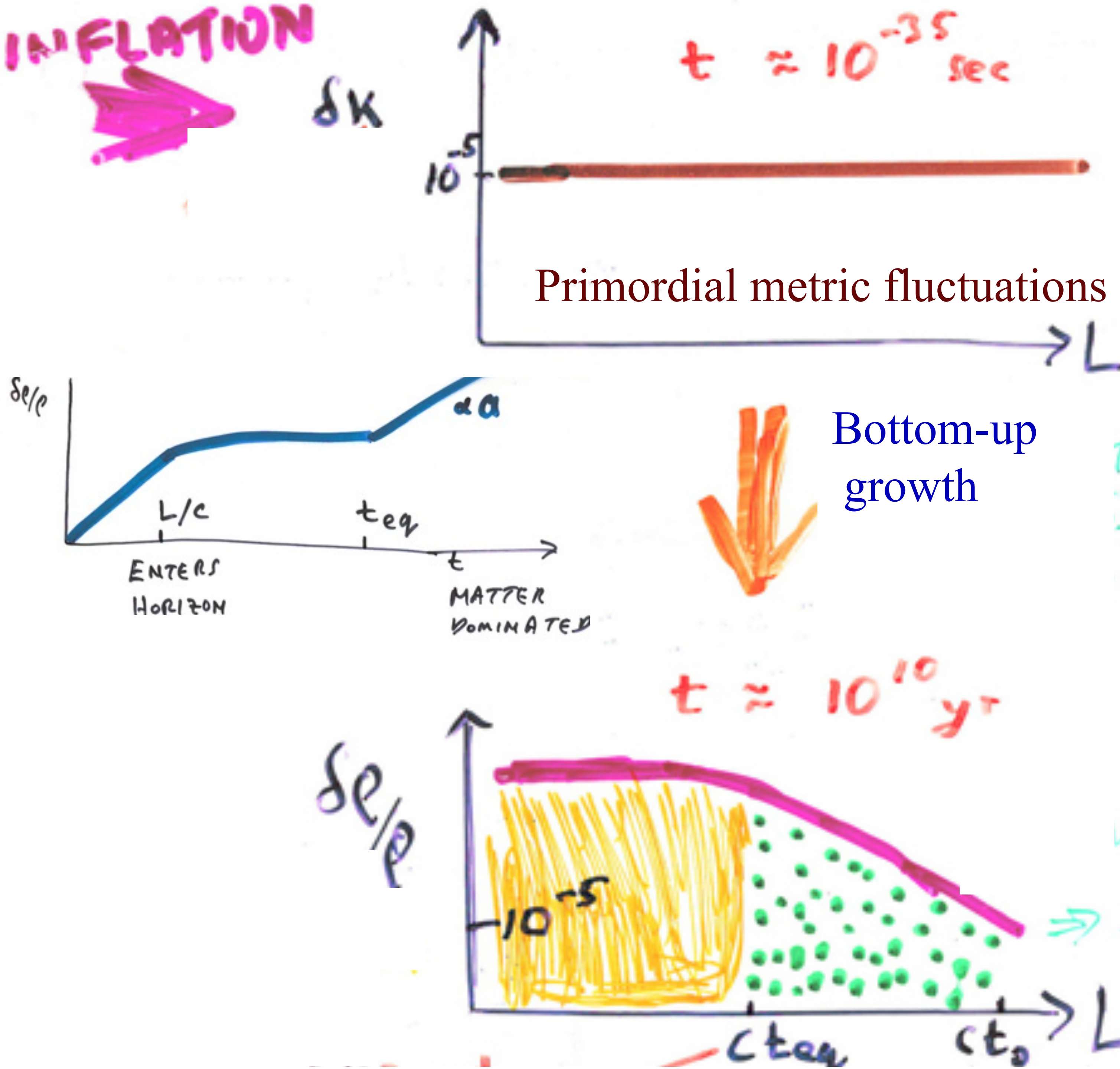
THE CHALLENGE OF GALAXY FORMATION

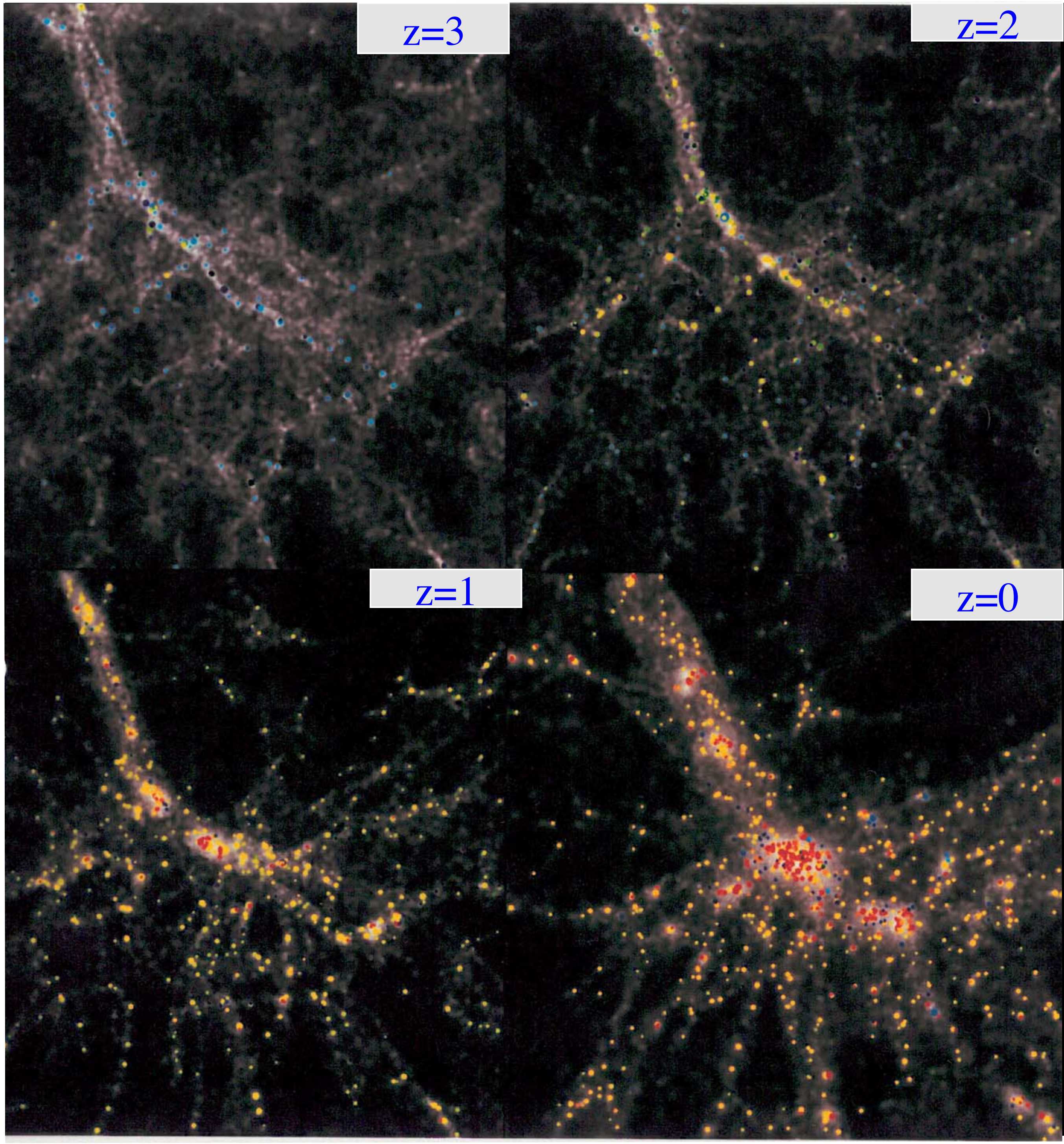
Joe Silk, Oxford
August, 2010

1. Structure formation
2. Disk galaxy formation
3. Spheroidal galaxy formation
4. Star formation

1. Structure formation

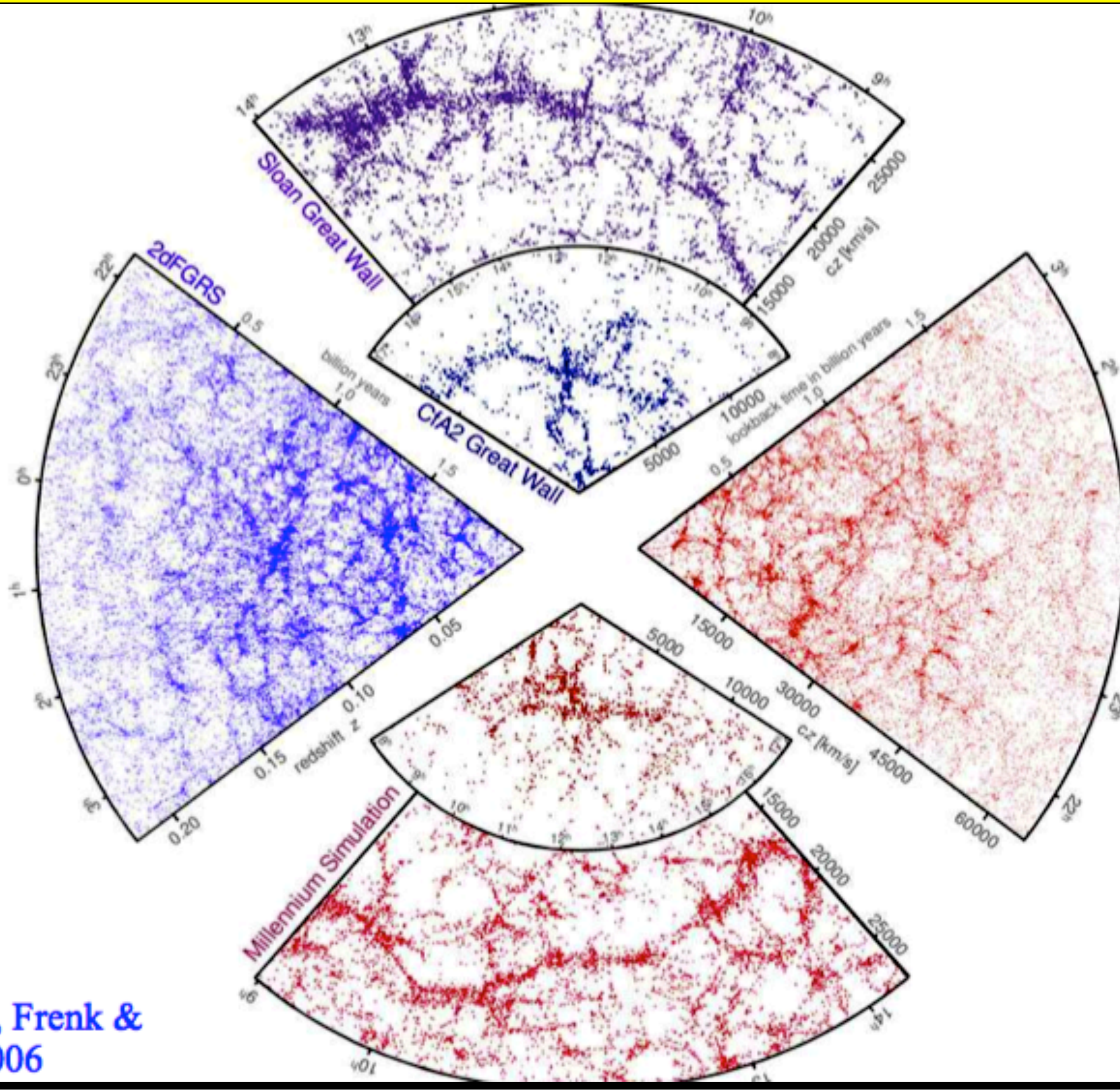

INFLATION
δK
t ≈ 10^-35 sec
10^-5
Primordial metric fluctuations
L
δρ/ρ
∝ a
L/c
t eq
t
ENTERS HORIZON
MATTER DOMINATED
Bottom-up growth
t ≈ 10^10 yr
δρ/ρ
10^-5
ct eq
ct 0
L

[redacted]



Galaxies form early in rare peaks

Virtual universe   Observed universe



Springel, Frenk & White 2006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2. Disk galaxy formation

Some analytic estimates

Gas surface density

Star surface density

$$\Sigma_{SFR} = (SFE)\,\frac{\Sigma_{gas}}{t_{dyn}}$$

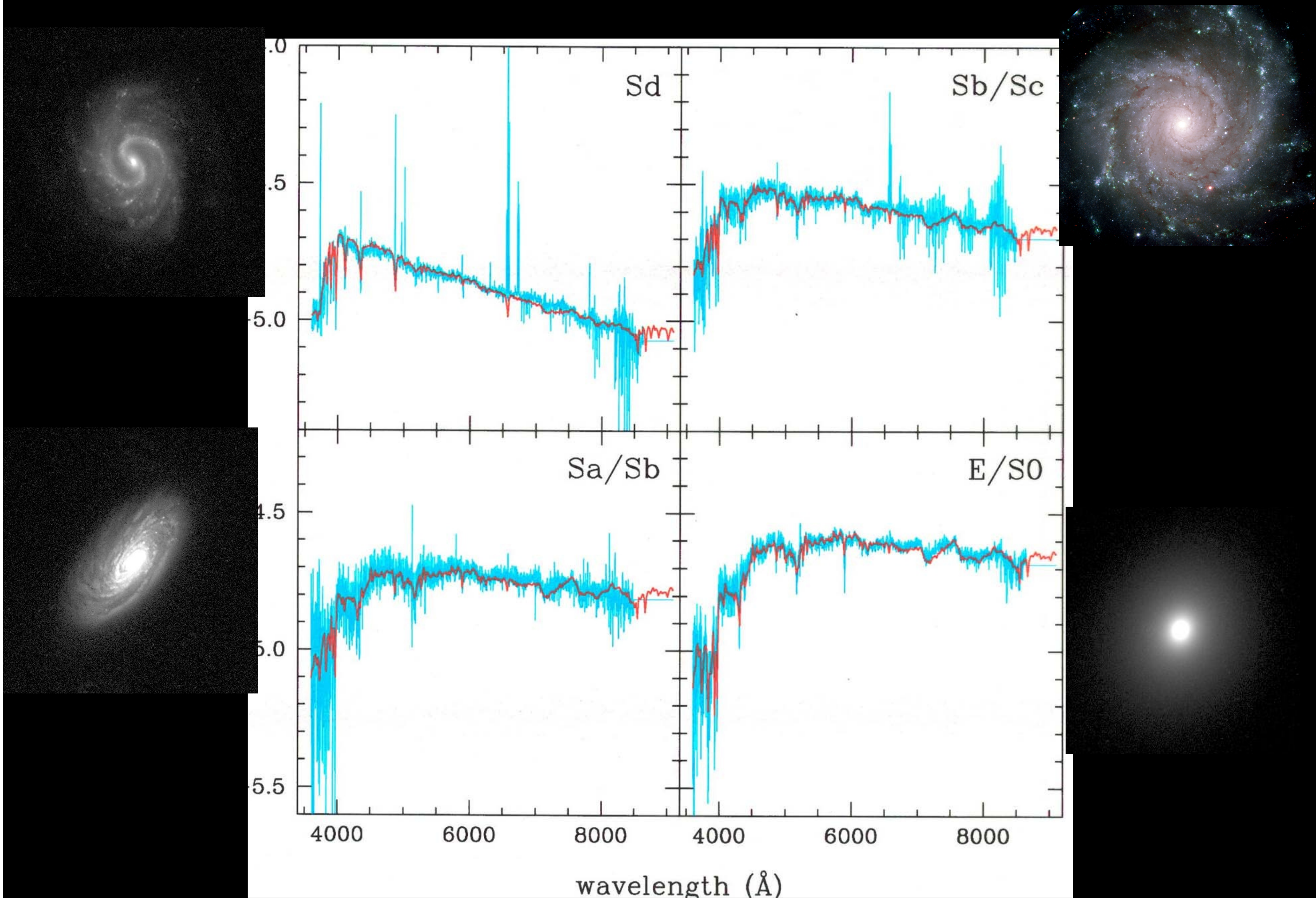
$$\propto \Sigma_{gas}\,\Omega$$

$$\underset{\sim}{\propto} \Sigma_{gas}^{3/2}$$

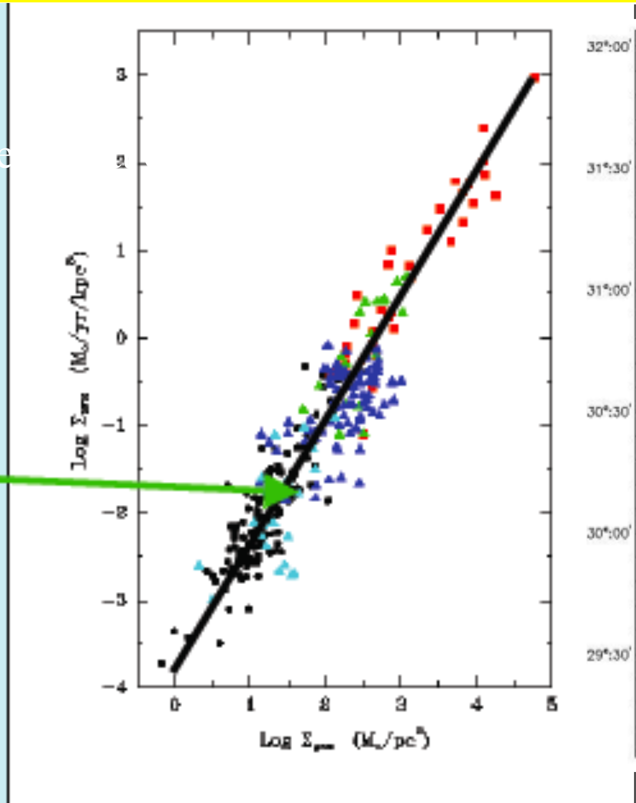
Star formation efficiency

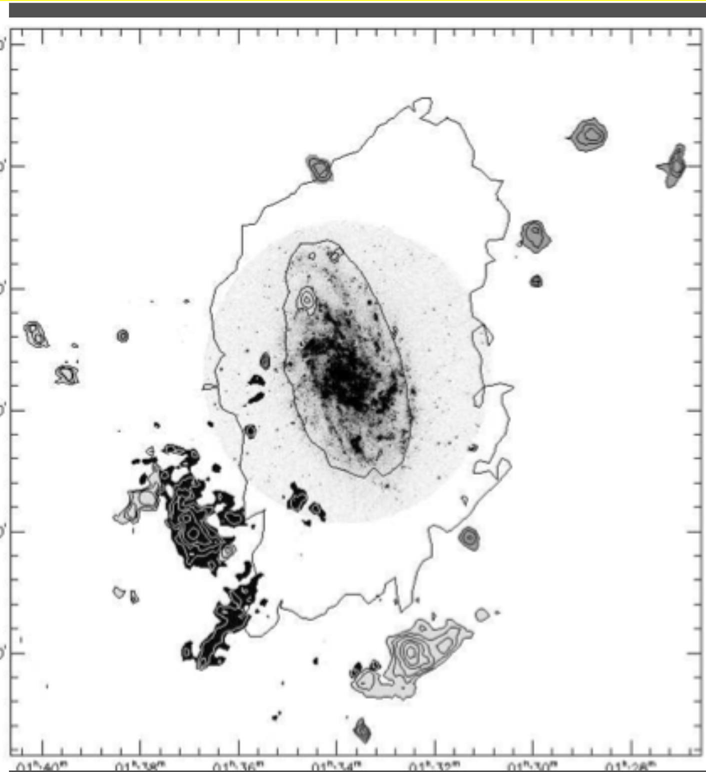
$$SFE = \frac{\sigma_{gas}\, v_{cool}\, m_{*,SN}}{E_{SN}^{initial}}$$

$$\approx 0.02$$


Sd
Sb/Sc
Sa/Sb
E/S0
4.5
5.0
5.5
4000
6000
8000
wavelength (Å)

