Quasars and active galactic nuclei

STFC Summer School 2012

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- How are they laid out and what is happening in them?
- Active galactic nuclei as probes of the Universe
- How have they evolved over cosmic time?
- How do they influence galaxy evolution?
    - Recent results using Herschel and Chandra.

What are active galactic nuclei?

- Black holes at the centres of galaxies grow by accretion as active galactic nuclei (AGN).
- They emit emitting copious amounts of radiation and/or relativistic particles.
- AGN is a catch-all term for a whole zoo of objects including Seyfert galaxies, QSOs, radio galaxies, quasars and BL Lac objects.

Why study them?

- AGN are the Universe's ultimate power houses, radiating up to 10^{41} W for long periods of time.
- They play an important role in galaxy evolution.
- They produce a significant part of the Universe's energy budget.
- They allow us to study gravity in the most extreme conditions.
- They are useful probes of the Universe to high redshift.

How are AGN powered?

Black holes: getting energy from throwing things into bottomless pits.

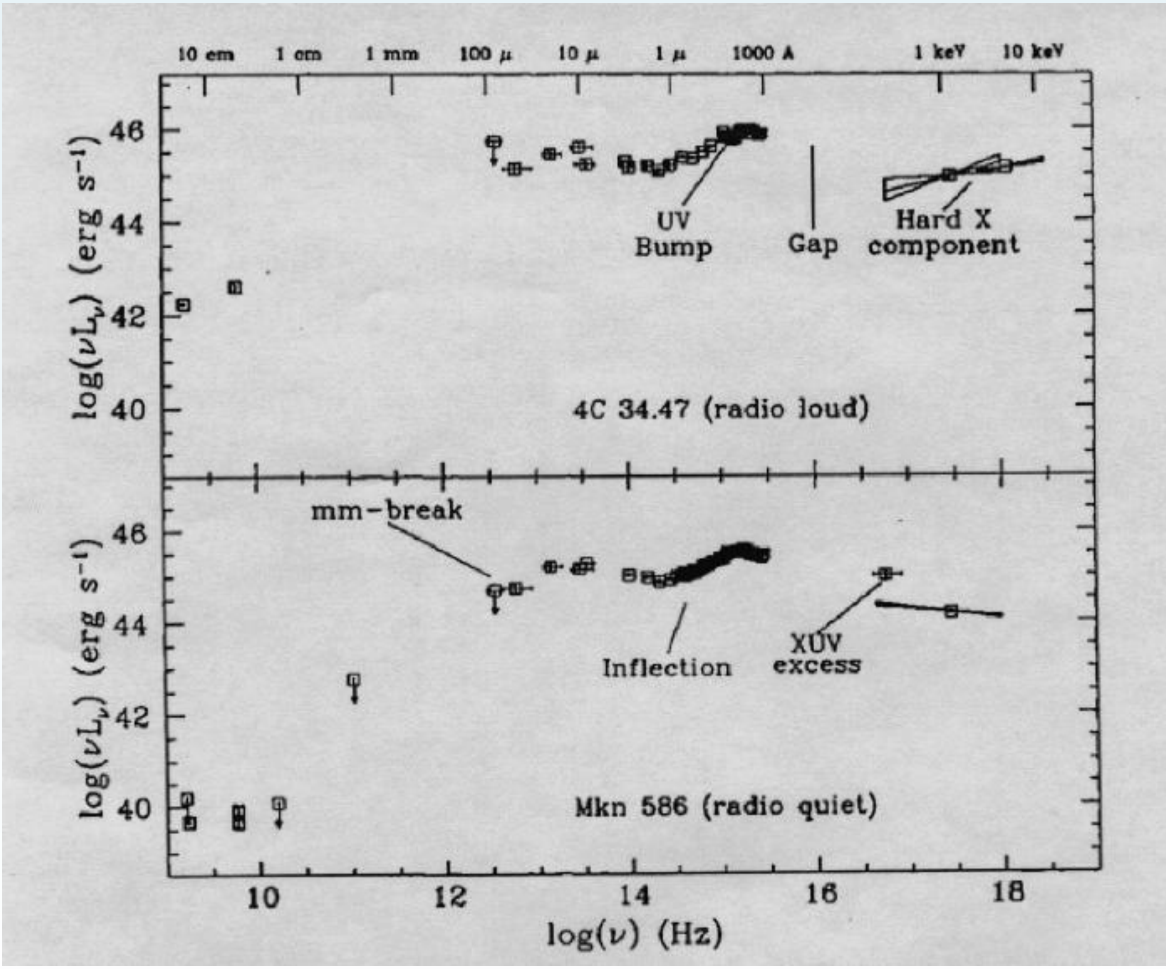
- Black holes do not have a solid surface
- Nothing can escape from within the Schwarzschild radius (non-rotating hole)
- $R_S=2GM/c^2$
- If E per unit mass = GM/R, E= $0.5c^2$ at R_S
- So naively might expect accretion efficiency of ~0.5

Getting the energy out

- No physical surface -> no impact!
  - (c.f. neutron star or white dwarf, 50% of energy released at surface)
  - The energy can be “advected” into the hole.
  - So any energy that is going to come out has to escape before the material gets to R_S
- This means that the accretion disk will be the primary source of radiation in an accreting black hole
- Efficiency will be < 50% (realistically ~10%)

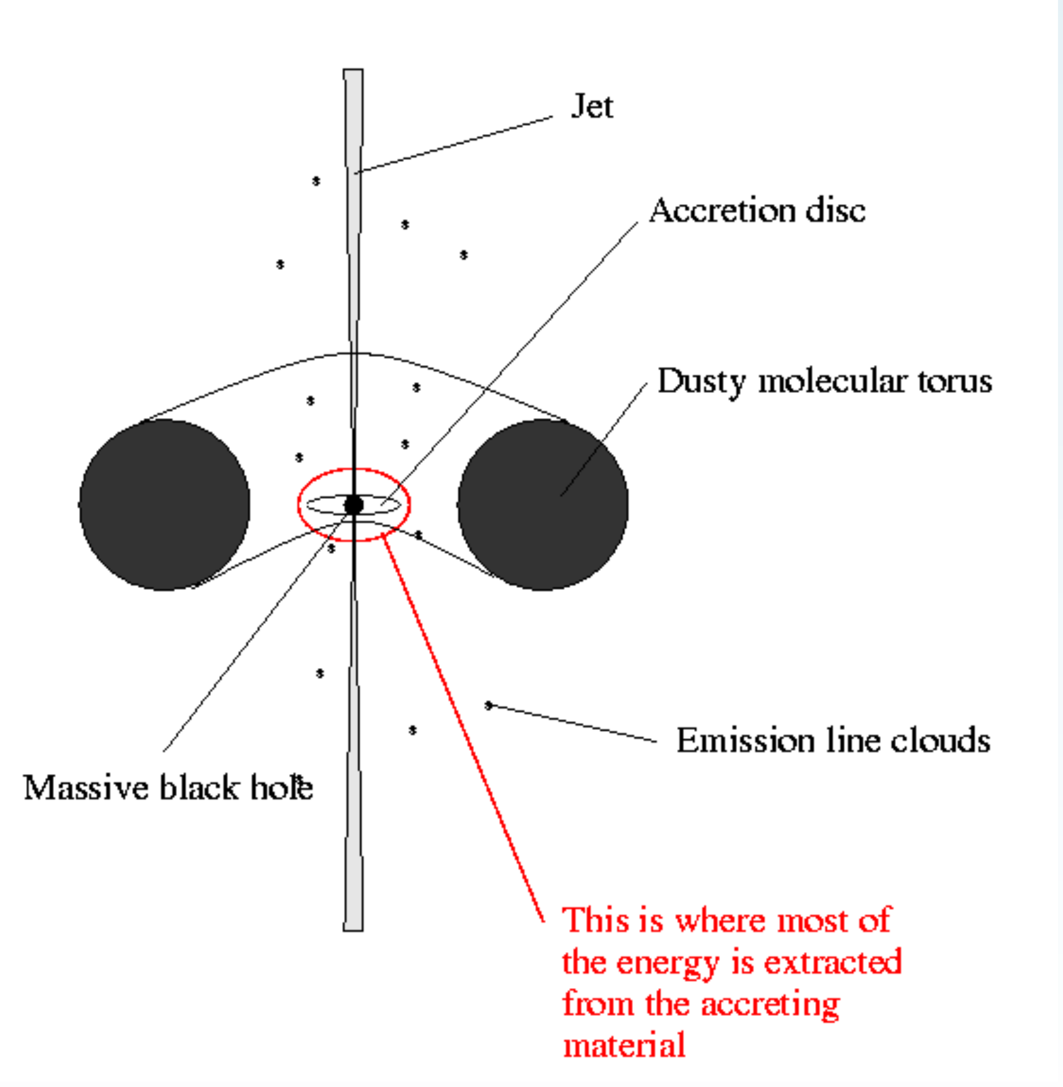
How are AGN laid out?

- AGN emit throughout the electromagnetic spectrum.



