

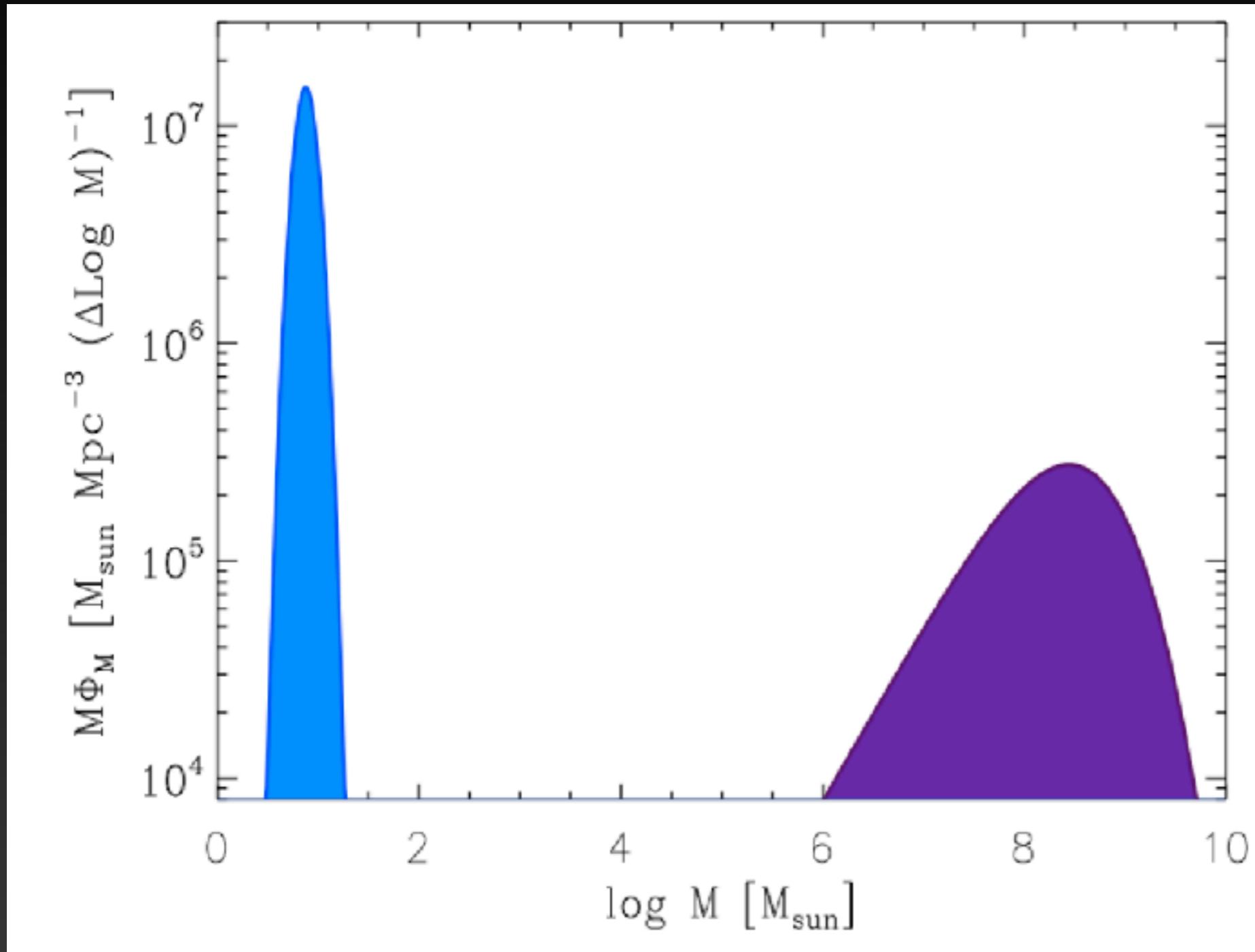
전자기파를 이용한 전통적인 블랙홀 관측 연구에 대한 소개

Minjin Kim (KNU)
(중력파를 모르는) 관측천문학자

Contents

1. Supermassive black hole (SMBH) 소개
2. 전자기파를 이용한 SMBH 찾기 소개
 - 2020년 노벨물리학상 포함
3. 쌍(거대질량)블랙홀에 대한 관측 연구 소개
 - 중력파가 일어나기 이전과 일어난 후를 중심으로

Supermassive Black Hole (SMBH)



Merloni & Heinz 2013

Supermassive Black Hole (SMBH)

1. $M_{\text{BH}} > 10^{5-6}$ solar mass (M_{\odot}) located at **the center** of galaxies
2. **Ubiquitous** at least in massive galaxies with bulges
3. The majority of the SMBH population is dormant
4. BH-Host Galaxy correlation
5. Formation mechanism is still unknown

Supermassive Black Hole (SMBH)



M31 (Andromeda; $M_{\text{BH}} \sim 10^8 M_{\odot}$)



M33 ($M_{\text{BH}} < 1500 M_{\odot}$)

Supermassive Black Hole (SMBH)

Normal (Inactive) Galaxy



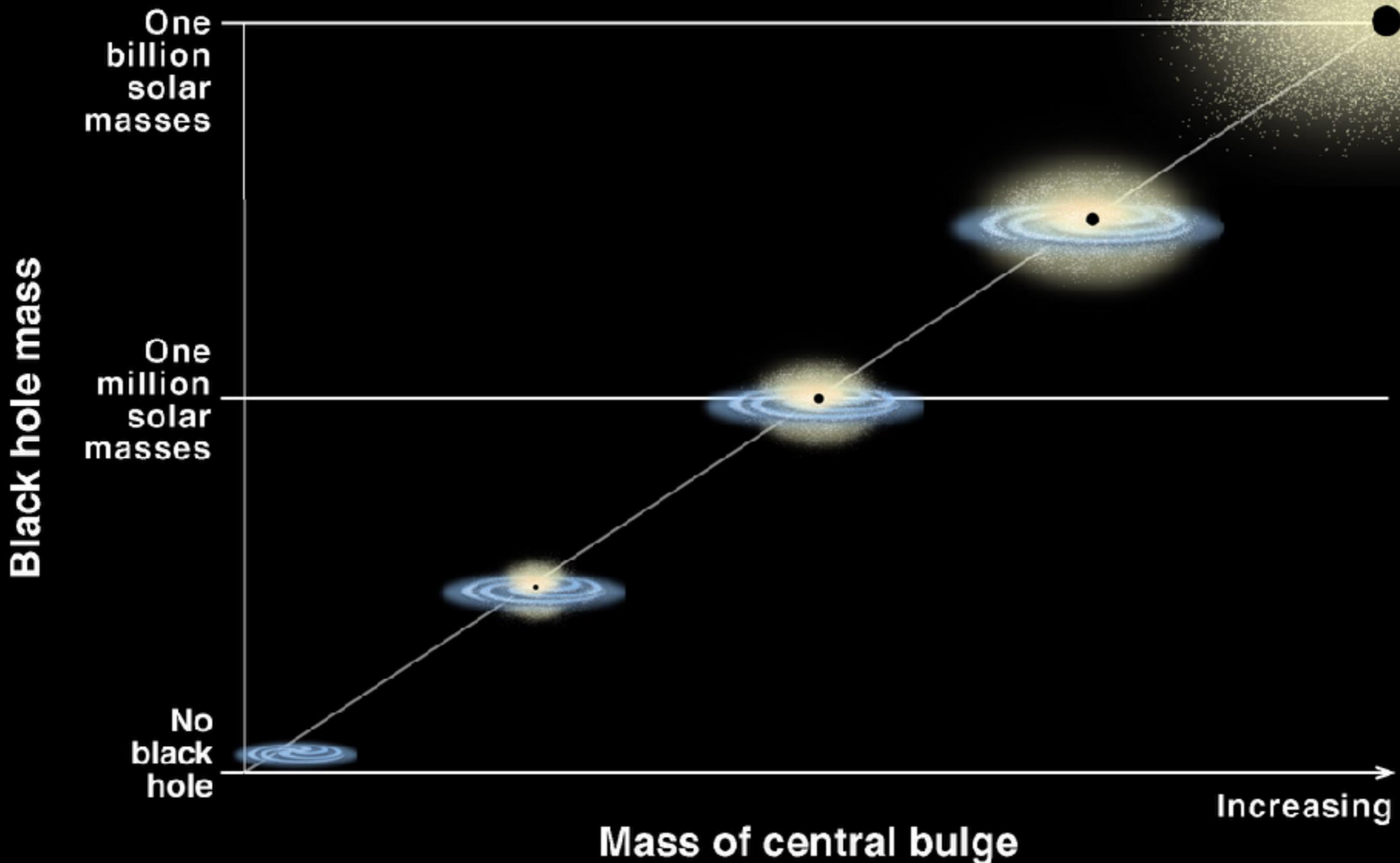
M31 (Andromeda; $M_{\text{BH}} \sim 10^8 M_{\odot}$)

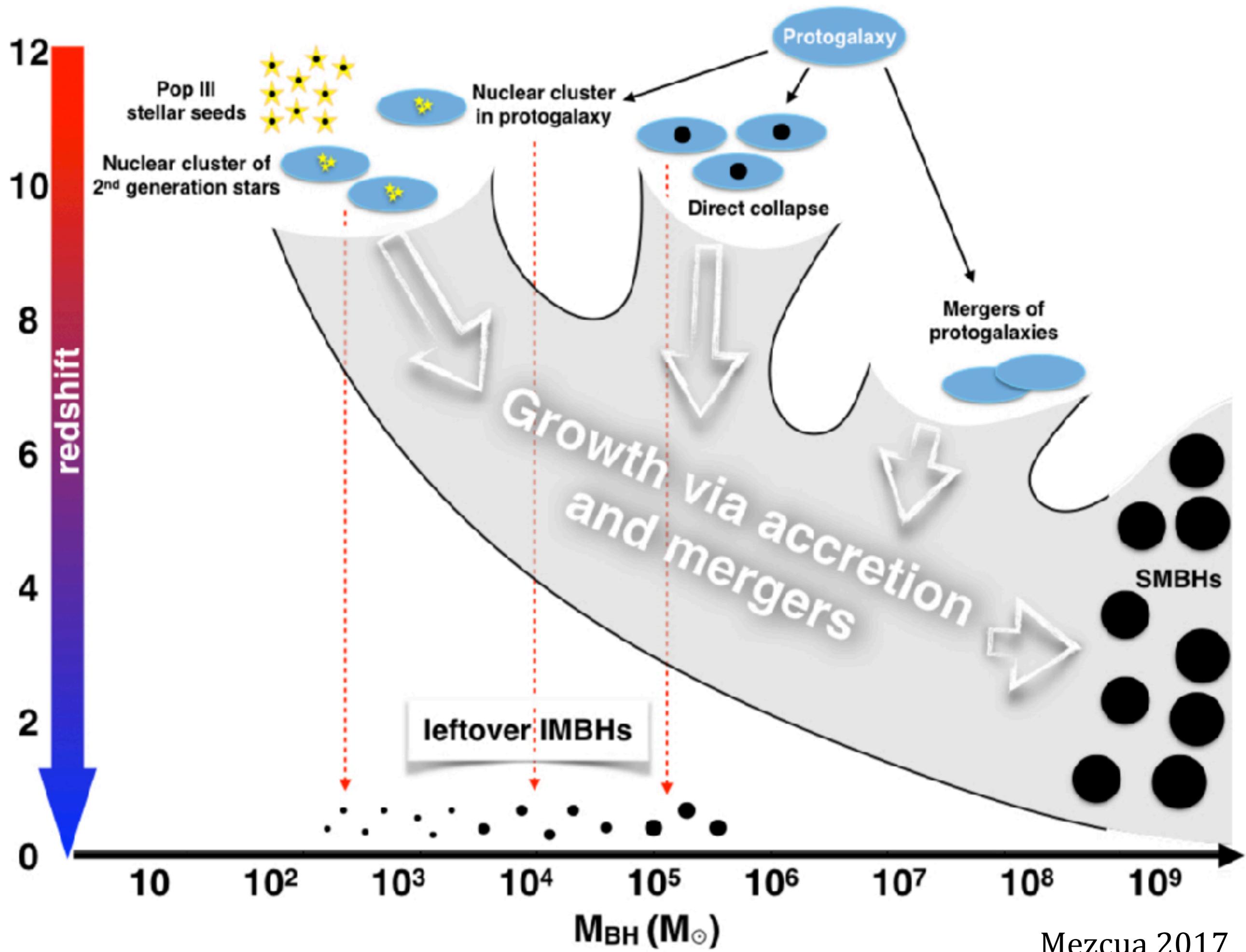
Active Galaxy (활동성은하)



M87 ($M_{\text{BH}} \sim 5-6 \times 10^9 M_{\odot}$)

Correlation Between Black Hole Mass and Bulge Mass





(Conventional) Methods of detecting SMBH

1. Normal Galaxy (~100 objects)

- Stellar dynamics
- Gas dynamics

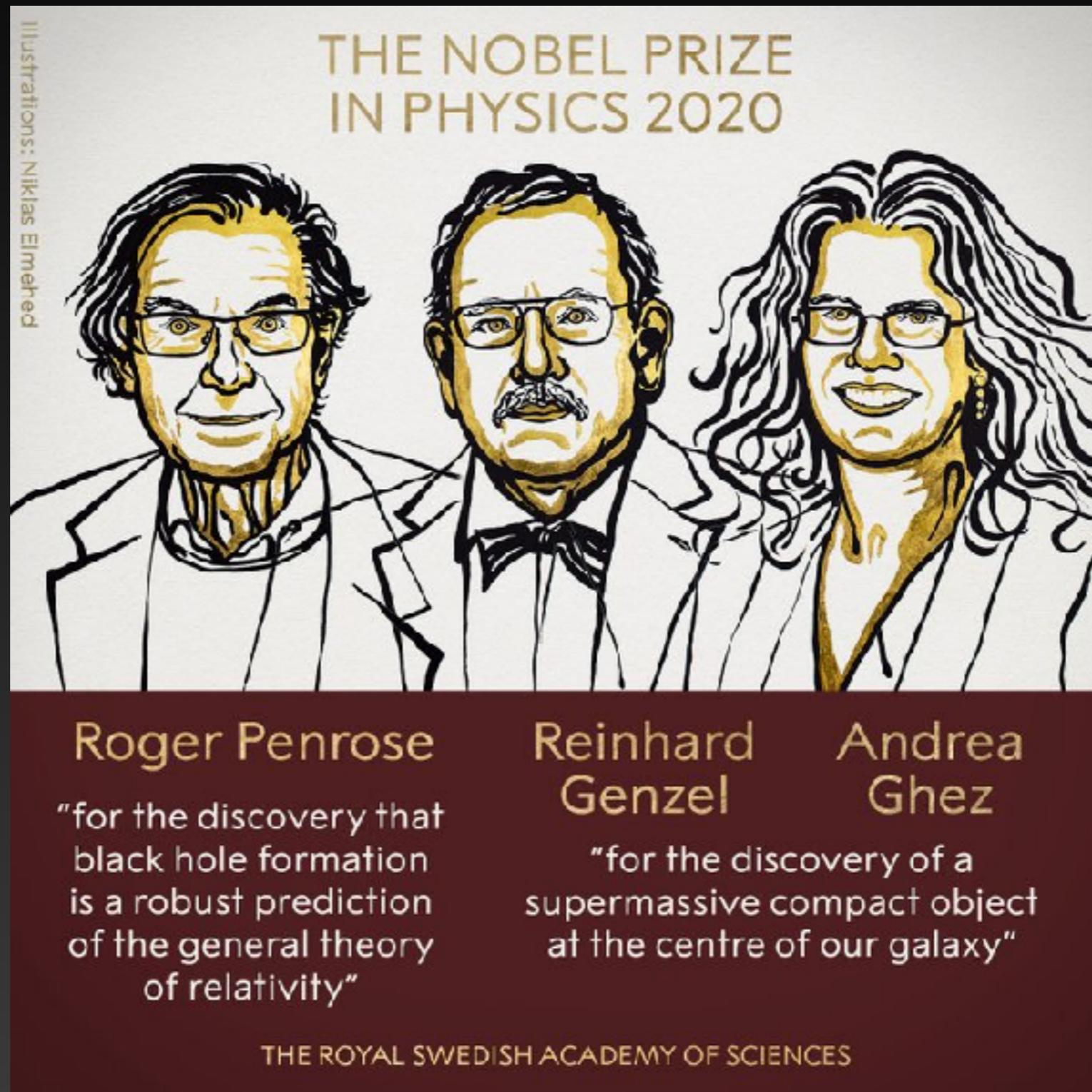
Keplerian Motion

2. Active Galaxy

- Megamaser
- Reverberation mapping method (반향효과)

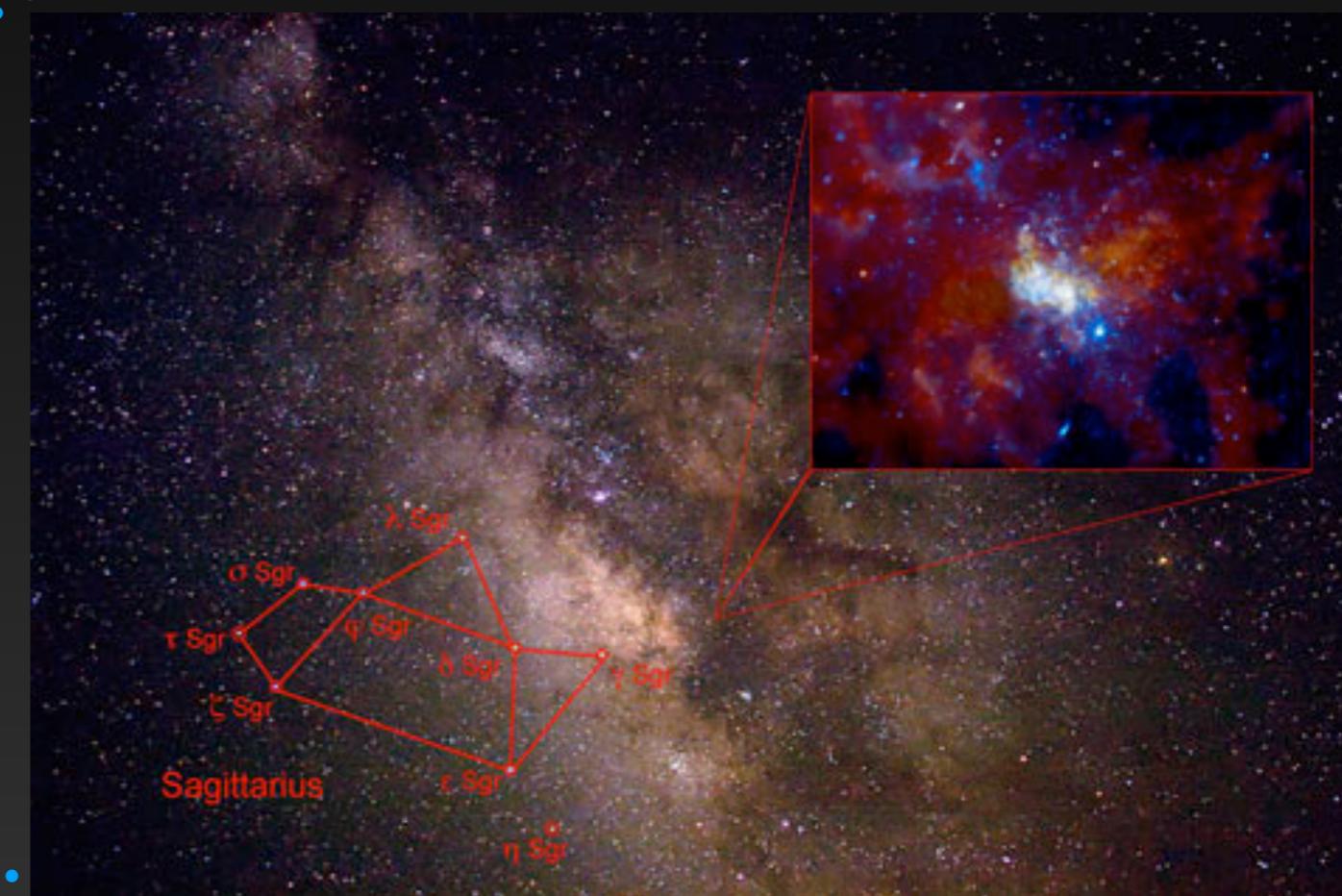
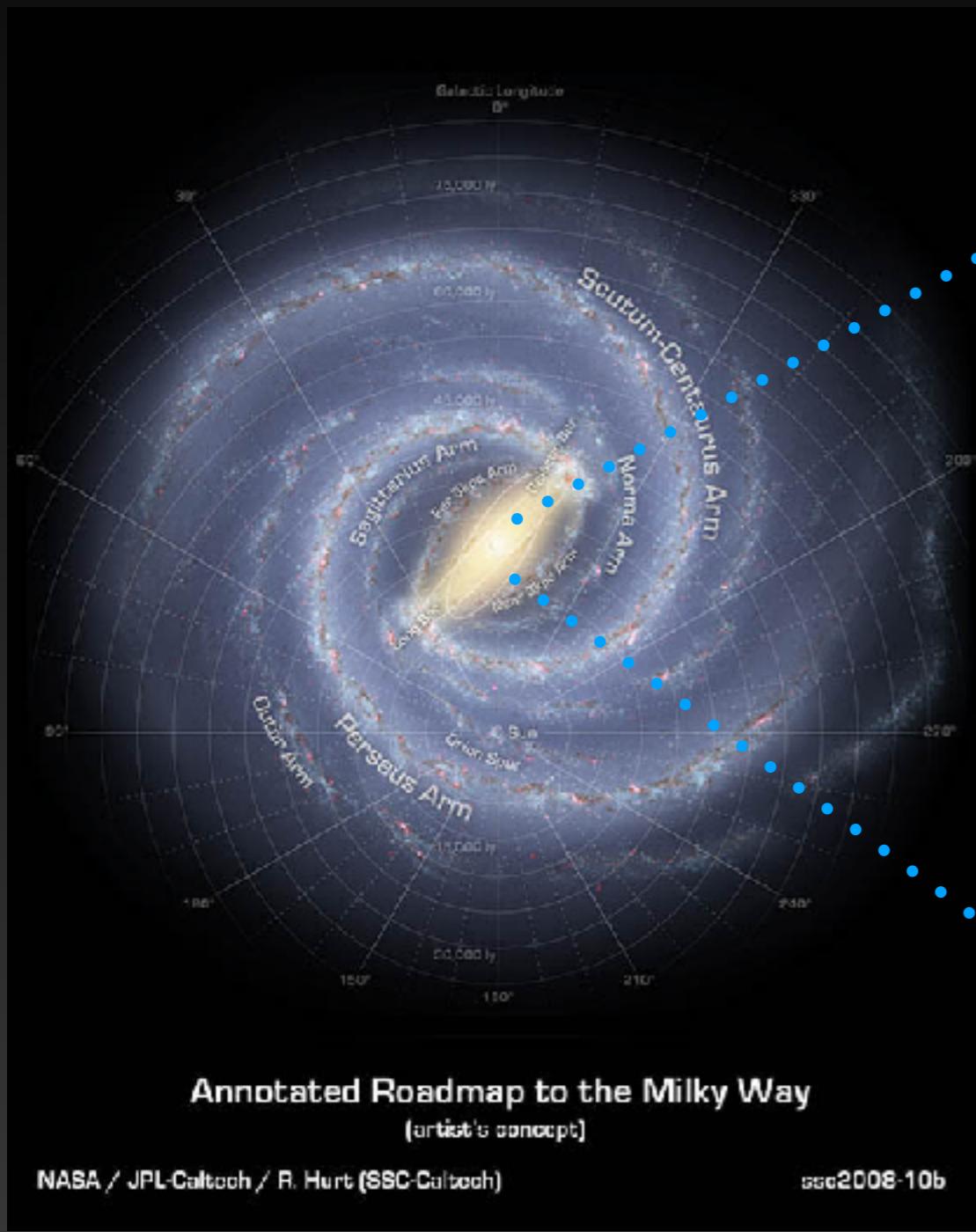
(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy



