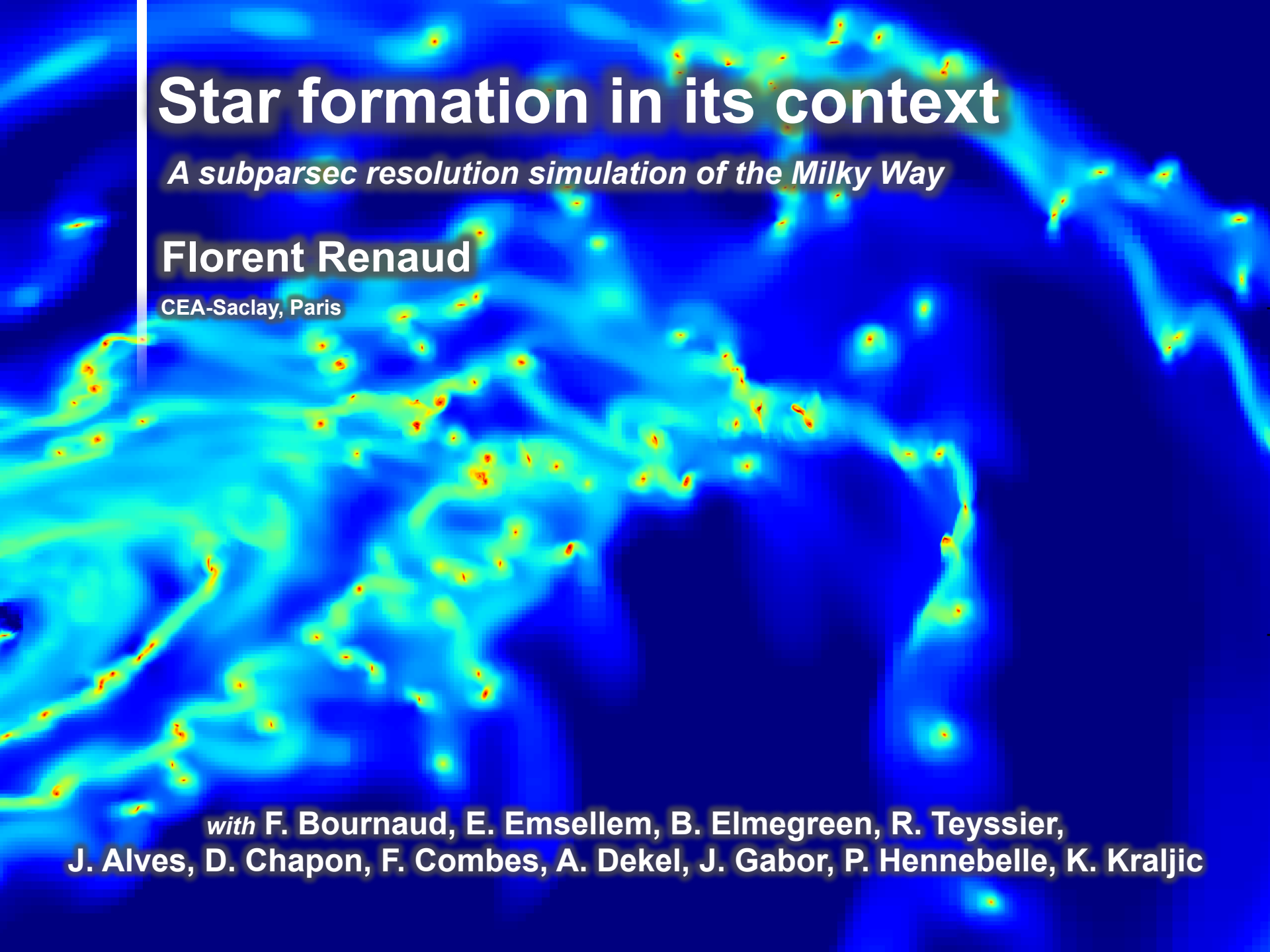


Star formation in its context

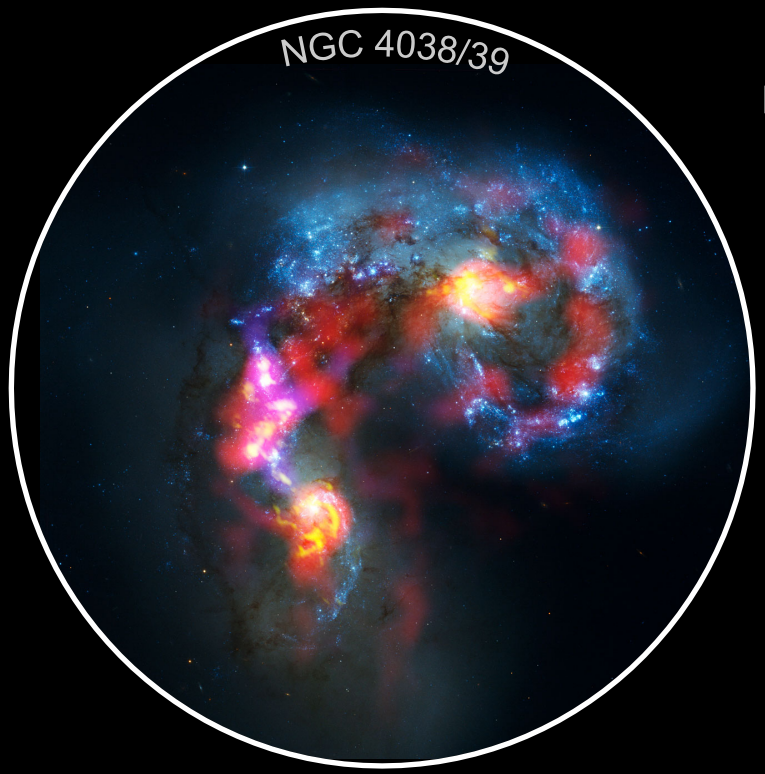
A subparsec resolution simulation of the Milky Way

Florent Renaud

CEA-Saclay, Paris

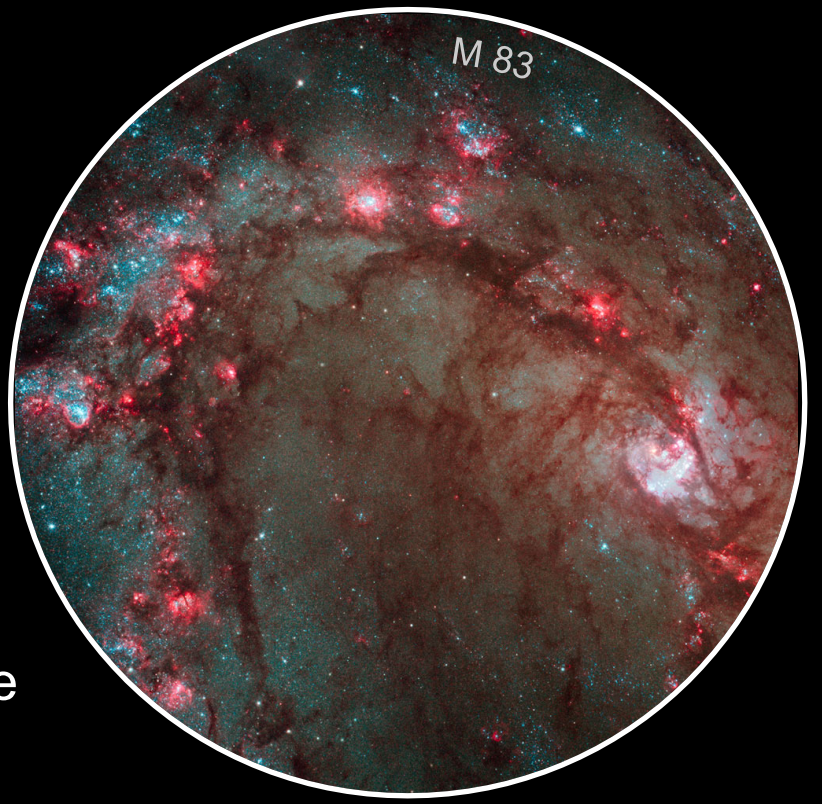
with F. Bournaud, E. Emsellem, B. Elmegreen, R. Teyssier,
J. Alves, D. Chapon, F. Combes, A. Dekel, J. Gabor, P. Hennebelle, K. Kraljic

