Cosmological simulations of galaxy formation

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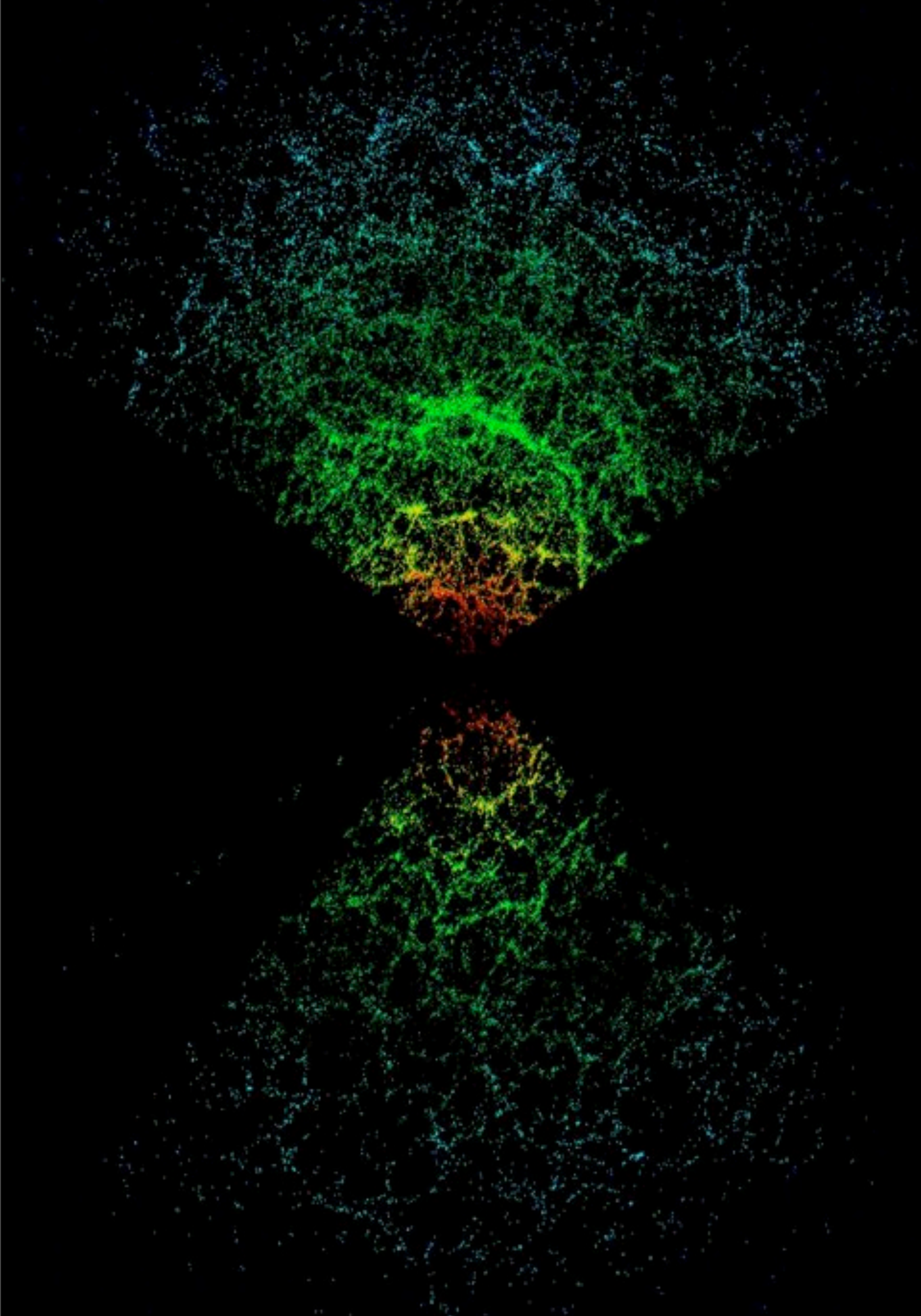
Outline

- Disc formation in LCDM cosmology
- Star formation efficiency and morphology connection
- The baryon fraction problem
- Star formation at high redshift: cold streams and clumpy galaxies
- Star formation in merging system: resolving the clumpy ISM

Ben Moore, Davide Martizzi, Oscar Agertz (Zürich)
Frédéric Bournaud, Damien Chapon (Saclay)
Avishai Dekel (Jerusalem)

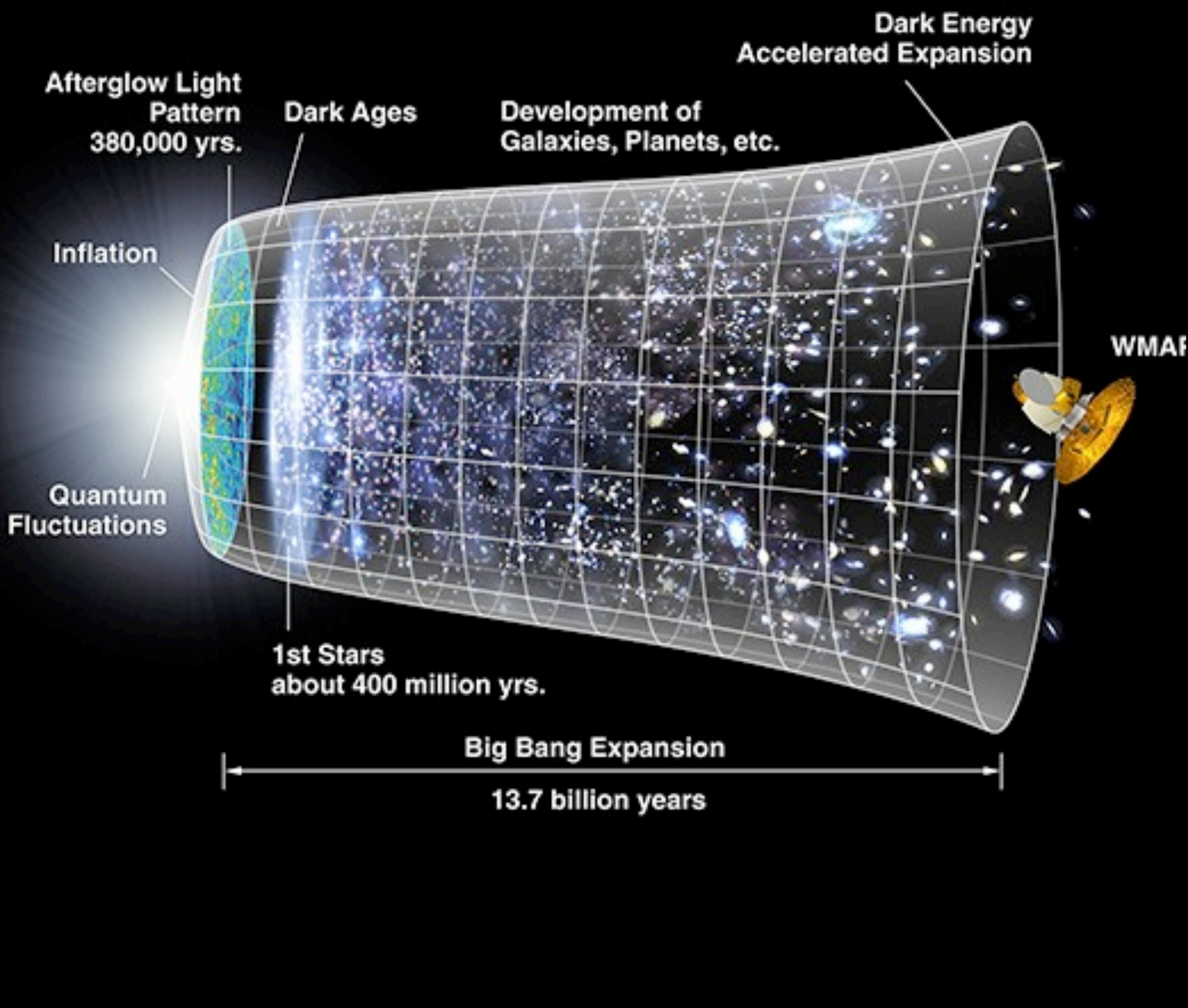
Galaxies in the universe



Sloan Digital Sky Survey 2003

Hubble Deep Field 2004

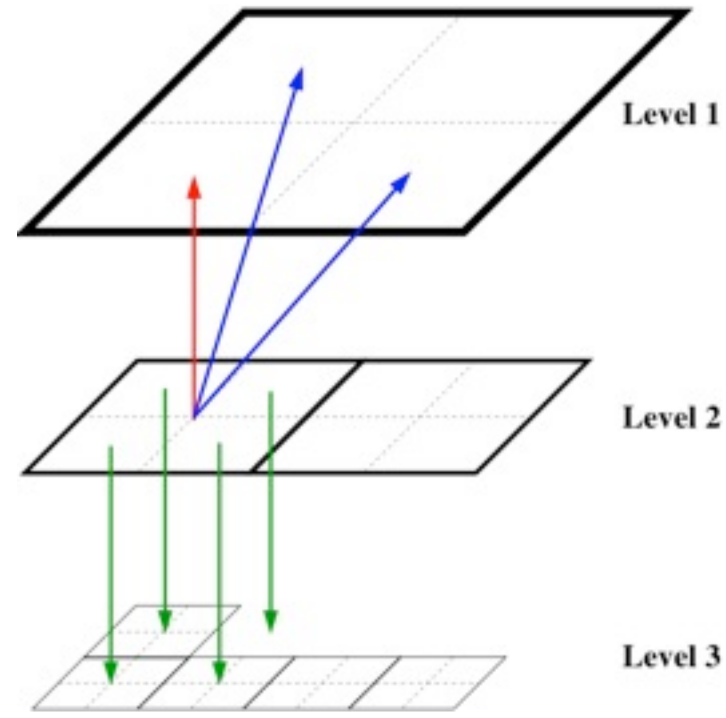
Cosmic structure formation



• Graded octree structure: the cartesian mesh is refined on a cell by cell basis

• Full connectivity: each oct have direct access to neighboring parent cells and to children octs (memory overhead 2 integers per cell).

• Optimize the mesh adaptivity to complex geometry but CPU overhead can be as large as 50%.



N body module: Particle-Mesh method on AMR grids. Poisson equation solved using a multigrid solver.

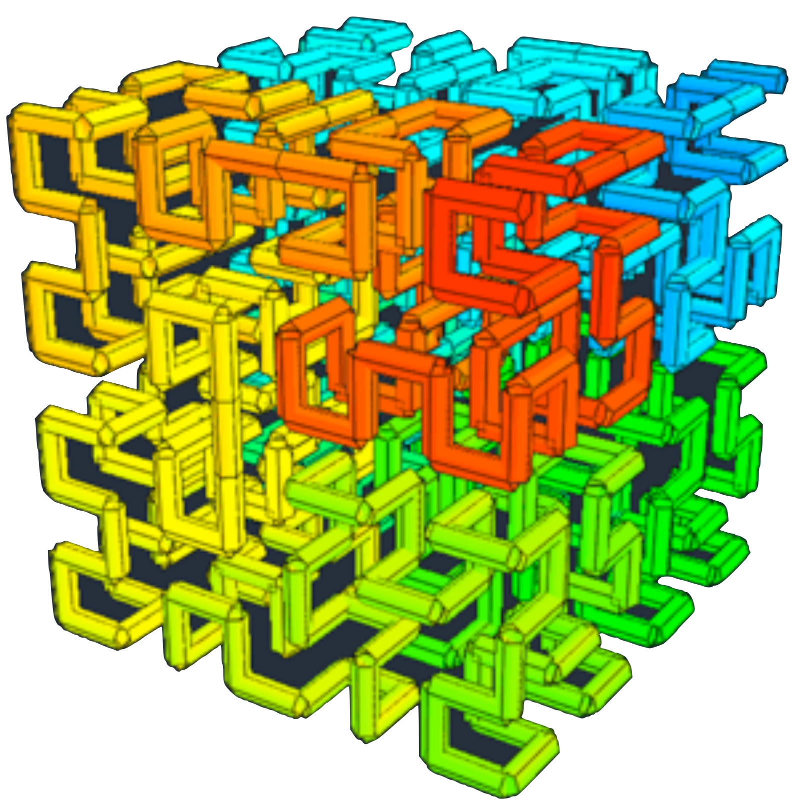
Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. New CT-based MHD solver.

Time integration: single time step or sub-cycling.

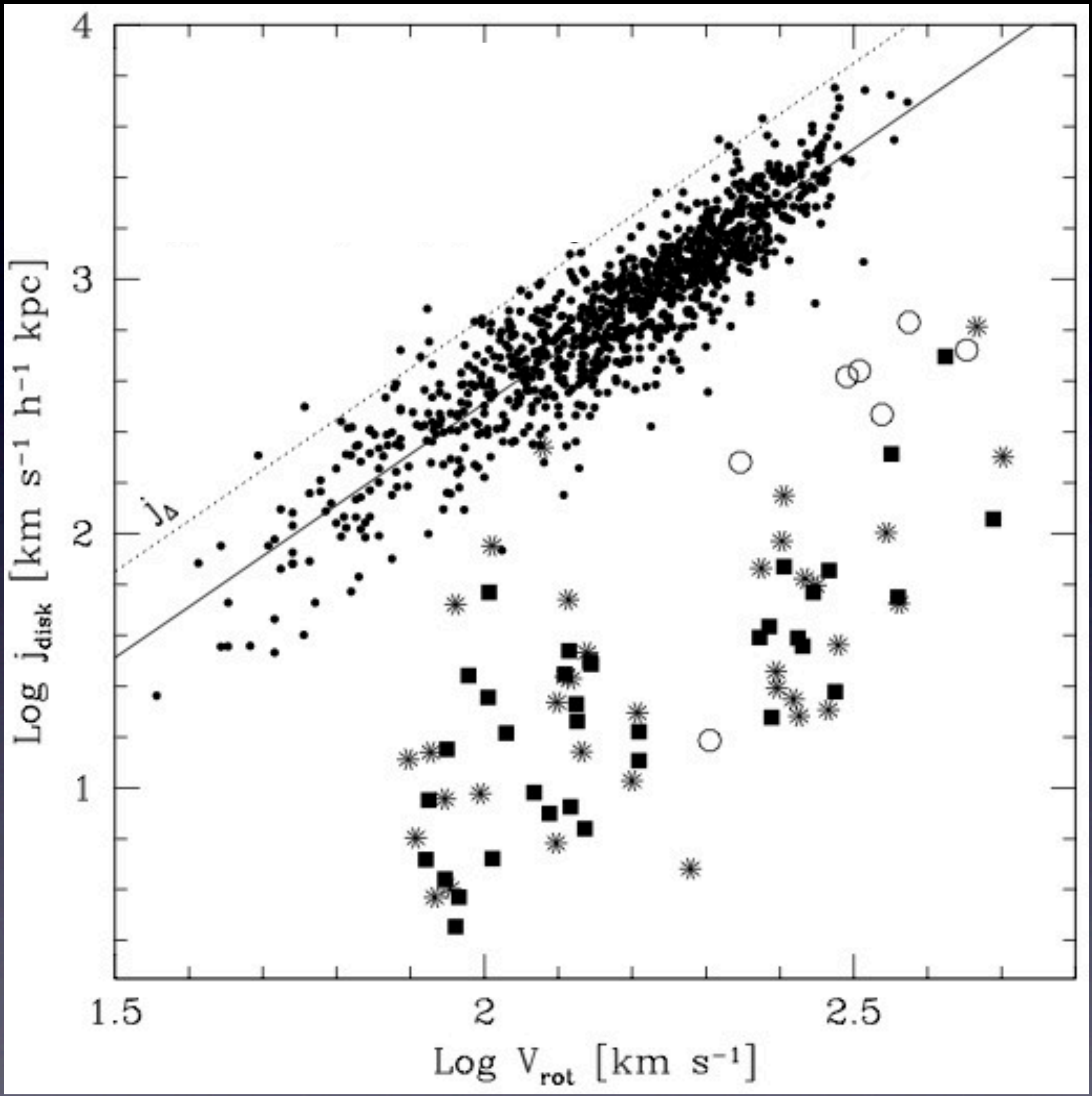
Other: Radiative cooling/heating, star formation, feedback.

MPI-based parallel computing using time-dependant domain decomposition based on Peano-Hilbert cell ordering.

Download at http://irfu.cea.fr/Projets/Site_ramses



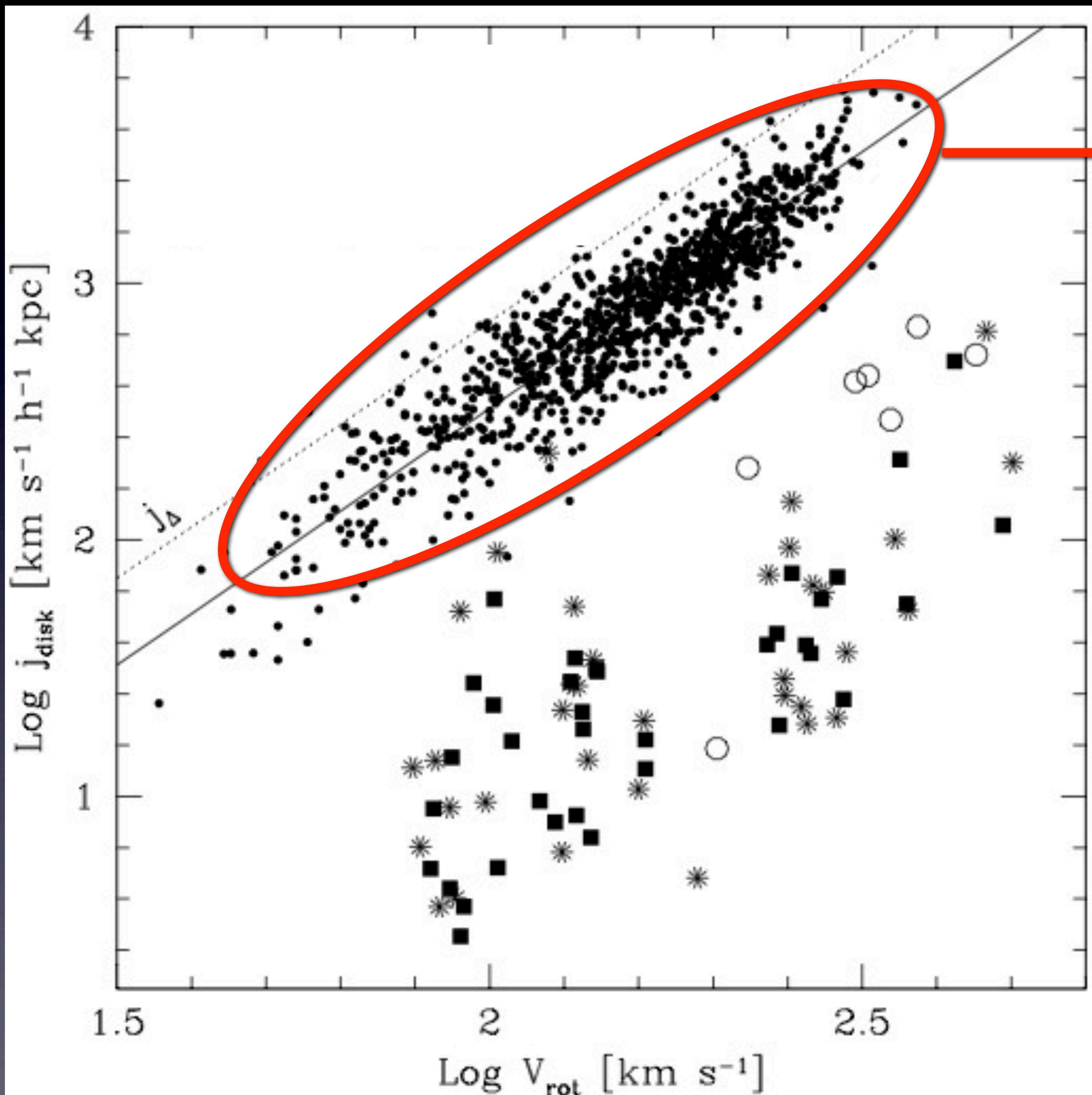
First galaxy formation simulations



The angular momentum problem

Navarro & Steinmetz 2000

First galaxy formation simulations

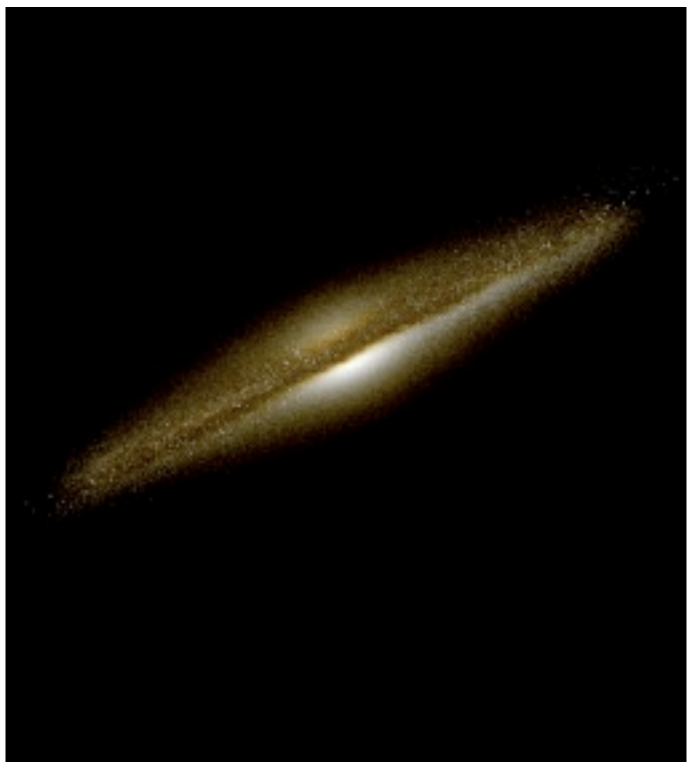


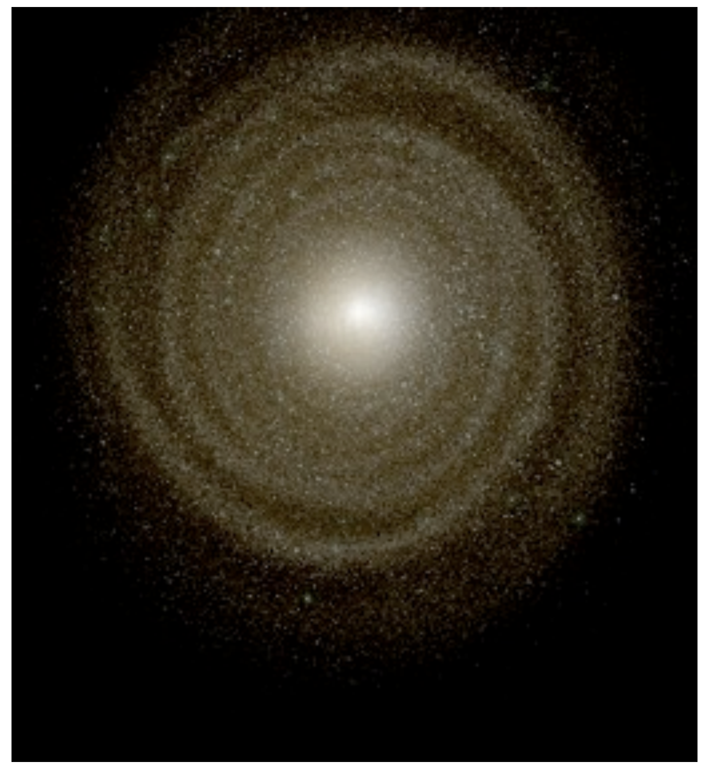
Courteau (1997)
Sb-Sc galaxies

The angular momentum problem

Navarro & Steinmetz 2000

Modern galaxy formation simulations

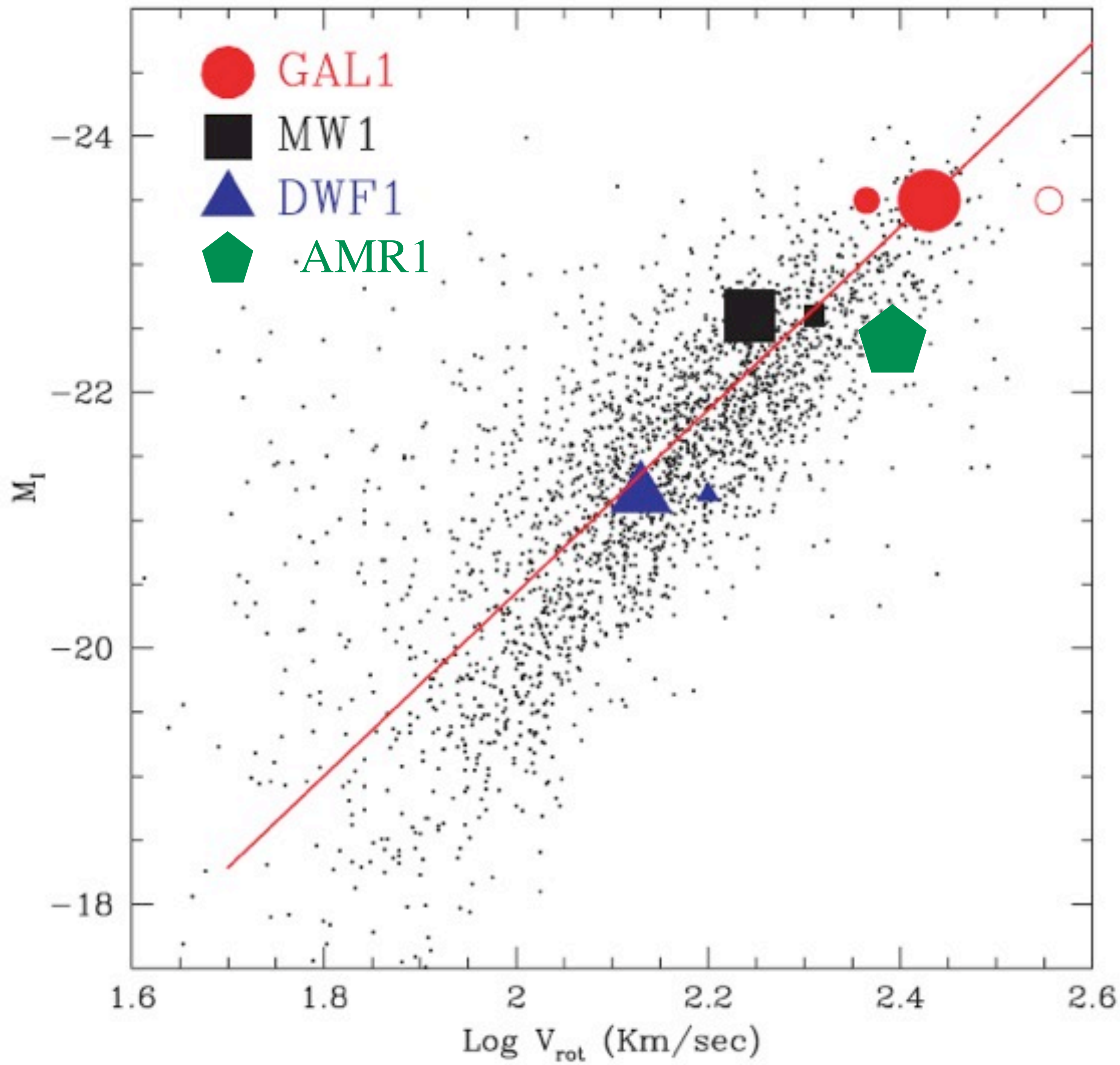




Mock gri SDSS composite image with dust absorption based on Draine opacity model.

