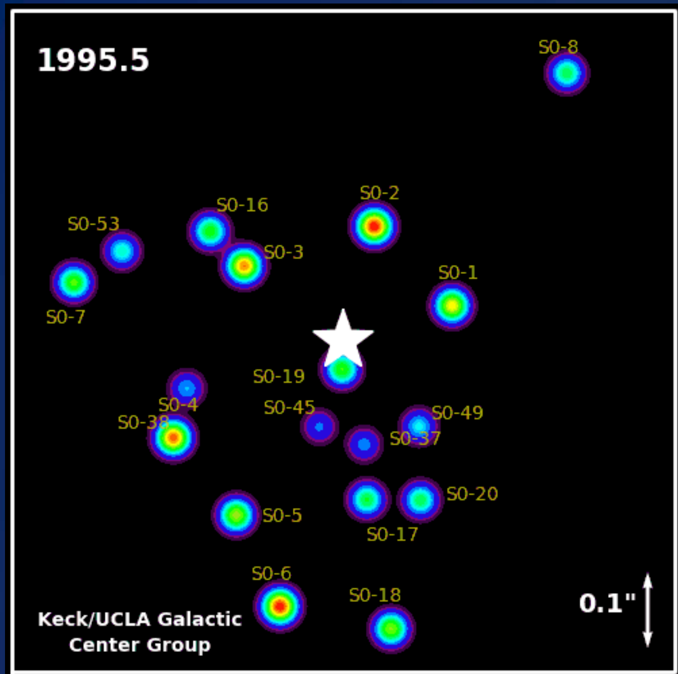
Tracing the Origins of the Relations between SMBHs and their Hosts

Benny Trakhtenbrot
ETH Zürich

With:
Meg Urry, Francesca Civano, Stefano Marchesi (Yale),
Martin Elvis (CfA), David Rosario (MPE),
Hyewon Suh (Hawaii IfA / Harvard CfA),
Kevin Schawinski (ETH), Angela Bongiorno (INAF Rome),
and Brooke Simmons (Oxford & UCSD)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S0-8
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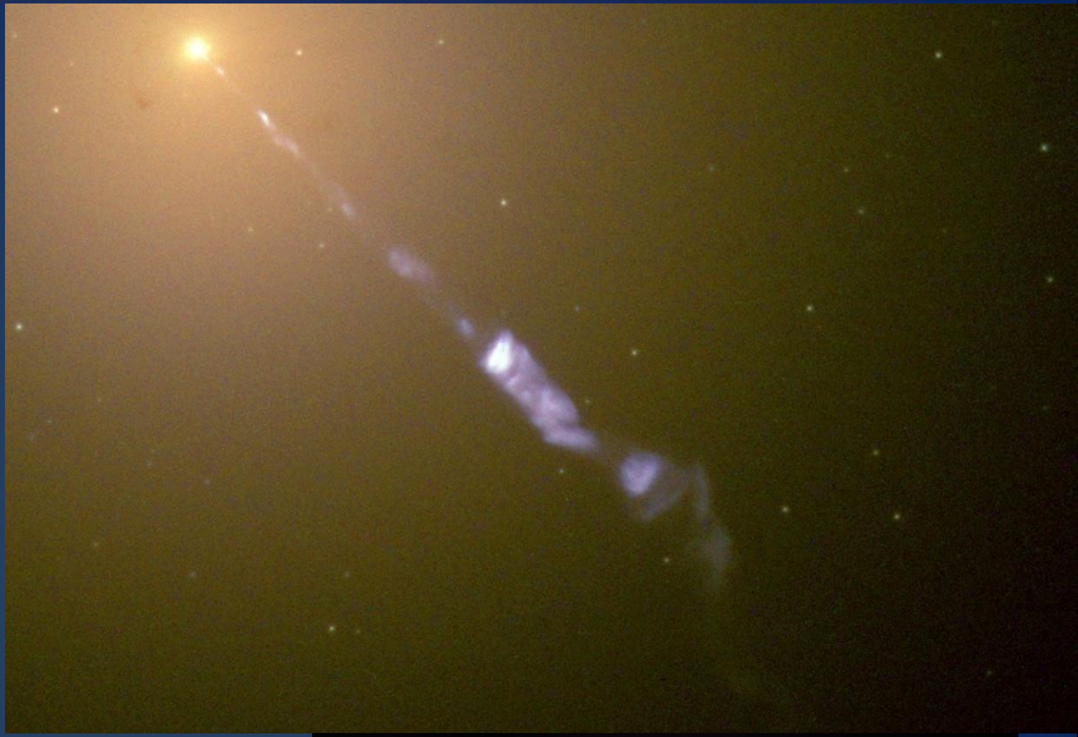
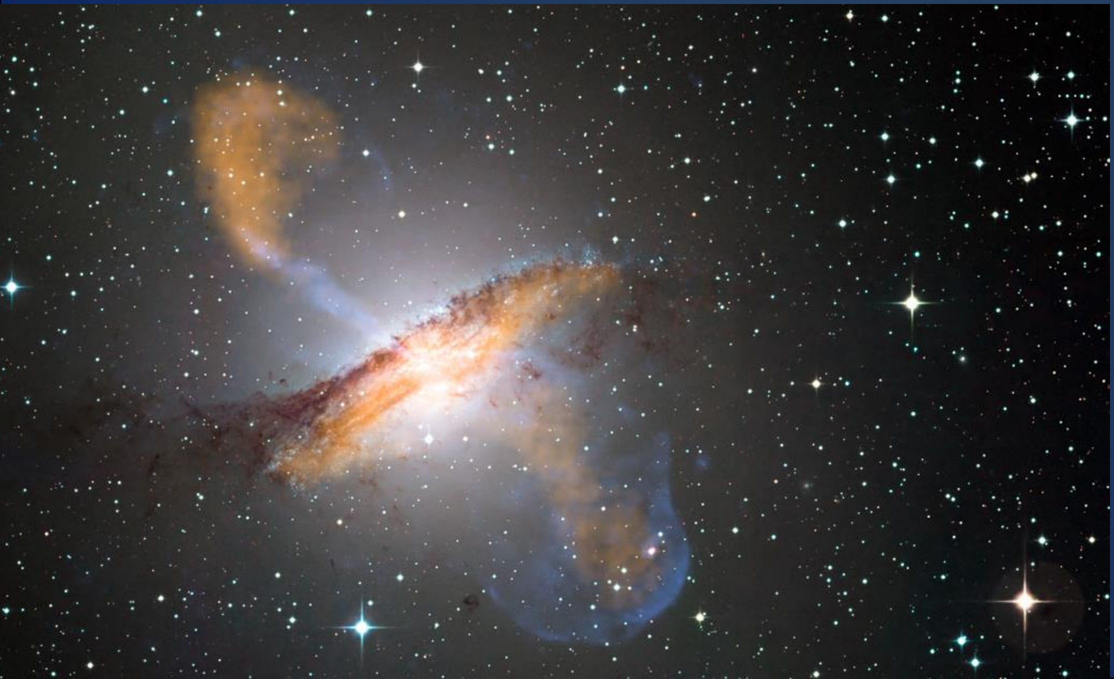
Keck/UCLA Galactic Center Group

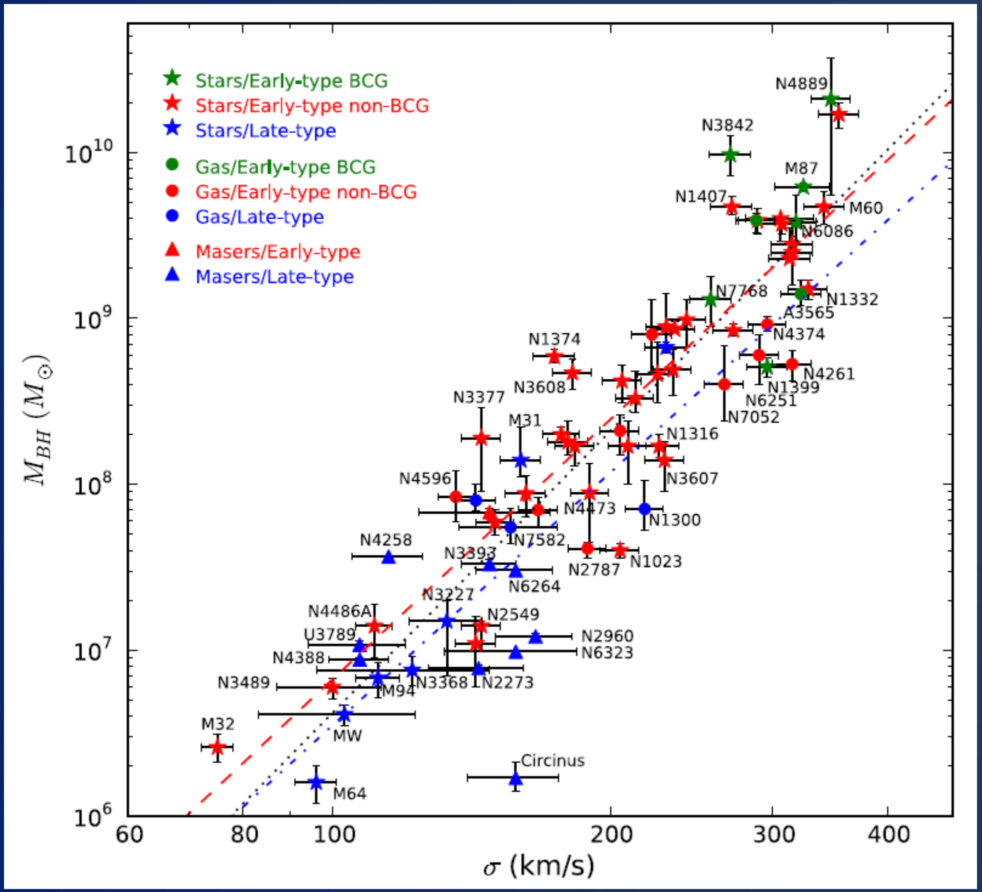




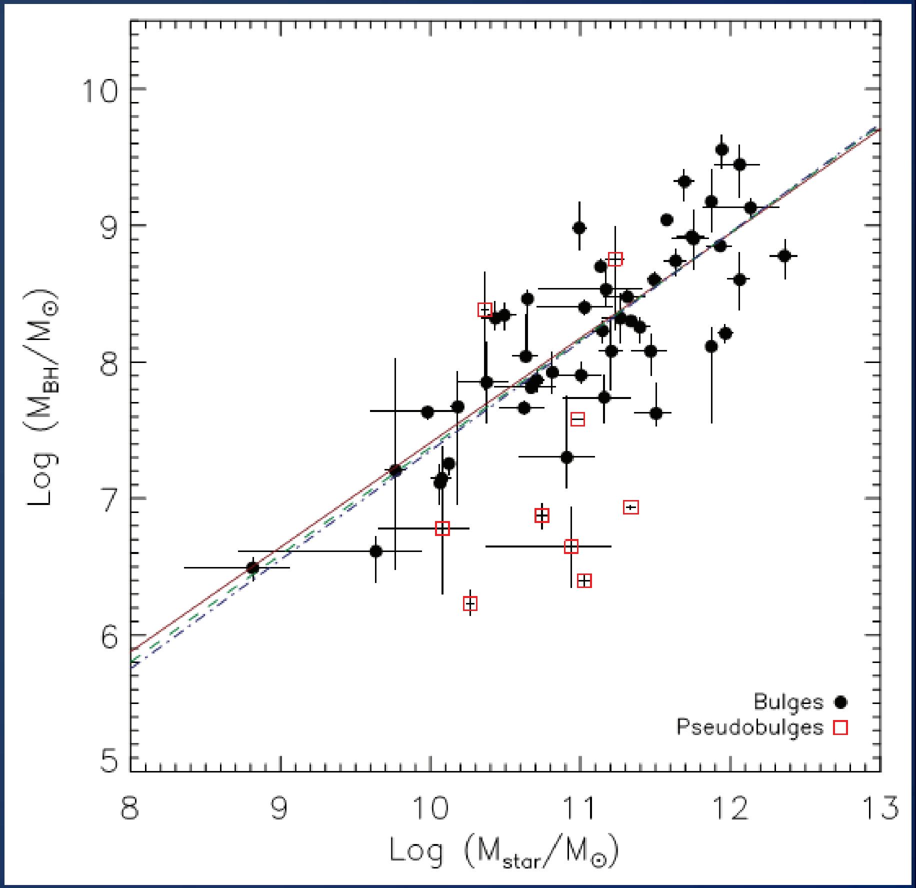
Evidence for SMBH-Host "Co-Evolution"

Strong relations between BH mass and host properties

$$M_* \sim 500 \times M_{\rm BH} \quad (200?\ 700??)$$



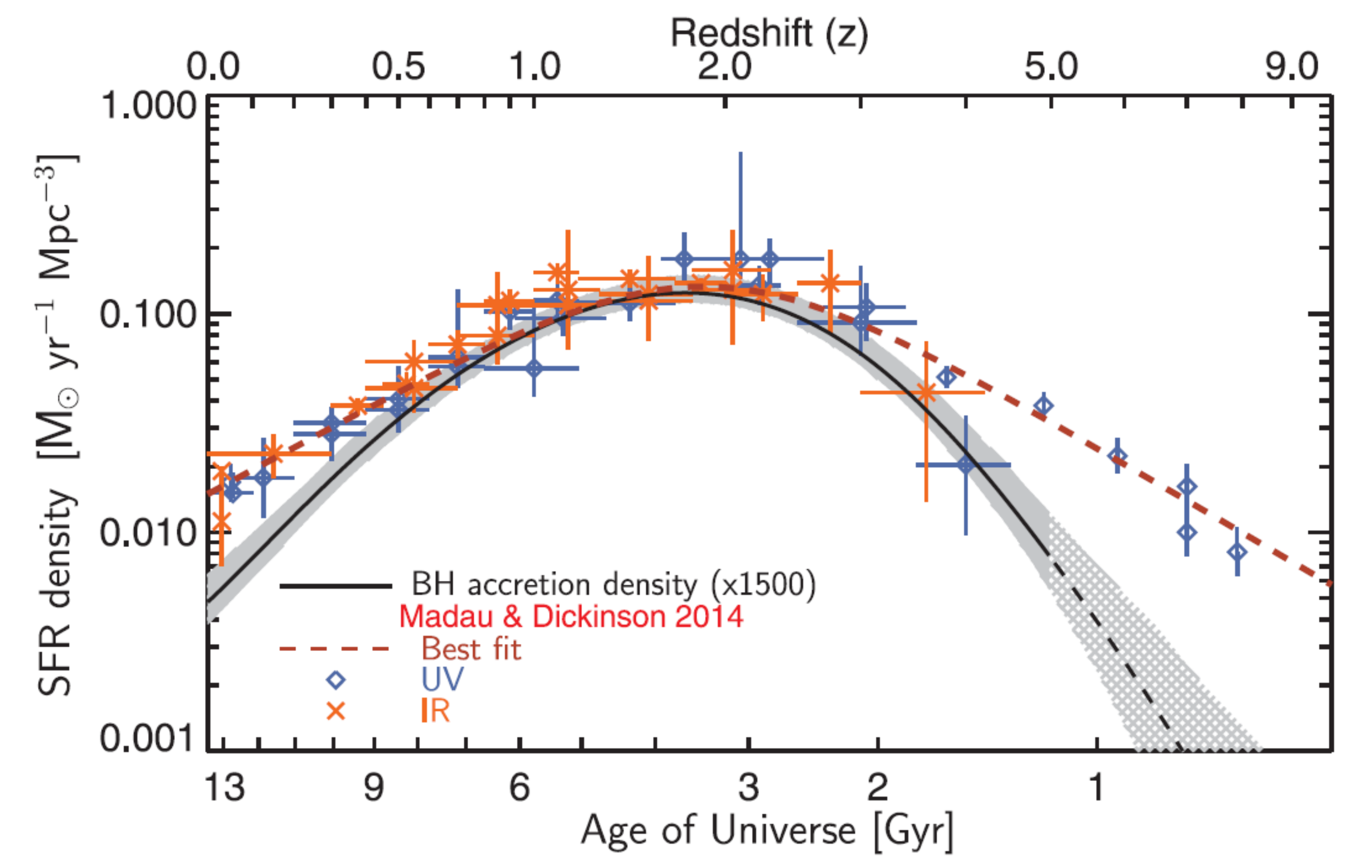
McConnell & Ma (2013)



Sani et al. (2011)

Evidence for SMBH-Host "Co-Evolution"

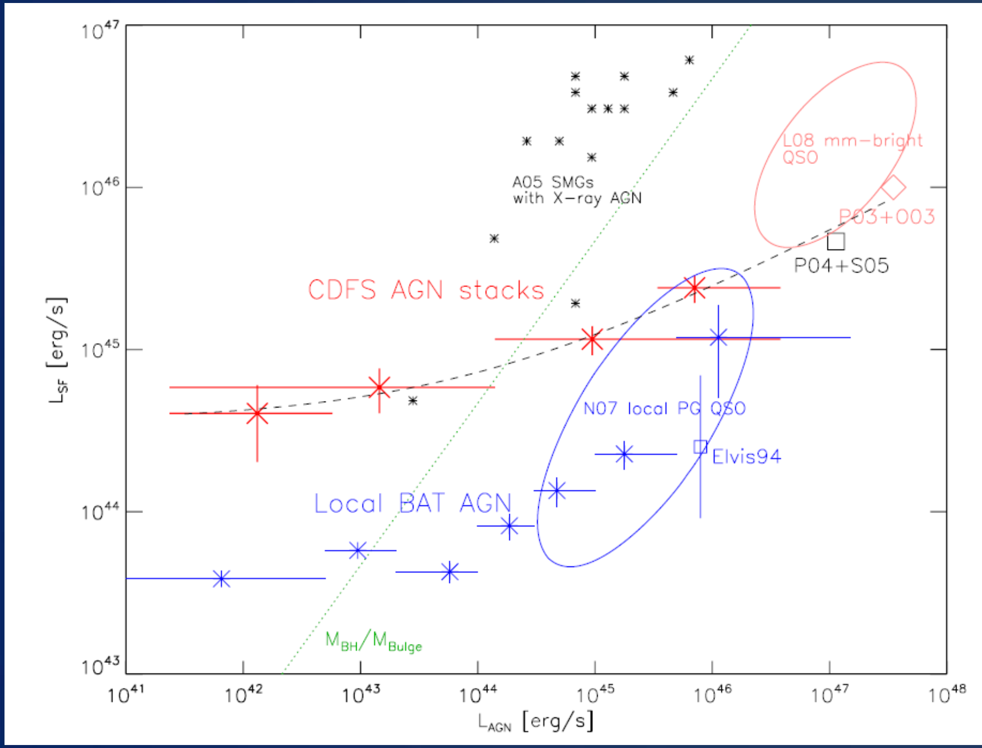
Integrated growth histories trace each other



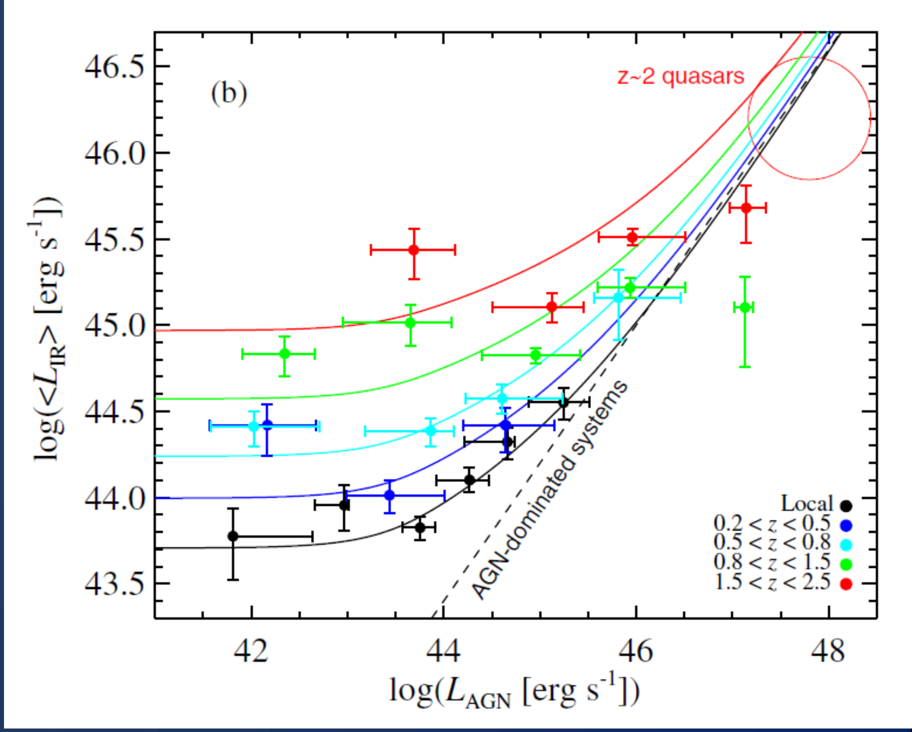
Aird et al. (2015)

Evidence for SMBH-Host "Co-Evolution"

Instantaneous growth rates trace each other (?)



