Relics of Galaxy Merging: Observational Predictions for a Wandering Massive Black Hole and Accompanying Star Cluster in the M31 Halo

Toshihiro KAWAGUCHI
(NAOJ, Astronomical Data Center)

Keywords: Floating massive black holes,
Trailing star clusters

References:

(A) SMBH Evolution via galactic merging in Andromeda:

- Miki, Mori, Kawaguchi, Saito Y., 2014
- Kawaguchi, Saito Y., Miki, Mori, 2014

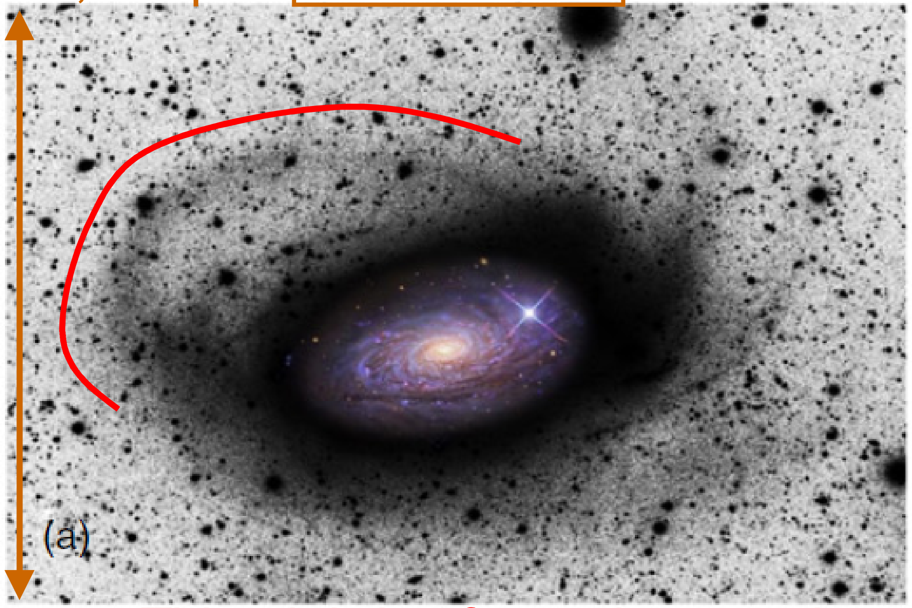
(B) Intermediate-mass BH (and surrounding stars)

- Godet, Plazolles, Kawaguchi et al. 2012

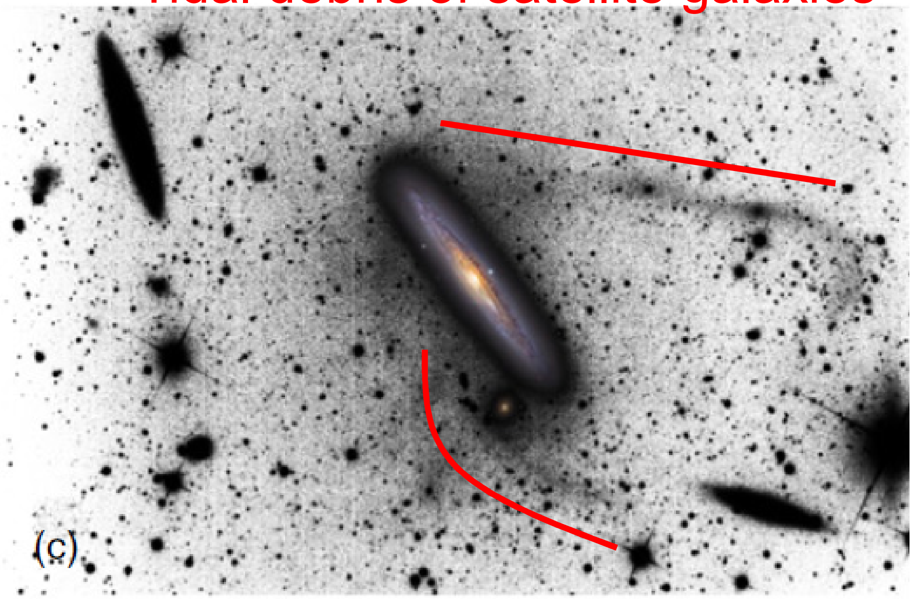
1. Evolution of galaxies via merging

Observation

27’, 65kpc



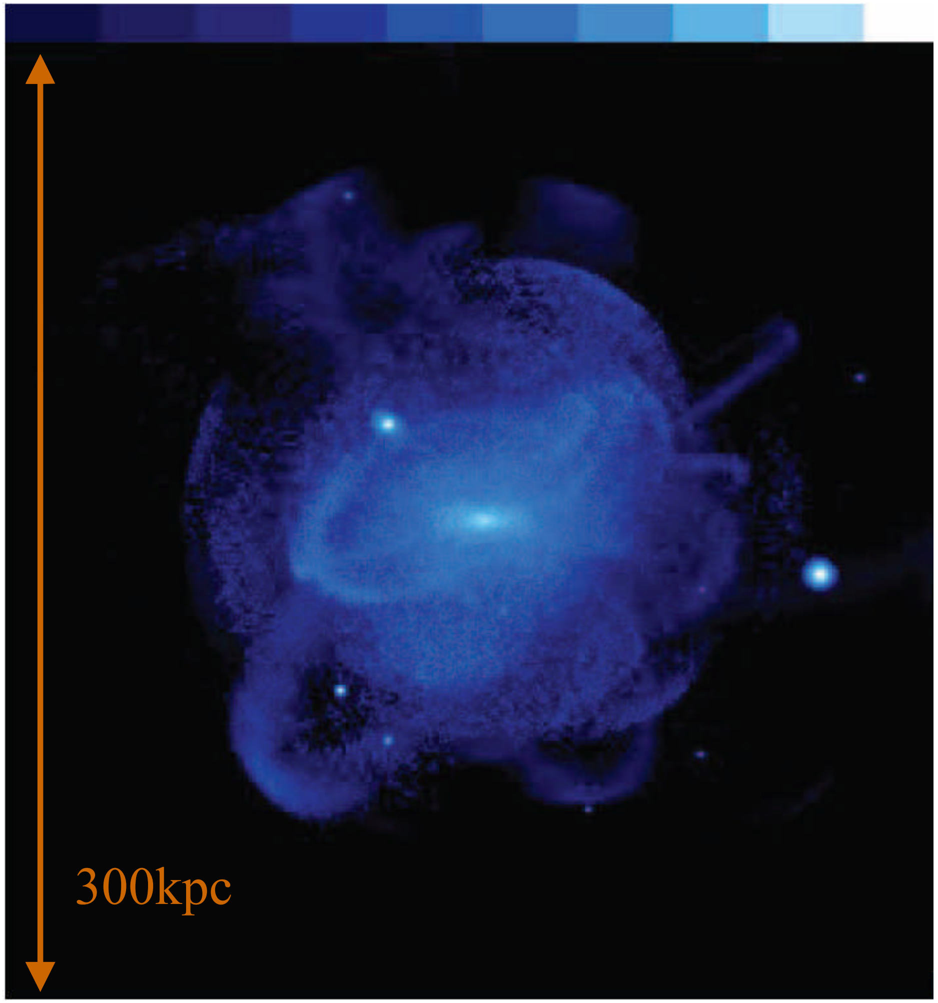
Tidal debris of satellite galaxies



Martinez-Delgado+2010

Theory

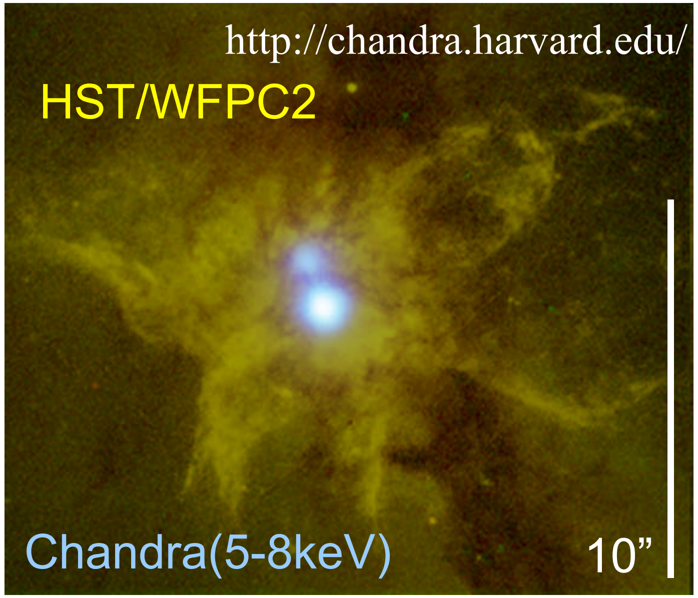
Stellar surface density



Bullock & Johnston 2005

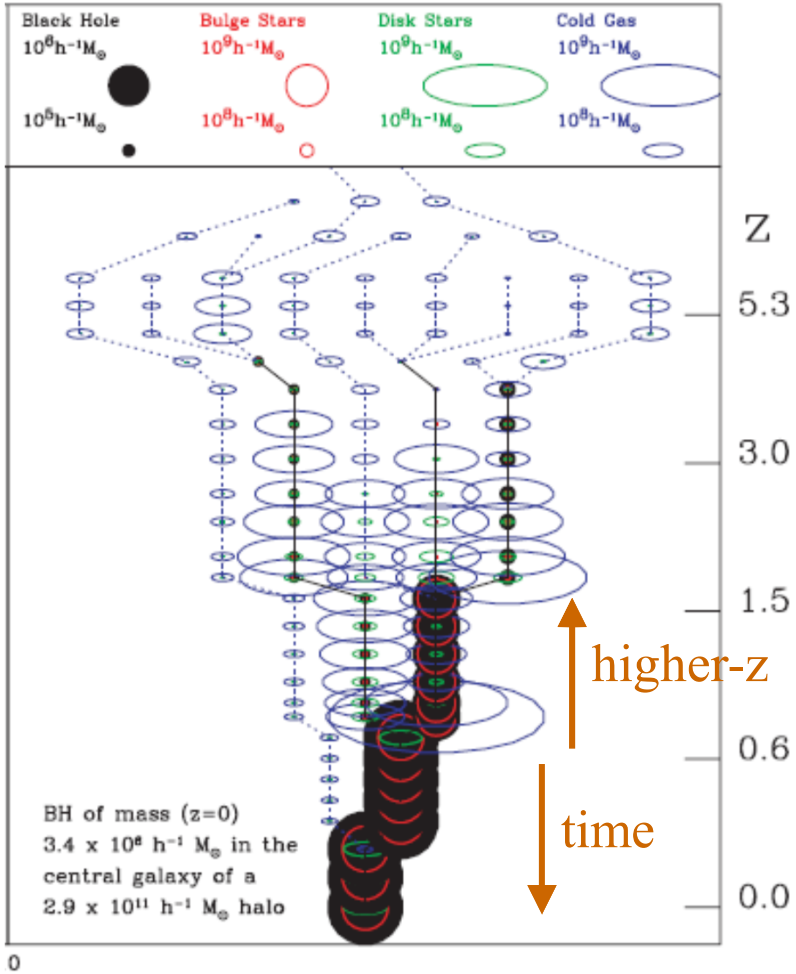
1. SMBH evolution and galaxy merging

- Multiple SMBHs in colliding galaxies: e.g., NGC6240 (Komossa+03)

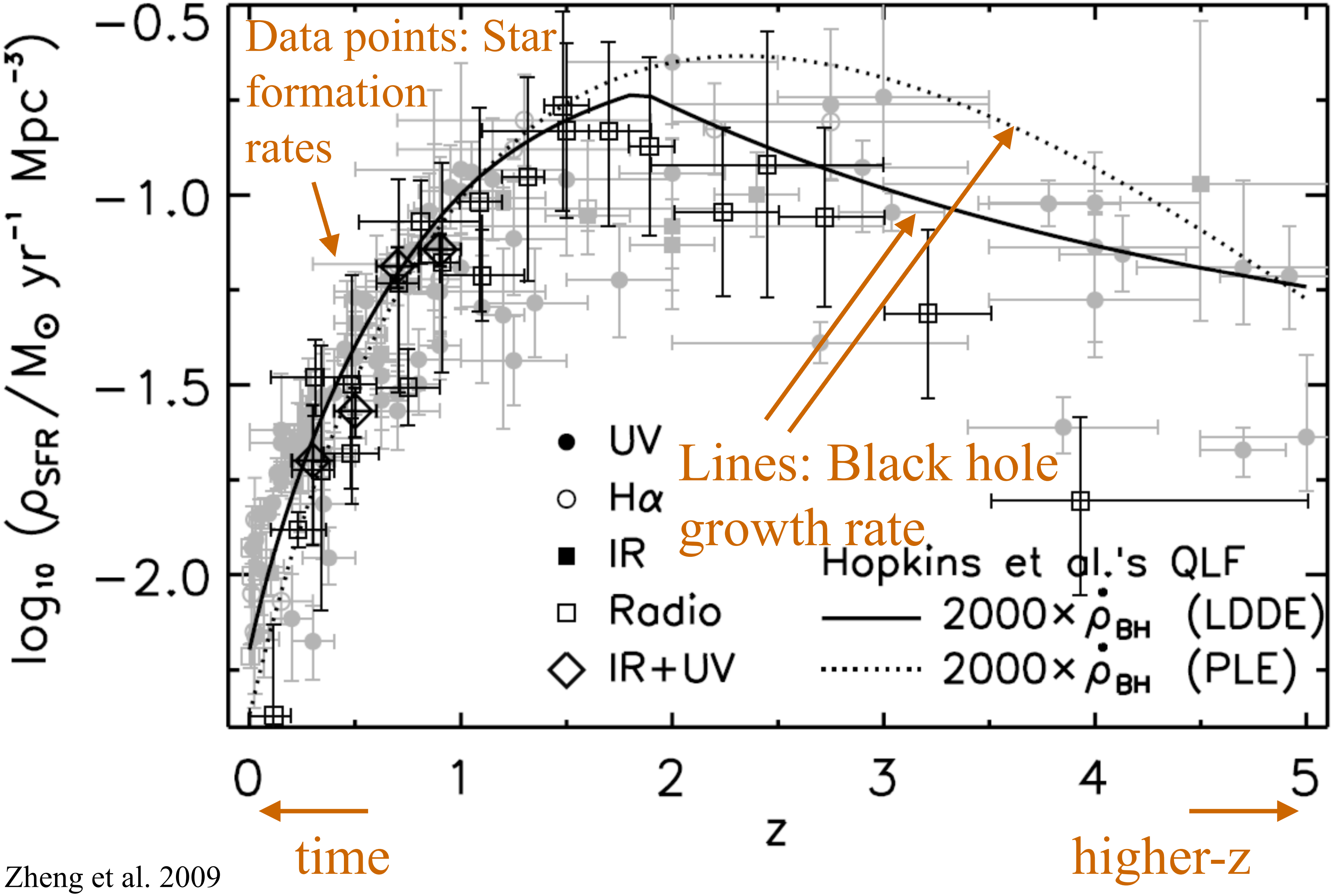


- Orbital motion of SMBH (Sudou+03)
- Double BLRs (Boroson+Bauer 09)

- Merging tree in a semi-analytical model (Malbon+07)



