Unraveling the properties of active galaxies in hierarchical cosmologies

Outline

- Observational facts
- Modelling active galaxies
- Cosmic evolution of active galaxies
- Unification of active galaxies
- Spatial distribution and clustering of active galaxies

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Active Galactic Nuclei

Active Galactic Nuclei (AGN)

- Very small angular size.
- High luminosities: 10^{40}-10^{48} erg/s.
- Broad-band continuum emission: from radio to γ-rays.
- Strong emission lines.
  - Type-1: broad and narrow lines
  - Type-2: only narrow lines
- Central supermassive black hole (BH): 10^{6}-10^{10} $M_{\odot}$.

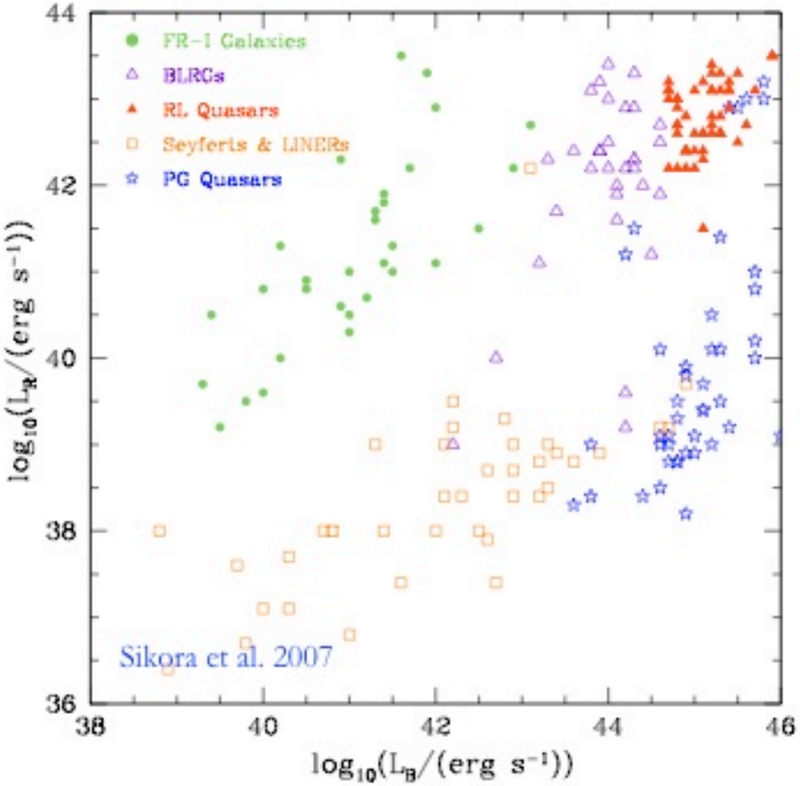
Centaurus A
NASA/CXC/SAO

AGN classification

- AGN can be divided into two classes:
  - Radio-loud objects (strong jets)

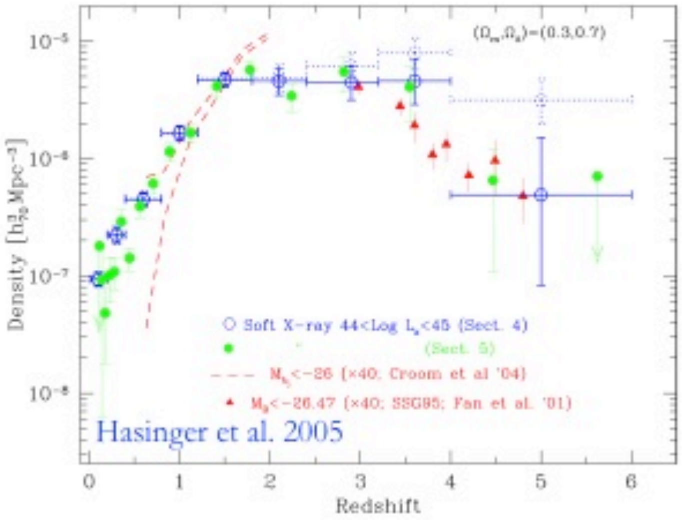
    Radio galaxies, radio-loud quasars, Faranoff-Riley type 1 & 2, BL Lac Objects (~10%)
  - Radio-quiet objects (weak/no jets).

    Radio-quiet quasars, Seyferts, LINERs (~90%)
- AGN form two distinct sequences on the $L_B - L_{Radio}$ plane:
  - Upper sequence: giant ellipticals with $M_{BH} > 10^8 M_\odot$ (radio-loud objects).
  - Lower sequence: ellipticals and spirals with $M_{BH} < 10^8 M_\odot$ (radio-quiet objects).

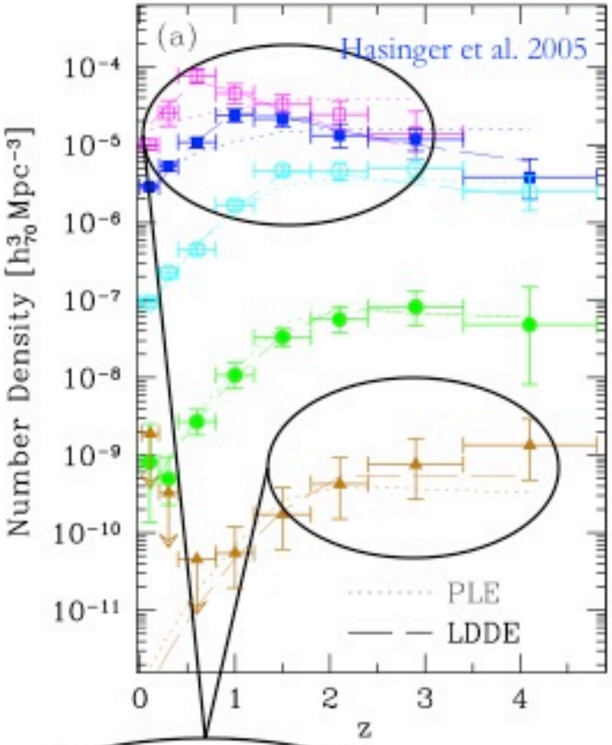


Sikora et al. 2007

AGN evolution



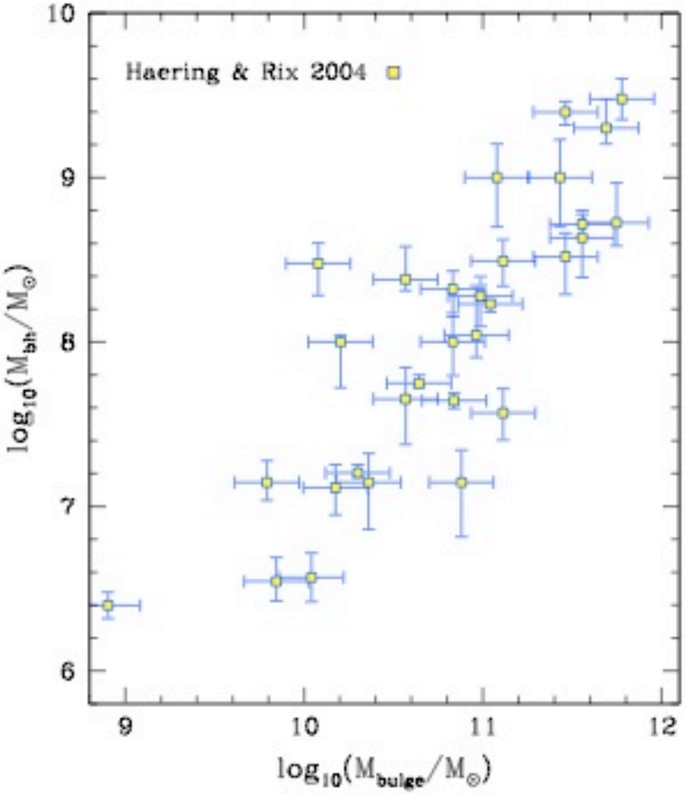
- AGN undergo significant cosmic evolution!
- The space density of AGN peaks at z~2-3, similar to the star formation rate history.
- Different luminosity populations evolve differently.



Strong differential evolution

AGN downsizing

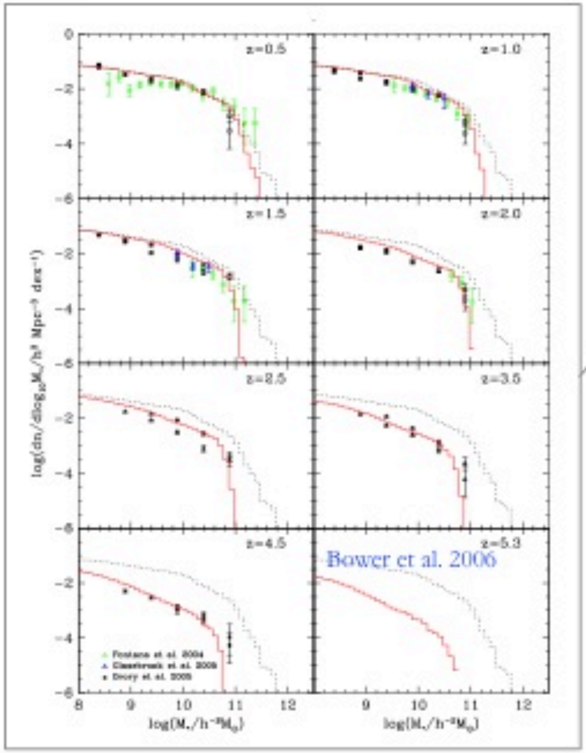
BH-host galaxy coevolution



- AGN represent a natural evolutionary stage of galaxies.
- During the AGN phase the central BH is fed with gas and grows prodigiously. (Lynden-Bell 1969)
- Despite the complicate mass assembly history at low redshifts the BH mass correlates with the mass of the host spheroid. (Marconi & Hunt 2003, Haering & Rix 2004)
- Such correlation suggests a strong link between galaxy evolution and BH growth!

