THE MAGNETIC FIELD PROPERTIES OF RADIO GALAXIES IN DIFFERENT ACCRETION STATES

SHANE O'SULLIVAN
INSTITUTO DE ASTRONOMIA
UNAM (shane@astro.unam.mx)

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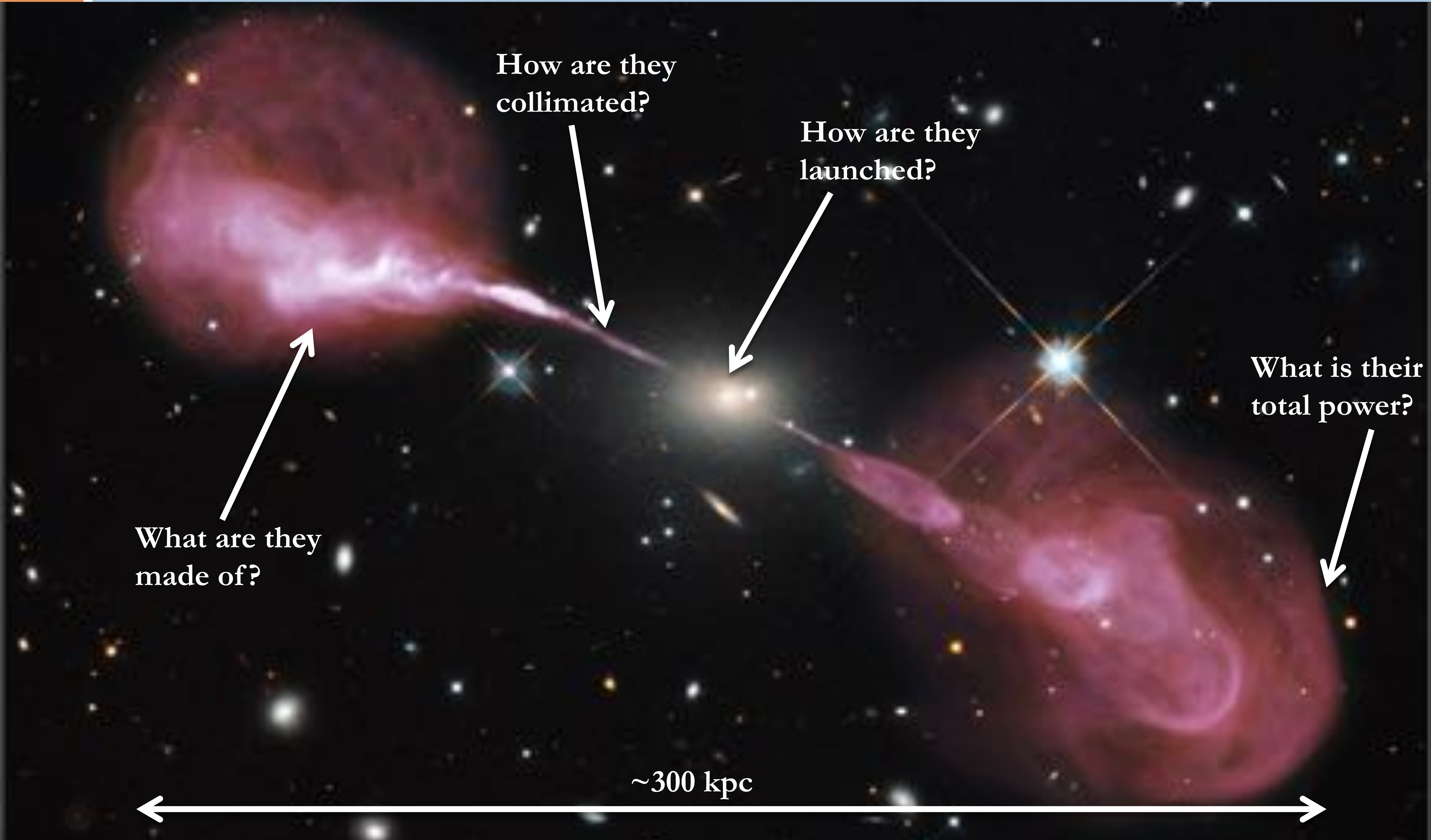
Guillermo Haro Workshop

Outline

- Introduction:
  - Impact of AGN on their local environment
  - Fueling modes of AGN activity
  - Radio-loud AGN: how do SMBHs produce jets?

- Observational tests
  - The importance of magnetic fields in jet formation
  - Magnetic field properties of radio-loud AGN in different accretion modes
  - Future prospects, upcoming radio surveys

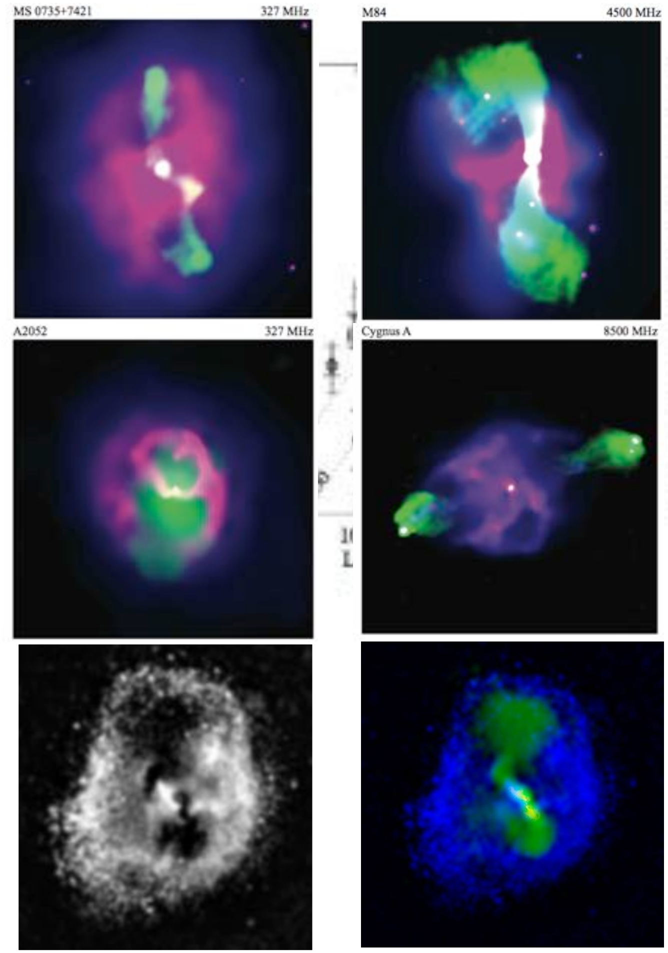
Example: Hercules A



Credit: *NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)*

The Power of AGN Jets

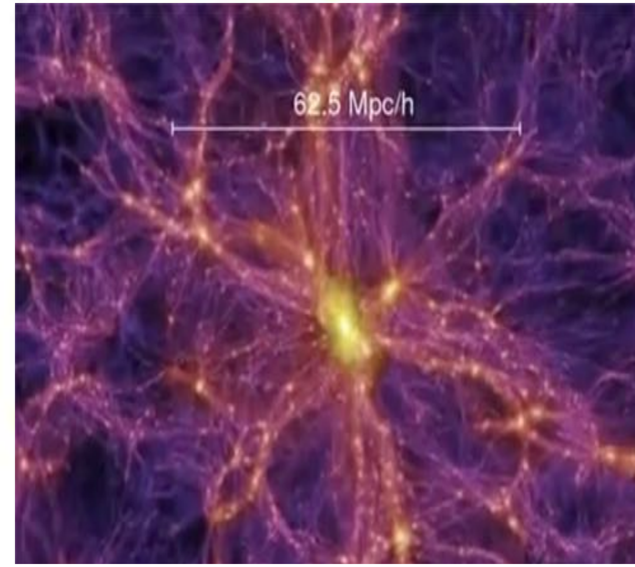
- Synchrotron power only a minor fraction of total power (Scheuer 1974)
- Mechanical power >> Synchrotron power, huge cavities blown in surrounding gas

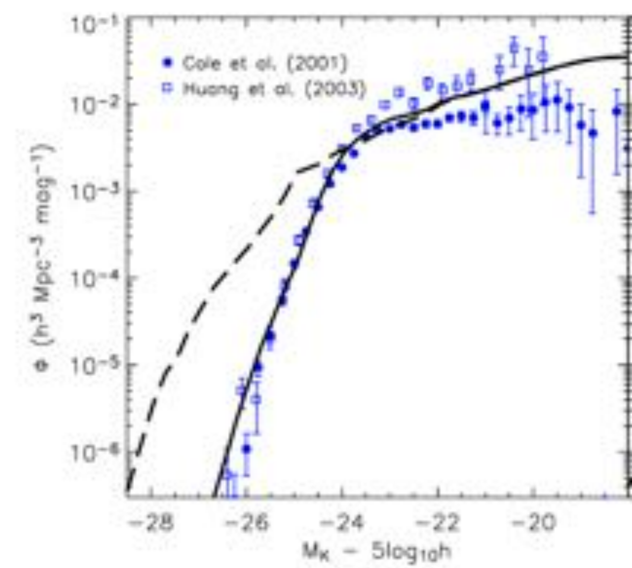


•Nulsen et al. (2002)
•Birzan et al. (2004)
•Wise et al. (2007)

The Power of AGN Jets

- Synchrotron power only a minor fraction of total power (Scheuer 1974)
- Mechanical power >> Synchrotron power, huge cavities blown in surrounding gas
- Enrichment of IGM with heavy elements
- Origin of magnetic field in IGM?
- Influence on cosmic structure formation
- AGN "feedback" has been used to reconcile the the overprediction of the bright end of the galaxy luminosity function from cosmological structure formation models (eg. Croton+06)





