Regulation of star formation: global scales

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Star formation on global scales:

Predicted star formation rates far too high: $\frac{M(H_2)}{t_{ff}}$ ~ few 100 $M_\odot$/year

Zuckerman & Evans 1974, Zuckerman & Palmer 1974

Actual star formation rate: ~ 4 $M_\odot$/year

e.g. Tinsley 1973, Diehl et al. 2006, Murray & Rahman 2009, Robitaille & Whitney 2010

Resolving the low star formation rate

- Only a small fraction of gas forms stars (low star formation efficiency)
- Gas takes longer than a free fall time to collapse (Zuckerman & Evans 1974: motions in clouds local, not global)
- Molecular clouds are not globally gravitationally bound
- Clouds are disrupted prematurely (by stellar feedback)
- Some combination of the above

What processes might be responsible?

- Stellar Feedback (Supernovae, Stellar winds, Radiation pressure, Ionisation, Outflows, Jets - see talks by Eve Ostriker, Christoph Federrath, Jim Dale, Laura Lopez, Stella Offner)
- Spiral shocks / Galactic shear
- Magnetic fields
- Cloud accretion / cloud-cloud collisions
- External accretion onto galactic disc
- External pressure (see Sharon Meidt's talk)

Some might also increase star formation

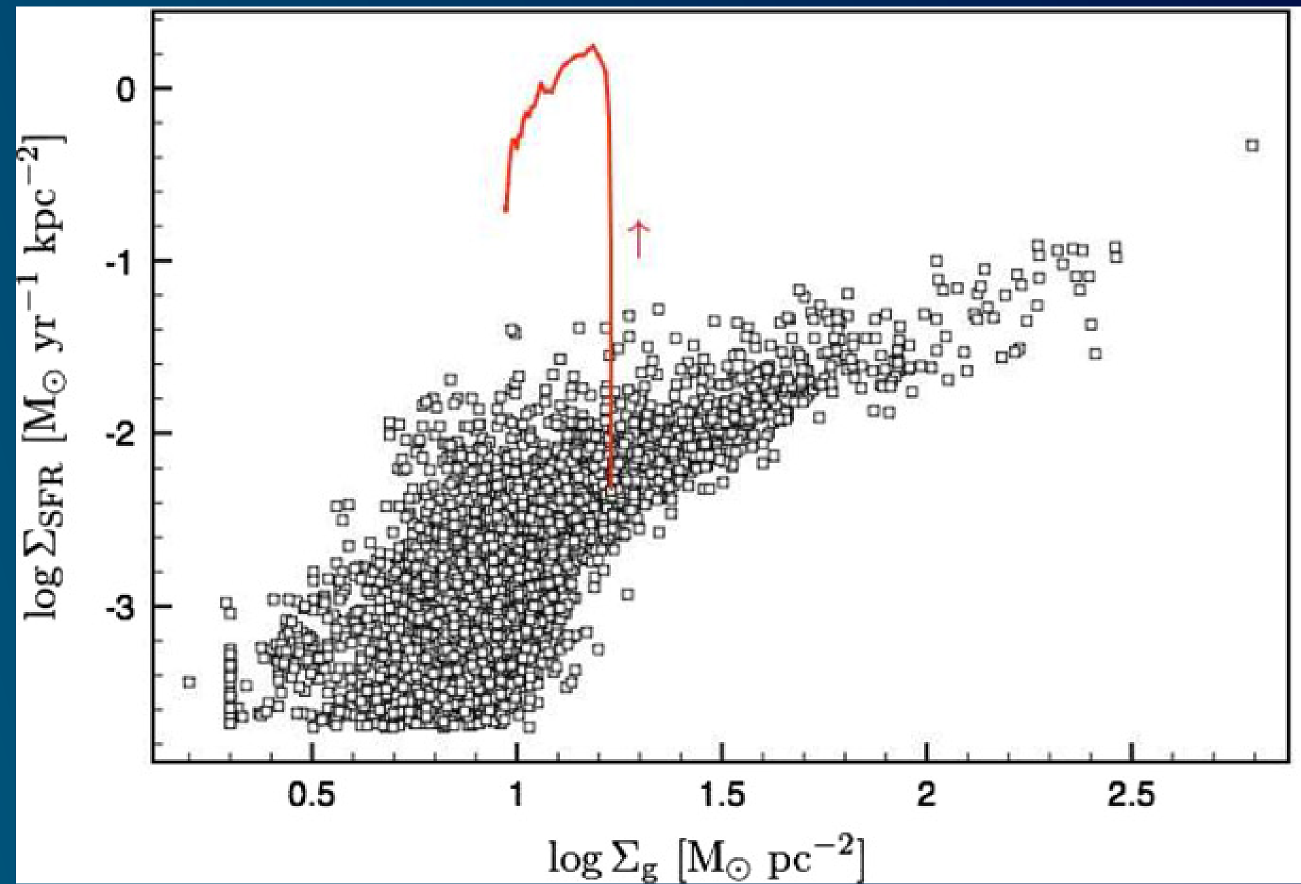
In the absence of feedback or magnetic fields:

Global disc simulations
or resimulations of
regions of galaxies

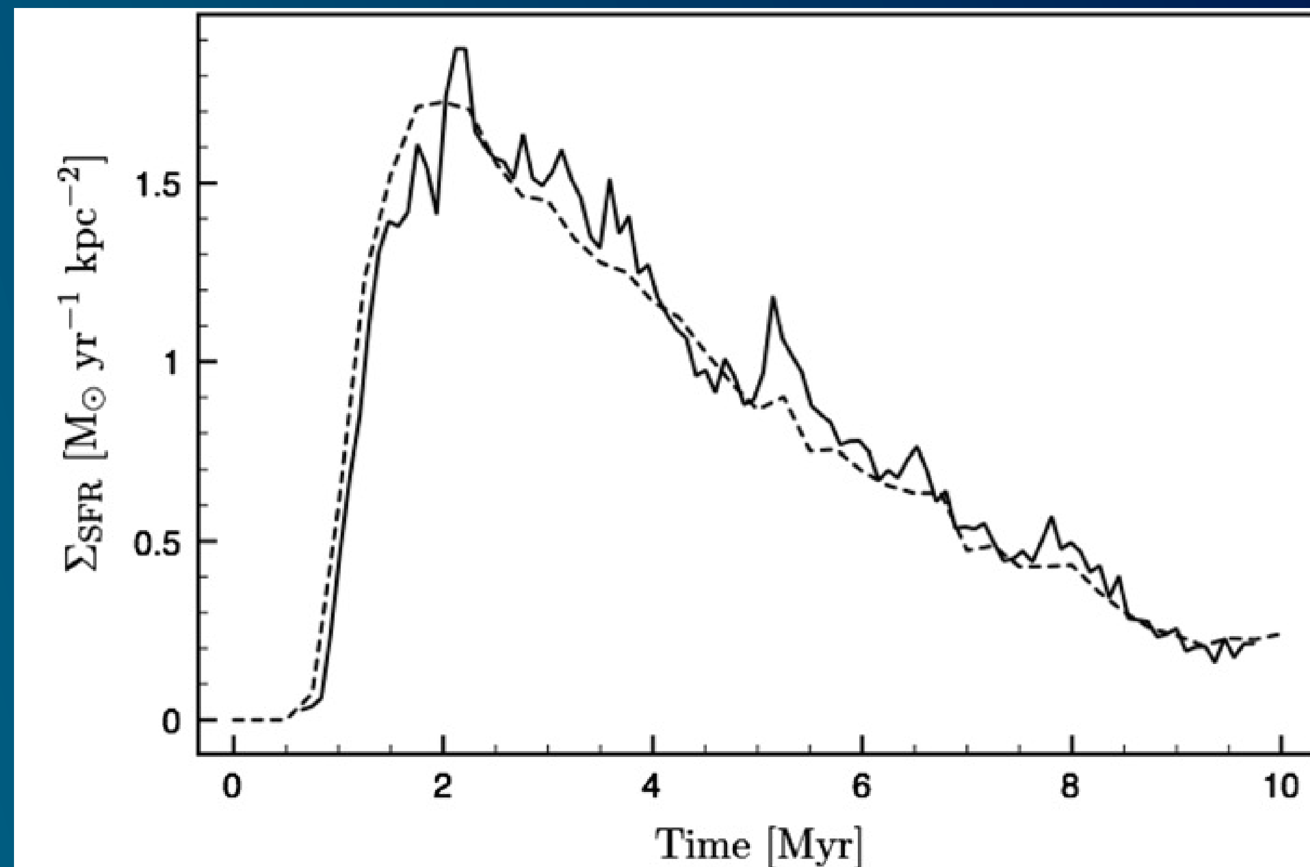
Star formation rates too high

Tasker 2011, Van Loo et al. 2013,
Bonnell et al. 2013

see talks by Tasker & Bonnell



Bigiel et al. 2008



Van Loo et al. 2013

Stellar Feedback

Energy injection into the ISM: (MacLow & Klessen 2004)

Protostellar Outflows:
$$\dot{e} \simeq (2\times10^{-28}\,\mathrm{erg\,cm^{-3}\,s^{-1}})\left(\frac{H}{200\,\mathrm{pc}}\right)^{-1}\left(\frac{f_\mathrm{w}}{0.4}\right)\times$$
$$\times\left(\frac{v_\mathrm{w}}{200\,\mathrm{km\,s^{-1}}}\right)\left(\frac{v_\mathrm{rms}}{10\,\mathrm{km\,s^{-1}}}\right)\left(\frac{\dot{\Sigma}_*}{4.5\times10^{-9}\,\mathrm{M_\odot\,pc^{-2}\,yr^{-1}}}\right),$$

Ionising radiation:
$$\dot{e} = \frac{3}{2}nkT\eta_c/\tau_\mathrm{OB} \simeq (5\times10^{-29}\,\mathrm{erg\,cm^{-3}\,s^{-1}})\left(\frac{n}{1\,\mathrm{cm^{-3}}}\right)\left(\frac{T}{10^4\,\mathrm{K}}\right)\left(\frac{\eta_c}{0.07}\right)\left(\frac{\tau_\mathrm{OB}}{100\,\mathrm{Myr}}\right)^{-1}$$

Supernovae:
$$\dot{e} = \frac{\sigma_{SN}\eta_{SN}E_{SN}}{\pi R_{sf}^2 H_c}$$
$$= (3\times10^{-26}\ \mathrm{erg\ s^{-1}\ cm^{-3}})\left(\frac{\eta_{SN}}{0.1}\right)\left(\frac{\sigma_{SN}}{1\ \mathrm{SNu}}\right)\left(\frac{H_c}{100\ \mathrm{pc}}\right)^{-1}\left(\frac{R_{sf}}{15\ \mathrm{kpc}}\right)^{-2}\left(\frac{E_{SN}}{10^{51}\ \mathrm{erg}}\right).$$

Stellar winds: Dependent on mass (but could be ~ supernovae)

Radiation pressure: dependent on luminosity (but could be ~ supernovae)

Stellar Feedback

Analytical models

e.g. Goldbaum et al. 2011, Ostriker et al. 2010

cannot take into account inhomogeneity of clouds, stochasticity etc.

