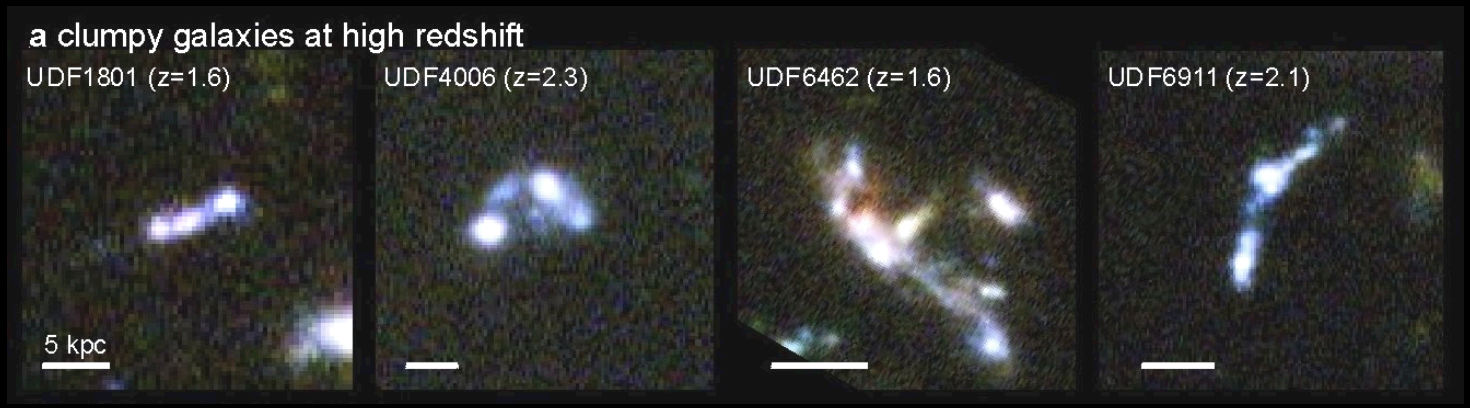
The high-redshift progenitors of exponential disk galaxies

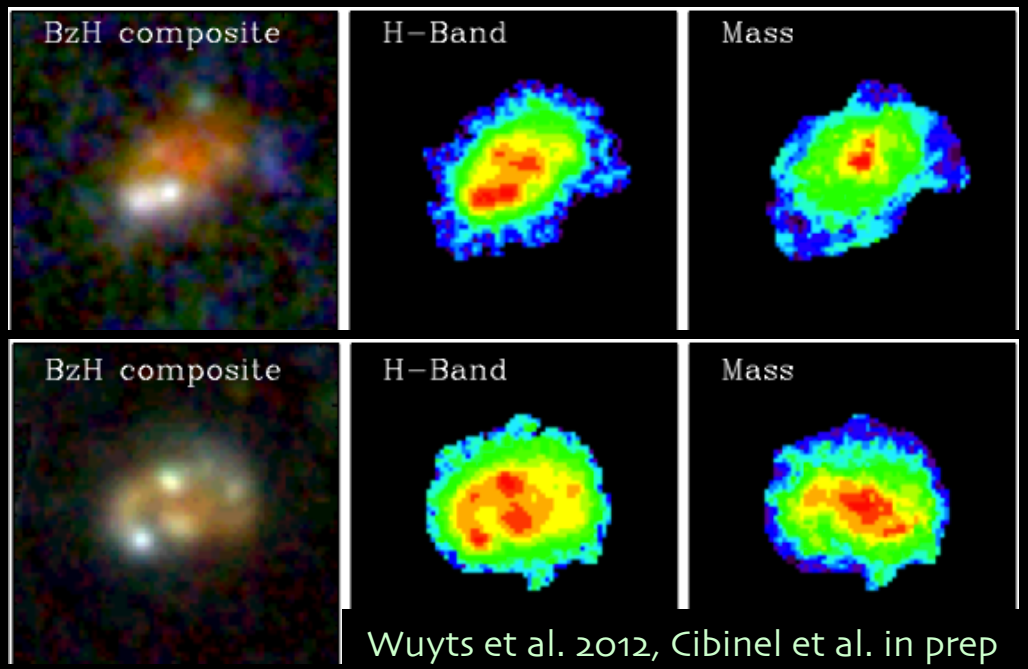


Frédéric Bournaud – CEA Saclay

High-redshift star forming galaxies



Elmegreen et al. 2007



Wuyts et al. 2012, Cibinel et al. in prep

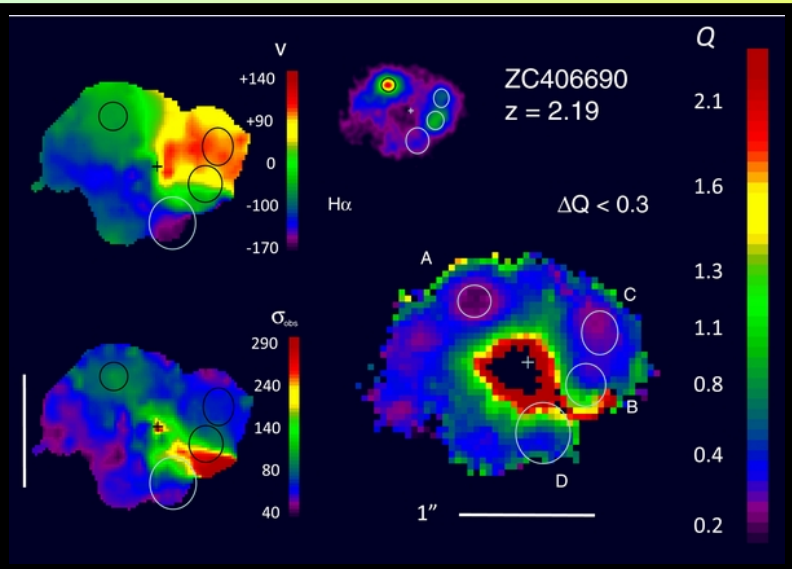
Typical star-forming galaxies at z=1-3

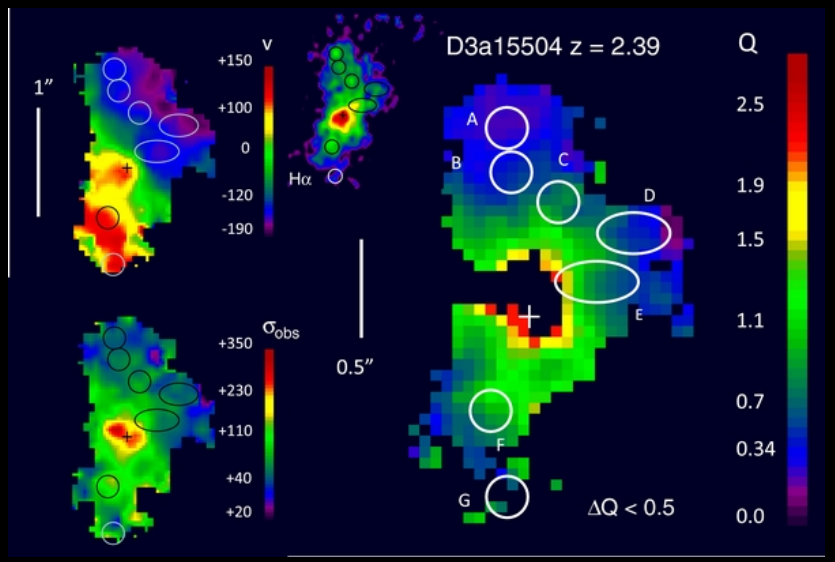
Irregular clumpy disks
S.F in giant clumps of $10^{8\text{-}9} M_o$

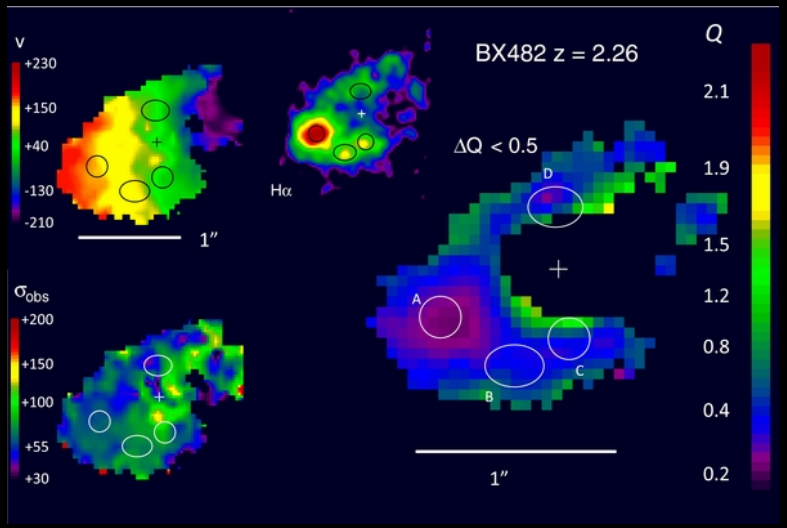
Rotating + velocity dispersion 50km s^{-1}

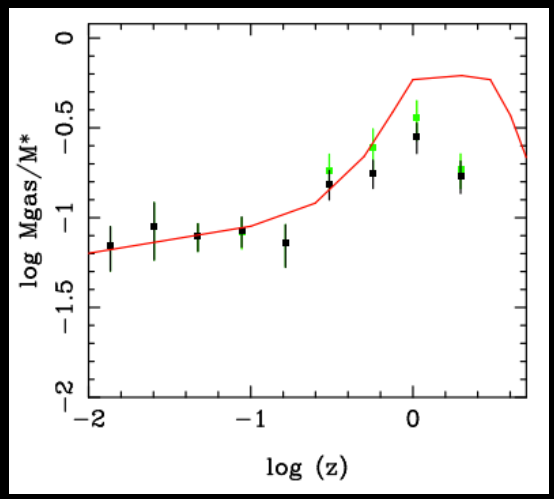
High gas fractions (50%) => unstable disks

High-redshift star forming galaxies









Combes et al. 2012

Genzel+06, Forster-Schreiber+11, Daddi+10, Bournaud+08.....

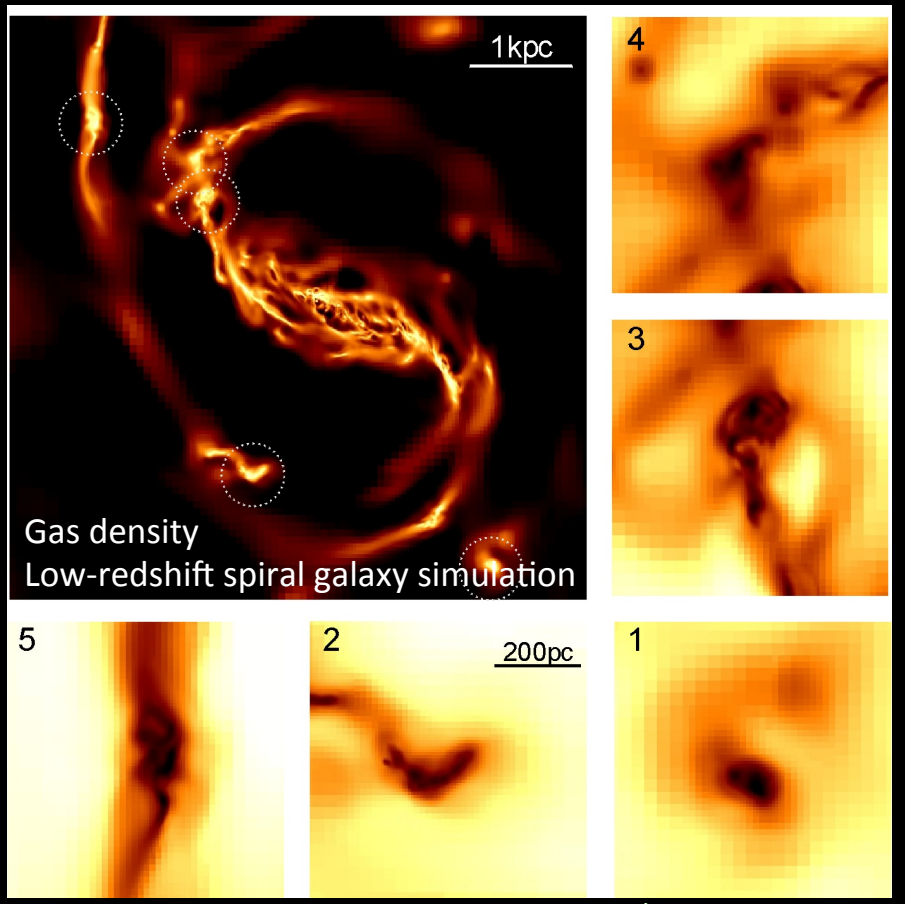
Modeling ISM structure and stellar feedback

New generation of simulations
at parsec-scale resolution, with:

- multiphase ISM structure
- entire galactic dynamics
  - Gas self-gravity
  - Stellar dynamics
- Gas cooling to <100K allowing high Mach numbers
- star formation and feedback
  density-based or shock-induced SF
  supernovae explosions
  HII regions
  radiation pressure...

} *Complete stellar feedback owing to resolved HII regions*

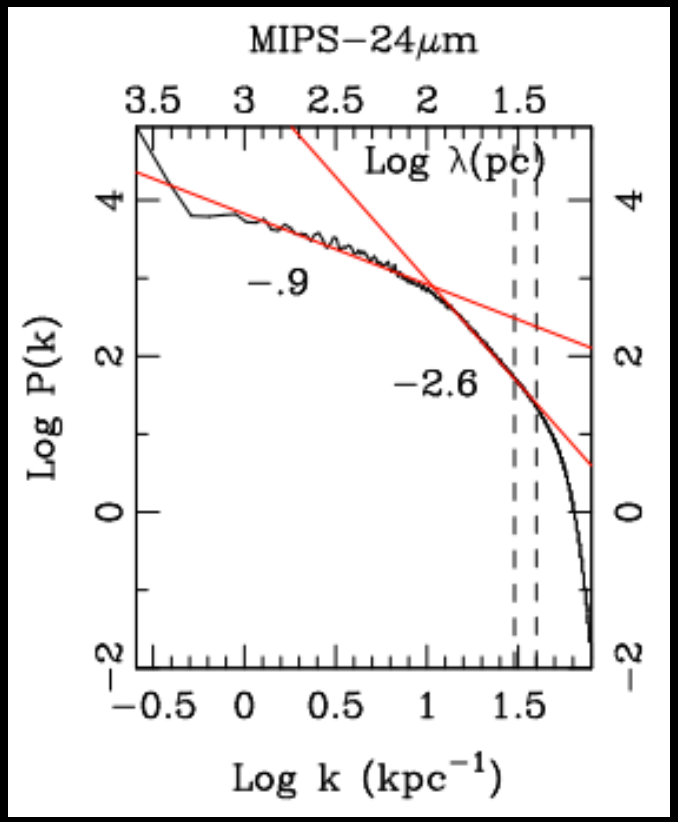
+ AGN feedback



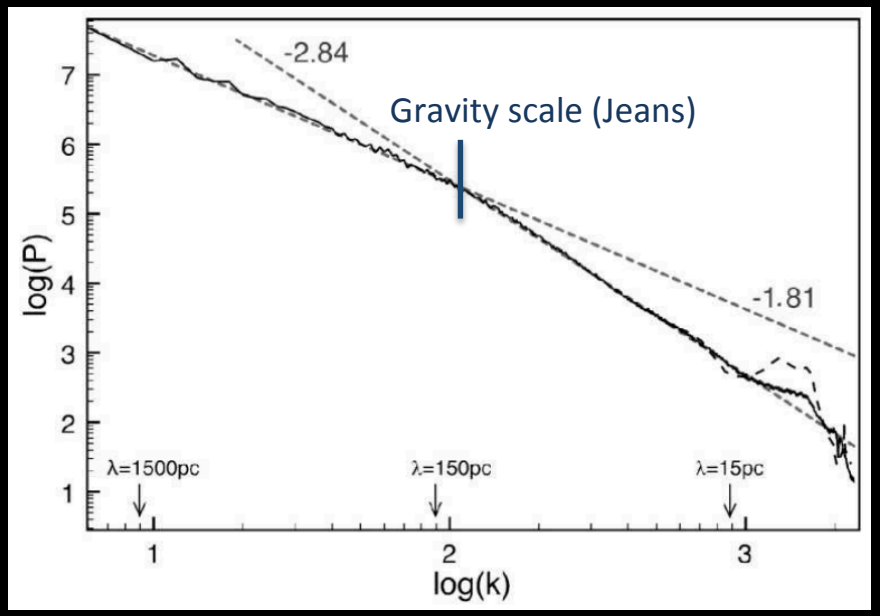
Tasker & Bryan 2008
Agertz et al. 2009
Bournaud et al. 2010

Here we use the RAMSES code (Teyssier 2002)
One strength is the strong scaling of the code, allowing very high resolution and accuracy

Modeling ISM structure and stellar feedback



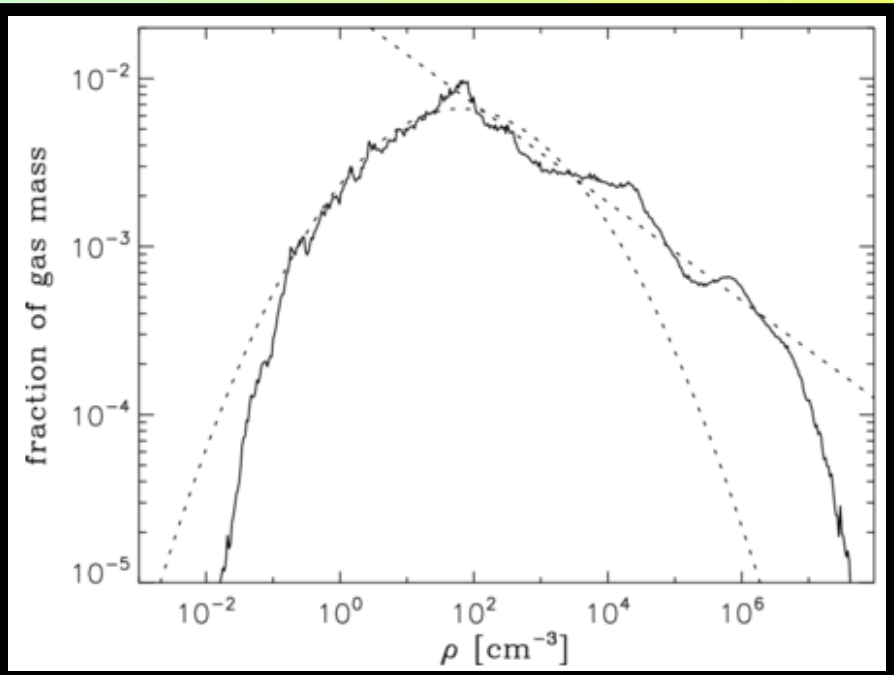
Combes et al. 2013 real M33 data



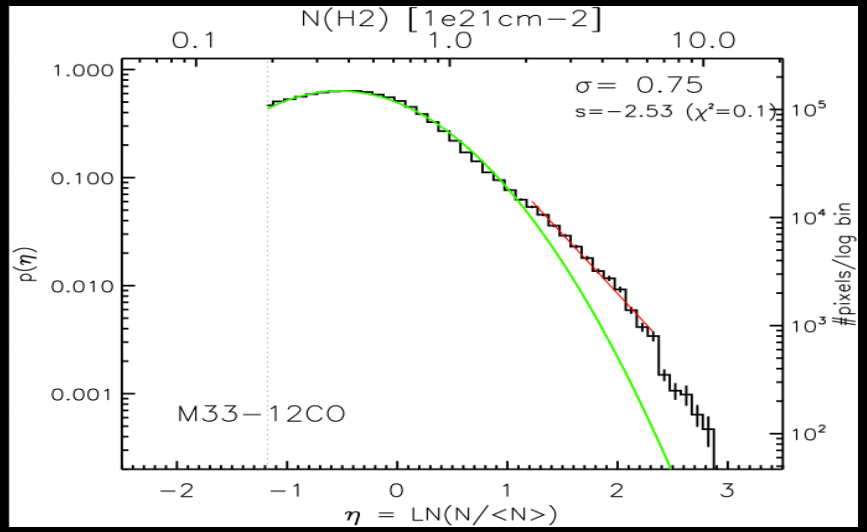
Bournaud+10 simulation of M33-mass disk

- Simulations produce a realistic power spectrum
- **Turbulence cascade from gravity + hydro instabilities**
- Stellar feedback in only a regulation process to preserve a steady state in the turbulence cascade

