Radio-selected AGN

Vernesha Smolčić (University of Zagreb, Croatia)
What types of AGN are selected in the radio band?

Effective range of black hole mass & Eddington ratio probed in radio?

What types of AGN are not selected in the radio band? Selection effects are at play?

How well do we understand the evolution of radio AGN?

Big picture context

Need for future facilities
Introduction
The role of radio AGN in galaxy evolution
Galaxy evolution

- Bimodality in galaxy populations
  - Red sequence: early type/spheroidals, no/little star formation
  - Blue cloud: disk galaxies, abundant star formation

- Evolution of galaxies through cosmic time: Blue $\rightarrow$ red
  - Via conversion of gas reservoir into stars
  - Via passive fading of stars & galaxy mergers
  - Aided by AGN feedback

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Impact of AGN onto galaxy evolution?
AGN feedback in cosmological models

- "truncation" mode
- Merger driven
- Vigorous BH mass growth
- Quasar wind expels gas from galaxy’s center

Termination of quasar & starburst phase
- Not necessarily linked to radio outflows

Once a static hot (X-ray) halo forms around galaxy

- Modes BH growth
- Radio outflows
- Truncation of further stellar mass growth

QUASAR MODE

RADIO MODE

Croton et al. 2006; Bower et al. 2006; Sijacki et al. 2006, Hopkins et al. 2006, Fanidakis et al. 2012...

Allows good reproduction of observed galaxy properties

Faber et al. 2007

U-B color

RED SEQUENCE

GREEN VALLEY

BLUE CLOUD

Log Stellar Mass [M☉]
AGN feedback in cosmological models

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RADIO MODE
- “maintenance” mode
- Once a static hot (X-ray) halo forms around galaxy
- Modest BH growth
- Radio outflows heat surrounding gas
  - truncation of further stellar mass growth

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E.g., Croton et al. (2006); Bower et al. (2006); Sijacki et al. (2006), Hopkins et al. (2006), Fanidakis et al. (2012); Croton et al. (2016)
Radio-mode AGN feedback in cosmological models

Croton et al. (2006)
Impact of AGN onto galaxy evolution?

Radio-mode AGN feedback in cosmological models

Croton et al. (2006)
Source of observed radio emission & the quest for a physically motivated classification of radio AGN
Observed radio emission

- **Synchrotron emission**
  - $\lambda_{\text{obs}} \sim \text{MHz/GHz}$ (151MHz, 1.4GHz, 3GHz)
  - Power-law spectrum: $F_\nu \sim \nu^\alpha$

1. **Star formation:** supernovae remnants
2. **Active galactic nuclei:** jets
Radio AGN classifications

1. Radio morphology: FRI vs. FRII

2. Radio spectrum: steep vs. flat, CSS, GPS

3. Radio loudness: Radio-loud vs. radio-quiet

   \[ R_K = \log(L_{rad}) - K \log(L_{opt/MIR}) \]

   - \( K=0 \): radio luminosity threshold
   - \( K=1 \): radio-to-optical/MIR threshold

4. Optical spectroscopy: low vs. high excitation radio AGN

see e.g. Smolčić (2016); Tadhunter et al. (2016)
4. Optical spectroscopy: low vs. high excitation AGN

- [OIII] 5007 equivalent widths
- Diagnostic diagrams:
  - selected emission line ratios $\rightarrow$ HII regions ionized by young stars $\rightarrow$ Seyfert vs. LINER (Low Ionization Nuclear Emission-line Regions)
- Seyfert + QSOs (i.e., Type 1 & 2) $\rightarrow$ HERAGN
- LINER + absorption line galaxies (i.e., low-L AGN) $\rightarrow$ LERAGN

Morić et al. (2010)

Hine & Longair (1979);
Baldwin, Phillips, Terlevich (1981);
Laing et al. (1994);
Kauffmann et al. (2003);
Kewley et al. (2001, 2006);
Buttiglione et al. (2010)
LE vs. HE radio AGN: Fundamental physical differences

