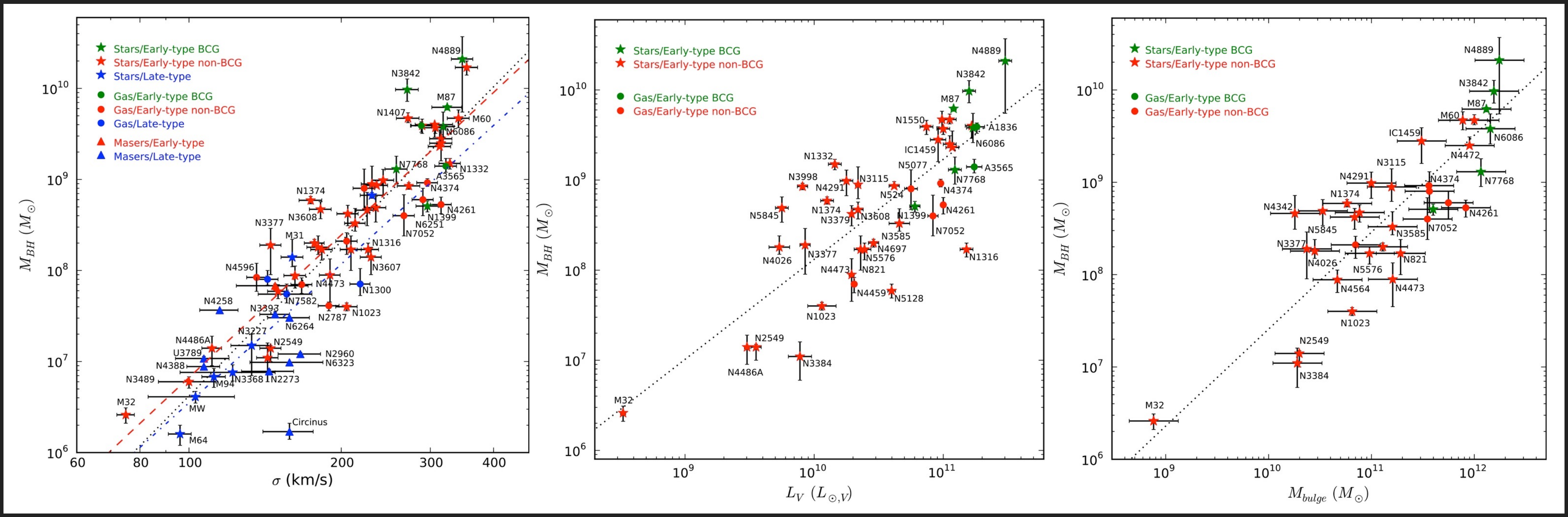
LAURA FERRARESE

NATIONAL RESEARCH COUNCIL OF CANADA

EXTREMELY BIG EYES ON THE CO-EVOLUTION OF GALAXIES AND SUPERMASSIVE BLACK HOLES

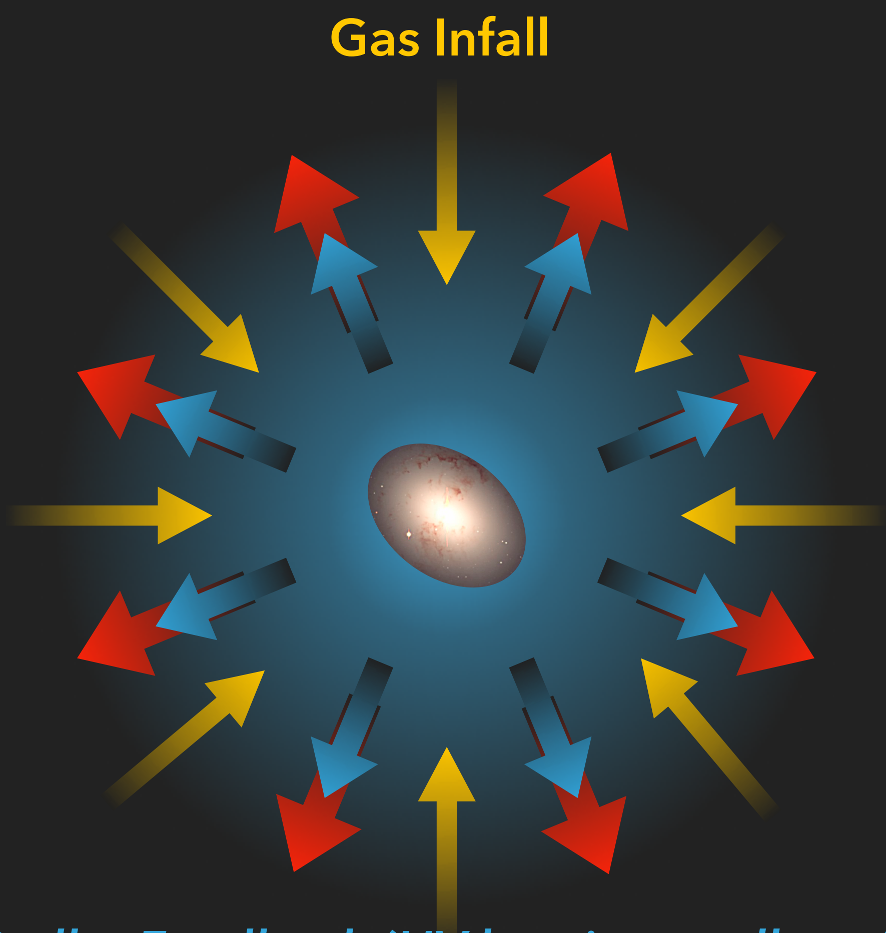
CONTEXT



McConnell & Ma 2013

- The growth of Supermassive Black Holes (SMBH) is connected to the physical processes that drive the growth of their host galaxies
- Such processes imprint a distinctive signature on the evolution of the relations between SMBH mass and the host galaxies' properties

CONTEXT



AGN Feedback

Bower et al. 2006; Croton et al. 2006; Sijacki et al. 2007; Somerville et al. 2008; Guo et al. 2010; Booth & Schaye 2011; Vogelsberger et al. 2014a; Henriques et al. 2015; Somerville & Dave 2015; Schaye et al. 2015; Dubois et al. 2016; McCarthy et al. 2017; Bower et al. 2017; Weinberger et al. 2018;…

Radio Mode Feedback ($\dot{M}_{SMBH}/\dot{M}_{Edd} \lesssim 0.01$). AGN feedback energy is deposited into a bipolar outflow that heat the circumgalactic and halo gas

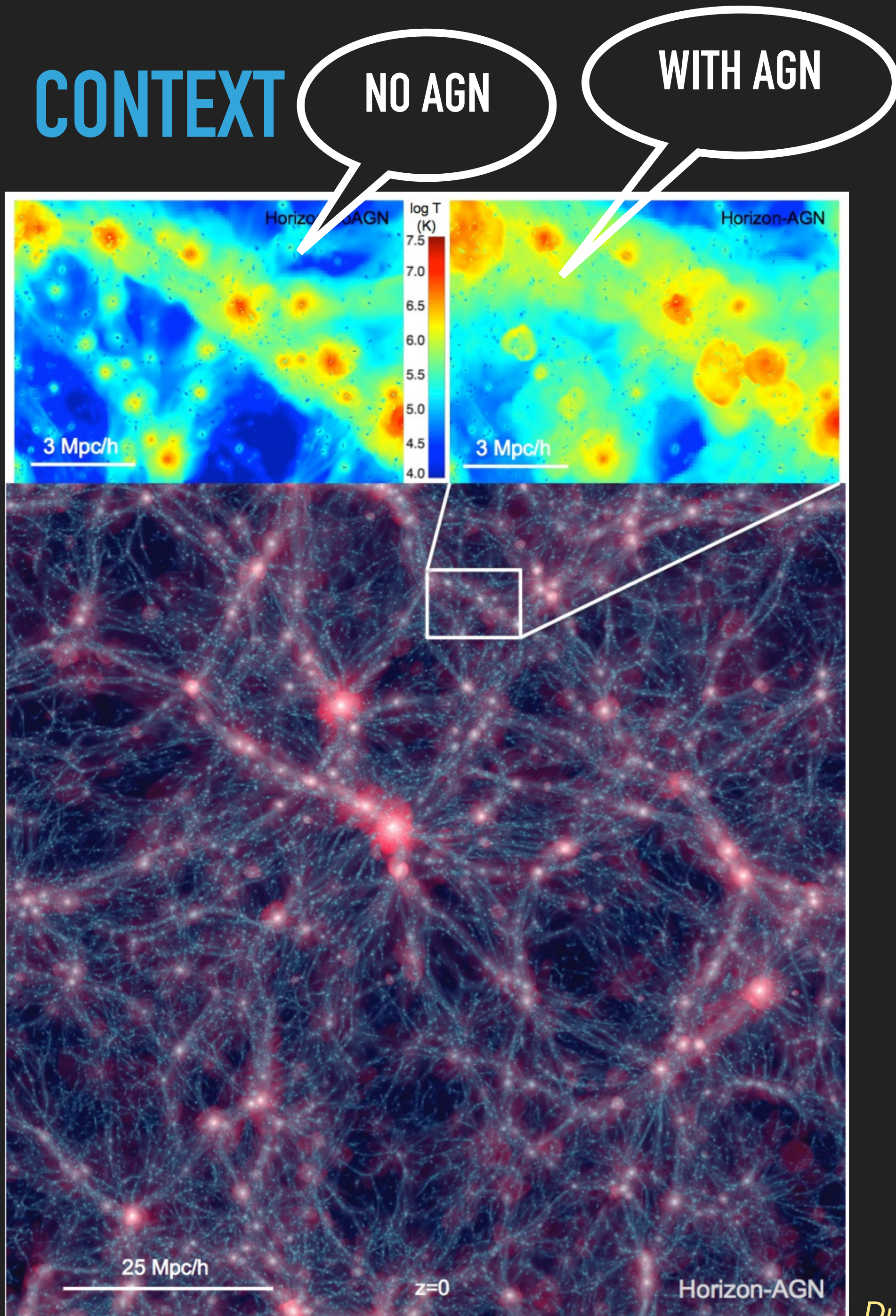
Quasar Mode Feedback ($\dot{M}_{SMBH}/\dot{M}_{Edd} \gtrsim 0.01$). Kpc-scale, massive, high velocity winds driven by radiation and energetic winds powered by the central AGN.

Stellar Feedback (UV heating, stellar winds, SNe)

- *Increasingly important as galaxy mass decreases; dominant in galaxies with haloes $\lesssim 10^{10}$ $M_\odot$*
- *50% of ejected gas is later re-accreted (e.g. Christensen et al. 2016)*

Silk 2003; Springel & Hernquist 2003; Bouch´e et al. 2010; Dutton et al. 2010; Oppenheimer et al. 2010; Hopkins et al. 2011; Bower et al. 2012; Dav´e et al. 2012; Peng & Maiolino 2014; Dekel & Mandelker 2014; Birrer et al. 2014; Muratov et al. 2015; Dubois et al. 2016; Christensen et al. 2016; Pontzen et al. 2017; Su et al. 2018; Choi et al. 2018;….