• SF depends on the Environment



redshift

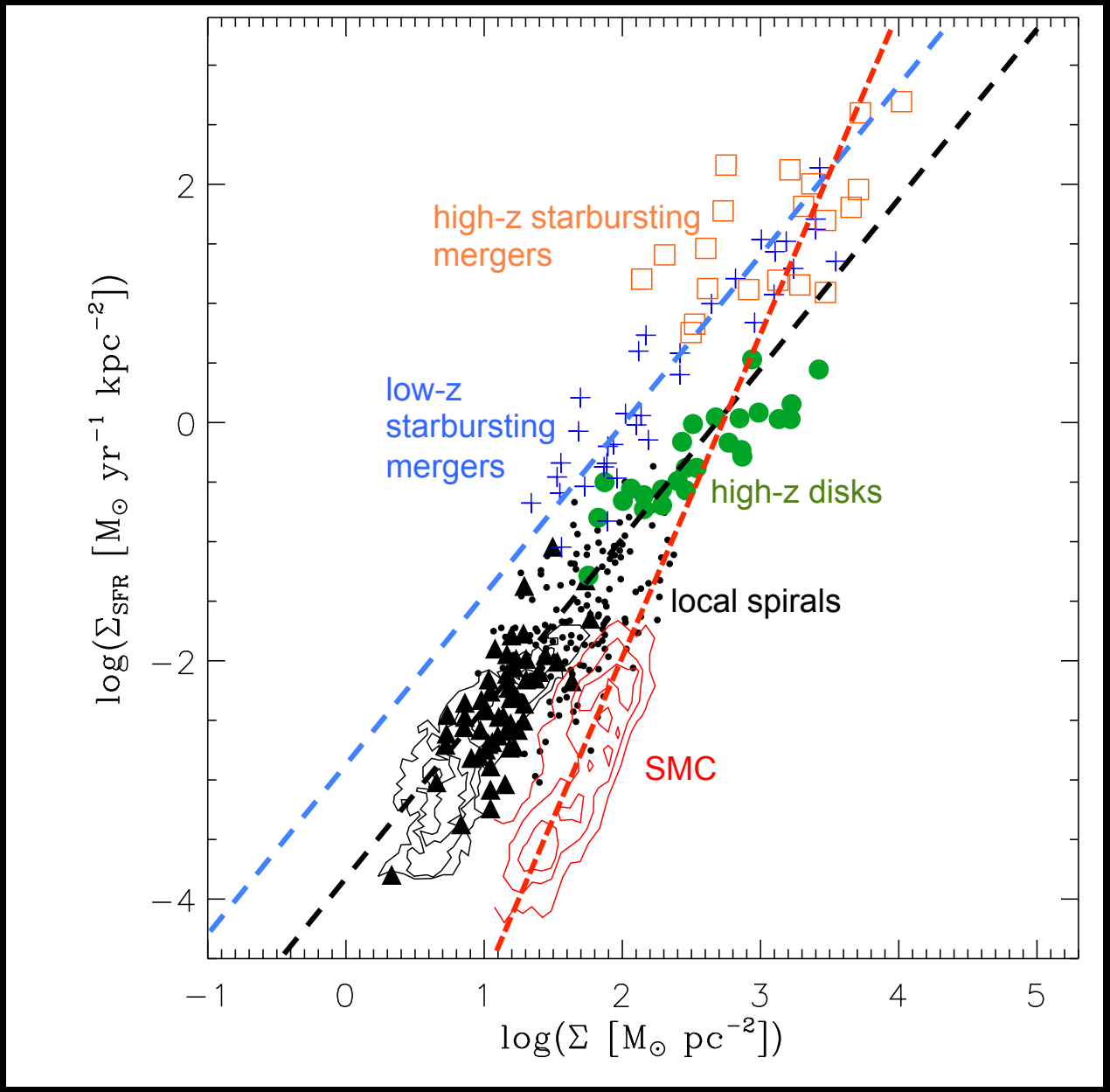
galaxy-galaxy interaction(s)



(intrinsic) galaxy evolution

galaxy structure

Observed SF Laws



Kennicutt+(1998)

Kennicutt+(2007)

Bigiel+(2008)

Tacconi+(2010) ; Daddi+(2010a)

Kennicutt+(1998)

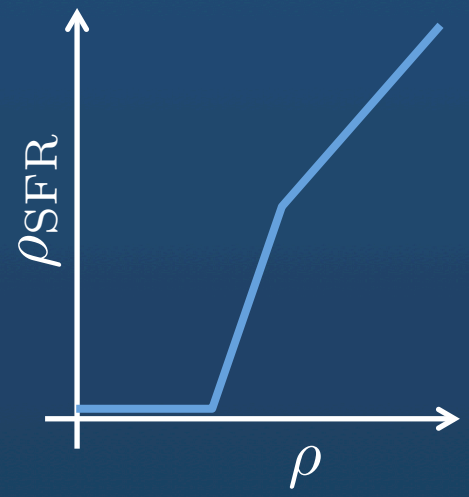
Bouché+(2007) ; Bothwell+(2009)

Bolatto+(2011)

widely inspired by Daddi+ (2010b)
(see also Genzel+ 2010)

Analytical Star Formation

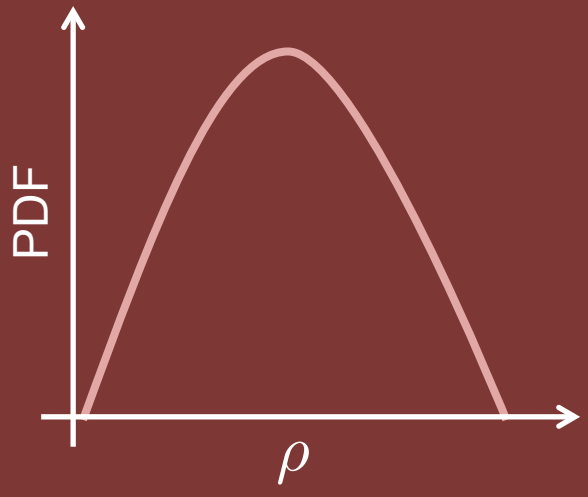
Local SF law



density threshold
+ constant SFE per ff time
+ regulation (e.g. feedback)

Elmegreen (2002)
Renaud et al. (2012)

Global distribution of density



log-normal PDF

Vazquez-Semadeni (1994)
Nordlund & Padoan (1999)
Wada & Norman (2001)

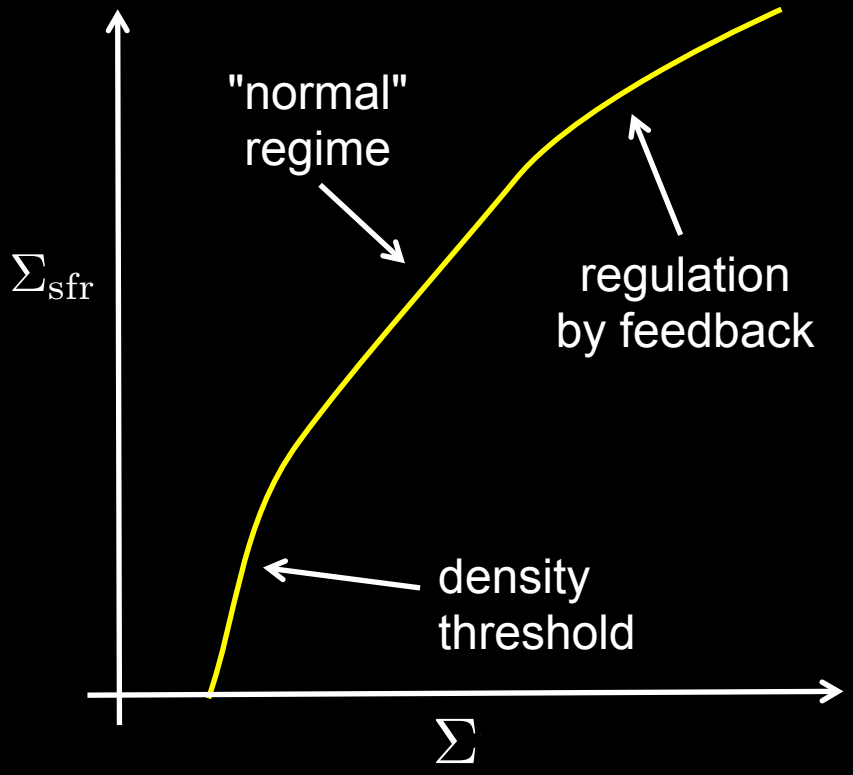
see also Padoan & Nordlund (2011), Hennebelle & Chabrier (2011), Federrath & Klessen (2012)

Model

$$\Sigma_{\rm sfr} = \Sigma^{3/2}\epsilon\sqrt{\frac{8G}{3\pi}}\frac{\exp\left(\frac{3\sigma^2}{8}\right)}{\sqrt{h}}\left[\mathrm{erfc}\left(\frac{\ln\left(\frac{\rho_0 h}{\Sigma}\right)-\sigma^2}{\sigma\sqrt{2}}\right) - \mathrm{erfc}\left(\frac{\ln\left(\frac{3\pi\epsilon_s^2 h}{32Gt_s^2\epsilon^2\Sigma}\right)-\sigma^2}{\sigma\sqrt{2}}\right)\right]$$

$$+\Sigma\frac{\epsilon_s}{2t_s}\mathrm{erfc}\left(\frac{\ln\left(\frac{3\pi\epsilon_s^2 h}{32Gt_s^2\epsilon^2\Sigma}\right)-\frac{\sigma^2}{2}}{\sigma\sqrt{2}}\right)$$

Renaud, Kraljic & Bournaud (2012)

