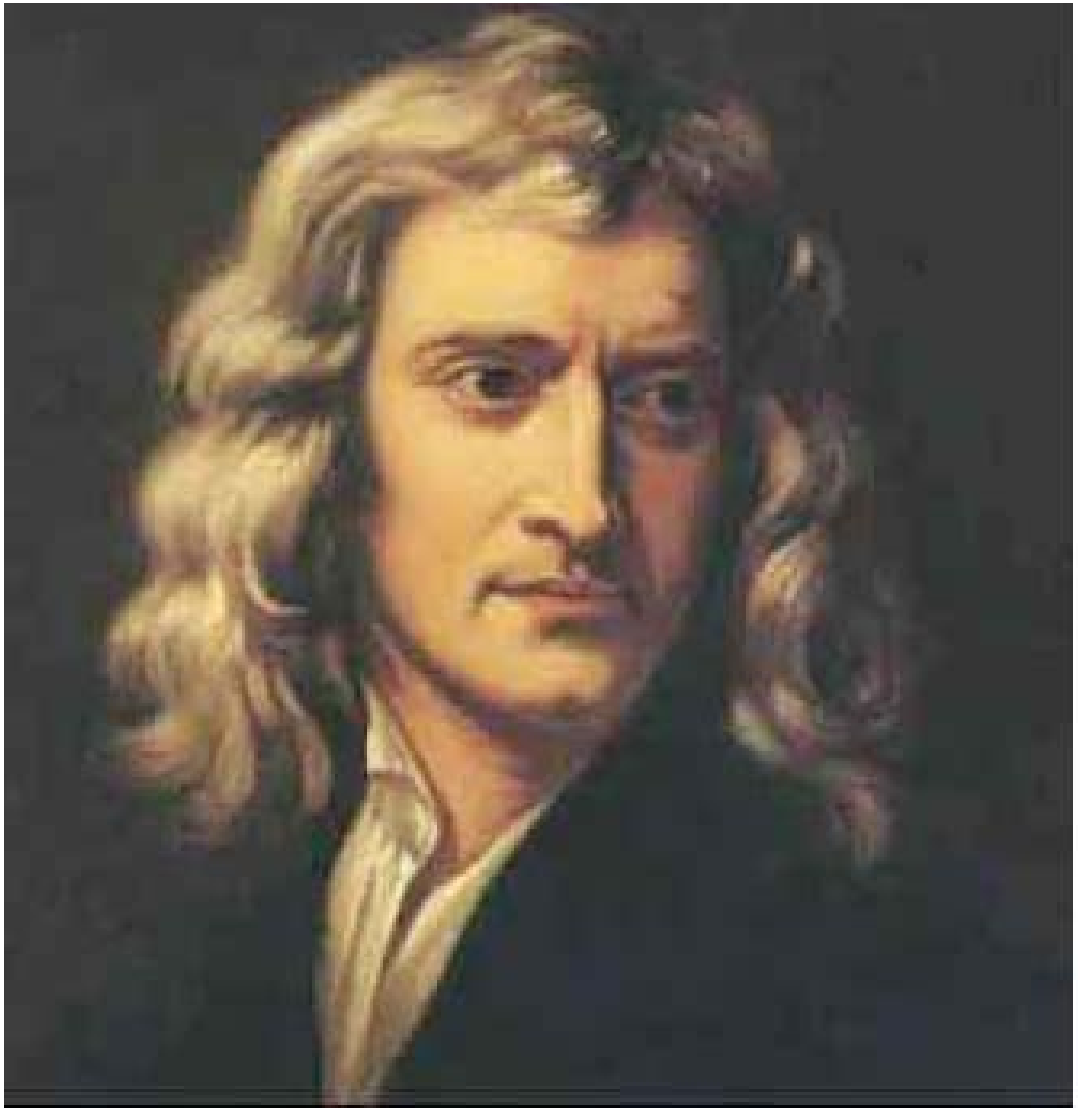
Let There Be Light: Galaxy Formation for the Novice

Joe Silk

University of Oxford

May 30 2008



Isaac Newton 1643-1727

As to your first query, it seems to me that if the matter of our sun and planets and all the matter of the universe were evenly scattered throughout all the heavens,and every particle had an innate gravity toward all the rest, and the whole space throughout which this matter was scattered was but finite, the matter on the outside of this space would, by its gravity, tend toward all the matter on the inside and, by consequence, fall down into the middle of the whole space and there compose one great spherical mass. But 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.

December 10, 1692

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)

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

James Jeans:

"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."

Criterion for gravitational stability found by Jeans (1902):

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

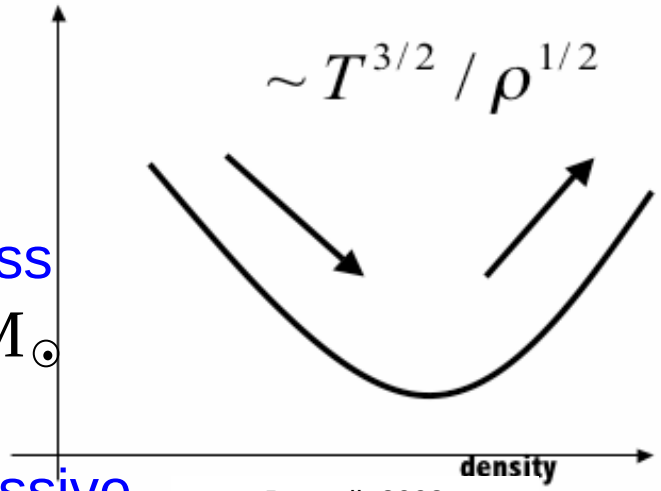
imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion, "What 'happens' is the

Arthur Eddington (1882-1946)

"We can imagine a physicist on a cloud-bound planet who has neve
the stars calculating the ratio of radiation pressure to gas pressure
globes of gas of various sizes, starting, say, with a globe of mass 10
gm., 1000 gm., and so on, so that his *n*th globe contains 10^n gm
as a tussle between matter and aether (gas pressure and radiation
contest is overwhelmingly one-sided except between Nos. 33-35, v
expect something interesting to happen.
What 'happens' is the stars.
We draw aside the veil of cloud beneath which our physicist has been working
and let him look up at the sky. There he will find a thousand million globes of
gas nearly all of mass between his 33rd and 35th globes – that is to say, between
$\frac{1}{2}$ and 50 times the sun's mass."

Sir Arthur S. Eddington: The Internal Constitution of the Stars, 1926

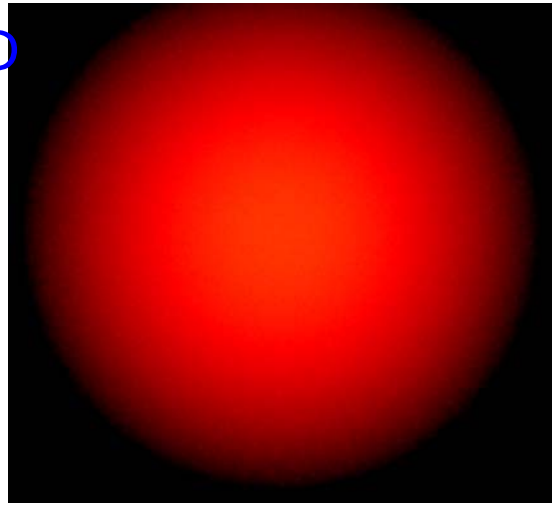
Keys to Star Formation



- Fundamental 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

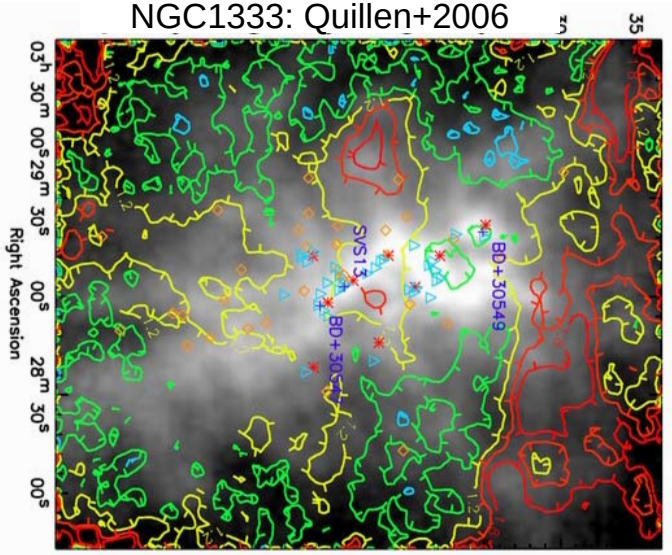
$\dot{M}_{gas} \sim V_s^3 / G \Rightarrow$ first stars were massive

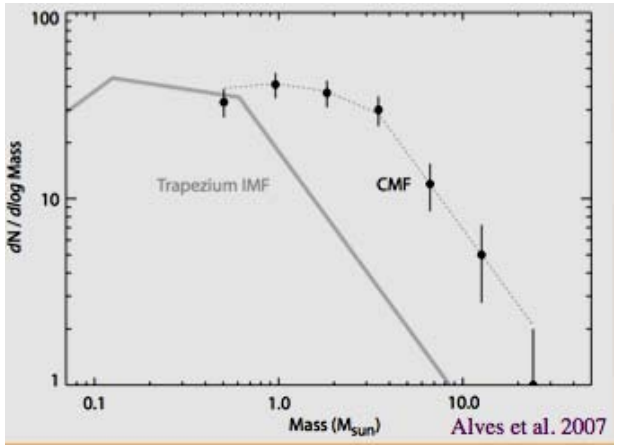
Bonnell+2008

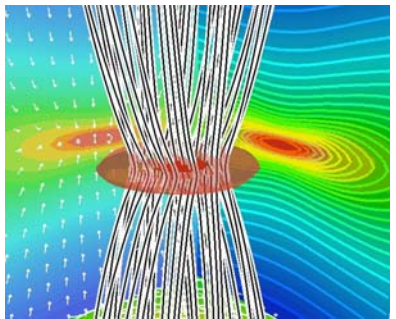


- halted by ***feedback*** : taps stellar energy via MHD turbulence
- In addition IMF most likely also involves *continued fragmentation*

NGC1333: Quillen+2006







THE MYSTERY OF GALAXY FORMATION

Initial density fluctuations are needed

Naive expectation :

in a static medium : $t_{inst} \sim 1/\sqrt{G\rho}$ and $\frac{\delta\rho}{\rho} \sim e^{t/t_{inst}}$

dispersion relation: $\omega^2 = k^2 v_s^2 - 4\pi G\rho$ (Jeans instability)