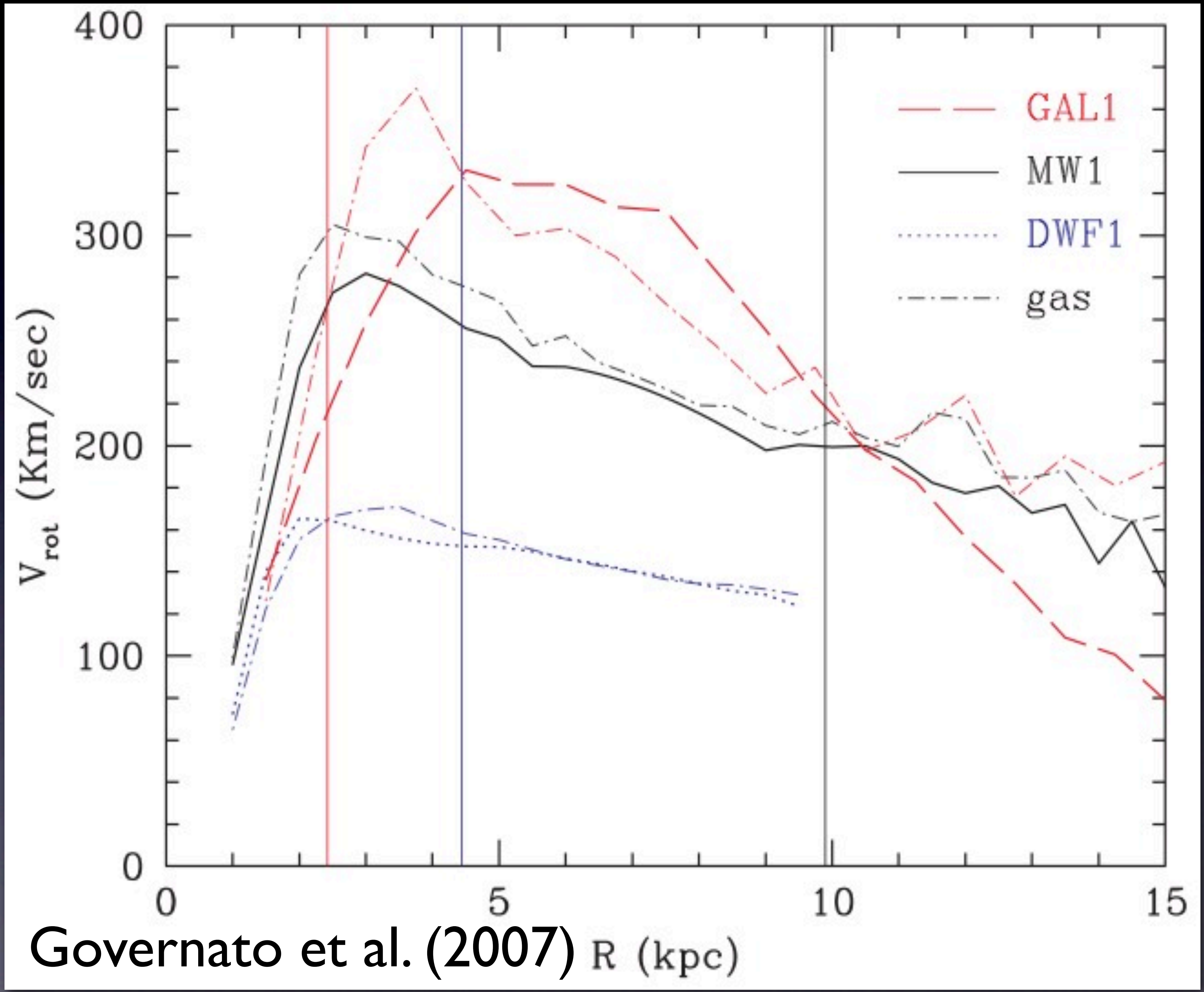
NGC4622 as seen from HST

Stronger feedback, higher resolution



I Band Tully-Fisher relation
GASOLINE data from Governato et al. 2007, Mayer et al. 2008

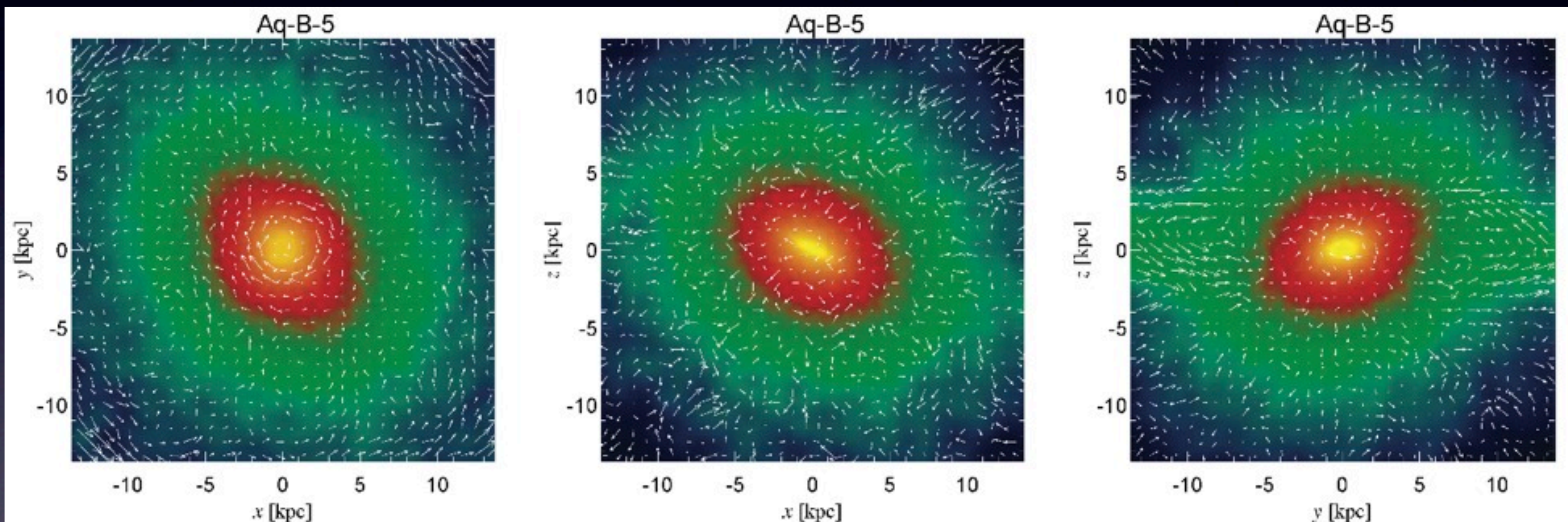
Rotation curves are still strongly peaked !



Governato et al. (2007)

Disks are still too small !

Galaxy formation in 8 Milky Way haloes (Scannapieco et al. 2009)
(Hydro + N-body simulations of the Aquarius halos)



Sophisticated models of SNe feedback, winds, star formation etc.
Largest D/T ~ 0.2!!!

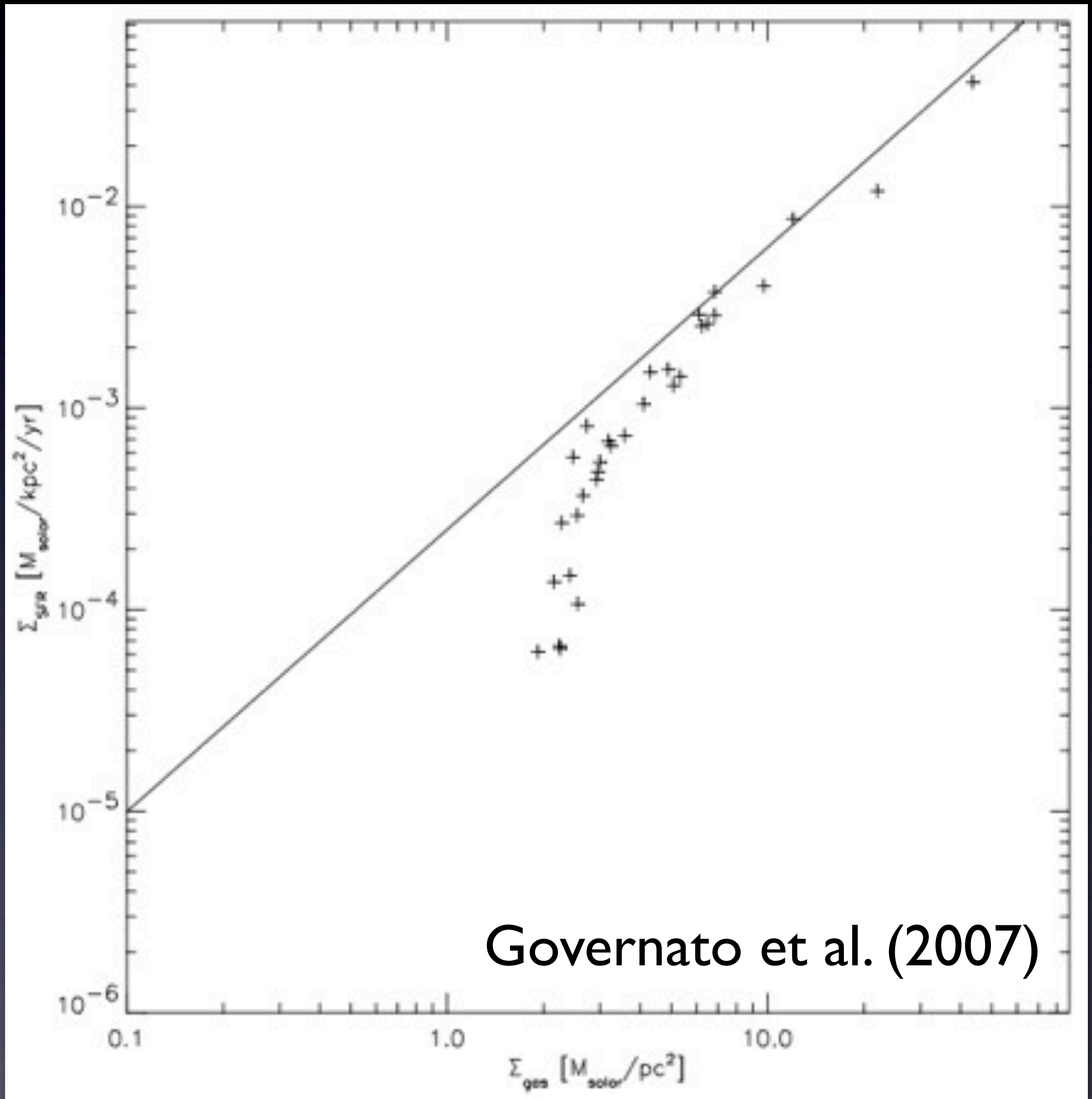
Standard practice of star formation and feedback in simulations of galaxy formation...

1. Tune the star formation efficiency and supernovae feedback to the Kennicutt-Schmidt relation (Kennicutt 1998), using an isolated disk.

$$\dot{\rho}_* = \epsilon_{\rm ff} \frac{\rho_{\rm g}}{t_{\rm ff}} \text{ for } \rho > \rho_0$$

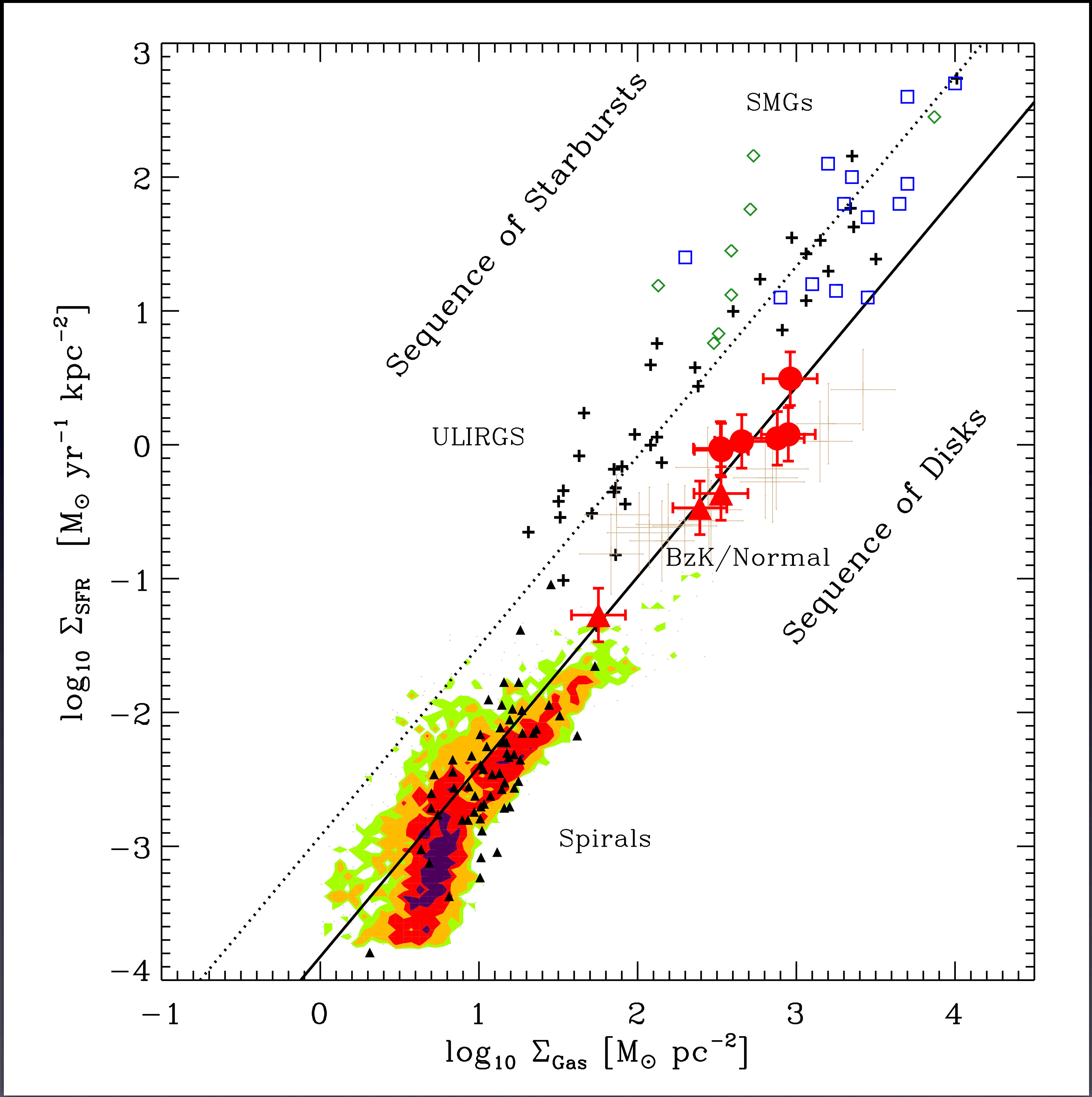
↓

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^N$$



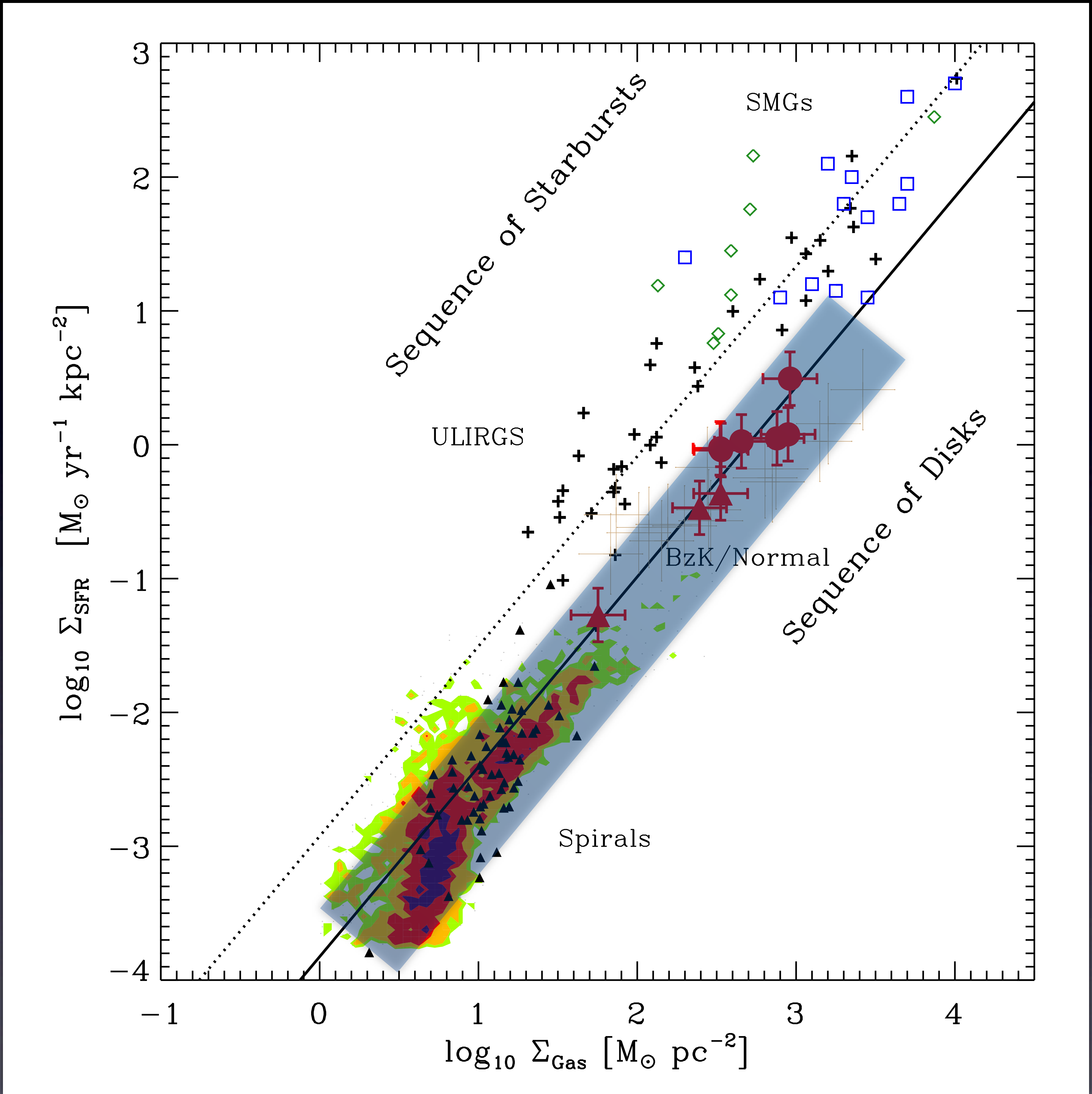
2. Assume star formation is regulated by supernovae explosions at high-z. Dump E_{SNII} into the ISM (kinetic, thermal, cooling shutoff etc).

Abadi et al. (2003), Okamoto et al. (2009), Governato et al. (2004, 2007, 2009, 2010), Piontek & Steinmetz (2009), Scannapieco et al. (2008, 2009)



Daddi et al. 2010
Genzel et al. 2010

The way gas is converted into stars is observed to vary *among* different galaxies, *within* galaxies and at different cosmic epochs!



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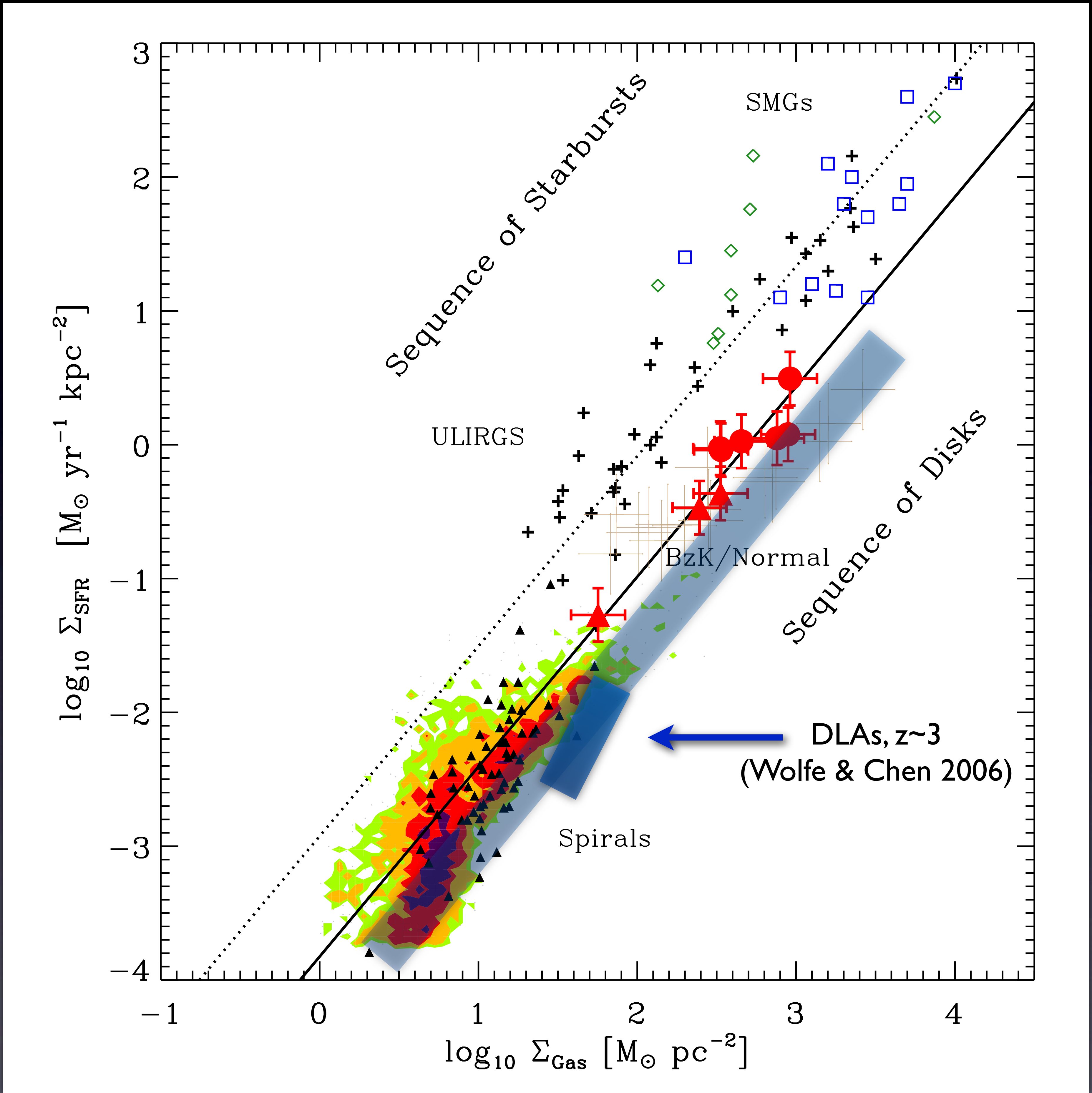


Daddi et al. 2010
Genzel et al. 2010

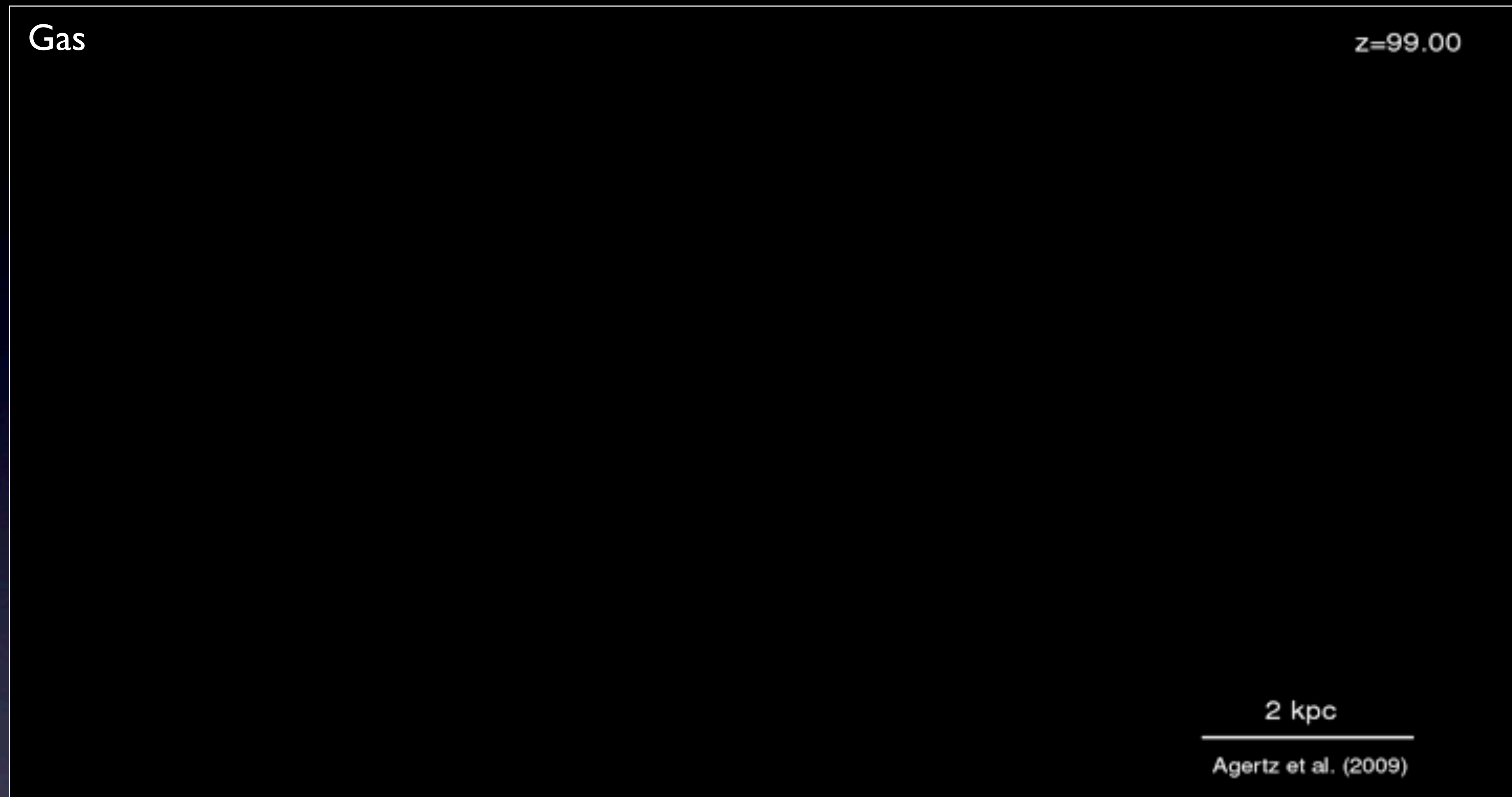
The way gas is converted into stars is observed to vary widely *among* different galaxies, *within* galaxies and at different cosmic epochs!

What kind of star formation regulation leads to a realistic spiral galaxy?

Agertz, Teyssier & Moore, 2010

We performed a large suite of fully cosmological simulations of galaxy formation, targeting a 10^{12} M_{sun} dark matter halo.

Δx=300 pc



Gas removal via supernova driven winds (Type II SN)

vs.

