Università degli Studi di Firenze

Dipartimento di Fisica e Astronomia
Sezione di Astronomia
Università di Firenze

# Coevolution of AGN, BHs and their host galaxies: the observational foundations

*Beijing international summer school*

*"The physics and evolution of AGN"*

*September 3-9, 2011*

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# Outline of lectures

- Part 1: *Supermassive black holes in galactic nuclei: detections and mass measurements* (2 lectures)
- Part 2: *Scaling relations between black holes and their host galaxies* (2 lectures)
- **Part 3: *The cosmological evolution of AGN and BHs* (2 lectures)**
- Part 4: *The observational signatures of coevolution* (2 lectures)

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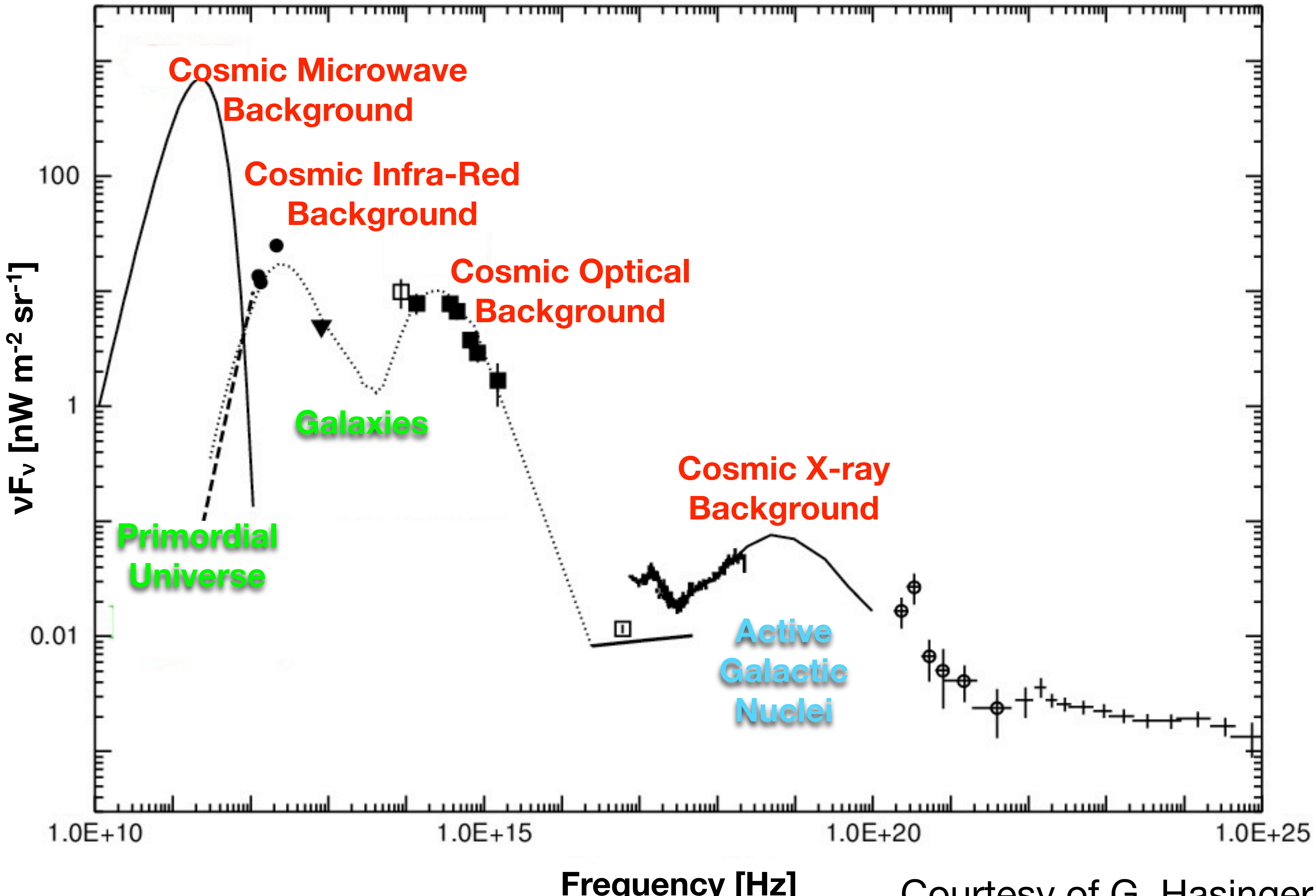
# Part 3: *cosmological evolution of AGN and BHs*

# The cosmological evolution of BHs

To follow the cosmological evolution of supermassive black holes and understand their role in galaxy evolution, it is not possible to measure their masses as it has been done in the local universe.

- One possibility (the only one at the moment) is to follow the cosmological evolution of AGN, which are accreting black holes.
  - study the optical luminosity functions of quasars or the X-ray (0.5-10 keV) luminosity functions of AGN in general
  - estimate BH masses in broad line AGN
- In general, AGN leave two remnants of their activity
  - *supermassive BHs in galaxy nuclei*
  - *background radiation*, i.e. the integrated emission from all AGN at all cosmic epochs which is almost devoid of contamination in the case of the *X-ray background (XRB)*

# Cosmic backgrounds




Courtesy of G. Hasinger

# Luminosity functions

The differential luminosity function $\phi(L,z)$ of a population of sources is

$$dN = \phi(L, z)\, dV\, dL$$

$dN$ is the number of sources per unit volume at z with luminosity $L$, $L+dL$

To estimate the luminosity function, one usually

- conducts a survey over a sky area $\Omega$
- identifies all the sources of the chosen population with fluxes in a given band $b$ $F_b > F_{b,lim}$ (usually the sensitivity limit)
- measures their *redshift z* hence *observed* $L_{b,obs}$ is known
- assuming a spectral shape for the sources, one then corrects to have *intrinsic* $L_b$ in band $b$ (K-correction).

Suppose we count $N$ sources in $L_b$, $L_b+\Delta L_b$ and $z+\Delta z$, over area $\Omega$ then

$$\Delta V = \frac{\Omega}{4\pi} \int_z^{z+\Delta z} \left( \frac{dV}{dz} \right)_{allsky} dz$$

$$\phi(L_b, z) \simeq \frac{N}{\Delta L_b\, \Delta V}$$

$dV$ is the comoving *all sky* volume

$\Delta V$ is the comoving volume occupied by the $N$ sources

# Luminosity functions

However, this estimate does not take into account that a source with luminosity $L_b$, might be below the survey flux limit in part of the $z$, $z+\Delta z$ bin.

A solution, proposed by Schmidt (1968) and refined by Avni & Bahcall (1980) consists in considering the maximum volume where object $i$ can be detected within the redshift bin $z$, $z+\Delta z$

$$\Delta V_{max,i} = \frac{\Omega}{4\pi} \int_z^{min(z_{max,i}, z+\Delta z)} \left( \frac{dV}{dz} \right)_{allsky} dz$$

$z_{max,i}$ is the redshift at which the object has flux larger than the survey limit, i.e. is given by the condition that

$$D_L(z_{max,i}) = \sqrt{\frac{L_{b,i}}{4\pi F_{b,lim}}} \qquad L_b \leq L_{b,i} \leq L_b + \Delta L_b$$

The luminosity function is then

$$\phi(L_b, z) \simeq \frac{1}{\Delta L_b} \sum_{i=1}^{N} \frac{1}{\Delta V_{max,i}}$$

# Luminosity functions

It is possible to improve by better accounting for the binning of the luminosity function (Page & Carrera 2000).
The expected number of objects in a given luminosity and redshift bin is

$$\langle N \rangle = \int_{L_b}^{L_b+\Delta L} \int_{z}^{z_{max}(L)} \phi(L,z) \frac{dV}{dz}\, dz\, dL$$

$z_{max}(L)$ is the maximum redshift for luminosity L

$dV$ is the comoving volume taking into account the survey area.

If bins are small enough that $\phi$ can be considered constant then

$$\phi(L_b, z) \simeq \frac{\langle N \rangle}{\int_{L_b}^{L_b+\Delta L} \int_{z}^{z_{max}(L)} (dV/dz)\, dz\, dL}$$

*errors are usually Poissonian on $N$*

*In general there are many more selection effects (e.g. survey completeness, spectral selection effects, different sensitivities in different areas etc.). This can be included in a "selection function $p(L,z)$*

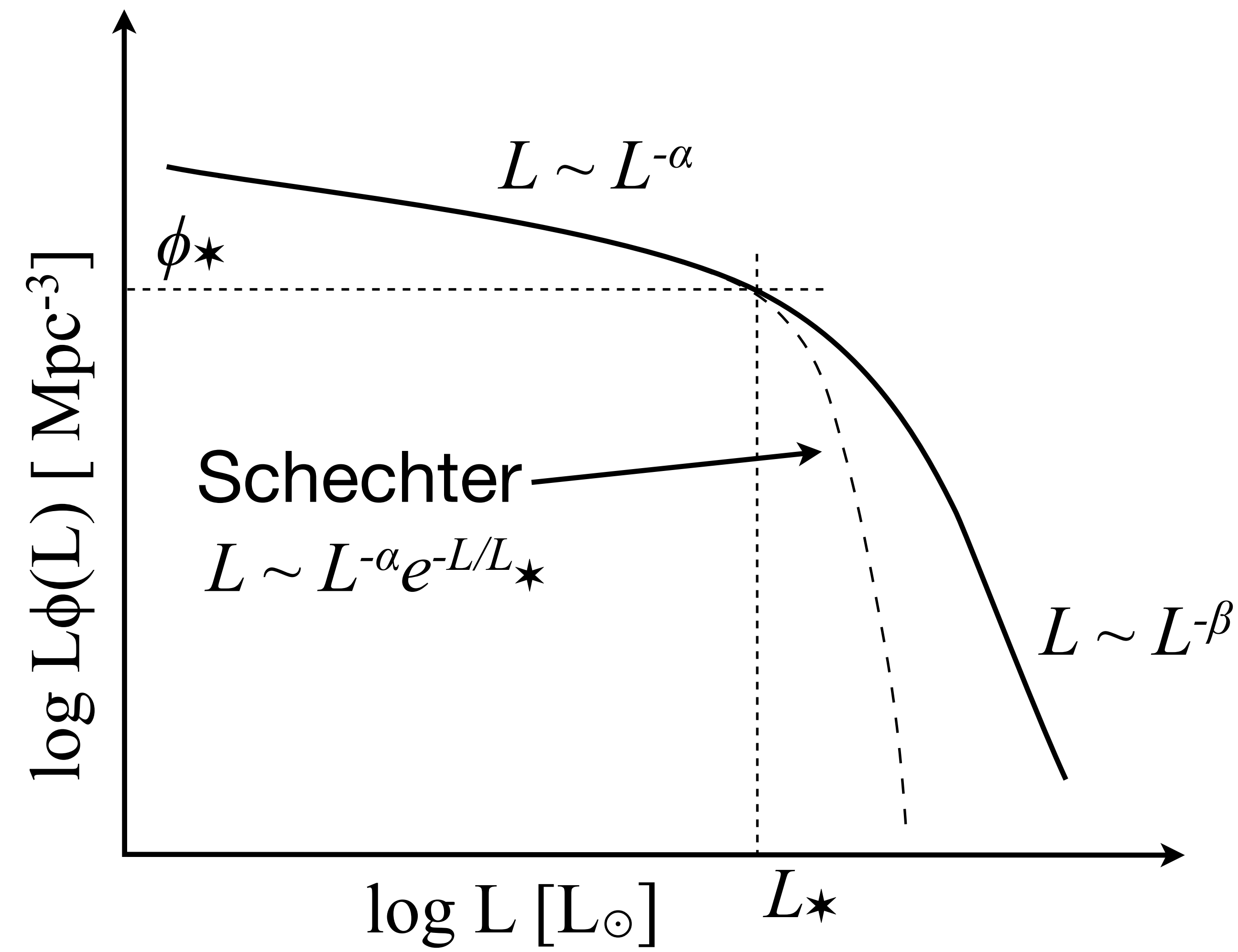
$$\phi(L_b, z) \simeq \frac{\langle N \rangle}{\int_{L_b}^{L_b+\Delta L} \int_{z}^{z_{max}(L)} p(L,z)(dV/dz)\, dz\, dL}$$

*In general, assume function ϕ and fit observed counts*

# AGN Luminosity Functions

AGN luminosity functions are usually parameterized with a double power law of the form

$$\phi(L) = \frac{\phi(L_\star)}{\left(\frac{L}{L_\star}\right)^{\alpha} + \left(\frac{L}{L_\star}\right)^{\beta}}$$




This is different from the luminosity function of galaxies characterized by the Schechter function

$$\phi(L) = \phi(L_\star)\left(\frac{L}{L_\star}\right)^{-\alpha} \mathrm{e}^{-\left(\frac{L}{L_\star}\right)}$$

The luminosity density $\rho_L = \int_0^{+\infty} L\phi(L)dL$

is dominated by the sources at the *knee* of the luminosity function i.e. sources with L~L$_\star$

# AGN LF: cosmological evolution

The redshift evolution of the luminosity functions is usually parameterized in two ways (or a combination of the two)

- luminosity evolution $L_\star = L_\star(z)$

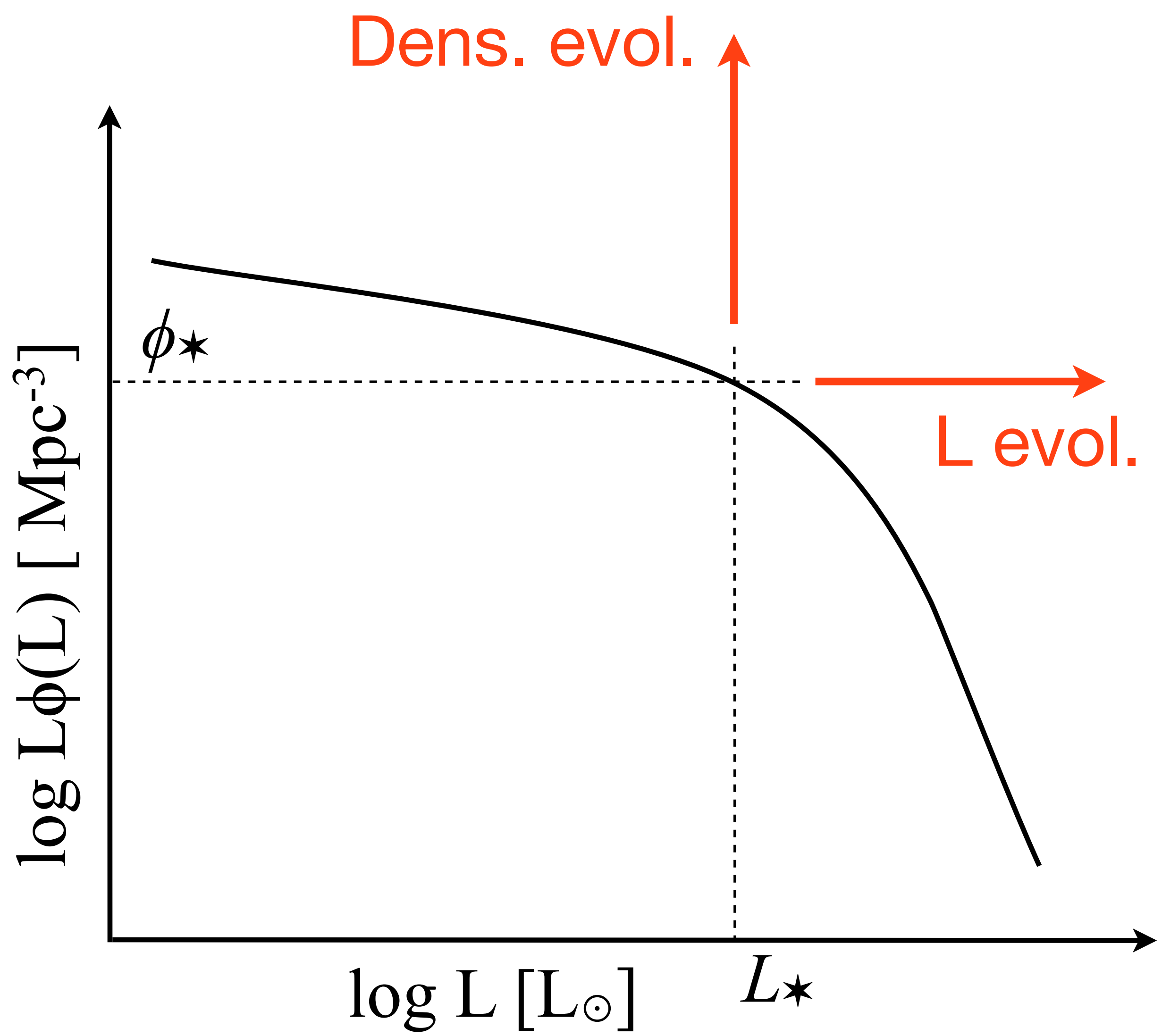
$$\phi(L,z) = \phi\left(\frac{L}{L_\star(z)}, 0\right)$$

- density evolution

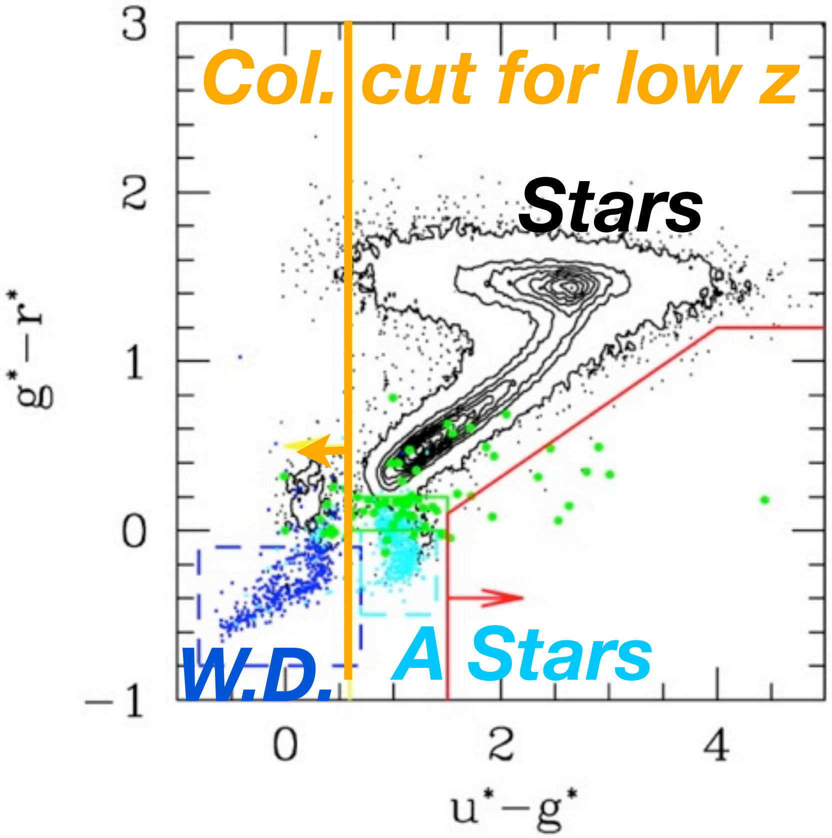
$$\phi(L,z) = n(z)\phi(L,0)$$

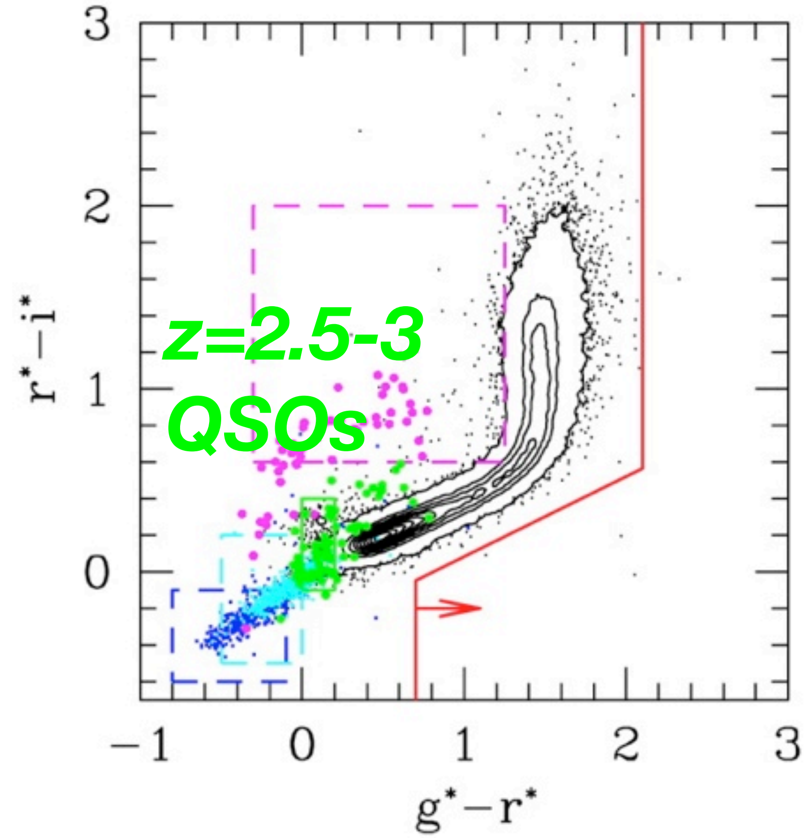
- luminosity-density evolution

$$\phi(L,z) = n(z)\phi\left(\frac{L}{L_\star(z)}, 0\right)$$



# Quasar luminosity functions

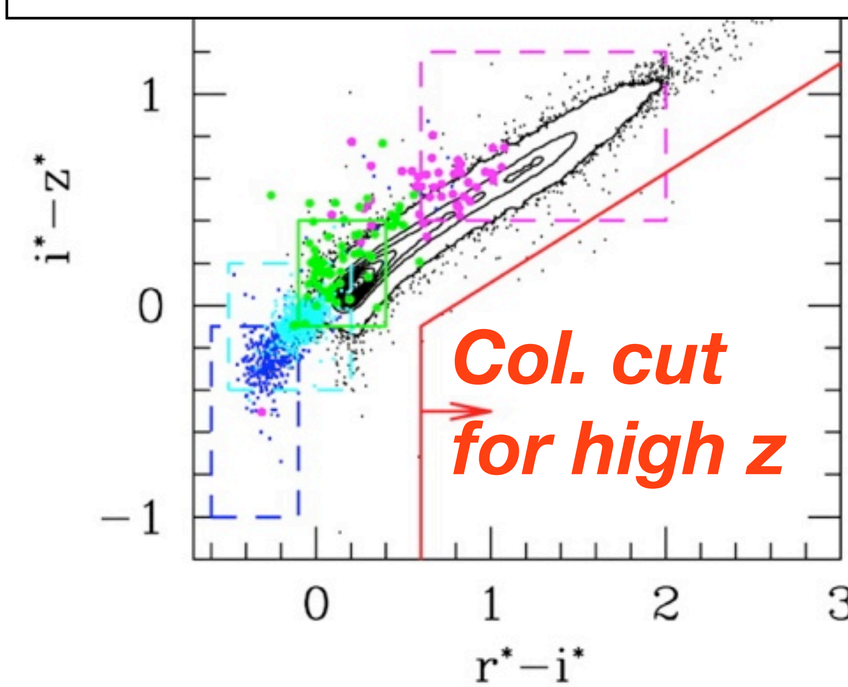



Quasar candidates are selected from multicolor images as:

- unresolved point sources ($L_{AGN}$ >> $L_{gal}$ and distances)

*Color selection for SDSS quasars(Richards+2002)*



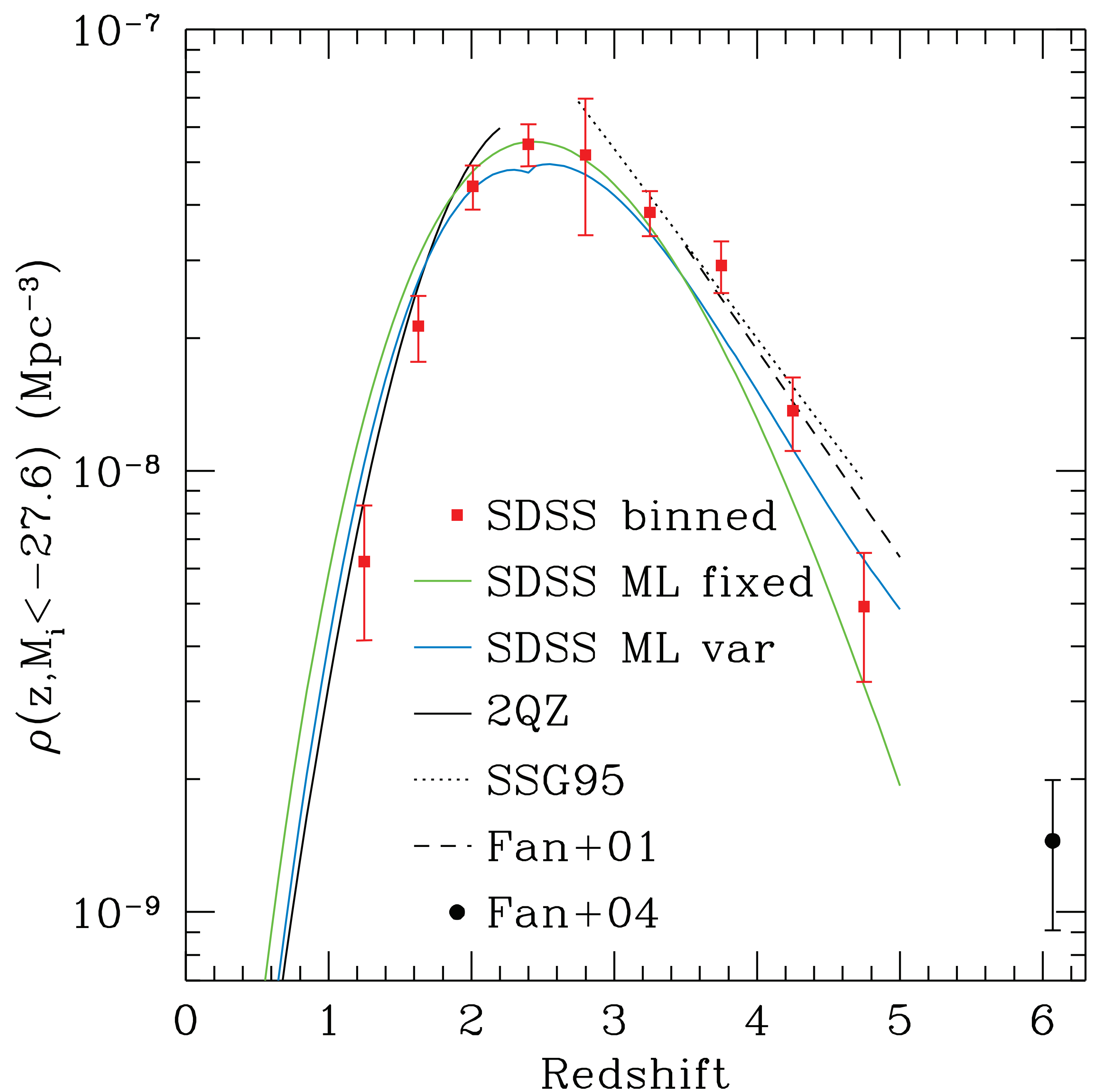

- color selection based on a combination of two or more filters
  - quasars are bluer than stars: classical color selection U-B < -0.4
  - color selection depends also on the redshift of the source

# Quasar luminosity functions

Usually quasars luminosity functions are well fit by *pure luminosity evolution* even if by increasing the depth of the surveys, there is the realization that the previous models for the luminosity functions are too simple (Richards+06, Croom+09).

