Let There Be Light: Galaxy Formation for the Novice

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University of Oxford

LAPTH 25 Fev 2010

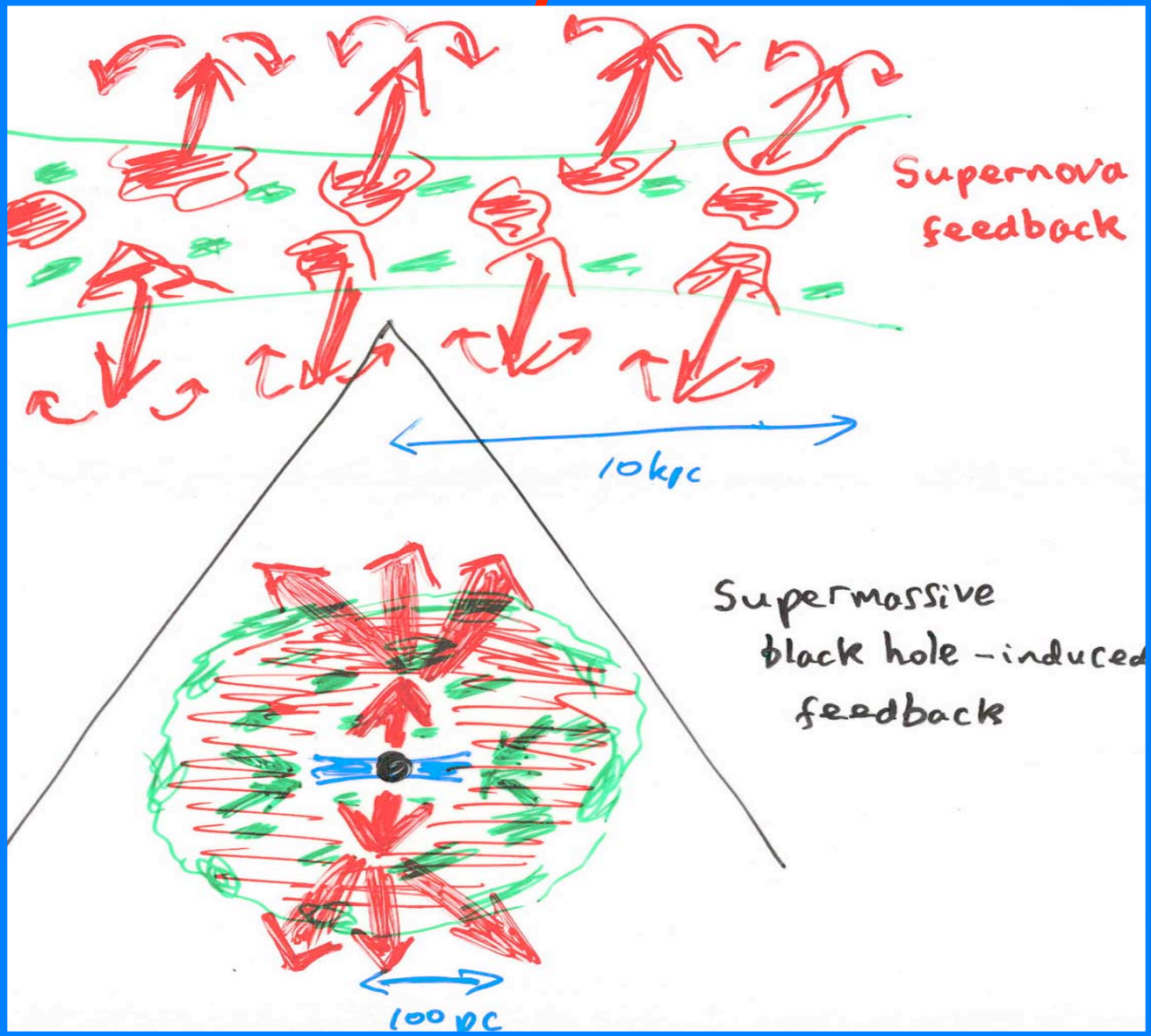
star formation

disk galaxy formation

spheroidal galaxy formation

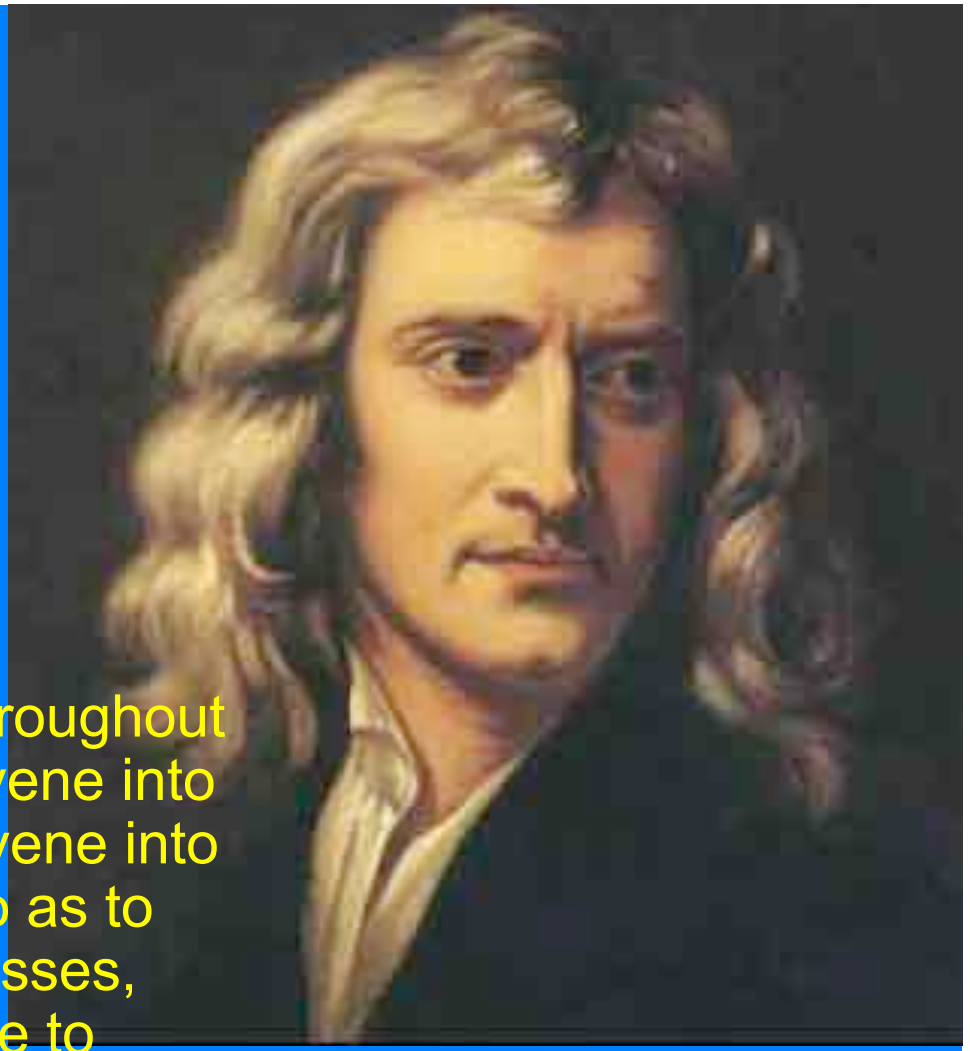
supermassive black holes

a hybrid model



Isaac Newton 1643-1727

December 10, 1692



if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space.And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

But how the matter should divide itself into two sorts, and that part of it which is to compose a shining body should fall down into one mass and make a sun and therest which is to compose an opaque body should coalesce, not into one great body, like the shining matter, but into many little ones; or if the sun at rest were an opaque body like the planets or the planets lucid bodies like the sun, how he alone should be changed into a shining body whilst all they continue opaque, or all they be changed into opaque ones whilst he remains unchanged, **I do not think explicable by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent.**

December 10, 1692

James Jeans (1877-1946)

Criterion for gravitational stability found by Jeans (1902):

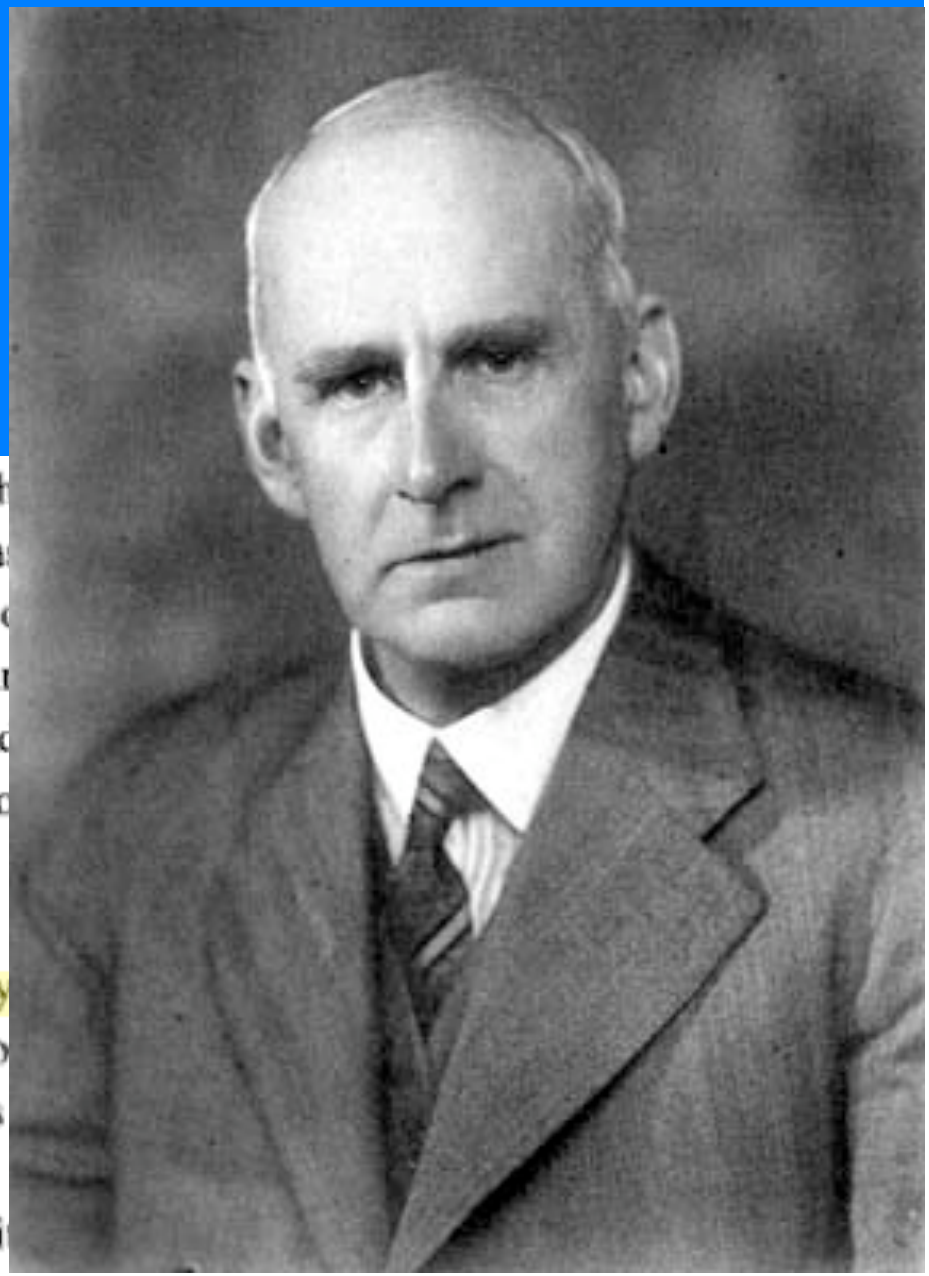
pressure opposes collapse: sound waves must cross region to communicate pressure changes before collapse

"We have found that as Newton first conjectured, a chaotic mass of gas of approximately uniform density and of very great extent would be dynamically unstable: nuclei would tend to form in it, around which the whole matter would eventually condense. All celestial bodies originate by a process of fragmentation of nebulae out of chaos, of stars out of nebulae, of planets out of stars and satellites out of planets."

"From the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician."

imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion, "What 'happens' is the stars."

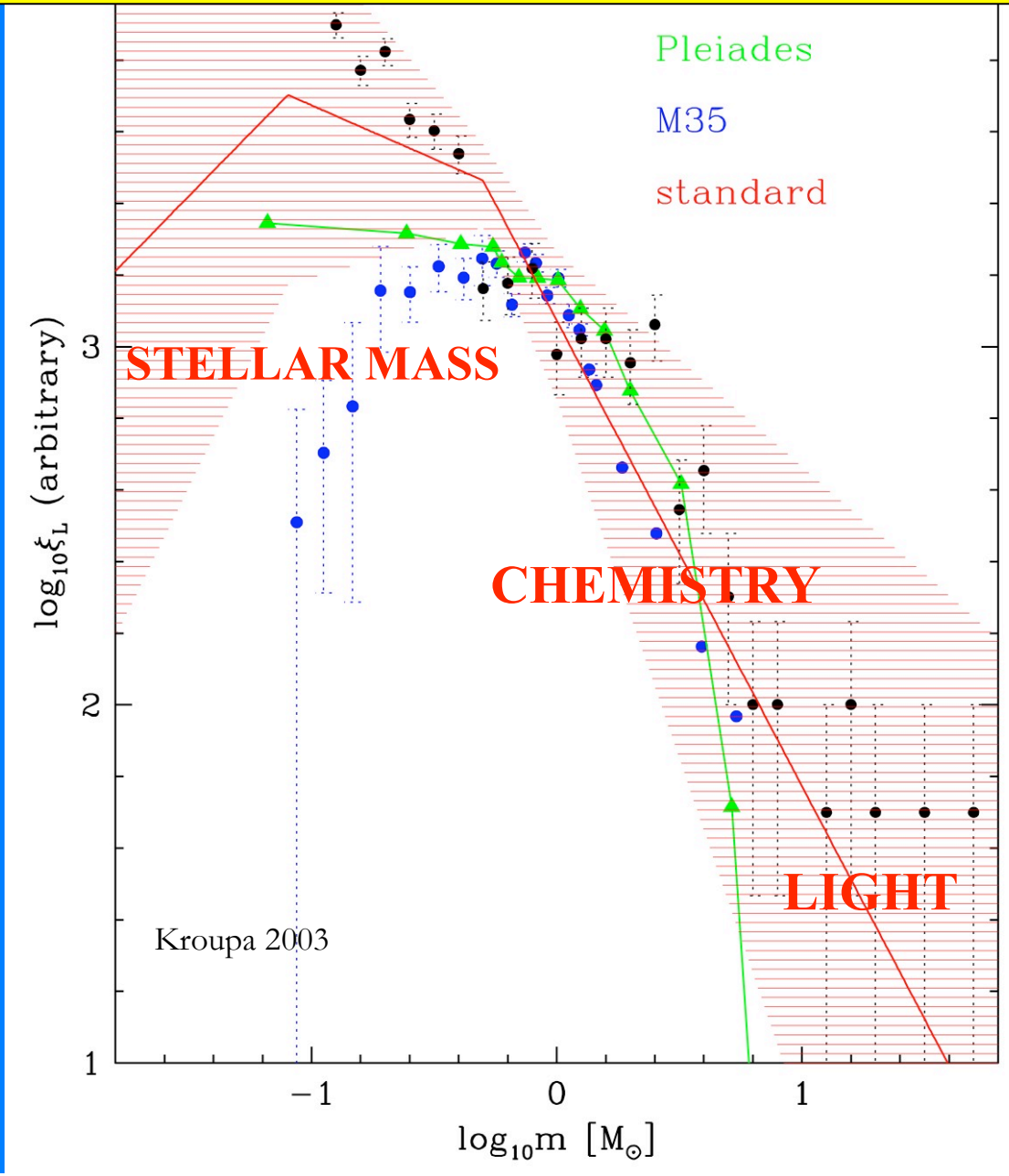
Arthur Eddington (1882-1946)



"We can imagine a physicist on a cloud-bound planet wh
the stars calculating the ratio of radiation pressure to ga
globes of gas of various sizes, starting, say, with a globe
gm., 1000 gm., and so on, so that his *n*th globe contai
as a tussle between matter and aether (gas pressure an
contest is overwhelmingly one-sided except between No
expect something interesting to happen.
What 'happens' is the stars.
We draw aside the veil of cloud beneath which our phy
and let him look up at the sky. There he will find a tho
gas nearly all of mass between his 33rd and 35th globes
$\frac{1}{2}$ and 50 times the sun's mass."

Sir Arthur S. Eddington: The Internal Consti

The initial mass function of stars



Keys to Star Formation

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

$$\sim \alpha_g^{-3/2} m_p \sim 0.01 \mathrm{M}_\odot$$

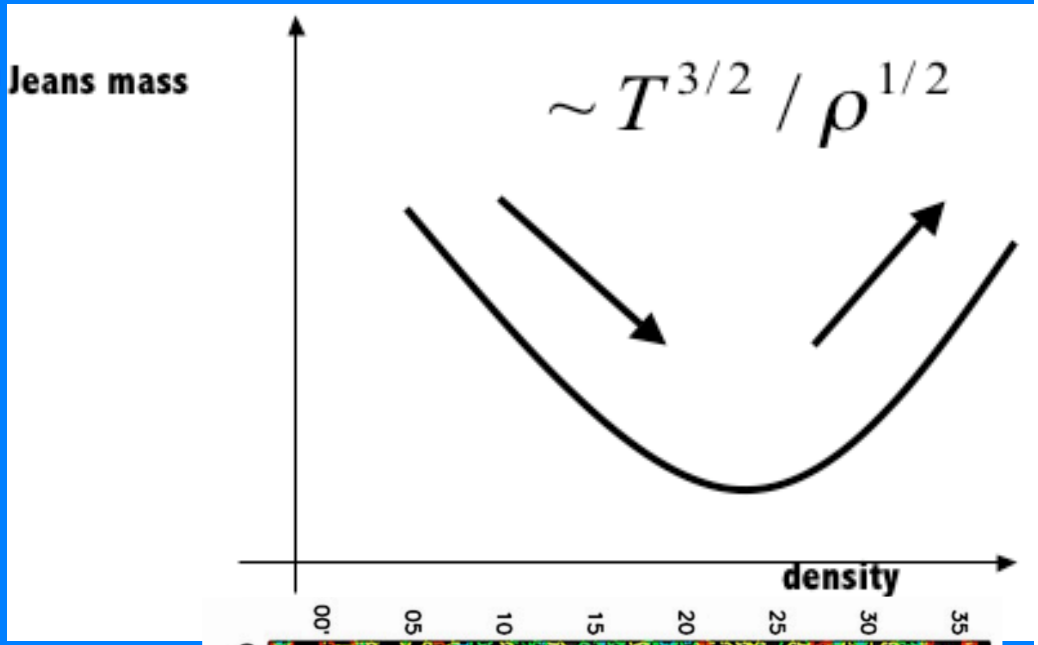
- resolution: ***accretion*** of cold gas

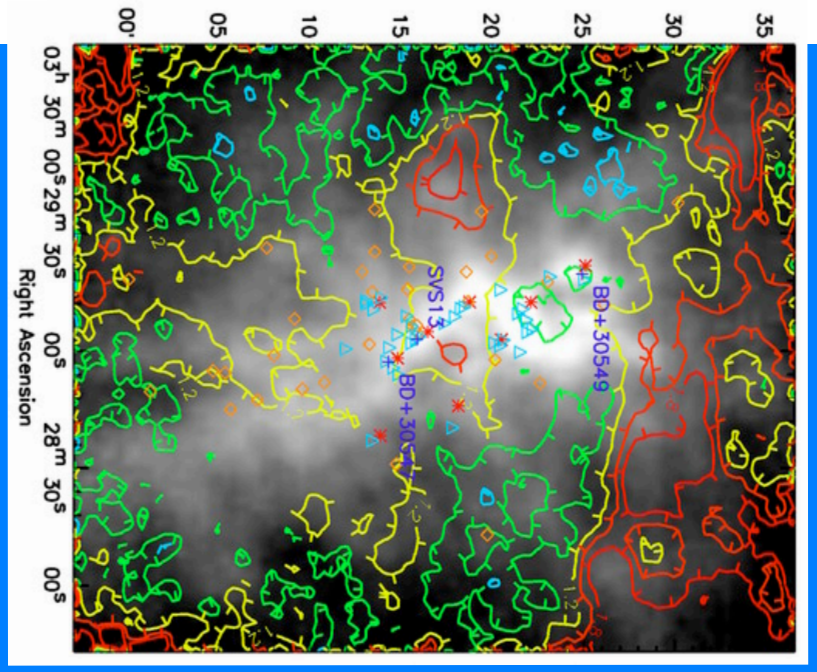
$$\dot{M}_{gas} \sim V_s^{\ 3}/G \Rightarrow$$

first stars were massive

10^{-6} M_{sun}/yr today at T=!0K
but 10^{-3} M_{sun}/yr at T=1000K

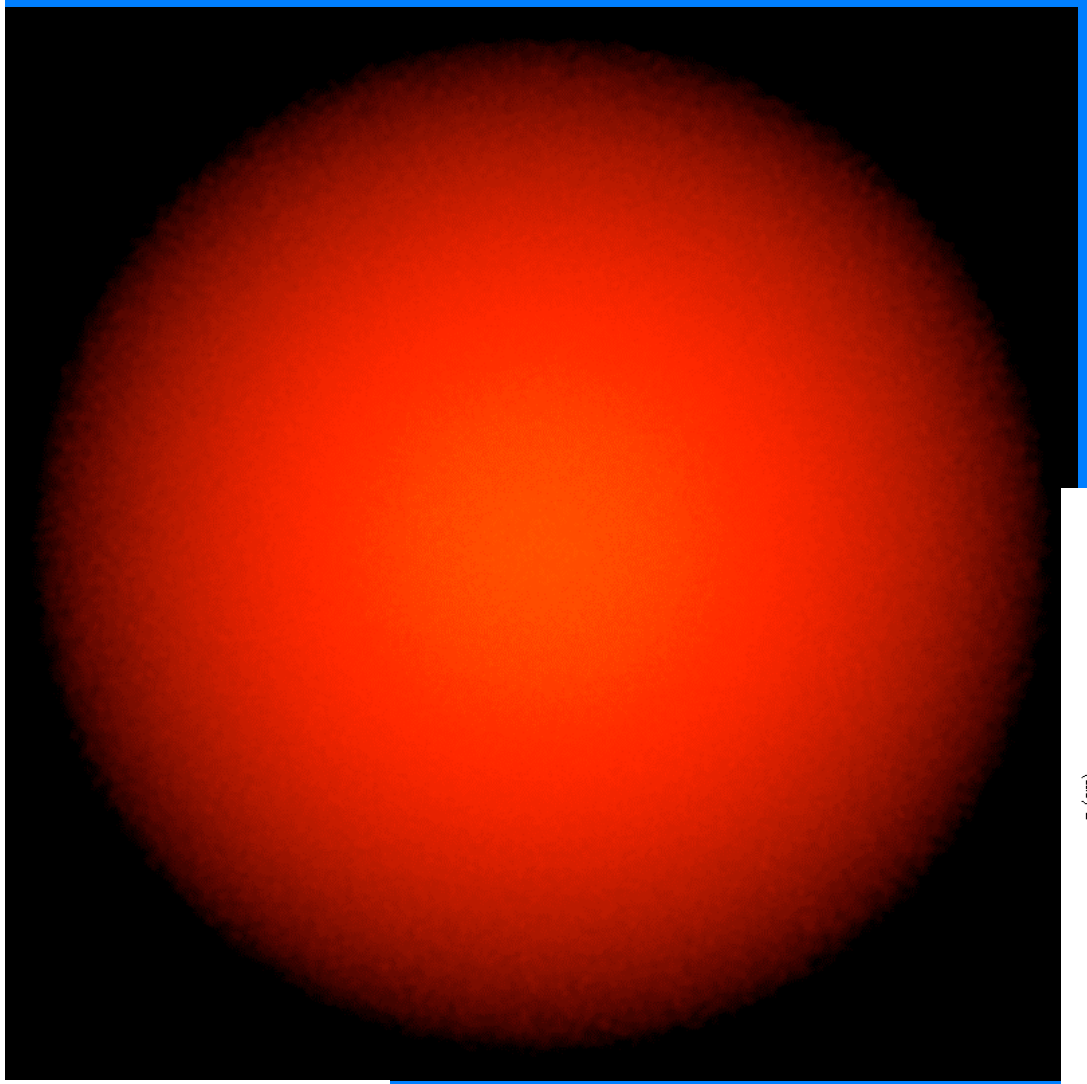
- halted by ***feedback*** : taps stellar energy via MHD turbulence