CONTEXT



Dubois et al. 2016

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Simulations shows that Quasar and Radio Mode AGN Feedbacks are able to drive hot gas out of dark matter haloes

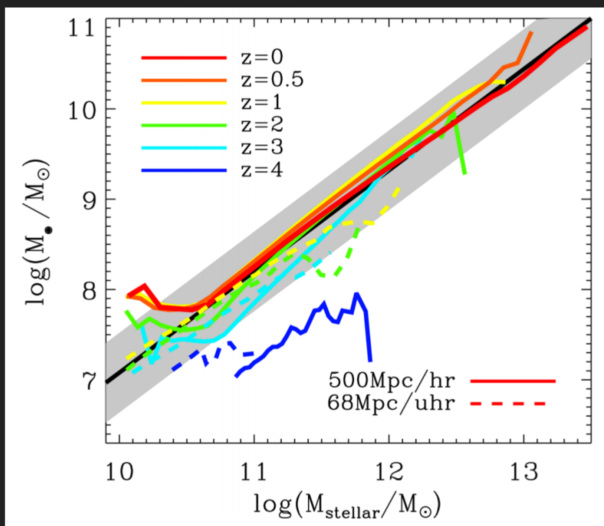
BUT

differ in the detailed predictions regarding:

- the characterization of the local scaling relations
- their cosmic evolution
- the SMBH occupation fraction and mass function

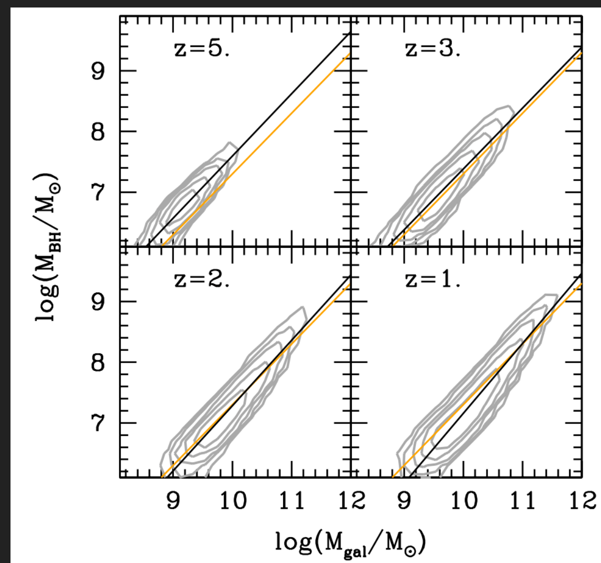
THEORY & SIMULATIONS

Hirschmann et al. 2014



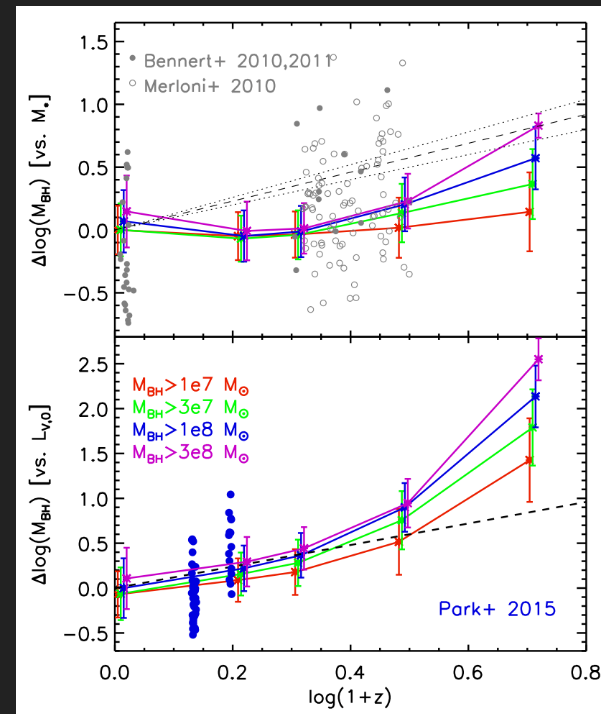
Galaxy growth precedes SMBH growth. Magneticum Pathfinder cosmological hydrodynamical simulations. At $z \gtrsim 1$ SMBHs are under massive for a given stellar mass (compared to the present day relation). At $z \lesssim 1$ the trend is reversed and the relation is shifted towards more massive galaxies.

Volonteri et al. 2016



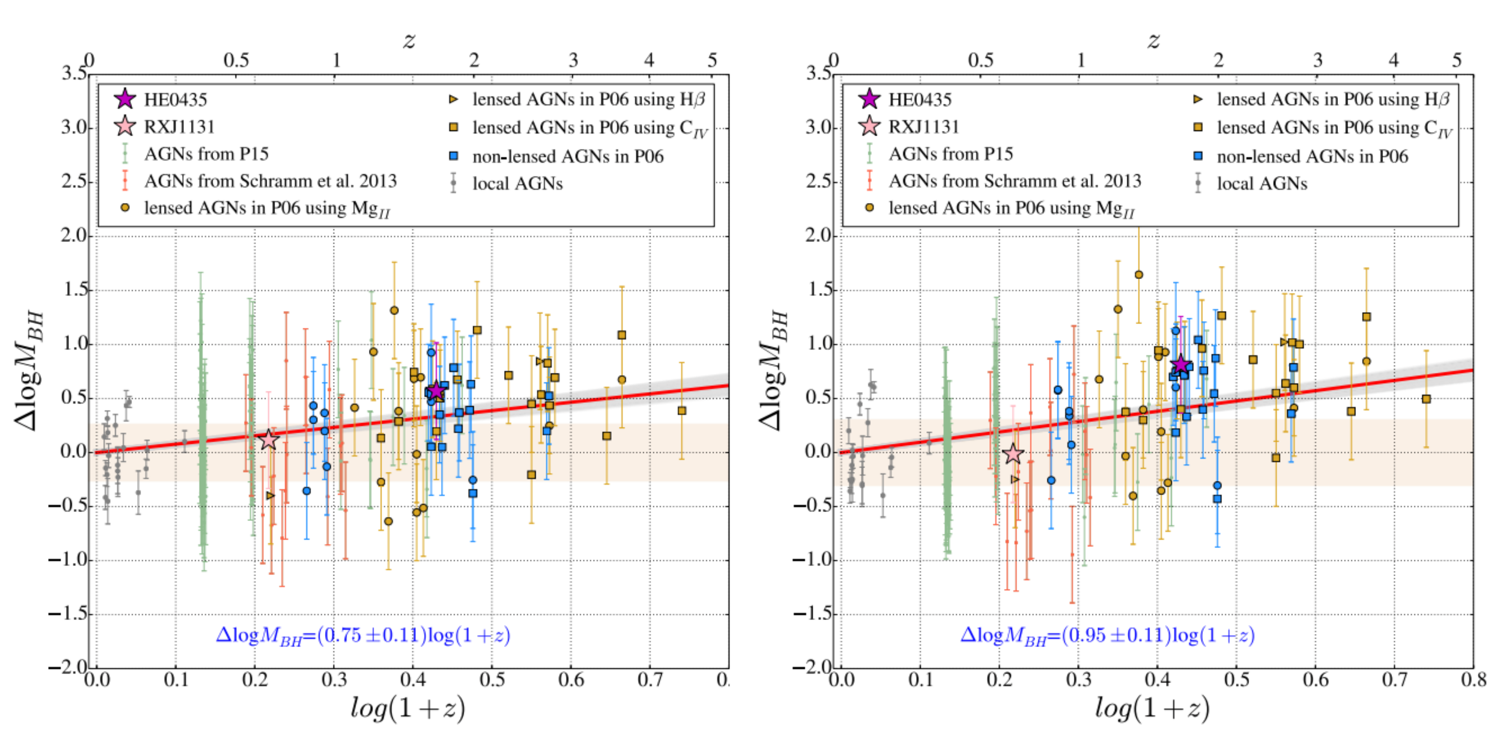
Lockstep evolution. Horizon-AGN cosmological hydrodynamical simulations. Very little evolution with redshift with $M_{\bullet} \sim 2 \times 10^3\ M_{gal}$ for SMBHs and galaxies hosted in haloes with mass > 8×10^{10} $M_{\odot}$.

DeGraf et al. 2016



SMBH growth precede galaxy growth. MassiveBlackII cosmological hydrodynamical simulations. No evolution up to $z \sim 1$ but significant mass-dependence at higher redshifts, where SMBHs (and in particular high-mass ones) are over massive compared to their hosts.

OBSERVATIONS



(a) Offset for $\mathcal{M}_{\rm BH}$-$L_{\rm bulge}$ relation using entire sample (b) Offset for $\mathcal{M}_{\rm BH}$-$L_{\rm total}$ relation using entire sample

Ding et al. 2017 (including data from Peng et al. 2006, Park et al. 2015; Bennert et al. 2010, 2011; Peterson et al. 2004; Schramm et al. 2013

SMBH growth precede galaxy growth. Once passive luminosity evolution is taken into account, SMBH in the more distant Universe reside in less luminous galaxies than today as $M_\bullet/L_{host} \propto (1+z)^\gamma$ with γ ~ 0.6 if $L_{host} = L_{bulge}$ and 0.8 if $L_{host} = L_{total}$

See also: Park et al. 2015; Peng et al. 2006; Treu, Malkan & Blandford 2004; Salviander et al. 2006; Woo et al. 2006; Jahnke et al. 2009; Schramm & Silverman 2013; DeGraf et al. 2015

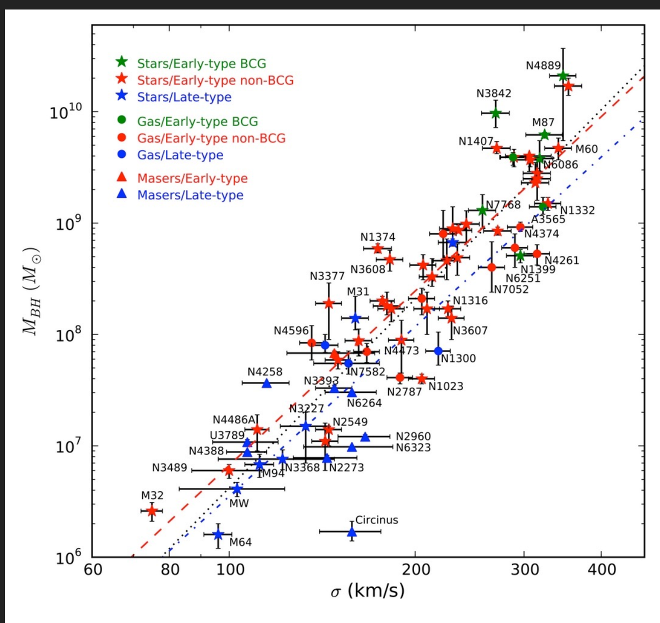
OBSERVATIONS: COSMIC EVOLUTION

HOWEVER:

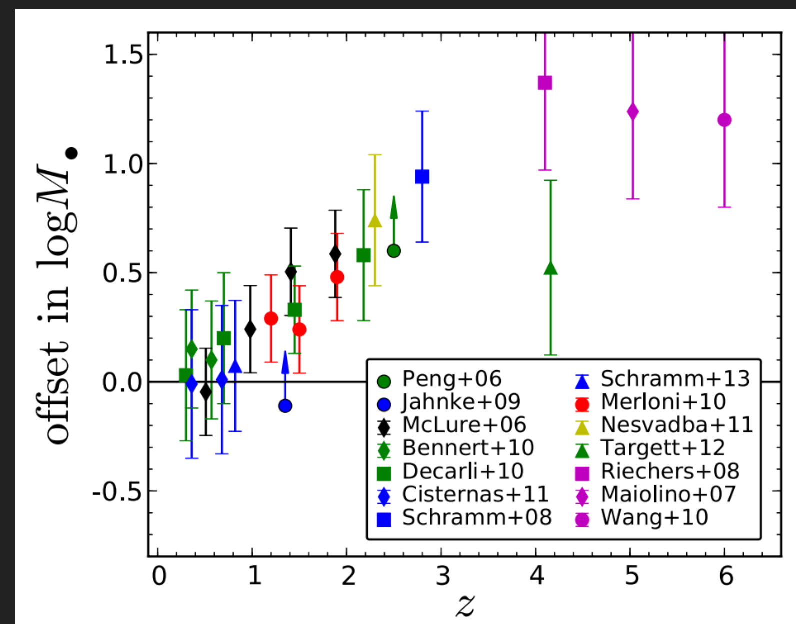
1. Both local and high redshift relations are affected by potentially severe observational biases (e.g. Schulze & Wisotzki 2013; Shankar et al. 2016)

2. At low and high redshifts, SMBH masses are estimated using different techniques and in fundamentally different samples.