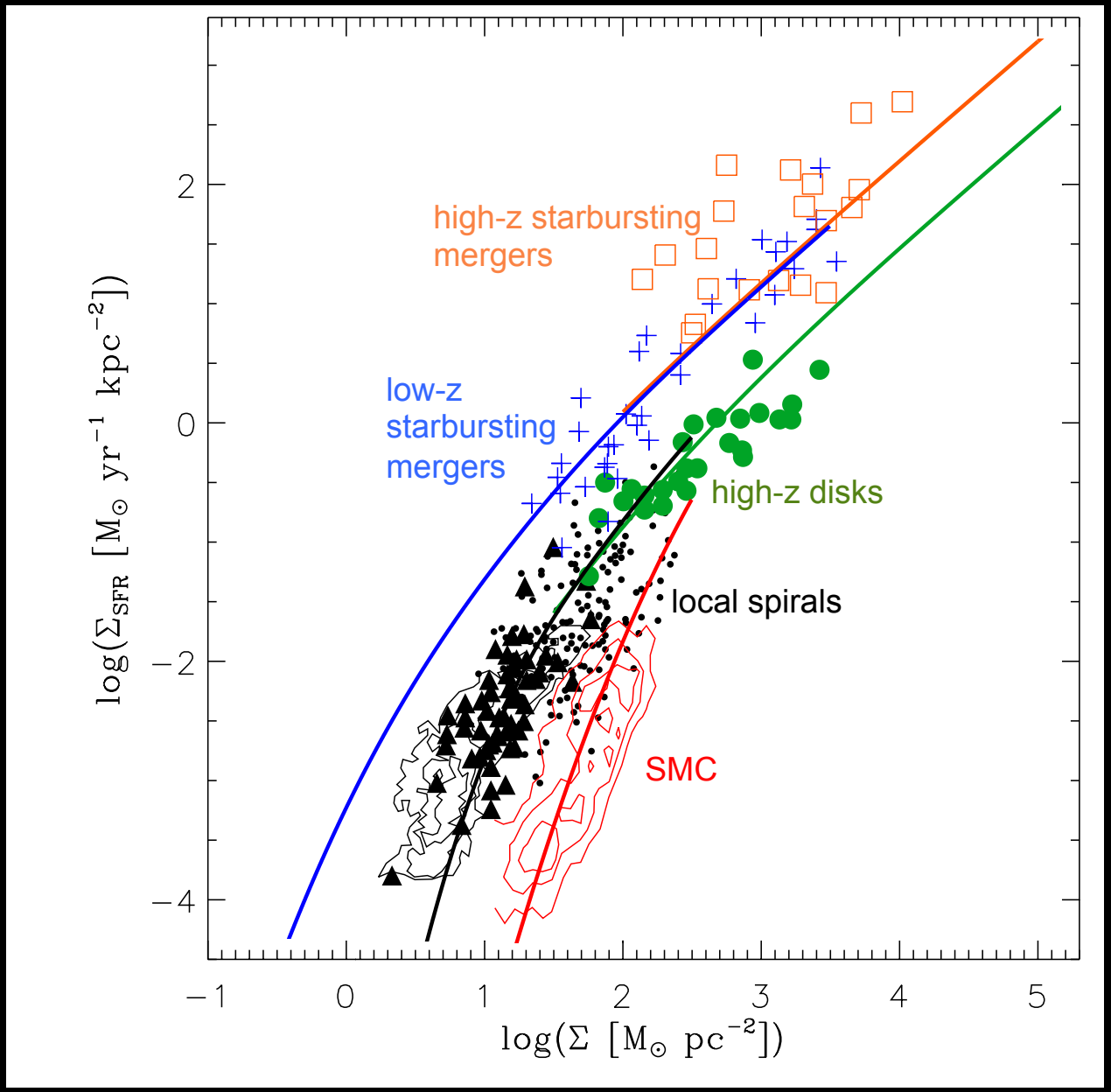


3 Parameters

$\mathcal{M}$	Mach number	*Turbulence*
h	Scale-height	*Geometry (Turbulence)*
ρ_0	Density threshold	*Turbulence*

cloud self-shielding	~ 1 cm^{-3}	Schaye (2004)
supersonic onset	~ 10 cm^{-3}	Renaud et al. (2012)
molecule formation	~ 100 cm^{-3}	Krumholz et al. (2009)

Modeled SF ~~Laws~~ Relations



by injecting typical values in the equation *(not fitting)*

Renaud, Kraljic & Bournaud (2012)

• WHY ~~IS~~ HAS IT BEEN SO DIFFICULT?

Resolving star forming cores,
in the galactic context

cores: 0.01 pc (= 2000 AU)

galaxy: 100 kpc (= 2×10^{10} AU)

7 orders of magnitude
(= "sub-sub-sub" on the Goodman scale)

in space AND time

M31

A First Method

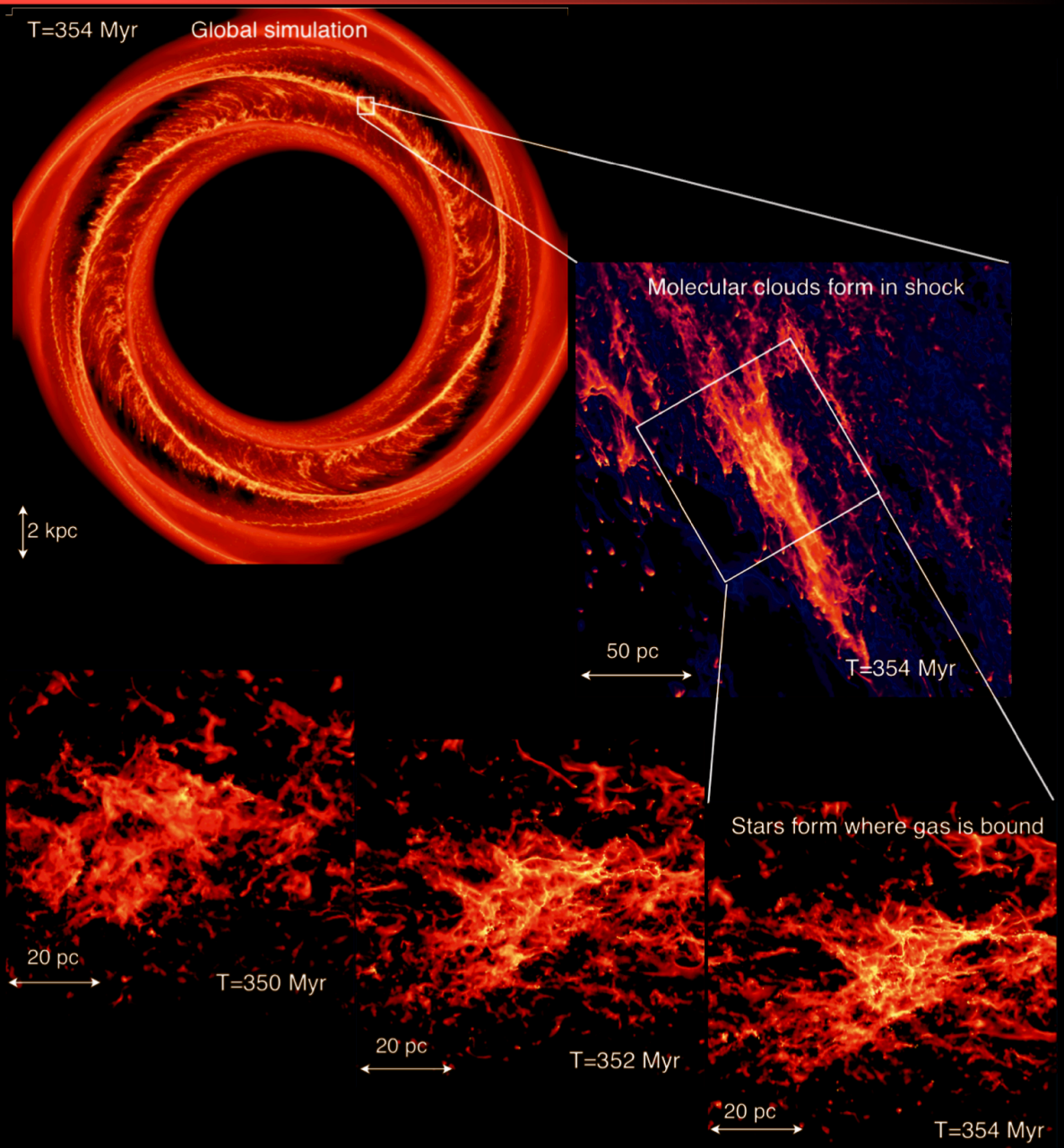
Bonnell et al. (2013)

Gas in spiral potential

Selection of a SF cloud

Re-simulation
at high resolution (~ 0.1 $M_\odot$)

see Ian's talk on Thursday



Another Approach

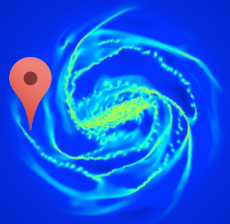
Resolving star forming cores,
in the galactic context

How:

self-consistent simulation of a galaxy,
at subparsec resolution

M31

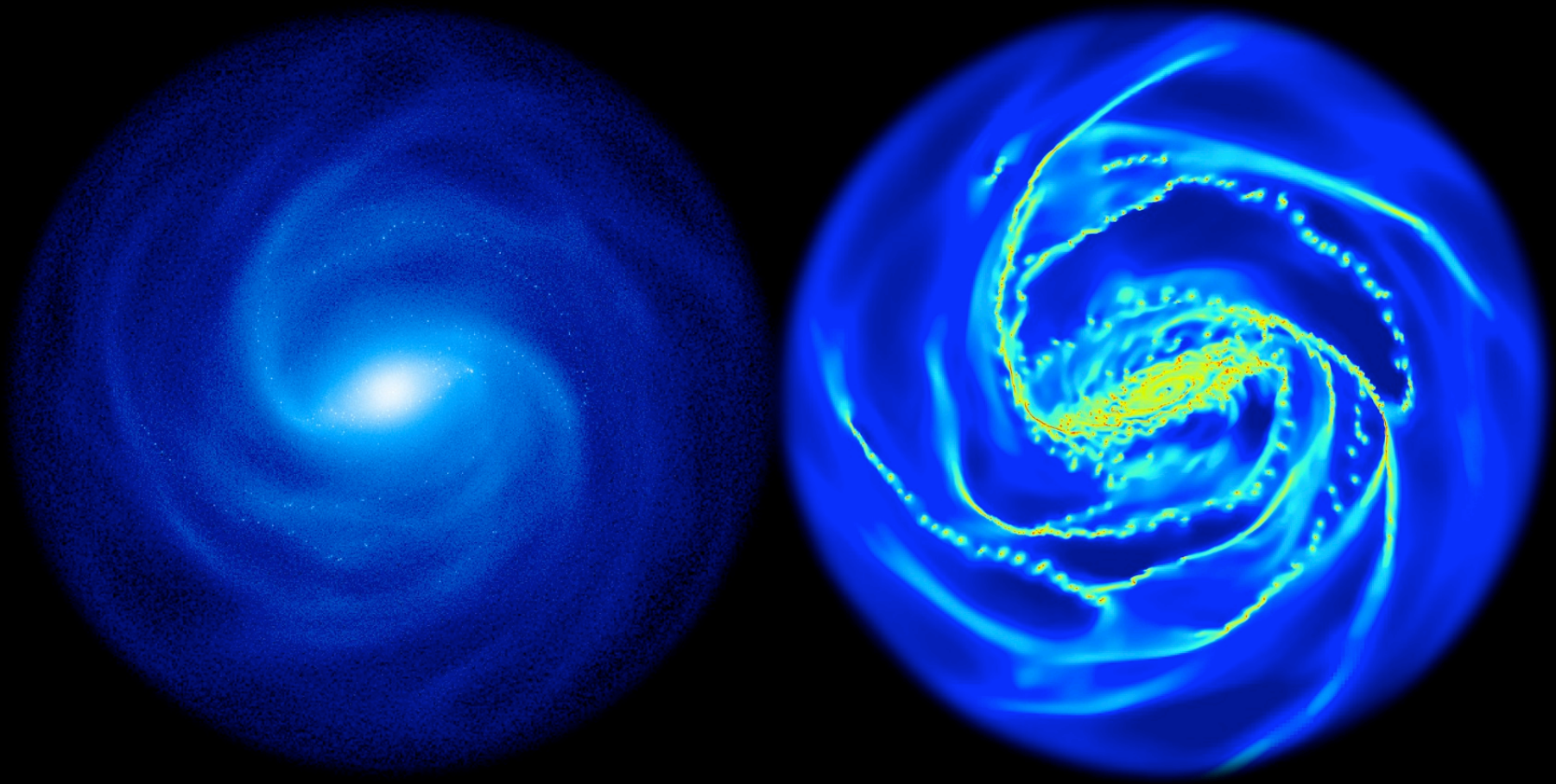
Milky Way maps



http://irfu.cea.fr/Pisp/florent.renaud/mw.php

Milky Way Simulation

Renaud et al. (submitted)



resolution: 0.05 pc (21 AMR levels)

turbulence cascade described (almost ...) down to dissipation scale

Larson (1981)

Initial Conditions, Code

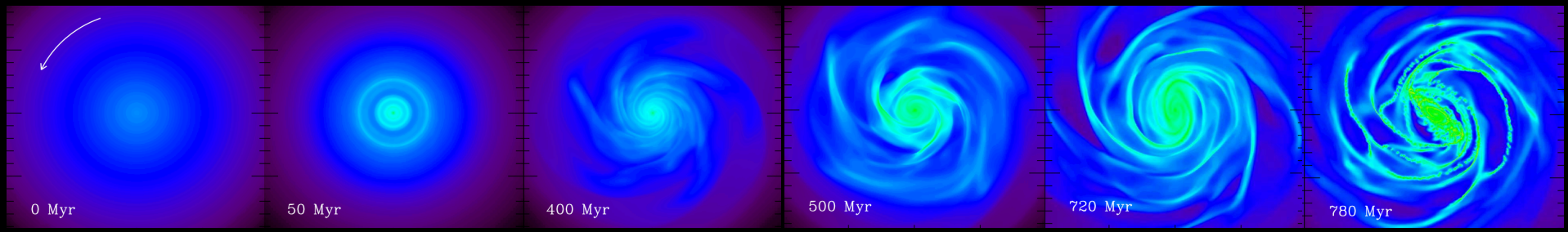
pyMGE — Emsellem et al. (1993); Emsellem & Renaud (in prep)

Besancon model — Robin et al. (2003)

DM halo + Spheroid + Bulge + Thick and thin disks + Black hole

= 60M particles

Gas disk: analytical setup on grid (~ 2.4 x 10^8 cells)



RAMSES — Teyssier (2002)

Polytropic EoS — Bournaud et al. (2010)

Star formation — Schmidt (1959); Katz (1992)

$$\rho_{\rm SFR} = \epsilon \frac{\rho}{t_{\rm ff}} \propto \epsilon \rho^{1.5}$$

Stellar feedback:

HII regions — Renaud et al. (submitted)

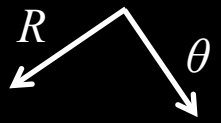
+ radiative pressure

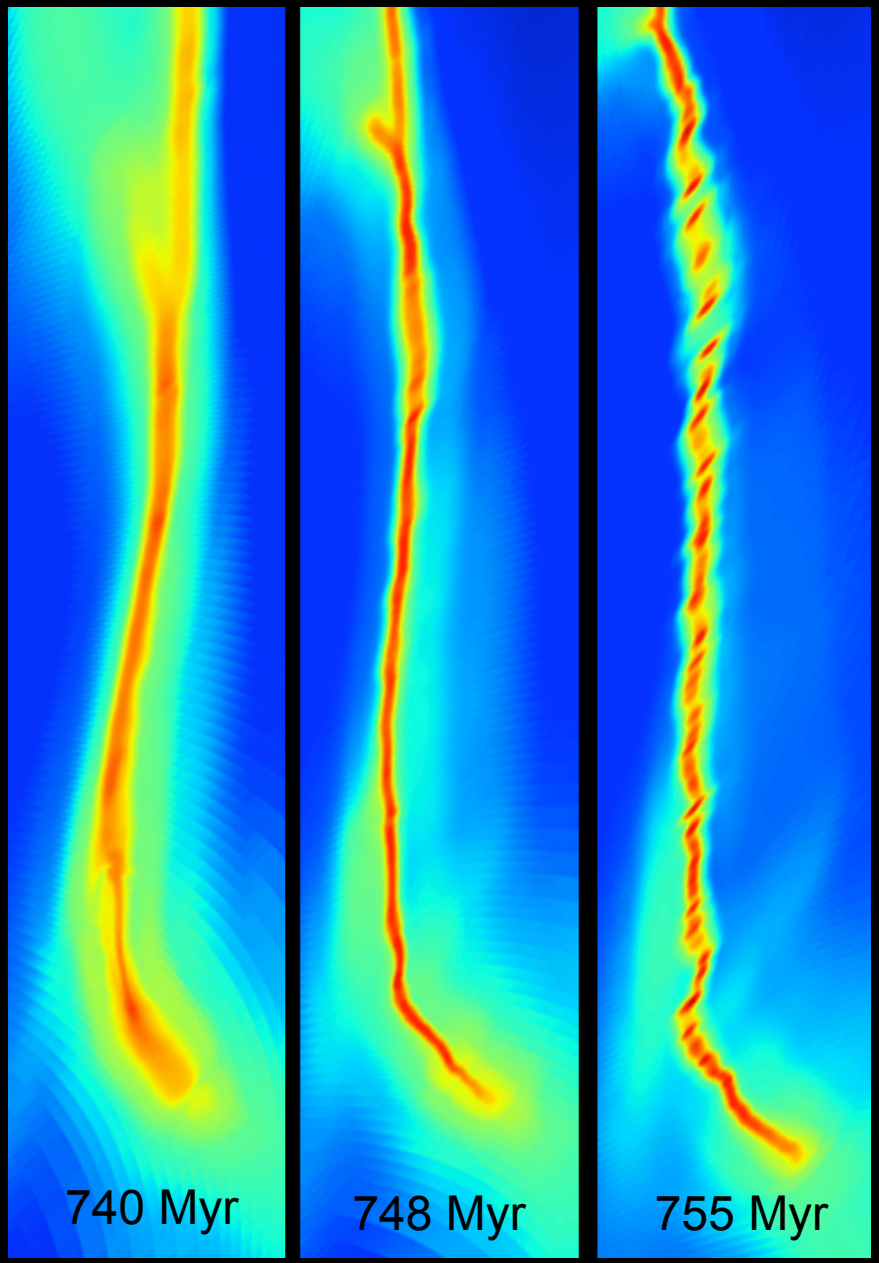
+ SNe — Dubois & Teyssier (2008)

