AGN in hierarchical galaxy formation models

Nikos Fanidakis
and
C.M. Baugh, R.G. Bower, S. Cole,
C. Done, C. S. Frenk

Physics of Galactic Nuclei, Ringberg Castle, June 18, 2009

Durham
University

MARIE CURIE ACTIONS

ICC Institute for Computational Cosmology

Outline

- Brief introduction to hierarchical galaxy formation
- Supermassive black hole (SMBH) growth in hierarchical cosmologies
- Cosmological black hole (BH) spin evolution
- Predicting the optical and radio luminosity of active galactic nuclei (AGN)
- Conclusions

The idea of hierarchical cosmology

Hierarchical cosmology

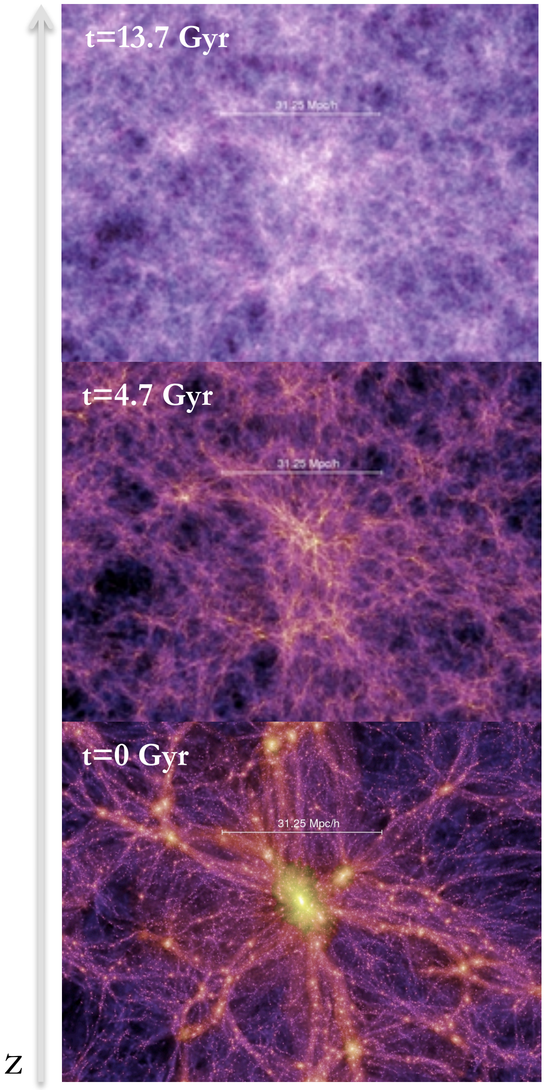
Initial quantum fluctuations

gravity

Small structures

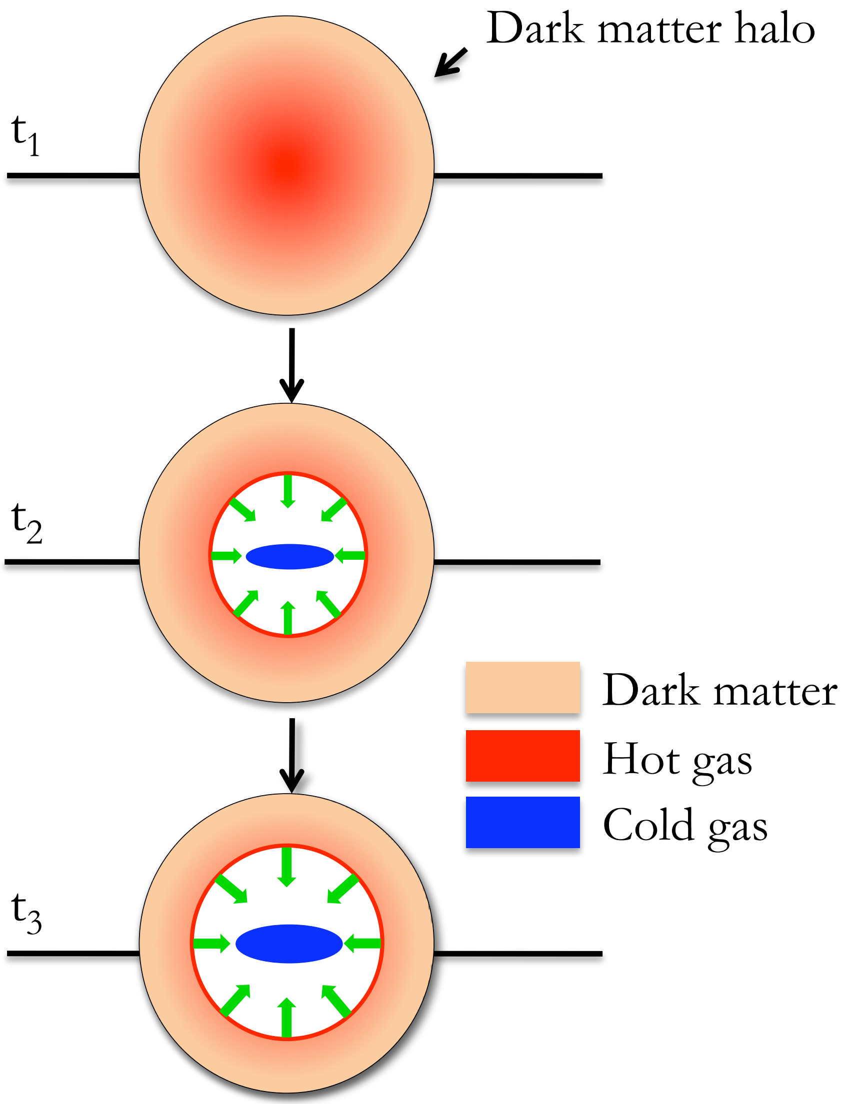
mergers

Big structures



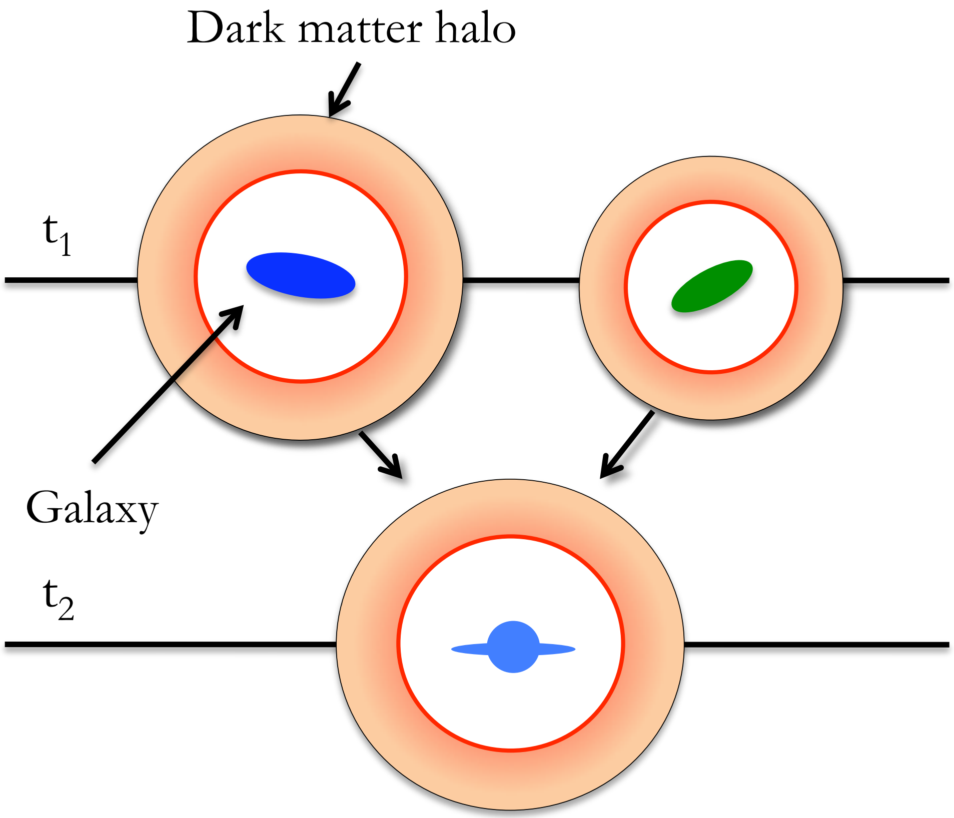
Springel et al. (2005)

Formation of disk galaxies



- Simple model: dark matter haloes are spherically symmetric.
- Baryons in halo collapse and get shock heated.
- Gas cools by radiative transitions.
- Formation of disk galaxies.