SDSS/NVSS (0.04<z<0.1) “main” spectroscopic sample (~7000 radio sources from Kimball & Ivezic 2008 catalog; ~500 radio AGN selected following Kewley et al. 2006)

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Green vs. Red
Low vs. high stellar mass

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Low vs. high stellar mass
Low vs. high BH mass
High vs. low BH accr. rate

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- Chandra & XMM-Newton X-ray spectral analysis of the nuclei of 22 (z<0.1) 3CRR radio galaxies (Evans et al. 2006)
  - FRII (HERAGN)
    - Nuclear X-ray emission dominated by heavily absorbed components ($N_H > 20^{23} \text{ cm}^{-2}$)
      $\rightarrow$ radiative efficient accretion flow surrounded by a putative torus
  - FRI (LERAGN)
    - Nuclear X-ray emission unabsorbed
    - Any accretion flow related component likely to be highly sub-Eddington, and must have low radiative efficiencies

**HERAGN**
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- LERAGN (HERAGN) accrete from hot (cold) gas phase (Hardcastle et al. 2007)

\[ \log(P_{\text{jet}} / 10^{43} \text{ erg/s}) \] vs. \[ \log(P_{\text{Bondi}} / 10^{43} \text{ erg/s}) \]

Allen et al. (2006)
Models: thin disk vs. ADAF

- **ADAF**: advection dominated accretion flow
  (Rees 1982; Narayan & Yi 1994; Abramowicz et al. 1995)

- **RIAF** – radiatively inefficient accretion flow
- **Thin-disk** – ADAF switch at $\dot{M} \sim 1$-10% $\dot{M}_{\text{Edd}}$
- **Geometrically thick, optically thin disks** → quasi-spherical geometry

![Graph showing log $L_{\text{bol}}/L_{\text{Edd}}$ vs. log $\dot{M}/\dot{M}_{\text{Edd}}$]

- **ADAF** → LERAGN
- Thin disk

- Log $L_{\text{bol}}/L_{\text{Edd}}$ vs. log $\dot{M}/\dot{M}_{\text{Edd}}$, according to Narayan et al. (1998) model developed by Esin et al. (1997)

- ADAF regime (jet efficient): $\dot{M} < 0.01\dot{M}_{\text{Edd}}$
- Thin-disk regime (jet inefficient): $\dot{M} > 0.01\dot{M}_{\text{Edd}}$

Image: Heckman & Best (2014)

Adapted from Fanidakis et al. (2011)
LE vs. HE radio AGN: Fundamental physical differences

High-excitation ~ thin disk ~ radiatively efficient accr. flow
- Strong emission lines in optical spectrum
- X-ray, MIR, optical AGN (Unified model for AGN)

Low-excitation ~ thick disk ~ radiatively inefficient accr. flow
- Optical spectrum devoid of strong emission lines (usually LINER, absorption line AGN)
- Identified as AGN in the radio window

Image credit: Torres (2004)

Image: Heckman & Best (2014)
HERAGN or HERG or Cold-mode AGN or Radiative-AGN or Quasar-mode or High SMBH accretors or Thin-disk

LERAGN or LERG or Hot-mode AGN or Jet-mode AGN or Radio-mode or Low SMBH accretors or Thick-disk, ADAF, RIAF

Image credit: Heckman & Best (2014)
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**Image credit:** Heckman & Best (2014)
What types of AGN are selected in the radio band?
Radiatively efficient (Seyfert, QSO; high-excitation) & inefficient (LINER, absorption line; low-excitation) AGN

Effective range of black hole mass & Eddington ratio probed in radio?
LERAGN: \( M_{\text{BH}} \sim 10^9 M_{\odot} \); \( L < 0.1 L_{\text{EDD}} \)
HERAGN: \( M_{\text{BH}} \sim 10^8 M_{\odot} \); \( L \sim L_{\text{EDD}} \)

What types of AGN are not selected in the radio band? Selection effects are at play?

All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from star formation in the host galaxies rather than jets associated with the SMBH.

