The dark and the light: Black holes, dark halos, and their influence on galaxy evolution

Ryan C. Hickox
Dartmouth College

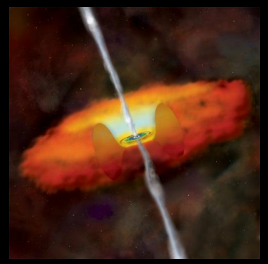
Dartmouth

Berkeley Cosmology Seminar
12 February 2013

Illustration courtesy NASA

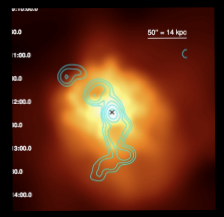
credit: Andy Goulding

Outline



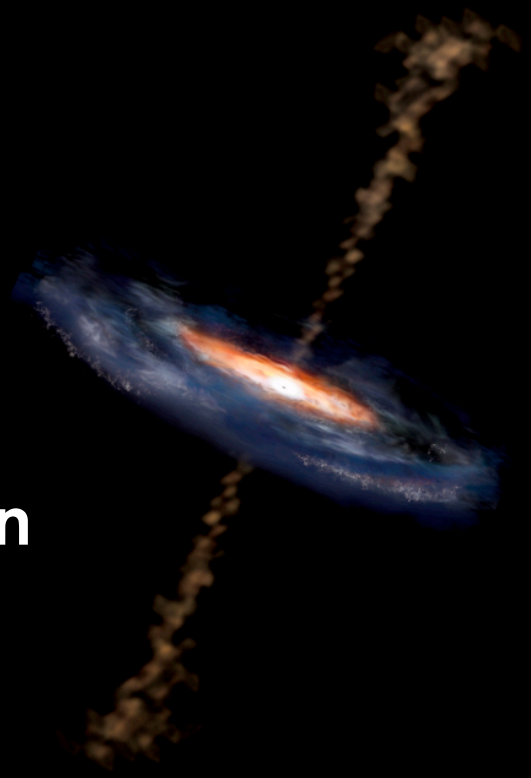
(Brief) introduction to supermassive black holes and active galactic nuclei

The cosmic growth of AGN and large-scale structures: **Do AGN follow star formation or prevent star formation?**



Where and when is AGN feedback important?

Prospects for the future



What drives the growth of black holes?

D.M. Alexander [a,*], R.C. Hickox [a,b]

[a] Department of Physics, Durham University, South Road, Durham DH1 3LE
[b] Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, United States

arXiv:1112.1949

Evolution of active galactic nuclei

A. Merloni[*,1] and S. Heinz[†,2]

[1]Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstr., D-85741, Garching, Germany
[2]Astronomy Department, University of Wisconsin-Madison, Madison, WI 53706

arXiv:1204.4265

Observational Evidence of AGN Feedback

A.C Fabian

Institute of Astronomy, Madingley Road Cambridge CB3 0HA, UK

arXiv:1204.4114

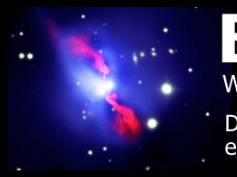
What drives the growth of black holes?

An international workshop

Durham University

~~*19th-22nd April 2010*~~ 26th-29th July 2010

Durham, England



BLACK HOLE FEEDBACK 2012

What is the role of AGN in the evolution of galaxies?

Dartmouth-Durham extragalactic workshop

30 July - 3 August 2012

Dartmouth College

Black holes and galaxies at Dartmouth

Dartmouth

PhD students:

Chien-Ting Chen

First-years:

Mackenzie Jones

Christine Black

Visiting:

Stefano Marchesi

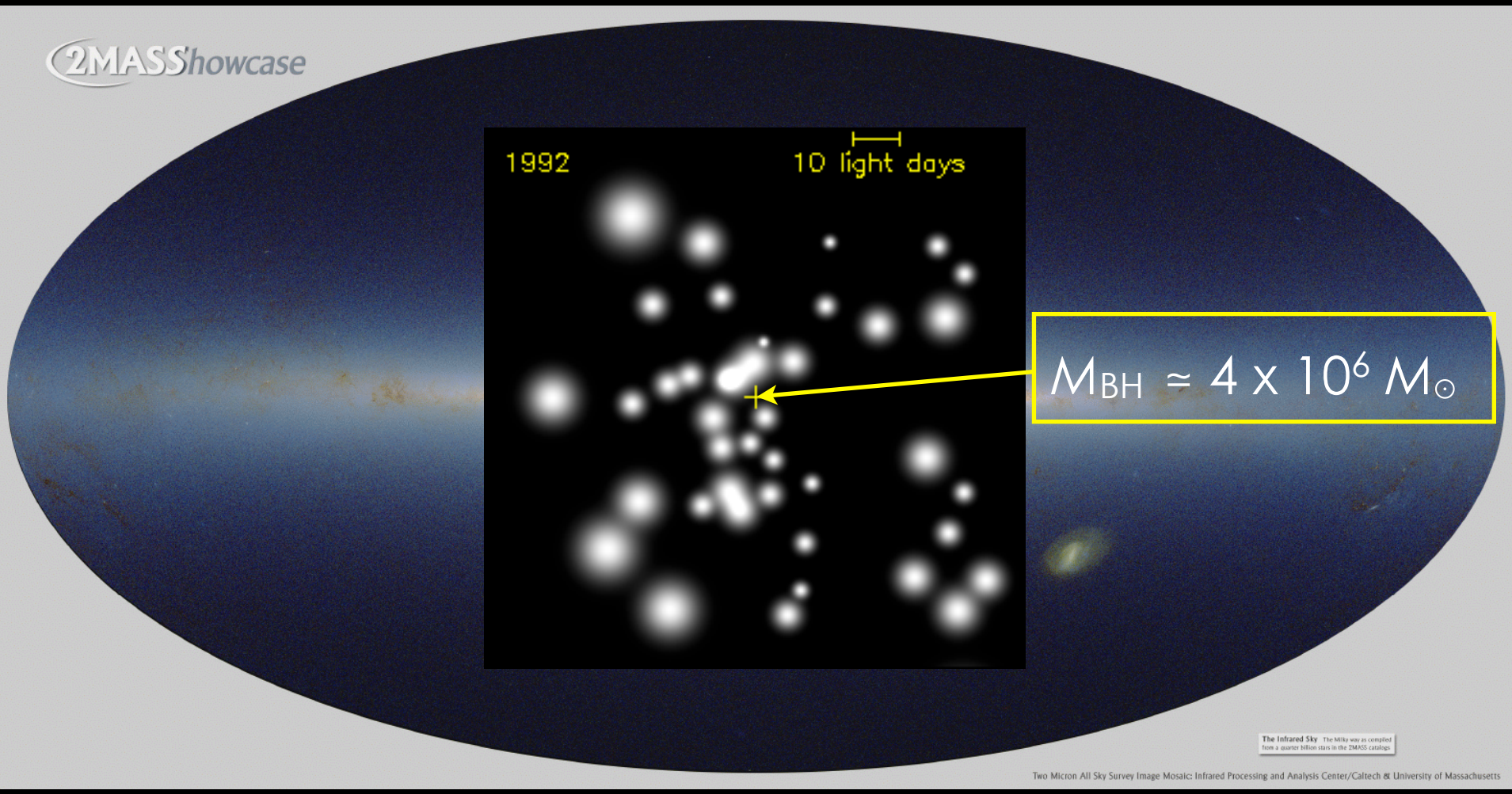
Postdocs:

Kevin Hainline

Francesca Civano

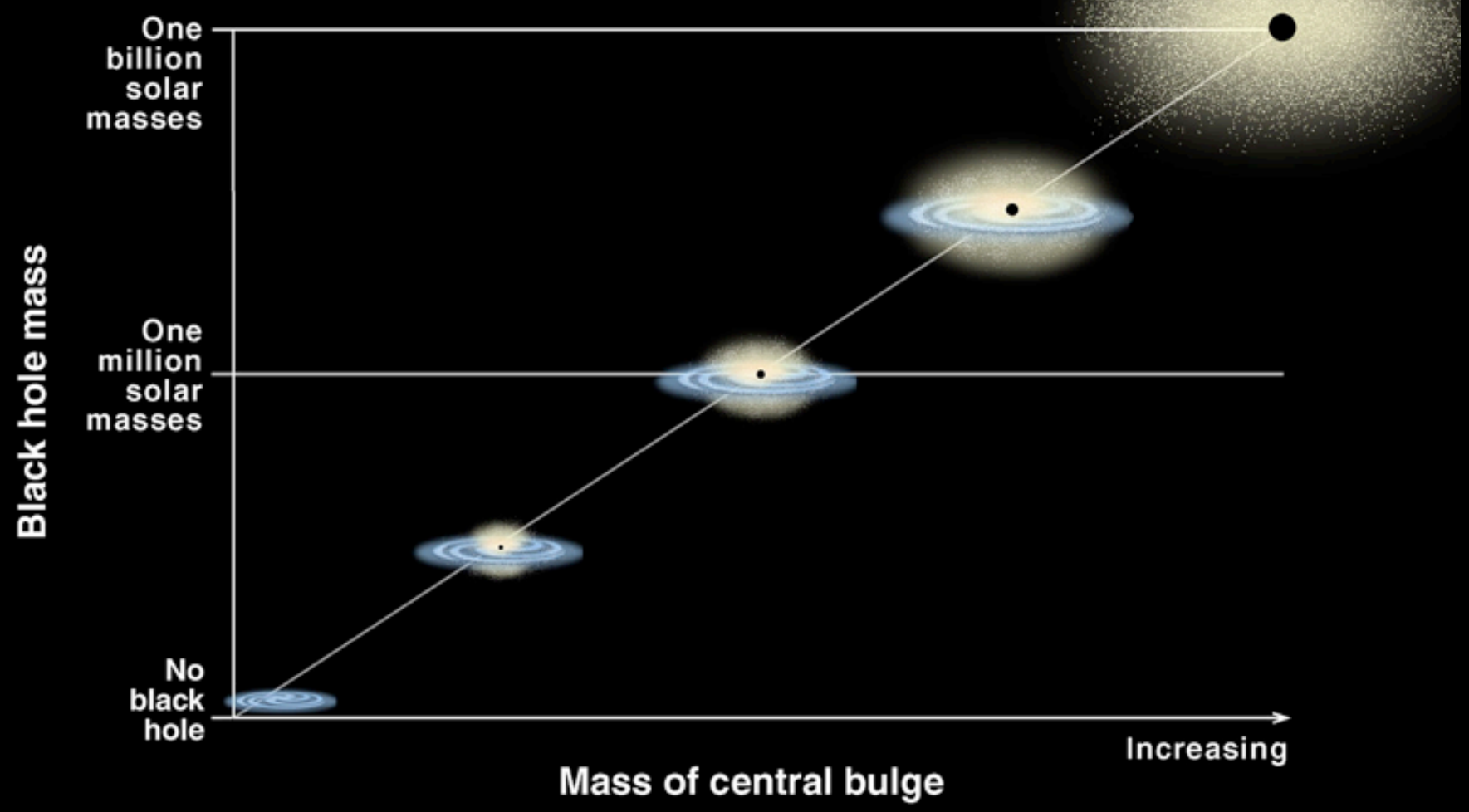
Undergrad: Tom Whalen

Overview of supermassive black holes and AGN

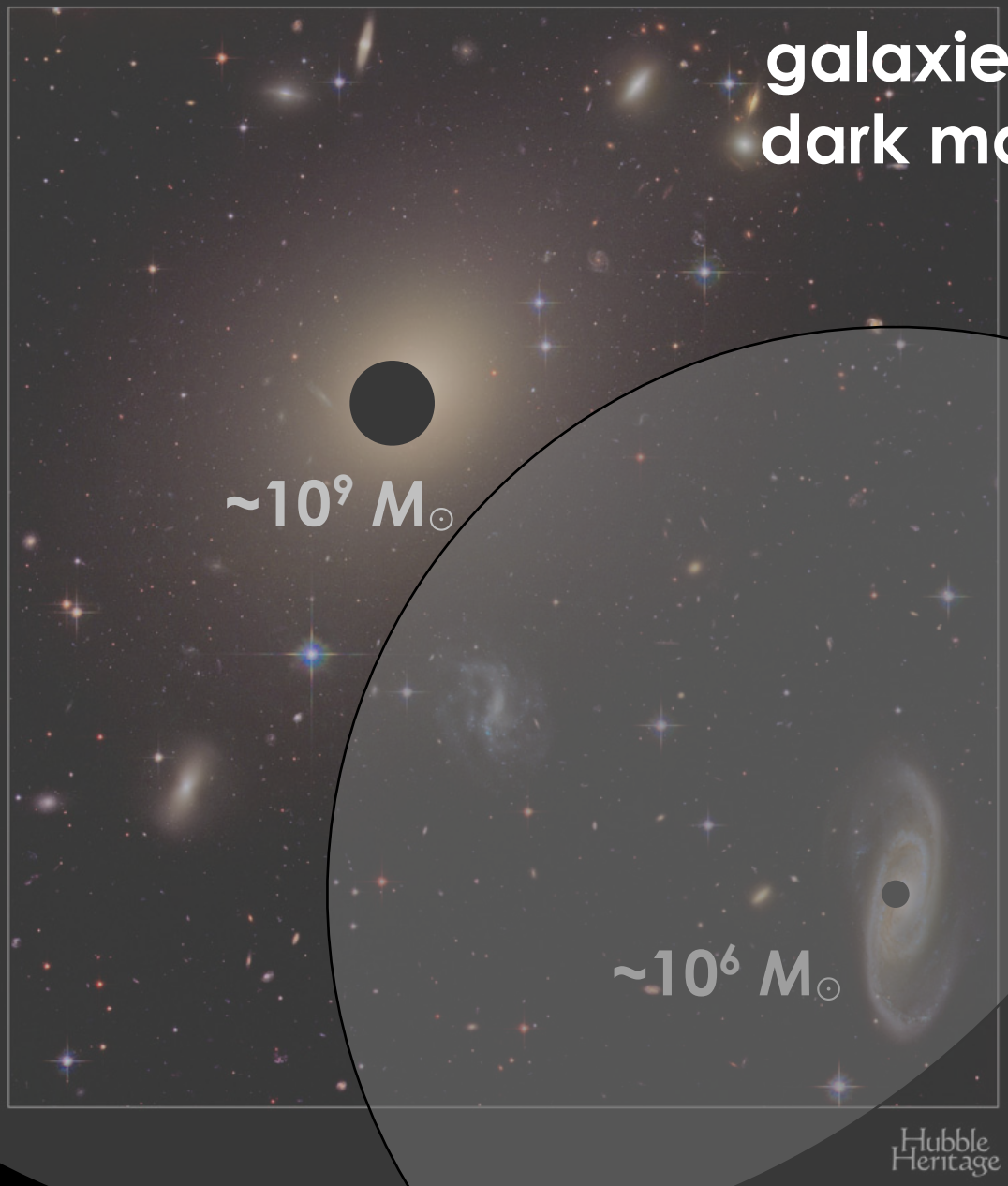


see e.g., Ghez et al. (2008), Gillessen et al. (2009)

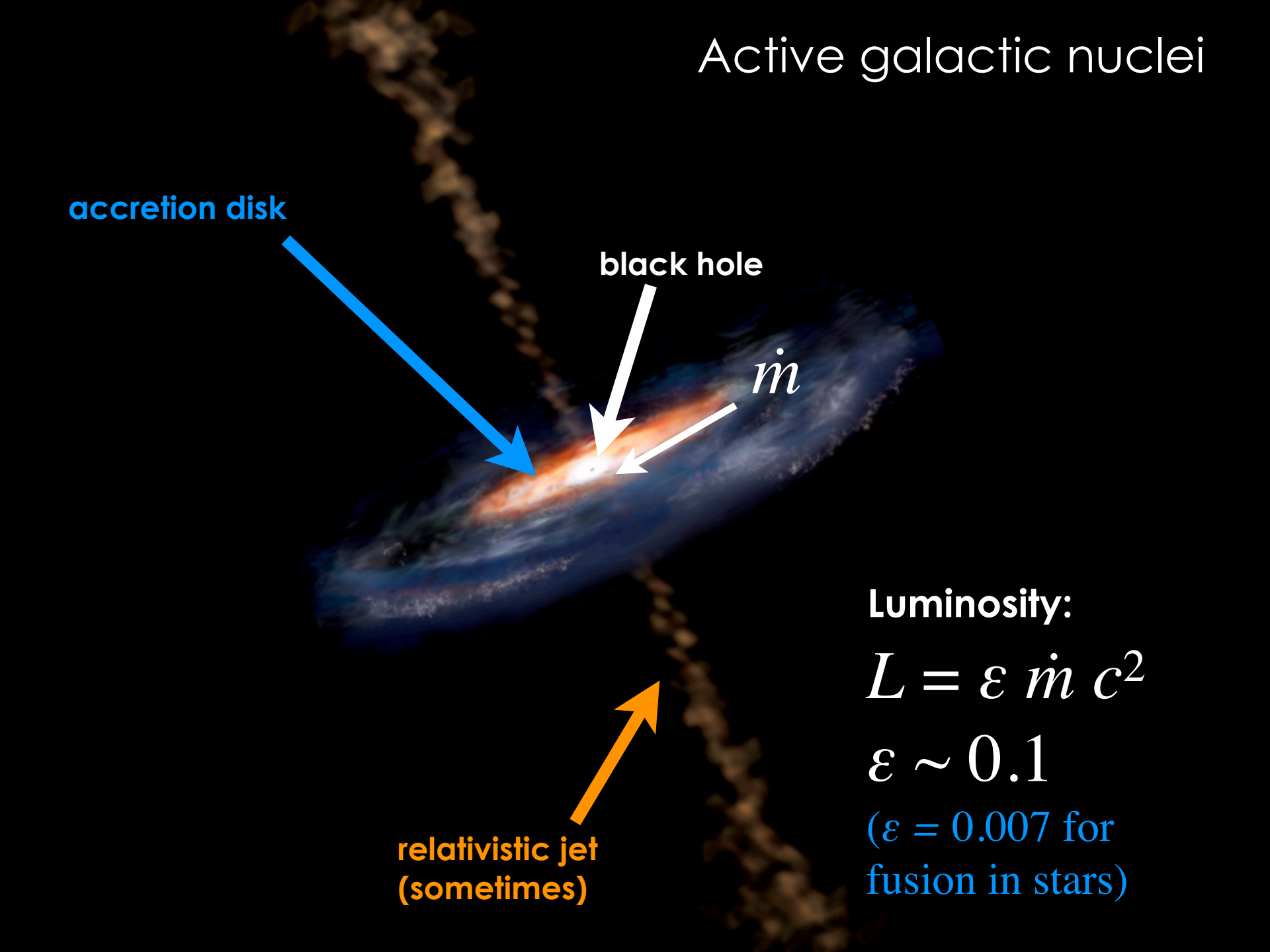
Correlation Between Black Hole Mass and Bulge Mass



galaxies reside in dark matter halos



Active galactic nuclei



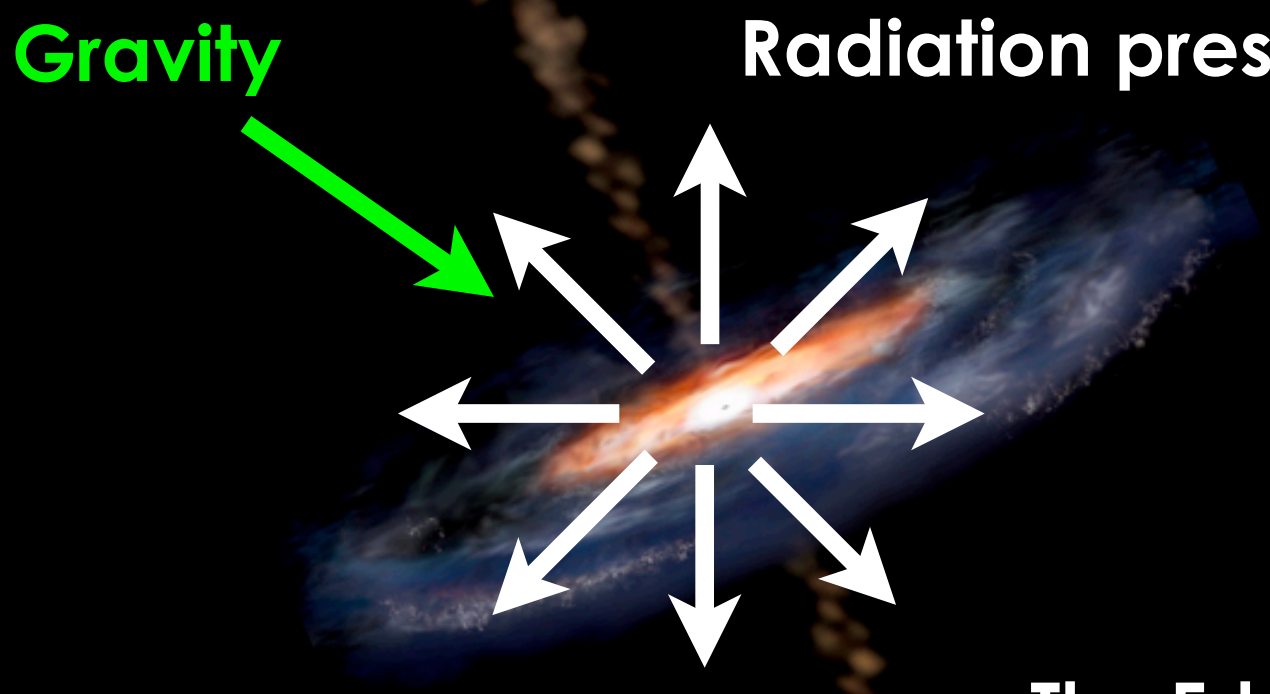
Luminosity:

$$L = \varepsilon \, \dot{m} \, c^2$$

$$\varepsilon \sim 0.1$$

(ε = 0.007 for fusion in stars)