Local, small scale star formation physics

(unresolved physics e.g stellar feedback, H_2 fraction, turbulence, UV field)

$$E_{\mathrm{SNII}}$$

$$0, 1, 2 \text{ and } 5 \times 10^{51} \text{ ergs}$$

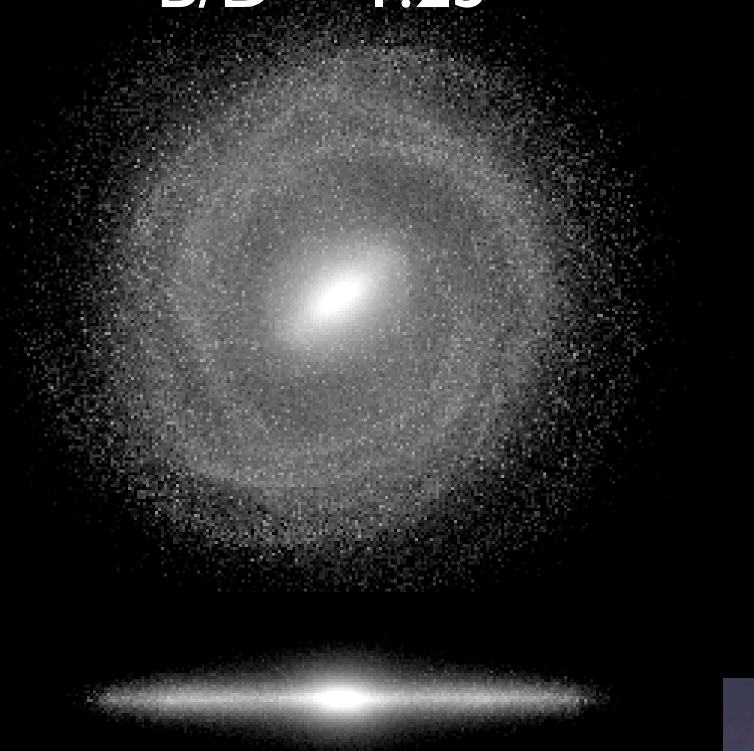
$$\epsilon_{\mathrm{ff}}$$

$$1, 2, \text{ and } 5\,\%$$

Stellar disks at z=0

$$E_{\rm SNII} = 10^{51}\,{\rm ergs}$$
$$\epsilon_{\rm ff} = 5\,\%$$

B/D ~ 1.25



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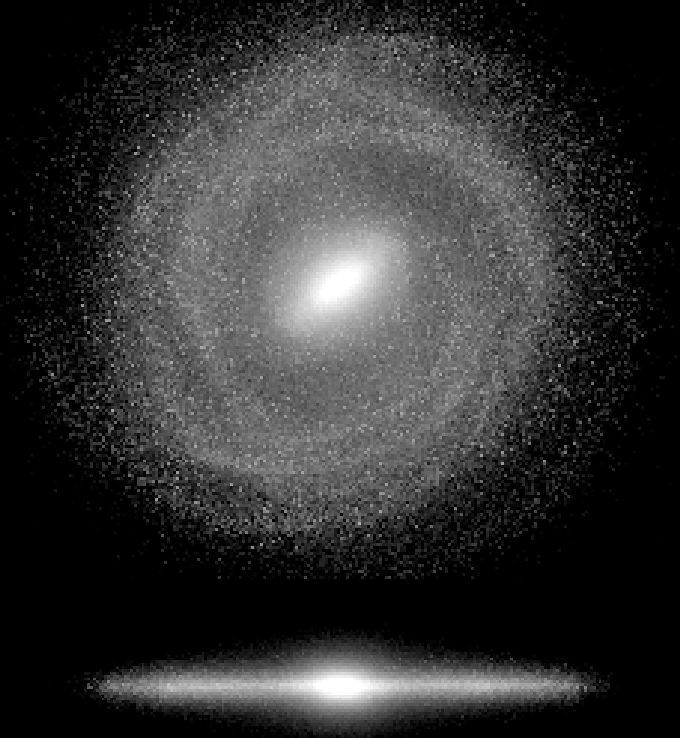
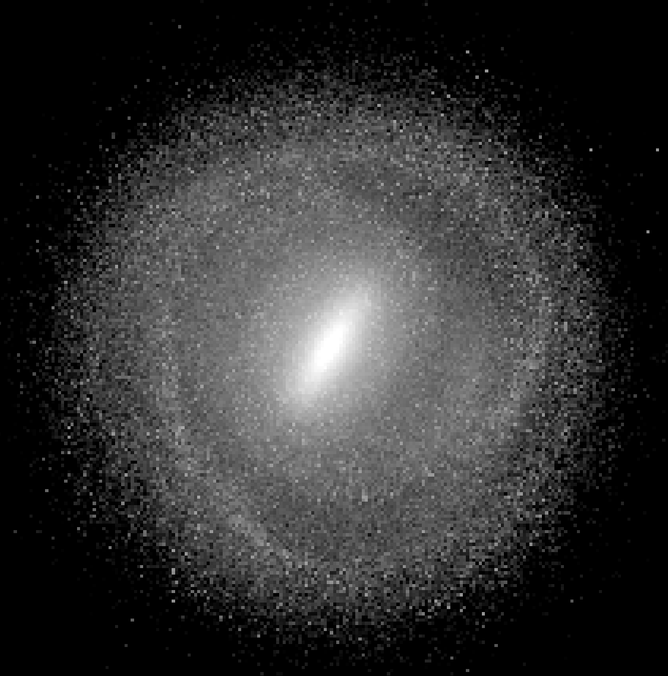


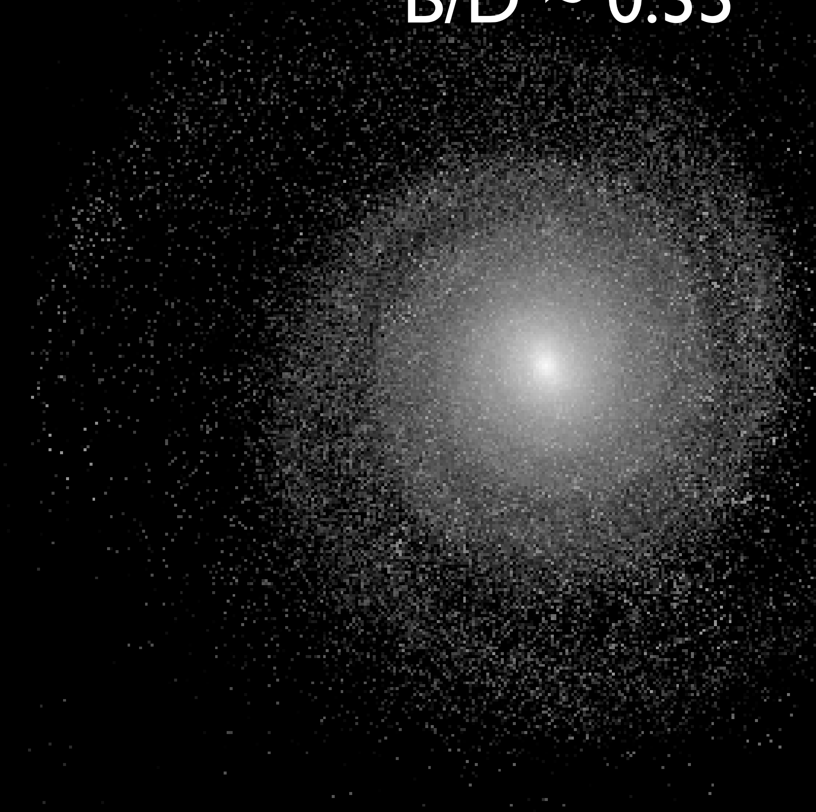
$$E_{\rm SNII} = 2 \times 10^{51}\ {\rm ergs}$$

B/D ~ 1.16



$$E_{\rm SNII} = 5 \times 10^{51}\ {\rm ergs}$$

B/D ~ 0.35



Stellar disks at z=0

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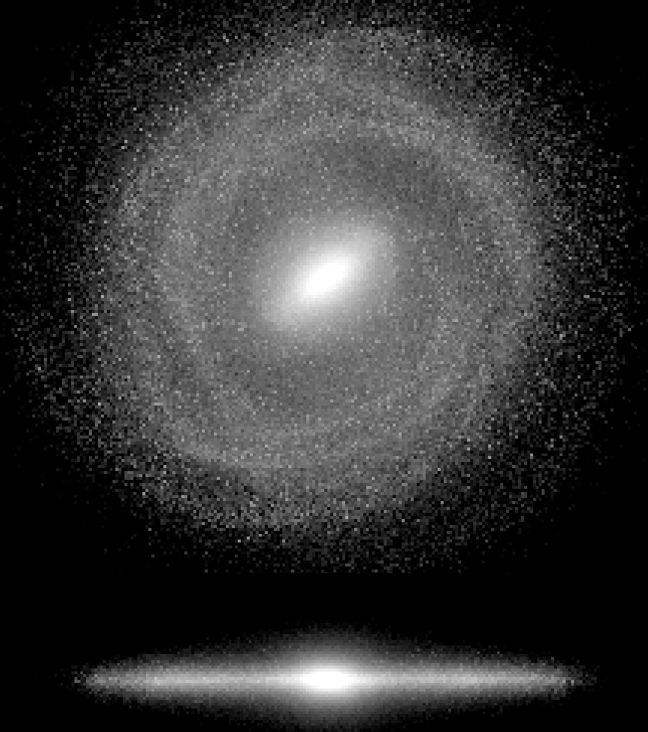
B/D ~ 1.25



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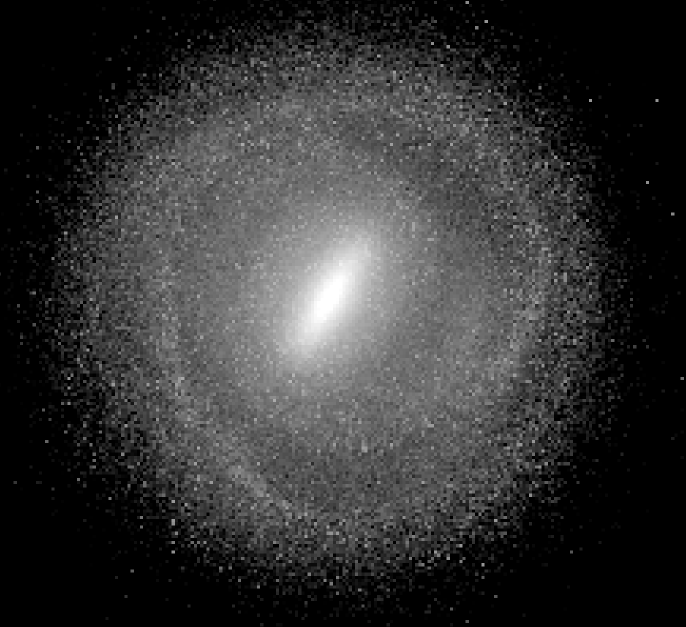
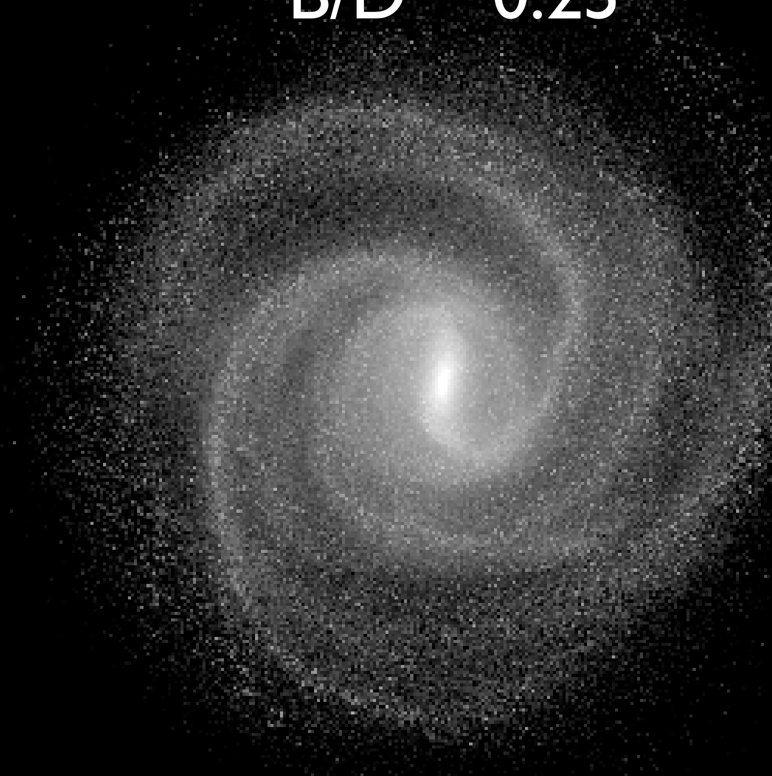


$$E_{\rm SNII} = 5 \times 10^{51}\,{\rm ergs}$$
B/D ~ 0.35

$$\epsilon_{\rm ff} = 2\,\%$$
B/D ~ 0.5

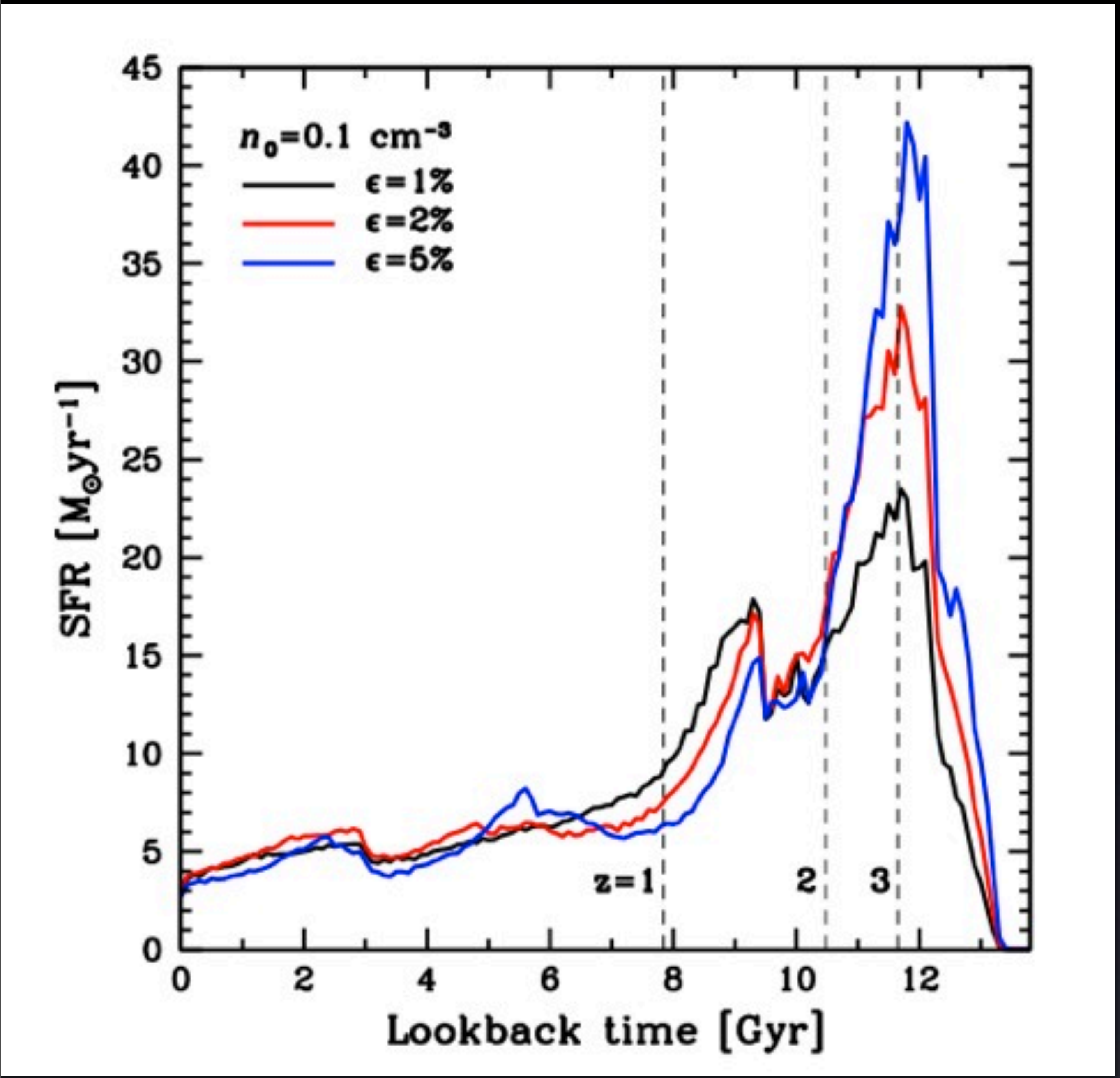
$$\epsilon_{\rm ff} = 1\,\%$$
B/D ~ 0.25



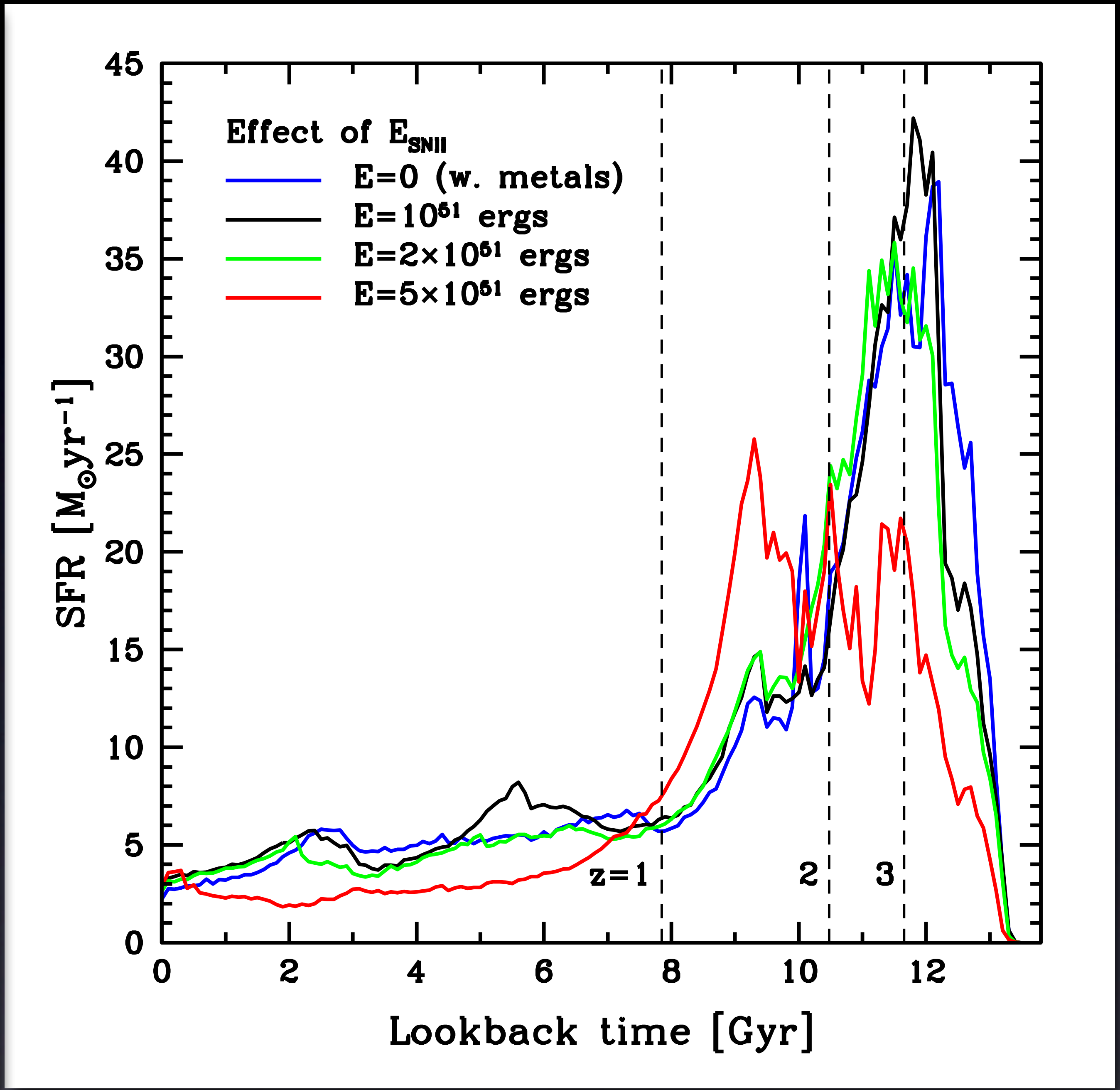
Pseudo bulge!!