Elvis et al. 1994, ApJS 95, 1

Generic layout of an AGN

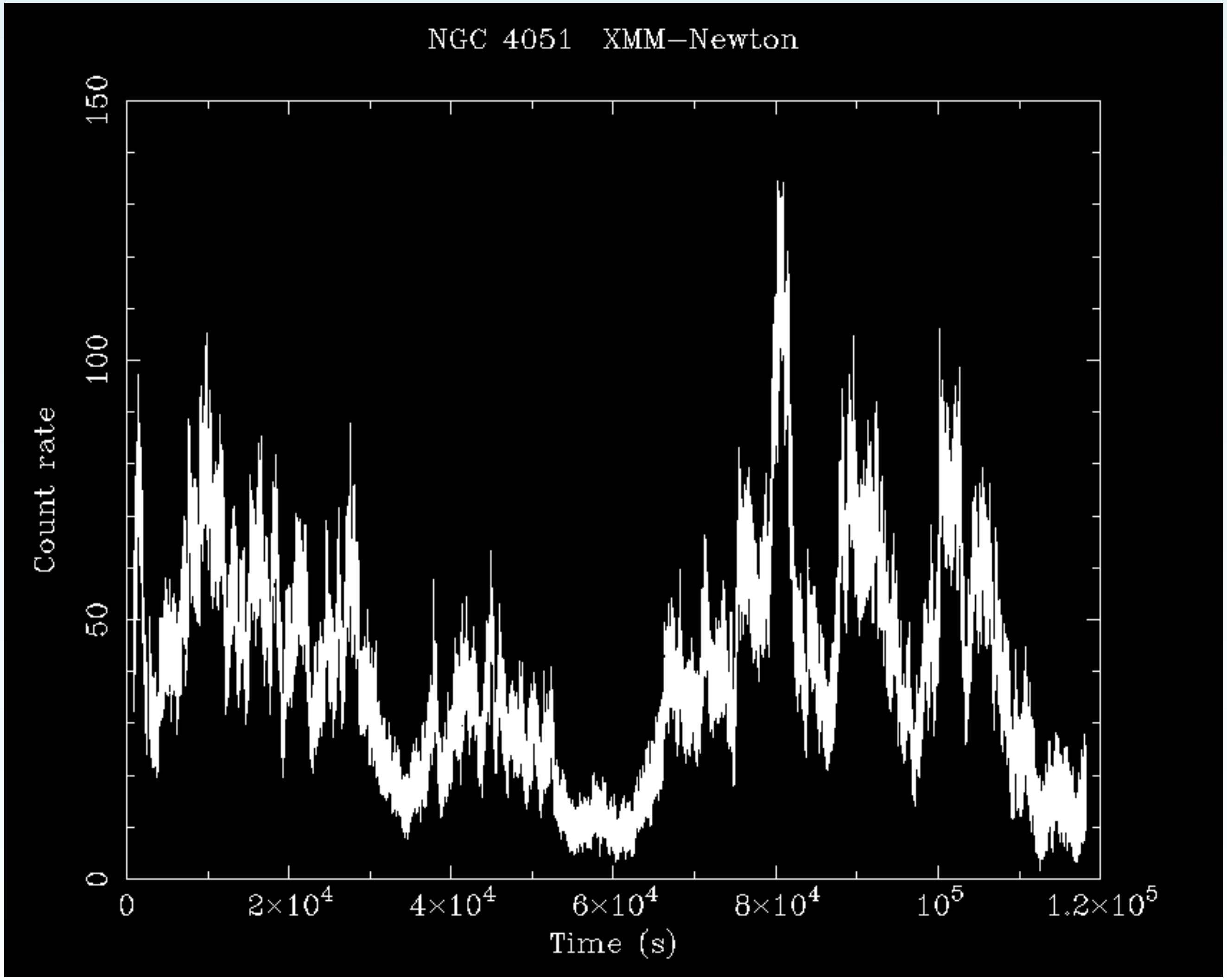


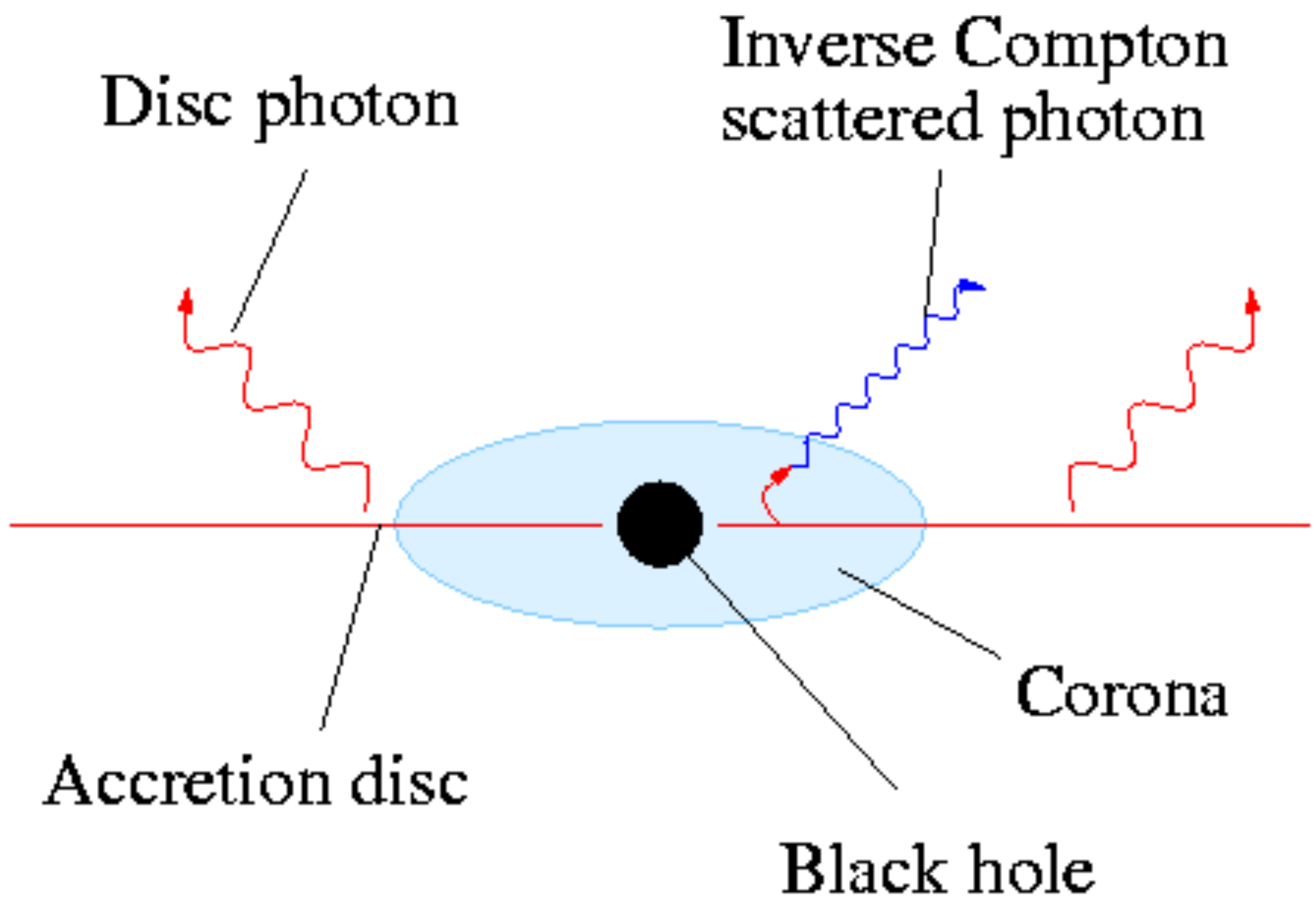
What's coming from where?

- Variability is a key diagnostic
  - Timescale of variations cannot be smaller than the light travel time across the emission region

- In non-beamed sources
- Far infrared: years
- Broad optical emission lines: weeks
- Optical – ultraviolet continuum: days
- X-rays, (+γ-rays): tens of minutes

