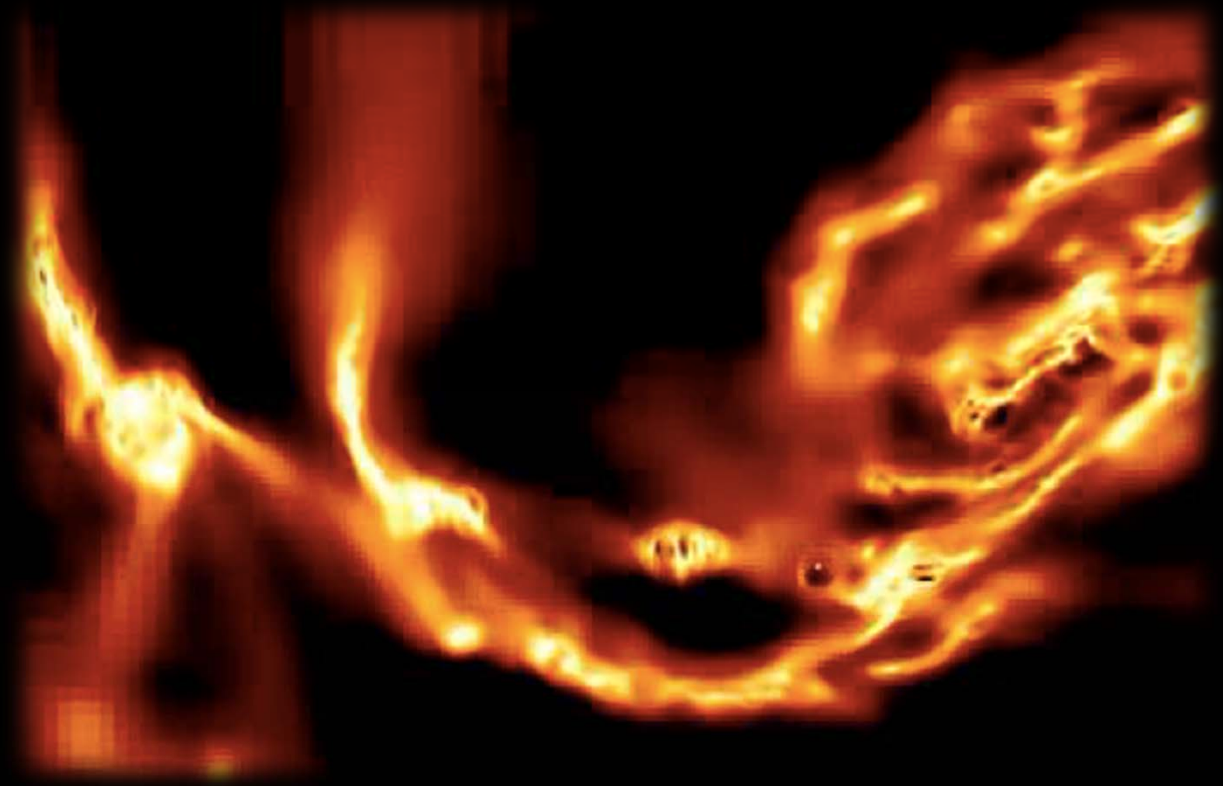
The status of numerical models of the Galactic (and extra-galactic) InterStellar Medium



Frédéric Bournaud – CEA Saclay

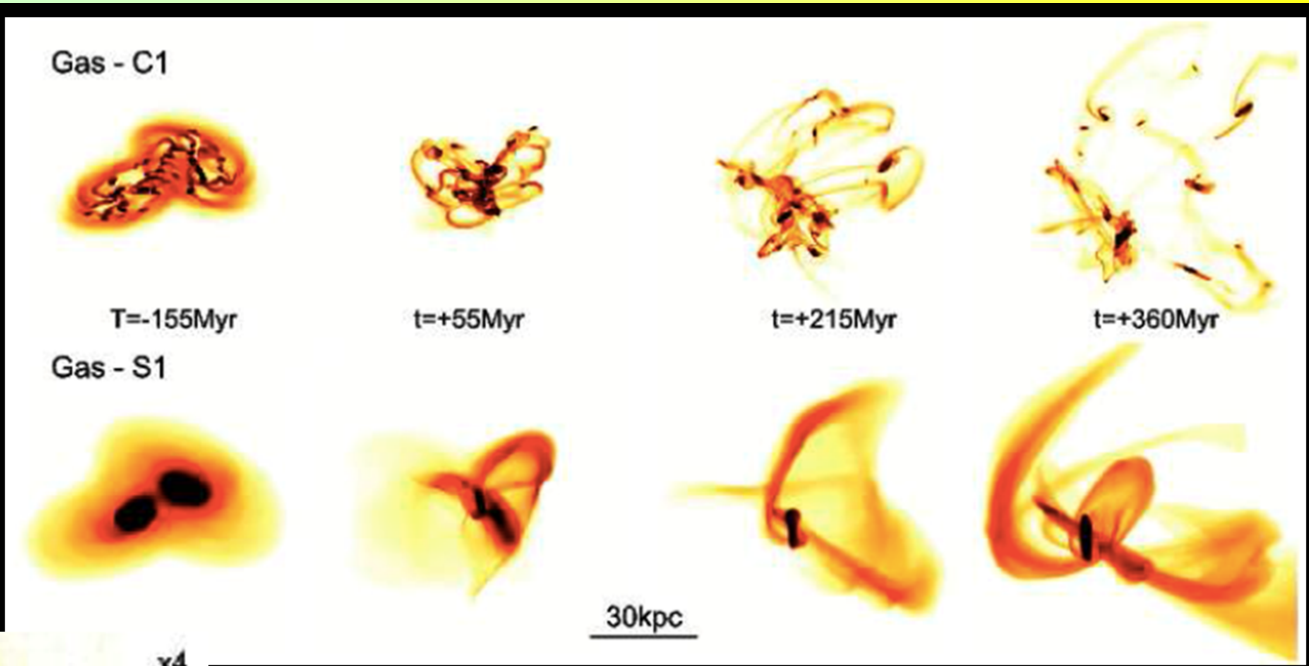
The status of numerical models of the Galactic (and extra-galactic) InterStellar Medium

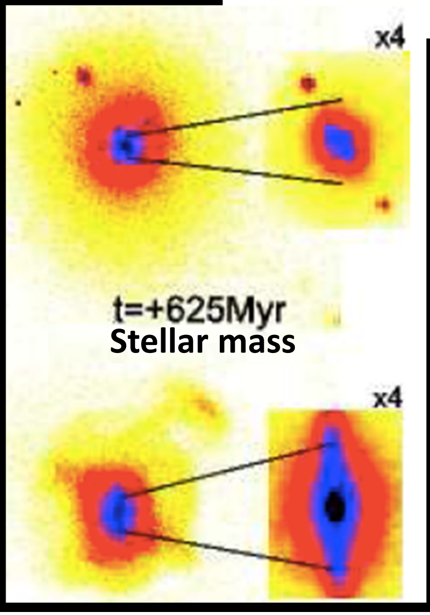
Frédéric Bournaud – CEA Saclay

The status of numerical models
of the Galactic (and extra-galactic) InterStellar Medium

Frédéric Bournaud – CEA Saclay

The strong impact of ISM physics on galaxy evolution





Model of the same high-redshift major merger with:

- a "multiphase ISM" model
  top: 6 pc resolution, cooling to 100K
- a "stabilized ISM" model
  bottom: ~100pc and >10^4K

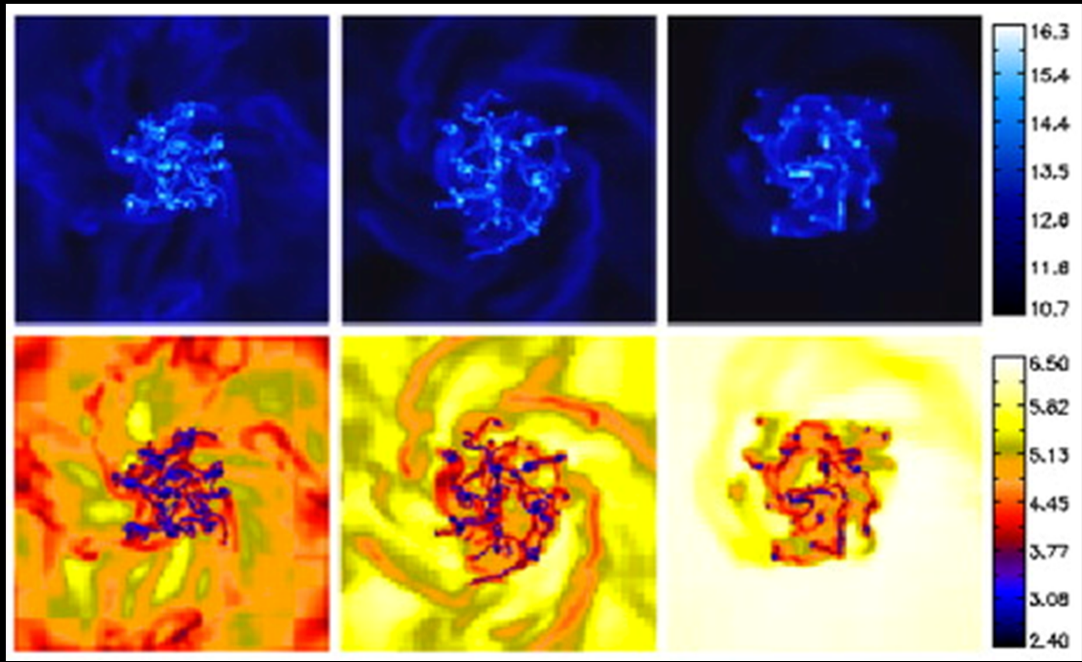
The post-merger stellar structure is fully different (left)

Bournaud et al. 2012

Disk galaxy simulations with "resolved ISM"

New generation of simulations since 2006-10, with:

- multiphase ISM structure
- entire galactic dynamics
    - Gas self-gravity
    - Accurate stellar dynamics
- star formation and feedback
    - density-based or shock-induced SF
    - molecule formation
    - supernovae explosions
    - HII regions
    - radiation pressure...



Tasker & Bryan 2006, 2008, Agertz et al. 2009

Massively parallel supercomputers
+
Numerical codes with strong scaling
(SPH, AMR, Arepo...)

=> Resolving 1-10pc, T~10-100K, $10^{2\text{-}3} M_{sun}$

=> Formation of dense (molecular) "clouds", denser substructures, response to SF..

Disk galaxy simulations with "resolved ISM"

New generation of simulations since 2006-10, with:

- multiphase ISM structure
- entire galactic dynamics
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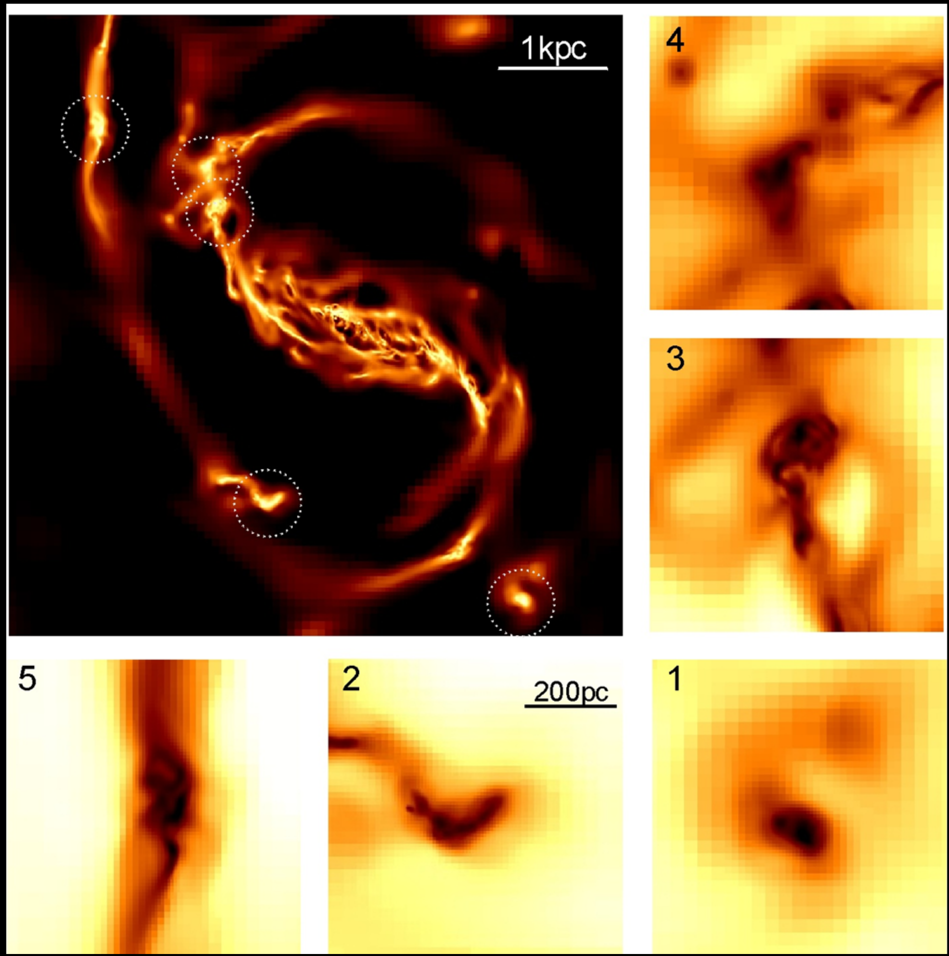
  - radiation pressure...

