Molecular cloud formation and dispersal by stellar feedback

Stefanie Walch

I.Physics Institute, University of Cologne

D. Seifried, S. Haid, F. Dinnbier (University of Cologne)
T. Naab, A. Gatto, T. Peters (MPA Garching)
P. Girichidis (AIP Potsdam)
R. Wünsch (Czech Academy of Sciences, Prague)
R. Klessen, S. Glover (ITA Heidelberg)
P. Clark (Cardiff University)
J. Mackey (Dublin Institute for Advanced Studies)

Interstellar Medium in the nearby Universe
Bamberg – 27.3.2018

SFB 956 Cologne | Bonn
DFG Priority Program 1573 ISM-SPP Interstellar Medium
erc European Research Council
The SILCC project

www.astro.uni-koeln.de/silcc

Overview

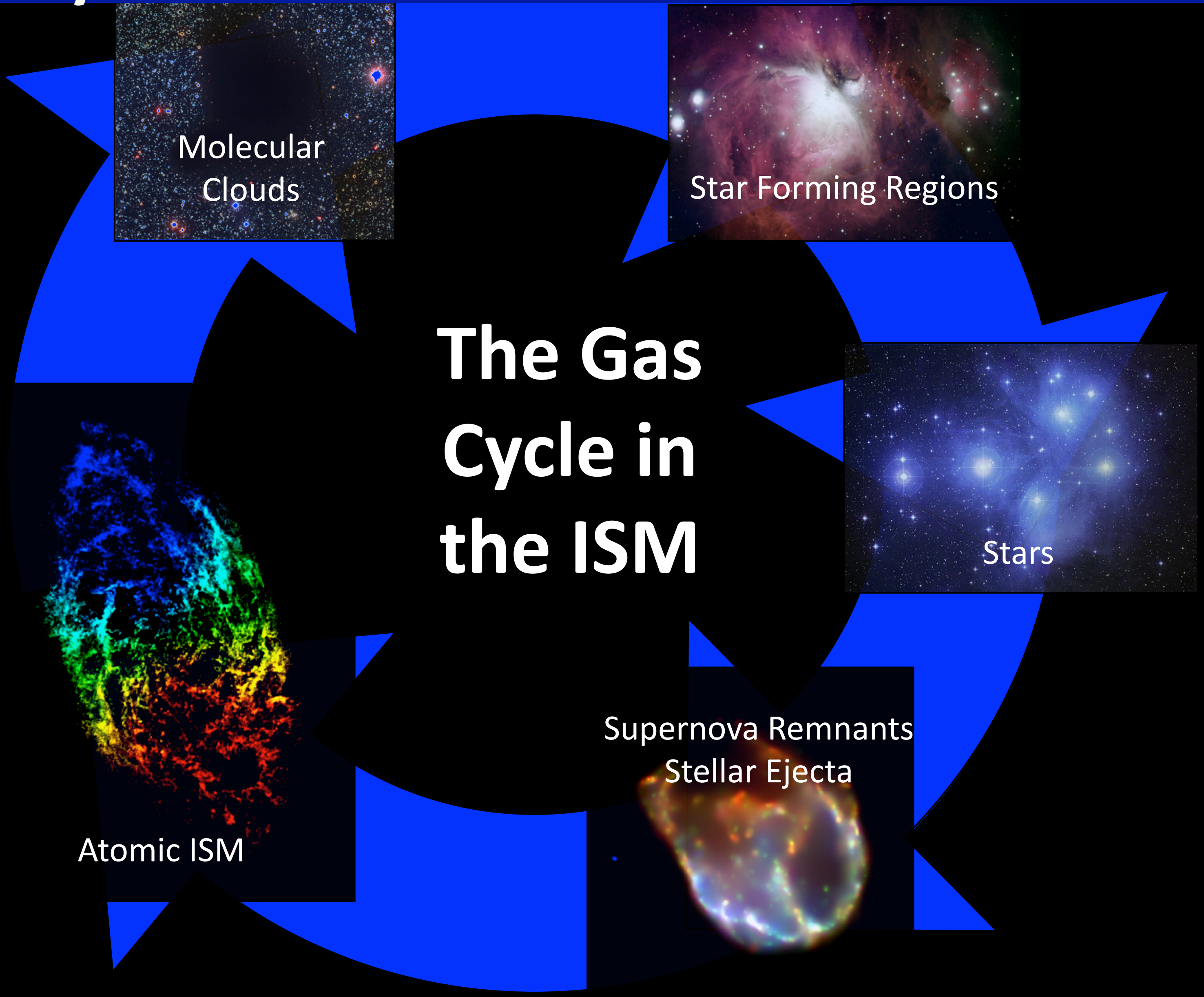
1) Properties of molecular clouds (brief overview)