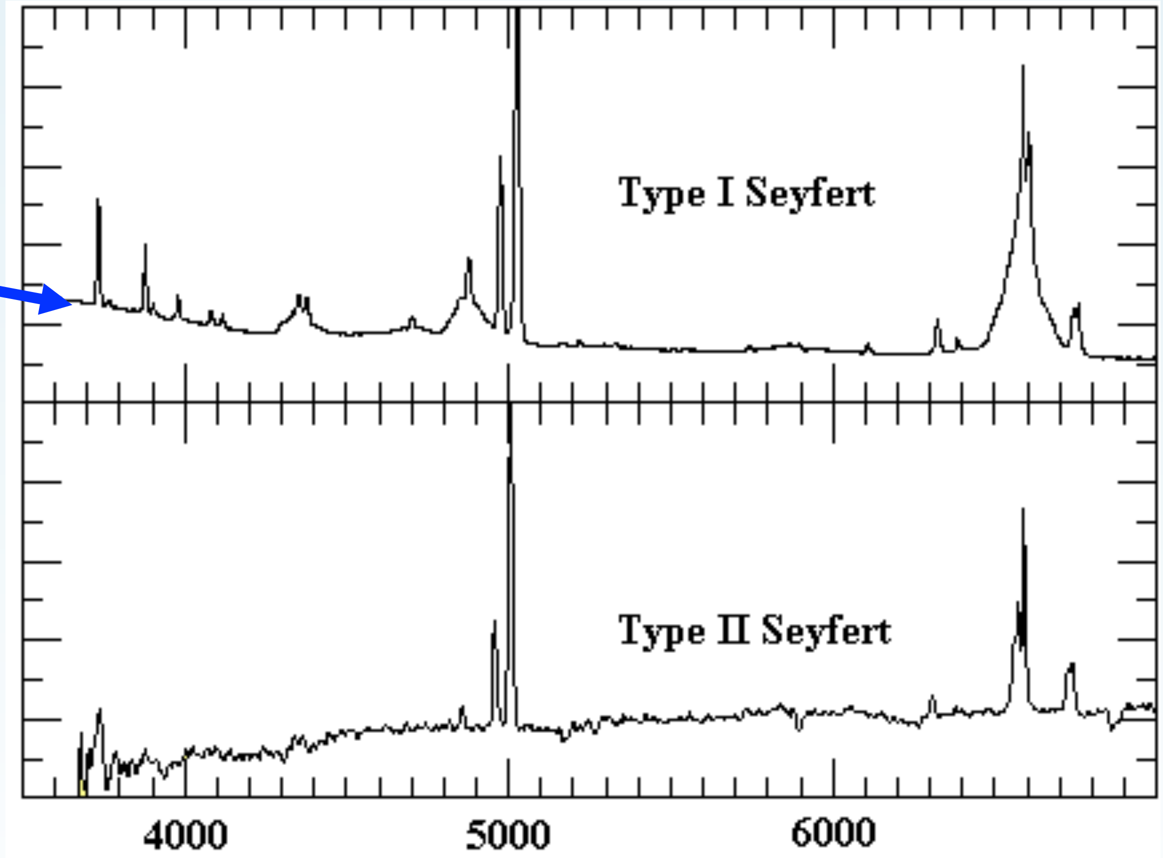
A day in the X-ray life of NGC4051




Disc photon
Inverse Compton scattered photon
Corona
Accretion disc
Black hole

Optical spectra of AGN

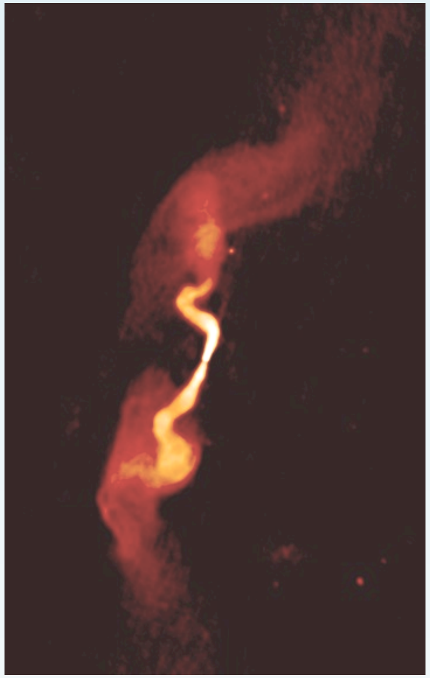
Blue continuum comes from the accretion disc, which dominates the overall power



From Bill Keel's website

Relativistic jets

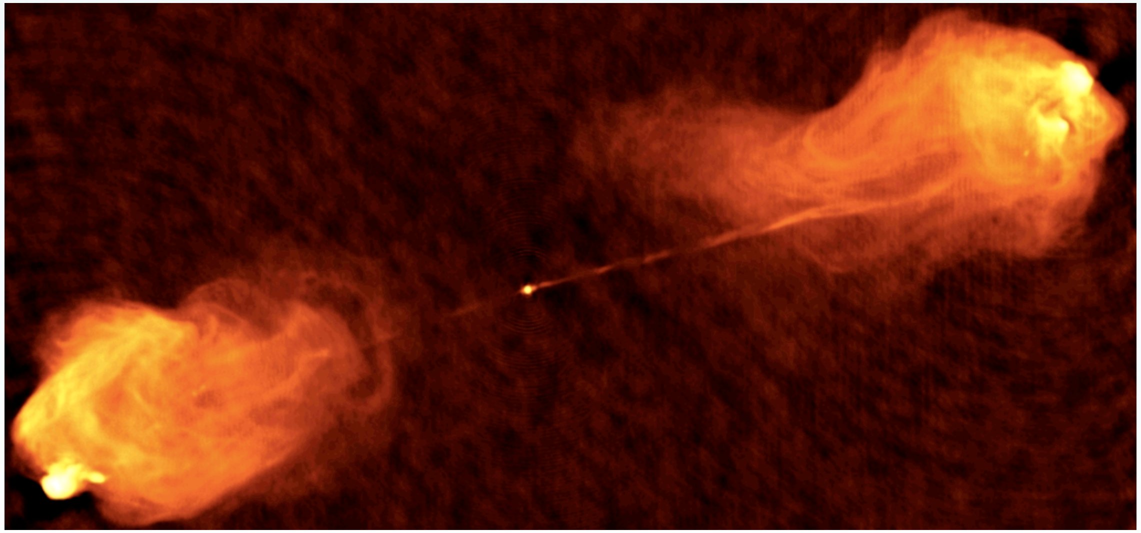
<u>Some</u> active galaxies emit jets of relativistic material.



This example is 3C311, a Faranoff-Riley class 1 radio galaxy.

FR1s are the lower luminosity radio galaxies, with diffuse lobes which darken at the ends

Cygnus A is a Faranoff-Riley class II radio galaxy. These are more powerful than FR-1s, and the ends of the lobes are brightened with hot spots.



Open questions - I

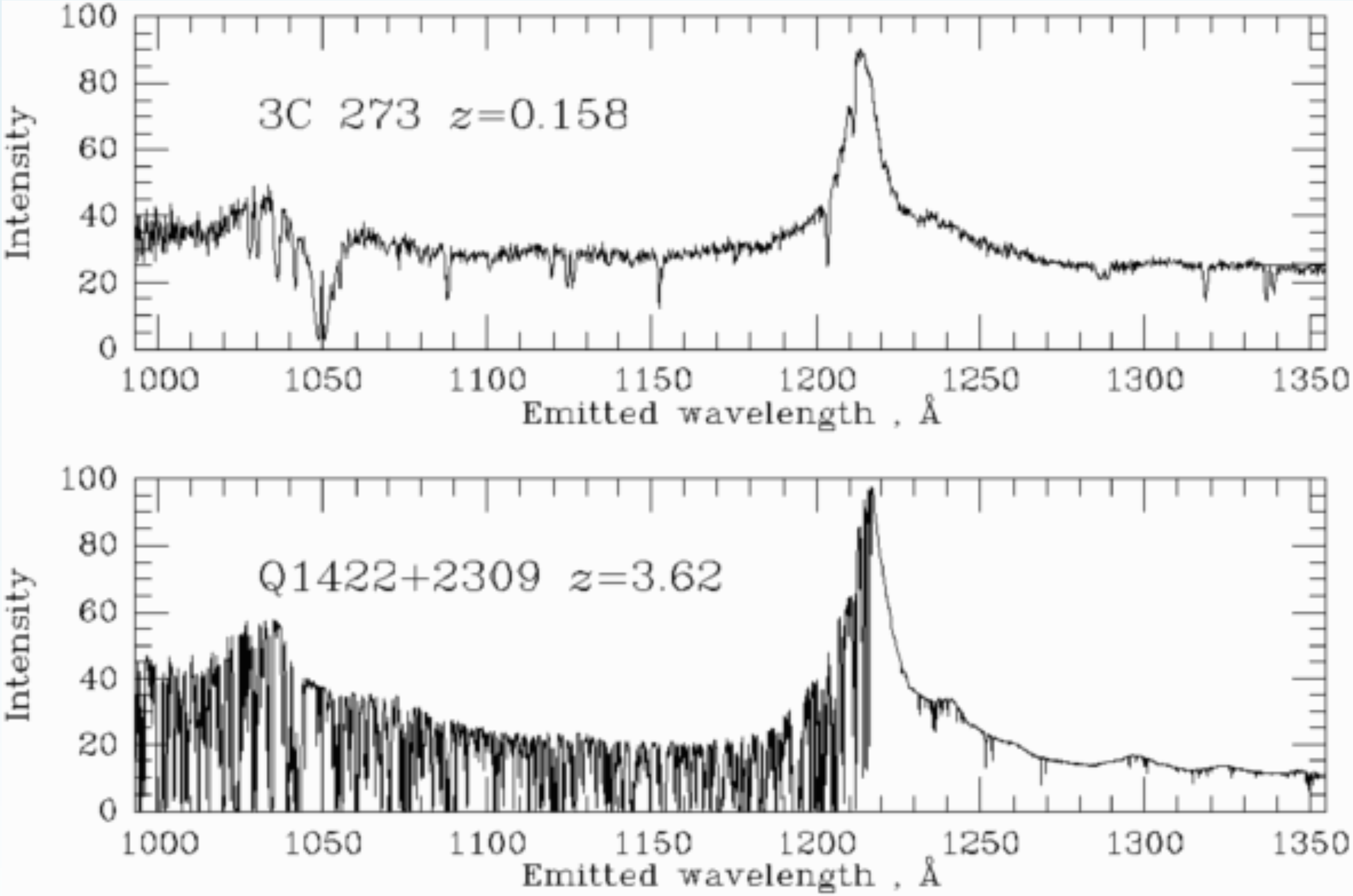
- Do all AGN have this structure?
  - We know that some do for certain, but we don't know that all do, and there's some evidence to suggest that some objects may not have obscuring tori at all.
- Where do the emission line clouds come from (and go to)?
  - Are they on circular orbits, and is the distribution flattened or spherical? Are these clouds on the way in, from the torus, or on the way out, from the accretion disc?
- Where is the X-ray corona?
  - Is it interior to the disc, or above and below it?