Important test for galaxy formation models: reproduction of BH scaling relations and AGN phenomenology/ evolution.

A new AGN model

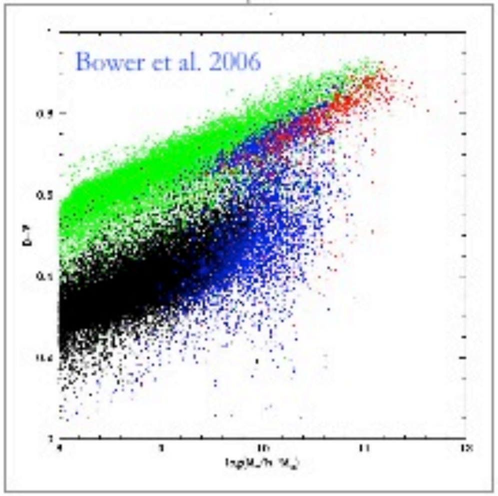


Bower et al. 2006

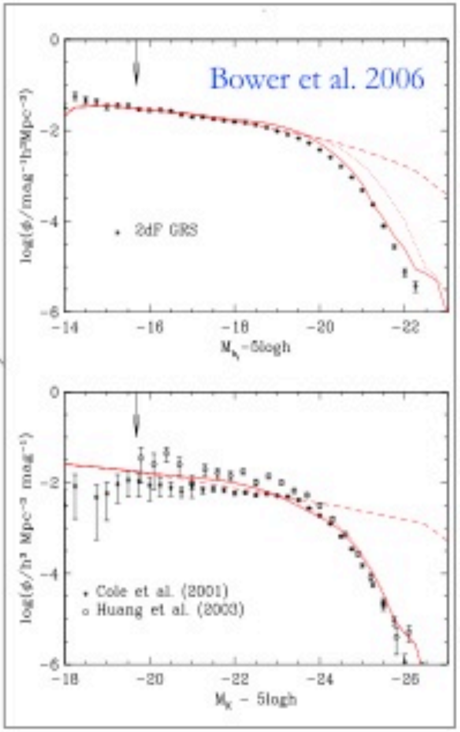
Millennium simulation
Springel et al 2005

+

GALFORM:
Cole et al. 2000
A hierarchical galaxy formation model

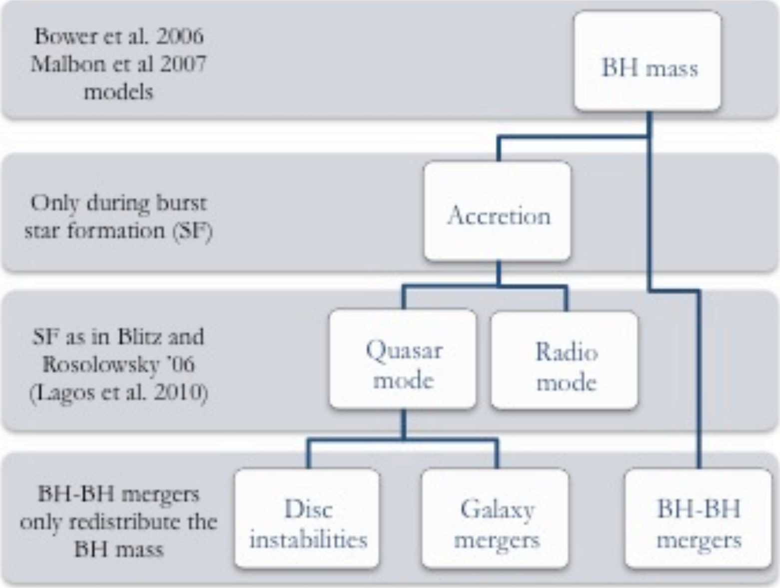


Bower et al. 2006



Bower et al. 2006

Building the BH mass



Bower et al. 2006
Malbon et al 2007
models

BH mass

Only during burst
star formation (SF)

Accretion

SF as in Blitz and
Rosolowsky '06
(Lagos et al. 2010)

Quasar mode

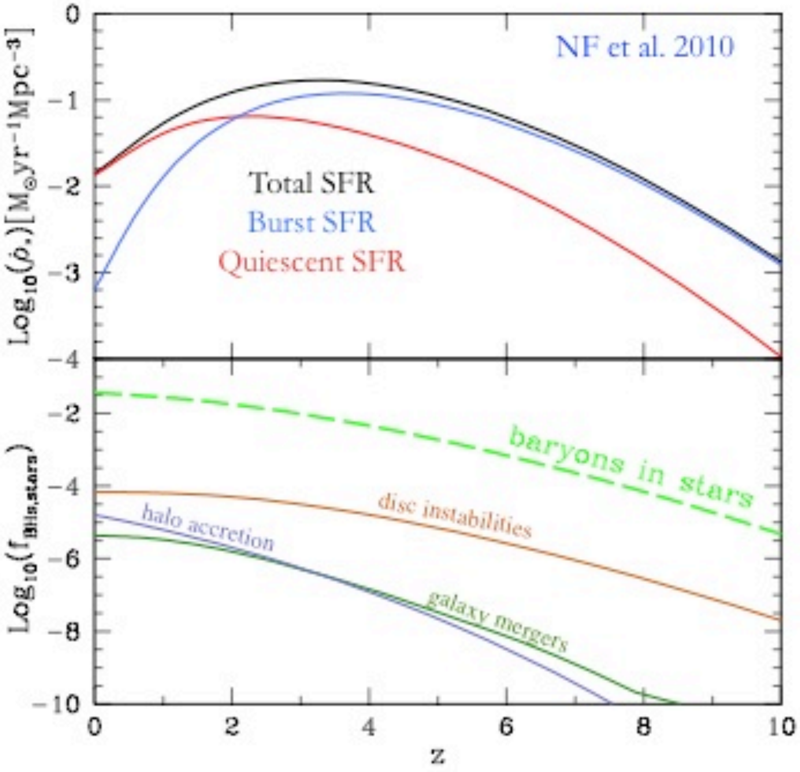
Radio mode

BH-BH mergers
only redistribute the
BH mass

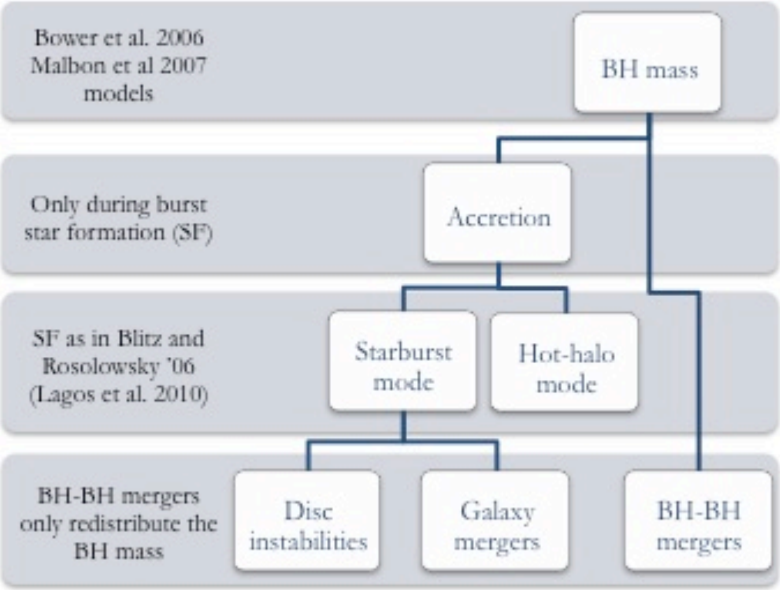
Disc instabilities

Galaxy mergers

BH-BH mergers



Building the BH mass



Bower et al. 2006
Malbon et al 2007
models

BH mass

Only during burst star formation (SF)

Accretion

SF as in Blitz and Rosolowsky '06 (Lagos et al. 2010)