Halo and galaxy mergers: formation of spheroids

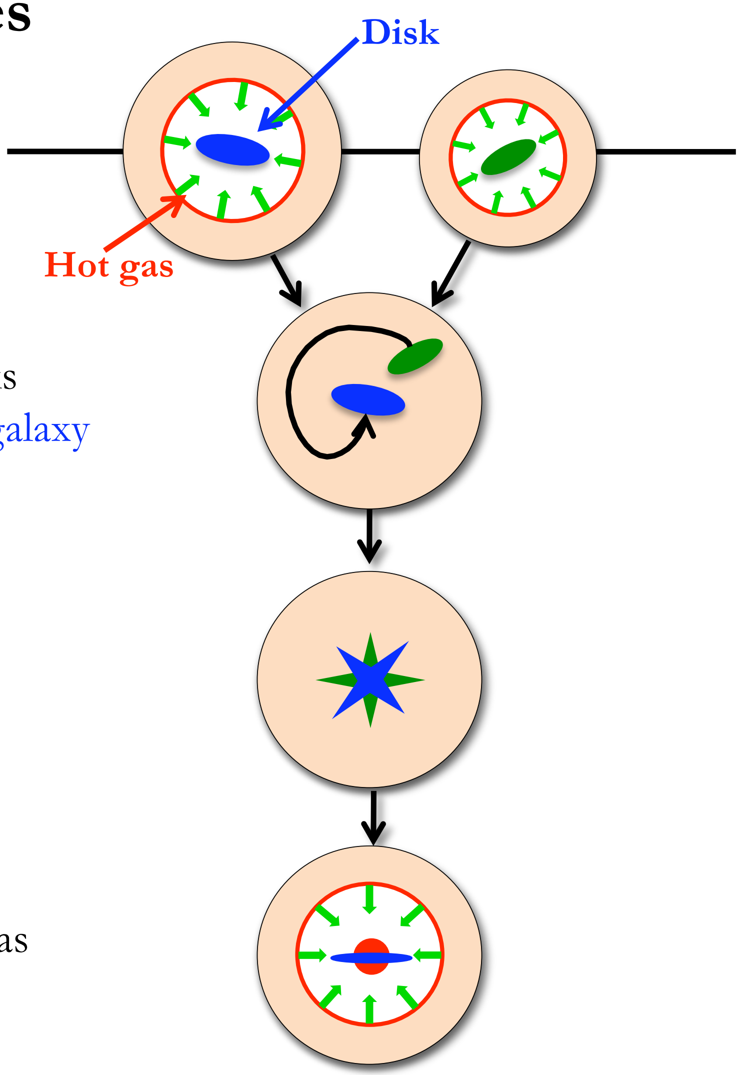


- Haloes merge.
- Galaxies merge through dynamical friction.
- Merger could be accompanied by star bursts.
- Galaxy morphology may change – formation of spheroids.

Galaxy mergers and SMBH evolution?

Host galaxies

- Progenitor haloes
- DM haloes merge
- Satellite galaxy sinks towards the central galaxy
- Major merger
- Starburst and spheroid formation
- Accretion of hot gas forms new disk

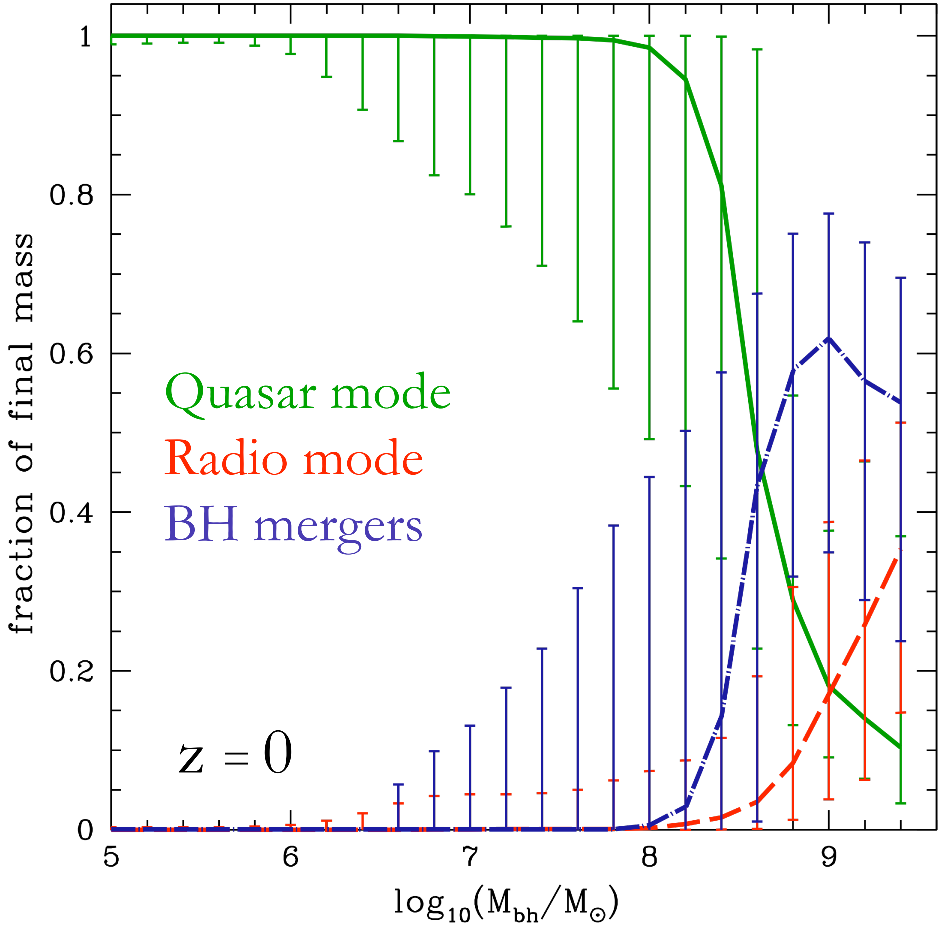


SMBHs

- Each disk hosts a SMBH
- DM haloes merge
- Satellite SMBH sinks towards the central SMBH
- BH binary forms – emission of GW
- Binary merger
- Gas accretes onto the SMBH
- Quiescent accretion of gas from the hot halo onto the SMBH

The channels of SMBH growth in ΛCDM

- Channels of SMBH growth:
    - Quasar mode (cold gas accretion)
    - Radio mode (hot gas accretion)
    - BH binary mergers
- Quasar mode dominates BH growth

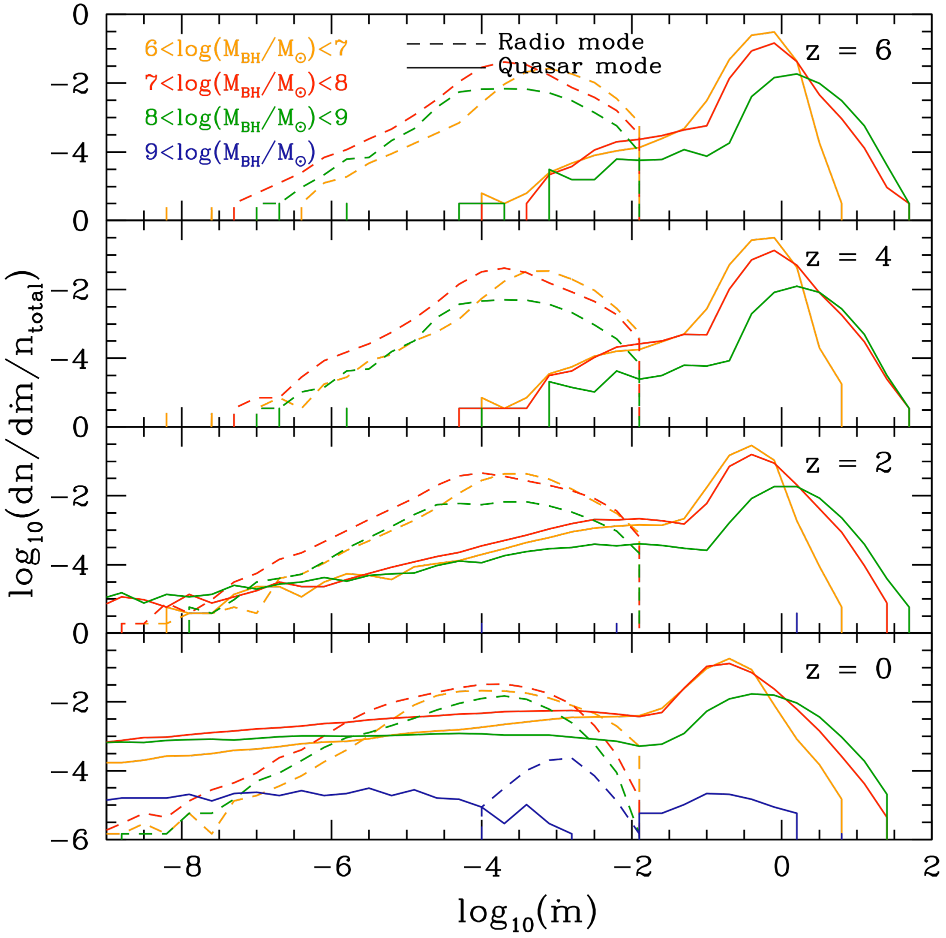


Accretion rates

- BHs accrete more efficiently at high redshifts.
- BHs in the radio mode accrete at:

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

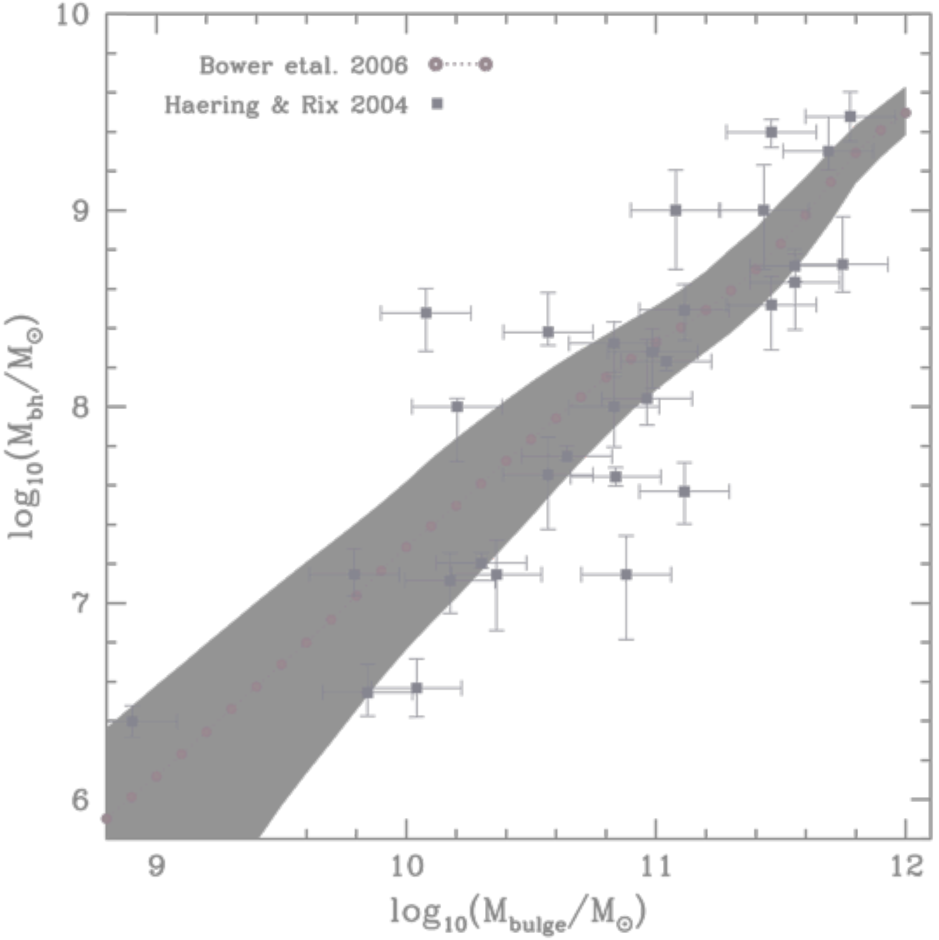
- Accretion rates peak at 0.01 in the quasar mode at z=0.



The M_{bh}-M_{bulge} relation

- The resulting M_{bh}-M_{bulge} relation fits well the data.
- BH mass density at z=0:

$$\rho_{bh} = 3.05\times10^{5}\mathrm{M_{sun}Mpc^{-3}}$$

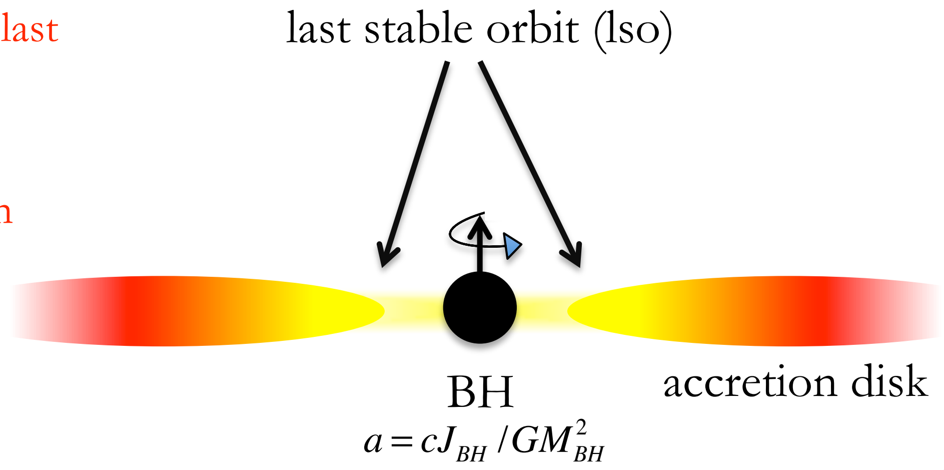


BH spin change due to accretion and mergers

- Gas accreted via an accretion disk transfers its angular momentum at the last stable orbit to the BH:
  - Co-rotating gas – spin up
  - Counter-rotating gas – spin down

$$a_f = \frac{r_{lso}^{1/2}}{3} \frac{M_{BH}^{in}}{M_{BH}^{fin}} \left[4 - \left(3 r_{lso}^{1/2} \frac{M_{BH}^{in}}{M_{BH}^{fin}} - 2 \right)^{1/2} \right]$$

Bardeen (1970)



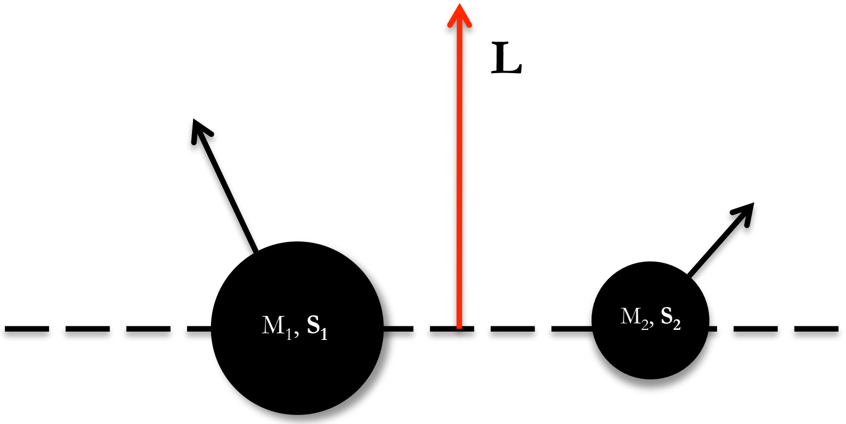
last stable orbit (lso)

BH

$a = cJ_{BH} / GM_{BH}^2$

accretion disk

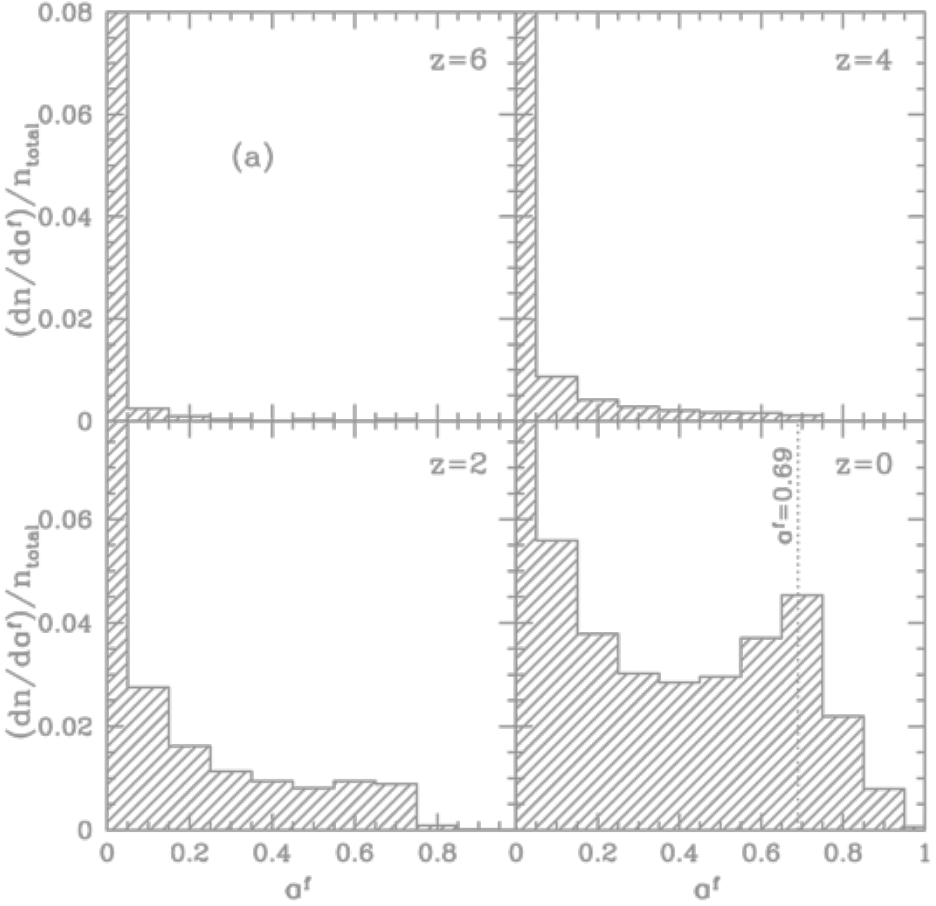
- During a binary merger the satellite BH transfers its angular momentum and spin to the central BH.
- The final remnant is always a rotating BH.



