FEEDBACK IN GALAXY FORMATION

Disks

SMBH growth

AGN and star formation

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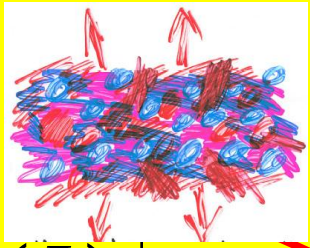
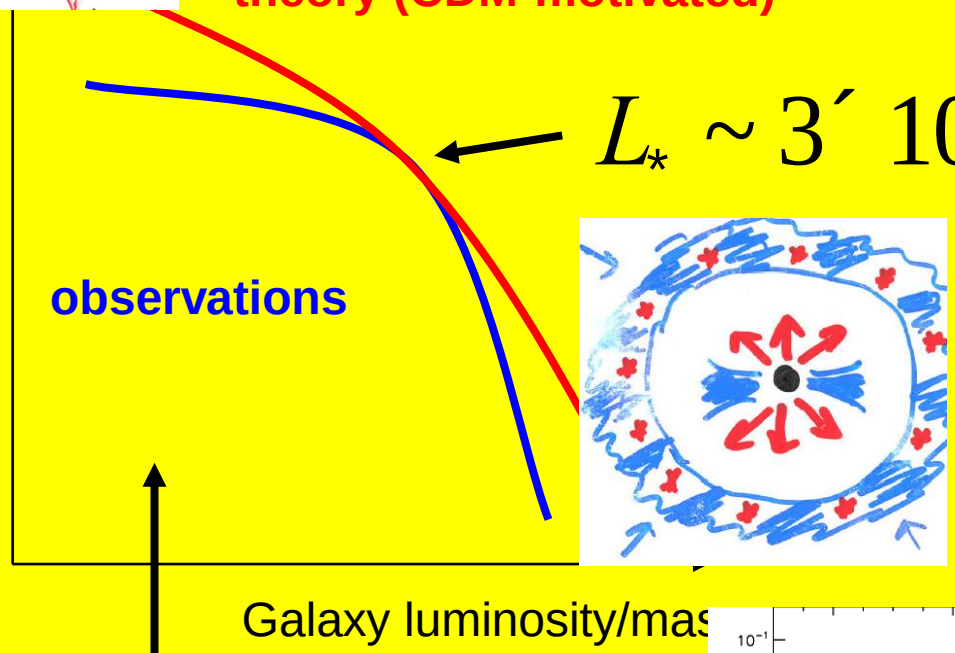
Collaborators: Vincenzo Antonnucio-Deloglou, Volker Gaibler, Sadegh Khochfar

Feedback is needed



$$M_{cooled\text{-}baryons} \sim a_g^{-2} a^3 \left(\frac{m_p}{m_e}\right)^2 \left(\frac{t_{cool}}{t_{dyn}}\right) T^{1+2b}$$

$$\alpha_g = G m_p^2 / e^2$$



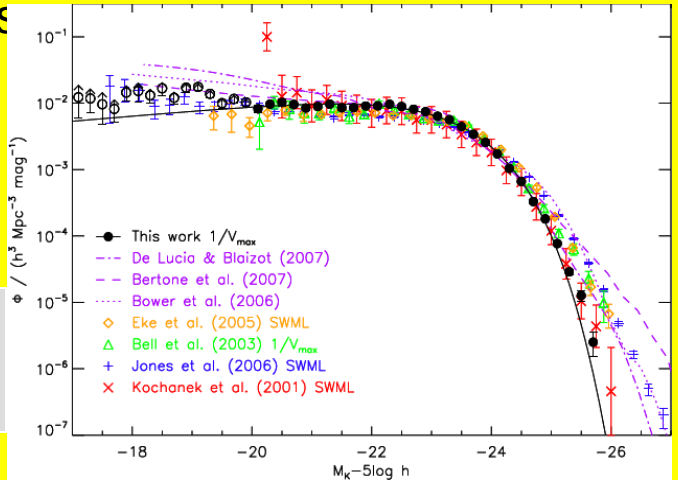
$$t_{cool} \sim \frac{nkT}{\Lambda(T) n^2}$$

$$t_{dyn} \sim \frac{1}{\sqrt{G m_p n}}$$

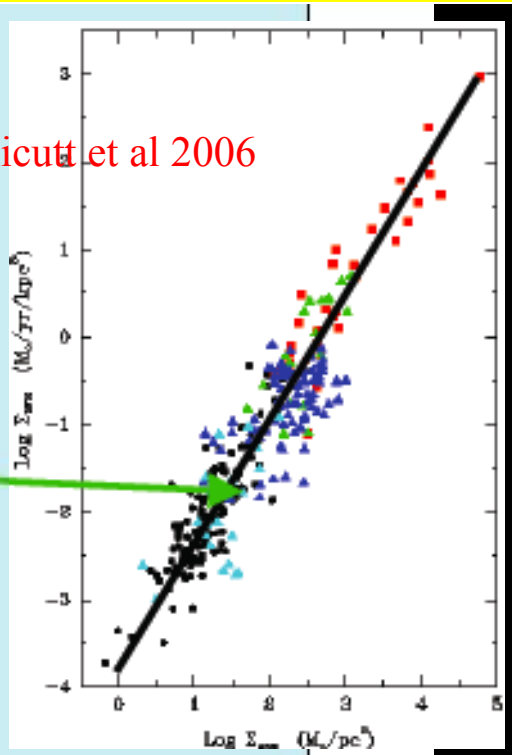
Reionization
Supernovae
Tidal stripping
Active galactic nuclei
Infall heating

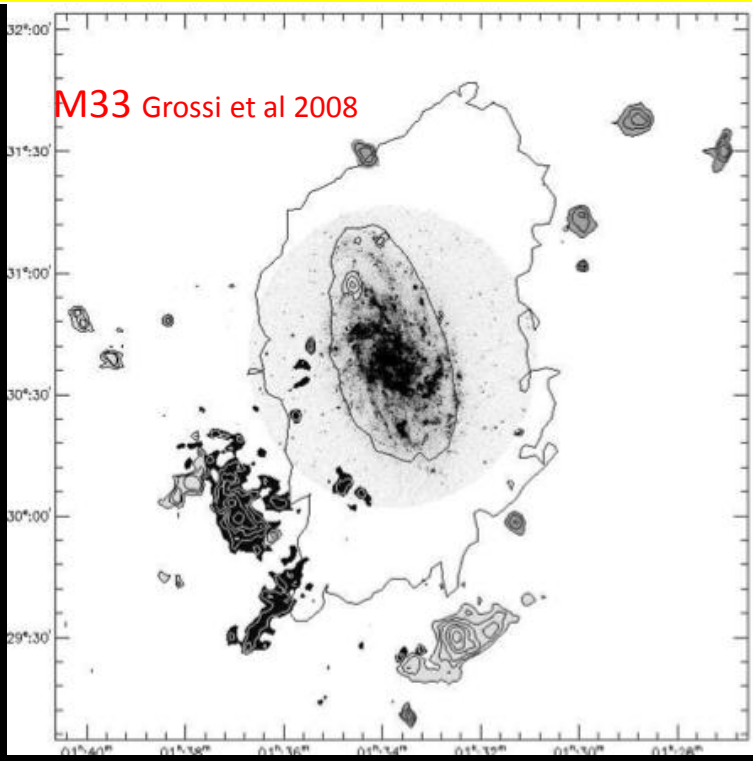
SN

AGN



A GLOBAL STAR FORMATION LAW





SFR=0.02 (GAS SURFACE DENSITY)/t_{dyn}

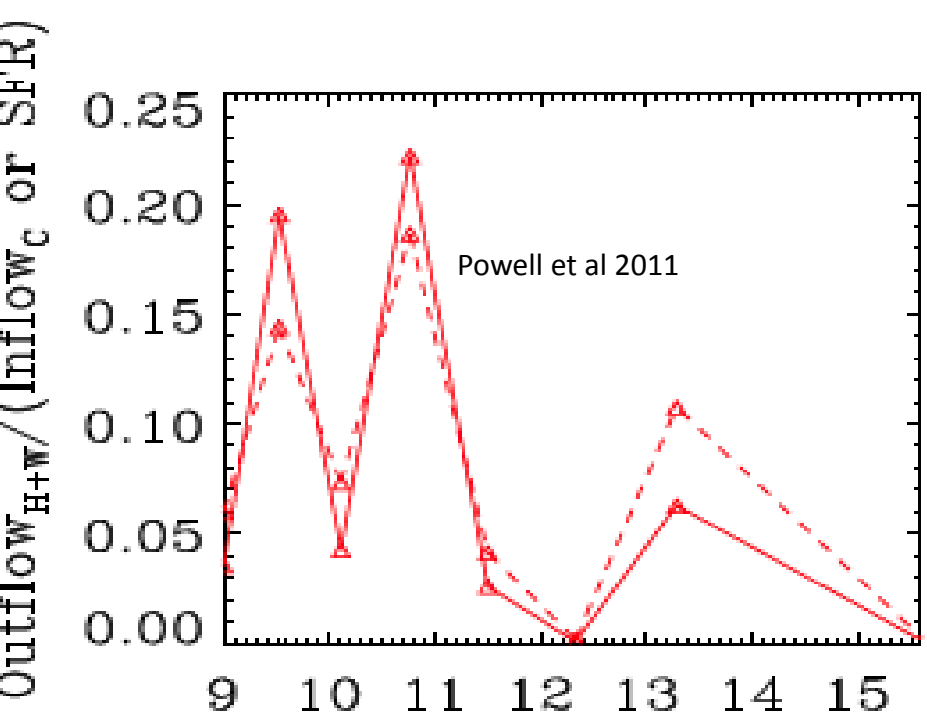
SFE: $\varepsilon = \sigma_{gas}\, v_{cool}\, m_{*,SN} / E_{SN} = 0.02$

low efficiency due to SN feedback

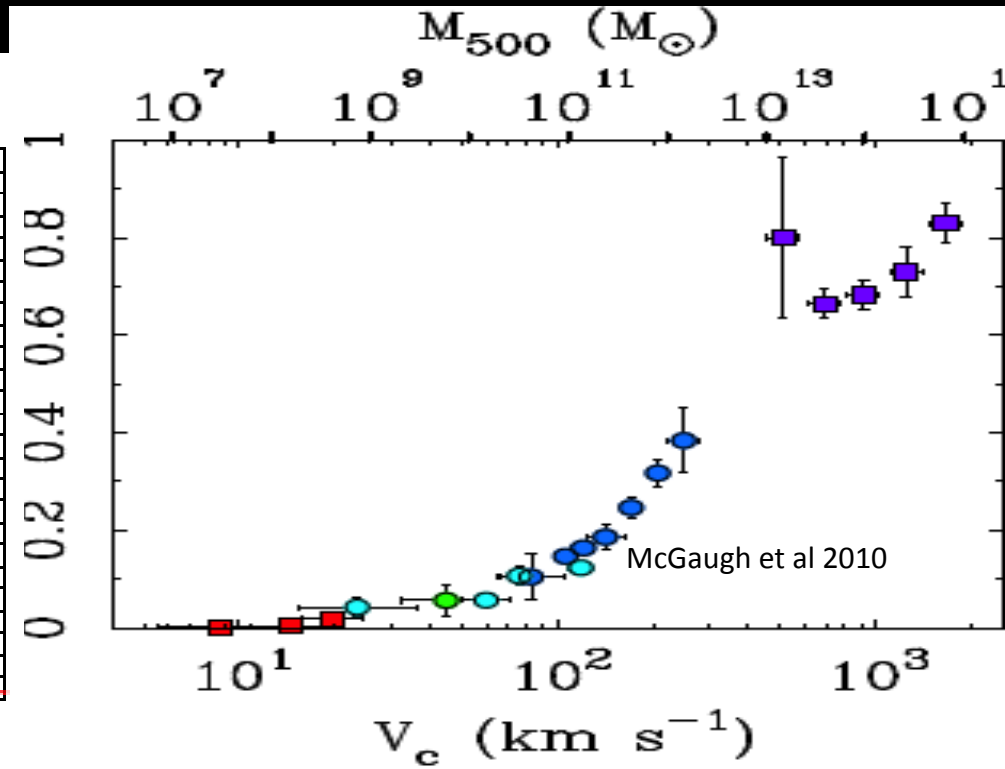
cold gas accretion/global disk instability

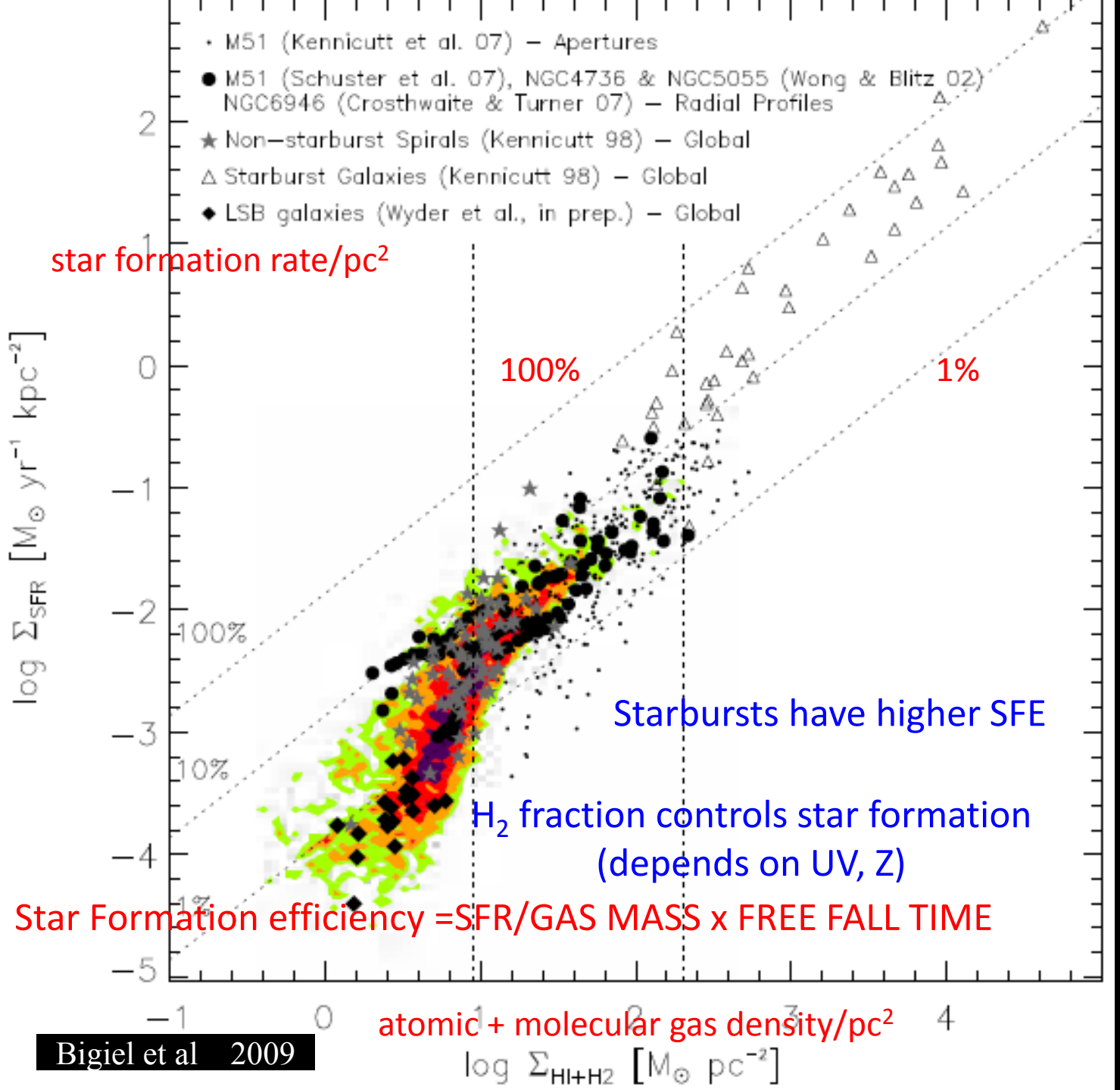
But SNe do not eject enough baryons even from dwarfs