The Eddington limit

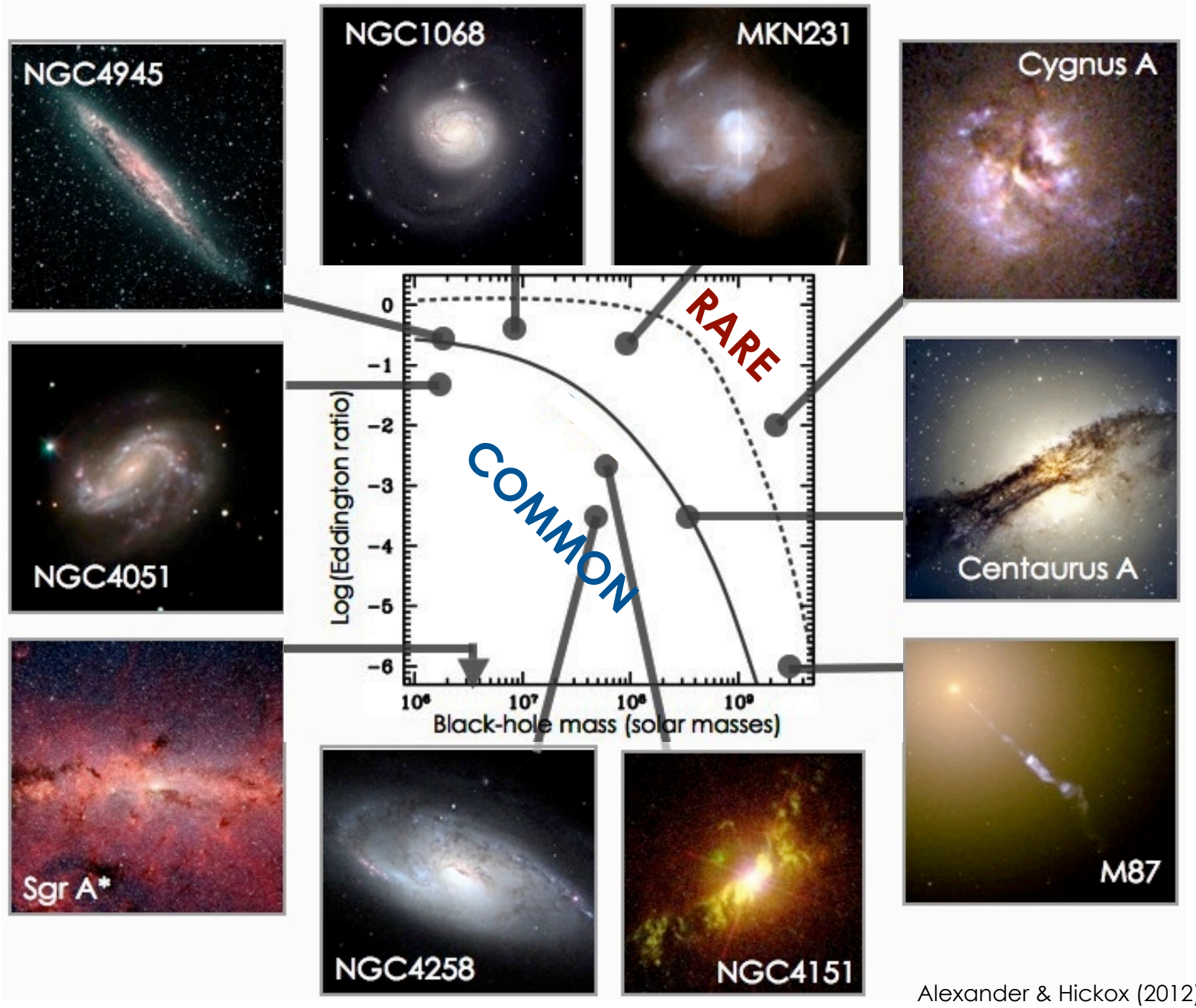


The Eddington ratio

$$L_{Edd} \approx 10^{38}\ \mathrm{erg\ s^{-1}}\ M_{\mathrm{BH}}$$

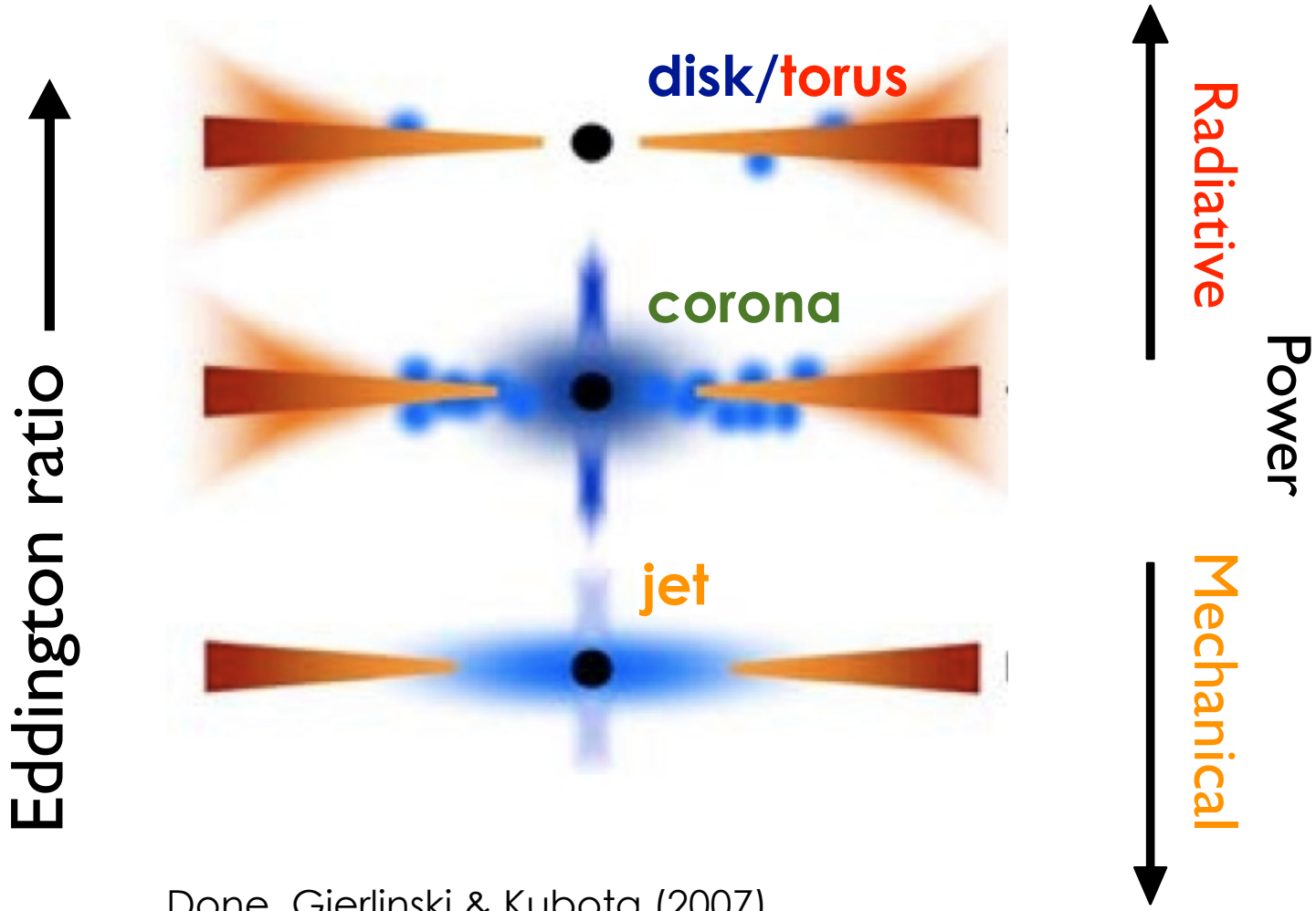
$$\lambda = L/L_{Edd}$$

Larger black holes can grow more rapidly



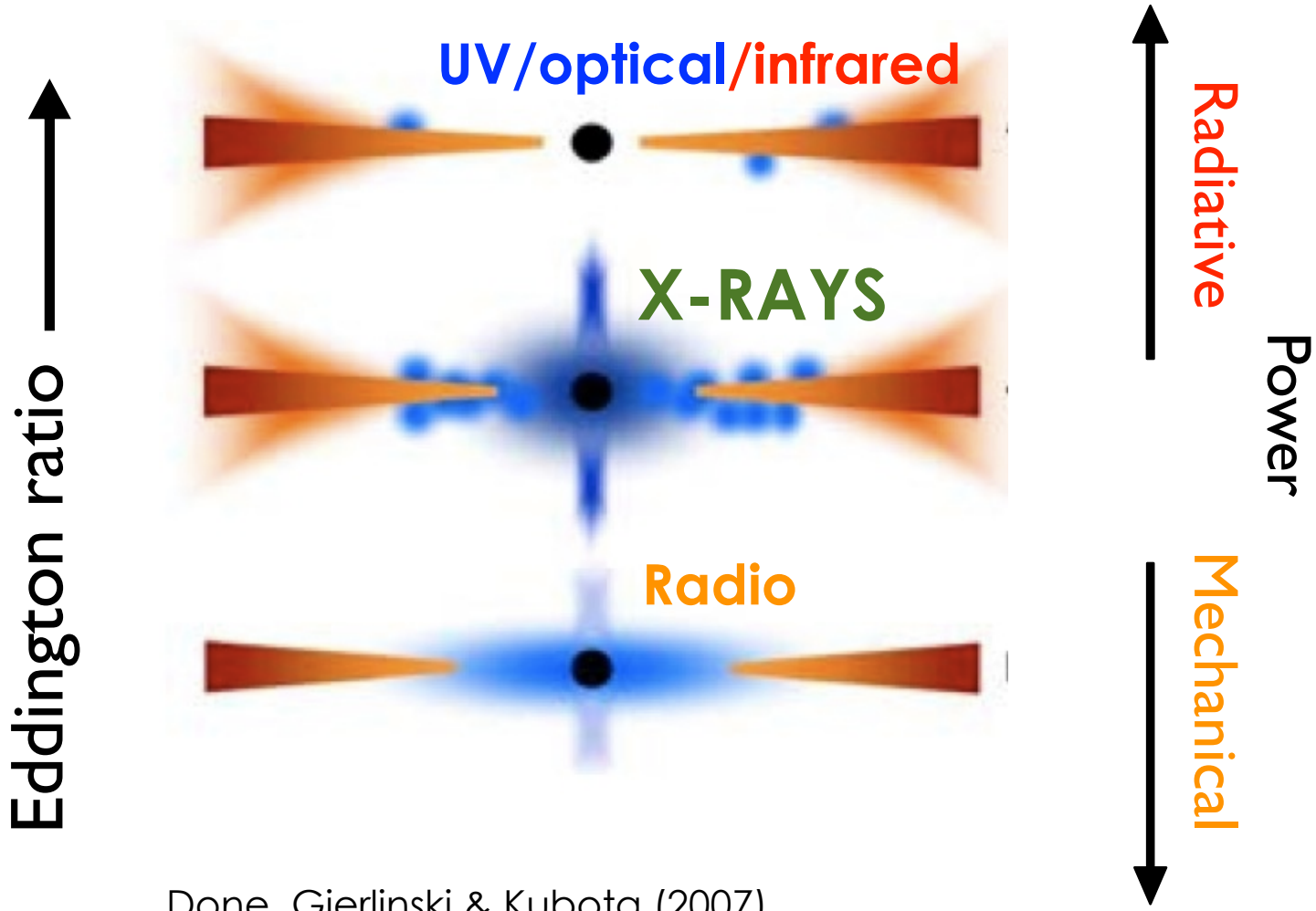
Alexander & Hickox (2012) *New Astronomy Reviews*

Accretion state **changes with Eddington ratio**



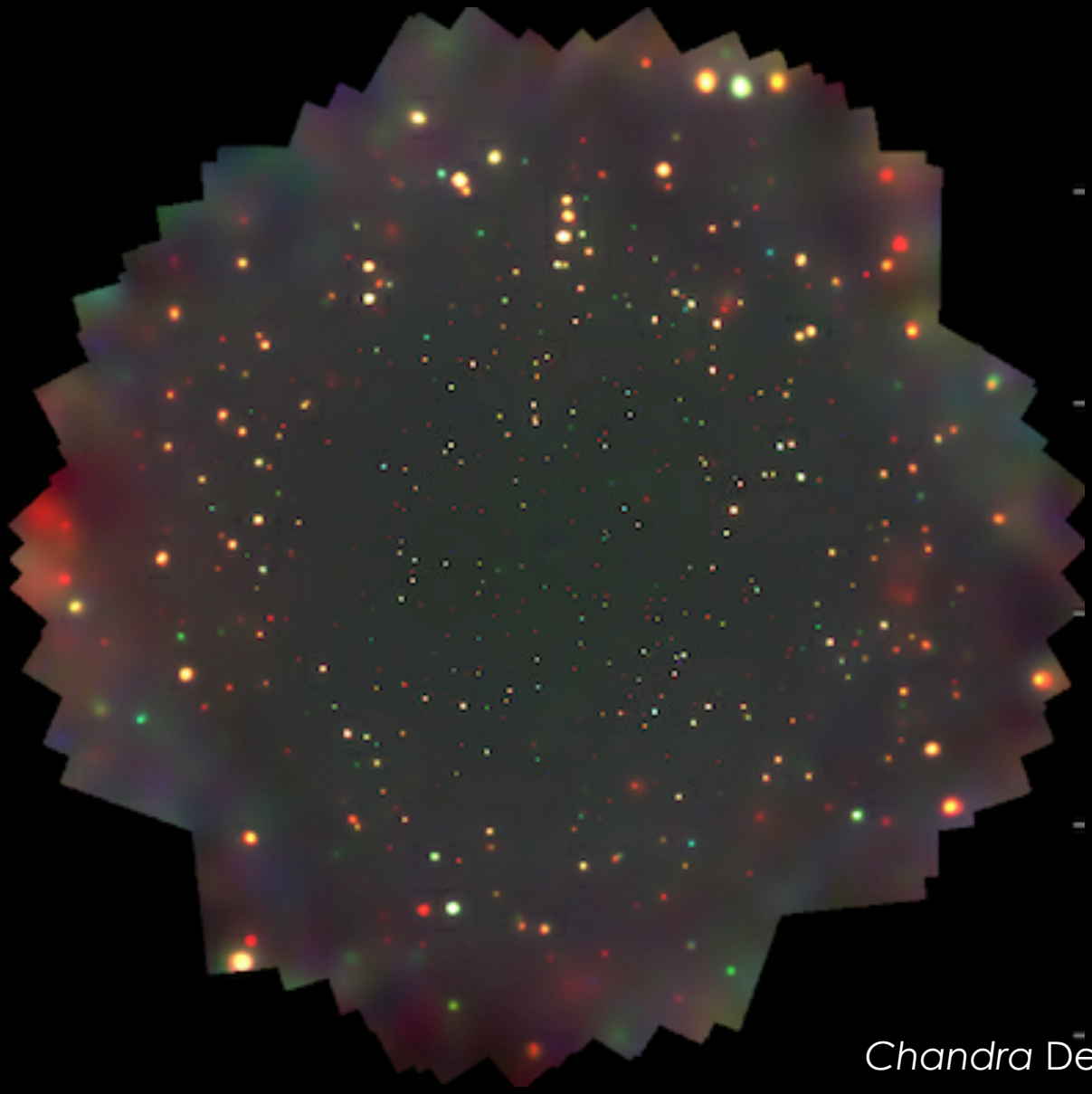
Done, Gierlinski & Kubota (2007)
see also Hopkins, Hickox et al. 2009

Accretion state **changes with Eddington ratio**

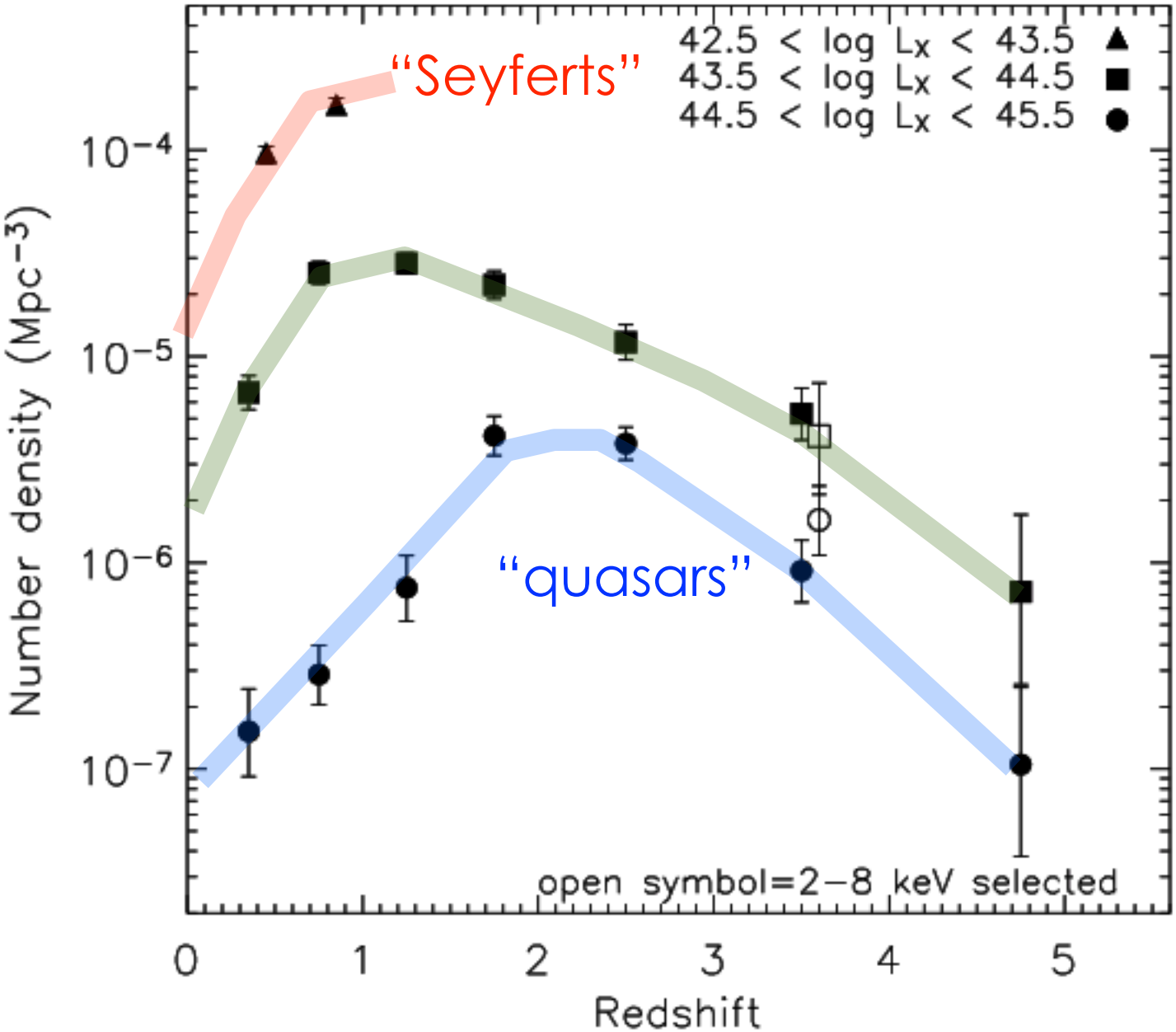


Done, Gierlinski & Kubota (2007)
see also Hopkins, Hickox et al. 2009

Identifying black holes with surveys



Chandra Deep Field South



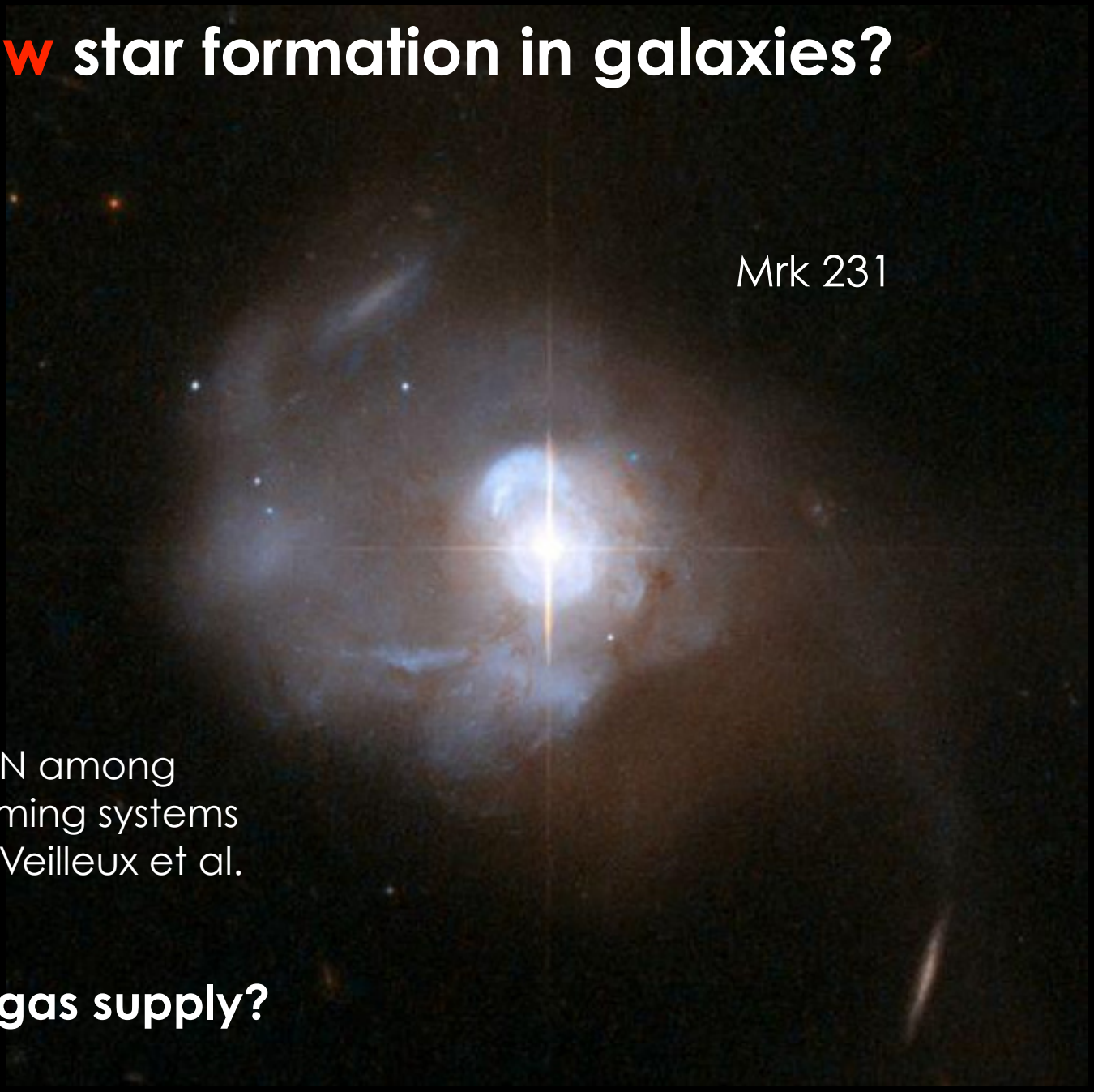
Silverman et al. (2010)

Do AGN follow star formation in galaxies?

OR

Do AGN prevent star formation in galaxies?

Do AGN follow star formation in galaxies?

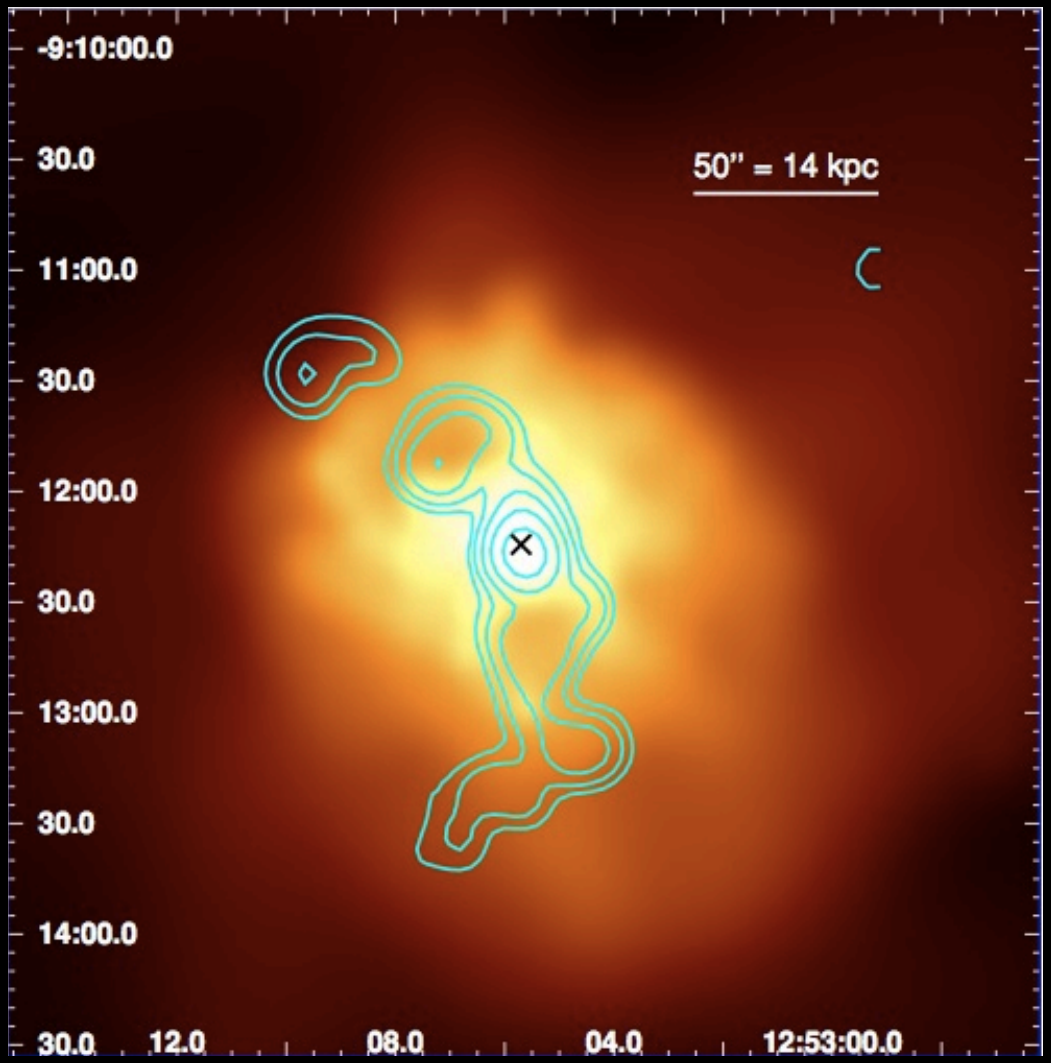


Higher fraction of AGN among more strongly star-forming systems (e.g., Kim et al. 1998, Veilleux et al. 1999, Tran et al. 2001)

A common cold gas supply?

Do AGN prevent star formation in galaxies?

