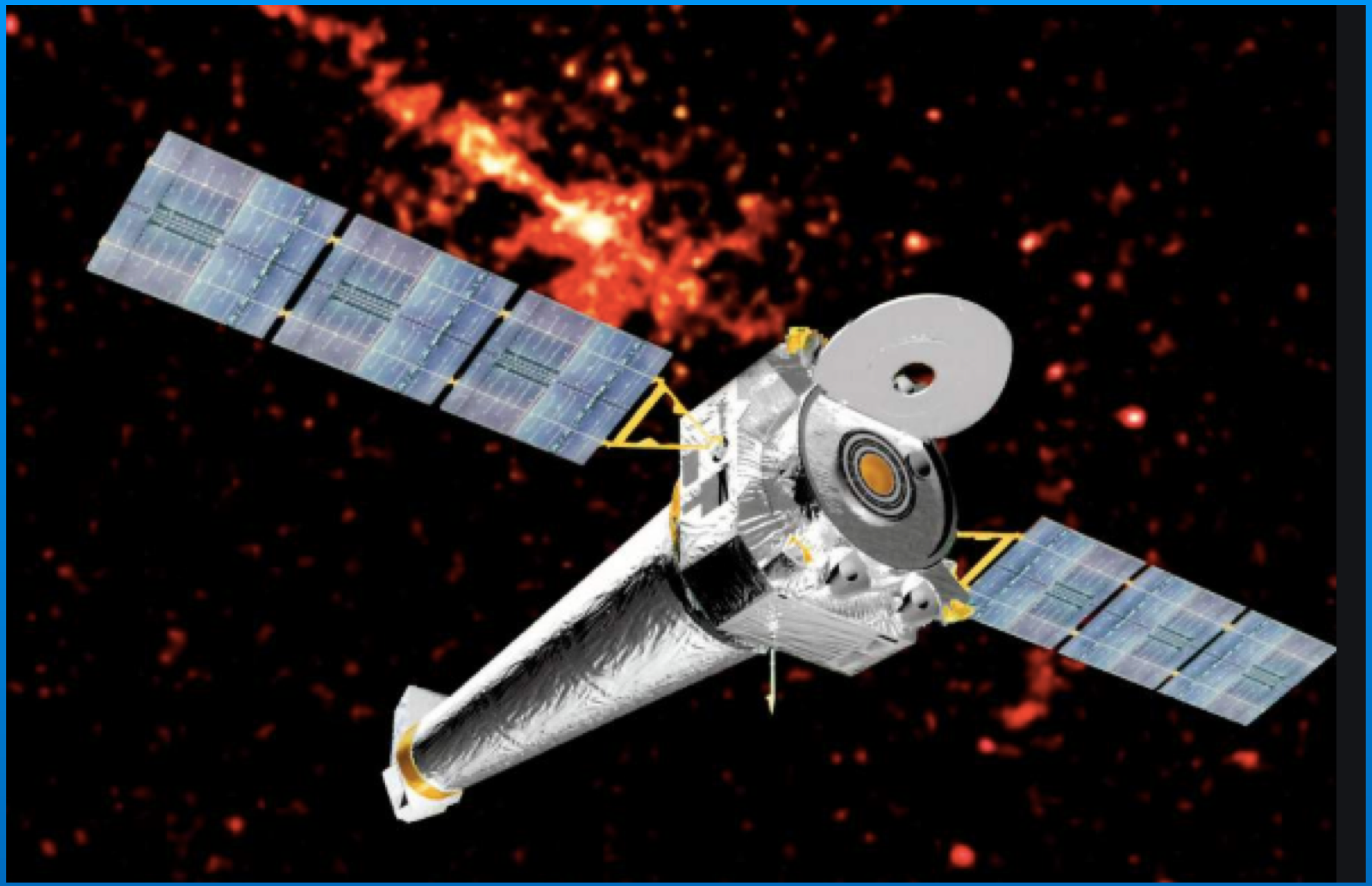
UNVEILING SUPERMASSIVE BLACK HOLES IN THE NEAR & FAR UNIVERSE



TWENTY YEARS OF CHANDRA SCIENCE SYMPOSIUM
December 3 - 6, 2019

THANKS TO GIACCONI & TANENBAUM

PRIYAMVADA NATARAJAN
Yale University

TALK OUTLINE

CURRENT STATUS OF OUR UNDERSTANDING OF SUPERMASSIVE BLACK HOLES (SMBHs)
From individual sources to the population to the deep fields

THE FORMATION OF SEED BLACK HOLES AT HIGH REDSHIFT
Light & Massive Initial Seeds of SMBHs

THE FUELING AND GROWTH OF SMBHs
Accretion of gas & Luminosity Output from SMBHs; Role of Mergers

FEEDBACK FROM ACCRETING SMBHs
How SMBHs couple to their host galaxies and environments

THE BIG OPEN QUESTIONS
IMBHs: where are they?
UMBHs: how common are they?
Obscured SMBHs: how incomplete is our census?
BH seeds: when and how do they form?

KEY PHYSICS CHALLENGE OF SCALES
INTERPLAY OF STARS, GAS AND DARK MATTER

FOR A MILLION SOLAR MASS BH

Schwarzchild radius 10^{12} cm

$$\mathbf{R = 2\ GM/c^2}$$

Galactic nucleus 10^{20} cm

Stellar extent of galaxy 10^{22} cm

Dark Matter Halo of galaxy 10^{23} cm

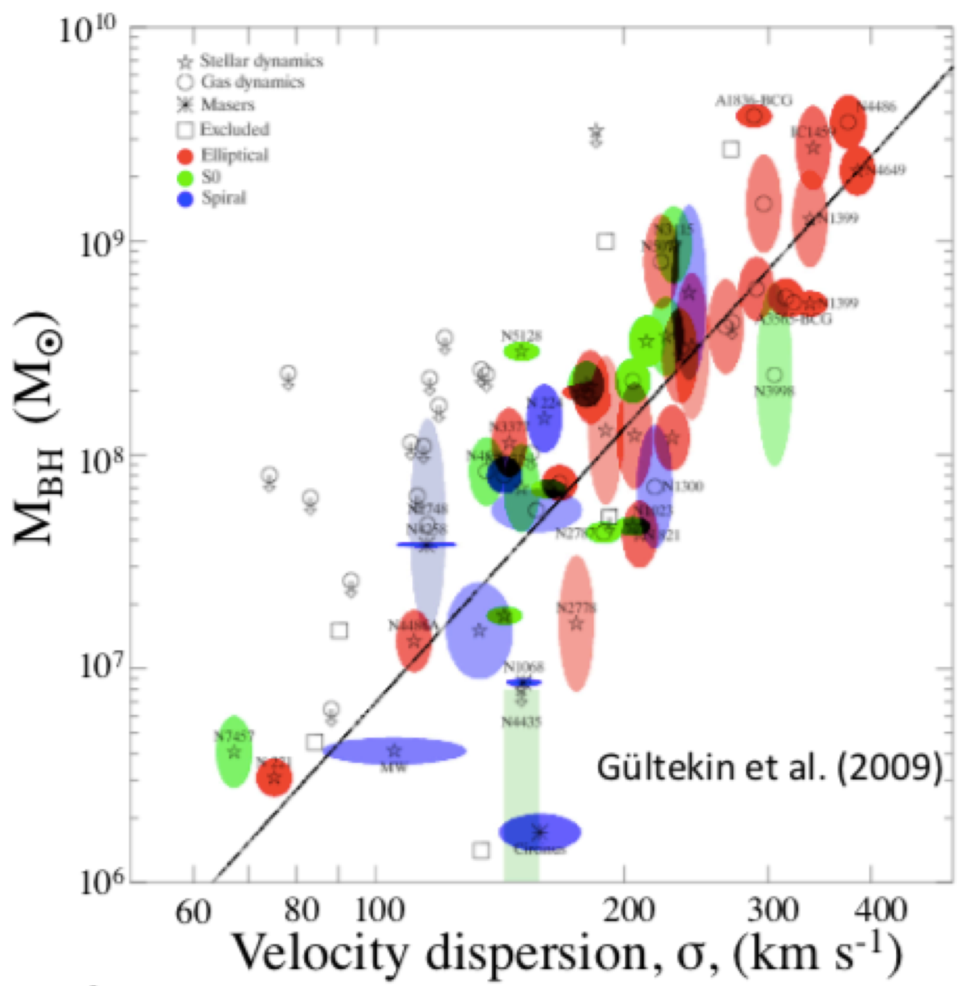
Cosmological scales 10^{26} cm

GROWTH HISTORY OF ACTIVE SMBHs FROM CHANDRA

SMBHs with M_{BH}~10^6 - 10^{10} $M_\odot$ are found at the centres of most (if not all) galaxies in the local Universe

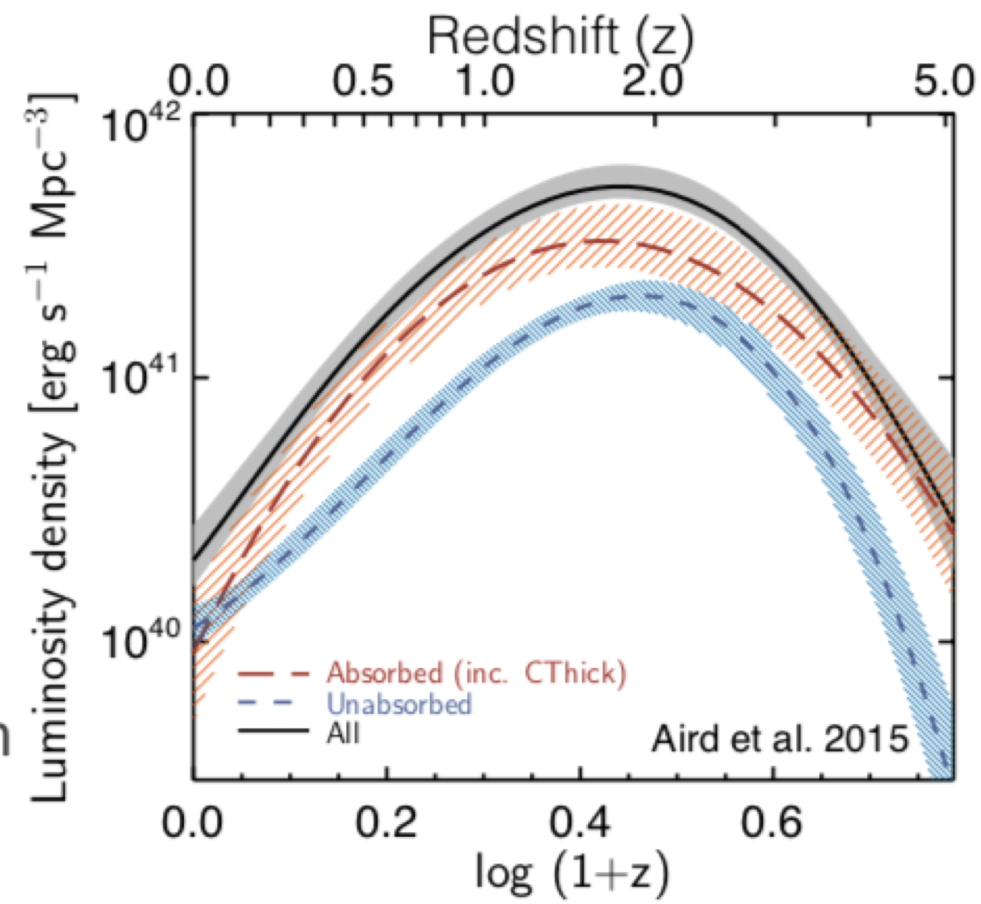
Bulk of SMBH mass is built up via accretion (AGN), peaking at z~1-3

SMBH mass



~host galaxy bulge mass

Rate of SMBH growth via accretion



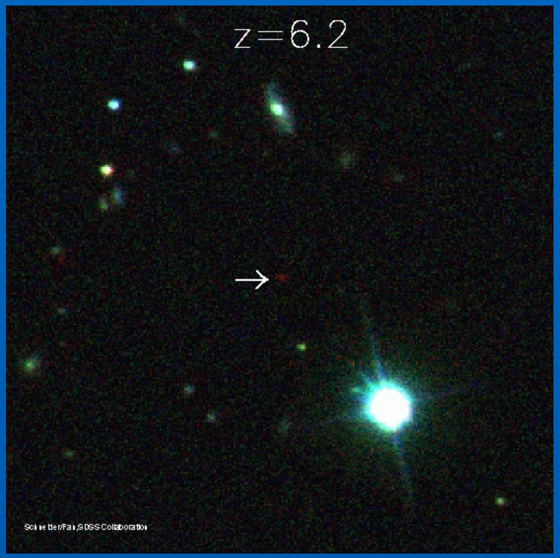
Late (recent) cosmic time

Early cosmic times

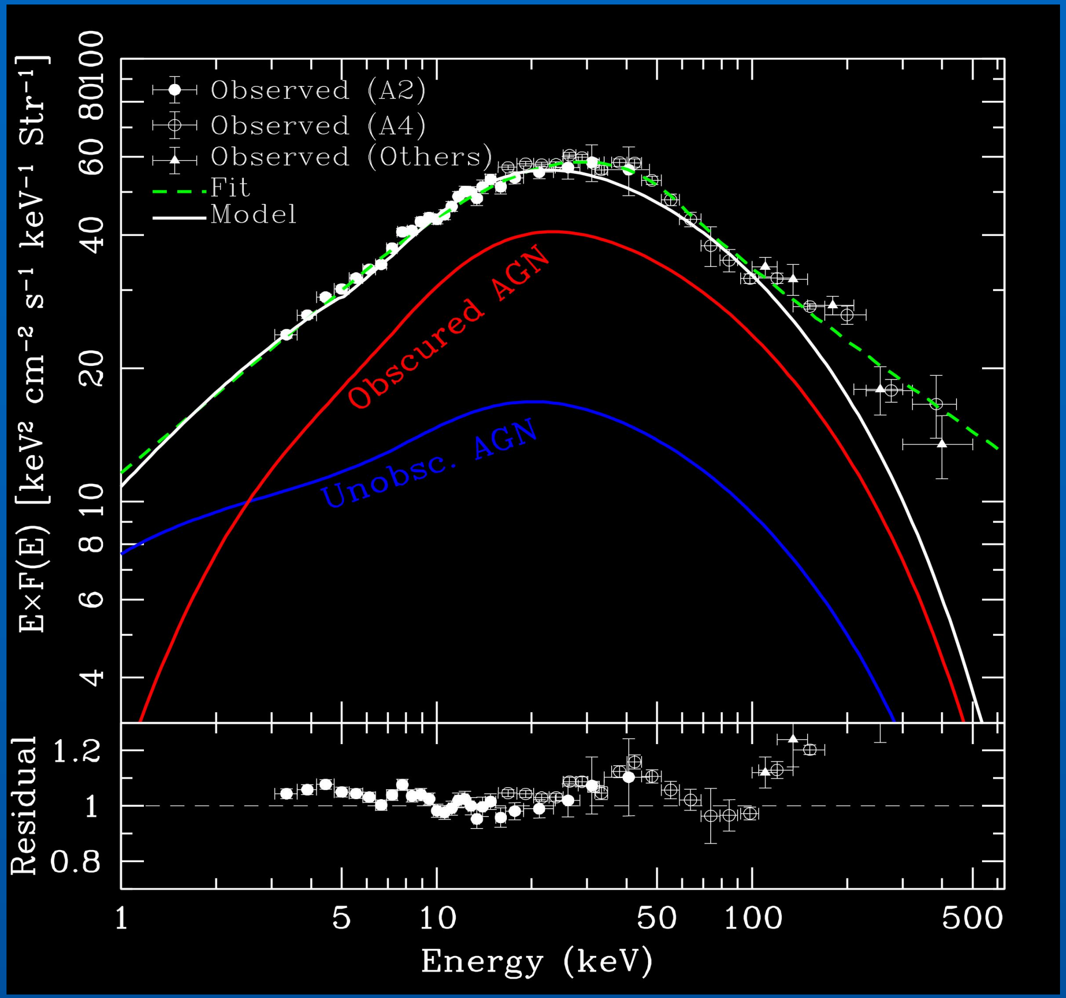
Gultekin+; Aird+; Treister+; Alexander+; PN+; Gilli+; Hasinger+; Merloni & Heinz