Outflow/inflow



Baryon fraction



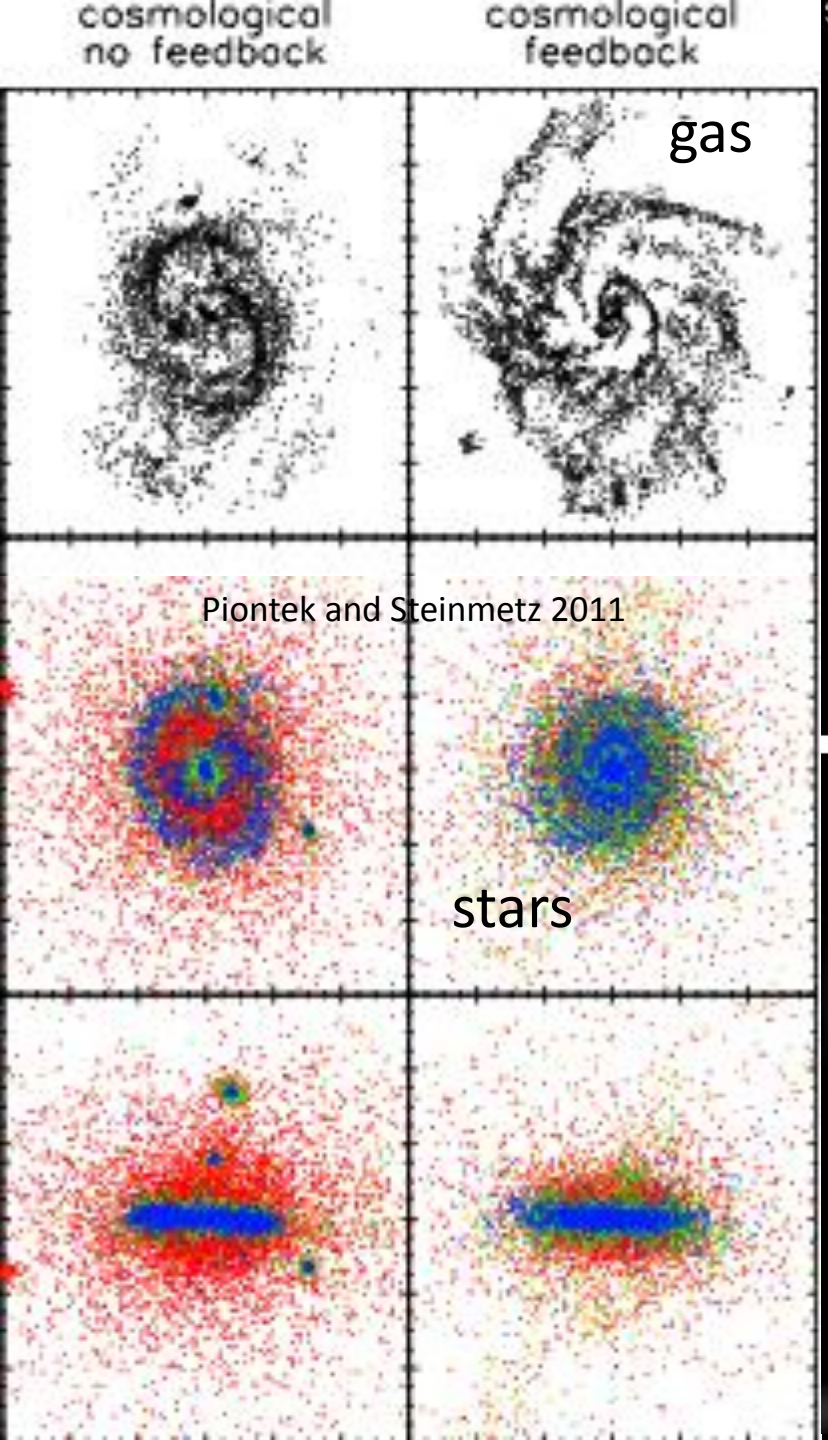


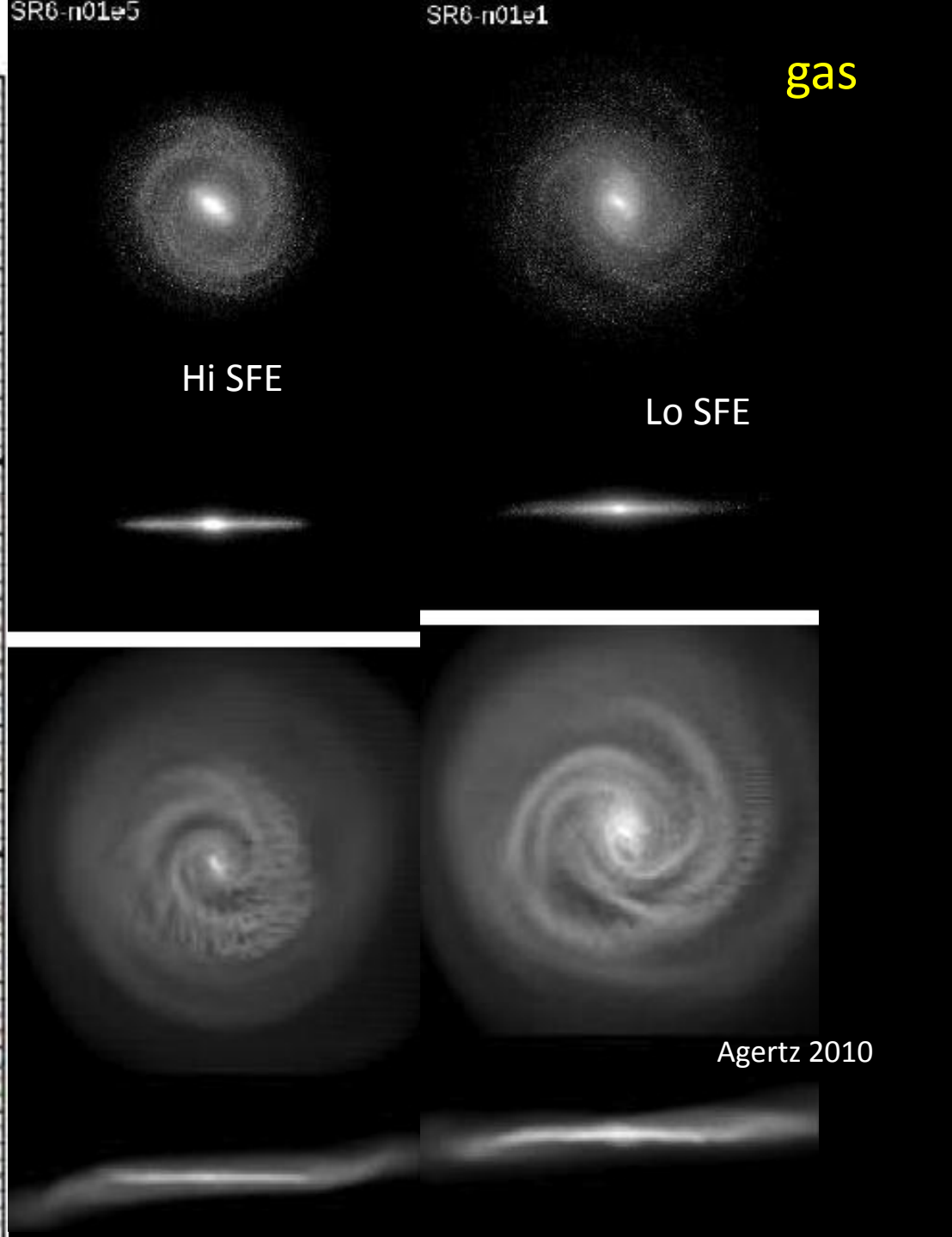
Bigiel et al 2009

The angular momentum problem

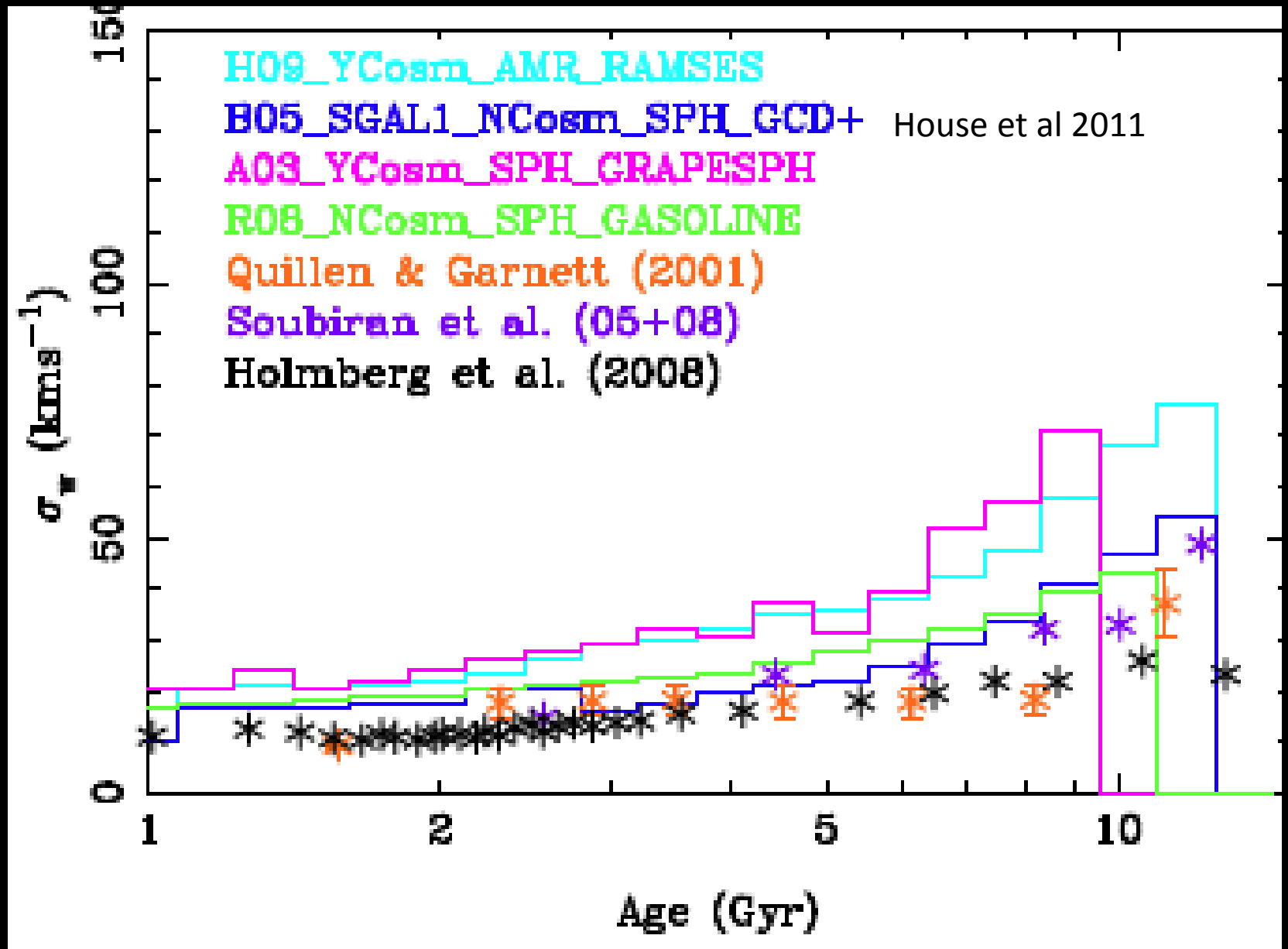
- Bulge/disk ratio is too large due to dynamical friction on dark matter …. causes angular momentum loss of infalling substructures

- Solved by SN-driven wind feedback …. but at a price


cosmological
no feedback
cosmological
feedback
gas
Piontek and Steinmetz 2011
stars