McConnell & Ma 2013



Schulze & Wisotzki 2013



LOCAL SCALING RELATIONS (< 100 MPC):
- RESOLVED KINEMATICS
- MOSTLY QUIESCENT GALAXIES

COSMIC EVOLUTION (> 100 MPC):
- SECONDARY SCALING RELATIONS
- EXCLUSIVELY AGNS

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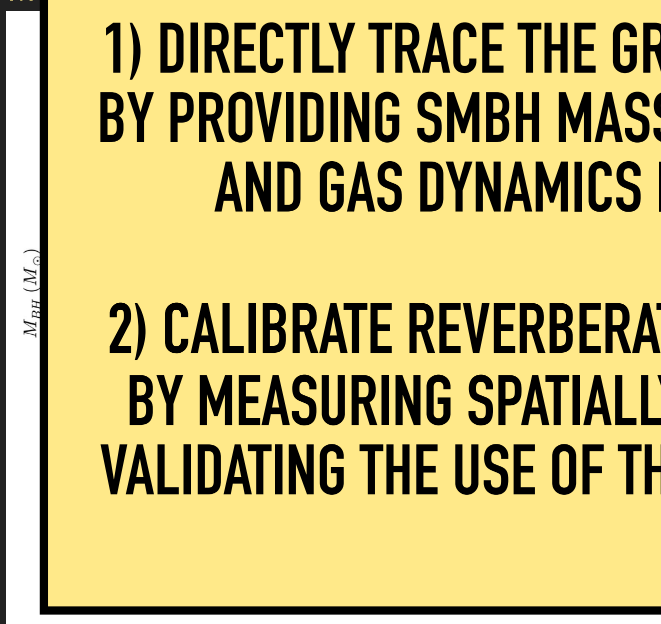
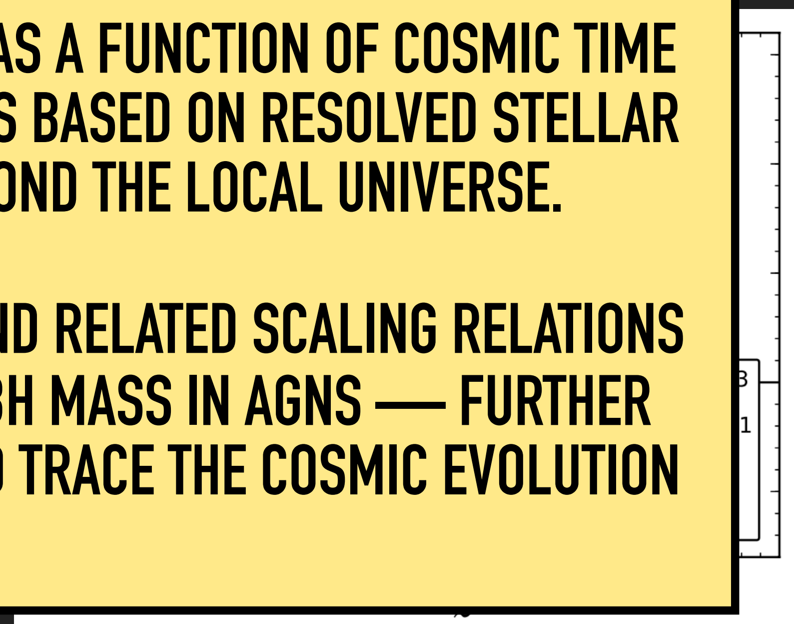


TWO OF ELTS' CONTRIBUTIONS WILL BE TO:

1) DIRECTLY TRACE THE GROWTH OF SMBH AS A FUNCTION OF COSMIC TIME BY PROVIDING SMBH MASS MEASUREMENTS BASED ON RESOLVED STELLAR AND GAS DYNAMICS IN GALAXIES BEYOND THE LOCAL UNIVERSE.

2) CALIBRATE REVERBERATION MAPPING AND RELATED SCALING RELATIONS BY MEASURING SPATIALLY-RESOLVED SMBH MASS IN AGNS — FURTHER VALIDATING THE USE OF THESE METHODS TO TRACE THE COSMIC EVOLUTION OF SMBHS.



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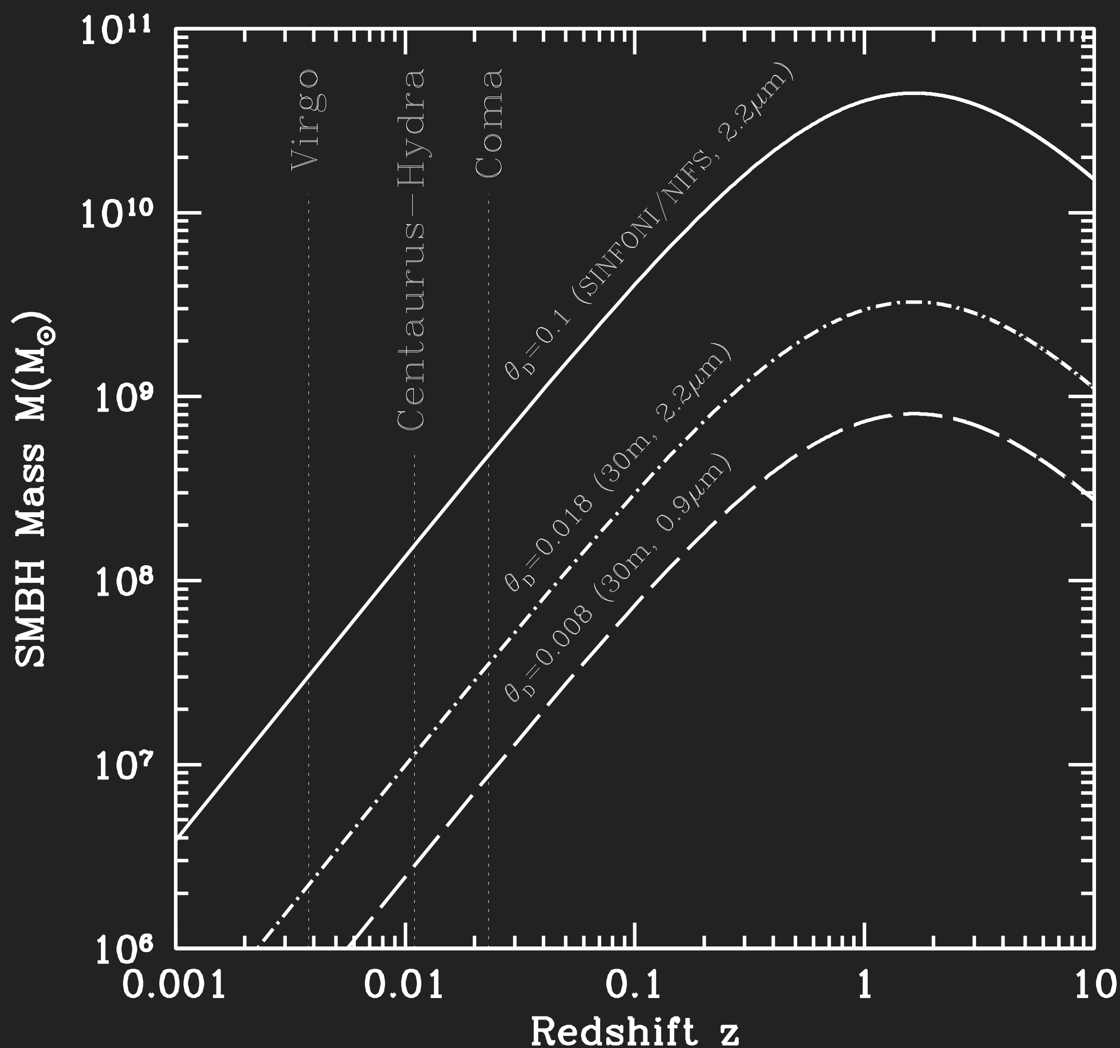
OBSERVATIONAL CONSTRAINTS I. SPATIAL RESOLUTION



- Need to resolve the SMBH "sphere of influence"

$$r_h = \frac{GM_\bullet}{\sigma^2}$$

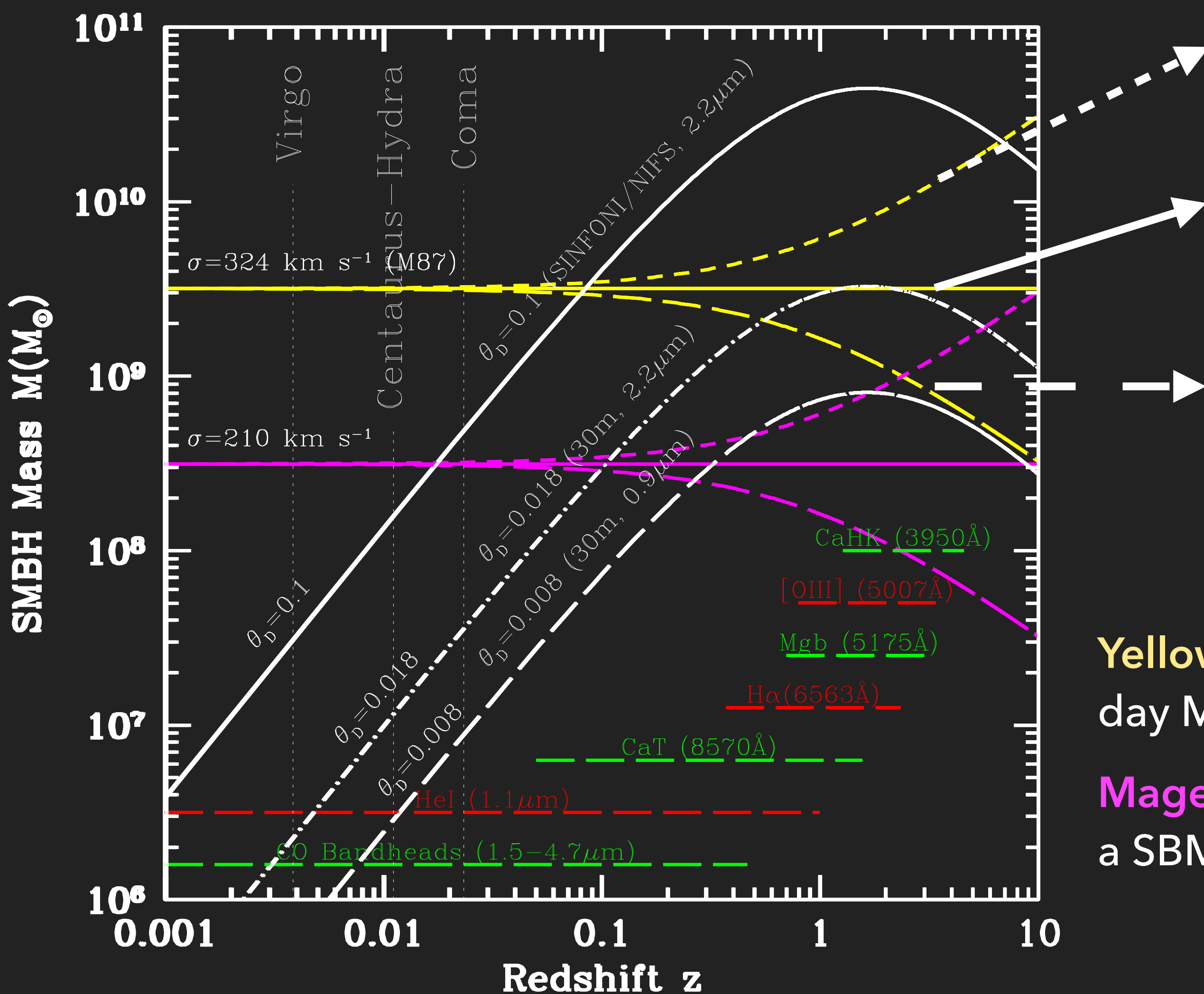
- Cosmological angular diameter distance

$$D_A = \frac{c}{H_0(1+z)} \int_0^z (\Omega_M(1+z')^3 + \Omega_\lambda)^{-1/2} dz'$$