Starburst mode

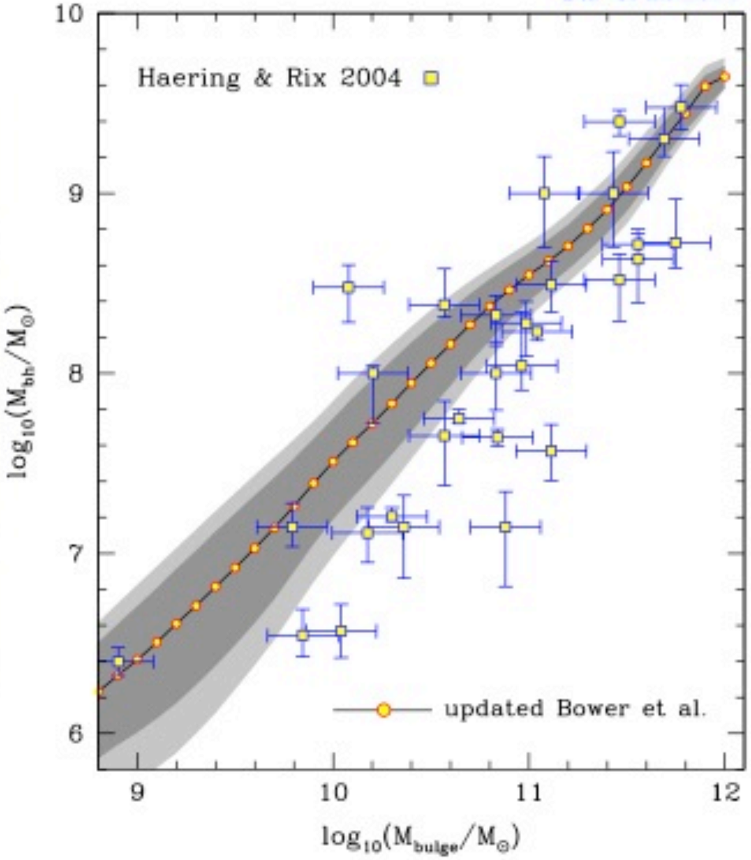
Hot-halo mode

BH-BH mergers only redistribute the BH mass

Disc instabilities

Galaxy mergers

BH-BH mergers



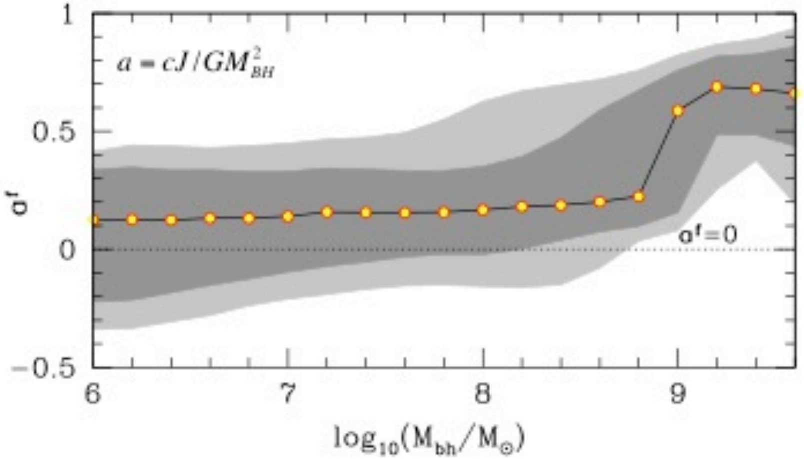
NF et al. 2011

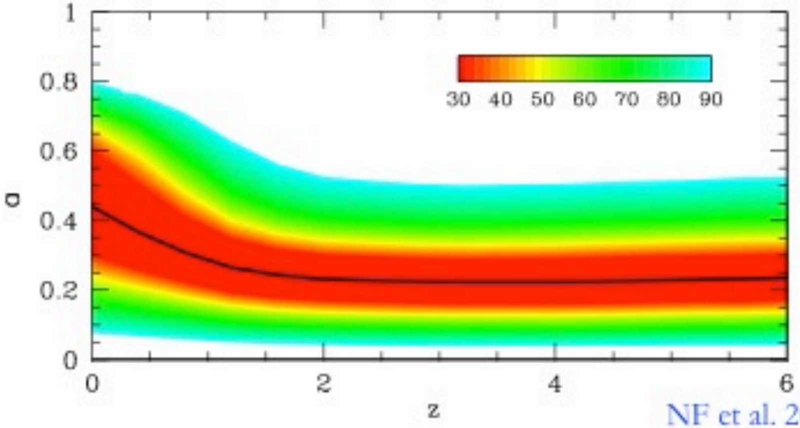
BH spin evolution

Gas accretion is episodic and random.

As a result the net spin is kept low!

BH-BH mergers, however, have the opposite effect!