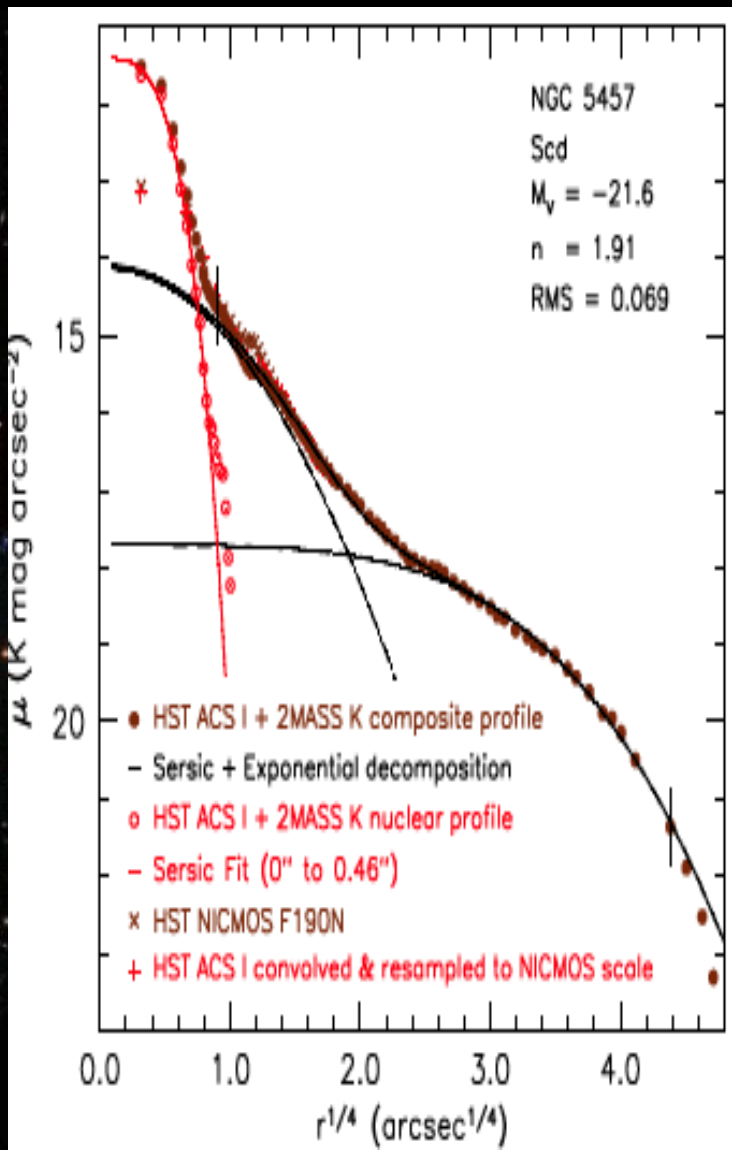

SR6-n01e5
SR6-n01e1
gas
Hi SFE
Lo SFE
Agertz 2010

But the disk overheats…

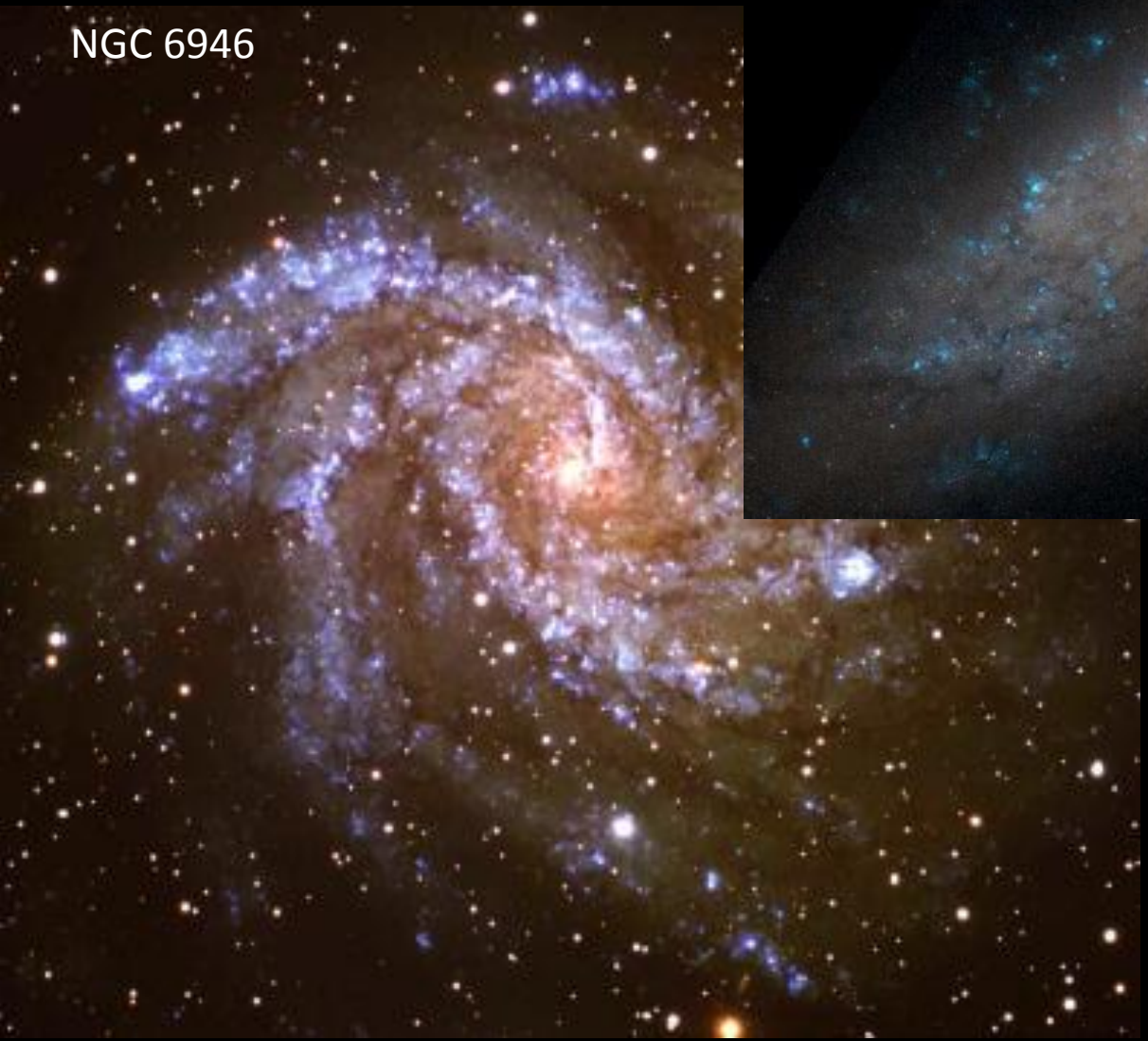


NGC 545 a pure thin disk galaxy

Kormendy et al 2010

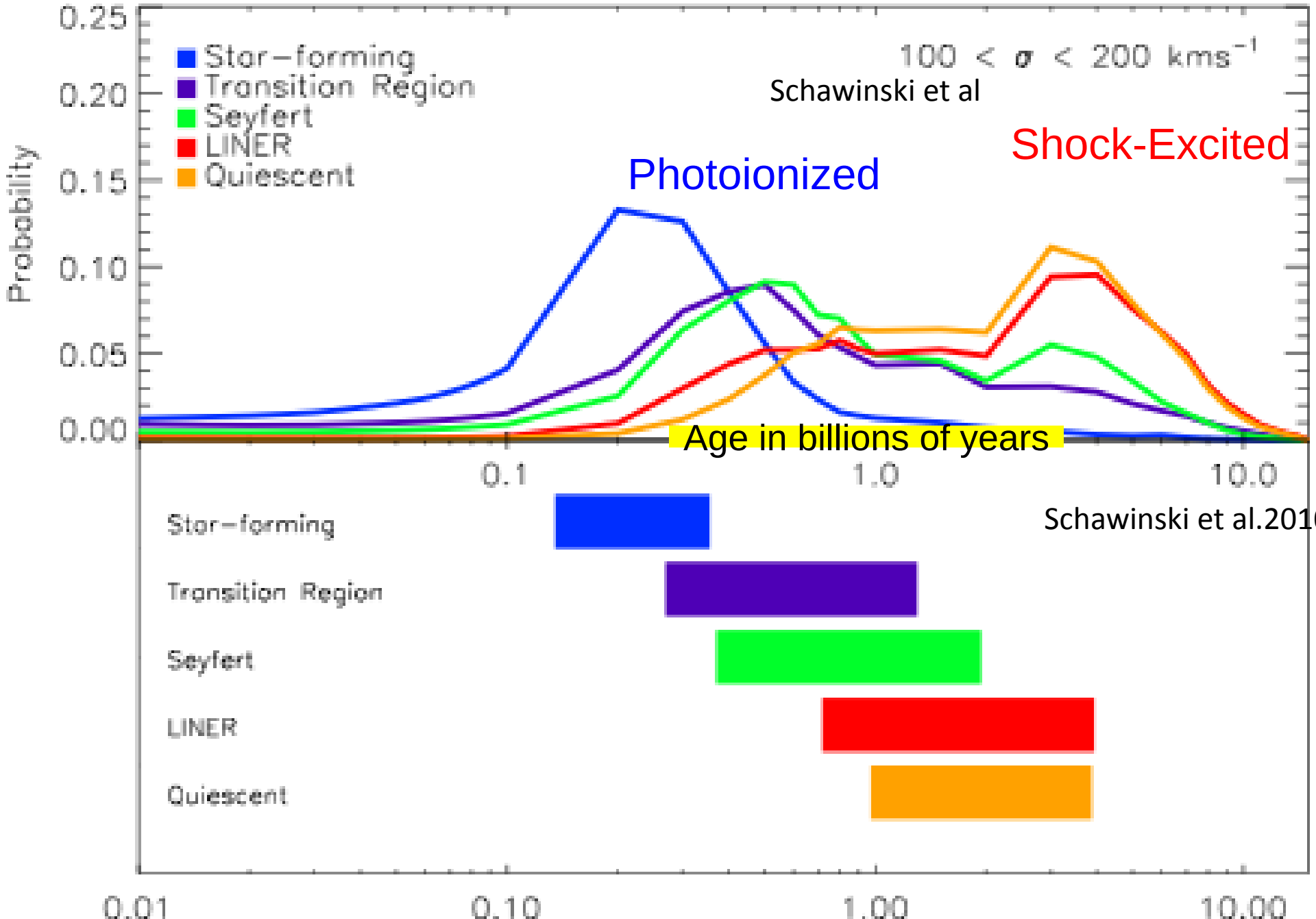


More massive pure disk galaxies



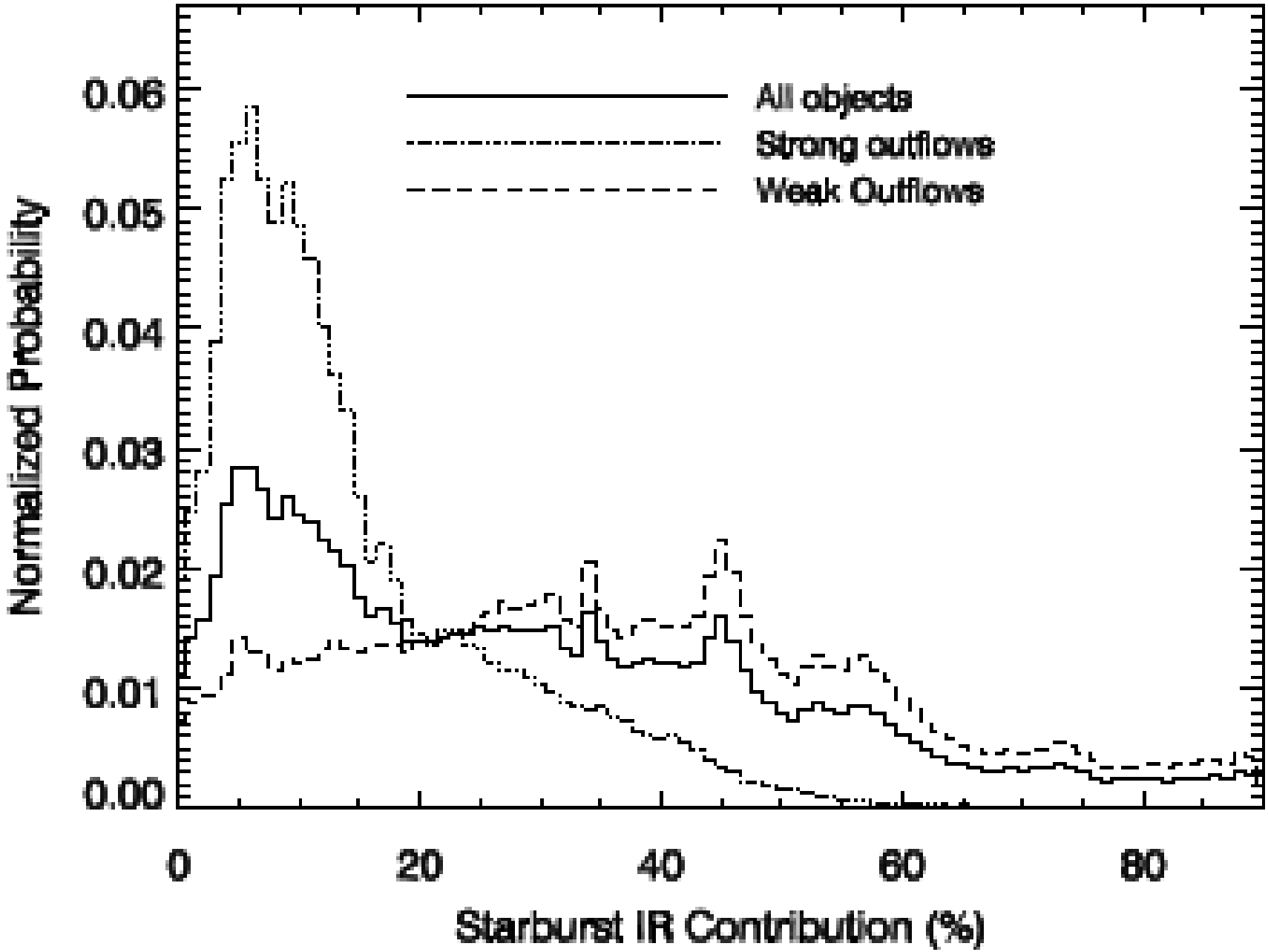
FEEDBACK BY AGN

AGN are observed to quench star formation….