Modeling ISM structure and stellar feedback



Renaud+2013

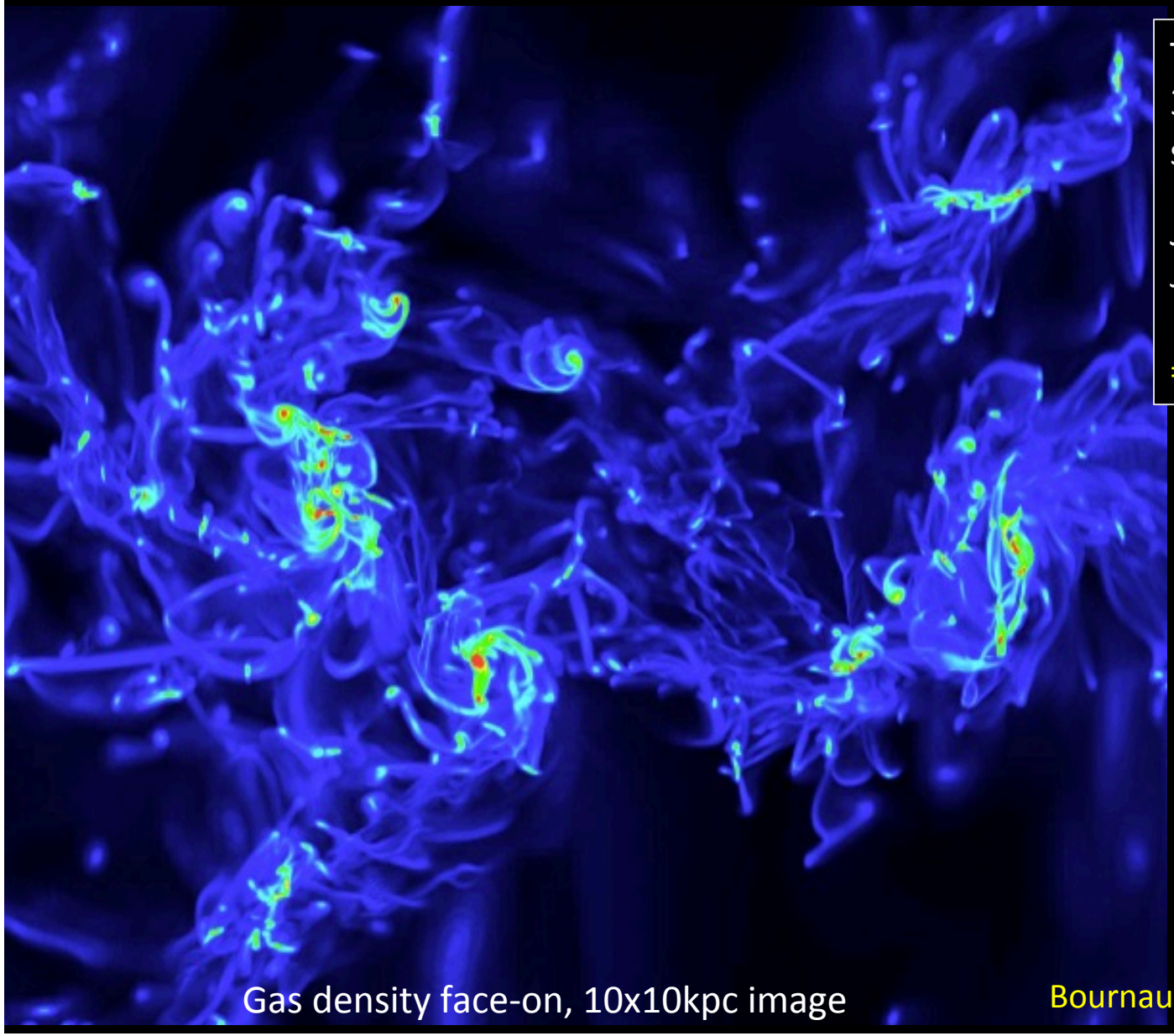


M33 - Druart+2014

The density PDF of an entire galaxy is mostly log-normal
=> expected for "pure" supersonic turbulent pressure (e.g. Padoan & Nordlund 99)

A power-law tail contains 1-3% of the ISM mass at high densities
The power-law shape is theoretically expected from self-gravity (e.g. Elmegreen 2011)

Giant clumps and outflows

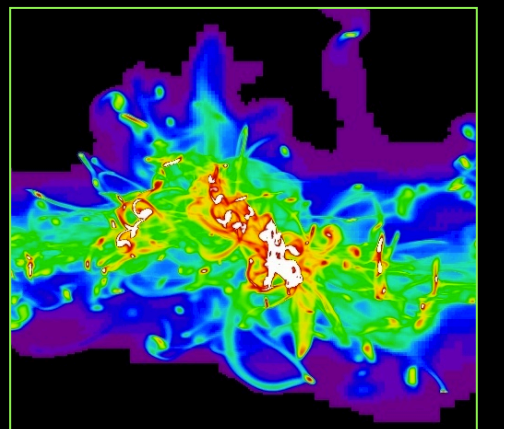


Gas density face-on, 10x10kpc image

Turbulence increases to 30-60km s^{-1}, until self-regulation at Q=1

Jeans mass of 10^{8-9} Msun
Jeans lentgh ~kpc

=> Giant clump formation

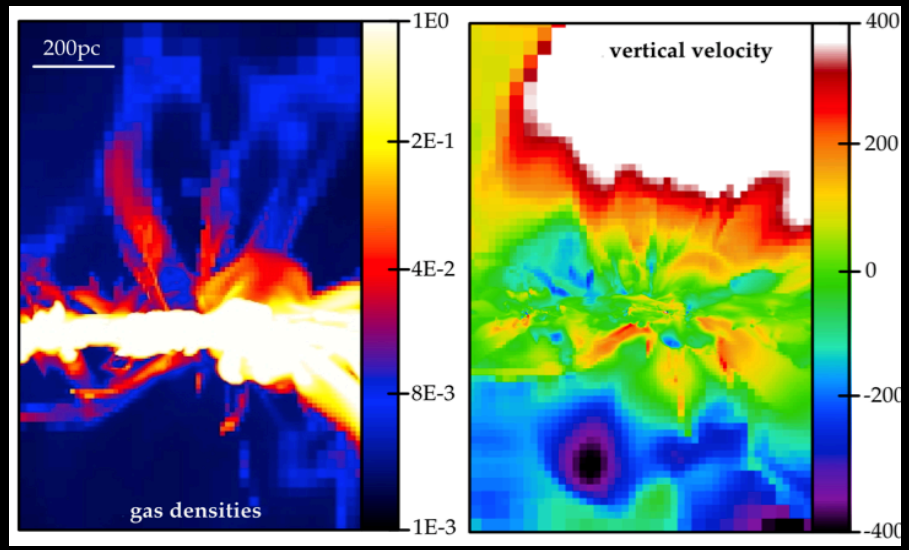


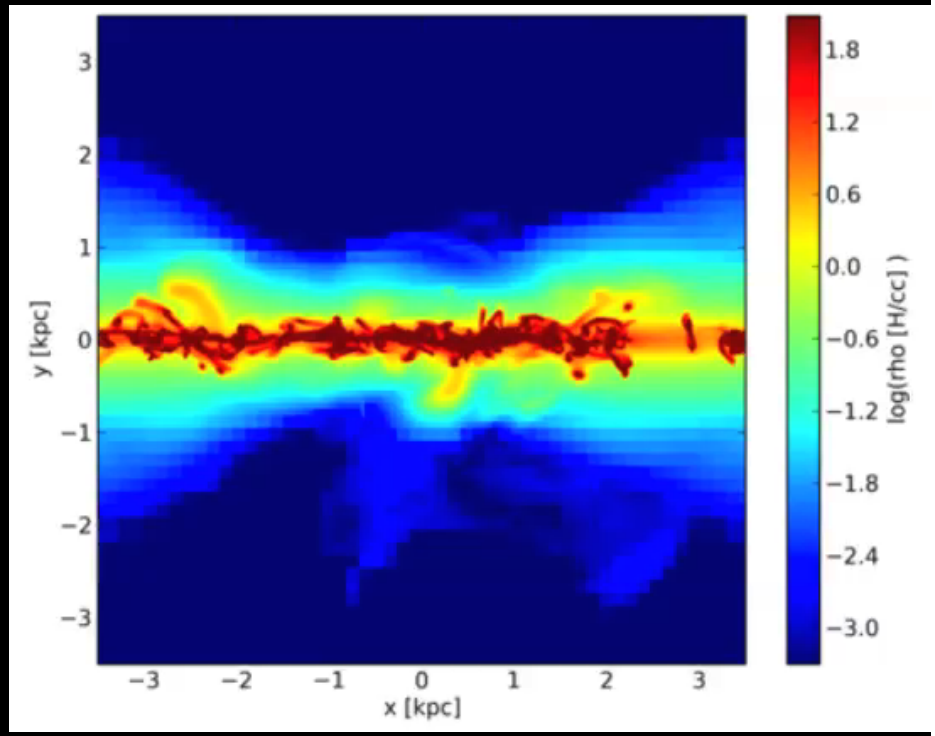
1kpc zoom on a giant clump

Limited fraction of ISM is in high-density phases

Bournaud, Perret, Renaud et al. 2014

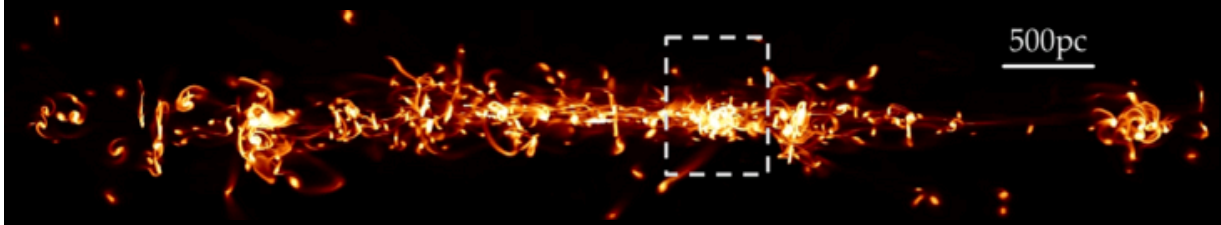
Giant clumps and outflows





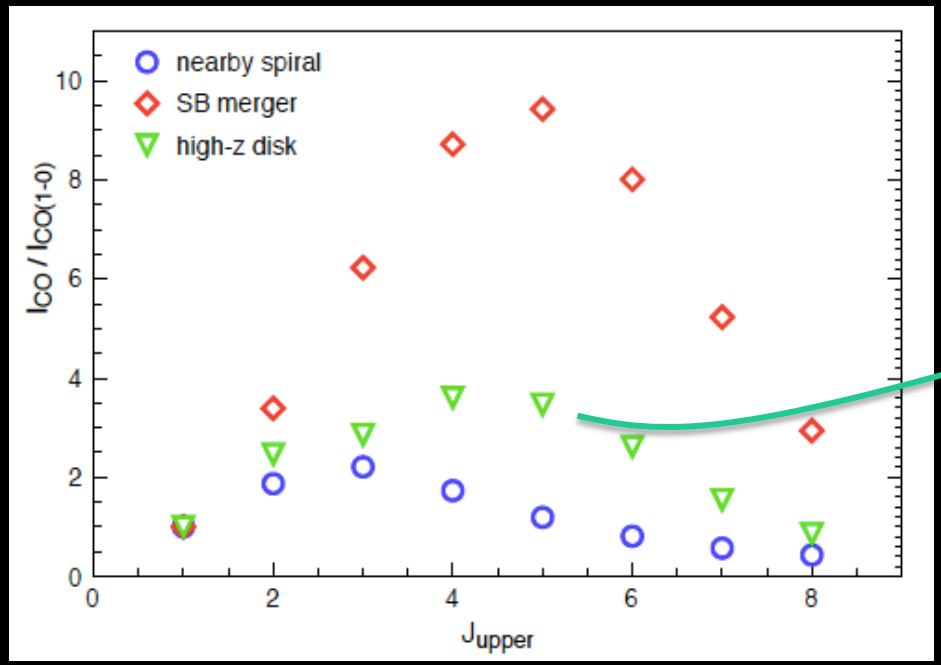
Outflow rate close to the SFR,
above the escape velocity,
giant clumps can survive a few 10^8 yr

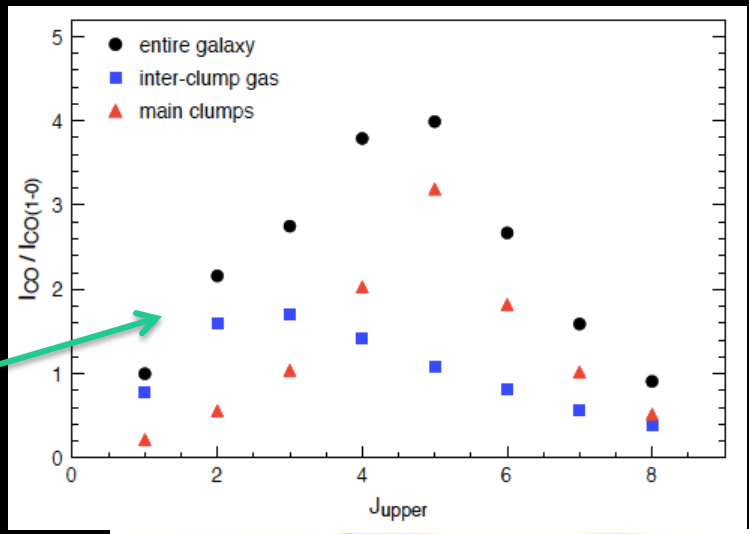
Outflows owing to SN+HII+Radiative feedback

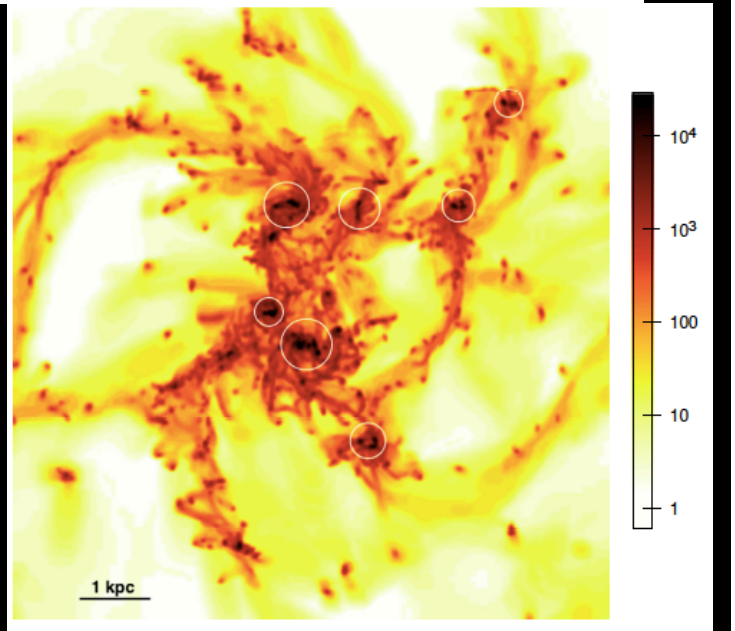


Renaud+ 2013, Perret+ 2014
Bournaud, Perret, Renaud + 2014

Giant clumps and high-excitation molecular gas





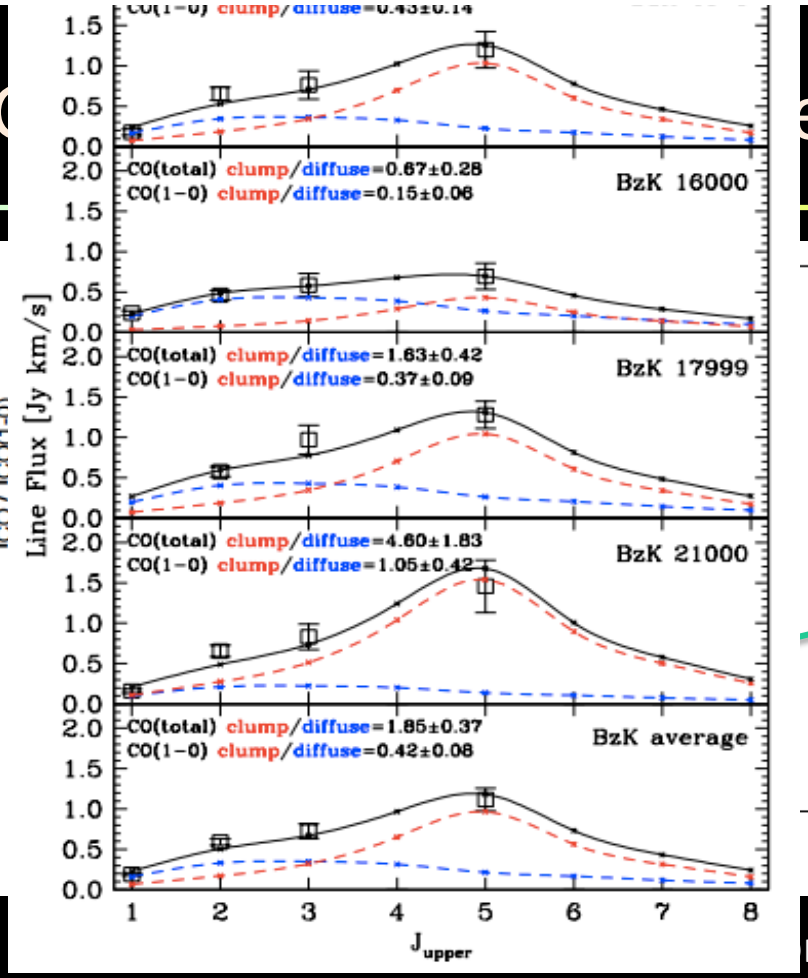


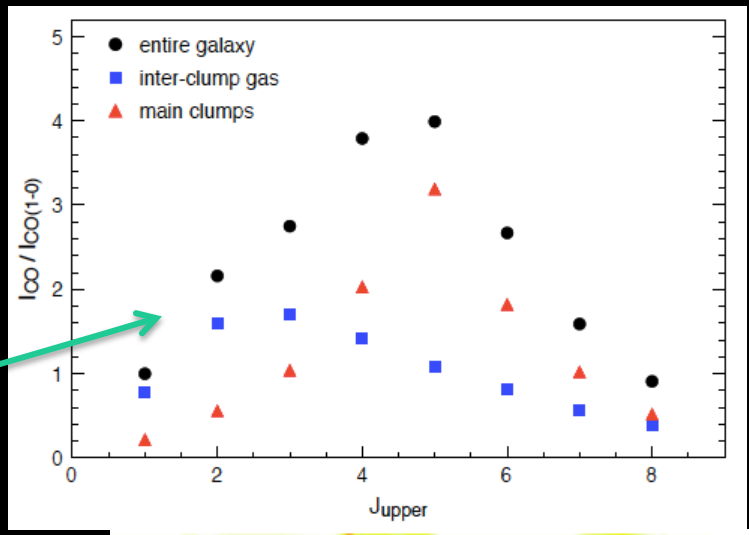
LVG modeling applied to AMR simulations:

- Relatively low-excitation galaxies (and high α_{CO})
- But high-excitation components in the clumps
- Turbulent heating + feedback heating in clumps

Bournaud, Daddi, Weiss et al. 2014

excitation molecular gas



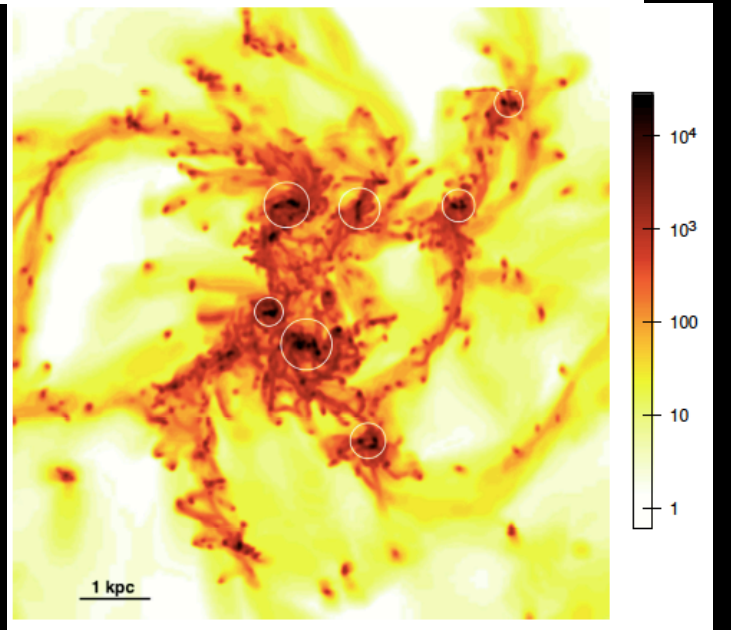


ns:

- Relatively low-excitation galaxies (and high α_{CO})
- But high-excitation components in the clumps
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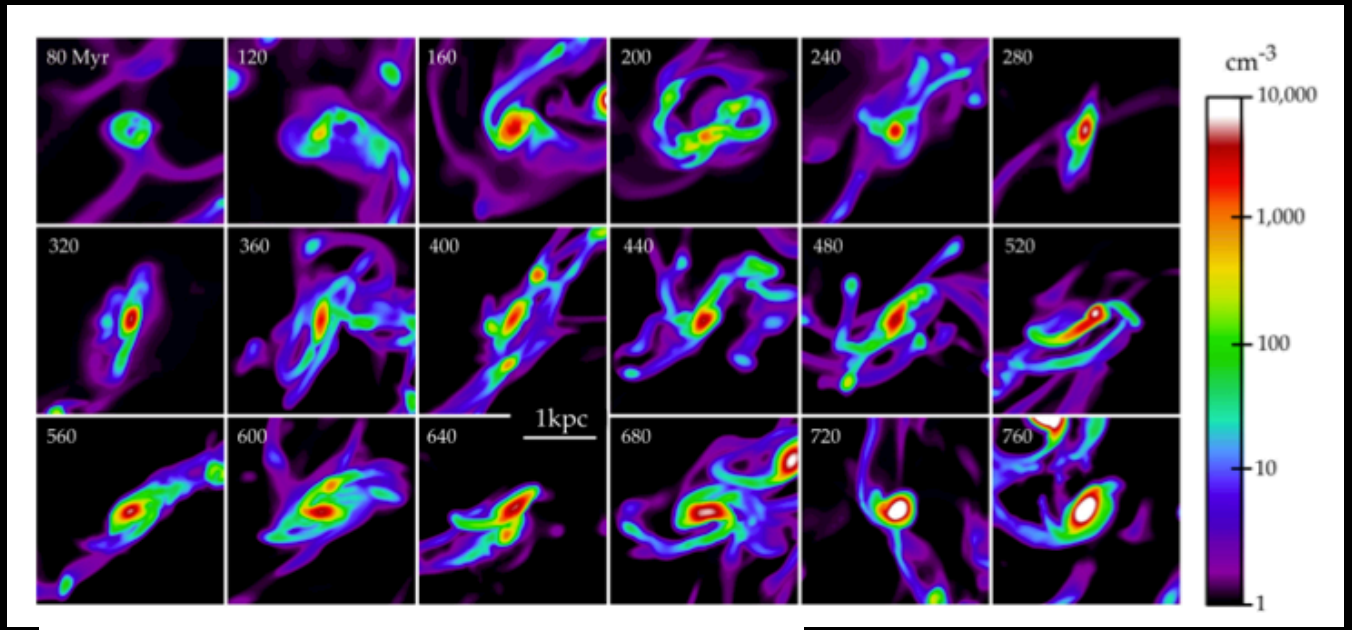
Consistent with new data (Daddi+2014)

Clumps = mini-starbursts, locally high-excitation, and launch galaxy-wide outflows



Bournaud, Daddi, Weiss et al. 2014

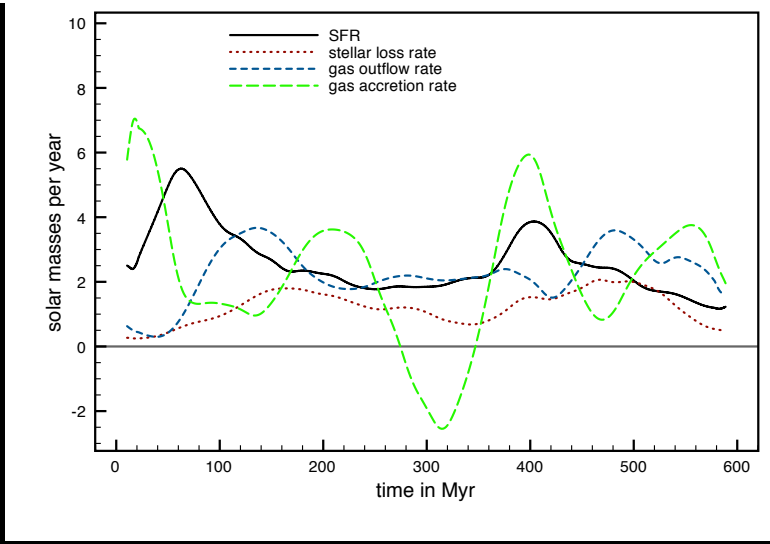
Re-accretion and clump survival



A long-lived clump seen face-on

Note how gas mass fluctuates : outflows, re-accretion

Aged stars also gradually leave the clump

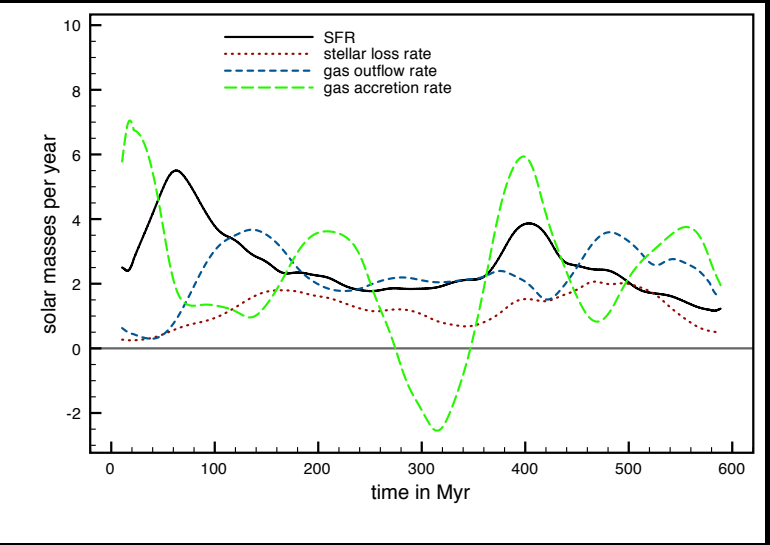


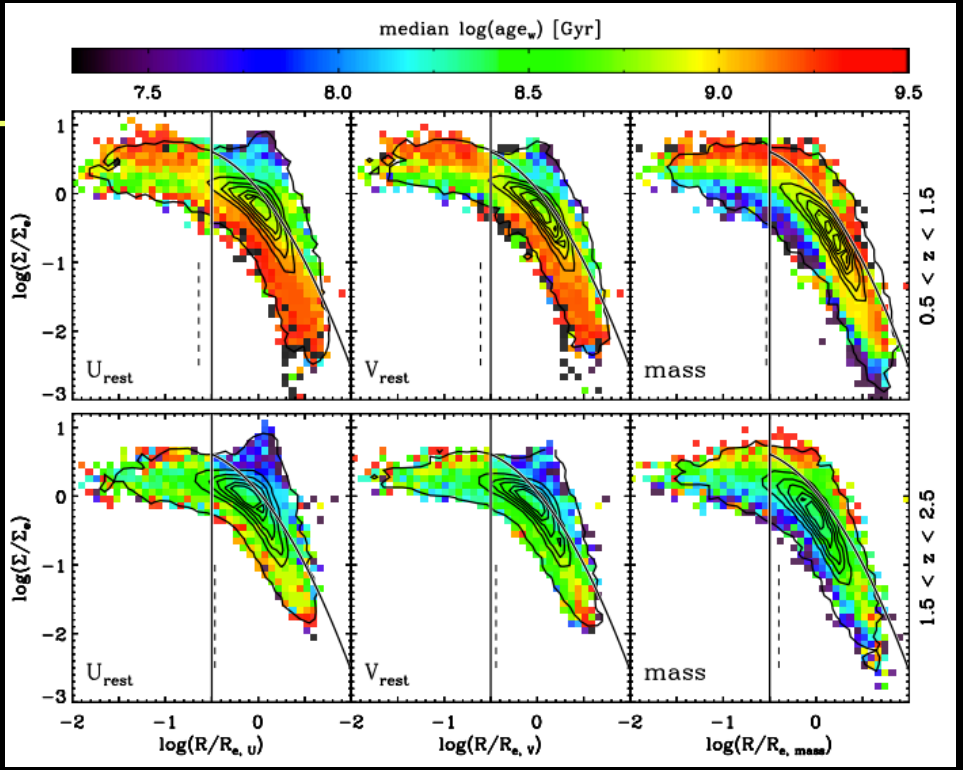
Clumps naturally re-accrete gas from the surrounding disk, at a rate compensating for the outflows and tidal effects.

Aged stars are also lost.

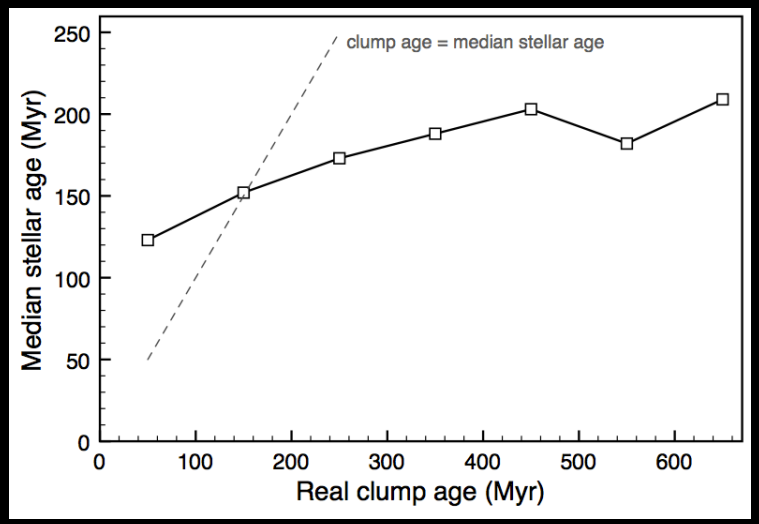
Bournaud, Perret, Renaud + 2014
See also Dekel & Krumholz 2013

Clump ages





Wuyts et al. 2012 : Observed clumps (large radius + high density) contain stellar ages up to 200Myr



The clump can reach 600Myr lifetimes, but stellar content of a clump saturates at an age of 150-200Myr at most

Bournaud, Perret, Renaud + 2014
See also Dekel & Krumholz 2013

Clump migration and bulge growth



Formation of an exponential spiral disk
and a central bulge

from the evolution of a gas-rich primordial disk

evolving through a clumpy phase



Models from Bournaud, Elmegreen & Elmegreen 2007

Typical star-forming galaxies at z=1-3

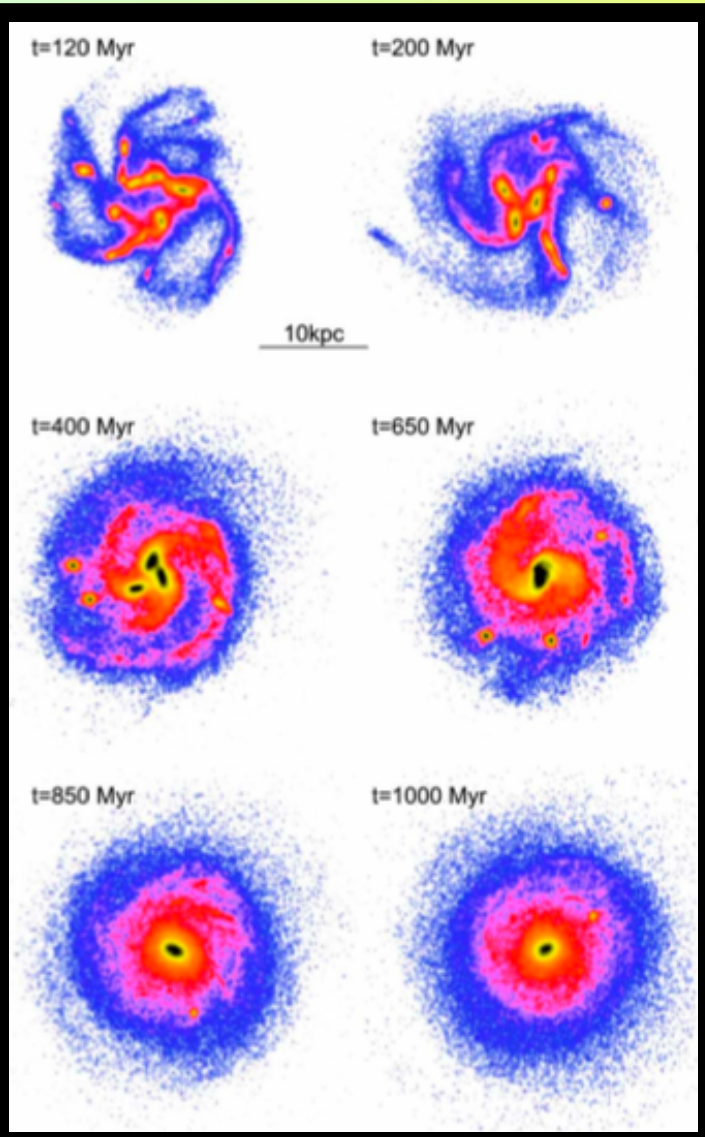
Irregular clumpy disks S.F in giant clumps of $10^{8\text{-}9} M_o$

Rotating + velocity dispersion around 50km s^{-1}

High gas fractions => unstable disks

Noguchi 99, Bournaud Elmegreen & Elmegreen 07

Clump migration and (classical) bulge growth



Giant clumps can interact,

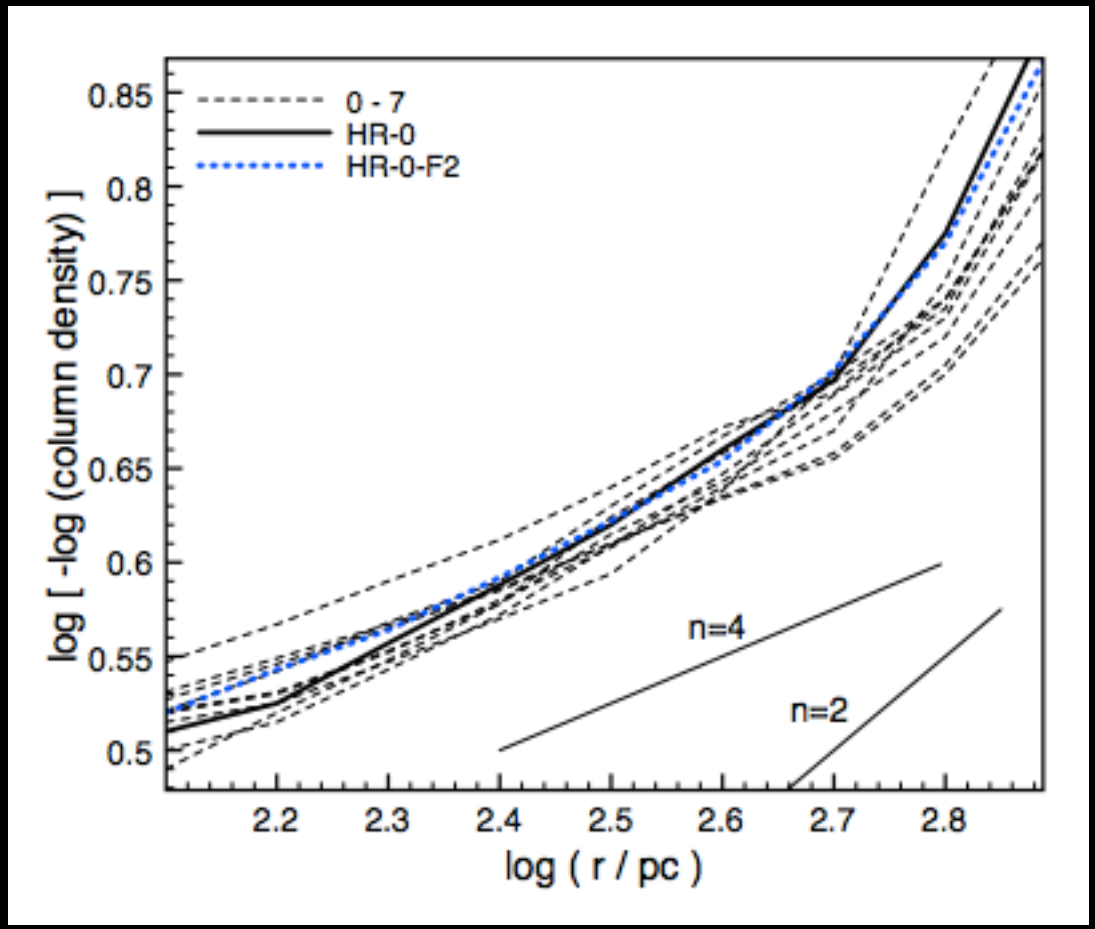
Migrate radially,

Coalesce in a central bulge,

Redistribute disk mass into an exponential profile

Noguchi 99, Immeli+04, Bournaud Elmegreen & Elmegreen 2007, Agertz Teyssier & Moore 2009