CHANDRA REVEALED ACTIVELY ACCRETING SOURCES & MULTI-WAVELENGTH COUNTER-PARTS

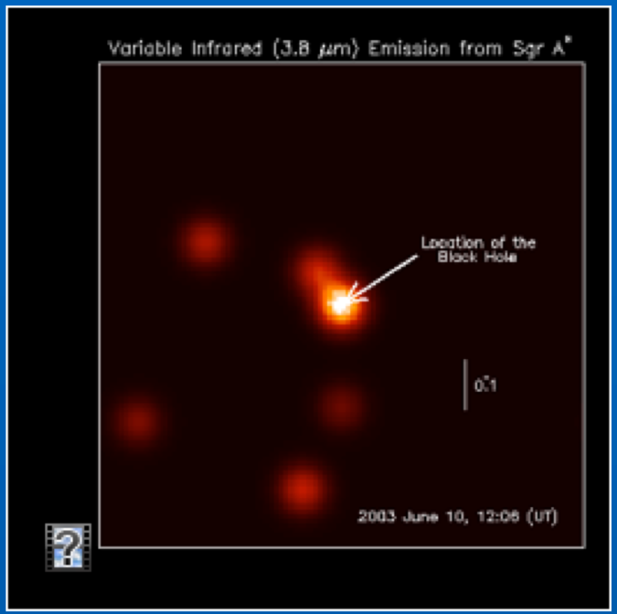
Observed quasars

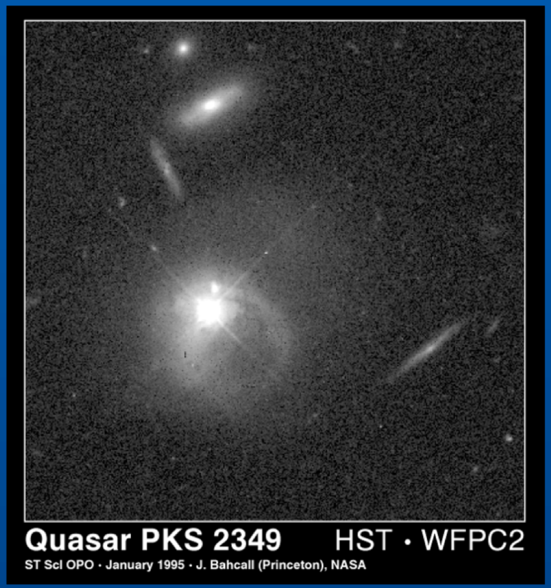


CXRB



z=0

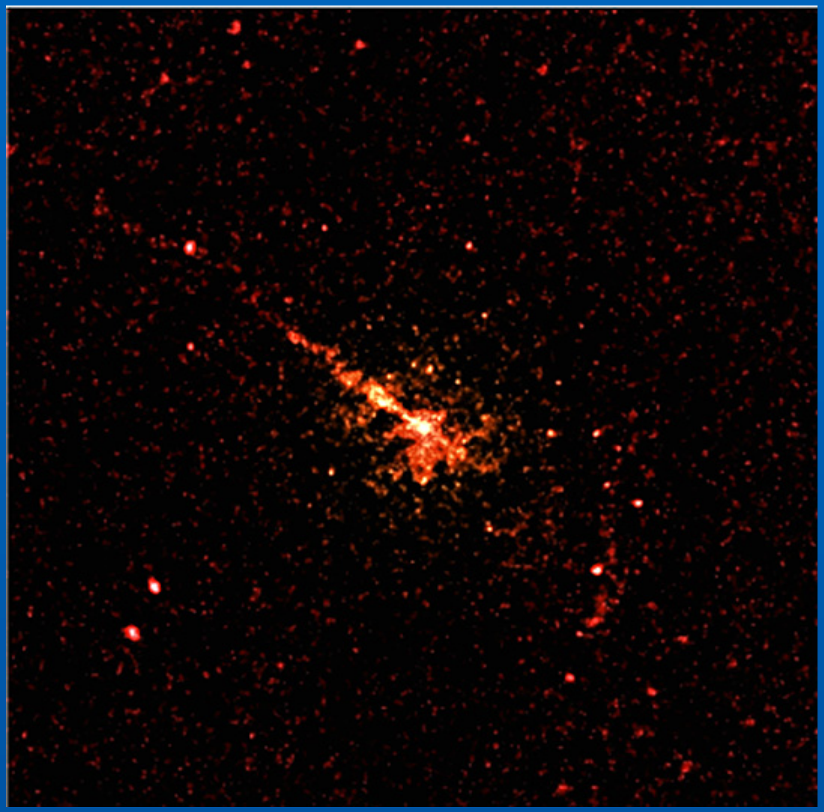


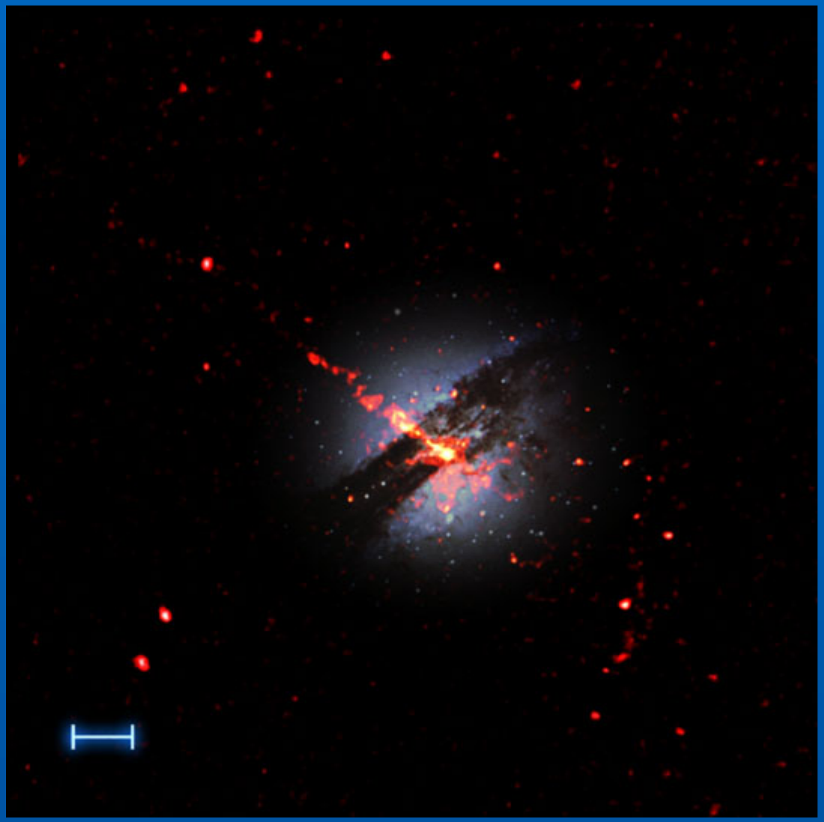


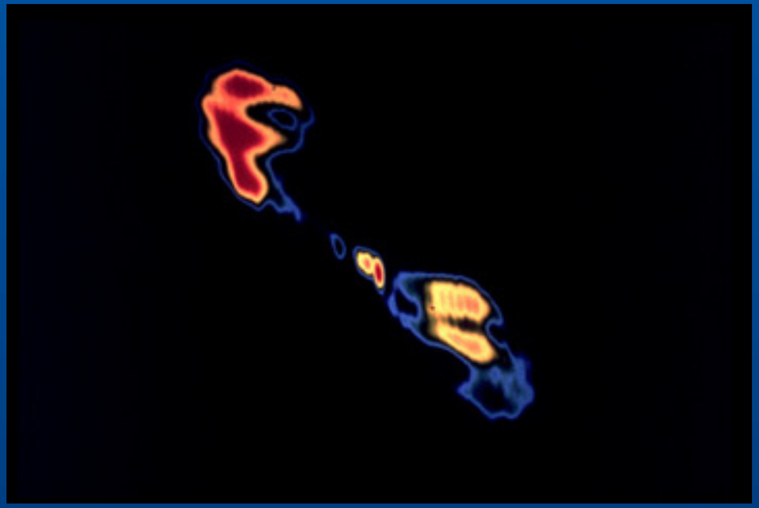
Urry+; Treister+; Scoville+; Sanders; Faber+;Wu+; Ferguson+; Harrison+; Hasinger+; Comastri+; Gilli+

SMBHs: FROM THE MARGINAL TO STARRING ROLE
Chandra data bridged scales for individual sources

1999 CXC Press Release of Centaurus A (NGC 5128)

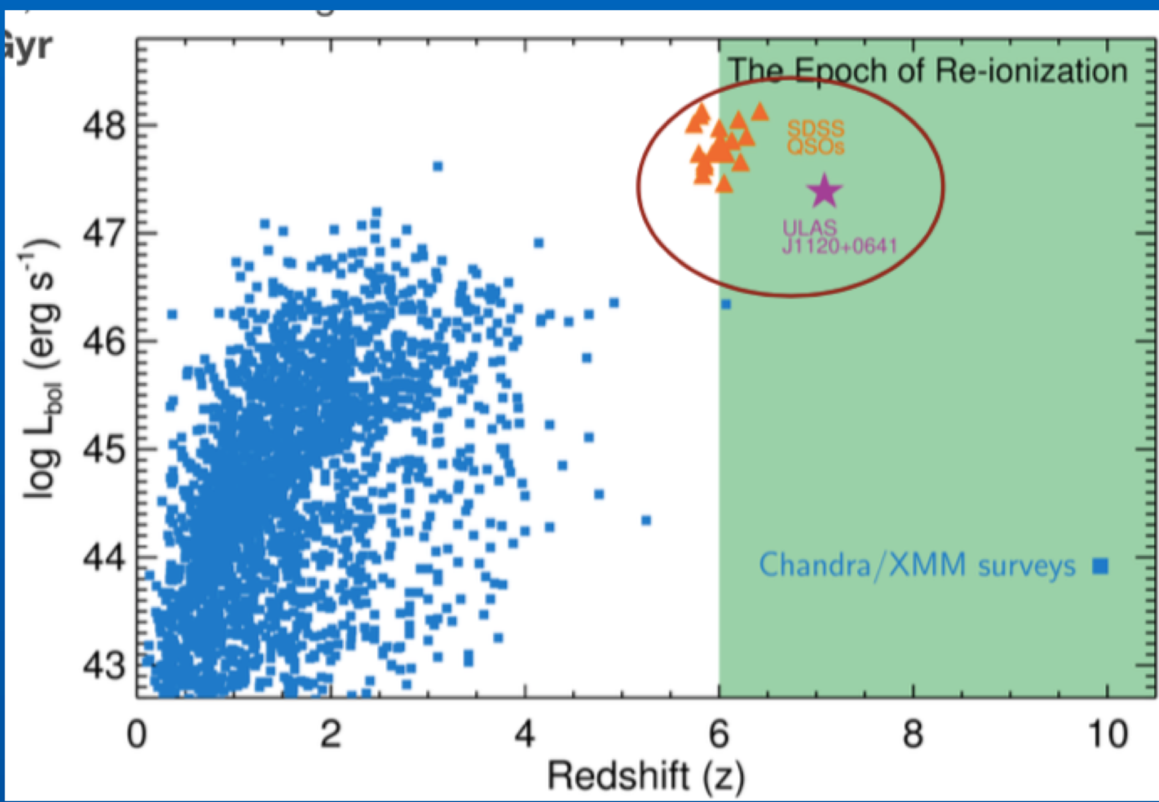


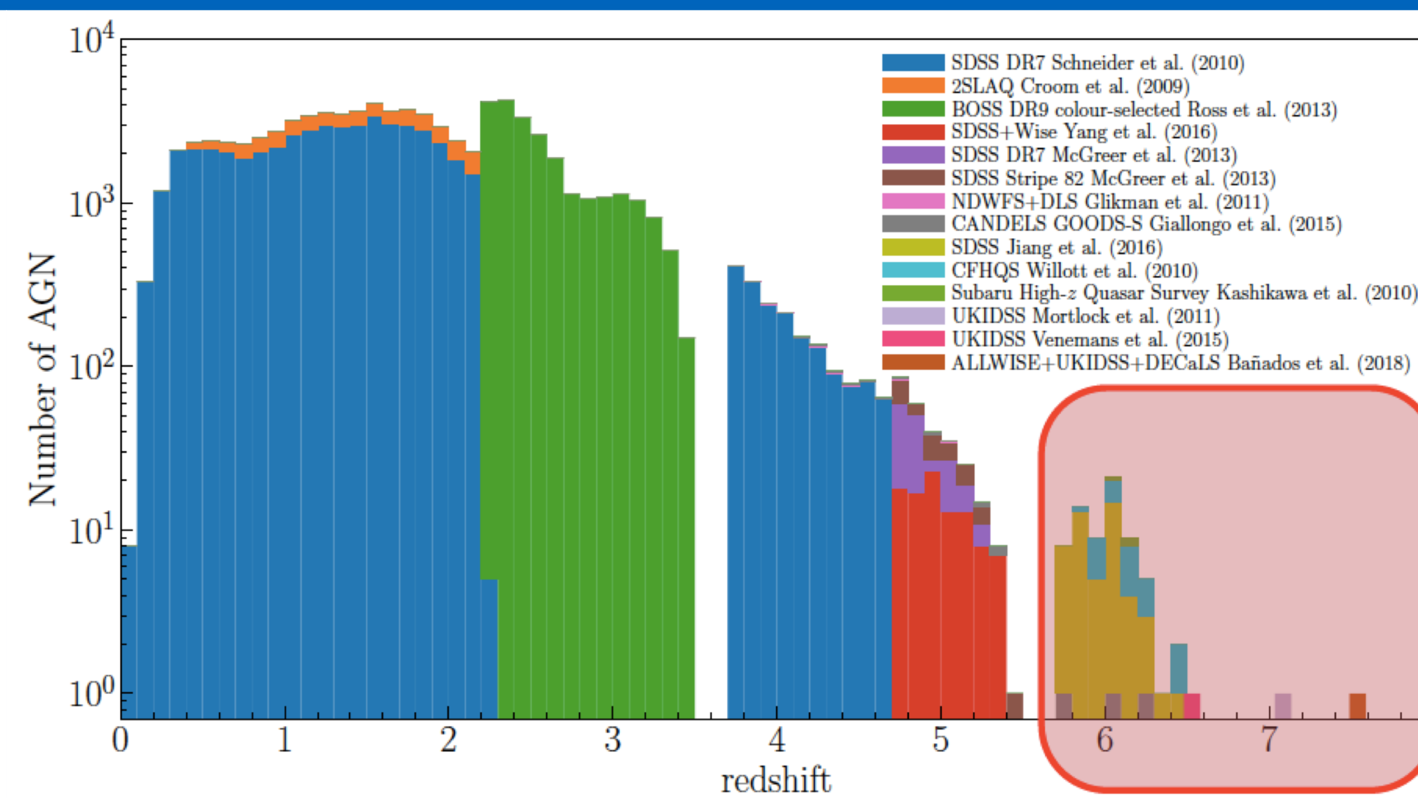




UNVEILING ACCRETING POPULATIONS OF SMBHs

CHANDRA DATA extended our knowledge to z ~ 5 spanning luminosity range





AGN dominate over X-ray emission from host galaxy

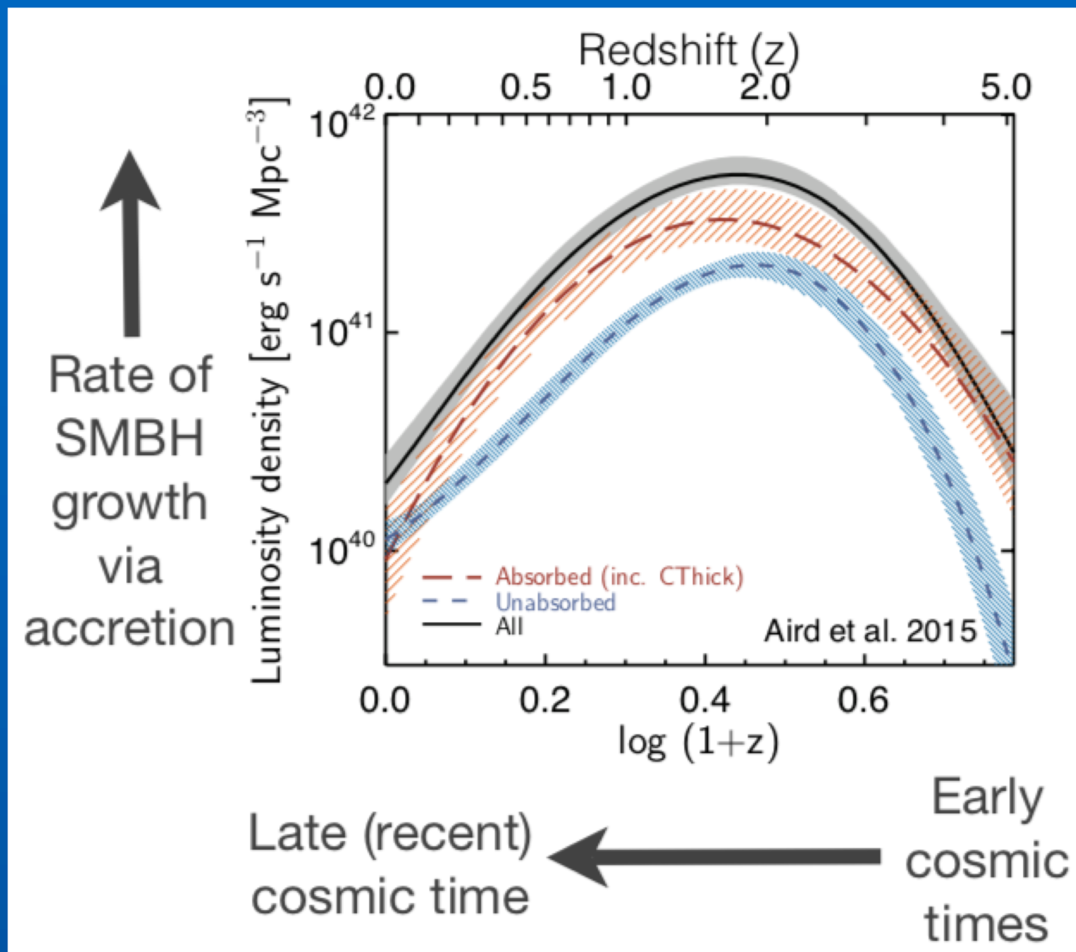
Fainter AGN missed in Optical/IR

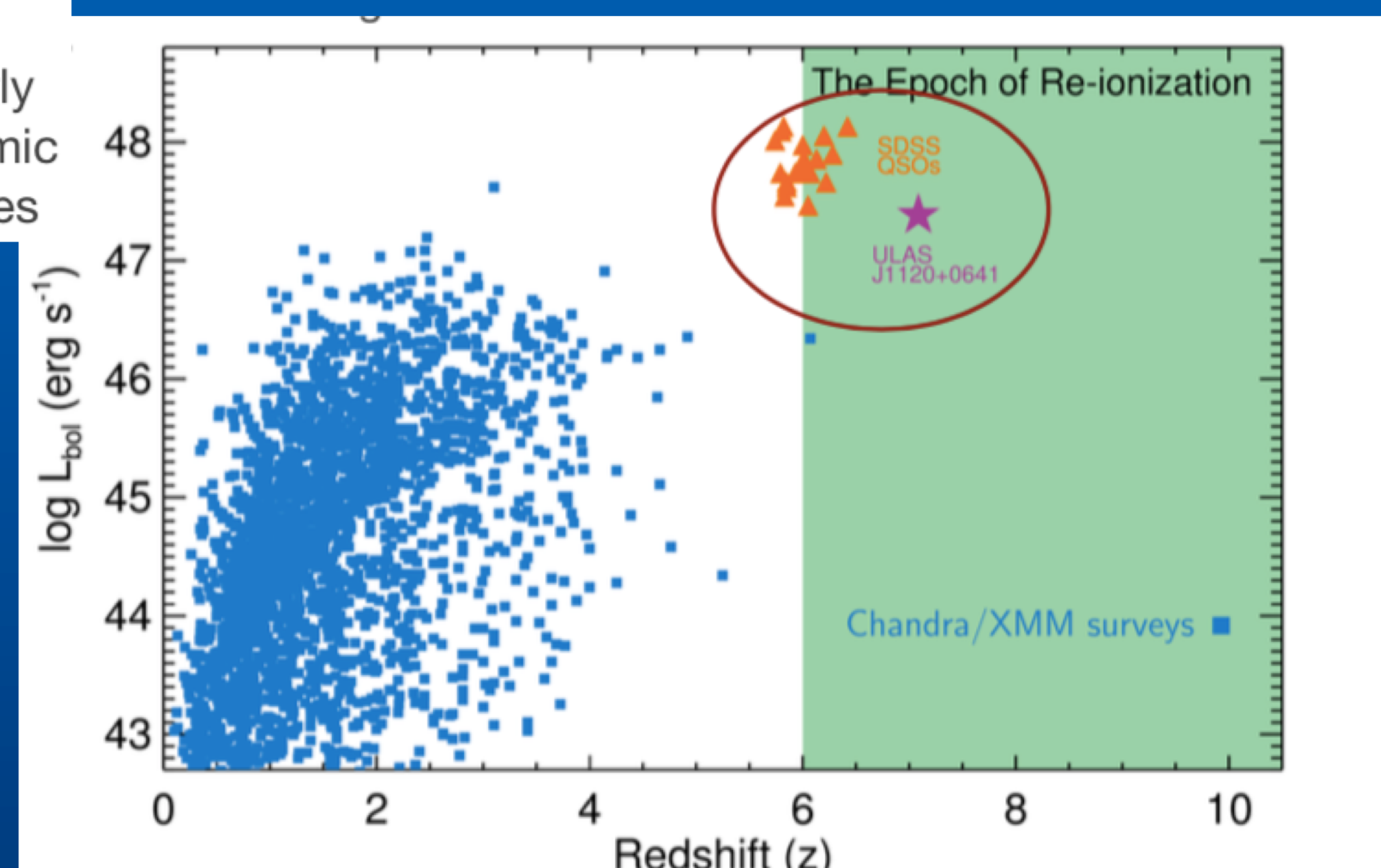
Less affected by obscuration than Optical/UV

Banados+ 17; 18; Kulkarni+ 18; PN & Volonteri 14; Trakhtenbrot+17

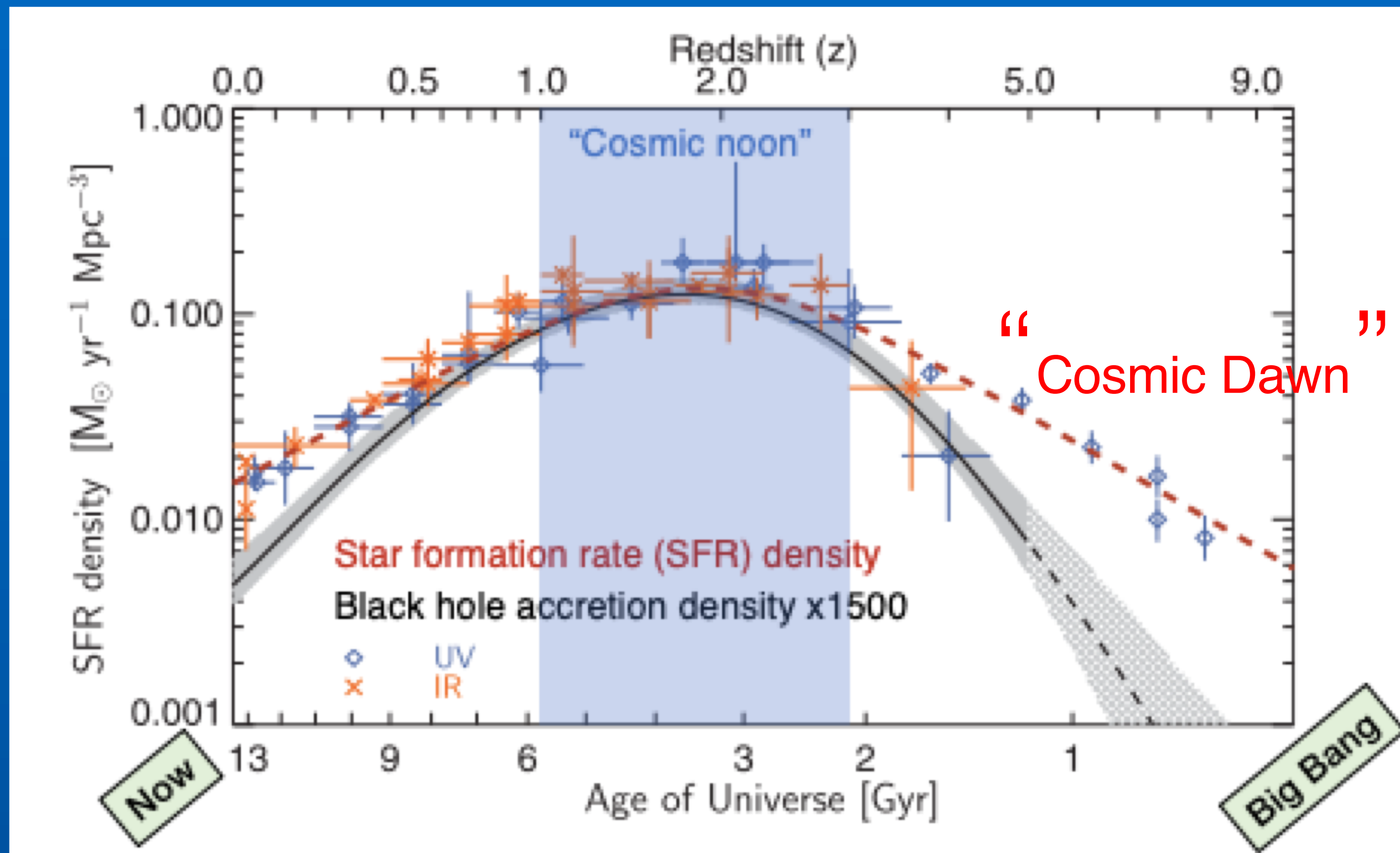
EFFICIENCY OF X-RAY SURVEYS IN AGN CENSUS