Open questions - 2

- How is the torus arranged and distributed, and supported?
  - Results from Spitzer in particular suggest that the torus is clumpy rather than homogeneous. Is it really a doughnut shape?
- What drives the winds we see in the ultraviolet and X-ray spectra?
  - Are winds coming from all objects or just a subset?
- How does material get to the accretion disc?
  - We don't see inflowing material, so it must come in from the sides where we can't see it in absorption. Are the torus and disc connected? Could the torus be a warped or swollen outer part of the accretion disc?

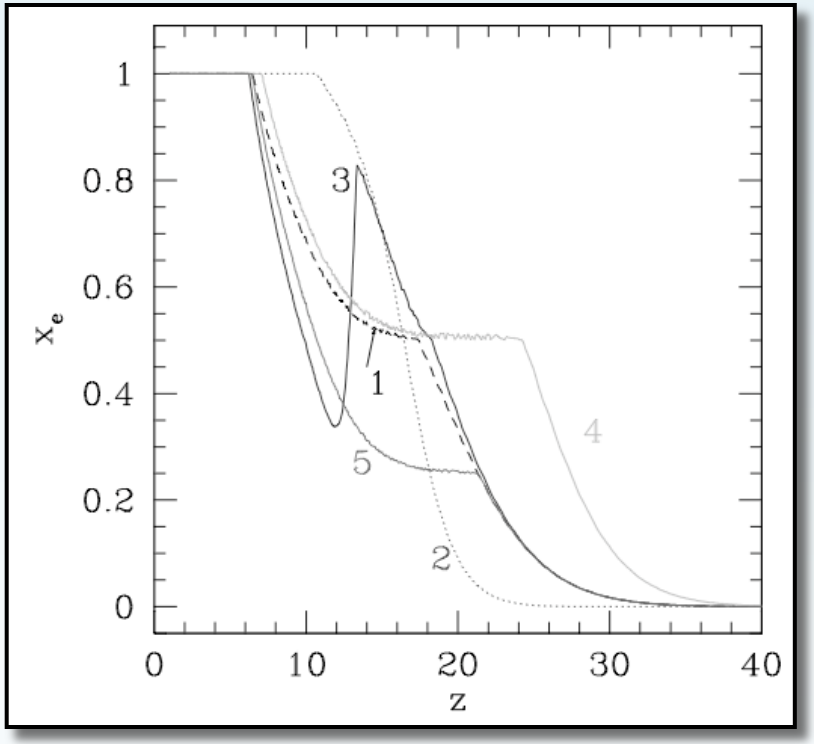
AGN as probes

- The large luminosities of AGN make them excellent beacons shining from the distant Universe.
- This light shines through intervening galaxies, gas clouds and the intergalactic medium, all of which leave an imprint in the form of absorption lines.
- Most prominent is the Ly alpha transition of neutral hydrogen, which produces the “Lyman alpha forest”.
- Can be used to probe the space density, clustering, chemical composition and ionization state of intervening clouds.

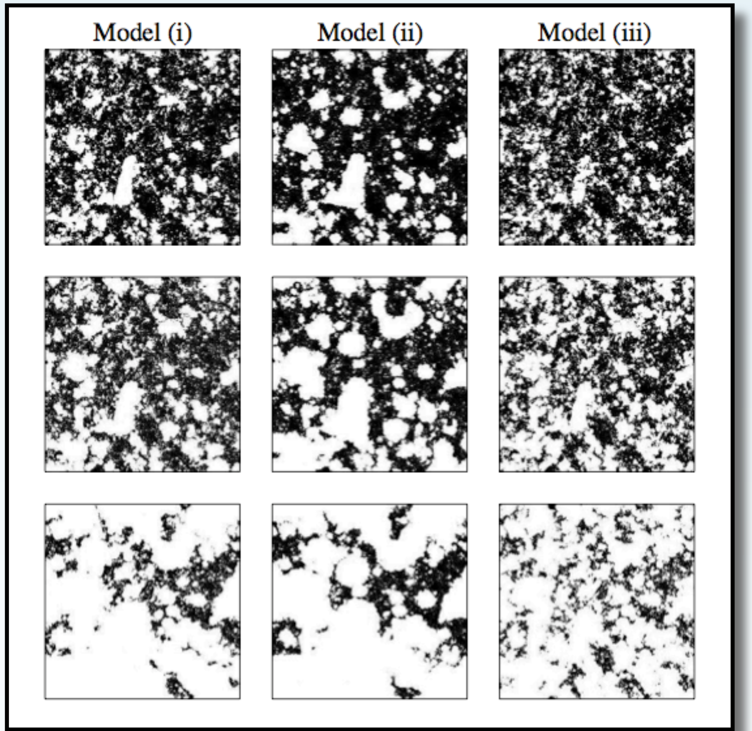


From Bill Keel's website

Major issue: probing the epoch of reionization



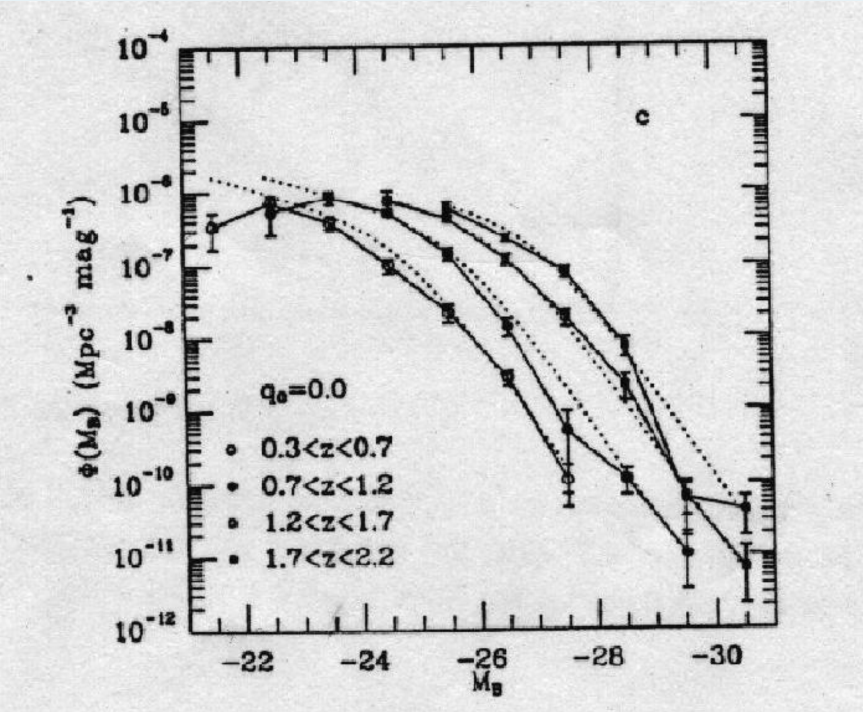
Holder et al 2003, ApJ 595, 13

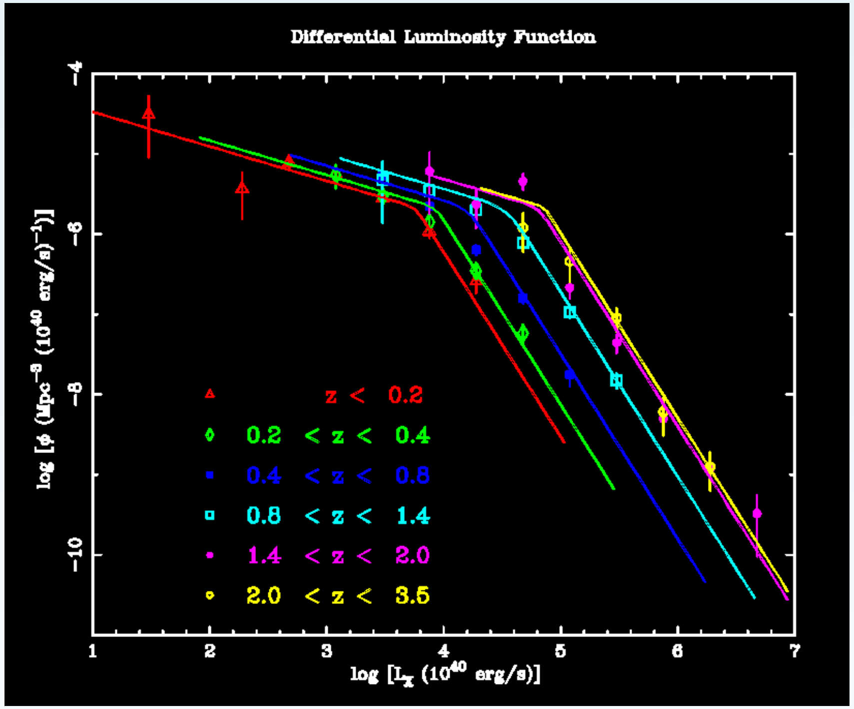


McQuinn et al 2007, MNRAS 377, 1043

Neither the time sequence of reionization, nor the dominant source of ionizing photons, nor the way that the ionized bubbles spread or percolate are known.

How have AGN evolved with cosmic time?