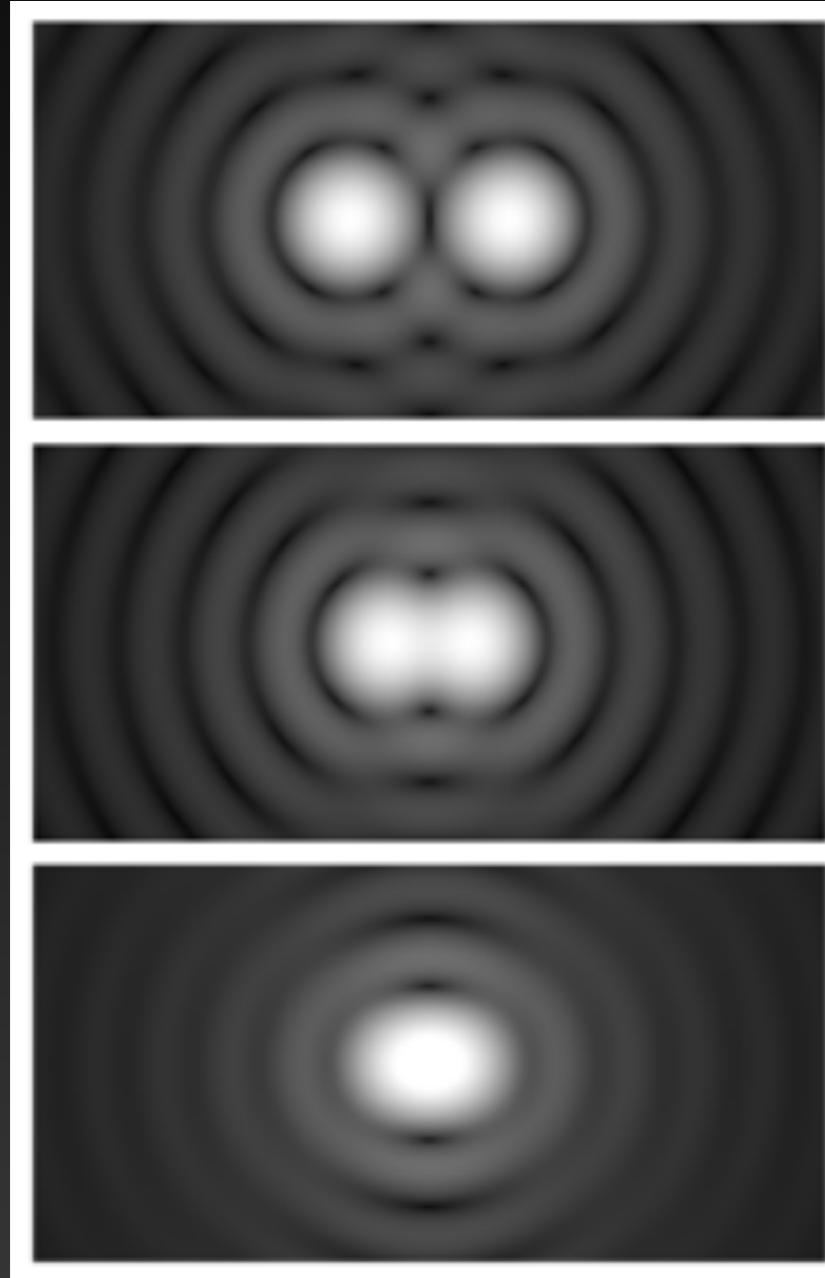
(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy

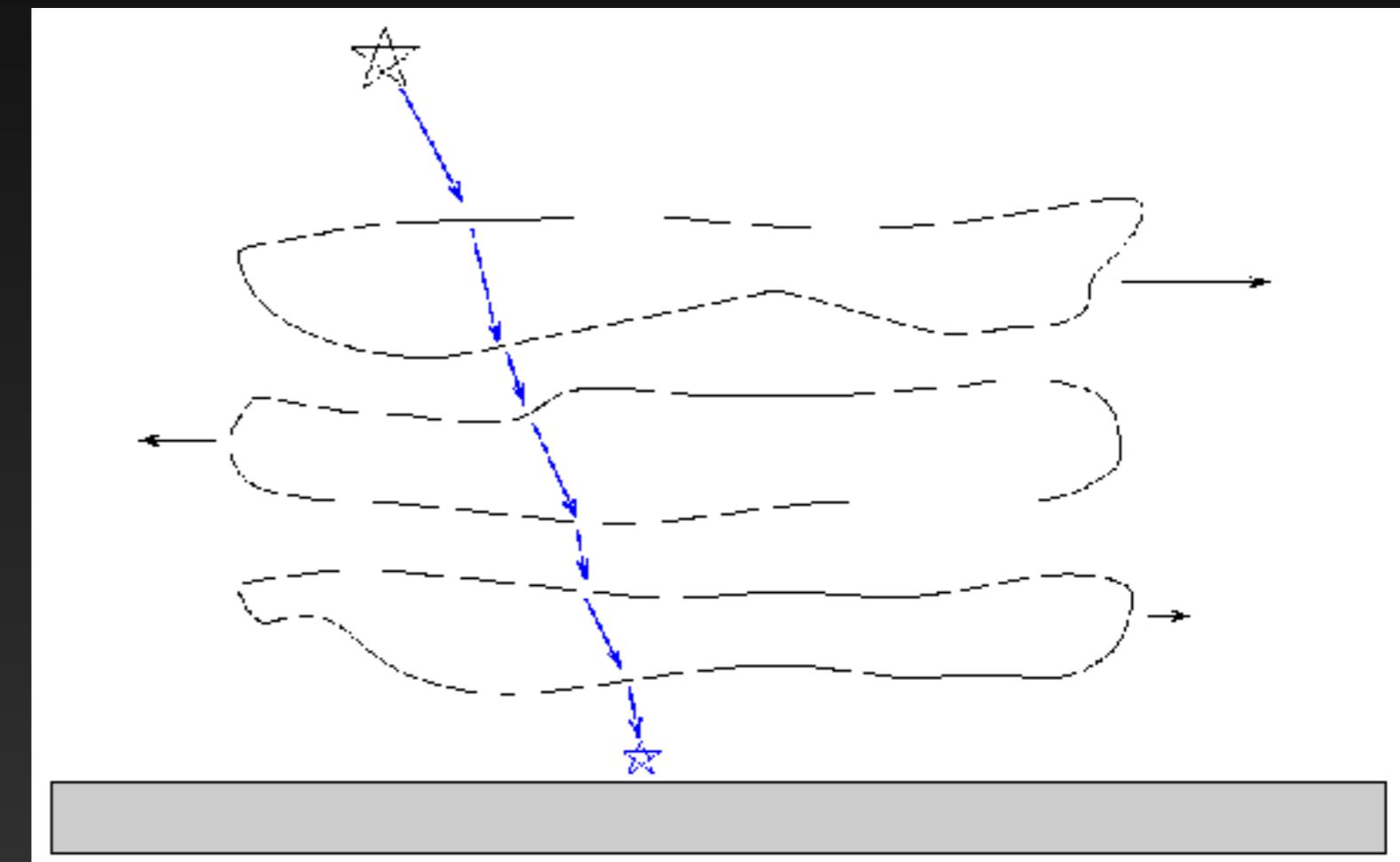


(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy



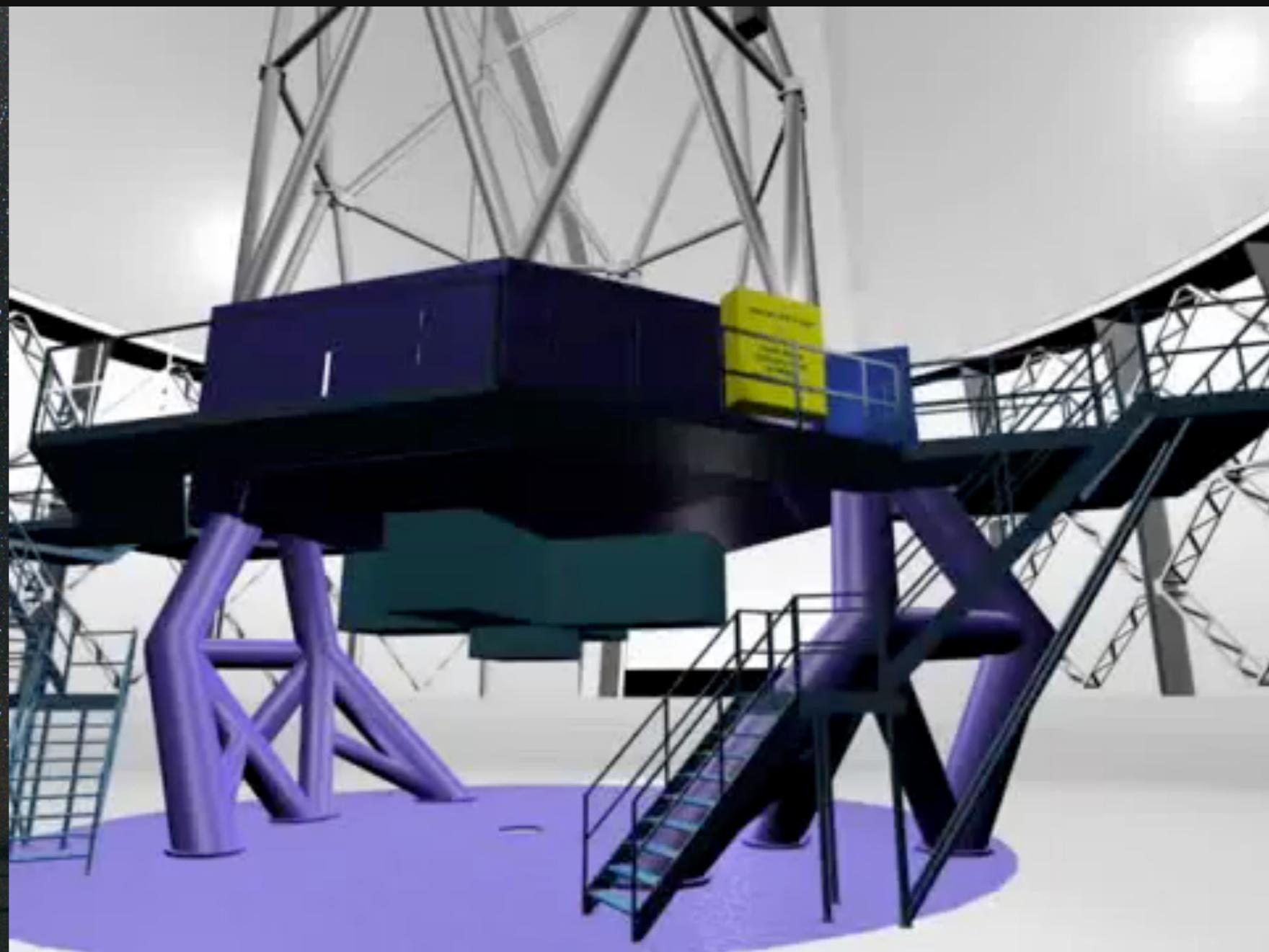
망원경의 분해능 (Seeing) : 대기에 의해서 결정



(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy

적응 광학 (Adaptive Optics)



(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy

궁수자리 (Sagittarius A*)

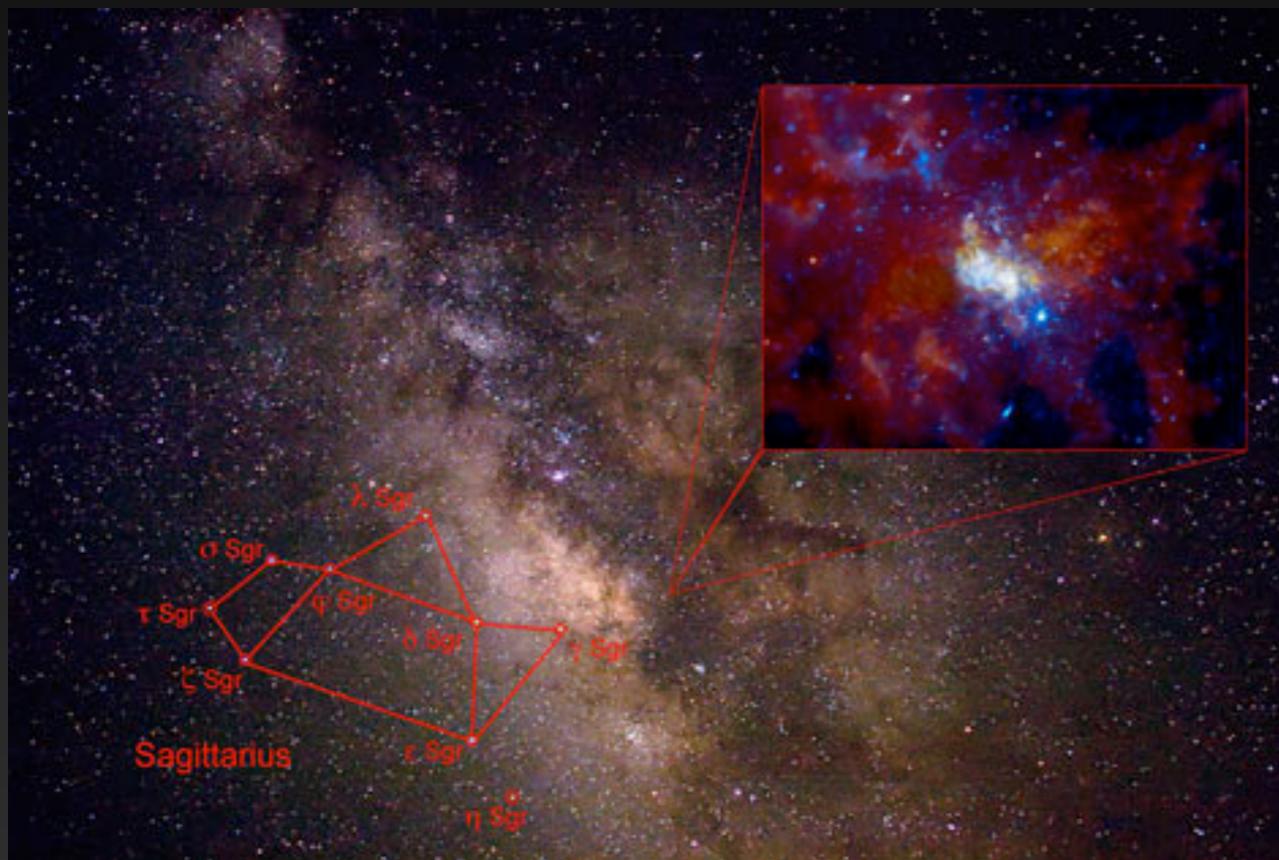
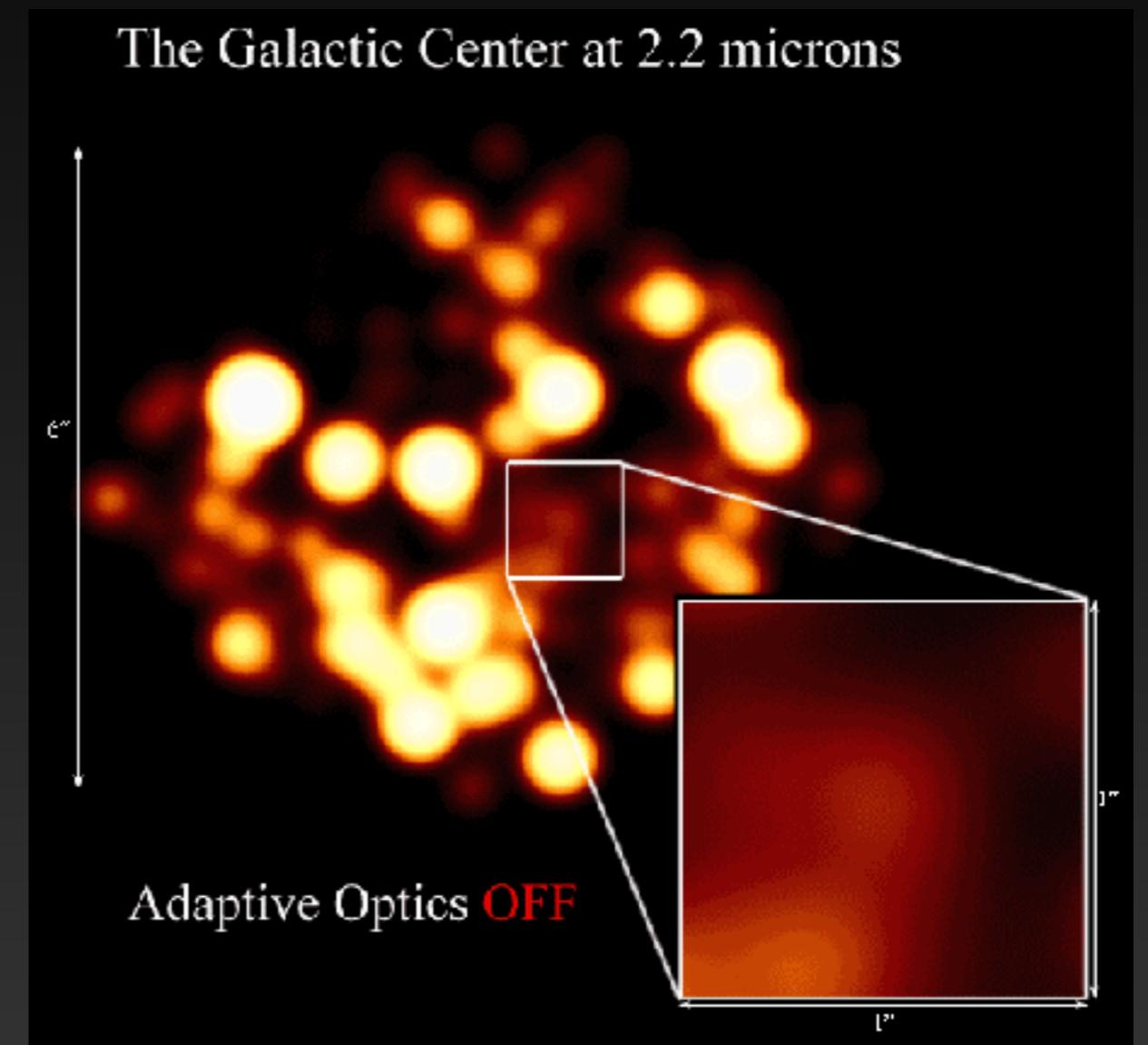


Image credit : Moondigger and
NASA/CXC/MIT/F. Baganoff, R. Shcherbakov et al.

The Galactic Center at 2.2 microns

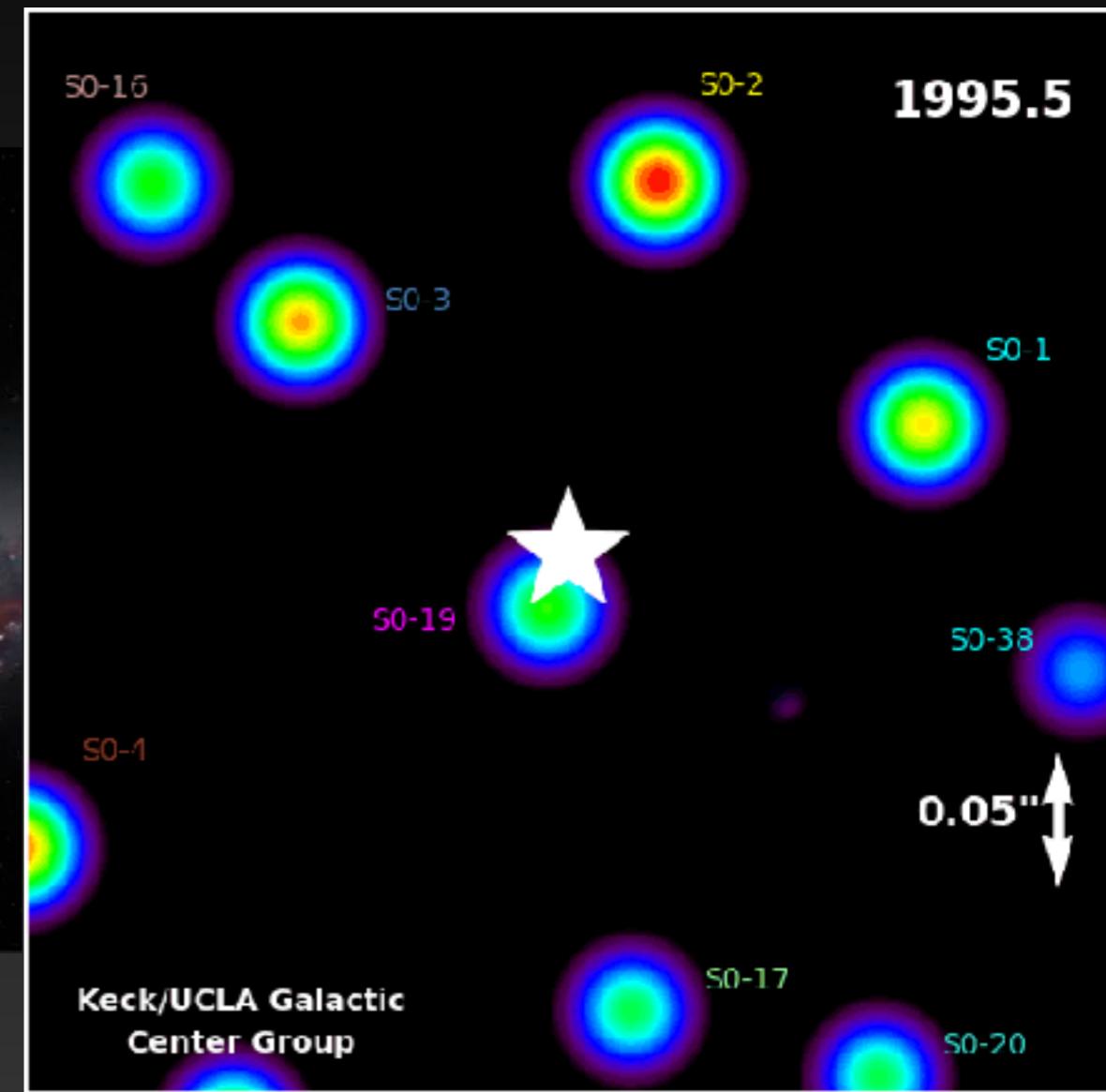


(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy



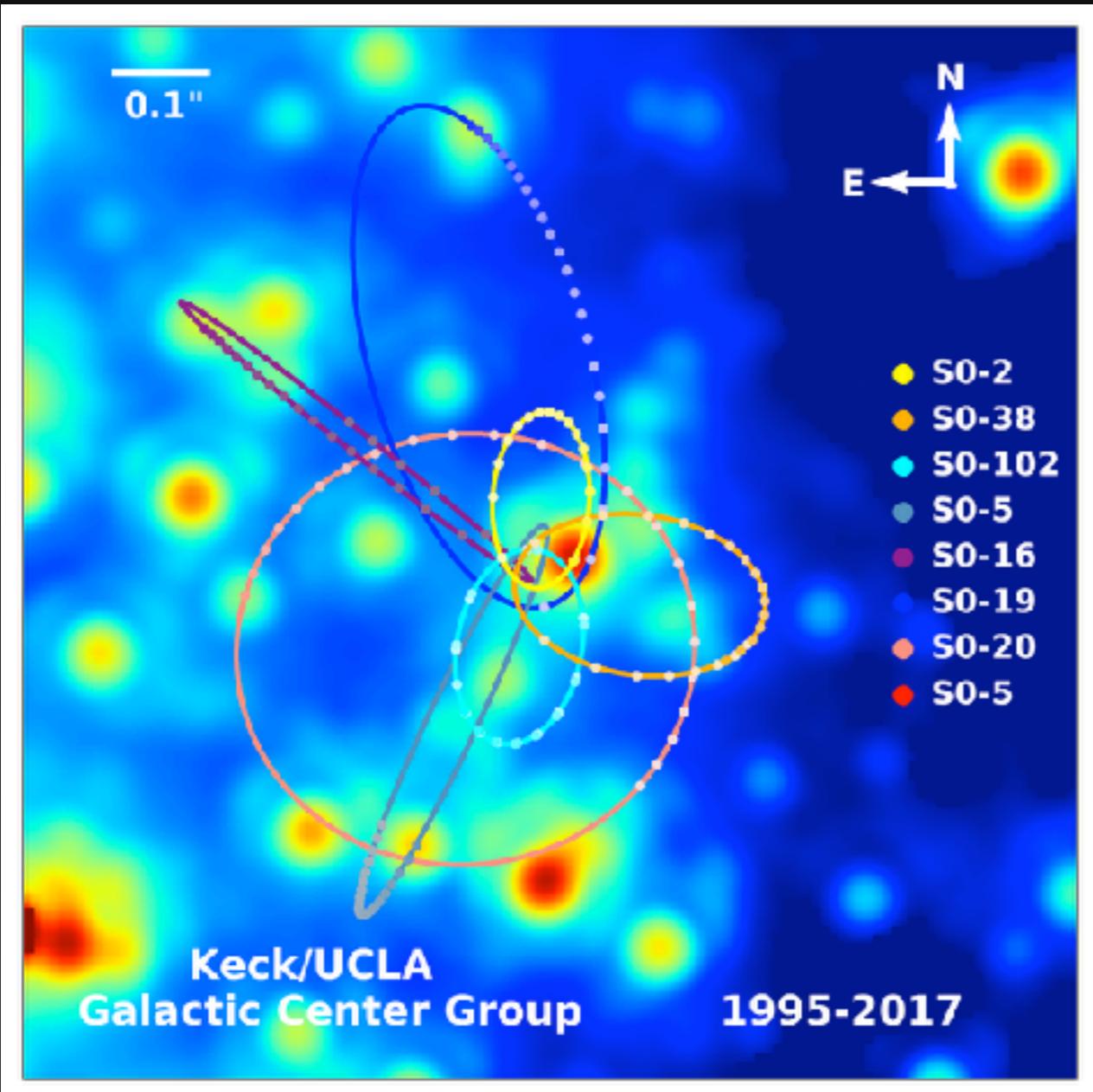
Galactic Centre Group at MPE



Keck/UCLA Galactic Center Group

(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Our Galaxy



- Kinematics of resolved stars
 - $r \sim 0.0031$ pc
 - $v \sim 3000$ km/s
- $M \sim 4 \times 10^6 M_{\odot}$
- 빛을 내지 않는 어두운 천체
→ SMBH