Star formation histories

Effect of SFE

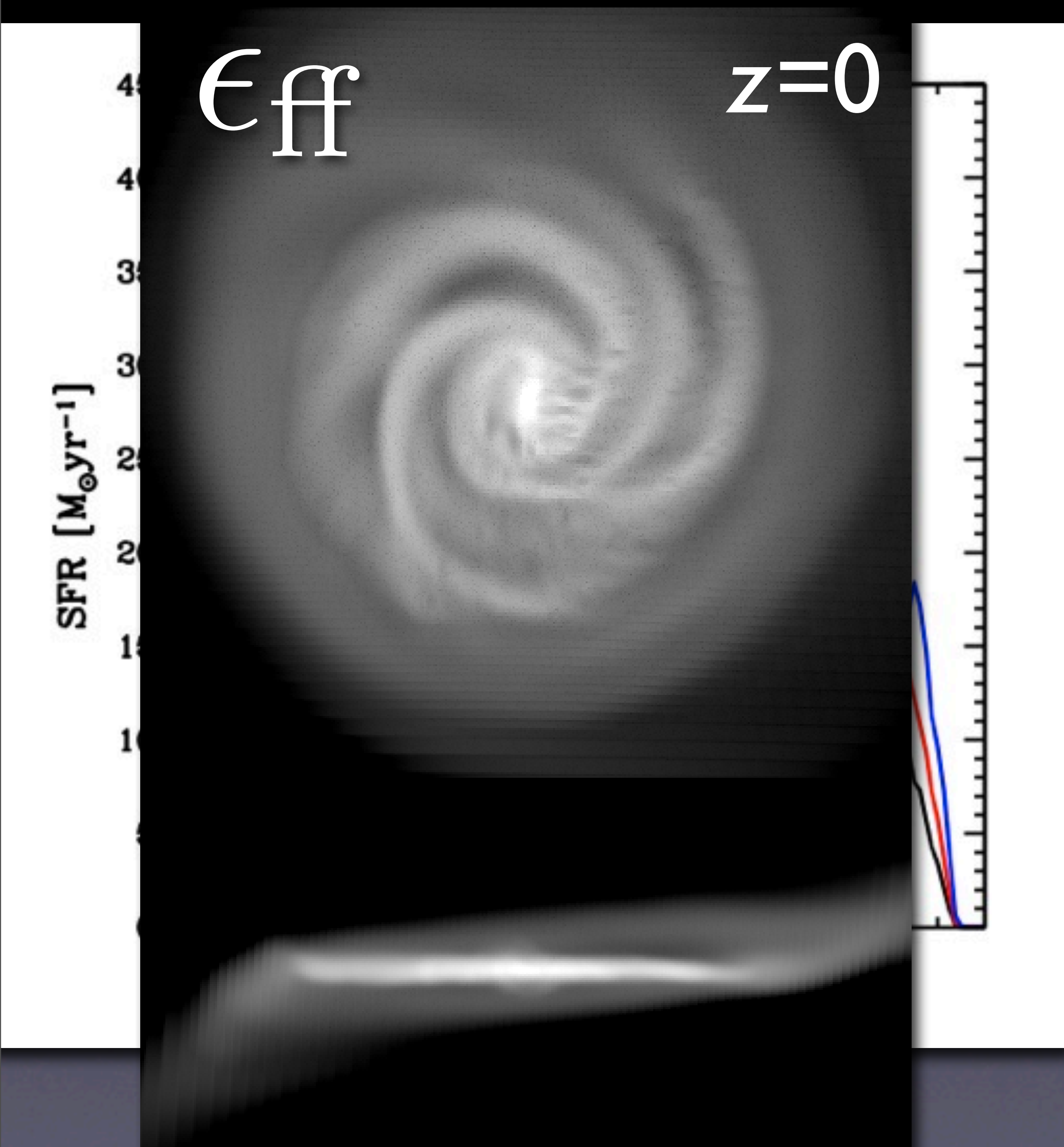


Effect of SNe feedback

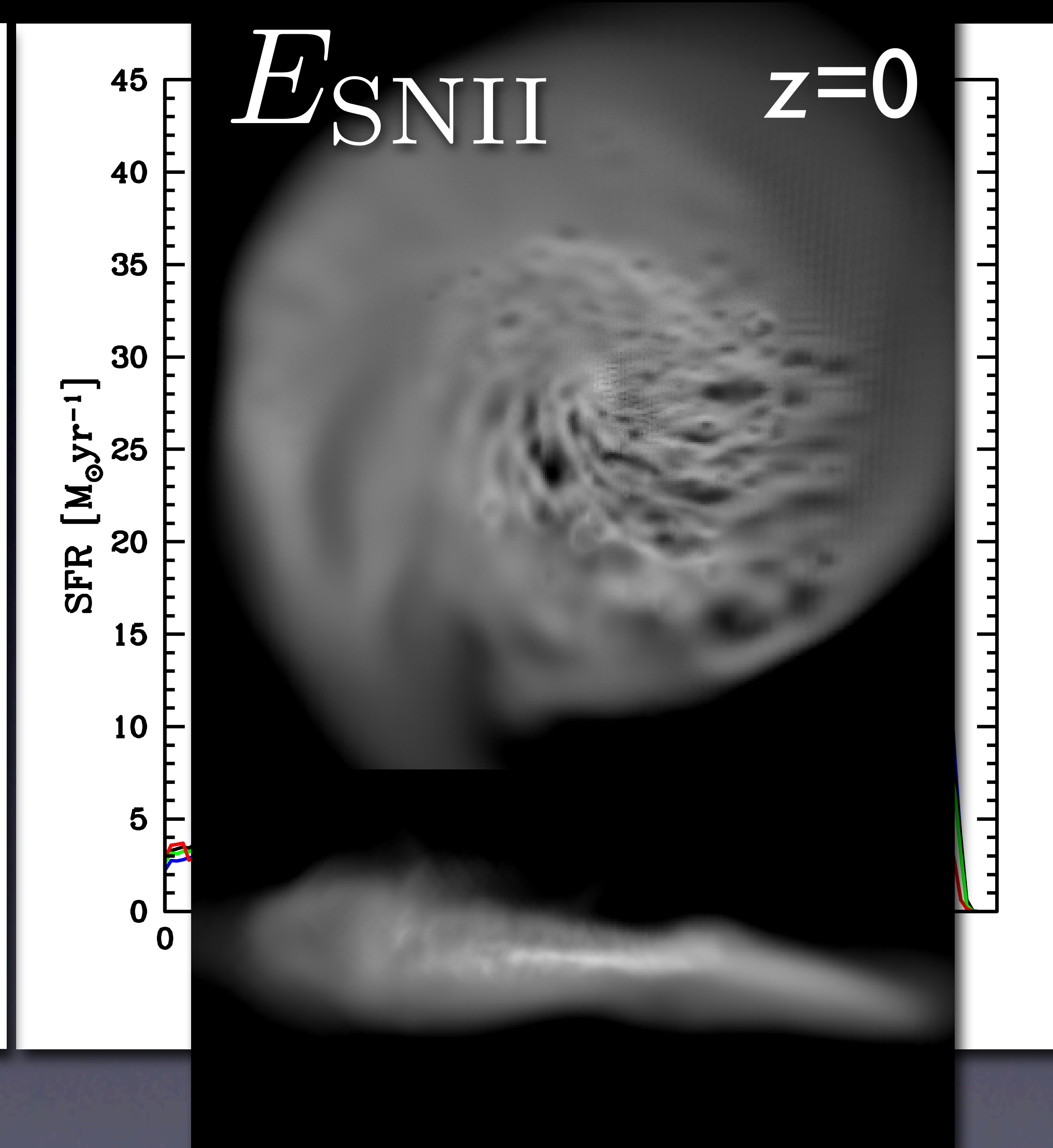


Star formation histories

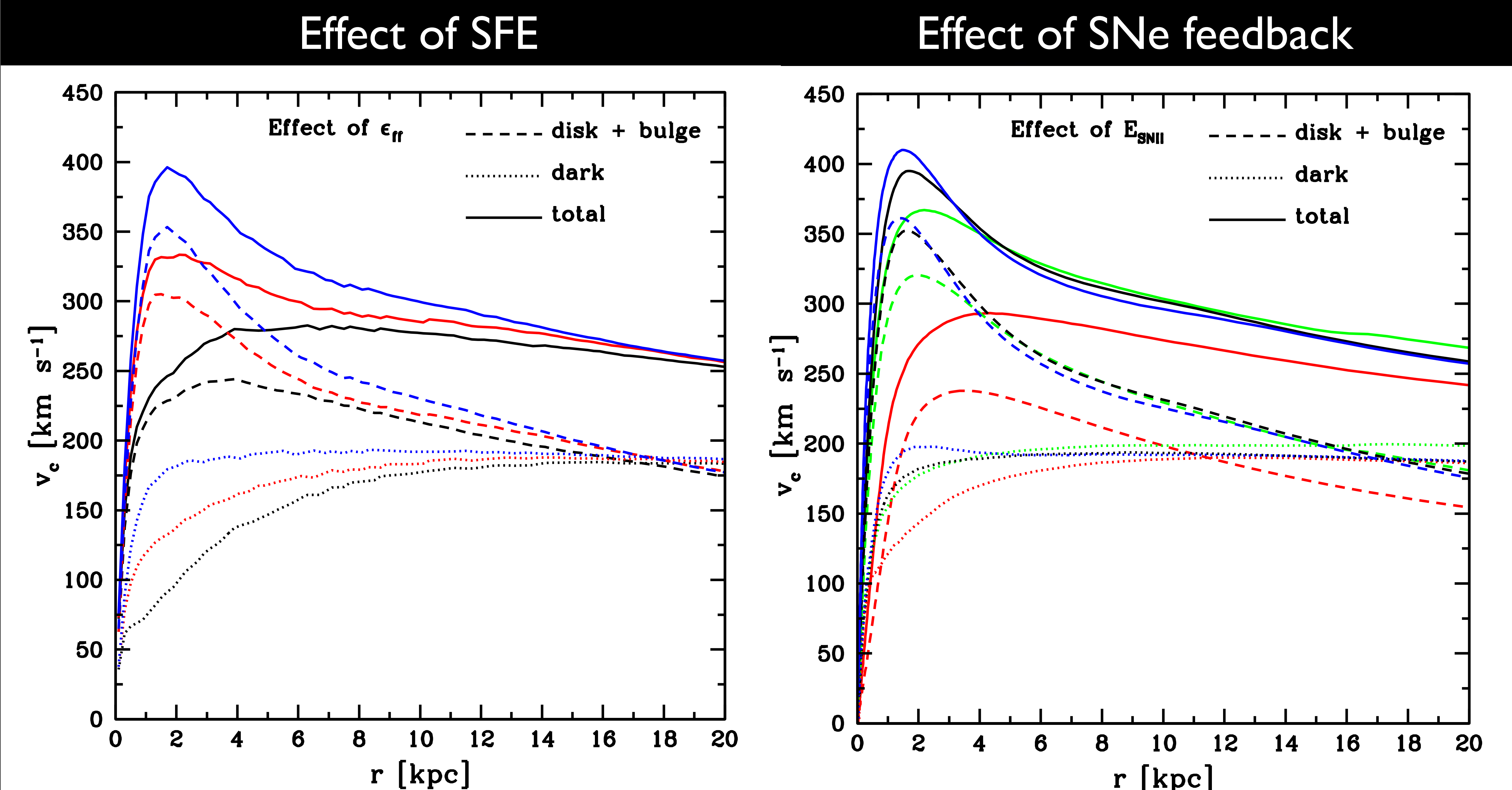
Effect of SFE



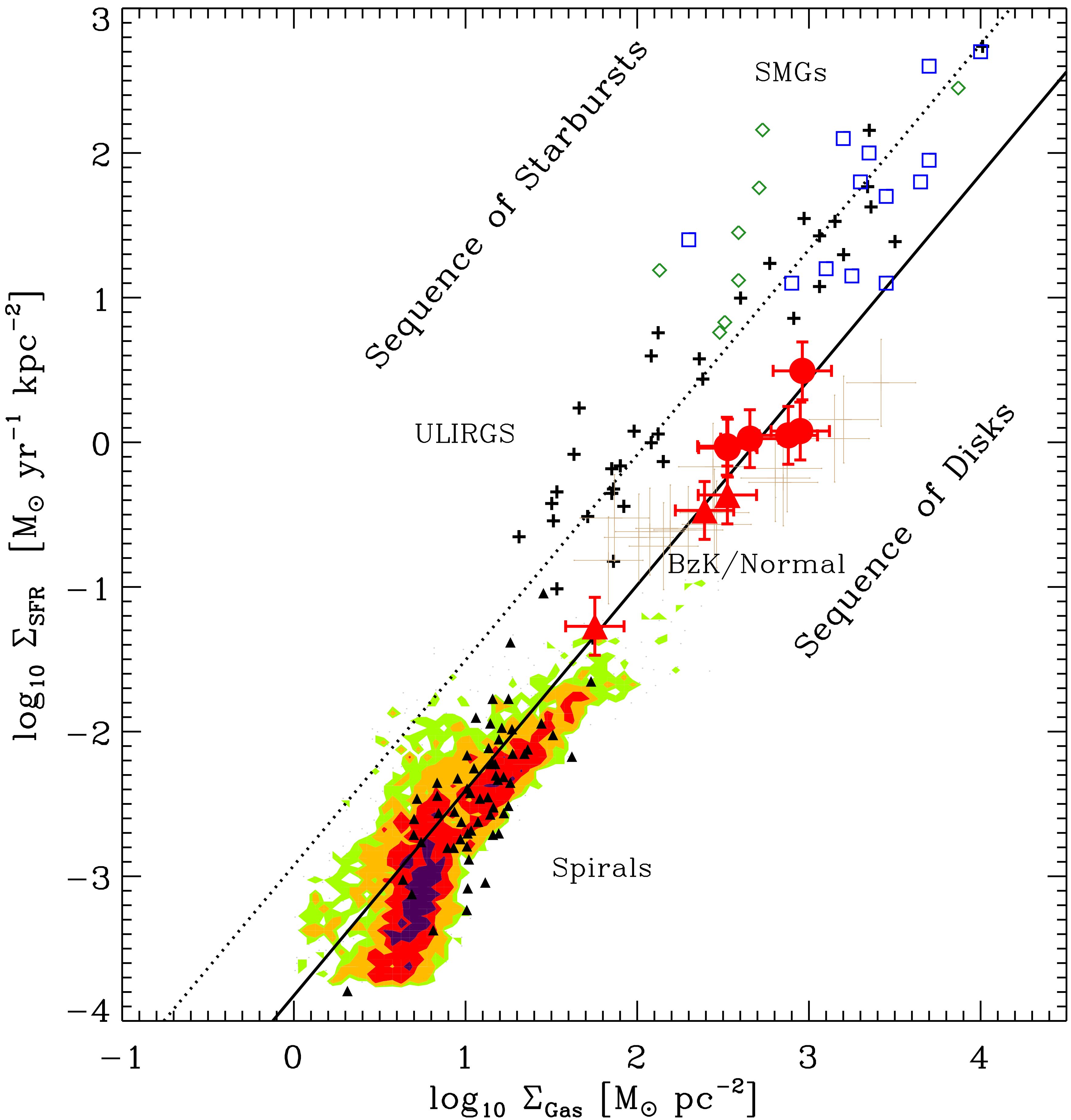
Effect of SNe feedback



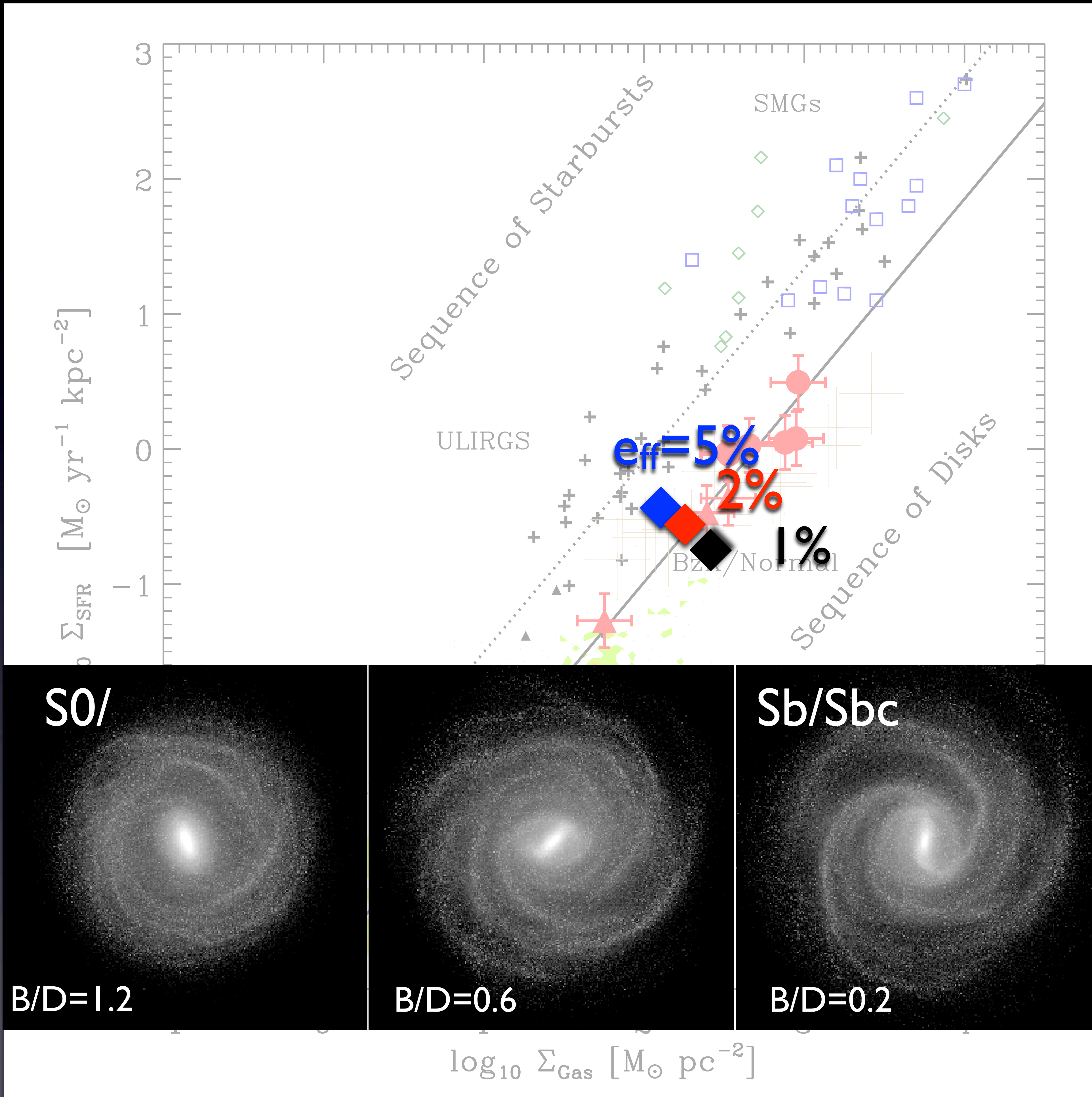
Circular velocities



10-20% scaling recovers the Milky Way



Daddi et al. 2010
Genzel et al. 2010

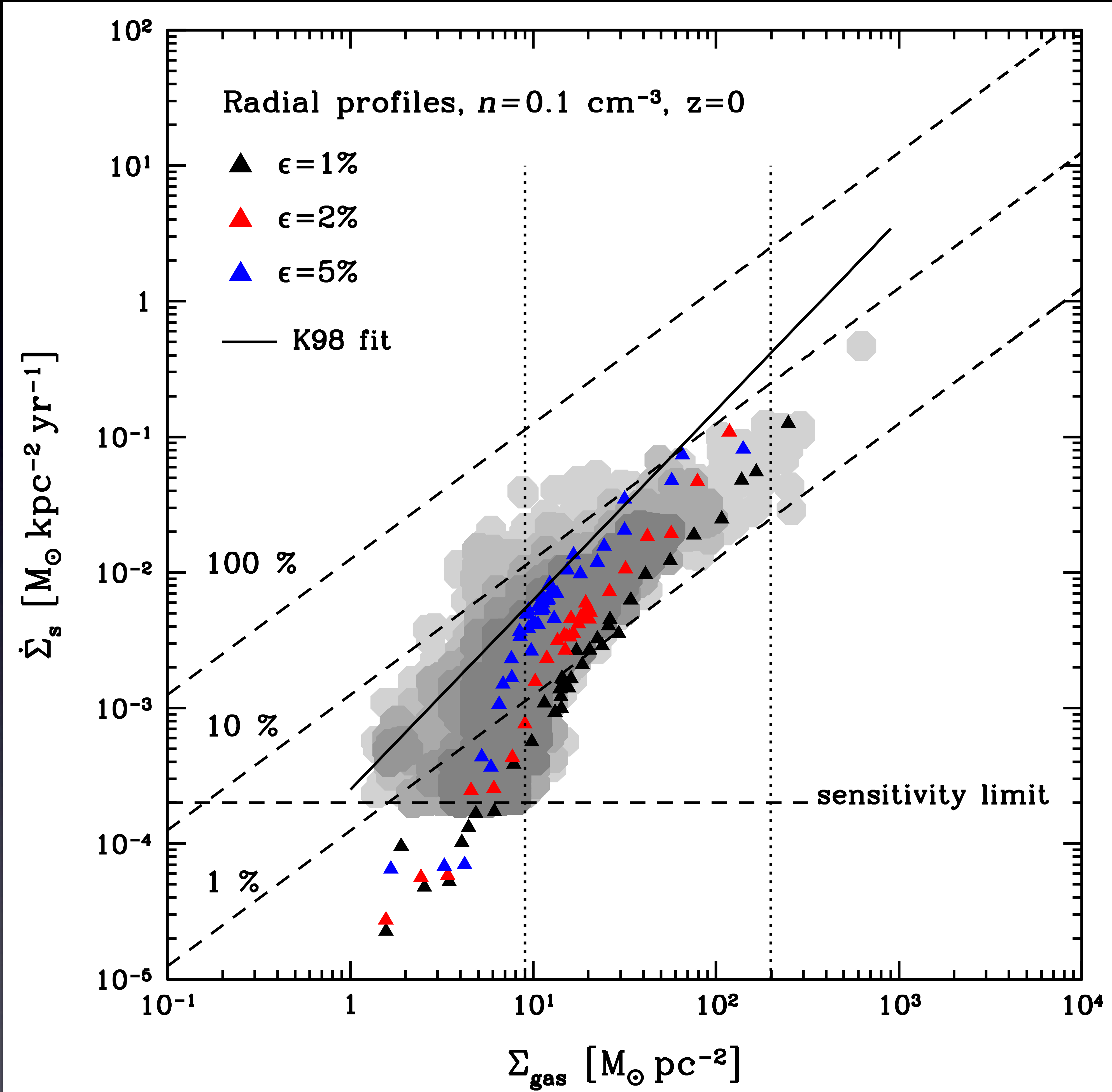


Daddi et al. 2010
Genzel et al. 2010

Observe simulated disks @ z=3

The simulated disks with a low B/D @ z=0 correspond to lower Σ_{SFR} @ z=3 in the discs' sequence.

Romain Teyssier



Observe simulated disks @ z=0

Kennicutt-Schmidt relation + THINGS data (Bigiel et al. 2008)

Romain Teyssier

The baryon fraction problem

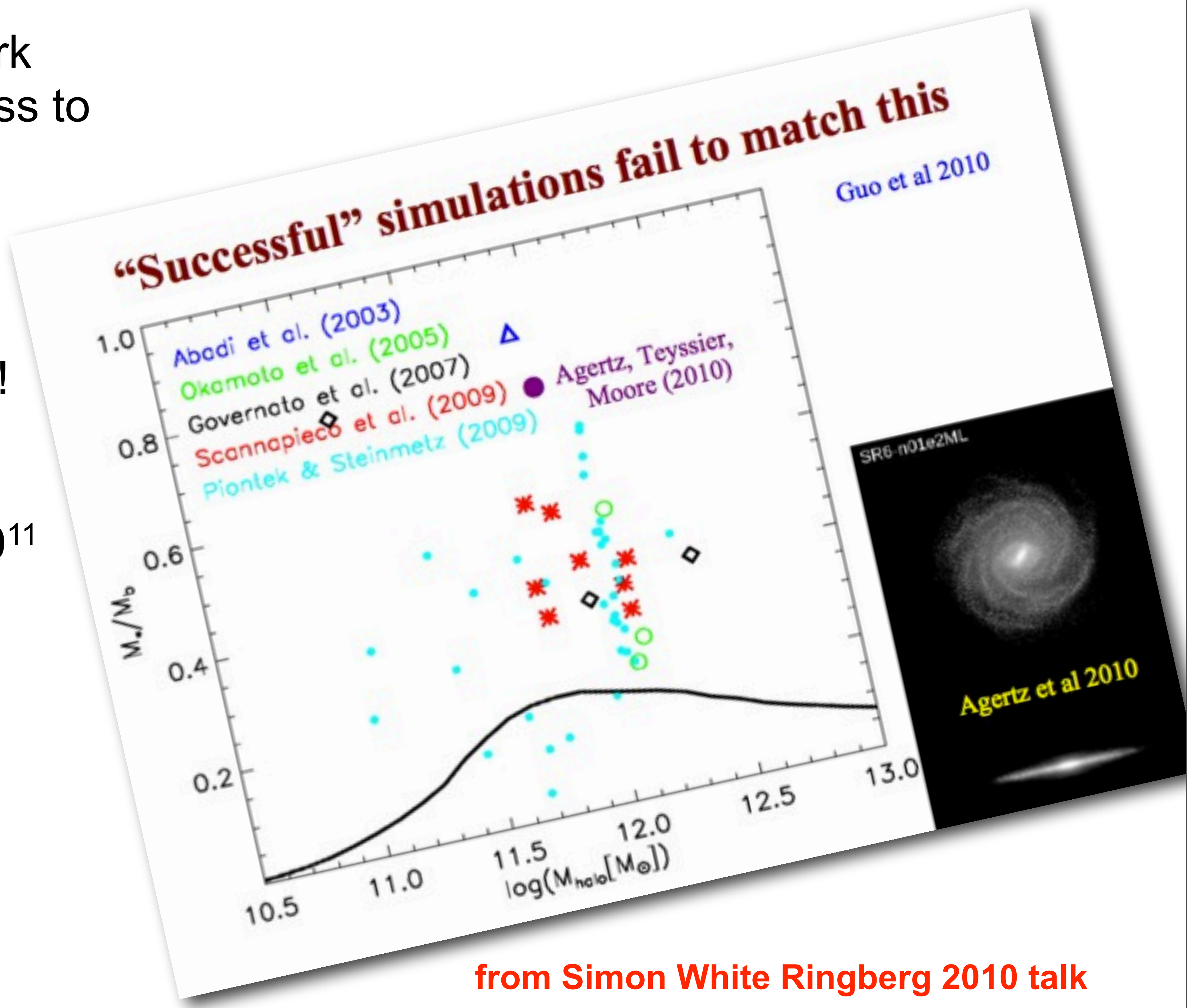
Using abundance matching with dark halos, one can relate the stellar mass to the halo mass.

This gives M_{halo}=2x10^{12} M_{sol} for the Milky Way and 25% baryon fraction!

Our simulation suggests M_{halo}=7x10^{11} M_{sol} with 80% baryon fraction.

Low baryon fraction in MW models requires very efficient feedback.

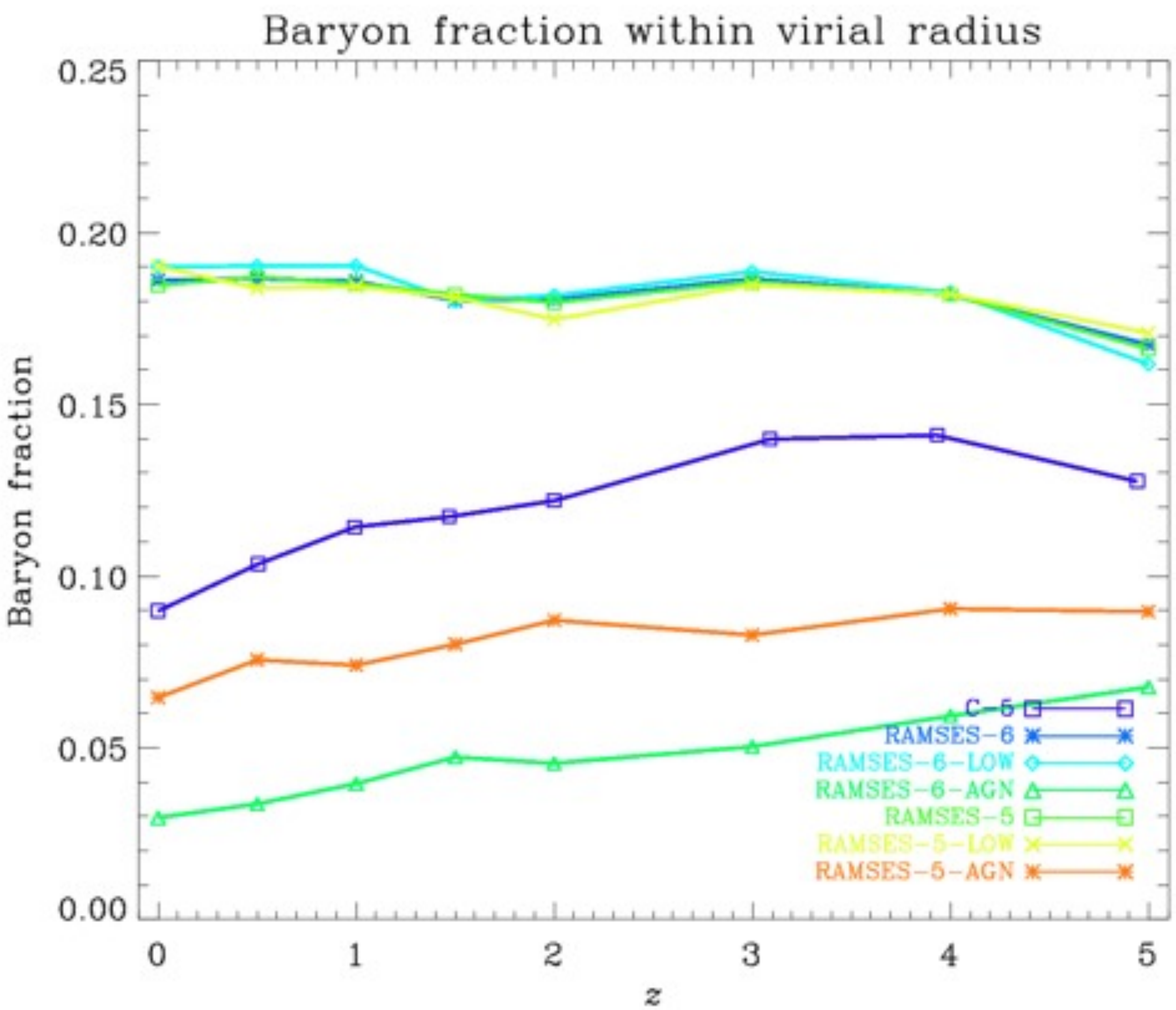
Very efficient feedback leads to the formation of early-type galaxies.

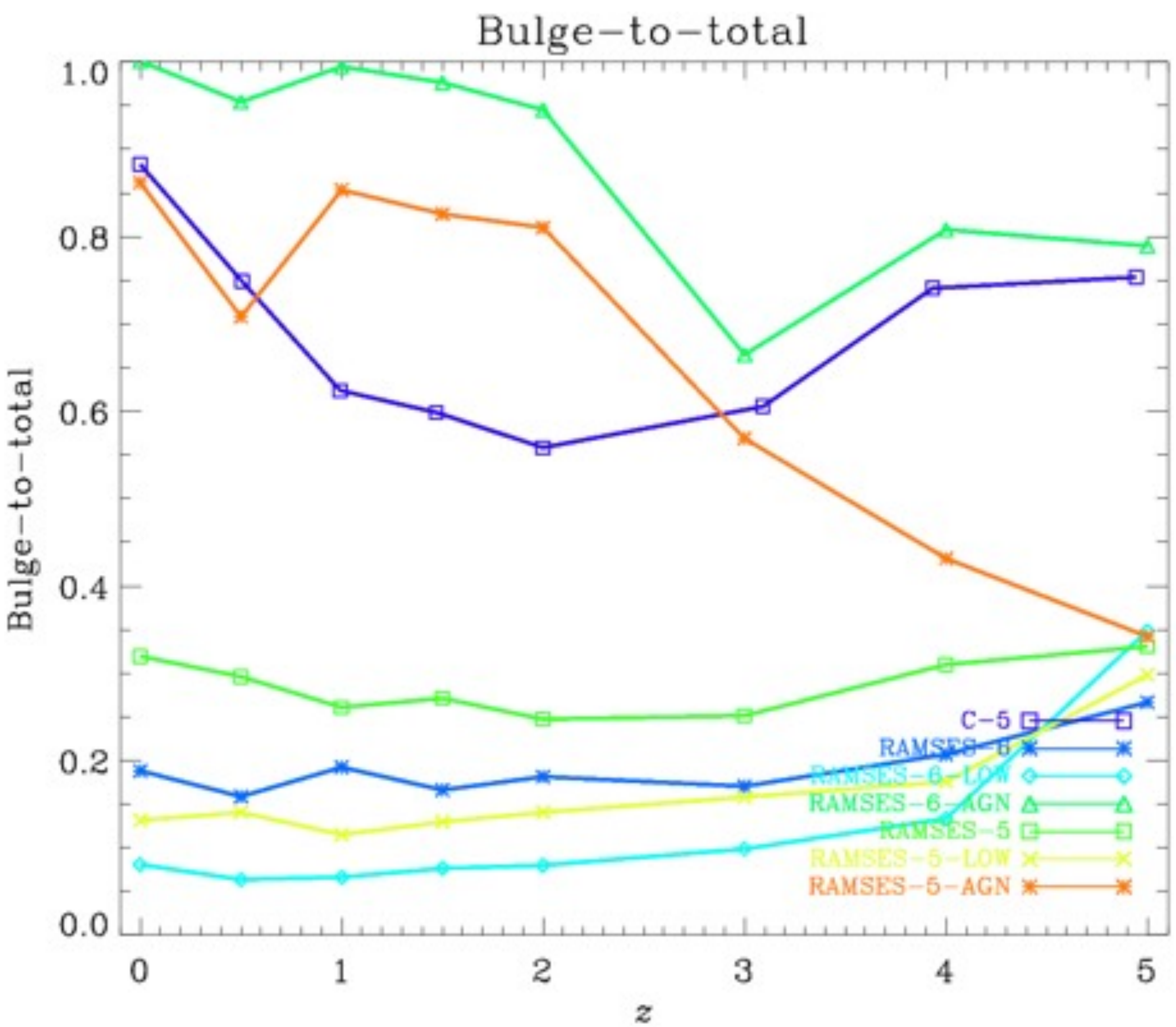


from Simon White Ringberg 2010 talk

Strong feedback remove baryons from the halo...

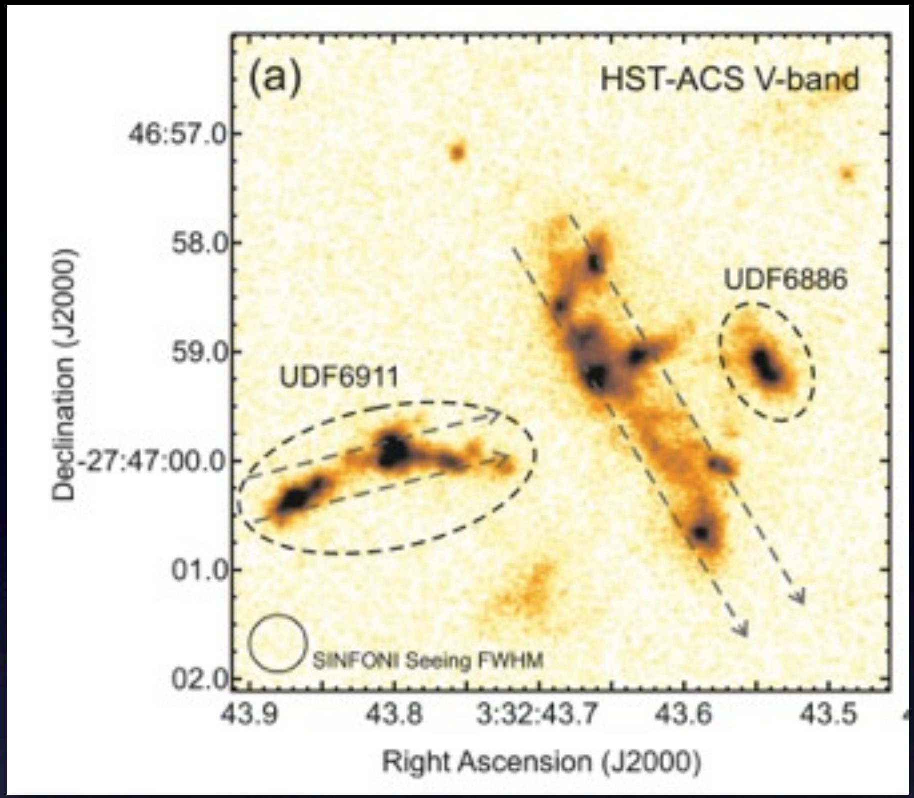
We adapted to AMR the AGN feedback model of Booth & Schaye (2010).