CHANDRA DATA extends to z ~ 5
Mapping AGN population
&
ANCHORS MODELS

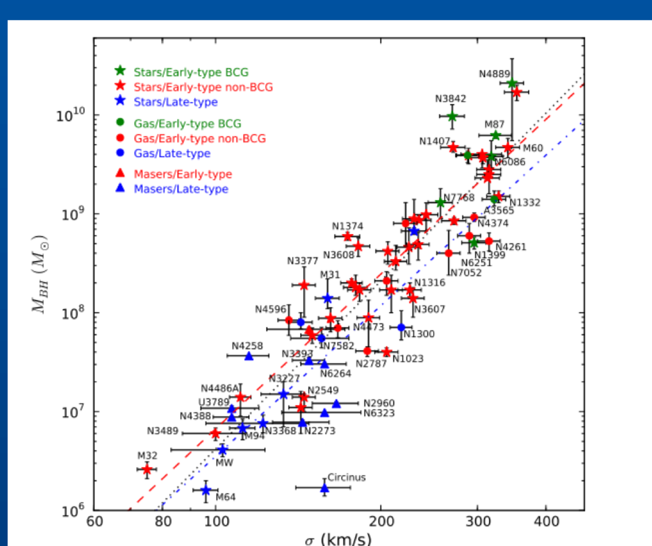


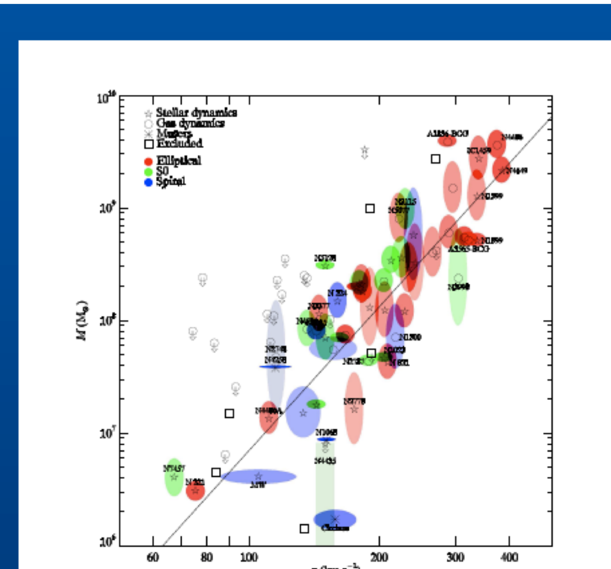


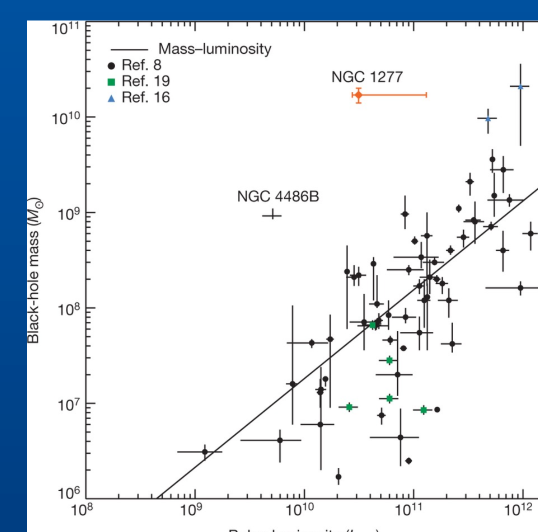
CO-EVOLUTION OF GALAXIES & BLACK HOLES OVER COSMIC TIME



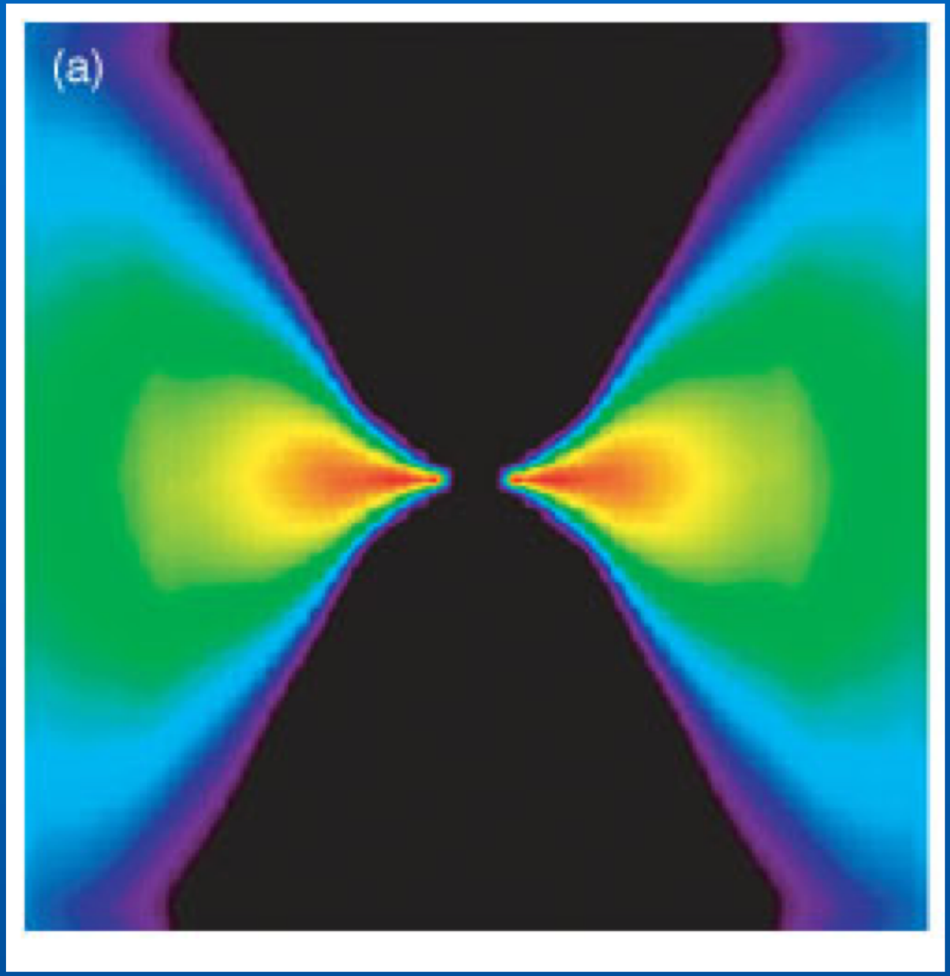
Mullaney+; Elbaz+;
Barger+;
Madau & Haardt;
Shankar+; Brusa+;
Cimatti+;
Treister+;





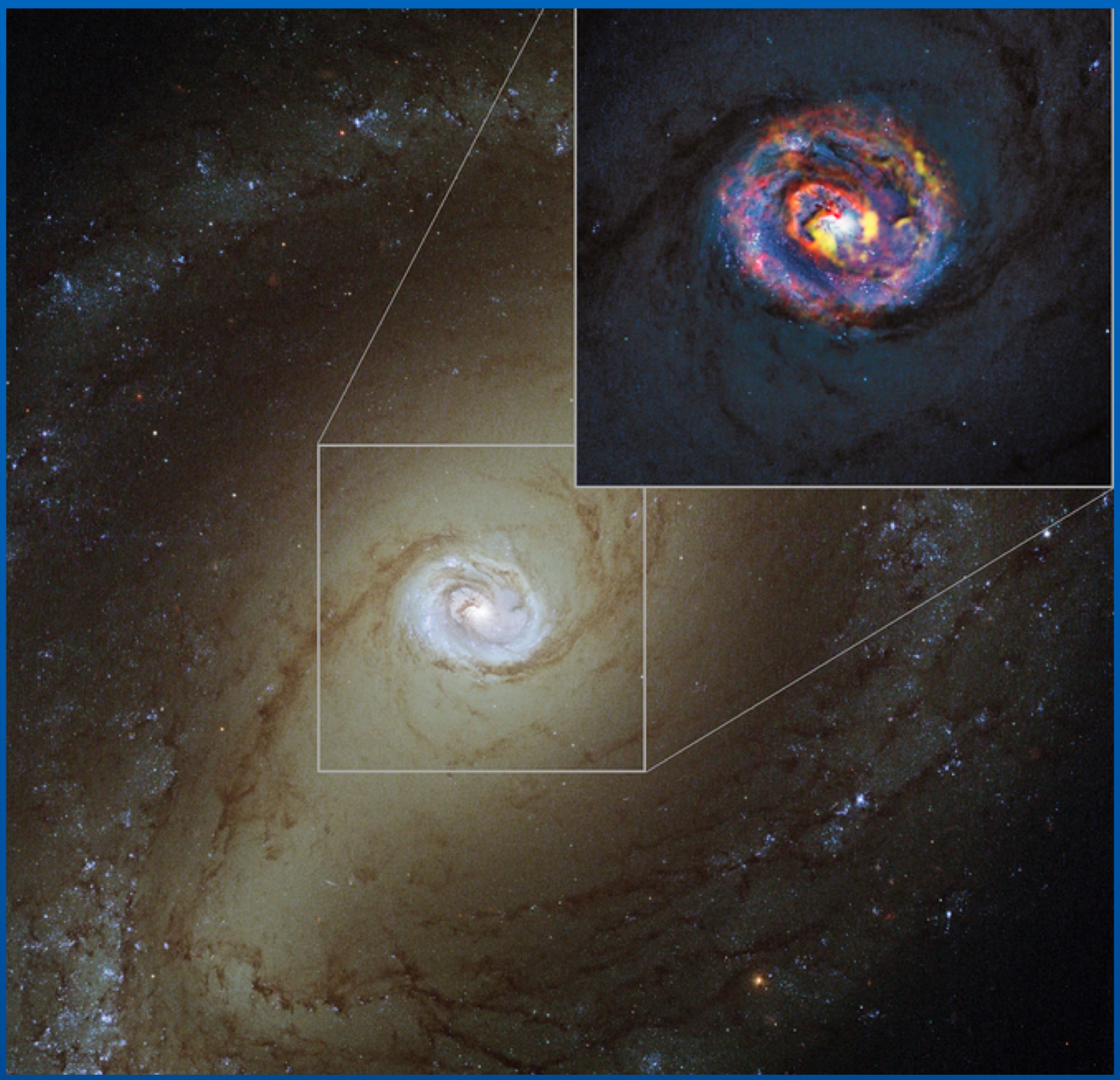


HOW DO BLACK HOLES GROW ?

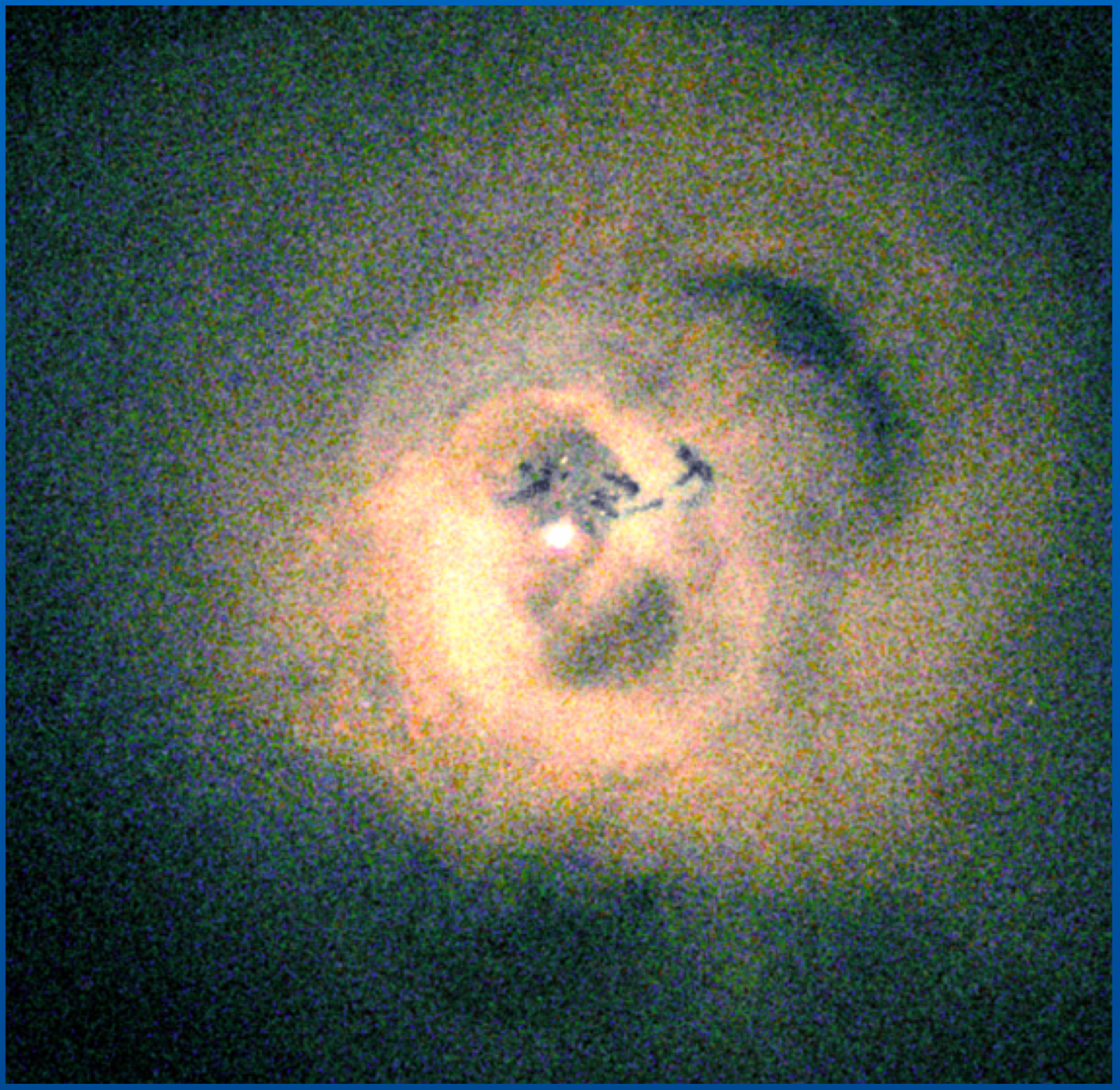


Accretion
Merger-triggered accretion
BH Mergers

EVIDENCE FOR IMPACT OF BHs ON THEIR ENVIRONMENT



On the smallest scales ALMA data of NGC 1433 outflows & molecular disk

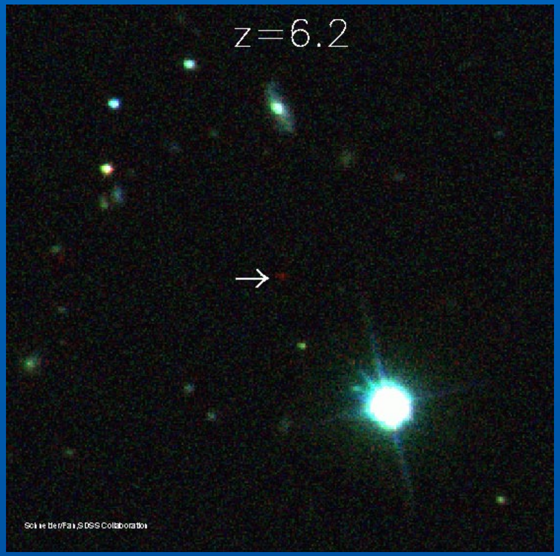


On the largest scales CHANDRA data of the Perseus cluster outflows & shells

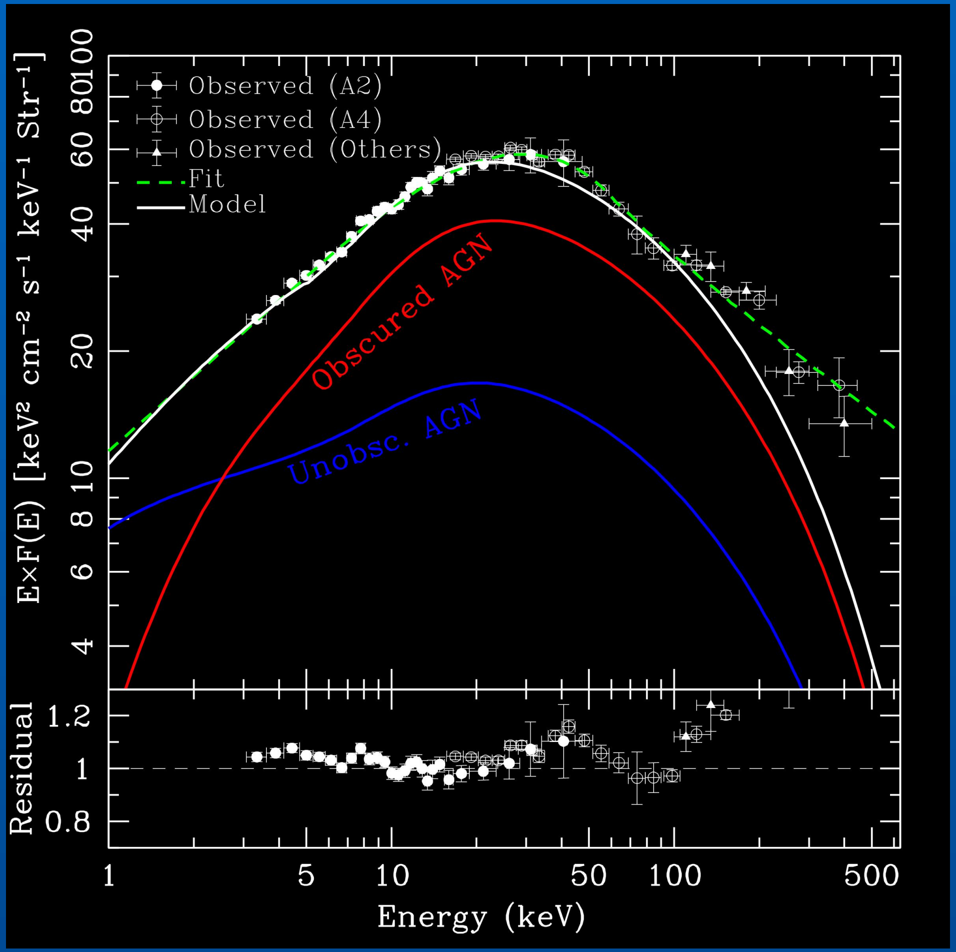
OBSERVATIONAL CONSTRAINTS FOR BH GROWTH MODELS