(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Beyond Our Galaxy



r_h : Sphere of influence of the black hole

$$\frac{\sigma^2}{2} = \frac{GM_{\text{BH}}}{r_h}$$

σ : 블랙홀 주변에서의 별의 운동 평균적인 속도

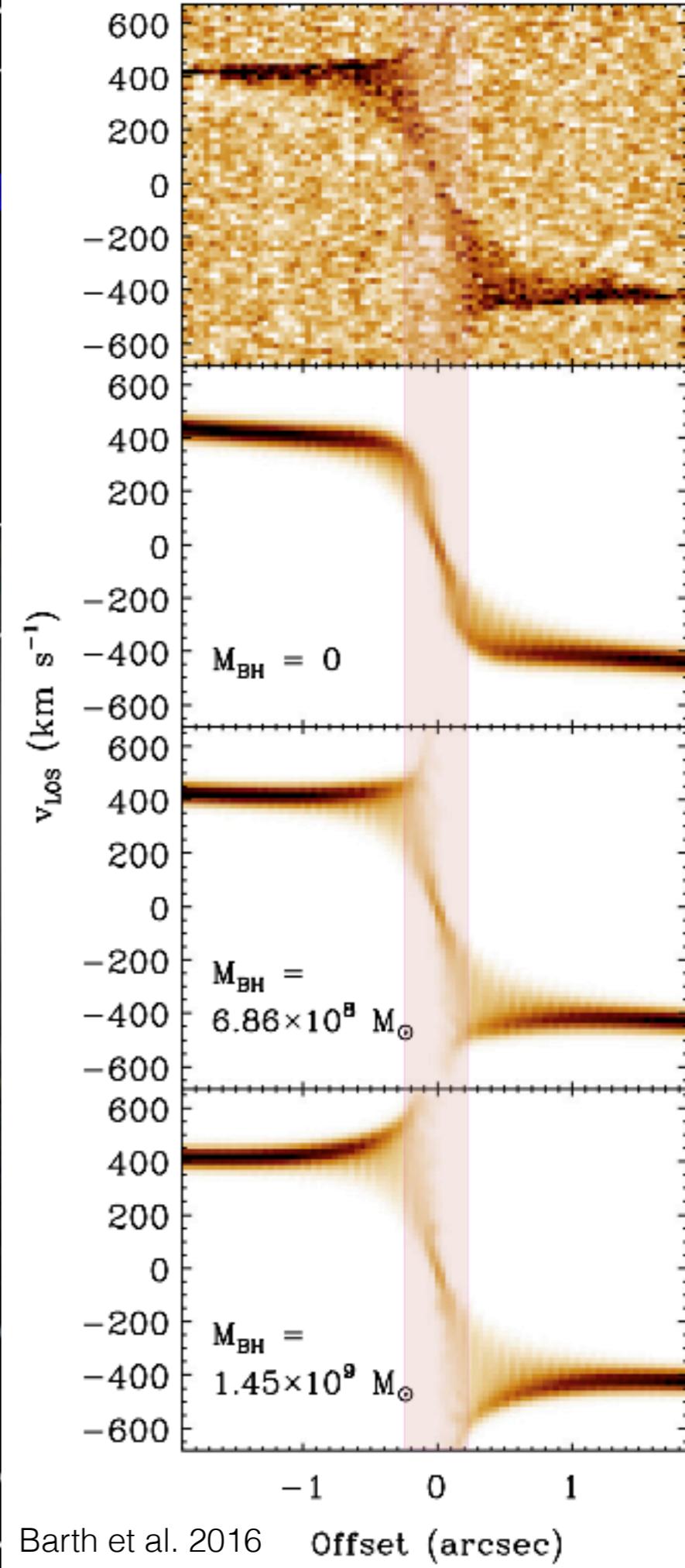
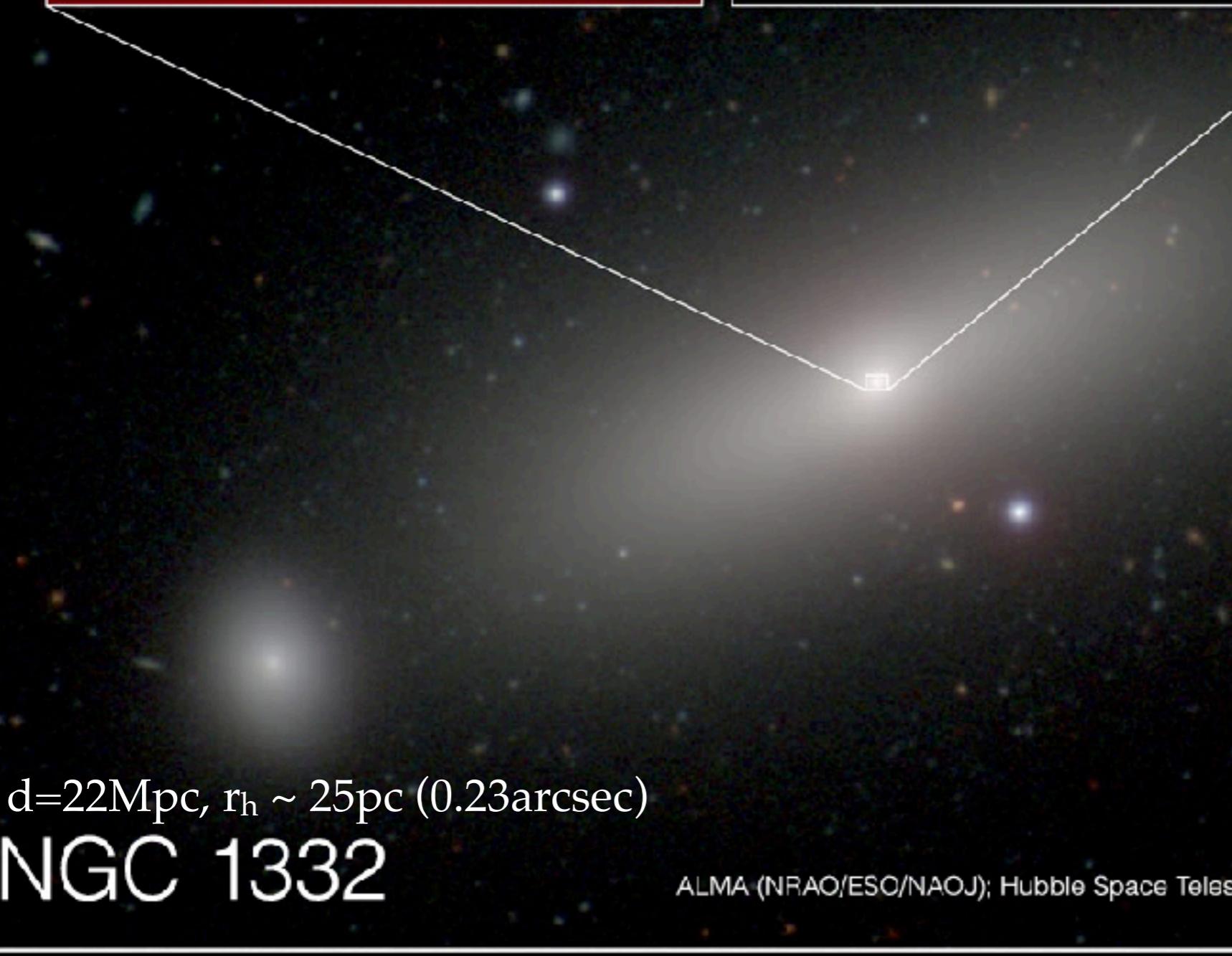
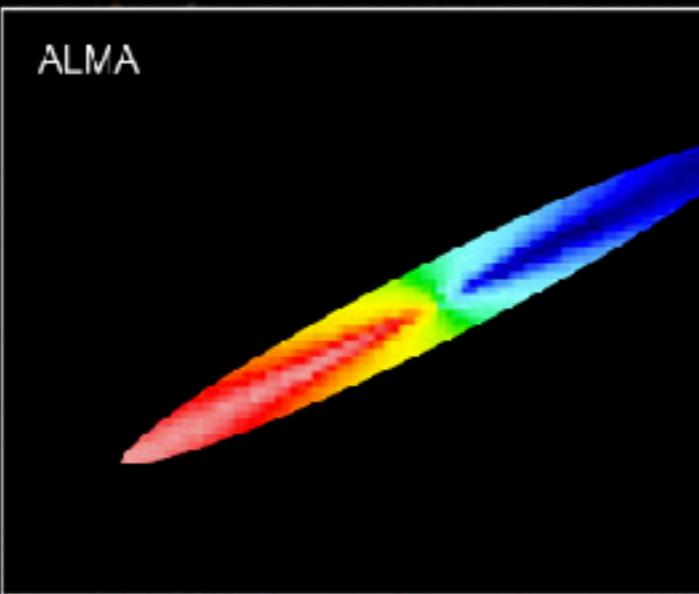
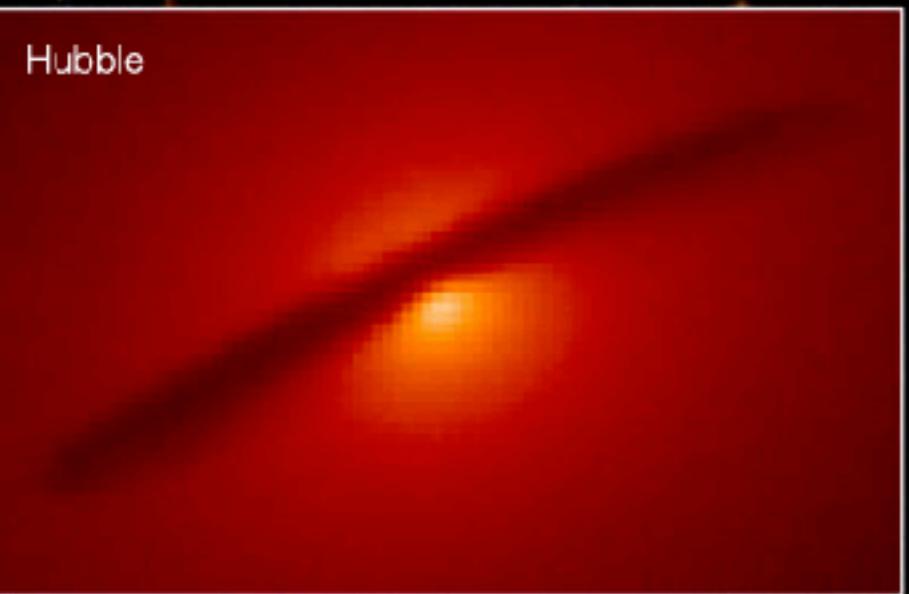
$$r_h = \frac{2GM_{\text{BH}}}{\sigma^2} \approx 10^6 r_s$$

r_s : Schwarzschild radius

ex) 10^8 solar mass, $\sigma=300\text{km/s}$

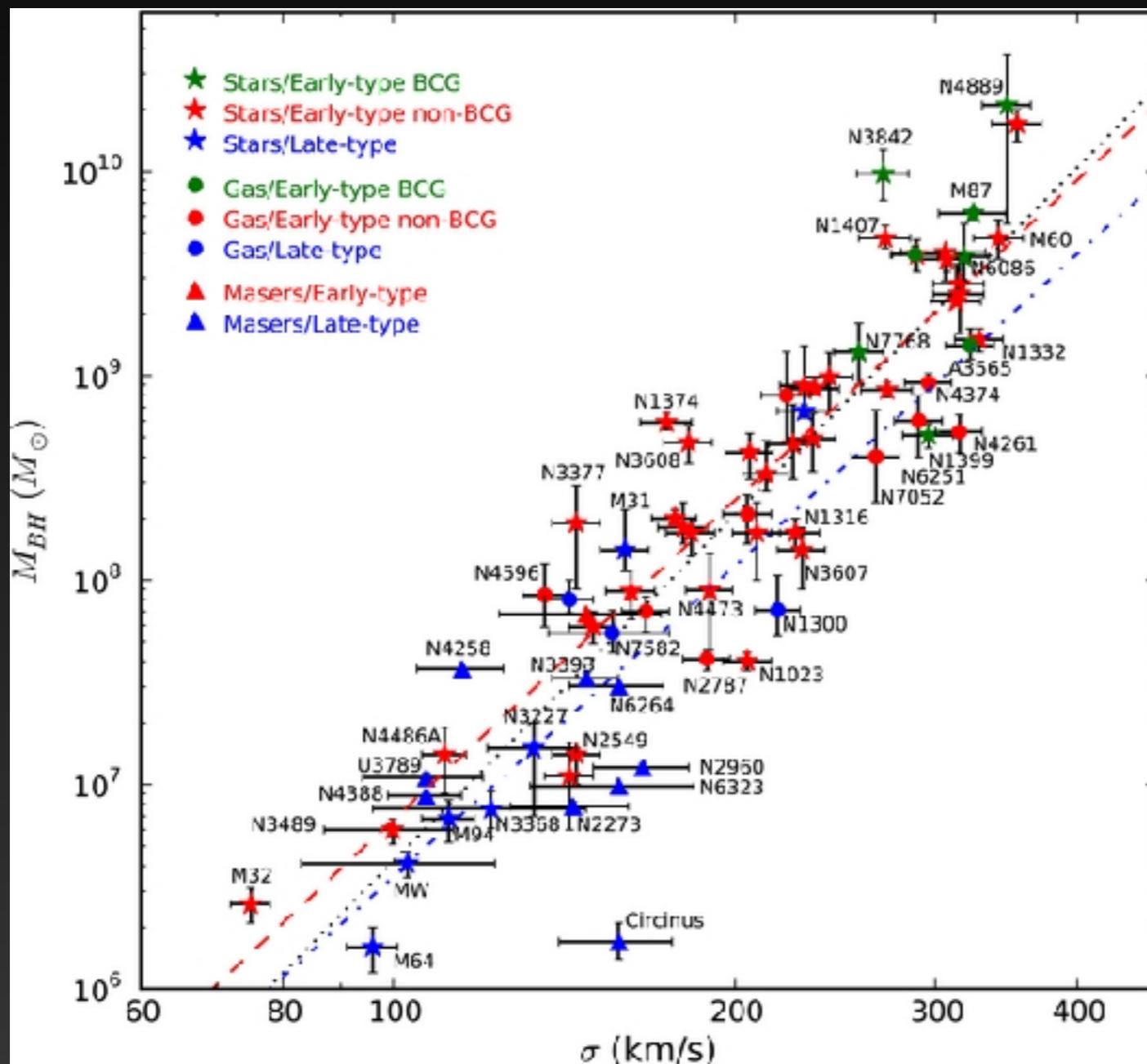
$$r_h \sim 5 \text{ pc}$$

distance	r_h (arcsec)
1Mpc	1.0
10Mpc	0.1
1000Mpc	0.001



(Conventional) Methods of detecting SMBH

1. Normal Galaxy : Beyond Our Galaxy



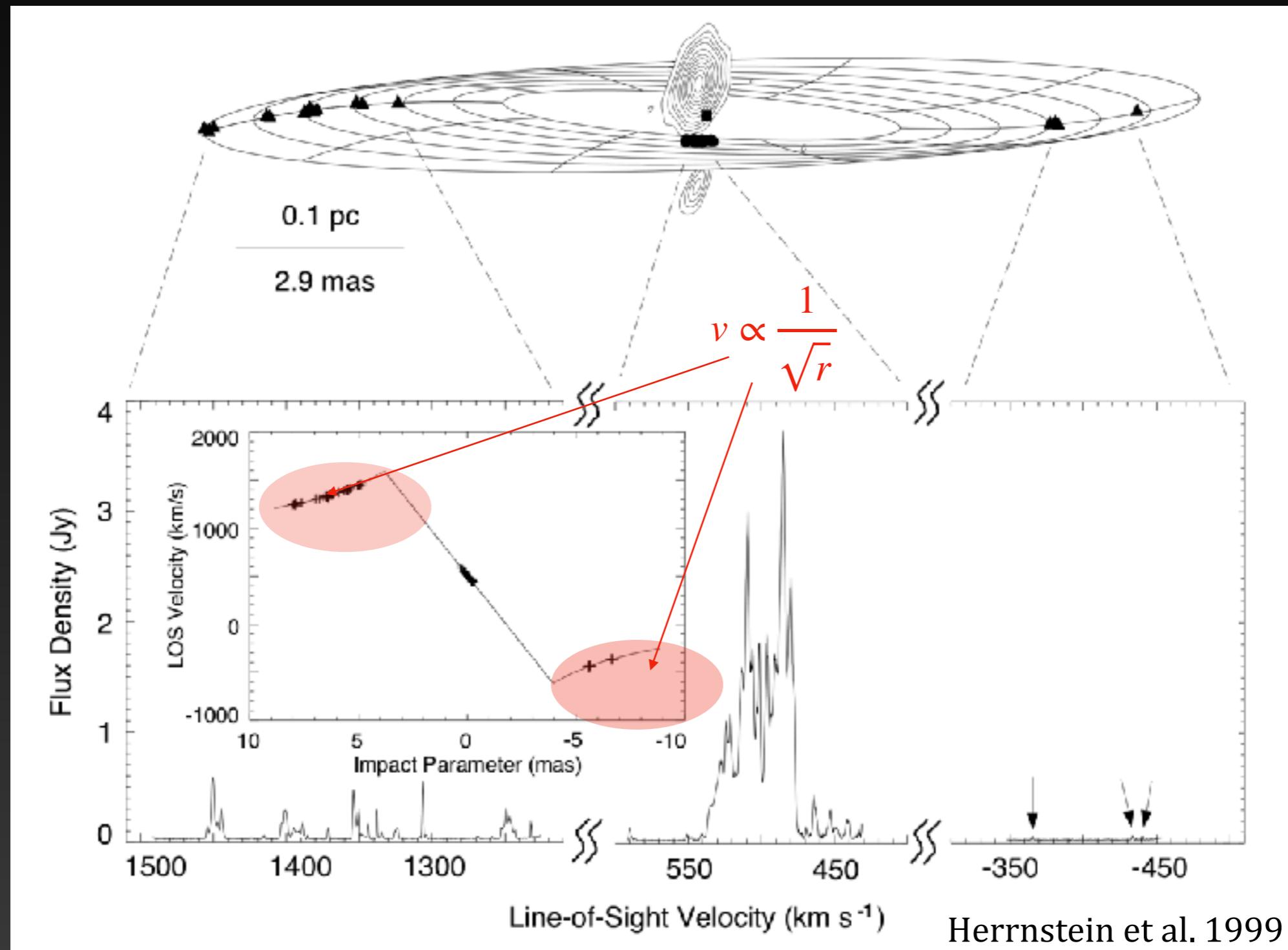
$$r_h = \frac{2GM_{\text{BH}}}{\sigma^2}$$

- Kinematics of integrated stars or gas
-> r_h 가 비교적 큰 100여개 정도의 가까운 은하
- 생각해 볼 문제 :
Sample bias가 없을까?

McConnell & Ma 2013

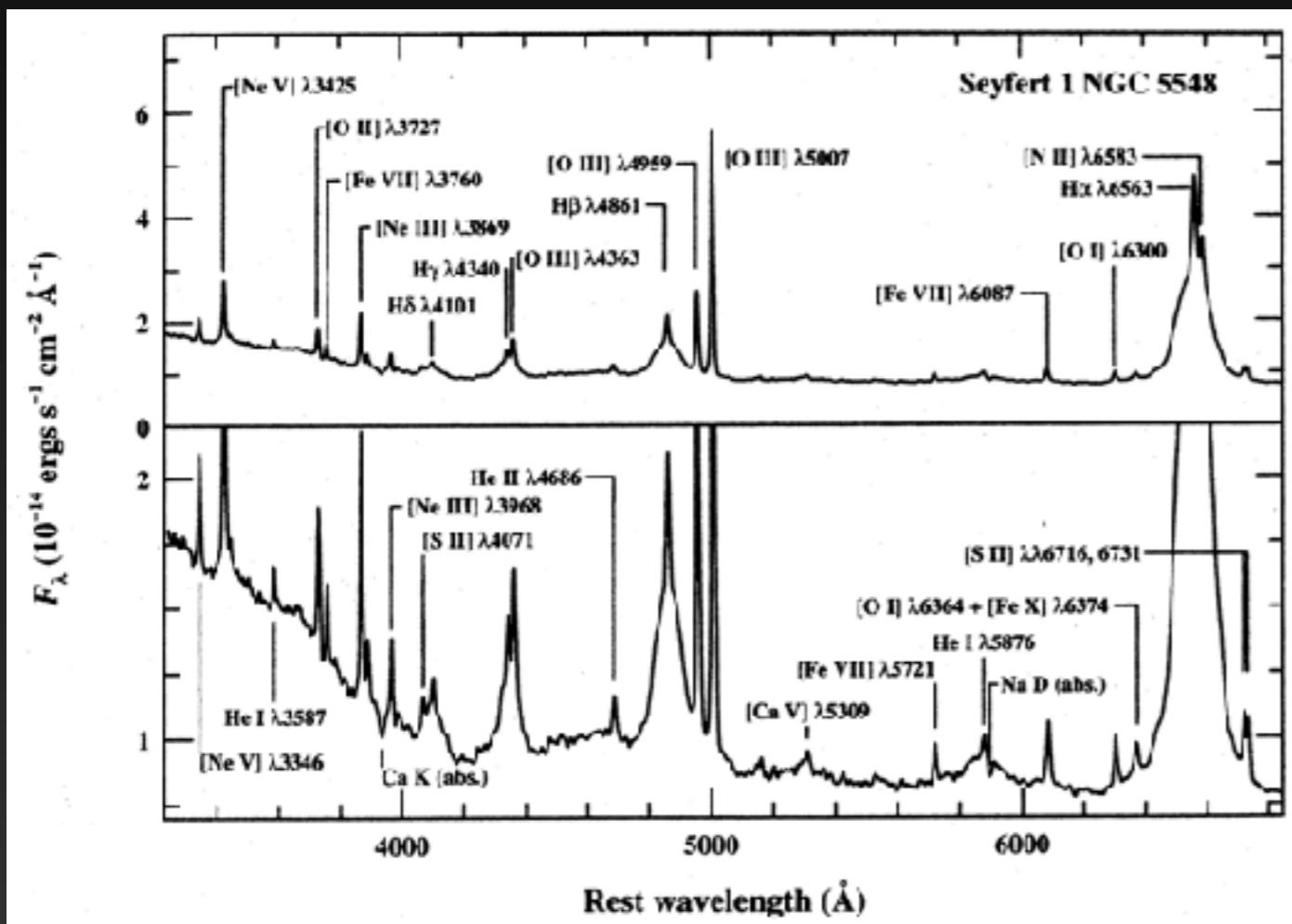
(Conventional) Methods of detecting SMBH