1. Coevolution of galaxies and massive BHs

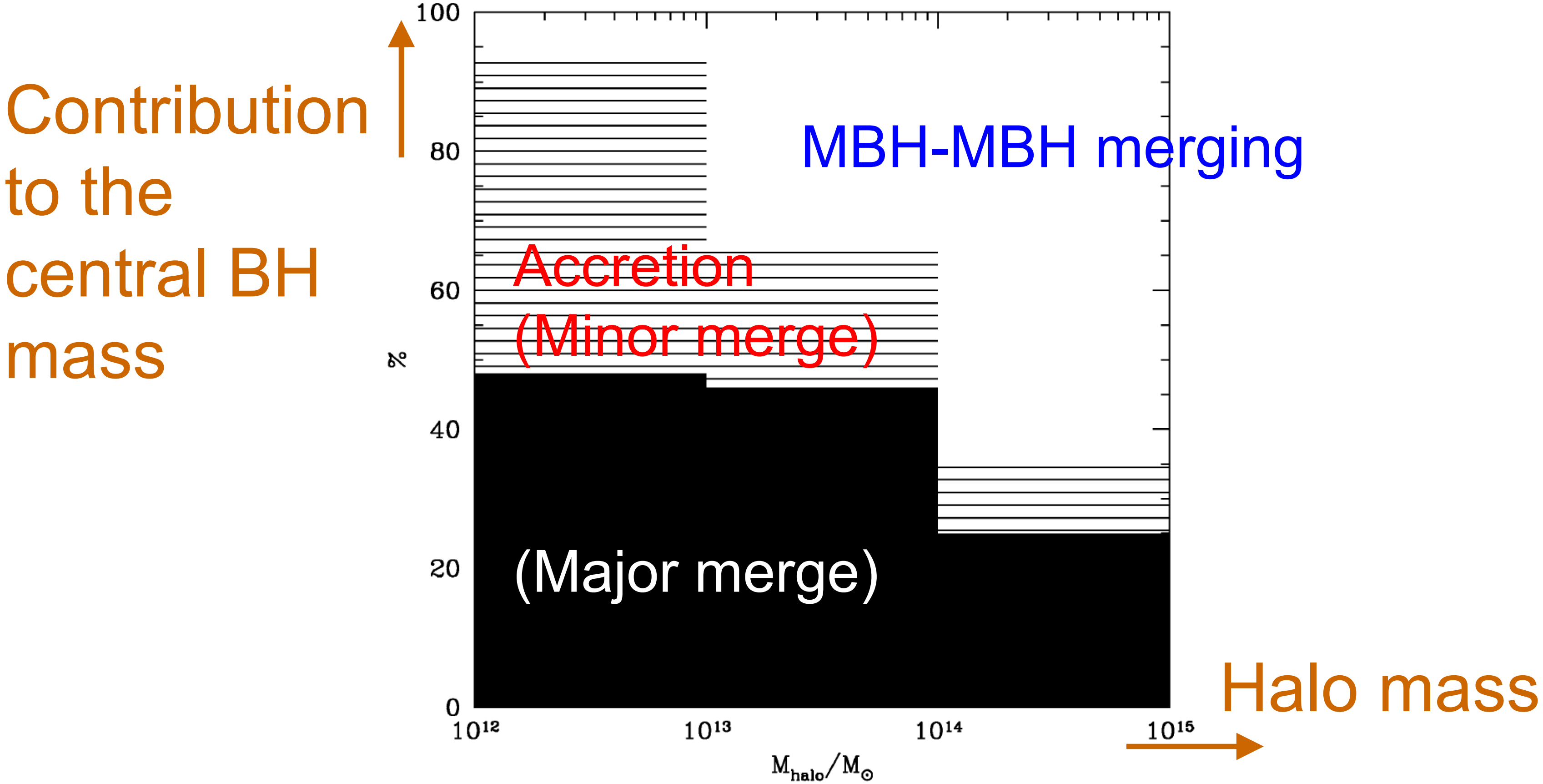


Zheng et al. 2009

1. Formation/growth of massive BHs: merging or accretion?

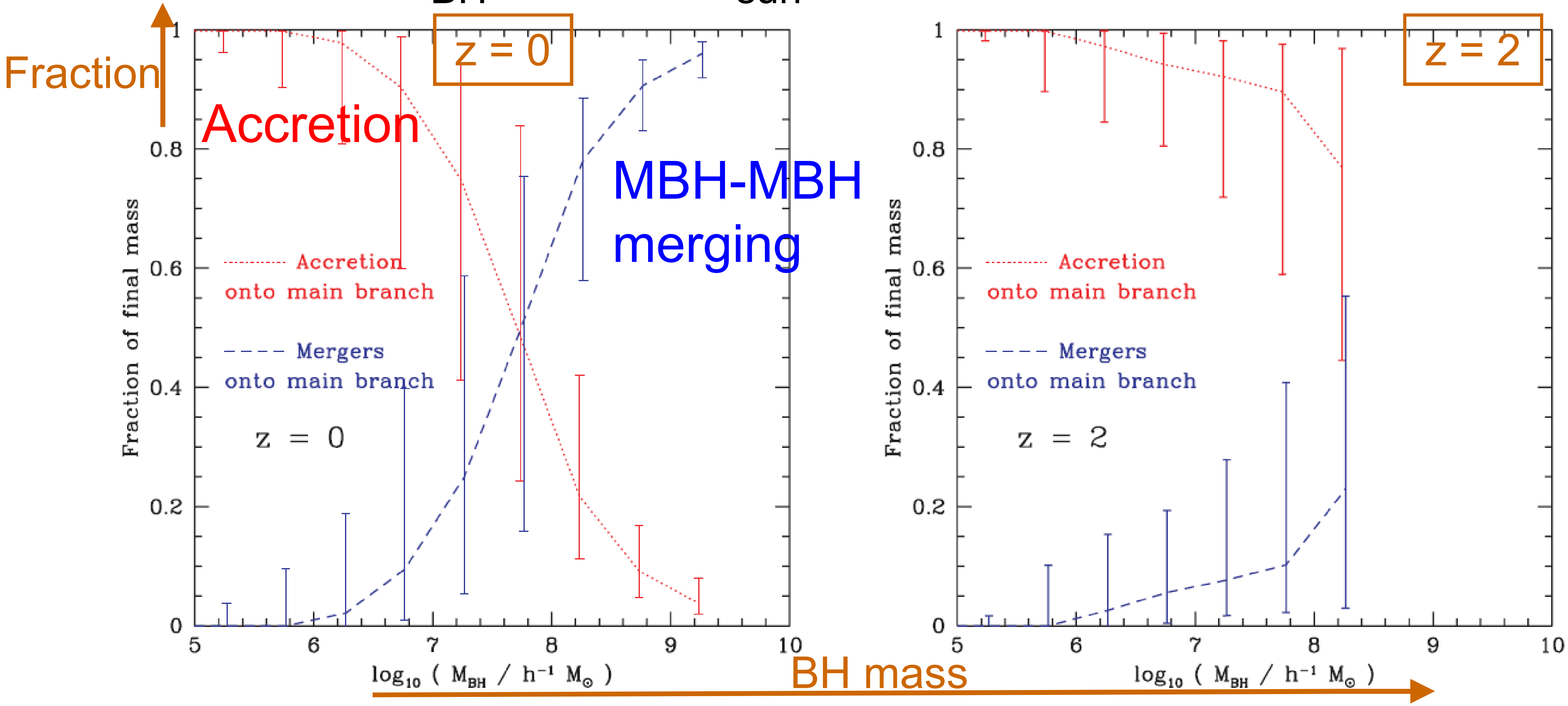
- MBH-MBH merging: important at low-z and high-M_{BH} ($\gtrsim 10^{7.5}\ M_{sun}$)

(Malbon+07; Cattaneo 02)



1. Formation/growth of massive BHs: merging or accretion?

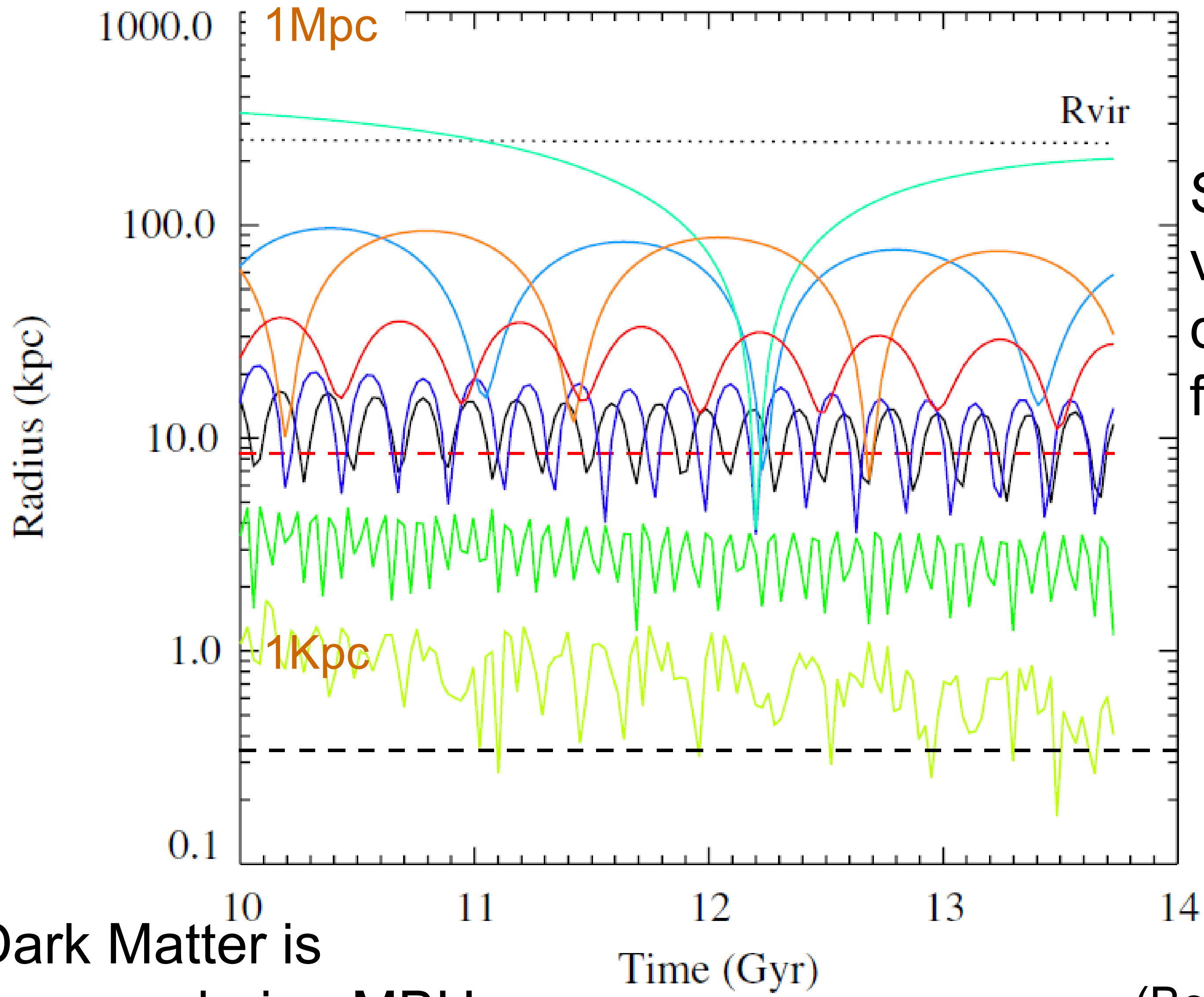
- MBH-MBH merging: important at low-z and high-M_{BH} ($\gtrsim 10^{7.5}\,M_{sun}$) (Malbon+07; Cattaneo 02)



- Super-Eddington accretion at high-z (Kawaguchi+04a)

1. Wandering BHs in galactic halos

Distance of massive BHs (satellites' central BHs) from the central galaxy



Sinking via dynamical friction

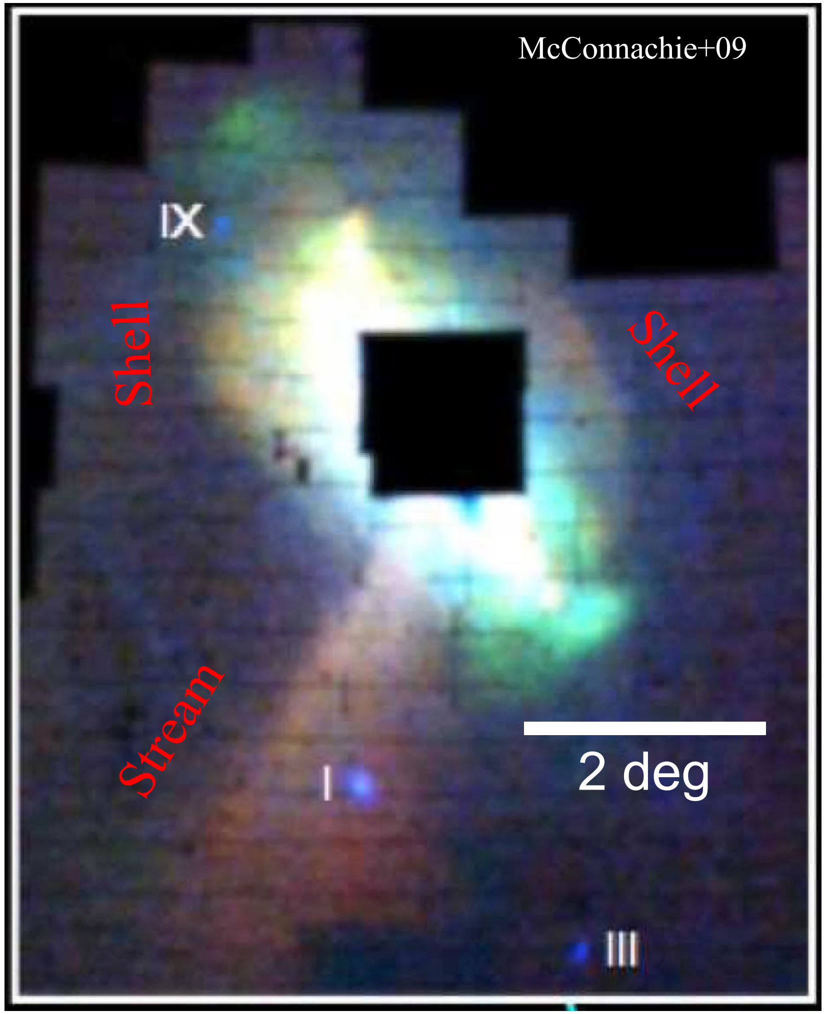
If Cold Dark Matter is true, many wandering MBHs.

