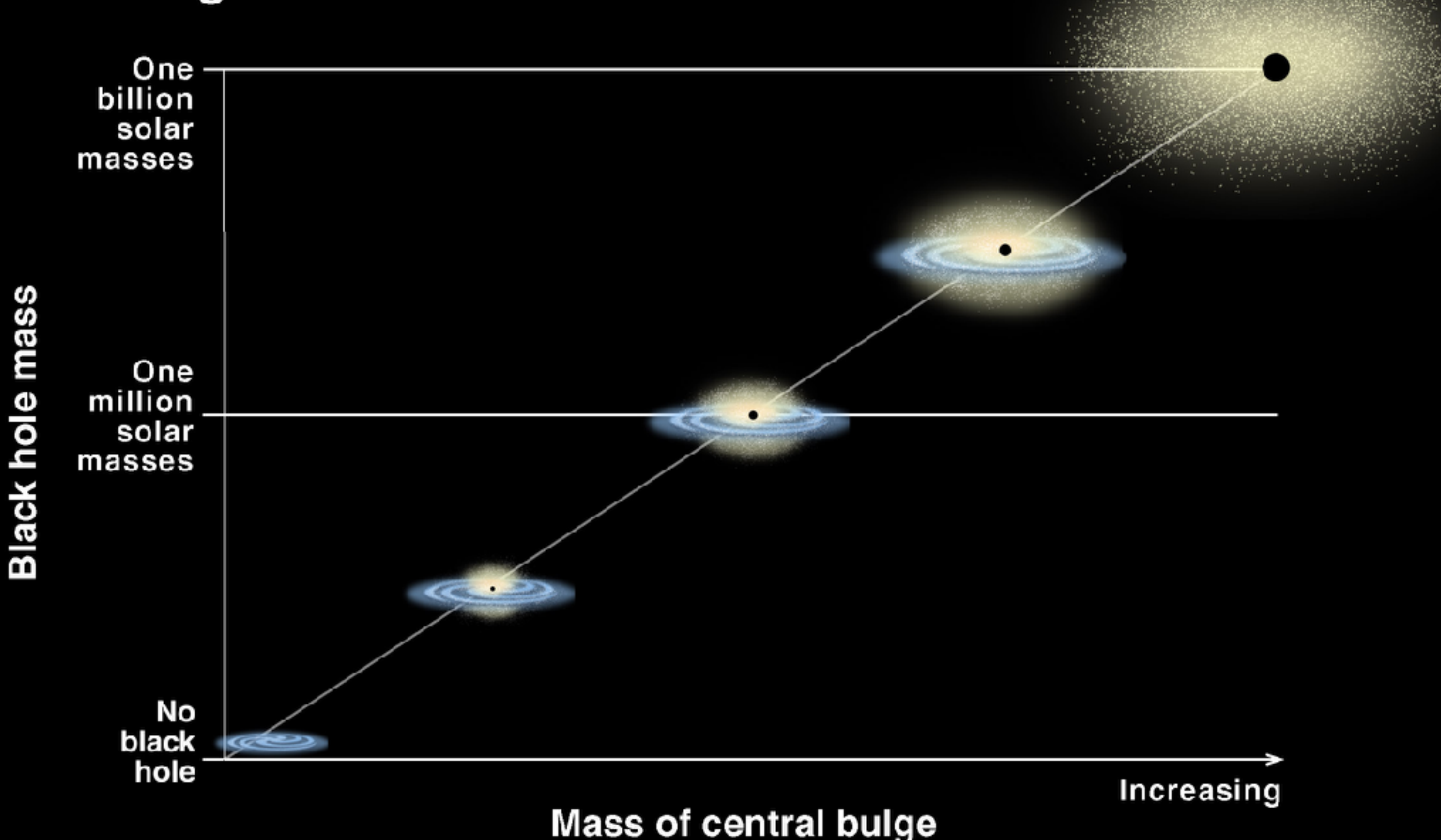
(Conventional) Observational Studies on the Origin and Evolution of Supermassive Black Holes

Minjin Kim (KNU)

Correlation Between Black Hole Mass and Bulge Mass



Credit: K. Cordes & S. Brown (STScI)

Supermassive Black Holes

1. $M_{BH} > 10^{5\text{-}6}$ solar mass ($M_\odot$) at the center of galaxies.

2. Ubiquitous at least in massive galaxies with bulges

3. BH-Host Galaxy correlation

4. Formation mechanism is still unknown

Contents

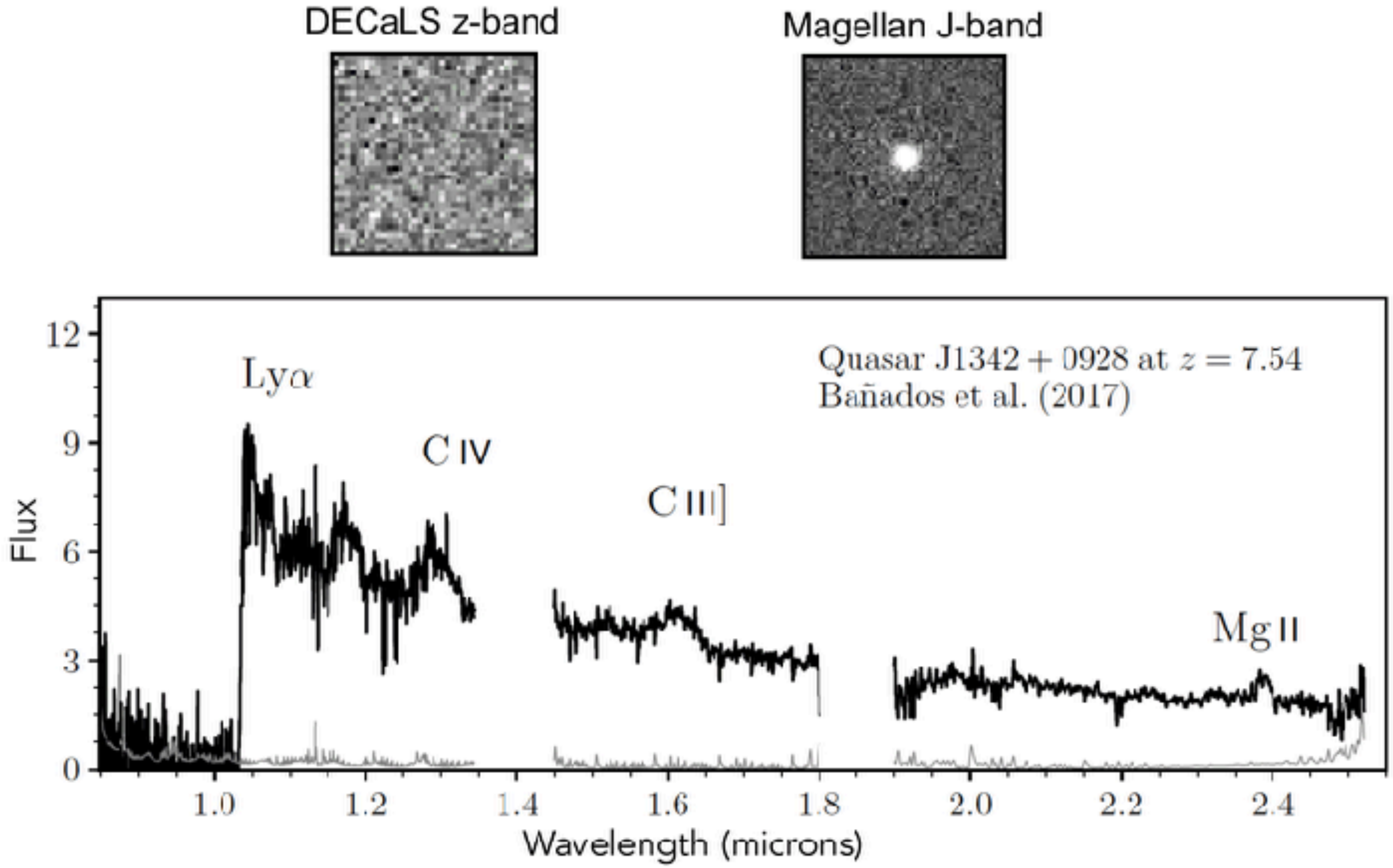
- A Candidate of Intermediate mass black hole (IMBH) in NGC 5252

- Star Formation in Active Galaxies
  - explore BH growth and star formation rate

A Candidate of Intermediate mass black hole (IMBH) in NGC 5252

Origin of SMBH

most distant QSOs @ z~7.5 (0.7Gyr) : $M_{BH} \sim 1\times10^8\ M_\odot$



Banados+2018

Origin of SMBH

Eddington limit : BH growth rate is limited!

$$F_{rad} = \frac{L\sigma_T}{4\pi c r^2}$$

$$F_{grav} = \frac{GM_{\mathrm{BH}} m_p}{r^2}$$

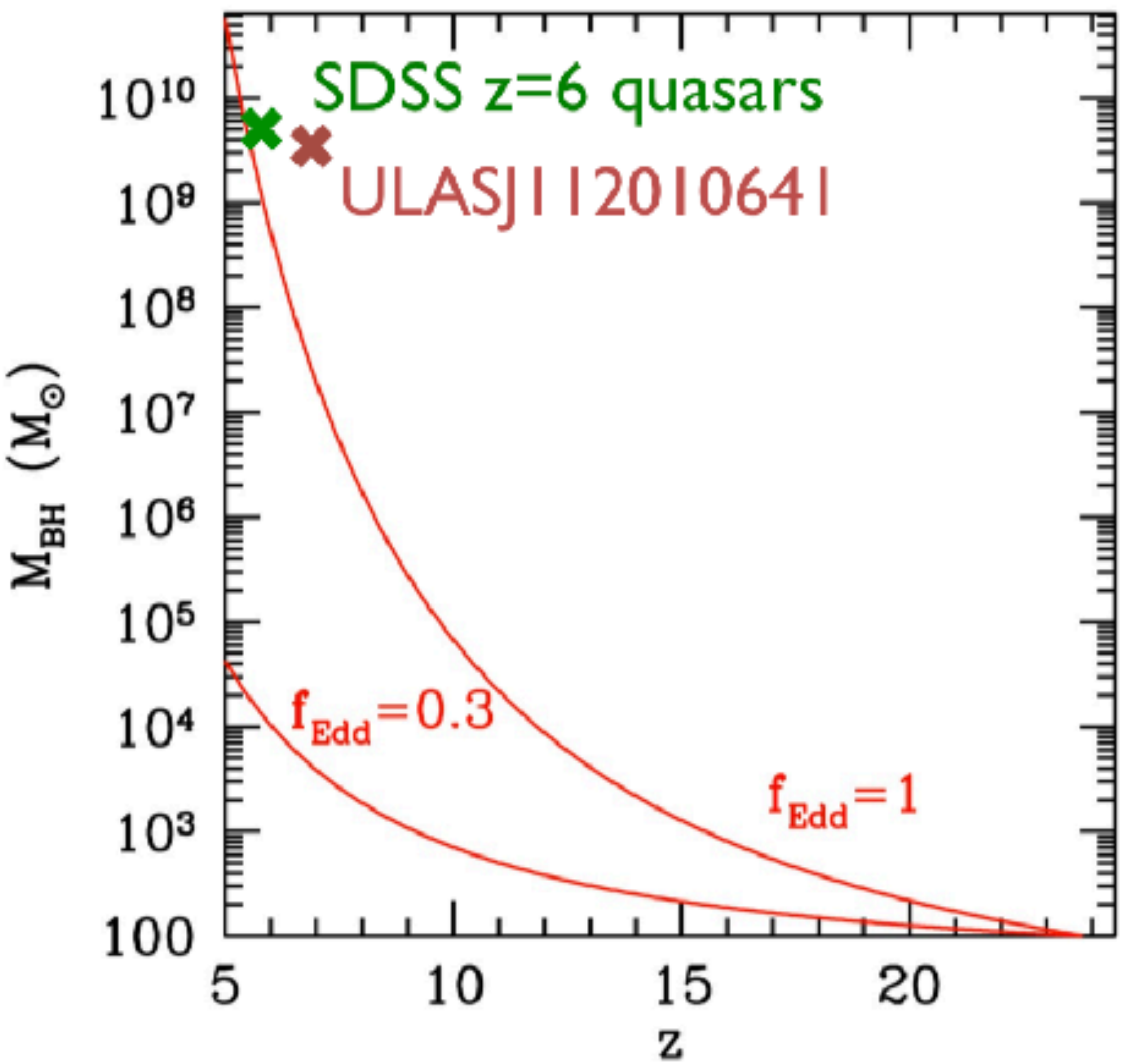
$$\eta \dot{m} c^2 = L < \frac{4\pi G m_p c}{\sigma_T} \times M_{\mathrm{BH}}$$

η : Radiative Efficiency

Origin of SMBH

Eddington limit : BH growth rate is limited!

$$M_{\rm BH}(t) = M_{\rm BH,init}\, e^{\frac{1-\eta}{\eta}\frac{t}{0.45{\rm Gyr}}}$$



Credit : Marta Volonteri

Origin of SMBH

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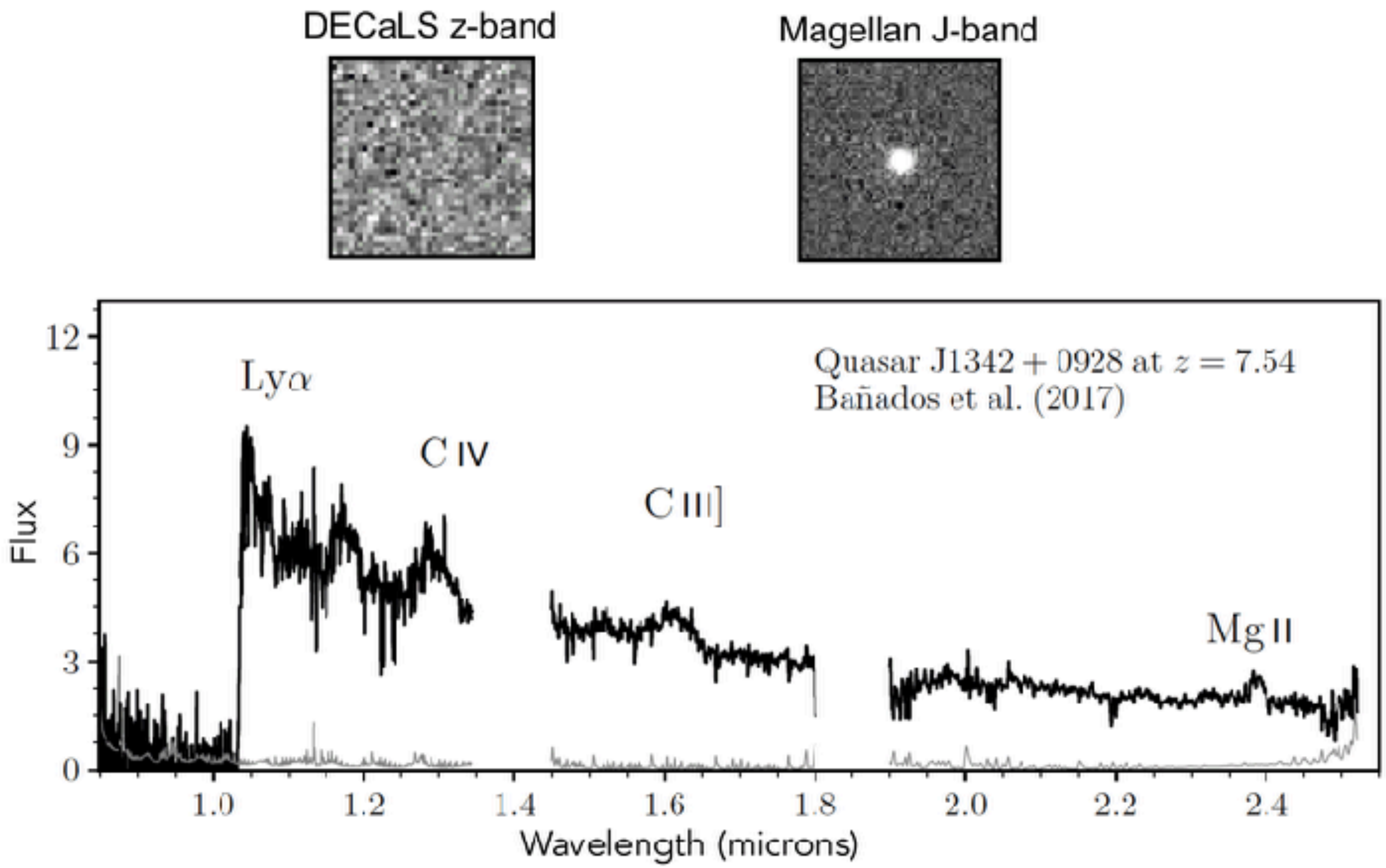
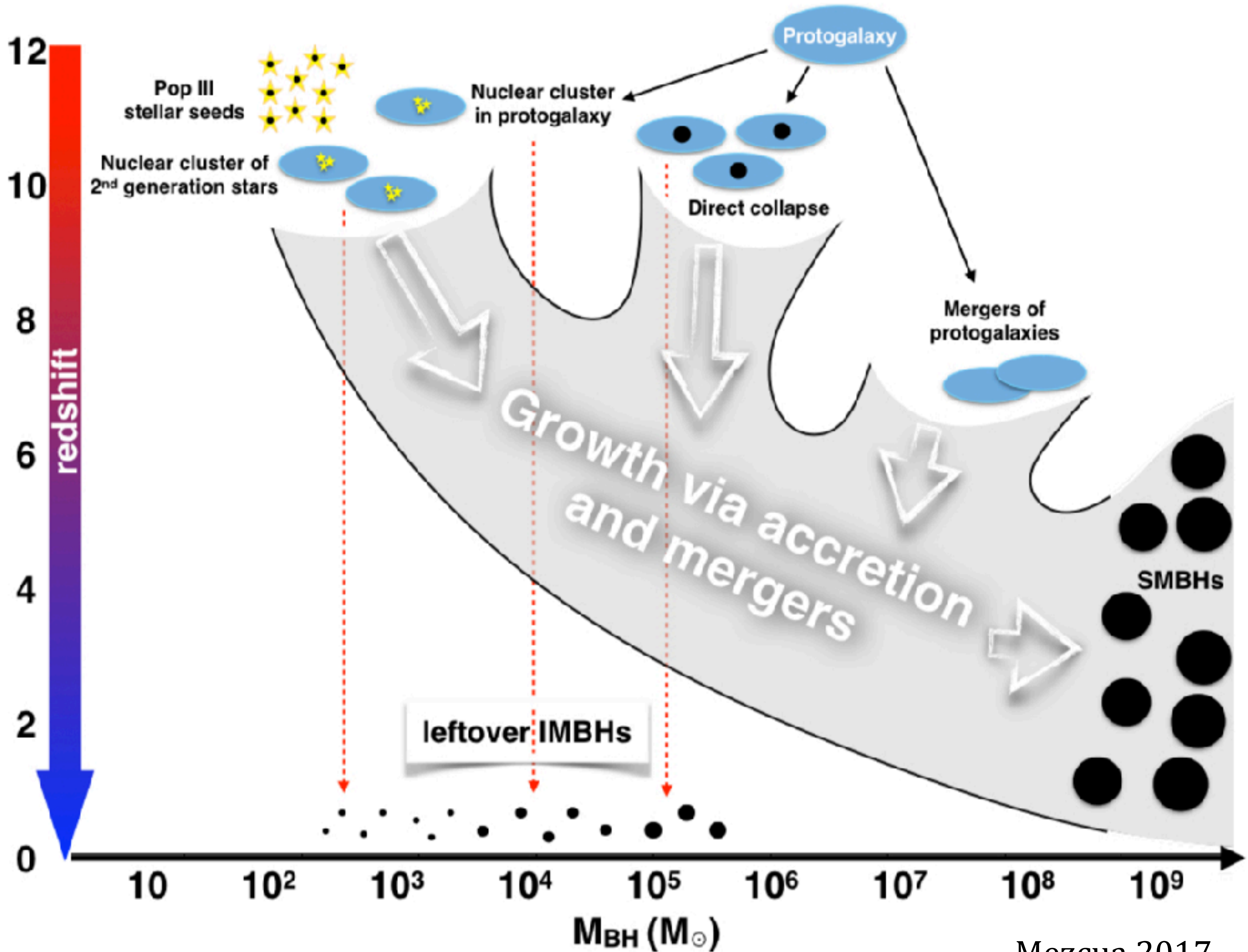


$M_{BH,init} > 1\times10^4\ M_\odot$

Banados+2018

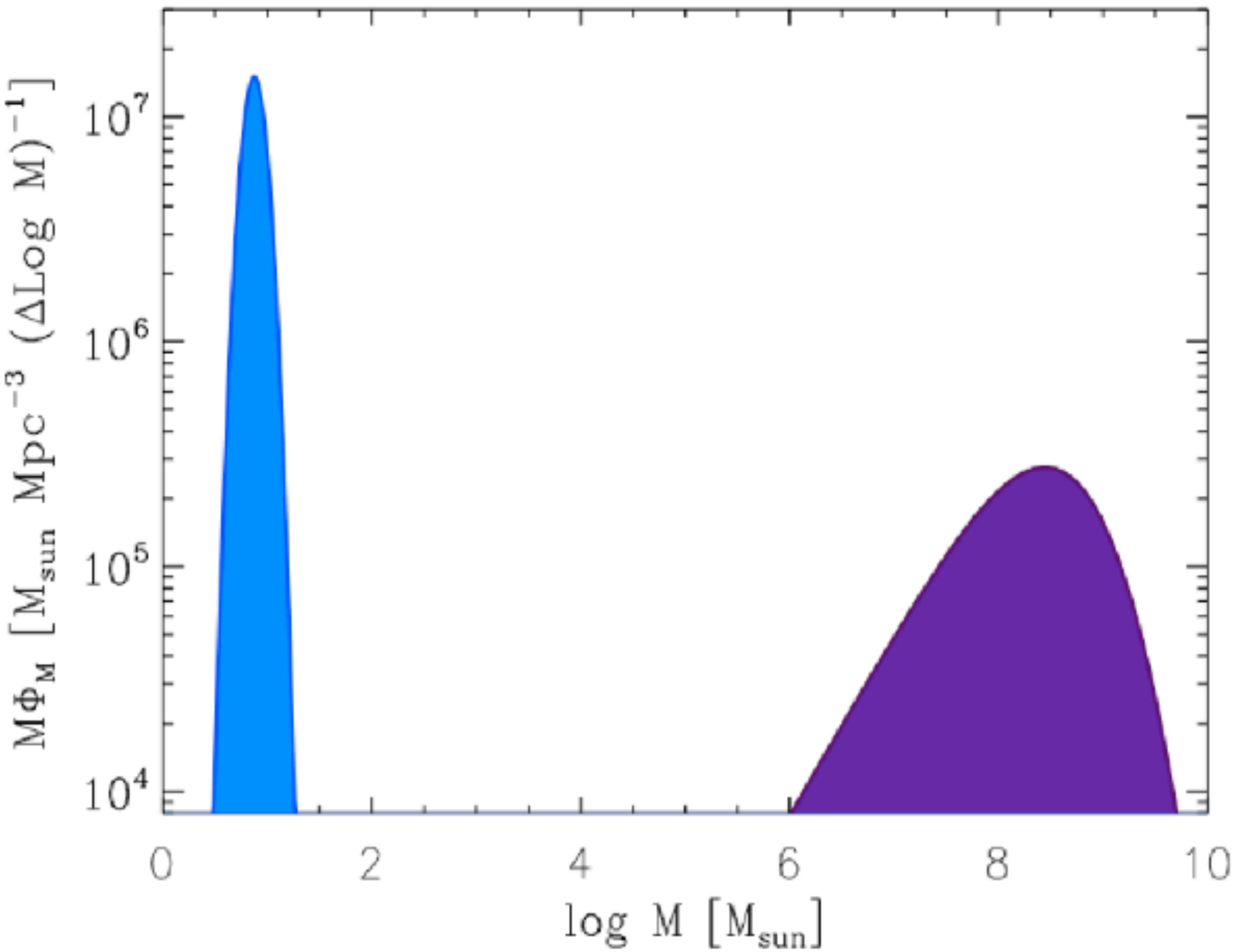


Protogalaxy
Pop III stellar seeds
Nuclear cluster in protogalaxy
Nuclear cluster of 2nd generation stars
Direct collapse
Mergers of protogalaxies
Growth via accretion and mergers
SMBHs
leftover IMBHs
redshift
12
10
8
6
4
2
0
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
M_BH (M_⊙)

Mezcua 2017

Intermediate-mass Black Holes (IMBH)

- 10^2 - $10^5 M_{\odot}$ BH
- Missing link between stellar mass BH and supermassive BH



Merloni & Heinz 2013

Origin of SMBH

Controversy?

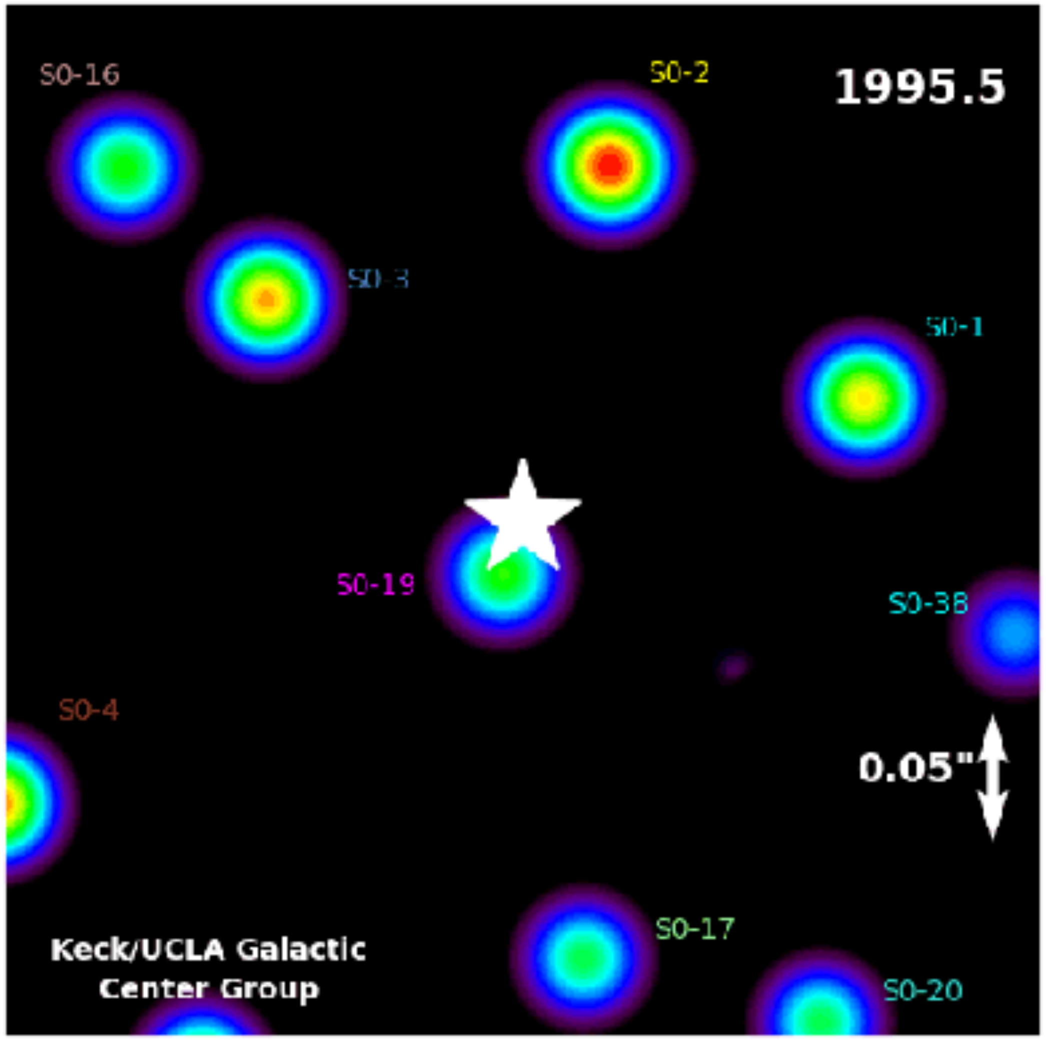
We suppose that the initial black holes form via a coherent collapse. This probably implies $M_{\rm BH} \gtrsim 10^6 M_\odot$. Formation of lower mass holes would be less efficient, for at least two reasons. Primordial clouds of mass less than $\sim 10^9 M_\odot$ are readily disrupted by supernova-driven winds (Dekel and Silk 1986). Given the observed efficiency of black hole formation, the formation of black holes of mass below $\sim 10^6$ M is likely to be inhibited.

Silk & Rees 1998

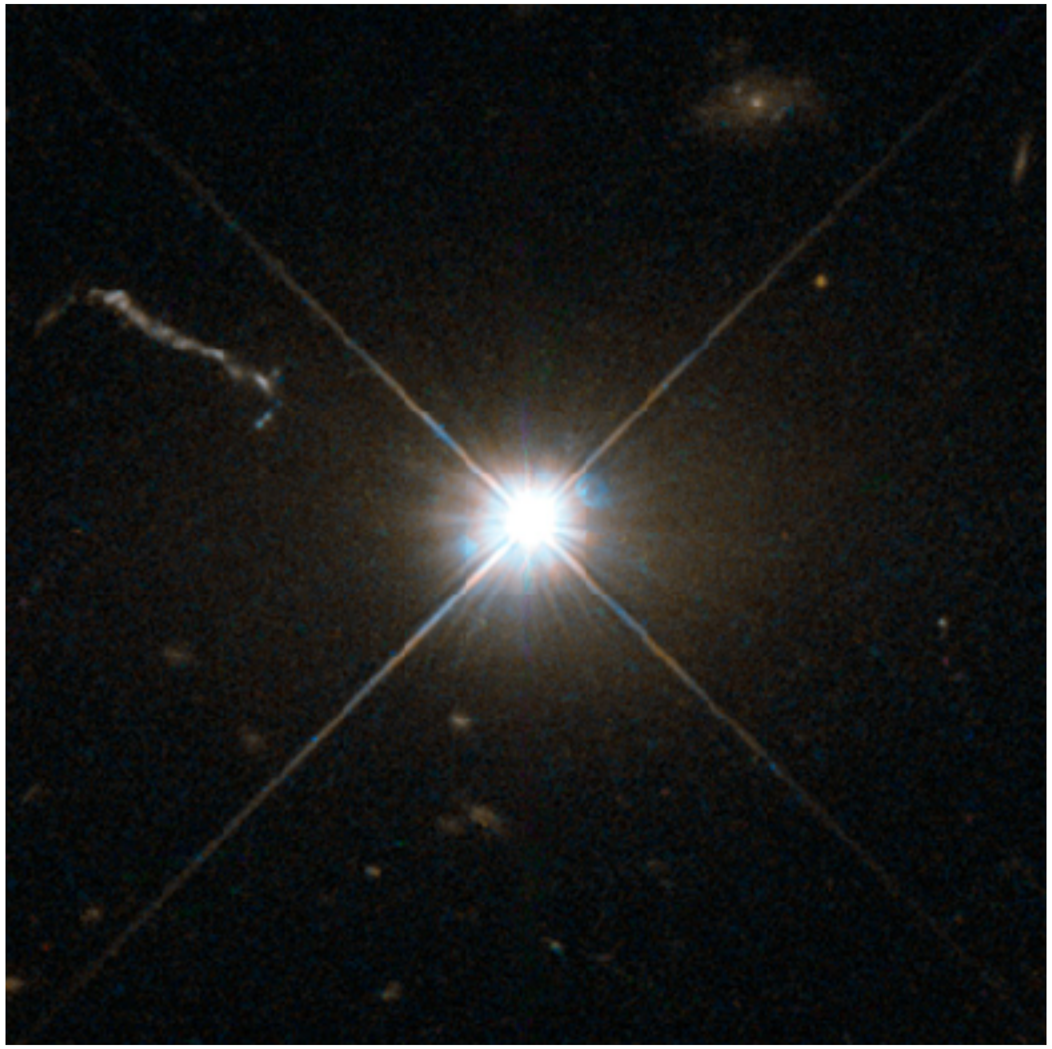
Intrinsically Rare vs. Detection limit?

