The evolution of the mass functions of active supermassive black holes and their host galaxies out to $z \sim 2$

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Tsukuba Uchu Forum

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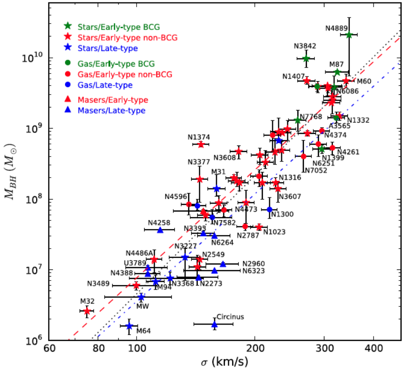
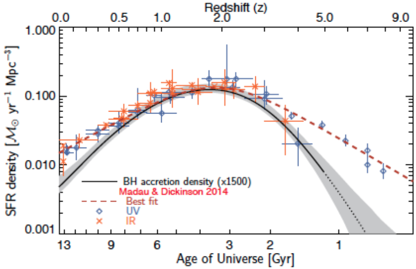
Black hole - galaxy coevolution

$M_\bullet - \sigma_*$ relation



McConnell & Ma (2013)

integrated cosmic BH accretion history parallel to SF history



Aird et al. (2015)

⇒ link between black hole growth and galaxy evolution

⇒ how are black holes growing?

Black hole - galaxy coevolution

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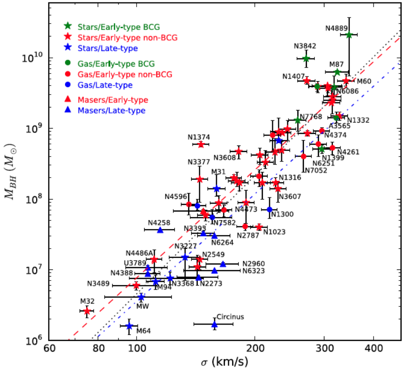

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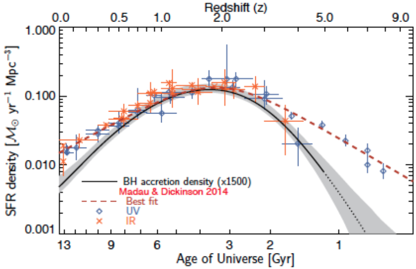


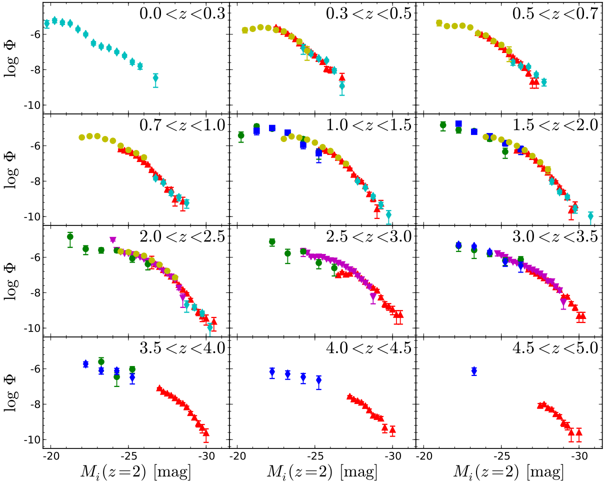
Aird et al. (2015)

⇒ link between black hole growth and galaxy evolution

⇒ how are black holes growing? => need census

AGN demographics: The AGN LF

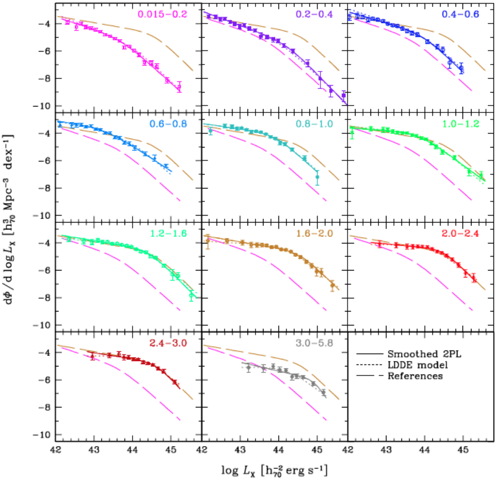
AGN Luminosity function is main demographic quantity



optical: Schulze et. al (in prep.)

AGN demographics: The AGN LF

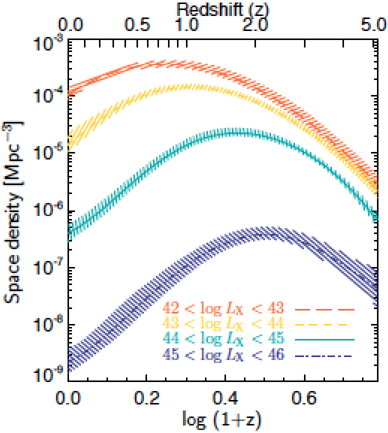
AGN Luminosity function is main demographic quantity



X-ray: Miyaji et. al (2015)

