Hunting a Wandering Supermassive Black Hole in M31 Halo Hermitage using GPU Cluster

(YM, Mori, Kawaguchi, Saito, 2014, ApJ, 783, 87)

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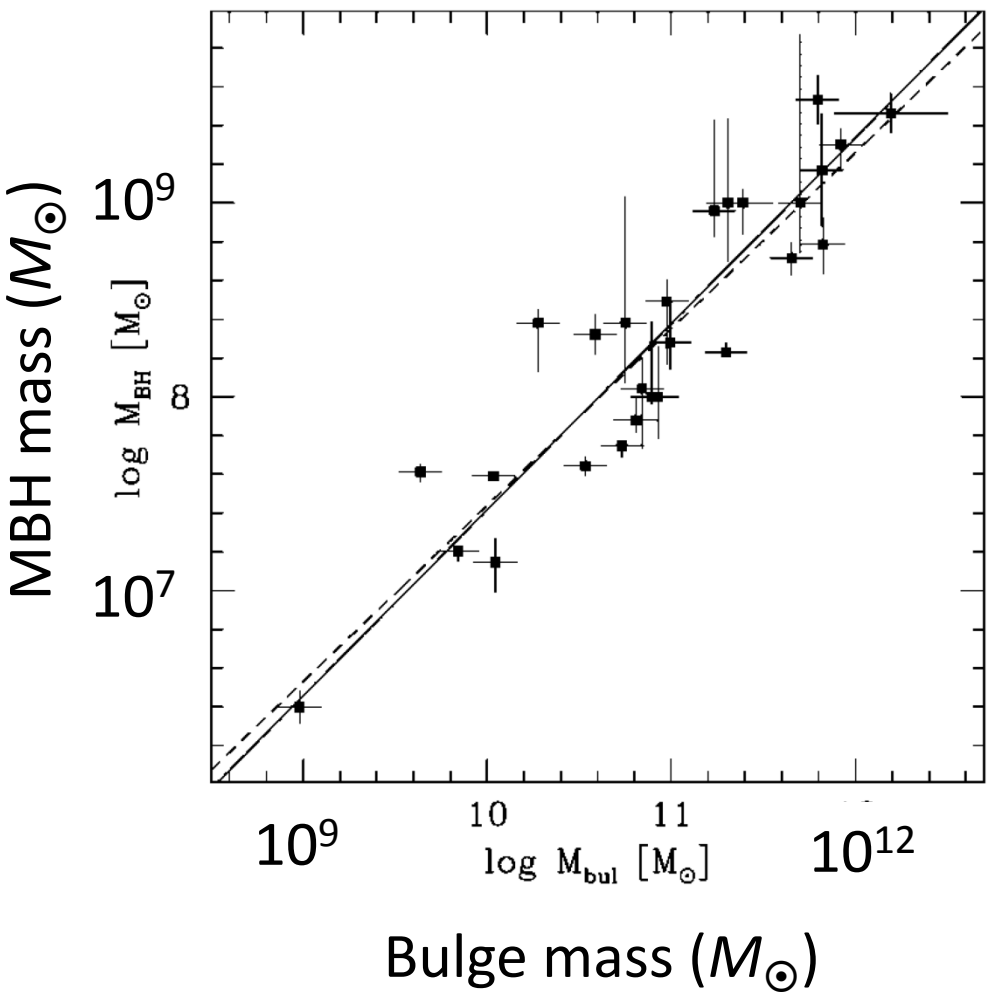
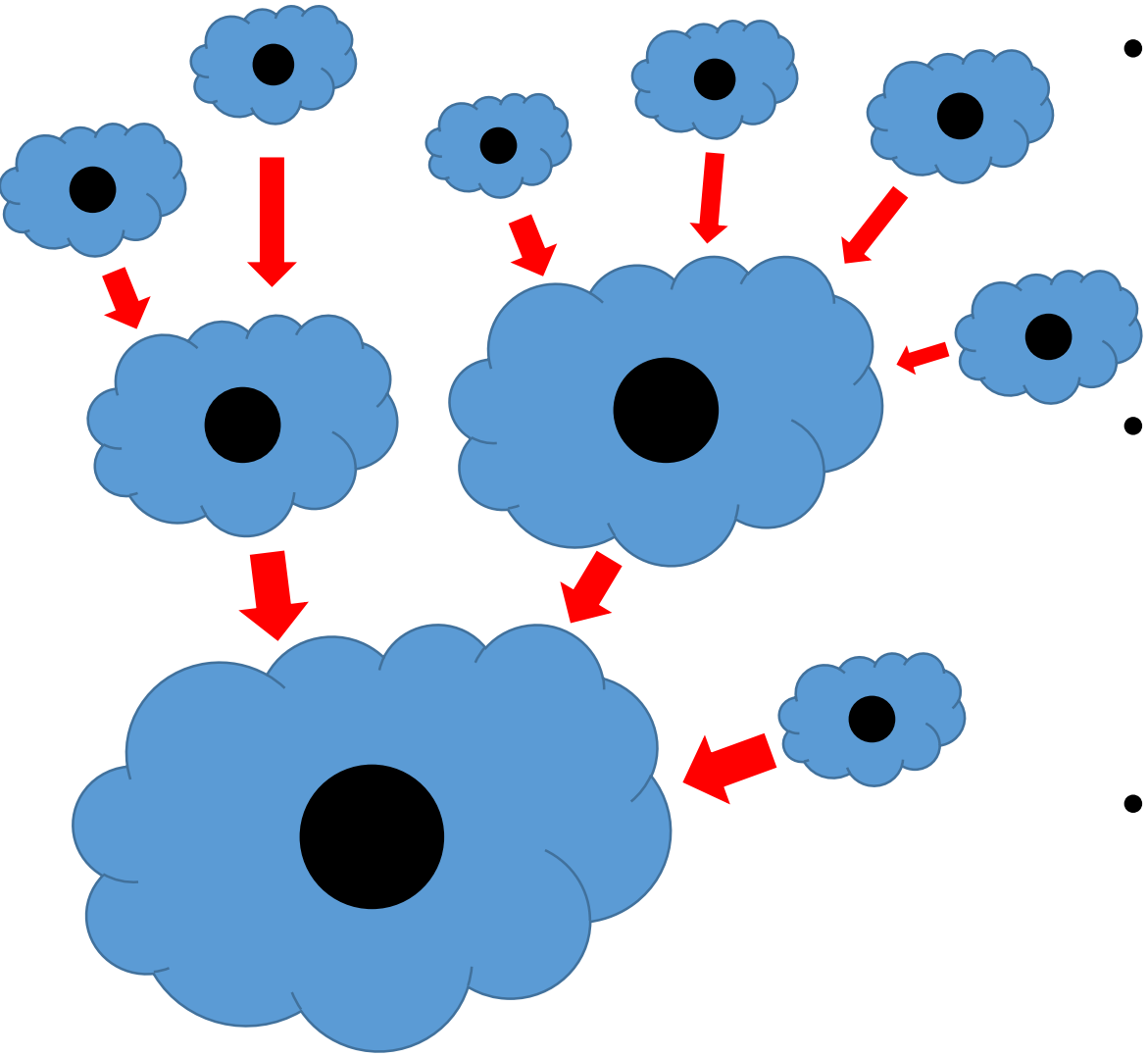
Introduction: Magorrian relation