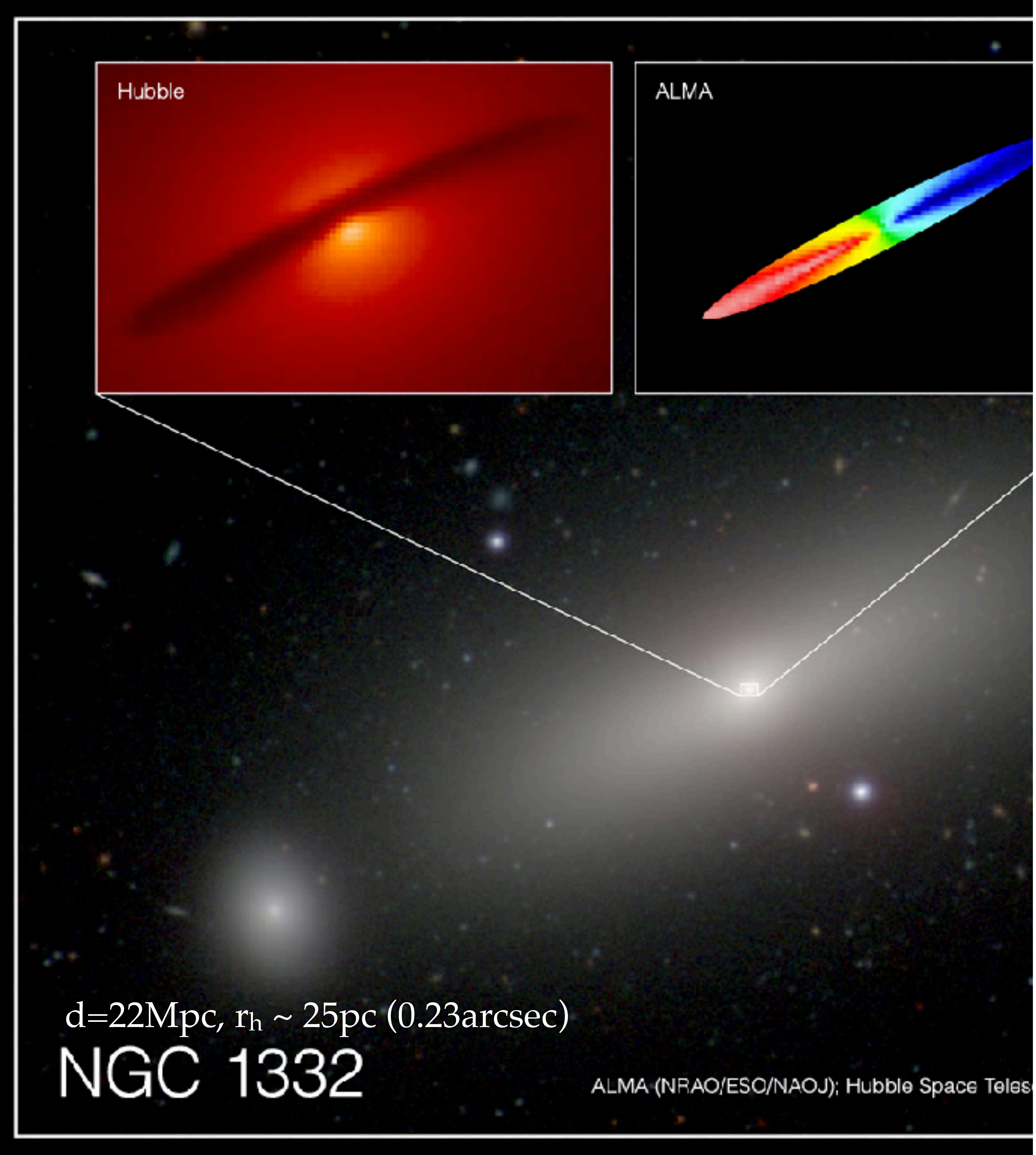
Normal Galaxies
(Sphere of influence)

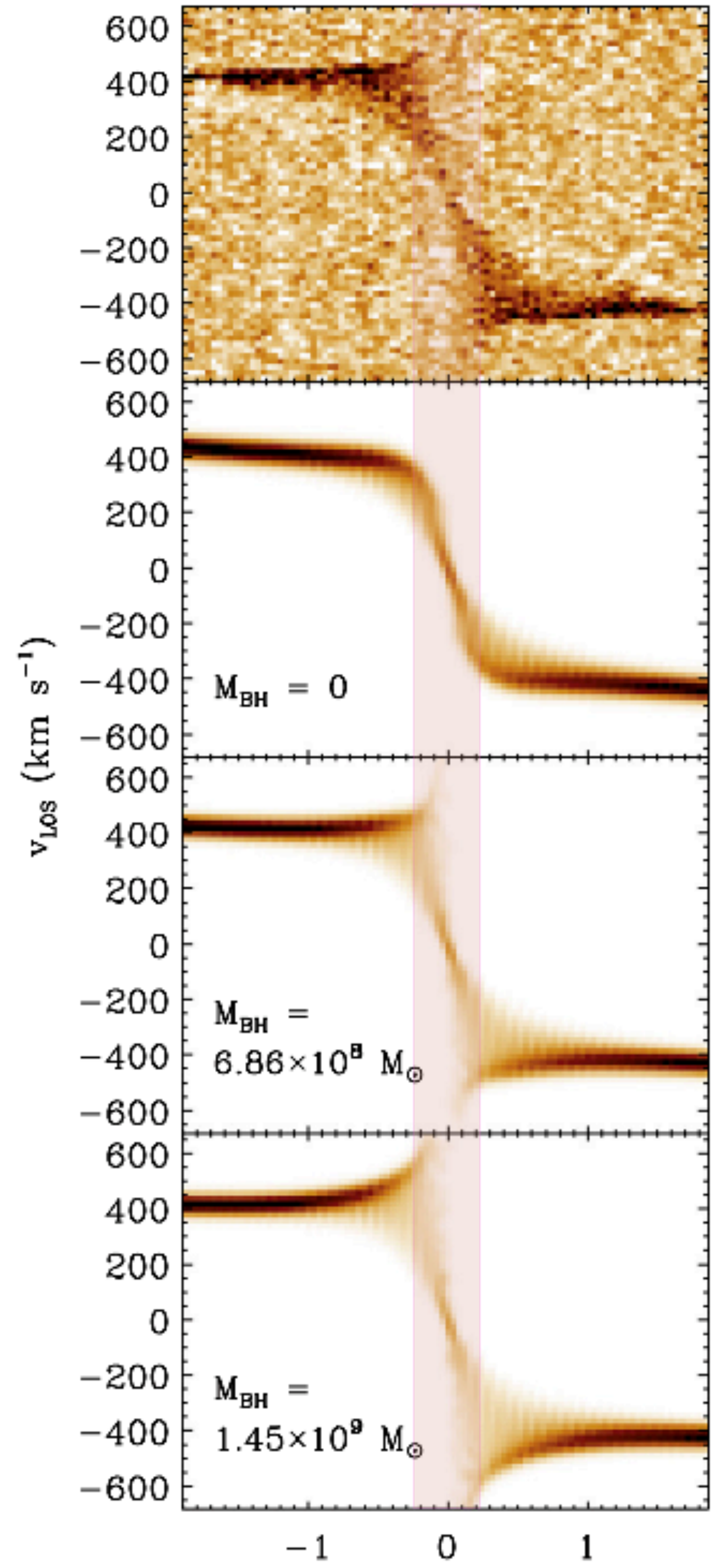
$$r_h = \frac{G \times M_{\rm BH}}{\sigma^2}$$



Active Galaxies







Barth et al. 2016

IMBH Candidates

- Where are leftover IMBHs? (methods to search for IMBH)

  - Low-mass active galaxies
  (e.g., Greene & Ho 2005; Reines et al. 2013; Ho & Kim 2016; Woo et al. 2019)

  - Ultraluminous X-ray sources (ULXs)
  (e.g., Kaaret et al. 2001; Farrell et al. 2009; Mezcua et al. 2015; Kim et al. 2015)

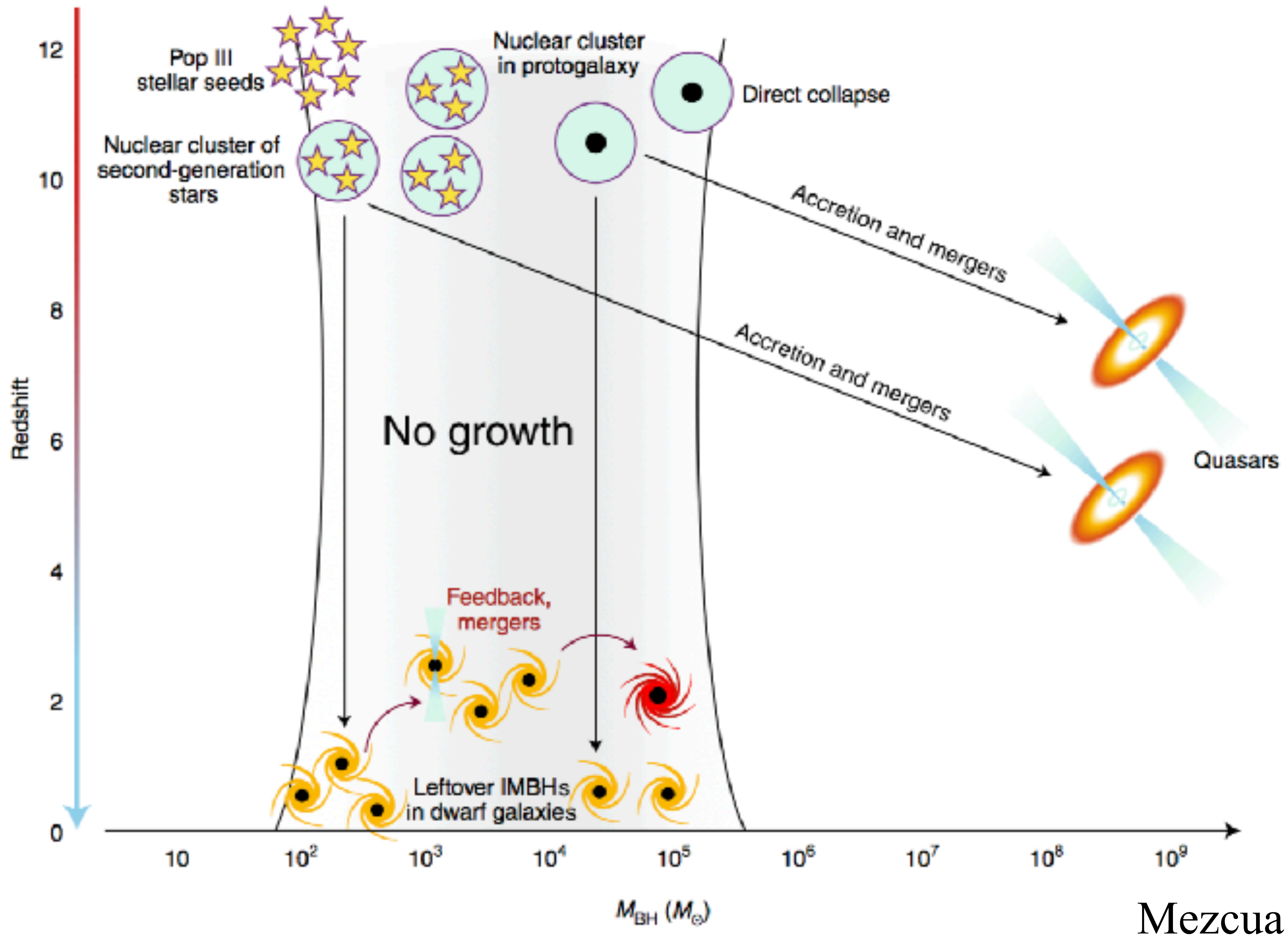
  - Massive star clusters (47 Tuc, G1, *w* Cen, M54)
  (e.g., Kızıltan et al. 2017; Gebhardt et al. 2005; Noyola et al. 2010)

  - Tidal Disruption Events
  (e.g., Krolik & Piran 2011; Kuin et al. 2019)

  - Gravitational wave

Searching for IMBH

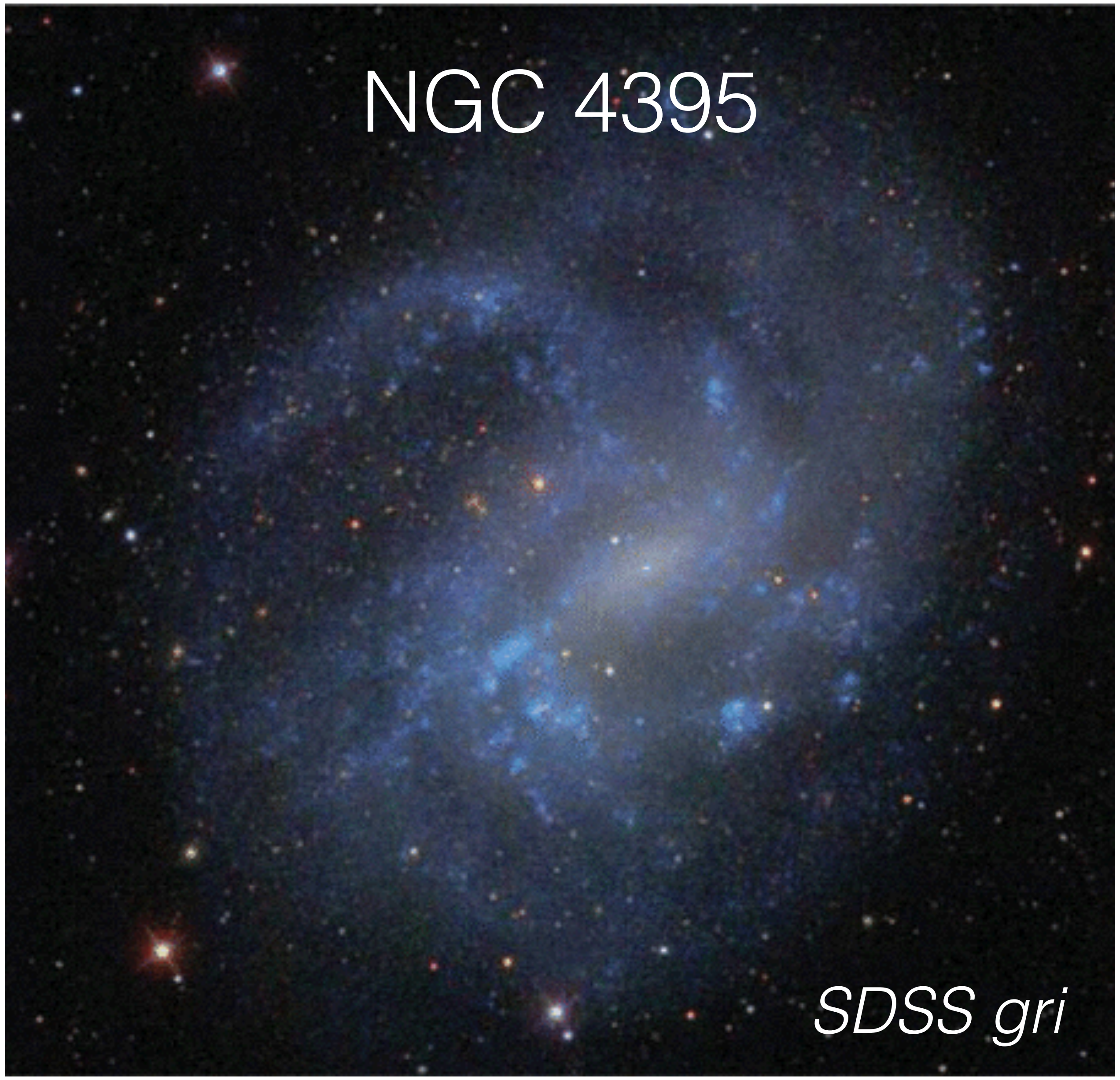
- (Leftover) IMBHs in dwarfs

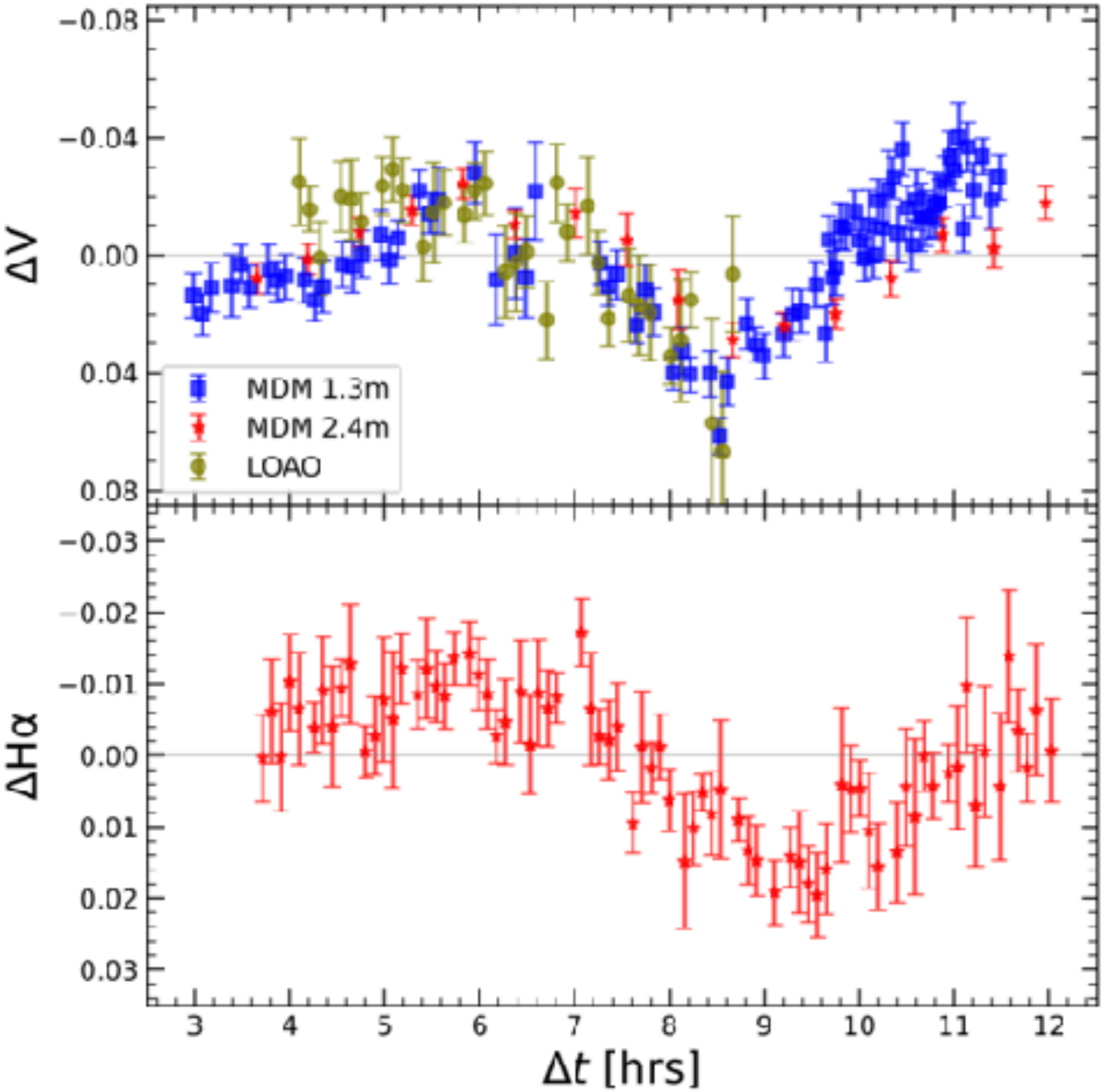


Mezcua 2018

IMBH in dwarf galaxy

$M_{BH} \sim 10,000\ M_{\odot}$



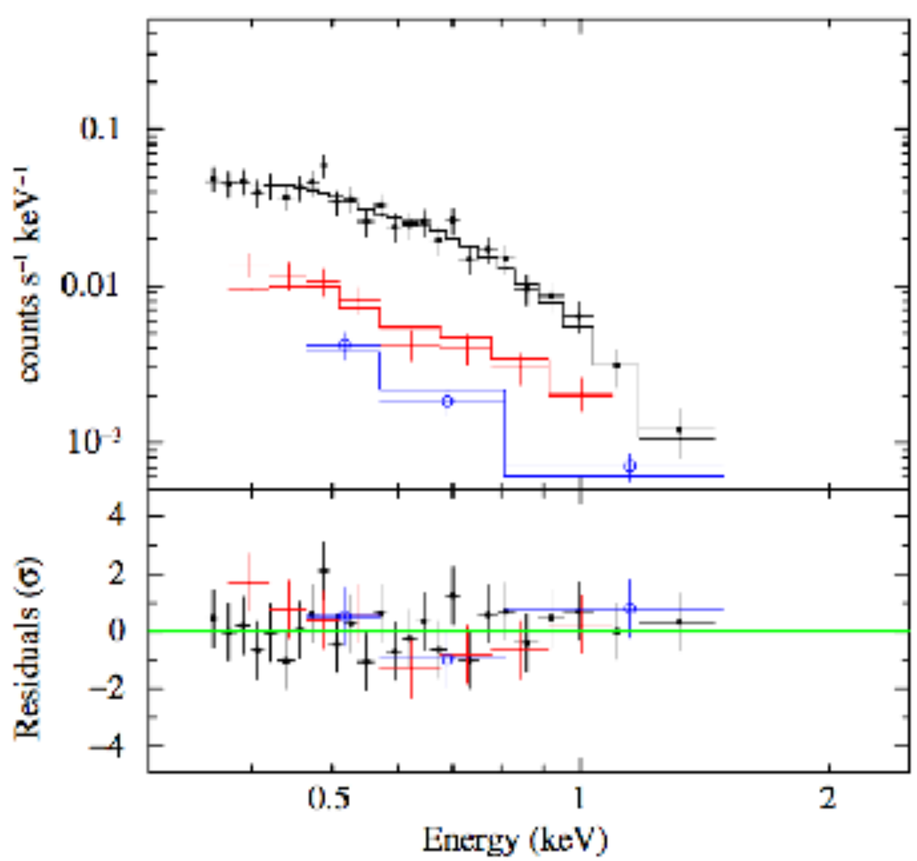


Woo et al. 2019

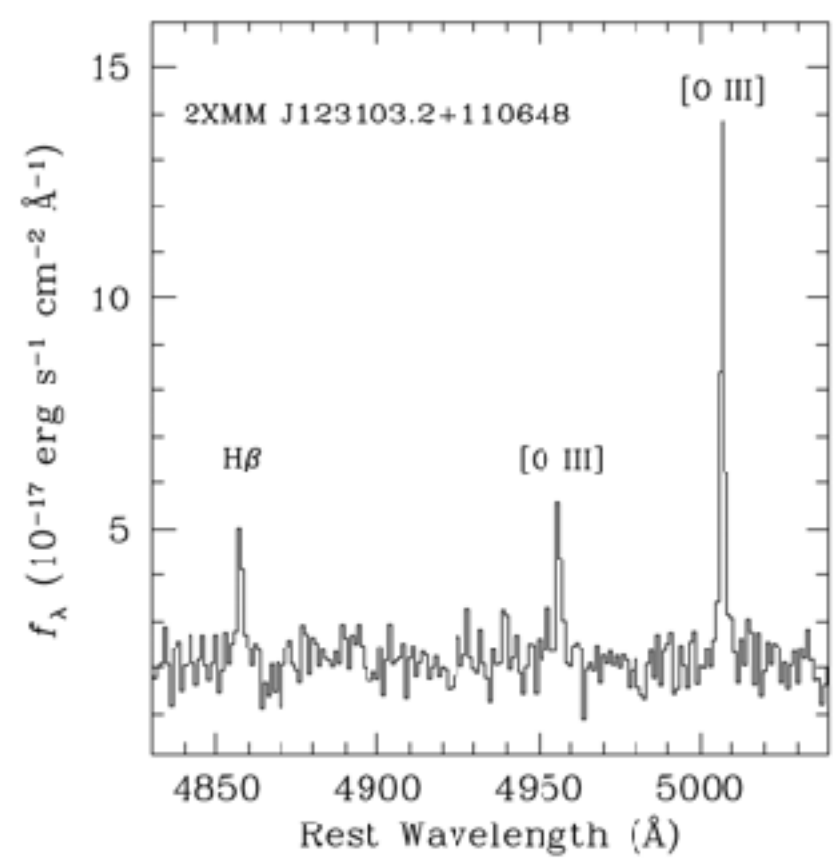
IMBH in dwarf galaxy

- Low mass active galaxies (Variability in X-ray)
  - J1231+1106 : $M_{\rm BH} \sim 3\text{-}7 \times 10^4\, M_\odot$

X-ray spectrum



Magellan/IMACS spectrum

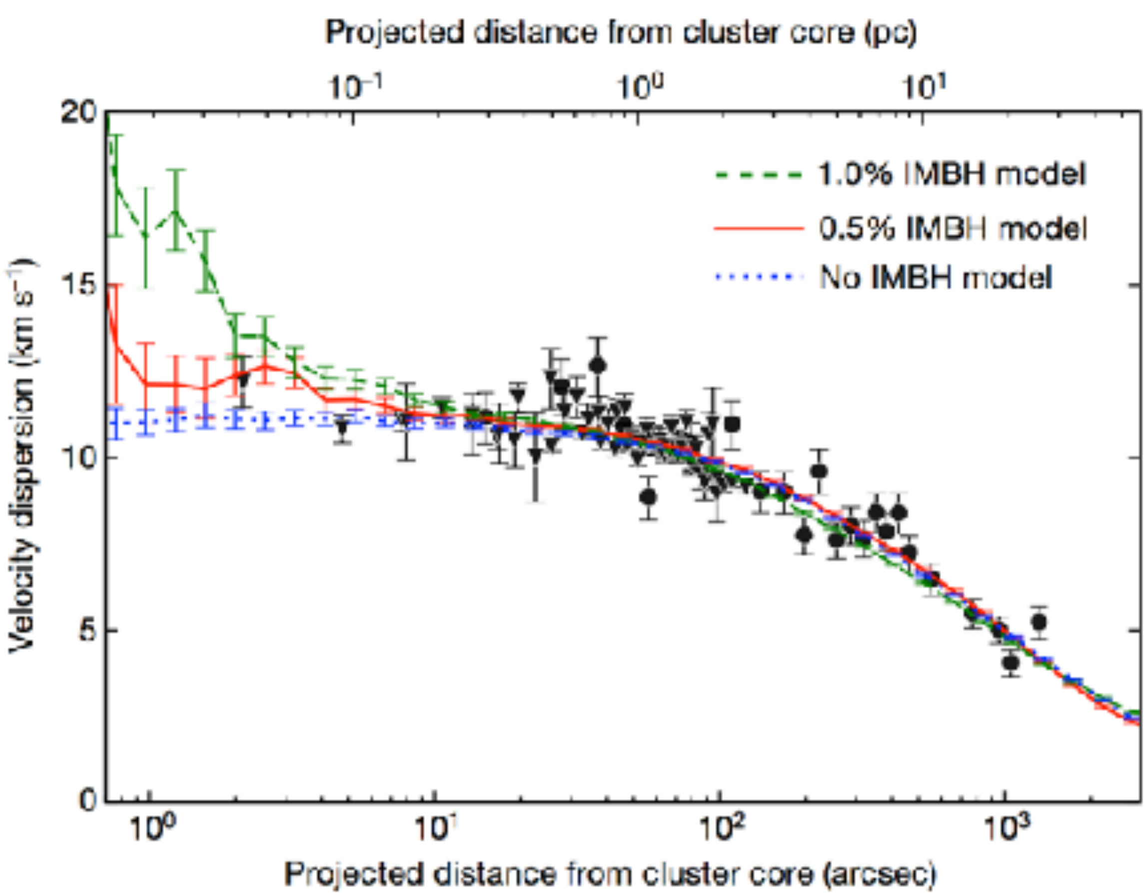


Terashima et al. 2012; Kamizasa et al. 2012 Ho, Kim, Terashima 2012; Ho & Kim 2016

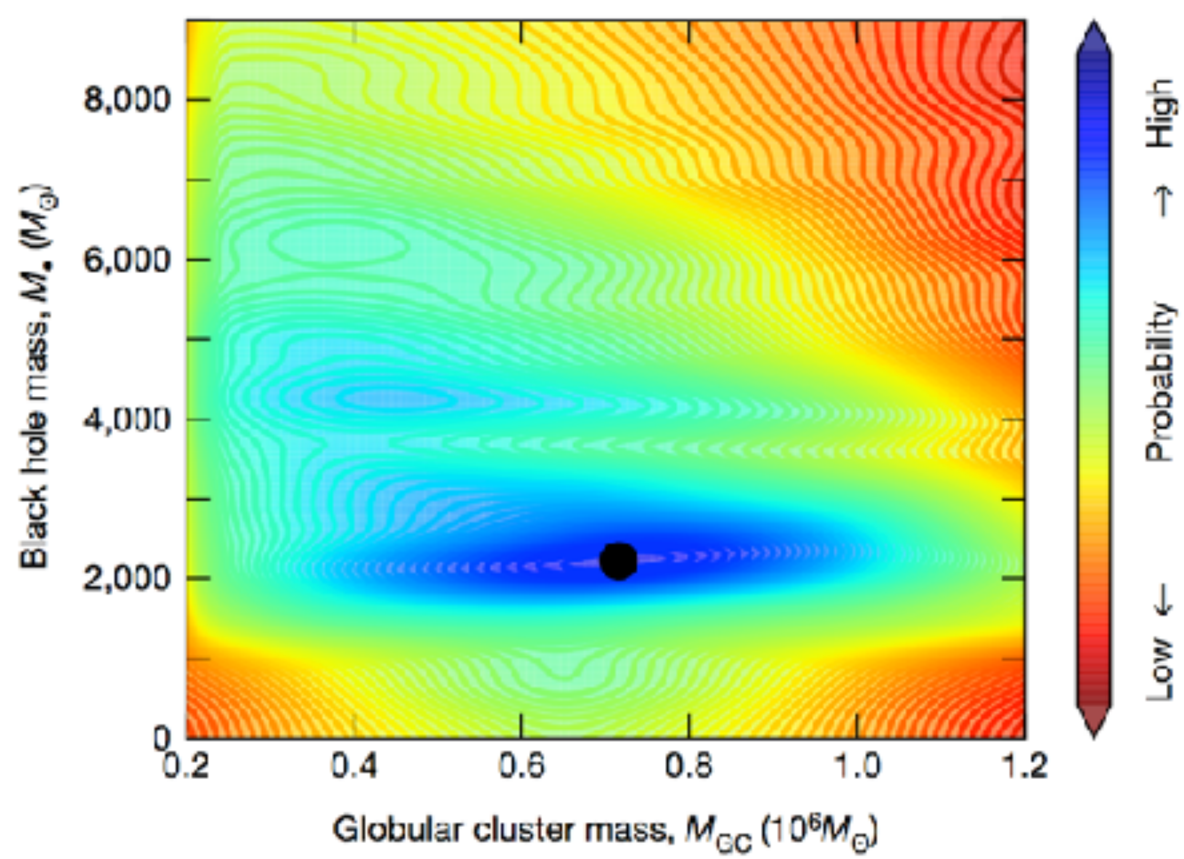
IMBH in Globular Cluster

- Massive globular cluster
  - 47 Tuc : $M_{\mathrm{BH}} \sim 2200\ M_{\odot}$

N-body simulation vs. observation



Pular acceleration

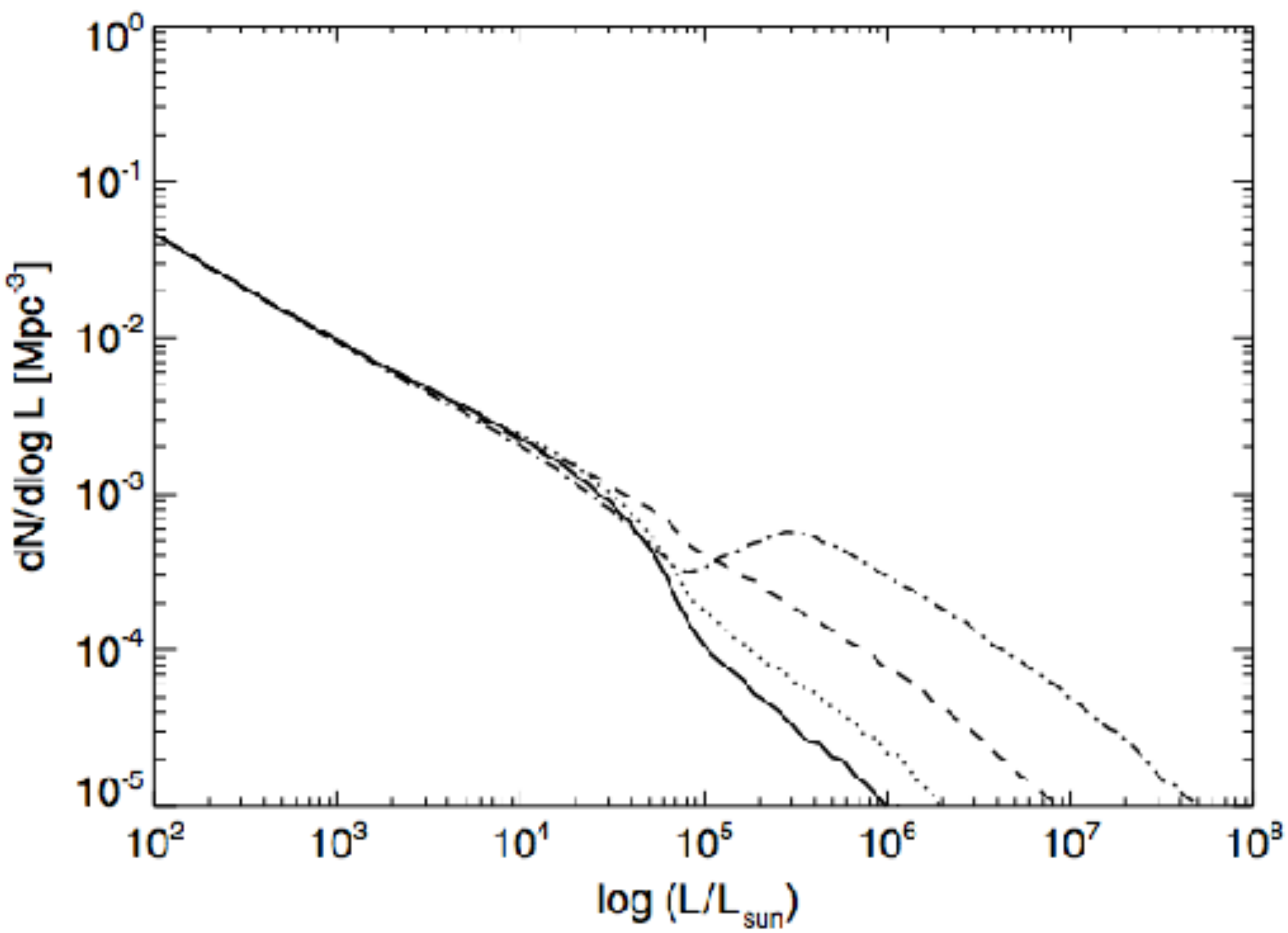


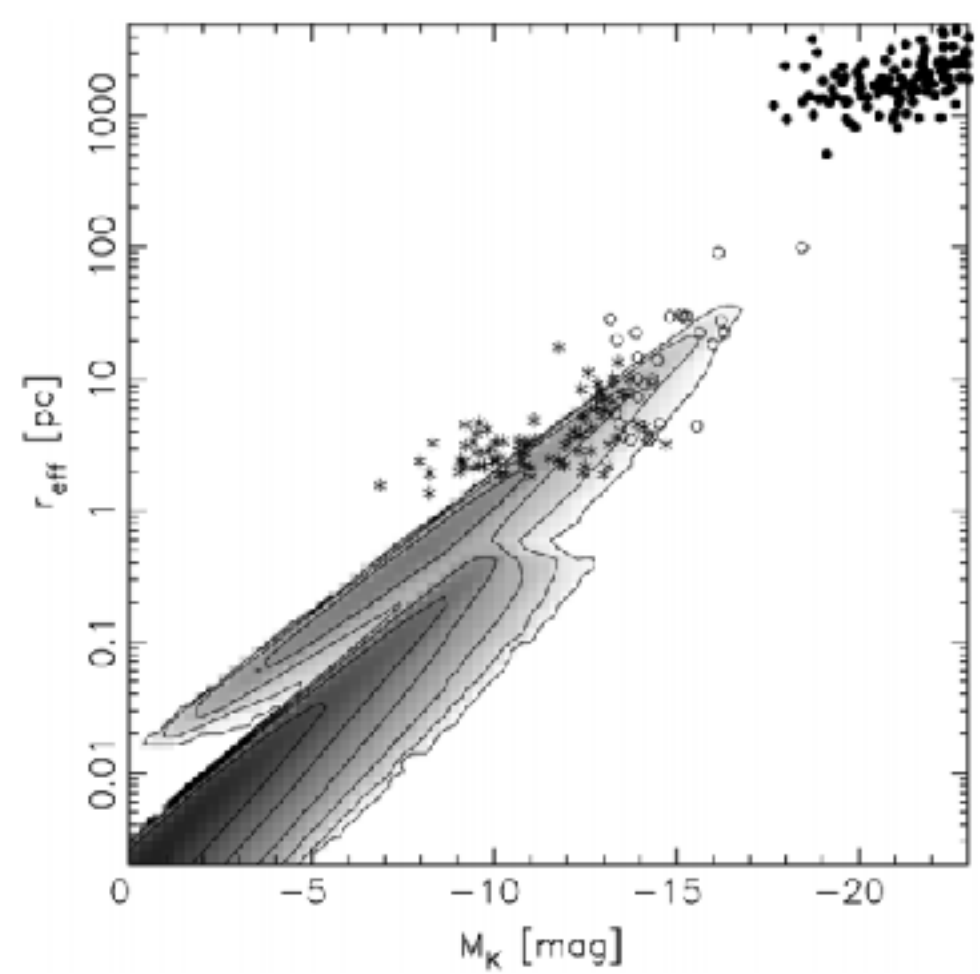
Kızıltan et al. 2017 Nature

IMBH in Compact Star Clusters

- Hyper compact star clusters (recoiling BH)