Formation of GMCs

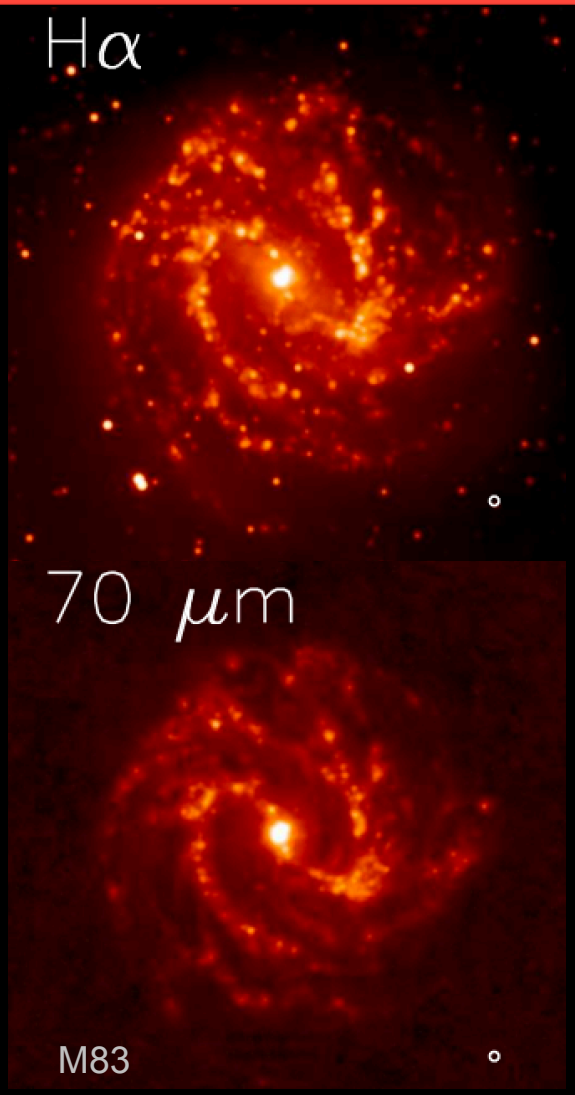
Fragmenting spiral

Formation of *beads on a string* within 10-15 Myr





Beads on a String



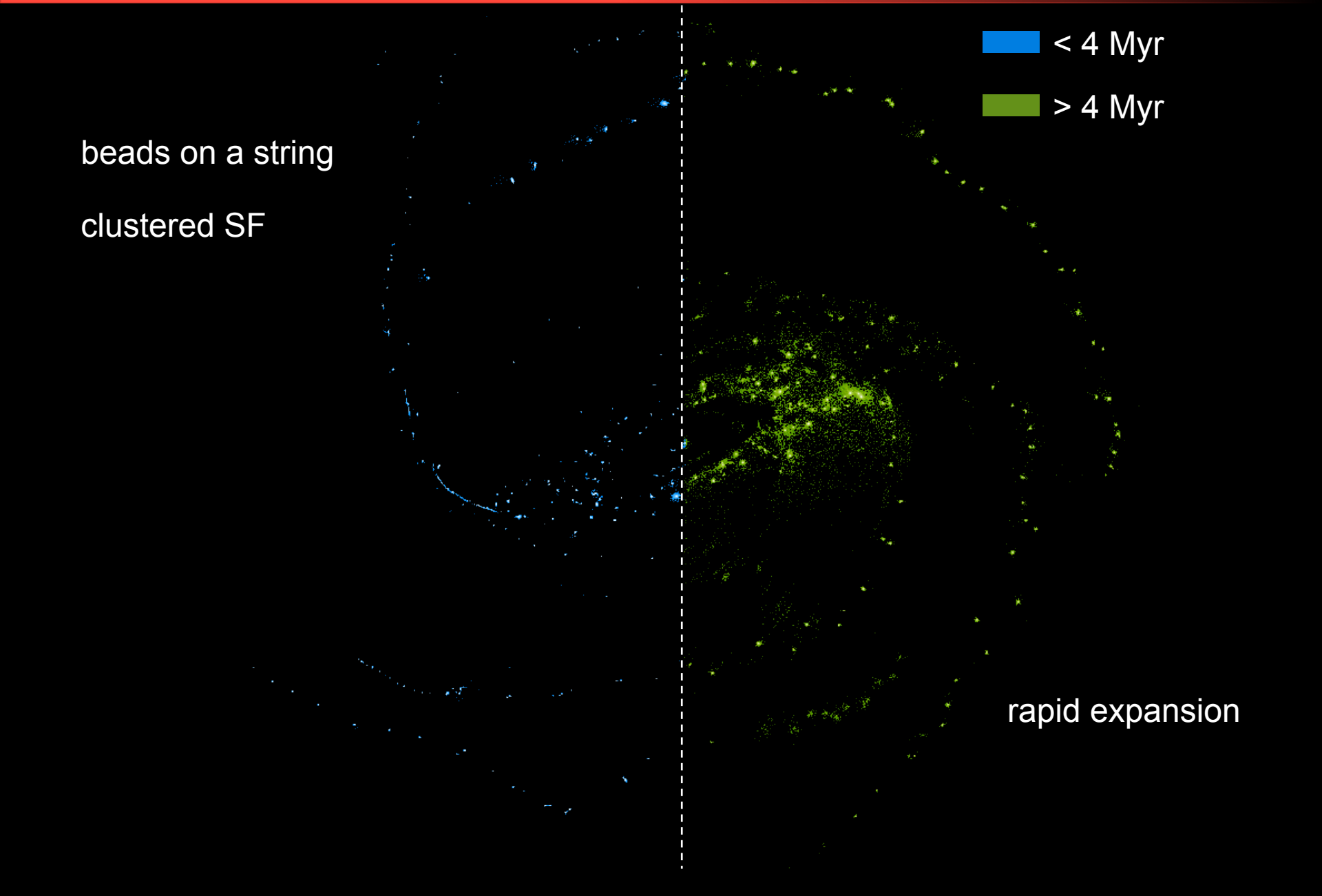
Foyle et al. (2013)

NGC 628

Gusev & Efremov (2013)

see also Elmegreen & Elmegreen (1983)

Star Formation



Gas density PDF, SF Threshold

Log-normal

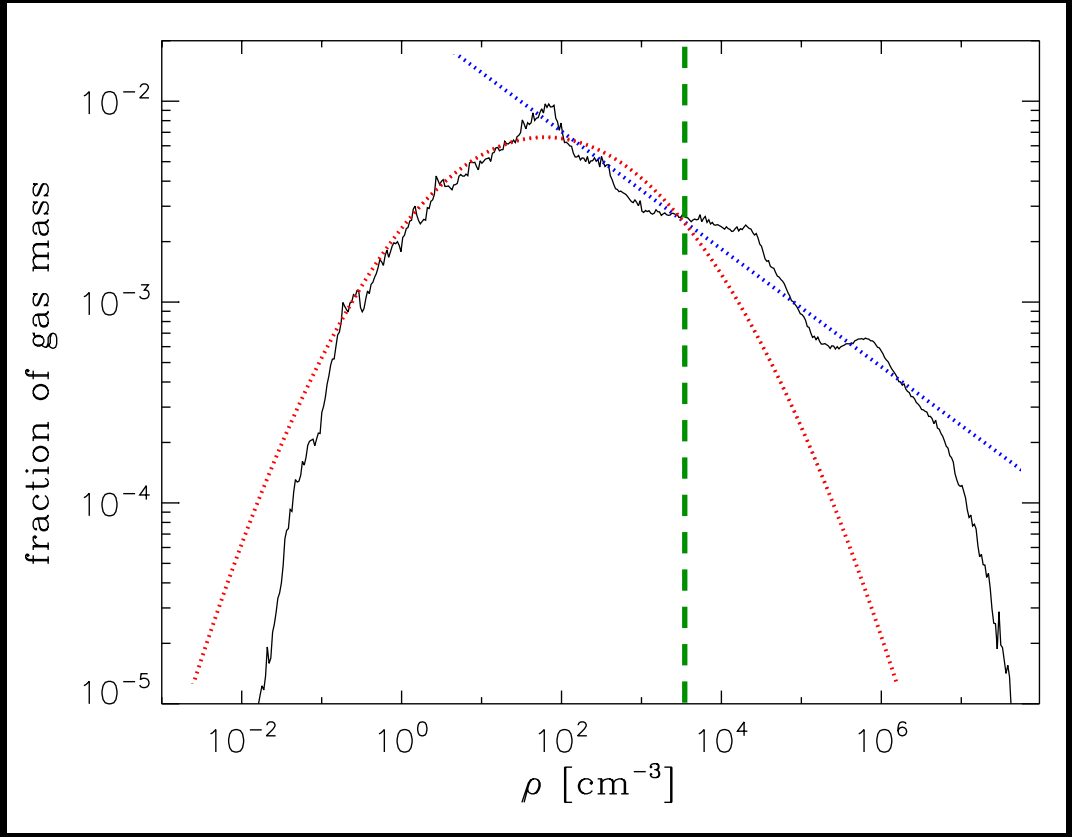
usually good for isothermal, supersonic ISM

Vazquez-Semadeni (1994)
Nordlund & Padoan (1999)
Wada & Norman (2001)
...

Power-law tail

self-gravitating clouds

Klessen (2000)
Hennebelle & Chabrier (2008)
Lombardi et al. (2008, 2010)
Elmegreen (2011)
...



Star formation threshold (2000 cm^{-3})

when the transition is resolved

Radial profile of GMCs

Slope of the self-gravity PL

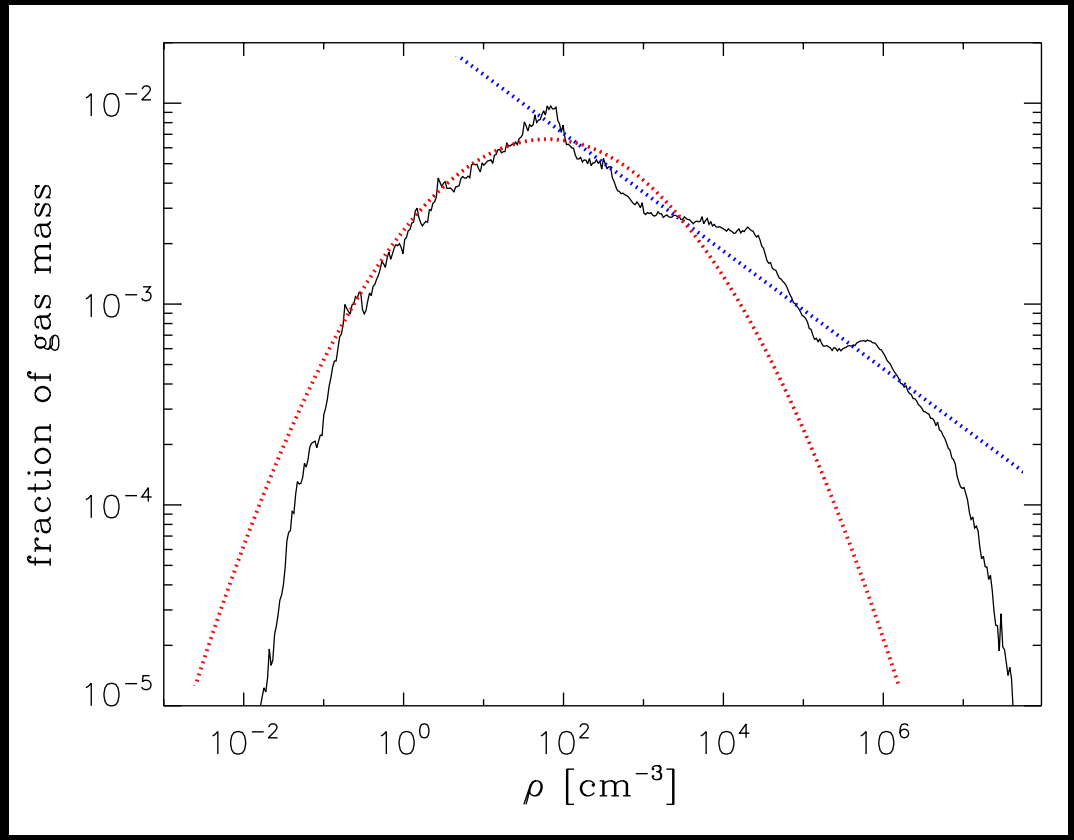
$$-\frac{3}{\beta}-1$$

measured: $\beta \approx 2.33$

Radial profile of GMCs

$$\rho \propto r^{-\beta}$$

Elmegreen (2011)

