Fundamental modes of AGN activity in the local Universe and beyond

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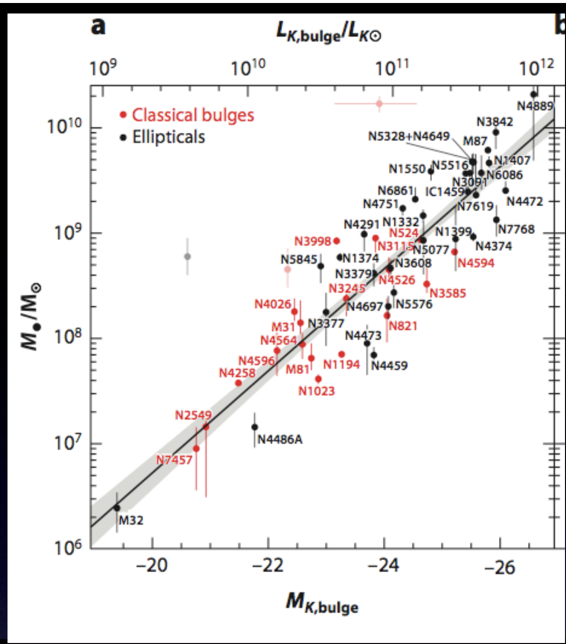
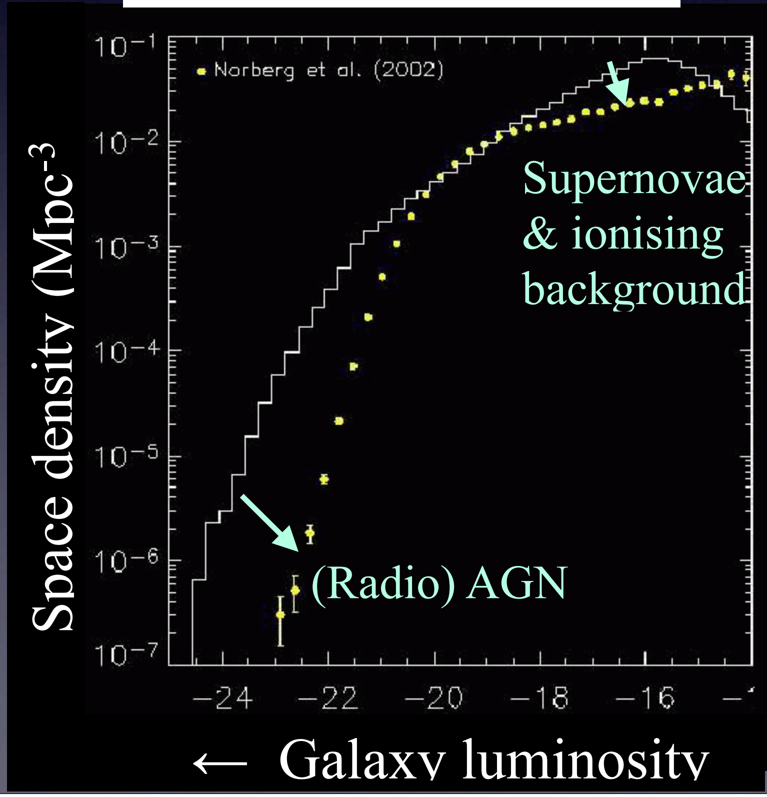
"AGN feedback"

"AGN feedback" is currently postulated to explain many issues in galaxy evolution:

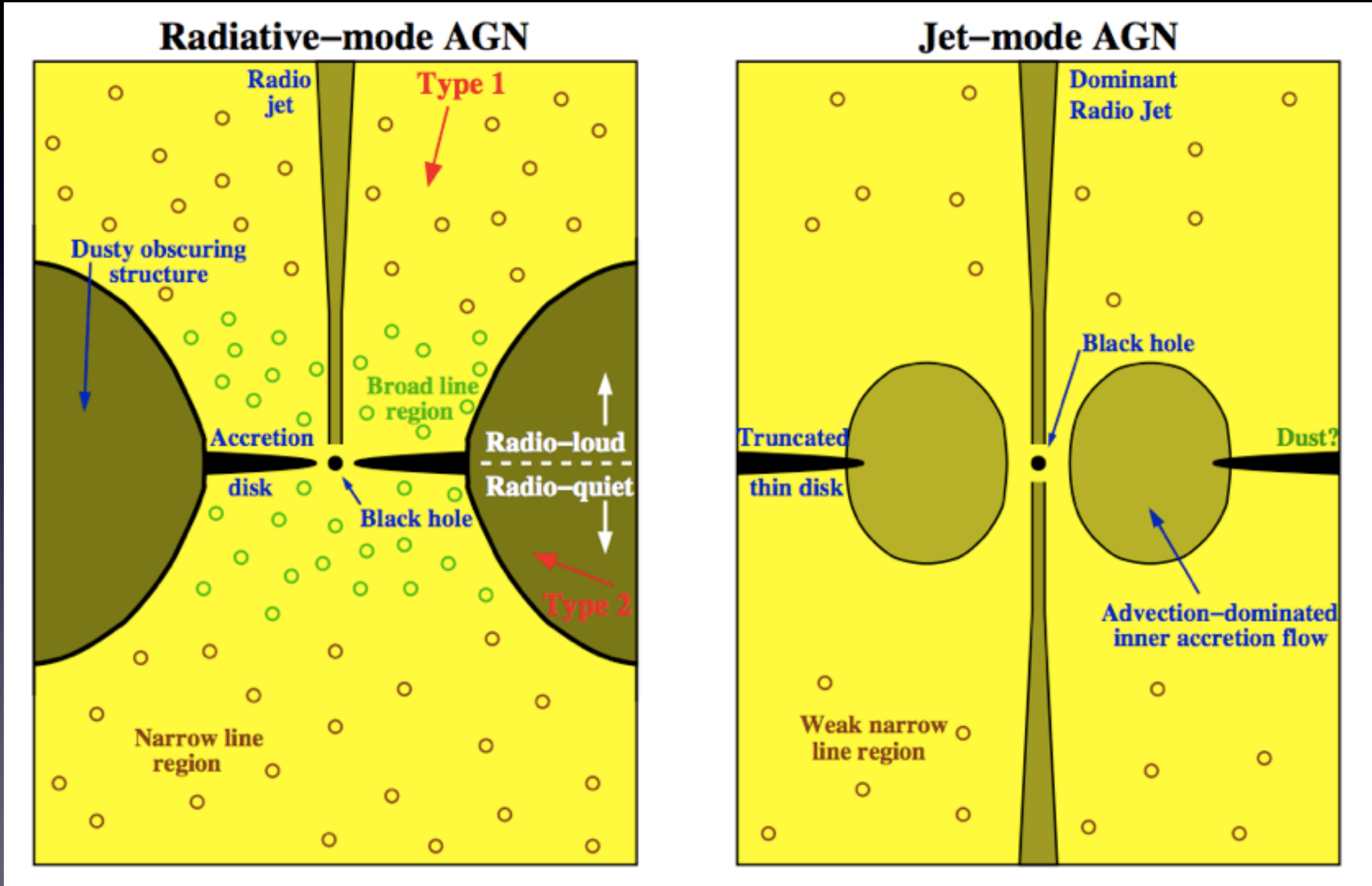
- The origin of the black hole mass vs bulge mass relation (implies connection between galaxy and black hole growth)
- Avoidance of over-production of massive galaxies
- "Old, red and dead" appearance of massive ellipticals

(Radio-loud?) AGN activity is thought to be responsible for these latter two.