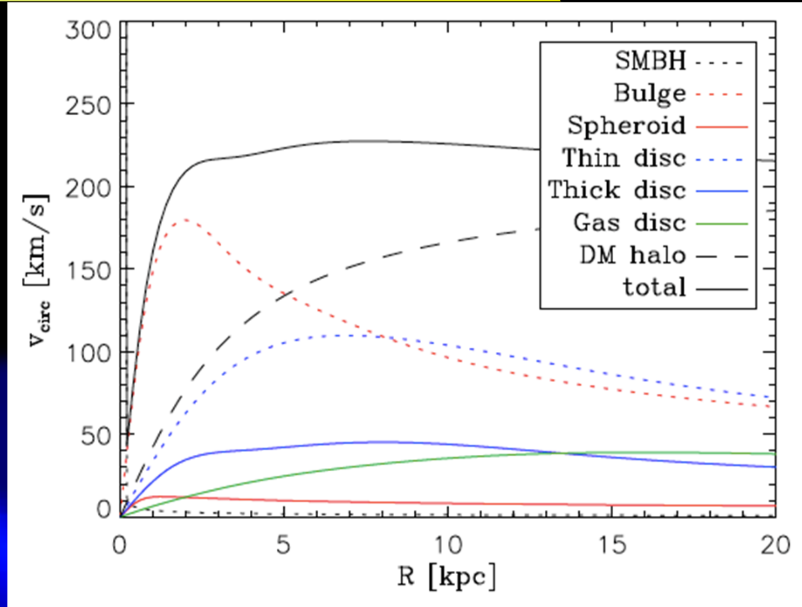


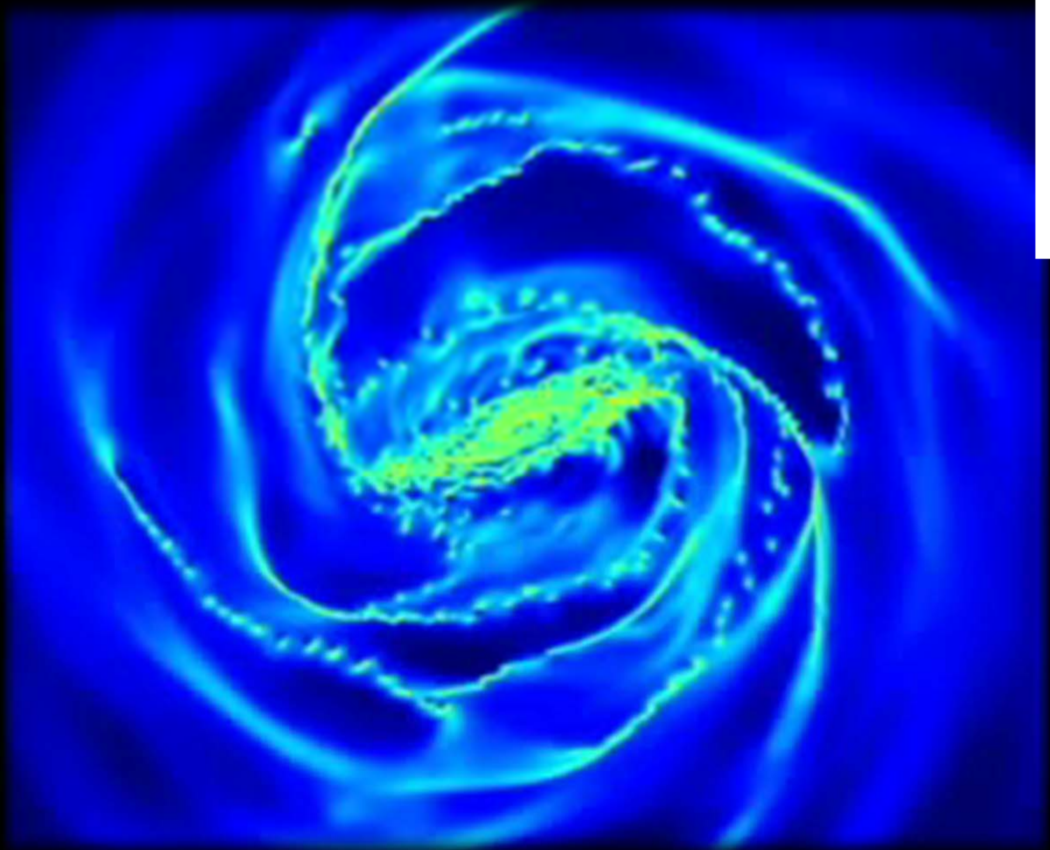
Bournaud, Teyssier, Elmegreen + 2010

=> Formation of dense (molecular) "clouds", denser substructures, response to SF..

A ultra-high resolution Milky Way model

Milky Way model based on the Besançon (Robin+05) multi-component mass model





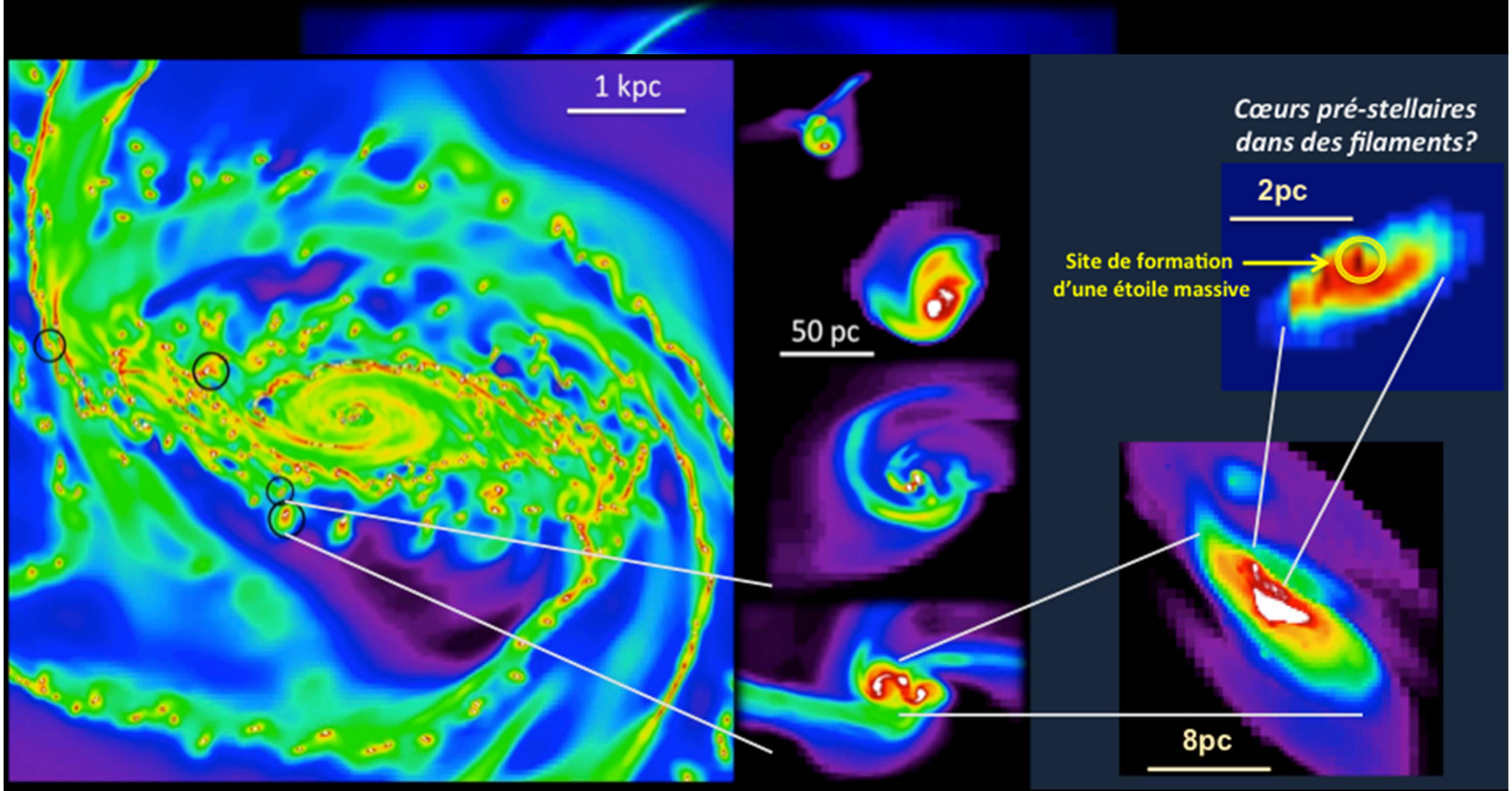
Resolution of $100M_{solar}$ and 0.05pc (for a few Myr)

Detailed stellar feedback :

Supernovae + photo-ionization (HII)
+ radiation pressure

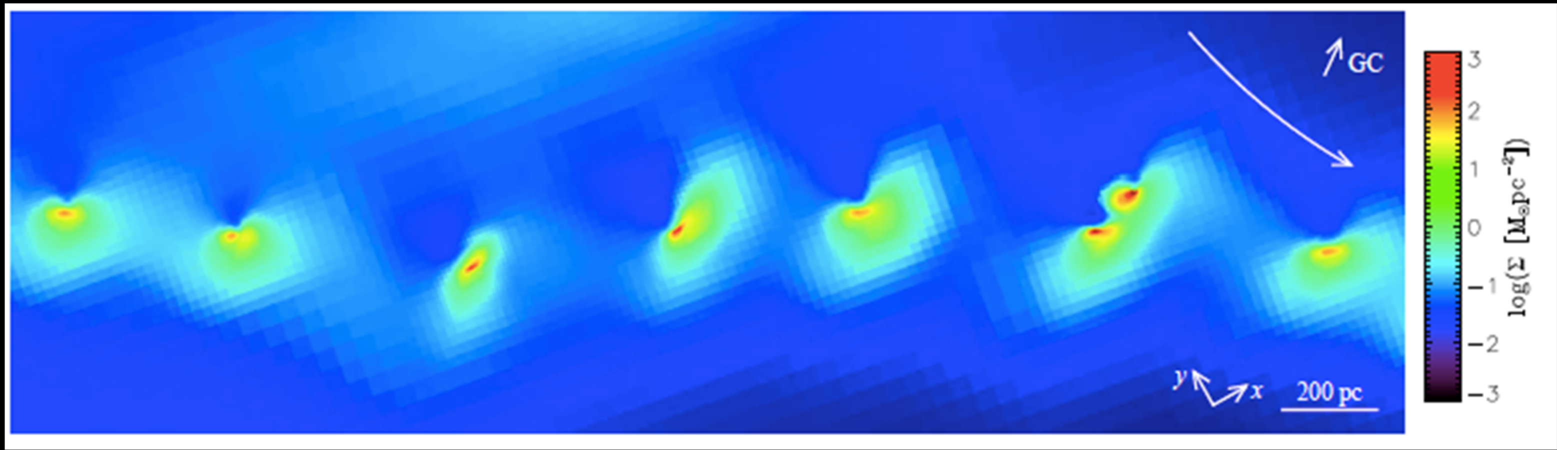
Renaud, Bournaud, Emsellem + 2013
Krlajic + 2014, Emsellem+2014

A ultra-high resolution Milky Way model



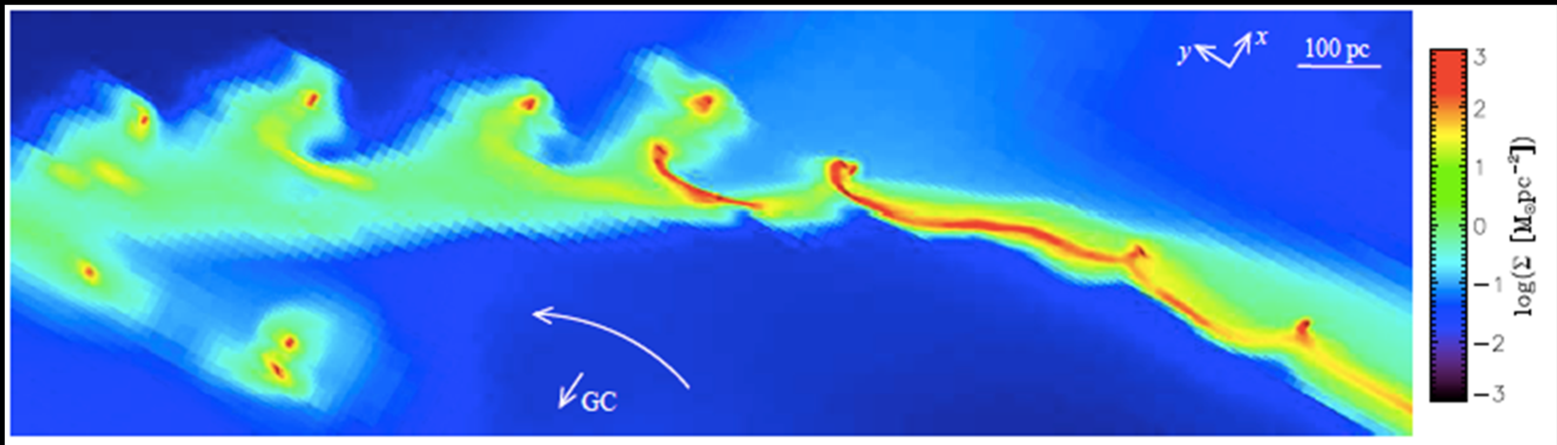
Renaud + 2013

Various families of GMCs in the Milky Way ?