How well do we understand the evolution of radio AGN?

Downsizing – more powerful AGN evolve faster than weaker AGN.

Evolution of rad. eff. & inefficient AGN over broad \( L_{\text{radio}} \) range (~10\(^{21}\) ~10\(^{30}\) W/Hz) still to be constrained, and modeled.

Big picture context

Radio-mode AGN feedback – key ingredient of cosmological models to reproduce number of massive galaxies.

Better observational (and theoretical) constraints/understanding needed.

Need for future facilities

Deep, high-resolution radio observations of large, statistical samples of AGN \( \rightarrow \) NGVLA, SKA

Multi-\( \lambda \) data, spectroscopy @high-z \( \rightarrow \) SF/AGN separation & understanding role in galaxy evolution

! Numbers to be taken only as very rough estimates!
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<td>Thick-disk, ADAF, RIAF</td>
<td></td>
</tr>
<tr>
<td><strong>Radio luminosity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High ( (L_{20cm} \geq 10^{26}\text{W/Hz}) )</td>
<td>Lower ( (L_{20cm} \leq 10^{26}\text{W/Hz}) )</td>
<td>e.g., Kauffmann et al. 2008, Best &amp; Heckman 2012</td>
</tr>
<tr>
<td><strong>Optical color</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Red</td>
<td>e.g., Baum et al. 1992; Baldi &amp; Capetti 2008; Smolčić et al. 2008; Smolčić 2009</td>
</tr>
<tr>
<td><strong>Stellar mass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower than ( )</td>
<td>Highest ( (\geq 5 \times 10^{10}\text{M}_\odot) )</td>
<td>e.g., Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009</td>
</tr>
<tr>
<td><strong>Gas mass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher ( (3 \times 10^8\text{M}_\odot) )</td>
<td>Low ( (&lt; 4.3 \times 10^7\text{M}_\odot) )</td>
<td>e.g., Smolčić &amp; Riechers 2011</td>
</tr>
<tr>
<td><strong>BH mass</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower than ( )</td>
<td>Highest ( (~10^9\text{M}_\odot) )</td>
<td>e.g., Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009</td>
</tr>
<tr>
<td><strong>BH accretion rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~Eddington</td>
<td>sub-Eddington</td>
<td>e.g., Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009</td>
</tr>
<tr>
<td><strong>BH accretion mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiatively efficient</td>
<td>Radiatively inefficient</td>
<td>e.g., Evans et al. 2006; Merloni &amp; Heinz 2008; Fanidakis et al. 2012</td>
</tr>
</tbody>
</table>
Source of radio emission in HE- & LERAGN

- NVSS+IRAS+SDSS “main” galaxy sample
  - \( z = 0.04 \rightarrow 0.3 \)
  - Spectroscopic sub-sample selection:
    - Star forming galaxies
    - Composite galaxies
    - Seyferts (=HERAGN)
    - LINERS + absorption line systems (=LERAGN)

- SFR from SED fitting \( \rightarrow \) excess of radio emission assumed due to AGN contribution

Morić et al. (2010)
Source of radio emission in HE- & LERAGN

- Higher SFR/sSFR in HERAGN vs. LERAGN (Gurkan et al. 2015; Herschel-ATLAS fields; see also Hardcastle et al. 2013)

- QSOs (see e.g., Kimball et al. 2011; Condon et al. 2013; Chi et al. 2013; White et al. 2015; Herrera Ruiz et al. 2016; Maini et al. 2016)

---

**Table:**

<table>
<thead>
<tr>
<th>Galaxy Types</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>AGN</td>
</tr>
<tr>
<td>SF</td>
<td>100%</td>
</tr>
<tr>
<td>Composite</td>
<td>81.3%</td>
</tr>
<tr>
<td>Seyfert</td>
<td>56.8%</td>
</tr>
<tr>
<td>Abso+LINER</td>
<td>11.3%</td>
</tr>
</tbody>
</table>

Morić et al. (2010)
What types of AGN are selected in the radio band?
Radiatively efficient (Seyfert, QSO; high-excitation) & inefficient (LINER, absorption line; low-excitation) AGN

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How well do we understand the evolution of radio AGN?