Hot atmosphere heating by jets



HCG 62 (Gitti et al. 2010), see many others for similar examples

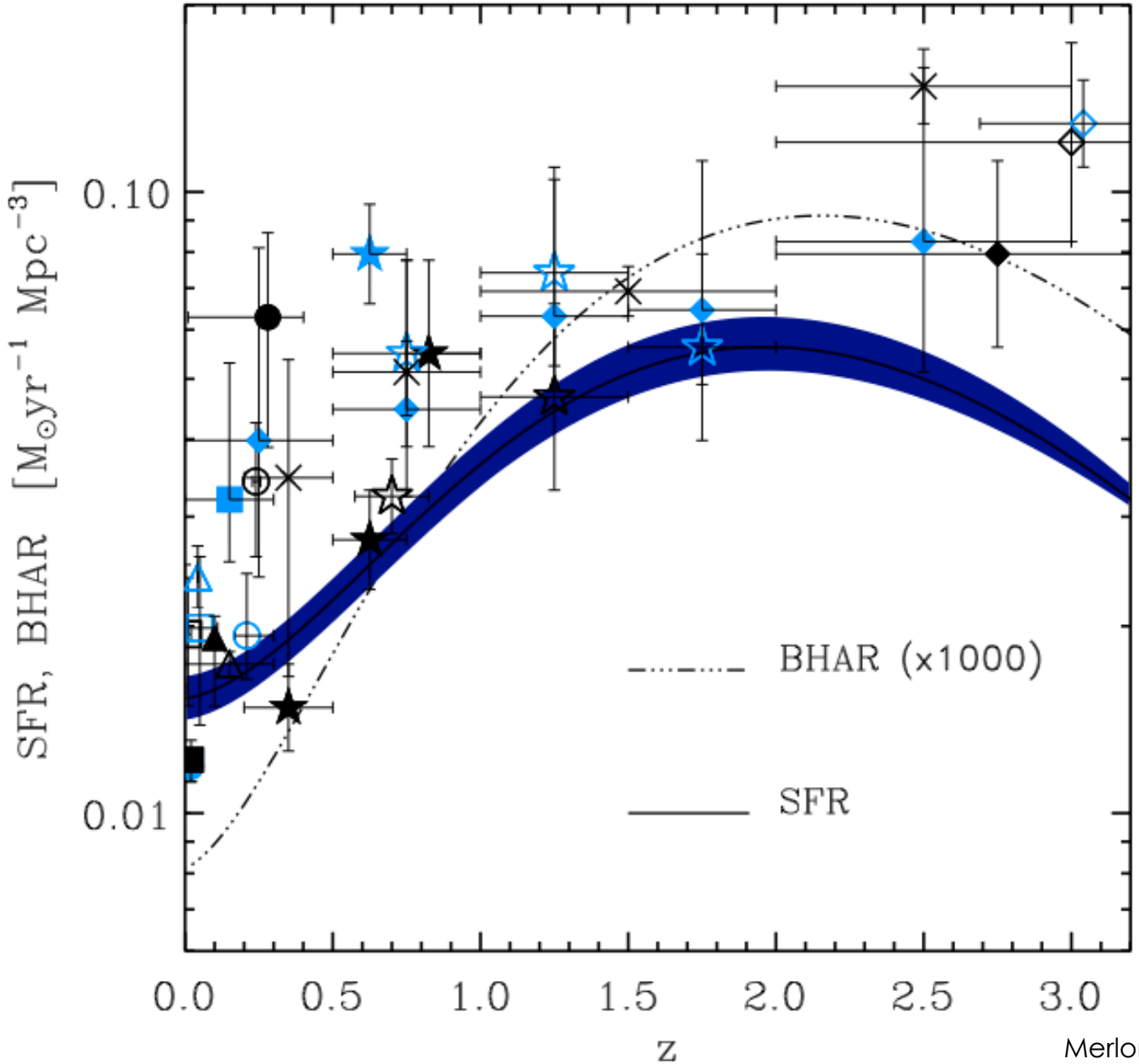
Do AGN follow star formation?

OR

Do AGN prevent star formation?

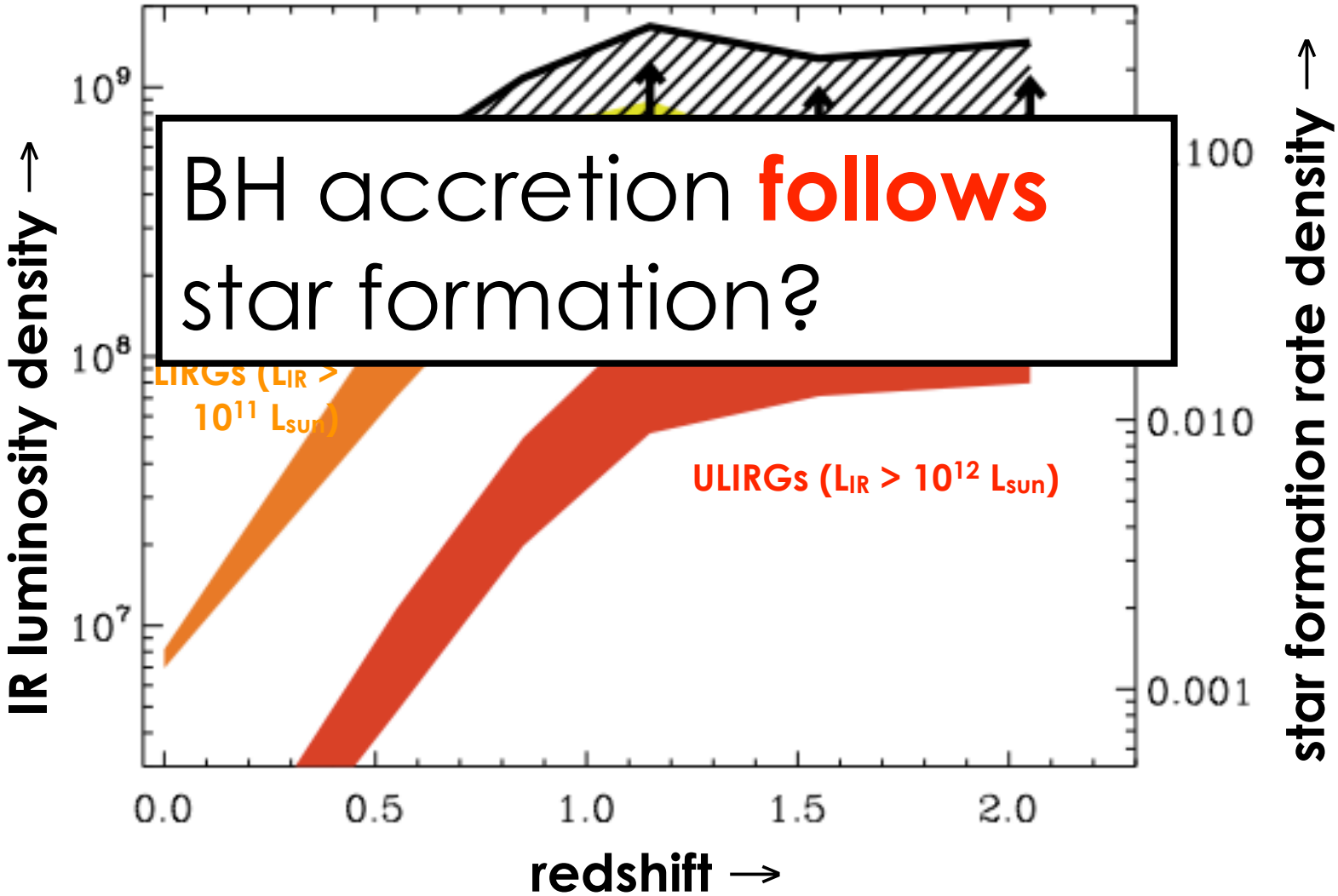
YES

Cosmic evolution of star formation



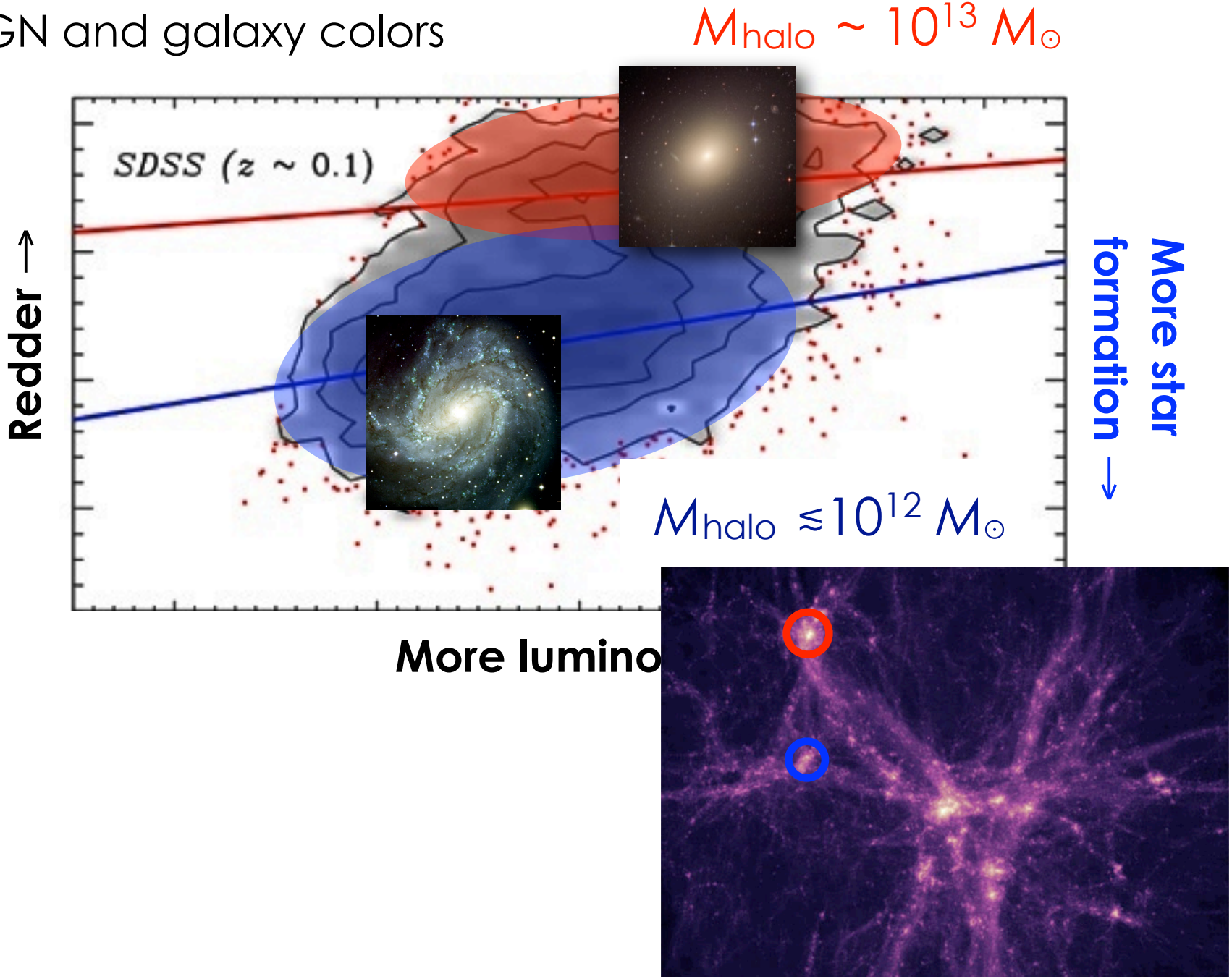
Merloni & Heinz (2012)

Cosmic evolution of star formation

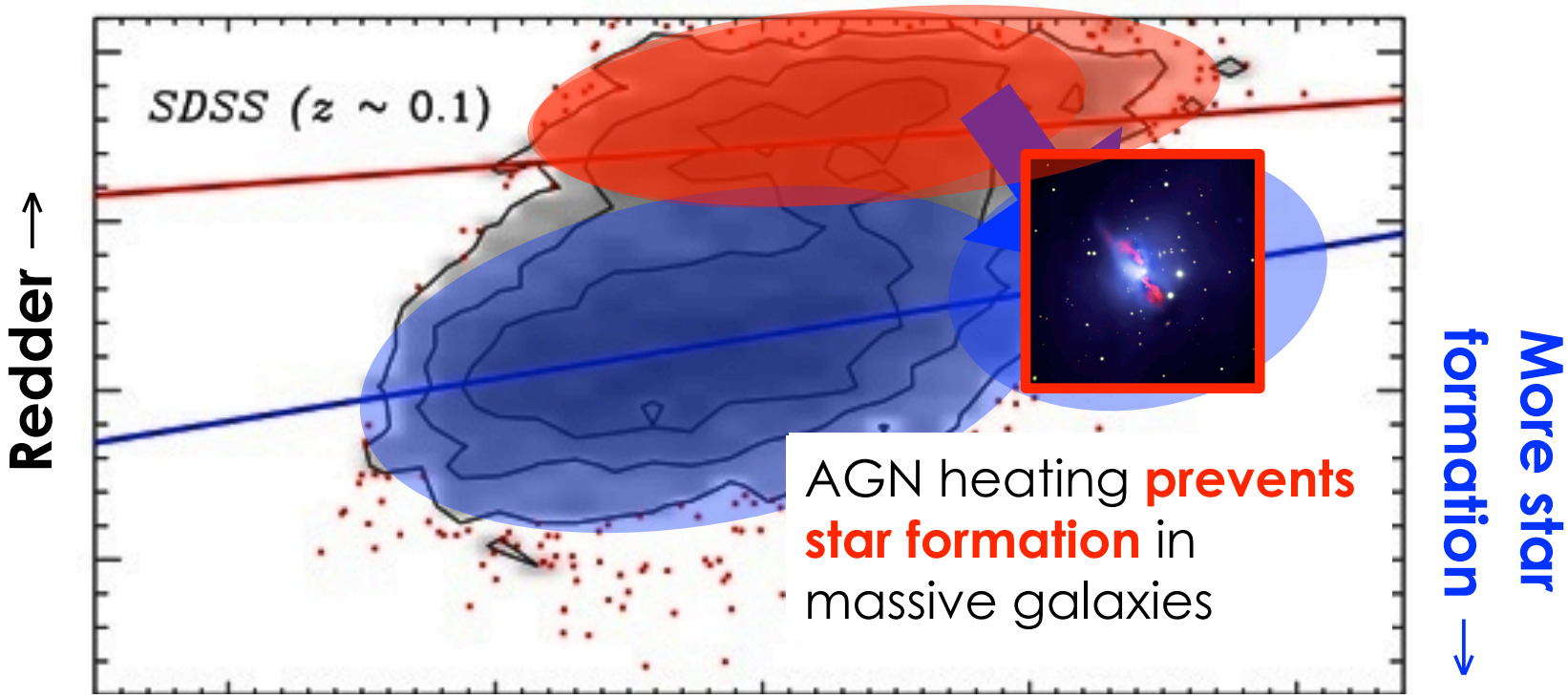


Magnelli et al. (2009)

AGN and galaxy colors

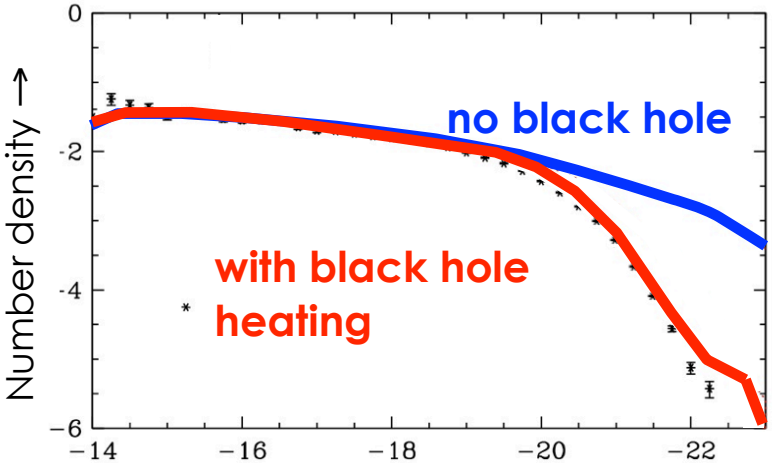


Black hole feedback

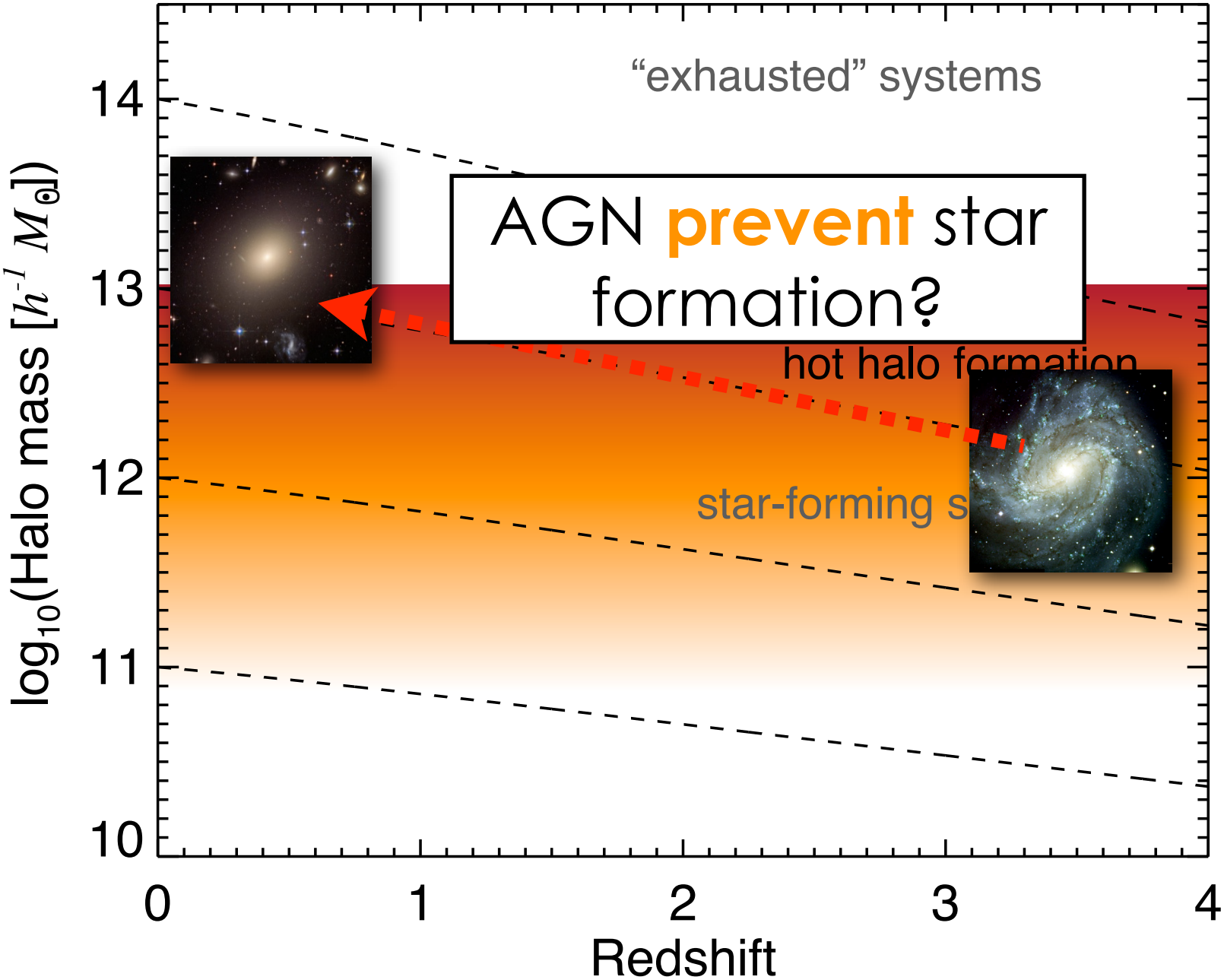


More luminous →

Blanton (2006)

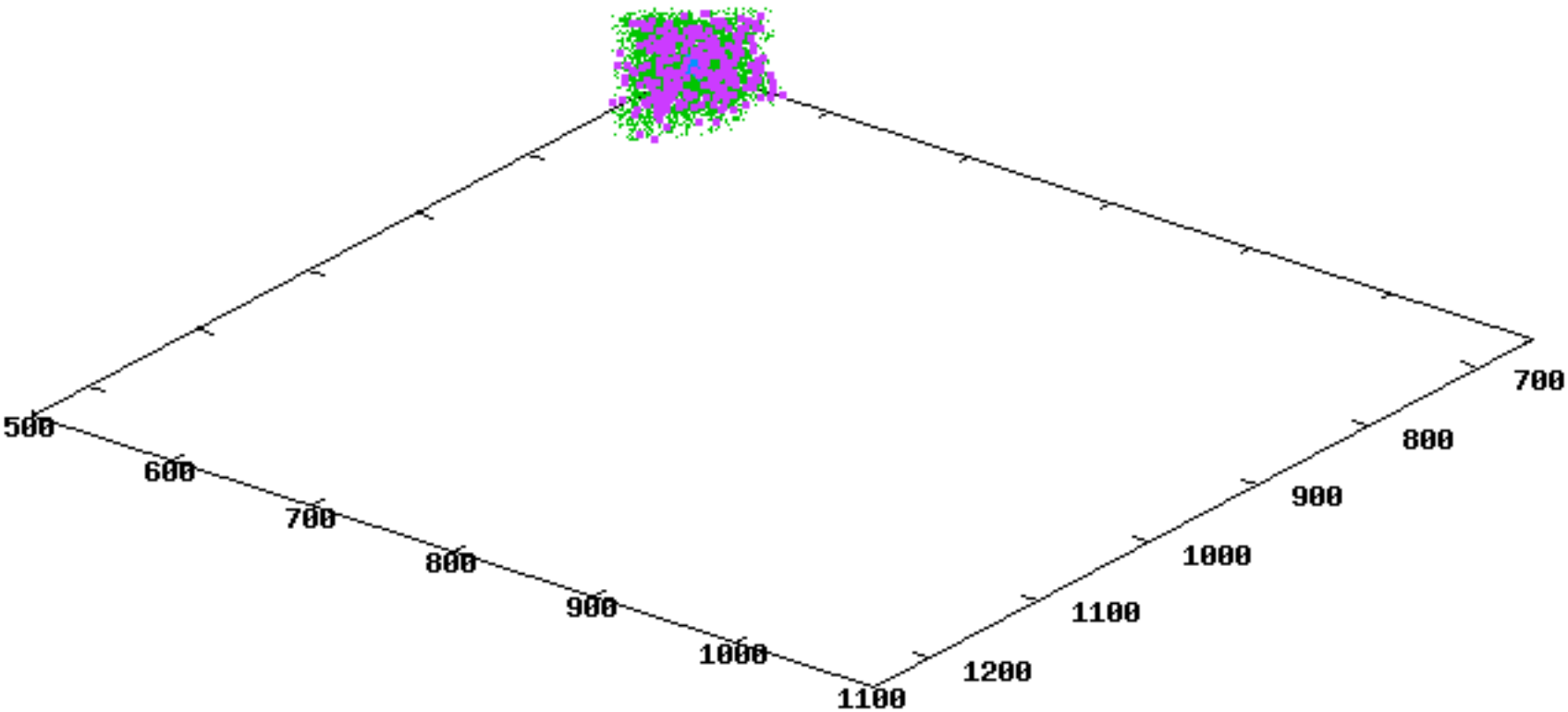


Bower et al. (2006), see also Croton et al. (2006), etc.