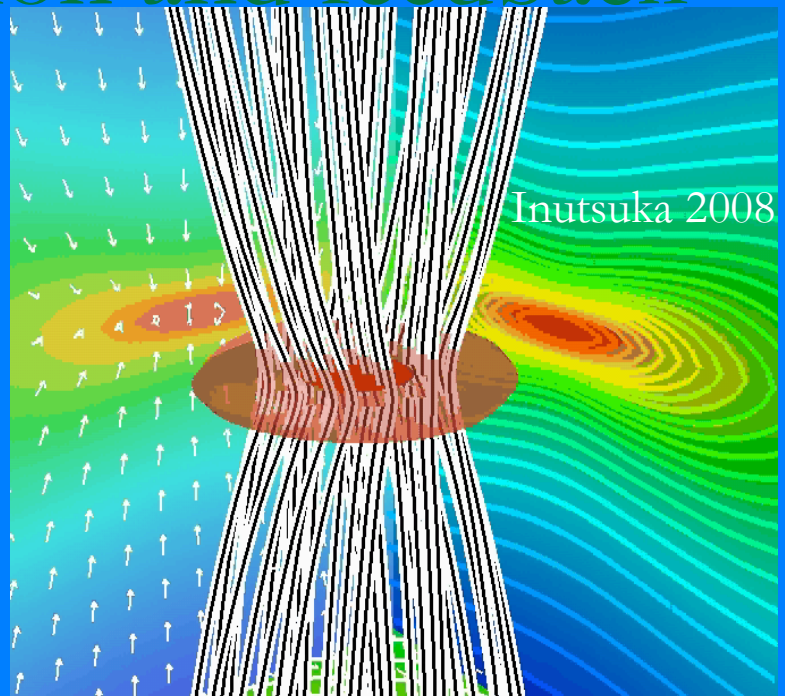


NGC1333: Quillen+2006

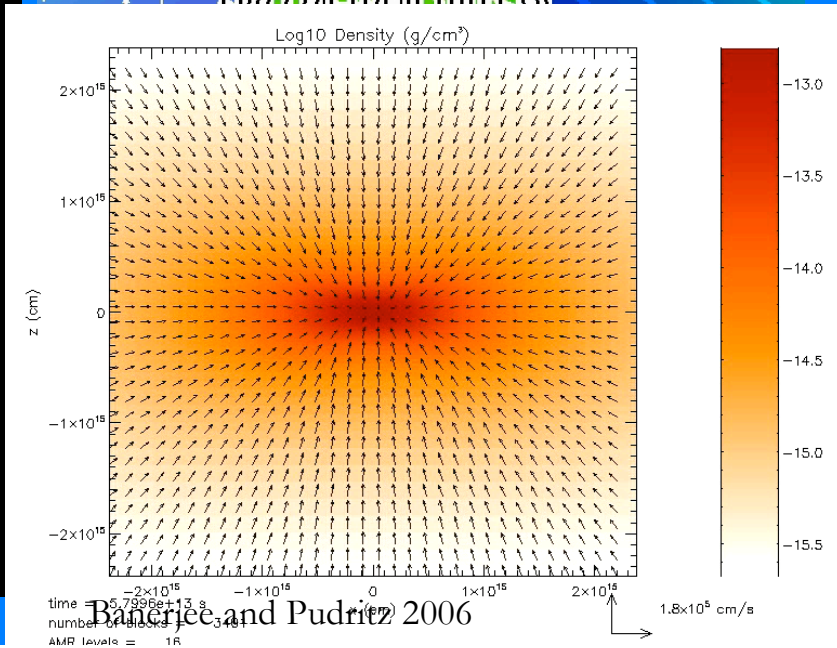
Fragmentation, accretion and feedback



Bonnell+2008



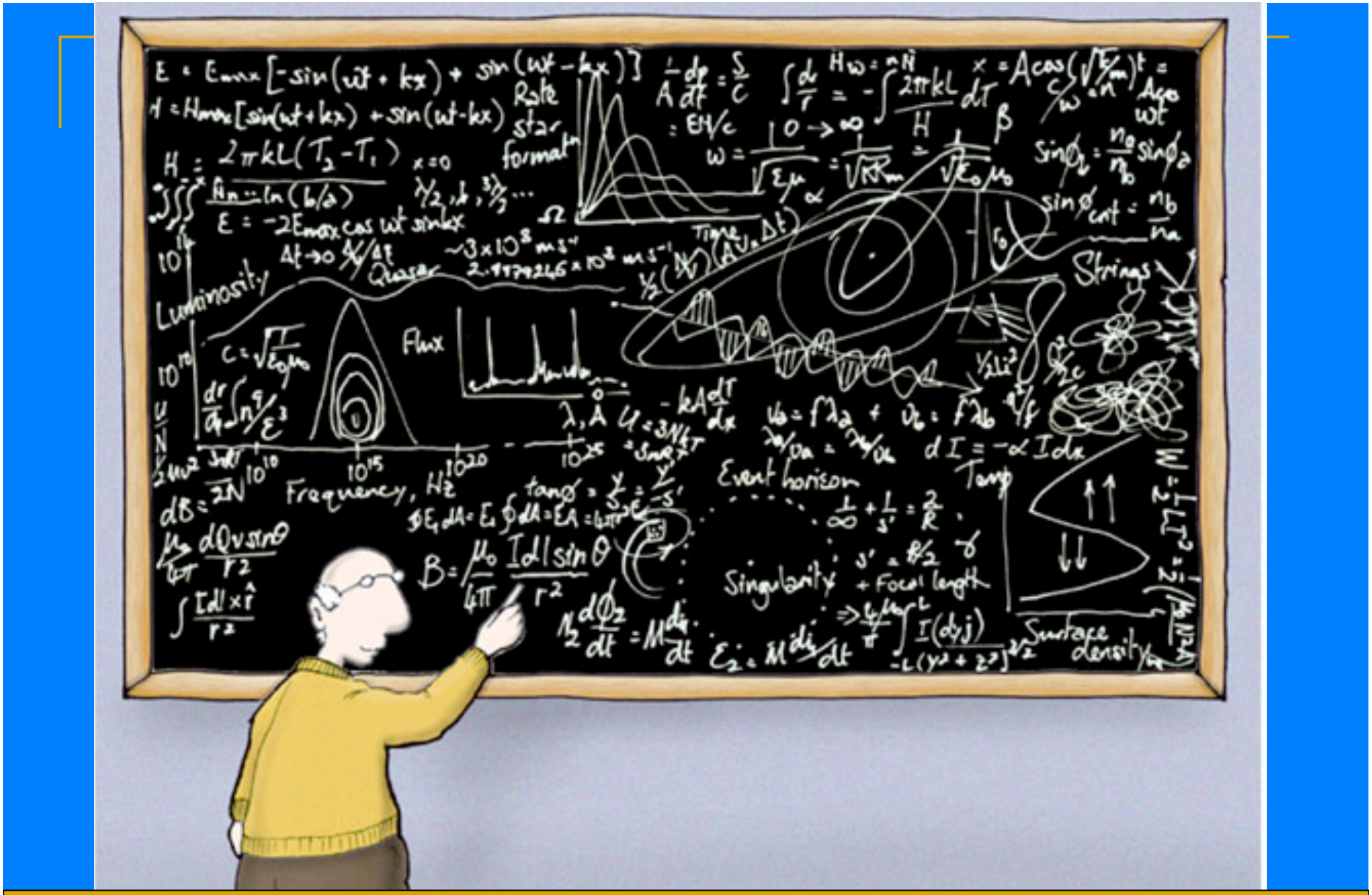
Inutsuka 2008



Banerjee and Pudritz 2006

- **Can we predict the initial stellar mass function?** — **No**
- **Can we account for the efficiency of star formation?** — **No**
- **Can we account for the galactic star formation rate?** — **No**
- **Do we understand supermassive black hole feedback?** — **No**

What's missing?
A robust theory of star formation



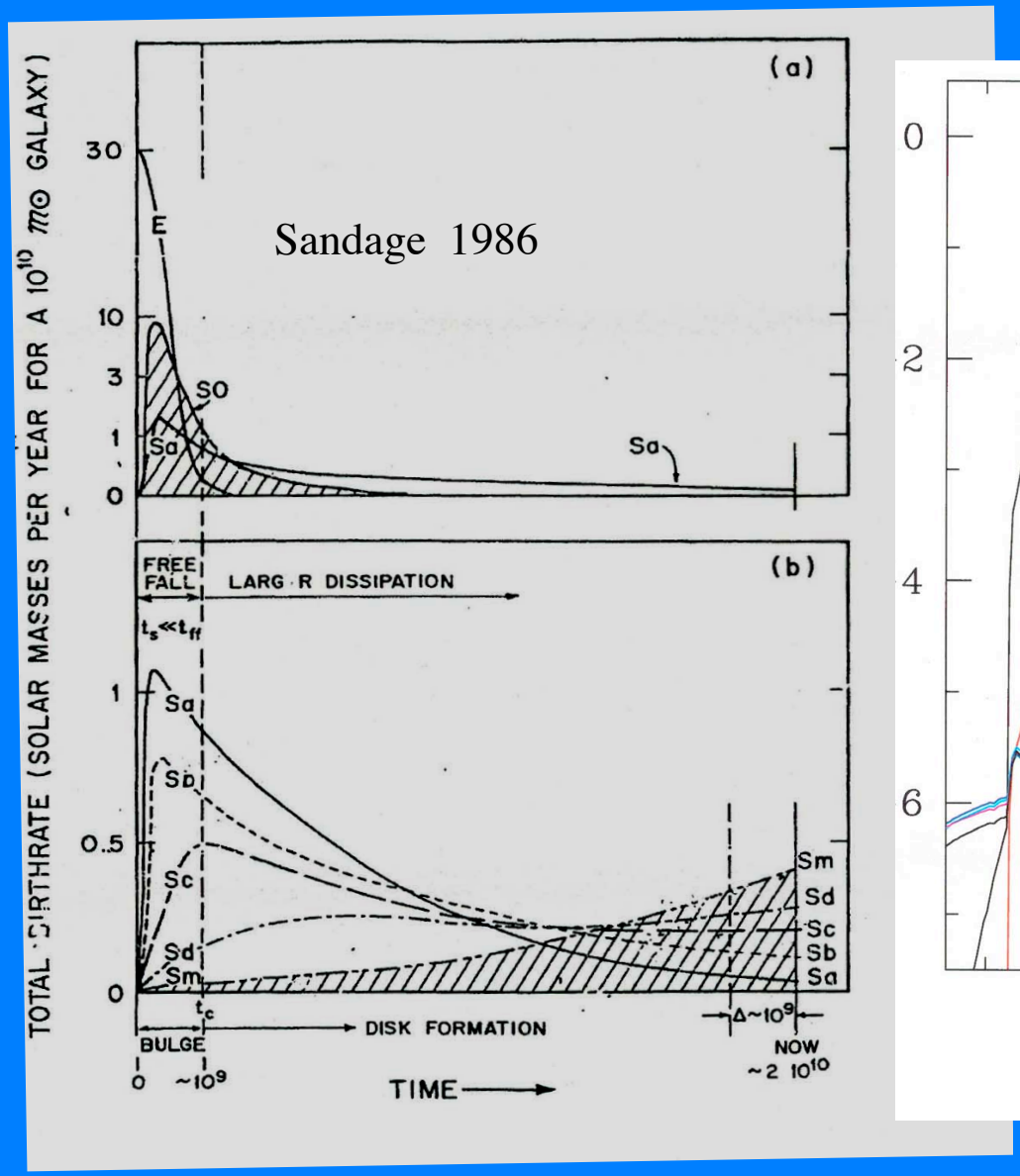
so we use phenomenological recipes for star formation

Disk galaxies form by infall at low z

Massive spheroids form by mergers at high z

Supermassive black holes

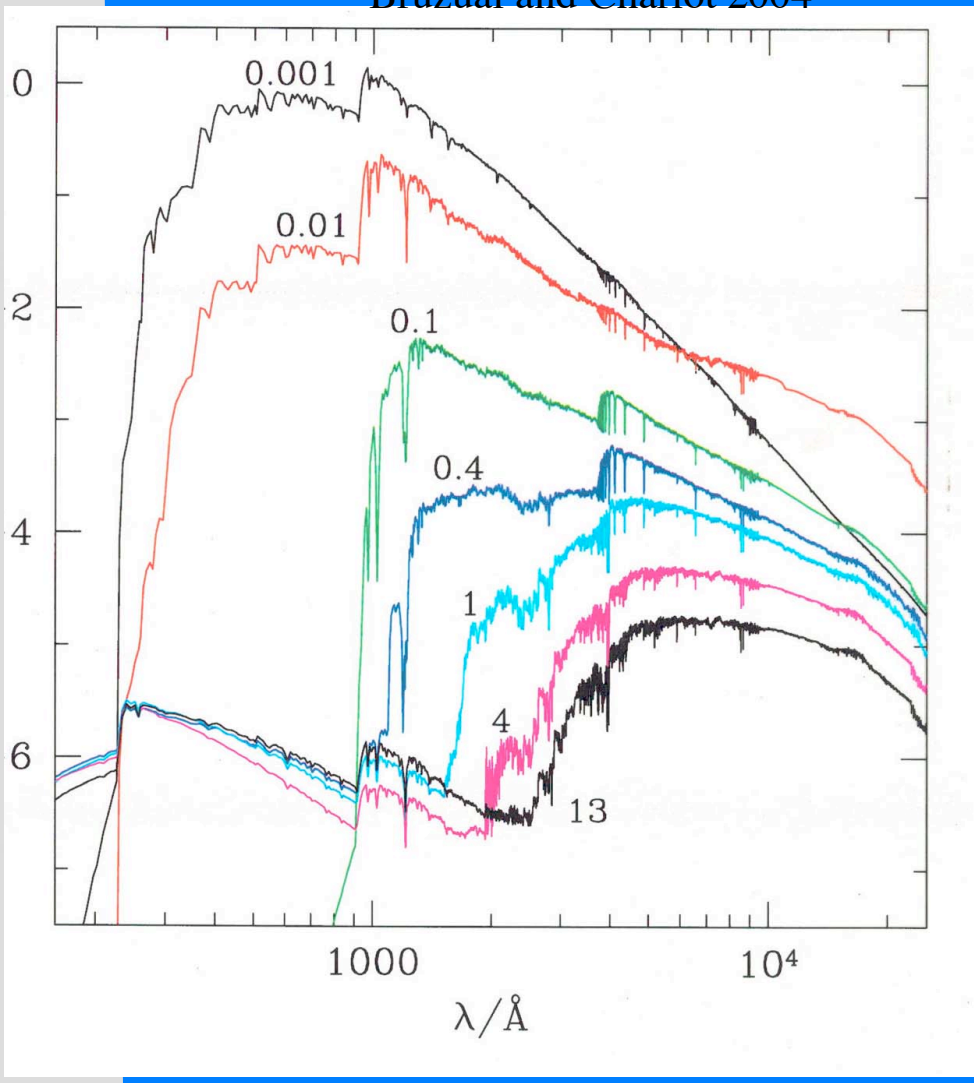
STAR FORMATION RATE HISTORY OF GALAXIES

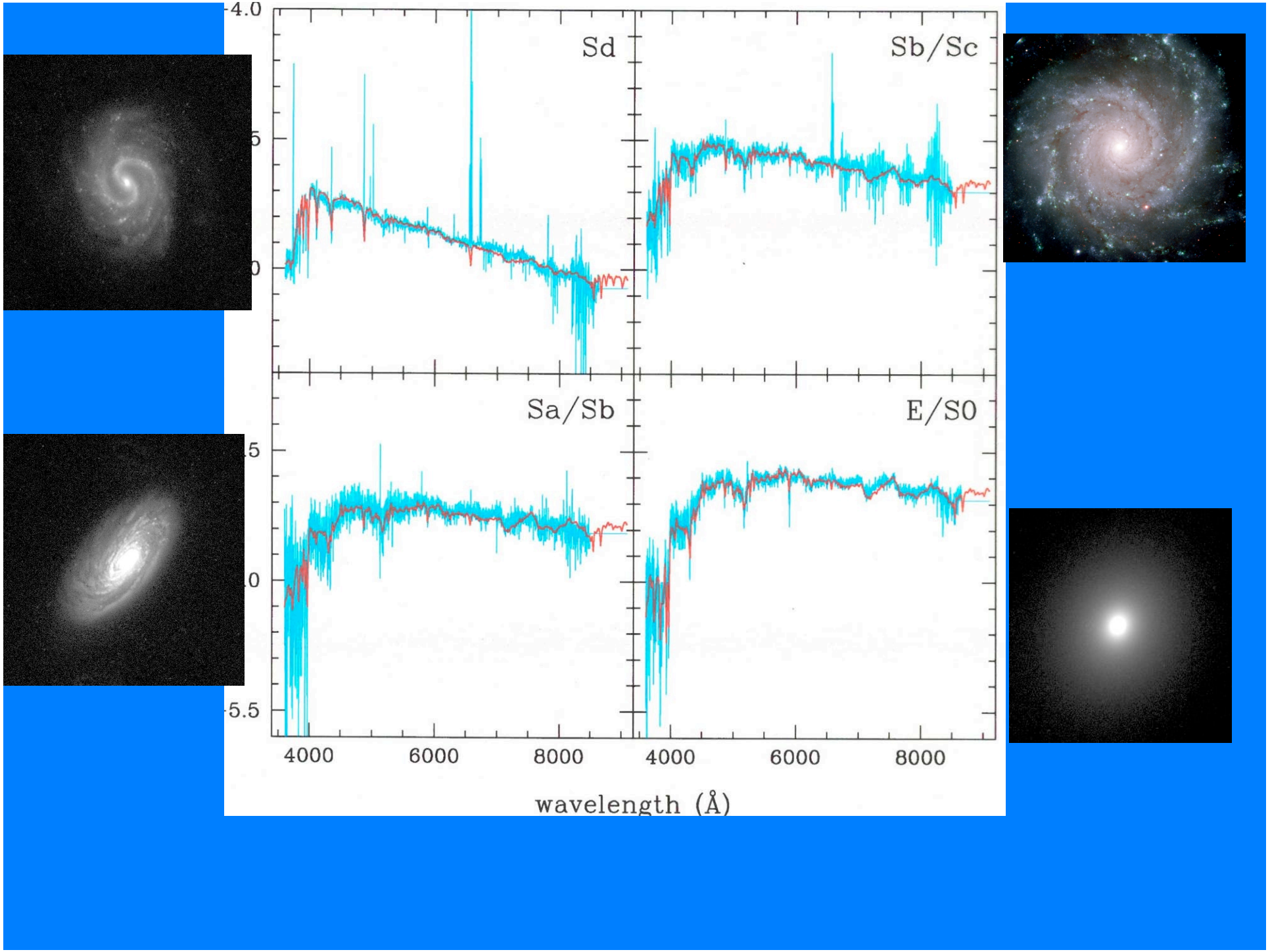


Sandage 1986

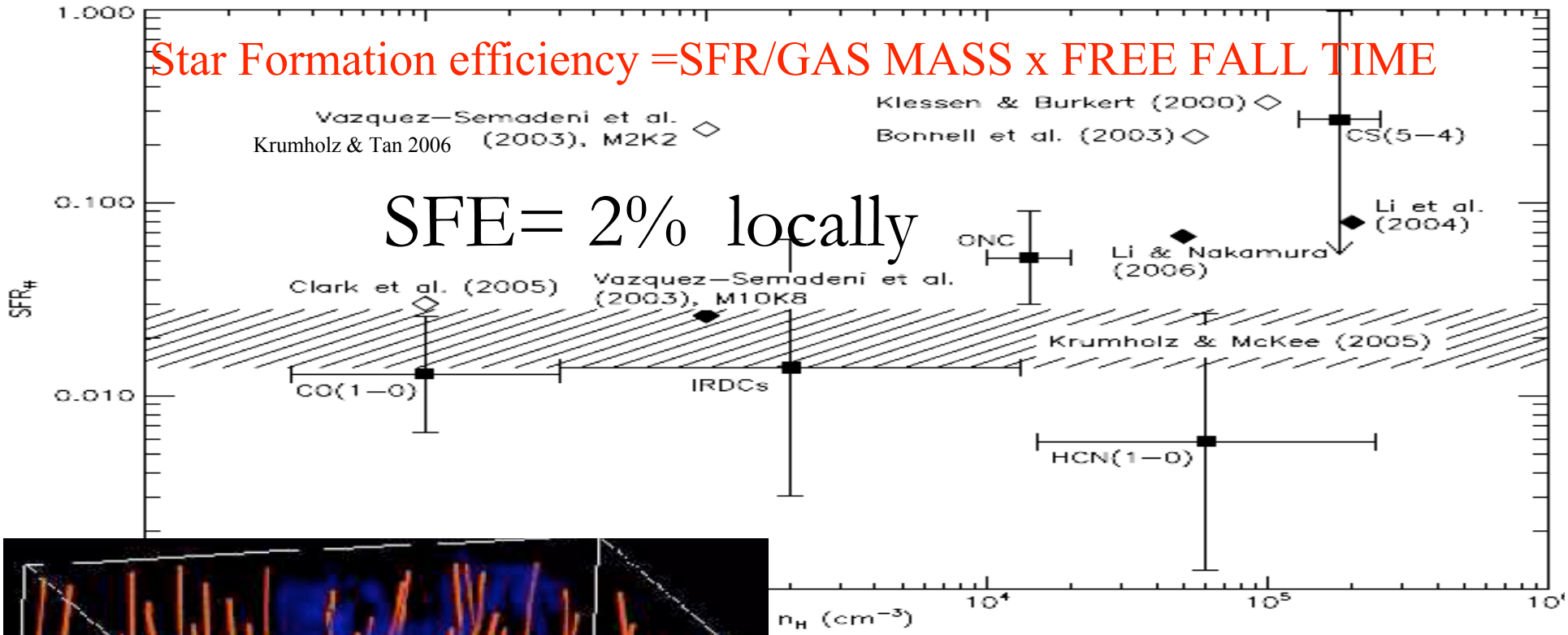
EVOLUTION OF SPECTRAL ENERGY DISTRIBUTION OF A GALAXY