Big picture context

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! Numbers to be taken only as very rough estimates!
Cosmic evolution of radio AGN

- **Radio luminosity function** (Willott et al. 2001)
  - 365 (steep-spectrum) sources with complete redshift coverage
  - Samples
    - 7CRS (e.g., Riley et al. 2001):
      - \( S_{151\text{MHz}} > 0.5 \text{ Jy} \)
      - 72 deg\(^2\)
    - 3CRR (Laing, Riley & Longair 1983):
      - \( S_{178\text{MHz}} > 10.9 \text{ Jy} \)
      - 13,787 deg\(^2\)
    - 6CE (Baldwin et al. 1985):
      - \( S_{151\text{MHz}} = 2 - 3.93 \text{ Jy} \)
      - 338 deg\(^2\)

- **Evolution model**
  - Differential density evolution for dual population
  - Low-L end unconstrained beyond \( z = 1 \)
  - Downsizing – more powerful AGN evolve more rapidly than weaker AGN

see also e.g. Laing et al. (1983); Dunlop & Peacock et al. (1990); Waddington et al. (2001); Tasse et al. (2008); Smolčić et al. (2009); Rigby et al. (2011); McAlpine et al. (2011, 2013); Williams et al. (2015)
Cosmic evolution of radio AGN

Willott et al. (2001)
LERAGN & HERAGN radio luminosity functions

- **FIRST + SDSS AGN at z<0.75**
  (LARGESS; ~900 deg², i<20.5; Ching 2015)

- **LE vs. HERAGN separation based on optical spectra**
  (SDSS, 2SLAQ, 2QZ, 2dF, WiggleZ, GAMA; Ching 2015)

- **z<0.75: HERAGN evolve more rapidly than LERAGN**
  (HERAGN: k_L=2.93 or k_D=7.41 vs. LERAGN: k_L=0.06 or k_D=0.46)

See also Filho et al. (2006); Best & Heckman (2012); Heckman & Best (2014); Best et al. (2014)
Probing high-z: Star forming galaxies vs. AGN

- **Optimal**: spectroscopic diagnostic tools; $z<1$ (Baldwin, Phillips; Terlevich 1981; Kauffmann et al. 2003; Kewley et al. 2001, 2006)

- **Deep radio surveys**:
  - $i_{AB} \rightarrow 26$; spectroscopy not available for full sample

- **Solution**: proxies
  - X-ray + IR-selected AGN (e.g. Brusa et al. 2007; Donley et al. 2013; Padovani et al. 2011; Bonzini et al. 2013)
  - Rest-frame optical-NIR colors (e.g. Smolčić et al. 2006, 2008, Ilbert et al. 2010, 2012)
  - IR-radio correlation (e.g. Padovani et al. 2011, Bonzini et al. 2013; Baran et al., in prep; Delvecchio et al., to be submitted)
VLA-COSMOS 3GHz LP (>11.5 µJy) (Smolčić et al., A&A accepted)
+ COSMOS MIR sources (Laigle et al. 2016)

Radiatively efficient AGN

Star forming galaxies

Radiatively inefficient AGN

1. X-ray AGN ($L_X > 10^{42}$ erg/s)
2. MIR AGN (Donley+12)
3. SED AGN (Delvecchio+16)

Rest-frame color (Ilbert+10)
- Blue & green, $M_{NUV} - M_r < 3.5$
- Red, $M_{NUV} - M_r > 3.5$ & Herschel detection
- Quiescent Red, $M_{NUV} - M_r > 3.5$ & no Herschel detection

Radio-excess (Delvecchio+16)

Baran et al. (in prep.)
Properties of radiatively efficient and inefficient radio AGN @ high-z