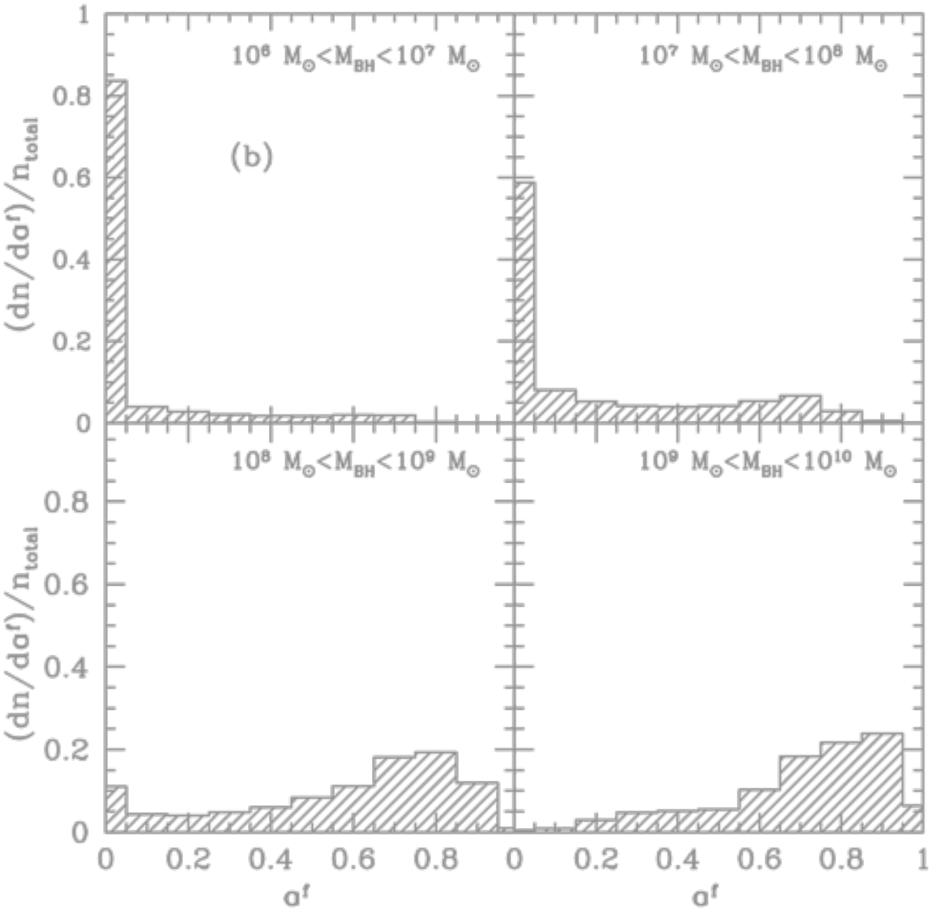
Evolution of SMBH spins

mergers only

Evolution of spin with redshift



Distributions in different mass bins

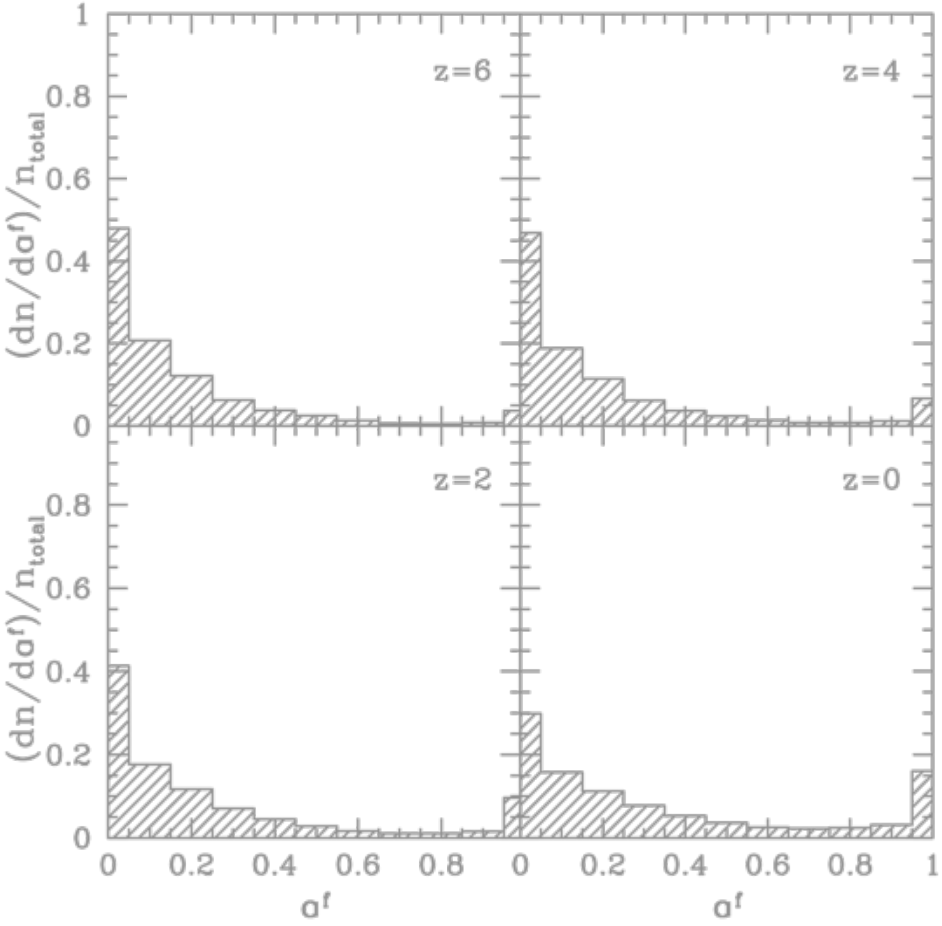


$10^5 M_\odot < M_{bh} < 10^{10} M_\odot$

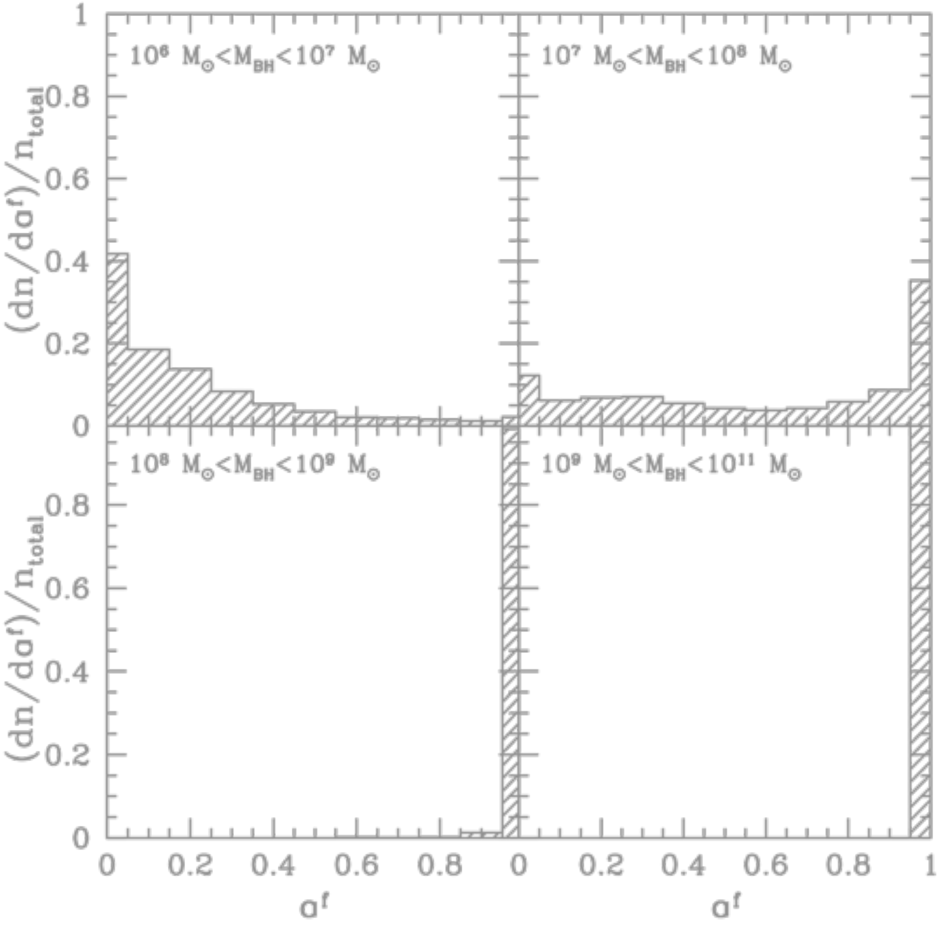
Evolution of SMBH spins

mergers + accretion

Evolution of spin with redshift



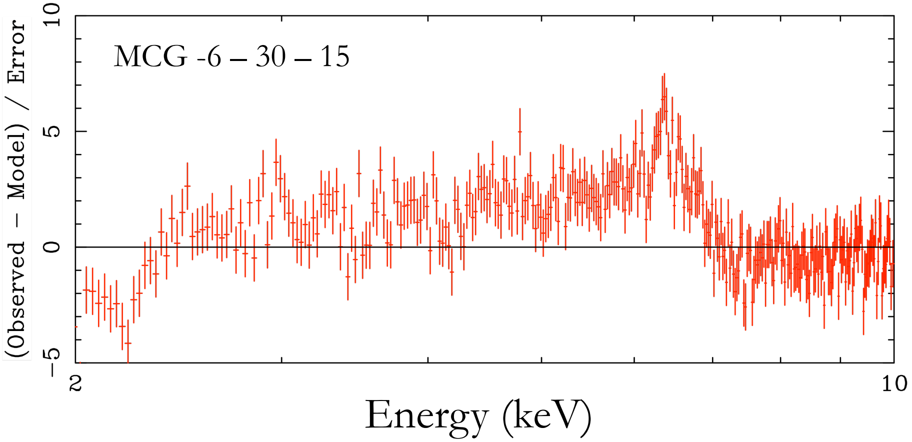
Distributions in different mass bins



$10^5 M_\odot < M_{bh} < 10^{10} M_\odot$

SMBH spins in astrophysics

Spin: what do we observe?