2. Active Galaxy (활동성 은하) - Megamaser (~20개)

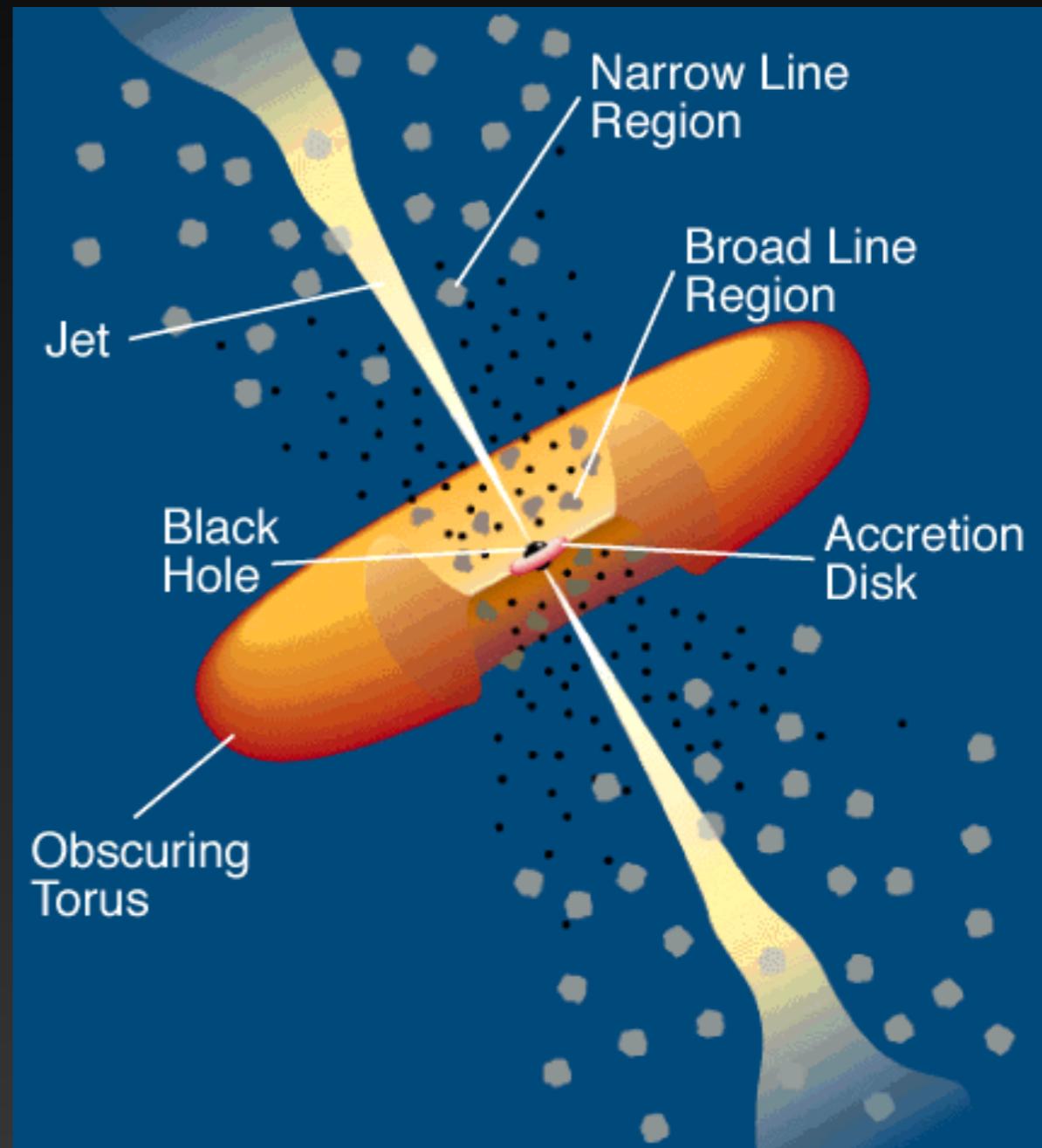


(Conventional) Methods of detecting SMBH

2. Active Galaxy (활동성 은하) - Reverberation mapping (반향효과)

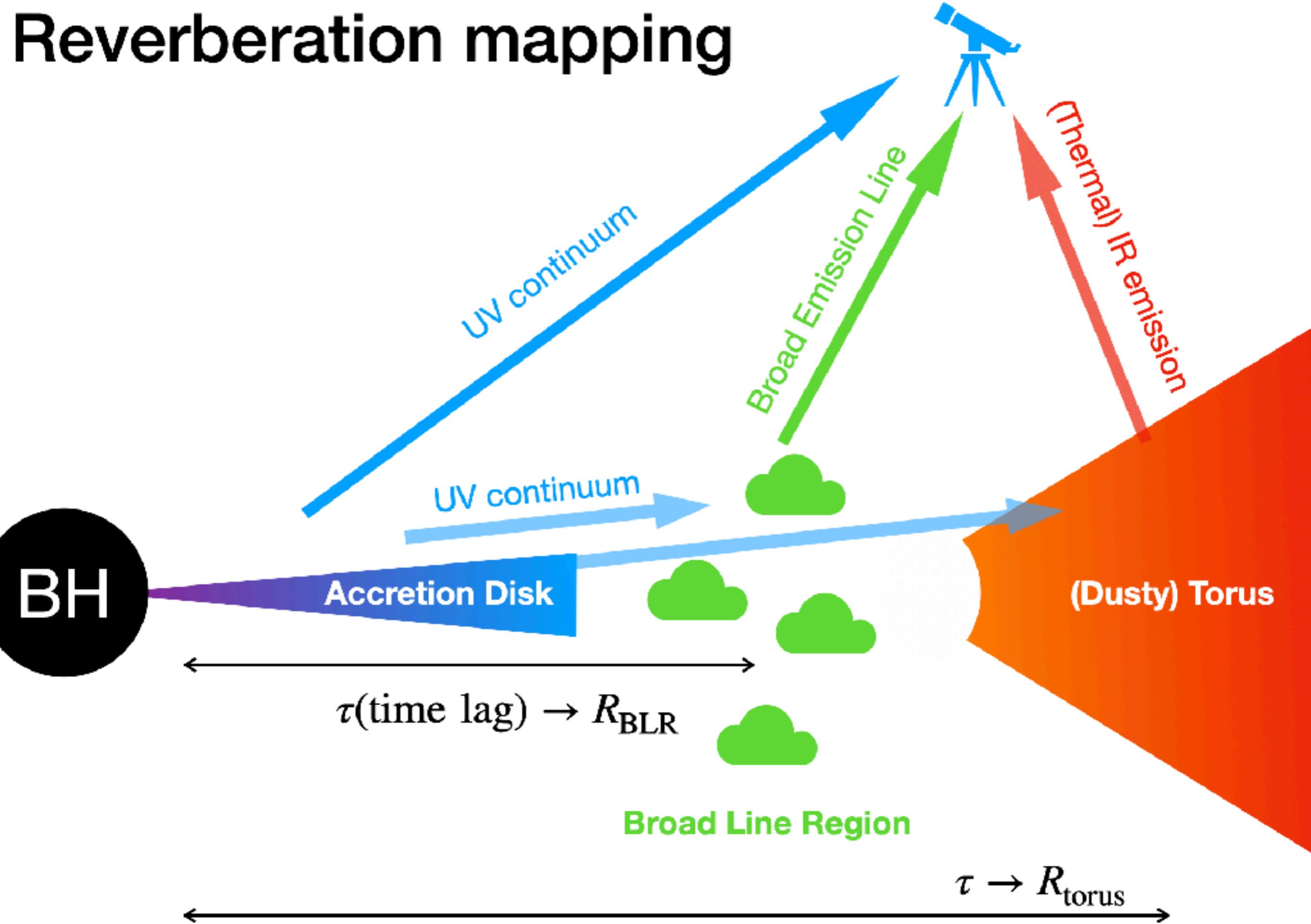


Data courtesy of A. V. Filippenko



Urry & Padovani 1995

Reverberation mapping

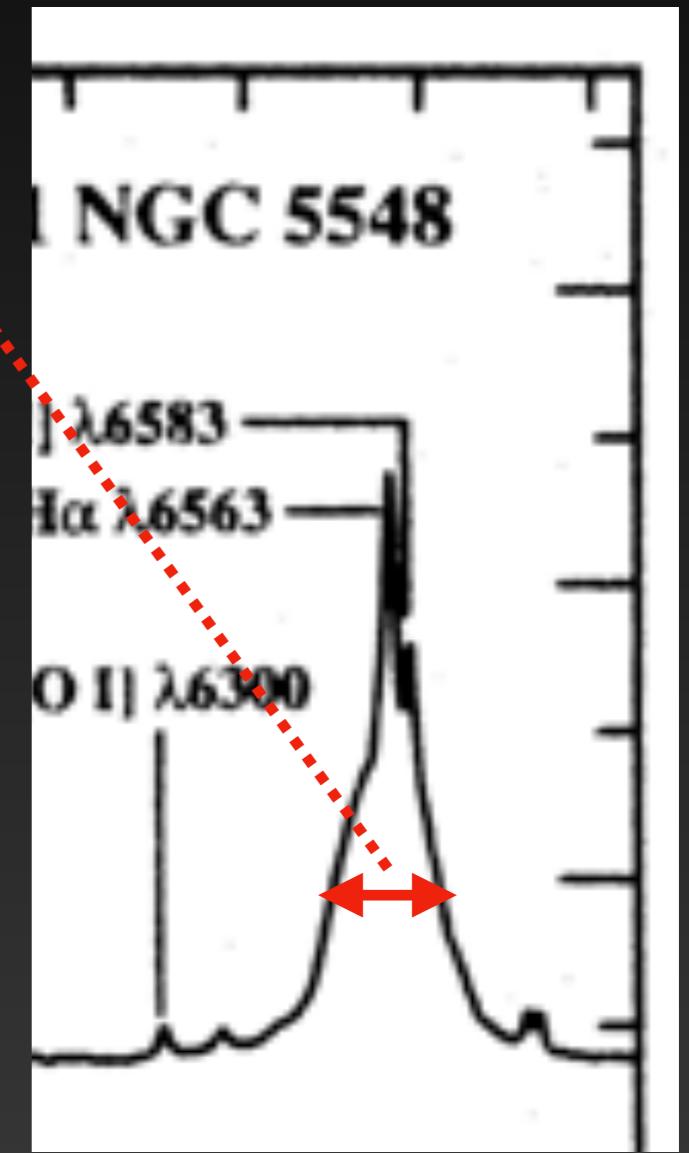
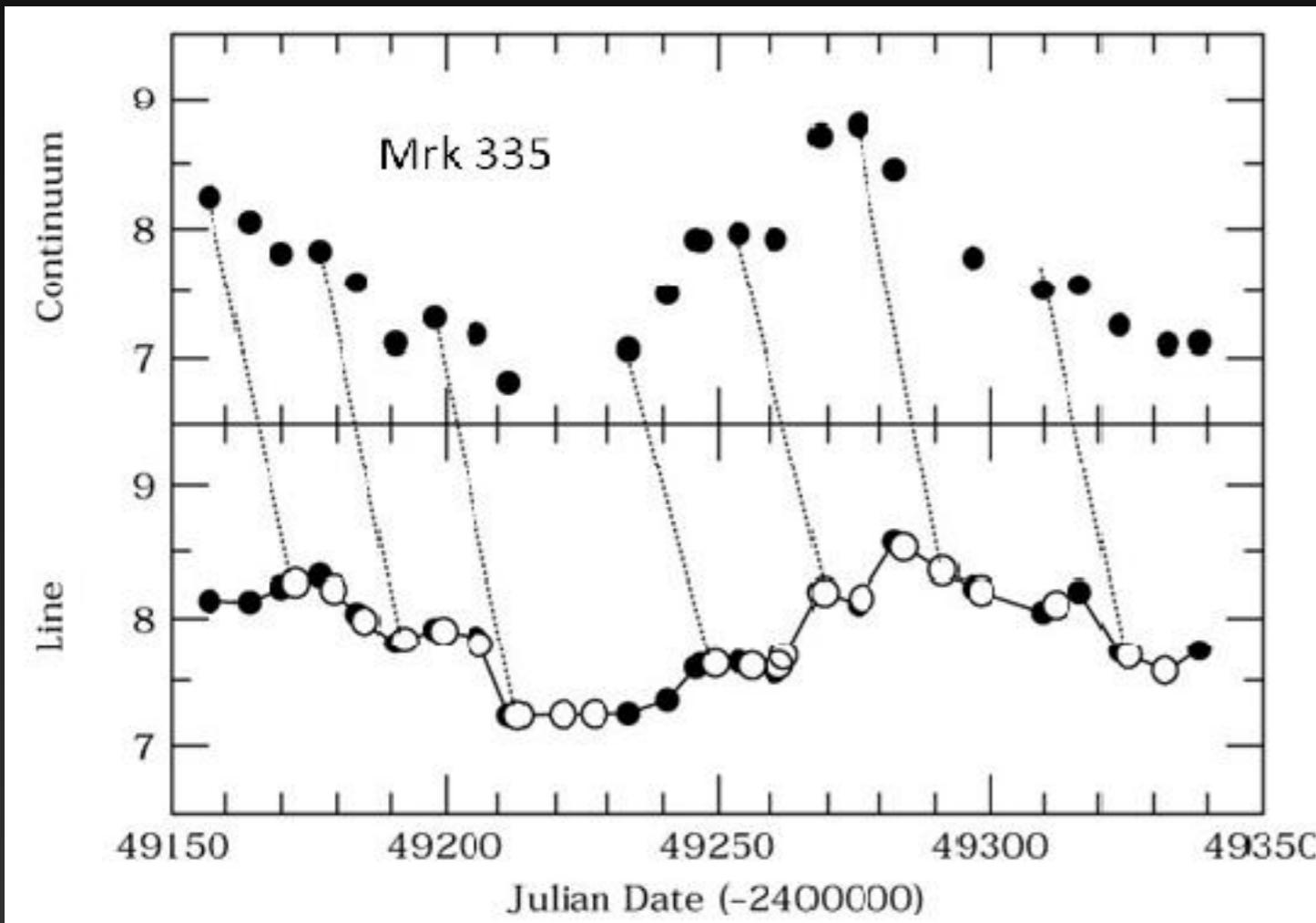


(Conventional) Methods of detecting SMBH

2. Active Galaxy (활동성 은하) - Reverberation mapping (반향효과)

$$R \approx c\Delta\tau$$

$$M_{BH} \approx \frac{Rv^2}{G}$$



(Conventional) Methods of detecting SMBH

2. Active Galaxy (활동성 은하) - Reverberation mapping (반향효과)

$$M_{BH} \approx \frac{Rv^2}{G}$$

1. 매우 비싼 관측

- 수년간 주기적으로 측광/분광 관측 데이터를 얻어야 함.

2. time lag을 못 얻을 가능성도 있음.

3. 대략 100여개의 활동성 은하에 대한 BH 질량 측정이 이루어졌음.

쌍거대질량블랙홀(SMBH binary)

GW 이전과 이후에 어떤 일이?

Galaxy Evolution

The Illustris Collaboration

Visualization: Shy Genel



Extreme Science and Engineering
Discovery Environment



PARTNERSHIP FOR
ADVANCED COMPUTING
IN EUROPE

Mark Vogelsberger

Shy Genel

Volker Springel

Paul Torrey

Debora Sijacki

Dandan Xu

Greg Snyder

Simeon Bird

Dylan Nelson

Lars Hernquist



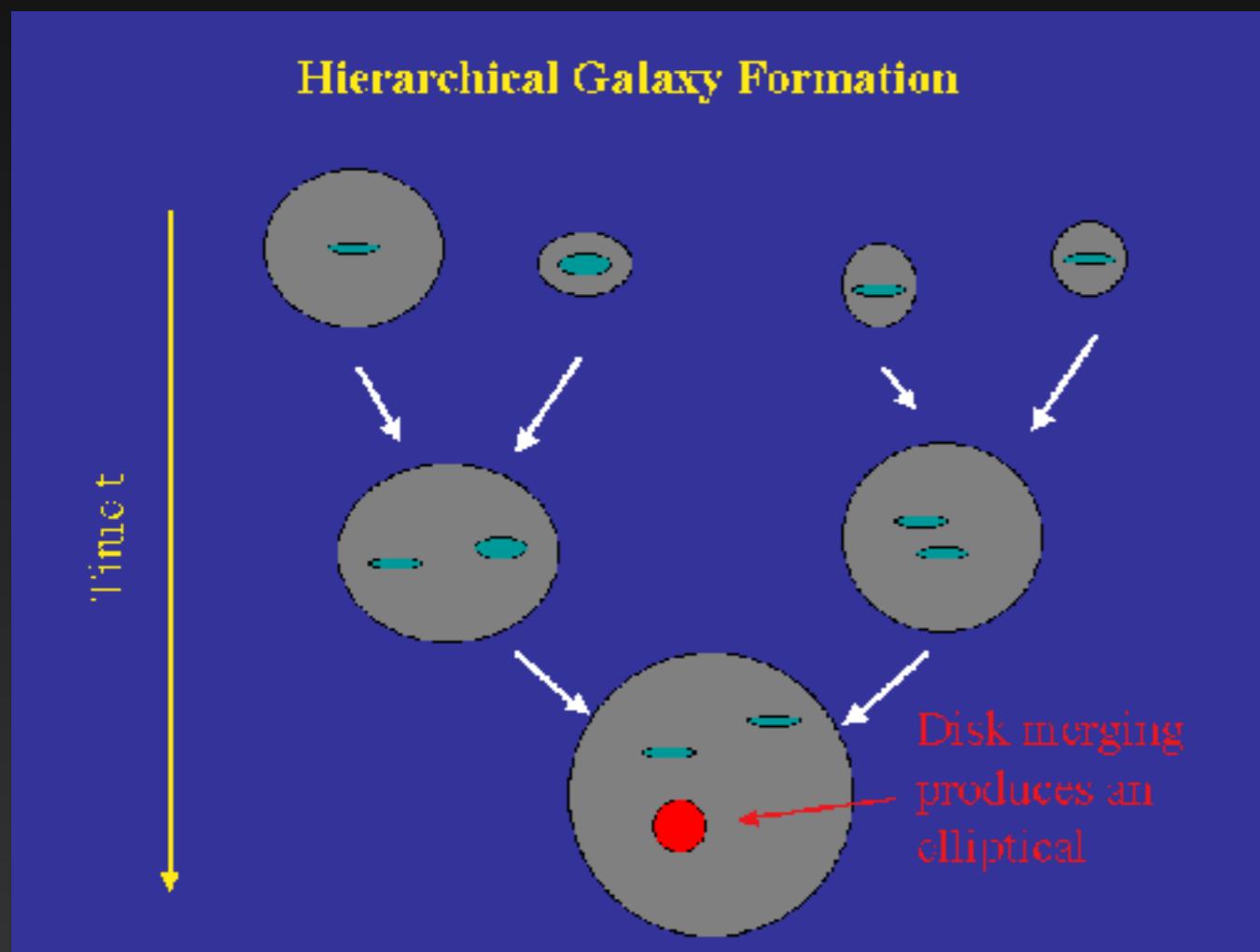
SPACE
TELESCOPE
SCIENCE
INSTITUTE



Galaxy Evolution

Hierarchical galaxy formation

Massive galaxies have undergone at least one major merger in their life time!

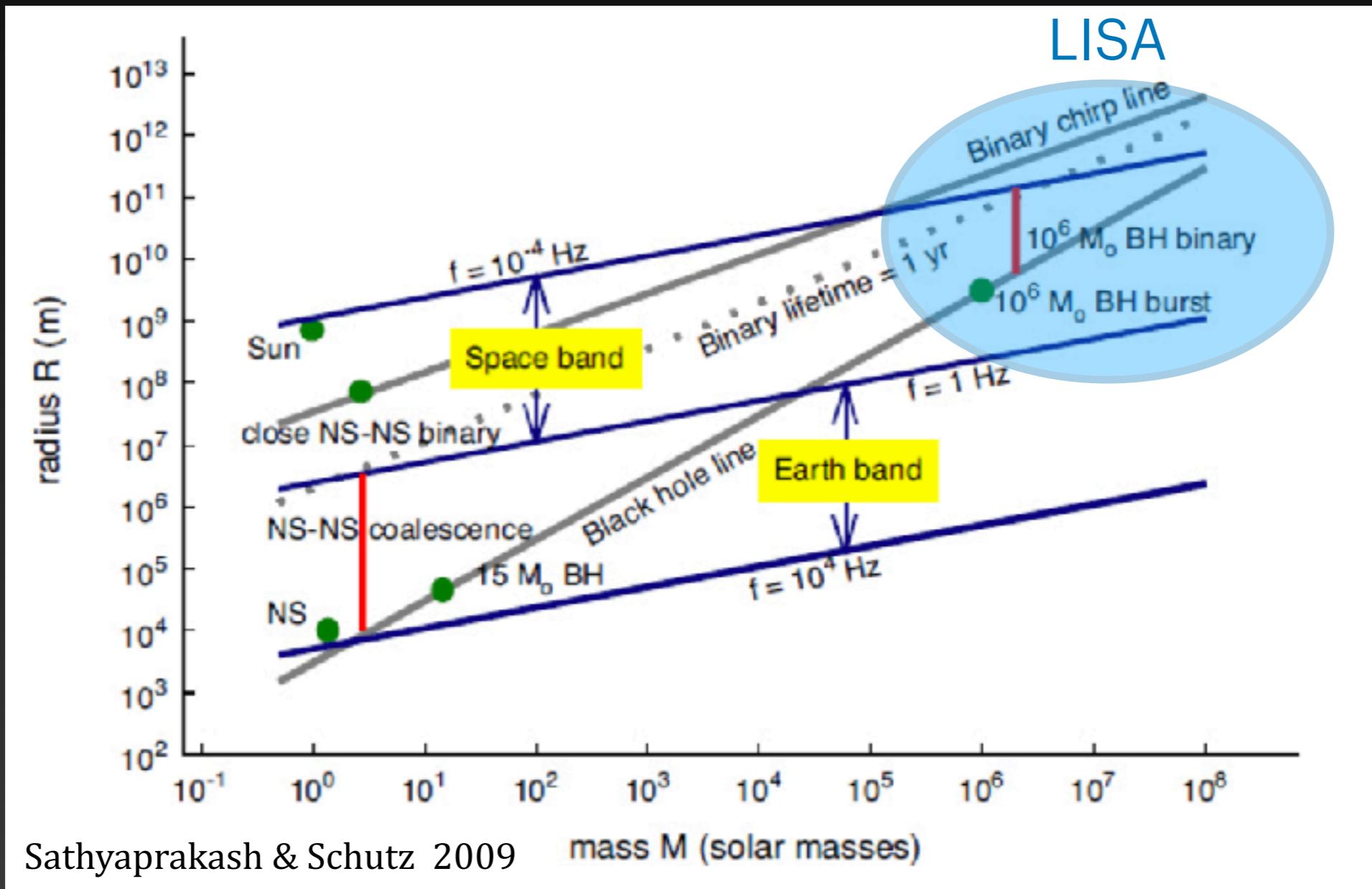


Credit: NASA, ESA, the Hubble Heritage Team
(STScI/AURA)-ESA/Hubble Collaboration and K. Noll (STScI)

GW from SMBH binary

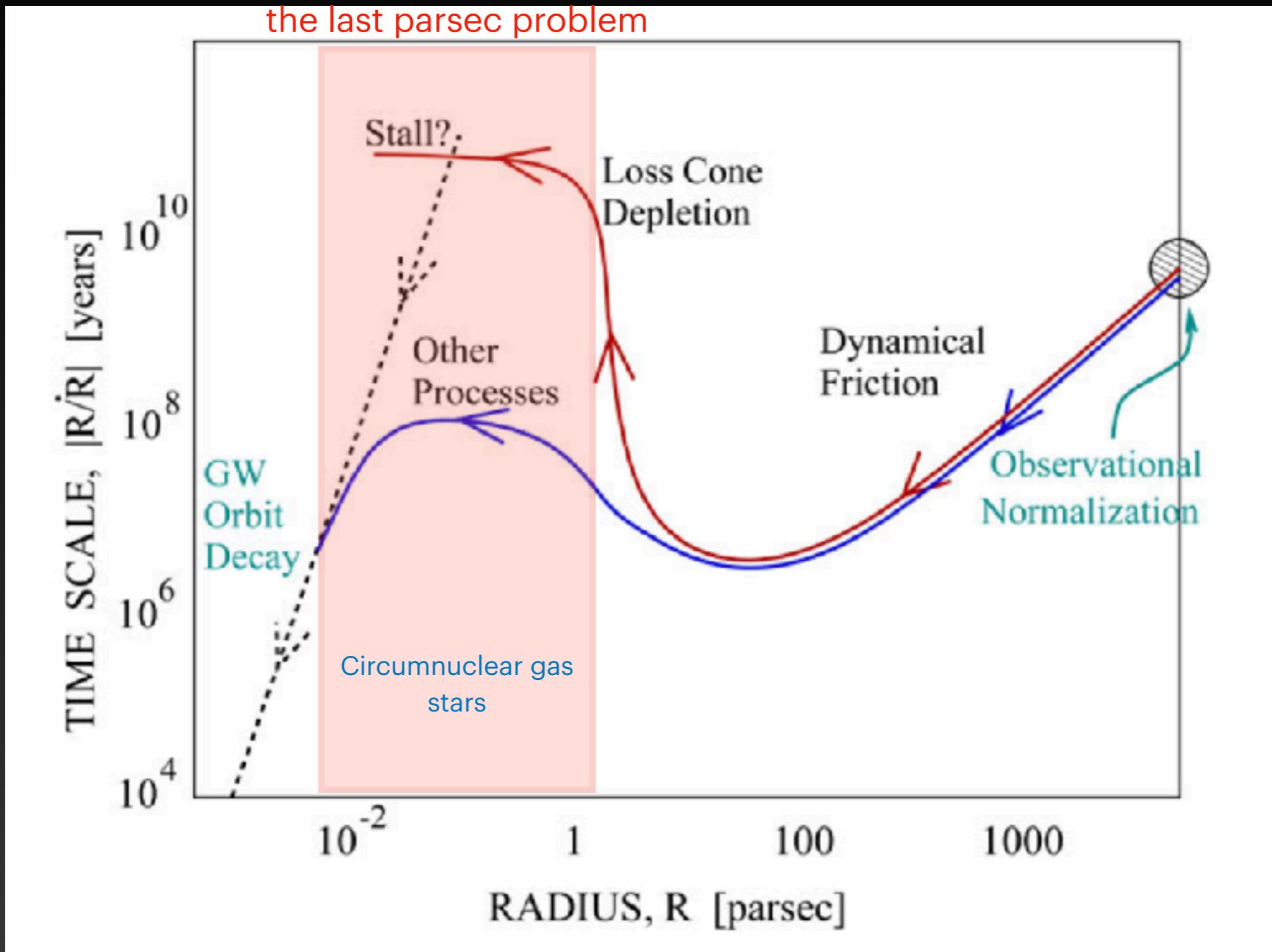
Characteristics frequency

$$f_0 = \sqrt{G\rho/4\pi} = \frac{1}{4\pi} \left(\frac{3M_{\text{BH}}}{r_s^3} \right)^{1/2} \approx 1\text{kHz} \left(\frac{10M_\odot}{M_{\text{BH}}} \right) \quad r_s = \frac{2GM_{\text{BH}}}{c^2}$$

