential to represent the influence of M31, and no models consider the possible effect of a live disk.
- Present constraints on the progenitor properties are weak.

These issues motivate us to explore the effect of the accreting satellite using the first self-consistent, *N*-body model of M31 that has a disk, bulge, and dark matter halo.

Estimation of the progenitor mass

Dekel & Woo (2003)

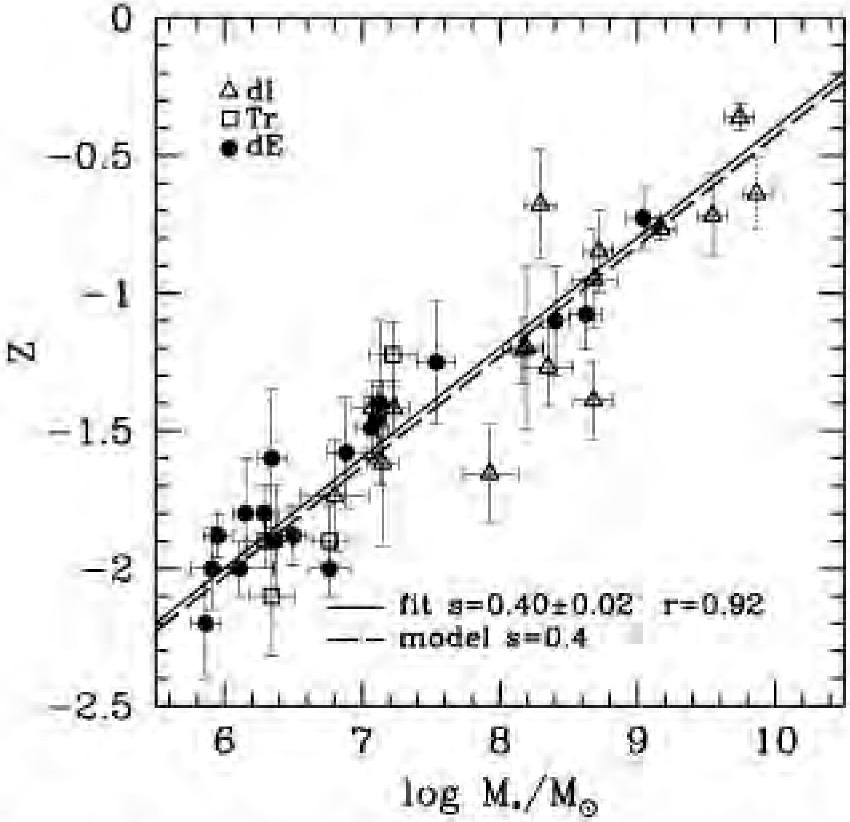


Figure 2. Metallicity versus stellar mass for the Local Group dwarfs (WD). The regression line $Z \propto M_*^{0.40}$ and the toy-model theoretical prediction $Z \propto M_*^{0.4}$ (normalized for best fit) are shown.

Stellar mass:

Metallicity of the stream

[Fe/H]=−1

(Koch et al. 2008)

Mass-metallicity relation of the local dwarfs

(Dekel & Woo 2003)

$$M_{\rm star} \geq 5\times 10^{8}\, M_{\rm sun}$$

eg. Ibata et al. (2004); Font et al. (2006)

Dynamical mass of the satellite：I

We look to the present day thickness of the disk to limit the progenitor mass. We estimate the disk heating by dynamical friction, which is caused by the scattering of the disk stars into an overdense wake that trails the orbiting body, exerting a force opposite to the orbital motion.

Dynamical friction by Chandrasekhar’s formulae：

$$F_{drag} = \frac{4\pi \ln\Lambda\, G^2 {M_s}^2 \rho_d}{{\upsilon_s}^2}\left[\mathrm{erf}(X) - \frac{2X}{\sqrt{\pi}}\exp(-X^2)\right],$$

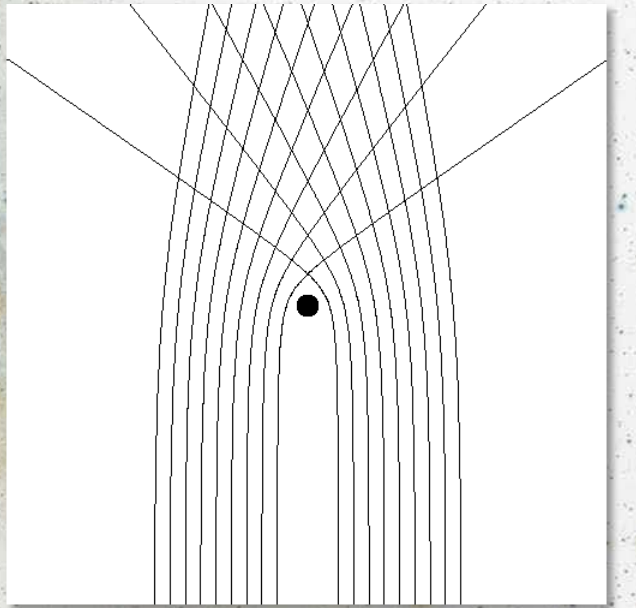
$$X \equiv \upsilon_s / \sqrt{2}\sigma_z$$

$$\Rightarrow \quad \Delta E = \int F_{drag}\, dz \approx \frac{4\pi G^2 {M_s}^2 \Sigma_d}{{\upsilon_s}^2}$$

$$\Rightarrow \quad \Delta{\sigma_z}^2 = \frac{2\Delta E}{M_s} \approx \frac{8\pi G^2 M_s \Sigma_d}{{\upsilon_s}^2} \quad \cdots(1)$$