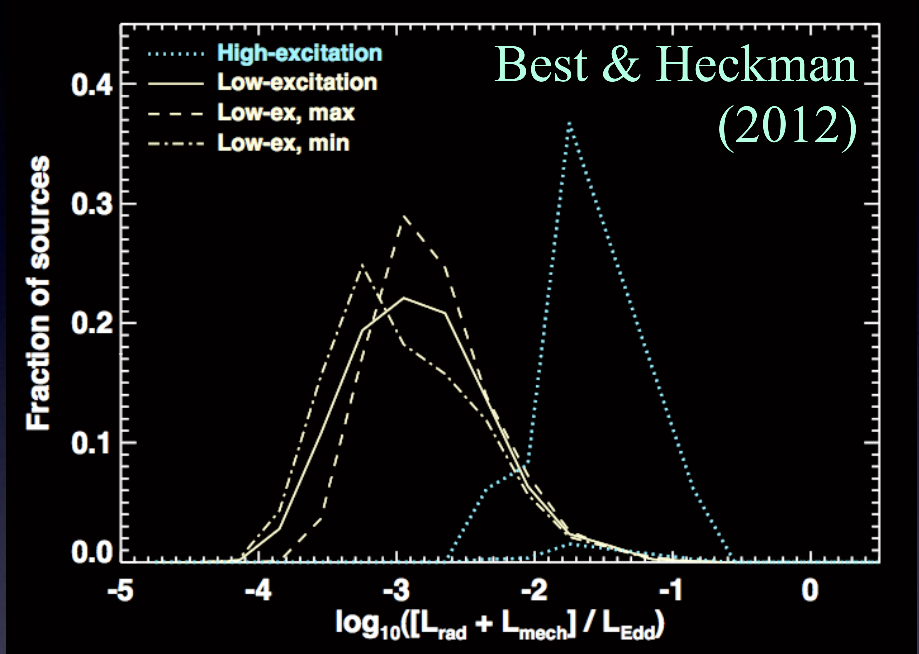


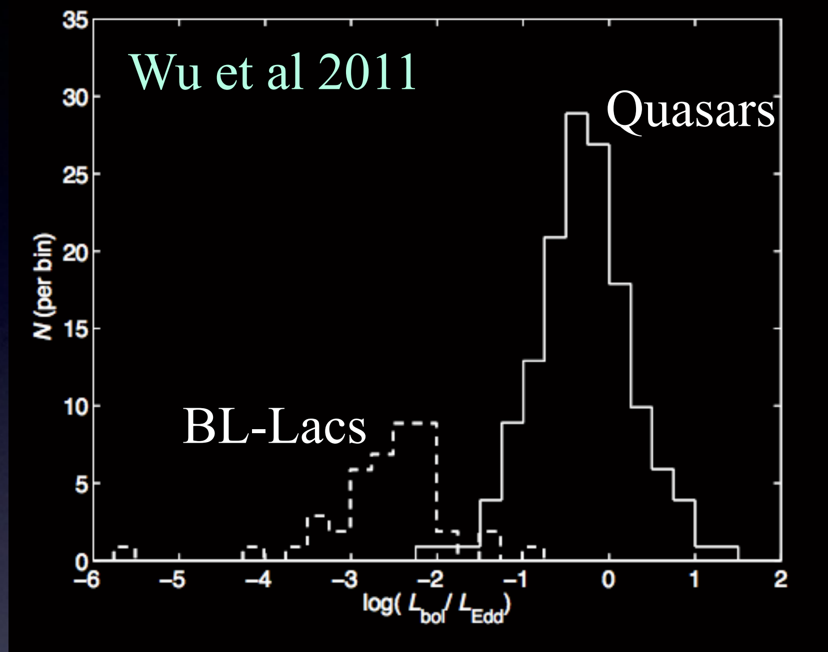


Two modes of AGN activity



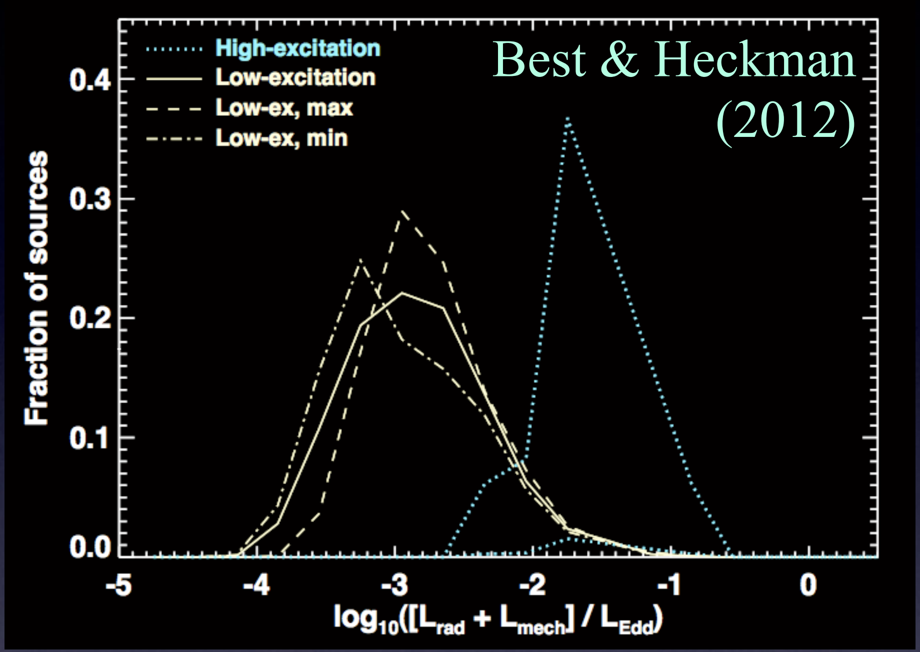
Eddington rates of radio AGN

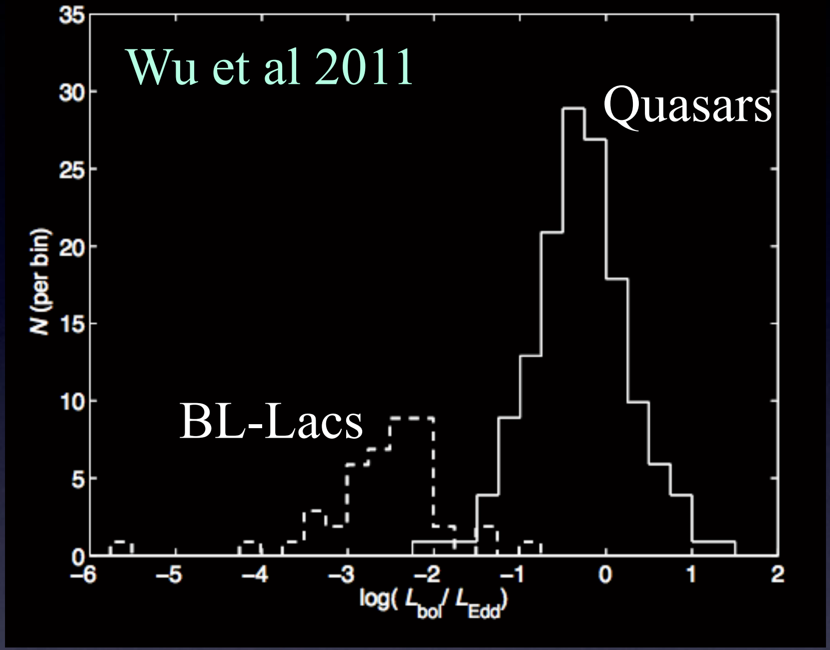




- Best & Heckman (2012): used radio galaxies in Sloan Digital Sky Survey (SDSS), classified by type, and estimated accretion rates
  - Clear dichotomy in Eddington-scaled accretion rates between the two source classes
- Similar dichotomy seen between BL-Lacs and flat-spectrum quasars - the beamed counterparts (e.g. Wu et al 2011)