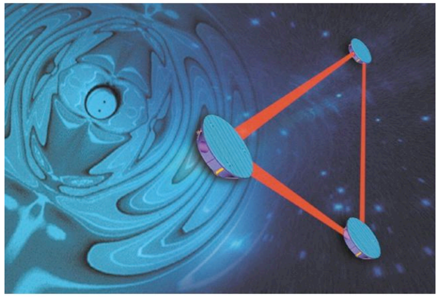


NF, masters thesis (2007)

MCG -6 – 30 – 15: nearby Seyfert whose X-ray spectrum shows a prominent iron line at 6.4KeV.

The emission originates at $\sim 2r_{\mathrm{sch}}$, indicating: $a \geq 0.94$

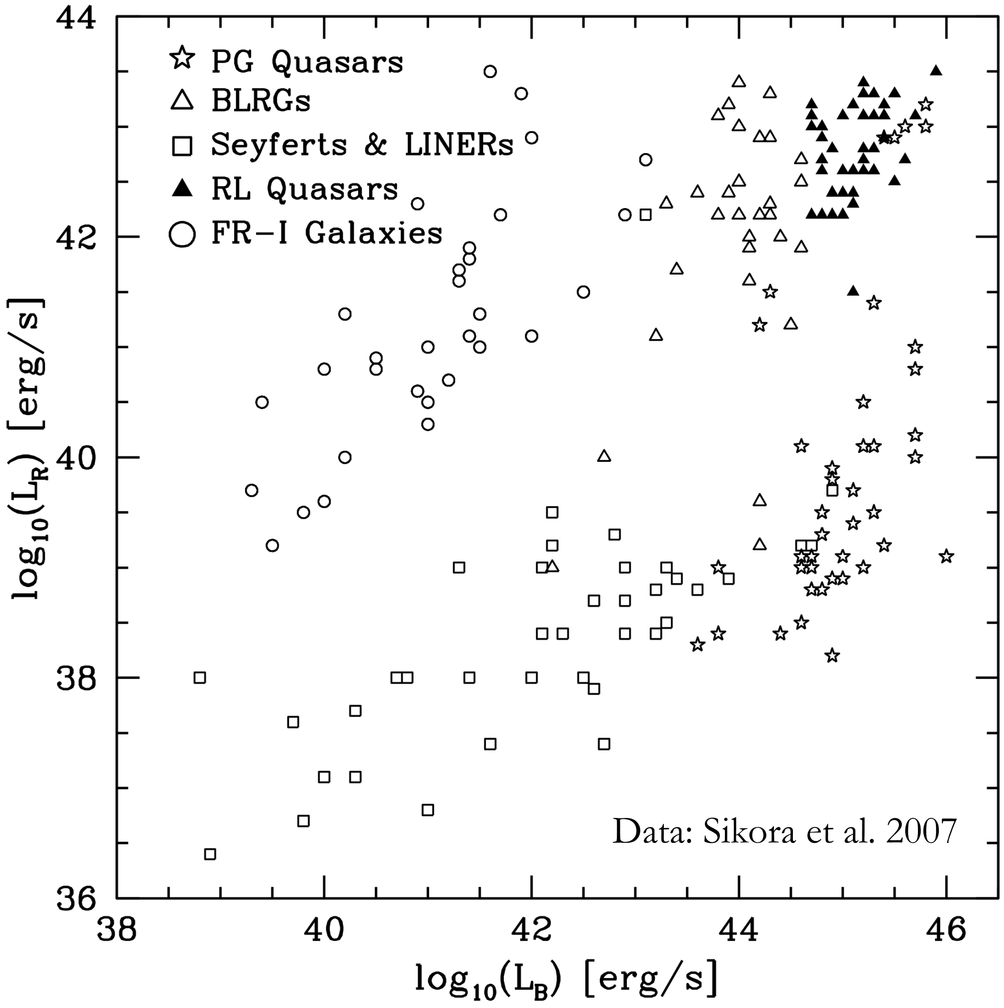
What will LISA observe?



LISA (to be launched in 2018) will directly observe the spin of the final remnant in BH binaries.

Need for an indirect way of testing the spin evolution!

Radio-loud vs. radio-quiet AGN

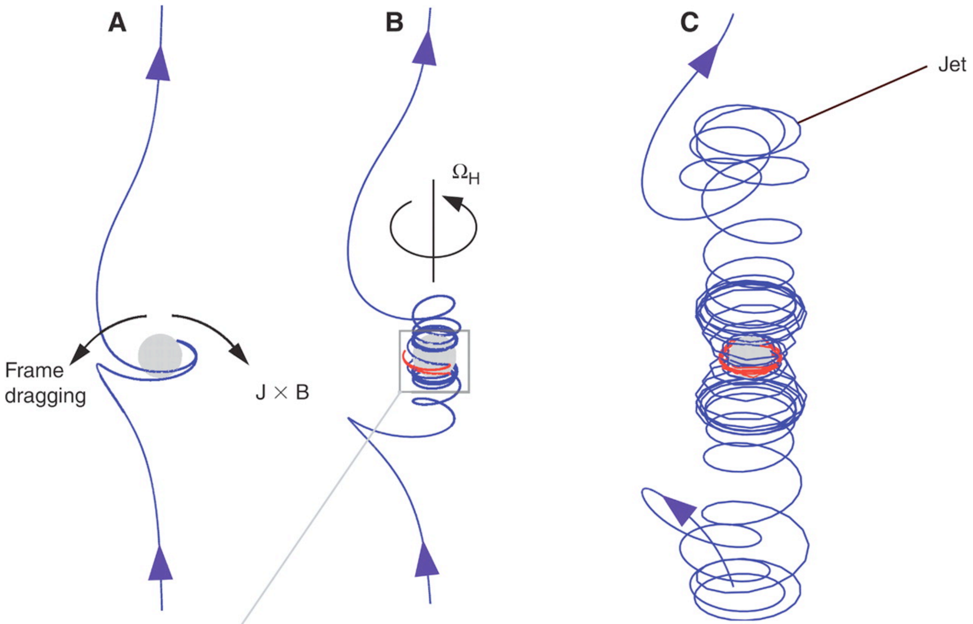


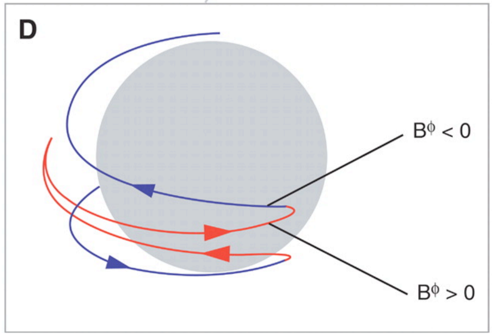
Data: Sikora et al. 2007

Observational facts

- AGN can be divided into two classes:
  - Radio-loud objects (strong jets).
  - Radio-quiet objects (no jets).
- AGN form two distinct sequences on the L_B –L_{Radio} plane:
  - Upper sequence: giant ellipticals with $M_{SMBH}>10^8M_\odot$
  - Lower sequence: ellipticals and spirals with $M_{SMBH}<10^8M_\odot$
- Spin paradigm: the BH spin is believed to determine the radio loudness of an AGN.

AGN Jets





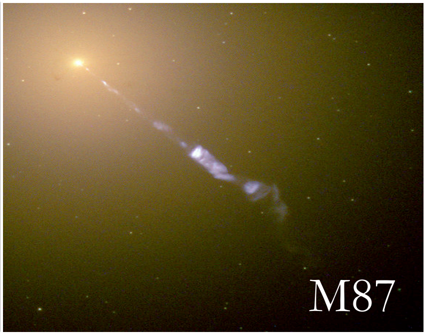


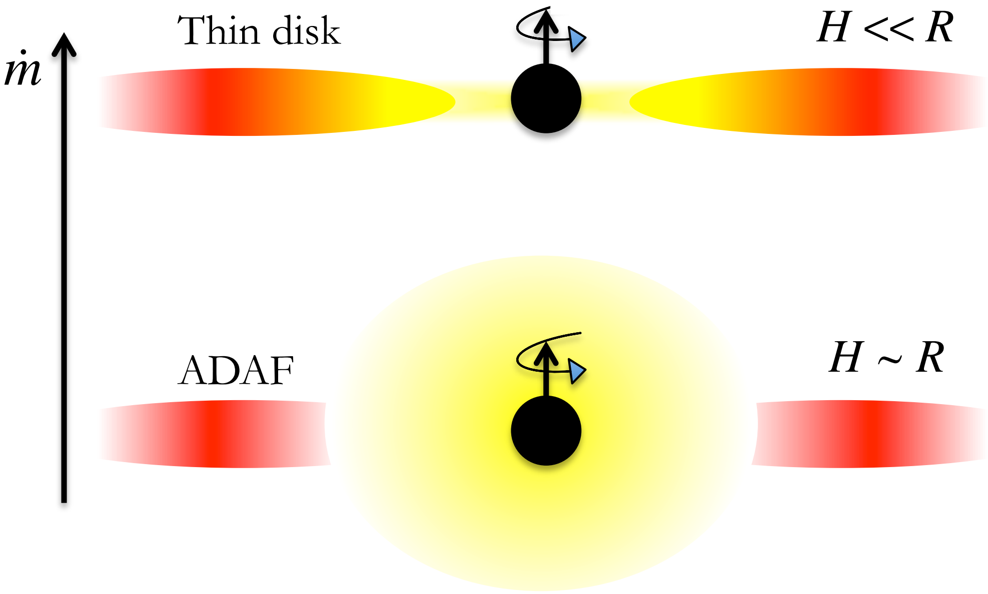
Image source: Narayan+05

- Jet formation:
  - Twisted magnetic lines collimate outflows of plasma.
  - The jet removes energy from the disk/BH.
  - The plasma trapped in the lines accelerates and produces large-scale flows.
- The jet power increases proportionally to the BH spin:

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

Blandford & Znajek 1977

AGN in **GALFORM**: modelling the disk/jet



Disk geometry depends on the accretion rate!