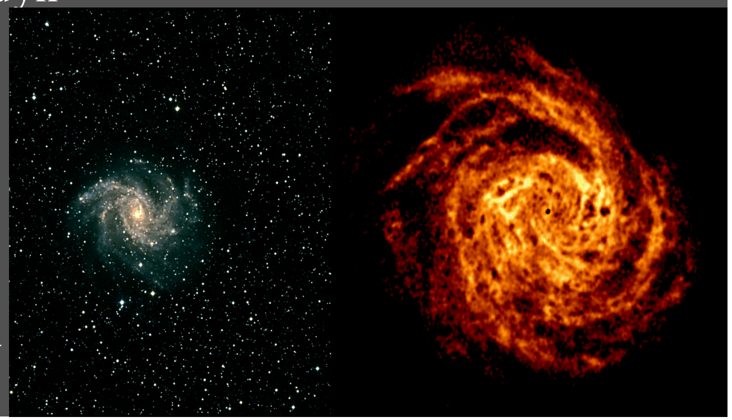
A GLOBAL STAR FORMATION LAW





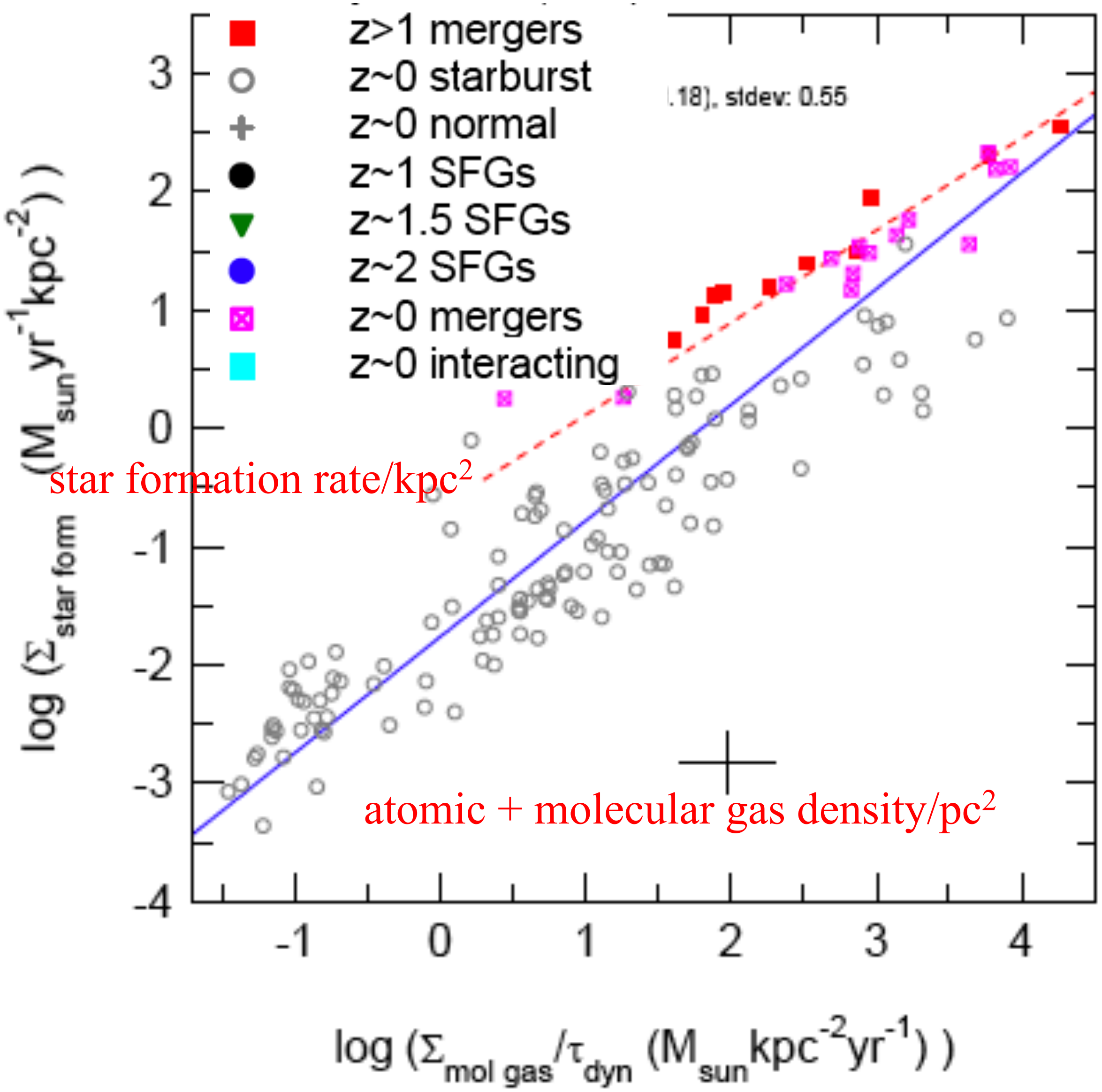
SFR=0.02 (GAS SURFACE DENSITY)/t_{dyn}

NGC 6946



fits disk galaxies (& M51 complexes)

low efficiency due to SN feedback
+ cold gas accretion/global disk instability



Star Formation efficiency

=SFR/GAS MASS x ROTATION TIME

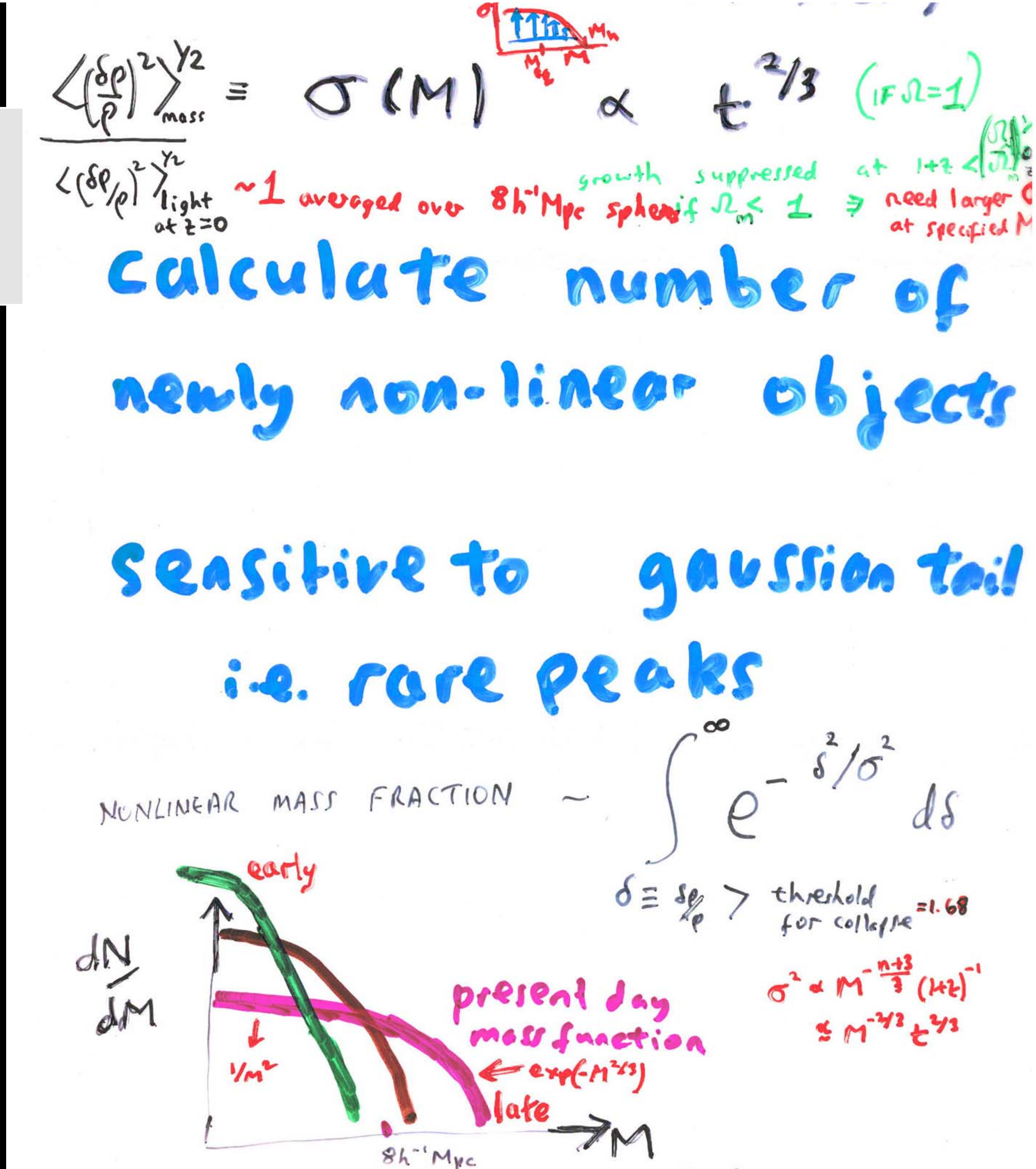
=2.5%

Genzel et al 2010

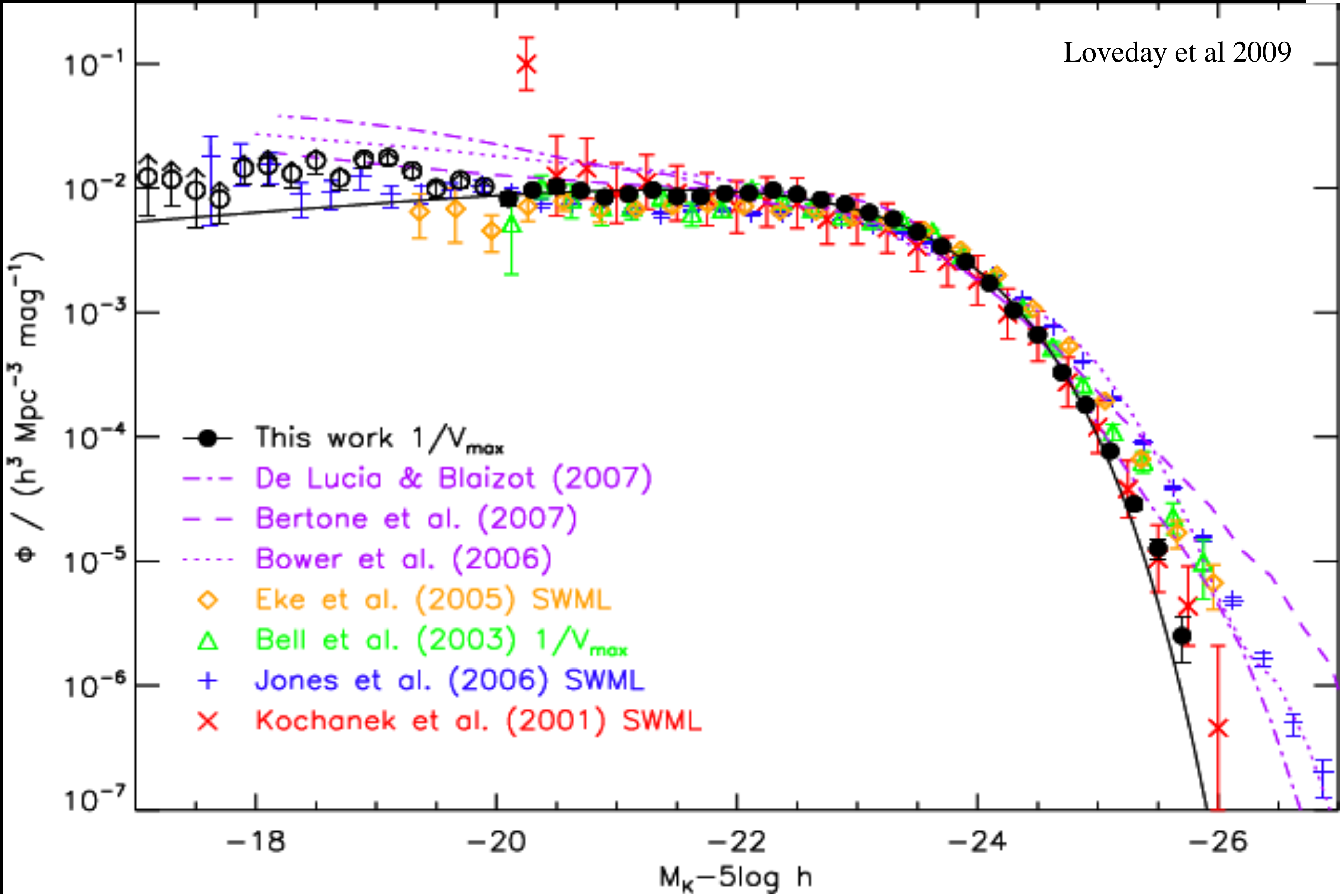
Molecular 'Elmegreen-Silk'-relation for mergers and SMGs. Symbols

Press-Schecter theory

(refined by Sheth & Tormen…)



Luminosity function of galaxies



FEEDBACK IS ESSENTIAL

Reionization

Supernovae

Tidal stripping

Active galactic nuclei

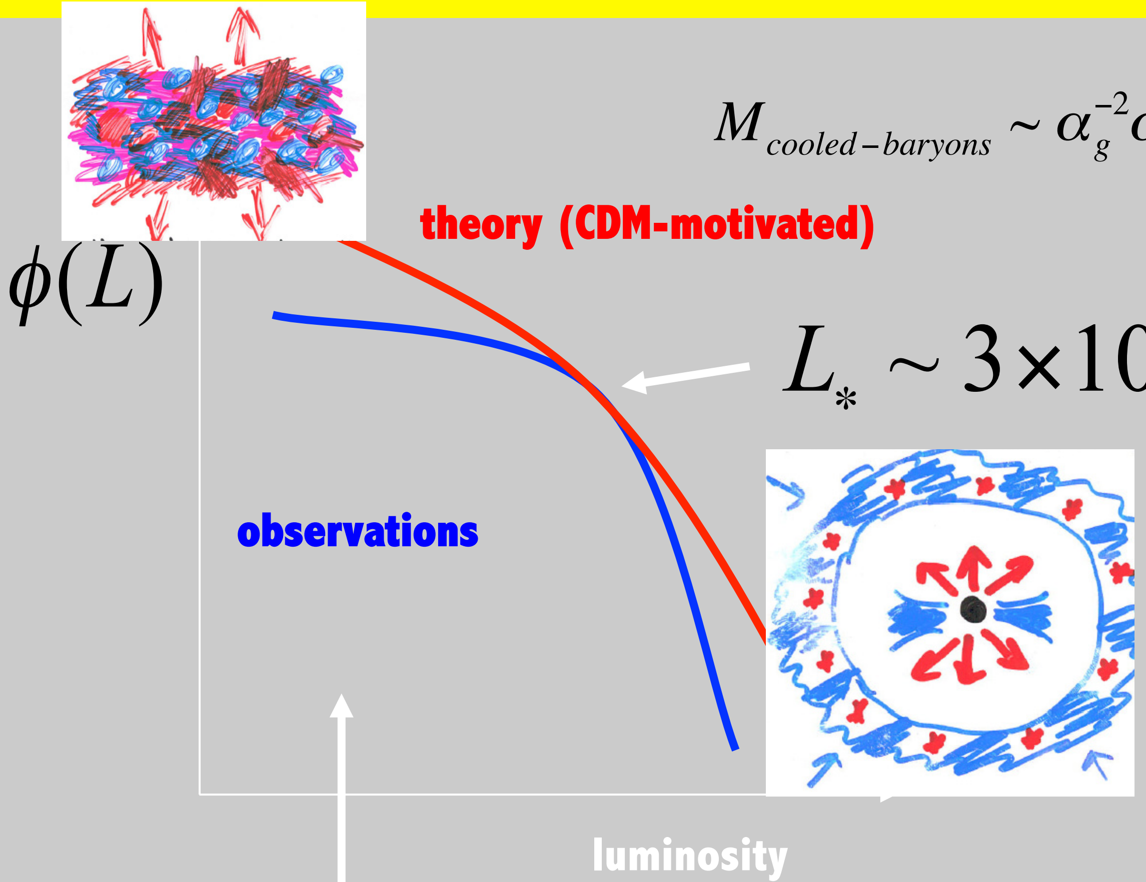
Feedback is needed

$$M_{cooled-baryons} \sim \alpha_g^{-2}\alpha^3\left(\frac{m_p}{m_e}\right)\left(\frac{t_{cool}}{t_{dyn}}\right)T^{1+2\beta}$$