Eddington rates of radio AGN

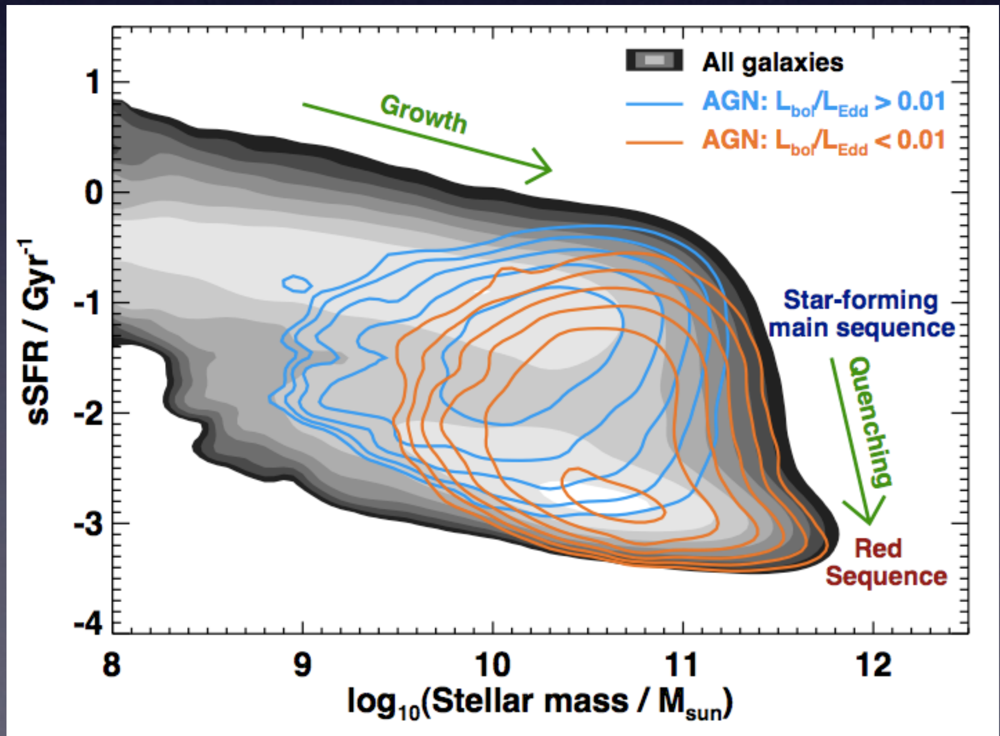




- Matches theoretical expectations for a change in the nature of the accretion flow from standard thin discs to advection-dominated accretion flows (ADAFs) at accretion rates below a few % Eddington

Local galaxies and their AGN

- Look at the demographics of galaxies in local Universe
- AGN selected from SDSS by emission lines or radio emission
  - Radiative-mode AGN: responsible for quenching process?
  - Jet-mode AGN: responsible for maintaining quenched state?



Radiative-mode AGN

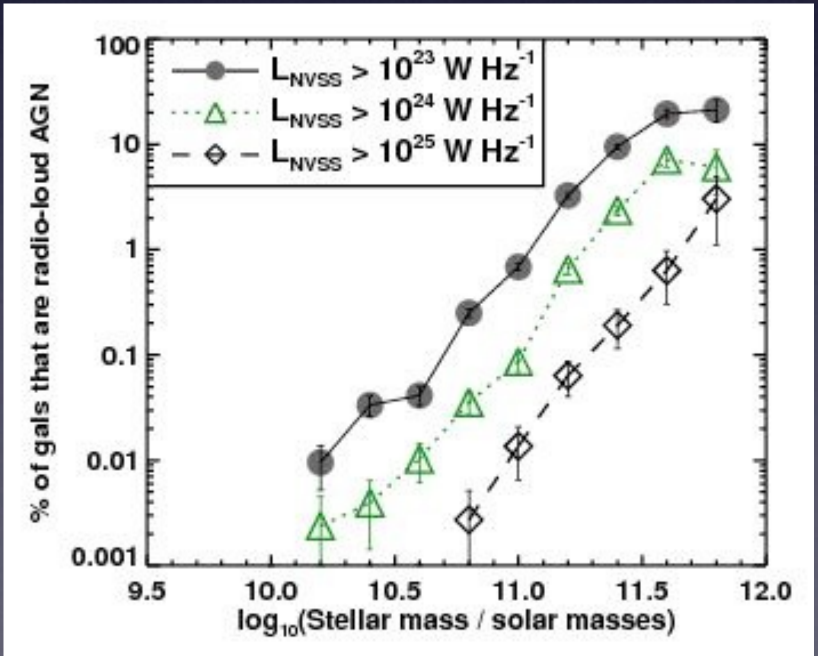
Not the focus of this talk (mostly these are radio-quiet, though they include the high-excitation radio AGN), but some relevant points:

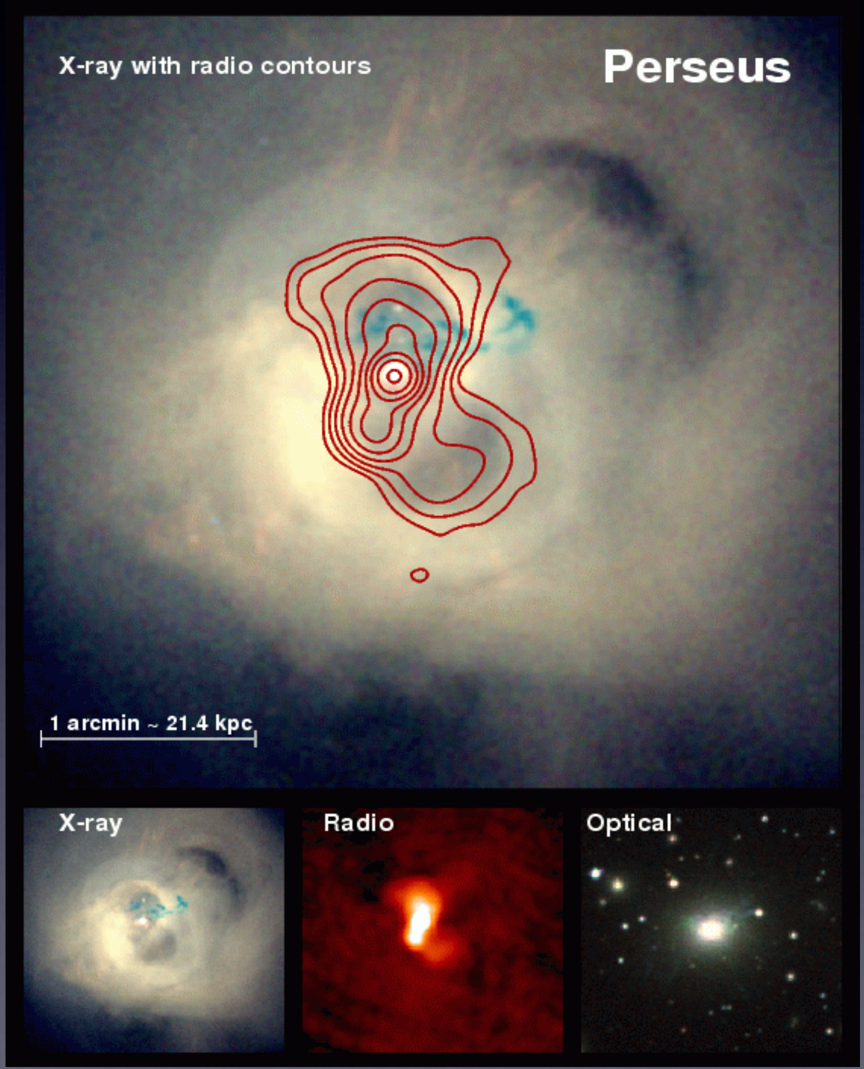
- see e.g. Heckman & Best 2014, ARA&A for details