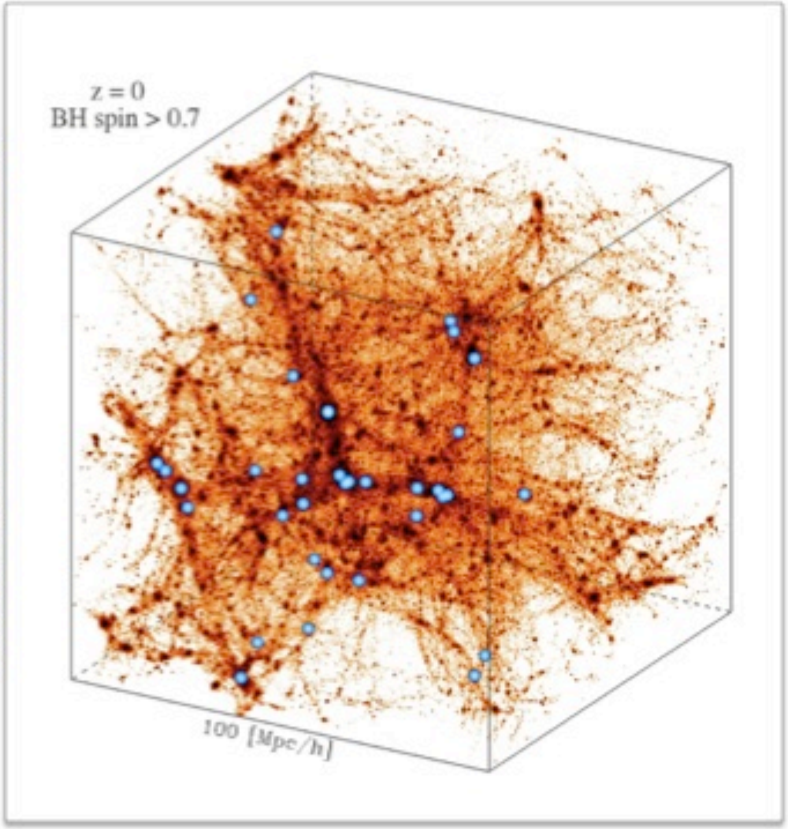


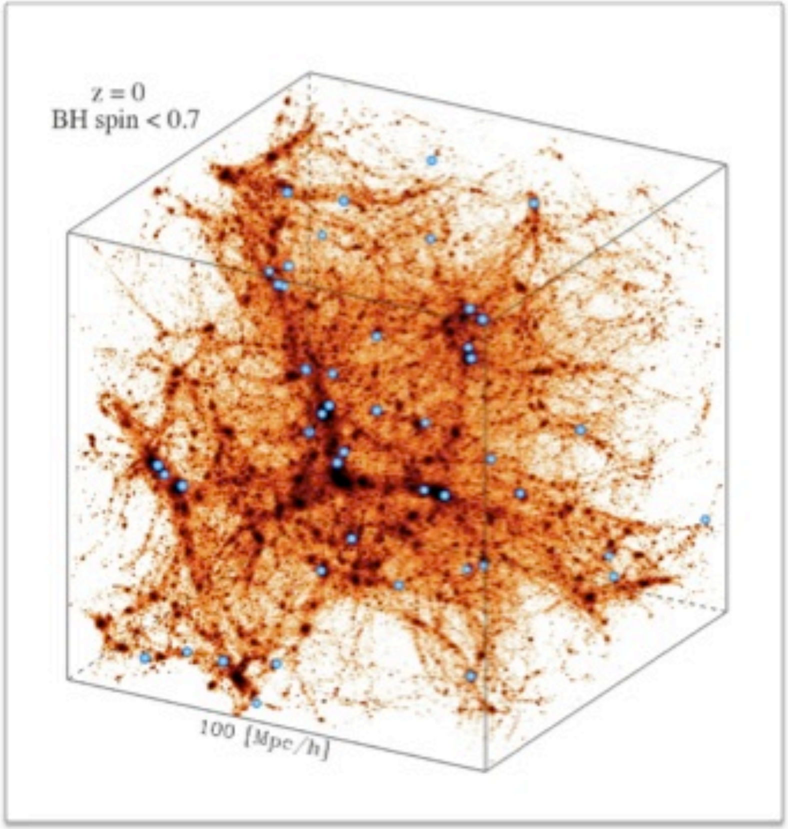


NF et al. 2010

Spinning BHs in the Millennium simulation

Millennium simulation, Springel et al. 2005





NF et al. 2010

Modelling the active nucleus

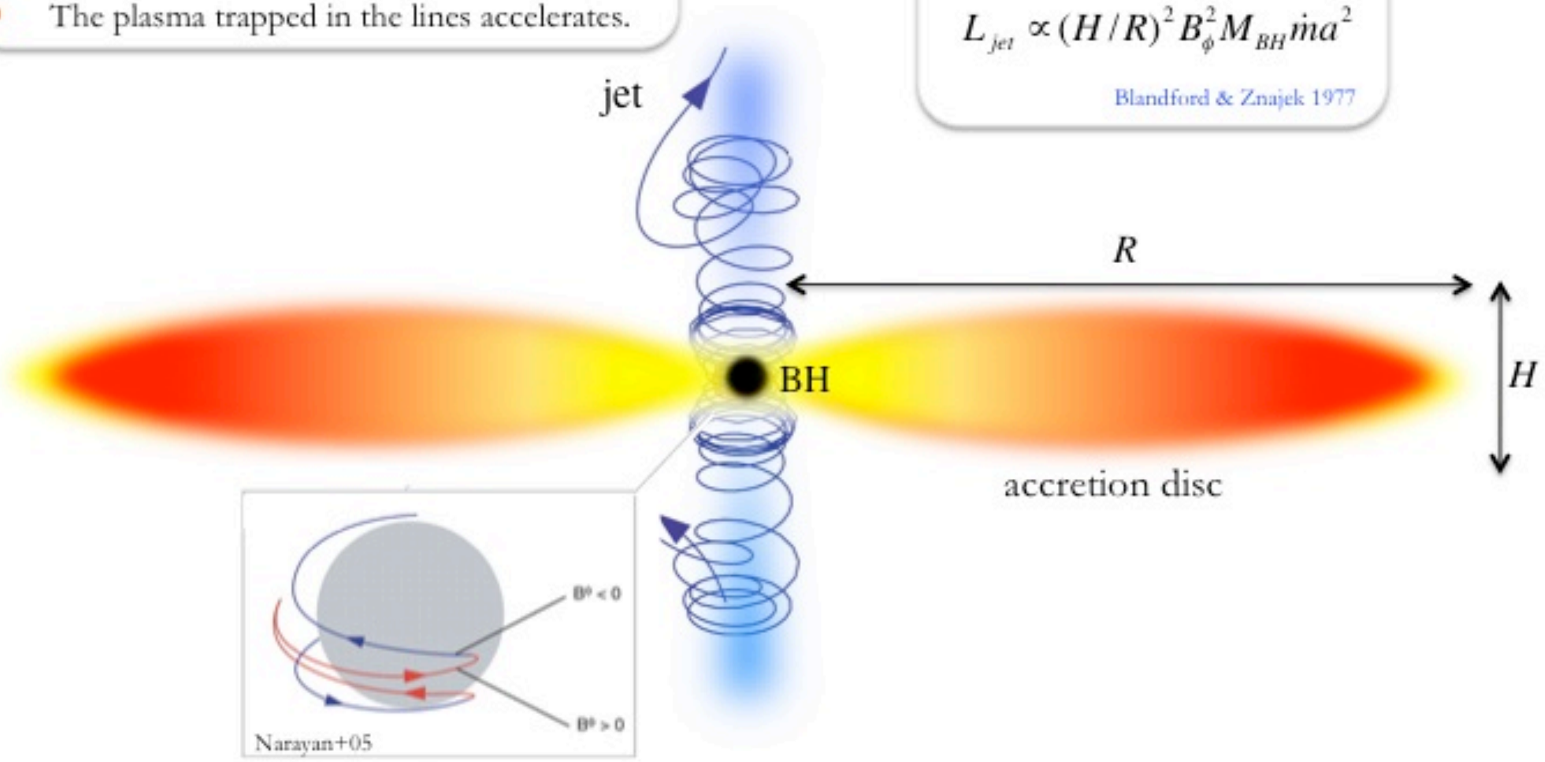
Jet formation

- The magnetic lines twist and collimate.
- The jet removes energy from the BH.
- The plasma trapped in the lines accelerates.

The jet power is proportional to the square of BH spin:

$$L_{jet} \propto (H/R)^2 B_\phi^2 M_{BH} \dot{m} a^2$$

Blandford & Znajek 1977

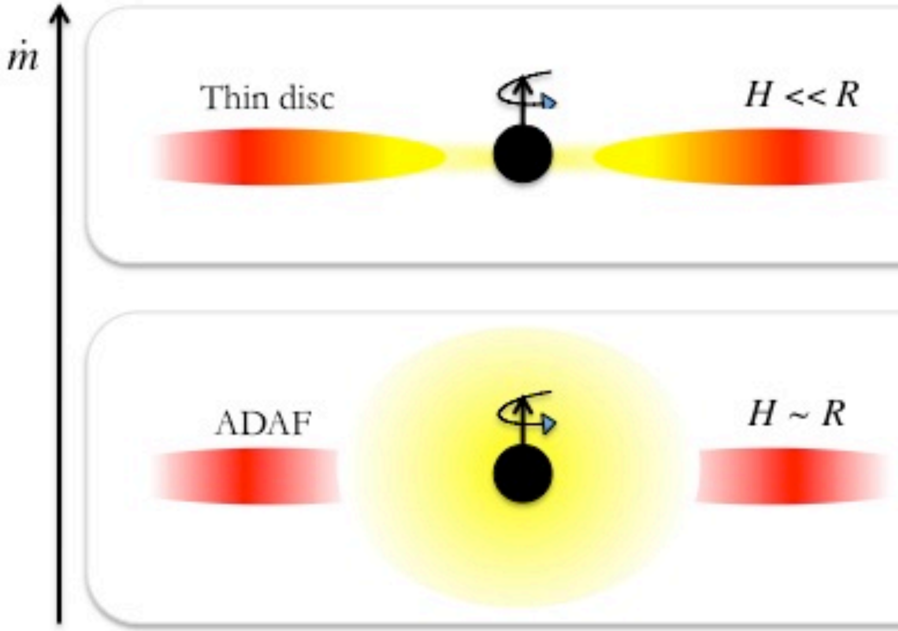


Narayan+05

Modelling the active nucleus

The geometry of the accretion flow depends on the accretion rate!

Done, Gierliński & Kubota 2007



$\dot{m} = \dot{M} / \dot{M}_{Edd} > 0.01 \rightarrow$ Thin disc

- Disc $\rightarrow L_{bol,TD} = \varepsilon M_{BH} \dot{m}\ c^2$
- Jet $\rightarrow L_{jet,TD} = 7.9 \times 10^{35} M_{BH}^{1.1} \dot{m}^{1.2} a^2$

$\dot{m} = \dot{M} / \dot{M}_{Edd} < 0.01 \rightarrow$ Thick disc

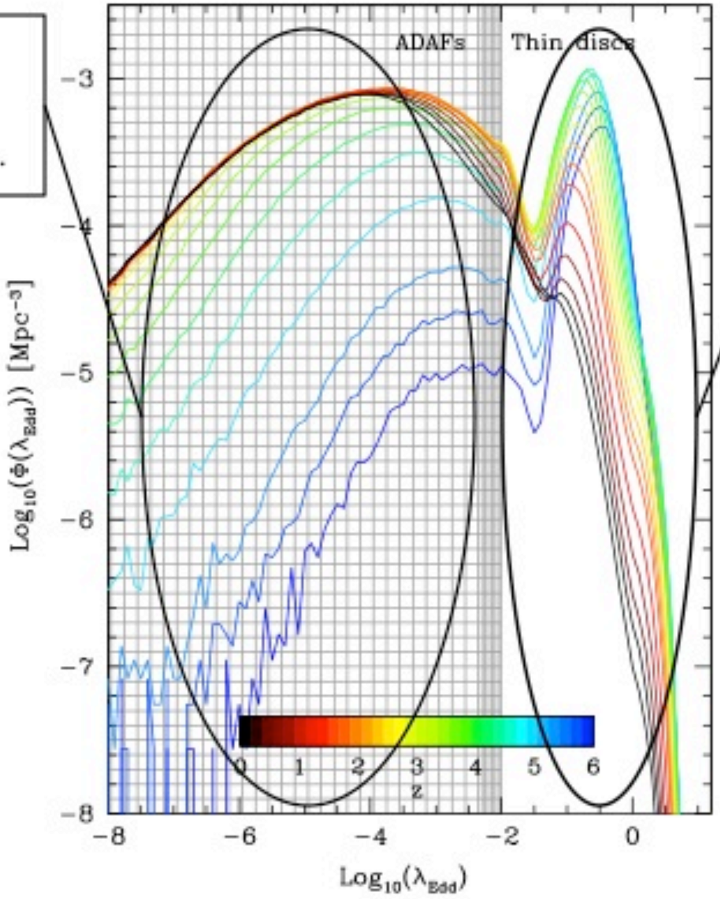
- Disc $\rightarrow L_{bol,ADAF} \propto M_{BH} \dot{m}^2$
- Jet $\rightarrow L_{jet,ADAF} = 2 \times 10^{38} M_{BH} \dot{m} a^2$

L_{bol} is limited to $L_{bol} = L_{edd}(1 + \ln \dot{m})$ for super-Eddington flows

NF et al., 2011

The bimodal distribution of λ ($L_{\mathrm{disc}}/L_{\mathrm{Edd}}$)

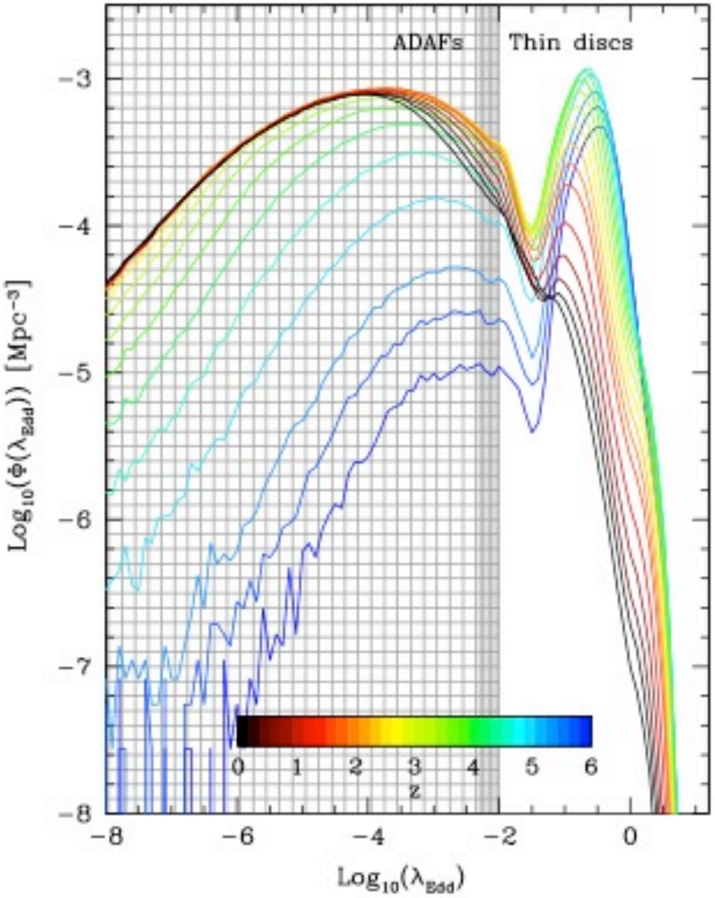
- Low disc luminosities.
- Accretion primarily during the hot-halo mode.