Prediction from the theoretical model





Merritt et al. 2009

IMBH in Compact Star Clusters

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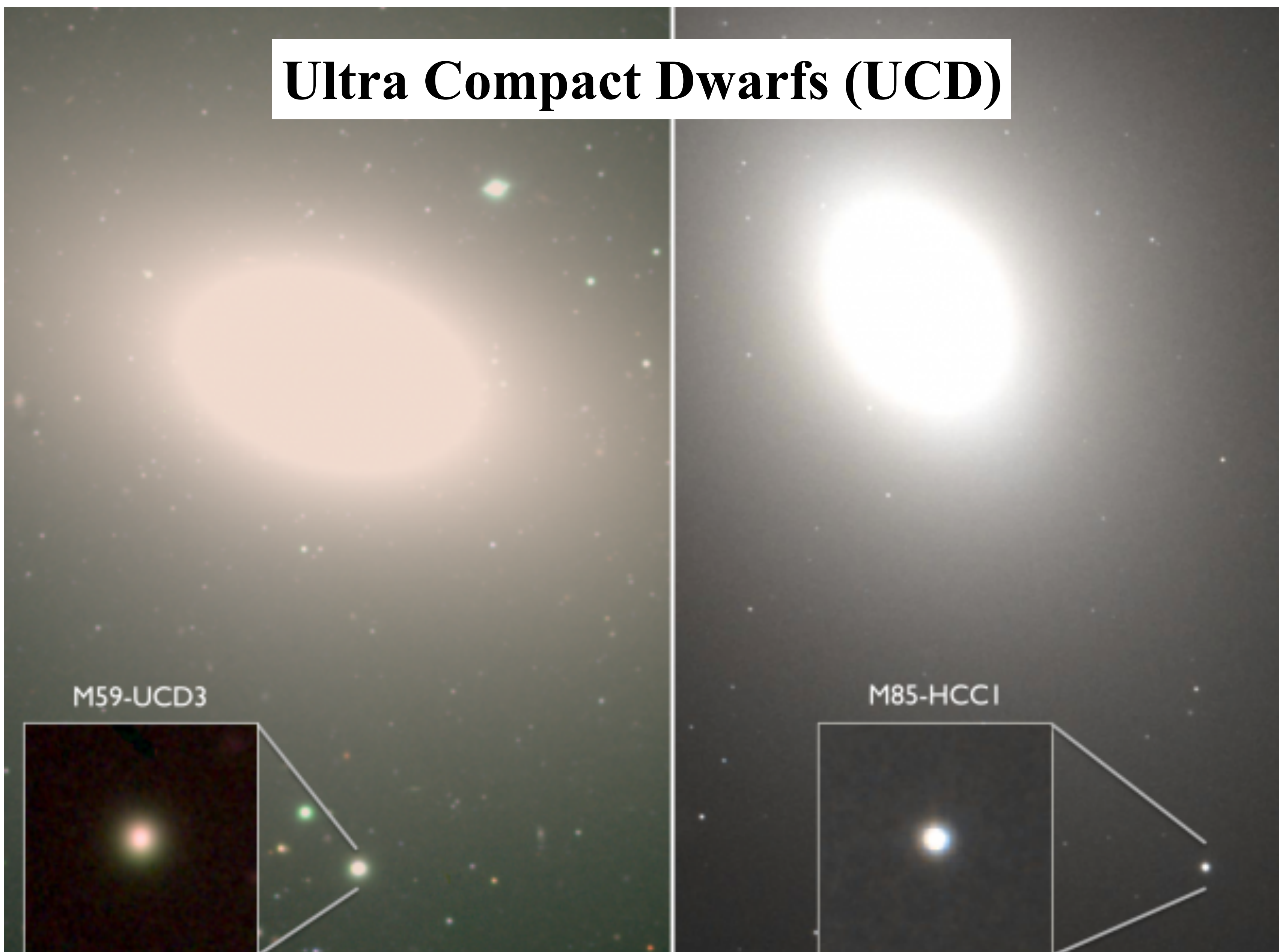


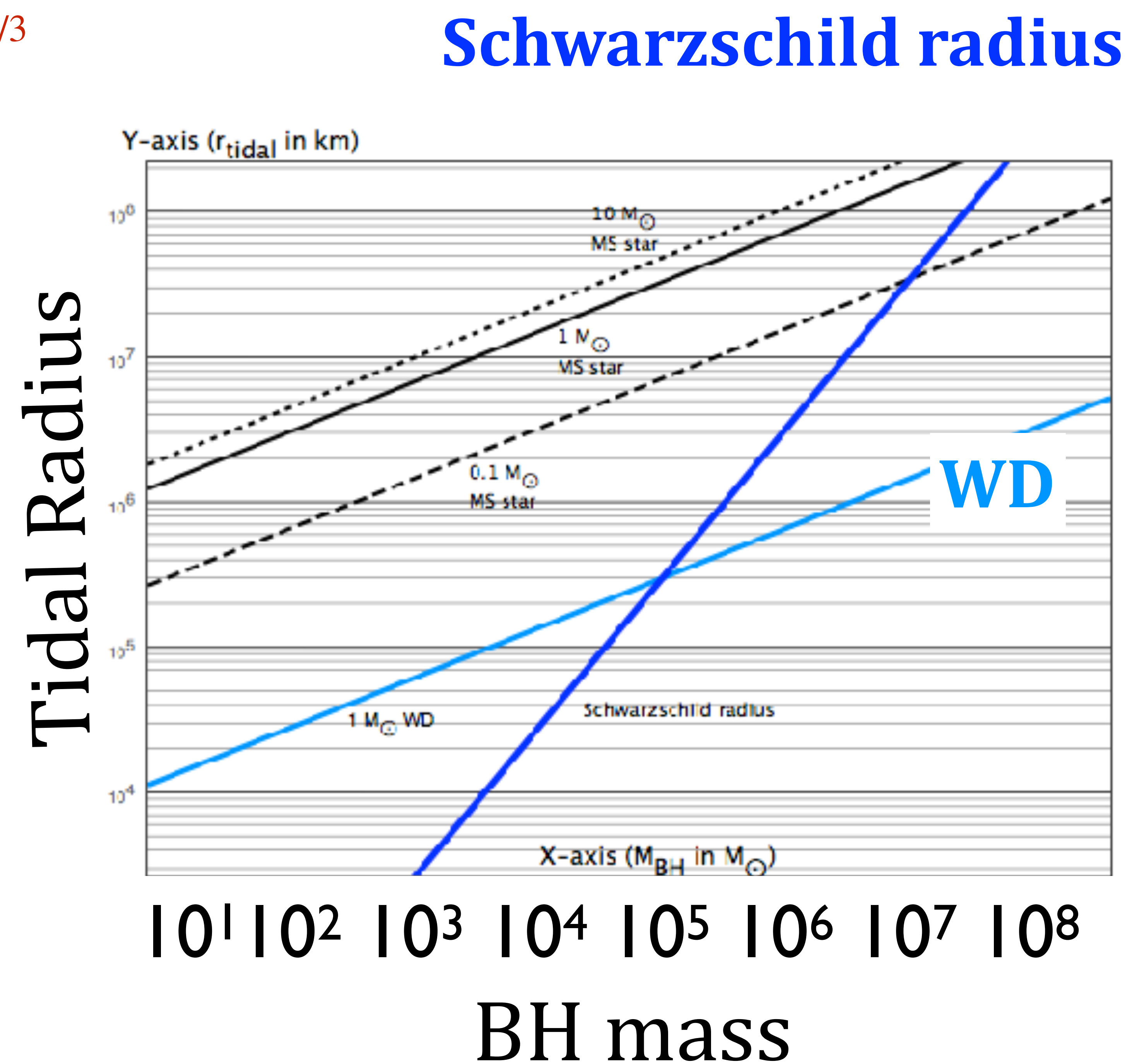
Sandoval et al. 2015

IMBH from TDE

- Tidal Disruption Event with white dwarfs

$$\frac{R_t}{R_s} \approx 3 \times 10^3 \left(\frac{M_\odot}{M_{\rm BH}}\right)^{2/3} \left(\frac{M_\odot}{M_{\rm WD}}\right)^{2/3}$$

Credit : NASA Goddard



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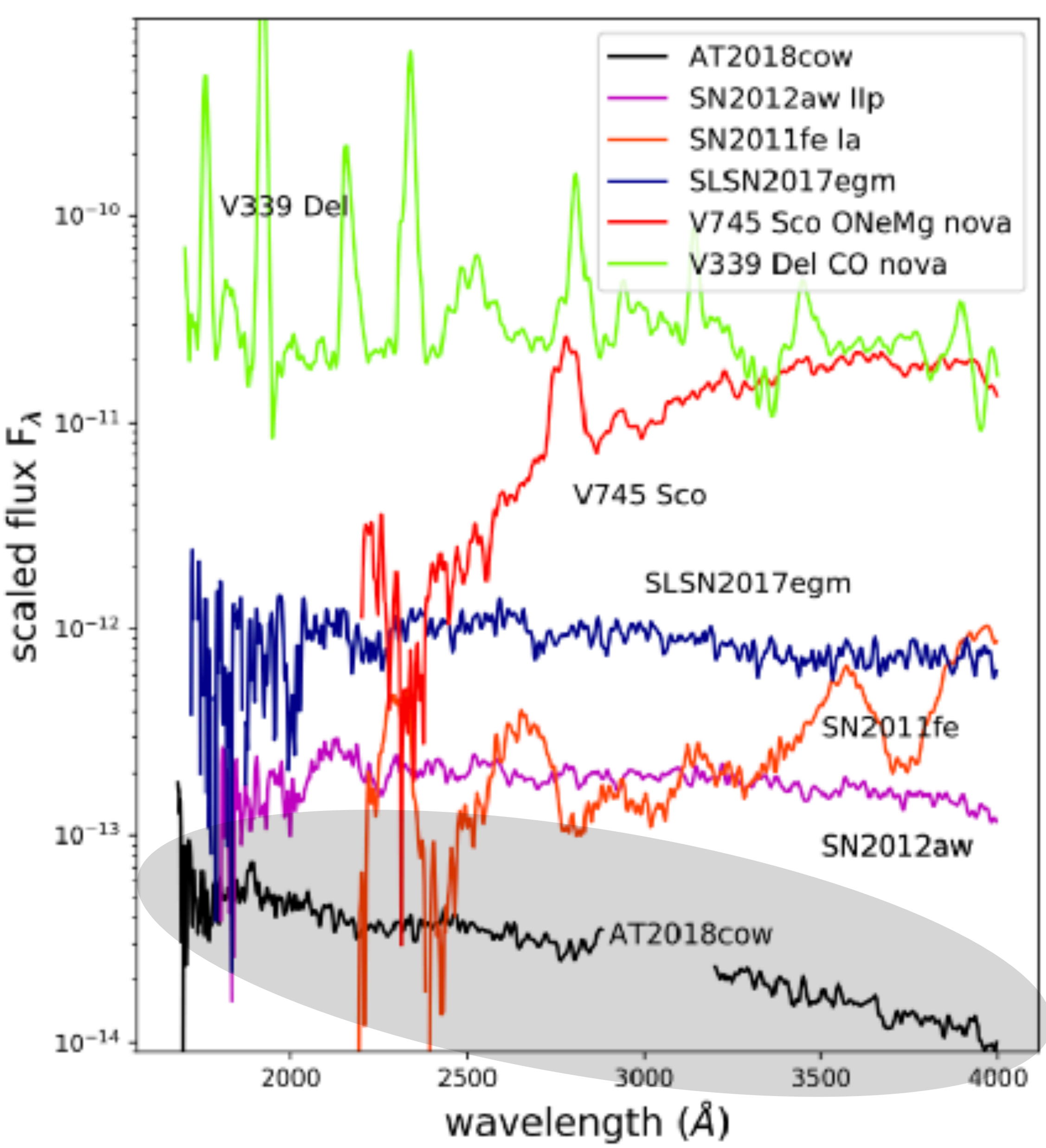
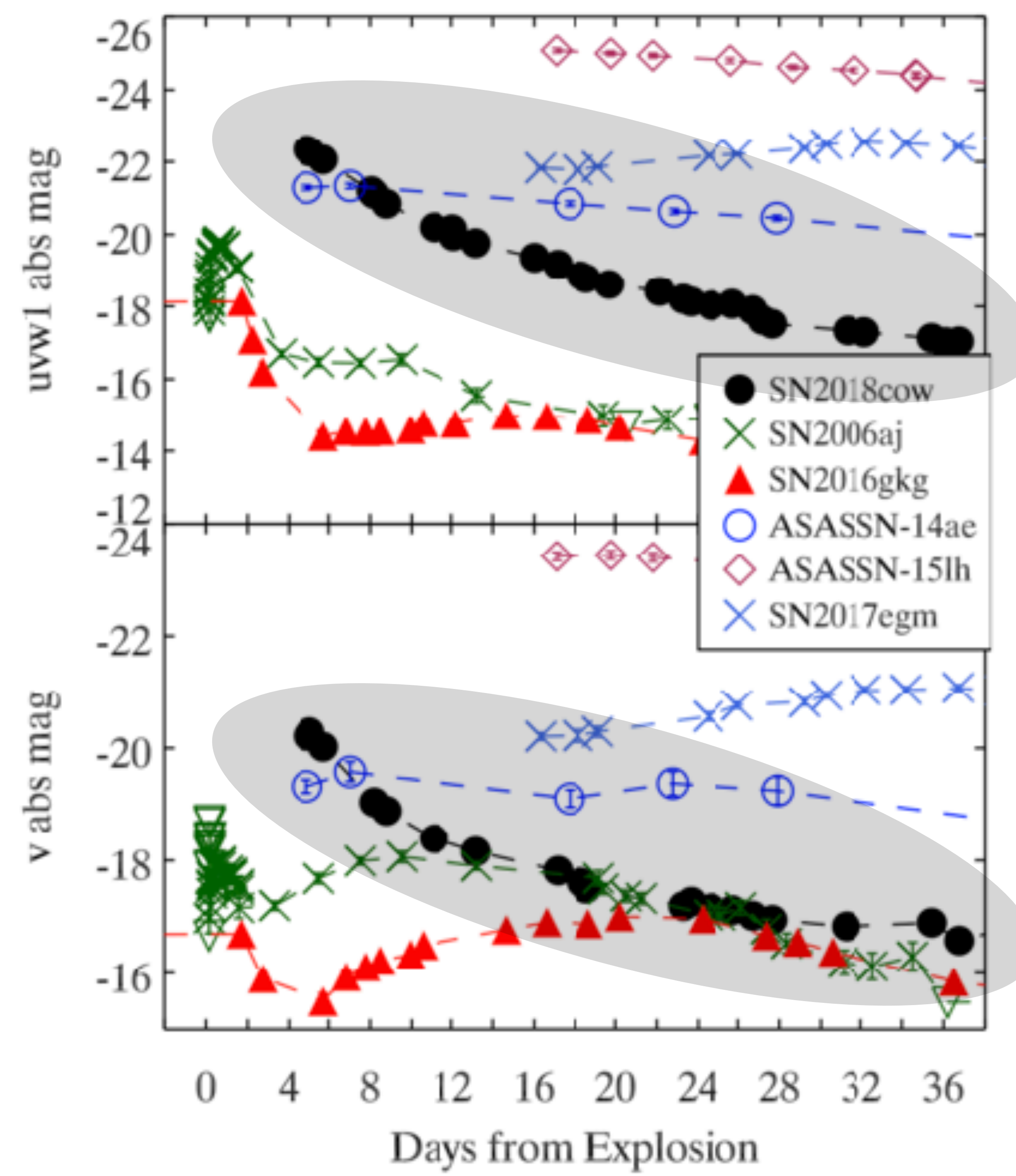




Kuin et al. 2019

IMBH

- Where are they? (methods to find IMBH)

  - Low-mass active galaxies (Greene & Ho 2005, Reines et al. 2013, Ho & Kim 2016, etc.)

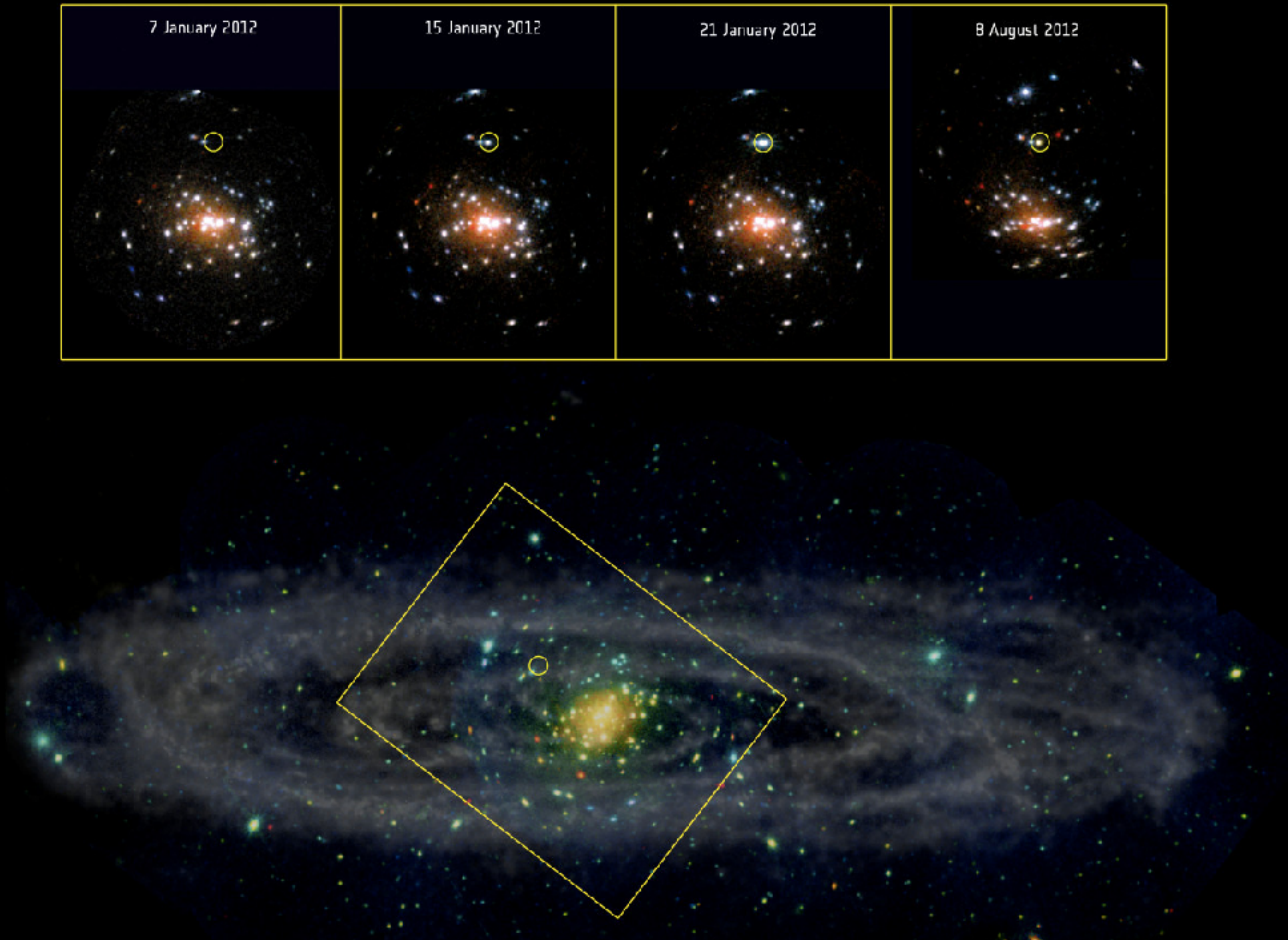
  - Massive star clusters (47 Tuc, G1, *w* Cen, M54)

  - Hyper-compact star clusters

  - Tidal Disruption Events

  - GW!

  - Ultraluminous X-ray sources (ULXs)

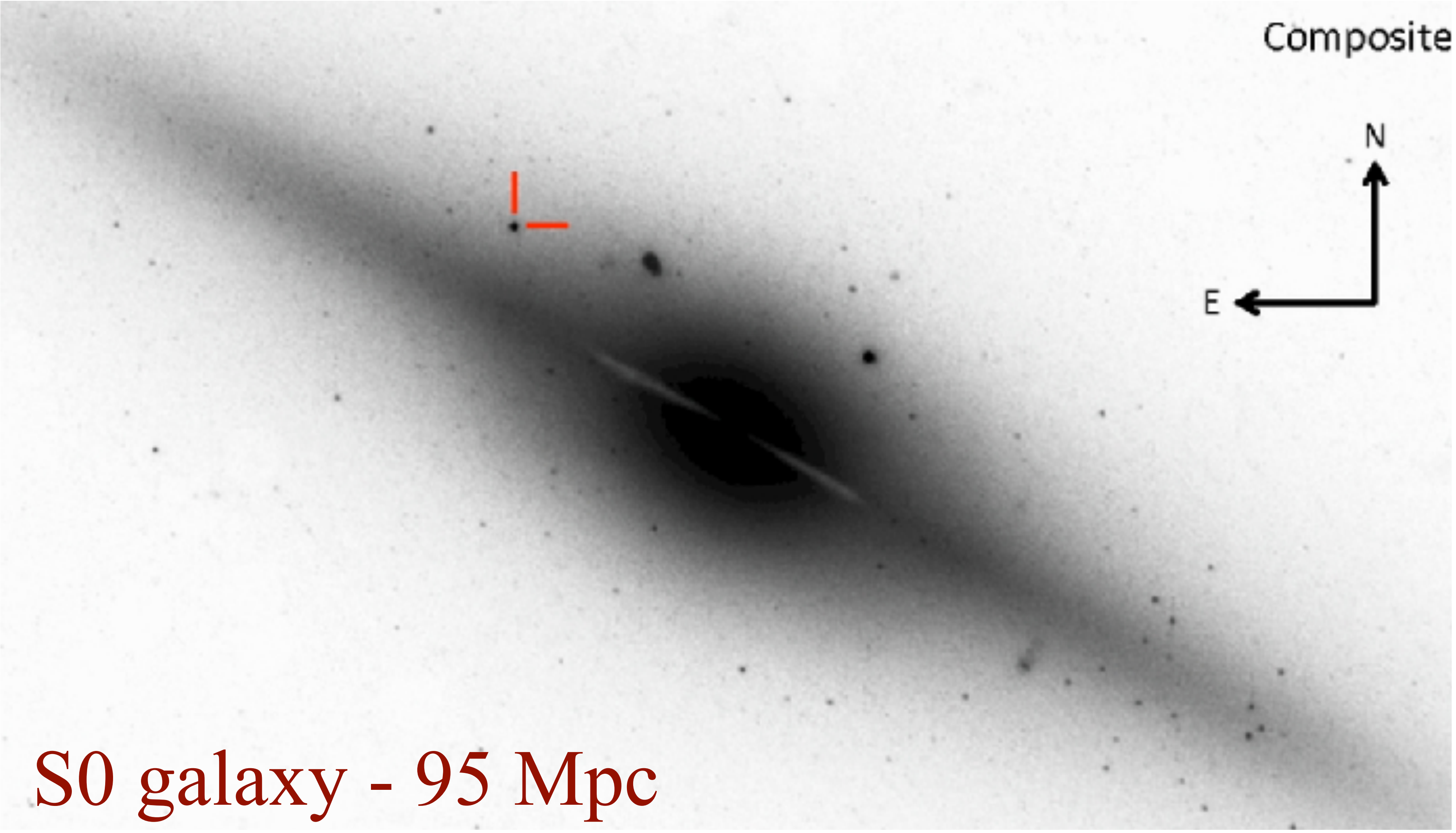


Credit : ESA/XMM-Newton/MPE

Ultraluminous X-ray sources (ULXs)

- off-nucleus
- $L_{\text{x-ray}} > 2 \times 10^{39}$ erg s^{-1}
- strong candidates of IMBHs
- very faint optical counterpart
- often associated with low-metallicity HII region

Example 1 : HLX-1 in ESO 243-49



Farrell et al. 2012

Example 1 : HLX-1 in ESO 243-49

- One of the strongest candidates for IMBH

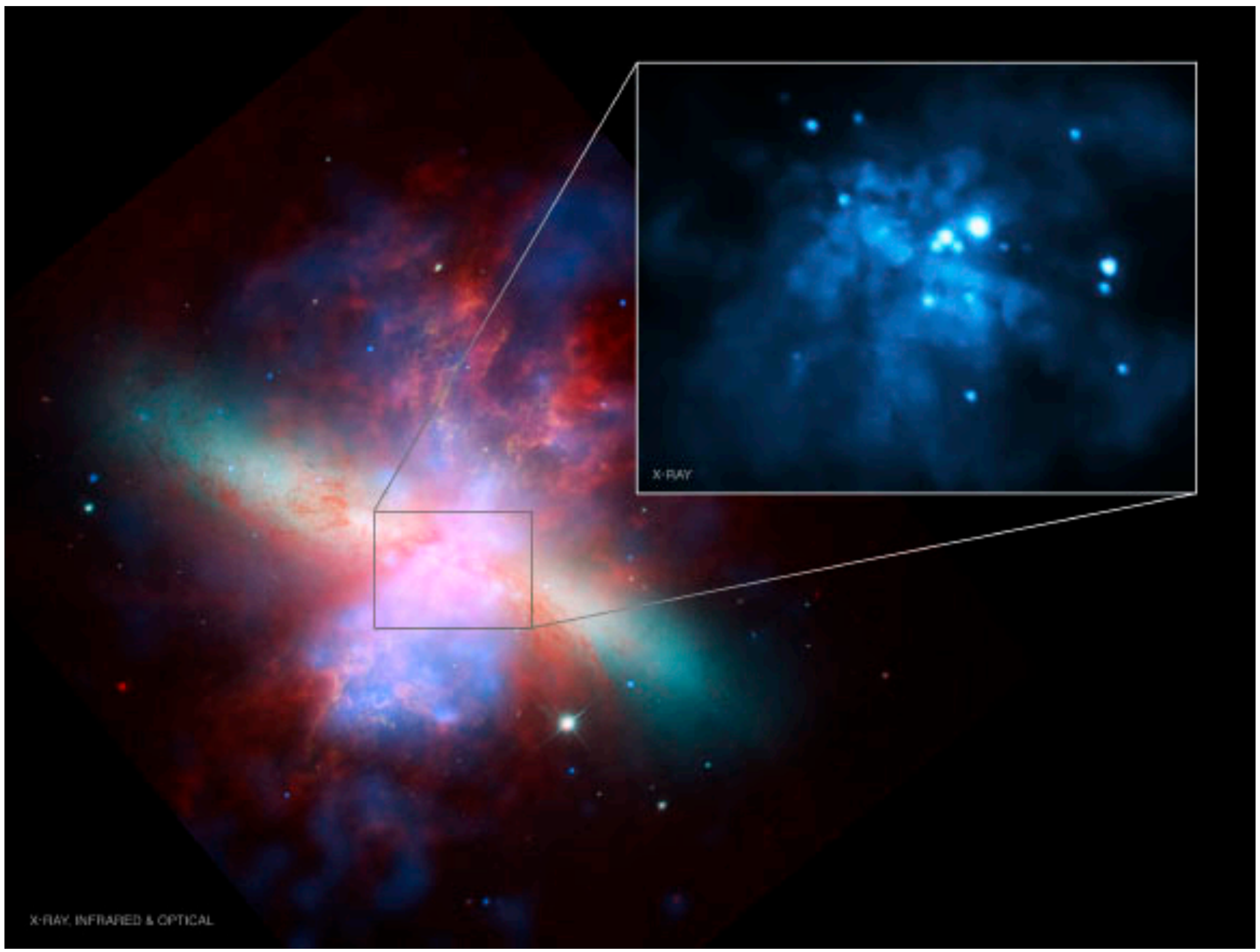
  - Hyperluminous X-ray source ~ 10^{42} erg s^{-1}

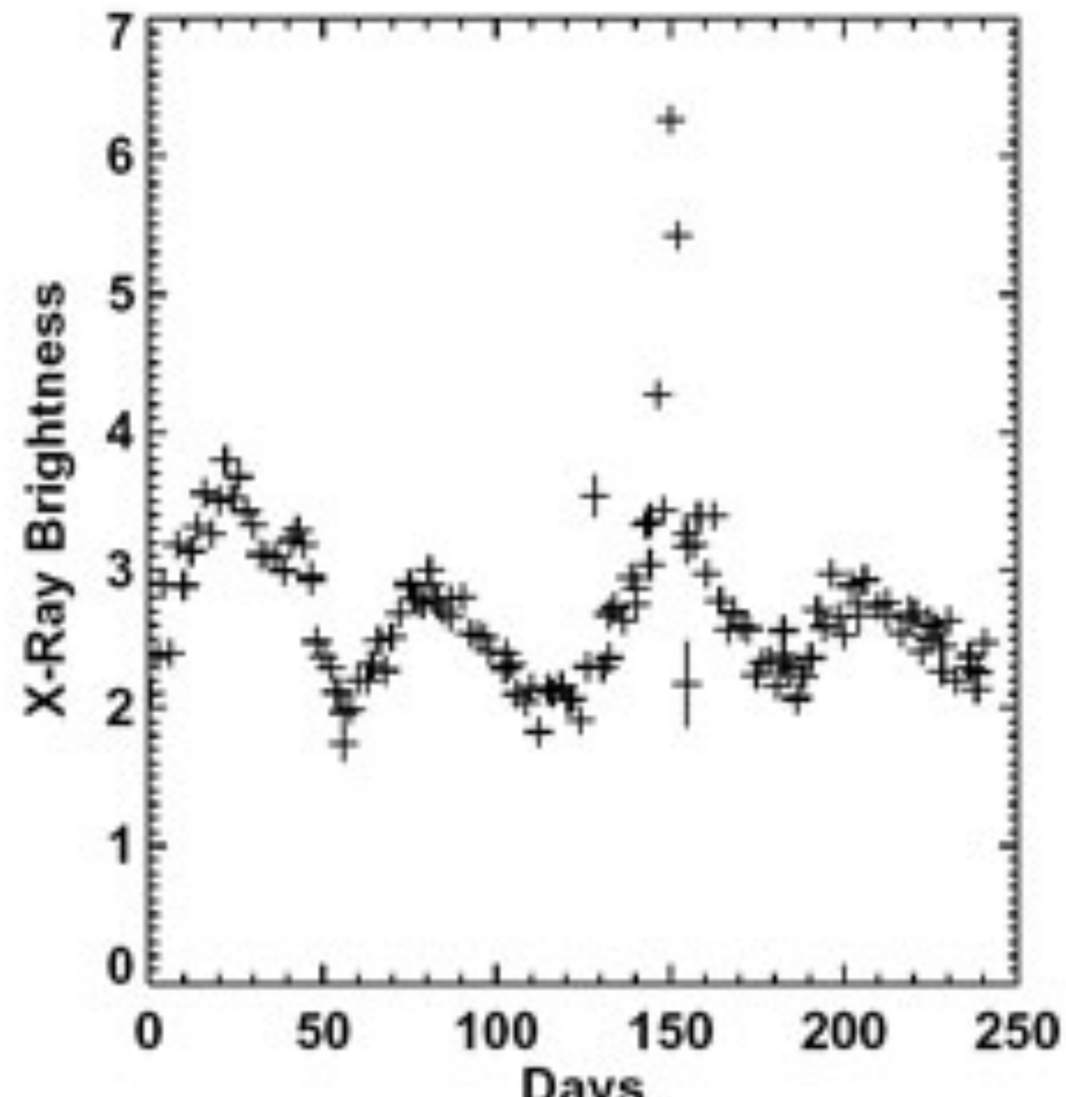
    400 times brighter than Eddington limit of $20 M_\odot$ of (stellar) BH