- AGN activity is strongly connected with star-formation activity
  - more specifically, depends on star-formation near the nucleus
  - radiative-mode AGN activity needs dense cold gas in nucleus
- At fixed mass and star formation rate, radiative AGN activity is independent of merger activity, and environment
  - AGN needs nuclear gas supply but doesn't care where that comes from
  - typical Seyfert: secular fuelling by non-axisymmetric perturbations (eg. bars)
- Specific SFRs of AGN hosts are typical of all SF galaxies, at all z.
  - Radiative-AGN evolution, like SF, driven by increase in gas availability
- Little evidence for large-scale AGN-driven outflows in 'typical Seyferts'
  - Situation may be different for most powerful AGN, and radio-loud AGN

Fuelling of powerful jet-mode AGN

- Hot gas is the most viable fuelling source for powerful radio sources
  - found in massive galaxies
  - often in groups and clusters
  - have X-ray emitting hot gas haloes





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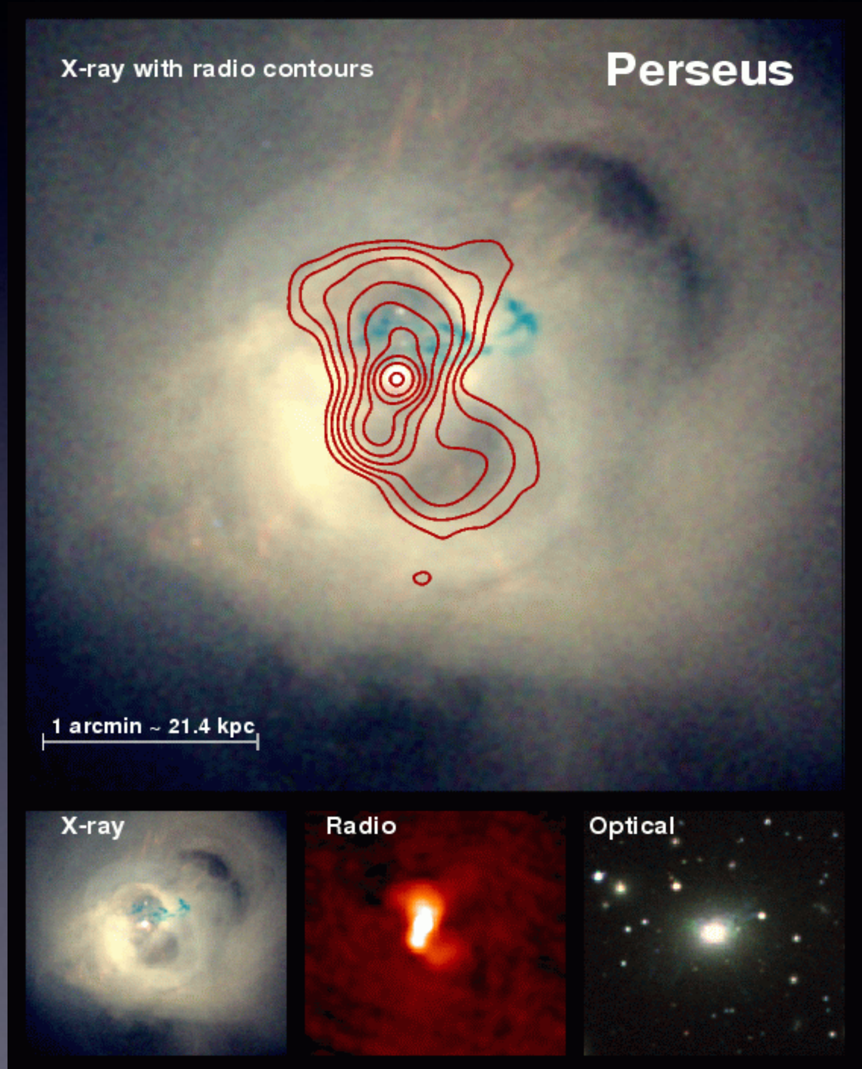
- Bondi accretion?
  - $dM_{Bondi}/dt = 4 \pi \lambda (G M_{BH})^2 \rho / c_s^3$
  - insufficient to explain energetics
- Gas is cooling: hydro simulations (Gaspari et al. 2013) suggest cold chaotic accretion at ~100 x Bondi
  - also show that accretion rate can respond quickly to system changes
    - ★ required feature of feedback



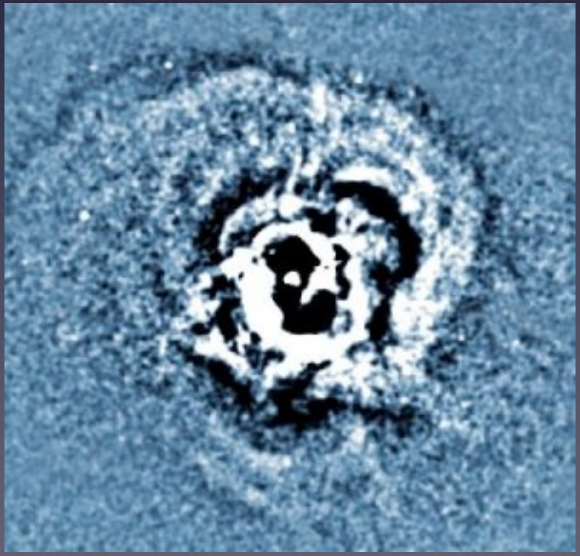
Jet-mode AGN feedback

Conditions just right for an AGN feedback cycle:

- AGN fuelled from cooling hot gas
- AGN jets deposit the energy back into the same hot gas

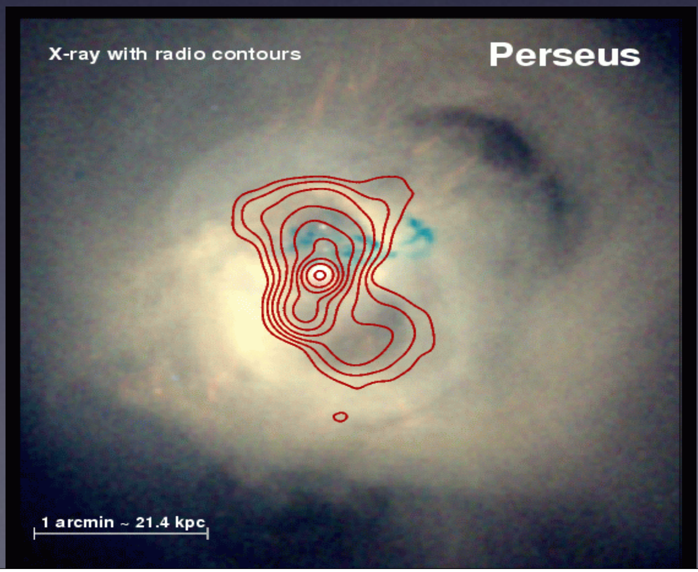
Radio source distributes energy around whole environment by dissipative sound/shock waves driven by expanding radio bubbles