Clump migration and (classical) bulge growth

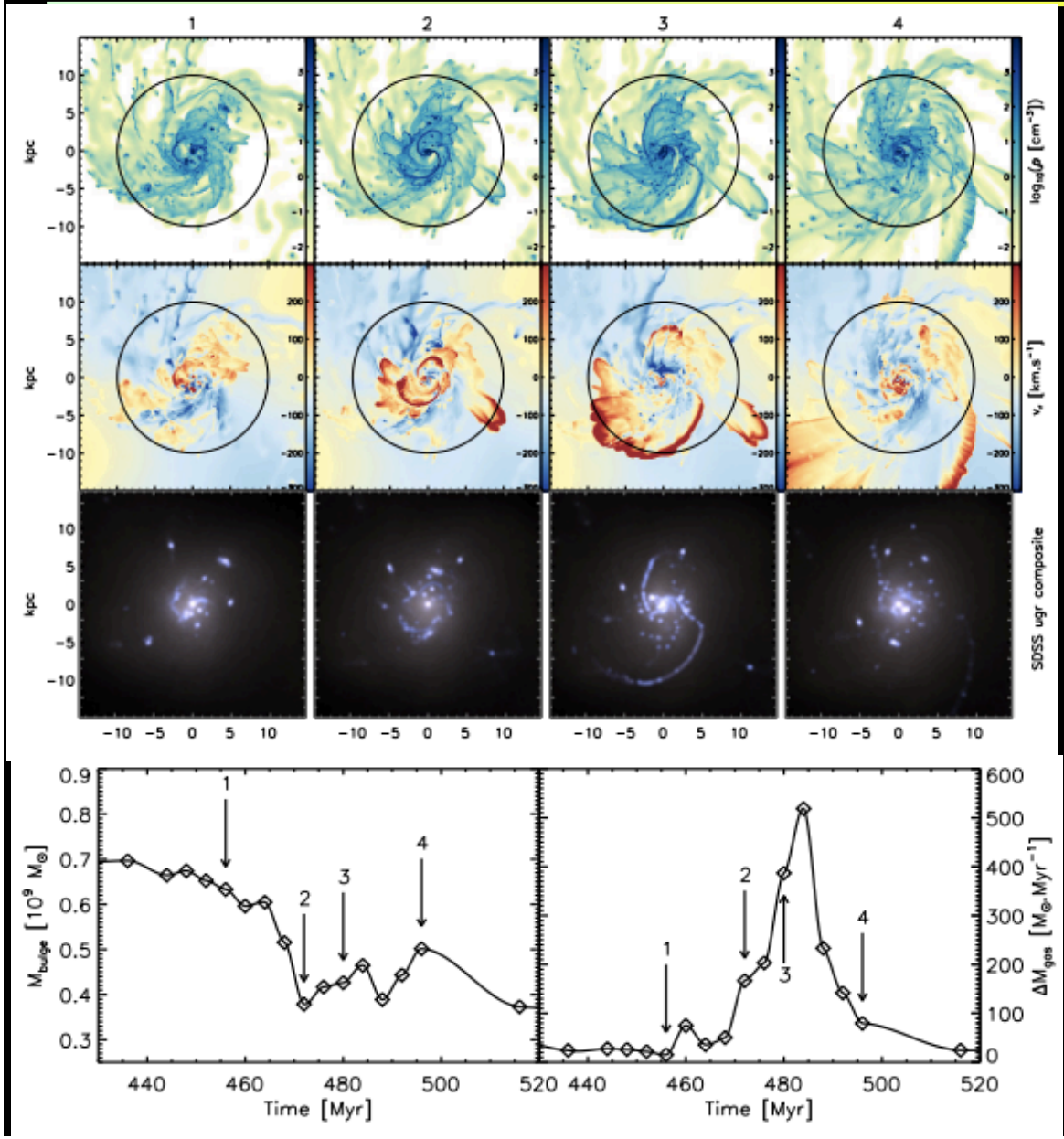


Clump-clump coalescence induces relaxation and formation of a high-Sersic index bulge

Here simulations with weak stellar feedback (SN only)

Elmegreen, Bournaud & Elmegreen 2008

Feedback and bulge growth regulation



« Complete » stellar feedback :

Gas-rich clumps merge centrally

⇒ Central starburst, feedback, expulsion of large gas amounts

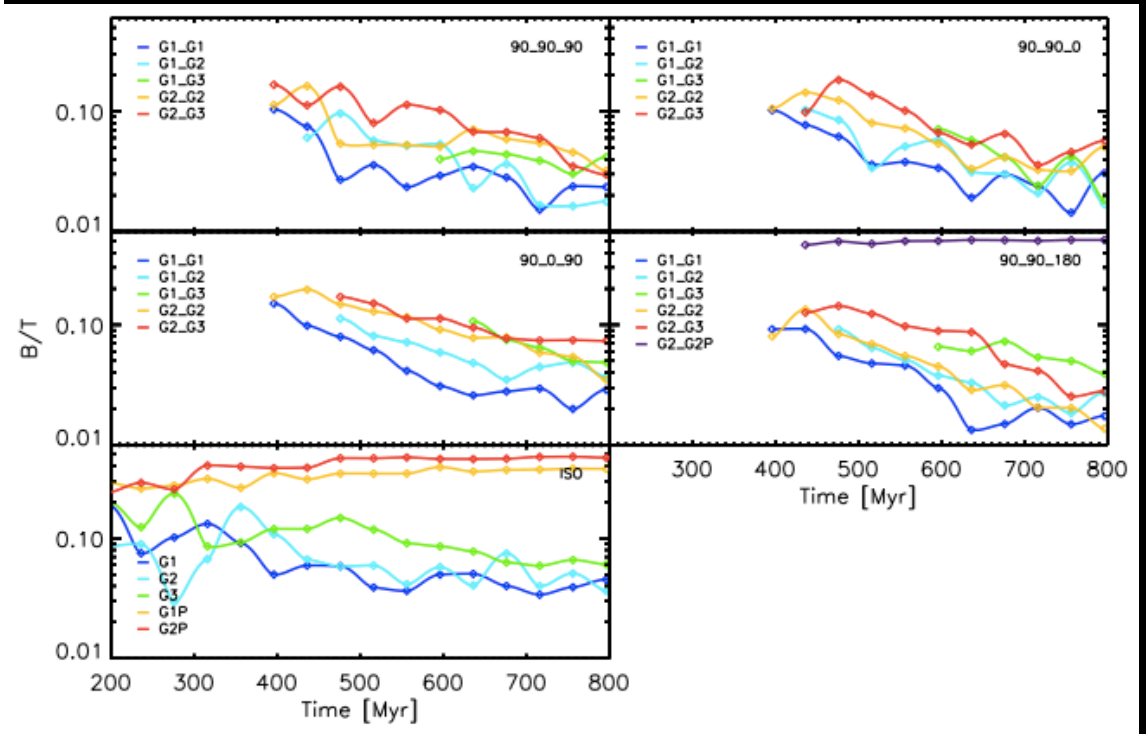
⇒ Relaxation and dispersion of the pre-existing bulge stars

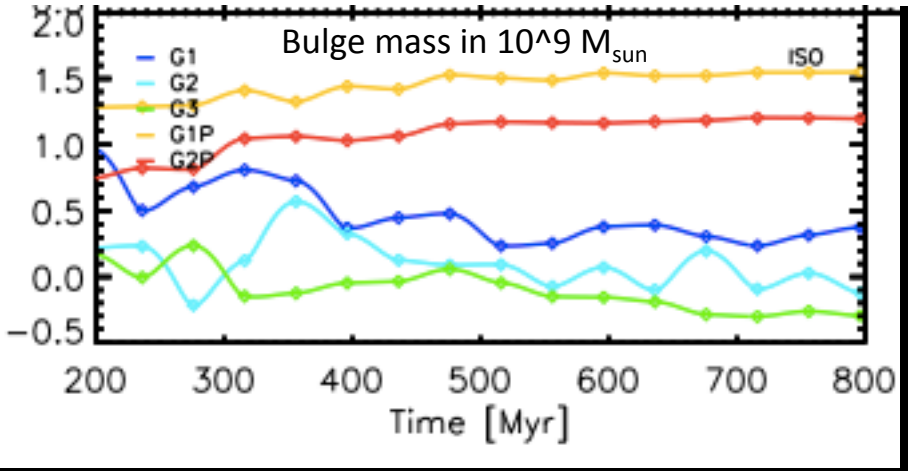
Feedback has two effects:
- keeps the clumps gas-rich
- Induces central relaxation

=> The bulge mass saturates at ~10^9 M_{sun} in galaxies with Ms_{tars}=3x10^10

Perret et al. 2014, 2015

Feedback and bulge growth regulation





« Complete » stellar feedback :

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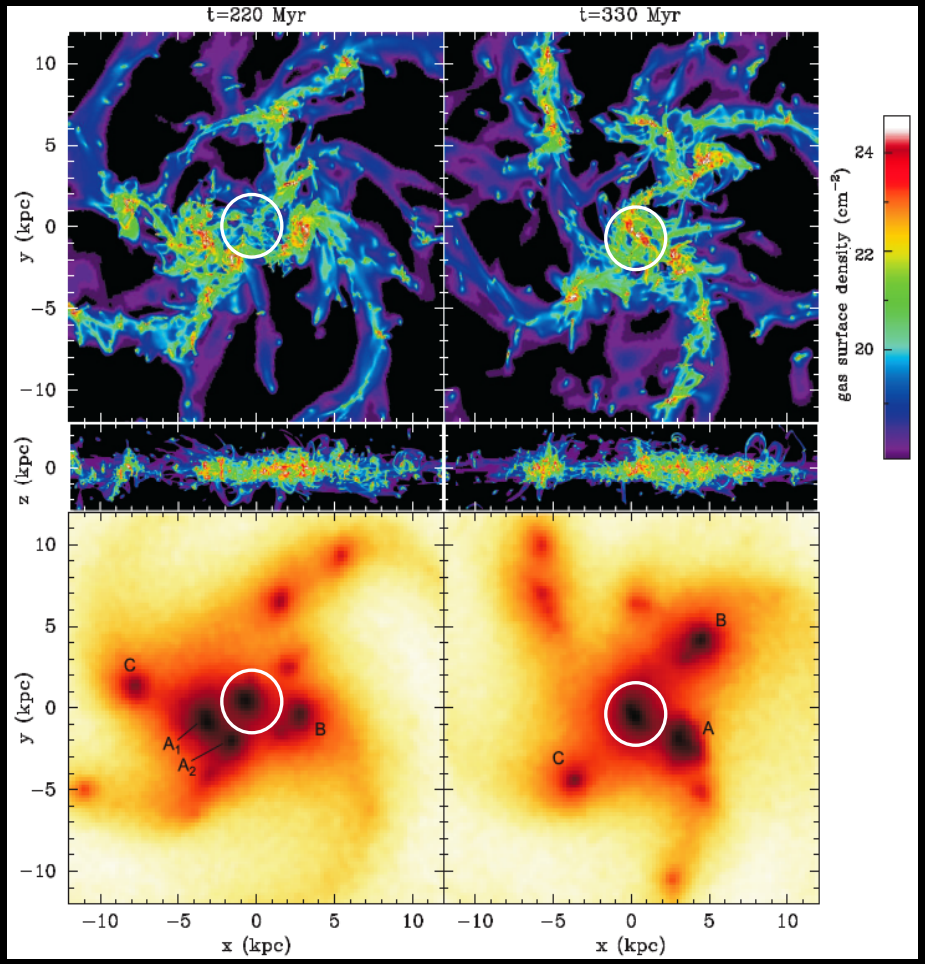
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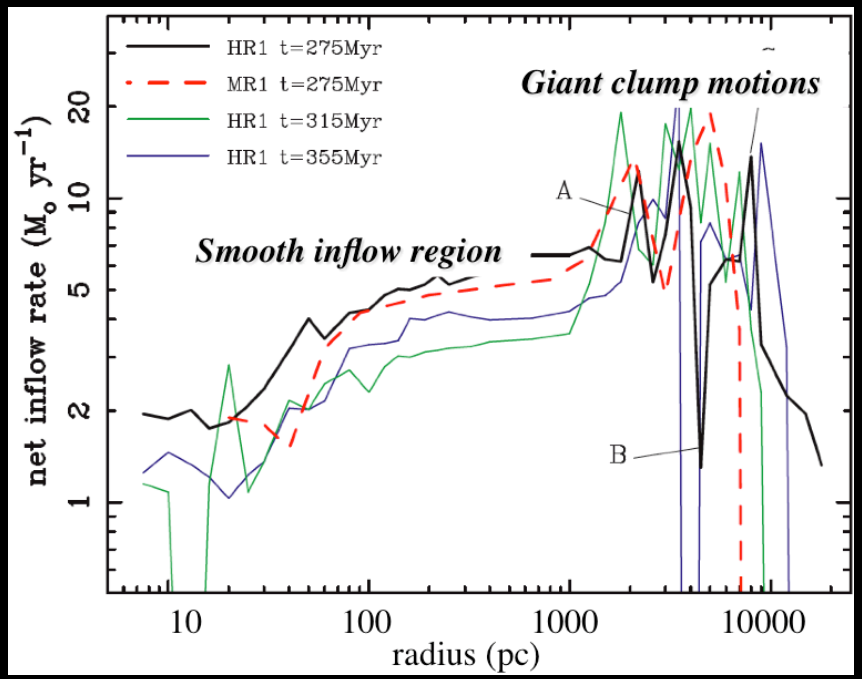
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- keeps the clumps gas-rich
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=> The bulge mass saturates at ~10^9 M$_{sun}$ in galaxies with Ms$_{tars}$=3x10^10

Perret et al. 2014, 2015

Clump-driven inflow and (pseudo) bulge growth

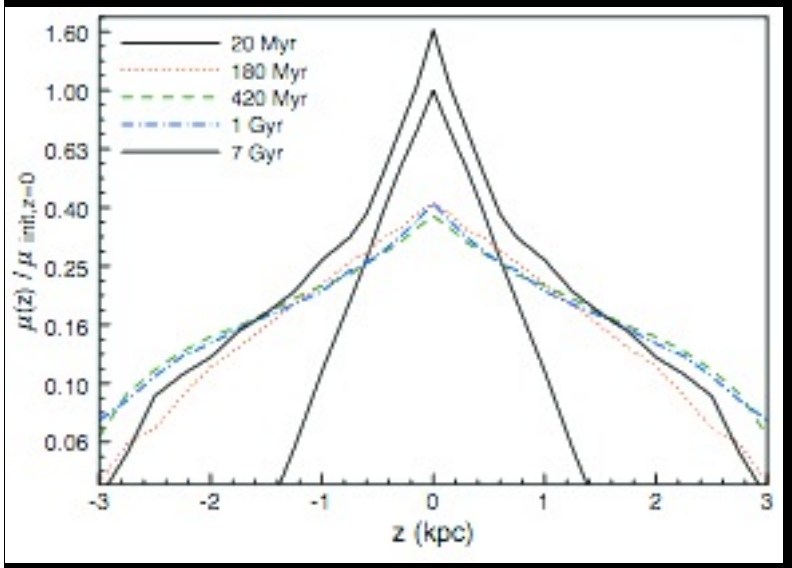


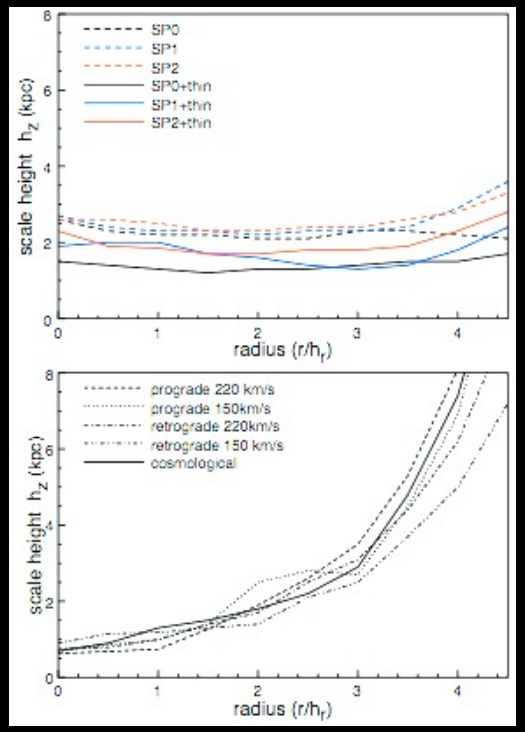


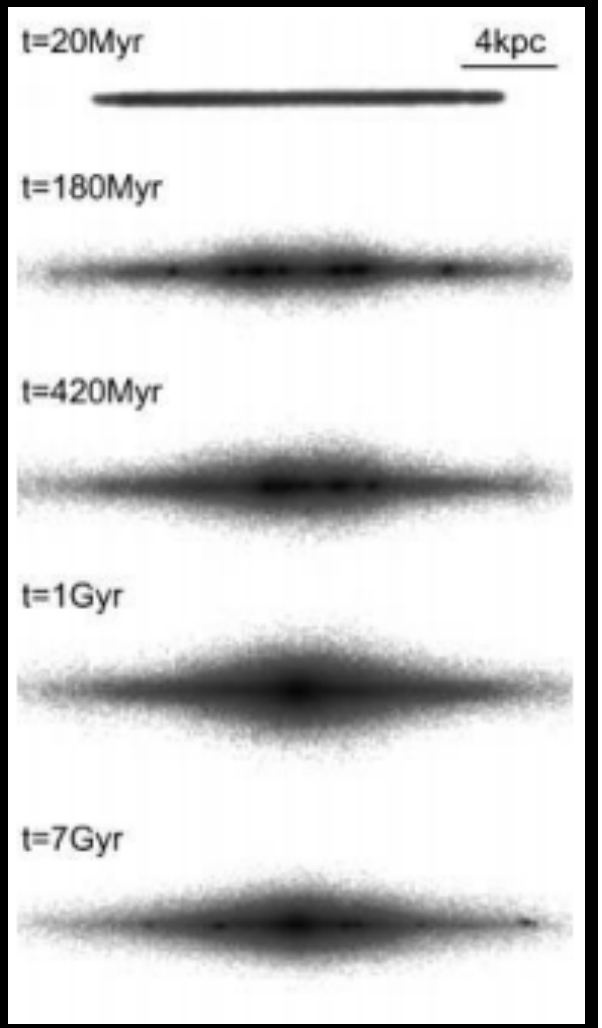
- Inflow rate compensates for turbulent losses.
- 10Msolar/yr in the disk.
- 1-2Msolar/yr at the center, in spite of gas consumption.