Marconi & Hunt (2003)



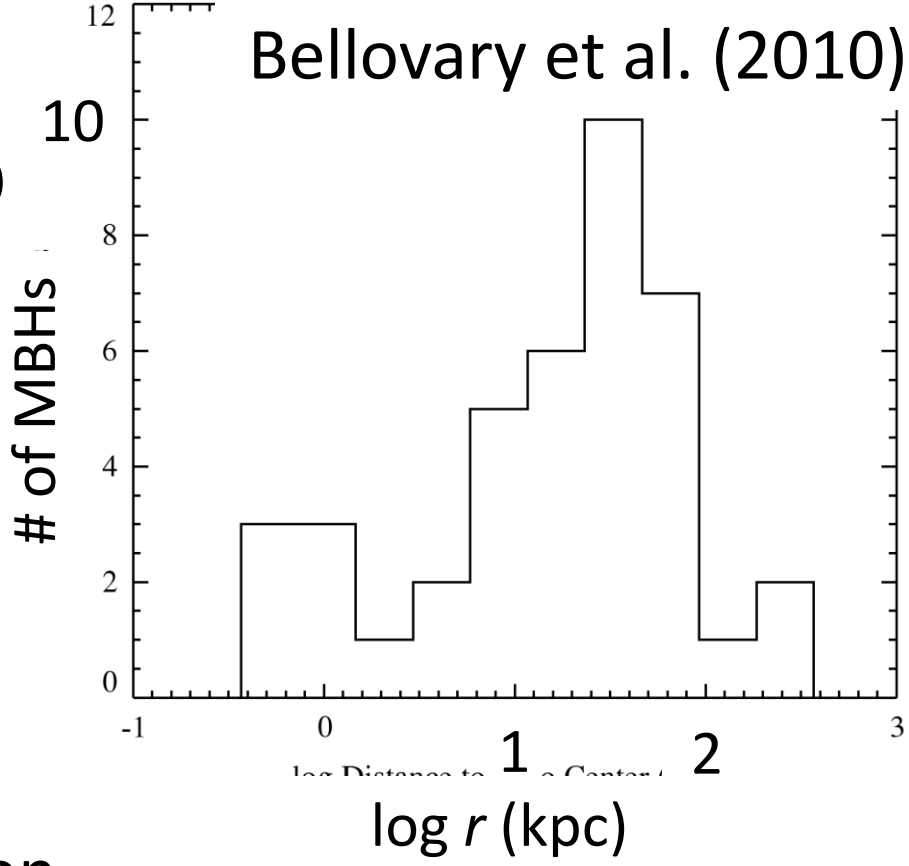
- Galaxies host massive black holes (MBHs; 10^6-10^9 $M_\odot$) in their central region.
- $M_{BH} \sim 0.002 M_{bulge}$
- The formation and evolution process of the MBHs has not yet well understood.
  - Gas accretion
  - Merger of MBHs

Hierarchical structure formation



- In a cold dark matter universe, large galaxies have enlarged through multiple mergers with smaller galaxies.
- MBHs finally sink toward the central region of the host galaxy under dynamical friction.
- If MBHs in the galactic center also merge, the relation $M_{\mathrm{BH}} \propto M_{\mathrm{bulge}}$ is held.

