Numerical Simulations of Galactic Collision and Evolution

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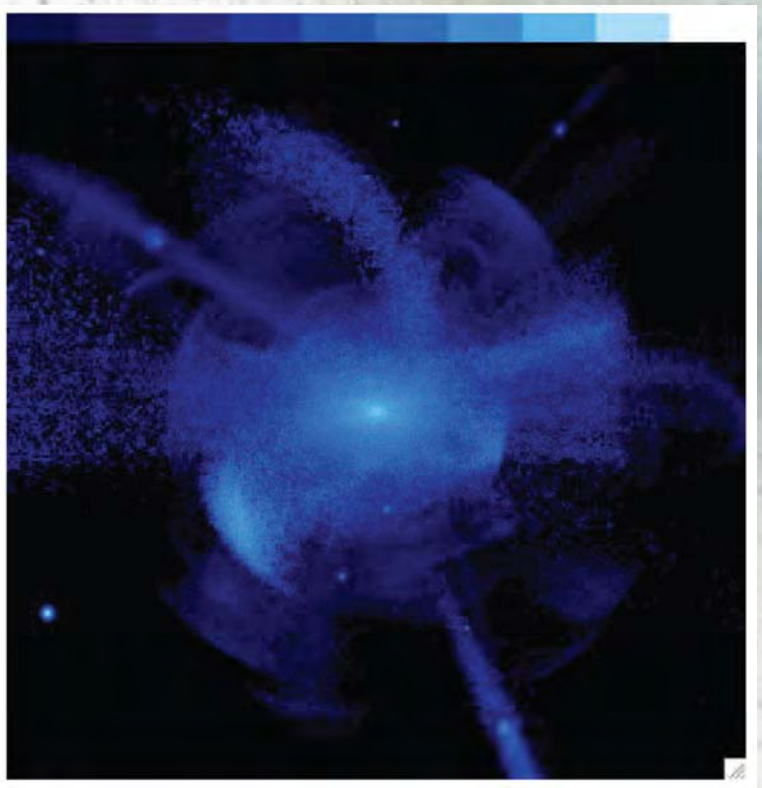
Outline

- Hierarchical structure formation and observational properties of faint features around Andromeda galaxy (M31).
- N-body simulations of the formation of the Andromeda stream and other structures
- Morphology and orbit of the progenitor galaxy
- Summary

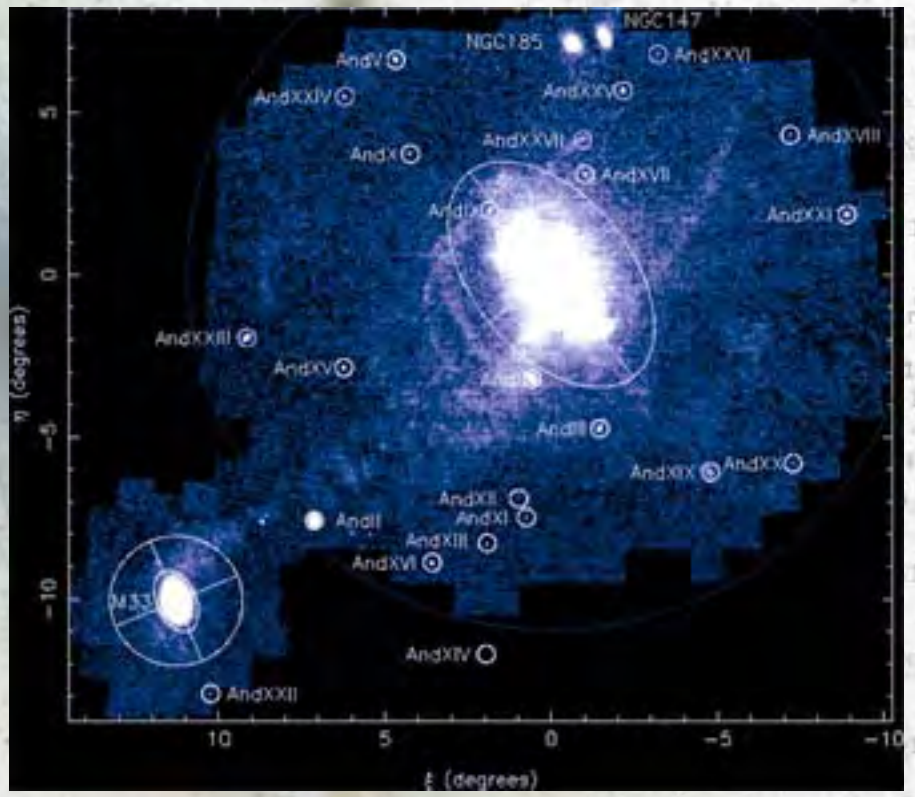
Hierarchical structure formation in the universe