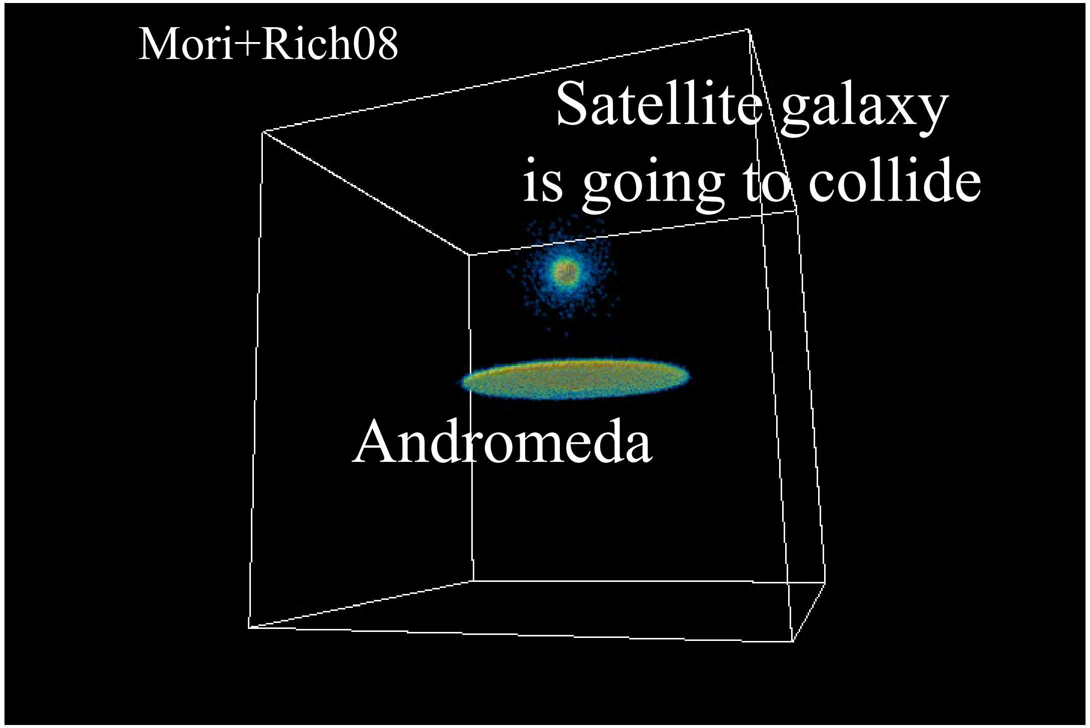
(Bellovary+10)

2. galaxy merging in M31 (Andromeda galaxy)

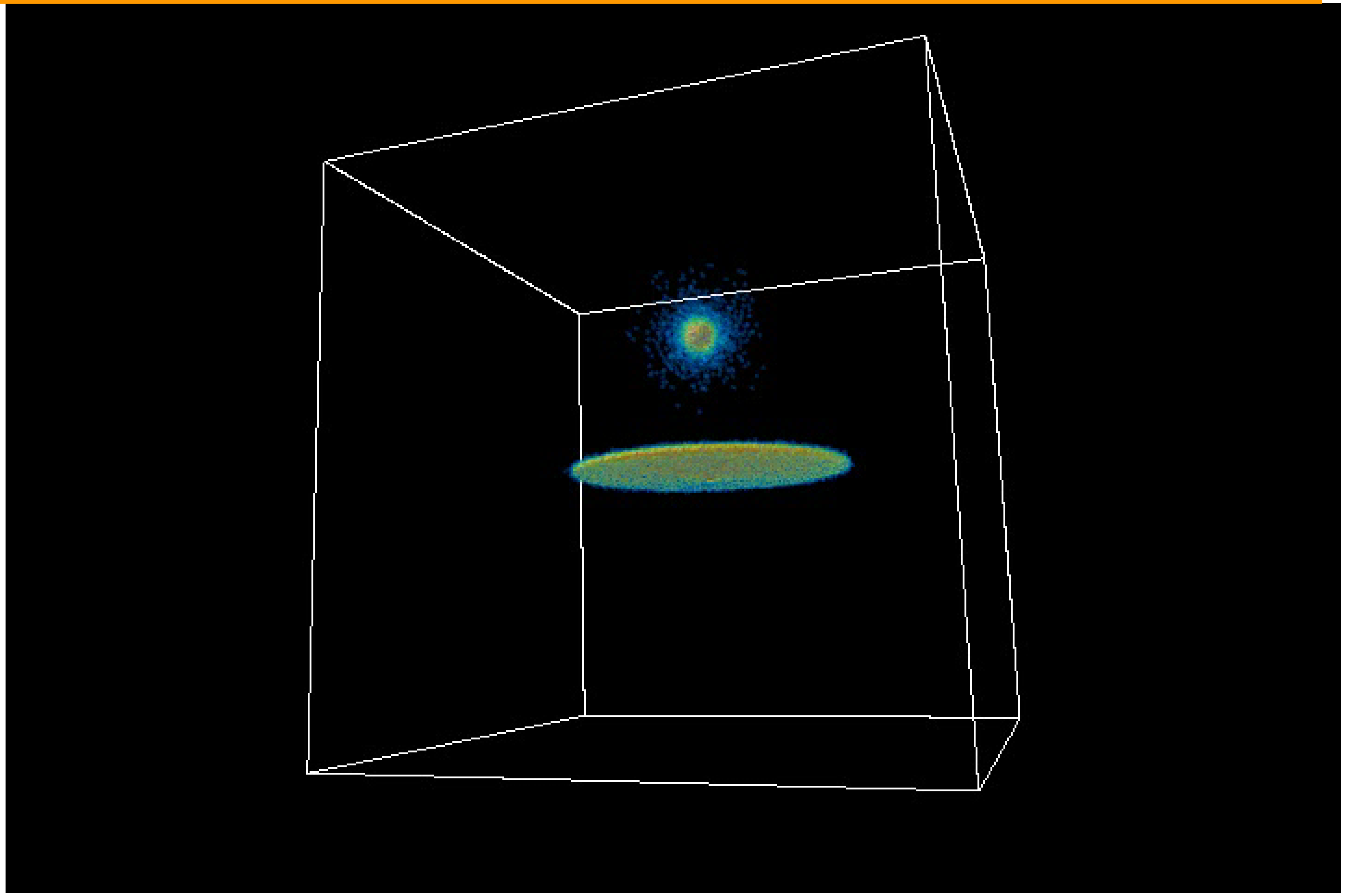
◎ Extremely close to us (nearest big galaxy)

◎ Stellar structures indicate a satellite galaxy fell ~1Gyr ago. Orbit & mass, well constrained. ⇒ Best laboratory to see the SMBH growth with galaxy merging.





2. Galaxy merging with Andromeda: simulations

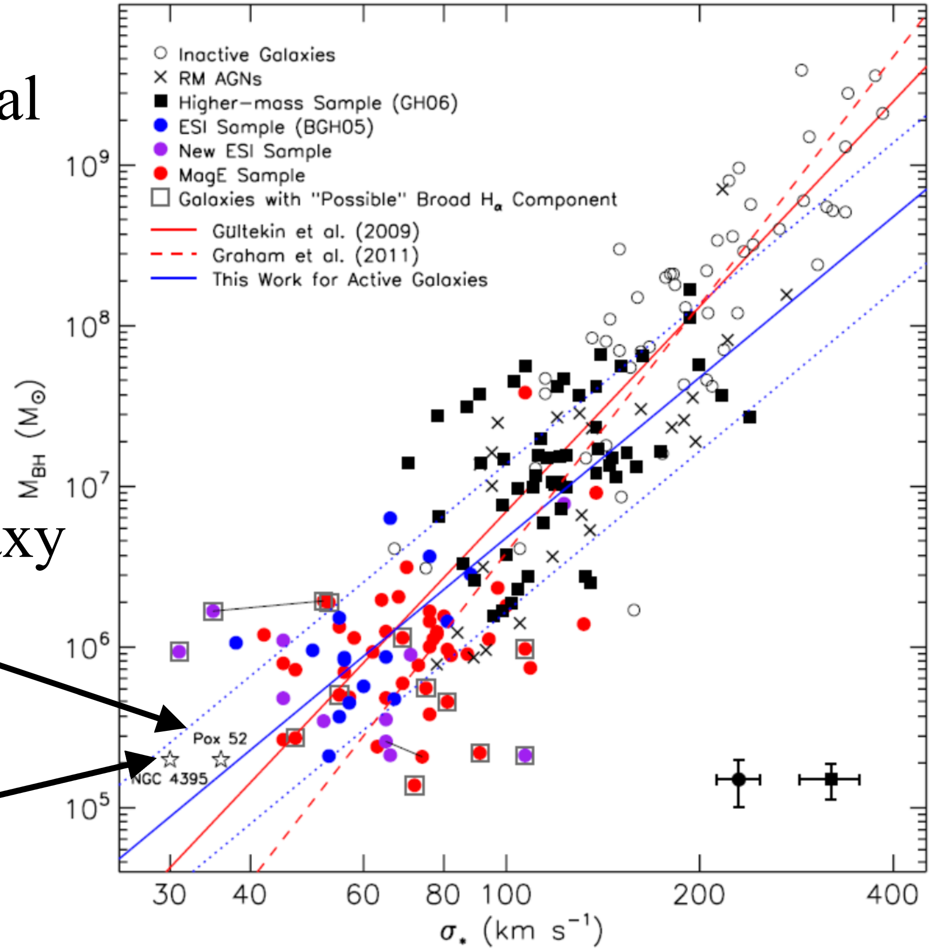


Mori & Rich (2008)

- Satellite galaxy is destroyed, and debris is expanding.
- Expanding velocity < escape velocity.
  → will fall back later. Evolution of Andromeda galaxy
- We want to follow/search the associated SMBH growth.

2. Colliding galaxy and its central black hole (BH)

- Upper limit on the satellite galaxy: 5 x 10^9 M_{sun} (Mori & Rich 08)
  Lower limit on its stellar mass: 5 x 10^8 M_{sun} (Ibata+04)
- M-σ relation ⇒ $M_{BH} \sim 10^7$ M_{sun}
- Current low-mass end of M-σ relation: $M_{BH} \sim 10^5$ M_{sun}
  → The satellite galaxy would harbor a central massive BH.



dwarf ellipitical galaxy (M_I~18.4mag)

"dwarf Seyfert" (bulgeless galaxy)

(Xiao+11; Jiang+11)

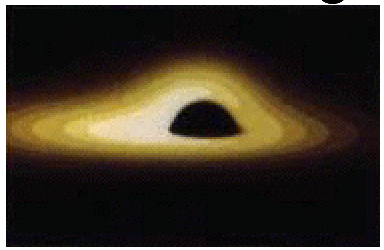
2. Searching for the wandering MBH of the satellite galaxy

◆ If we really find it,

○ First example to see the SMBH evolution via galaxy merging, from both observational and theoretical sides.

○ New population of BHs: Many wandering MBHs are missing.

○ Clean Lab. for imaging of BHs.



http://quasar.cc.osaka-kyoiku.ac.jp/~fukue/

Step 1) M31 stellar structures constrain the orbit of the satellite galaxy and location of the wandering MBH. (Miki et al. 2014)

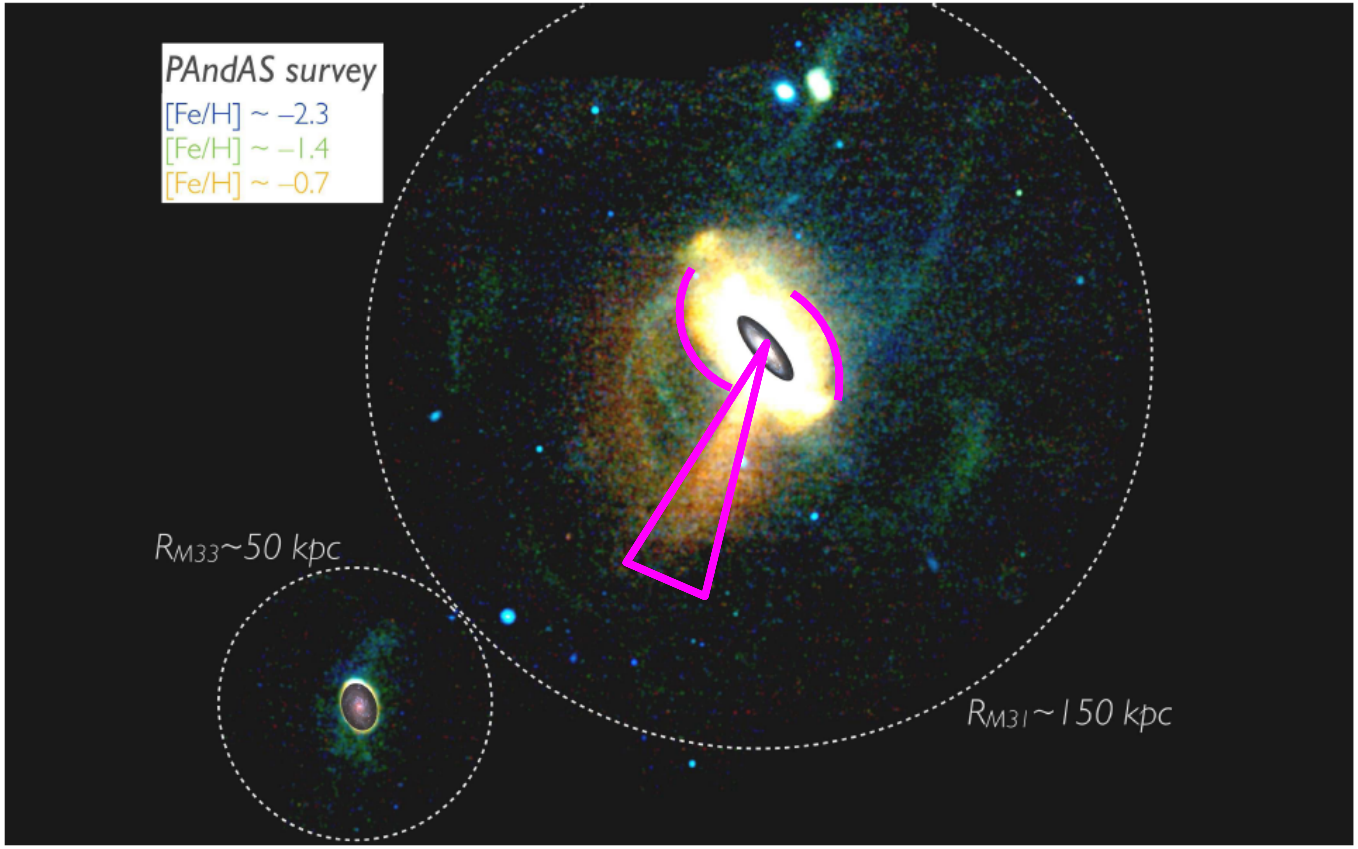
Step 2) Emission from the accretion flow around the MBH and from the trailing star cluster. (Kawaguchi et al. 2014)

3. Prediction of the current position

-- Step 1 -- (Miki + 2014)

We search for orbit models that reproduce

* Giant stream: position
* East and West shells: position, sharpness
* Brightness ratio among E, W shells and stream



Martin + (2013)

3. Prediction of the current position

N-body simulations

1) Low-resolution study:

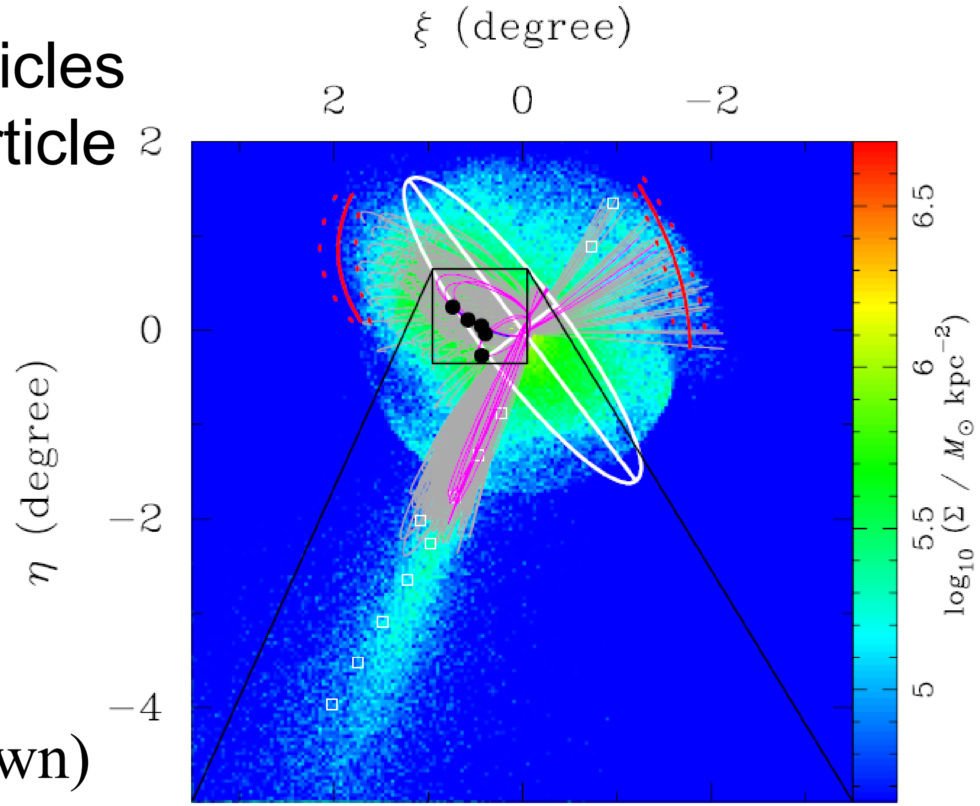
Satellite galaxy = 65000 particles

⇒ Among 5.7 million orbits, 138 orbit reproduce the observed stellar structure.

