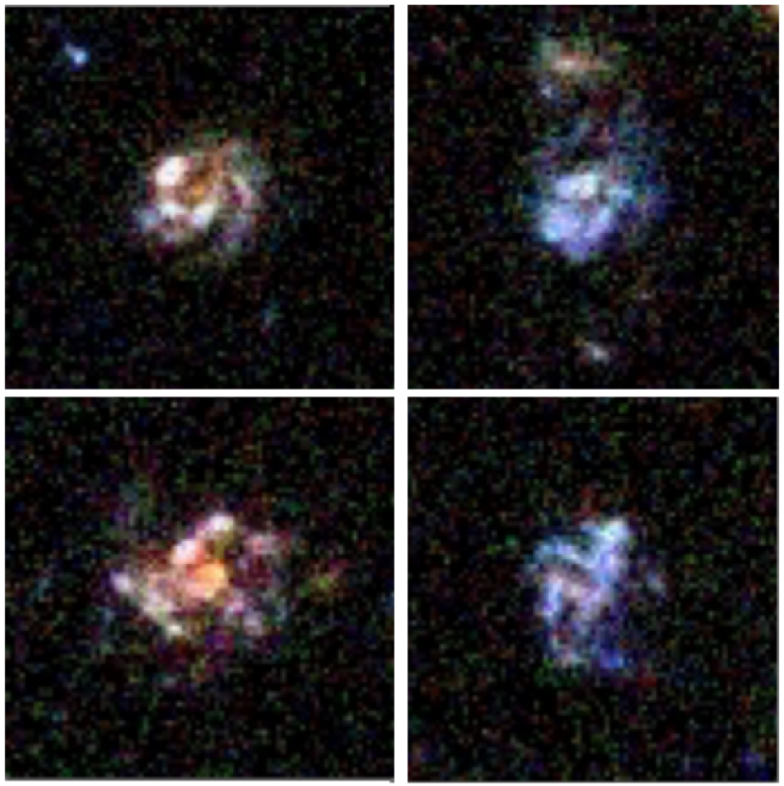
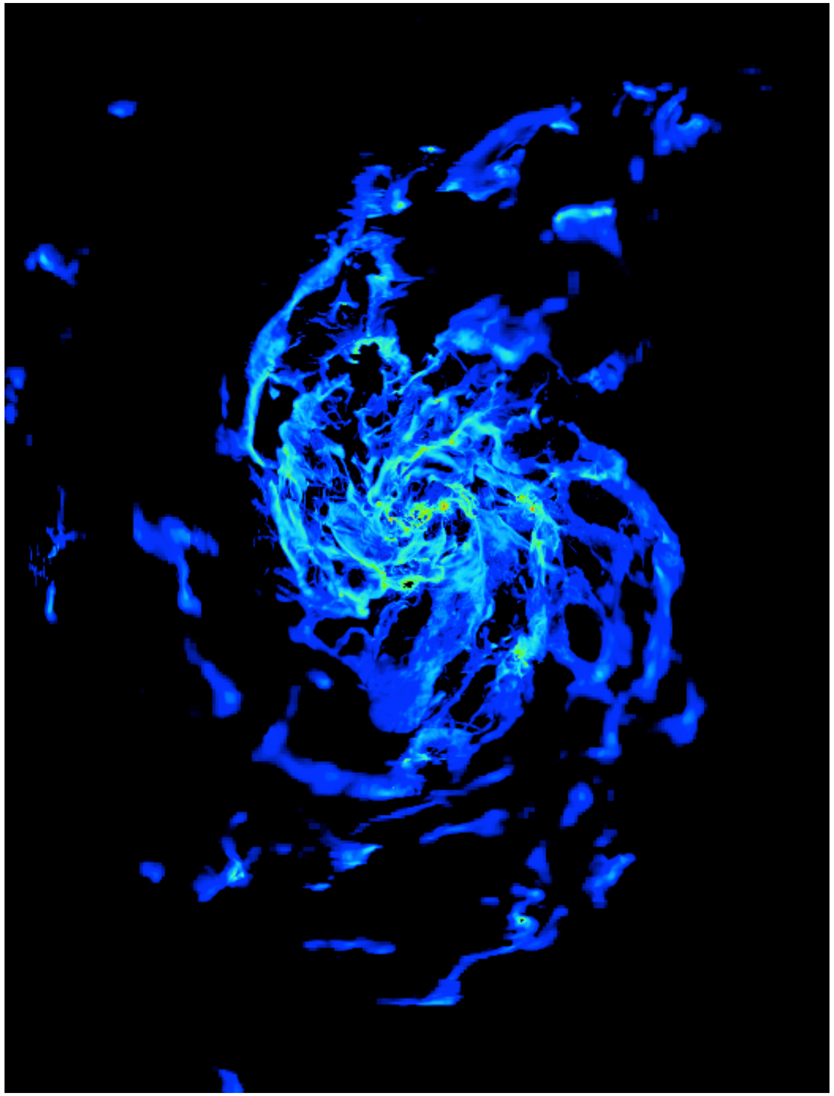
Star formation in high-density environments:
High-redshift disks, mergers, galaxy centers



Frederic Bournaud - CEA Saclay

with Florent Renaud, Katarina Kraljic, Jared Gabor (Saclay), Valentin Perret (Marseille)
Eric Emsellem, Avishai Dekel, Bruce Elmegreen, Romain Teyssier....

Parsec-scale galaxy simulations with detailed feedback



- RAMSES AMR code (Teyssier 2002)
- 1-5pc and 100-1000M_O resolutions
- Cooling down to <100K

Stellar feedback:
local efficiency of 1-2% per free-fall time (at 1-5pc)

Stellar feedback:
- *photoionization:* HII regions around young stars, computed with a Strömgren-sphere approximation

(Renaud+13)

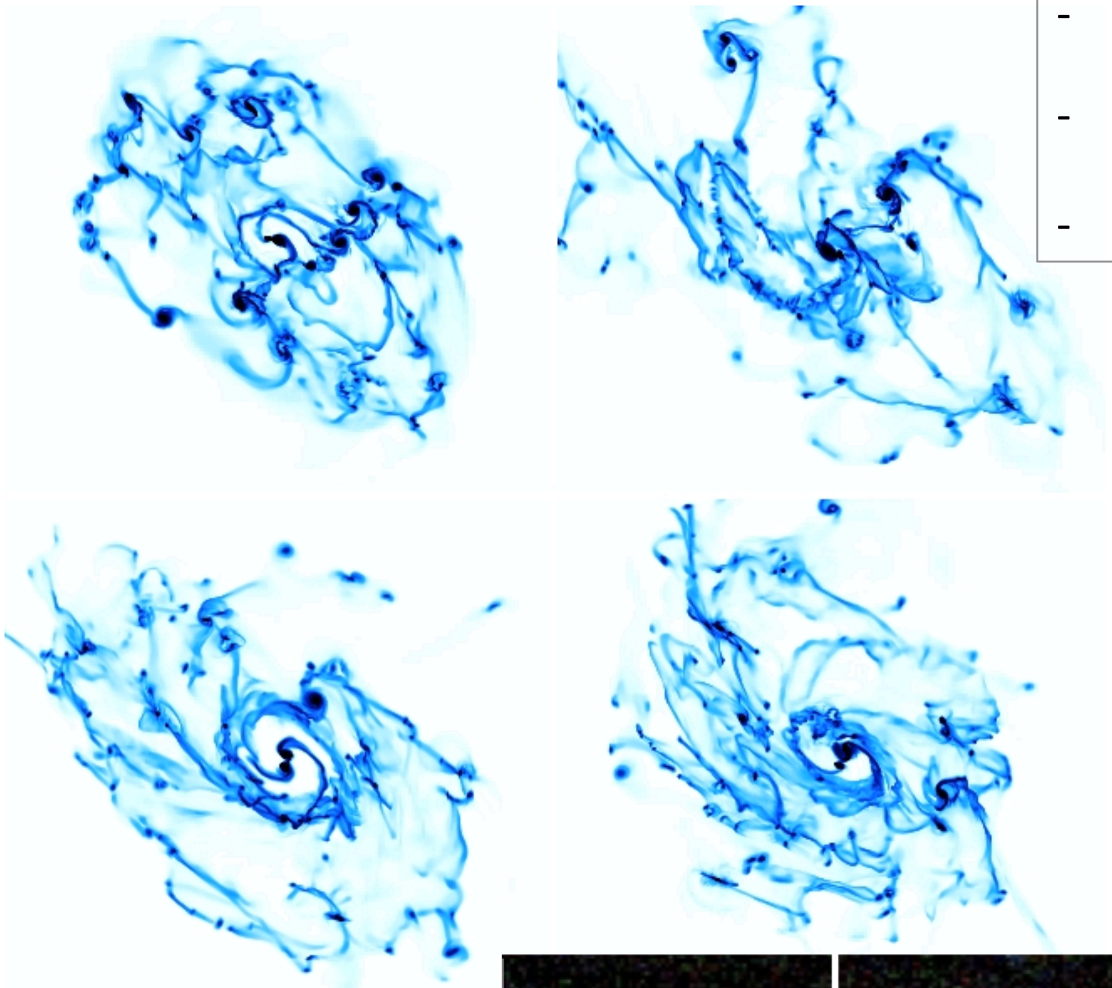
- *radiation pressure:* available momentum $m x v$
what is m and what is v?
most momentum is carried by ionizing photons
no need to impose $v=v_{escape}$ as done in other models

(Renaud+13)

- *supernovae feedback* with energy dissipation rate adjusted for non-thermal processes (~2Myr)

(Teyssier+13)

High-redshift disk models



Gas density maps every 150Myr

Optical imaging at z=2, Barro+13

- Typical Milky-Way progenitors at z=2
- High gas fractions around 50%
- Specific SFR ~$1 Gyr^{-1}$

Such models naturally get :

- strong turbulence 50 km s^{-1}
- giant clumps of $10^{8-9} M_O$,
  (also diffuse gas and small clouds)
- instability-driven inflows

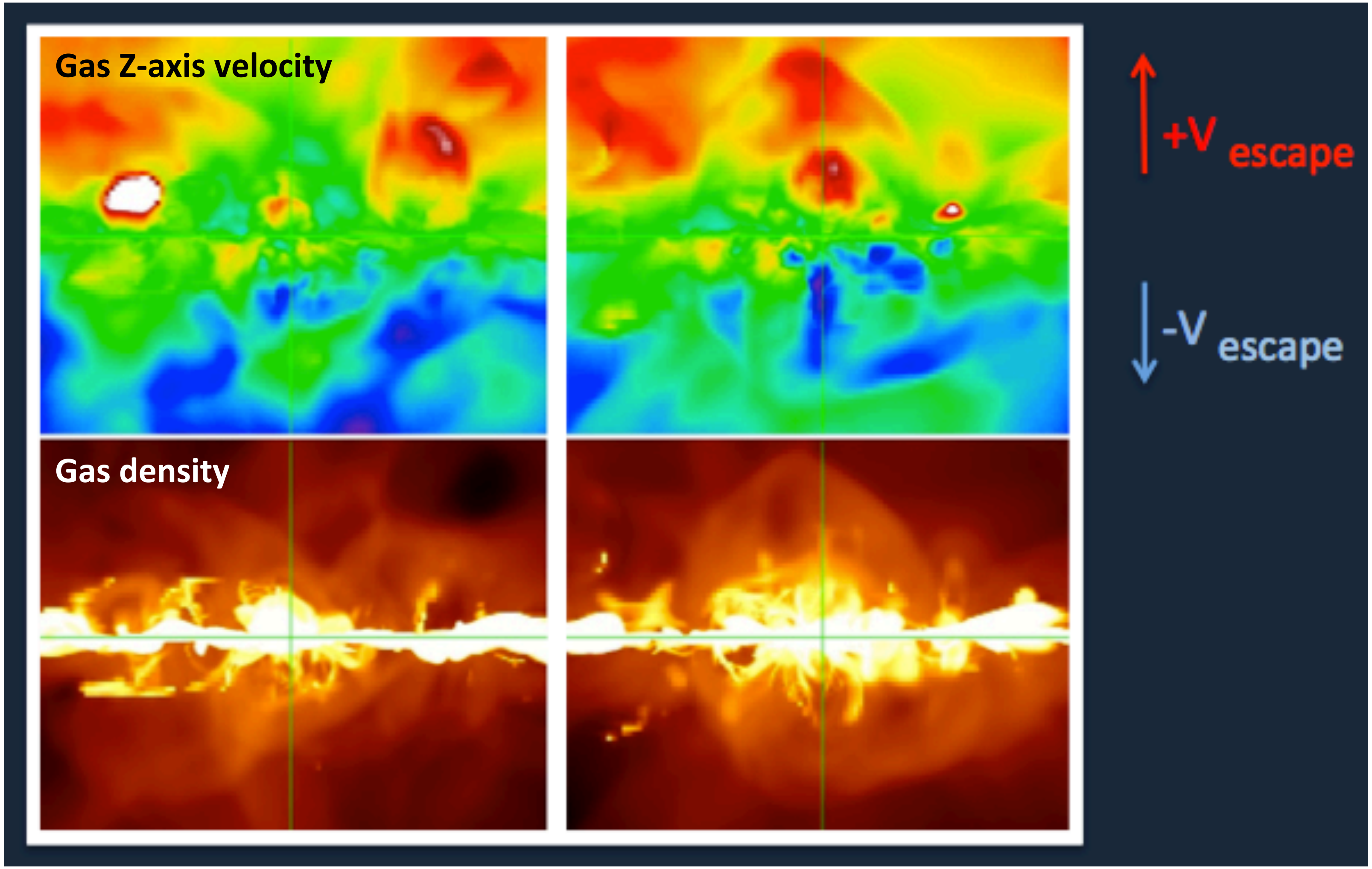
(Noguchi+99 Immeli+04 Bournaud+07,12 Genel+12...