$\rho \propto t^{-2}$, expect power-law growth rate

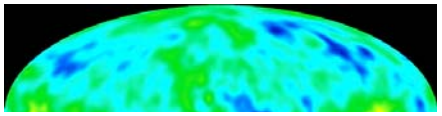
Structure formation is bottom-up

$$\delta K \sim \frac{G\,\delta M}{L\,c^2} \sim G\,\frac{\delta\rho\,L^2}{c^2}$$

$$\sim \left(\frac{\delta\rho}{\rho}\right)\left(\frac{L}{ct}\right)^2$$

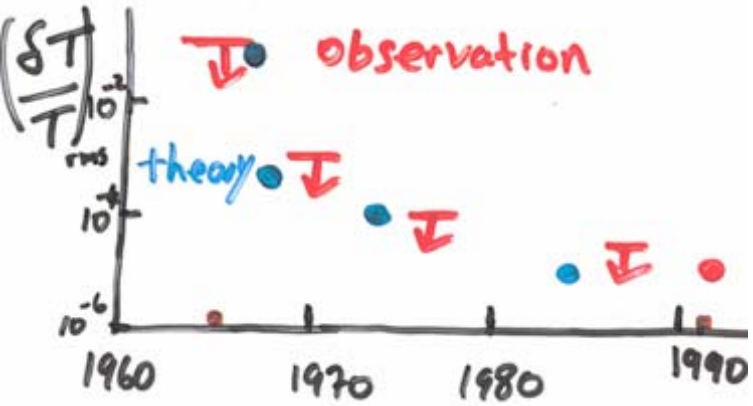
$$\frac{\delta\rho}{\rho} \propto t^{2/3} M_{comoving}^{-2/3}$$

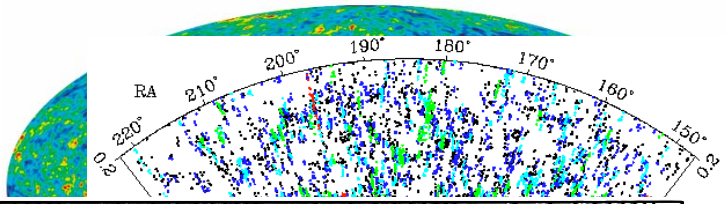
BOTTOM-UP CONFIRMED

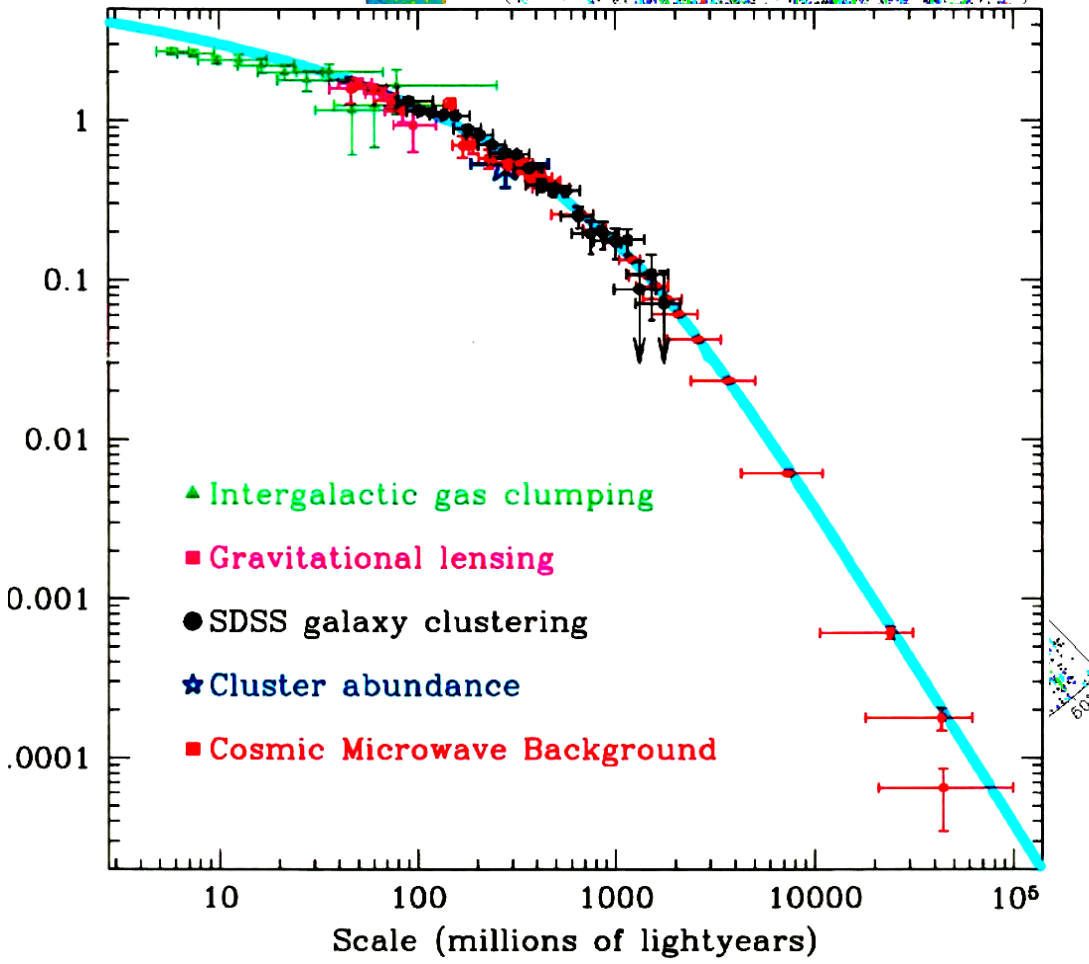


gravitational instability hypothesis $\delta\rho/\rho \sim M^{-\alpha} \cdot t^{2/3}\,\Omega$