”beads on string” along spiral arms

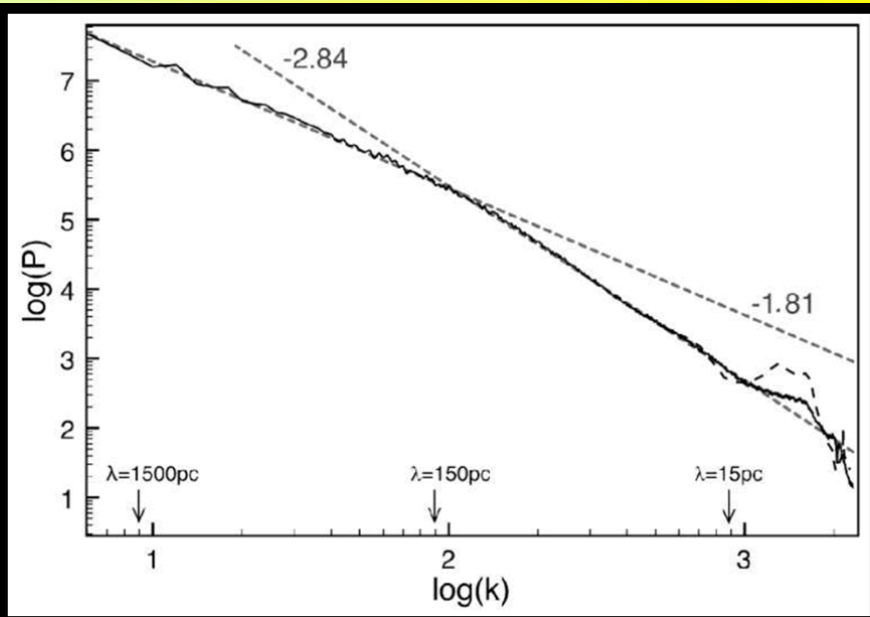
“spur clouds” on the leading side of spiral arms



Cloud type depend on $t_{free\text{-}fall}$ vs. $t_{K\text{-}H}$

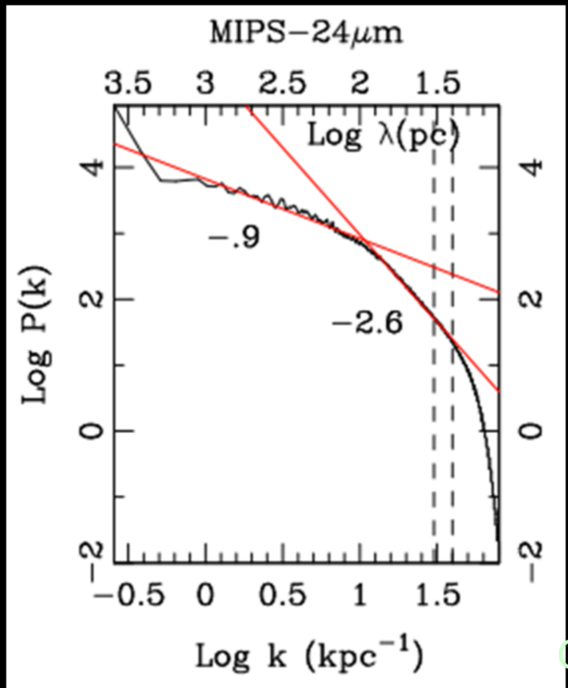
Renaud, Bournaud, Elmegreen + 2013

ISM structure in hydrodynamic simulations



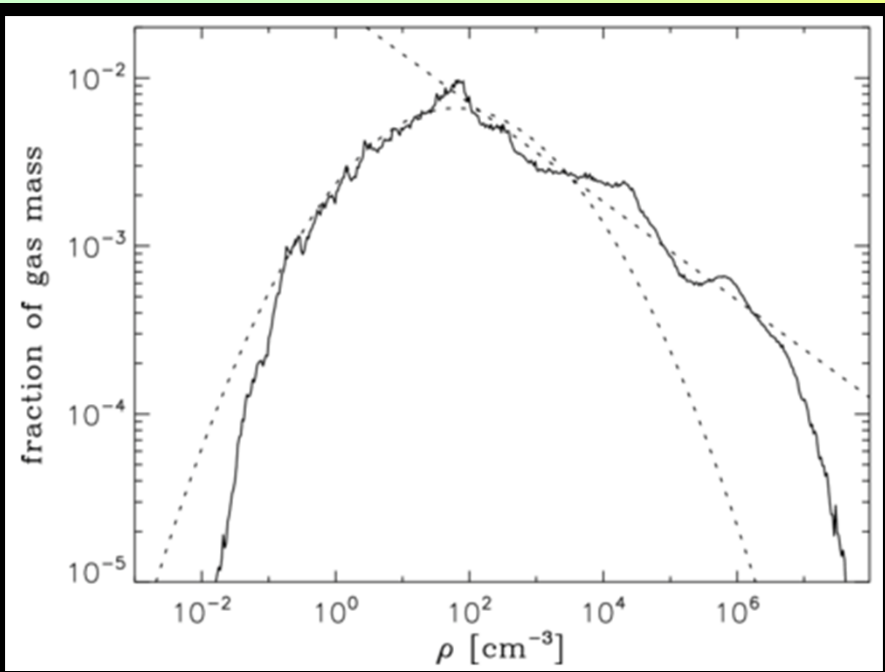
Simulation of M33-mass disk

- 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**

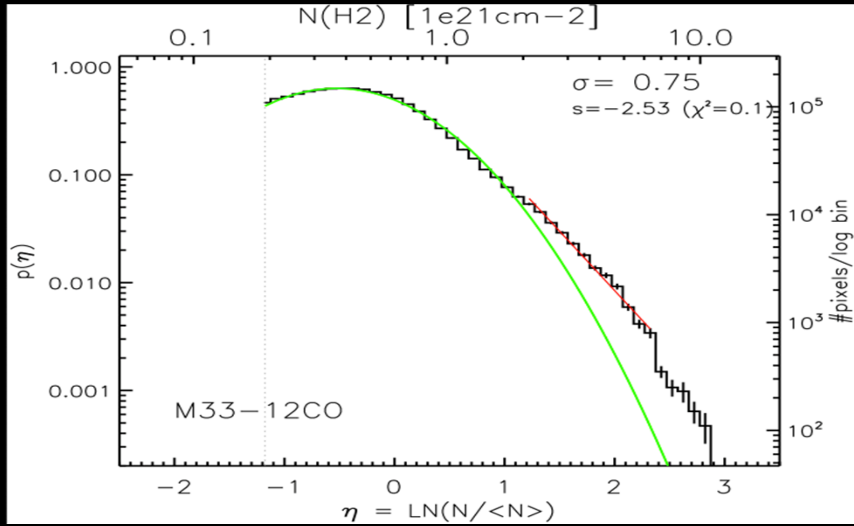


Combes et al. 2013 real M33 data

ISM structure in hydrodynamic simulations



Renaud+2013



Druart+2014

The density PDF of an entire galaxy is mostly log-normal

=> expected for “pure” supersonic turbulent pressure (e.g. Padoan & Nordlund 99)

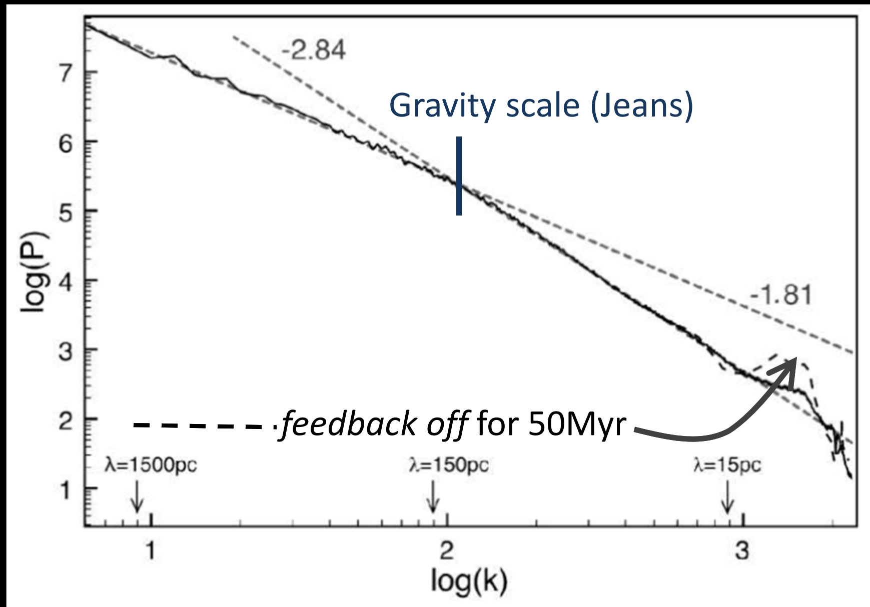
A power-law tail contains 1-3% of the ISM mass at high densities

The power-law shape is theoretically expected from self-gravity (e.g. Elmegreen 2011)

SF in inefficient on galaxy scale because the (gravity+hydro-driven) turbulence cascade forms only a limited amount of high-density gas

The drivers of ISM turbulence : gravity or feedback?

- Simulations produce a realistic power spectrum
- **Stellar feedback in only a regulation process to preserve a steady state in the turbulence cascade, but does not drive the turbulence cascade properties**
- **Turbulence cascade from gravity + hydro instabilities**



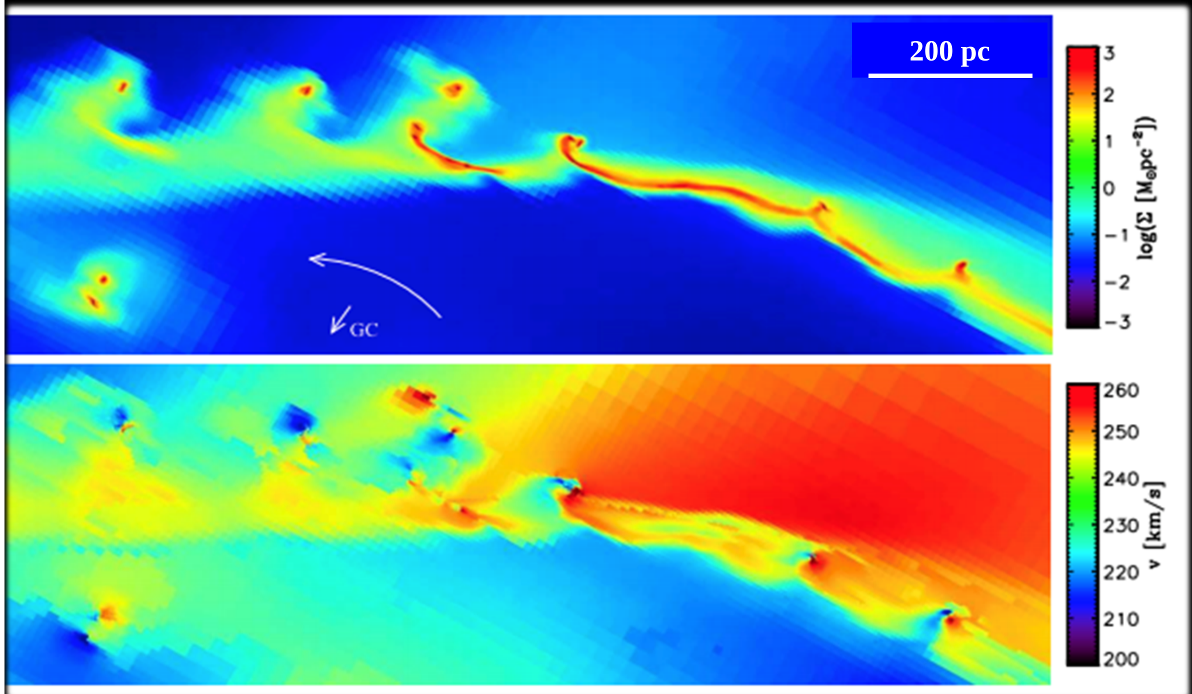
Bournaud+2010, Hopkins+2011, Elmegreen+2011, Renaud+2013

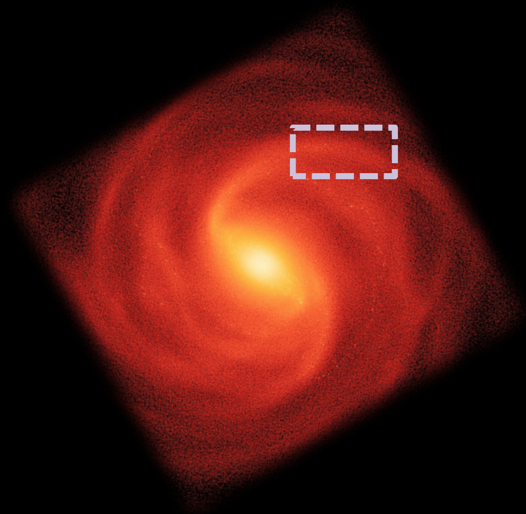
The drivers of ISM turbulence : gravity or feedback?