Open issues:

- *Get the needed outflows?*
- *Short-lived clumps?*
- *Stellar mass evolution?*

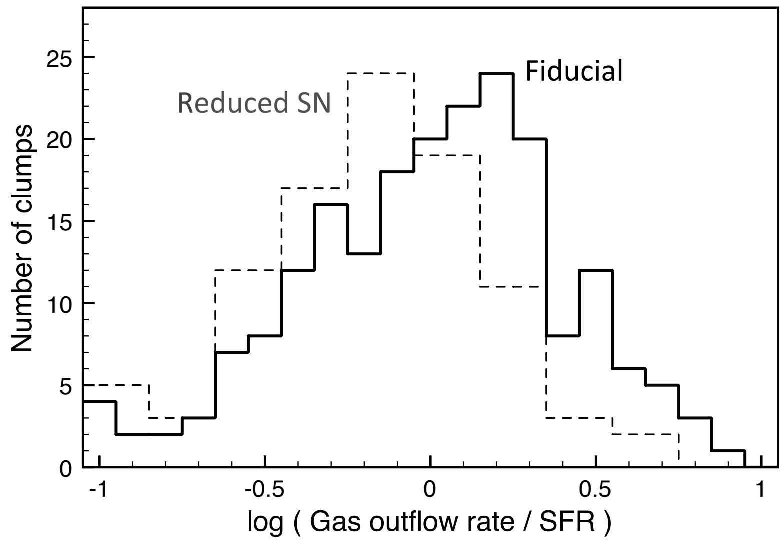
Bournaud et al. 2013, Perret et al. 2013

Galactic-scale outflows and clump-scale outflows



Bournaud, Perret, Renaud et al. 2013

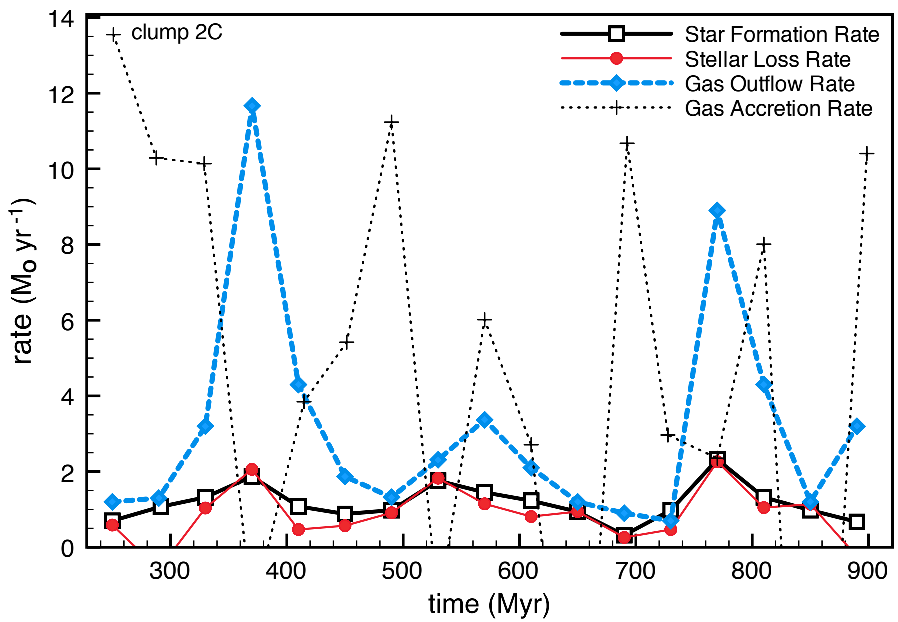
Clump-scale outflows

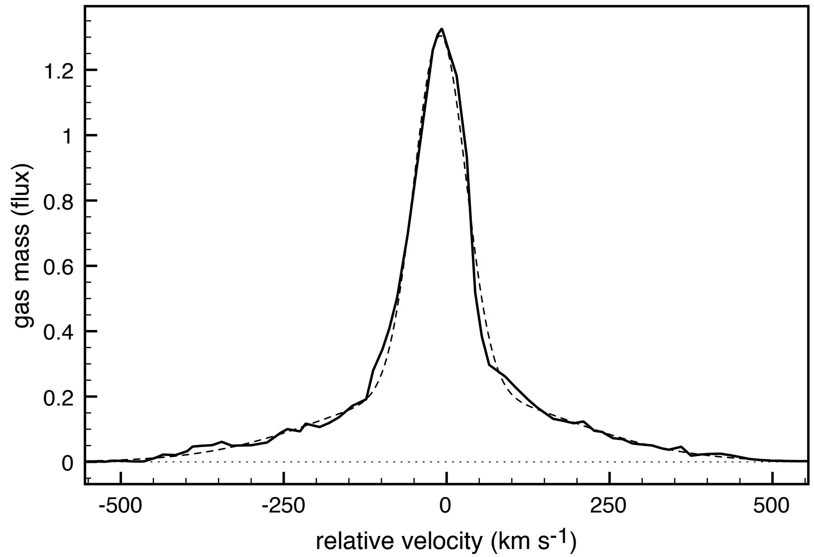


At the scale of clumps:
- Outflow rate of the order of SFR,
- Bursts at several times the SFR,

weaker outflow if weaker SN feedback

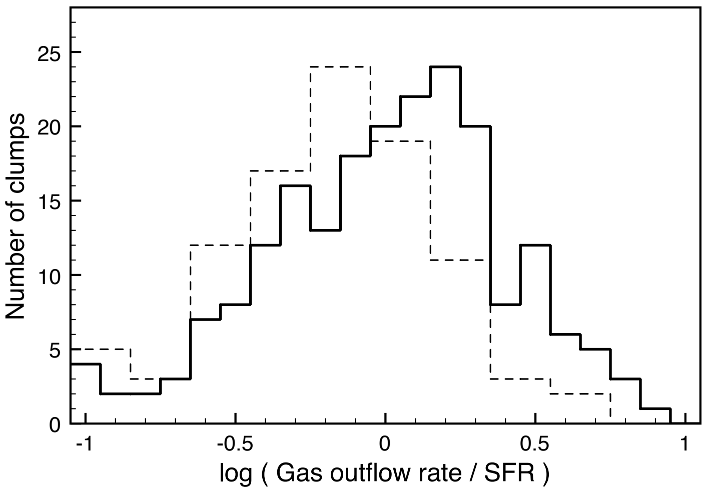
simulated spectra (here face-on galaxy orientation) have broad components tracing the outflow

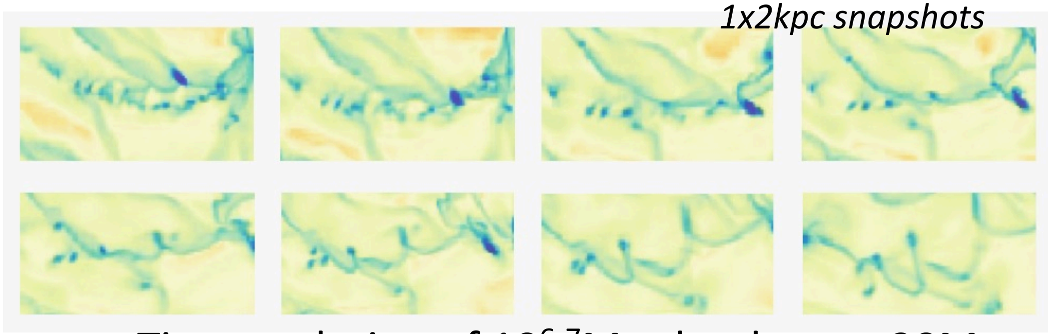




Bournaud et al. 2013

Clump-scale outflows

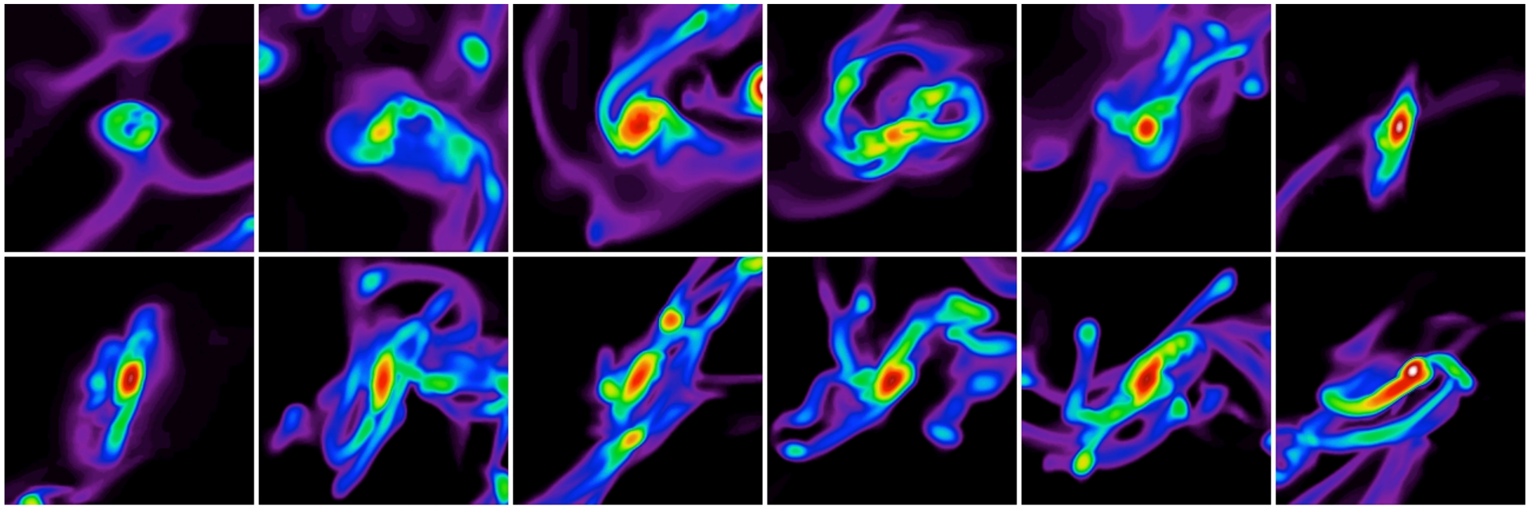




Time evolution of $10^{6\text{-}7}M_O$ clouds over 20Myr

These feedback-driven outflows:

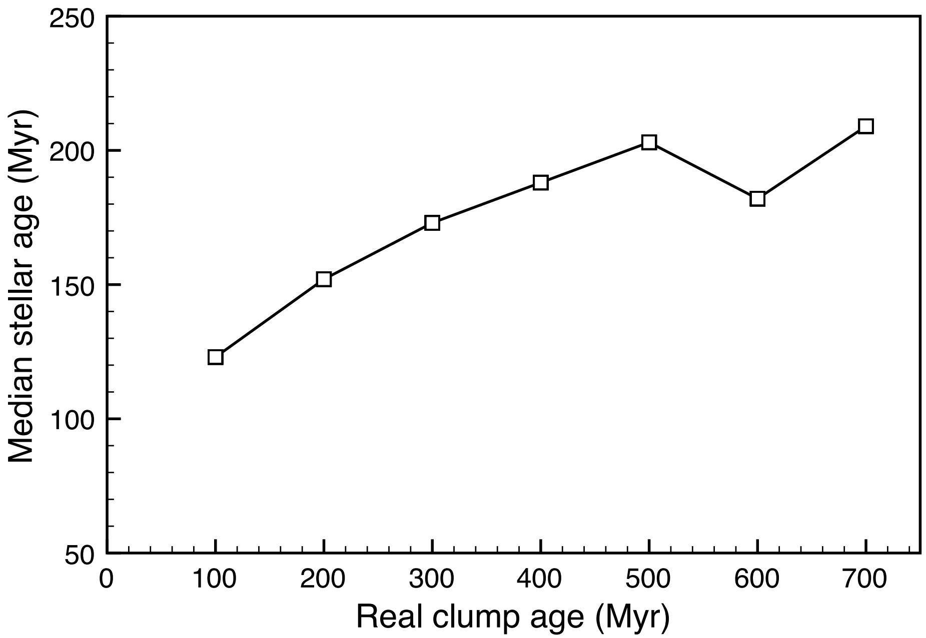
- Disrupt small clumps and GMCs, as should be
- Do not prevent giant clumps to survive for 100s of Myr



Time evolution of a $10^{8\text{-}9}M_O$ giant clump over 600Myr

Bournaud et al. 2013

Clump evolution, accretion, and dynamical mass loss



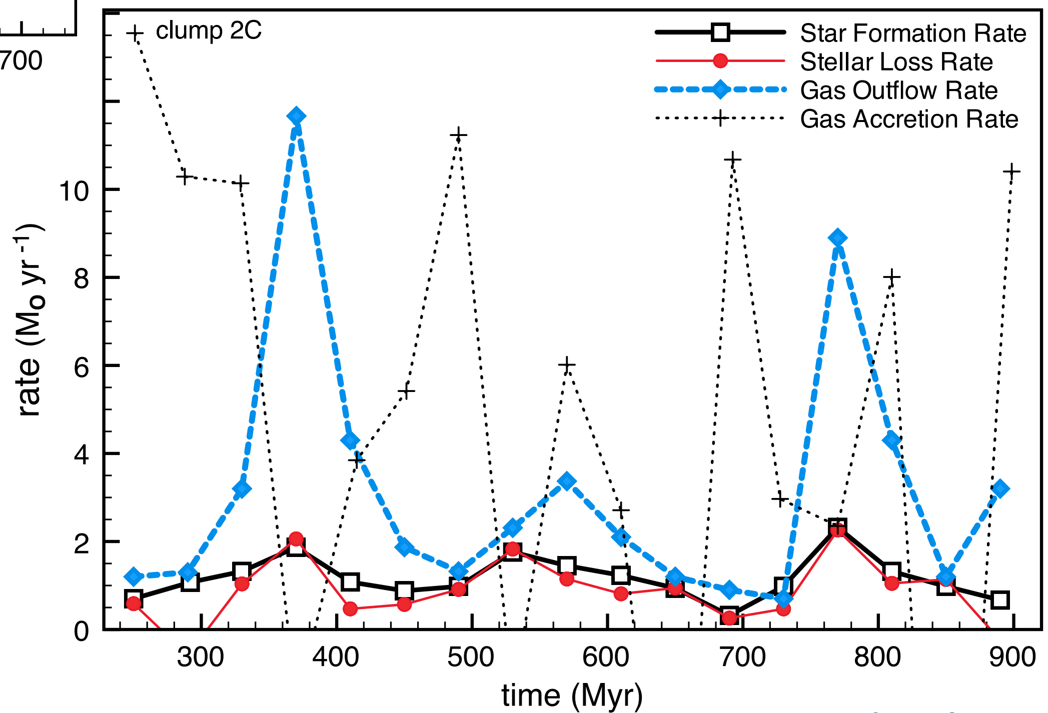
Clumps also loose their aged stars by dynamical evaporation, galactic tidal field.