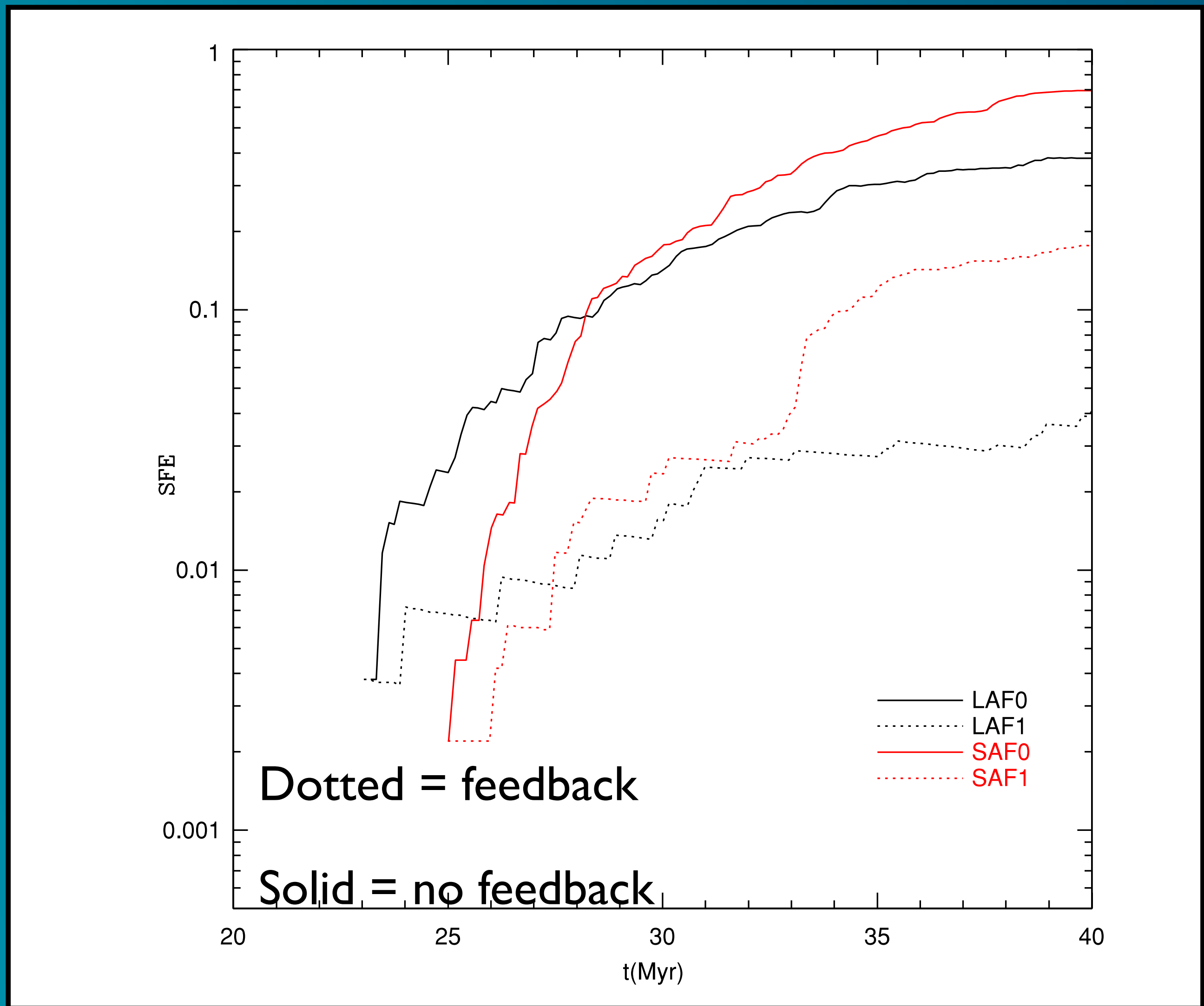
Simulations

include feedback by inserting thermal energy and / or momentum

models vary, and difficult to include many processes

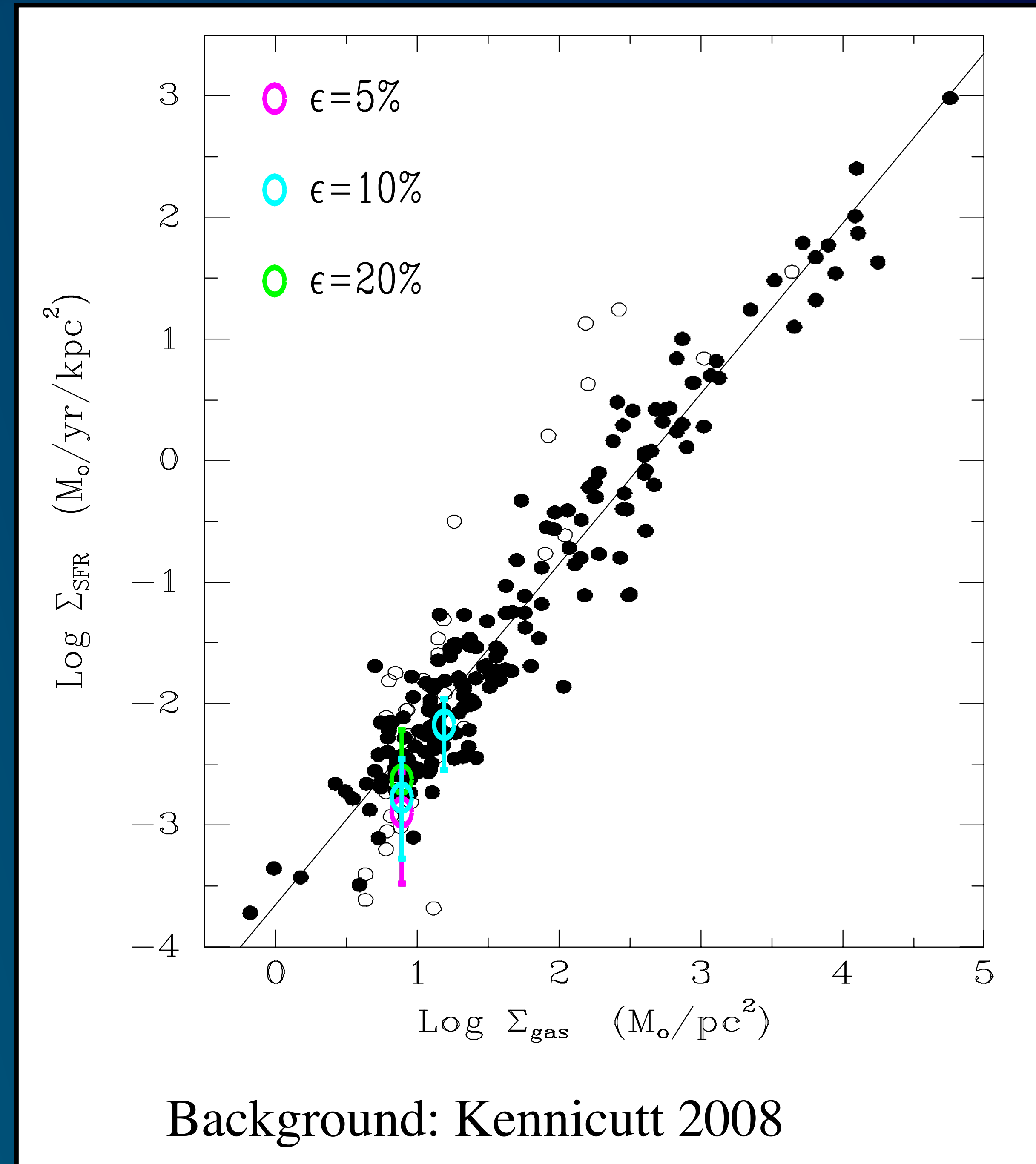
- simulations / models universally show a reduction in SFR, or propose a regulation of SFR with stellar feedback
- supernova rate ~ 1 per 50 years (e.g. Diehl et al. 2006)

Stellar Feedback



Vazquez-Semadeni et al. 2010:
SFE= instantaneous star formation efficiency
HII feedback, ~10^4 $M_\odot$ cloud

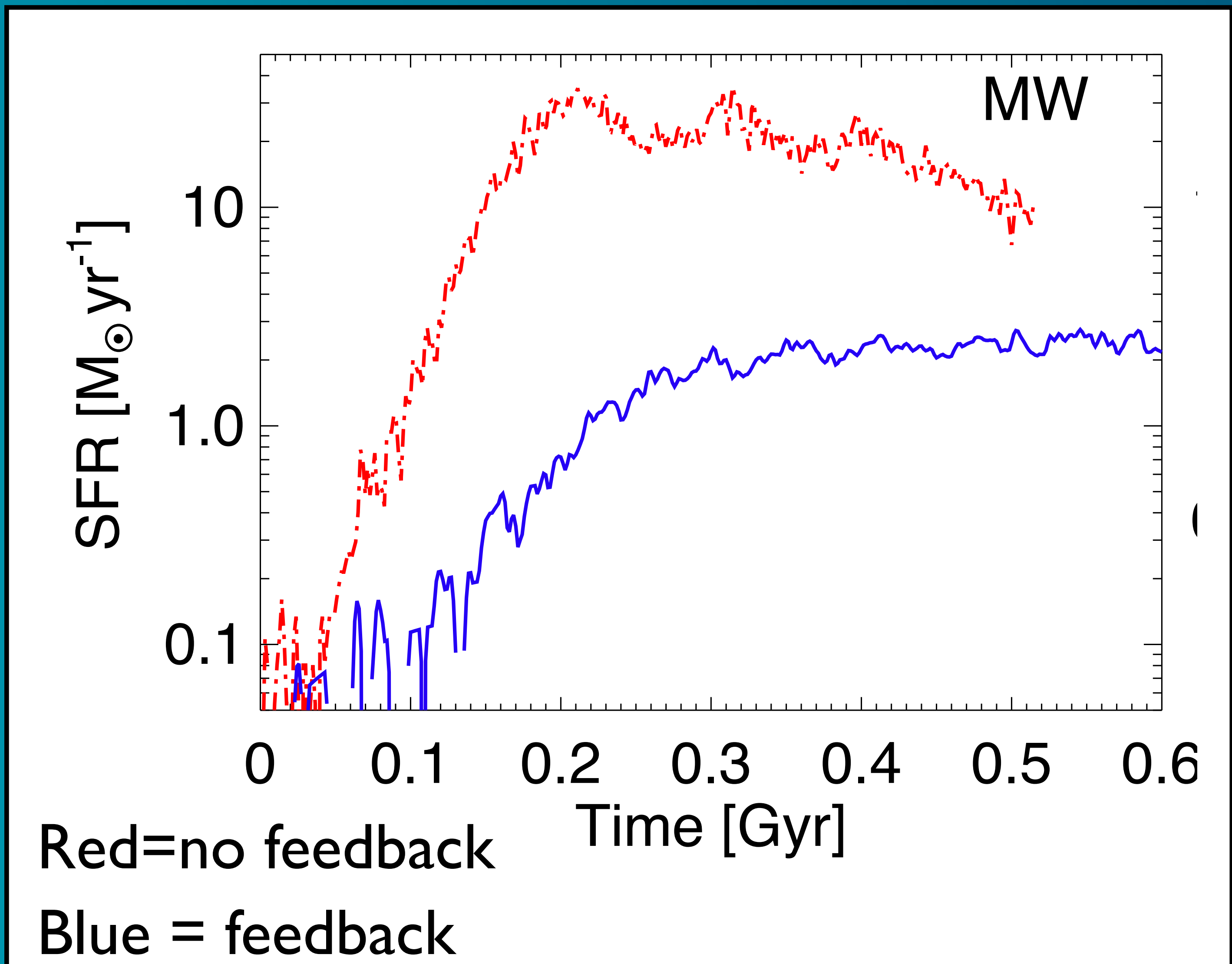
Reduces star formation rate



Dobbs et al. 2011, kinetic + thermal feedback equal to supernovae
ε=0, order of magnitude too high

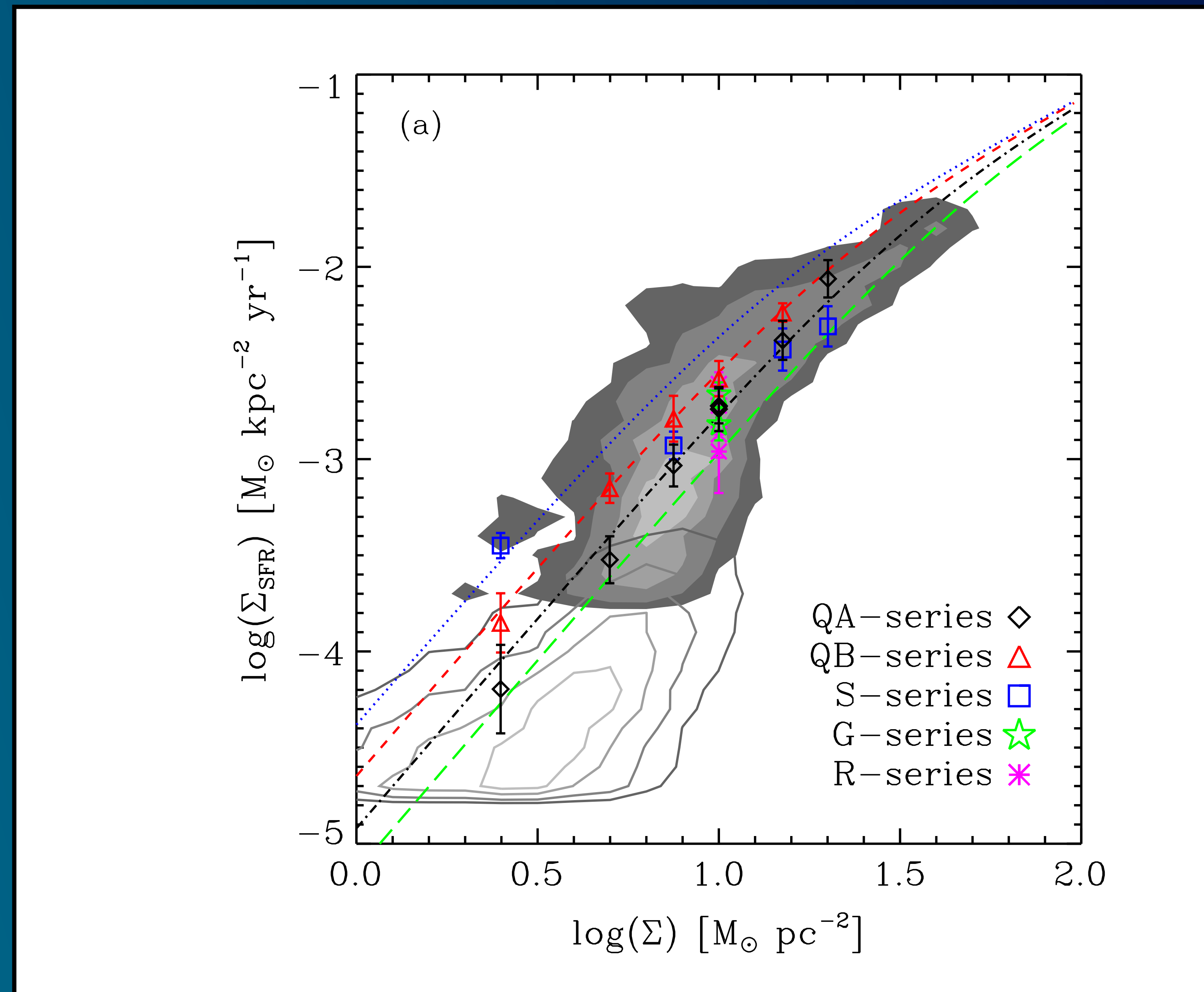
SFR close to KS

Stellar Feedback



Hopkins et al. 2011, galaxy disc

radiation pressure, + winds, supernovae



Kim, Kim & Ostriker 2011

supernovae feedback

What impact does stellar feedback have?

<u>Effects of feedback</u>

1. Disperses gas - 'evacuates gas from dense regions' (Colin et al. 2013) prematurely terminating star formation

2. Ejects energy locally into the ISM

3. Ejects energy globally into the ISM

4. Ejects gas to regions of minimal star formation, e.g. outside disc (e.g. Tasker & Bryan 2006, Paolo's talk, Adam's talk)

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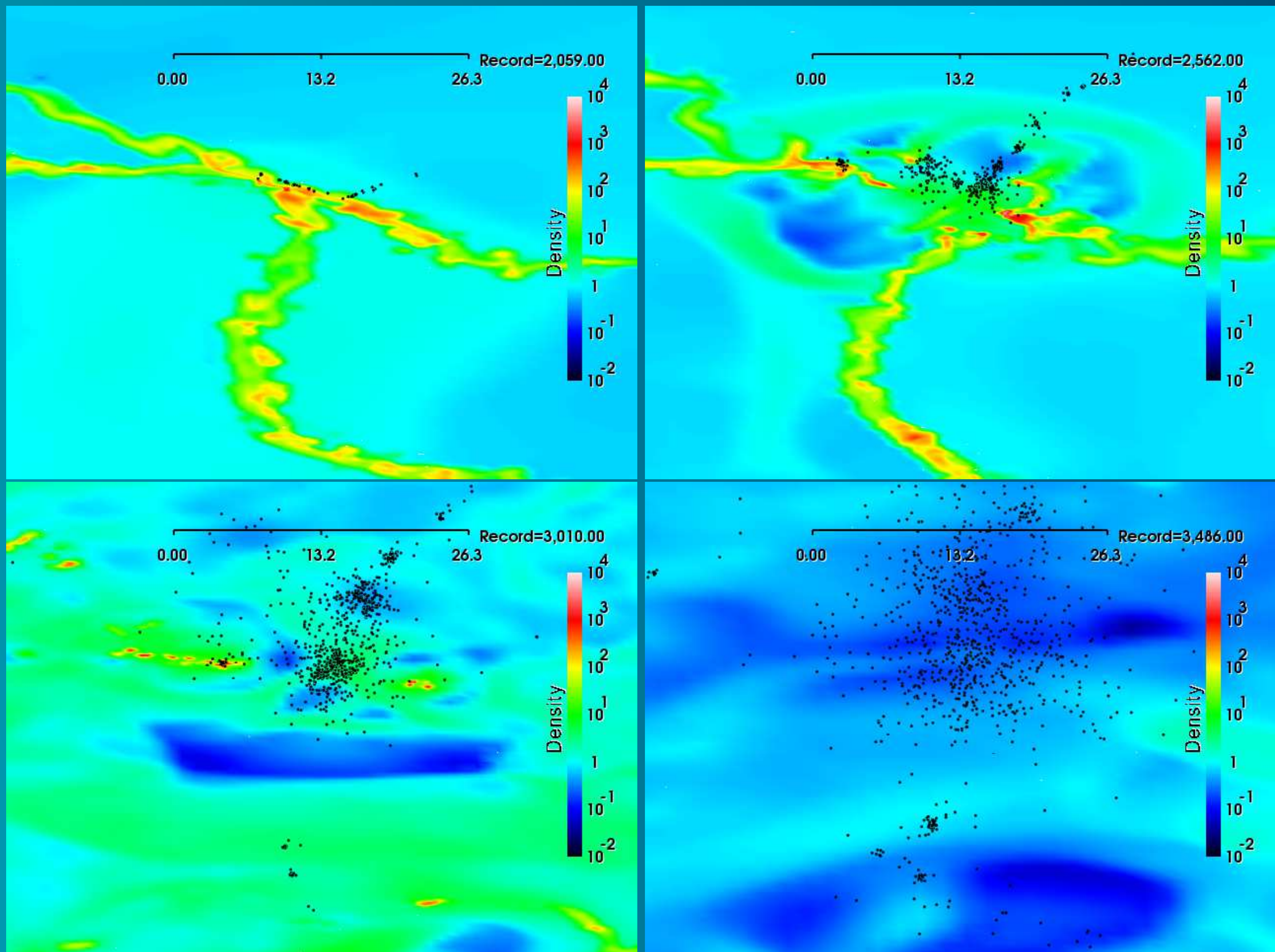
Different models:

1. Hierarchical global collapse (Hartmann et al. 2012)

2. Clouds in ~virial equilibrium supported by internal turbulence

3. Clouds unsupported / dominated by external motions

Feedback in action (1)