  - V ~ 24 mag (~ 10^6 $M_\odot$ stellar mass)

  - But, very weak optical and radio emission

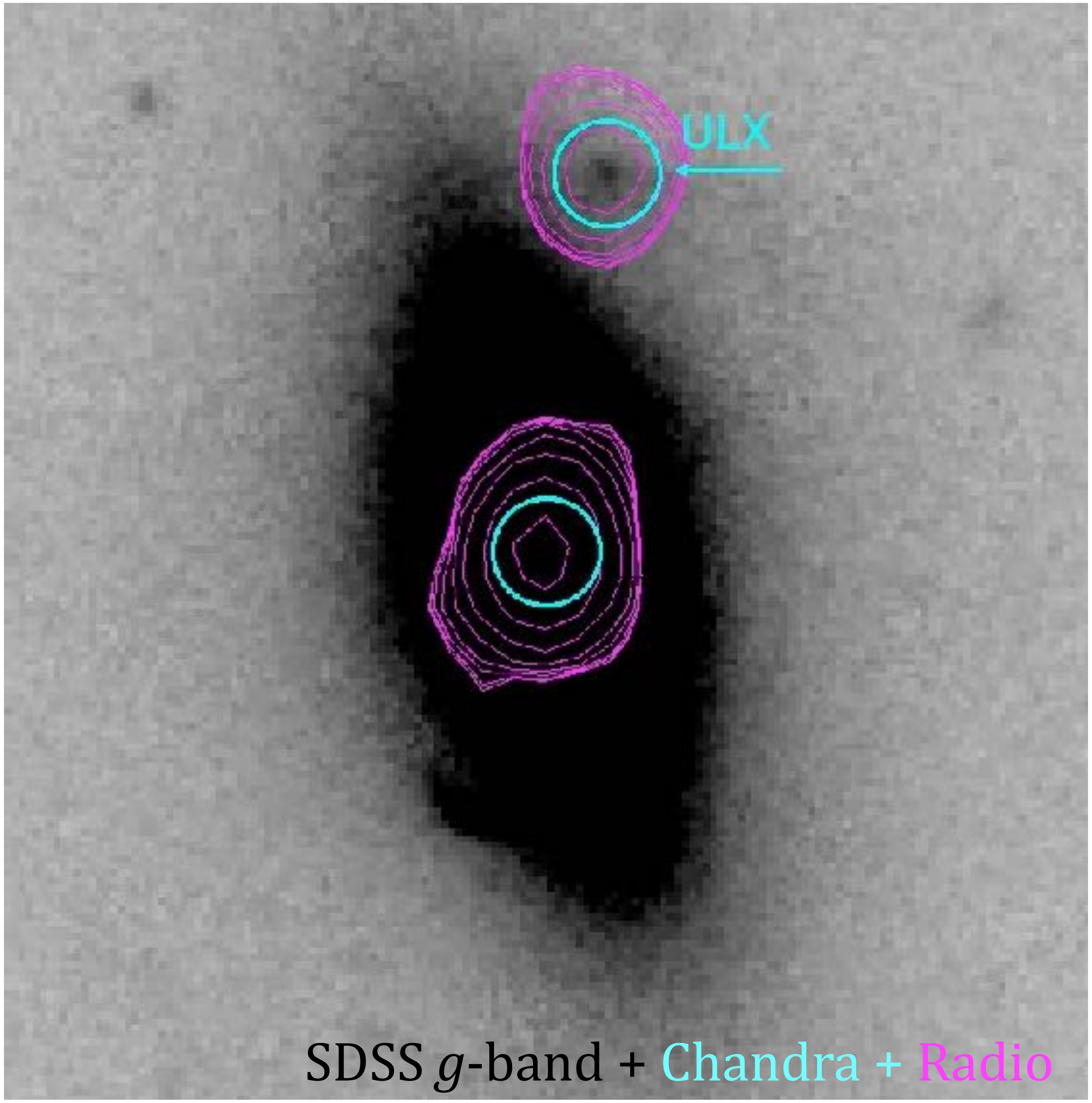
Example 2 : M82 X-1





Pasham et al. 2014

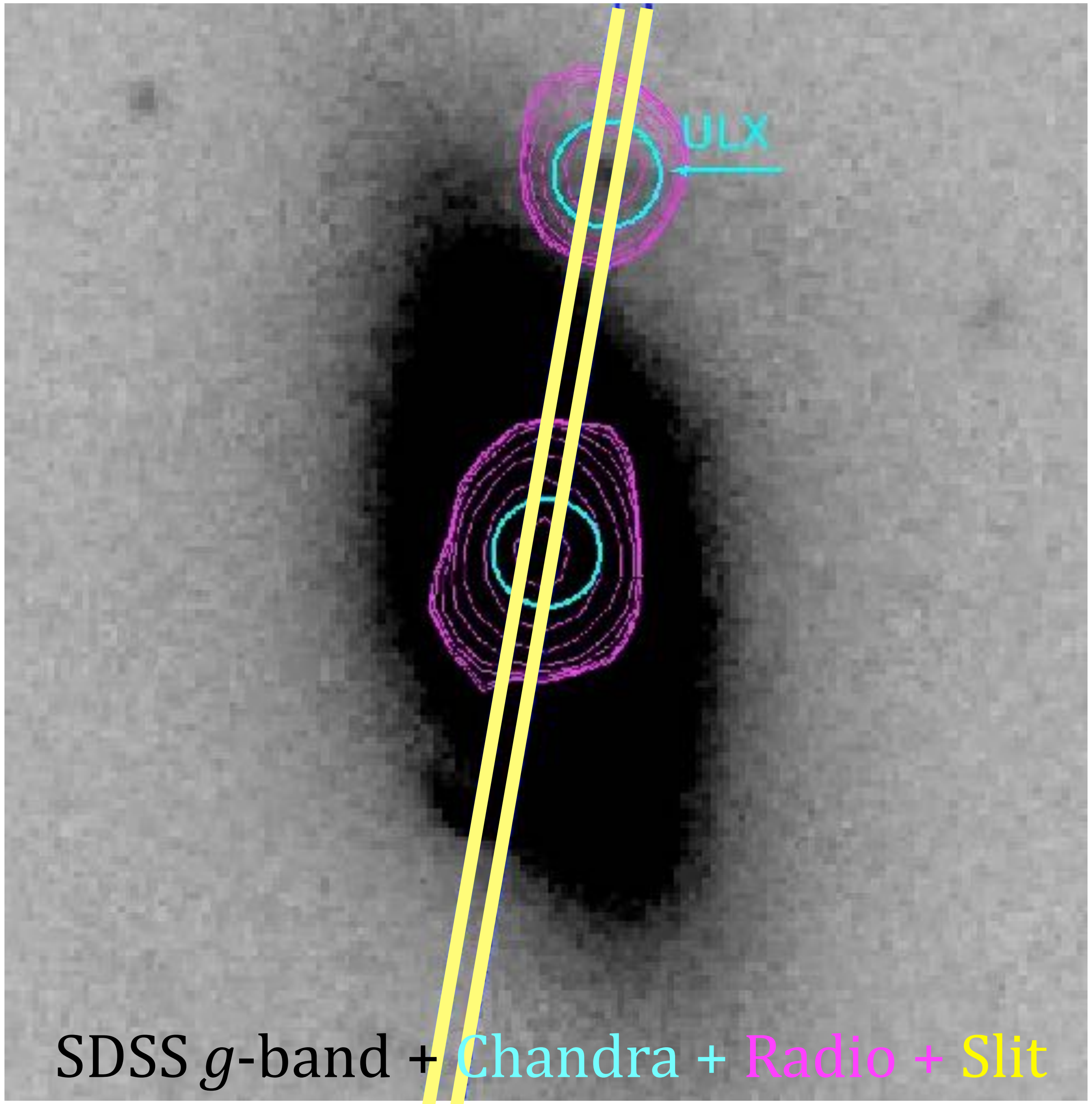
ULX in NGC 5252



Kim et al. 2015

- $L_{\text{X-ray}} \sim 10^{40}$ erg s^{-1}
- $N_{\mathrm{H}} << 10^{22}$ cm^{-2}
- $L_{5\mathrm{GHz}} \sim 10^{21}$ W Hz^{-1}

Magellan/IMACS spectrum of the ULX



Kim et al. 2015

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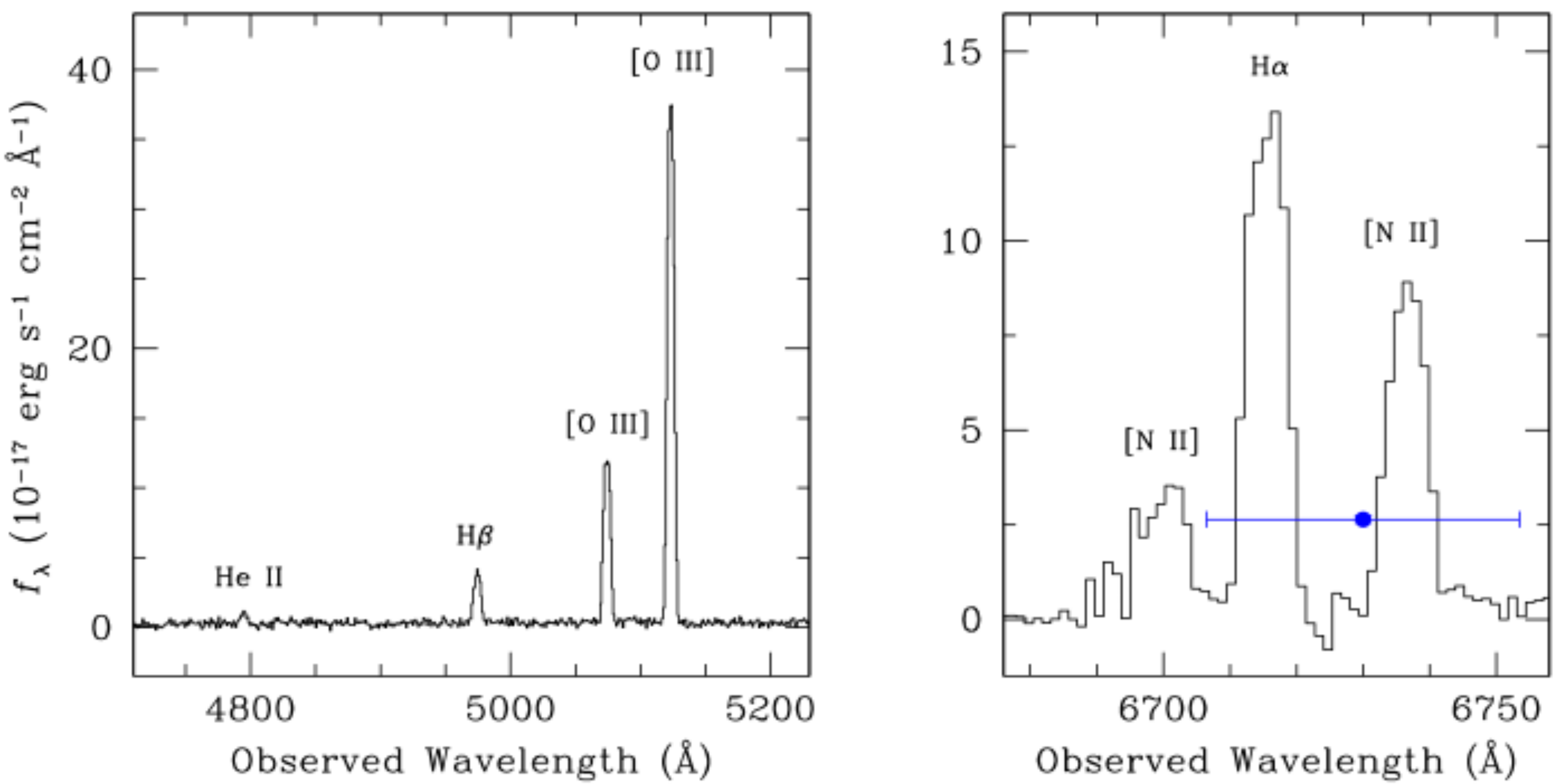
- $N_{\text{H}} << 10^{22}$ cm^{-2}
- $L_{5\text{GHz}} \sim 10^{21}$ W Hz^{-1}

Magellan/IMACS spectrum of the ULX

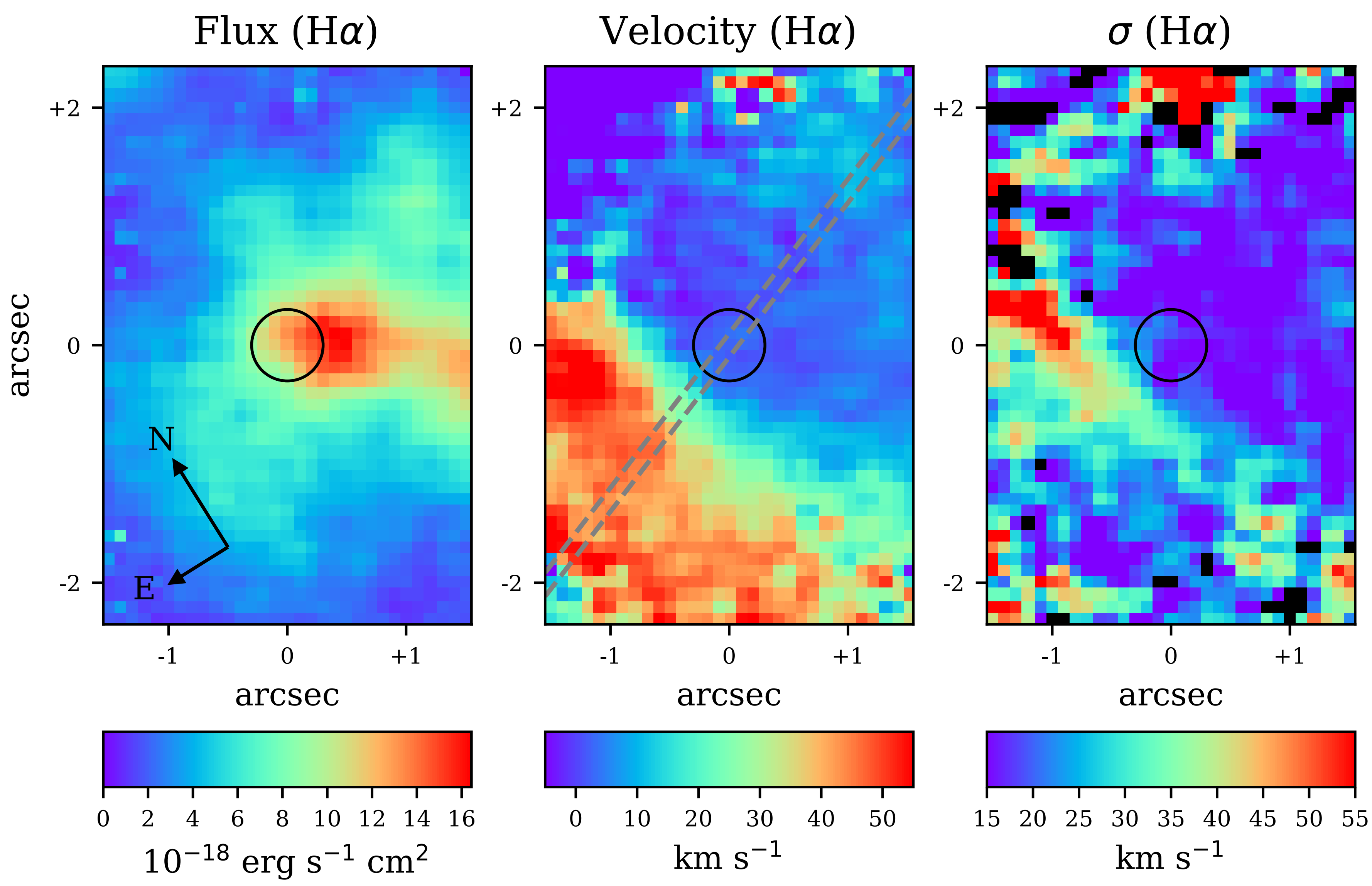
- Appears to be associated with the host galaxy (NGC 5252)
- Seyfert-like spectrum



Kim et al. 2015

Gemini/GMOS IFU Follow-up

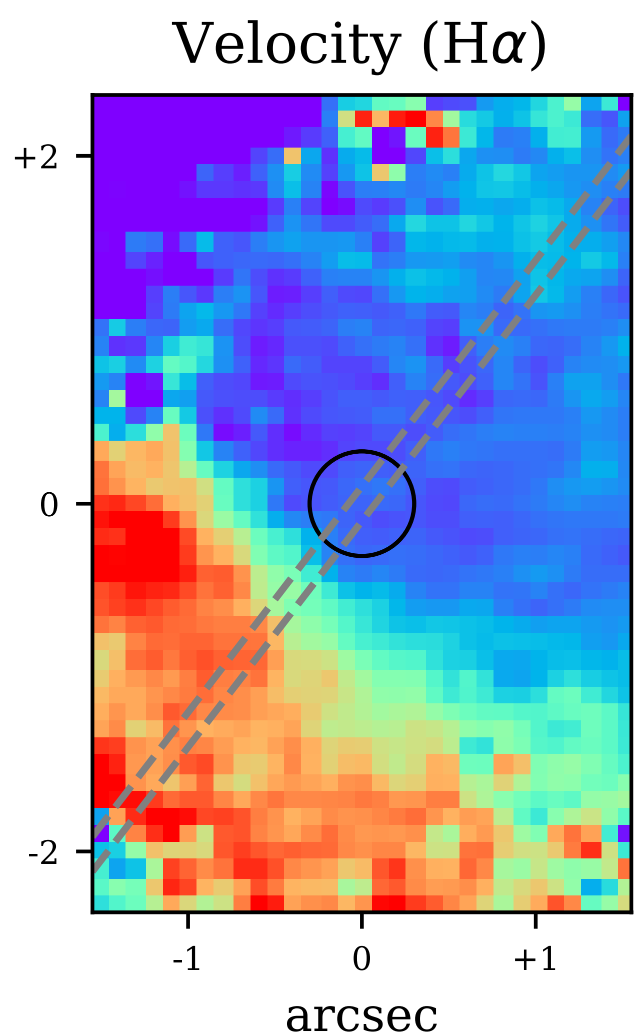
- GMOS/IFU observation

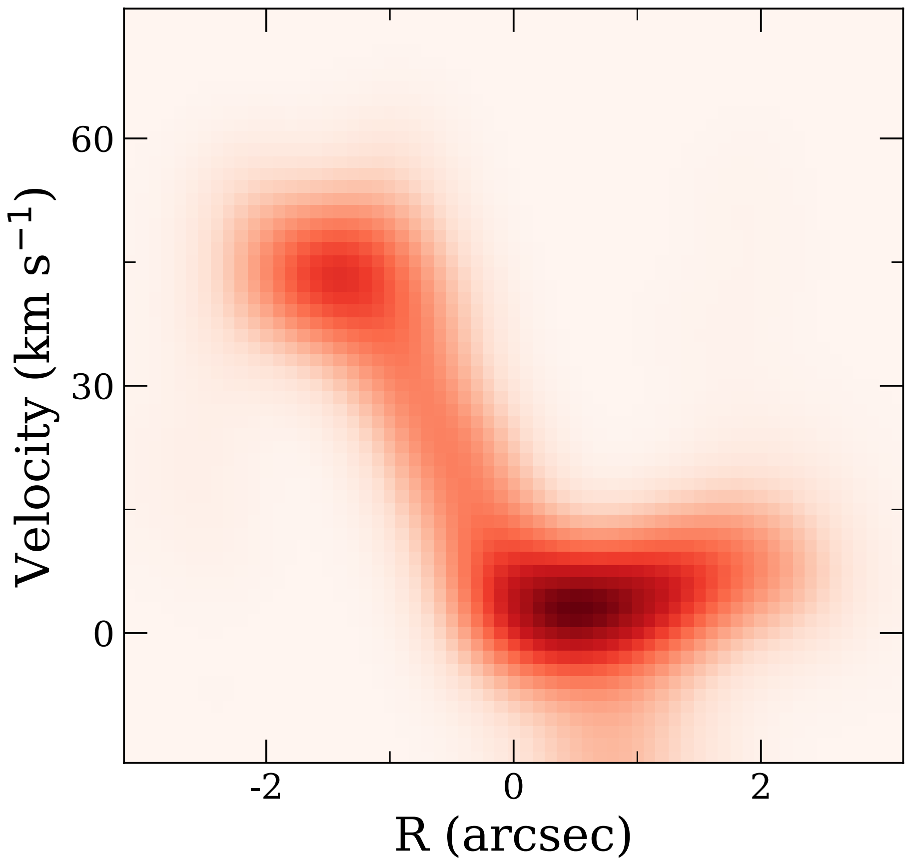


Kim et al. 2017

Gemini/GMOS IFU Follow-up

- Relatively low σ (20-30 km/s) and high [OIII]/Hβ
  -> shock is unlikely to be responsible for the ionization
- Sign of rotation : $M_{\rm dyn} \sim 10^{7.5}\ M_{\odot}$ (upper limit of BH mass)

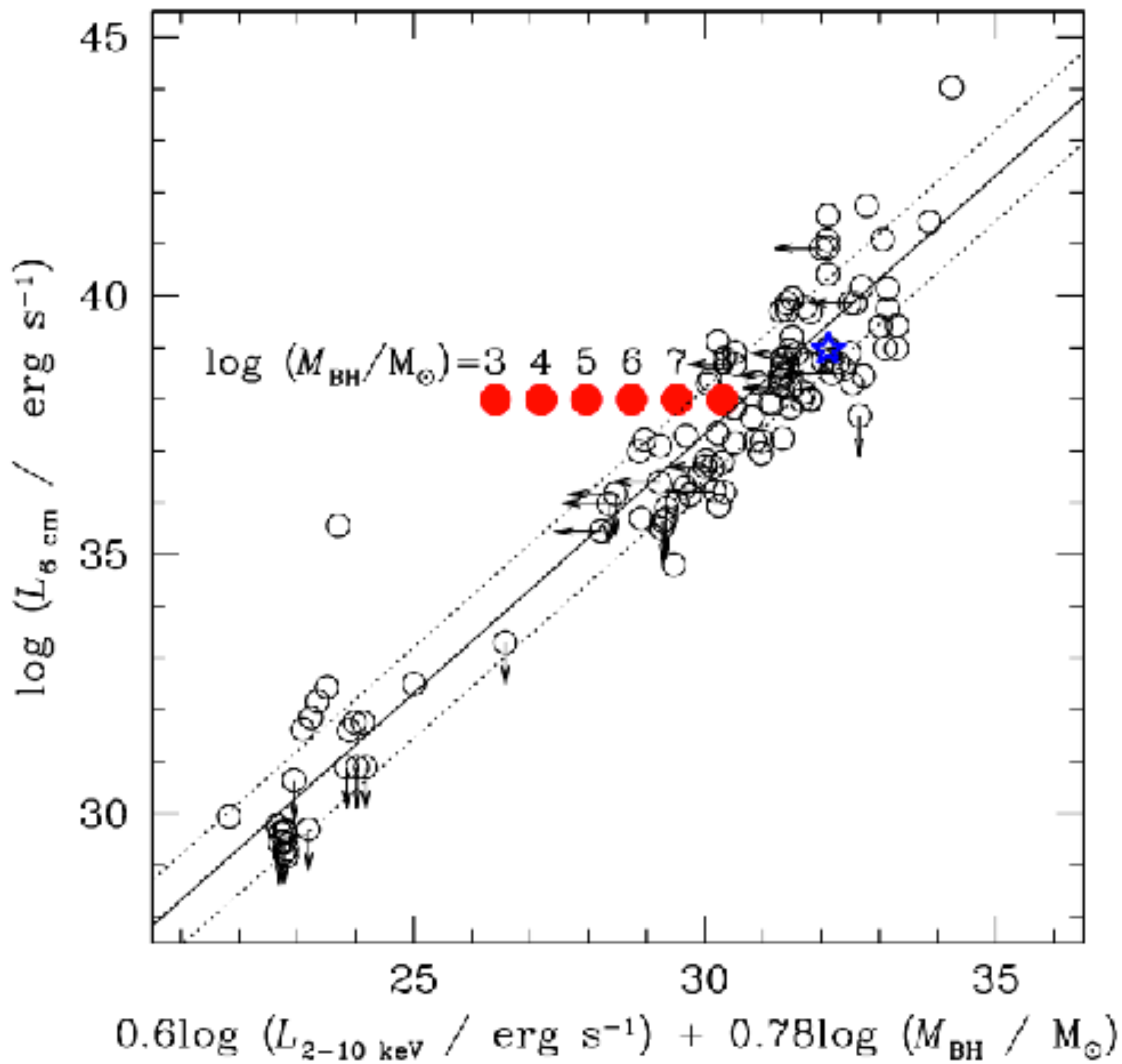




Kim et al. 2017

BH mass of the ULX?

BH Fundamental Plane



Kim et al. 2015

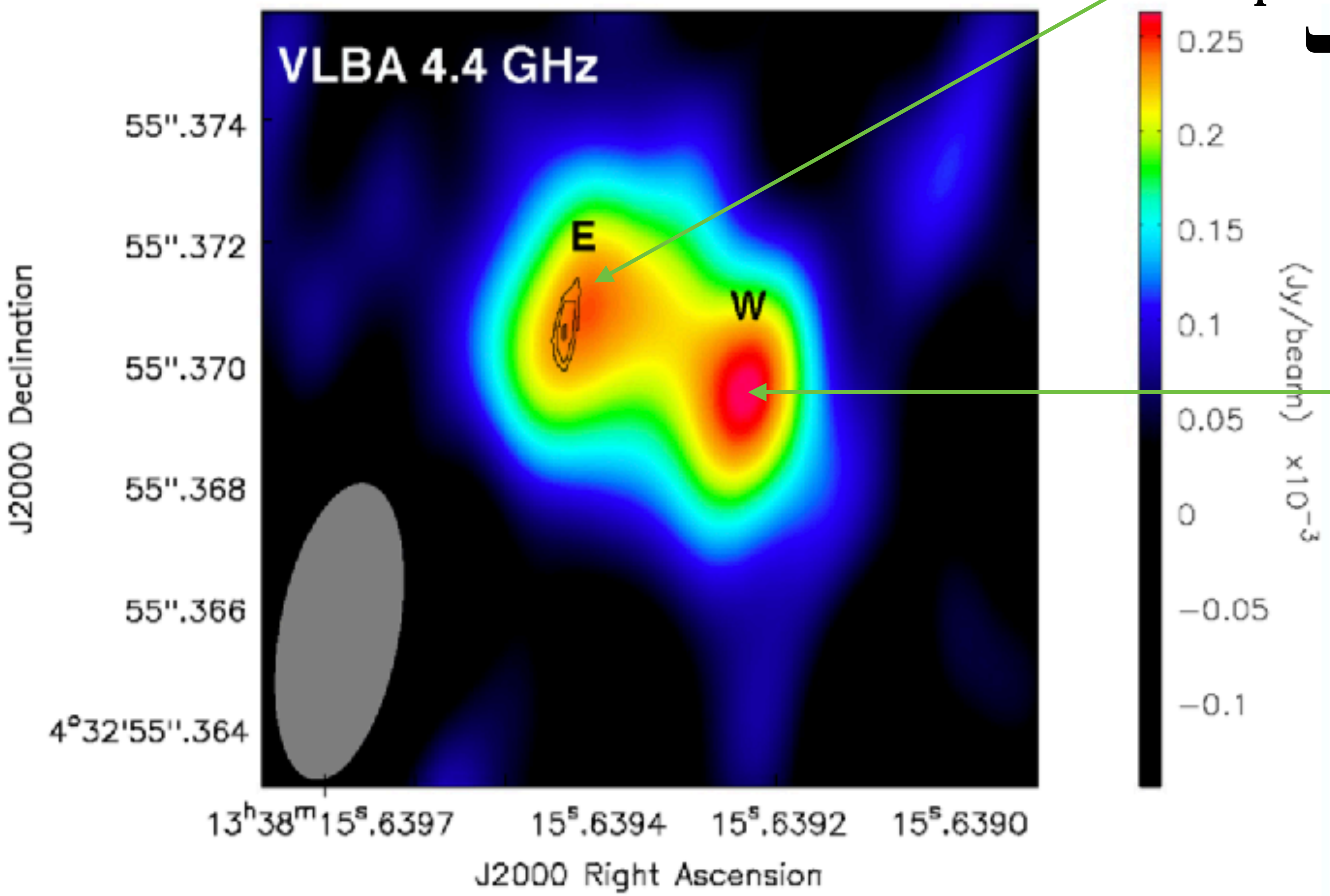
$10^7\ M_\odot < M_{BH} < 10^9\ M_\odot$

(off-nucleus SMBH?)

(1) Follow-up studies (VLBA)

Contour : 7.6 GHz

Extended morphology
Spectral index : -2.0
➥ Radio lobe



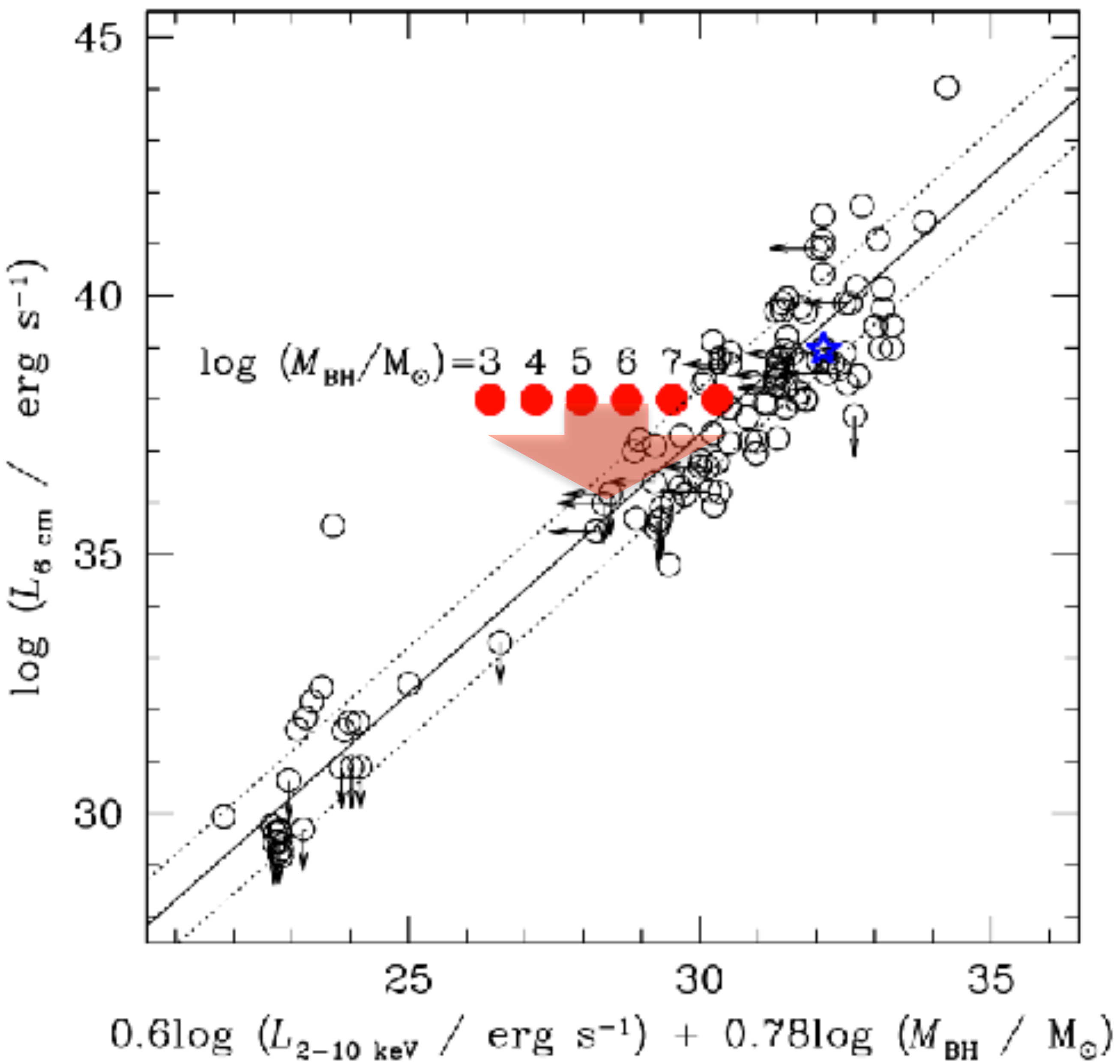
Unresolved
Spectral index < -0.6
➥ Core

Beamsize : 5×2 mas

Mezcua, MK, et al., 2018

BH mass of the ULX?

BH Fundamental Plane



Kim et al. 2015

$10^7\ M_\odot < M_{BH} < 10^9\ M_\odot$

(off-nucleus SMBH?)