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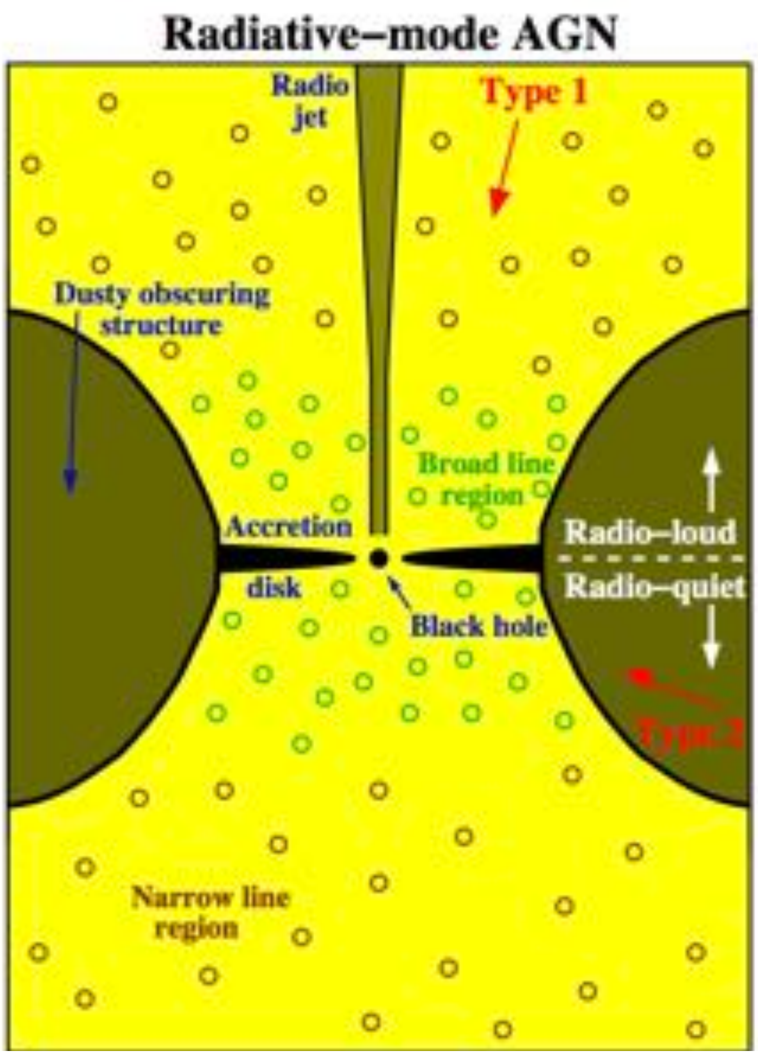
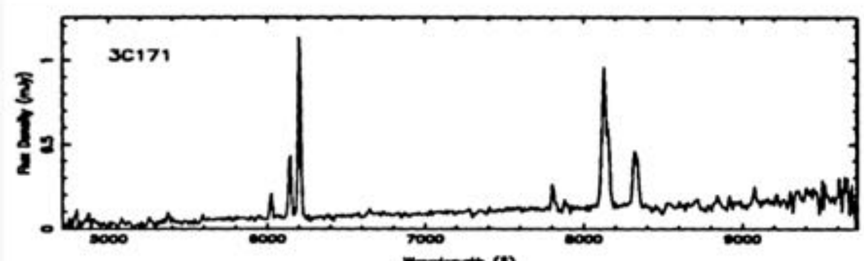
Classical AGN Paradigm

Heckman & Best (2014)



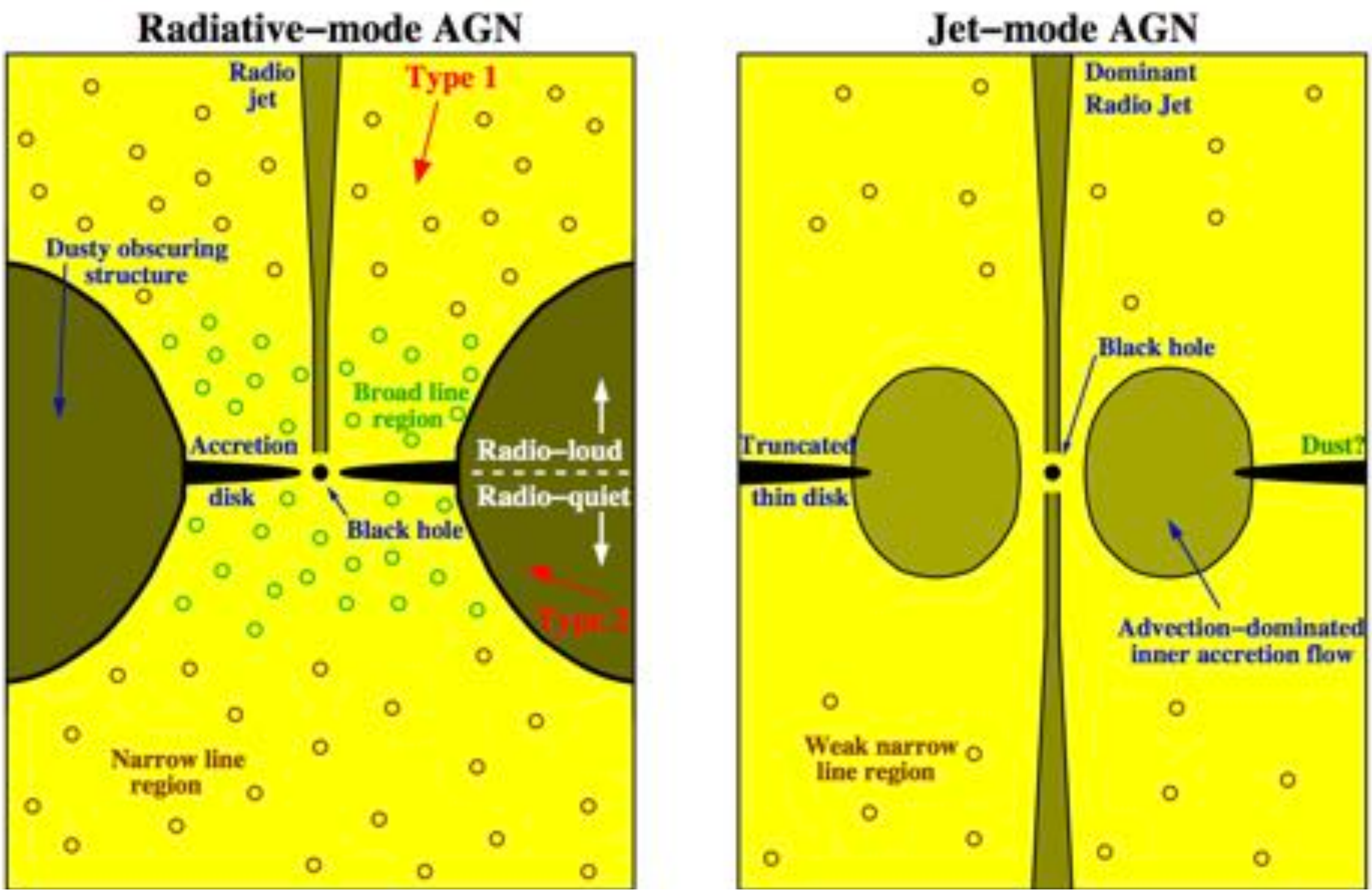
- Majority are radio-quiet
- However, in ~10% of sources, they have powerful radio jets
- Type 1:
  - Radio-loud QSO
- Type 2:
  - High-excitation radio galaxy (HERG)



Laing et al. (1994)

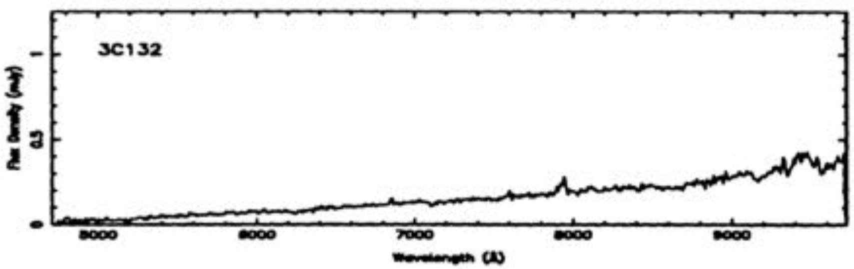
Radiatively-inefficient AGN

Heckman & Best (2014)



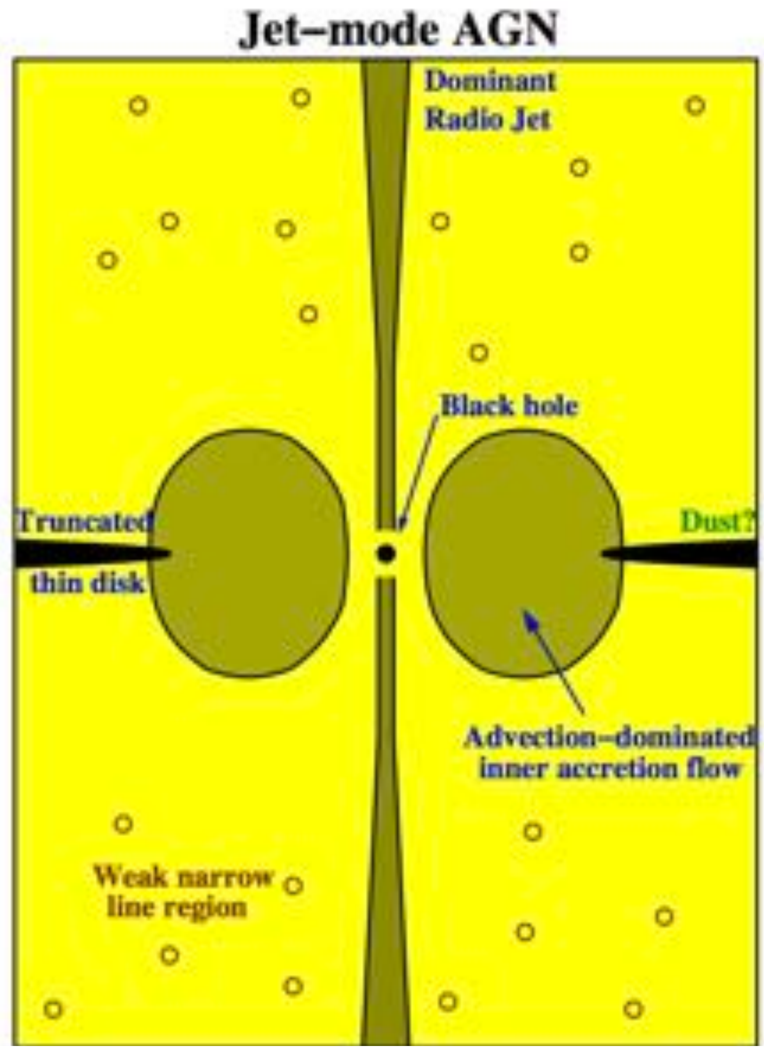
Dominant in local Universe

- Jet-mode AGN
- Radio-loud
  - Low-excitation radio galaxy (LERG)



Laing et al. (1994)

- Radio-quiet
  - Low-Ionisation Nuclear Emission-line Region (LINER)



Heckman & Best (2014)

AGN terminology

- Radiative mode/jet mode
- Quasar mode/radio mode
- Cold mode/hot mode
- HERG/LERG
- Strong-line/weak-line radio galaxy
- Radiatively-efficient/radiatively-inefficient
- Thin disk/thick disk (α-disk/ADAF)