Colin et al. 2013

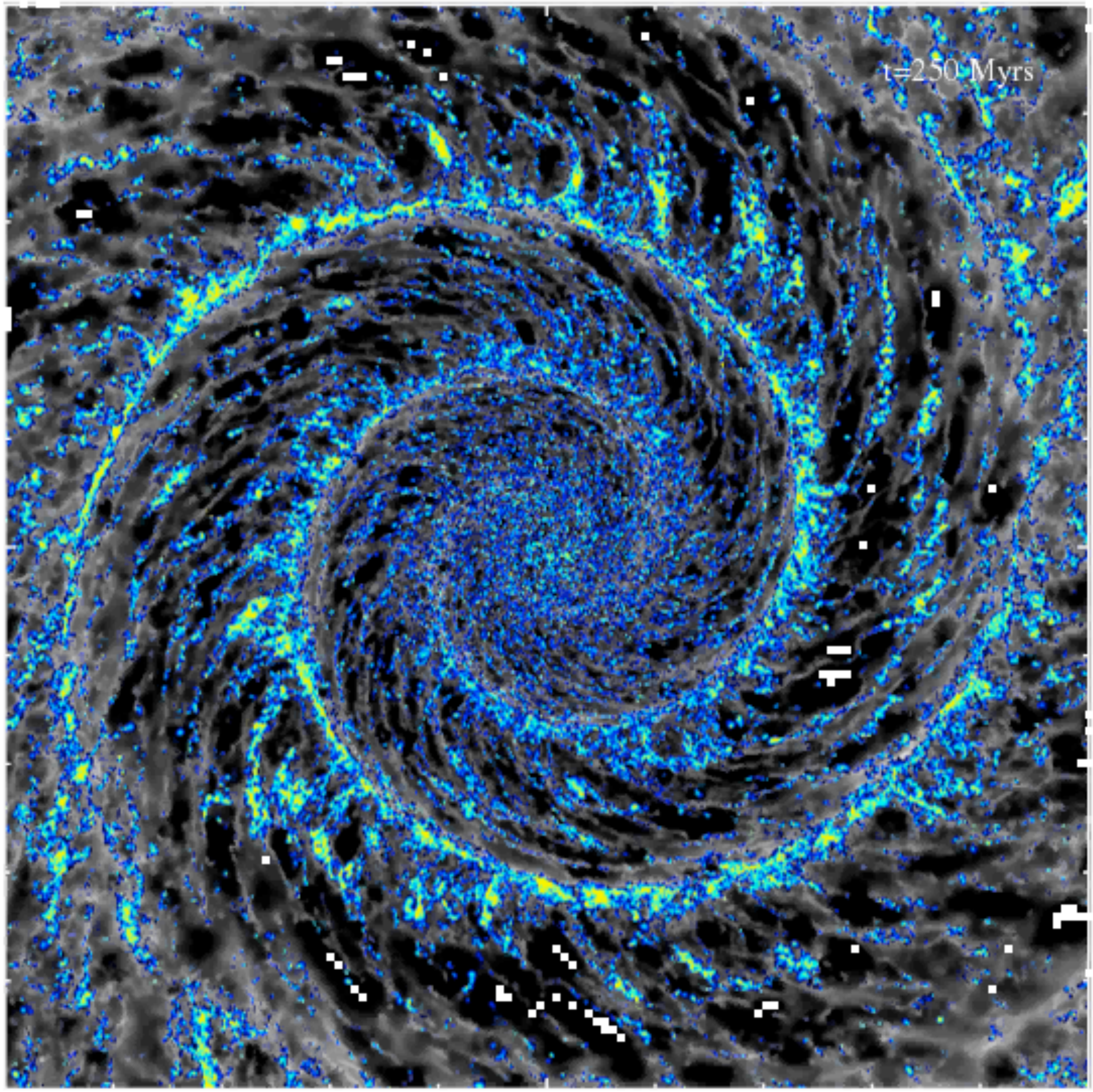
HII feedback (10^4M cloud)

(see also Jim Dale's tak)

Feedback completely disperses cloud

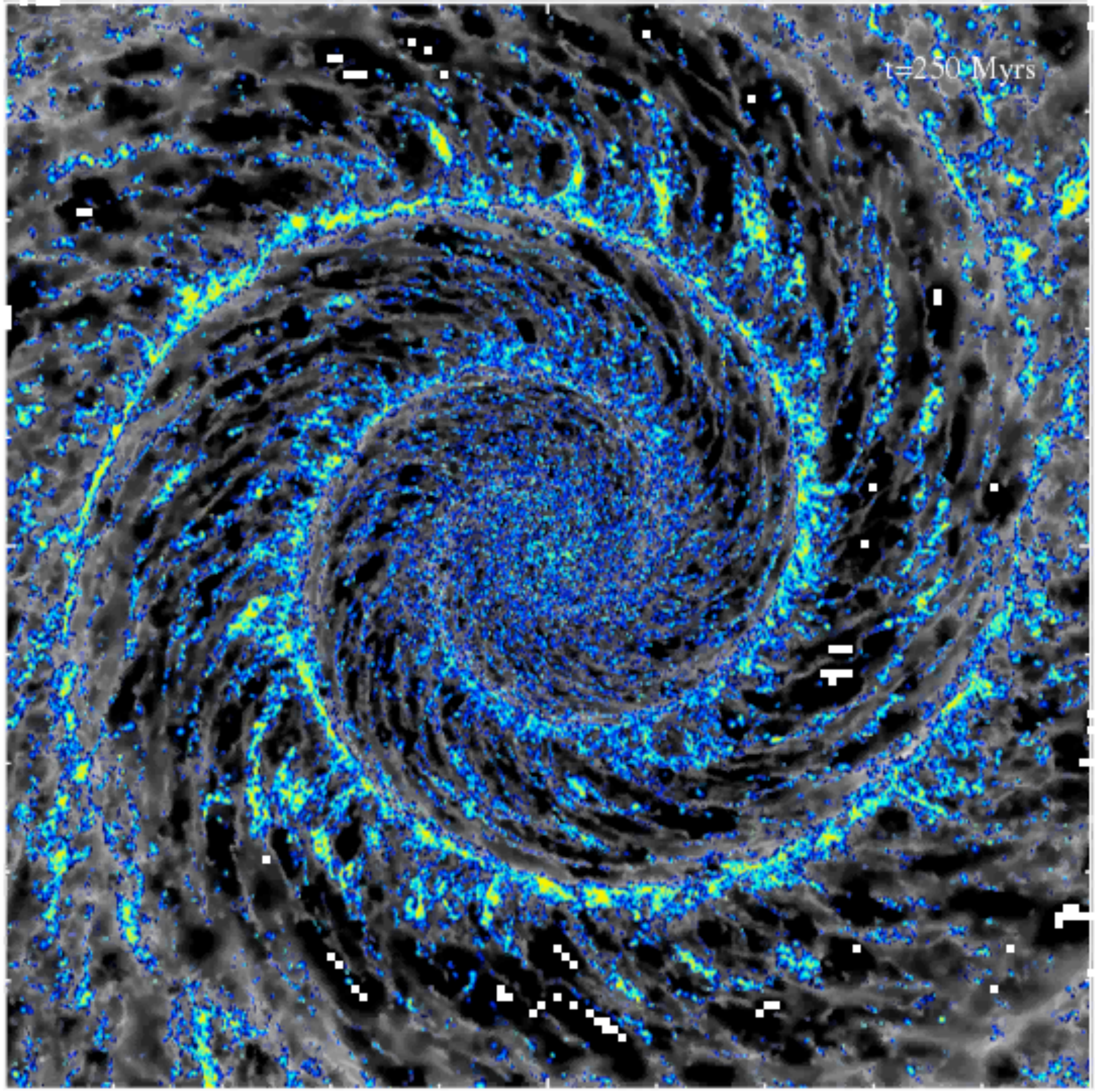
(see also Eve Ostriker's talk, with radiation pressure)