M_s : satellite mass, ρ_d : disk density,

Σ_d : disk column density, υ_s : satellite velocity



Dynamical mass of the satellite：II

Equation of motion and Poisson equation

$$\frac{1}{\rho_d}\frac{\partial(\rho_d {\sigma_z}^2)}{\partial z}+\frac{\partial \Phi}{\partial z}=0,$$

$$\frac{\partial^2 \Phi}{\partial z^2}=4\pi G\rho \quad \Rightarrow \quad \frac{\partial \Phi}{\partial z}\approx 2\pi G\Sigma_d\,,$$

$$\text{assuming} \quad \rho_d \propto \exp(-z/z_d),\ \sigma_z : \text{const.}$$

$$\Rightarrow \quad \Delta z_d = \frac{\Delta {\sigma_z}^2}{2\pi G \Sigma_d} \cdots (2)$$

Finally.

$$M_s \le 5\times10^9\, M_{sun}\left(\frac{M_d}{7\times10^{10}\, M_{sun}}\right)^{\frac{1}{2}}\left(\frac{\upsilon_s}{150\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\Delta z_d}{0.3\,\mathrm{kpc}}\right)^{\frac{1}{2}}$$

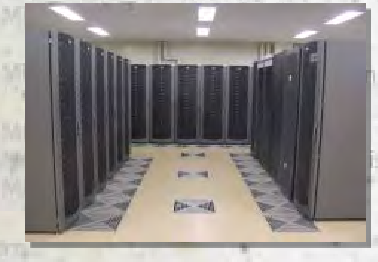
Mori & Rich 2008

