The cosmic growth of the active black hole population

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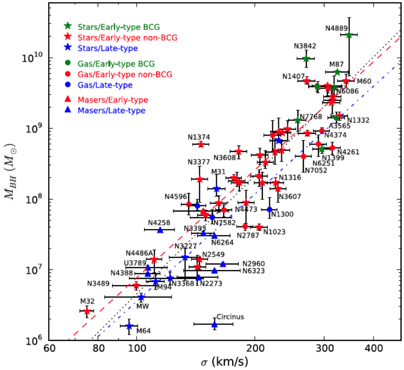
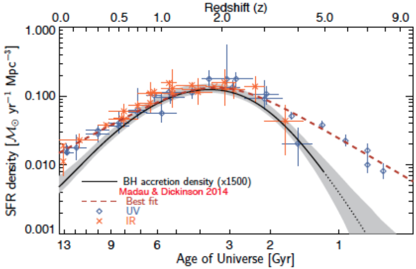
Black hole - galaxy coevolution

$M_\bullet - \sigma_*$ relation



McConnell & Ma (2013)

integrated cosmic BH accretion history parallel to SF history



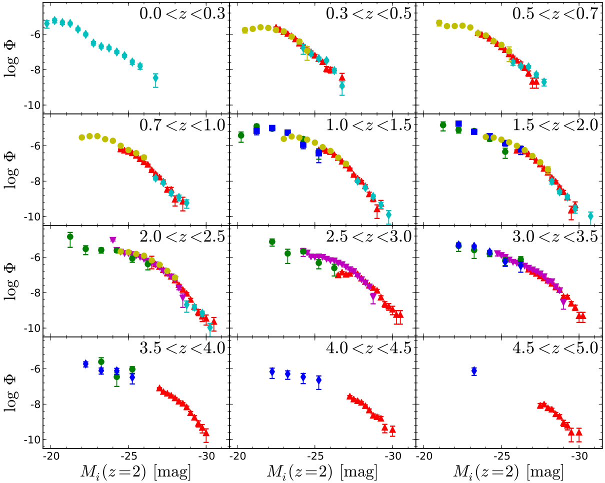
Aird et al. (2015)

$\Rightarrow$ link between black hole growth and galaxy evolution

$\Rightarrow$ how are black holes growing?

AGN demographics: The AGN LF

AGN Luminosity function is main demographic quantity



optical: Schulze et. al (in prep.)

AGN demographics: The AGN LF

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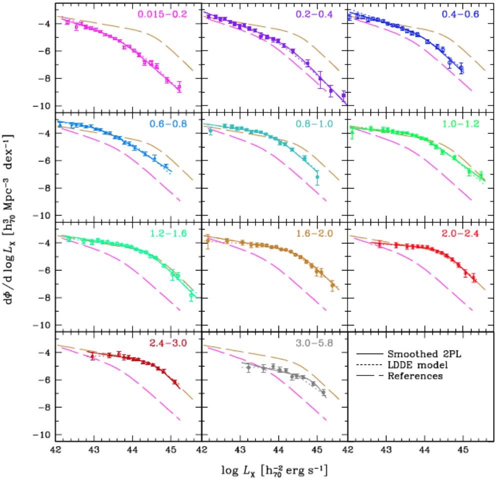
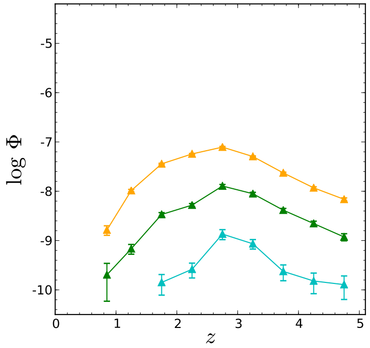


X-ray: Miyaji et. al (2015)

AGN demographics: AGN LF evolution

AGN Luminosity function is main demographic quantity

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



optical: SDSS (Richards et al. 2006)

AGN demographics: AGN LF evolution

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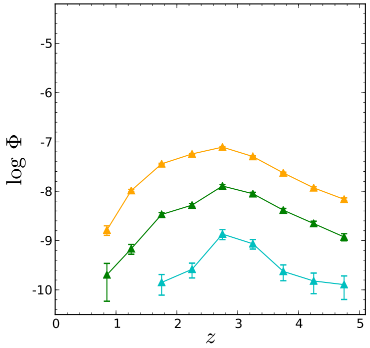
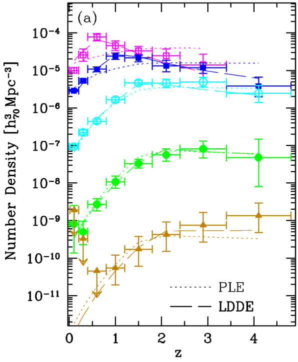
- peak is shifted towards lower z for fainter AGN