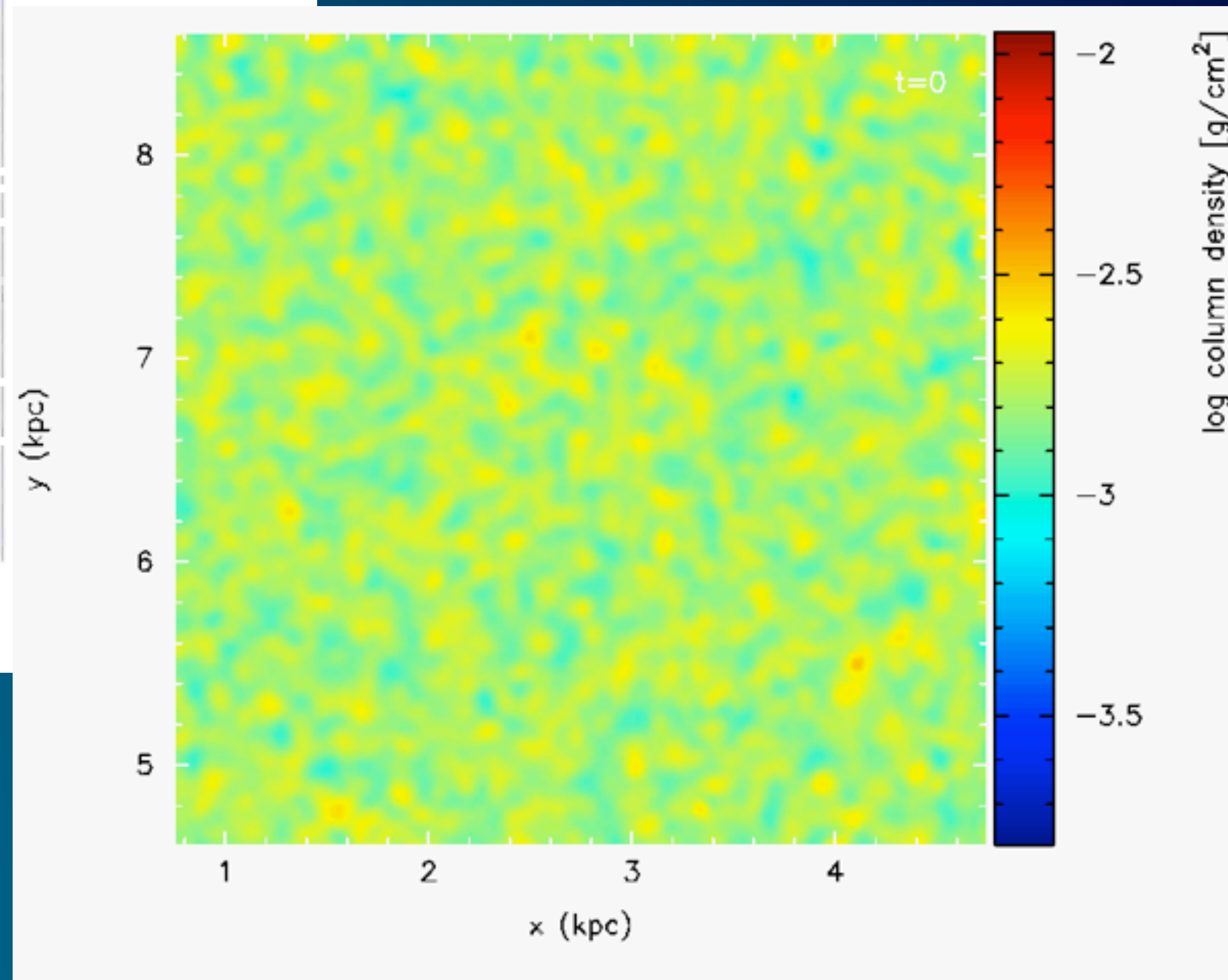
Dobbs & Pringle 2013



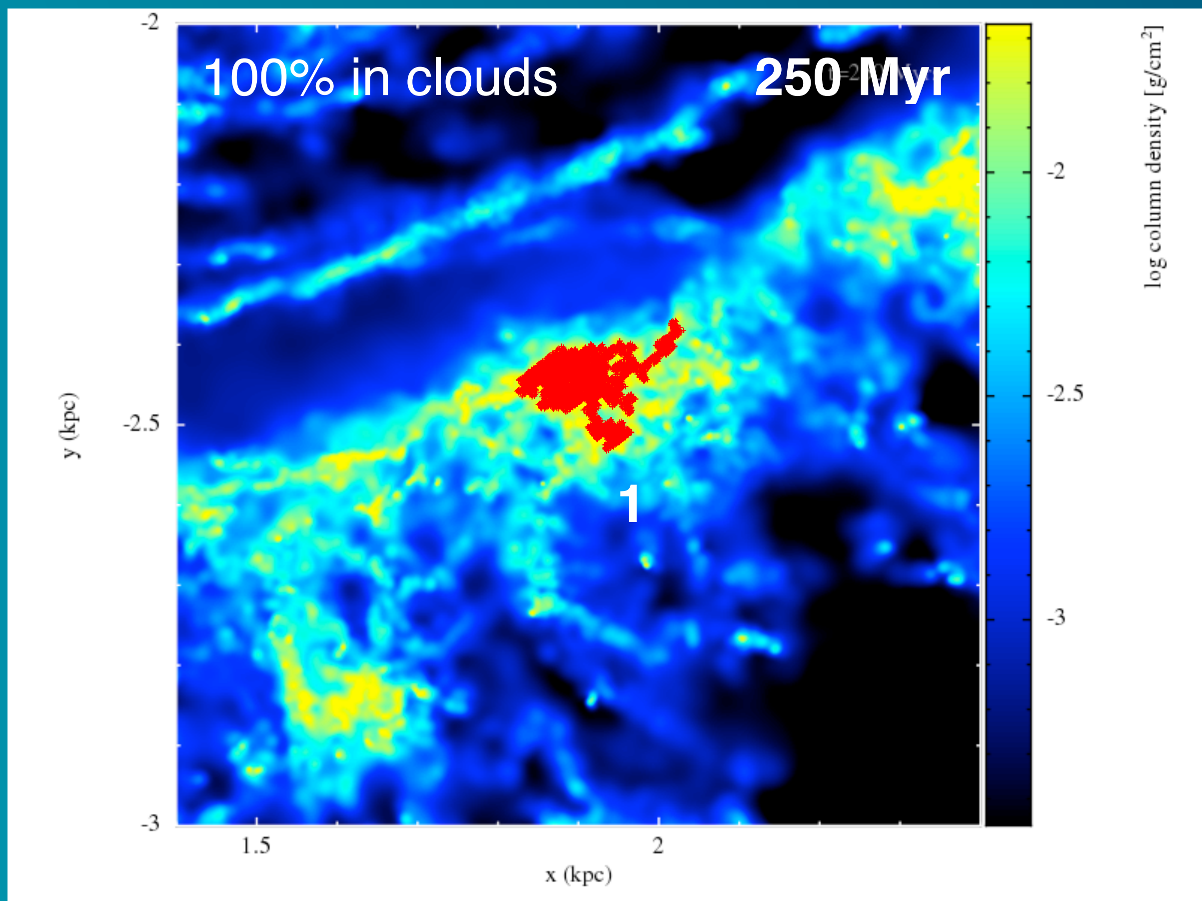
log H_2

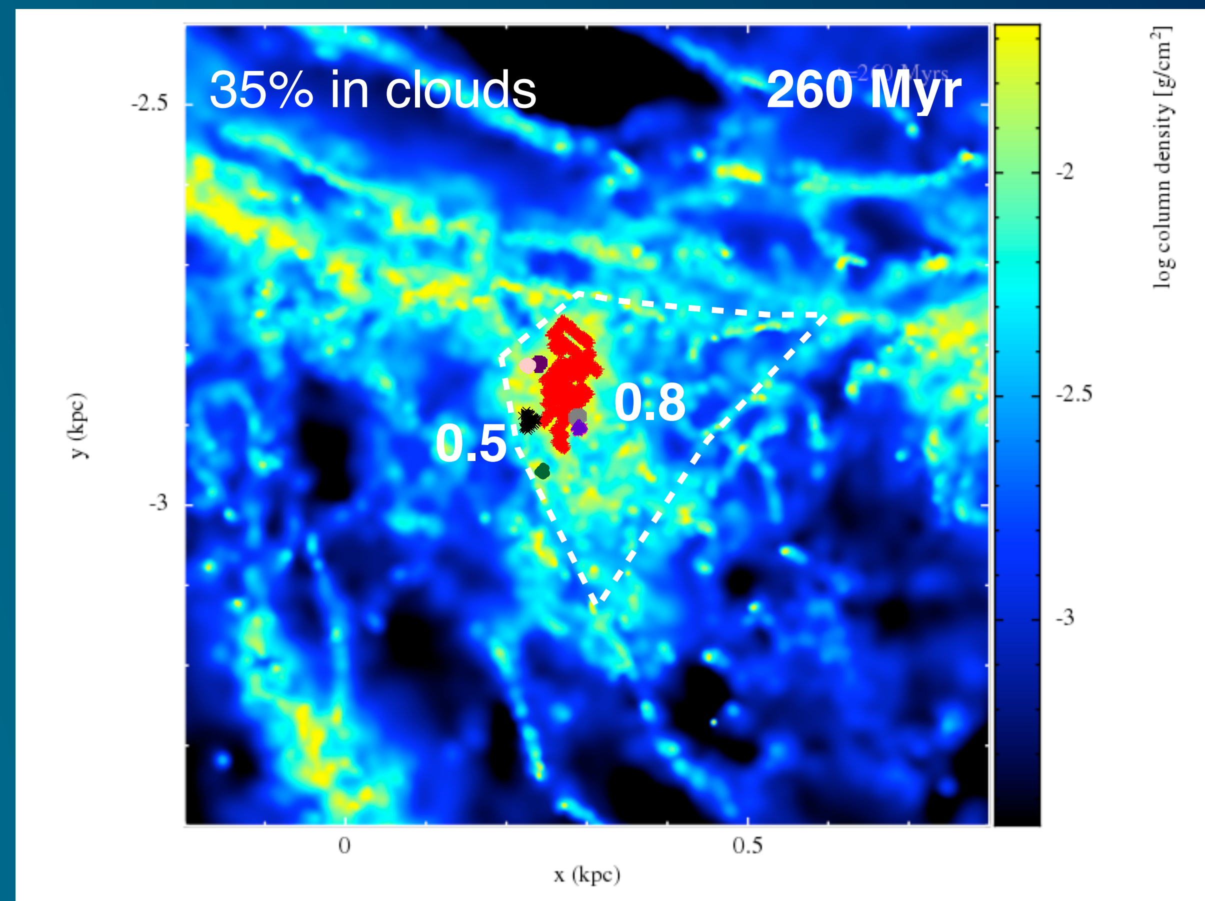
Dobbs & Pringle 2013

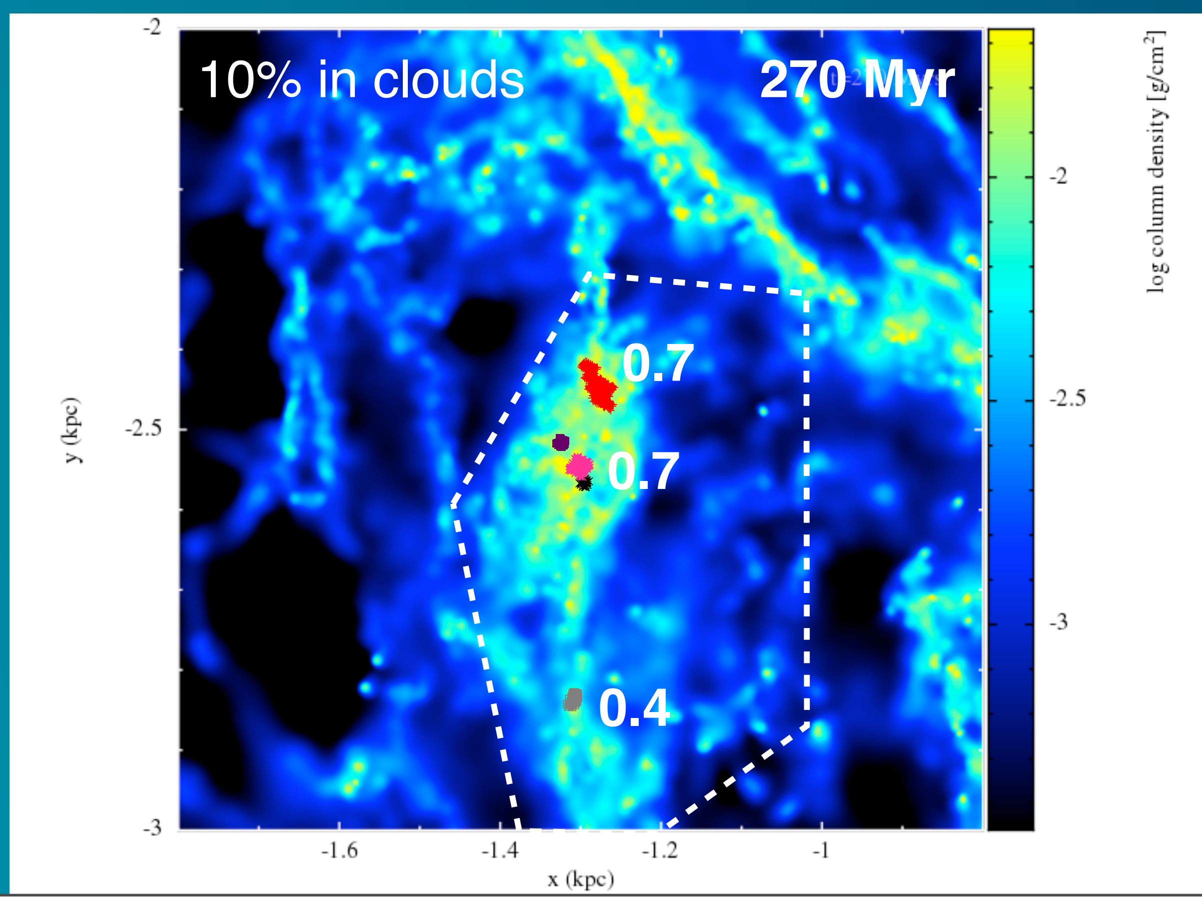




Feedback in action (2)







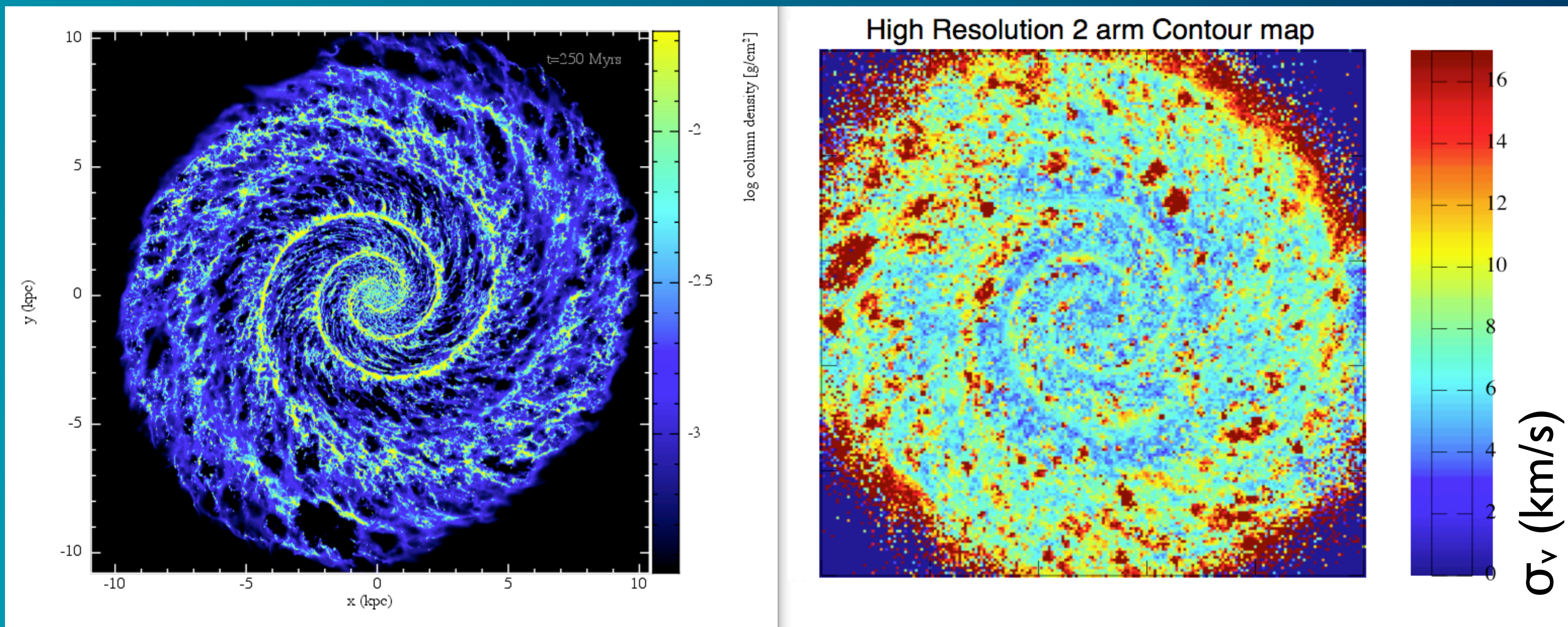
Feedback splitting up and dispersing a $2x10^6$ $M_\odot$ cloud over 20 Myr

Cloud lifetimes ~ crossing time of the cloud

Dobbs & Pringle 2013

Feedback in action (3)

Dobbs et al. 2011: feedback largely determines the velocity dispersion of the gas in the disc



ε (%)	σ (km/s)
1	2-4
5	4-8
20	8-20

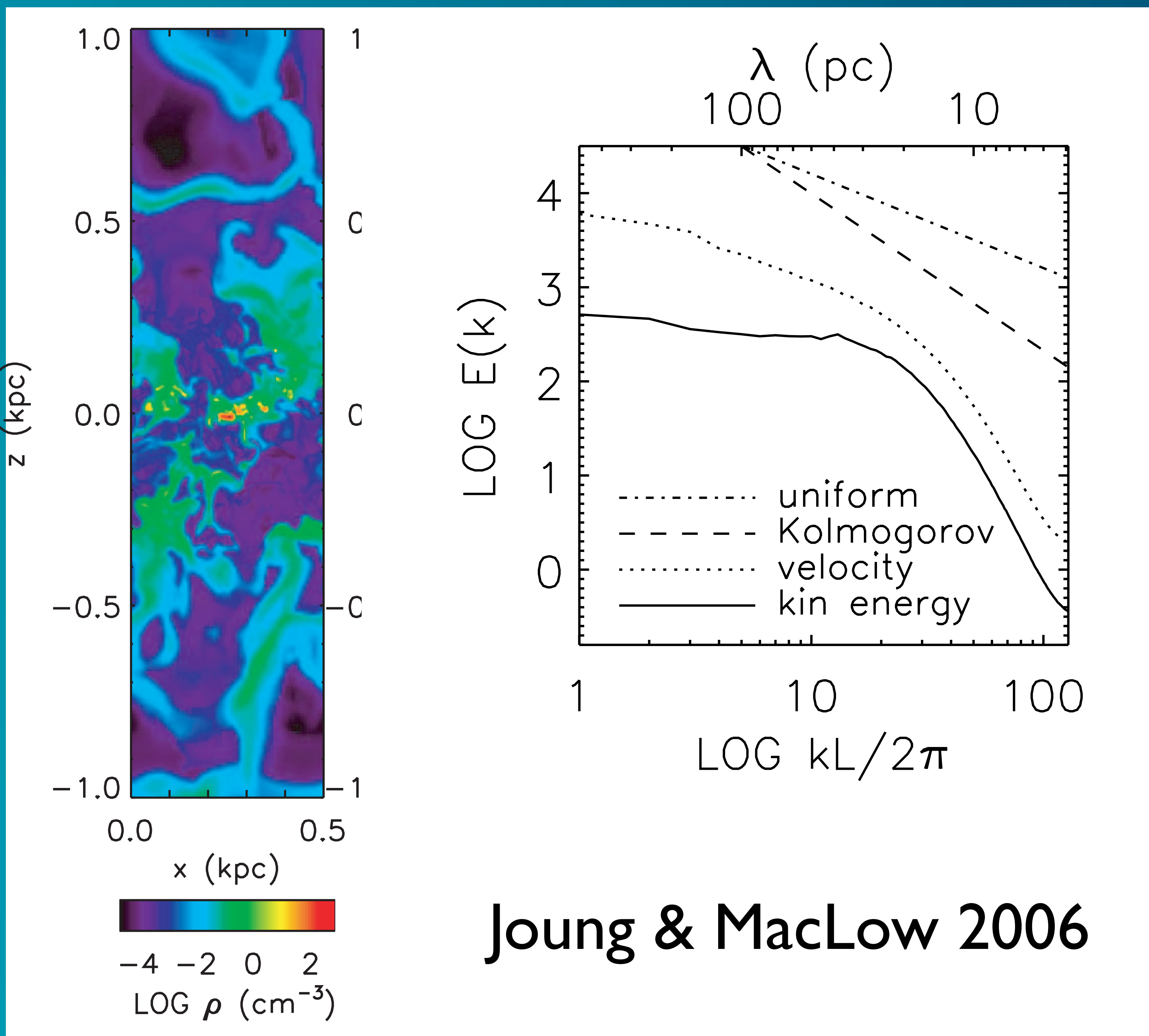
Freya Aldred, Mphys student

Maintain a linewidth of at least a few km/s everywhere (on 10's pc scales)

Feedback in action (3)

Turbulent-like power spectra obtained

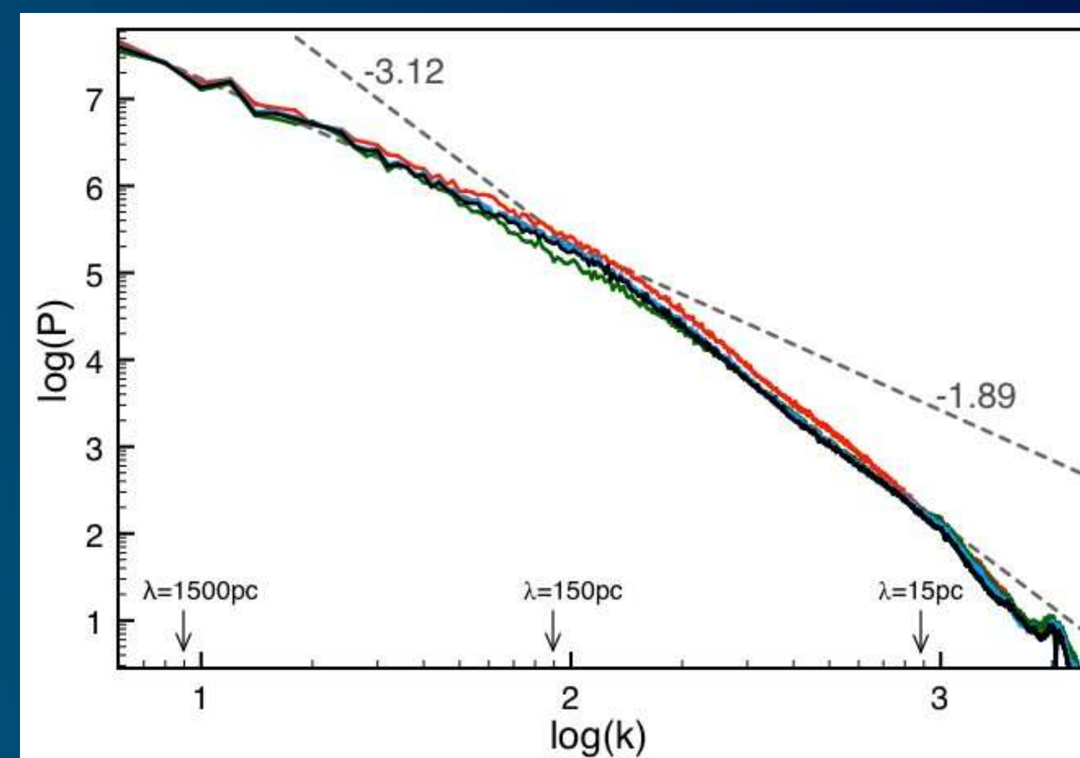
Supernovae in a 3D box



Joung & MacLow 2006

also Bournaud et al. 2010

Find power spectra arising from gravity, though without feedback, the spectra becomes unrealistic with time