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

$\dot{m} < 0.01$: ADAF

Disk $\rightarrow$ $L_{bol,ADAF} \propto M_{BH} \dot{m}^2$ Mahadevan 1997

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

Meier 1999

$\dot{m} > 0.01$: Thin disk

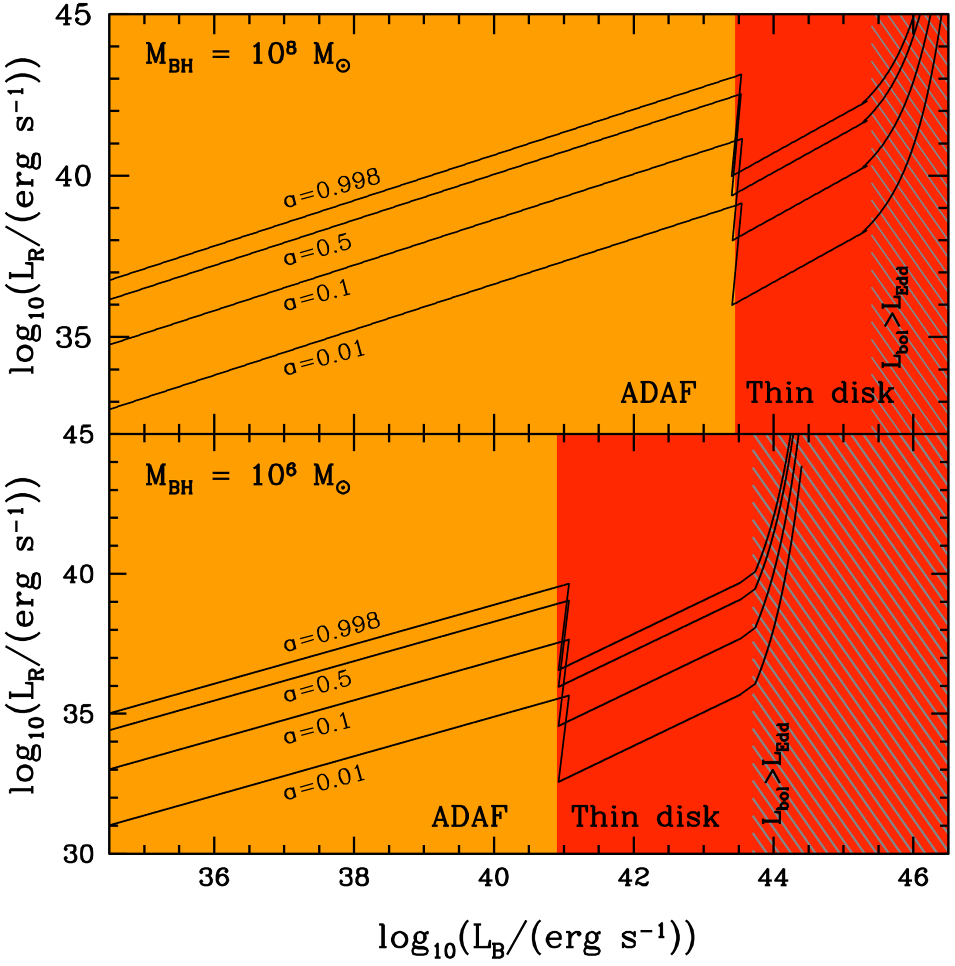
Disk $\rightarrow$ $L_{bol,TD} = \varepsilon M_{BH} \dot{m} c^2$

Jet $\rightarrow$ $L_{jet,TD} = 4 \times 10^{36} M_{BH}^{1.1} \dot{m}^{1.2} a^2$

Meier 1999

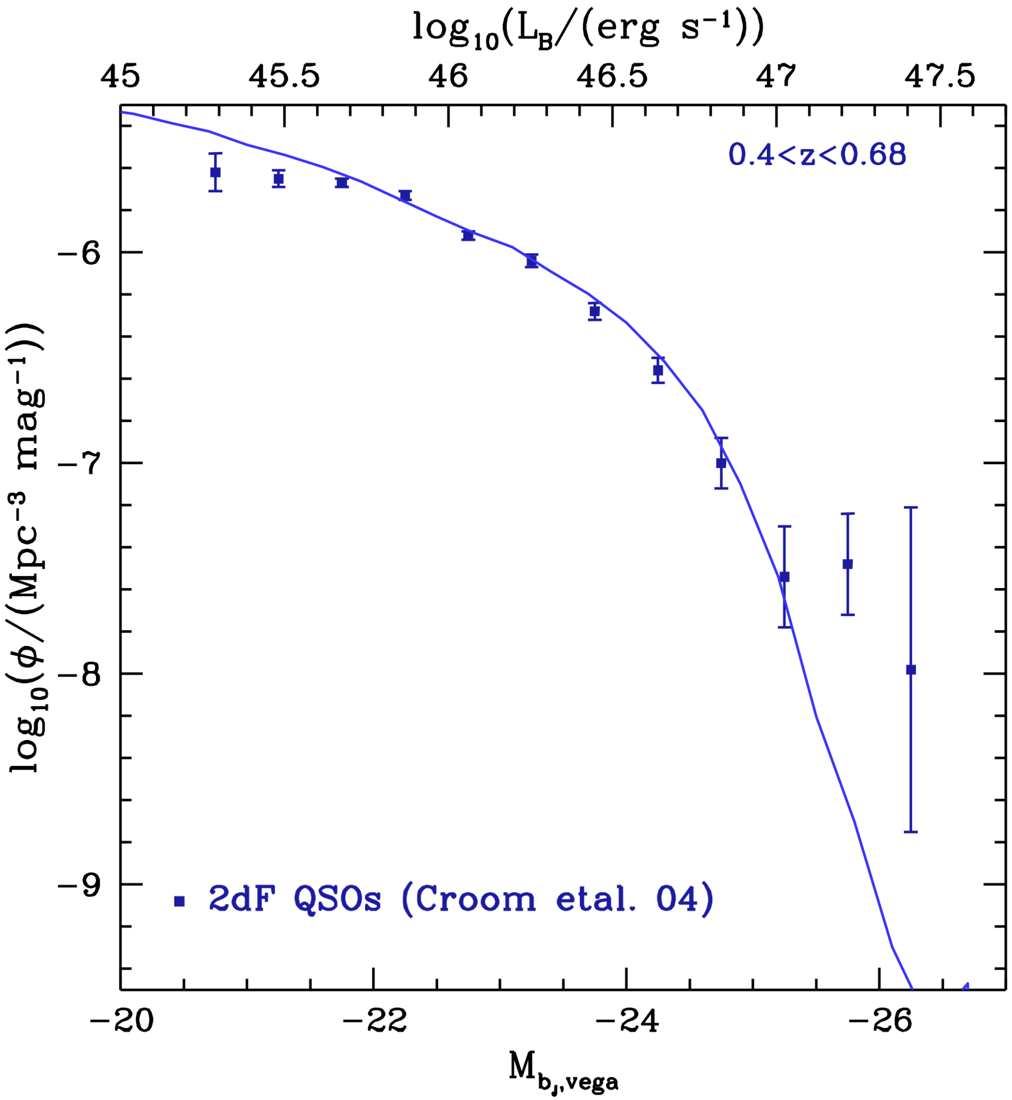
The optical-radio plane

- The position of the objects on the optical-radio plane depends on:
    - the BH mass
    - the accretion rate
    - the BH spin
- The jet strength is strongly affected by the accretion regime (ADAF/thin-disk)