AGN demographics: AGN LF evolution

- space density of bright QSOs peaks at $z \approx 2 - 3$



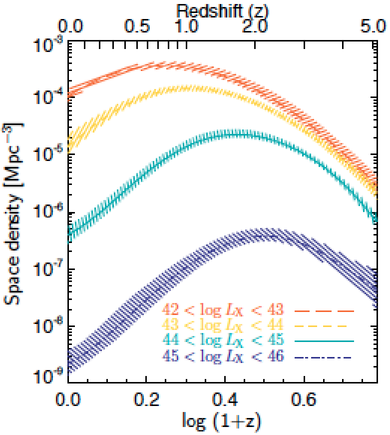
Aird et. al (2015)

AGN demographics: AGN LF evolution

- space density of bright QSOs peaks at $z \approx 2-3$
- peak is shifted towards lower z for fainter AGN

$\Rightarrow$ AGN cosmic downsizing

$\Rightarrow$ implies anti-hierarchical BH growth

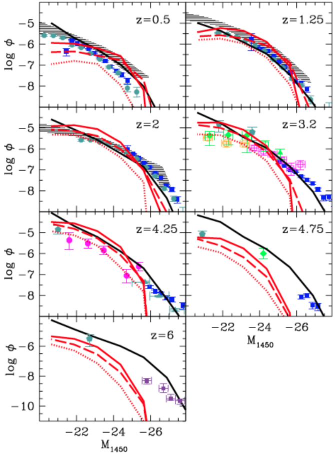


Aird et. al (2015)

Constraints on theoretical models

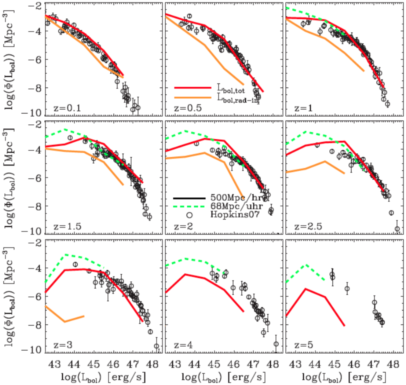
- SAMs & numerical simulations able to reproduce AGN LF and downsizing

SAMs



Menci et. al (2014)

Numerical simulations



Hirschmann et al. (2014)

How can we trace black hole growth?

Limitation of AGN LF:

Physical quantities of black holes:

- black hole mass $M_\bullet$
- accretion rate / Eddington ratio $\lambda = L_{\rm bol}/L_{\rm Edd}$

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Active black hole mass function - $\Phi_\bullet(M_\bullet)$
Eddington ratio distribution function - $\Phi_\lambda(\lambda)$

- well-defined AGN sample
- black hole mass estimates

Black hole masses for broad line AGN

- for virial motion in BLR:

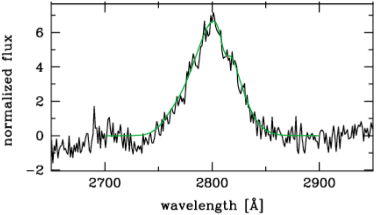
$$M_\bullet = f \frac{R_{\mathrm{BLR}} \Delta V^2}{G}$$

Black hole masses for broad line AGN

- for virial motion in BLR:

  $M_\bullet = f \frac{R_{\mathrm{BLR}} \Delta V^2}{G}$

- ΔV from broad line width



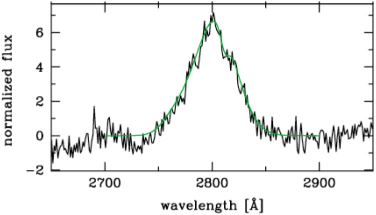
Black hole masses for broad line AGN

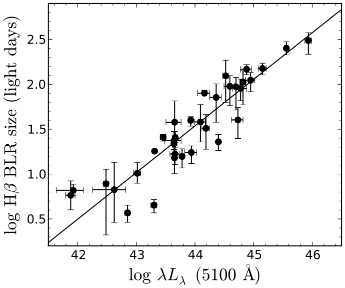
- for virial motion in BLR:

  $$M_\bullet = f \frac{R_{\mathrm{BLR}} \Delta V^2}{G}$$

- ΔV from broad line width
- scaling relation between BLR size and continuum luminosity (via reverberation mapping)

  $$R_{\mathrm{BLR}} \propto L_{5100}^{0.5}$$





Bentz et al. (2009)

Black hole masses for broad line AGN

- for virial motion in BLR:

  $$M_\bullet = f \frac{R_{\rm BLR} \Delta V^2}{G}$$

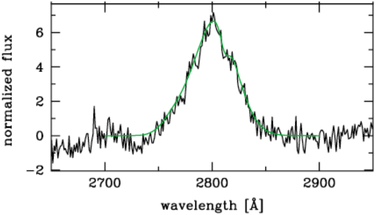
- ΔV from broad line width
- scaling relation between BLR size and continuum luminosity (via reverberation mapping)

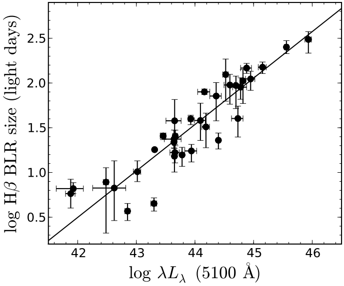
  $$R_{\rm BLR} \propto L_{5100}^{0.5}$$

- estimate $M_\bullet$ from spectrum

  $$M_\bullet \propto L_{5100}^{0.5} \Delta V^2$$

$\Rightarrow$ feasible to estimate $M_\bullet$ for large samples of broad line AGN out to high z