AGN jet formation

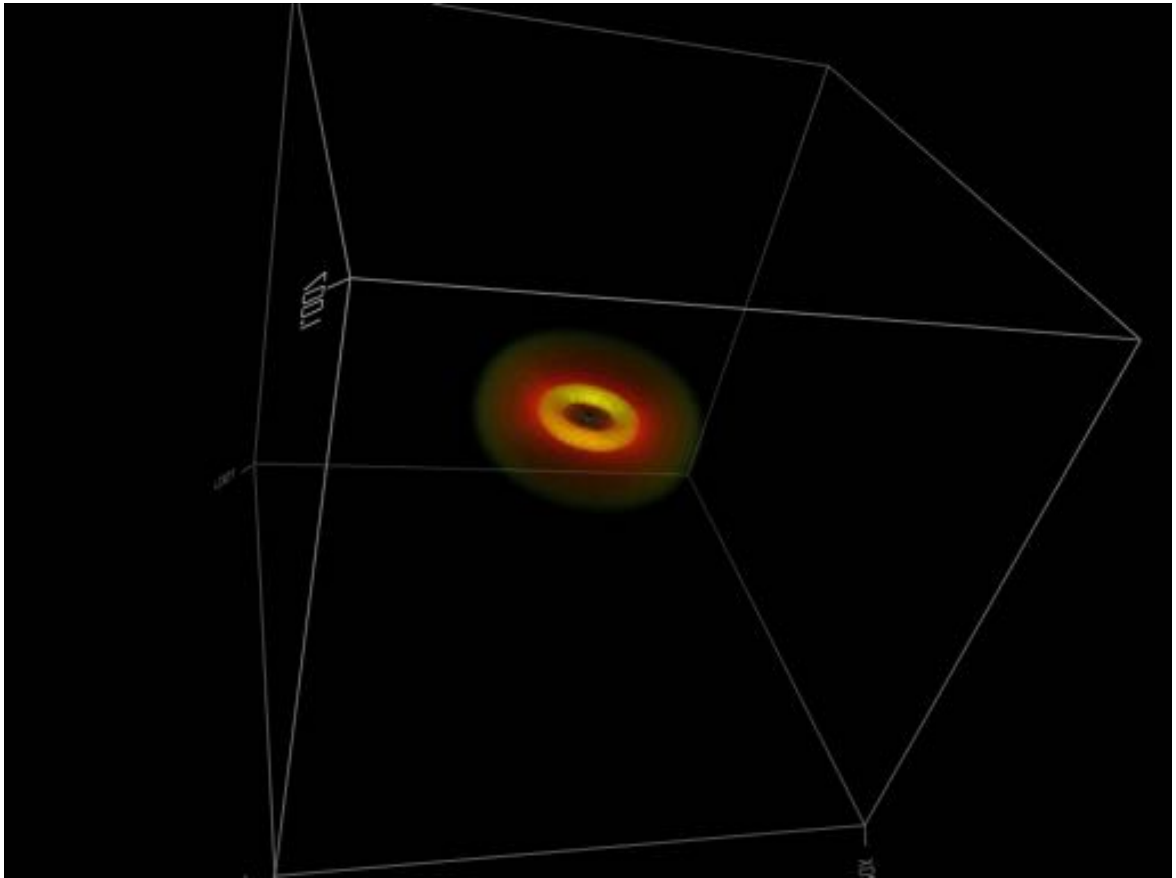
- What triggers a powerful AGN jet?
  - ~10% of quasars
- Galaxies of similar appearance (in the local universe): some produce jets, others don't. Why?

ESO 325-G004

M87

3D GRMHD simulations

- McKinney & Blandford (2009): powerful jet formed, through BZ mechanism, with initial dipolar magnetic field, and stable out to 10^3 Rg, bulk relativistic outflow up to $\Gamma \sim 10$, opening angle $\phi \sim 5°$

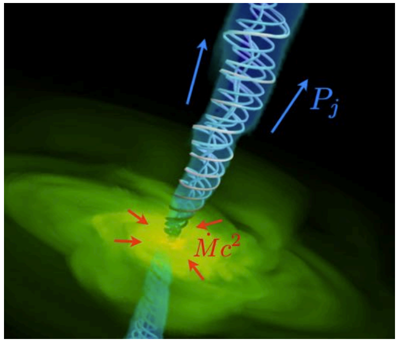


Jet formation (simulations)

- Extraction of the spin energy of the SMBH

(Blandford & Znajek 1977; Semenov et al. 2004):

$$P_{\rm jet} \propto \left(\frac{a\Phi_{\rm h}}{M}\right)^2, \qquad \eta_{\rm jet} \equiv P_{\rm jet}/(\dot{M}_{\rm BH}c^2)$$



- Push as much magnetic flux as possible onto the black hole

$$\eta_{\rm MAD} \approx 130 \left(\frac{h}{0.3}\right) a^2 \text{ per cent},$$

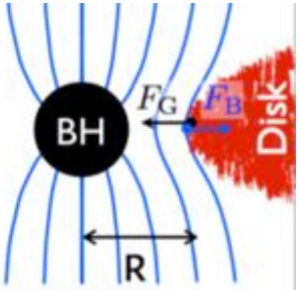
where $h \equiv H/r$ (Tchekhovskoy & McKinney 2012;

- Gravity limits BH B-field strength (Narayan+ 03):

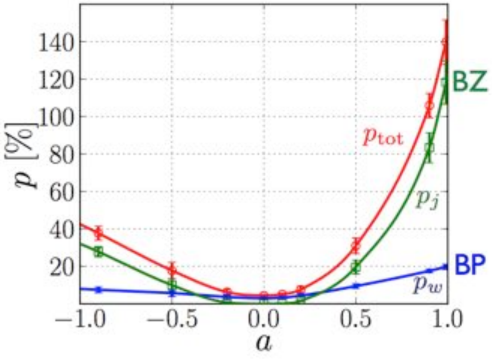
$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi}4\pi R^2 \lesssim \frac{GM_{\rm BH}M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



Maximum Jet Power vs. Spin (h/r~0.3)

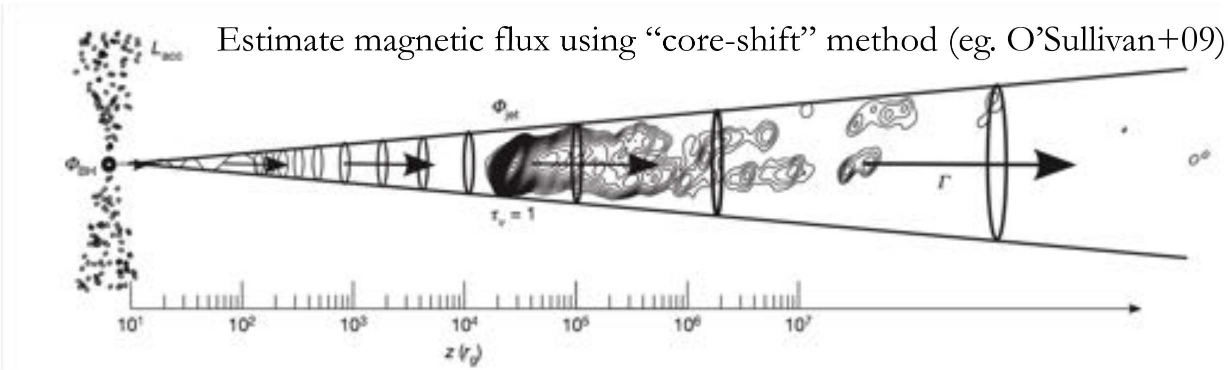


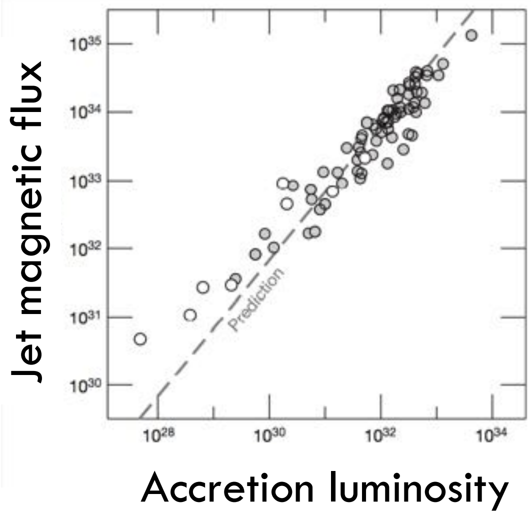
(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

At high spin, most of the power comes from black hole spin (BZ effect).

Jet formation (observations)

- Quasars and BL Lacs: Zamaninasab et al. (2014)

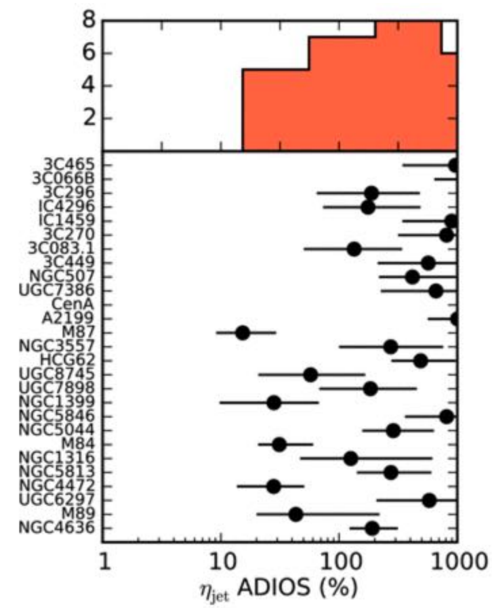




- Radio Galaxies: Nemmen & Tchekhovskoy (2015)
  - ADAF: $\dot{M}_{\rm BH} \approx 0.3\dot{M}_{\rm B}$
  - ADIOS: $\dot{M}_{\rm BH} \sim 10^{-3}\dot{M}_{\rm B}$
  - M87: $\dot{M}_{\rm BH} \lesssim 7\times 10^{-3}\dot{M}_{\rm B}$ (Kuo et al. 2014)

$$\dot{M}_{\rm BH}/\dot{M}_{\rm B} \ll 1 \qquad P_{\rm jet} \gtrsim \dot{M}_{\rm BH}c^2$$

=> AGN jets need high spin and strong magnetic fields



High spin + magnetic field

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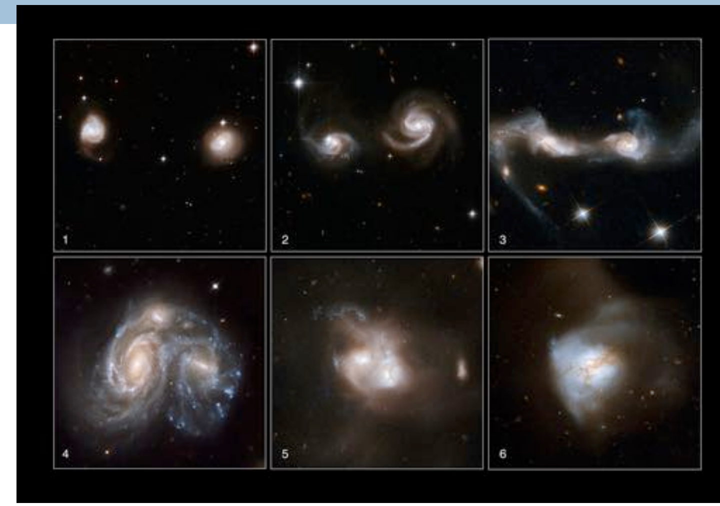
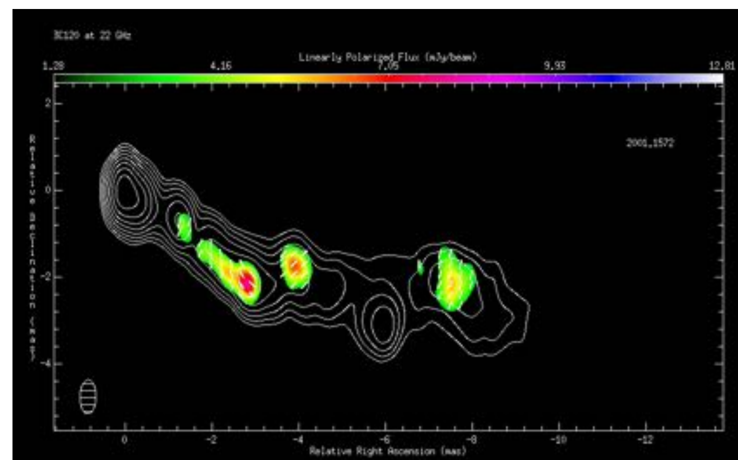
- SMBH spin: evolution of host galaxy, merger history