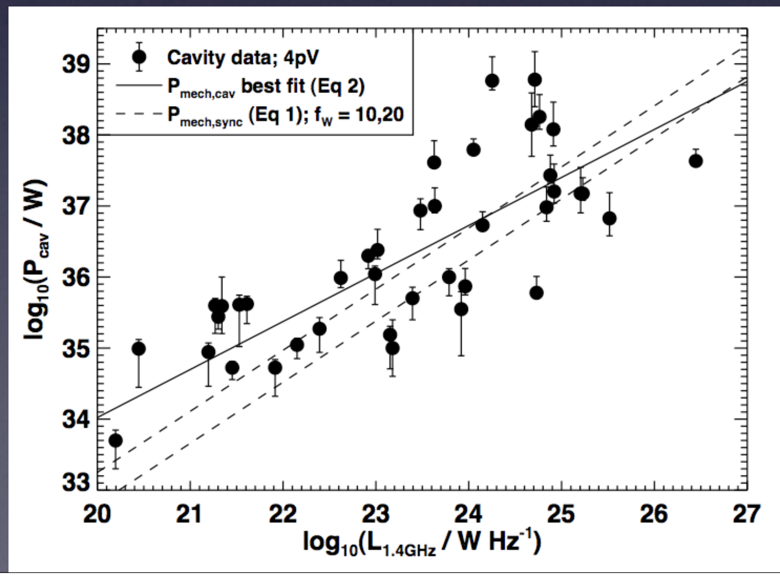
- cf. Perseus cluster studies of Fabian et al (2003,2005.2006)



Jet-mode AGN energetics

- One estimate uses cavities blown in hot gas by radio sources:
  - $E_{cav} = f_{cav}\, pV \quad (f_{cav} \sim 4)$
  - $P_{mech,cav} = 7 \times 10^{36} f_{cav} (L_{1.4GHz}/10^{25} \mathrm{W\,Hz^{-1}})^{0.68}$ W
- Alternative uses minimum energy condition for synchrotron
  - $P_{mech,sync} = 4 \times 10^{35} (f_W)^{3/2} (L_{1.4GHz}/10^{25} \mathrm{W\,Hz^{-1}})^{0.85}$ W
  - $f_W \sim$ 10-20 incorporates the uncertainty factors
    - ★ nature of jet plasma; low energy synchrotron cutoff; etc





Jet-mode AGN energetics

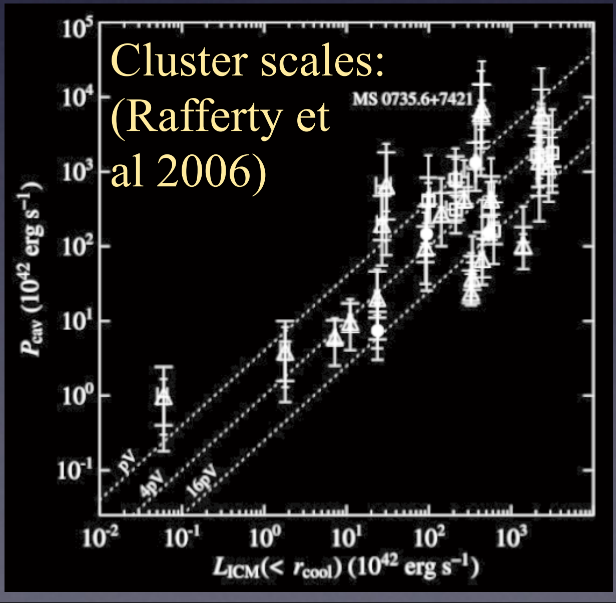
Energetics are (more than) sufficient to balance the gas cooling:

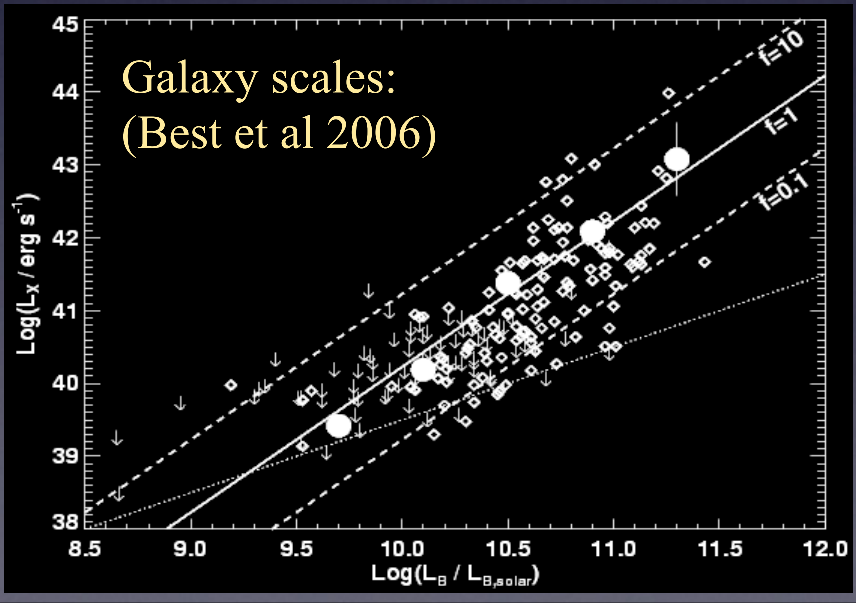
Cooling flow clusters:

- almost all contain active radio source
- instantaneous mechanical jet powers match X-ray cooling rates

Galaxy scales:

- instantaneous heating exceeds cooling, but most gals "switched off".
- time-averaged rate from recurrent activity (over-)balances cooling





A radio-AGN feedback cycle

Hot gas emits in X-rays and cools.
(faster in more massive systems)

Cooling rate increases; some gas falls onto the central black hole

Radio-AGN switched on. Jets deposit energy into surrounding gas

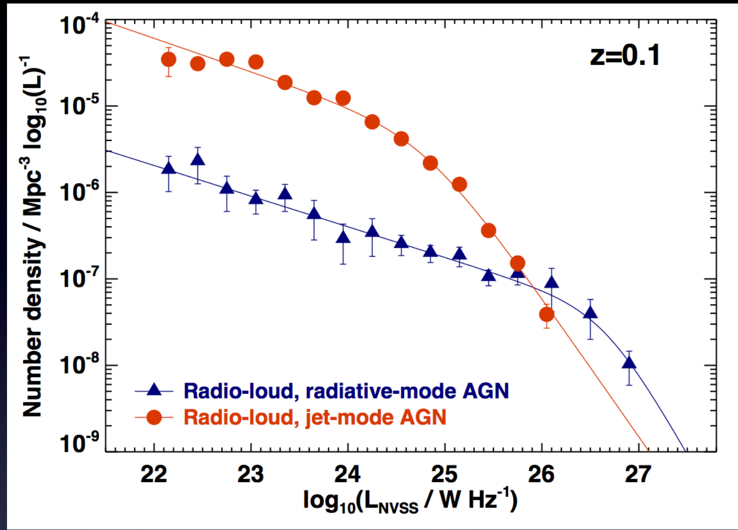
Hot X-ray gas is heated by AGN; gas cooling stops