confirmed by CMB fluctuations $\delta T/T$

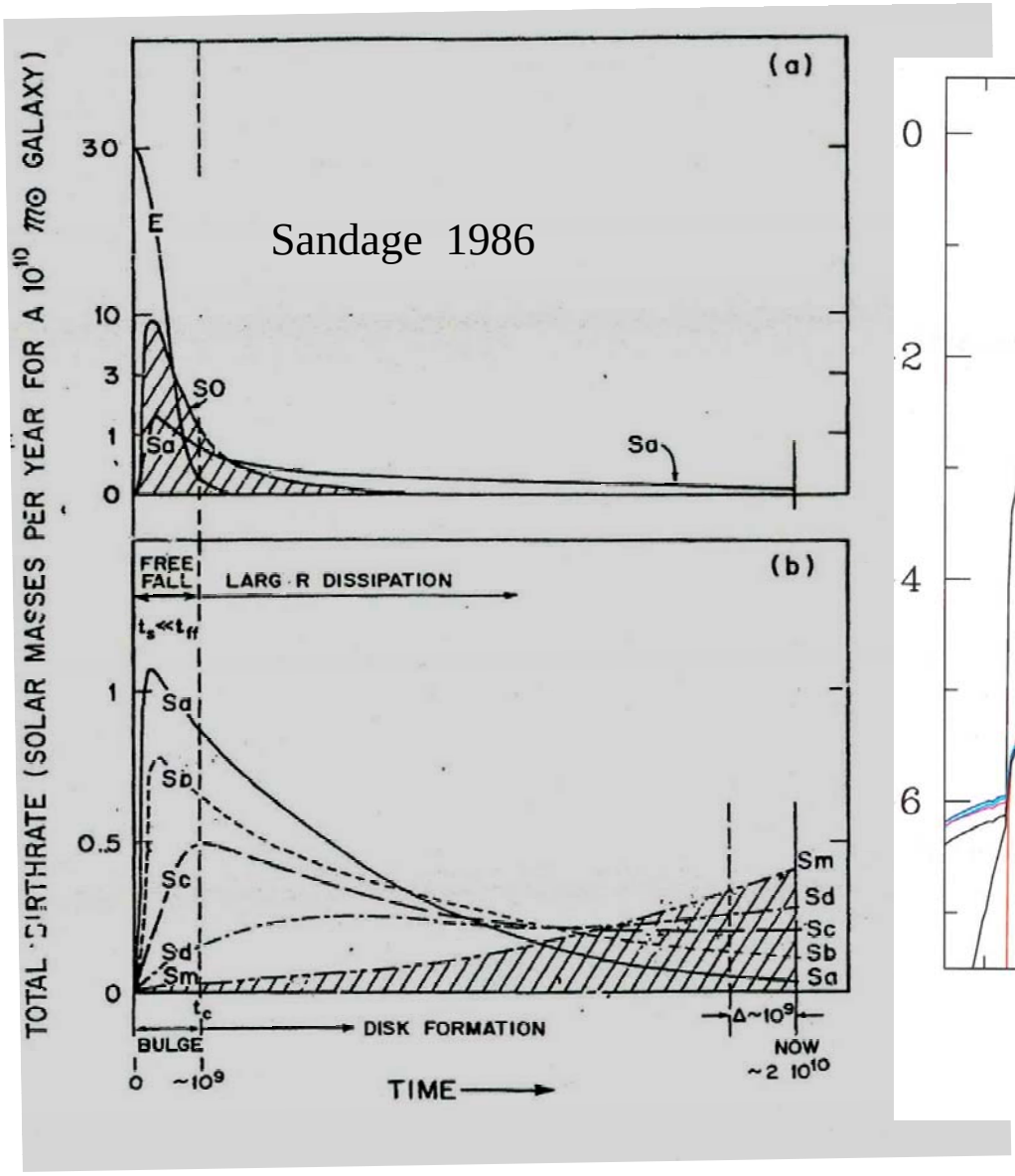






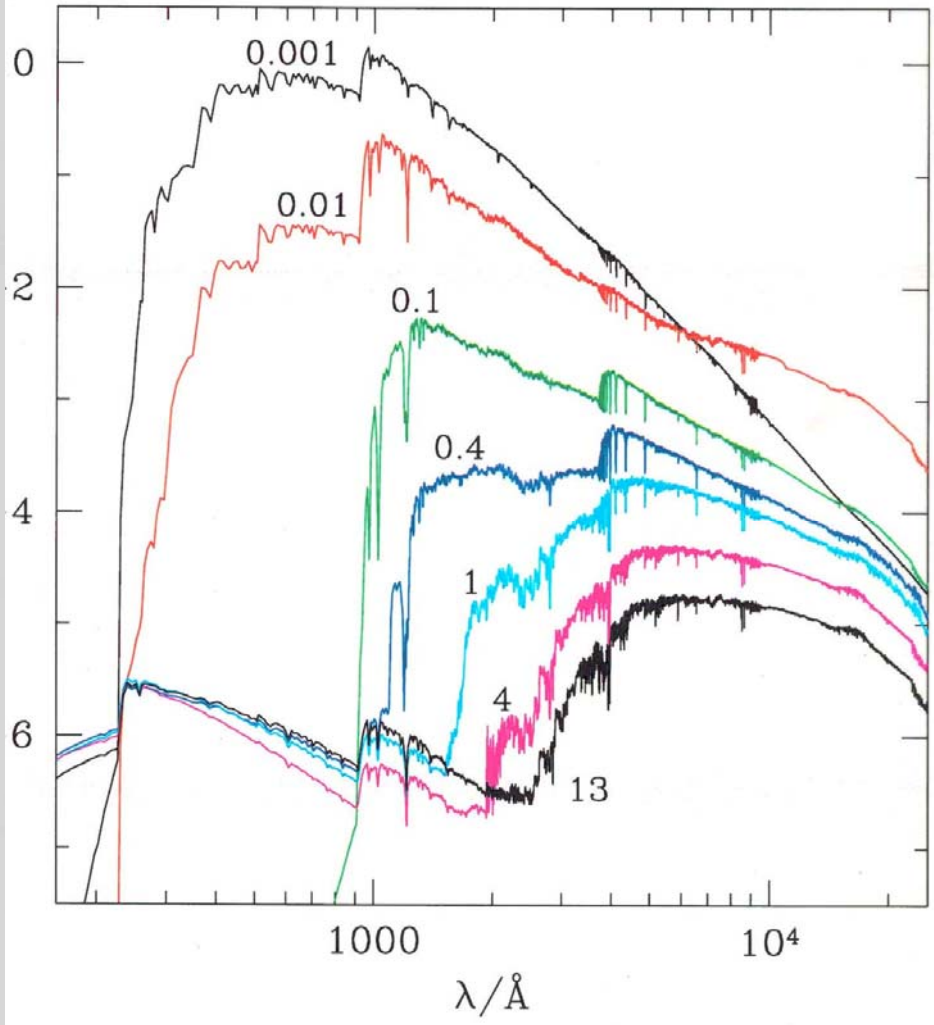
TAR FORMATION RATE HISTORY OF GALAXIES

EVOLUTION OF SPECTRAL ENERGY DISTRIBUTION OF A GALAXY



Sandage 1986

Bruzual and Charlot 2004



DISK MODE OF STAR FORMATION

motivated by gravitational instability of cold disks

star surface density

gas surface density

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

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

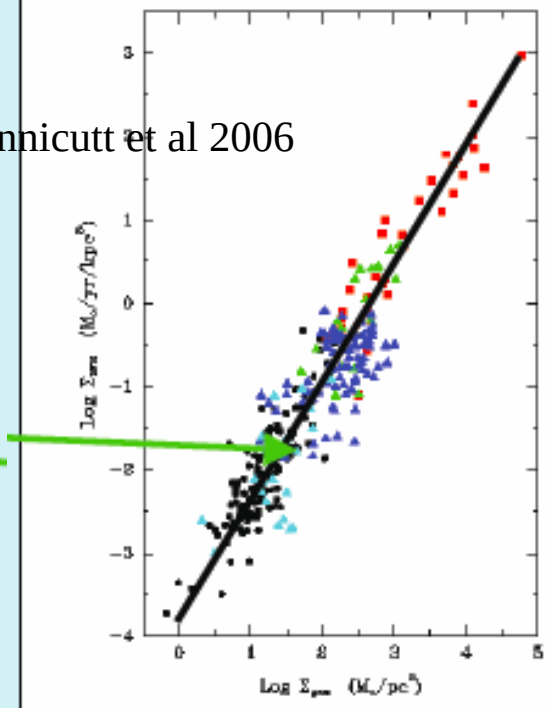
$$\propto \Sigma_{gas}^{3/2}$$

Star formation efficiency

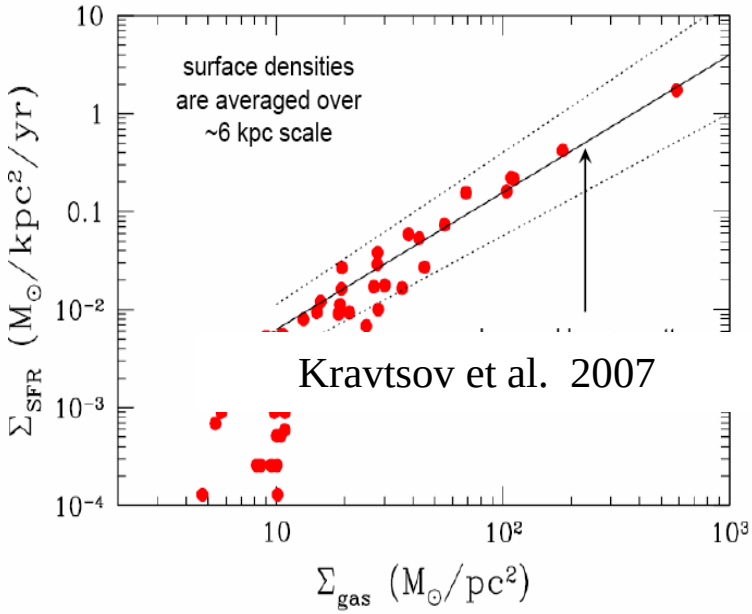
$$SFE = \frac{\sigma_{gas}\, v_{cool}\, m_{*,SN}}{E_{SN}^{initial}} \approx 0.02$$

A GLOBAL STAR FORMATION LAW

Kennicutt et al 2006



assume SFR = const x ρ_{H2} in cells with f_{H2}>0.1



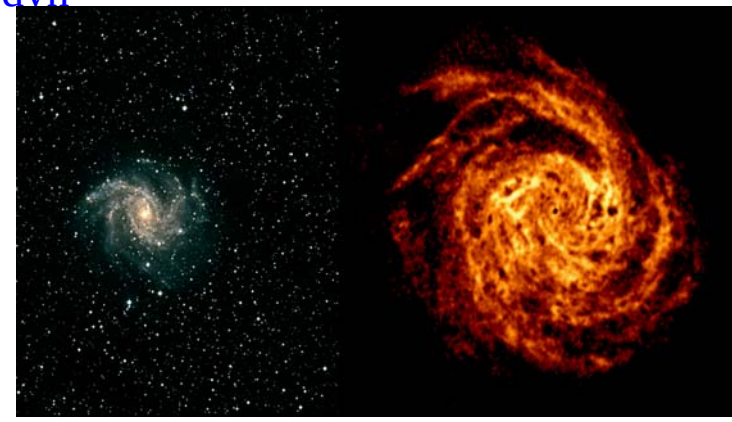
Kravtsov et al. 2007

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

fits quiescent & star-bursting galaxies (& M51)