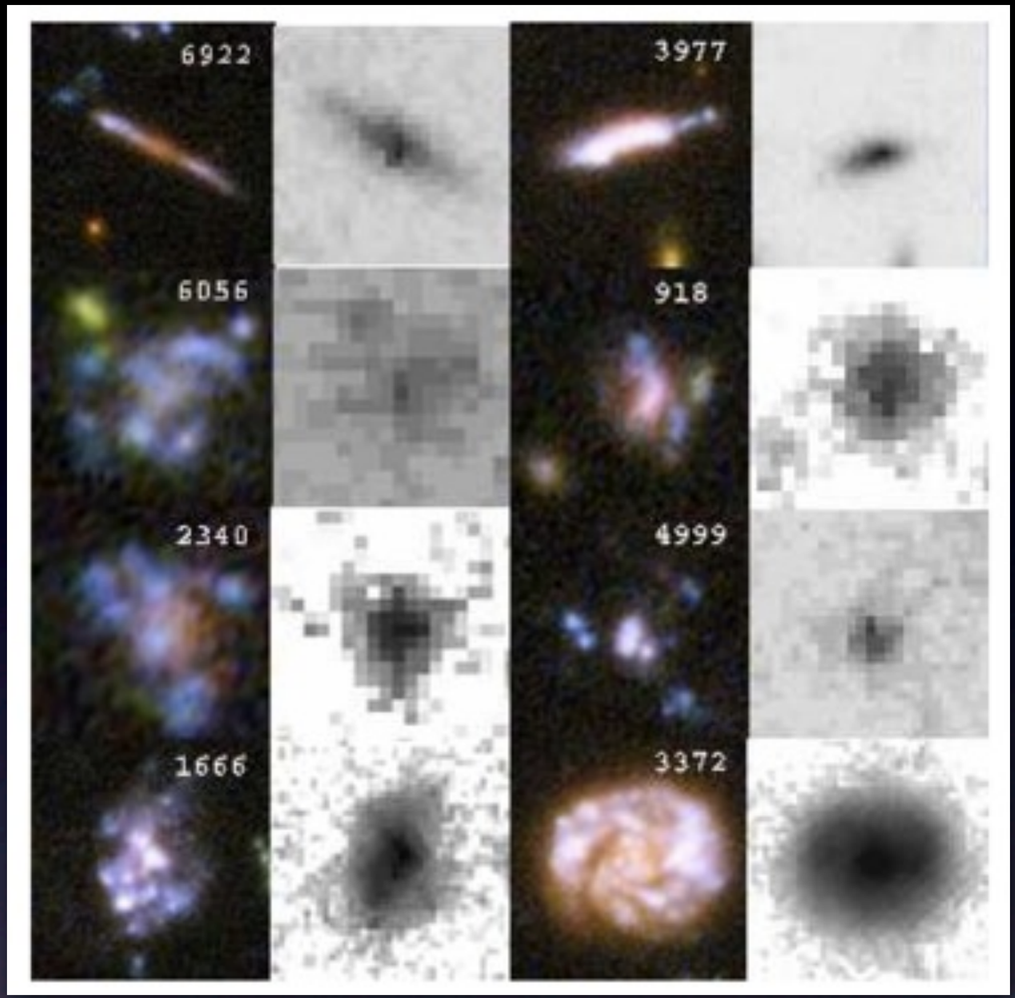


...but lead to the formation of dead spheroids.

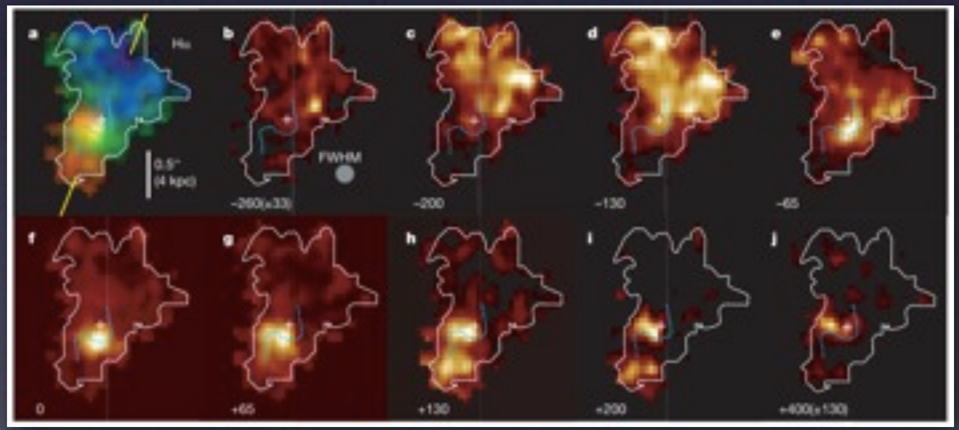
High-z disk galaxies (z~1-5)



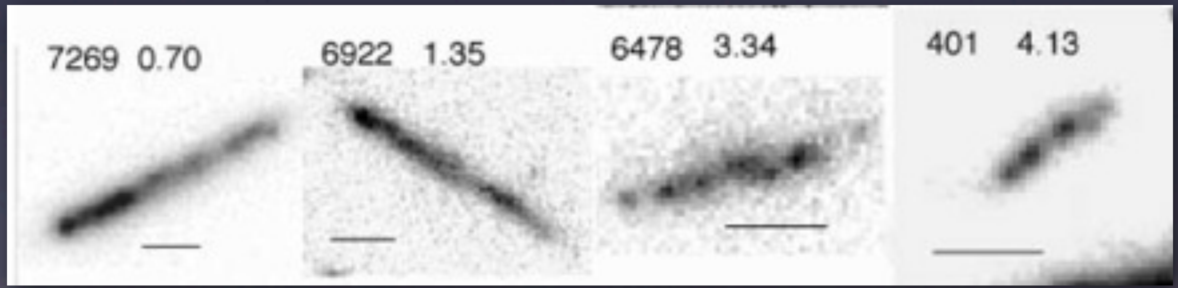
HST-ACS, UV restframe, Bournaud et al. et al. (2008)



HST-ACS, UV restframe, Elmegreen et al. (2009)



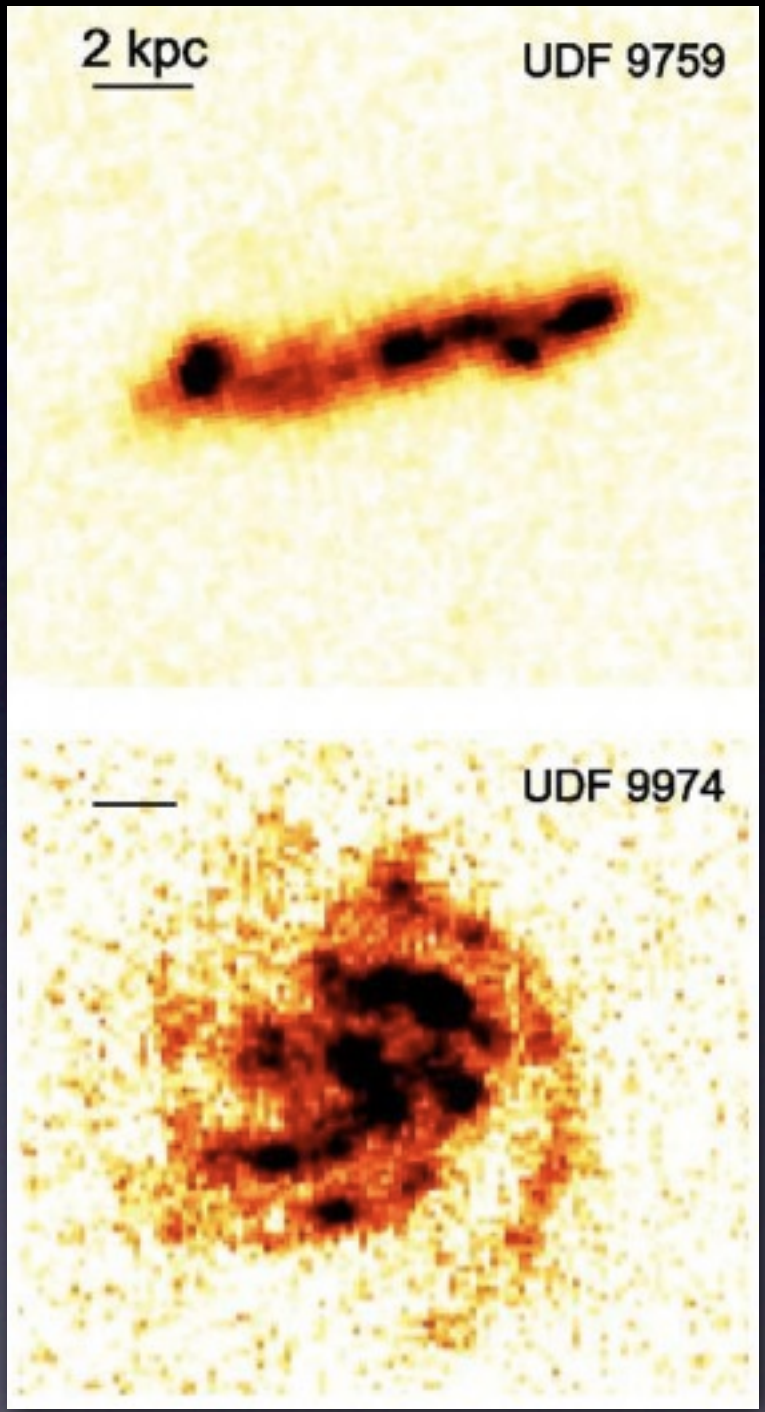
VLT, Halpha, Genzel et al. (2006)



e.g. Cowie et al. (1995), van den Bergh (1996), Steidel (1999), Daddi et al. (2004), Genzel et al. (2006), Förster-Schreiber et al. (2006), Elmegreen & Elmegreen (2005, 2006, 2007, 2009), Shapiro et al. (2008), Stark et al. (2008), Law et. al (2009)

High-z disk galaxies (z~1-5)

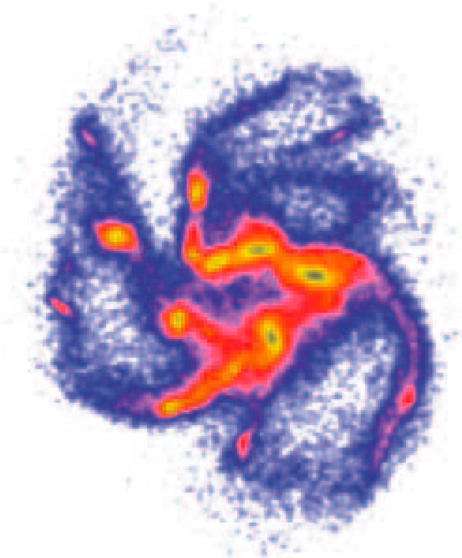
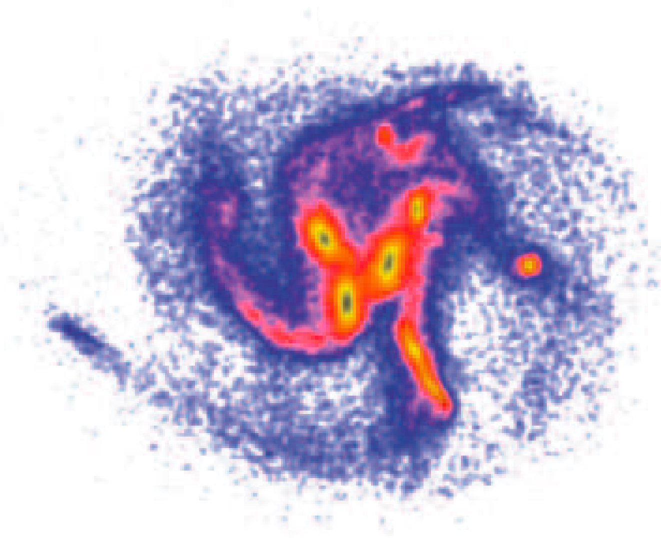
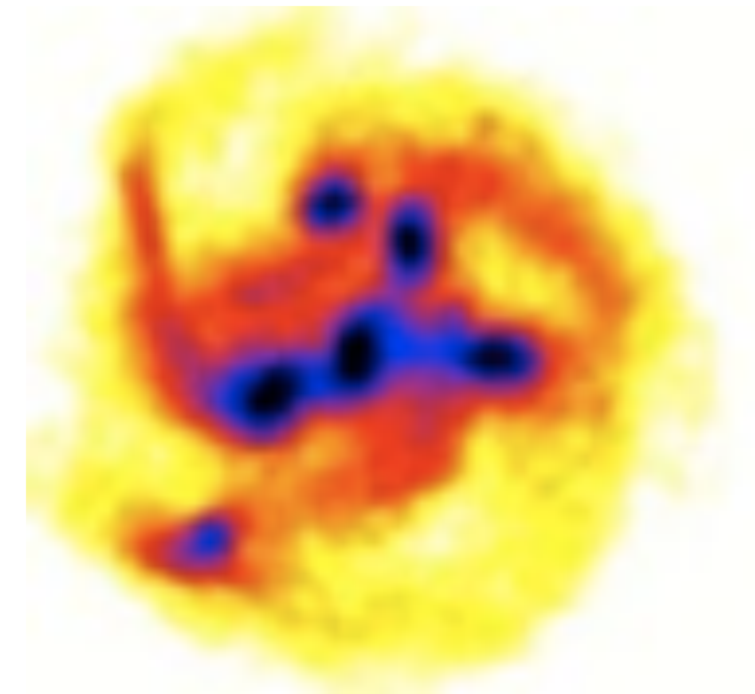
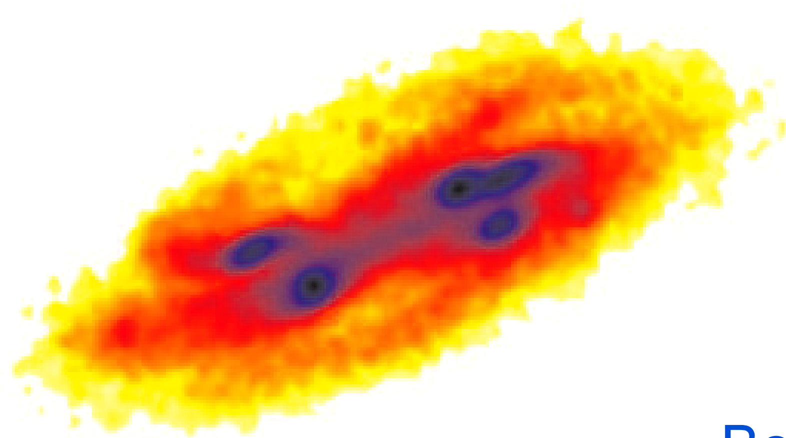
- Clumpy galaxies dominate quiescent disks for z>1 (Elmegreen et al. 2007, 2009)
- Stellar masses ~ 10^{10} - 10^{11} M_{sun}
- Gas fractions ~ 50%
- Young (few 100 Myr) clumps of mass of 10^7-10^9 M_{sun}!
- $\Sigma_{\rm gas} \sim 100 M_\odot\,{\rm pc}^{-2}$
- $\sigma \sim 30-60\,{\rm km/s}$
- ${\rm SFR} \sim 30-200\,M_\odot\,{\rm yr}^{-1}$



What drives this clumpy epoch in a galaxy's life?

A simple model for high-redshift clumpy discs

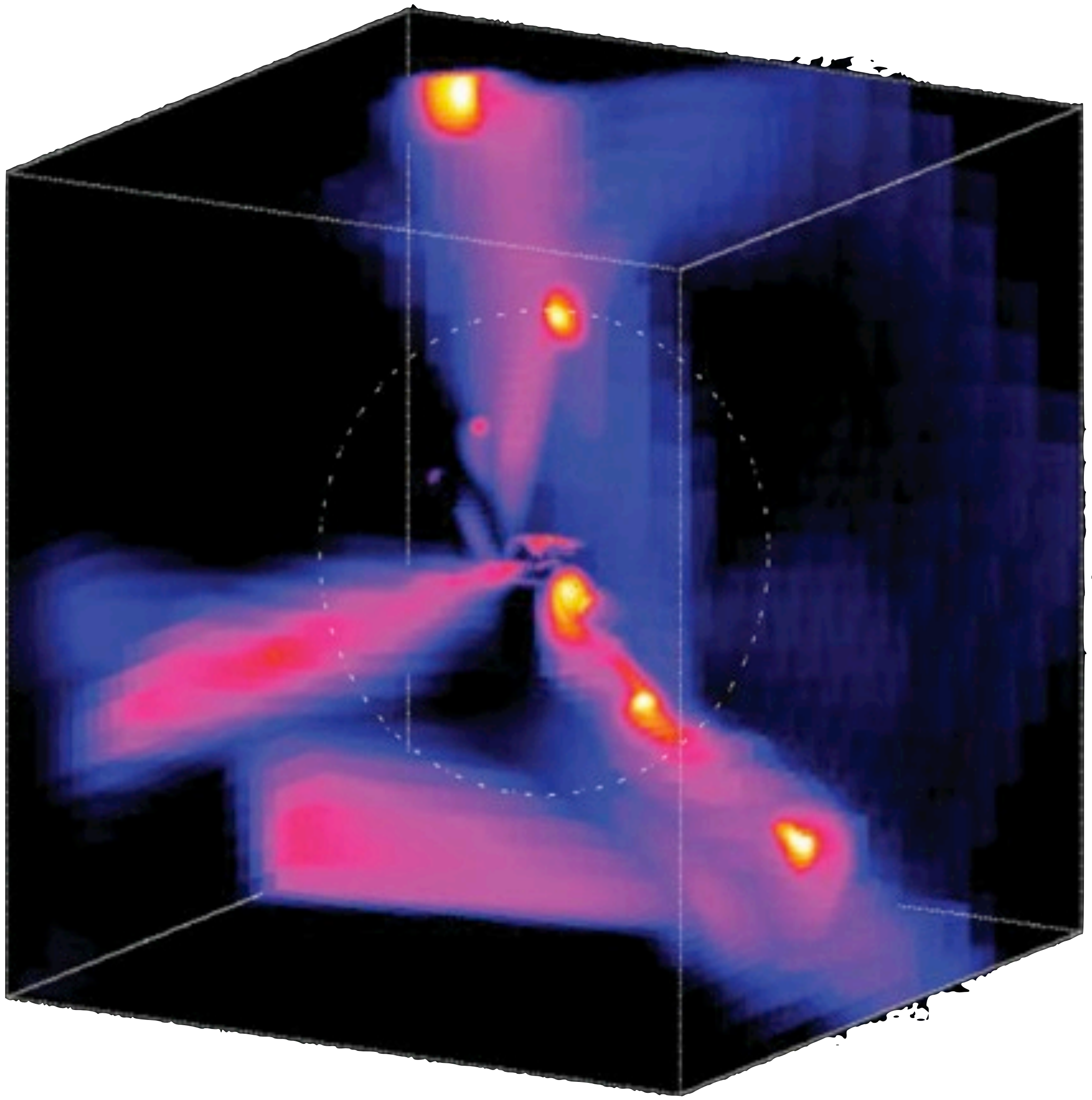
Starting with smooth, gas rich unstable discs:

Bournaud, Elmegreen & Elmegreen 2007

Fragmentation into realistic clump-clusters/chains in 100-300Myr

Cold streams in the high-redshift universe



The MareNostrum simulation (2007)

1 billion dark matter particles
3 billion gas cells
100 000 galaxies

4 weeks of computation on 2048 core

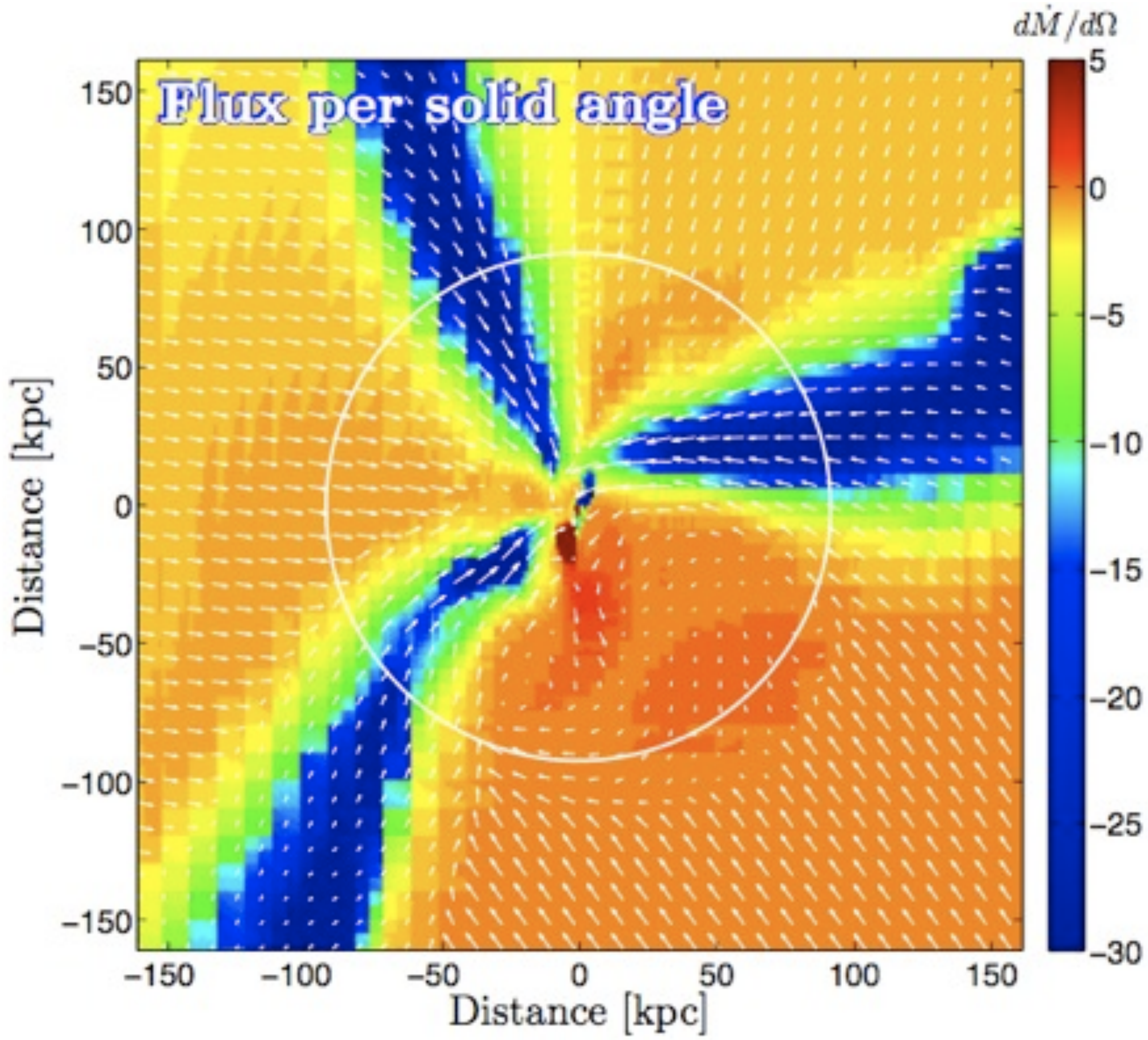
At high redshift, gas accretion proceeds through cold diffuse streams

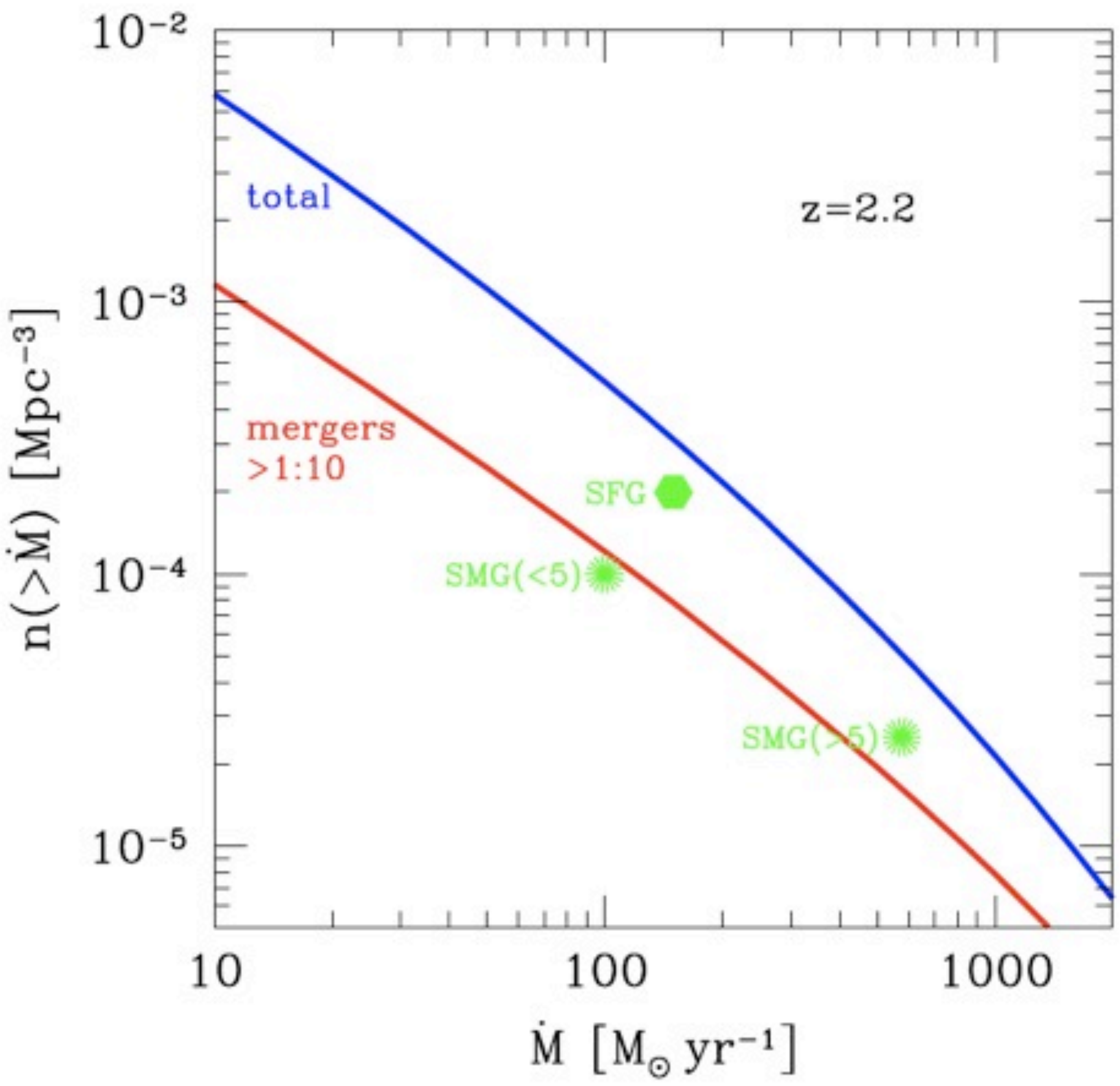
Kravtsov 2003, Birnboim & Dekel 2003

Keres et al. 2005; Ocvirk et al. 2008

Cold streams in the high-redshift universe

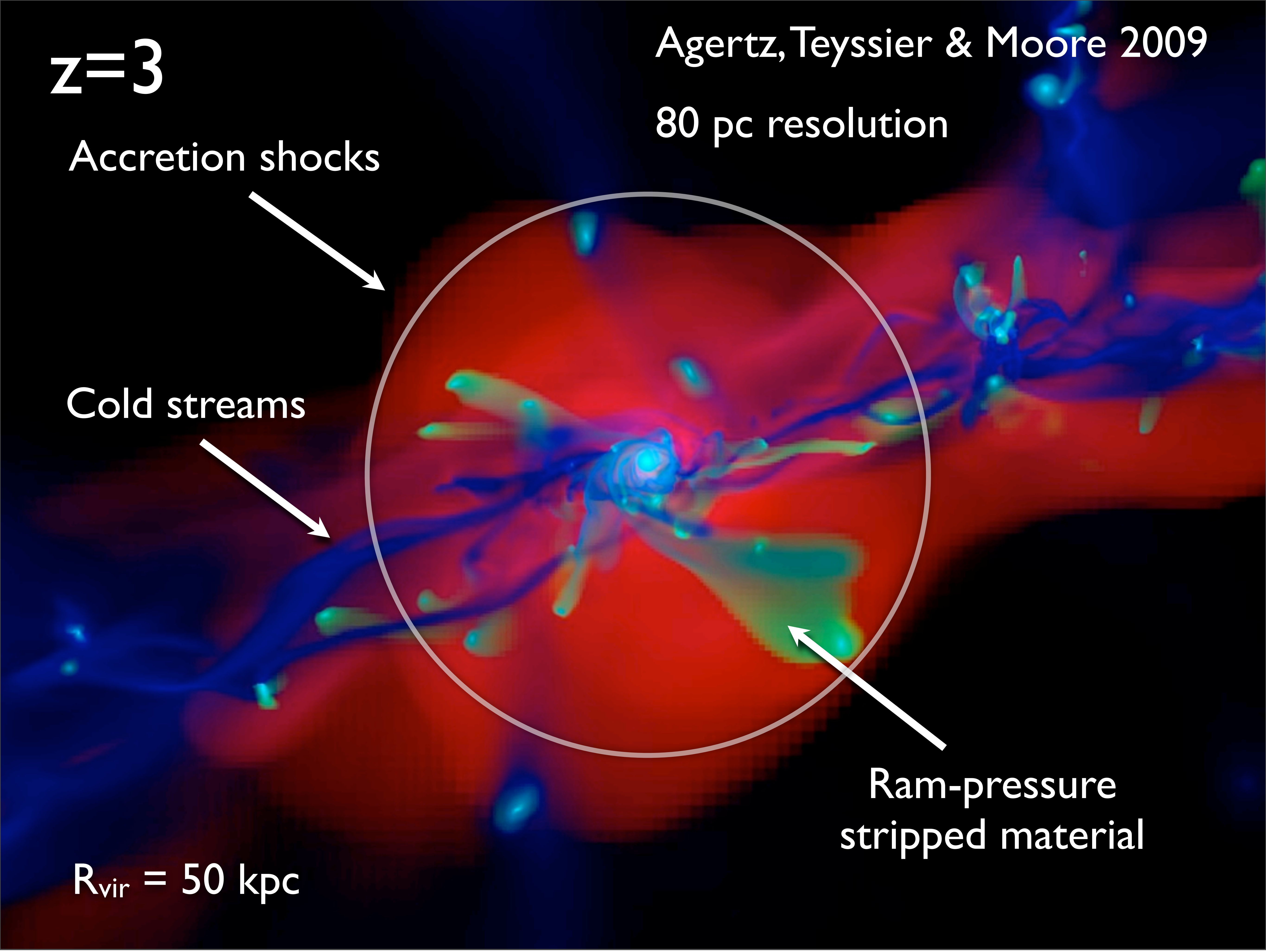
$$\dot{m}_R(r,\Omega) = \frac{\partial \dot{M}}{\partial \Omega} = \rho_R \mathbf{v}_R \cdot \mathbf{n}\, r^2$$