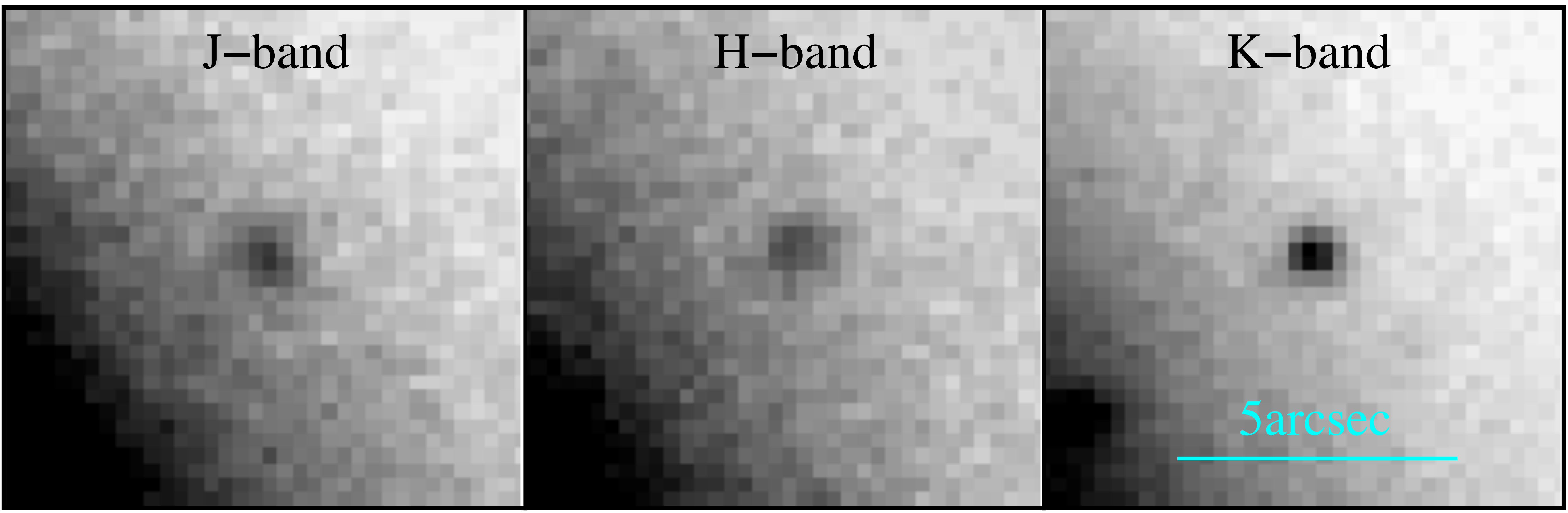
$M_{BH} < 10^6\ M_\odot$

(IMBH? or SMBH?)

(2) Follow-up studies (NIR photometry)

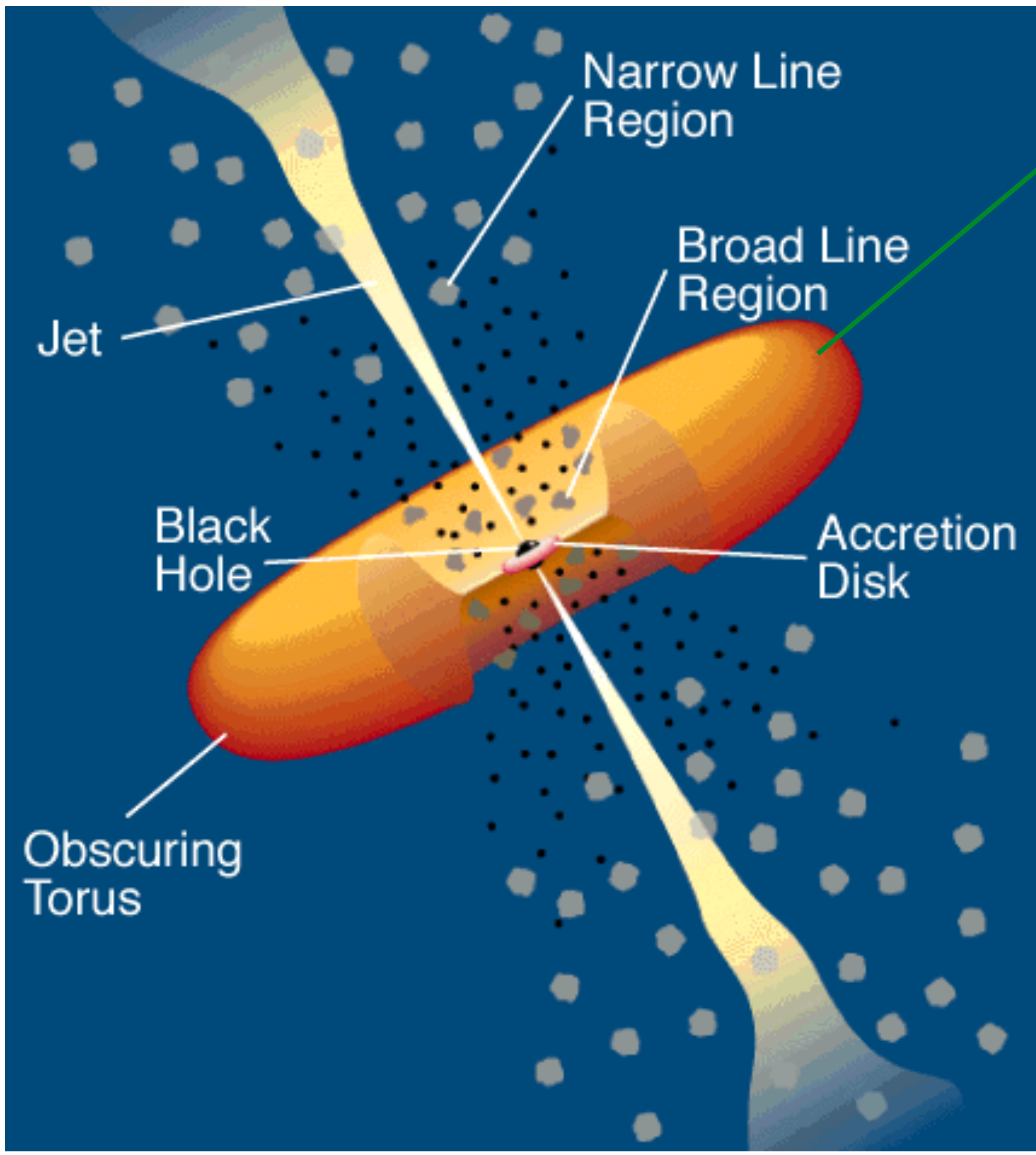
- $M_K \sim$ -16.6 mag ➜ $M_* \sim 10^{7.9} M_\odot$ (cf. $M_{\rm dyn} \sim 10^{7.5} M_\odot$)

NIR images (William Herschel Telescope)



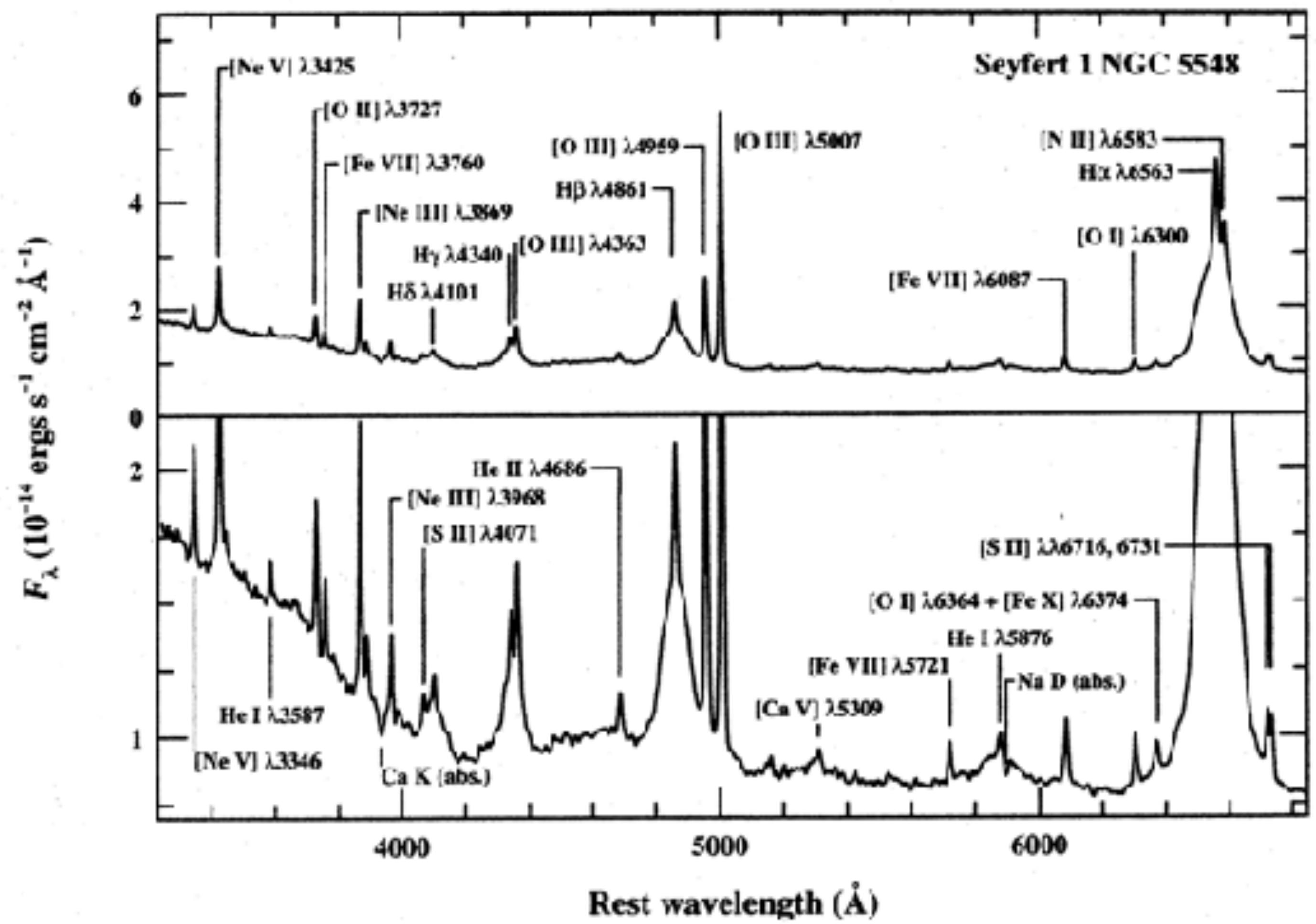
Kim et al., submitted

(2) Follow-up studies (NIR photometry)



Urry & Padovani 1995

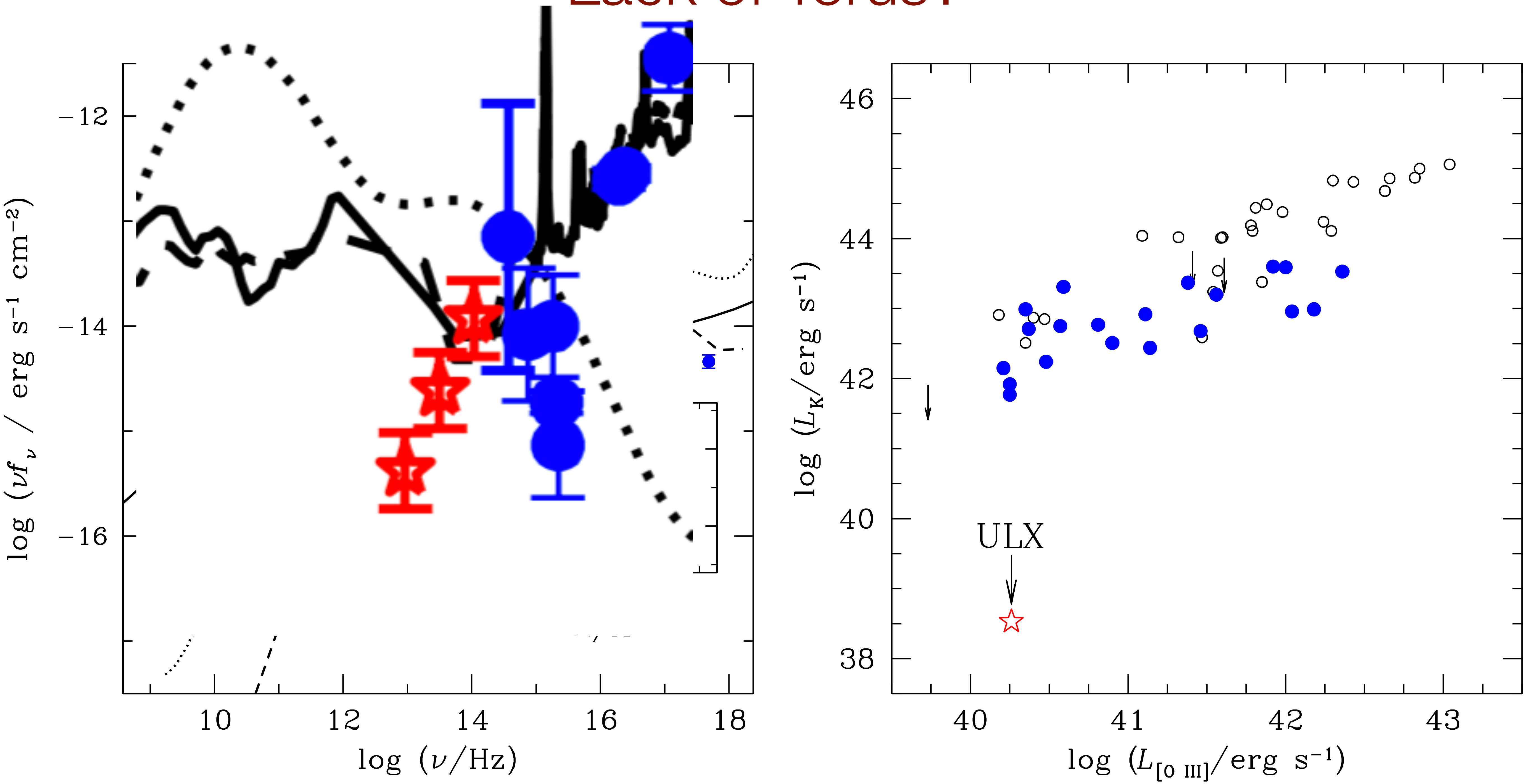
NIR source : Dusty Torus



Data courtesy of A. V. Filippenko

(2) Follow-up studies (NIR photometry)

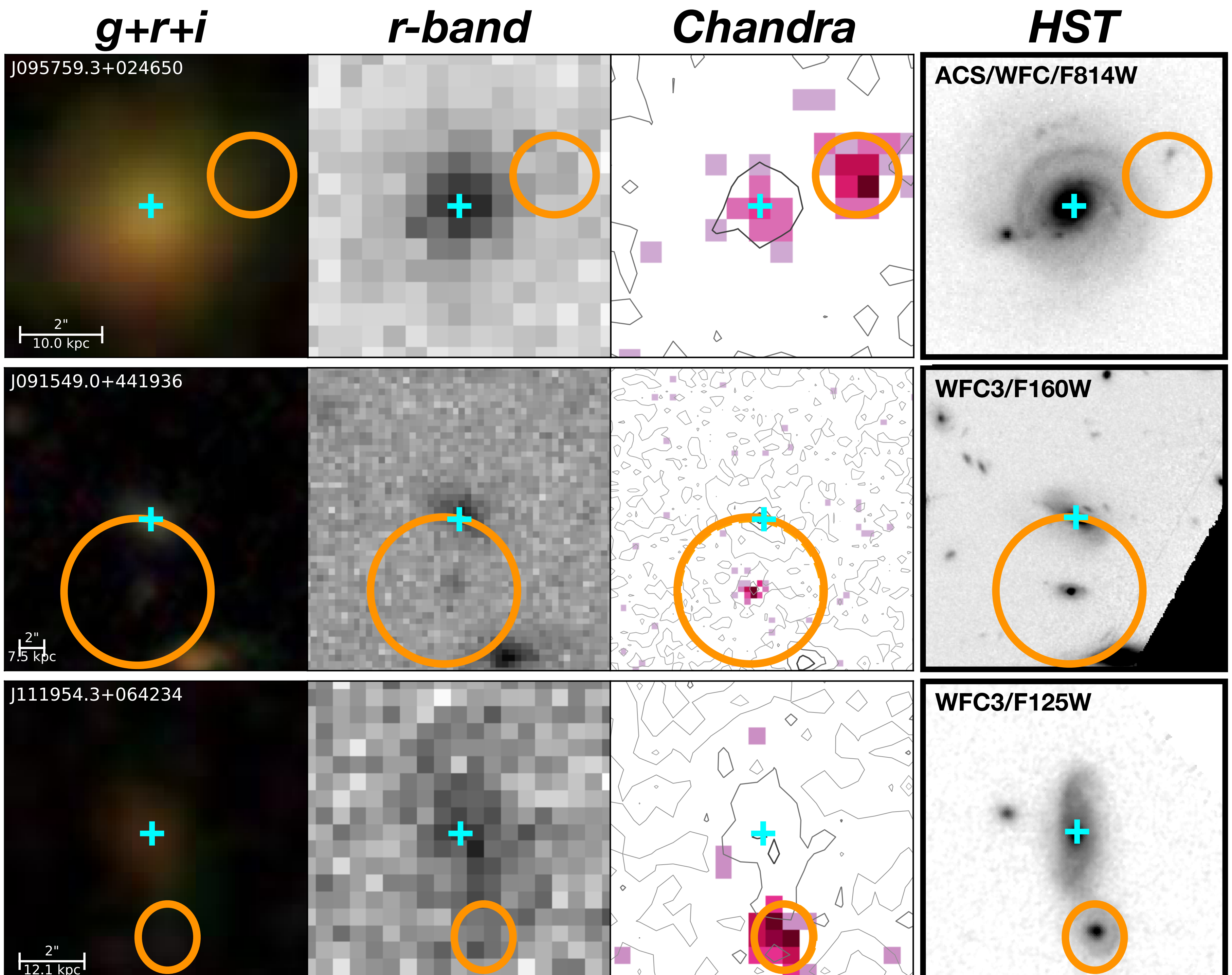
Lack of Torus?



Kim et al., submitted

Future Work with HLX

Optical Follow-up of Hyper-luminous X-ray sources



$L_{\mathrm{X-ray}} > 10^{41}$ erg/s

Barrows et al. 2019

Summary (1)

- We found an IMBH (or SMBH) candidate possibly accreted onto NGC 5252.

- IFU observation (Dynamical mass)
  ➙ Upper limit of $M_{\rm BH} \sim 10^{7.5} M_{\odot}$

- VLBA observation (BH fundamental Plane)
  ➙ Upper limit of $M_{\rm BH} \sim 10^{6} M_{\odot}$

- NIR observation (Stellar mass)
  ➙ $M_{*} \sim 10^{7.9} M_{\odot} \rightarrow M_{\rm BH} < 10^{6} M_{\odot} (?)$
  ➙ Deficit of NIR : Lack of Torus?

SMBH-Host connection

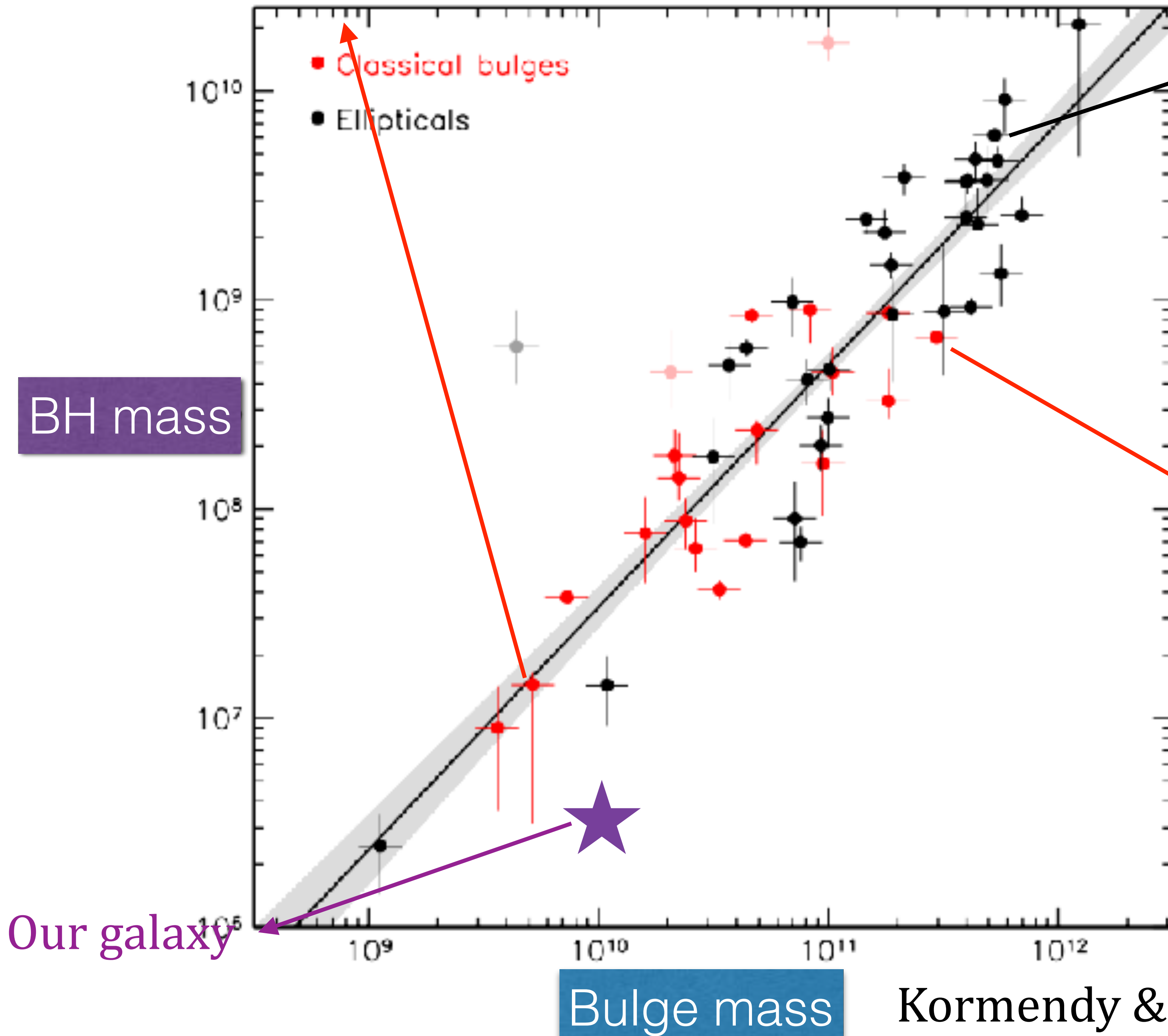
- SMBH ... now each ... tent durin...
- Ph...

(1)

(2) ... of

LC...

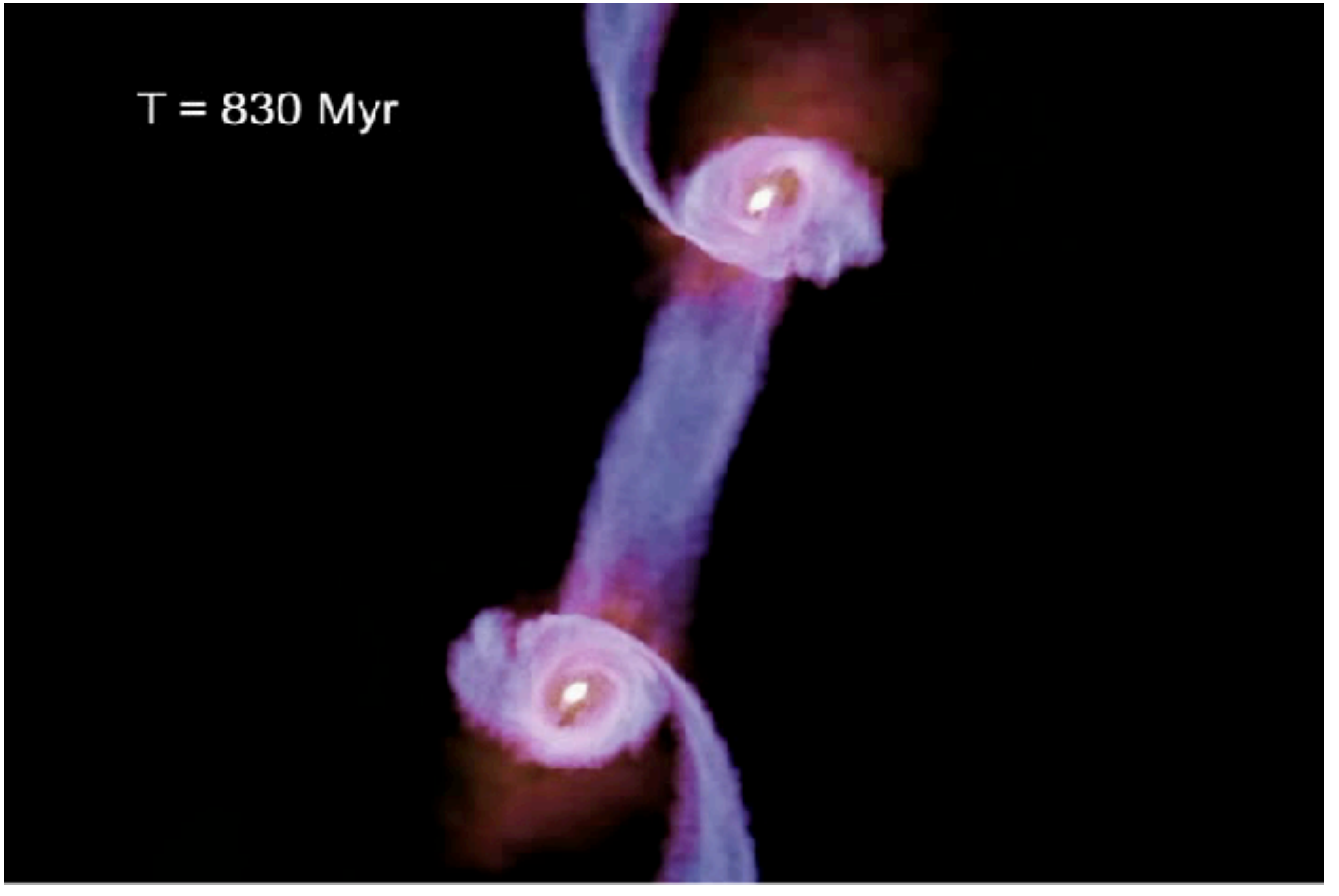
(3)



Kormendy & Ho 2013

SMBH-Host connection

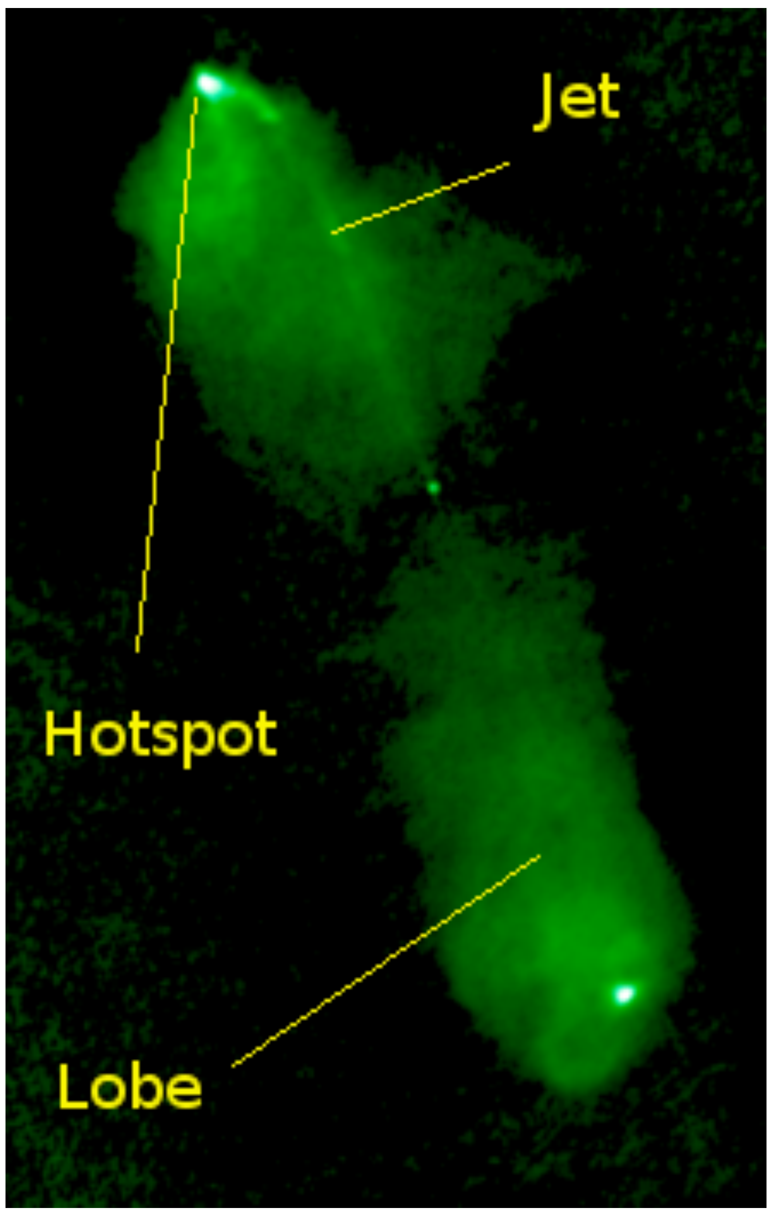
- AGN feedback : (1) QSO mode feedback (radiative)

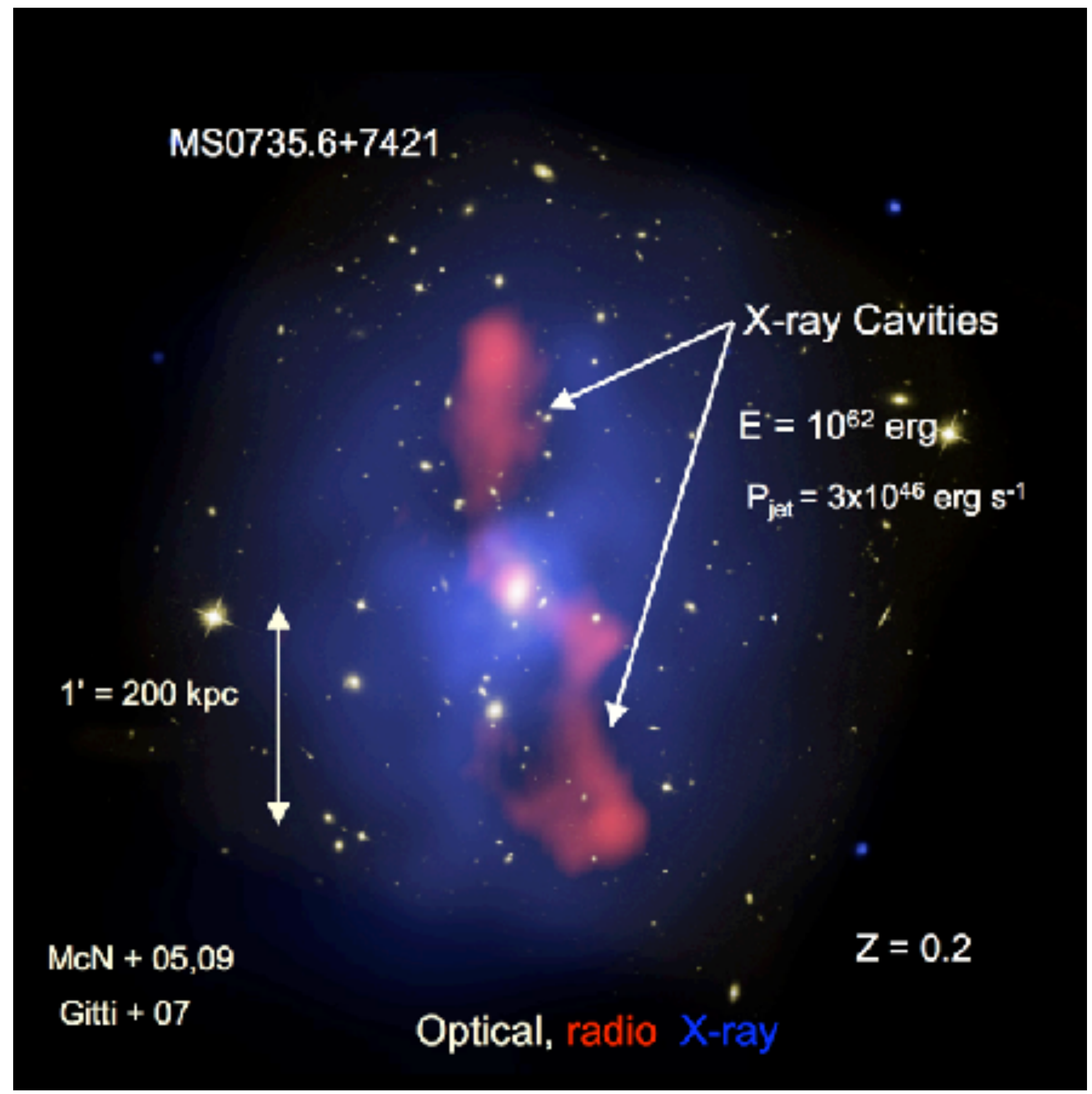


Courtesy of Phillip Hopkins

SMBH-Host connection

- AGN feedback : (2) radio mode feedback (kinematic)