MBHs in galactic halo

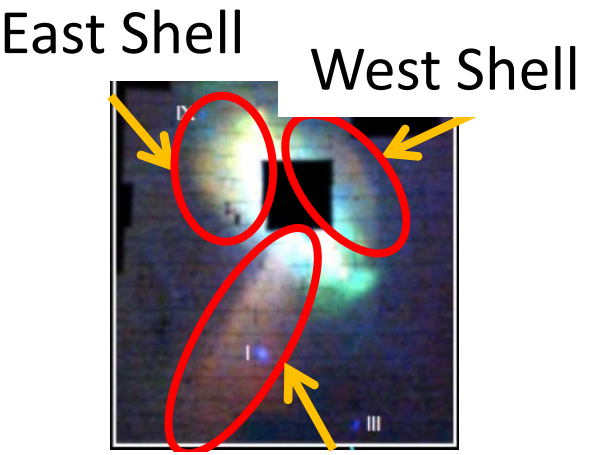


- MW like galaxies would host 5—15 MBHs within their halos.
  - However, such MBHs have not yet been confirmed by observations.
- Prediction of the MBH position helps future observational detection of the wandering MBHs in galactic halos.
  - We simultaneously track the orbit of the MBH and reproduce observed merger remnants using *N*-body simulation.
  - We can predict the current location of wandering MBHs.
  - Giant stellar stream in M31 is a suitable object.

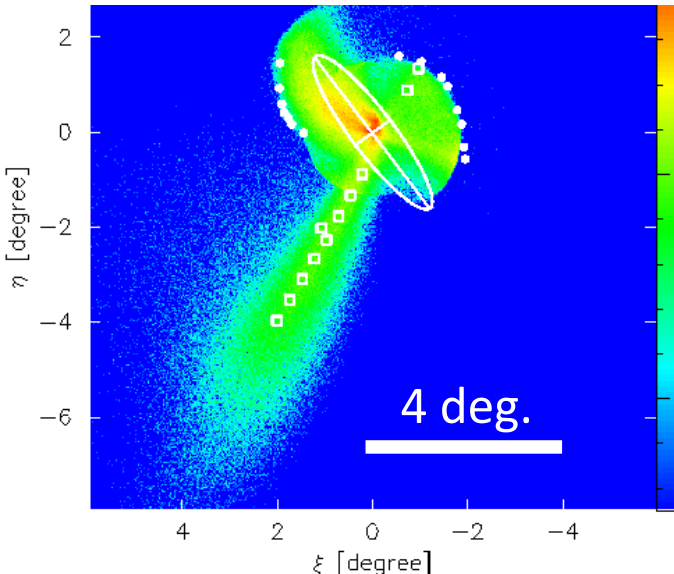
Merger remnants in the M31 halo

- Observed structures (stream, shells: Ibata et al. 2001; McConnachie et al. 2009) are the merger remnant of a tidally-disrupted dwarf galaxy about 1 Gyr ago (Fardal et al. 2007; Mori & Rich 2008).
- The dynamical mass or the infalling satellite is $\sim 10^9\ M_\odot$.
  - The progenitor likely has an MBH whose mass is 10^5 -$10^6\ M_\odot$ (Magorrian relation).
  - The most uncertainty of the MBH position is caused by uncertainty about the infalling orbit of the satellite.

McConnachie et al. (2009)