$\Rightarrow$ AGN cosmic downsizing



optical: SDSS (Richards et al. 2006)



X-rays: Hasinger et. al (2005)

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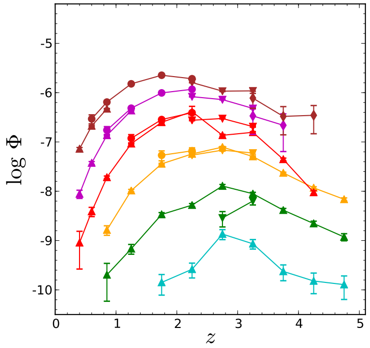
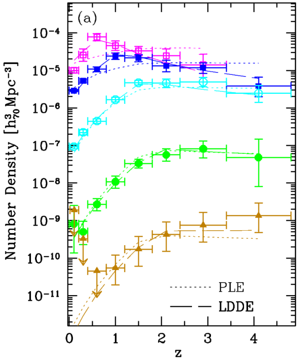


optical: various surveys

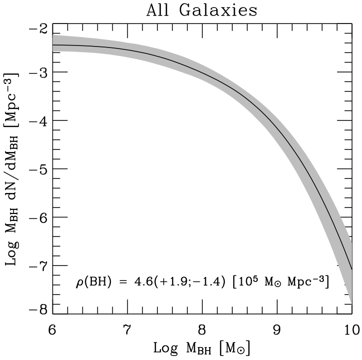


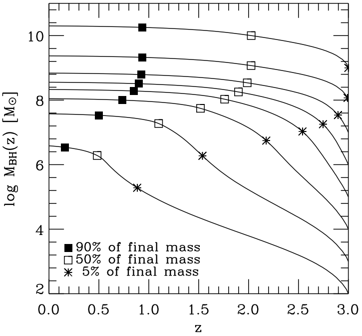
X-rays: Hasinger et. al (2005)

Implications for BH growth

- BH mass density accreted during QSO phases = local BH mass density (Soltan argument)
- most BH growth takes place in luminous AGN phase

⇒ AGN downsizing implies anti-hierarchical BH growth



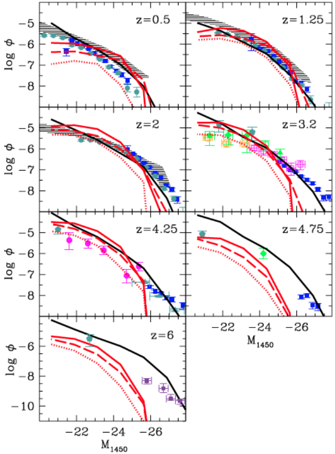


Marconi et. al (2004)

Constraints on theoretical models

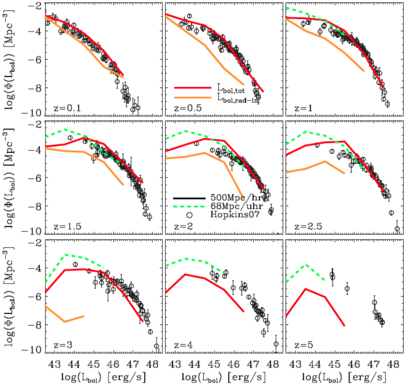
- SAMs & numerical simulations able to reproduce AGN LF and downsizing

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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$\Rightarrow$ additional $M_\bullet$ information able to break this degeneracy

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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:

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

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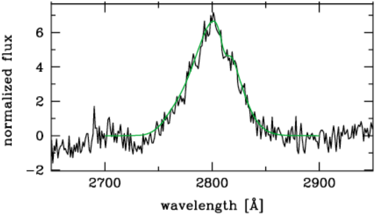
- ΔV from broad line width



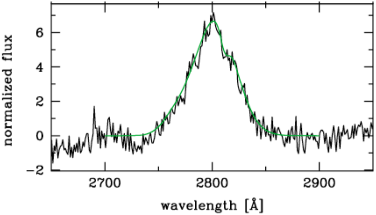
Black hole masses for broad line AGN

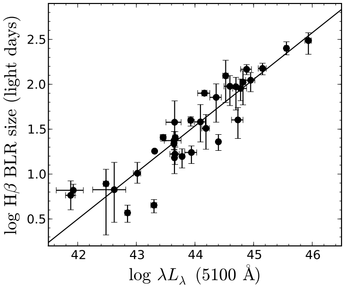
- for virial motion in BLR:

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

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

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





Bentz et al. (2009)

Black hole masses for broad line AGN

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

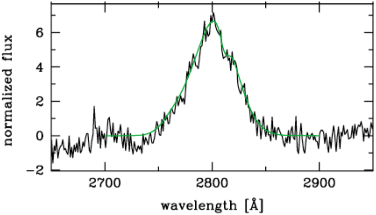
- ΔV from broad line width
- scaling relation between BLR size and continuum luminosity (via reverberation mapping)

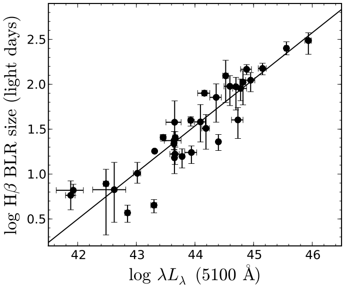
  $$R_{\mathrm{BLR}} \propto L_{5100}^{0.5}$$

- 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



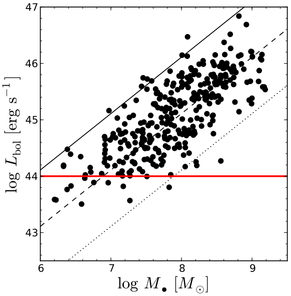


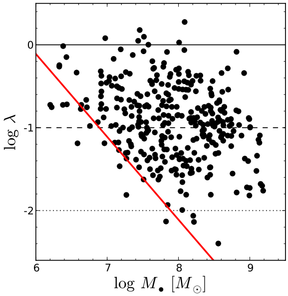
Bentz et al. (2009)

What is an *active* black hole?

define *active* BH:

- ⇒ active BHs limited to broad line AGN
- ⇒ luminosity limit poor criteria for BHMF (incompleteness at low mass by definition)
- ⇒ define active black hole by Eddington ratio limit
- ⇒ **active BH:** type-1 AGN with log $\lambda > -2$



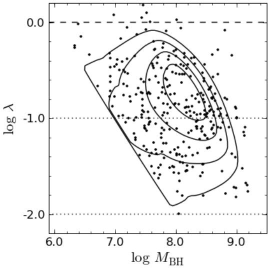


The bivariate distribution function of BH mass and Eddington ratio

- **model DF via fitting of bivariate distribution function of $M_\bullet$ and λ**
  - $\Rightarrow$ Black hole mass function (BHMF) and Eddington ratio distribution function (ERDF) determined jointly by fitting probability distribution in $M_\bullet - \lambda$-plane
  - $\Rightarrow$ via Maximum likelihood method (Schulze & Wisotzki 2010) or via Bayesian framework (Kelly et al. 2009)

ML approach

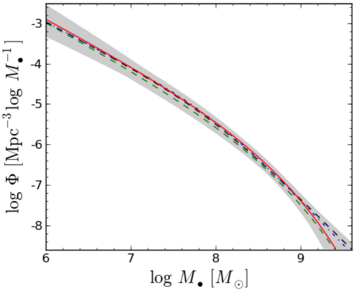
	BHMF
$+$	ERDF
$+$	survey selection function
$=$	probability distribution



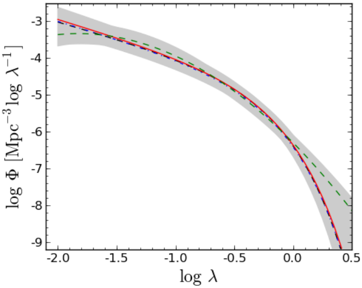
The local active black hole mass function and Eddington ratio distribution function

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

Active black hole mass function



Eddington ratio distribution function

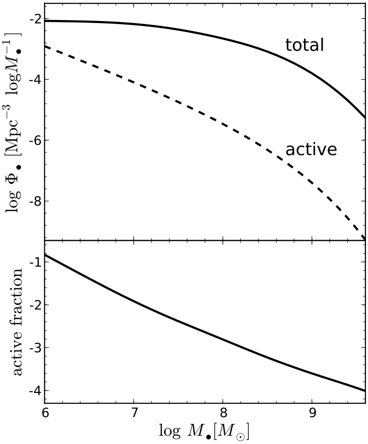


Schulze & Wisotzki (2010)