- Jet variability: can only be related to magnetic field variations
  - inner part of accretion disk collapses when magnetic pressure exceeds gravity, MAD

- Required magnetic field?
  - Created by magnetic dynamo in disk
  - Dragged with gas from ISM





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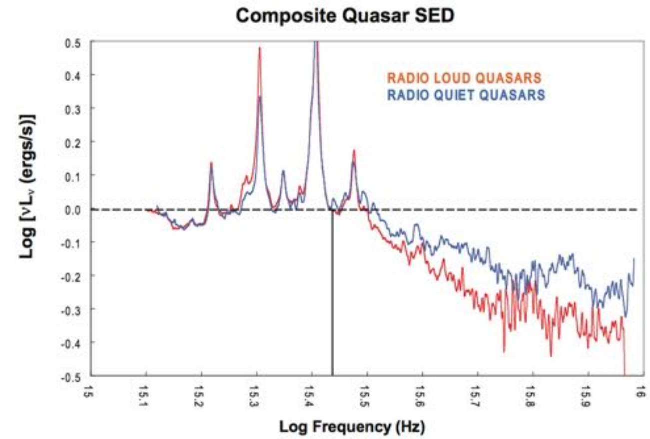
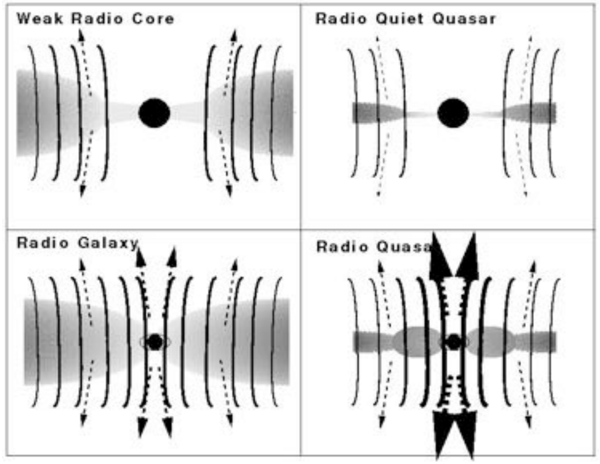
High spin + magnetic field

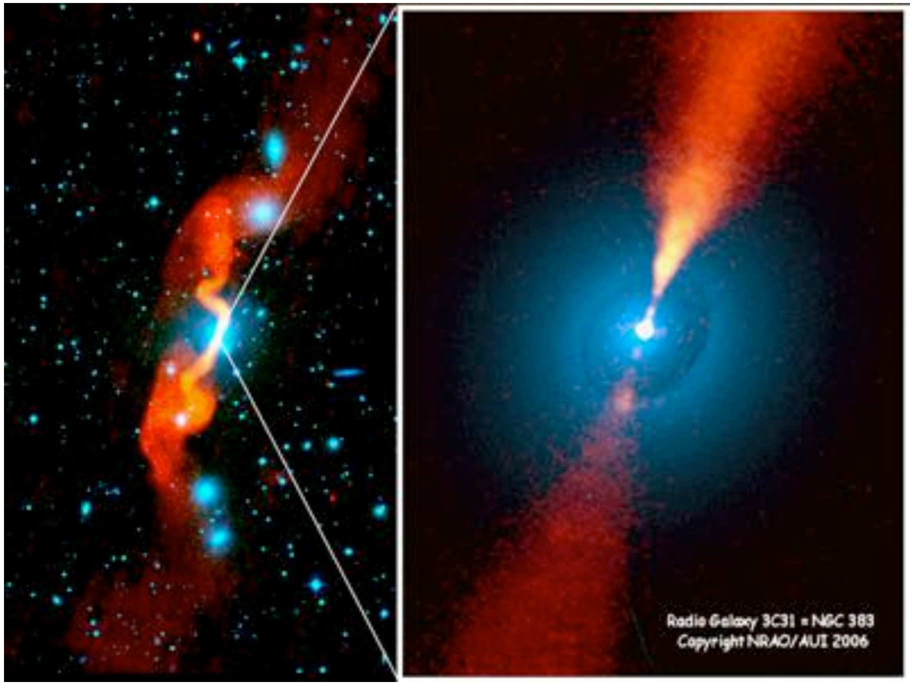
- Punsly (2015): UV deficit in radio-loud quasars compared to radio-quiet quasars => disruption of inner accretion disk in radio-loud quasars by MAD
- Magnetic flux paradigm (Sikora & Begelman 2013)
  - HERGs and radio-loud QSOs (radiative-mode AGN): Produced by merger of disk galaxy with an elliptical undergoing hot accretion for some time with a relatively coherent magnetic field that can be dragged inward
  - LERGs (jet-mode AGN): Efficient accumulation of magnetic field near black hole in geometrically-thick accretion flows facilitates jet launching





Magnetic field properties of radio-loud AGN

- Can the large scale magnetised environment influence jet formation? (O'Sullivan et al. 2015, ApJ, 806, 83)



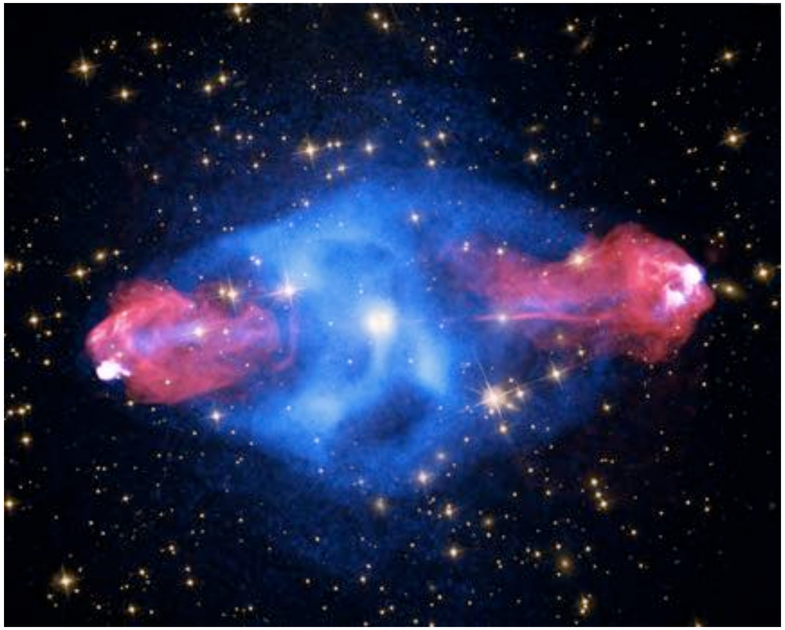


Image Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA

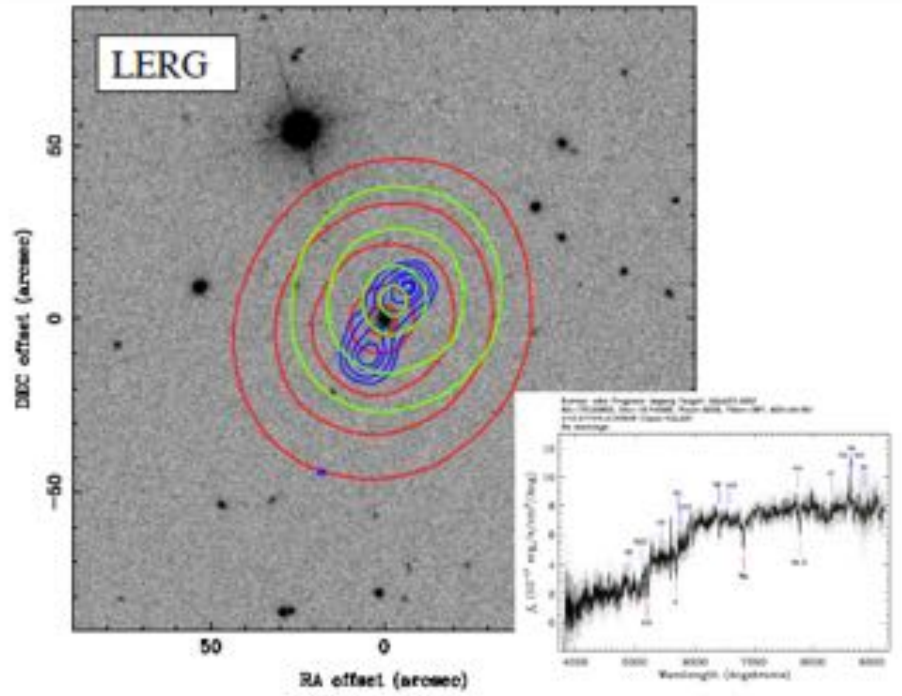
Sample construction

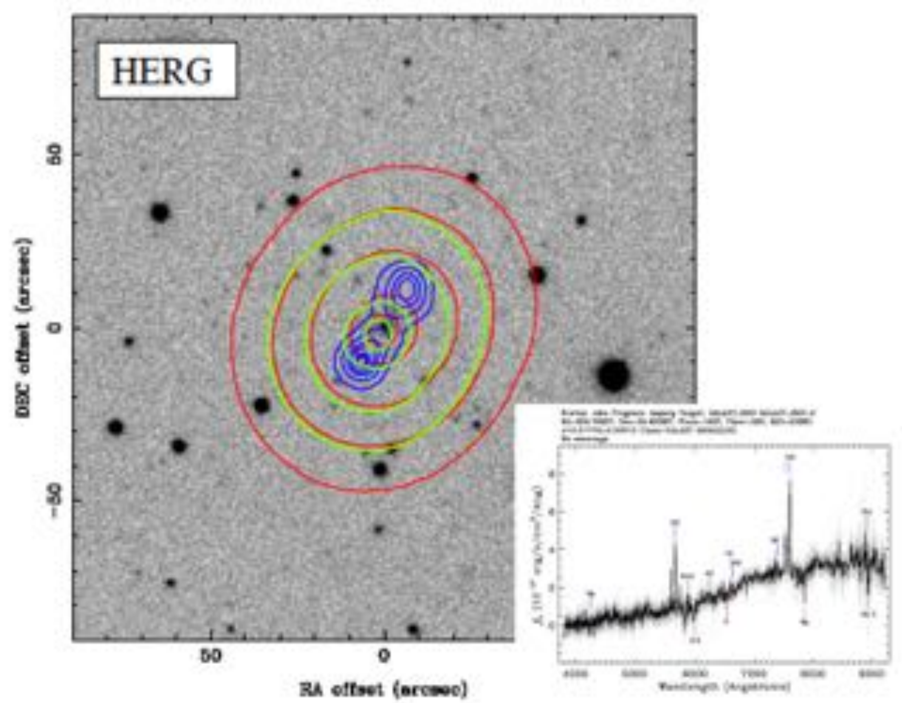
- Radiative-mode AGN (HERG & QSO)
  - cold gas accretion
- Jet-mode AGN (LERGs)
  - hot gas accretion

- Combine:
  - NRAO VLA Sky Survey (NVSS)
    - 1.4 GHz with polarization at 45” (Condon+98)
    - 82,768 polarized sources (>8σ)
  - Sloan Digital Sky Survey (SDSS)
    - 10,344 radio-loud AGN with accretion state classifications (Best & Heckman 2012)
    - 4,003 radio-loud QSOs (Hammond+12)