Feedback in action (3)

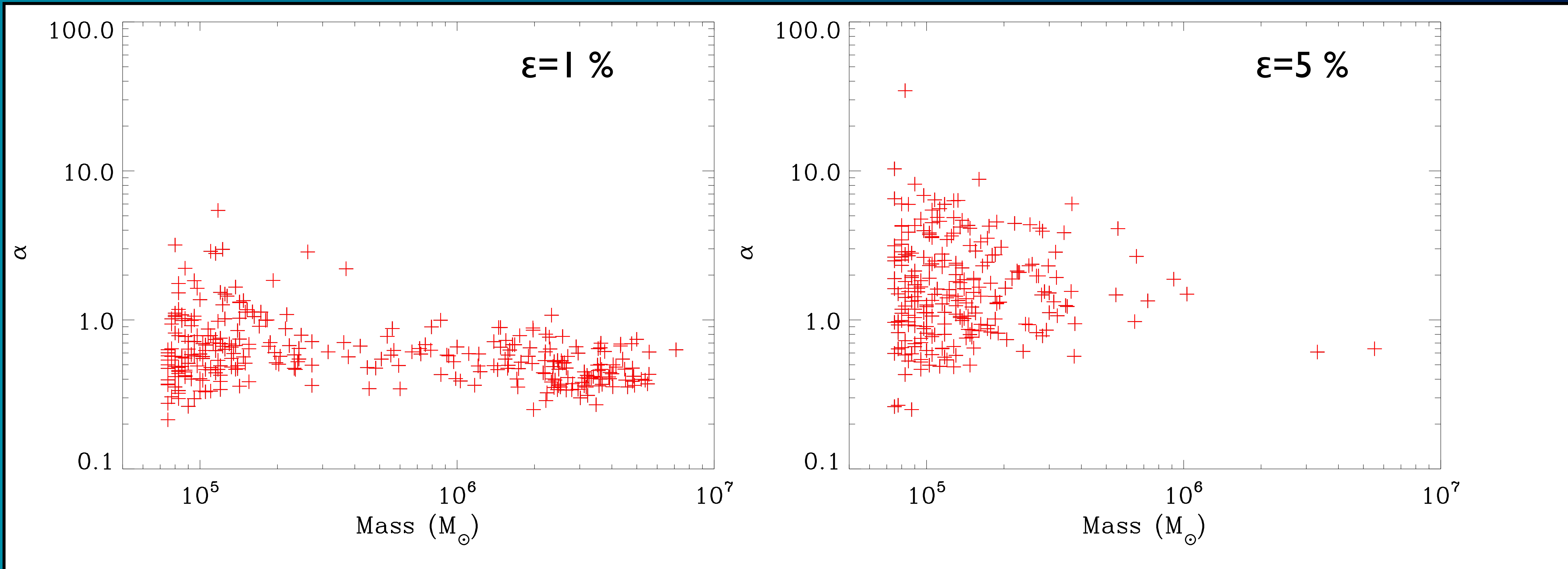
Cloud	Mass (10^5 $M_\odot$)	No. particles	α	Location at $T_0 = 250$ Myr	Nature of cloud evolution	Nature of cloud dispersal
Cloud380	20	6386	2.9	Spiral arm (R=3.1 kpc)	forms from and disperses into smaller clouds	shear + feedback
Cloud788	1.7	559	3.7	Spiral arm (R=4.3 kpc)	remains of, and progenitor of more massive cloud	feedback
Cloud877	3.1	999	1.8	Spiral arm (R=4.1 kpc)	forms from and disperses into smaller clouds	shear + unbound
Cloud355	0.96	305	3.6	Inter-arm (R=3.3 kpc)	remains of more massive GMC	shear + unbound
Cloud159	2.7	863	2.7	Outer disc (R= 8.3 kpc)	forms from and disperses into smaller clouds	unbound
Cloud1198	13	4291	0.8	Spiral arm (R=3.4 kpc)	remains of more massive GMC	feedback

Dobbs & Pringle 2013

Clouds marked simply ‘unbound’, or ‘shear+unbound’, are not associated with much recent stellar feedback themselves, but still have relatively high velocity dispersions

- shear can also be important for disrupting clouds

Unbound clouds



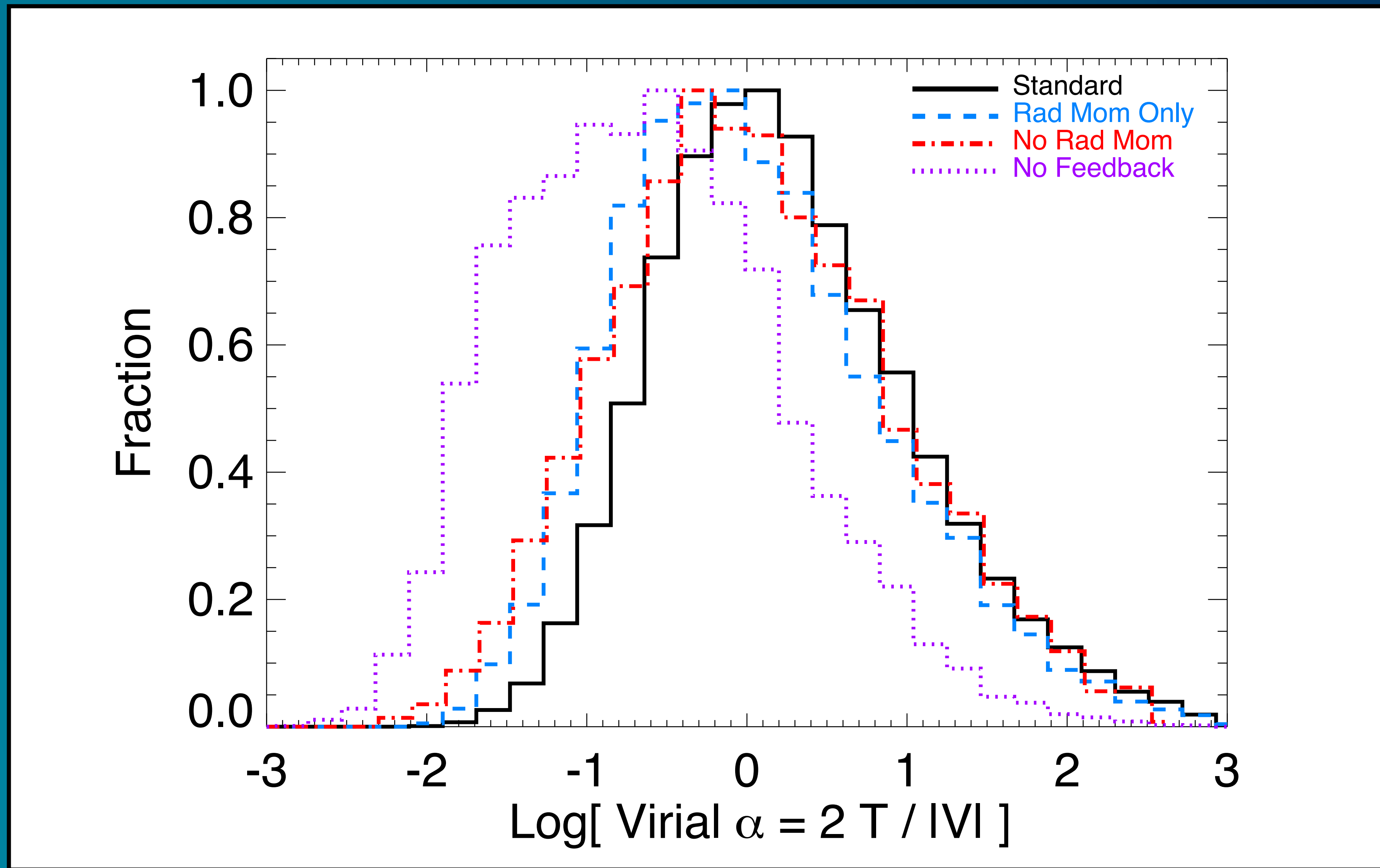
Dobbs et al 2011

Virial parameters higher with feedback - a majority of clouds unbound

Unbound clouds help reduce star formation, but alone probably too small fraction to explain low star formation rates

Also unboundedness ultimately linked to feedback

Virial parameters of clouds

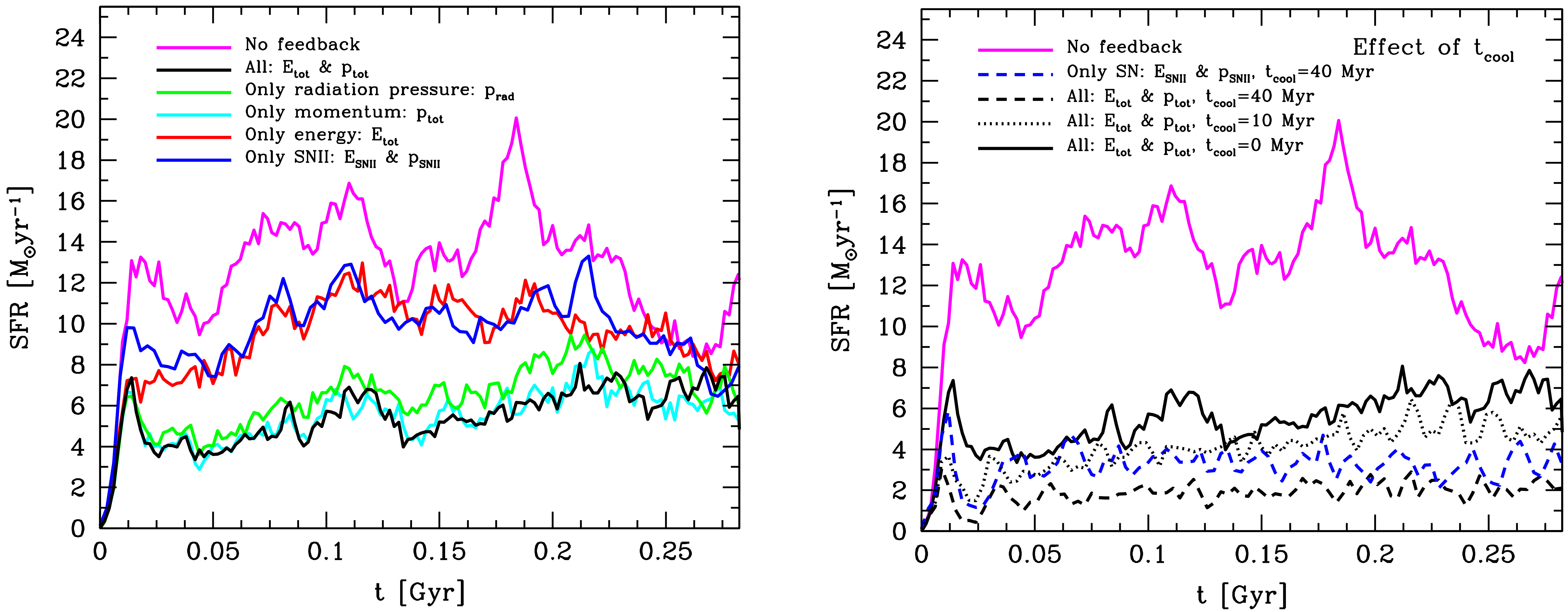


Hopkins et al. 2012

also find that distribution of virial parameters shifts to lower / higher values with / without feedback

(but see Van Loo et al. 2013, unbound clouds without feedback)

Does it matter how feedback is included?



Agertz et al. 2013

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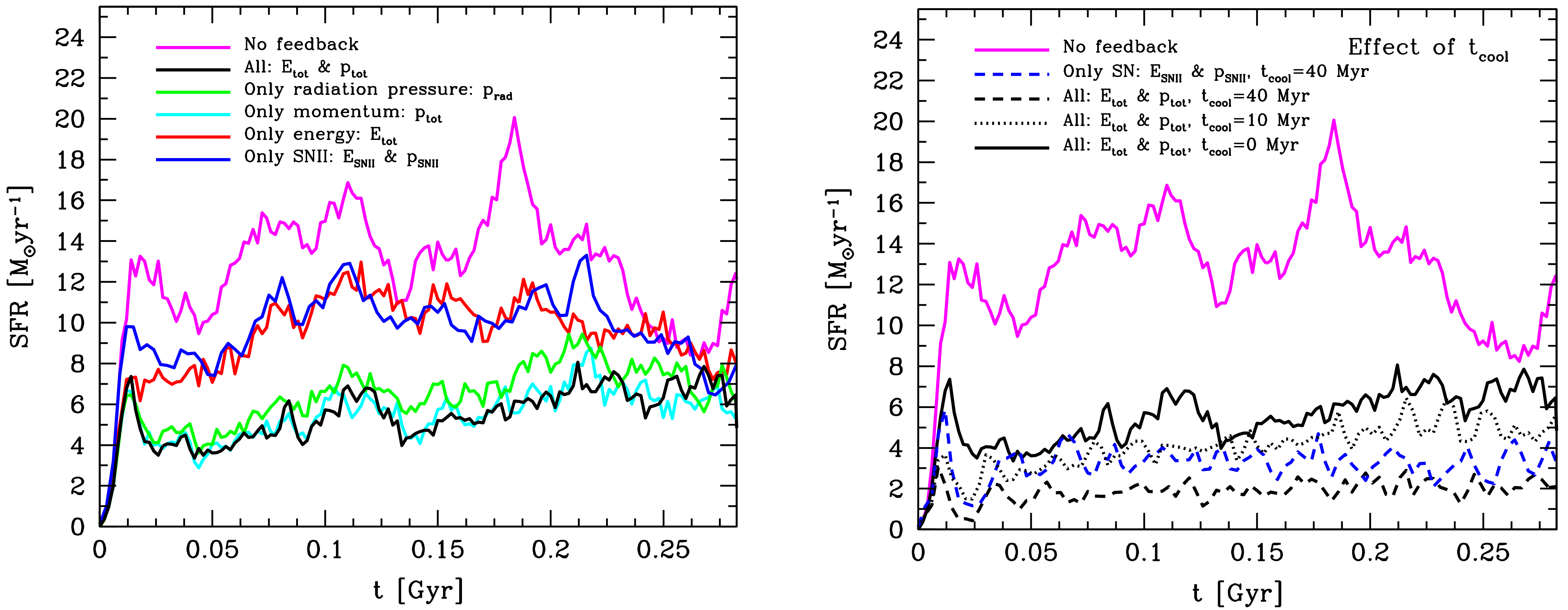