2) Molecular cloud formation out of the diffuse ISM
⇒different scenarios
⇒models that follow molecule formation
⇒remarks on “clumpology”

3) Limiting the star formation efficiency of molecular clouds
⇒Stellar feedback? Which process? How efficient?

4) Reviews:
-Heyer & Dame (2015) ARAA
“Molecular clouds in the Milky Way”
-Dobbs et al. (PPVI chapter)
“Formation of MCs and global conditions for star formation”
-Klessen & Glover (2014, Saas Fee lectures; arxiv:1412.5182)
“Physical processes in the ISM”

Multiphase ISM and
the cycle of star formation and feedback



The Gas Cycle in the ISM

Molecular Clouds

Star Forming Regions

Stars

Supernova Remnants
Stellar Ejecta

Atomic ISM

Photo Credits: R. Gendler ,the FORS Team, D. Malin, SAO/Chandra, D. Thilker

Key stellar feedback mechanisms

1. Ionizing radiation
2. Stellar winds
3. Supernova explosions
4. Cosmic Rays
5. Radiation pressure on gas and dust

(1) Properties of molecular clouds

Leroy +2008: Star formation associated with molecular clouds
(e.g. THINGS, talk by Brinks)

Individual molecular clouds:

Mass distribution: **Milky Way (Roman-Duval, 2010); M33 (Gratier, 2012)**

Mass range: $10^2 - 10^7\ M_\odot$ with powerlaw distribution $dN/dM \sim M^\gamma$
Powerlaw index:

- **γ~-2…-1.5 in H_2-rich regions (inner regions of galaxies)**
- **γ~-2.5…-2 in H2-poor regions (outer regions of galaxies or lower metallicity, SMC, LMC)**
- **γ>-2 implies that most of the mass is in big clouds!**

Surface densities:
~100 $M_\odot/pc^2$, although depends on exact definition of the “molecular cloud” (see later)
⇒keyword “Clumpology”

~ log-normal surface density distribution as measured from CO
(caveat: sensitivity! Optical depth!)

(1) Properties of molecular clouds

Velocity dispersions: few km/s on scales of ~10 pc

$\sigma = (\alpha \pi G \Sigma R / 5)^{1/2}$ with $\alpha \approx 1$ (Heyer et al. 2009)

Could be caused by

(1) virialization (Heyer +2009)

(2) pressure-confinement (Field +2011)

(3) free-fall collapse (Ballesteros-Paredes +2011)

Difference is sqrt(2)

=> cannot distinguish from observations!!