VLA-COSMOS 3GHz Large Project
(Smolčić et al., accepted)
- 384 hours, 3 GHz (10cm)
- 2sq.deg., resolution ~0.75"
- depth ~2.3 µJy/beam
- 7,339 sources out to z~5
(Baran et al., in prep;
Delvecchio et al., to be sub.;
Ceraj et al., in prep.)

green/blue vs. red
z<1: low vs. high stellar mass
z>1: high vs. low stellar mass
high vs. low AGN power
~ HERAGN ~ LERAGN

Delvecchio et al. (to be submitted)
Source of radio emission in radiatively efficient and inefficient radio AGN @ high-z

- **COSMOS, z<6** (Delvecchio et al., to be submitted)
  - For ~70% of Rad. Eff. AGN \( L_{\text{radio}} \) consistent with SFR in host galaxy
  - Fractional AGN contribution to the radio emission in Rad. Ineff. AGN ~80–90%

- Consistent with:
  - **z<1 results** (e.g. Morić et al., 2010; Hardcastle et al. 2013; Gurkan et al. 2015)
  - **E-CDFS results** (Bonzini et al. 2015; see also Bonzini et al. 2013, Padovani et al. 2011)
    - 1.4GHz, 0.3 deg\(^2\), best rms 6\(\mu\)Jy/beam
    - ~900 radio sources out to \( z=4 \)
    - Radio loud AGN selection: \( q_{24\text{obs}} \) radio excess
    - Radio quiet selection: No \( q_{24\text{obs}} \) radio excess, but clear AGN signature in X-ray (\( L_{2-10\text{keV}}>10^{42} \) erg/s) or MIR (Donley et al. 2013)

Baran et al. (in prep.)
Radio luminosity decomposition

\[ L_{\text{radio}} = L_{\text{radio}}(\text{SF}) + L_{\text{radio}}(\text{AGN}) \]

\[ L_{\text{IR}} \rightarrow \text{SFR} \rightarrow L_{\text{radio}}(\text{SF}) \rightarrow L_{\text{radio}}(\text{AGN}) \]

SED fitting
(Mahphys + AGN component; Delvecchio et al., to be submitted)

Using evolving q(z)
(Delhaize et al., to be submitted)

Ceraj et al. (in prep.)
Cosmic evolution of radiatively efficient and inefficient radio AGN

- VLA-COSMOS 3GHz LP
  - ~3,000 AGN, z<6

- Decomposed radio luminosity:
  \[ L_{1.4\text{GHz}}^{(\text{AGN})} \]

- Luminosity functions
  - \( V_{\text{max}} \) method

- Simple evolution model
  - Pure density evolution
  - Pure luminosity evolution
  - Fixed local LFs
    - Rad. Ineff: Sadler et al. (2002)
    - Rad. Eff: Pracy et al. (2016)

- Rad. Eff. AGN evolve stronger than Rad. Ineff. AGN (see L. Ceraj’s poster; E2)

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i) good source separation,
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Downsizing – more powerful AGN evolve faster than weaker AGN
Evolution of rad. eff. & ineff. AGN over broad $L_{radio}$ range ($\sim 10^{20} - 10^{30}$ W/Hz) still to be constrained, and modeled

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Multi-$\lambda$ data, spectroscopy @high-$z \rightarrow$ SF/AGN separation & understanding role of radio AGN in galaxy evolution
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Need for future facilities
Radio-mode feedback in cosmological models

Croton et al. (2006)

![Graph showing radio-mode feedback in cosmological models](image)
Radio-mode feedback in cosmological models

Croton et al. (2006): Volume averaged kinetic heating rate over the full simulation as a function of redshift
Radio-AGN feedback models vs. observations

Similarity between cosmological model and observations is encouraging for the idea of ‘radio mode’ feedback in the context of massive galaxy formation, but many uncertainties remain to be solved.