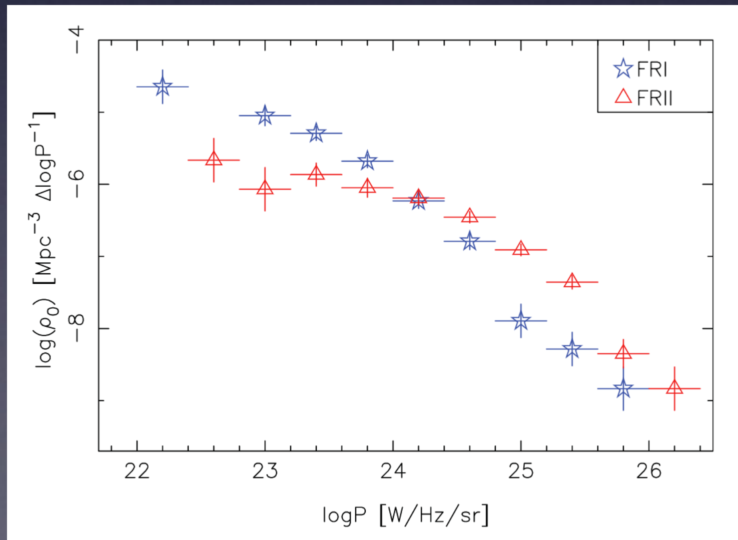
No more fuel for black hole, so radio-AGN is switched off

Radio-AGN act as a "cosmic thermostat" controlling the cooling of the hot gas. Maintains host galaxy as "old, red and dead"

Radio morphologies

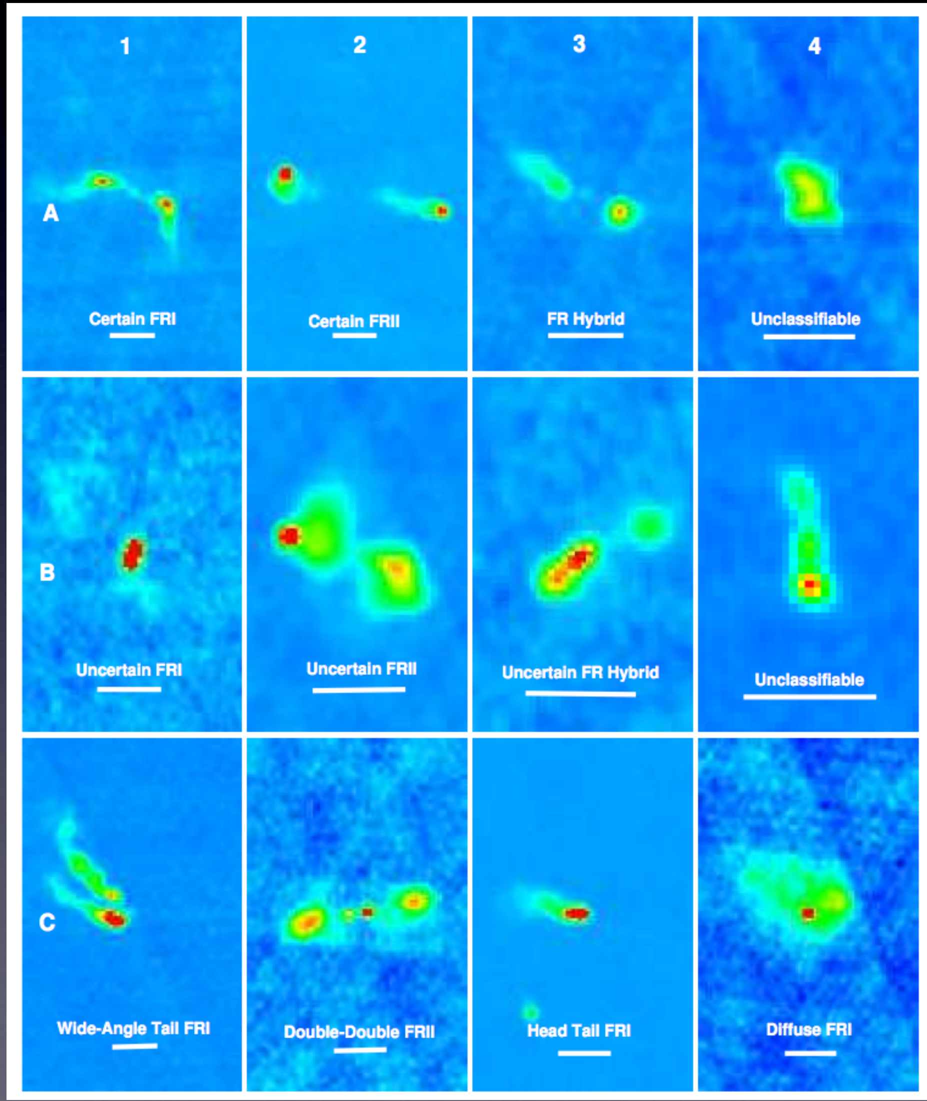
- Extended radio sources have also historically been classified by morphology, into Fanaroff-Riley Classes 1 and 2.
  - most FR1s are LERGs (few HERGs)
  - most FR2s are HERGs (but significant LERG population)
- What is the connection between morphology & excitation class?
  - just that both dichotomies depend on radio luminosity? (see LFs of Best et al 2012; Gendre et al 2013)





Radio morphologies

- Using SDSS sample, visually classified ~1300 extended local radio galaxies brighter than $S_{1.4GHz} = 40$mJy
  - Miraghaei & Best 2017, subm.
  - sample large enough to investigate origin of each of FR classification and HERG/LERG dichotomies, independent of the other
  - Also investigated difference between extended and compact objects



HERG/LERG vs FR1/2 differences

Many radio-AGN properties depend on radio luminosity & mass

- Match in these parameters, as well as morphology/excitation state
  - e.g. compare FR1/2 of same excitation state, mass and radio luminosity

Sample	FRII-FRI		HERG-LERG	
Matched properties	$L_{rad,t}$-$M_\star$		$L_{rad,t}$-$M_\star$	
Sample size	M=N=77		M=15, N=45	
Significance thresholds	D_{95}=0.22, D_{99}=0.26		D_{95}=0.40, D_{99}=0.48	
$L_{rad,c}$	0.58	>99%	-0.36	-
$L_{rad,t}$	-	-	-	-
R_{50}	-0.35	>99%	-0.10	-
g-r	0.21	-	0.36	-
4000Å break	0.20	-	0.74	>99%
R_{90}/R_{50}	0.32	>99%	0.45	>95%
μ_{50}	0.38	>99%	-0.30	-
M_{BH}	0.35	>99%	0.47	>95%
Density	0.36	>99%	0.43	>95%
Tidal	0.15	-	0.42	>95%
Richness	0.28	>99%	0.24	-
PCA1	0.30	>99%	0.53	>99%
PCA2	-0.31	>99%	-0.19	-
$L_{[OIII]}$	0.38	>99%	-0.90	>99%

HERG/LERG vs FR1/2 differences

Results confirm many previous results but without worry of biases:

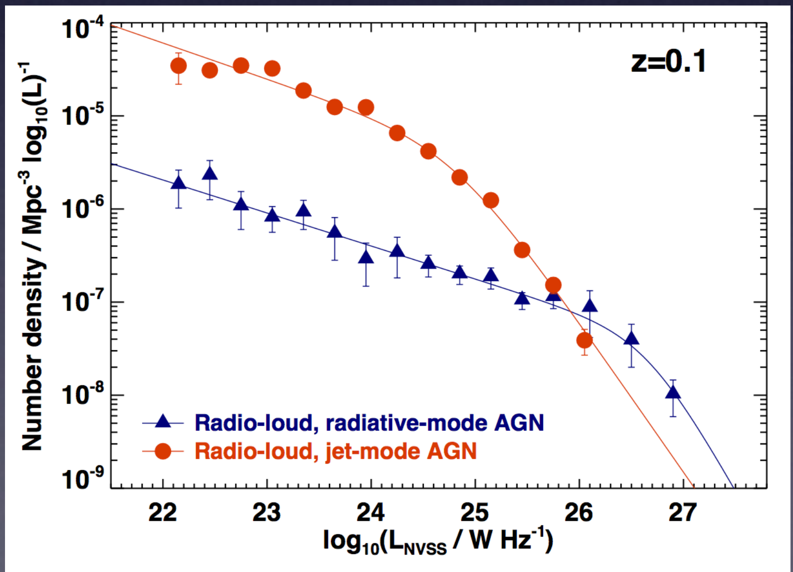
- HERG/LERG classification seems to depend on gas supply to galaxy:
  - HERGs are more likely to be in star-forming galaxies
  - LERGs favour denser environments (where hot gas cooling expected)
- FR1/2 classification depends on host galaxy & environment
  - FR1s favour denser environments and more bulge-dominated galaxies
  - Consistent with models whereby FR1 jets are disrupted by environment