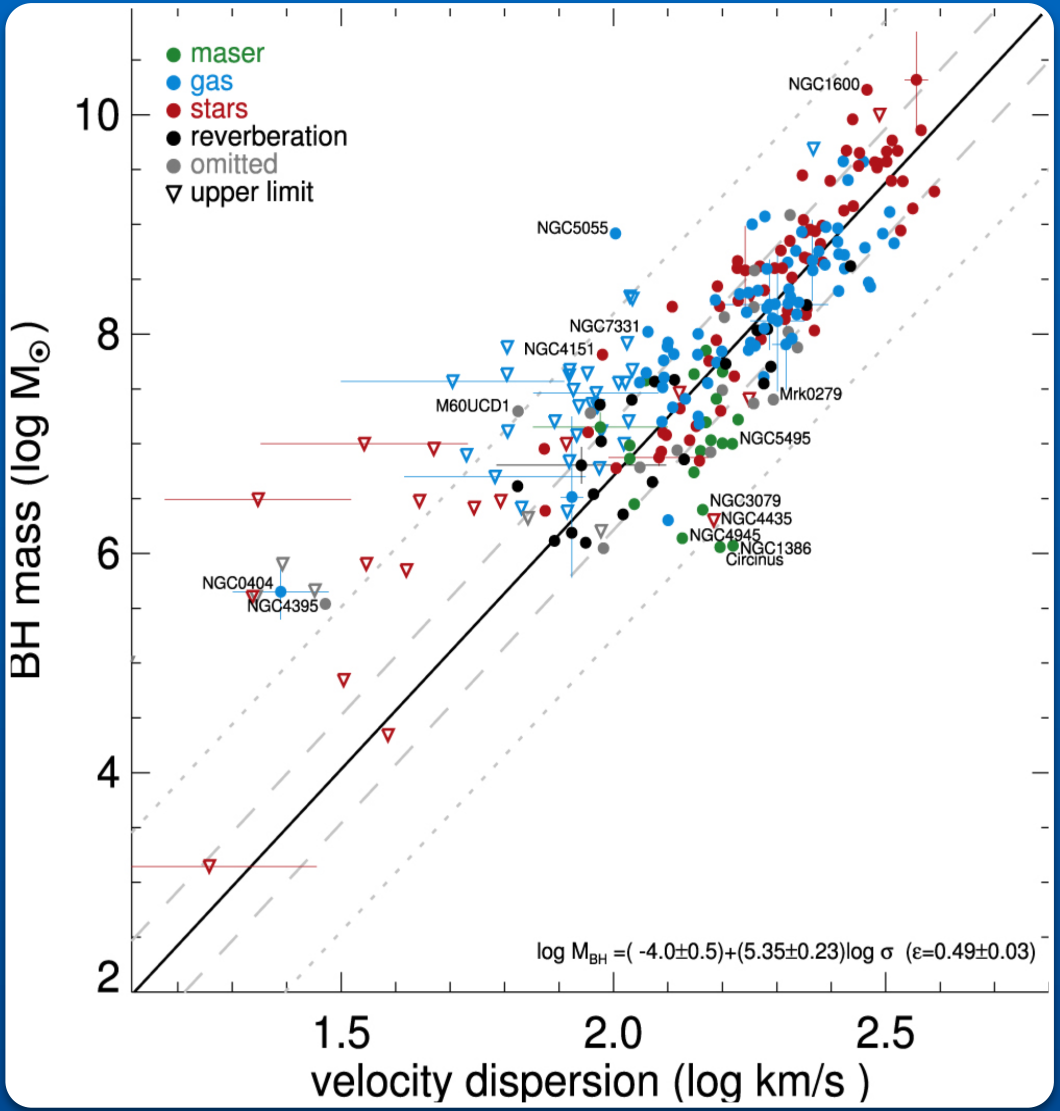
z=0

Abundance & LF of high & low z quasars



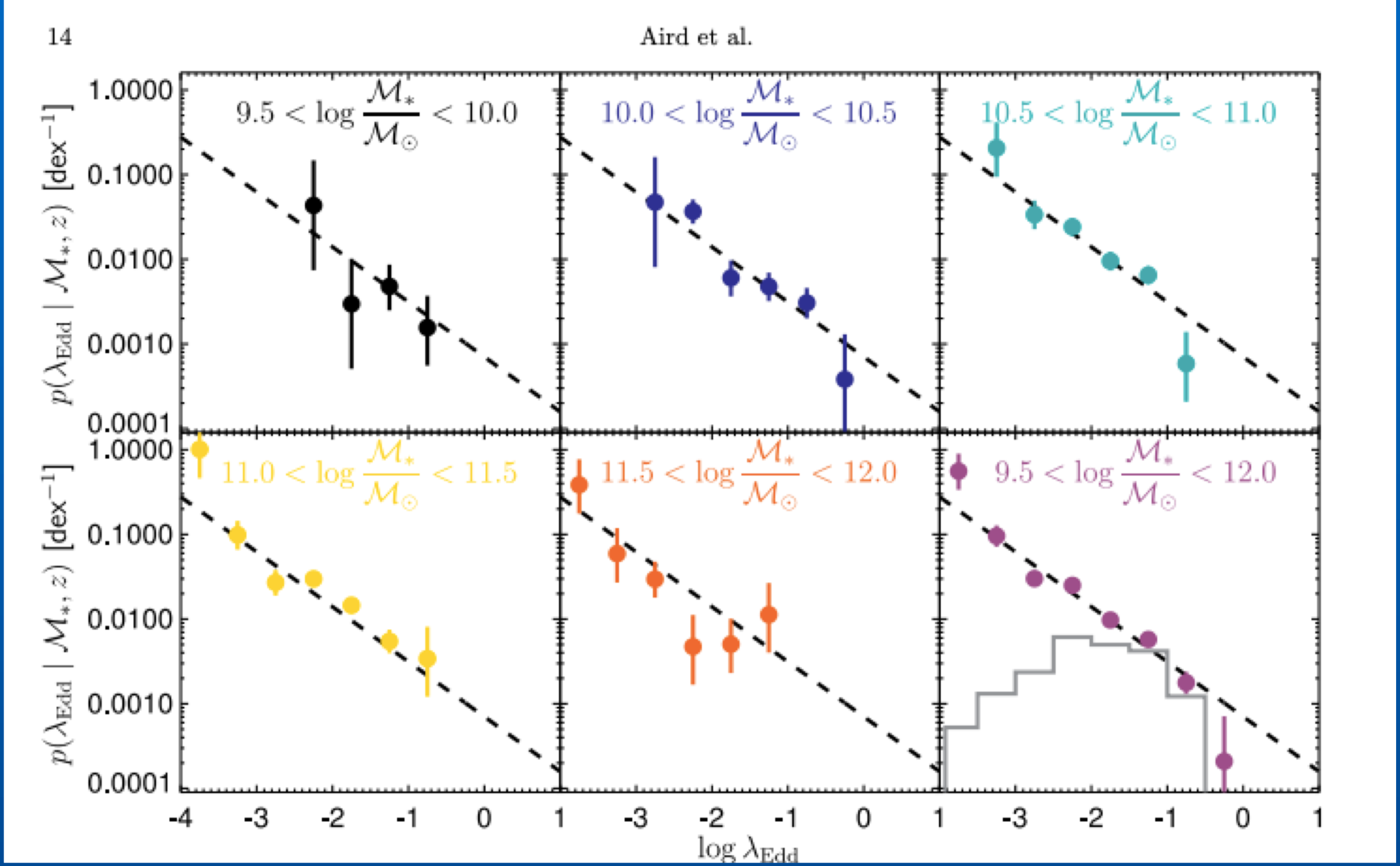
CXRB





Lauer+ 05, 06; Bernardi+ 06; PN & Treister 09; McConnell+ 11,12; PN & Volonteri 13; Marziani & Sulentic 12; Mortlock+ 14; Wu+ 2015; Kulier+15; Thomas+ 16; van den Bosch+ 16; Reines+ 14; McConnell+ 13; Jiang, Greene & Ho 11; Gultekin+09 Ferrarese+ 2006; Ferrarese & Merritt 2002; Tremaine+ 2002; Kaspi+ 2005; Cowie+ 14; 17; ; Barger+ 03; 14 Census from SDSS and 2dF Fan+ 2007; Croom+ 2004; Comastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004;

EDDINGTON RATIO DISTRIBUTION & ITS EVOLUTION WITH z



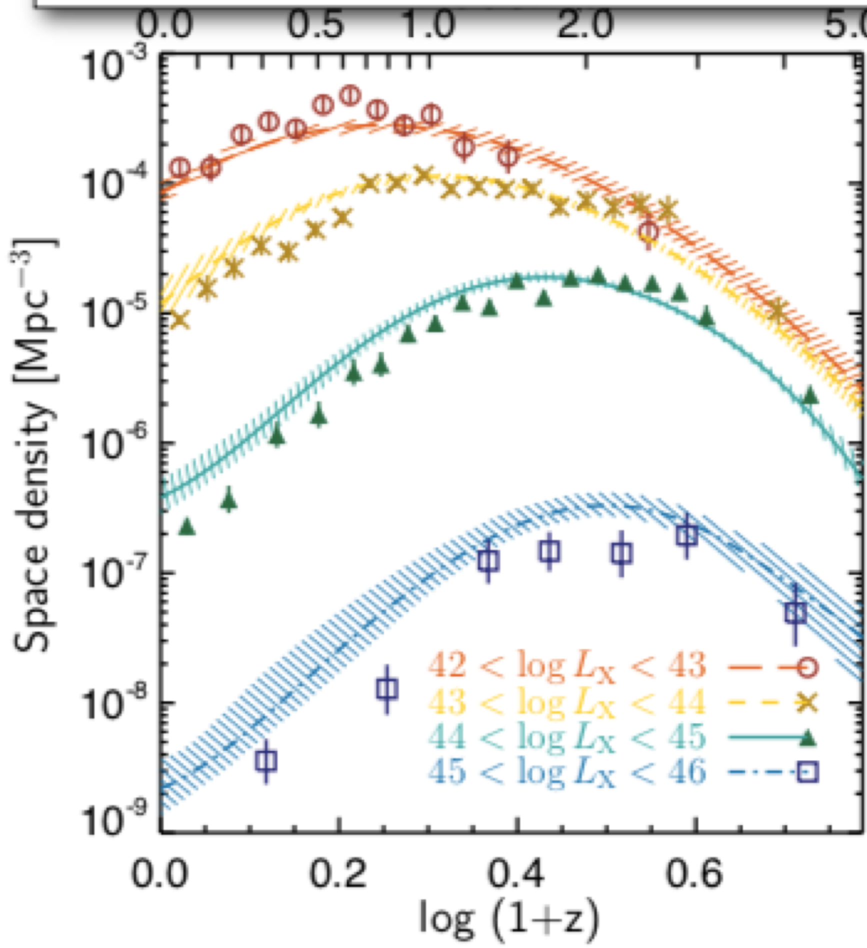
KEY INPUT TO AGN DEMOGRAPHIC MODELS

flickering on short time-scales?

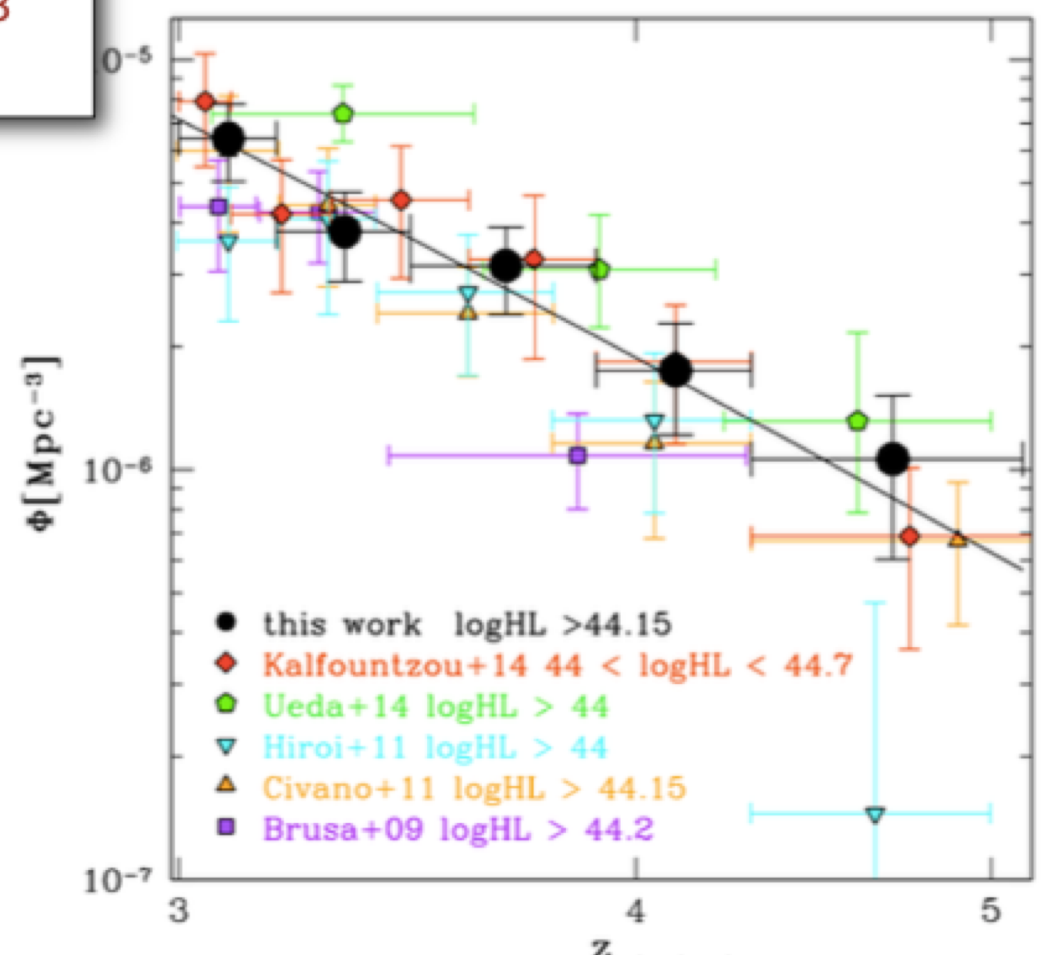
Elvis+; Sieminginowska+; Narayan &Yi; Fabbiano+; McDowell +

EVOLUTION OF THE SPACE DENSITY OF AGN
z = 0 - 5

- **Luminosity-dependent** evolution
- Strong decline in space densities at $z > 3$ for **all** luminosities



Data points= Miyaji et al. (2015)
Lines+shading = Aird et al. (2015)



High redshift →

Vito et al. (2014)
see also Georgakakis et al. (2015), Weigel et al. (2015)

SYSTEMS APPROACH TO THE PROBLEM

LSS framework

Cosmological Simulations
LCDM model

Initial Seeding

Seed formation
Analytic model
Early seed Growth
Simulations

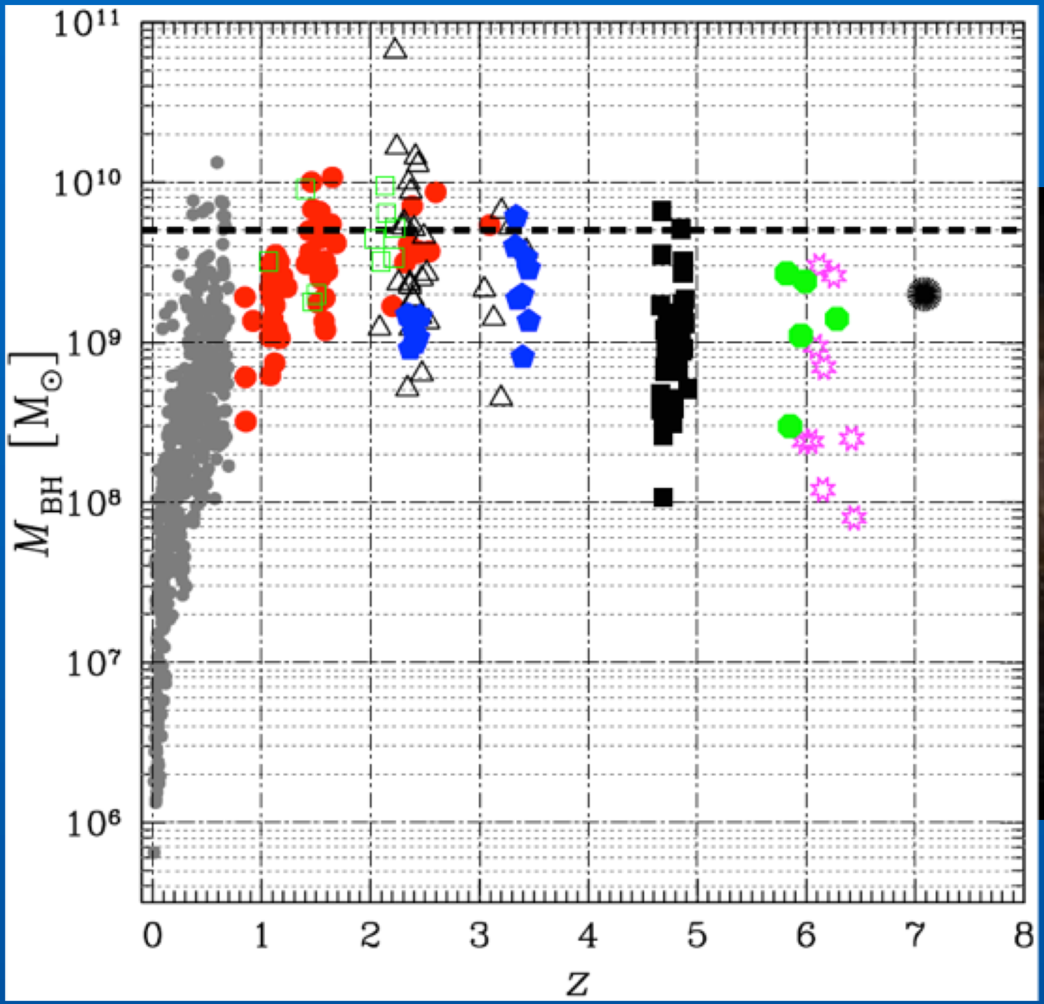
Accretion Physics

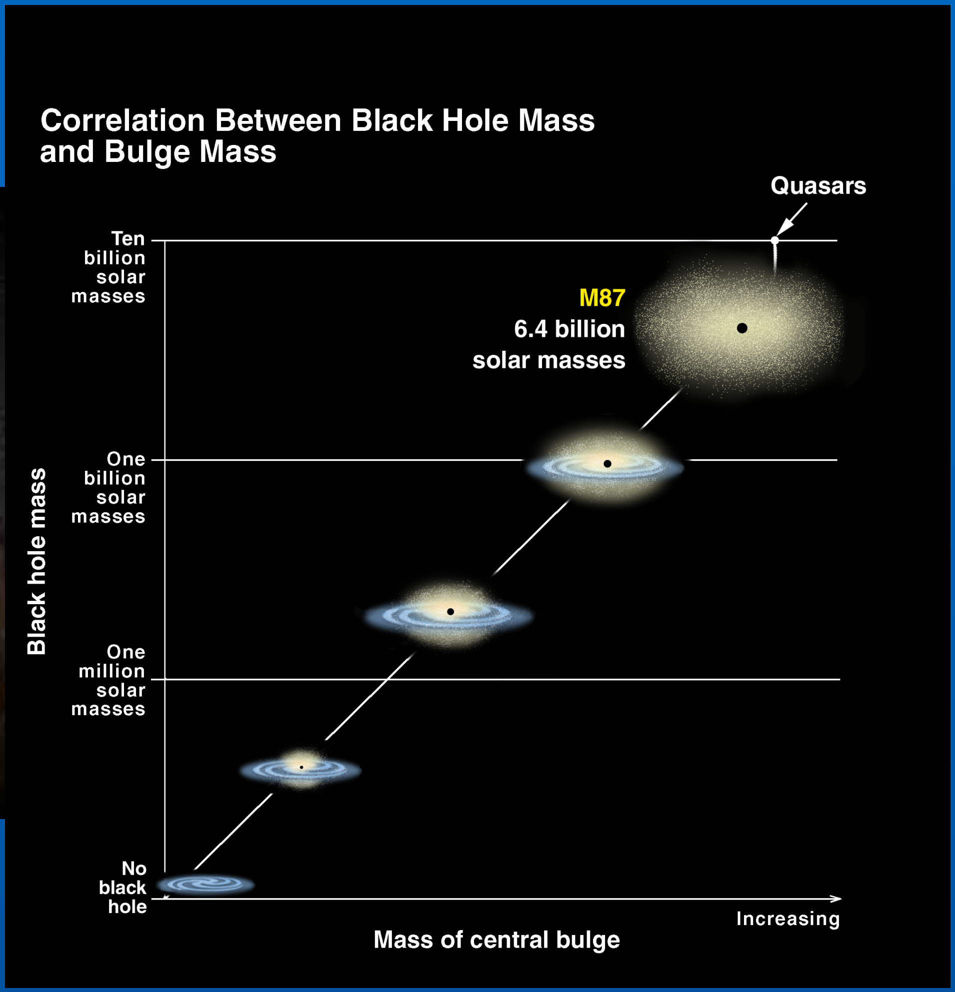
High resolution
GRMHD simulations

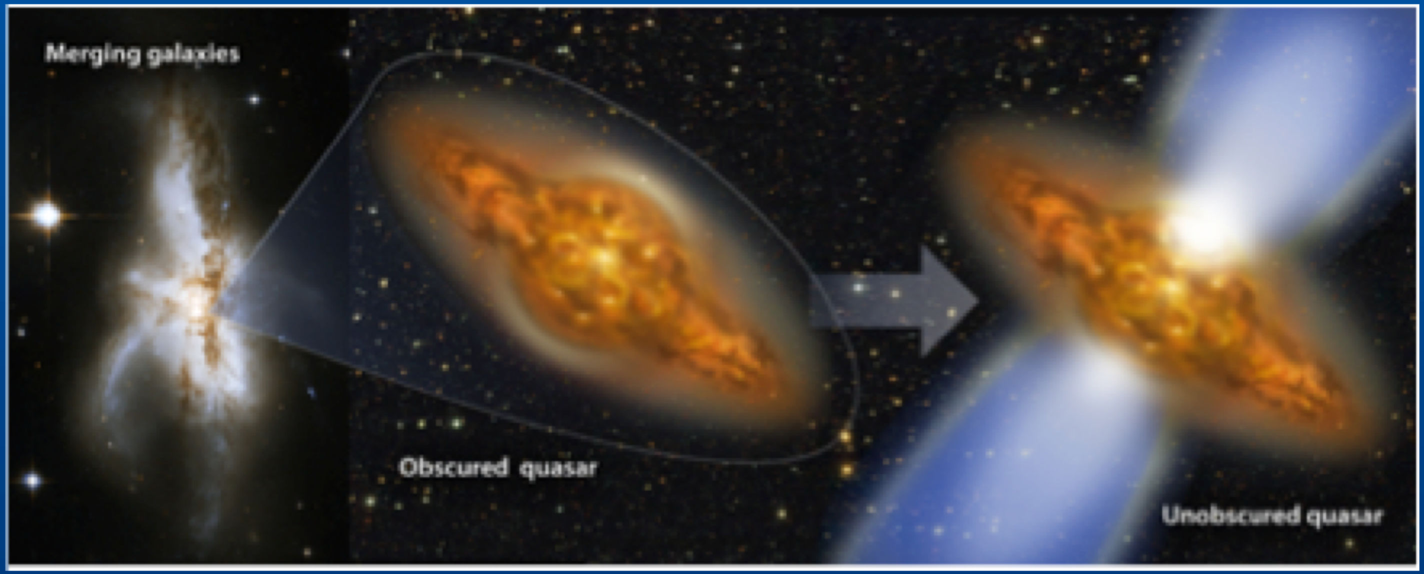
Merging Dynamics

GR simulations

TRACKING GROWTH HISTORY OF BLACK HOLES OVER COSMIC TIME







INSIGHTS FROM CHANDRA DATA THAT INFORM MODELING

KEY CHANDRA INPUTS FOR MODELING ACCRETION PHYSICS

INFERRED EDDINGTON RATIO DISTRIBUTIONS
INSIGHTS INTO GEOMETRY OF INNER REGIONS OF AGN
CENSUS OF OBSCURED VS. UNOBSCURED POPULATIONS
CONSTRAINTS FROM CXRB