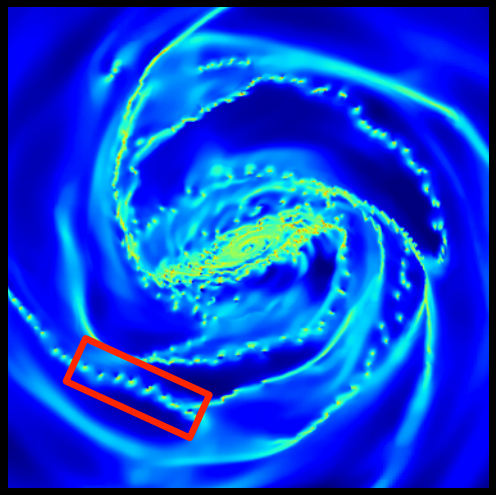


Confirmed with measured profiles

Comparable to self-similar collapse of isothermal sphere ($\beta = 2$)

Shu (1977)

Asymmetric Drift

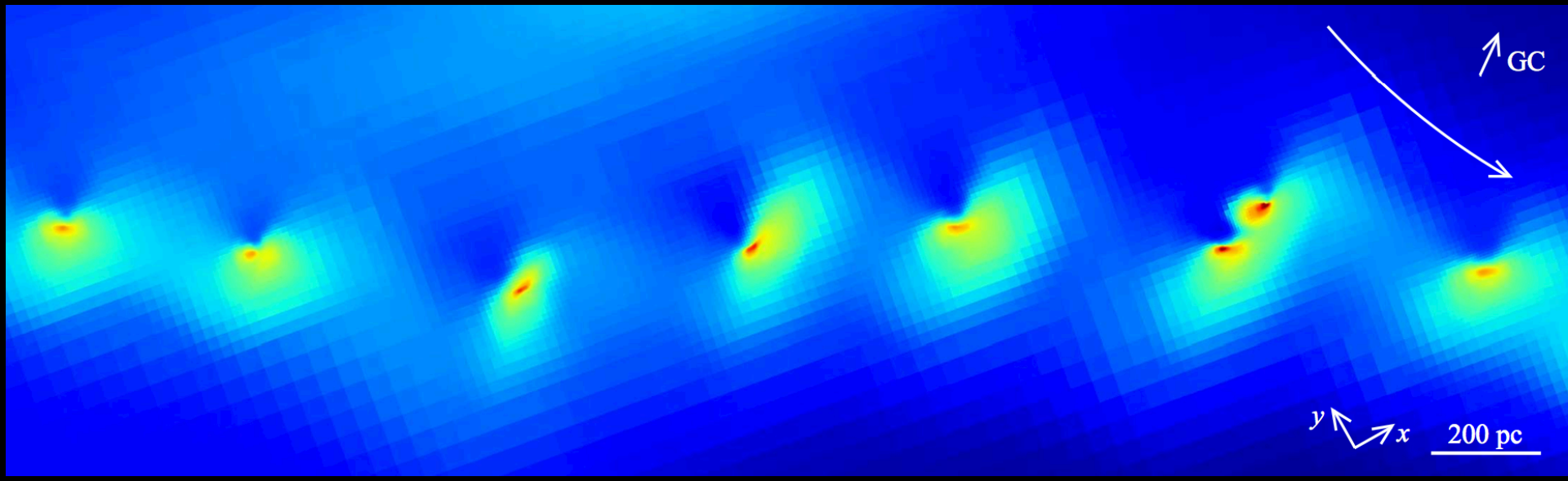


when stars form: $\sigma_\star = \sigma_{\rm gas} \approx 10\ {\rm km/s}$

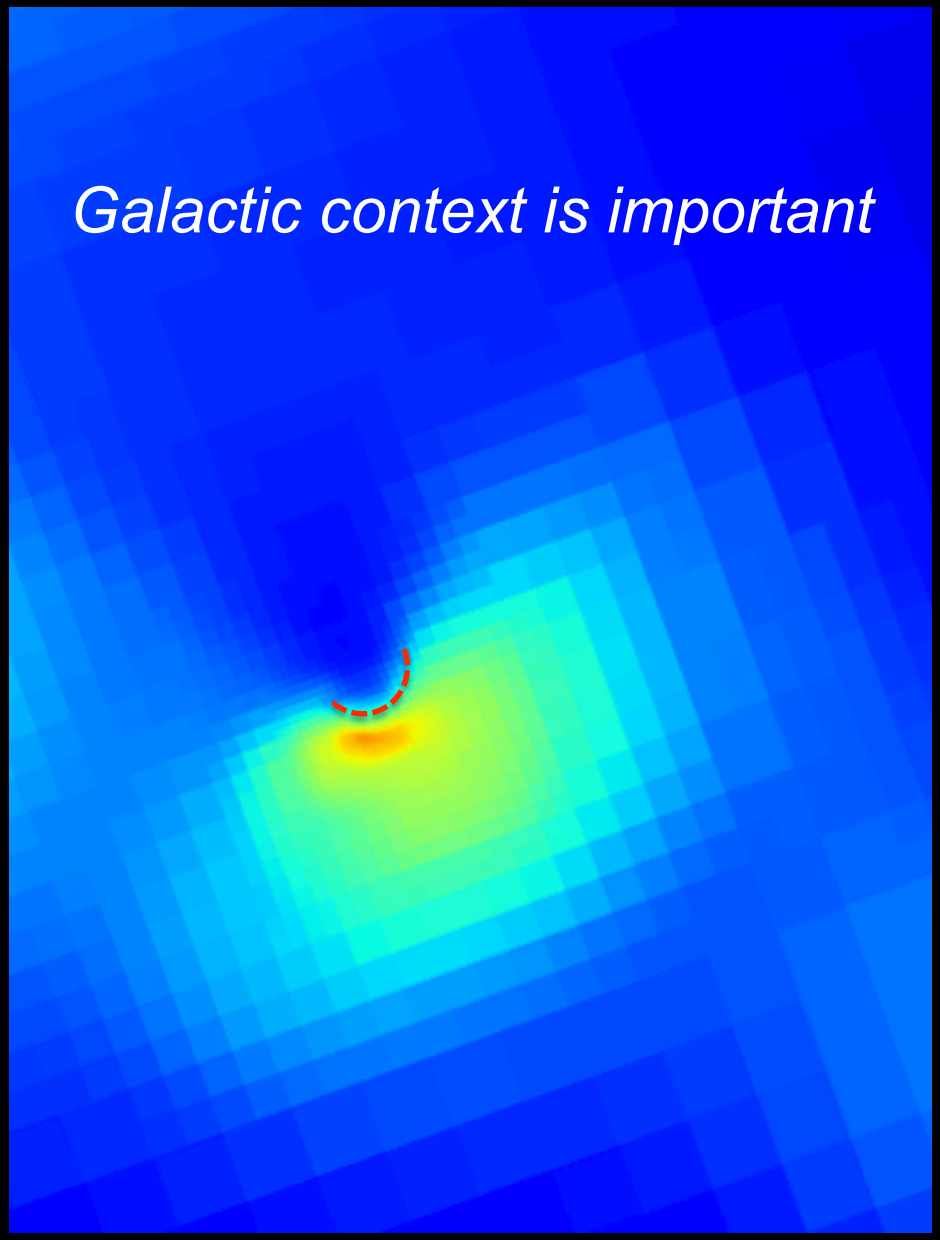
10 Myr later: $\sigma_\star \approx 15\ {\rm km/s}$ (relaxation...)