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

Active fraction of local black holes

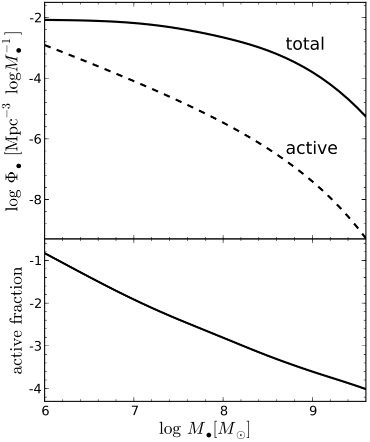
compare to quiescent BHMF of Marconi et al. 2004



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

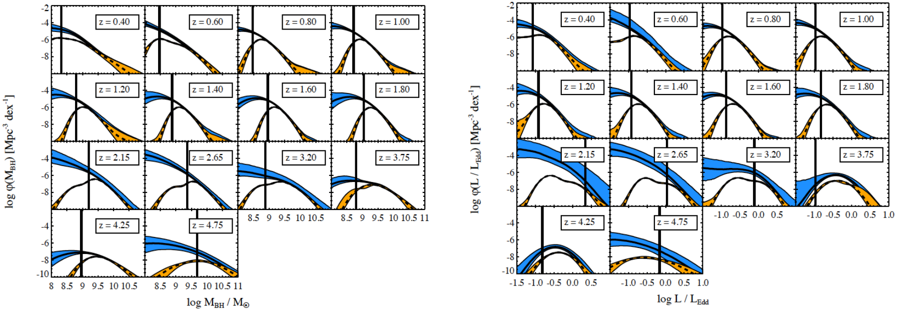


Active BHMF and ERDF at higher redshifts

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**)

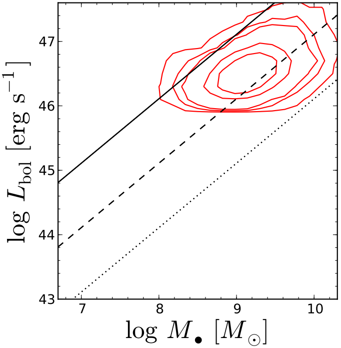
SDSS:	$i < 19.1$	$\Omega_{\rm eff} = 6248$ deg^2
	color selection	
VVDS:	wide: $I_{\rm AB} < 22.5$	$\Omega_{\rm eff} = 4.5$ deg^2
	deep: $I_{\rm AB} < 24.0$	$\Omega_{\rm eff} = 0.6$ deg^2
	random selection	
zCOSMOS:	$I_{\rm AB} < 22.5$	$\Omega_{\rm eff} = 1.6$ deg^2
	random + X-ray selection	

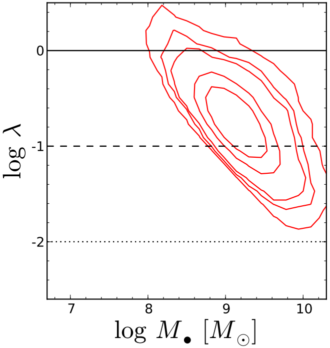
BH demographics from VVDS, zCOSMOS and SDSS

⇒ 1.1<z<2.1

⇒ use MgII BH masses

⇒ SDSS: ∼ 28000 AGN





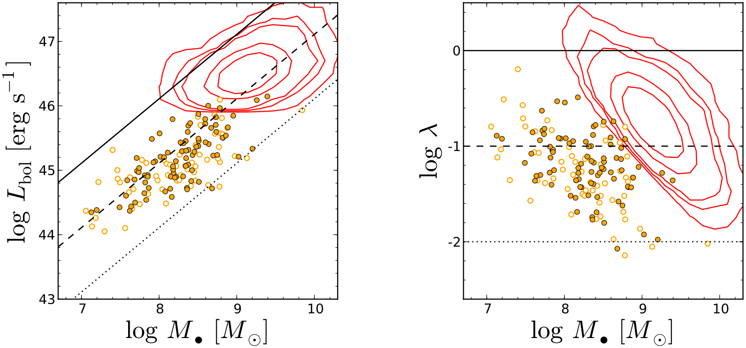
BH demographics from VVDS, zCOSMOS and SDSS

⇒ 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

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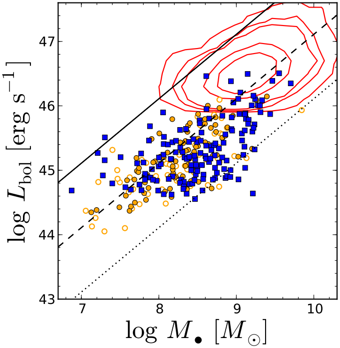
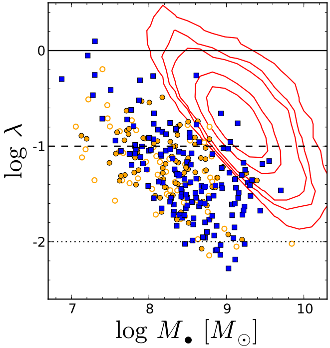
⇒ SDSS: ∼ 28000 AGN