Theory



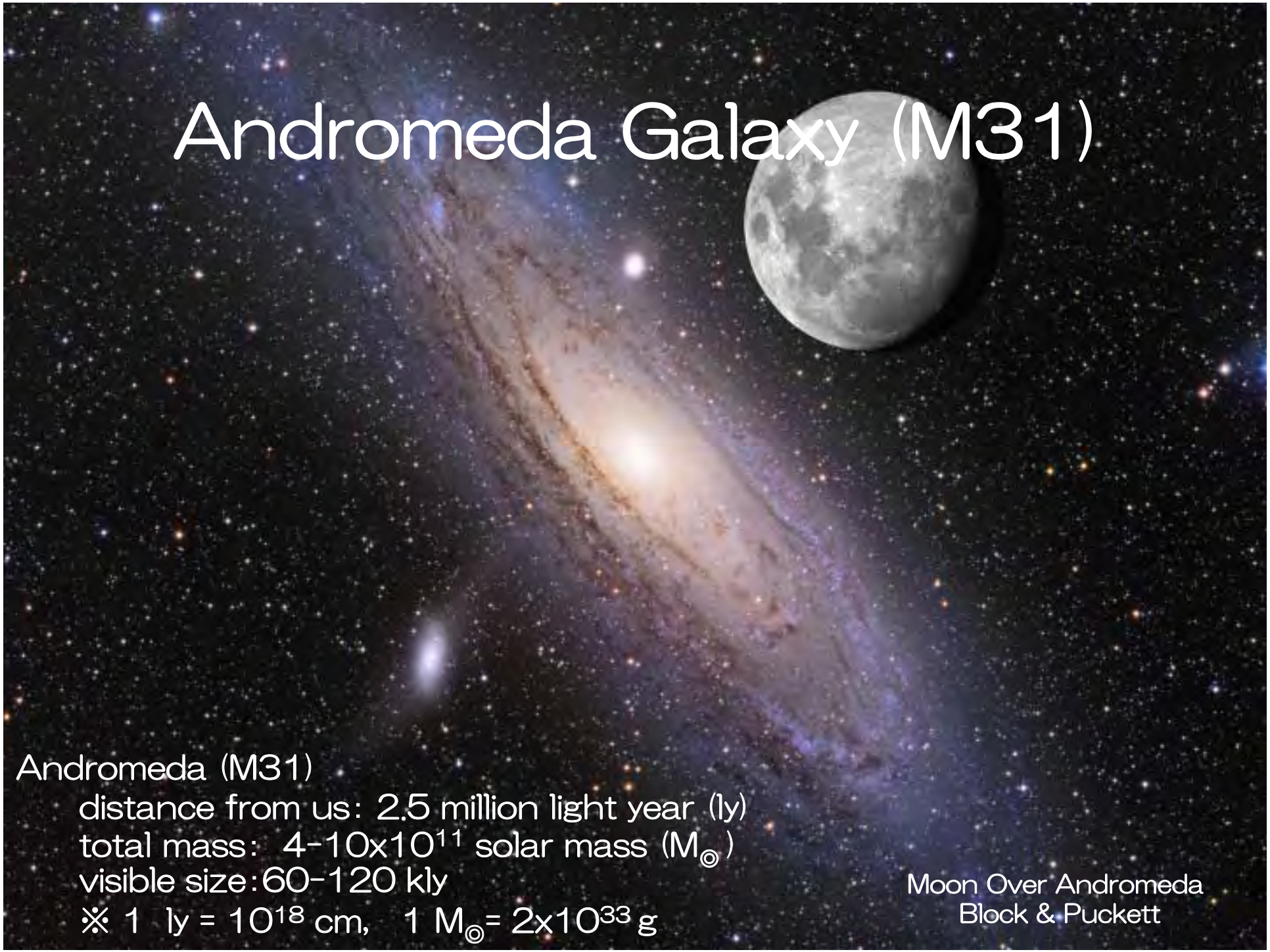
Bullock & Johnston 2005

Observation (Andromeda galaxy)



Richardson et al. (2011)

Andromeda Galaxy (M31)



Andromeda (M31)

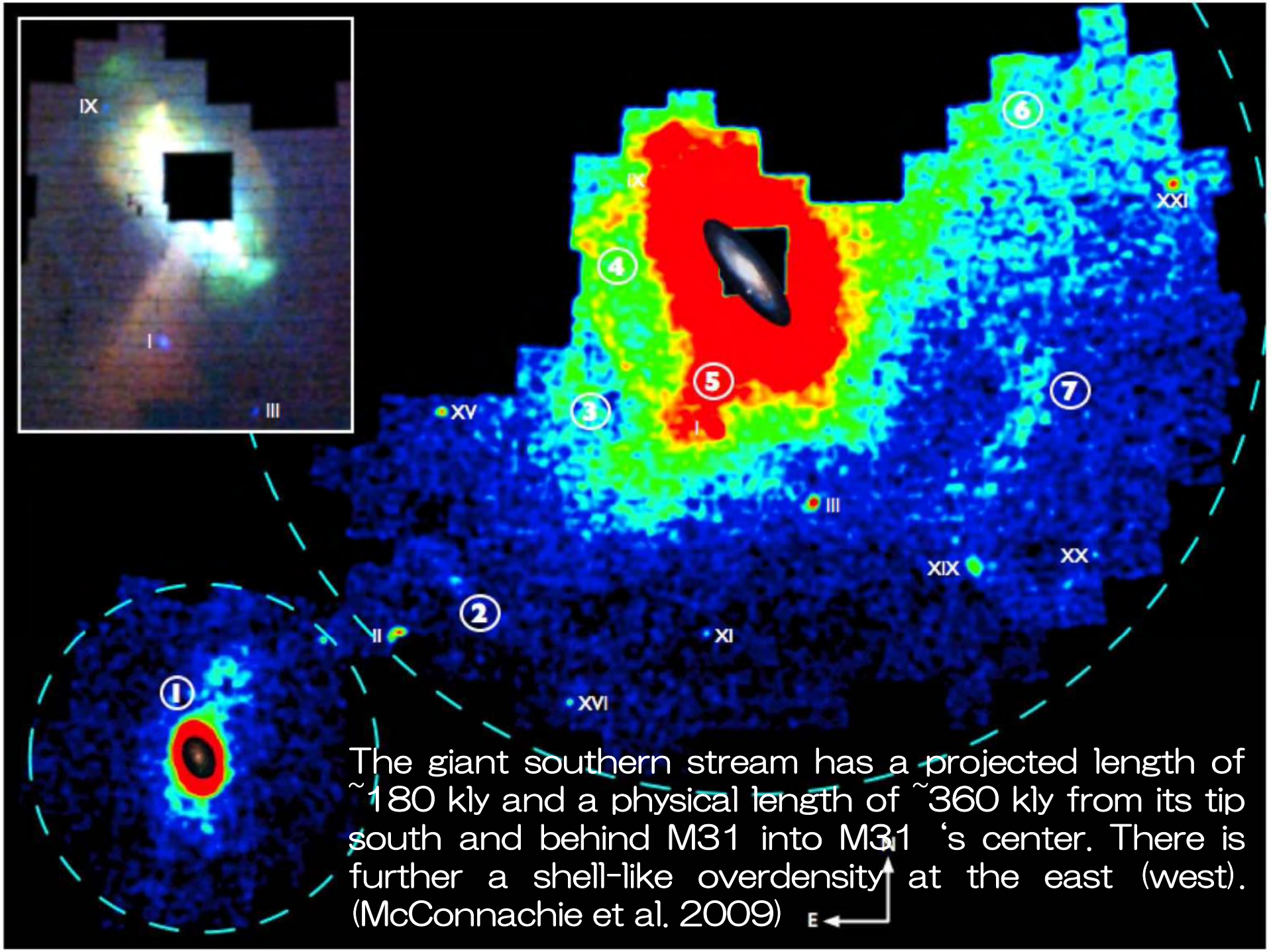
distance from us: 2.5 million light year (ly)

total mass: 4-10x10^{11} solar mass ($M_\odot$)

visible size: 60-120 kly

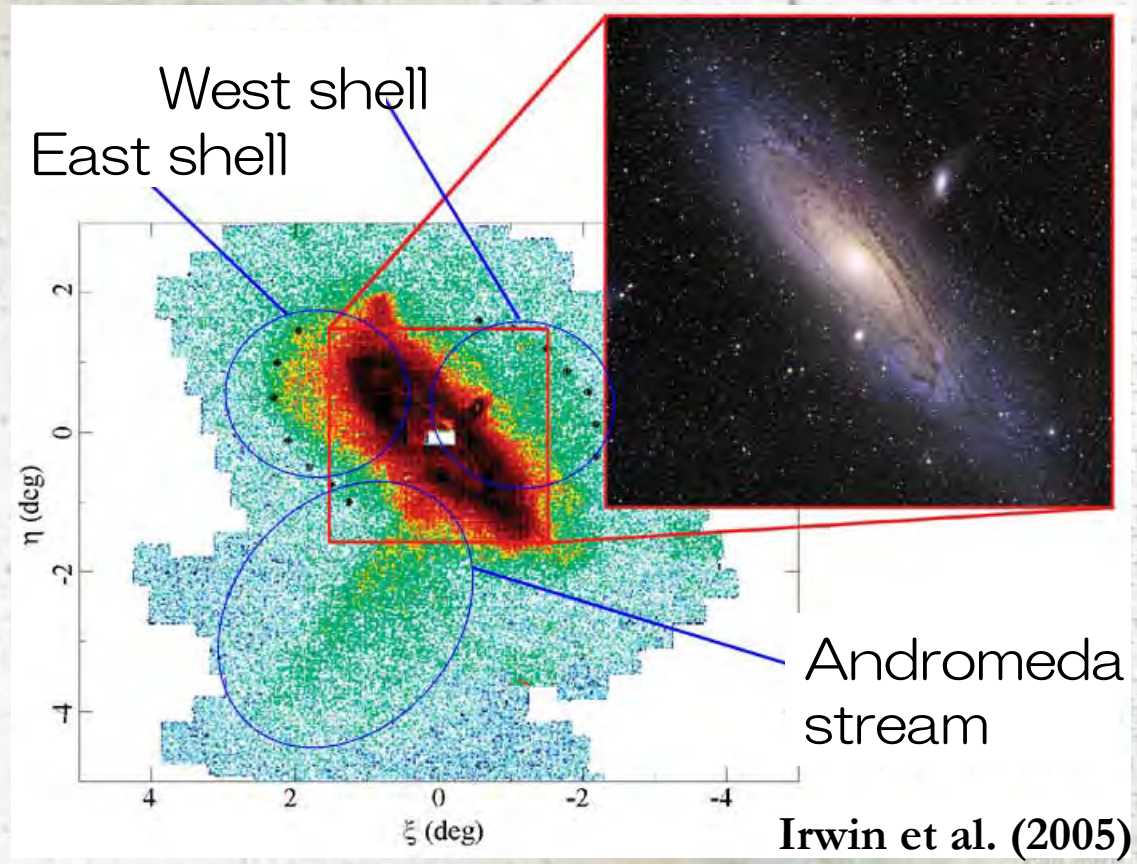
※ 1 ly = 10^{18} cm, 1 $M_\odot$ = 2x10^{33} g