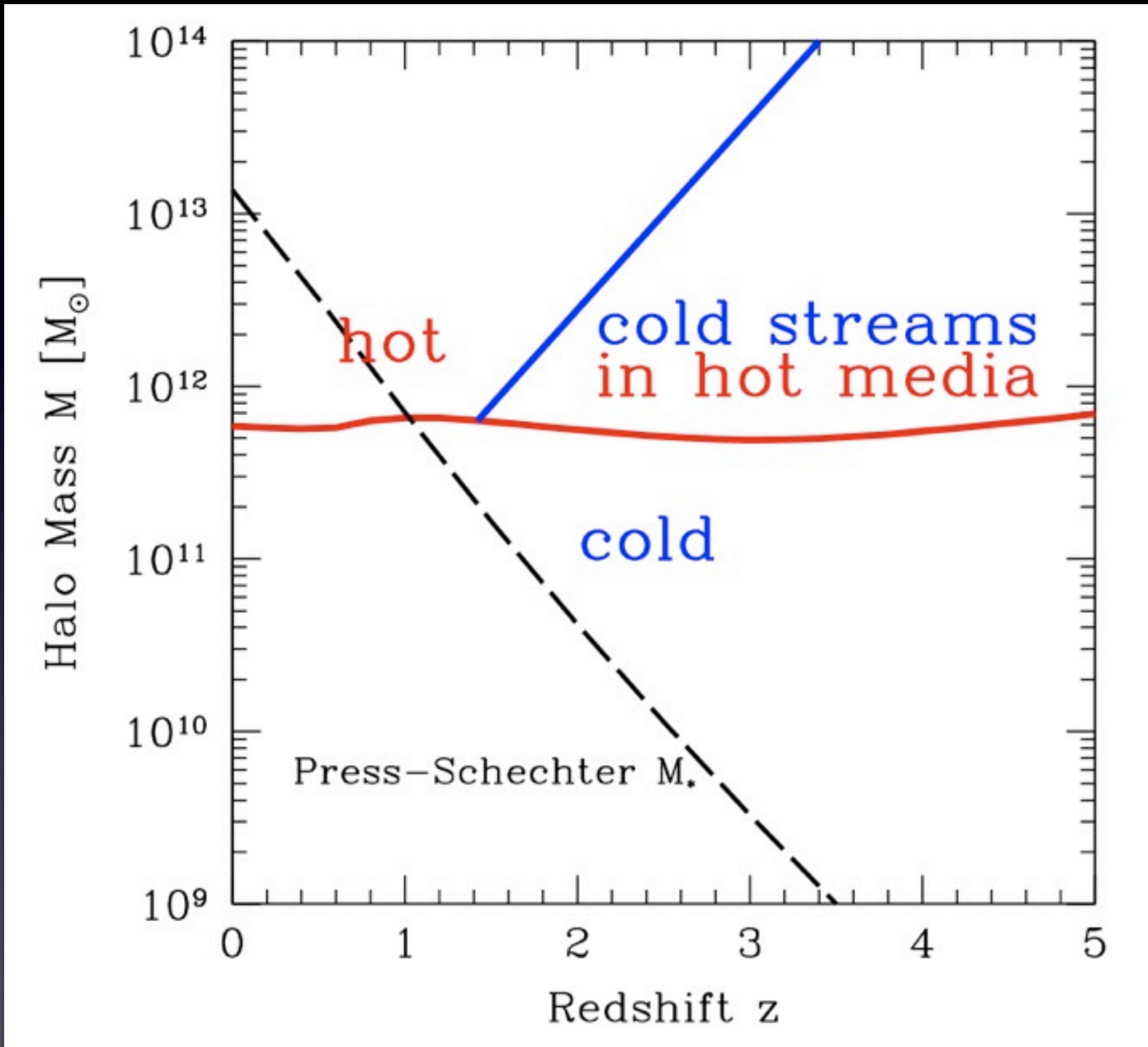


Star formation at high redshift (BzK galaxies) proceeds through efficient gas accretion via cold streams. Major mergers (sub-mm galaxies) are not frequent enough and cannot explain the disk-like morphologies.

Dekel et al. 2009

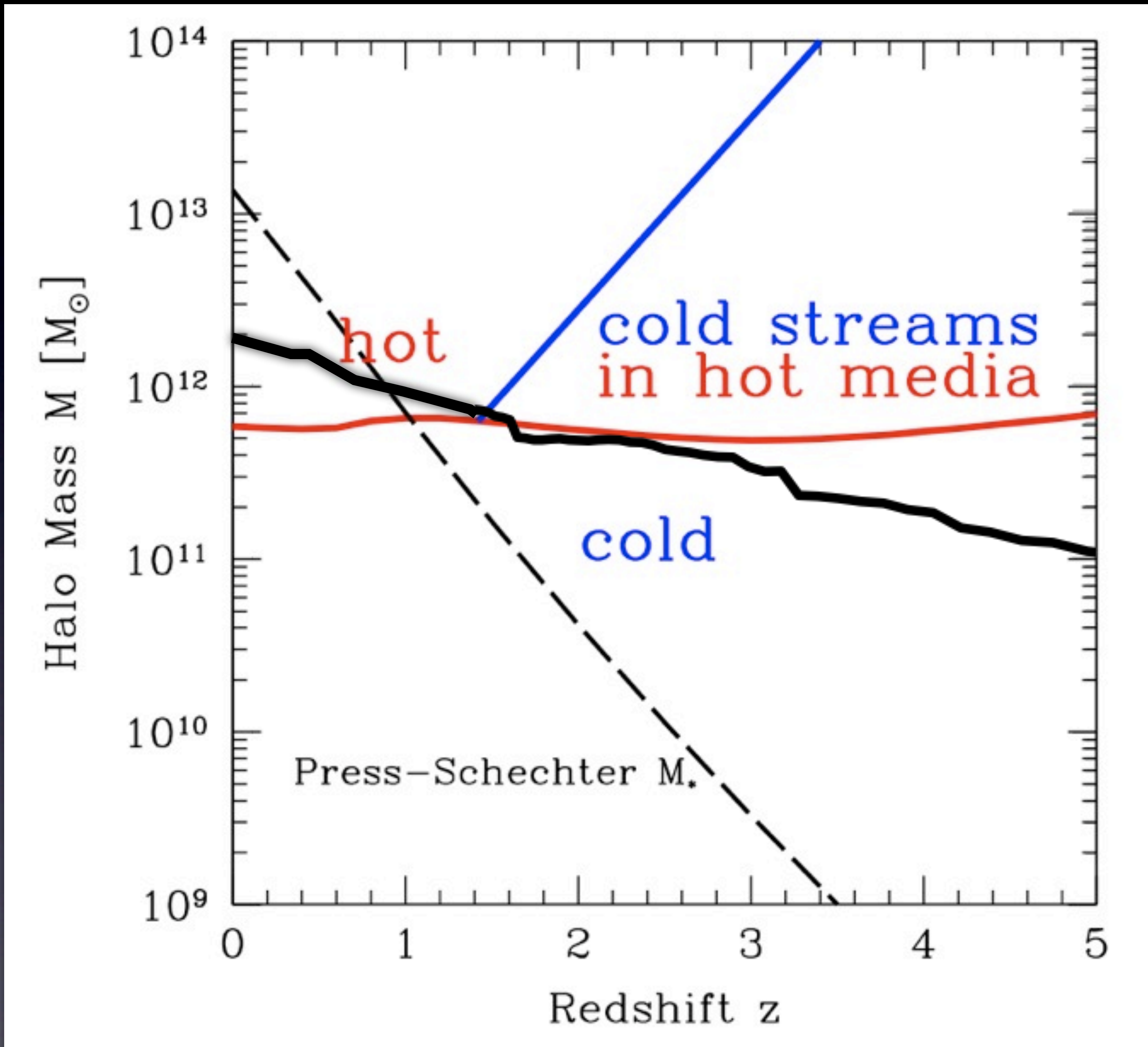

z=3
Agertz, Teyssier & Moore 2009
80 pc resolution
Accretion shocks
Cold streams
Ram-pressure
stripped material
R_{vir} = 50 kpc

Relevance of cold accretion



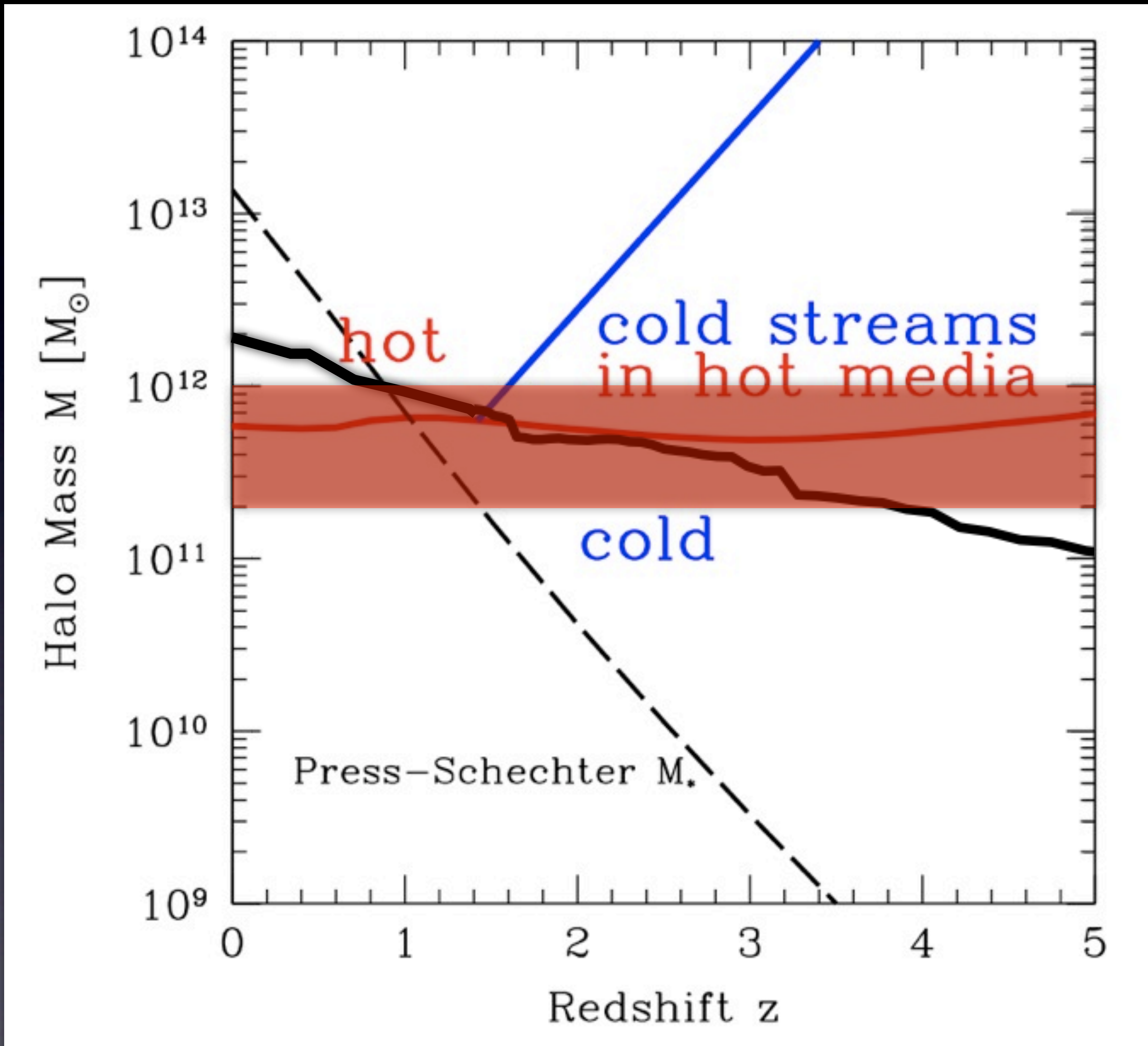
Dekel & Birnboim (2006)

Relevance of cold accretion



Dekel & Birnboim (2006)

Relevance of cold accretion



$Z = 0.3\, Z_\odot$

$Z = 10^{-3}\, Z_\odot$

Dekel & Birnboim (2006)

Disk properties at z=2-3

- *Globally* the disk is marginally stable considering Q_g and Q_s (e.g. Rafikov 2001). The gas is *locally* unstable and fragmentation occurs in massive arms

- ~1/3 of the gas mass is in Q<1 regions

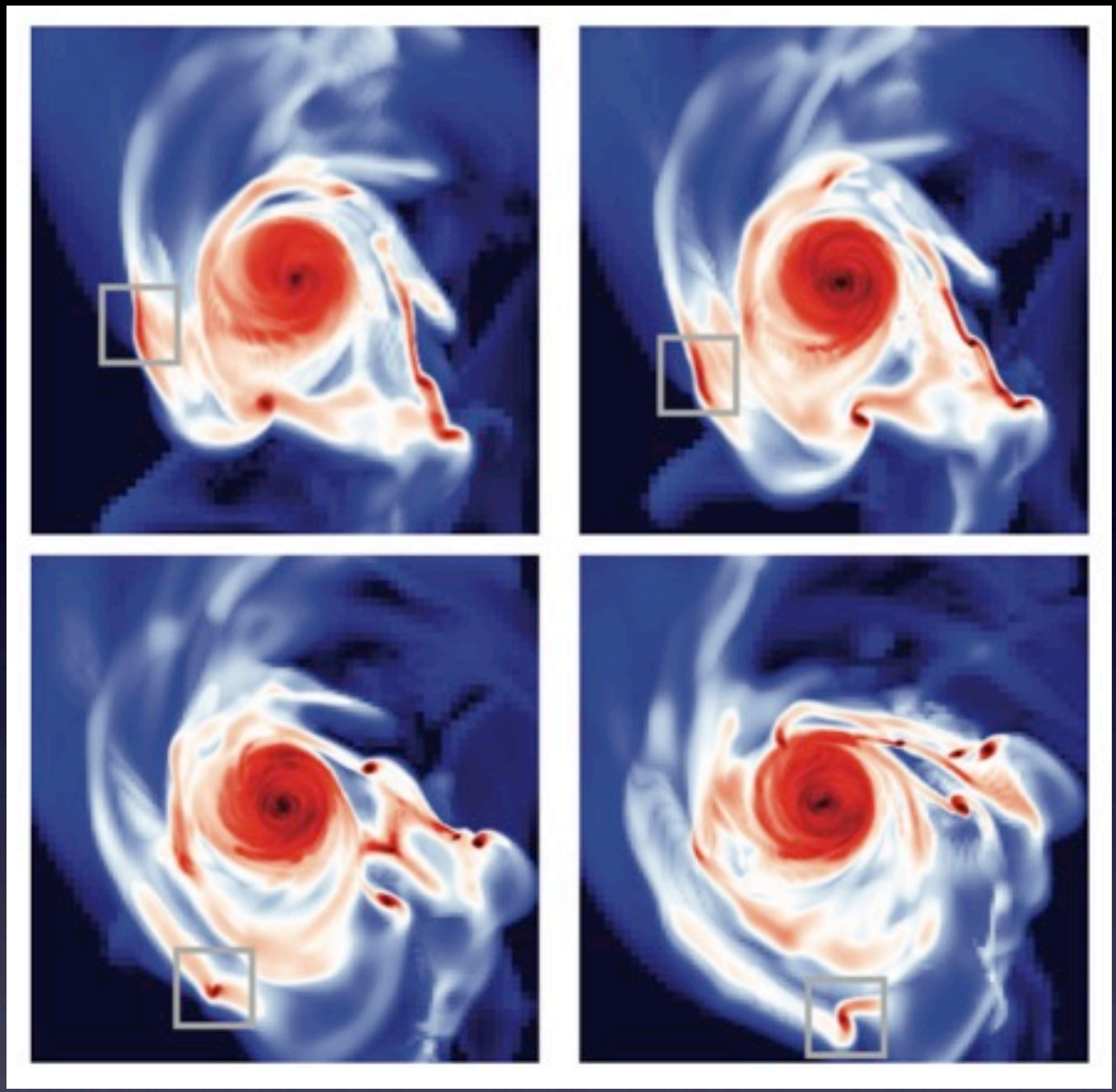
- the disk gas fraction f_g ~ 40-50% compared to ~20% at z=1

- typical average $\Sigma_{\rm g} \sim 40 - 100\, M_\odot\, {\rm pc}^{-2}$

- large velocity dispersions $\sigma_{\rm turb} \sim 30\, {\rm km\, s}^{-1}$

- clump fraction ~ 15% of disk mass

- a compact bulge exists which dominate the galaxy mass (B/D >1.0)



$$M_J = \frac{\sigma^4}{G^2\Sigma} \sim 2.3 \times 10^8\, M_\odot$$

$$M_{\rm patch} = 3 \times 10^8\, M_\odot$$

Disk properties at z=2-3

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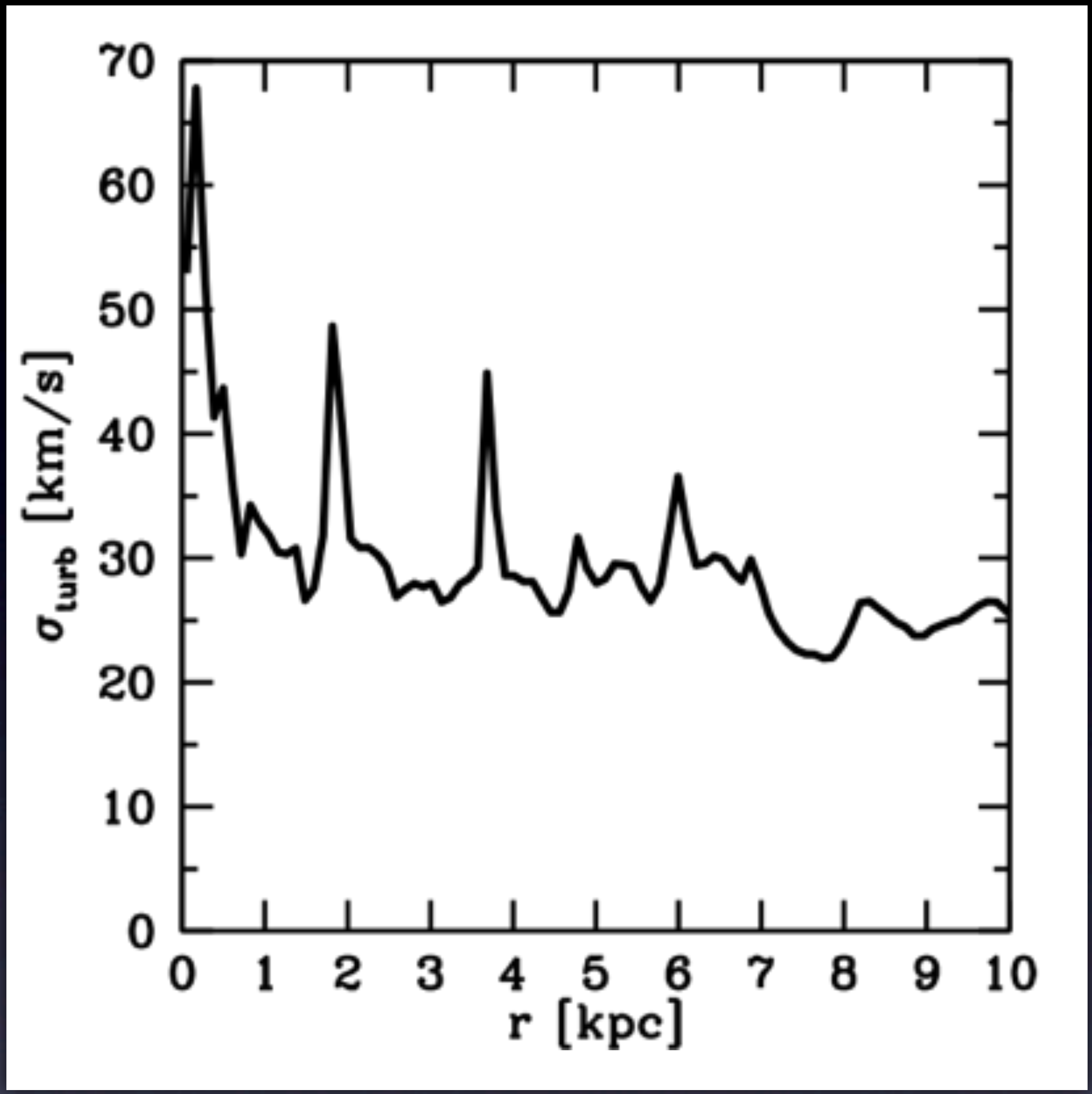

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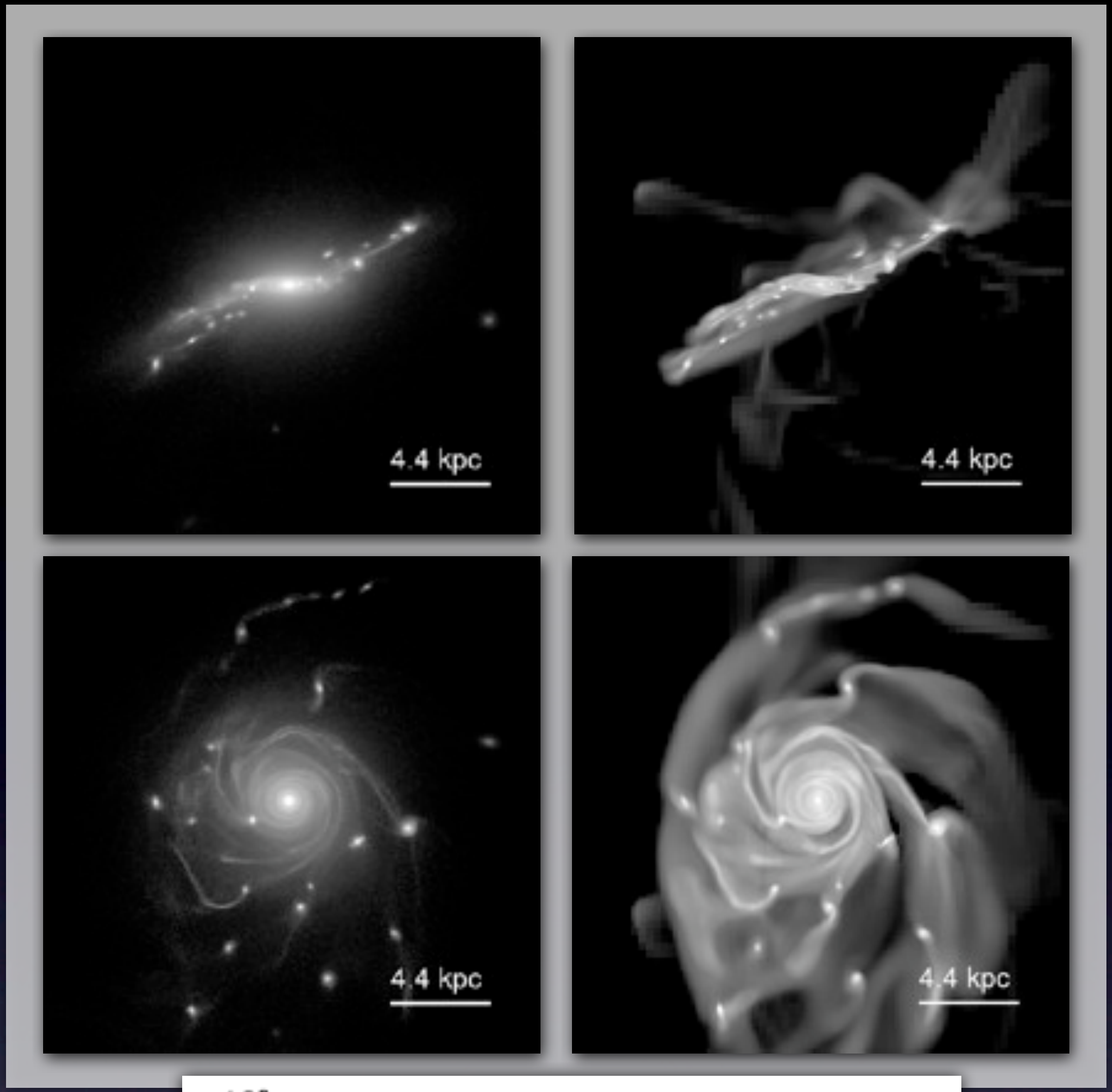
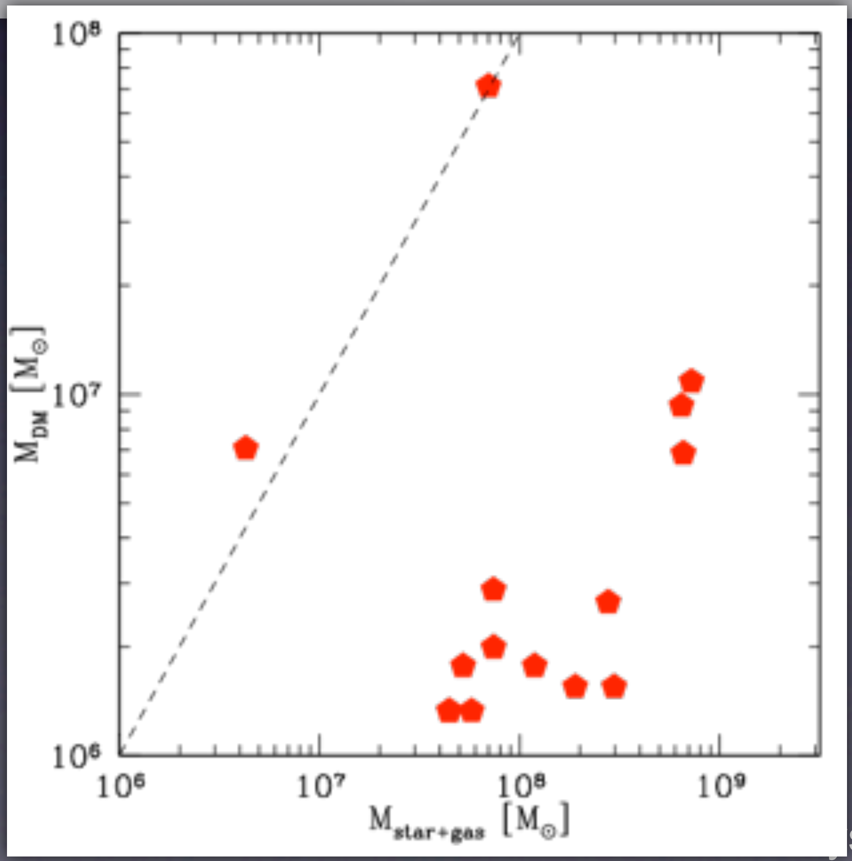
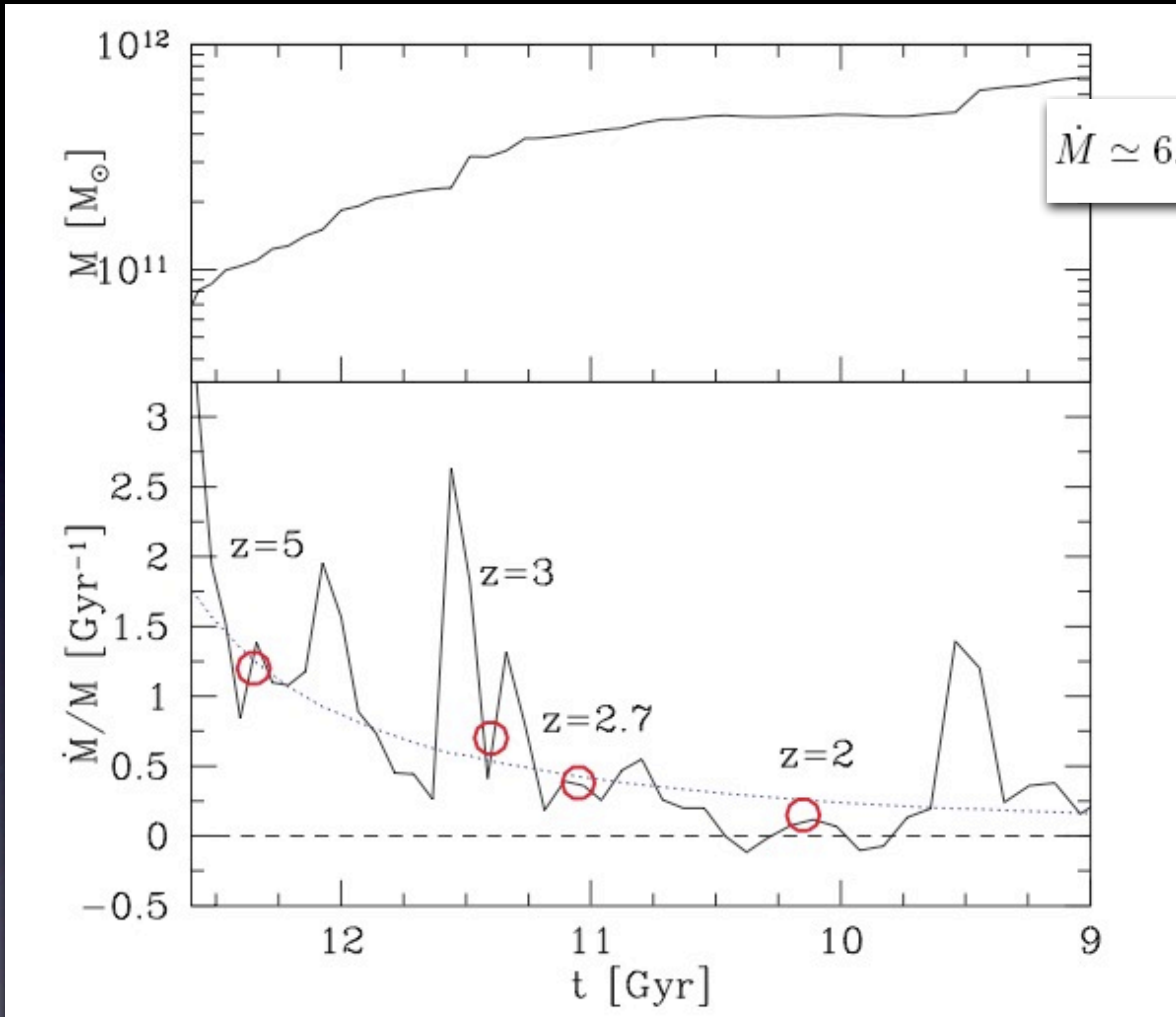






$$\dot{M} \simeq 6.6\, M_{12}^{1.15}\, (1+z)^{2.25}\, f_{.165}\; M_\odot\, \mathrm{yr}^{-1} \;,$$