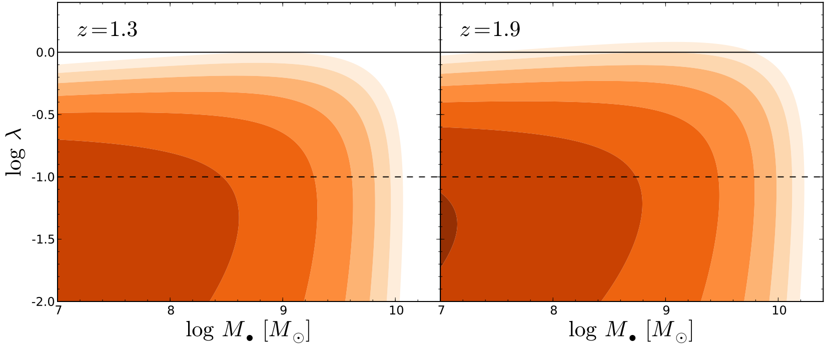
⇒ VVDS: 86 + 61 AGN

⇒ zCOSMOS: 145 AGN





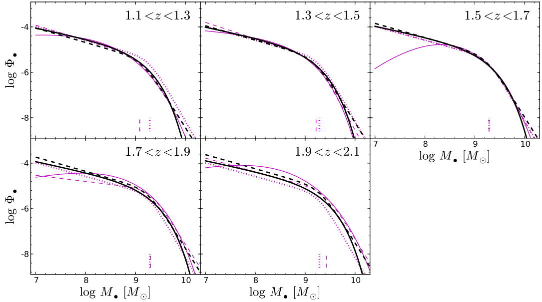
Bivariate distribution function of $M_\bullet$ and λ at $1 < z < 2$



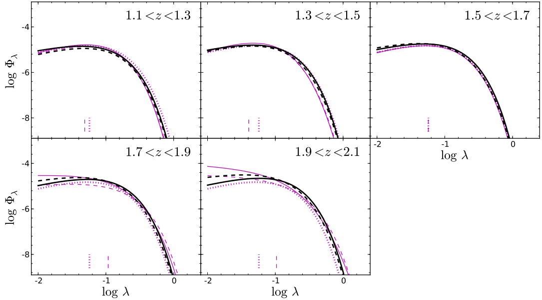
Schulze et al. (2015)

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

active black hole mass function

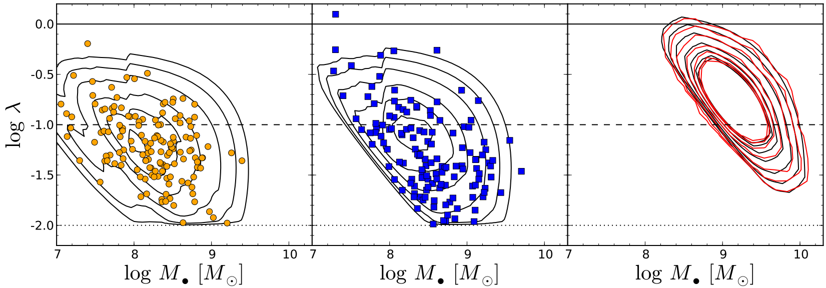


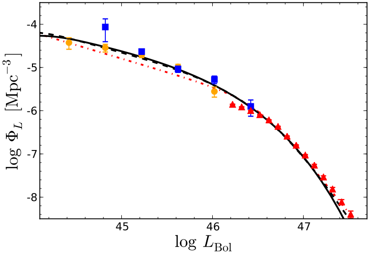
Eddington ratio distribution function



Schulze et al. (2015)

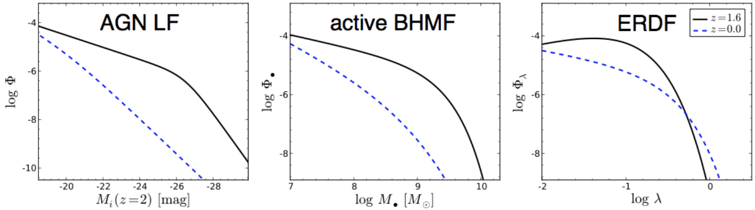
Comparison with $M_\bullet - \lambda$ plane and AGN LF





By construction the BHMF & ERDF is consistent with observed $M_\bullet - \lambda$ plane and with bolometric AGN LF