$$\alpha_g = Gm_p^2/e^2$$

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

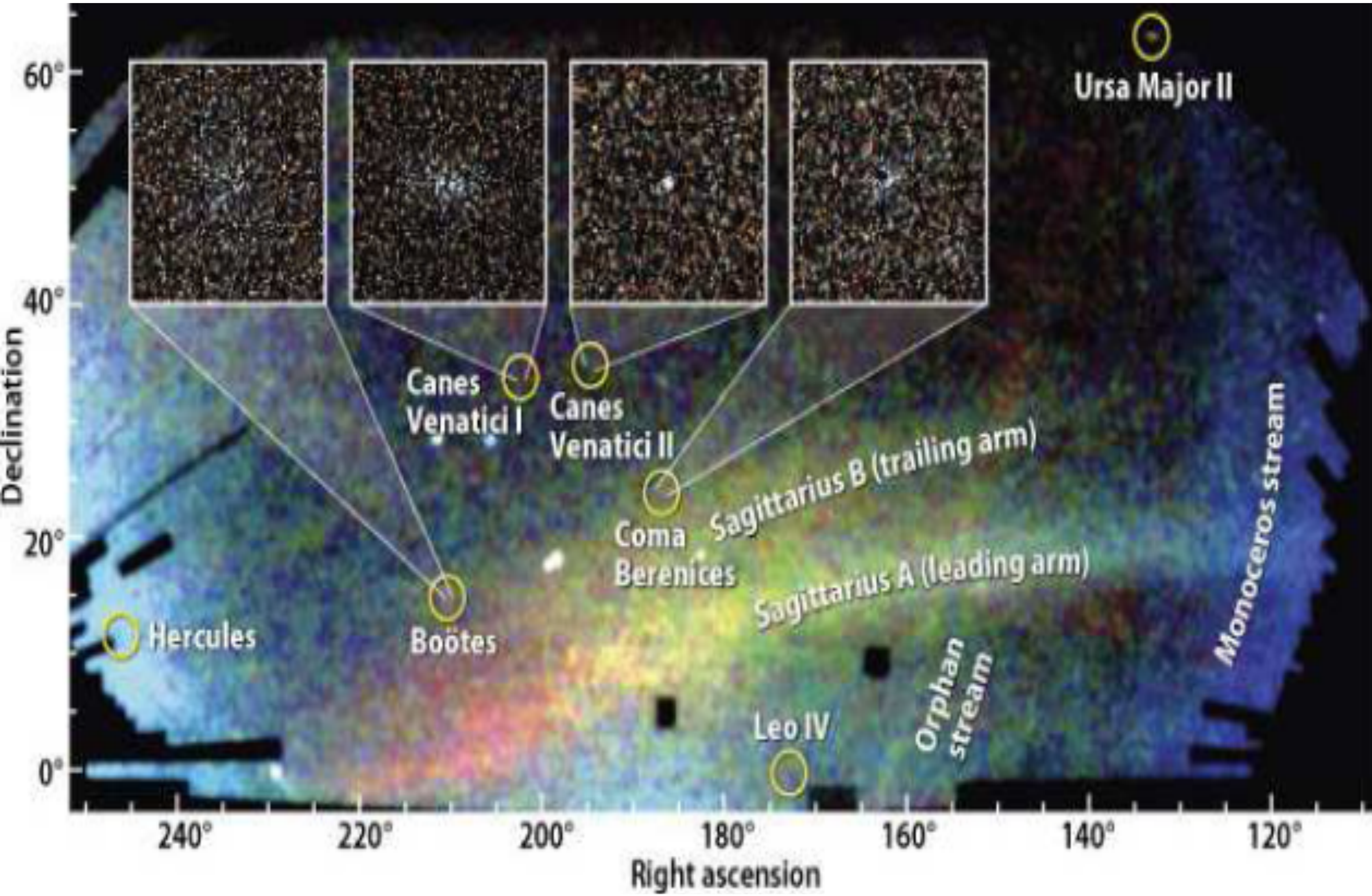
$$t_{dyn} \sim \frac{1}{\sqrt{Gm_p n}}$$



$$L_* \sim 3\times10^{10}L_\odot$$

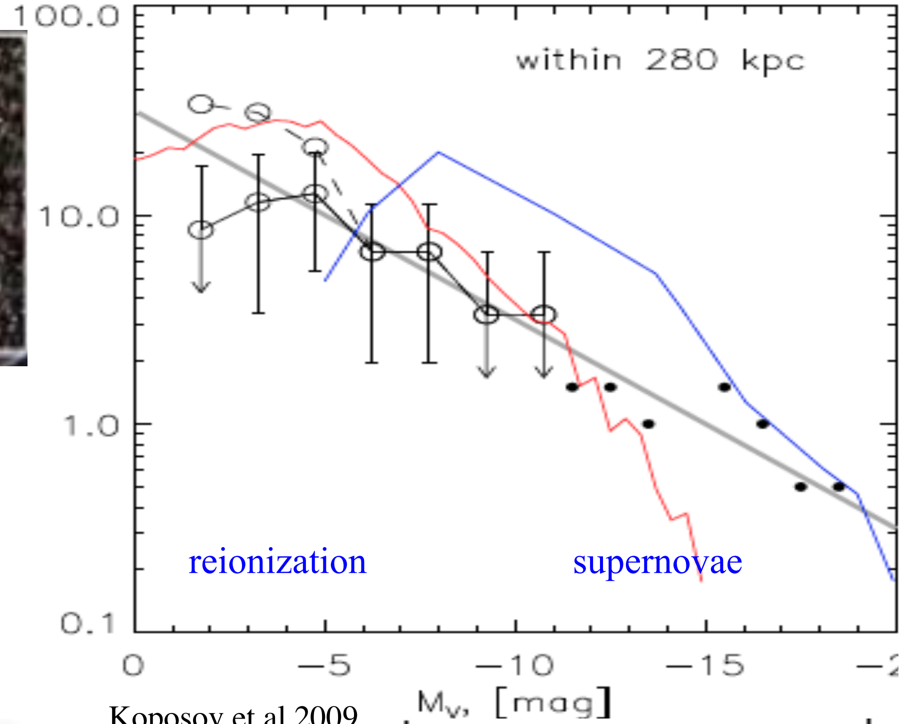
SN

AGN

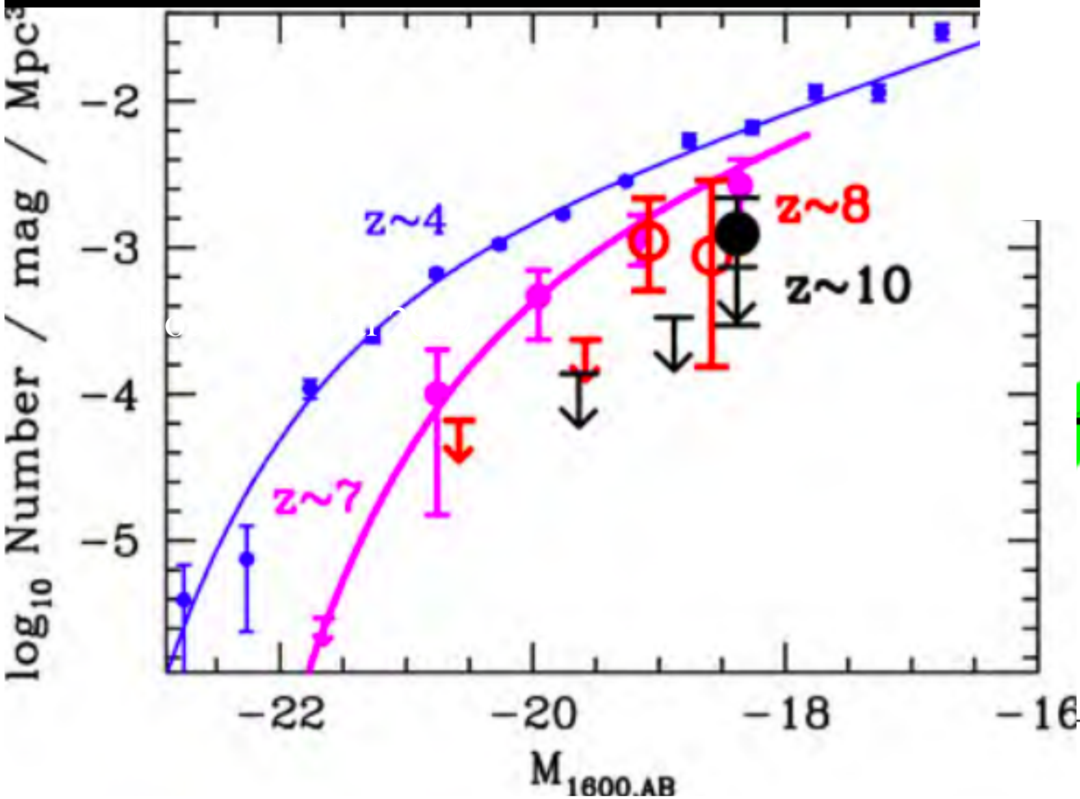


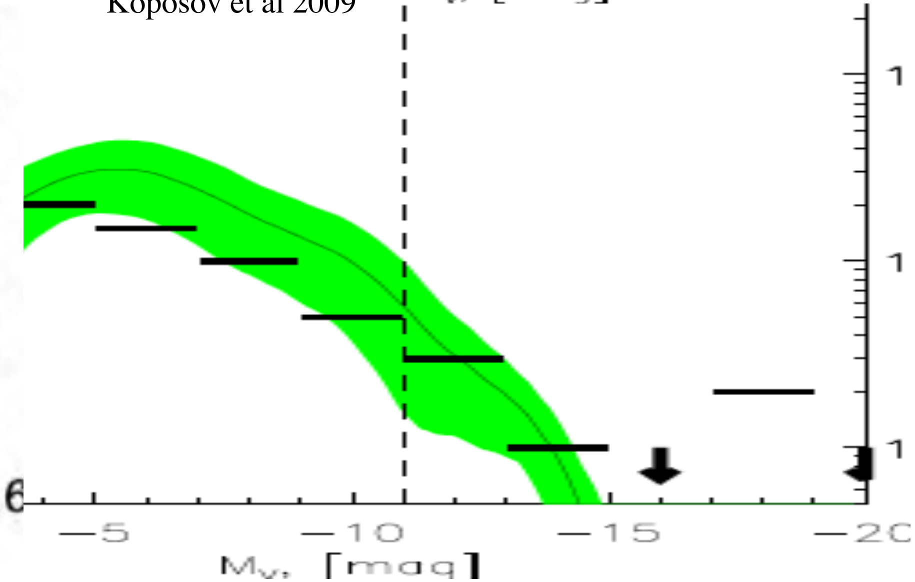
Ursa Major II
Canes Venatici I
Canes Venatici II
Sagittarius B (trailing arm)
Monoceros stream
Coma Berenices
Sagittarius A (leading arm)
Hercules
Boötes
Leo IV
Orphan stream
60°
40°
20°
0°
Declination
240°
220°
200°
180°
160°
140°
120°
Right ascension

Feedback in low mass galaxies



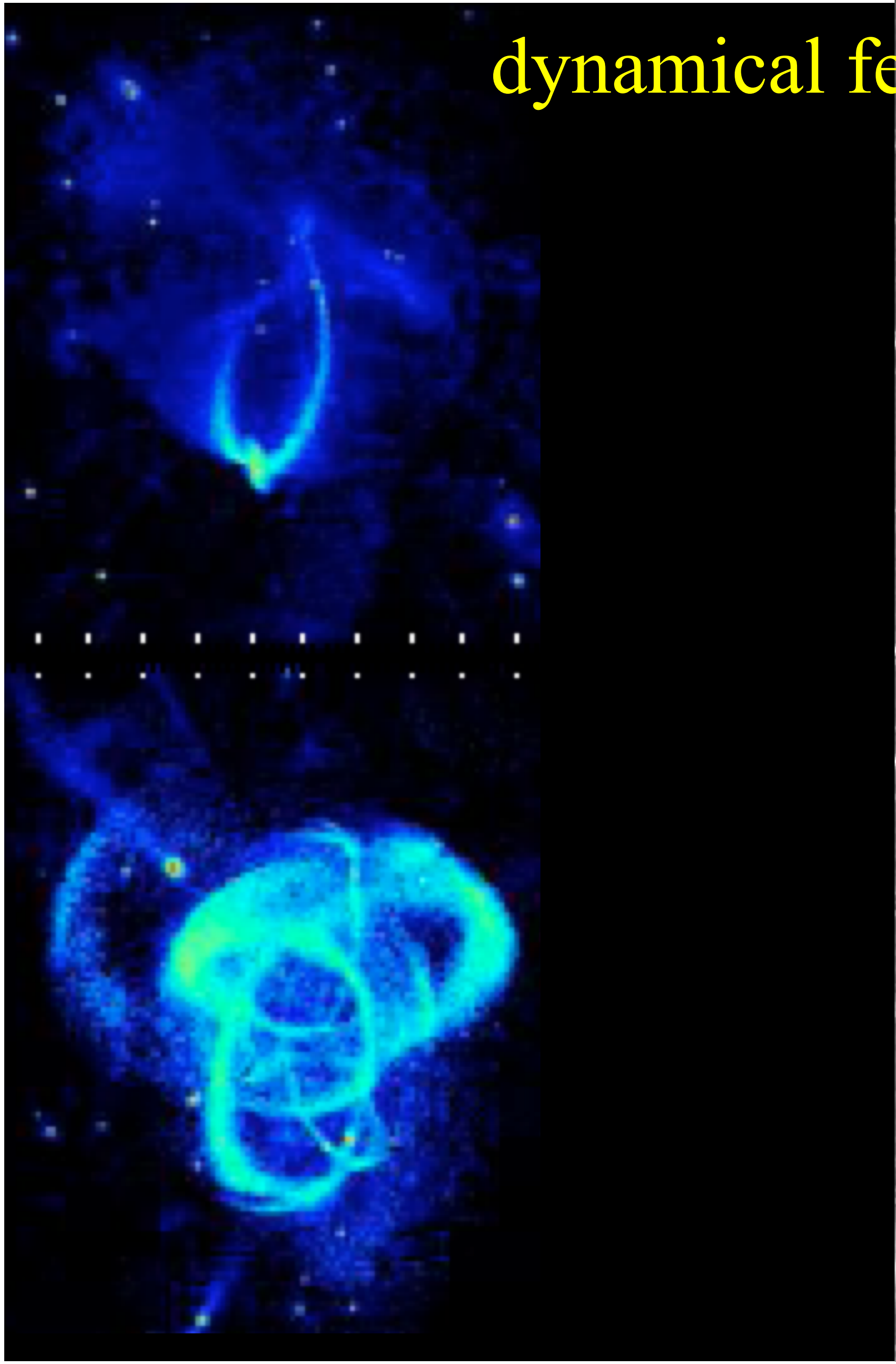
Koposov et al 2009





dynamical feedback

Martinez-Delgado et al 2008



BUT WE CAN'T EXPLAIN > 15% OF GALAXIES!

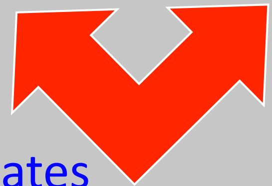
3. Spheroidal galaxy formation

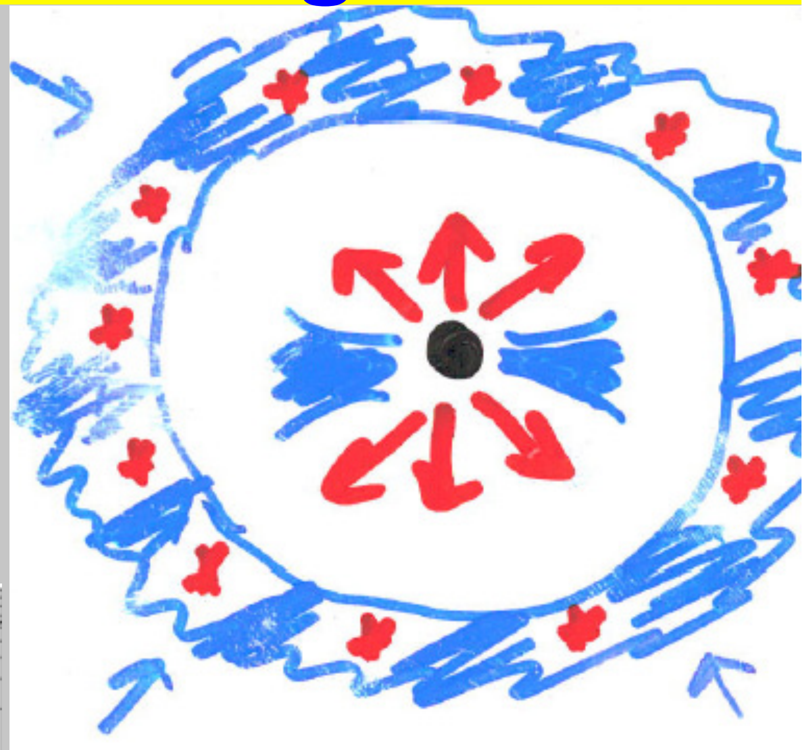
Feedback by massive galaxies

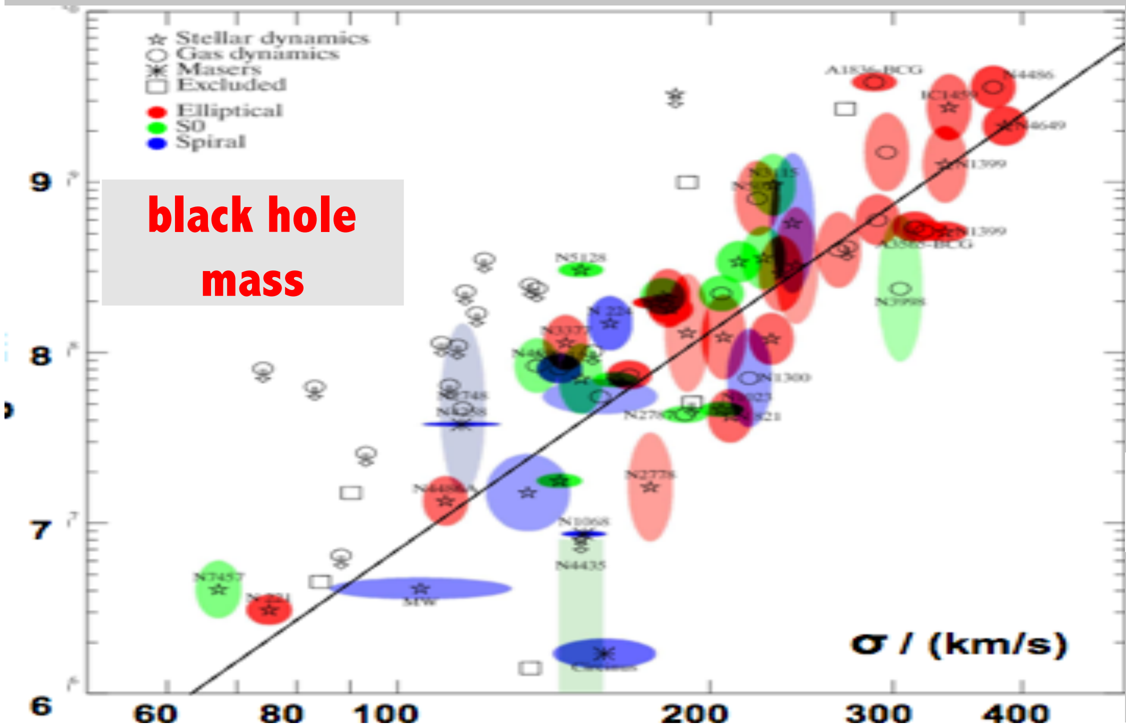
$L_{Edd}/c = GMM_{gas}/r^2$

$$M_\bullet = 3\times10^9\,Msun\left(\frac{\sigma}{300\,\frac{\text{km}}{\text{s}}}\right)^4$$