- One major result is that the number density of luminous QSOs has a strong evolution with redshift: quasars were much more common at z~2-3 (the so-called *quasar epoch*)

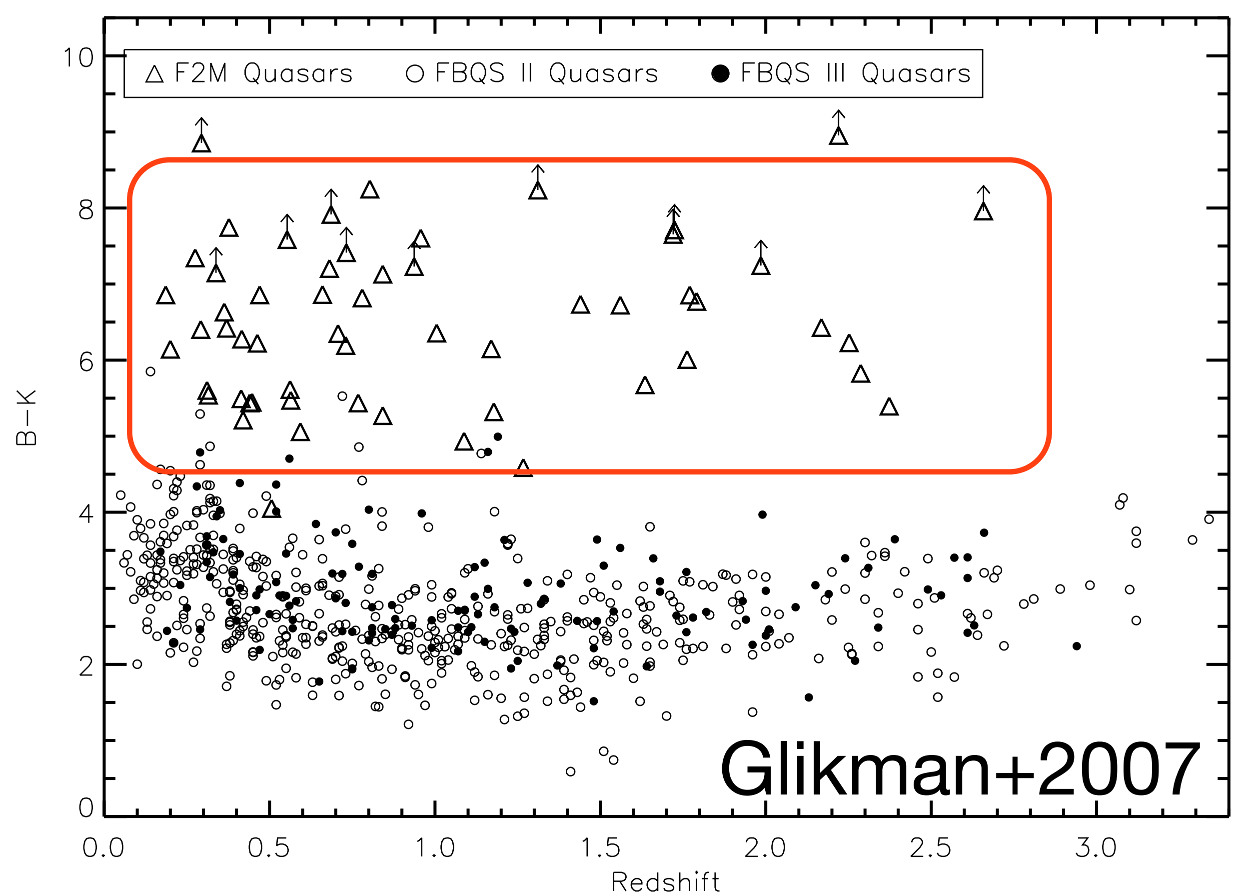
- *Quasar surveys select blue (unobscured) quasars.*



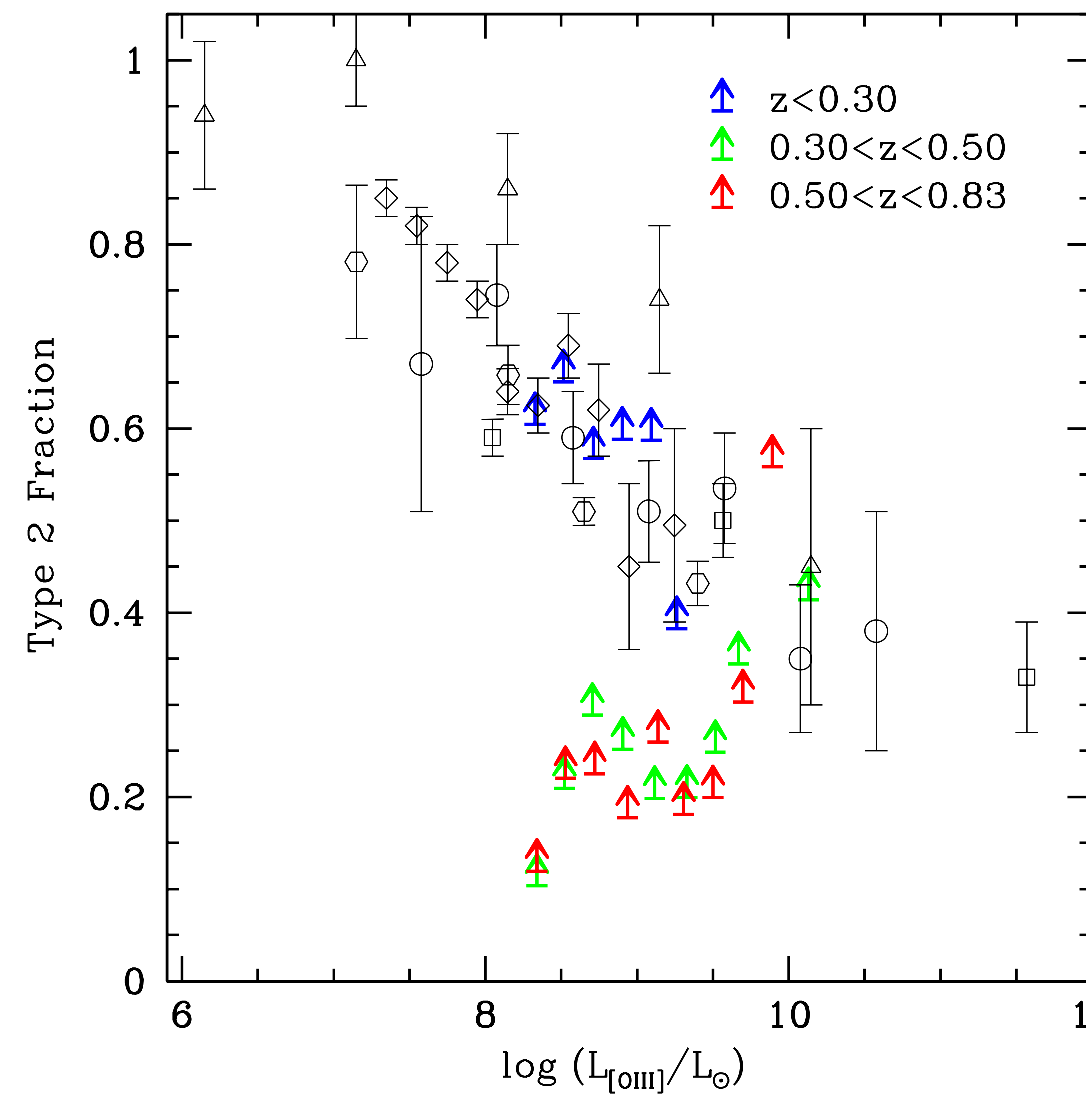

*Number density of luminous quasars ($M_i$ < -27.6, $L_{bol}$ > $10^{13}$ $L_\odot$); Richards+06*

# Quasar luminosity functions

- Quasars with red (less blue) continua are missed by the blue color cuts used to select candidates for spectroscopy (blue color cuts reduce the number of *contaminants*).
- Moreover, from the unified model we expect AGN with no broad lines and quasar-like luminosities, the so-called *quasar 2* in analogy to Seyfert 2.



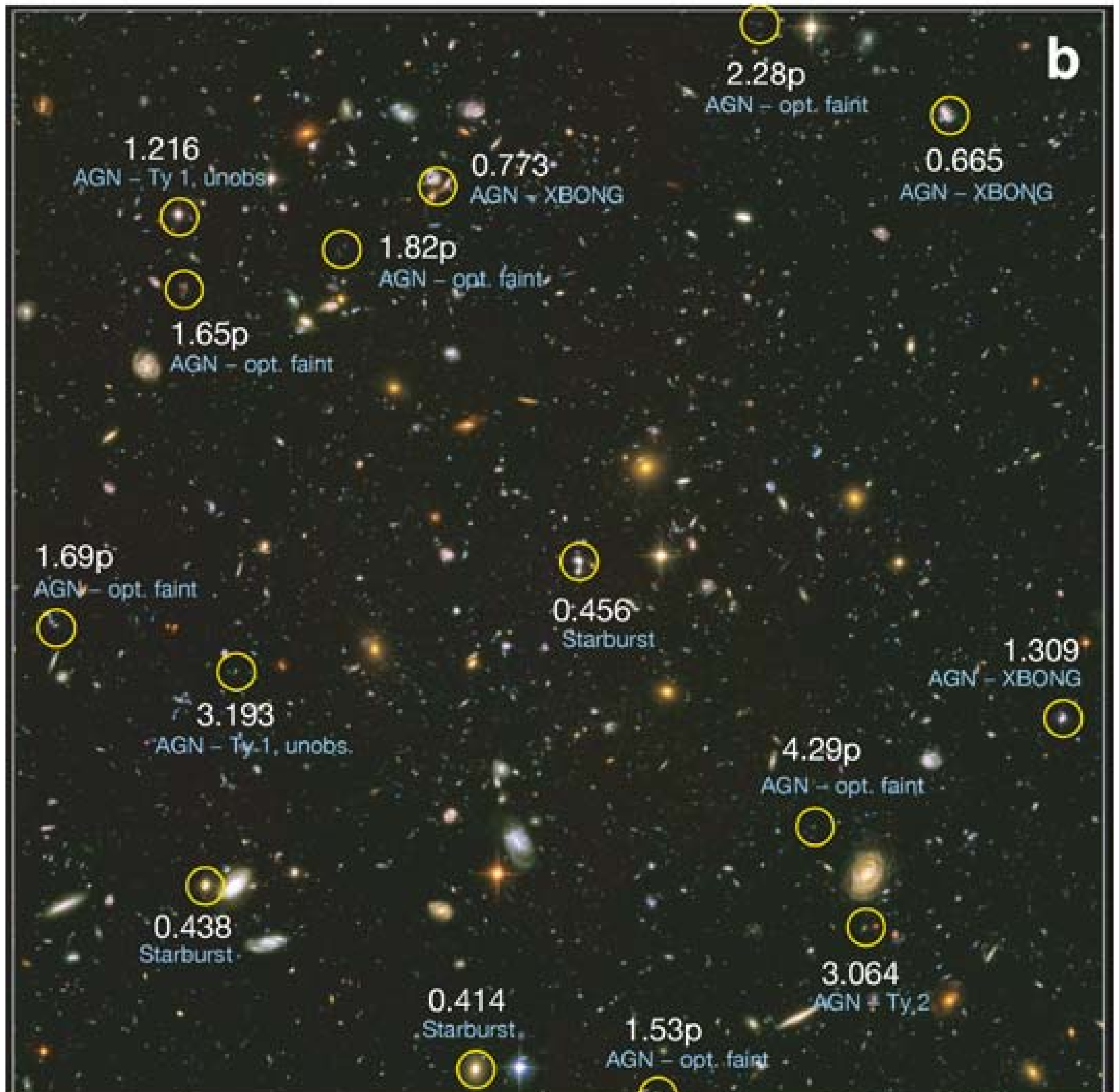

*Red quasars selected by combining FIRST (radio) and 2MASS (near IR)*



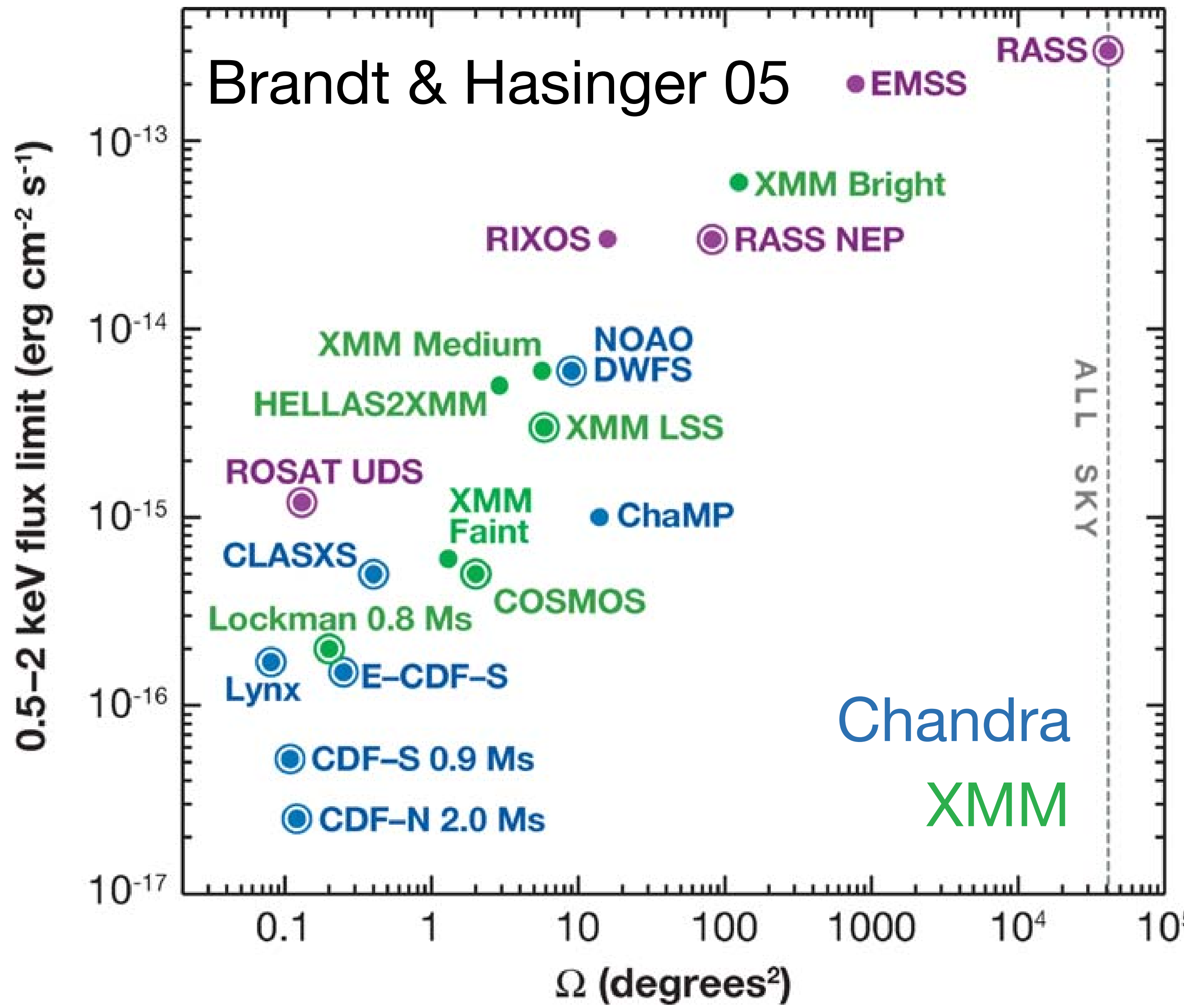

*Estimate of type 2 quasar fraction from several works and Reyes+08 (colors) who uses SDSS spectra to identify type 2 AGN with high L.*

# X-ray luminosity functions

In recent years deep X-ray surveys conducted especially by Chandra and XMM has provided a breakthrough in our understanding of AGN evolution.




Hubble UDF with Chandra sources (Brandt & Hasinger 05)

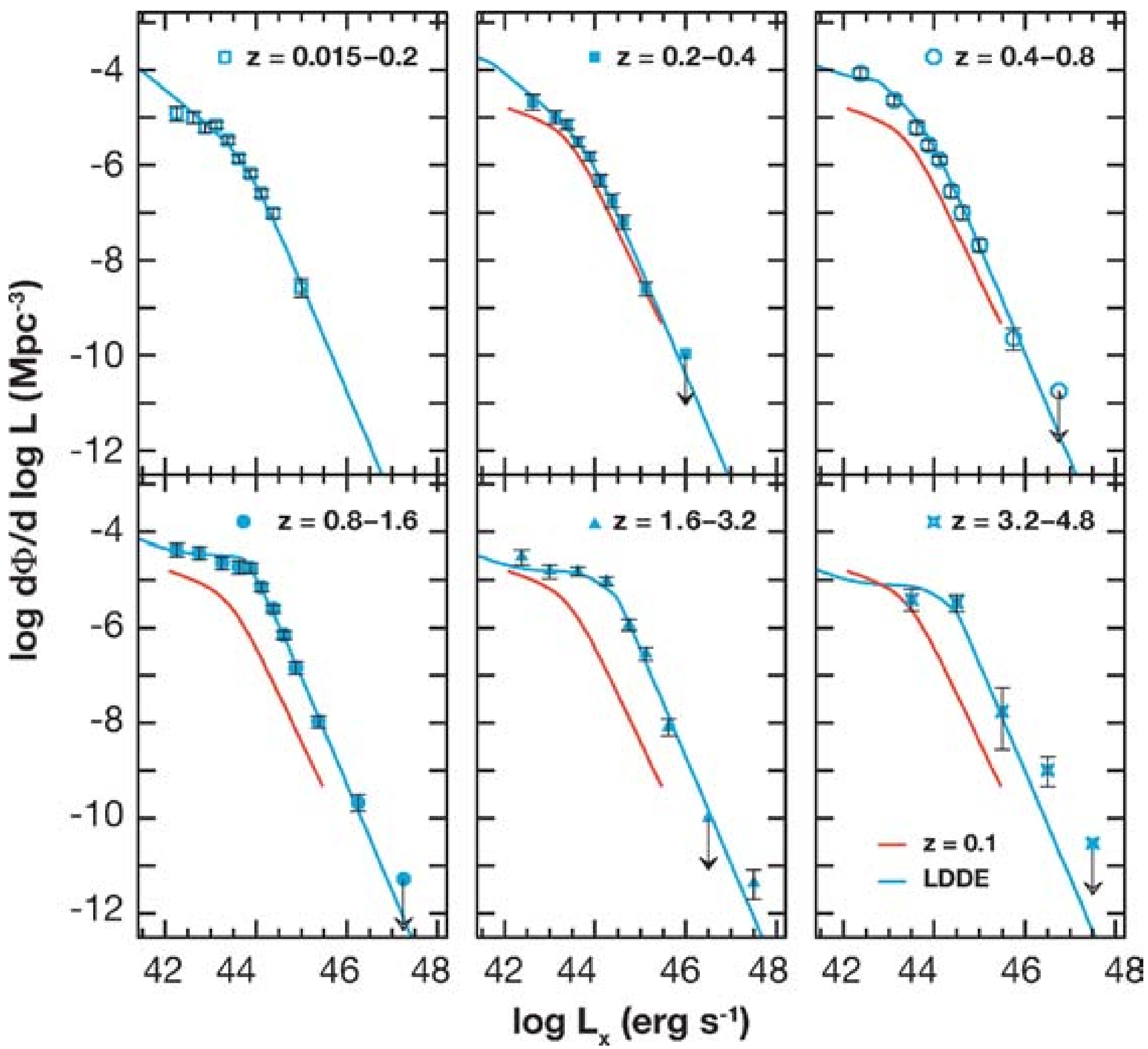



Several advantages:

- an xray source is almost certainly an AGN (unless at the lowest flux levels)
- they are not biased toward blue objects but can select obscured (absorbed) AGN

# X-ray luminosity functions

- X-ray emission is relatively unaffected in hard X-rays > 2 keV even for moderate column densities ($N_H$<10 $^{23}$ cm$^{-2}$); X-ray surveys are much more “complete” than quasar surveys.
- Deep X-ray surveys conducted with Chandra & XMM are usually sensitive up to $N_H$ ~10$^{-24}$-10$^{-25}$ cm$^{-2}$ depending on sensitivity.

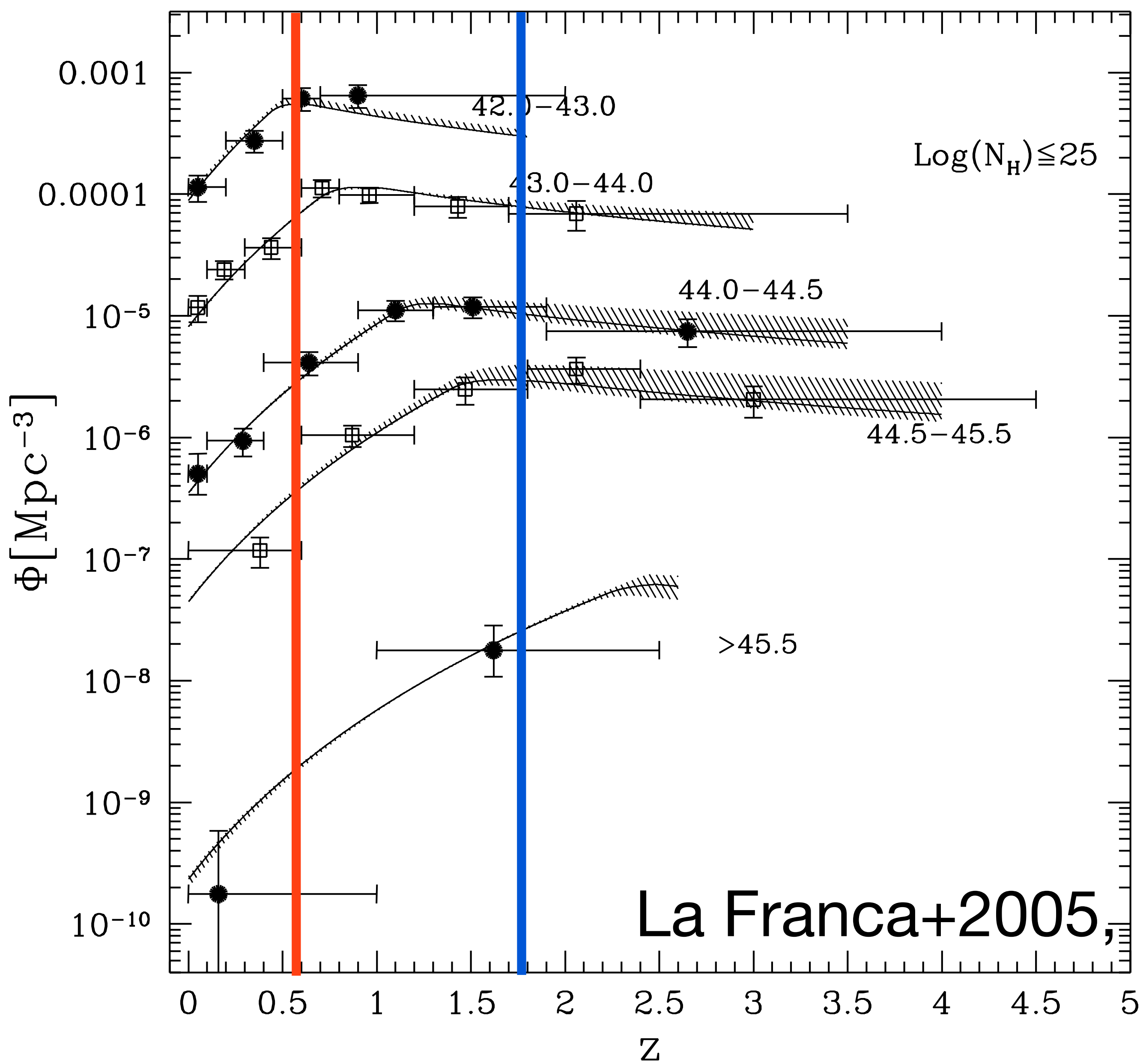


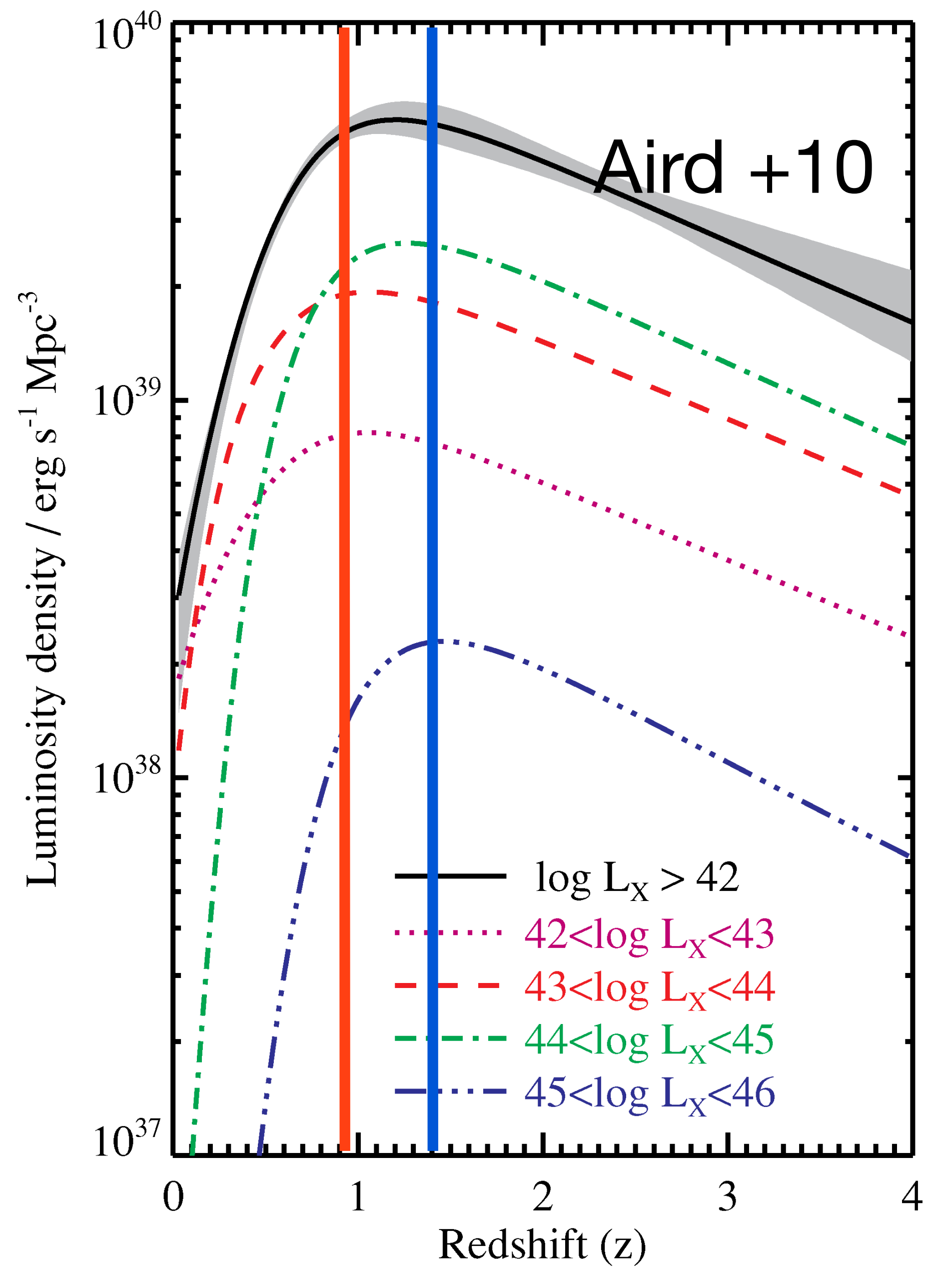

- X-ray luminosity functions have a different behaviour than quasars and a luminosity density evolution (LDE) is usually required (eg Mijayi+00, Ueda+2003; La Franca+2005; Hasinger+05, Silverman+2008)

*Example of LDE: red line is LF at z~0.1; if pure LE shape should be preserved (Hasinger +05, Brandt & Hasinger 05)*

# X-ray luminosity functions

- One of the most important results have been the discovery of the *downsizing* of AGN sources: the number densities of AGN in given luminosity bins peak at different redshifts.
- *High-L AGN number density peaks at larger redshifts than low L ones.*

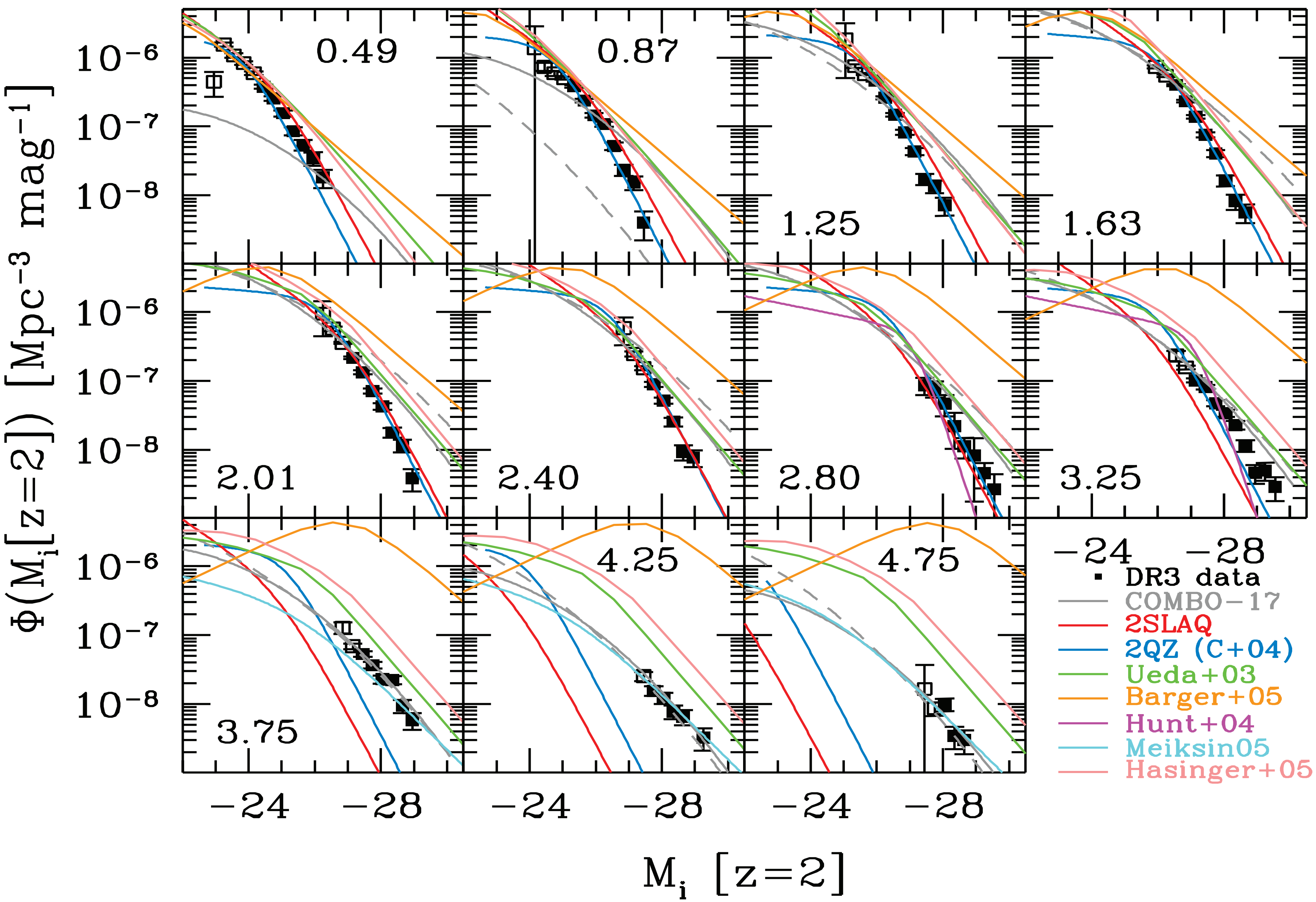



e.g. Ueda+2003, Fiore+2004, La Franca+2005, Hasinger+2005

# AGN luminosity functions

- Usually quasar luminosity functions and X-ray luminosity functions (and other LF from different bands) are not well in agreement; this is obviously due to the different selection effects involved.
- This is also telling us that these surveys miss a different part of the AGN population, but there might be worries on their real consistency.