Bruzual and Charlot 2004

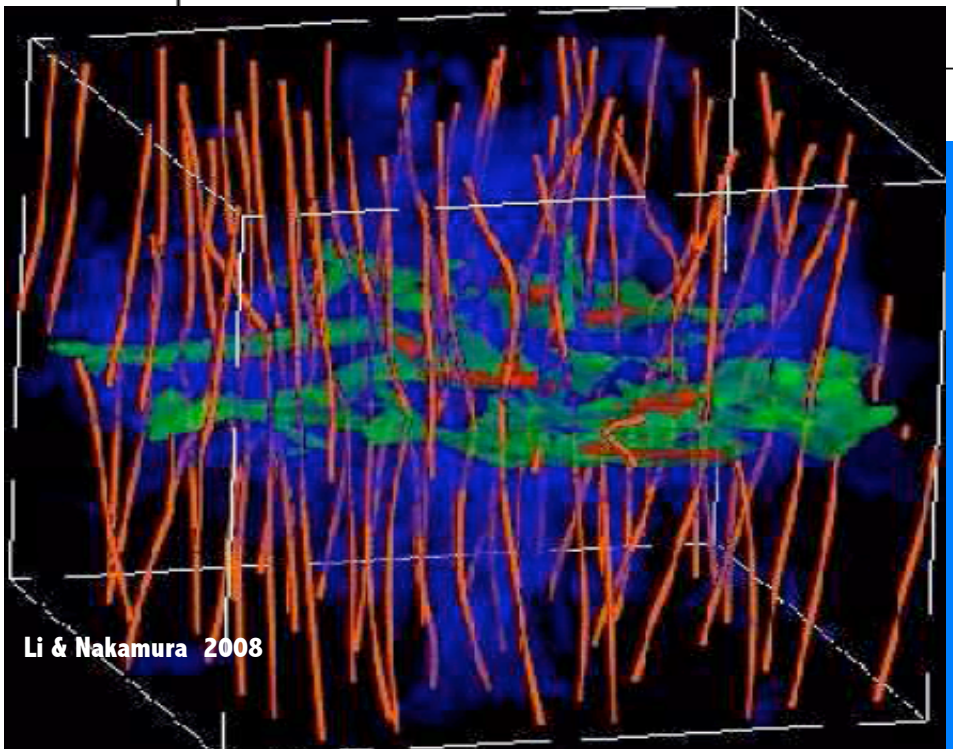



Sd
Sb/Sc
Sa/Sb
E/S0
4000
6000
8000
wavelength (Å)

Star Formation efficiency =SFR/GAS MASS x FREE FALL TIME



SFE= 2% locally



magnetic regulation
protostellar outflows
OB stars: HII regions, winds

DISK MODE OF STAR FORMATION

motivated by gravitational instability of cold disks

Feedback from supernovae is crucial to avoid too high a global star formation rate

Star formation efficiency

$$SFE = \frac{\sigma_{gas}\ v_{cool}\ m_{*,SN}}{E_{SN}^{\ initial}} \approx 0.02$$

gas surface density

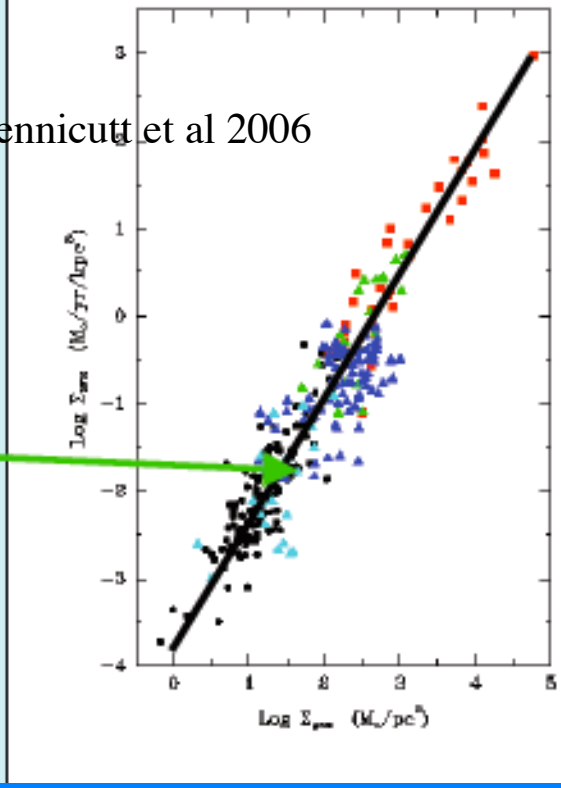
star formation rate

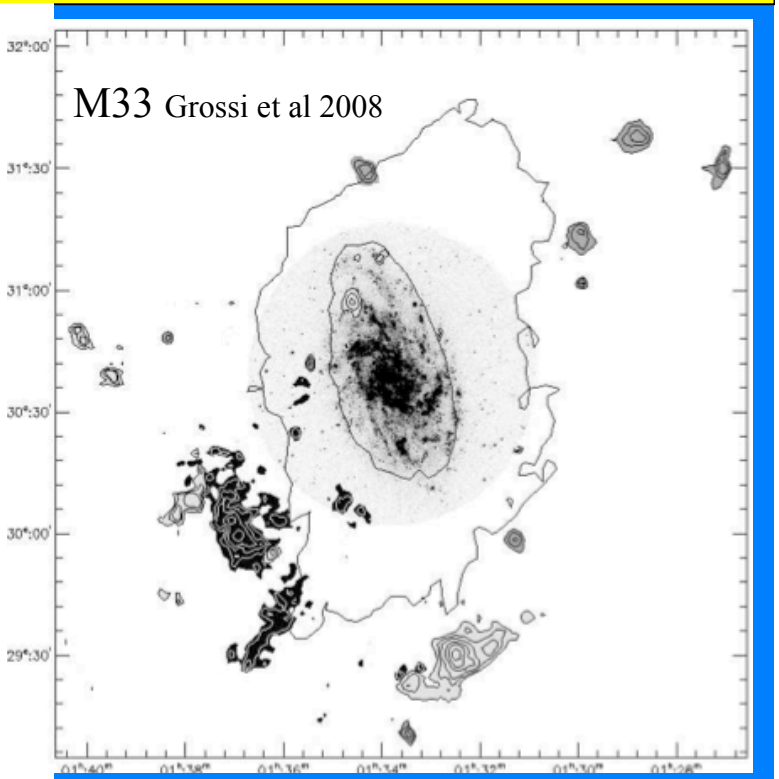
$$\Sigma_{SFR} = (SFE)\,\frac{\Sigma_{gas}}{t_{dyn}}$$

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

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

A GLOBAL STAR FORMATION LAW





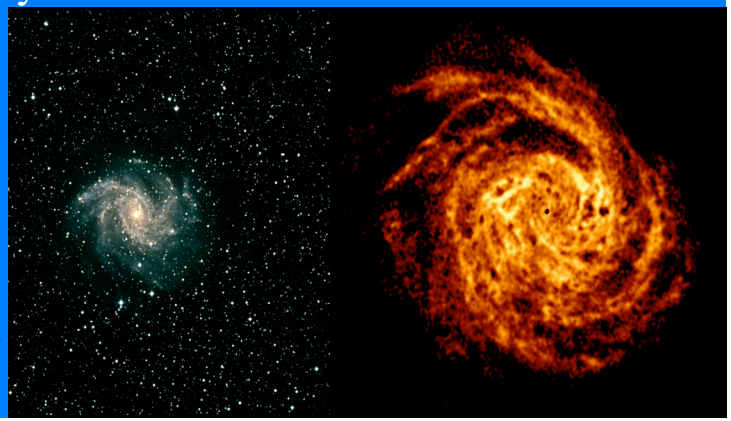
SFR=0.02 (GAS SURFACE DENSITY)/t_{dyn}

fits disk galaxies (& M51 complexes)

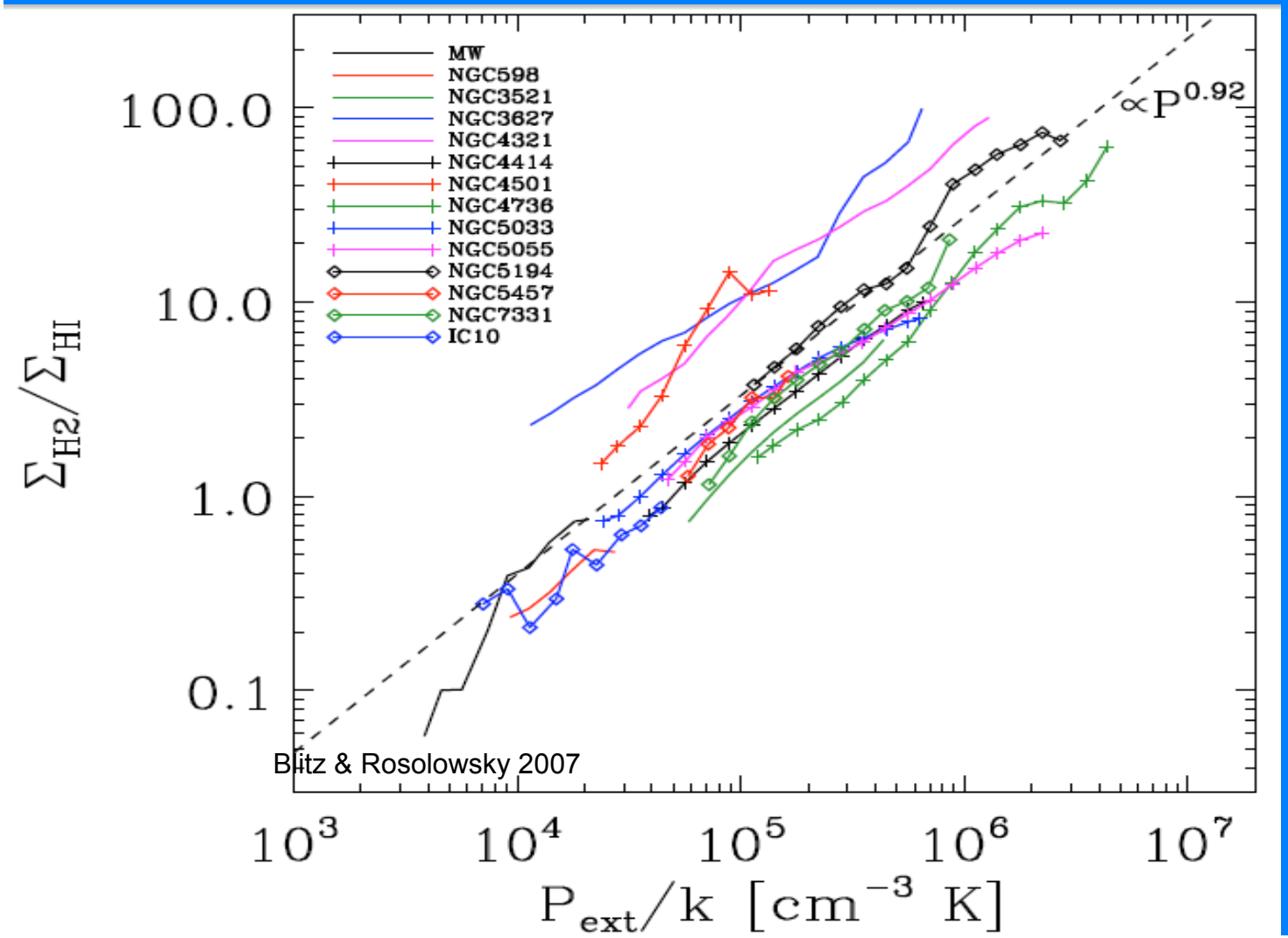
low efficiency due to SN feedback

+ cold gas accretion/global disk instability

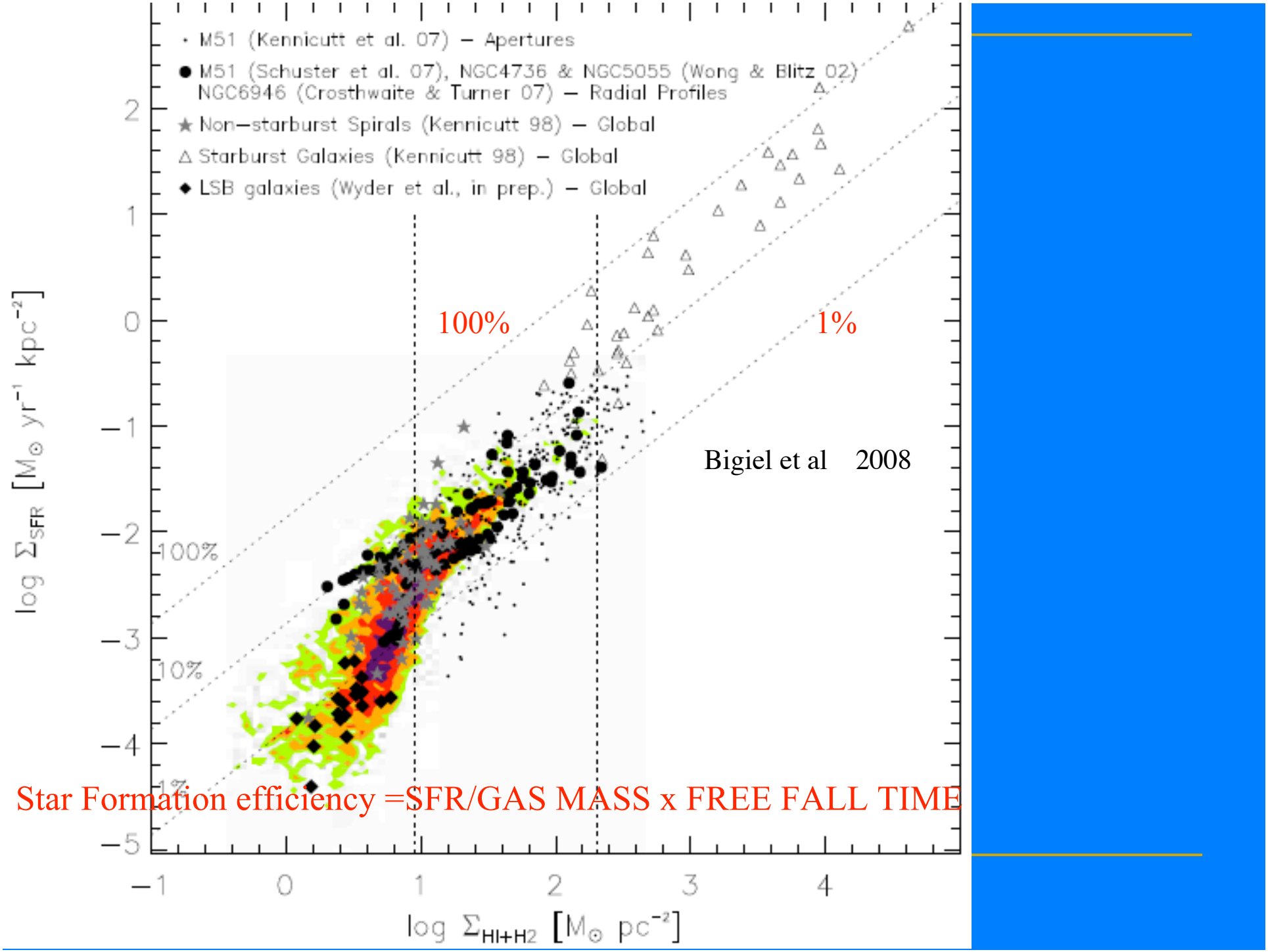
NGC 6946



molecular fraction is regulated by turbulent pressure



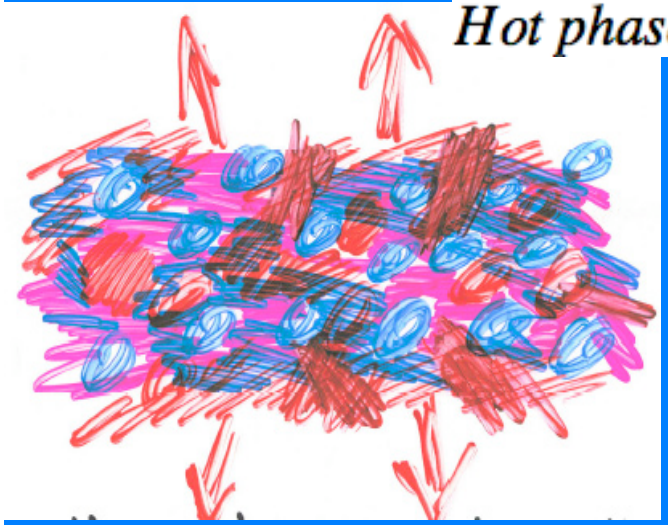
Blitz & Rosolowsky 2007



Star Formation efficiency =SFR/GAS MASS x FREE FALL TIME

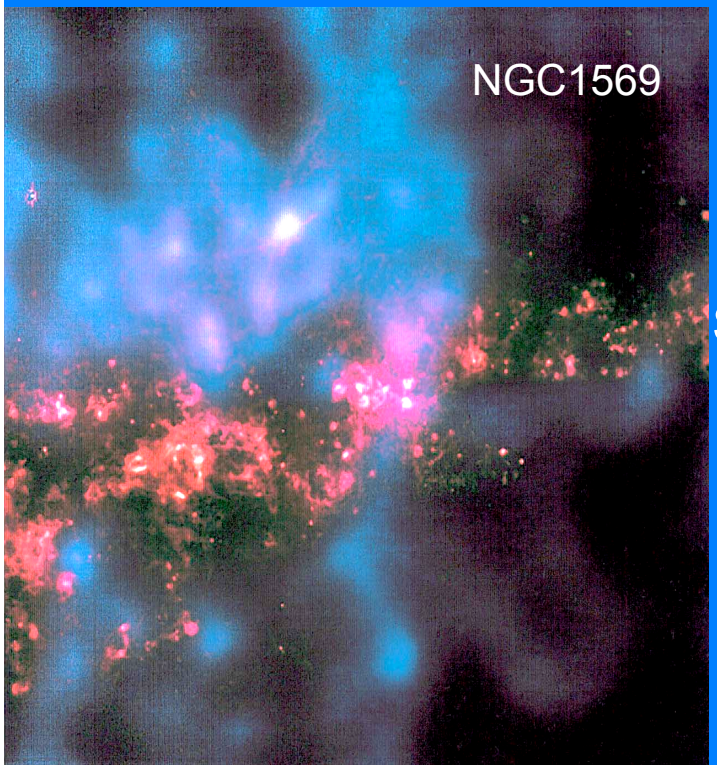
Star Formation in a multi-phase interstellar gas

$Hot\ phase \sim 10^6 K$ $\quad HI \sim 1000K$ $\quad H_2 \sim 10-100K$



$$\text{porosity} \sim \begin{pmatrix} \text{number of} \\ \text{SN bubbles} \\ \text{generated} \\ \text{per unit time} \end{pmatrix} \times \begin{pmatrix} \text{maximum 4 - Volume} \\ \text{of a bubble limited by} \\ \text{ambient ISM pressure} \end{pmatrix}$$

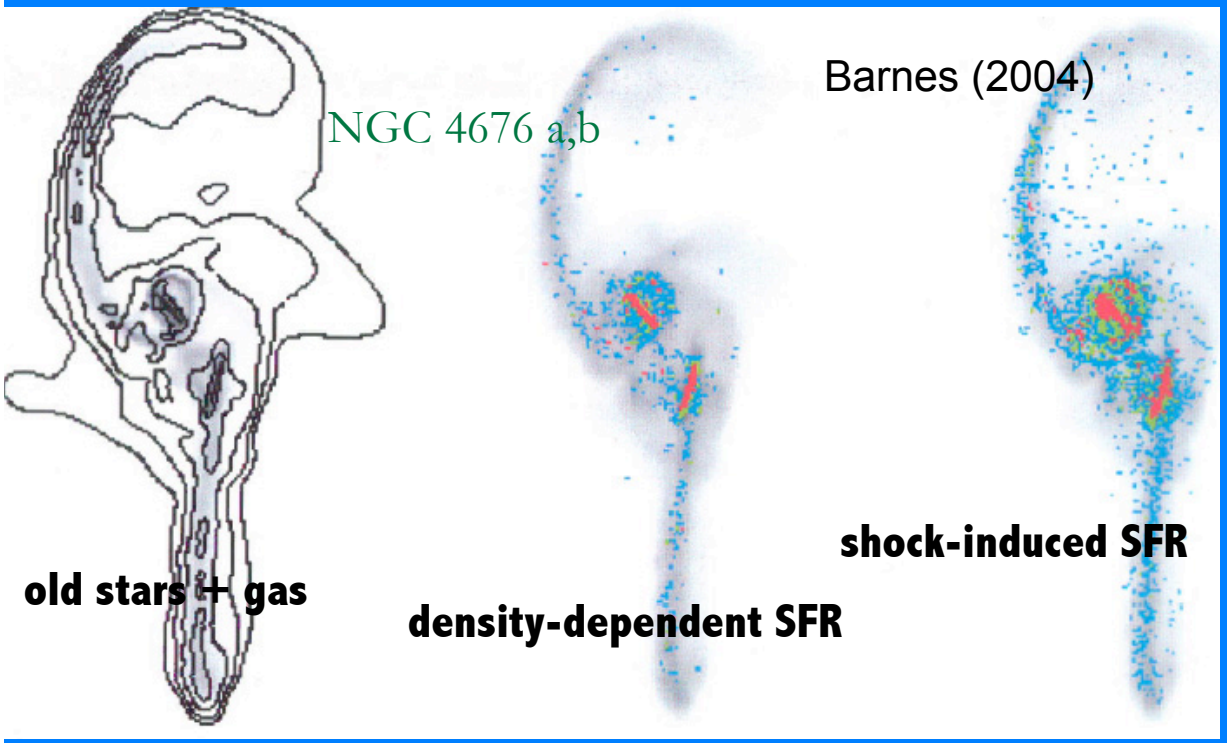
$$\sim (\text{star formation rate}) \times \left(\frac{1}{(\text{pressure})^{1.36}} \right)$$