2) High-resolution study:

Satellite galaxy = 520000 particles + a MBH particle

⇒ Among 138, 5 orbit models are successful.



Color: Stellar surface density of (debris of) satellite galaxy

White lines: Andromeda disk (Stars of Andromeda are not shown)

3. Prediction of the current position

Miki et al. 2014

Color: Stellar surface density of (debris of) satellite galaxy

White lines: Andromeda disk (Stars of Andromeda are not shown)

Red lines: shells

White box: Giant stream

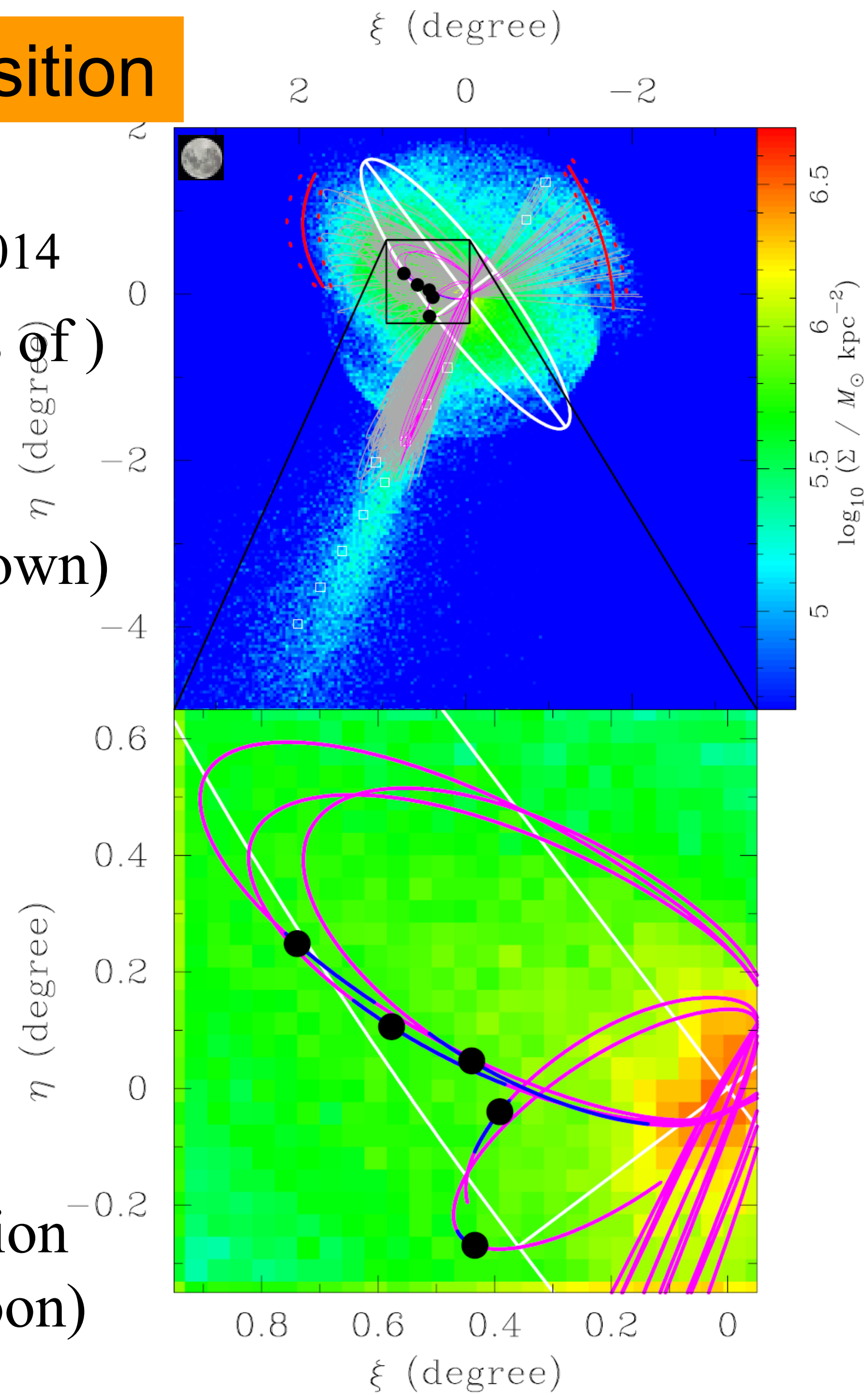
Gray: 138 orbit models

pink: 5 successful orbits

blue curves: best timing

black points: central black hole

→ search for the BH in this region (~ 0.6deg x 0.7deg ~ moon)

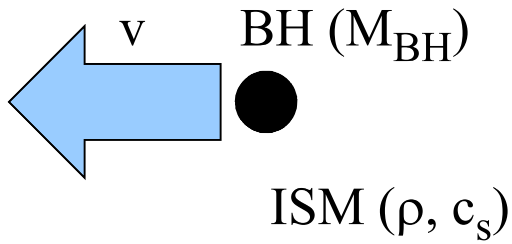


4. Emission from wandering MBH: Gas accretion rate

-- Step2 --

○ Hoyle-Lyttleton accretion of ISM onto the BH assumed:

$$\dot{M}_{HL} \propto \frac{\rho M_{BH}^{2}}{(v^2 + c_s^2)^{3/2}}$$



$\Rightarrow$ Large accretion rate is expected (i.e. luminous) when :

velocity is small (apocenter), or

density is large (pericenter)

○ Assumptions for ISM gas :

Density profile: exponential (disk), Hernquist model (bulge),

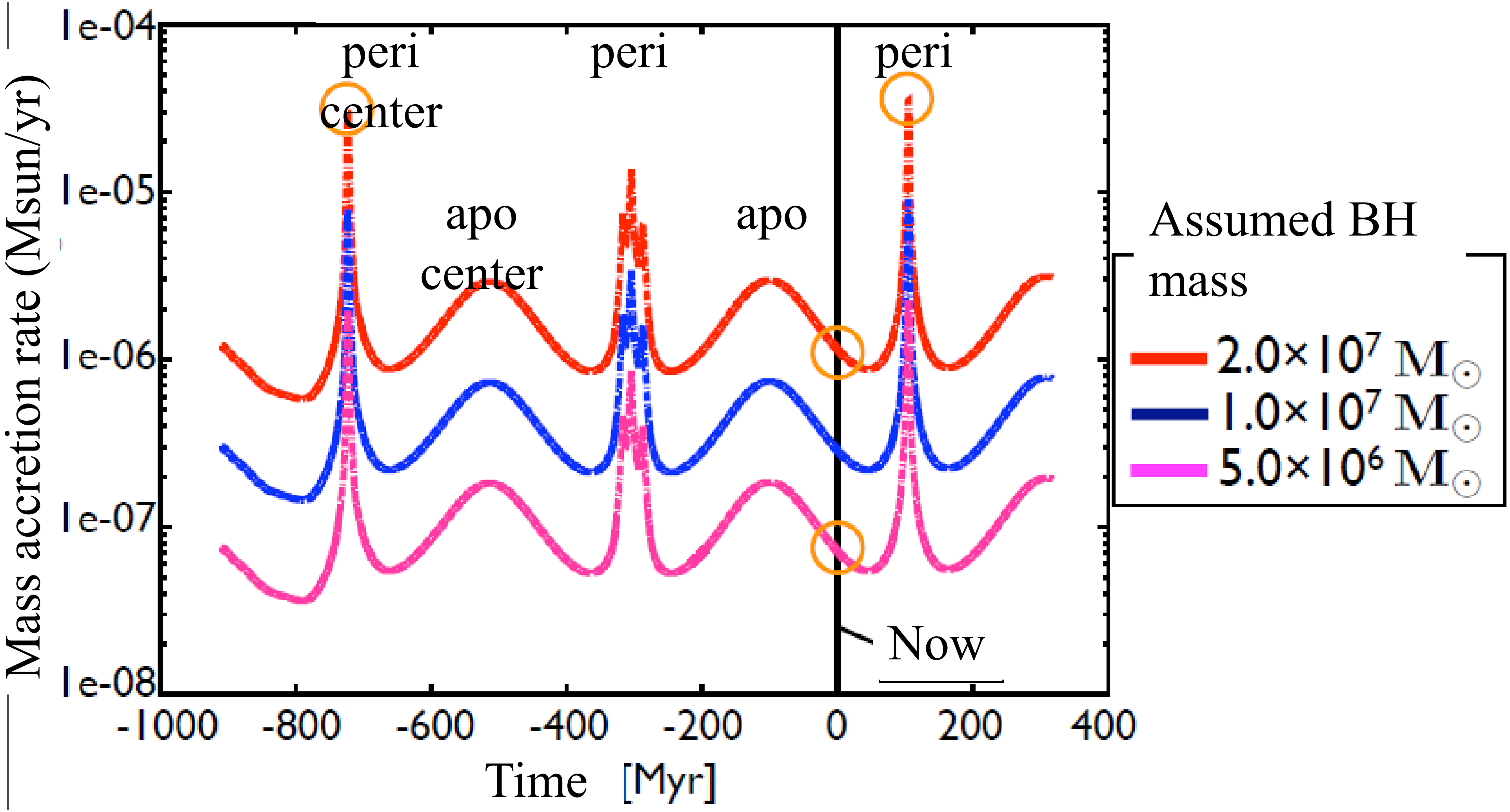
NFW (halo)

Density = 0.1 x (star + DM + gas)

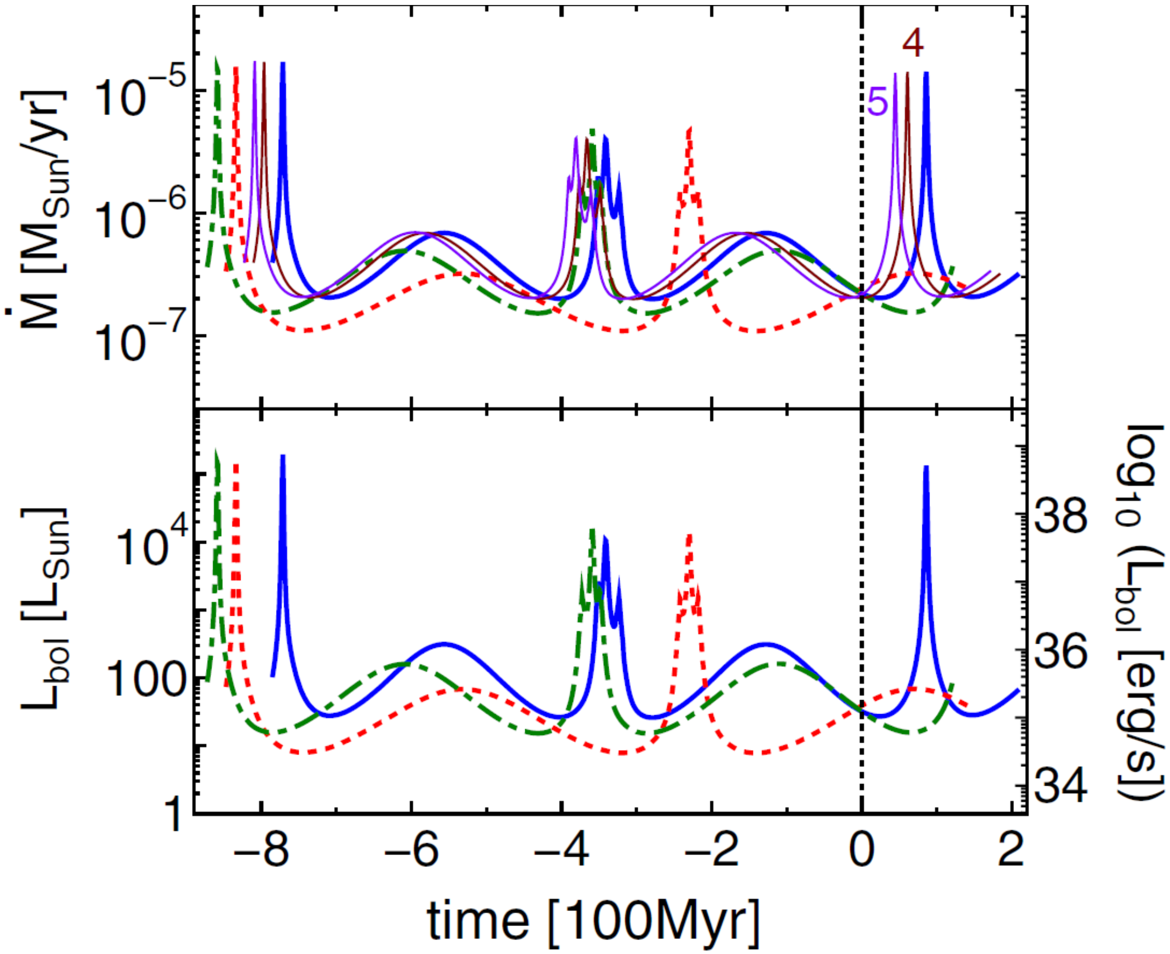
Temperature = 10^4 K (disk, bulge), 10^6 K (halo)

4. Accretion rate (Bondi accretion assumed)

Example of accretion rate



4. Results for the 5 orbits models: Current acc. rate are similar.



Even at the peaks, $\dot{M} << \dot{M}_{Eddington}$ (~ 0.2 M_{sun}/yr)

→ ADAF model (Narayan & Yi 1995; Mahadevan 97)

