The AGN-galaxy connection out to the highest redshifts

Philip Best

Institute for Astronomy
University of Edinburgh

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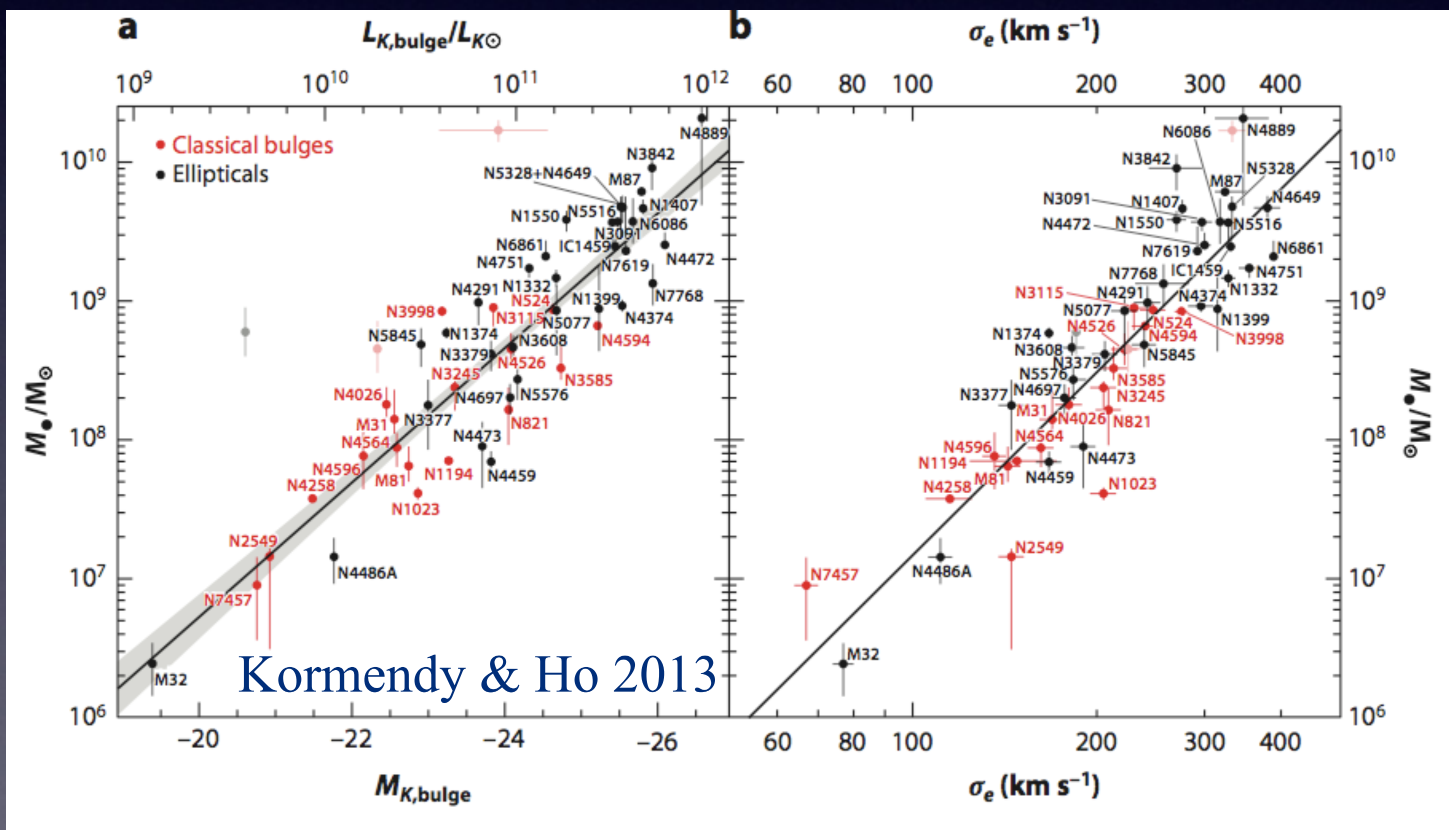
Outline

- AGN in the contemporary Universe
  - Two fundamental modes of AGN activity
  - The properties of AGN host galaxies
- ‘Radiative-mode’ AGN
  - The star-formation vs AGN connection
  - The origin of fuelling gas
  - Evidence for ‘quasar feedback’
- ‘Jet-mode’ AGN
  - Radio AGN feedback cycle in massive galaxies
- Cosmic evolution of the AGN-galaxy connection
  - Census of AGN activity at high redshift
  - The evolving AGN-SF connection

Black hole mass relations

- Black hole mass scales tightly with both the luminosity (or mass) of the galaxy bulge, and with the velocity dispersion
- Implies causal connection between galaxy & black hole growth

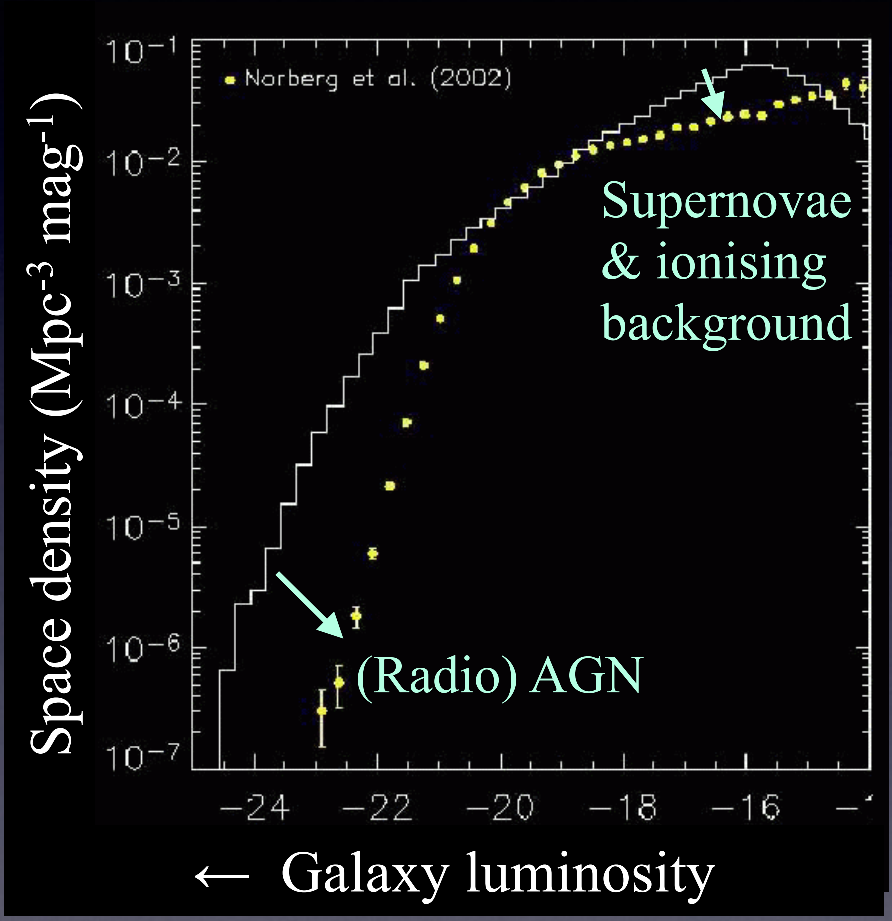


“AGN feedback” in galaxy models

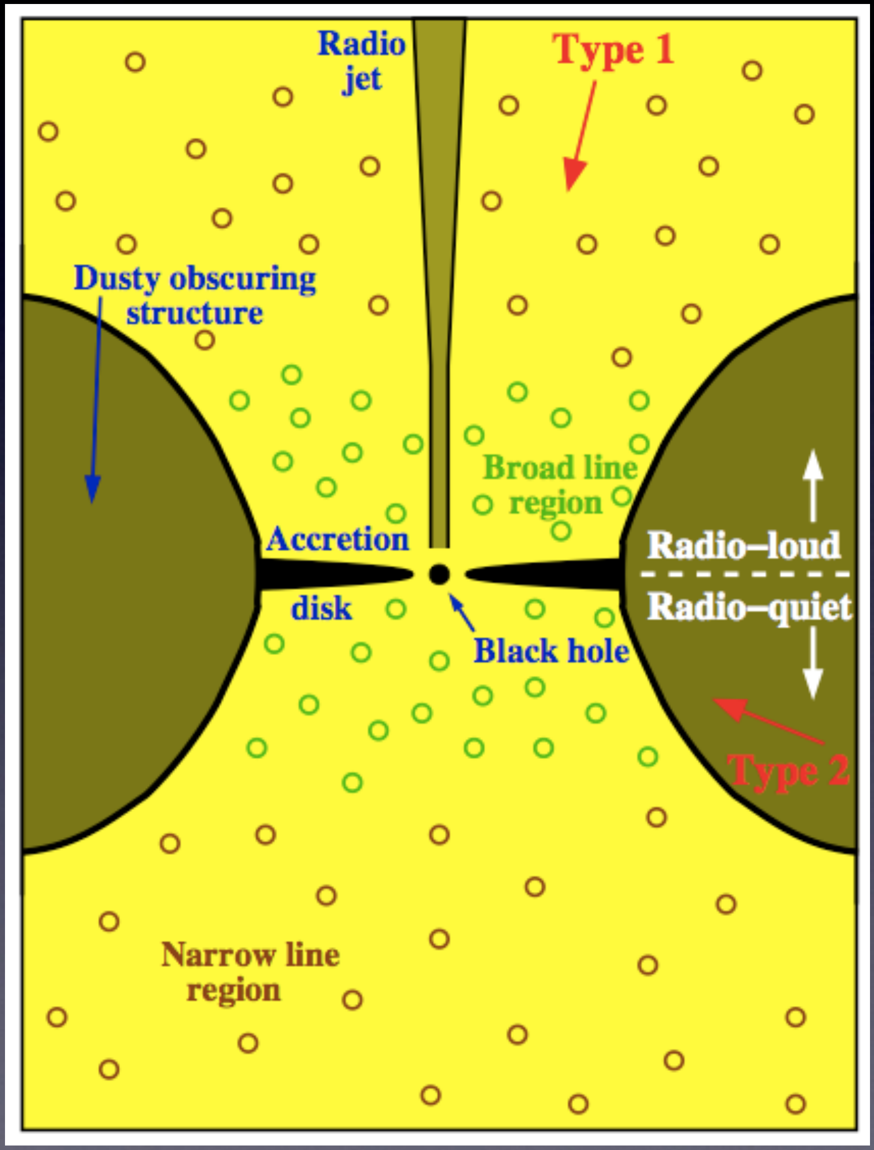
As well as the bulge mass vs black hole mass relation, “AGN feedback” is currently postulated to explain many issues in galaxy evolution:

- 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.



Schematic: "standard" AGN activity

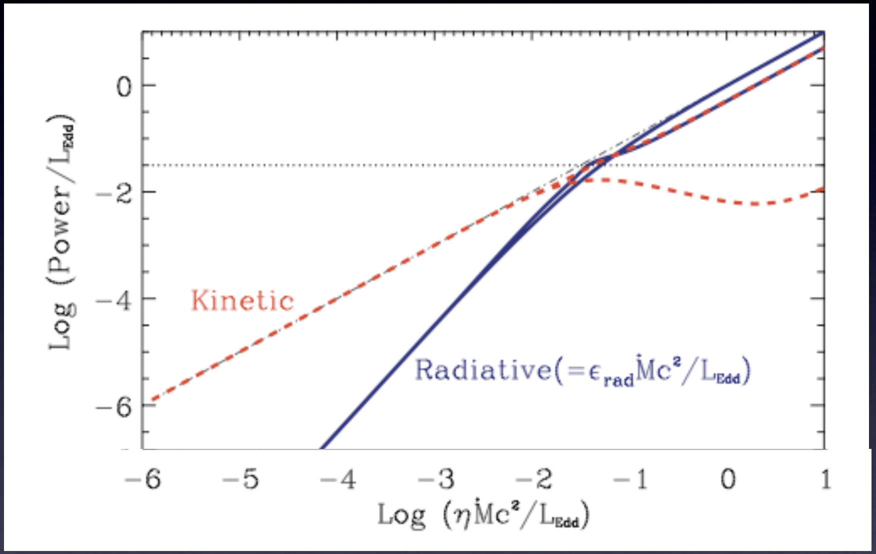


"Standard" AGN have:

- Luminous accretion disk
  - optically thick
  - geometrically thin
  - associated X-ray corona
- Bright line emission
  - UV ionising radiation from disk
- Dusty obscuring structure
  - emits in IR/sub-mm
- Orientation-dependent observed properties
  - Type 1 vs Type 2 AGN
- Sometimes, extended radio jets