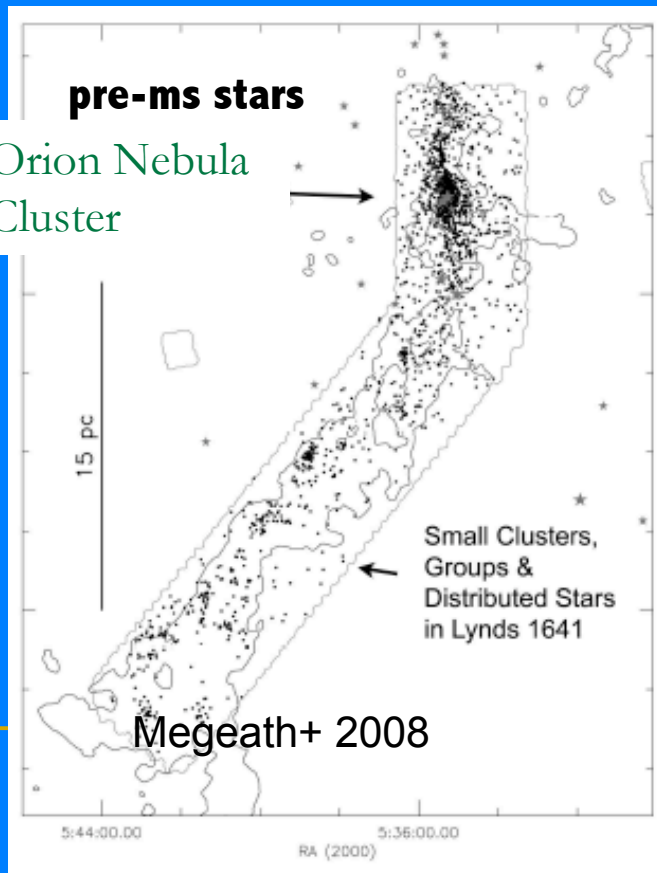


SFR = POROSITY x (TURBULENT PRESSURE)$^{1.36}$

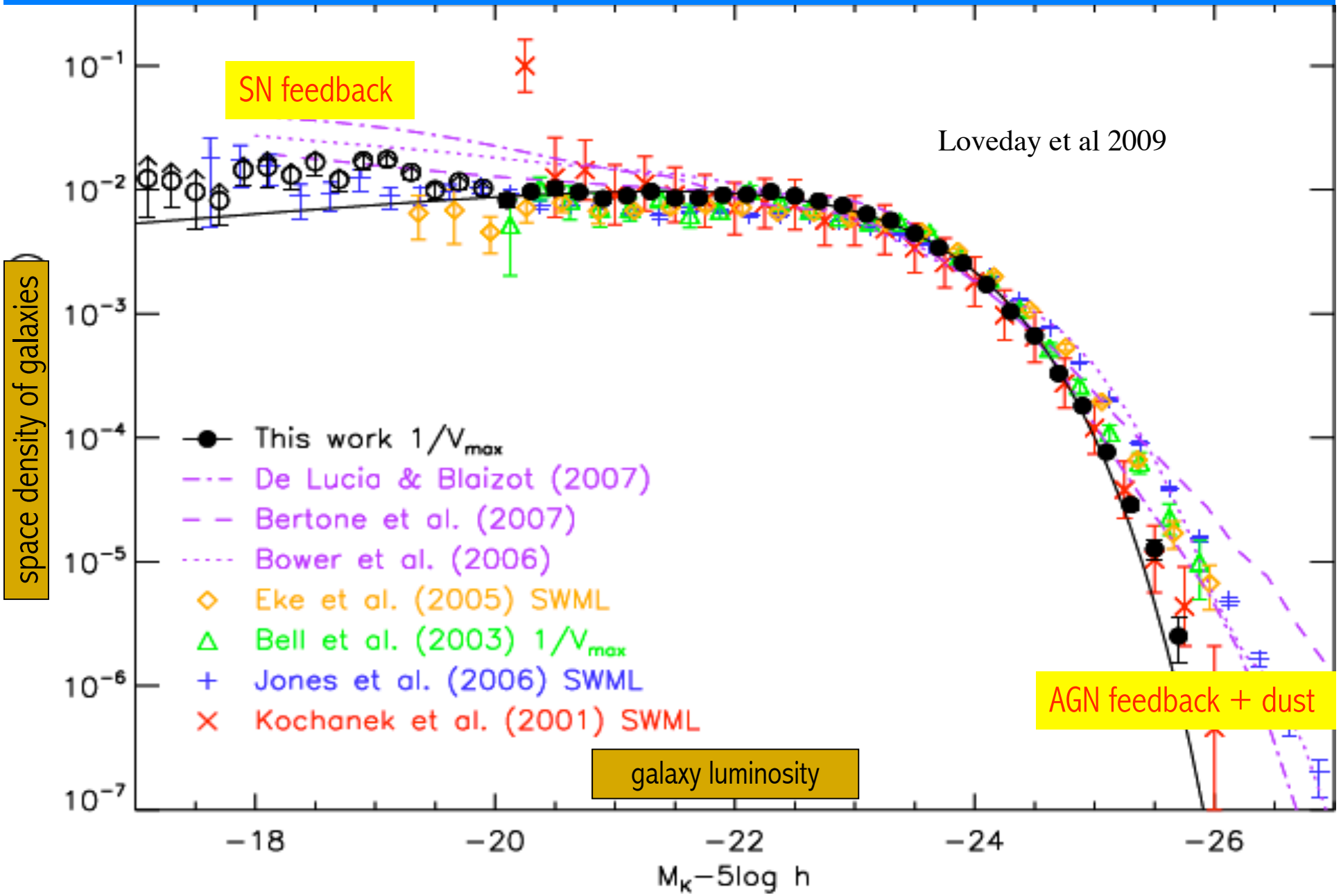
Perhaps porosity self-regulates!

distributed star formation

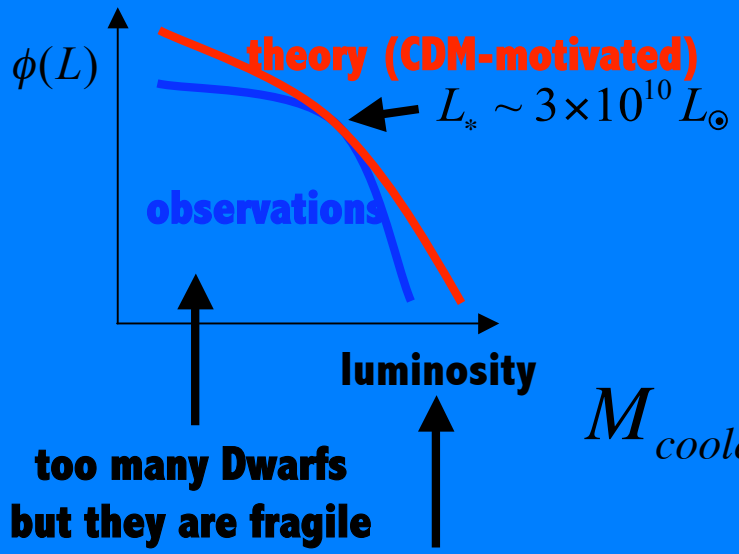




Luminosity function of galaxies



What determines the mass of a galaxy?



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

$$\sim 10^{69} m_p$$

$$\alpha_g = Gm_p^2/e^2 \qquad \beta \sim -0.5$$

Gas cooling time-scale $t_{cool} \sim \dfrac{nkT}{\Lambda(T)n^2}$

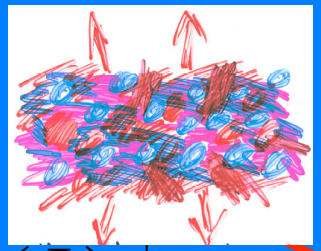
Dynamical time-scale $t_{dyn} \sim \dfrac{1}{\sqrt{Gm_p n}}$

Necessary condition for star formation is cooling:

the KEY ISSUE is astrophysical feedback

I see here that the universe is thought to be full of dense cold clumps

Feedback: low mass galaxies



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

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

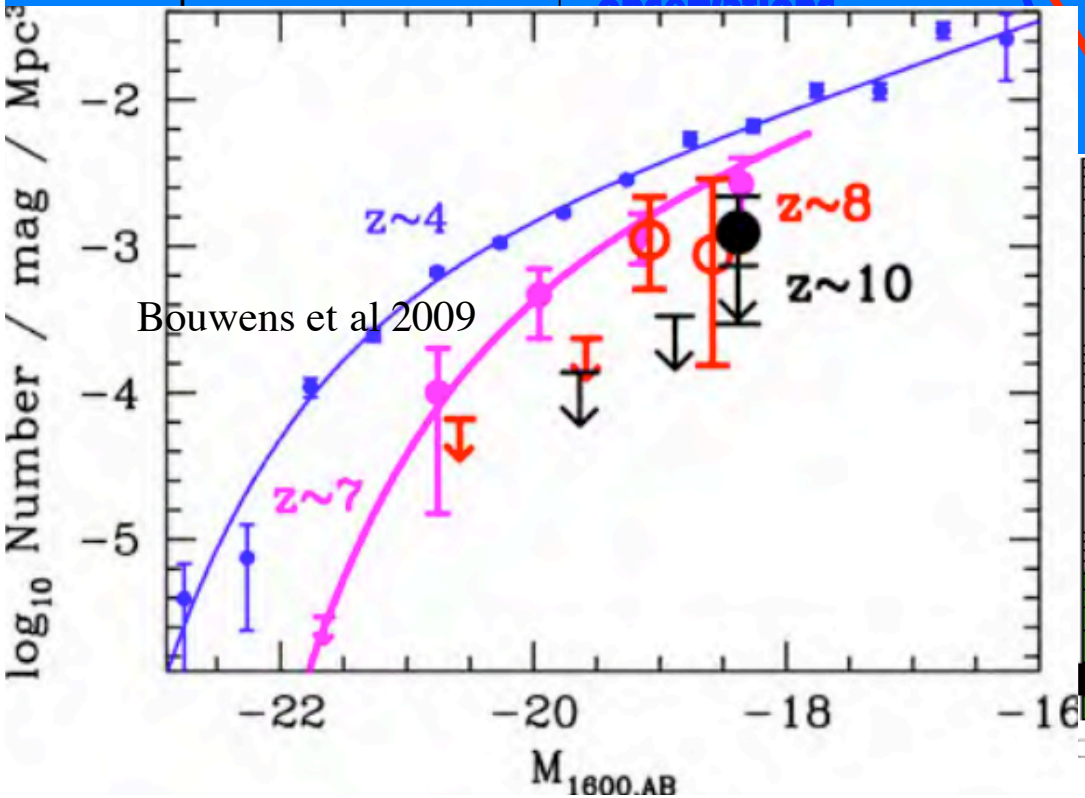
$$t_{cool} \sim \frac{nkT}{\Lambda(T)n^2}$$

$\phi(L)$

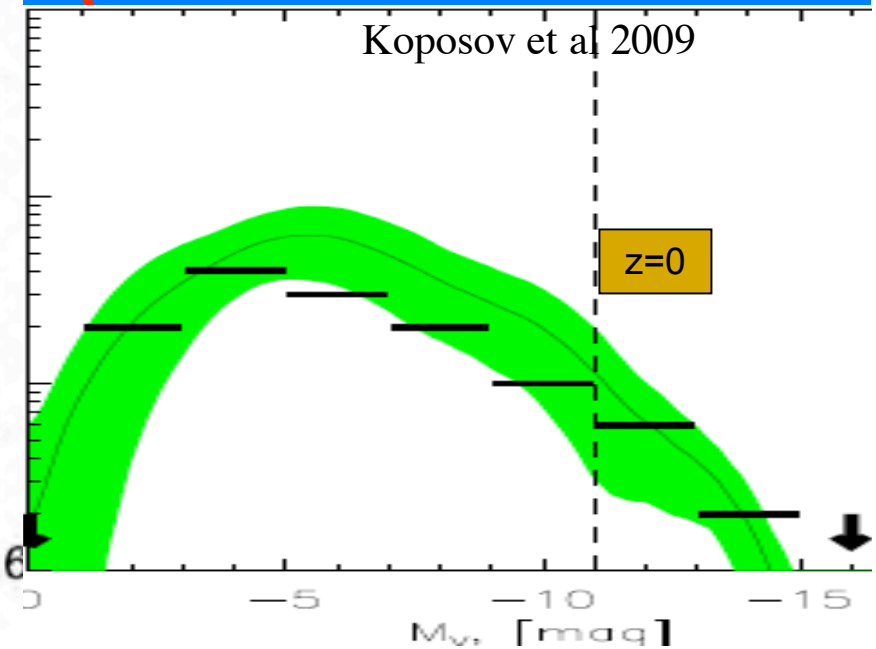
theory (CDM-motivated)

observations

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



Bouwens et al 2009



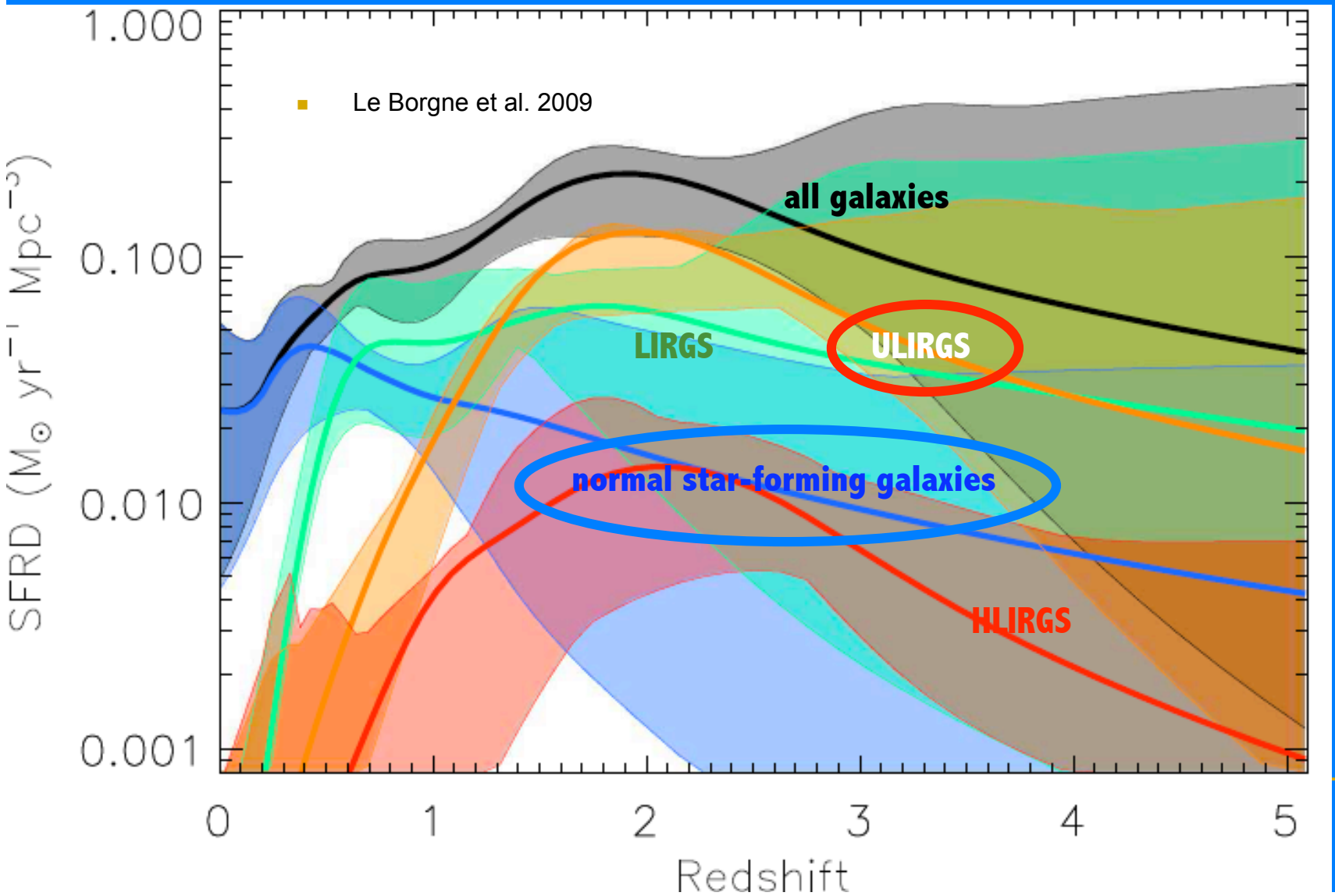
Koposov et al 2009

Disk galaxies form by infall at low z

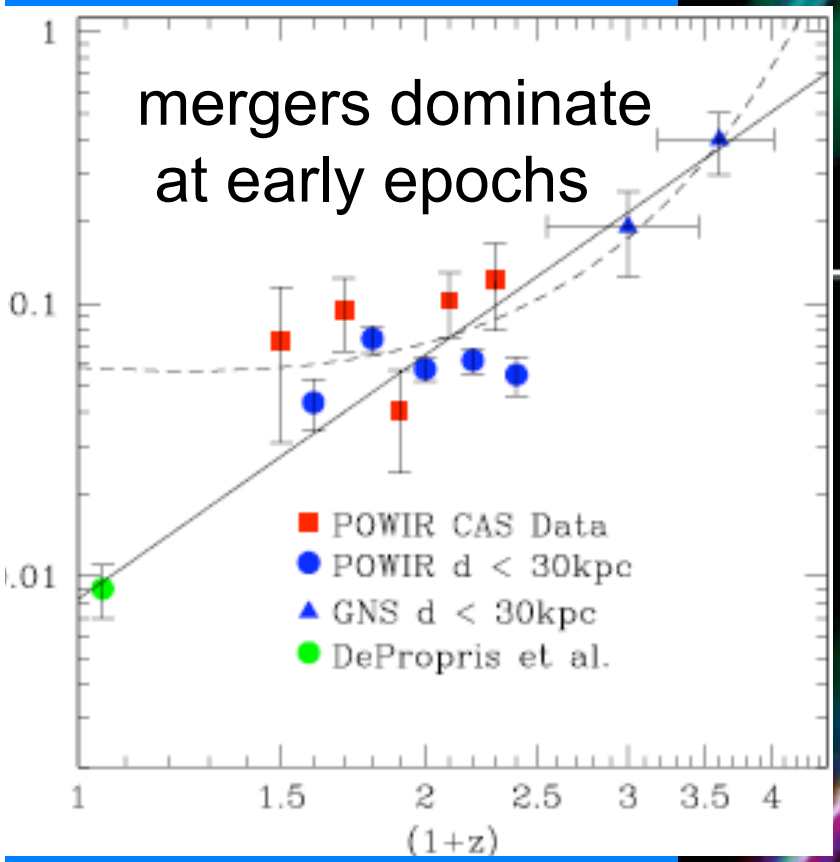
Massive spheroids form by mergers at high z