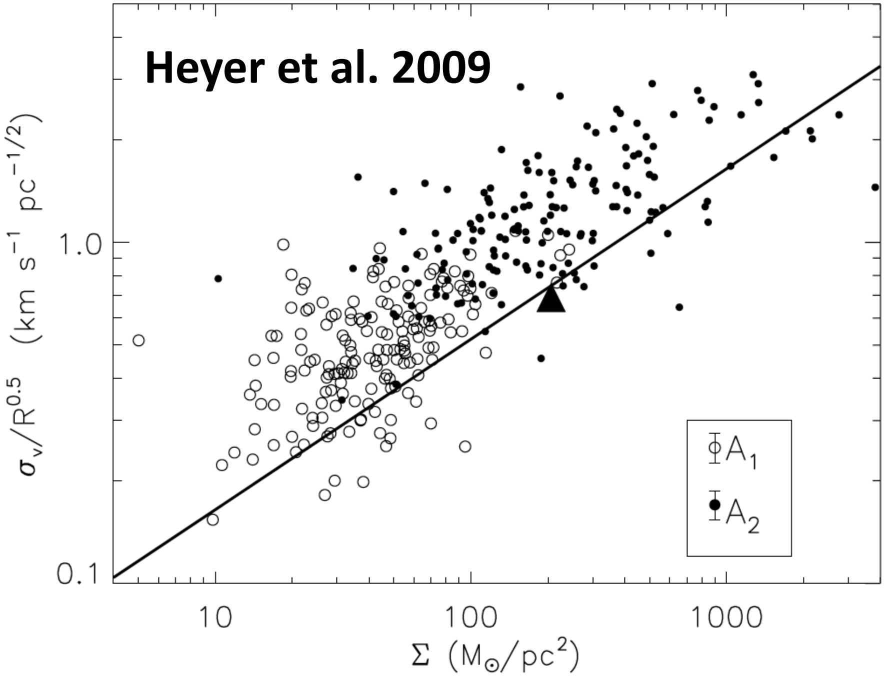


Figure 7. Variation of the scaling coefficient, $v_\circ = \sigma_v / R^{1/2}$, with mass surface density derived within the SRBY cloud boundaries (open circles) and the 1/2 maximum isophote of H_2 column density (filled circles). The filled triangle denotes the value derived by SRBY. The solid line shows the loci of points corresponding to gravitationally bound clouds. There is a dependence of the coefficient with mass surface density in contrast to Larson's velocity scaling relationship. The error bars in the legend reflect a 20% uncertainty of the distance to each cloud.

(1) Properties of molecular clouds

Long depletion time (2 Gyr), i.e. in 2 Gyr the cloud would turn all of its mass into stars.

But cloud lifetimes are not that long!!

⇒clouds just don't live that long and therefore only a fraction of a cloud's mass is turned into stars within its life time.
⇒Something is dispersing the cloud before!
⇒What is dispersing the cloud? Shear? Stellar feedback? Turbulence?

We will address this now!

Feedback efficiency suggested to depend on cloud mass (see later):

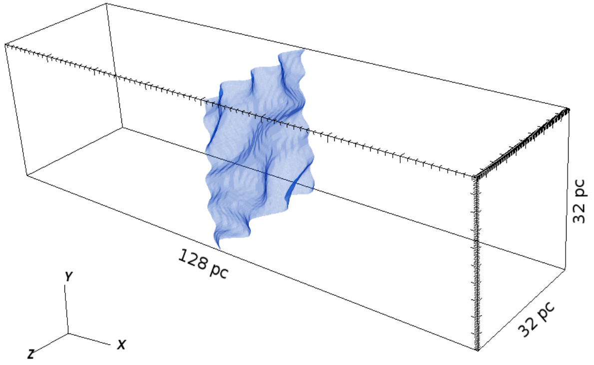
In isolated clouds, even when not set up in free-fall collapse, turbulence will decay
⇒net increase of SFR with time (models: Goldbaum +2011, Zamora-Aviles +2012, +2018)
⇒These are results on isolated clouds

⇒Differences between isolated and self-consistently formed clouds in simulations?

(2) Molecular cloud formation out of the diffuse ISM

Check e.g. PPVI chapter by Clare Dobbs et al. for an overview

Colliding flows (Banerjee+2009, Vazquez-Semadeni+2011, Körtgen+2016, Joshi+ in prep.)
Colliding HI streams
Cannot make large clouds! => Maximum mass:
Mean ISM surface density x (scale height)^2 ~ 10^4 - 10^5 $M_\odot$



Cloud collisions, e.g. in spiral arms
(e.g. Dobbs & Pringle, 2013; Tasker & Tan, 2009; e.g. Fukui +2016)
Collision time usually low, unless near/in spiral arm
=> Can build up 10^6 $M_\odot$ clouds

Gravitational and magneto-Jeans instability (controlled by Toomre Q)
(e.g. Li +2005 in spiral arm; Kim & Ostriker 2006)
GI: would gather really big clouds 10^7-10^8 $M_\odot$ + fragmentation or in spiral arm (lower Q)
⇒naturally gives "beads on a string" morphology