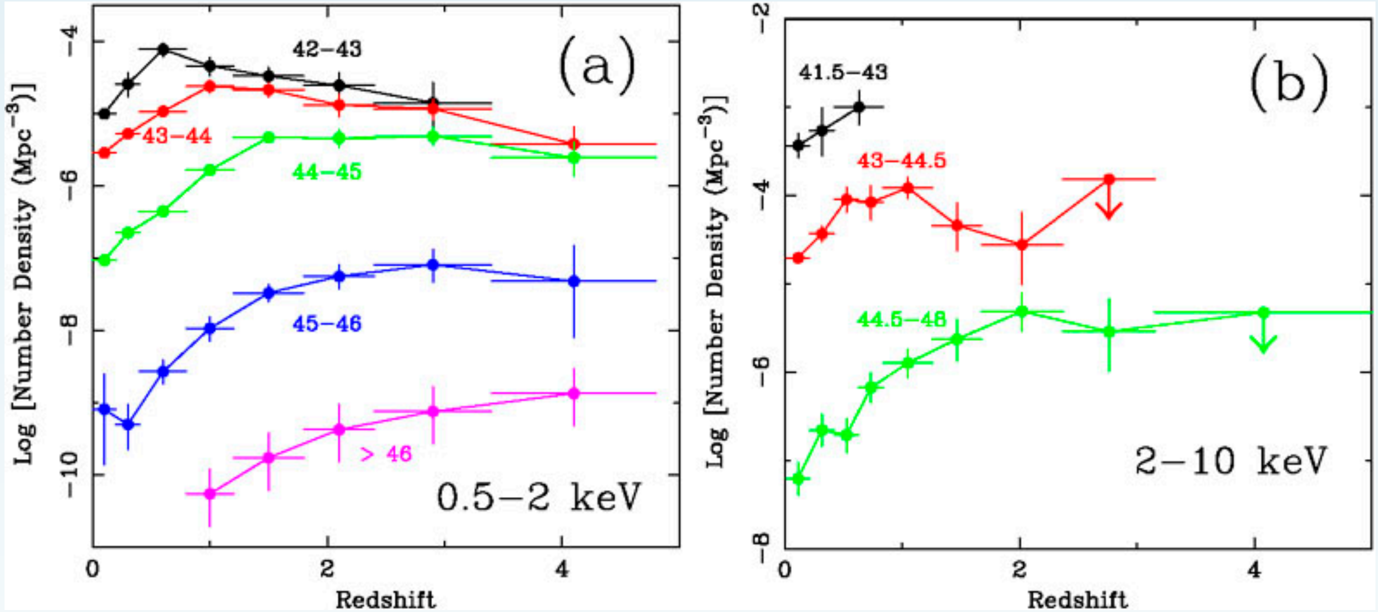


Boyle, Shanks & Peterson 1988, MNRAS 235, 935:

- optical L.F.
- peak at z~2

Page et al. 1997, MNRAS 291, 324:

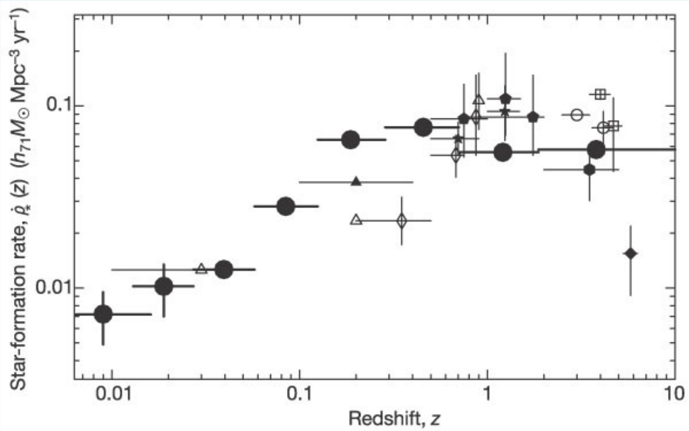
- X-ray L.F.
- peak at z~2



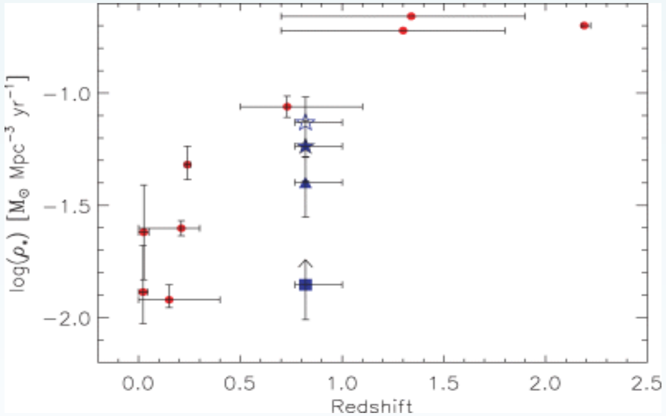
Hasinger et al. 2005, A&A, 441, 417

- Powerful AGN ‘died off’ at earlier times than less powerful AGN; less luminous AGN may even have peaked at redshift below 1.
- This AGN ‘downsizing’ mirrors what is seen in galaxies: the most massive galaxies were formed at z>1.

- QSOs had their heyday at z~2.
  - Most vigorous period of black hole growth.
  - If black holes and stars grow together, QSOs should also be forming stars rapidly.
- Peak of star formation rate also at 1< z < 3.