Loss rate close to SFR,
timescale for a star to leave the clump ~200Myr

-- Median stellar age in a clump rarely exceeds 200Myr, even for 700Myr-old clumps

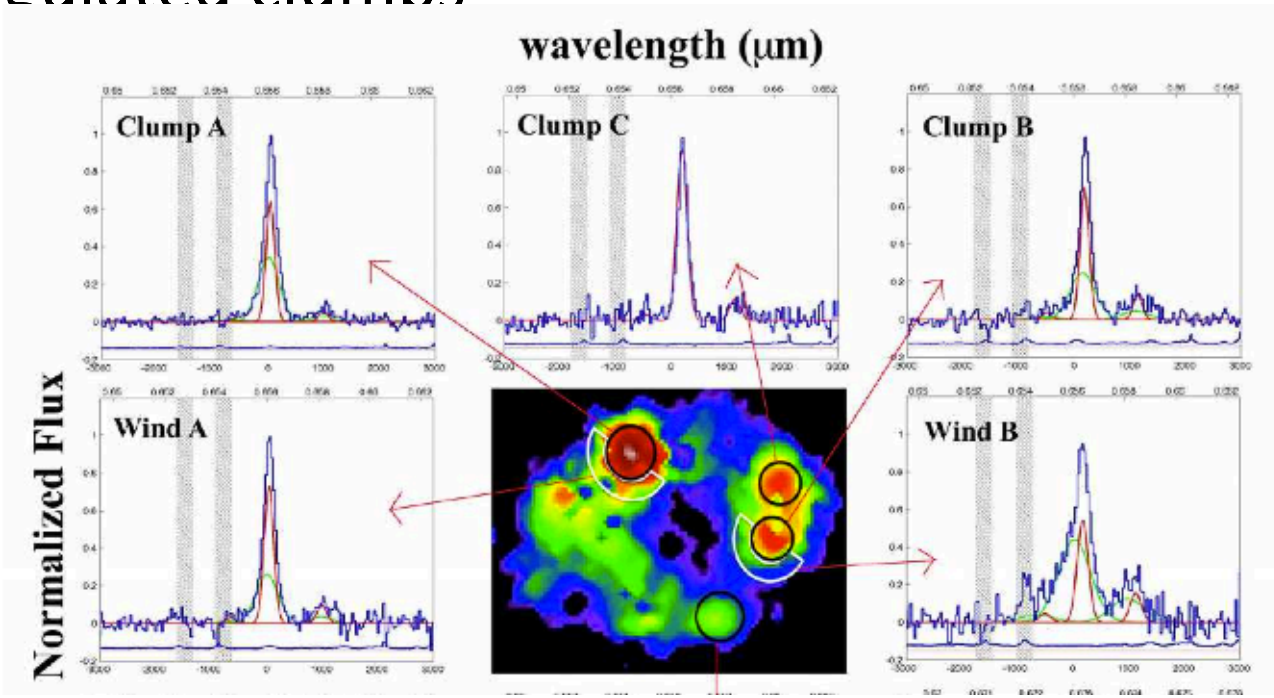
-- At the same time clump accrete gas from the surrounding gas, at a few $M_O yr^{-1}$, compensating for the outflows

(see also Dekel & Kumholz 2013)



Bournaud et al. 2013

Long-lived self-regulated clumps



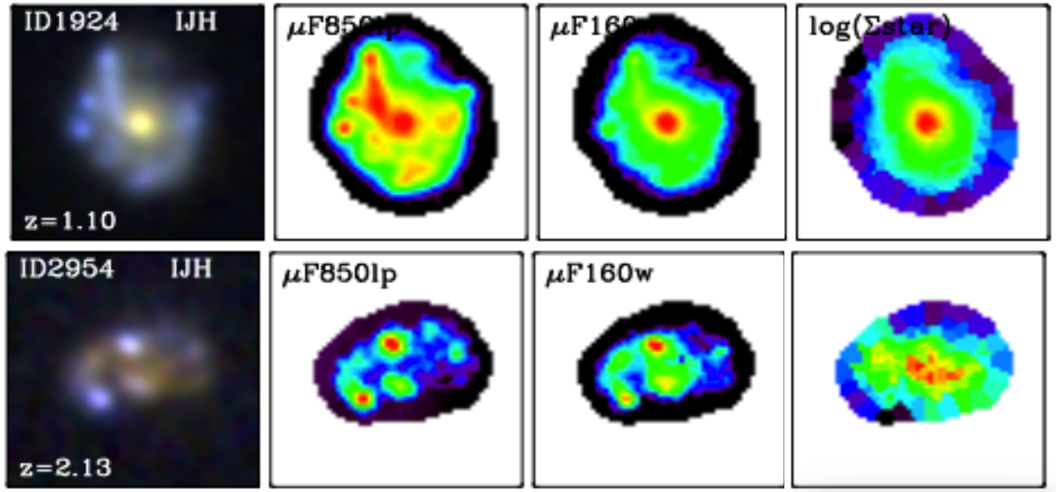
Observed outflows from giant clumps, Genzel et al. 2011, Newman et al. 2012

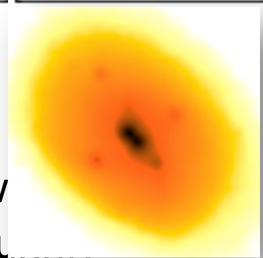
- Balance of inflows and outflows. Giant clumps survive with a roughly constant mass and migrate in the disk, can grow the central bulge

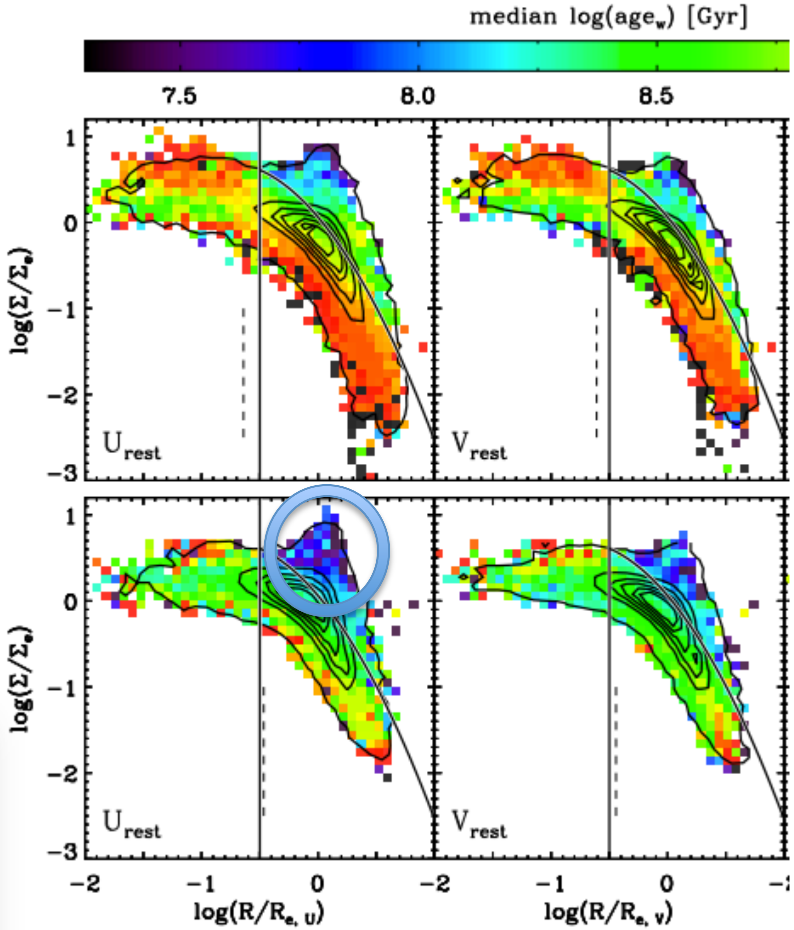
- Clumps launch outflows

- Clump stellar populations remain young (100-200Myr)

Long-lived self-regulated clump







Stellar ages in clumps up to 200Myr, Wuyts et al. 2012

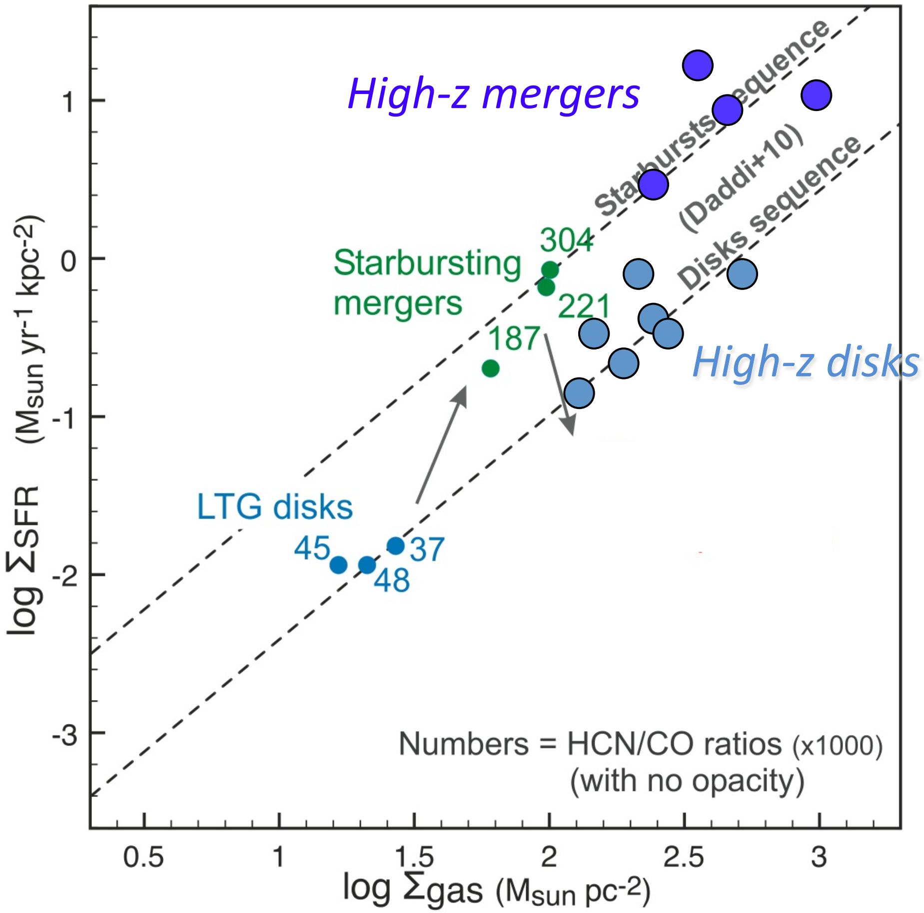
Elmegreen& Elmegreen 2005

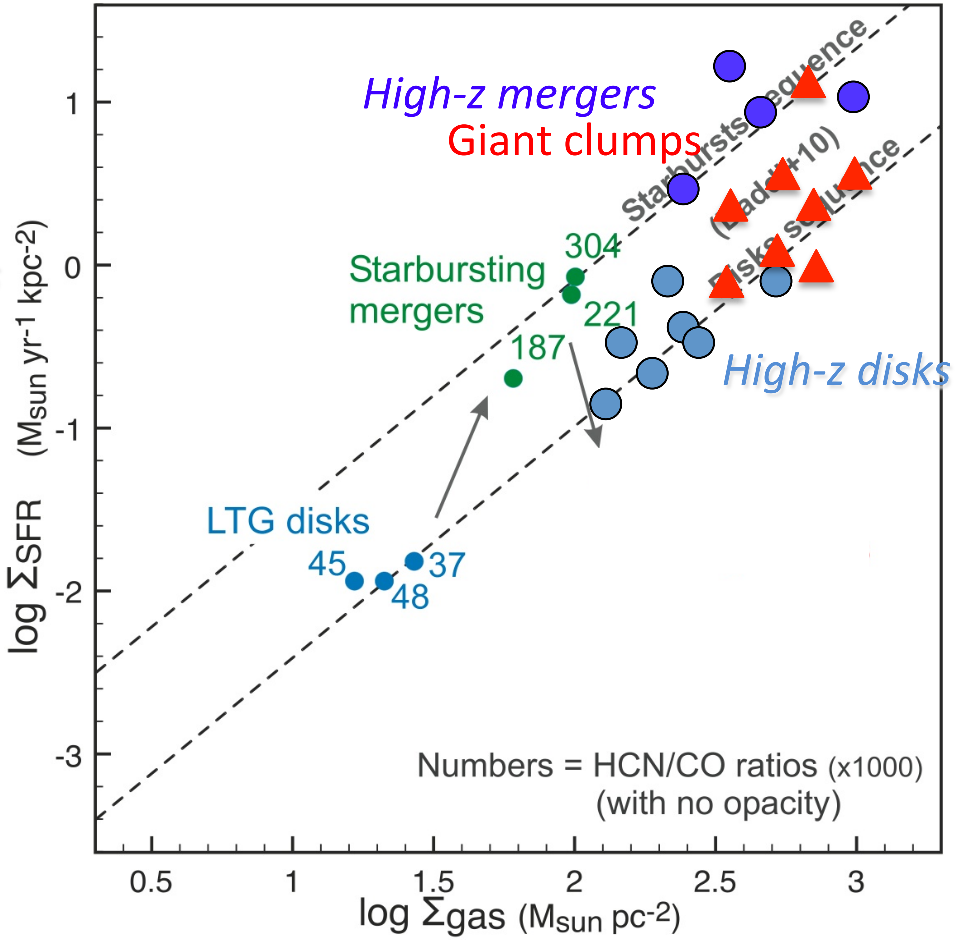
- Balance of inflows and outflow
  Giant clumps survive with a rou
  constant mass and migrate in the disk,
  can grow the central bulge

- Clumps launch outflows

- Clump stellar populations remain young (100-200Myr)

Do these giant (long-lived) clumps change SF laws?





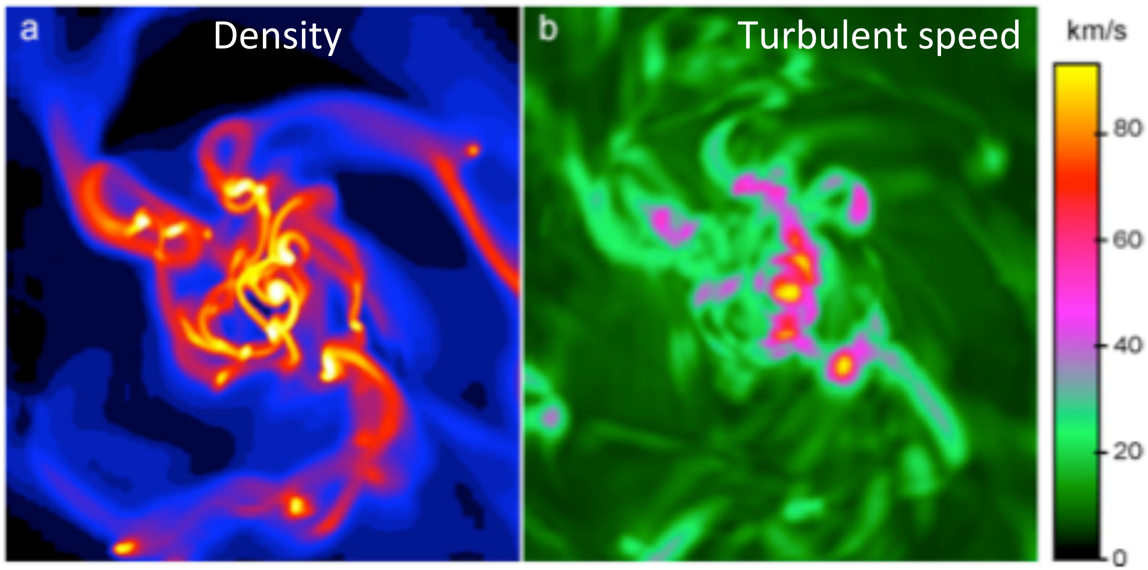
NO

High gas density but “normal” SF efficiency, even at the scale of big clumps

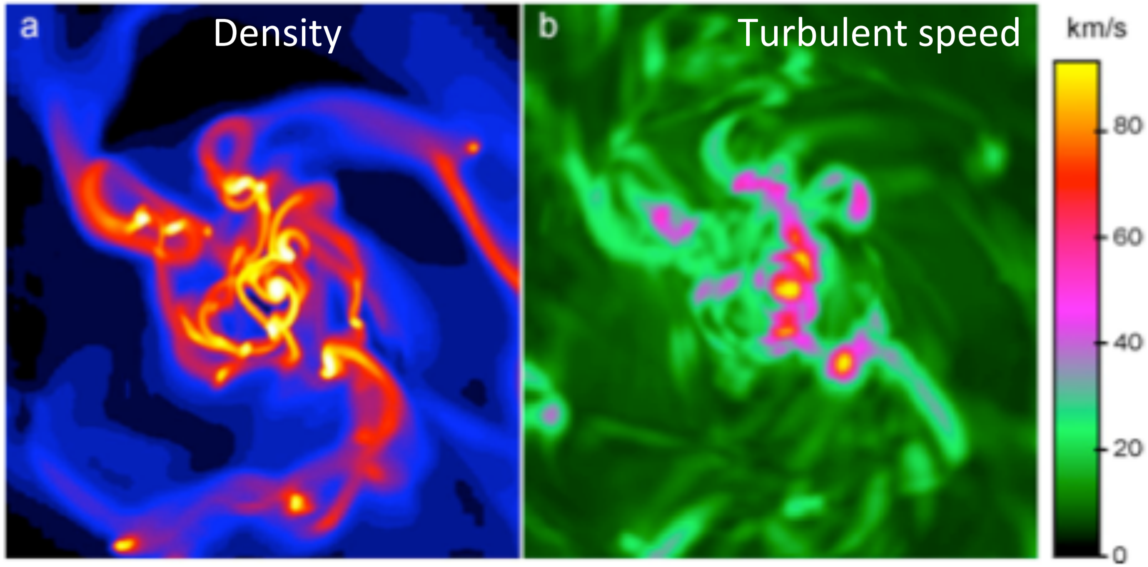
Same driving processes at in nearby spirals (gravity + turbulence cascade + feedback)