$\sigma_{\rm gas} \approx 9\ {\rm km/s}$ (dissipation...)

$$v^2_{\rm rotation} \approx v^2_{\rm circular} - \sigma^2$$



Asymmetric Drift & Feedback



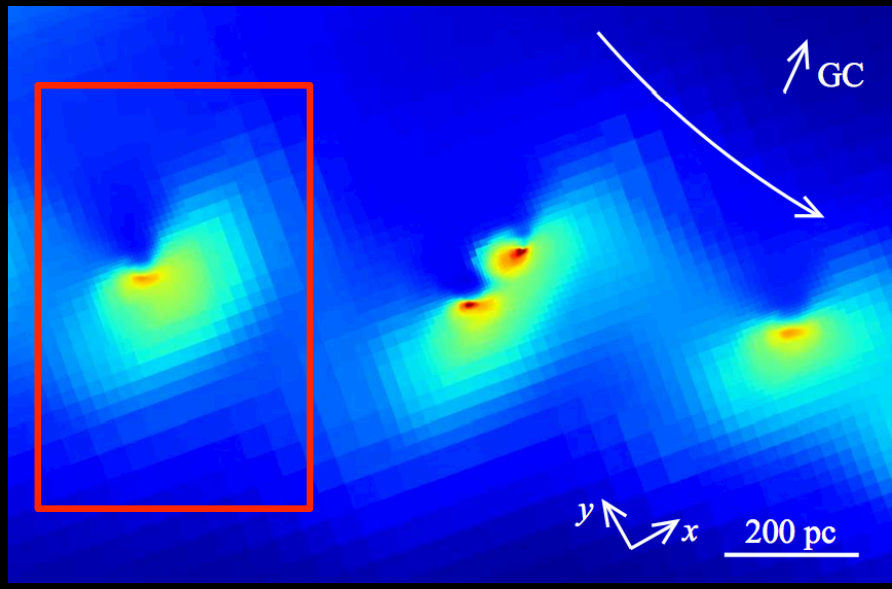
Decoupling star-gas

SN progenitors lag behind the cloud

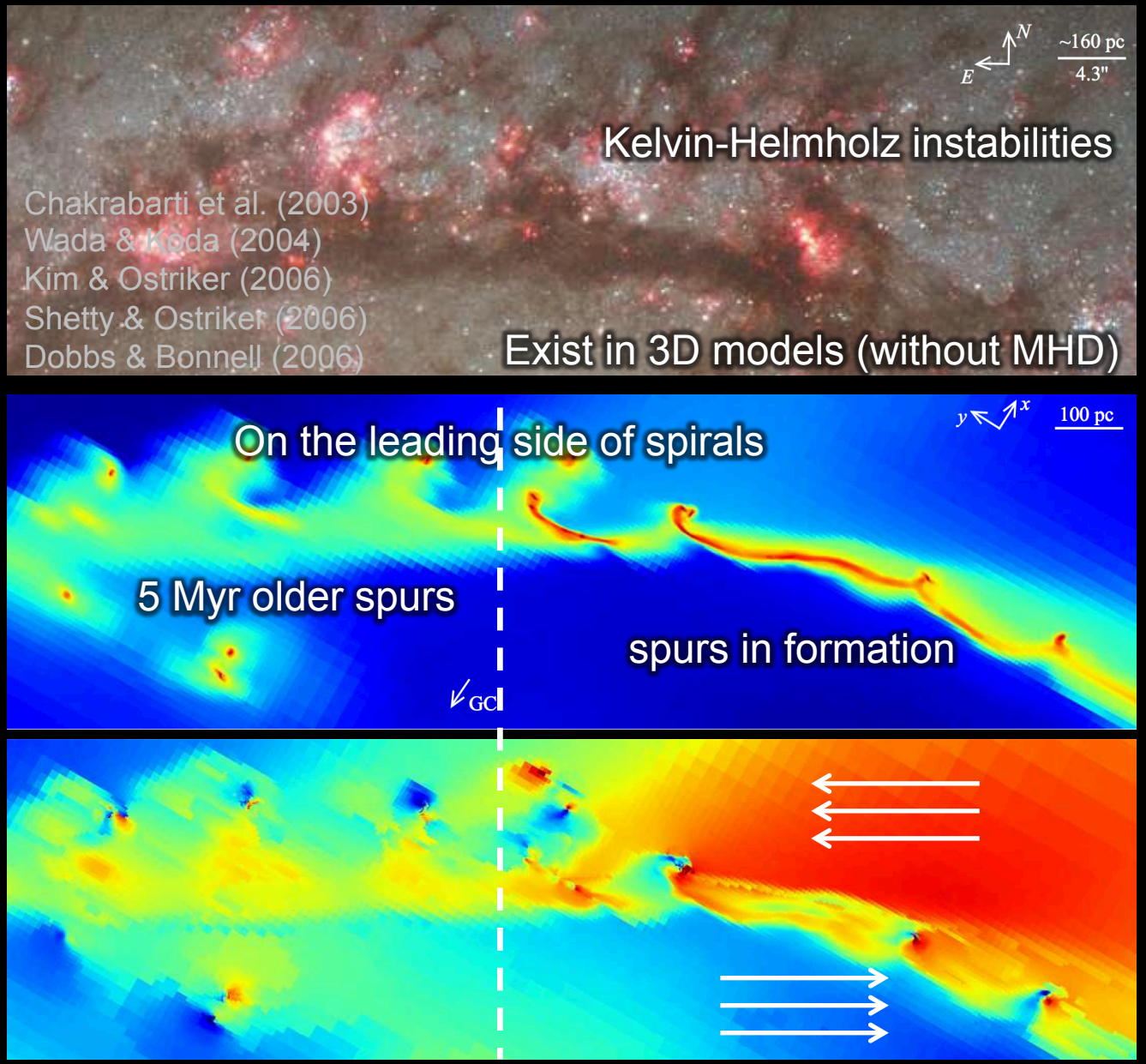
Asymmetric, offset feedback

Inefficient at destroying clouds

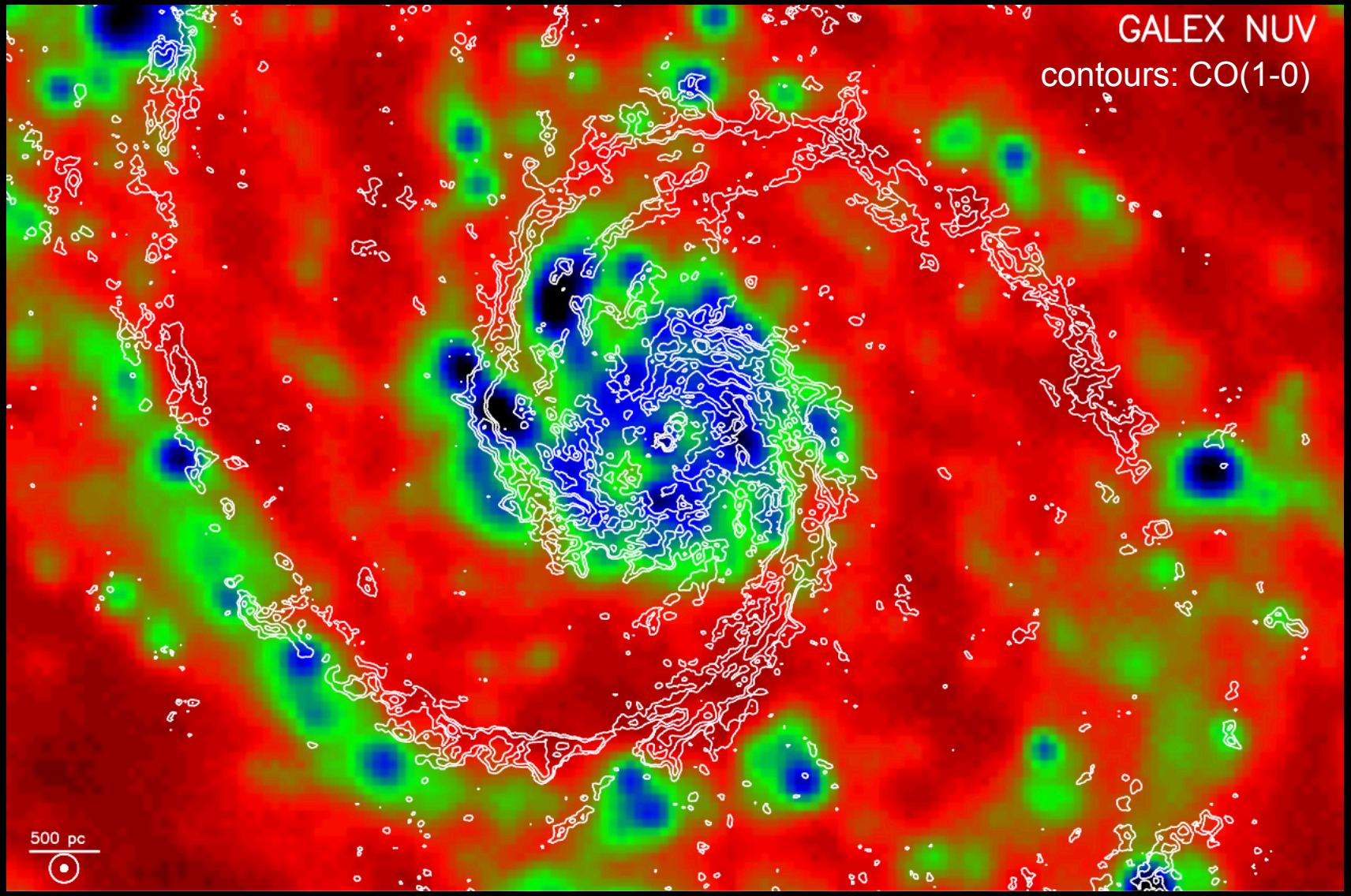
Triggered SF?