Agertz et al. 2013

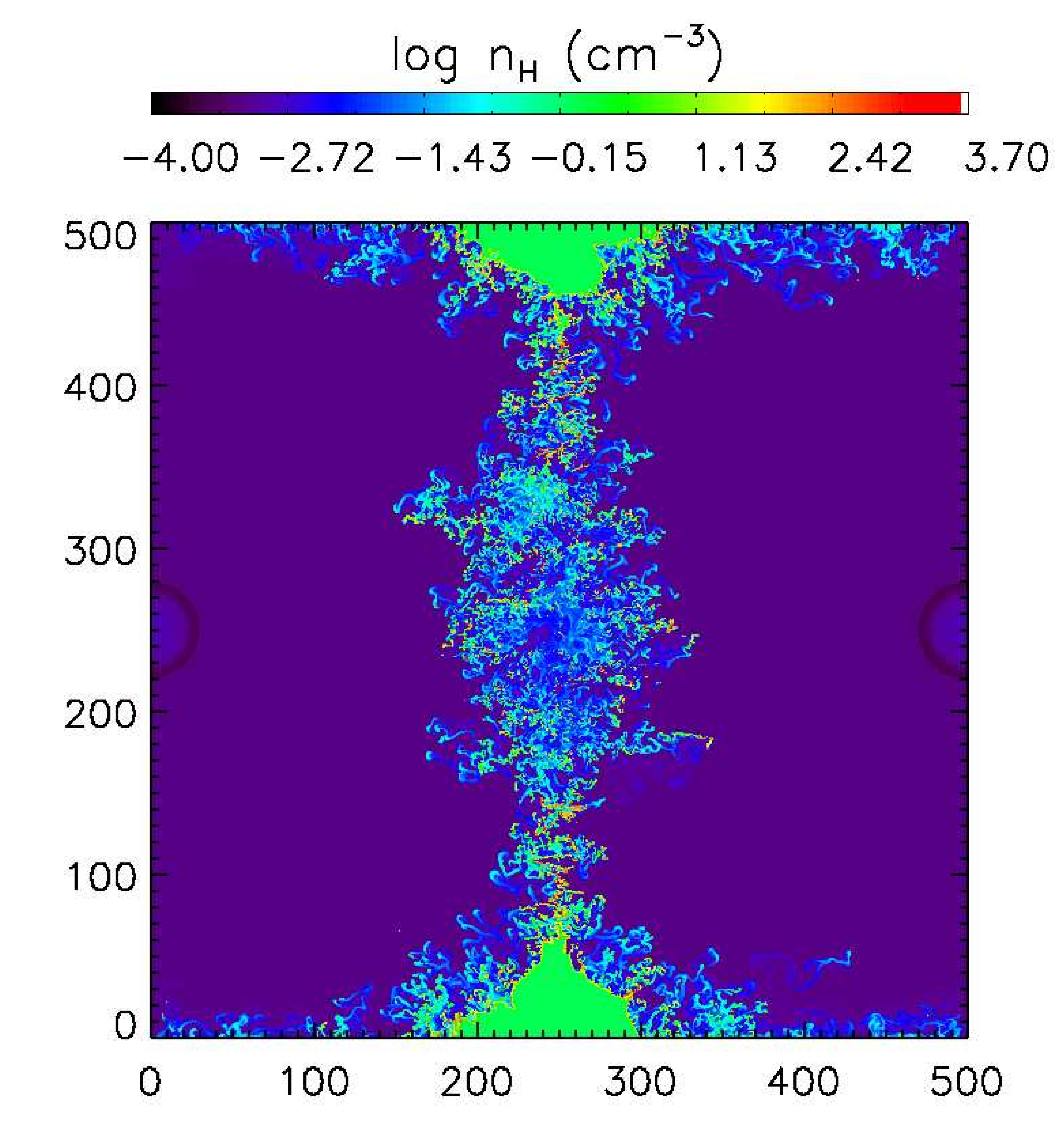
Delayed input of energy - less effective (just supernovae)

Initial input of energy, or energy added over time OK (rad. pressure, winds + supernovae)

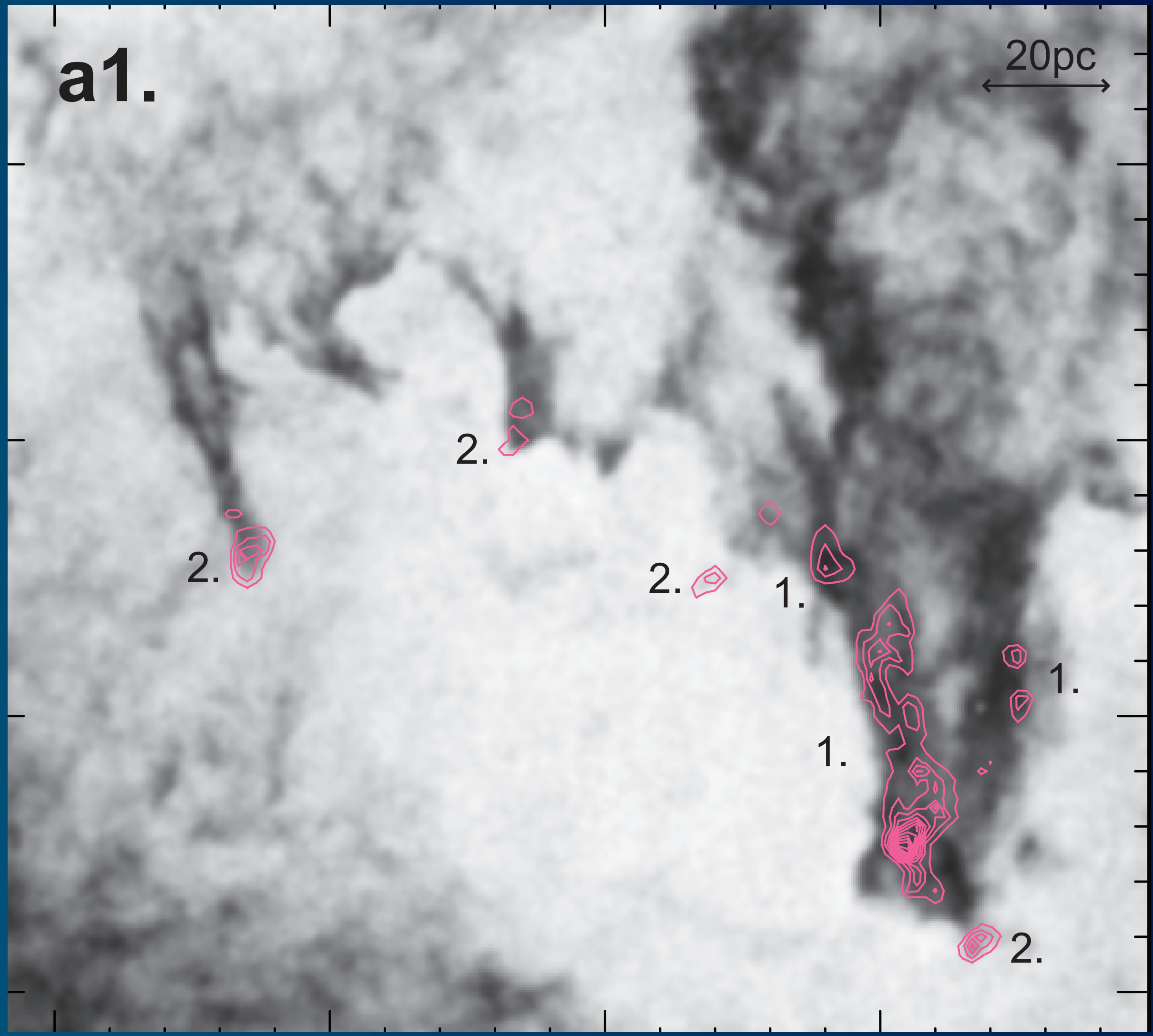
See also Stinson et al. 2013, Friday's beer discussion

What about star formation triggered by supernovae etc.?

see Sarah Kendrew's talk



Ntormousi et al. 2011: 2 adjacent supernovae bubbles



Dawson et al. 2011

CO emission at edges of supershells

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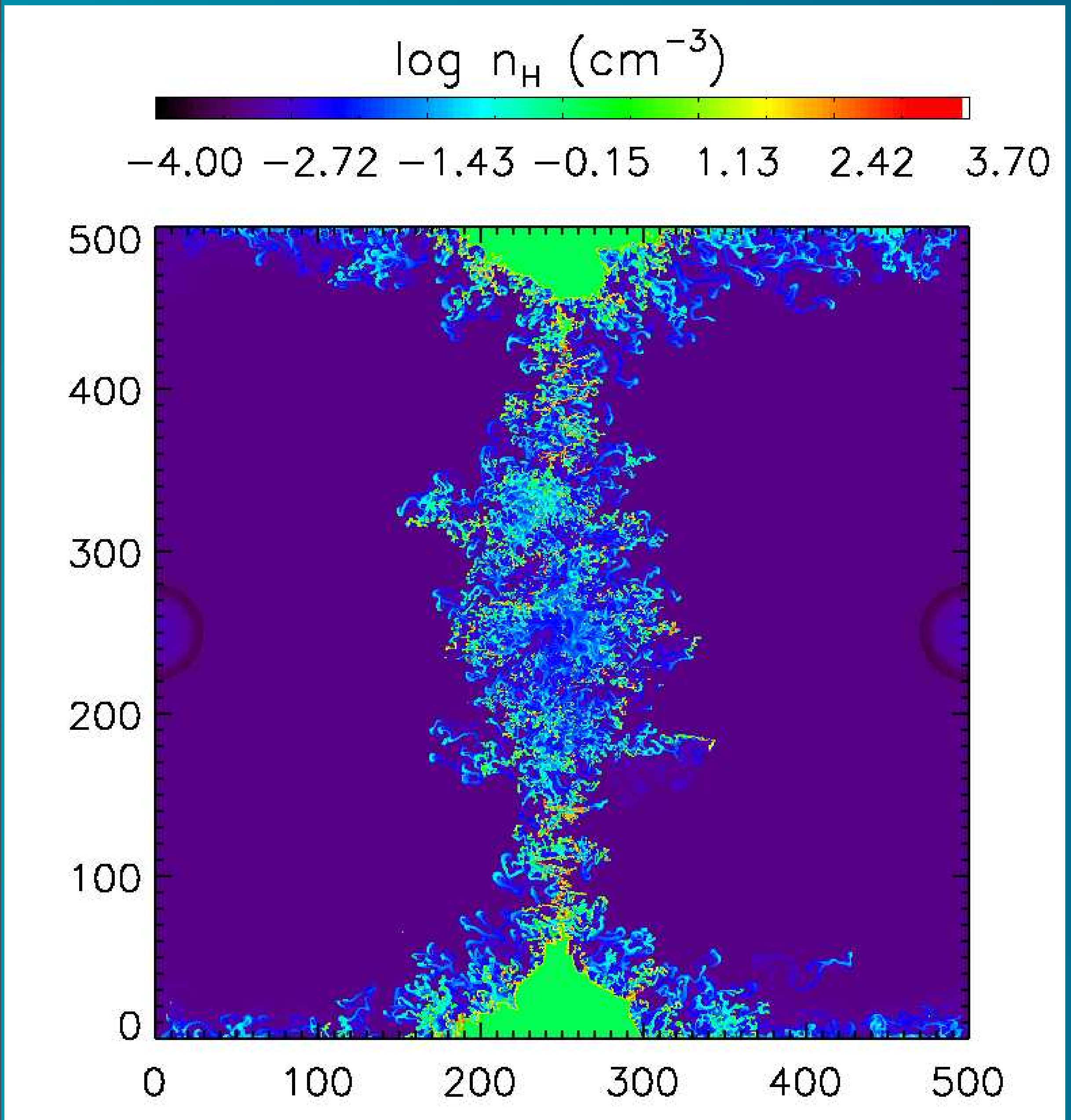

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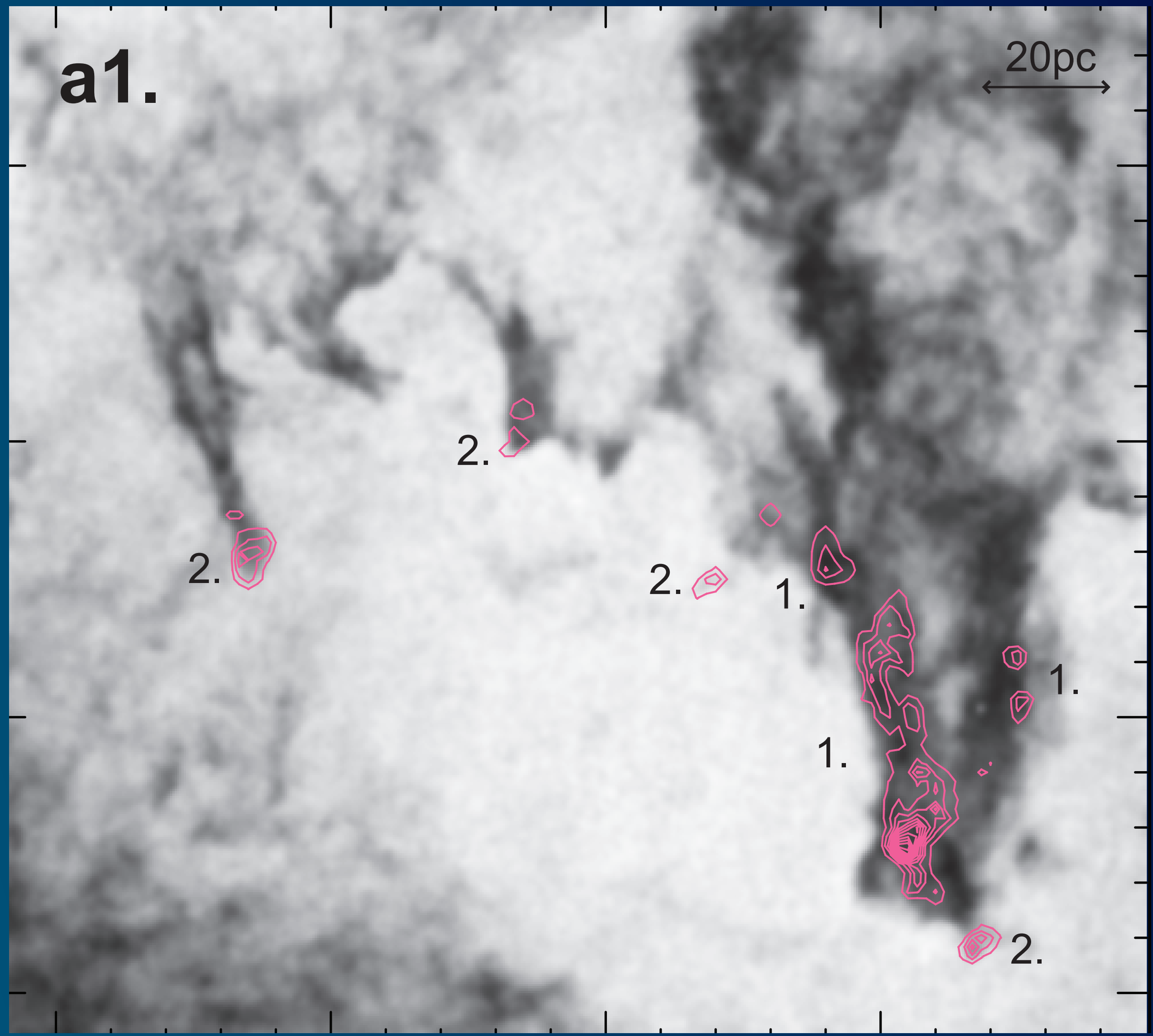


Dawson et al. 2011

CO emission at edges of supershells

LMC: responsible for only few % of clouds (Dawson, et al. 2013)

gas would form stars anyway, in absence of feedback →

Spiral shocks

- Triggering star formation vs rearranging molecular clouds

 - Roberts (1969): spiral shock triggering of star formation

 - Elmegreen & Elmegreen (1986): 'Do density waves trigger star formation?'