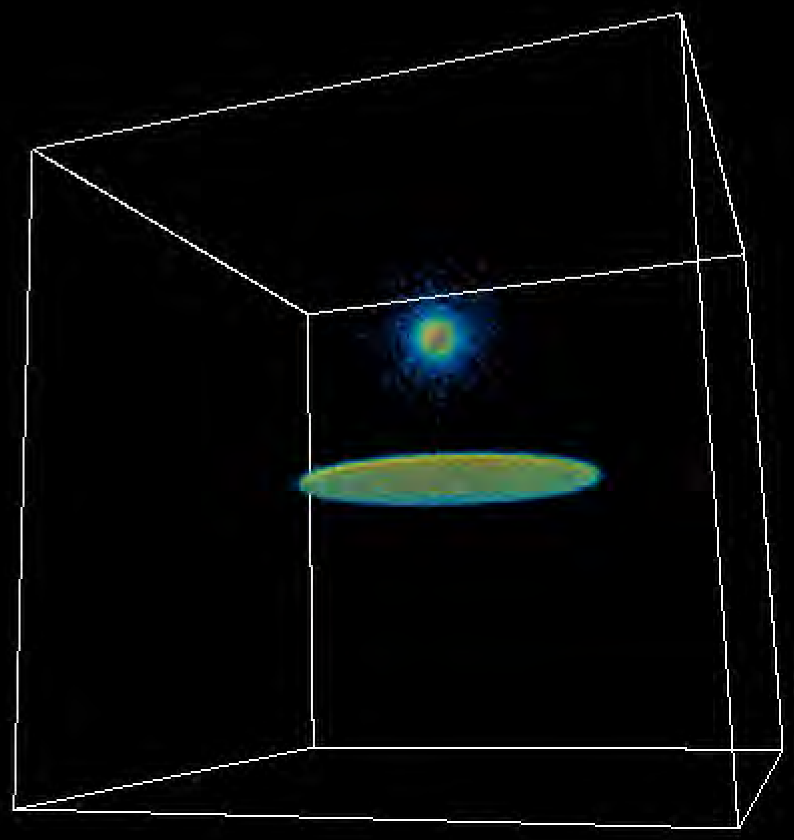
Model and parameters

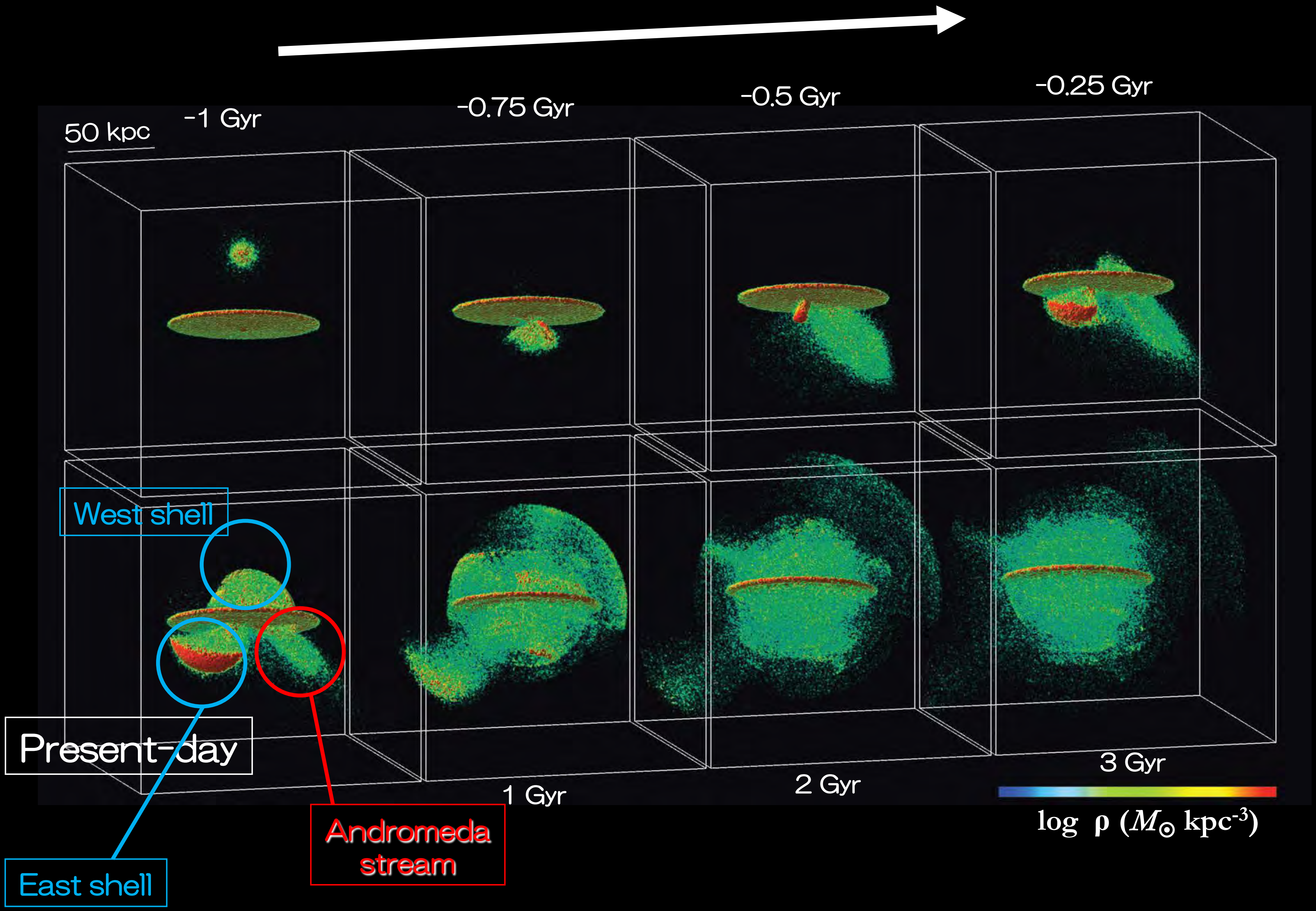
- Model of Andromeda: Widrow, Perret & Suyu (2003)
  - bulge: King model(mass: $2.5\times10^{10}\ M_\odot$)
  - disk: exponential profile
    - mass : $7\times10^{10}\ M_\odot$, scale length : 5.4 kpc, thickness : 0.3 kpc
  - dark matter : lowered Evans model
    - mass : $3.2\times10^{11}\ M_\odot$

- Satellite: Plummer model (scale length : 1kpc)
  - Model A: $10^9\ M_\odot$, (Model B: $5\times10^9\ M_\odot$, Model C: $10^{10}\ M_\odot$)
  - initial position and velocities taken from Fardal et al. 2007

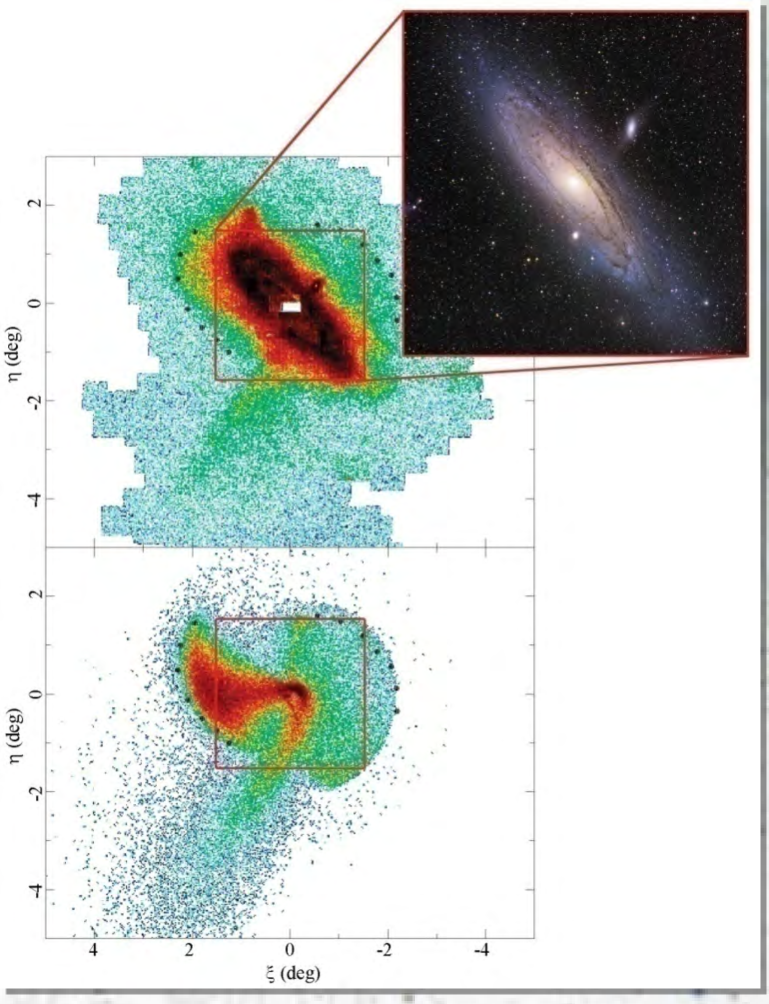
- Simulation code : GADGET2 (Springel 2005) , AFD (Mori & Umemura 2006)
- FIRST cluster(CCS, U. Tsukuba)
- T2K-Tsukuba






50 kpc
-1 Gyr
-0.75 Gyr
-0.5 Gyr
-0.25 Gyr
West shell
Present-day
East shell
Andromeda stream
1 Gyr
2 Gyr
3 Gyr
log ρ ($M_\odot$ kpc^{-3})