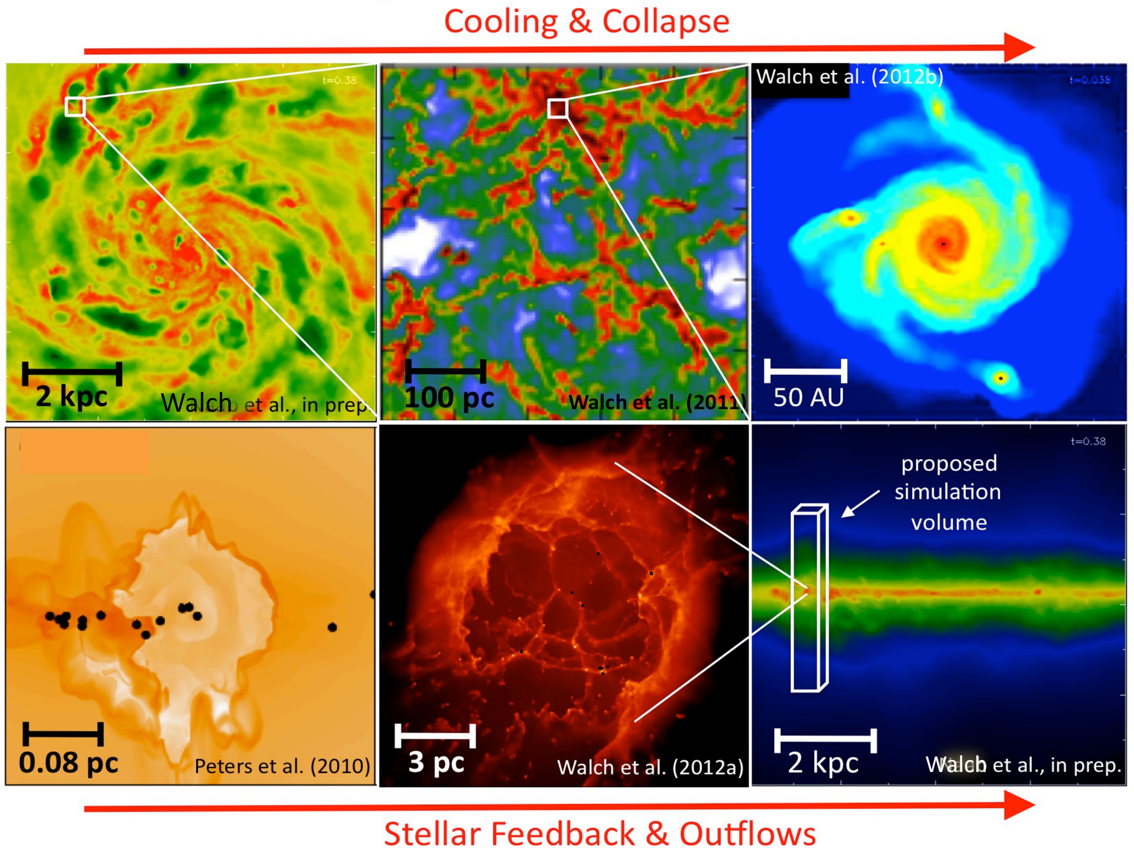
Parker + thermal instability (e.g. Mouschovias +2009) => does it work in turbulent ISM??

Consecutive Supernova explosions sweeping up the gas (Inutsuka, 2017)

In any case: we need to form H_2

SILCC Project
SImulating the **L**ife**C**ycle of Molecular **C**louds

University of Cologne: S. Walch, D. Seifried, F. Dinnbier, S. Haid
MPA Garching: T. Naab , T.-E. Rathjen
Czech Academy of Sciences Prague: R. Wünsch
ITA Heidelberg: R. Klessen, S. Glover
AIP Potsdam: P. Girichidis Cardiff University : P. Clark



AMR code FLASH 4 with…

- Self-gravity
- External galactic potential
- ideal MHD
- Heating & Cooling and
- Molecule Formation
- TreeRay (diffuse radiation for shielding + radiative transfer from point sources)
- Sink Particles with subgrid cluster model/massive star model
- Supernova Feedback
- Wind
- Cosmic Rays