The density PDF is log-normal (or very close to)

Origin of (strong) turbulence



Origin of (strong) turbulence

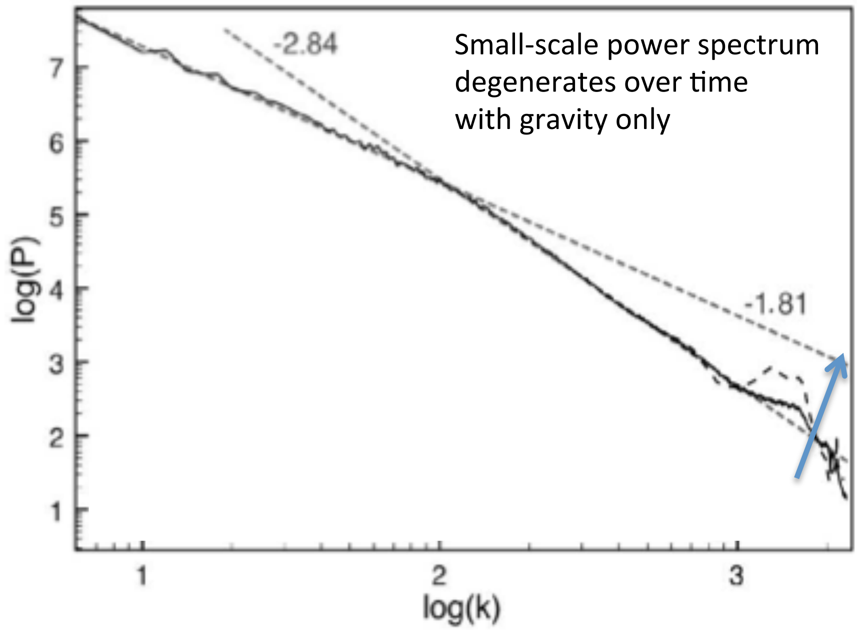


Gravity (instabilities+inflow)
Can power realistic dispersions
>20km/s everywhere
50+km/s near the clumps

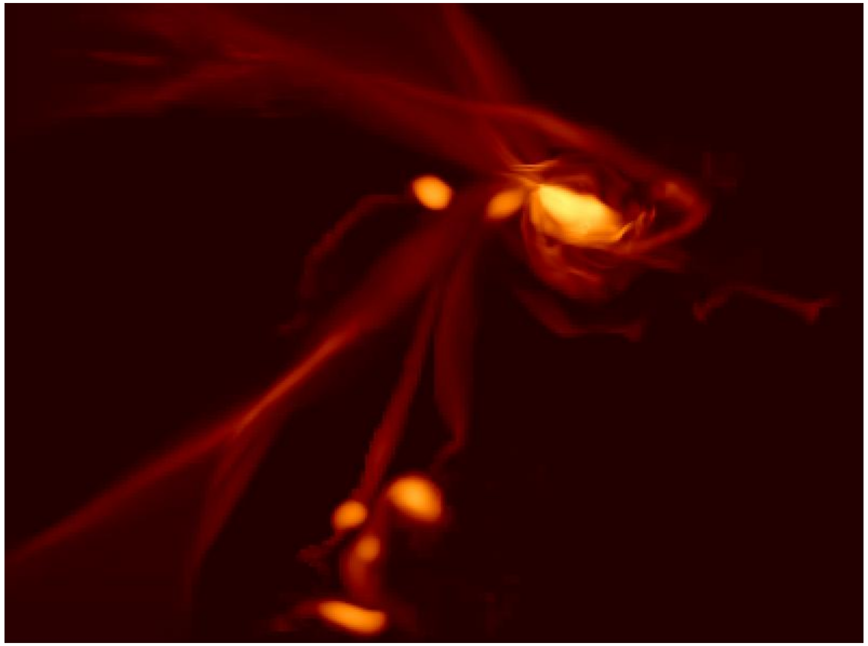
Here the observed "Q=1 level" turbulence is powered by gravitational energy, feedback was turned off.

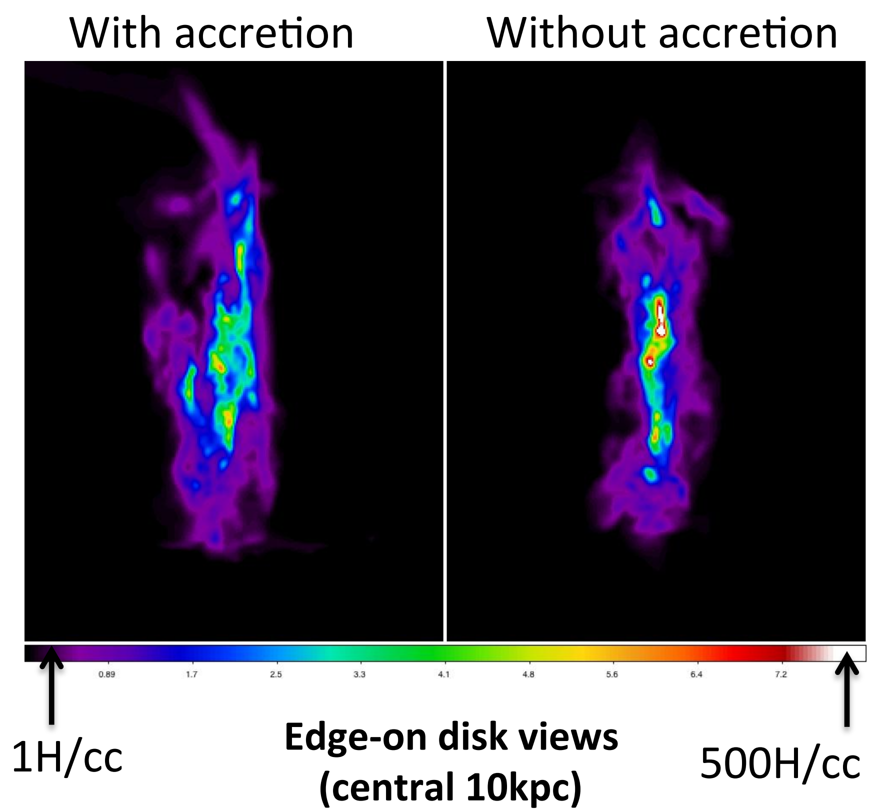
Both processes saturate at Q=1
impossible to disentangle in a simulation

Gravity **can** be enough,
But we **need** some feedback for regulation



Some externally-driven turbulence?

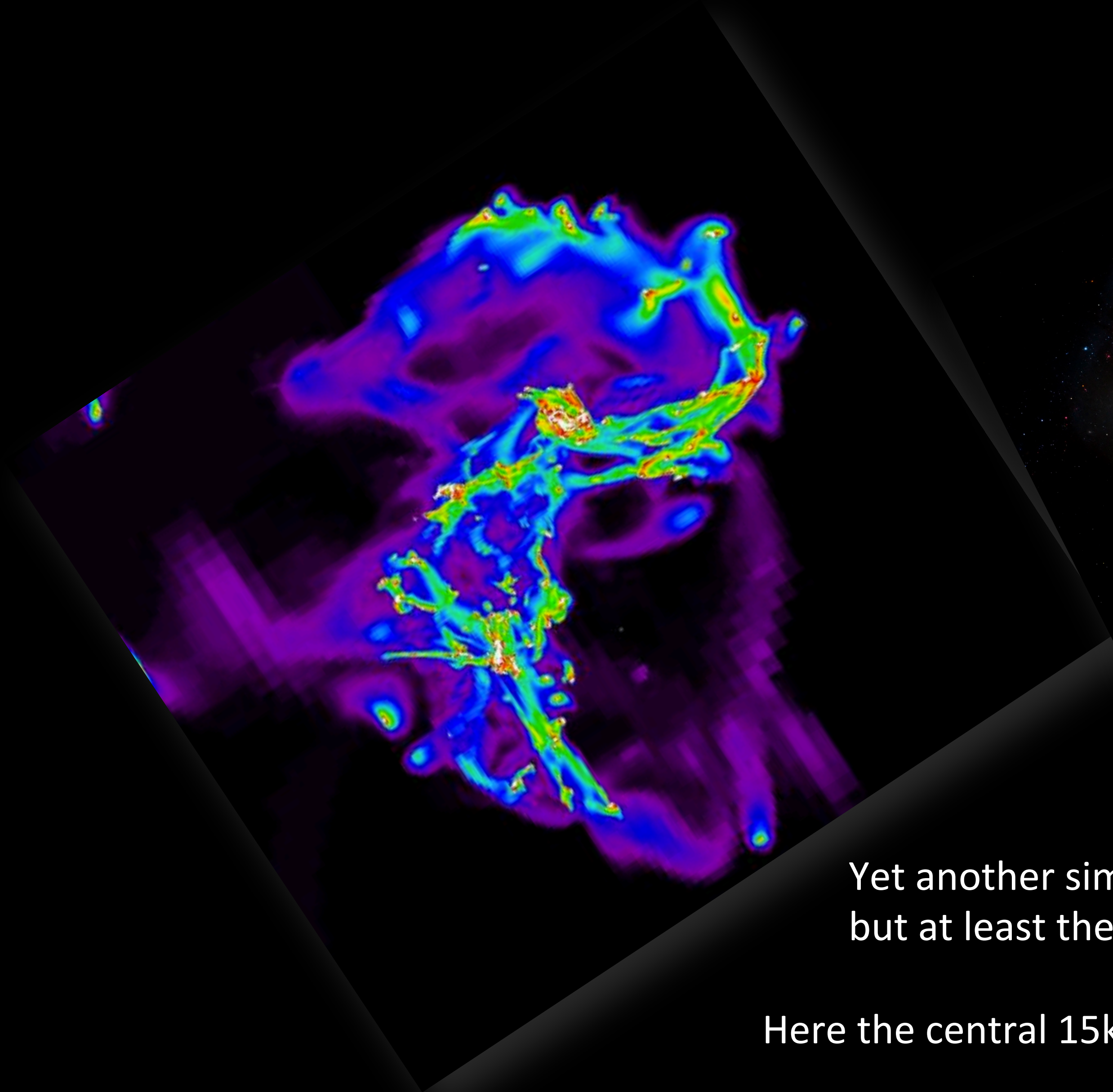




External mass infall (idealized cold flows)
can increase the dispersions by a factor of 2-3,
compared to internal sources(gravity+feedback)

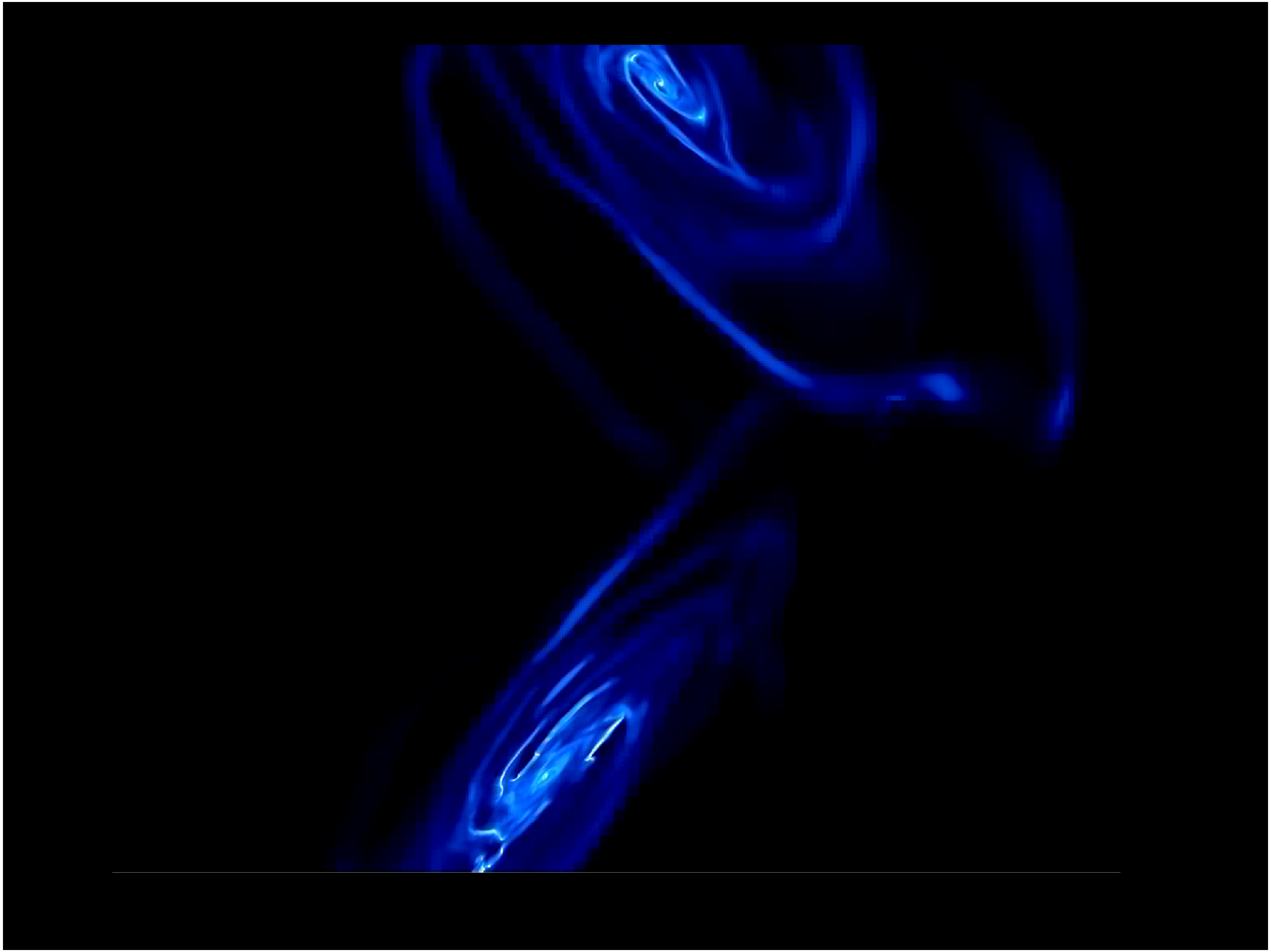
Gabor & Bournaud in prep.