KEY CHANDRA INPUTS FOR MODELING FEEDBACK

RELATION BETWEEN AGN ACTIVITY & STAR FORMATION IN HOSTS
INSIGHTS INTO POPULATION FROM CHANDRA DEEP FIELDS

DERIVING OBSERVATIONAL PREDICTIONS FROM MODELS

SEEDING MODELS

massive and light initial seeds (only high-z seeding)

ACCRETION MODELS

- AGNMS: BHAR = 1e-3 x SFR (Mullaney+ 12)
- PowerLaw: Eddington ratio distribution derived from XLFs

MERGER DYNAMICS

SMBHs instantly merge with a 10% probability after the dynamical friction timescale after a major merger, wander otherwise

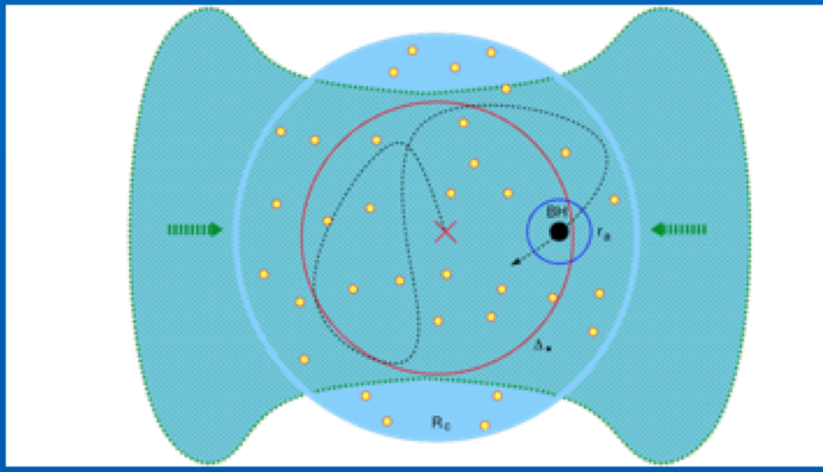
↓

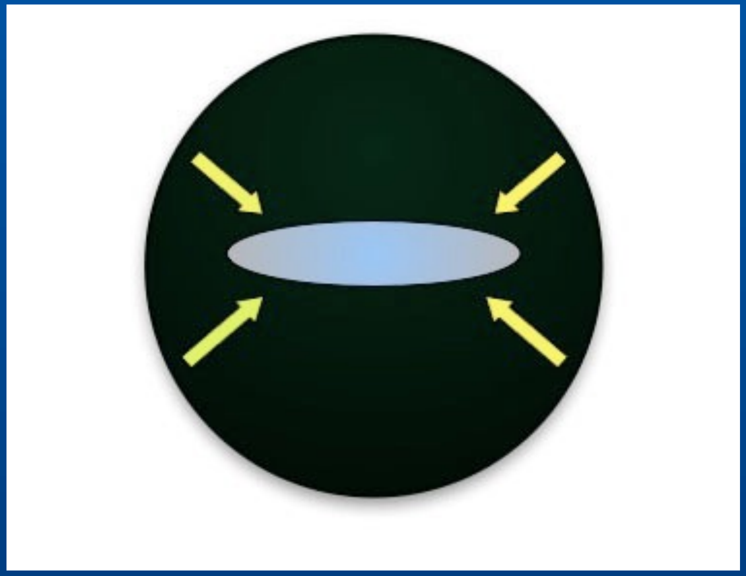
PREDICTED PROPERTIES FOR THE BH POPULATION

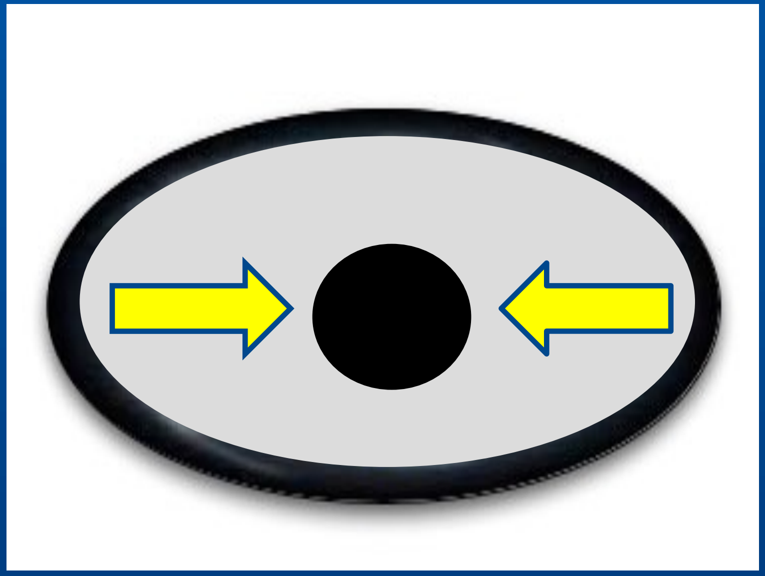
Ricarte & PN 18b; PN, Ricarte+ 19 NASA LISA Science Team Decadal White Paper

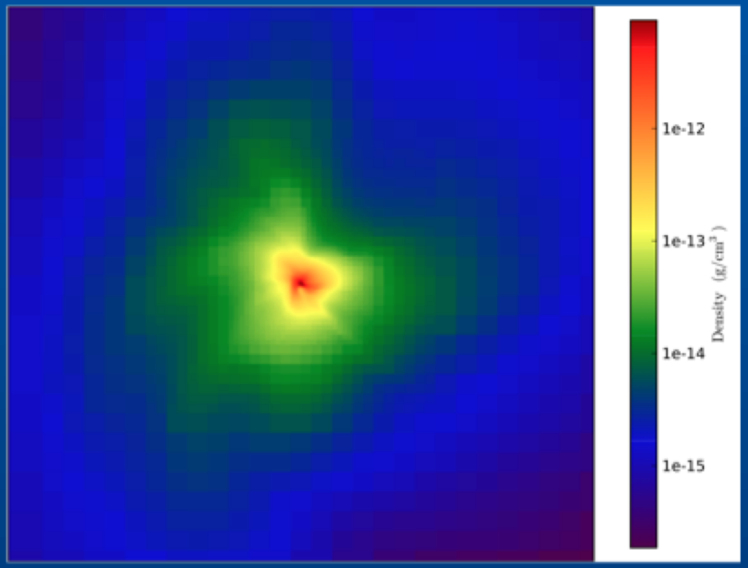
HOW DO THE FIRST SEED BLACK HOLES FORM?

EARLY AMPLIFIED GROWTH









STANDARD ACCRETION & SLIM DISK ACCRETION

$0.01\dot{M}_{Edd} < \dot{M} < \dot{M}_{Edd}$

$$L = L(\dot{M})$$

$\dot{M} > \dot{M}_{Edd}$

Begelman+; Choi+; Park+; Pacucci & Ferrara; Pacucci+; PN+

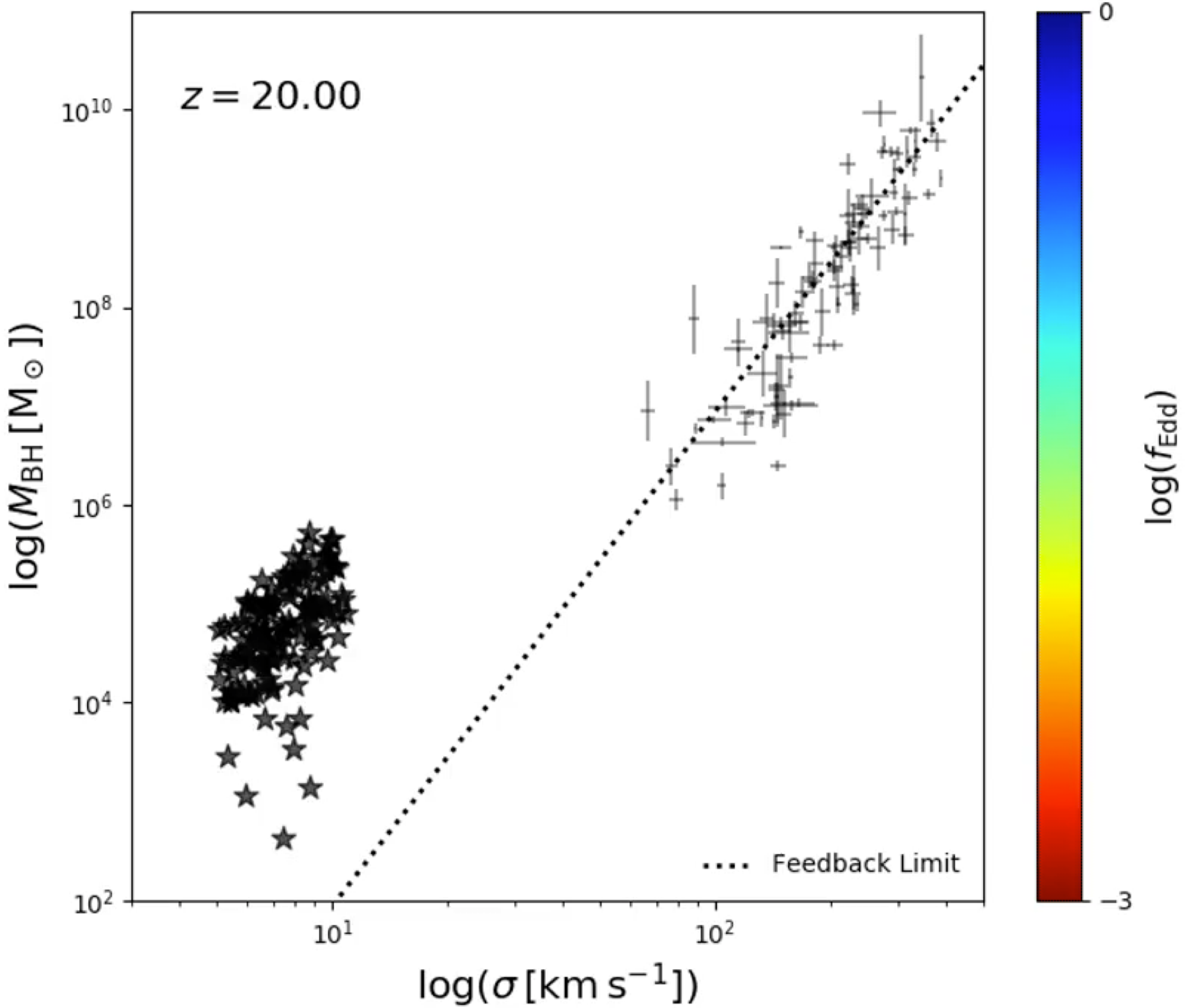
EARLY BH SEED MASS BUILD-UP AT HIGH REDSHIFT

THIN DISK ACCRETION
FEEDBACK LIMITED MODE
Inefficient growth, outflows,
High radiative efficiency
~ 15% or so of gas accreted
Eddington limited accretion rate

SLIM DISK ACCRETION
GAS SUPPLY LIMITED MODE
Efficient growth, outflows
unimportant, low radiative
efficiency, radiation advected in
~ 80% or so of gas accreted
Super-Eddington accretion rates

Growth is jump-started for larger initial black hole seed masses
$\mathbf{M_{gas} > M_{crit}}$

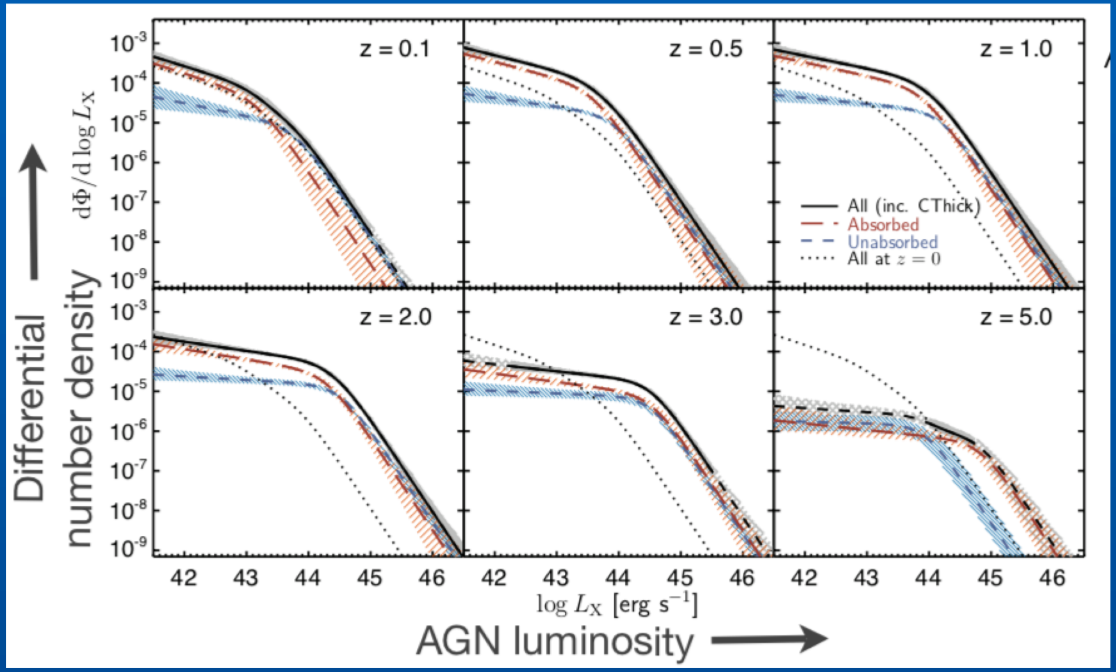
Alexander & PN 14; Park, Ricotti, PN+15; Pacucci+15; Pacucci, PN+ 18

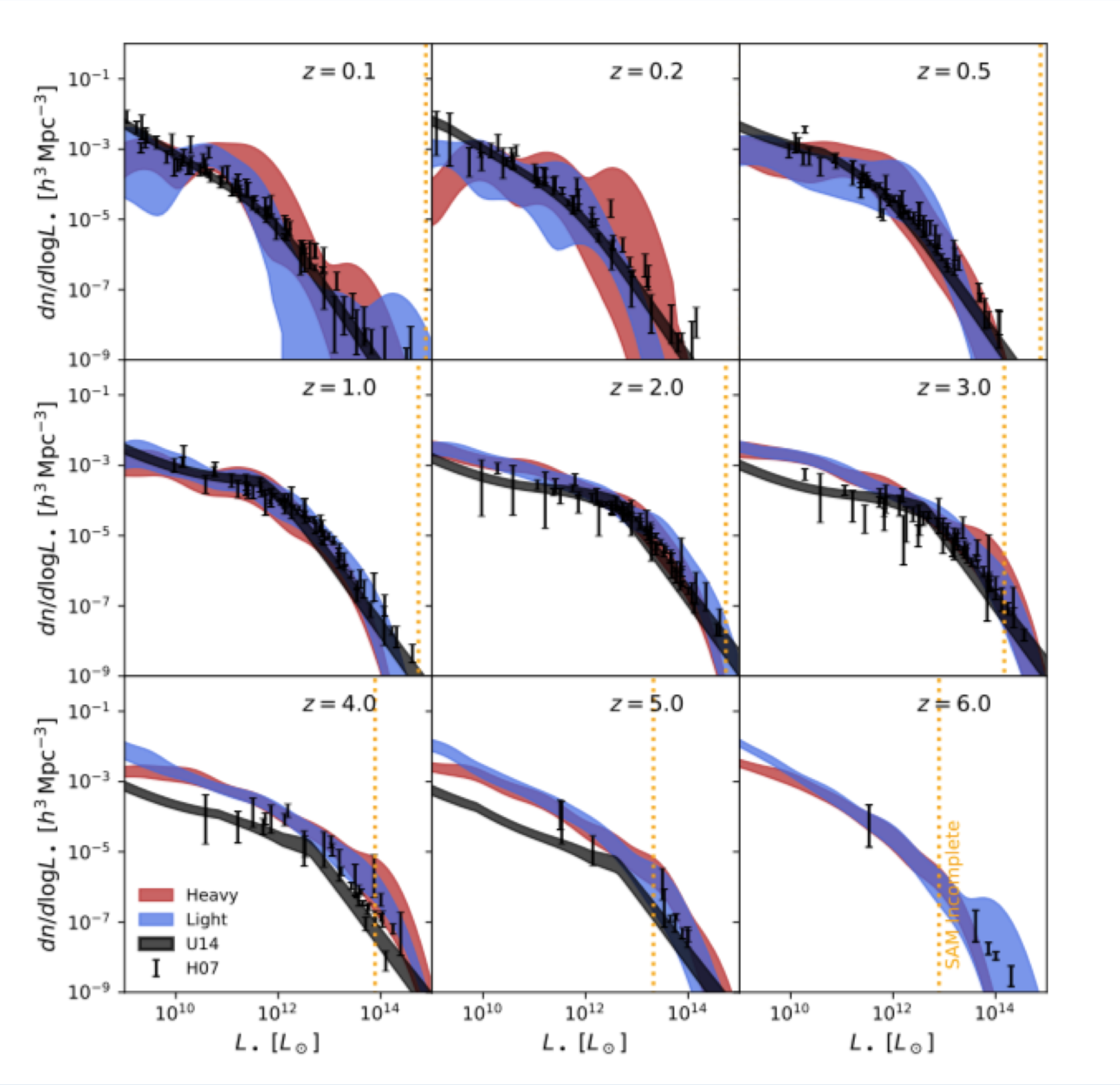


$z = 20.00$
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{1}
10^{2}
$\log(M_{\rm BH}\,[{\rm M}_\odot])$
$\log(\sigma\,[{\rm km\,s^{-1}}])$
Feedback Limit
0
−3
$\log(f_{\rm Edd})$

AGN LUMINOSITY FUNCTIONS FROM X-RAY DATA & MODELS

DATA FROM WIDE+DEEP CHANDRA SURVEYS
CDFS-4Ms, AEGIS 800ks, C-COSMOS
STRONG EVOLUTION SEEN
Luminosity+density evolution for all AGN
Evolving mix of obscured & unobscured