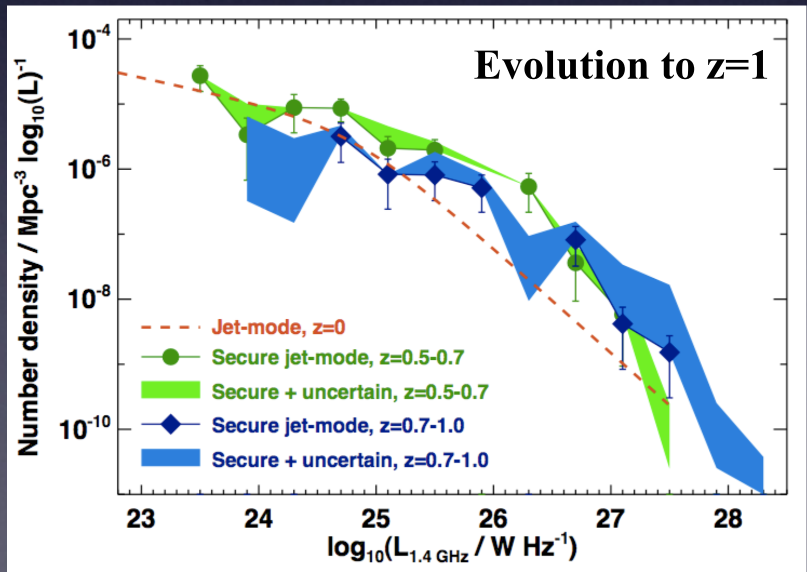
Indication: two distinct processes but driven by similar factors:

- Accretion rate
  - If high enough then crosses threshold for a HERG
  - Higher accretion = more powerful jet, likely to survive disruption: FR2
- Environment
  - Hot gas cooling in dense environment typically low accretion rate: LERG
  - Dense environment more likely to disrupt jets: FR1

Cosmic evolution of jet-mode AGN

- Evolution of radio luminosity function established for many years.
  - But evolution of just "jet-mode" AGN needs source classification
- Best & Heckman (2012): first separate luminosity functions
- Best et al (2014): first measure of evolution of jet-mode AGN
  - weak (luminosity-dependent) increase to z~0.5, then falls at low-L
  - see also Pracy et al 2016; find similarly very low evolution

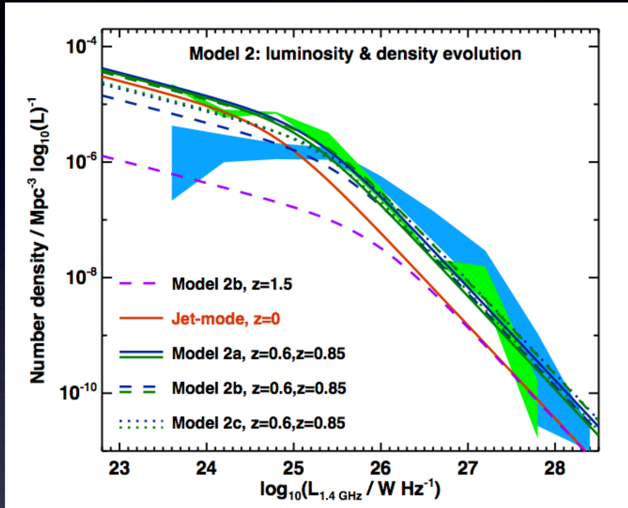


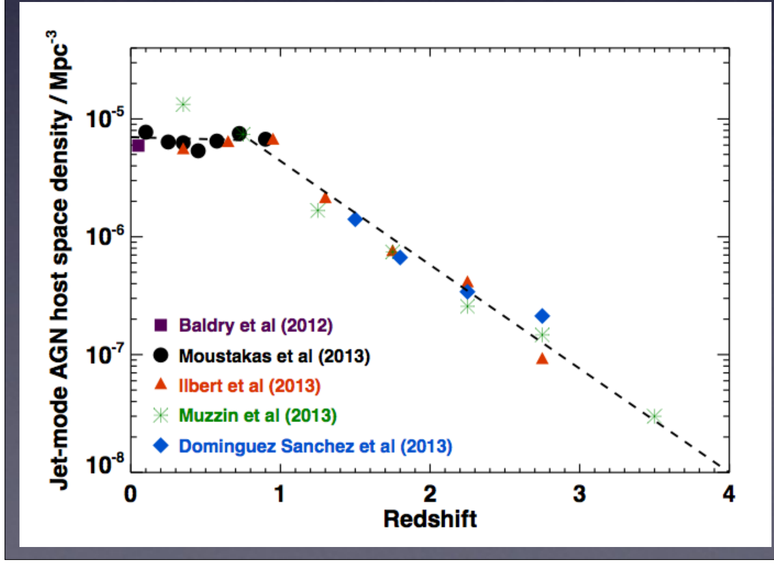


Left: radio luminosity functions of jet- and radiative-mode AGN (Best & Heckman 2012)
Right: cosmic evolution of jet-mode AGN to z~1 (Best et al. 2014).

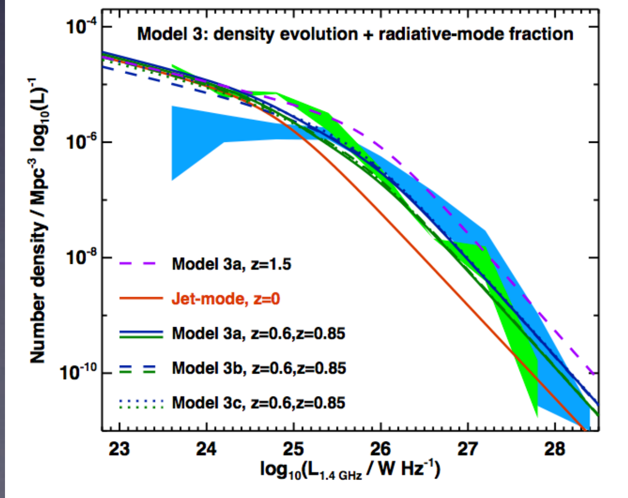
Cosmic evolution of jet-mode AGN

- Compare to evolution of massive quiescent galaxies (potential hosts):
  - declining availability of massive hot haloes; broadly fits weak radio-AGN evolution.
  - but extra complications: luminosity evolution, triggering time delay (~2Gyr), or contribution of dying cold-gas fuelled sources
  - extending analysis to z~1.5 is critical test