*Quasar LF from Richards+06 compared with other quasar and X-ray surveys*

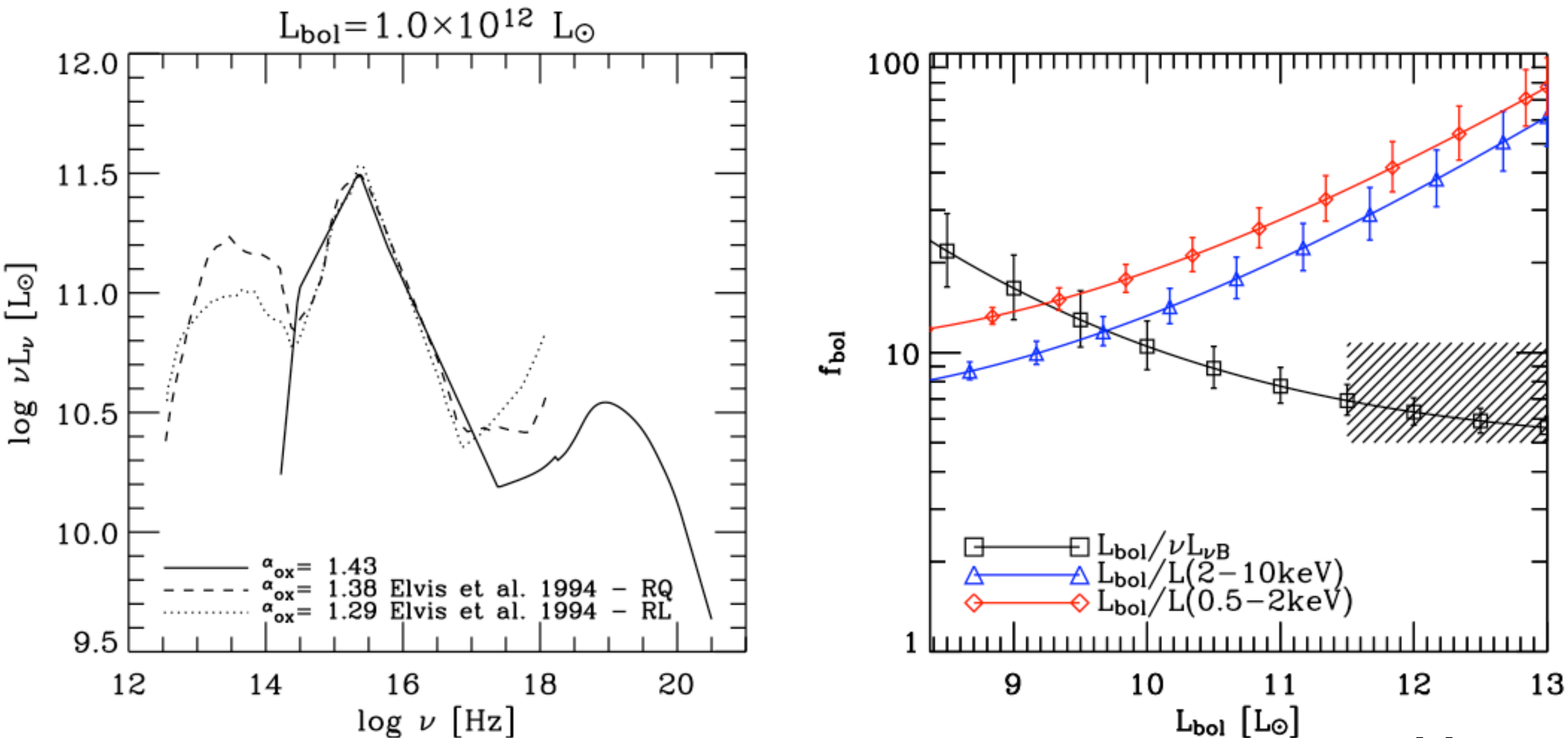
# AGN bolometric luminosity function

- To compare LF obtained in different bands, and obtain the AGN bolometric LF one possibility (e.g. Marconi+04, Hopkins+07) is
  - assume an AGN typical Spectral Energy Distribution
  - find the corrections from the observed band $b$ to bolometric luminosity
  - possibly correct for obscured AGN with, eg,
    *f = obscured (missed) / unobscured (detected)*
  - obtain the AGN bolometric luminosity function $\phi(L,z)$ as

$$\phi(L,z)dL = [1+f(L_b,z)]\phi(L_b,z)dL_b$$

$L = b(L_b)L_b$ $b$ is the bolometric correction

# AGN bolometric luminosity function




Marconi+04

Example of AGN SED and derived bolometric corrections.

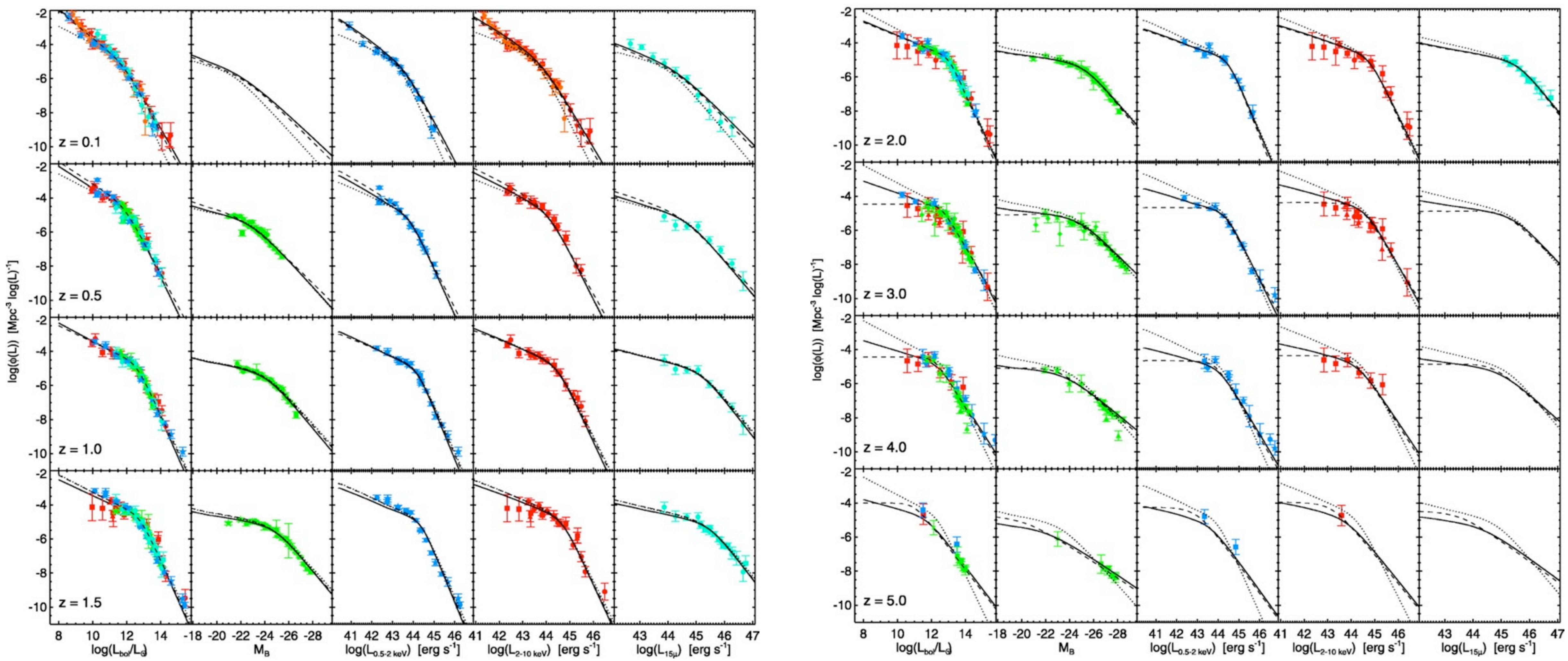
The optical/X-ray ratio ($\alpha_{OX}$) depends on luminosity.

Note the missing IR bump in the Marconi+04 SED: this is reprocessed radiation, and *SHOULD NOT* be included when considering luminosity from accretion

# AGN bolometric luminosity function

One notable example is the work by Hopkins+07 who combin AGN LF from optical, soft and hard X-rays, near and mid IR to derive the AGN bolometric luminosity function.

They show that when selection effects (and obscuration) are taken into account observed LF are in agreement.




bol | opt (B) | 0.5-2 keV | 2-10 keV | 15 μm

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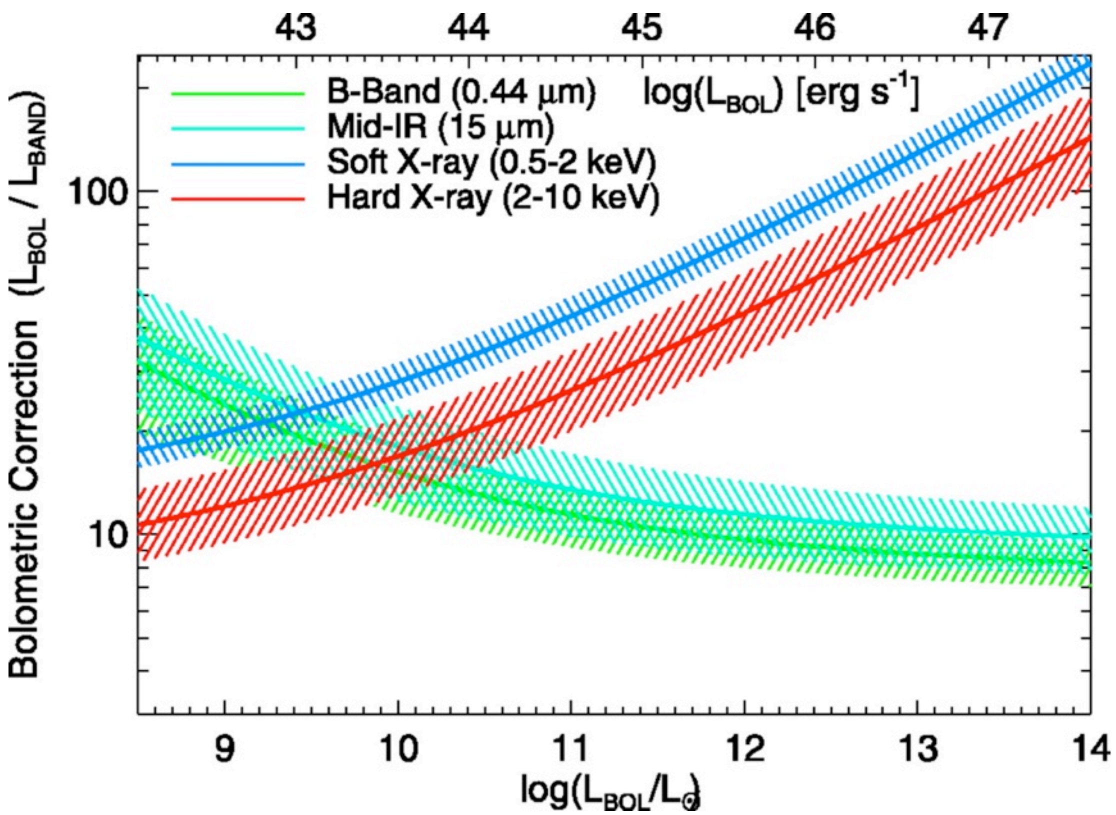
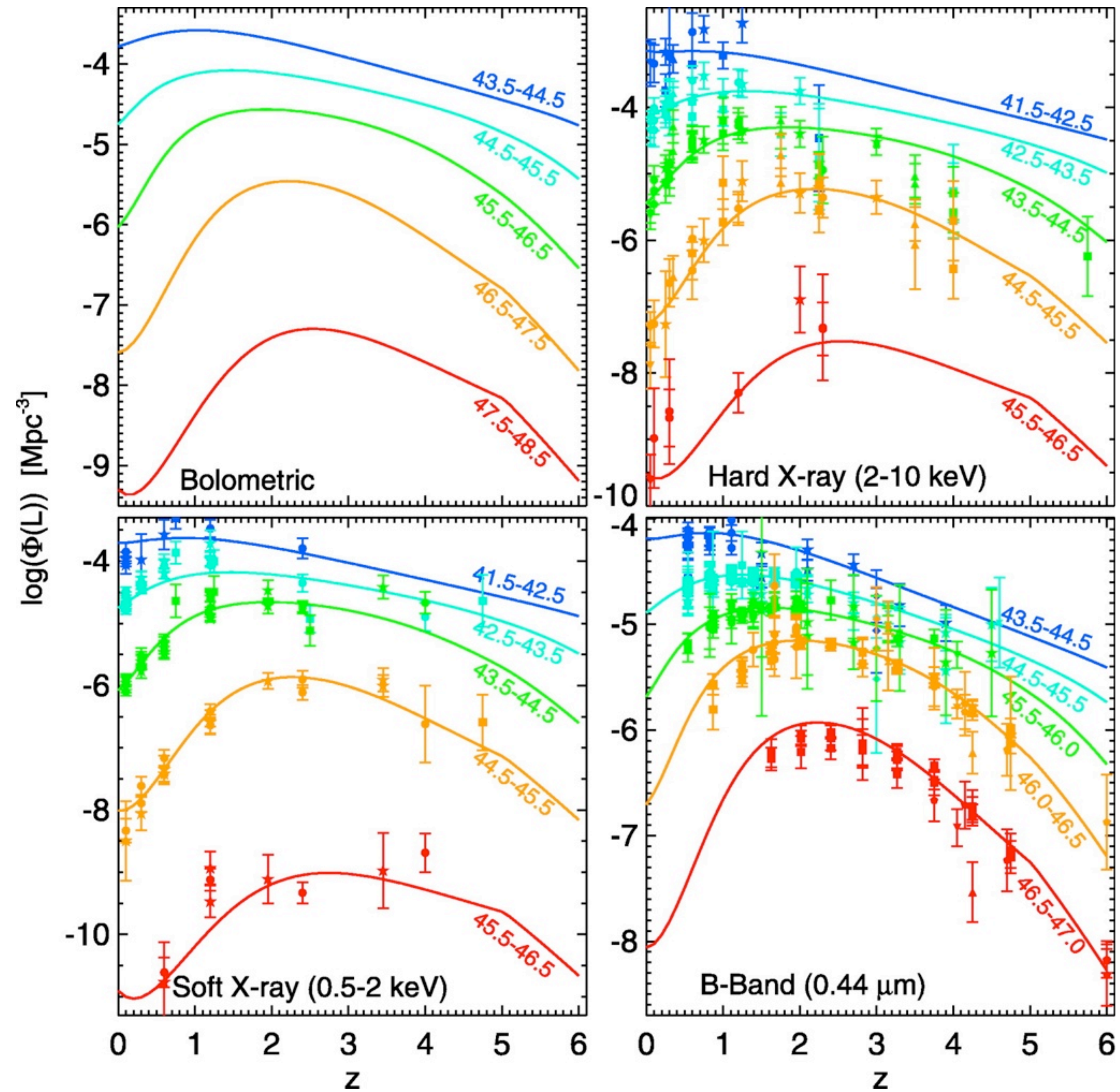
Hopkins+07

# AGN bolometric luminosity function




*__Caveat__: these bolometric corrections include IR emission, therefore are overestimated if one needs pure accretion luminosity*

Hopkins+07

Caveat: in general these analysis might be biased, because

- ⭐ AGN SED likely depend also on AGN type
- ⭐ bolometric corrections might have a very large spread

(Vasudevan & Fabian 07)

# From previous lectures...

- Observational evidence for BHs ($10^6$-$10^{10}$ $M_\odot$) in ~50 nearby galaxies.
- BH mass and structural parameters of the host spheroid (e.g. M, L, $\sigma$) are tightly correlated.
- Most (maybe all) galaxies should host a supermassive BH in their nuclei.

*These results and assumptions have allowed a demography of local BHs.*

- AGN are powered by accretion onto supermassive black holes (i.e. leave massive BHs as remnants of past activity).
- AGN activity was much more common and powerful in the past.
- We expect many AGN remnants (“dormant” BHs) in the nuclei of nearby galaxies.

*Are local Black Holes consistent with expected remnants from AGNs?*

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*Are local Black Holes consistent with expected remnants from AGNs?*

Demography of local BHs ⟷ What is expected from AGN (remnants)

# Remnants of AGN

## *Sołtan's argument (Sołtan 1982)*

- BH growth rate for an AGN with luminosity L is

$$L = \varepsilon \dot{M}_{acc} c^2$$

$$\dot{M}_{BH} = (1-\varepsilon)\dot{M}_{acc}$$

$$\dot{M}_{BH} = \frac{1-\varepsilon}{\varepsilon\, c^2} L$$

$\phi(L,z)\,dL$ number per unit volume for AGN in $L$, $L+dL$ @*z*

$\dot{M}_{BH}(L)\,\phi(L,z)\,dL$ BH growth rate per unit vol. for AGN in $L$, $L+dL$ @z

$\dot{M}_{BH}(L)\,\phi(L,z)\,dL\left|\frac{dt}{dz}\right|dz$ BH mass per unit volume accreted from AGN emitting $L$, $L+dL$ during cosmic time *z, z+dz*

- The remnant BH mass density is then obtained by integrating for L and z (for all AGN at all cosmic times)

$$\rho_{BH} = \int_0^{+\infty} dz \int_0^{+\infty} dL \left(\frac{1-\varepsilon}{\varepsilon\, c^2} L\right) \phi(L,z)\,dL \left|\frac{dt}{dz}\right| dz$$

# Remnants of AGN

- The integrated comoving energy density from quasars is

$$u = \int_0^{+\infty} dz \int_0^{+\infty} dL \;\; \phi(L,z) L \left| \frac{dt}{dz} \right|$$

$\phi(L,z)\,dL$ number of AGN (quasars) in $L$, $L+dL$ per unit volume @z

$L\,\phi(L,z)\,dL$ Luminosity density of AGN in $L$, $L+dL$ @z

$L\,\phi(L,z)\,dL\,dt$ Energy density of AGN in $L$, $L+dL$ radiated in z, z+dz

- Then the expected remnant mass density density is simply

$$\rho_u = \frac{(1-\varepsilon)}{\epsilon c^2} u$$

- Sołtan (1982) used the luminosity function in B band to get bolometric luminosity function; transform $L_B$ to bolometric L (eg L ~10 $\nu_B L_{\nu,B}$)

$$\phi(L_B, z) dL_B = \phi(L,z) dL$$

# Remnants of AGN

- integrated comoving energy density from quasars (Sołtan 1982)

$$u = \int_0^{+\infty} dz \int_0^{+\infty} dL\, \phi(L,z) L \left| \frac{dt}{dz} \right| = 1.3 \times 10^{-15}\,\mathrm{erg\,cm^{-3}}$$

- with efficiency ε, the expected “relic” mass density density is

$$\rho_u = \frac{(1-\varepsilon)u}{\epsilon c^2} = 2.2 \times 10^5\,\mathrm{M_\odot\,Mpc^{-3}} \qquad \text{with } \varepsilon = 0.1$$

- Local mass density is $\sim 3.5\text{-}5.5 \times 10^5\, M_\odot\, pc^{-3}$ a factor 1.6-2.5 larger.

- ... AGN are not only unobscured, blue quasars!
- ... $\rho_{BH}$ depends strongly on efficiency ε

# Remnants of AGN

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No correction for "obscured" AGNs ... when taken into account:

Marconi +04: $\rho_{AGN} \simeq 3.5 \times 10^5\, M_\odot\, Mpc^{-3}$ (ε≃0.1; hard X LF, Ueda +03)

Shankar +08: $\rho_{AGN} \simeq 4.5 \times 10^5\, M_\odot\, Mpc^{-3}$ (ε≃0.07; hard X LF, Ueda +03)

# The X-ray background

- The X-ray background (XRB) was discovered in the early '60 by Riccardo Giacconi and collaborators (Giacconi et al. 1962);
- Peaks at ~30 keV;
- Recent surveys have resolved up to ~90% of XRB in the 2-8 keV range
- Its spectral shape was different from the typical power laws of AGN X-ray spectra; its interpretation has remained elusive until Setti & Woltjer (1989) showed that many absorbed AGN at different z could explain its shape.
- Several successful synthesis models have been presented since then (e.g. Comastri et al. 1995, Gilli et al 2001, Treister & Urry 2005, Gilli, Comastri & Hasinger 2007, Treister et al. 2009)
- The X-ray background intensity at energy E is given by

$$I(E) = \frac{1}{4\pi}\int_0^{z_{max}}\int_0^{+\infty} \boxed{\frac{(1+z)f[E(1+z)]L_X}{4\pi\, D_L^2}} \phi(L_X, z)\, dL_X \frac{dV}{dz} dz$$

*flux expected at E from source at z*

$\phi$ is the luminosity function in band X

*f(E)* is the *normalized* spectrum of the source with unit luminosity in band X

# The X-ray background

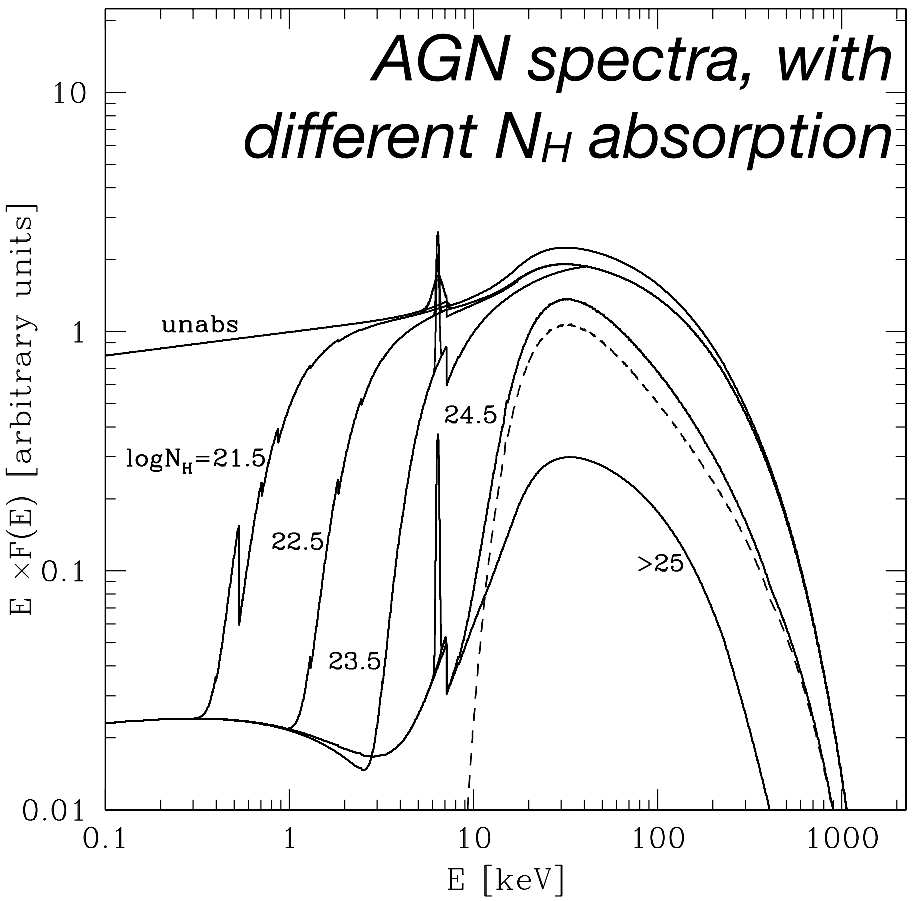
However sources have different spectral shapes depending on obscuration, therefore for a given $N_H$ distribution

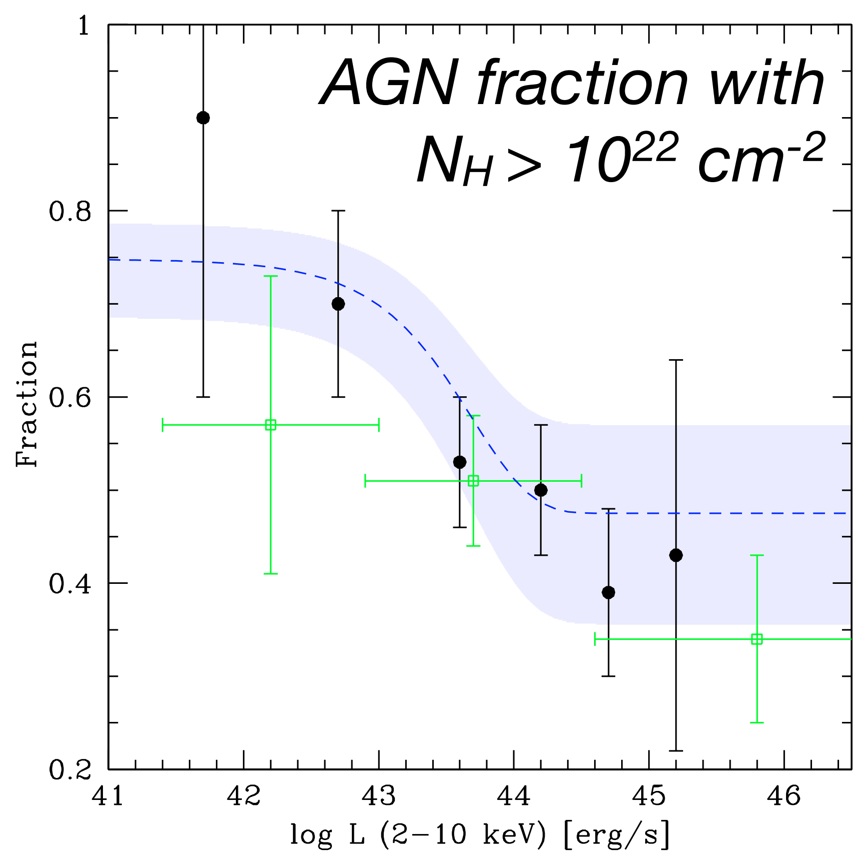
$$I(E) = I(E)_{unabs} + I(E)_{abs} = I(E|0) + \int_0^{+\infty} I(E|N_H)p(N_H)dN_H$$

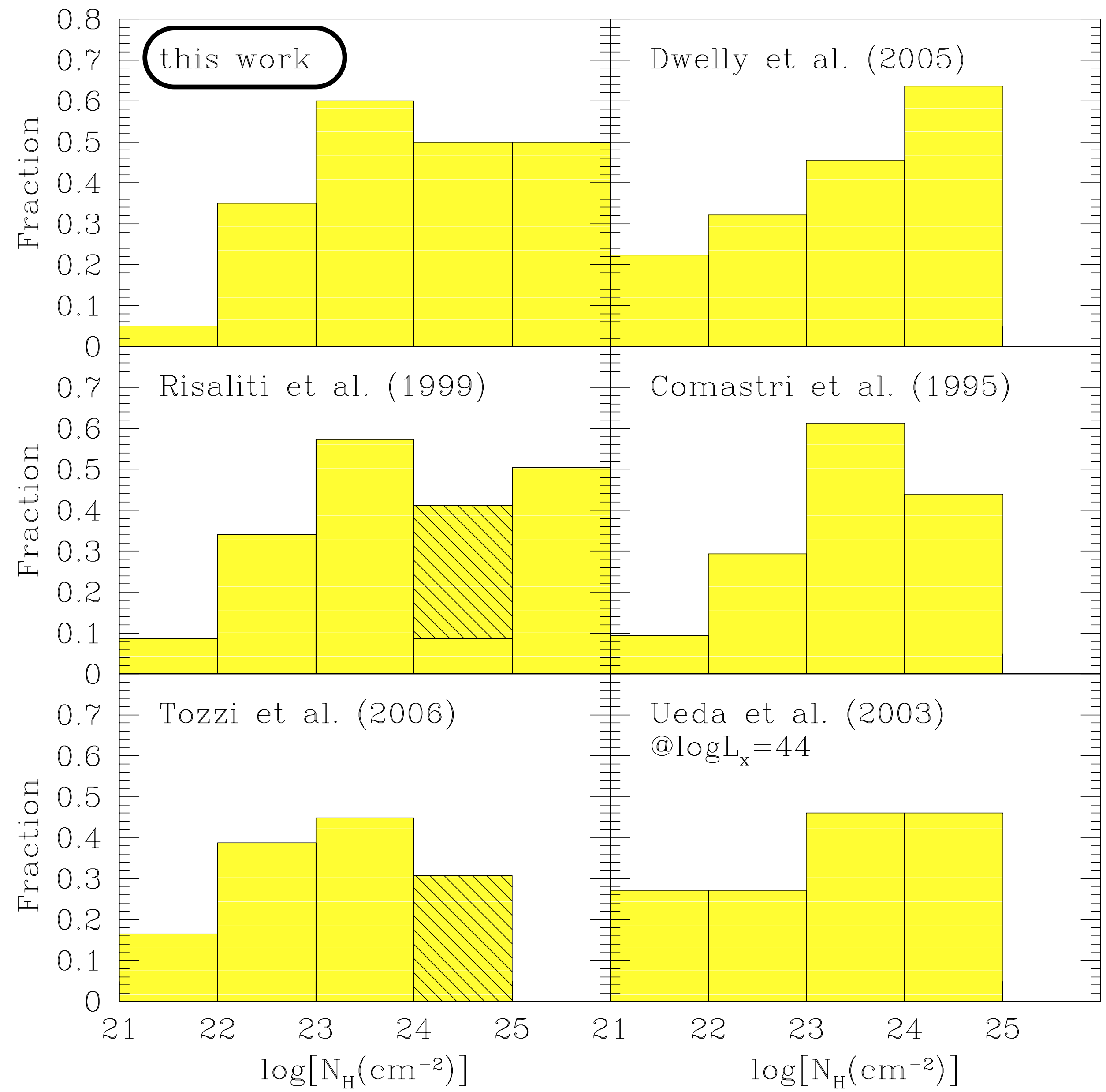
The ingredient which are needed are (Gilli et al. 2007)

- the shape of the unabsorbed spectrum, usually a power law with a high energy cutoff plus a reflected component
- the luminosity function of unabsorbed (type 1) AGN, usually all those with $N_H < 10^{21}$ cm$^{-2}$
- the intrinsic spectral shape of absorbed (type 2) AGN, usually the same as that of type 1
- the luminosity function of absorbed (type 2) AGN, usually the same as that of type 1 but with a different normalization i.e. the ratio absorbed/unabsorbed, eventually a function of L, z
- the $N_H$ distribution, usually assumed constant with z