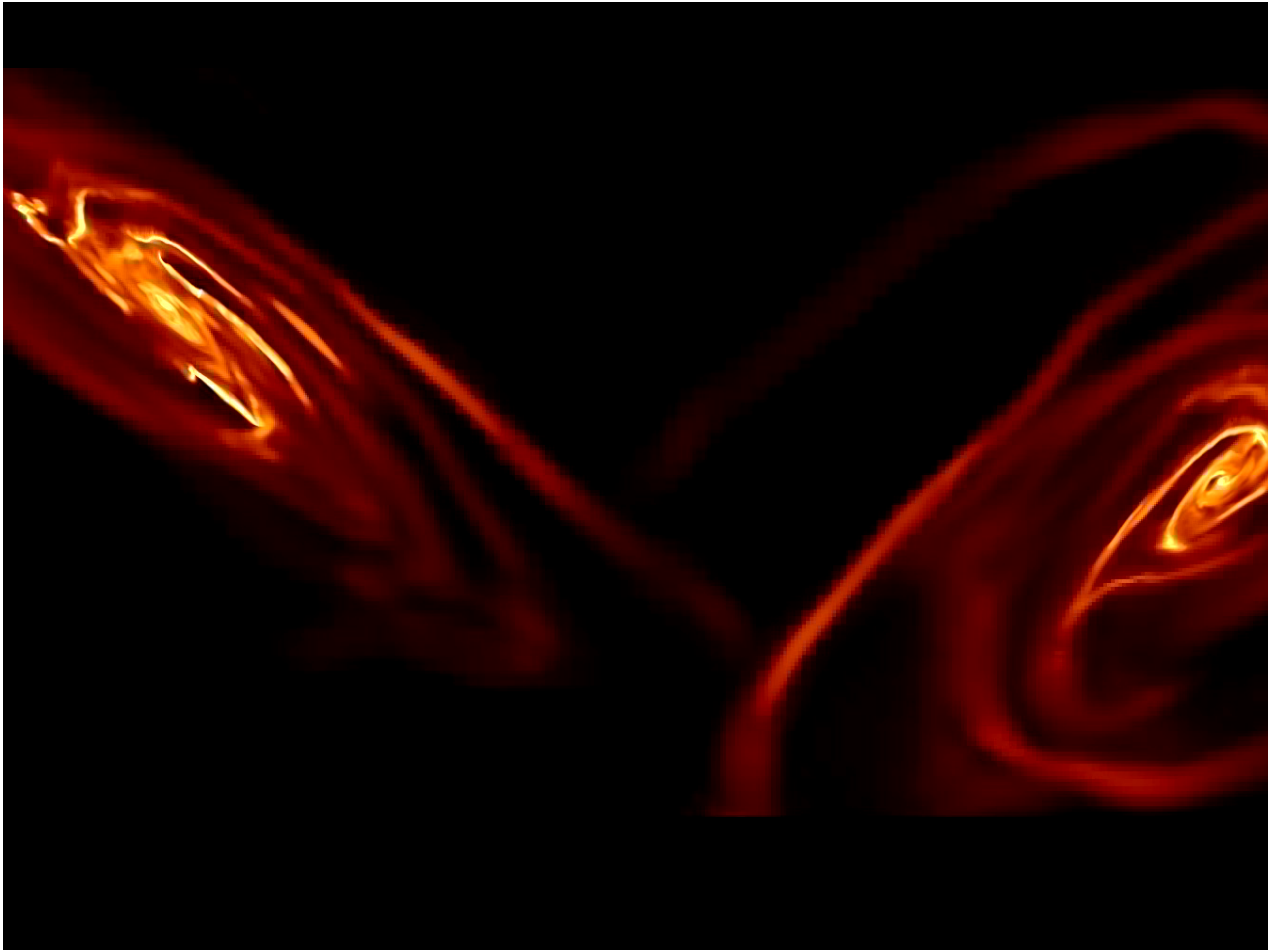
Is star formation different in mergers ?



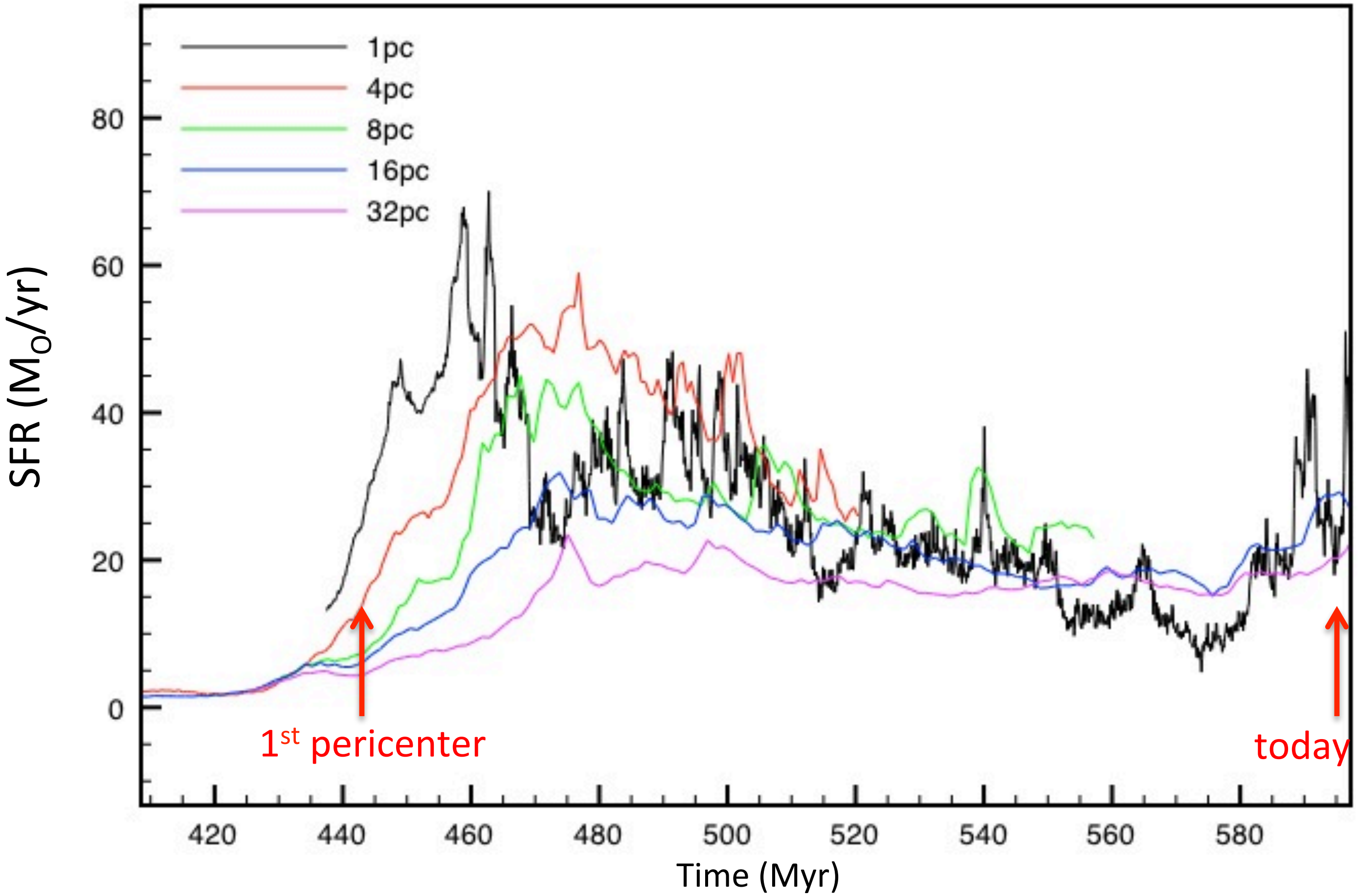
Yet another simulation of the Antennae,
but at least the SF histories converge.

Here the central 15kpc at the "observed" instant



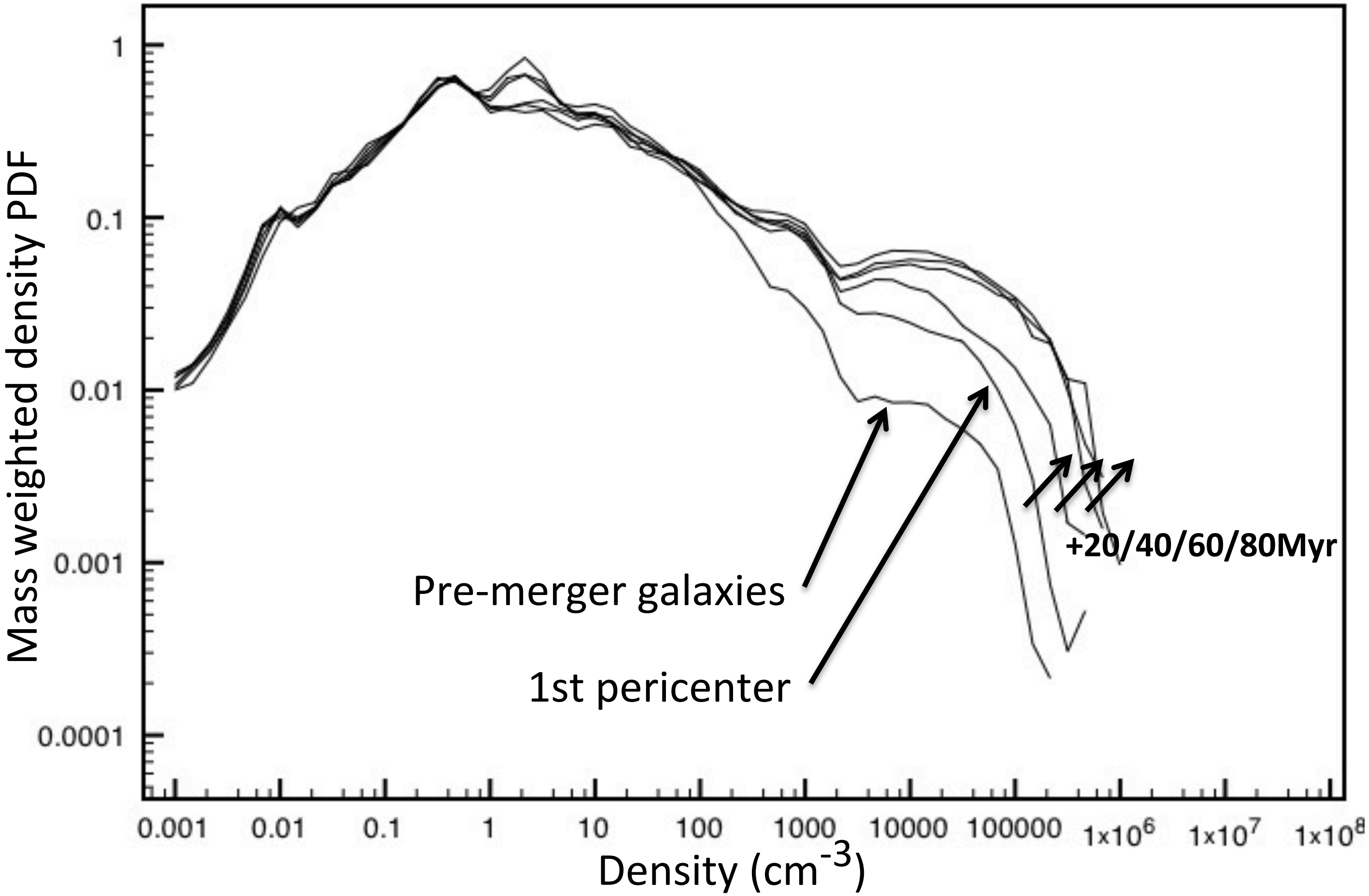


Can models converge on the SF history of mergers?