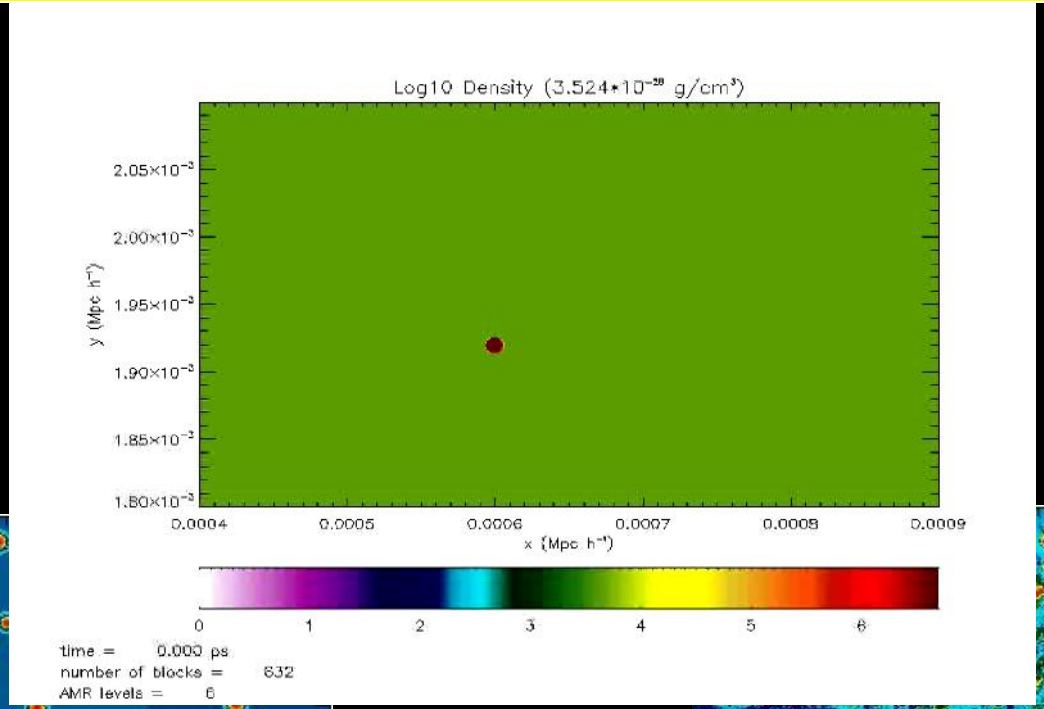


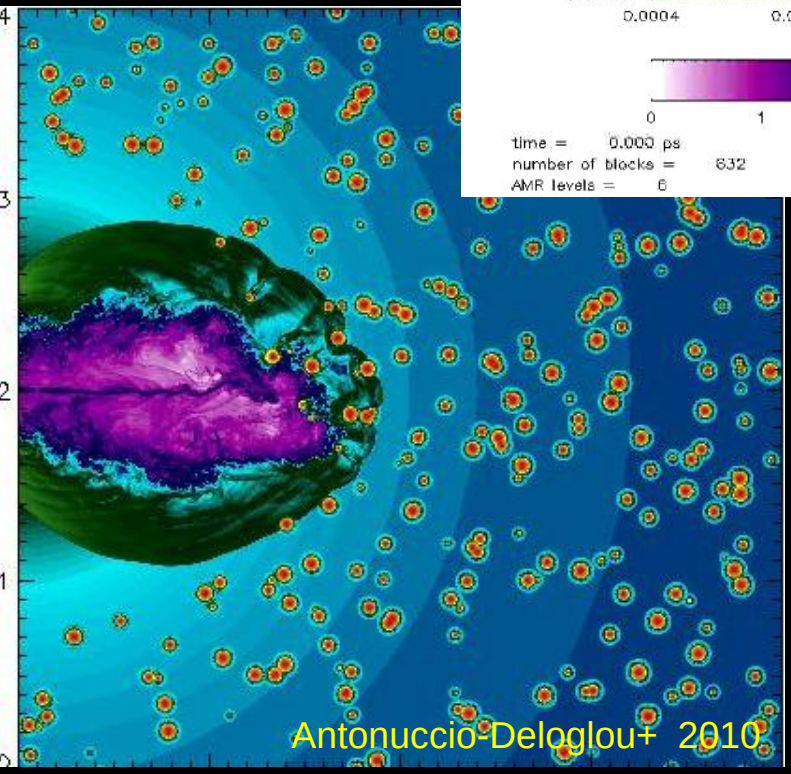
Farrah et al 2012

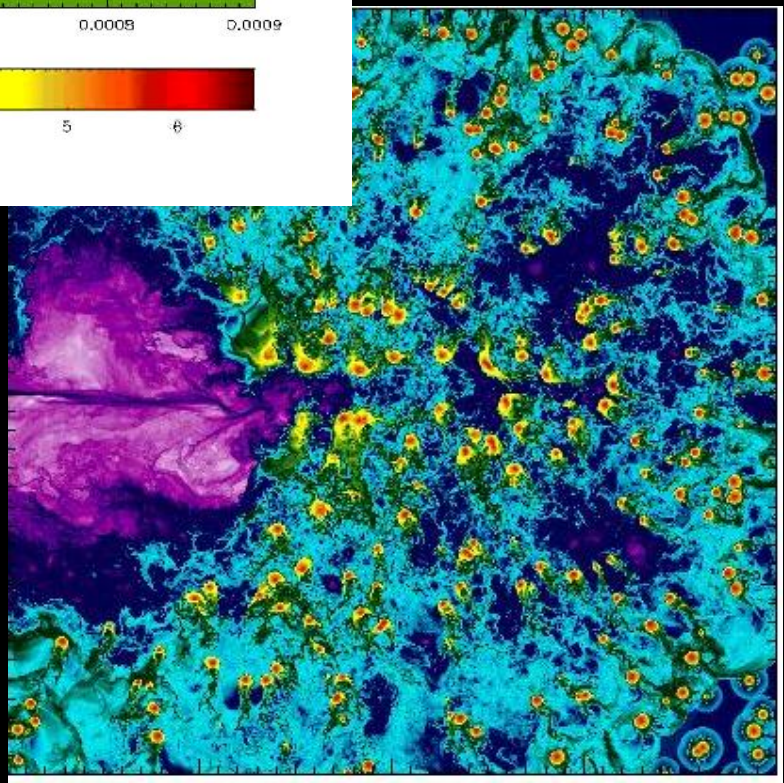
AGN-driven ouflows anticorrelate with obscured star formation



star formation rate is quenched by AGN

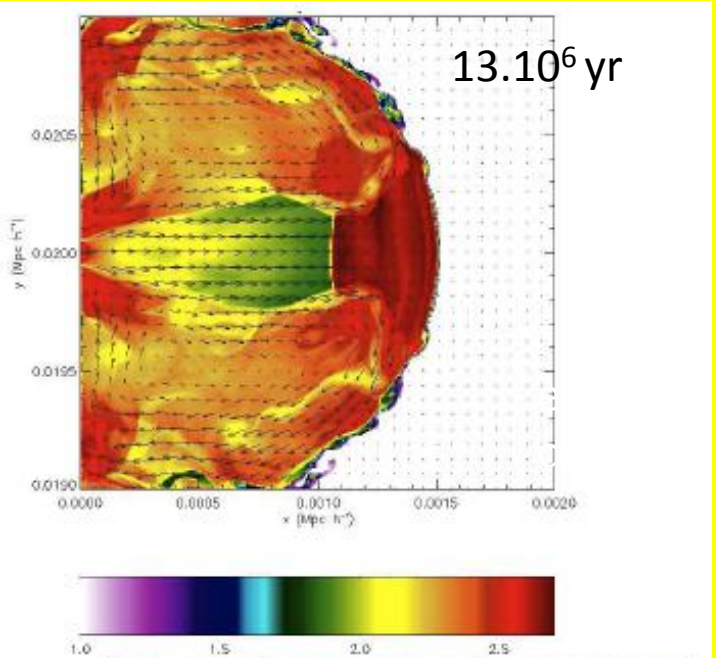


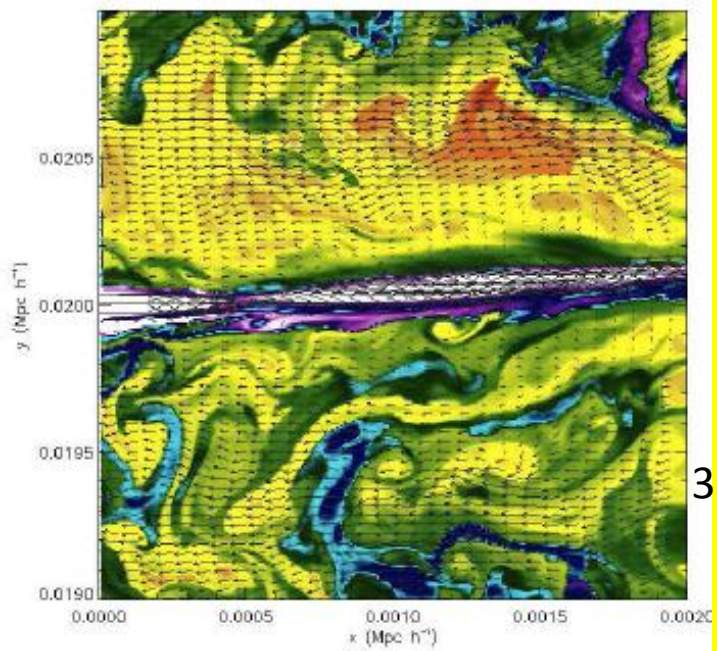




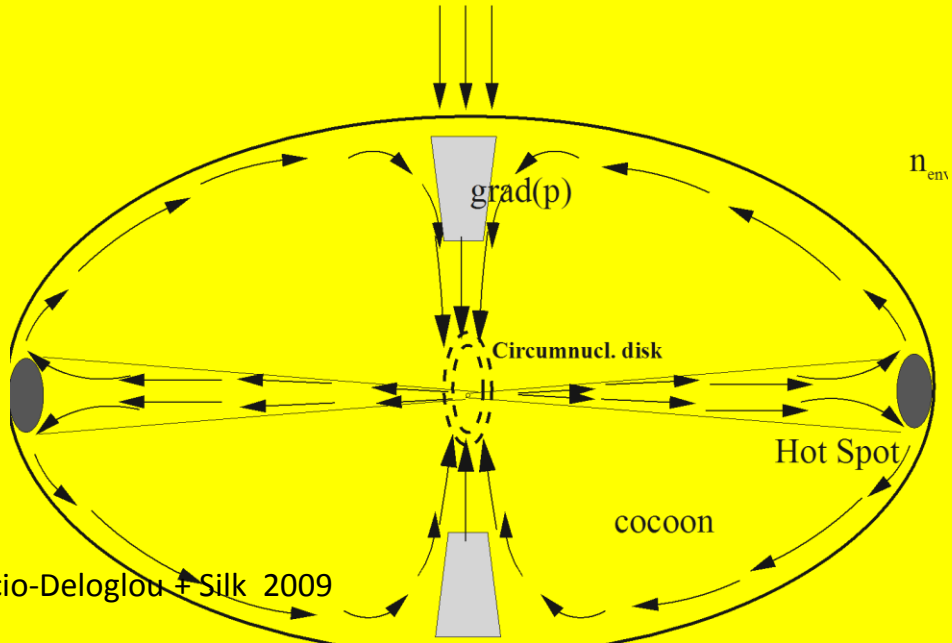
Antonuccio-Deloglou+ 2010

AGN jet-induced backflow feeds the SMBH





30.10^6 yr

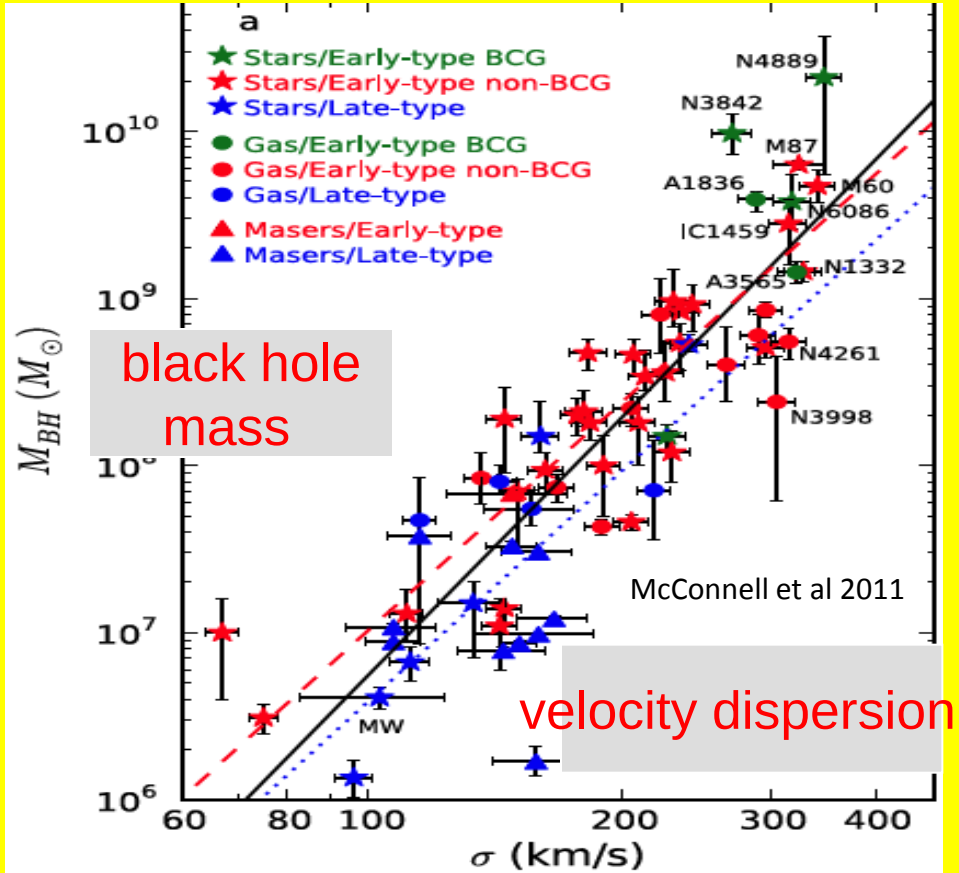


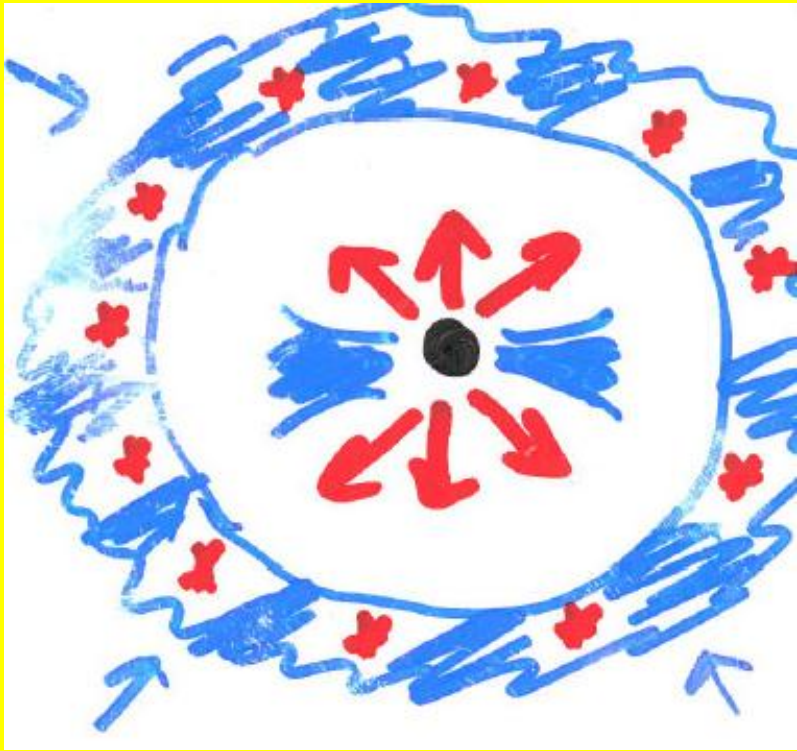
Antonuccio-Deloglou + Silk 2009

Feedback by massive black holes

$$L_{Edd}/c = GMM_{gas}/r^2$$

$$M_{\bullet} = 3 \times 10^9 \, Msun \left(\frac{s}{300 \, \frac{km}{s}} \right)^4$$