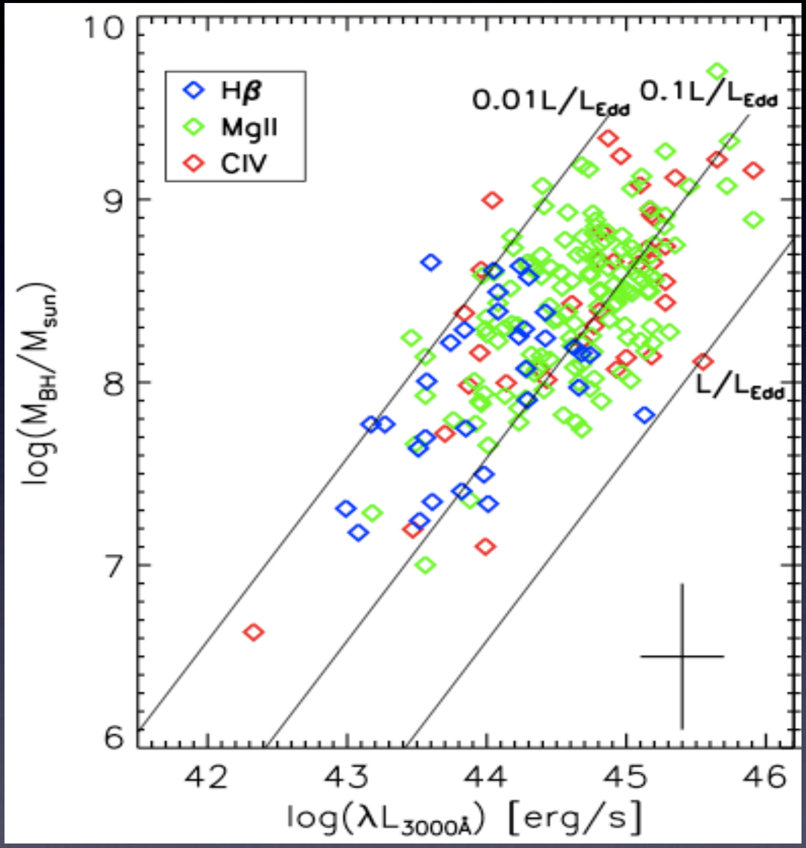
Accretion at low Eddington fractions

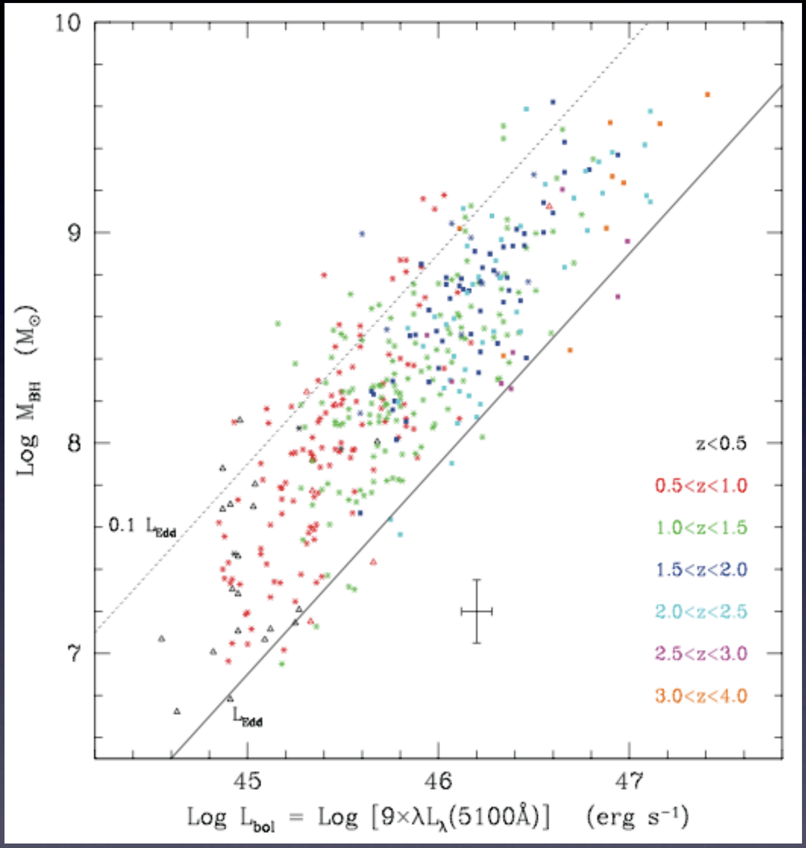
- Accretion flow modelling (e.g. Narayan & Yi 1994,5) indicates standard thin disks are unstable at low Eddington fractions
  - $L_{Edd} = (4 \pi G c m_p / \sigma_T) M_{BH}$
- Instead, advection-dominated (radiatively inefficient) accretion flows occurs (ADAFs / RIAFs)
  - geometrically thick, optically thin
- Most of the energy for ADAFs is predicted to come out in kinetic form, as radio jets



Schematic of the switch between kinetic AGN output for accretion rates at low fractions of Eddington, and radiative output at high fractions (Merloni & Heinz 2008)

Quasar minimum Eddington rates

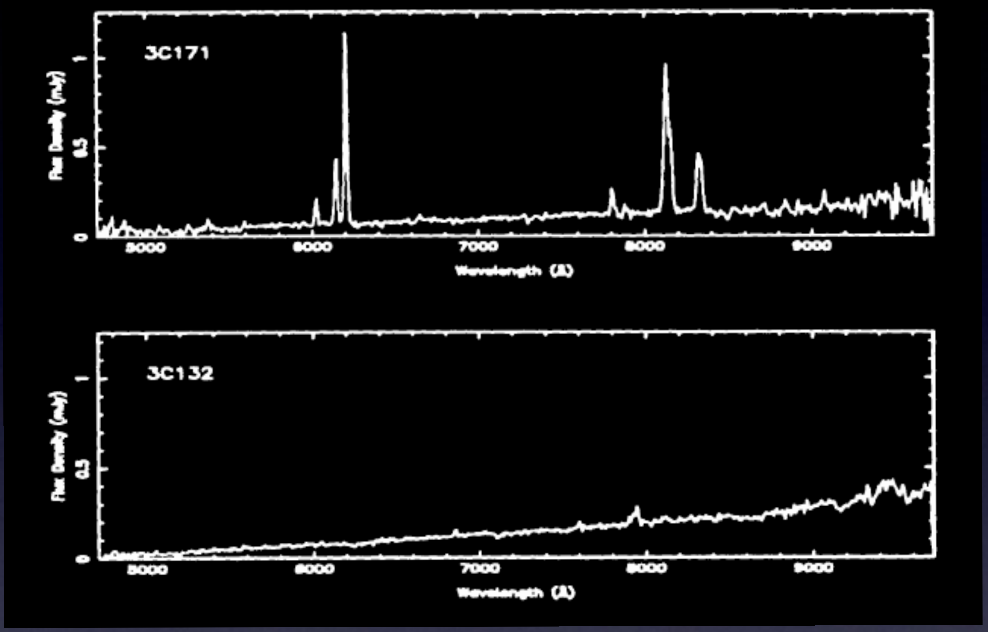




Minimum L/L_{Edd} values of ~0.01 are indeed seen in deep surveys of QSOs (radiative-mode AGN)

- PRIMUS (Trump et al 2009); zCOSMOS (Kollmeier et al 2006)

Low-excitation radio-AGN

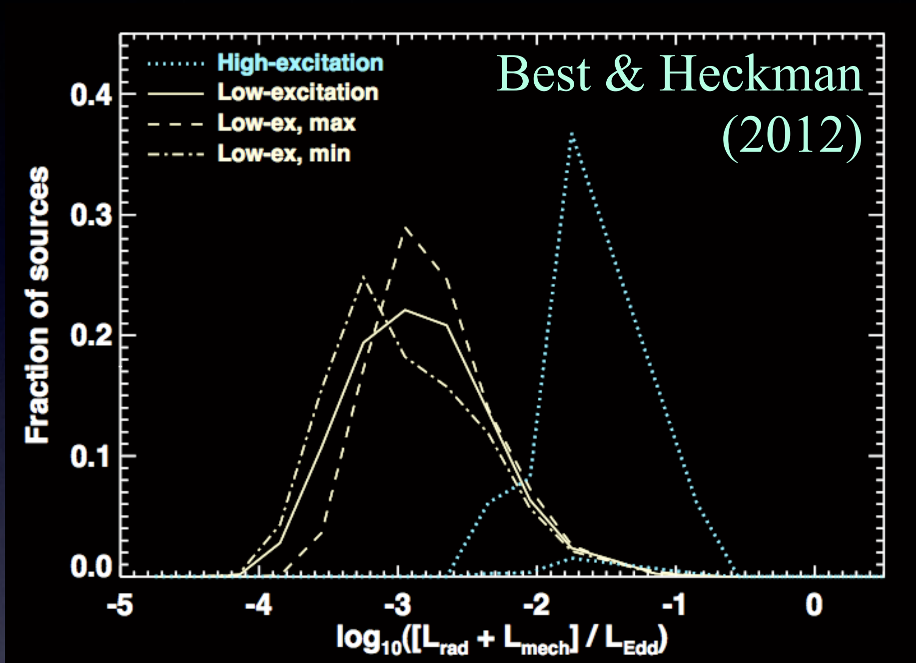


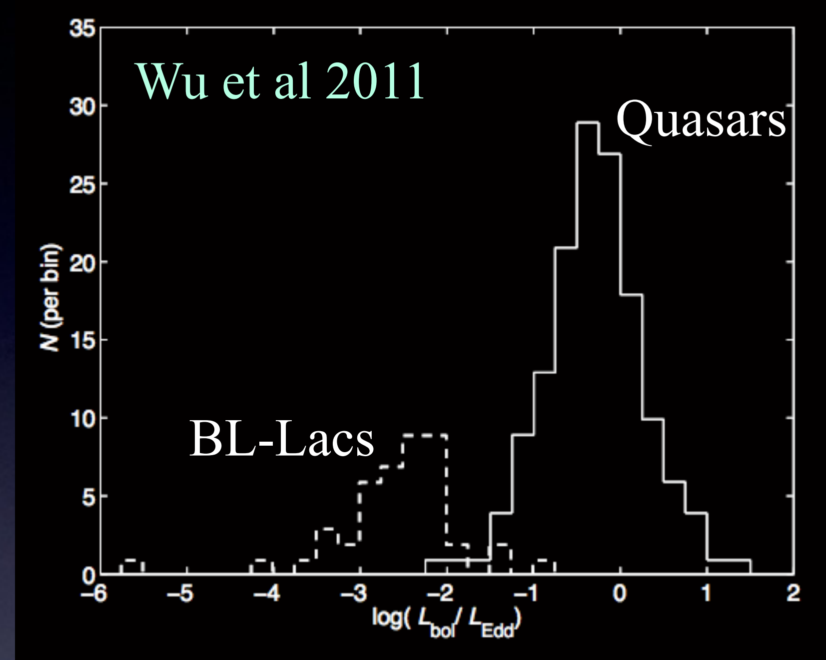
Also some radio AGN do not fit the “standard” AGN picture:

- No strong emission lines (e.g. Hine & Longair 1979)
- No IR torus emission
- No accretion-related X-ray emission (e.g. Hardcastle et al 2007)

Only sign of AGN activity is the radio jet.