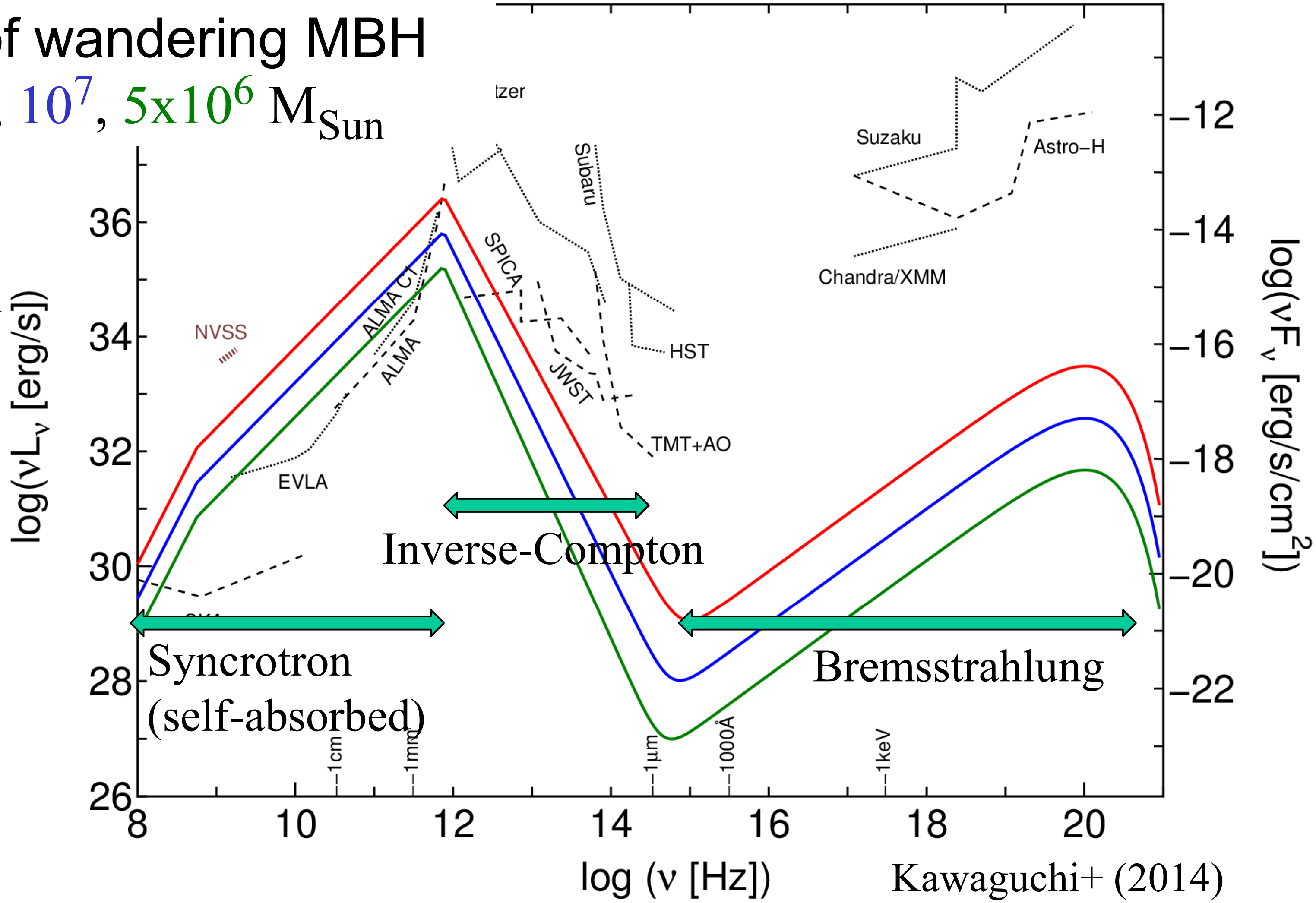
Current bolometric luminosity ~ 7--400 L_{sun}

4. Step 2: Emission from the wandering MBH

Lines=SED of wandering MBH

M_{BH} = $2x10^7$, 10^7, $5x10^6$ M_{Sun}

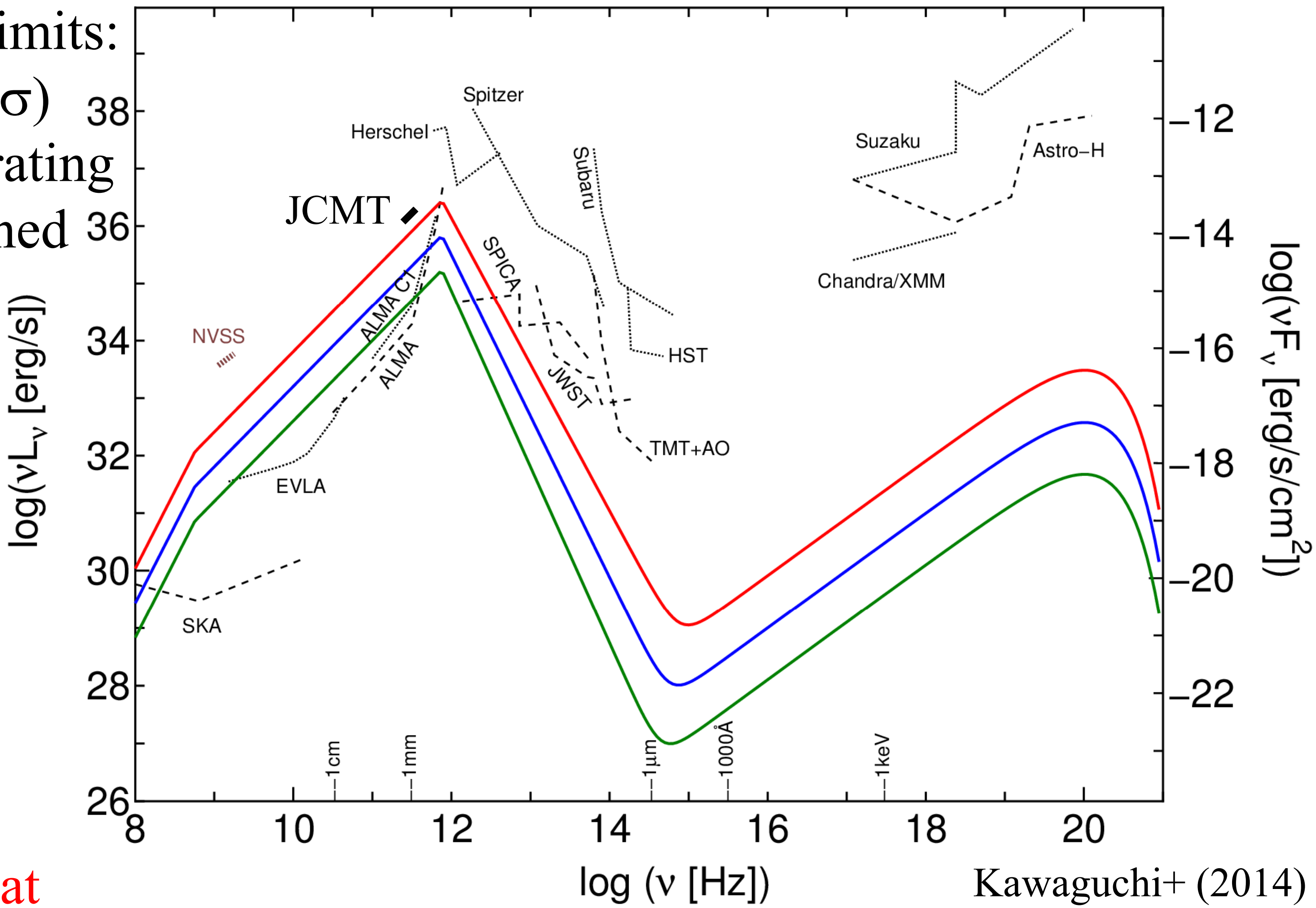
Optically-thin accretion flow (ADAF) model



Kawaguchi+ (2014)

4. Step 2: Emission from the wandering MBH

◇ Detection limits: (10^4sec, 10σ)
dotted = operating
dashed = planed



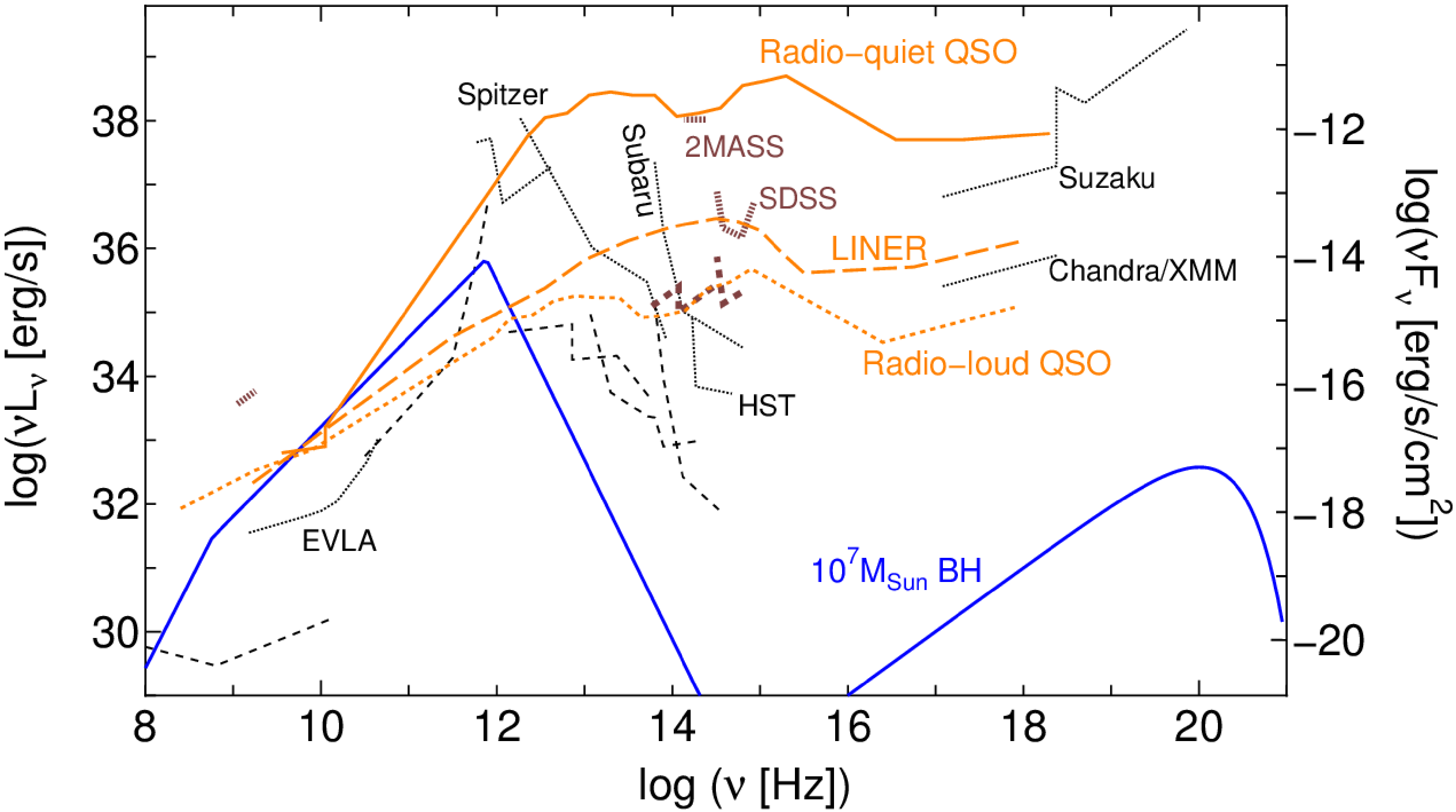
Kawaguchi+ (2014)

◆ Detectable at Radio (JVLA, ALMA, SKA)

4. SEDs of possible background sources

QSOs and LINER redshifted so that they have the same 5GHz flux

⇒ Different from our target.

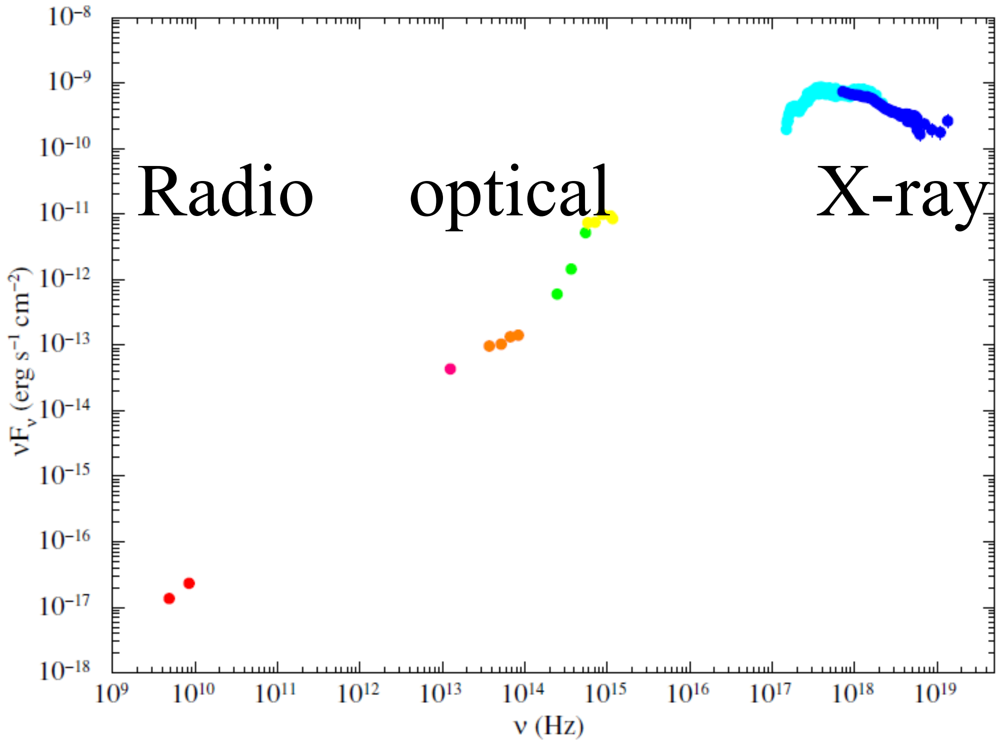


Kawaguchi+(2014)

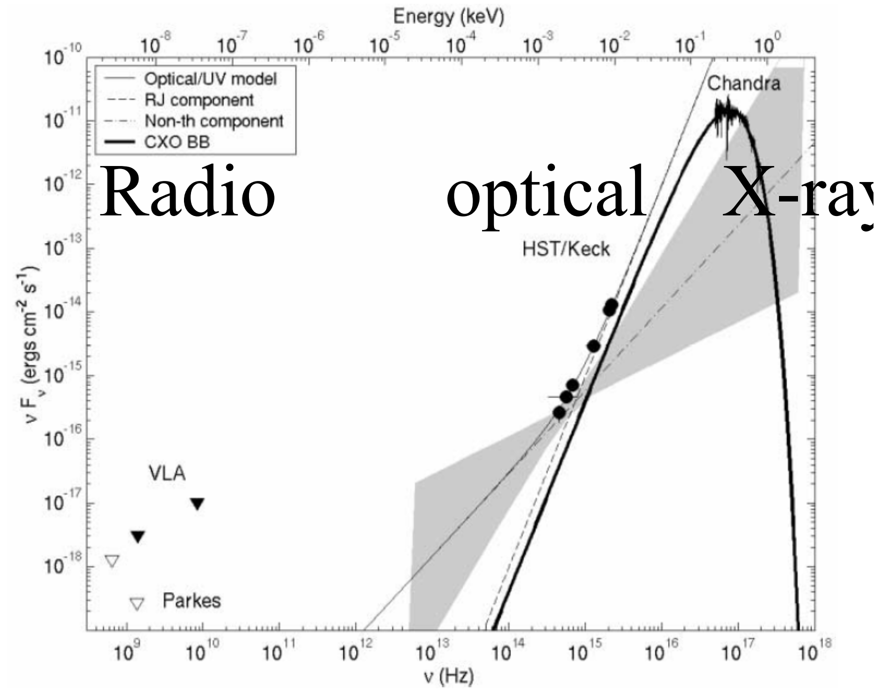
4. Radio-bright local sources (e.g., neutron stars)

Background & foreground objects will be brighter in X-ray (& optical, IR) than our target.