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)

Motivations

So far, *N*-body simulations of the interaction between the progenitor of the giant stream and the Andromeda galaxy 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 the Andromeda galaxy, and no models consider the possible effect of a live disk.
- Constraints on the progenitor properties are weak.
- The newly discovered large scale structures have not yet been modeled.

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

Model and parameters

- Model of the Andromeda galaxy

  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 halo: lowered Evans model

  mass : $3.2\times10^{11}\ M_\odot$

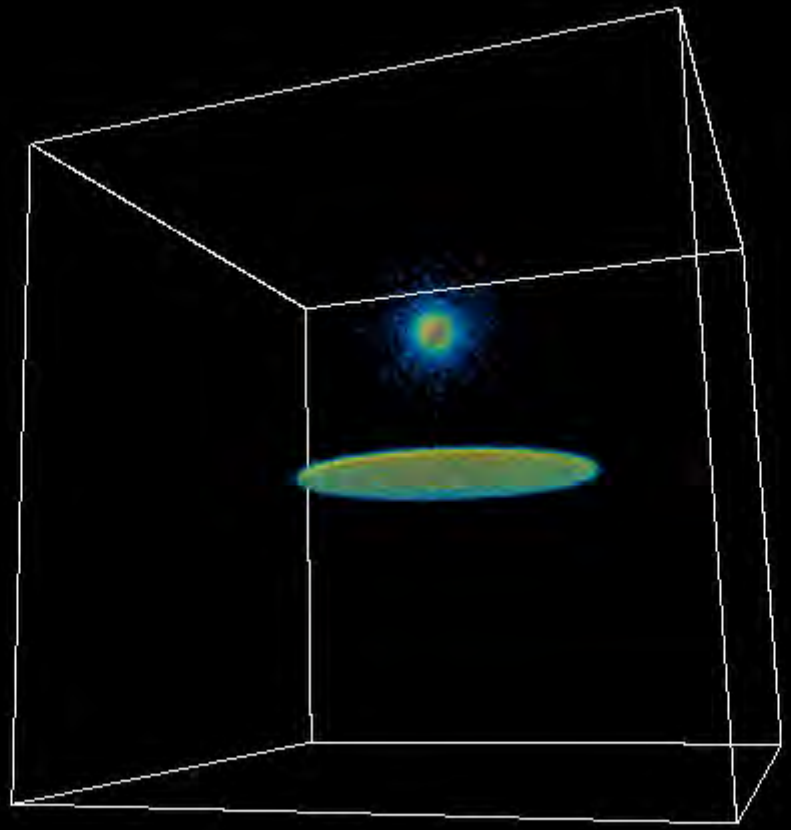
- Satellite: Plummer model (scale length : 1kpc)

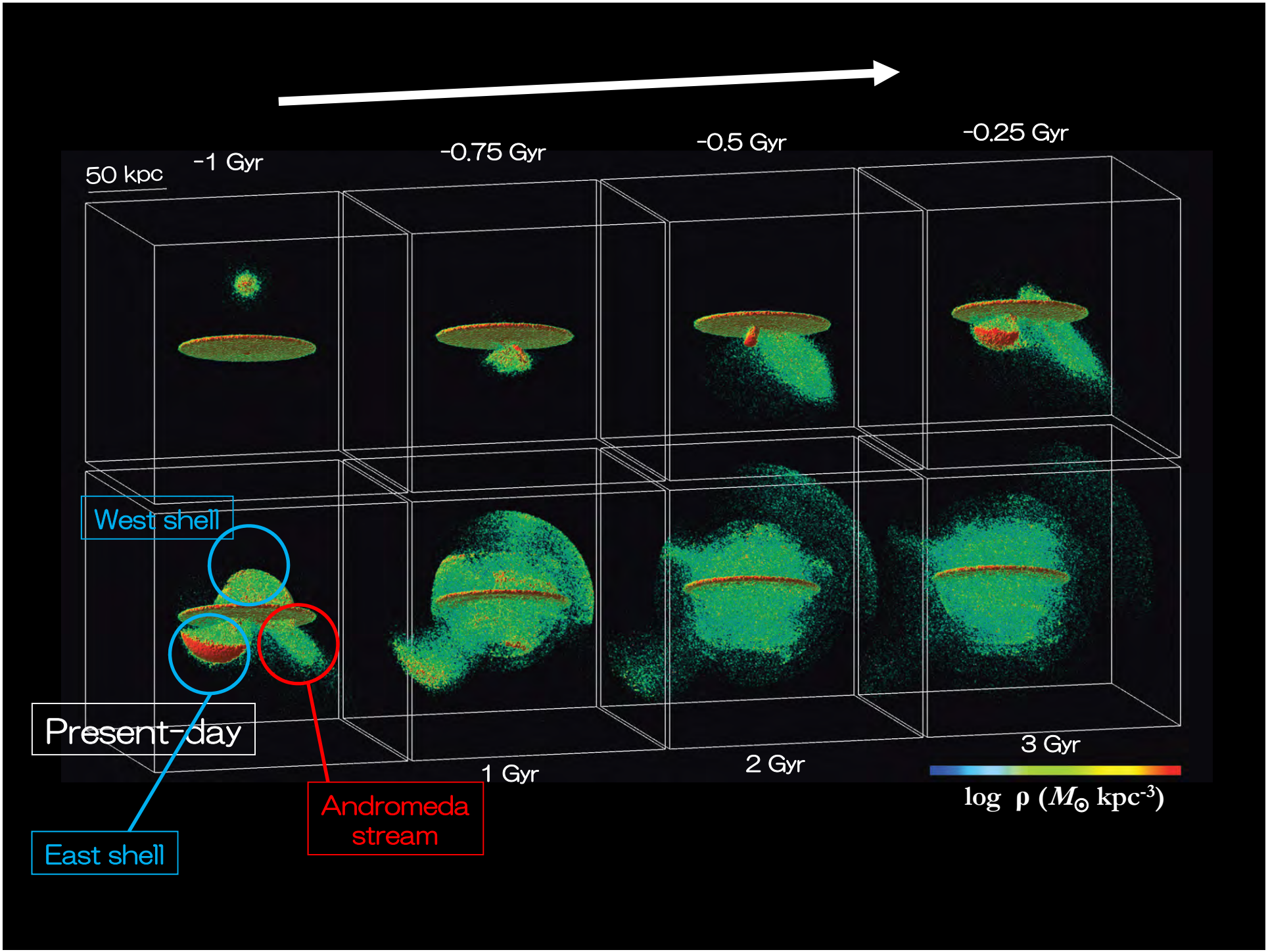
  Model A: $10^9\ M_\odot$, (Model B: $5\times10^9\ M_\odot$,