"exhausted" systems
AGN prevent star formation?
hot halo formation
star-forming s
14
13
12
11
10
0
1
2
3
4
Redshift
log10(Halo mass [h-1 M⊙])

Observing the co-evolution of galaxies and black holes

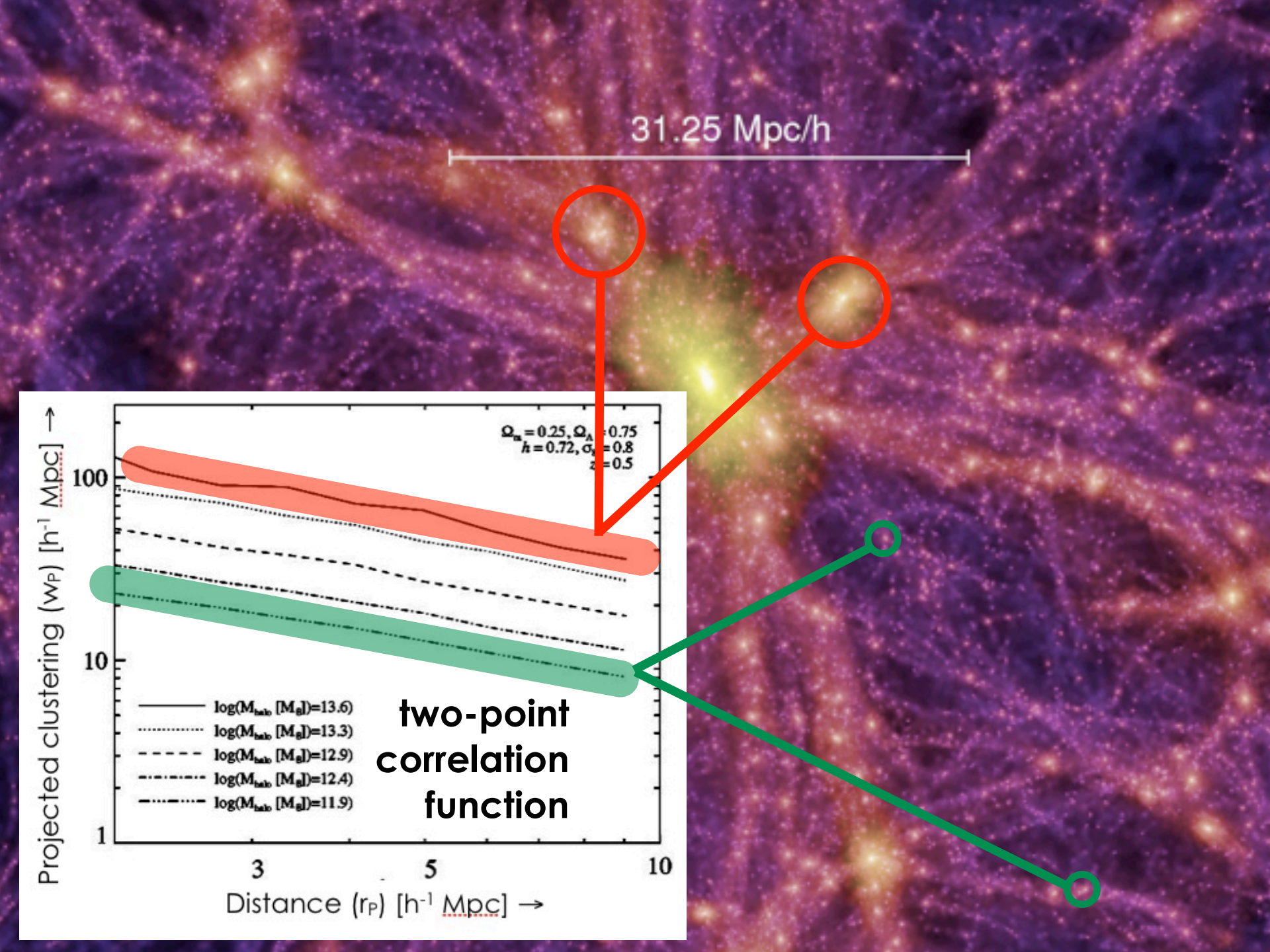
galaxies
X-ray AGN



XBootes/AGES (S. Murray/C. Kochanek)

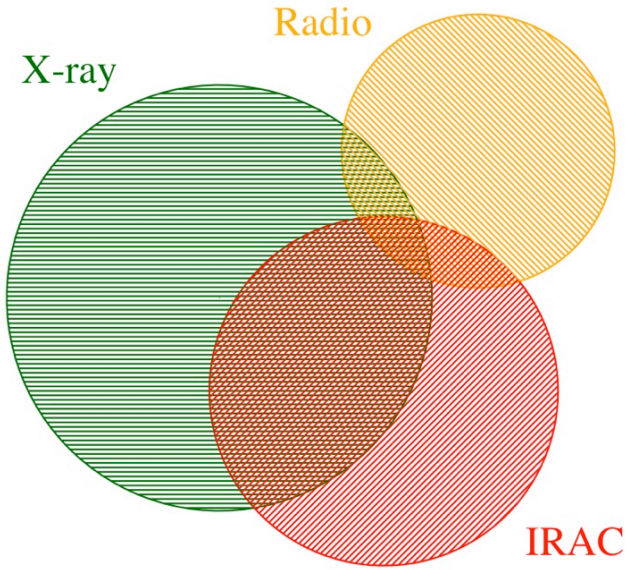
How do we measure dark matter halo mass?

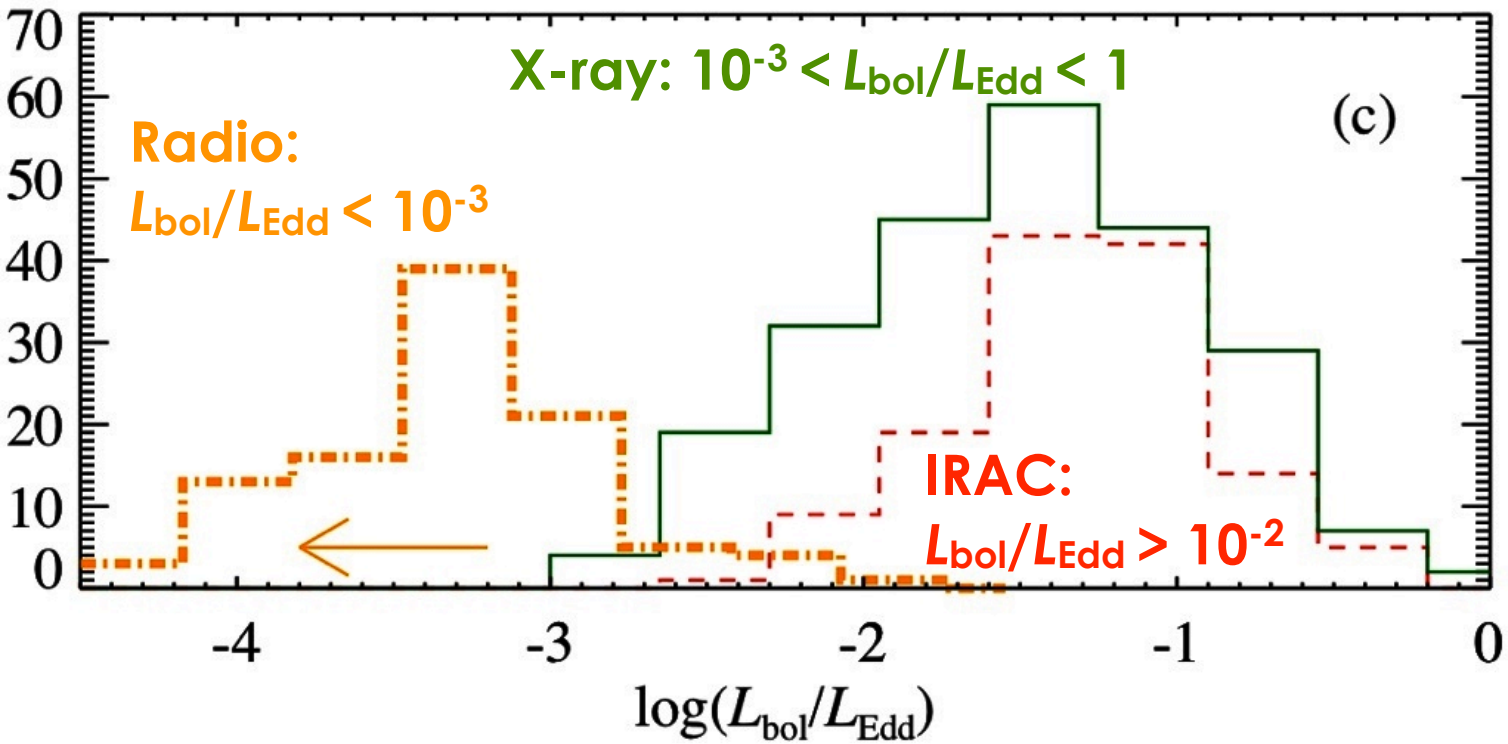
Courtesy Virgo consortium

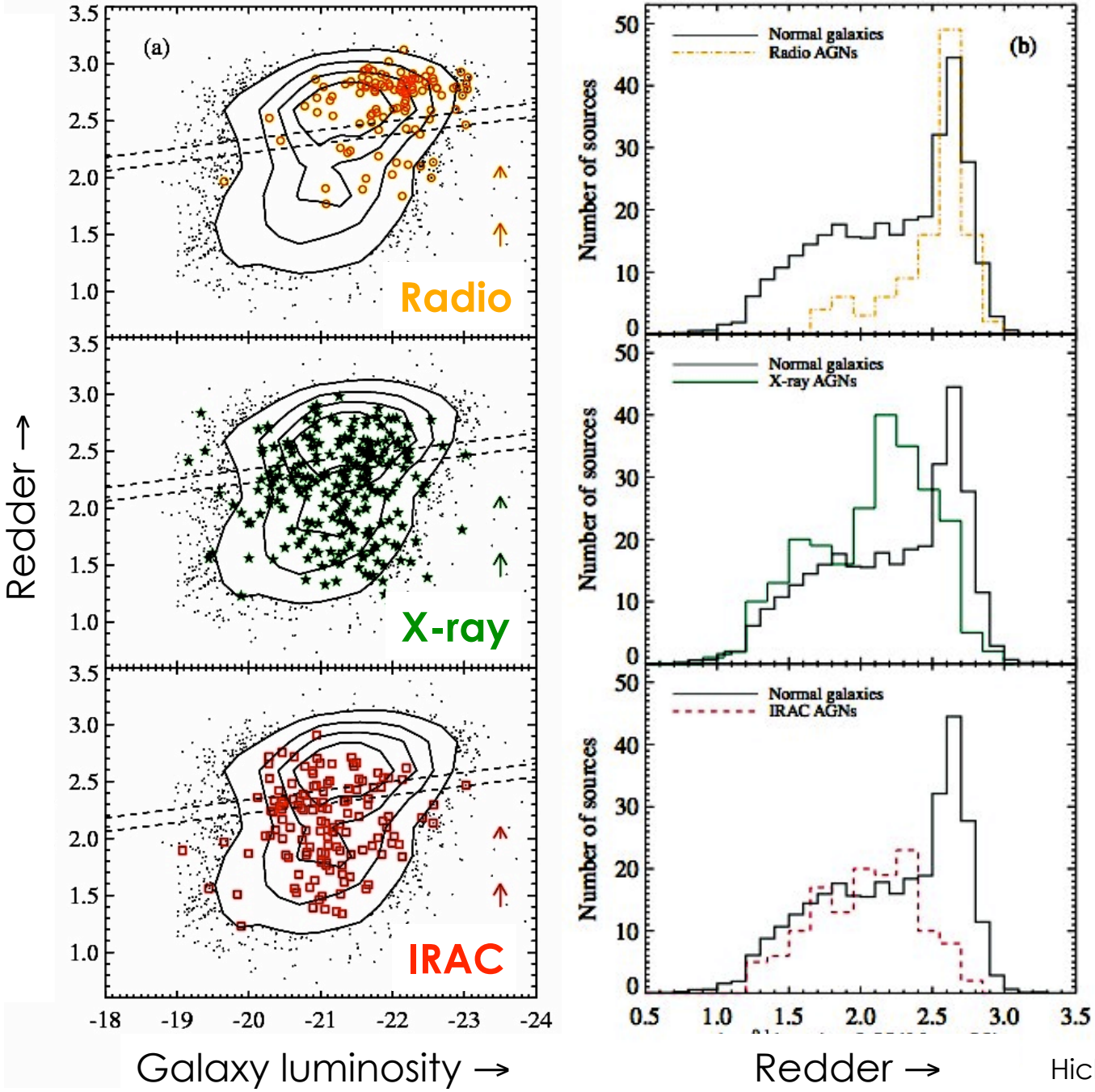

31.25 Mpc/h
Projected clustering (wP) [h-1 Mpc] →
Distance (rP) [h-1 Mpc] →
100
10
1
3
5
10
log(Mhalo [Mg])=13.6)
log(Mhalo [Mg])=13.3)
log(Mhalo [Mg])=12.9)
log(Mhalo [Mg])=12.4)
log(Mhalo [Mg])=11.9)
two-point correlation function

AGN populations at z ~ 0.5

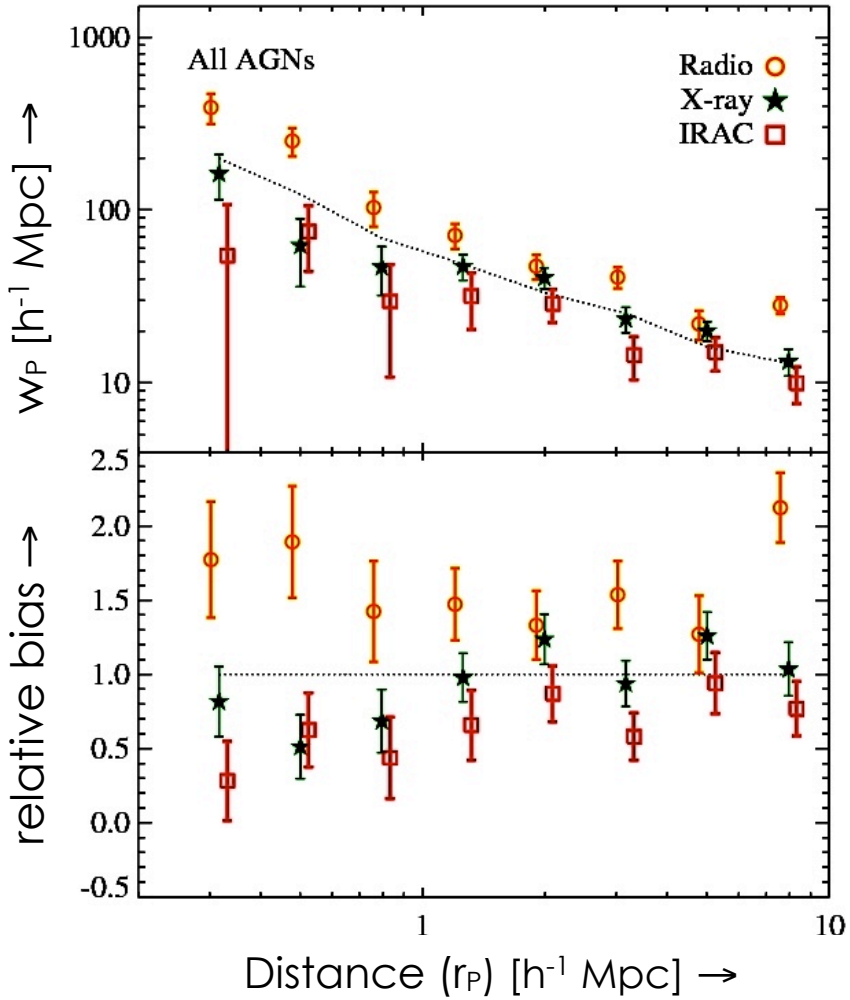
Hickox et al. (2009)



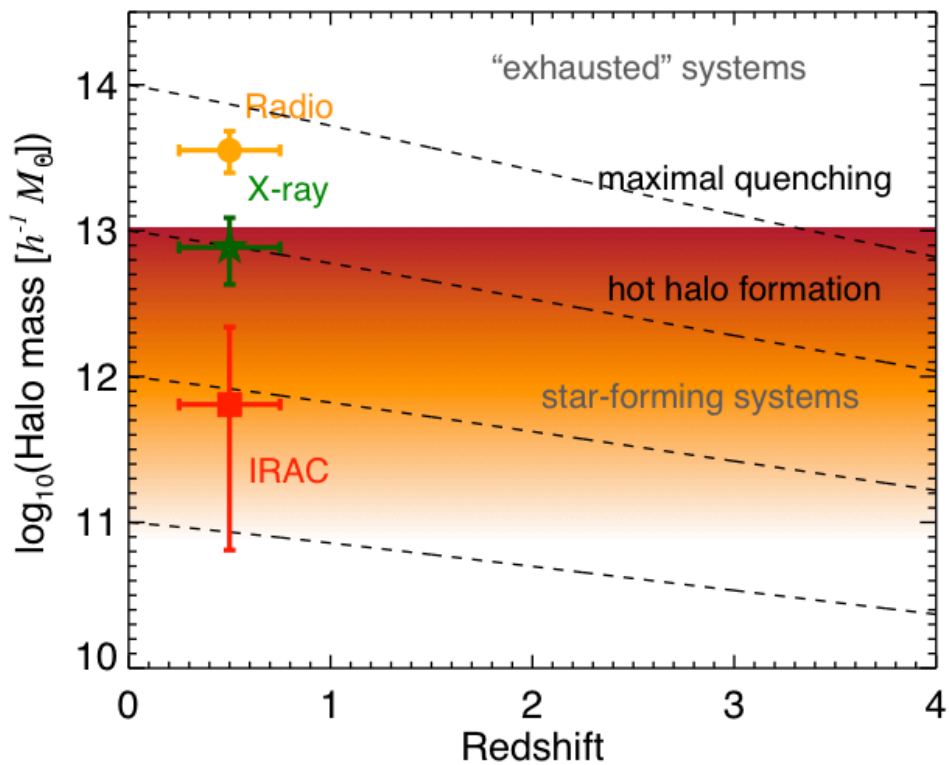




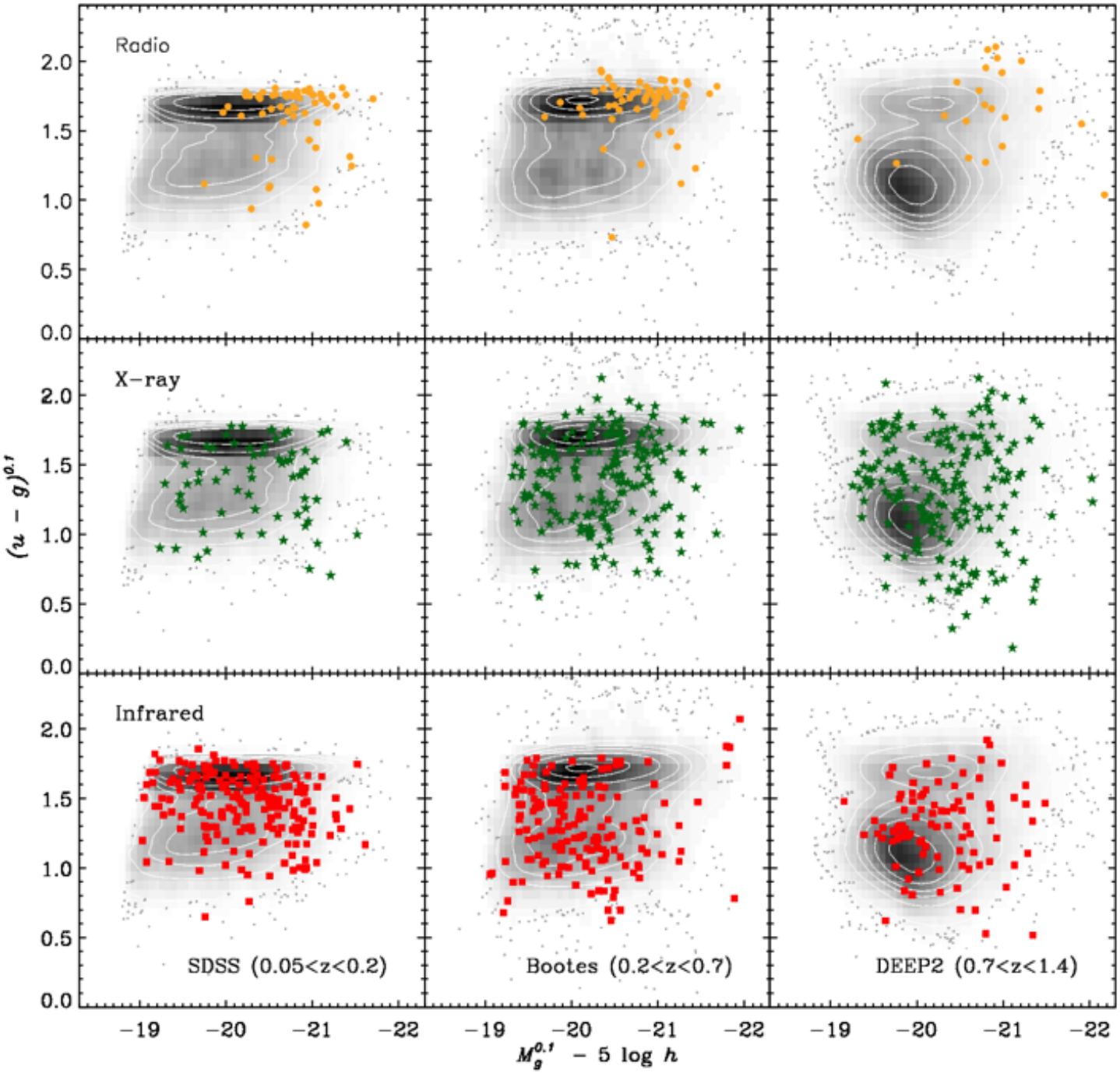
Hickox et al. (2009)



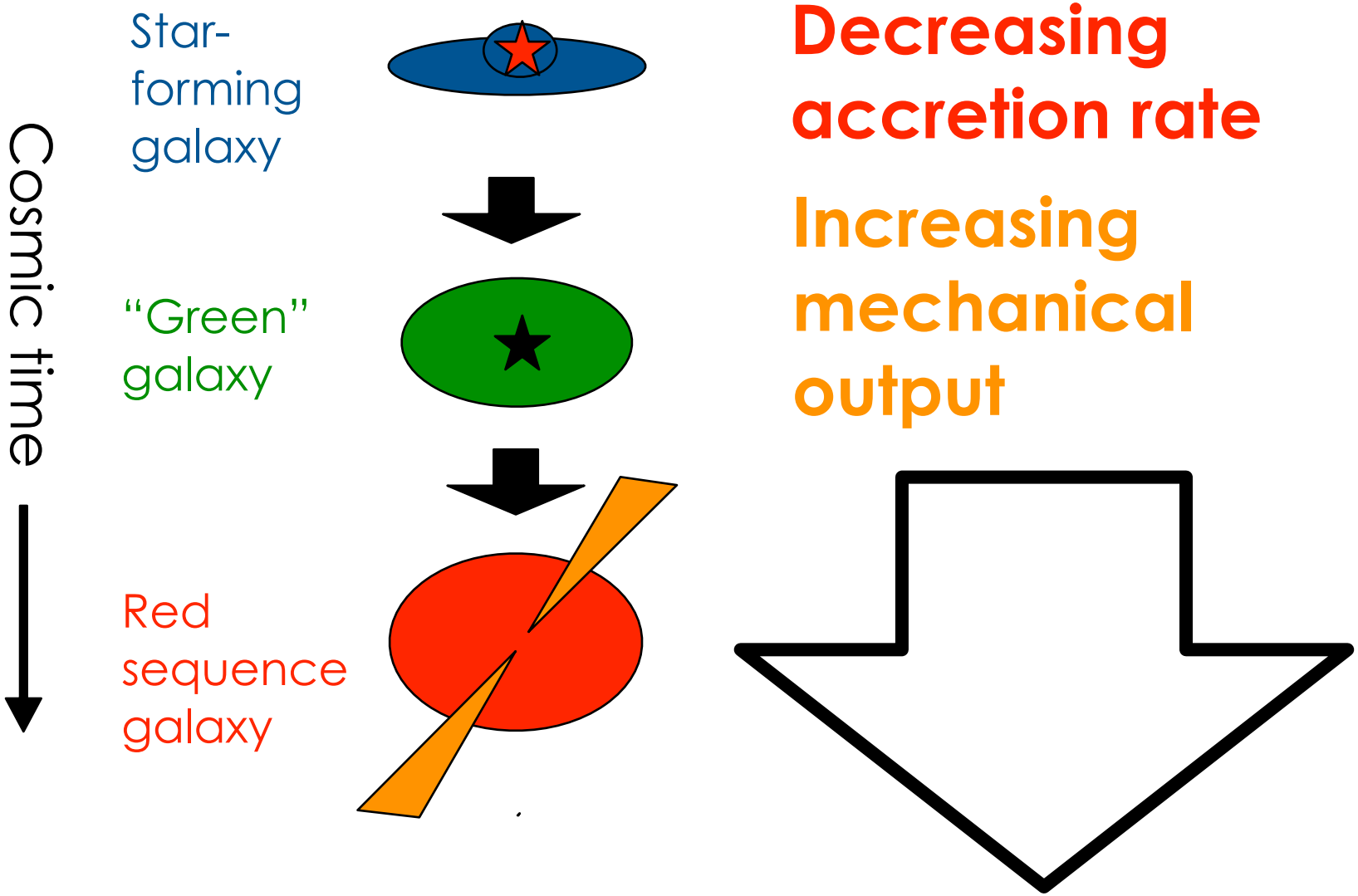
Hickox et al. (2009)