νF_ν



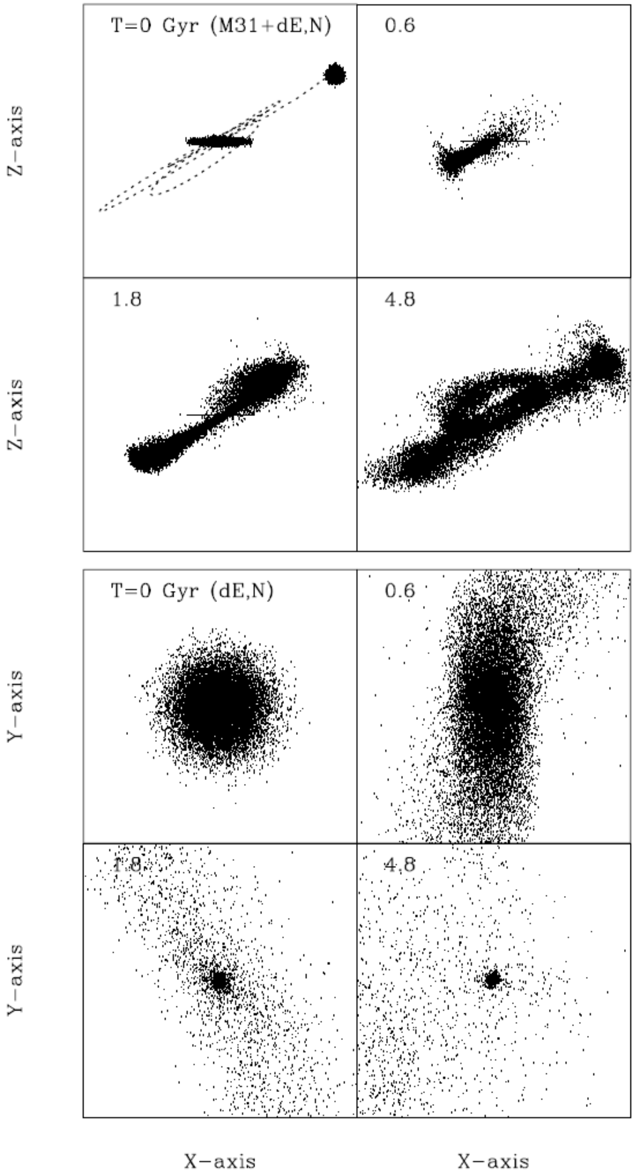
(Migliari et al. 2010)



(Kaplan et al. 2003)

5. Stars trailed by the wandering black hole

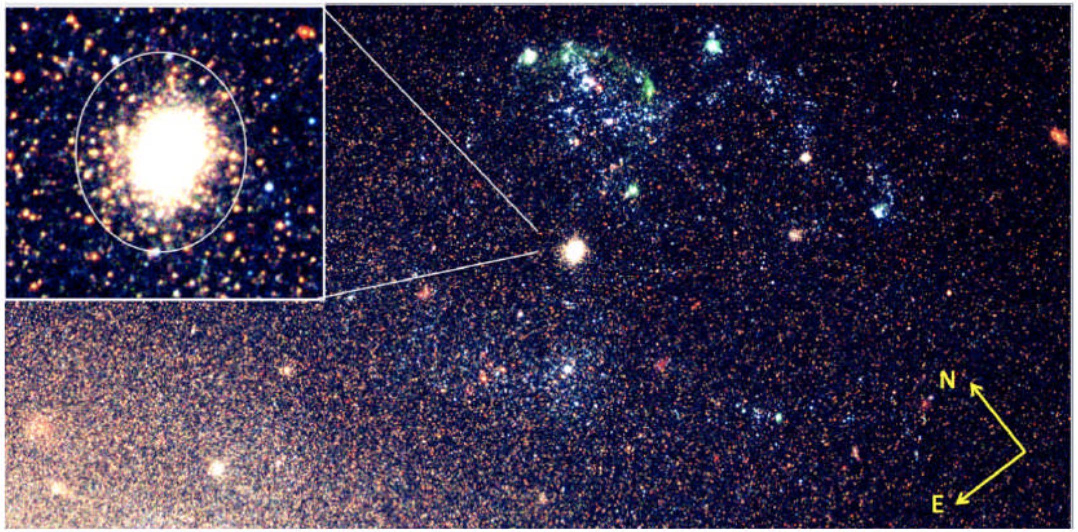
Remnant star cluster?: stars of the satellite galaxy



M31+satellite

Close view of satellite gal.

(Bekki+Chiba 04)



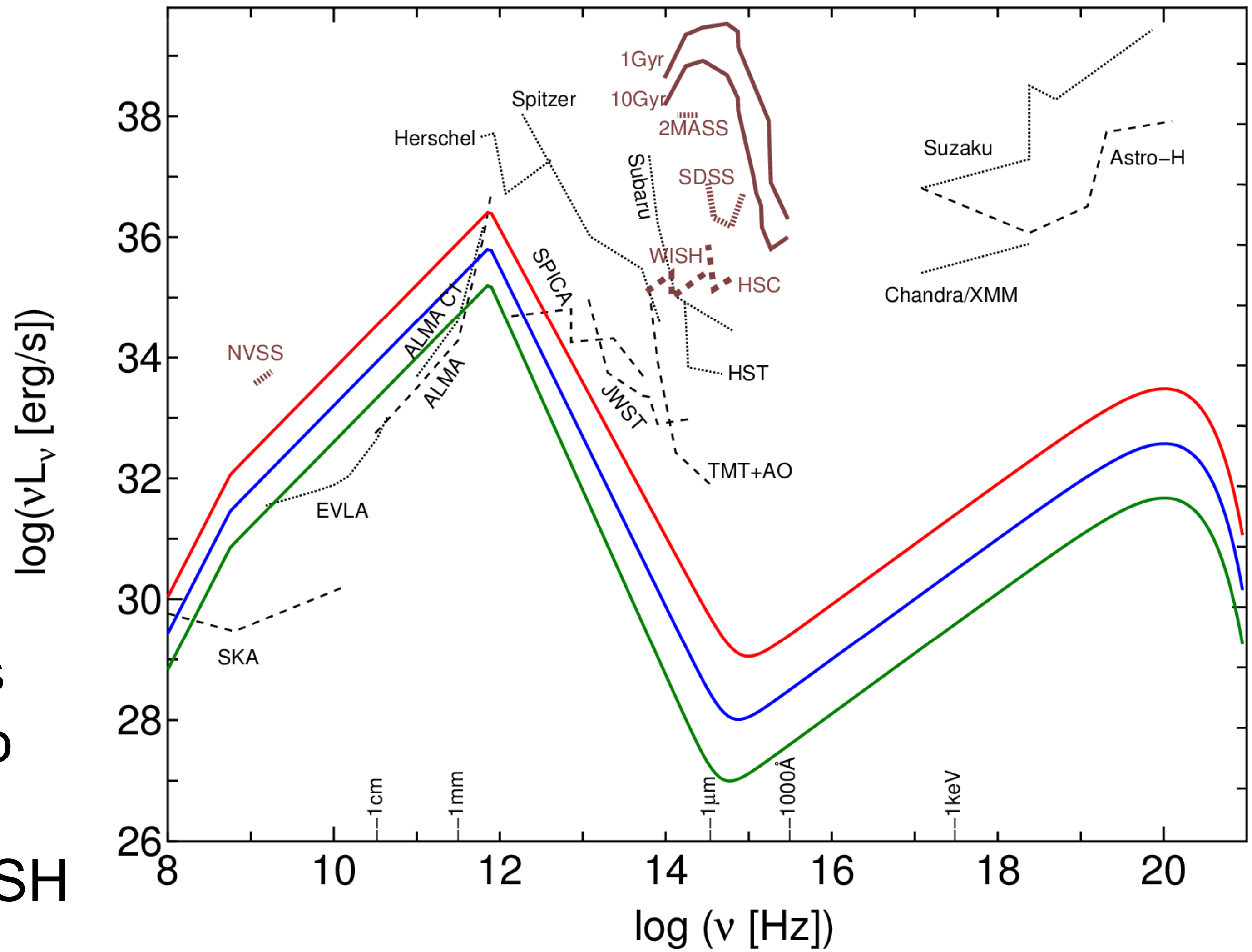
(Annibali+ 12)

5. Stars surrounding the wandering MBH

- Stars survived against tidal shear ~ 0.1 M_{BH} ~ 10^6 M_{sun}
- likely metal rich

SED of stars (PEGASE model)

- well above 2MASS, SDSS limits
- detectable up to 80Mpc with HSC, WISH



Kawaguchi+(2014)

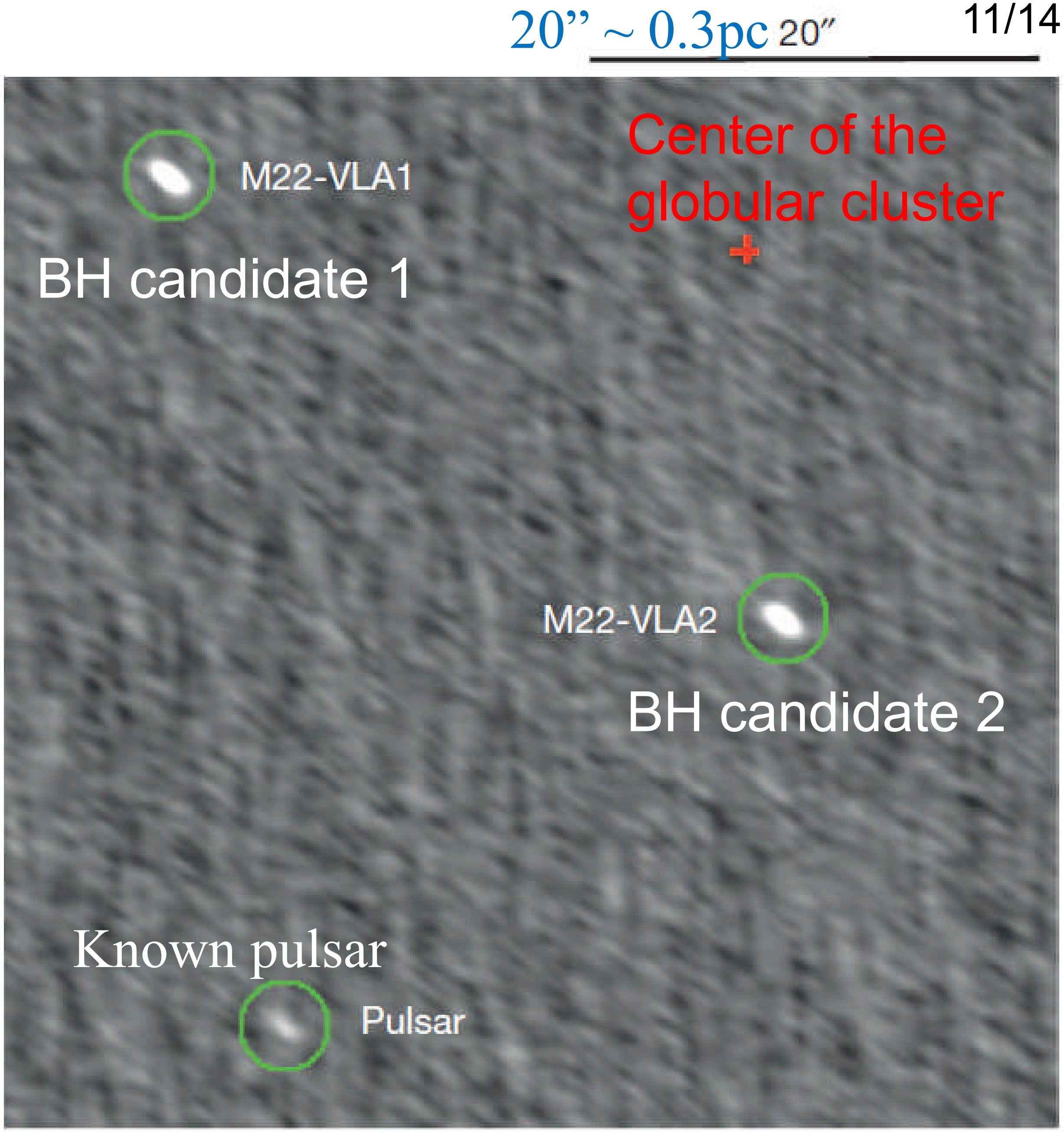
6. Discussion: Radio search for BHs in globular clusters

M22: glbular cluster
with a large core
radius

Discovery:
2 BH candidates

BH candidate 1:
coincident with
0.34 Msun star
(HST archive).
BH-star binary?

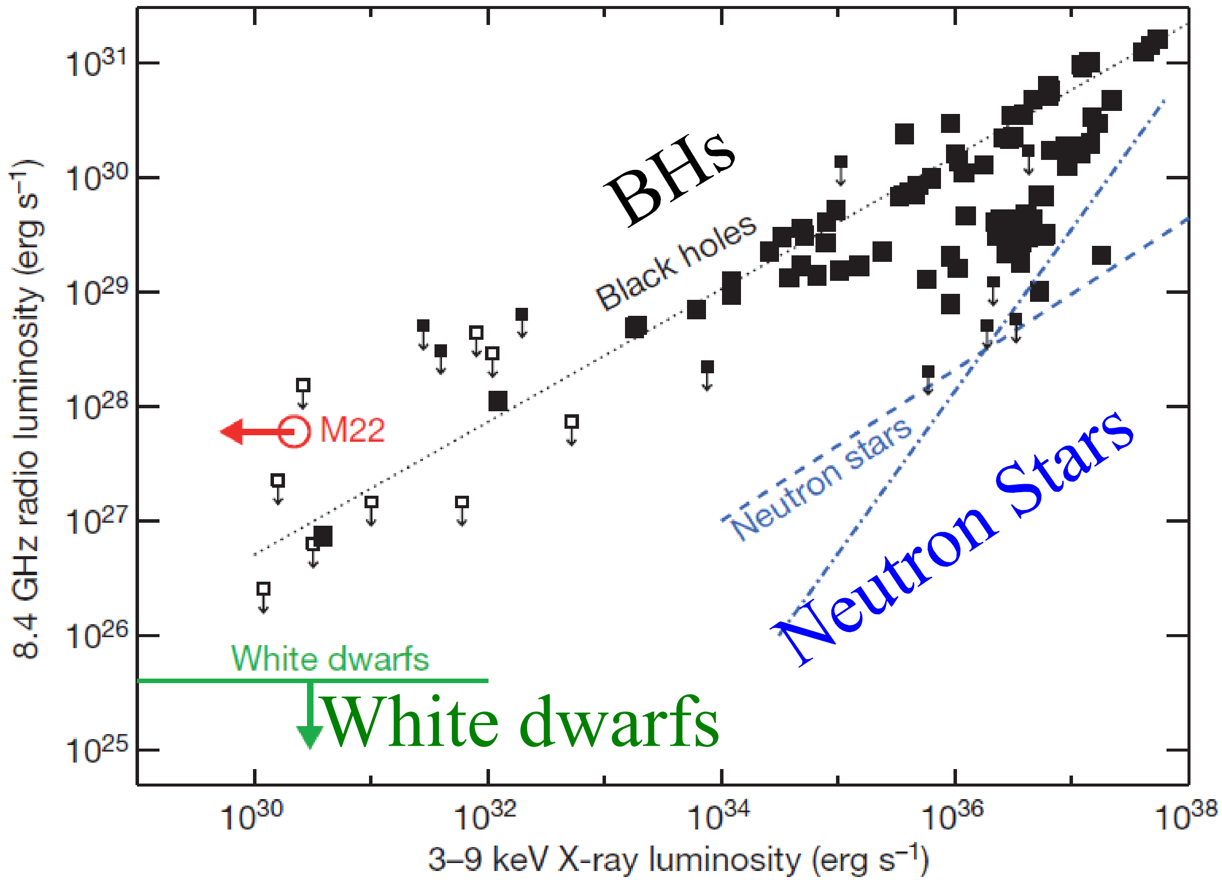
Strader+12



6. Discussion: Radio search for BHs in globular clusters

No detection in X-ray (Chandra).