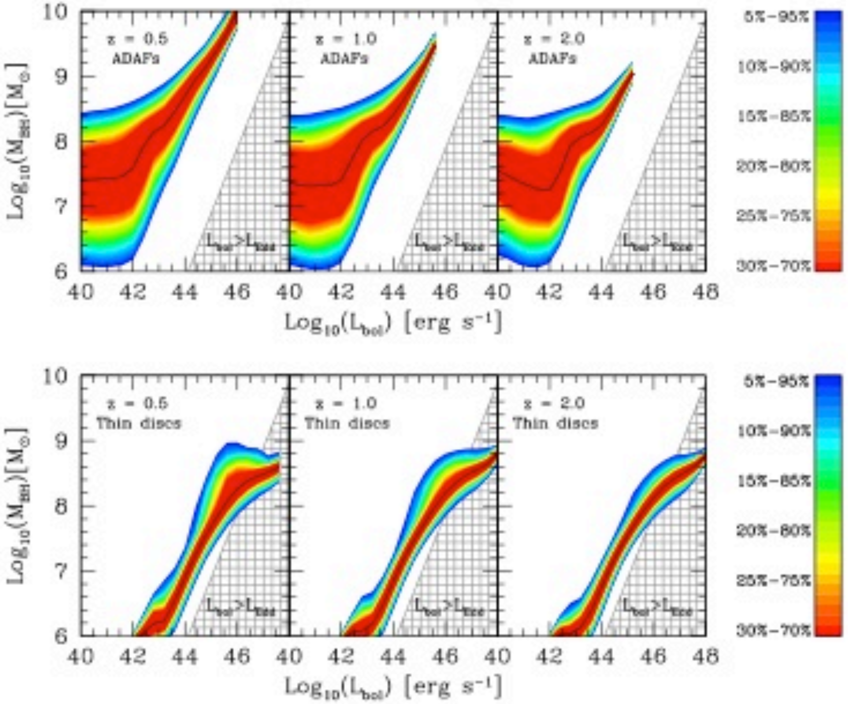


- High disc luminosities.
- Accretion exclusively during the starburst mode.

NF et al. 2010

The bimodal distribution of λ ($L_{\rm disc}/L_{\rm Edd}$)



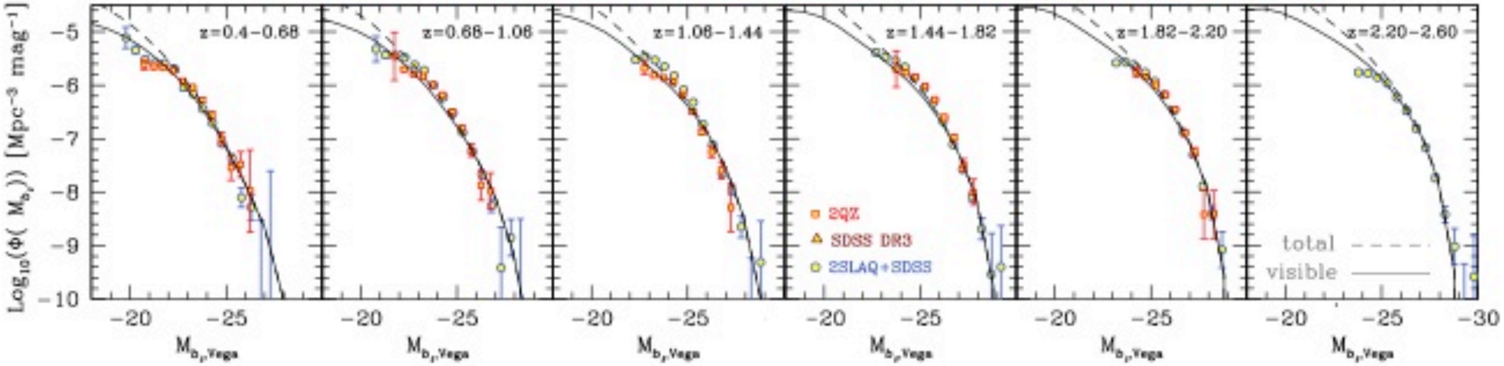


NF et al. 2010

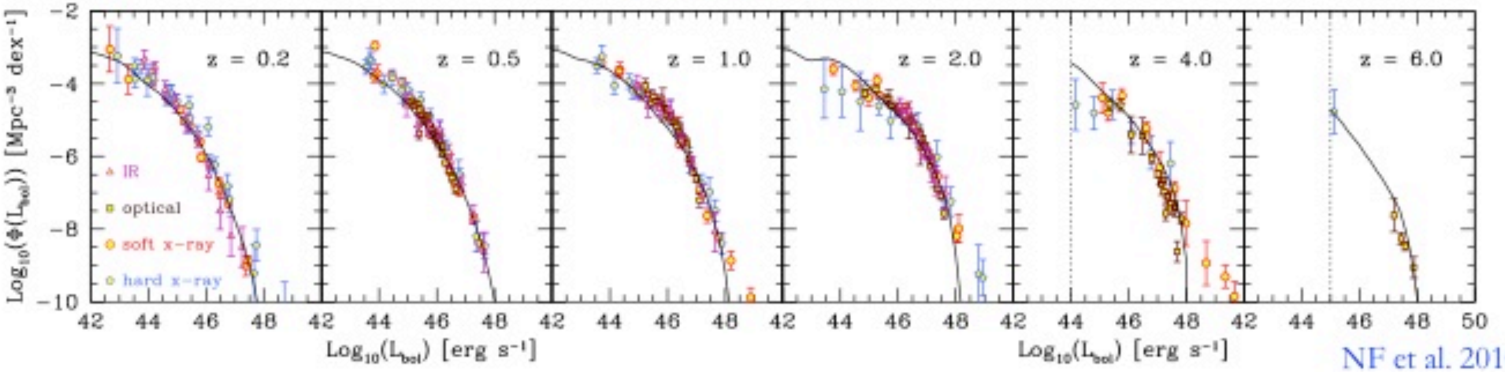
Quasar luminosity functions

Optical

AGN are strongly obscured in the optical (and soft X-rays): $f_{obsc}=f_{obsc}(z,L)$