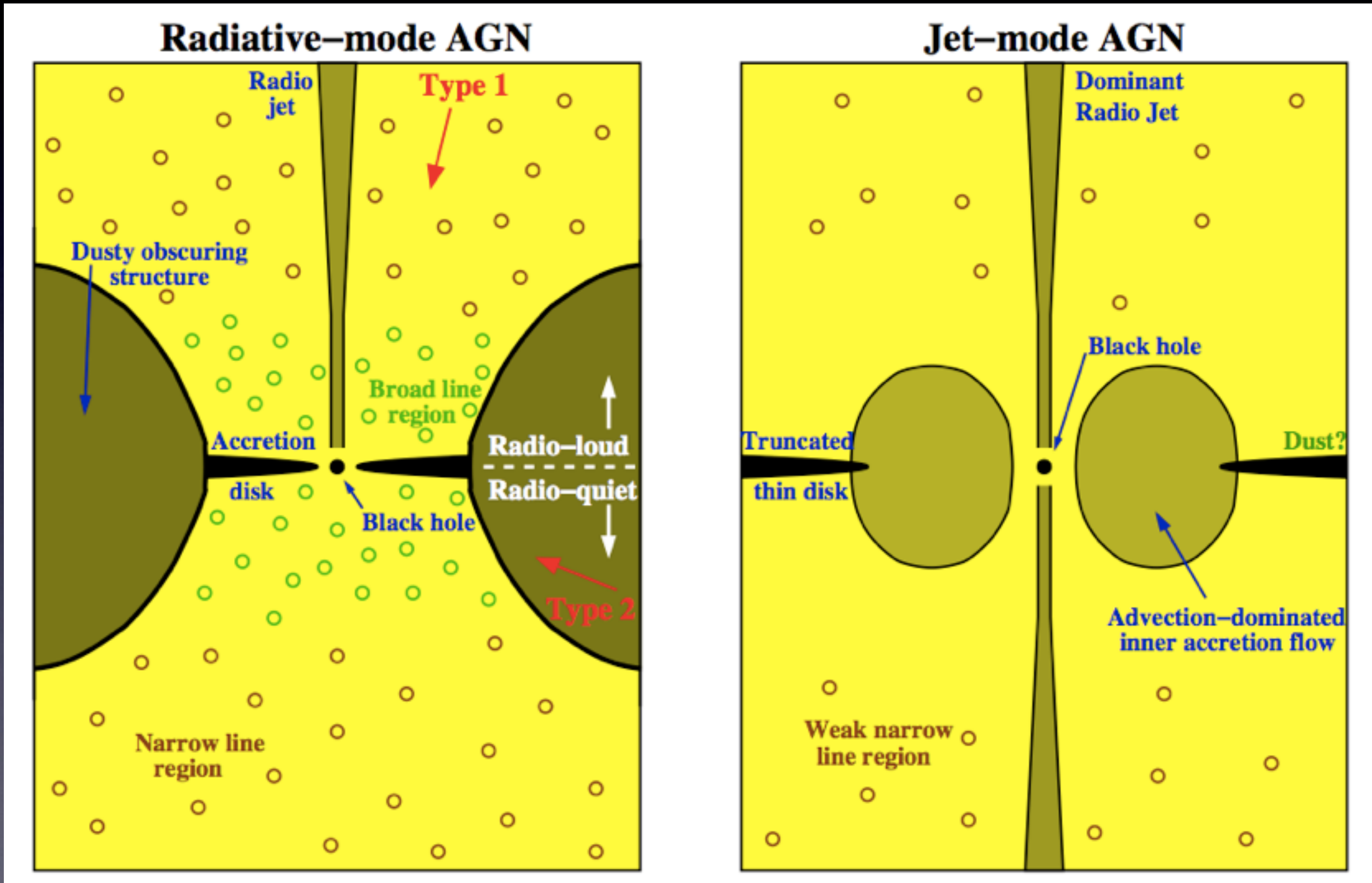
Eddington rates of radio AGN

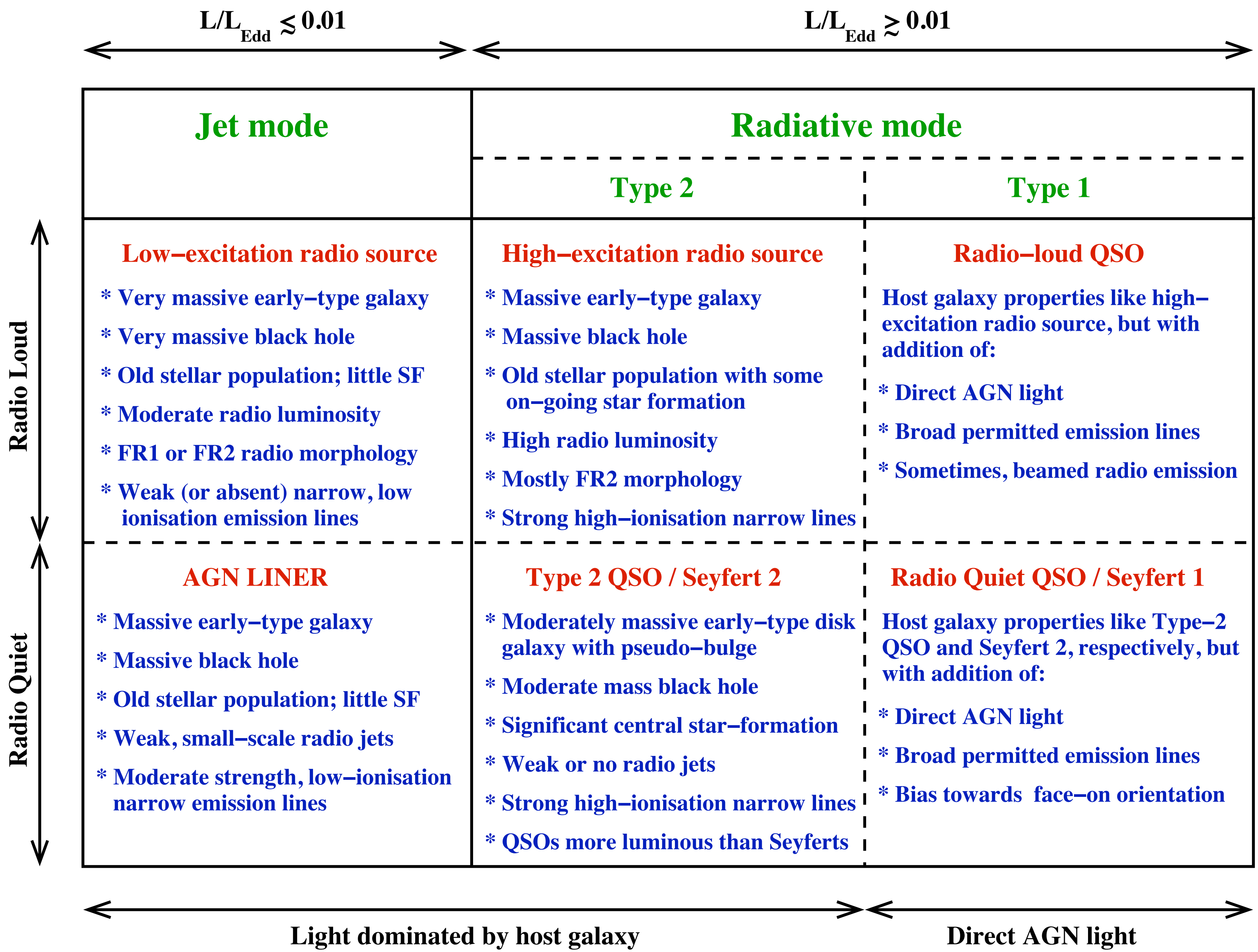




- Best & Heckman (2012): clear dichotomy in Eddington-scaled accretion rates between the two source classes (from SDSS).
- Matches theoretical expectations for ADAFs setting in below few % Eddington
- Similar dichotomy seen between BL-Lacs and flat-spectrum quasars - the beamed counterparts (e.g. Wu et al 2011)

Schematics of AGN activity

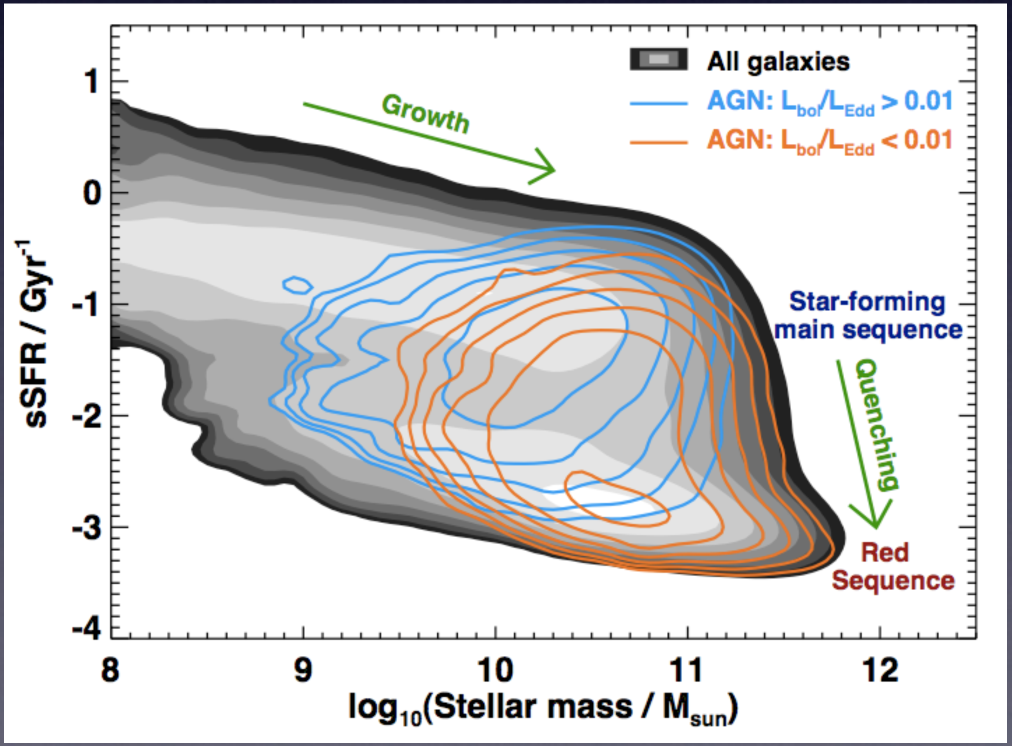




$L/L_{Edd} \lesssim 0.01$
$L/L_{Edd} \gtrsim 0.01$
Jet mode
Radiative mode
Type 2
Type 1
Radio Loud
Low−excitation radio source
* Very massive early−type galaxy
* Very massive black hole
* Old stellar population; little SF
* Moderate radio luminosity
* FR1 or FR2 radio morphology
* Weak (or absent) narrow, low ionisation emission lines
High−excitation radio source
* Massive early−type galaxy
* Massive black hole
* Old stellar population with some on−going star formation
* High radio luminosity
* Mostly FR2 morphology
* Strong high−ionisation narrow lines
Radio−loud QSO
Host galaxy properties like high−excitation radio source, but with addition of:
* Direct AGN light
* Broad permitted emission lines
* Sometimes, beamed radio emission
Radio Quiet
AGN LINER
* Massive early−type galaxy
* Massive black hole
* Old stellar population; little SF
* Weak, small−scale radio jets
* Moderate strength, low−ionisation narrow emission lines
Type 2 QSO / Seyfert 2
* Moderately massive early−type disk galaxy with pseudo−bulge
* Moderate mass black hole
* Significant central star−formation
* Weak or no radio jets
* Strong high−ionisation narrow lines
* QSOs more luminous than Seyferts
Radio Quiet QSO / Seyfert 1
Host galaxy properties like Type−2 QSO and Seyfert 2, respectively, but with addition of:
* Direct AGN light
* Broad permitted emission lines
* Bias towards face−on orientation
Light dominated by host galaxy
Direct AGN light

Local galaxies and their AGN

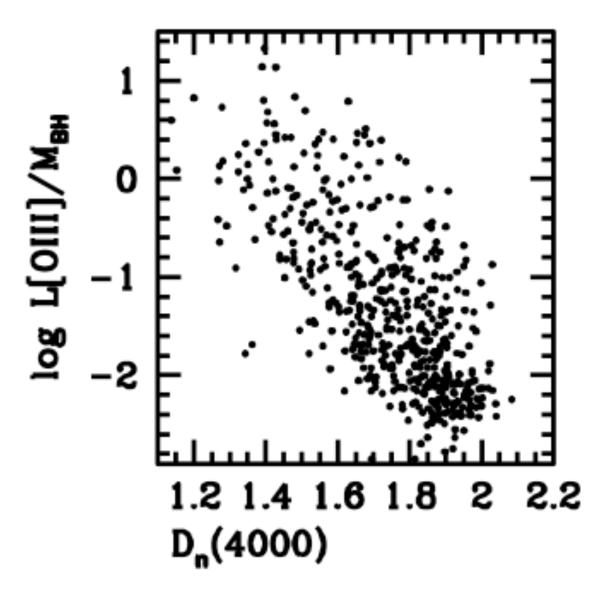
- Look at the demographics of galaxies in local Universe
- AGN selected from SDSS by emission lines or radio emission
  - Radiative-mode AGN: responsible for quenching process?
  - Jet-mode AGN: responsible for maintaining quenched state?