Simulation and observation

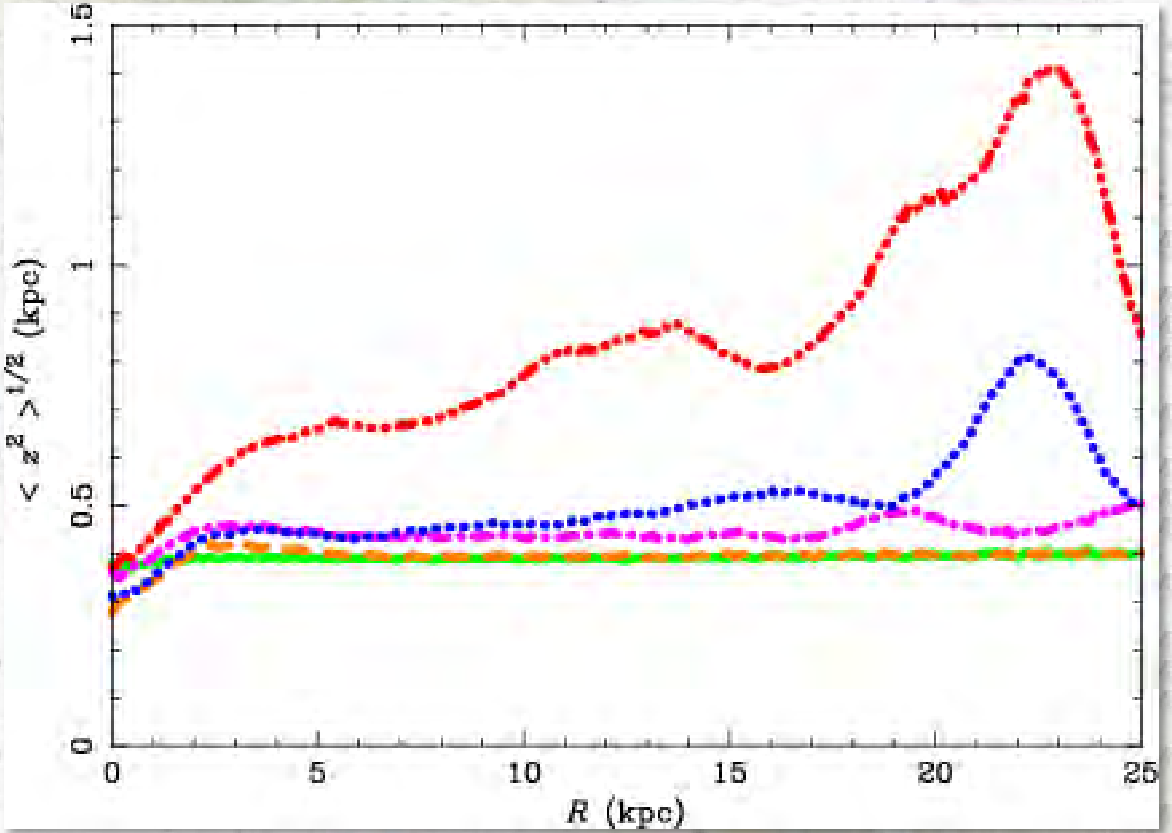


The map of stellar density around M31 observed by Irwin et al. (2005) and the projected stellar density at the present-day in our simulation.

The satellite is entirely disrupted, and the giant stream of debris arising from the tidal destruction of the accreting satellite at the southern part of M31 is observed.

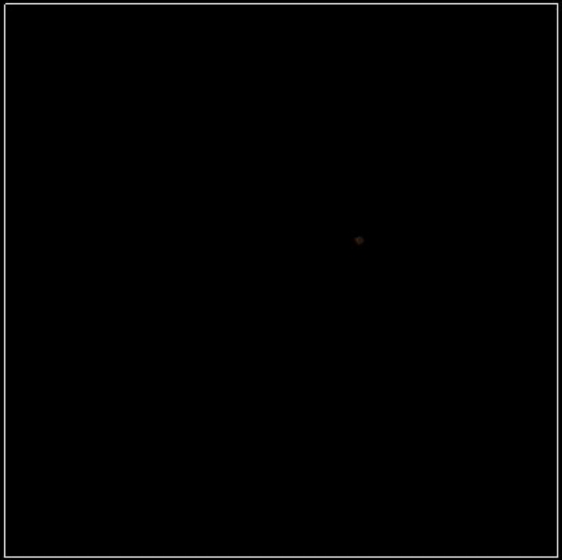
The simulation reproduces the butterfly-shaped shells in the northeast and the west part of M31.

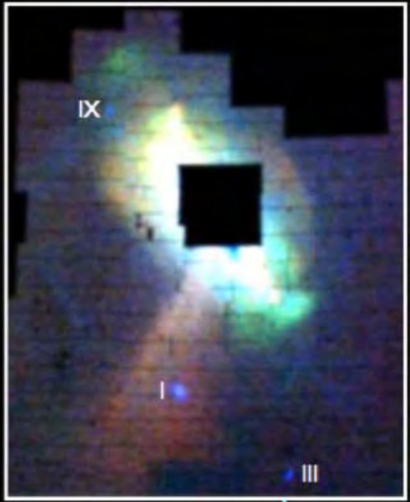
Vertical extent of the disk for different impact satellite masses



Vertical extent of the disk at the present-day for different impact satellite masses. The solid line and the dashed line show the initial radial profile and the resultant radial profile after 5 Gyr without a collision, respectively. The dot-dashed line, the dotted line and the dot-dot-dot-dashed line correspond to the satellite mass of $10^9\ M_\odot$ (Model A), $5\text{x}10^9\ M_\odot$ (Model B) and $10^{10}\ M_\odot$ (Model C), respectively.