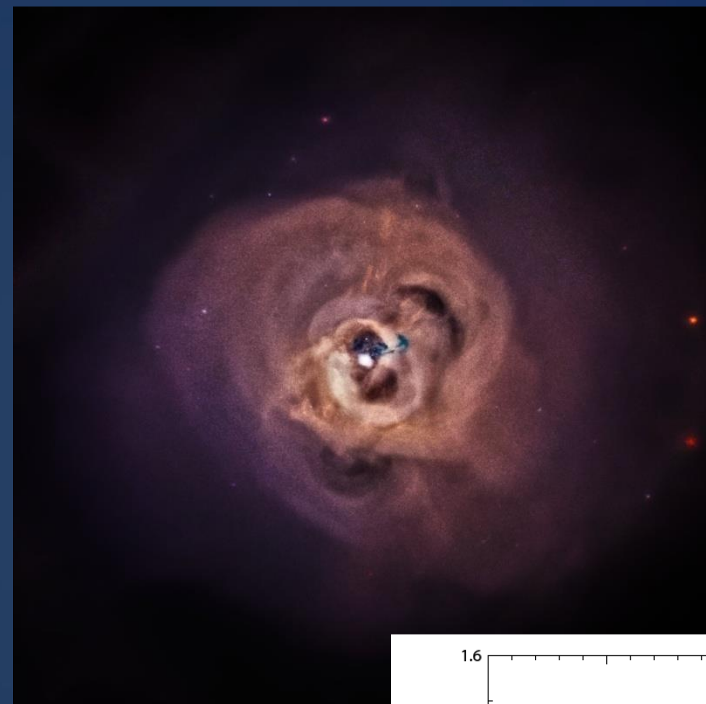
Lutz et al. (2010)



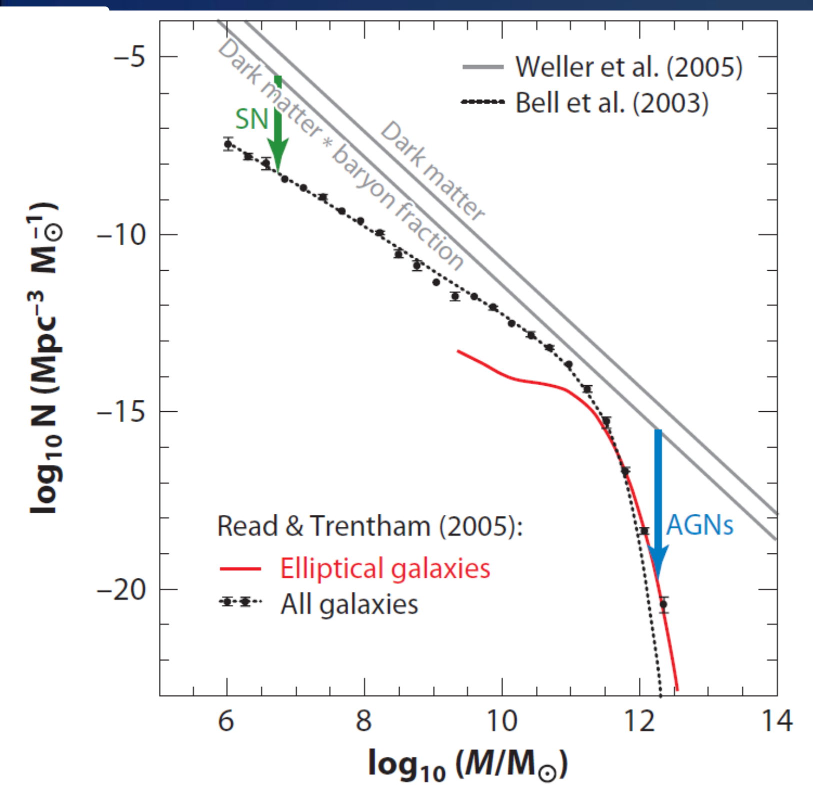
Rosario et al. (2012), Hickox et al. (2014)

Evidence for SMBH-Host "Co-Evolution"

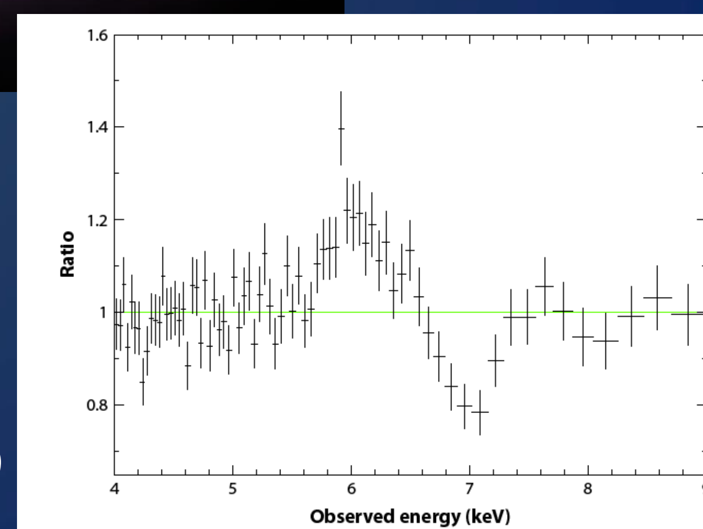
AGN-driven "feedback"



Fabian (2012)



Kormendy & Ho (2013)



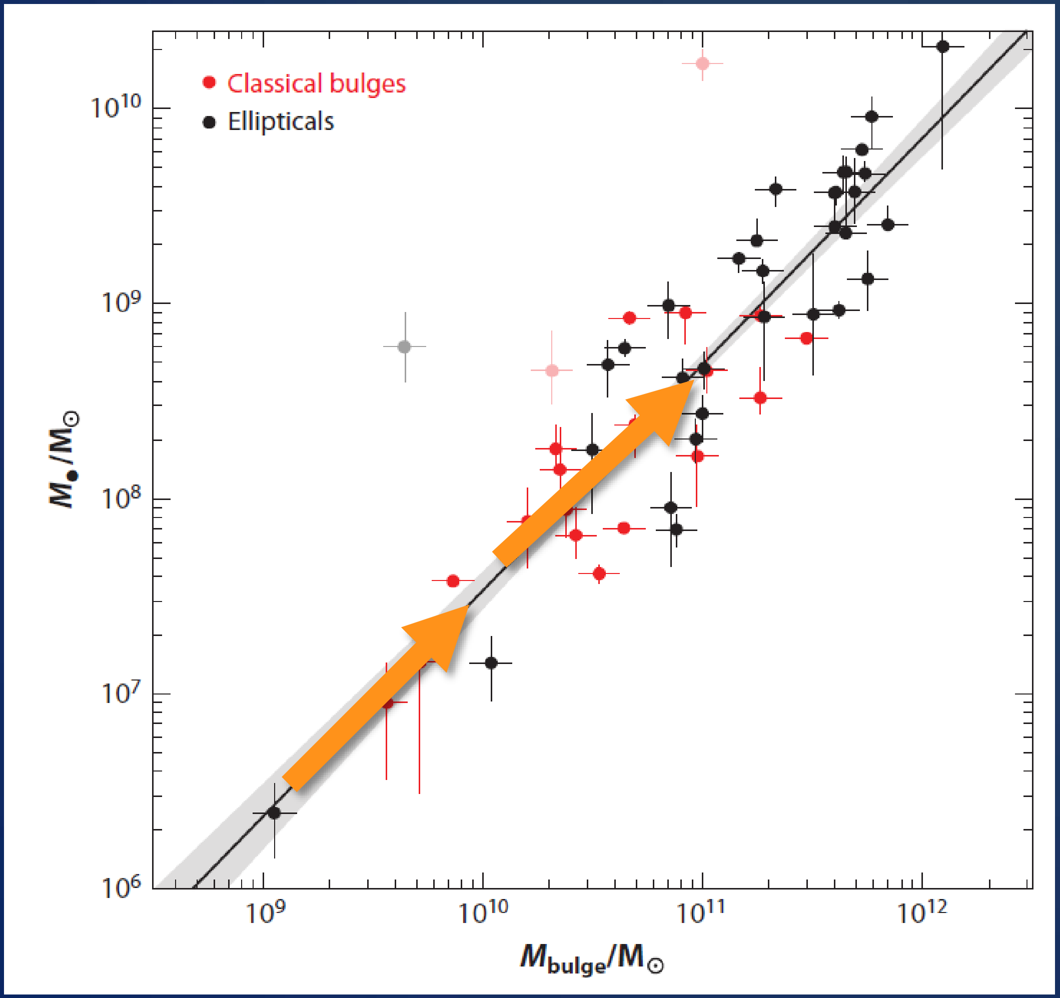
King & Pounds (2015)

Outline

- SMBH-host Relations and Evolution:
  - Expectations from Models
  - Observational challenges
  - Hints for evolution out to z~2
- A Keck Campaign for COSMOS AGNs at *z*~2.5-3.5:
  - Why "faint"? Why COSMOS?
  - An over-massive BH in a "normal" galaxy
  - Preliminary results from the sample
- How will ALMA solve everything?
- Summary

Evolutionary Scenarios of SMBH-Host Relations

Scenario 1: Host & BH grow "hand in hand"



Requires:

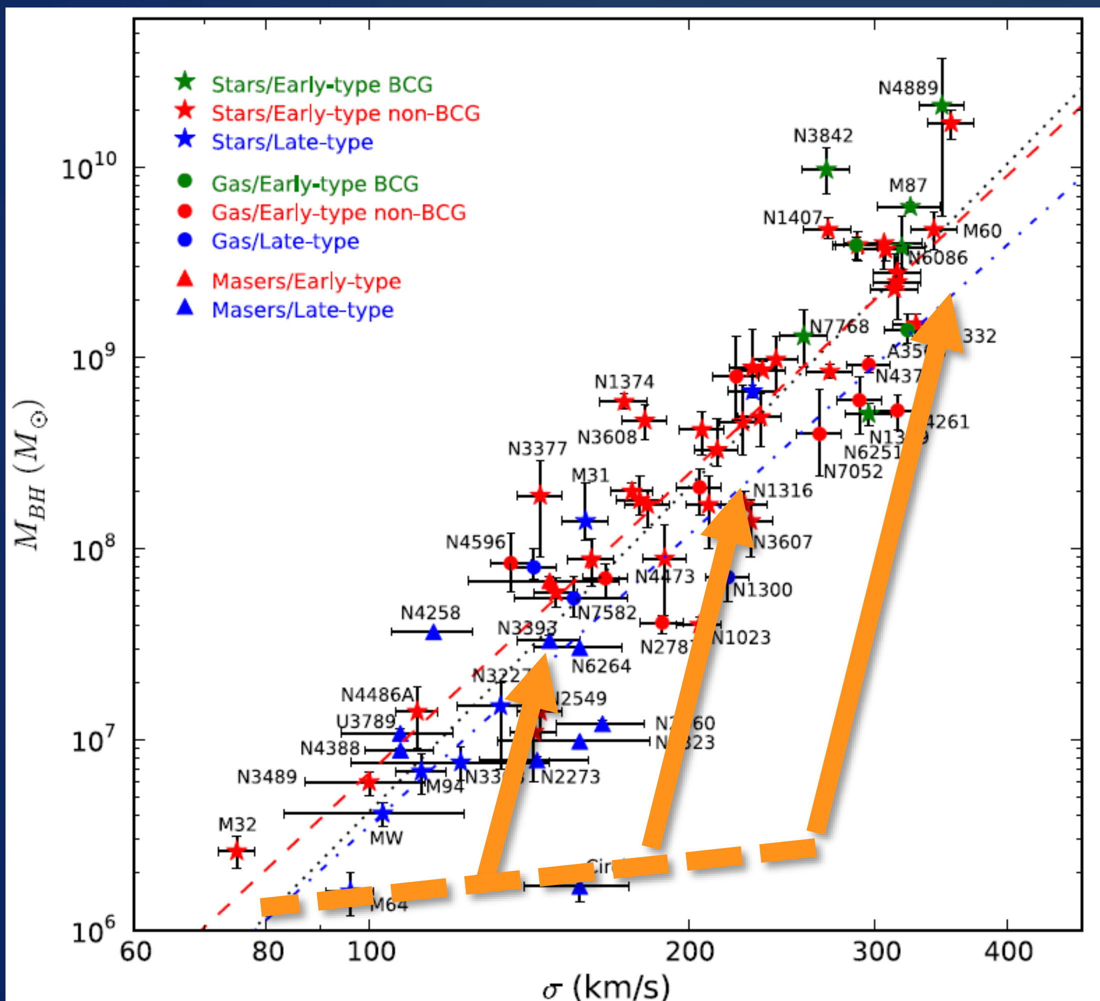
$\mathrm{SFR} \approx 500\times\ \mathrm{d}M_{\mathrm{BH}}/\mathrm{dt}$

Inconsistent with SFRD vs. BHARD

Kormendy & Ho (2013)

Evolutionary Scenarios of SMBH-Host Relations

Scenario 2: BH blows host-wide "shell", stopping accretion



Silk & Rees (1998):

$$M_{\rm BH} \approx 10^{7} \, (\sigma/200)^{5}$$

(energy-driven)

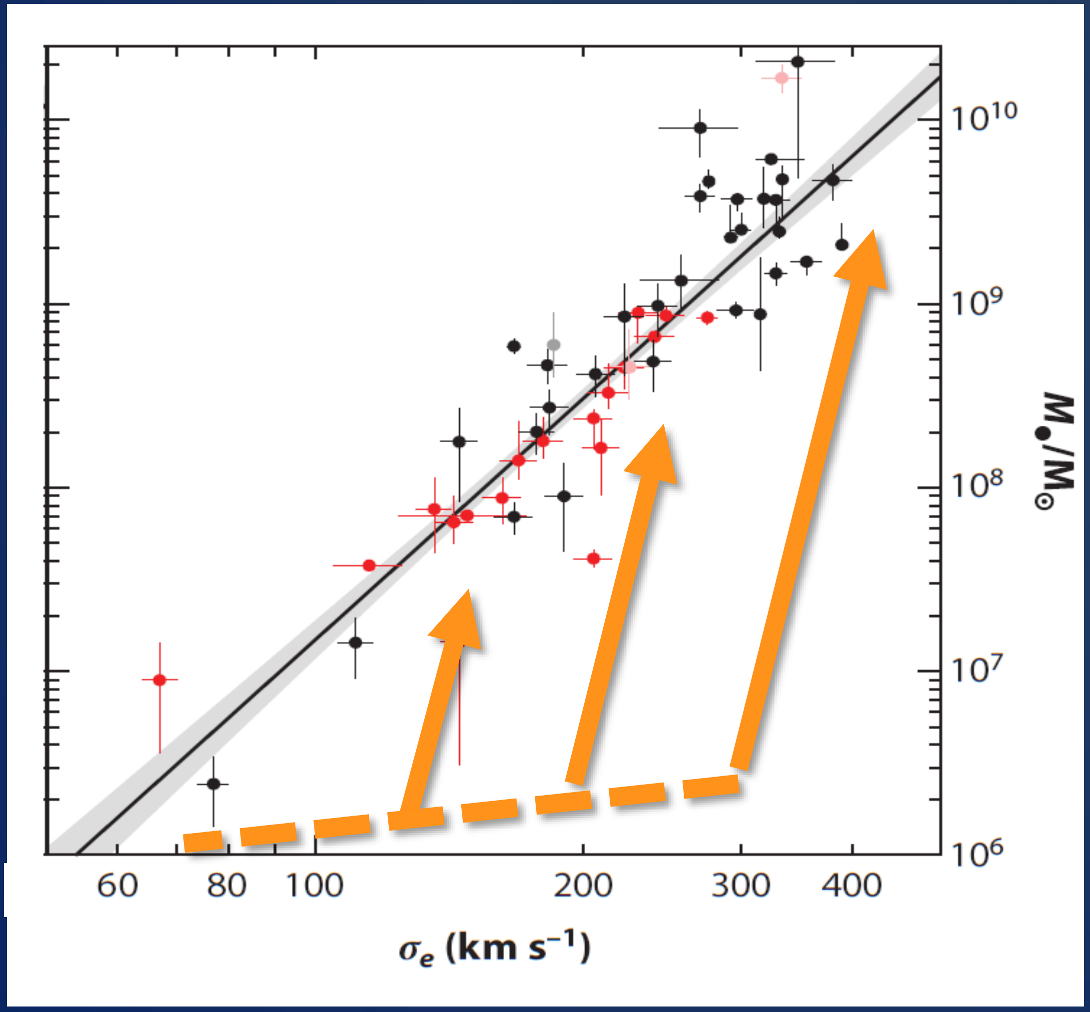
Observed:

$$M_{\rm BH} \approx 2.5 \times 10^{8} \, (\sigma/200)^{5.2}$$

McConnell & Ma (2013)