- 741 LERGs, 55 HERGs, 815 QSOs

- What 1.4 GHz integrated polarization tell us?
  - Intrinsic order and large-scale uniformity of jet/lobe magnetic field structure
  - Depolarization caused by the effect of Faraday rotation





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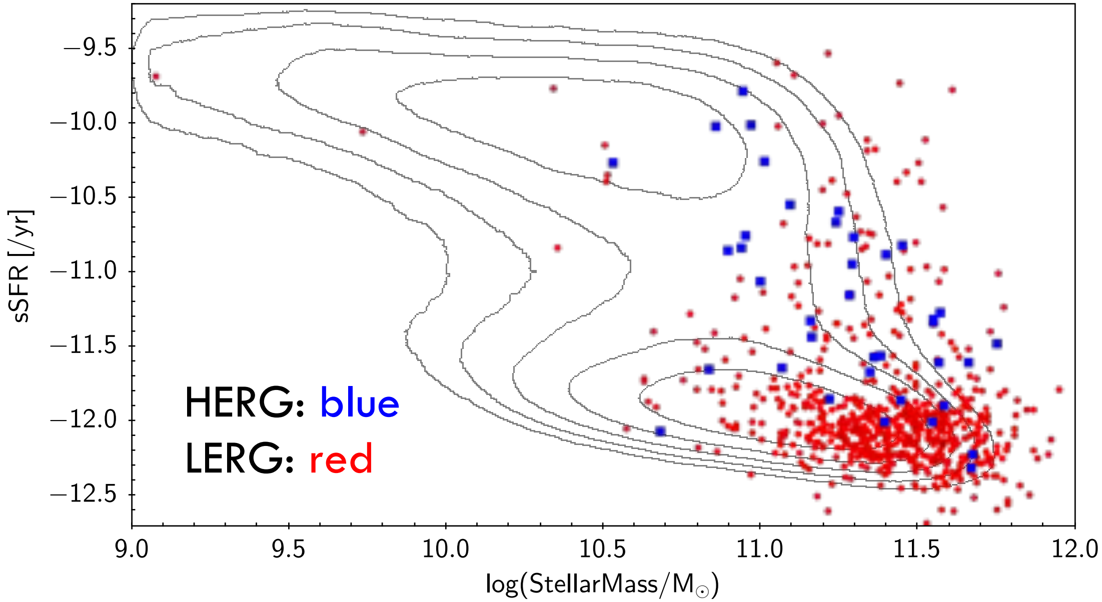
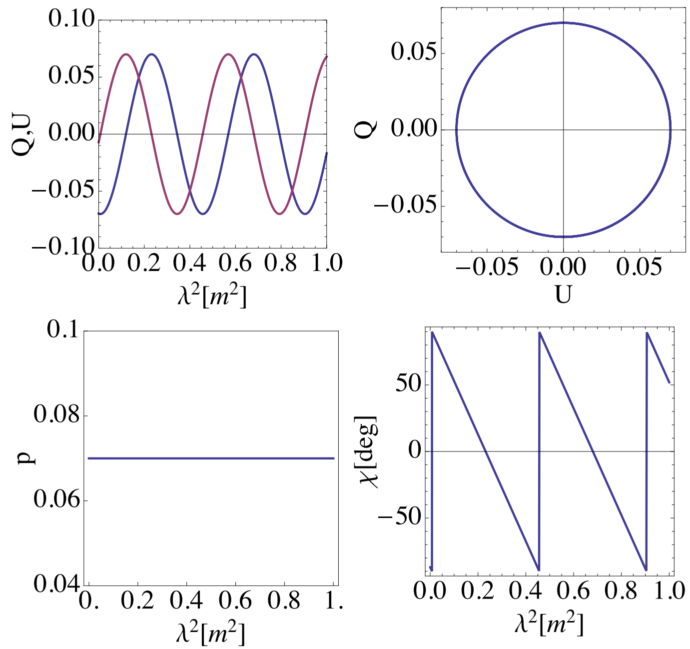
Host galaxy properties

- Distribution of polarized HERGs and LERGs in sSFR vs stellar mass plane
- All the polarized radio-loud AGN (with redshift) in the local Universe (excluding QSOs)
- Host galaxies of polarized HERGs typically have bluer colours than the LERGs.
- Consistent with HERGs host galaxy having substantial cold gas supply and LERGs in queiscient ellipticals with hot gas halos (cf. Heckman & Best 2014)



Grey contours: all SDSS galaxies in Brinchmann et al. (2004)

Integrated polarization ($\Pi_{1.4\ \mathrm{GHz}}$)



$$P = Q + iU$$

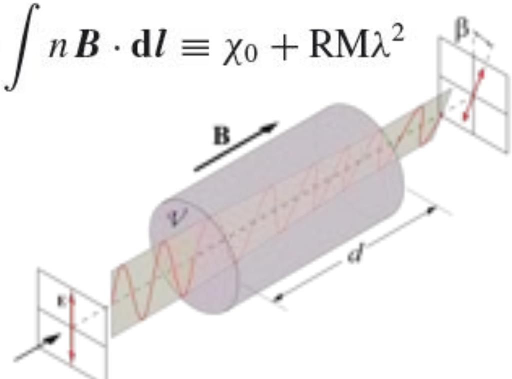
$$P = p_0 e^{2i(\chi_0 + \mathrm{RM}\lambda^2)}$$

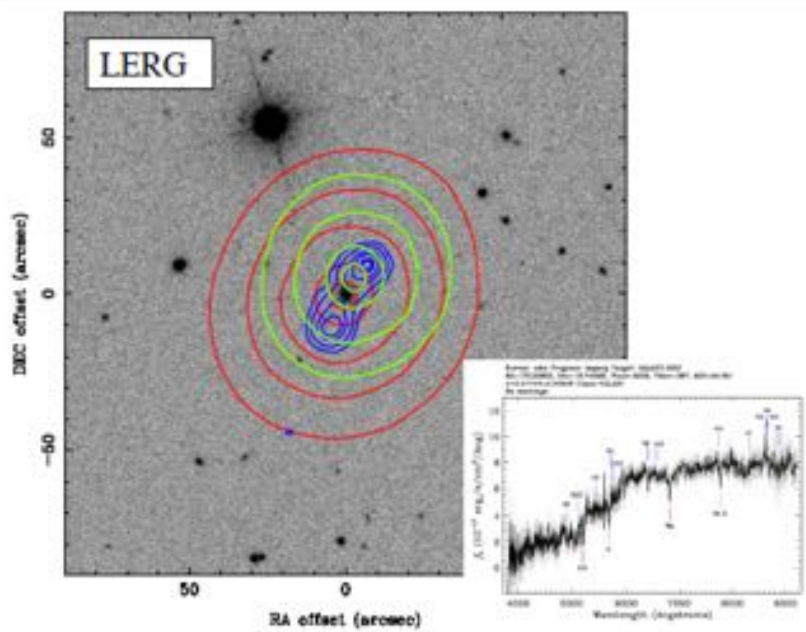
$\mathrm{RM} = -7\ \mathrm{rad\ m^{-2}}$
$p_0 = 7\ \%$
$\chi_0 = 93°$

Rotation measure: $\mathrm{RM} = \frac{d\chi}{d\lambda^2}$

- Ideal Faraday thin case rarely observed

$$\chi_{\mathrm{obs}} = \chi_0 + \frac{e^3\lambda^2}{8\pi^2\varepsilon_0 m^2 c^3}\int n\,\boldsymbol{B}\cdot\mathbf{d}\boldsymbol{l} \equiv \chi_0 + \mathrm{RM}\lambda^2$$