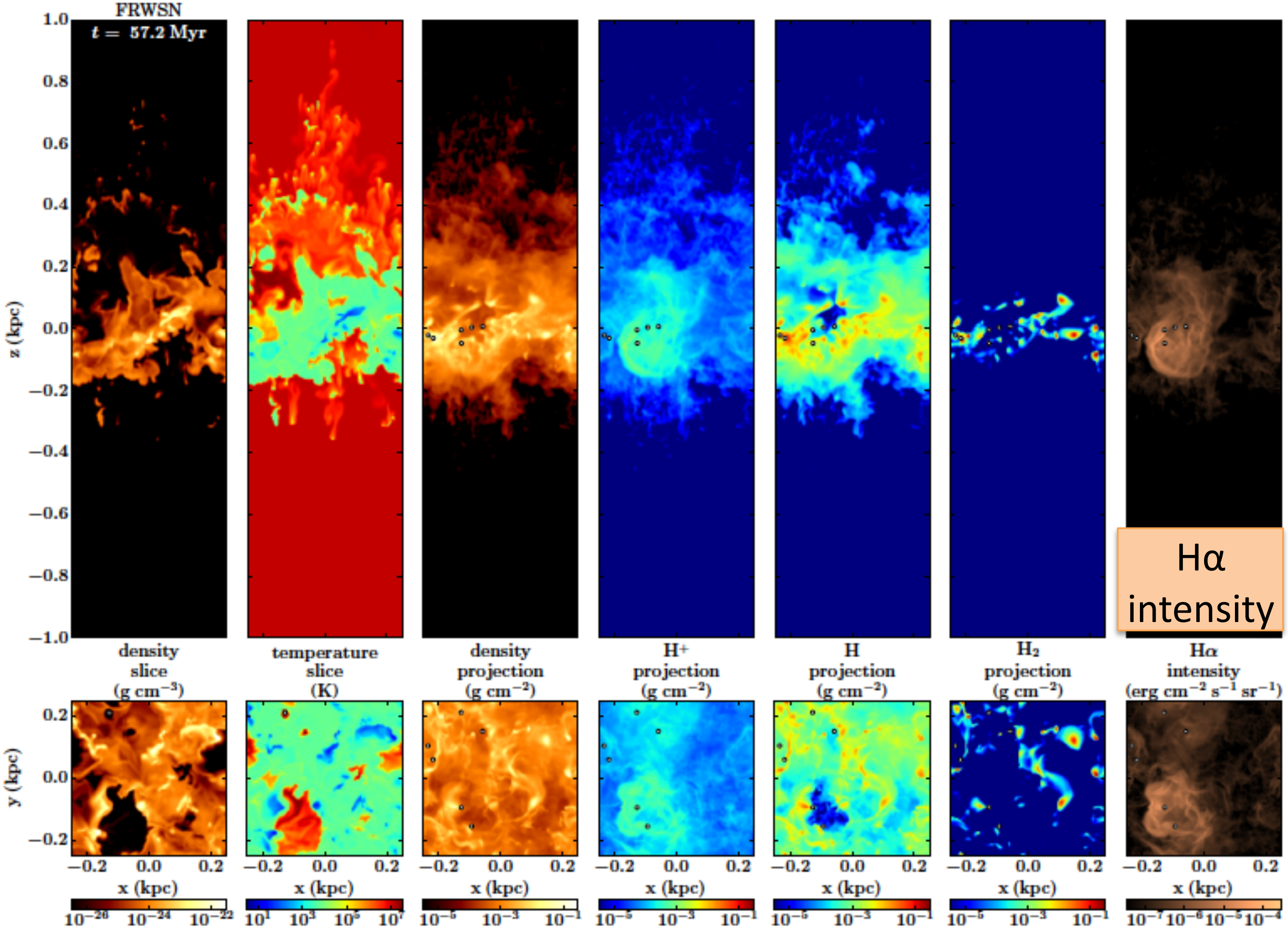
www.astro.uni-koeln.de/silcc

Walch +15, Girichidis +16
Peters+17, Gatto+17, Seifried+17, +18

SILCC simulations: Including winds, ionizing radiation, Sne

Gatto+SILCC, 2017; Peters+SILCC, 2017

with Fervent RT scheme in FLASH (Baczynski +2016)