Evolutionary Scenarios of SMBH-Host Relations

Scenario 2: BH blows host-wide "shell", stopping accretion



King (2003):

$$M_{BH} \approx 2 \times 10^8 \, (\sigma/200)^4$$

(momentum-driven)

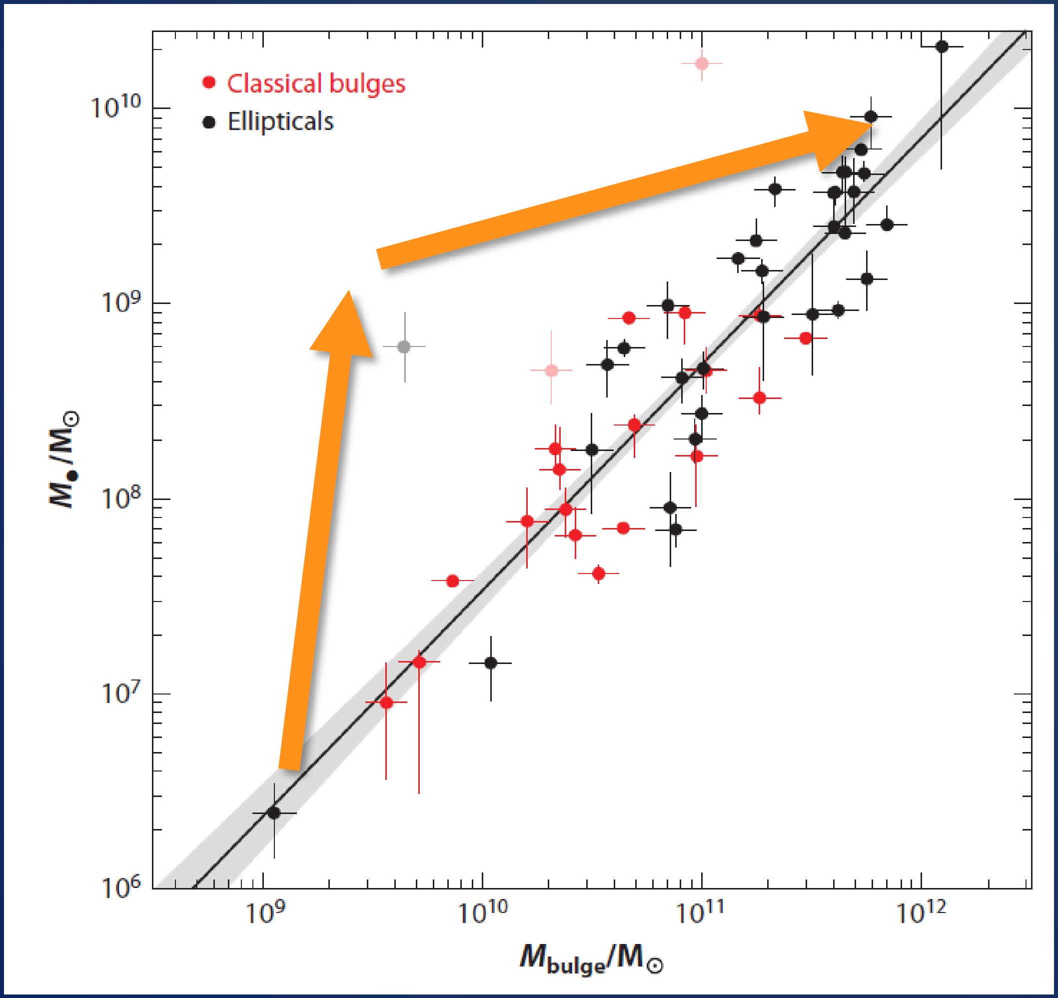
Observed ?

$$M_{BH} \approx 3 \times 10^8 \, (\sigma/200)^4$$

Kormendy & Ho (2013)

Evolutionary Scenarios of SMBH-Host Relations

Scenario 3: BH growth precedes Host growth (mergers?)



Requires:

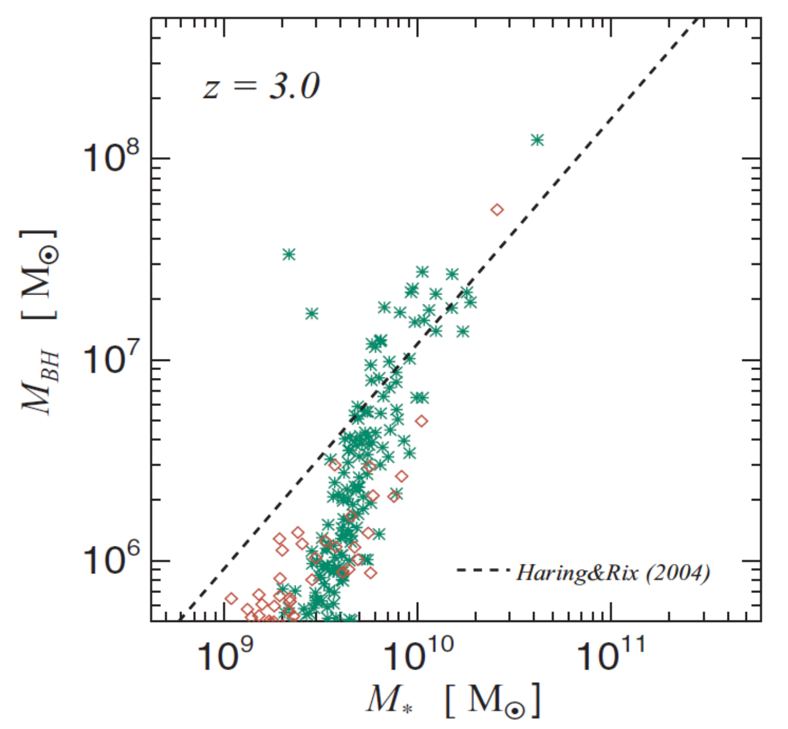
Efficient fueling of nuclear BH *without* SFR

Early epochs, when fragmentation is limited?

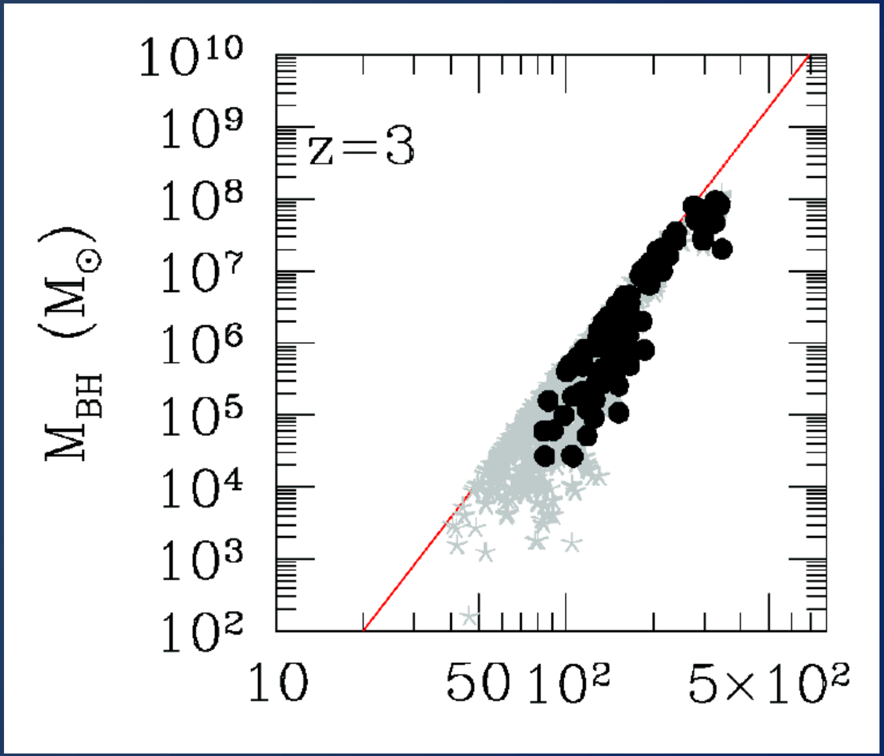
Kormendy & Ho (2013)

Models for the Evolution of SMBH-Host Relations

different models, different evolutionary paths …



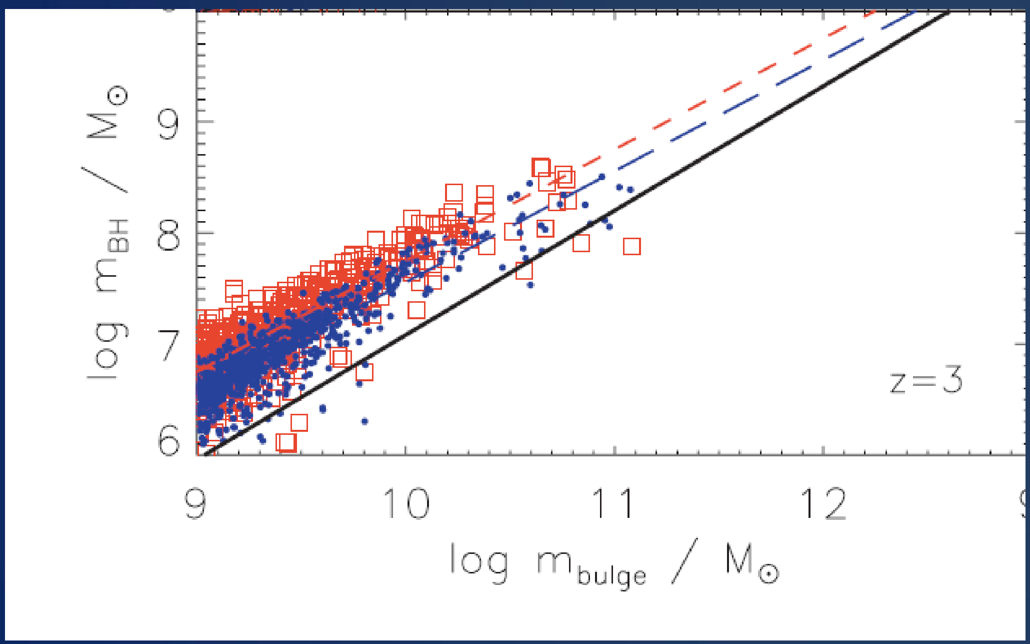
Sijacki et al. (2007)
N-body [SPH], <2^3 Mpc^3



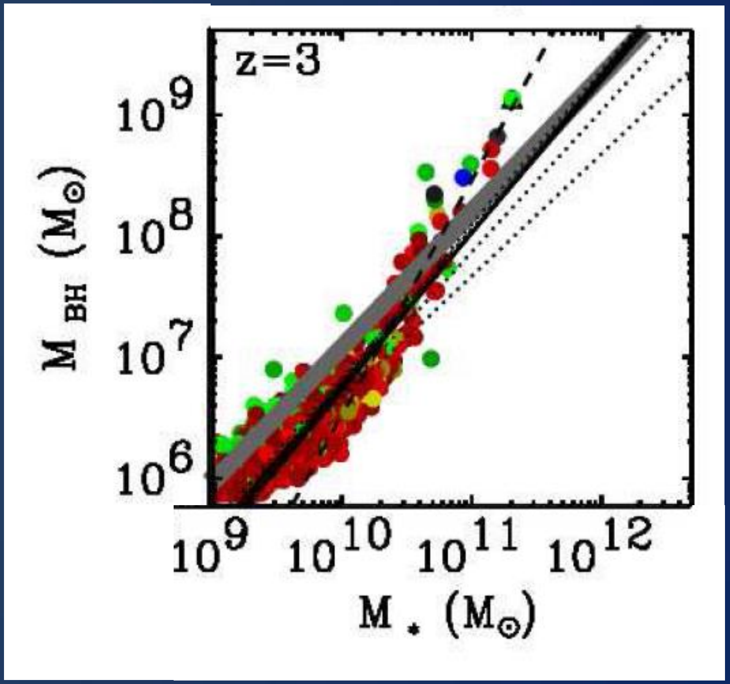
Volonteri & Natarajan (2009)
SAM

Models for the Evolution of SMBH-Host Relations

different models, different evolutionary paths …



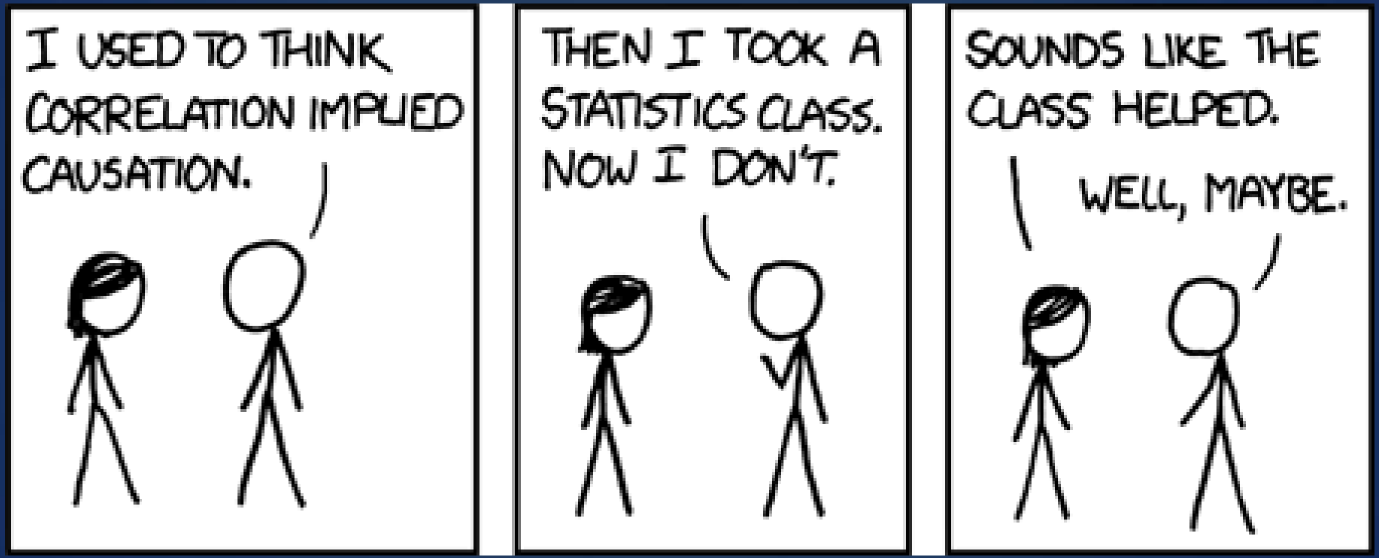
Croton (2006)
SAM (Millennium Run)



Di Matteo et al. (2008)
N-body [SPH], <50^3 Mpc^3

Models for the Evolution of SMBH-Host Relations

Correlation does not imply causation …



Randall Munroe, xkcd.com

Models for the Evolution of SMBH-Host Relations

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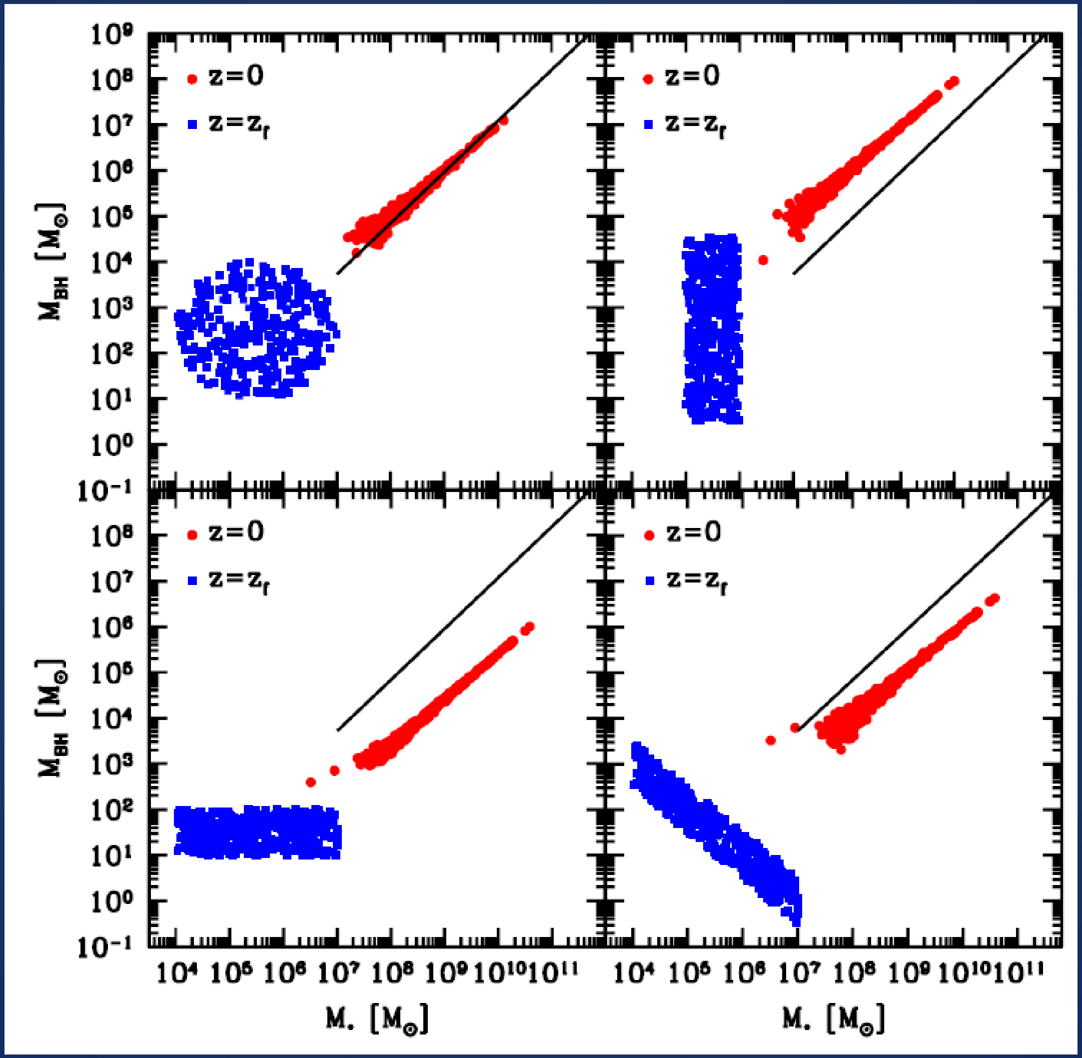