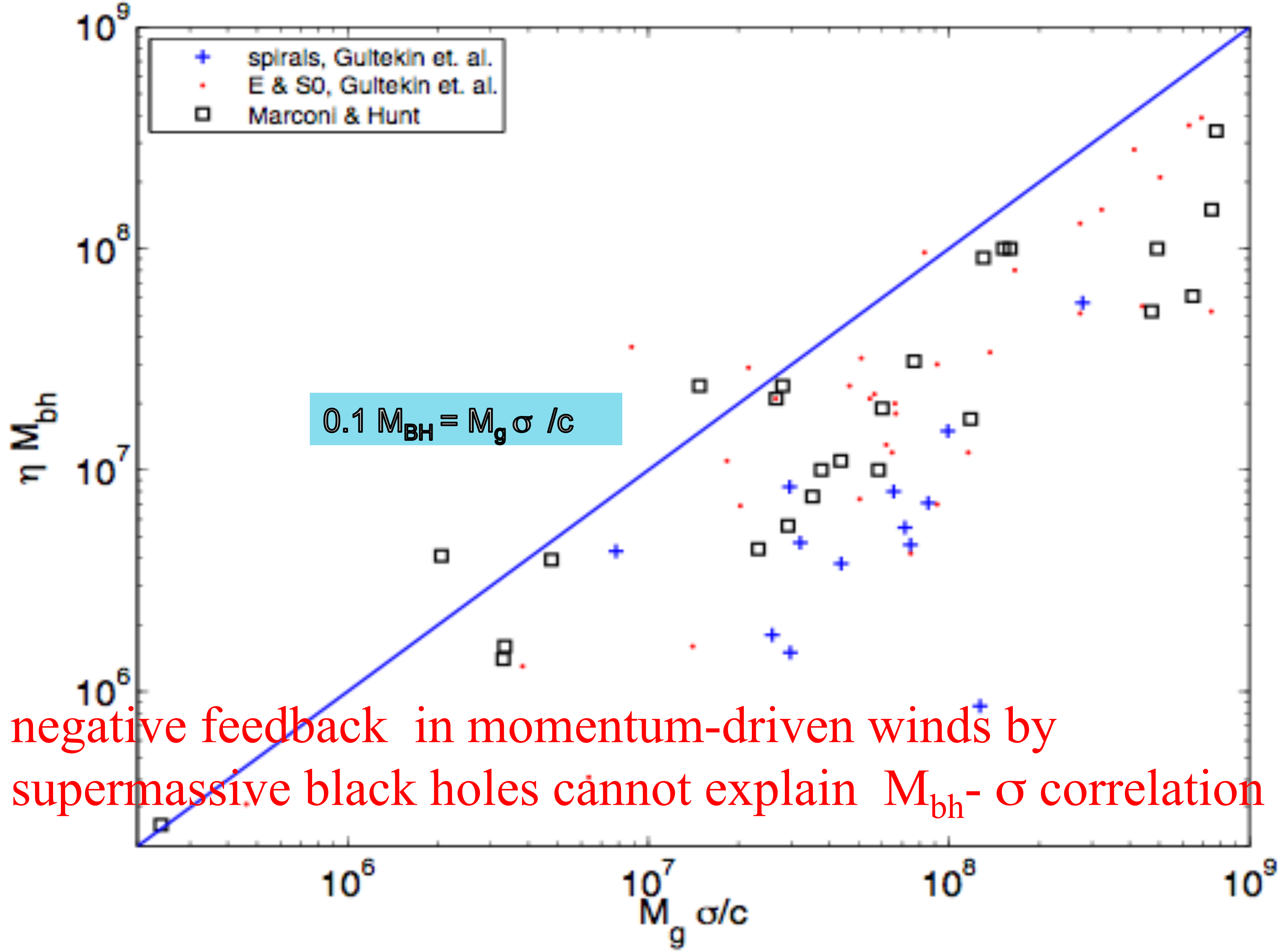
Blowout occurs/star formation terminates
when SMBH-σ relation saturates



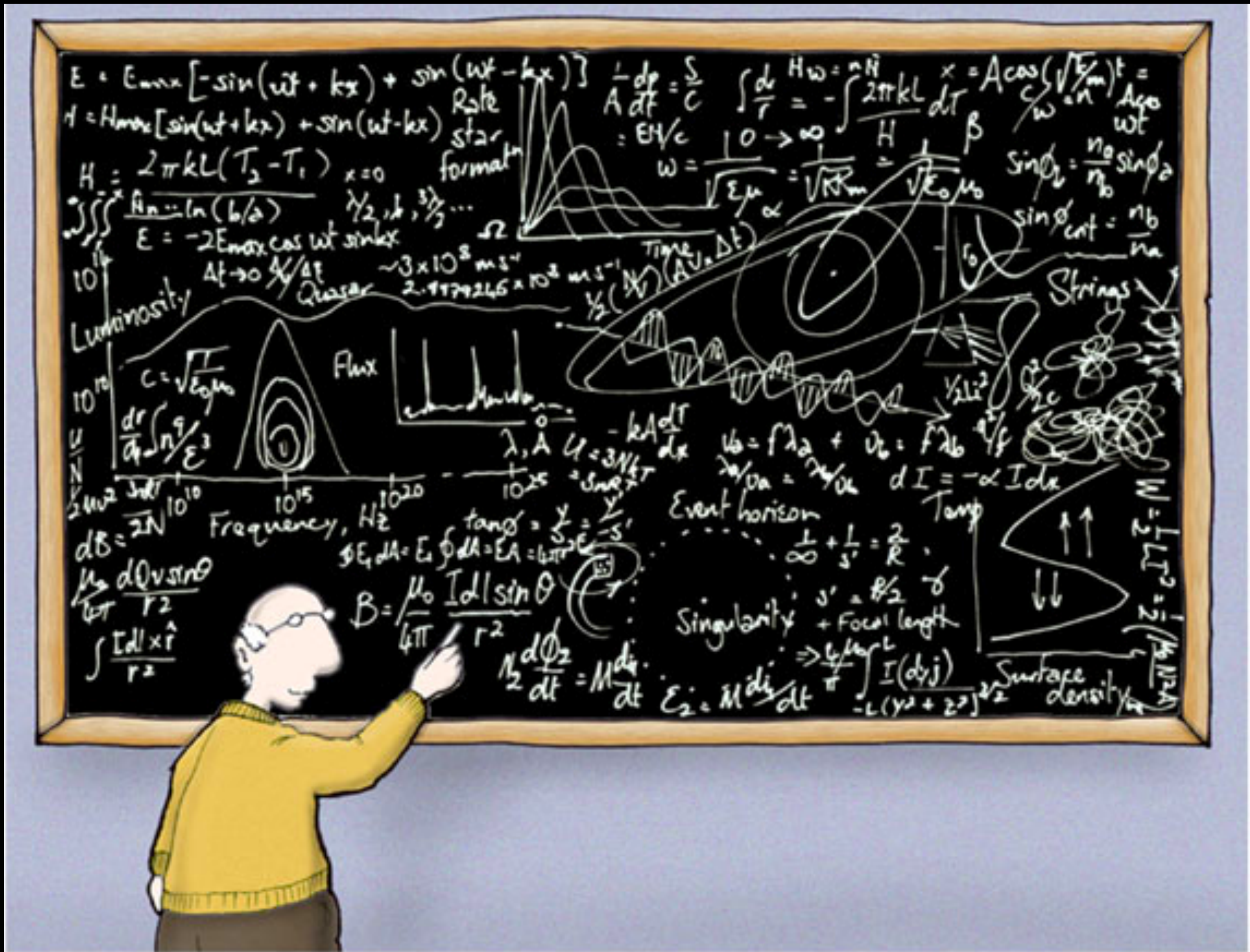




$$L_{Edd} = 4\pi c G M_{BH} m_p/\sigma_T$$



negative feedback in momentum-driven winds by supermassive black holes cannot explain M_{bh}- σ correlation



Back to the drawing board…

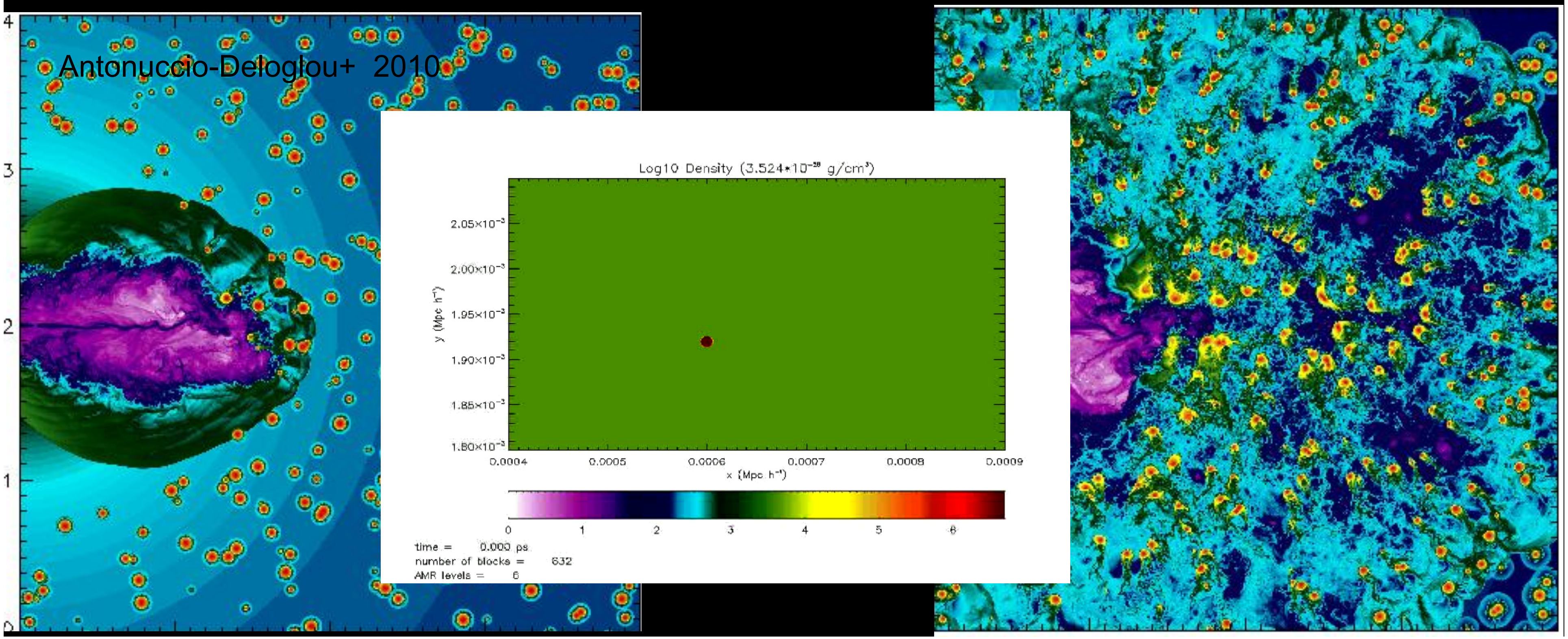
Its not supernovae,
its not active galactic nuclei…
maybe its both!

start formation rate is boosted by AGN

If AGN-driven outflows trigger star formation,

JS + C. Norman 2008

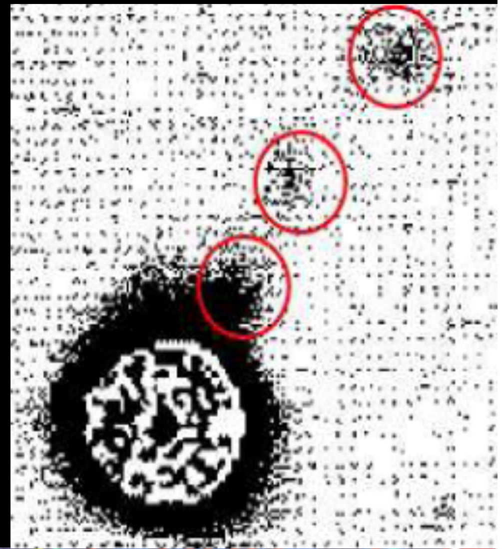
the star formation rate is boosted by factor t_{dyn}/t_{jet}
and the outflow momentum is amplified by supernovae