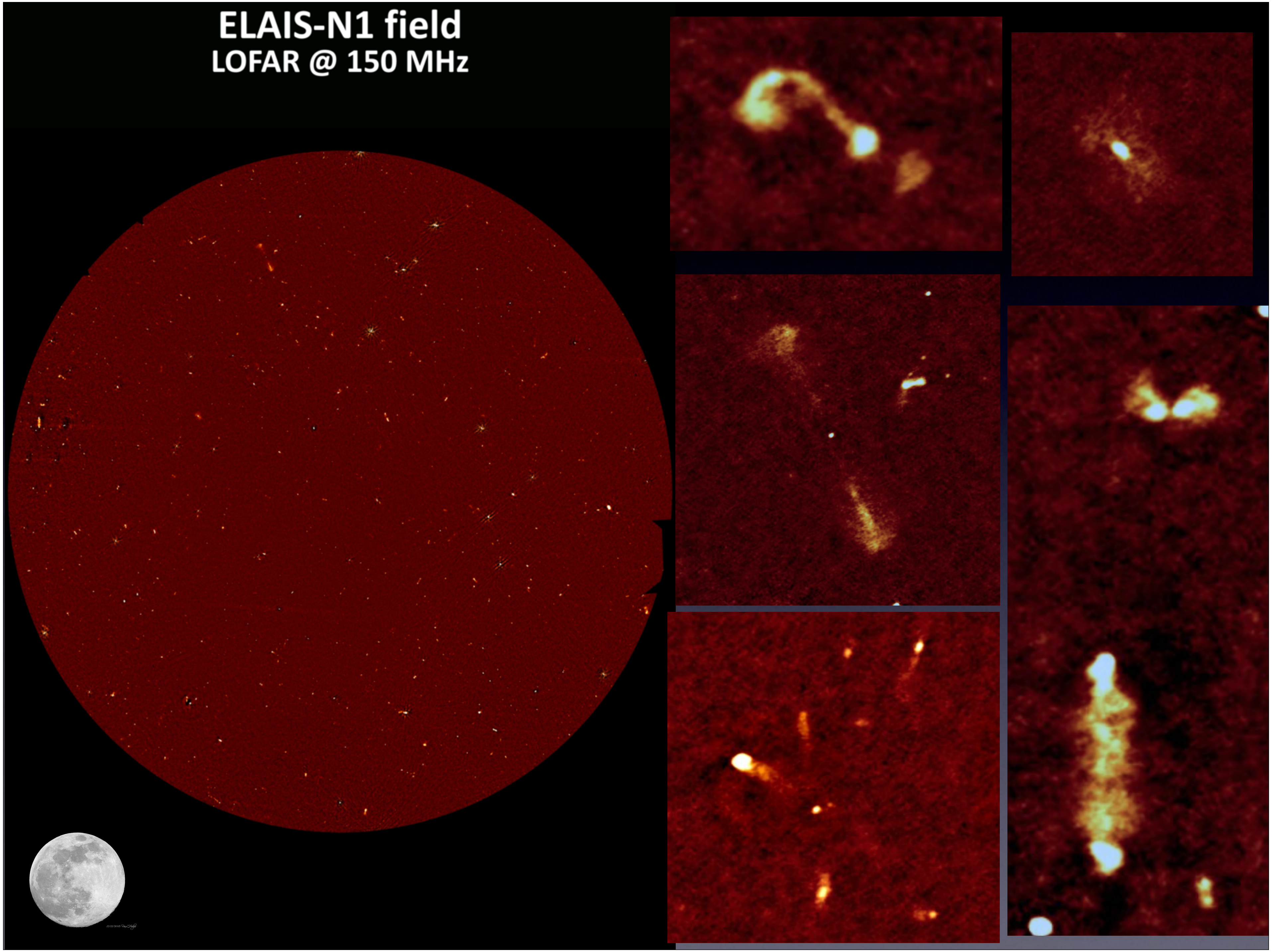
Left: cosmic evolution of potential jet-mode AGN hosts
Right: modelling of jet-mode AGN evolution



LOFAR Surveys

To go beyond this we need deeper wide-area radio surveys: LOFAR

- LOFAR is optimised for deep wide-field imaging:
  - Observes ~15 deg^2 at a shot (multi-beam capability)
- LOFAR Surveys Key Science Project imaging the whole northern sky to 100 microJy rms @ 150 MHz with 5 arcsec resolution
  - To date, about 10% of northern sky observed
  - See Rottgering et al 2011; Shimwell et al in press
- Deeper Tiers of observation in best-studied degree-scale fields
  - Deepest observations in Elais-N1; 250 hrs of data so far
- Going to be very exciting for a wide range of science (both AGN and star-forming galaxies)
  - Will hugely increase accuracy of jet-mode cosmic evolution measurements at $z<1$, and allow analyses to be extended to $z\sim2$.


ELAIS-N1 field
LOFAR @ 150 MHz

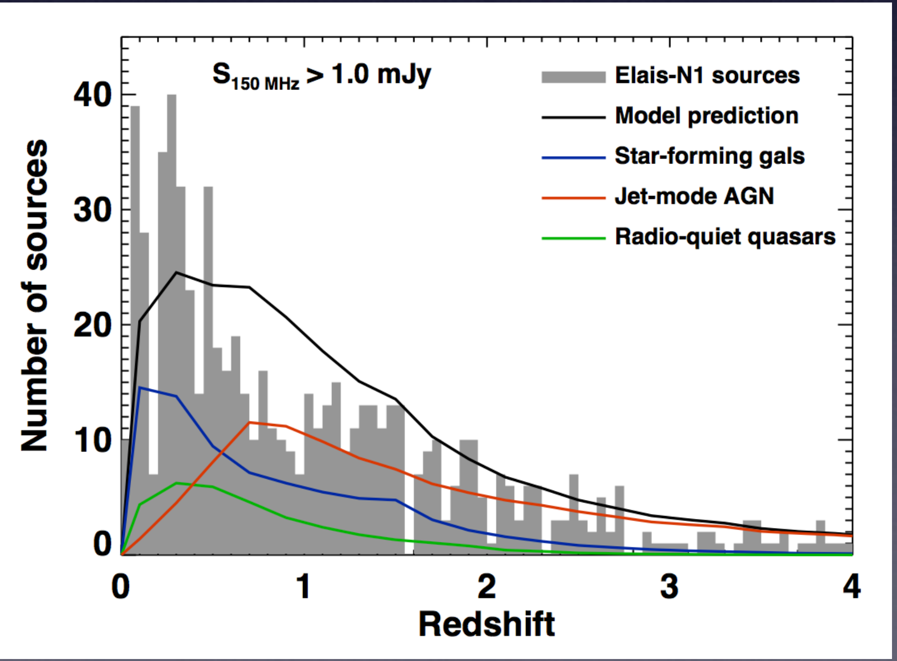
Radio sources in Elais-N1

Wealth of available optical/IR data & spectroscopy

- PanSTARRS Medium Deep Field (grizy; to i~25.5)
- UKIDSS LAS (JK, to K~22)
- Spitzer SWIRE and SERVS (3.6, 4.5 microns)
- Dedicated BOSS DR10 spectroscopy & WHT AF2 spectroscopy

From 1st 8-hr dataset:

- Over 95% identification fraction
- ~40% spectroscopic redshifts
- Roughly equal mix of SFGs and jet-mode radio AGN
- Fewer high-z sources than SKA simulated sky model predictions (where jet-mode AGN dominate)



Summary

- Radiative mode AGN
  - typically in moderate mass galaxies (~$10^{10.5}$ M_{sun})
  - AGN activity correlated with central star formation
  - fuelled by cold dense gas, supplied through secular processes
  - little evidence for AGN feedback except in extreme cases
- Jet-mode AGN
  - Eddington-scaled accretion rates below ~1%
  - advection-dominated accretion flow; most energy output into jet
  - massive galaxies, fuelled by hot gas cooling from X-ray hot haloes
  - AGN-feedback cycle, maintaining galaxies “old, red & dead”
  - cosmic evolution traces massive passive gals, but with complications
- LOFAR
  - operating extremely well, carrying out deep & wide radio surveys
  - deep data in Elais-N1 will trace jet-mode cosmic evolution to z>1