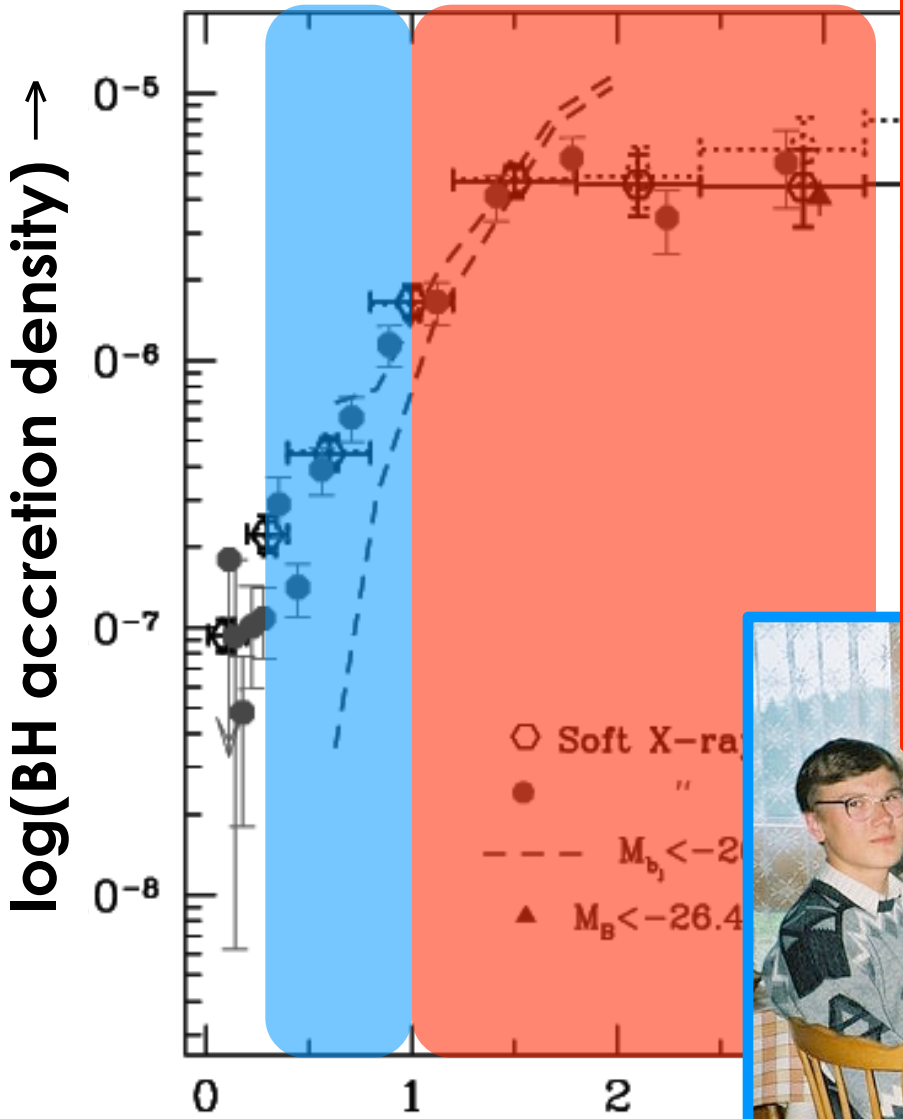
see also Li et al. (2006), Coil et al. (2009), Wake et al. (2008), Mandelbaum et al. (2008)



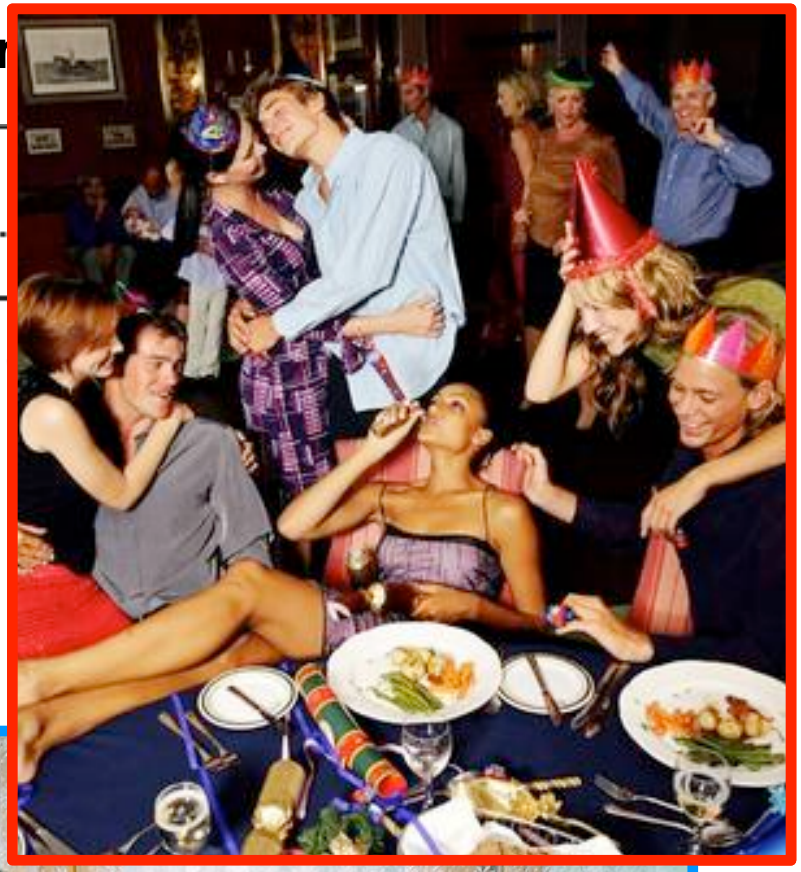
Goulding et al. (in prep)

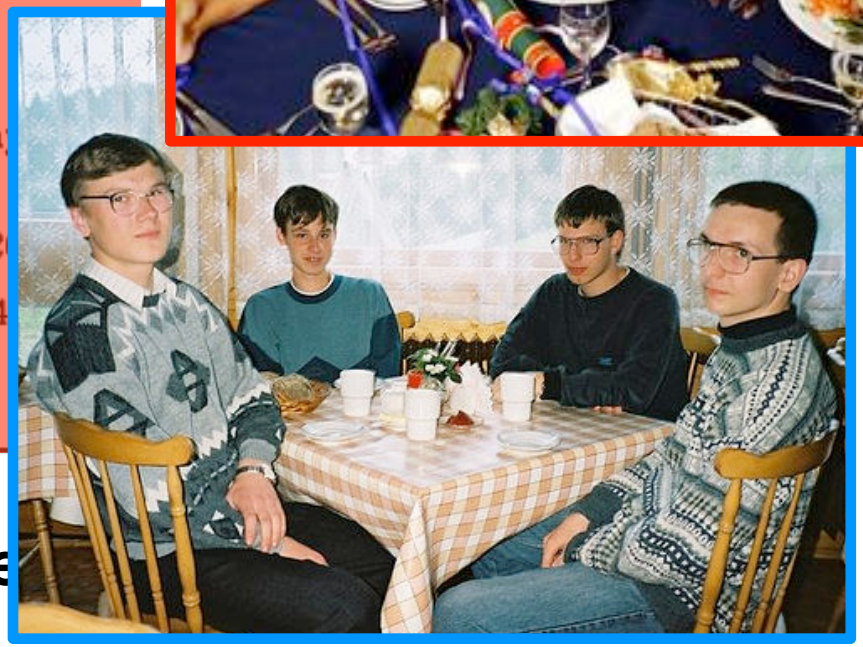

Cosmic time
Star-forming galaxy
"Green" galaxy
Red sequence galaxy
Decreasing accretion rate
Increasing mechanical output

← Cosmic ti

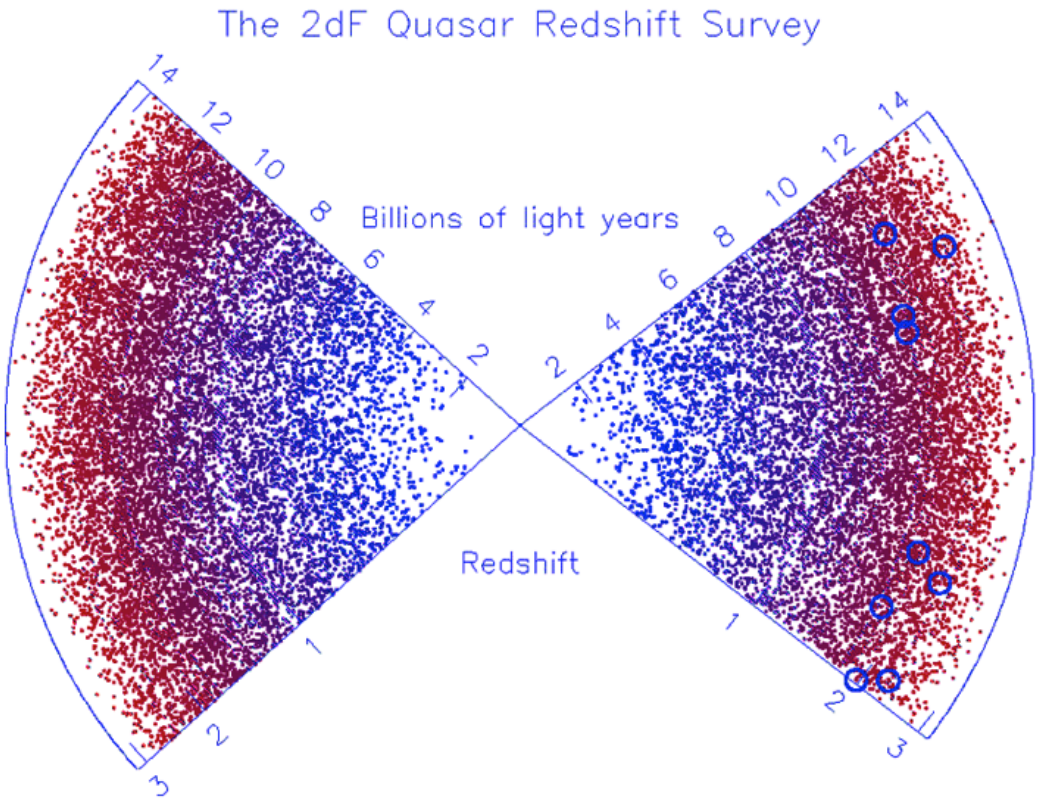


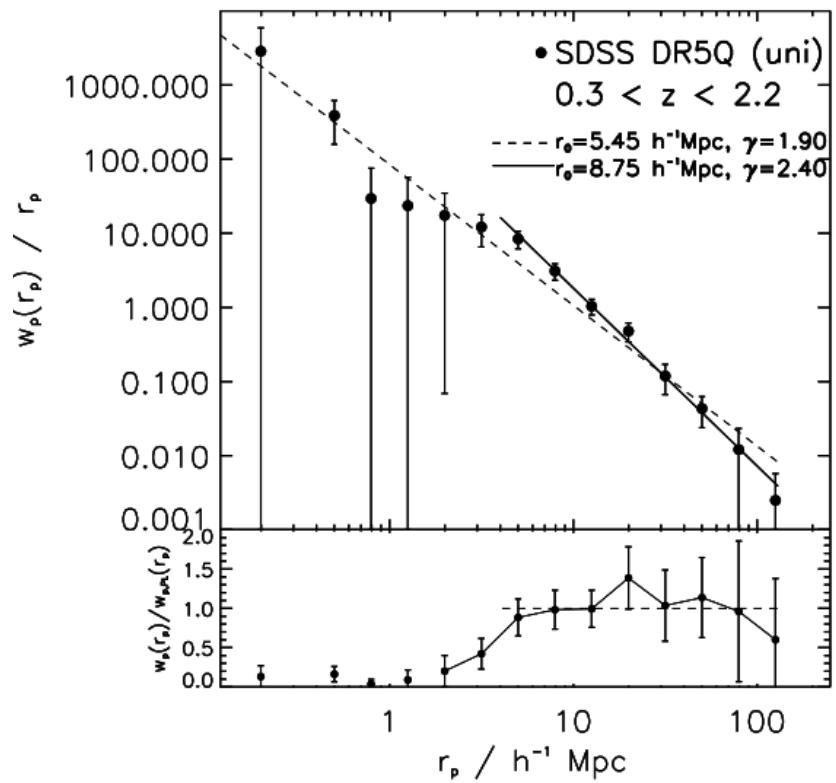
re



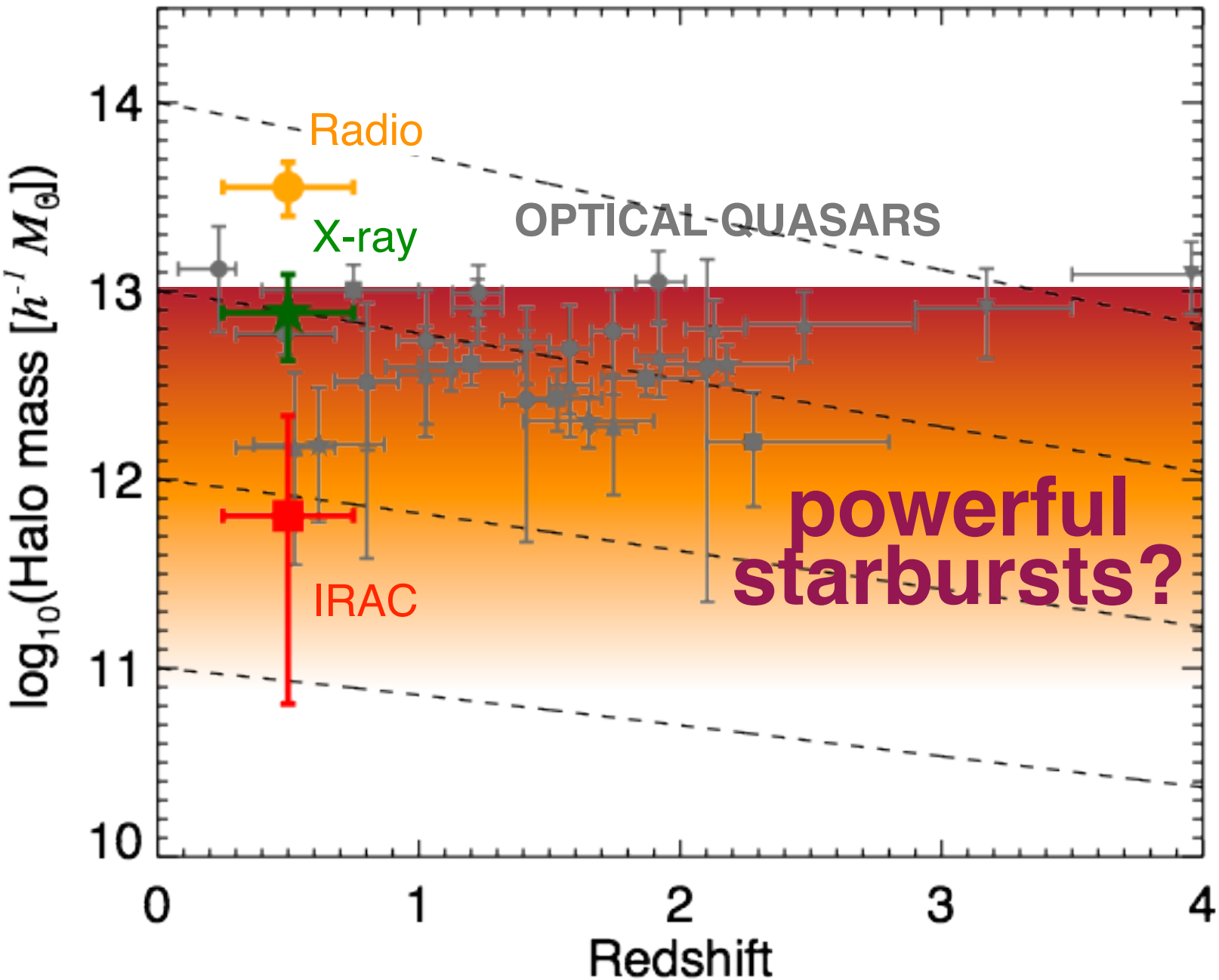


Clustering of quasars





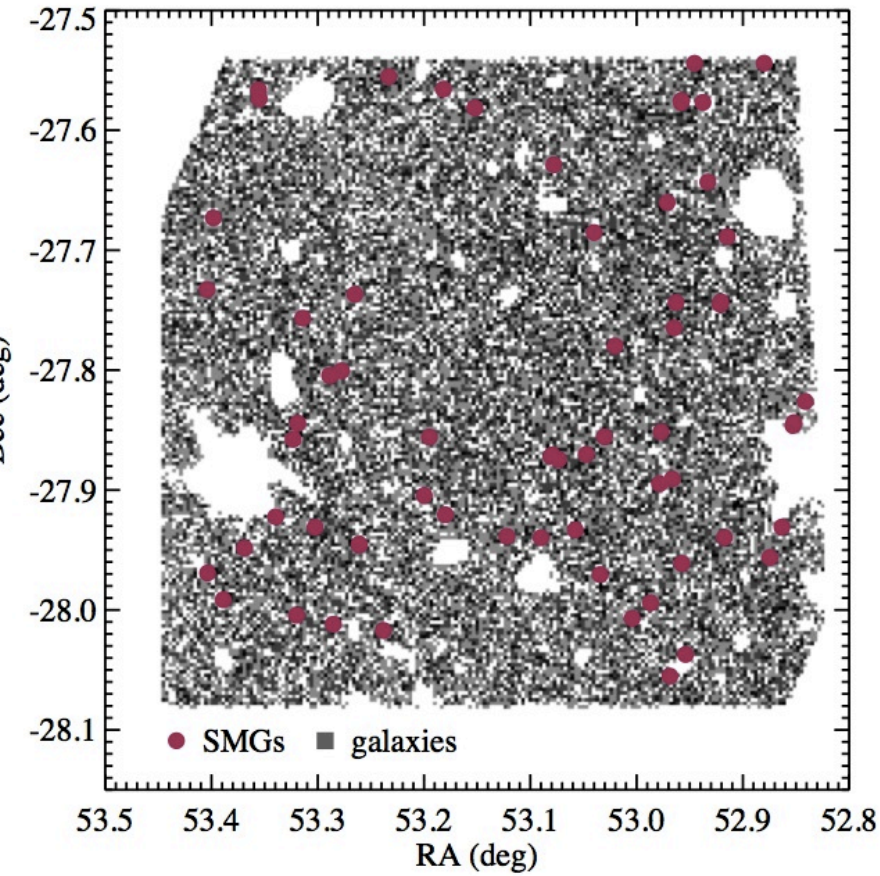
Ross et al. (2009) , see also Croom et al. (2005), Myers et al. (2006), da Angela et al. (2008), Hickox et al. (2009), many others


Radio
X-ray
OPTICAL QUASARS
IRAC
powerful starbursts?
log10(Halo mass [h^-1 M⊙])
Redshift
14
13
12
11
10
0
1
2
3
4