Total accretion values agree well with EPS theory of Neistein et al. (2006)

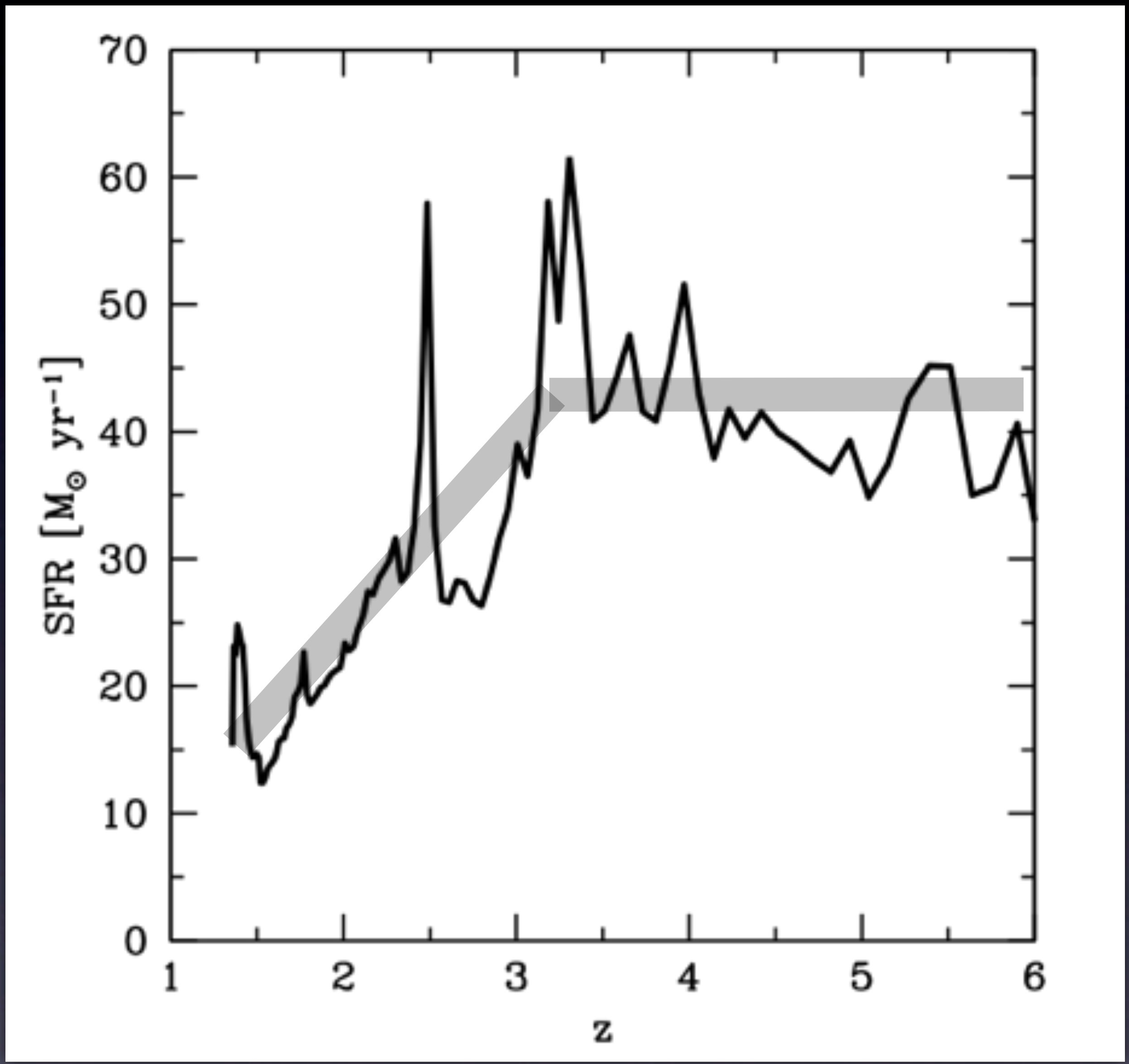
Clumpy galaxies form after period of intense diffuse gas accretion through cold streams

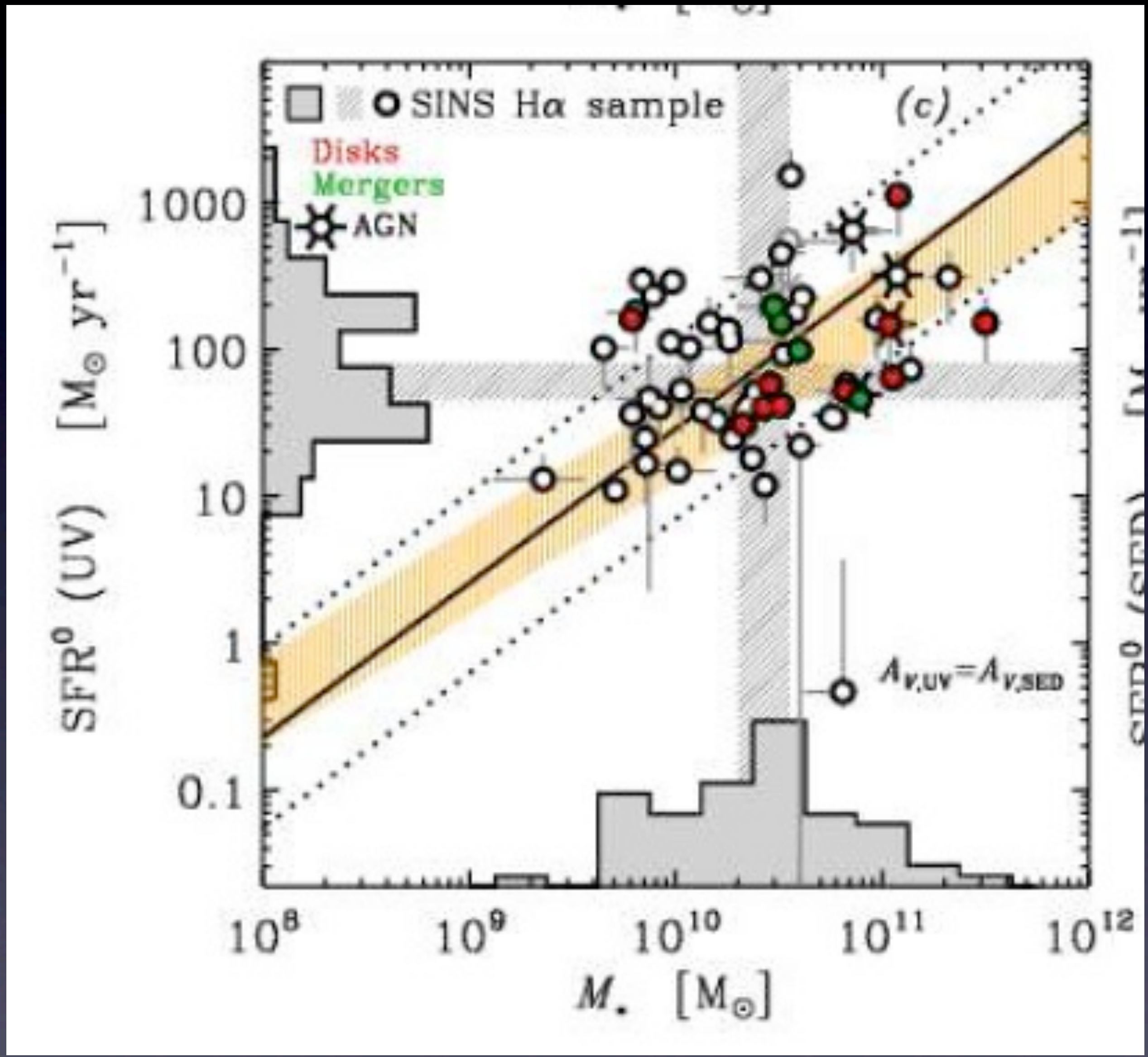
Clumps form in the outer disc and then migrate inwards into the bulge

Star formation rates

Mergers induce the high SFR peaks

$$z = 2.5 - 3.5$$
$$\mathrm{SFR} = 35 - 45\, M_{\odot}\, \mathrm{yr}^{-1}$$
$$M_* = 4 - 7 \times 10^{10}\, M_{\odot}$$





Cold streams contribute with a steady 20-40 M_{sun}/yr

Förster-Schreiber et al. (2009)

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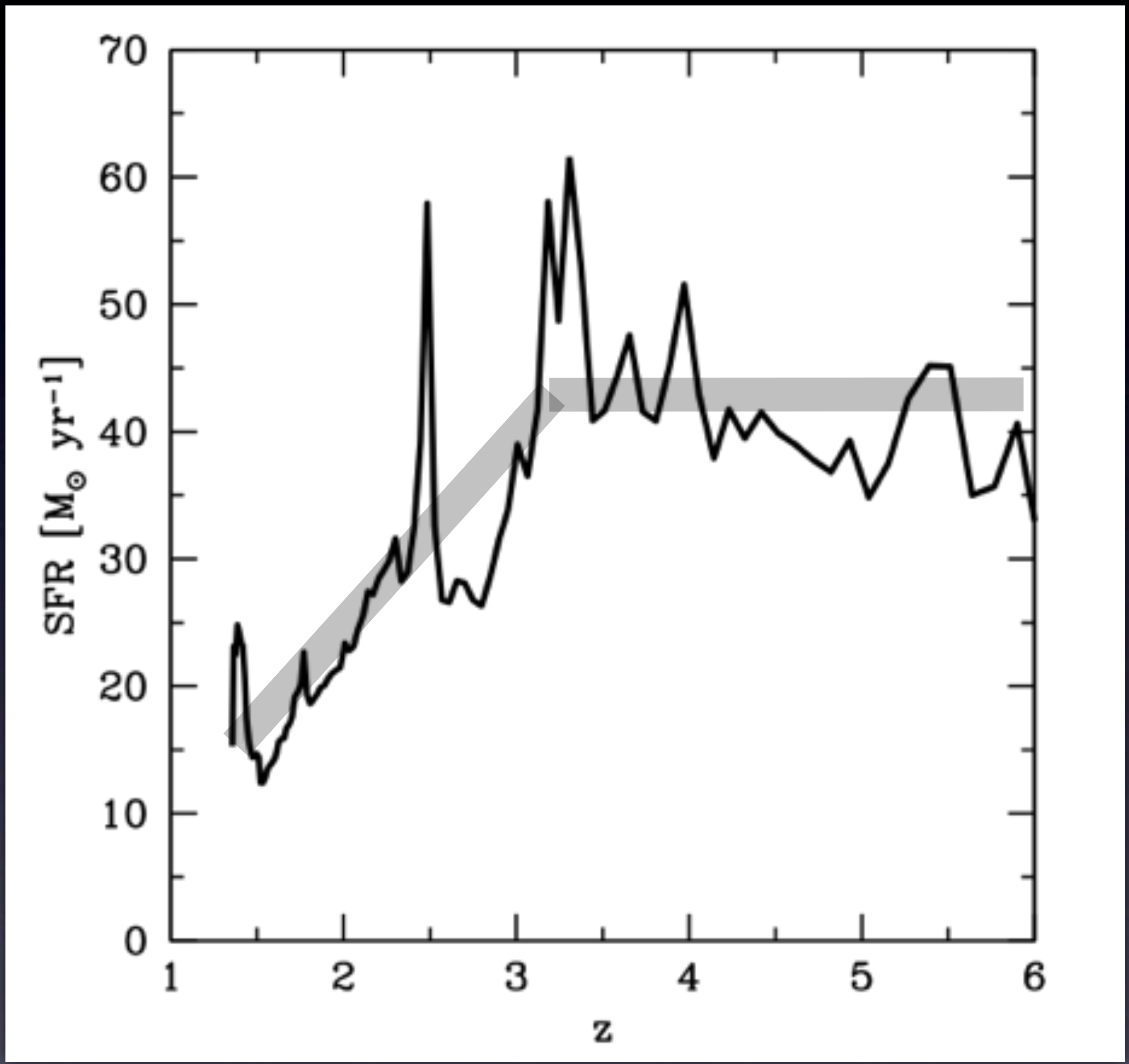

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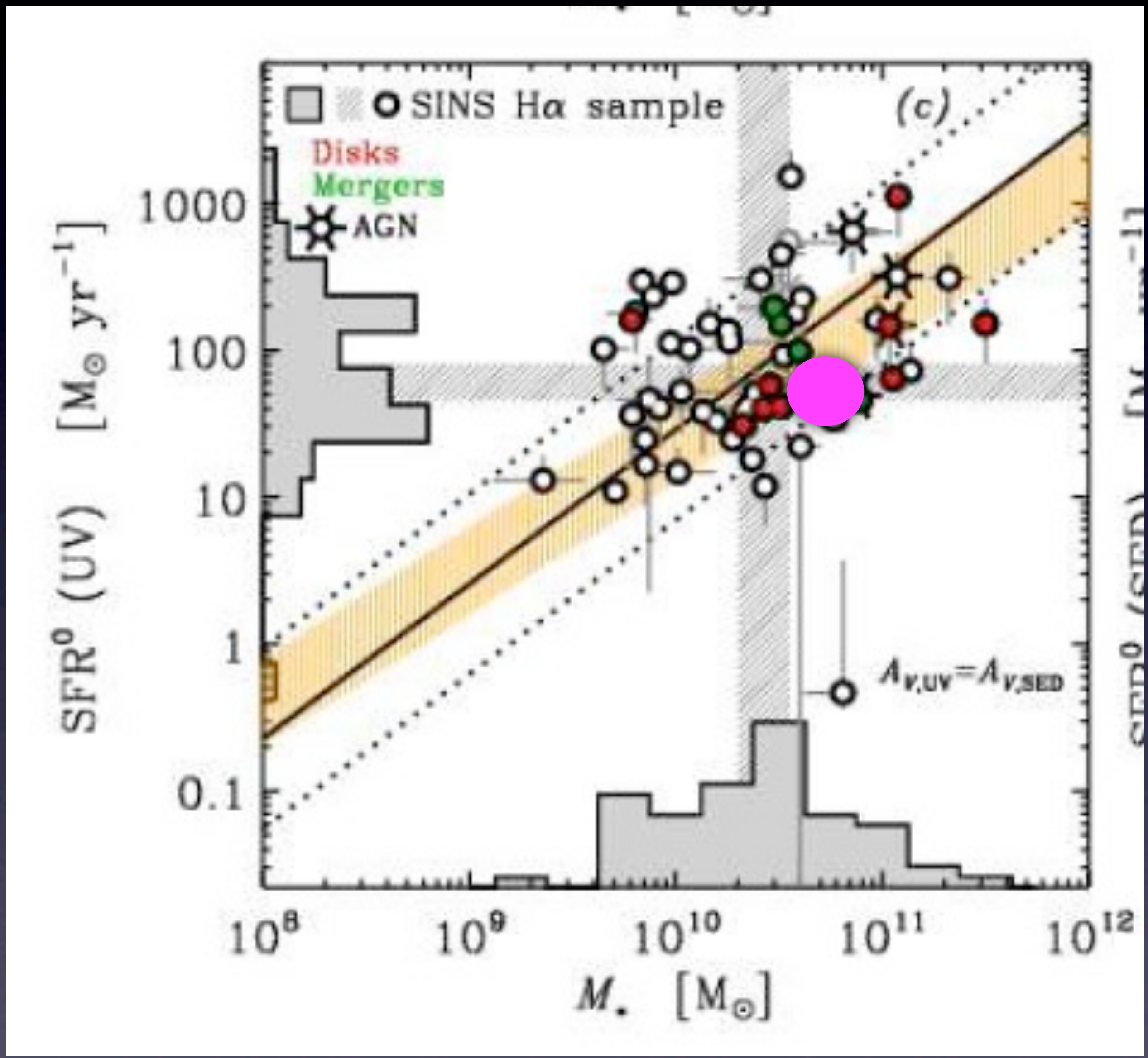
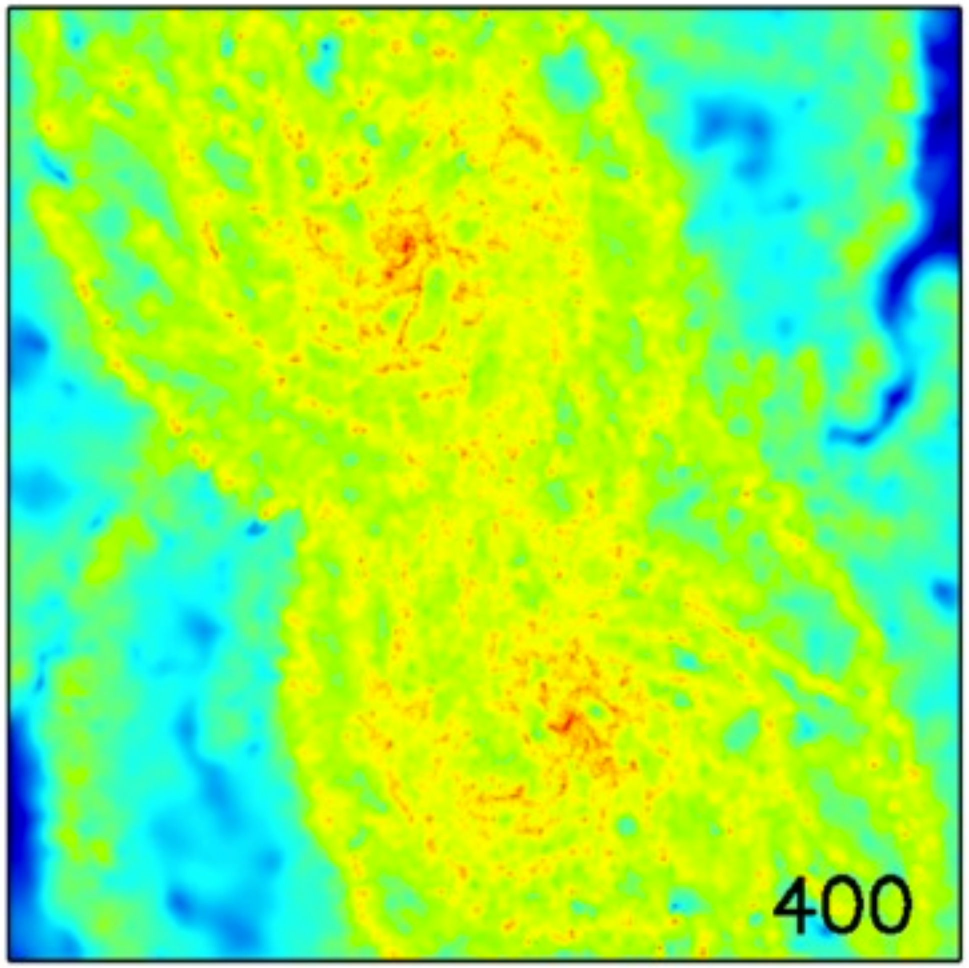
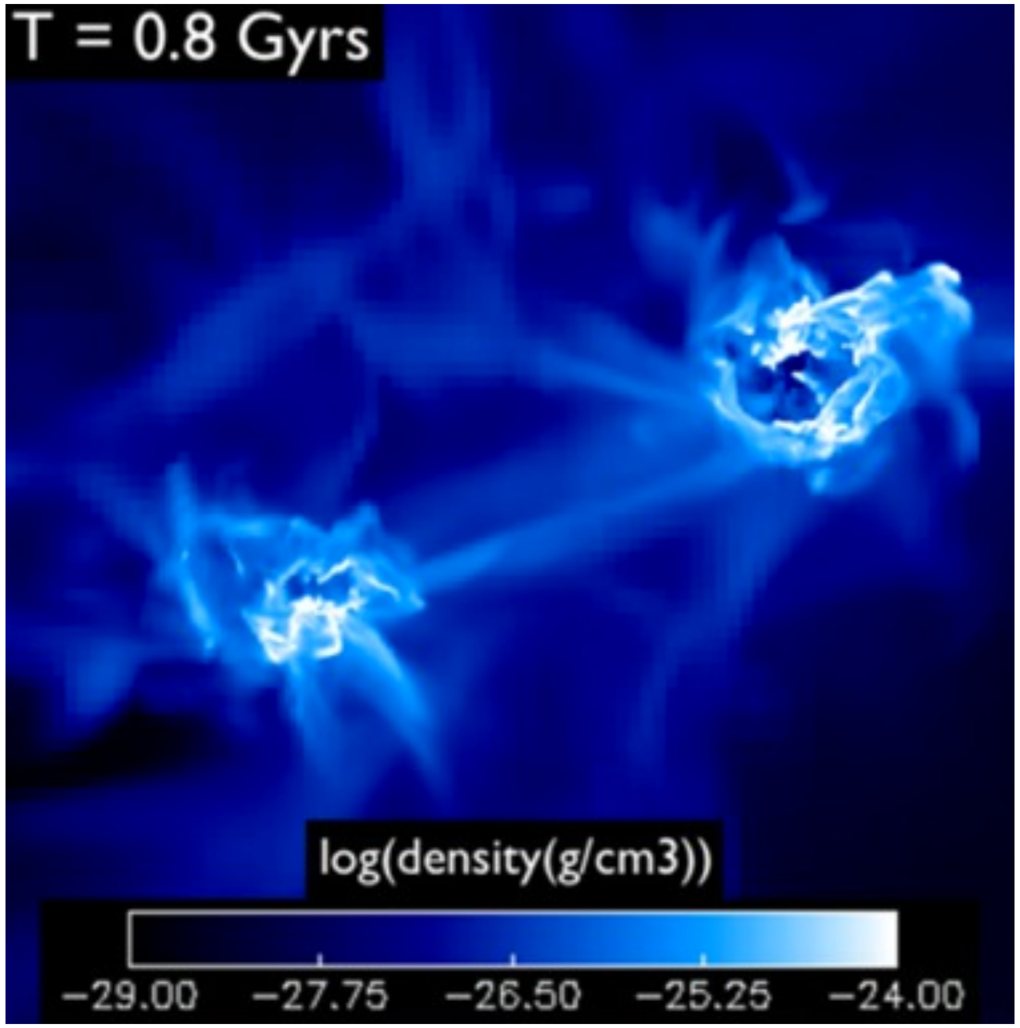


Förster-Schreiber et al. (2009)

High-resolution simulations of mergers

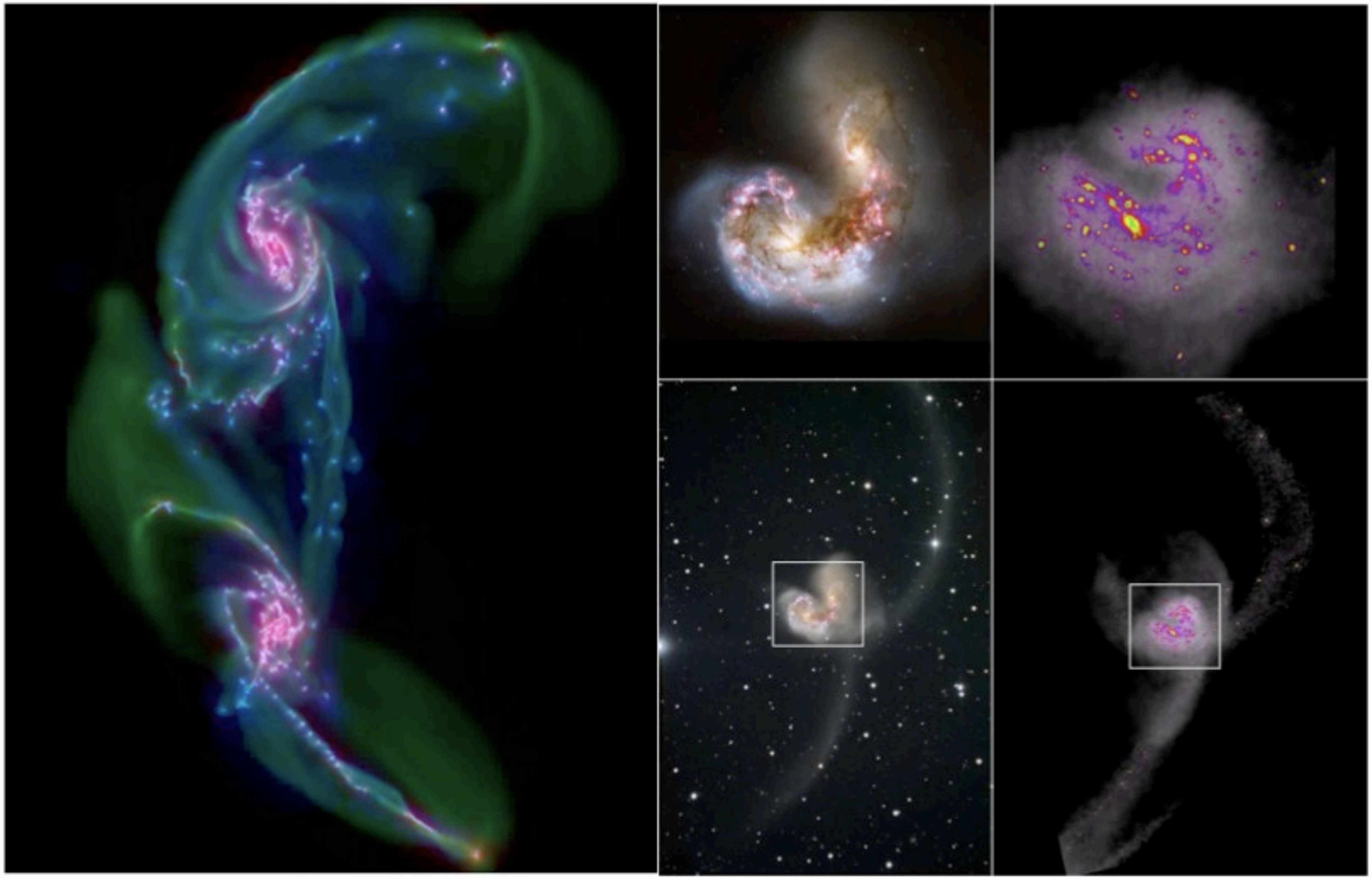
Saitoh et al. (2009)
Shock-induced star formation