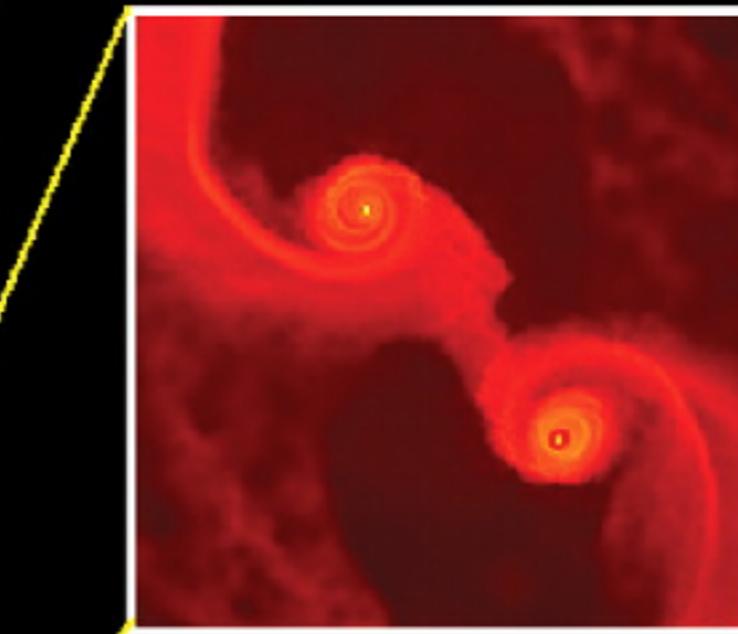
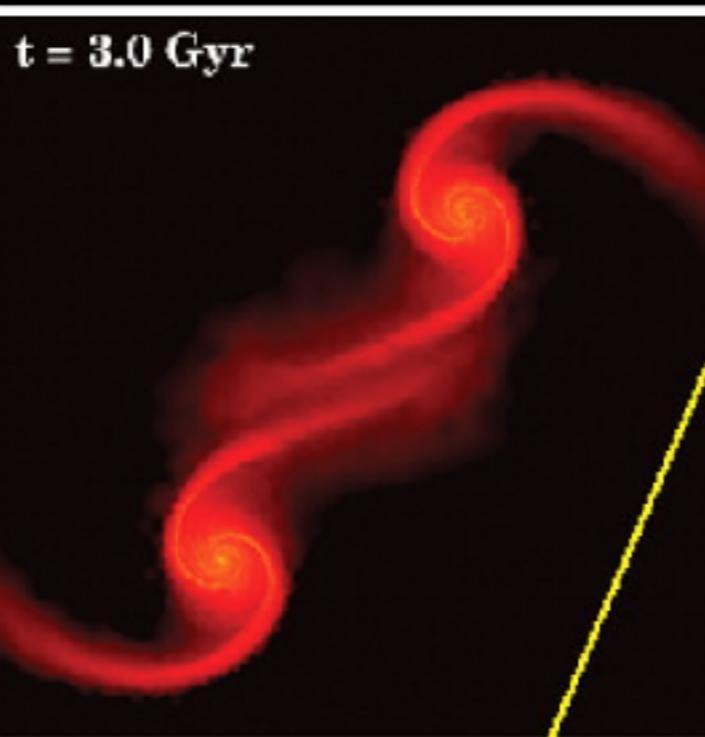
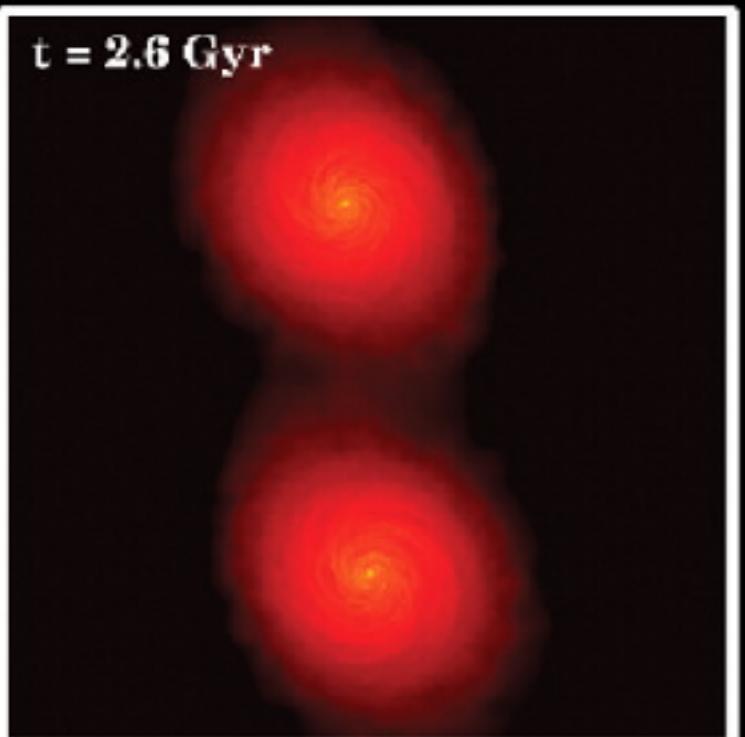


Evolution of SMBH binary

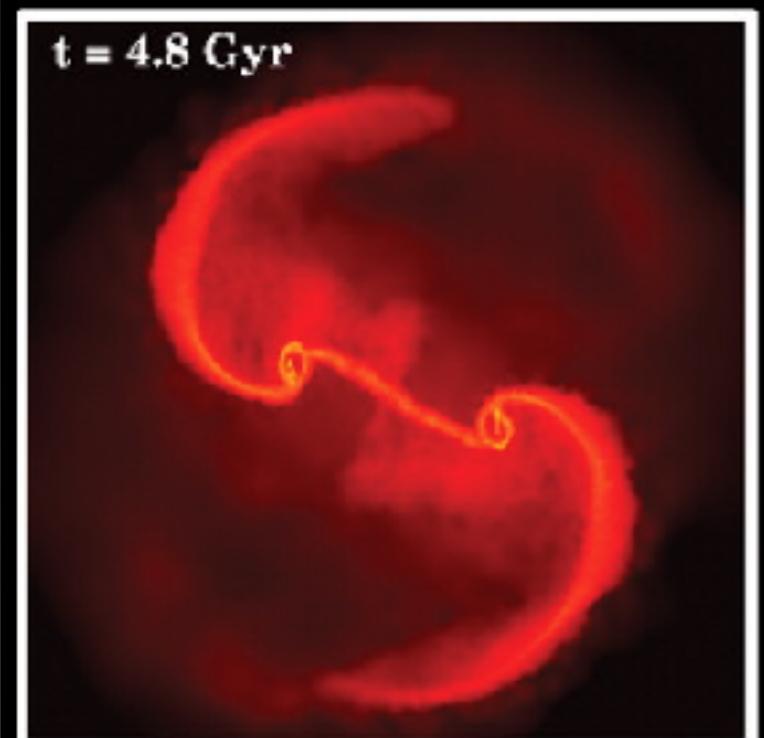
the last parsec problem



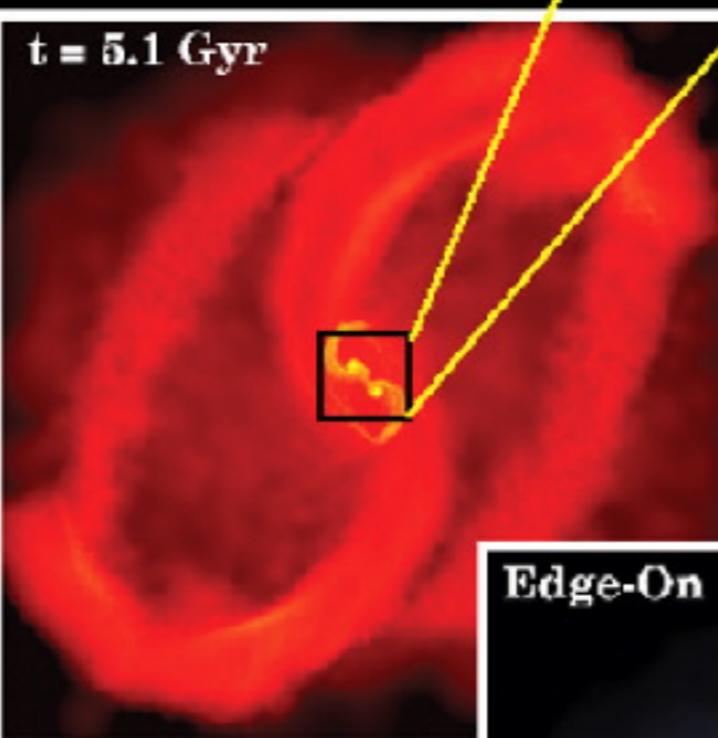
$t = 2.6 \text{ Gyr}$



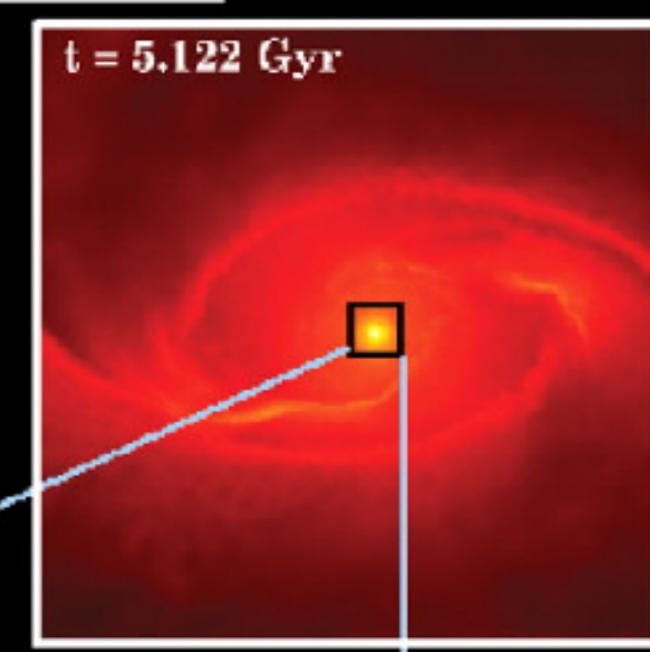
$t = 4.8 \text{ Gyr}$



$t = 5.1 \text{ Gyr}$



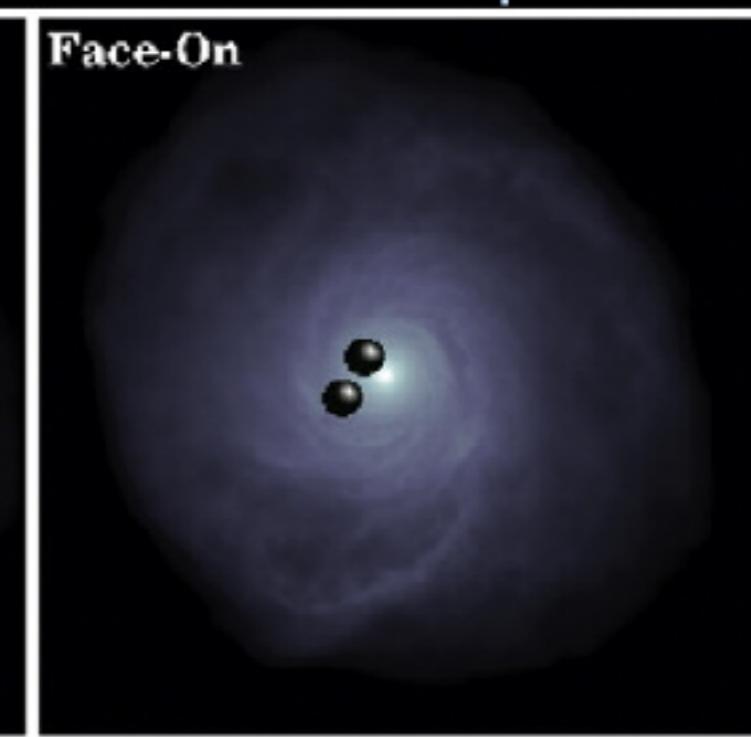
$t = 5.122 \text{ Gyr}$



Edge-On

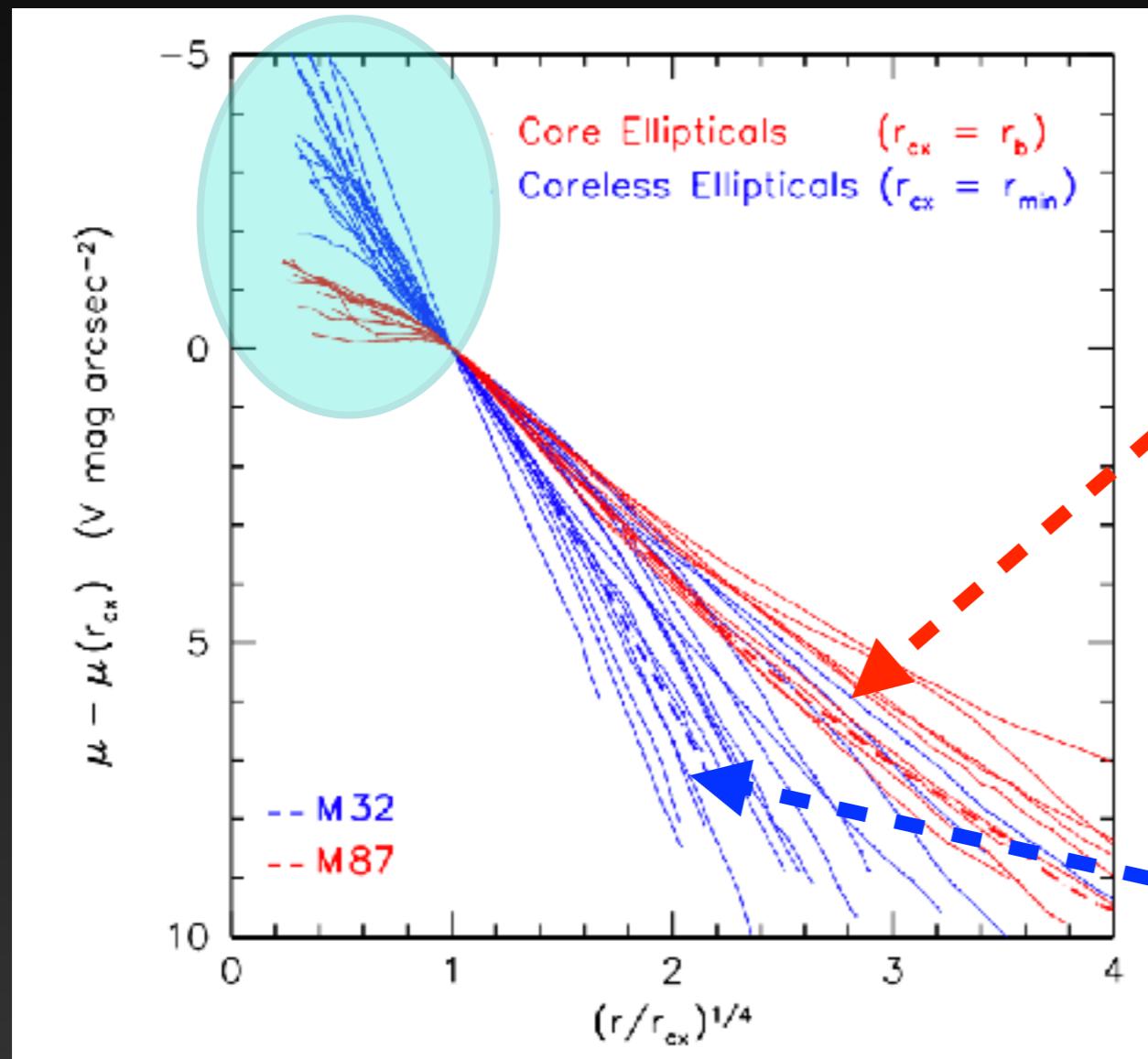


Face-On

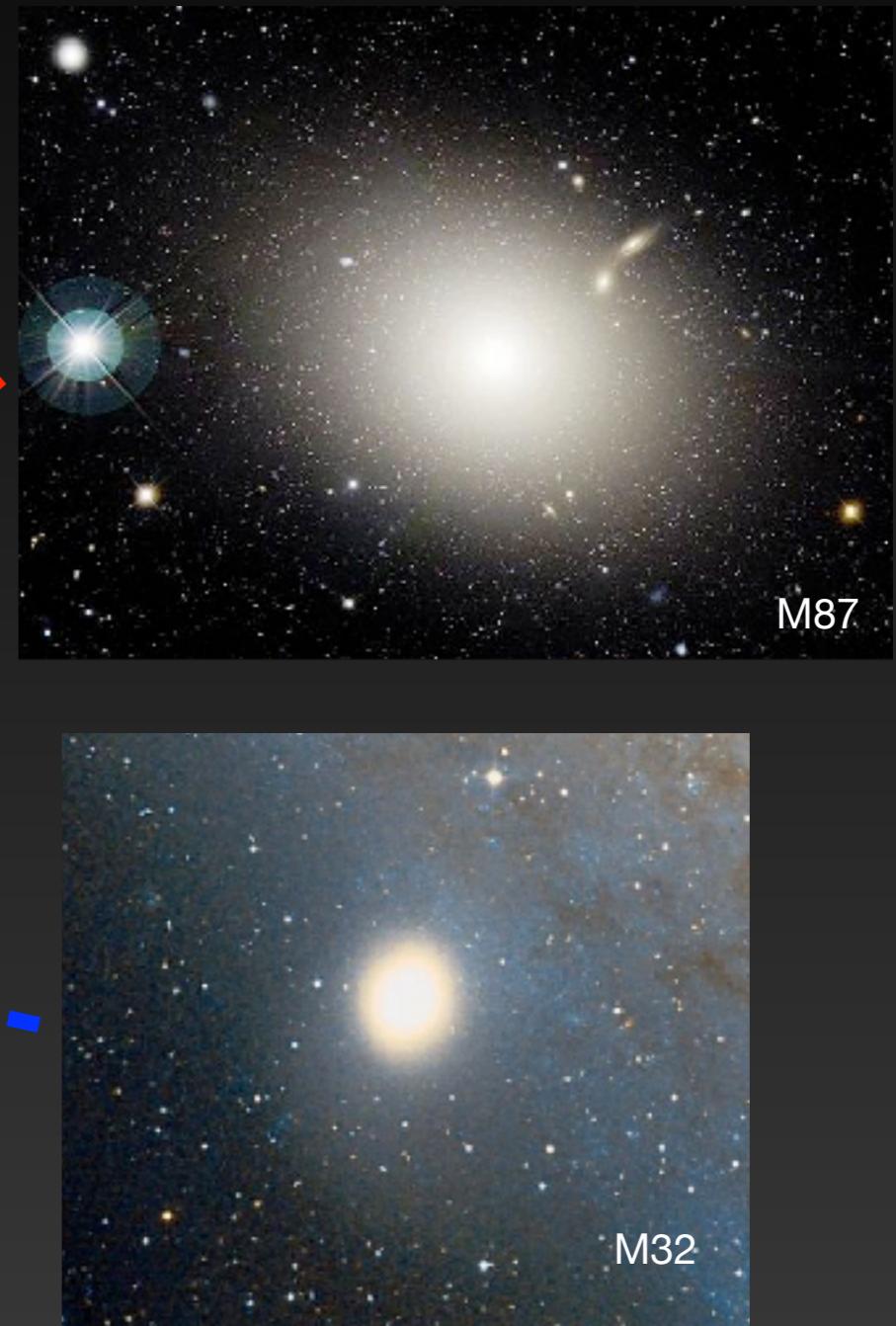


Indirect Evidence of SMBH merger?

result of BH hardening?

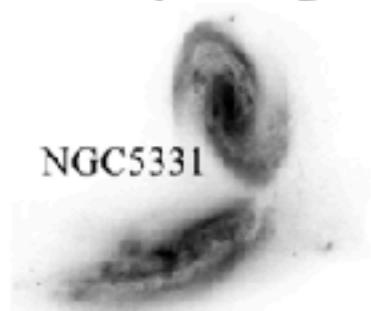


Kormendy et al. 2010



Evolution of SMBH binary

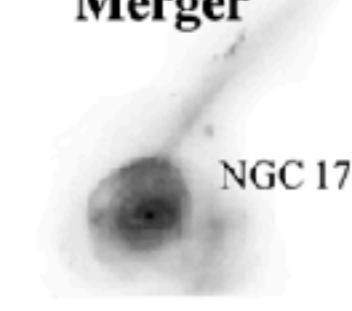
Galaxy Merger



NGC 5331

Dynamical friction drives massive objects to central positions

Stellar Core Merger



NGC 17

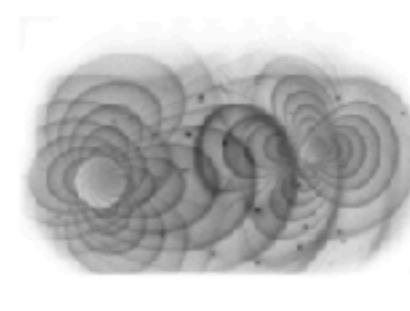
Dynamical friction less efficient as SMBHs form a binary.

Binary Formation



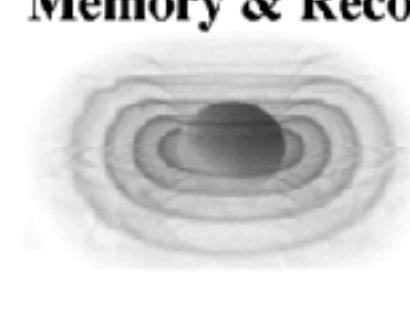
Stellar and gas interactions may dominate binary inspiral?

Continuous GWs



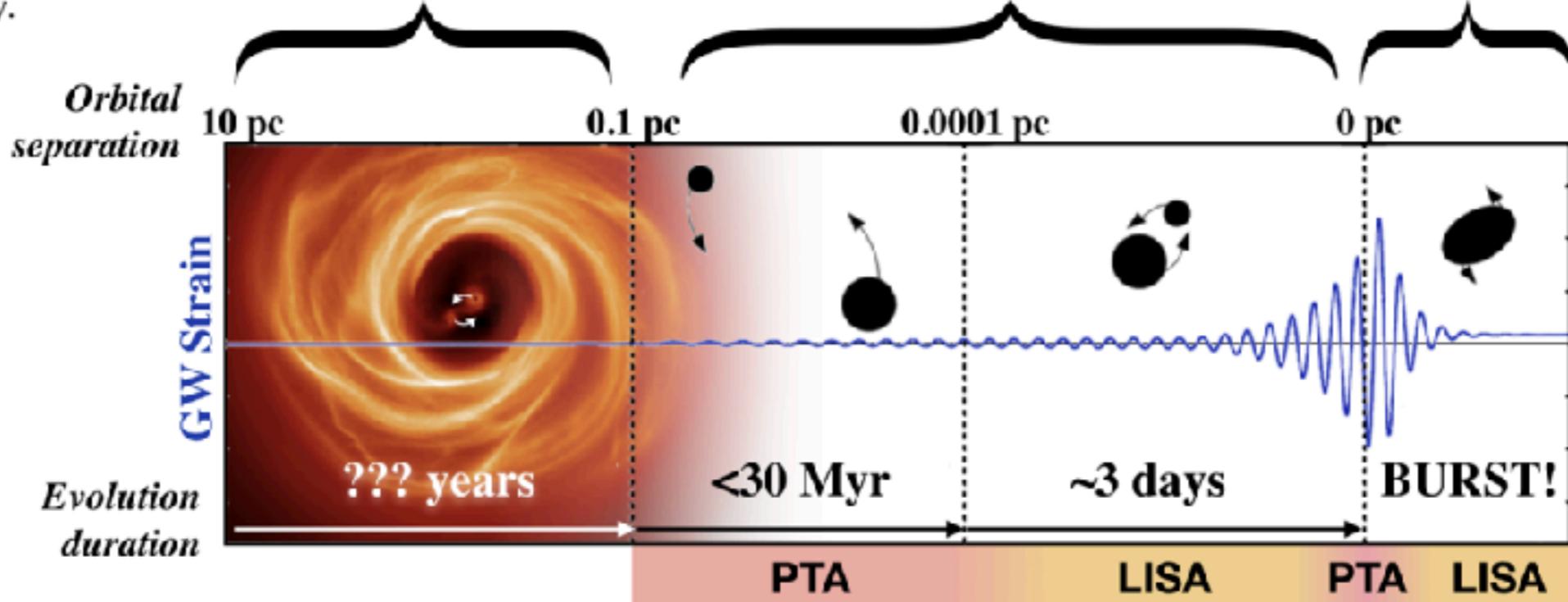
Gravitational radiation provides efficient inspiral. Circumbinary disk may track shrinking orbit.