Bournaud Dekel et al. 2012

Thick disks grow along with bulges





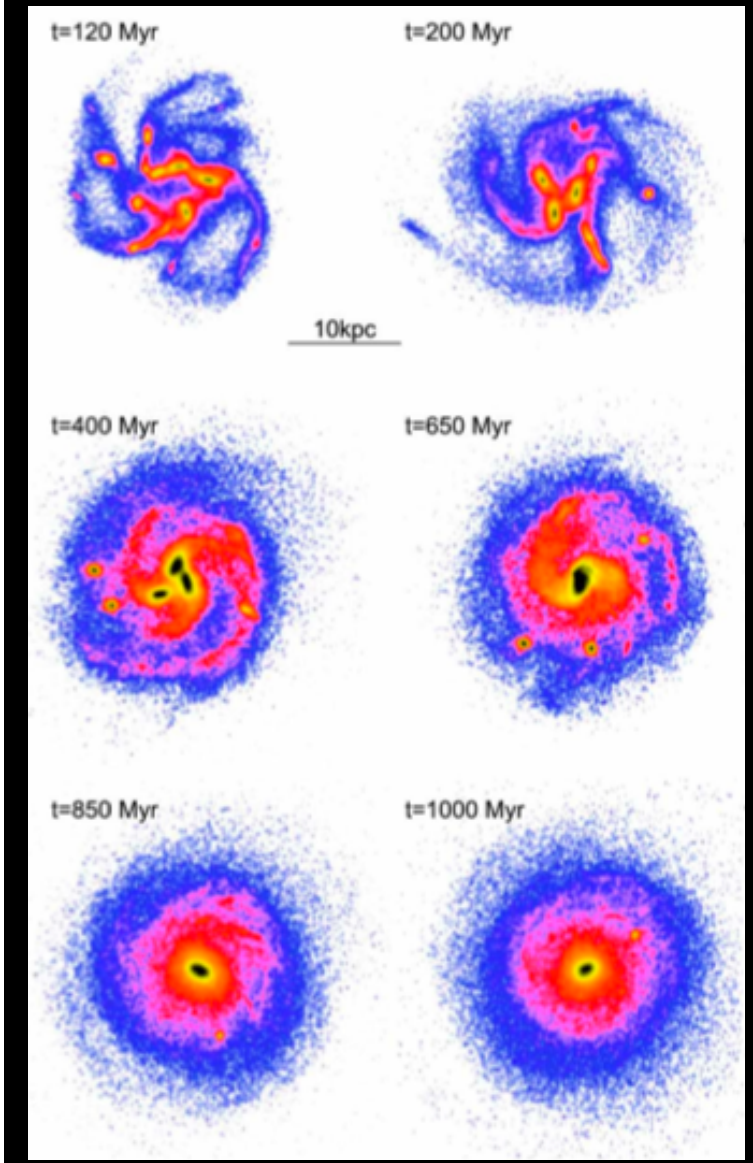


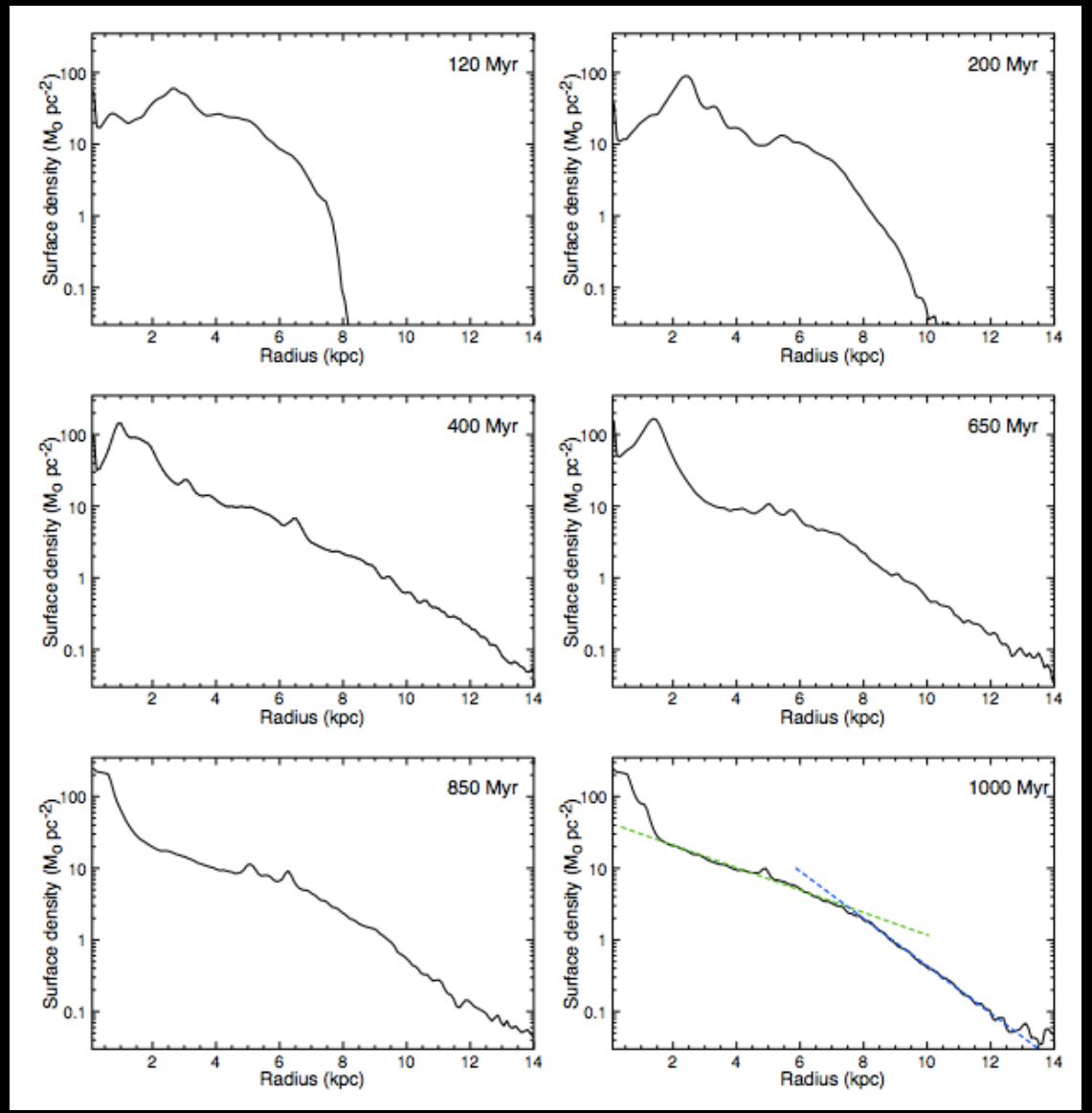
- Vertical scattering by the dense clumps
- Stars formed before/during the clumpy phase build a thick disk
- After the instability phase star formation in a thin disk

⇒ Thick+thin disk as a double component – not just an extended tail
⇒ Thick disk present at all radii, even central regions

Bournaud Elmegreen & Martig 2009

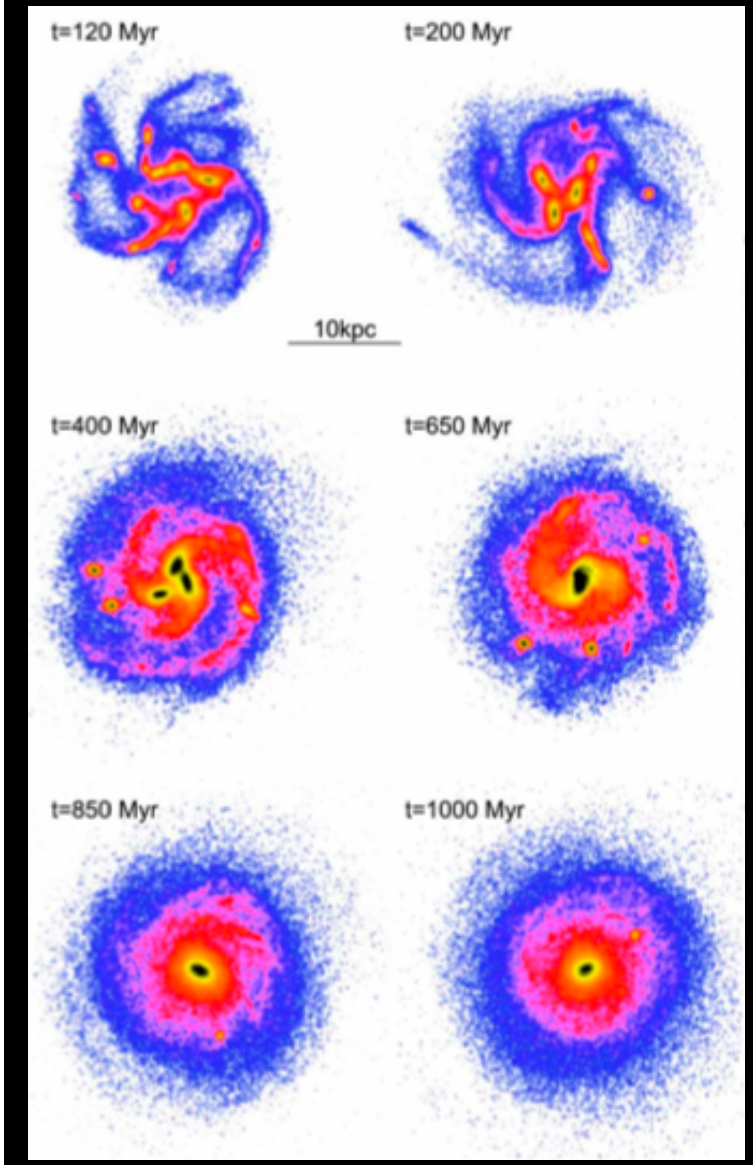
Exponential disk formation

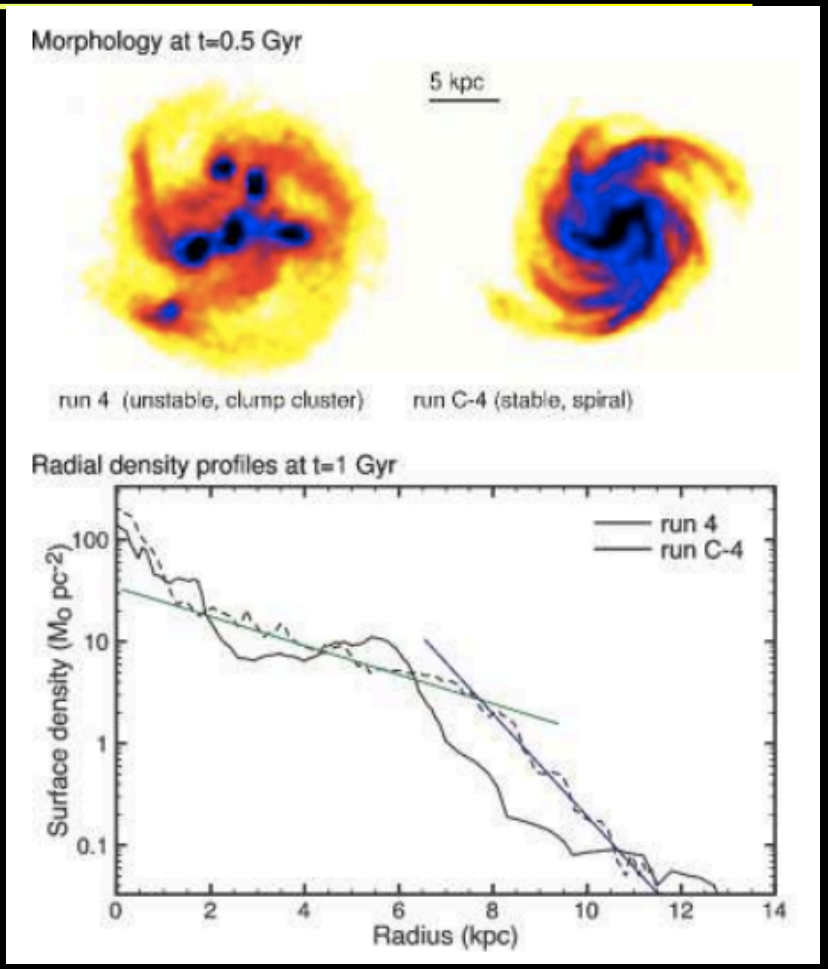




Double exponential for both the thin and the thick disk Bournaud, Elmegreen & Elmegreen 2007

Exponential disk formation

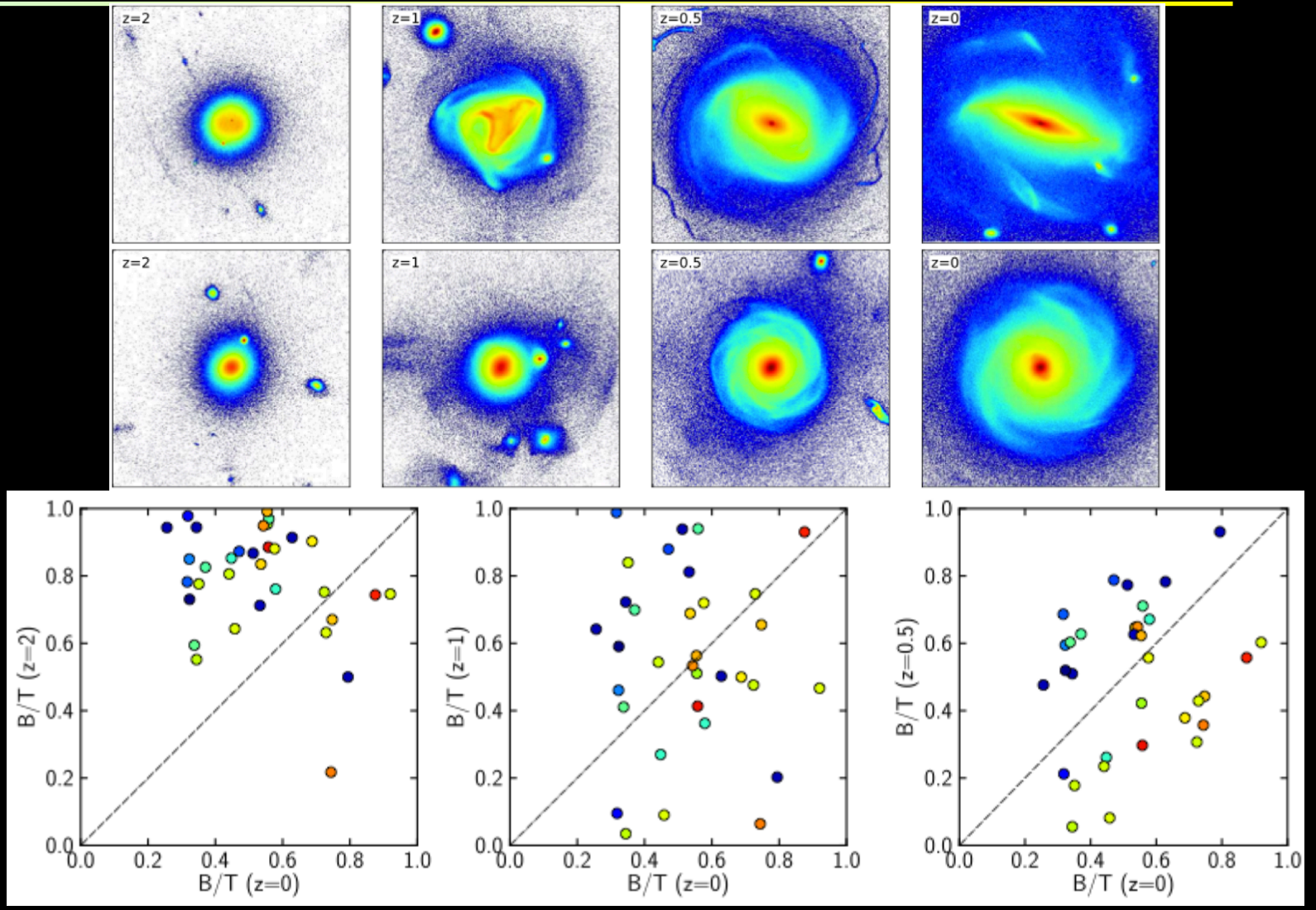




Density waves (bars and spirals) do not create exponentiels on similar timescales

Bournaud, Elmegreen & Elmegreen 2007

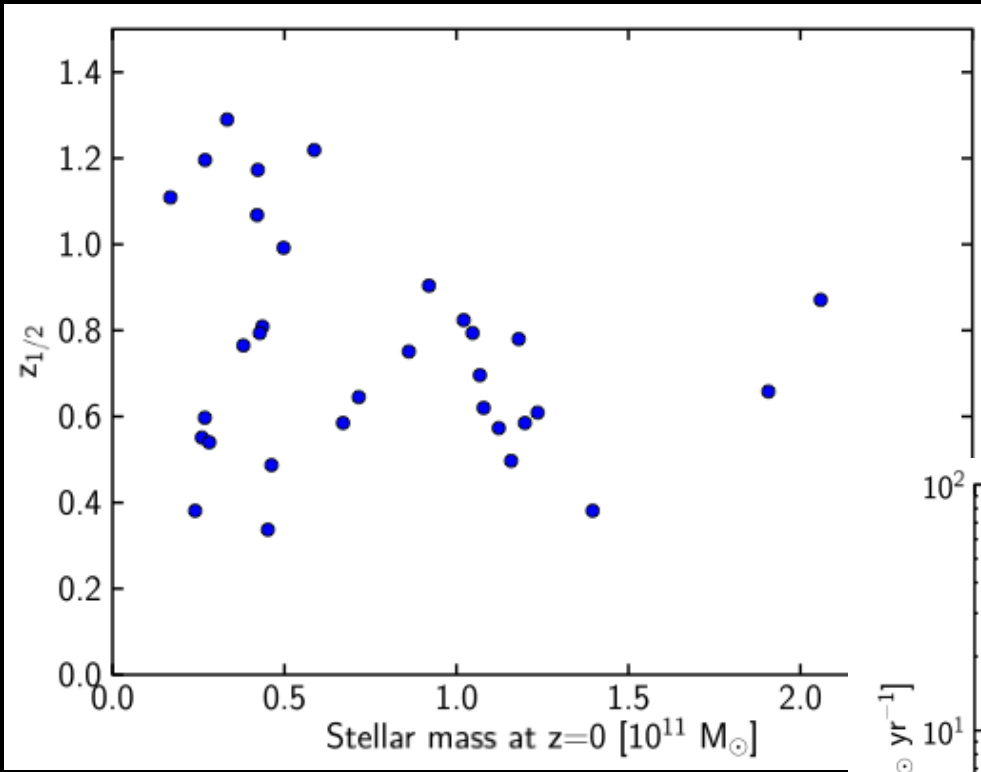
Transition from high-z irregular to modern spirals



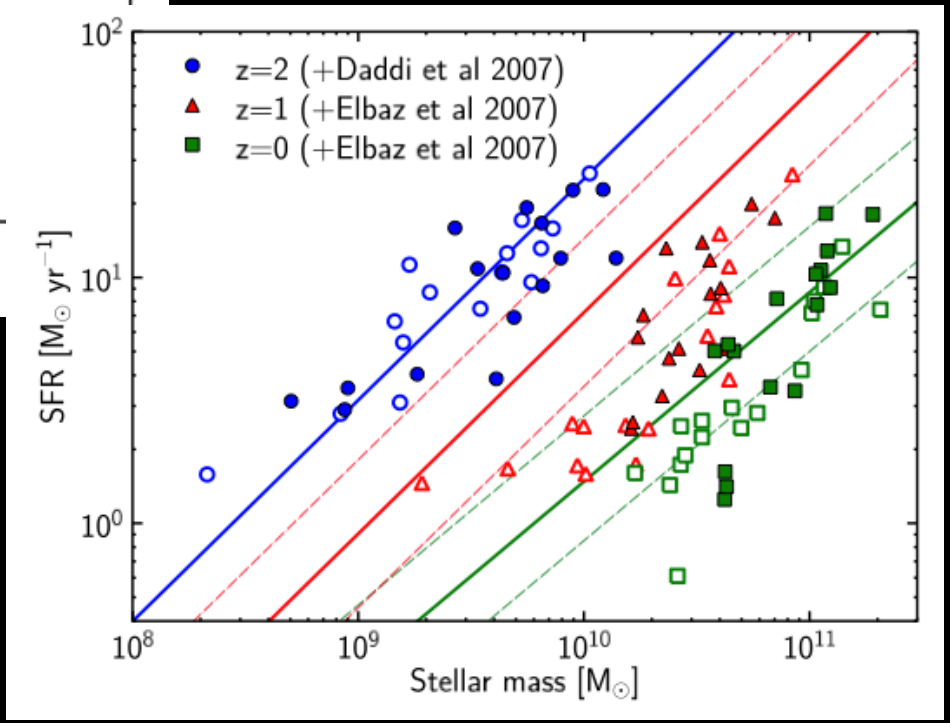
There is little dorrelation between the z=2 structure (B/T) and the z=0 one.
Final morphology about stabilized at z=0.7