Bentz et al. (2009)

The bivariate distribution function of BH mass and Eddington ratio

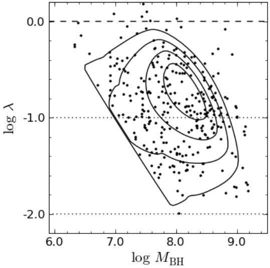
⇒ Black hole mass function (BHMF) and Eddington ratio distribution function (ERDF) determined jointly by fitting probability distribution in $M_\bullet - \lambda$-plane

⇒ via Maximum likelihood method (Schulze & Wisotzki 2010) or via Bayesian framework (Kelly et al. 2009)

⇒ **active BH:** type-1 AGN with log $\lambda > -2$

ML approach

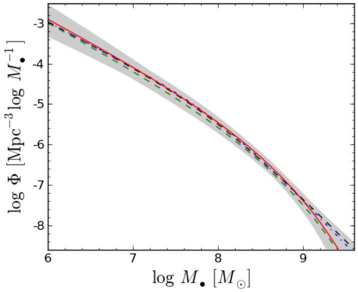
$\quad$ BHMF
$+$ ERDF
$+$ survey selection function
$=$ probability distribution



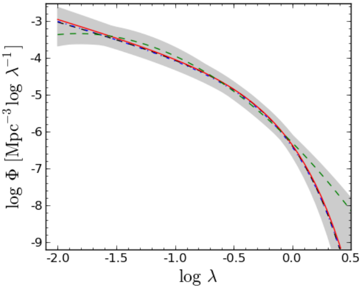
The local active black hole mass function and Eddington ratio distribution function

Local ($z < 0.3$) BHMF and ERDF from the Hamburg/ESO Survey

Active black hole mass function



Eddington ratio distribution function

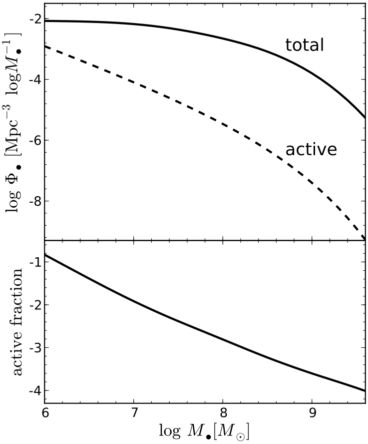


Schulze & Wisotzki (2010)

$\Rightarrow$ No evidence for downturn at low black hole mass or at low Eddington ratio

Active fraction of local black holes

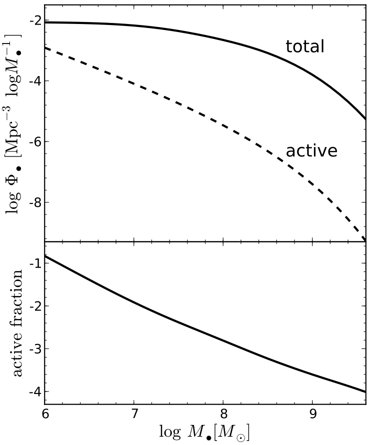
compare to quiescent BHMF of Marconi et al. 2004



Active fraction of local black holes

compare to quiescent BHMF of Marconi et al. 2004

- significant decrease of active fraction toward higher $M_\bullet$
- indication for cosmic downsizing in black hole mass

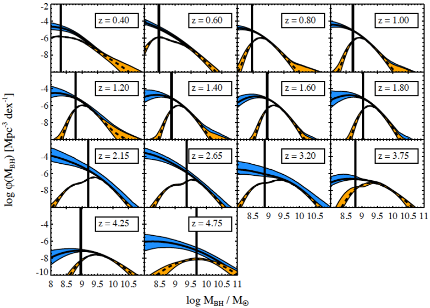


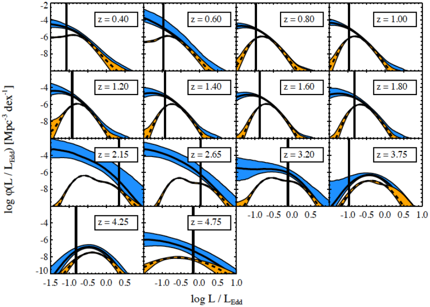
Active BHMF and ERDF at higher redshifts

at $z > 0.4$ BHMF and ERDF determined from SDSS QSO sample

$\Rightarrow$ evidence for black hole mass downsizing

$\Rightarrow$ only high mass end of BHMF, high λ end of ERDF





Kelly & Shen (2013)

BH demographics from VVDS, zCOSMOS and SDSS

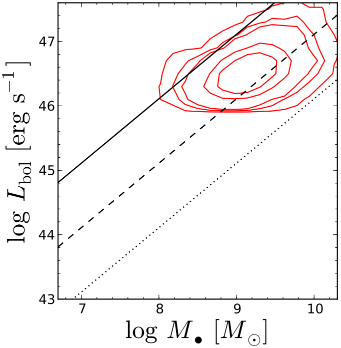
combine bright, large area surveys (**SDSS**) with deep, small area AGN surveys (**VVDS, zCOSMOS**)