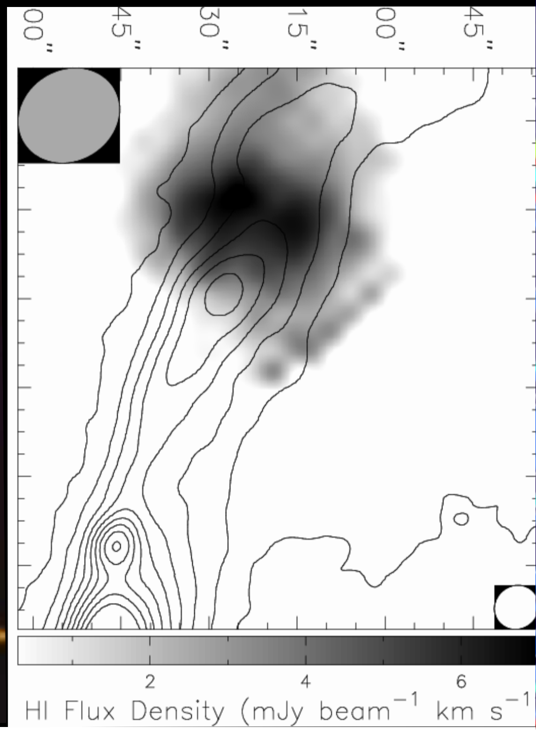
momentum boost by AGN +star formation

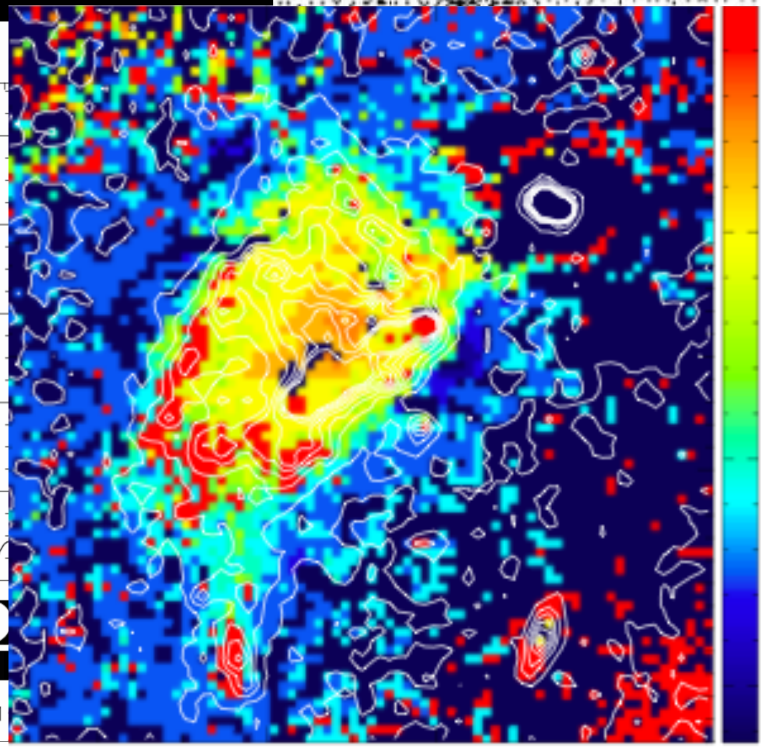
JS + A. Nusser 2010

z = 4.7 quasar + CO

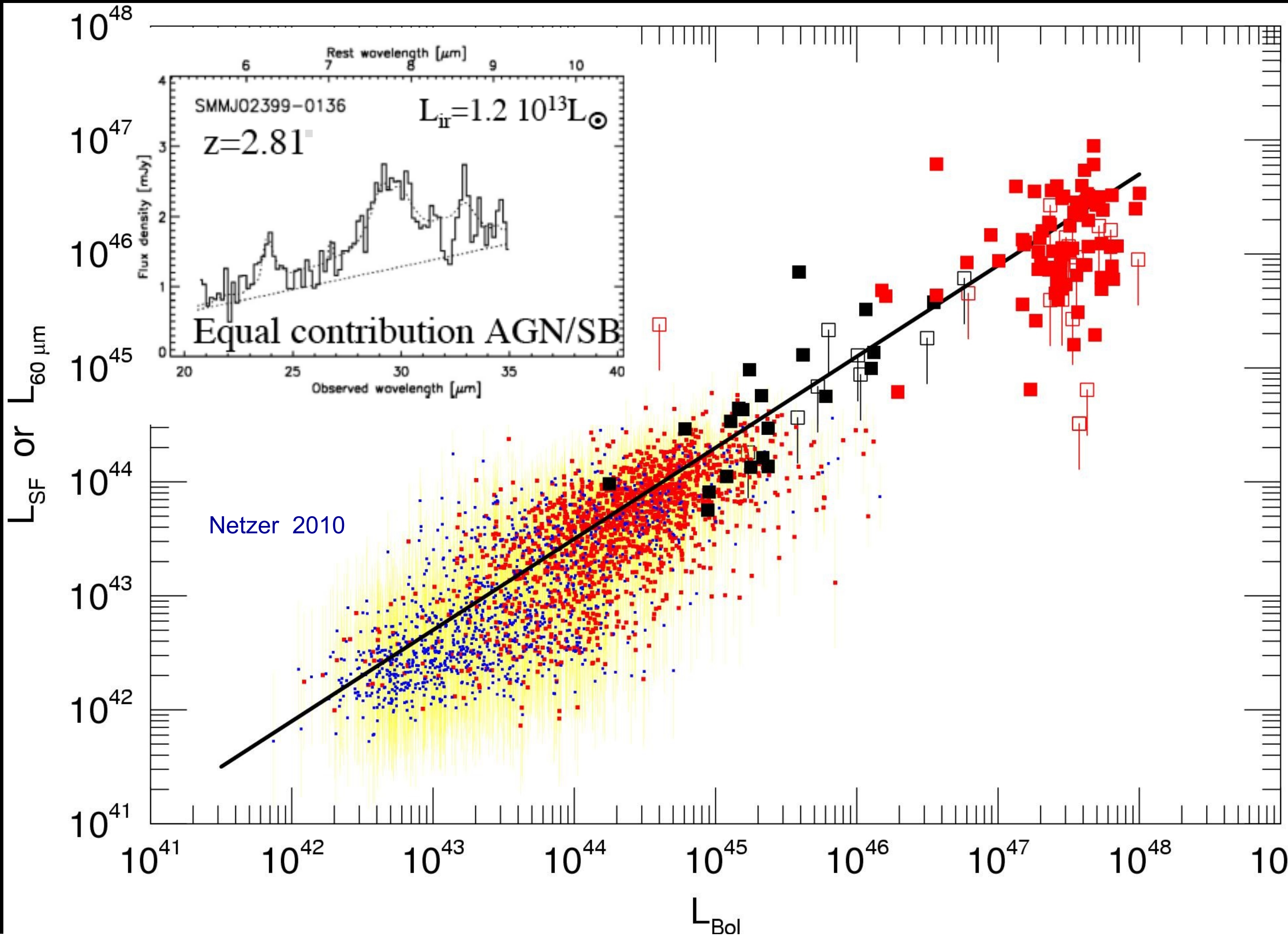


Momentum boost =
supernova momentum/Eddington momentum
~ 10

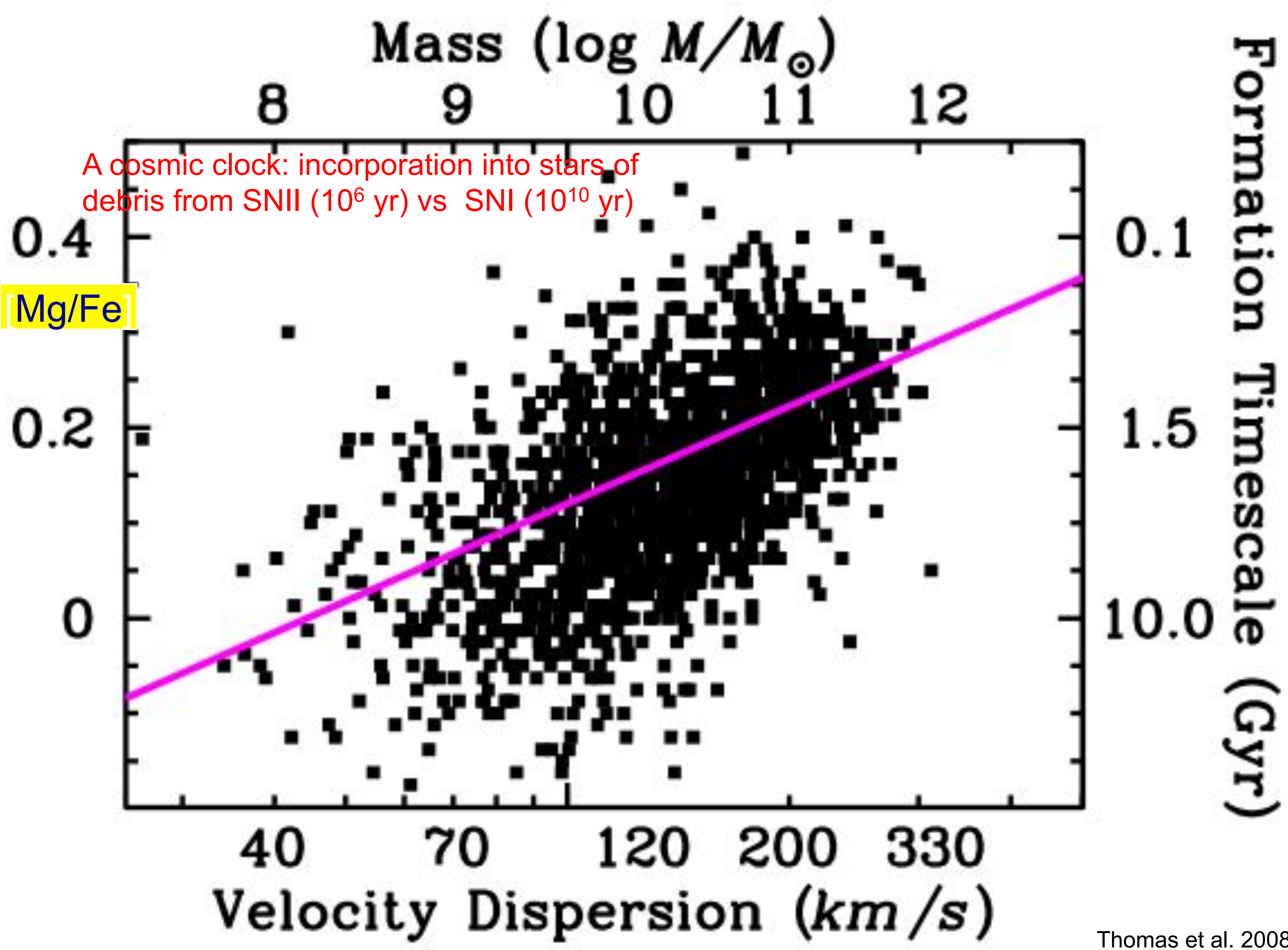




connection between AGN and starbursts



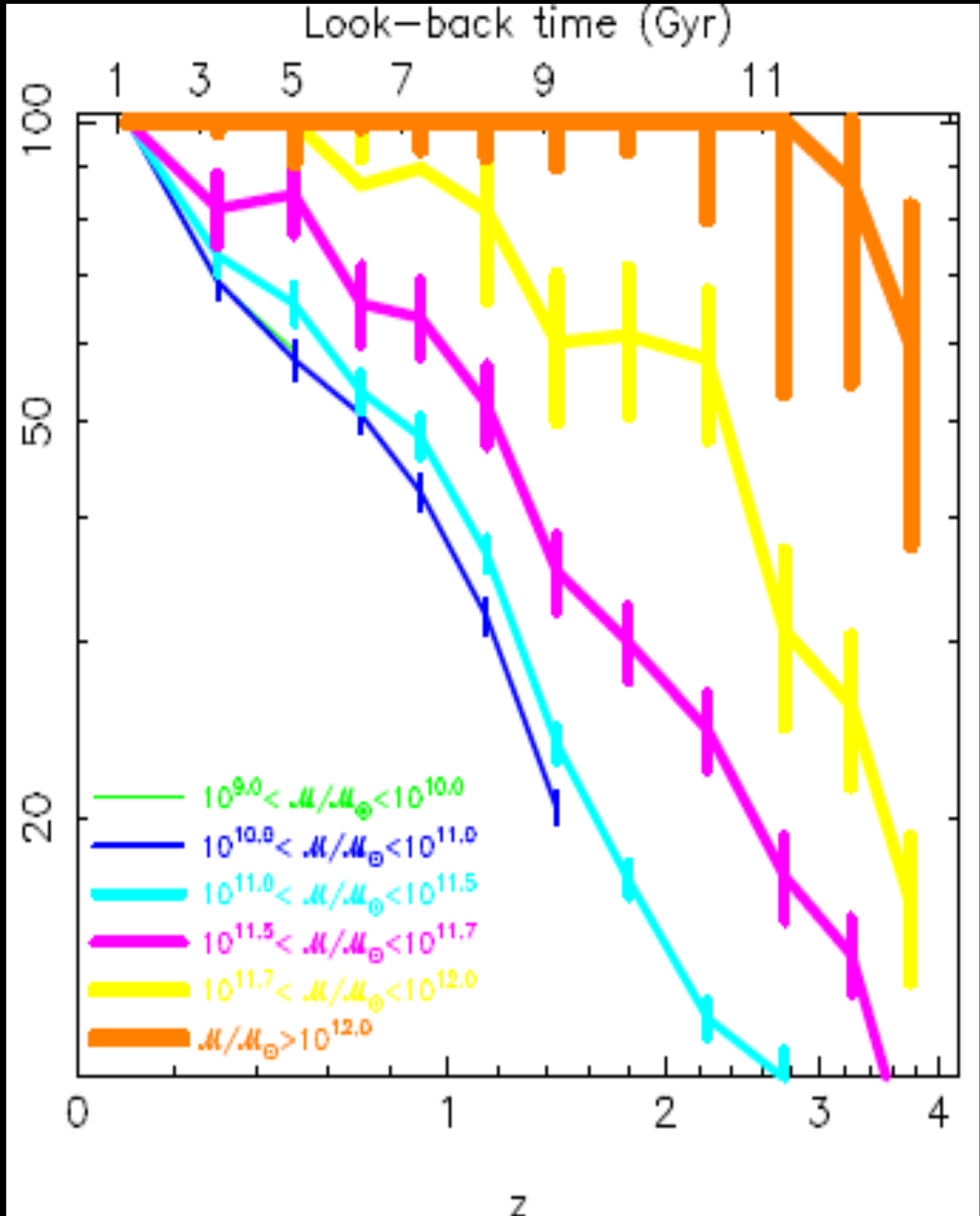
DOWNSIZING INFERRED: A SURPRISE



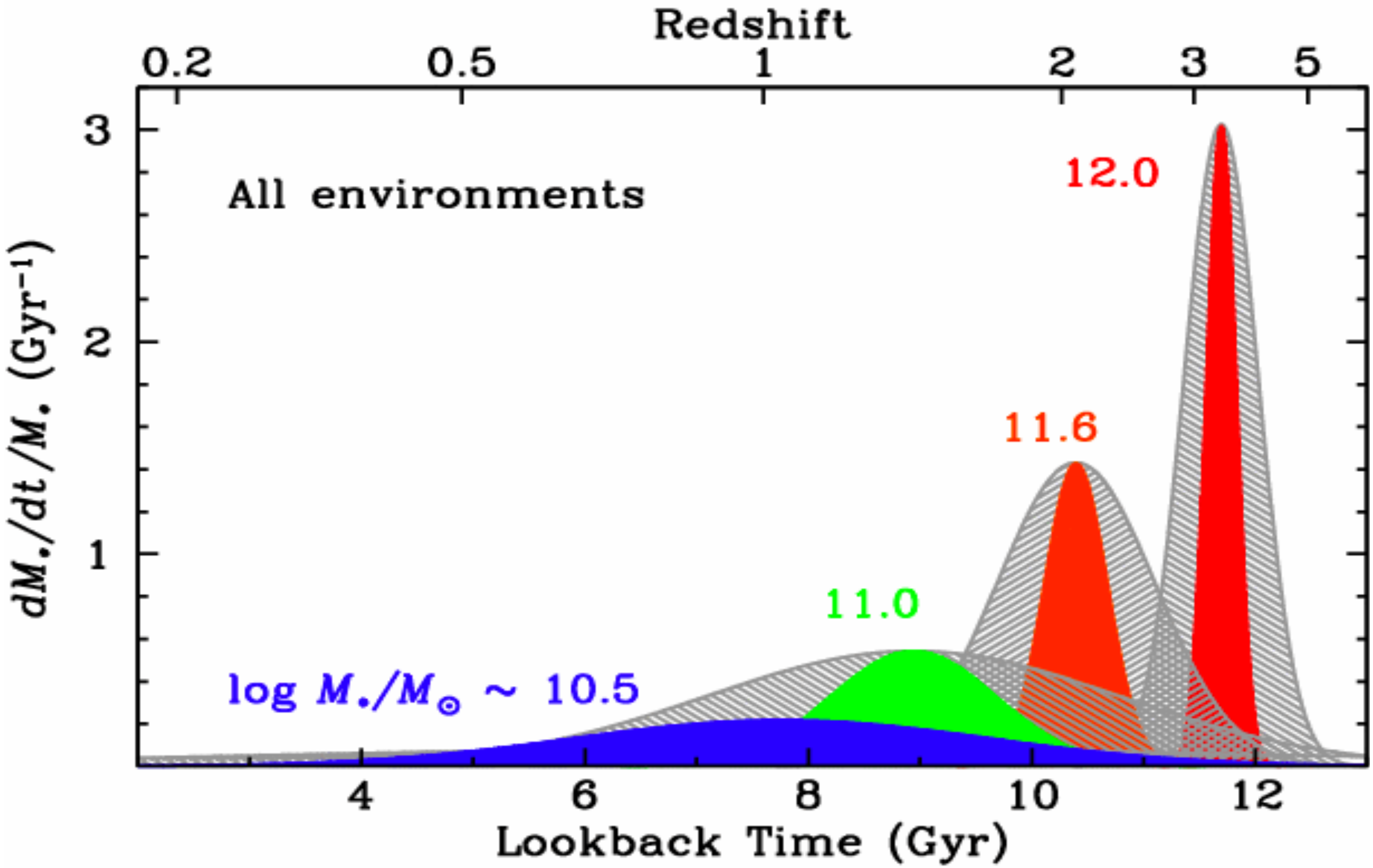
Thomas et al. 2008

DOWNSIZING IN STELLAR MASS

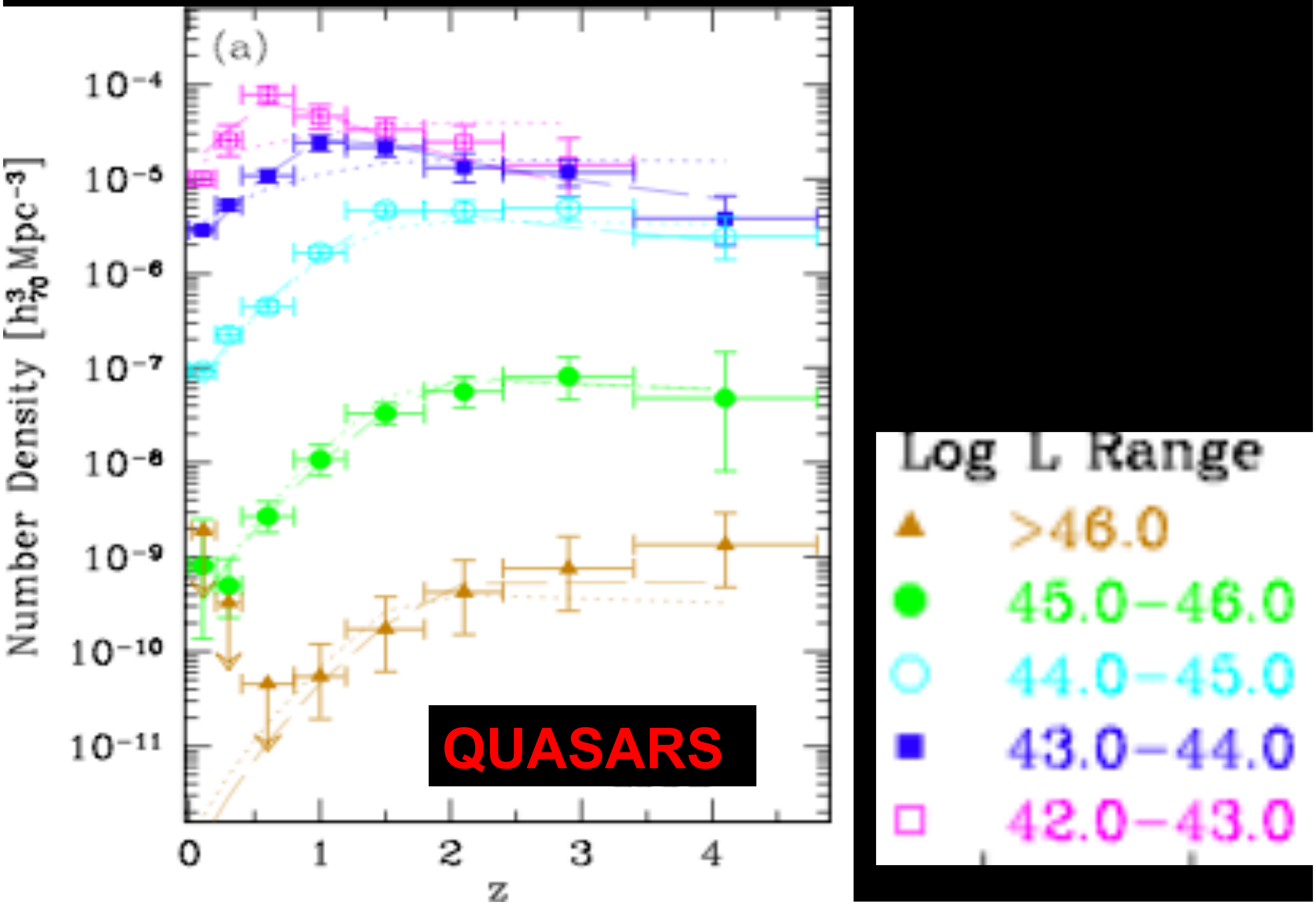
Perez-Gonzalez et al. 2007



DOWNSIZING SUMMARIZED



DOWNSIZING IN BLACK HOLE MASS



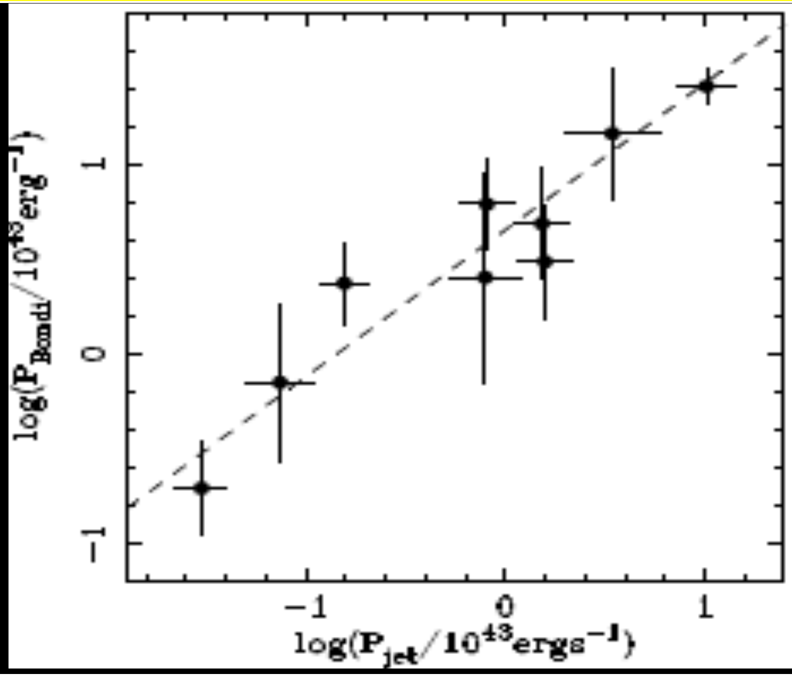
Why efficient formation of massive spheroids ?

- assume AGN-driven outflows trigger/regulate star formation

Why downsizing of massive spheroids and AGN?