Star-formation AGN connection

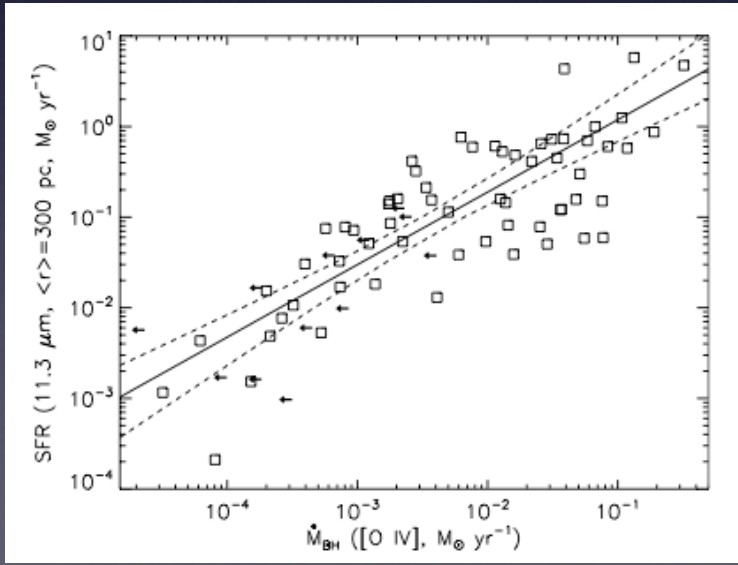
For radiative-mode, AGN activity tightly connected with SF.

- Depends on star-formation rate near galaxy nucleus
- Larger-scale star-formation is necessary but not sufficient
- Implies need for cold dense gas supply to nuclear regions



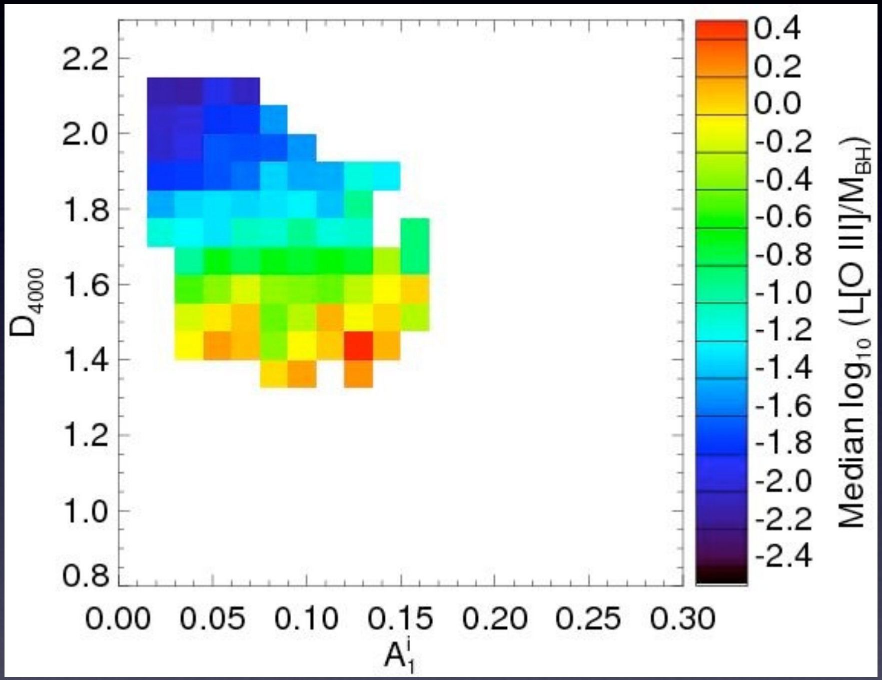
Left: correlation of SDSS fibre star-formation vs AGN accretion rate (Kauffmann et al 2007).

Right: tighter correlation when measured on 300pc scales (Diamond-Stanic et al. 2012)



Merger triggering of AGN?

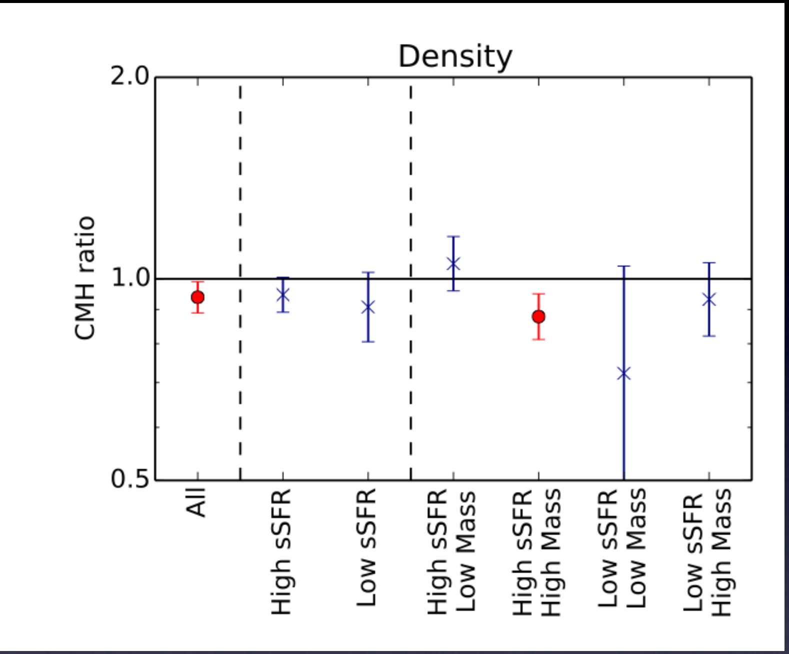
- Many studies show that the prevalence of radiative-mode AGN is enhanced in galaxies undergoing mergers / interactions.
  - However, so is star-formation
  - SDSS allows these two effects to be separated
- Correlation of AGN activity with mergers is a secondary effect of underlying correlations between mergers and SF, and SF and AGN
  - at least, for "typical" radiative-mode AGN

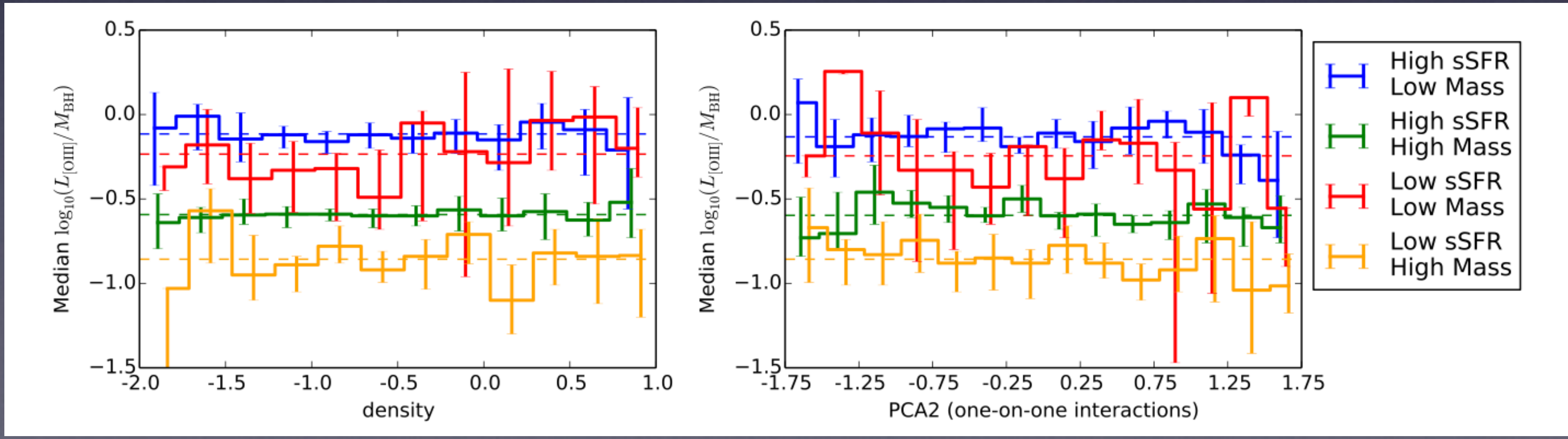


AGN luminosity on the D(4000) vs galaxy lopsidedness (A^i_1) plane (from Reichard et al. 2009). The horizontal nature of the contours indicates no independent dependence on mergers

Environmental effects?

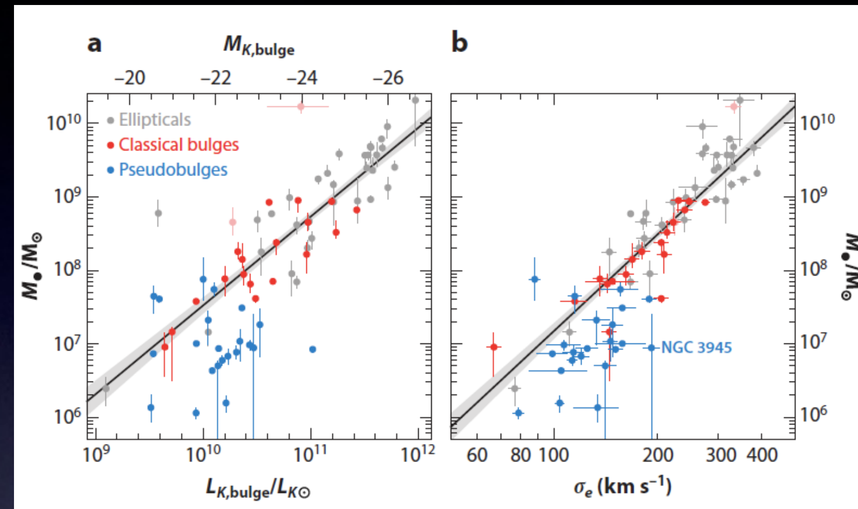
- Likewise AGN fraction depends on large-scale environment.
  - But if you account for the effects of mass and central SFR, these also go away (Sabater et al. 2015).
- Radiative-mode AGN need a cold dense gas supply, but it doesn't matter where this comes from.



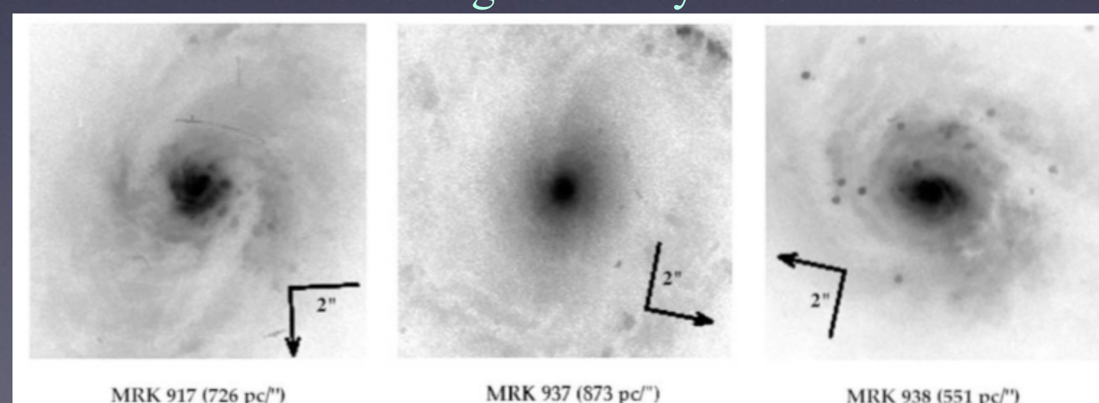


Secular fuelling of radiative-AGN

- Slow but significant gas inflow can be driven by internally-driven non-axisymmetric perturbations
  - bars, over distortions, spiral arms
- Such disturbances also lead to creation of pseudo-bulge
  - dynamically cold bulge with star-formation
  - typically found below $\sigma \sim 150$km/s, $M \sim 10^{10.5} M_{sun}$
- Exactly the type of galaxy in which 'typical' radiative-mode AGN activity is seen.