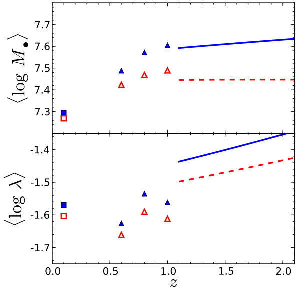
Evolution of the active black hole mass function and Eddington ratio distribution function



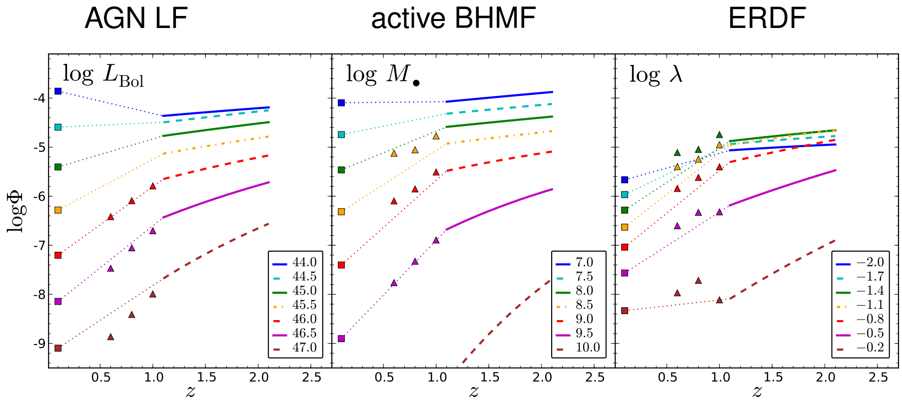
comparison with local distribution functions

⇒ strong downsizing in the active BHMF

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



Evolution of the AGN space density



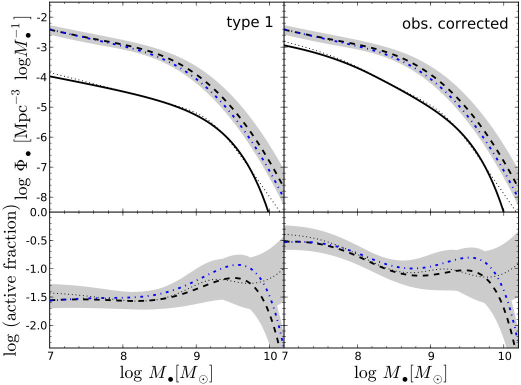
⇒ strong downsizing in the active BHMF

⇒ moderate evolution in ERDF

Active black hole fraction at $z \sim 1.5$

compare to quiescent BHMF derived from stellar mass function

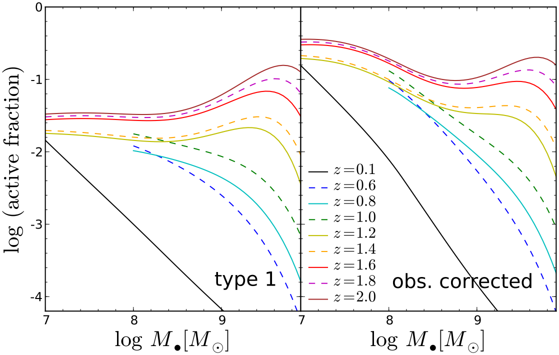
at $z \approx 1.5$ broad line AGN active fraction almost independent of $M_\bullet$



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

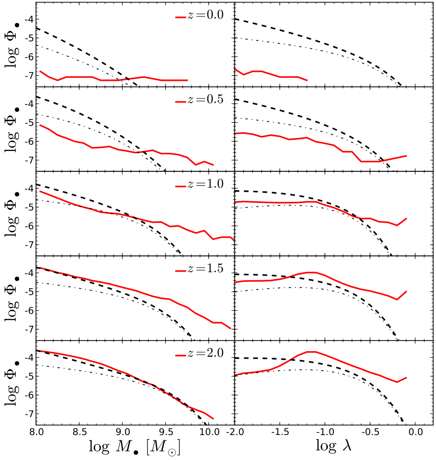
$\Rightarrow$ comparison with galaxy evolution models

$\Rightarrow$ discriminate between different models of galaxy evolution, AGN feedback, ...