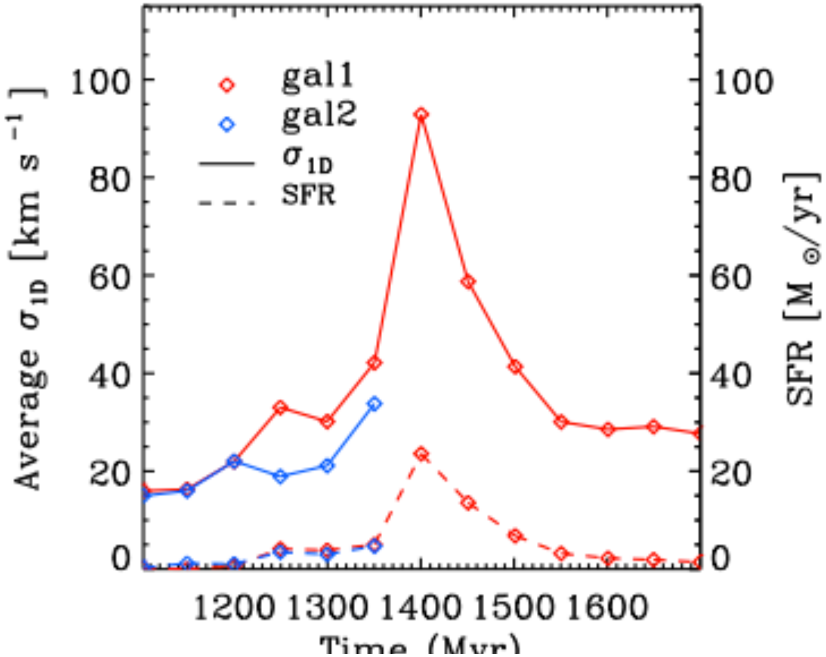
- The SF history converges at 2-4pc resolution
- The ability to resolve gas fragmentation/cloud properties (i.e. resolution) has <u>more</u> impact than the chosen code, the interaction orbit, the <u>SF and feedback models</u>
- Post-starburst conditions in today's Antennae, in particular in the *overlap region*

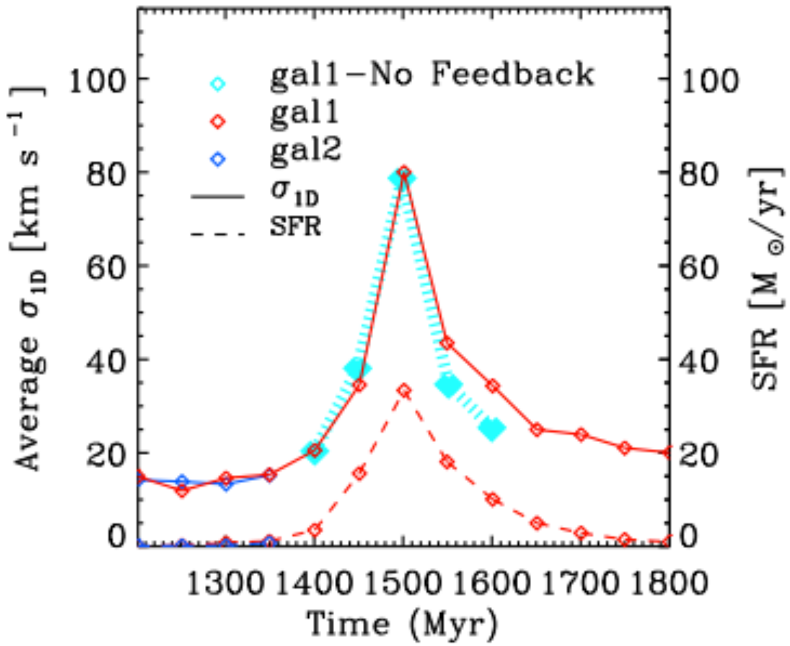
Dense gas excess from the tidal interaction

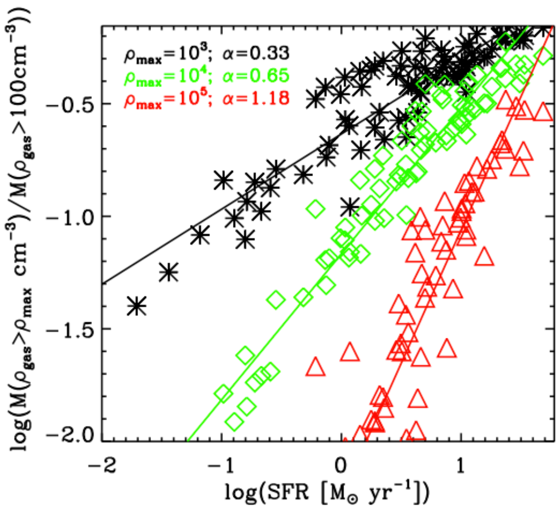


- Excess of high-density gas appear rapidly after the pericenter.
- The global galactic density has not changed (yet) – no nuclear inflows
- Increased fragmentation and turbulence associated to the dense gas excess

Increased turbulence is a key starburst triggering mechanism



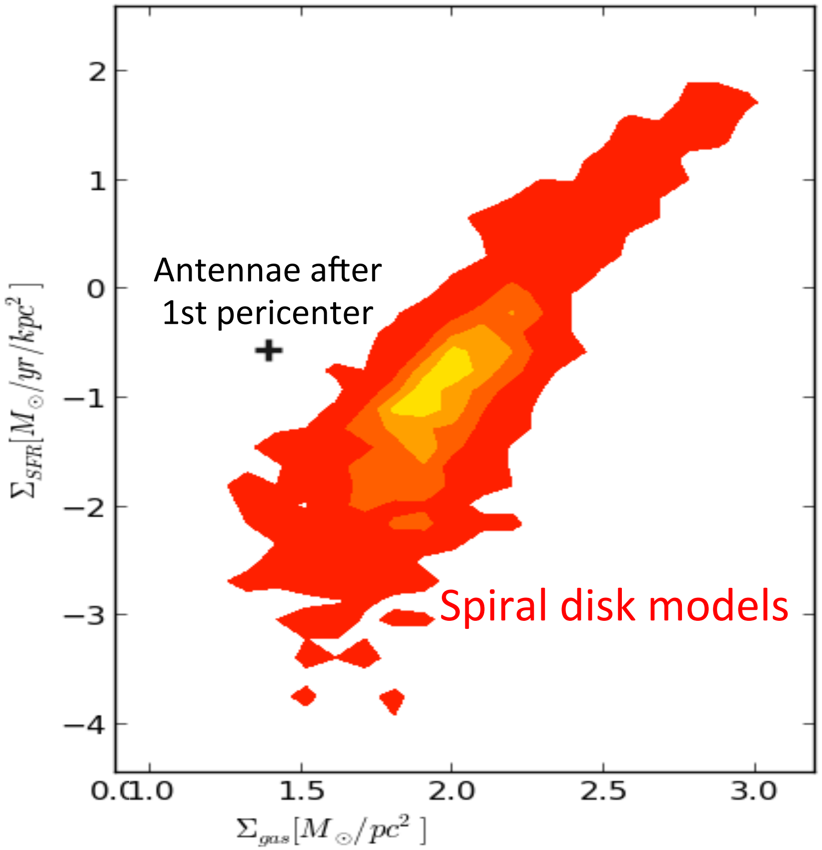




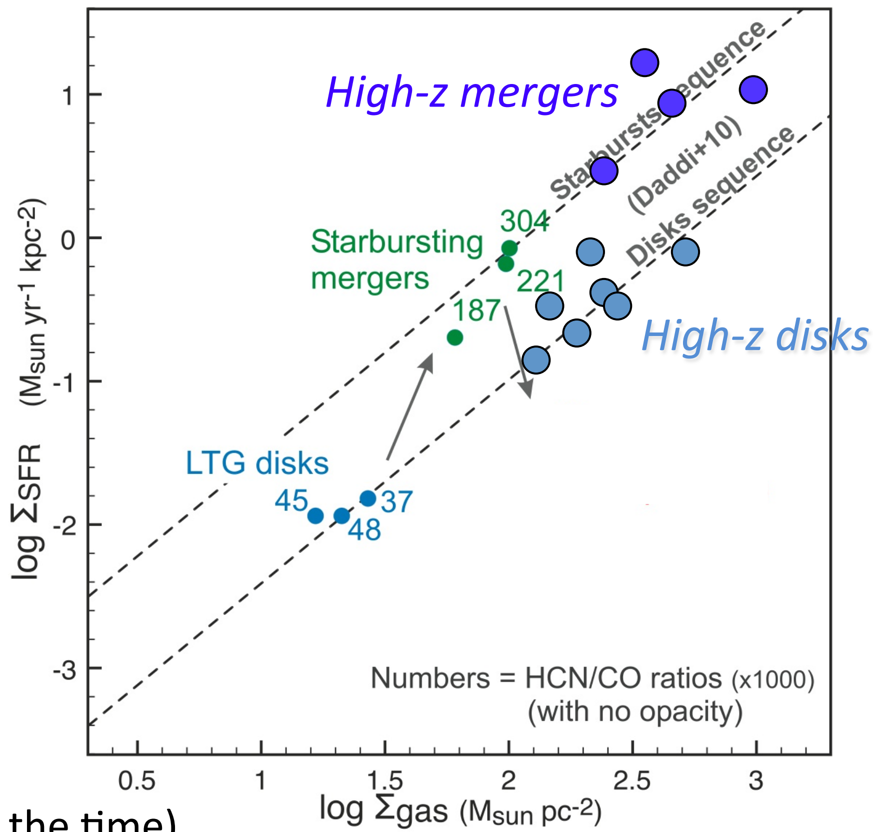
The SF burst is
1 - correlated to the excess of high-density gas
2 - associated to a peak in
the gas non-thermal dispersion,
which is a cause ratherthan a consequence
(still there if feedback is turned off before the burst)

Powell et al. 2013

A different mode of SF in mergers



Renaud et al. 2012, Powell et al. 2013, Kraljic et al. in prep.



There **is** a different mode (even if not all mergers all the time)

Here higher density turns into higher SF efficiency

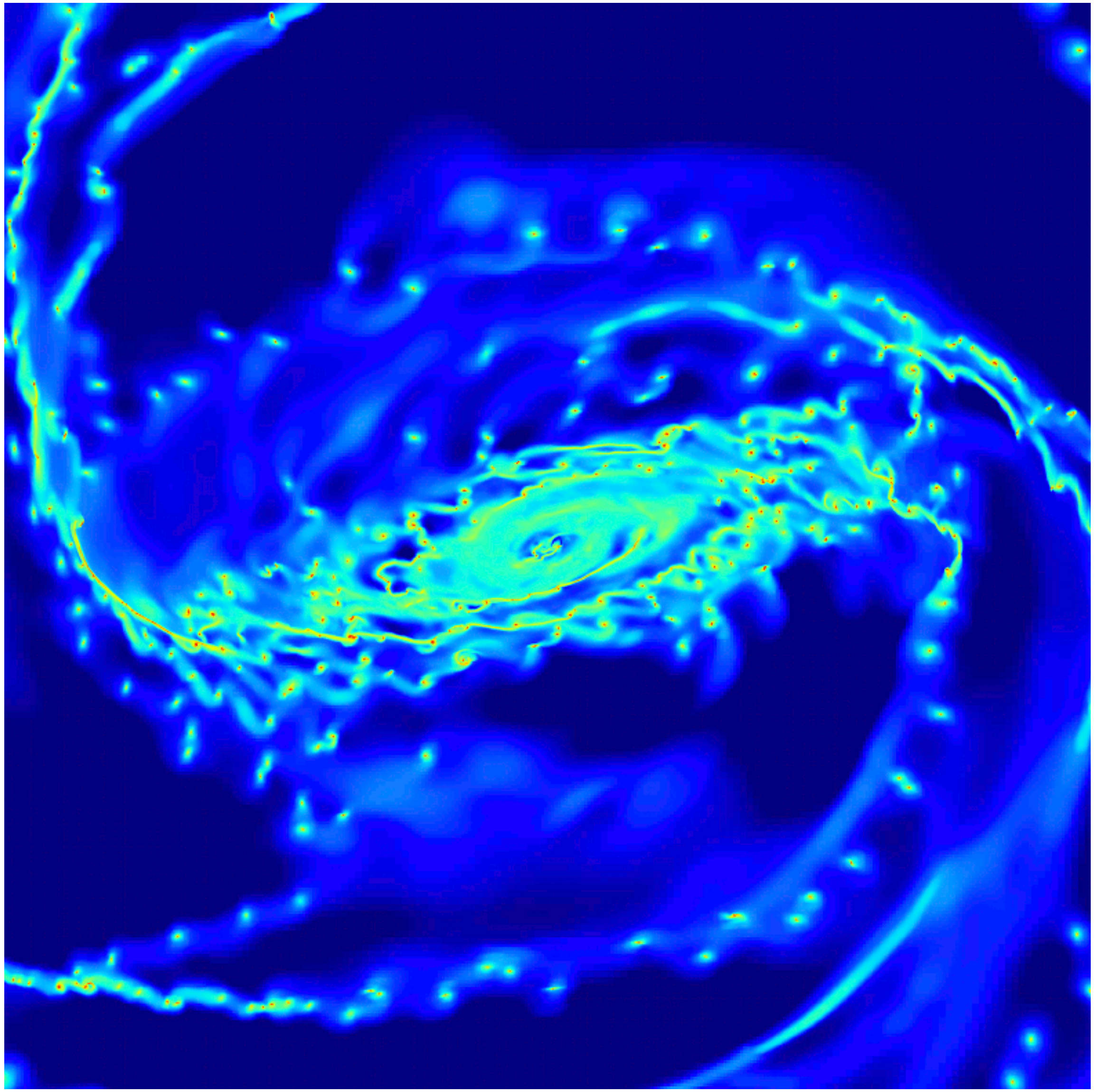
Why? Because at a surface given density, there is an excess of high-3D-density gas on small-scales

Why? The turbulent speed is higher (50km/s vs 10km/s in spirals), turbulence can compress gas...

But this was also true in high-redshift disks. So, is the turbulent forcing different in mergers?

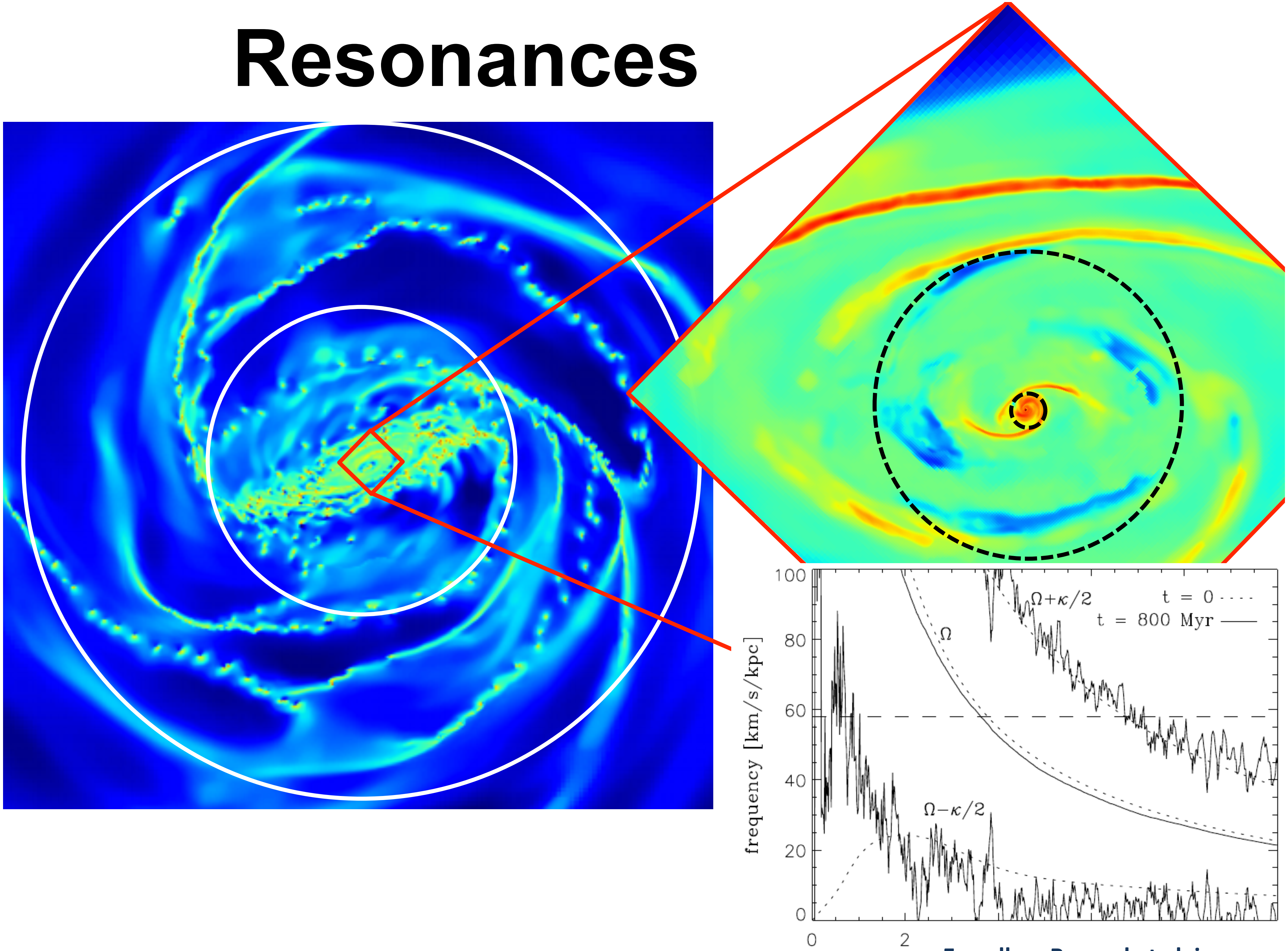
Is usual regulation overcomed? *(see Federrath+12 idealized turbulence models)*

Is star formation different in galaxy centers?