Bolometric

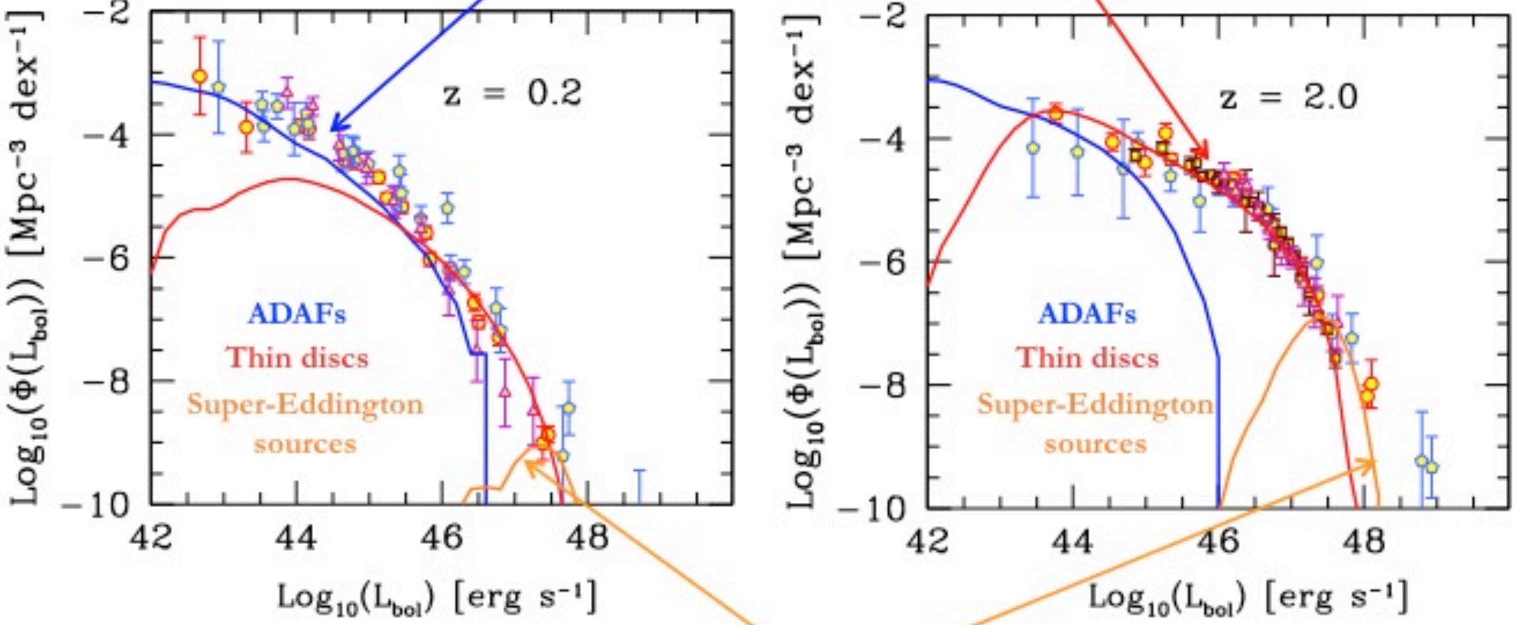


NF et al. 2010

Quasar luminosity functions

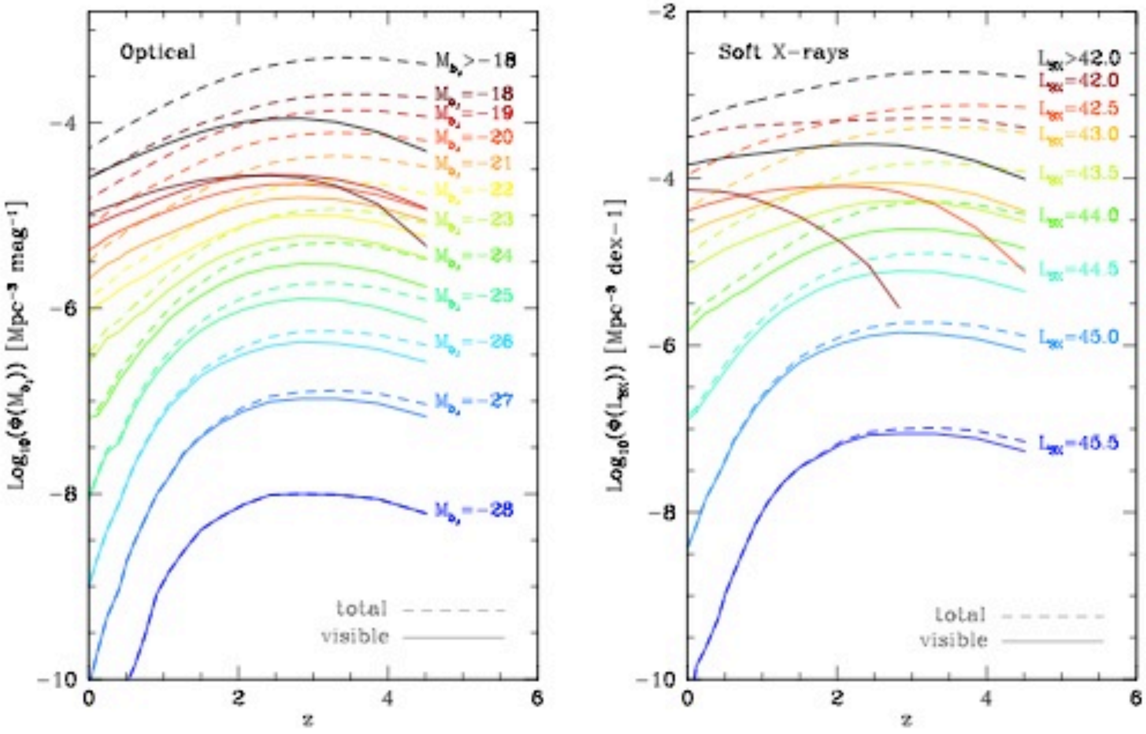
ADAFs dominate the faint end at low z's: massive BHs with low acc. rates!

Thin discs dominate at high z's: rapidly growing BHs!



Super-Eddington quasars become more numerous with increasing z's: cold gas more abundant at high z's!

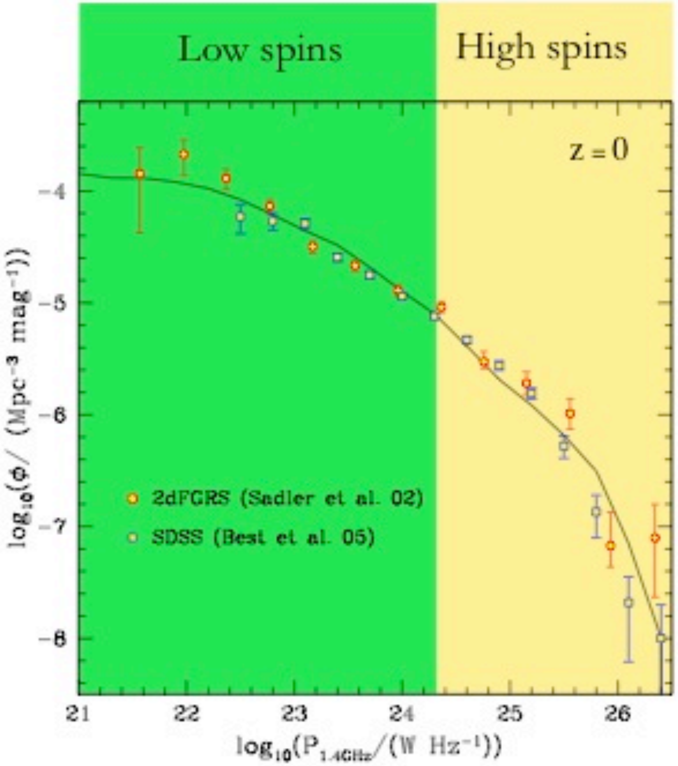
AGN downsizing



- The differential growth of the density of faint and bright AGN indicates downsizing.
- The density of faint AGN peaks at lower redshift (z<2) than that of bright AGN (z~2-3) due to the obscuration.

NF et al. 2010

The radio luminosity function



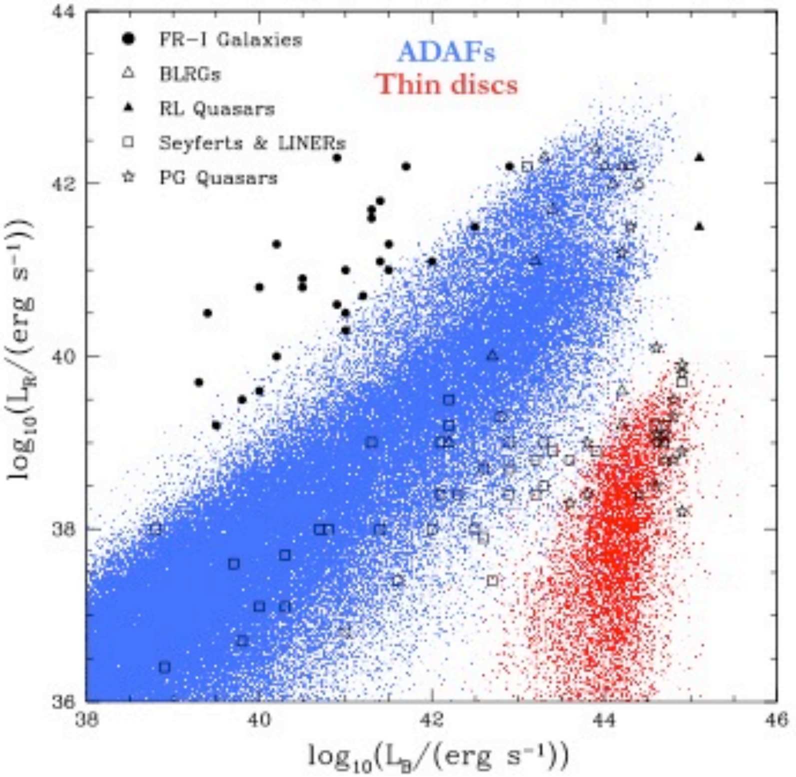
- Calculation of the radio output using the fundamental plane. (Merloni et al. 2003)
- The model gives a good fit to the data when:

  low mass BHs have low spins.

  high mass BHs have high spins.

NF et al. 2011

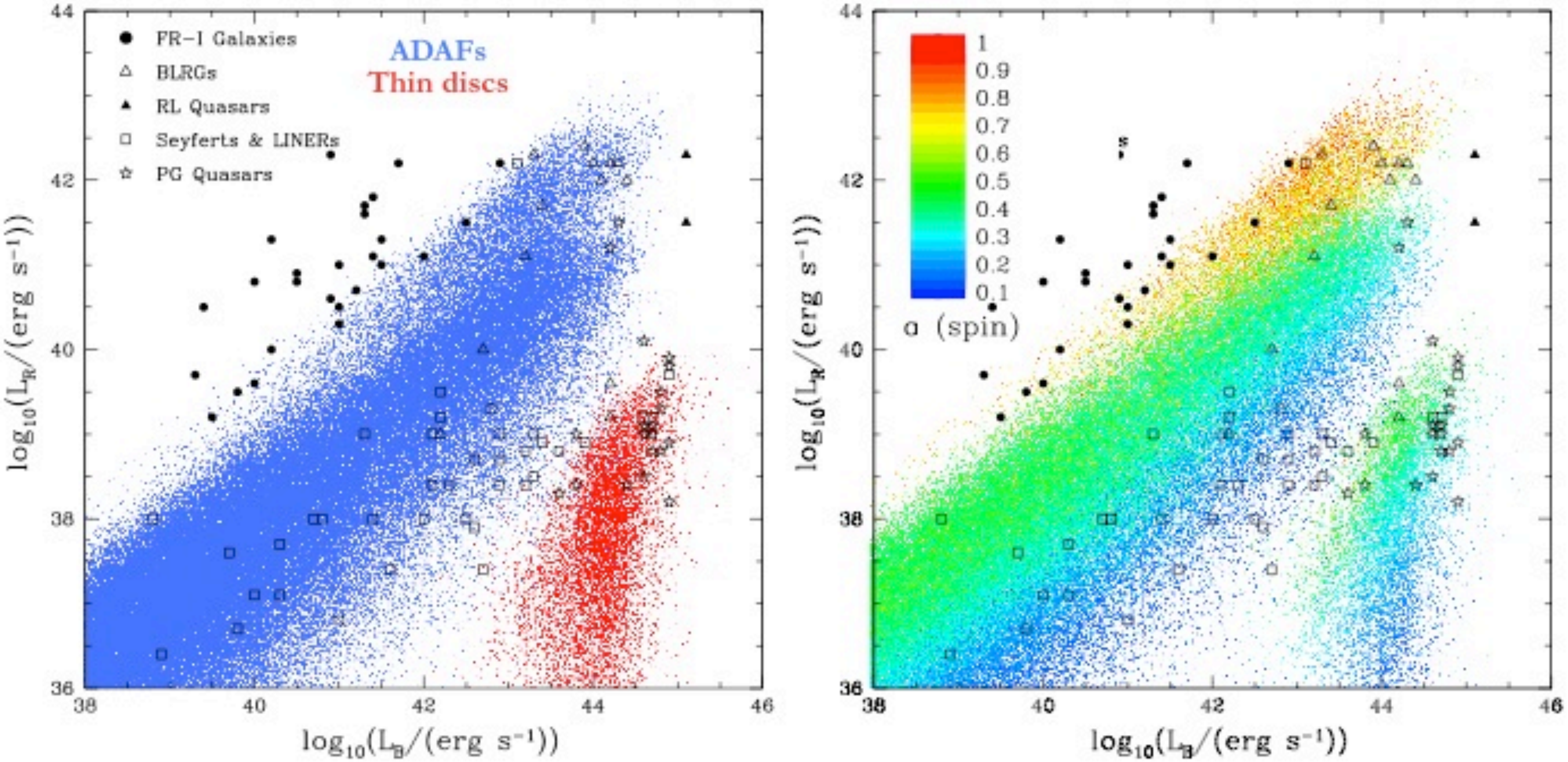
Radio vs. optical AGN plane



- FR-I, Radio galaxies, LINERs (and some Seyferts) are powered by ADAFs.
- The most radio-loud sources host rapidly rotating $>10^8\ M_\odot$ BHs.
- Seyferts and quasars are powered by thin discs.
- These AGN exhibit a variety of BH masses ($<10^9\ M_\odot$) and spins.