Jahnke & Maccio (2011)

Observational Challenges

The only direct probes of SMBHs at z>0 are AGNs – the actively growing population

unobscured – “Type I”

- UV-optical SED dominated by the AGN accretion disk (power law)
- BH properties can be obtained: M_{BH} , L_{bol} , L/L_{Edd}
- The host is barely resolved, and M_* & SFR are not available and/or challenging

obscured – “Type II”

- UV-optical SED dominated by stellar light
- Host properties can be obtained: M_* , SFR $\longrightarrow$ sSFR, (morphology? σ_* ?)
- Only L_{bol} is observed, but M_{BH} cannot be estimated

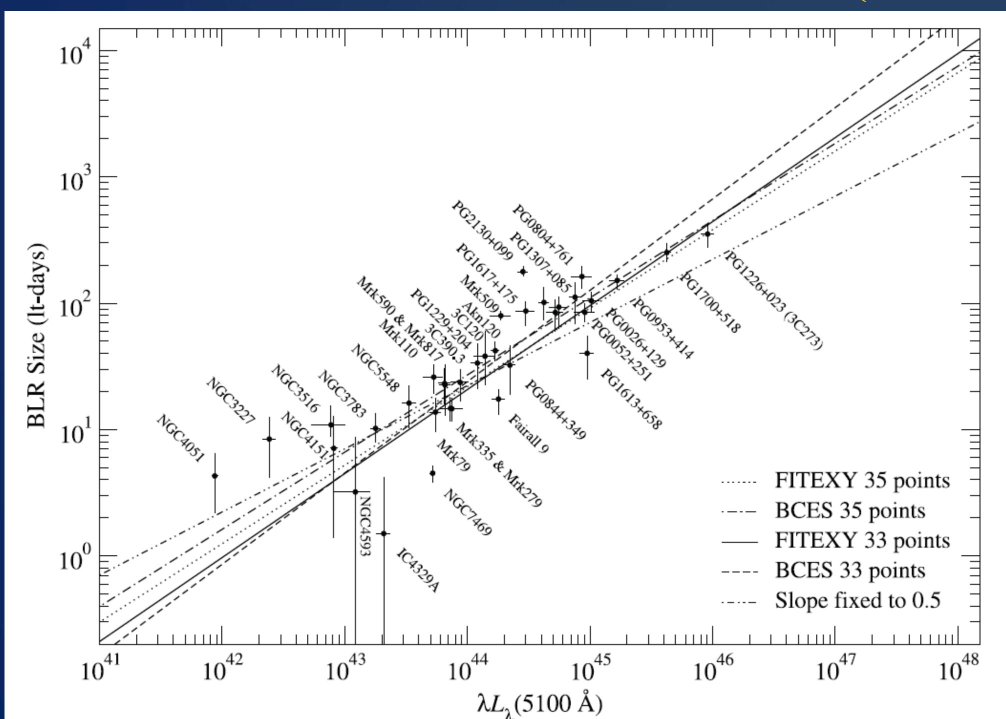
Measuring BH Masses in Unobscured AGNs

$M_{\rm BH}$ can be reliably estimated from broad emission lines

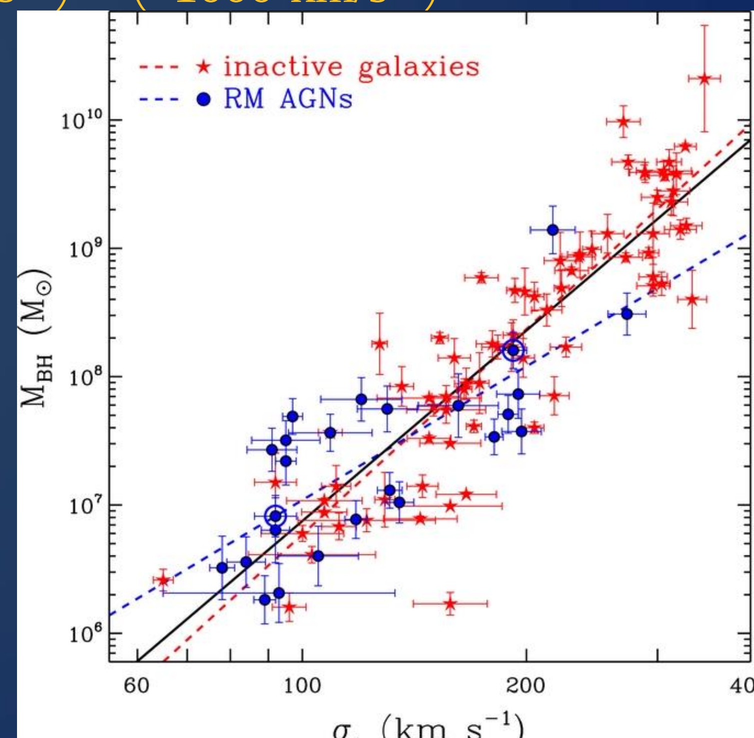
at z>0, we use empirical calibrations, based on reverberation mapping

$$M_{\rm BH} = f\, G^{-1} \quad R_{\rm BLR} \quad V_{\rm BLR}^{\;2}$$

$$M_{\rm BH} = 1.05 \times 10^{8} \left(\frac{\lambda L_{\lambda}[5100\text{Å}]}{10^{46}\ \text{km/s}} \right)^{0.65} \left(\frac{\text{FWHM[H}\beta\text{]}}{1000\ \text{km/s}} \right)^{2} M_{\odot}$$



Kaspi et al. (2005)



Woo et al. (2013)

Indirect arguments for rising $M_{\mathrm{BH}}/M_{\mathrm{Host}}$

High-mass BHs at z~2 → extremely high-mass hosts?

○ z~6.2
Willott+10, Kurk+07

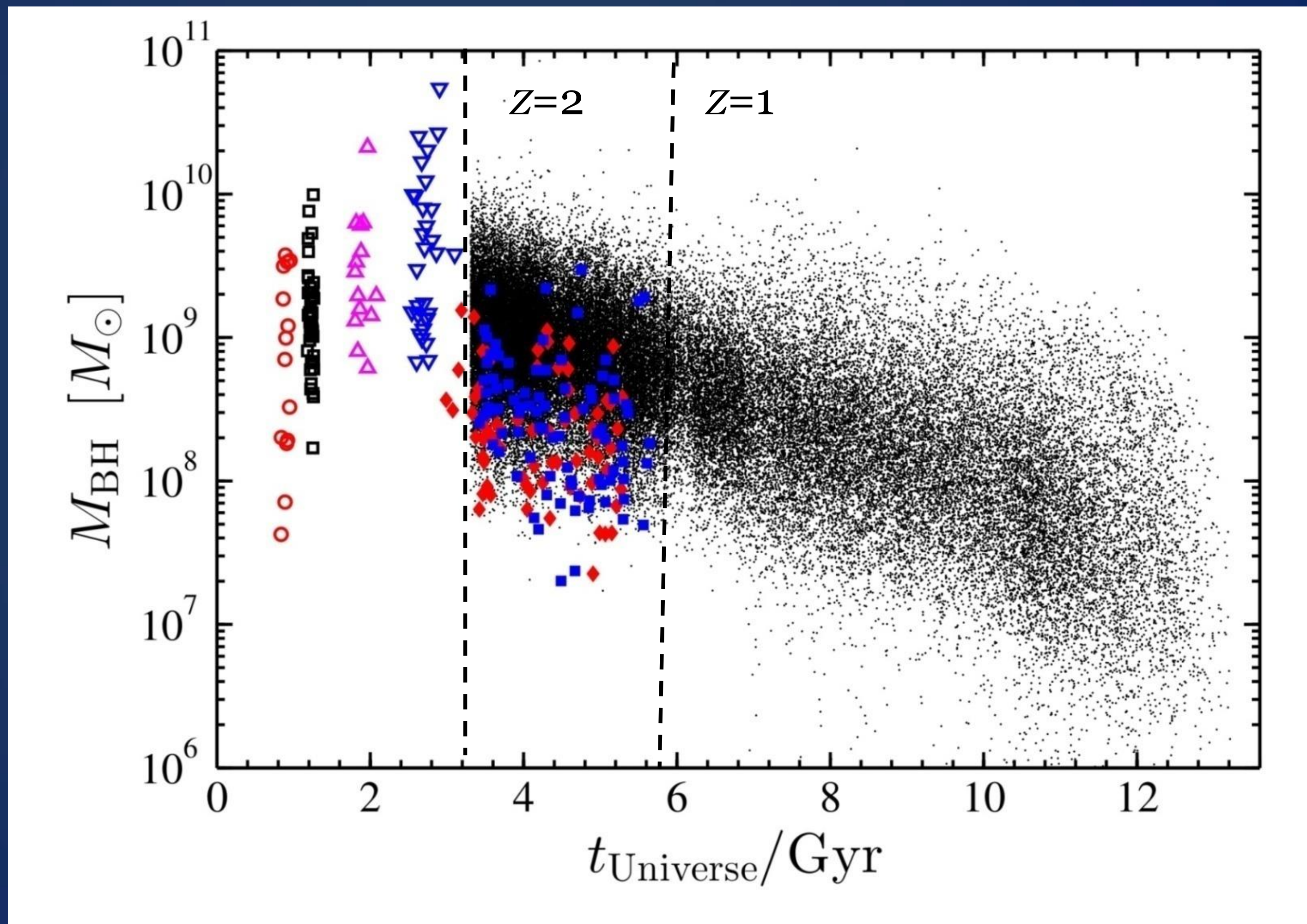
□ z~4.8
Trakhtenbrot+2011

△ z~3.3
Netzer+07,Shemmer+04

▽ z~2.4
[Netzer+07,Shemmer+04]

• z<2
SDSS; Trakhtenbrot & Netzer (2012)

• • faint surveys
zCOSMOS, VVDS
Schulze et al. (2014)



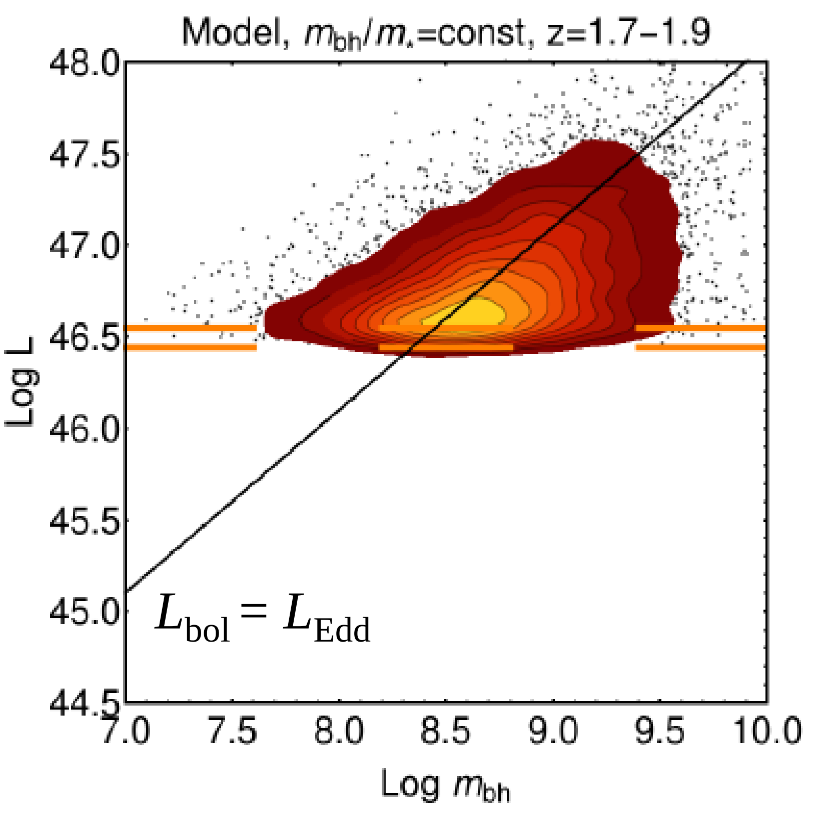
Trakhtenbrot & Netzer (2012)

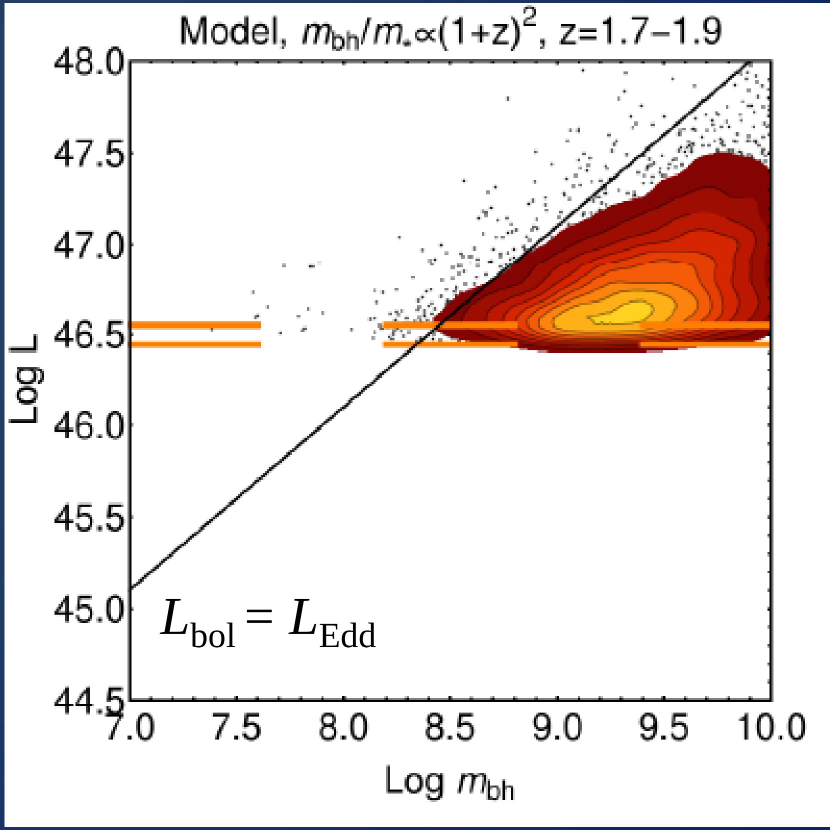
Indirect arguments for rising $M_{\mathrm{BH}}/M_{\mathrm{Host}}$

$$L_{\mathrm{bol}} \propto M_* \times (M_{\mathrm{BH}}/M_*) \times L/L_{\mathrm{Edd}}$$

Quasar LF = Galaxy MF ⊗ mass ratio ⊗ Edd.-Ratio-distribution

→ super-Eddington quasars, unless $M_{\mathrm{BH}} / M_* \sim (1+z)^2$





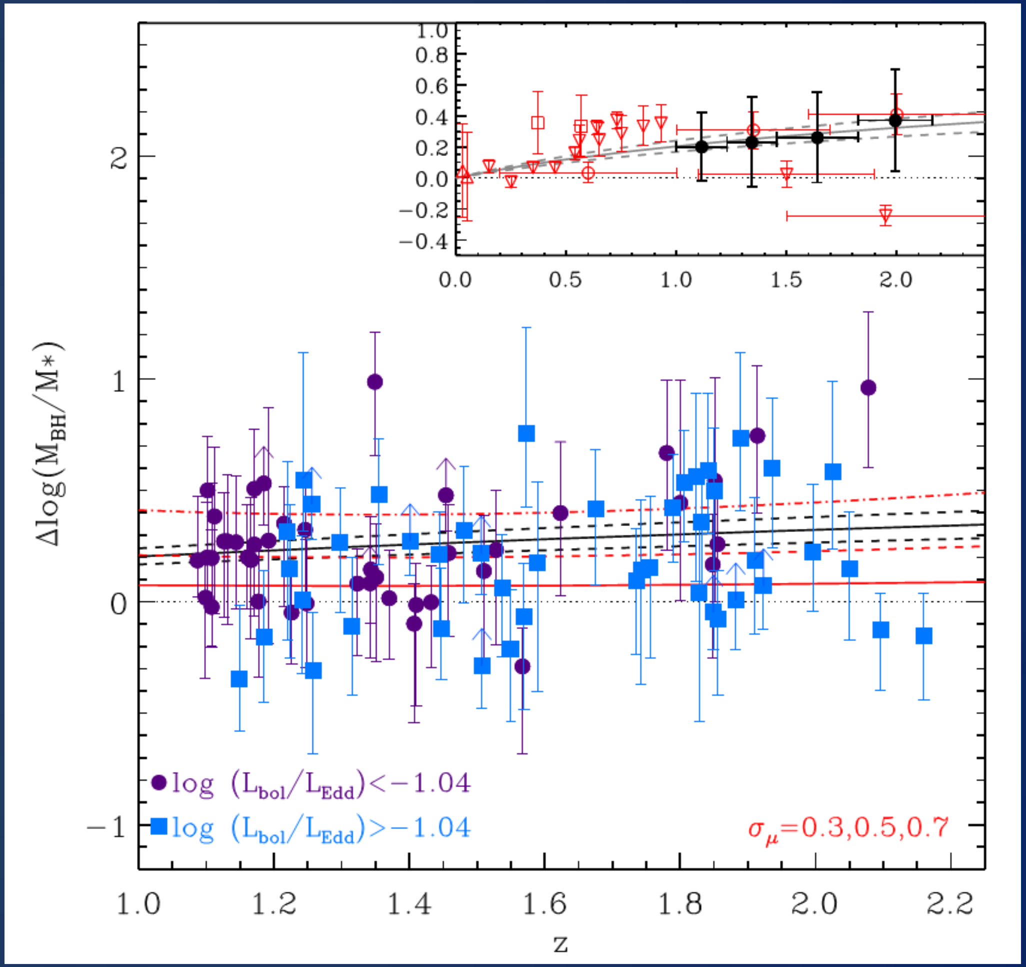
Caplar, Lilly & Trakhtenbrot (2015)

Direct evidence for rising M_{BH}/M_{Host}

- Most studies suggest that M_{BH}/M_* rises:

  $M_{BH}/M_* \sim (1+z)^{1-1.4}$

- Hosts should *over*-grow their SMBHs by factors of ~2-3 (or more?), since z~2 ?