  Model C: $10^{10}\ M_\odot$)

  initial position and velocities

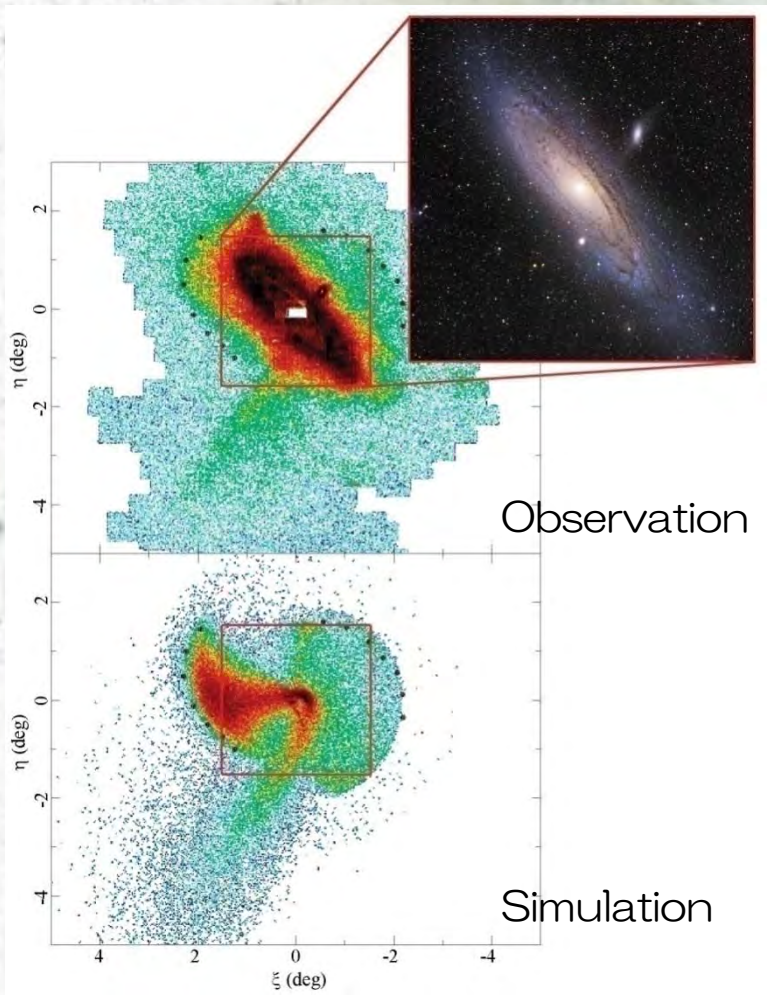
  taken from Fardal et al. 2007




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})

Stellar density map around the Andromeda galaxy: simulation and observation

Mori & Rich, 2008, ApJ, 674, L77



Irwin et al. (2005)

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

Our result of simulations shows that the galaxy collision occurred at 700 million years ago, and the satellite mass must be less than $5 \times 10^9 M_\odot$.

Parameter study for accreting orbit of the satellite galaxy

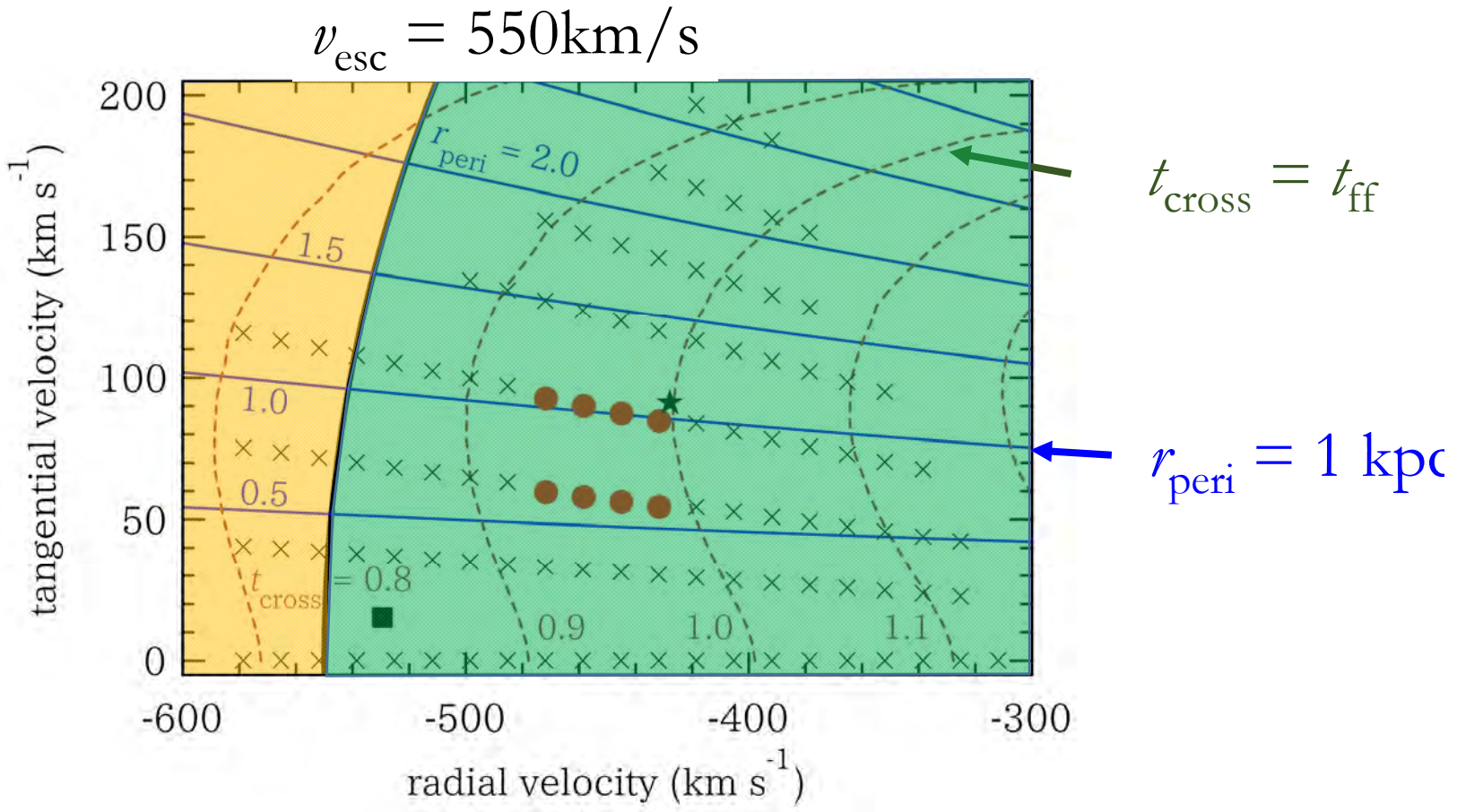
Miki, Mori, Kawaguchi & Saito, 2014, Astrophysical Journal, 783, 87