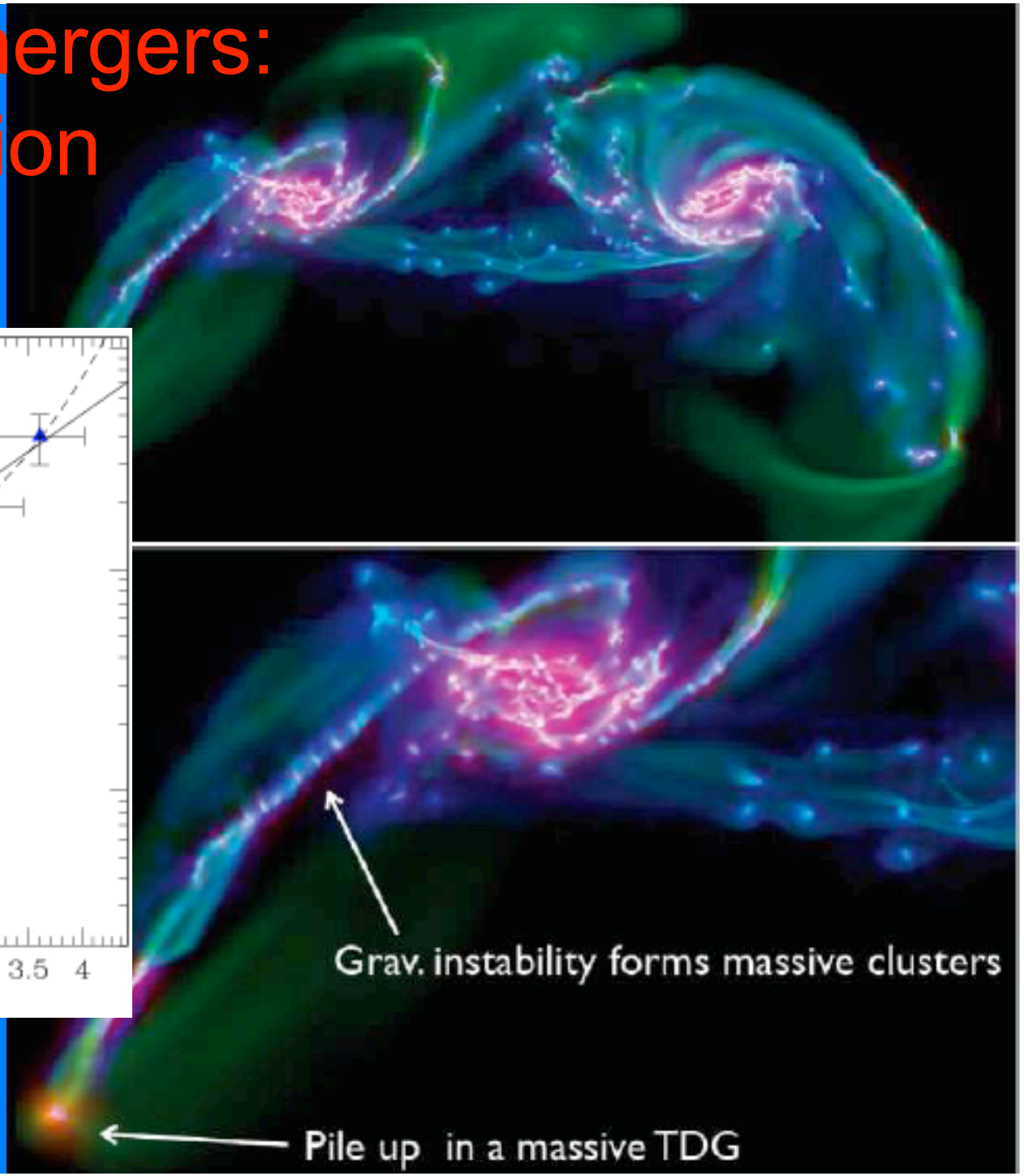
Supermassive black holes

cosmic star formation history

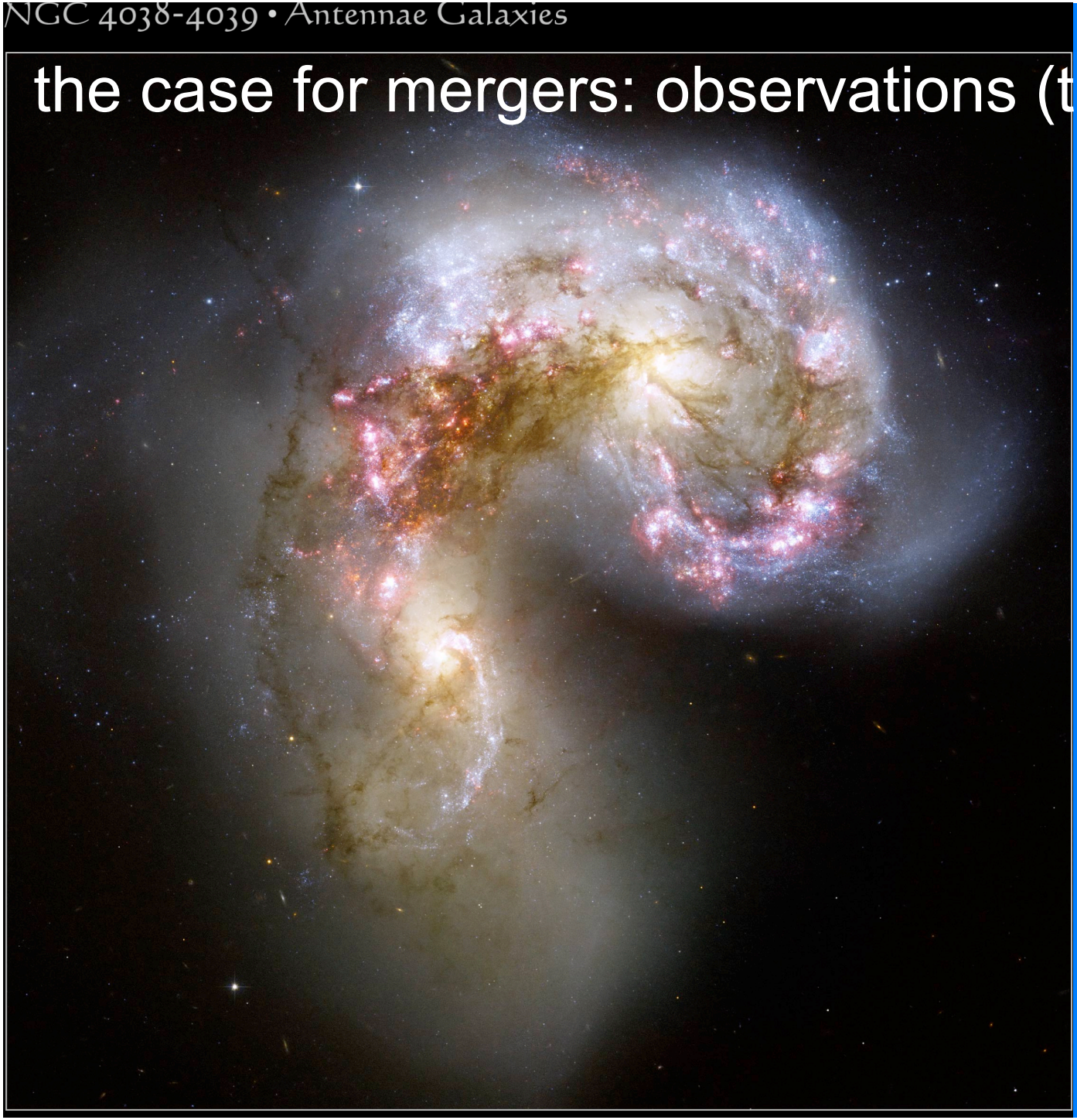


the case for mergers: a simulation

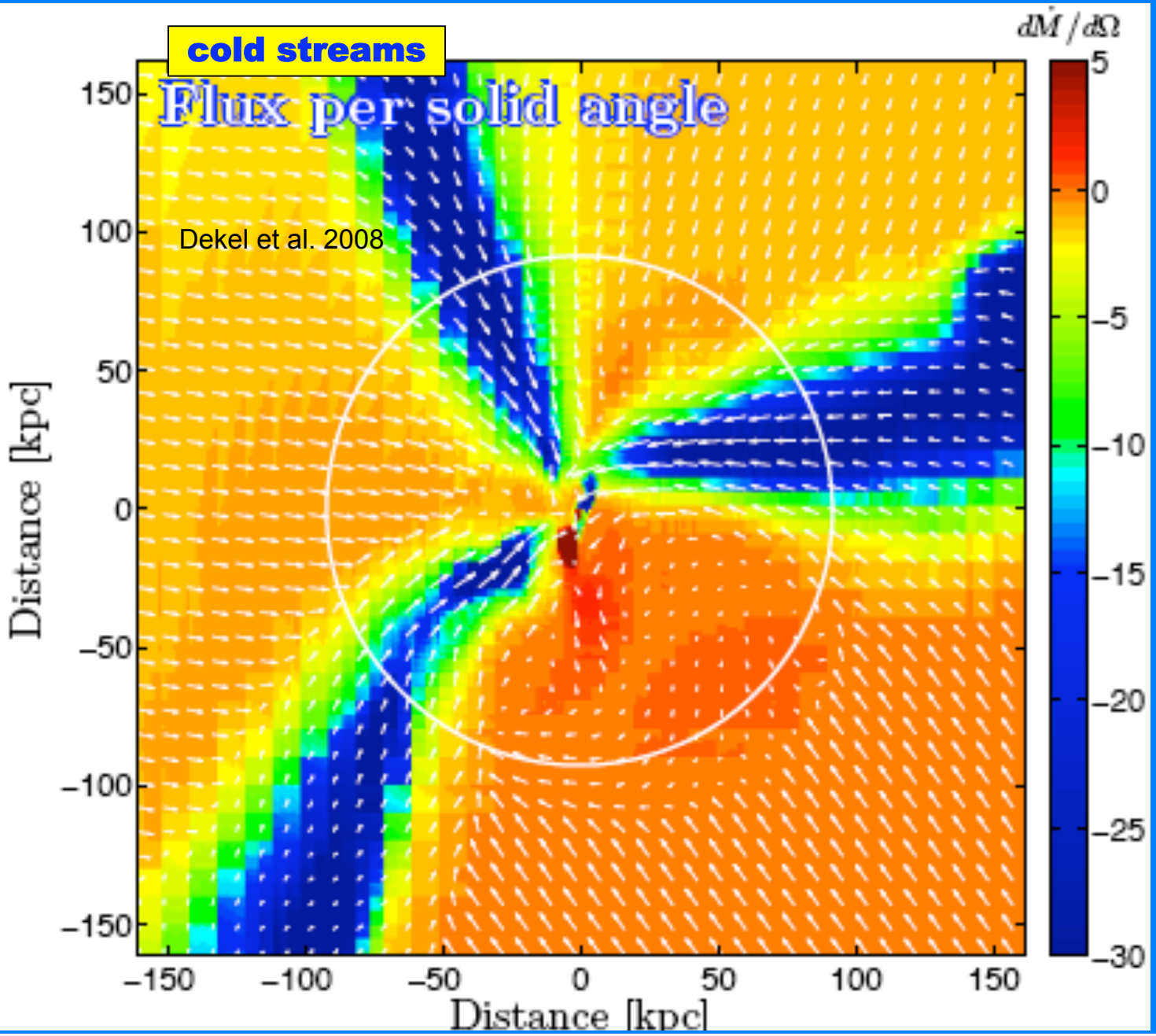


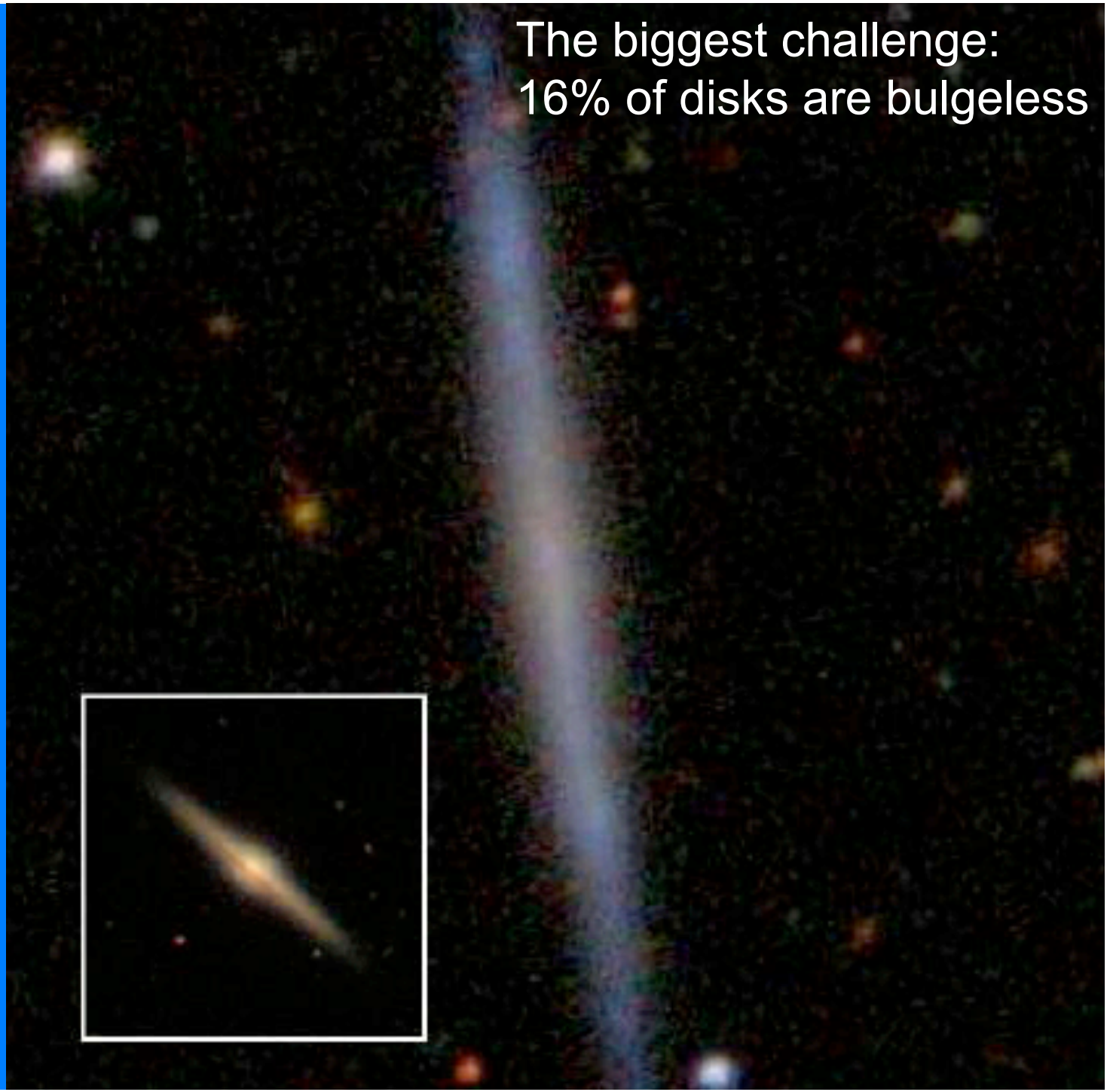


the case for mergers: observations (the Antennae)



the case for infall: a simulation





Kautsch 2009

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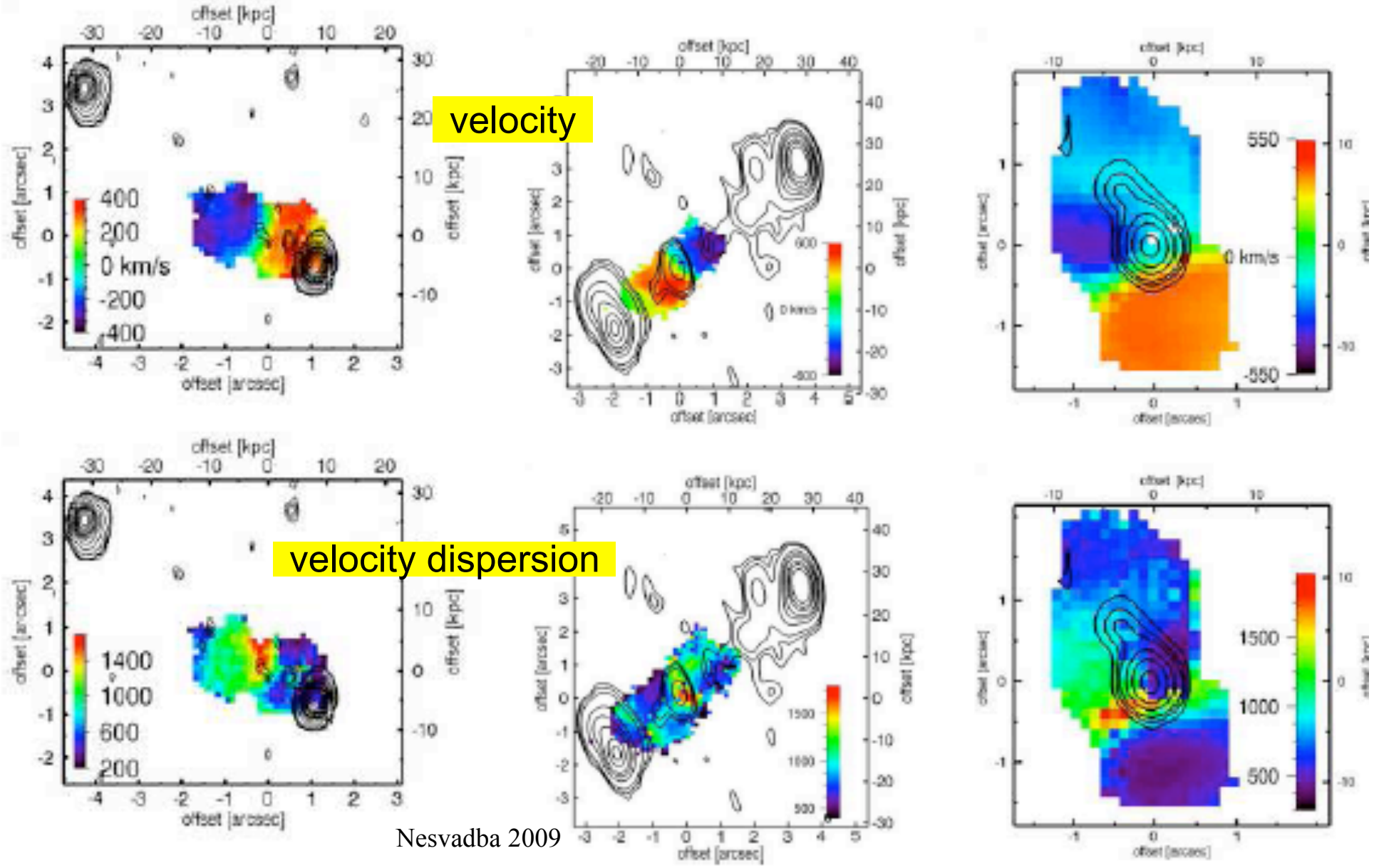
Massive spheroids form by mergers at high z

Supermassive black holes :negative feedback

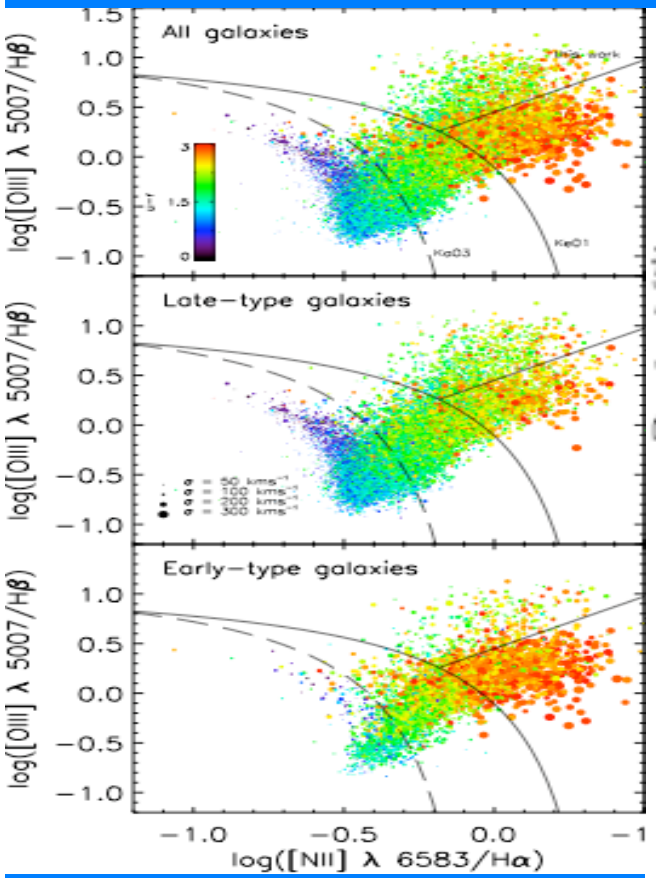
z=3.6 z=2.4 z=2.6

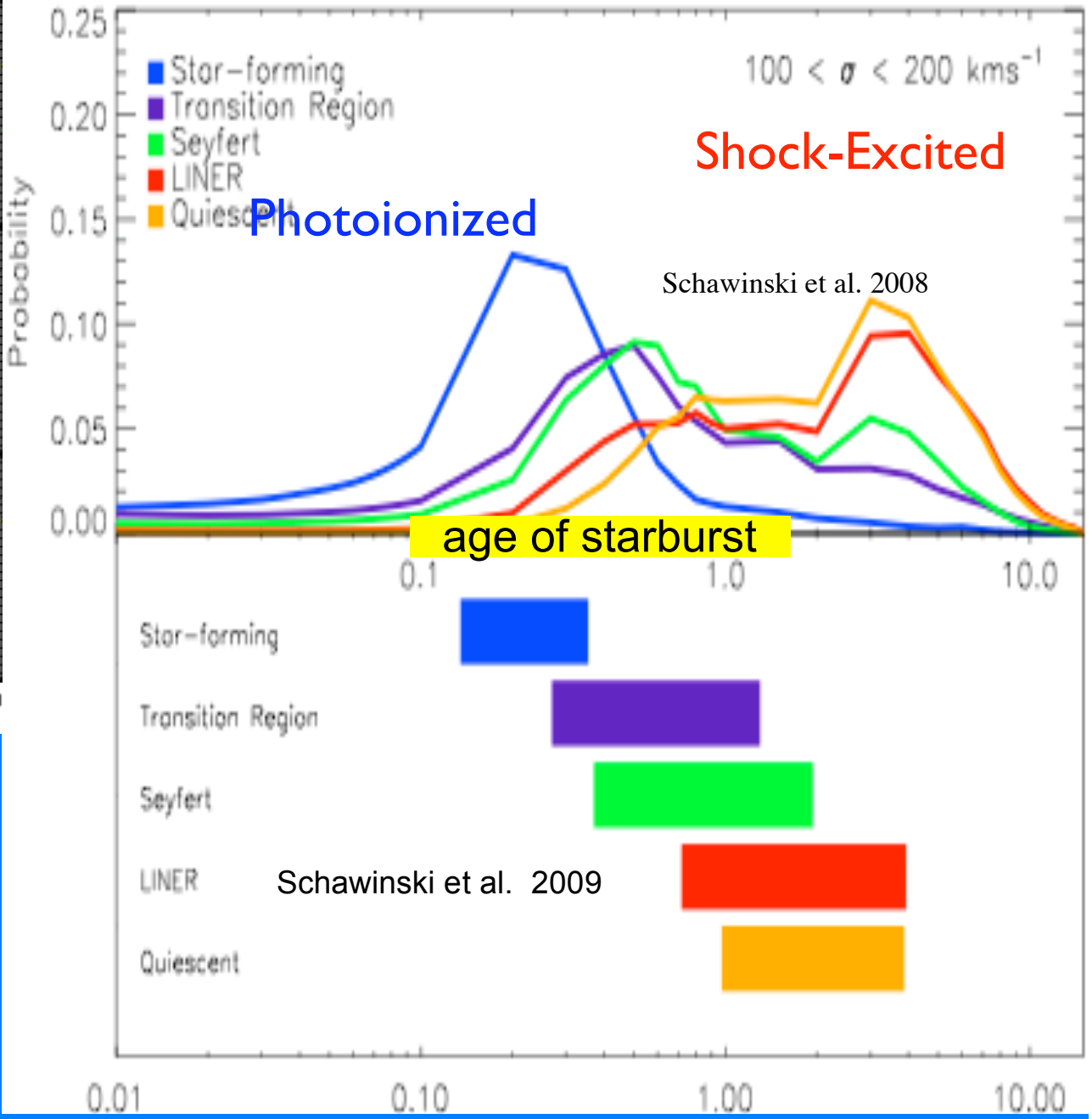
radio jets drive gas outflows and turbulence



Nesvadba 2009

Do AGN arise from/quench star formation ?





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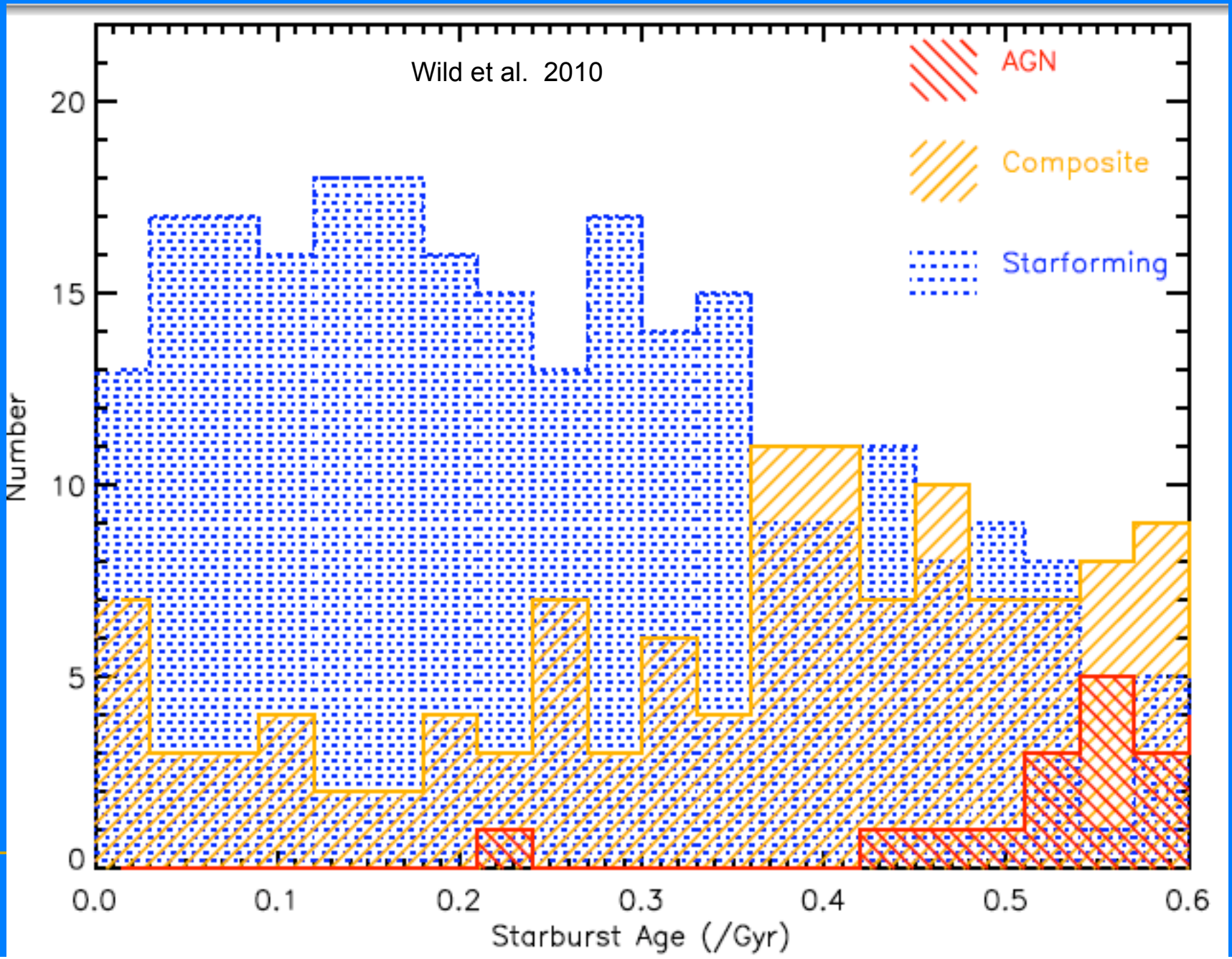
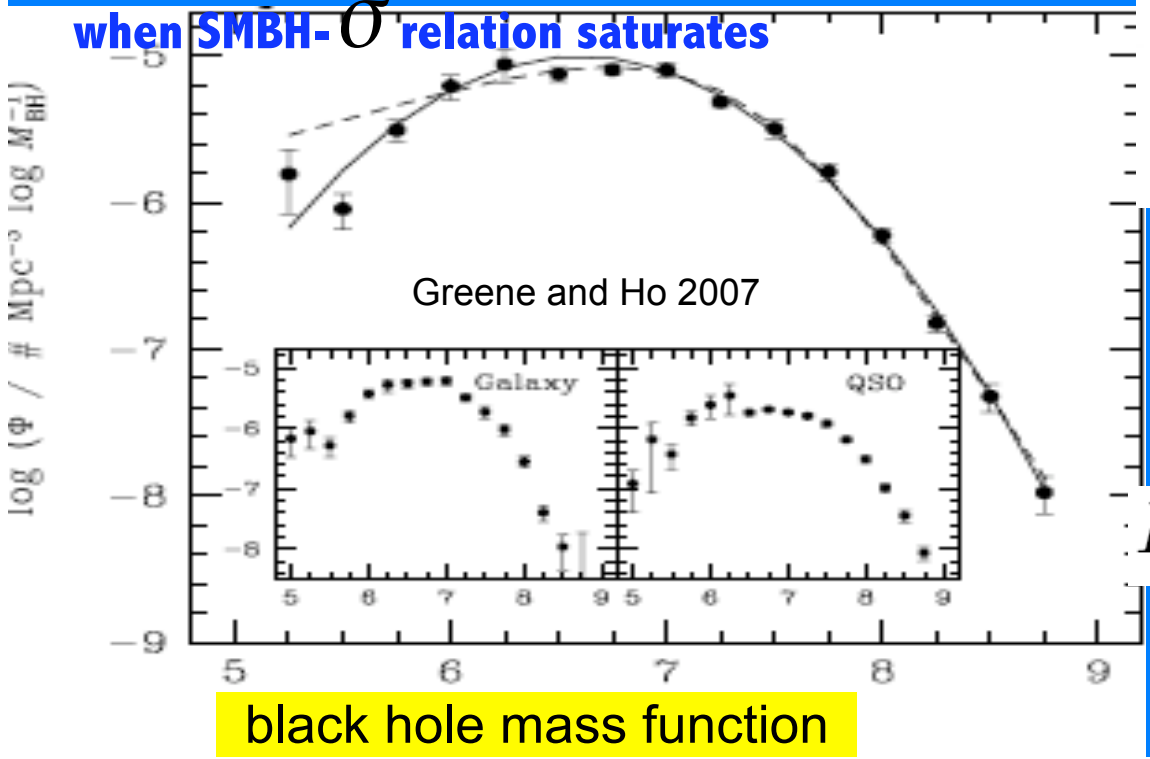