Merloni et al. (2010)

Direct evidence for rising M_{BH}/M_{Host}

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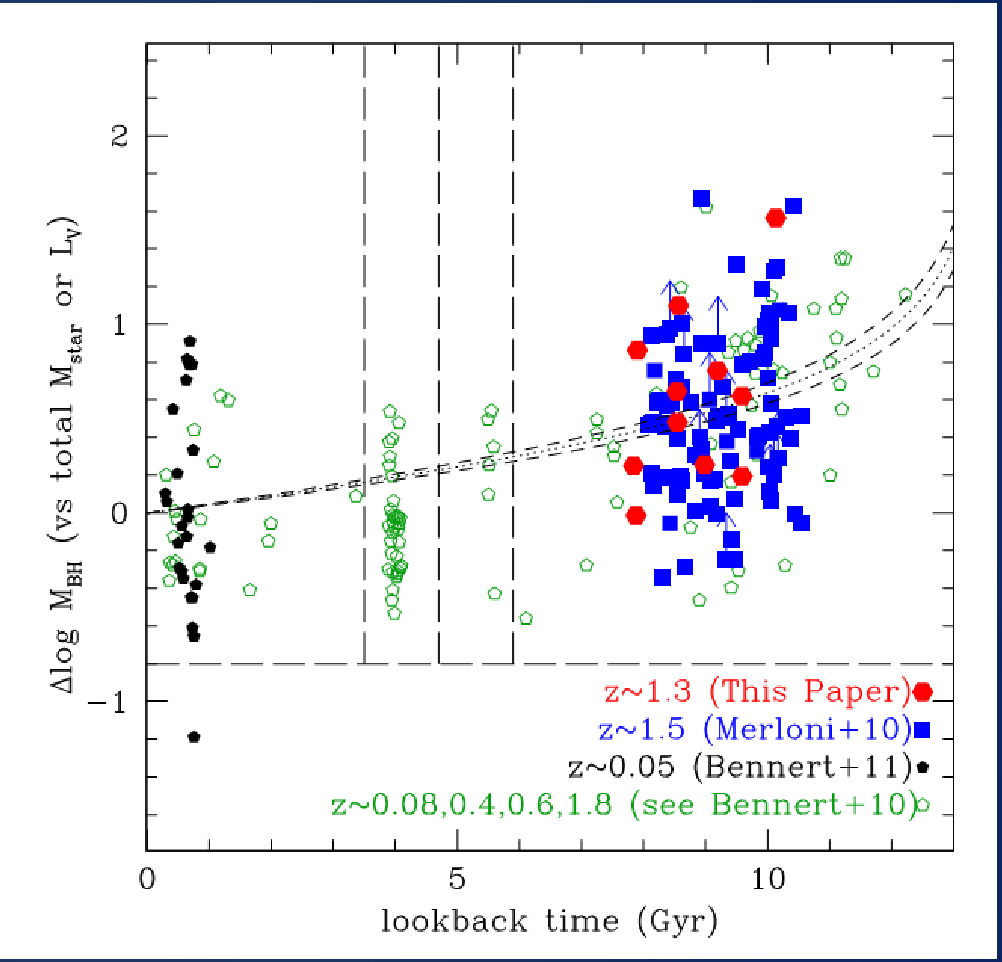

Bennert et al. (2011)

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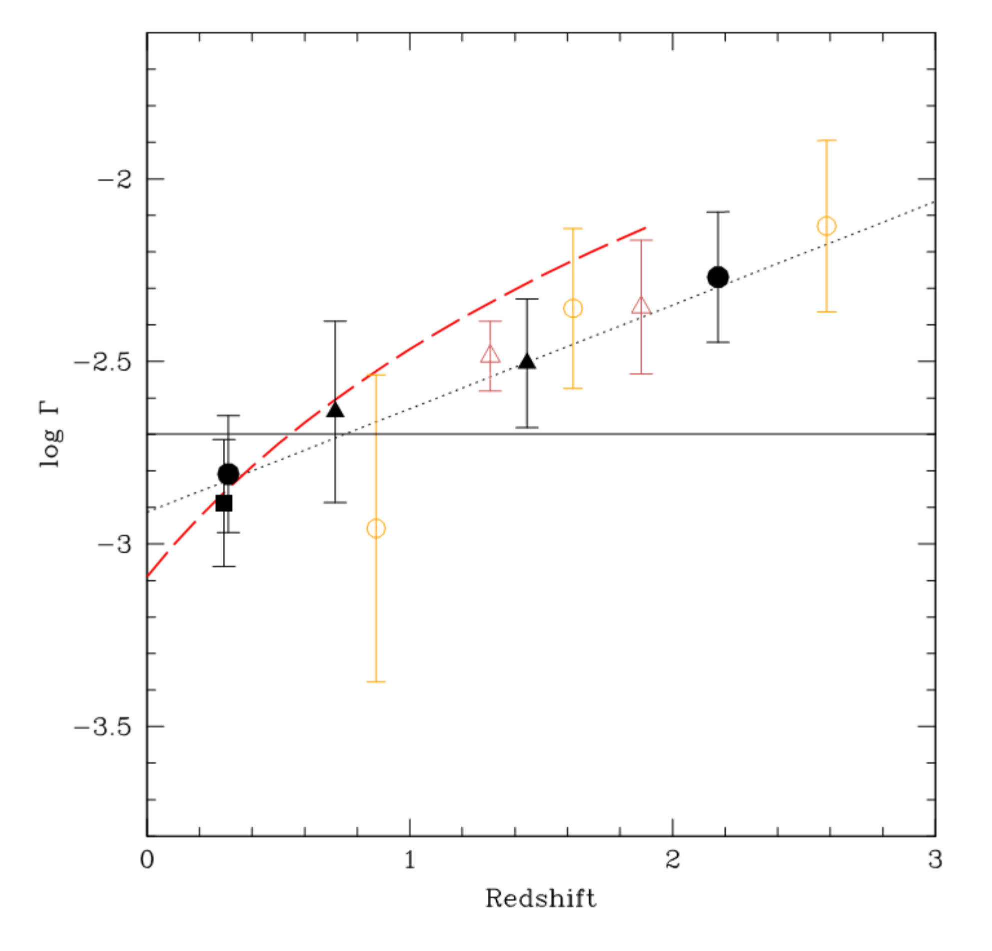

Decarli et al. (2010)

Direct evidence for rising M_{BH}/M_{Host}

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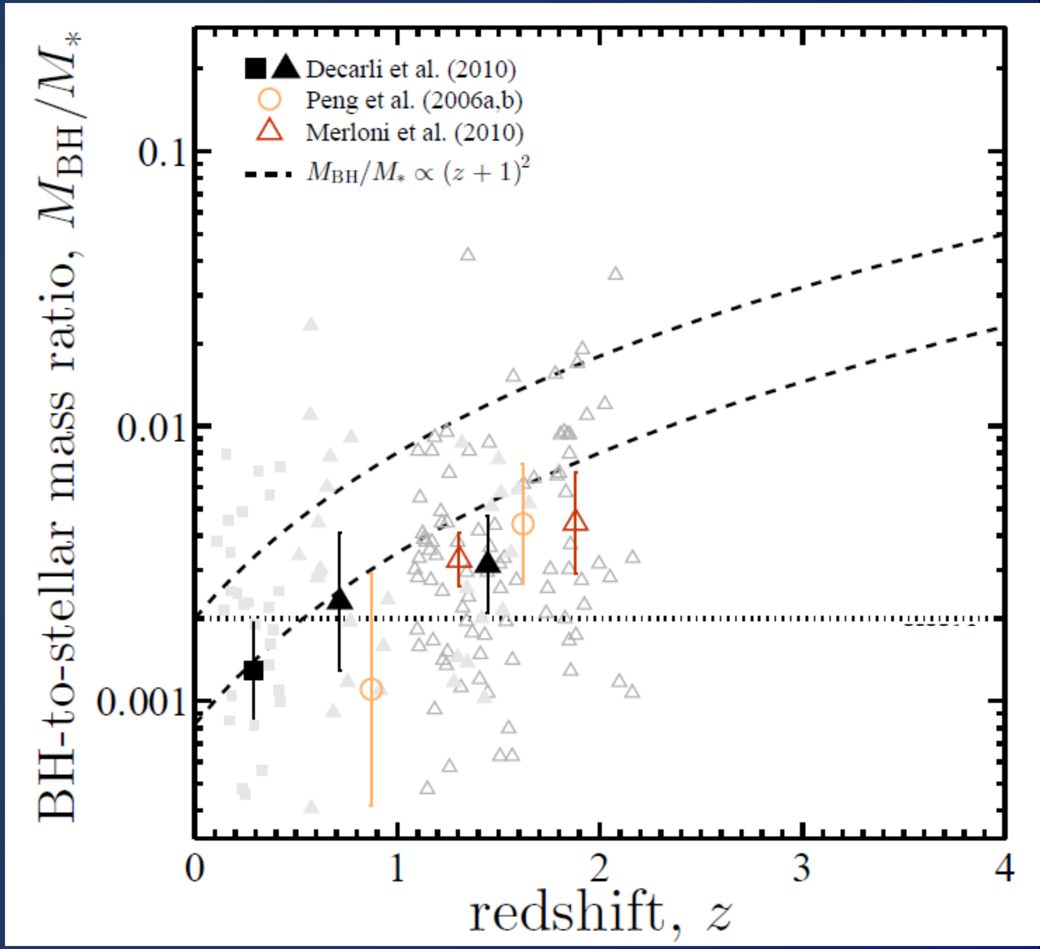
  [comparison at const. M_{BH}? see BT & Netzer (2010)]



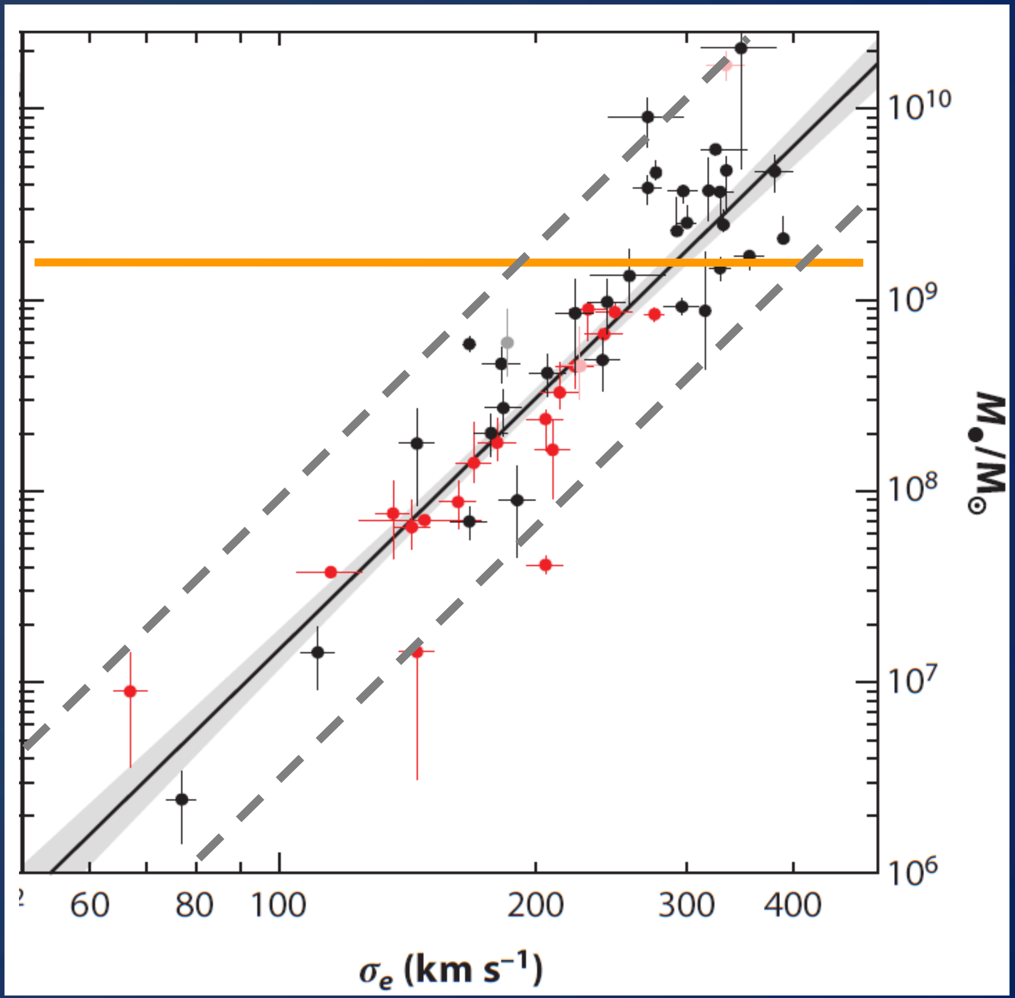
What happens beyond z~2?

Observational Challenges

Selection effects for luminous AGNs at z>0

- M_{BH} depends on luminosity
  physics: $L_{bol} \propto M_{BH} \times L/L_{Edd}$
  surveys: flux limit
  measurement: $M_{BH} \propto L^{0.65}$

- High masses/luminosities
  low number densities
  intrinsic scatter matters
  outliers dominate?



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  low number densities
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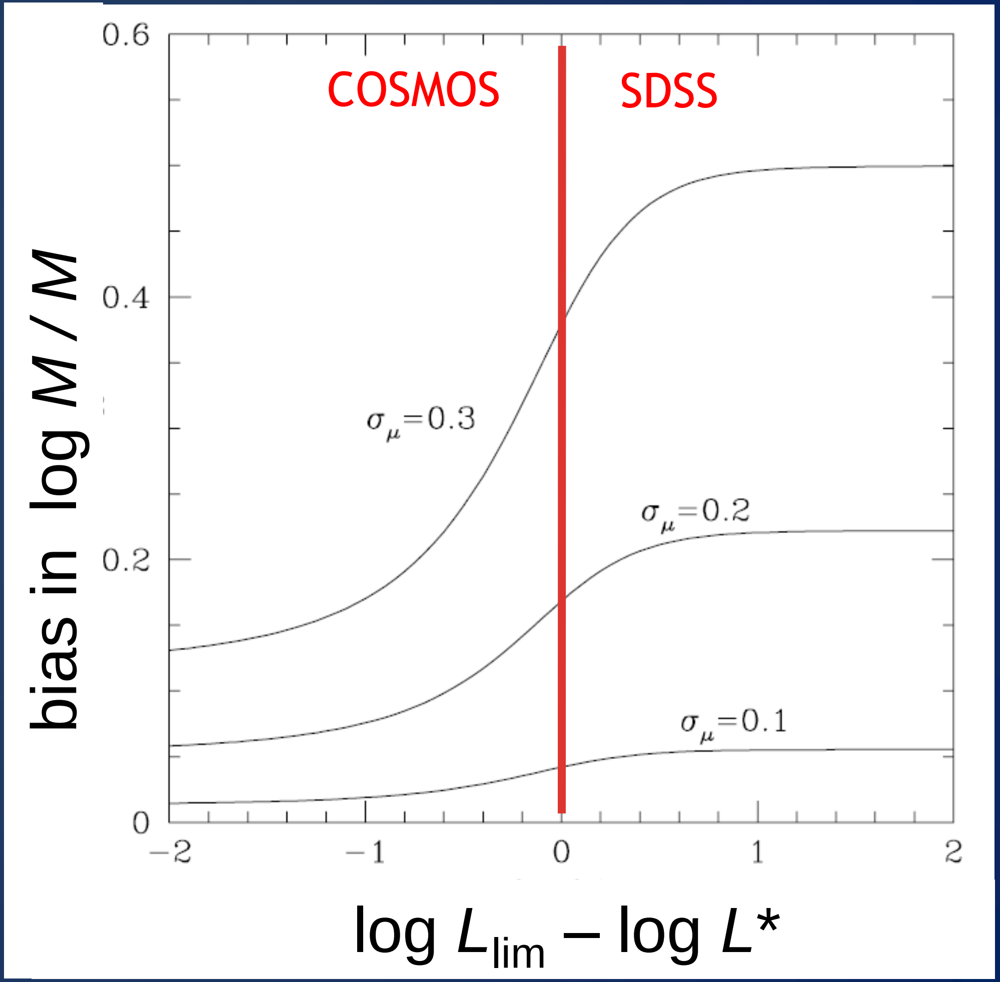
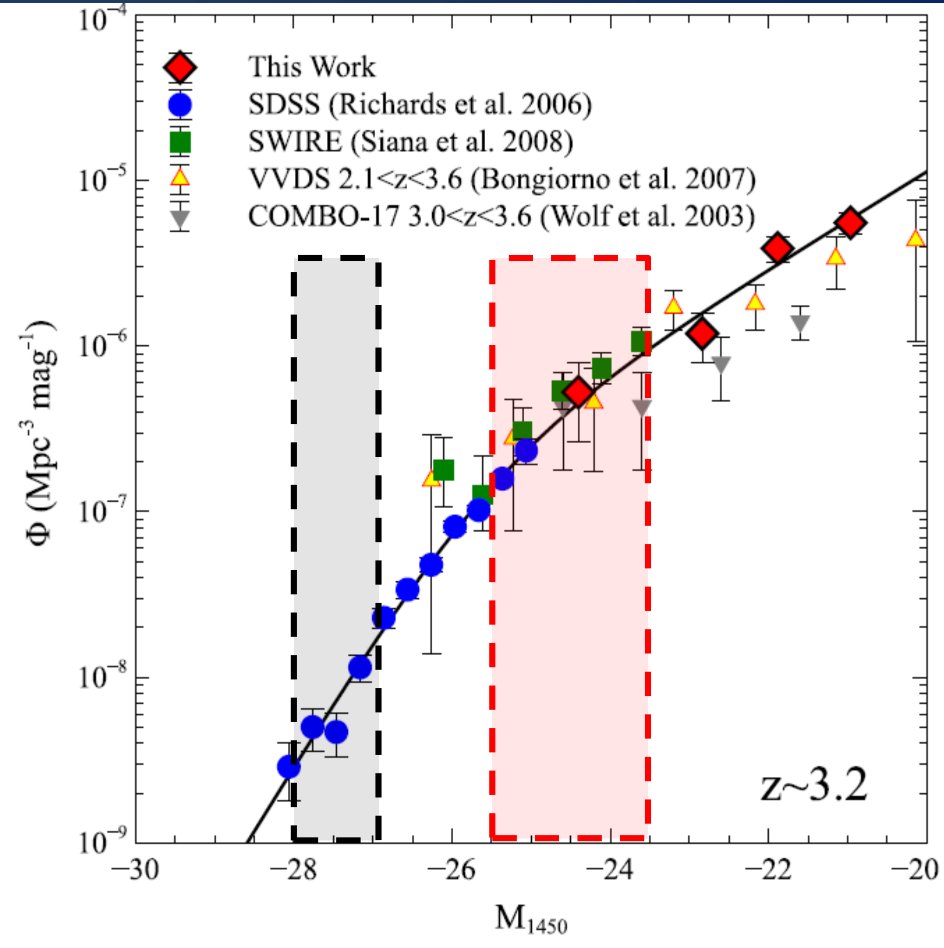
➔ Target the faintest AGN samples!