- To examine the infalling orbit of the satellite galaxy,

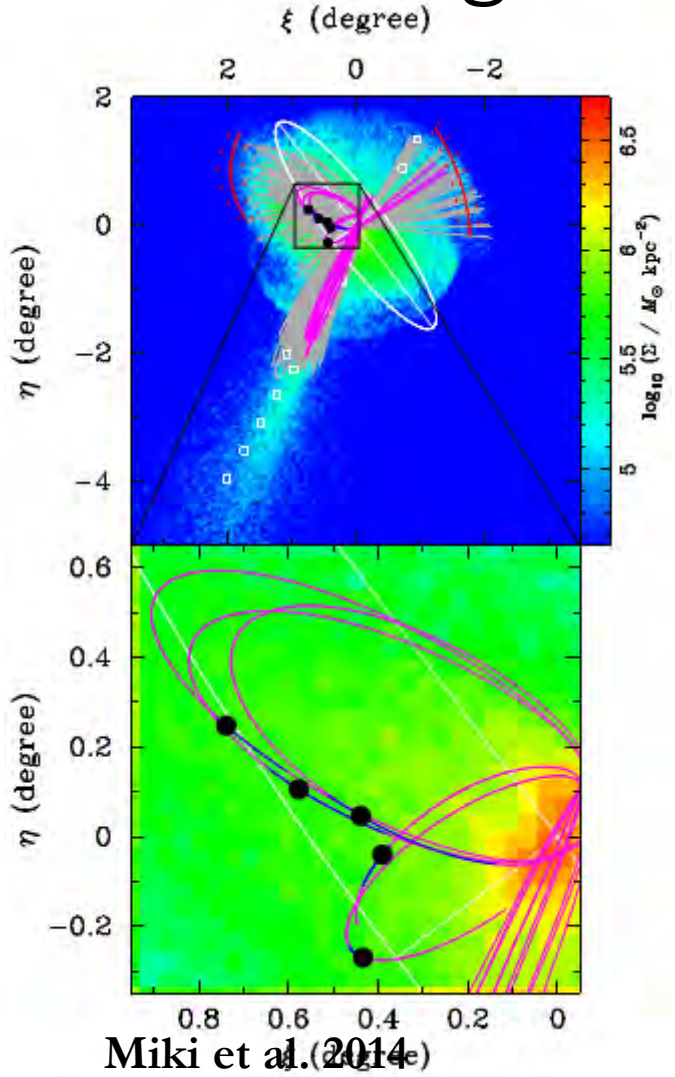
  we assume,
  - the initial distance from the M31 center
  - the Andromeda galaxy is modeled as an axisymm system
- We have utilized HA-PACS, a GPU cluster.
  - A fast *N*-body code based on CUDA (Miki+12, 13).
  - ～1,000 runs/day @ N = 65,536 using 128GPUs.