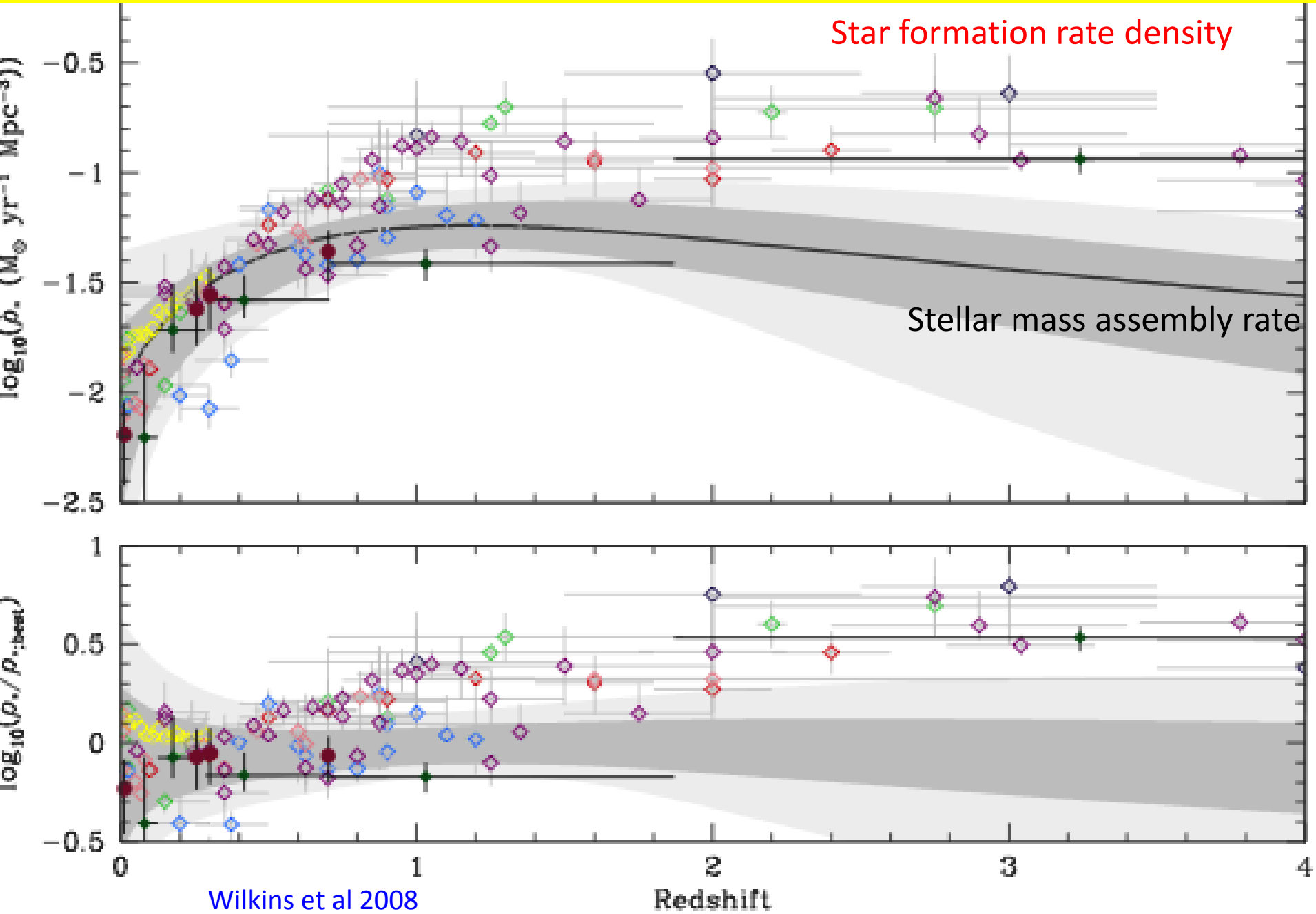


Blowout occurs/star formation terminates when SMBH- S relation saturates

$$L_{Edd} = 4\pi c G M_{BH} m_p / \sigma_T$$

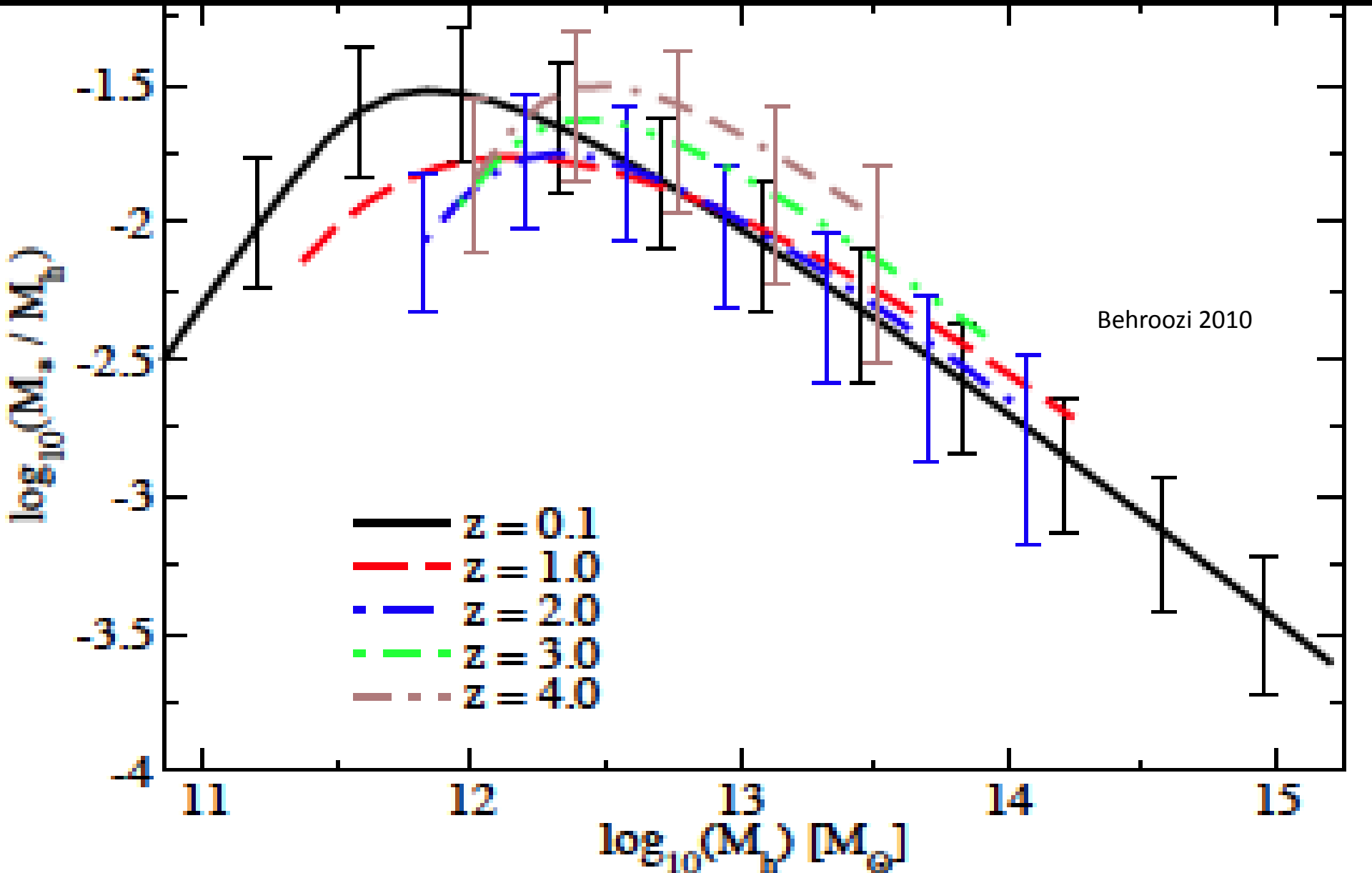
BH GROWTH AND STAR FORMATION

star formation rate density vs. mass assembly rate

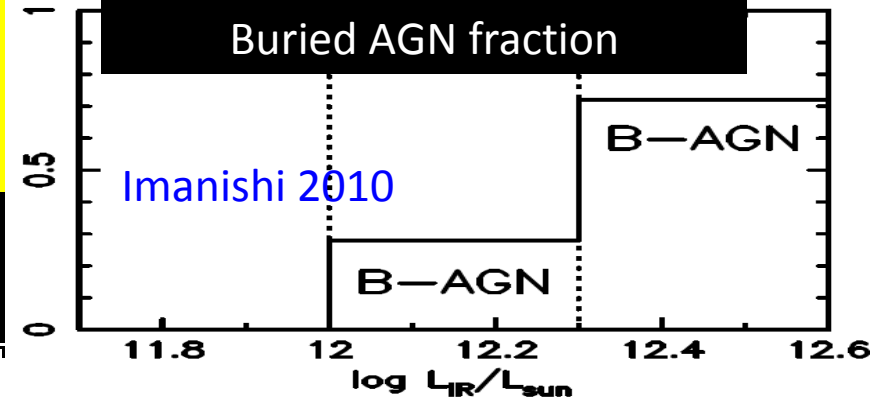


Wilkins et al 2008

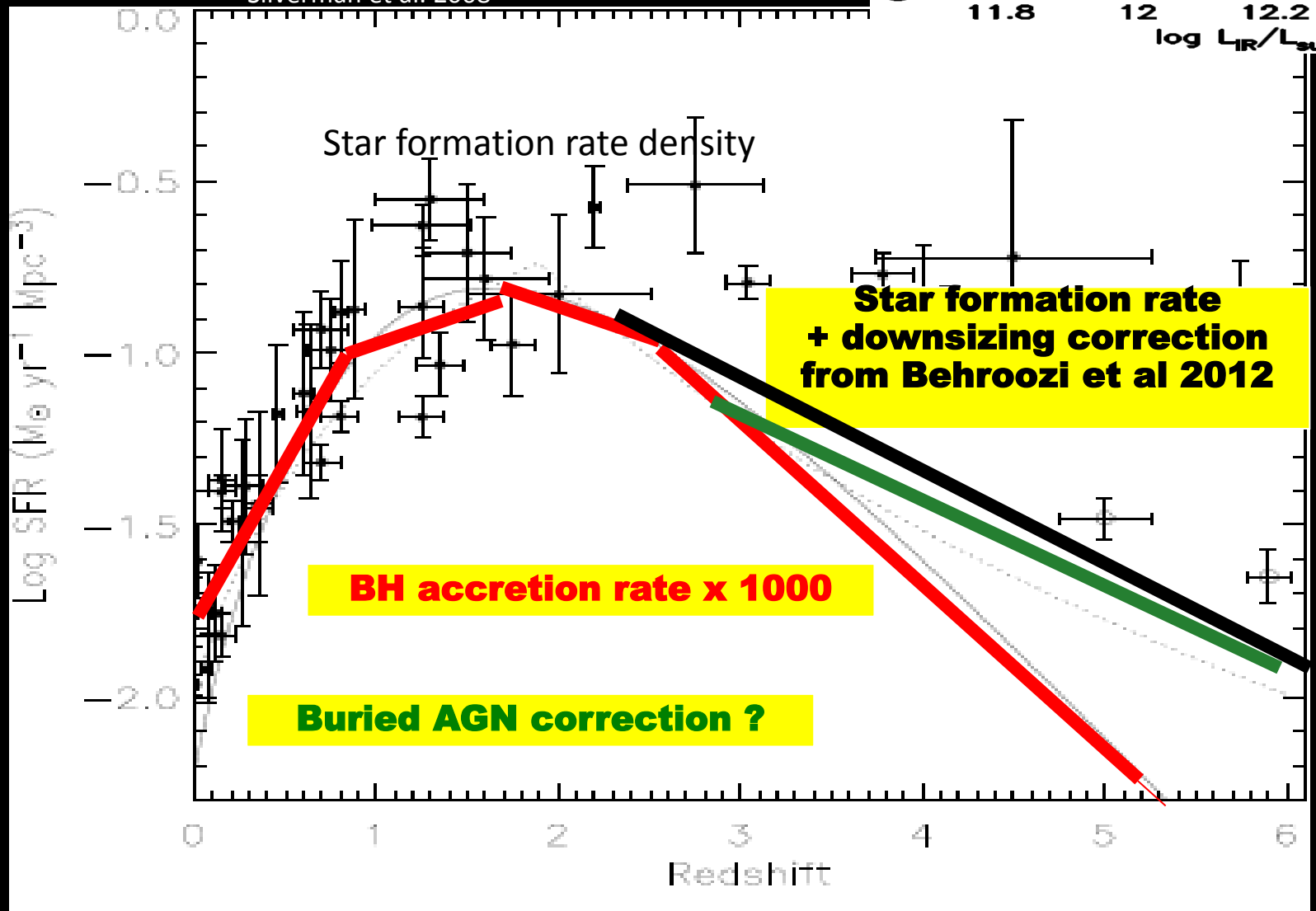
DOWNSIZING via galaxy stellar mass fraction (centrals) efficiency via abundance matching to z=4