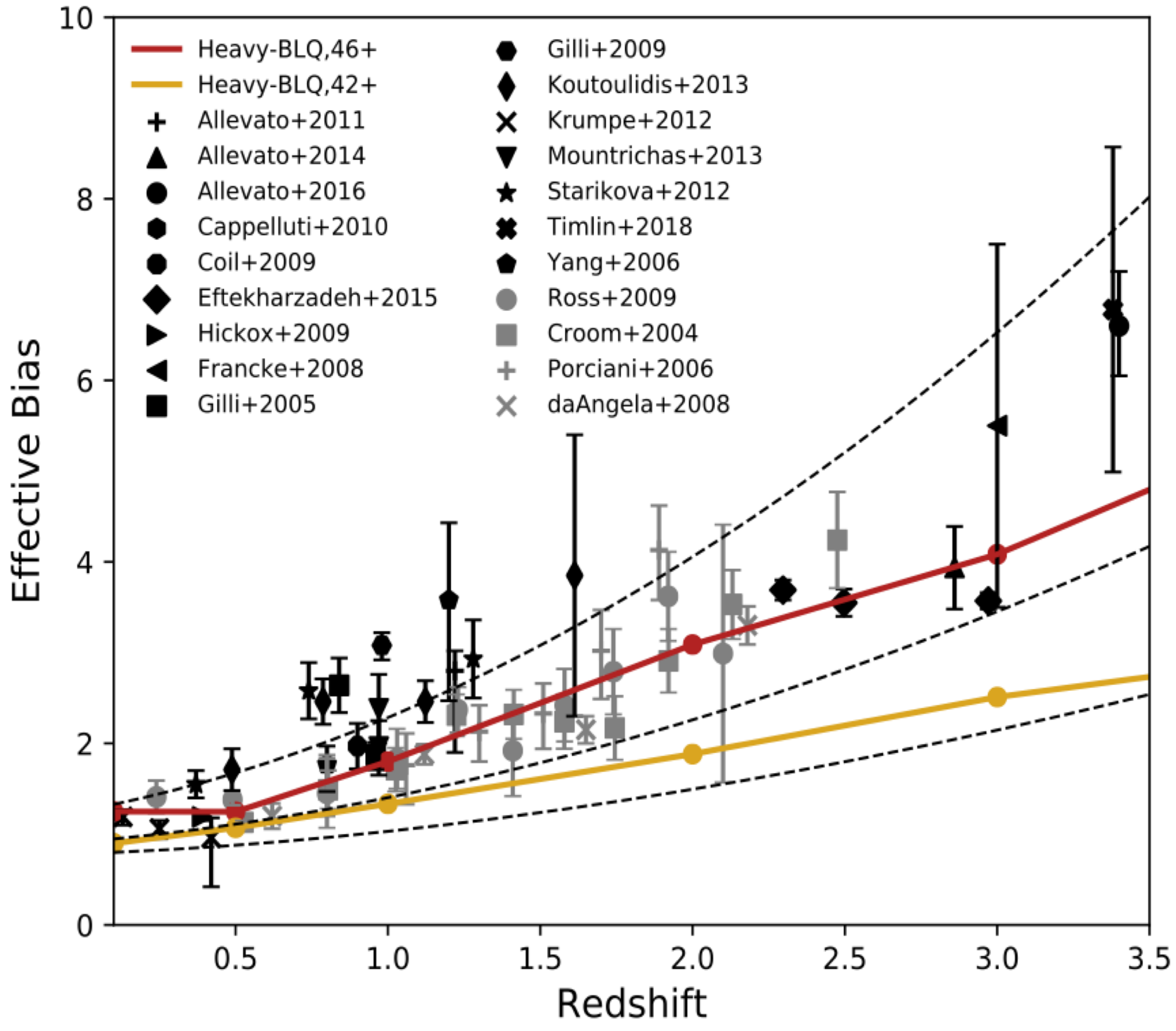




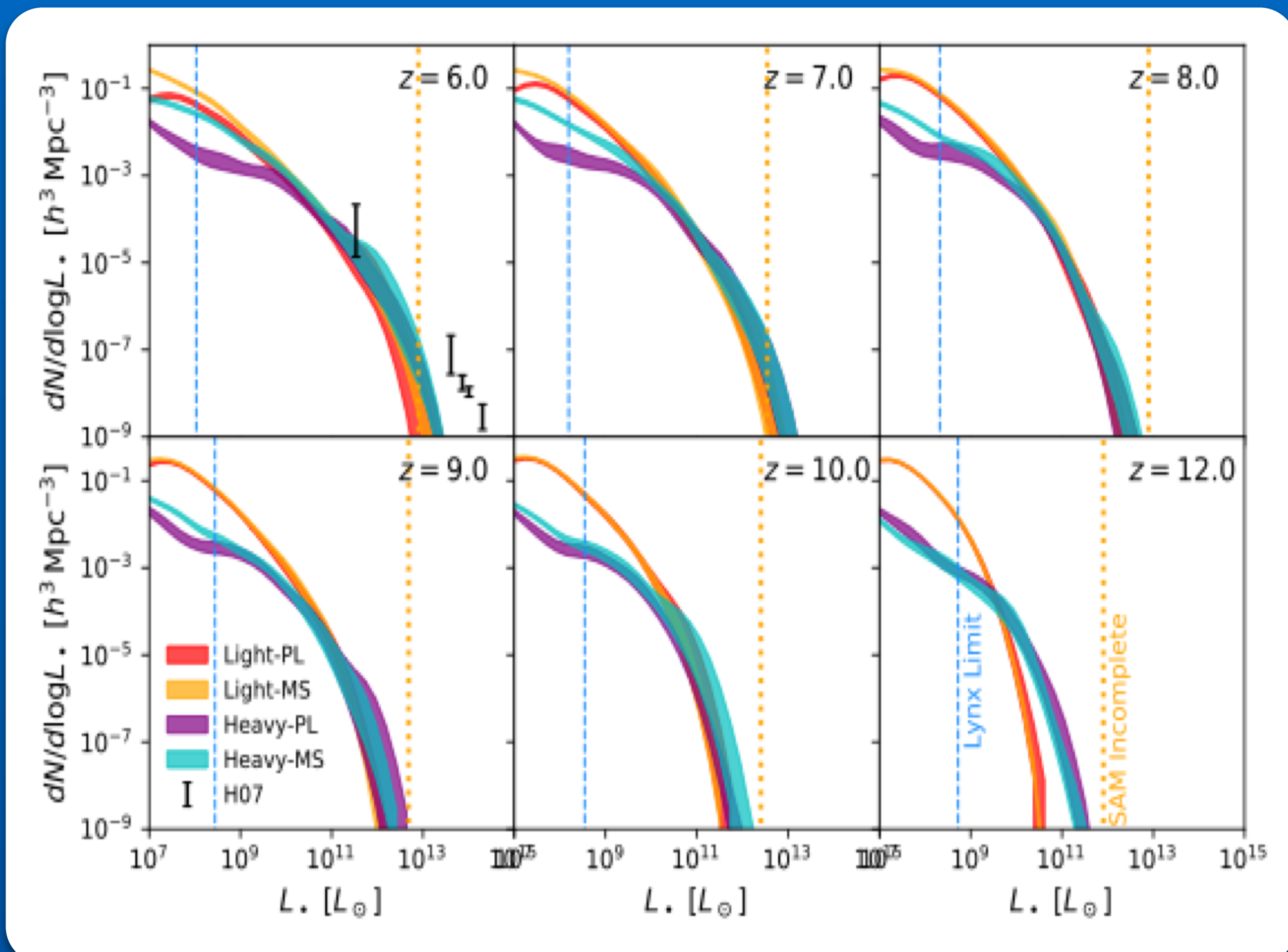
Model Predicted Bolometric LFs as a function of BH seed mass

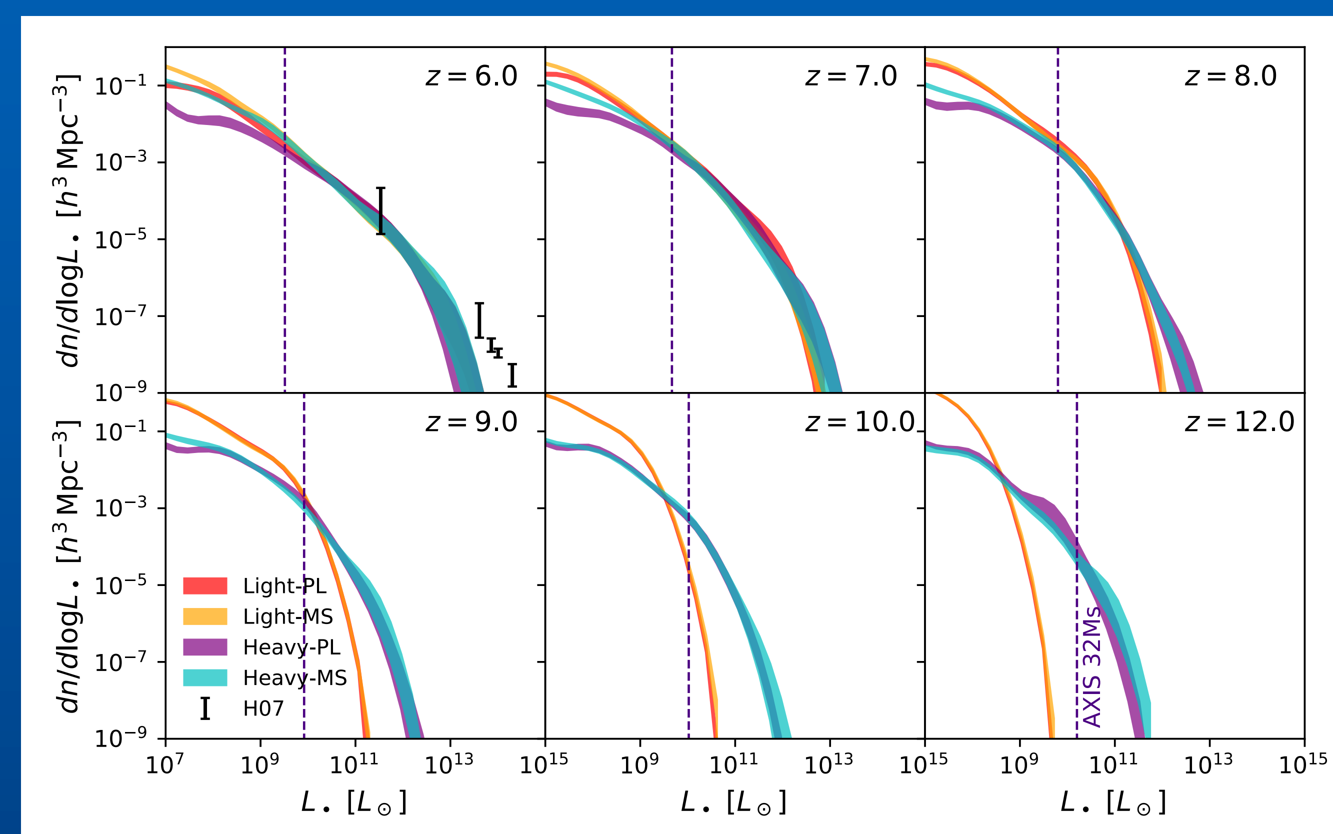
Ricarte+; PN+; Pezzuli+; Shankar+; Volonteri+; Aird+; Hickox+; Powell+; Steffen+; Ueda+; Miyaji+; Buchner+; Cappelluti+; Civano+; Treister+; Koss+; Gilli+; Lusso & Risaliti+

PREDICTIONS & MATCH WITH AGN CLUSTERING DATA



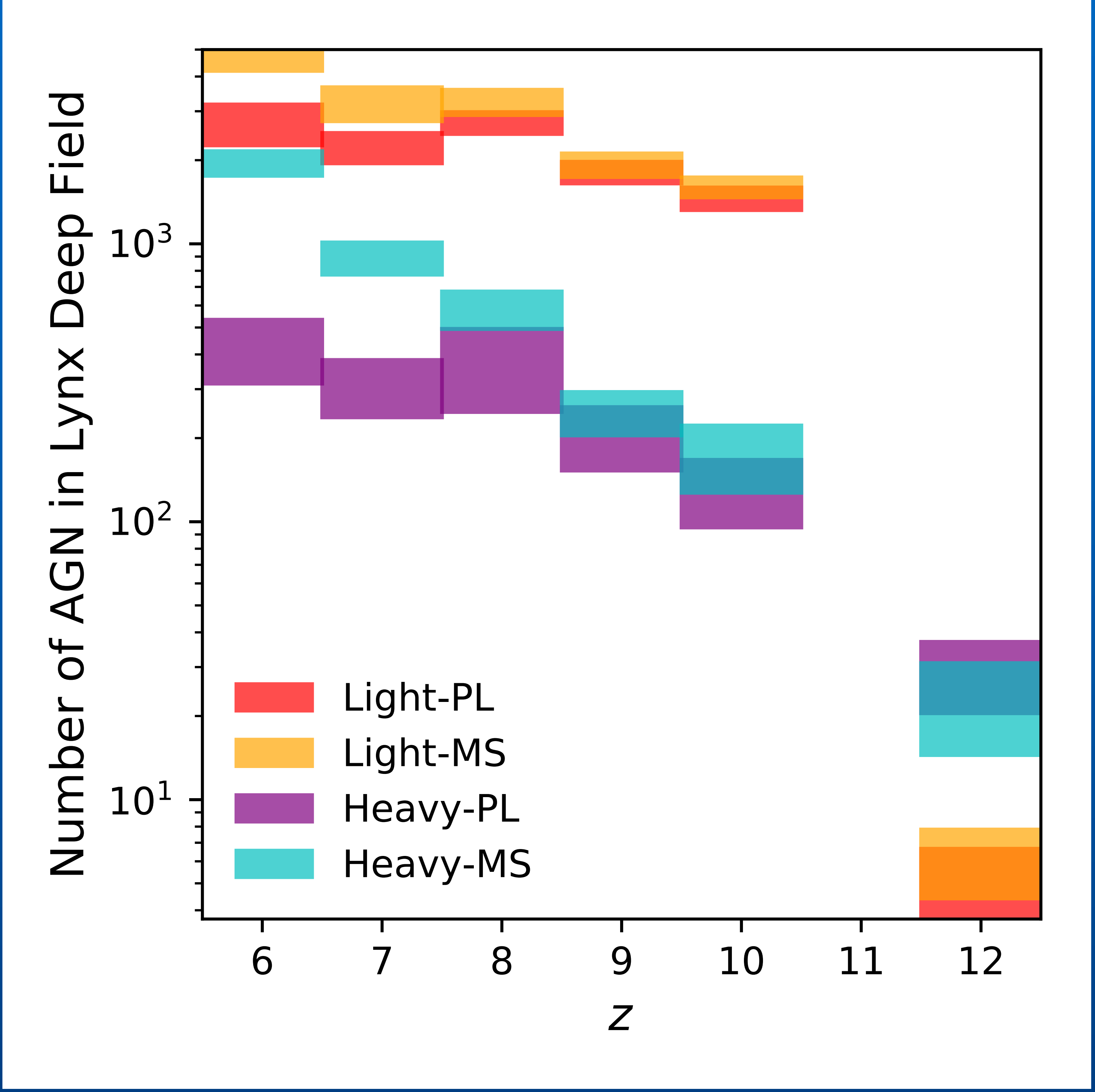
PREDICTED HIGH REDSHIFT LUMINOSITY FUNCTIONS



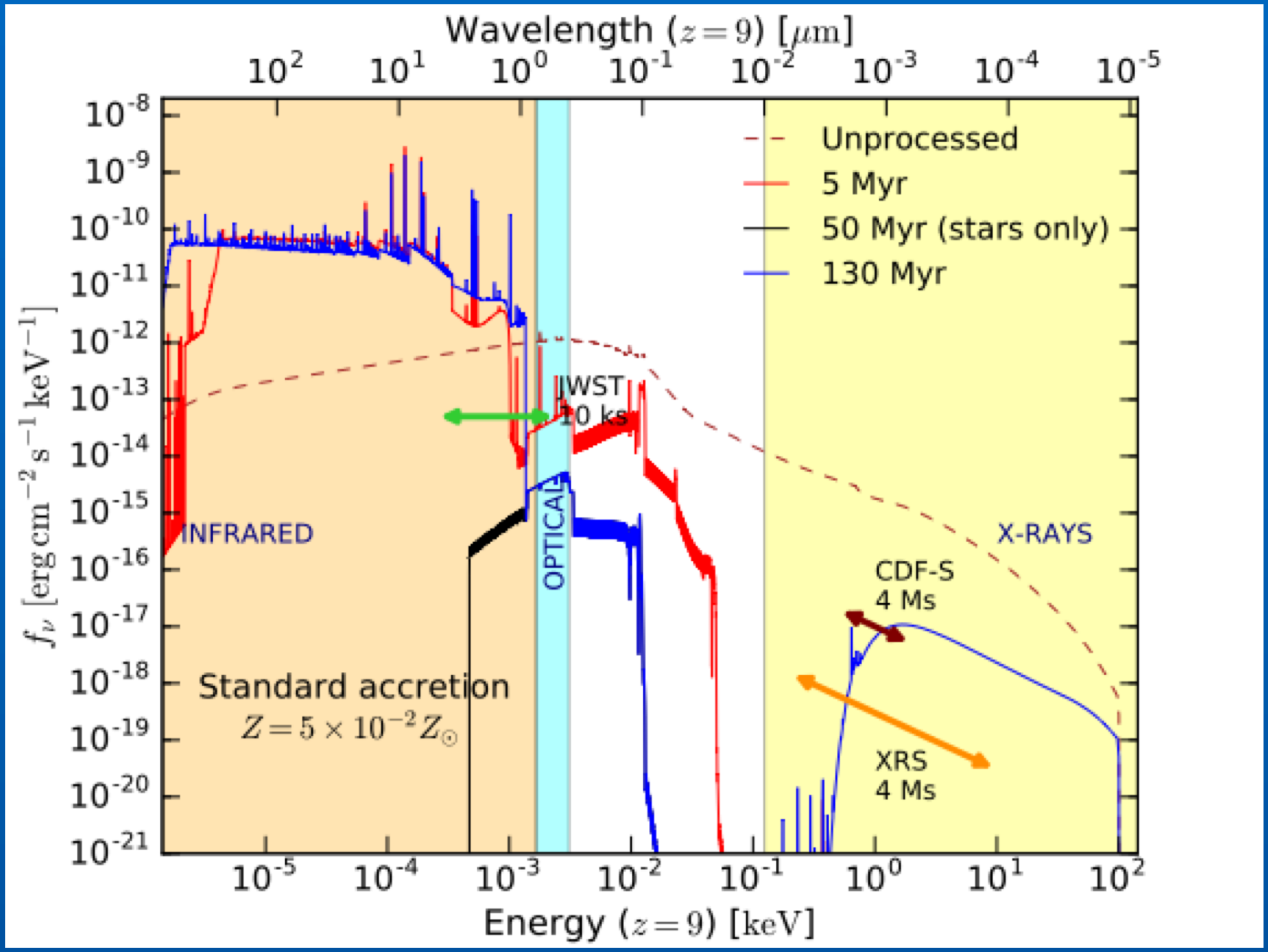


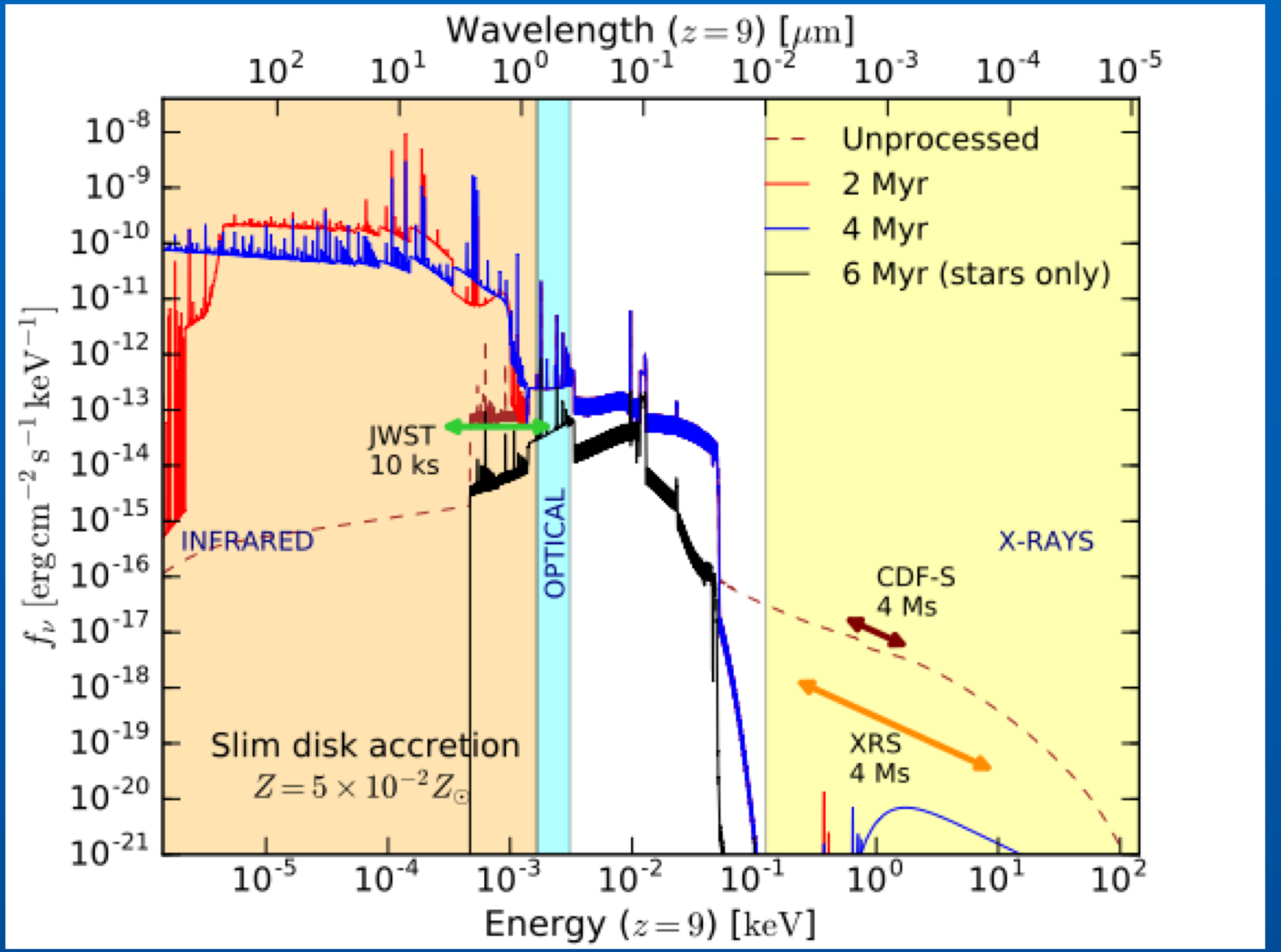
A LynX deep field down to a flux limit of 10^{-19} erg $s^{-1}cm^{-2}$