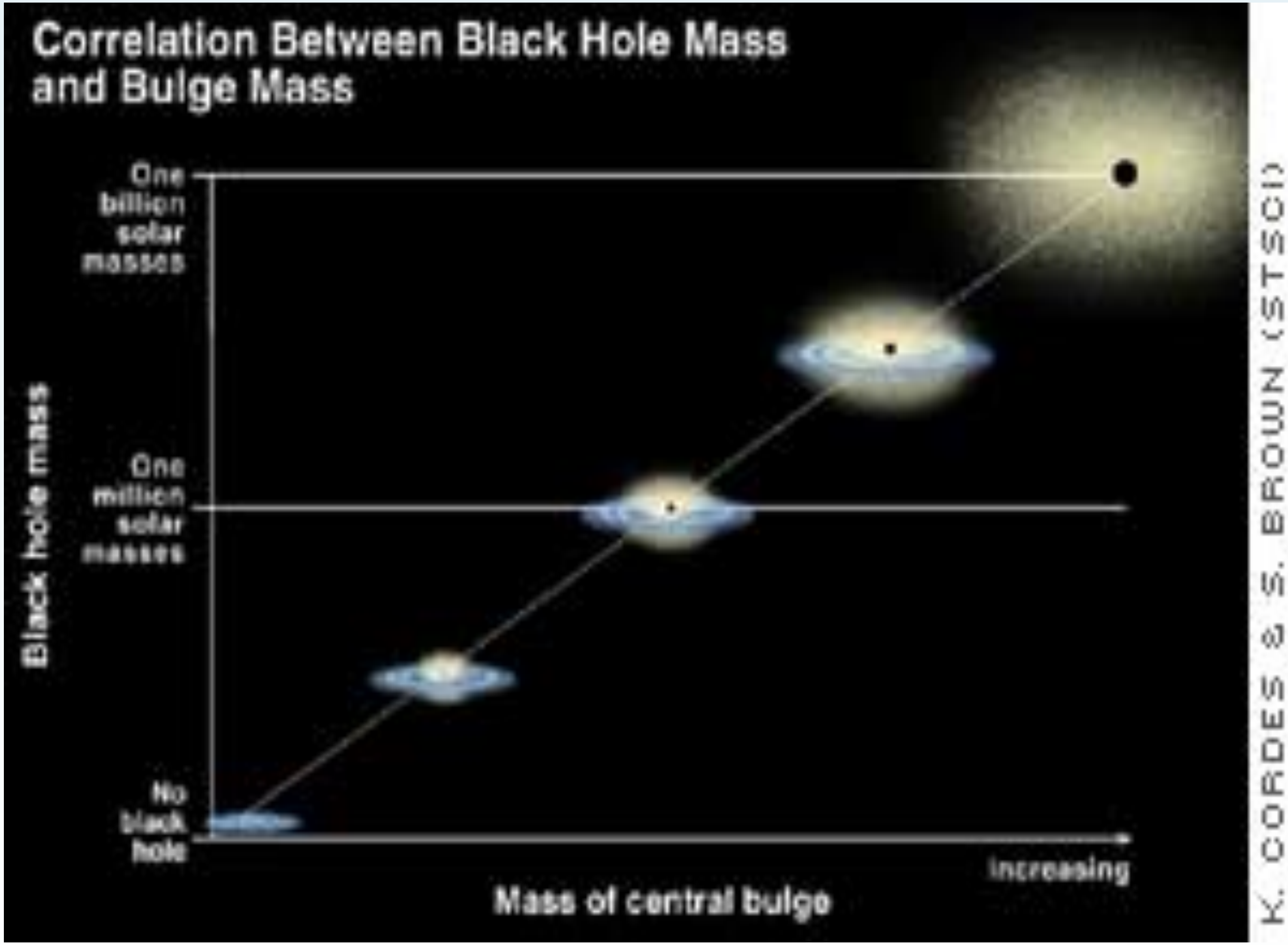


Heavens et al. 2004, Nature 428,625



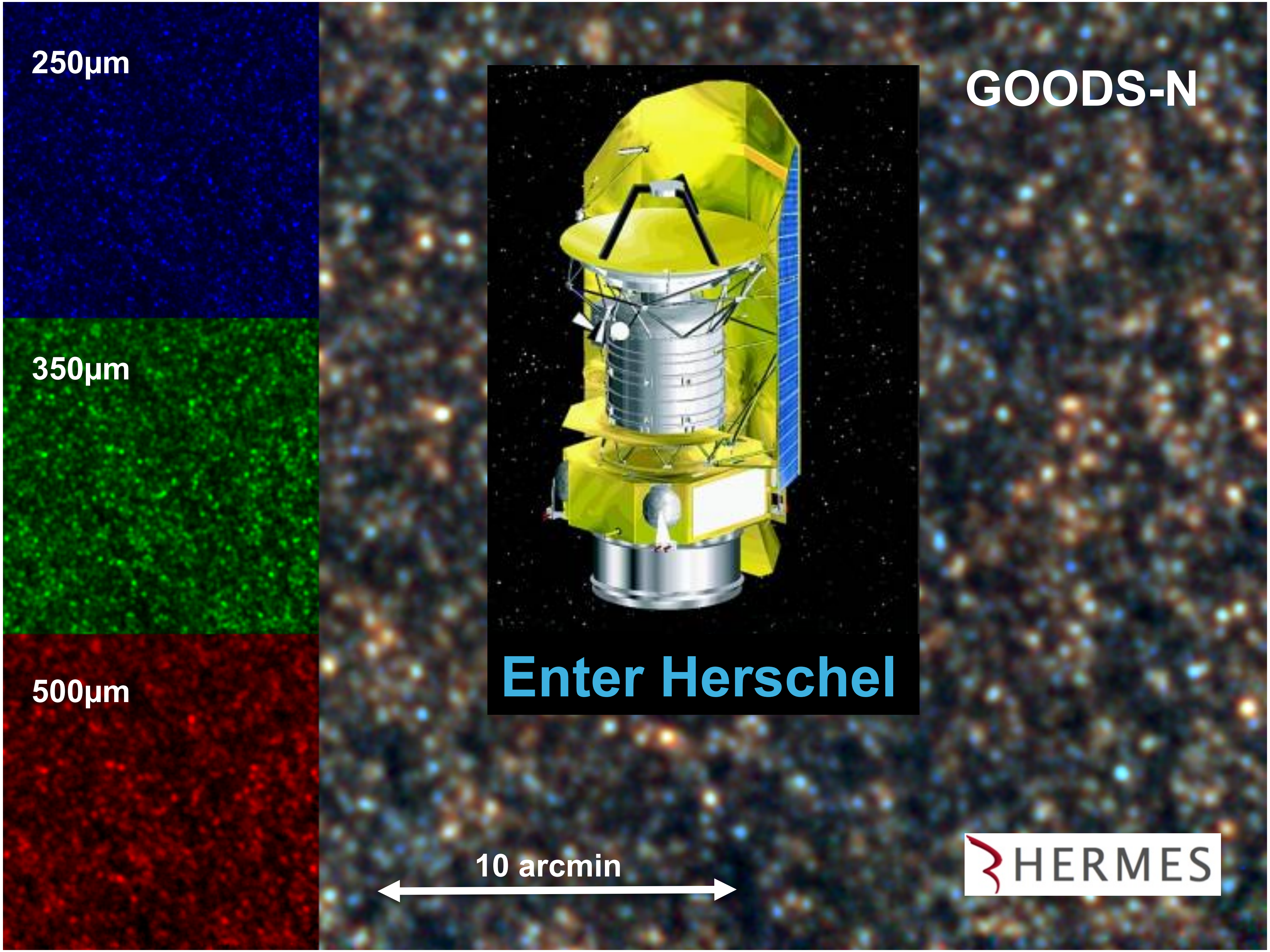
Doherty et al. 2006, MNRAS 370,371

Black hole / bulge mass relation



How do AGN influence galaxy evolution?

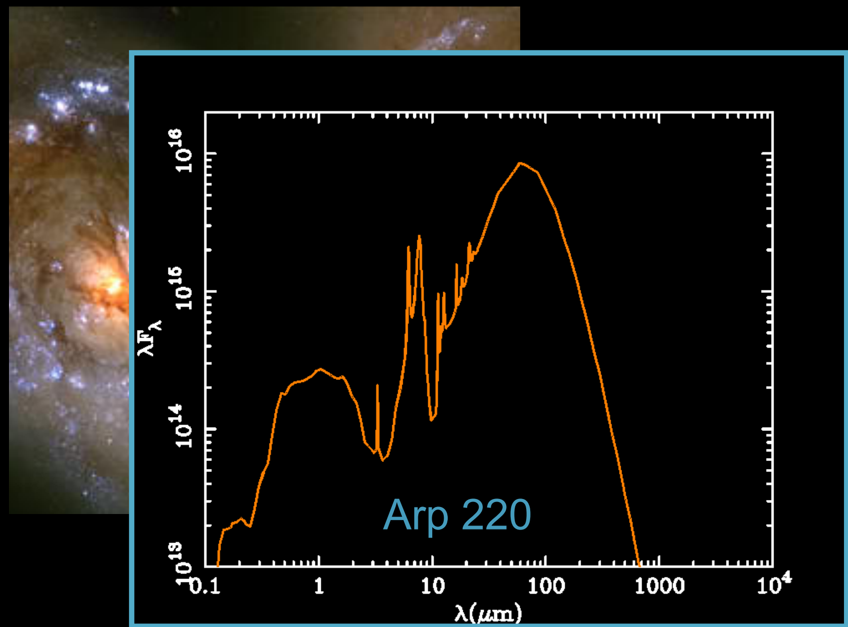
Looking at star formation in the host galaxies of AGN in the $1<z<3$ epoch of galaxy formation


250µm
350µm
500µm
GOODS-N
Enter Herschel
10 arcmin
HERMES

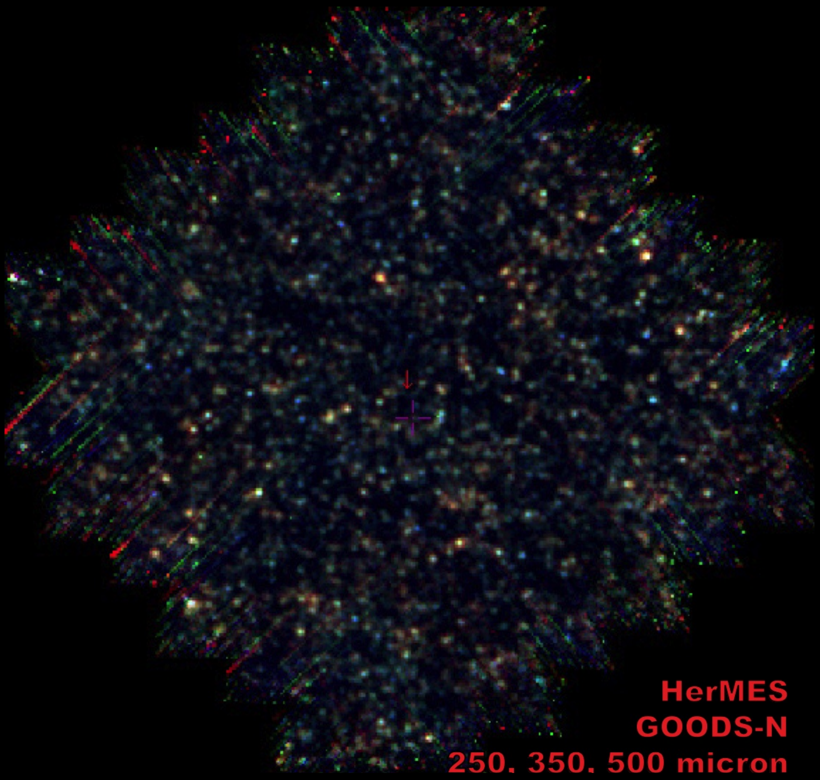
Energy release from black holes and stars

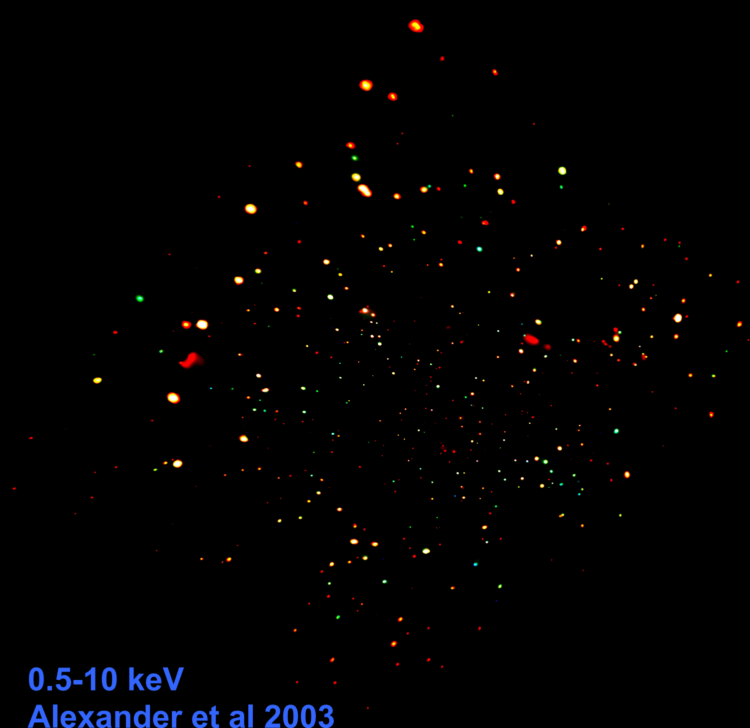
Black holes growing by accretion are best found by X-ray emission