Black hole accretion rate

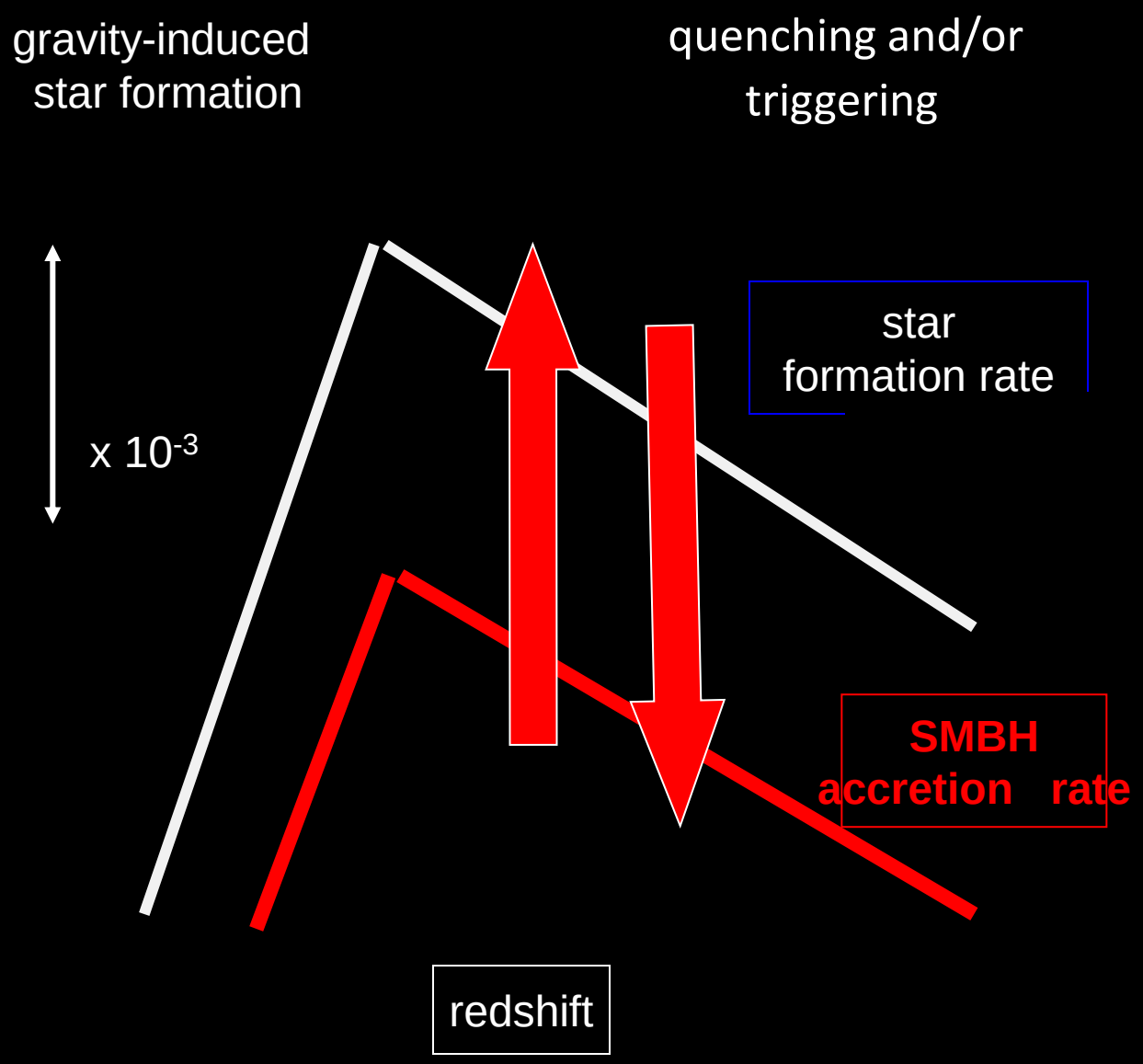


Silverman et al. 2008

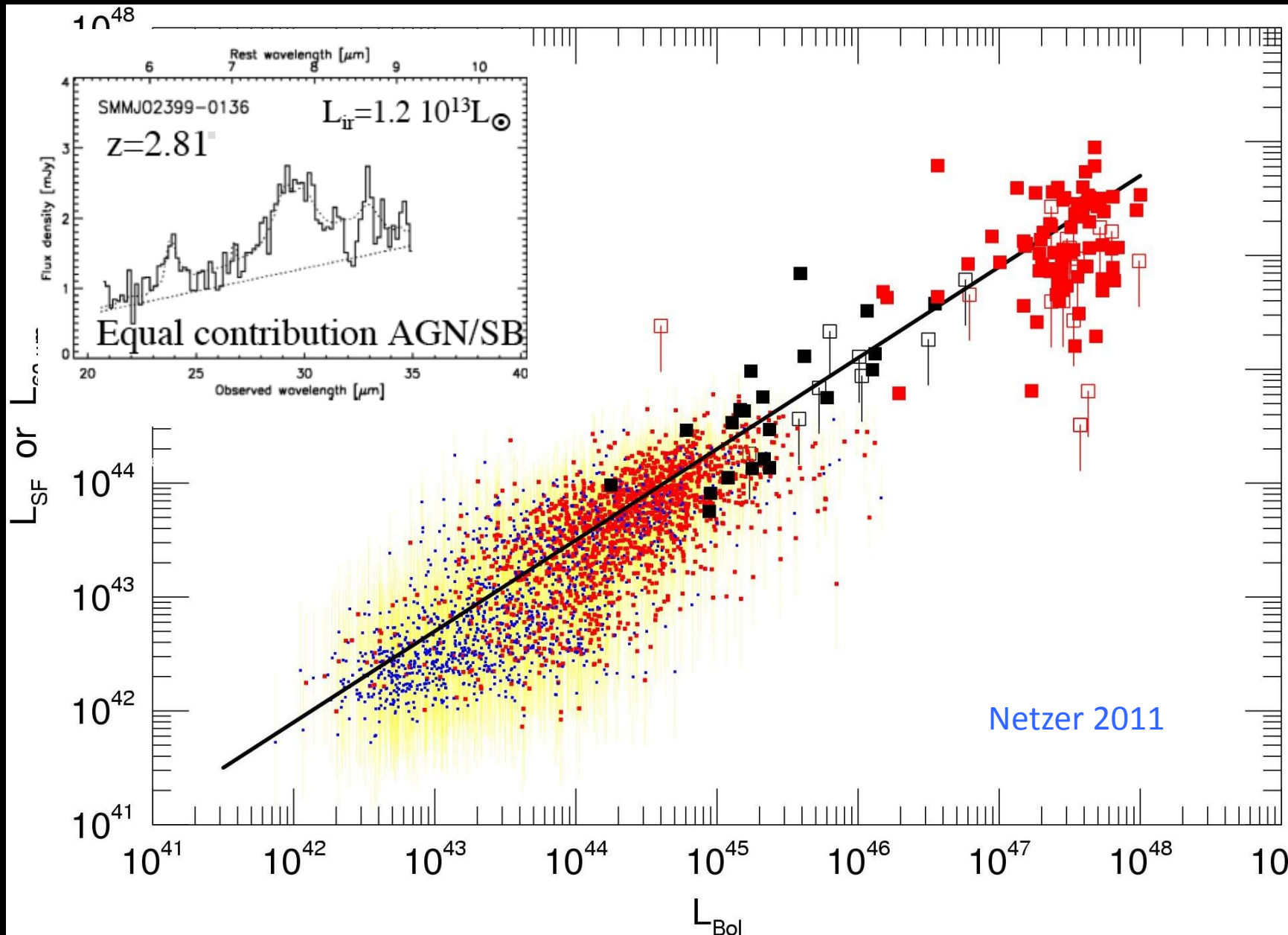


Active galactic nuclei:

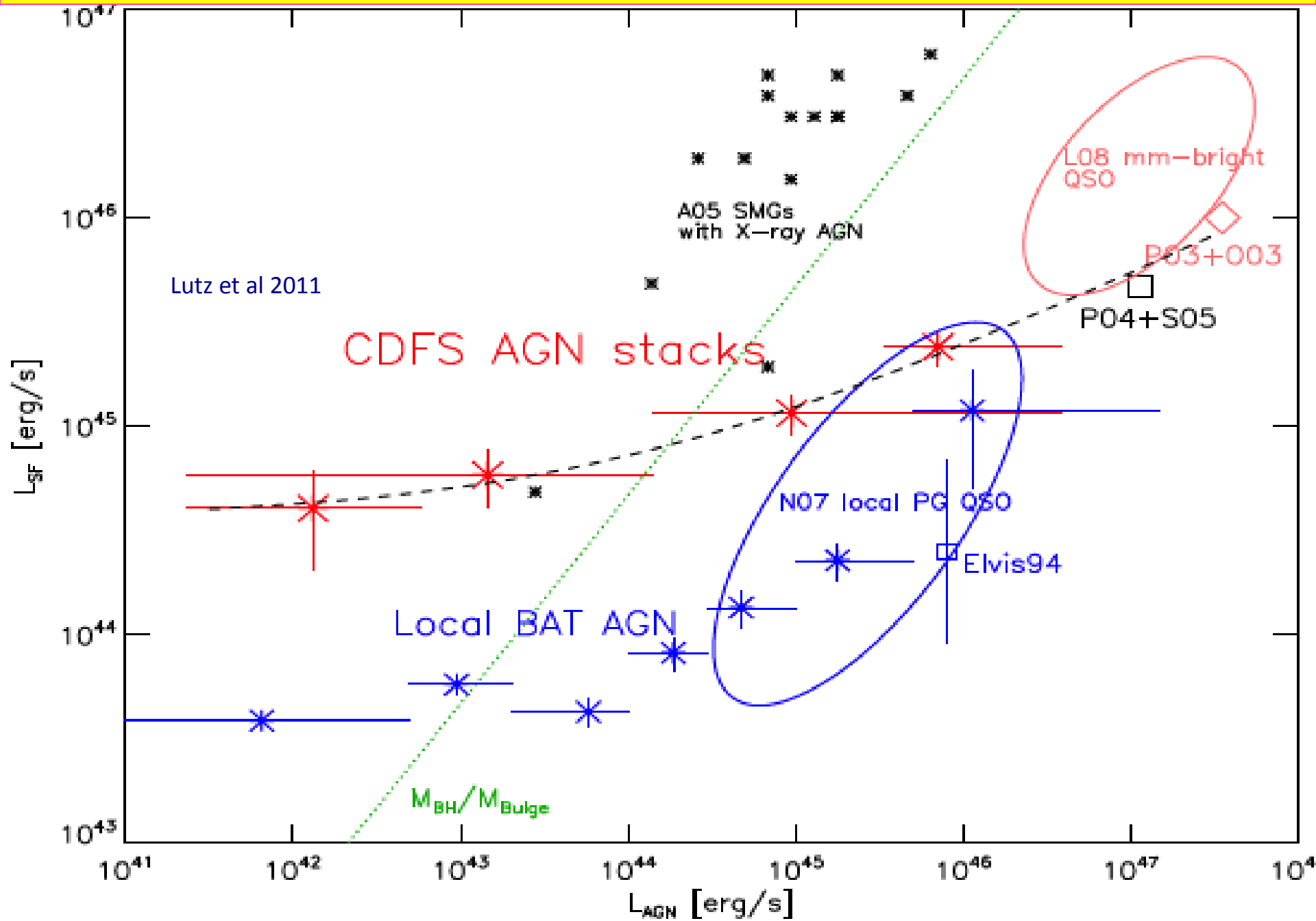
aftermath or precursor to star formation?