Lauer et al. (2007)

COSMOS-MOSFIRE Campaign: Probing "typical" AGNs at $z > 2$

- Faint, X-ray selected AGNs in the COSMOS field
  (Elvis et al. 2009, Civano et al. 2015, Marchesi et al. 2015)
- Number density is higher by ×25 compared to SDSS AGNs
- Lower AGN luminosity allows to study hosts



Masters et al. (2012)

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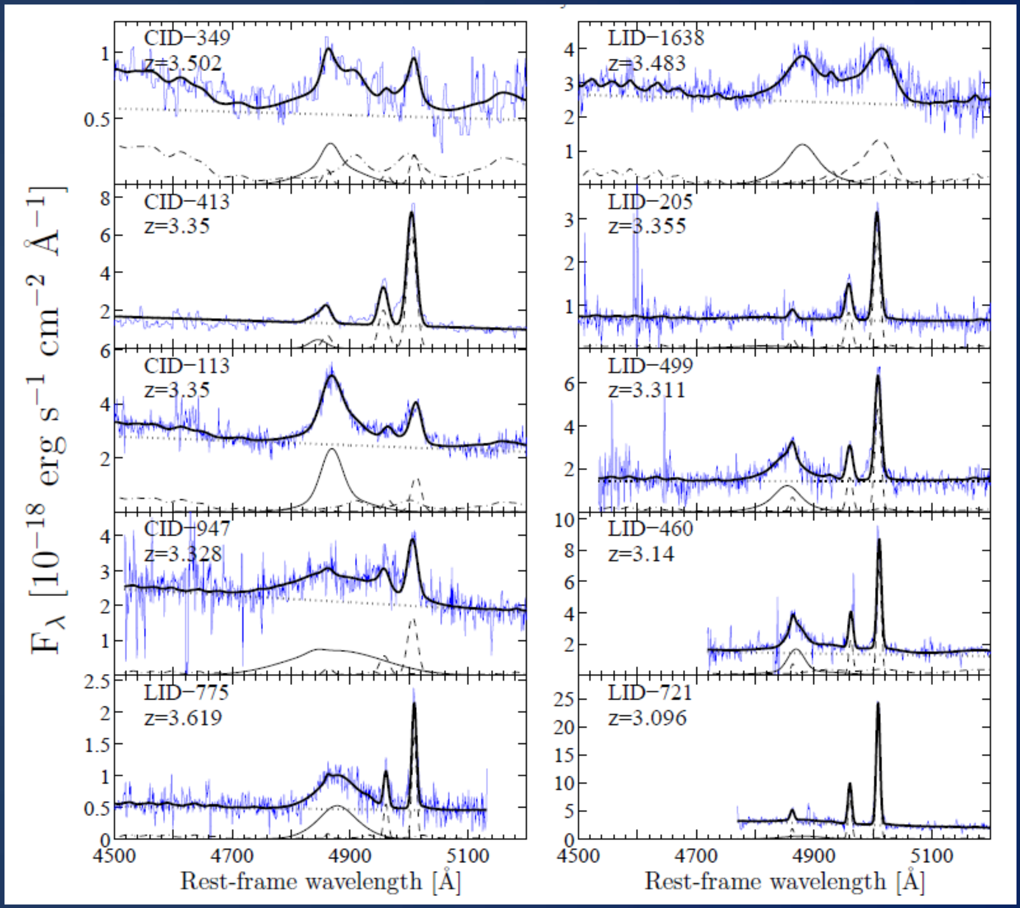
- *K*-band spectroscopy with Keck/MOSFIRE (6 nights)
- Host information is available from COSMOS



Trakhtenbrot et al. (sub.)

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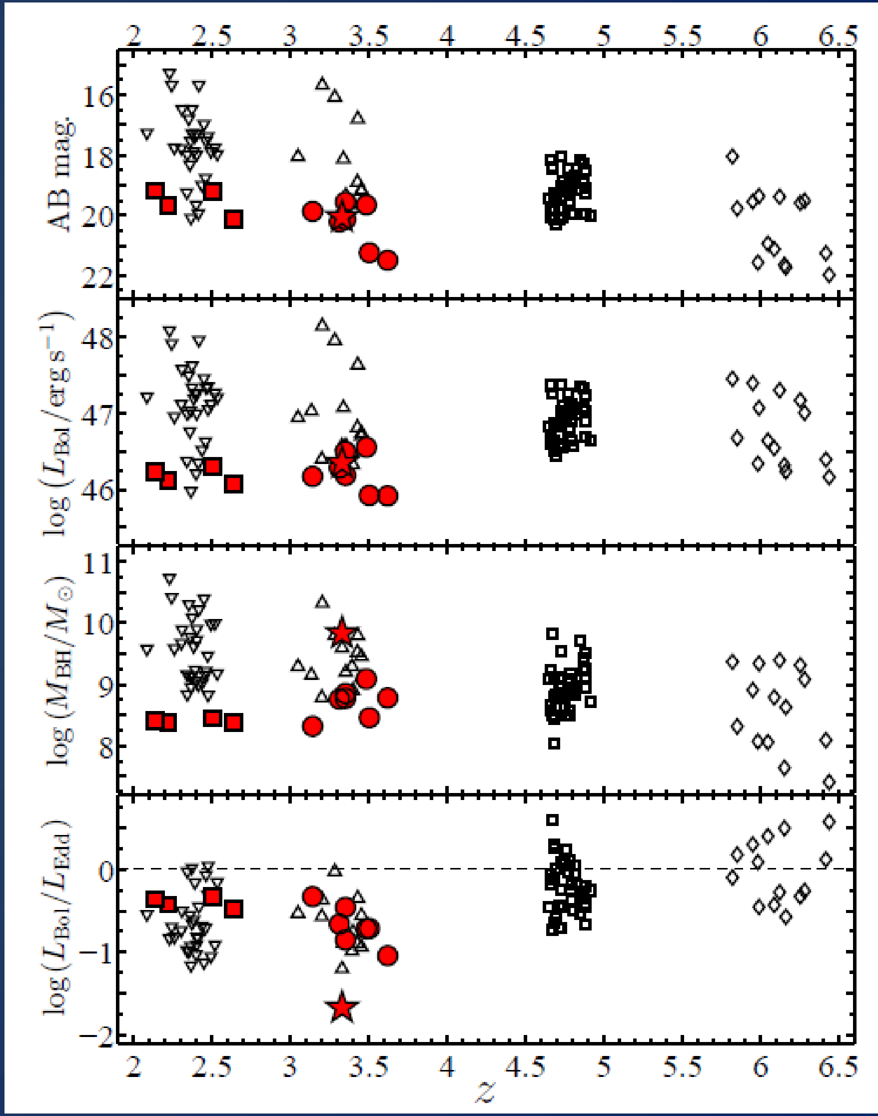


Trakhtenbrot et al. (sub.)

CID-947: an Over-Massive BH at $z \sim 3.3$

- Broad Hβ, FWHM~13000 km/s → high mass:

$$M_{BH} \approx 7 \times 10^{9} M_{\odot}$$

comparable to M87 (Gebhardt+11)

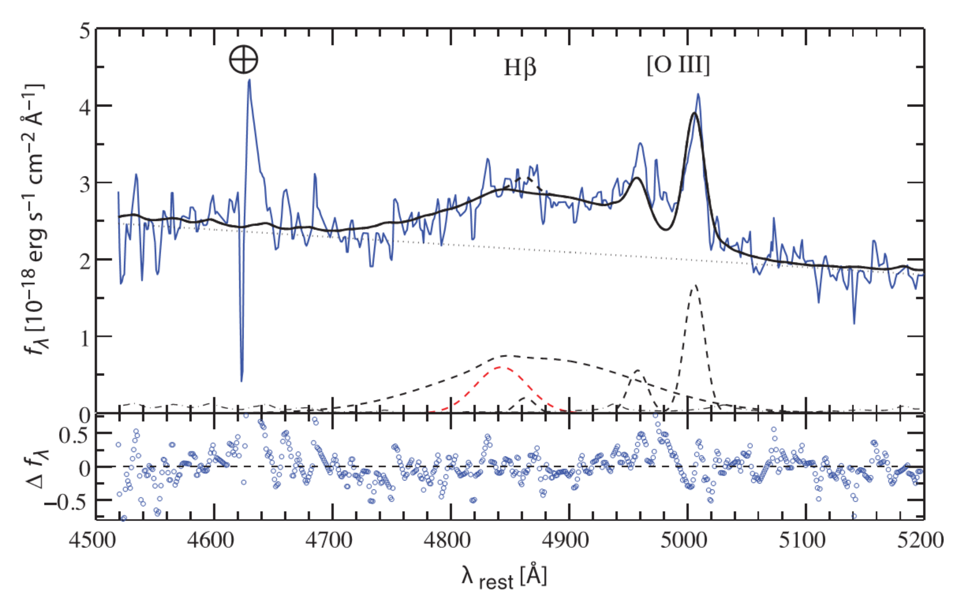
- Low Eddington ratio

$$L/L_{Edd} \approx 0.02$$

lower by x10 than other high-mass AGNs at z~3-4 (Shemmer+04, Netzer+07, Marziani+09)

- Had to accrete faster in the past to explain high mass

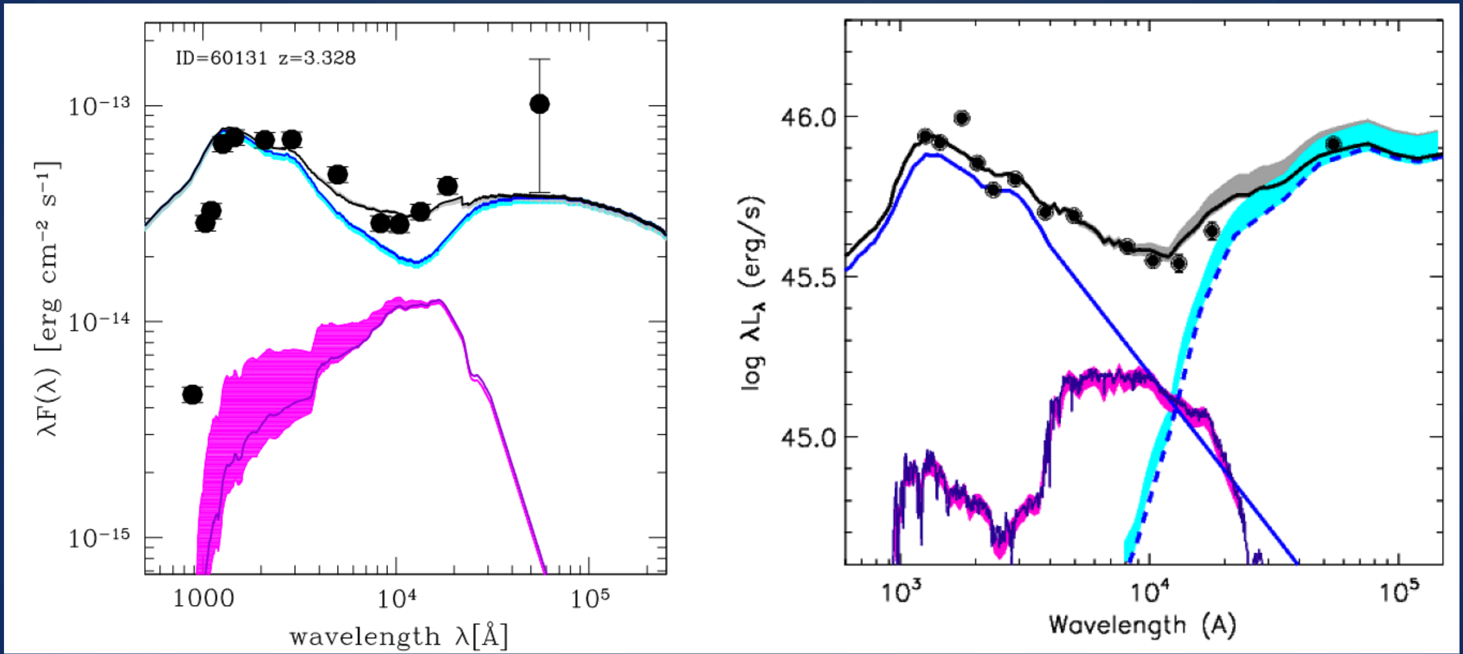
BT et al. (2015, *Science*, 349, 168)



➔ Final stages of SMBH growth

CID-947: an Over-Massive BH at $z \sim 3.3$

- Host SED - UV-to-IR:
  - “Archival” (Bongiorno+12), and “New” (UltraVISTA) SEDs
  - decomposition into AGN (+torus) and stellar components

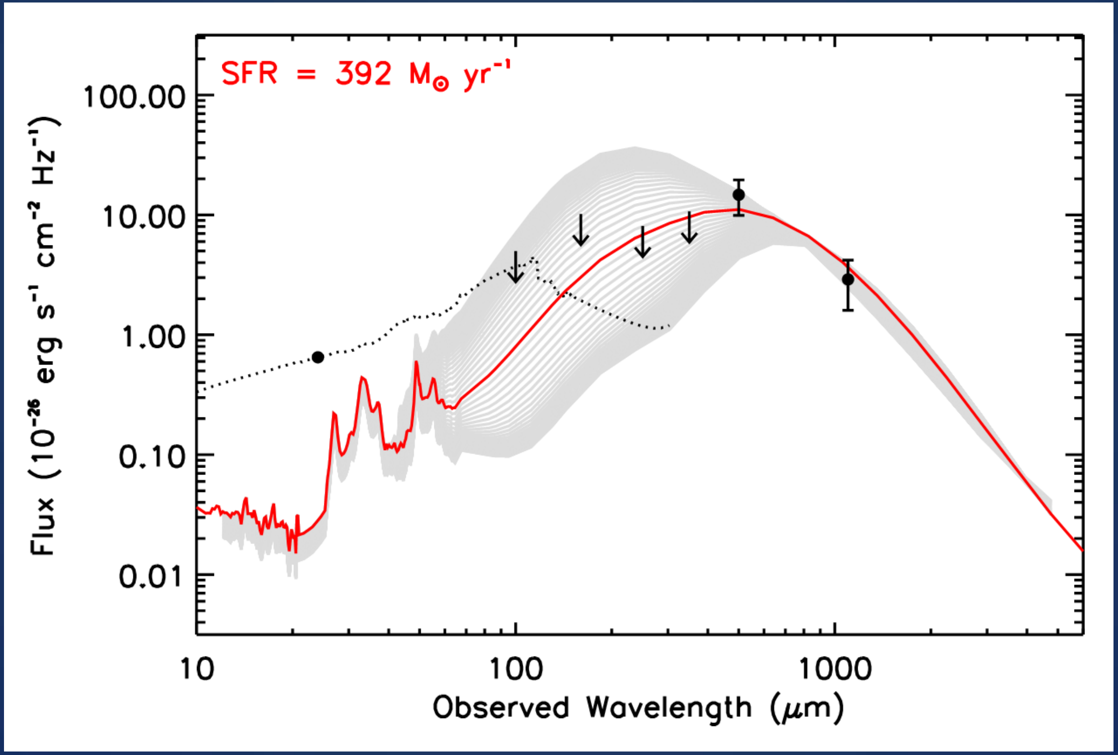


- Stellar mass: $M_* = 5.7 \times 10^{10} M_\odot$
  - Consistent with “typical” galaxy masses, M^* (e.g., Ilbert+13)

Trakhtenbrot et al. (2015)

CID-947: a typical SF host galaxy at $z \sim 3.3$

- Host SED - FIR-to-mm:
  - Detections at 500 μm (Herschel/PEP) and 1mm (AzTEC)
  - AGN contribution to (rest-)FIR is small



- SFR ~ 400 $M_\odot$ / yr - consistent with "Main Sequence"
  (Lee+11, Bouwens+12, Whitaker+12…)

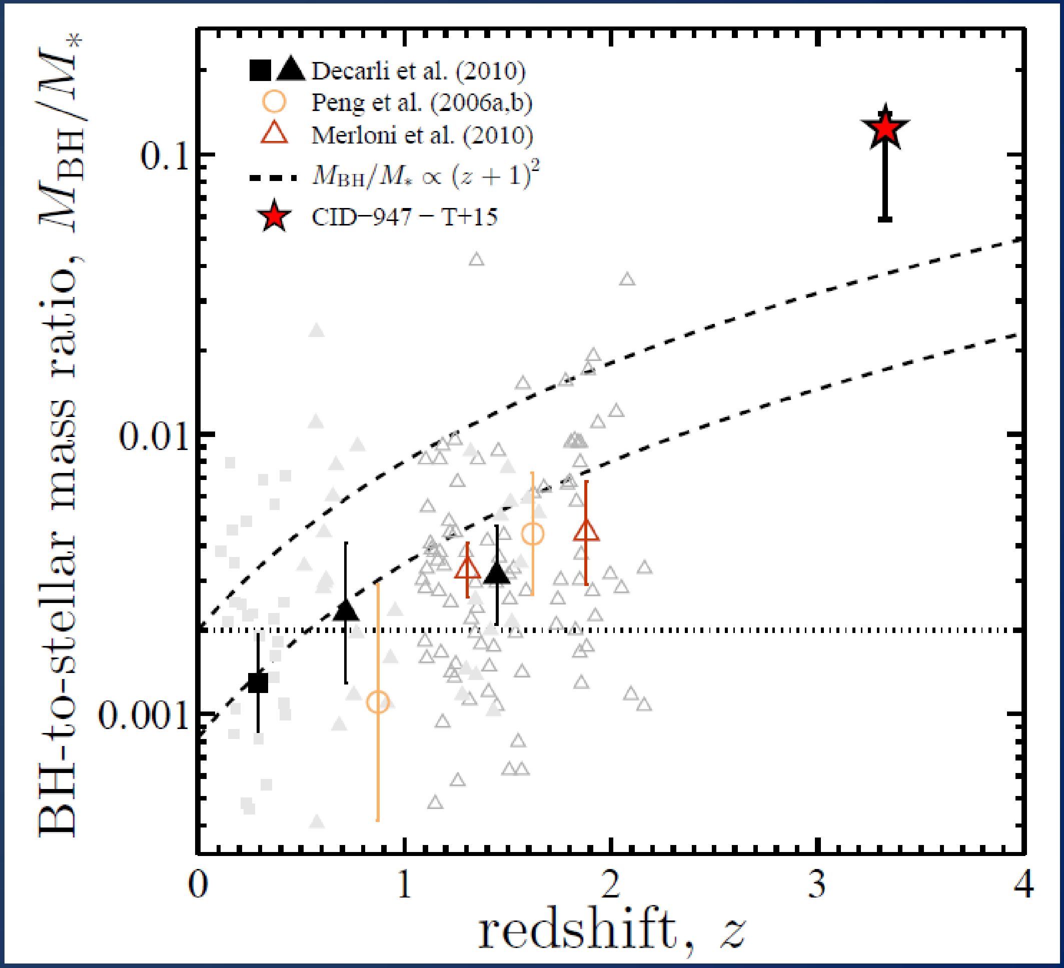
Trakhtenbrot et al. (2015)