# The X-ray background



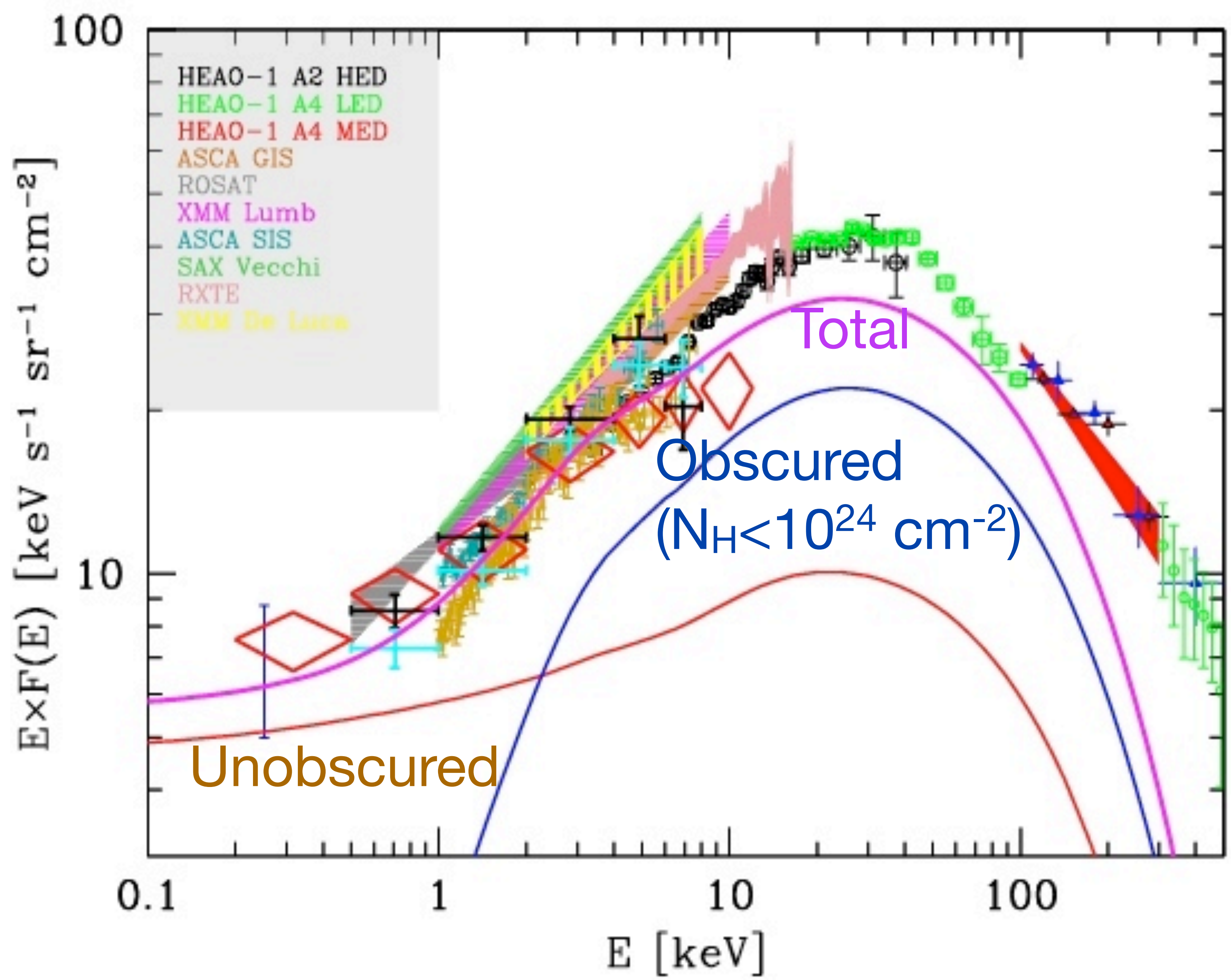




*local $N_H$ distributions*

Gilli+2007

# The X-ray background

- Performing the integration the background peak is not reproduced;
- however AGN detected in 0.5-10 keV are those with $N_H < 10^{24}$ cm$^{-2}$,
- the missing emission is due to AGN with **$N_H > 10^{24}$ cm$^{-2}$** the so-called **Compton Thick AGN**
- Include CT assuming they have the same LF as unobscured and less-obscured AGN;
- the only *free* parameter is then the *CT fraction*, if one further assumes that it has the same $L,z$ dependence as less obscured AGN

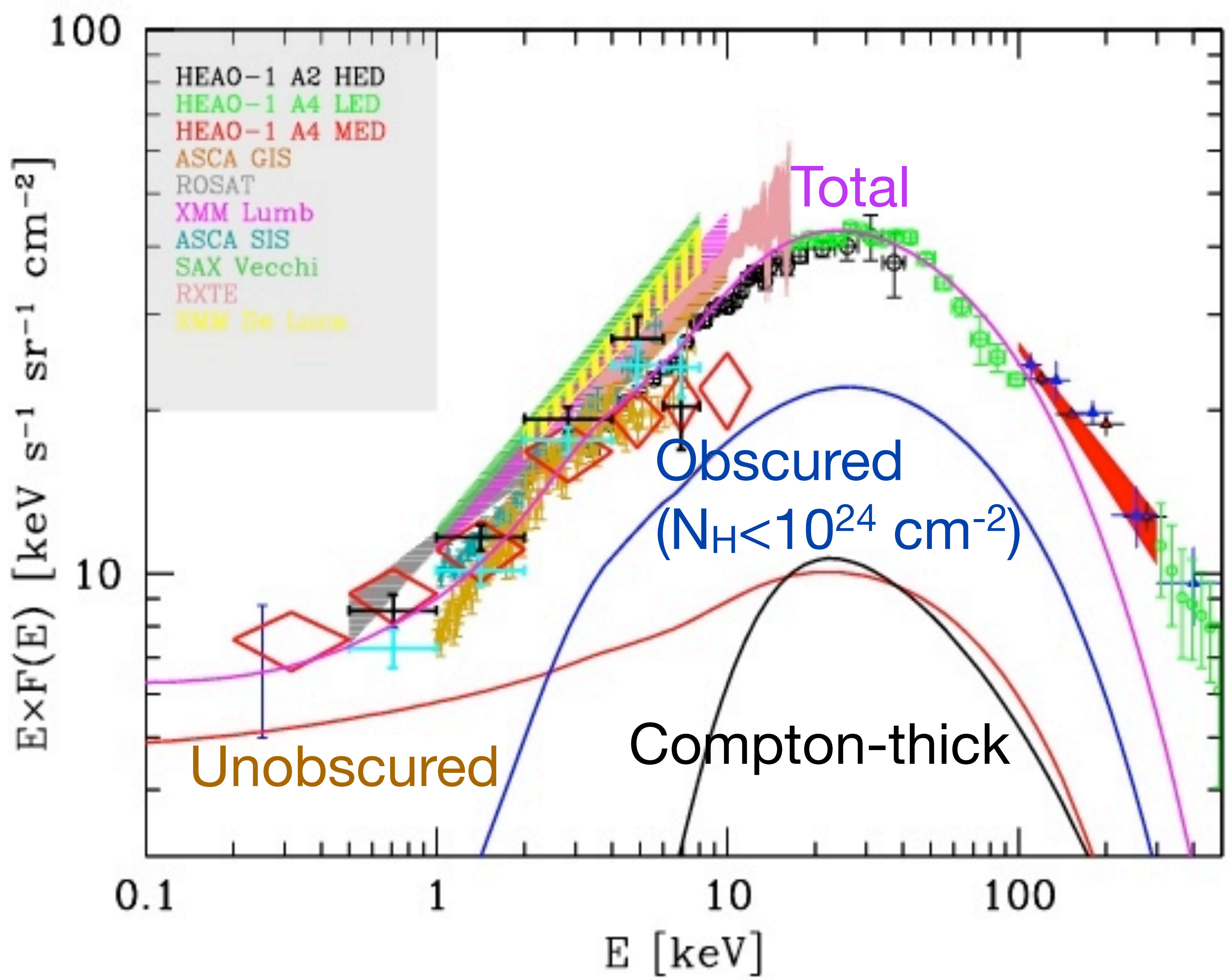



Gilli, Comastri & Hasinger 2007

# The X-ray background

- When Compton-thick AGN are included the peak is well reproduced.
- But ... the spectrum of a CT AGN consists only of the reflected component; its normalization depends on $L_X f_{scatt}$ where $f_{scatt}$ is the scattering efficiency
- $f_{scatt}$ usually not well know from observations (even in local universe); assume $f_{scatt} = 0.02$.
- XRB cannot constrain the fraction of CT AGN but only the ratio

$$\frac{R_{\mathrm{CT}}}{f_{\mathrm{scatt}}}$$




*$R_{CT}$ = CT / unobscured*

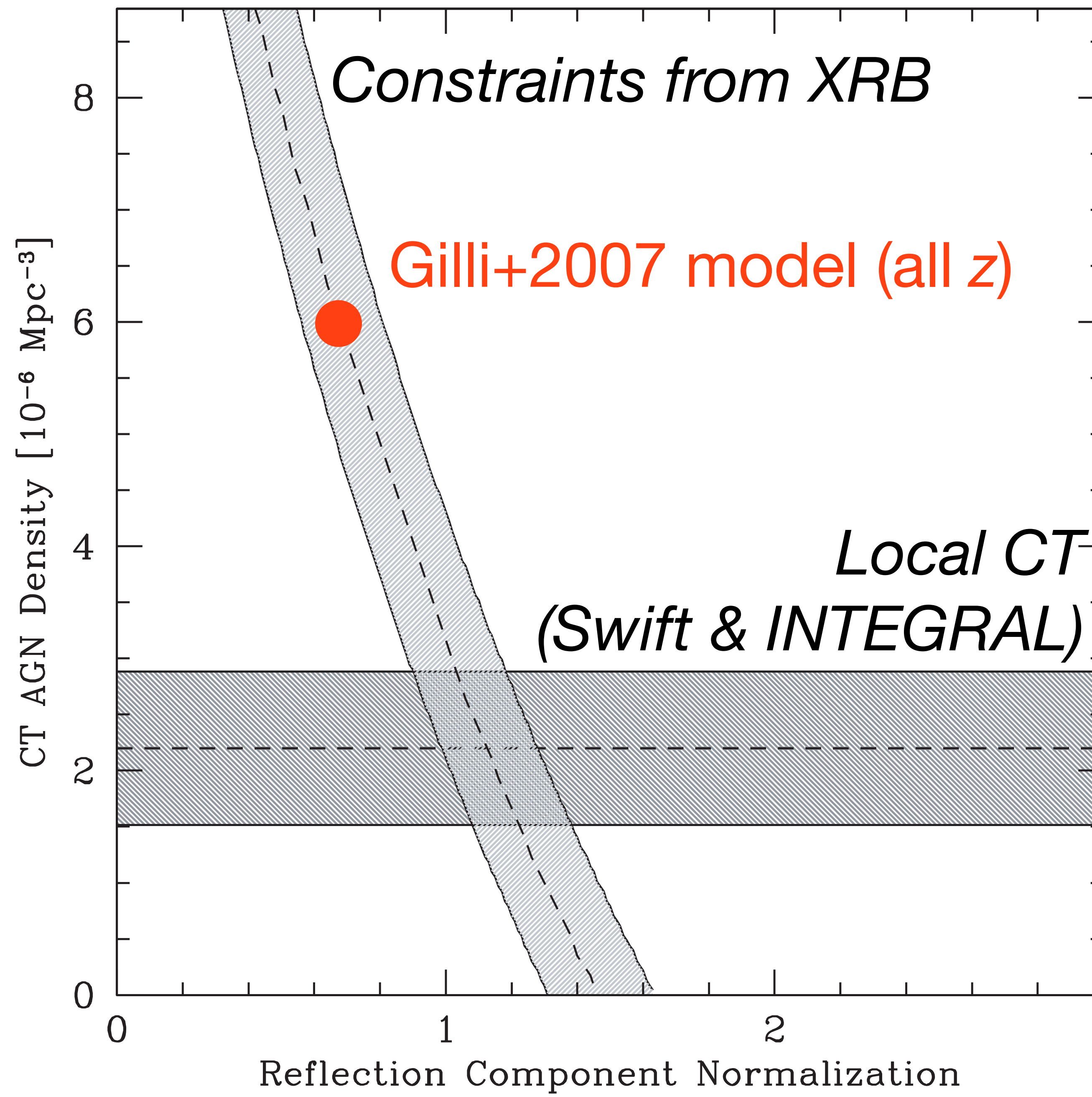
Gilli, Comastri & Hasinger 2007

# Compton Thick AGN

Treister et al. 2009 discuss the constraints on CT AGN that can be obtained from the XRB (degeneracy on the normalization of the reflection component) and the hard X-ray surveys at z~0.

- Estimate density of local CT AGN from 10 CT AGN detected by Swift and INTEGRAL in complete samples at z<0.03
- They are probably still missing $N_H > 10^{25}$ cm$^{-2}$ ...
- The number of CT AGN is still totally unconstrained at high z!
- With their estimates of the CT fraction, Treister+2009 still obtain

  *$\rho_{BH} \simeq 4.5 \times 10^5\ M_\odot\ Mpc^{-3}$ ($\varepsilon$=0.1) meaning that unless there is very large population of CT AGN we are completely missing, estimates are quite stable.*

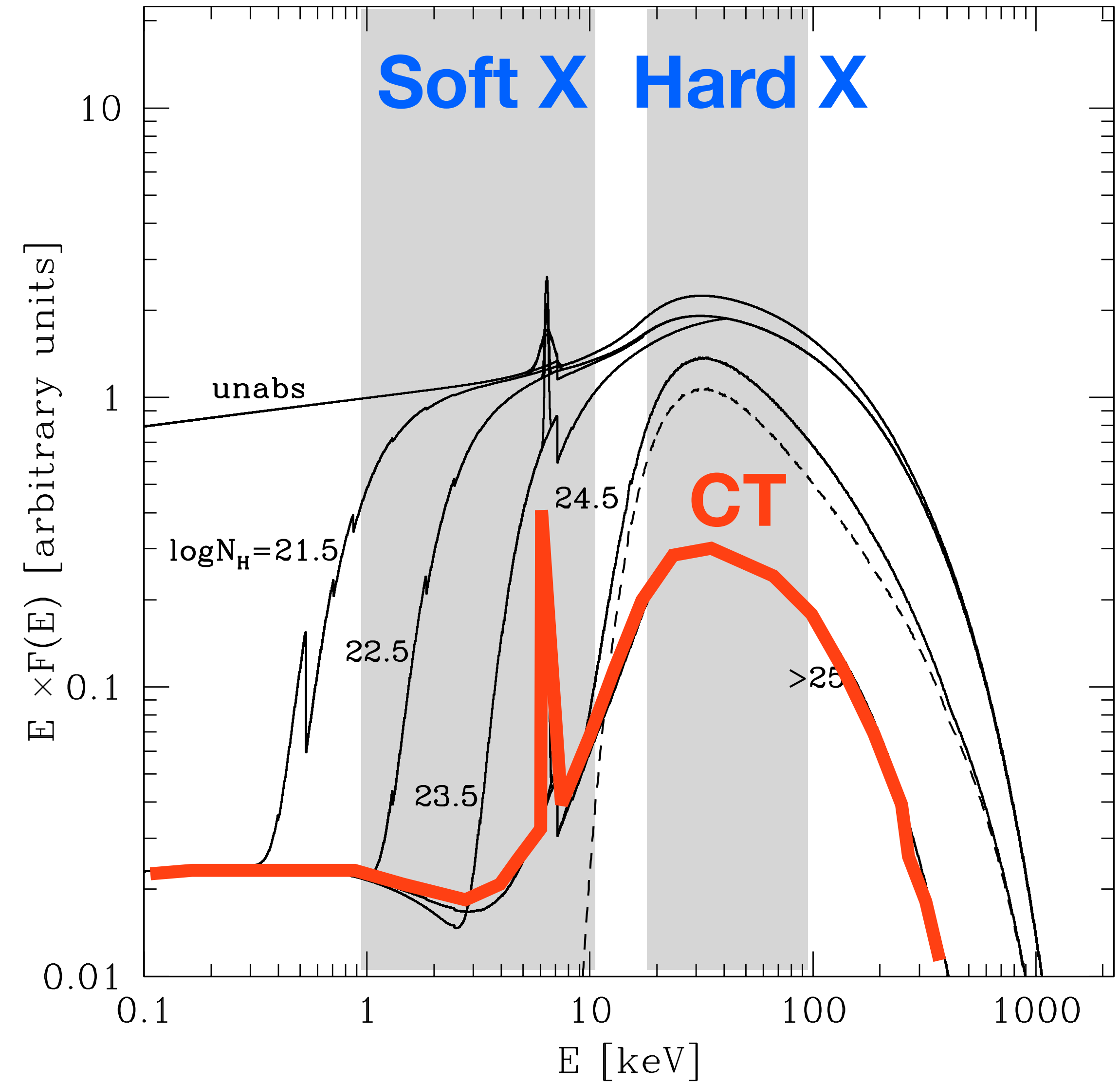


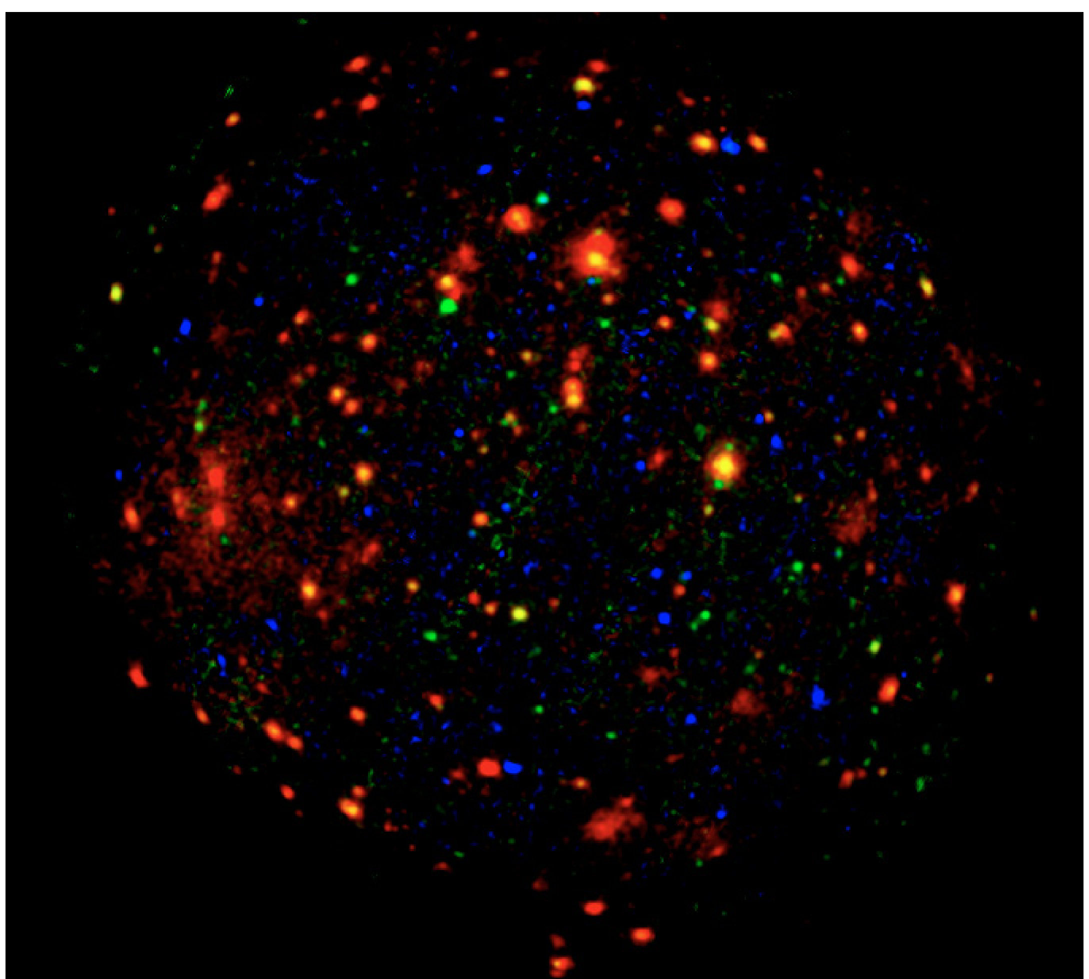

Treister+2009

# Compton Thick AGN

Several methods have been proposed to search for CT AGN (eg intro of Ballantyne+2011)

- Hard X-ray surveys (> 20 keV; Bassani +1999, Tueller+2008, Burlon+2011)
  - *but still low sensitivity for z>0*
- Extremely deep X-ray surveys (2-10 keV; eg Tozzi +06, Comastri+11)
  - but huge observing times required (> 1 Msec, up to 10 Msec!)



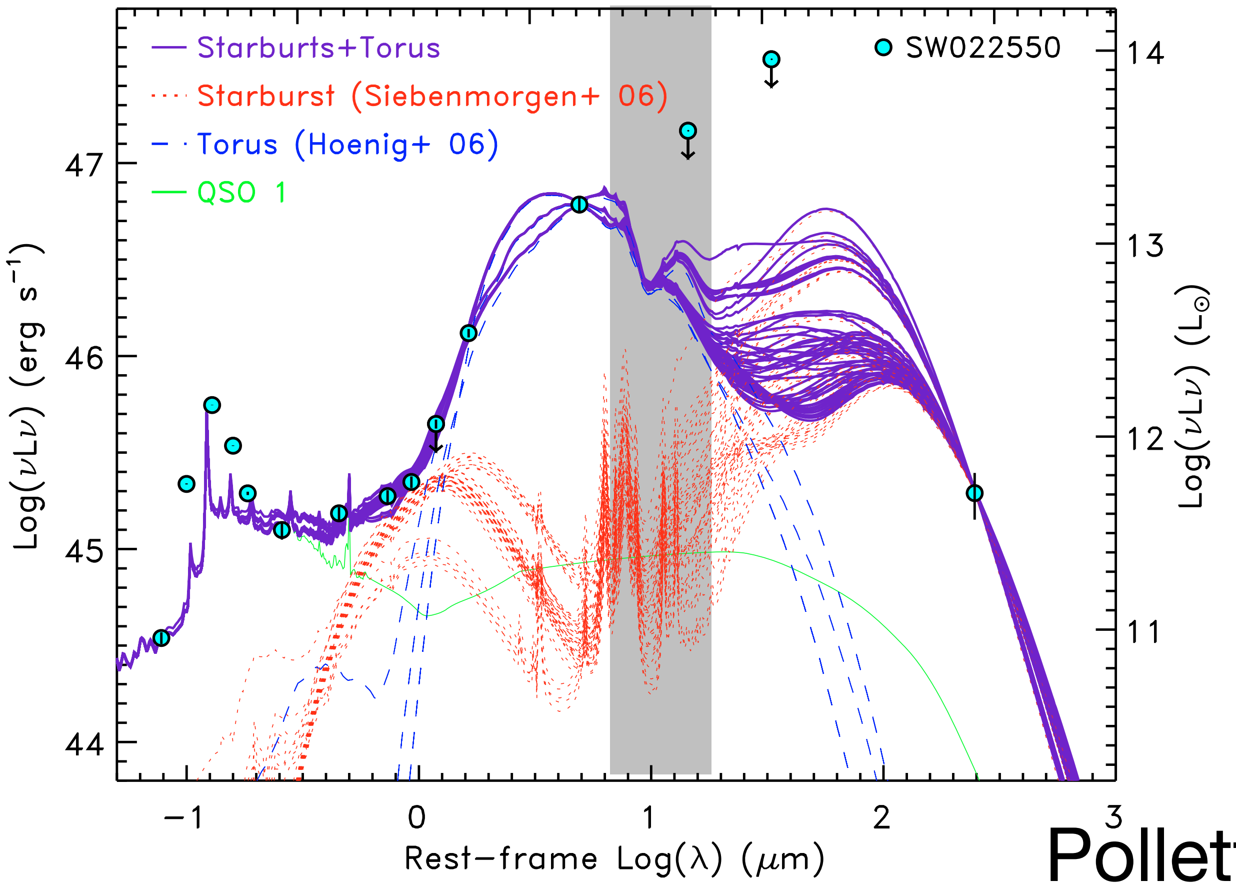
*Deep XMM exposure (~3.3 Ms) of the Chandra deep field south (Comastri+2011). Red (0.4–1 keV), green (1– 2 keV) and blue (2–8 keV) band. CT sources are detected which escape other non-X selections (see later).*

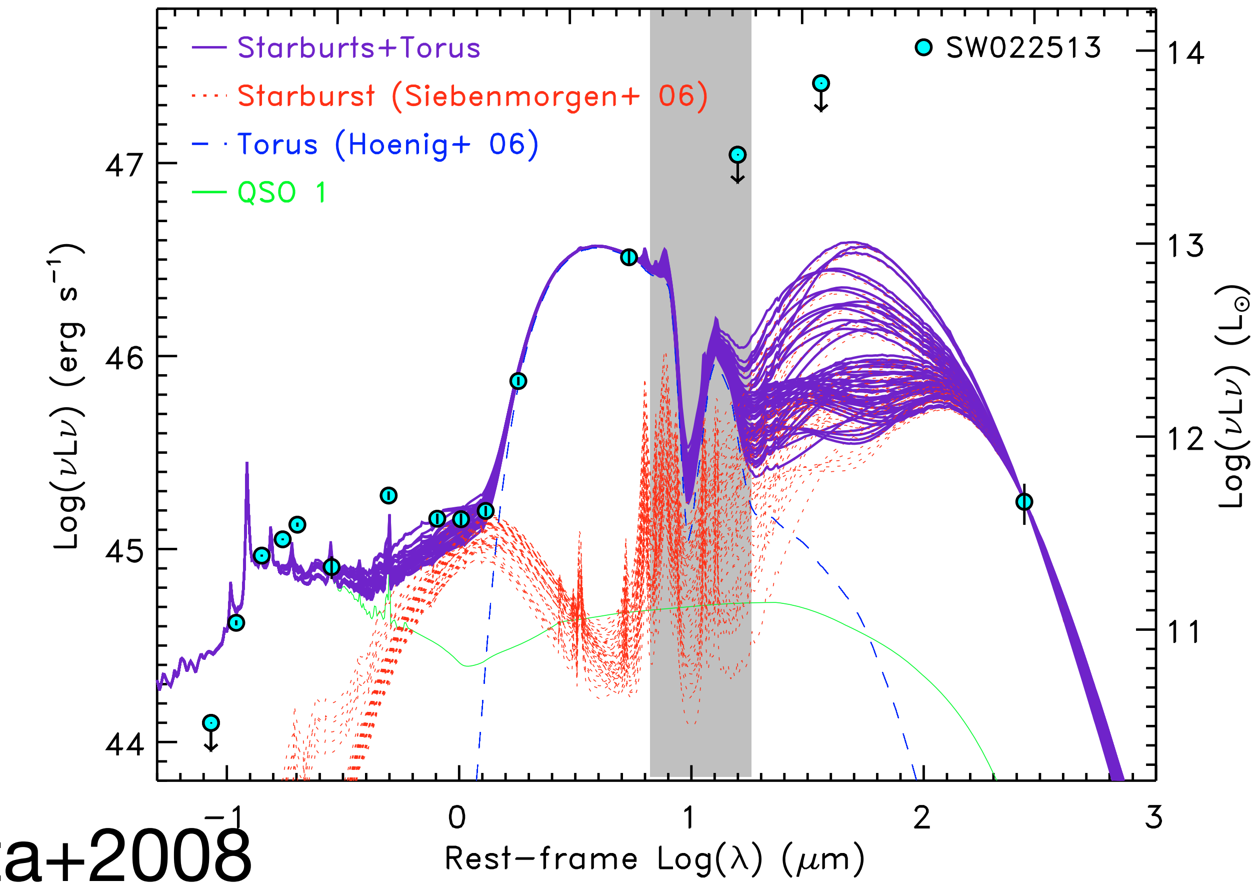
# Compton Thick AGN

- Mid-IR selection (i.e. search for emission of dust heated by AGN; e.g., Stern+2005, Polletta+2006, Daddi+2007, Alexander+2008, Fiore+2008,2009)
  - but possible problems disentangling from Starburts emission

*The 'trick' is that AGN dust is 'hotter' than dust heated by starbursts, therefore sources with high mid-IR emission (and no X-ray emission) are candidate obscured AGN.*

*For example, Fiore+2008, select sources with large F(24 mu)/F(R) and red R-K colors.*



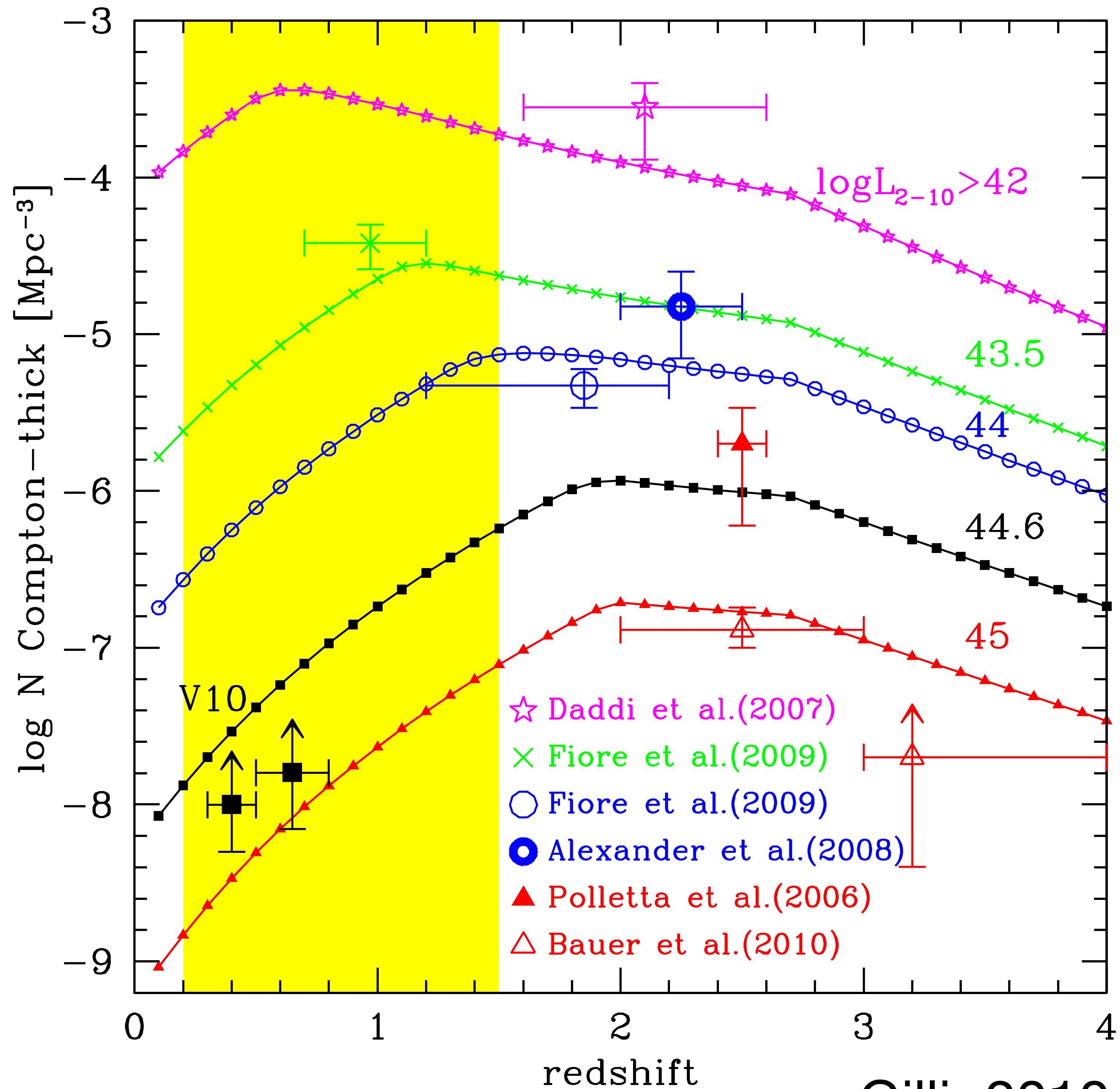

Polletta+2008

# Compton Thick AGN

- Search for particular optical or X-ray features
  - high ionization lines e.g. [NeV] (Gilli+2011)
  - high EW of Fe Ka line (e.g. La Mass+2009, Comastri+2011, Feruglio+2011)