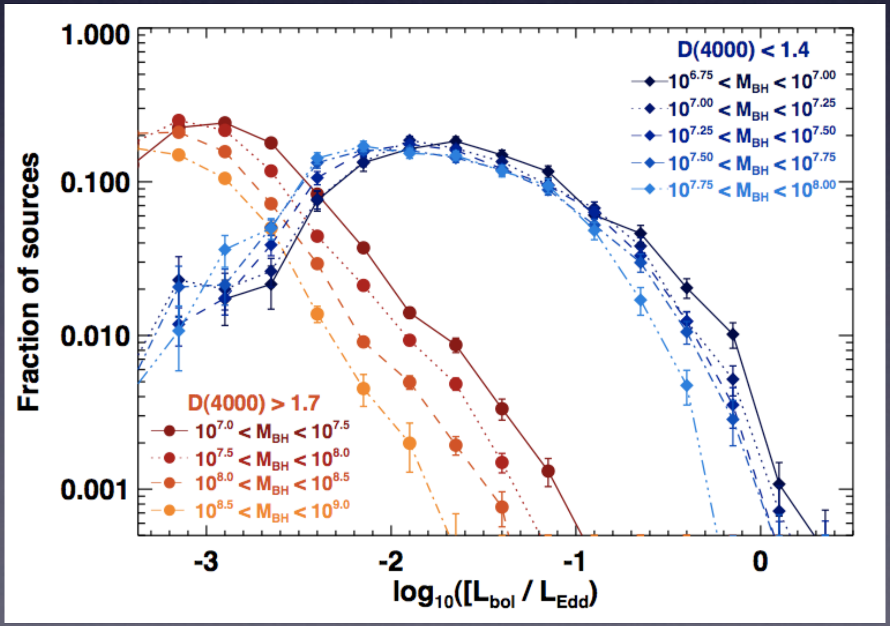
Up: comparison of classical bulges vs pseudo-bulges (Kormendy & Ho 2013)
Down: HST images of typical Seyferts, showing non-axisymmetric distortions



Eddington ratio distributions

Consider Eddington ratios of emission-line AGN split by D(4000)

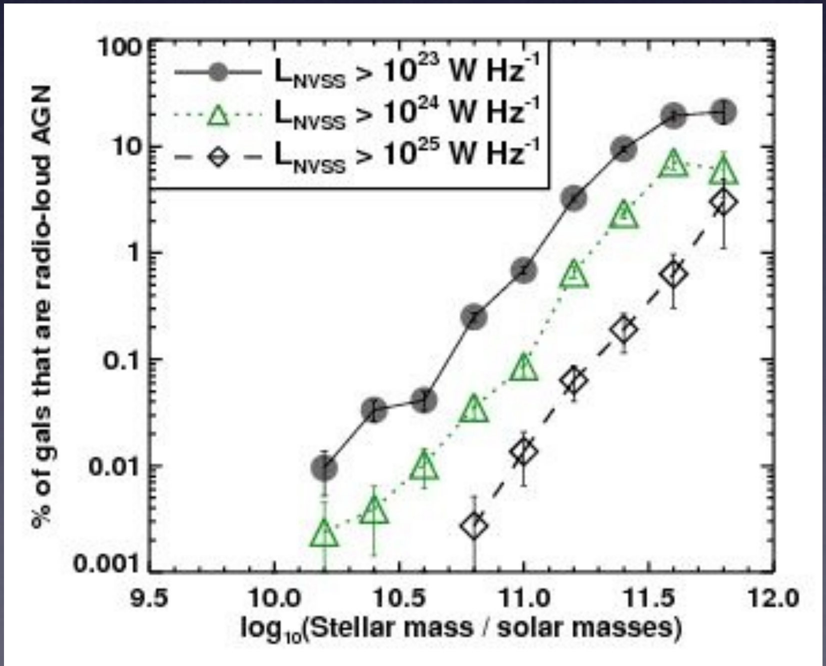
- Star-forming galaxies show distribution peaked at a few percent of Eddington, largely independent of black hole mass
  - if there is sufficient gas supply, black hole self-regulates its growth?
- Quenched galaxies show a power-law distrib., scaling with M_{BH}

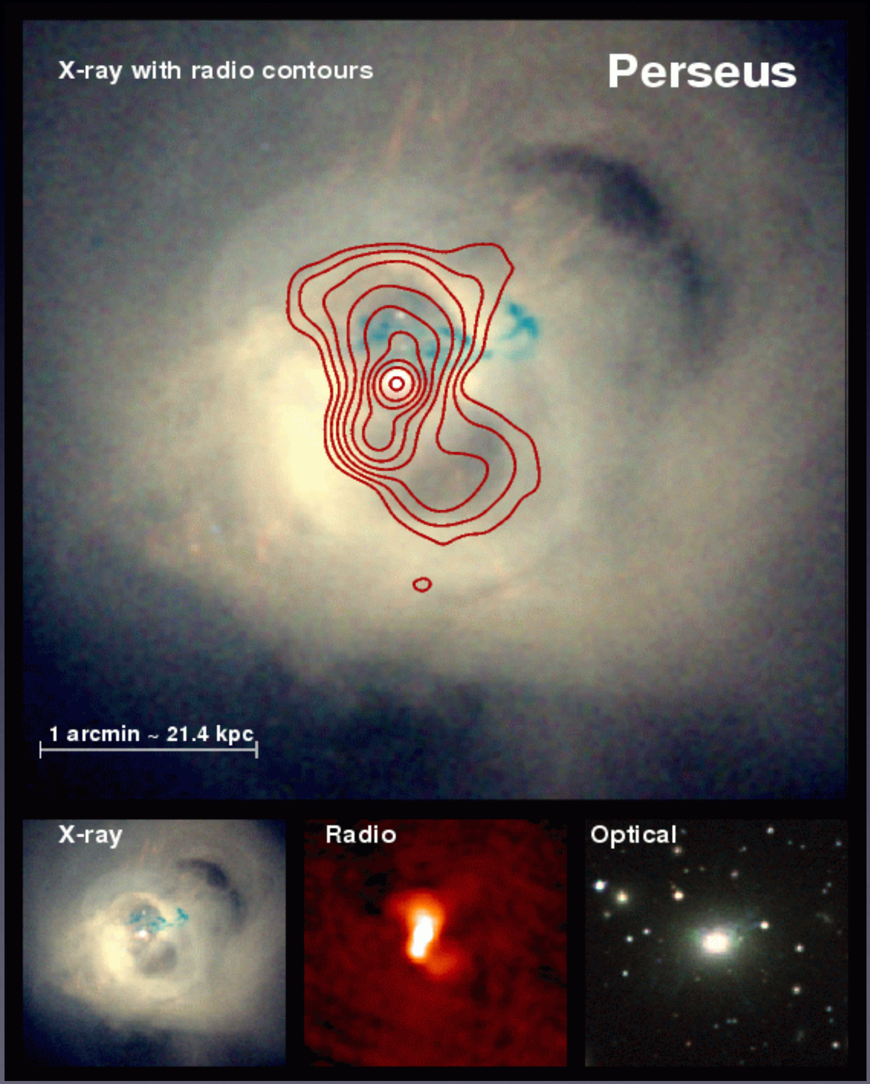


Eddington rate distributions of emission-line AGN, split into star-forming and passive host galaxies. Adapted from Kauffmann & Heckman (2009).

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





Fuelling of powerful jet-mode AGN

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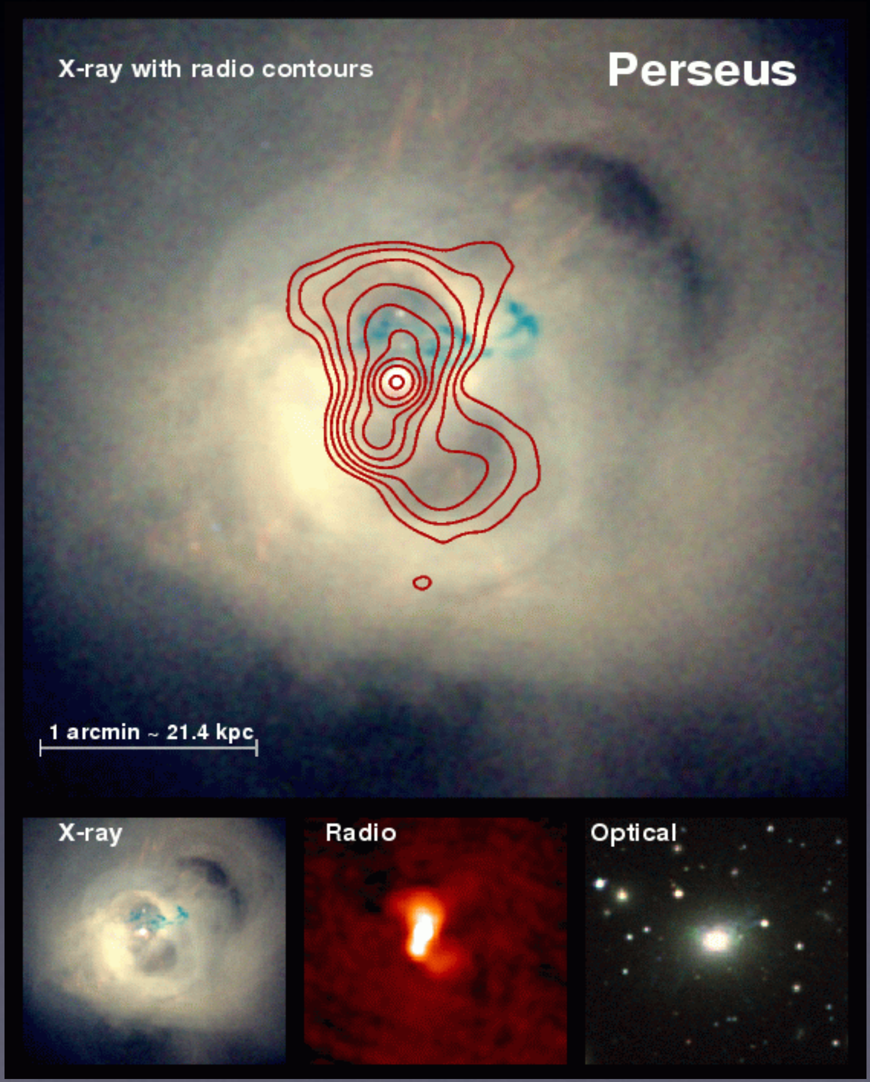
- Bondi accretion?
  - $dM_{Bondi}/dt = 4 \pi \lambda (G M_{BH})^2 \rho / c_s^3$
  - insufficient to explain energetics
- Gas is cooling: hydro simulations (Gaspari et al. 2013) suggest cold chaotic accretion at ~100 x Bondi
  - also show that accretion rate can respond quickly to system changes
   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



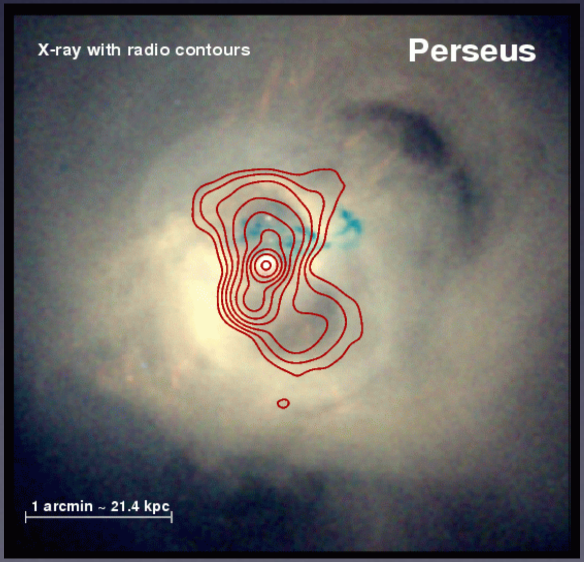
Jet-mode AGN feedback

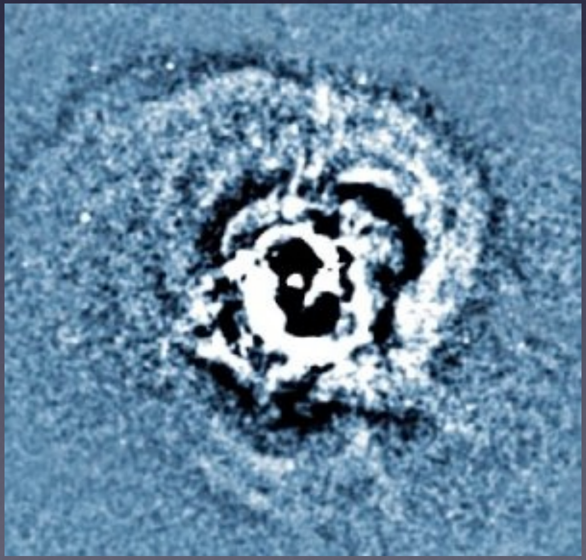
Conditions just right for an AGN feedback cycle:

- 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

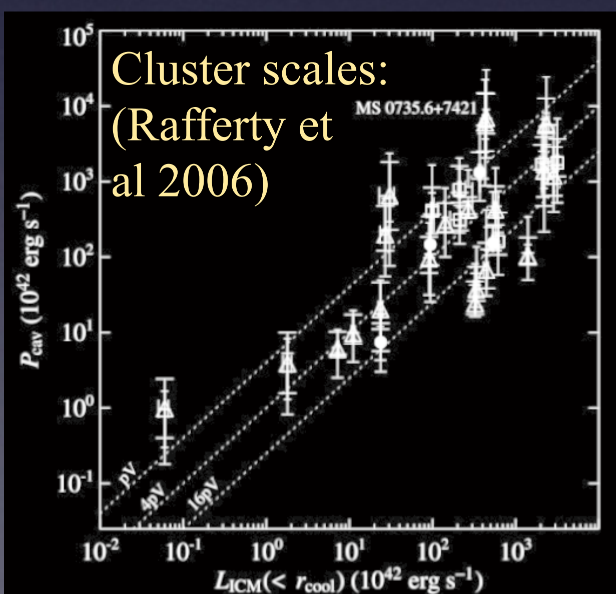
Can estimate mechanical energy of radio jet from inflated cavities.