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

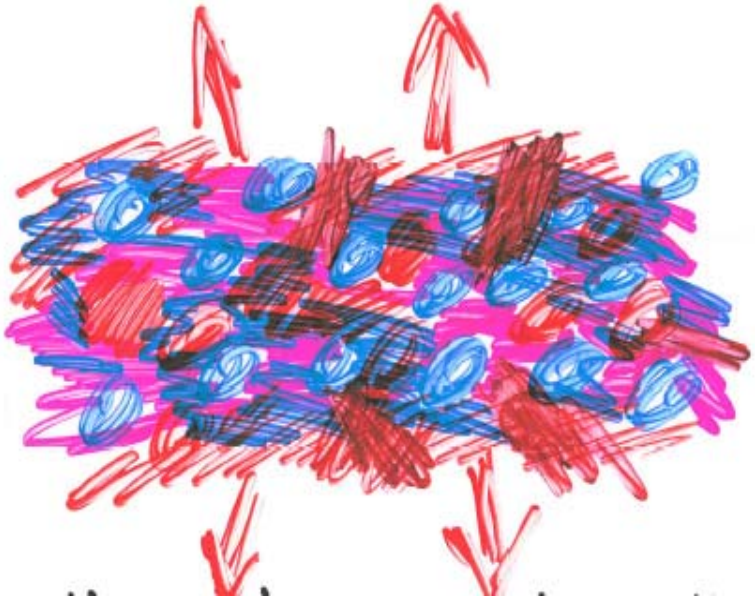
NGC 6946



Star Formation in a multi-phase ISM

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

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



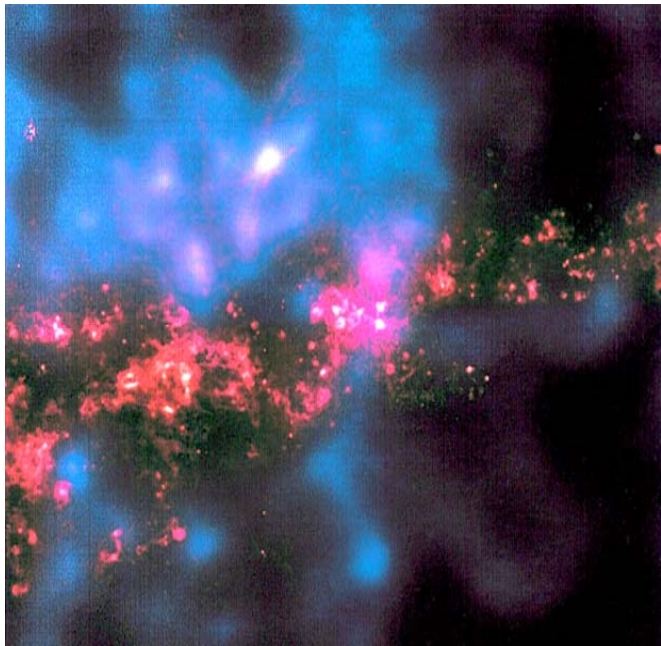
$HI \sim 1000K$

$H_2 \sim 10 - 100K$

$Hot\ phase \sim 10^6 K$

Three-phase ISM

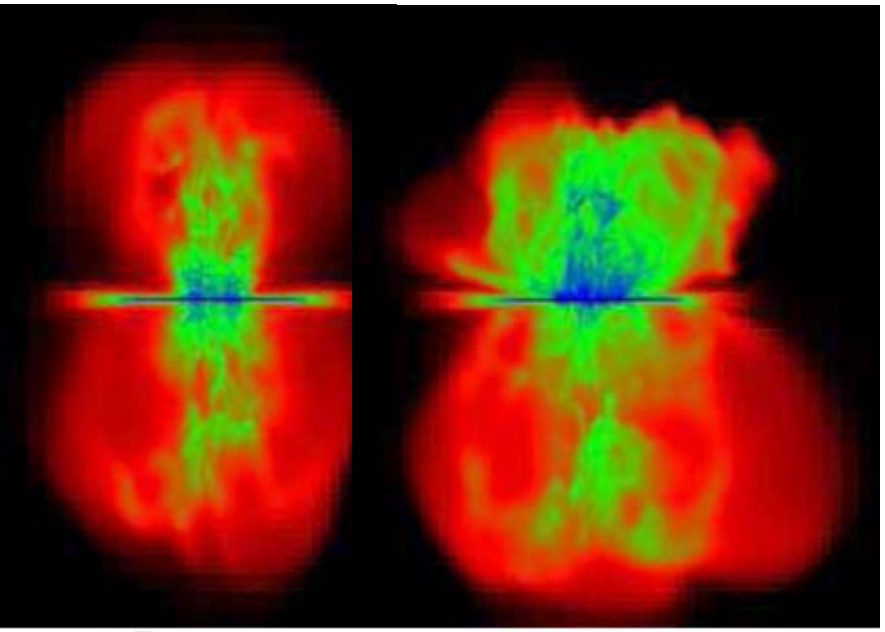
NGC1569

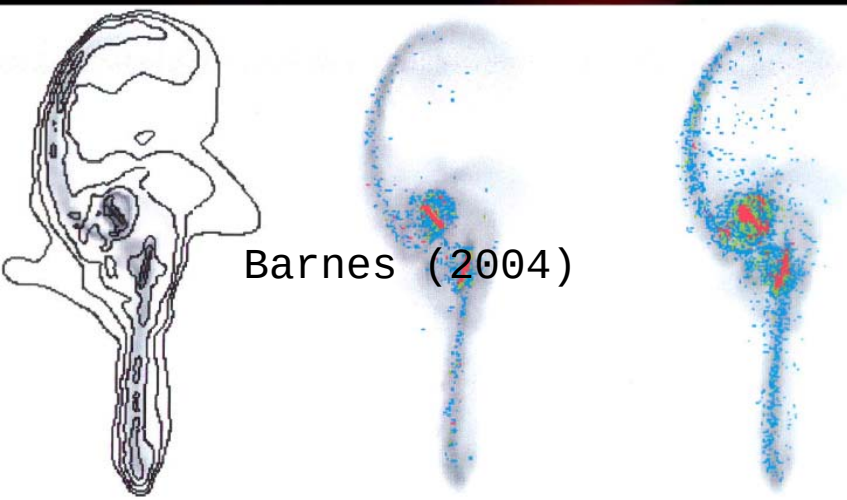


Perhaps porosity self-

ERNOVA FEEDBACK IN A MULTIPHASE

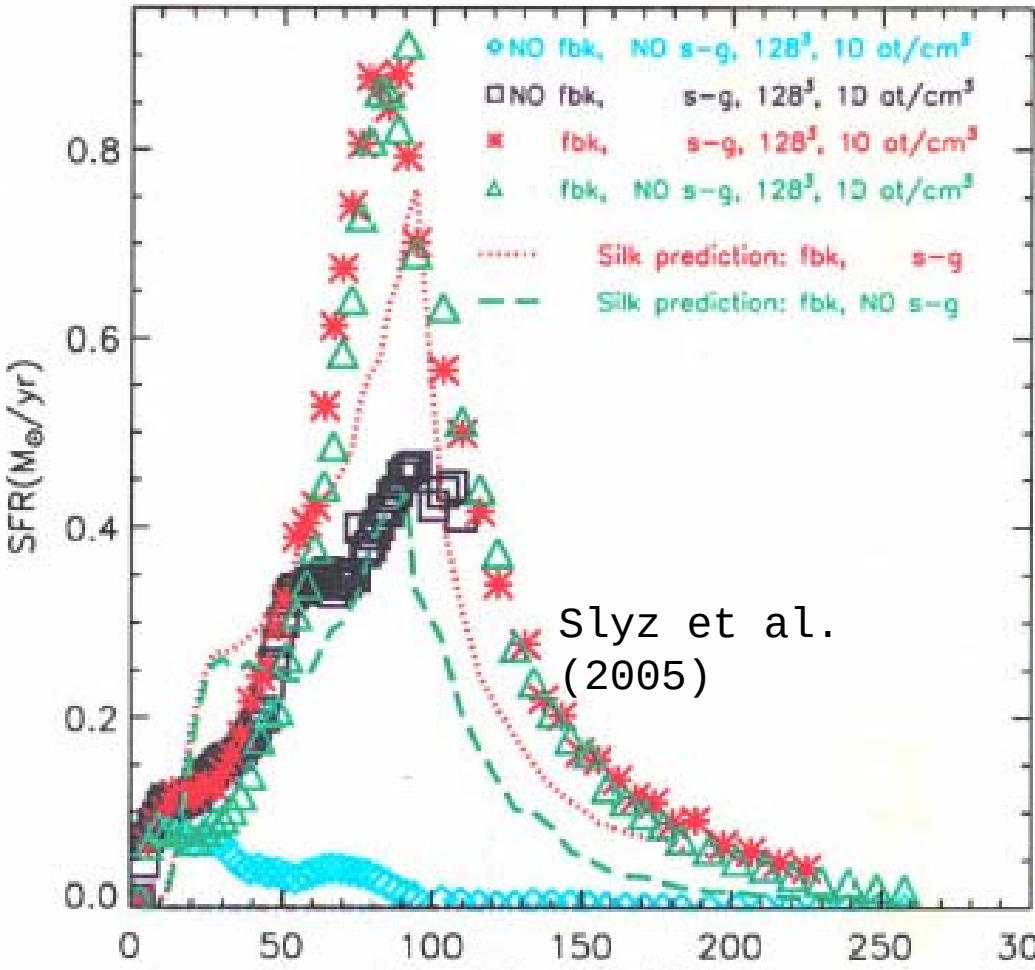
Tasker & Bryan 2007





Barnes (2004)

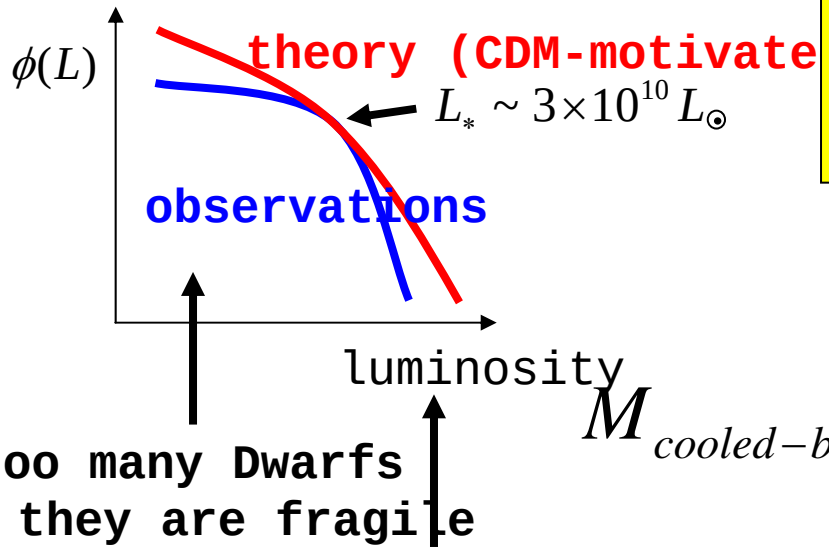
SFR with turbulent



Slyz et al. (2005)

SFR with SN porosity in a m

What determines the mass of a galaxy?