Results of the parameter study

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



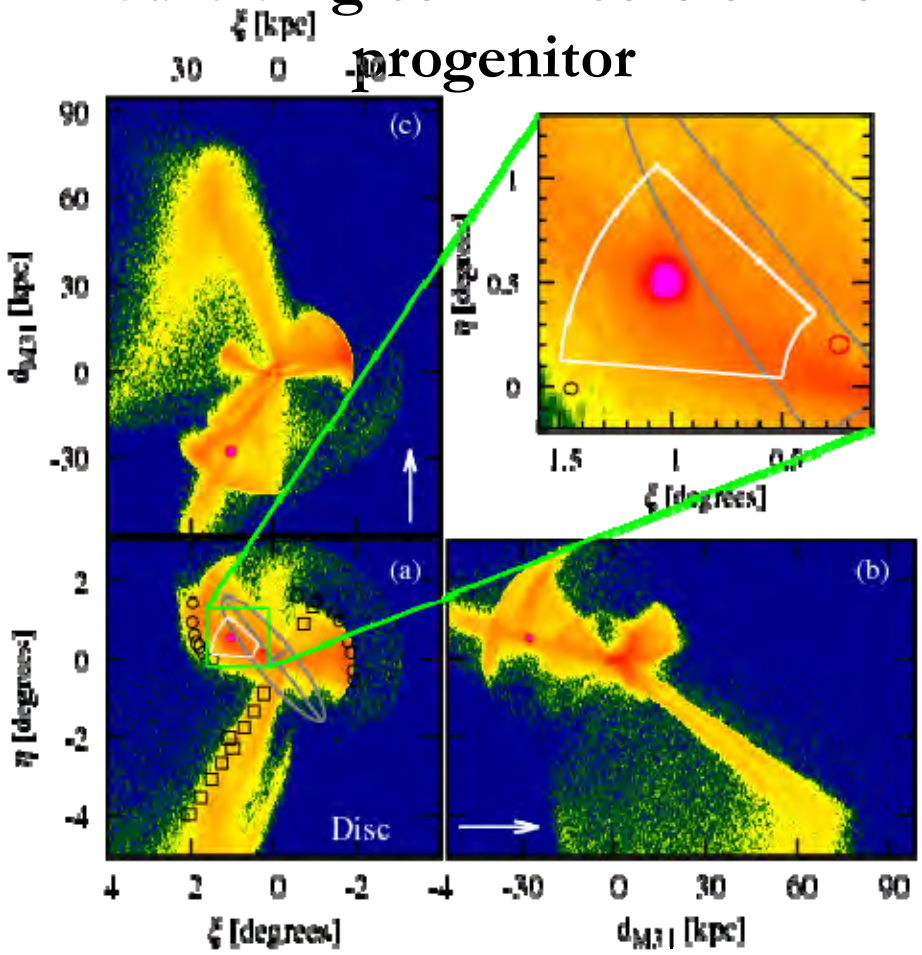
Wandering SMBH



Miki et al. 2014

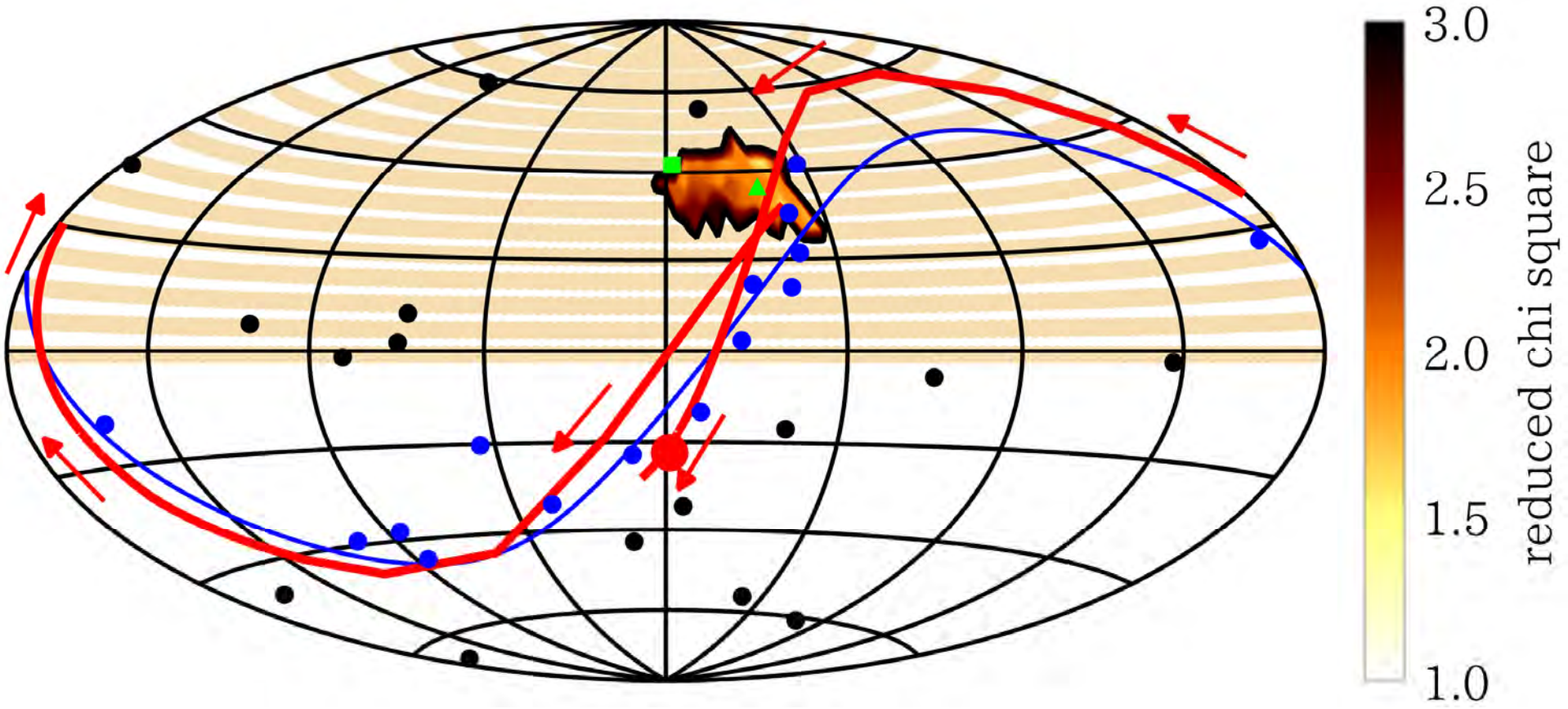
See also Kawaguchi et al. 2014

Surviving central core of the progenitor



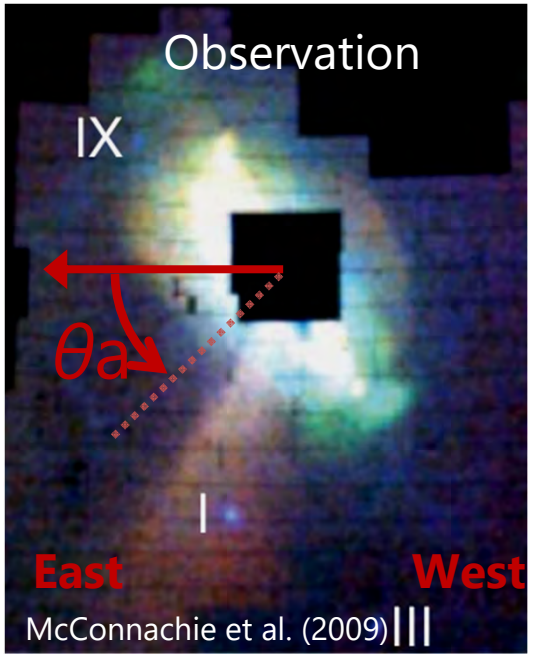
The position does not depend on the progenitor's morpholog

Sky map from M31

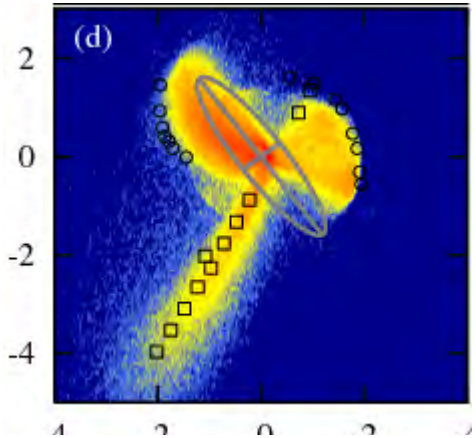


Miki, Mori, Kawaguchi & Saito, 2014, Astrophysical Journal, 783, 87

Asymmetric surface brightness profile of the Andromeda Giant Stream

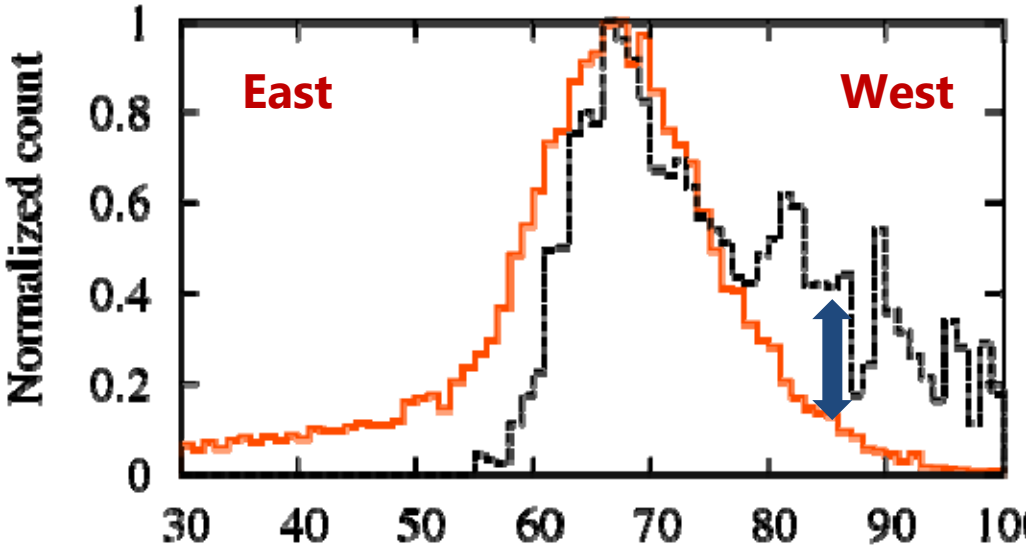


spherical dwarf galaxy



Kirihara, Miki & Mori, submitted to MNRAS

Azimuthal surface brightness(SB) profile of the GSS



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:

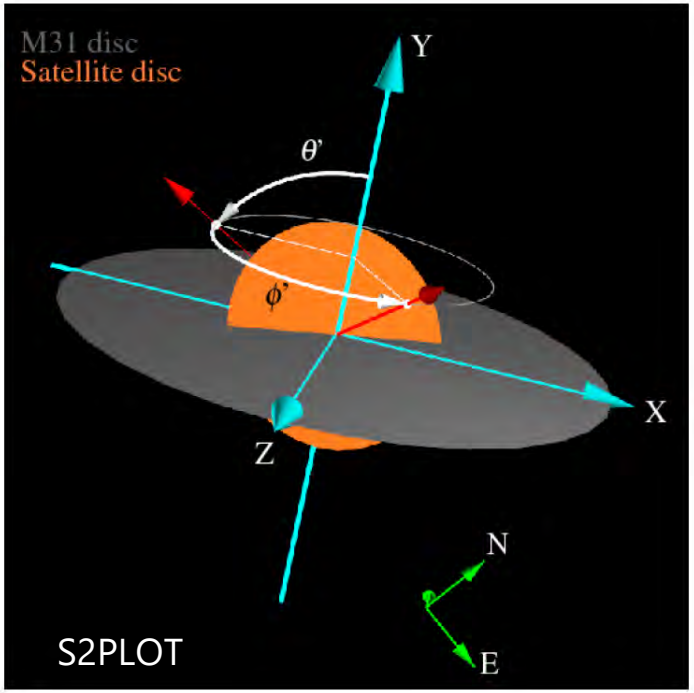
DM $4\times10^{9}M_{\odot}$

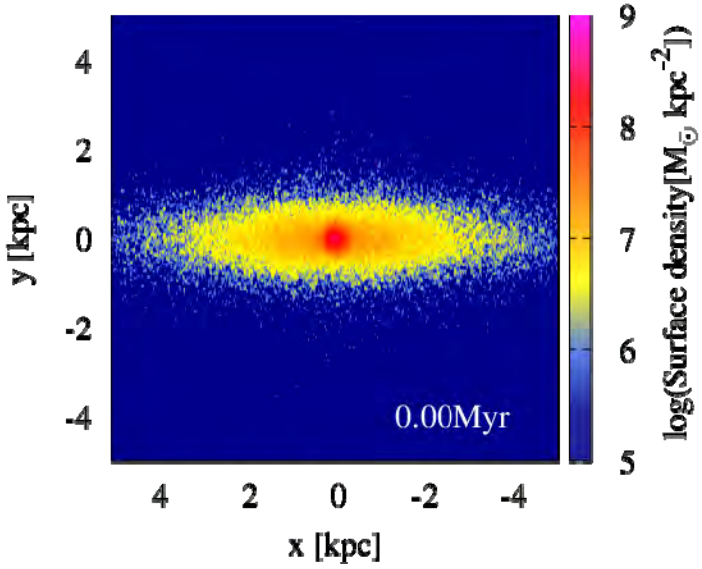
Disk $7\times10^{8}M_{\odot}$

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

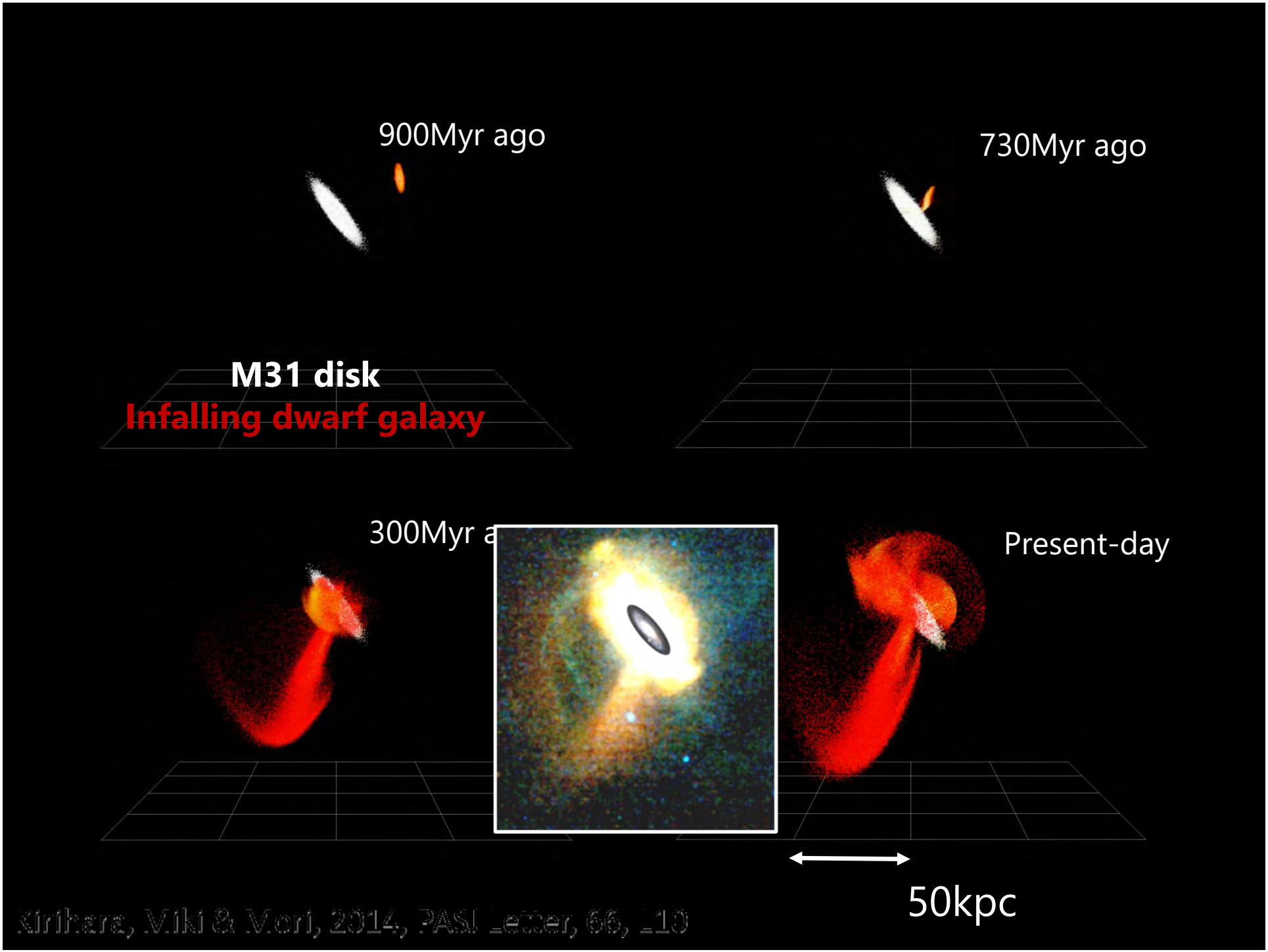
$N\sim 2\times10^{5}$(stellar: $N\sim 5\times10^{4}$)