CID-947: an Over-Massive BH at $z \sim 3.3$

- Extremely high BH-to-host mass ratio:

  $M_{BH} / M_* \sim 0.1$

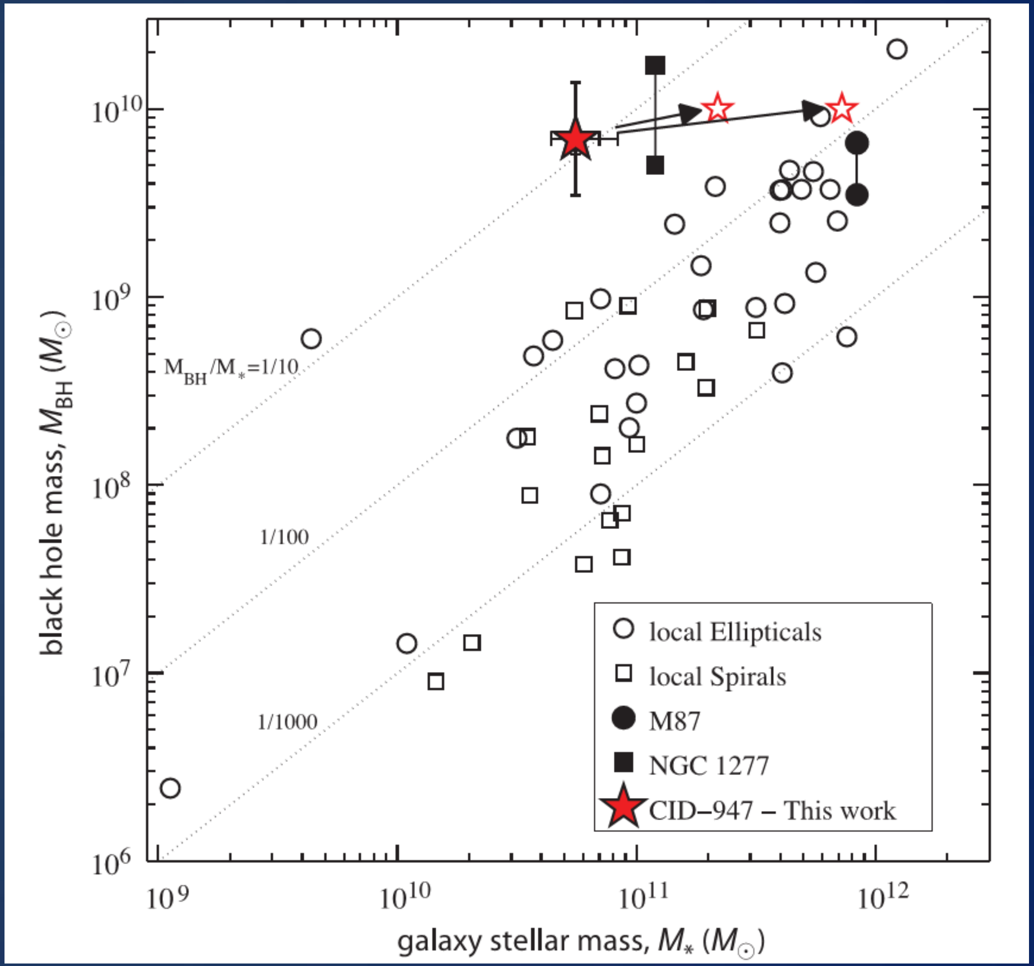
- Compared with $M_{BH} / M_* \sim 0.002\text{-}0.005$ (Kormendy & Ho 2013)



Trakhtenbrot et al. (2015)

CID-947: subsequent evolution of BH & host

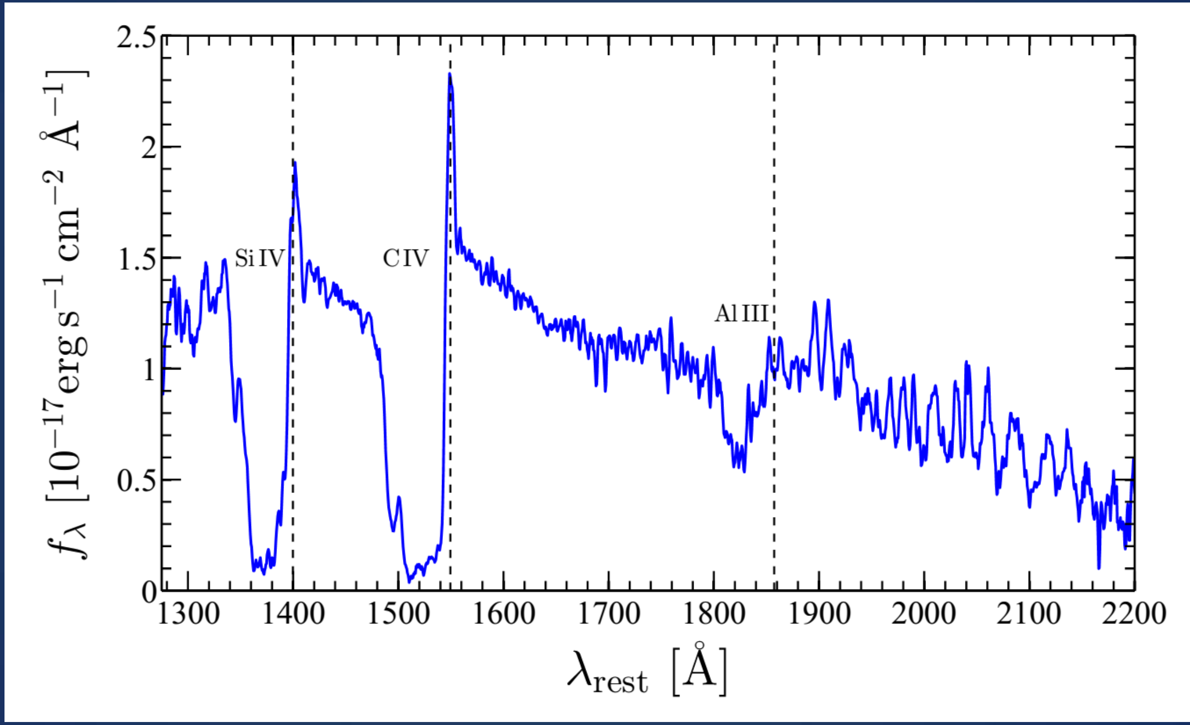
- SMBH is in final stages of growth
  $\rightarrow M_{BH} \sim 10^{10}\, M_{\odot}$
- Host still forming stars
  $\rightarrow M_{*} \sim 2\times 10^{11}\text{-}10^{12}\, M_{\odot}$
- Mass ratio will remain extreme
  $\rightarrow M_{BH} / M_{*} > 0.01$
- Progenitor of systems like NGC 1277? (M/M~1/7)



Trakhtenbrot et al. (2015)

CID-947: AGN-driven outflow, feedback?

- Broad Absorption lines (BAL QSO) – in SiIV, CIV, …
  $\longrightarrow$ AGN-driven outflow, with v_{max}~ 12,000 km/s

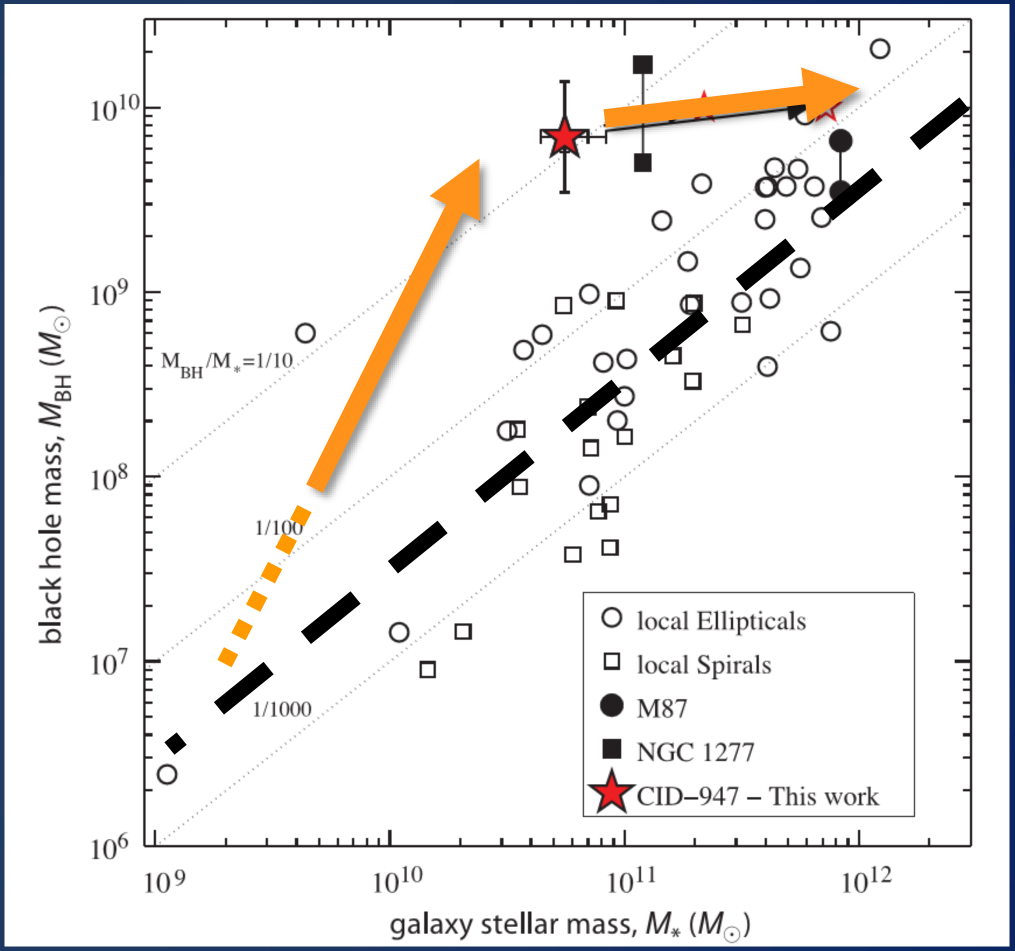


- Observed in ~20% of quasars, R~0.1-1 kpc, dM/dt~100 $M_\odot$ / yr
- Under reasonable assumptions, *this* outflow requires $L/L_{Edd} > 0.2$
- Follow-up campaign to constrain location etc.

Trakhtenbrot et al. (2015)

CID-947: an Over-Massive BH at $z \sim 3.3$

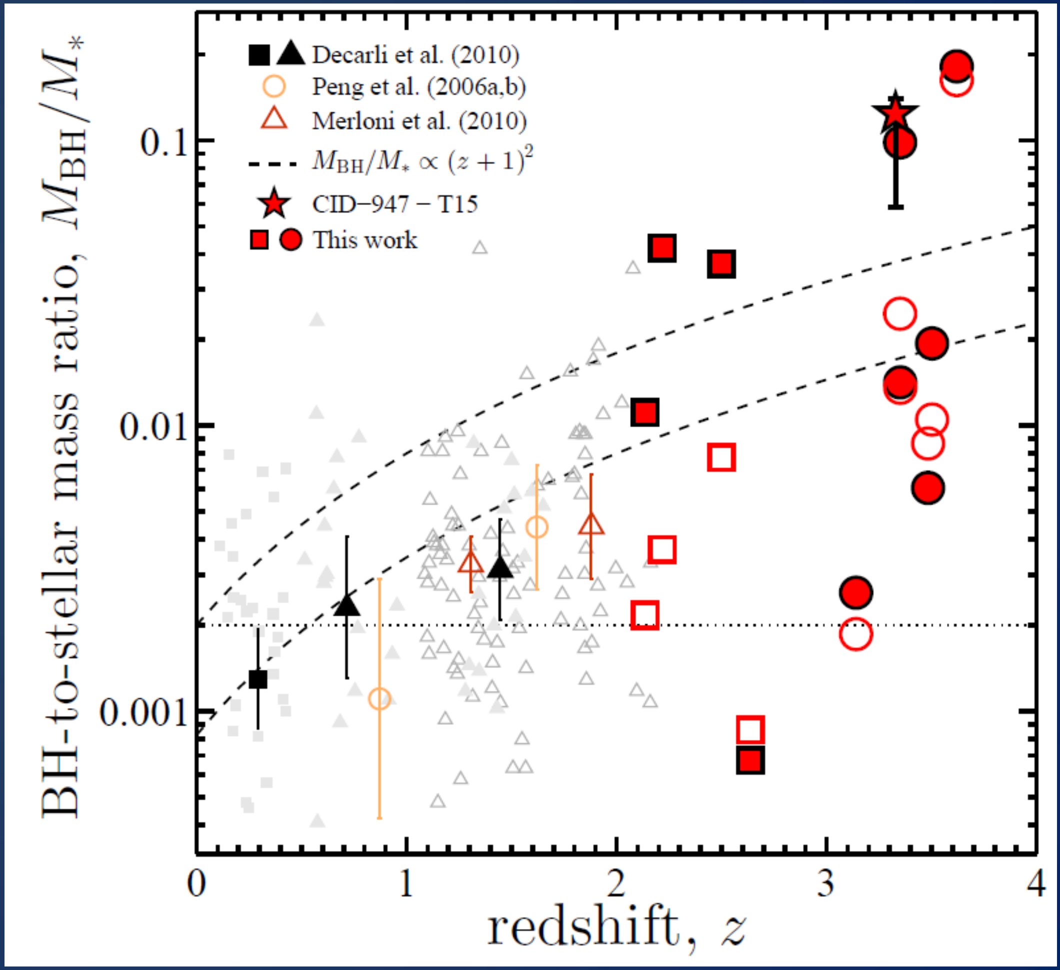
- SMBH in final growth phase
- Grew much faster in the past, launched an outflow
- The host is a typical SF Galaxy, still growing, but will never exceed $M_{BH}/M_* \sim 0.01$
- The AGN-driven outflow has *not* stopped the SF (and probably never will…)



➔ Two-phase growth? No "co-evolution"?

COSMOS-MOSFIRE campaign:
Preliminary Results for "typical" AGNs at $z > 2$

- 11 AGNs with safe $M_{\rm BH}$ and M_* estimates
- More sources with high $M_{\rm BH} / M_*$, some > 0.01 but large scatter
- Higher-than-local mass ratios across host mass range



Trakhtenbrot et al. (in prep.)

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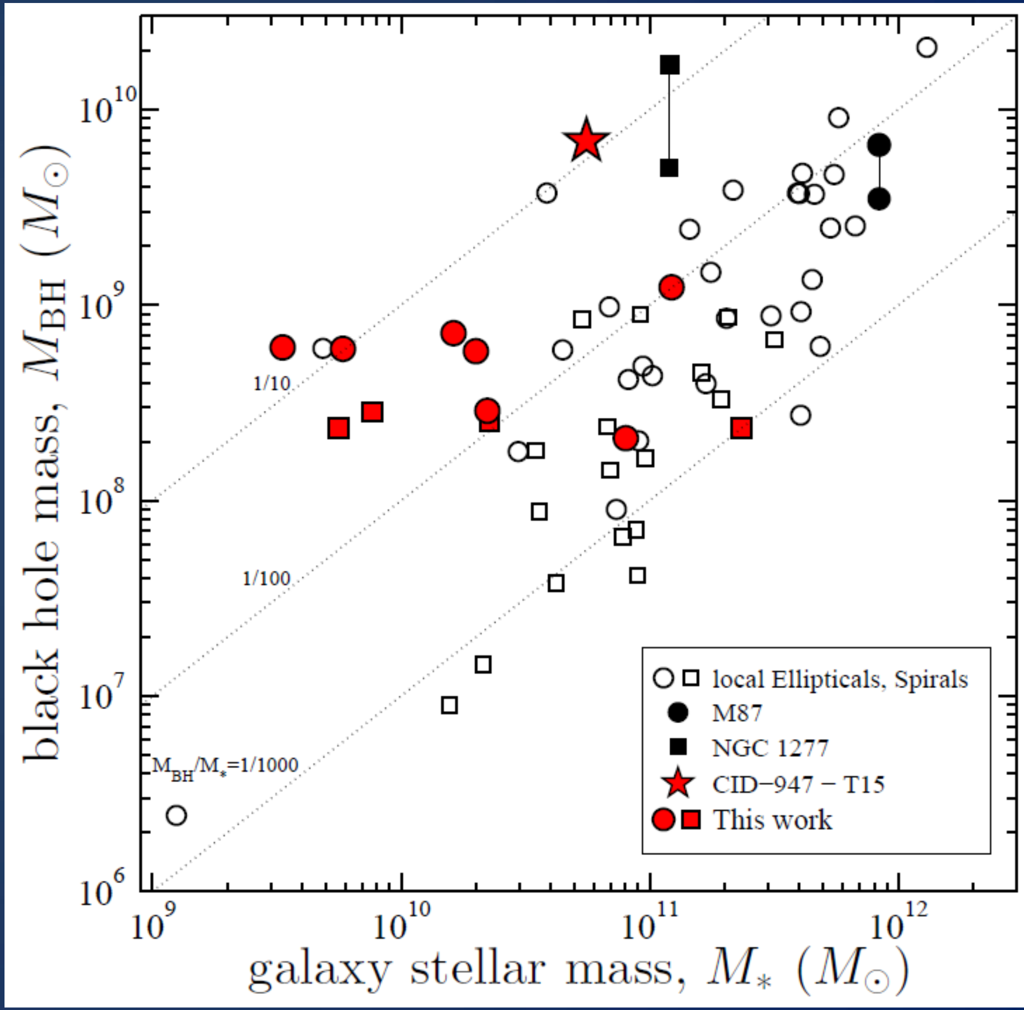