Giant Stellar Stream

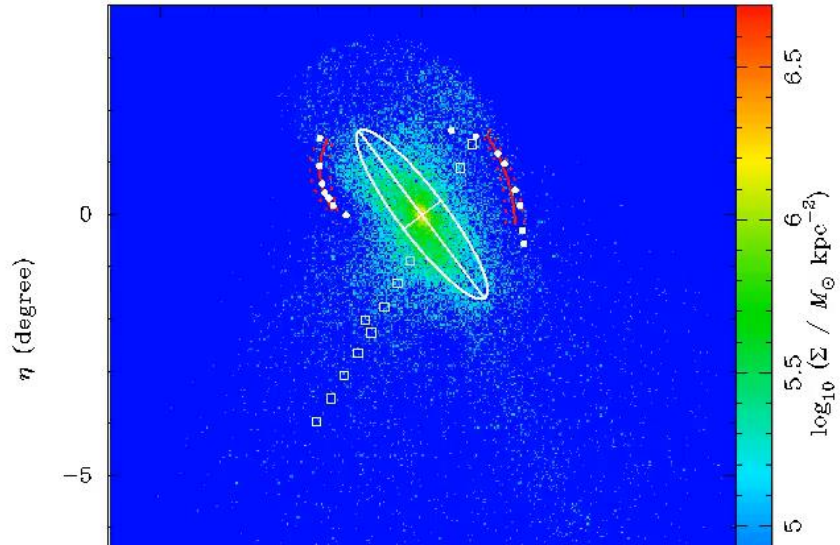


Parameter study for infalling orbit

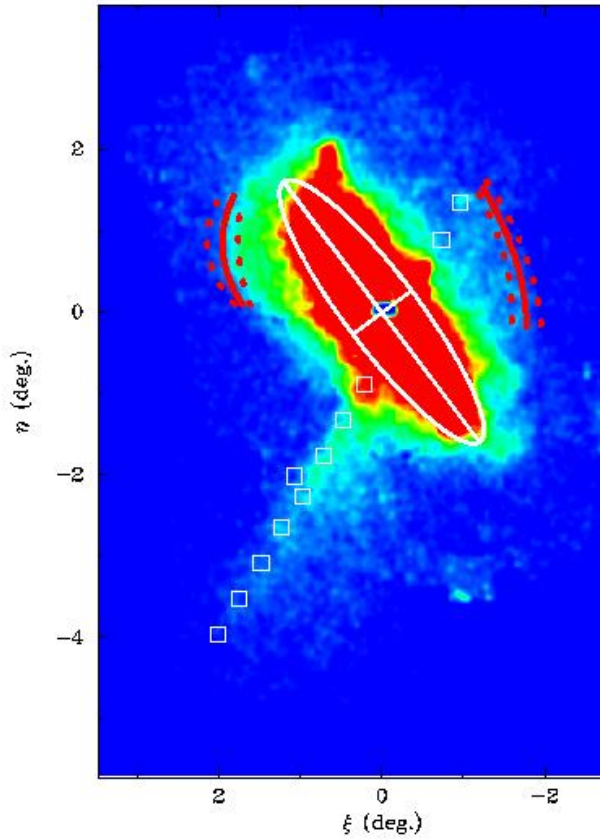
- To determine the observational field for the future observational detection of the MBH,
  we must evaluate the uncertainty about the orbit.
- The number of dimension is four (= 6 - 2).
  - Fix the initial distance from the M31 center.
  - M31 is modeled as an axisymmetric system.
- We have utilized HA-PACS, a GPU cluster.
  - A fast *N*-body code based on CUDA (YM+12, 13).
  - ～1,000 runs/day @ N = 65,536 using 128GPUs.

Criterion for on-the-fly analysis

- Is the stream reproduced?
  - Position of the stream.
- Are the shells reproduced?
  - Shapes and positions of the shells.
- Is the contrast among the stream and two shells reproduced?