Predicted AGN abundance expected in future deep fields



MULTI-WAVELENGTH SPECTRAL PREDICTIONS

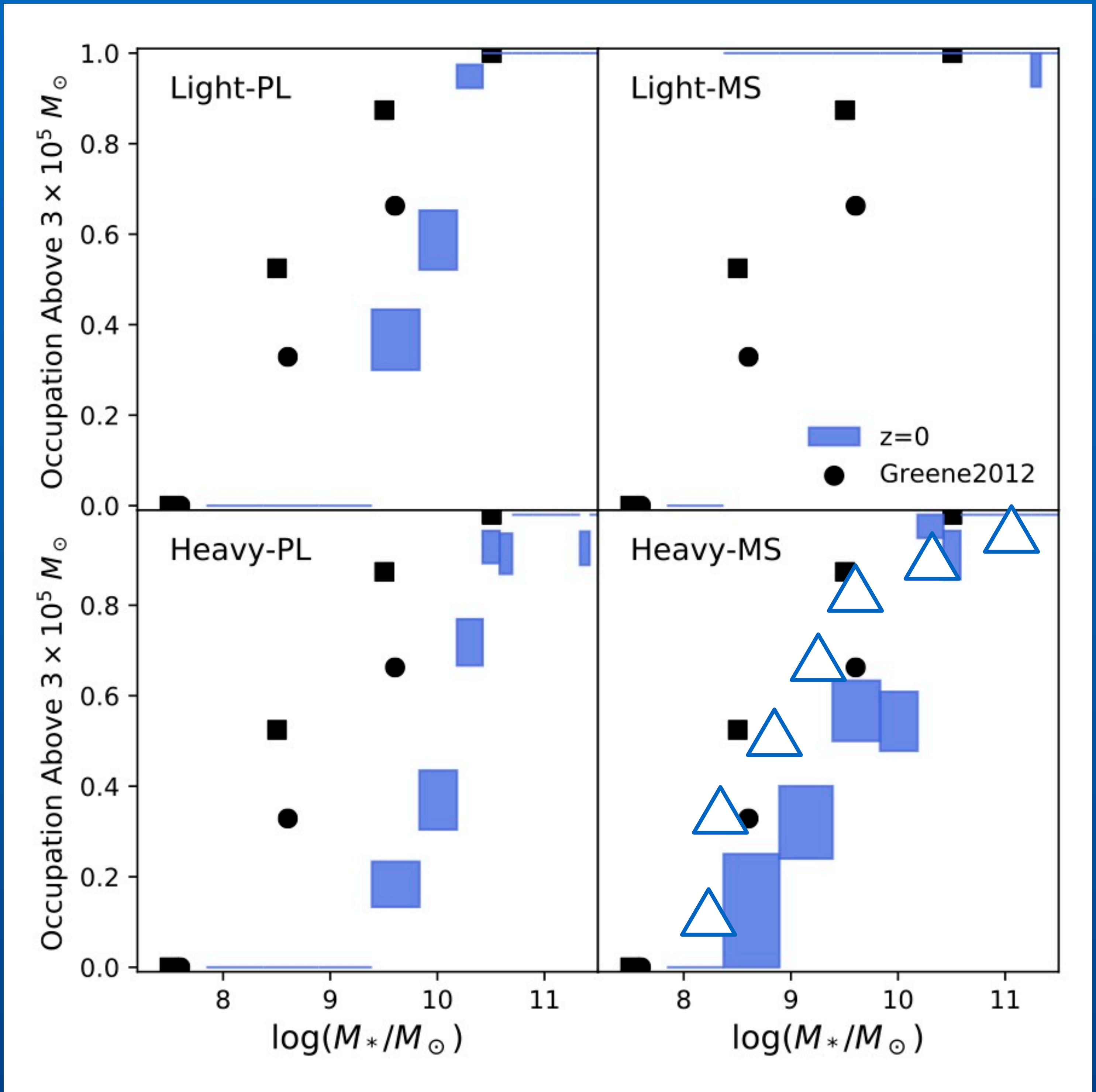




GROWING DCBH SEED + STELLAR COMPONENT
SLIM DISK AND STANDARD DISK
SLIM DISK: X-RAY OBSCURED, IR BRIGHT SOURCES
STANDARD DISK: X-RAY BRIGHT, IR BRIGHT SOURCES

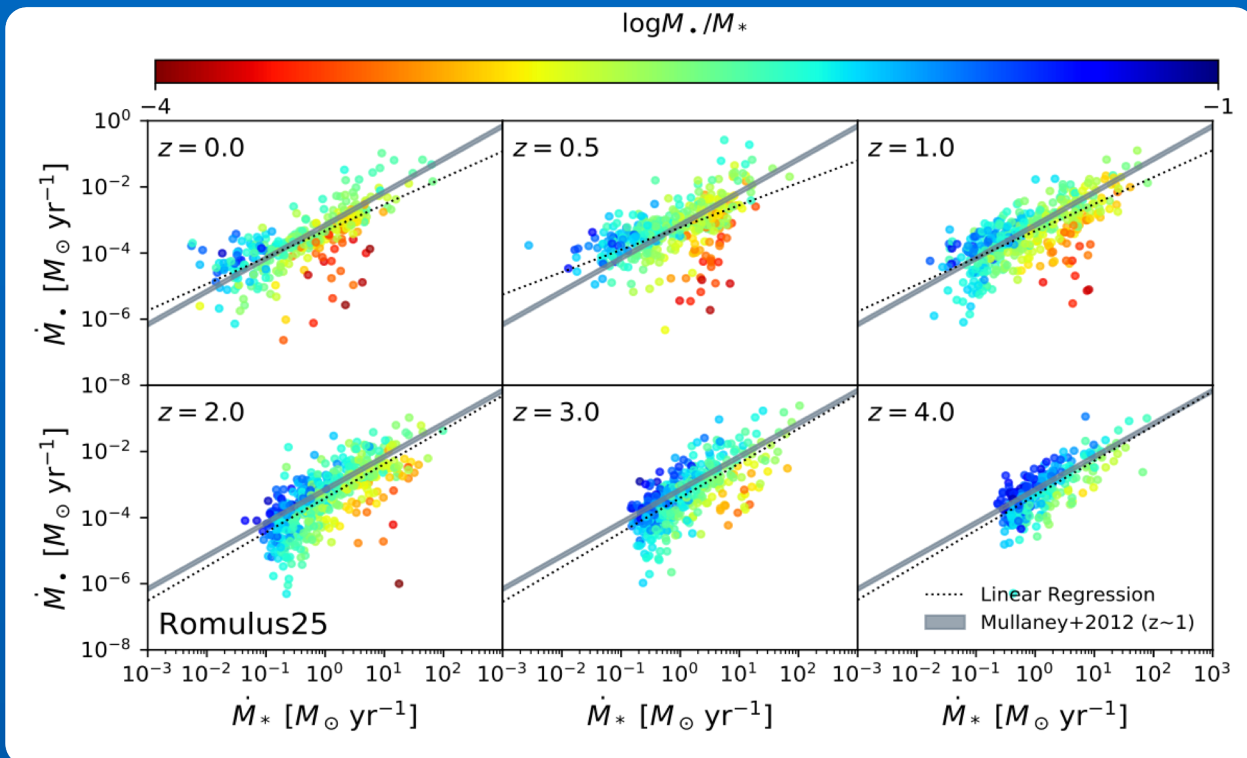
Volonteri+; PN+; Pacucci+; Pezzuli+; Stark+; Tanaka+; Ricotti+

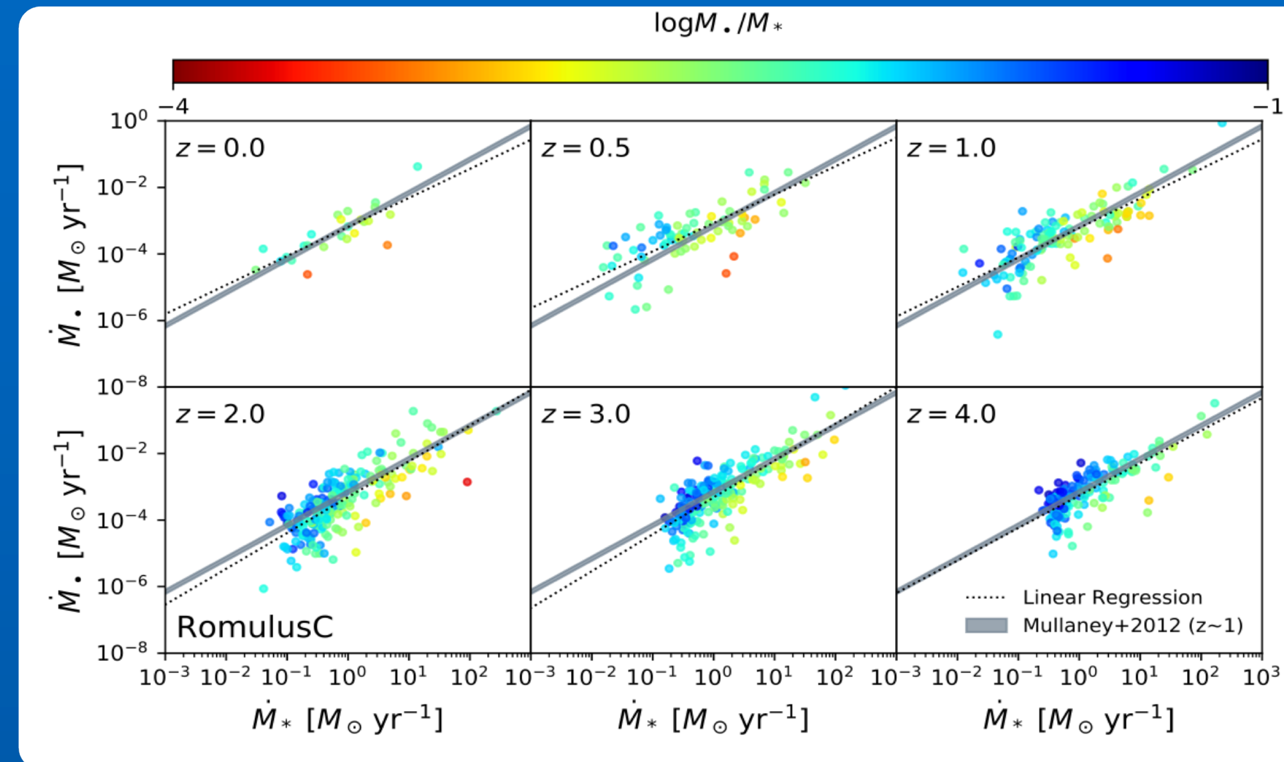
LOCAL OCCUPATION FRACTION OF BHs
dependence on seeding & accretion model



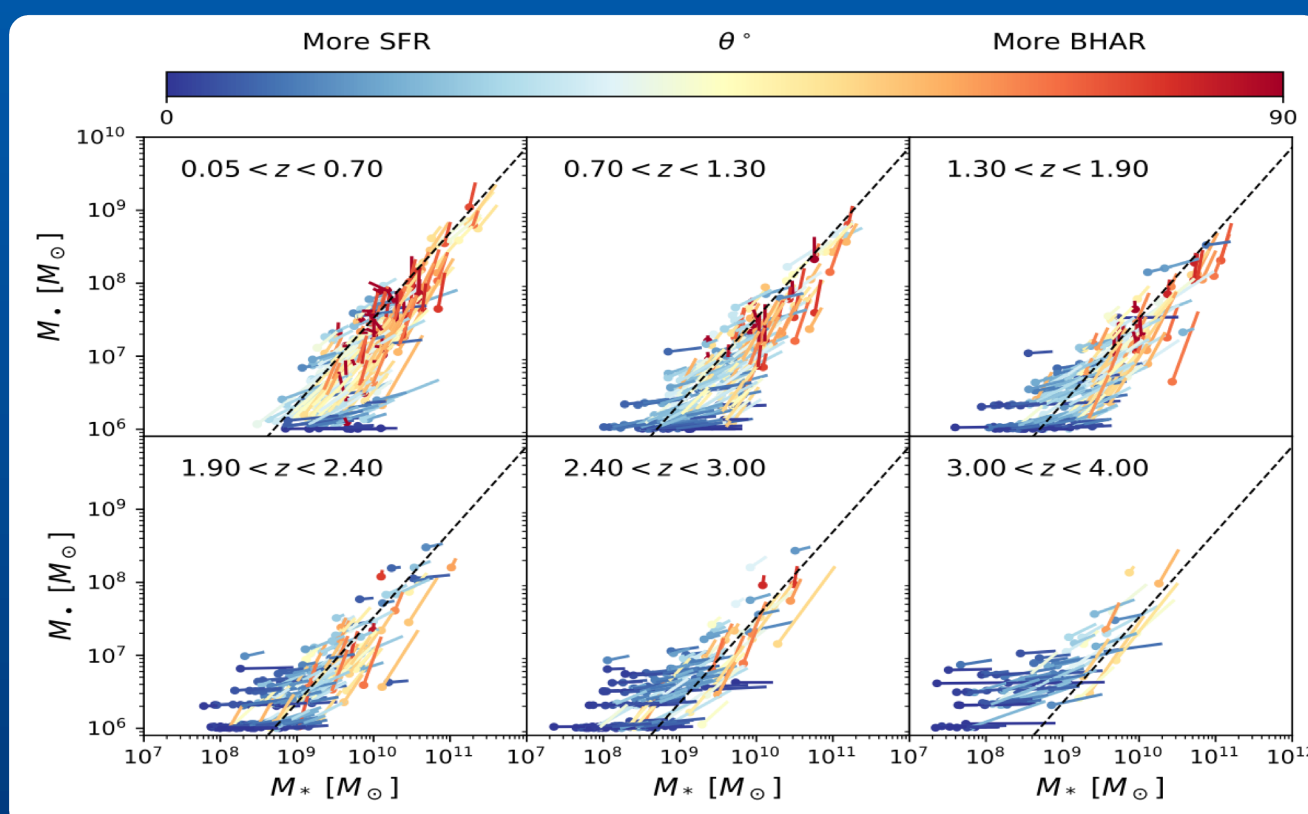
Greene+, Reines+, Baldassare+, Gallo+, Desroches & Ho+, Ricarte & PN, Tremmel+; Sharma+

EXPLORING CORRELATIONS IN THE ROMULUS SUITE





BH growth traces star-formation independent of larger-scale environment



SMBHs & their host galaxies co-evolve

ROLE OF MERGERS & INSIGHTS INTO CO-EVOLUTION

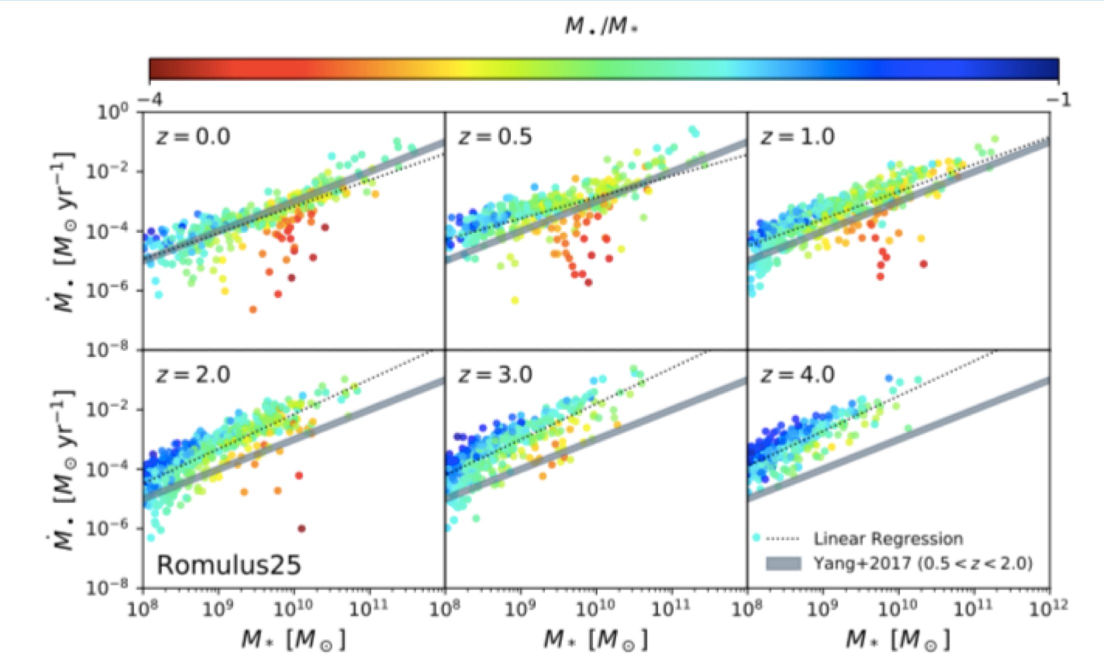


Figure 8. As in Figure 5, but for stellar mass instead of SFR. Although the relationship is tighter than with SFR, a redshift dependence is required. A relationship derived from 18,000 galaxies in the CANDELS/GOODS-South field is overplotted (Yang et al. 2017).

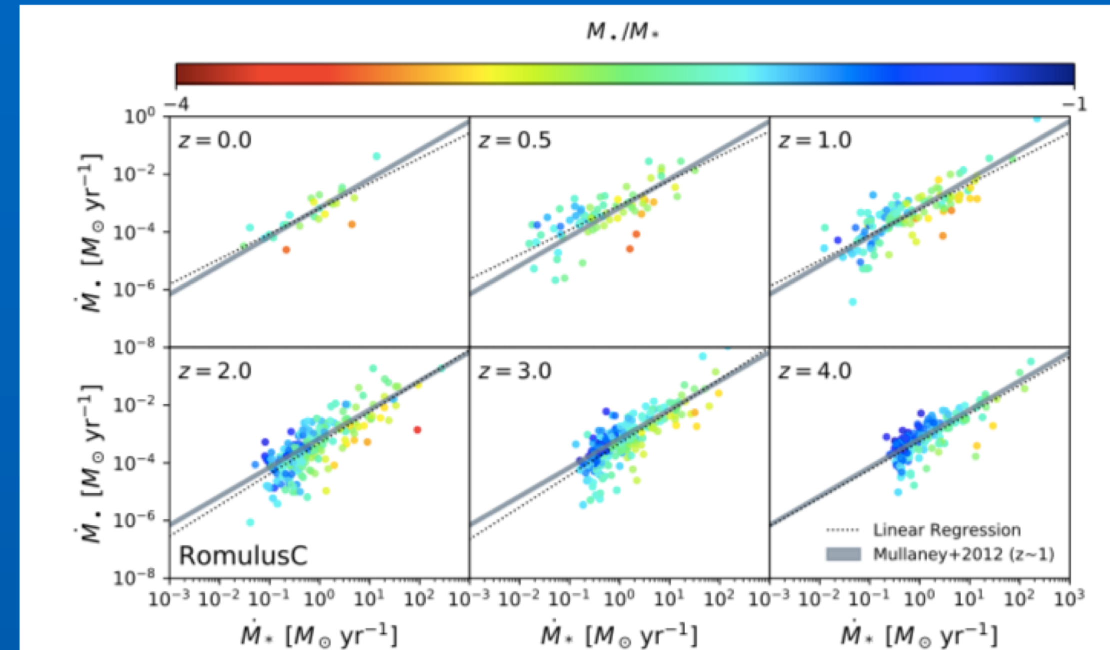
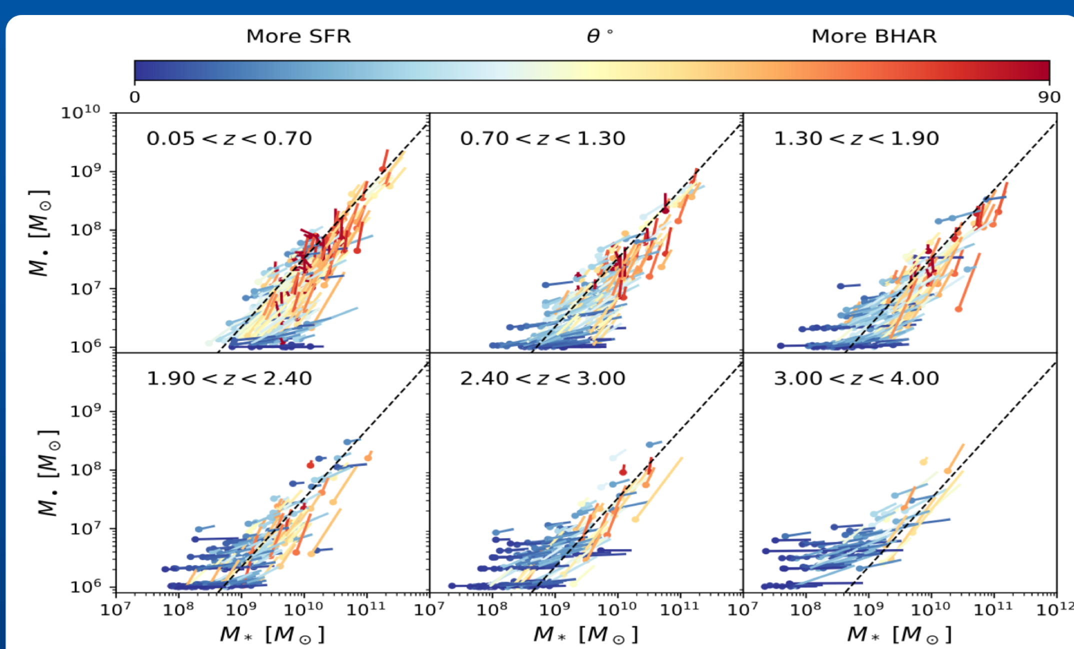


Figure 7. As in Figure 5, but for RomulusC. There are fewer points at low-redshift because only star-forming galaxies are included. Since the same relation from Mullaney et al. (2012) can describe both these cluster galaxies and the field galaxies in Fig. 5, there appears to be no difference between the field and the cluster environments.