The most rapidly star-forming galaxies are often highly obscured, emitting the bulk of their energy in the far infrared

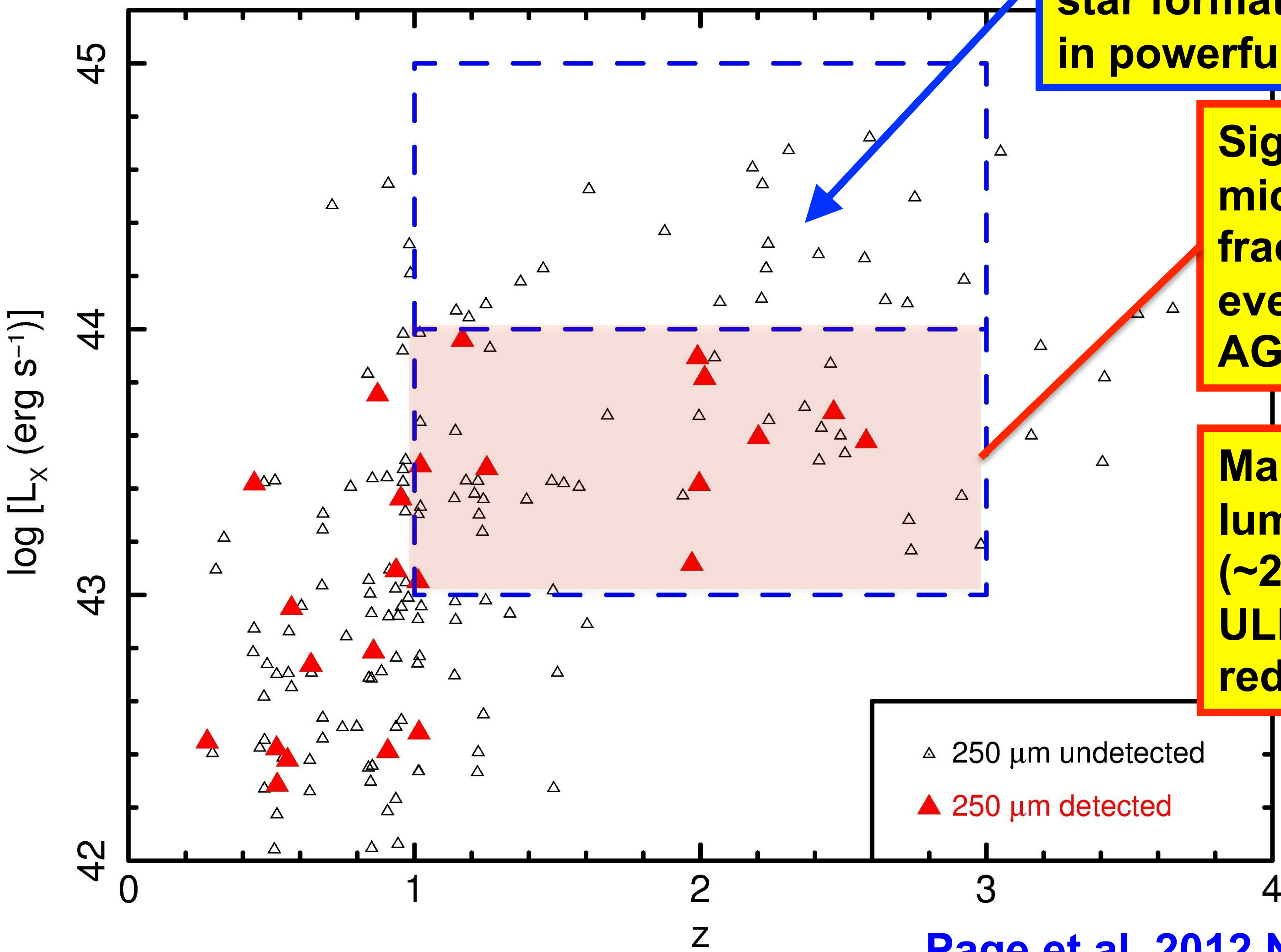


- Herschel allows us to dig much deeper for star formation around AGN at redshifts of 1-3.
- HerMES SPIRE observations of the Chandra Deep Field North: deepest 250 micron image ever taken.





Probing star formation right down the AGN luminosity function at z~2



No 250 micron detections: prolific star formation is rare in powerful AGN.

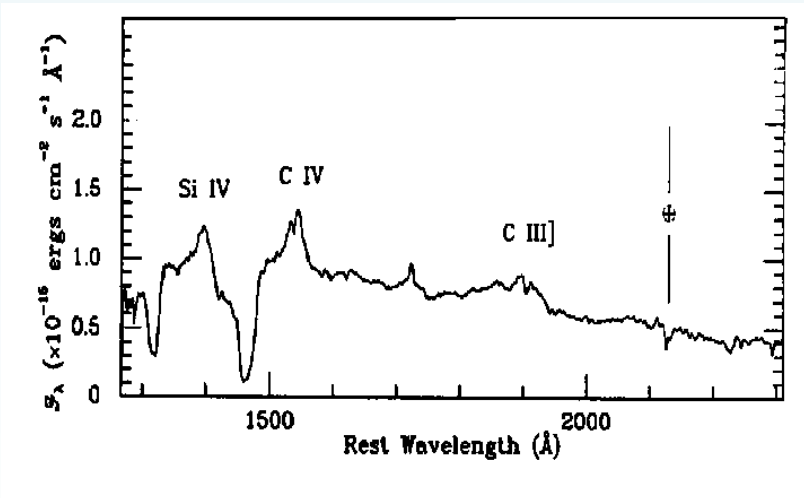
Significant 250 micron detection fraction at z>1, even at moderate AGN luminosities.

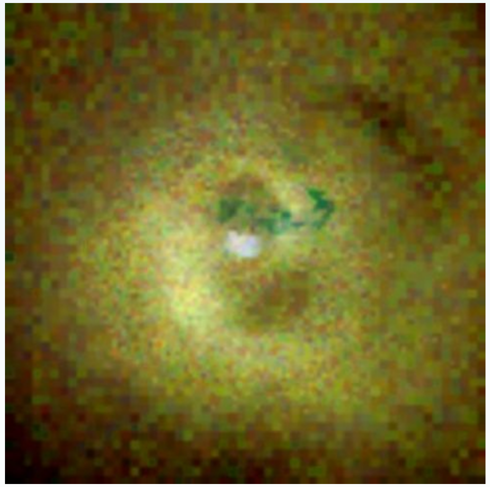
Many moderate luminosity AGN (~25%) lived in ULIRGs between redshifts of 1 and 3.

Page et al. 2012 Nature 485, 213

Why is this so important?

- **AGN feedback has become the standard paradigm in cosmological modelling of the galaxy population.**
  - **Without it, the (semi-analytic) models don't give us the right galaxy luminosity function.**
  - **(see e.g. Croton et al. 2006, MNRAS, 365, 11, Bower et al. 2006, MNRAS 370, 645)**
- **There are now 2 concepts of AGN feedback.**
  - **(radiative) feedback from luminous AGN. "quasar mode"***
  - **kinetic feedback from old, underfed AGN. "radio mode"***





Perseus cluster imaged by Andy Fabian's group

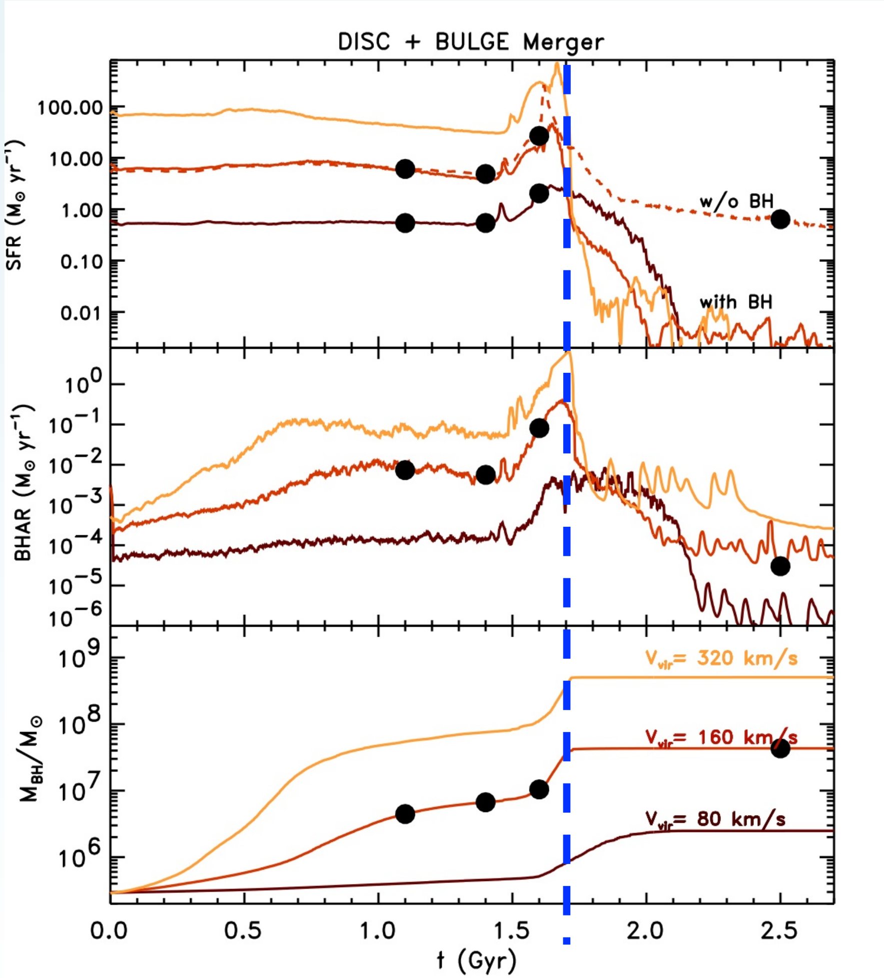
*** radio and quasar modes are terrible titles, but they seem to have stuck.**

Why is this so important?