Shear and KH instabilities
are a nice example of :
- gravo-hydrodynamics turbulence
- regulation of star formation

Feedback not driving here

Self Gravity (including stars)
↳ Spiral Density Waves
↳ Shear and density gradients
↳ Instabilities
↳ Regulated collapse





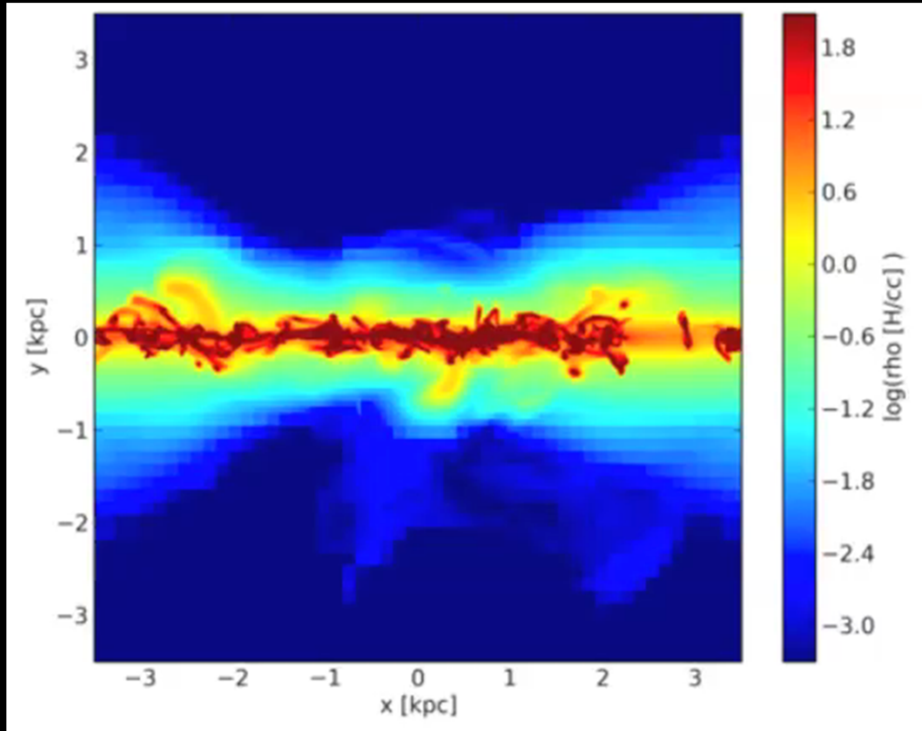
Renaud et al. 2013

Feedback, outflows, and SF efficiency

Feedback (from stars or AGN) produce outflows, the ouflow rate can reach about the SFR.

The dense star-forming regions are unaffected (new in high-res models)

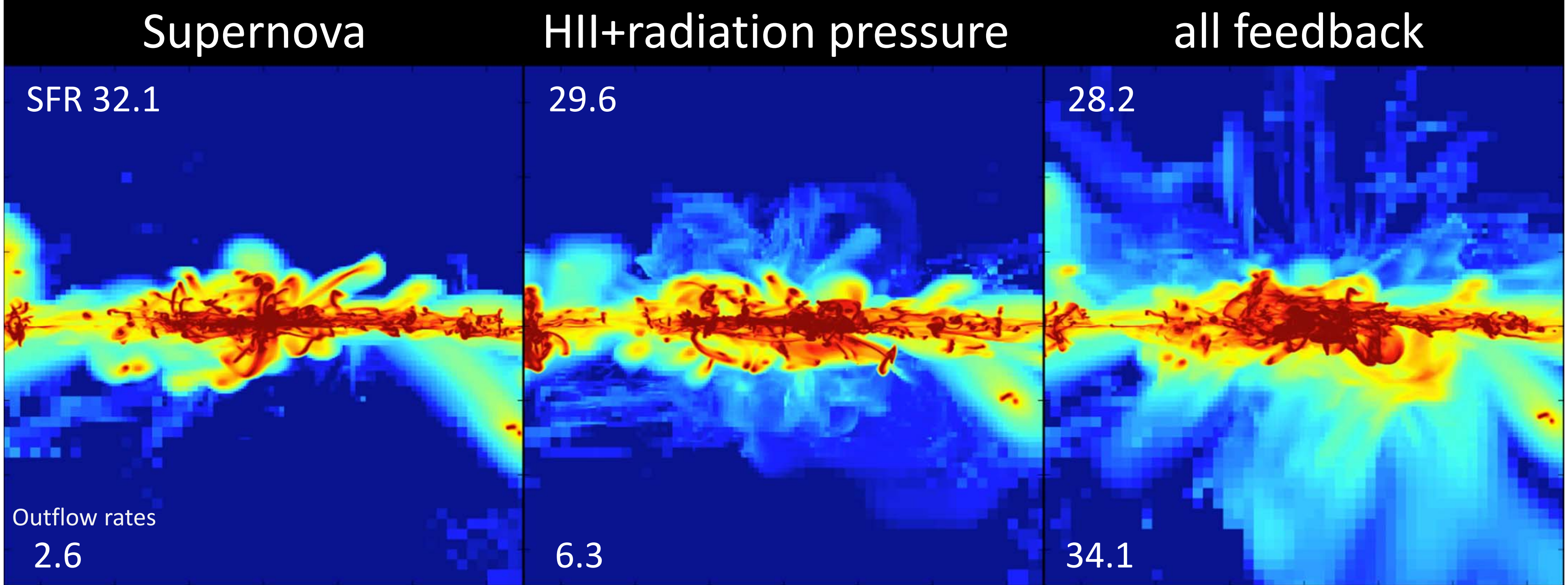
The SFR/Mgas ratio is not lowered,
The only effect on SFR is the long-term decrease in Mgas



Bournaud, Perret, Renaud + 2014

Feedback, outflows, and SF efficiency

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

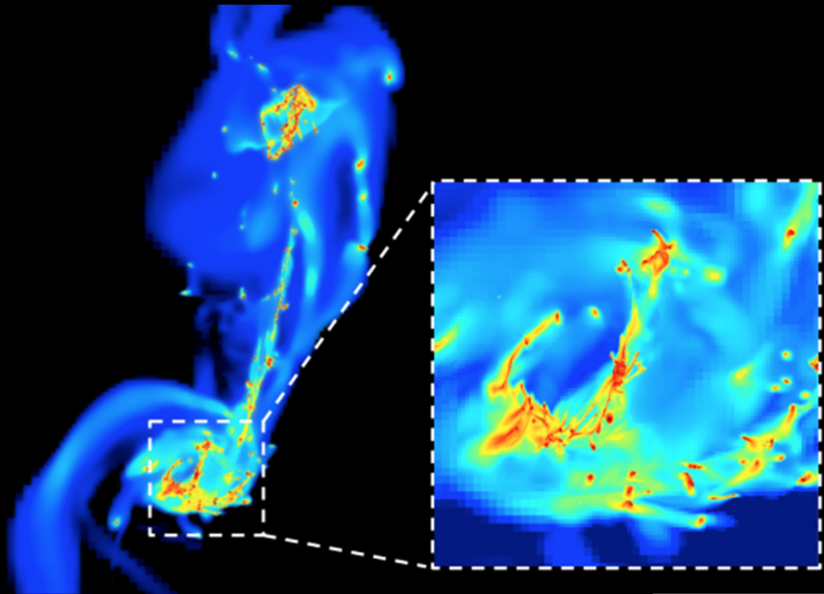


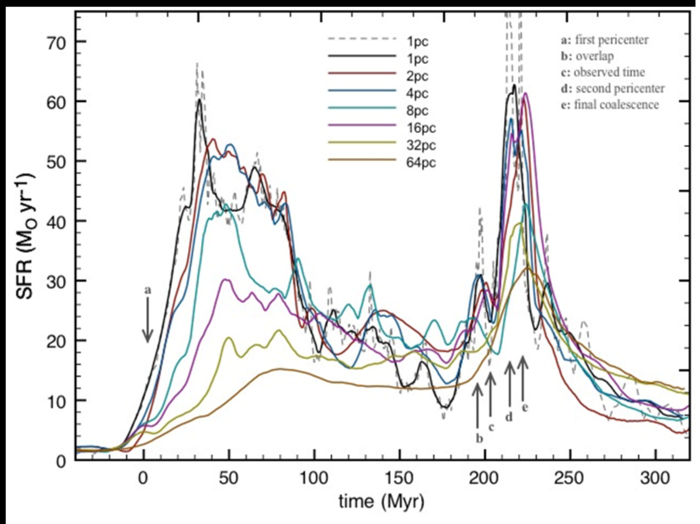
Outflow rate rapidly reaches 20-40 Msun/yr = SFR

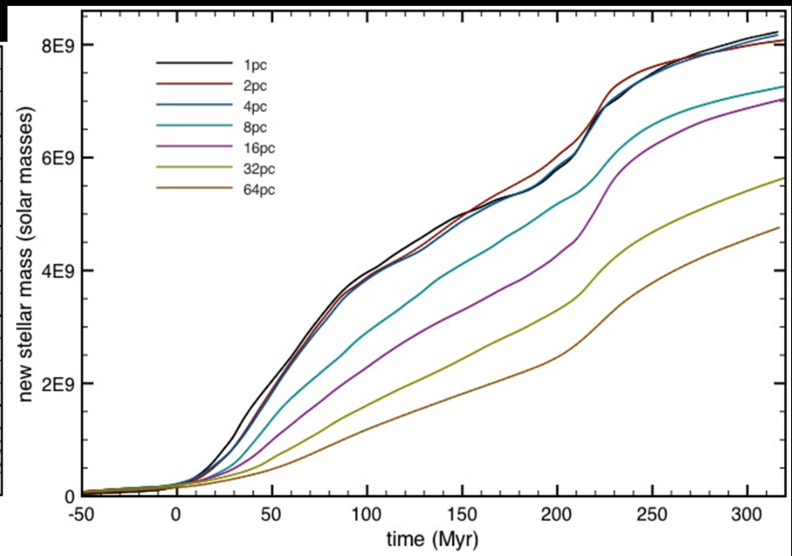
Supernovae alone don't do much

Can we trust the star formation properties?

Towards a convergence of galaxy simulations







SFR converges
at ~4pc resolution

Can we trust the star formation properties?

Towards a convergence of galaxy simulations

Simulations converge because they resolve the ISM turbulent flow structure (compressive/solenoidal modes)

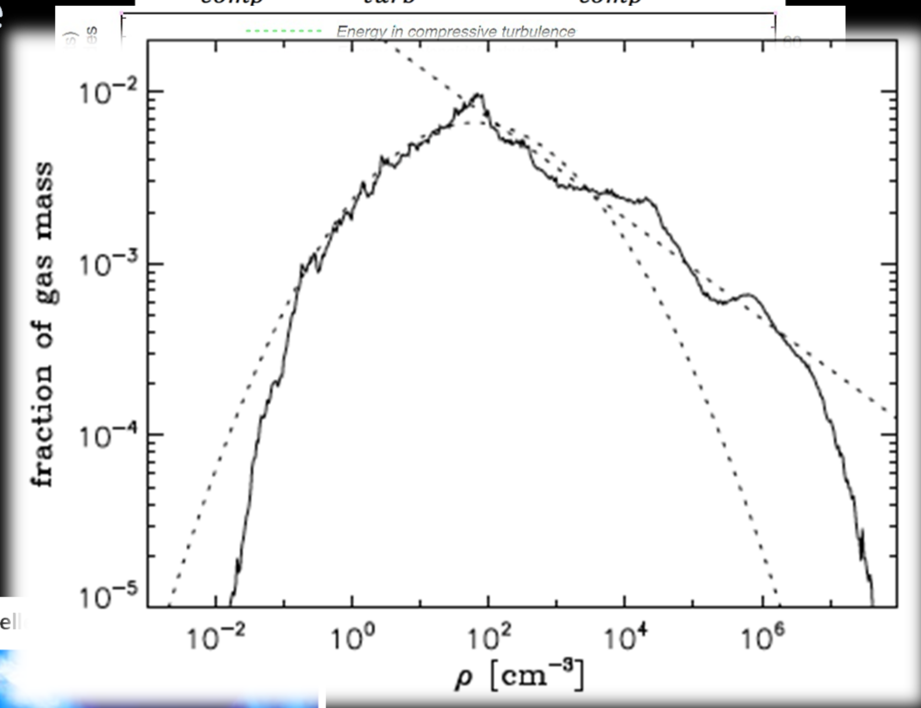
2-4pc is the typical scale

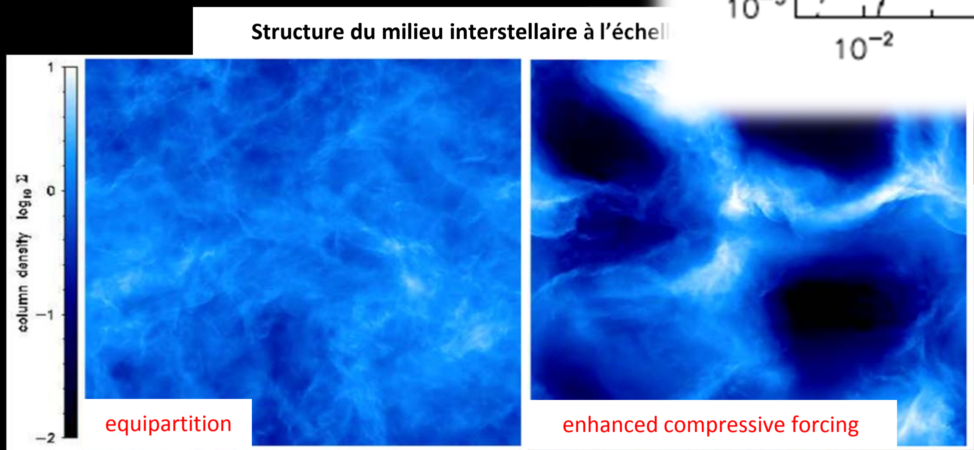
The SFR absolute value also converges
Because dense gas production is the main limitation to the SFR and is resolved