- Assuming an $M_\bullet - \sigma_*$ relation of the form $M_\bullet = 10^\alpha\ (\sigma_* / \sigma_0)^\beta$, then

$$M_\bullet = \left[\frac{D_A\theta_D}{G}\left(\frac{\sigma_0^2}{10^{2\alpha/\beta}}\right)\right]^{(1-2/\beta)^{-1}}$$

OBSERVATIONAL CONSTRAINTS I. SPATIAL RESOLUTION



SMBH growth precedes galaxy growth: $M_\bullet \propto (1+z)^{0.95}$

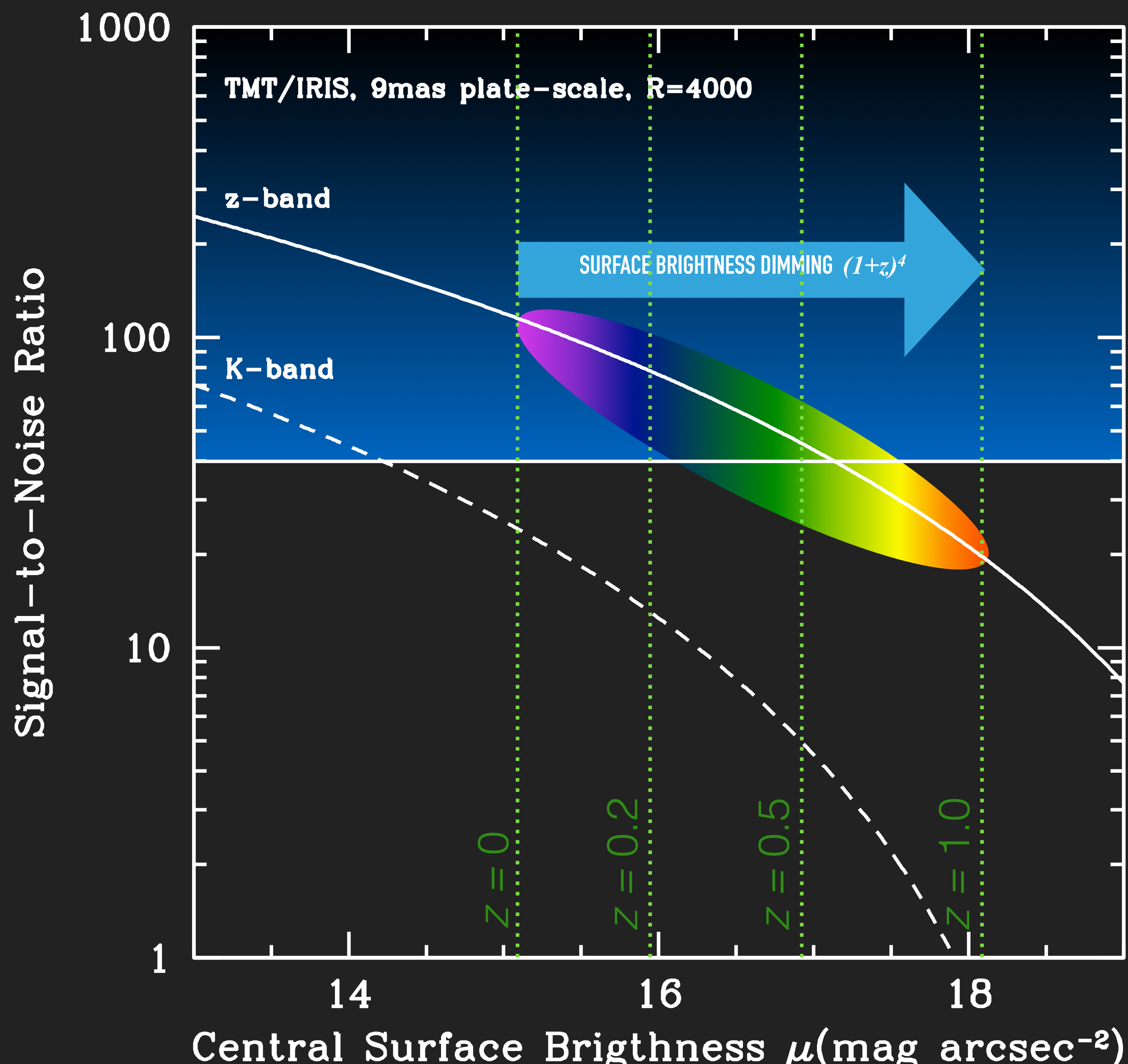
Lockstep Evolution

Galaxy growth precedes SMBH growth: $M_\bullet \propto (1+z)^{-0.95}$

Yellow: SMBH evolution for a present day M87-like galaxy

Magenta: evolution for a galaxy hosting a SBMH with mass lower by a factor 10.

OBSERVATIONAL CONSTRAINTS II. SENSITIVITY



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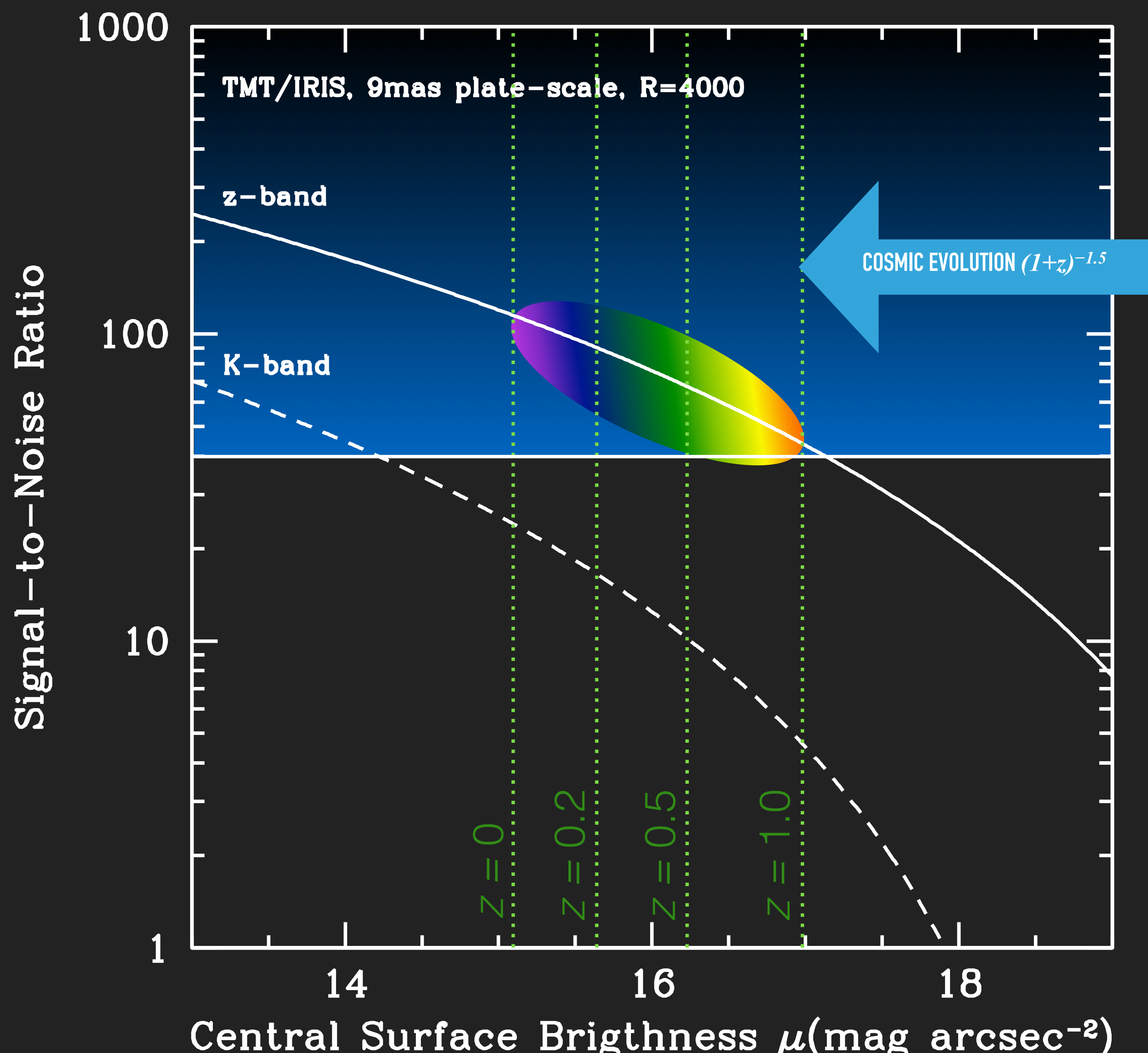