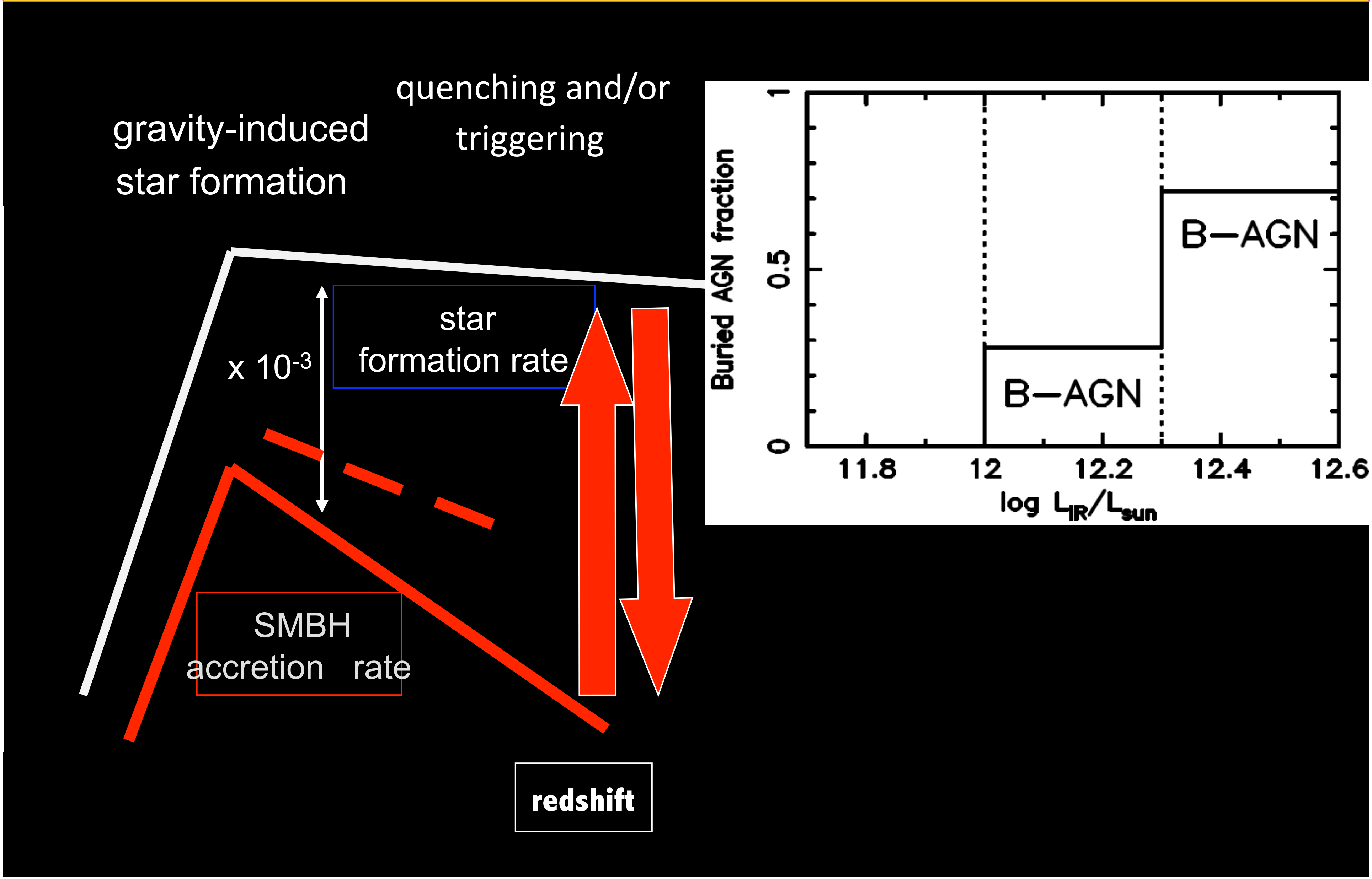
- Need SMBH feeding and outflow

to be nonlinear function of SMBH mass

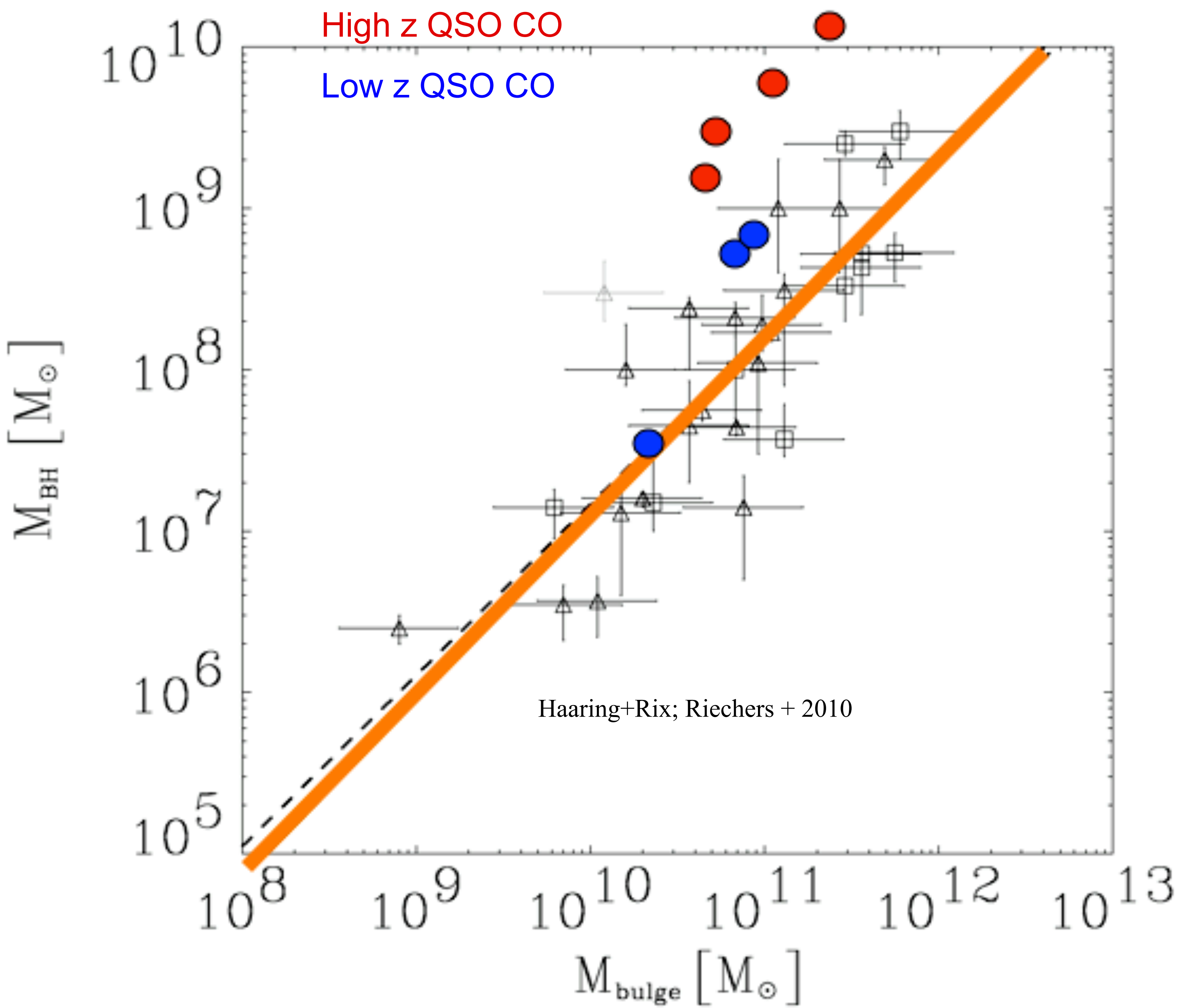


Active galactic nuclei-

an aftermath or precursor to star formation?



SMBH in z ~ 6 quasars lie high….



4. Star formation

two modes of star formation:

A: without active galactic nuclei

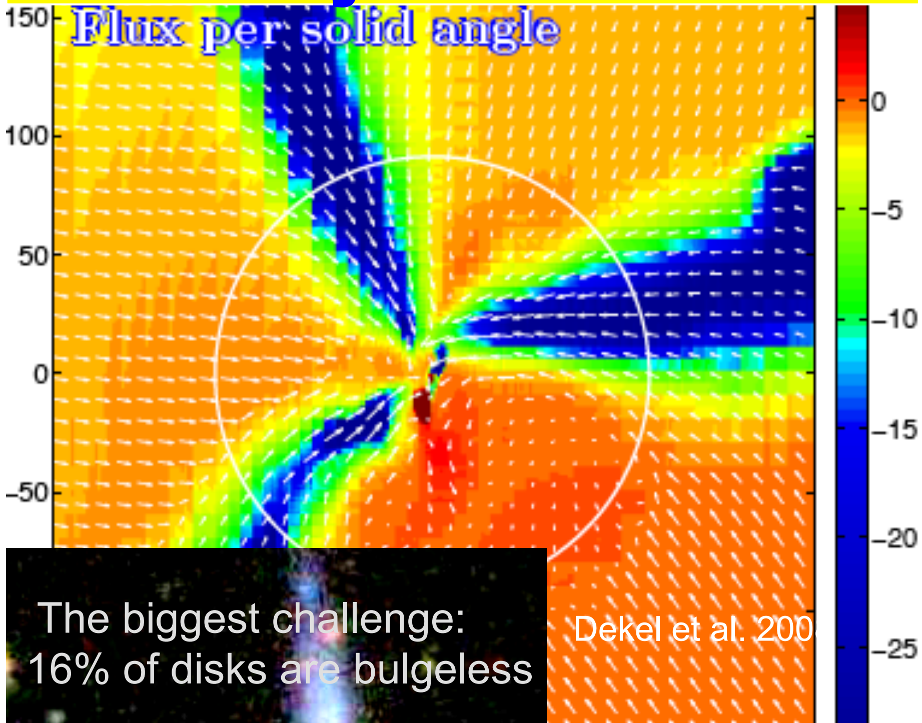
B: with active galactic nuclei

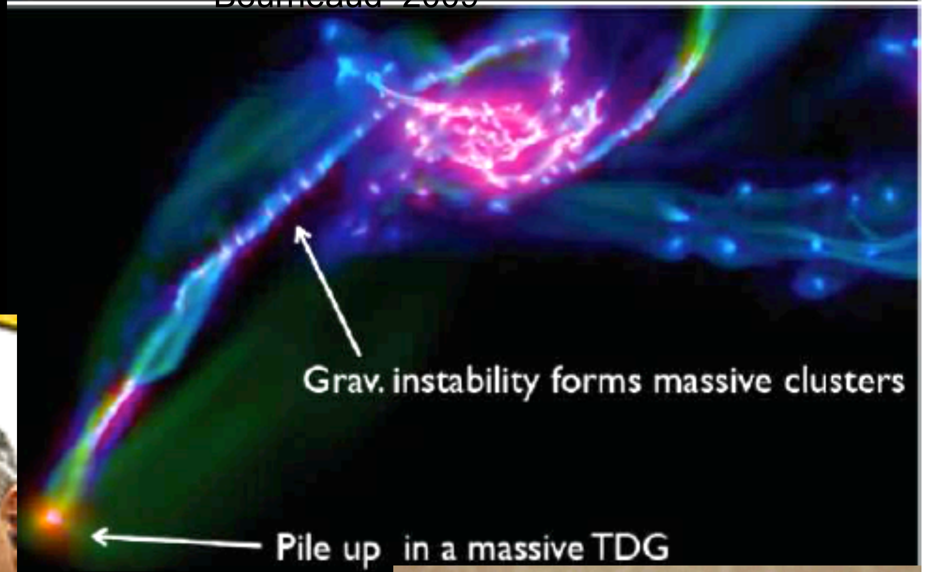
two modes of gas accretion:

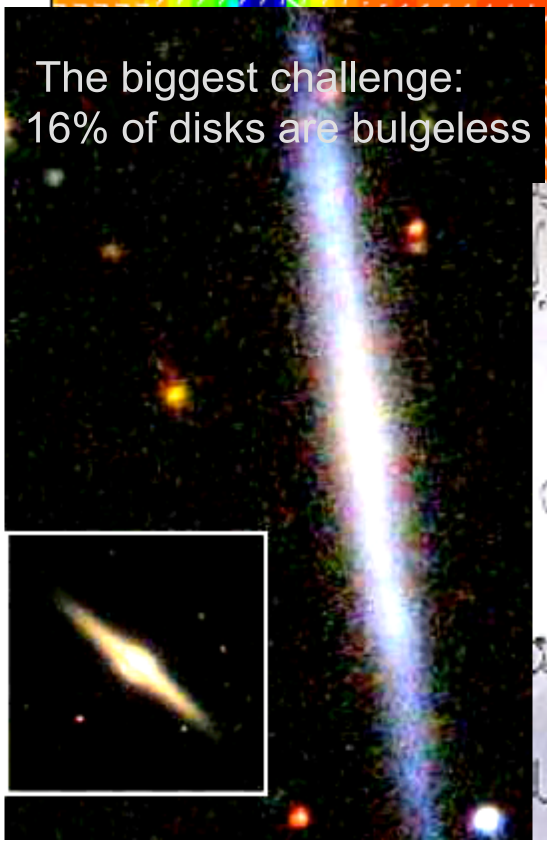
A: cold streams/minor mergers

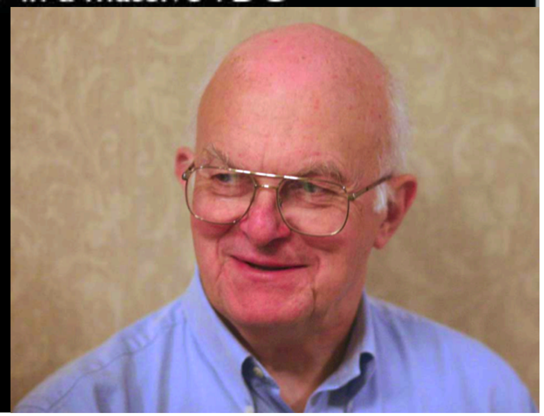
B: major mergers/cooling flows

Infall by cold streams

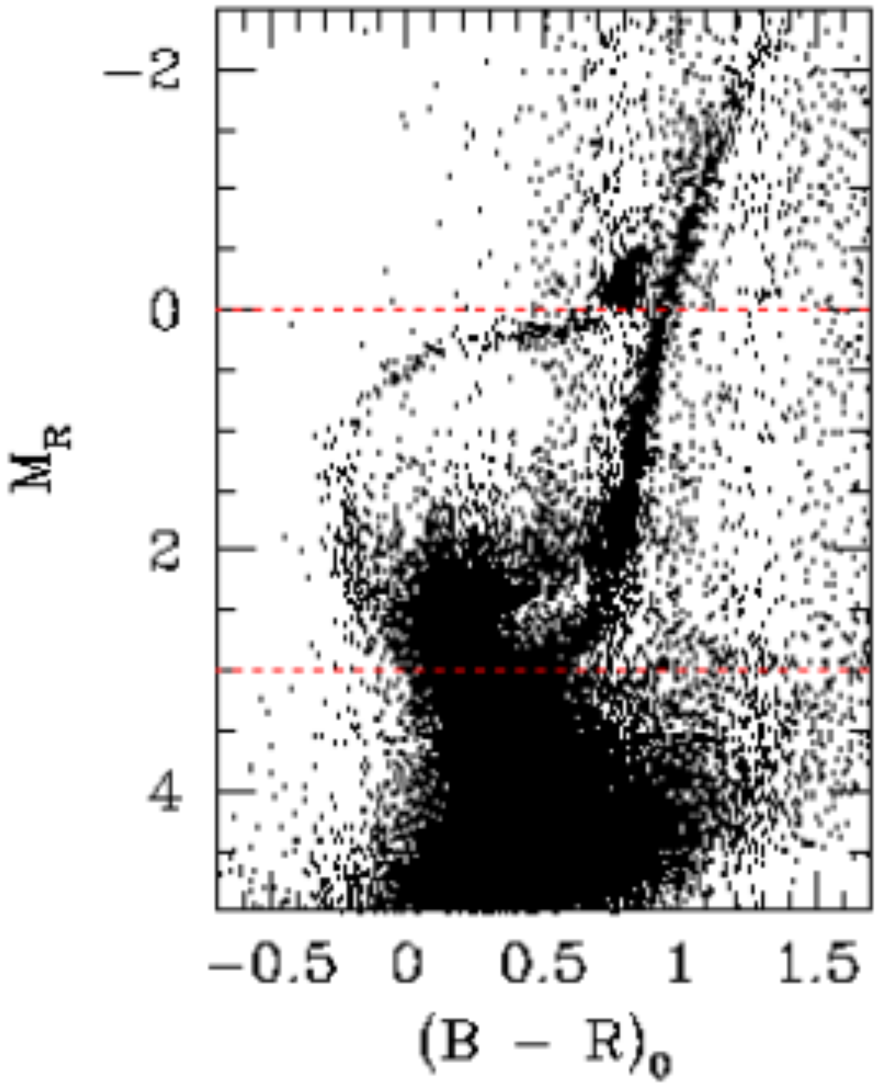


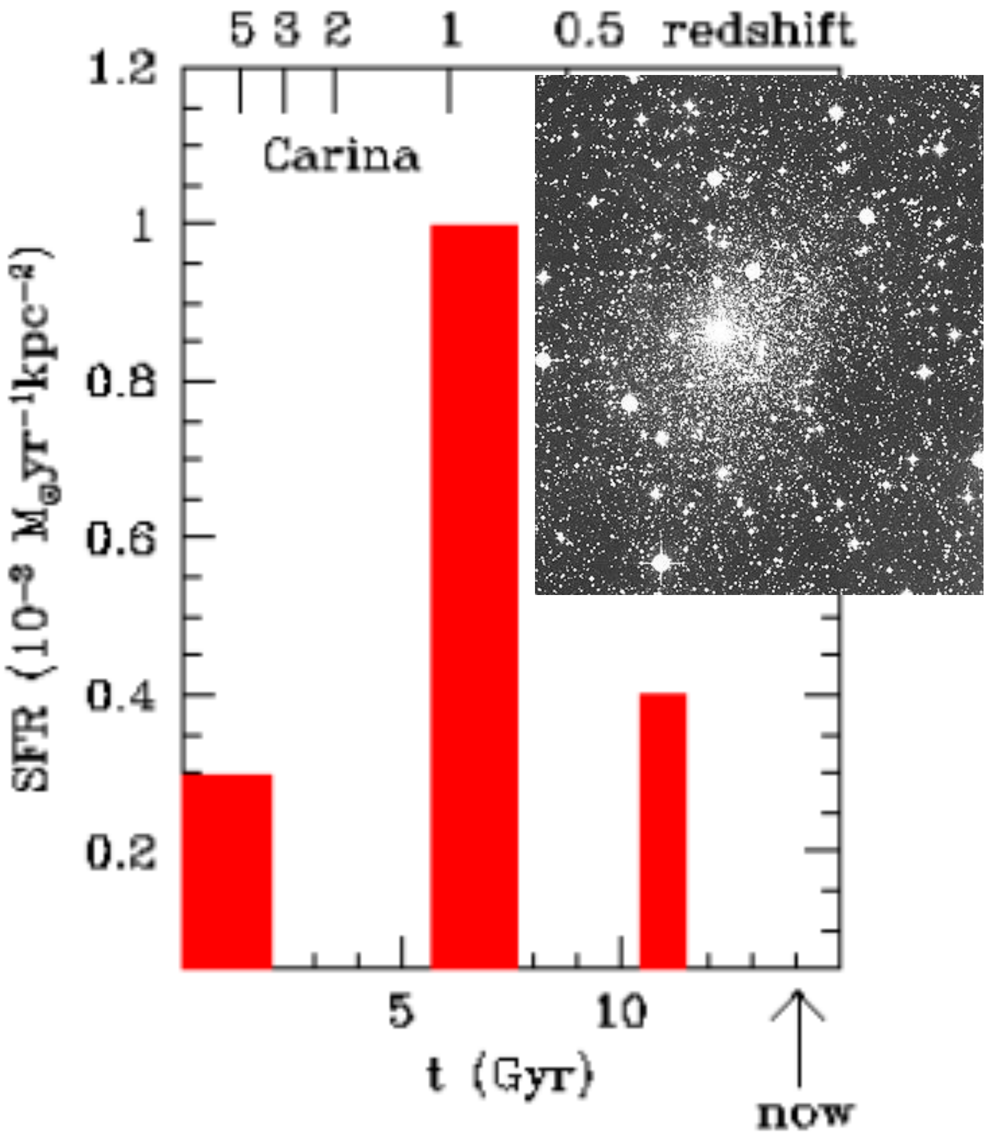




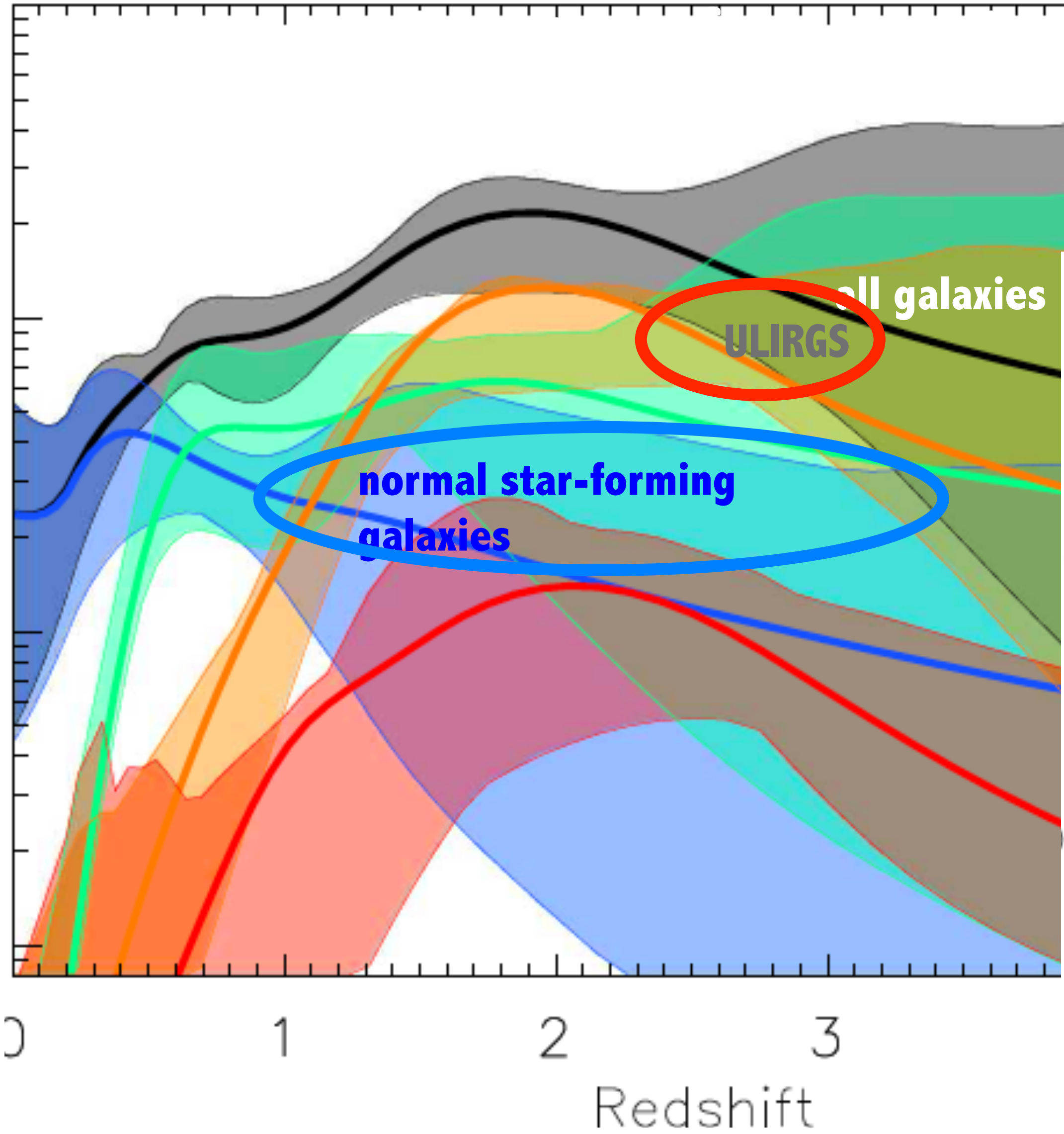


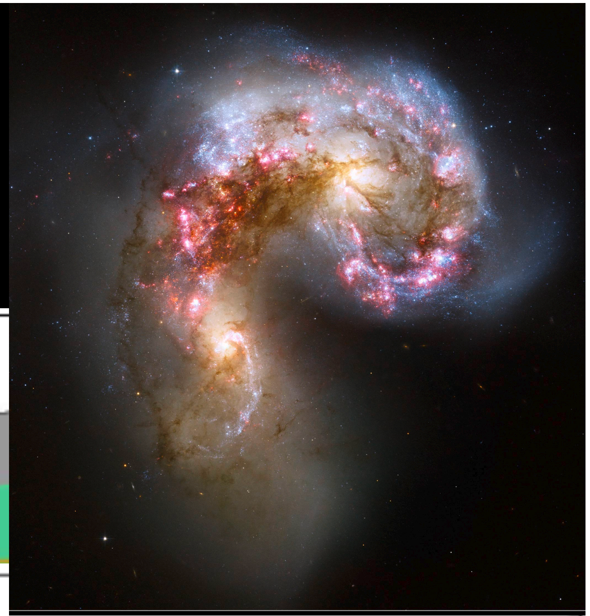
cold accretion dominates for disks and dwarfs

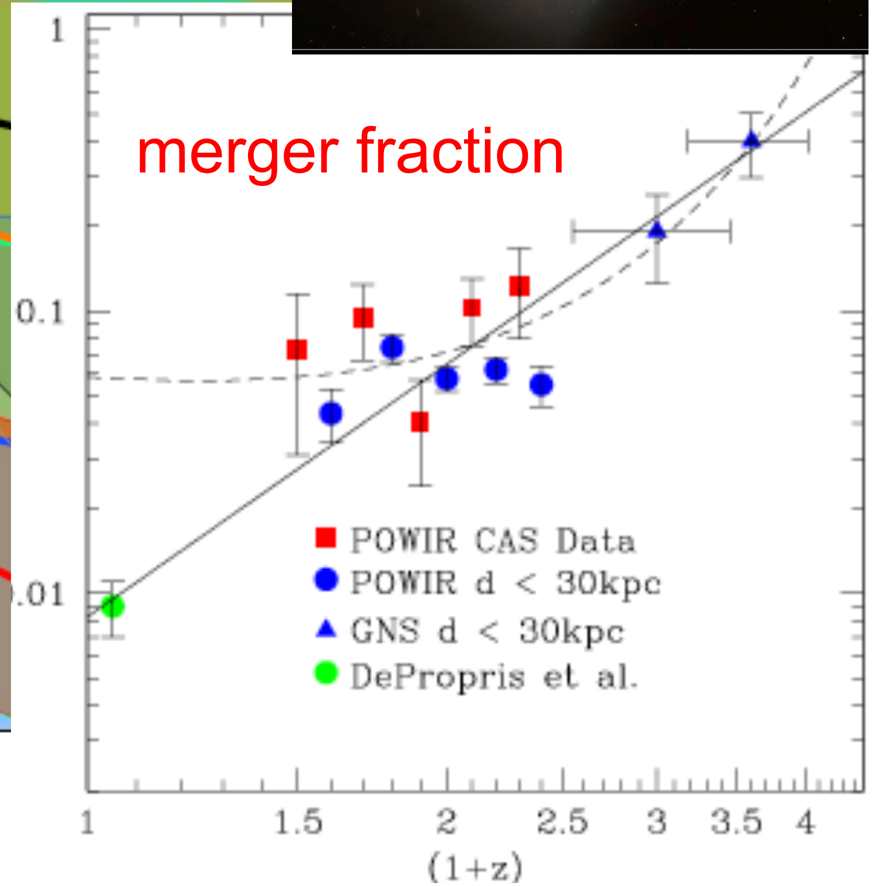




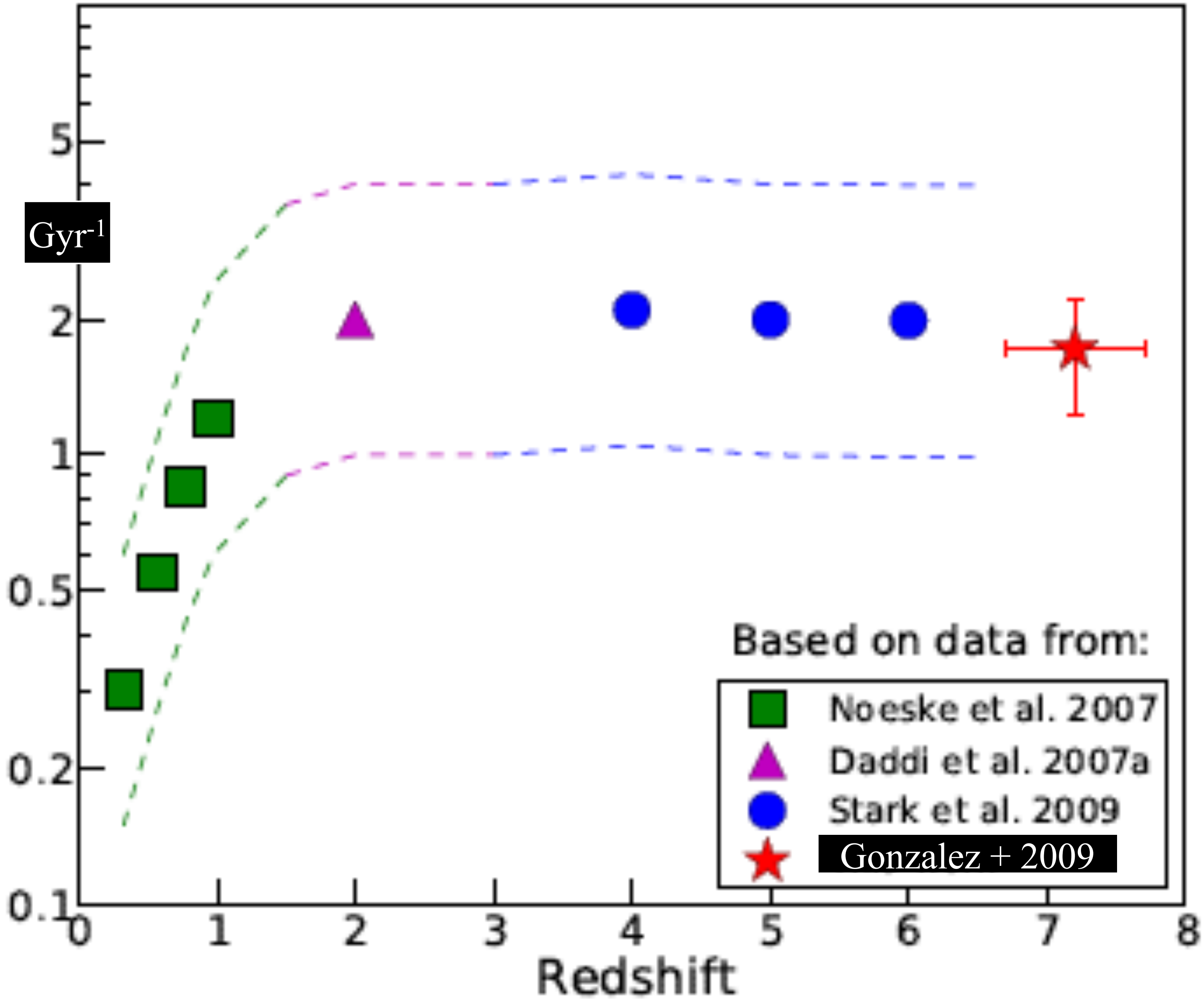
Cosmic star formation rate





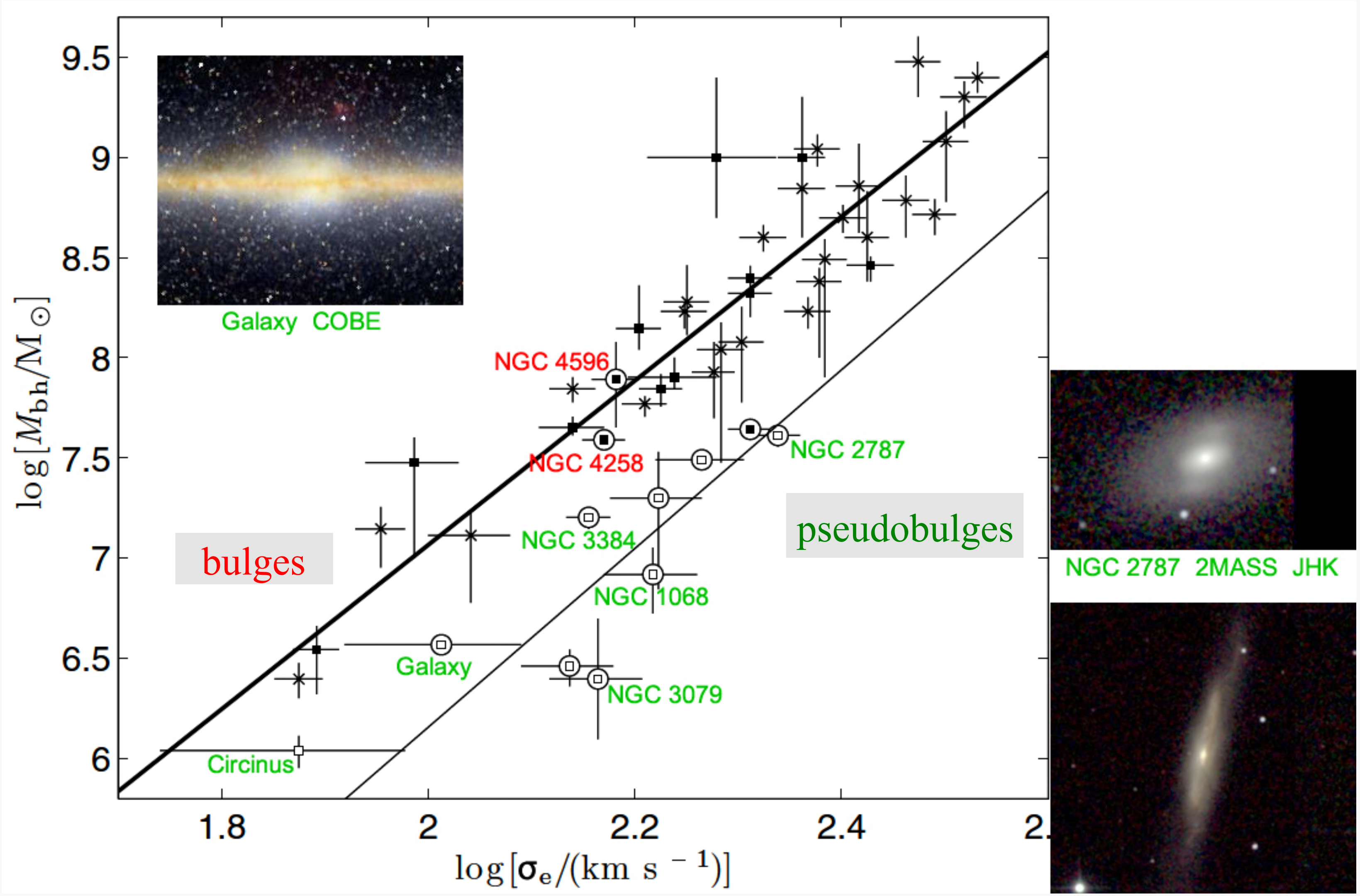


specific star formation rate =SFR/stellar mass

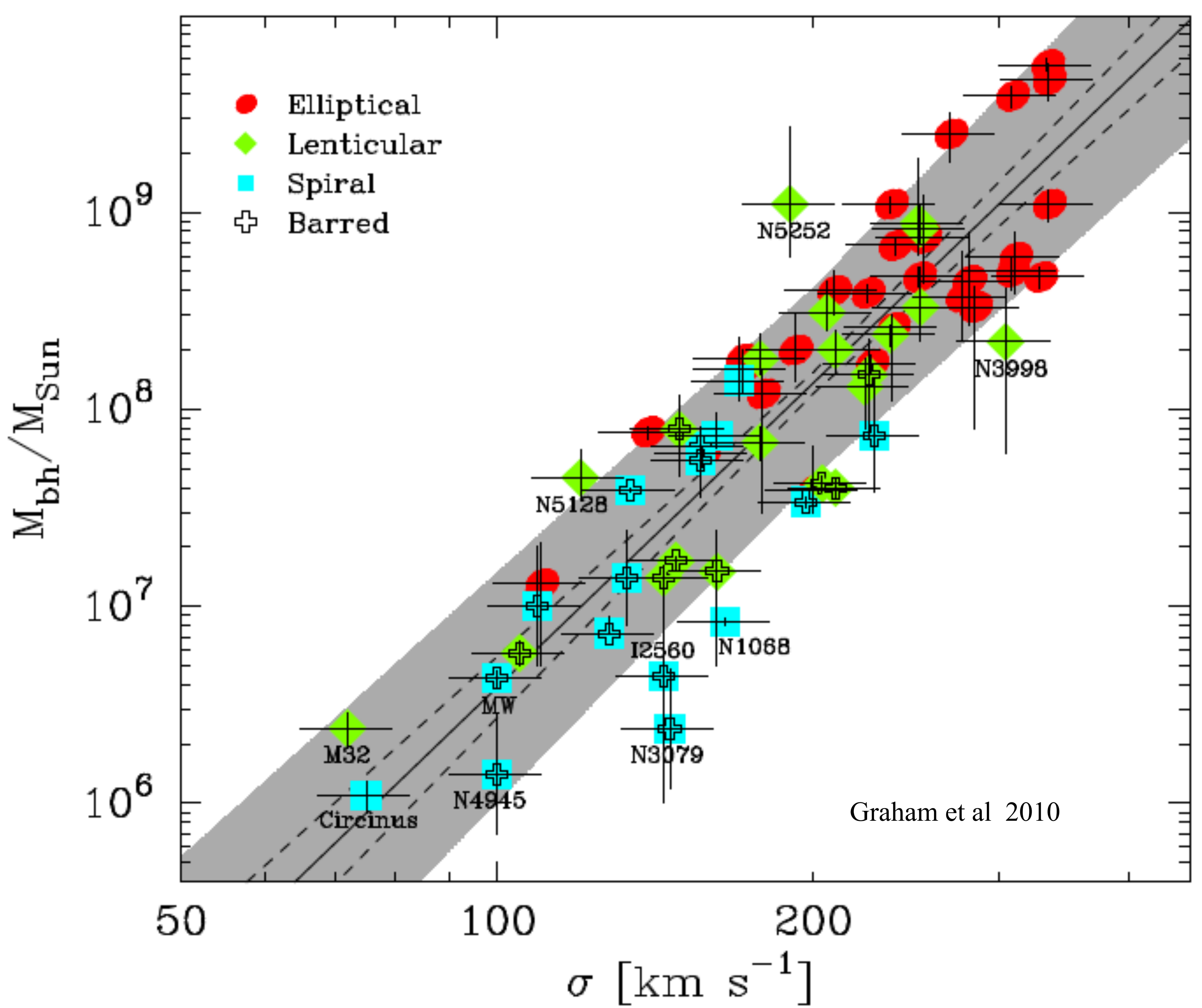


SMBH in pseudobulges lie low….