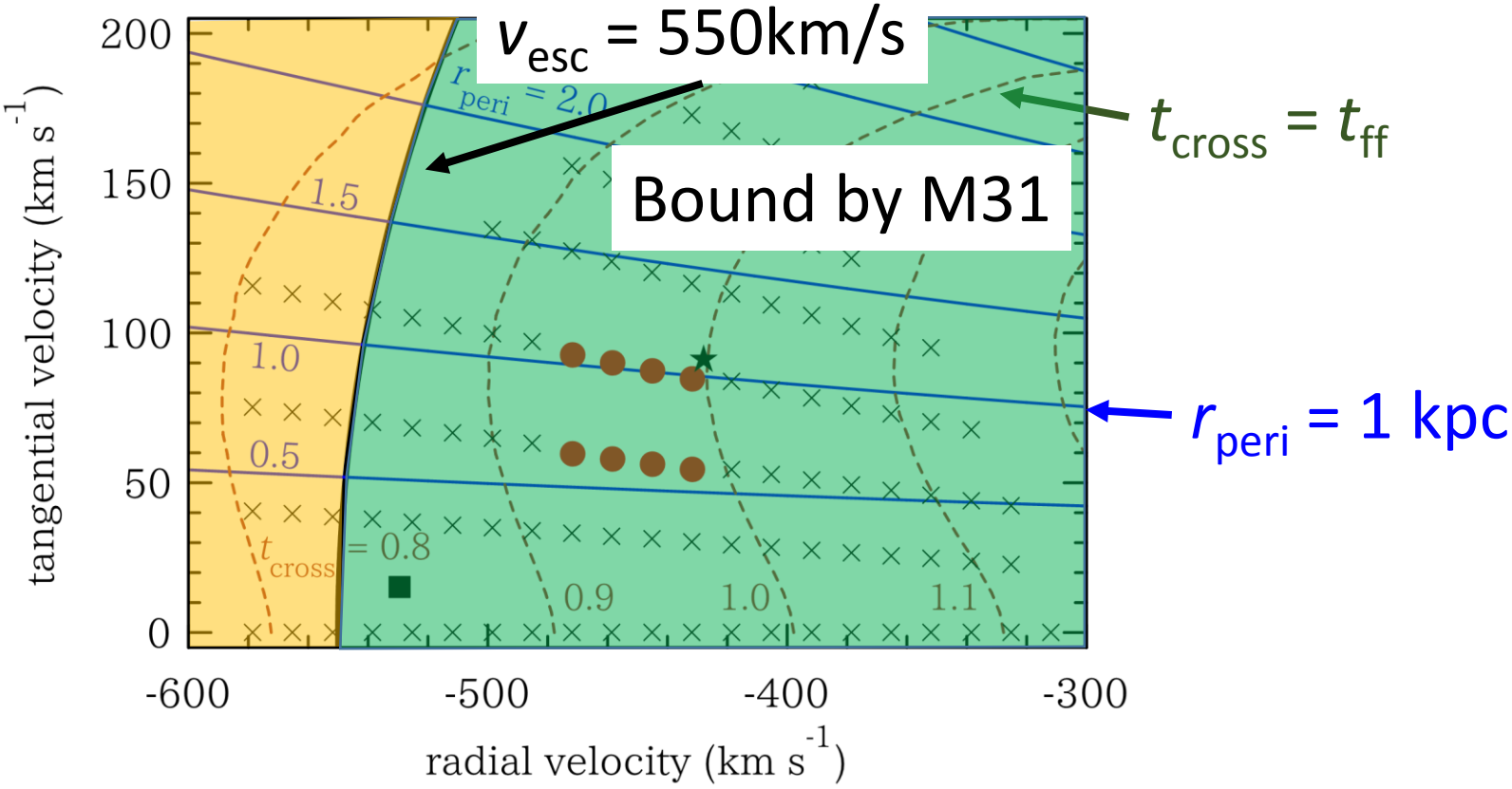


Made from
Irwin et al. (2005)



Results of the parameter study (1/2)

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



Results of the parameter study (2/2)

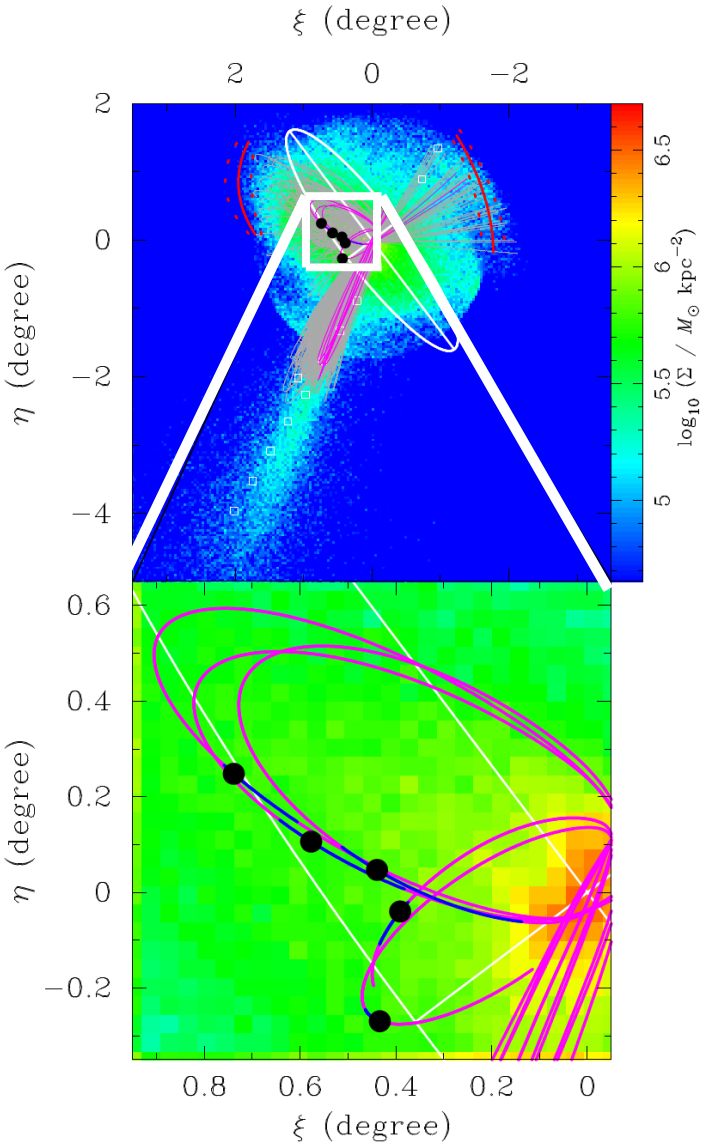
- Periapsis distance is about 1 kpc.
  - Tidal forces exerted by the bulge of M31 stretch and disrupt the infalling satellite.
  - It is the first collision between M31 and the satellite.
- $t_{\rm cross} \sim t_{\rm ff} = 15$ Myr
- The infall velocity is slower than $v_{\rm esc}$ ~550 km/s.
  - The satellite was bound by M31.
- A new mystery: the collision that occurred several hundred megayears ago should have been the first collision of the infalling satellite.