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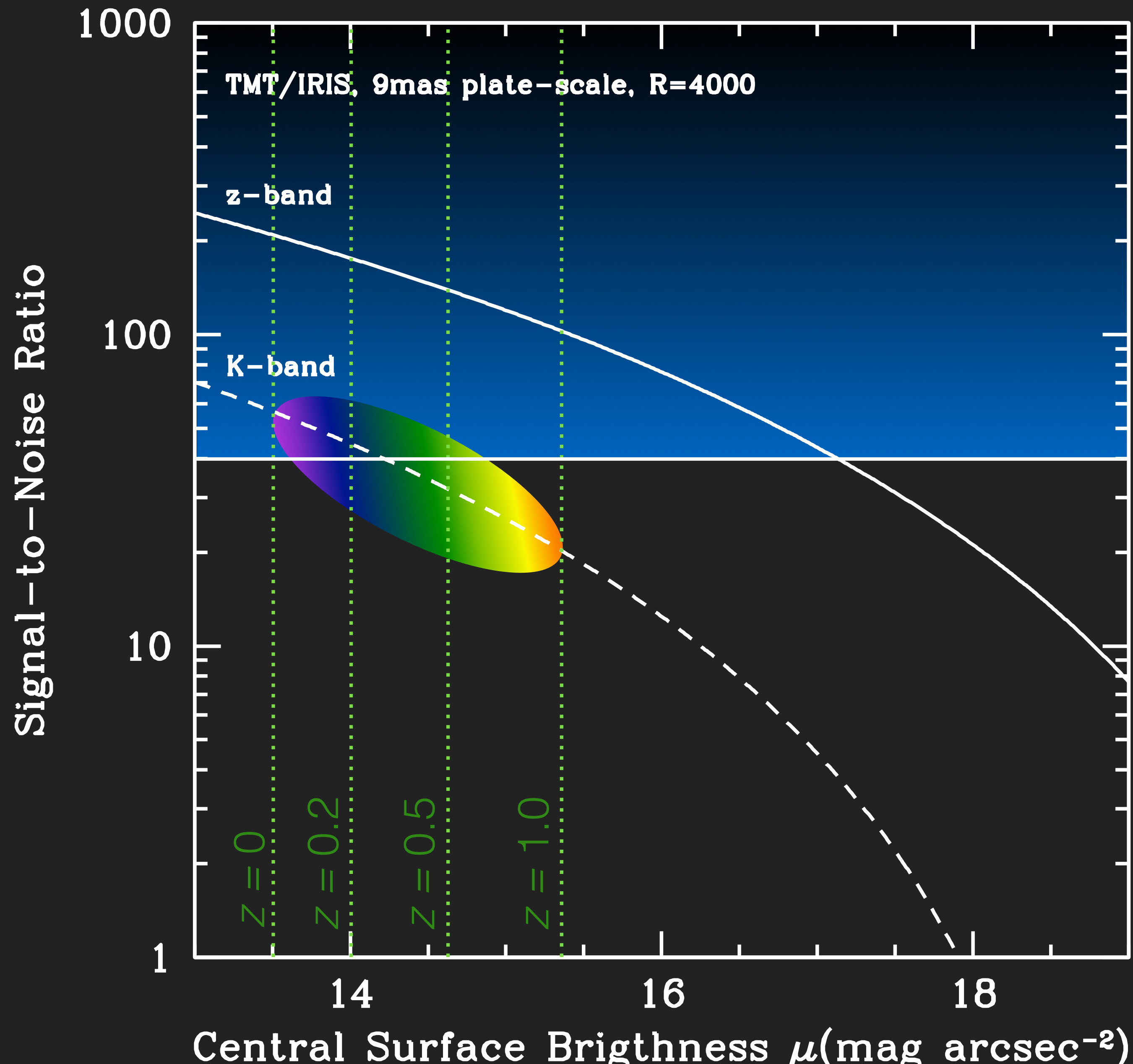
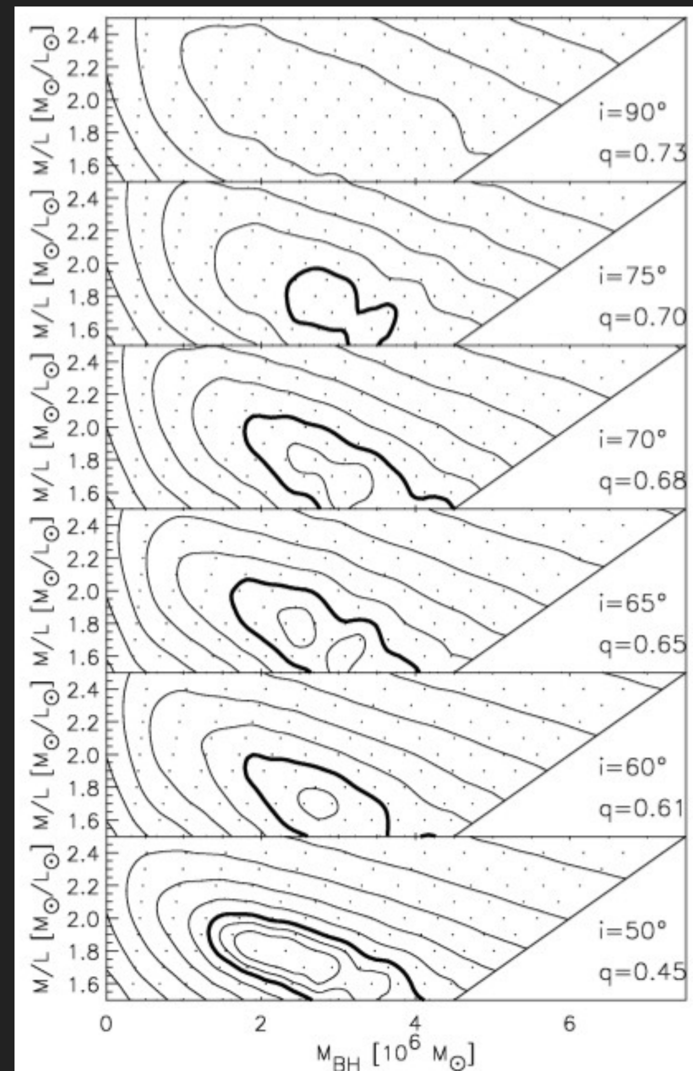


OBSERVATIONAL CONSTRAINTS III. FIELD OF VIEW

Necessary to move into a phase of precision BH demographics.

- Constrain spatial gradients in the stellar mass-to-light ratios (e.g. McConnel et al. 2013)
- constrain the galaxy shape (van den Bosch & de Zeeuw 2009)
- simultaneously constrain DM halo and BH (Gebhardt & Thomas 2009; Gebhardt et al. 2010)

REQUIRES COORDINATION BETWEEN ELTs AND 8-10m CLASS FACILITIES WITH LARGE SCALE (10s of arcsec) FOVs.



HST/STIS + 4 Long Slits
$\mathcal{M} = (2.8\pm1.2) \times 10^6\ \mathcal{M}_\odot$
$\mathcal{M}/L = 1.75\pm0.25\ \mathcal{M}_\odot/L_\odot$
i < 75 deg

Verolme et al. (2002)
[also van der Marel et al. 1998; van den Bosh & de Zeeuw 2009]

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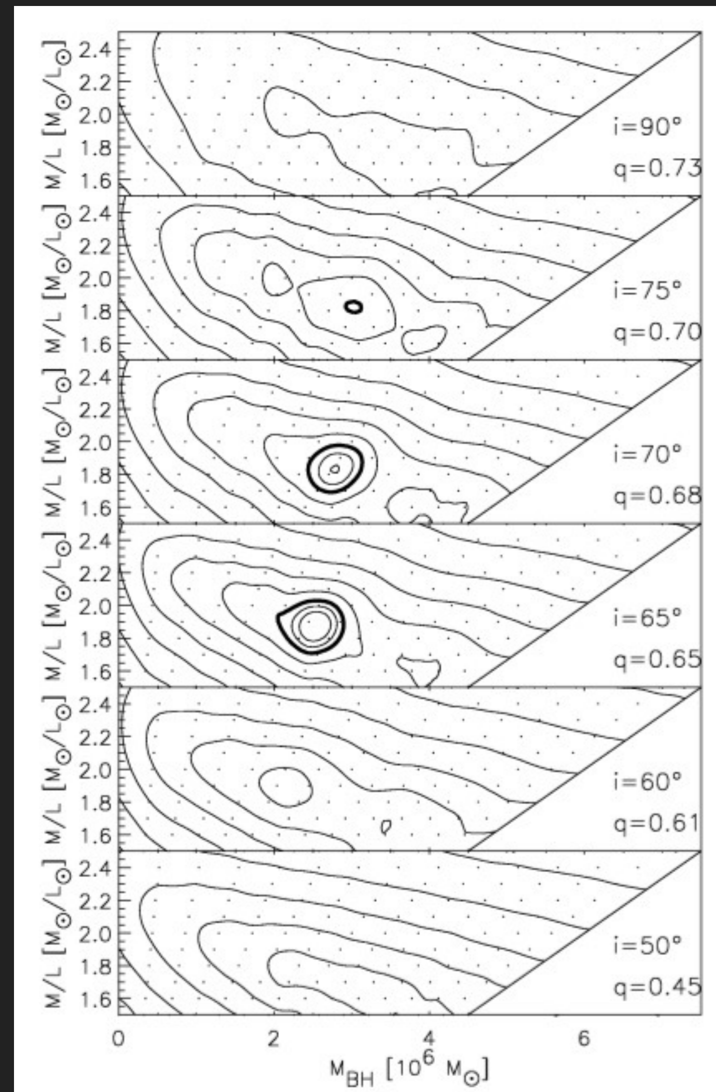

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OBSERVATIONAL CONSTRAINTS III. FIELD OF VIEW

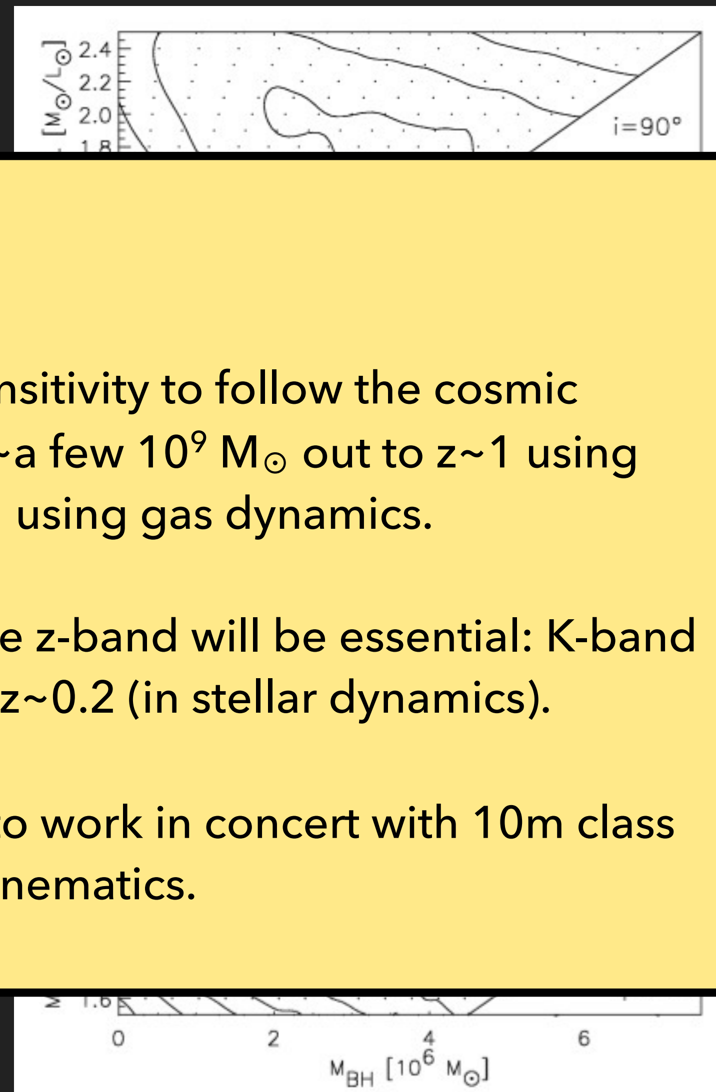
Necessary to move into a phase of precision BH demog...

- Co... lig...
- co... Ze...
- si... (G...

REQUI... 8-10m ... arcsec)

COSMIC EVOLUTION: SUMMARY

- ELTS will have enough resolution and sensitivity to follow the cosmic evolution of SMBHs more massive than ~a few 10^9 $M_\odot$ out to z~1 using stellar dynamics; and potentially beyond using gas dynamics.
- Diffraction-limited AO observations in the z-band will be essential: K-band observations will likely only reach out to z~0.2 (in stellar dynamics).
- Due to their limited FOV, ELTs will need to work in concert with 10m class telescopes to constrain the large scale kinematics.