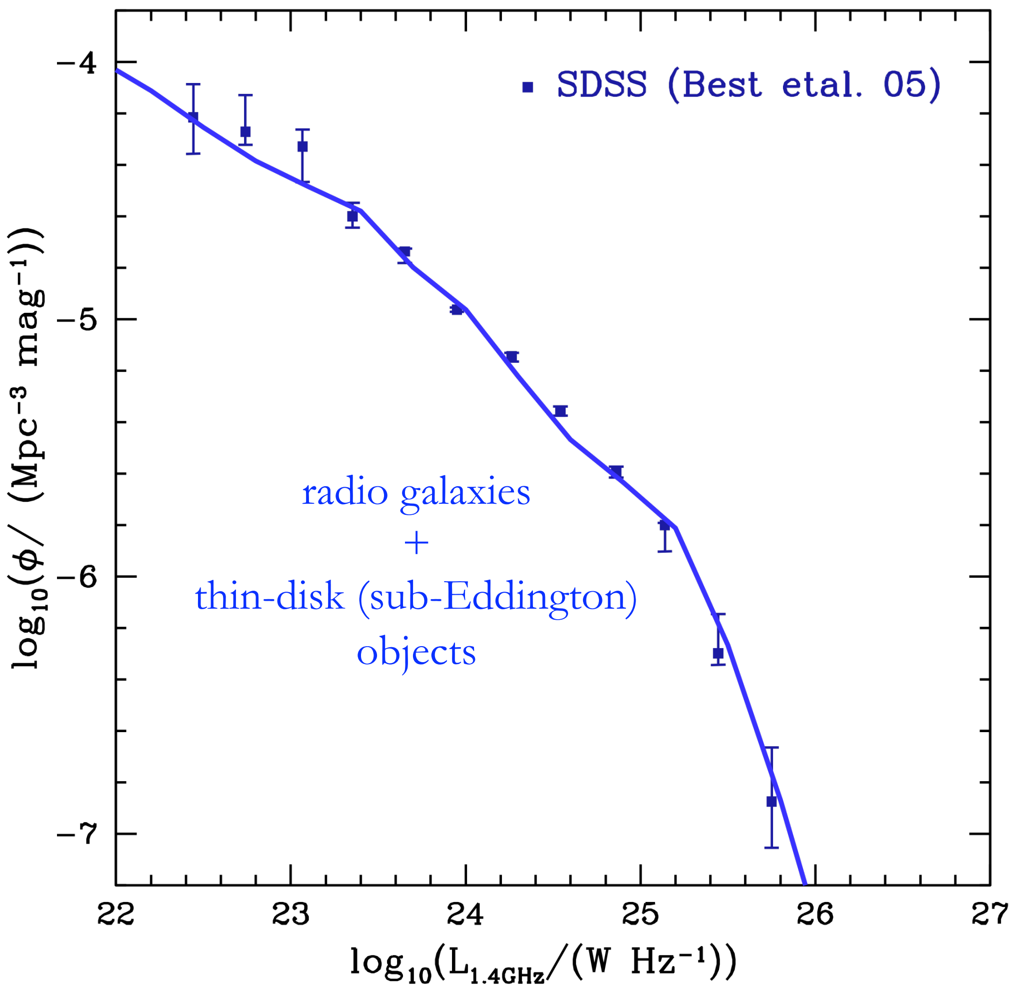
Results: quasar luminosity function

- Only objects accreting in the thin-disk regime are used.
- Super-Eddington objects are limited to $(1+\ln\dot{m})L_{Edd}$.
- $t_{quasar} = 10 \times t_{dyn.\ bulge}$
- Average accretion efficiency, $\varepsilon_{eff} \approx 0.1$



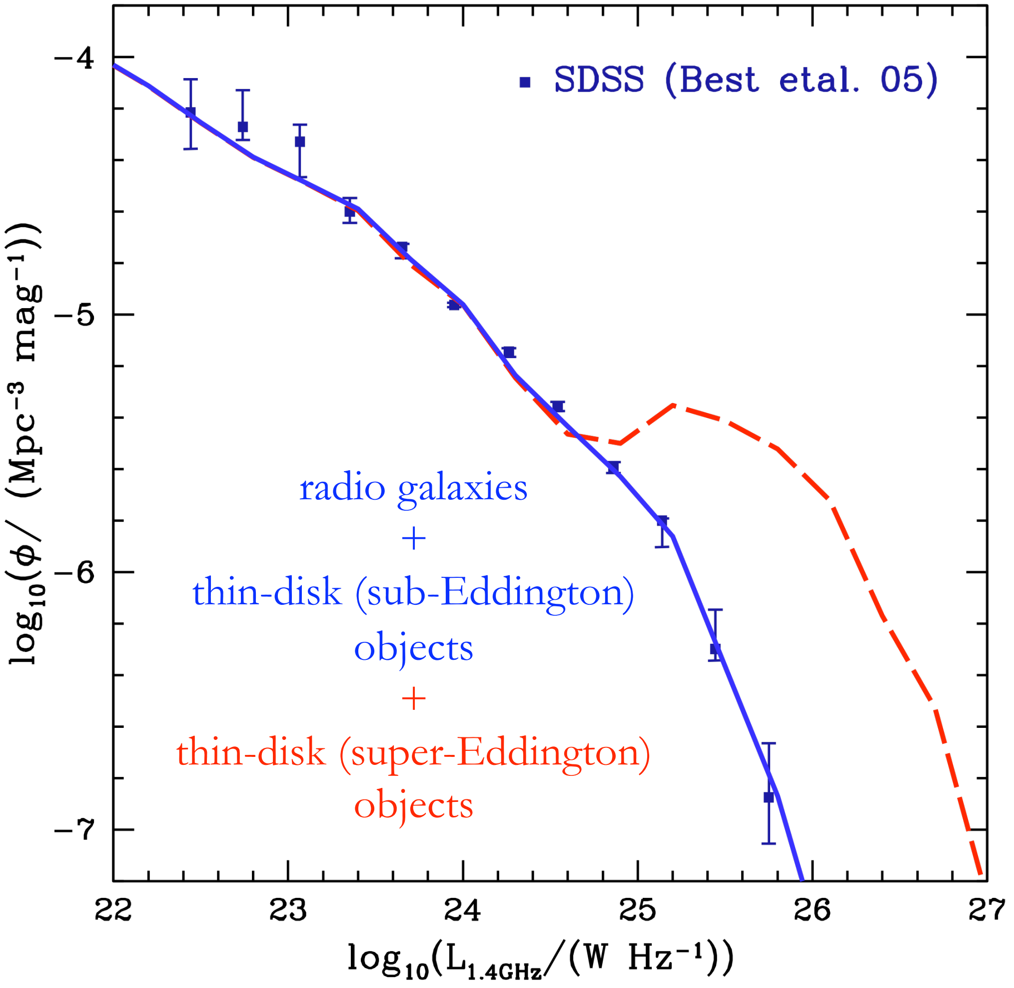
Results: radio luminosity function

- Good fit provided a sample of ADAF and thin-disk (sub-Eddington) powered AGN.



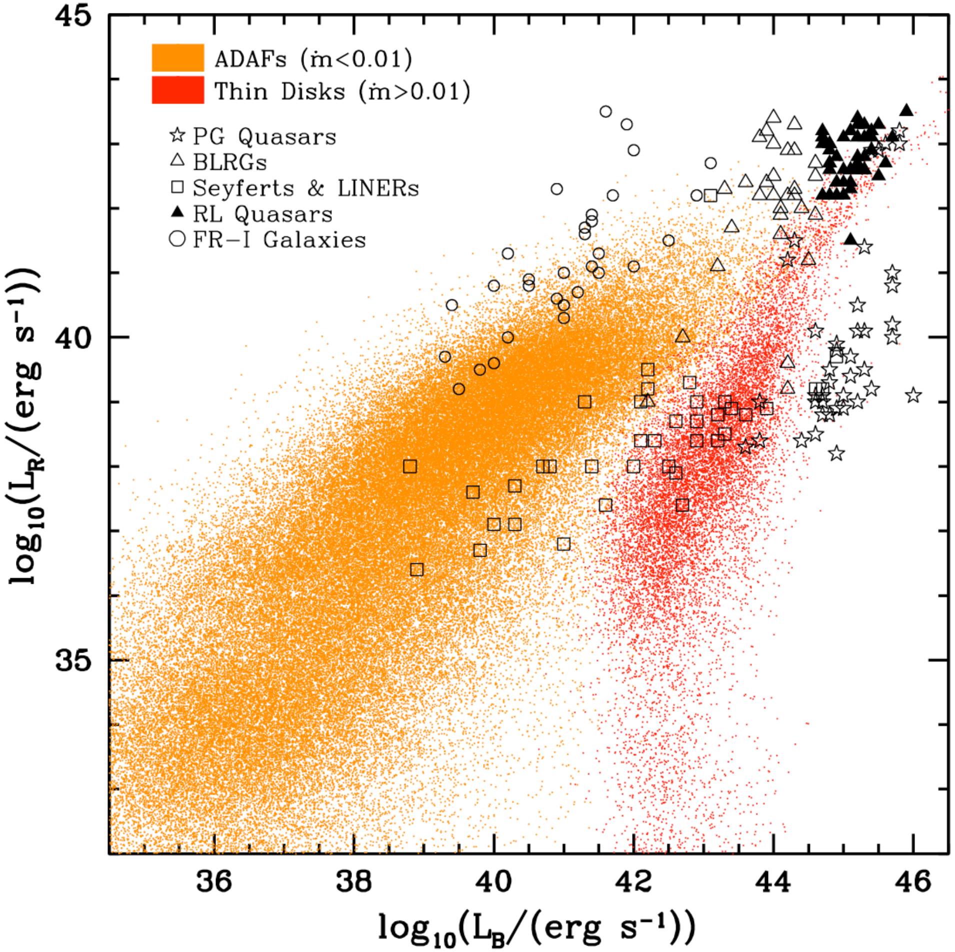
Results: radio luminosity function

- Good fit provided a sample with ADAF and thin-disk (sub-Eddington) powered AGN.
- Super-Eddington objects cause a big bump at the bright end – jet physics quite uncertain!