The radio--X-ray plot ⇒ these two radio objects likely BHs



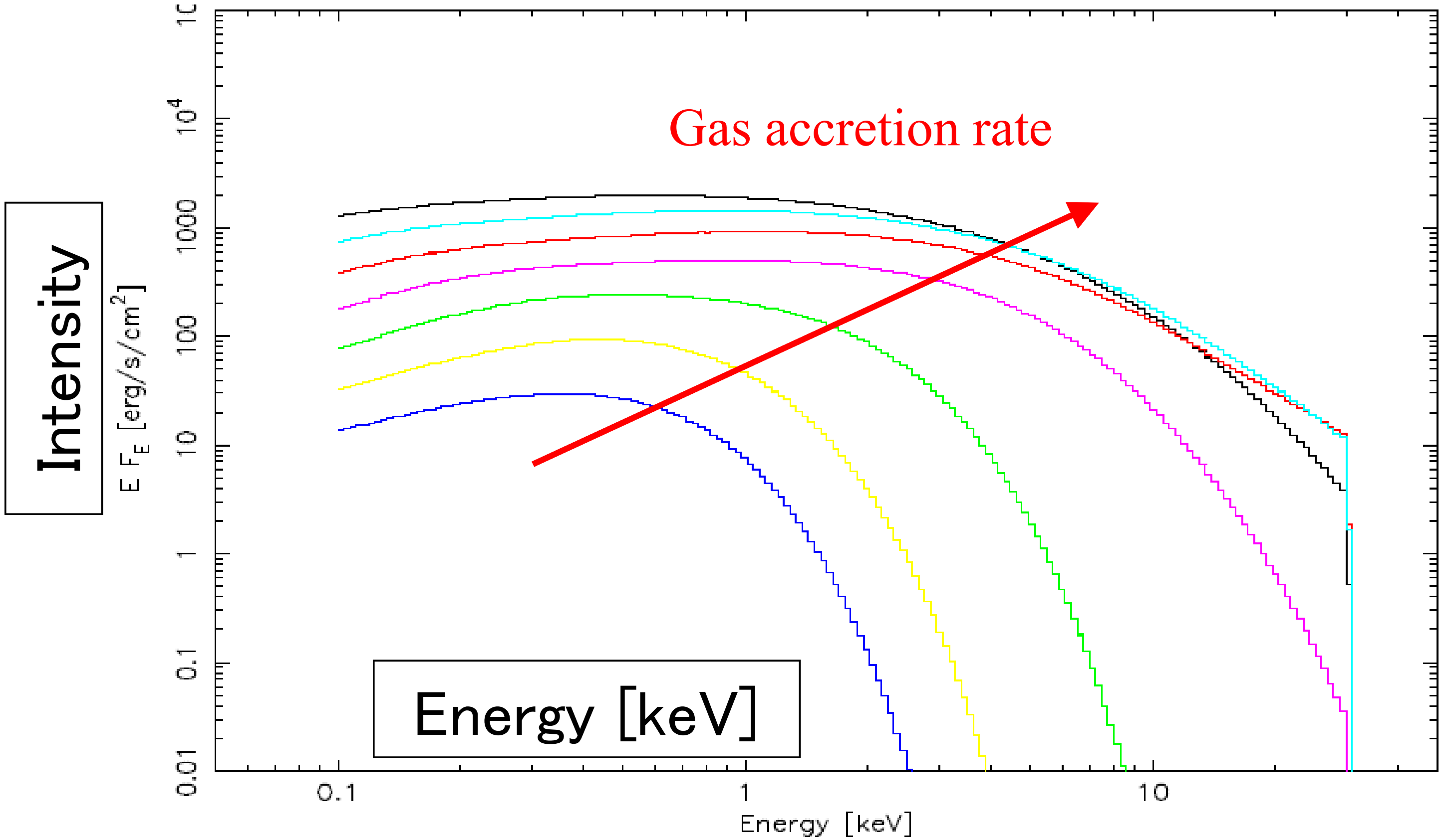
Radio waveband is a good window for BH search.

7. Are there Intermediate-Mass BHs?

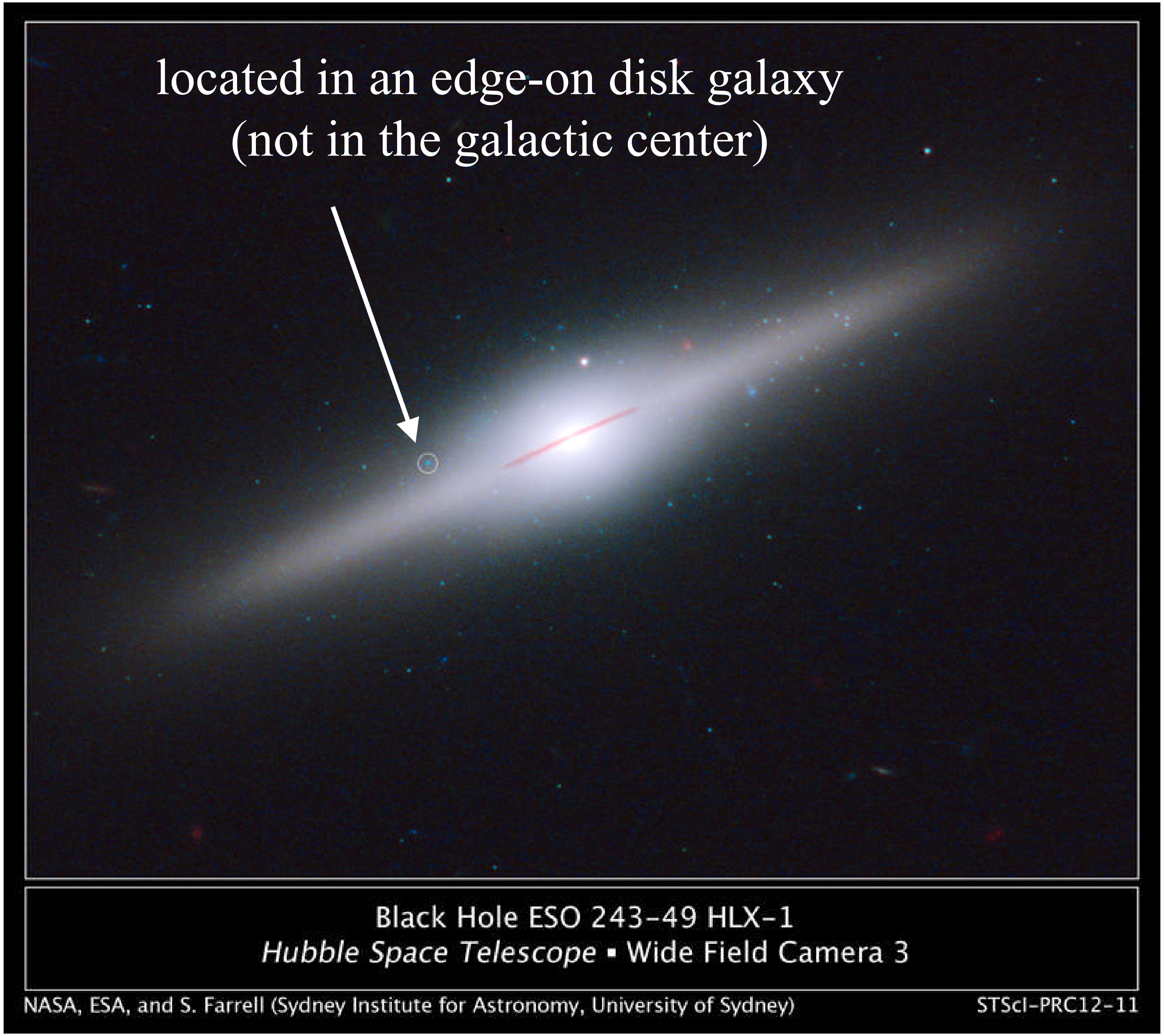
Spectral model for sub- and super-Eddington accretion disks

(Kawaguchi 2003)

* Important physics (eg., electron scattering) included.
* Publically available at HEASAC (NASA) since 2006
* Useful for objects with unknown BH mass



7. Hyper-luminous X-ray source

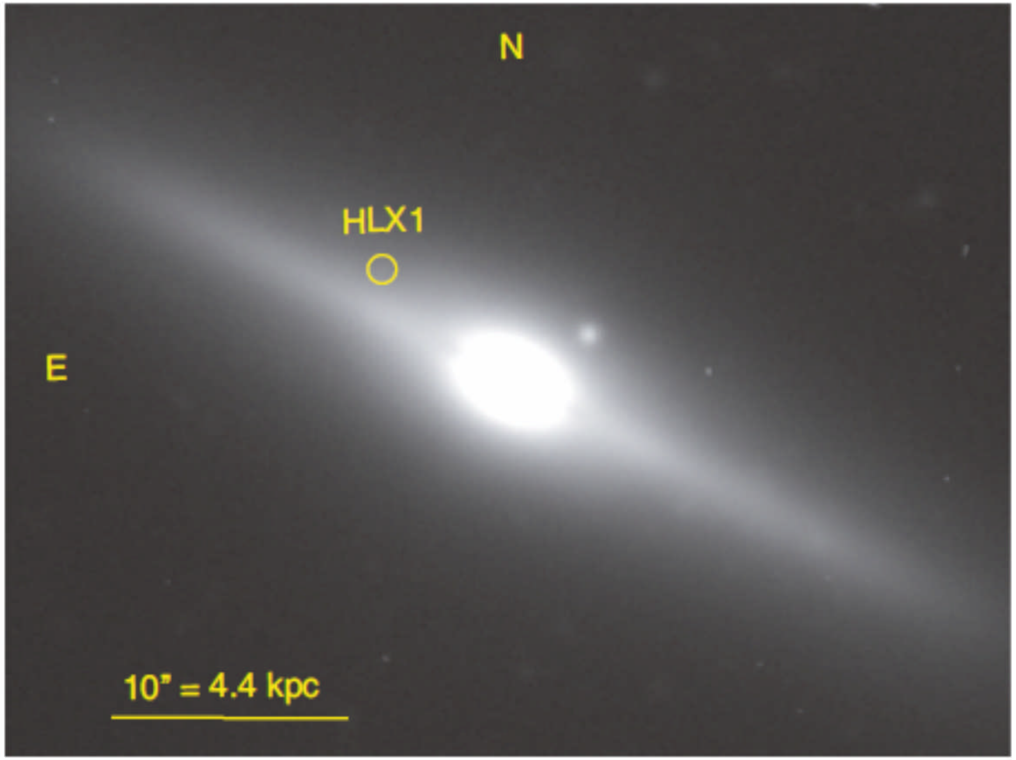


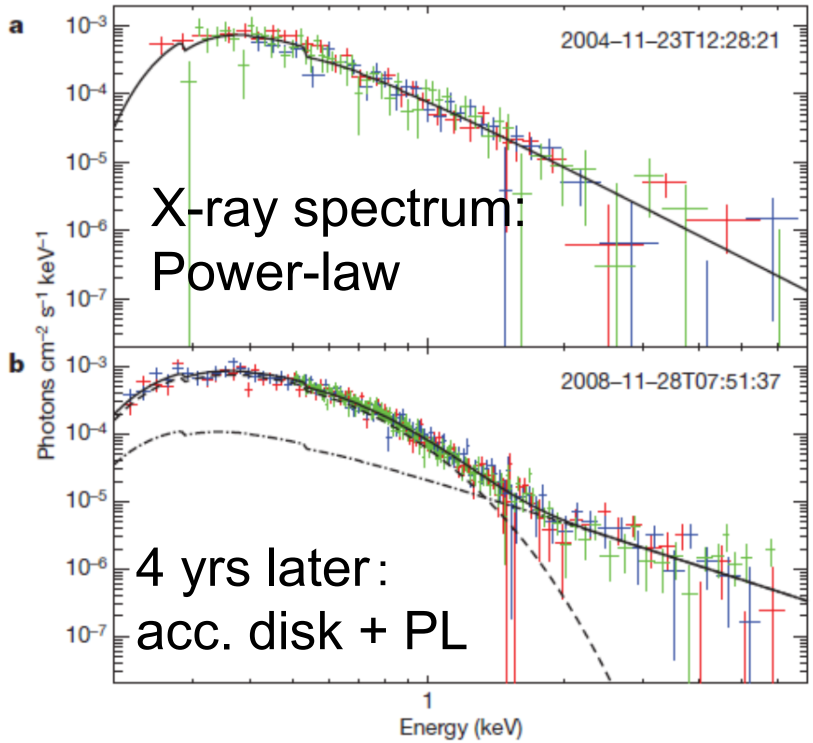
(Farrell+2009, Webb+2010, Wiersema+2010)

Best candidate of Intermediate-mass black hole

7. Hyperluminous X-ray Source?

(Farrell+2009, Webb+2010)



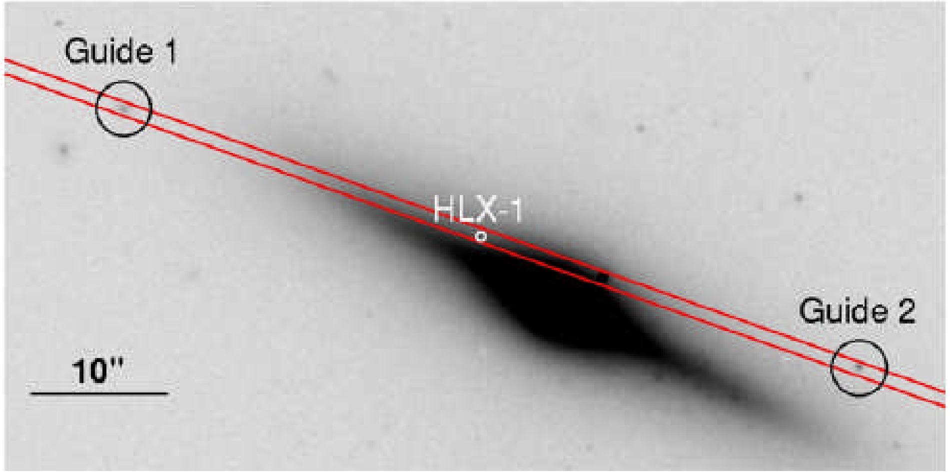


- Spectral state transitions: common in compact accreting objects

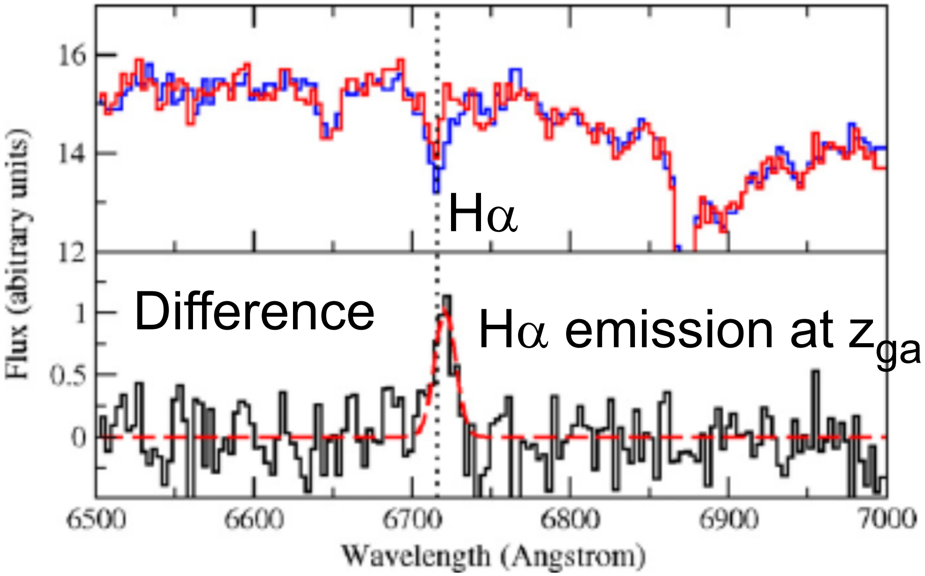
- If located in this galaxy,
  ⇒ then 1dex yet more luminous than the most luminous ULX M82 X-1
  ⇒ Best candidate for intermediate-mass black hole

cf. Super-Eddington accretion model for M82 X-1 (Okajima, Ebisawa, Kawaguchi 2006) → ~30M_{sun} + ~20M'_{Edd}