Martig, Bournaud, Teyssier & Dekel 2012

Transition from high-z irregular to modern spirals



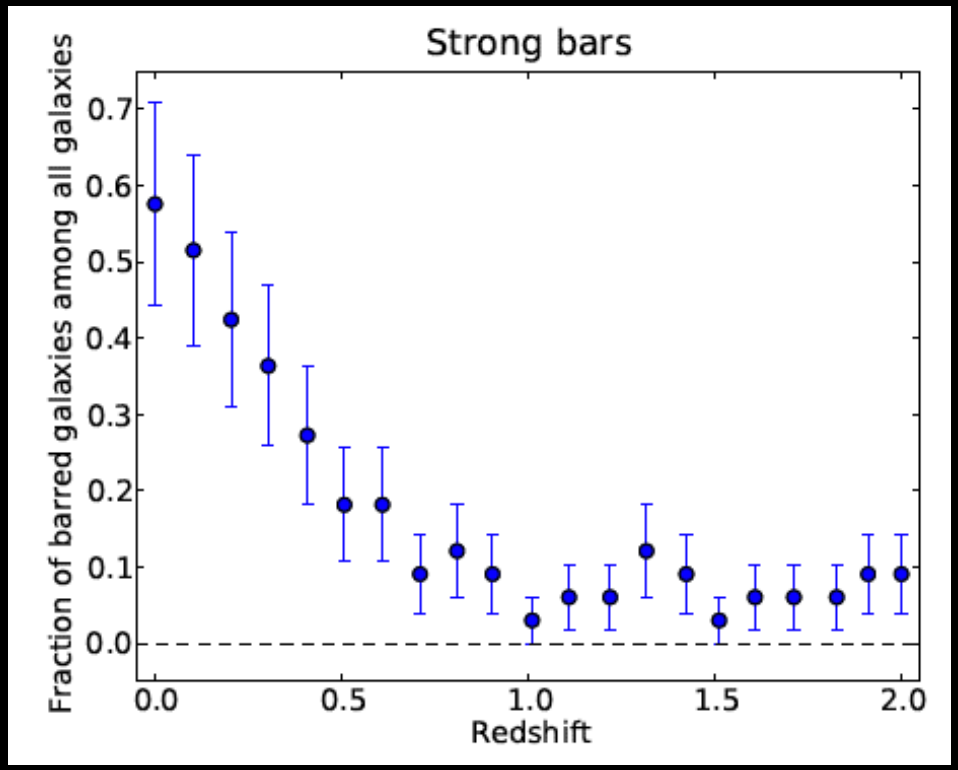
Galaxies reach 50% of their final stellar mass around z=0.7



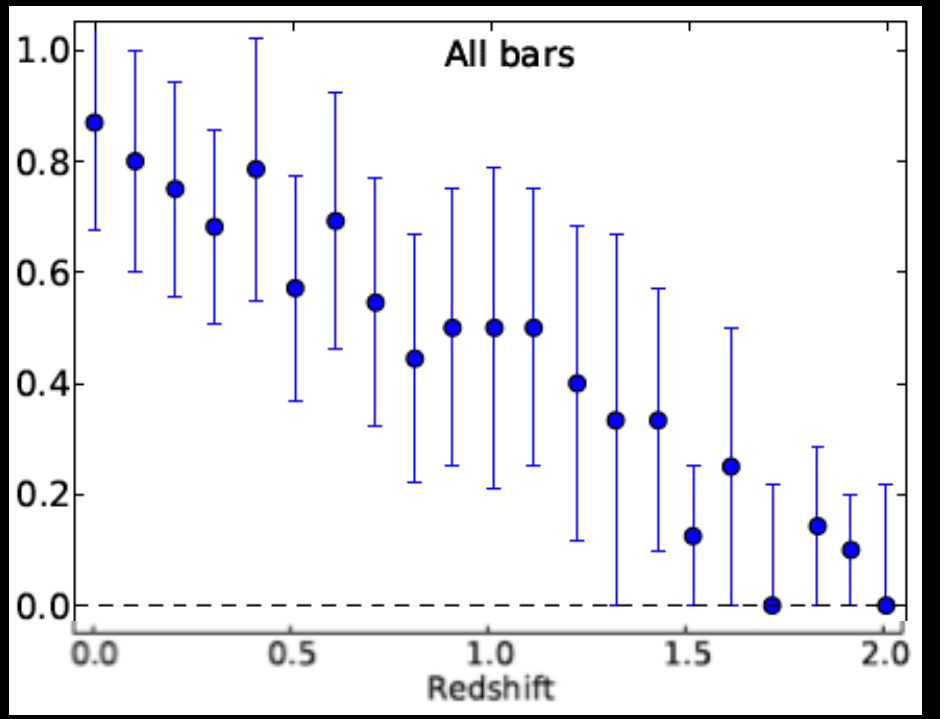
SSFR history almost realistic
(slightly too fast at z=2-z=1)

Martig, Bournaud, Teyssier & Dekel 2012

The bar fraction history



Strong enough to detect
In COSMOS, CANDELS, etc

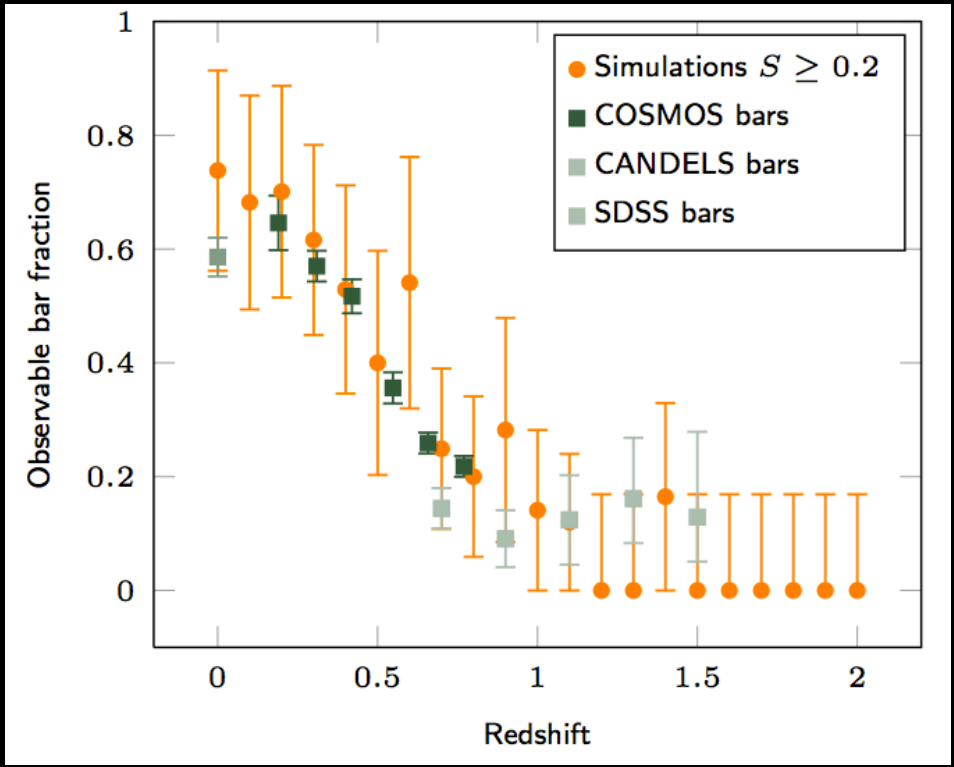


All bars

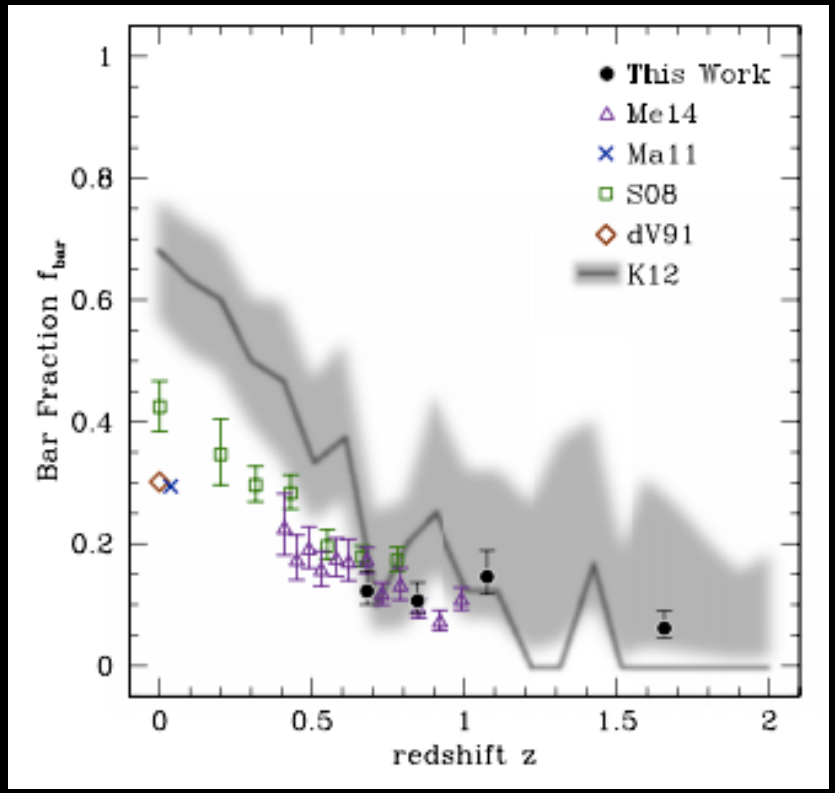
- Bars very rare at z=2
- Some bars between z=1 and z=2, but rarely observable (very weak/short)
- Rapid increase in the fraction of observable/strong bars after z=1

Kraljic et al. 2012

The bar fraction history



COSMOS (Sheth+2008)
Candels (Herrington+2014)

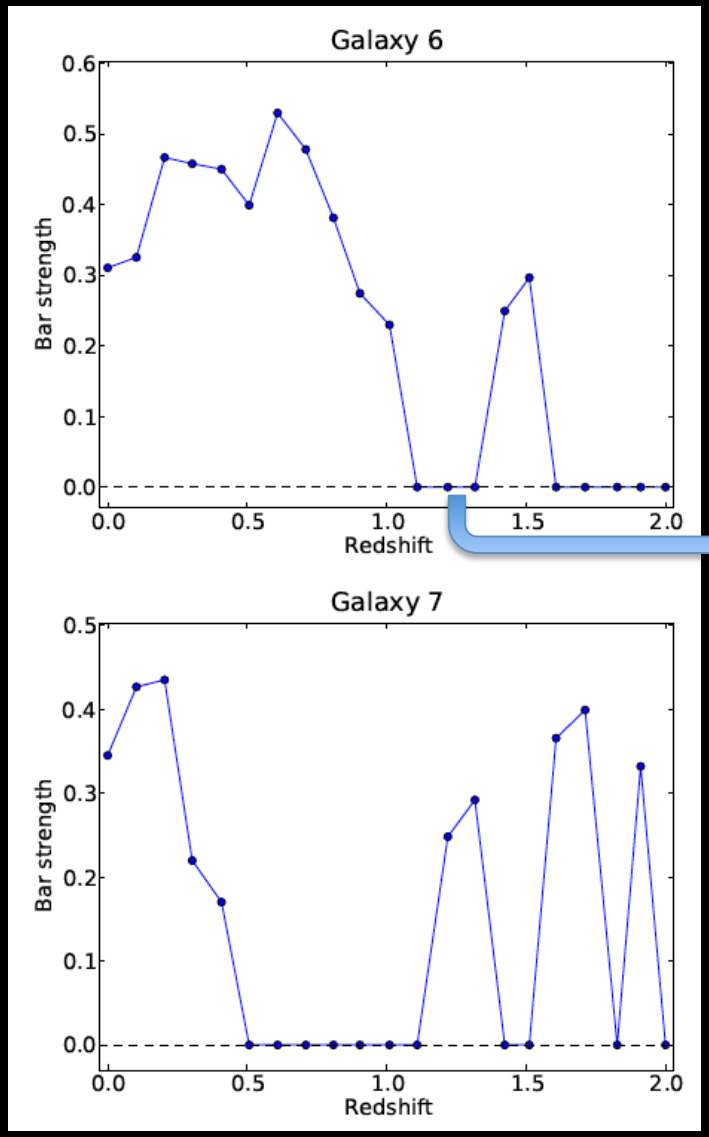


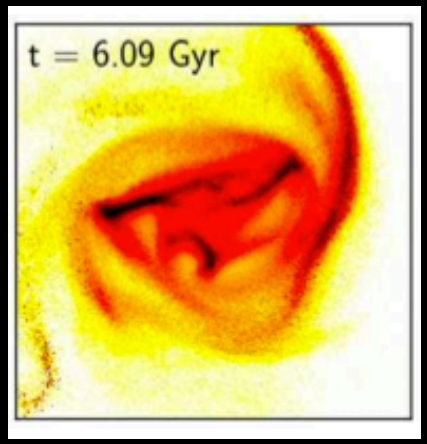
Candels-Galaxy Zoo (Simons+2014)

- Bars very rare at z=2
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Kraljic et al. 2012

The bar fraction history



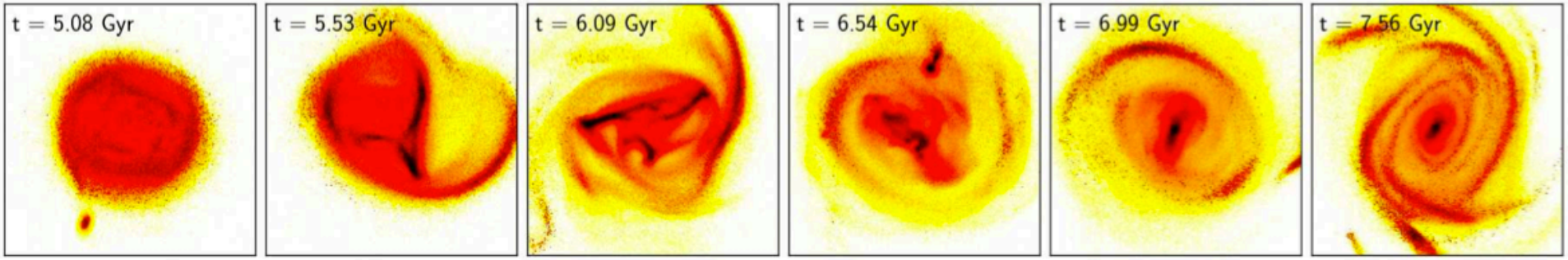


- Bars at z>1 are transient (if any)
- Destroyed mostly by mergers, and by clumpy disk instabilities

Too much gas accretion => disk gets
Very gas-rich => fragments into clumps

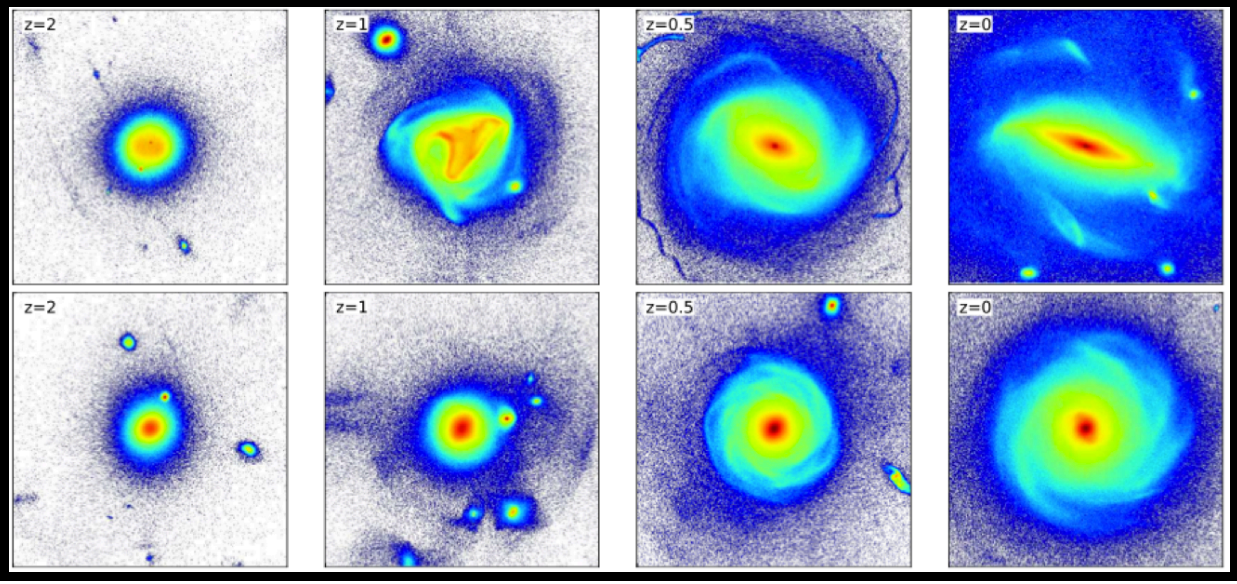
Kraljic et al. 2012

Transition from high-z irregular to modern spirals



The epoch at which bars really emerge (around z=0.8 for MW mass) is the epoch at which the rate of external infall + mergers is low enough to have a long-lived thin disk.

Earlier on: rapid gas accretion => clumps, plus mergers, so no strong bar has time to form
Later on: most galaxies will grow a bar (and it seems to survive down to z=0, but see later)

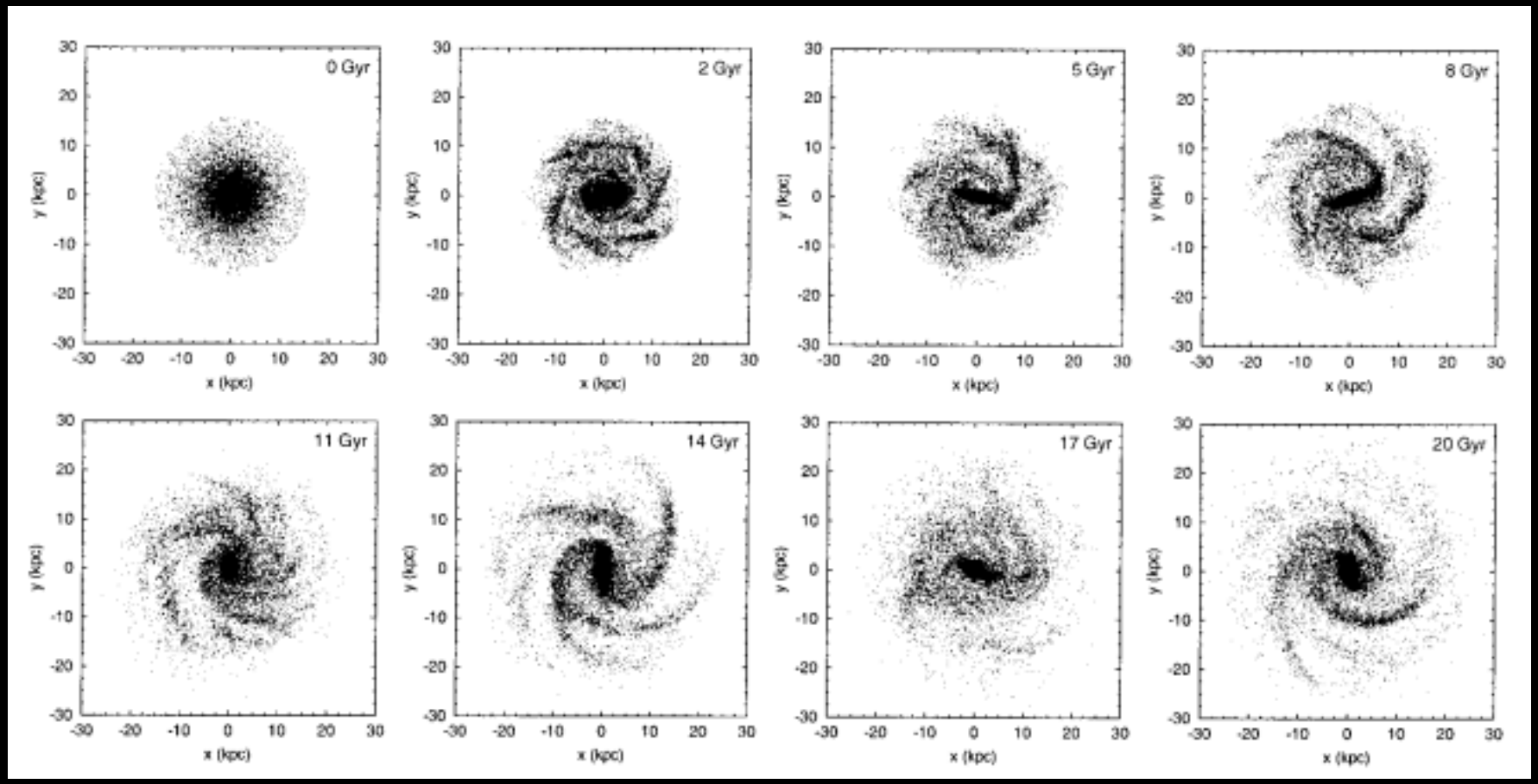


Transition between an early *violent* phase (clumps, mergers) and a late *secular* phase