Outflows from supermassive black holes quench star formation

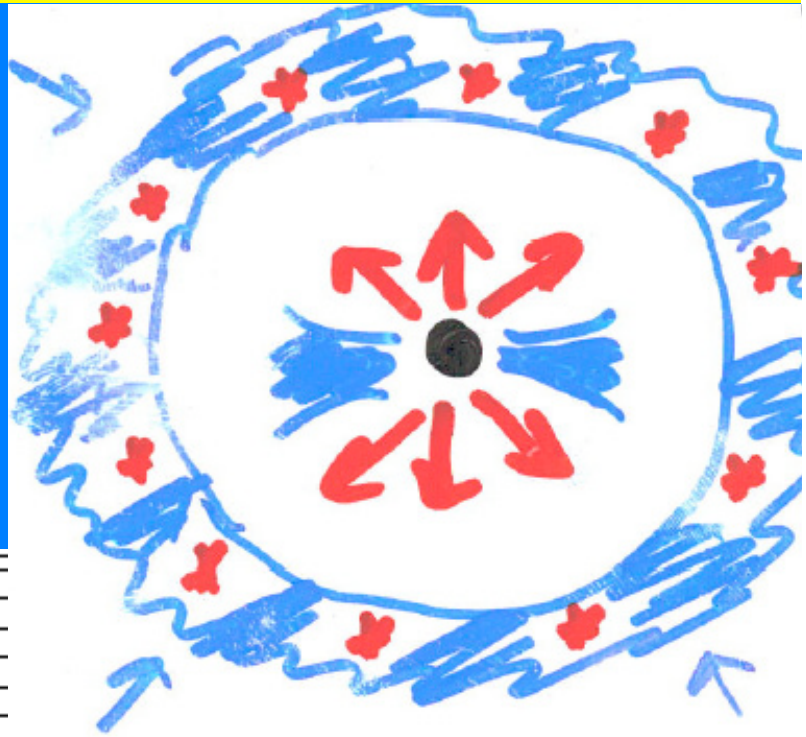
$L_{Edd}/c = GMM_{gas}/r^2$

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

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

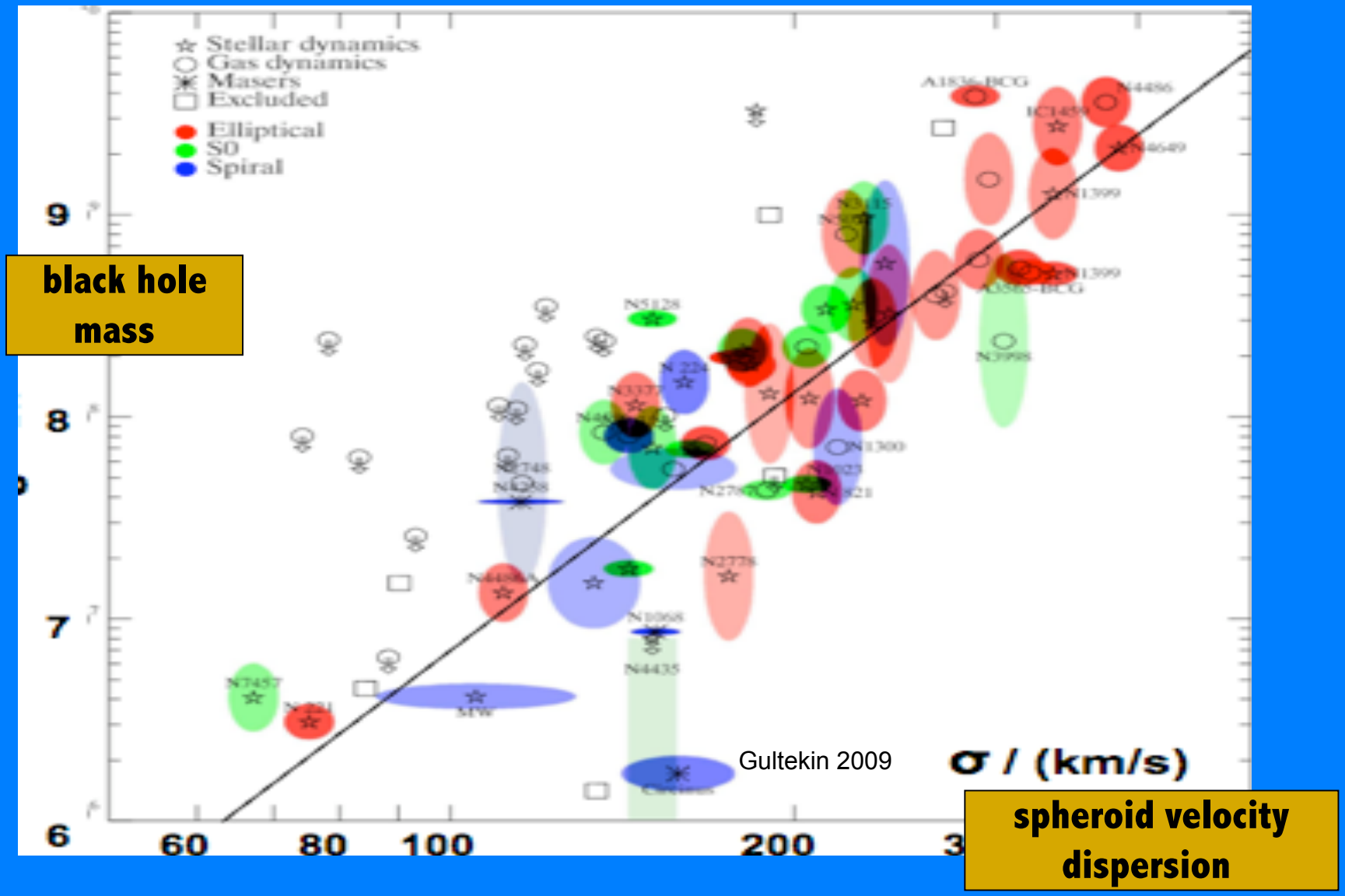


black hole mass function

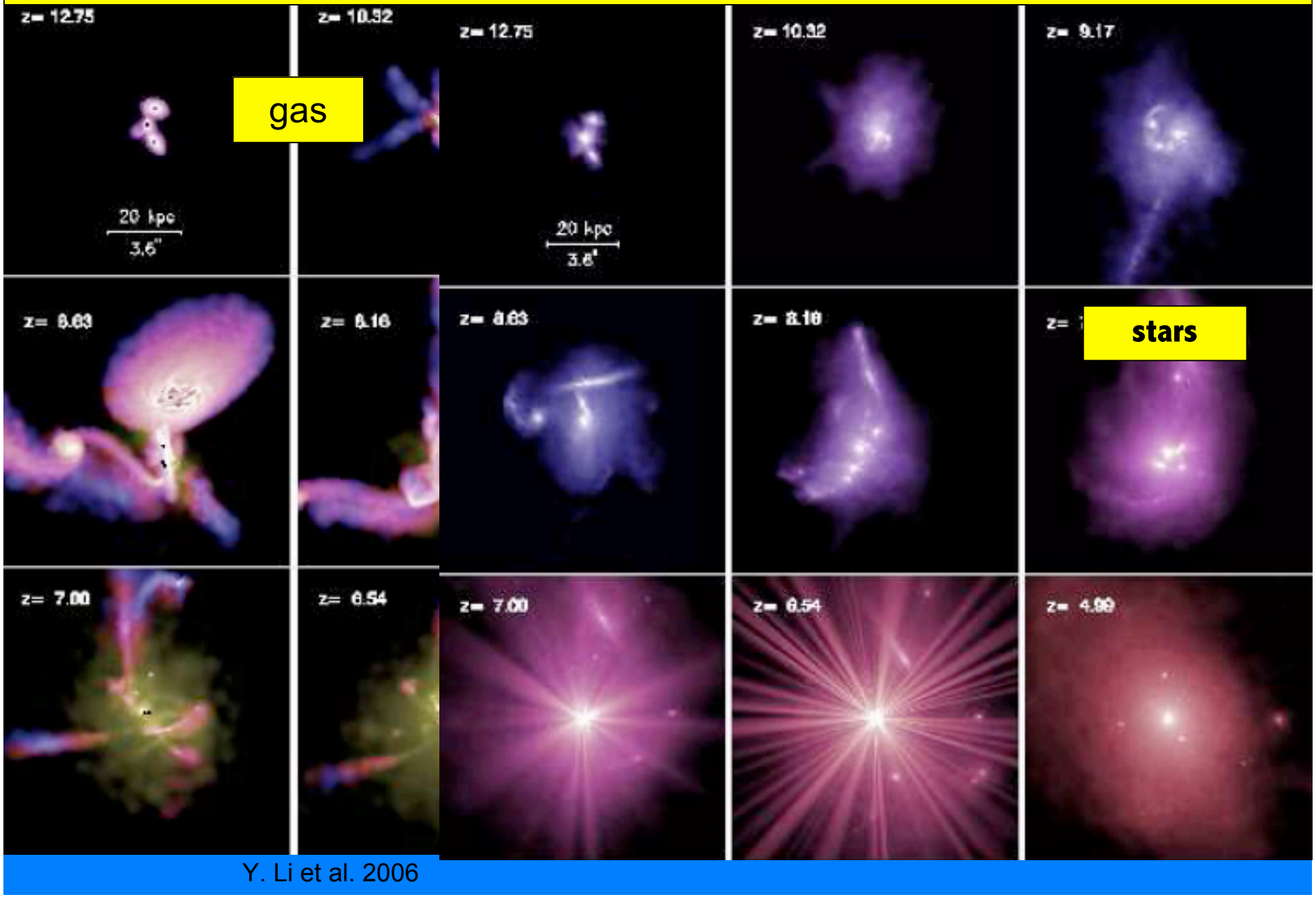


$$L_{Edd} = 4\pi cGM_{BH}m_p/\sigma_T$$

Supermassive black hole correlation with spheroid velocity dispersion demonstrates coevality/quenching



NUMERICAL SIMULATIONS OF SMBH FEEDBACK



Y. Li et al. 2006

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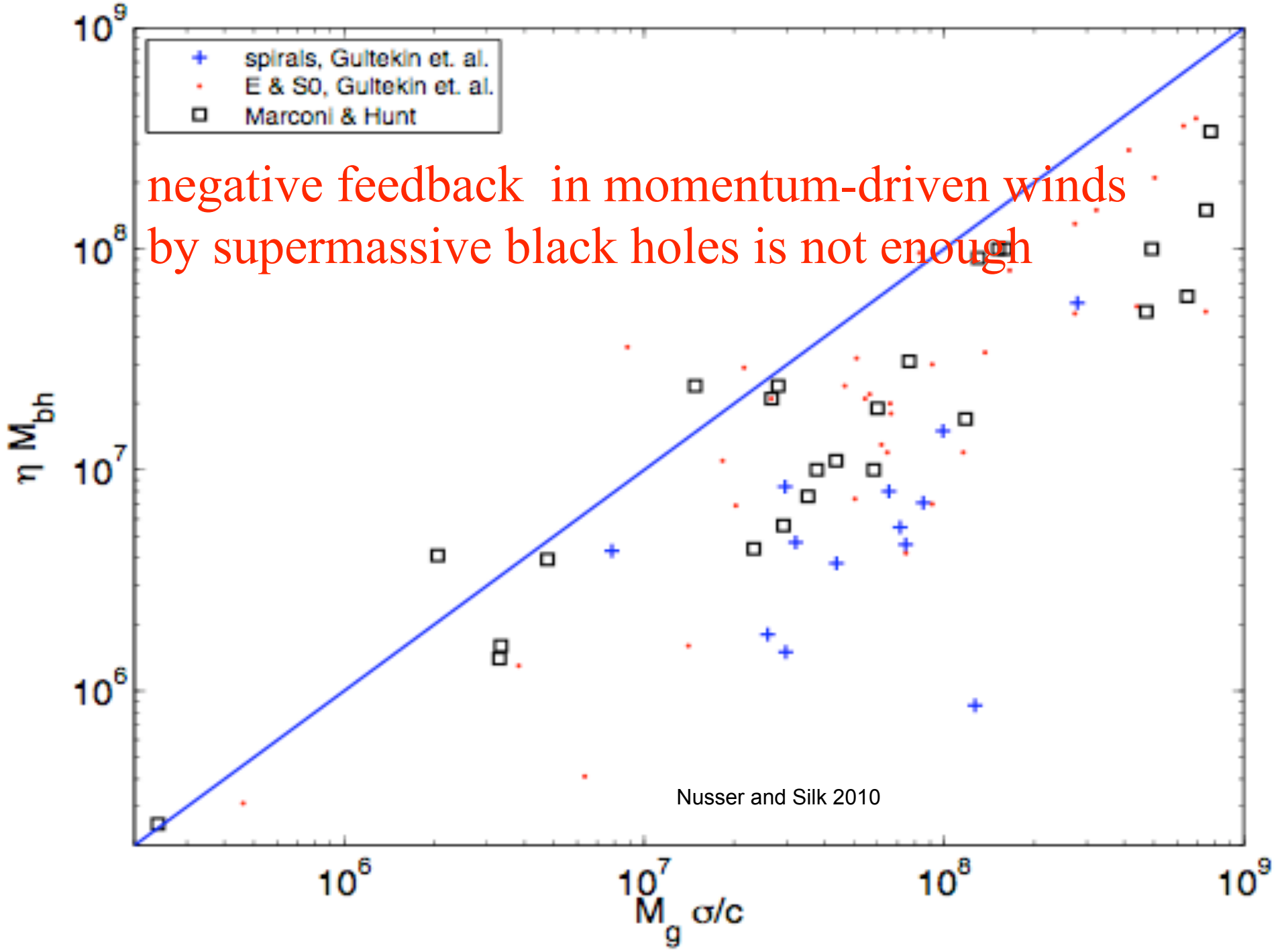
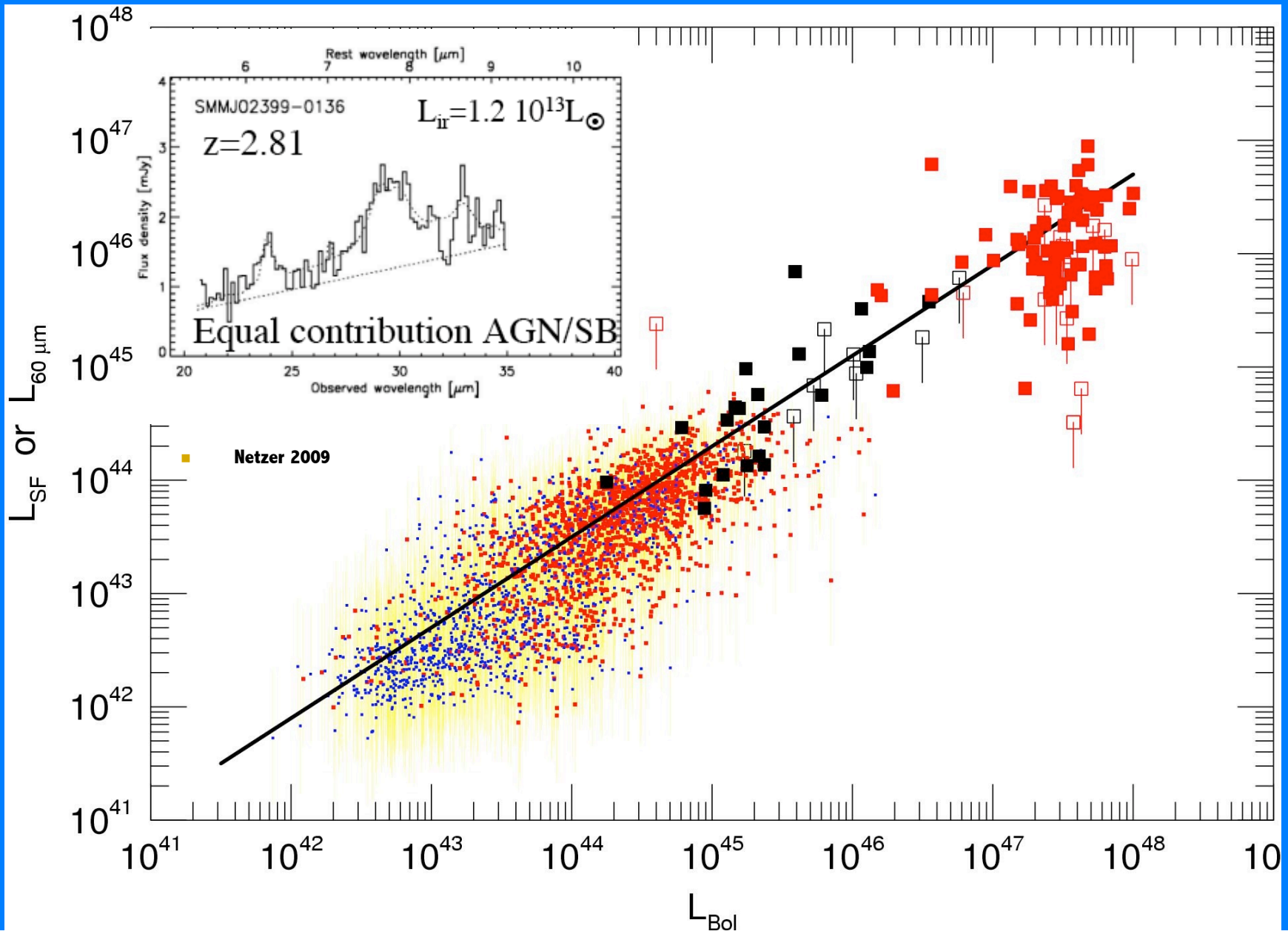
Supermassive black holes :positive feedback


spirals, Gultekin et. al.
E & S0, Gultekin et. al.
Marconi & Hunt
negative feedback in momentum-driven winds
by supermassive black holes is not enough
Nusser and Silk 2010
10^9
10^8
10^7
10^6
ηM_{bh}
10^6
10^7
10^8
10^9
$M_g \sigma/c$

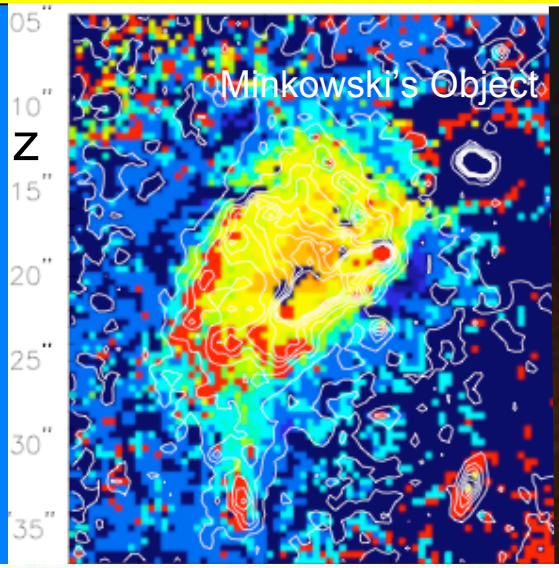
connection between AGN and starbursts

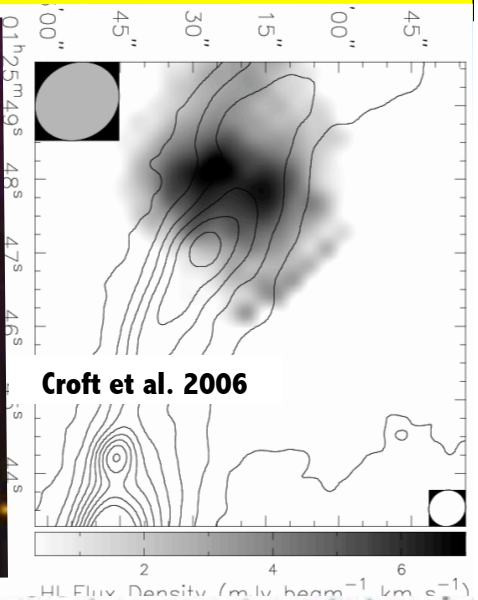


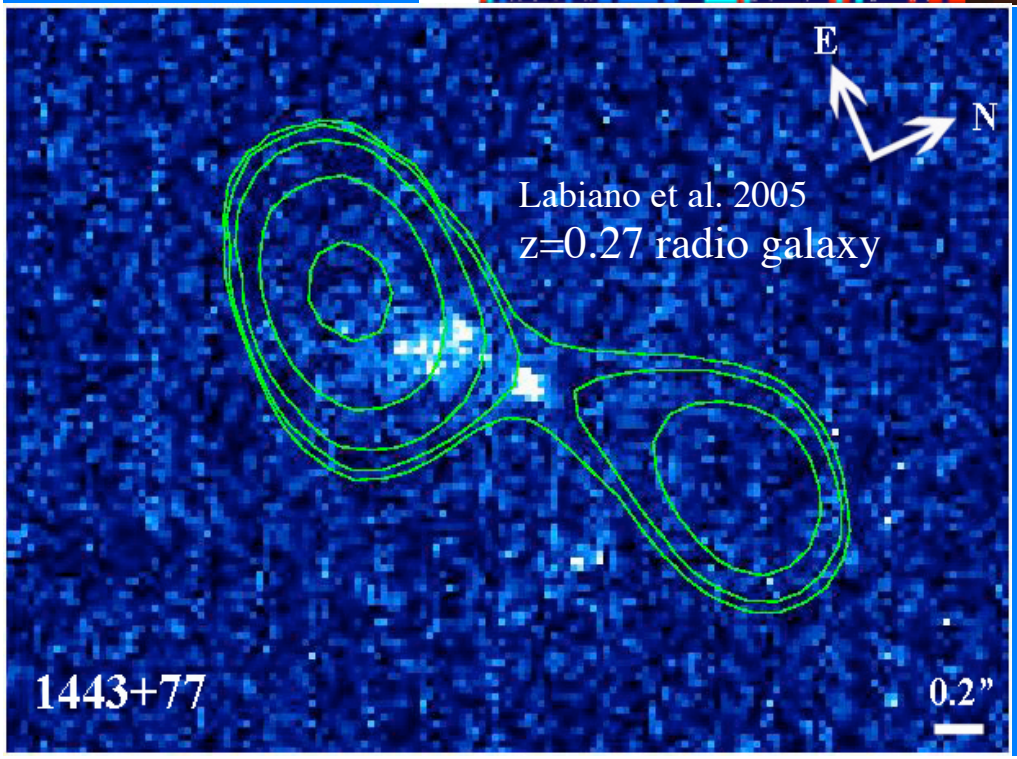
a triggered mode of global star formation?

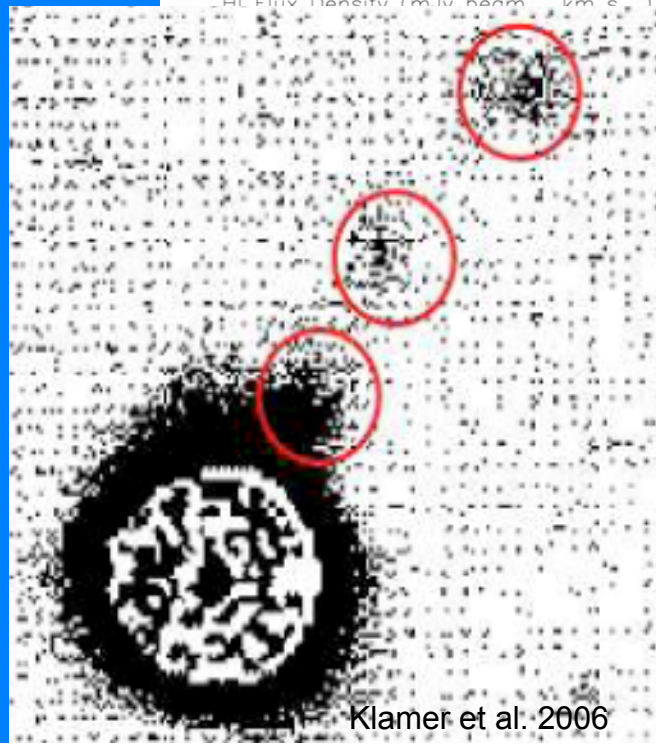
1.We may need it at high z

2. We see it









Why efficient formation of massive spheroids ?