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

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

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

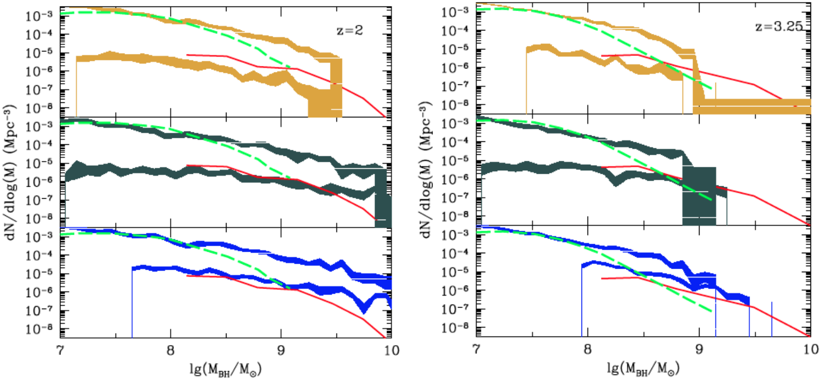


Schulze et al. (2015)

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

Connecting AGN demographics to the quenching of star formation

quenching of star formation
(e.g. Peng+10)

- environment quenching
  - $\Rightarrow$ satellite galaxies
- mass quenching
  - $\Rightarrow$ SN Feedback?
  - $\Rightarrow$ strangulation? (at low mass?)
  - $\Rightarrow$ AGN feedback?

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quenching of star formation
(e.g. Peng+10)

- environment quenching
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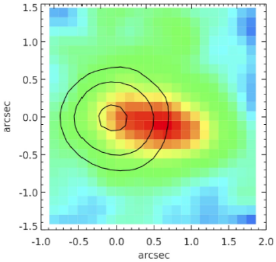
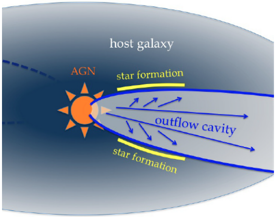
outflows observed in luminous AGN

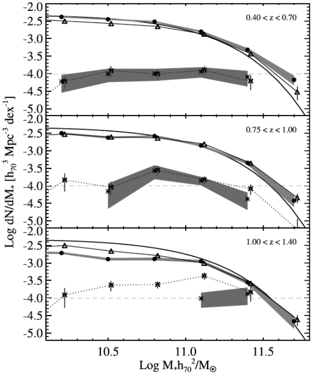


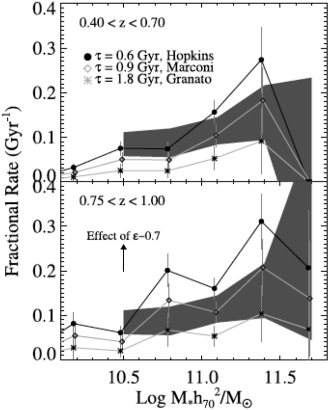


Cresci et al. (2014)

Linking AGN to the quenching of star formation

Bundy+08: determined AGN host galaxy mass function within $0.4 < z < 1$ from AEGIS





Bundy et al. (2008)

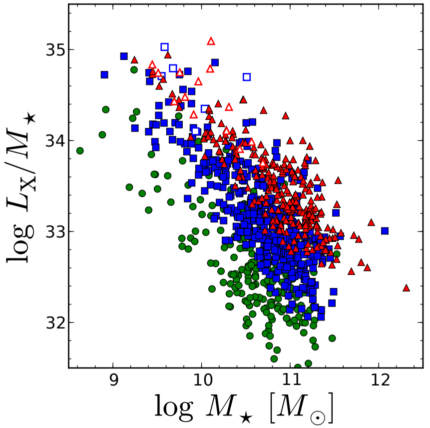
$\Rightarrow$ AGN trigger rate matches star formation quenching rate

AGN host galaxy mass function in COSMOS

determine the AGN host galaxy mass function

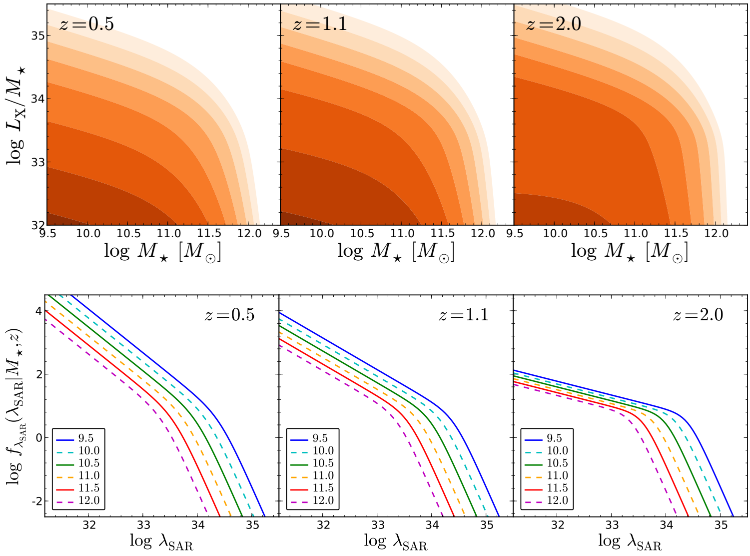
Sample: hard X-ray selected AGN from XMM-COSMOS