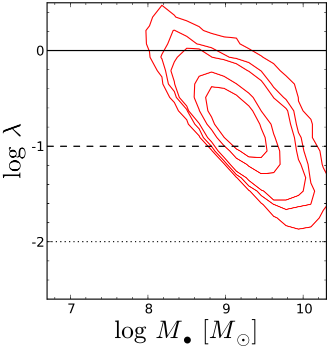
SDSS:	$i < 19.1$	$\Omega_{\rm eff} = 6248$ deg^2
	color selection	
VVDS:	wide: $I_{\rm AB} < 22.5$	$\Omega_{\rm eff} = 4.5$ deg^2
	deep: $I_{\rm AB} < 24.0$	$\Omega_{\rm eff} = 0.6$ deg^2
	random selection	
zCOSMOS:	$I_{\rm AB} < 22.5$	$\Omega_{\rm eff} = 1.6$ deg^2
	random + X-ray selection	

BH demographics from VVDS, zCOSMOS and SDSS

- ⇒ 1.1<z<2.1
- ⇒ use MgII BH masses

⇒ SDSS: ∼ 28000 AGN

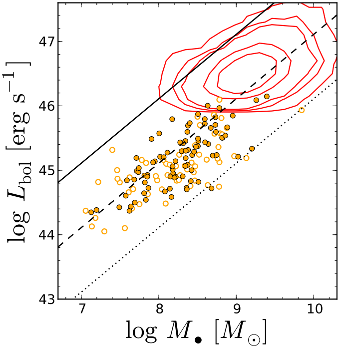


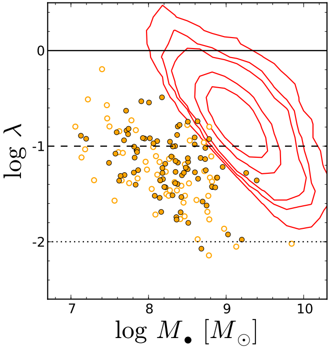


BH demographics from VVDS, zCOSMOS and SDSS

- ⇒ 1.1<z<2.1
- ⇒ use MgII BH masses

- ⇒ SDSS: $\sim$ 28000 AGN
- ⇒ VVDS: 86 + 61 AGN





BH demographics from VVDS, zCOSMOS and SDSS

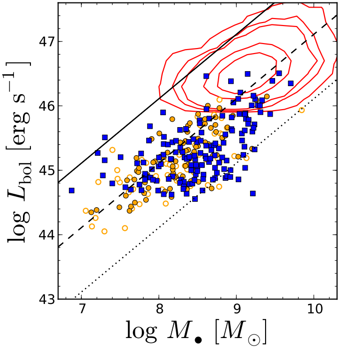
⇒ 1.1<z<2.1

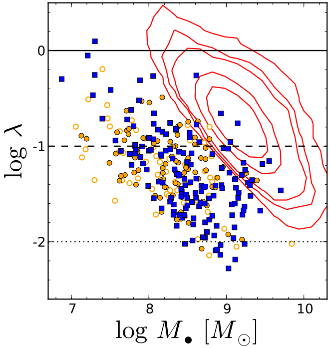
⇒ use MgII BH masses

⇒ SDSS: ∼ 28000 AGN

⇒ VVDS: 86 + 61 AGN

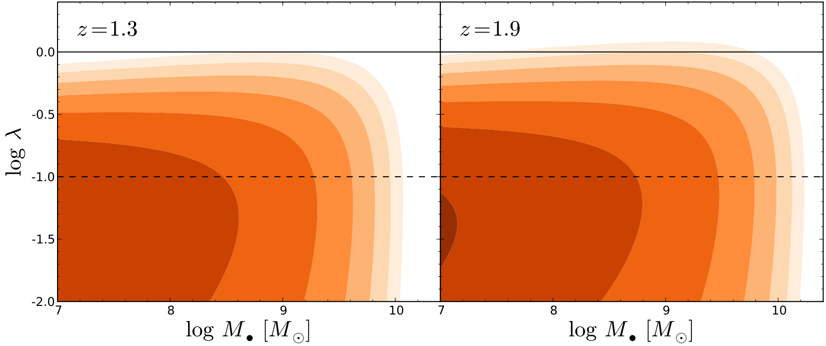
⇒ zCOSMOS: 145 AGN





Bivariate distribution function of $M_\bullet$ and λ at $1 < z < 2$

$\Psi(M_\bullet, \lambda, z)$



active black hole mass function

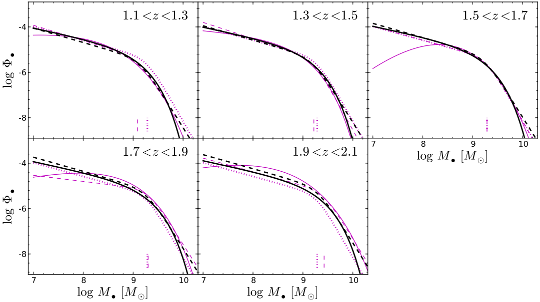
$\Phi_\bullet(M_\bullet, z) = \int \Psi(M_\bullet, \lambda, z)\, \mathrm{d}\log\lambda$