Kim, Wise and Abel (2009)
Hot gas outflows

Clump formation in the Antennae galaxy

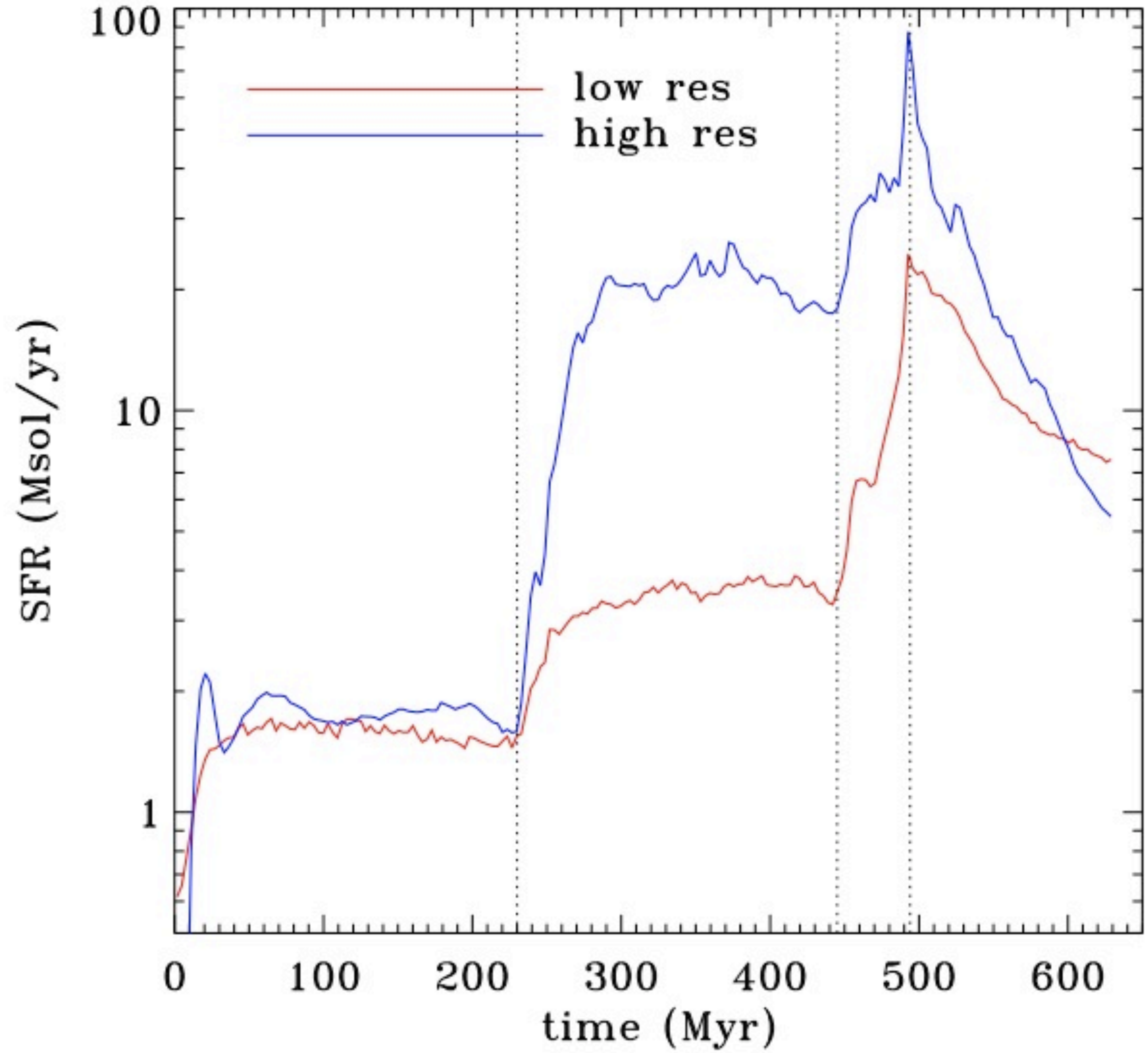


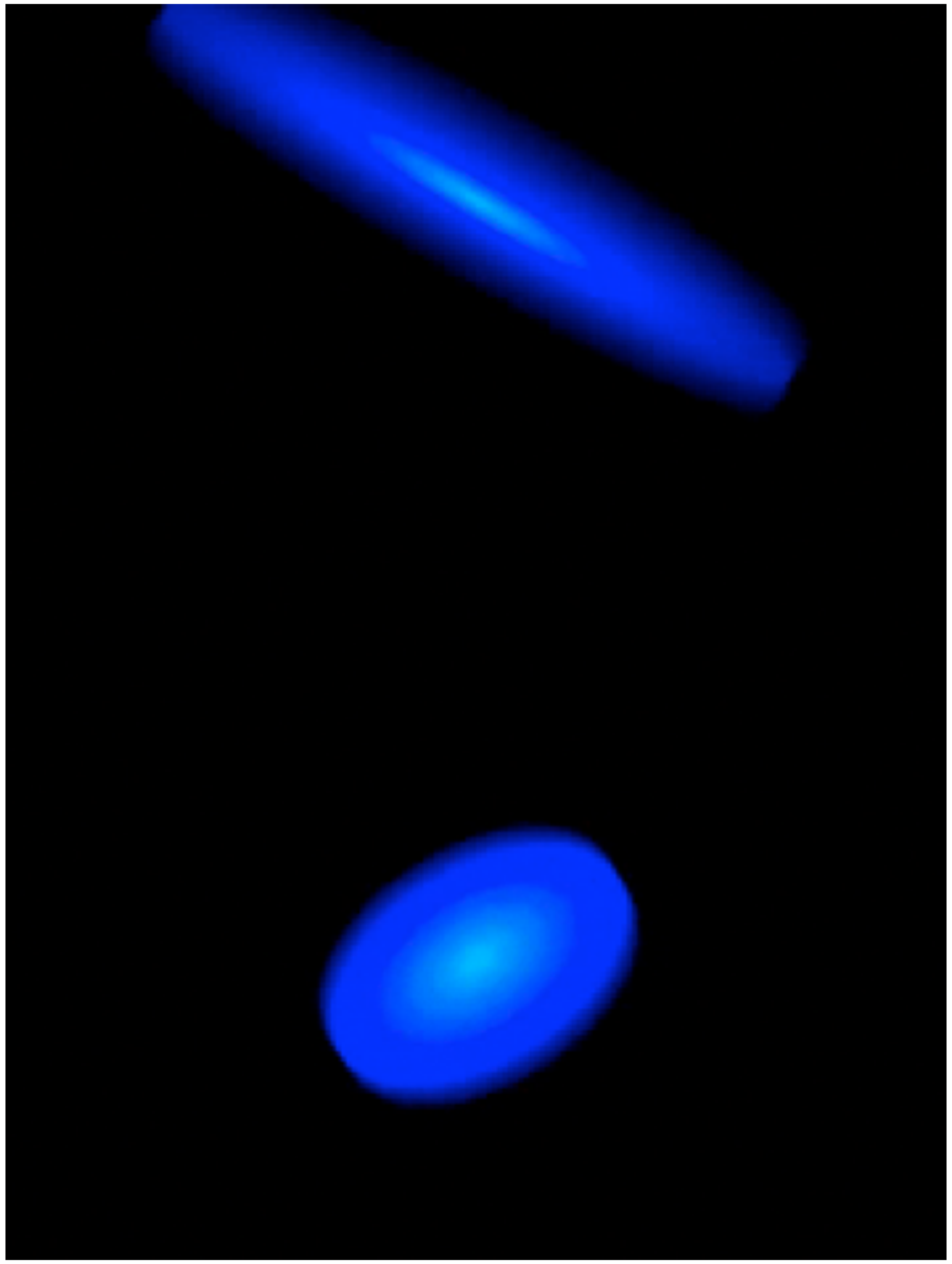
No feedback. Star formation with 1% efficiency for gas density above 10 H/cc.

12 pc resolution, 40×10^6 gas cells 20×10^6 particles

Teyssier, Chapon & Bournaud, 2010, ApJL, arxiv1006.4757.

Associated star formation history

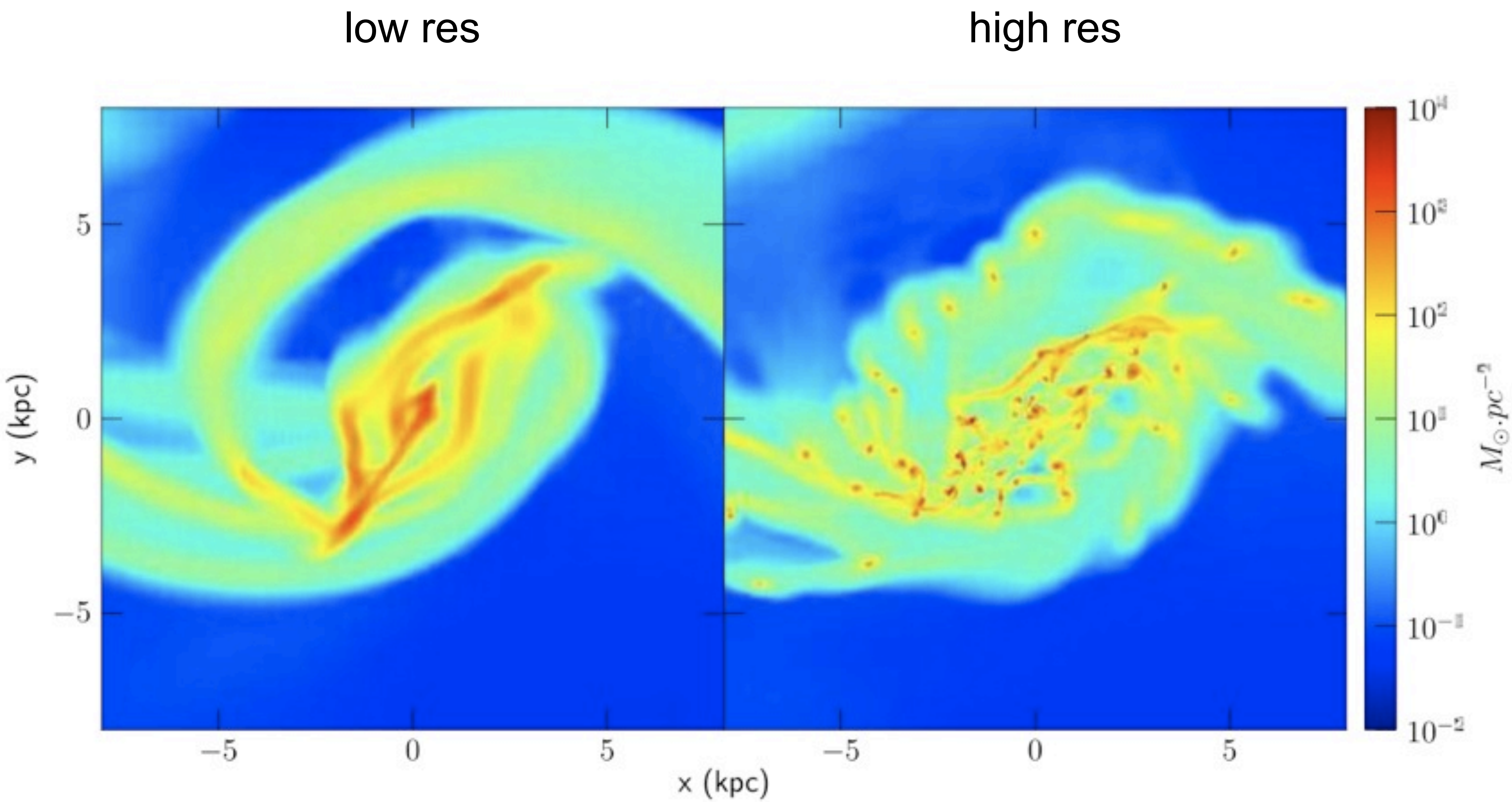




Movie: Daniel Pomarède with SDvision

Between first and second pericentric passages, smooth disc models (96 pc) find SFR ~ 3-4 Msol/yr, a factor of 5-10 below clumpy disc models (12 pc) !

Fragmentation: the driving mechanism for starbursts ?



Tidal interactions drive a strong m=2 perturbation. With high res and low T cooling, the dense spiral arm is gravitationally unstable and fragments in massive clumps (10^7 M_{sol})

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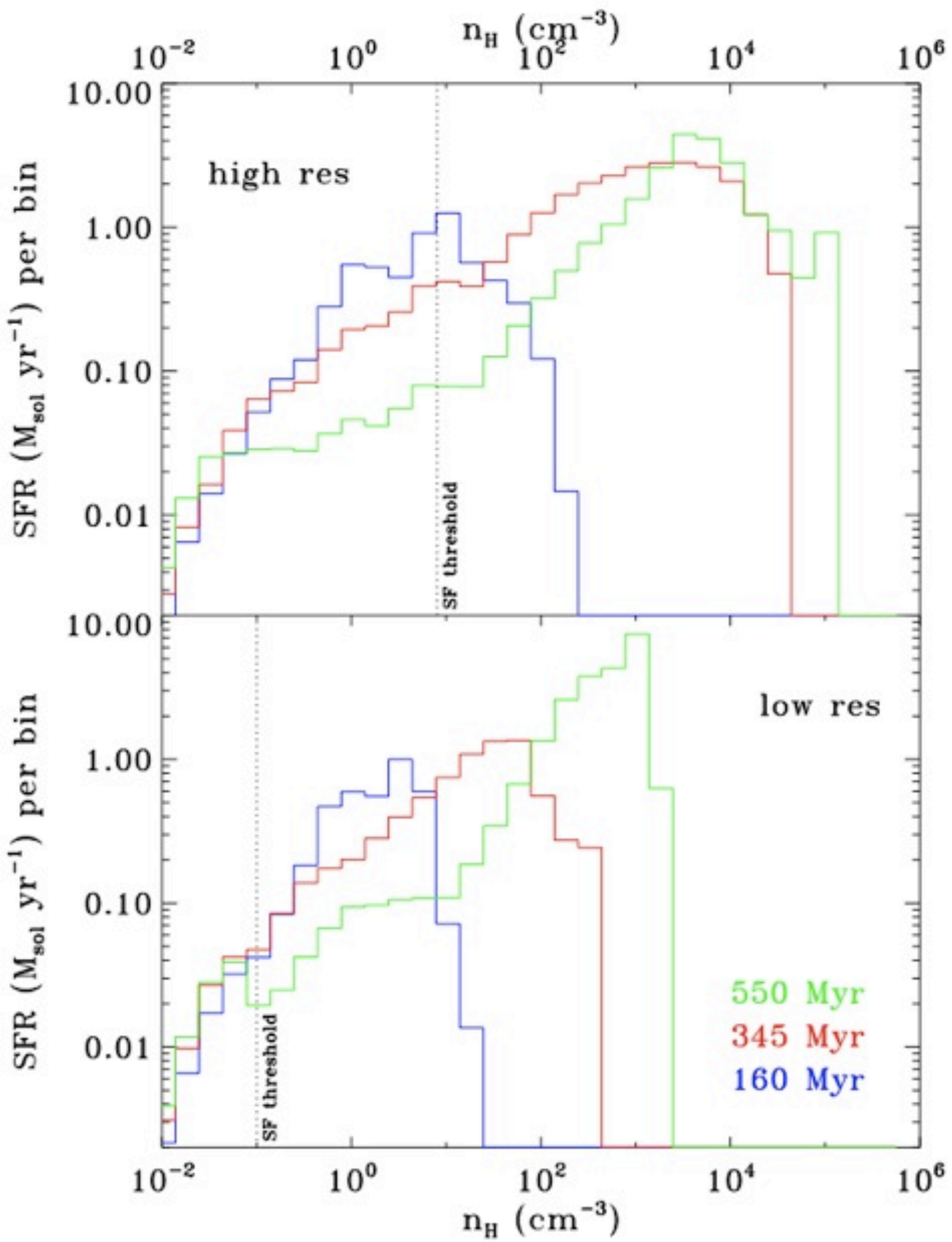
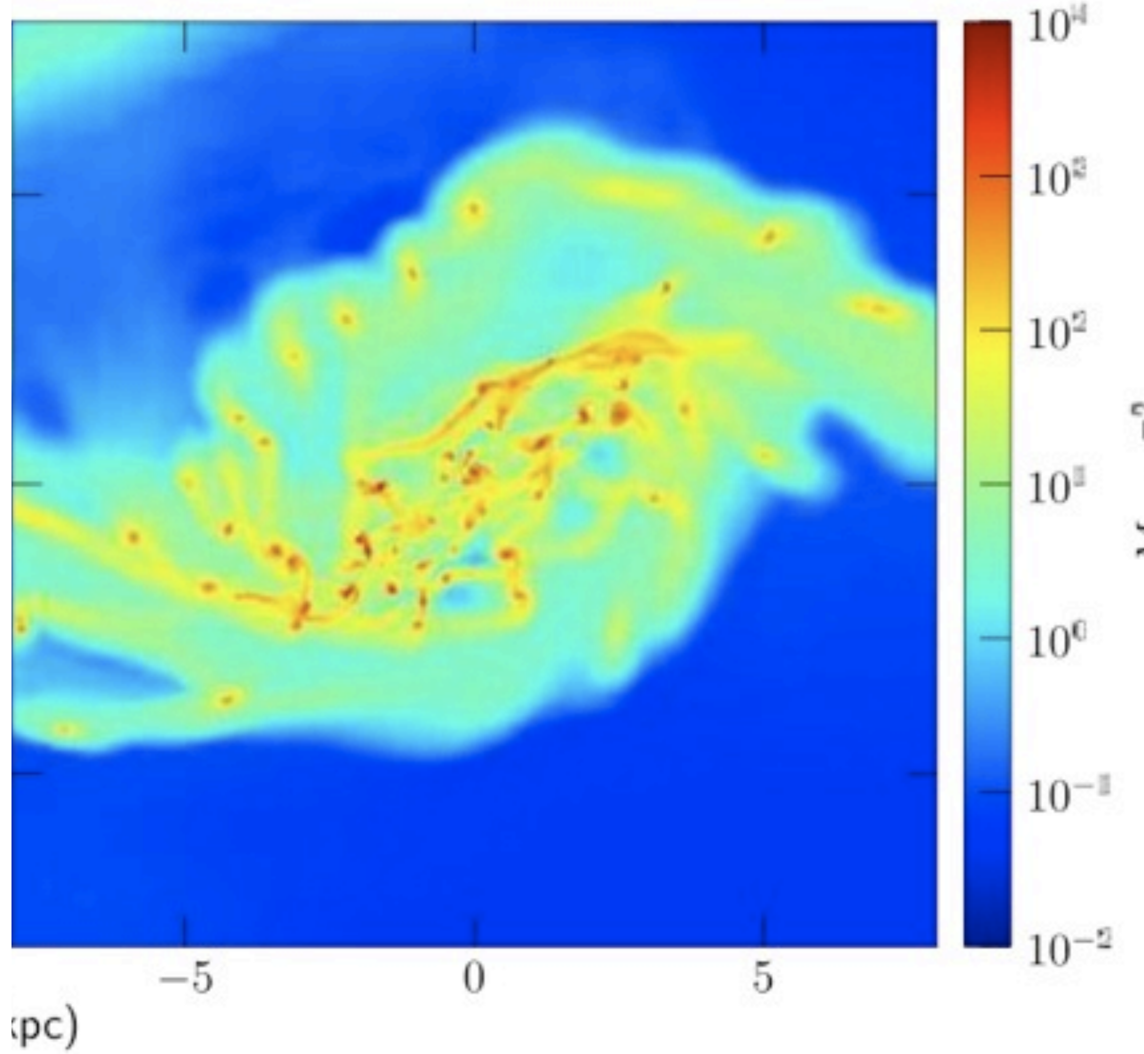


high res



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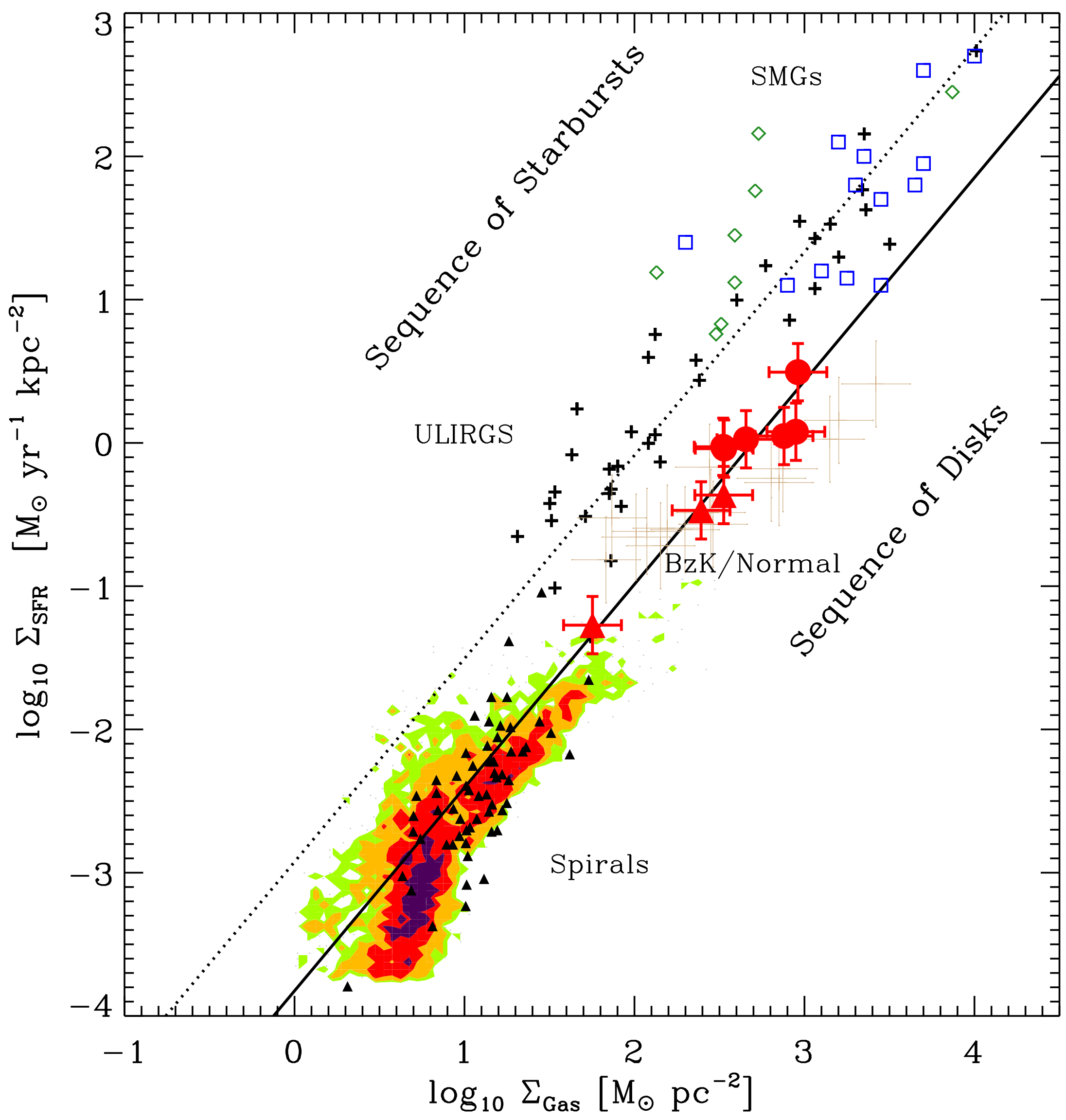
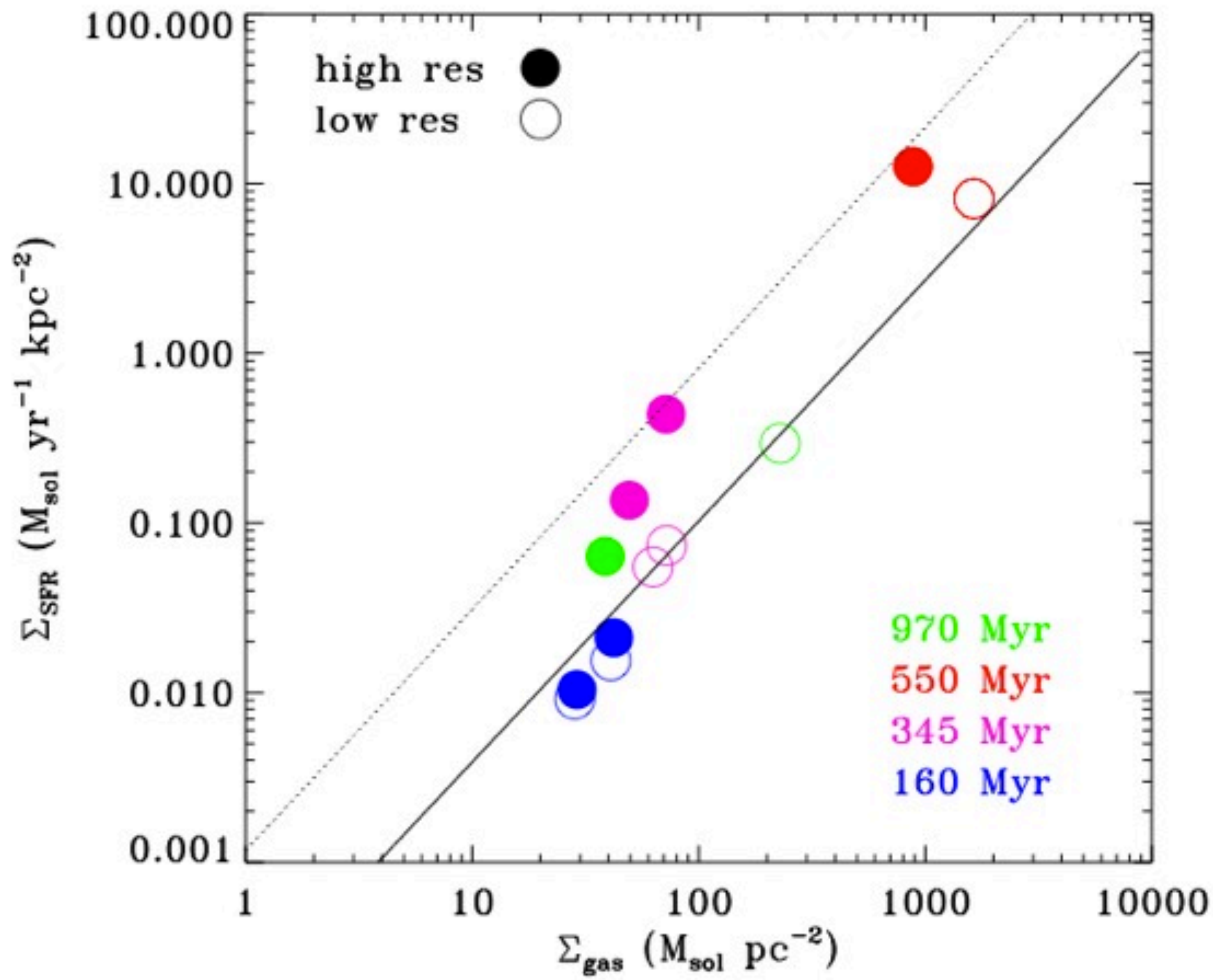
Kennicutt-Schmidt diagram

Daddi et al. 2010
Genzel et al. 2010



Teyssier et al. 2010



What have we learned ?

• Low star formation efficiency leads to the formation of disc dominated systems.

• Internal processes (SF+FBK) play an important role in shaping galaxies.

• Low baryon fraction in the stellar component can be obtained with strong (AGN?) feedback but at the expense of destroying the disk. What is wrong with abundance matching ? What is wrong with our feedback models ?

• With smooth discs (low res > 100 pc), the SF efficiency cannot be self-consistently predicted. We need a more predictive model !

• High redshift galaxies develop a clumpy structure after strong burst of diffuse accretion: key role played by cold stream accretion. Cold streams have not been observed yet !

• With clumpy colliding discs (high res < 100 pc), we capture a strong, non linear evolution in the global SFE: transition from quiescent to starburst regime ?

• To get a clumpy ISM for quiescent low redshift disc galaxies, we would need a resolution < 10 pc !