Transition occurs when mass doubling time ~ 3 disk rotation

Kraljic et al. 2012

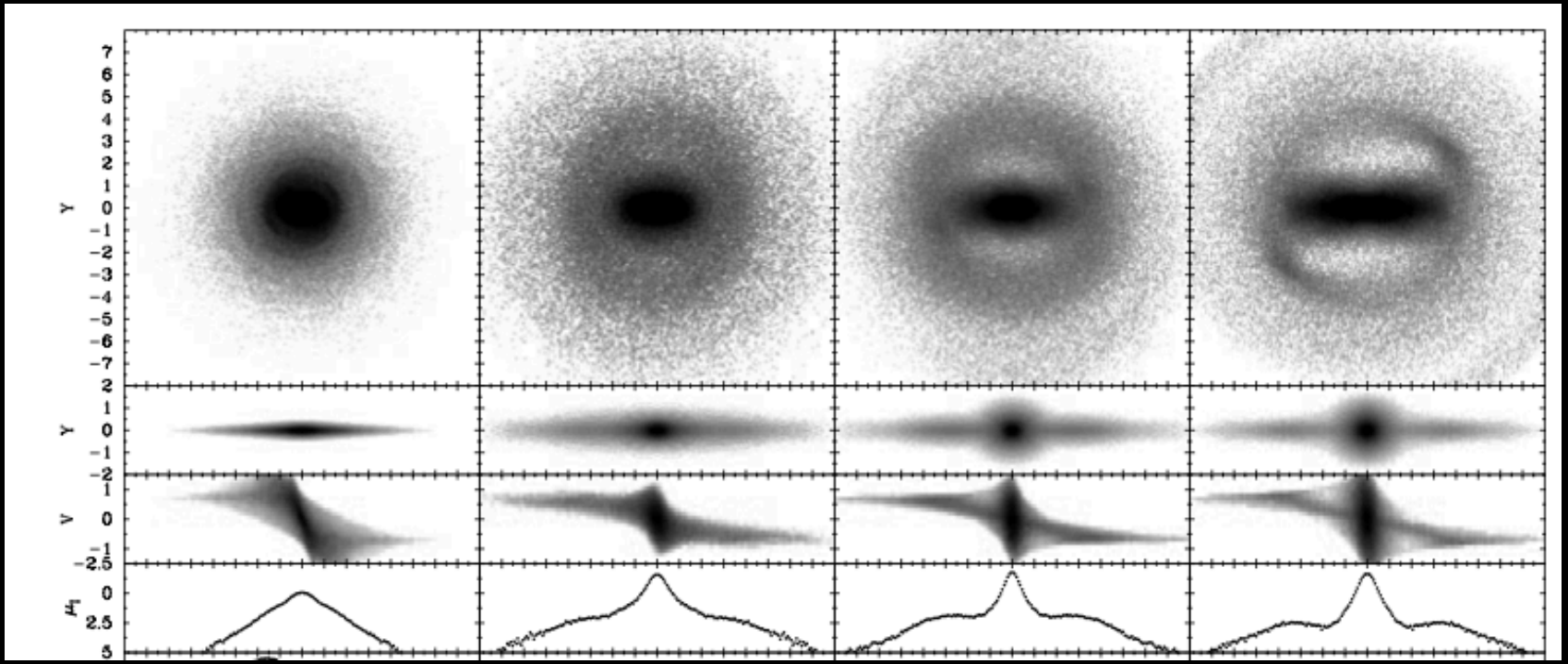
Bars – long lived or not ?



Bournaud & Combes 2002

External infall – but initial galaxy already massive, stable (Q>1 overall), not like z=2 systems

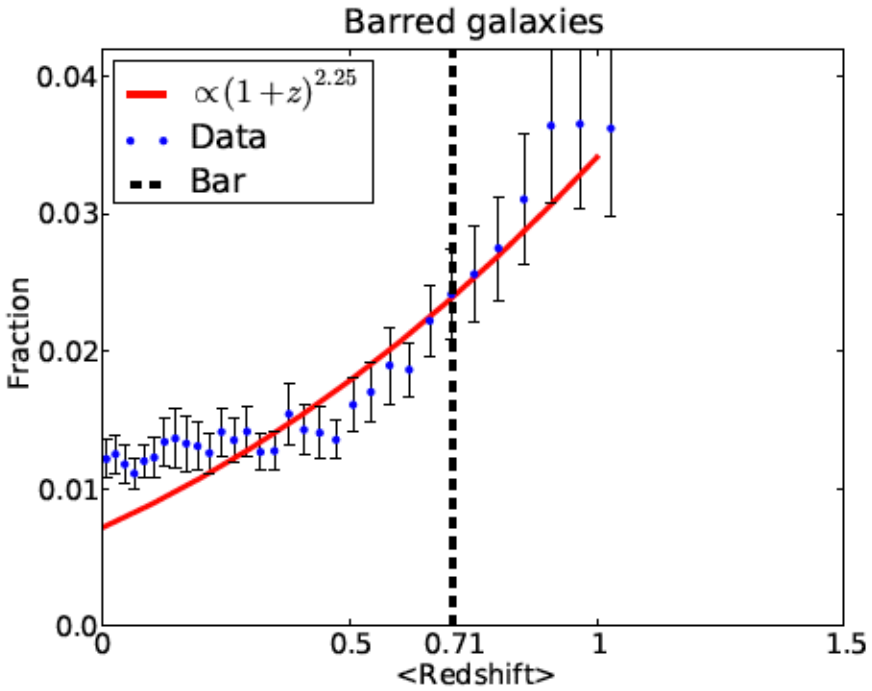
Bars and pseudo-bulge growth

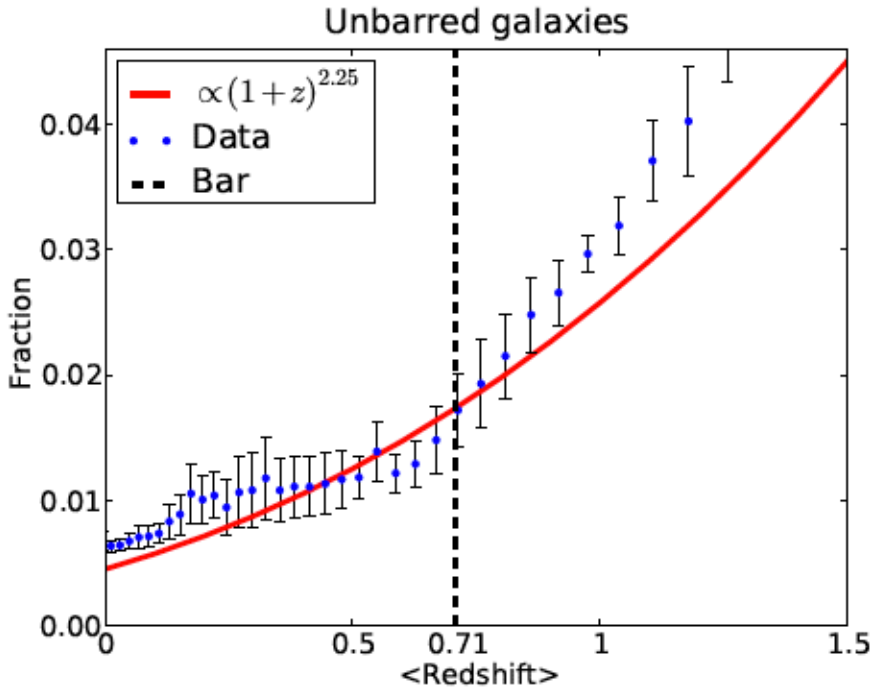


Pfenniger, Combes, Norman… 90-95; Bureau & Athanassoula 2005, …

- Fraction of the (pseudo)-bulge formed in redshift bins
- Significant growth at z<0.5, stronger in barred galaxies
- Bars have a measurable contribution, but “only” 20% or so.

Bars and pseudo-bulge growth in cosmological context



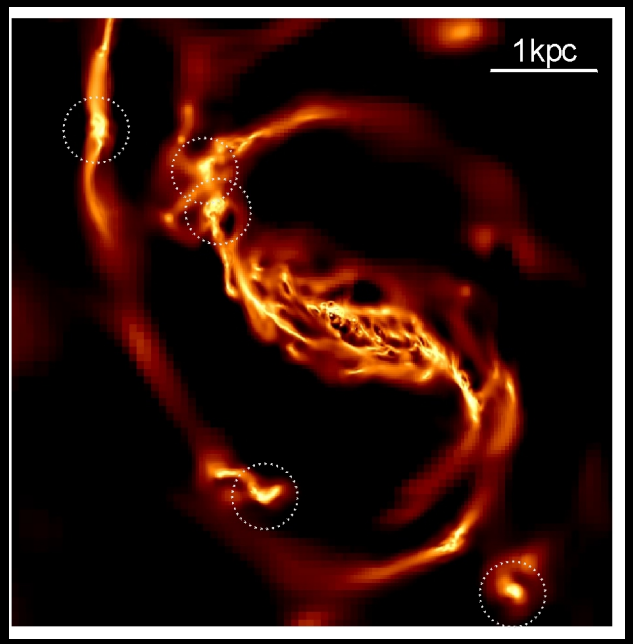


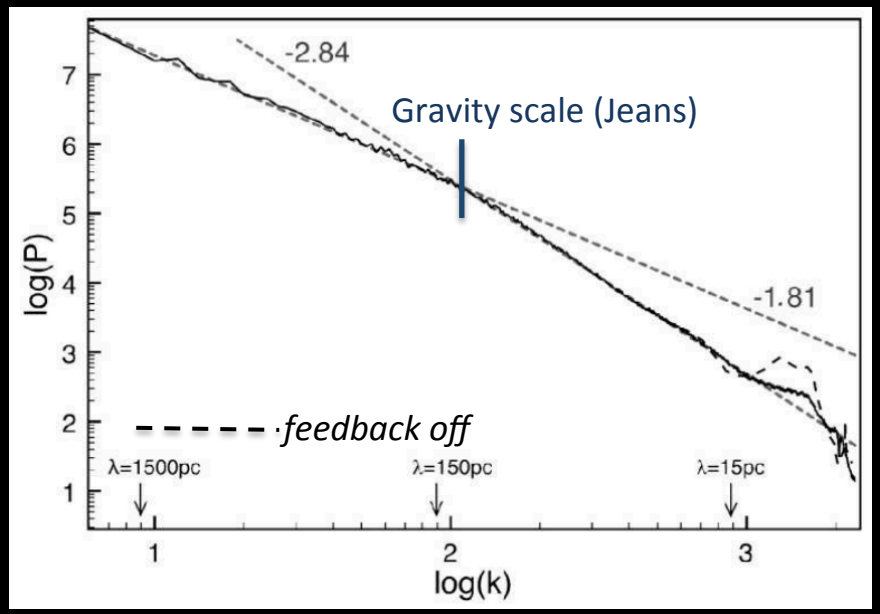
- Plots show the epoch at which stars found in the (pseudo-)bulge at z=0 start to belong to the bulge (i.e. birth time or epogh of disk => bulge conversion)

- Global trend follows the infall rate (mergers, cold streams feeding unstable disks, etc)

- Barred galaxies show an excess in the late secular phase => more stars brought to the bulge component in the late barred secular phase
  statistically robust, but ~15% of the bulge mass budget.

Back to feedback : SFE regulation



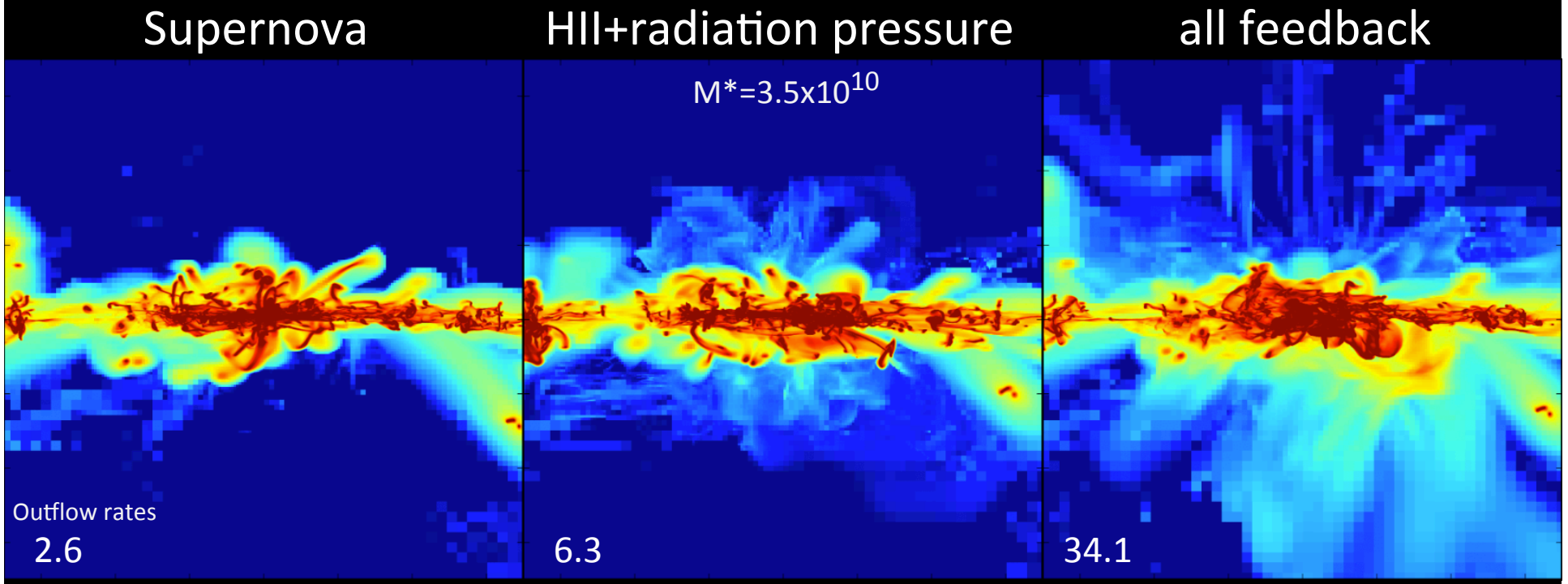


Bournaud+10 simulation of M33-mass disk

- Simulations produce a realistic power spectrum
- **Stellar feedback in only a regulation process to preserve a steady state in the turbulence cascade**
- **Turbulence cascade from gravity + hydro instabilities**

Back to feedback : do winds imply quenching ?

Three runs with different feedback processes, all evolved for 80Myr

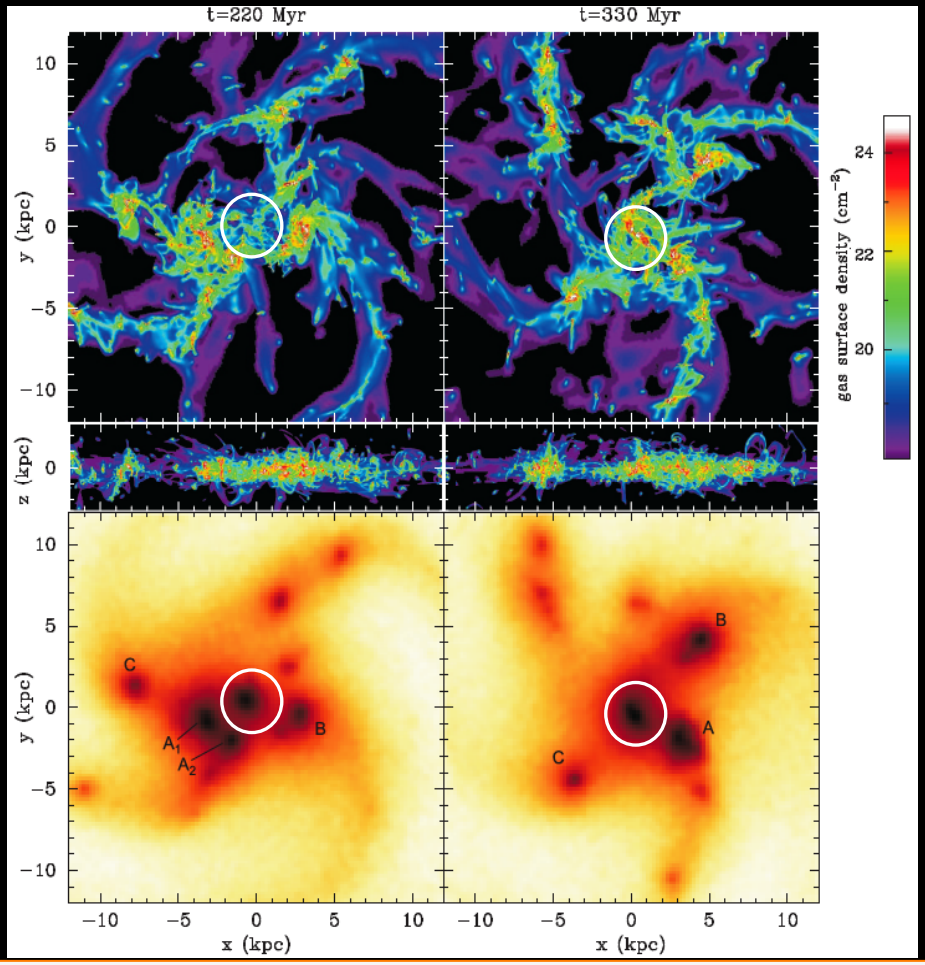


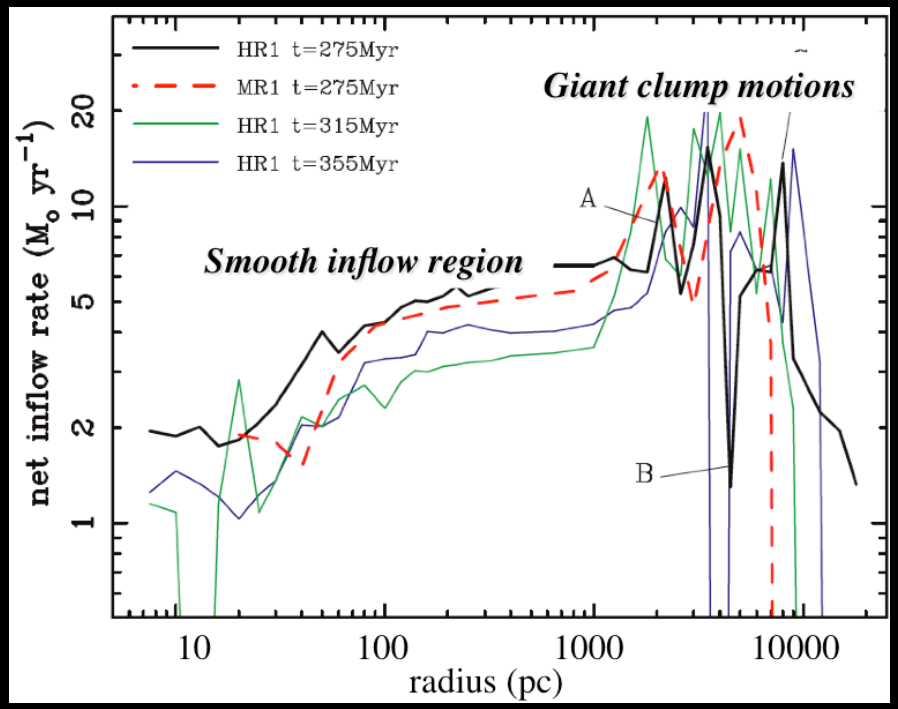
Outflow rate rapidly reaches 20-40 Msun/yr = SFR