Suggests disk mode formation of SMBH is distinct from spheroid mode



Kormendy & Tremaine 2009

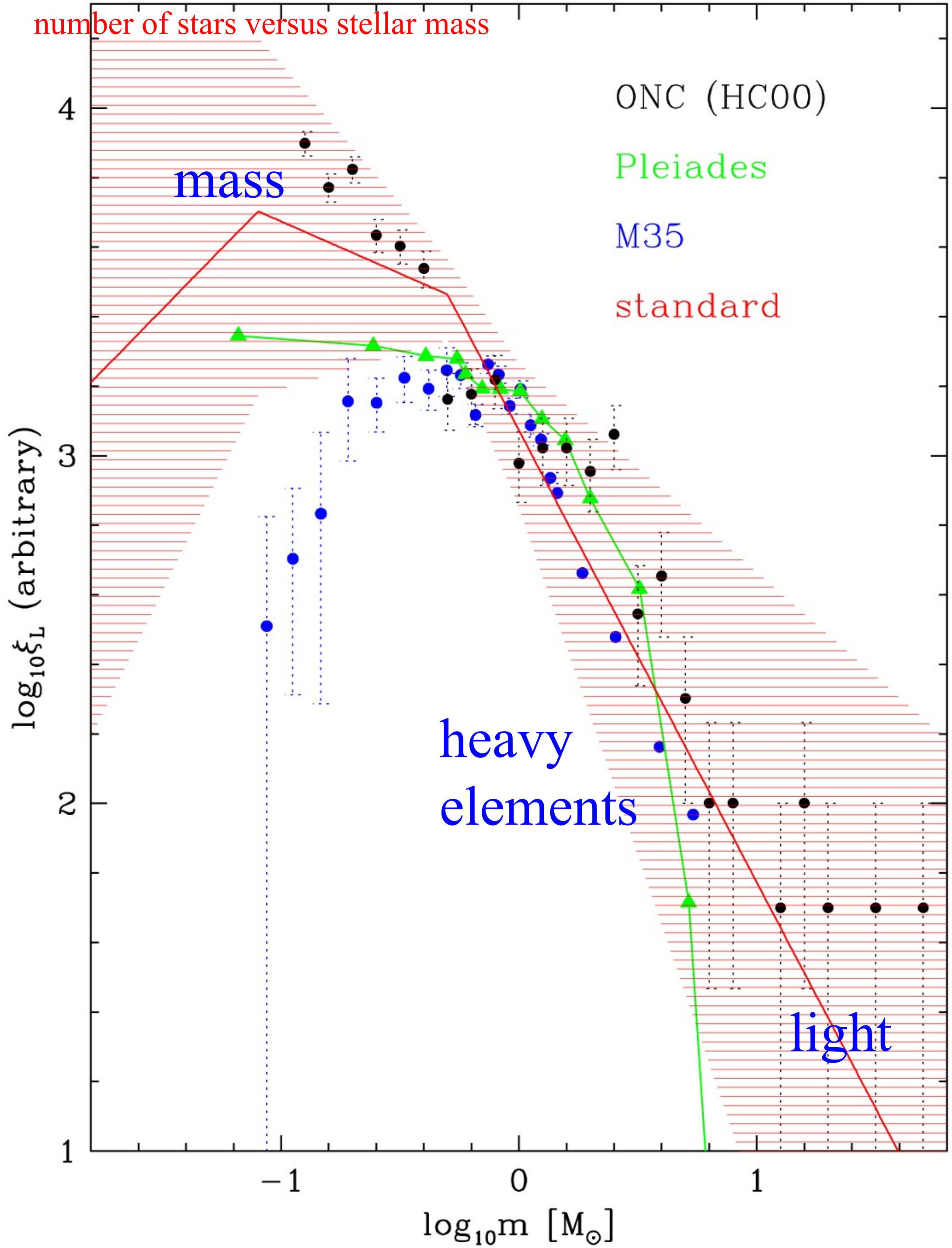


Elliptical
Lenticular
Spiral
Barred
M_{bh}/M_{Sun}
10^9
10^8
10^7
10^6
N5252
N3998
N5128
I2560
N1068
MW
M32
N3079
N4945
Circinus
Graham et al 2010
50
100
200
σ [km s^{-1}]

What’s missing?
A robust theory of star formation

Kroupa 2003

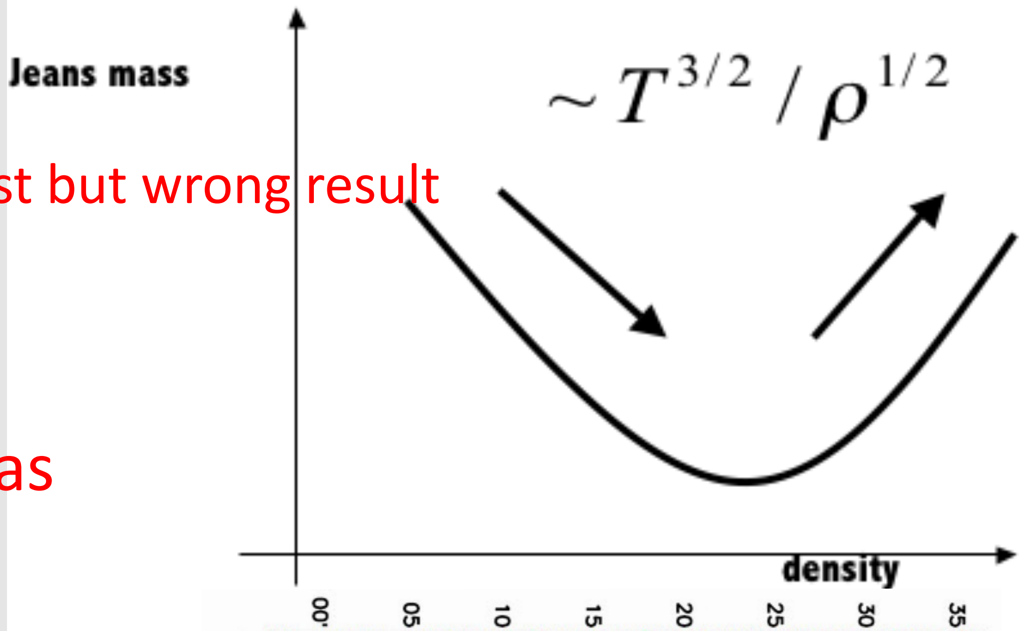
Initial mass function of stars: a fundamental theory is lacking



Feedback: star formation

fragmentation theory applied to collapsing interstellar cloud implies minimum fragment mass…….a robust but wrong result

$$\sim \alpha_g^{-3/2} m_p \sim 0.01\,M_\odot$$



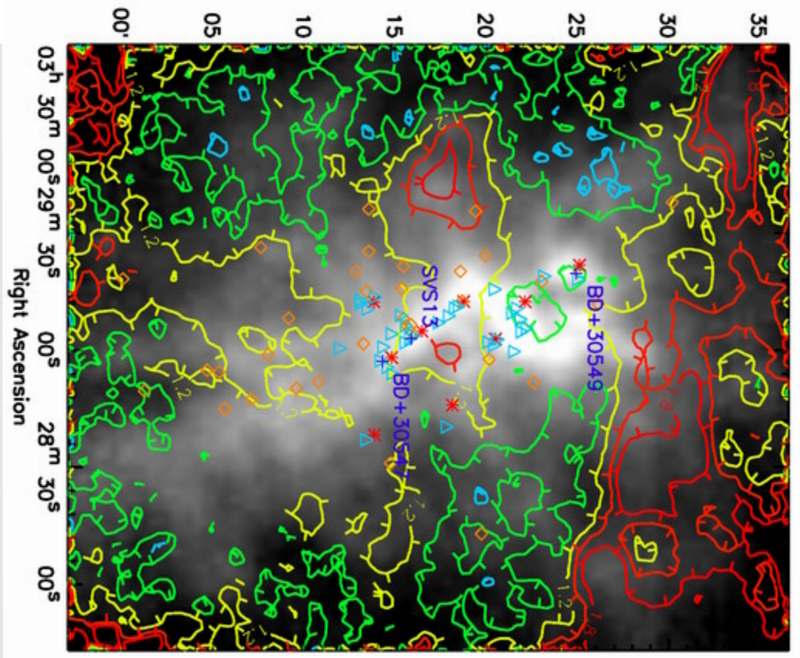
resolution: ***accretion*** of cold gas

$$\dot{M}_{gas} \sim V_s^{\ 3} / G \Rightarrow$$

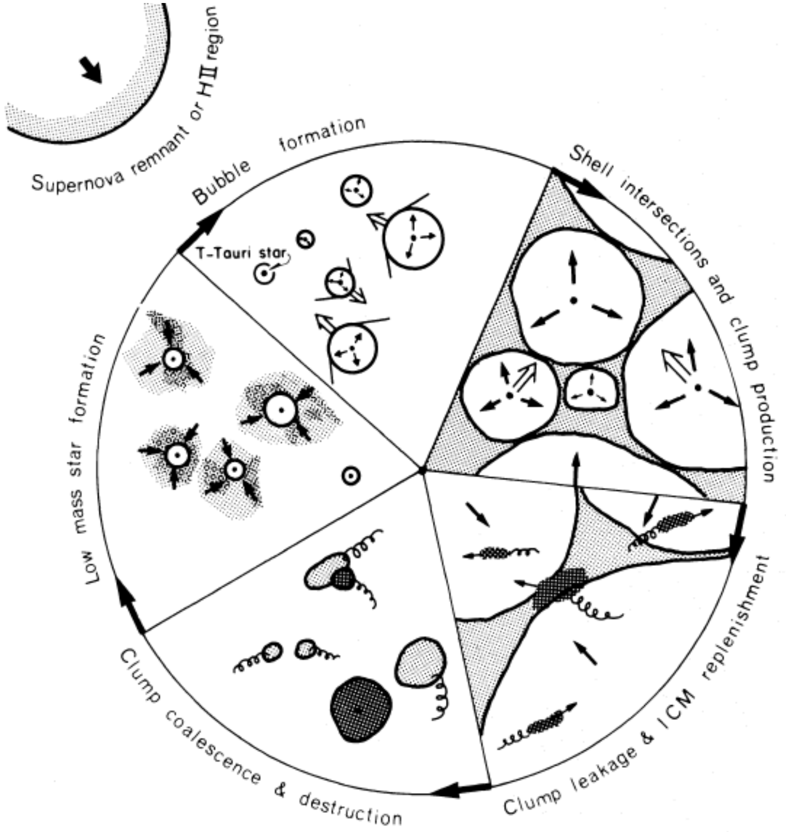
$\sim 10^{-6}\ M_{sun}$/yr today at T=10K
but $\sim 10^{-3}\ M_{sun}$/yr at T=1000K

first stars were massive

halted by ***feedback*** : taps stellar energy via MHD turbulence



NGC1333: Quillen+2006

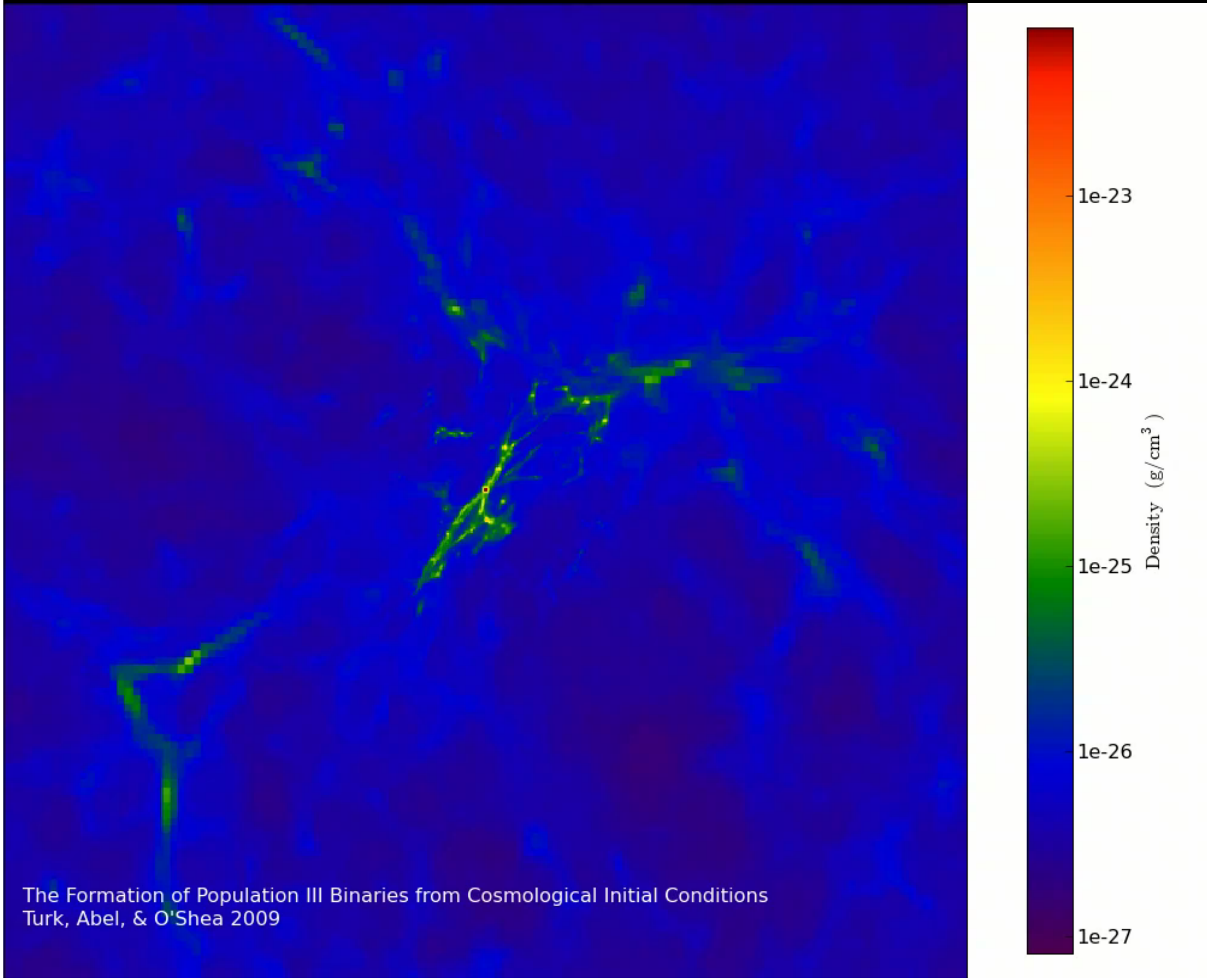


current epoch feedback: cloud cores

Silk & Norman 1980
Li & Nakamura 2008
Abel & Nakamura 2010

Protostellar outflows
(in magnetised clouds)

The first stars: fragmentation



a hybrid model

cold gas flows via filaments/minor mergers lead to disk formation/bulges

at low efficiency

major mergers + hot infall + cooling forms massive spheroids

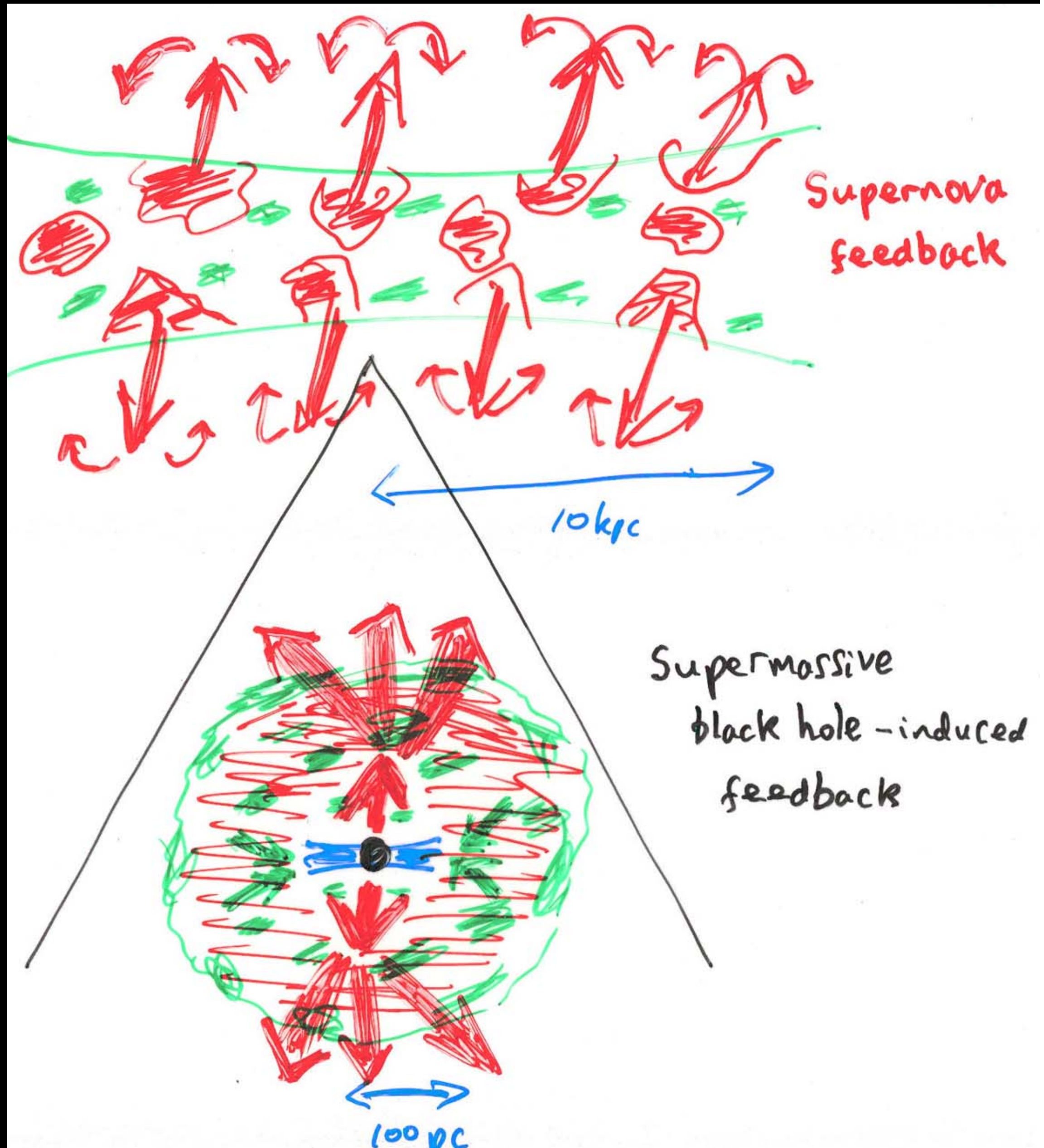
at high efficiency

role of supermassive black holes

quenching of star formation

Intracluster gas heating

triggering of star formation



GALAXY FORMATION CHALLENGES COSMOLOGY

RESURRECTION VIA FUNDAMENTAL PHYSICS

- MODIFYING THE NATURE OF DARK MATTER?
- MODIFYING GRAVITY?

RESURRECTION VIA ASTROPHYSICS

- FEEDBACK via SUPERNOVAE and AGN
- UNDERSTANDING STAR FORMATION

IMPROVED RESOLUTION IN THEORY AND IN OBSERVATION IS ESSENTIAL FOR CREDIBILITY