 - star formation in arms versus inter-arms: Eden et al. (2012), Foyle et al (2010) find no difference

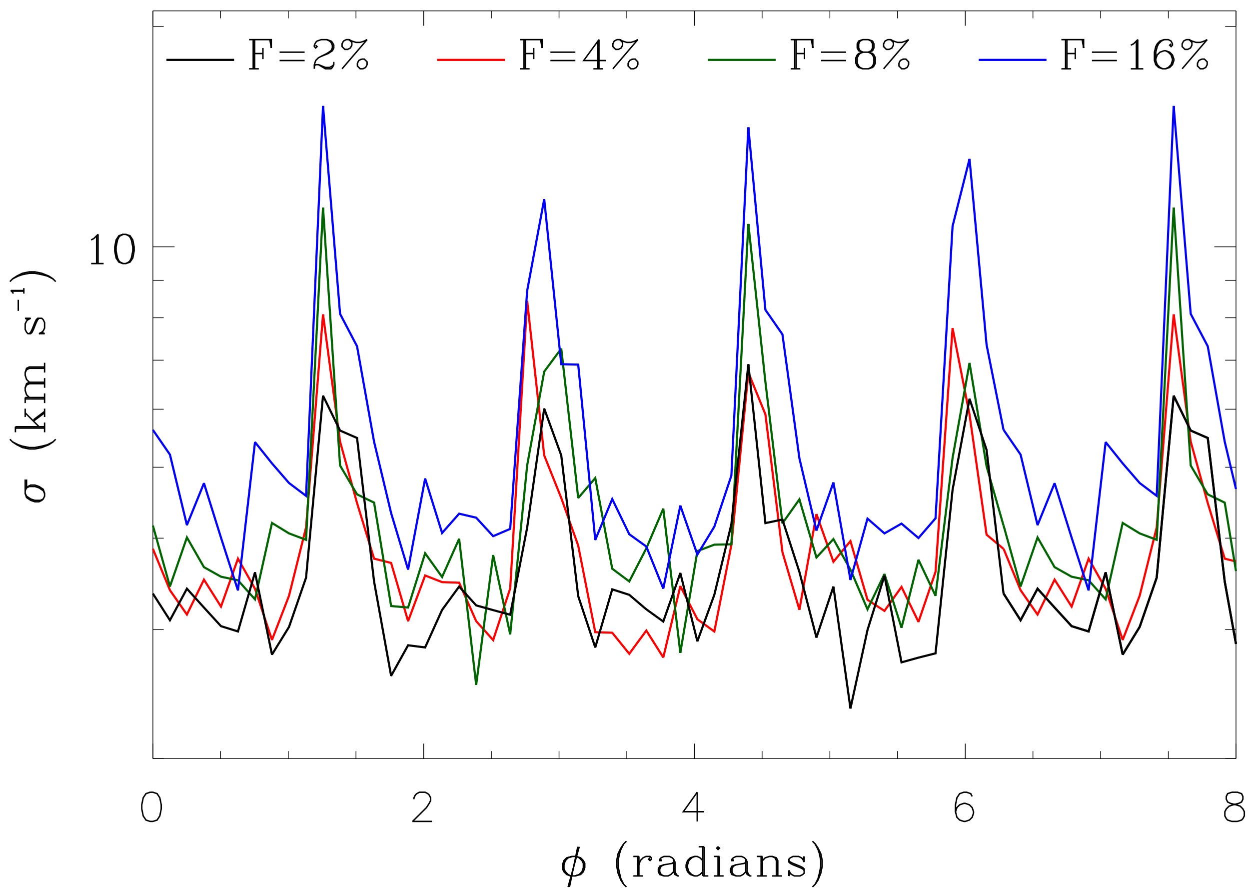
 - but correlation of Hα and shock strength (Seigar & James 2002)

- Also a potential source of random motions

Spiral shocks

- Spiral shocks increase velocity dispersion (see also Bonnell et al. 2005, Kim, Kim & Ostriker 2006)

F=strength of spiral shock



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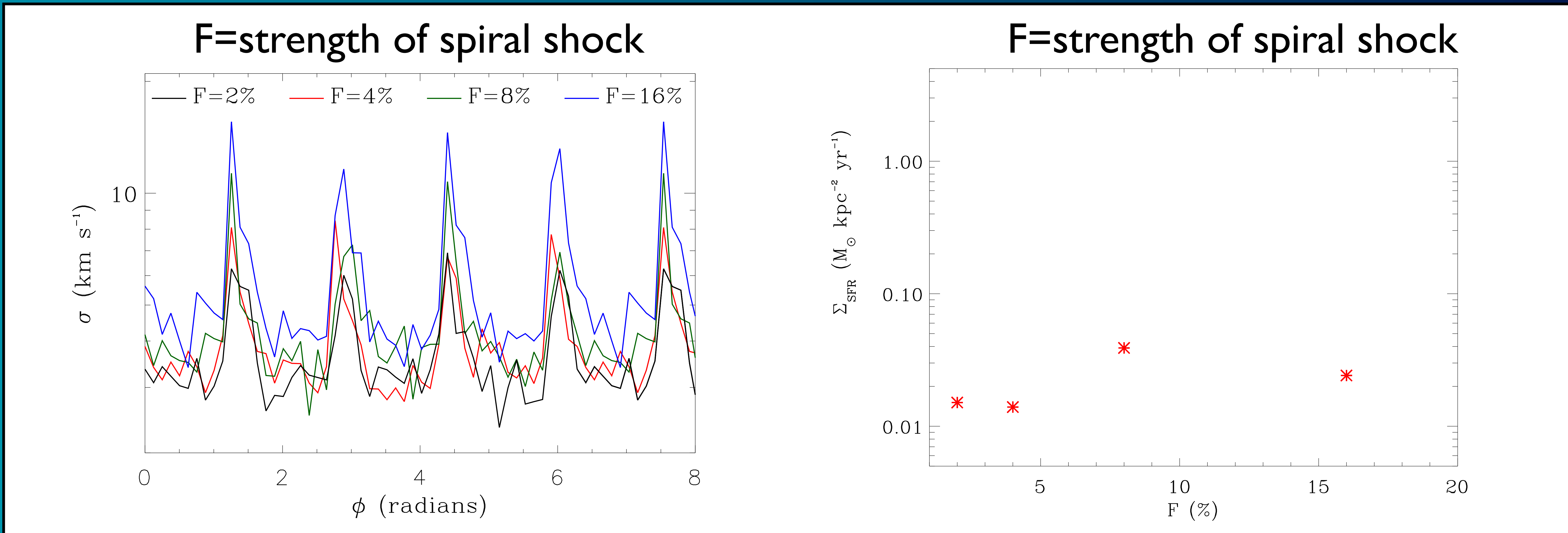


- Offsets increased densities in spiral arms

  amount of bound gas stays the same

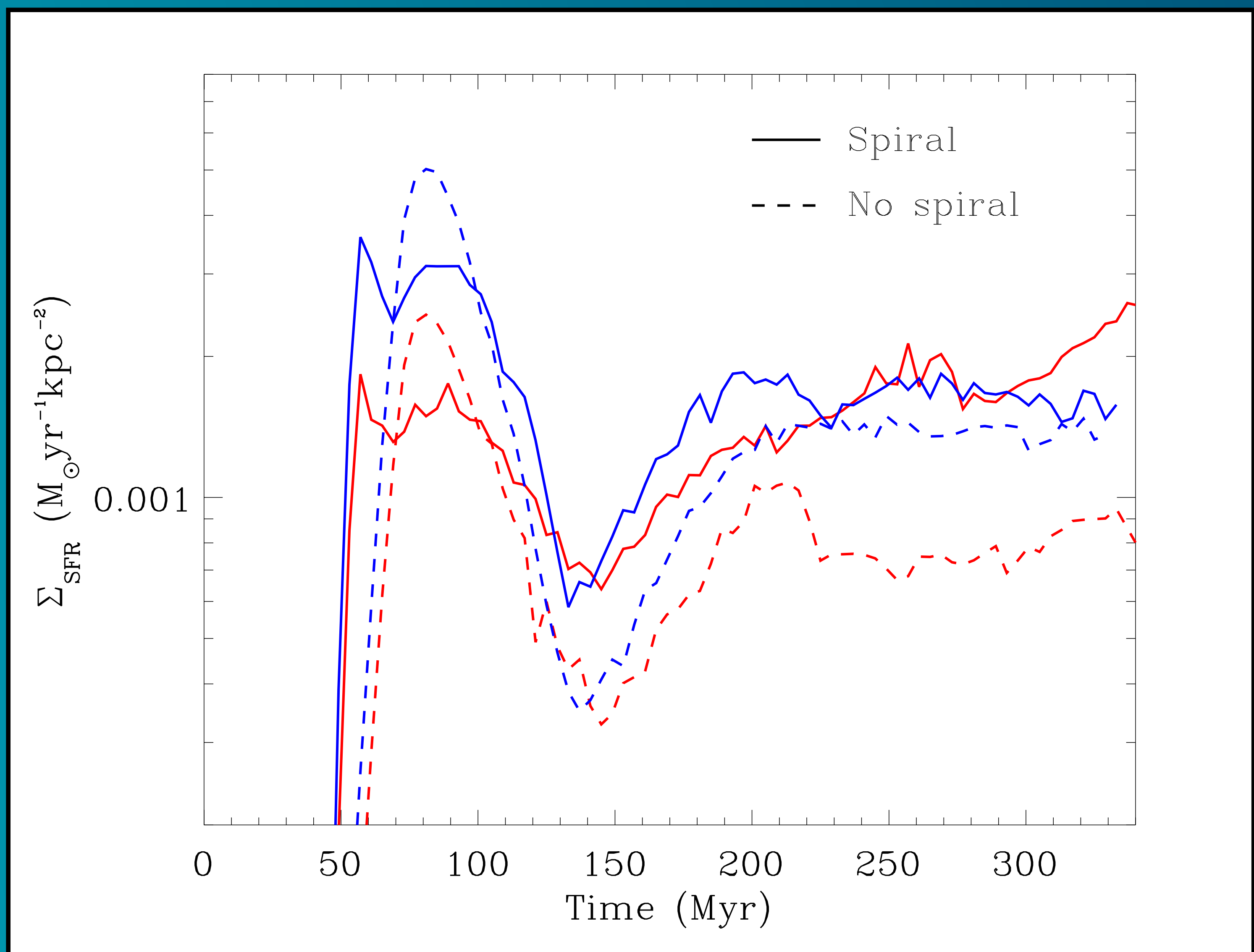
  but these calculations did not include stellar feedback