Supernovae alone don’t do much

Feedback : AGN in “normal” galaxies

Torquing of inter-clump material and smaller clumps



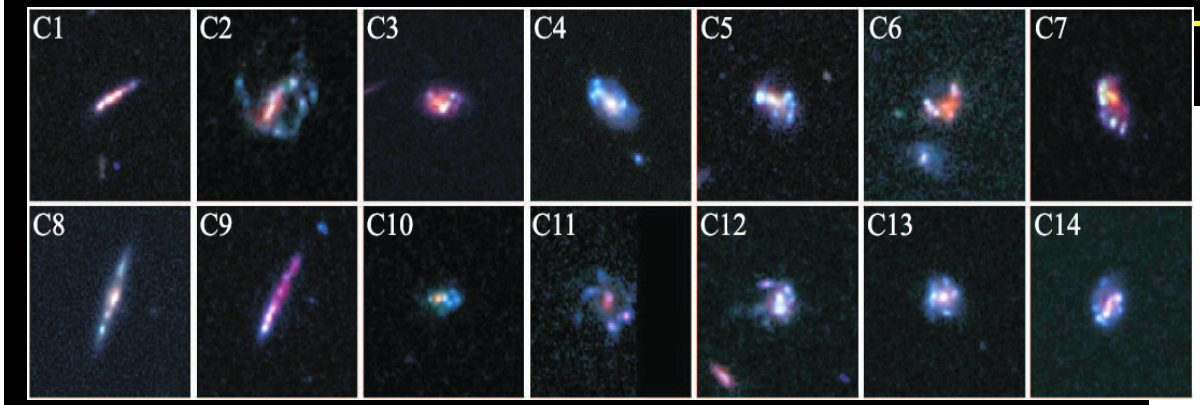


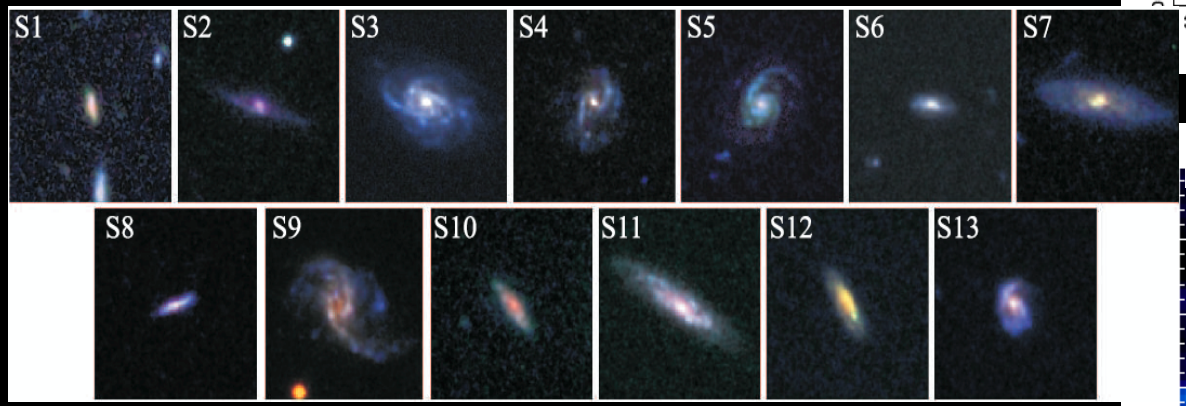
- Inflow rate compensates for turbulent losses.
- 10Msolar/yr in the disk.
- 1-2Msolar/yr at the center, in spite of gas consumption.

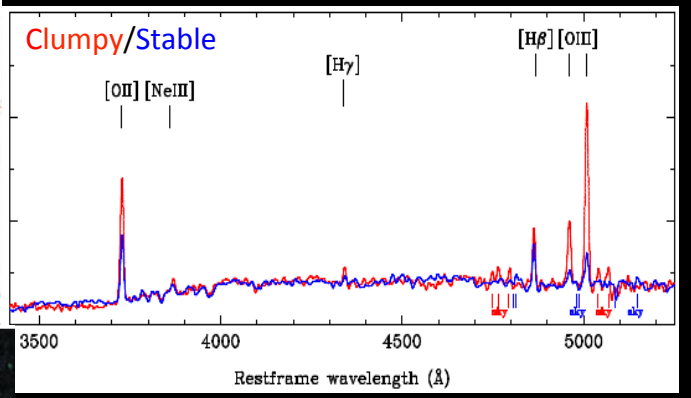
Possible SMBH/AGN feeding from the inflow

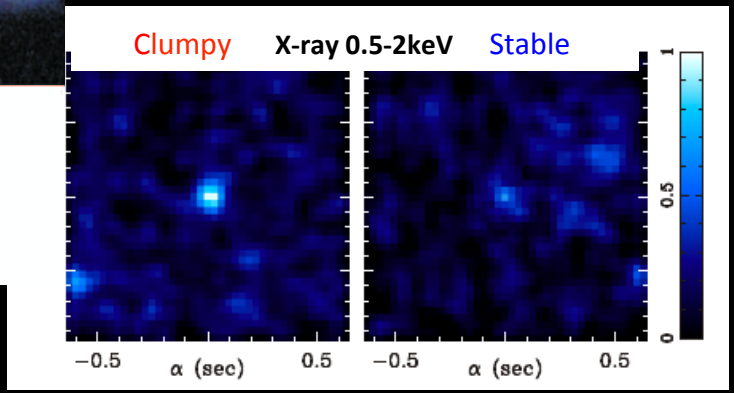
Bournaud Dekel Teyssier et al. 2012

Feedback : AGN in “normal” galaxies





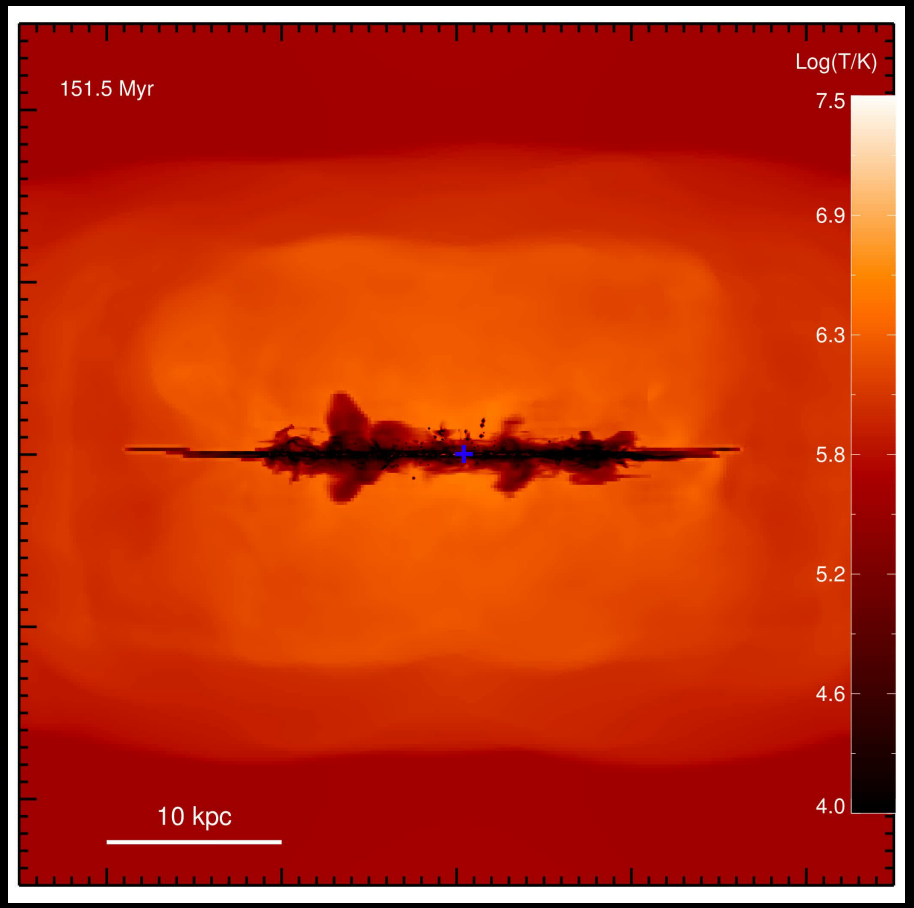


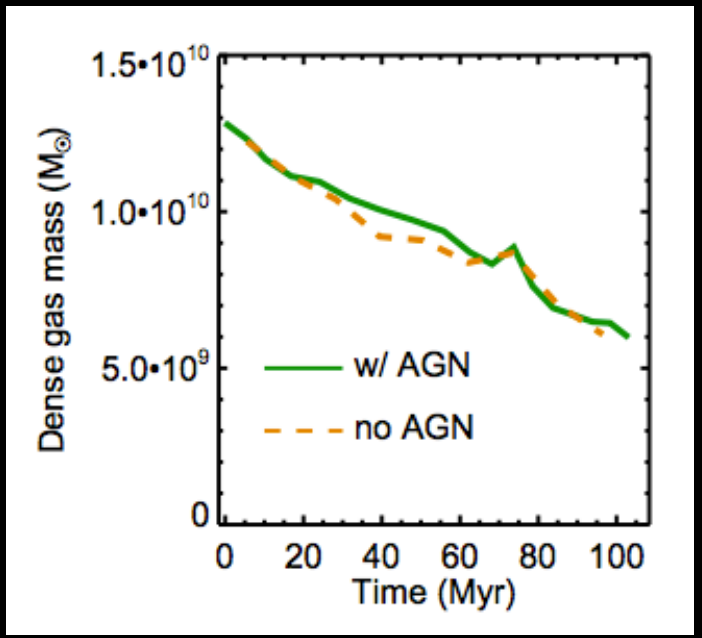


- Mass-matched and redshift-matched samples of *clumpy disks* and *stable disks (spiral/bars)* in GOODS-South with VLT optical spectra
- Evidence for AGN excess ($L_{bol} \sim 10^{43+}$ erg s^{-1}) in clumpy disks: [OIII] excitation + X-ray stacking

Bournaud et al. 2012, ApJ 757, 81

Feedback : AGN in “normal” galaxies



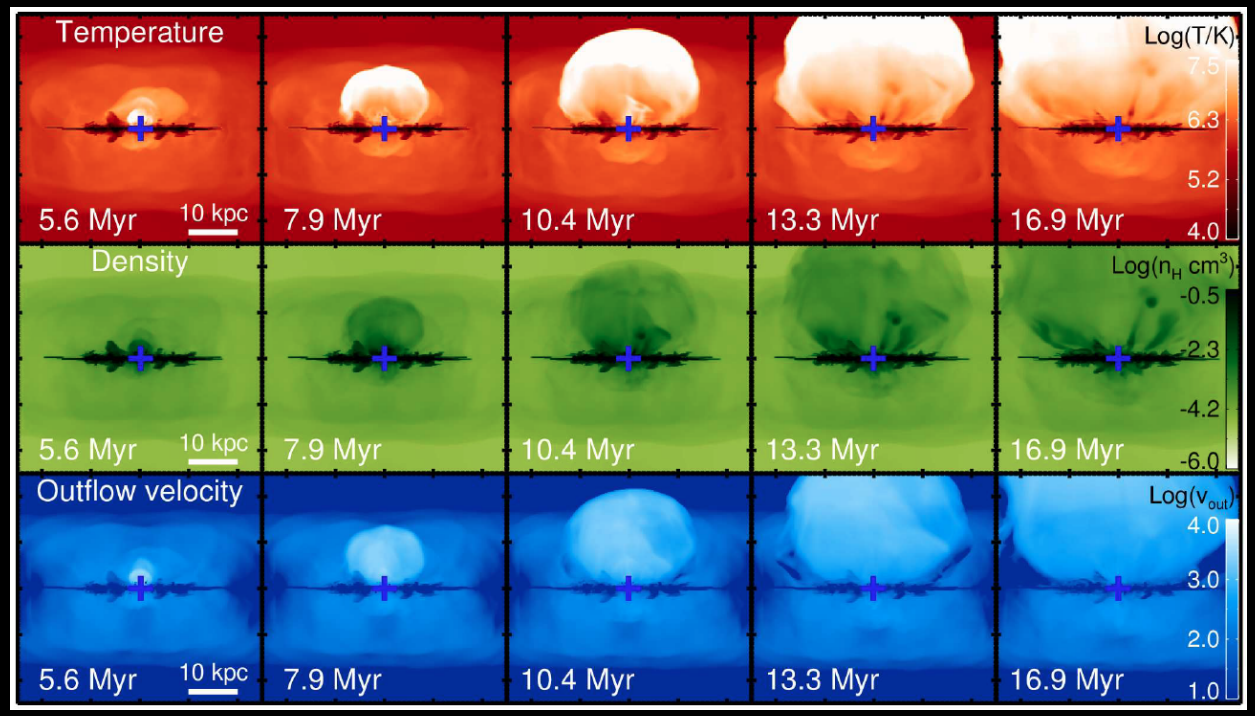


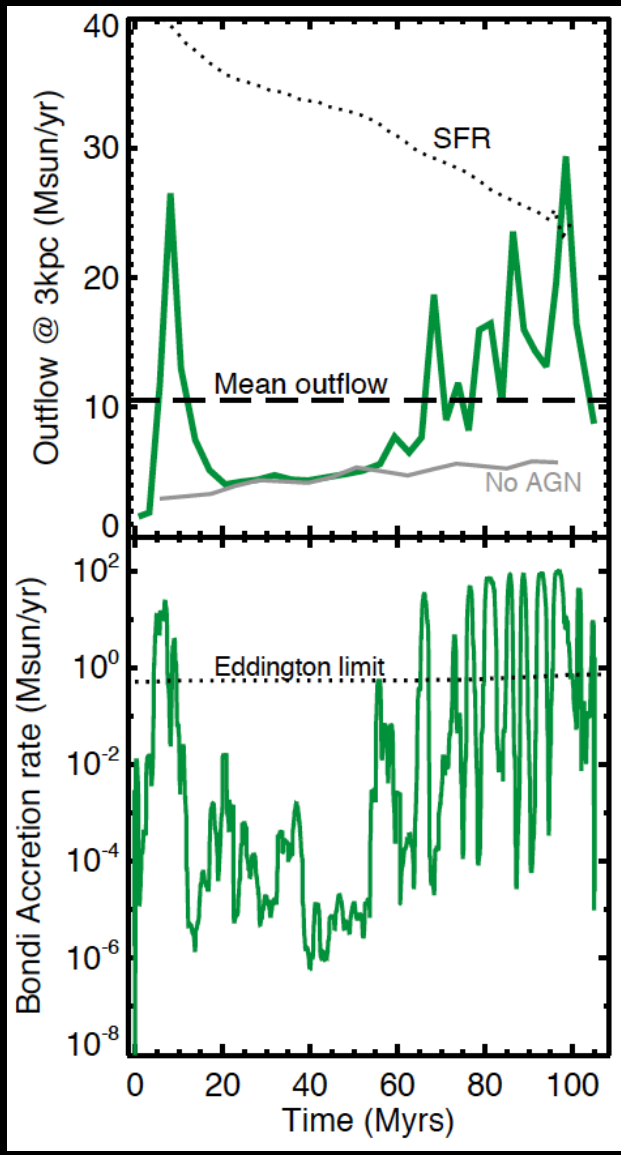
Very high velocity winds
1,000 – 3,000 km s^{-1}

Outflow rate 30-50% of SFR
Feedback on SFE is weakly positive

Gabor & Bournaud 2014, Roos et al. 2014 arXiv1405.7971

Feedback : AGN in “normal” galaxies





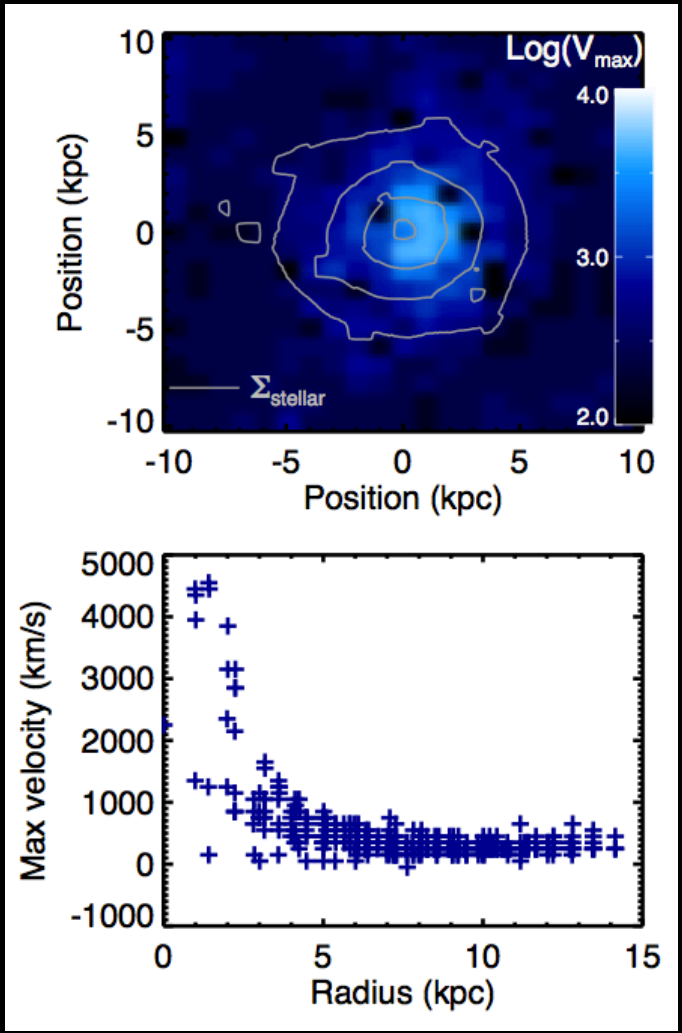
AGN outflows can have very high velocities, sometimes 10,000 km s^{-1}

AGN-driven outflow rate sometimes close to SFR

AGN outflows do not quench AGN feeding or SFR

Gabor & Bournaud 2014

Feedback : AGN in “normal” galaxies



Color scale is outflow velocity
Contours are stellar mass surface density
⇒ High-velocity outflow is spatially concentrated
central AGN >1000km s^{-1}
extended SF ~ 200km s^{-1}

Average mock IFU observation of a face-on Main Sequence galaxy with an AGN-driven outflow

- The outflow is relatively collimated and centrally concentrated
- The AGN-driven outflow may still be observed in the circum-galactic medium once the AGN is off

Gabor & Bournaud 2014

Conclusion

- High-redshift progenitors of (barred, spiral) exponential disks are irregular galaxies
- High gas fractions trigger instabilities and strong turbulence => giant clumps
- The giant clumps behave a bit like « local starbursts »: high excitation, outflows…
- The rich gas reservoirs help clump survival, migration, mass re-distribution

  => exponential disks, thick disk formation, (regulated) bulge growth

  => regulation of the galaxy mass (outflows, also from AGN)

- Transition to modern types around redshift 0.5-1.0 (with rependence on mass)
- Bars form from z=0.5-1.0 and grow over a few Gyrs, mostly long-lived, transient and relatively rare bars at z>1
- Bulge growth dominated by high-z mergers and instabilities, bars and secular instabilities are more secondary in the bulge mass budget.