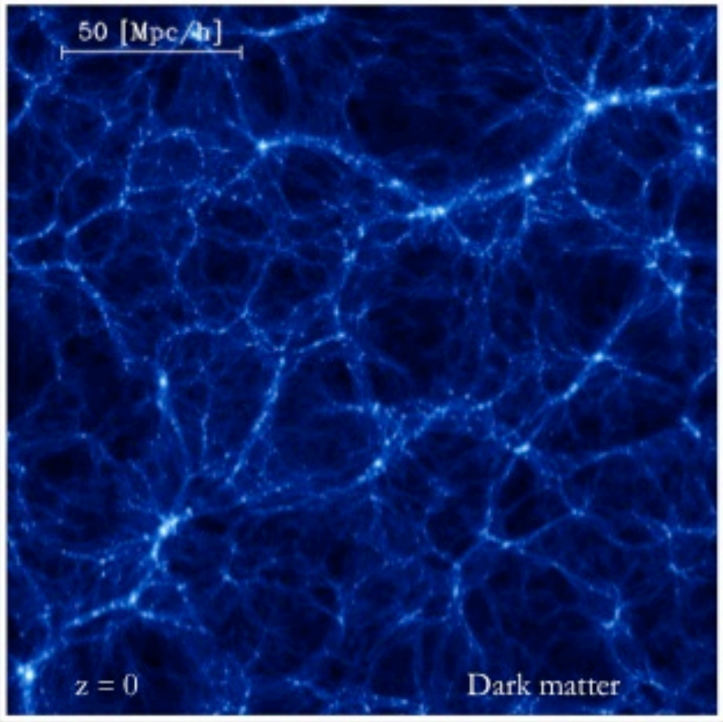
NF et al. 2011

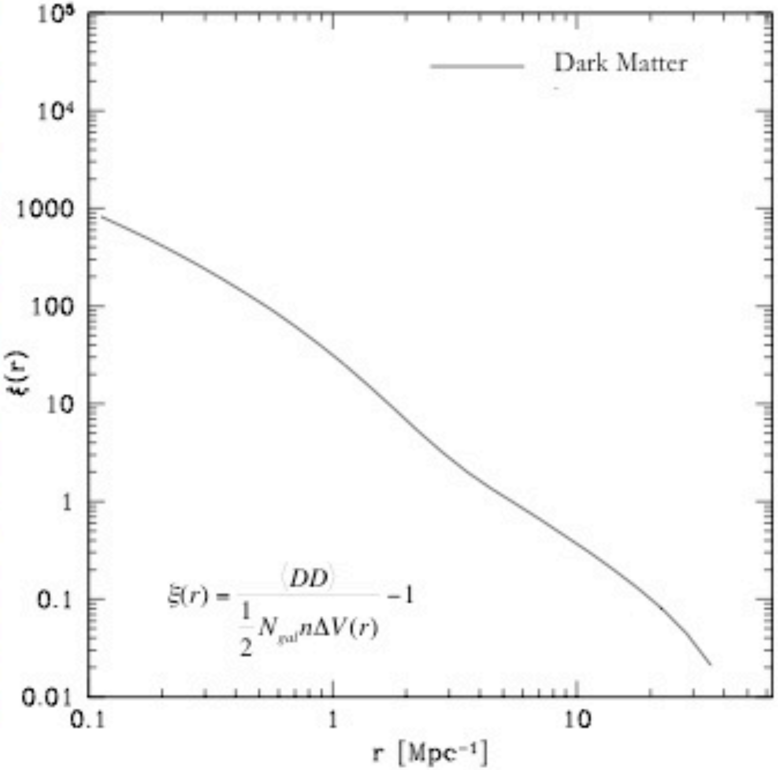
Radio vs. optical AGN plane



NF et al. 2011

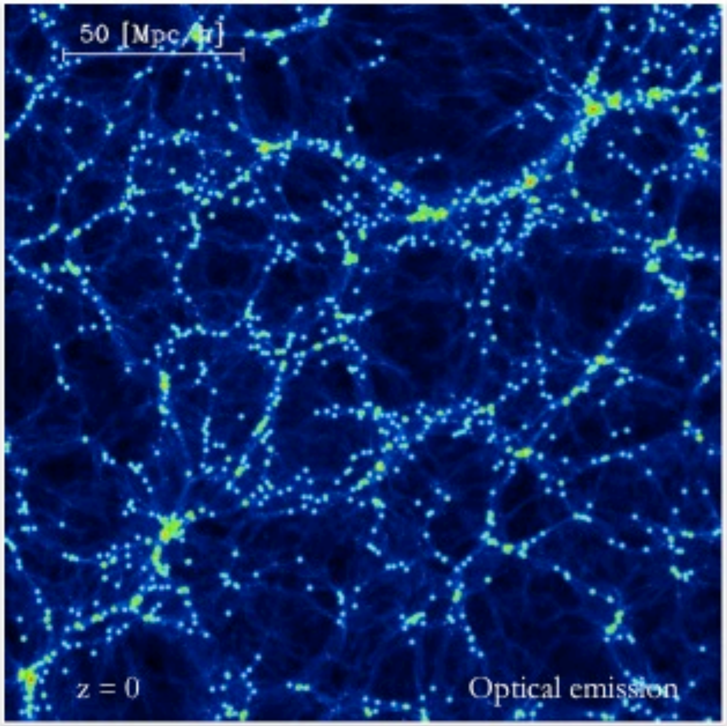
The clustering of AGN

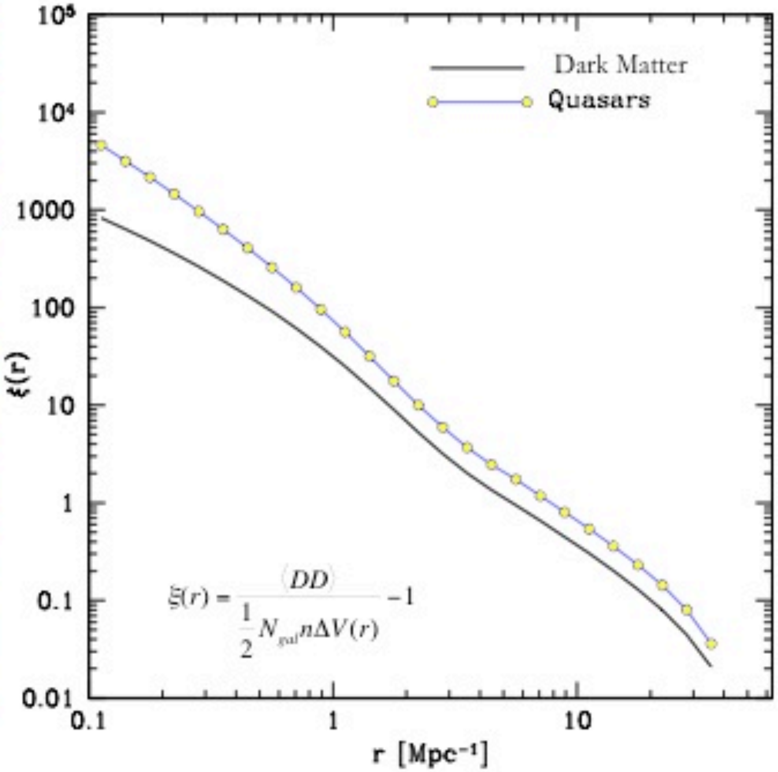




NF et al., in prep.