Eddington ratio distribution function

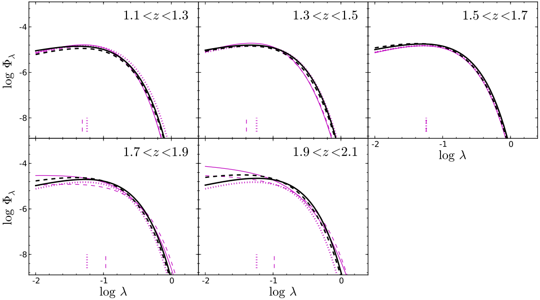
$\Phi_\lambda(\lambda, z) = \int \Psi(M_\bullet, \lambda, z)\, \mathrm{d}\log M_\bullet$

Active black hole demographics at $1 < z < 2$

active black hole mass function

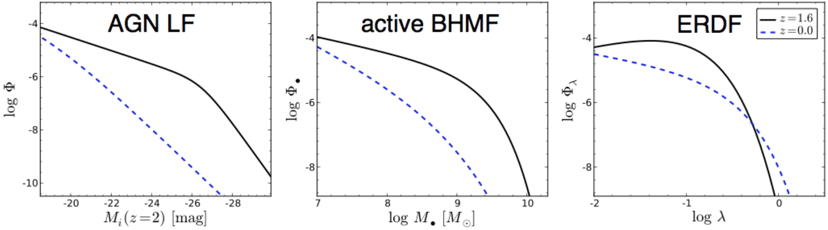


Eddington ratio distribution function



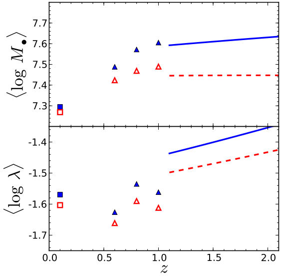
Schulze et al. (2015)

Evolution of the active black hole mass function and Eddington ratio distribution function



$z \sim 1.5$ Schulze et al. (2015)

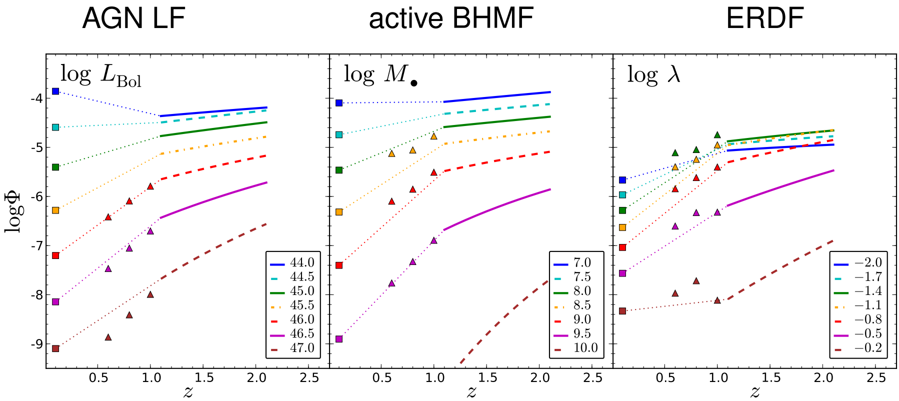
$z \sim 0.0$ Schulze & Wisotzki (2010)



⇒ strong downsizing in the active BHMF

⇒ decrease of average Eddington ratio towards $z = 0$

Evolution of the AGN space density



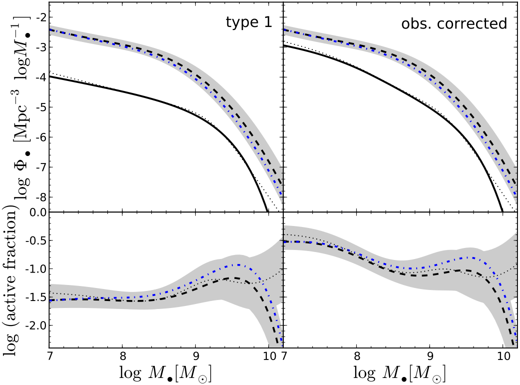
⇒ strong downsizing in the active BHMF

⇒ moderate evolution in ERDF

Active black hole fraction at $z \sim 1.5$

compare to quiescent BHMF derived from stellar mass function

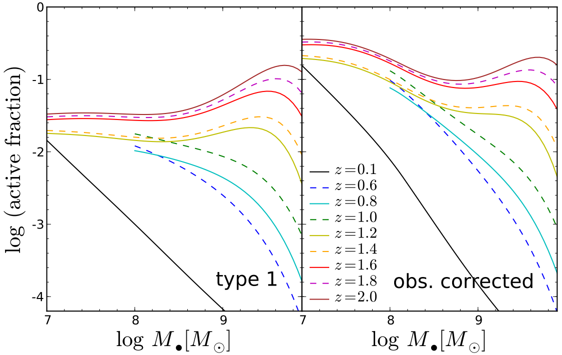
at $z \approx 1.5$ broad line AGN active fraction almost independent of $M_\bullet$



The evolution of the active black hole fraction

week evolution at
$\sim 10^7\ M_\bullet$

strong evolution
at $> 10^9\ M_\bullet$



$\Rightarrow$ witness shutoff of black hole growth at the high mass end between $z = 2$ and $z = 0$

Constraints on theoretical models

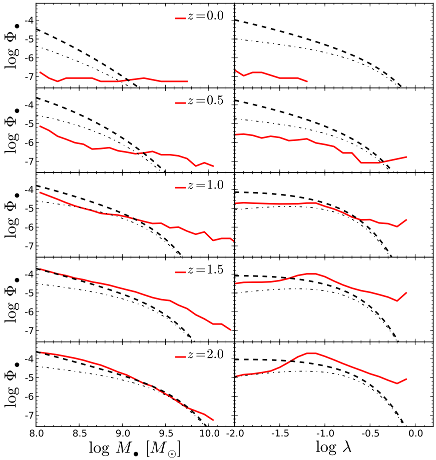
⇒ comparison with galaxy evolution models

⇒ discriminate between different models of galaxy evolution, AGN feedback, ...