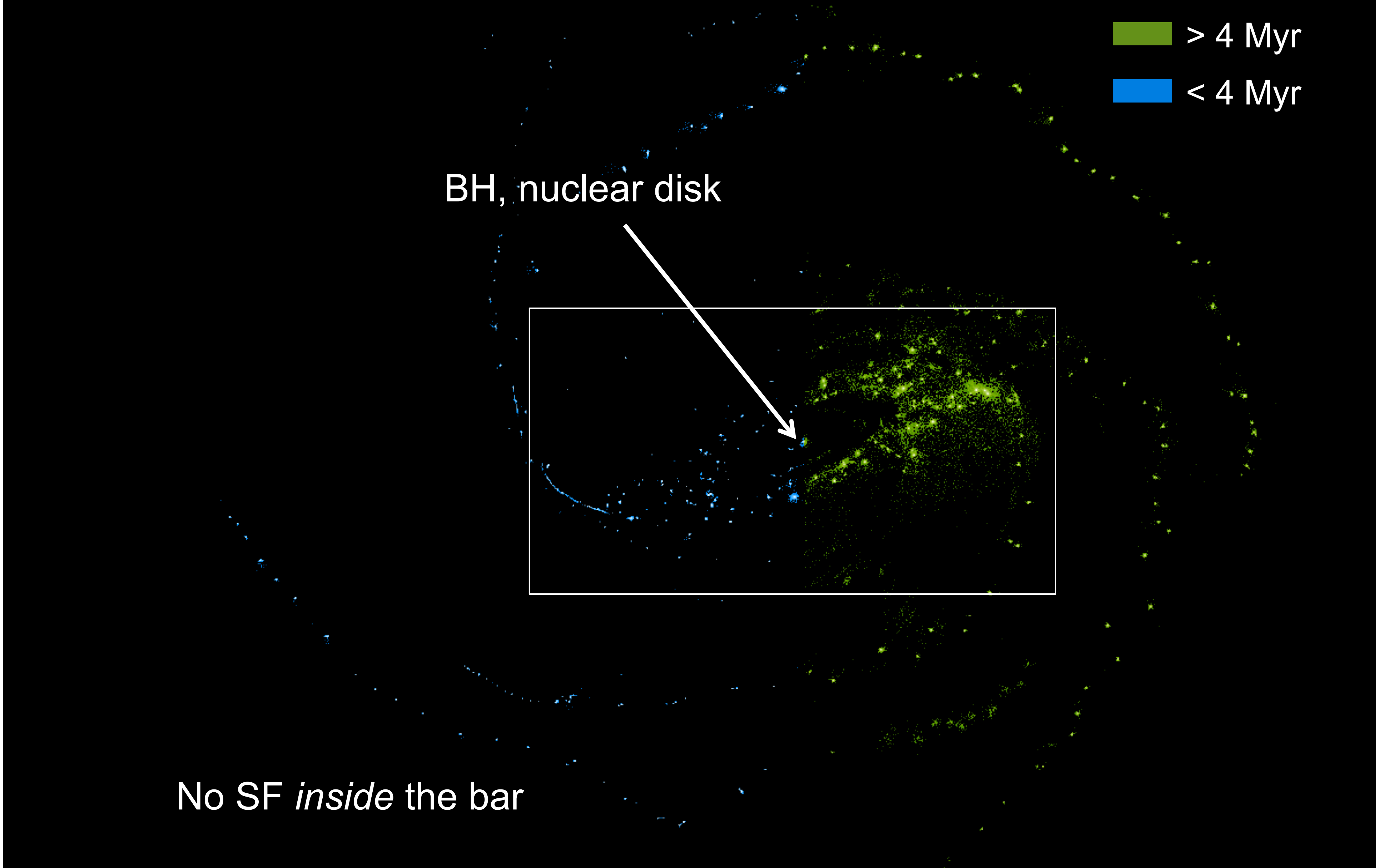
***Renaud et al. 2013*, sub-pc-scale MW simulation**
Central SF analysis by *Emsellem et al. in prep.*

Resonances



Emsellem Renaud et al. in prep

Sites of Star formation

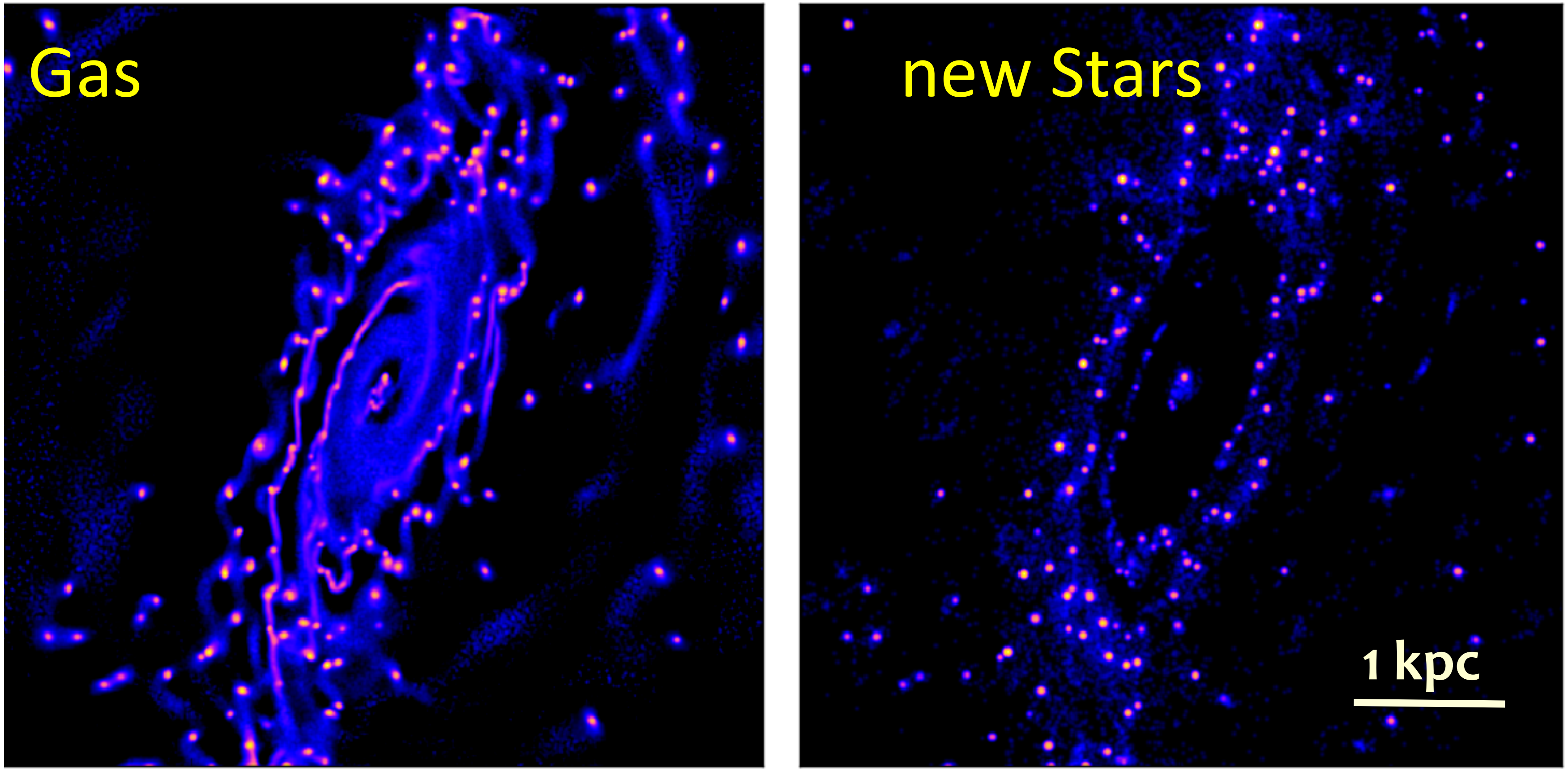


Emsellem Renaud et al. in prep

Star formation versus Gas

- *Inflow of gas*
  - ➔ *star forming regions only in the inner ring*

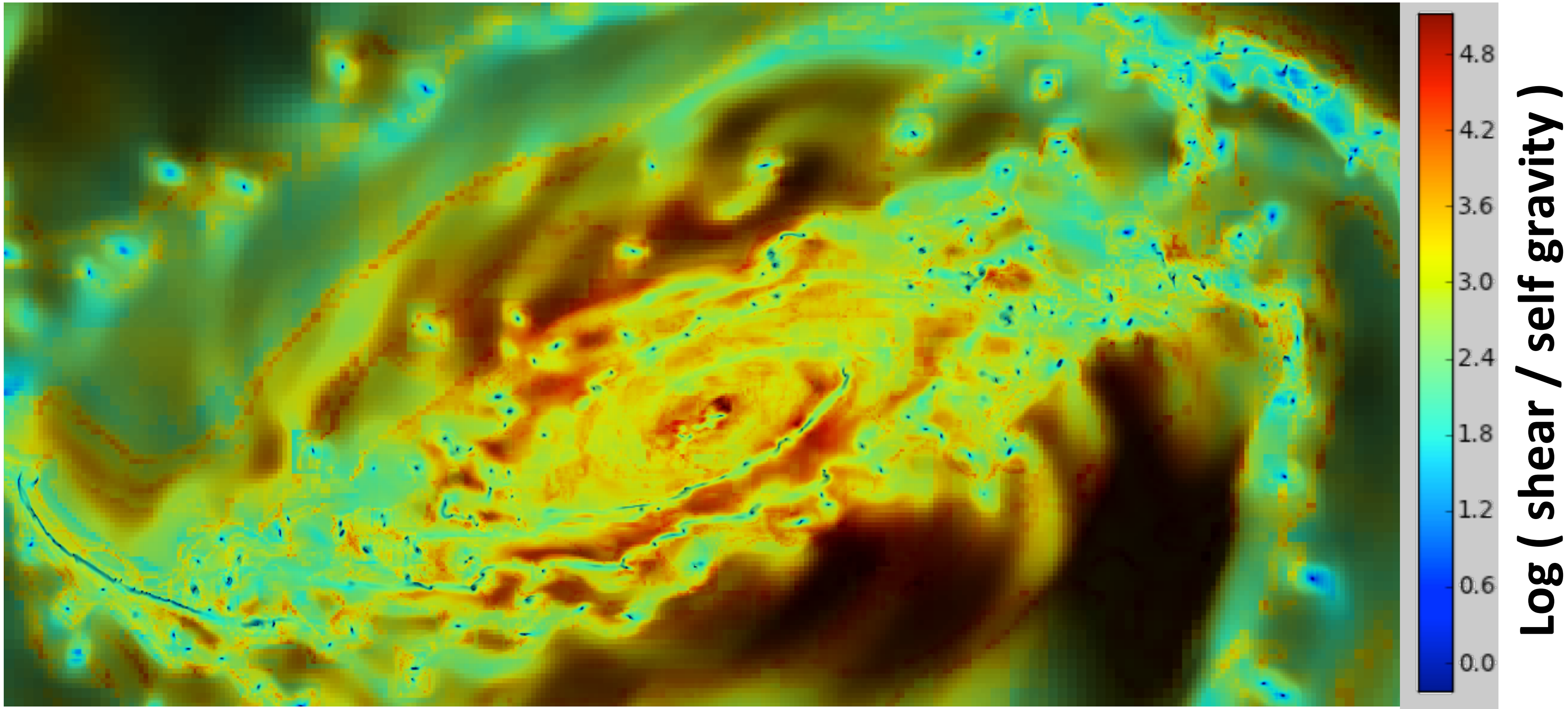
(this would probably not be the same at lower resolution)



Emsellem Renaud et al. in prep

Star formation in the Bar

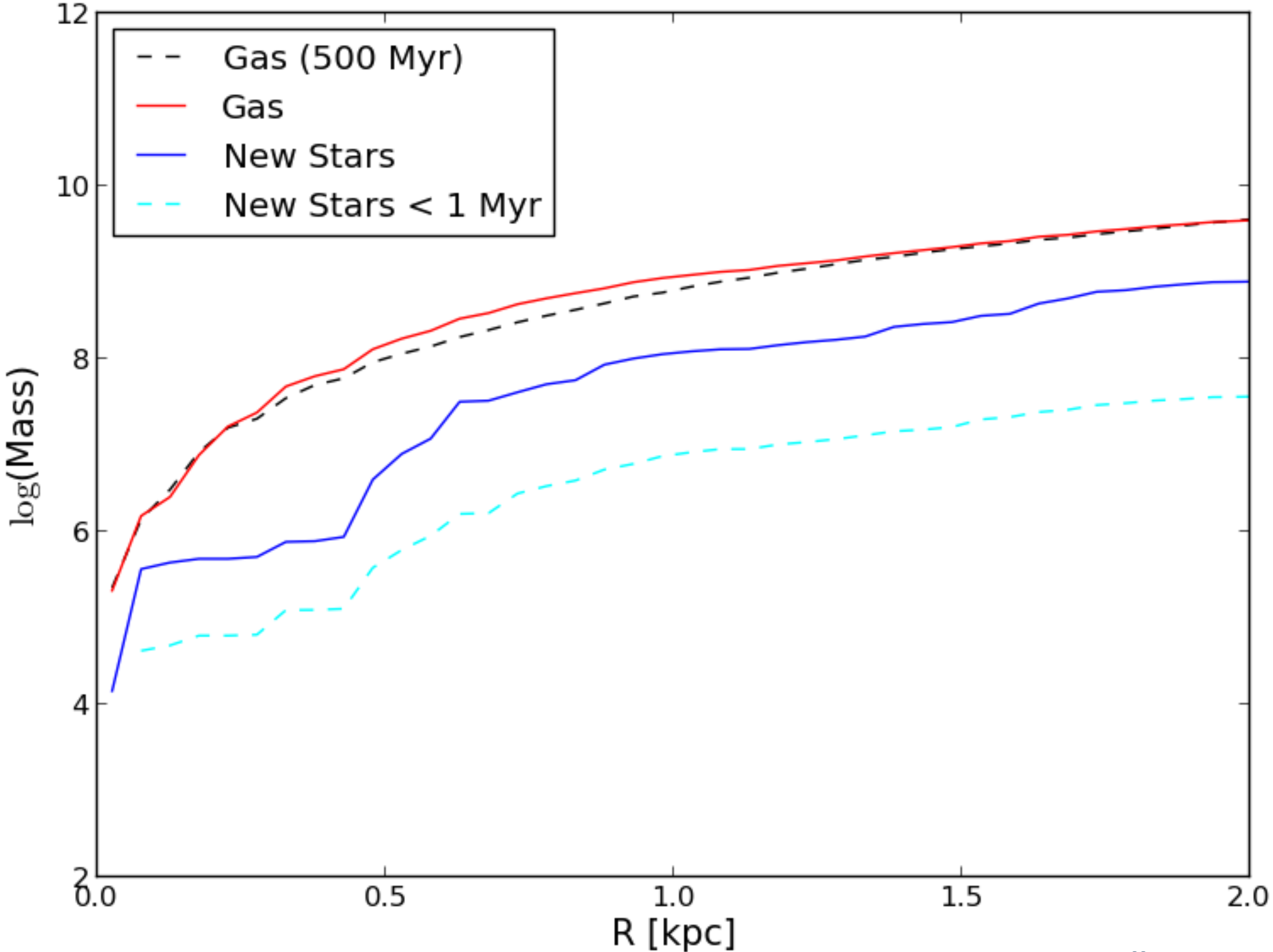
- *Shear and Tidal forces*
  ➔ *tidal forces are weak within the bar*