7. Optical spectroscopy for Hyperluminous X-ray Source



(Wiersema+2010)
VLT DDT



(0.024)

Position of HLX-1
neighbouring sub-apertures

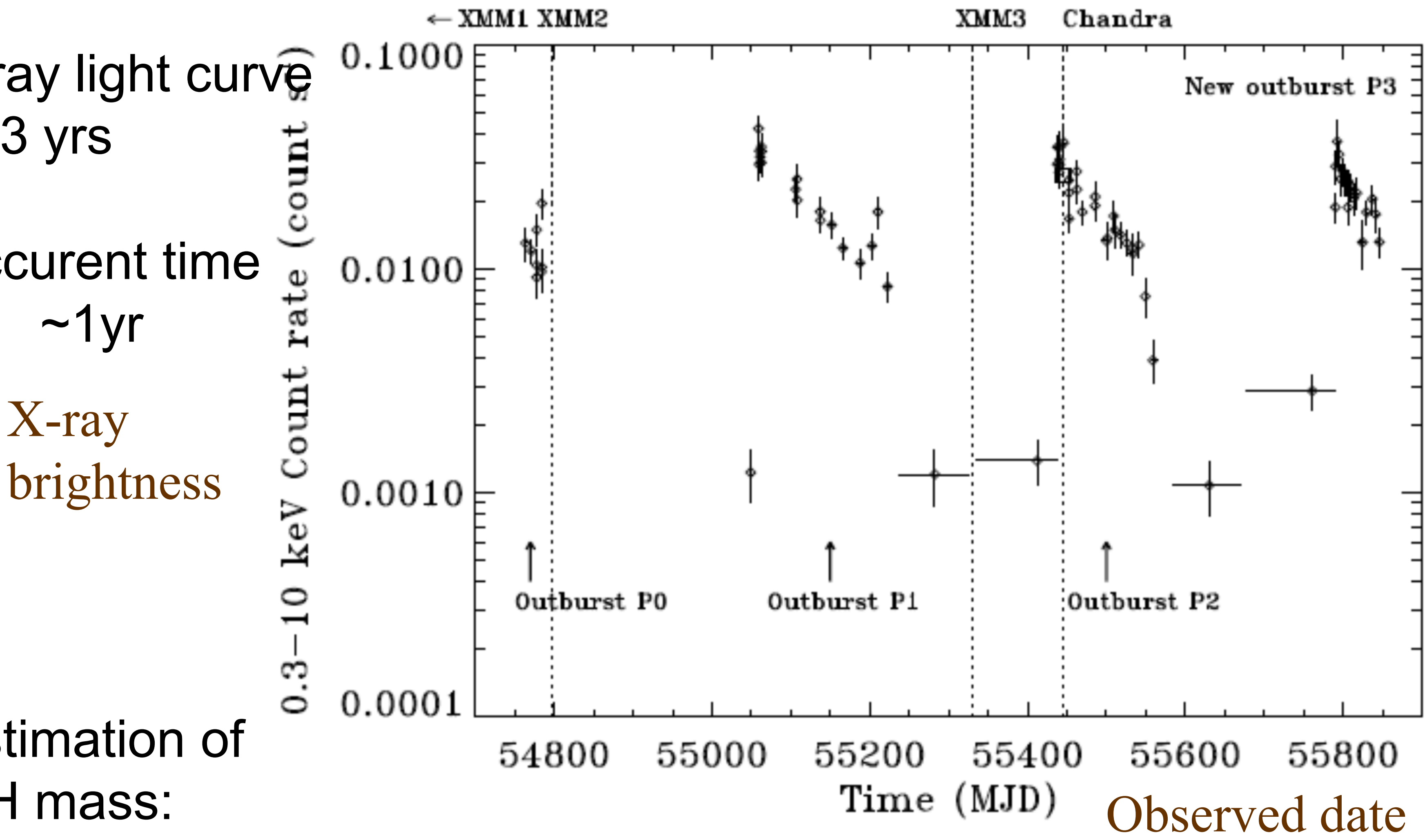
⇒ HLX is located at the same redshift

7. HLX: Black hole mass

(Godet, Plazolles, Kawaguchi+ 2012)

●X-ray light curve over 3 yrs

- reccurent time ~1yr



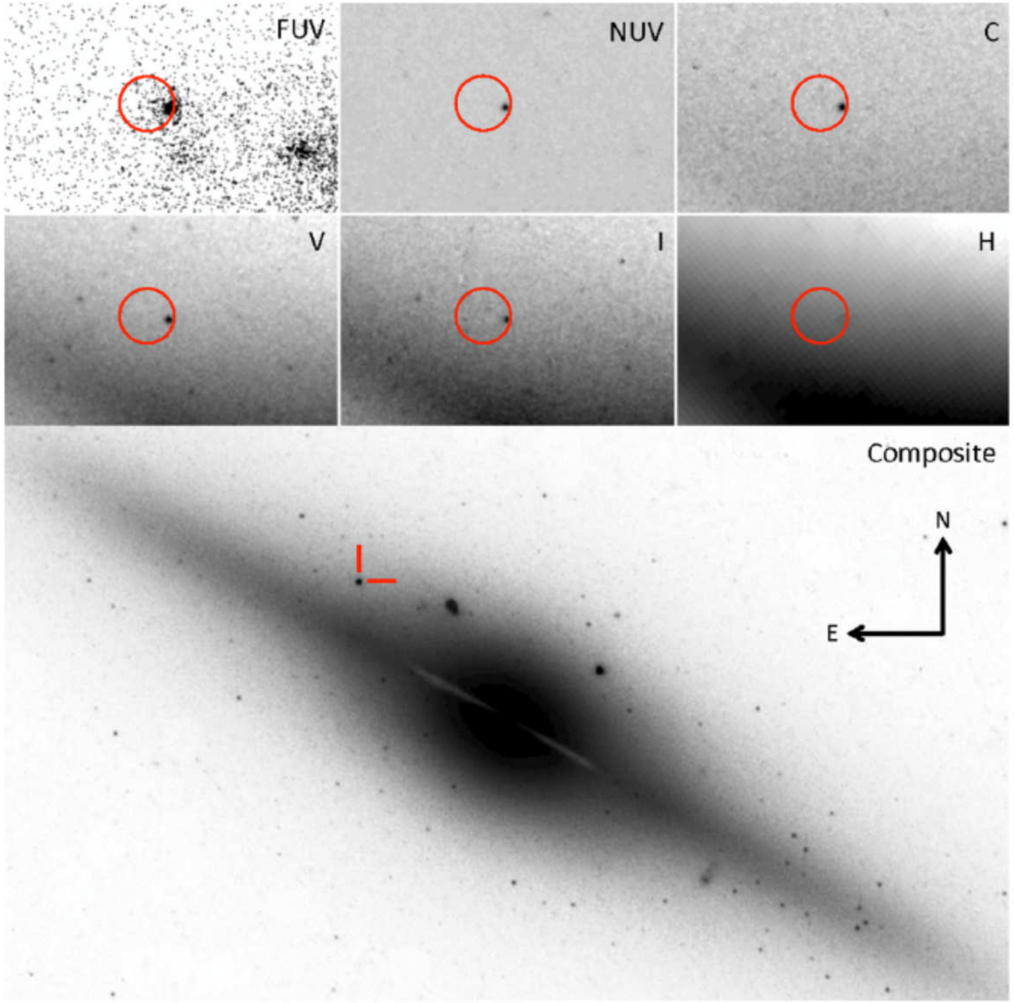
●Estimation of BH mass:

Spectra at various brightness + Spectral model

⇒ (1.4--1.9)10^4 M_{sun}, intermediate-mass black hole.

7. Wandering IMBH and surrounding stellar cluster

UV – optical -- NIR images



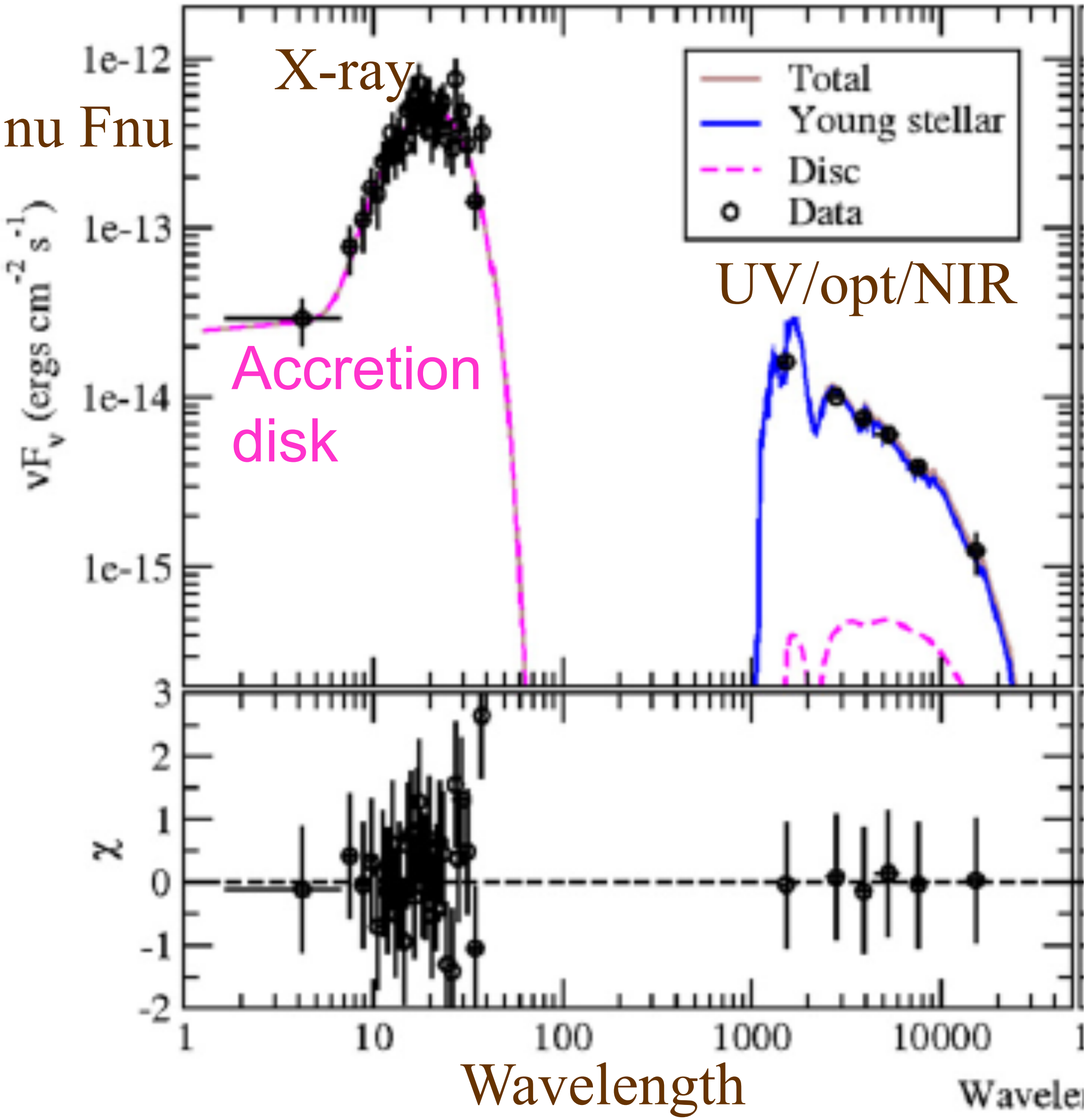
HST, Farrel et al. 2012

- Detected at NIR/optical/UV
- Star cluster with $M_{star} \sim 4\ 10^6 M_{sun}$

↓

- Debris of satellite galaxy? (central BH + stars still surrounding it; Farrel+12)

7. Star cluster surrounding the Intermediate-mass BH

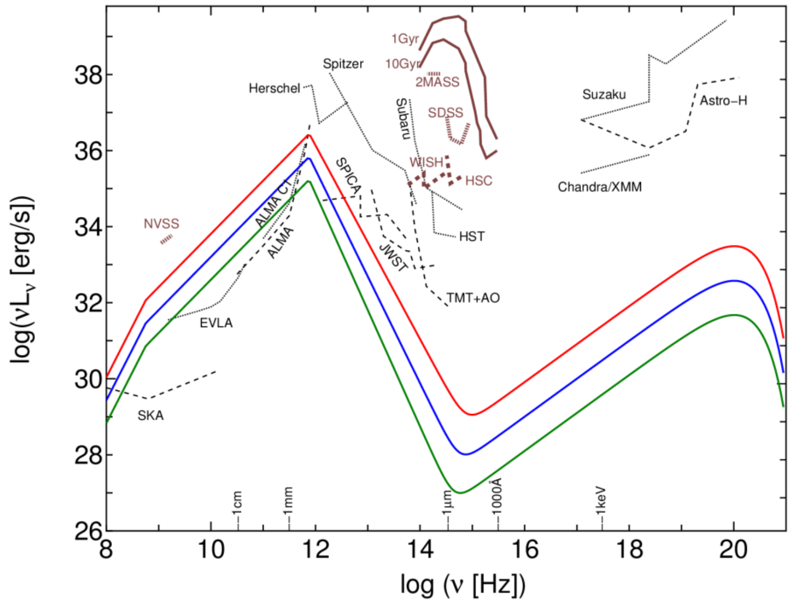


Star cluster at
Age~10Myr,
M_{star}~4 10^6Msun

(Farrel et al. 2012)

Summary: SMBH evolution via galaxy merging

1. Satellite galaxy colliding with Andromeda
   - ○ Central MBH：detectable at radio
   - ○ Stars (remnants of galactic center)



2. Intermediate-mass BH candidate + Star cluster：
   - ○ ~ 2 10^4 M_{sun} BH
   - ○ Debris of satellite galaxy?