*Usually candidates CT are not detected in X-rays, one typical technique is then to stack X-ray observations for those sources.*
*Usually, X-ray emission at the level expected from CT AGN is detected in the stacks (but not in single object observations).*

Overall the observed number densities of CT are ~ consisted with those used in XRB models (eg. Gilli+2007, Gilli+2010)




Gilli+2010

# X-ray background and BHs

The XRB is the integrated emission of all AGN, therefore it can be used to estimate the total BH mass density similarly to the Soltan argument applied to quasars:

- consider $\phi_{all}$ of unobscured + obscured +CT AGN;
- $f_{bol,X}$ is the bolometric correction to obtain $L_{bol}$ from $L_X$ in band X
- integrate on E

$$I(E) = \frac{1}{4\pi}\int_0^{z_{max}}\int_0^{+\infty}\frac{(1+z)f[E(1+z)]L_X}{4\pi\, D_L^2}\phi_{all}(L_X,z)dL_X\frac{dV}{dz}dz$$

Noting that $dV = 4\pi D_L^2 c\, dt$

Finally obtain

$$I_X = \int_0^{+\infty} I(E)dE = \frac{c}{4\pi}\int_0^{z_{max}}\int_0^{+\infty}\frac{1}{1+z}L_X\phi_{all}(L_X,z)\frac{dt}{dz}\,dL_X\,dz$$

# X-ray background and BHs

Comparing with expression from energy density in Soltan argument, one can then write

$$I_T = f_{bol,X}\, I_X$$

$$(1+\langle z\rangle)\frac{4\pi I_T}{c} = (1+\langle z\rangle)u_X^\star = u_X$$

$u_X^\star$ observed energy density

$u_X$ comoving energy density

to see effect of obscured AGN, use only unobscured AGN, and consider average fraction of obscured/unobscured to write

$$I_T = f_{bol,X}\,(1+f_{obs})I_{X,unabs}$$

It turns out that with the most recent X-ray surveys $\langle z\rangle \simeq 1$

$$u_X^\star = (1.0-2.3)\times 10^{-15}\,\mathrm{erg\,cm^{-3}}$$

(Elvis et al. 2002 - *rescaled by 2/3 to take into account lower bolometric correction*)

$$\rho_{BH,X} = \frac{(1-\varepsilon)}{\epsilon c^2}(1+\langle z\rangle)u_X^\star = (3.0-6.7)\times 10^5\,\mathrm{M_\odot\,Mpc^{-3}}$$

e.g. Fabian & Iwasawa 1999, Salucci+1999; Elvis+2002; Comastri 2003

# A refined Sołtan argument

Consider the probability of finding a BH with given mass and accretion rate at cosmic time t.
It is then possible to define the distribution function $F$ such that

$$d^2N = F(M, \dot{M}, t)\, dM\, d\dot{M}$$

is the number density of BHs with defined mass and accretion rate.
*If the number of BHs is conserved (no BHs are "created" or "destroyed"),*
$F$ will satisfy the collisionless Boltzmann equation like for the stars DF

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla} f - \vec{\nabla}\Phi(\vec{x}) \cdot \frac{\partial f}{\partial \vec{v}} = 0$$

Boltzmann equation for stars DF

$$\frac{dF}{dt} = \frac{\partial F}{\partial t} + \dot{M}\frac{\partial F}{\partial M} + \frac{d\dot{M}}{dt}\frac{\partial F}{\partial \dot{M}} = 0$$

here we do not have the equivalent of the Newton II Law to write $\frac{d\dot{M}}{dt}$ as a function of known quantities.

# A refined Sołtan argument

- It is possible to take moments of that equation rate and find analogs of Jeans equations (or Hydrodynamics equations).
- In particular by simple integration over accretion rate one obtains the continuity equation for BHs (Cavaliere +71, Small & Blandford 92):

$$\frac{\partial N(M,t)}{\partial t} + \frac{\partial}{\partial M}\left[N(M,t)\langle \dot{M}(M,t)\rangle\right] = 0$$

where

$$N(M,t) = \int_0^{+\infty} F(M,\dot{M},t)\,d\dot{M}$$

$$\langle \dot{M}(M,t)\rangle = \frac{1}{N(M,\dot{M},t)}\int_0^{+\infty} \dot{M}\,F(M,\dot{M},t)\,d\dot{M}$$

*average accretion rate*

$$\langle \dot{M}(M,t)\rangle = \delta(M,t)\dot{M}(M,t)$$

*$\delta(M,t)$ is the duty-cycle of BH (AGN) activity*

# A refined Sołtan argument

The term in the derivative is then

$$N(M,t)\langle\dot{M}(M,t)\rangle = \delta(M,t)\dot{M}(M,t)\,N(M,t)$$

where $$\dot{M} = \frac{1-\varepsilon}{\epsilon\, c^2}L$$

Considering the AGN luminosity function we can write

$$\delta(M,t)N(M,t)dM = \phi(L,z)dL$$

*An relation is needed to connect L and M.*
*The simplest is to assume accretion at given Eddington rate λ*

$$L = \lambda L_{Edd} = \frac{\lambda c^2}{t_E}M$$

$$t_E = \frac{\sigma_{\rm T} c}{4\pi G m_P} = 4.51\times 10^8\,\mathrm{yr}$$

# A refined Sołtan argument

Finally one obtains

$$\frac{\partial N(M,t)}{\partial t} + \frac{(1-\varepsilon)\,\lambda^2\,c^2}{\varepsilon\,t_E^2}\left[\frac{\partial}{\partial L}\,[L\phi(L,t)]\right]_{L=\lambda M c^2/t_e} = 0$$

if the AGN LF expressed in *log L* $\qquad \phi(L,t)\,dL = \phi'(\log L, t)\,d\log L$

$$\frac{\partial N(M,t)}{\partial t} + \frac{(1-\varepsilon)\,\lambda}{\varepsilon\,t_E(\ln 10)^2 M}\left[\frac{\partial \phi'(\log L,t)}{\partial \log L}\right]_{L=\lambda M c^2/t_E} = 0$$

This equation relates the BH mass function and AGN luminosity function assuming that

- *BH number is conserved (no BH created or destroyed, e.g, by merging)*
- *Active BH accrete at given Eddington rate λ*

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BH Mass Function
(AGN remnants)

AGN Luminosity Function

$$\frac{\partial N(M,t)}{\partial t} + \frac{(1-\varepsilon)\,\lambda}{\varepsilon\, t_E (\ln 10)^2 M}\left[\frac{\partial \phi'(\log L,t)}{\partial \log L}\right]_{L=\lambda M c^2/t_E} = 0$$

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# Fundamental ingredients ...

BH Mass Function
(AGN remnants)

AGN Luminosity Function

$$\frac{\partial N(M,t)}{\partial t} + \frac{(1-\varepsilon)\,\lambda}{\varepsilon\, t_E (\ln 10)^2 M}\left[\frac{\partial \phi'(\log L, t)}{\partial \log L}\right]_{L=\lambda M c^2/t_E} = 0$$

✱ *L is total (bolometric) accretion luminosity*
→ need to apply bolometric corrections to estrapolate from $L_{band}$ to L (eg Marconi +04, Hopkins+06)

✱ *ϕ(L,t) is the luminosity function of the **whole** AGN population.*
Usually, ϕ derived from surveys →need to account for missing AGN (obscured).
Hard X LF (2-10 keV) are the less affected by obscuration but are still missing most objects absorbed by $N_H > 10^{24}$ cm$^{-2}$ (Compton-Thick).
X-ray background and mid-IR surveys provide strong contraints to missing Compton-thick AGN (but still much work to do!)

# A refined Sołtan argument

The continuity equation can then be integrated as

$$N(M,z) = N(M,z_i) + \frac{(1-\varepsilon)\lambda}{\varepsilon\, t_E (\ln 10)^2 M} \int_z^{z_i} \left[\frac{\partial \phi'}{\partial \log L}\right]_{L=\lambda M c^2/t_E} \left|\frac{dt}{dz}\right| dz$$

To integrate, start at given redshift $z_i$ and add the contribution from the AGN luminosity function.

*Initial condition is usually assumption that all AGNs at $z_i$ are active*

$$N(M,z_i) = \left[\phi(\log L, z_i)\frac{d\log L}{dM}\right]_{L=\lambda M c^2/t_E}$$

For every redshift it is possible to estimate the AGN duty cycle as

$$\delta(M,z) = \left[\frac{\phi(\log L, z)}{N(M,z)}\frac{d\log L}{dM}\right]_{L=\lambda M c^2/t_E}$$

# A refined Sołtan argument

- The solution of the continuity equation provides the same expression for the mass density derived before.

$$N(M,z) = N(M,z_i) + \frac{(1-\varepsilon)\lambda}{\varepsilon\, t_E (\ln 10)^2 M} \int_z^{z_i} \left[\frac{\partial \phi'}{\partial \log L}\right]_{L=\lambda M c^2/t_E} \left|\frac{dt}{dz}\right| dz$$

Hint: integrate above expression after multiplying by M and consider that

$$\rho_{BH}(z) = \int_0^{+\infty} M\, N(M,z) dM$$

$$dM = \frac{t_E\ \ln(10)}{\lambda c^2} d\log L$$

one ends up with the expression used to get local BH mass density (z=0)

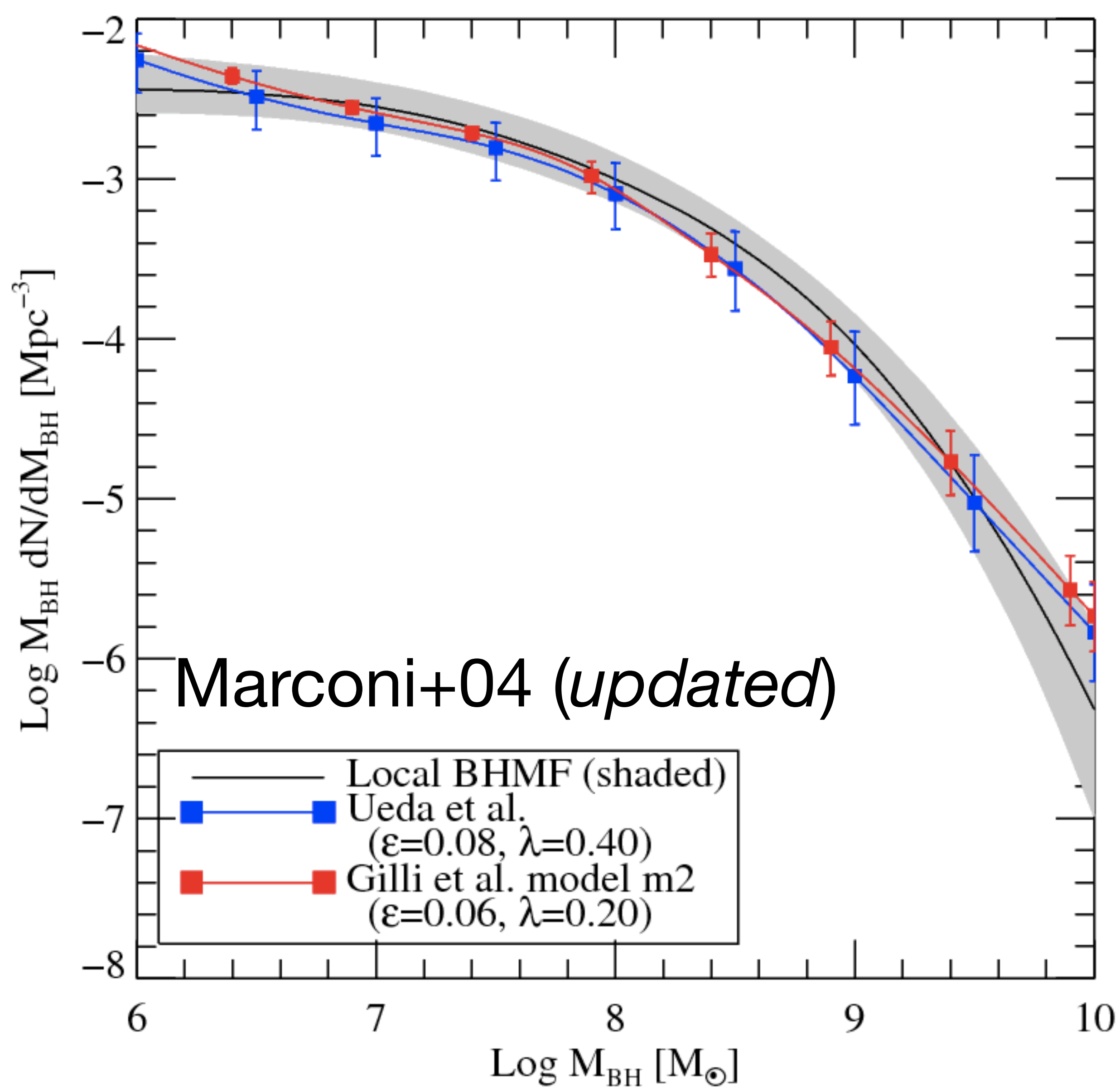
$$\rho_{BH}(z) = \rho_{BH}(z_i) + \frac{1-\varepsilon}{\varepsilon c^2} \int_z^{z_i} dz \int_0^{+\infty} dL\, L\phi(L,z) \left|\frac{dt}{dz}\right|$$

# Local BHMF vs AGN BHMF

We can now compare BH Mass function from AGN with that from local nearby galaxies.

There is a surprisingly good agreement between the BHMF in the local universe and the one expected from AGN activity
(for ε≃0.07, λ≃0.4 → see later)

- *Assumption of unit duty cycle at $z_i$ does not affect results; BHMF at z=0 much larger than at $z_i$ (i.e. most of BH mass grown at $z<z_i$)*
- *Shapes of local and AGN BHMF are very similar, assumption of no merging is a good one?*
- *Final results depend on bolometric corrections, ε, λ*



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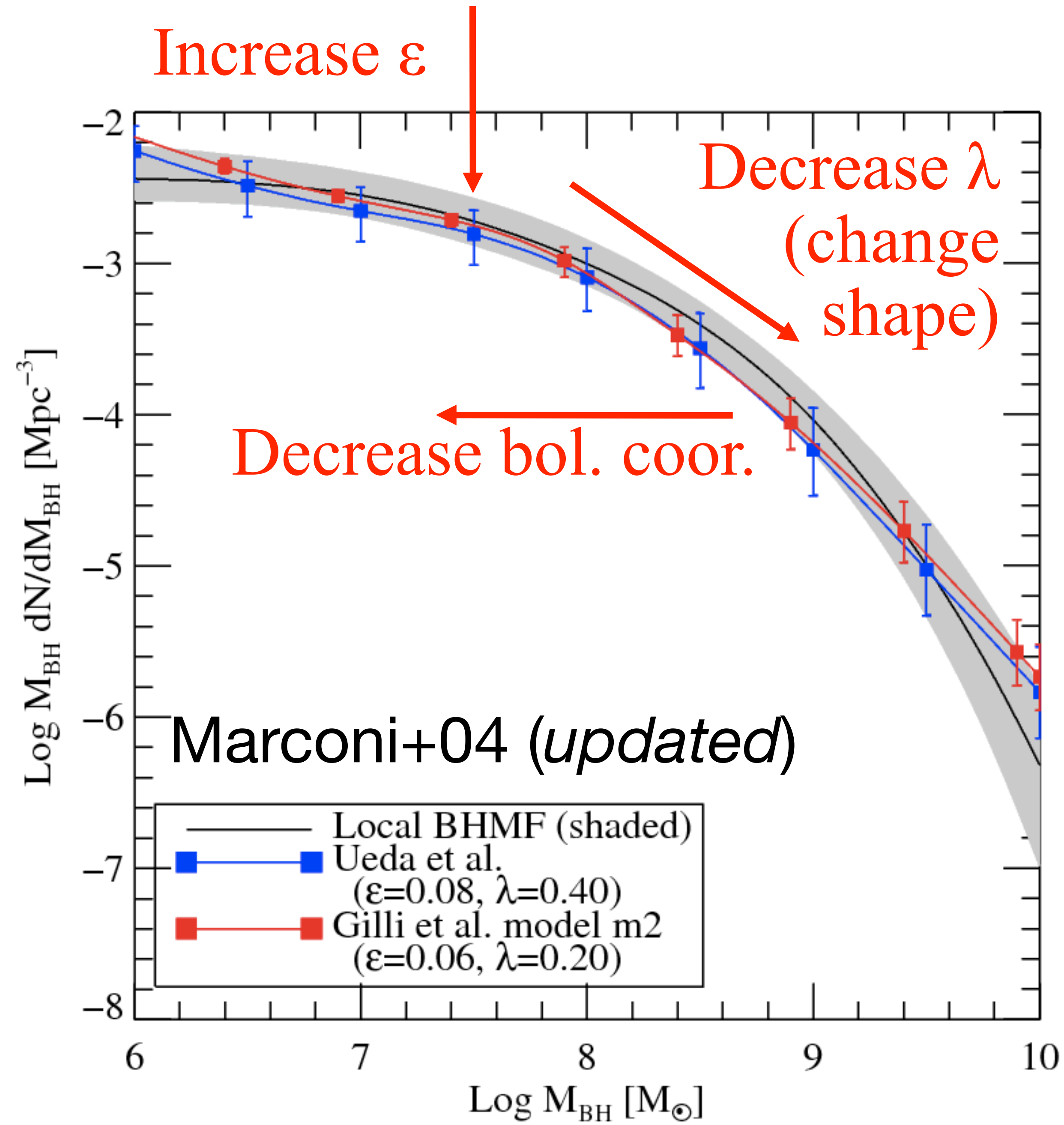
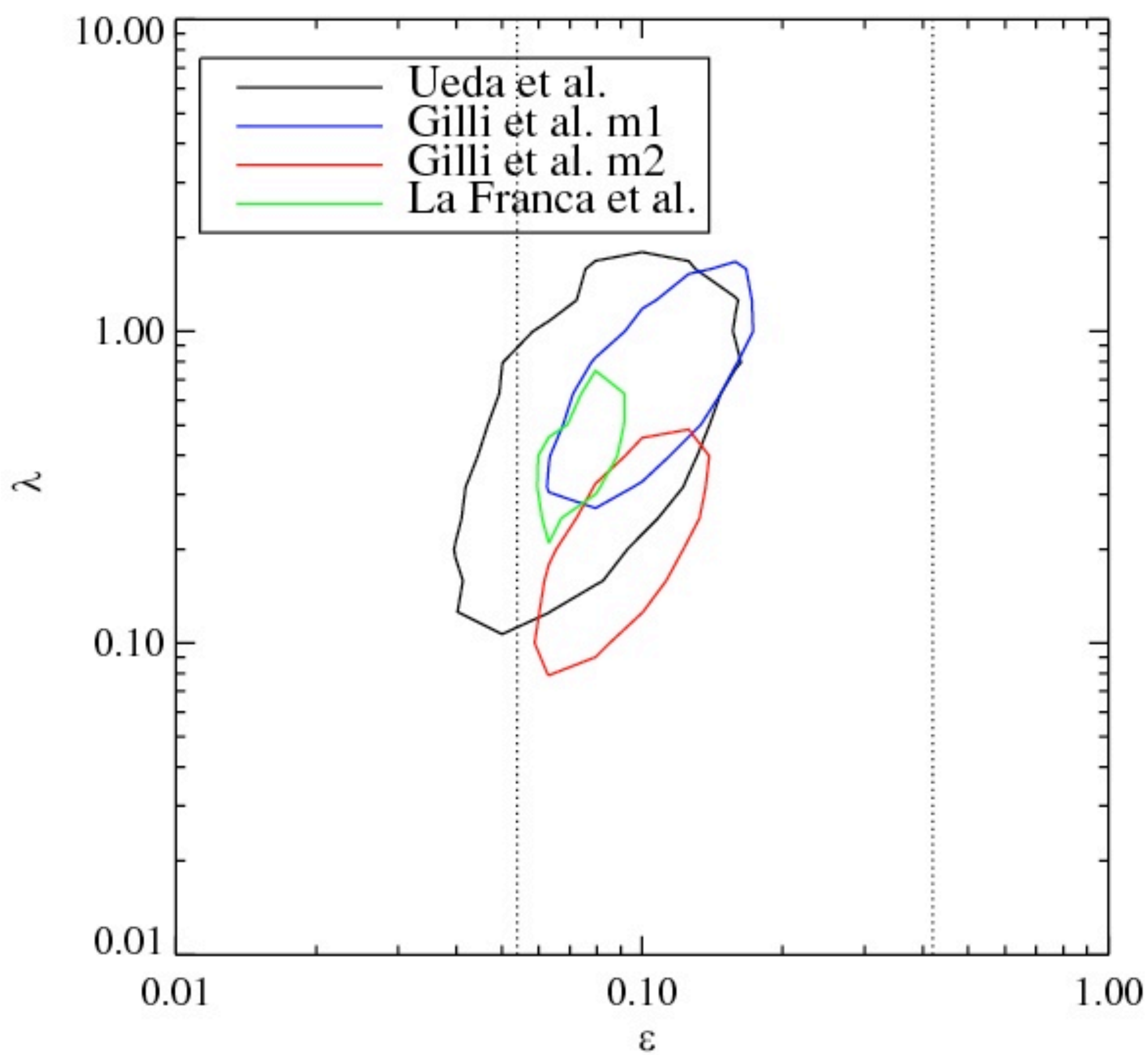


# Rad. Efficiency and Fraction of $L_{Edd}$

After correcting for missing Compton-thick sources, efficiency and fraction of Eddington luminosity are the only free parameters!
Determine locus in ε-λ plane where there is the best match between local and relic BHMF!
ε=0.06-0.15   λ=0.08-0.5 which are consistent with common 'beliefs' on AGNs



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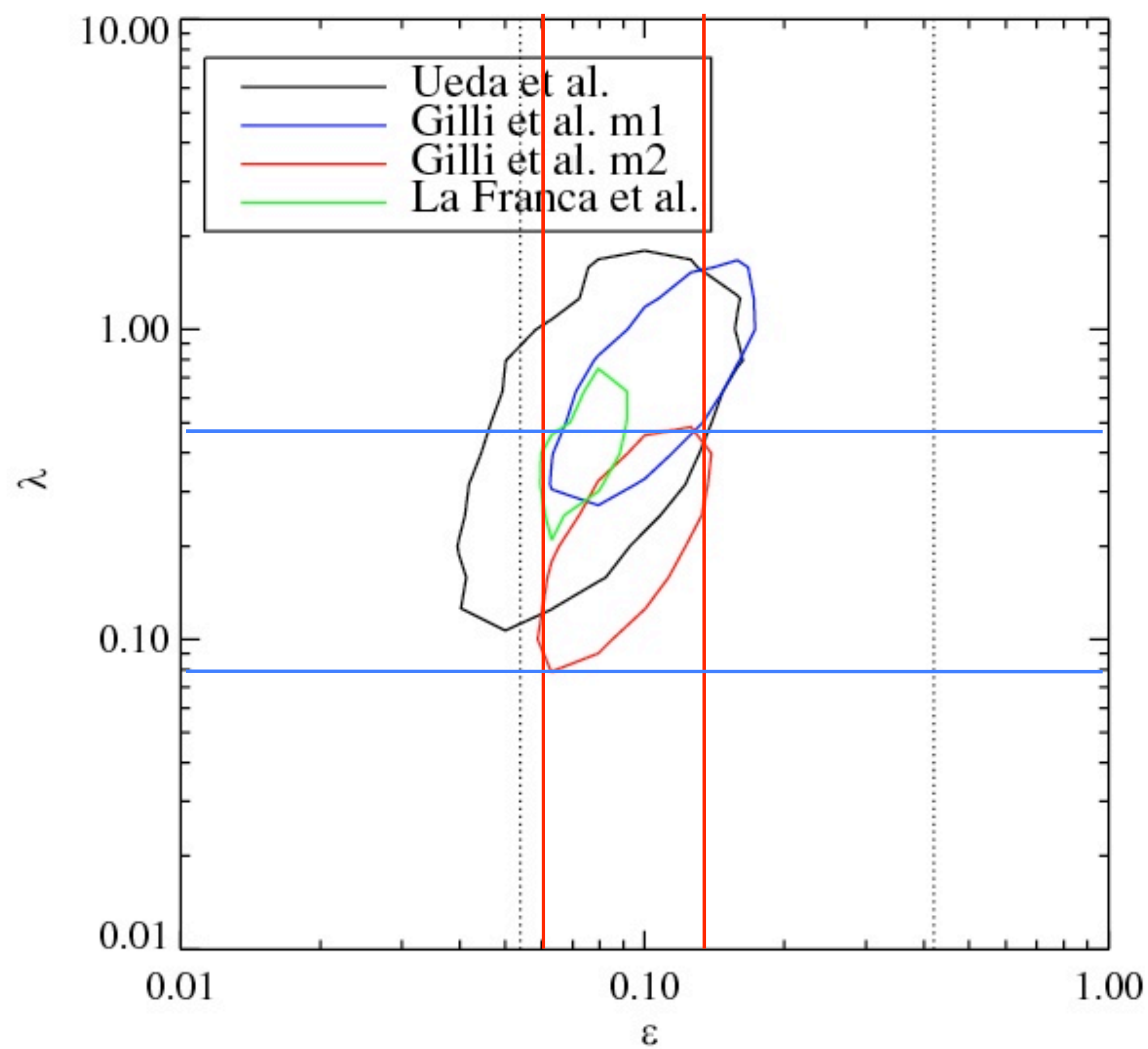


# Anti-Hierarchical BH growth

A by-product of the integration of the continuity equation is the duty cycle which allows to estimate the average accretion rate of a BH with mass *M* at cosmic time *t* and therefore the average BH growth *M(t)*

$$\langle \dot{M}(M,t)\rangle = \frac{1}{t_E \ln 10}\frac{(1-\varepsilon)\lambda}{\varepsilon N(M,z)}[\phi'(\log L,z)]_{L=\lambda M c^2/t_E}$$

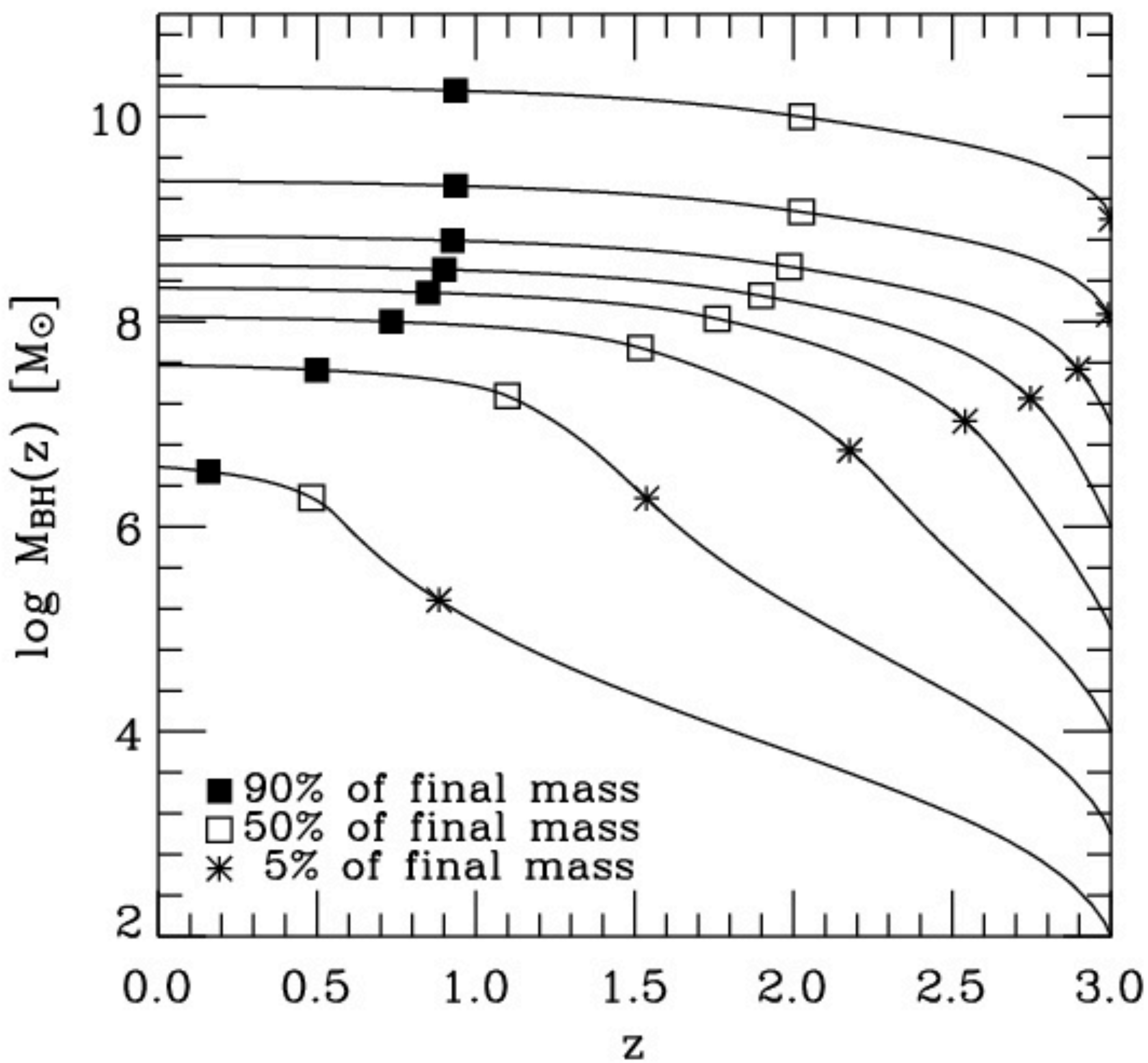
$$M(t+\Delta t) = M(t) + \langle \dot{M}(M(t),t)\rangle dt$$