The clustering of AGN

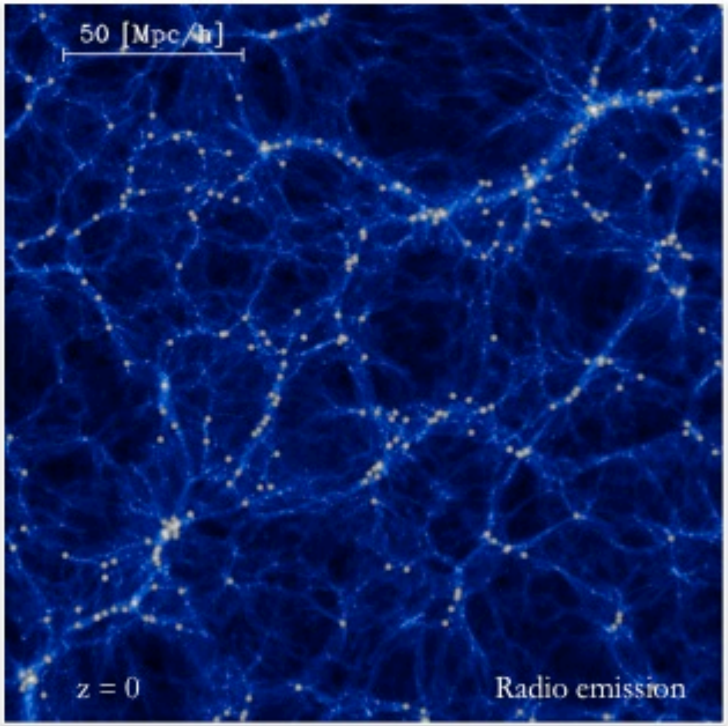


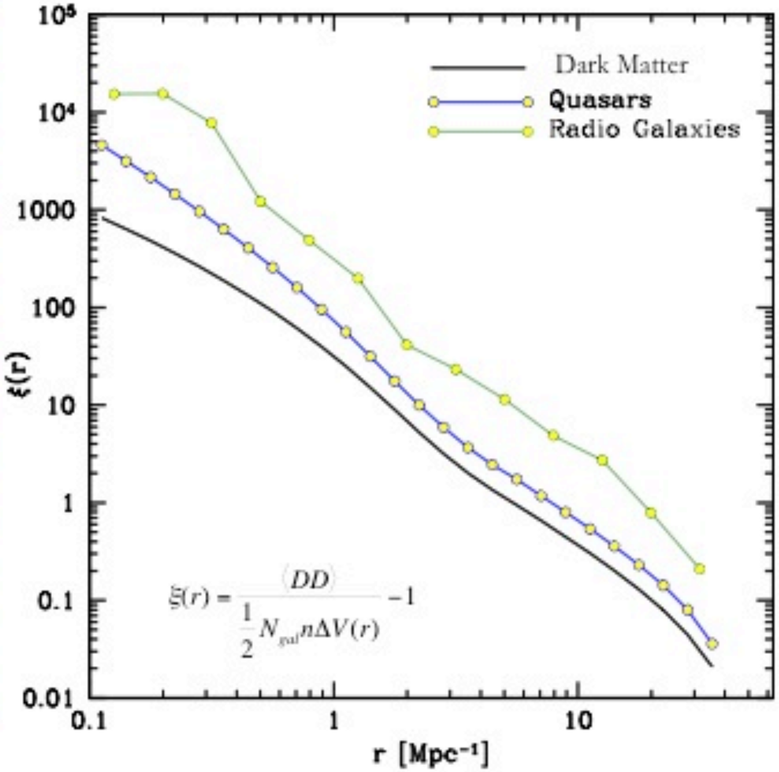


$$\xi(r) = \frac{\langle DD \rangle}{\frac{1}{2} N_{gal} n \Delta V(r)} - 1$$

NF et al., in prep.

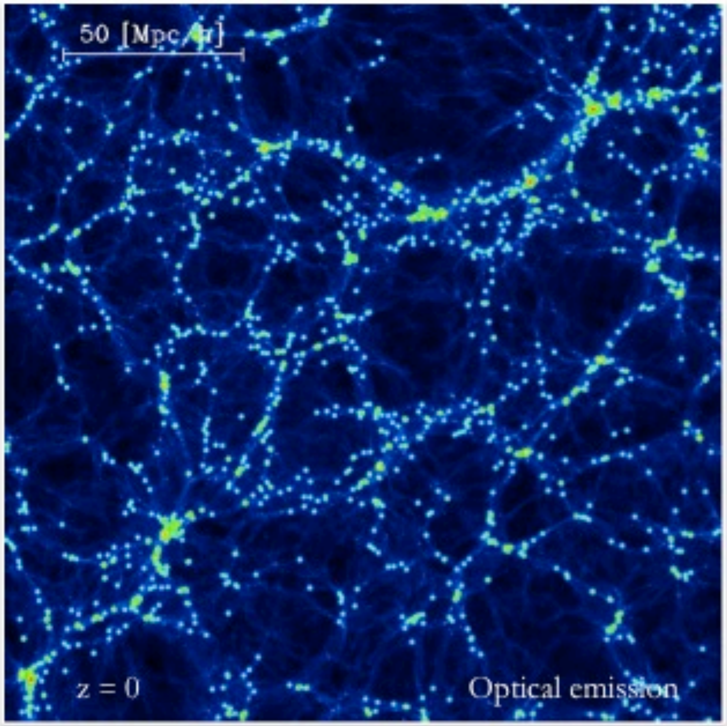
The clustering of AGN



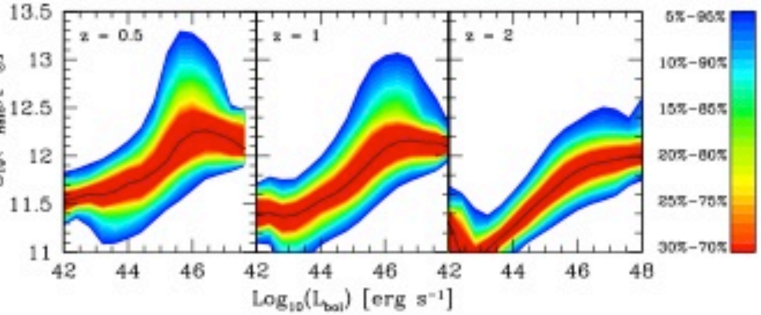


NF et al., in prep.

The environmental dependence of quasars



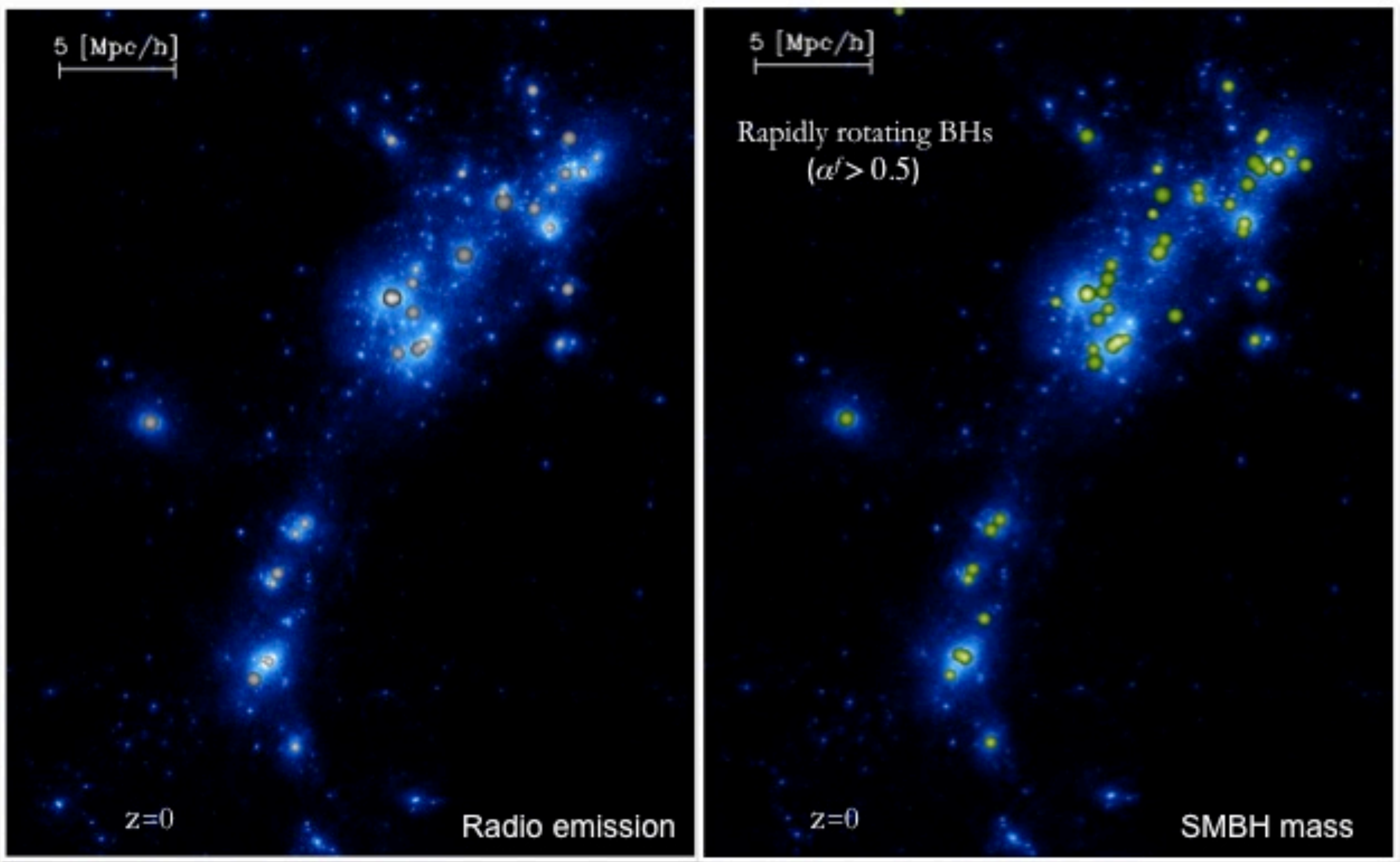
>10^{45} erg/s quasars are found in 10^{12-13} $M_\odot$ dark matter haloes at low redshifts



NF et al., in prep.

The environmental dependence of radio galaxies

Radio galaxies are found in $10^{13\text{-}15}$ $M_{\odot}$ dark matter haloes at low redshifts



NF et al., in prep.

Summary-Conclusions

- We have used the semi-analytical model GALFORM to study the cosmological evolution of BHs in a LCDM hierarchical universe.
- We find that:
  - Massive BHs ($>10^8$ $M_\odot$) tend to have higher spins than lower mass BHs.
  - The complex evolution of AGN (downsizing) arises naturally from the interplay between the hot-halo and starburst accretion modes.
  - The radio properties of an AGN seem to be determined by the spin and the accretion regime characterising the central BH.
  - Quasars live in average-mass haloes (10^{12} -10^{13} $M_\odot$). Radio galaxies on the other hand, are preferentially found in the densest dark matter environments ($>10^{13}$ $M_\odot$).

Open issues – Future directions

- Reproduce the correct evolution of radio galaxies: strong evolution of the brightest radio sources.
- Morphological properties of radio galaxies.
- Provide a complete clustering analysis of the AGN spatial distribution:
    - Comparison with SDSS.
    - Dependence of clustering on luminosity/redshift/obscuration.
    - Cross correlation with LRGs.
    - Halo occupation distributions for radio galaxies and quasars.
- Calculate the gravitational waves emitted during the evolution of BH-BH binaries: predictions for LISA and the Pulsar Timing Array Project.
- Study the role of radio jets as an AGN-feedback mechanism.
- Perform hydro simulations to probe the early growth of BHs ($z>6$) and the evolution of BH binaries during galaxy mergers.