Coalescence, Memory & Recoil



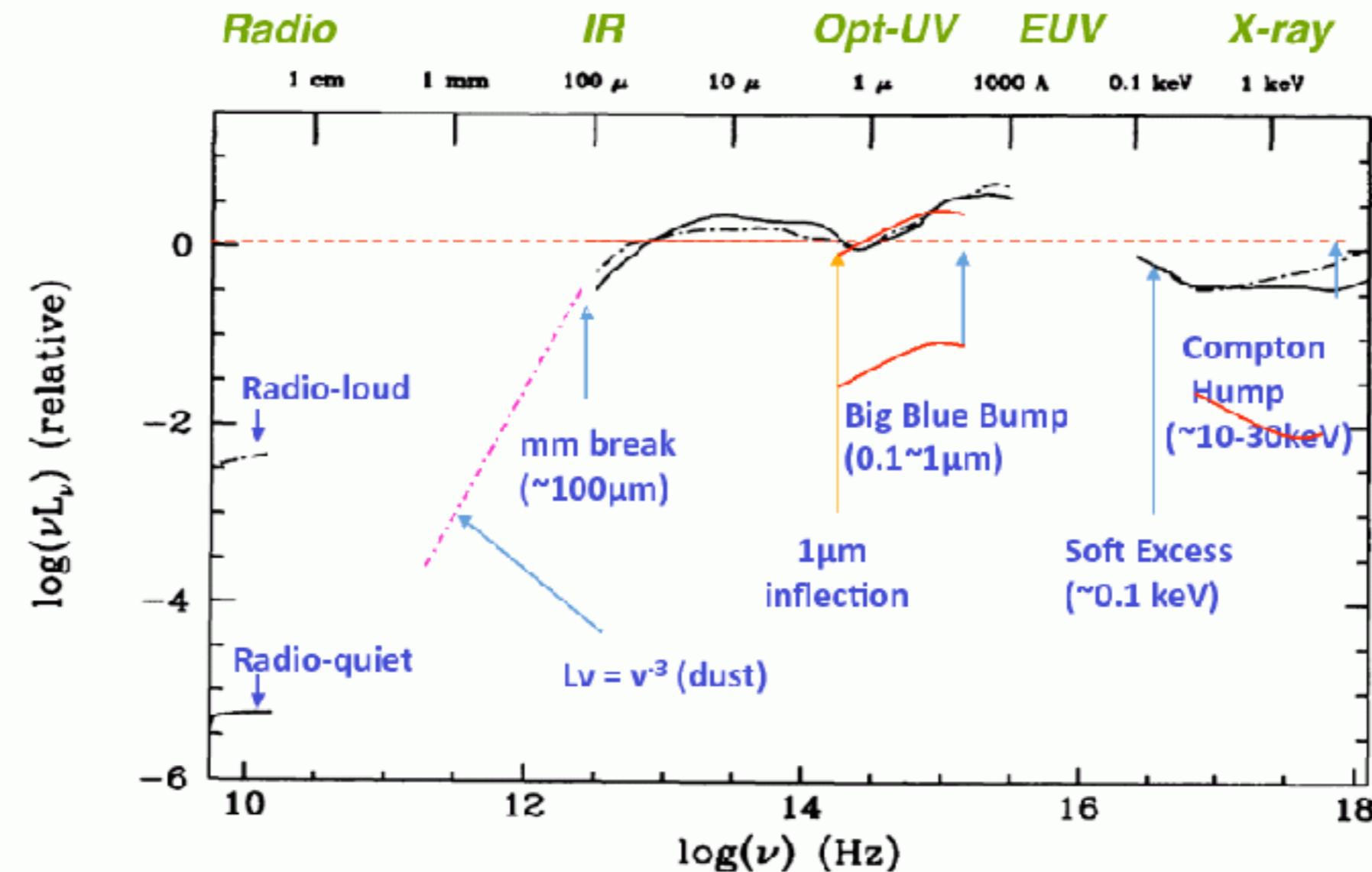
Post-coalescence system may experience gravitational recoil.

The Lifecycle of Binary Supermassive Black Holes



Method to detect dual AGNs?

Normal Galaxy vs. Active Galaxy?



Elvis et al., 1994, ApJS, 95, 1

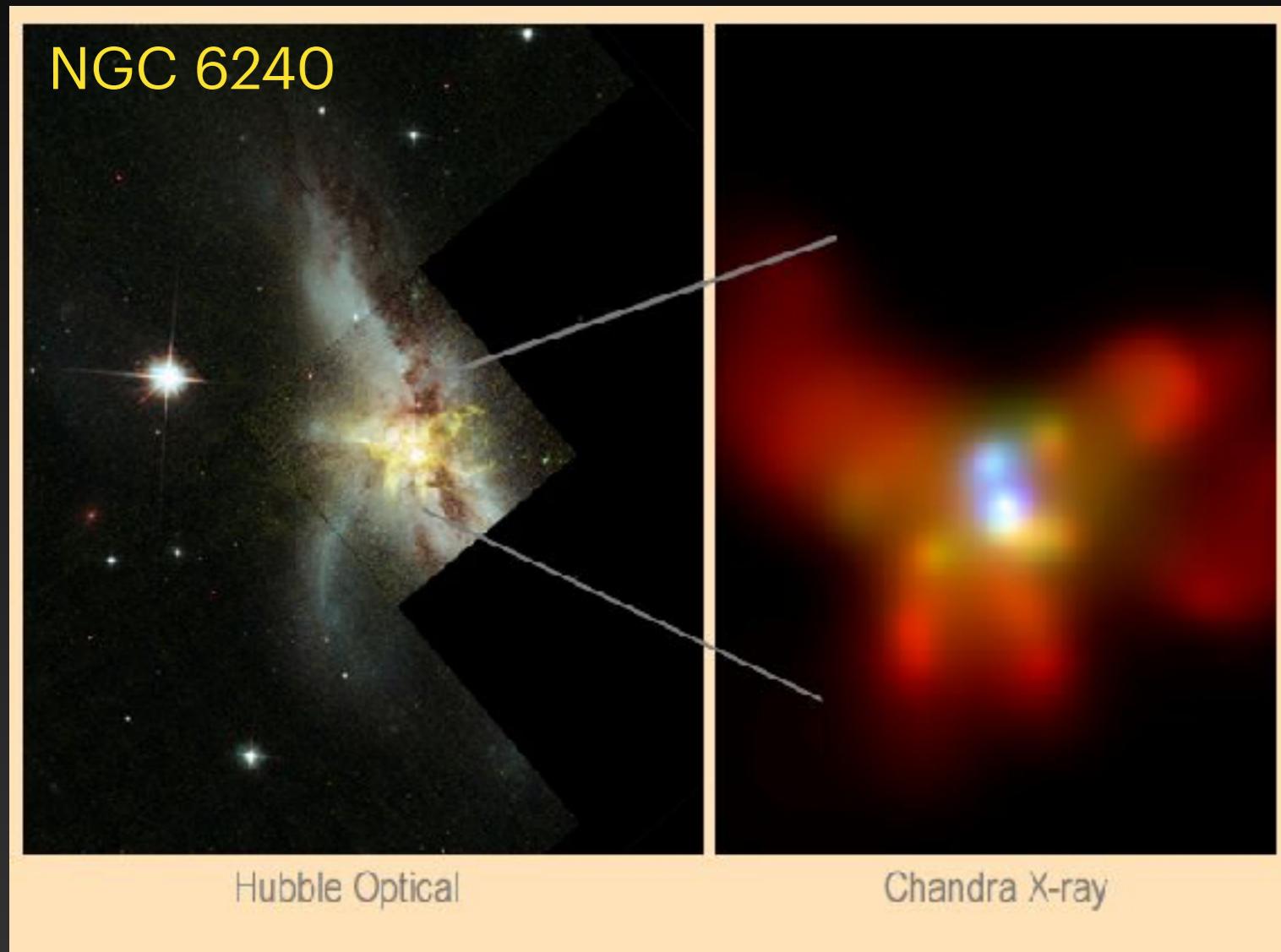
Method to detect dual AGNs?

1. Imaging : Spatially resolved dual AGNs (sub-pc~kpc scale)
2. Spectroscopy : Kinematically resolved dual AGNs (or single AGN; sub-pc~kpc scale)
3. Periodic variability : sub-pc scale

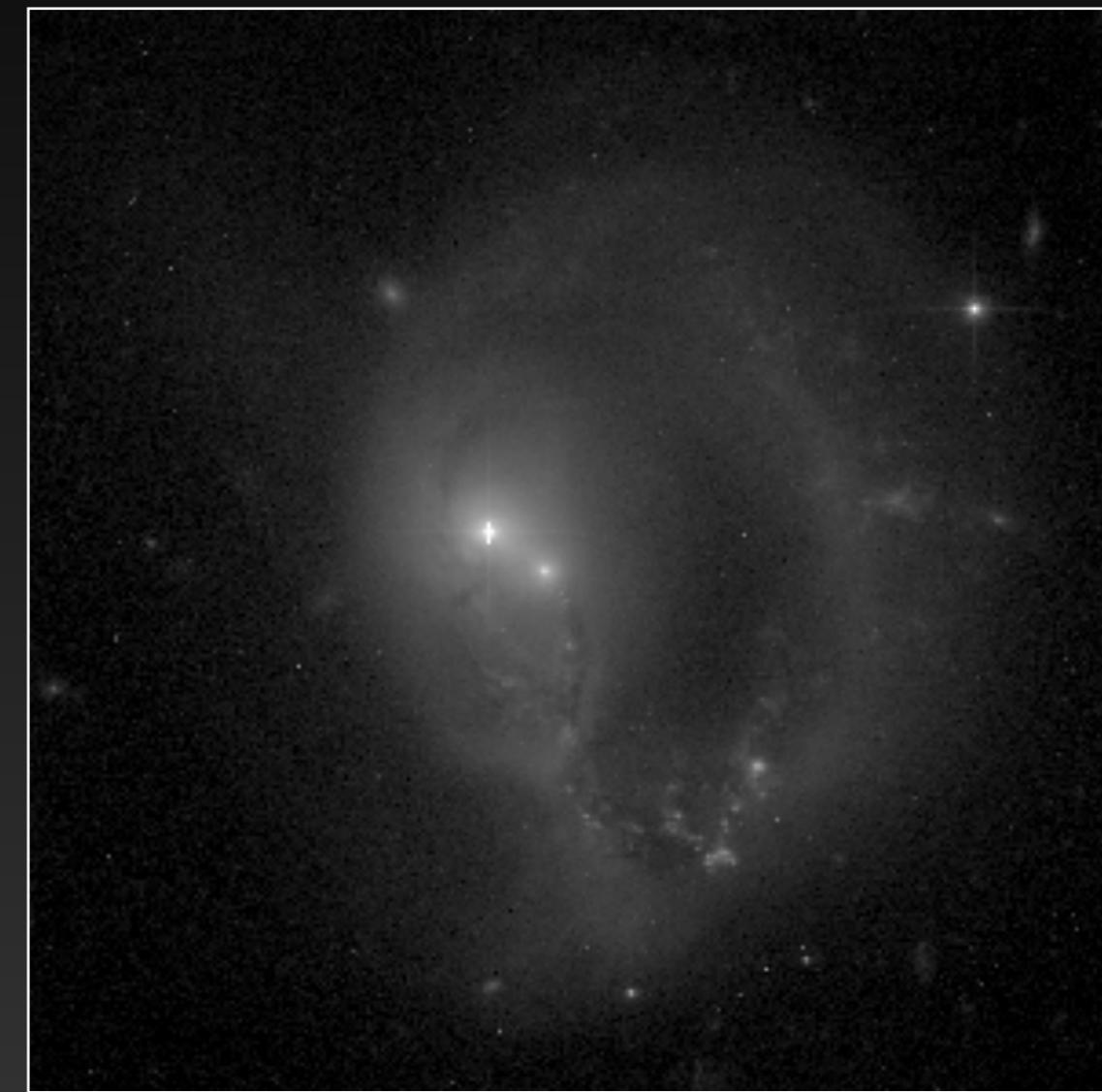
\sim kpc scale binary

Relatively common (~dozens)

NGC 6240



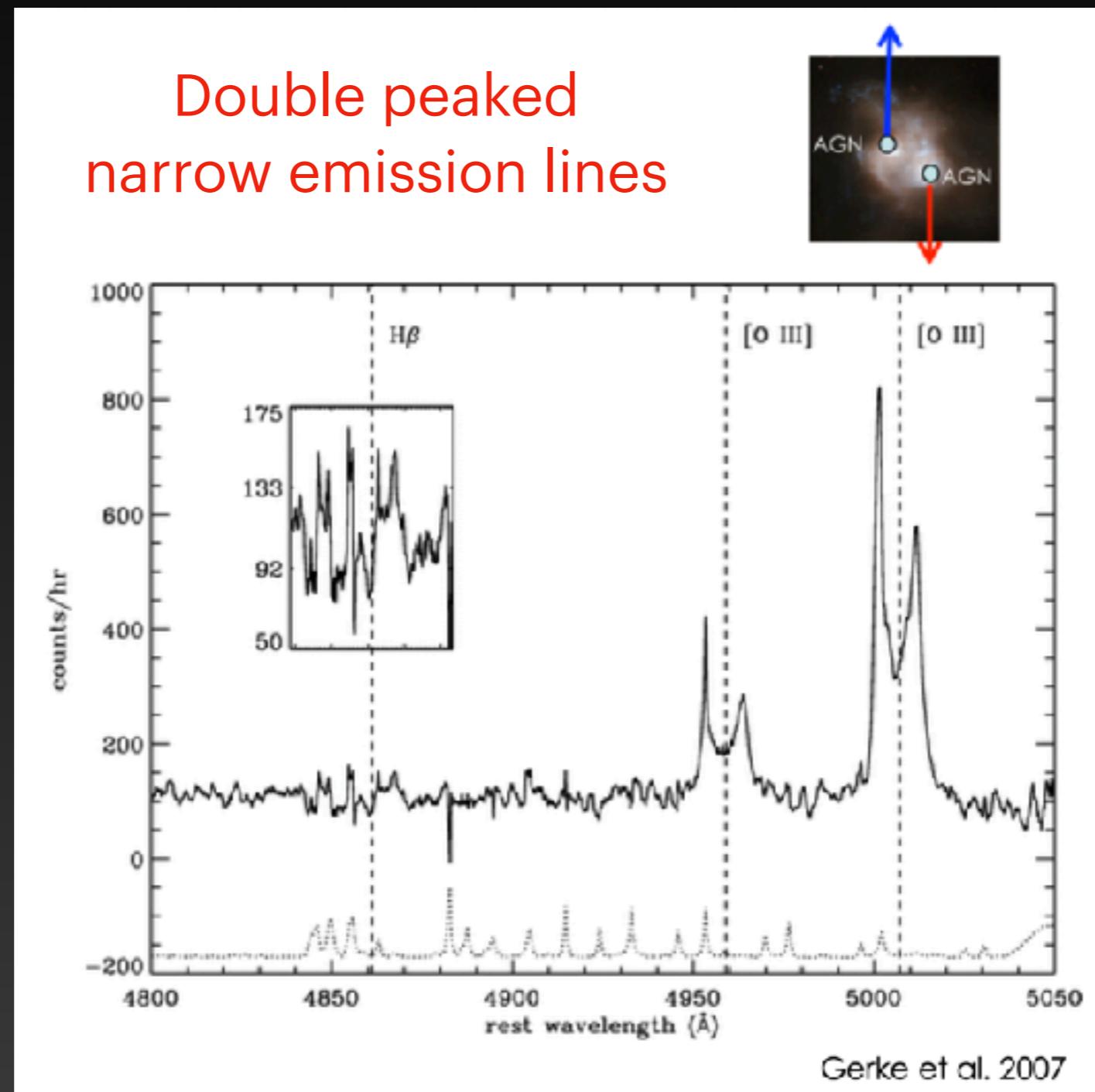
Optical: R.P.van der Marel & J.Gerssen (STScI), NASA;
X-ray: S.Komossa & G.Hasinger (MPE) et al., CXC, NASA



MK et al. 2021

\sim kpc scale binary

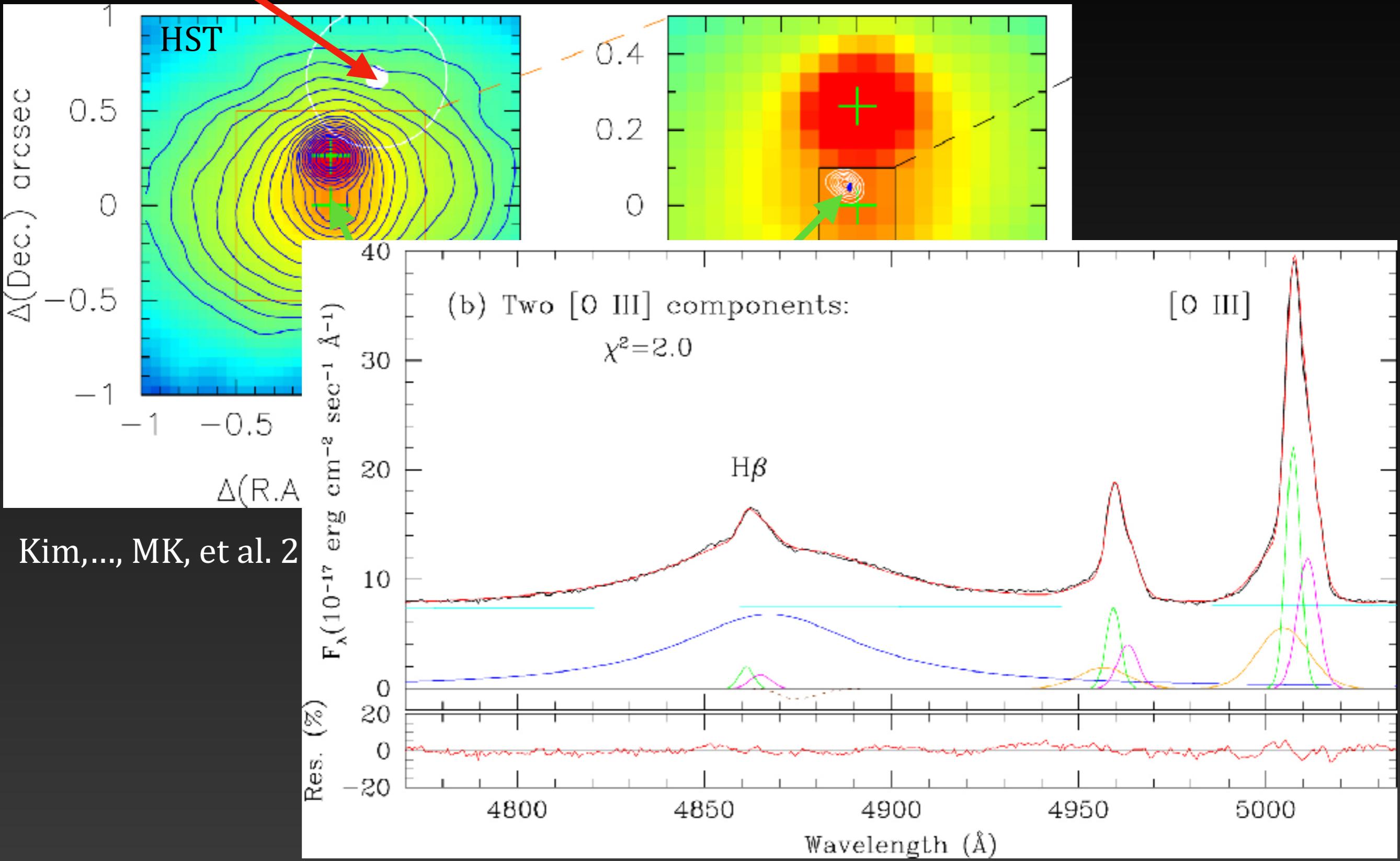
Kinematically selected candidates (~thousands)