$$v_{turb} = v_{sol} + v_{comp}$$

$$\nabla . v_{sol} = 0 \qquad \nabla\times v_{sol} = \nabla\times v_{turb}$$

$$\nabla . v_{comp} = \nabla . v_{turb} \qquad \nabla\times v_{comp} = 0$$

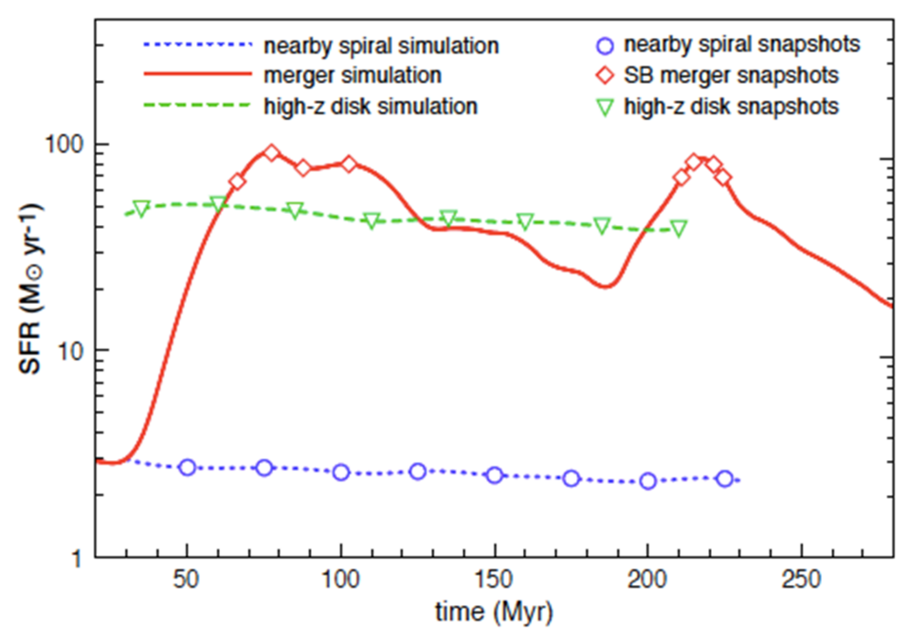




Renaud+2014
Karljic+2014

Federrath+2014

Modeling the molecular gas emission (AMR+LVG)

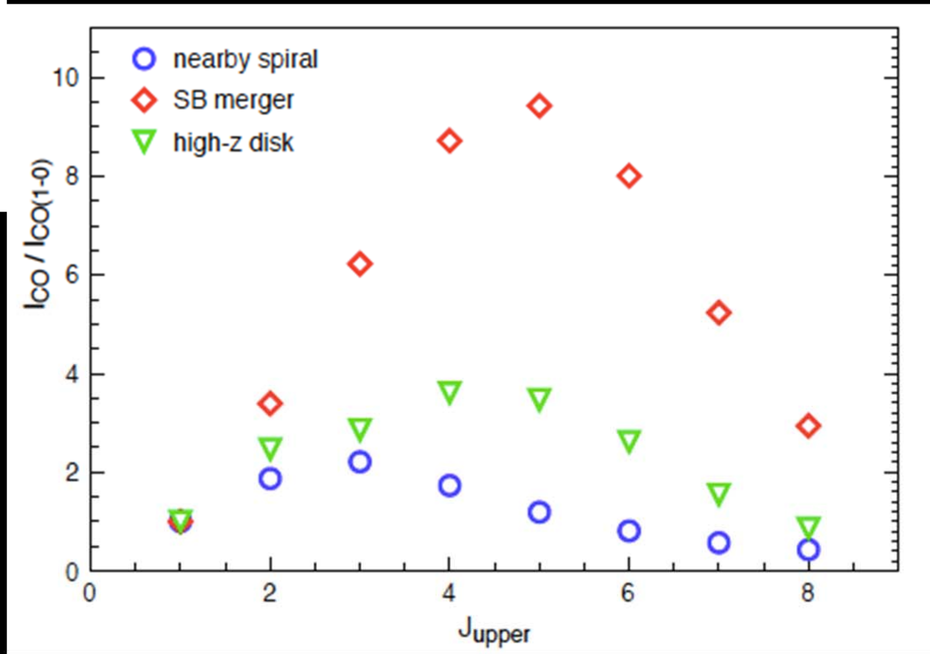


- Three simulations with identical physics

  1.5pc resolution, cooling to 10K

  low-z spiral / high-z disk / SB merger

Work at fixed Z=Zsun to probe effect of galxy type



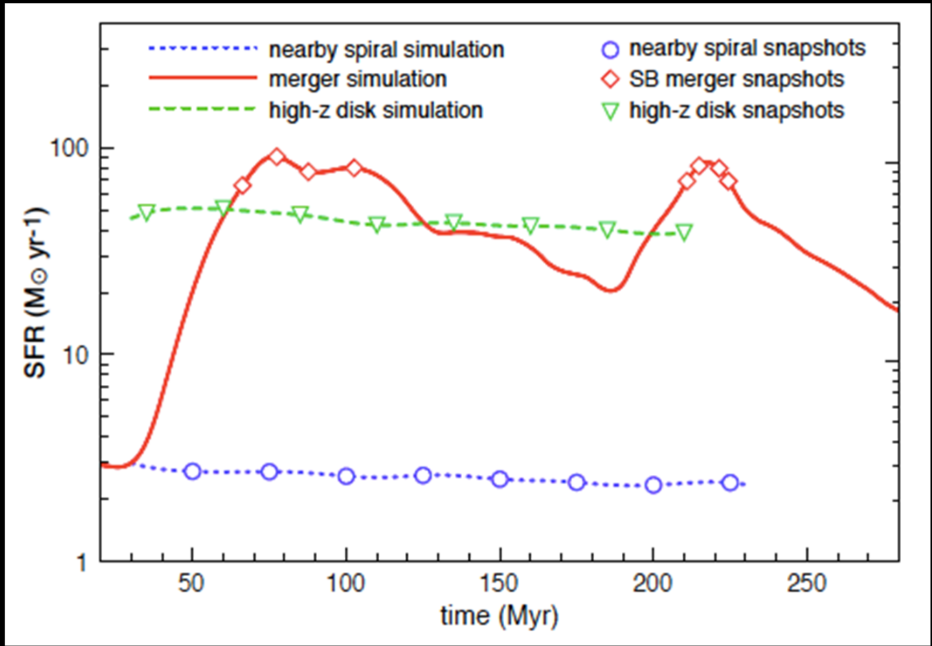
Post-processing with LVG model tables by Axel Weiss et al.

⇒ MW-like and ULIRG-like SLEDs are recovered

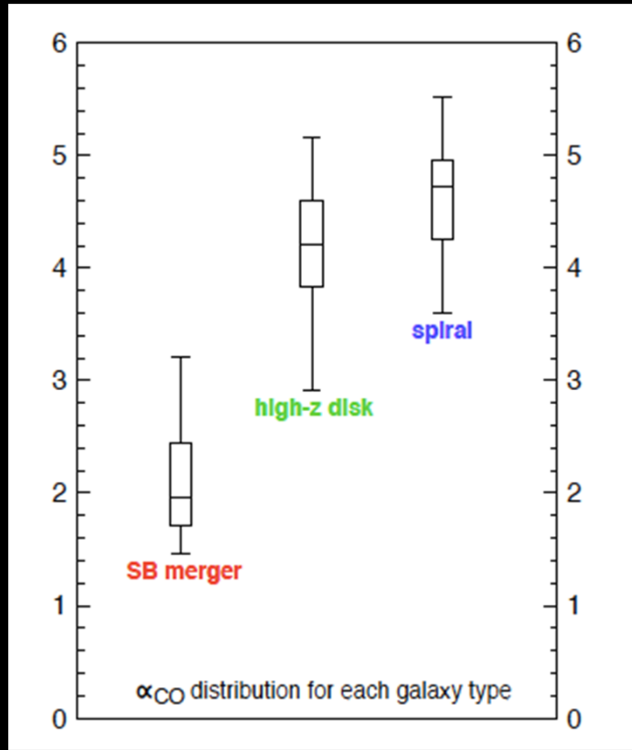
⇒ High-z disks are close to MW-like, but excess at J=4-5-6 (bumped SLED)

Bournaud, Daddi, Weiss, et al. 2014

Modeling the molecular gas emission (AMR+LVG)



Statistical α_{CO} range for many snapshots and projections



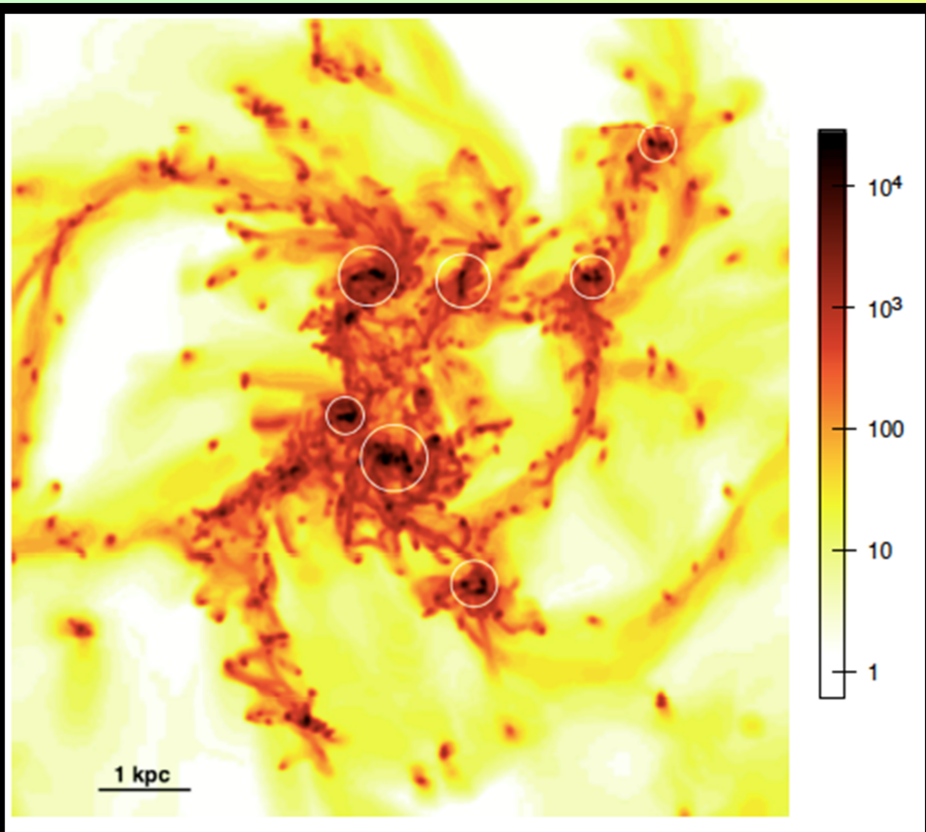
– α_{CO} depends slightly on SFR at fixed galaxy type
average change is 20% for factor 30 in SFR