SMBH-Host connection

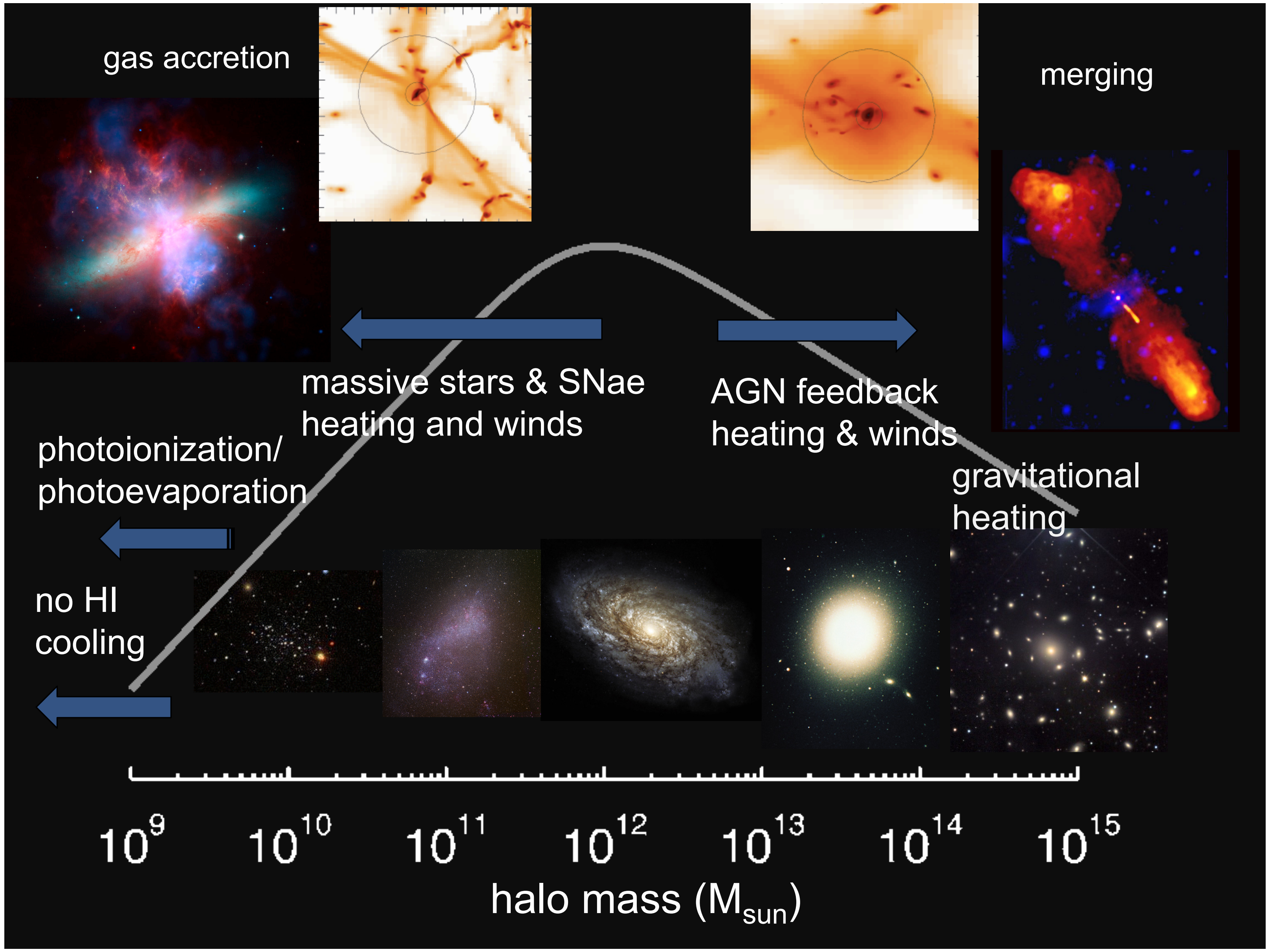
- AGN feedback

  - BH activity suppresses (regulates) star formation in host galaxies

  - probably important mechanism to make dead elliptical galaxies

SMBH-Host connection

- Low SF efficiency (AGN feedback)



log (Stellar Mass/Halo Mass)

log (Halo Mass)

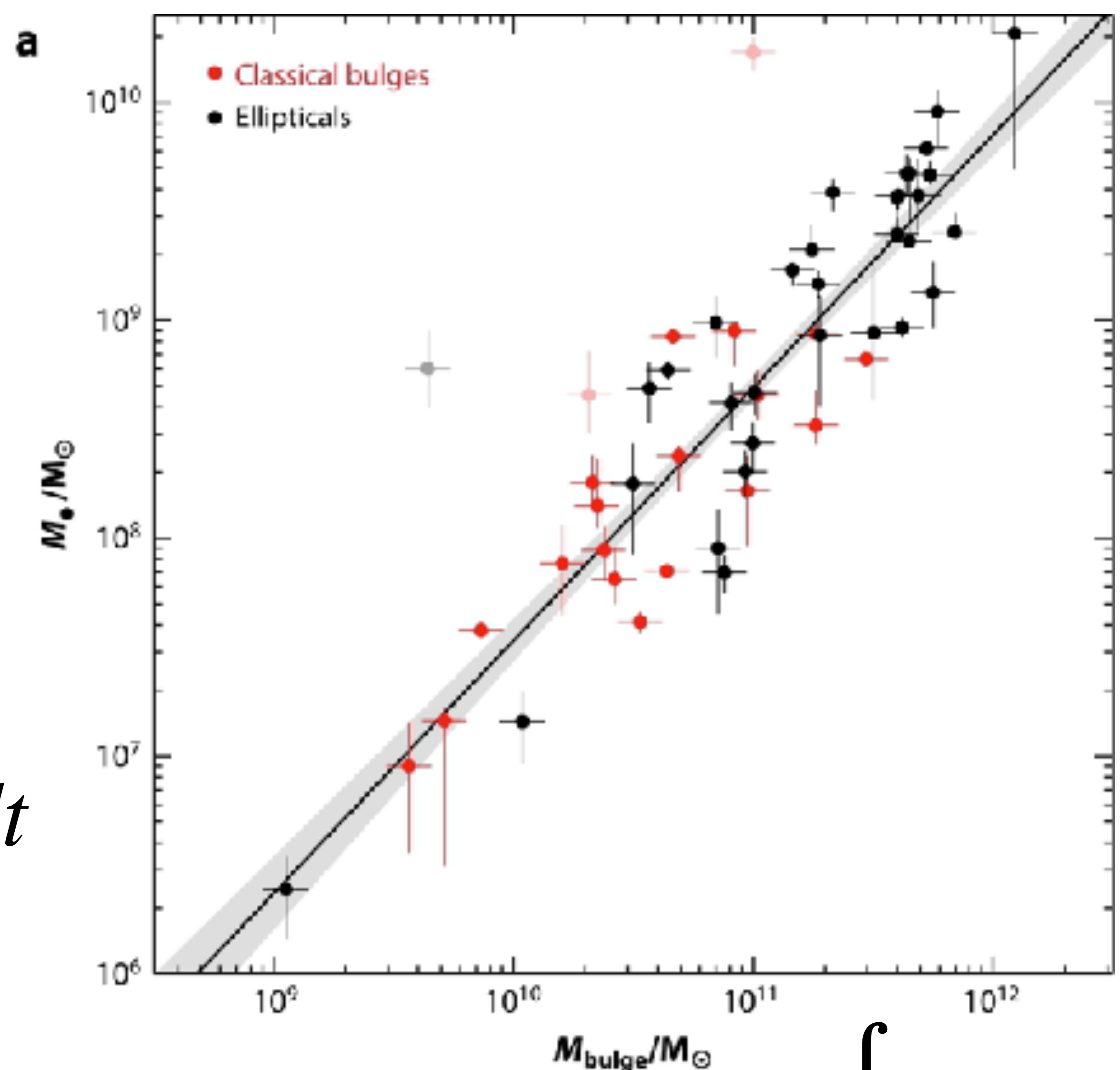
Credit : R. Somerville

SMBH vs. Galaxy (Bulge) mass

$M_{\rm BH} \sim 0.2\%$ of $M_{\rm bulge}$ or $M_{\rm bulge} \sim 500\ M_{\rm BH}$

BH Mass

$= \int \dot{m} dt$

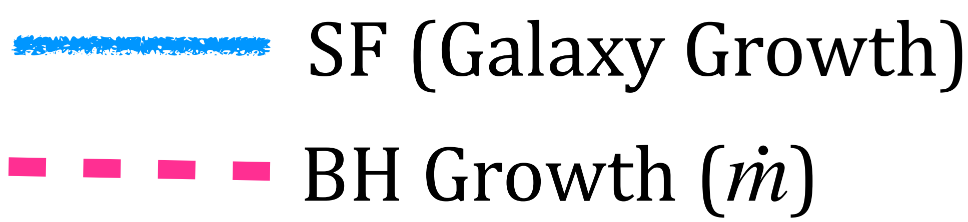


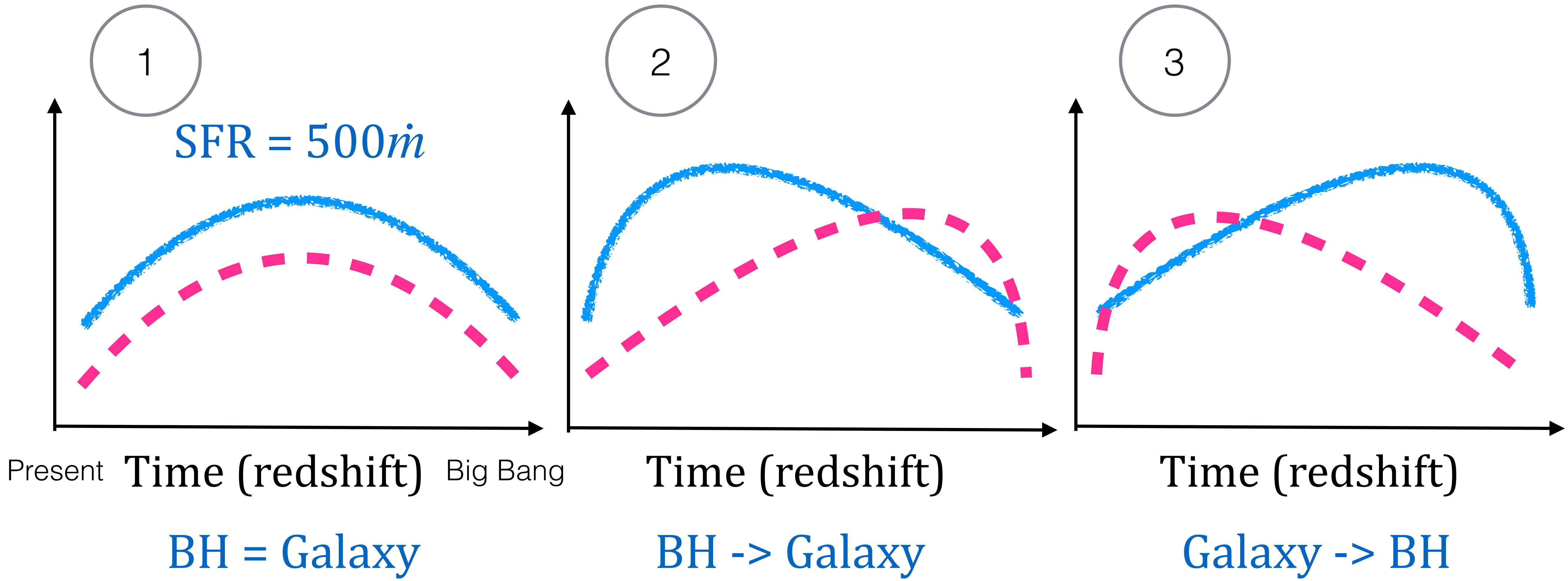
Bulge Mass $= \int {\rm SFR} dt$

Kormendy and Ho 2013

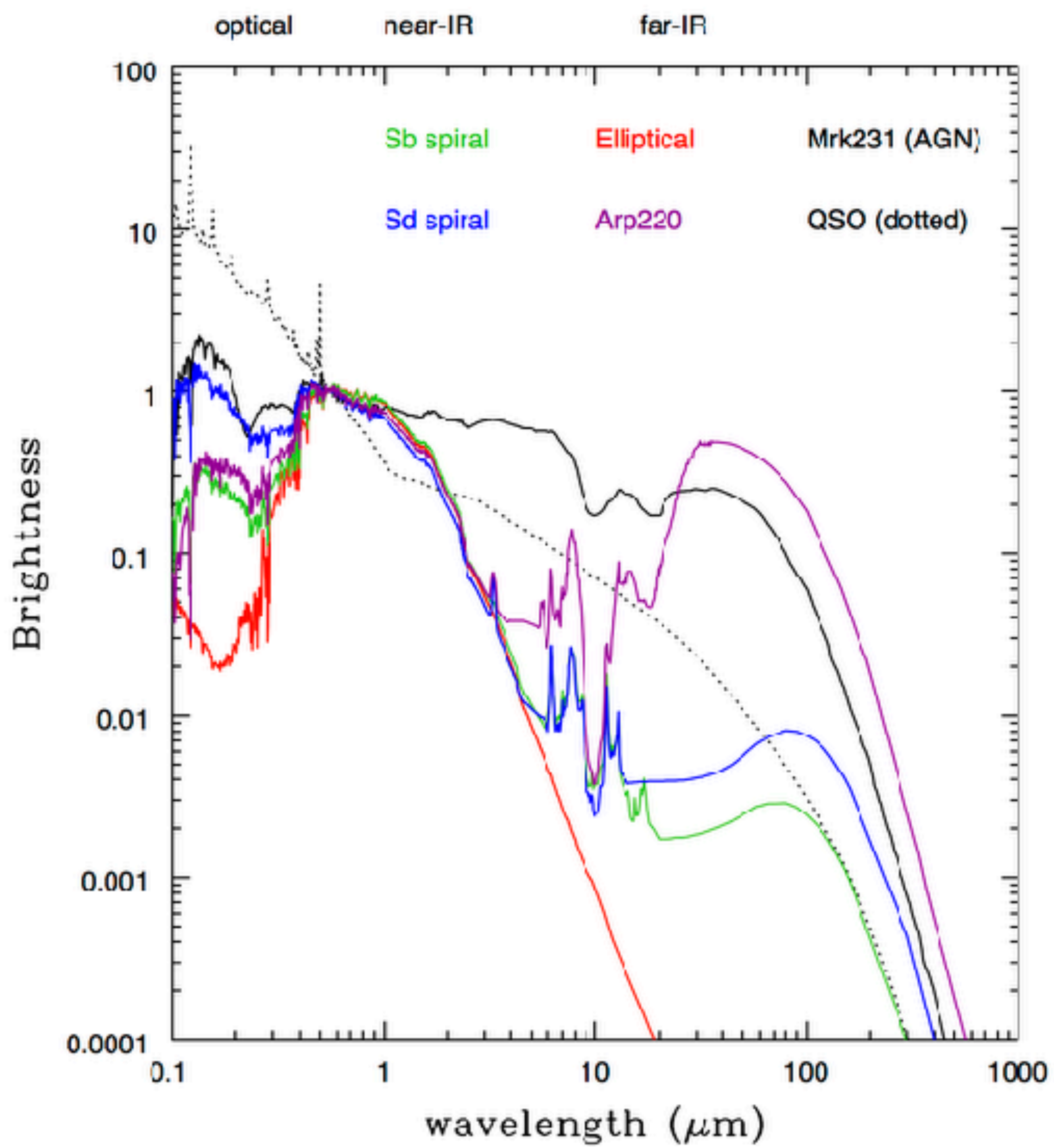
BH growth vs. SF

Direct Method : measurements of SFR and BH Growth rate in AGNs!





Technical Issues



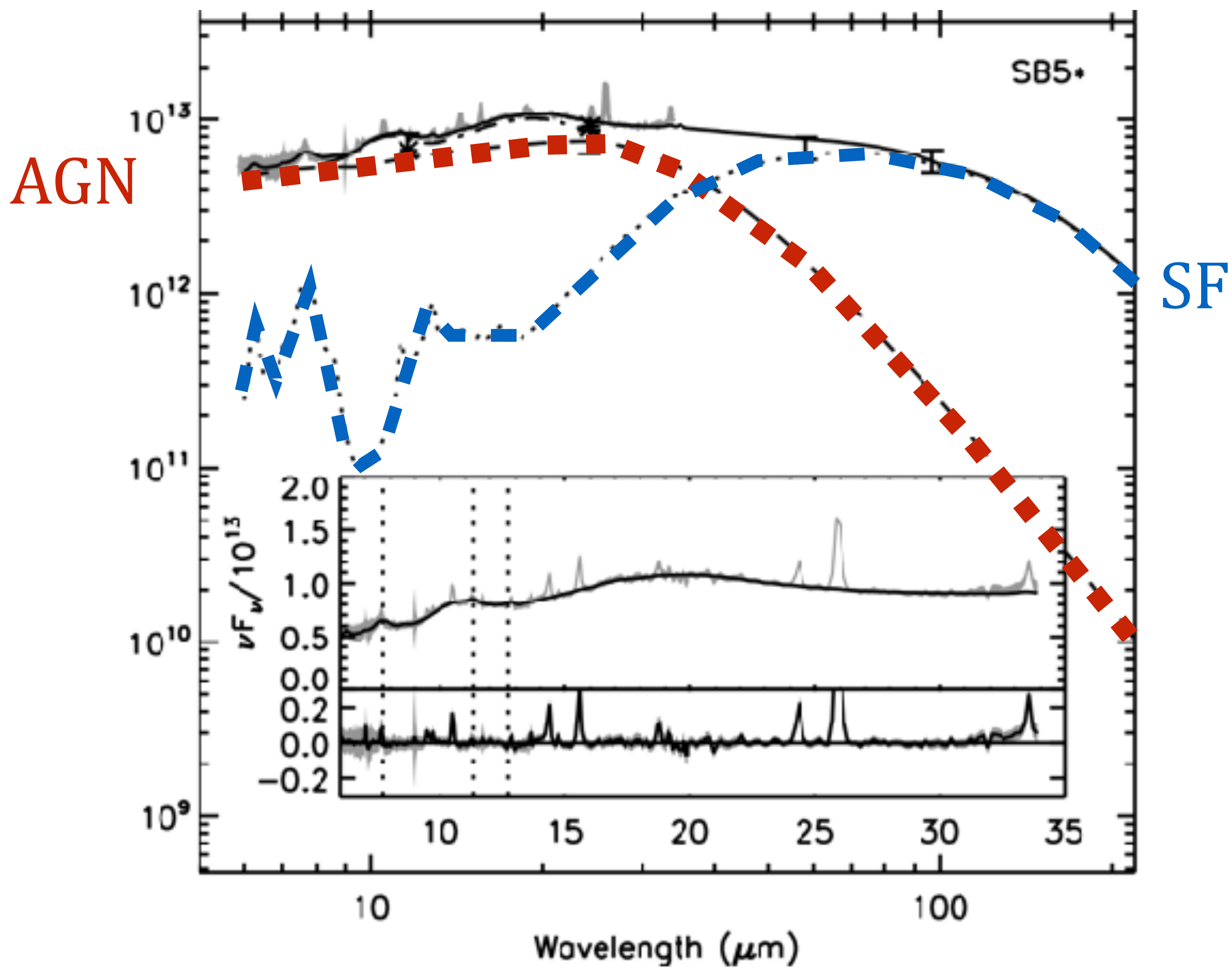
Technical Issues

Star Formation Rate (SFR; M⊙/yr) indicators

	Hα	UV	[OII]	X-ray	Radio	PAH	FIR
SFR	strong	strong	strong	weak	weak	strong	strong
AGN	strong	Y/N	weak	strong	strong	weak	weak

- X-ray -> AGN activity -> BH Growth rate
- FIR -> SFR

Spectral Decomposition in AGN

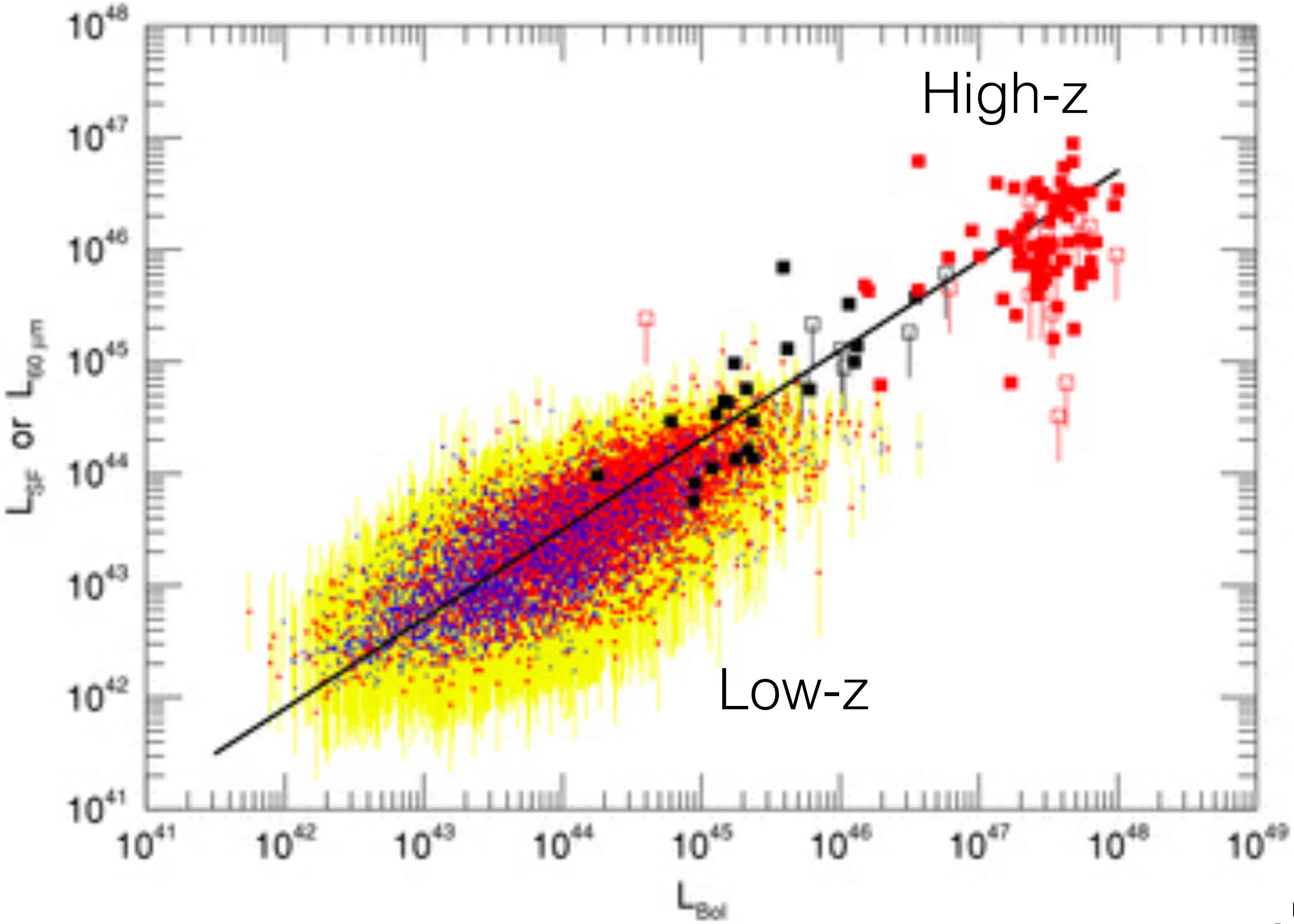


Mullaney et al. 2011

BH Growth vs. SFR (z~0)

SFR/BH Growth ~ 115 (c.f. SFR/BH Growth=500)

SF



AGN

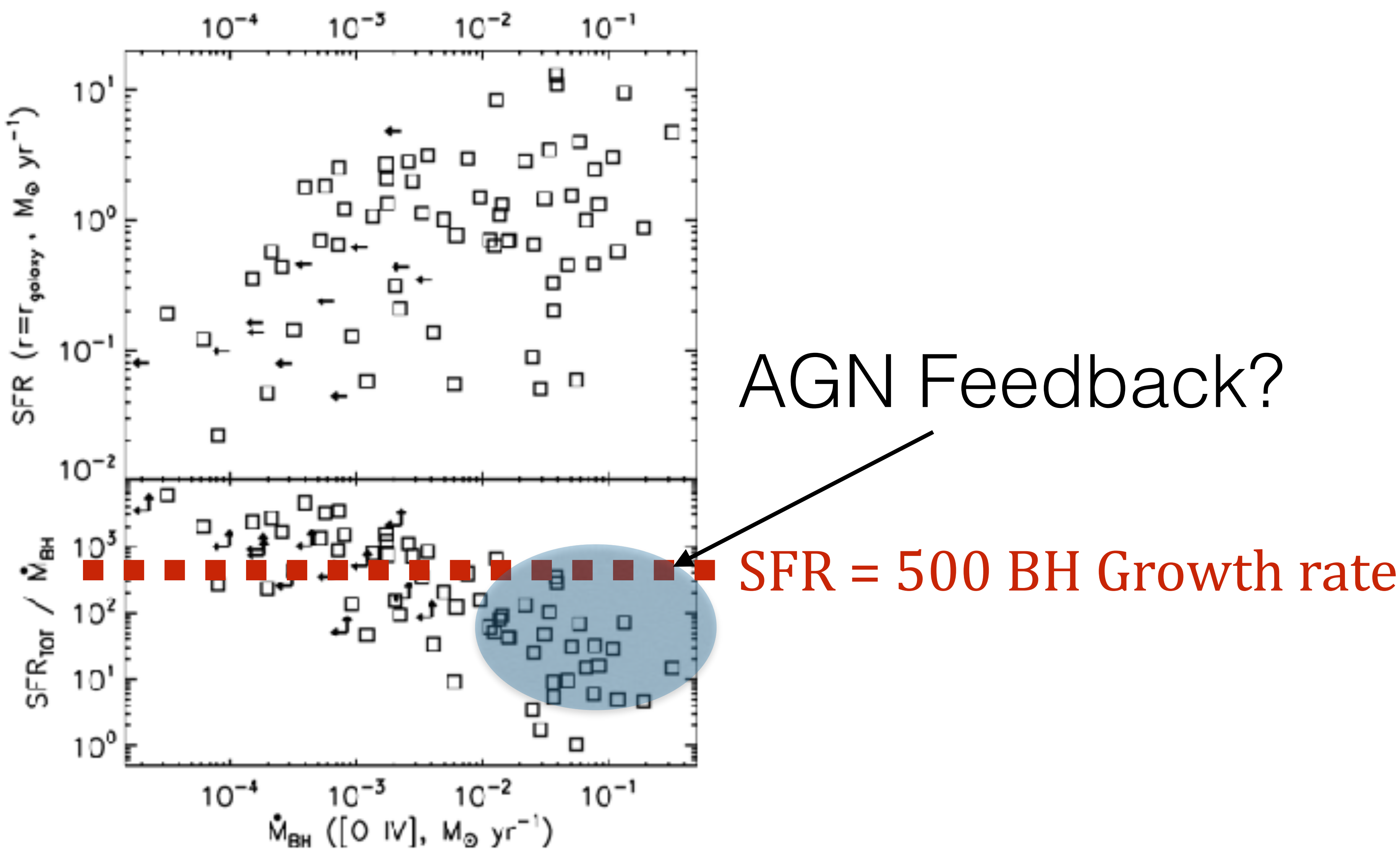
Netzer 2009

BH Growth vs. SFR (z~0)

@z~0 -> SFR < 500 x BH Growth in luminous AGNs

SFR (PAH)

SFR/BH Growth

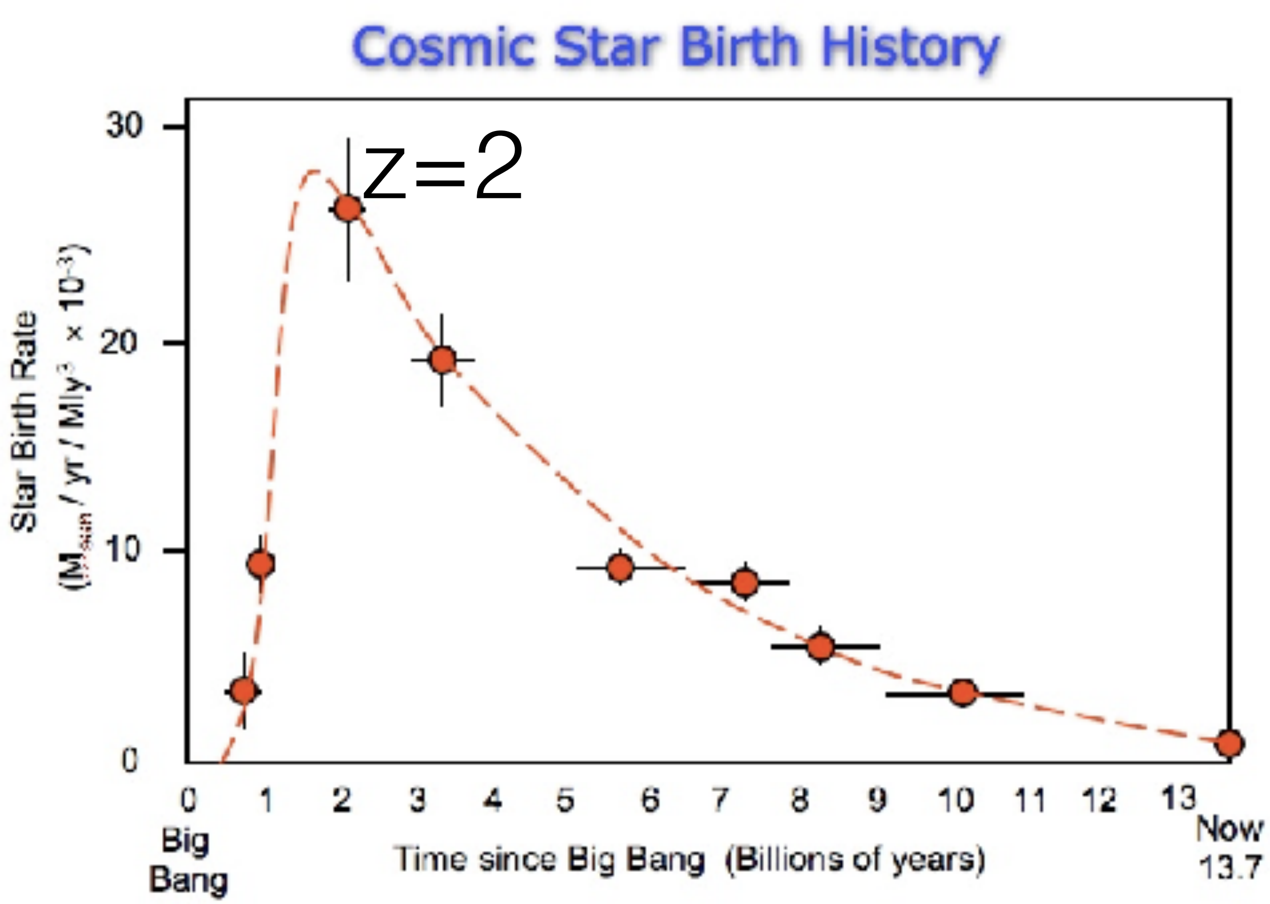


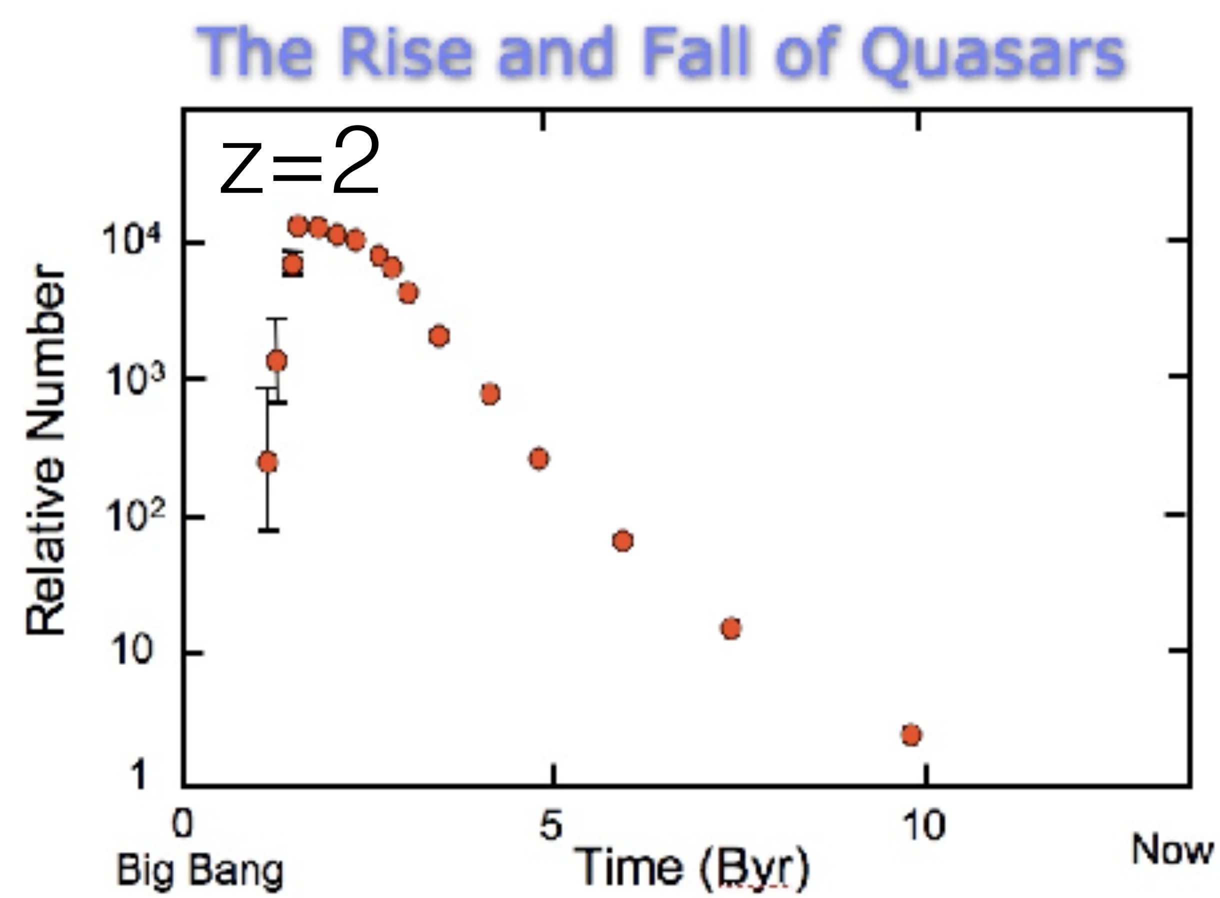
AGN

Diamond-Stanic 2012

But it is really crucial look at z~2

Galaxy and BH grows mostly at z~2!!!