X-ray

~kpc scale binary

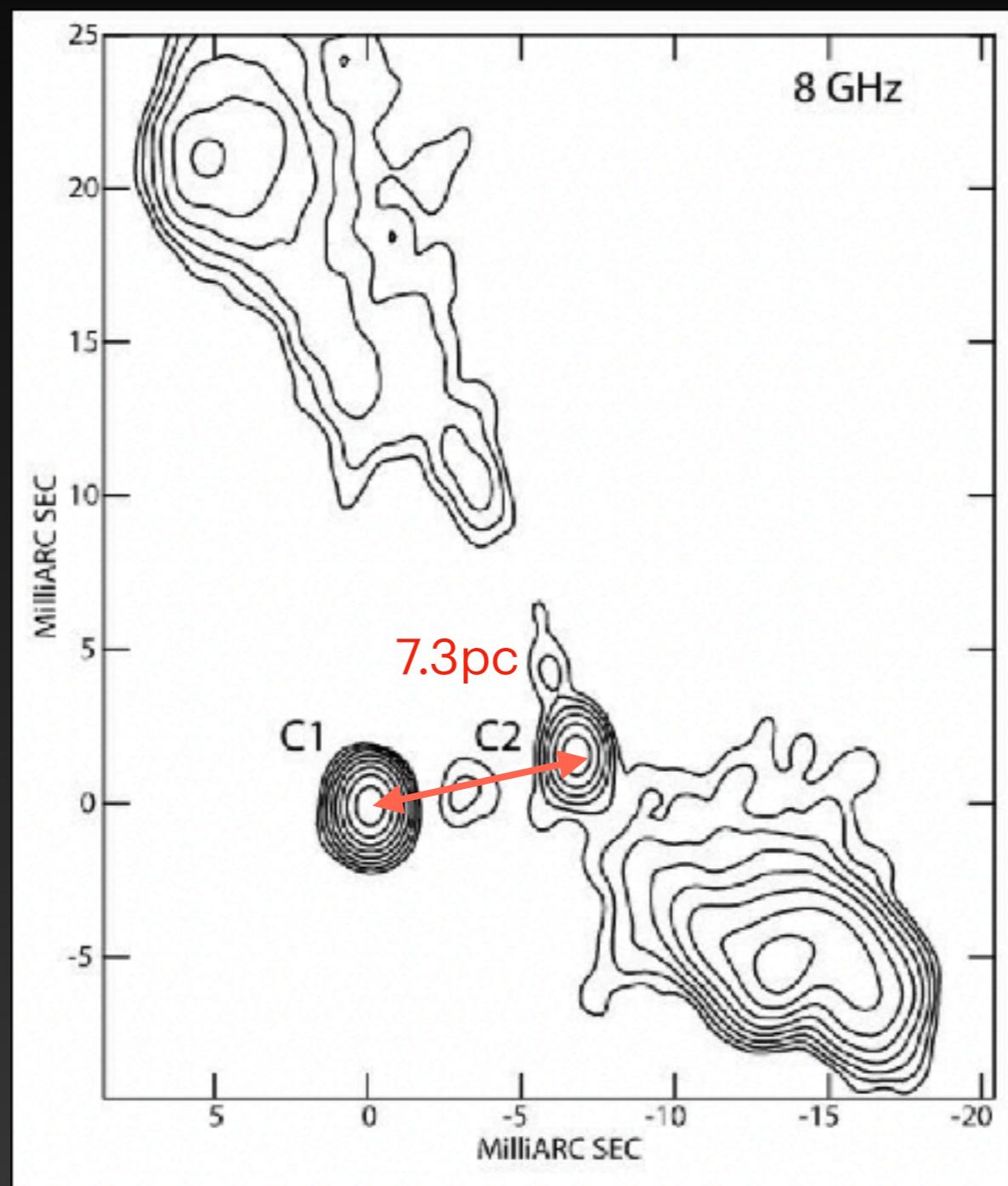
CXO J101527.2+625911



Kim,..., MK, et al. 2

pc to sub-pc scale binary

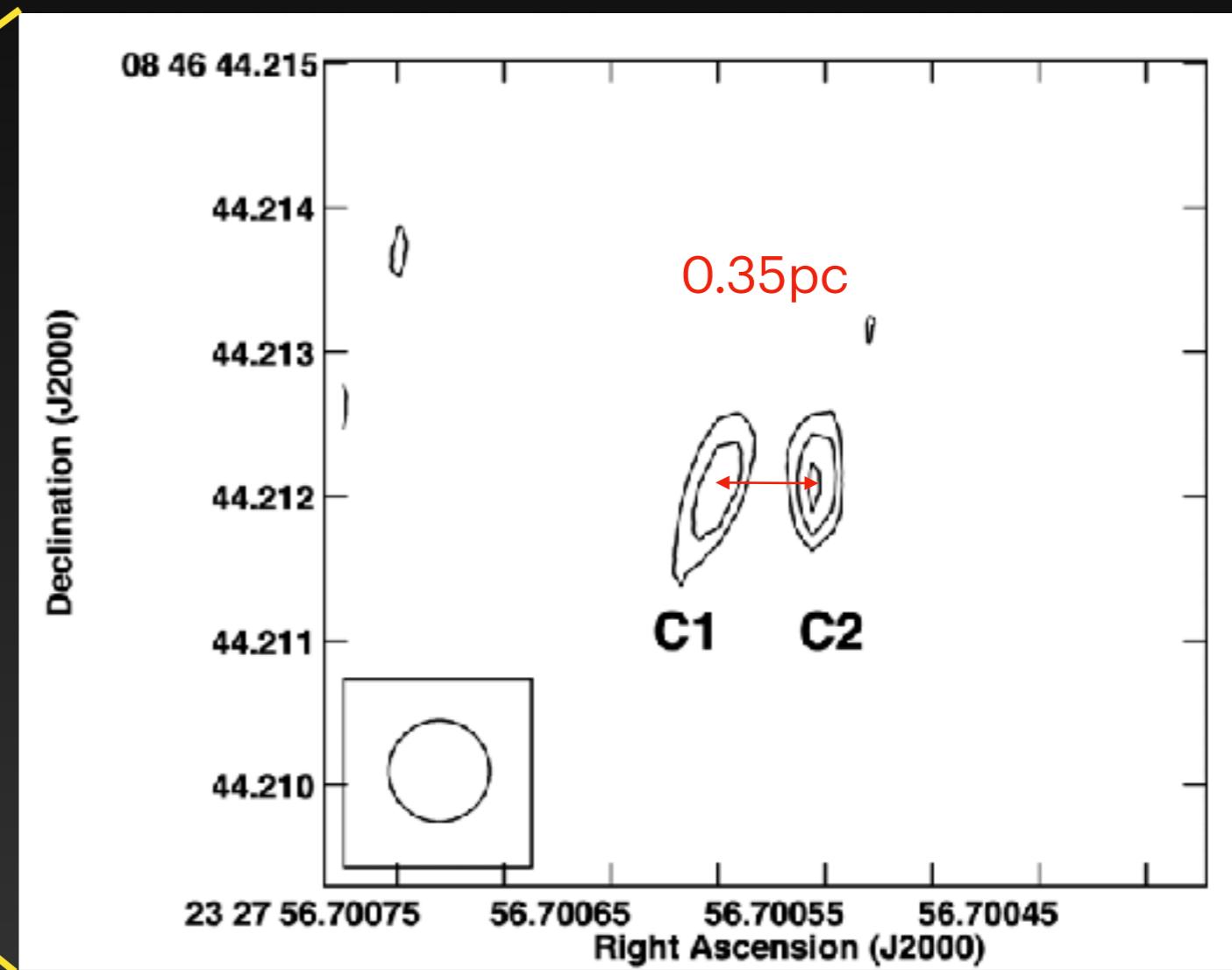
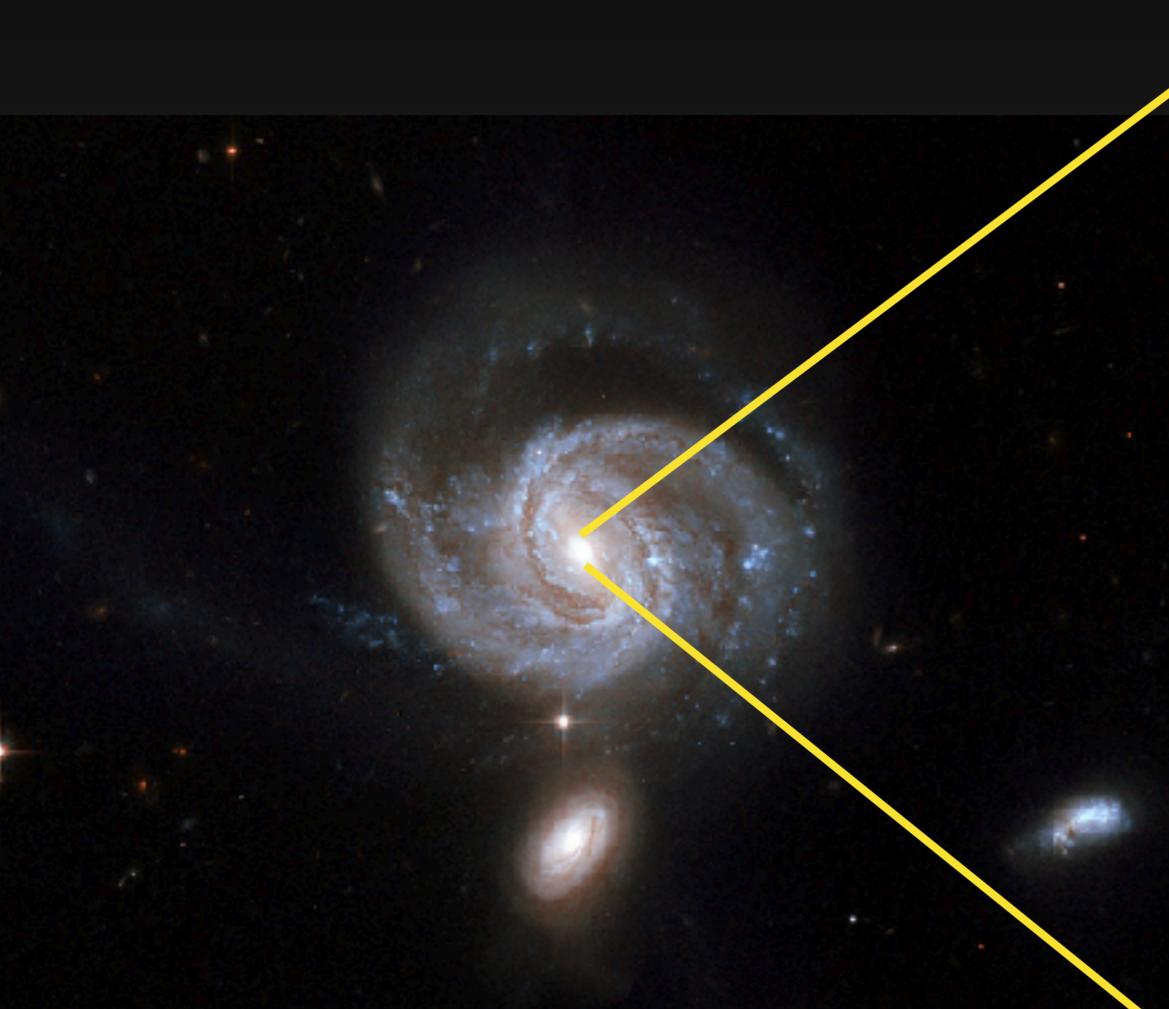
pc scale binary candidate



Rodriguez et al. 2017

pc to sub-pc scale binary

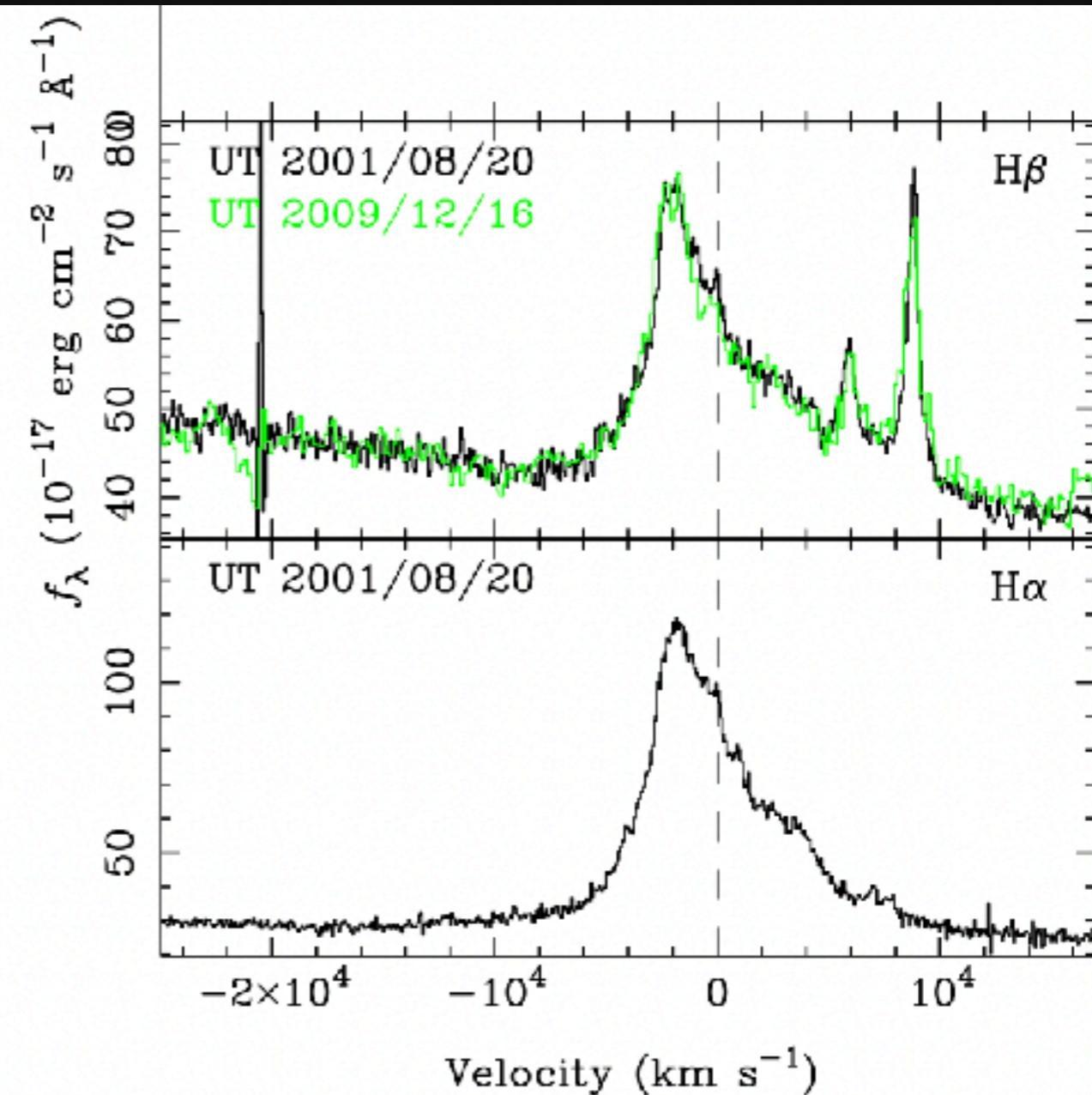
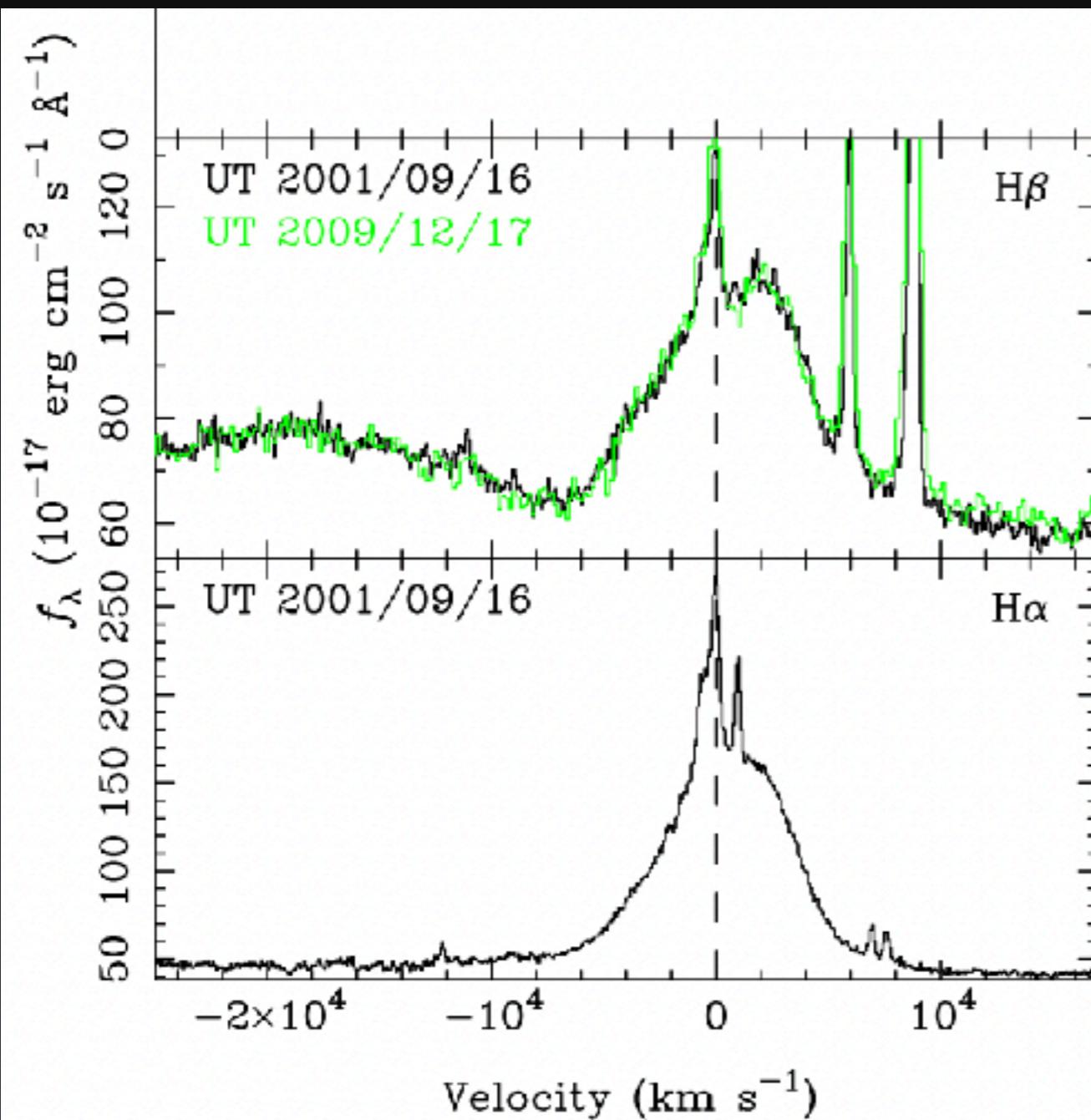
Sub-pc binary candidate



Kharb et al. 2017

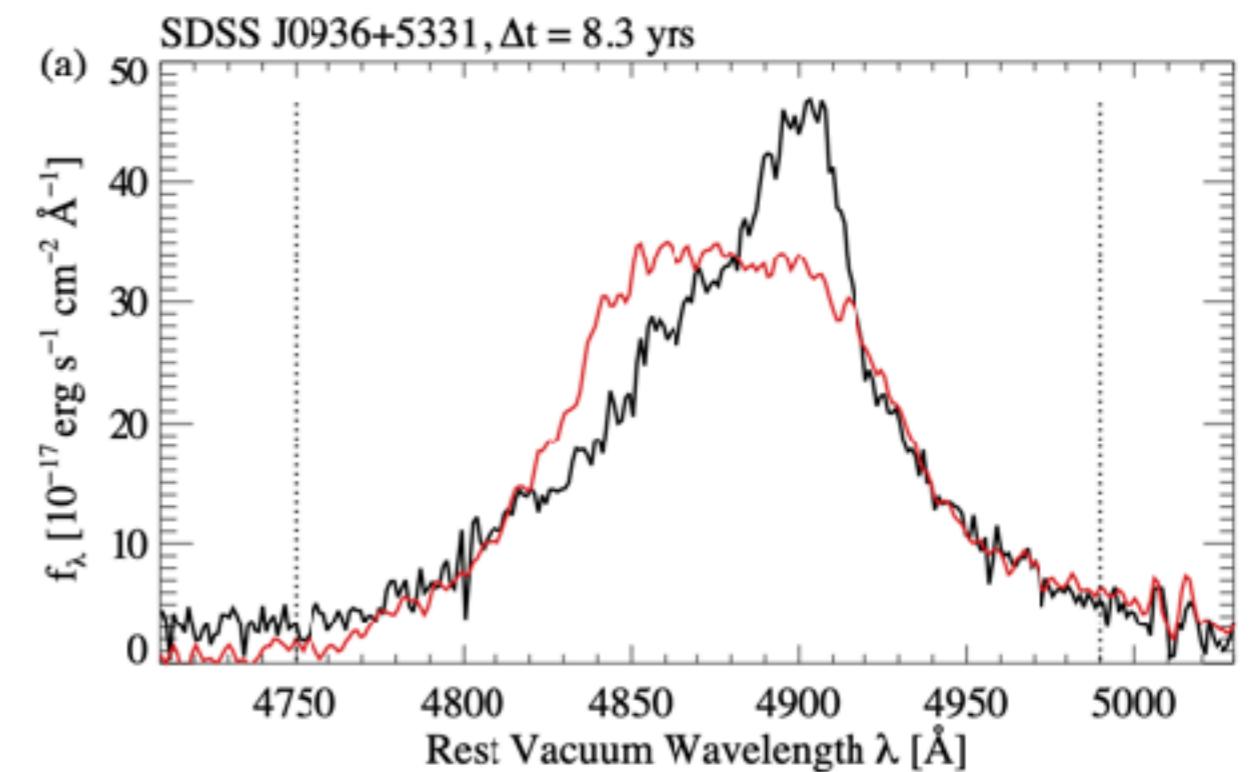
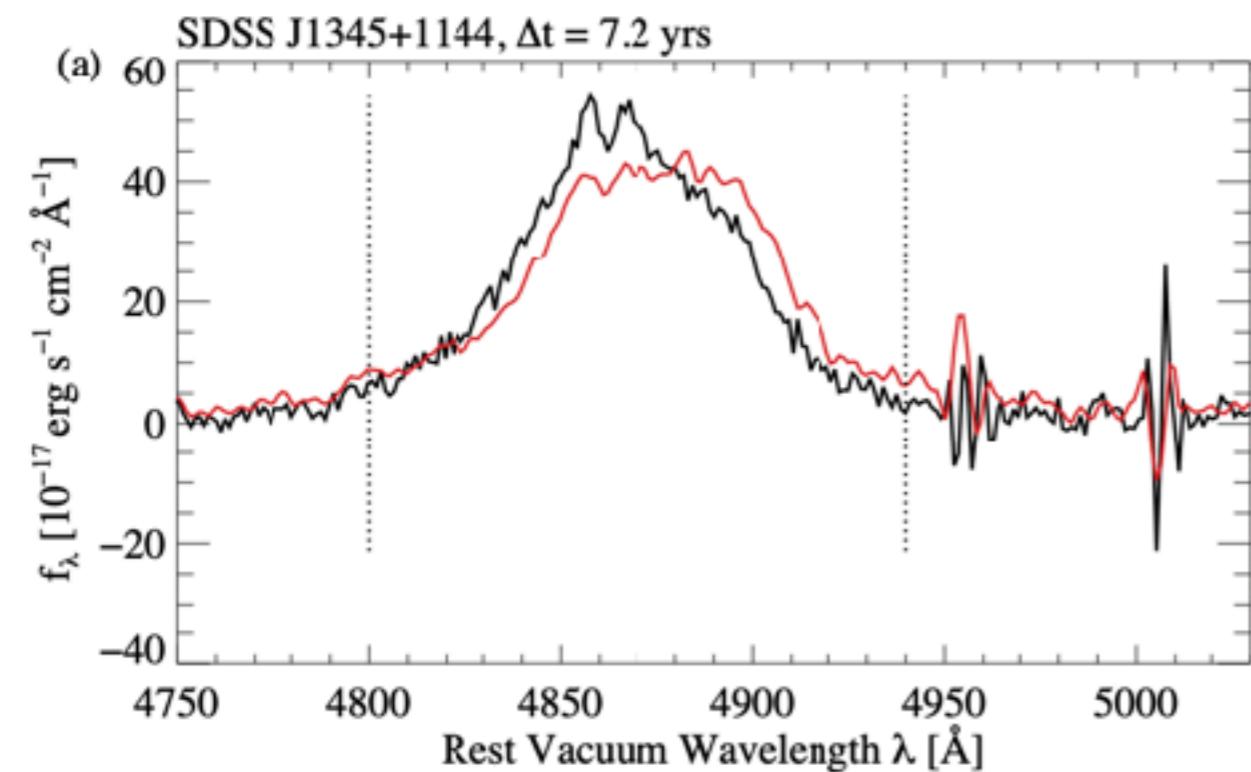
sub-pc scale binary

Kinematically selected candidates (~hundred)



sub-pc scale binary

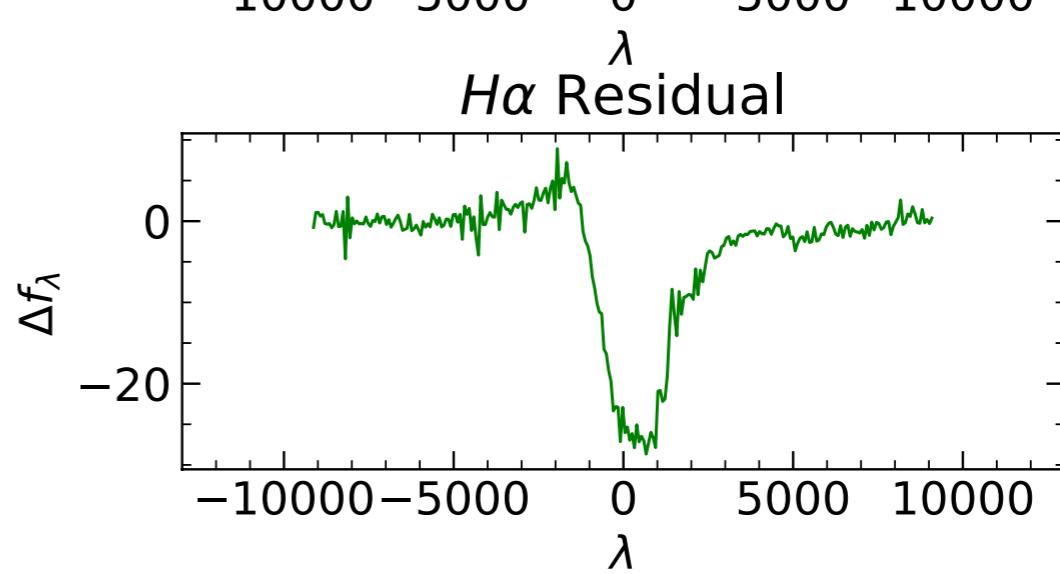
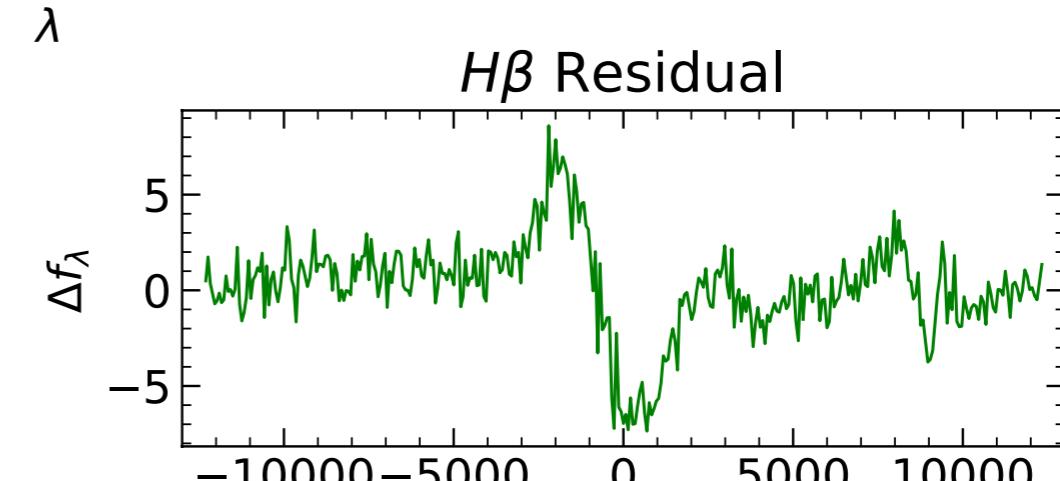
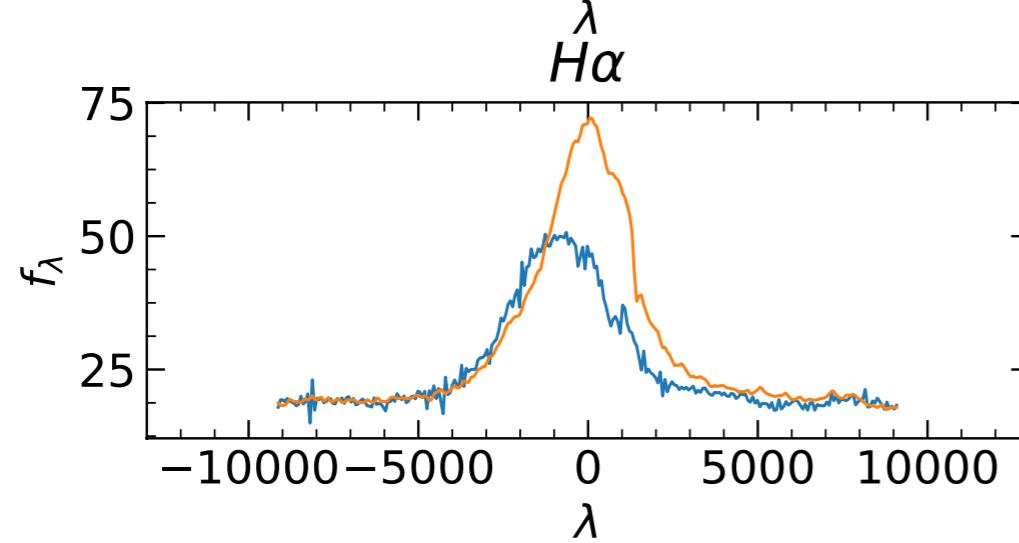
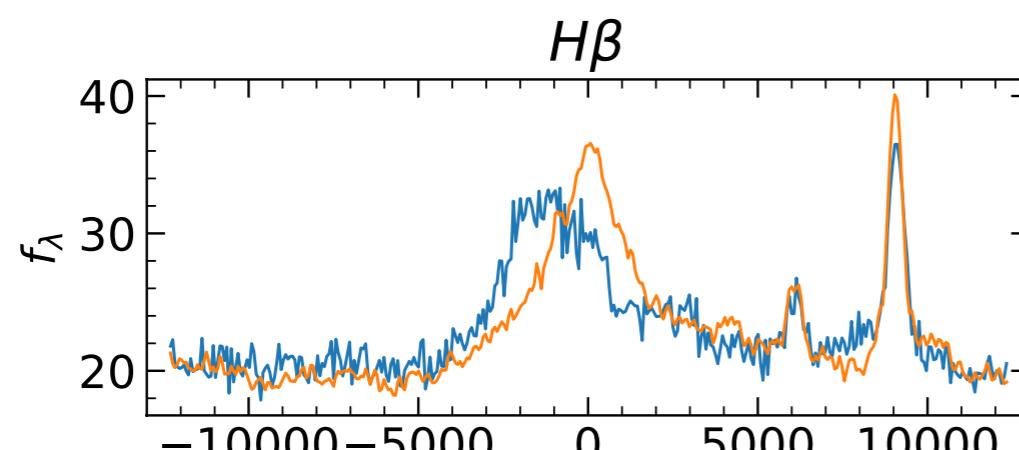
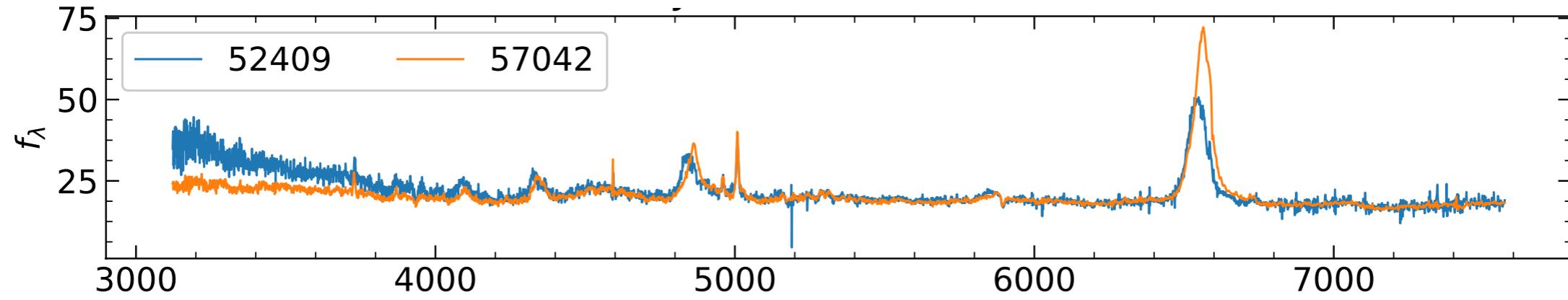
Kinematically selected candidates (~hundred)