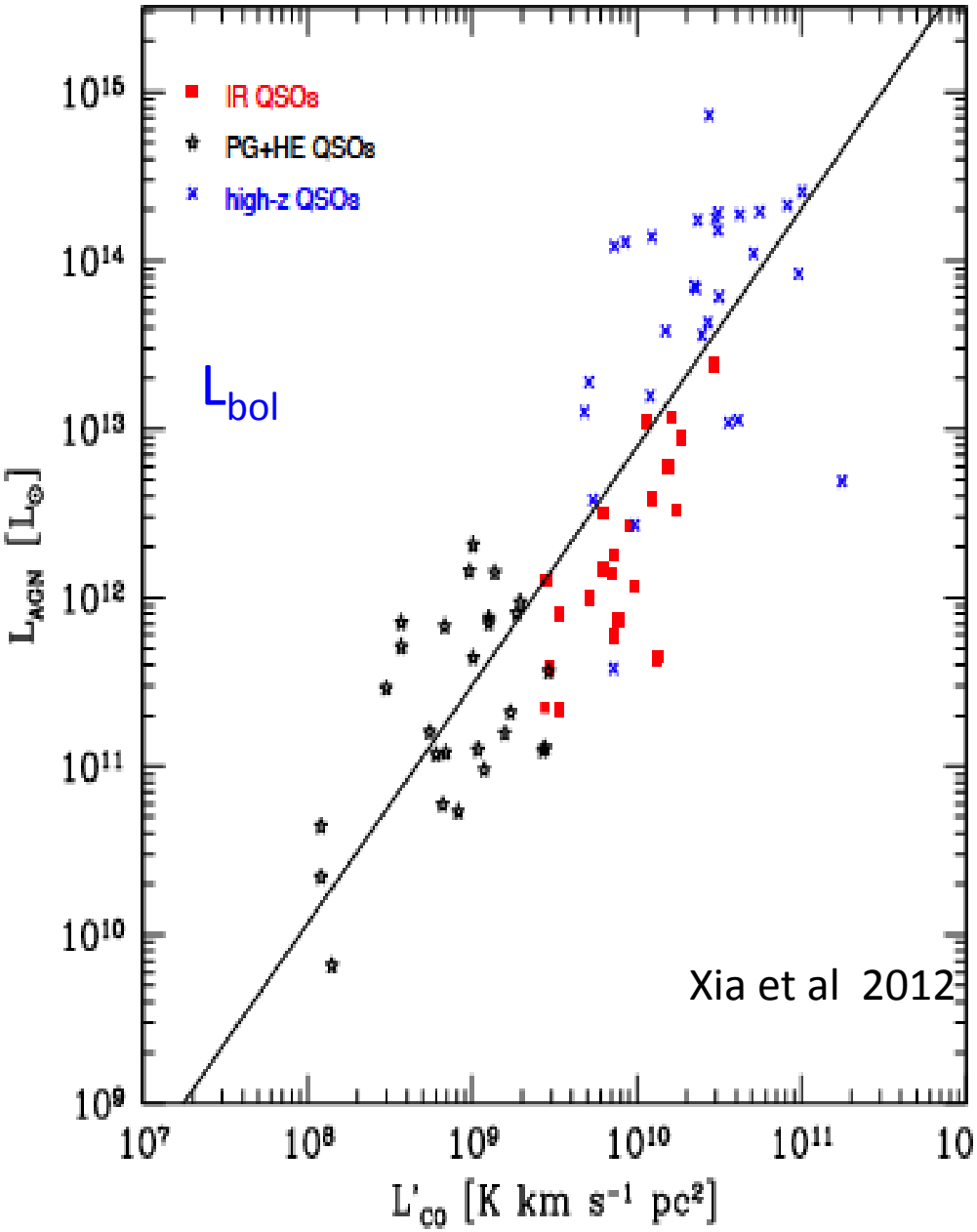
connection between AGN and starbursts

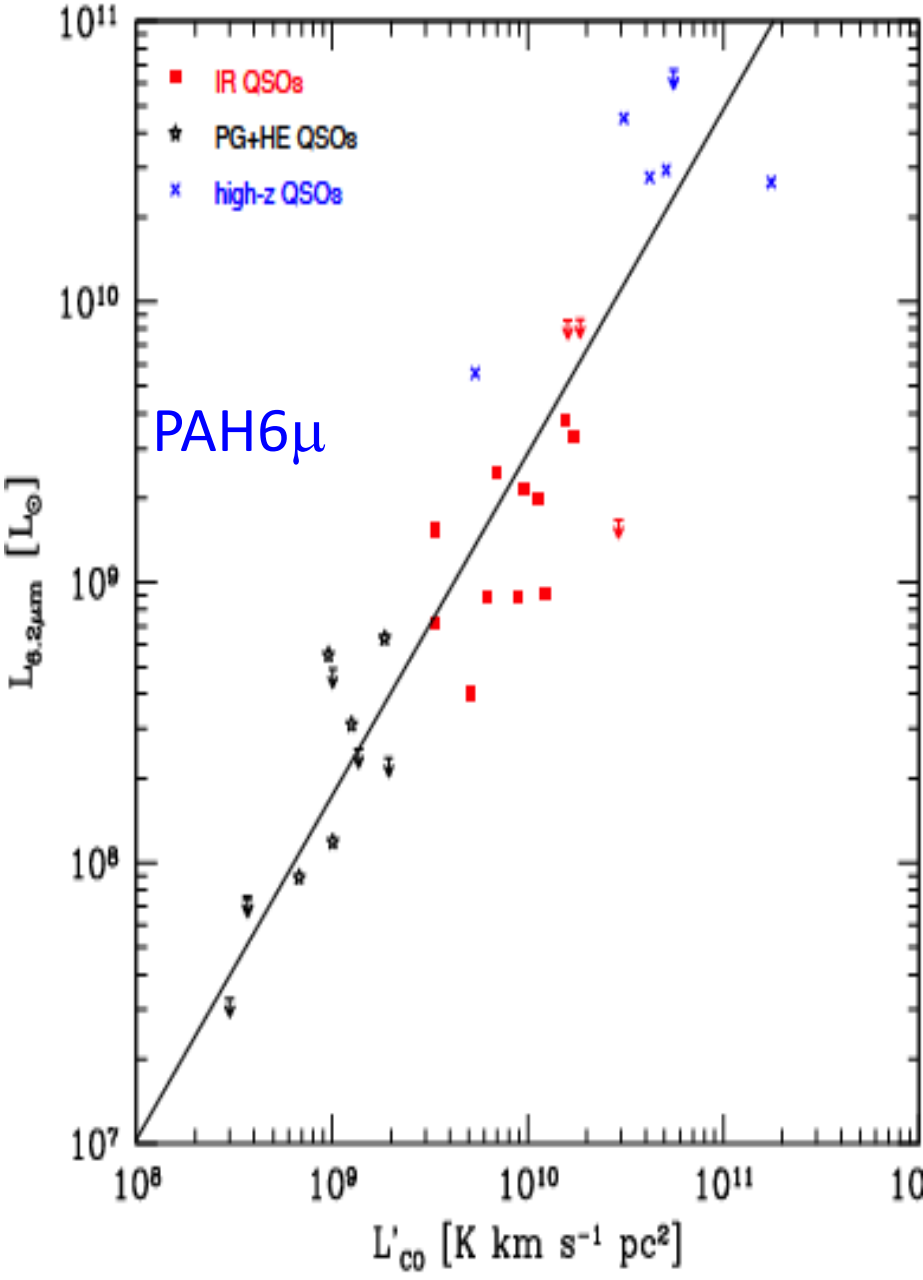


Luminous AGN correlate with star formation

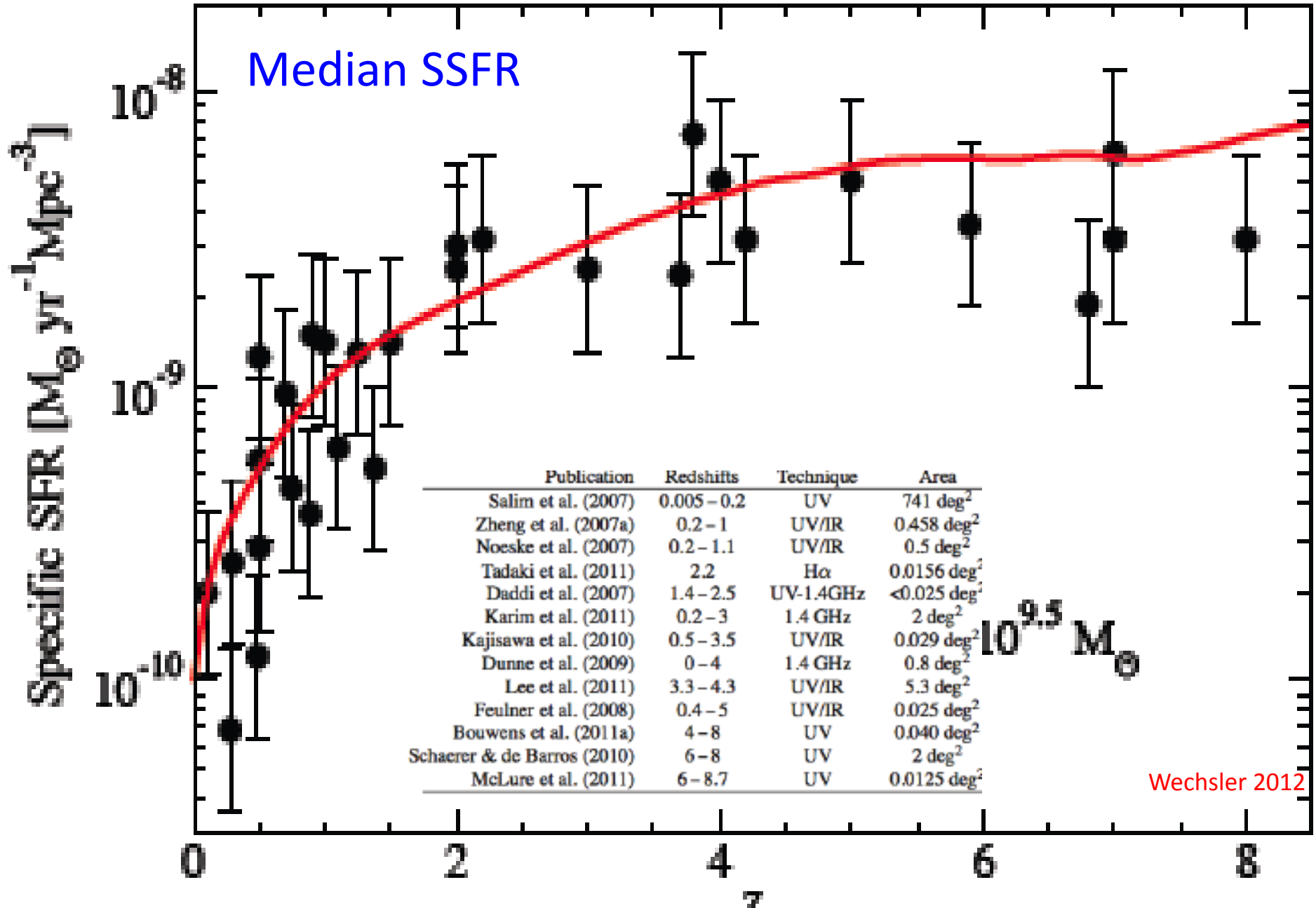


Common feeding of SMBH & SF by CO reservoir

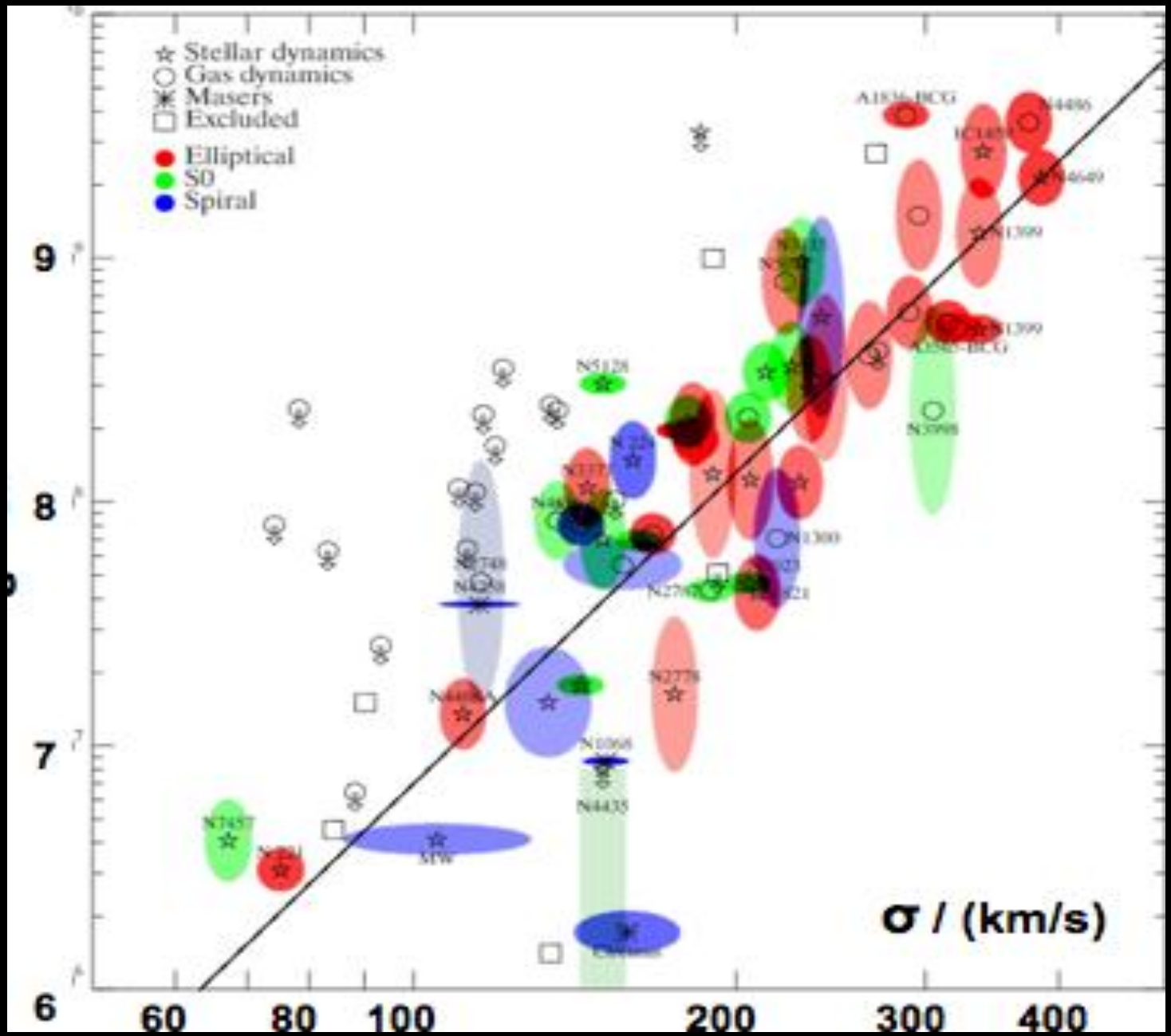




Specific star formation rate SFR/M_{star}

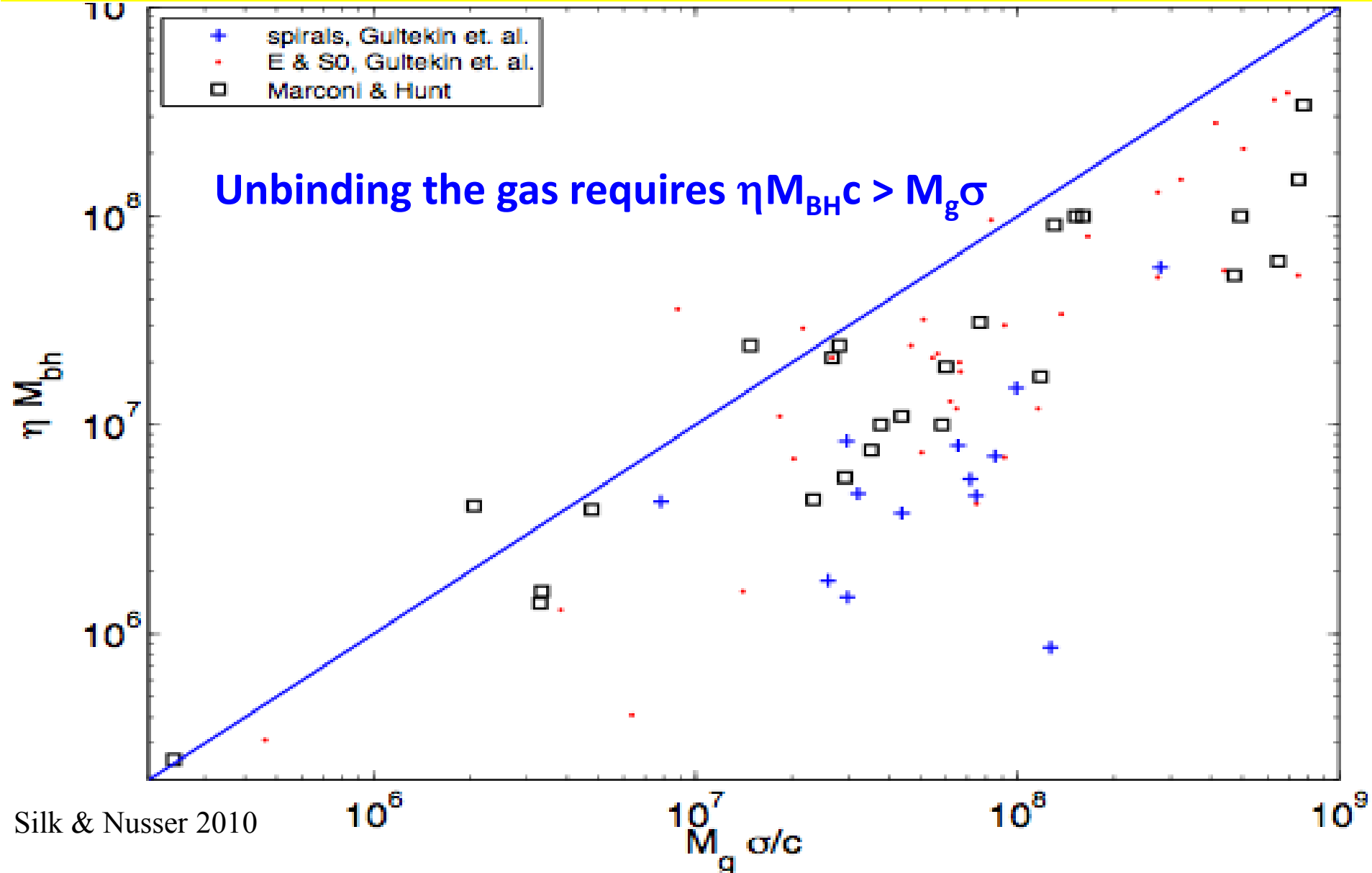


Publication	Redshifts	Technique	Area
Salim et al. (2007)	0.005 – 0.2	UV	741 deg^2
Zheng et al. (2007a)	0.2 – 1	UV/IR	0.458 deg^2
Noeske et al. (2007)	0.2 – 1.1	UV/IR	0.5 deg^2
Tadaki et al. (2011)	2.2	Hα	0.0156 deg^2
Daddi et al. (2007)	1.4 – 2.5	UV-1.4GHz	<0.025 deg^2
Karim et al. (2011)	0.2 – 3	1.4 GHz	2 deg^2
Kajisawa et al. (2010)	0.5 – 3.5	UV/IR	0.029 deg^2
Dunne et al. (2009)	0 – 4	1.4 GHz	0.8 deg^2
Lee et al. (2011)	3.3 – 4.3	UV/IR	5.3 deg^2
Feulner et al. (2008)	0.4 – 5	UV/IR	0.025 deg^2
Bouwens et al. (2011a)	4 – 8	UV	0.040 deg^2
Schaerer & de Barros (2010)	6 – 8	UV	2 deg^2
McLure et al. (2011)	6 – 8.7	UV	0.0125 deg^2



Gultekin 2009

momentum-driven AGN winds alone cannot explain the M_{BH}-σ relation



Silk & Nusser 2010

FEEDBACK PROBLEMS IN MASSIVE GALAXIES

1) Its not supernovae

2) Its not AGN momentum

3) maybe its both!
AGN triggering of star formation

star formation may be triggered by AGN

If AGN-driven outflows trigger star formation,

JS + C. Norman 2008

star formation rate boost factor ~ v_{cocoon}/σ ~10-100
+ outflow momentum amplified by supernovae

SFR = $\varepsilon M_{gas}/t_{ff}$

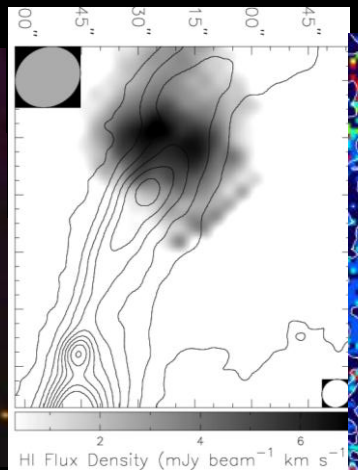
$(p_{AGN}/p_g)^{1/2} \approx v_{jet}/\sigma$

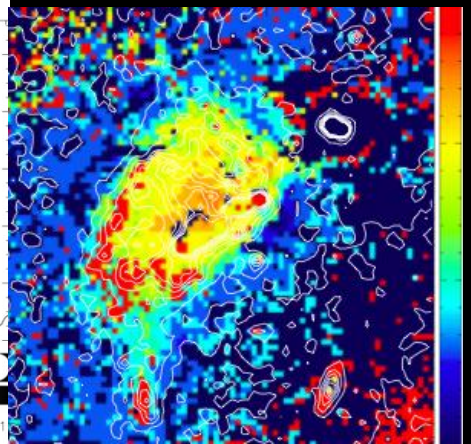
$\varepsilon_{SN} = \sigma \; v_{cool} \; m_{*,SN} / E_{SN}$