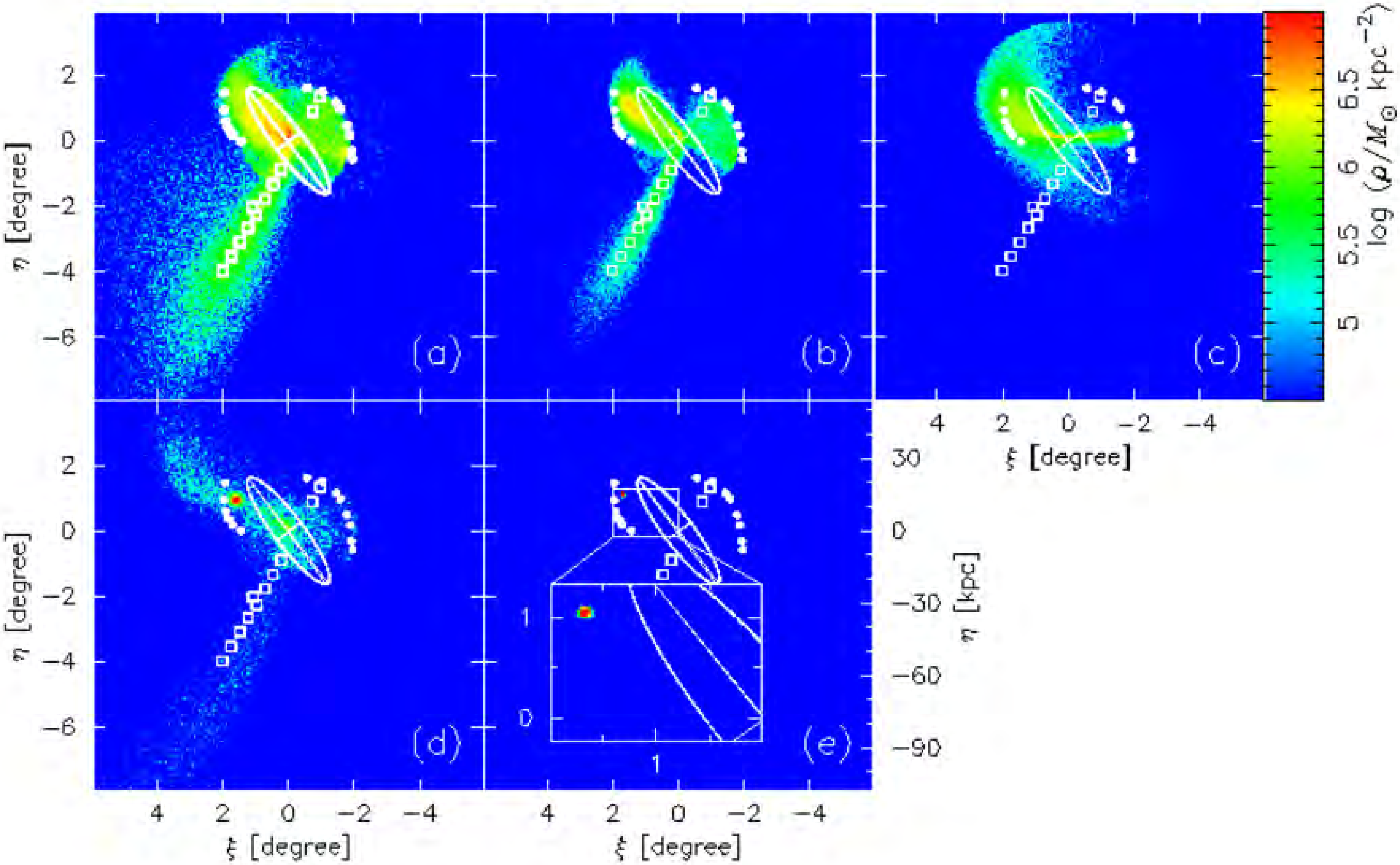
Mass distribution of the progenitor galaxy





McConnachie et al. 2009

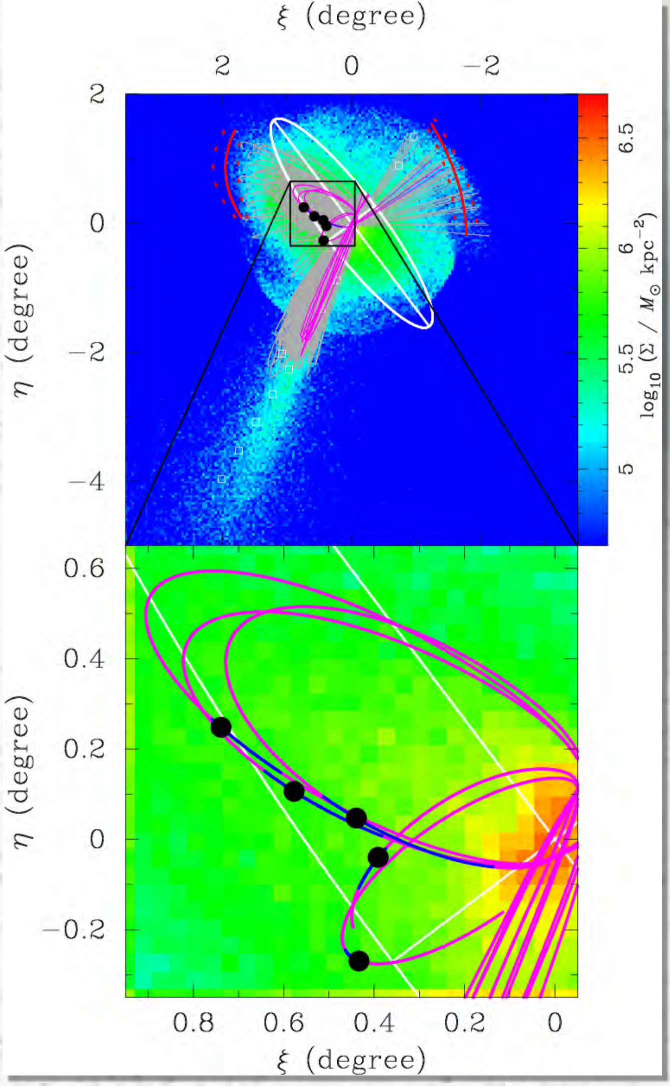
Mass distribution of the progenitor galaxy



We successfully constrain the physical properties of the progenitors which have a central surface density around $10^3\ M_\odot\ \mathrm{pc}^{-2}$.