Kuijken & Dubinski 1995,
Widrow et al. 2003



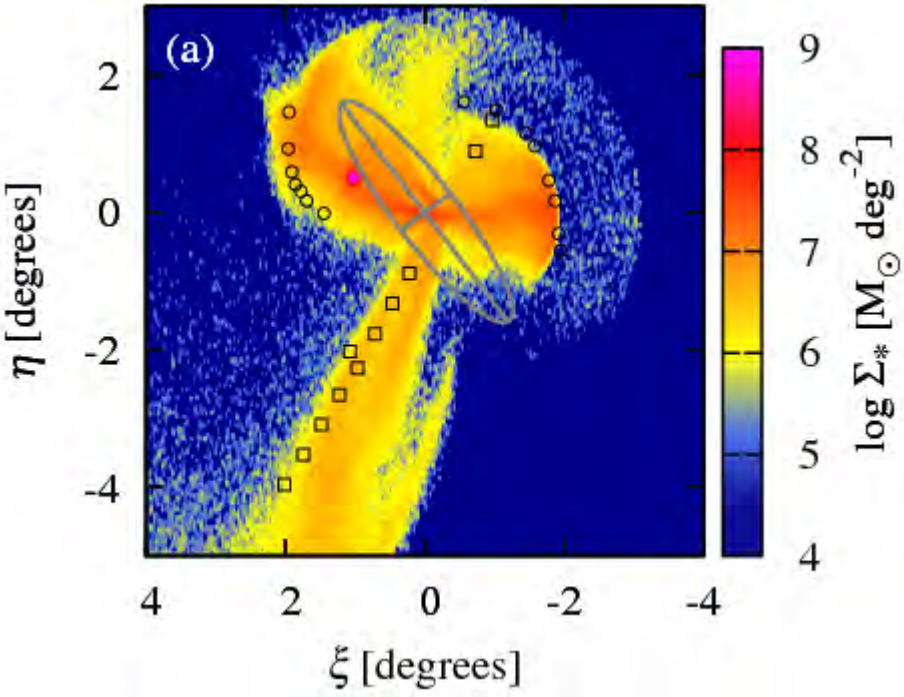


Orbit：Fardal et al. (2007)
Self-gravitation：Tree method（θ=0.6）
on T2K-Tsukuba, HA-PACS, COMA

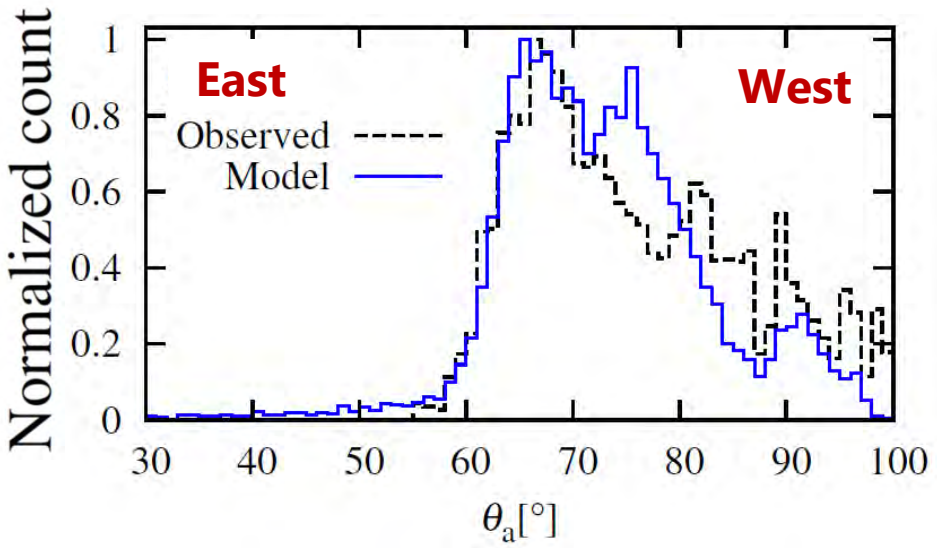

900Myr ago
730Myr ago
M31 disk
Infalling dwarf galaxy
300Myr a
Present-day
50kpc
Kirihara, Miki & Mori, 2014, PASJ Letter, 66, L10

Successful model

A case with a thick disk progenitor



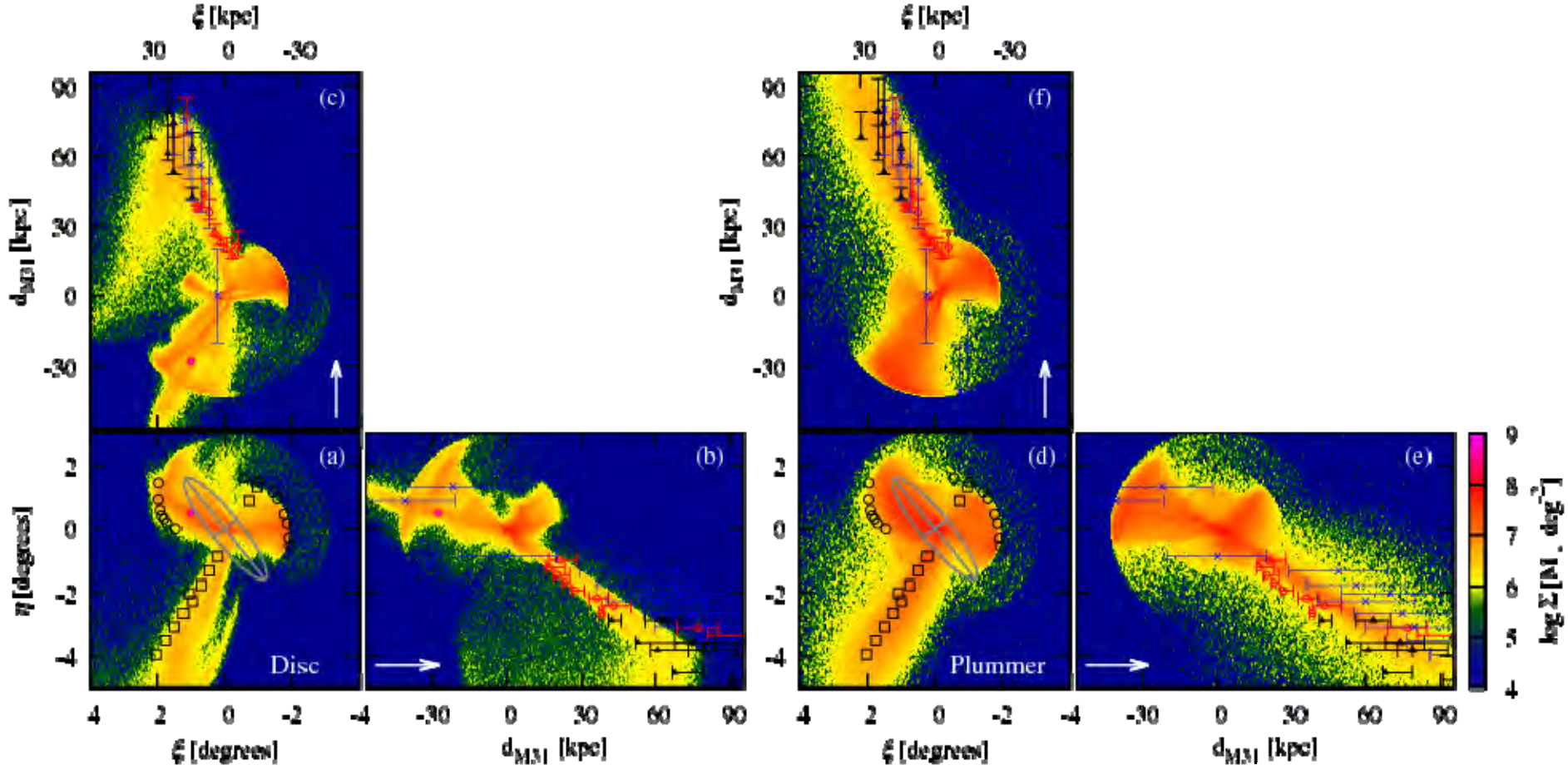
Azimuthal SB profile of the GSS



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, Miki, Mori, & Kawaguchi, submitted

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.