- comparison with numerical simulation from Hirschmann et al. (2014)

⇒ good match at $z > 1$ and $M_\bullet < 10^{9.5}$

⇒ disagreement at low-z and high $M_\bullet$ => caused by radio-mode AGN feedback implementation

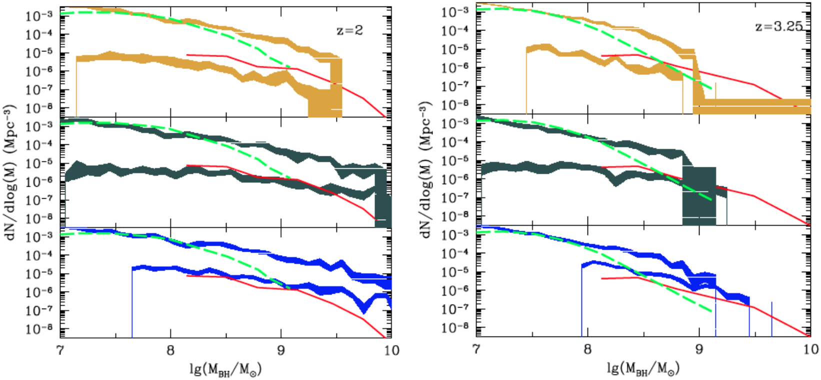


Schulze et al. (2015)

Constraints on SMBH seeds

⇒ comparison with models of merger-driven black hole growth

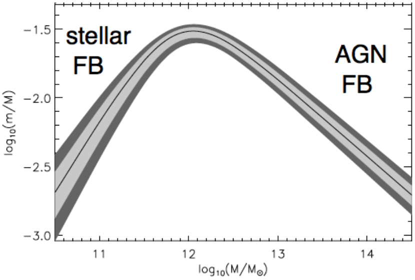
⇒ discriminate between different models of SMBH seeds



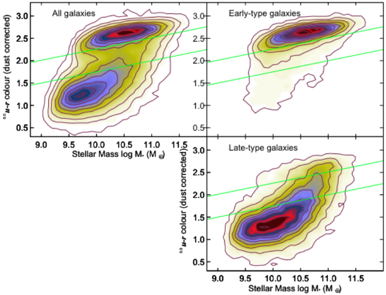
Natarajan & Volonteri (2012)

⇒ massive seed model preferred

The relevance of AGN feedback



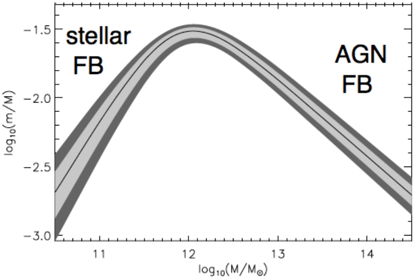
Moster et al. (2010)



Schawinski et. al (2014)

- AGN Feedback required to shut off SF in massive galaxies
- transition of galaxies from SF main sequence to passive red galaxies via SF quenching

The relevance of AGN feedback



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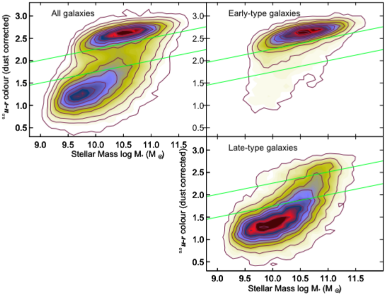

Schawinski et. al (2014)

- AGN Feedback required to shut off SF in massive galaxies
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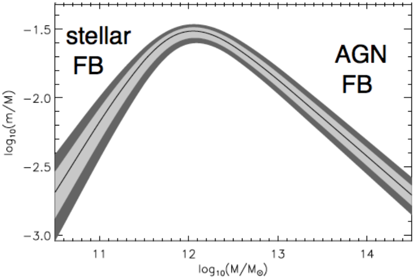
⇒ can AGN do it?

The relevance of AGN feedback



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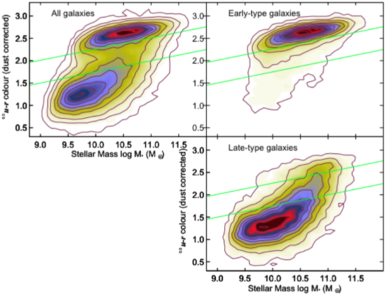


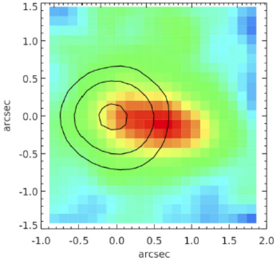
Schawinski et. al (2014)

- AGN Feedback required to shut off SF in massive galaxies
- transition of galaxies from SF main sequence to passive red galaxies via SF quenching

⇒ can AGN do it? ⇒ does their number density work out?