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

$\sim 10^{69} m_p$

$\beta \sim -0.5$

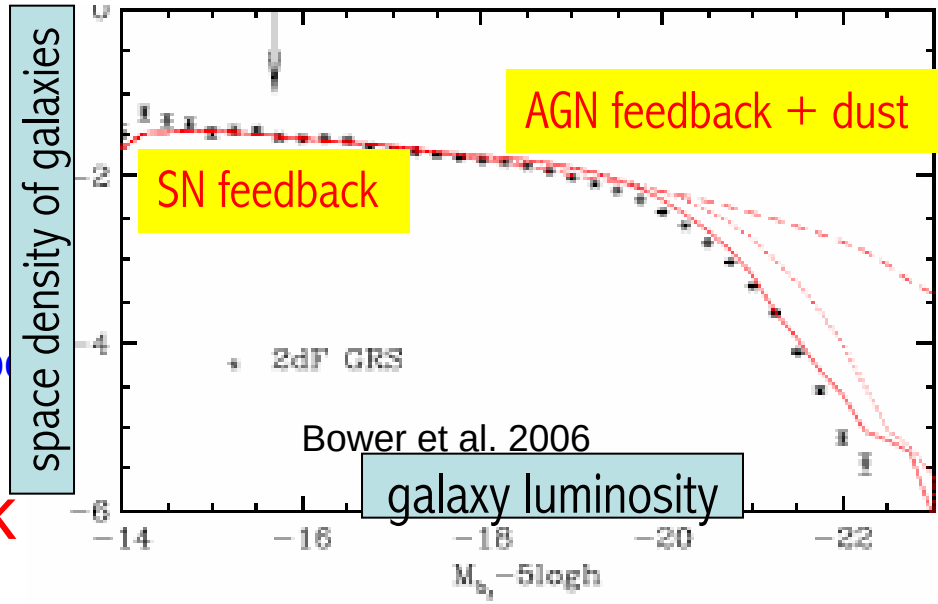
$\alpha_g = Gm_p^2/e^2$

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 co

the **KEY ISSUE** is astrophysical feedback

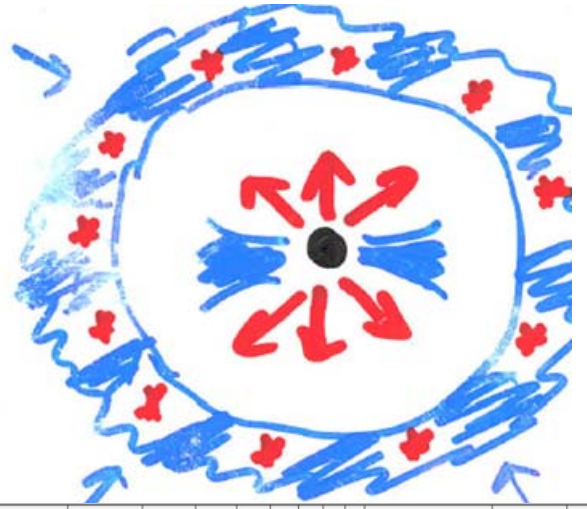


Supermassive black holes and galaxy spheroid formation

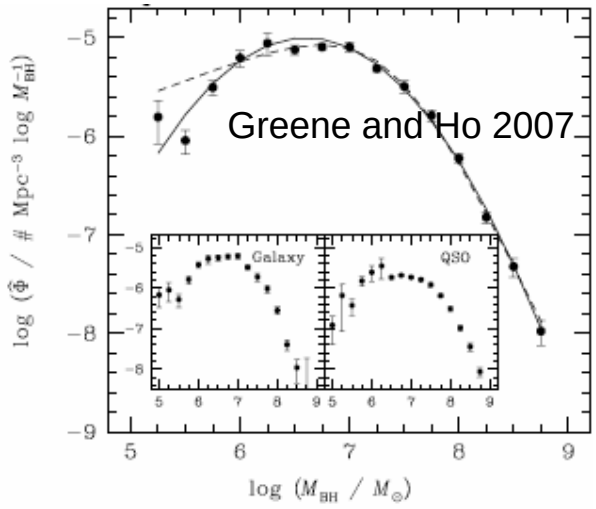
$$L_{Edd}/c = GMM_{gas}/r^2$$

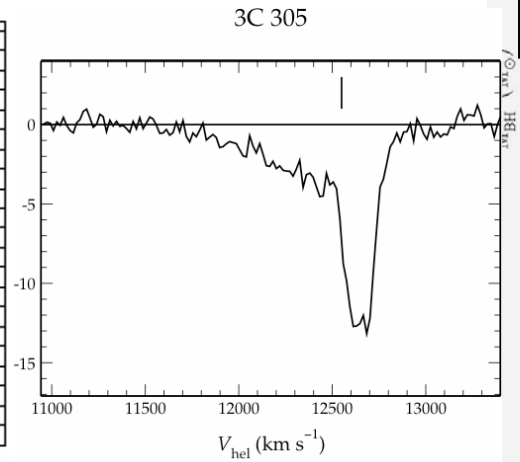
$$L_{Edd} \propto M_{SMBH}$$

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

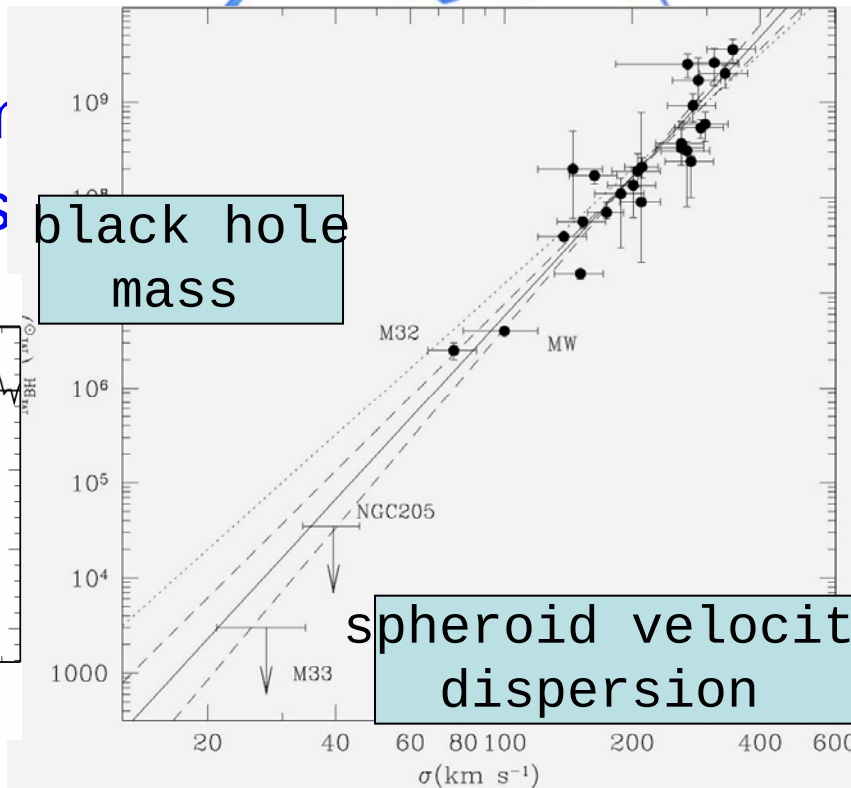


Blowout occurs/star formation term
when SMBH-σ relation saturates



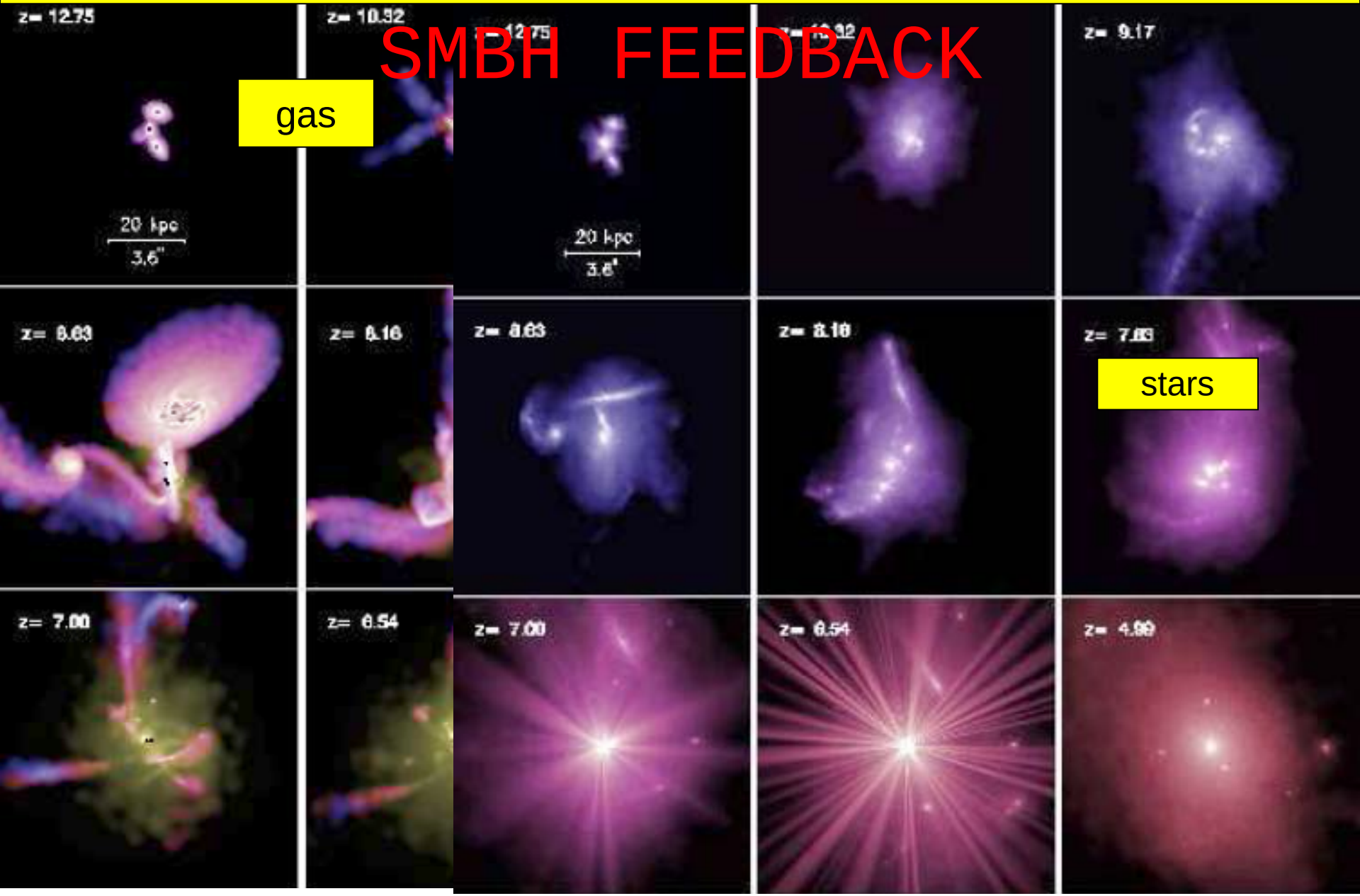


black hole mass



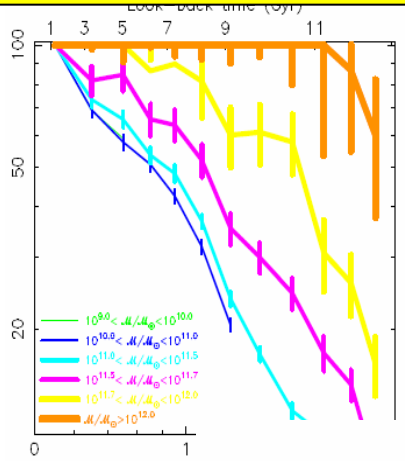
spheroid velocit dispersion

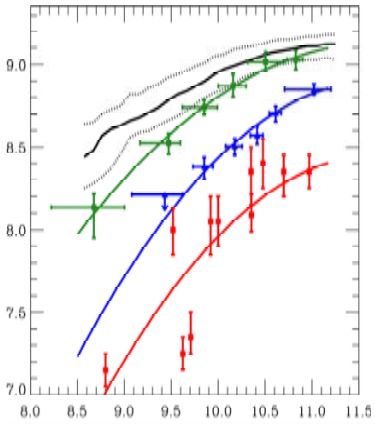
NUMERICAL SIMULATIONS OF SMBH FEEDBACK

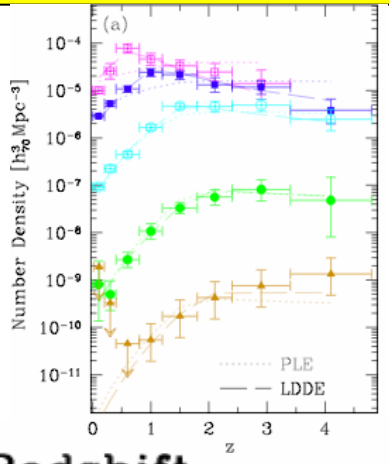


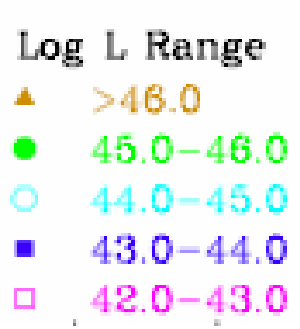
Y. Li et al. 2006

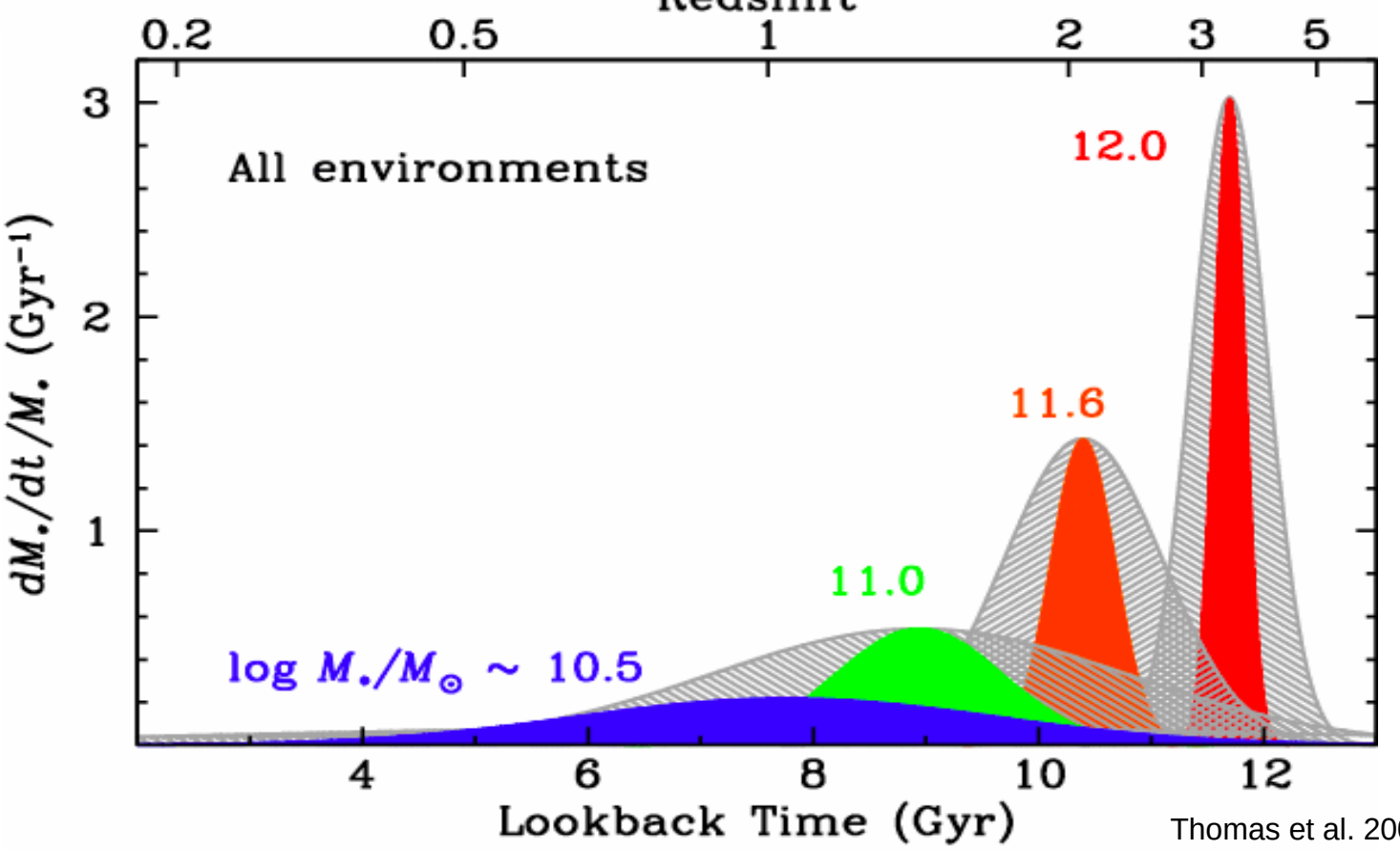
DOWNSIZING IN STELLAR MASS, STAR FORMATION, Z AND SMBH MASS











Thomas et al. 2008

Why efficient formation of massive spheroids ?