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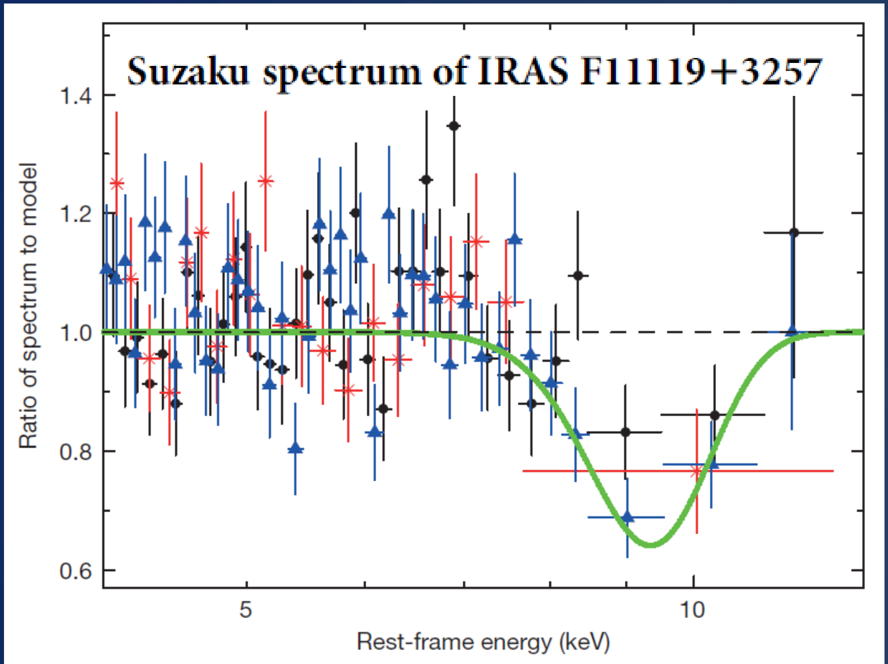
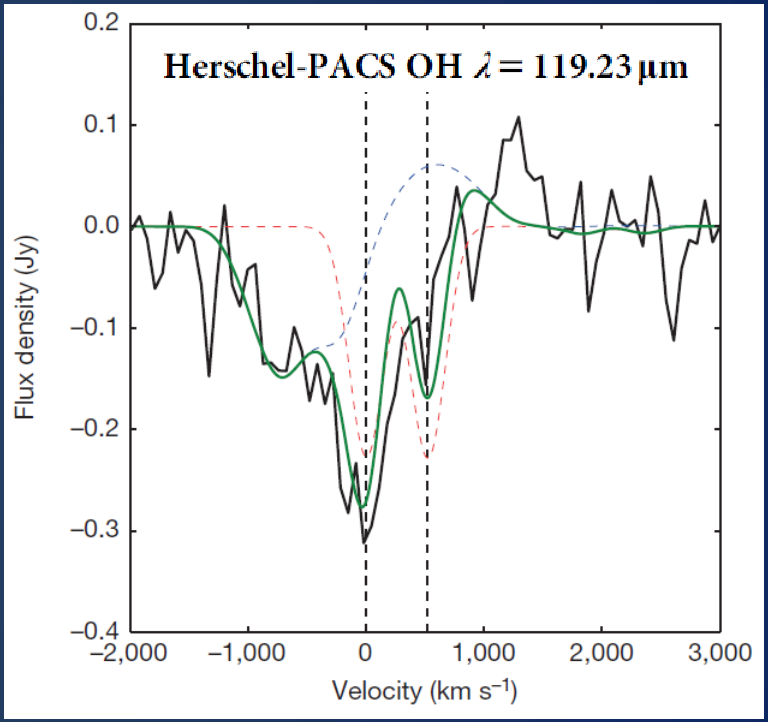
BH-Hosts Co-Evolution with ALMA

- Are AGN-driven outflows affecting the ISM in the host?





- Several local cases with both "ultra-fast", X-ray and molecular outflows
- Energy conserving? (unlike King 2003 model for M_{BH}-σ_*)

NOEMA time to detect CO line in CID-947

see Tombesi et al. (2015), Feruglio et al. (2015)

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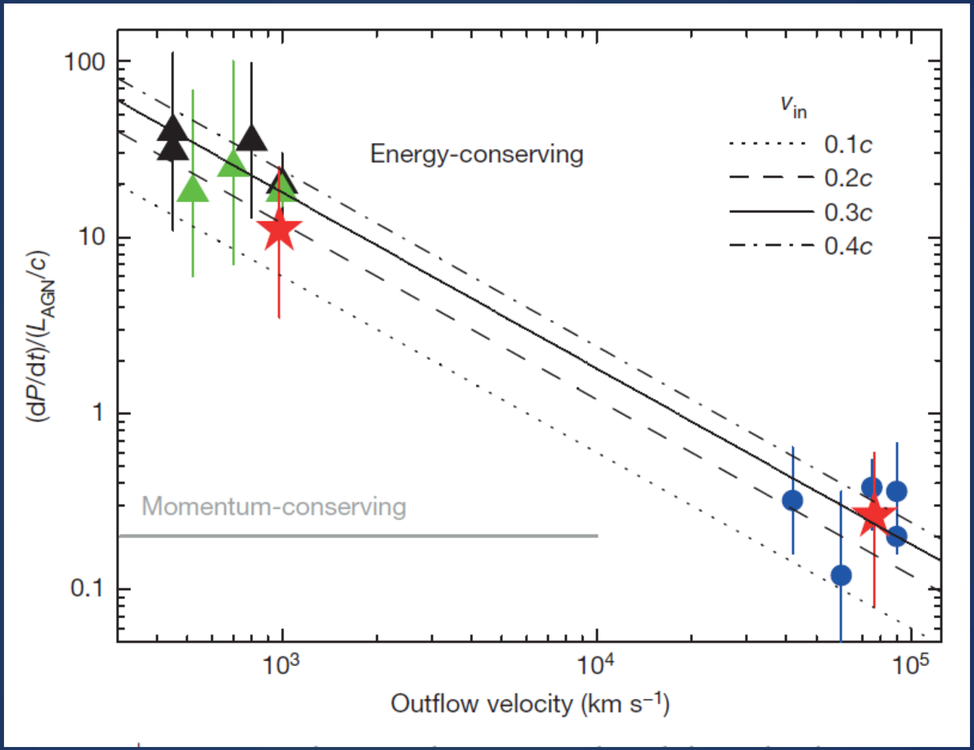

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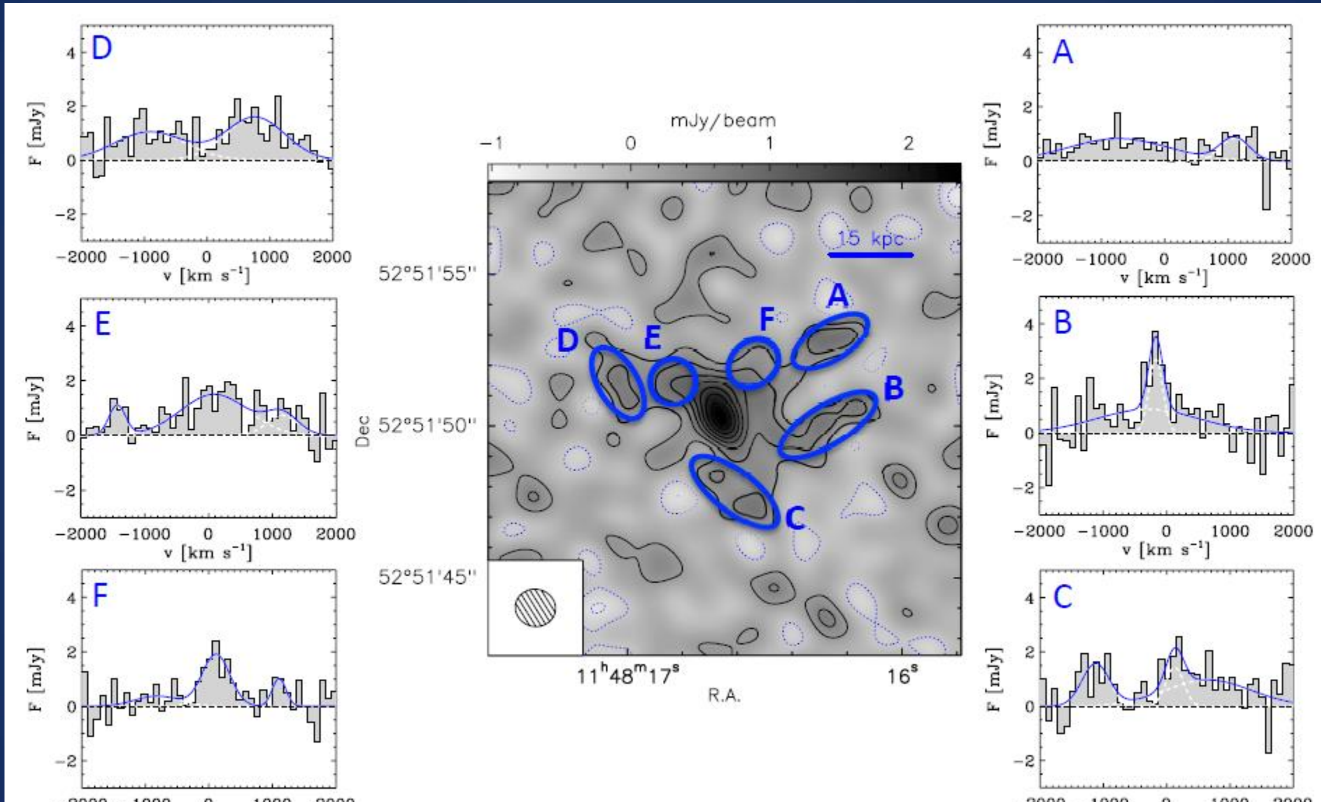


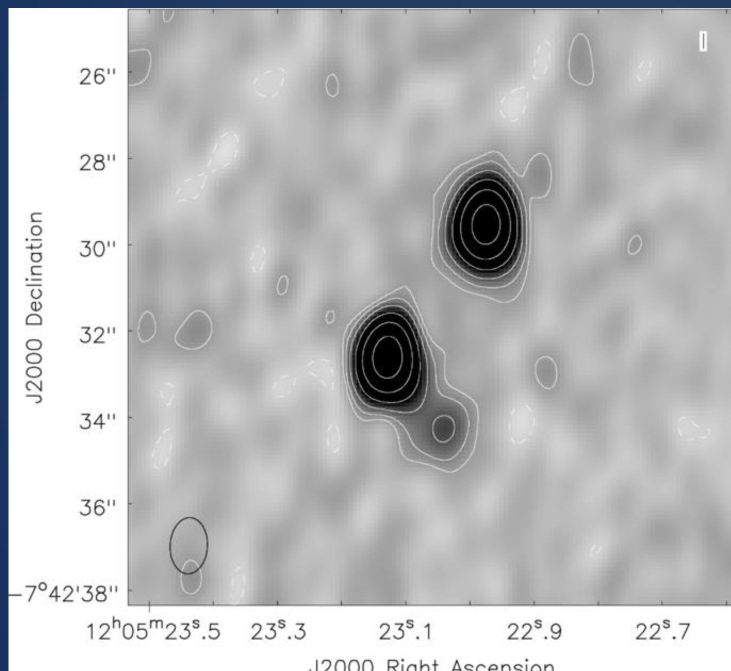
[C II] 158 μm emission of SDSS J1148+5251

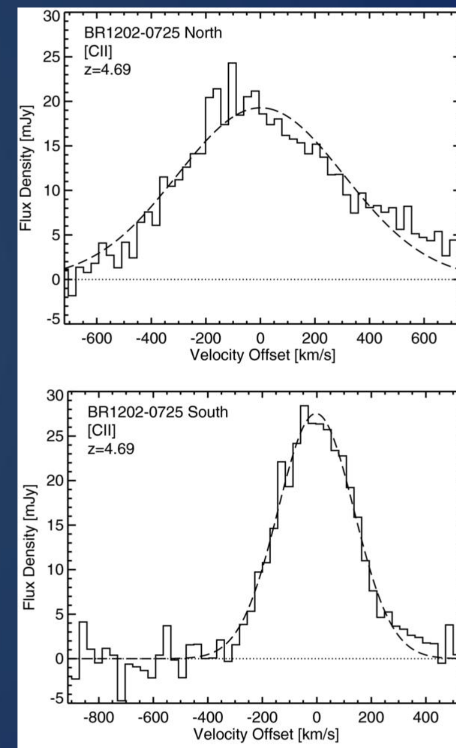
- Even at high-z (z~7) molecular lines allow to resolve outflow extent and velocity field

see Cicone et al. (2015)

BH-Hosts Co-Evolution with ALMA

- Is the co-evolution driven by mergers?
- What is the (dynamical) gas mass, and where will it end?





- at high-z (z~7) molecular lines allow to estimate dynamical masses

Obtained similar ALMA data for 6 luminous *z* ~5 AGNs

Wagg et al. (2012)

Summary

1. Tracing the evolution of SMBH-host relations in extremely challenging. Focus on samples of faint, unobscured AGNs.

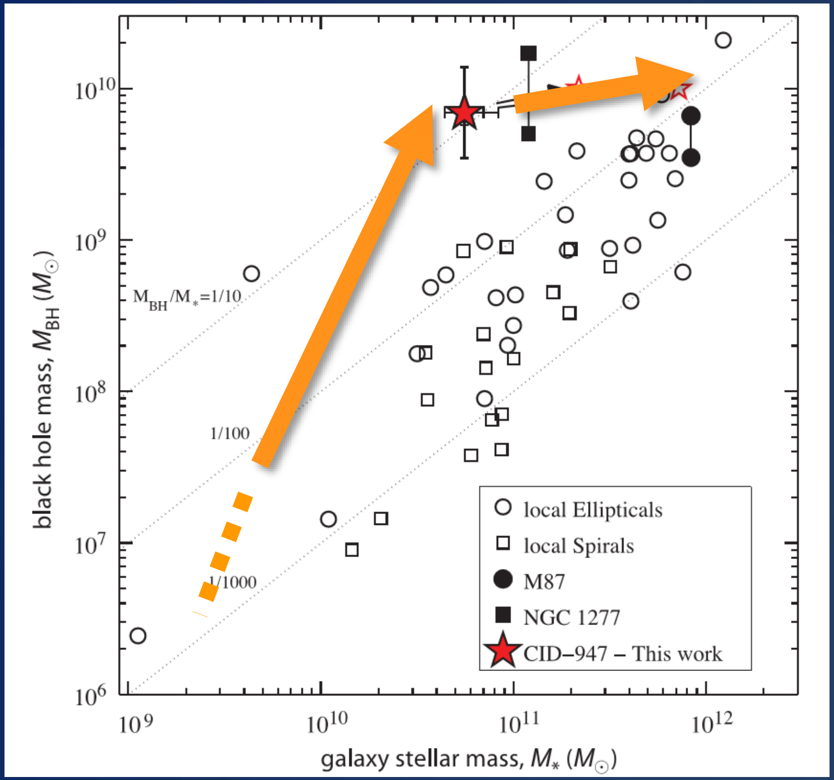
2. A dedicated Keck campaign in COSMOS to probe "typical" AGNs at $z \sim 2.5\text{-}3.5$:

   – CID-947: an over-massive BH in a normal SF galaxy
   – AGN-driven outflow does *not* stop SF
   – This sample and other arguments suggest $M_{BH} / M_{*} \sim (1+z)^2$

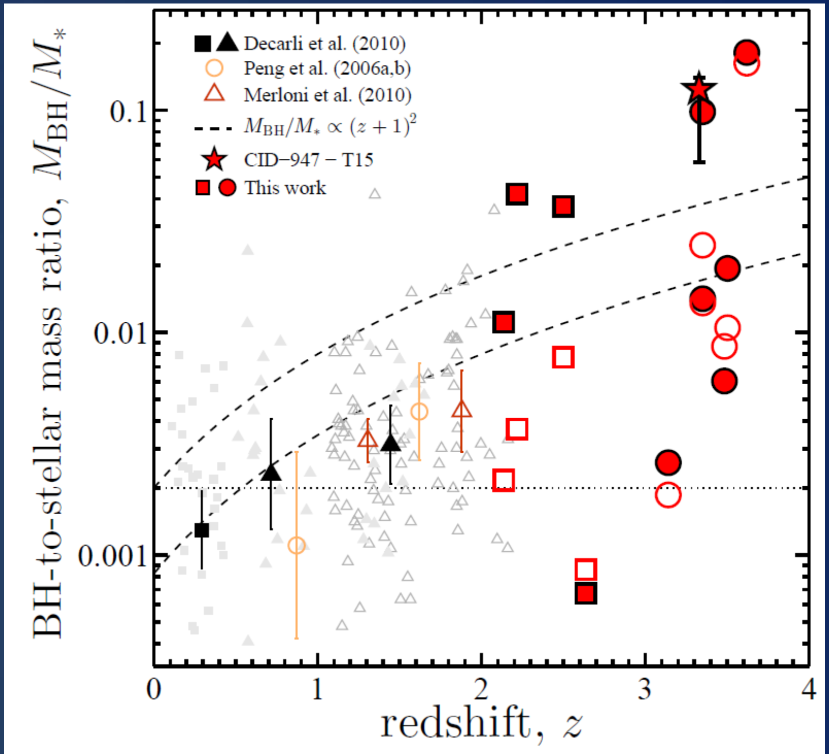
3. BH growth precedes stellar growth? is AGN feedback important? (on galaxy scales)

4. ALMA is critical to *resolve* the mechanisms that drive "co-evolution", out to z~5-6.

Thank you



black hole mass, M_{BH} ($M_\odot$)
galaxy stellar mass, M_* ($M_\odot$)
M_{BH}/M_*=1/10
1/100
1/1000
local Ellipticals
local Spirals
M87
NGC 1277
CID–947 – This work



BH-to-stellar mass ratio, M_{BH}/M_*
redshift, z
Decarli et al. (2010)
Peng et al. (2006a,b)
Merloni et al. (2010)
$M_{BH}/M_* \propto (z+1)^2$
CID–947 – T15
This work