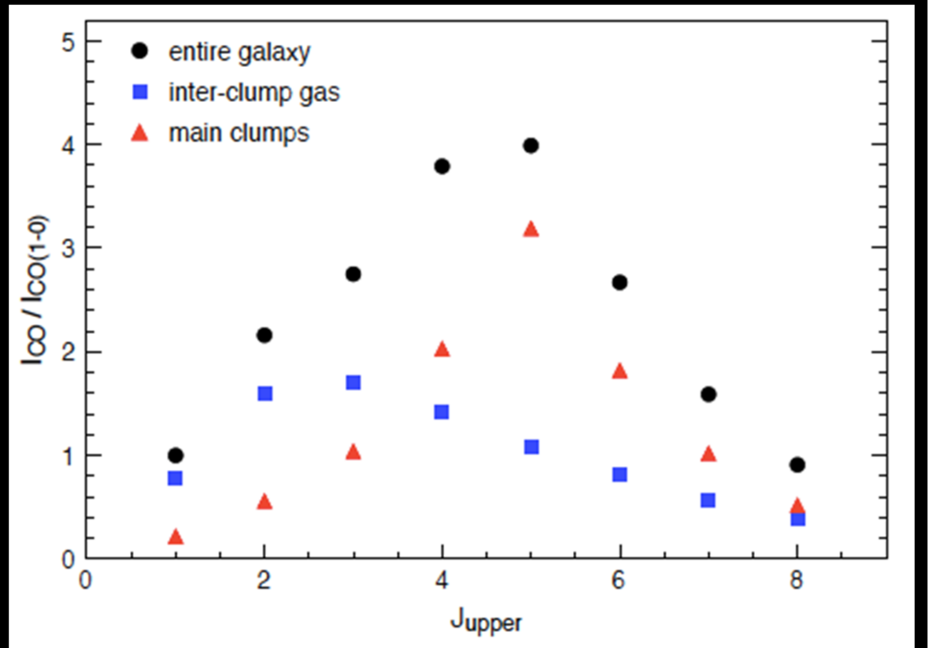
– α_{CO} depends much more strongly on galaxy type at fixed SFR
factor 2.3 between disks and mergers in the 50-100Mo yr^{-1} SFR range

There are of course other factors like metallicity, if the range of mass and Z is large

Bournaud, Daddi, Weiss, et al. 2014

Modeling the molecular gas emission (AMR+LVG)

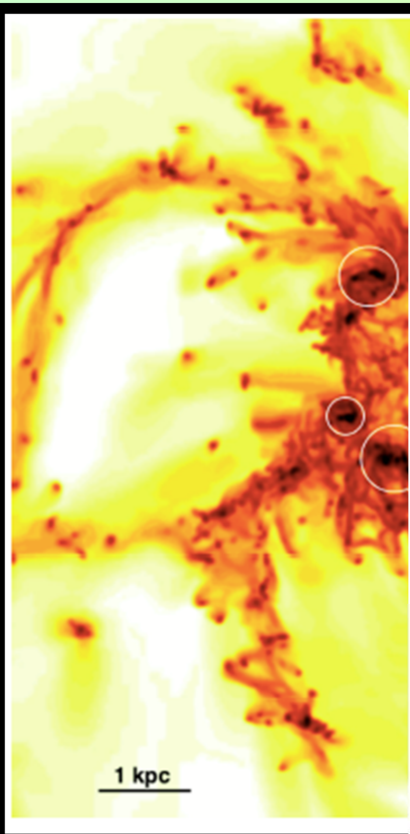


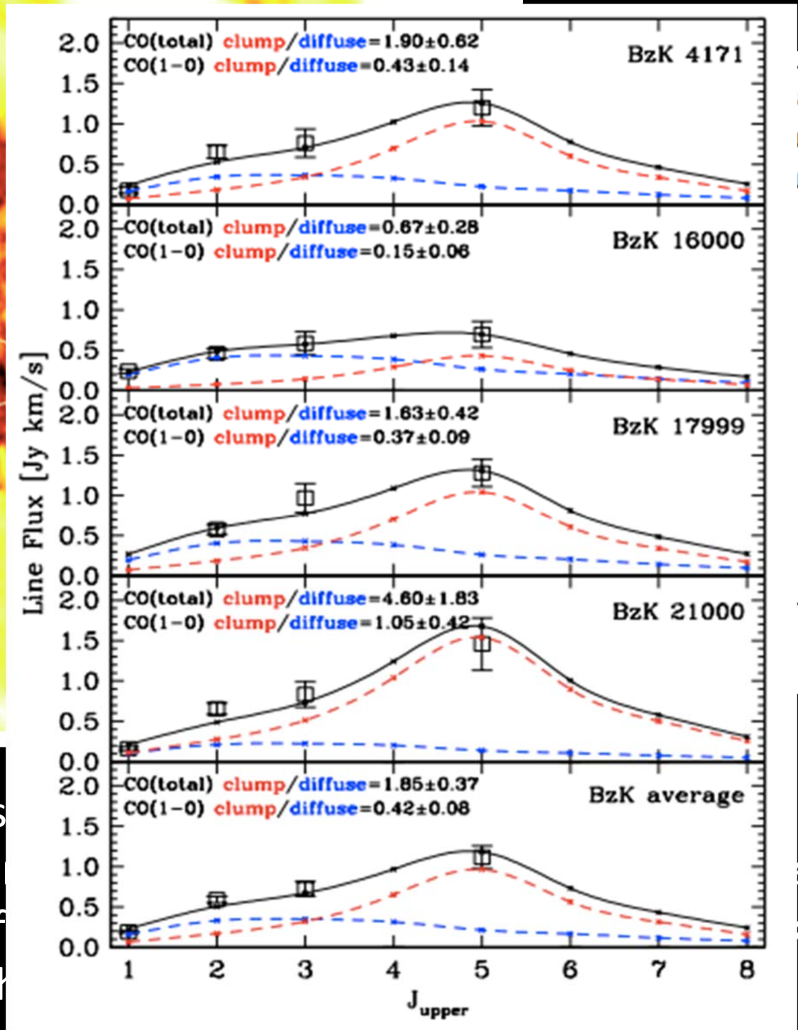


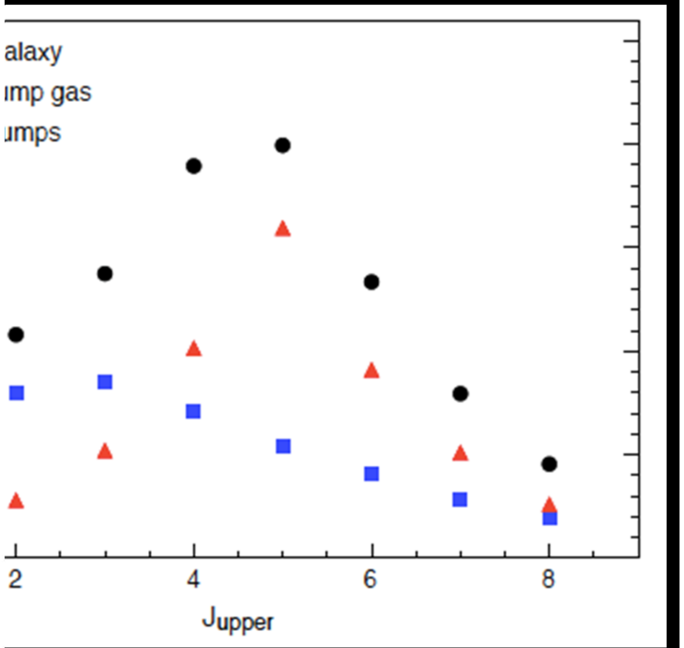
- The giant clumps are high-excitation regions
- No significant dense gas excess, but *warm* gas excess here (in the molecular phase)
- Resulting partly from excess turbulent compression/shocks, and largely from stellar feedback heating (see paper soon for details)

=> high-z star-forming galaxies should harbor bumped SLEDs, especially the most clumpy ones

Modeling the molecular gas emission (AMR+LVG)





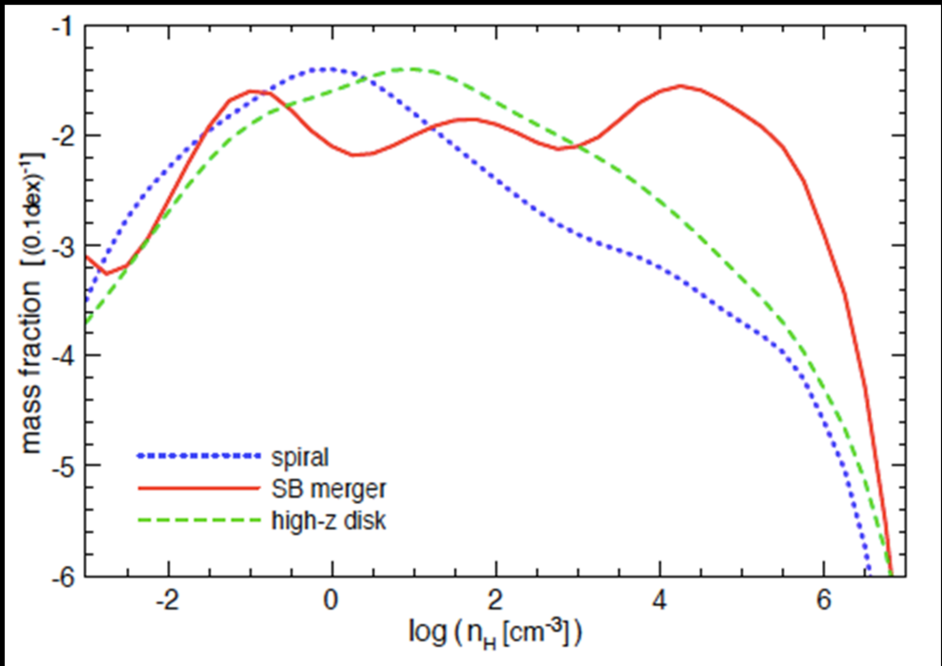


Daddi et al. 2014 in prep

- The giant clumps
- No significant de … e (in the molecular phase)
- Resulting partly f … ks, and largely from stellar feedback h

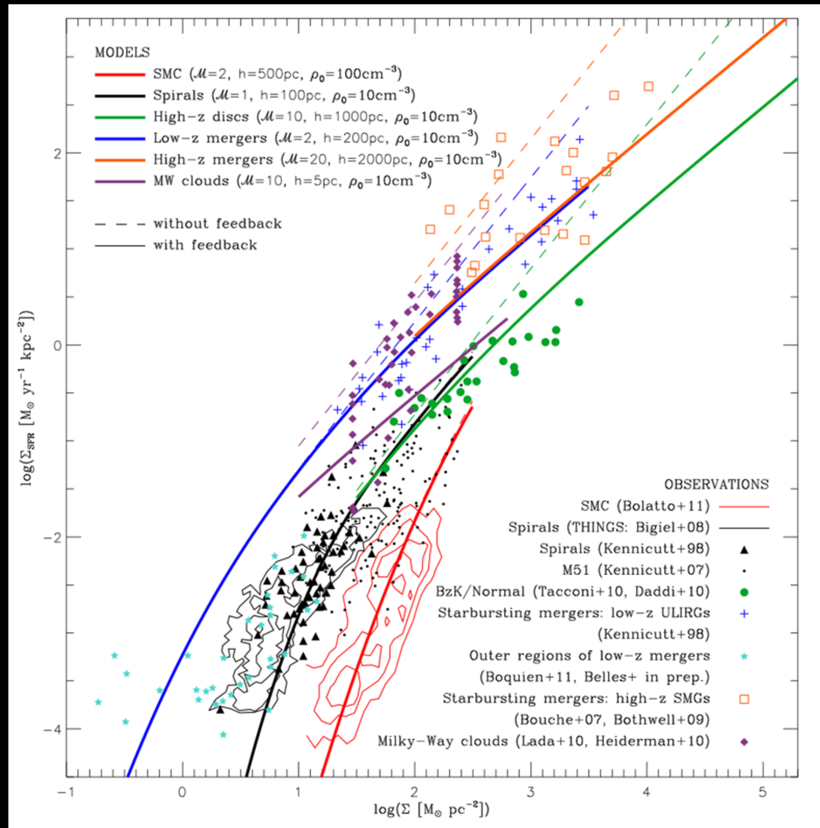
=> high-z star-forming galaxies should harbor bumped SLEDs, especially the most clumpy ones

The impact on galactic structure on ISM and SFR



Density PDF strongly depends on galaxy type

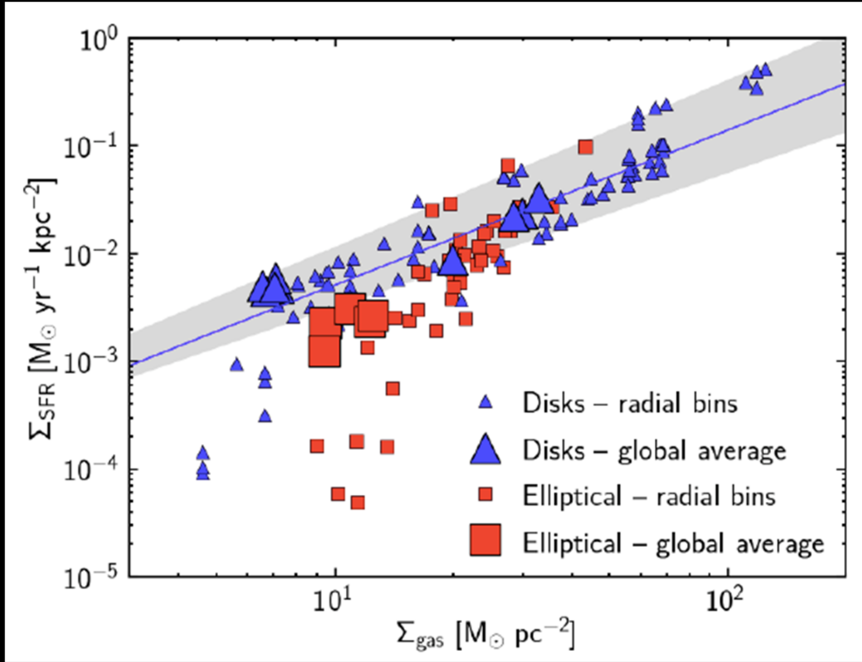
Kennicutt-Schmidt diagram strongly depends on galaxy type (observations+models)