$\dot{M}_* = (\epsilon_{SN}/\sigma) M_g (G p_g)^{1/2}$

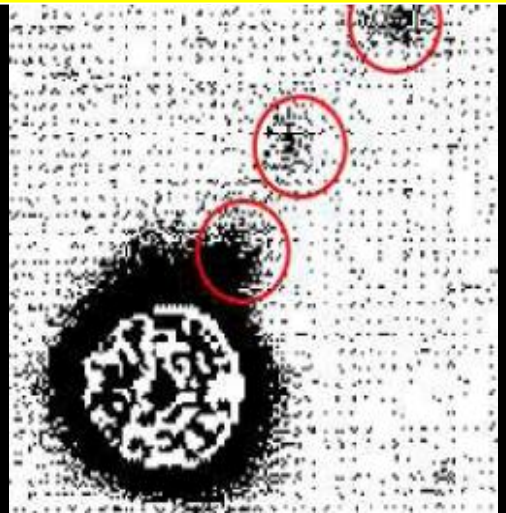
Klamer et al. 2006
z = 4.7 quasar + CO

Minkowski's object
Croft et al. 2006

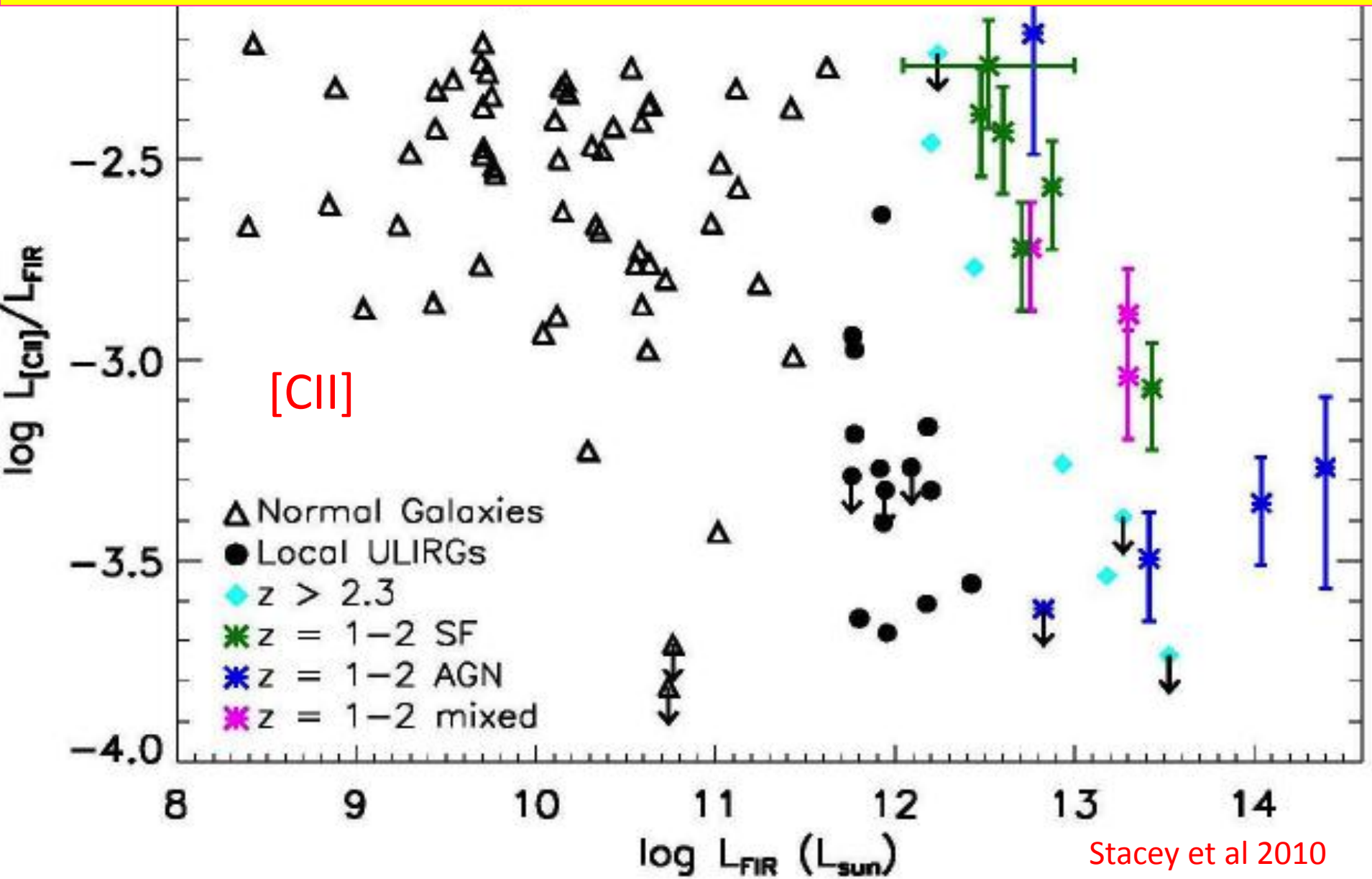




H_2 formation triggered by AGN

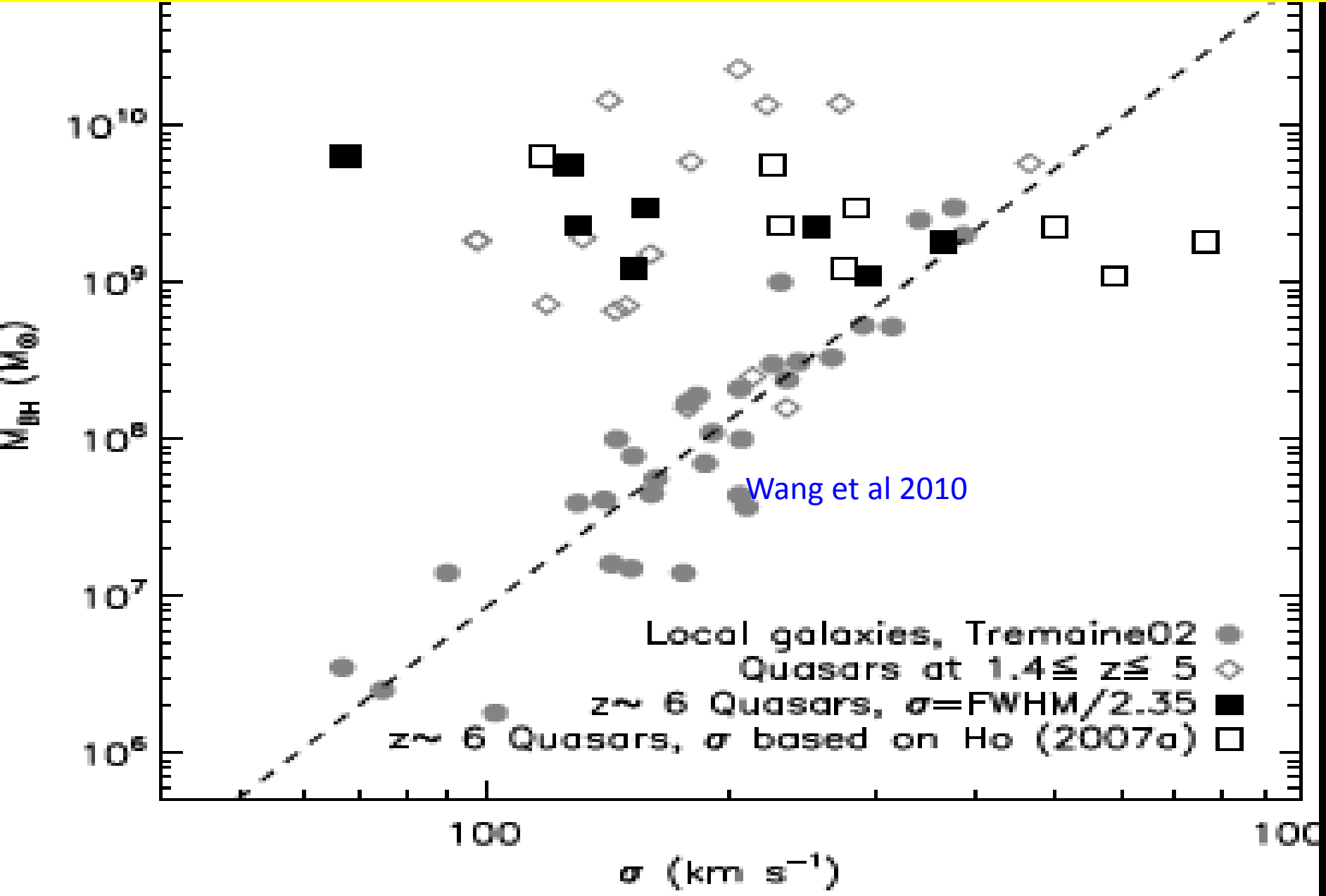


Intense central UV in PDR [CII]/FIR associated with extreme starburst

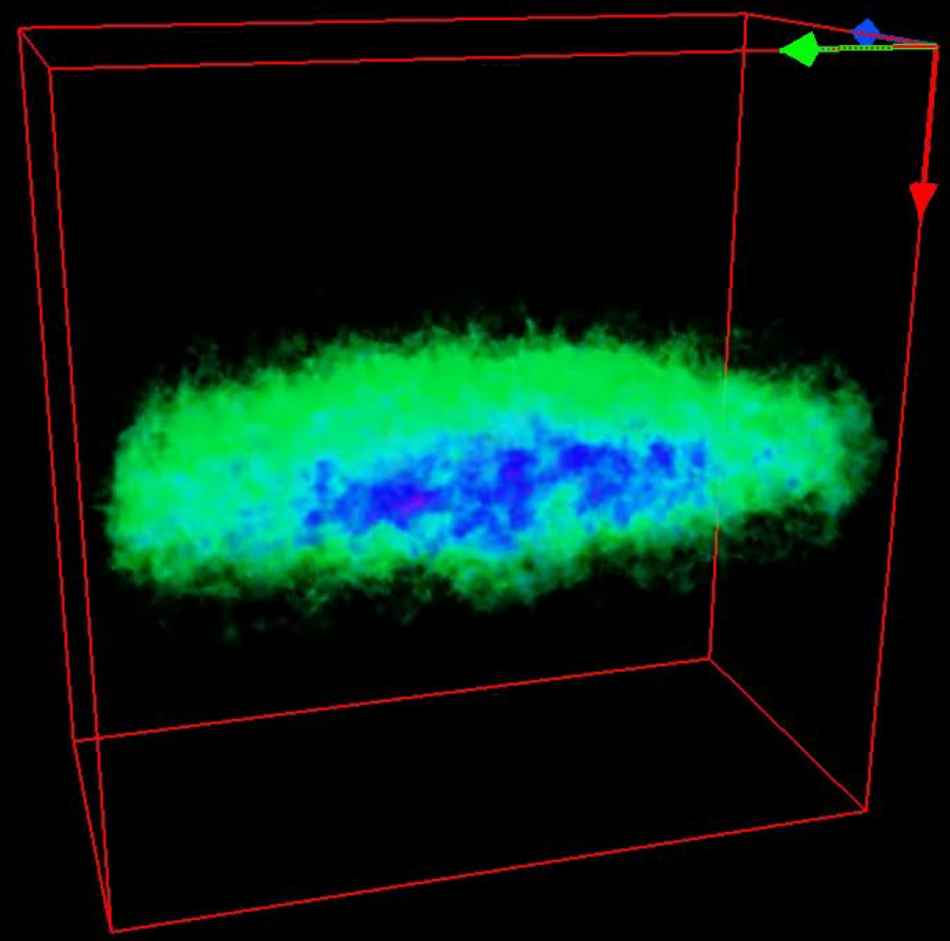


Stacey et al 2010

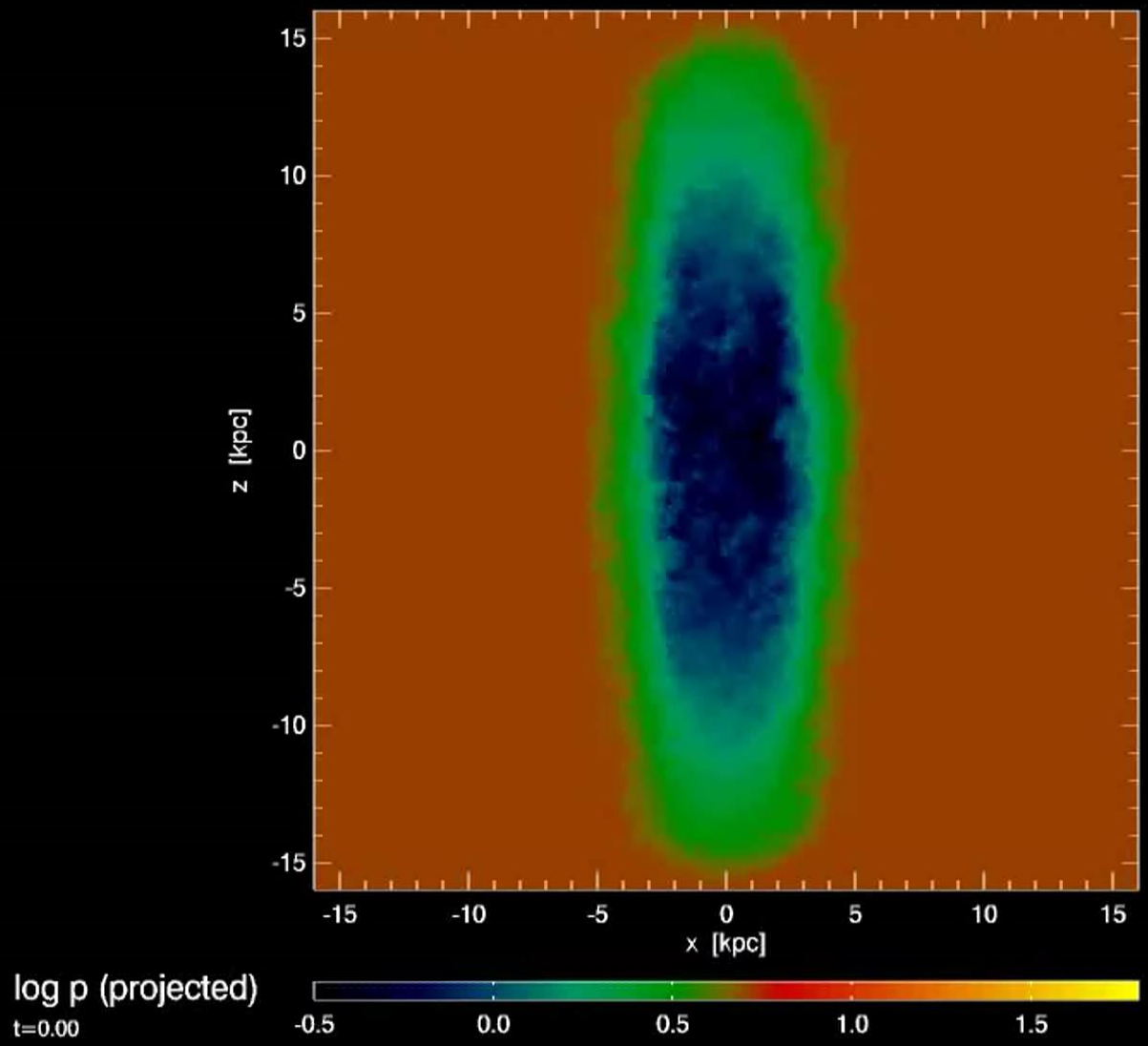
SMBH in z ~ 6 quasars lie high



3-d N-body + hydro: RAMSES code (simulations by V. Gaibler, S. Khochfar, M. Krause, JS 2011)
100 pc resolution, 10 cm^{-3} SF threshold



pressure


15
10
5
0
-5
-10
-15
z [kpc]
-15
-10
-5
0
5
10
15
x [kpc]
log p (projected)
t=0.00
-0.5
0.0
0.5
1.0
1.5

stars

t = 0.0 Myr

5 kpc

UNSOLVED FEEDBACK PROBLEMS IN GALAXY FORMATION

How do we form bulgeless (> 15%) galaxies ?

How are baryons lost from galaxies ?

Are there two modes of star formation ?

Why downsizing in Z, M*, SSFR, M_{BH} ?

How are SMBH formed at early epochs ?

How are stars formed in extreme environments ?