Miki, et al. in prep.

Hunting a Wandering Super Massive Black Hole in the M31 Halo Hermitage



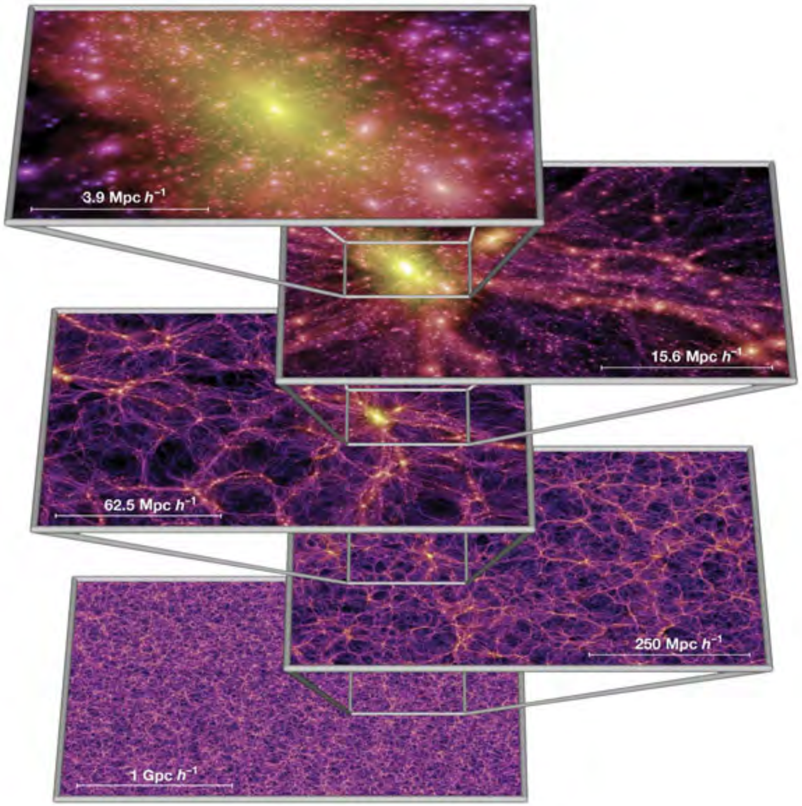
Mass distribution (column density) maps of the debris of the dwarf galaxy in standard coordinates centered on M31 with the color scale shown at the upper right corner.

In the upper panel, global distribution of *N*-body particles are shown as a color image while white curves and lines show the disk of M31.

The lower panel is a 1 ° x 1 ° enlarged view of the black square in the upper panel. Black circles show the most probable current position of the SMBH.

Miki, et al. accepted to ApJ (arXiv:1401.4645)

Theory of the structure formation



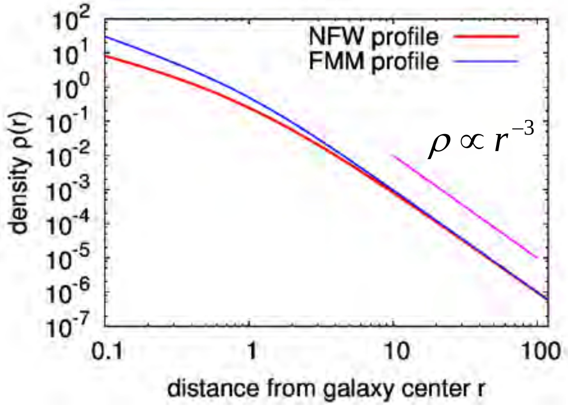
Springel, V et al. (2005)
structure formation in the universe
using cosmological *N*-body simulation

Recent cosmological simulations suggest that cold dark matter (CDM) halos have a universal mass-density profile (Navarro, Frenk & White 1995; Fukushige & Makino 1997; Moore et al. 1998).

Mass density of CDM outer halos decreases with the cube ($\rho \propto r^{-3}$) of the distance from the galactic center.

However

So far, observational verification of this theoretical prediction is not yet sufficient



Methods and parameters for simulation

- Models of progenitor dwarf galaxy as an *N*-body system
  - Number of particles is 49,512
  - Other conditions are taken from Fardal et al.(2007)
- M31 is treated as the fixed potential
  - With the Hernquist bulge, the exponential disk and the DM halo
- Mass density profile of DM halo of M31

$$\rho_{DMhalo}(r) = \frac{\rho_{0,a}}{(r/r_{s,a})(1+r/r_{s,a})^{\textcircled{a}}}$$