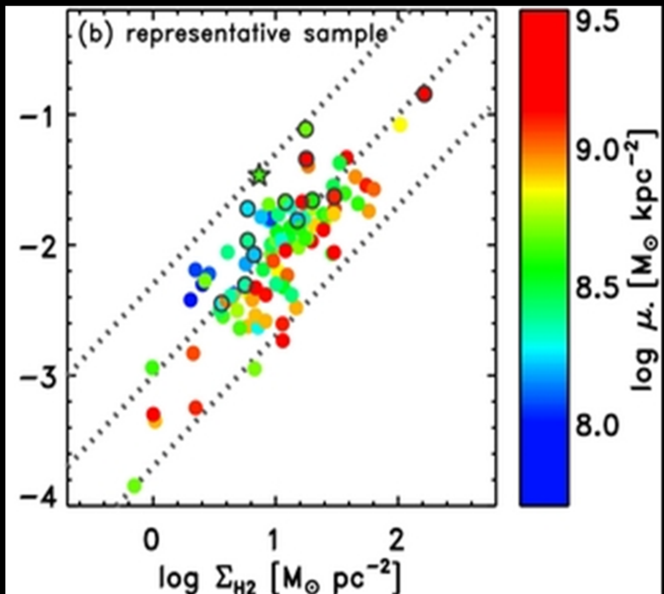


The impact on galactic structure on ISM and SFR

Simulations of spirals and ellipticals with « similar » initial gas disks

Martig et al. 2009, 2013



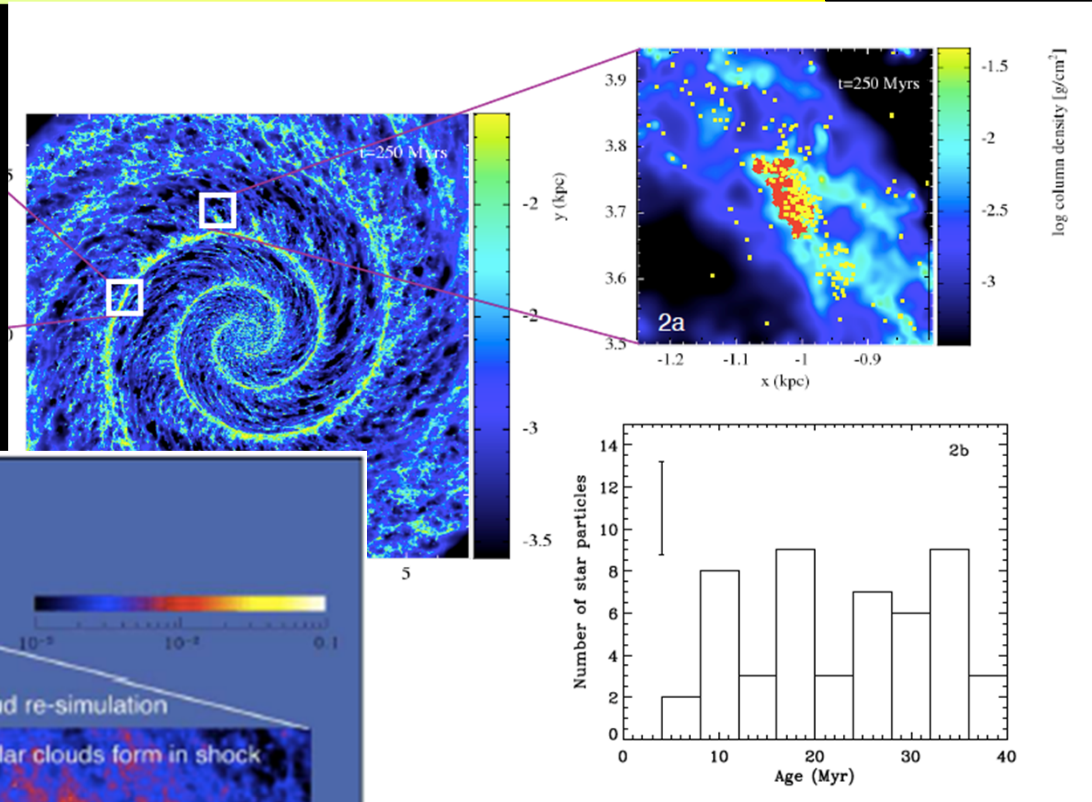


Instantaneous star formation is very inefficient compared to galaxtic dynamical timescales
COLD-GASS Survey

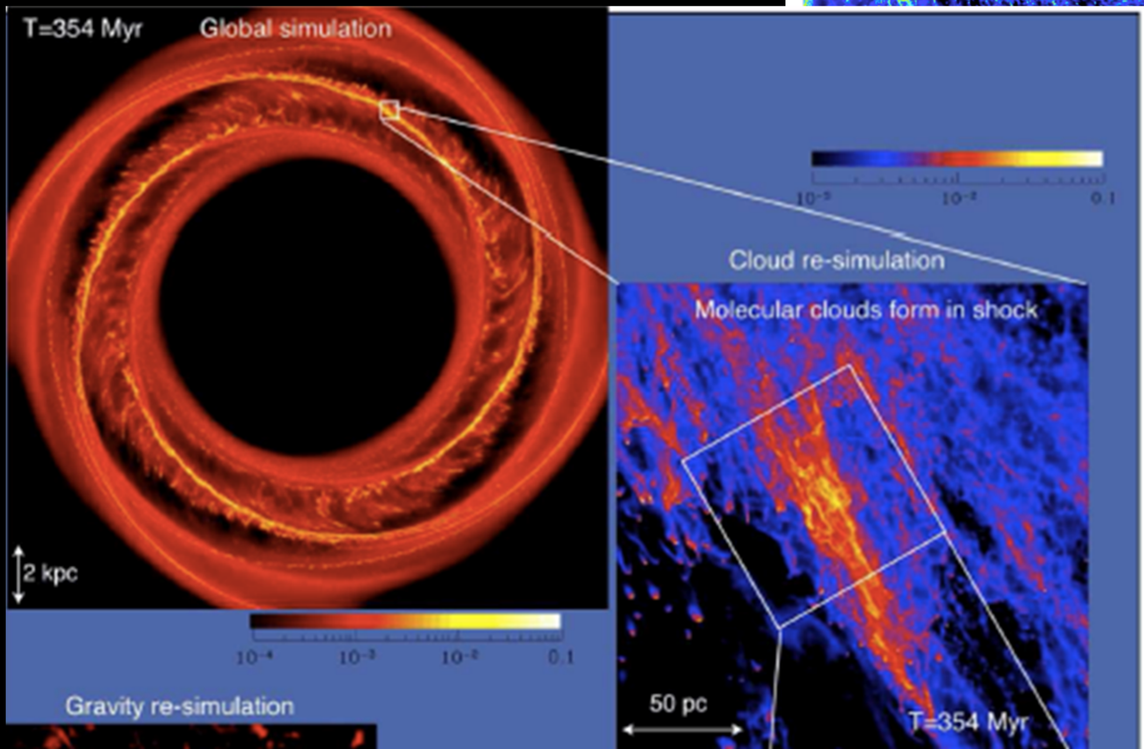
Saintonge et al. 2012

The impact on galactic structure on ISM and SFR

Simulations with simplified galactic structure have key advantages, but may include severe biases

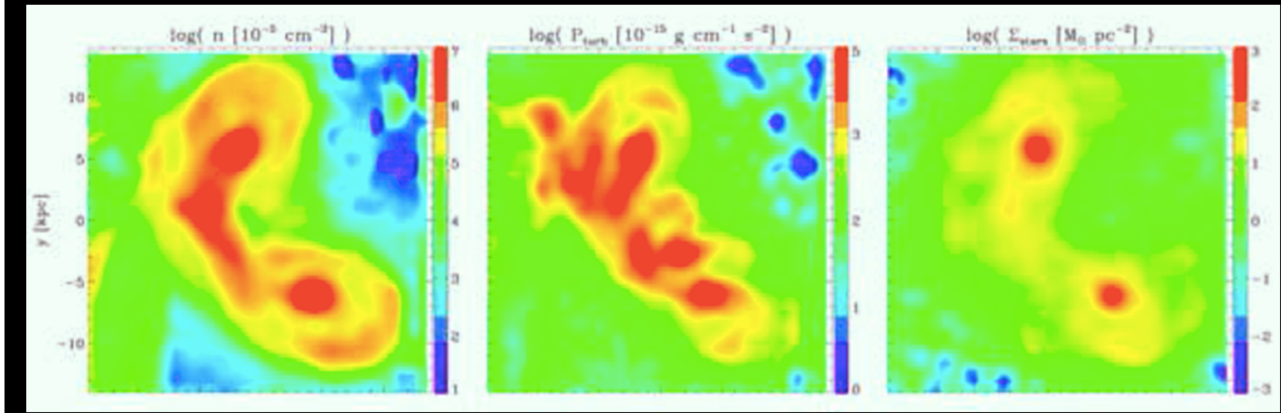


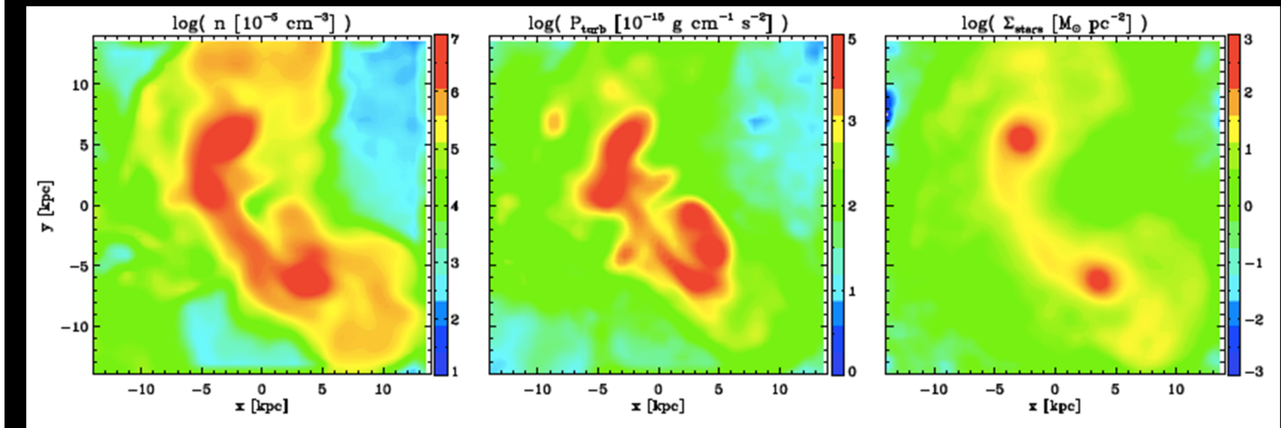
Dobbs+13



Bonnell+13

The magnetic field on galactic scales





Antennae-like merger with SPH-MHD (top)

(no B field = bottom)