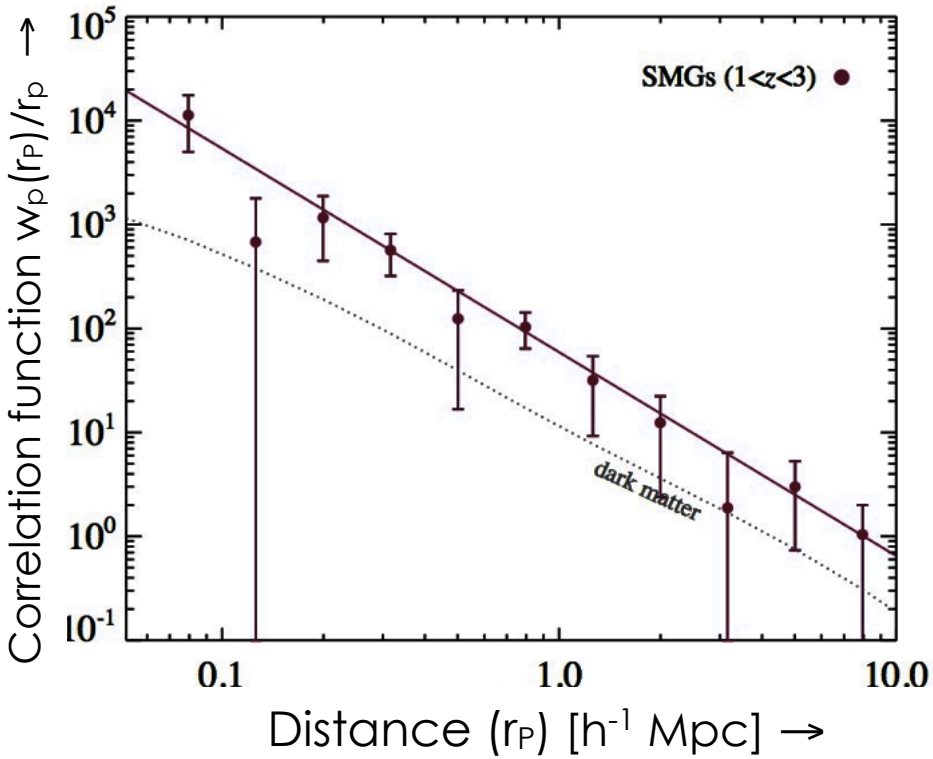
Clustering of submillimeter galaxies

870 μm SMGs: SFR ~ 1000 $M_\odot$ yr^{-1}

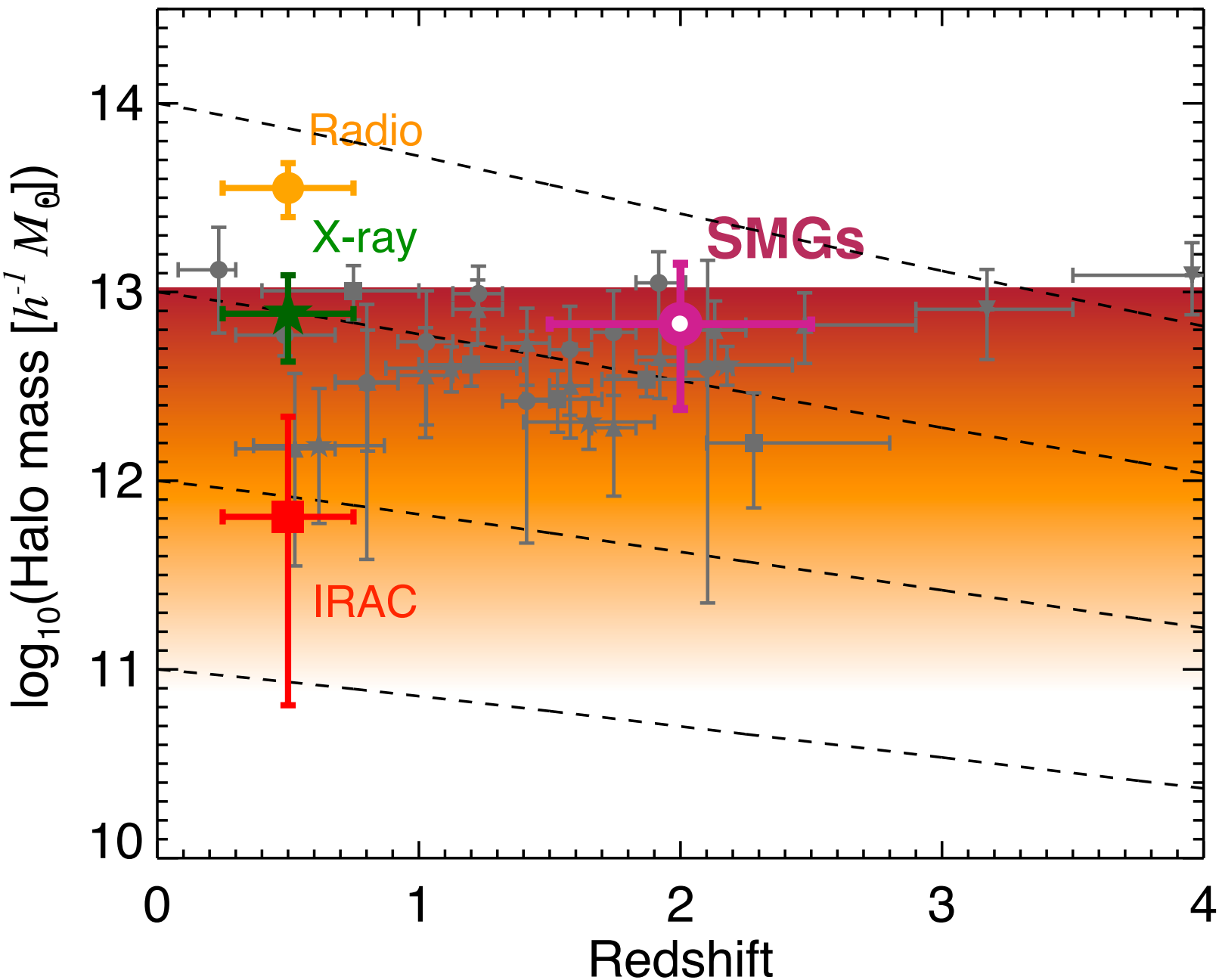
IRAC galaxies

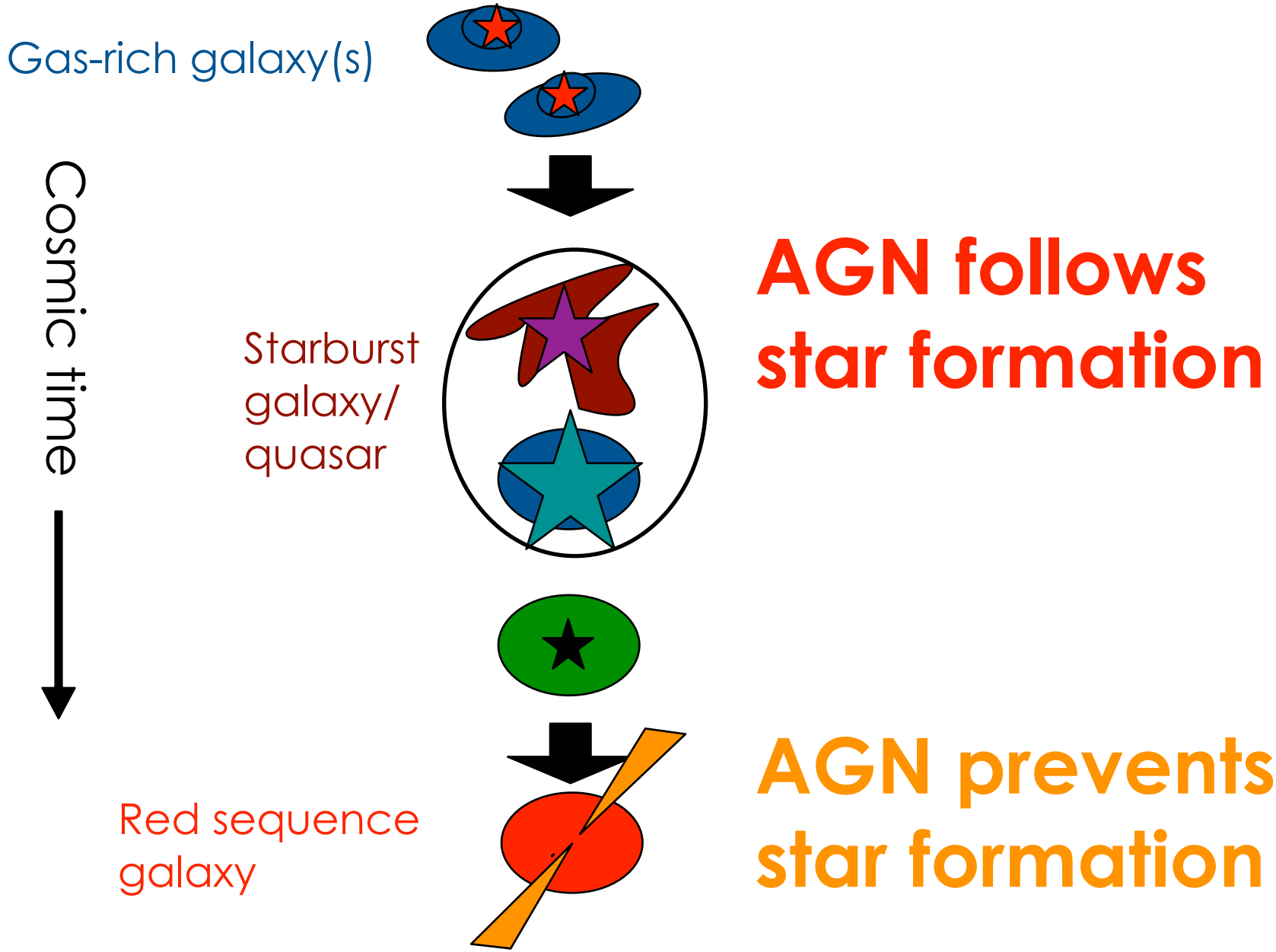


LESS Survey, Weiß et al. (2009)



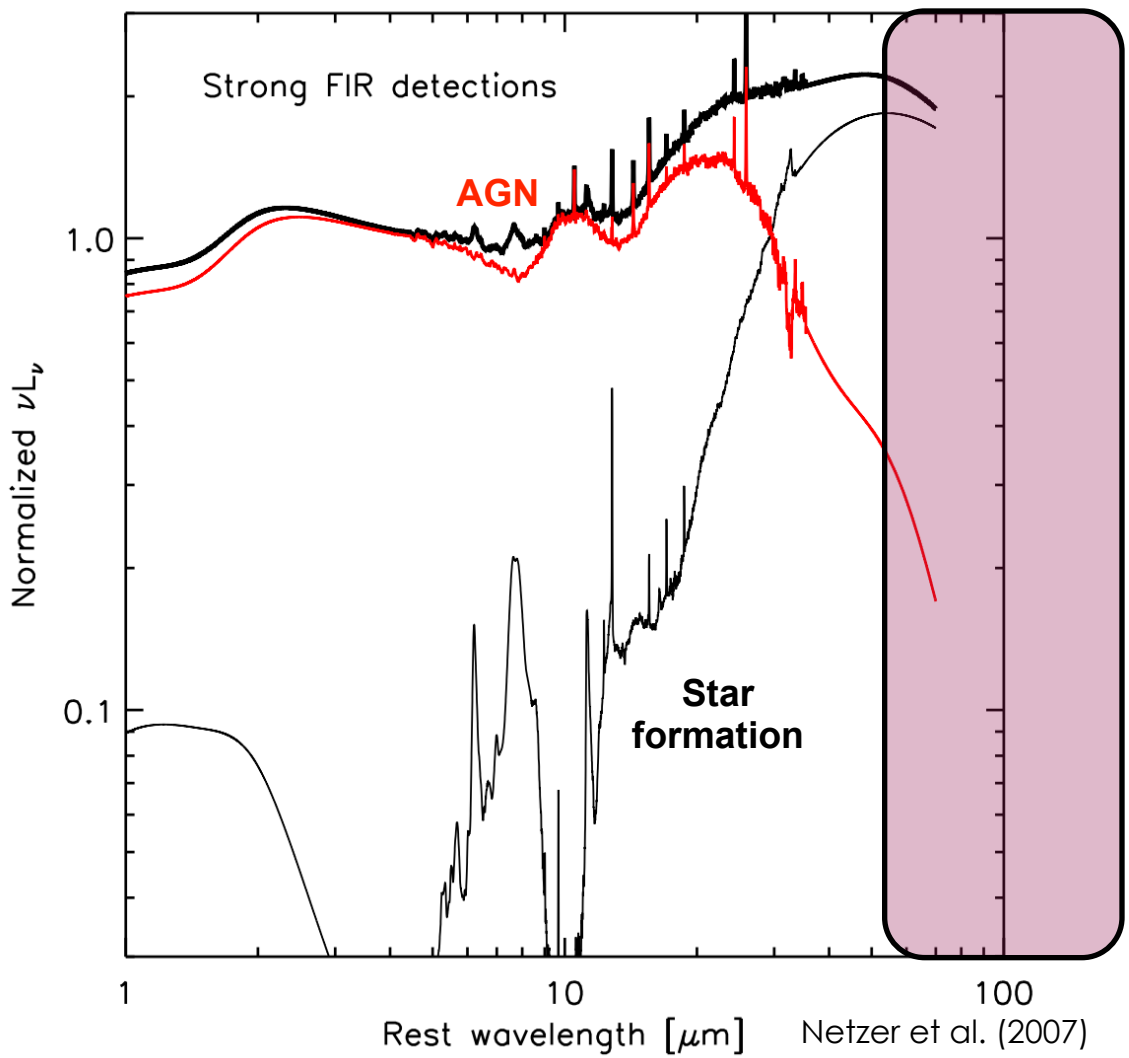
(Hickox et al. 2012)

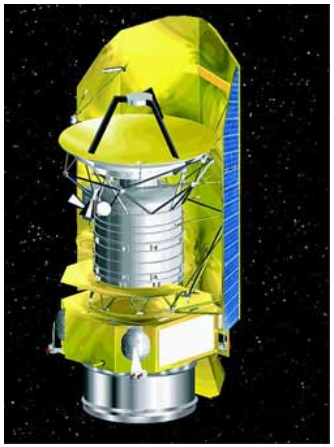

Radio
X-ray
SMGs
IRAC
14
13
12
11
10
0
1
2
3
4
Redshift
log10(Halo mass [h-1 M⊙])


Gas-rich galaxy(s)
Cosmic time
Starburst galaxy/ quasar
AGN follows star formation
Red sequence galaxy
AGN prevents star formation

Why doesn't EVERY
star-forming galaxy
host an AGN?

Use the **far-IR** to measure the SFR of an AGN-hosting galaxy -- ***Herschel***

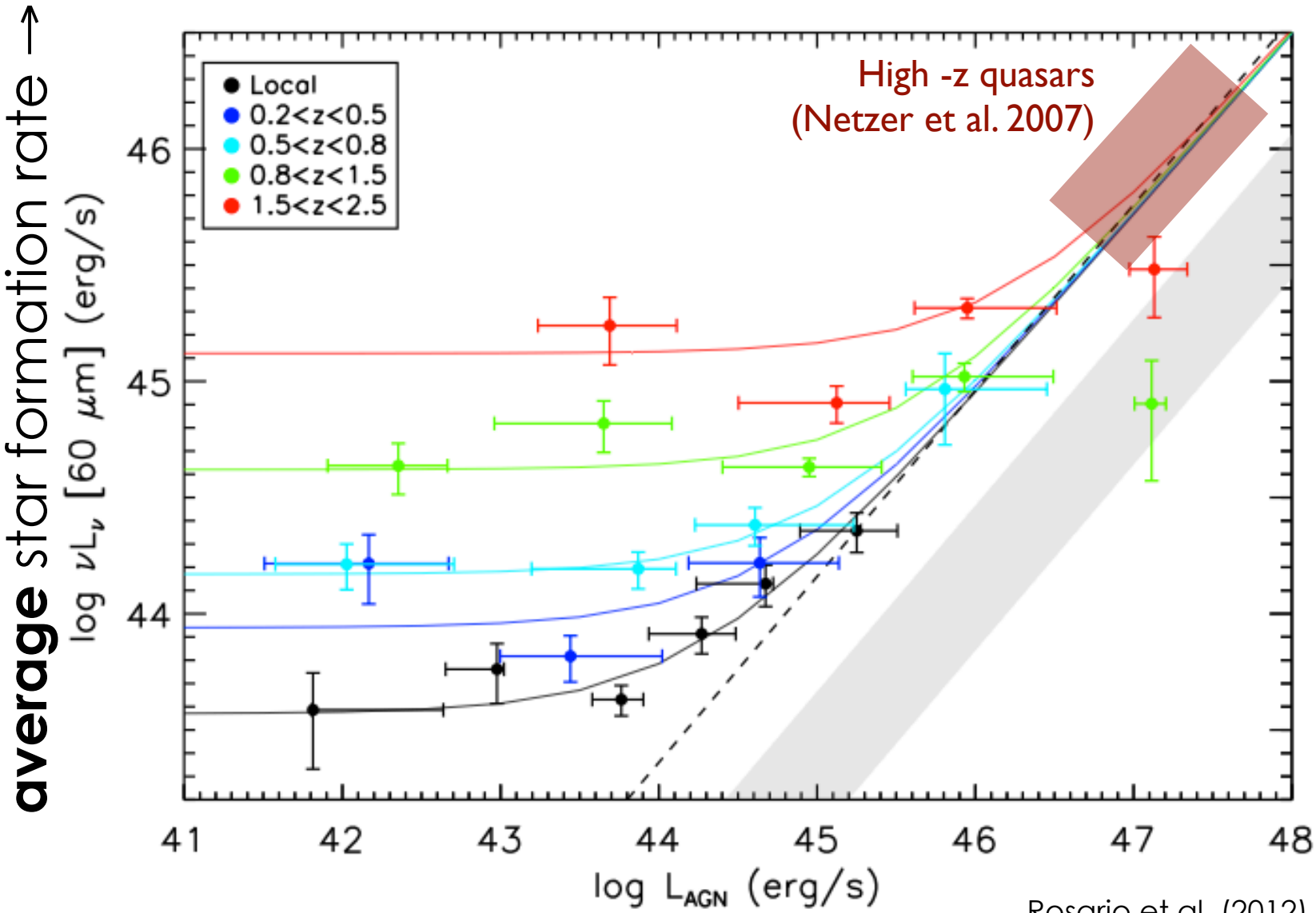




Netzer et al. (2007)

Also: Mullaney et al. (2011)

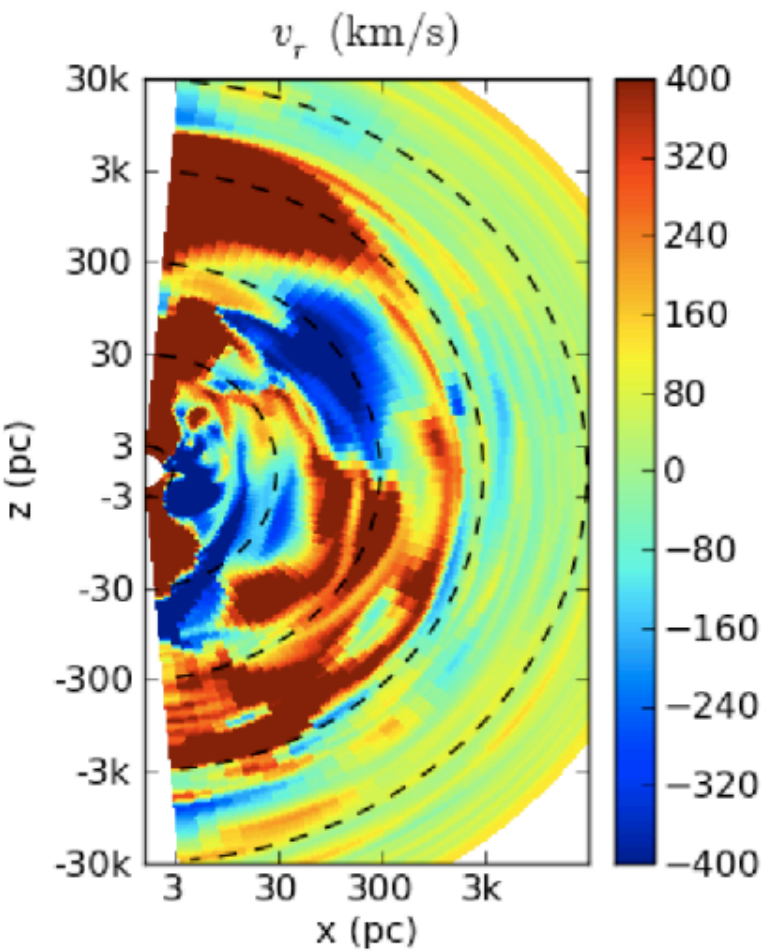
"Typical" AGN: no connection to host star formation?

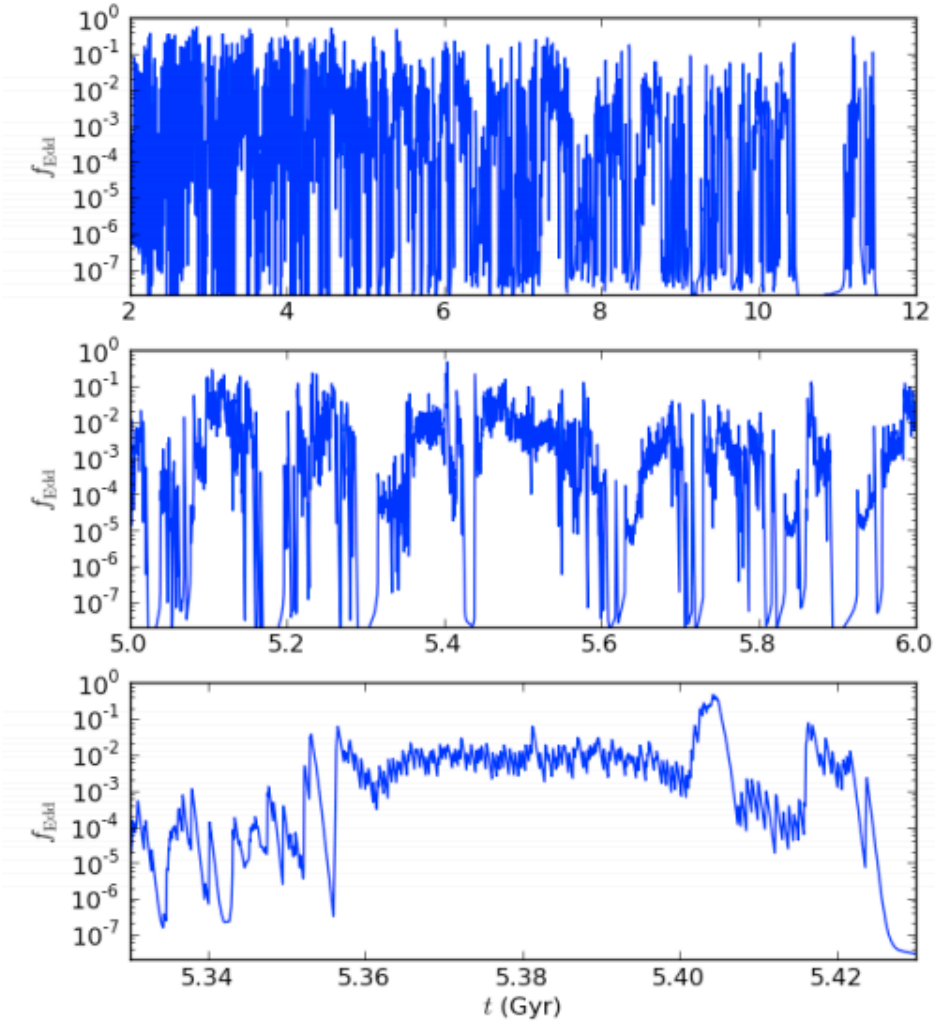


observed AGN luminosity →

Rosario et al. (2012), see also Shao et al. (2010), Mullaney et al. (2010, 2012)

Importance of AGN **variability**

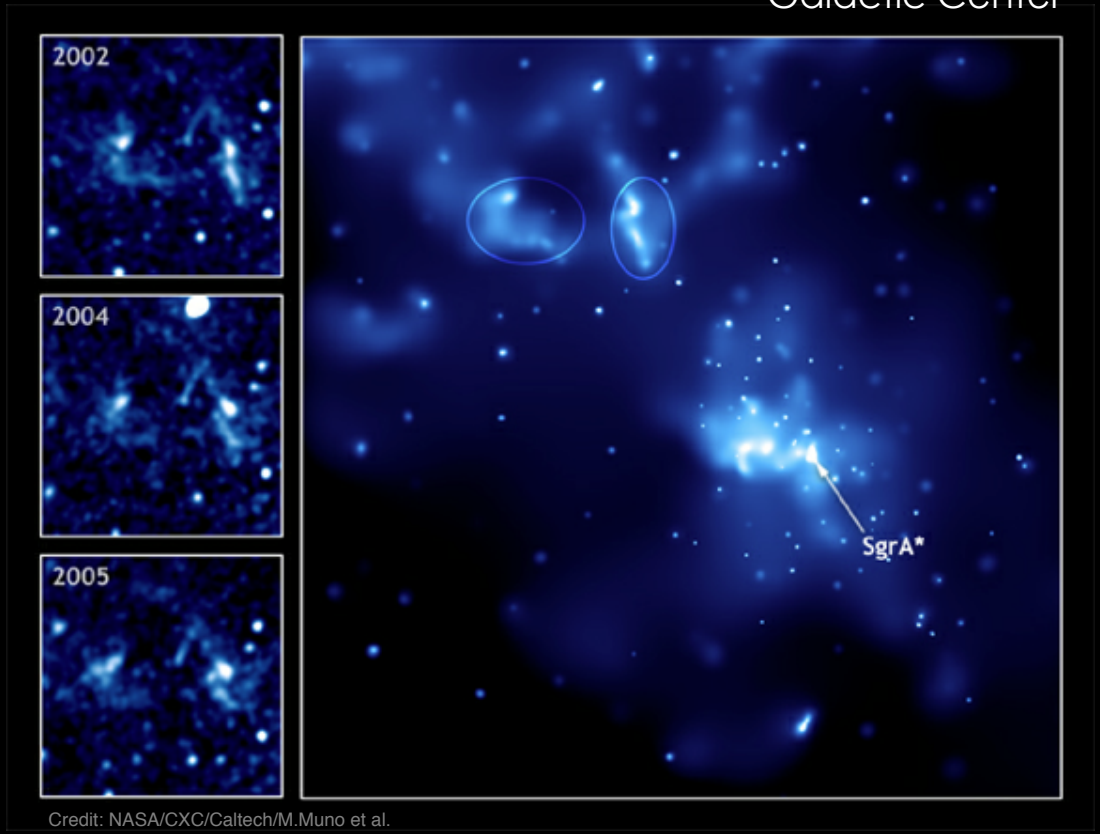




Novak et al. (2011)

Real examples of **long-term variability**

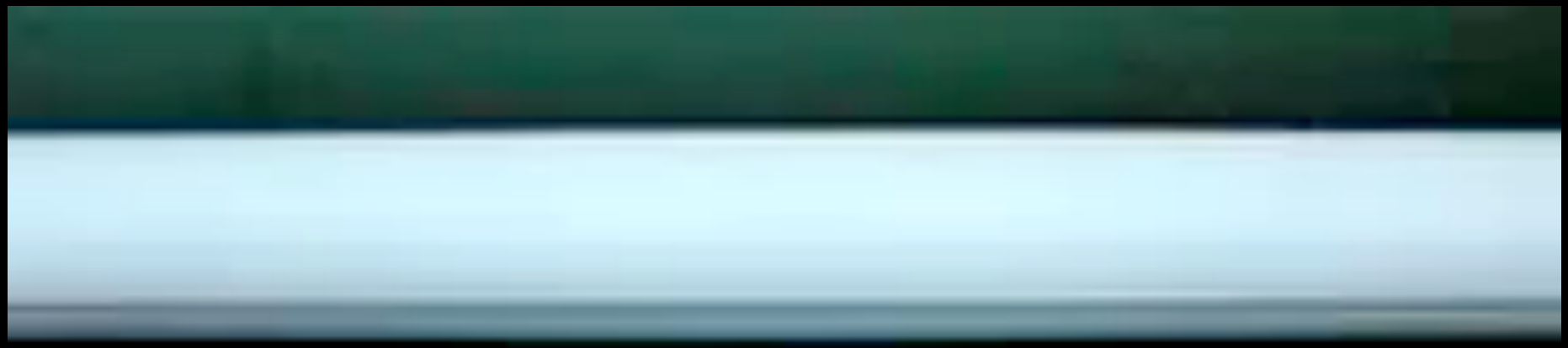
Galactic Center



Muno et al. (2007), Ponti et al. (2010)

Schawinski et al. (2011), Keel et al. (2011)

What does it mean for an AGN to be **“on”**?