- assume AGN-driven outflows trigger star formation

Star formation rate is boosted by facto
due to AGN triggering of supernovae

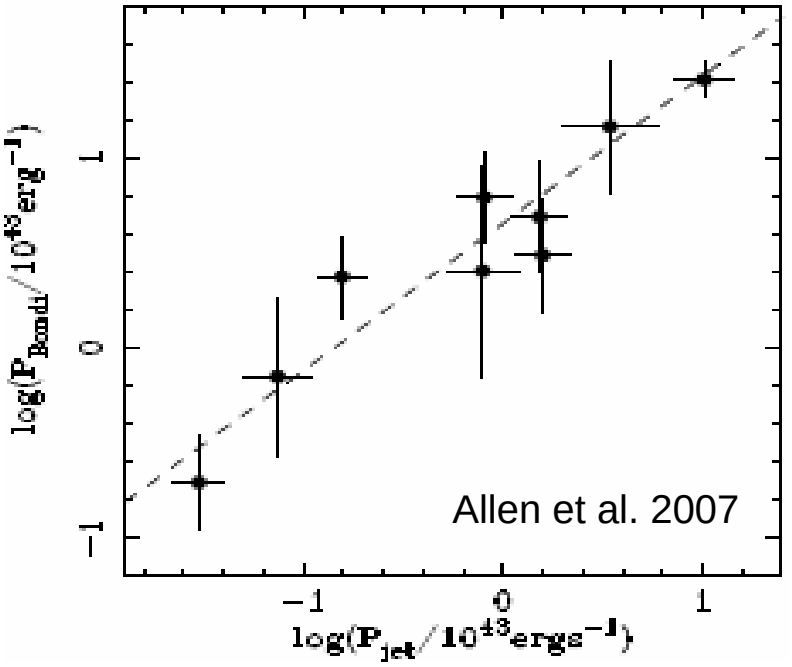
Why down-sizing of massive spheroids and AGN?

- Need SMBH feeding and outflow

to be nonlinear function of SMBH mass

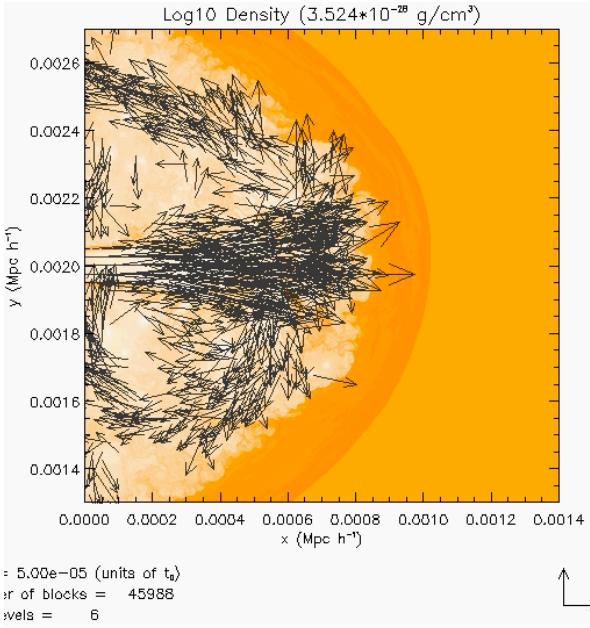
e.g. accretion rate~ M_{SMBH}^2 (Bondi)

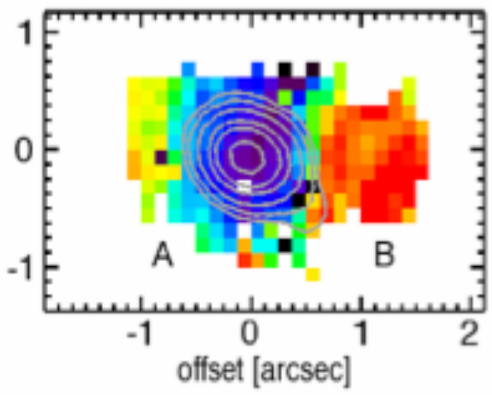
and outflow rate~ 0.1 accretion rate

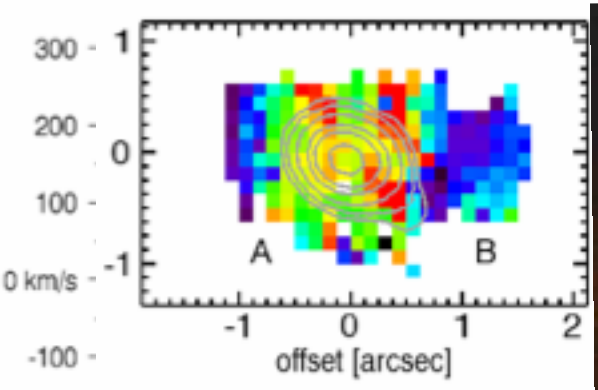


LETS BLAME THE SUPERMASSIVE BLACK HOLE!

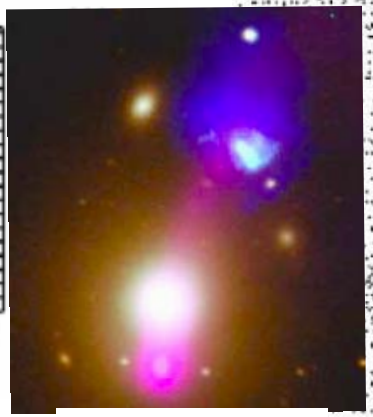
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.



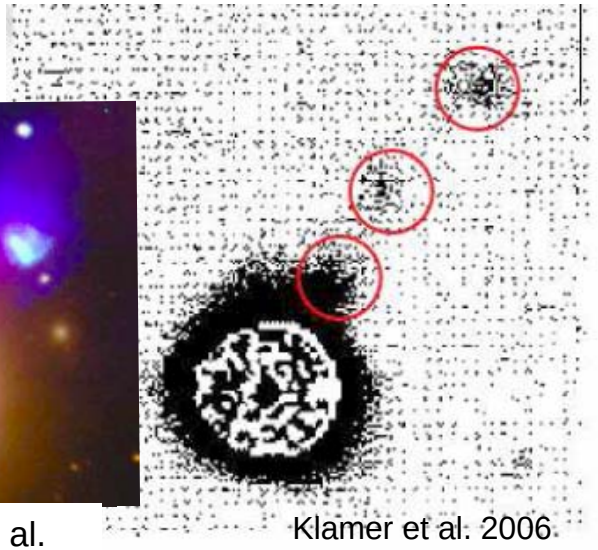




Nesvada et al 2007

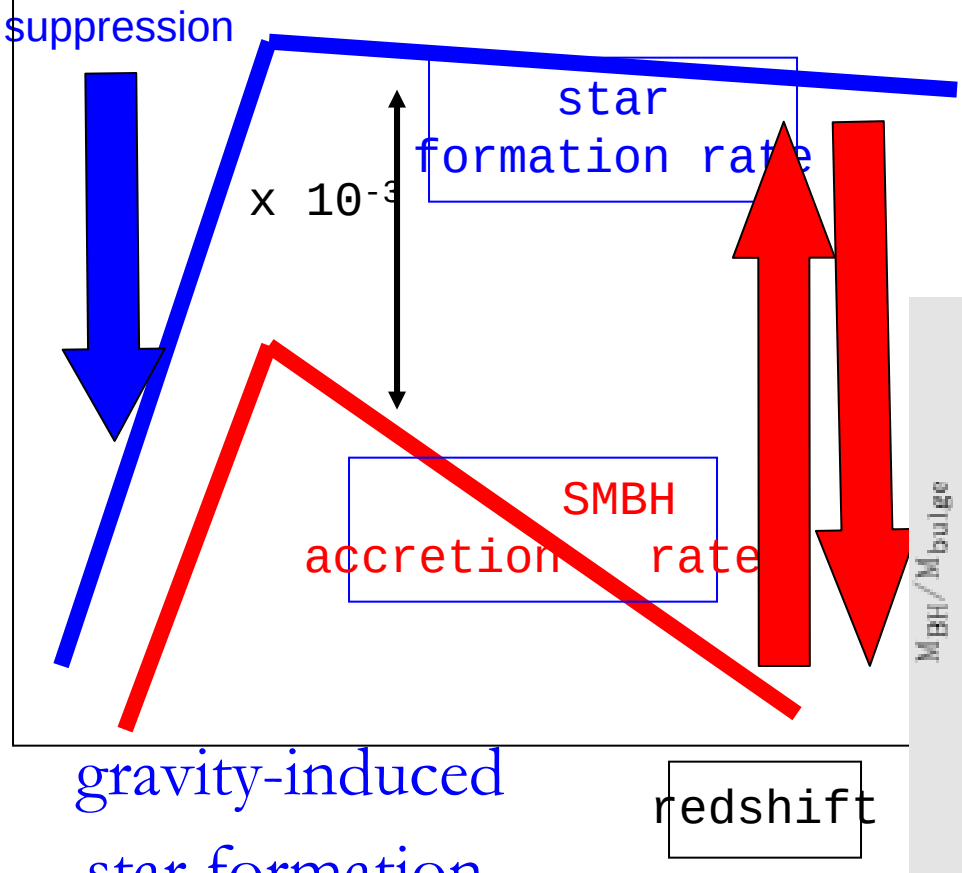


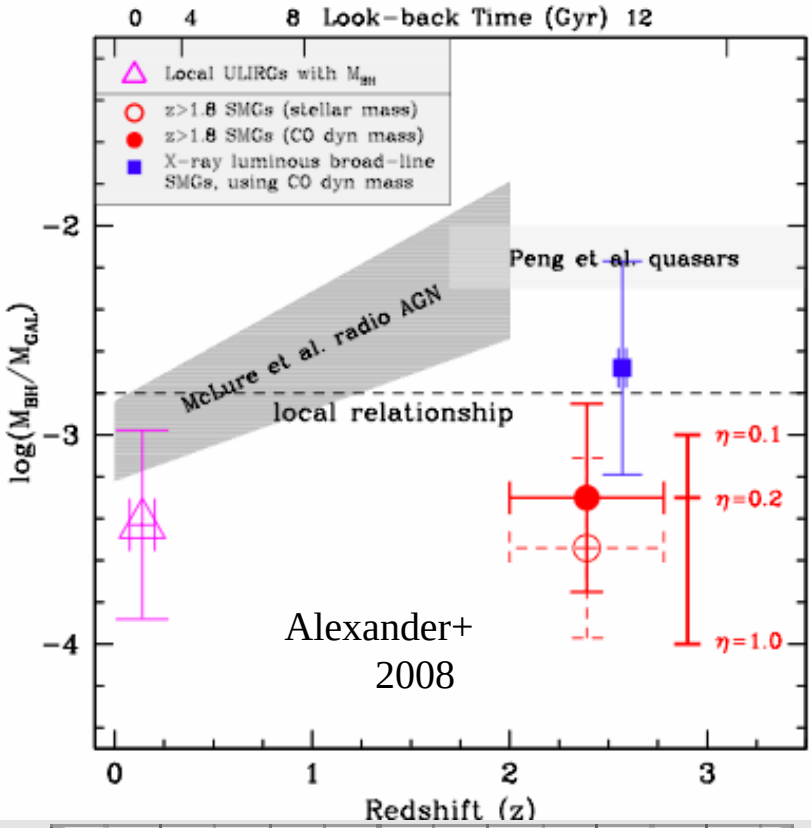
Croft et al.