sub-pc scale binary

Kinematically selected candidates (~hundred)

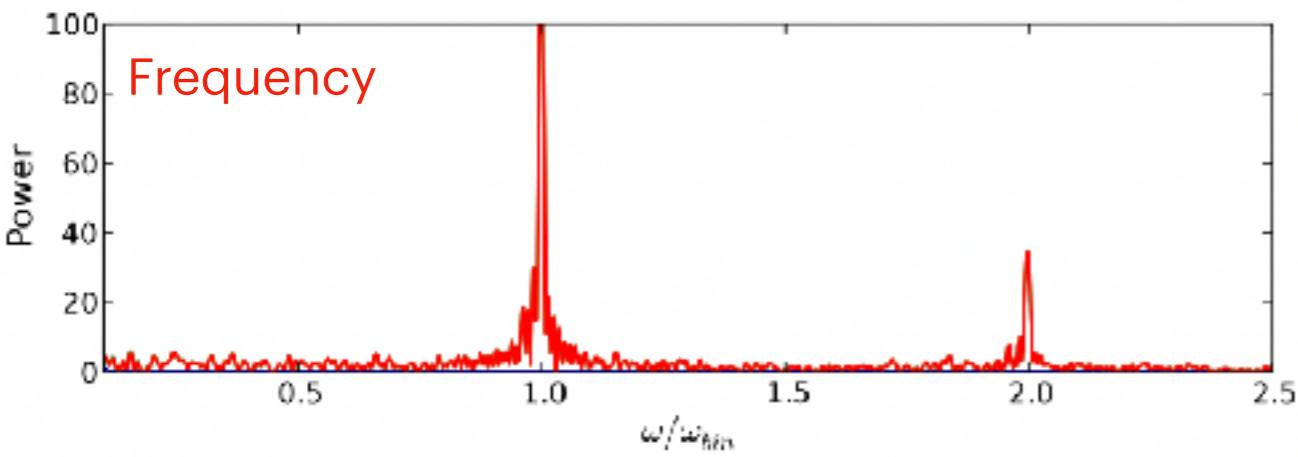
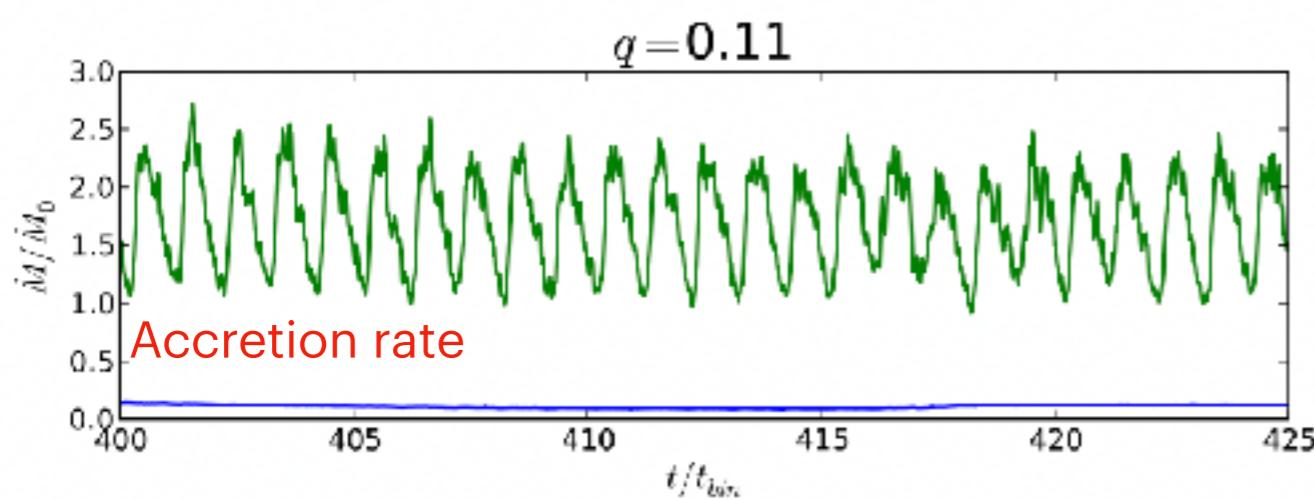
Sung, MK et al., in preparation



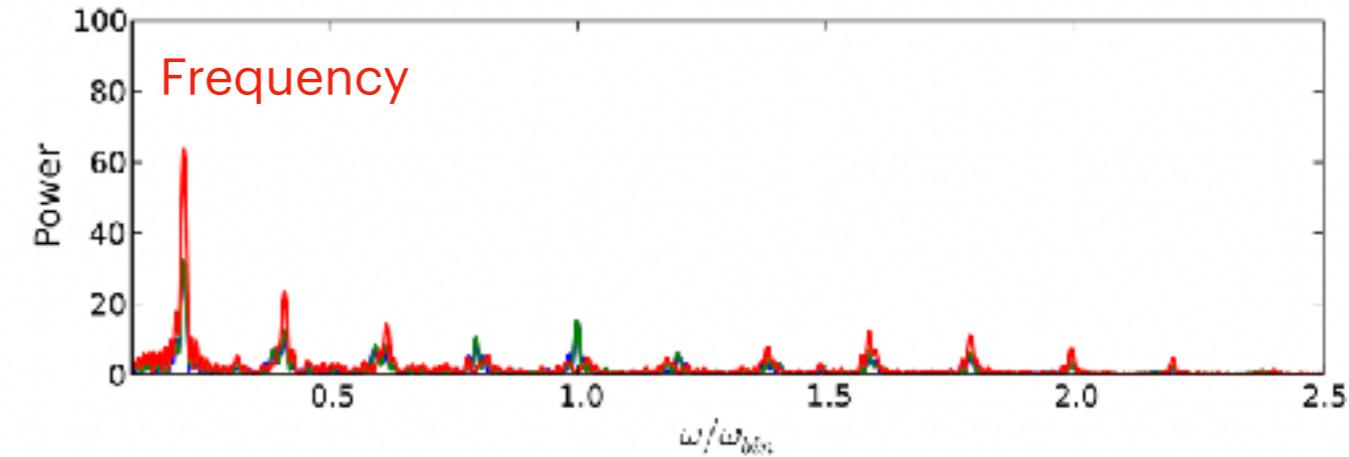
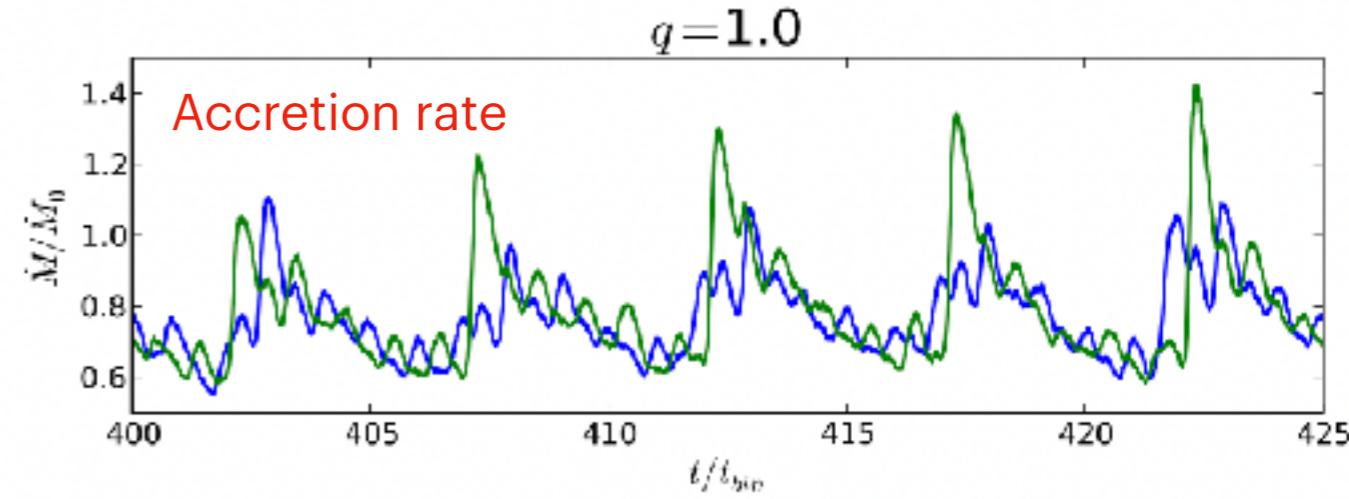
sub-pc scale binary

Periodic variability (a few candidates)

q =mass ratio 1:10 merger



1:1 merger

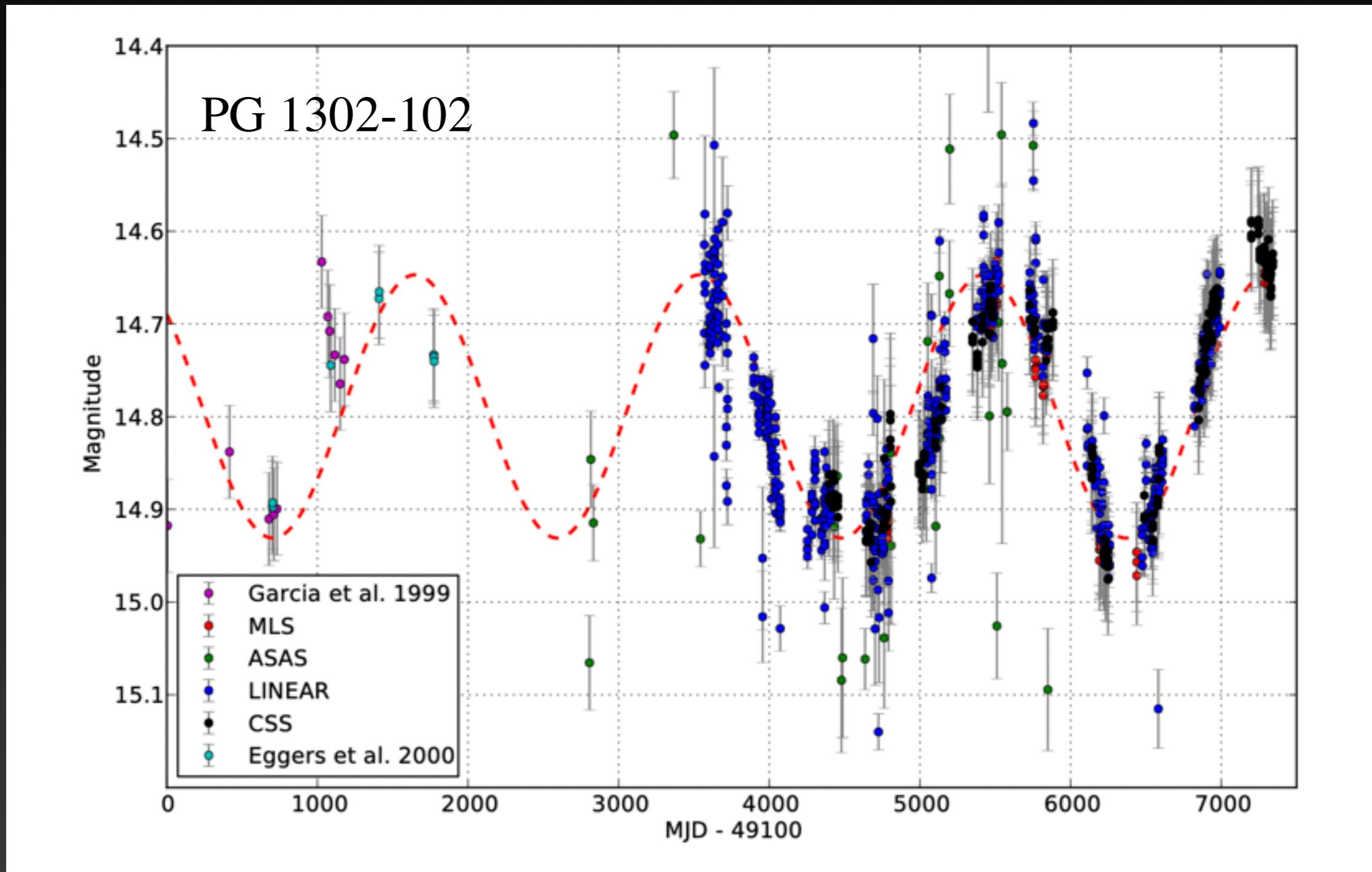


- Green : primary
- Blue : secondary

Farris et al. 2014

sub-pc scale binary

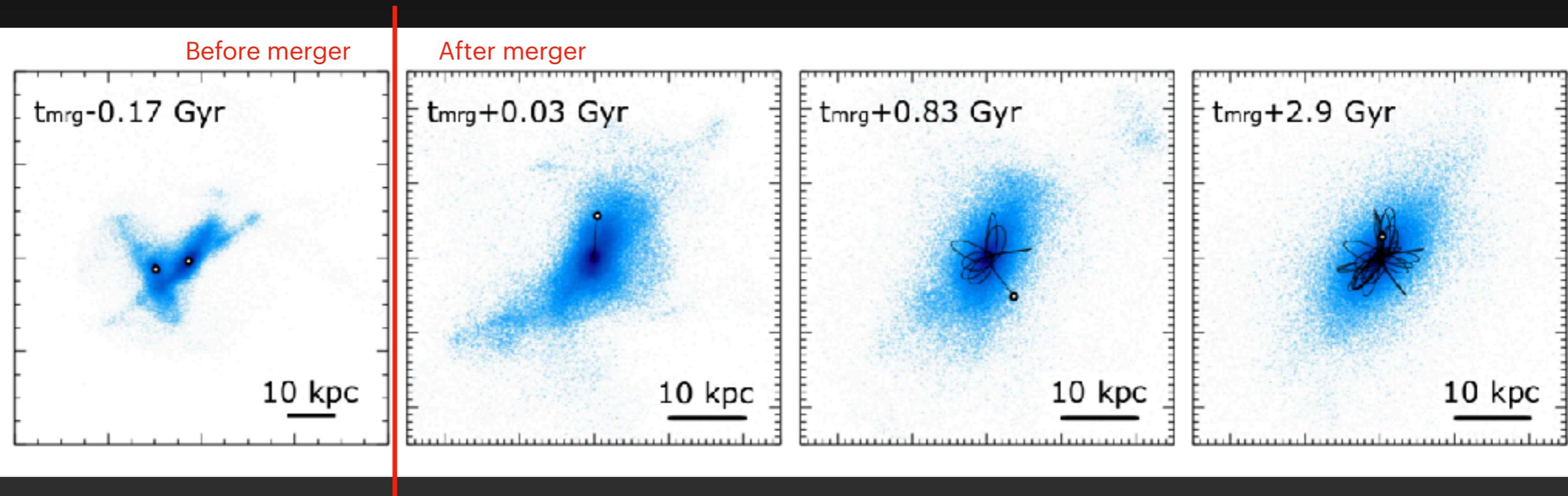
Periodic variability (a few candidates)



Method to detect recoiling BH?

Theoretical Prediction : spatial + kinematic offset

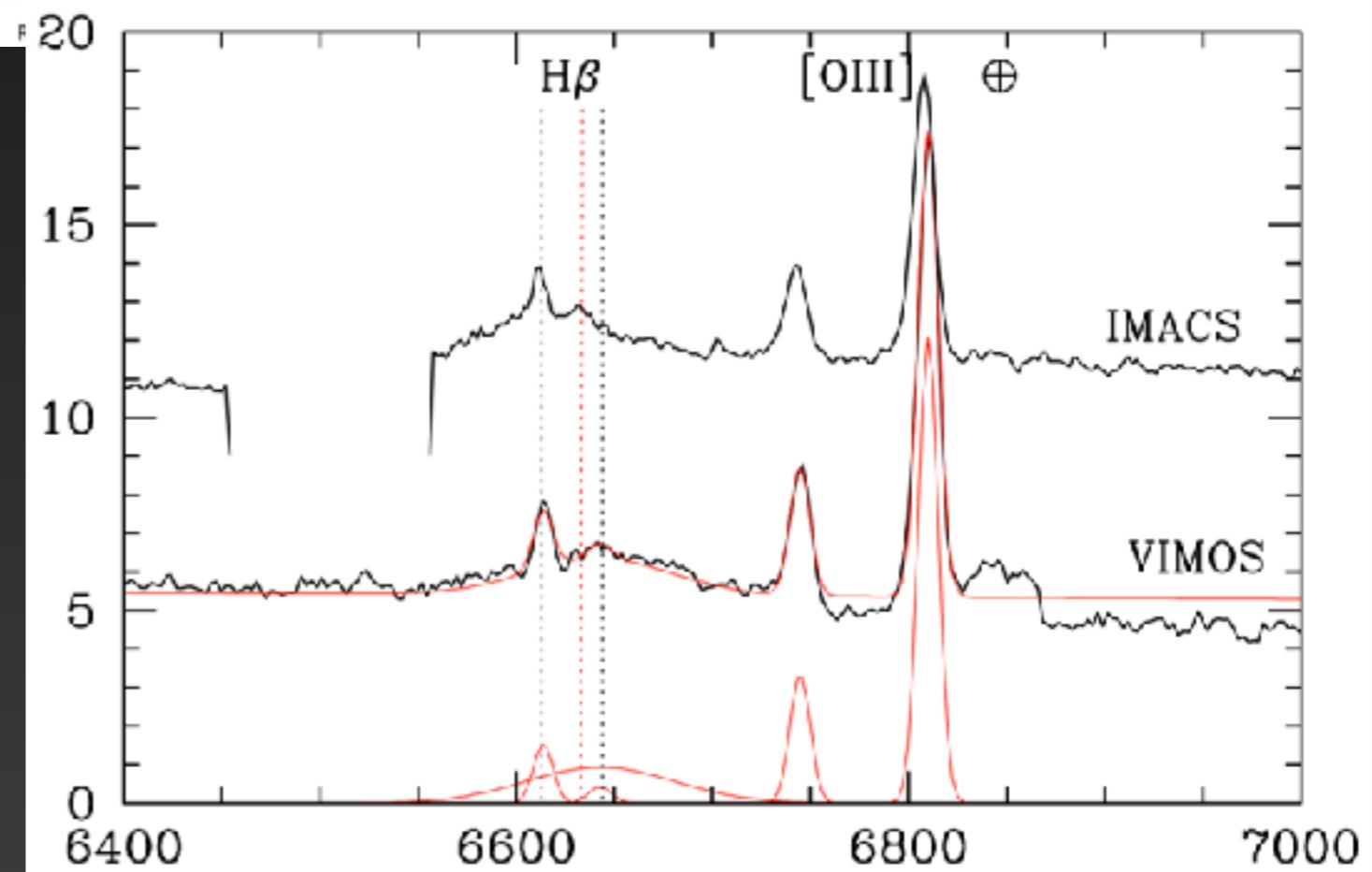
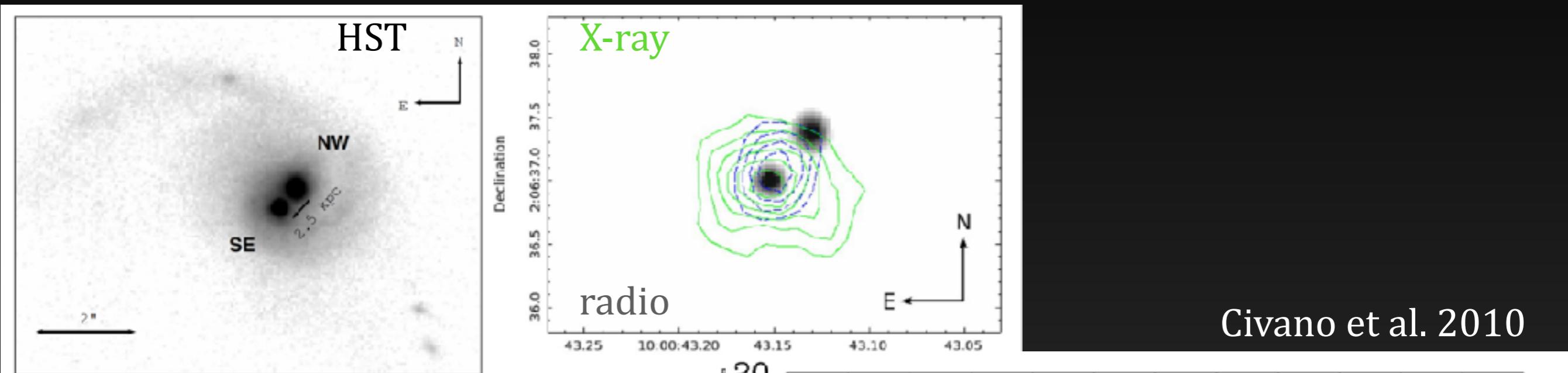
Kick velocity : $\Delta v = 100 - 4000 \text{ km s}^{-1}$



Blecha et al. 2011

Recoiling SMBH

Promising Candidate : CID-42 spatial offset + kinematic offset



Known SMBH binary from EM?

1. kpc scale : ~ dozens confirmed + thousands candidates
2. pc scale : few hundreds candidates
3. Recoiling BH : a few candidates