Jet kinetic luminosity density:
- Model: \( \Omega L_{\text{kin}} = 0.1mc^2 \); Croton et al. (2006, 2016)
- Observations: \( \Omega L_{\text{kin}} : L_{\text{kin}} \leftrightarrow L_{1.4\text{GHz}} \) via Willott et al. (1999)

see also e.g. Smolčić et al. (2009); Merloni & Heinz (2008); La Franca et al. (2010); Best et al. (2014); Pracy et al. (2016)
Radio (cm) sky surveys in context

Area [sq.deg]

Depth [\mu Jy/beam]

1000

10

1

0.1

0.01

0.001

VLA-COSMOS 3GHz (Smolcic+,2016)

EMU

VLA-COSMOS 1.4GHz (Schinnerer+04,07,10)

XXL-S (Smolcic+15; Buttler+, in.prep.)

JVLA-SWIRE (Condon+12)

E-CDFS (Miller+08,13)

VLA-COSMOS 3GHz (Smolcic+,2016)

WODAN

NVSS (Condon+98)

FIRST (Becker+94)

VLASS all-sky

SKA1 All Sky

SKA1 Deep

Lockman

ATHDSS

AGN-N

SSA-13

Deep-SWIRE

ATLAS

ELAS

FLS

PDS

ATHDFS

HDF-N

SUMMS
1.4 GHz luminosity $\rightarrow$ jet kinetic luminosity

- Scaling relation based on
  - radio galaxies in galaxy clusters (Bîrzan et al. 2004, 2008; Merloni & Heinz 2007; Cavagnolo et al. 2010; O’Sullivan et al. 2011; Godfrey & Shabala 2015): radio emission inflates buoyantly rising bubbles in X-ray plasma (i.e. cavities)
  - theoretical/analytic expectations (Willott et al. 1999)
- Large scatter/uncertainties

---

Abell 2052
X-ray (color)
Radio (contours)
(Blanton et al. 2001, 2003)

Dunn & Fabian (2004)
Bîrzan et al. (2004)
Allen et al. (2006)
Rafferty et al. (2006)
O’Sullivan et al. (2011)

Smolčić et al., (in prep)
Combined X-ray/radio analysis to study:
- Radiative – to – mechanical efficiency (y-axis)
- Eddington ratio distributions of our radio AGN classes (x-axis)
Models: thin disk vs. ADAF

- ADAF: advection dominated accretion flow
  (Rees 1982; Narayan & Yi 1994; Abramowicz et al. 1995)

- RIAF – radiatively inefficient accretion flow
- Thin-disk – ADAF switch at $\dot{M} \sim 1$-10% $\dot{M}_{\text{Edd}}$
- Geometrically thick, optically thin disks $\rightarrow$ spherical accretion

![Graph showing log $L_{\text{bol}} / L_{\text{Edd}}$ vs. log $M / M_{\text{Edd}}$.]

- ADAF $\rightarrow$ LERAGN
- Thin disk
- $L = 0.1 \dot{M} c^2$

Narayan et al. (1998); according to model developed by Esin et al. (1997)
Models: thin disk vs. ADAF

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- **GALFORM** semi-analytic model
  (Cole et al. 2000; Bower et al. 2006)

- **Jet production via Blandford-Znajek mechanism:**
  - Jets powered by extraction of rotational energy of the BH ($\alpha$)
  - Jet kinetic E proportional to the square of the poloidal magnetic field, $B_{\text{pol}} \sim (H/R)B_{\phi}$
  - ADAF: H$\rightarrow$R; Thin-disk: H$<<$R $\rightarrow$ jet production more efficient in ADAFs

- **Quasi-spherical corona around BH with transition to thin-disk far from BH**

- **Agreement with observations (e.g. radio-loudness; local radio AGN luminosity function)**

![Graph showing the comparison between ADAF and thin disk regimes](image)
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Radio-mode feedback in cosmological models

Croton et al. (2006): Volume averaged kinetic heating rate over the full simulation as a function of redshift

Radio-AGN feedback: this curve can be inferred from observations

Jet kinetic luminosity:

\[ L_{\text{BH, radio}} = 0.1 \dot{m} c^2 \]

(Croton et al. 2006, 2016)
Laor et al. (2000)
87 $z < 0.5$ PG quasars