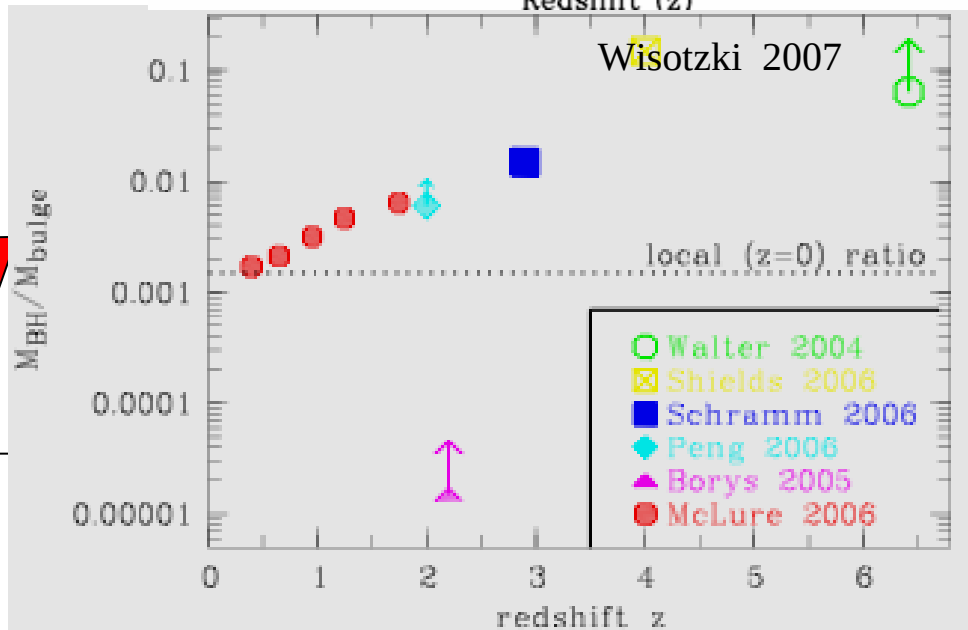


Klamer et al. 2006

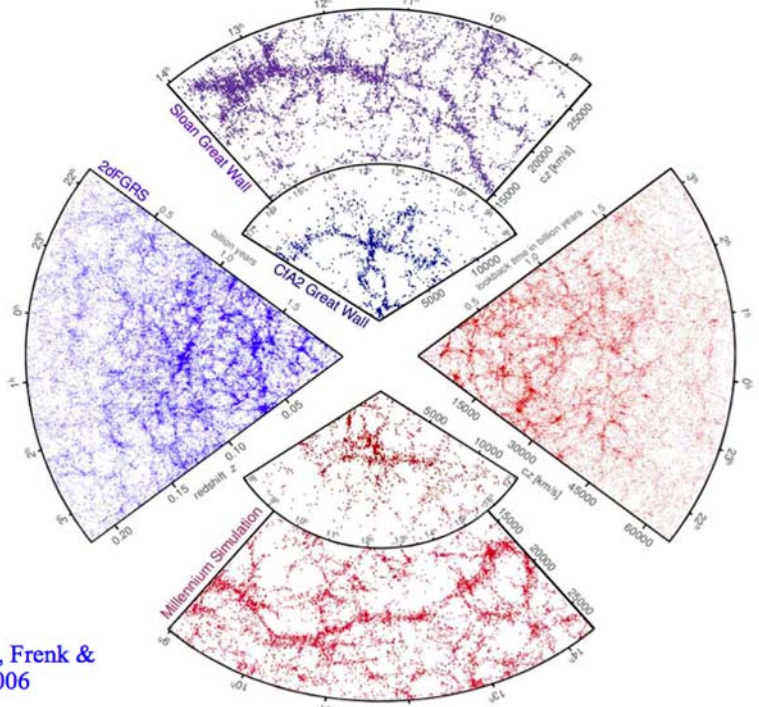
AGN-an aftermath or precursor to star formation?







Basic paradigm: baryons dissipate in halos of weakly interacting Cold Dark Matter



A great success for large-scale structure

But problems arise on galactic scales:

overabundance of satellites

observed cores in dark halos

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

DARK MATTER IS CHALLENGED BY COSMOLOGY

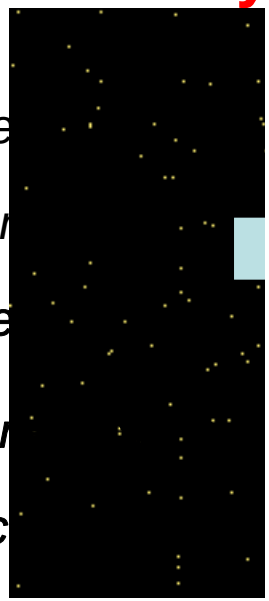
RESURRECTION VIA FUNDAMENTAL PHYSICS?

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

RESURRECTION VIA ASTROPHYSICS?