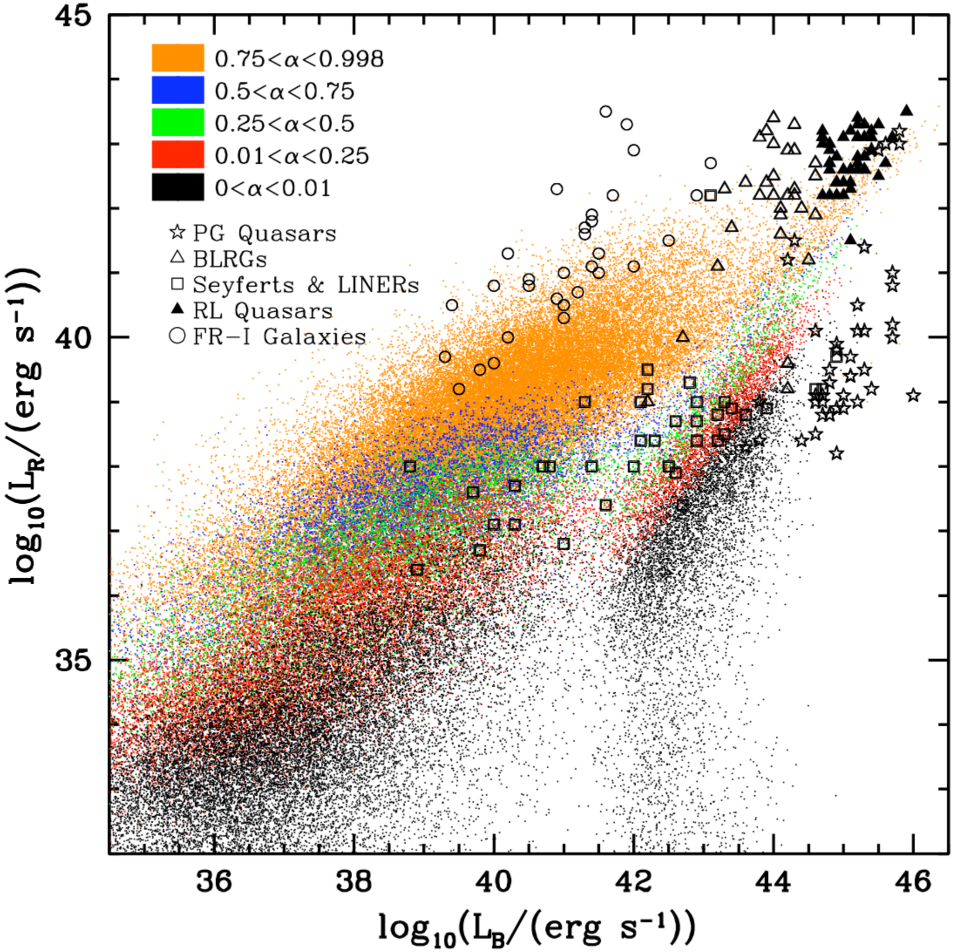
Results: AGN radio loudness

- AGN form two distinct populations:
  - Those powered by ADAFs
  - Those powered by thin disks



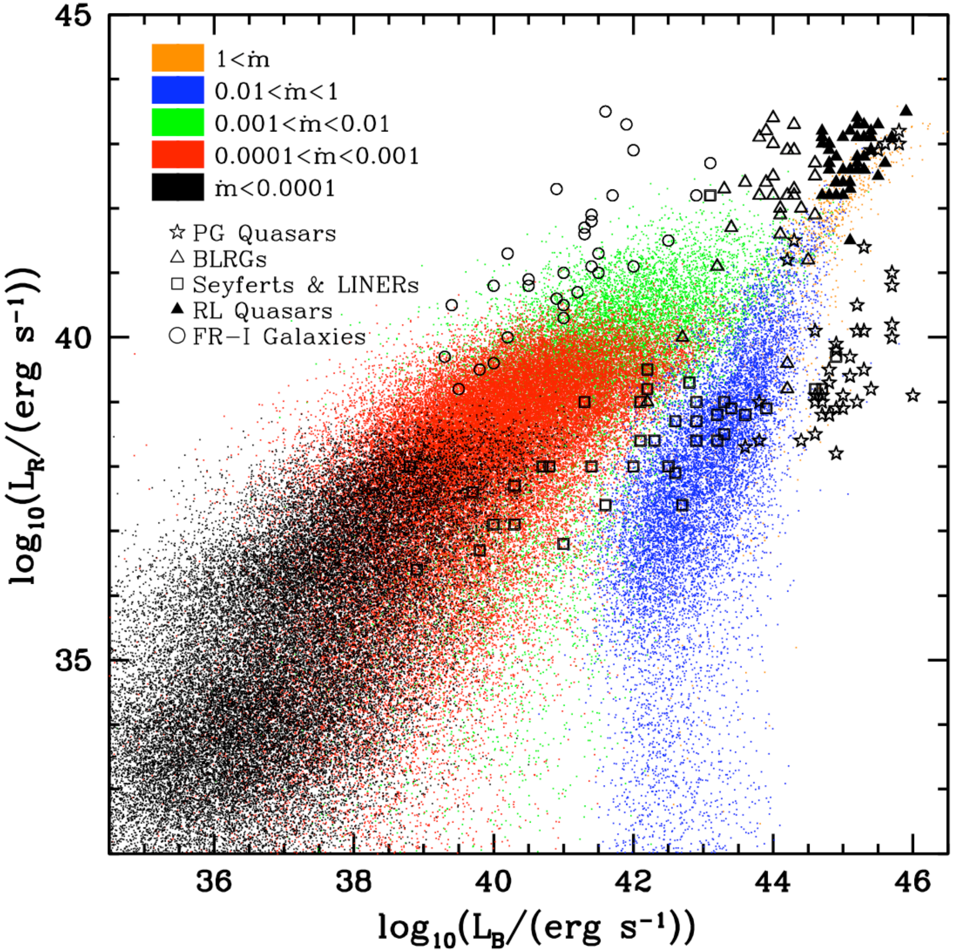
Results: AGN radio loudness

- AGN form two distinct populations:
  - Those powered by ADAFs
  - Those powered by thin disks
- Radio-loud objects host rapidly rotating BHs.



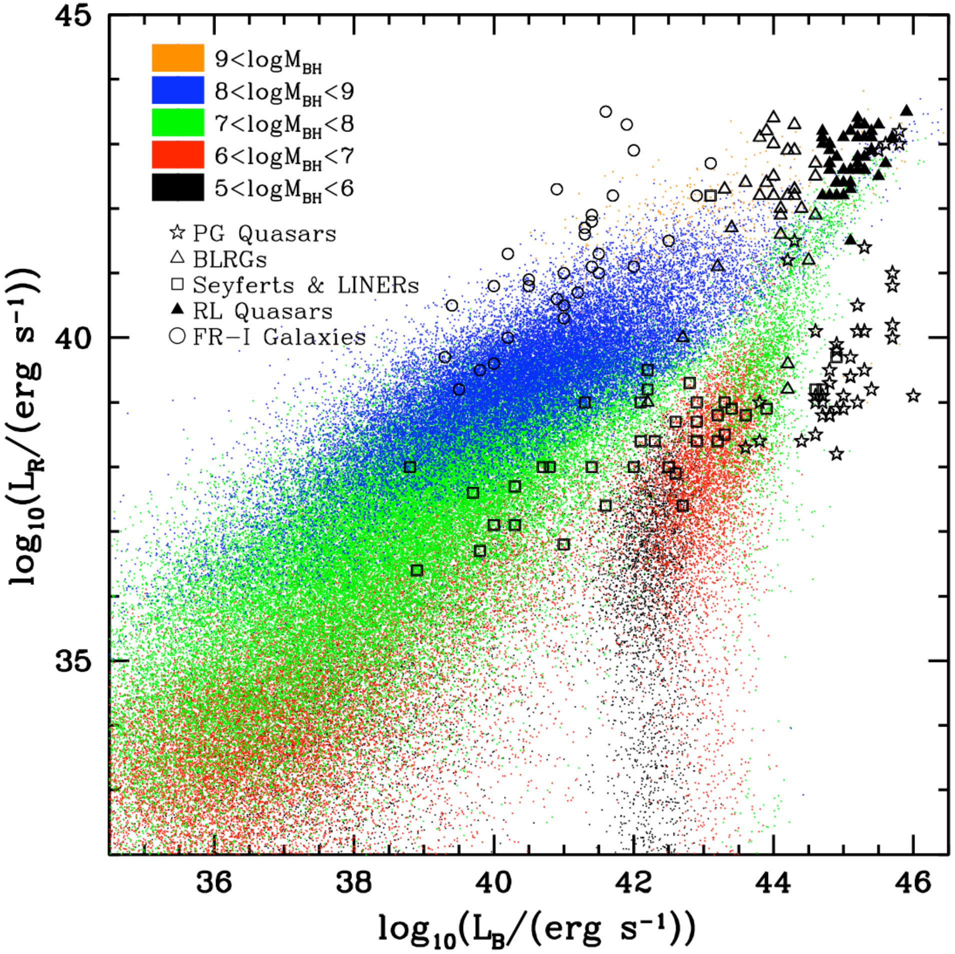
Results: AGN radio loudness

- AGN form two distinct populations:
    - Those powered by ADAFs
    - Those powered by thin disks
- Radio-loud objects host rapidly rotating BHs.
- BHs in Seyferts accrete in the 0.01-1 regime.



Results: AGN radio loudness

- AGN form two distinct populations:
    - Those powered by ADAFs
    - Those powered by thin disks
- Radio-loud objects host rapidly rotating BHs.
- BHs in Seyferts accrete in the 0.01-1 regime.
- Radio loud objects host BHs with $M_{BH}>10^8 M_\odot$.



Conclusions

- We have developed a model using `GALFORM` for explaining the radio loudness of AGN in hierarchical cosmological models.
- We find that in the present universe SMBHs have a bimodal distribution of spins.
- Giant ellipticals are found to host massive SMBHs ($M_{BH}>10^8 M_{sun}$) that rotate rapidly, which confirms the spin praqdigm.
- Using the Blandford-Znajek mechanism we model the radio emission from AGN. Our results are in good agreement with the observations.
- In our model the radio properties of an AGN seem to be determined by the spin and accretion rate characterising the central SMBH.
- Jet physics in super-Eddington objects is quite uncertain – need for better models.