Spurs

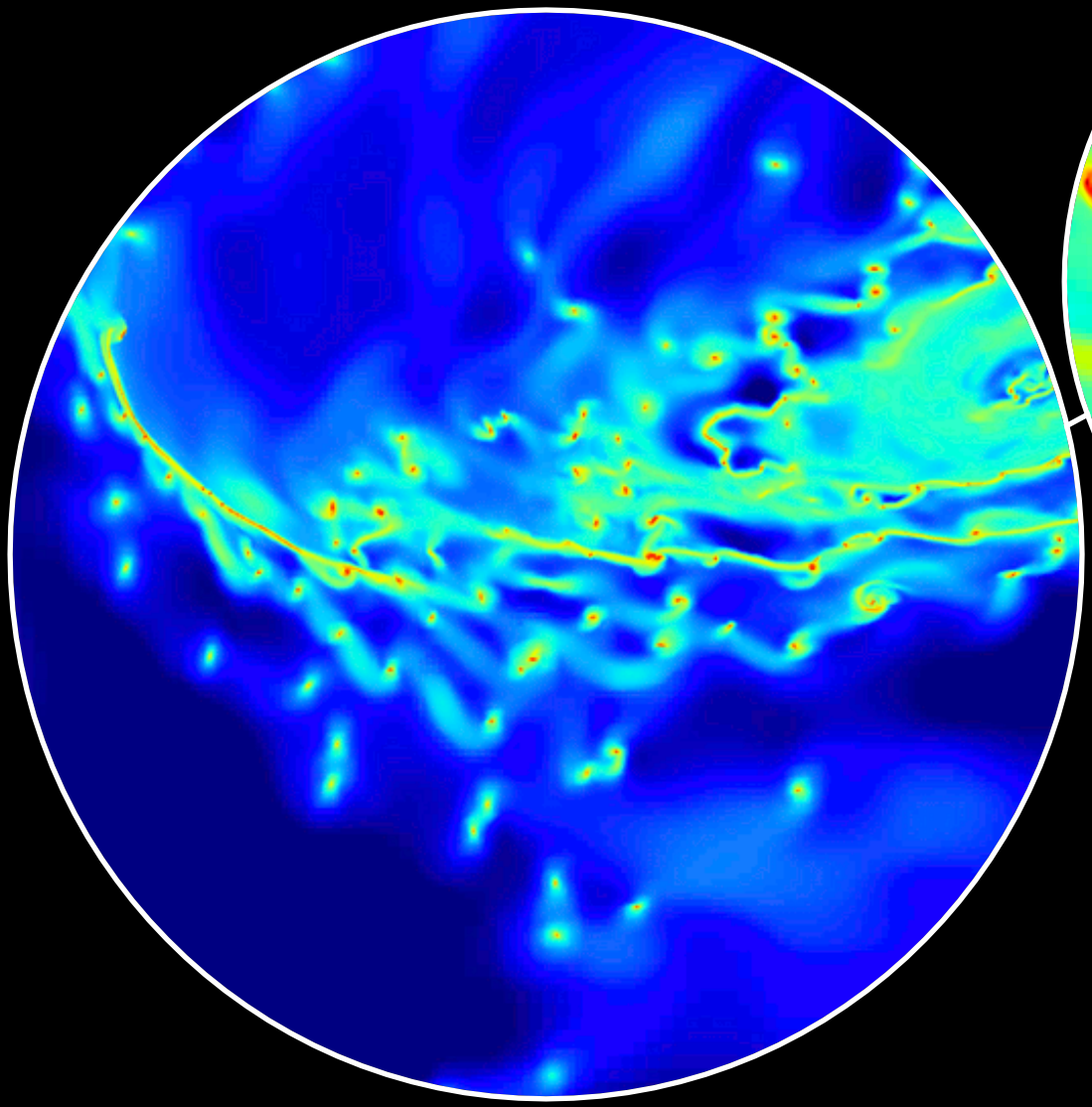

M 51
N
E
~160 pc
4.3"
Kelvin-Helmholz instabilities
Chakrabarti et al. (2003)
Wada & Koda (2004)
Kim & Ostriker (2006)
Shetty & Ostriker (2006)
Dobbs & Bonnell (2006)
Exist in 3D models (without MHD)
Surface density
y
x
100 pc
On the leading side of spirals
5 Myr older spurs
spurs in formation
GC
3
2
1
0
−1
−2
−3
log(Σ [M⊙pc−2])
Velocity (horizontal)
260
250
240
230
220
210
200
v [km/s]

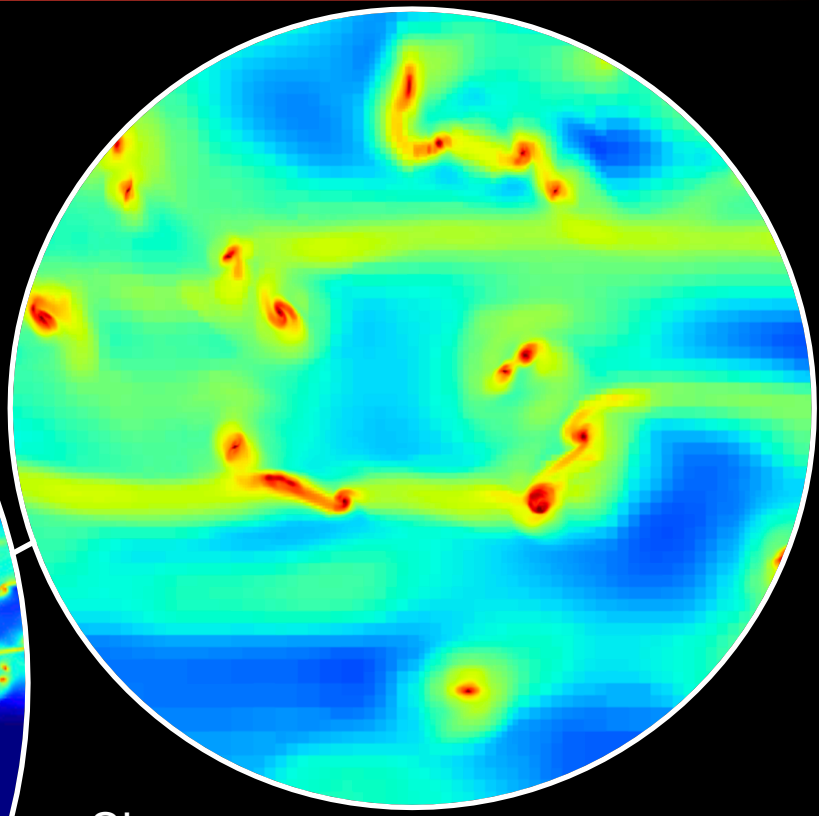
SF on the Leading Side



Schinnerer et al. (2013)

Tips of the Bar



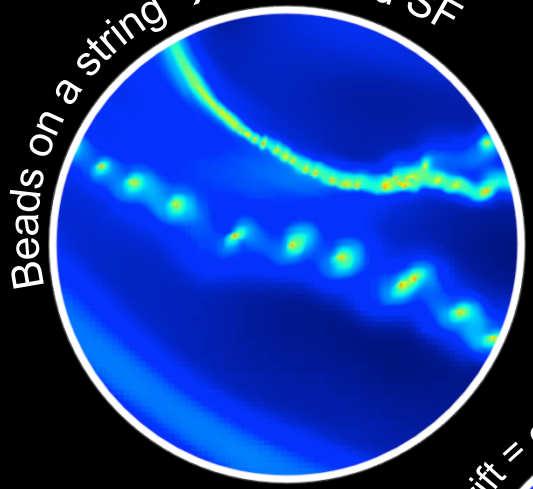


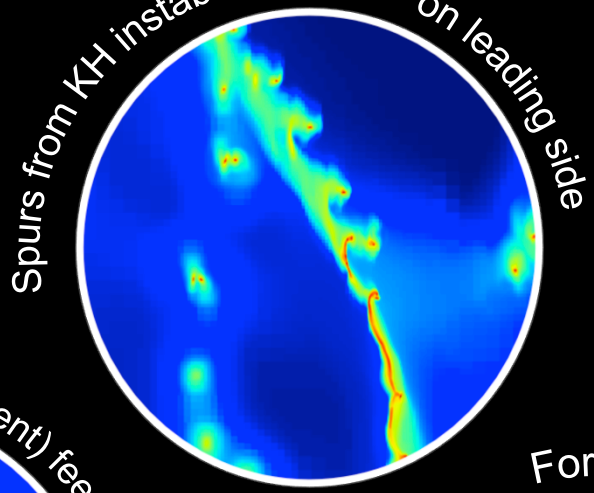
Shear
Cloud-cloud collisions
Tidal features

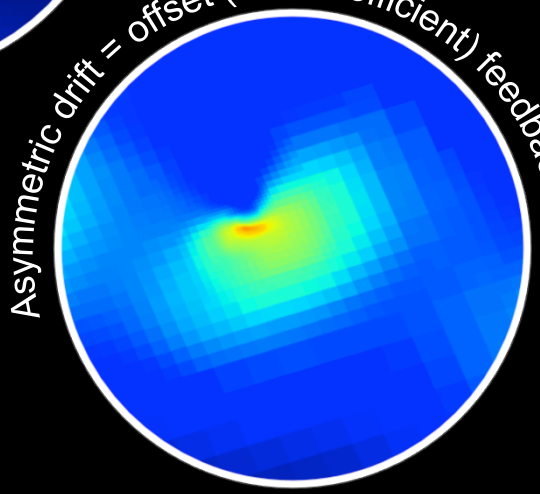
Probable SF enhancement

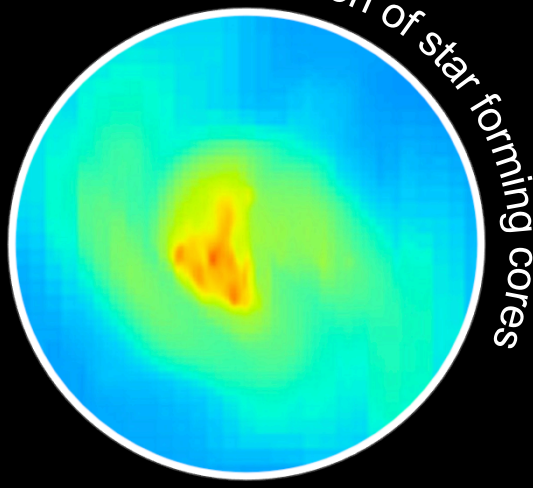
Tasker & Tan (2009)
Fukui et al. (2013)

Conclusions









SF is mostly regulated by supersonic turbulence

The galactic context matters!

Milky Way maps

http://irfu.cea.fr/Pisp/florent.renaud/mw.php