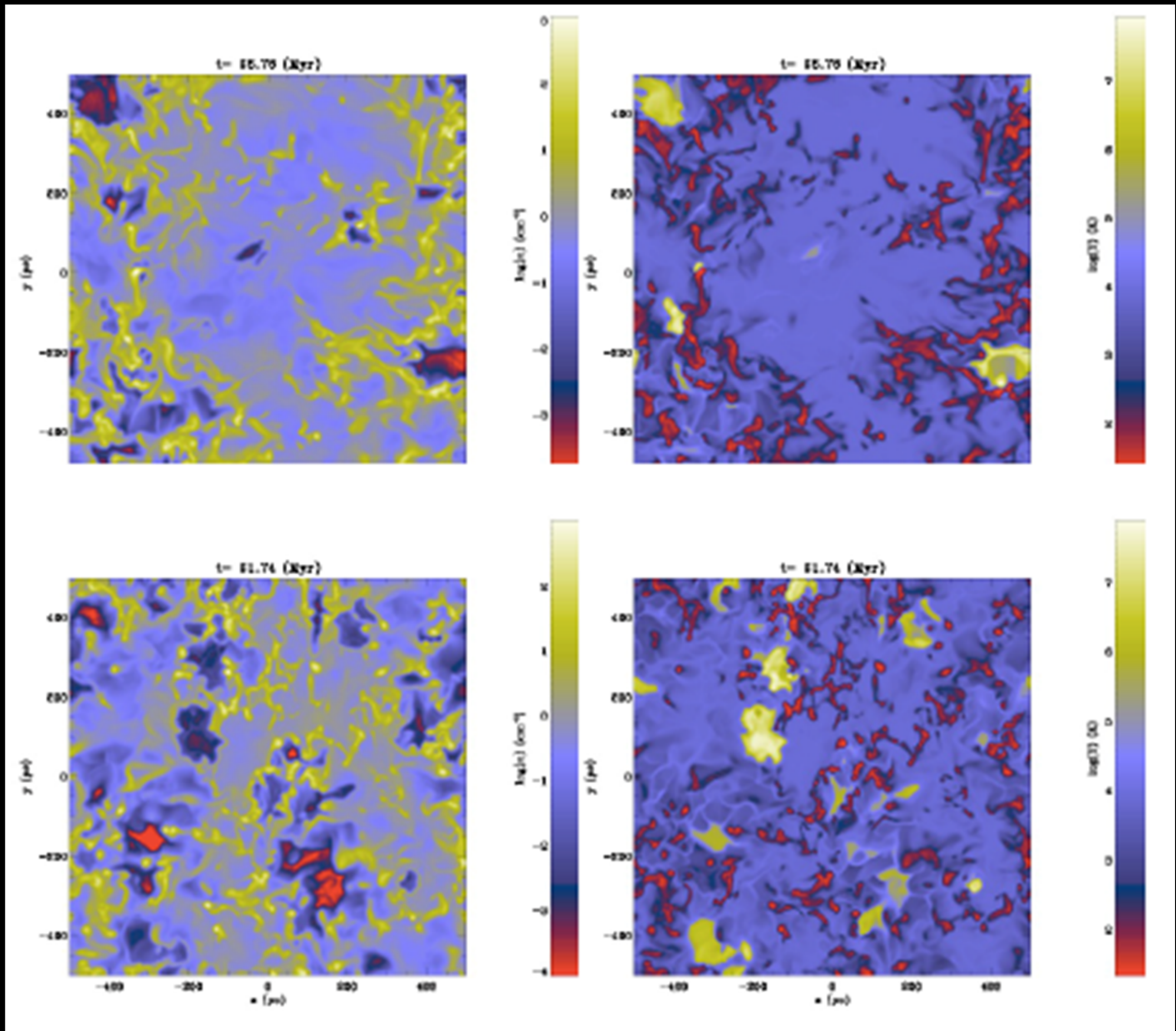
- Field amplification to 10μG in major mergers

- No effect on ISM structure, star formation rate and spatial distribution of star formation

… but at >100pc SPH resolution

Kotarba et al. 2011

The magnetic field on galactic scales



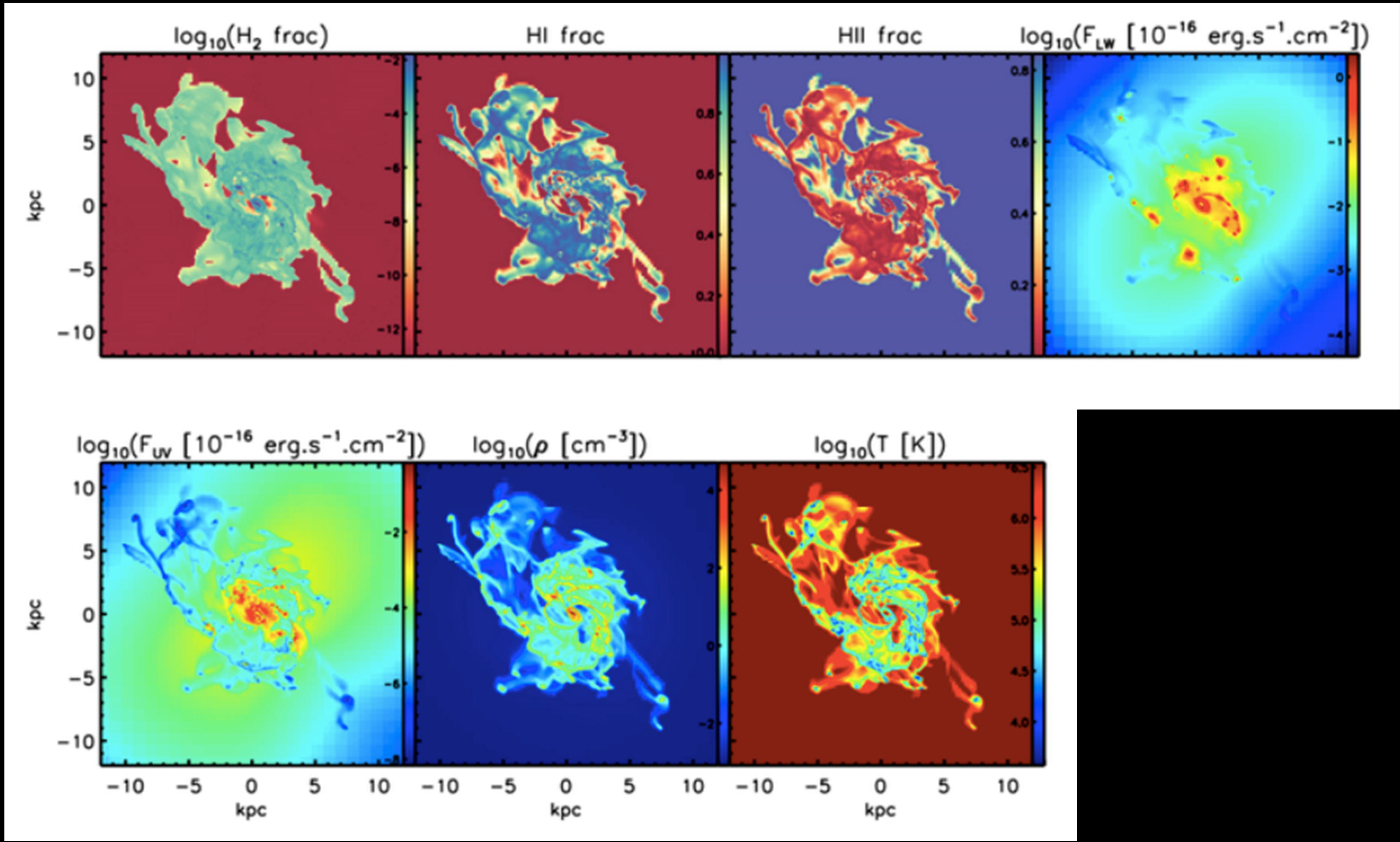
Galaxy slices simulations

- MHD (top)
- No-MHD (bottom)

Clear effect on dense gas structure, not resolved (yet) in models of entire galaxies

Hennebelle & Iffrig 2014

Radiative transfer on galactic scales

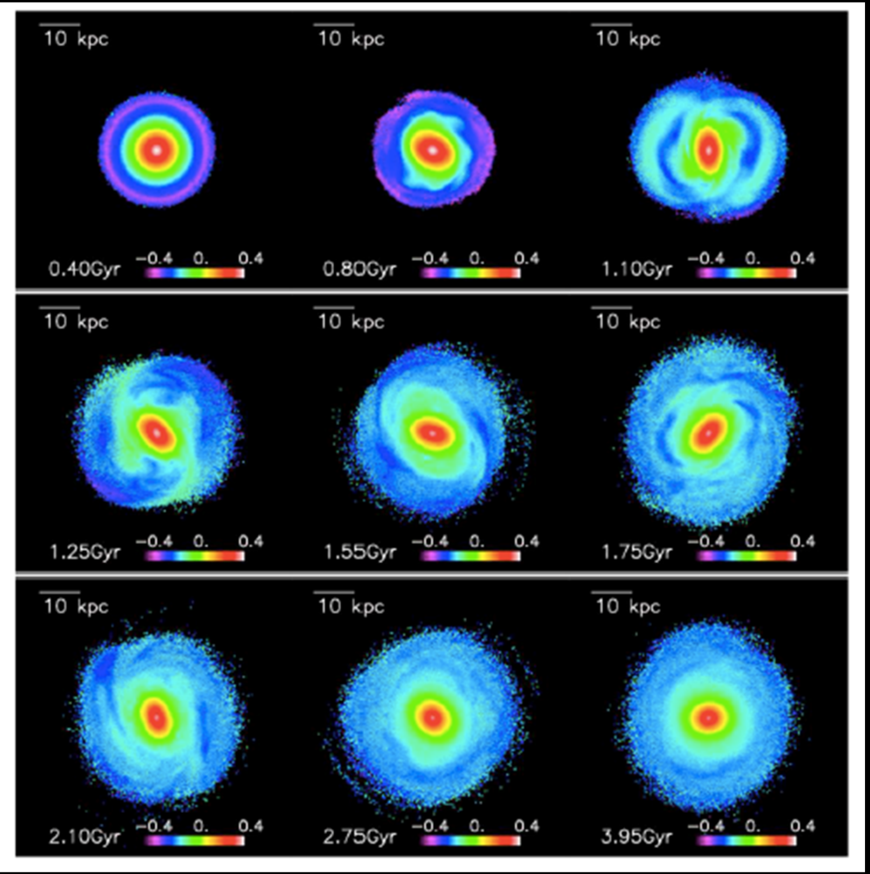


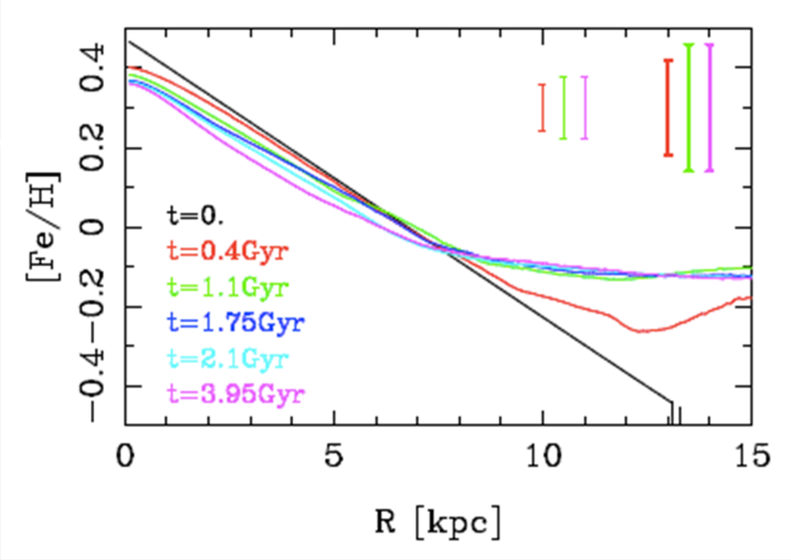
RAMSES-RT post-processing (1-3pc res.) and simulations (10-20pc res.) with detailed HI/H2/HII fractions, temperatures, UV fluxes

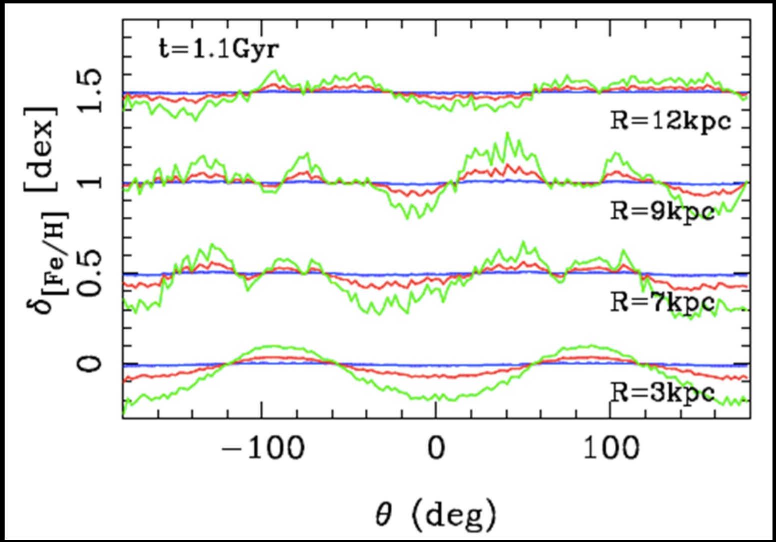
Perret et al. 2015

Detailed chemical evolution

Chemo-dynamics becomes possible with many species, very high N-body resolution, sometimes even in cosmological context







Radial and azimuthal density gradients due to bar-induced stellar migration

P. Di Matteo et al. 2013

What we can do today in galaxy-scale models

- Describe the parsec-scale structure of the ISM with realistic statistical structure, convergence on the SFR, and effect of galactic structure

  => balance between gravity+hydro and feedback

- Study GMC properties, star cluster formation, in the global galactic context

- Study new processes at very high accuracy, but decoupled from global galactic physics

  => magnetic field, radiative transfer, chemical evolution

What we *cannot* do within 5 yr in galaxy-scale models

We face some typical limitations of supercomputing

Having more CPUs is good for bigger problems, but not for longer problems (unless the code scales on increasing numbers of CPUs…)

Pushing the resolution means shorter timescales embedded in the global galactic timescale => increasing number of timesteps => longer problem very hard to simulate (or the simulation takes several years)

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But

Combining existing numerical codes with increasing numbers of CPUs can treat bigger problems, i.e. including more physics at a fixed resolution :

- Radiative transfer inside parsec-scale simulations
- Detailed predictions of observables (H2, CO…) for ALMA
- MHD simulations of the ISM on galactic scales
- Chemodynamics coupled to high-resolution ISM models