MBH hosted by the satellite

- The dynamical mass of the satellite is $\sim 10^9\,M_\odot$.
  - The Magorrian relation suggests the presence of an MBH whose mass is $10^{5\text{-}6}\,M_\odot$.
- We can predict the current position of the MBH by calculating the orbital evolution of an MBH particle.
- Re-simulation of time evolution of the satellite (M=3 × $10^9\,M_\odot$, r_t = 4.5 kpc, c = 0.7) and an additional MBH particle (M_{BH}=3 × $10^6\,M_\odot$).
  - N = 524,288 + 1
  - M_{BH}:M_{fs} ∼ 500:1

Current position of the MBH

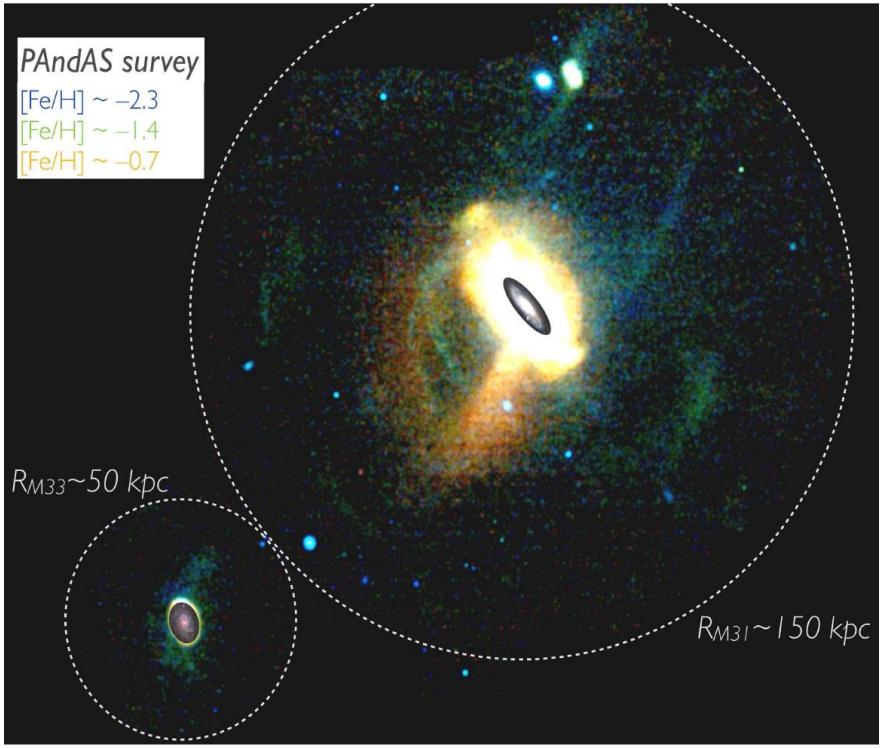
- Five orbit models reproduce the observed structures.
- The predicted positions of the MBH are confined to a small region.
  - An observational field of $0.6^\circ \times 0.7^\circ$ sufficiently covers the predicted area.
- The distance from the M31 center is 20-40 kpc.
  - The MBH locates in the M31 halo, not in the M31 center.