Hα intensity

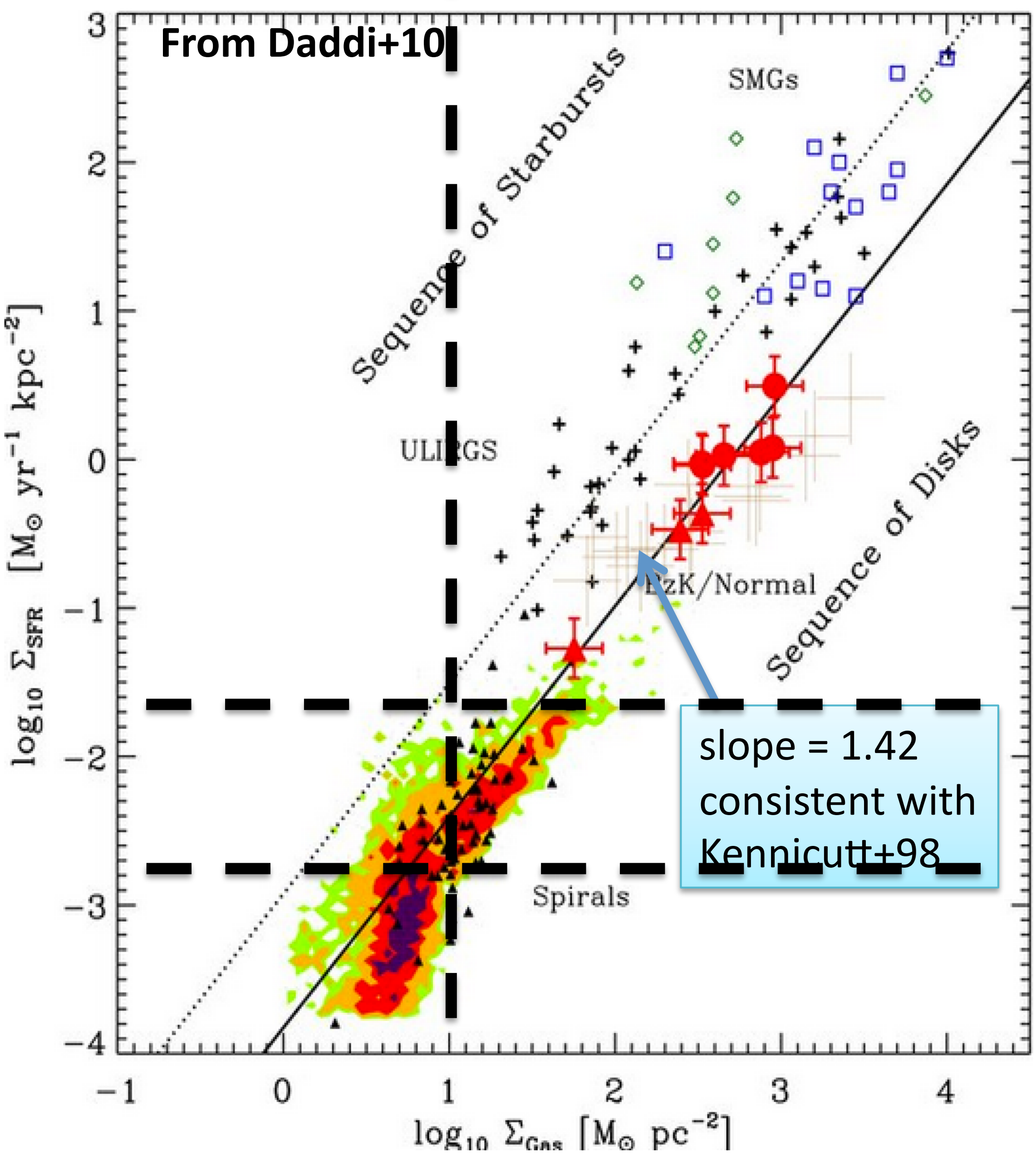
Kennicutt-Schmidt relation: Why is star formation so inefficient?

Scaling over many orders of magnitude!