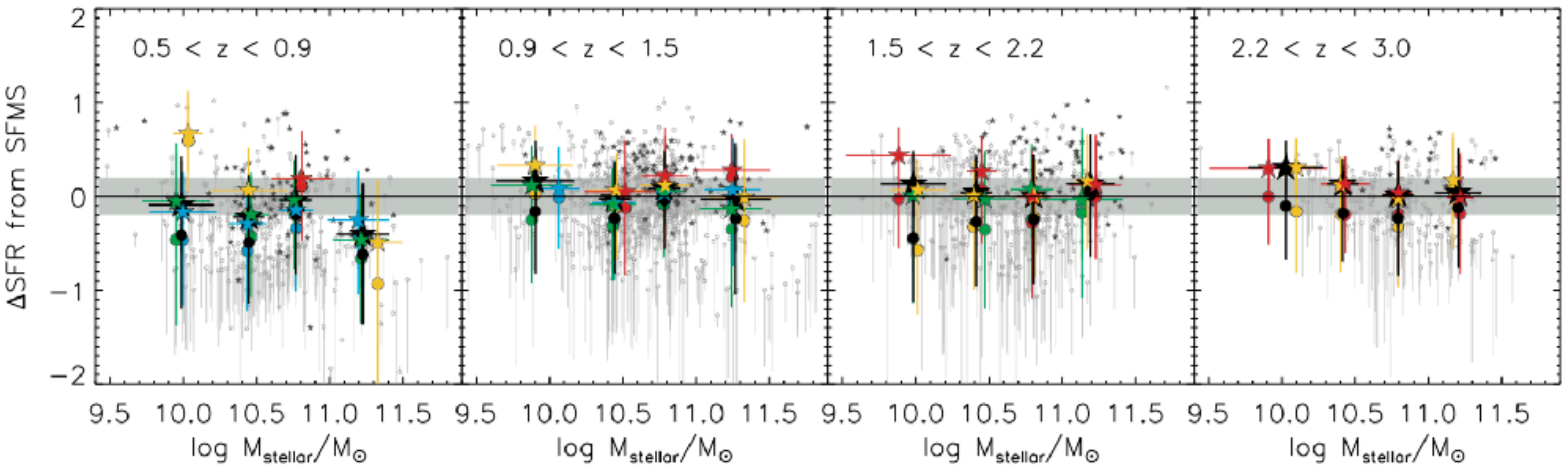


Madau et al. 1998

SF in AGNs at z~2

AGN host galaxies are SF Main Sequence
(X-ray selected AGNs)

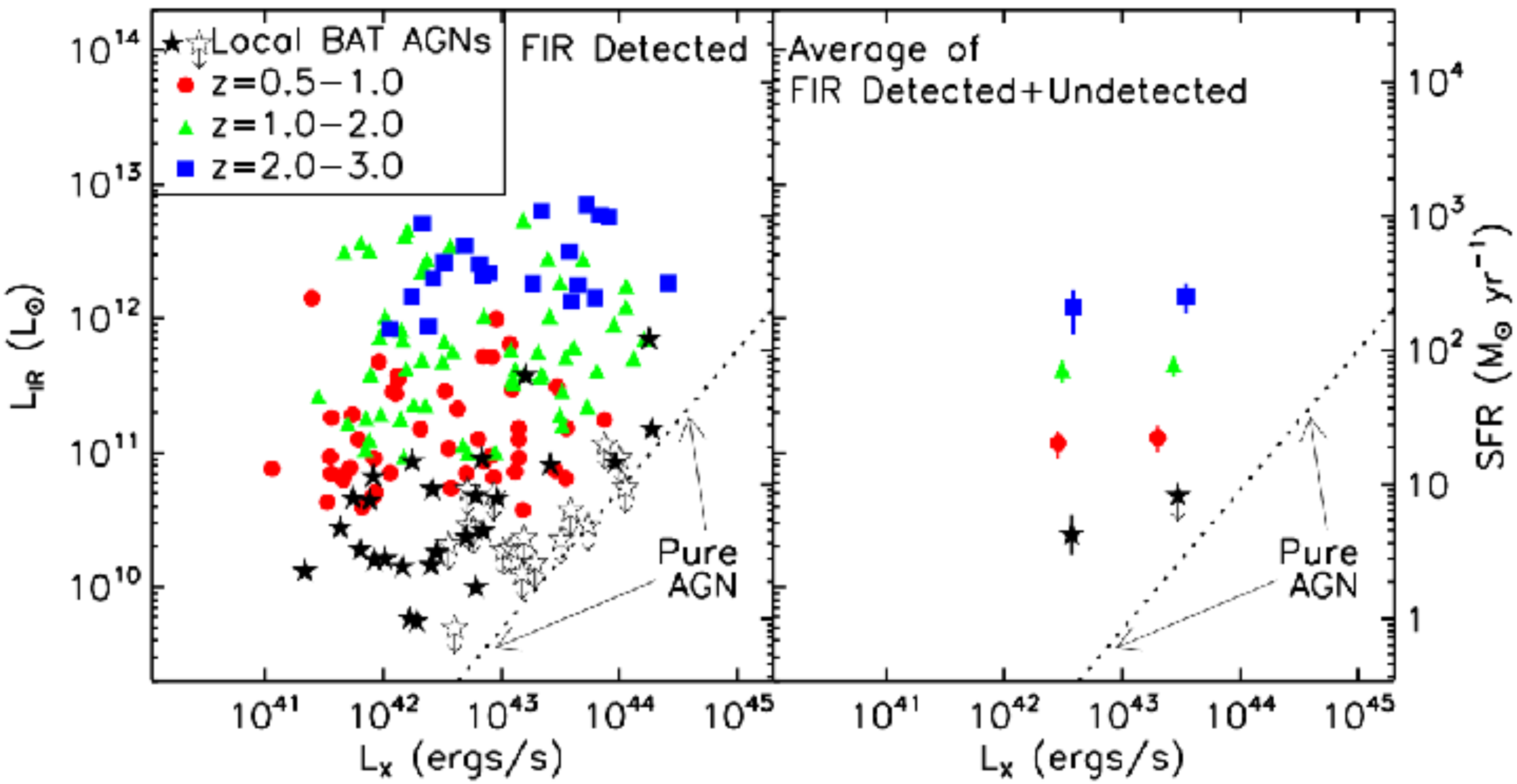
No AGN Feedback?



Suh et al. 2017; 2019

BH Growth vs. SFR for AGNs @ ~z<2

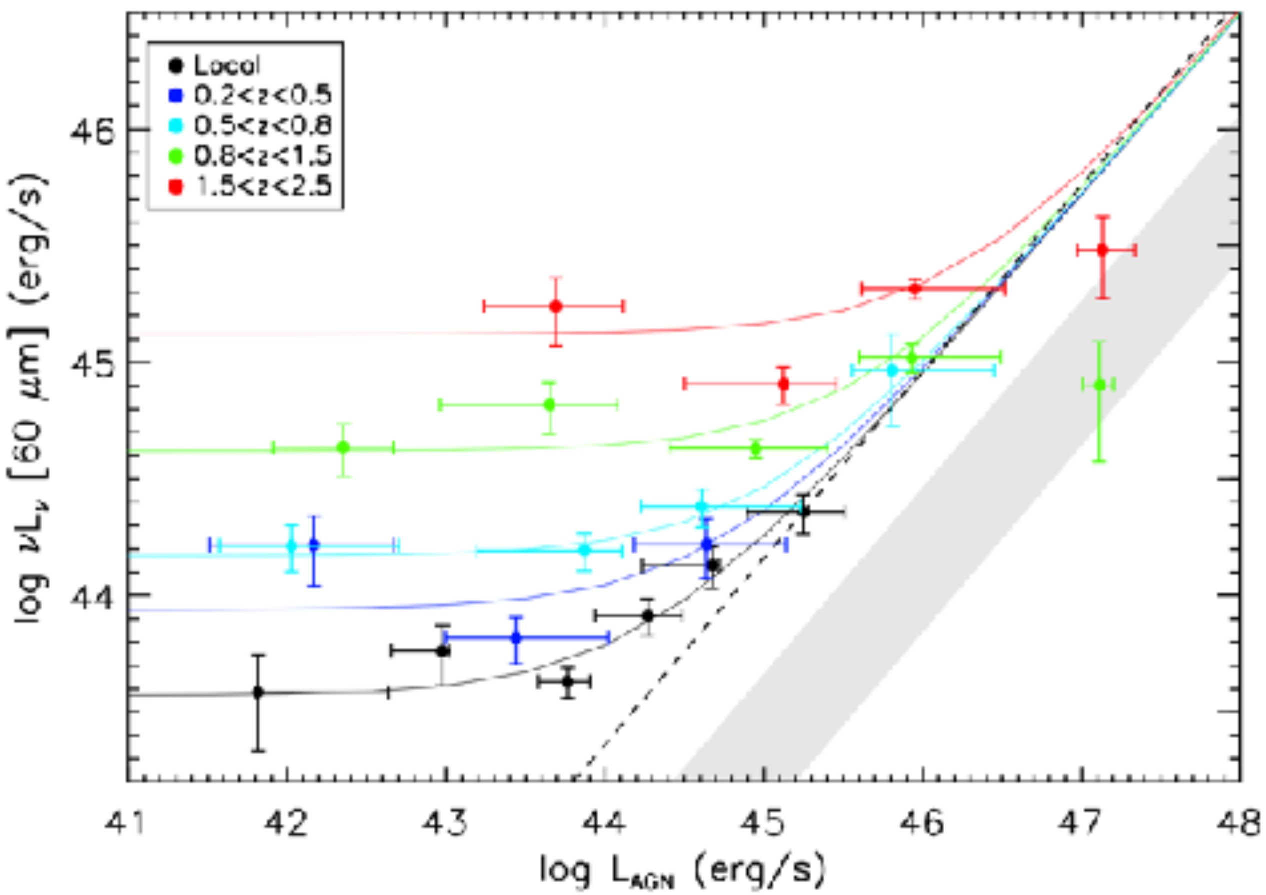
- No Link between BH growth and SFR???
- Strong Redshift dependency

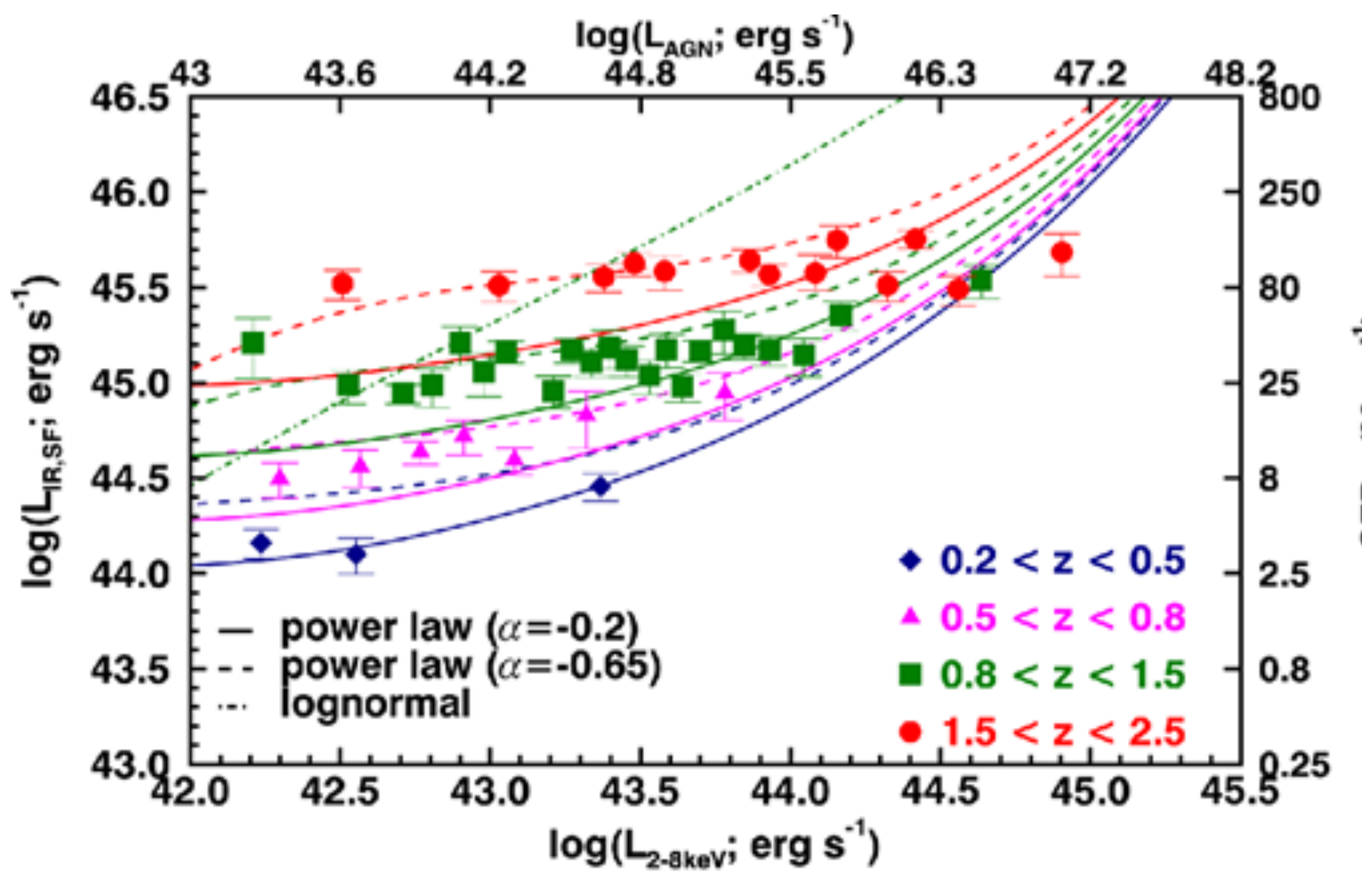


Mullaney et al. 2012

BH Growth vs. SFR for AGNs @ ~z<2

Flat features (no connection between SFR and BH Growth?)



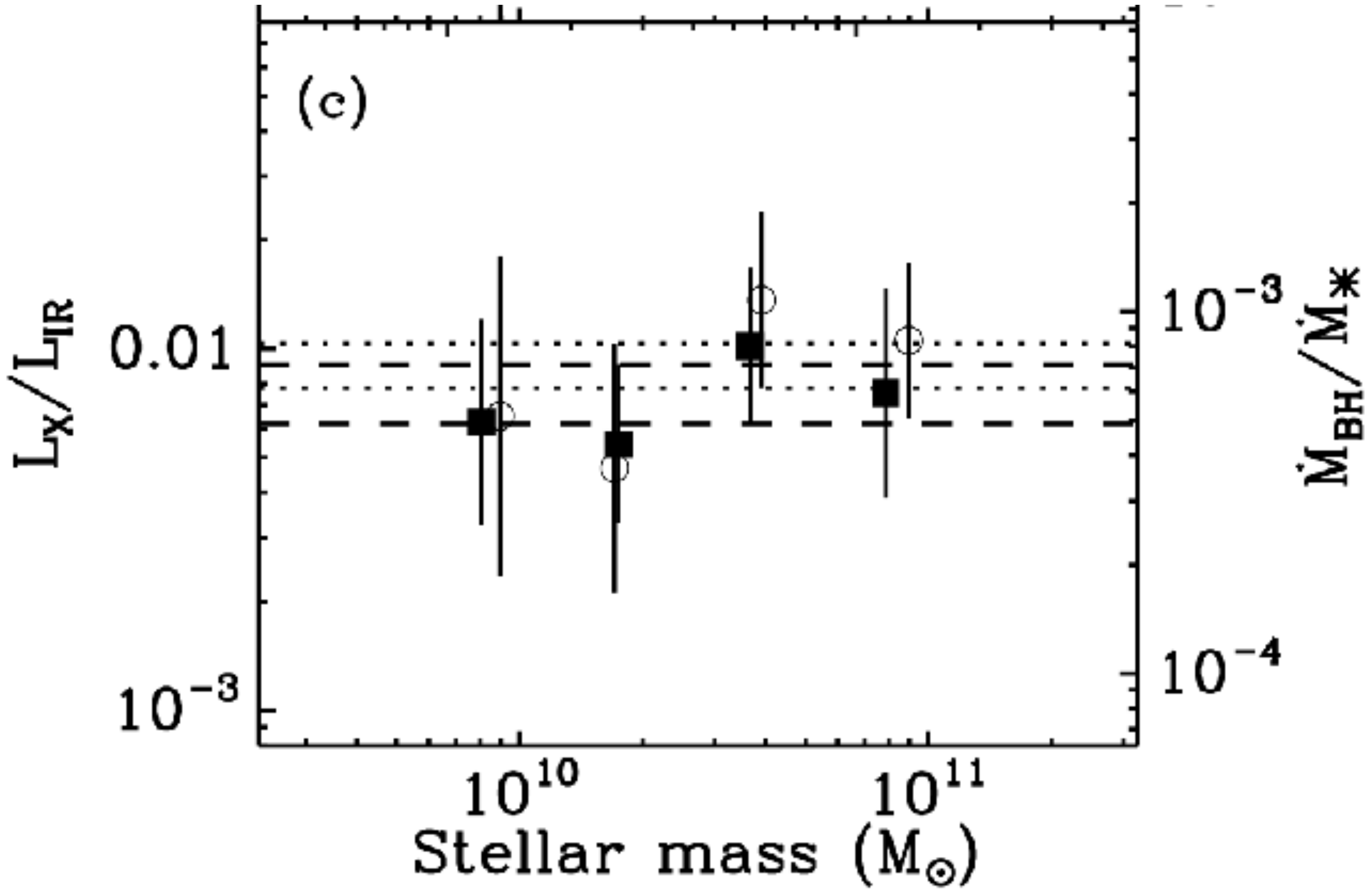


Rosario et al. 2012

Stanley et al. 2012

Timescale issue

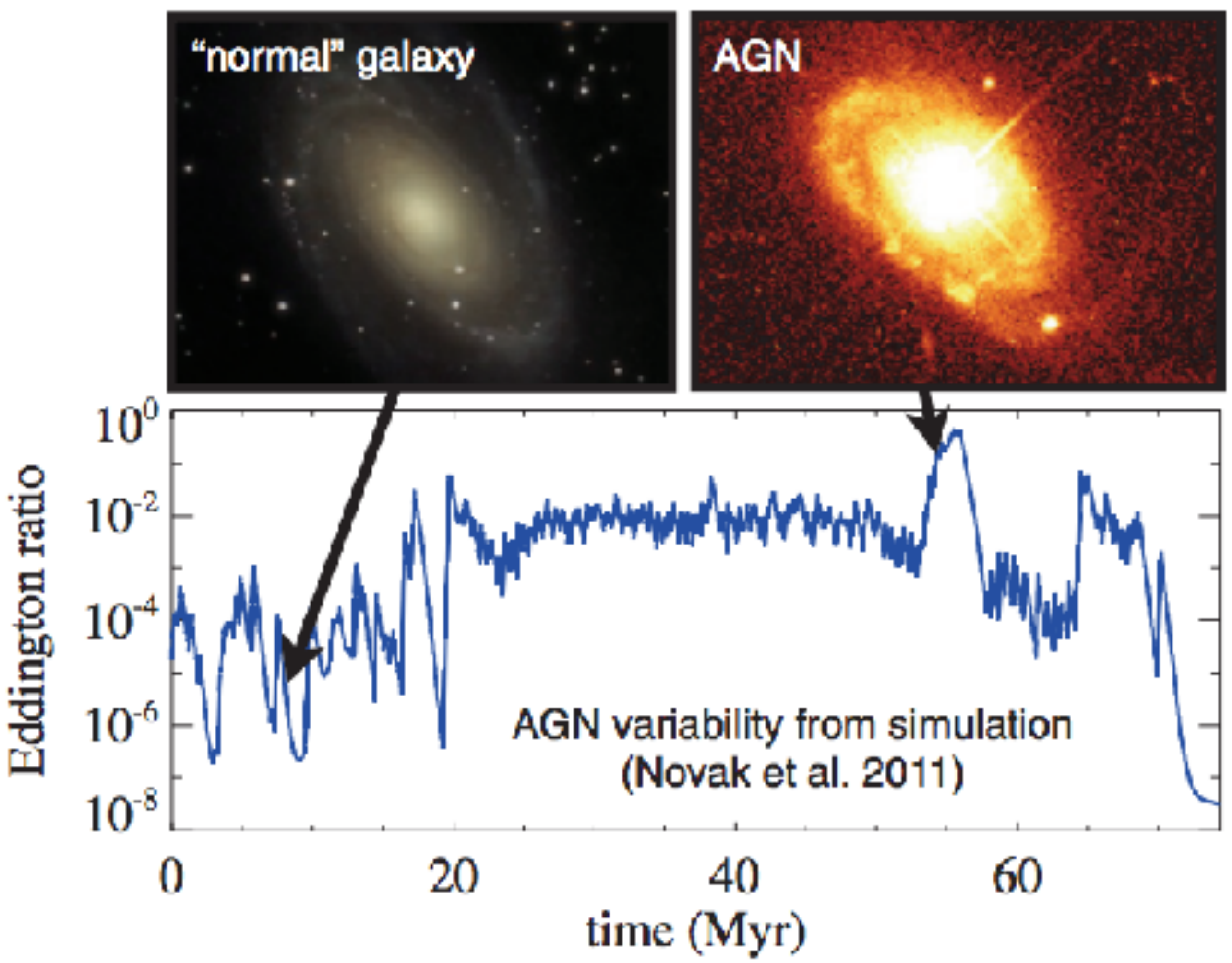
different time scale between
BH accretion (<<100Myr) and SF (~0.1-1Gyr)



Mullaney et al. 2012b

Timescale issue

SF and BH accretion is somewhat linked possibly through (1) merging process and/or (2) w/o any physical connection



(1) SFR ~ $\alpha\dot{m}$ on average

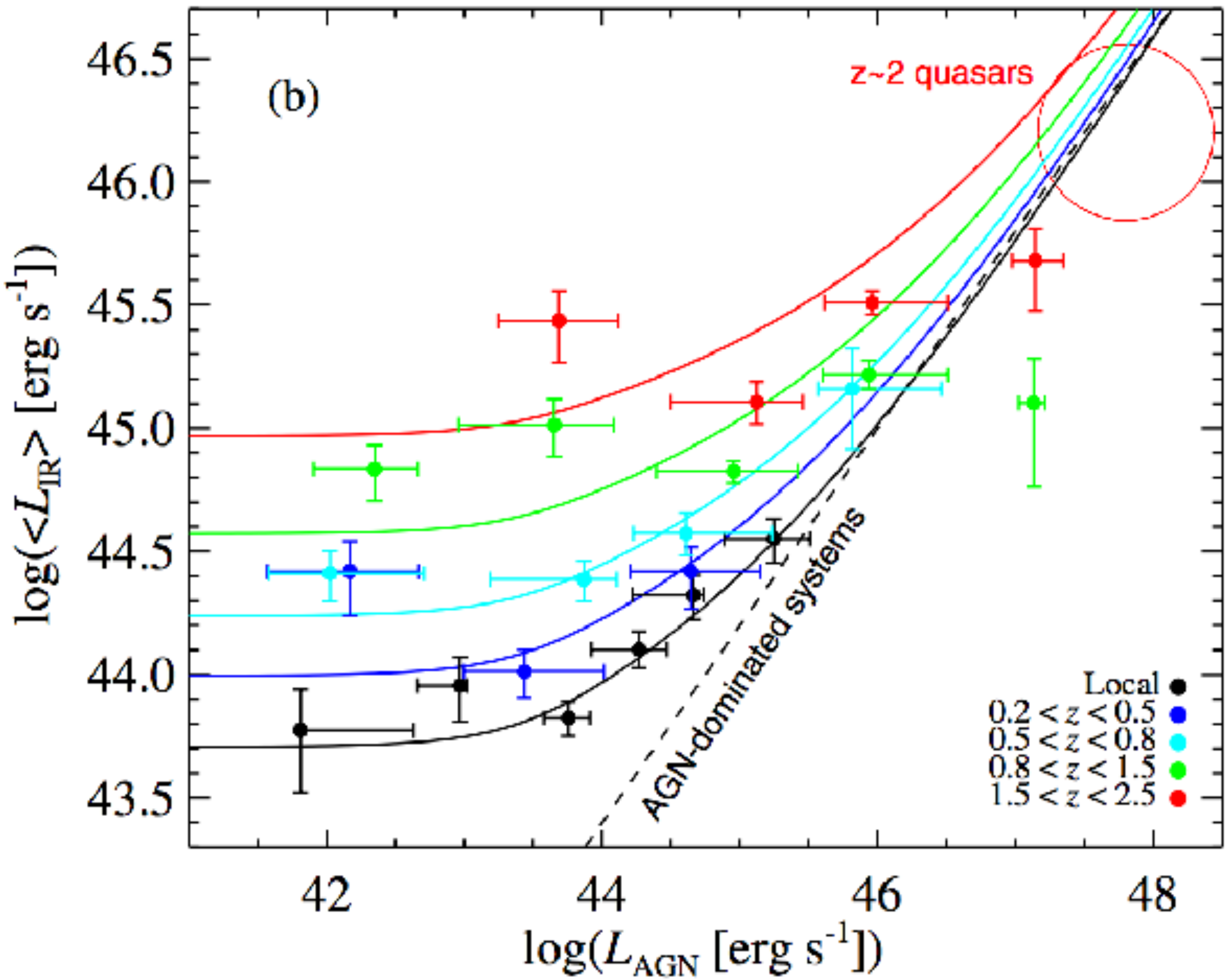
(2) time scale of SFR > $\dot{m}_{BH}$

(3) FIR LF for z~0-2

Hickox et al. 2014

Timescale issue

Successfully reproduced the observational trend!

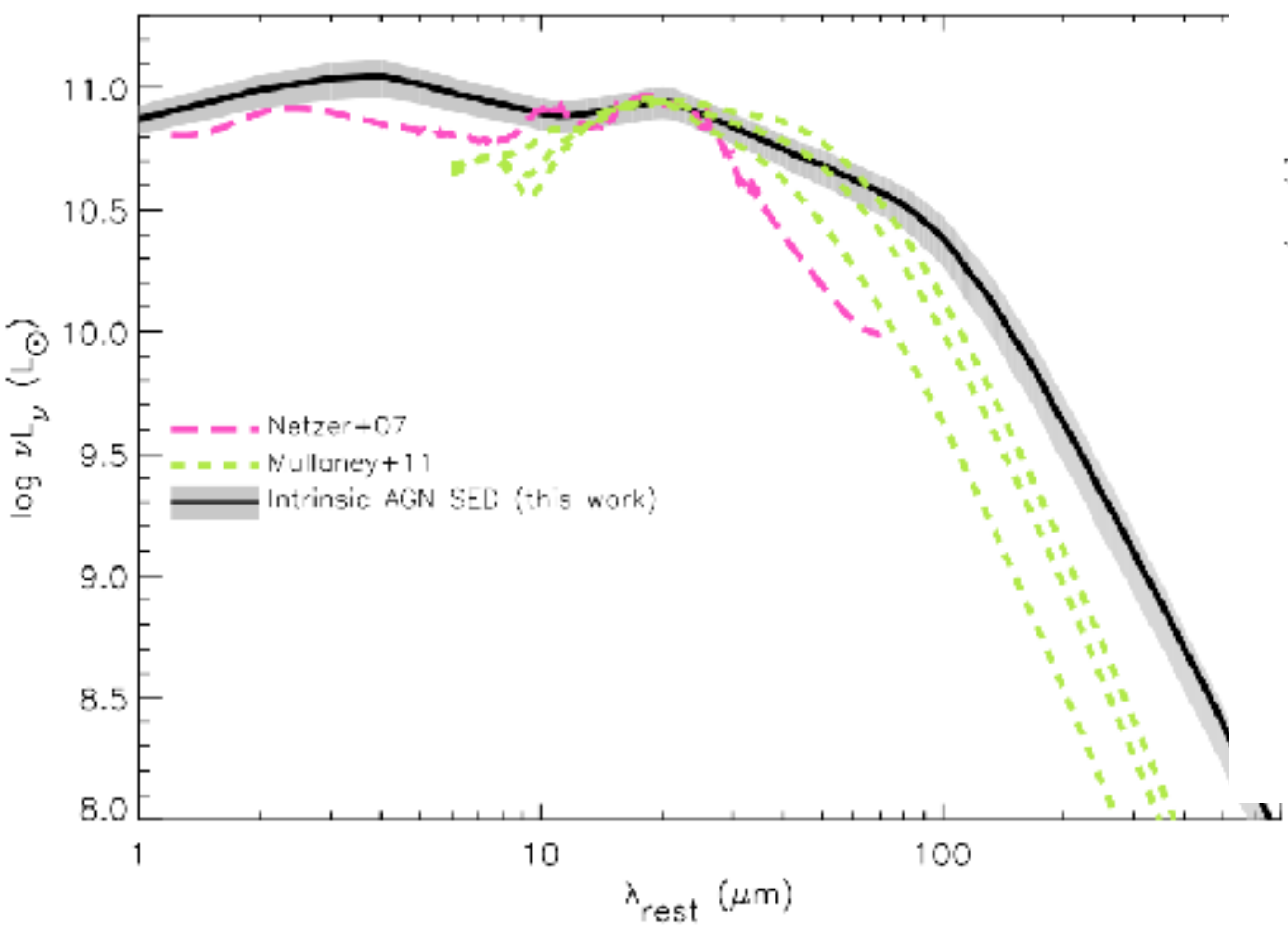


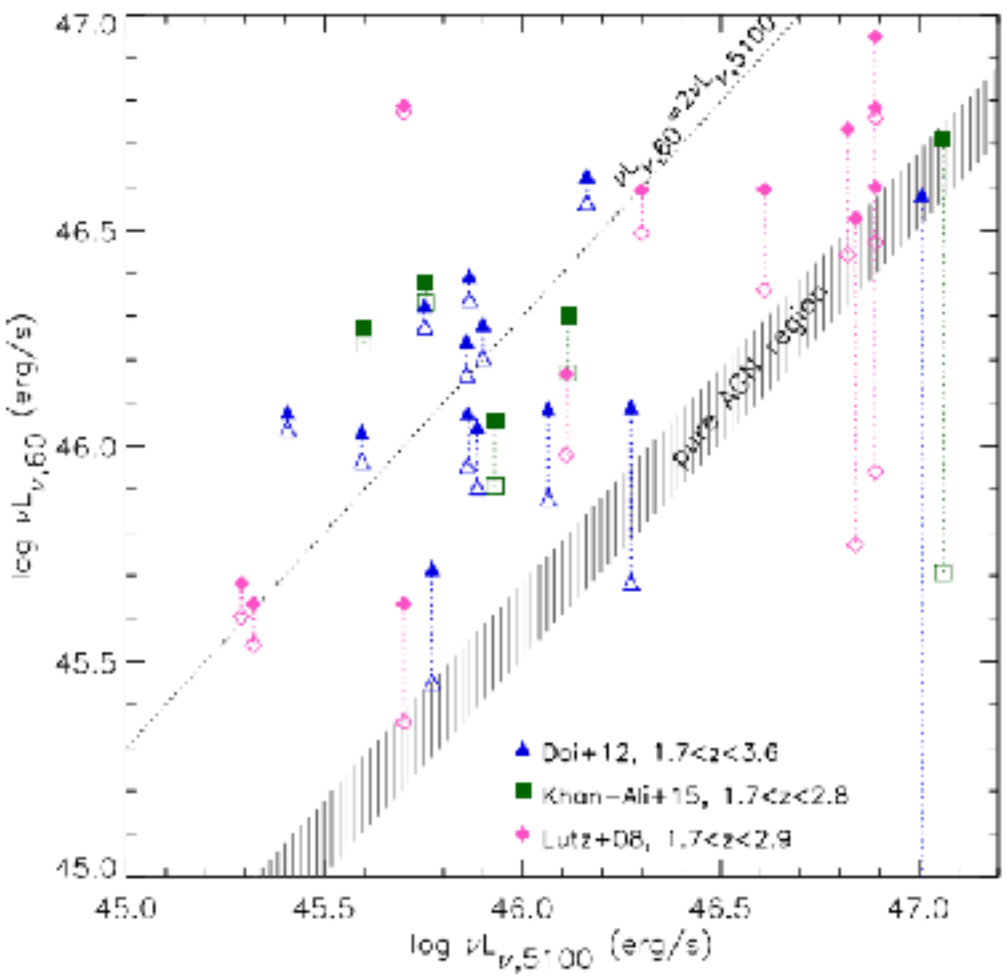
Hickox et al. 2014

Technical issue

AGN are cooler than you think (Symeonidis+2016)

With FIR one may overestimate SFR in AGNs!