$\rho_{0,a}$: the scale density

$r_{s,a}$: the scale length
of the DM halo respecting M31

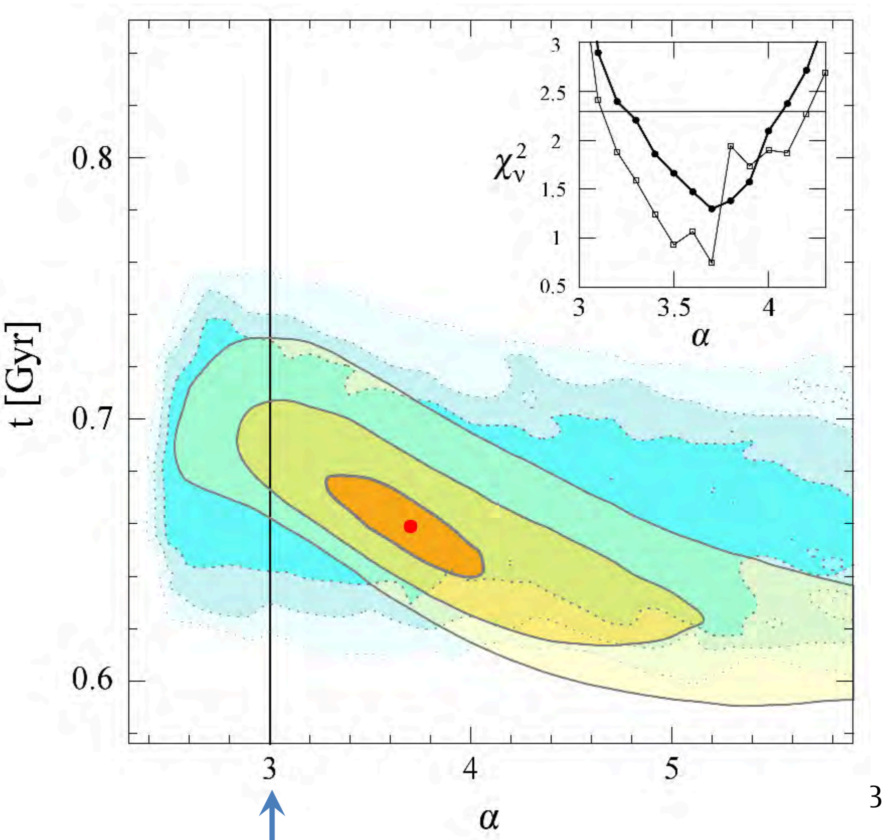
We change the power-law slope ***a*** **(1.5≦a≦4.0)**

※ a=2 ($\rho \propto r^{-3}$): the profile of the DM outer halo corresponds to the prediction of CDM model

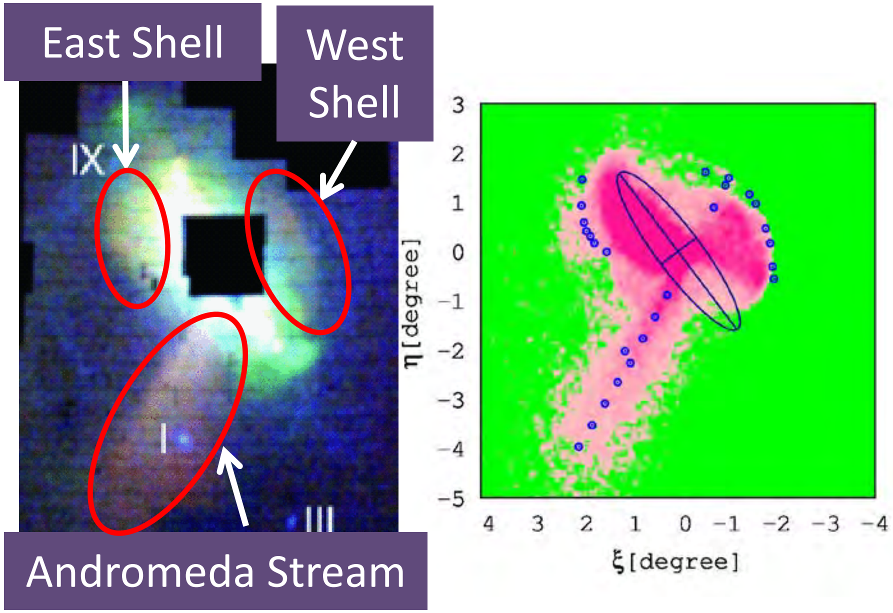
➡ examine the range of parameter ***a*** which reproduces the giant stream and shells with *N*-body simulations of galaxy collision

➡ **examine the theoretical prediction of the profile of the DM outer halo**

χ^2 analysis of the surface density ratio of stream and 2 shells between simulation and star count map of observation