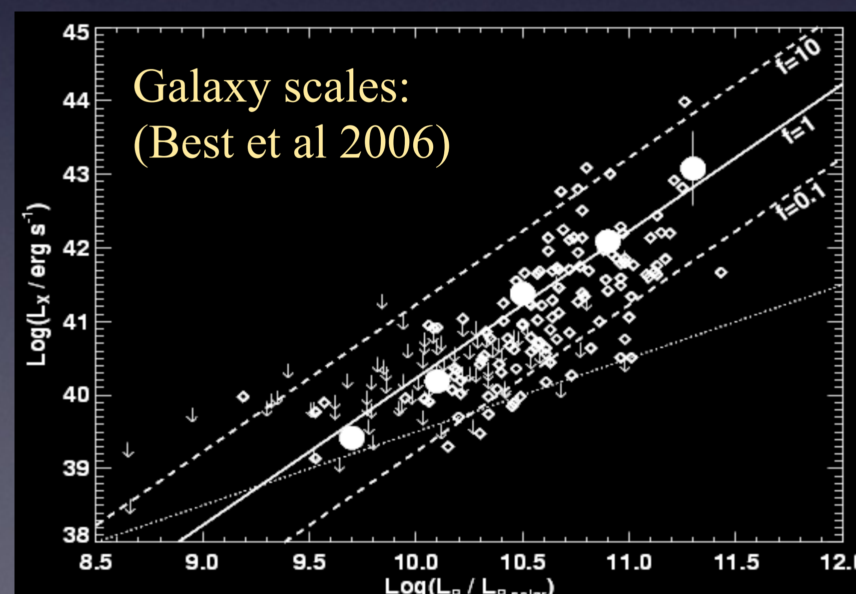
Cooling flow clusters:

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

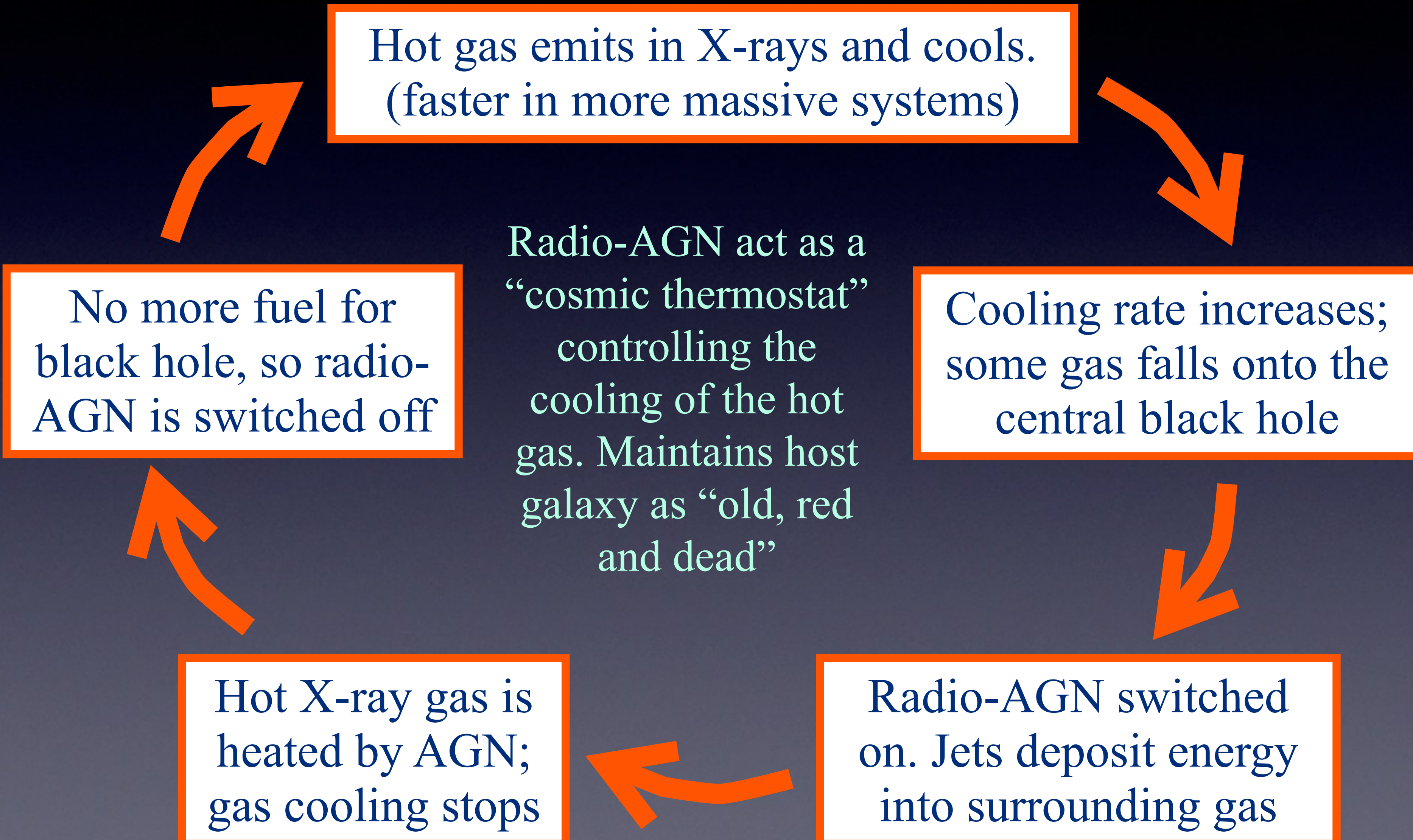
Galaxy scales:

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





A radio-AGN feedback cycle



Feedback from radiative-mode AGN?

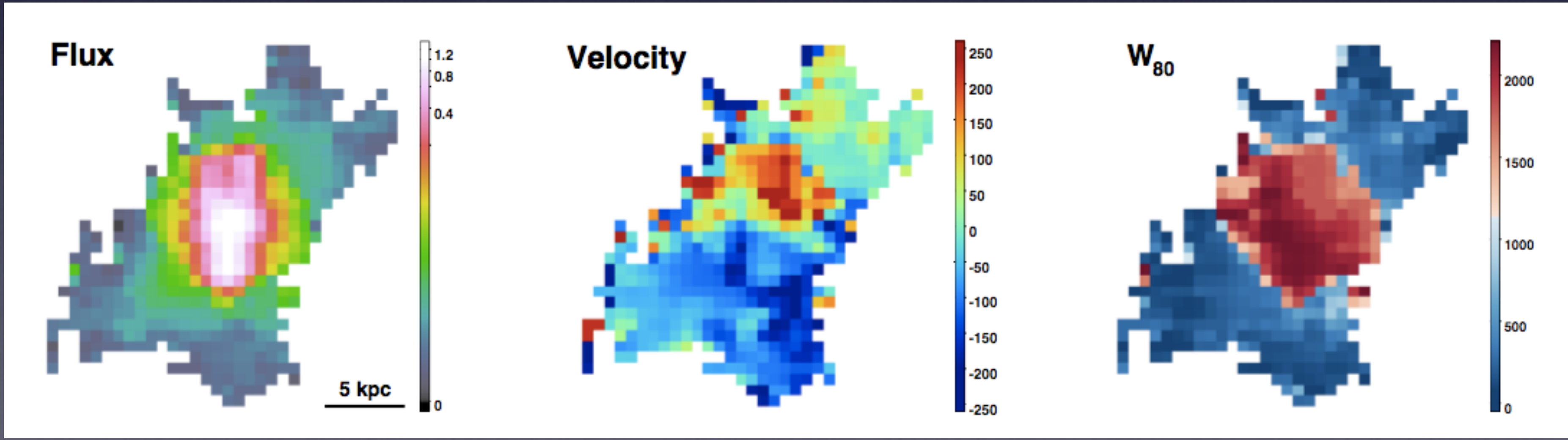
- Radiative mode AGN are found in star-forming galaxies, and star-formation can drive galactic-scale outflows
- Massive stars return ~10^{42} J in kinetic energy per M_{sun} of SF
  - equivalent to characteristic velocity of 1200 km/s
  - far larger than escape velocity

Great Observatories image of the star-forming galaxy M82 showing a starburst- driven biploar wind.

Yellow/green - visible light
Red: infrared emission
Orange: Hα emission
Blue: X-rays

AGN-driven feedback?

- AGN-driven outflows are common in radiative-mode AGN
  - 100's or 1000's km/s blueshifted emission lines in UV, optical, Xray
- Large-scale outflows convincingly seen in some extreme QSOs
- But in typical AGN, gas masses & outflow sizes unconstrained
  - outflows not seen in Seyfert 2s: sizes < 10s pc? low mass at large r?
  - no evidence that 'typical' AGN show black-hole-driven feedback



Gemini IFI obs. of [OIII] line in powerful QSO J0319-0019 (Liu et al. 2013)

So what does quench galaxies?

Two critical timescales for gas infall onto galaxies:

- Dynamical timescale (t_{dyn}) [time taken to fall in]
- Cooling timescale (t_{cool}) [time taken to radiate away energy]

Low mass galaxies, $t_{cool} < t_{dyn}$

- gas reaches galaxy in cold form, settles in to disk, forms stars

High mass galaxies, $t_{cool} > t_{dyn}$

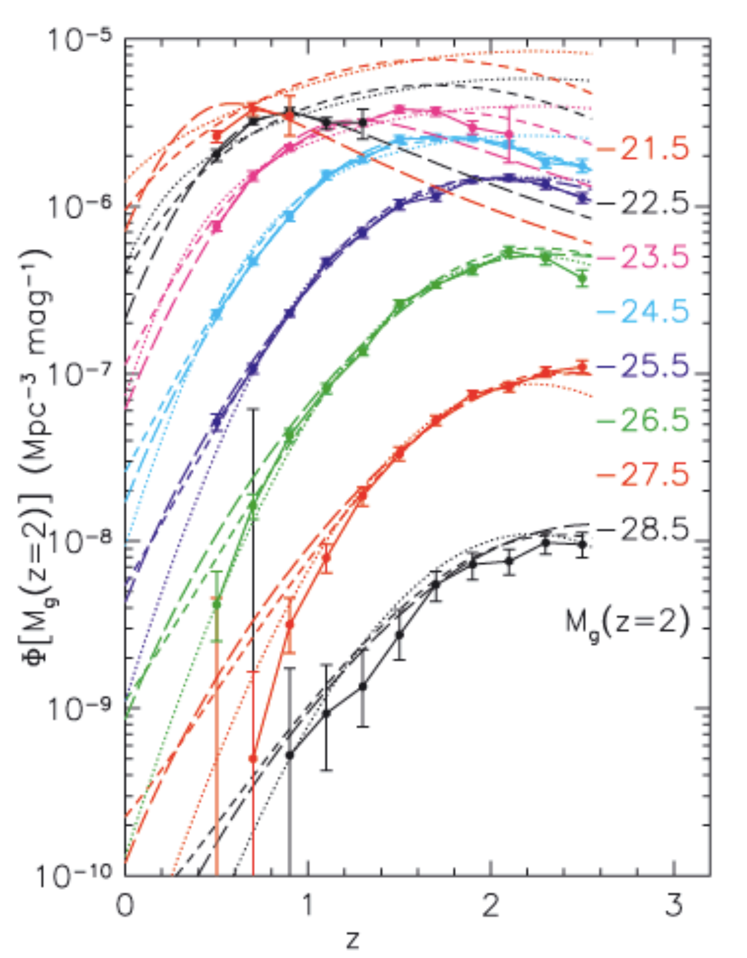
- gas heated to virial temperature and forms a hot (X-ray) halo.
- immediate star-formation suppressed: quenching
- gas would radiate & cool gradually, but jet-mode AGN keep it hot