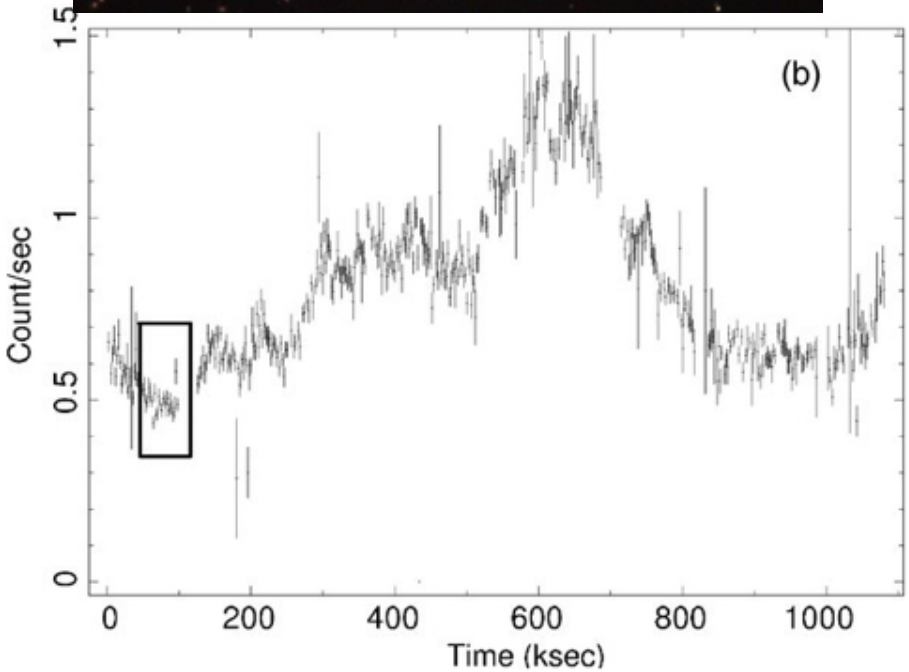


A fluorescent bulb at 1000 frames per second (http://www.youtube.com/watch?v=5pNtjOYkAbA)

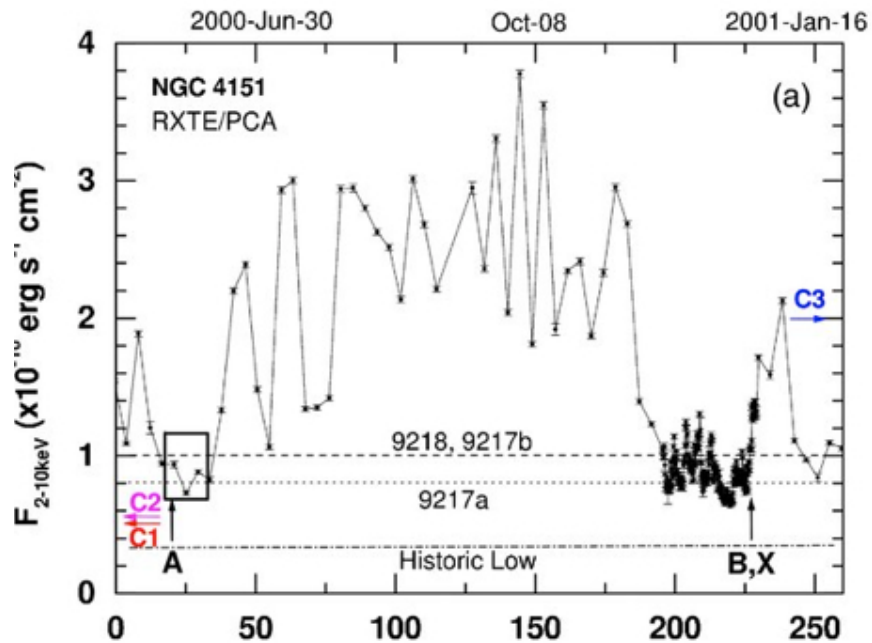
BUT…

NOT observable as "variability"

Wang et al. (2010)

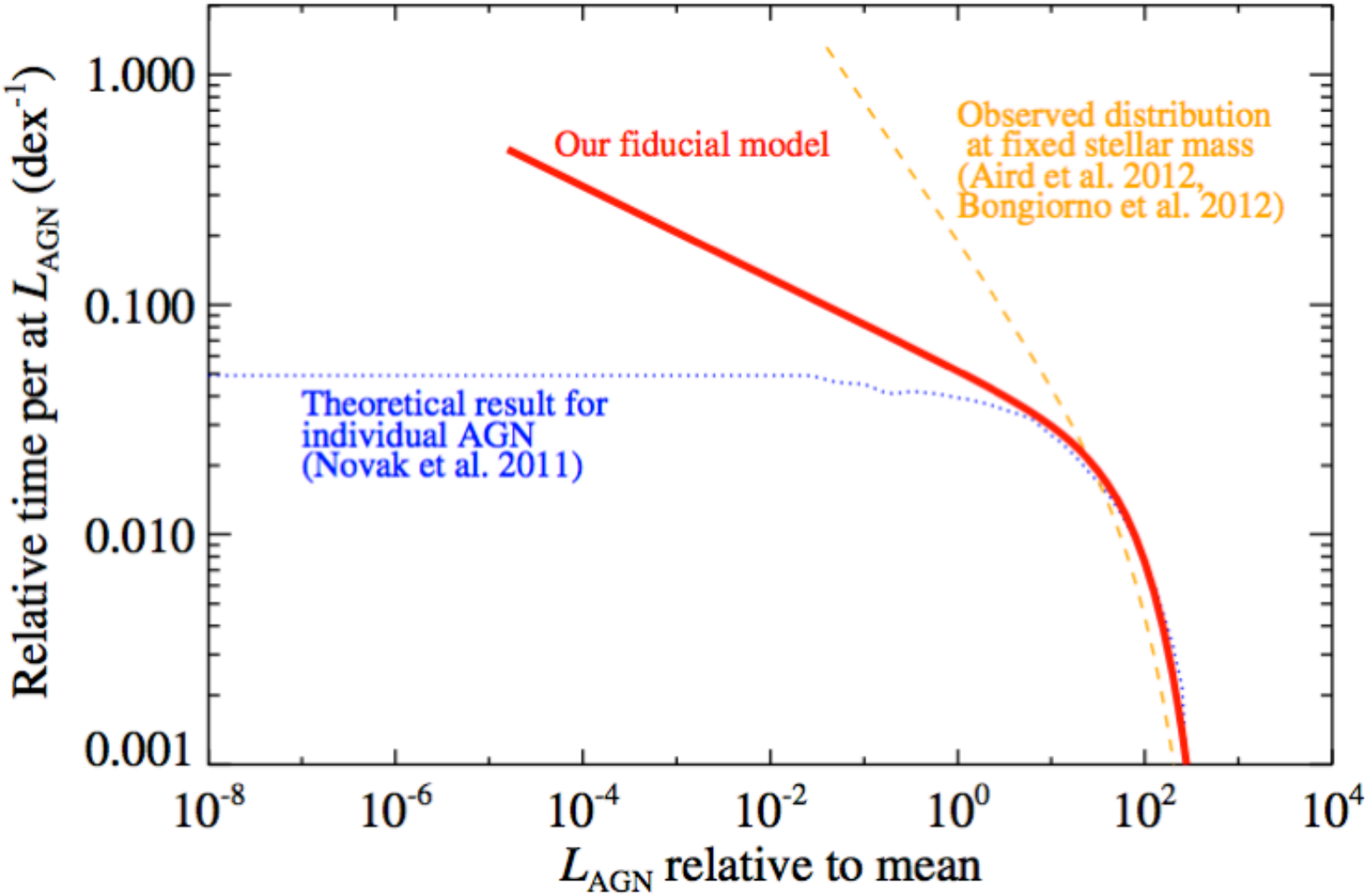


~days



~months

Variation over many orders of magnitude



INGREDIENTS

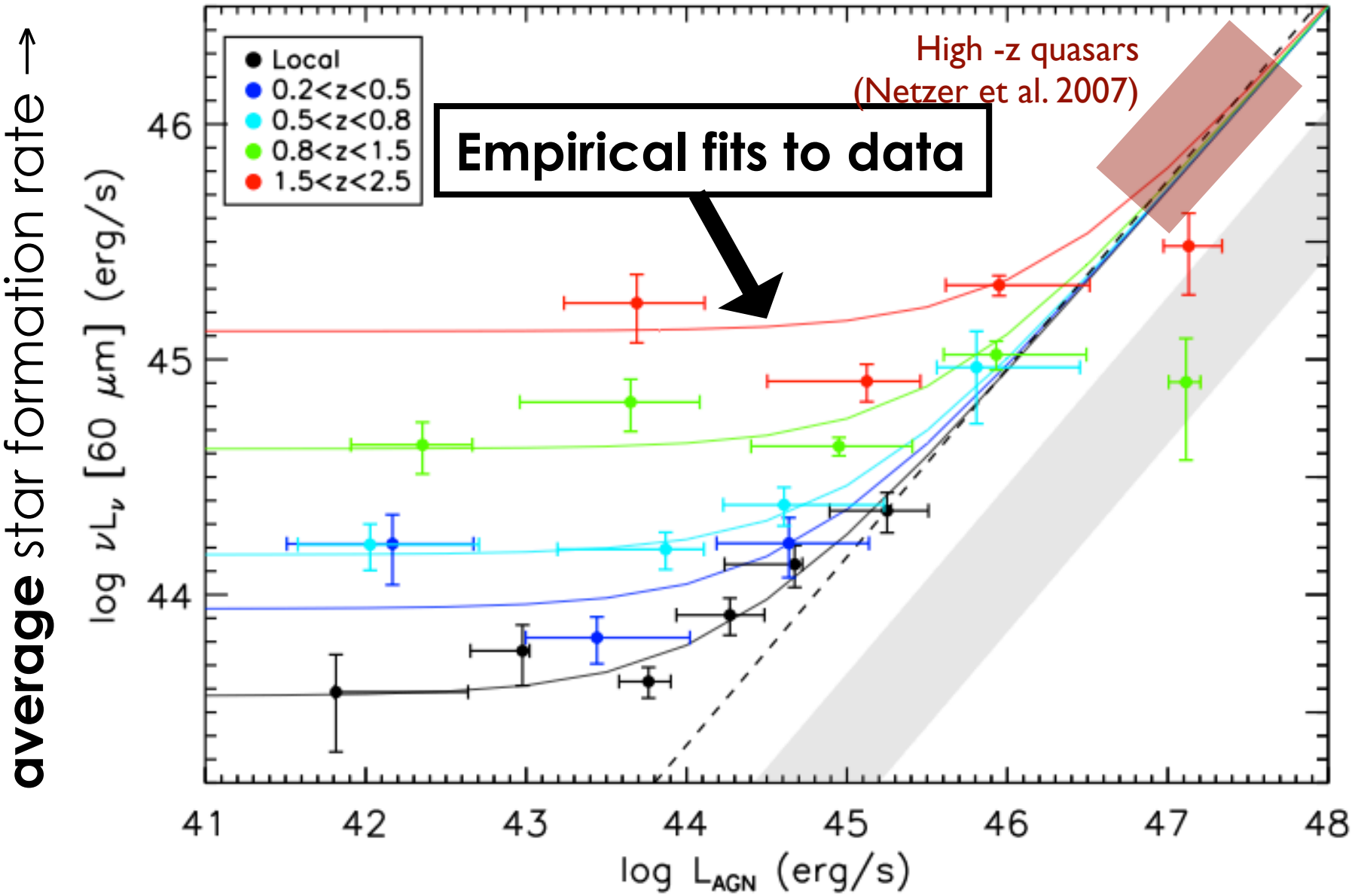
1. Observed infrared luminosity function (Rodighiero et al. 2010)

2. Kennicutt (1998) relation between SFR to L_{IR}

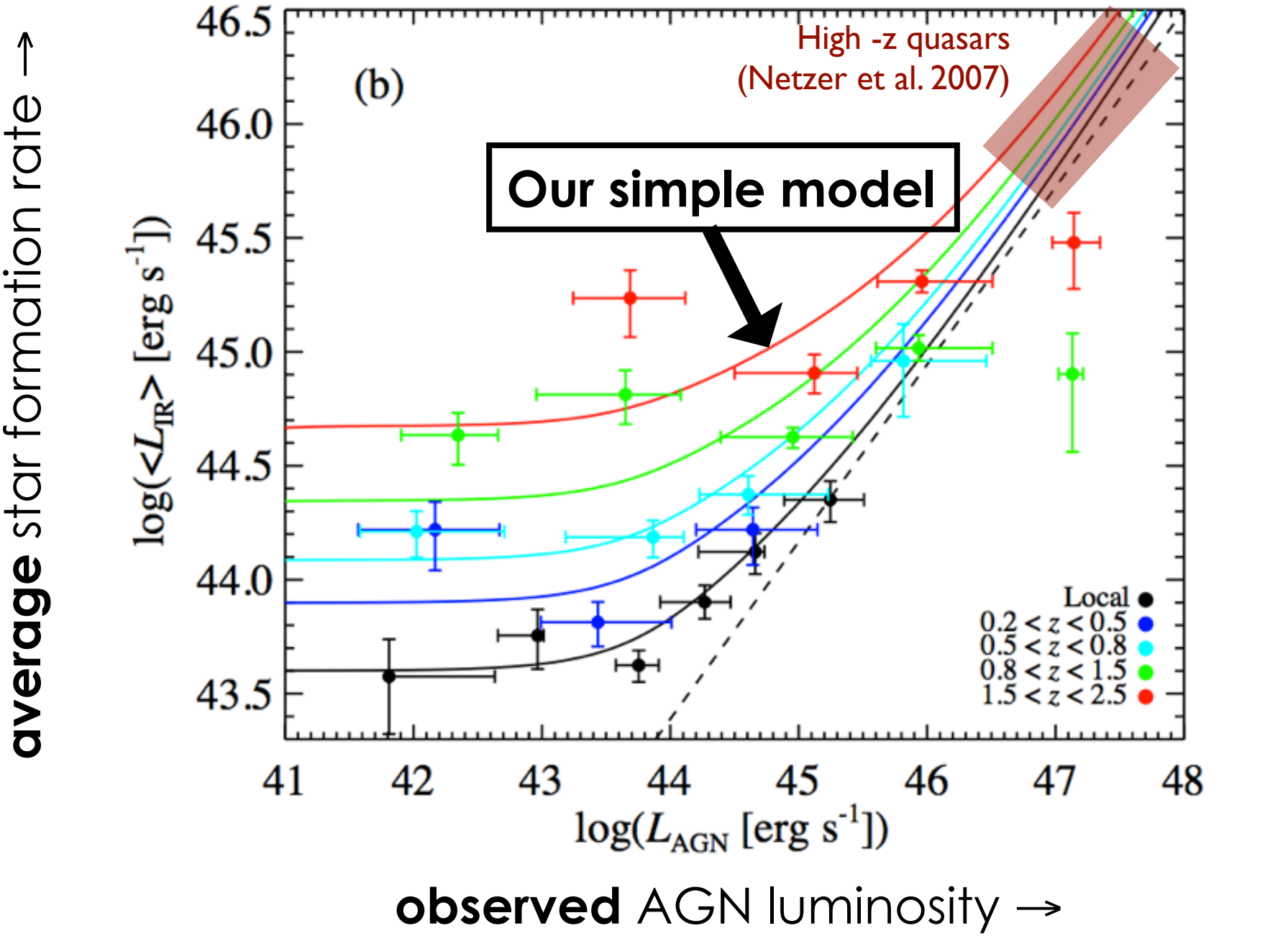
3. *Average* BH accretion rate = SFR / 3000
(motivated by Magorrian et al. 1998)

4. *Instantaneous* AGN luminosity follows a simple power-law distribution with exponential cutoff

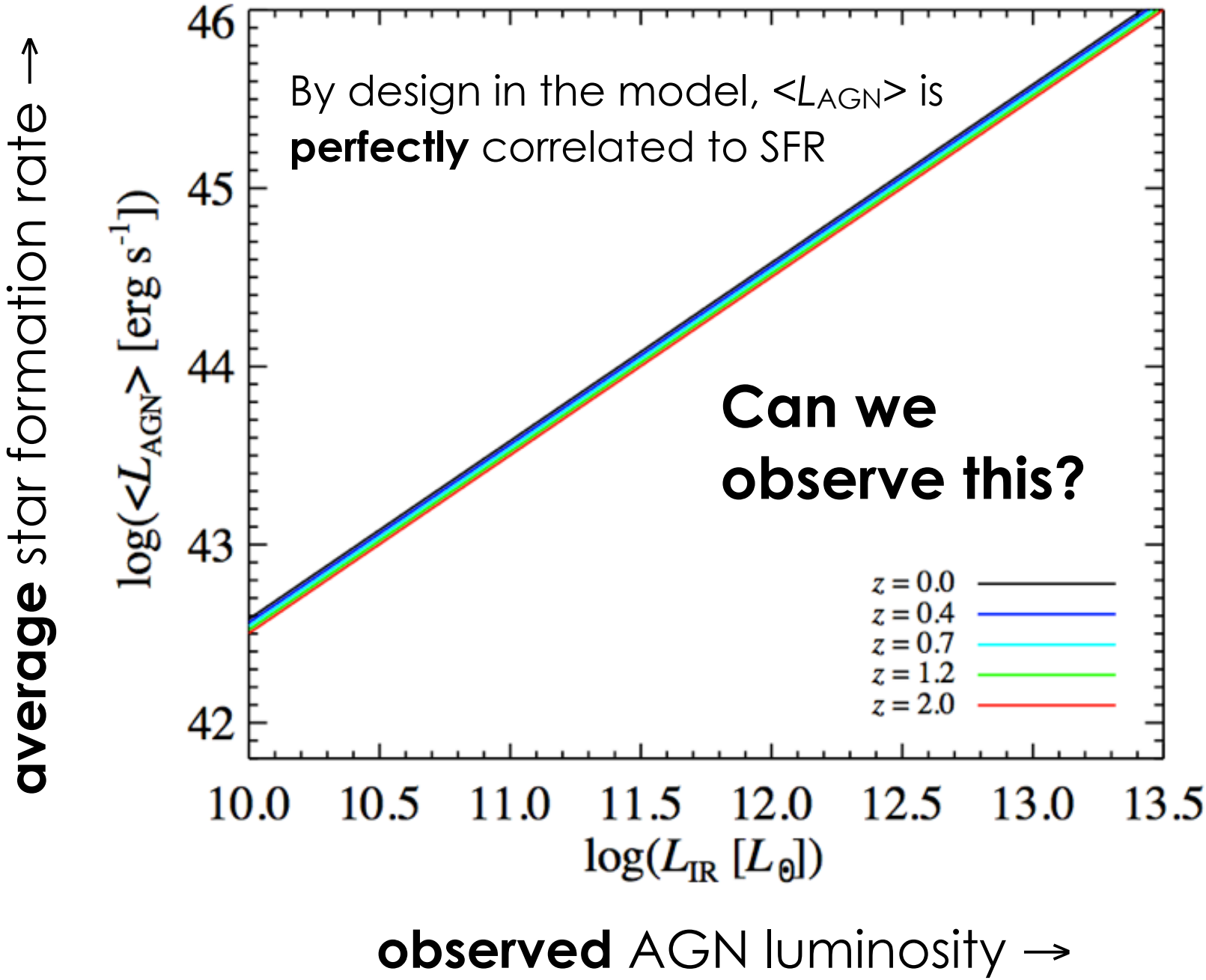
5. $L_{AGN} = 0.1$ BHAR c^2



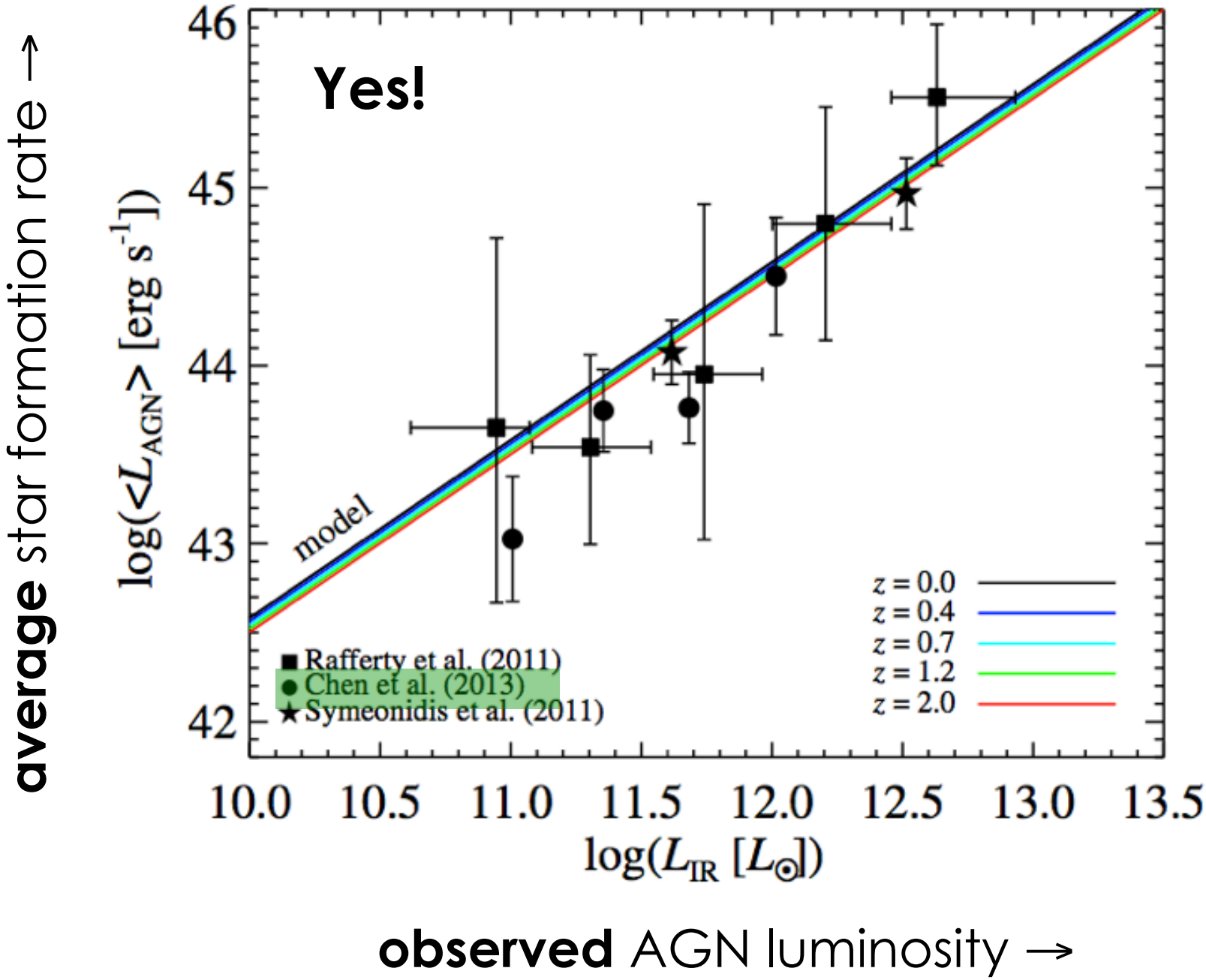
Rosario et al. (2012)



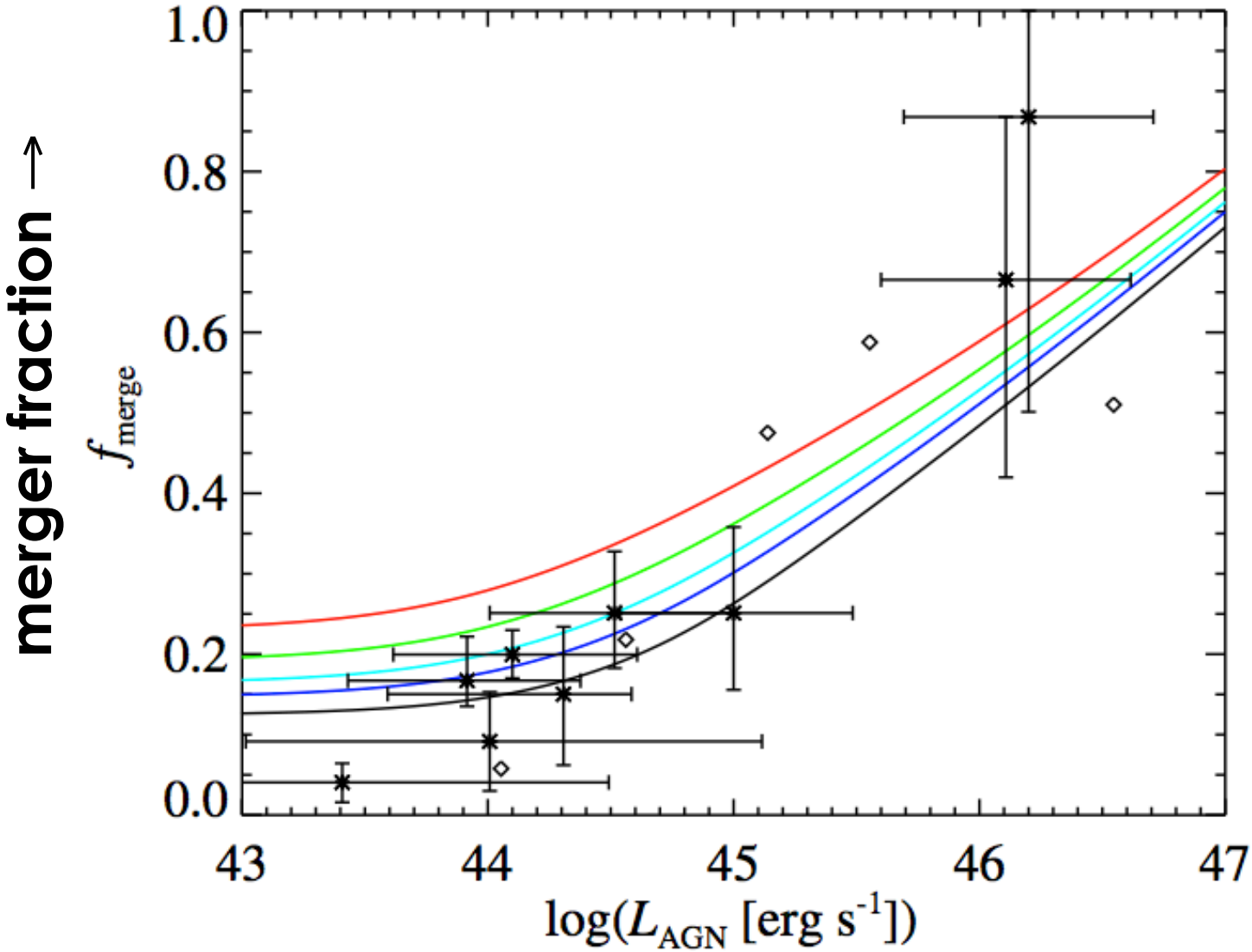
Hickox et al. (in preparation)