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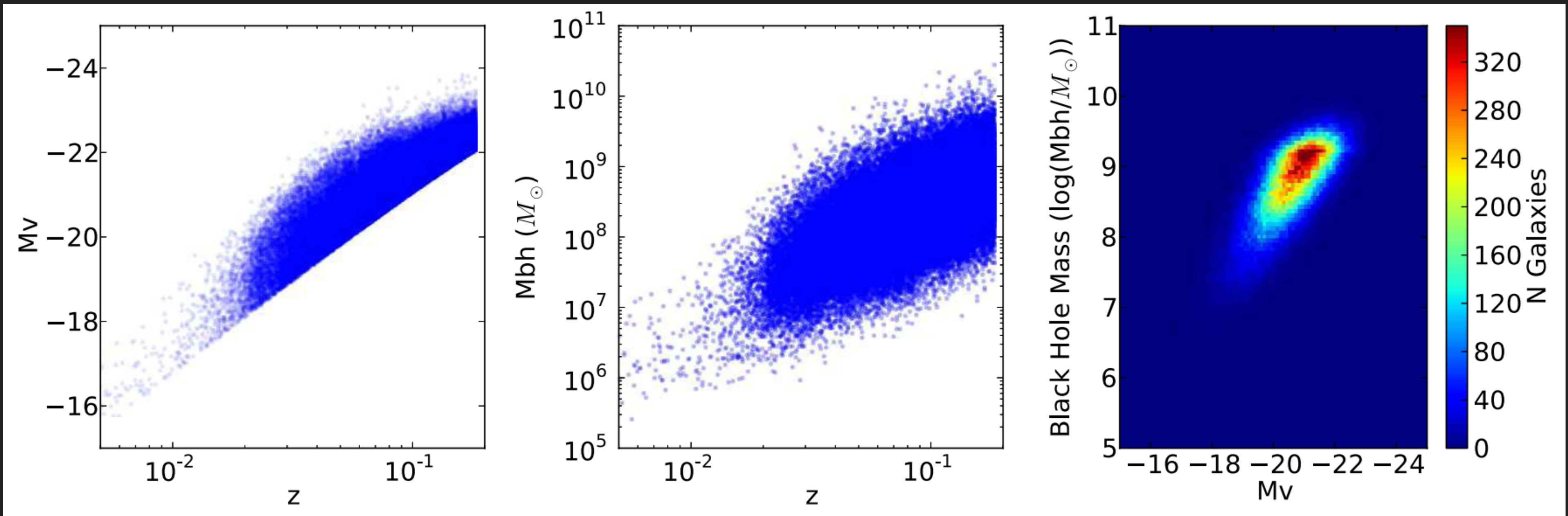
THE LOCAL UNIVERSE: ADDITIONAL CLUES

- TMT/IRIS simulations: AO-assisted IFS; 0.9 - 2.2 microns; R=4000; 4mas (FOV 0."45×0."51 FOV) and 9mas (FOV 1."01 ×1."15) pixel scales



Do et al. 2014

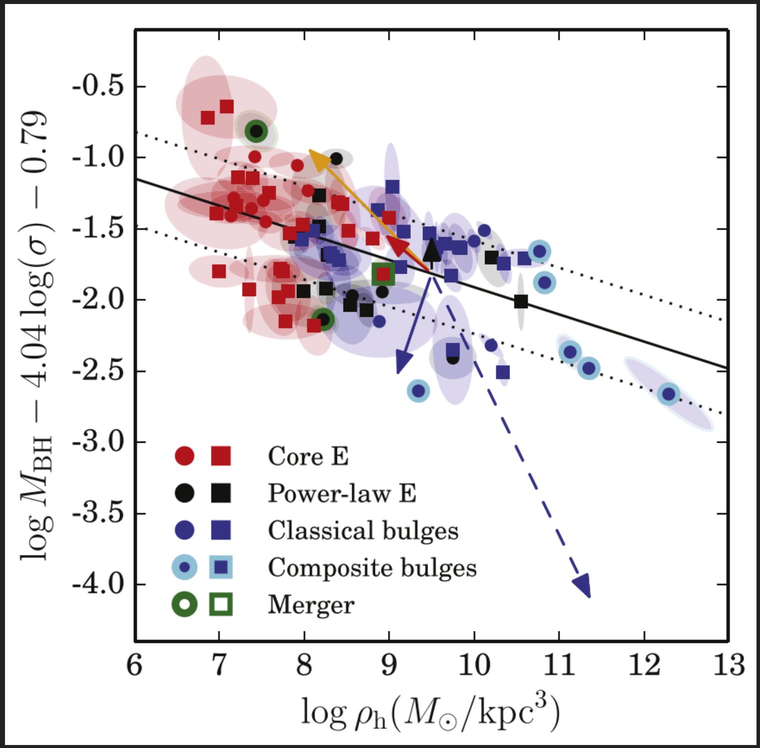
In 2h integration/galaxy (or less), TMT/IRIS will be able to observe 4000 galaxies in K and 10^5 galaxies in Z with S/N > 40

THE LOCAL UNIVERSE: ADDITIONAL CLUES

- Securing calibrations; addressing biases and systematics

BY BEING ABLE TO DRAW FROM SAMPLES OF TENS OF THOUSAND OF LOCAL ($z < 0.2$) GALAXIES WITH SMBHs IN THE RANGE $10^6 < M < 10^{10}$ $M_\odot$, IN CLUSTERS, GROUPS AND THE FIELD, ELTs TELESCOPES WILL

- ENABLE A COMPARISON OF SMBH MASSES USING BOTH GAS AND STELLAR DYNAMICS; INVESTIGATE POSSIBLE BIASES INTRODUCED BY THE DETECTION METHOD
- CHARACTERIZE THE LOCAL RELATION (scatter, slope, normalization) AS A FUNCTION OF GALAXY STRUCTURAL PARAMETERS
- ADDRESS BIASES AND SYSTEMATICS THAT CAN AFFECT THE SLOPE AND NORMALIZATION OF THE SCALING RELATIONS (e.g. Shankar et al. 2016)
- POTENTIALLY PROVIDE SPATIALLY RESOLVED KINEMATIC ESTIMATE OF SMBH MASSES IN REVERBERATION MAPPED AGN, THEREBY CONTRIBUTING TO A DIRET CALIBRATION OF THE TECHNIQUE.



Saglia et al. 2016

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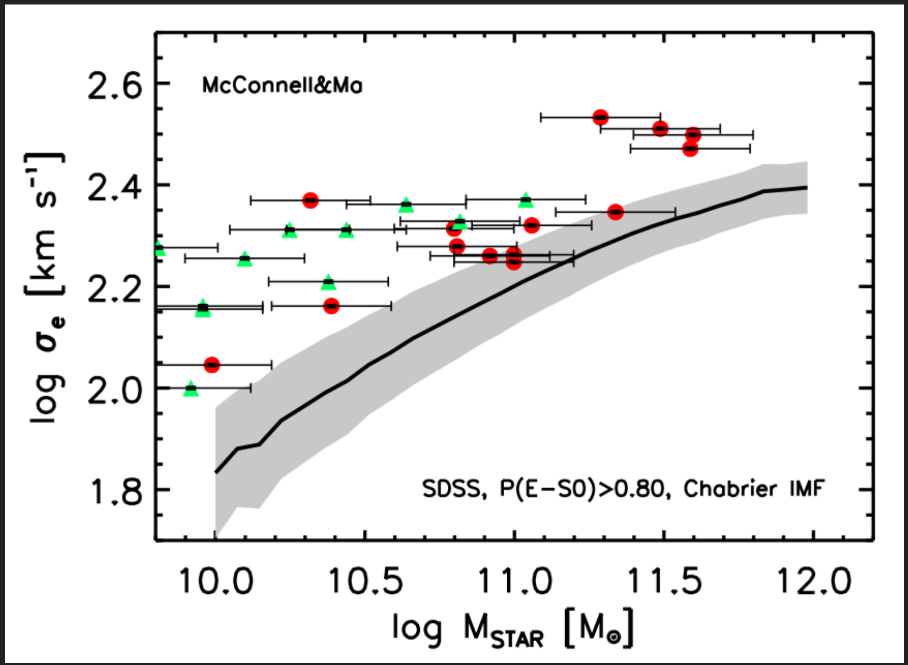
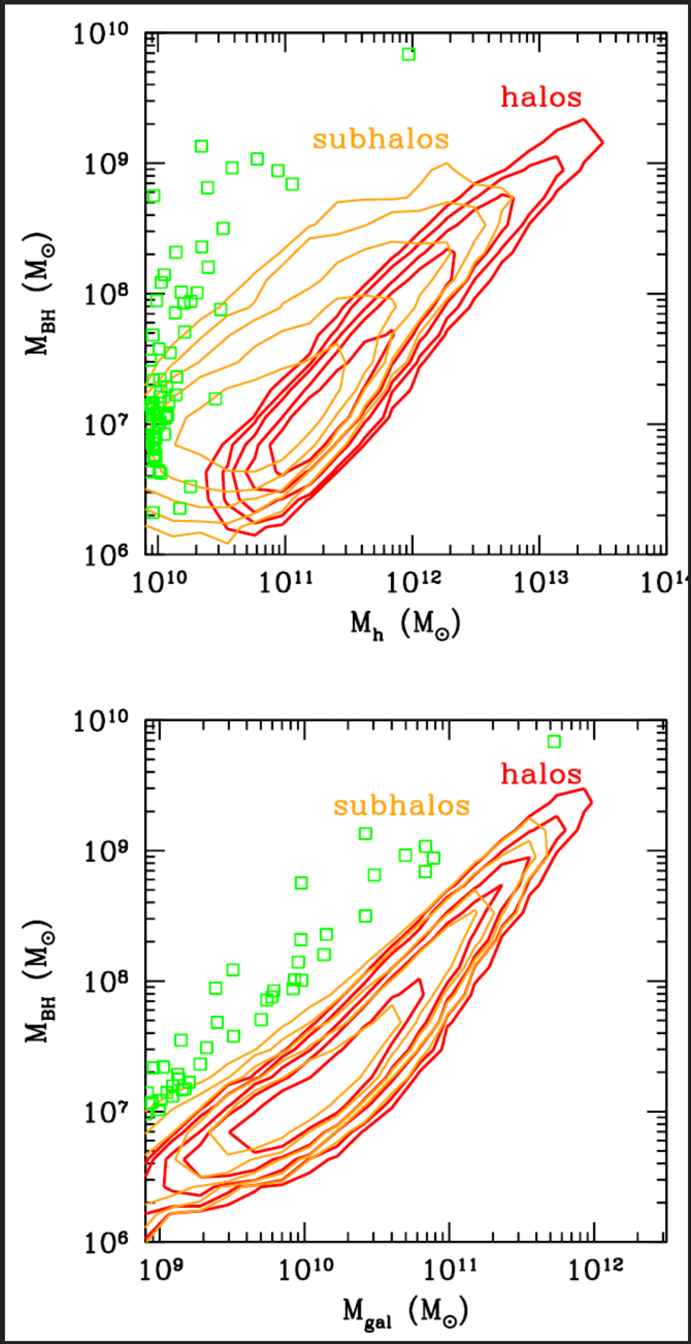


Shankar et al. 2016

THE LOCAL UNIVERSE: ADDITIONAL CLUES

- Stripping and over-massive SMBH
  - Simulations (Volonteri et al. 2016): Only 0.2% of haloes (~0.5% of subhaloes) host "over-massive" SMBHs with $M_\bullet \geq 0.01\ M_{gal}$
  - Observations: ~6% of SMBH appear to be over-massive

BY BEING ABLE TO DRAW FROM SAMPLES OF TENS OF THOUSAND OF LOCAL $(z < 0.2)$ GALAXIES WITH SMBHs IN THE RANGE $10^6 < M < 10^{10}\ M_\odot$, IN CLUSTERS, GROUPS AND THE FIELD, ELTs WILL EXPLORE THE LINK BETWEEN SMBH MASS, THE ENVIRONMENT, AND THE STRUCTURAL PARAMETERS OF THE HOST GALAXIES.