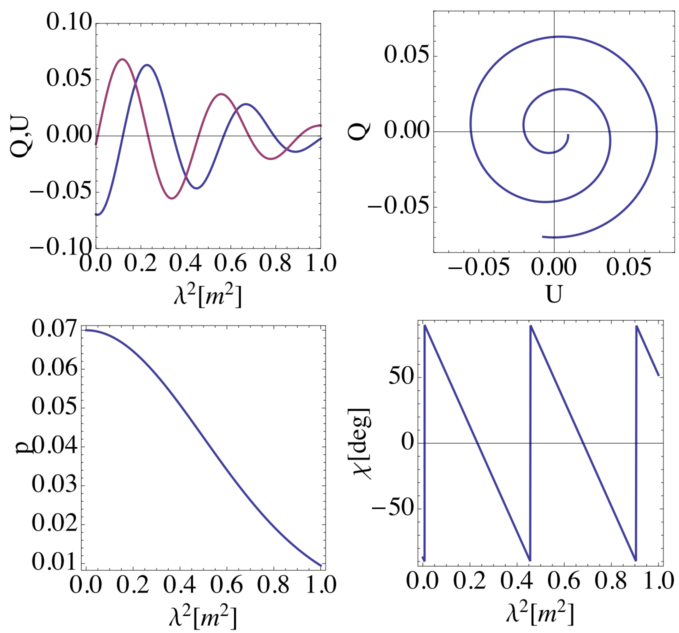


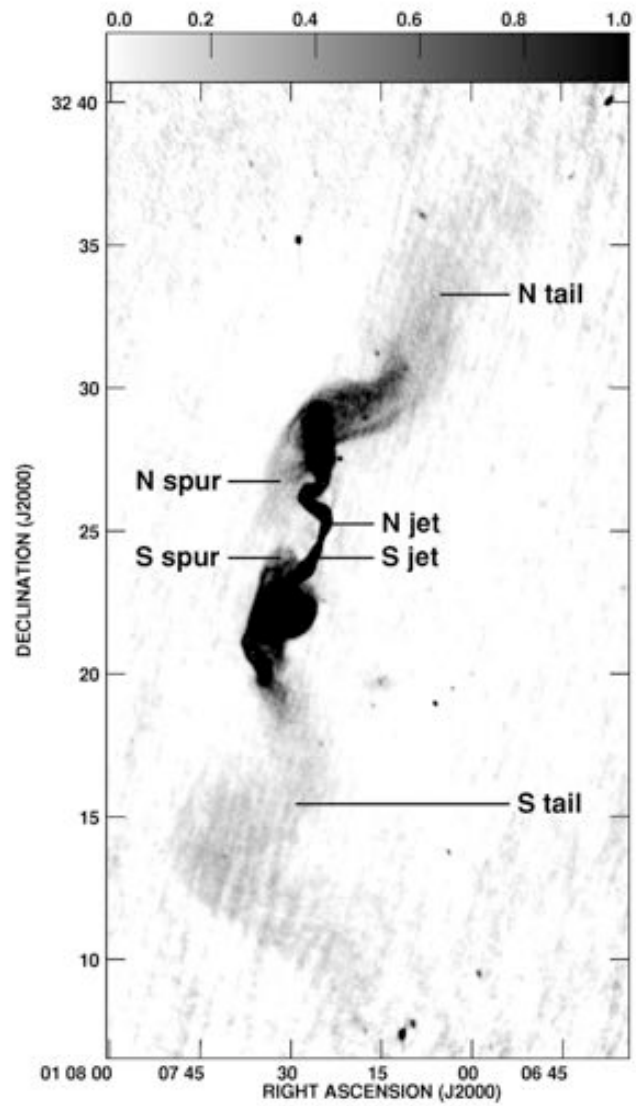


Depolarization: probe of the environment

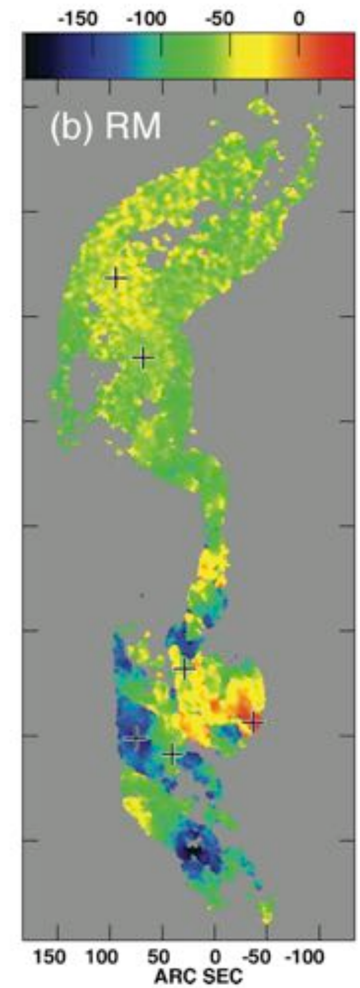
- External Faraday Dispersion

Burn Law: $P = p_0 e^{2i\chi} e^{-2\sigma^2 \lambda^4}$



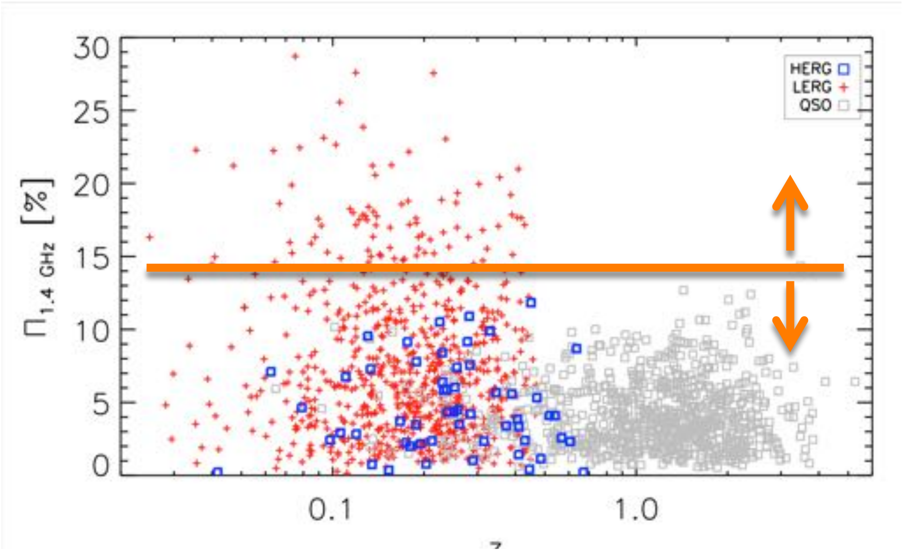


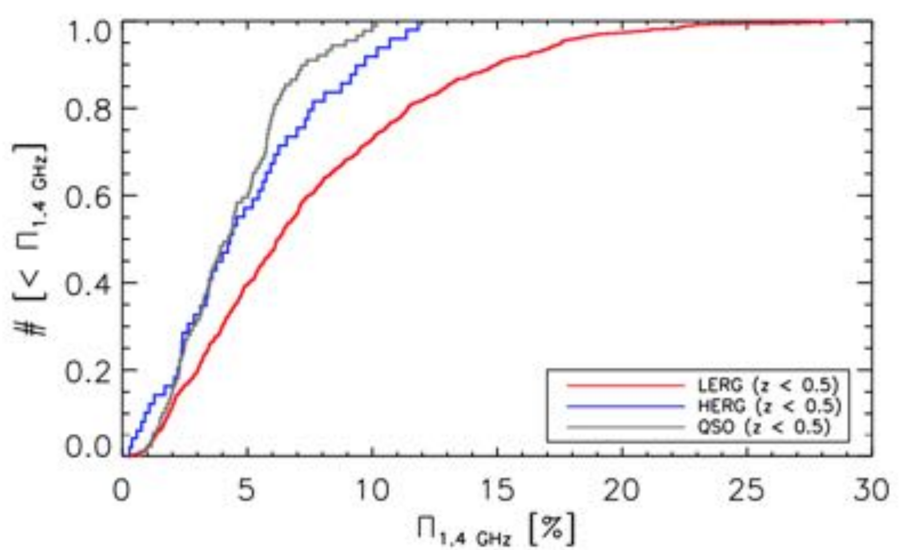
Laing+08



Polarized LERGs and HERGs/QSOs

- 741 LERGs, 55 HERGs, 815 QSOs
  - $z_{median\_LERG} = 0.18$, $\Pi_{1.4\ GHz\_med\_LERG} = 6.2\%$
  - $z_{median\_HERG} = 0.25$, $\Pi_{1.4\ GHz\_med\_HERG} = 4.1\%$
  - $z_{median\_QSO} = 1.26$, $\Pi_{1.4\ GHz\_med\_QSO} = 3.7\%$
- LERGs dominate in the local universe
- Restricting sample to $z < 0.5$:
  - 741 LERGs, 55 HERGs, 89 QSOs
  - ~5 times more polarized LERGs
- LERGs can achieve integrated degrees of polarization ($\Pi_{1.4\ GHz}$) up to ~30%
- HERGs & radio-loud QSOs limited to $\Pi_{1.4\ GHz} < 15\%$
- Different $\Pi_{1.4\ GHz}$ distribution for radiative-mode and jet-mode AGN (KS test: >10σ)
  - ~6σ for $z < 0.5$
  - ~3σ for LERGs vs HERGs only



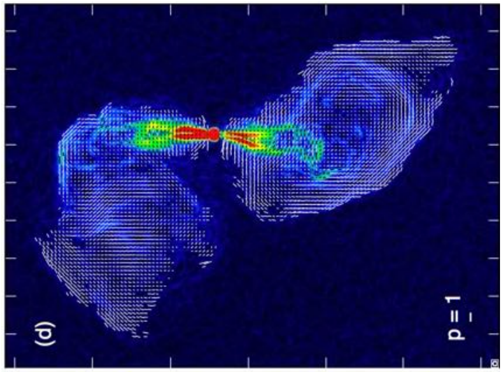


Intrinsic magnetic field

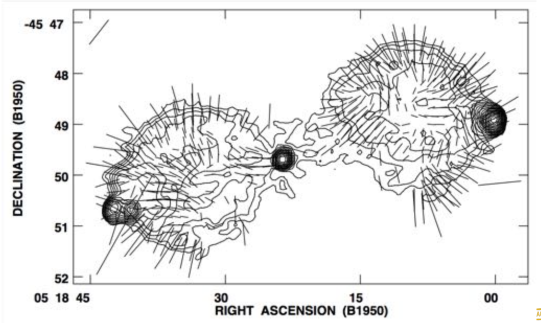
- HERGs (and radio-loud QSOs) restricted in the maximum integrated fractional polarization they can achieve at 1.4 GHz (<~15%)
- LERGs can achieve $\Pi_{1.4\ \mathrm{GHz}}$ up to ~30%

- What causes difference in $\Pi_{1.4\ \mathrm{GHz}}$ between radiative-mode and jet-mode AGN?

- Different intrinsic magnetic field properties:
  - LERGs with FRI morphology
    - more uniform magnetic fields => higher $\Pi_{1.4\ \mathrm{GHz}}$?
  - HERGs with FRII morphology
    - hotspots dominate, polarization cancellation?



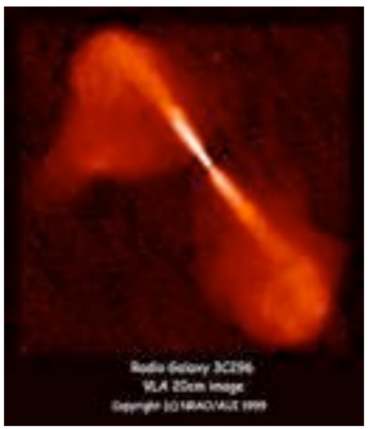
Laing et al. (2011)



Perley et al. (1997)

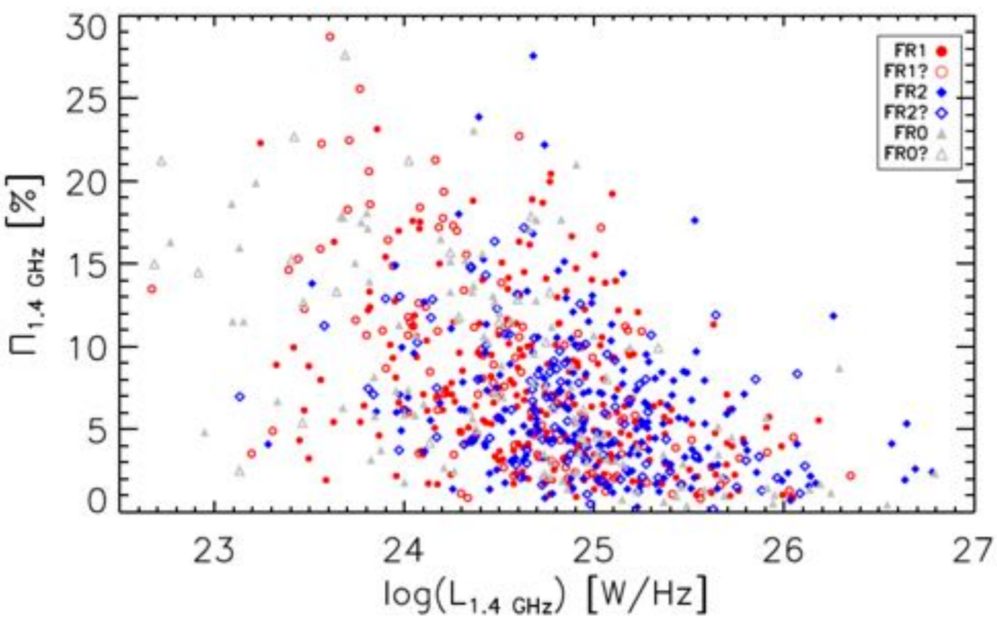
LERG/HERG vs FRI/FRII

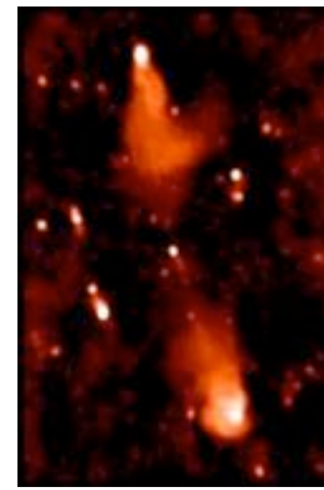
- FIRST radio morphological classification (5” resolution)
  - c.f. Best (2009), Lin et al. (2010), Gendre et al. (2013)