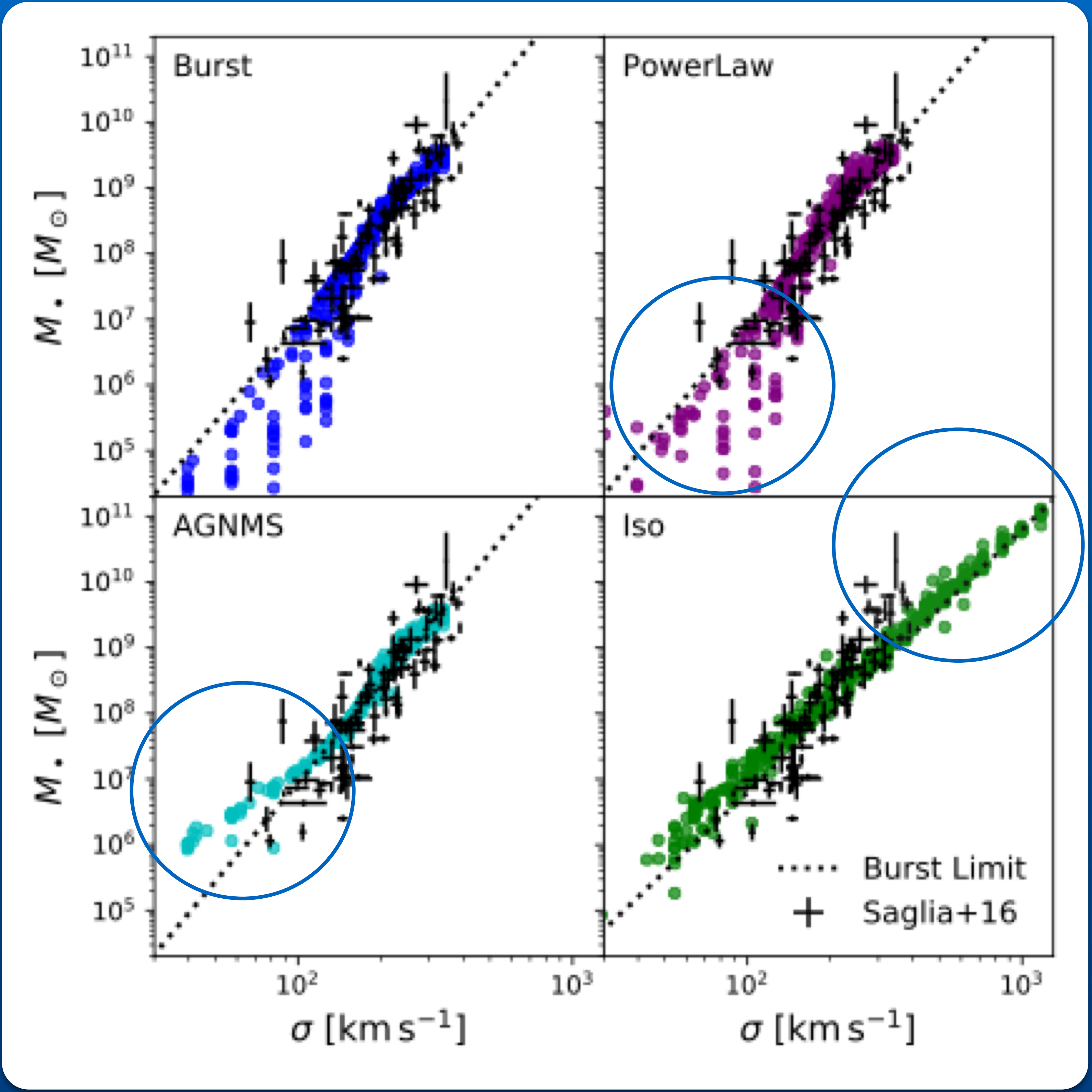
Hosts with stellar masses 10^8- 10^{12} Msun and star-forming co-evolve independent of mass, environment, redshift or stellar mass!

Ricarte, Tremmel, PN+

M-SIGMA AND THE FOUR MODEL VARIANTS

No Steady Mode

Burst + Steady drawn from ERDF



Burst + steady BHAR = SFR/1000

PowerLaw, but old sigma mapping

OPEN QUESTIONS: BH IMFs & IMBHs?

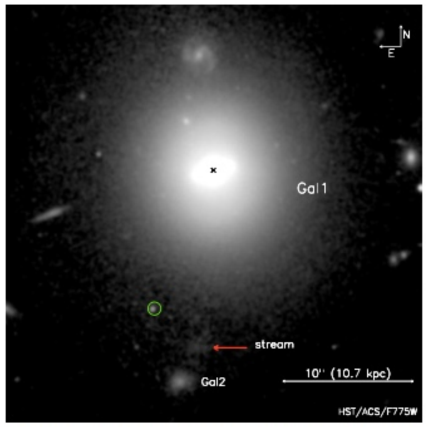
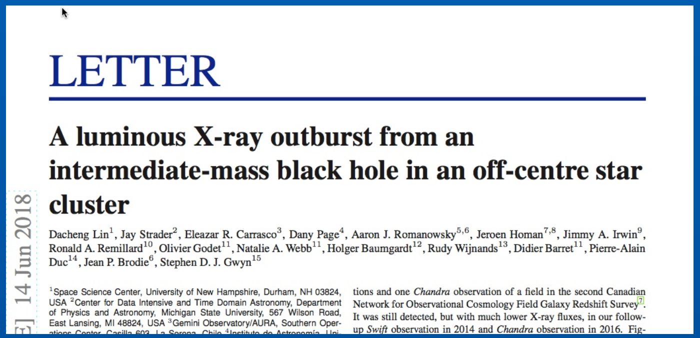


Figure 1 | The *HST*/ACS F775W imaging around the field of J2150−0551. The image was smoothed with a 2-D gaussian function of $\sigma = 0.1$ arcsec. J2150−0551 appears to be in a barred lenticular galaxy Gal1. The X-ray position of J2150−0551 from the *Chandra* observation C2 is marked with a green circle, whose radius, for clarity, is twice as large as the 99.73% X-ray positional error (0.25 arcsec). The source has a faint optical counterpart, at an offset of only 0.14 arcsec from the X-ray position. The galaxy at the bottom of the image (Gal2) could be a satellite galaxy connected with Gal1 through a tidal stream (red arrow), indicating that Gal1 is rich in minor mergers.



LETTER

A luminous X-ray outburst from an intermediate-mass black hole in an off-centre star cluster

14 Jun 2018

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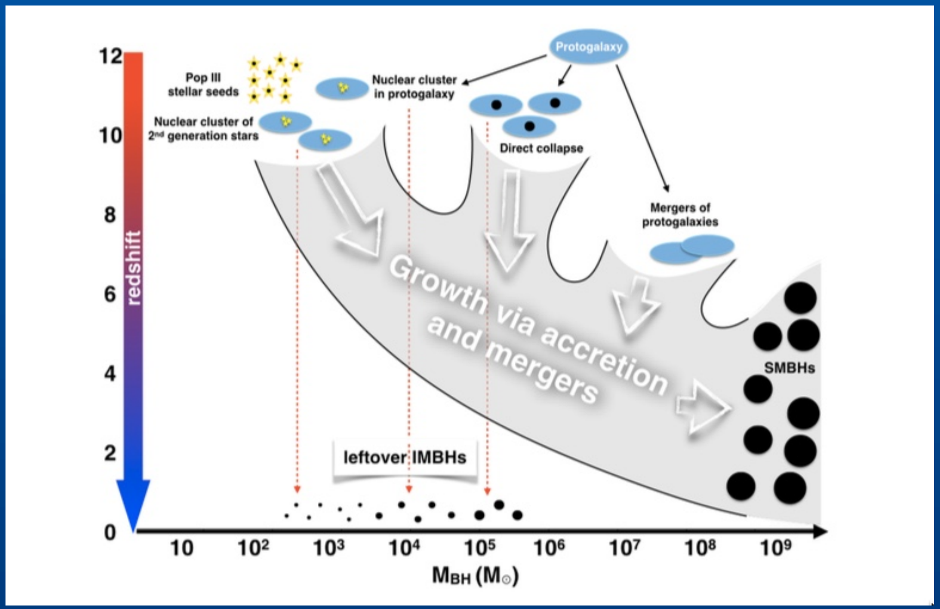
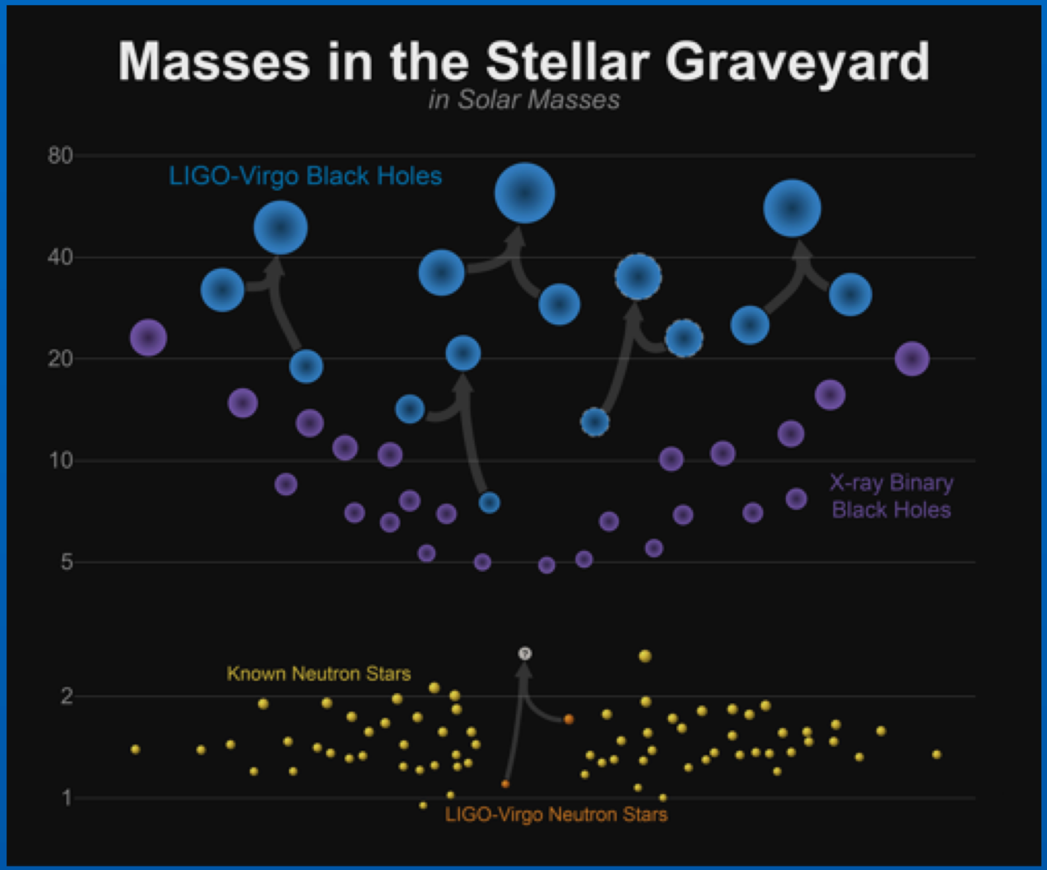
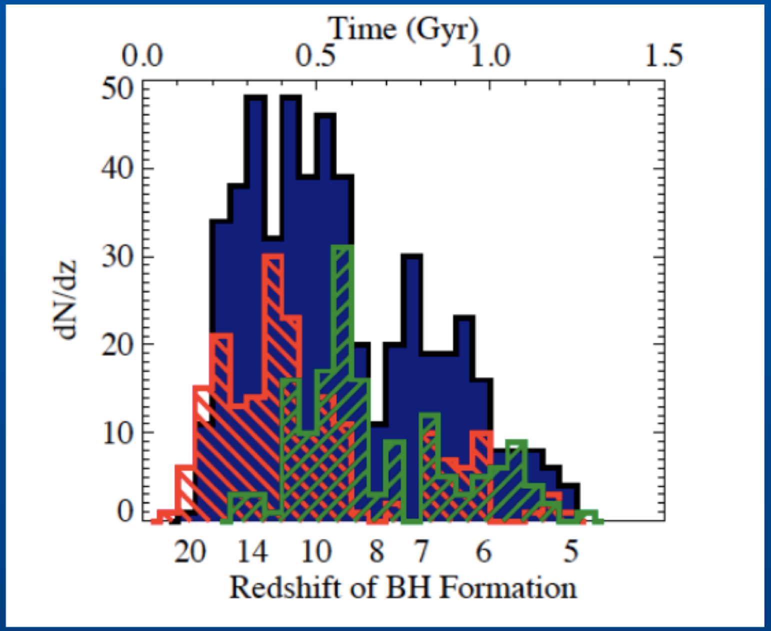
tions and one *Chandra* observation of a field in the second Canadian Network for Observational Cosmology Field Galaxy Redshift Survey[7]. It was still detected, but with much lower X-ray fluxes, in our follow-up *Swift* observation in 2014 and *Chandra* observation in 2016. Fig-



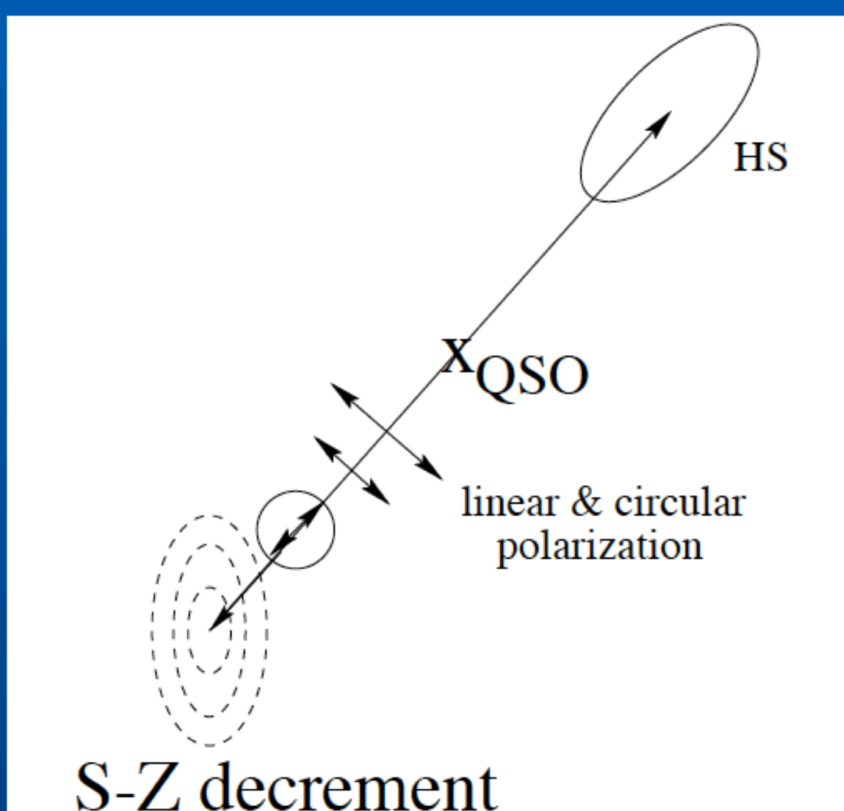


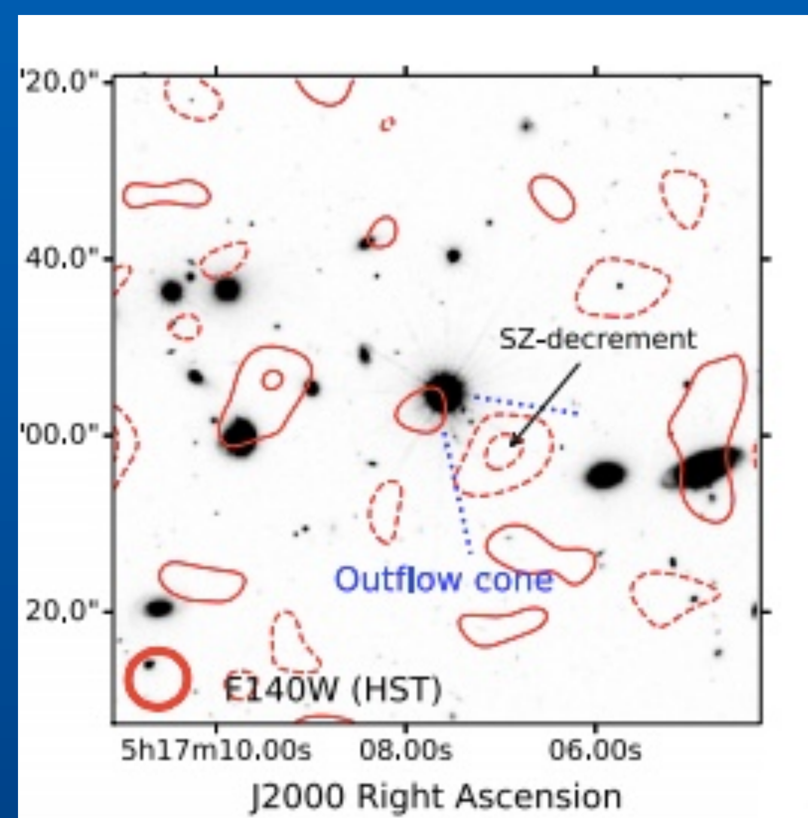


LONG-LIVED THERMAL & KINEMATIC S-Z FROM QUASAR OUTFLOWS
redshift distribution of from dormant high-z sources

$$\frac{\Delta T}{T} \sim 3 \times 10^{-4} \left(\frac{\tau}{10^{-2}}\right) \left(\frac{v_{\rm sweep}}{3000\, km\, s^{-1}}\right) \left(\frac{L_{\rm QSO}}{10^{48}\, erg\, s^{-1}}\right)^{\frac{1}{3}} \left(\frac{1+z}{1+3}\right)^{2}.$$

$$\frac{\Delta T}{T} = \left(\frac{2\, k\, T_e}{m_e\, c^2}\, \tau\right) = 3.45 \times 10^{-6} \left(\frac{T_e}{10^6\, K}\right),$$





High-z BHs from massive initial seeds will have larger S-Z decrements and will be detectable more easily

Natarajan& Sigurdsson 98; 99; Chatterjee+; Lacy+19; PN 19

CONCLUSIONS FOR NOW & FUTURE PROSPECTS

KEY OBSERVABLES FOR MODELS

high-redshift luminosity functions for accreting black holes

local occupation fraction of black holes

Xray/IR/Optical afterglows & pre-cursors from merging SMBHBs

Low & High mass end of the local SMBH mass function

Sunyaev-Zeldovich decrements from high-redshift quasar outflows

Low mass high z SMBHs GWs from SMBHB mergers - LISA events

⇓

Future observations with CHANDRA, JWST, WFIRST, LISA & ATHENA, LynX will help discriminate between seeding models & help disentangle seeding from accretion physics & dynamics

REFERENCES & SOURCES gratefully acknowledged (not complete)

Astro2020 Decadal White Papers: for example - Bellovary+; Haiman+; Pacucci+; Natarajan+; Wang+; Kashlinsky+….others

Early Galaxies: Bouwens+; Bradac+; Oesch+; Atek+; Coe+; Zitrin+; McLoed+; Livermore+; Infante+; Laporte+; Bradley+; Salmon+; Behroozi+; Harikane+; Ishigaki+; Bowler+; Trenti+; Finkelstein+; Springel+; Robertson+; Madau+; Naidu+; Smit+; Stark+; Schmidt+…others

Early Black Holes: Natarajan+; Ricarte+; Pacucci+; Agarwal+; Volonteri+; Capelo+; Angels-Alcazar+; Hopkins+; Haiman+; Inayoshi+; Ferrara+; Schneider+; Pezzuli+; Bromm+; Wise+; Abel+; Khochfar+; Stacy+; Omukai+; Greene+; Reines+; Pretorius+; Campanelli+; Holley-Bockelman+; Bellovary+; Mayer+; Sesana+…….others