- ⇒ 915 AGN in redshift range $0.3 < z < 2.5$
- ⇒ $M_\star$ from SED fitting
- ⇒ account for obscuration via N_H distribution
- ⇒ define AGN by cut in specific accretion rate $\log L_X/M_\star > 32$
- ⇒ AGN X-ray LF used as additional constraint

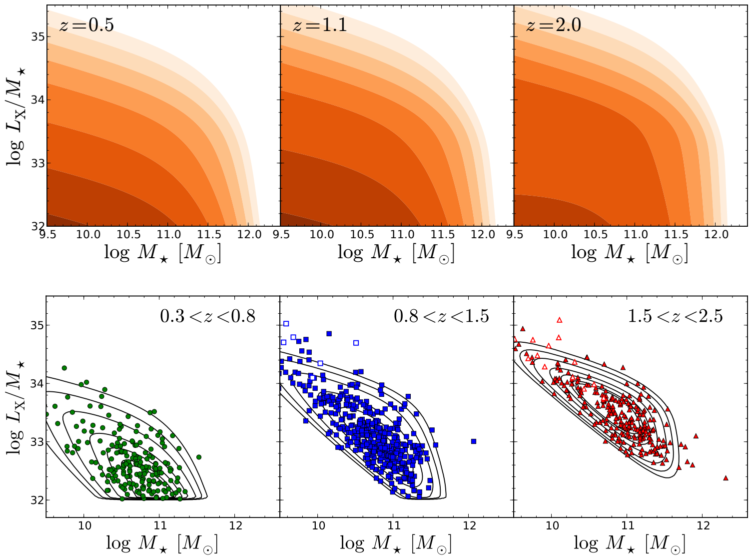


Bongiorno, AS et al. (in prep.)

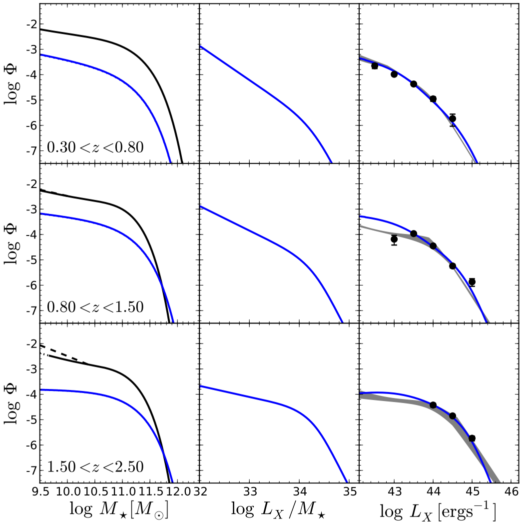
Joint distribution function of $M_\star$ and $L_X/M_\star$



Joint distribution function of $M_\star$ and $L_X/M_\star$



Host galaxy mass function and $L_X/M_\star$ function



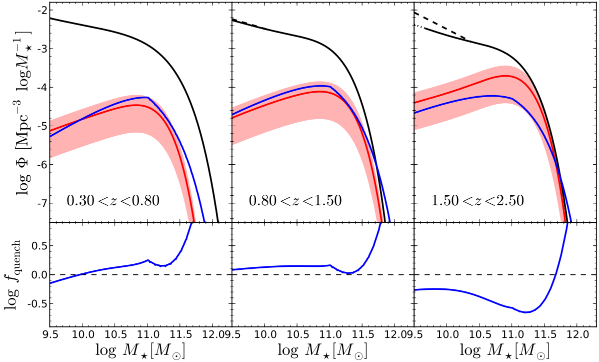
Bongiorno, AS et al. (in prep.)

AGN as driver for mass quenching of galaxies?

Compare:

⇒ mass function of galaxies in the process of being mass-quenched, based on Peng et al. (2010) model (red)

⇒ AGN host galaxy mass function of luminous AGN, log $L_X > 43$ (blue)



luminous AGN can accommodate quenched galaxy population

Bongiorno, AS et al. (in prep.)

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

- determined AGN host galaxy mass function at $0.3 < z < 2.5$

$\Rightarrow$ luminous AGN population consistent with mass quenching of massive galaxies