Emsellem Renaud et al. in prep

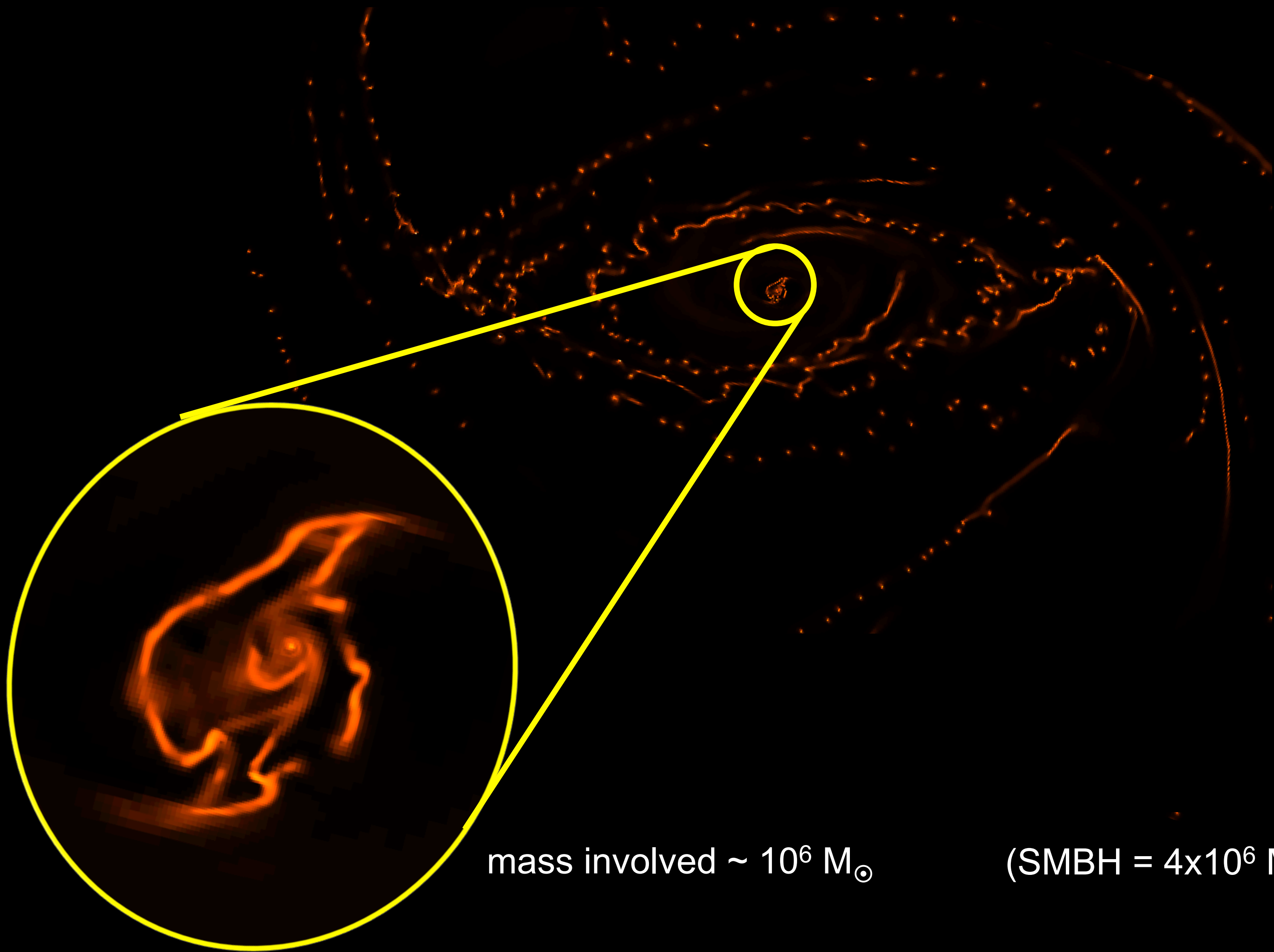
Gas inflow within the bar

- *A few 10^7 Msun of gas inside 2 kpc*
- *But star formation does NOT just follow the gas inflow*



Emsellem Renaud et al. in prep

Central Structure

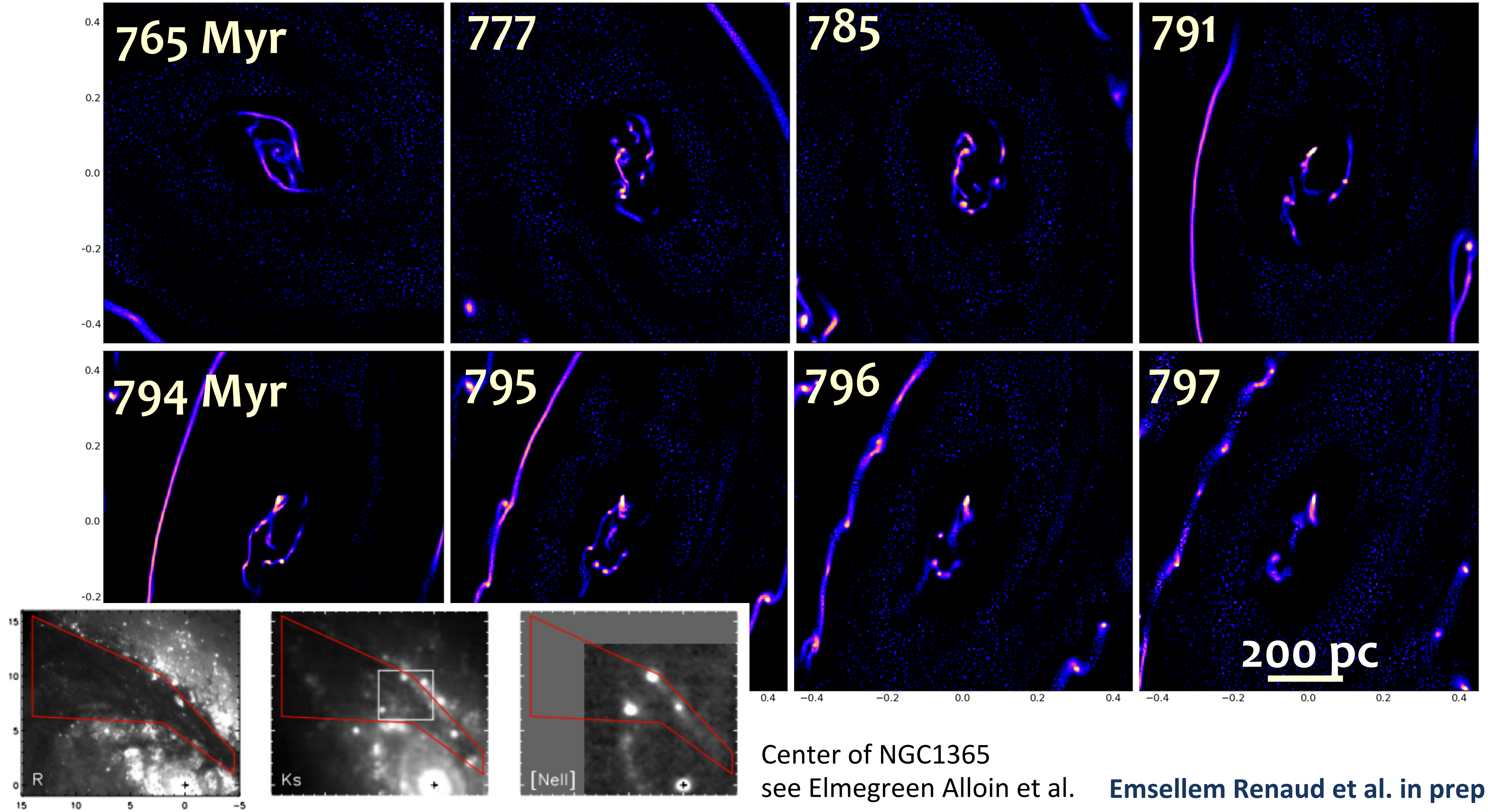


mass involved ~ $10^6\ M_\odot$ (SMBH = $4\times10^6\ M_\odot$)

Emsellem Renaud et al. in prep

The central 200pc

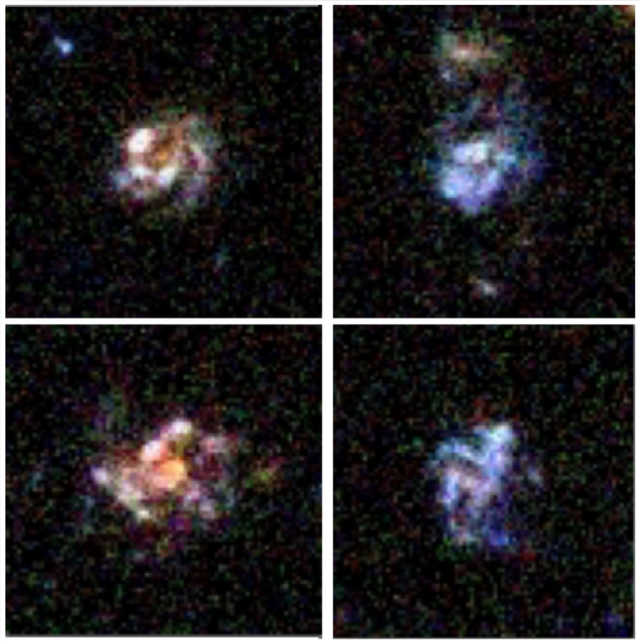
- *Accumulation of gas ➔ formation of a ring-like structure*
- *Fast evolution and collapse ➔ SF versus AGN*
- *Fueling cycles*



Center of NGC1365
see Elmegreen Alloin et al.

Emsellem Renaud et al. in prep

Conclusions - Star formation in high-density environments

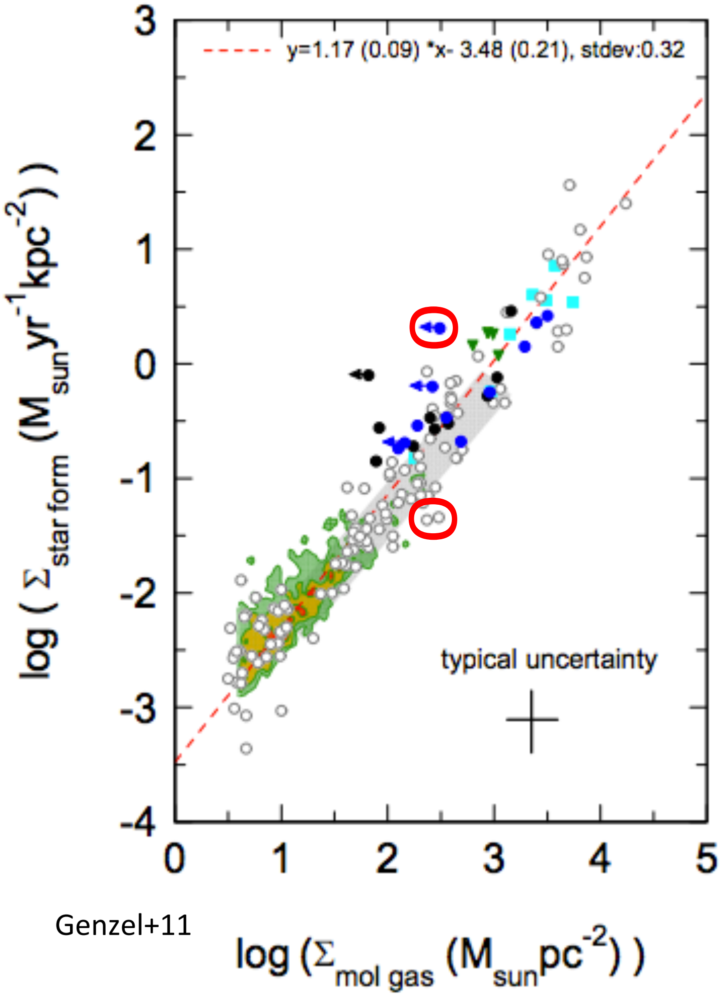


High-density doesn't imply high efficiency star formation:
High-redshift disks have very peculiar dynamics (long-lived giant clumps, mass inflows)
but their SF efficiency is just « normal »

High gas densities are met in mergers and in this case the SF efficiency *can* become much higher, for the same global surface density of gas.
This relates to stronger turbulence and dense gas excess, not nuclear inflows, but requires a different turbulent forcing to be explained (?)

At the opposite SF and nuclear fueling can be quenched and delayed, with only cyclic triggering, in the high-density centers of spiral galaxies – stellar bars impose strong shear and ILRs

Conclusions - Star formation in high-density environments



Genzel+11

"Universal timescale" ~10^9yr ?

- Correlation over 3dex
- Scatter at fixed Σ_{gas} can be 2dex

It's impossible to form many stars with little gas available; it's impossible not to form many stars when huge amounts of gas are here.

Appart from this, the efficiency does not depend just on gas density, but it depends strongly on the galactic structure and dynamics which changes the triggering/regulation balance.

High-

High-

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High

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This relates to stronger turbulence and dense gas excess, not nuclear inflows, but requires a different turbulent forcing to be explained (?)

At the opposite SF and nuclear fueling can be quenched and delayed, with only cyclic triggering, in the high-density centers of spiral galaxies – stellar bars impose strong shear and ILRs