It is also possible to estimate the total time required to grow black holes as

$$\tau(M_0) = \int_0^{z_i} \delta[M(z,M_0),z]\left|\frac{dt}{dz}\right| dz$$

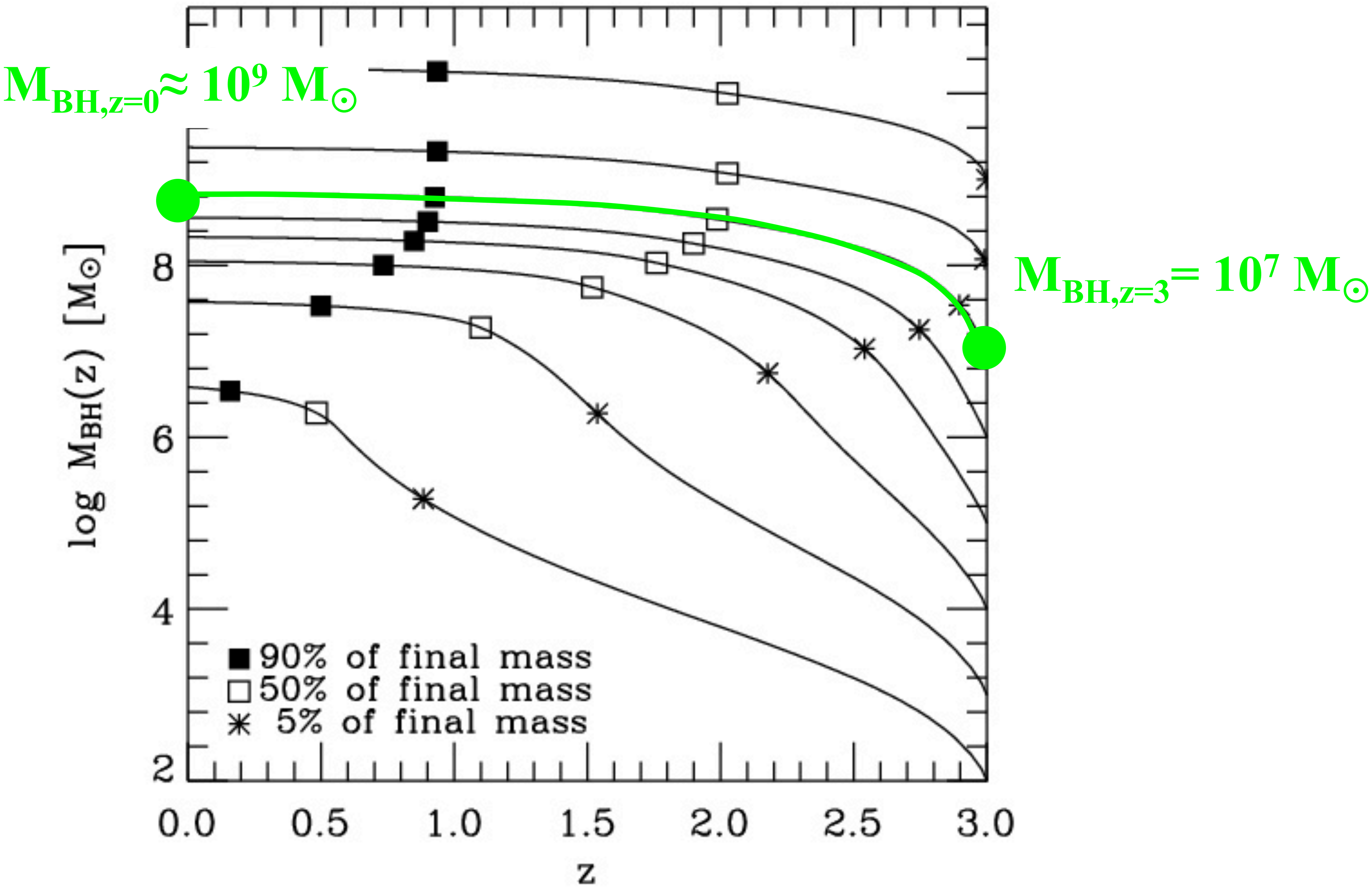
where the duty cycle is computed following the average growth of a BH which has mass $M_0$ at z=0 (see above):
$M(z, M_0)$ is the BH mass at z for a BH with mass $M_0$ at z=0

# Anti-Hierarchical BH growth




See also Merloni 04, Shankar+04,08, Merloni & Heinz 08.

# Anti-Hierarchical BH growth

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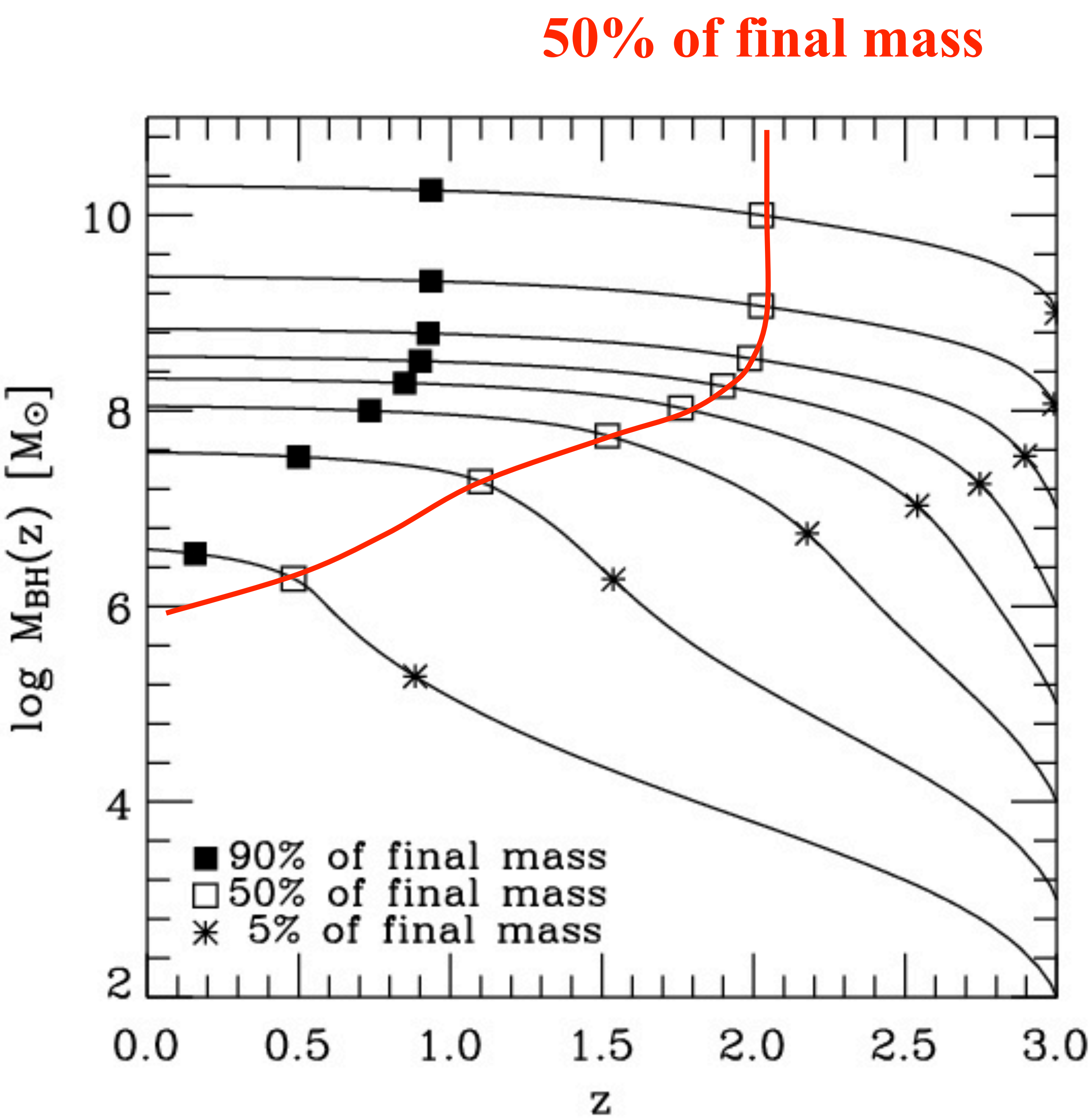


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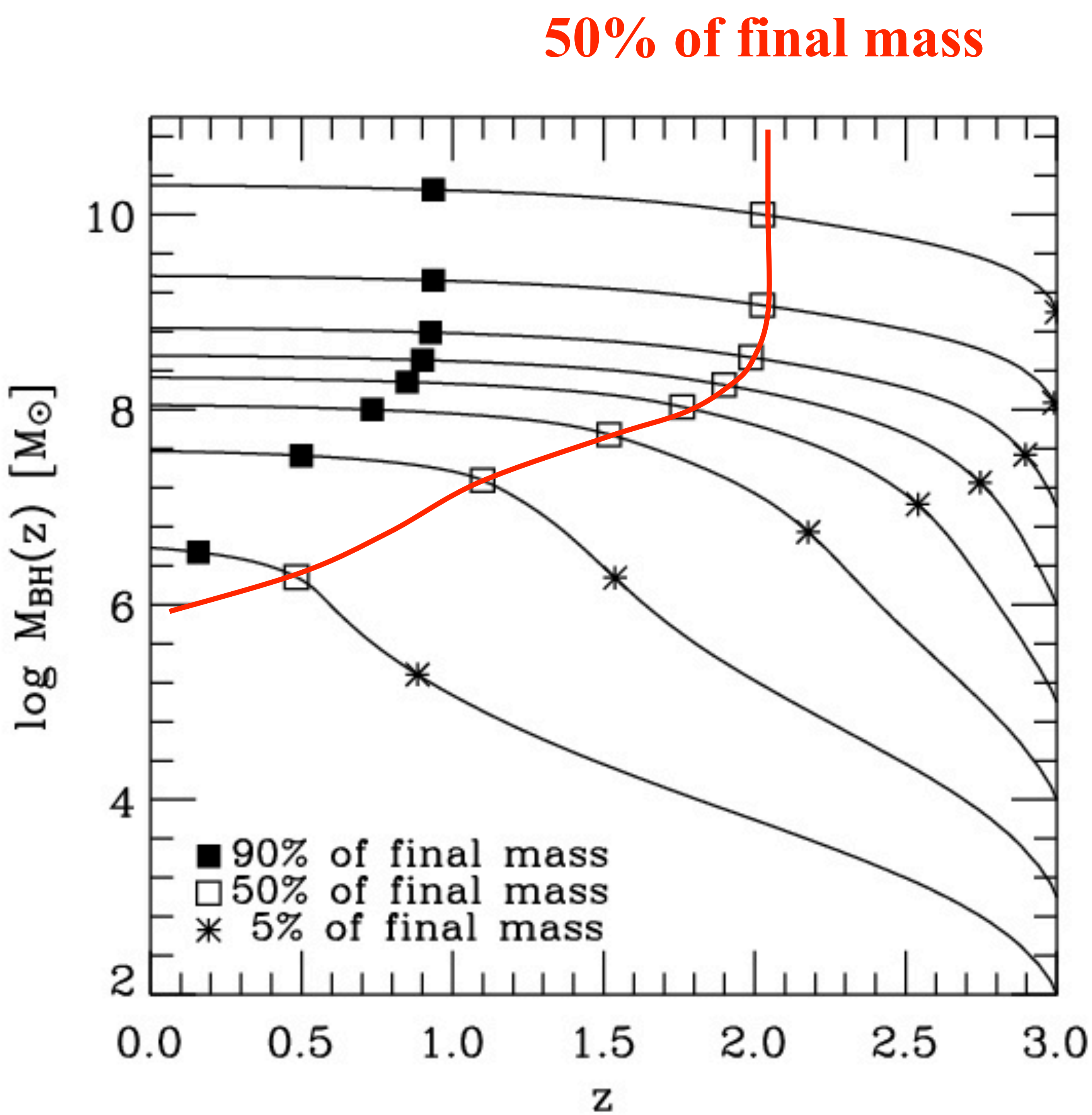



*Qualitatively* consistent with models of galaxy formation.
Big BHs form in deeper potential wells → they form first.
Smaller BHs form in shallower potential wells and are more subjected to feedback effects (star form., AGN), → they form later and take more time to grow.

*This is just the consequence of anti-hierarchical behaviour of AGN luminosity functions (e.g. Fiore+03, Ueda+03, La Franca +05)*

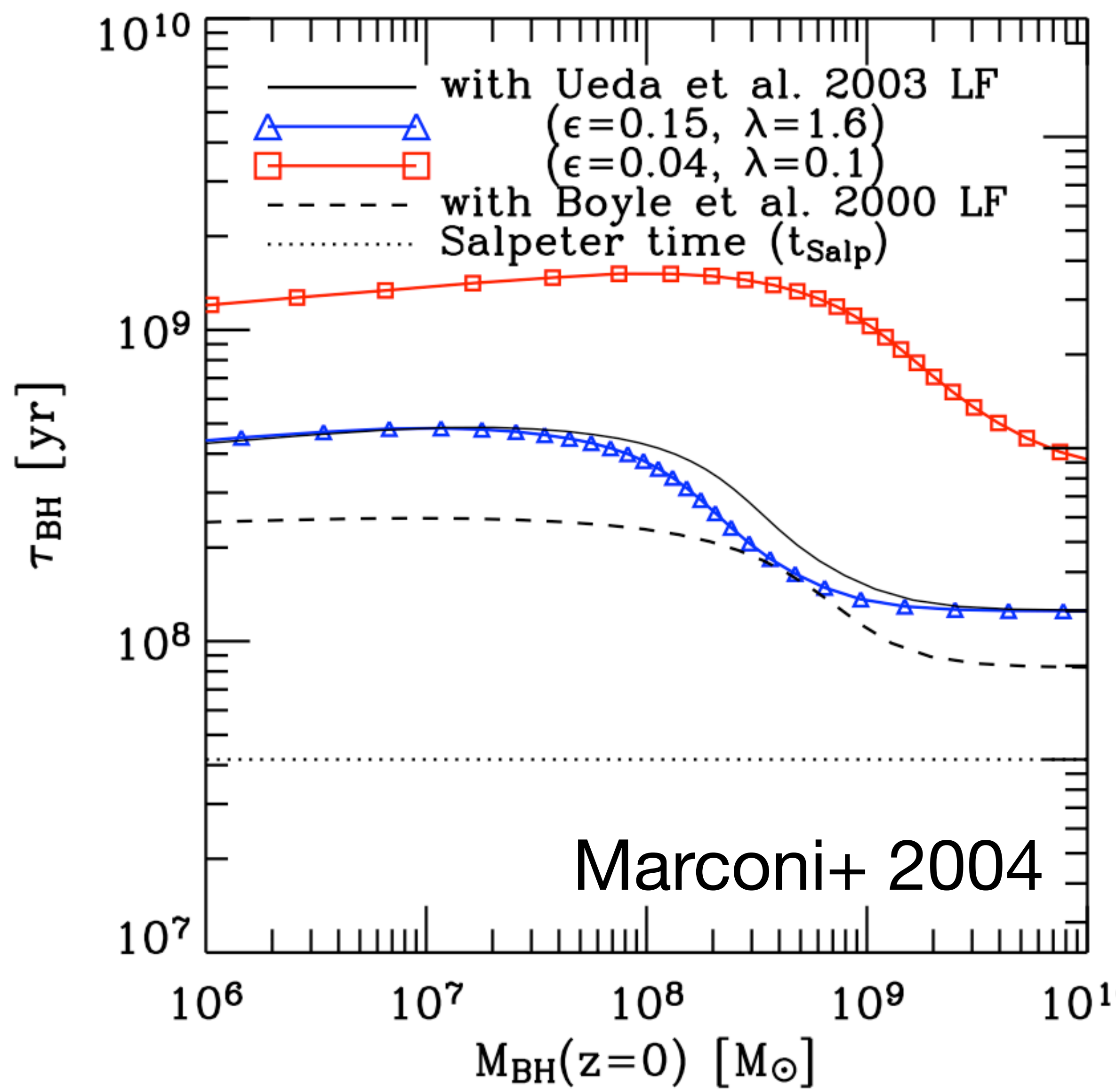
See also Merloni 04, Shankar+04,08, Merloni & Heinz 08.

# Time to grow black holes

Required time depends on mass, smaller black holes need more time to grow than more massive ones.

This time cannot be directly compared with observations:

- observations usually estimate the time scale of a single accretion episode (~$10^7$ yr), this is the sum of all accretion episodes which built the BH;
- moreover the BH is detectable with observations only when its observed flux in a given band is above the survey sensitivity (e.g. Shankar+2004).



# Duty cycle

It is possible to show that the duty cycle is given by (Wang+06,+08)

$$\delta(z) = \frac{\rho_{BH}(z)}{\rho_{acc}(z)}$$

mass density of active BHs at z

total mass density accreted onto BHs up to z

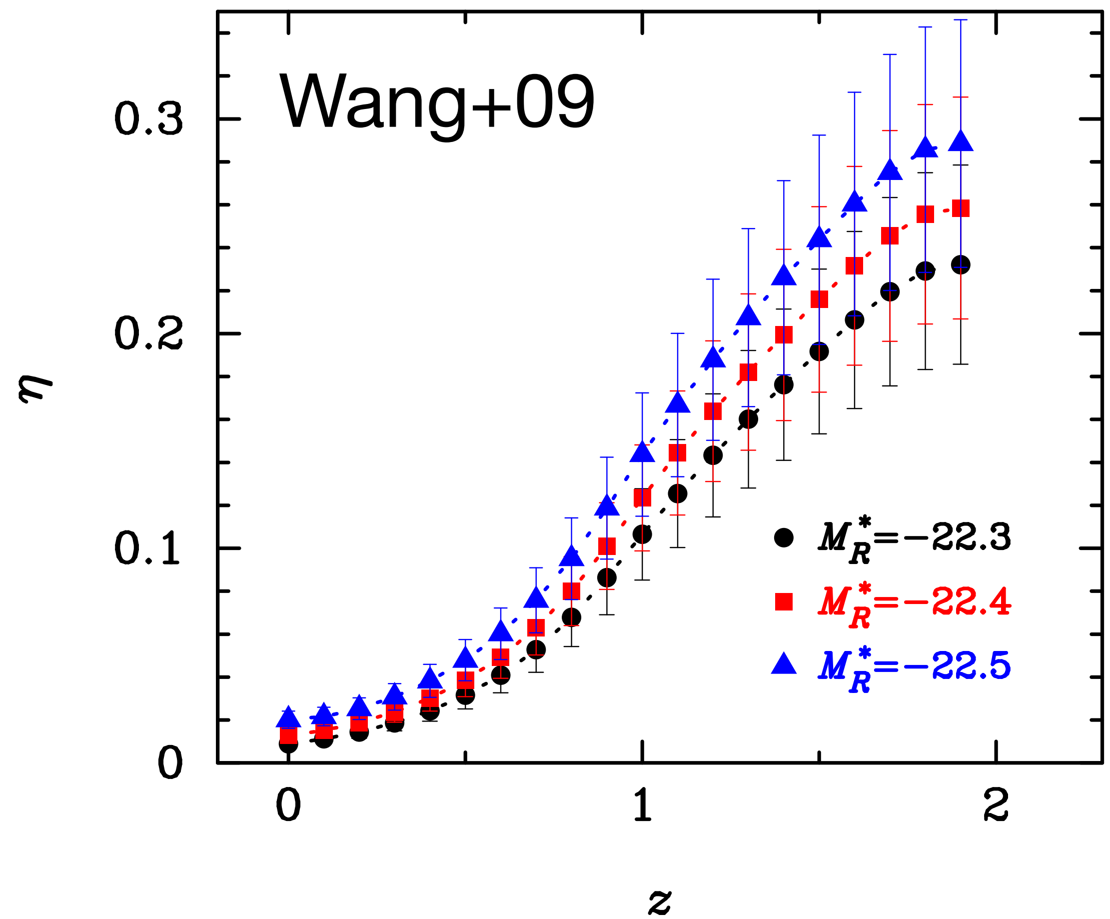
This relation allows to find the duty cycle in an alternative way to the continuity equation.

Finally one can show that

$$\frac{1}{\varepsilon} = 1 + \frac{c^2}{\mathcal{L}(z)} \left(\frac{dt}{dz}\right)^{-1} \frac{d}{dz}\left(\frac{\rho_{BH}(z)}{\delta(z)}\right)$$

$\mathcal{L}$ is the AGN luminosity density at z

That equation can be used to estimate the accretion efficiency, and whether it is constant with redshift.




High efficiency at high z means highly spinning BHs.

The spin is then reduced by episodic, randomly oriented accretion (Wang+09)

# Light bulbs?

So far we have assumed that AGN are 'light bulbs' i.e. they are either on with $L = \lambda\, L_{Edd}$ or off with $L=0$.

⭐ This assumption can be relaxed *provided the λ distribution is known.*

Recalling that

$$\langle \dot{M}(M,t) \rangle = \frac{1}{N(M,\dot{M},t)} \int_0^{+\infty} \dot{M}\, F(M,\dot{M},t)\, d\dot{M}$$

*average accretion rate*

we can write $$\frac{\partial N(M,t)}{\partial t} + \frac{\partial}{\partial M}\left[\int_0^{+\infty} \dot{M} F(M,\dot{M},t) d\dot{M}\right] = 0$$

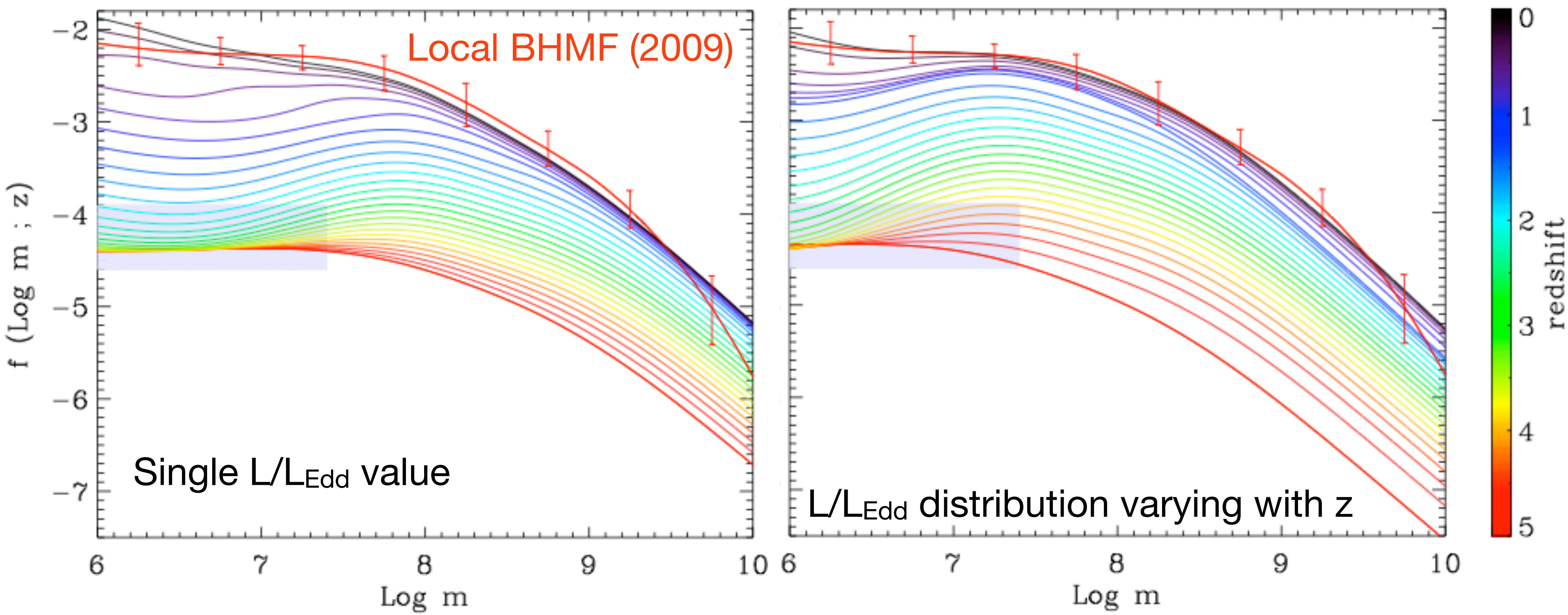
Applying Bayes Theorem $$F(M,\dot{M},t) = P(M|\dot{M})\, \Phi(\dot{M},t)$$

then $$\Phi(\dot{M},t) d\dot{M} = \phi(L,t) dL$$

with $$\dot{M} = \frac{1-\varepsilon}{\epsilon\, c^2} L$$

$P(M|\dot{M}) = p(M|L)$ is the $L/L_{Edd}$ distribution

# Light bulbs?




Sirigu, Marconi+ 2012

We can conclude that in terms of the local BHMF from AGN, considering a distribution of $L/L_{Edd}$ does not make a significant difference.
The differences are in the BHMF at redshifts different than z, and they are strongly dependent on $p(L/L_{Edd})$ and its shift evolution (see also Cao 2010).

# Too many free parameters ...

Adopting the total AGN luminosity function as derived by the Gilli +07 model and matching the local BH mass function (Marconi +04) it is possible to write:

$$\frac{1-\varepsilon}{\varepsilon}\left[1+R_{\rm Thin}+R_{\rm MThick}+R_{\rm HThick}\left(\frac{0.02}{f_{\rm scatt}}\right)+X_{\rm Enshrouded}\right]\simeq\begin{cases}50\ \ (L>2\times 11\,{\rm L}_{\odot})\\ 150\ (L<2\times 11\,{\rm L}_{\odot})\end{cases}$$

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R = Ratio obscured/unobscured

Compton Thin
(21 < log $N_H$ < 24)

Highly Compton Thick
(log $N_H$ > 25)

Mildly Compton Thick
(24 < log $N_H$ < 25)

Completely
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using Gilli +07 best model [R = 4+4 (low L); R= 1+1 (high L); Compton-Thick are ~ lower obscuration AGNs] and ε~0.06.