- **How/what AGN feedback happens is now central to understanding massive galaxies.**

Look at the predictions from the radiative feedback models.

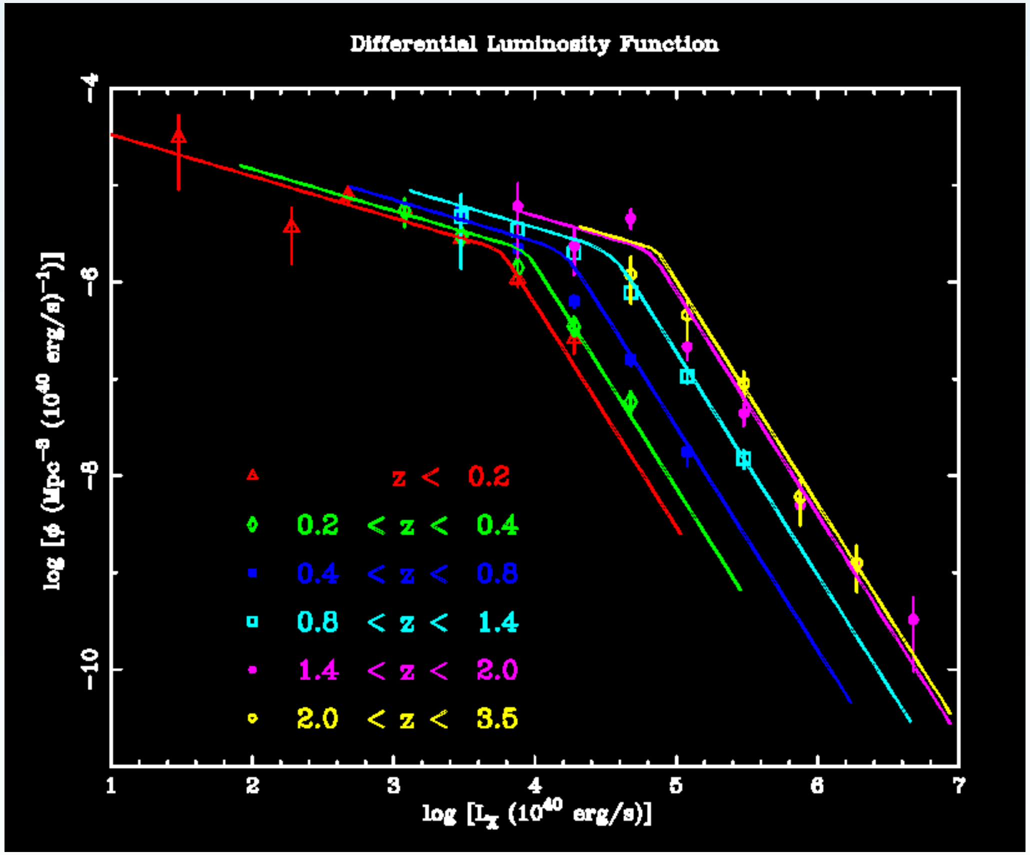
Di Matteo et al. 2005, Nature, 443, 604



- **The black hole peaks after the star formation peaks (note log y axis).**
- **True in all these kinds of models where the feedback terminates star formation.**
- **But still some star formation when black hole peaks.**
- **Black hole growth outlasts star formation.**
- **Splendidly consistent with our results ☺.**

Why am I equating "AGN peaking" with Lx>10^{44} ergs/s?

Page et al. 1997, MNRAS 291, 324

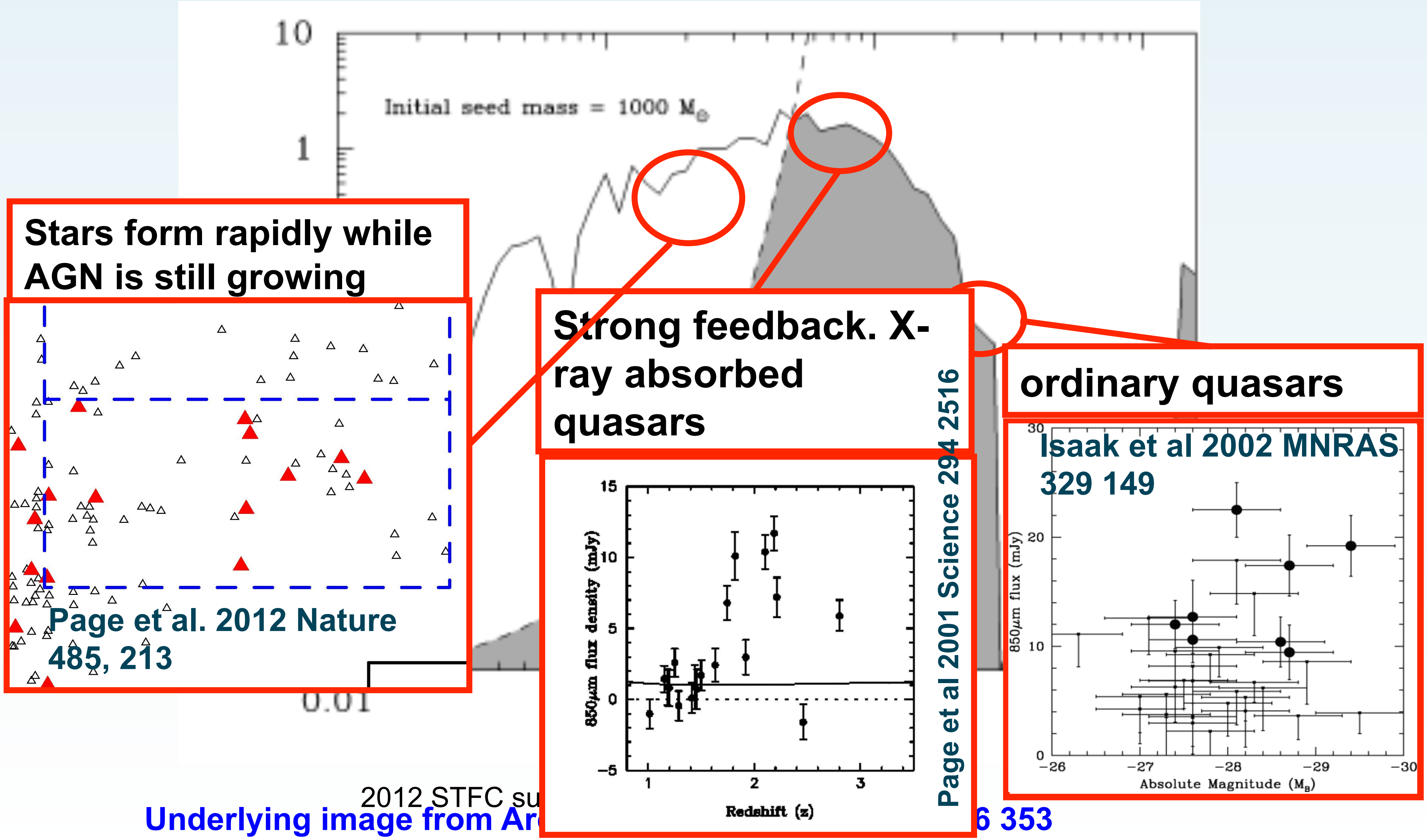


The AGN luminosity function is steep above 10^{44} ergs/s.

Statistically, beyond this point the population is always dominated by objects which will not get significantly more luminous (i.e. they are around their peak).

Cosmological evolution (essentially shifting of luminosity function to lower luminosities with redshift) reinforces this argument.

A cartoon of black holes and galaxy evolution



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Underlying image from Ar 6 353

Conclusions

- **AGN are accreting black holes in the centres of galaxies.**
- **They are the Universe's supreme power houses.**
- **They have a cylindrically symmetric structure of an accretion disc surrounded by some kind of torus.**
- **They are useful probes of the high redshift Universe.**
- **They have evolved strongly with cosmic epoch, peaking at redshift ~2.**
- **Black holes have a fundamental role in galaxy evolution.**
- **Normal, luminous, z=2 QSOs are not forming stars very fast.**
  - **They have peaked.**
- **Many moderate-luminosity z=2 AGN are prodigiously forming stars.**
  - **Probably, their black holes are still growing.**
- **Star formation is suppressed at high AGN luminosities. This is a key prediction of luminous/radiative/(quasar-mode) AGN feedback models.**