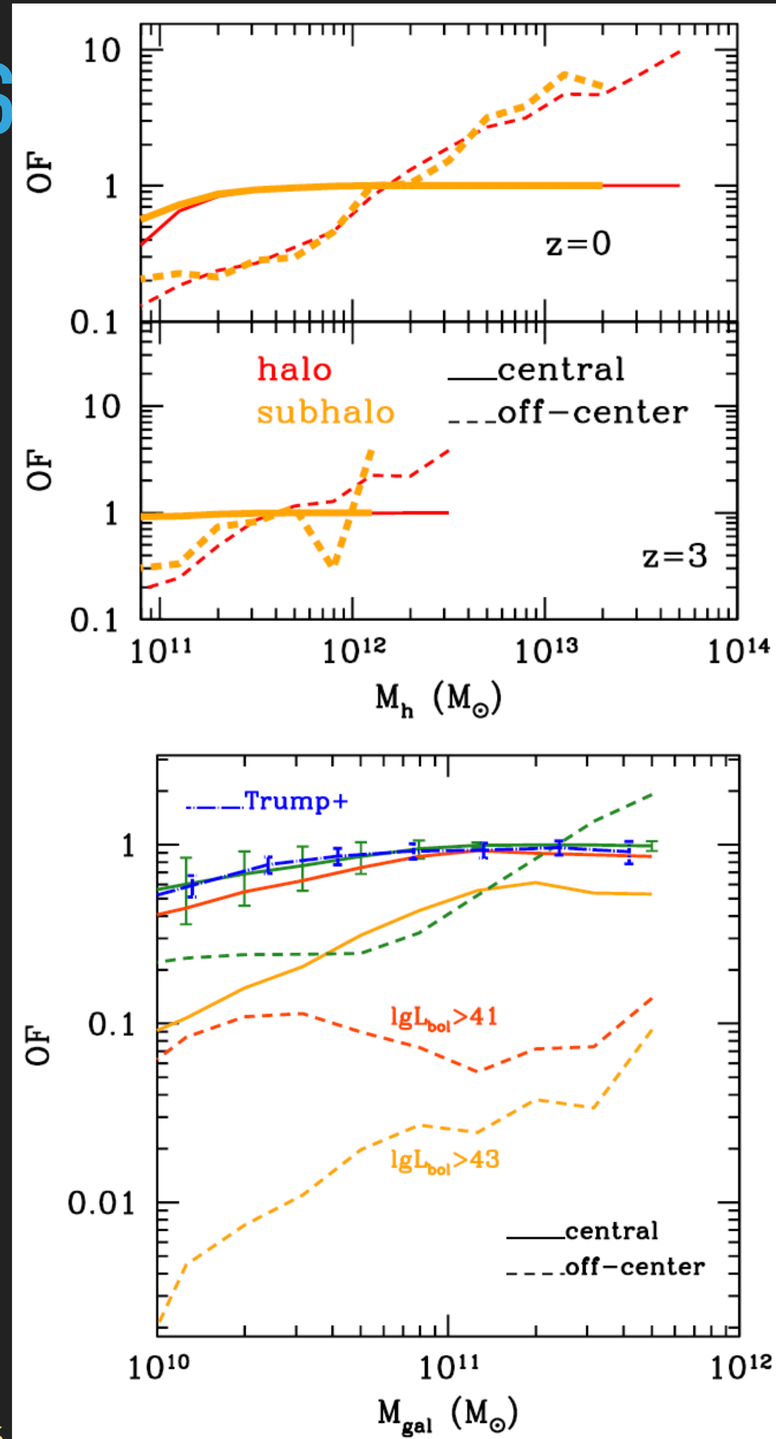


Volonteri et al. 2016

THE LOCAL UNIVERSE: ADDITIONAL CLUES

- Occupation Fraction and SMBH Seeds
  - The occupation fraction carries the imprint of the seeding mechanisms in the early universe. Additionally, some memory of the seeding process is retained in local low-mass galaxies that, by their very nature, are expected to have undergone minimal processing.
  - Simulations: Occupation fraction decreases with decreasing halo mass, is higher in sub-haloes rather than in haloes (Volonteri et al. 2016), and depends on the mass of the seeds (Greene et al. 2019).
  - Observational constraints are uncertain

ELTs WILL PUSH THE SMBH MASS FUNCTION TO ~$10^6\ M_\odot$ IN THE VIRGO CLUSTER, AND TO ~$10^4\ M_\odot$ IN MORE NEARBY GROUPS and GLOBULAR CLUSTERS.



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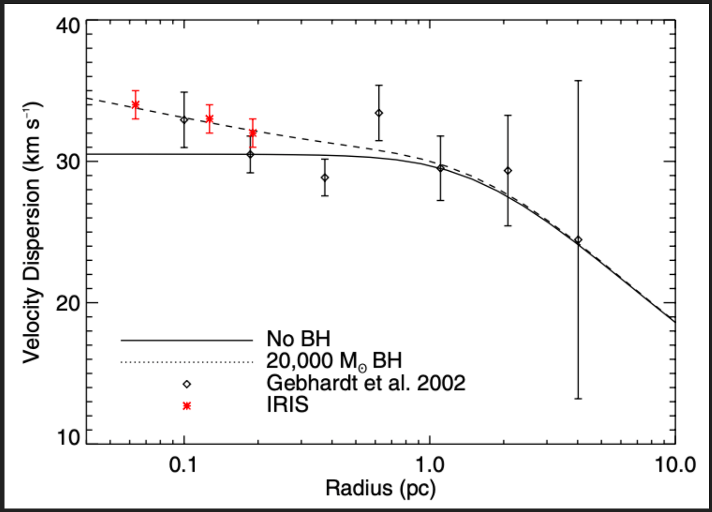
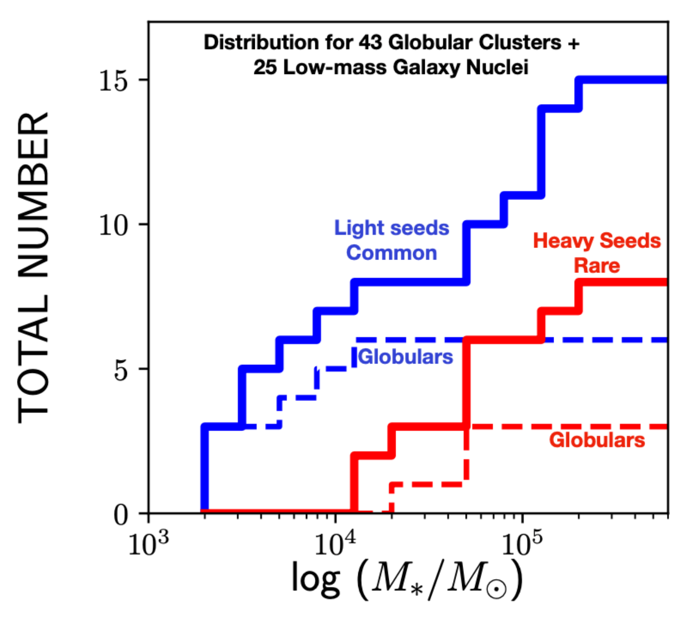
Simulations of a G1-type cluster, seen by TMT/IRIS in K-band (2.5h, R=8000)



Do et al. 2014



Greene et al. 2019

SYNERGIES WITH OTHER FACILITIES

- Wide-Field, Multiplexed Spectroscopy (e.g. Maunakea Spectroscopic Explorer)

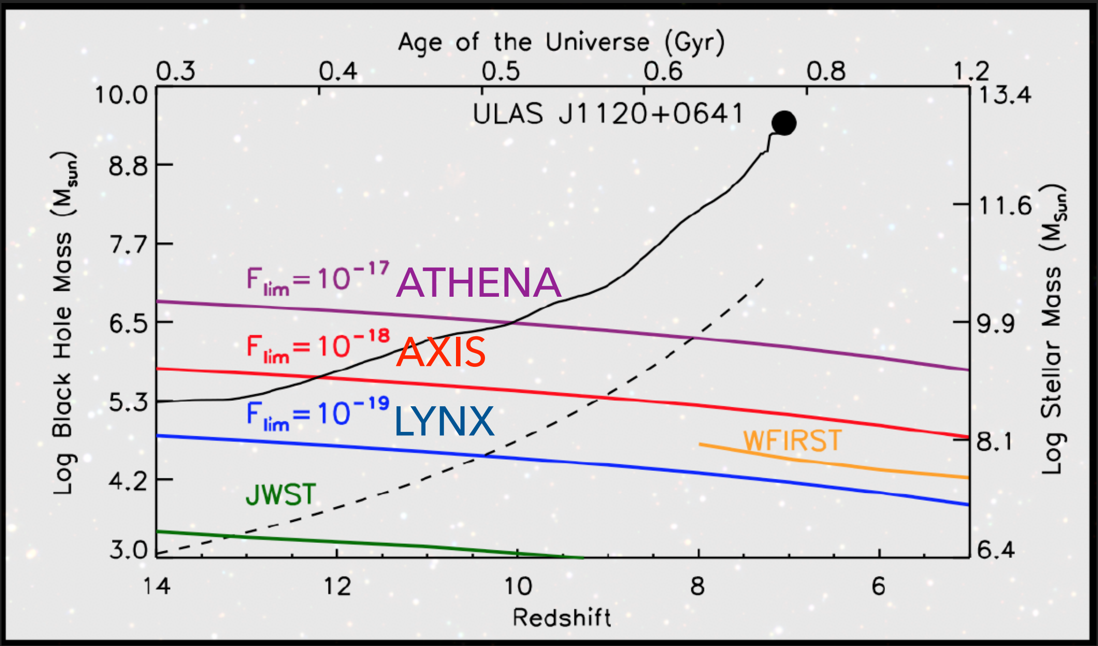
  - **Assists in the selection of galaxies to be targeted by ELTs for spatially-resolved gas dynamical studies:** by surveying local galaxies for the presence of broad forbidden emission lines that could indicate Keplerian rotation.

  - **Explore the cosmic evolution of SMBHs powering quasars up to $z \sim 3$ through time-resolved reverberation mapping**: a 600 hour program over a ~5 year period would yield 100 epochs and time lags for 5000 quasars, allowing us to determine their masses and map their inner regions .

  - **Explore the low-mass end of the SMBH mass function in AGN:** MSE can probe AGNs with bolometric luminosity $L_{bol}>5\times10^{41}$erg s^{-1}(or a SMBH mass of $10^{3.3}$ $M_\odot$ assuming accretion at 10% of the Eddington limit) using the narrow-line [OIII]/Hβ [NII]/Hα diagram as a diagnostic

SYNERGIES WITH OTHER FACILITIES

- X-ray (Athena, Lynx, AXIS):
  - **Census of massive, luminous AGNs at z > 6**: requires wide field (tens of square degrees) surveys at a depth equivalent of the faintest Chandra flux, such as can be achieved with Athena.
  - **Direct detection of the heavy SMBH seeds forming and growing at z = 10–15** : Athena will be able to detect these sources down to a mass scale ~ $10^6\ M_\odot$, while Lynx will reach ~ $10^4\ M_\odot$;
  - **Measure the faint end of the accreting black hole luminosity function**; **establish the AGN occupation fraction**, and **probe the mass distribution of SMBH seeds in local dwarf galaxies**: requires a combination of radio facilities such as ngVLA and the next generation of X-ray facilities such as Lynx and Athena.