If AGN-driven outflows trigger star formation,

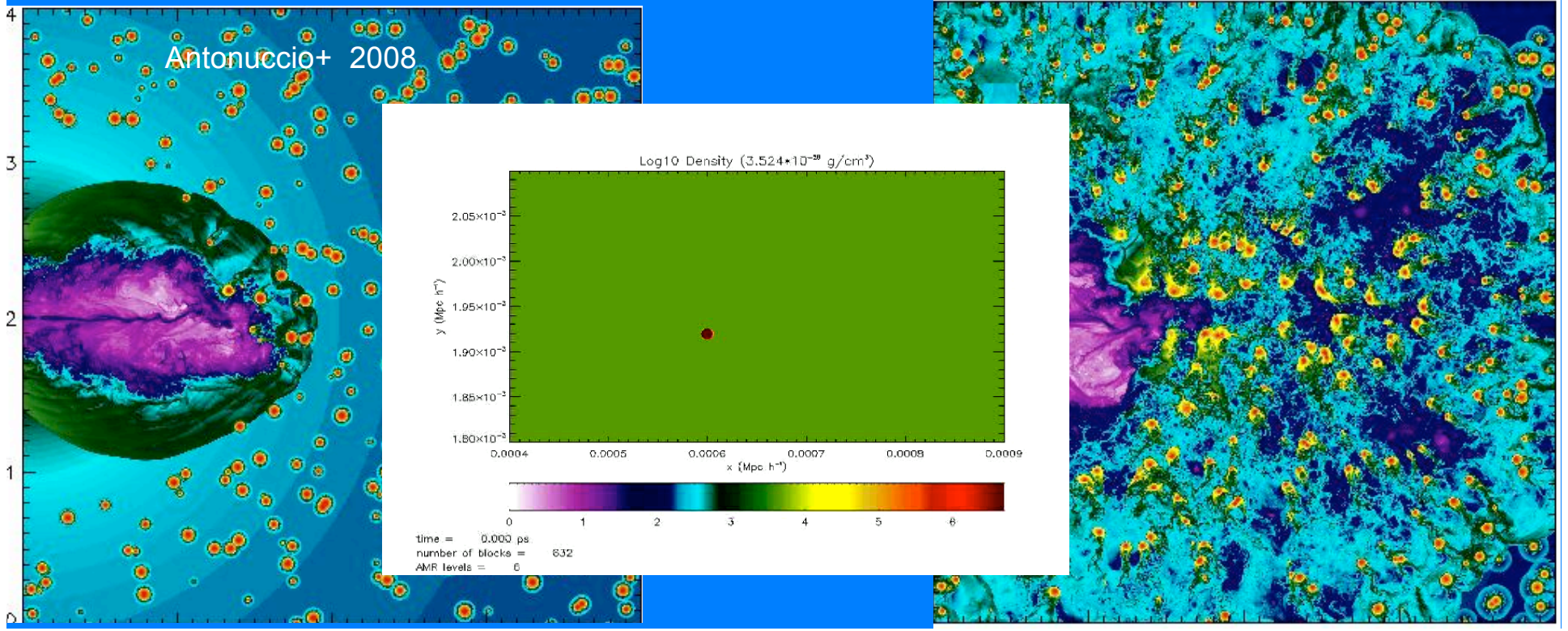
JS + C. Norman 2008

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

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

$$\dot{M}_* = (\epsilon_{SN}/\sigma)e^{-Q}M_g(Gp_g)^{1/2}$$

$$v_{jet} = (2GL^{AGN}\tau/c\sigma^2)^{1/2}$$

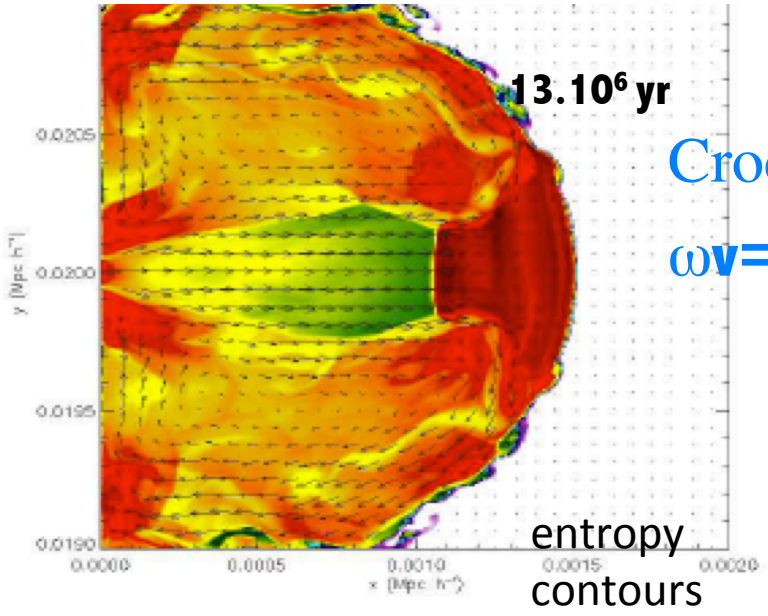


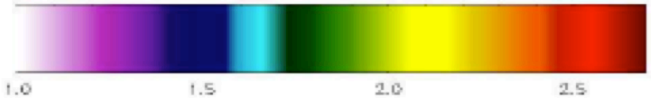
Backflow and AGN feeding

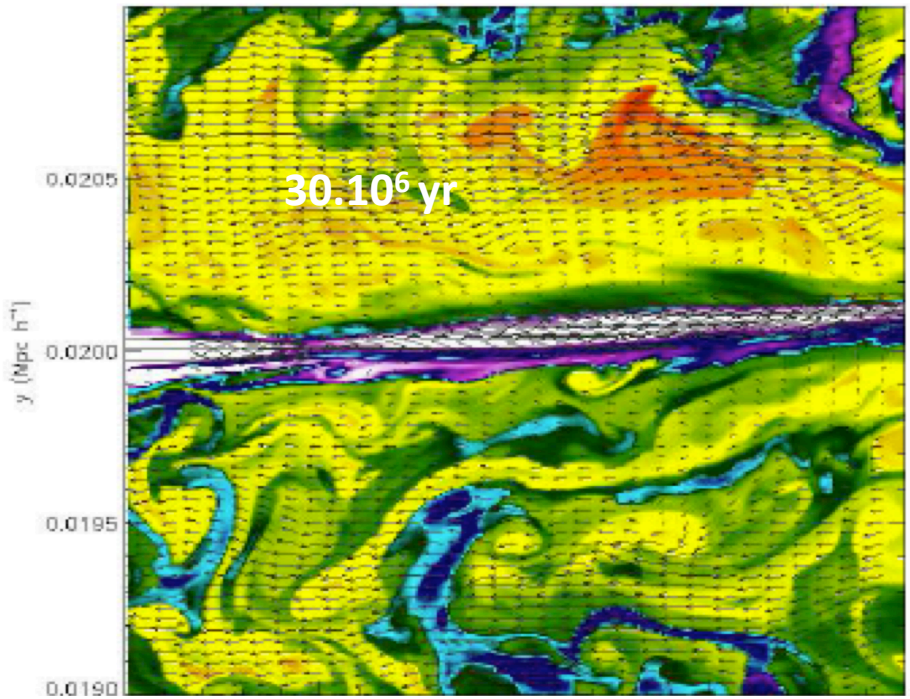
Crocco's theorem:

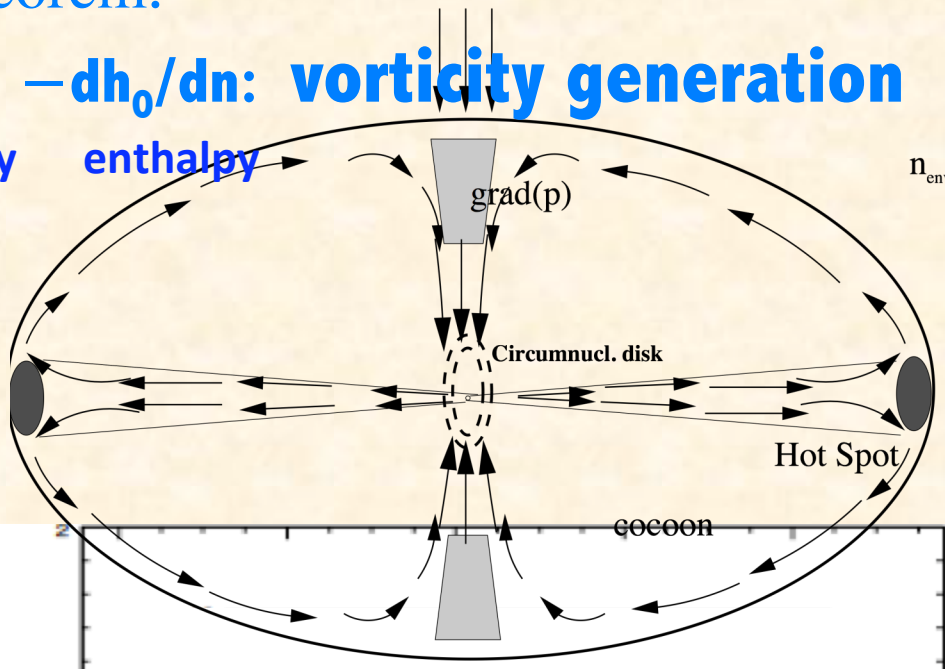
$\omega v = T\,ds/dn - dh_0/dn$: **vorticity generation**

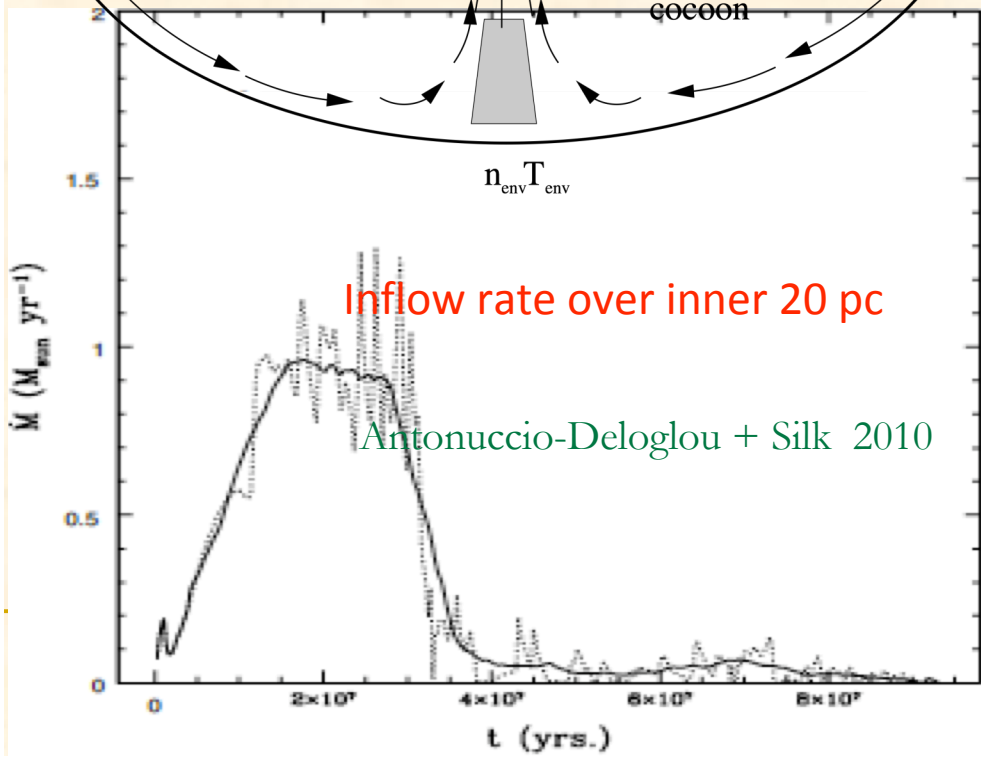
entropy **enthalpy**







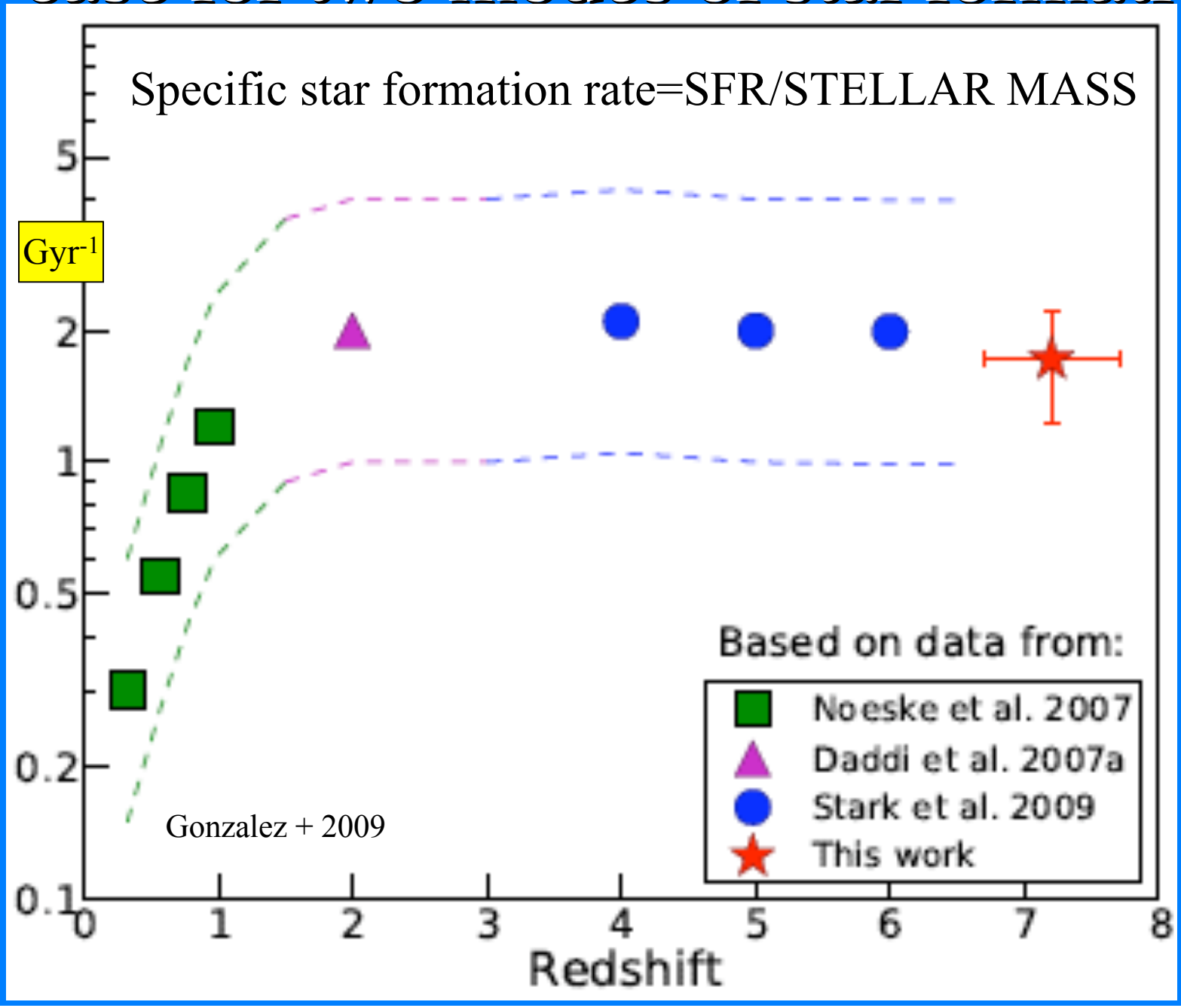




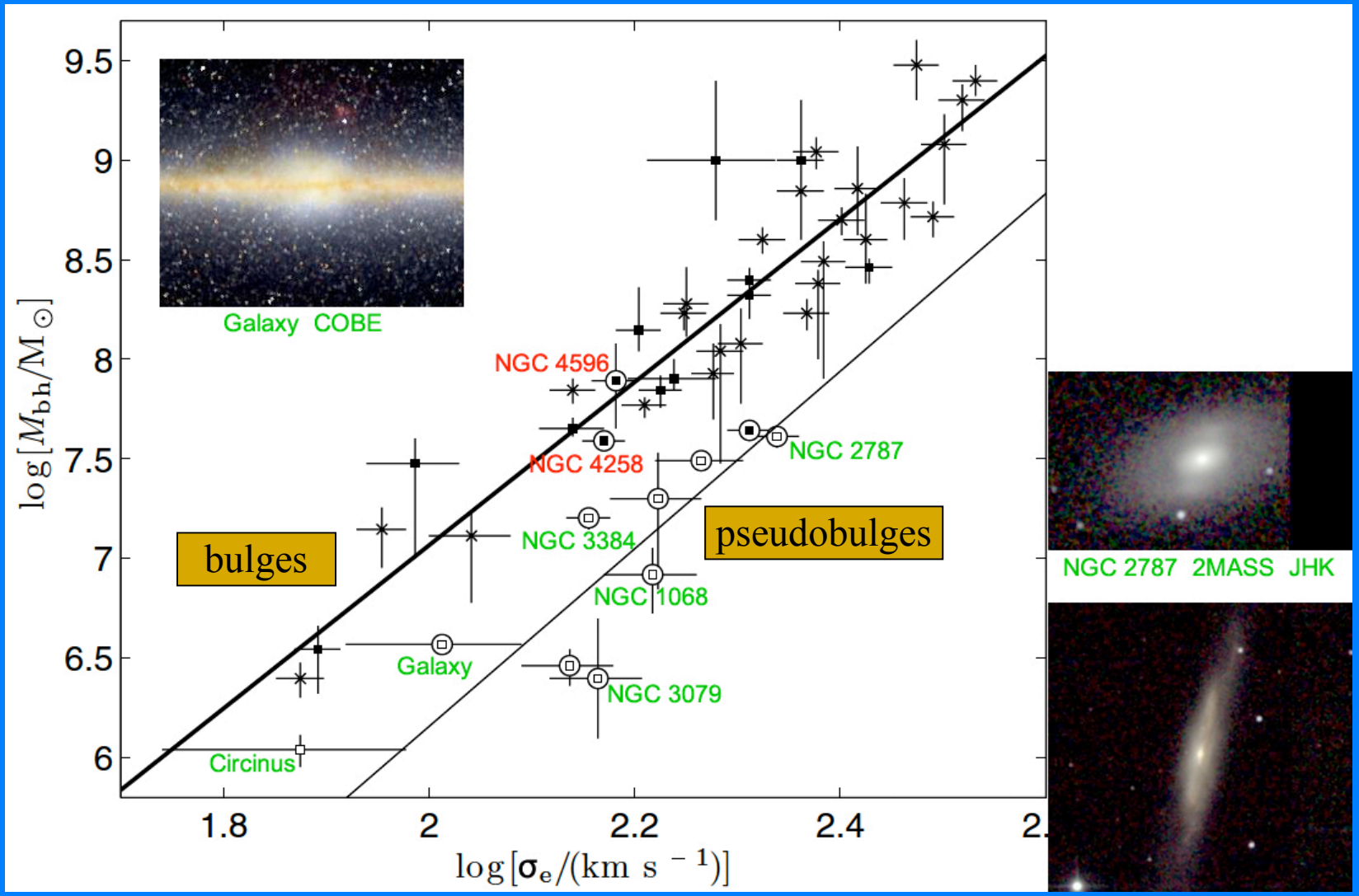
Inflow rate over inner 20 pc

Antonuccio-Deloglou + Silk 2010

The case for two modes of star formation



SMBH in pseudobulges lie low….
Suggests disk mode formation of SMBH is distinct from spheroid mode



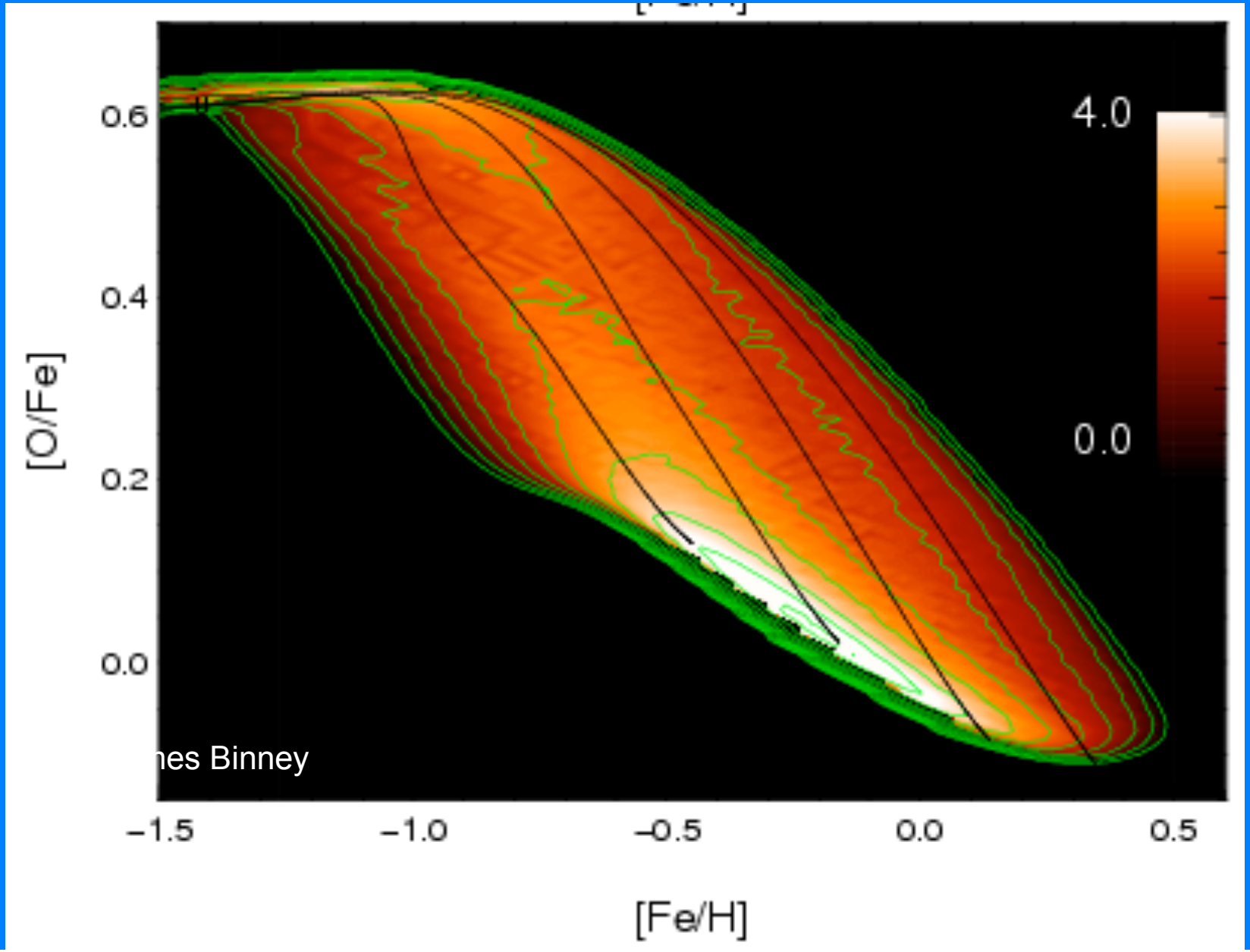
NGC 2787 2MASS JHK

Kormendy & Tremaine 2009

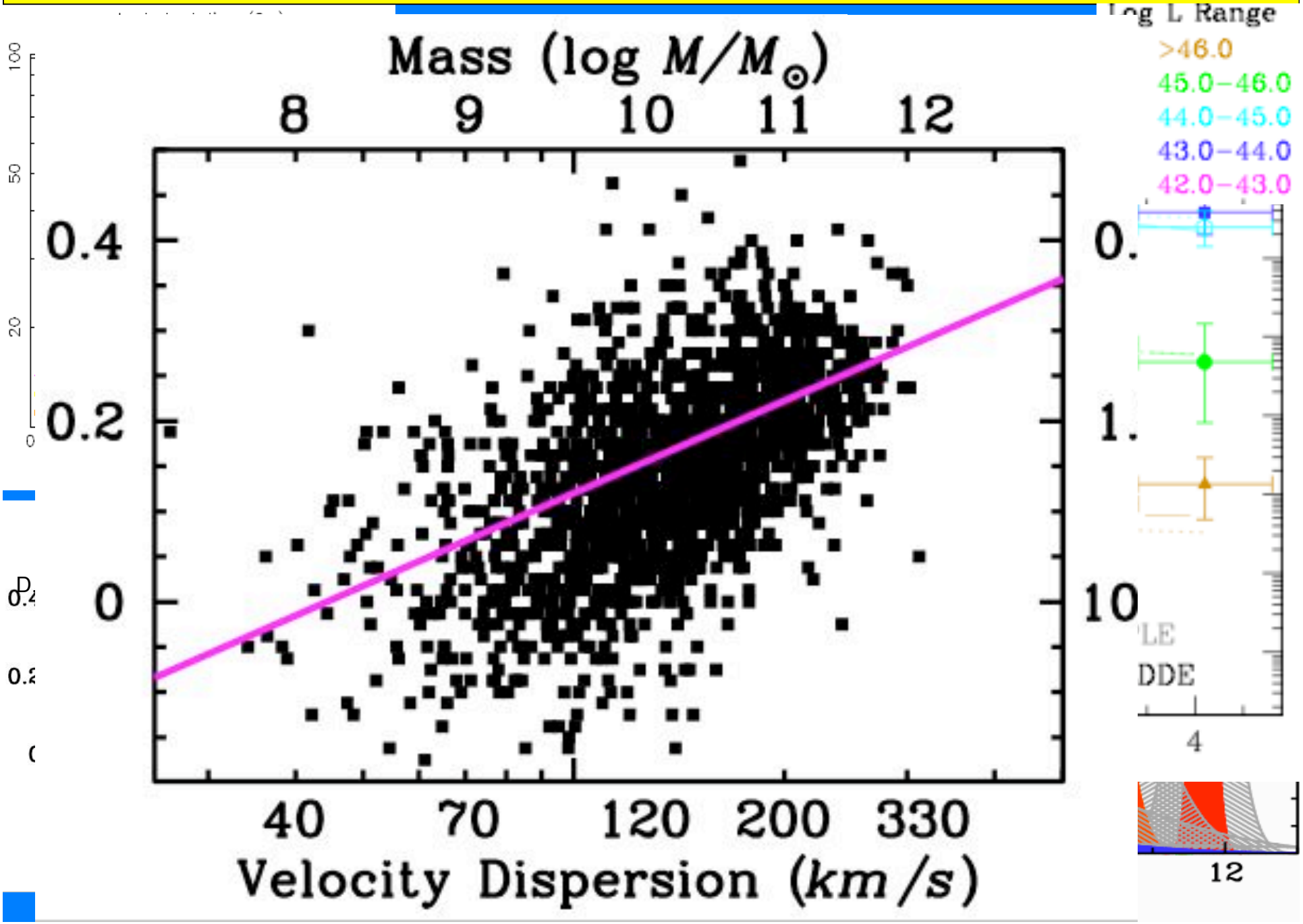
galaxies downsize: another connection with supermassive black holes?

