AGN in hierarchical galaxy formation models

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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
- Small structures
- 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 $\Lambda$CDM

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

![Graph showing BH growth modes]
Accretion rates

- BHs accrete more efficiently at high redshifts.
- BHs in the radio mode accrete at:
  \[ m = \frac{\dot{M}}{\dot{M}_{Edd}} < 0.01 \]
- 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 $z=0$:
  \[ \rho_{bh} = 3.05 \times 10^5 M_{\odot} \text{Mpc}^{-3} \]
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

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

Bardeen (1970)

- 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?

MCG -6 – 30 – 15: nearby Seyfert whose X-ray spectrum shows a prominent iron line at 6.4KeV. The emission originates at $\sim 2r_{\text{sch}}$, 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

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 $L_B - L_{\text{Radio}}$ plane:
  – Upper sequence: giant ellipticals with $M_{\text{SMBH}} > 10^8 M_\odot$
  – Lower sequence: ellipticals and spirals with $M_{\text{SMBH}} < 10^8 M_\odot$

• Spin paradigm: the BH spin is believed to determine the radio loudness of an AGN.
AGN Jets

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

 wildfires

 Thin disk

 $H \ll R$

 Disk geometry depends on the accretion rate!

 $H \sim R$

 $\dot{m} < 0.01$: 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 $\rightarrow L_{bol,TD} = \epsilon M_{BH} \dot{m} c^2$

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

 Meier 1999

Remember: $L_{jet} \propto (H/R)^2 B_\phi^2 M_{BH} \dot{m} a^2$
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 $t_{\text{quasar}} = 10 \times t_{\text{dyn. bulge}}$.
- Average accretion efficiency, $\epsilon_{\text{eff}} \approx 0.1$
Results: radio luminosity function

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

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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 $M_{BH} > 10^{8} M_{\odot}$. 
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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 paradigm.
• 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.