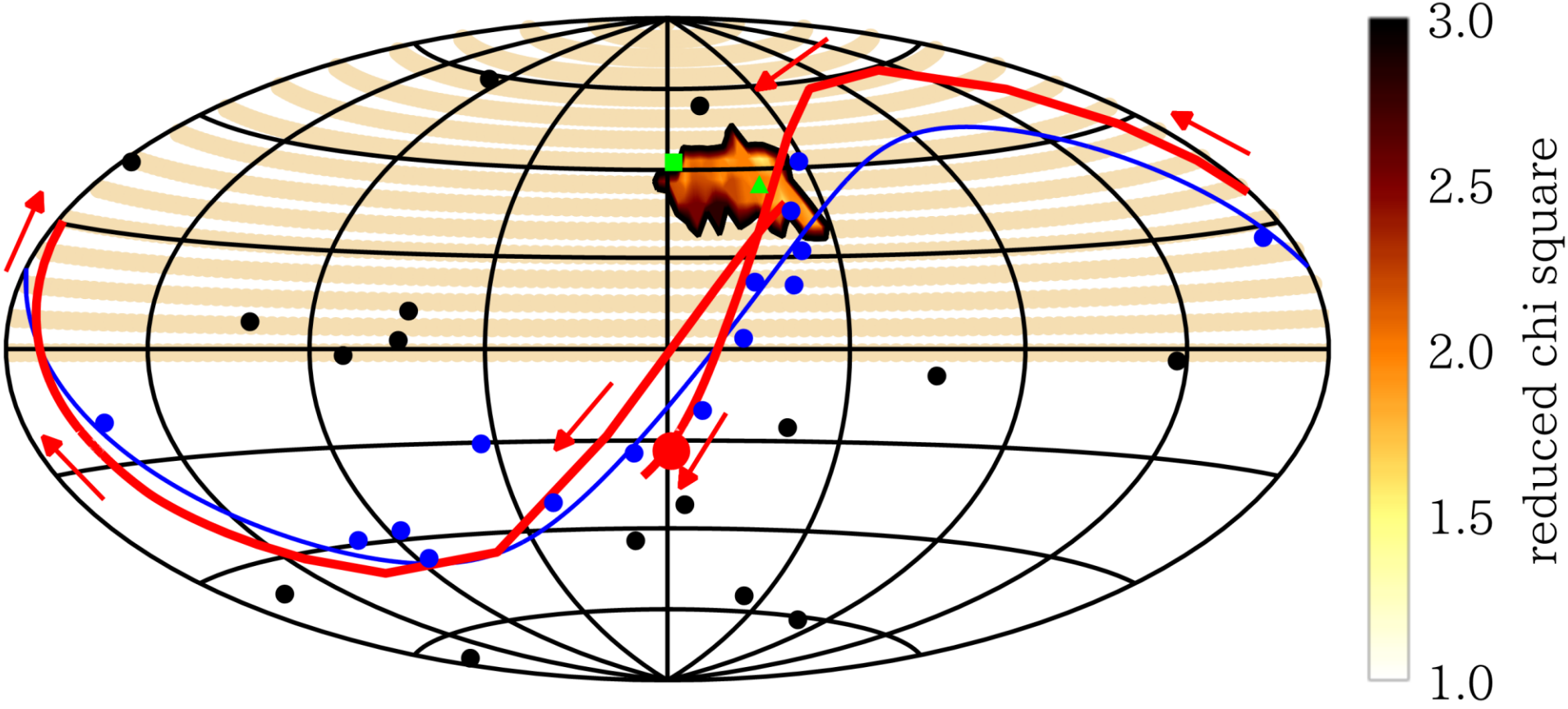
Pan-Andromeda Archaeological Survey

- Photometric survey around M31.
- A few tens of satellites.
  - The distance, radial velocity, and velocity dispersion have been already measured.
  - Conn+12, Collins+13
- Discovery of a disk-like structure of satellite galaxies.
  （Ibata+13, Conn+13）

Martin et al. (2013)