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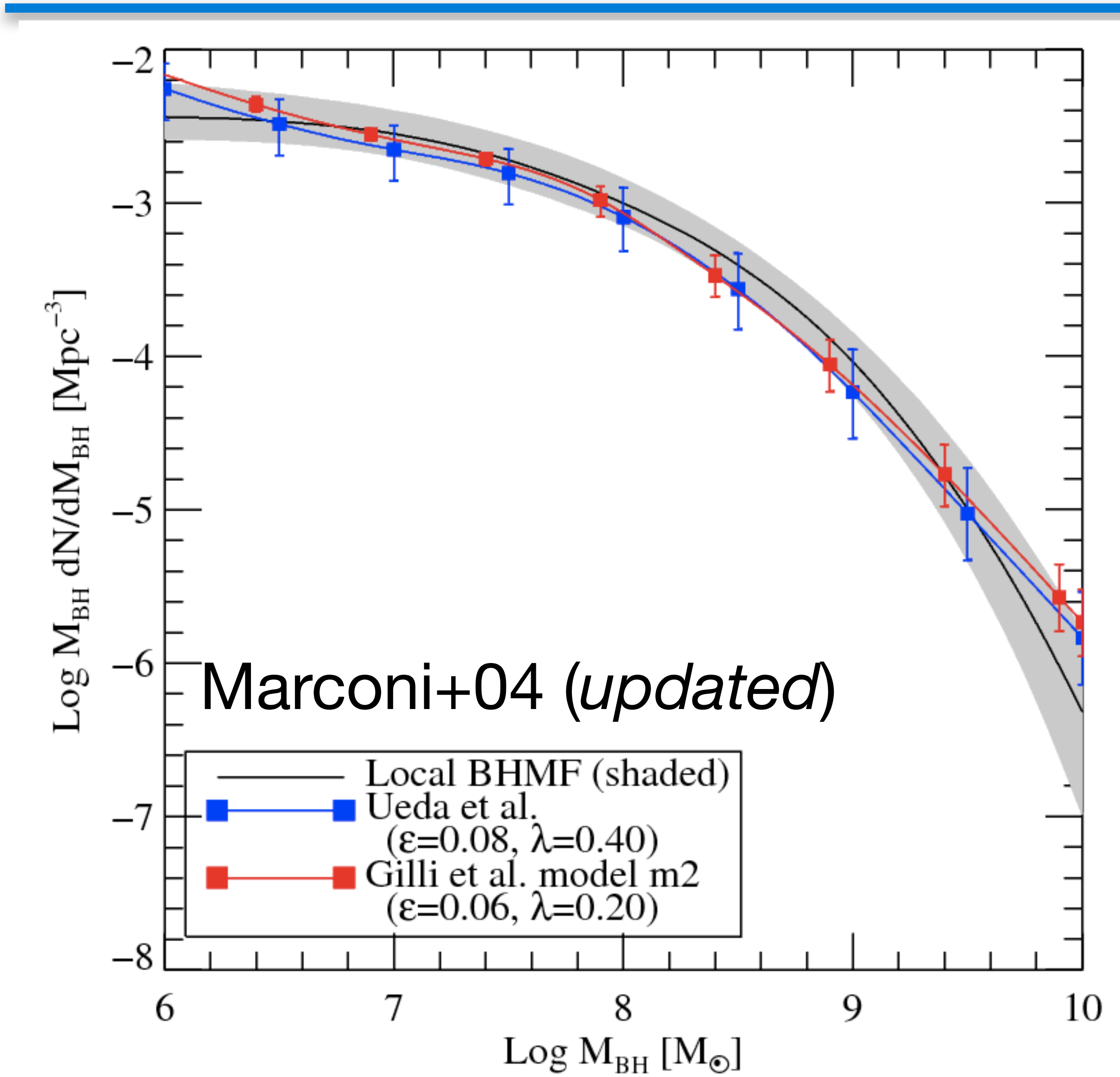
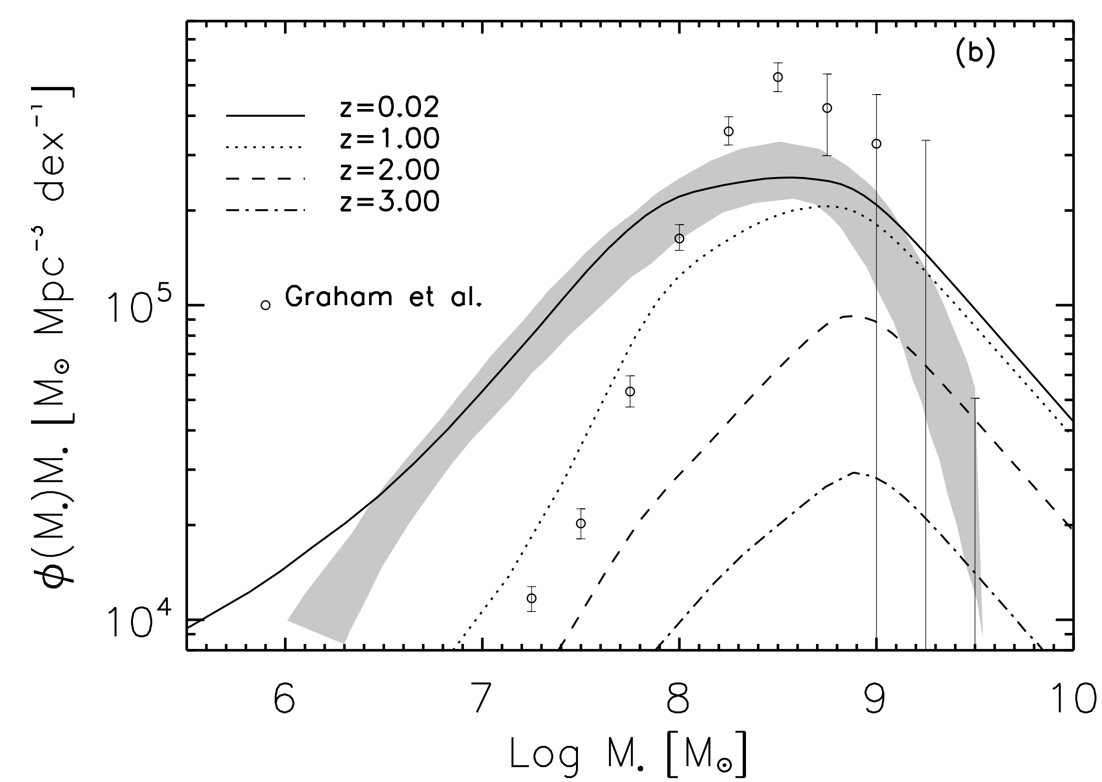
($24 < \log N_H < 25$)

using Gilli +07 best model [R = 4+4 (low L); R= 1+1 (high L); Compton-Thick are ~ lower obscuration AGNs] and ε~0.06.

Example: *assuming X~4 then with ε~0.08 (LL), 0.12 (HL) we can still satisfy the above equation! Little constraints from XRB and local BH mass function!*

# Local BHMF vs AGN BHMF




Shankar+08 (ε=0.065, λ=0.42)

There is a surprisingly good agreement between the BHMF in the local universe and the one expected from AGN activity (ε≃0.07, λ≃0.4)

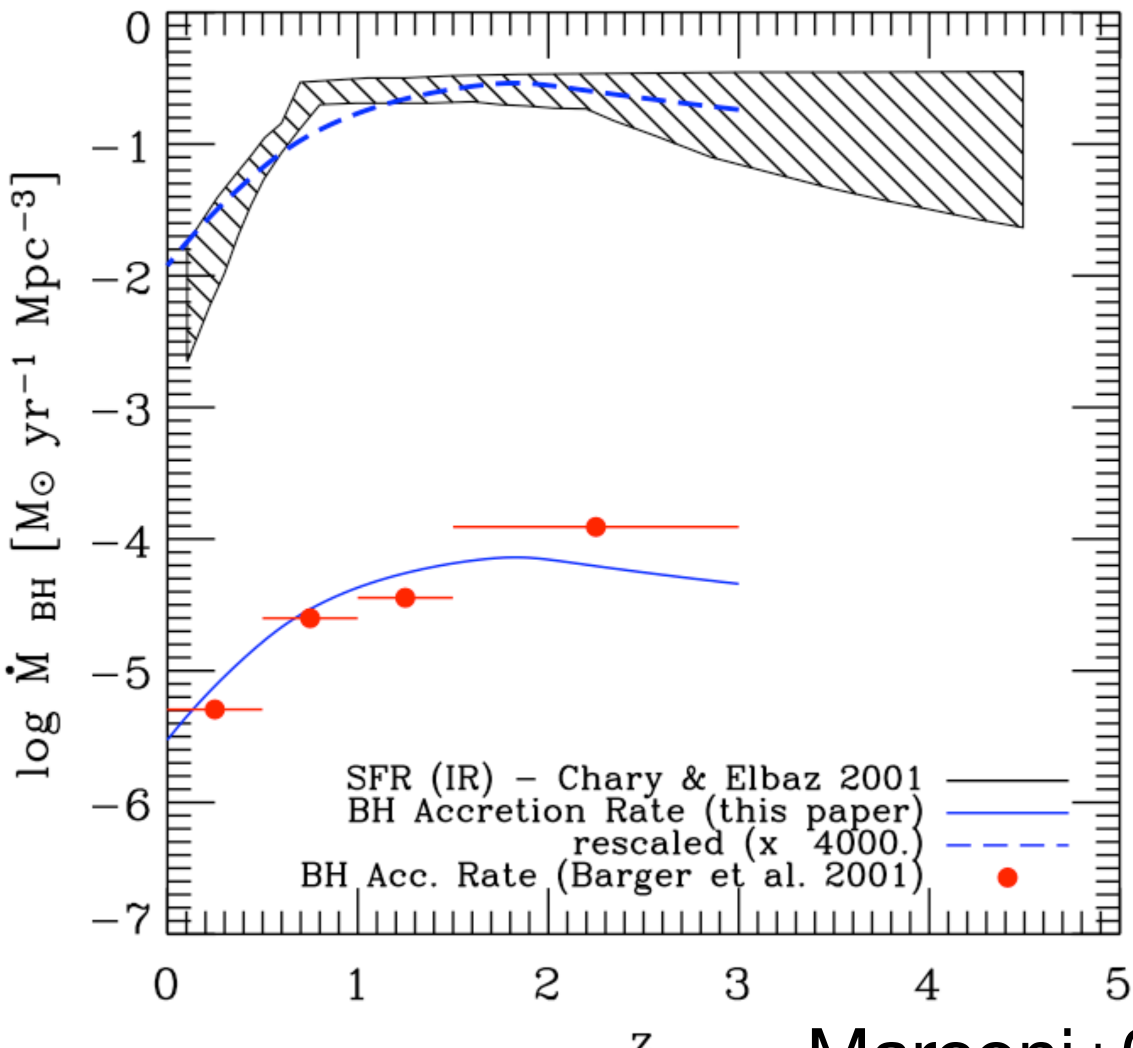
- *Local BHs are indeed remnants of past AGN activity*
- *Accretion efficiency is ε~0.1, i.e. BHs are grown efficiently*

# BH Accretion - Star Formation Rate

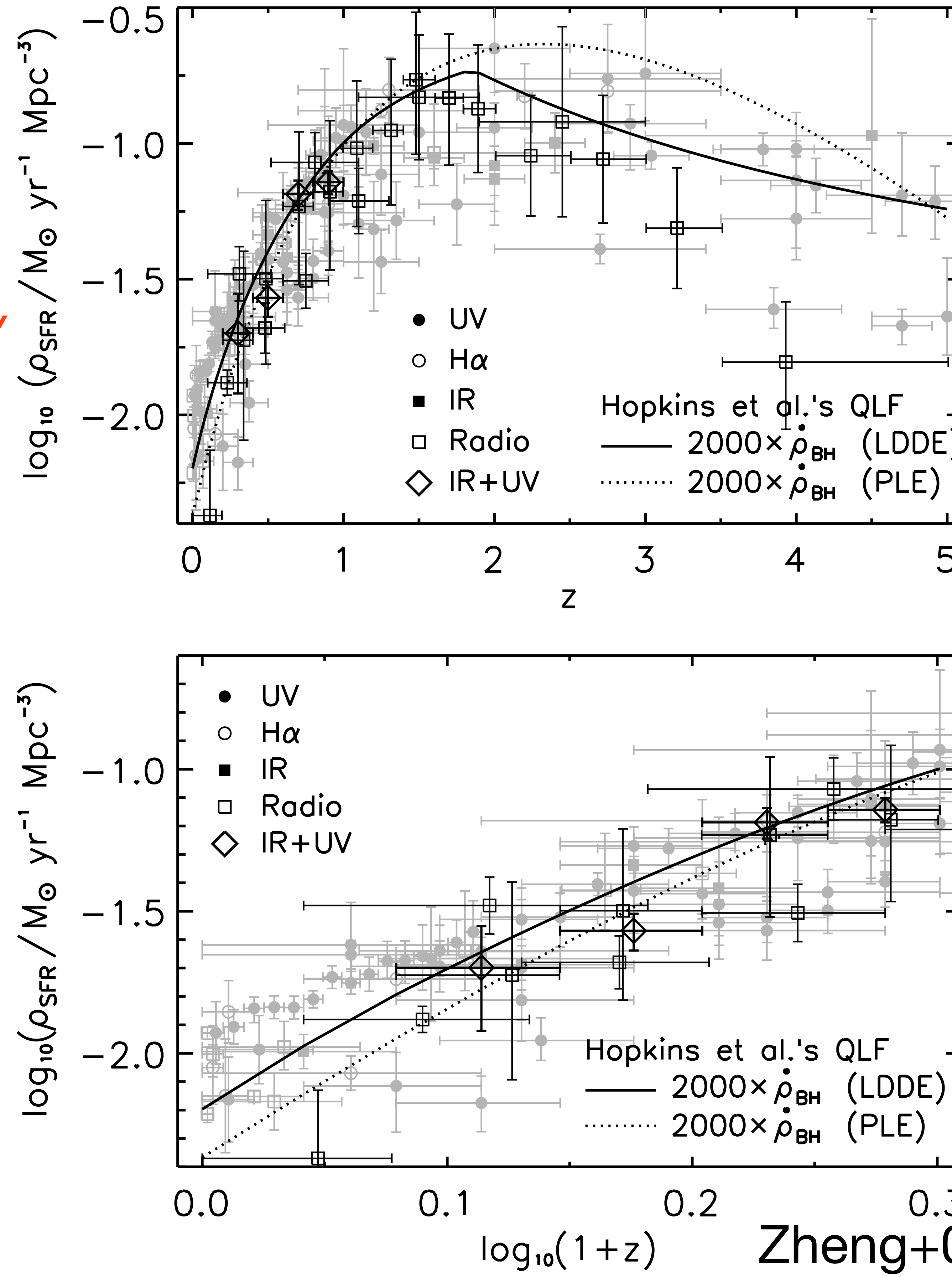
BH Accretion Rate (BHAR) is simply to cosmic accretion rate onto BHs,

$$BHAR = \int_0^{+\infty} \langle \dot{M}(M,t) \rangle N(M,t) dM$$

*Comparison of BH AR vs SFR clearly suggest coeval growth of BHs and galaxies.*




Marconi+04




Zheng+09

Active Galactic Nuclei

Quasars

Radio Galaxies

Seyfert Galaxies

Normal Galaxies

Active Galactic Nuclei

Quasars

Radio Galaxies

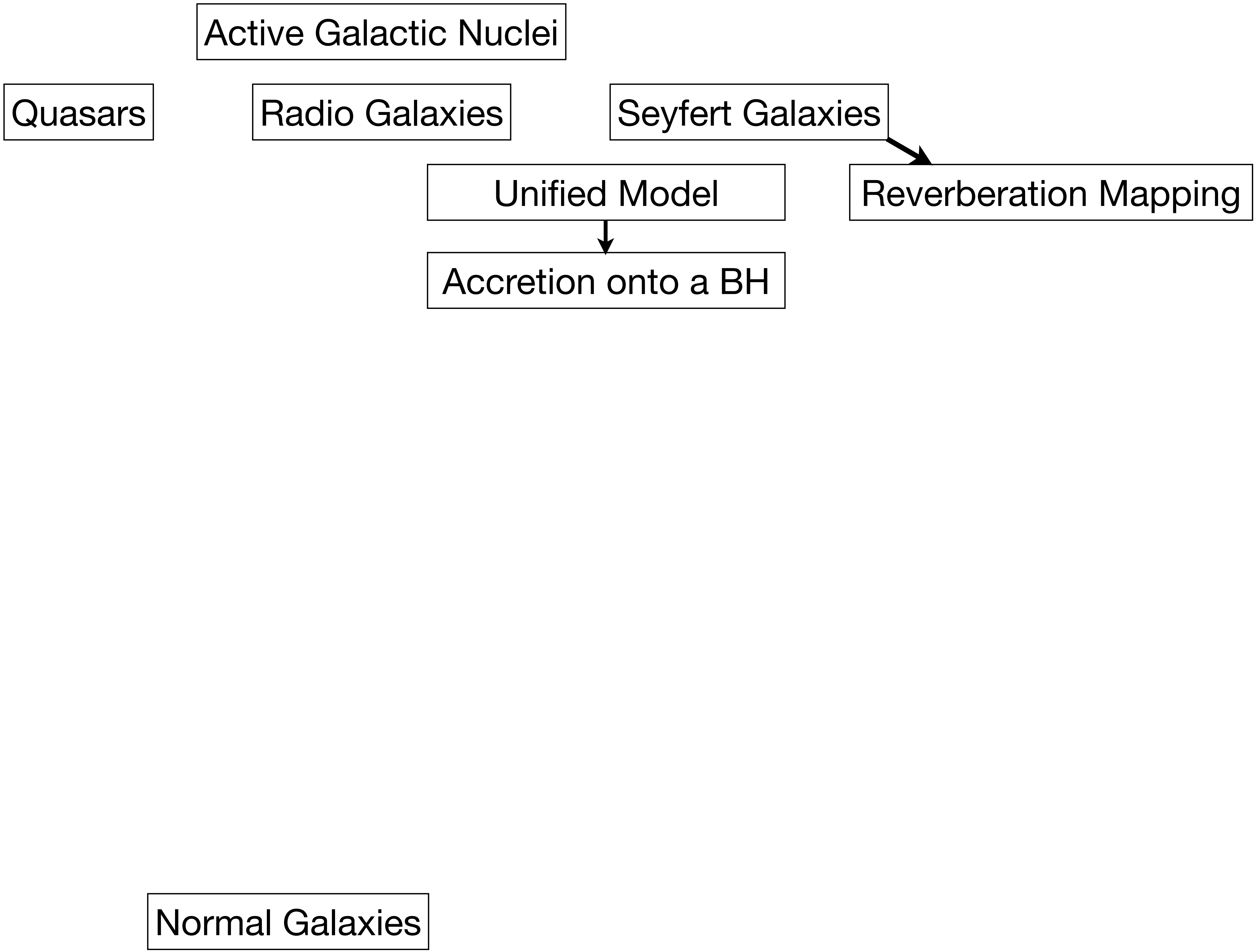
Seyfert Galaxies

Unified Model

↓

Accretion onto a BH

Normal Galaxies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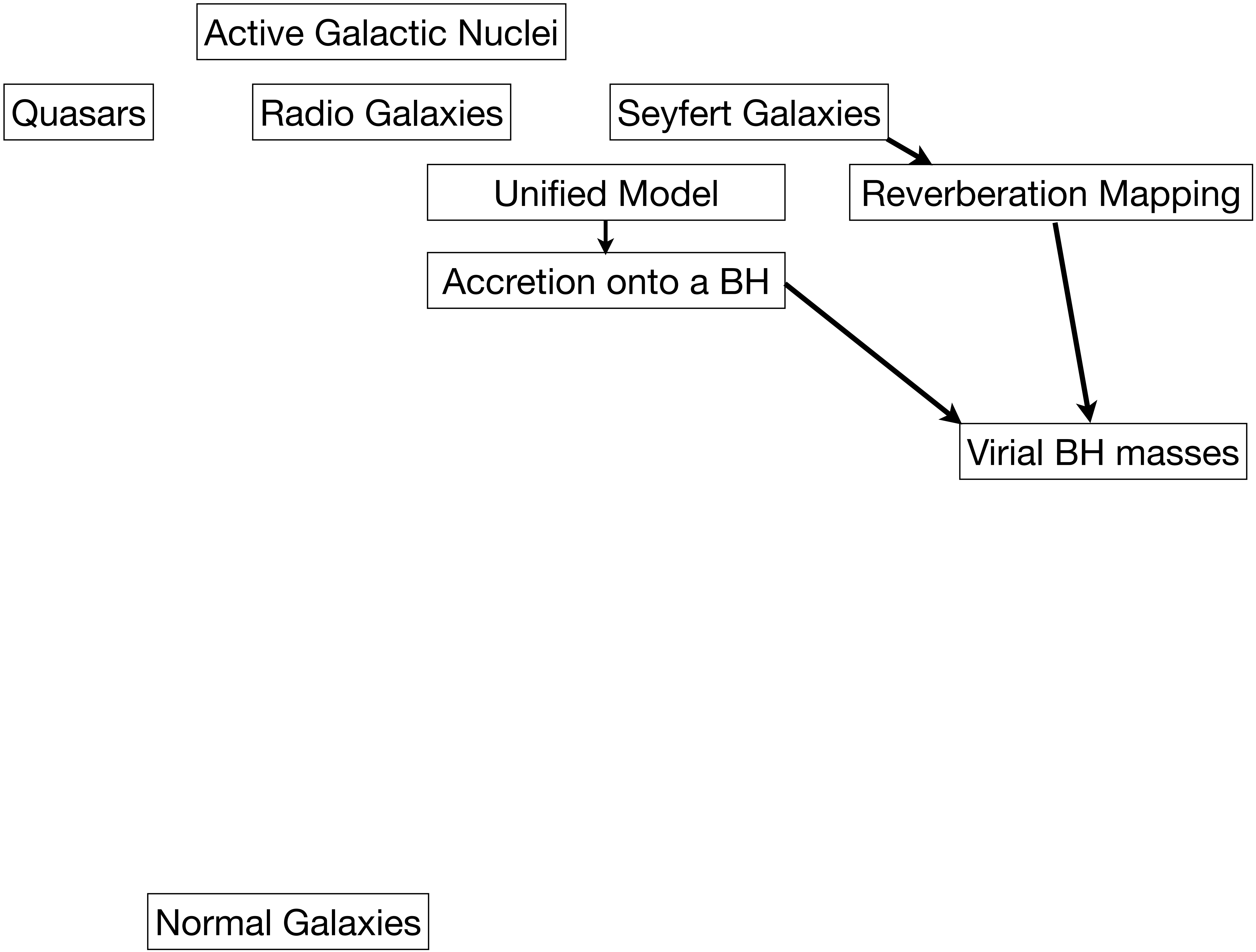
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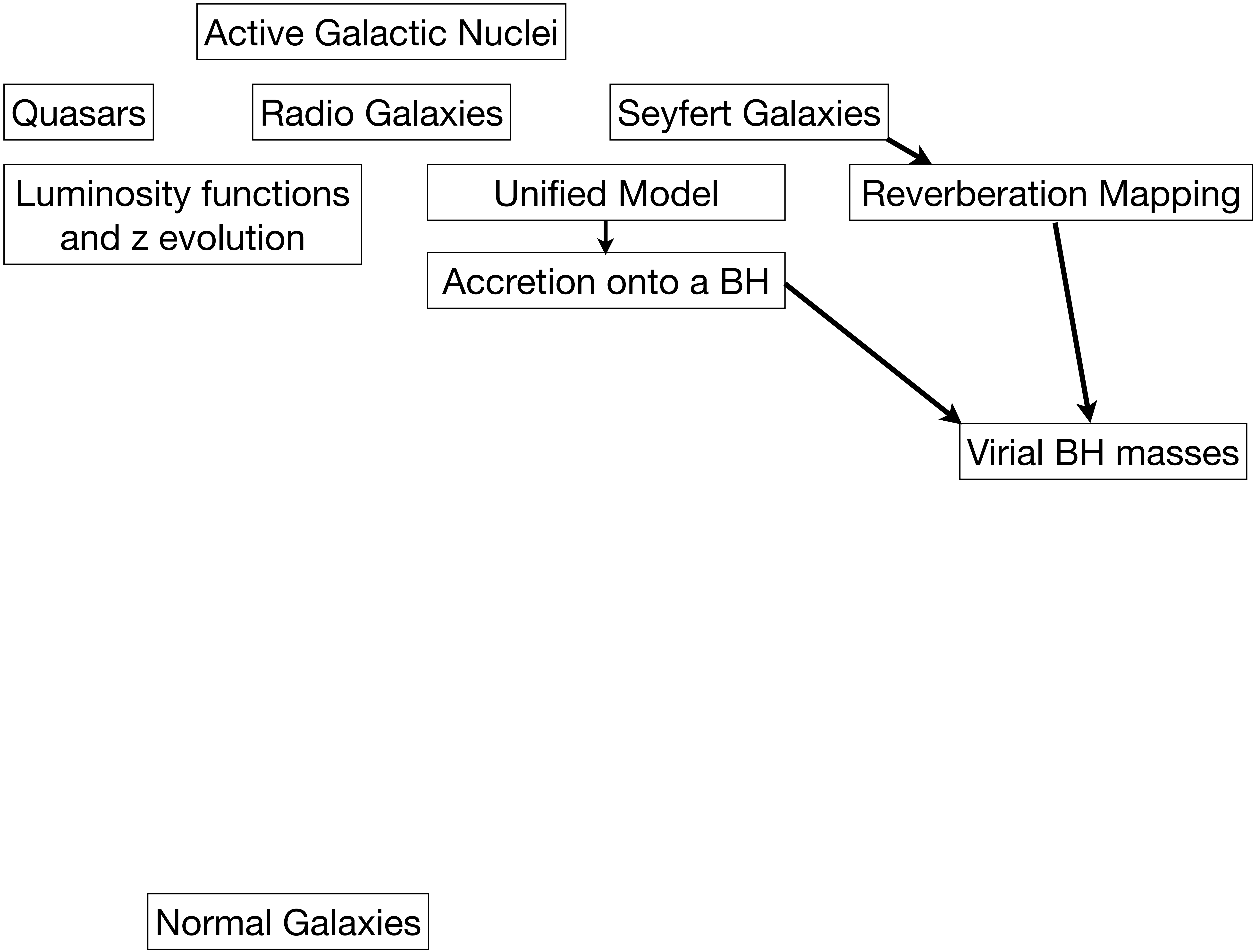
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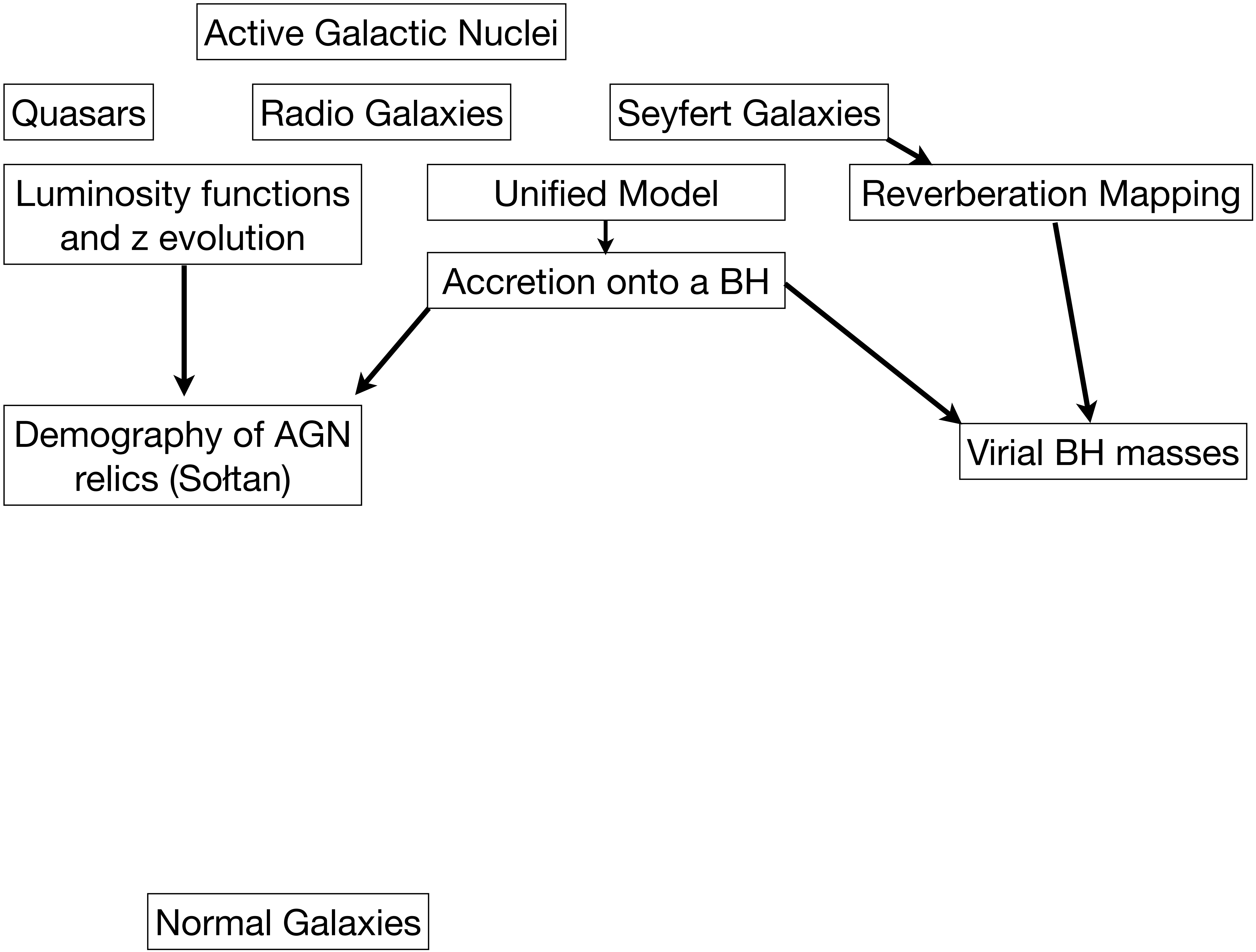
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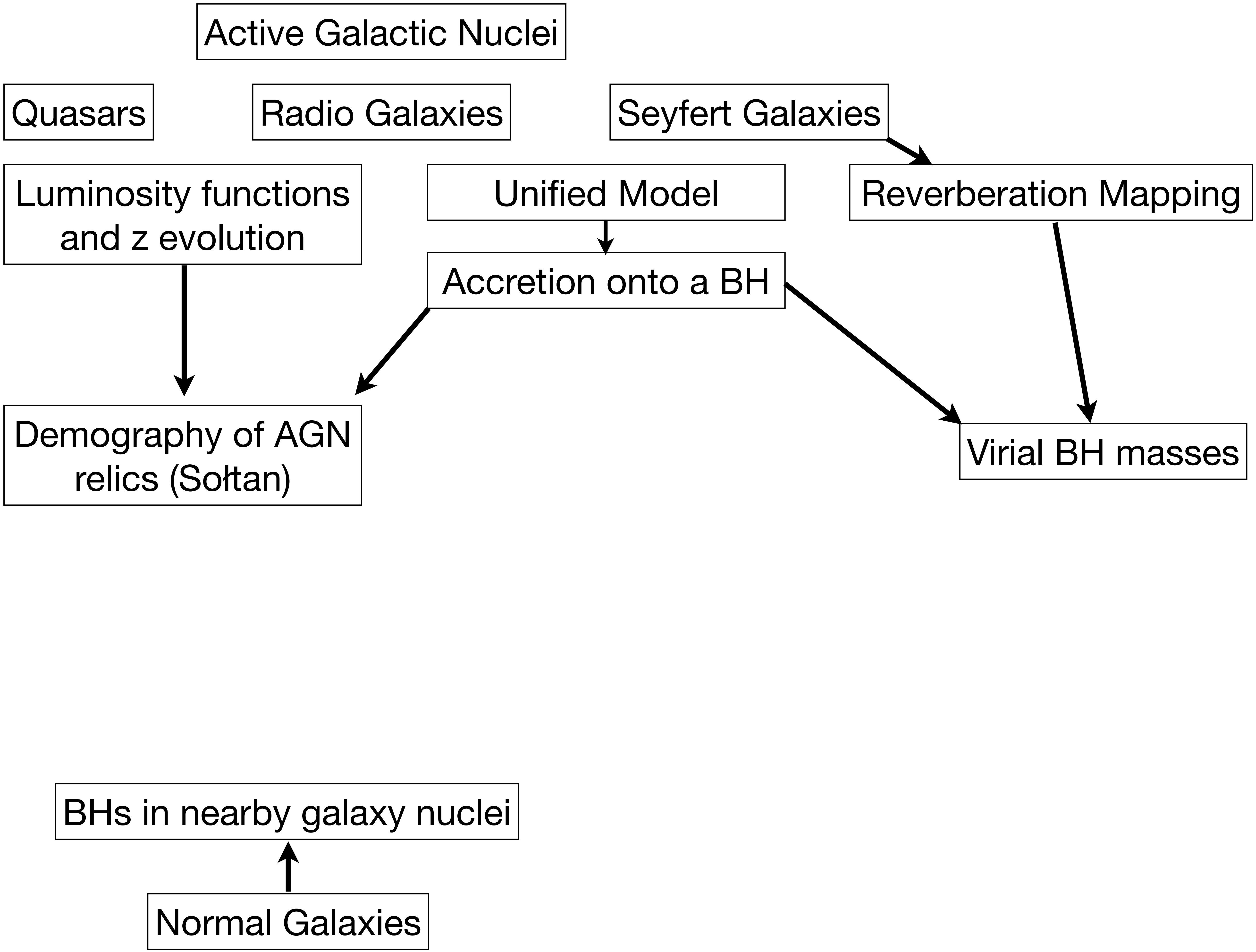
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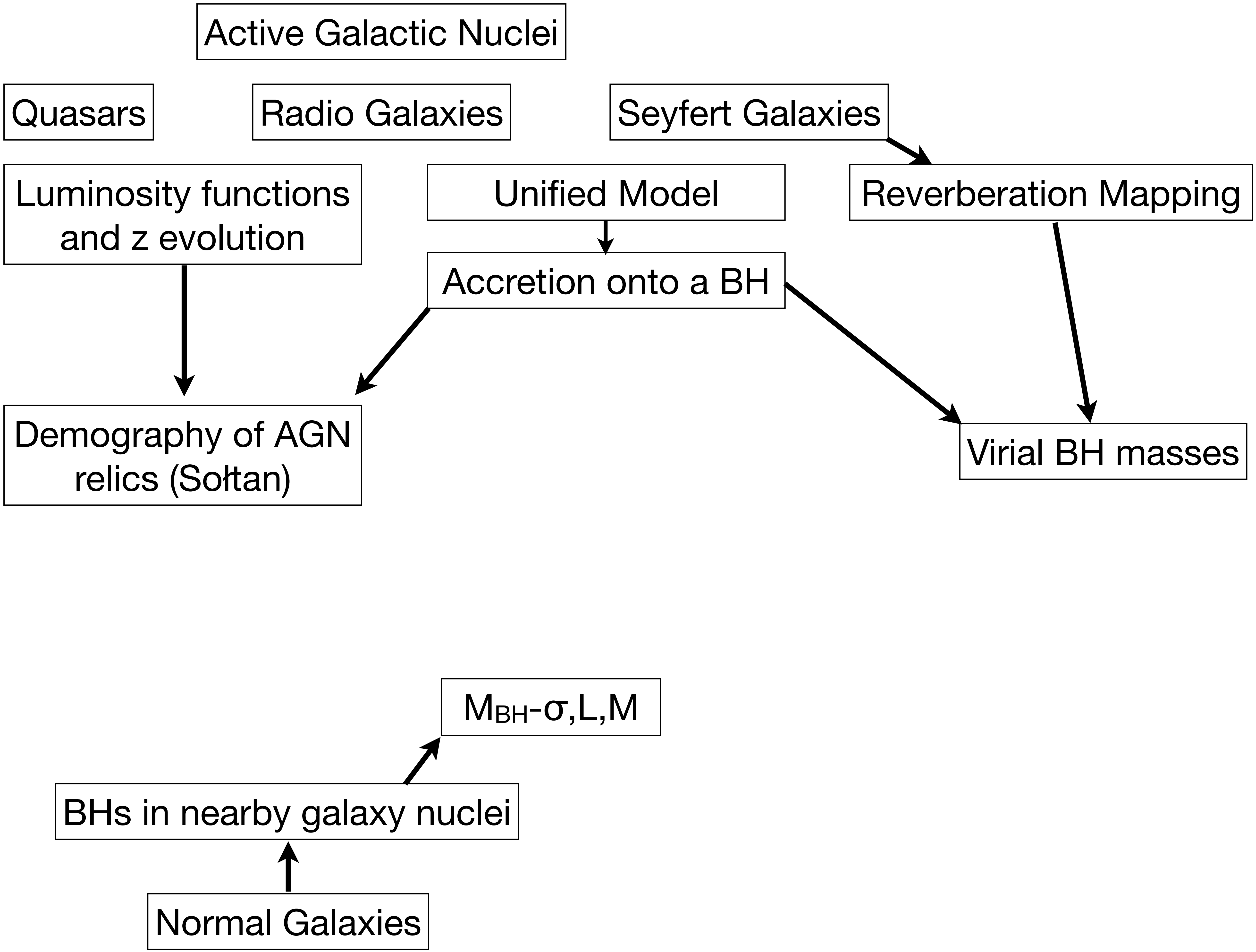
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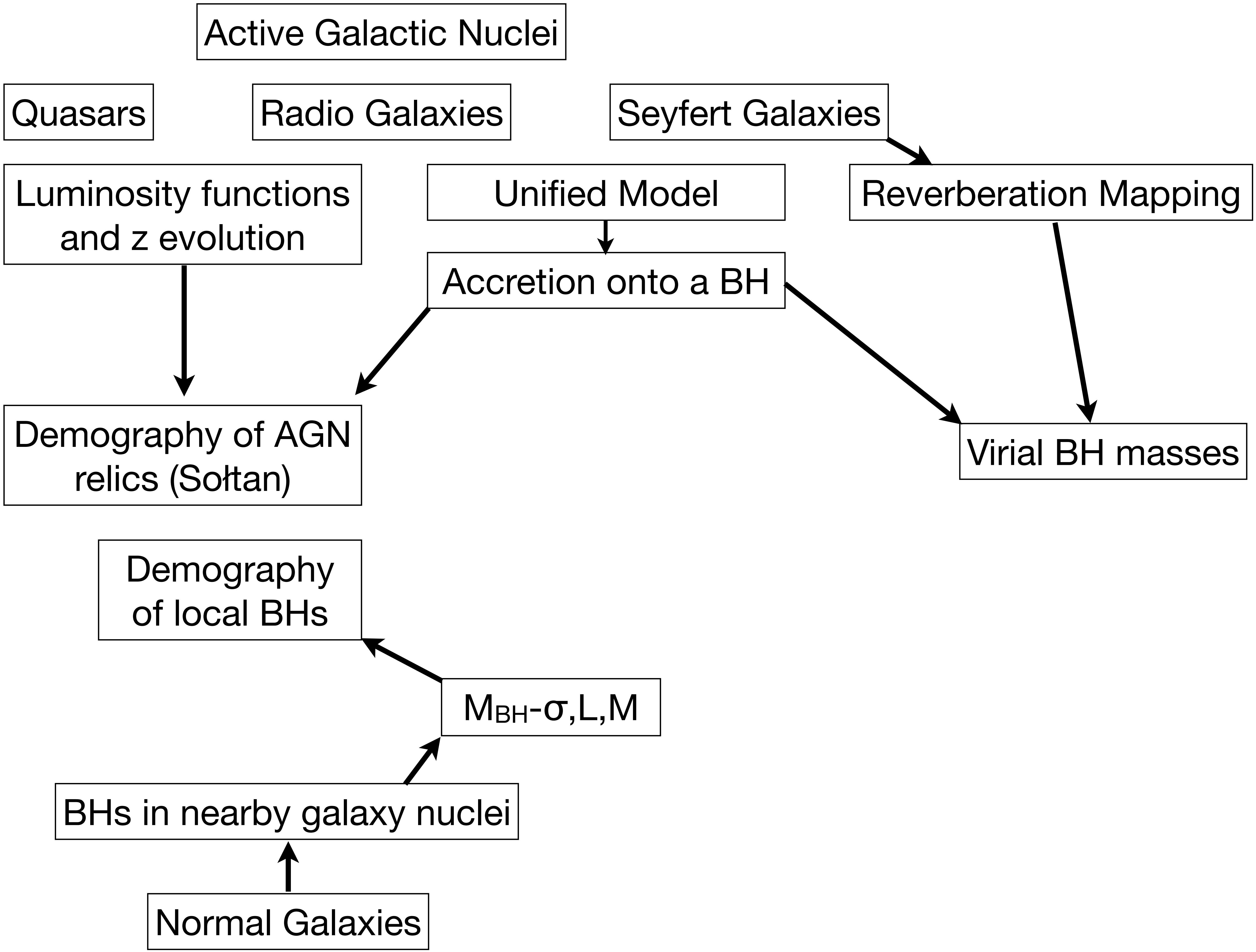
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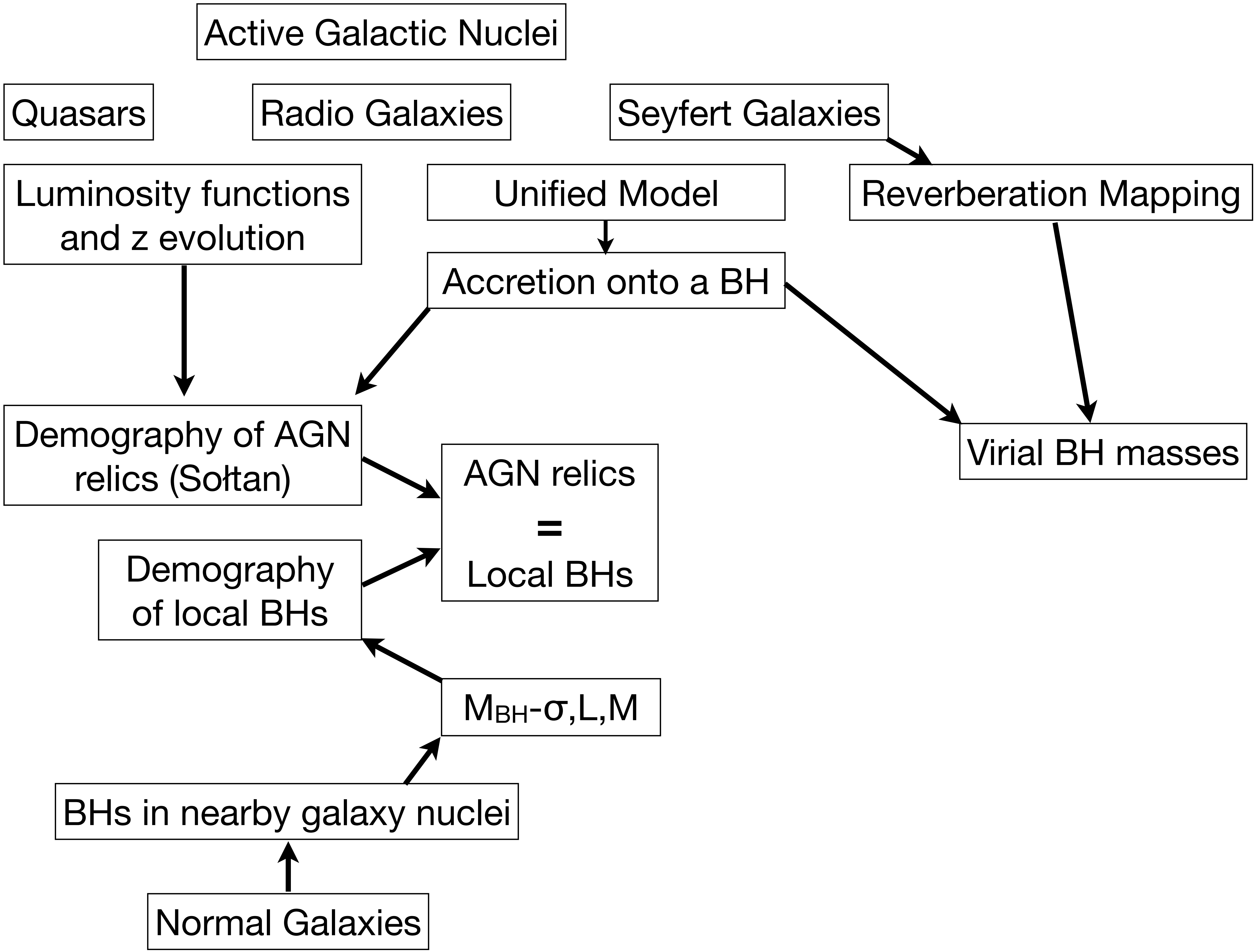