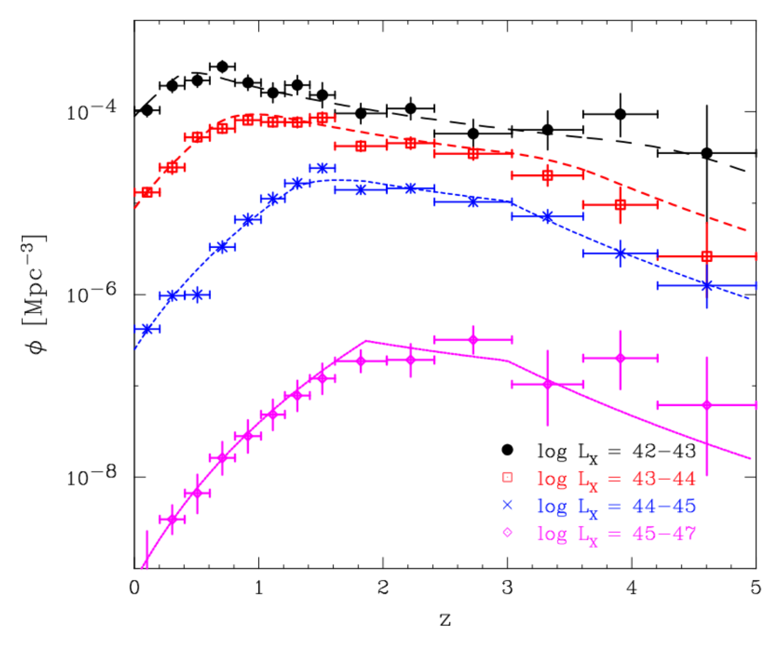
Switch corresponds roughly to transition mass between low-mass star-forming population and high-mass quenched population

- Mass-dependent 'accretion-mode quenching' only: not AGN
  - but merger/quasar events may be important for massive ellipticals

Cosmic evolution of AGN

- AGN luminosity functions indicate "down-sizing" of AGN

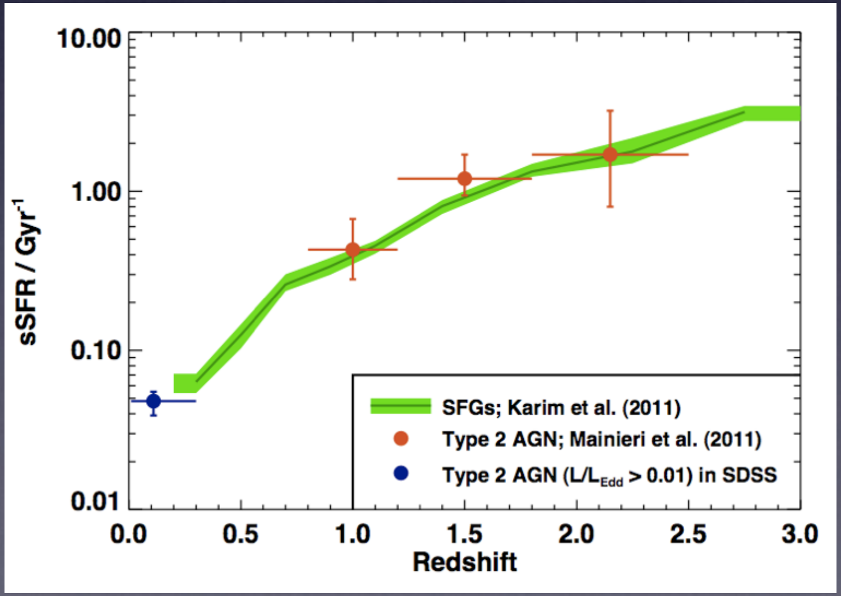




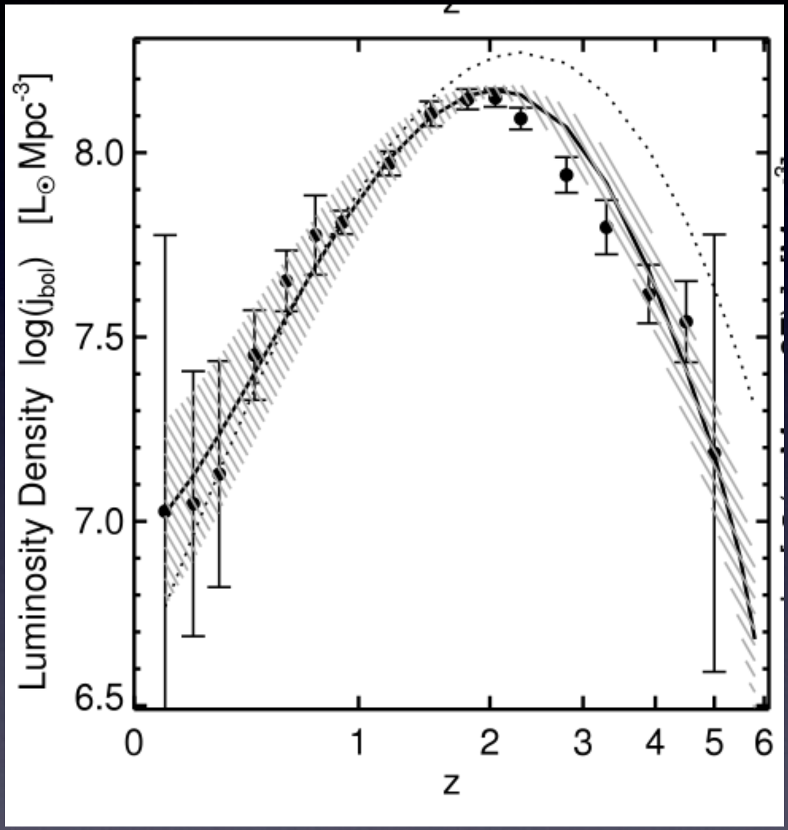
Left: the cosmic evolution of optically-selected AGN of different luminosities (Croom et al. 2009)
Up: the evolution of X-ray selected AGN of different luminosity (Ueda et al. 2014)

SF-AGN connection at high-z

- Radiative mode AGN typically more luminous at high redshift
- Typical star-formation rates of galaxies similarly increase with z
- At all redshifts, AGN host galaxies have specific SFRs which are typical for star-forming galaxies at that redshift.
  - Consistent with the contemporary Universe picture, with AGN evolution, like SF, being driven by an increase in gas availability



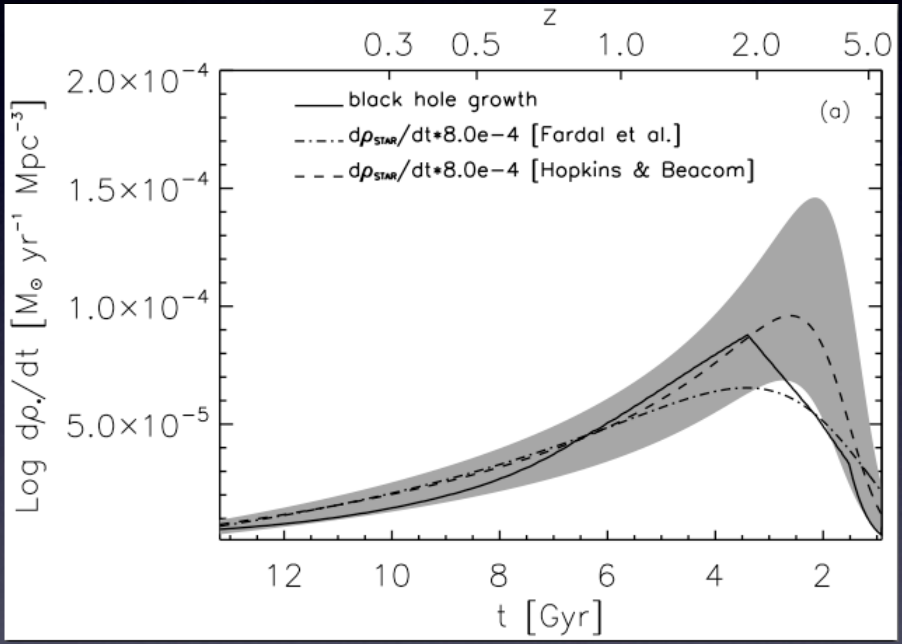
Cosmic evolution of black hole growth



- Can integrate quasar luminosity functions to measure cosmic history of black hole growth, as measured by AGN activity.
  - Peaks at z~2 and falls to high-z
  - Reminiscent of behaviour of cosmic star formation…

From Hopkins et al. (2007)

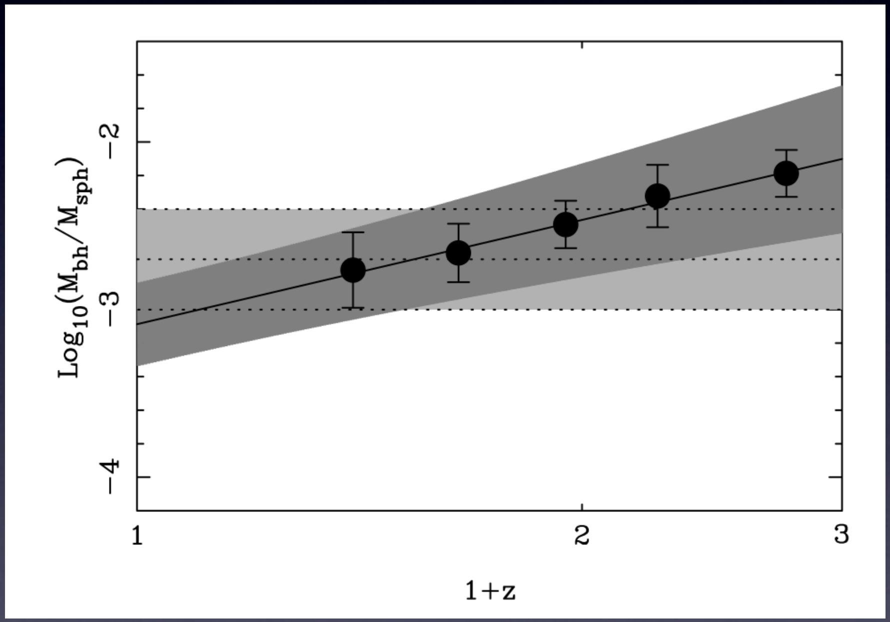
Cosmic evolution of black hole growth



From Shankar et al. (2009)

- Can integrate quasar luminosity functions to measure cosmic history of black hole growth, as measured by AGN activity.
  - Peaks at z~2 and falls to high-z
  - Reminiscent of behaviour of cosmic star formation…
  - solid black line: cosmic history of black hole growth, as measured by AGN activity
  - dashed line (shaded region gives uncertainty): cosmic history of star formation, scaled down by ~10^3
- SF-AGN connection seen across cosmic time

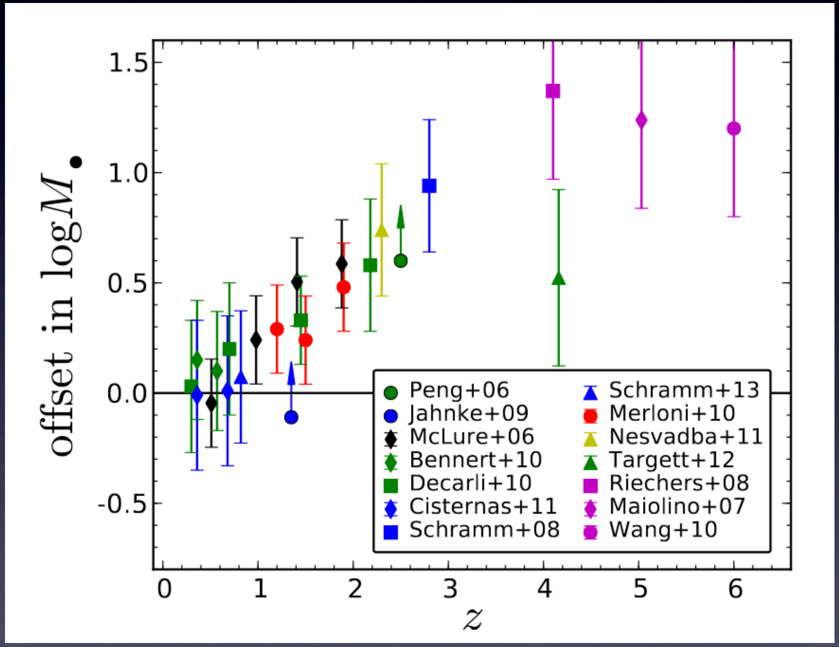
Evolving M_{BH} - M_{Bulge} relation?