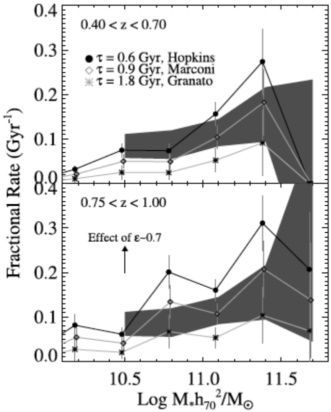
Linking AGN to the quenching of star formation

massive outflows in ionized and molecular gas observed in many AGN host galaxies



Cresci et al. (2015)

Bundy et al. (2008): demographic argument



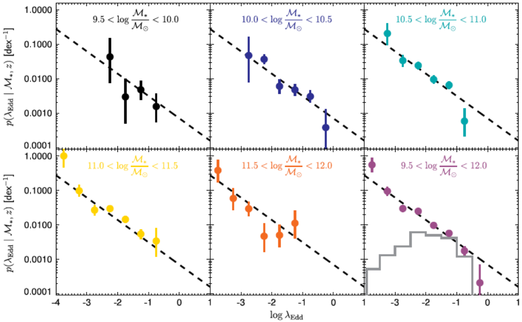
AGN trigger rate matches star formation quenching rate

The specific accretion rate distribution of AGN

$p(L_X/M_\star|M_\star, z)$

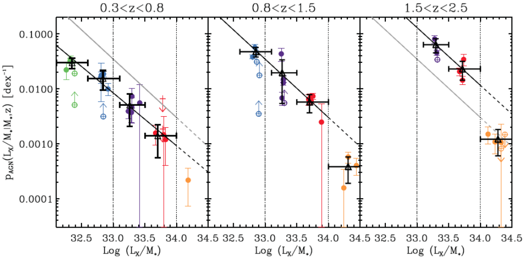
Aird et al. (2012):
$0.2 < z < 1.0$

$\Rightarrow$ distribution of accretion rates follows power law, independent of $M_\star$



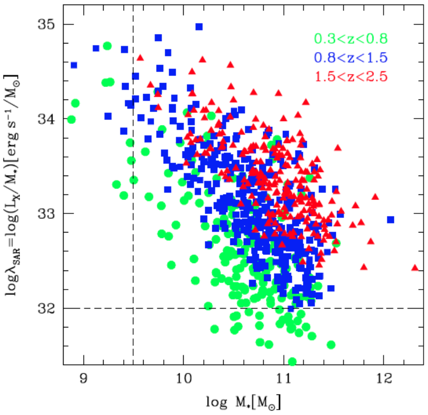
Bongiorno et al. (2012):

$\Rightarrow$ confirmed trend out to $z \sim 2.5$



AGN host galaxy mass function in COSMOS

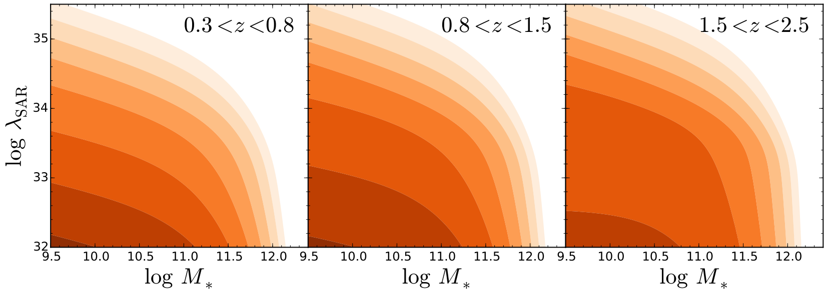
- $\Rightarrow$ 877 hard X-ray selected AGN from XMM-COSMOS at $0.3 < z < 2.5$
- $\Rightarrow$ $M_\star$ from SED fitting
- $\Rightarrow$ define: $\lambda_{\rm SAR} = L_{[2-10\rm keV]}/M_\star$
- $\Rightarrow$ define AGN by cut in specific accretion rate $\lambda_{\rm SAR} > 32$
- $\Rightarrow$ determine bivariate distribution function of $M_\star$ and $\lambda_{\rm SAR}$



Bongiorno, AS et al. (submitted)

Bivariate distribution function of $M_\star$ and $\lambda_{\rm SAR}$

$\Psi(M_*, \lambda_{\rm SAR}, z)$



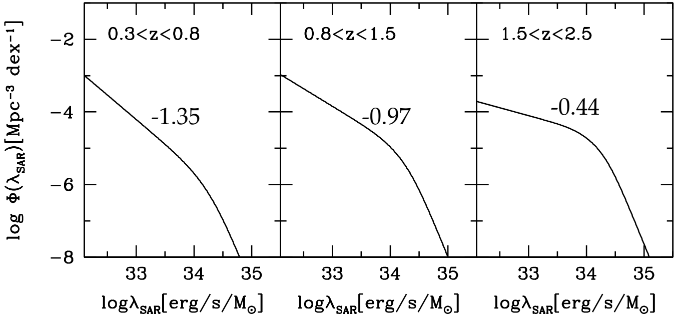
host galaxy mass function (HGMF)