CDM prediction

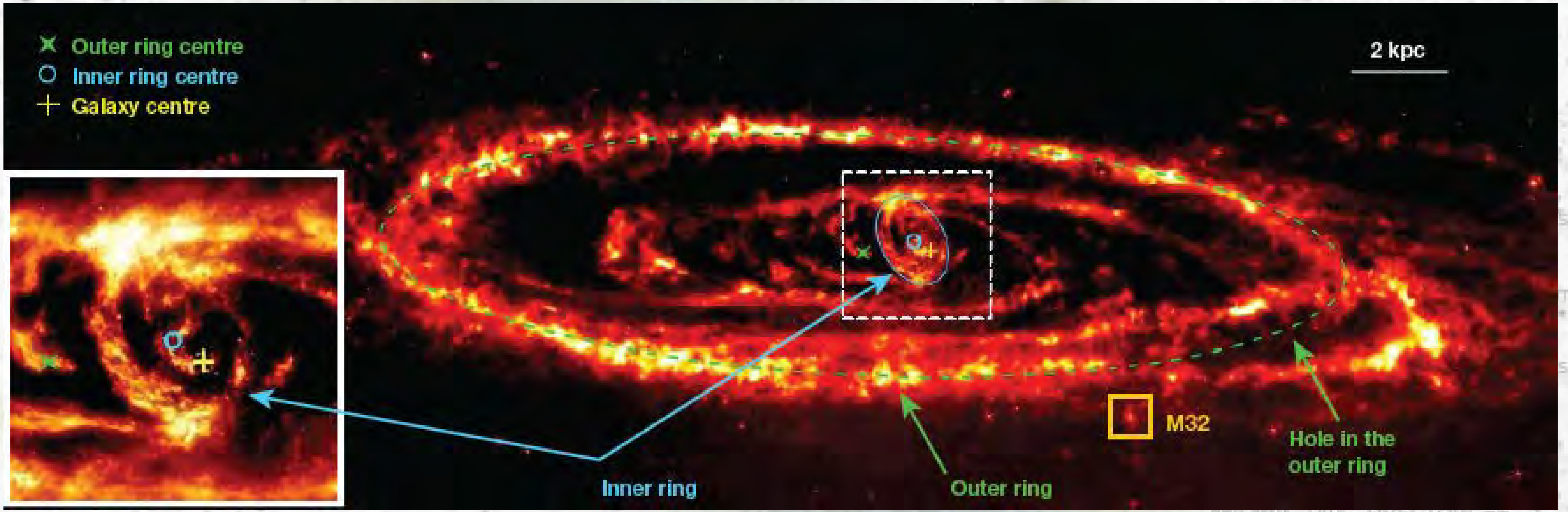


Only for the DM outer halo with a density power-law slope of **3.2< a < 4.1**, the results of simulations successfully reproduce the giant stream and the apparent shell structures that are observed in the star count map.

Our result indicates that the density profile of the DM outer halo of the Andromeda galaxy is steeper than the prediction of the CDM model.

Kirihara et al. submitted to PASJ Letter

N-body/hydrodynamics model for ring-like structure in M31 disk



Active project:

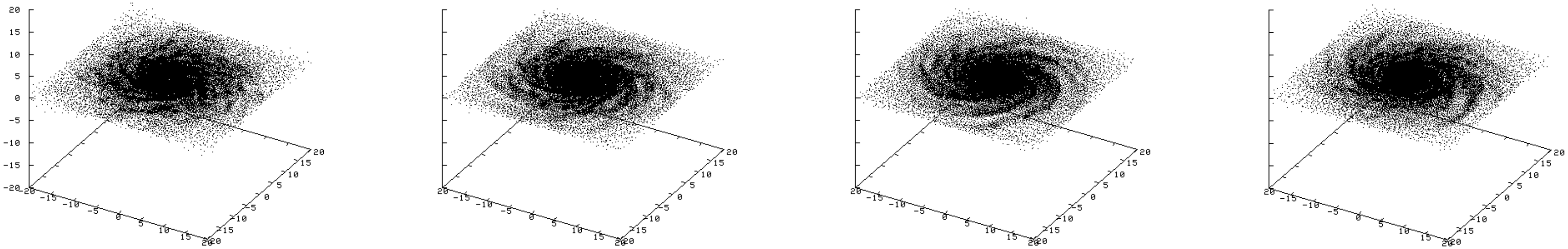
- Collisionless particles such as stars and dark matter
- Hydrodynamic component for gas with radiative cooling
- Star formation at the high density region compressed by the galaxy collision

→ Large scale simulation

Evolution of Gas Disc w/o Galaxy Collision
preliminarily result

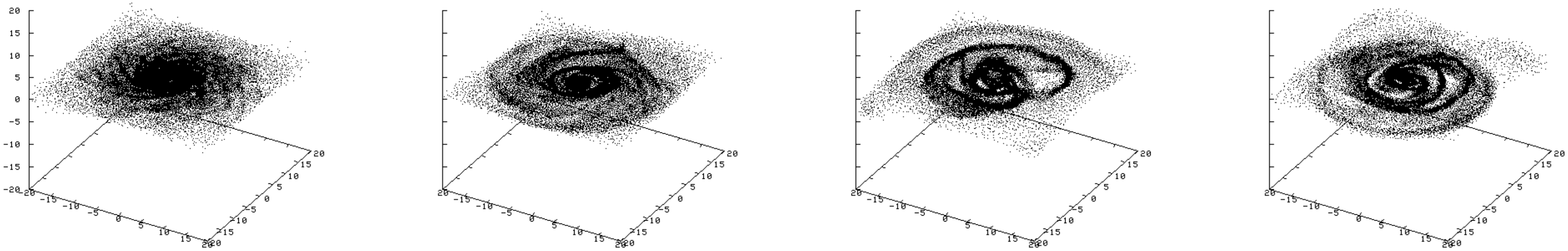
0.2 Gyr 0.4 Gyr 0.6 Gyr 0.8 Gyr

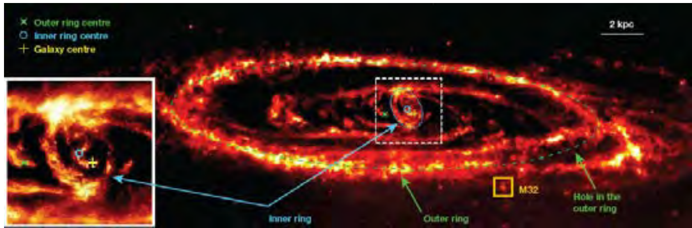
No merger



20 kpc

Merger





Summary

- We study the interaction between an accreting satellite and the Andromeda galaxy (M31) analytically and numerically, using a high-resolution N-body simulation with 4x10^7 particles.
- 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.
- Our result indicates that the density profile of the DM outer halo of the Andromeda galaxy is steeper than the prediction of the CDM model.
- We calculate possible orbits of the massive black hole within 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 find that an observational field of 1°x1° in the northeast region of the M31 halo contains almost all possible current position of the massive black hole.