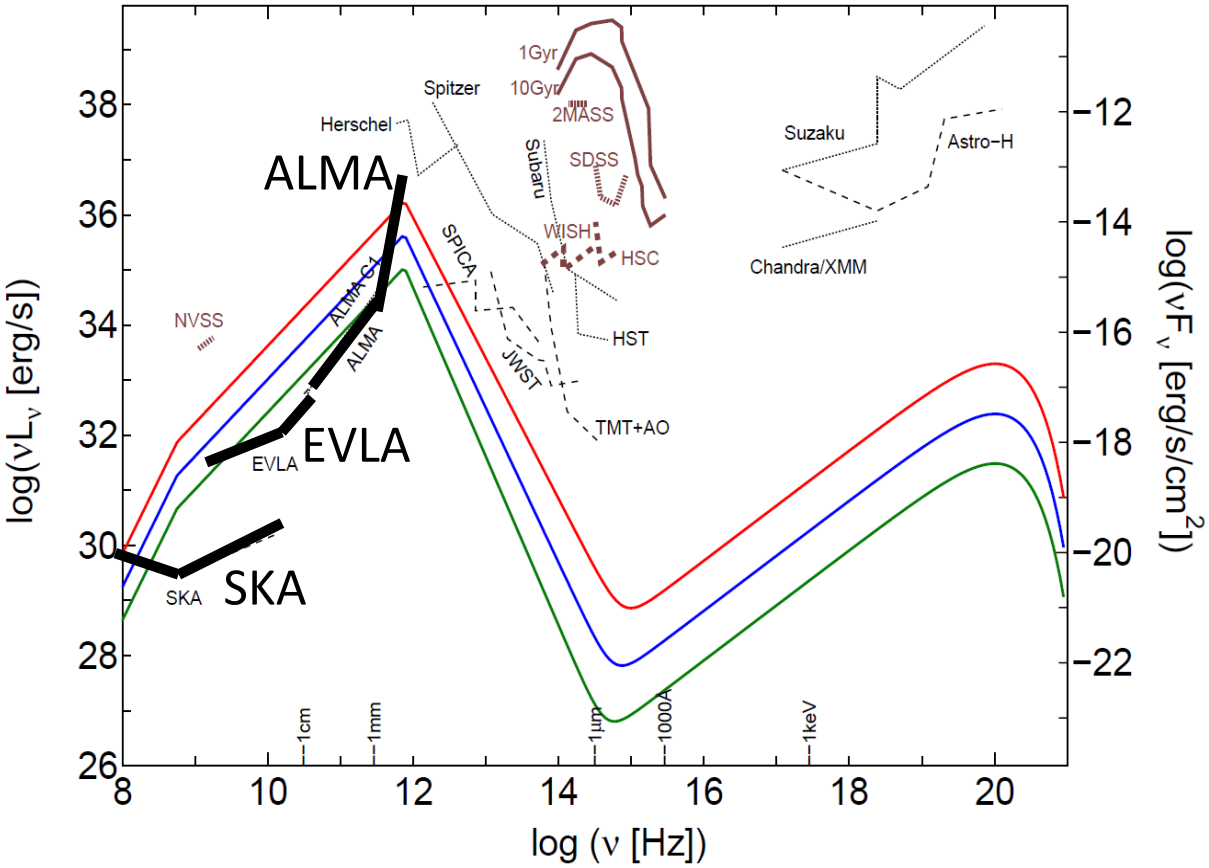


Sky map from M31



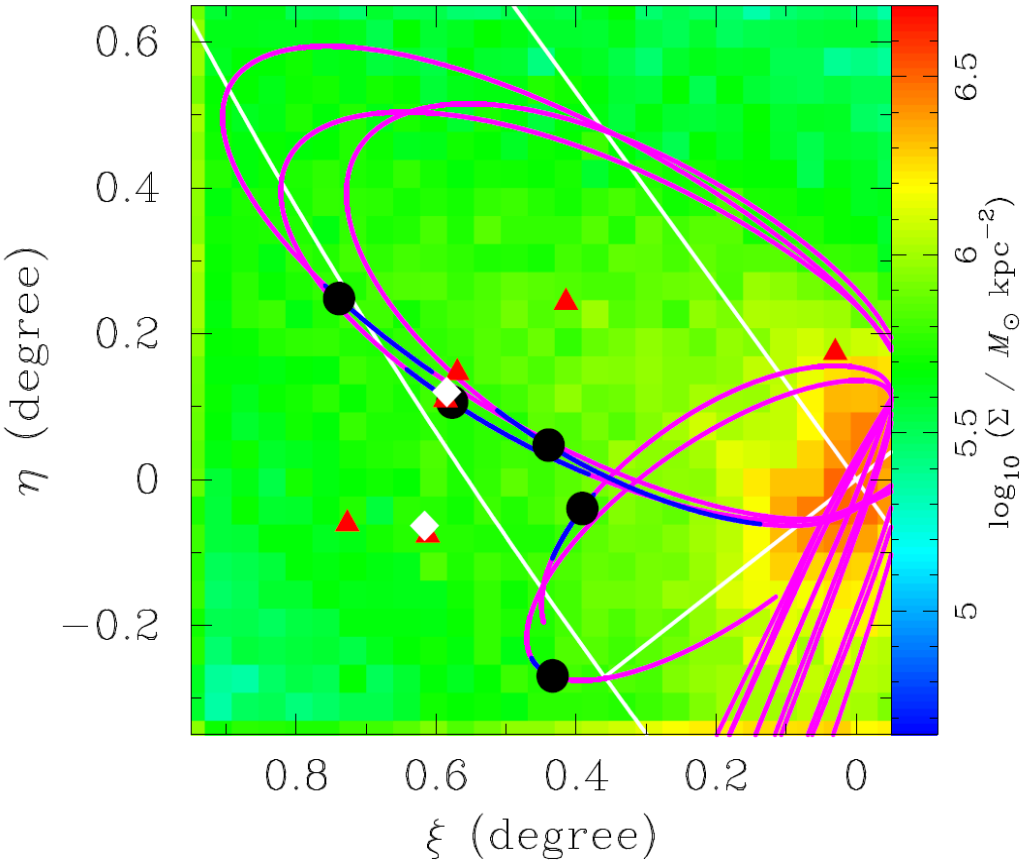
Discussion: expected spectrum from the wandering MBH in the M31 halo

- The MBH is detectable in the radio band.
  （Kawaguchi, Saito, YM, Mori, 2014, ApJL, 789, L13）



Have we already observed the wandering MBH ?

- Comparison between the predicted locations of the MBH and distribution of observed polarized radio sources.
  （Han+98, Giessuebel +13）
- Some radio sources locate near the predicted area.
  - A new possibility: we have already observed the wandering MBHs; however, we does not notice the fact.



Summary

- We have investigated the current likely positions of the wandering MBH in the M31 halo.
  - We performed a numerous parameter survey using GPUs to constrain the infalling orbit of the satellite.
  - About 5,700,000 orbit models were examined.
- The results show:
  - The MBH lies within the M31 halo, closer to the Milky Way than the M31 disk.
  - An observational field of $0.6^\circ \times 0.7^\circ$ sufficiently covers the predicted current positions of the MBH.
  - Current operating facilities such as EVLA and ALMA have enough sensitivities to detect the signal from the MBH.