$\Phi_*(M_*, z) = \int \Psi(M_*, \lambda_{\rm SAR}, z)\, \mathrm{d}\log \lambda_{\rm SAR}$

Specific accretion rate distribution function (SARDF)

$\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z) = \int \Psi(M_*, \lambda_{\rm SAR}, z)\, \mathrm{d}\log M_*$

Specific accretion rate distribution function

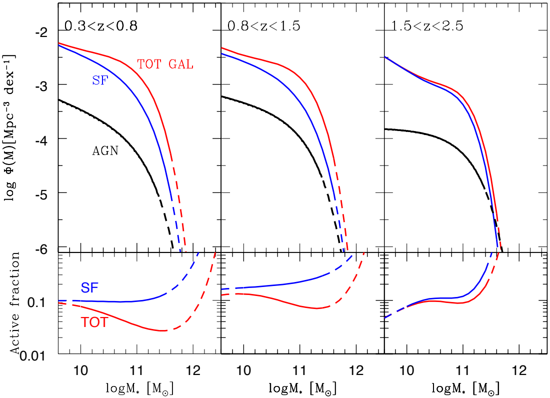


Bongiorno, AS et al. (submitted)

$\Rightarrow$ low λ_{SAR} slope of double power law flattens with z

$\Rightarrow$ normalization increases with z

Host galaxy mass function

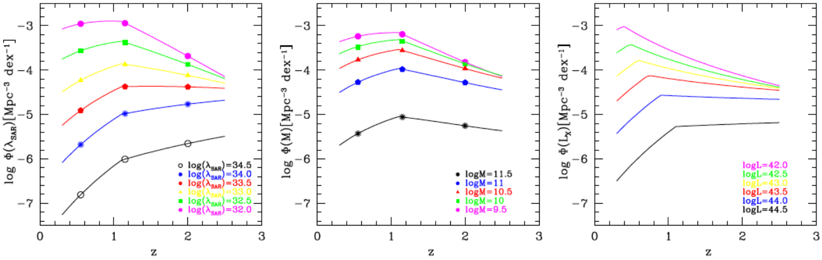


Bongiorno, AS et al. (submitted)

- ⇒ low mass slope of Schechter function flattens with z
- ⇒ density ratio compared to SF galaxies ∼constant with mass
- ⇒ active fraction shows *z* dependent mass dependence

Downsizing in $M_\star$ and $\lambda_{\rm SAR}$

$\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z)$ $\Phi_*(M_*, z)$ $\Phi_L(L_X, z)$

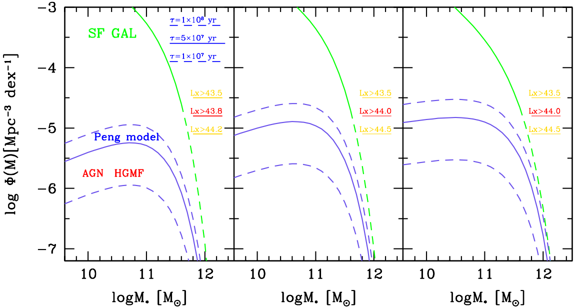


$\Rightarrow$ downsizing in $\Phi_{\lambda_{\rm SAR}}(\lambda_{\rm SAR}, z)$

$\Rightarrow$ moderate downsizing in $\Phi_*(M_*, z)$

AGN as driver for mass quenching of galaxies?

mass function of galaxies in the process of being mass-quenched, based on Peng et al. (2010) model (blue), $\tau_{\rm trans} = 10^6 - 10^7$ yr

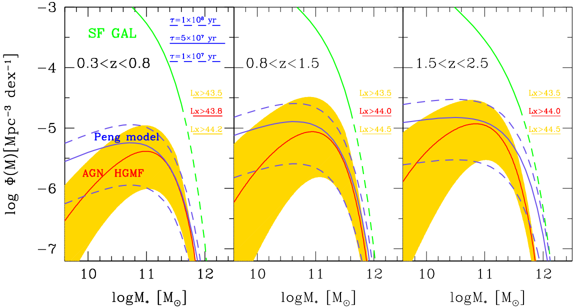


AGN as driver for mass quenching of galaxies?

mass function of galaxies in the process of being mass-quenched, based on Peng et al. (2010) model (blue), $\tau_{\rm trans} = 10^6 - 10^7$ yr

vs.

AGN host galaxy mass function of luminous AGN, $\log L_X > 44$ (red)



$\Rightarrow$ at high mass, the HGMF of Lx>43.5-44.5 AGN can reproduce well the model prediction for the transition population

Conclusions

- active BHMF and ERDF provide additional observational constraints on BH growth and galaxy evolution
- established at $z < 2$

$\Rightarrow$ downsizing in AGN LF mainly driven by downsizing in the BHMF

$\Rightarrow$ shutoff of black hole growth at the high mass end from $z = 2$ to $z = 0$

$\Rightarrow$ new observational constraints for theoretical models of galaxy formation and BH growth Schulze et al. (2015)

- determined AGN host galaxy mass function and specific accretion rate distribution function at $0.3 < z < 2.5$

$\Rightarrow$ luminous AGN population consistent with quenching of star formation in massive galaxies Bongiorno, Schulze et al. (2015)