Hickox et al. (in preparation)

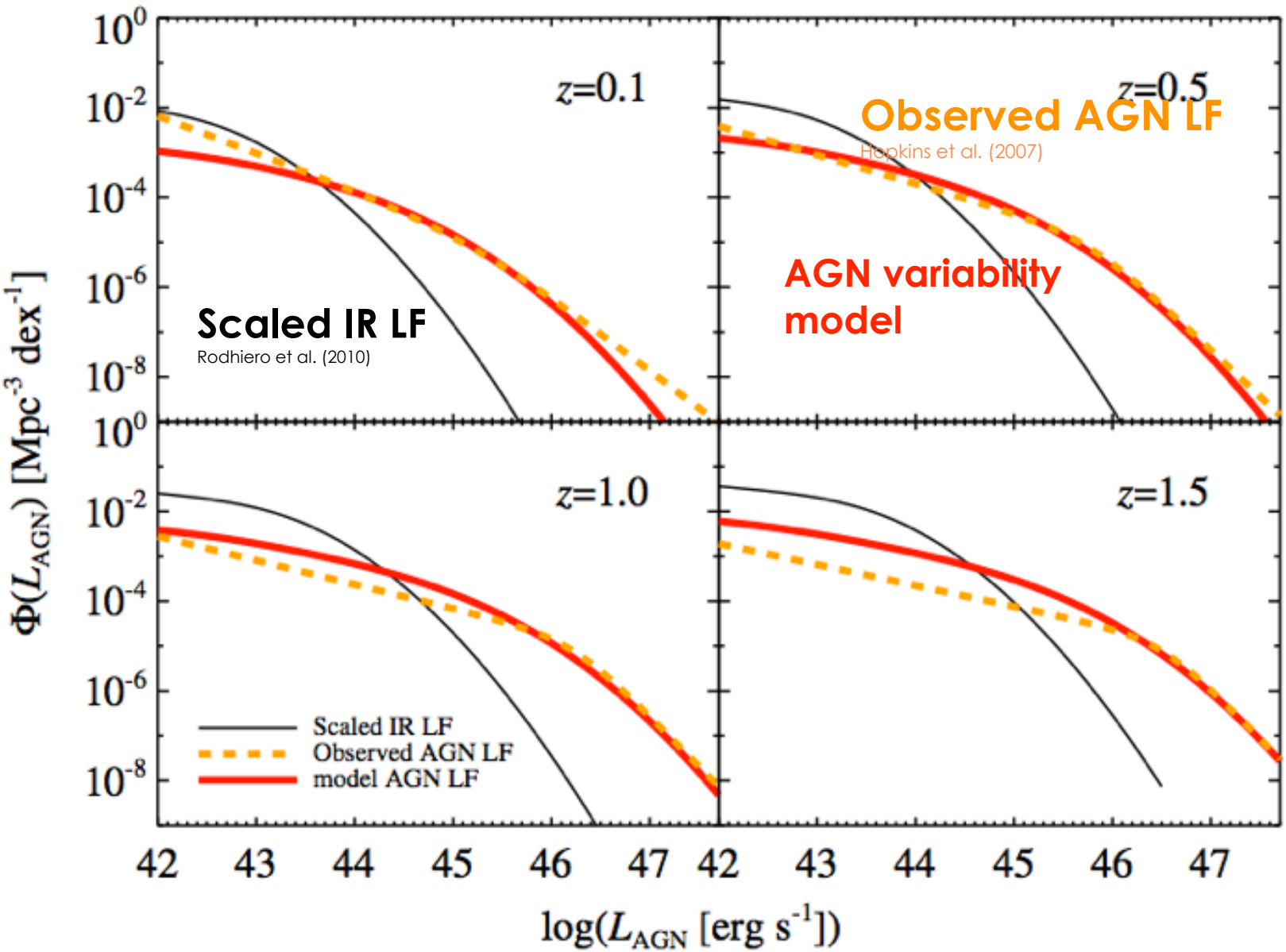

Yes!
model
Rafferty et al. (2011)
Chen et al. (2013)
Symeonidis et al. (2011)
z = 0.0
z = 0.4
z = 0.7
z = 1.2
z = 2.0
log(<L_AGN> [erg s^-1])
log(L_IR [L_⊙])
46
45
44
43
42
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
average star formation rate →
observed AGN luminosity →

Connection to **mergers**



Data from Treister et al. (2012)

Modeling the AGN **luminosity function**



Do ALL star-forming galaxies host AGN?
(over galaxy timescales)

=

Do AGN follow star formation?

OR

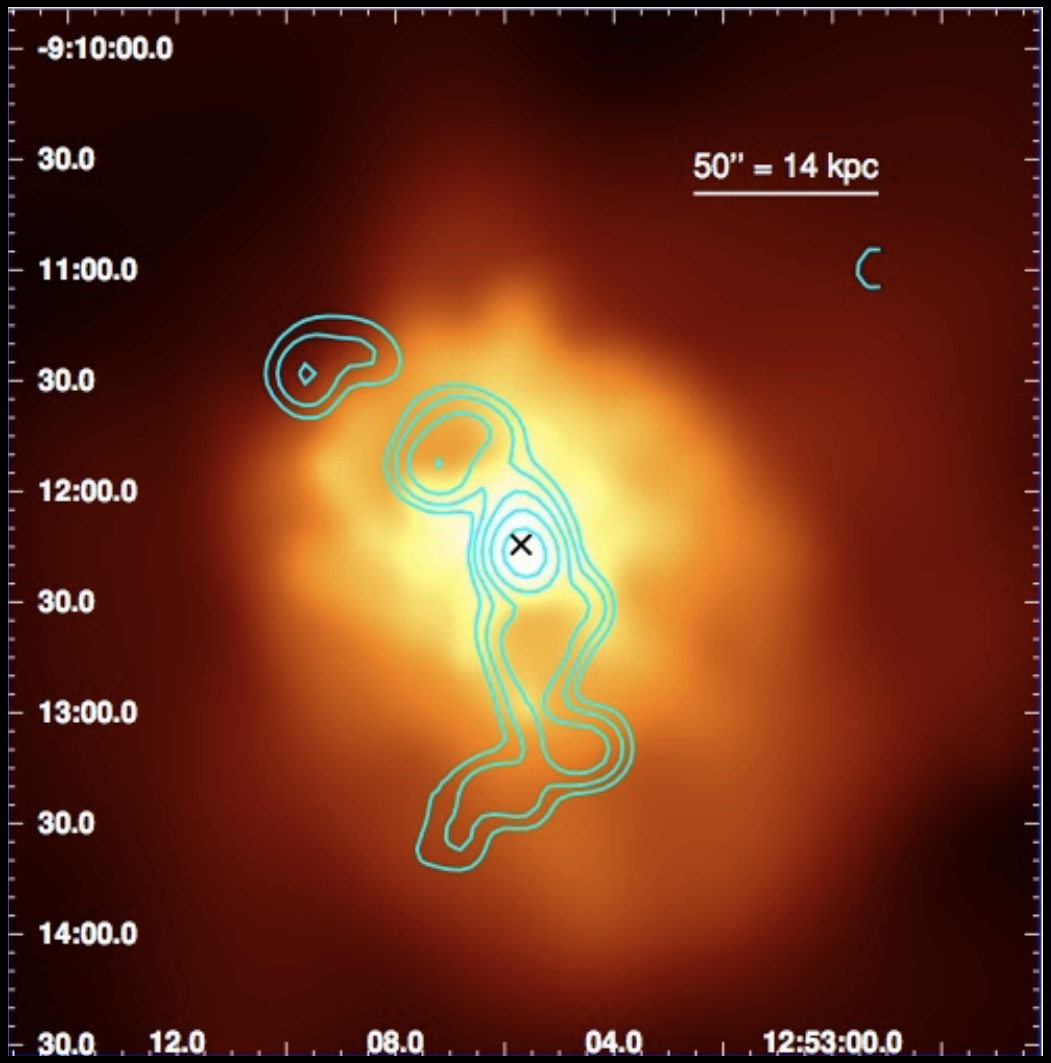
Do AGN prevent star formation?

YES

depending on evolutionary stage (and thus halo mass) and mode of accretion

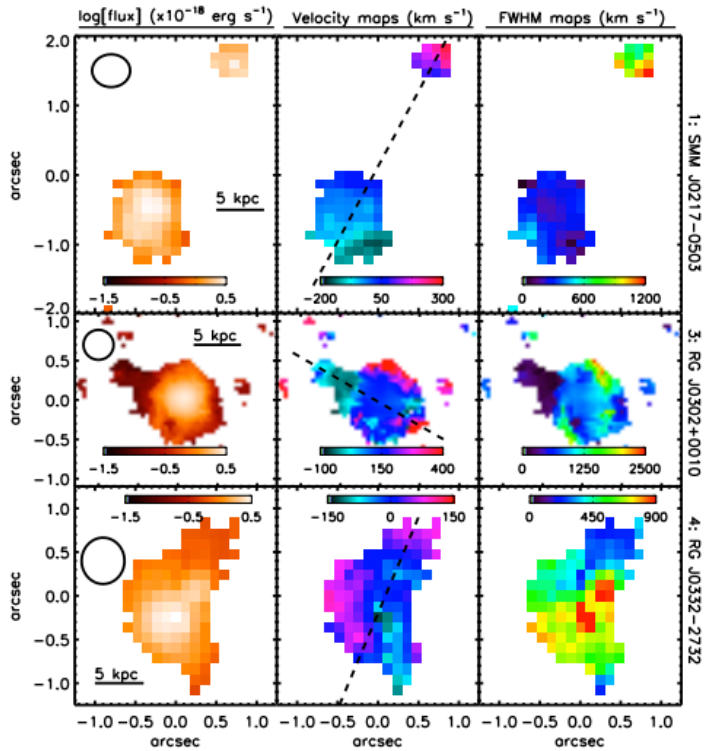
Where and when is AGN feedback important?

Hot atmosphere heating by jets



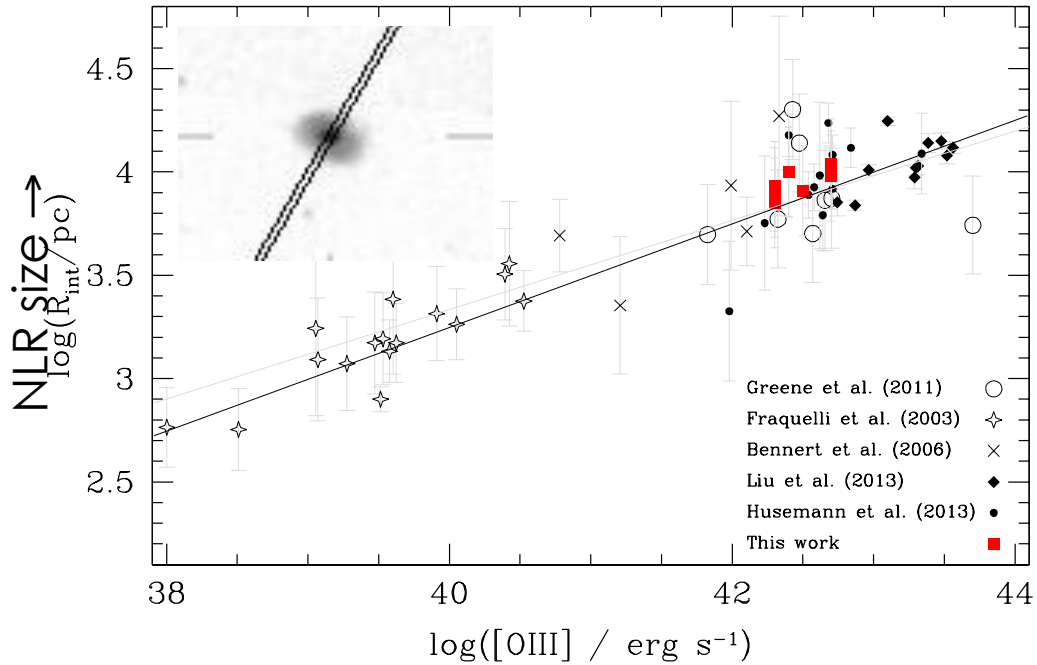
HCG 62 (Gitti et al. 2010), see many others for similar examples

Powerful radiatively-driven feedback



Broad (> 1000 km/s) high-velocity (200-500 km/s) [OIII] gas

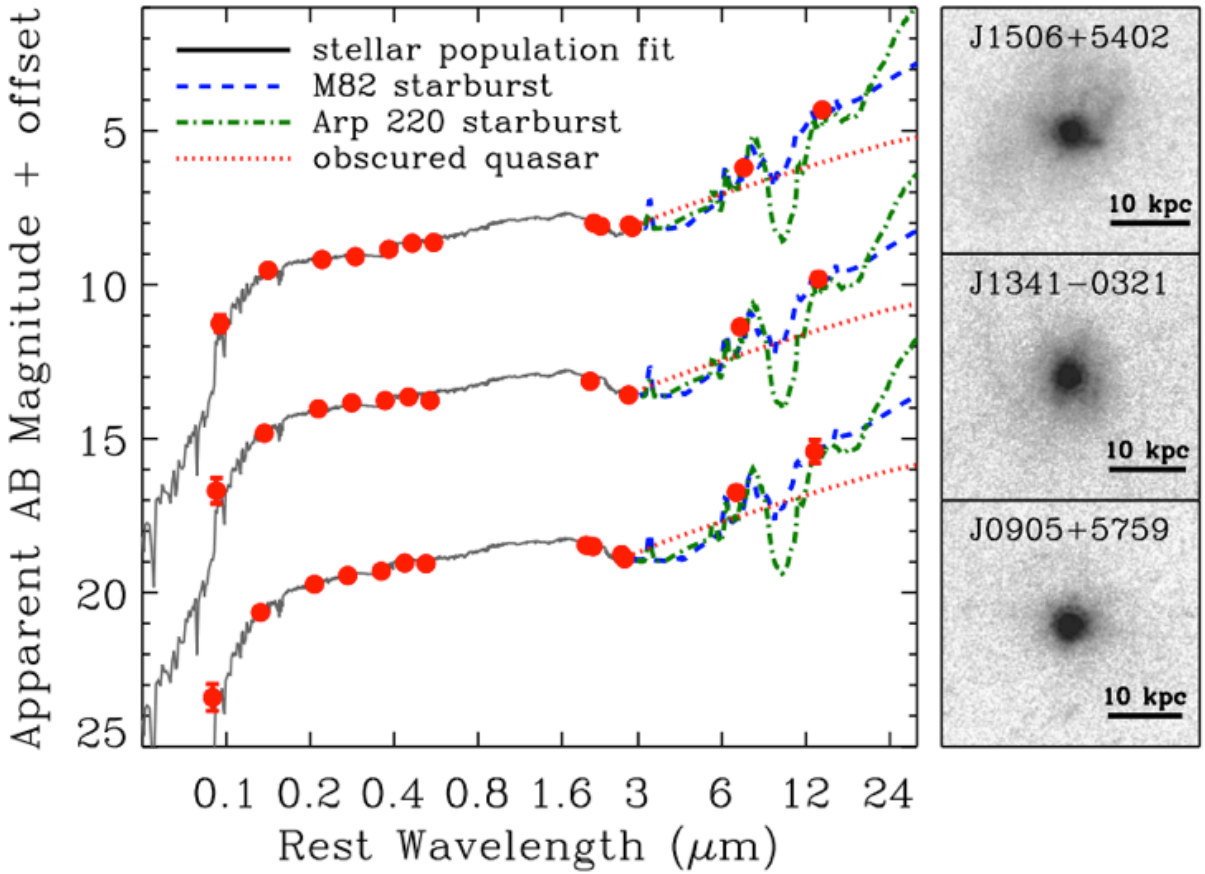
Harrison et al. (2012)



Galaxy-wide photoionization from powerful quasars

Hainline et al. (in prep)

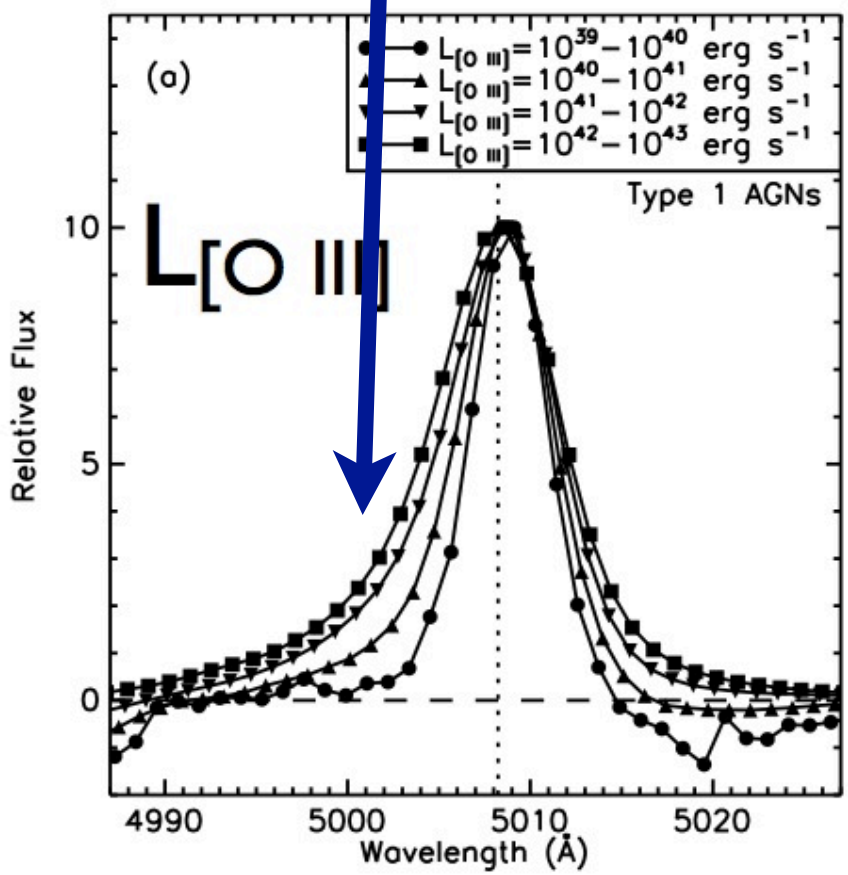
Perhaps AGN not **always** needed for high-velocity outflows?



SFR surface density > 2000 M_{sun} yr^{-1} pc^2!
Outflow velocity > 1000 km/s

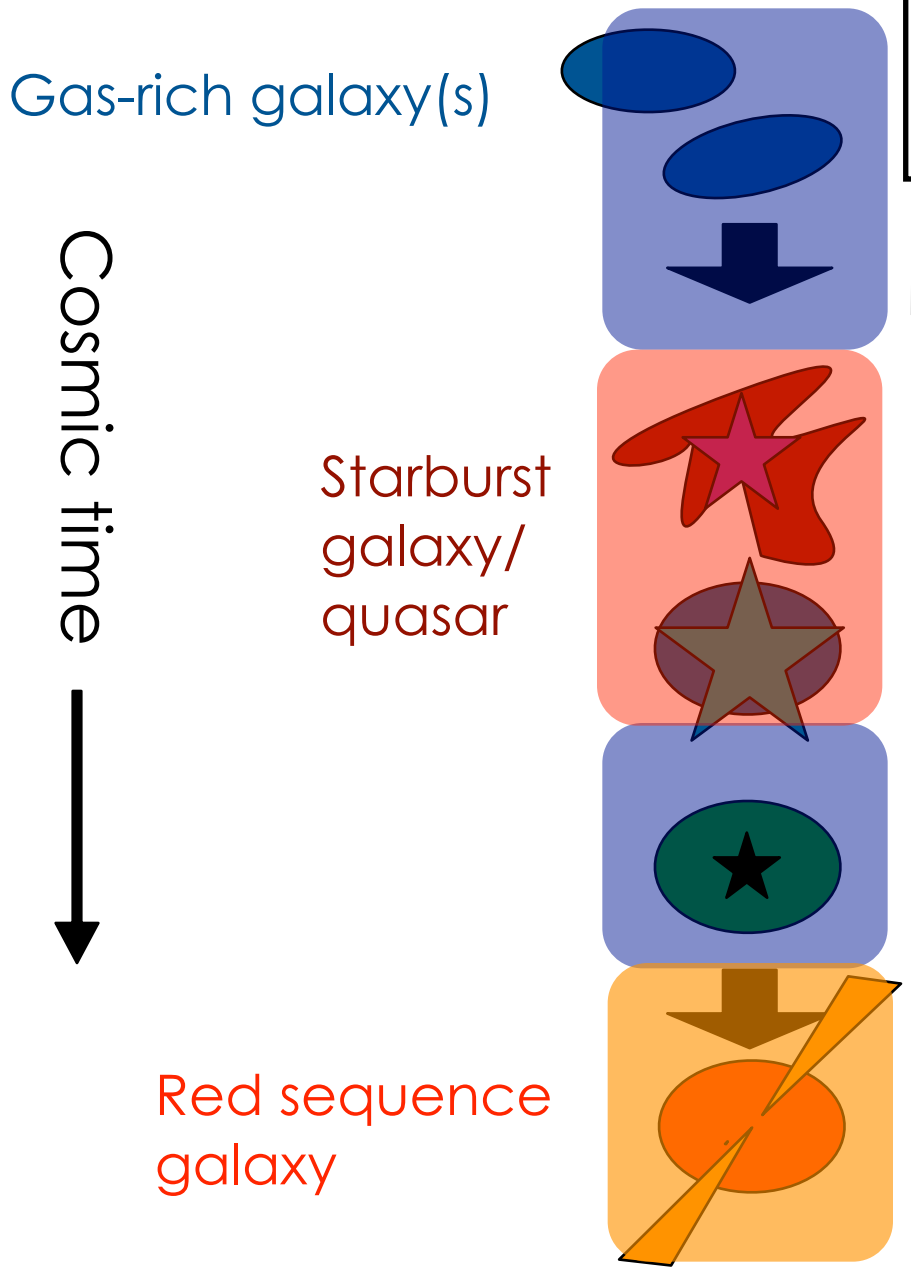
Diamond-Stanic et al. (2012)

Ubiquitous outflows in lower-luminosity AGN



Mullaney et al. 2013, MNRAS submitted

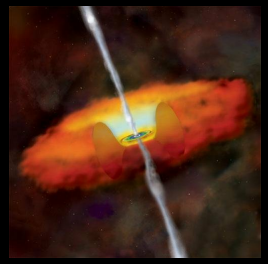
Black hole self-regulation?



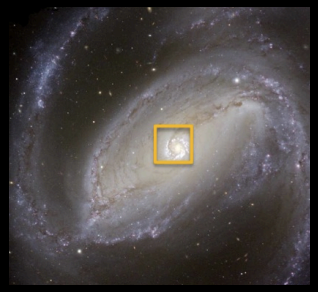
Radiative and **mechanical** feedback can strongly affect host

Black hole **self-regulation?**

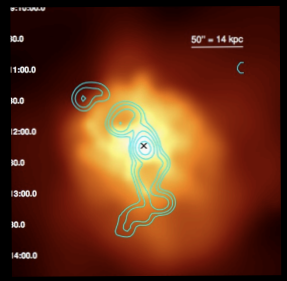
What have we learned?



- Accretion state depends on **Eddington ratio**, and different techniques **select different AGN populations**



- **In low-mass dark matter halos,** rapid black hole accretion appears to **follow** star formation



- **In high-mass dark matter halos,** mechanical feedback from low-level accretion appears to **prevent** star formation

THE FUTURE: BETTER STATISTICS!

X-ray:
Chandra XVP (COSMOS; PI Civano, proposal for Bootes for Cycle 15); also hard X-rays with *NuSTAR*

Infrared: WISE

Study **distribution** of accretion rates, and **halo occupation distribution** from clustering

Black hole evolution --> galaxy evolution