FRI

- HERG: 25% FRI, 75% FRII
- LERG: 56% FRI, 44% FRII





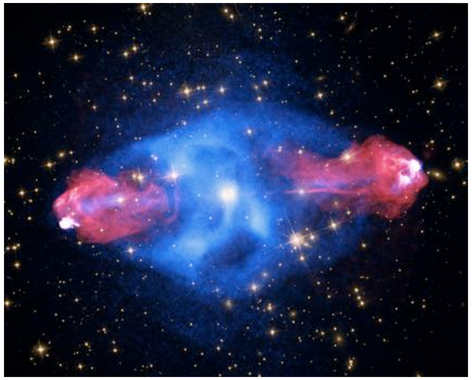
FRII

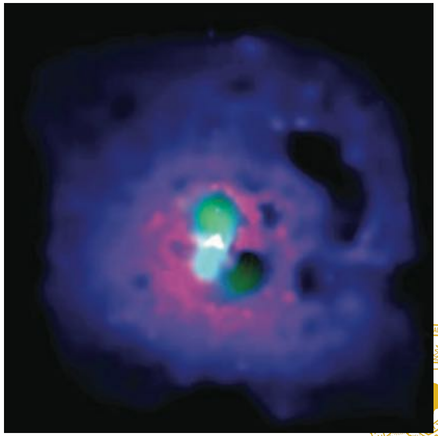
(Magnetoionic) environment

- HERGs (and radio-loud QSOs) restricted in the maximum integrated fractional polarization they can achieve at 1.4 GHz (<~15%)
- LERGs can achieve $\Pi_{1.4\ GHz}$ up to ~30%

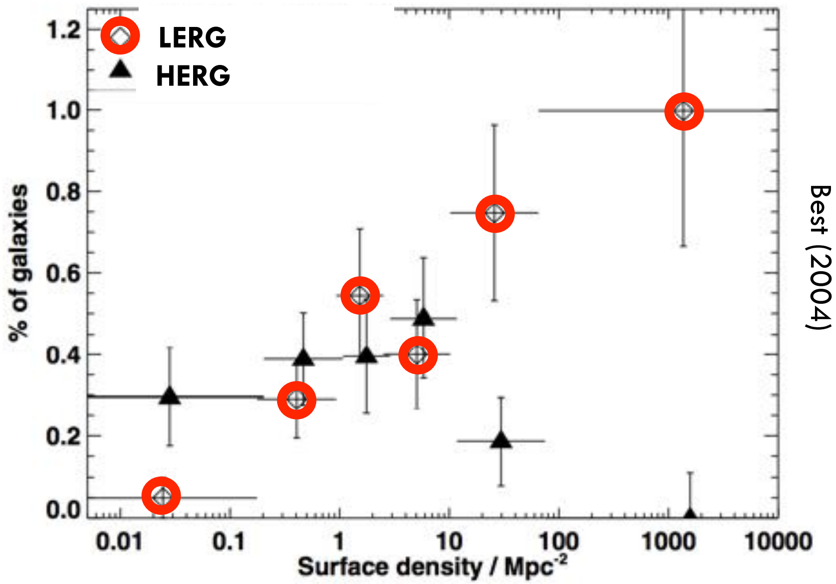
- What causes difference in $\Pi_{1.4\ GHz}$ between radiative-mode and jet-mode AGN?

- Different environments:
  - High $\Pi_{1.4\ GHz}$ LERGs in low density environments?
    - Less Faraday depolarization
  - HERGs in denser environments?
    - More Faraday depolarization



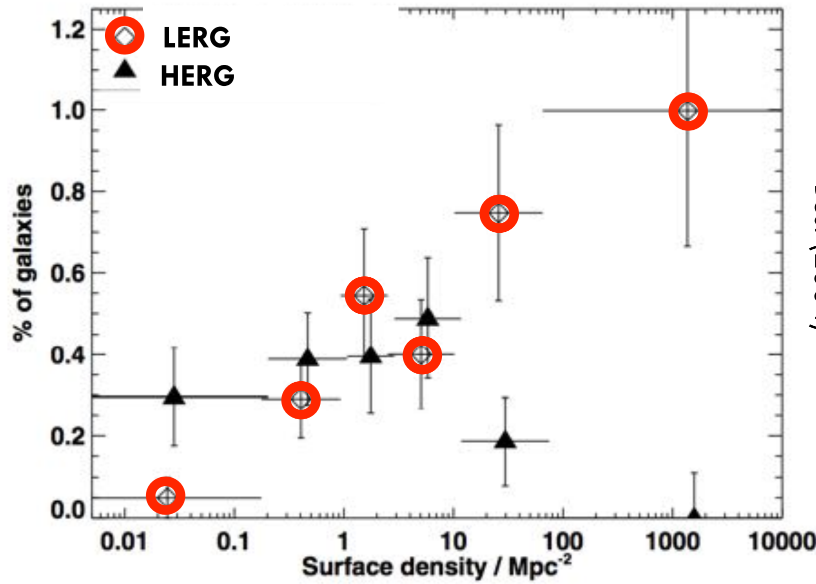


LERG environments



Best (2004)

LERG (magnetoionic) environments



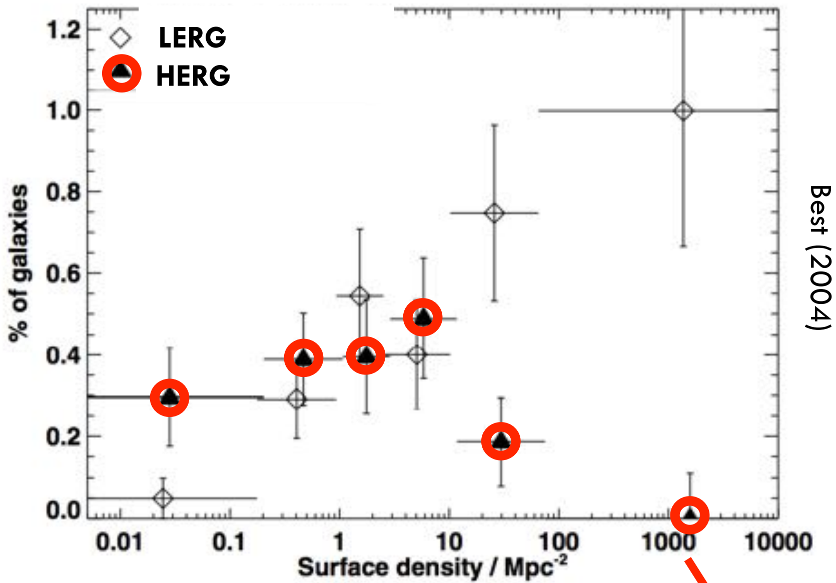
Best (2004)

Lower gas densities in IGM of poor groups. Magnetic fields??

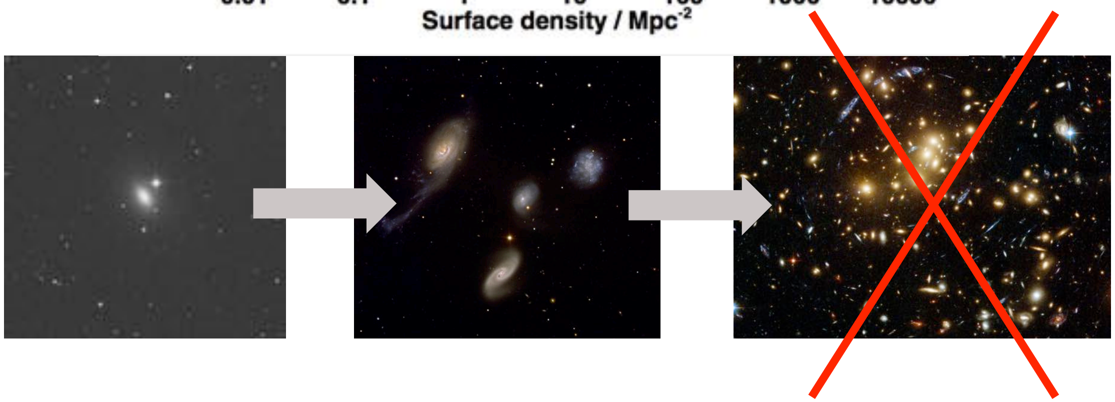
Strong, turbulent magnetic fields in dense gas environment (eg. Bonafede+10)

High $\Pi_{1.4\ \mathrm{GHz}}$ → Low $\Pi_{1.4\ \mathrm{GHz}}$

HERG environments



Best (2004)



But HERGs have higher radiative luminosities and jet power…

Eddington-scaled accretion rate

- L_{rad}: AGN radiative luminosity from OIII emission line (Heckman+04)

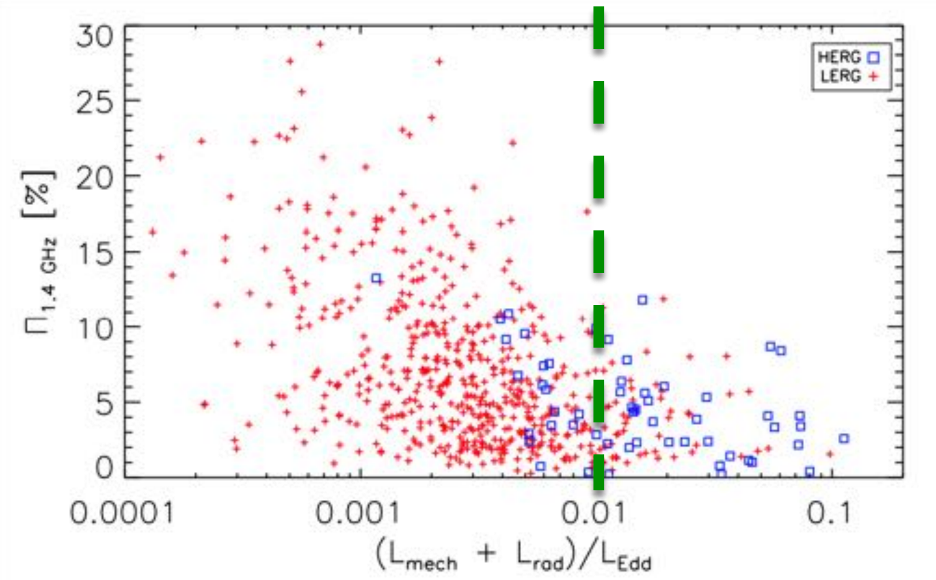
$$L_{\rm rad} = 3500 L_{\rm O\,III}$$

- L_{mech}: Jet mechanical luminosity (Cavagnolo+10, Godfrey & Shabala 2013)

$$L_{\rm mech} = 7.3 \times 10^{36} (L_{1.4\,\rm GHz}/10^{24}\ \rm W\,Hz^{-1})^{0.70}\ W.$$

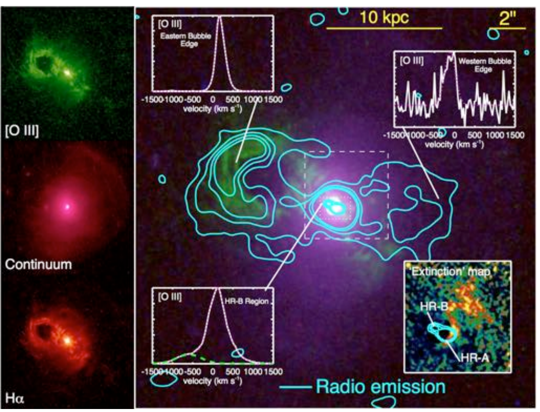
- Black hole mass from M_{BH}-σ_* relation (Tremaine+02)
- Eddington-ratio (λ): $\lambda = (L_{\rm rad} + L_{\rm mech})/L_{\rm Edd}$