Dobbs & Pringle 2009

Spiral shocks

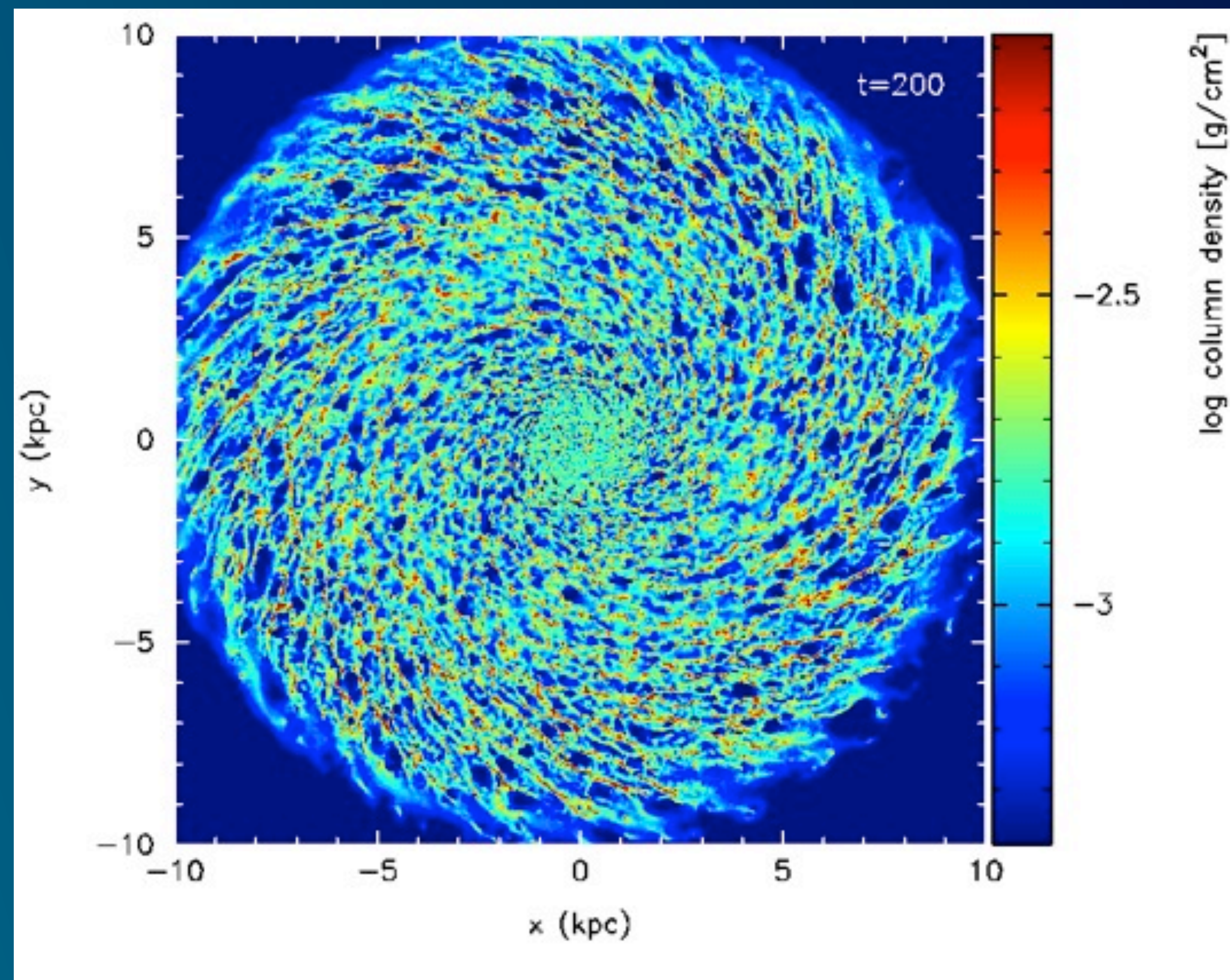
With feedback

still find similar star formation rate in galaxies with and without spiral arms



Dobbs et al. 2011

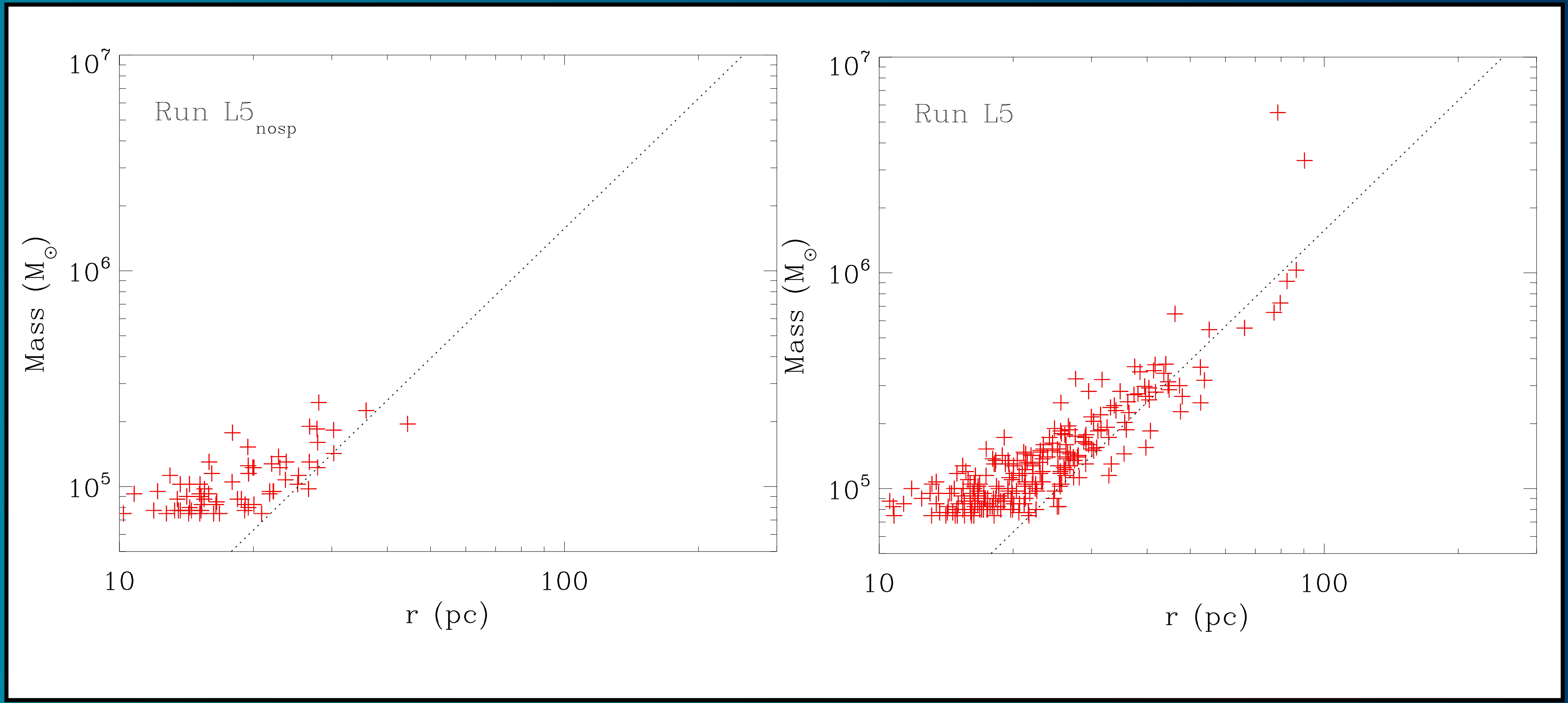
No spiral component of potential



Spiral shocks

but spiral arms do impact size / masses of the clouds

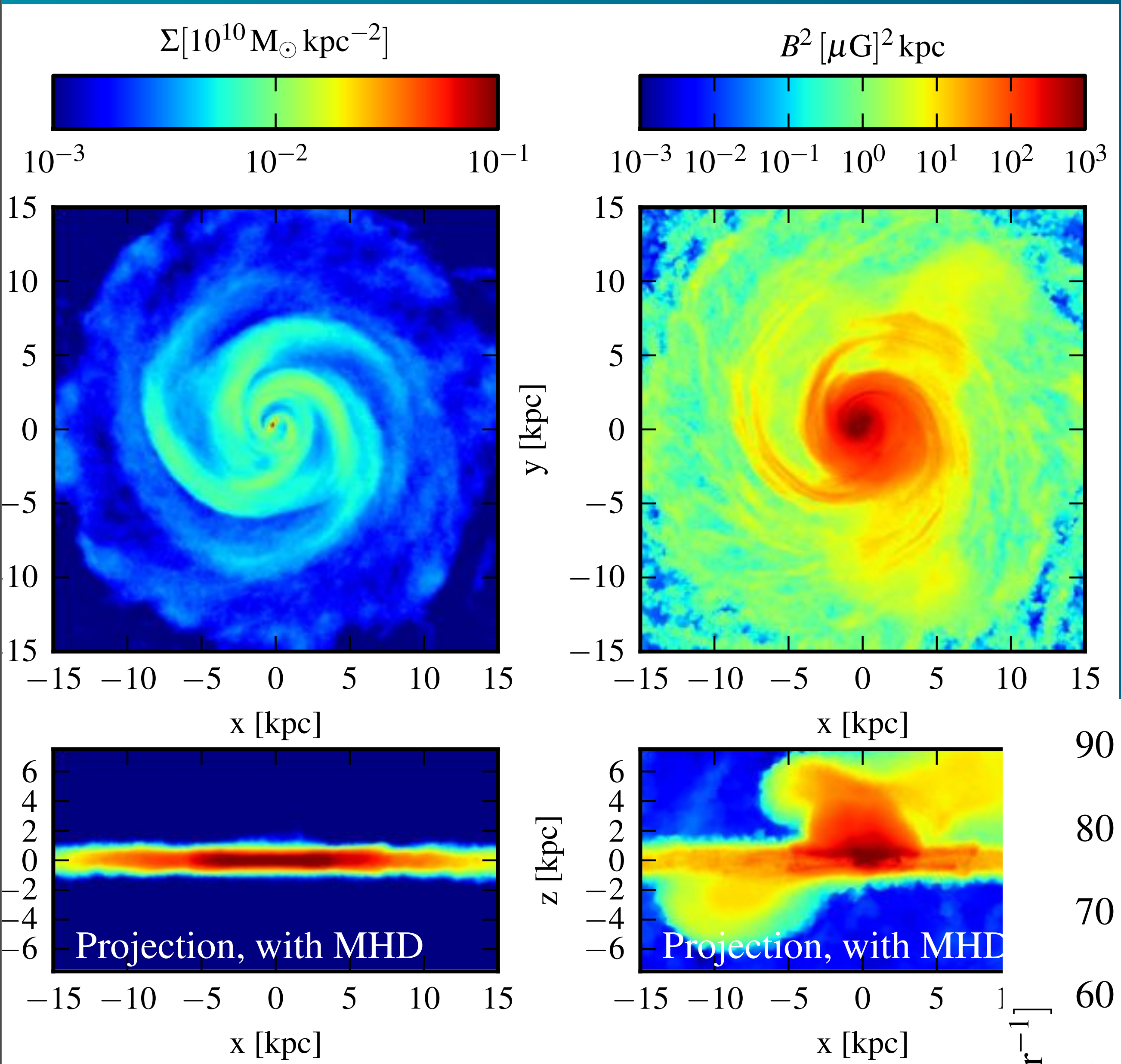
see talks by Annie Hughes, Sharon Meidt



Dobbs et al. 2011

Role of spiral arms to gather up gas into more massive clouds
(see Elmegreen & Elmegreen 86, Stark et al. 87, Vogel et al. 88)

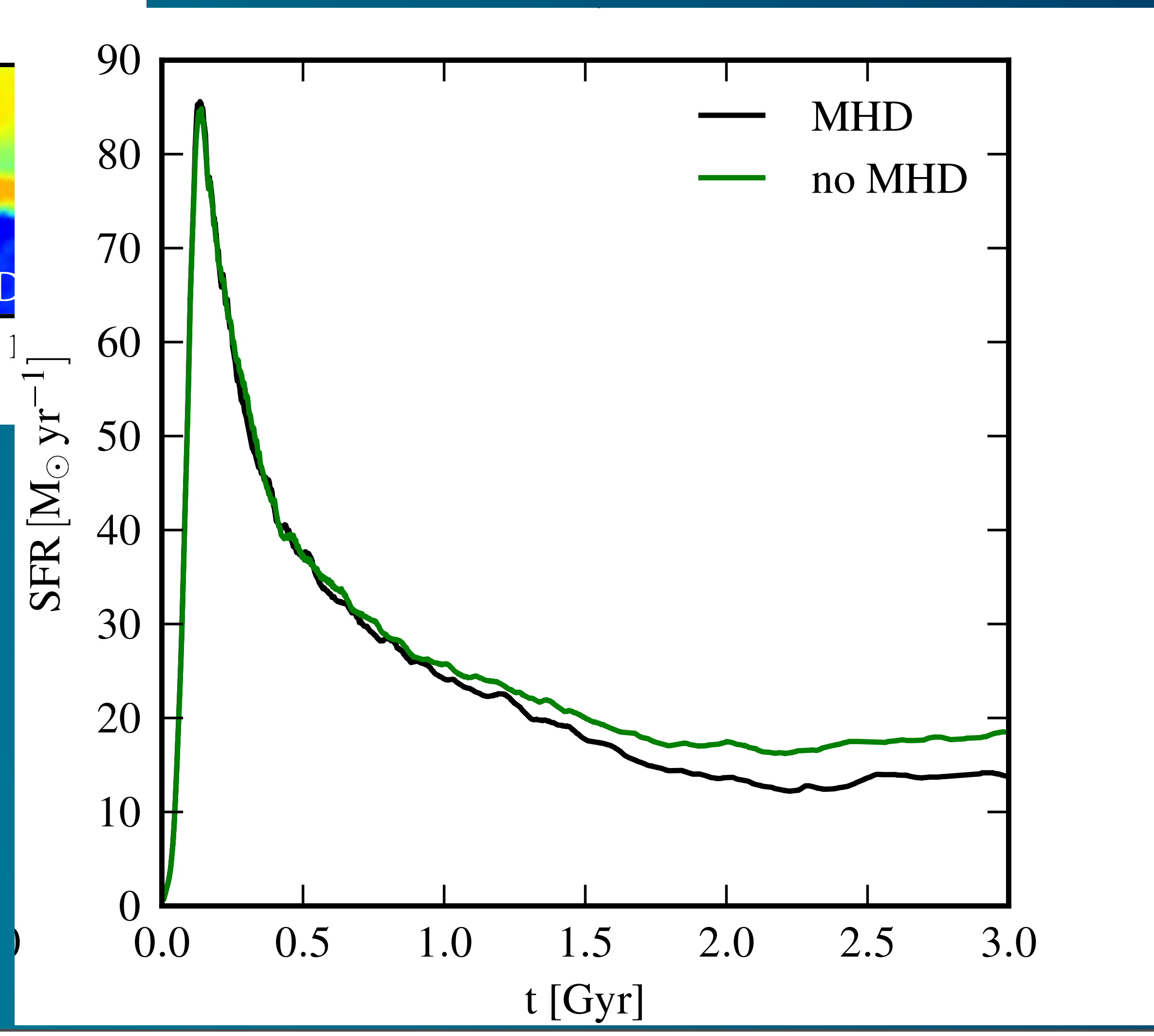
Magnetic fields



Pakmor & Springel (2013), see also Wang & Abel (2009)

small reduction in star formation rate

do not acquire such high resolution



see also Padoan & Nordlund 2011, Christoph's talk, find stronger dependence on B

Gas Accretion / Cloud-Cloud collisions

- Continuous gas accretion can be a source of energy to clouds (Klessen & Hennebelle 2010, Goldbaum et al. 2011)

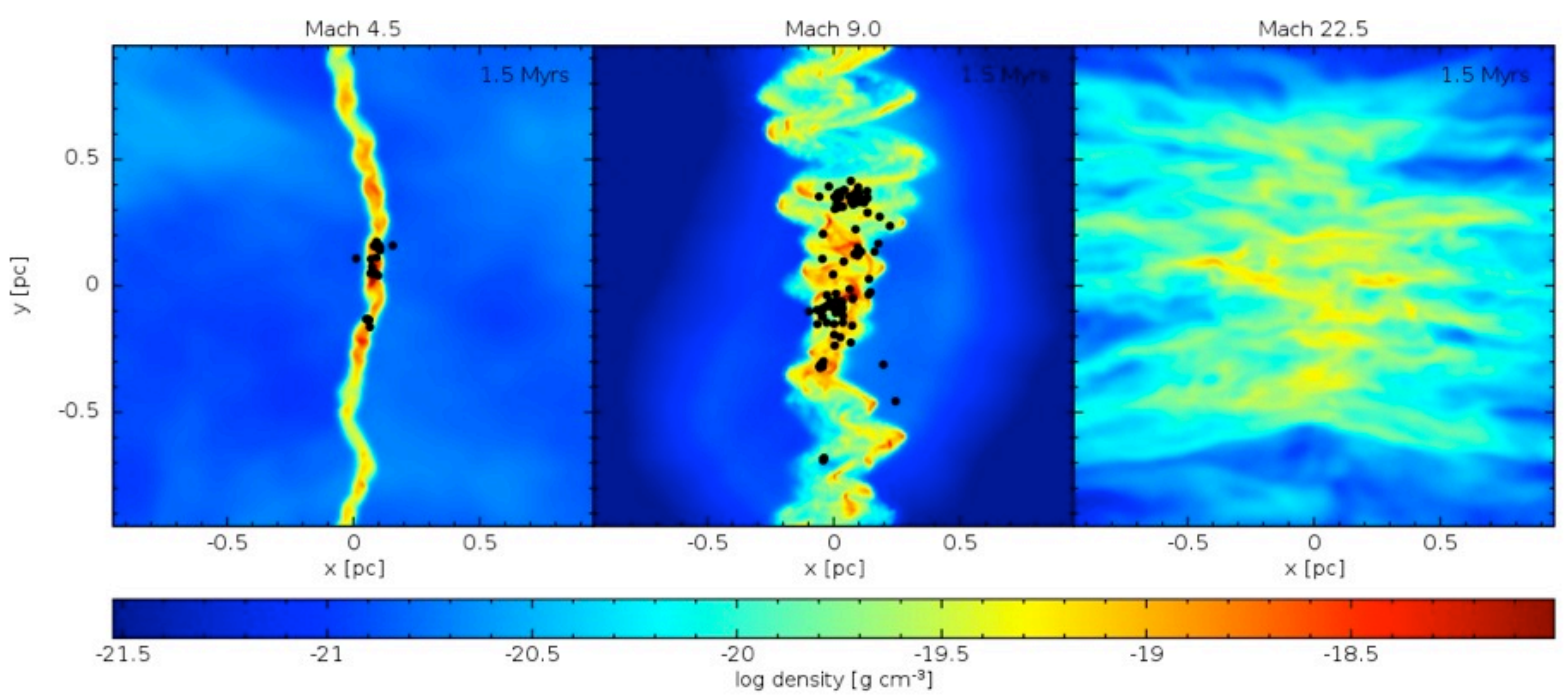
- Collisions increase velocity dispersion (Thomasson et al. 1991, Bonnell et al. 2006, Dobbs & Bonnell 2007)

- but also dissipative (Thomasson et al. 1991, Roberts & Stewart 1987, Silk & Norman 2009)

- Collisions may induce star formation (Tan 2000, Higuchi et al. 2010)

- alternative interpretation of Schmidt-Kennicutt relation (Kennicutt 1989, Wyse 1986, Wyse & Silk 1989, Tan 2000, 2010)

Cloud-Cloud collisions



McLeod et al., 2013, in prep.

see also Lattanzio & Henriksen 1986

colliding flows, e.g. Heitsch

Cloud-cloud collisions at different Mach numbers - structure due to NTSI
black points = sink particles

- very different levels of star formation: role of collisions unclear
- global simulations cannot attain anywhere near this resolution

A second issue: Gas depletion

Gas still expected to run out in ~2 Gyr

- Need accretion rate of ~few $M_{\odot} pc^{-2}$ to maintain Galactic star formation rate (e.g Fraternali & Tomasseti 2012)

- accretion regulated star formation (e.g. Genzel et al. 2010, Papovich et al. 2011, Fraternali & Tomassetti 2012, Feldmann 2013)

Conclusions

- Feedback on large scales is required to obtain global star formation rates comparable to KS relation

- Spiral shocks appear to have only a small effect

- On longer timescales, SFR must be regulated by external accretion

- About magnetic fields & cloud collisions there is no clear picture