From McLure et al. (2006)

- Using broad-line AGN (quasars) we can estimate black hole masses at high redshifts
  - indications that M_{BH}/M_{bulge} increases with increasing z

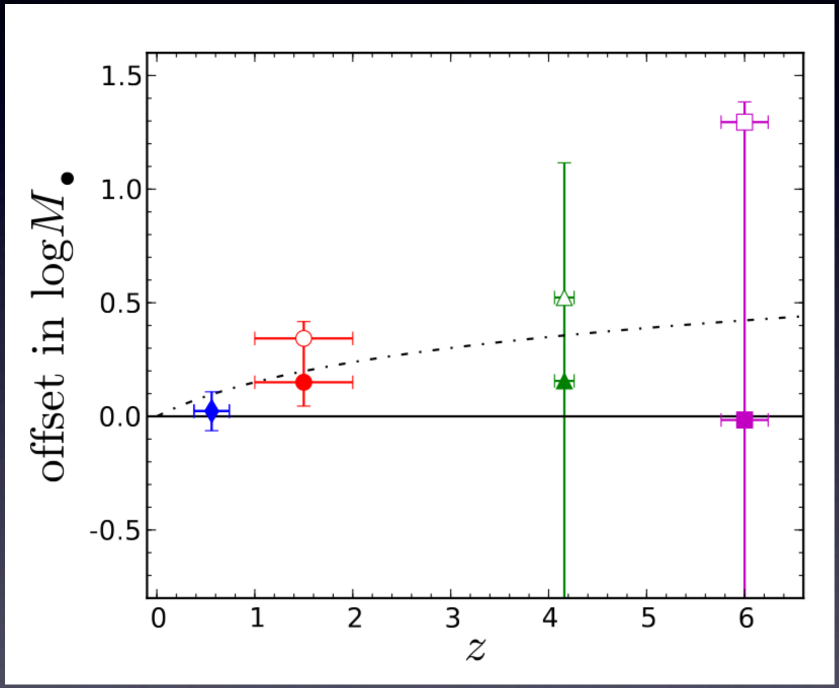
Evolving M_{BH} - M_{Bulge} relation?



Compilation from Schulze & Wisotzki (2014)

- Using broad-line AGN (quasars) we can estimate black hole masses at high redshifts
  - indications that M_{BH}/M_{bulge} increases with increasing z
- But….
  - selection of most luminous quasars automatically selects the most massive black holes!
  - representative of full population, or just top end of a scatter?

Evolving M_{BH} - M_{Bulge} relation?

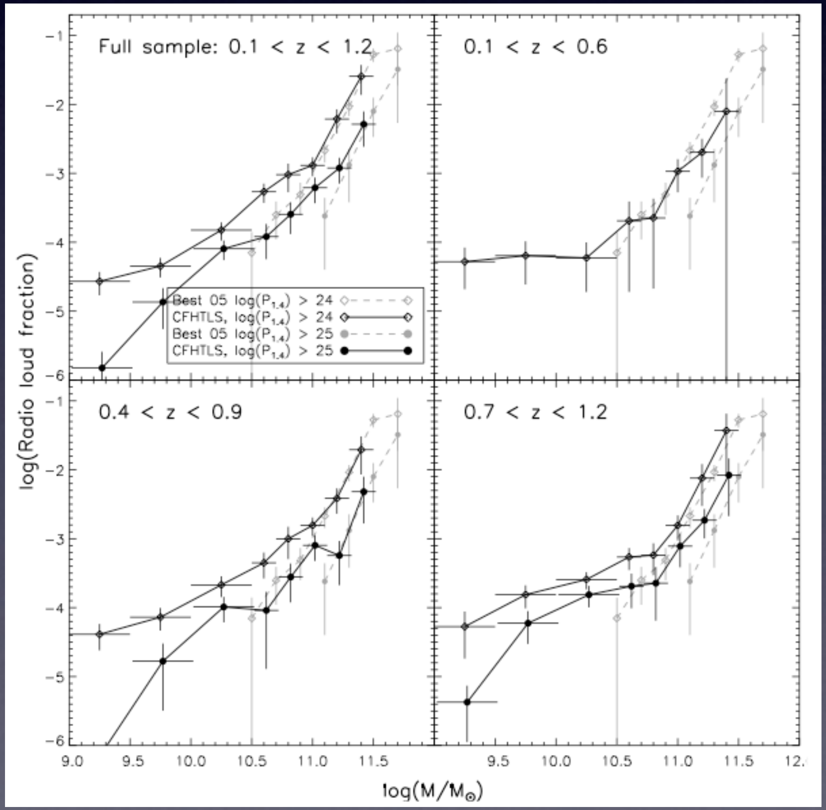


From Schulze & Wisotzki (2014)

- Using broad-line AGN (quasars) we can estimate black hole masses at high redshifts
  - indications that M_{BH}/M_{bulge} increases with increasing z
- But….
  - selection of most luminous quasars automatically selects the most massive black holes!
  - representative of full population, or just top end of a scatter?
- Attempts to model selection effects suggest any underlying evolution is much less strong.

Cosmic evolution of jet-mode AGN

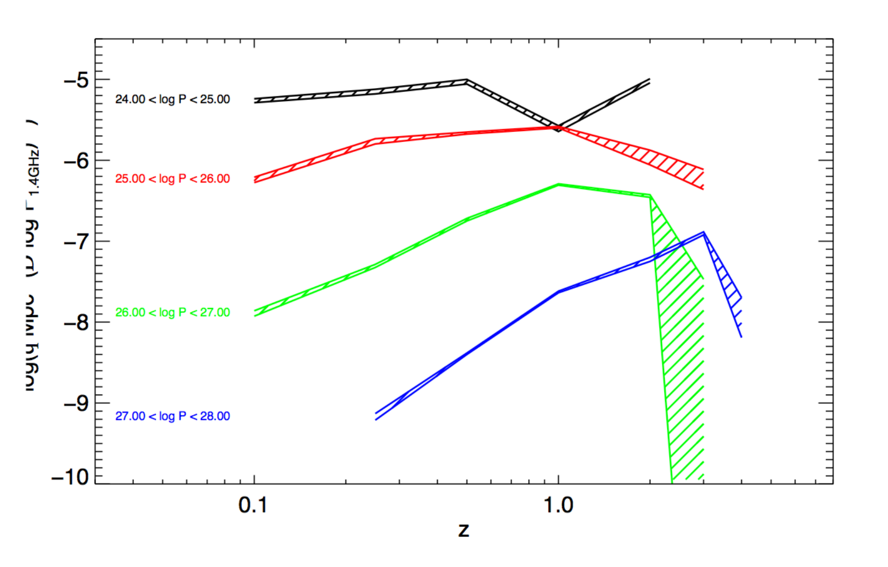
- Mass dependence of radio-AGN activity is same out to z~1, consistent with hosting by same massive passive galaxies in same AGN feedback

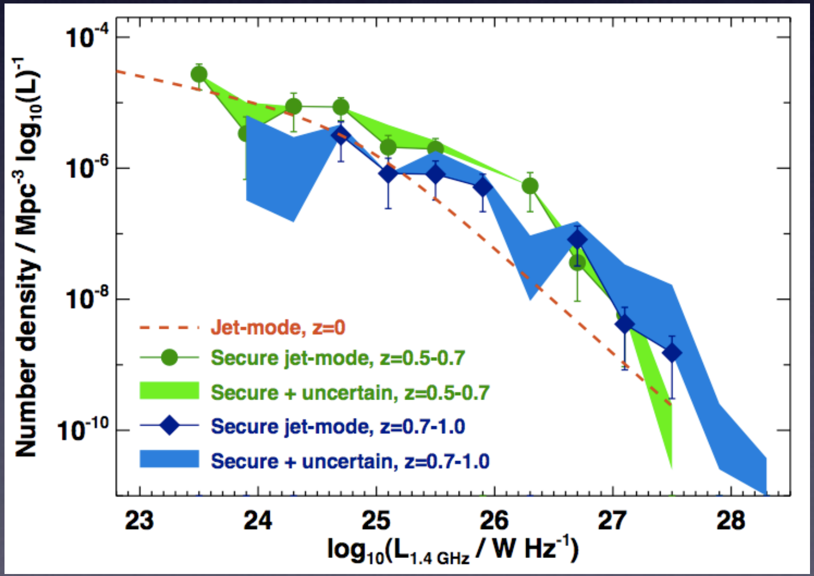


Tasse et al. 2008

Cosmic evolution of jet-mode AGN

- Radio luminosity function also shows “down-sizing”.
  - But evolution of just “jet-mode” AGN needs source classification
- Best et al (2014): first measure of evolution of jet-mode AGN
  - increase to z~0.5, then begins to fall

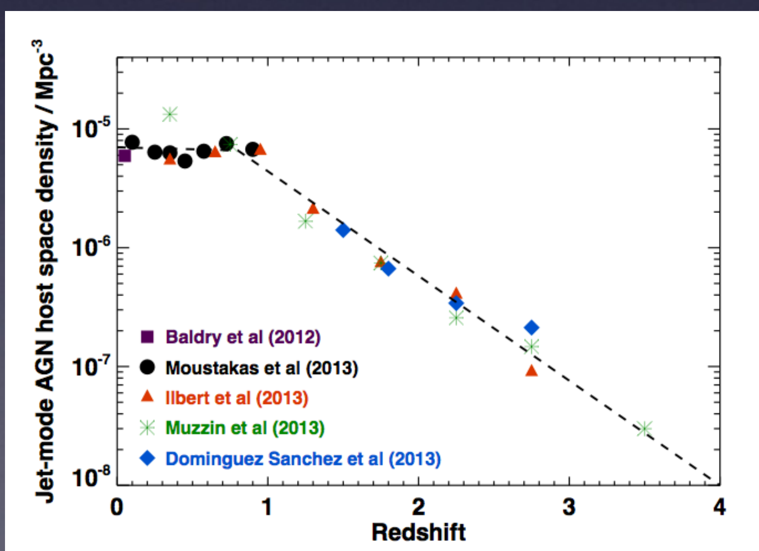




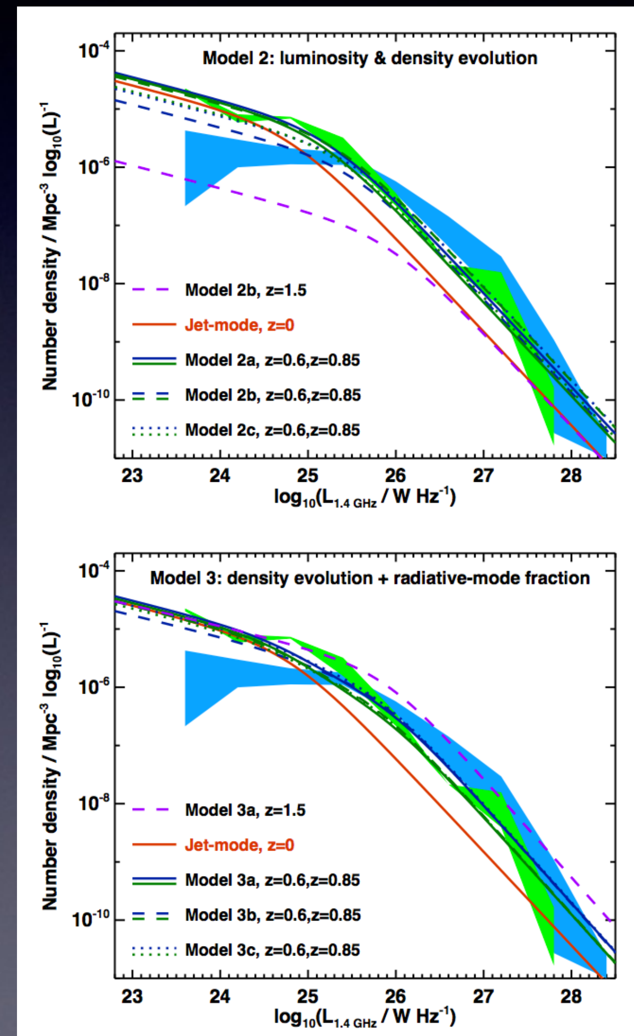
Left: cosmic down-sizing in the radio-AGN population (Rigby et al 2015)
Right: cosmic evolution of jet-mode AGN to z~1 (Best et al. 2014).

Cosmic evolution of jet-mode AGN

- Compare to evolution of massive quiescent galaxies (potential hosts):
  - declining availability of massive hot haloes
  - broad consistency with local Universe
  - but extra complications: luminosity evolution, triggering time delay, or contribution of dying cold-gas fuelled sources



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



Summary

- Radiative mode AGN
  - Eddington scaled accretion rates above ~1%
  - 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 objects
  - basically same in high redshifts (up-scaled due to high gas supply)
- Jet-mode AGN
  - Eddington-scaled accretion rates below ~1%
  - advection-dominated accretion flow; most energy output into jet
  - hosts are massive, passive ellipticals with massive black holes
  - 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