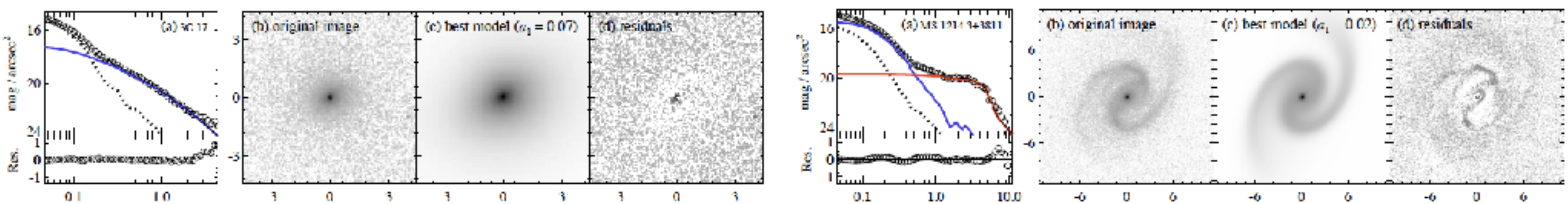
open symbols : pure SF

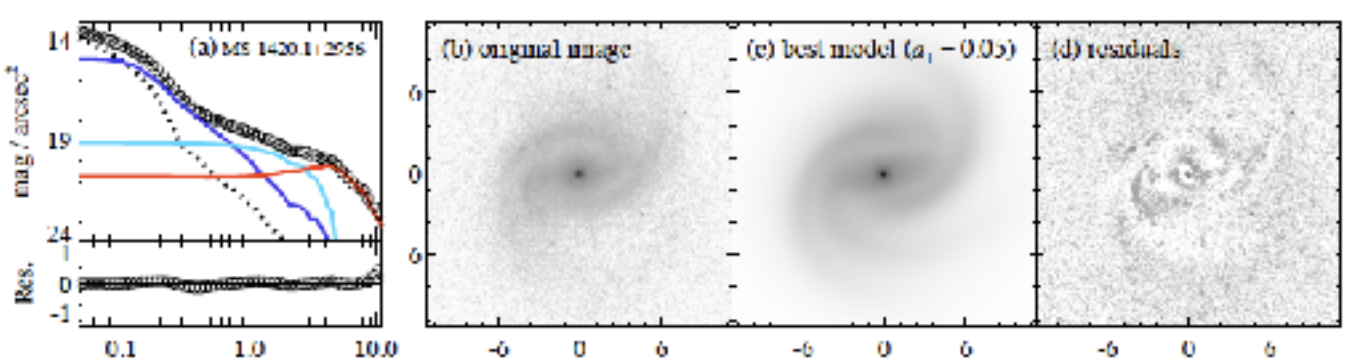
Summary of Previous Studies

- Different Studies reached different conclusions (possibly due to the biased sample and method).
- Mostly relied on FIR luminosity, which can be somewhat biased.
- Intriguing caveat : Time scales of SF and AGN are significantly different at least by an order of magnitude.
- Focused on type 2 AGNs (easy to estimate stellar mass but hard to measure BH mass)
- Our goal : **Time averaged** relative stellar growth rate (specific SF) and BH growth rate measured by **independent methods** (not FIR)!

Young Stars in (nearby) Type I AGNs

- Sample : 235 type I AGNs with deep HST images
- BH mass : Virial method (Single-epoch + multi-epoch)
- Bulge Luminosity : Imaging decomposition



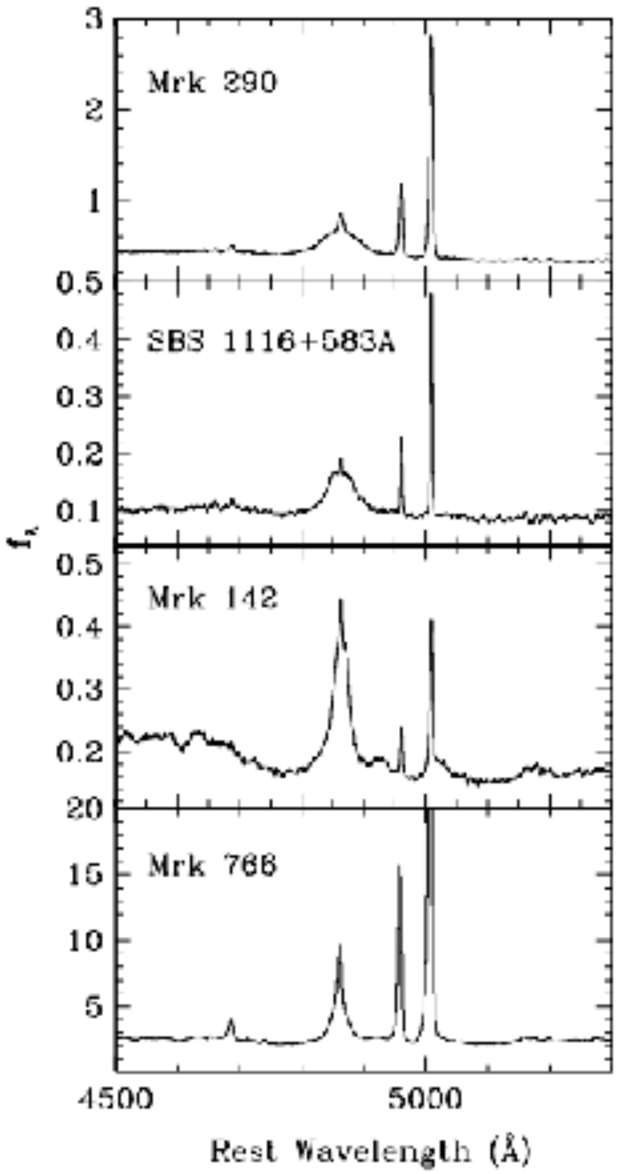


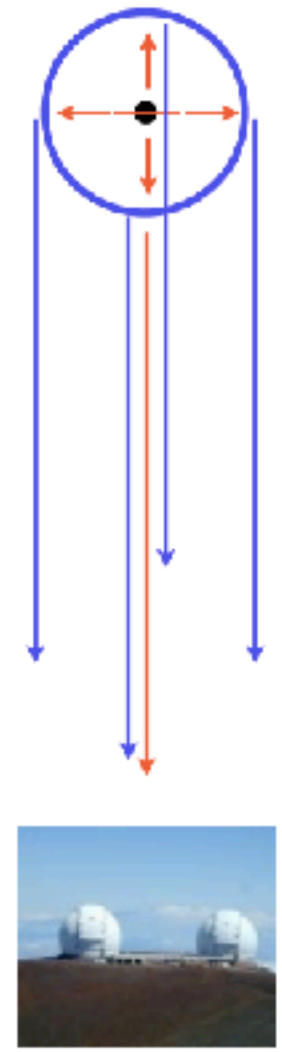
Kim et al. 2017a

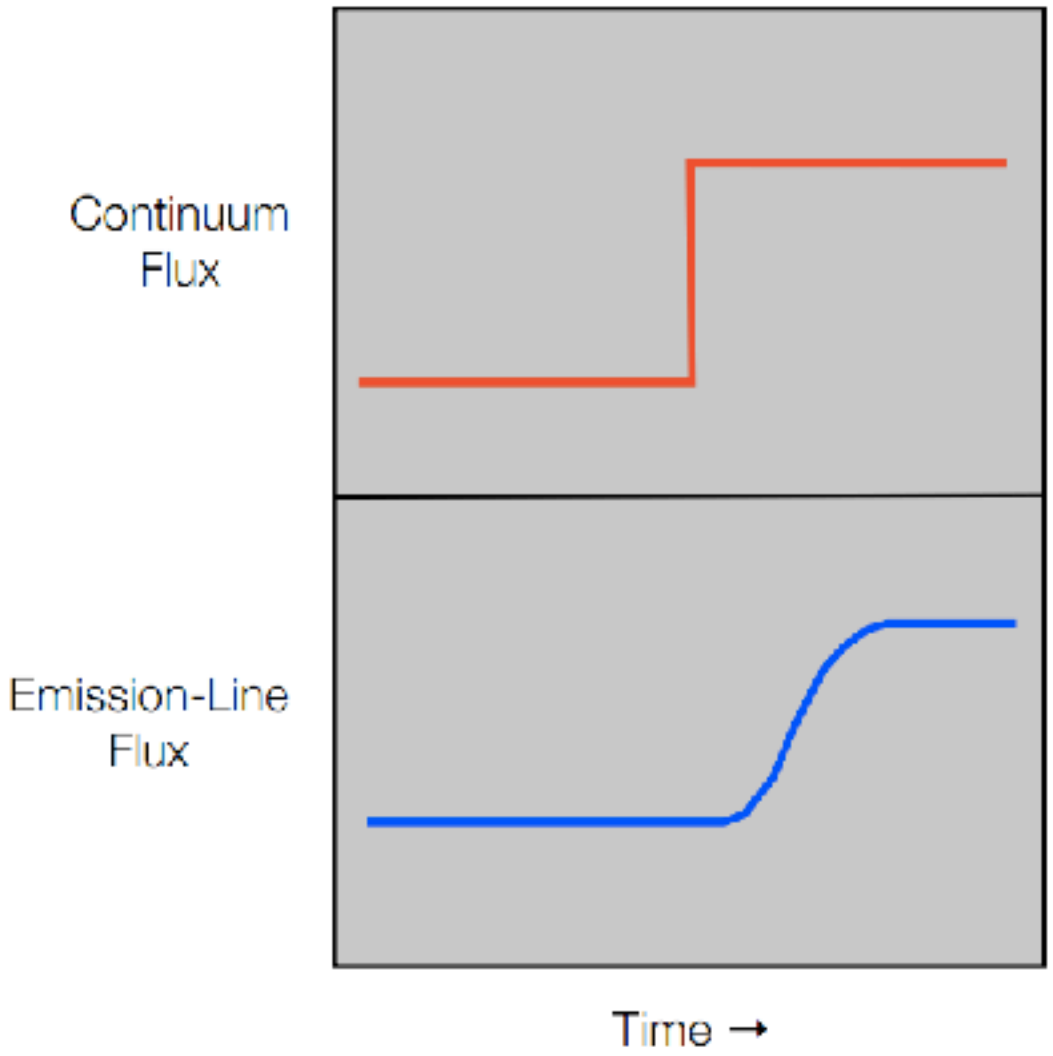
Decomposition of host galaxy

M_{BH} measurement in Active galaxy

- Reverberation mapping
  $M_{BH} \sim f \times r \times v^2 / G \sim ct \times FWHM^2$

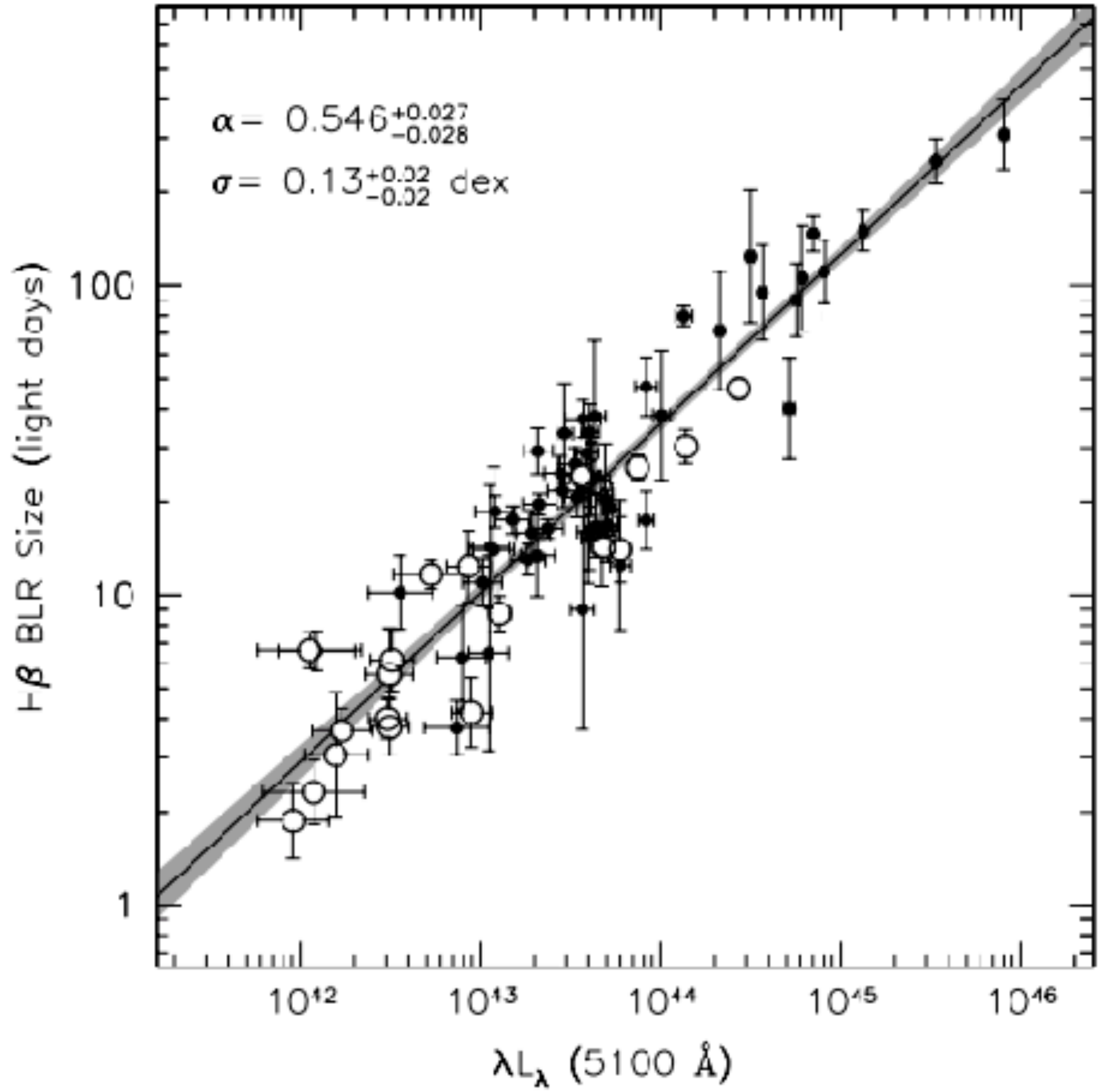






M_{BH} measurement in Active galaxy

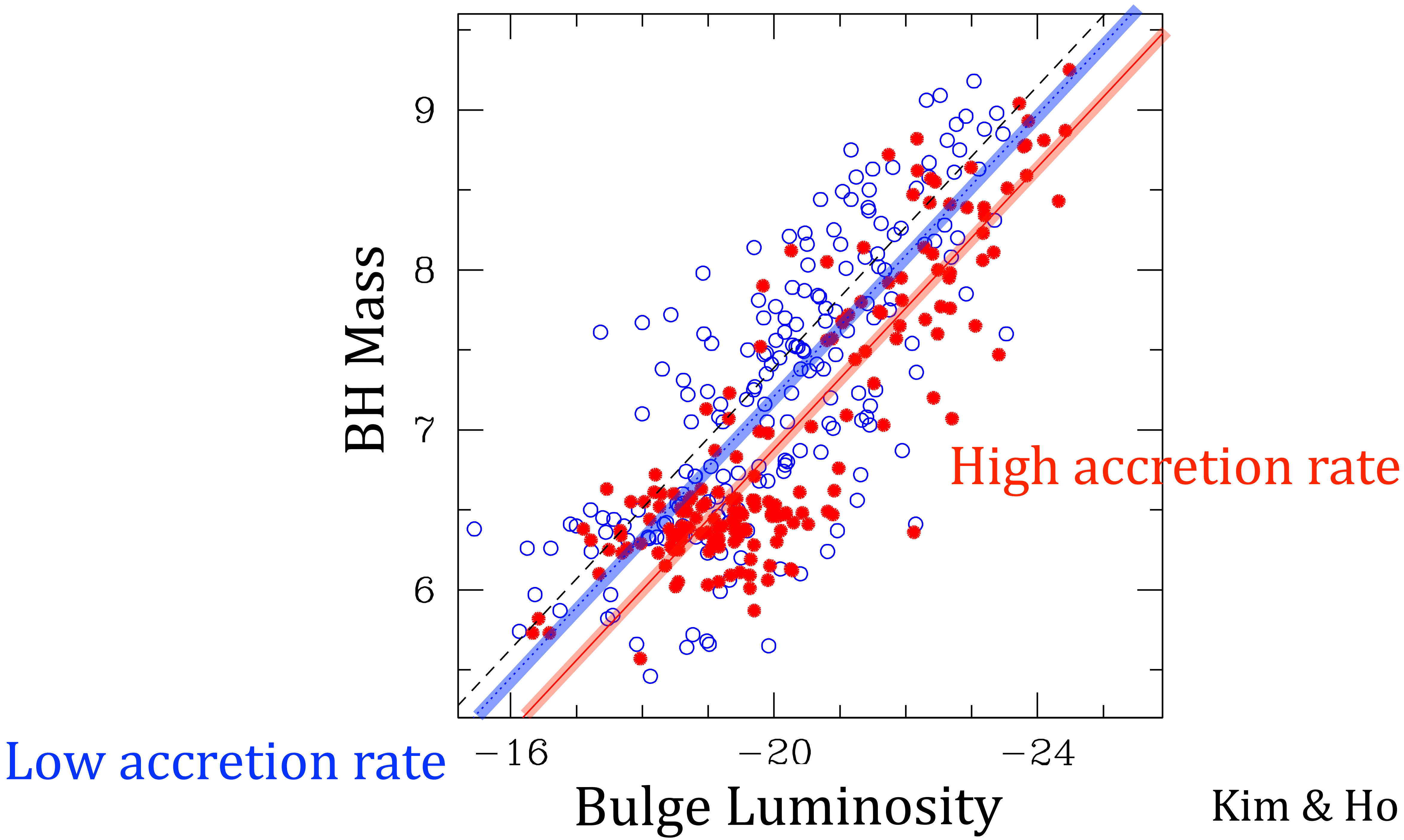
- Reverberation mapping
  $M_{BH} \sim f \times r \times v^2/G \sim f \times L \times v^2/G$



Bentz+ 2013

Young Stars in (nearby) Type I AGNs

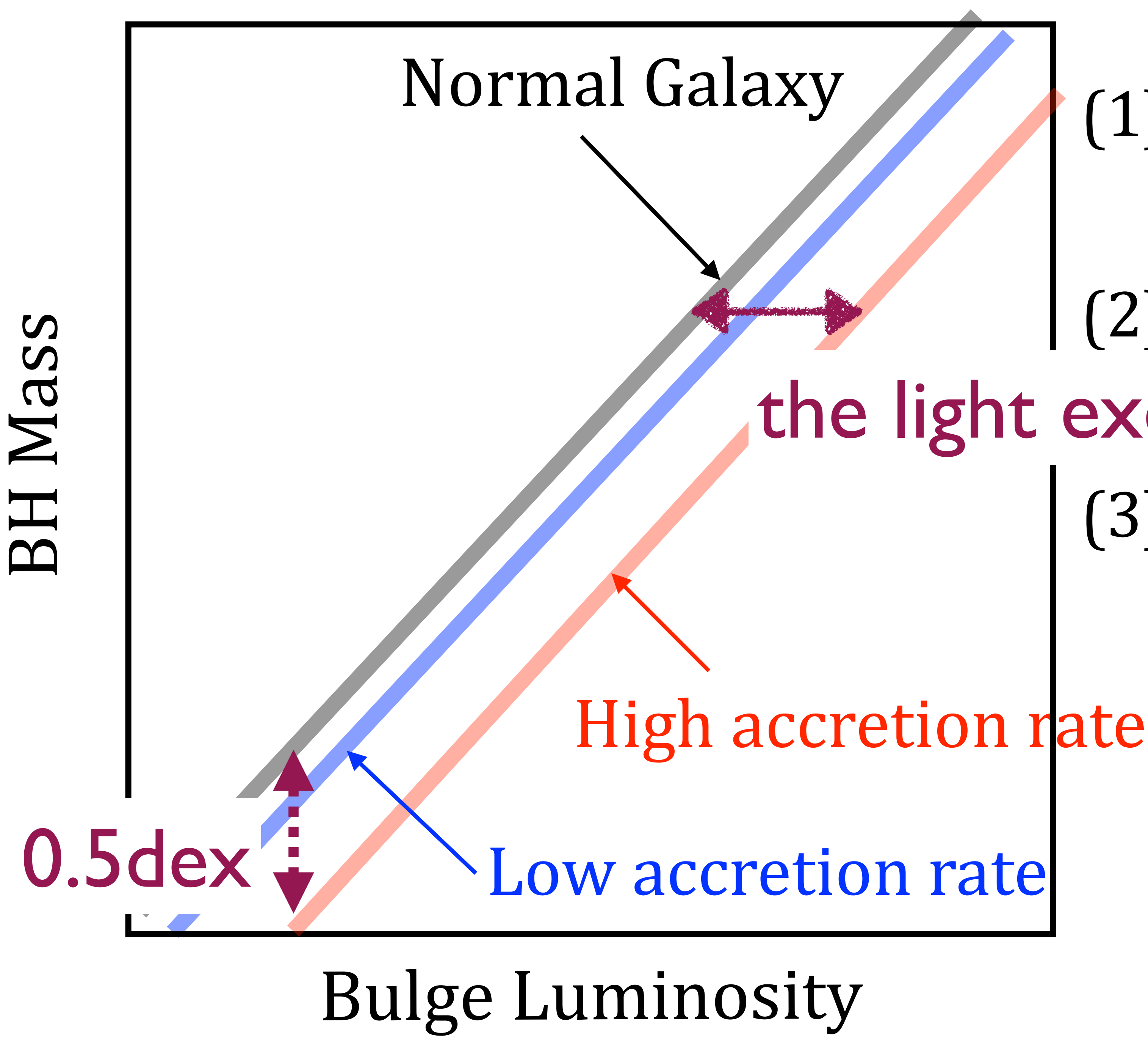
- Dependency on the accretion rate



Kim & Ho (2019)

Young Stars in (nearby) Type I AGNs

- Dependency on the accretion rate



the light excess of the bulge

(1) BH is actively growing? ✖

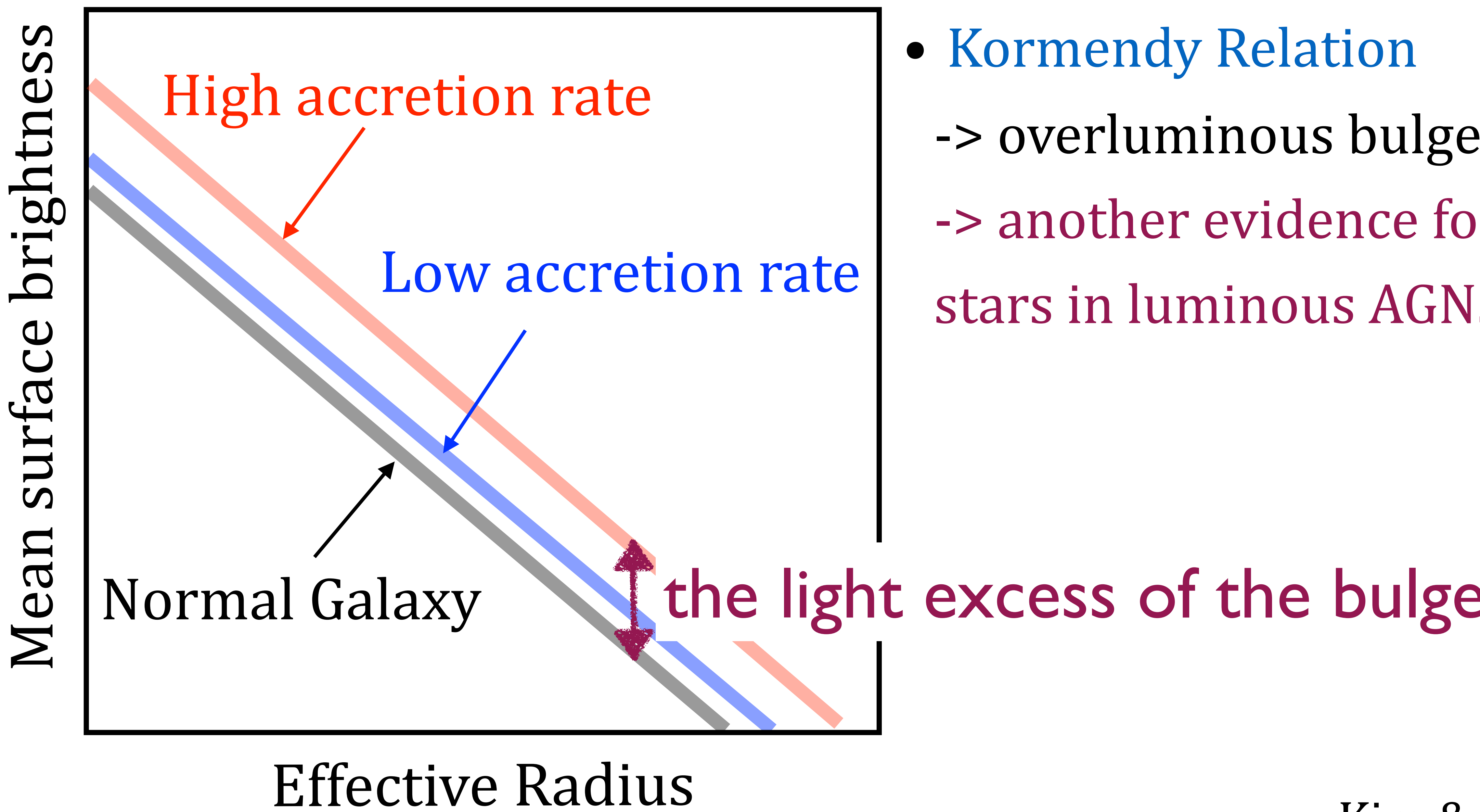
(2) M(BH) is underestimated? ✓

(3) host galaxy is overluminous due to young stars? ✔

Kim & Ho (2019)

Young Stars in (nearby) Type I AGNs

- Young stars in the host galaxies?



- Kormendy Relation

  -> overluminous bulges

  -> another evidence for young stars in luminous AGNs

Kim & Ho (2019)

Origin of light excess?

- Mass-Luminosity relation in stars

$$L \propto M^{3.3} \qquad \frac{M}{L} \propto M^{-2.3}$$

무거운 별이 많을수록 주어진 질량에서 더 밝게 보인다.

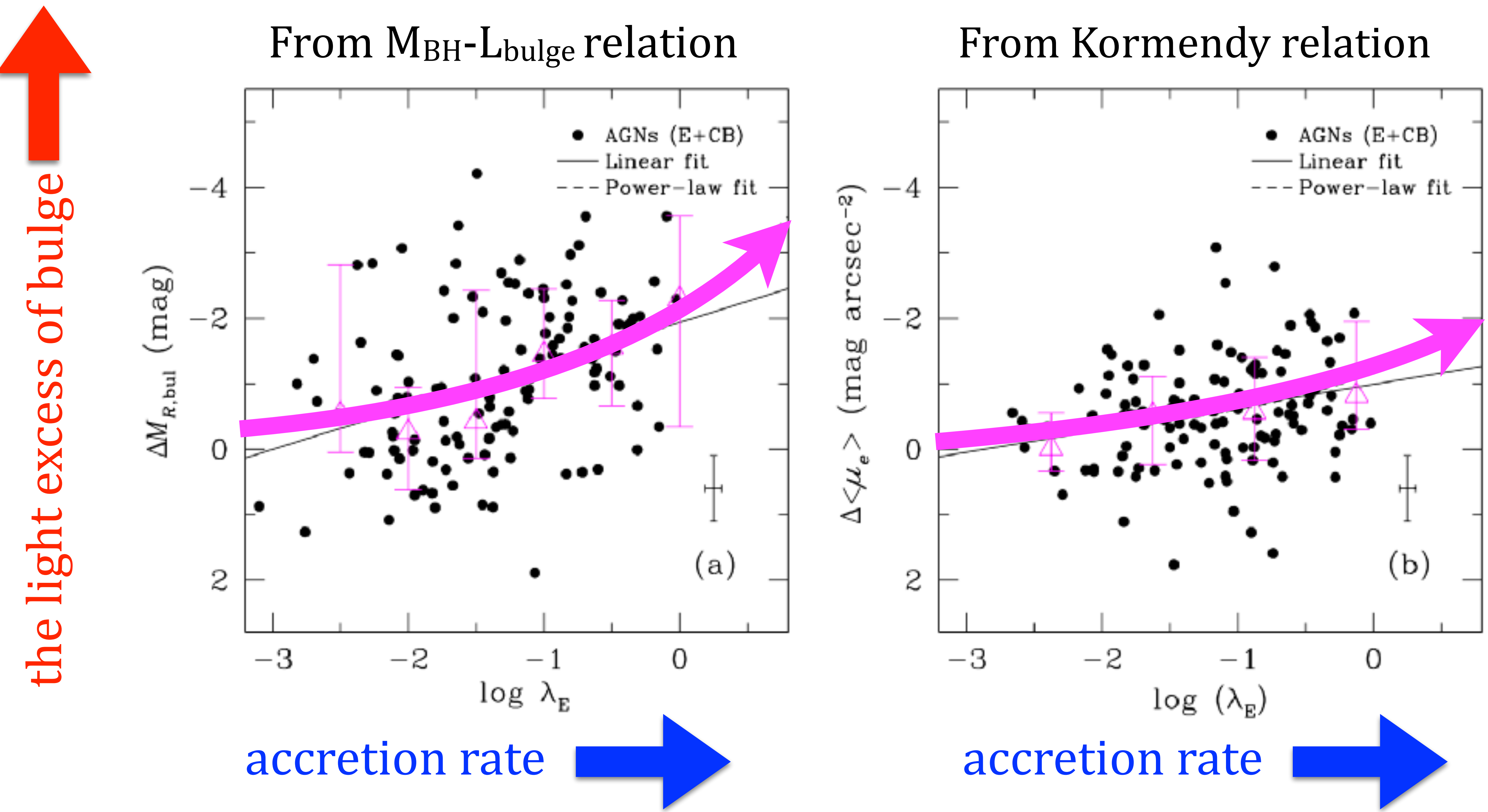
$$\tau \propto \frac{M}{L} \propto M^{-2.3}$$

무거운 별일수록 수명이 짧다.

☞ 은하가 젊을수록 M/L가 작아진다. 즉 주어진 질량보다 훨씬 밝게 보인다.

Light excess ⇒ young star (recent star formation)

Young Stars in (nearby) Type I AGNs

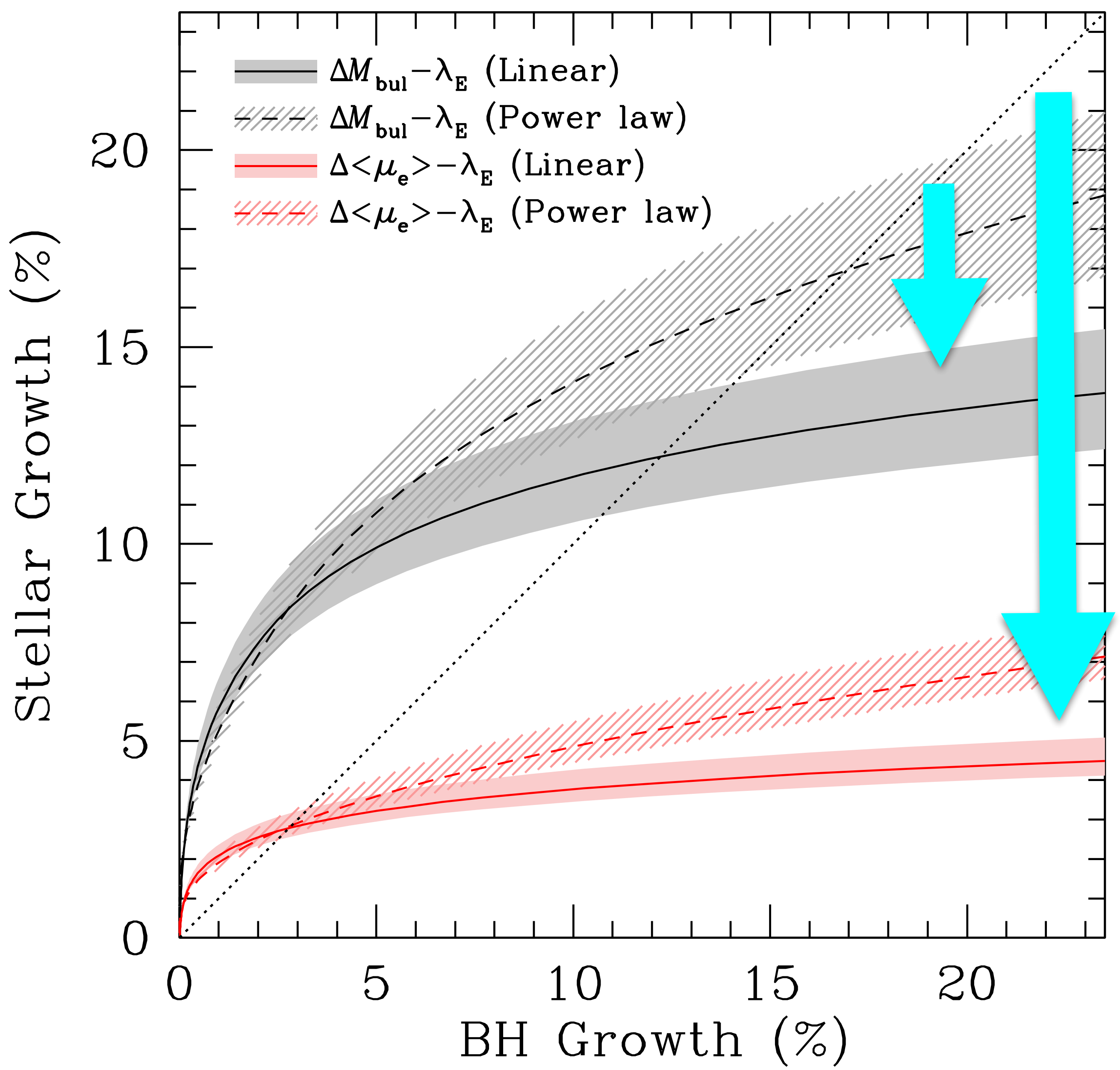


Kim & Ho (2019)

Young Stars in (nearby) Type I AGNs

$$\frac{M_{*,<500\,\mathrm{Myr}}}{M_{*,10\,\mathrm{Gyr}}} \times 100$$

the light excess of bulge



- Stellar growth rate and BH growth rate appears to be somewhat correlated.
  (but not one-to-one relation)
  ➥ SF Growth and BH Growth is not perfectly synchronized!

- Indirect signature of AGN feedback?

accretion rate → $\exp\left(\lambda_E \frac{1-\epsilon}{\epsilon} \frac{t_{AGN}}{t_{Edd}}\right)$

Kim & Ho (2019)