Civano et al. 2019

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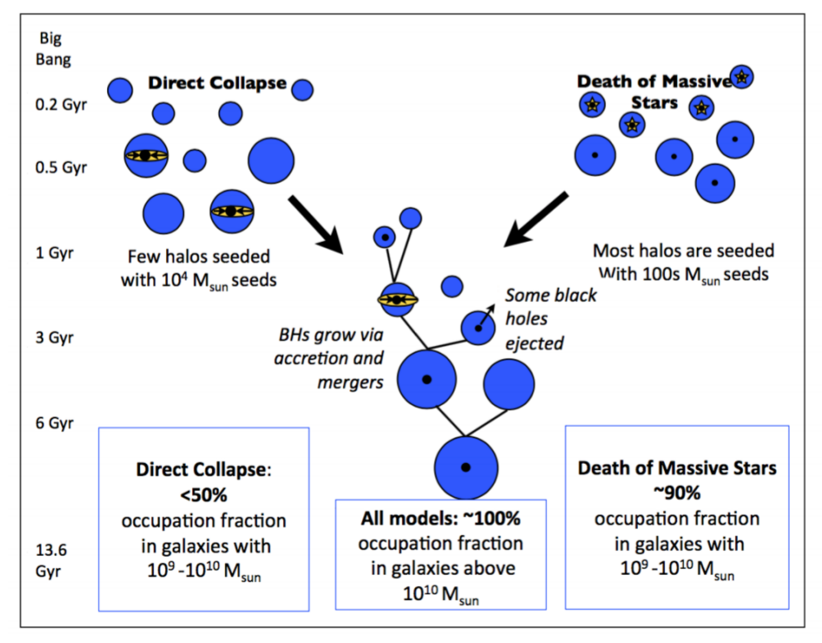
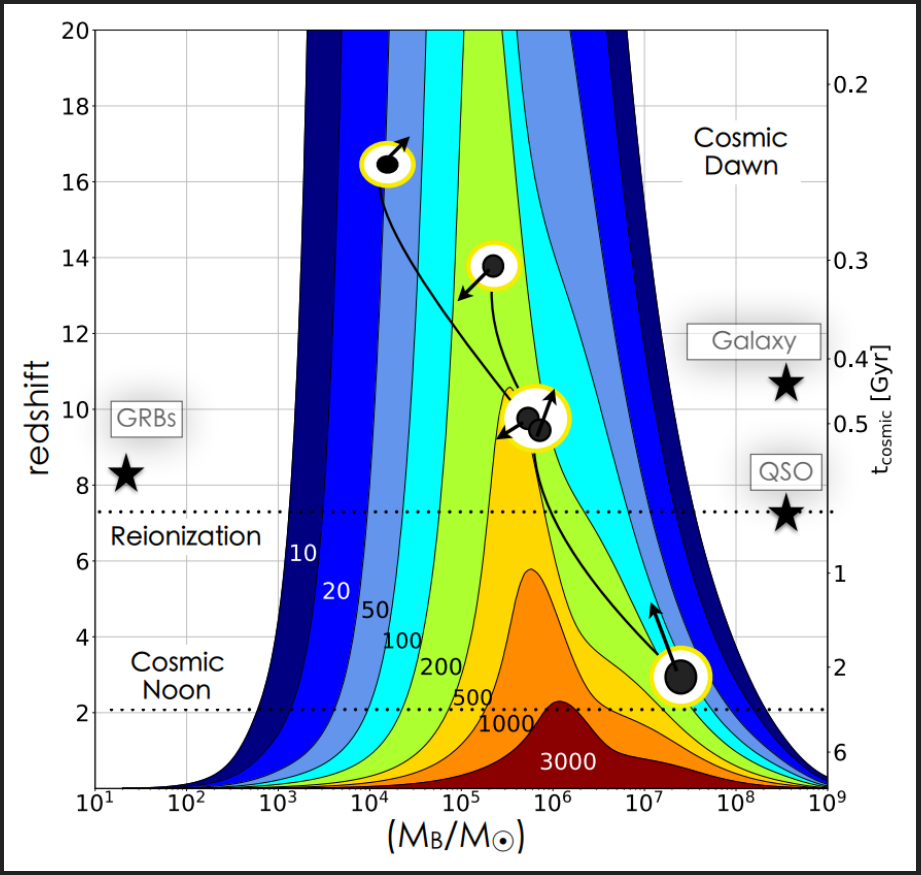


Gallo et al.

SYNERGIES WITH OTHER FACILITIES

- Gravitational Waves (LISA) :
  - **Explore the initial masses, occupation fraction, and early growth of the first seed BHs**: LISA will measure the masses and spins of coalescing MBHs to a few % accuracy in $10^4 - 10^7$ $M_\odot$ binaries out to $z \sim 20$.

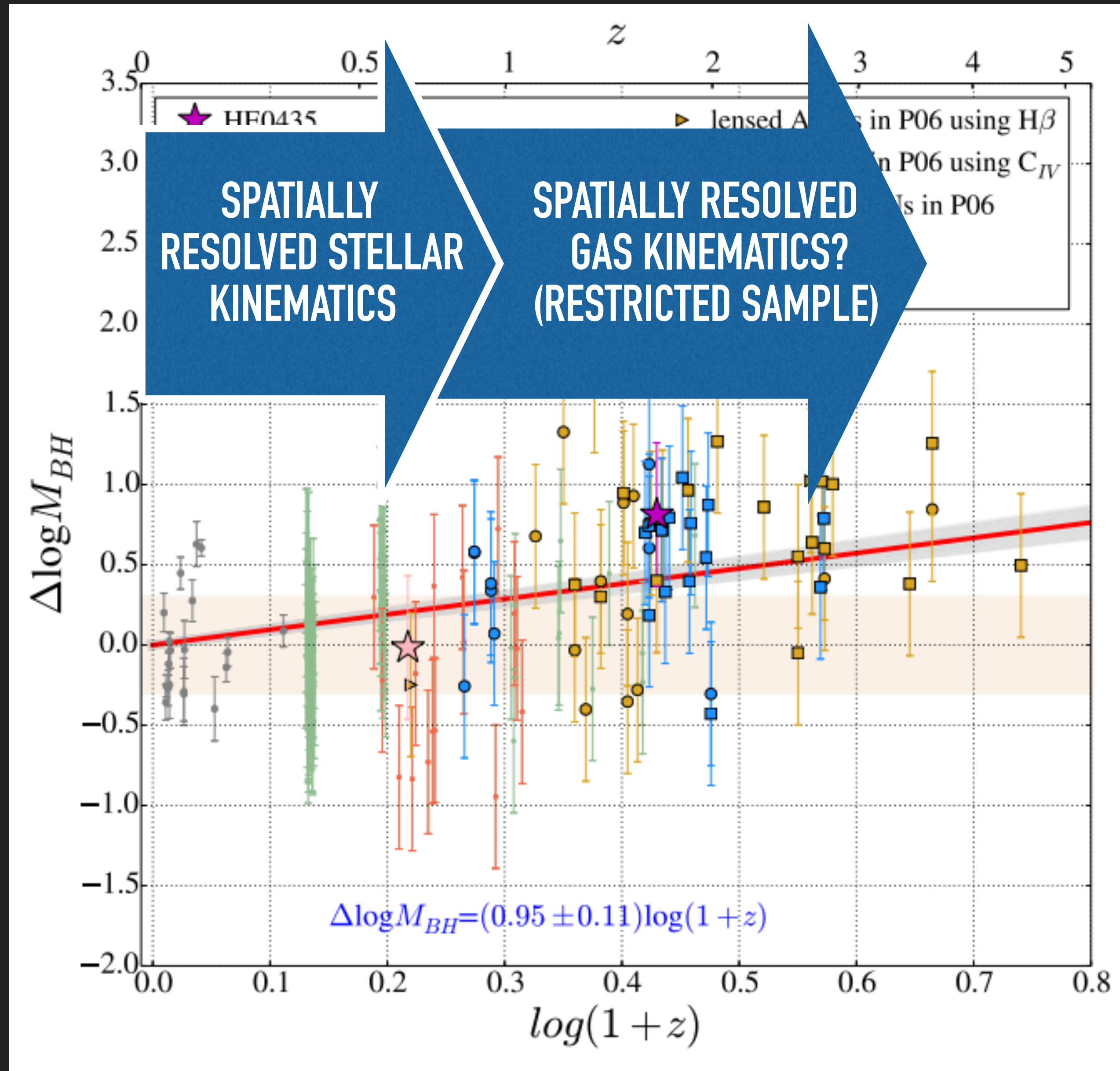
    LISA is expected to detect 2 – 20 mergers of ~ 10^5 $M_\odot$ heavy seeds in about 4 years of operation



Colpi et al. 2019

[See ASTRO2020 White Science Papers: Civano et al.; Colpi et al., Reines et al., Jacobs et al., Pacucci et al., Natarajan et al., Zoghbi et al, Gallo et al. 2019, Pasham et al., Kishimoto et al., …]

CONCLUSIONS



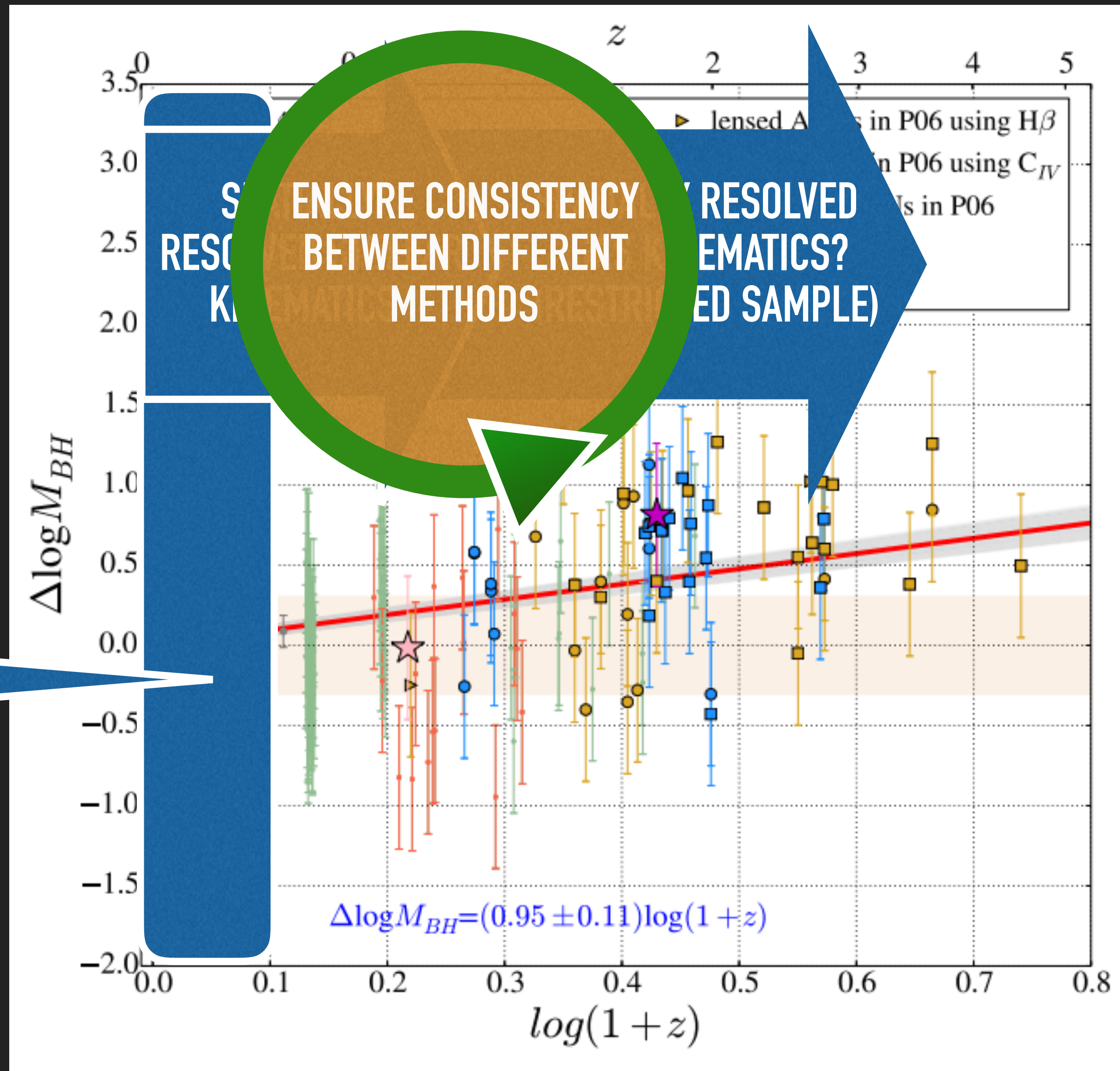
(b) Offset for $\mathcal{M}_{\rm BH}$-$L_{\rm total}$ relation using entire sample

Ding et al. 2017 (including data from Peng et al. 2006, Park et al. 2015; Bennert et al. 2010, 2011; Peterson et al. 2004; Schramm et al. 2013

CONCLUSIONS

ACCESS 100,000 GALAXIES AND GLOBULAR CLUSTERS WITH SMBH MASSES AS LOW AS 10^4:

- SECURE LOCAL SCALING RELATIONS AND EXPLORE DEPENDENCIES ON ENVIRONMENT, GALAXY PROPERTIES,..
- ADDRESS THE MASS OF SMBH SEEDS BY PROBING THE LOW-MASS END OF THE SMBH MASS FUNCTION
- EXPLORE THE CONSISTENCY OF DIFFERENT METHODS OF MEASURING SMBH MASSES (STELLAR DYNAMICS/ GAS DYNAMICS/REVERBERATION MAPPING)



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