- FEEDBACK FROM SUPERNOVAE / SUPERMASSIVE BLACK HOLES / DYNAMICAL HEATING

9 reasons why



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7 Cannot re Kara

Benson et a

8 cannot repro

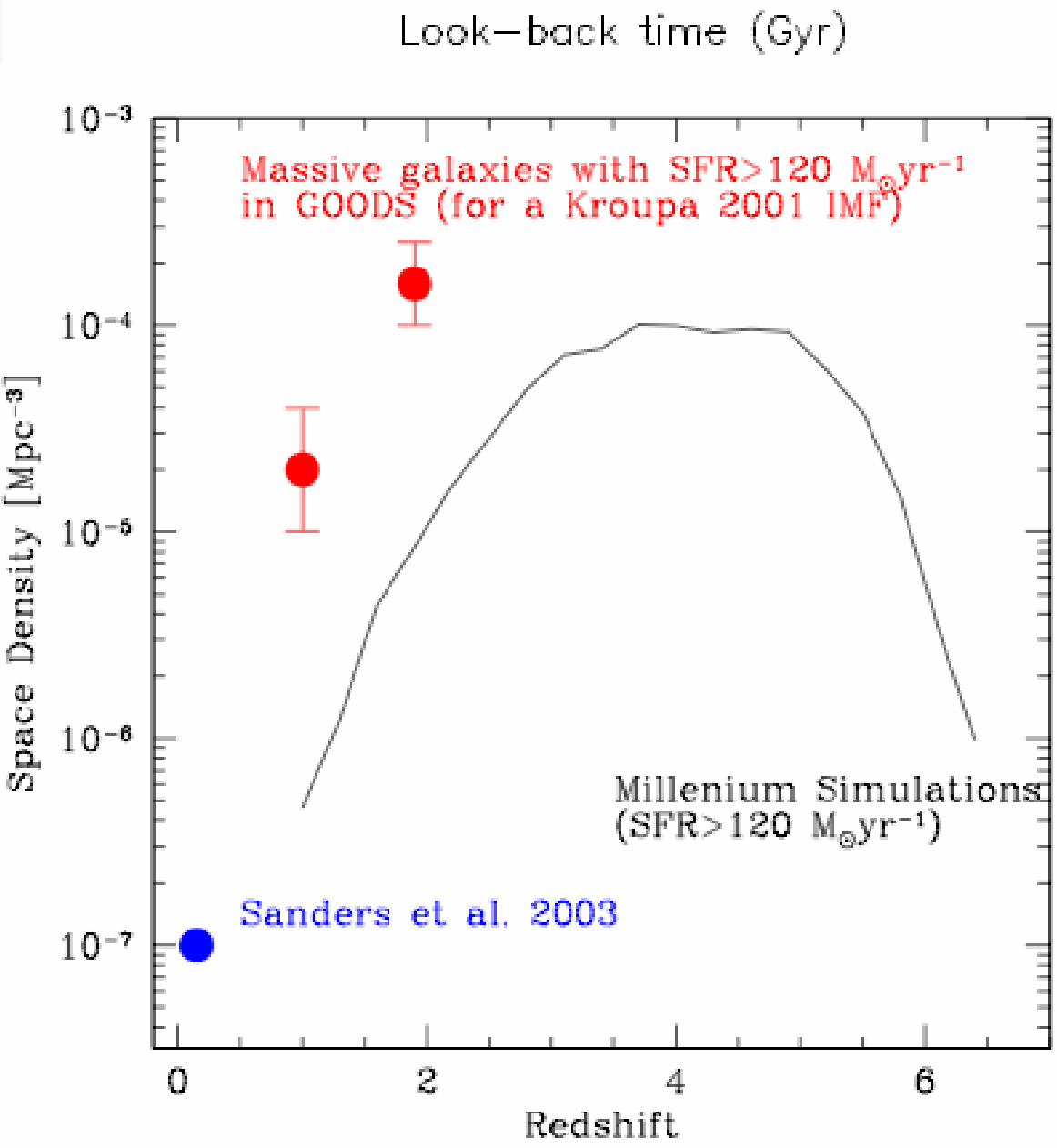
Daddi et al. 2007

9 cannot form

Steinmetz

Perez-Gonza

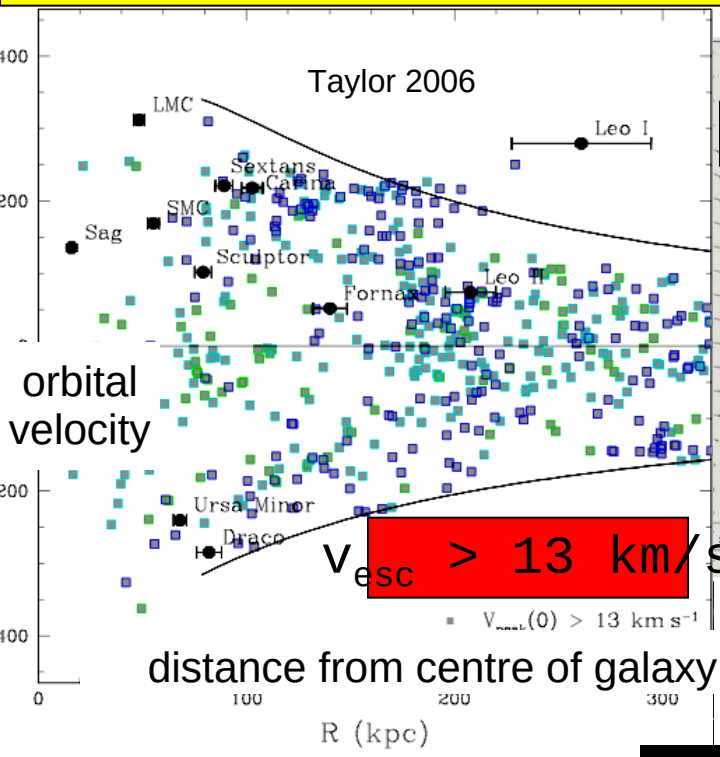
Taylor and Ba



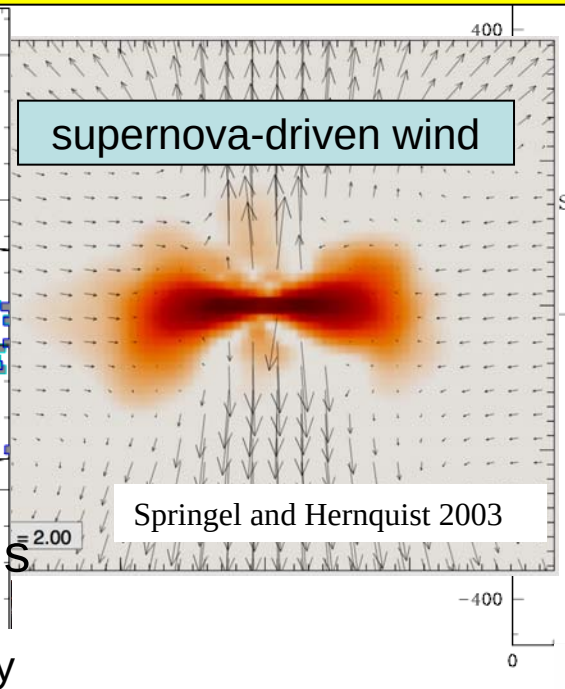
Of co

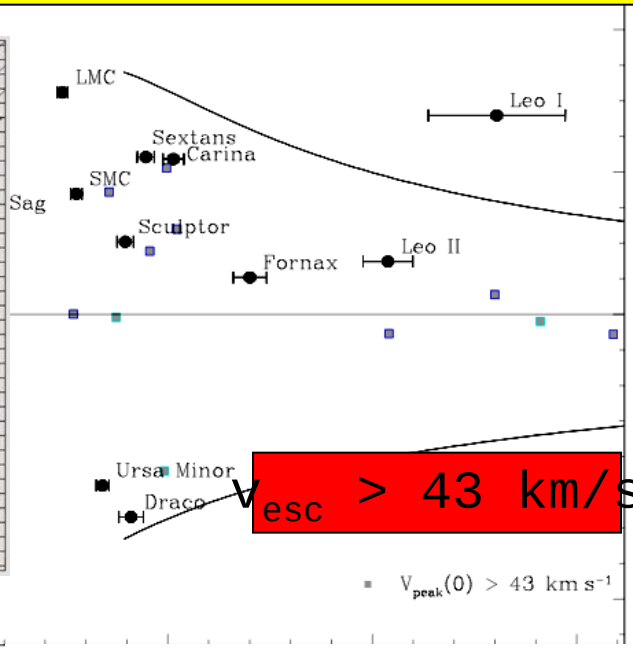
if we can improve the star formation physics....

Resolving the CDM dwarf excess with SN feedback

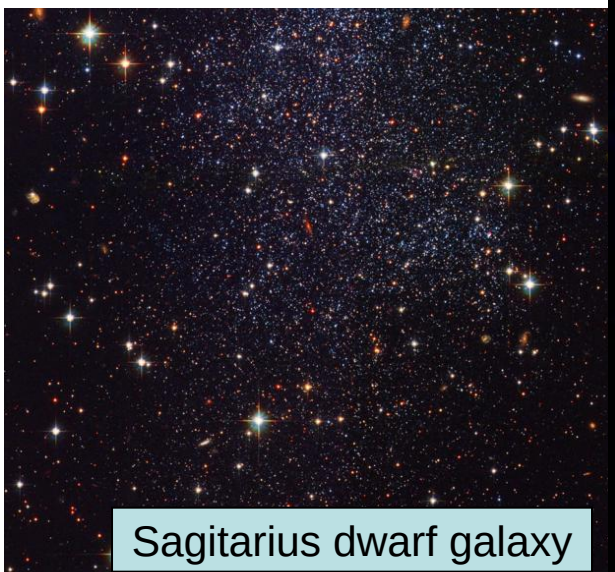


v_{esc} > 13 km/s

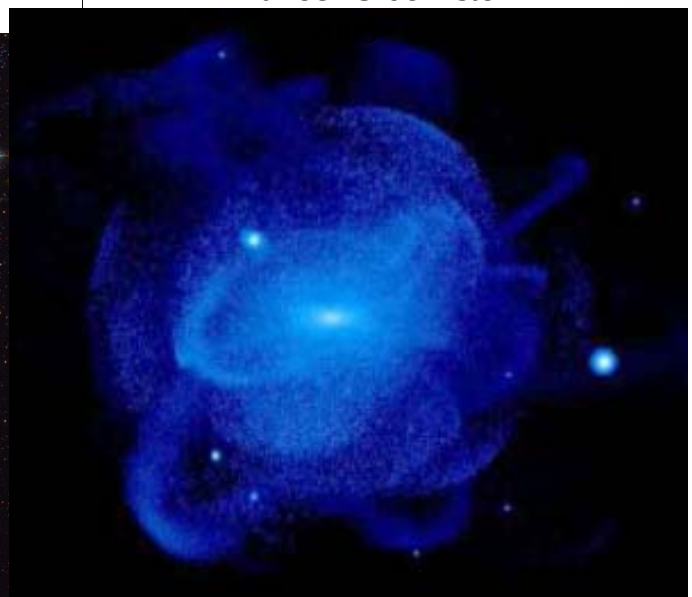


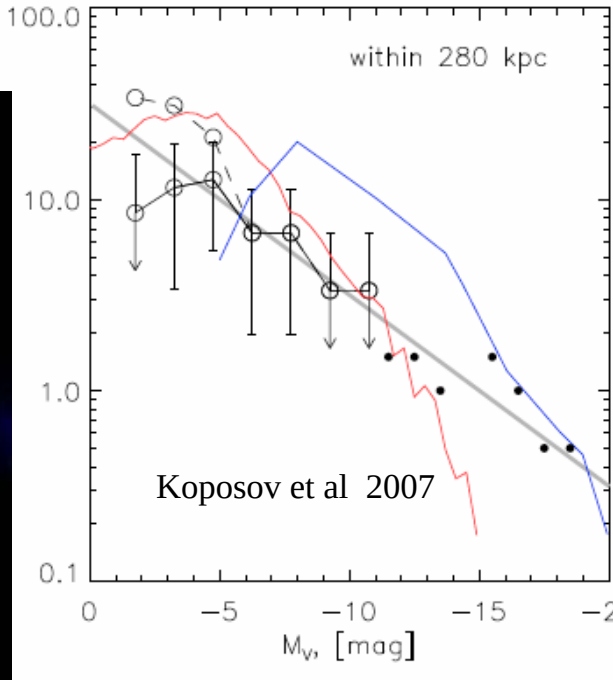


v_{esc} > 43 km/s

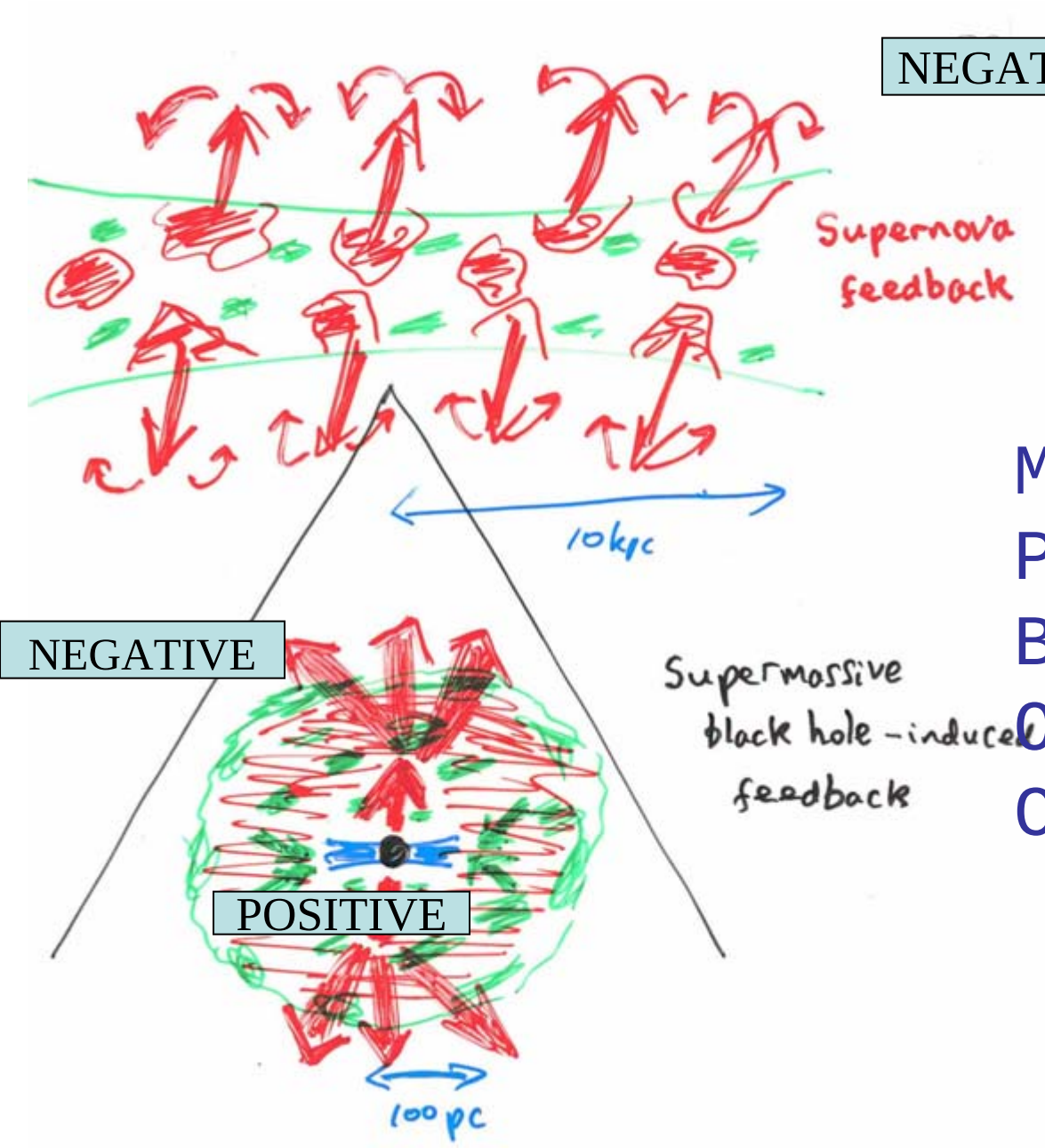


Bullock & Johnston





A UNIFIED THEORY



MANY PARAMETERS TO BE OBSERVATIONALLY CONSTRAINED!