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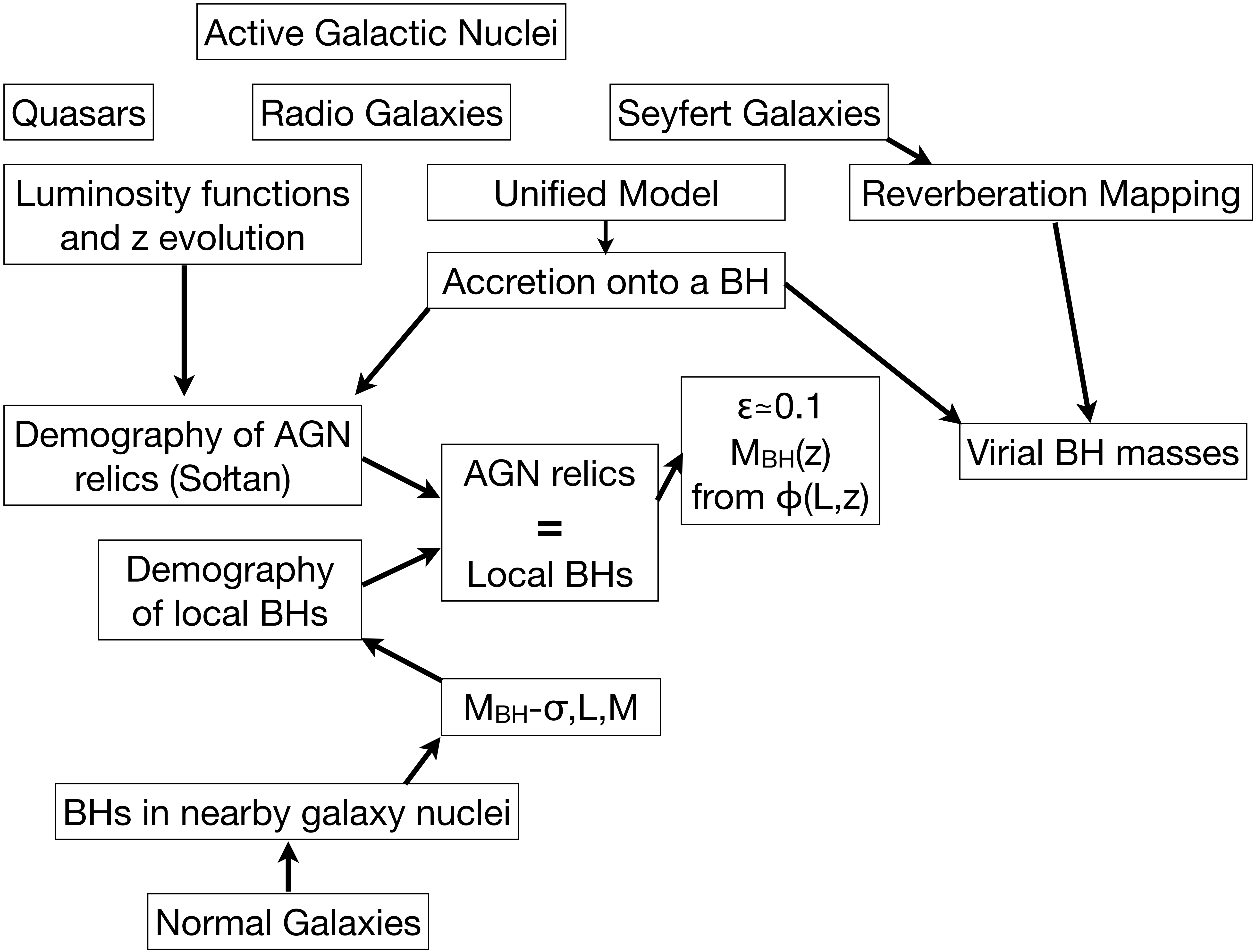
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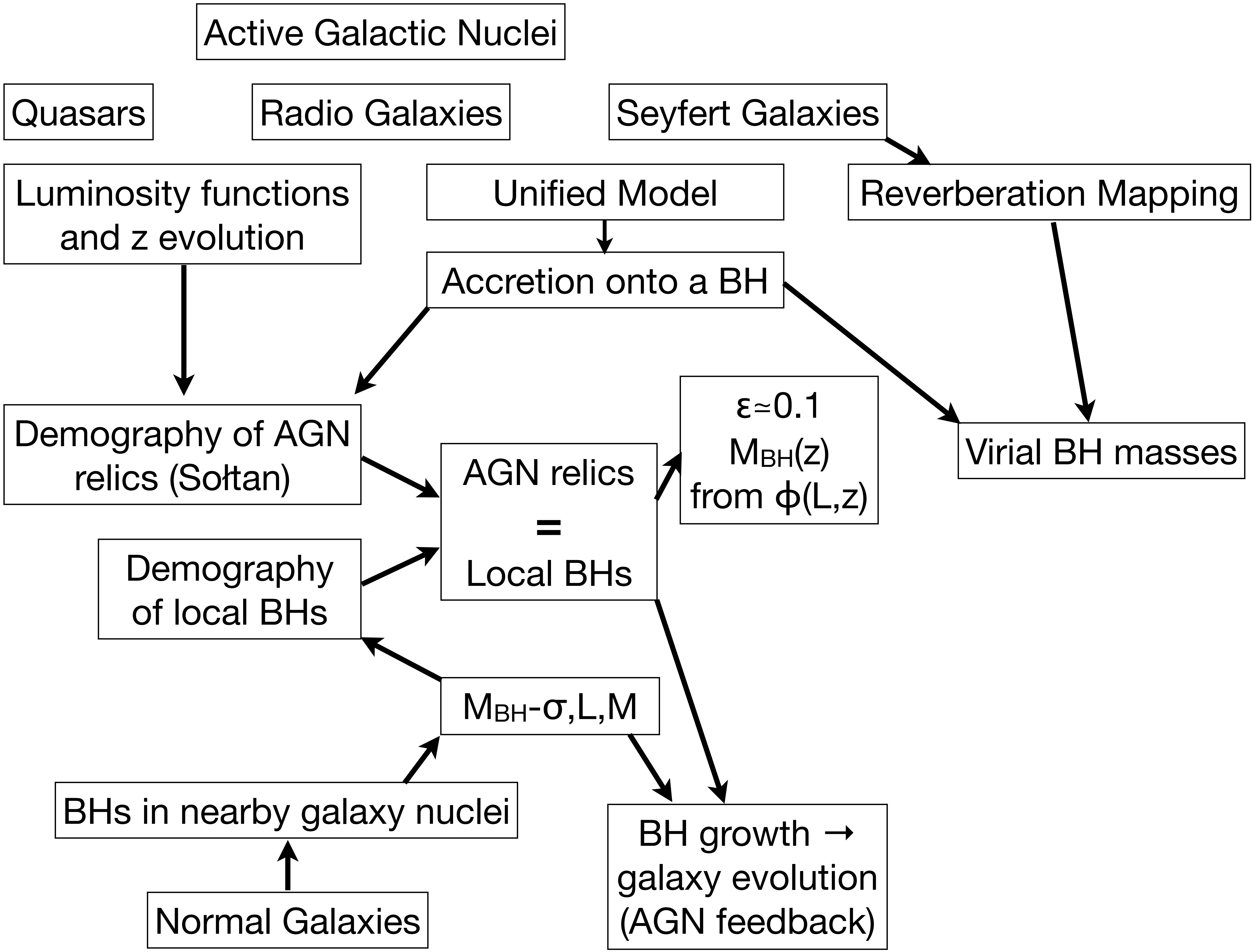

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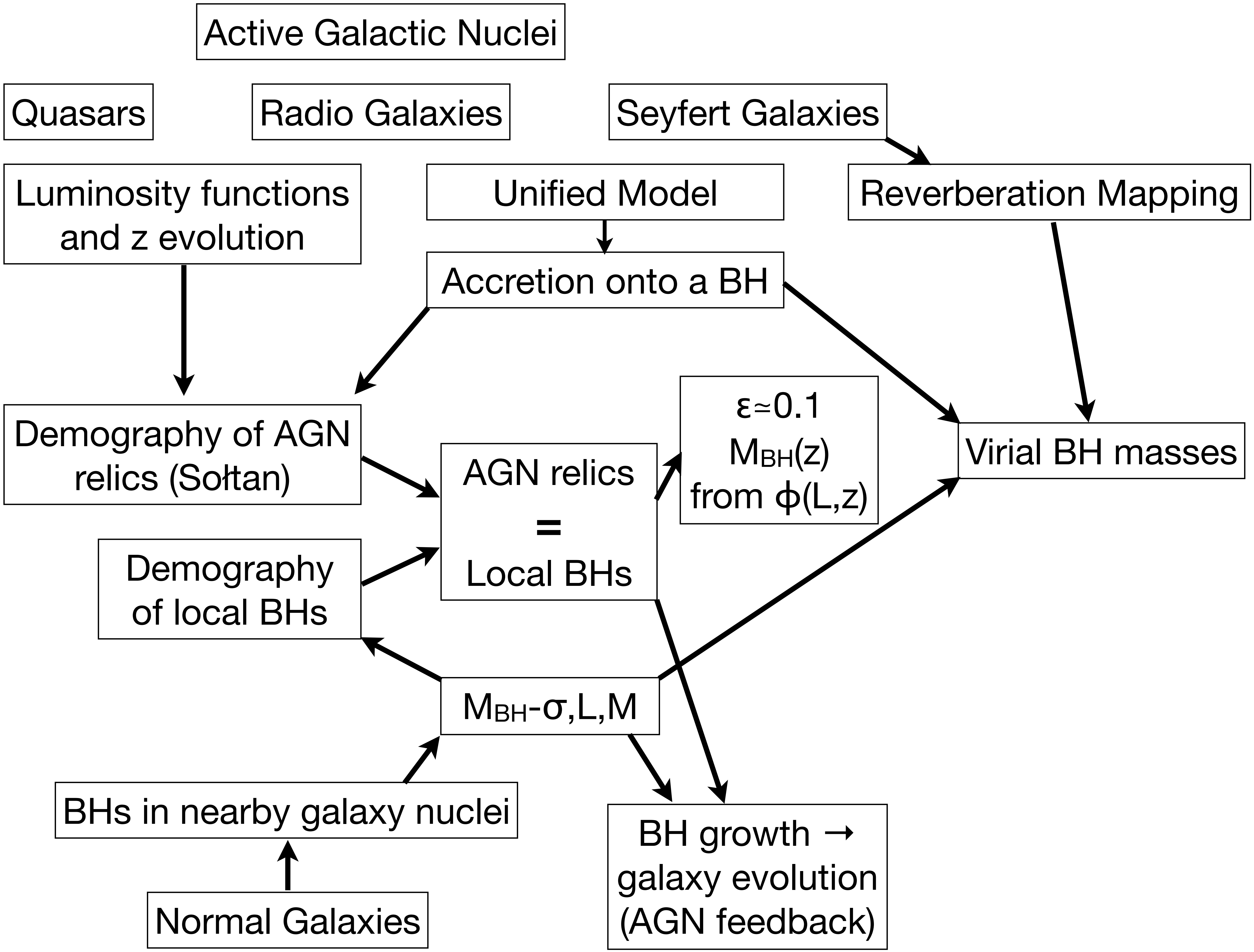

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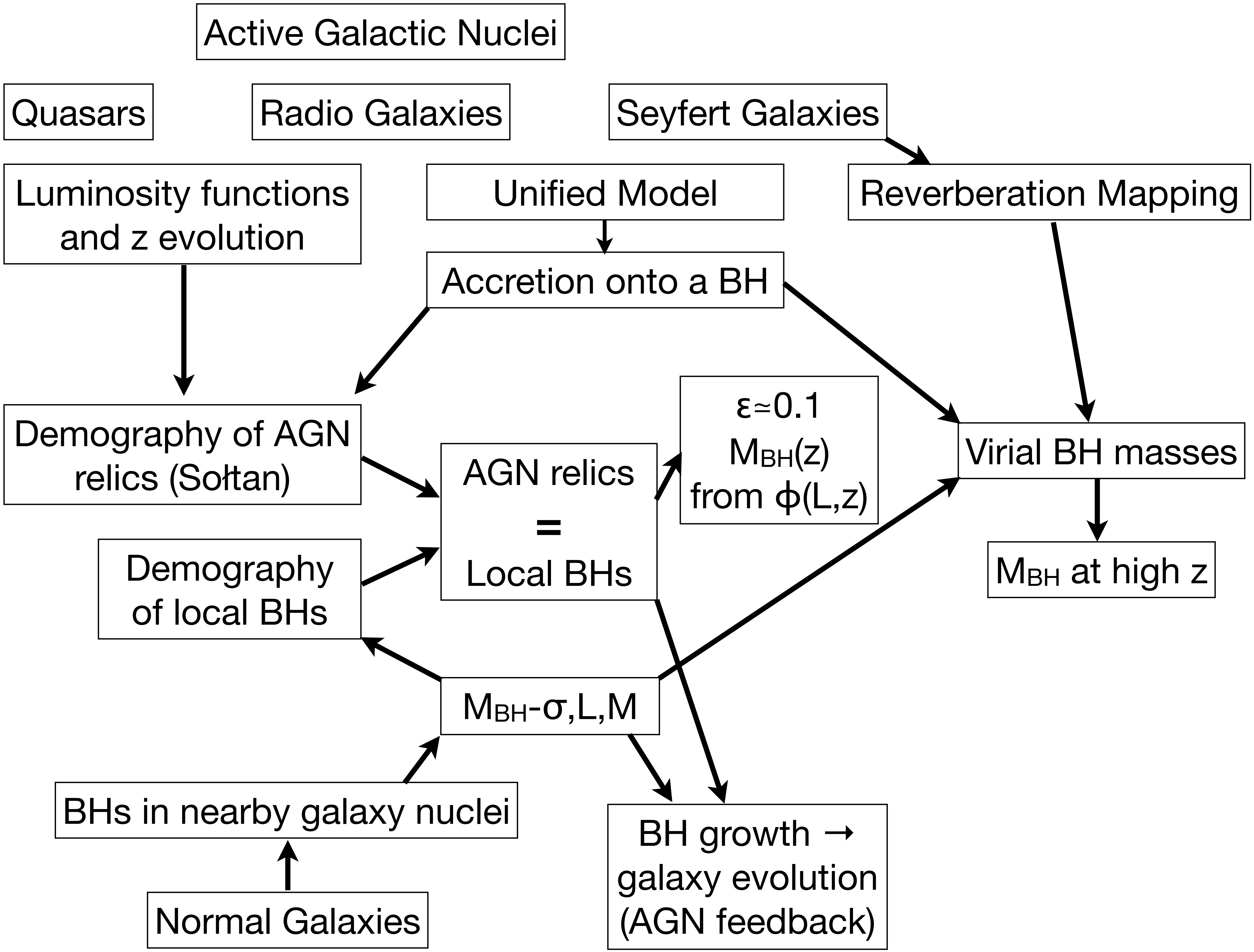
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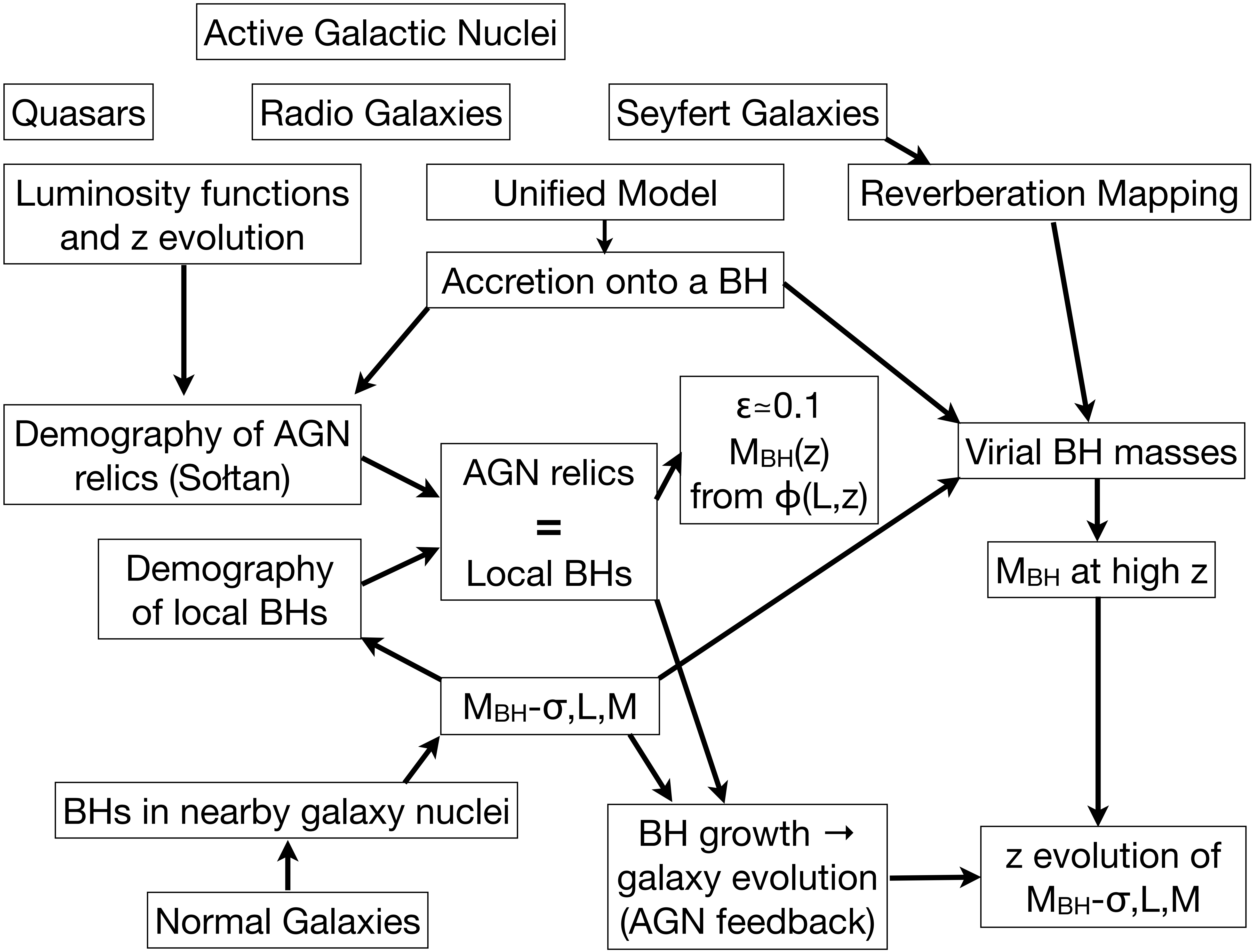
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