A cosmic clock: incorporation into stars of debris from SNII (10^6 yr) vs SNI (10^{10} yr)

We see a similar phenomenon in the local thick stellar disk



DOWNSIZING IN STELLAR MASS, Z, STAR FORMATION AND SMBH MASS

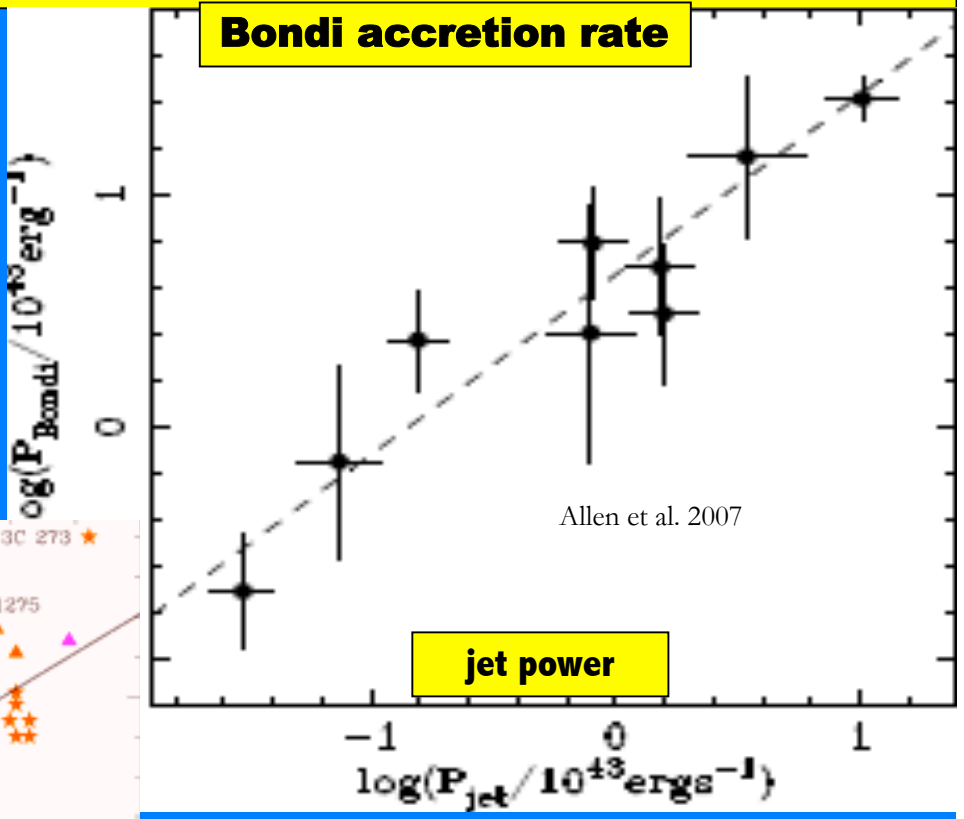


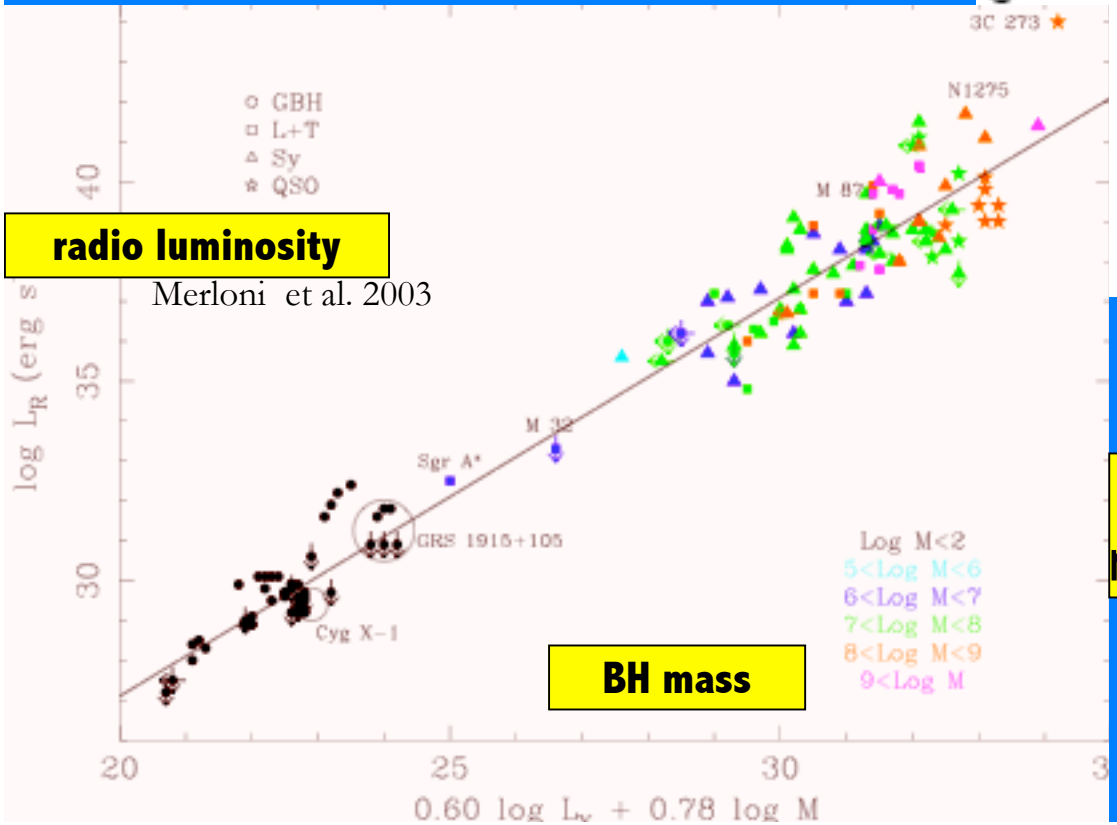
Why down-sizing of massive spheroids and AGN?

Need SMBH feeding and outflow to be nonlinear function of SMBH mass

e.g. accretion rate~ M_{SMBH}^2 (Bondi)

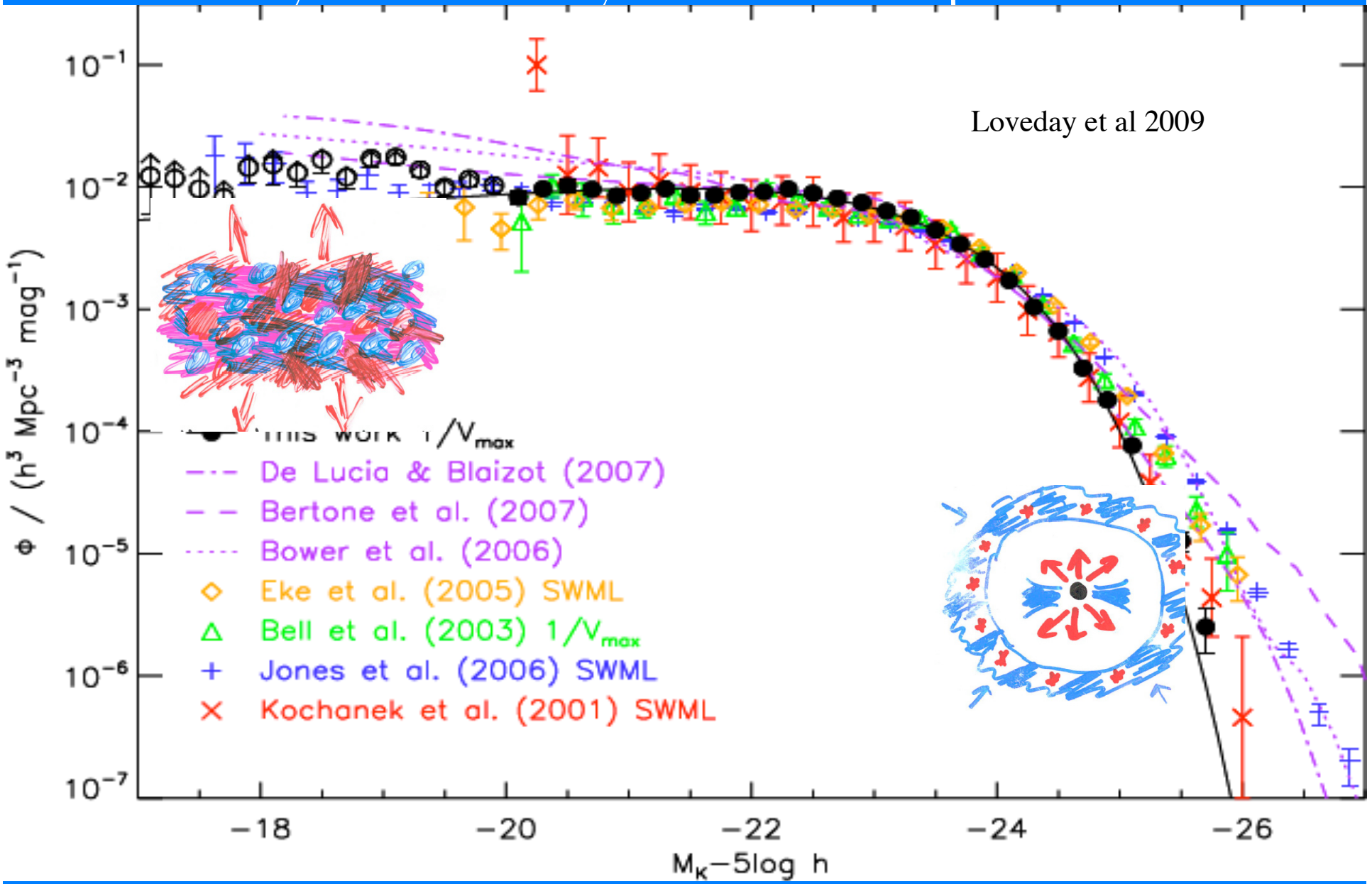
and outflow rate~ 0.1 accretion rate



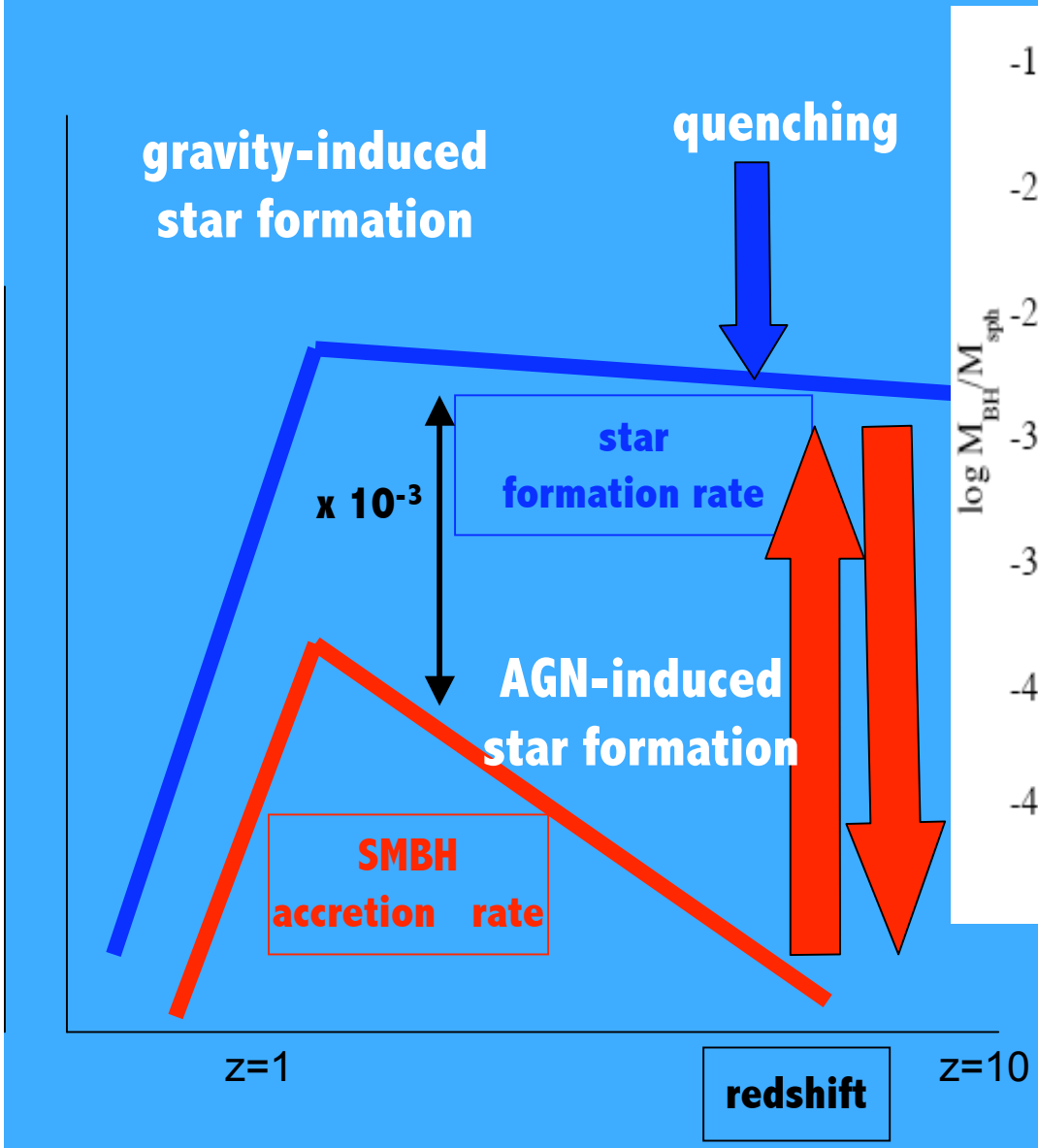


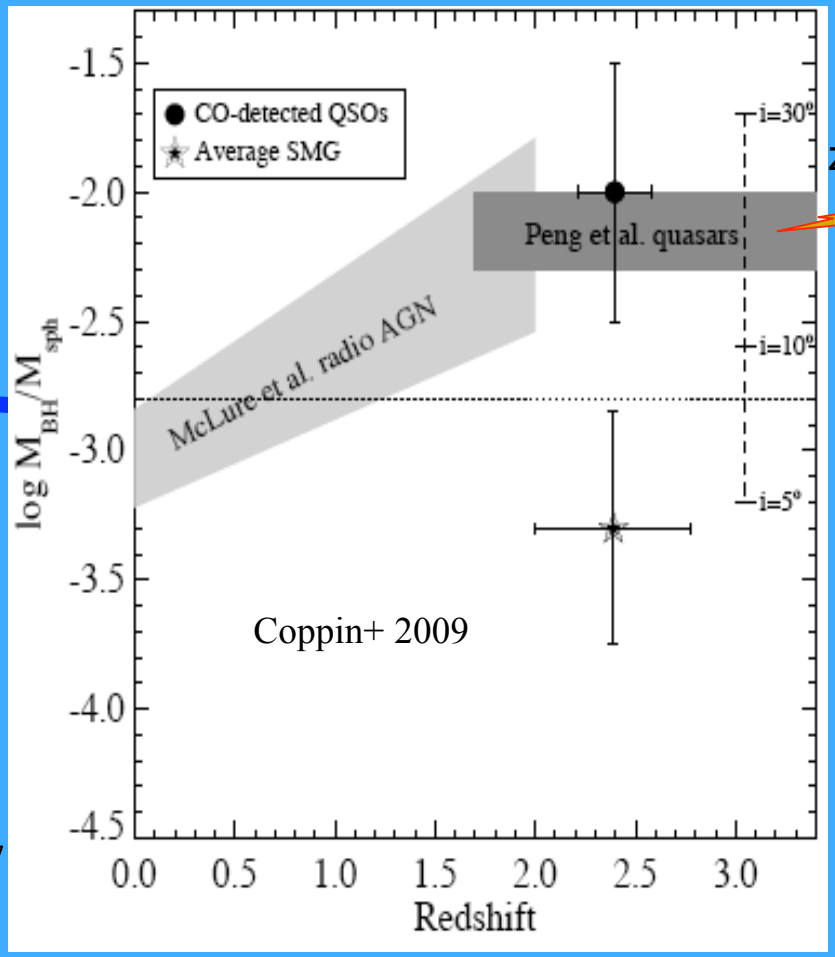
motivated by universality of magnetically regulated outflows

The Galaxy Luminosity Function explained



Acive galactic nuclei and quasars
-aftermath or precursor or coeval to star formation ?





z=6.4

a hybrid model

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

low star formation efficiency

hot infall via major mergers + cooling forms massive spheroids

high star formation efficiency rate

origin of supermassive black holes

intermediate mass black holes form in protodisks at 10^4K

+ black hole mergers

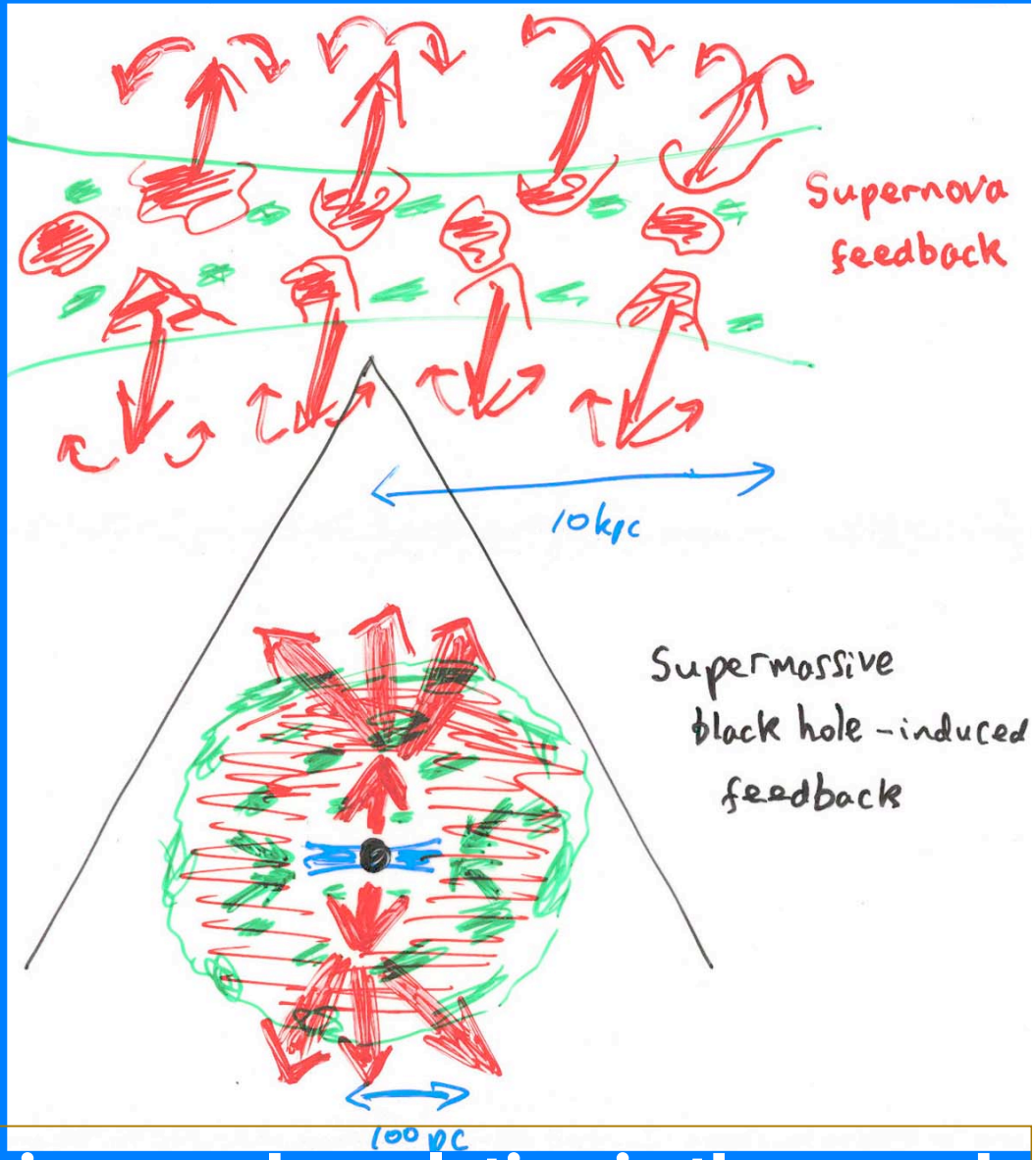
+ SMBH grow via gas accretion

role of supermassive black holes

quenching of star formation

triggering of star formation

intracluster gas heating



improved resolution in theory and observation will help…