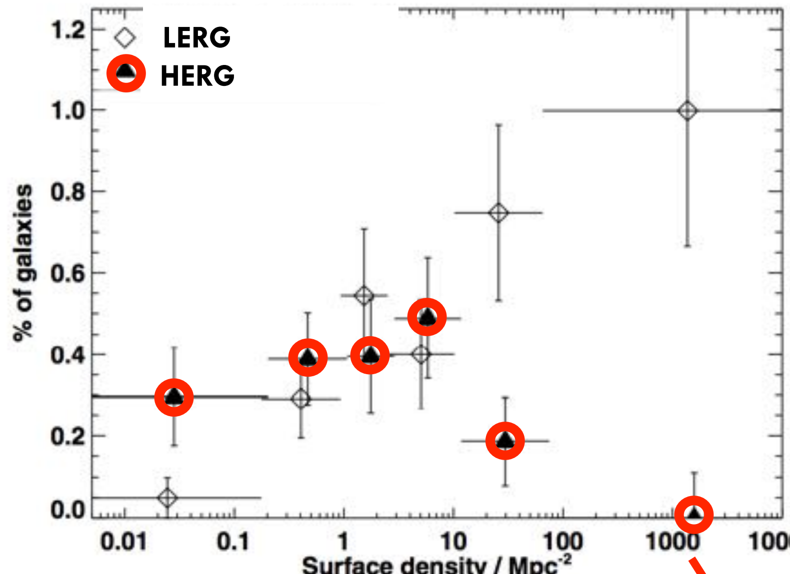
- HERGs: $\lambda \sim$ 1% to 10%
- LERGs: $\lambda <$ 1%
- LERGs: highest $\Pi_{1.4\ GHz}$ at low λ
- KS test on $\Pi_{1.4\ GHz}$ >< 1% (6.5σ)
- High λ LERGs: 'efficient' LERGs or in dense clusters (Mingo+14)



HERG (magnetoionic) environments

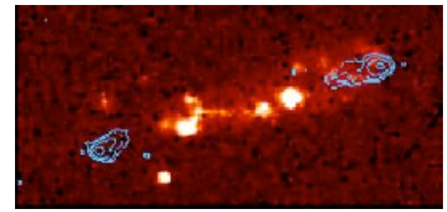
Large amounts of ionising radiation from central engine (Harrison+14)

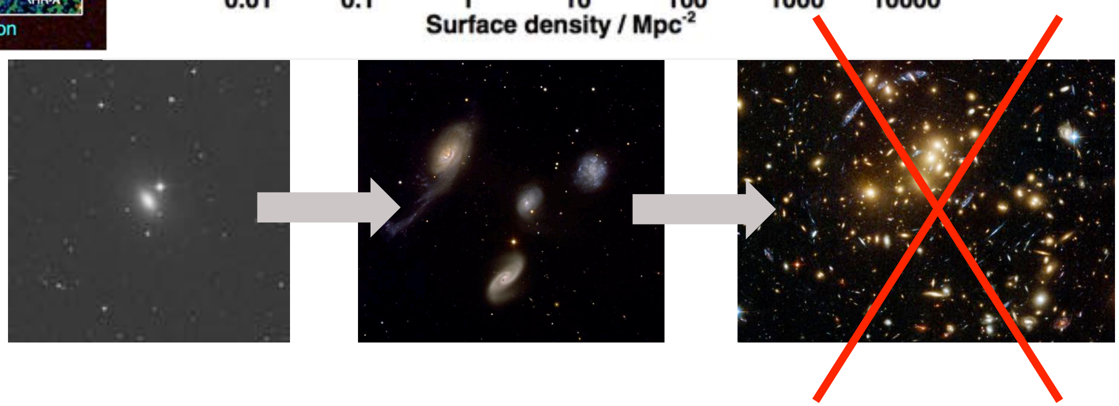




Best (2004)

Extended emission line regions correlated with regions of high depolarization (eg. McCarthy+87)





Lower $\Pi_{1.4\ \mathrm{GHz}}$ than LERGs in similar environment…?

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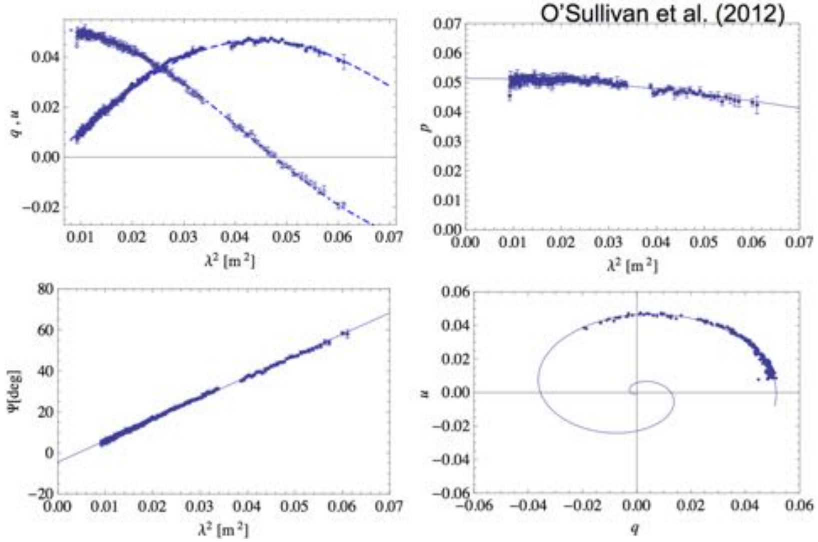
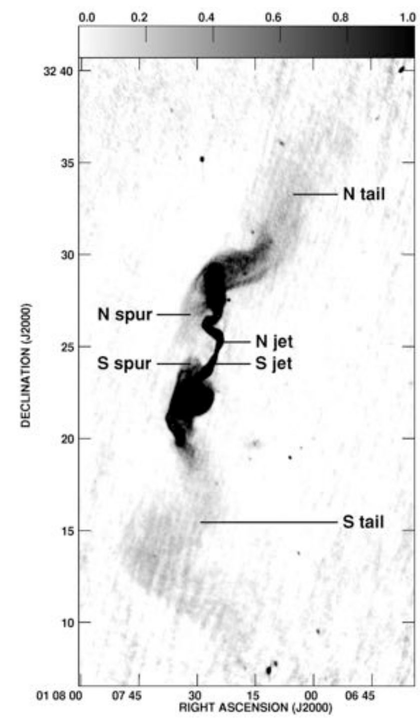
HERG/LERG magnetoionic environments

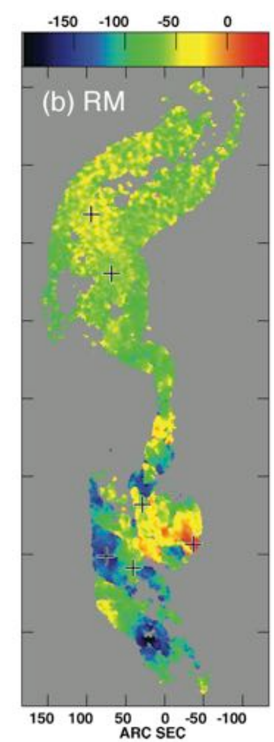
- Test hypothesis with new broadband radio polarization data
  - 79 HERGs, 83 LERGs
- Directly measure depolarization local to the source (σ_{RM})

$$P = p_0 e^{2i(\chi_0 + RM\lambda^2)} e^{-2\sigma_{\rm RM}\lambda^4}$$



Laing+08



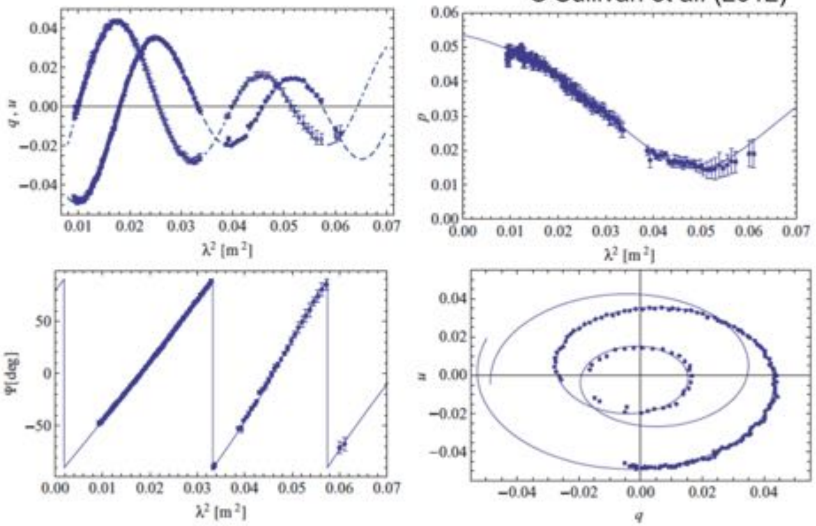


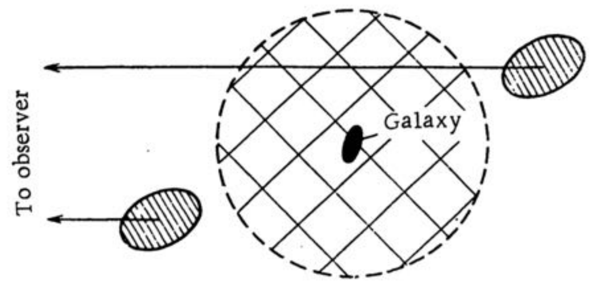
HERG/LERG magnetoionic environments

- Test hypothesis with new broadband radio polarization data
  - 79 HERGs, 83 LERGs
- Measure Faraday rotation local to the source (RM_1-RM_2)

$$P = p_{01} e^{2i(\chi_{01} + \mathrm{RM1}\lambda^2)} + p_{02} e^{2i(\chi_{02} + \mathrm{RM2}\lambda^2)}$$

O'Sullivan et al. (2012)





Slysh (1965)

Fig. 4. Relative position of the radio-emitting regions and the magnetized medium.

$$\mathrm{RM1} = 108.2 \pm 0.3 \text{ rad m}^{-2}$$
$$\mathrm{RM2} = 78.8 \pm 0.5 \text{ rad m}^{-2}$$

Next generation radio surveys

- ASKAP: Australian SKA Pathfinder
  - POSSUM: Polarization Survey of the Universe's Magnetism
  - Phased array feeds: 30 sq deg field of view
  - 700 – 1800 MHz
  - Early science: starting 2016 (~10k RM + depolarization)
  - Full survey: ~1 – 3 million RMs (~40k currently known)
- SKA-1 2020+…

POSSUM
POLARISATION SKY SURVEY OF THE UNIVERSE'S MAGNETISM

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Summary

- Strong evidence building (both observationally & from simulations) supporting AGN jet powering through extraction of spin energy of SMBH by dynamically important magnetic fields

- Magnetic field properties of radio-loud AGN in different accretion modes
  - Radiative-mode AGN: fueled by cold gas accretion
  - Jet-mode AGN: fueled by hot gas accretion
    - Different large scale gaseous environments responsible for the different accretion states of radiative-mode and jet-mode AGN (Best+05, Hardcastle+07)

  - Difference in $\Pi_{1.4\ GHz}$ between radiative-mode and jet-mode AGN (O'Sullivan et al. 2015)
    - Best explanation: due to the local environments of the radio sources, in terms of both the ambient gas density and the magnetoionic properties of this gas
  - Future work: More precise measurements + greater statistical power
    - Investigate if large scale magnetised environments can influence the formation of powerful AGN jets