Remember long depletion times ~ 1 Gyr and/or SF efficiency per free-fall time ~ 1%

Scatter for normal spirals is ~ factor 10 in Σ_{SFR} at $\Sigma_{gas} = 10\ M_{\odot}/pc^2$

Assume a standard stellar IMF to relate Σ_{SFR} to the supernova rate
⇒1 SN/100 $M_{\odot}$
⇒3x higher/lower SN rate



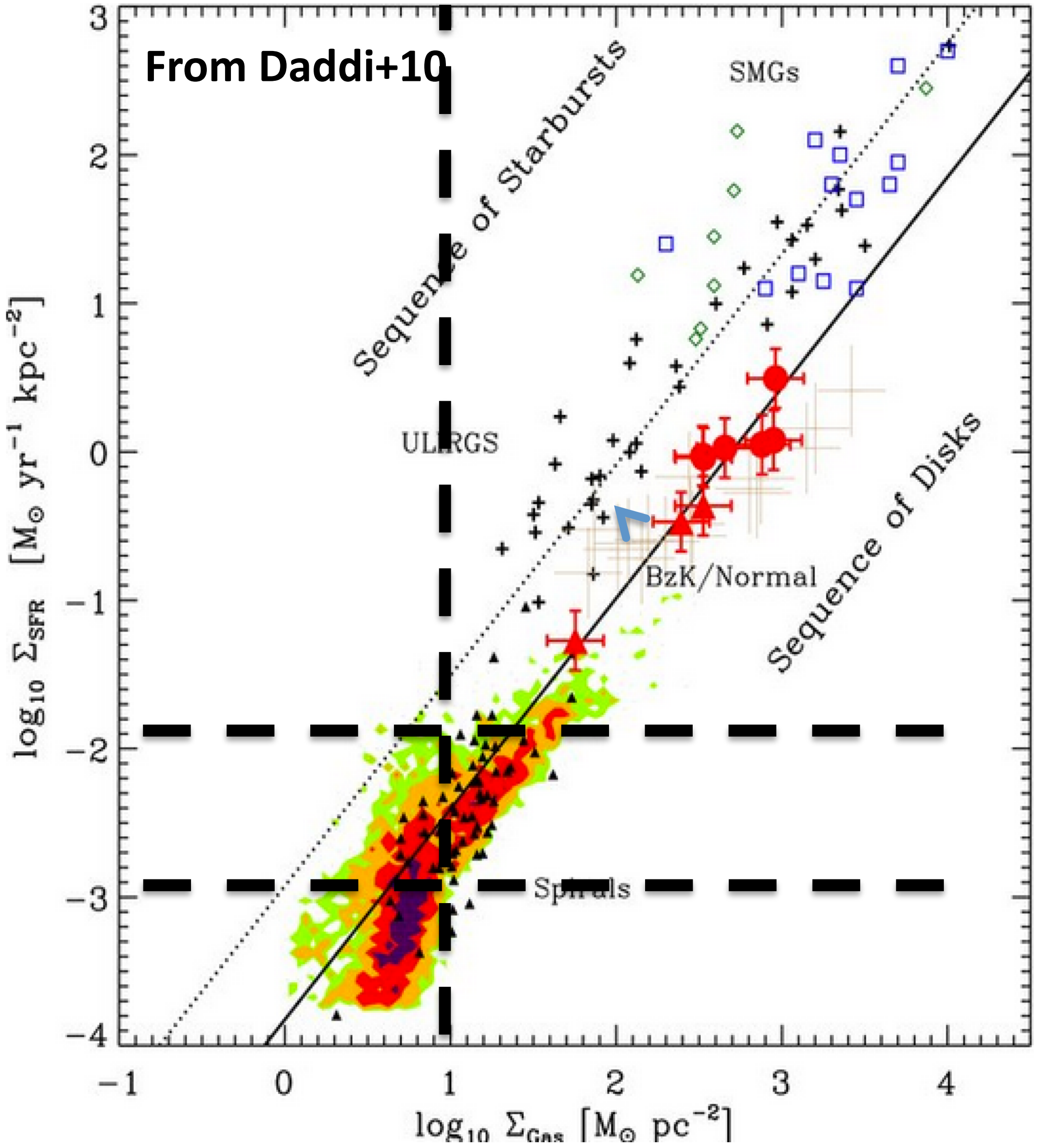
From Daddi+10

slope = 1.42 consistent with Kennicutt+98

The SILCC project (www.astro.uni-koeln.de/silcc)

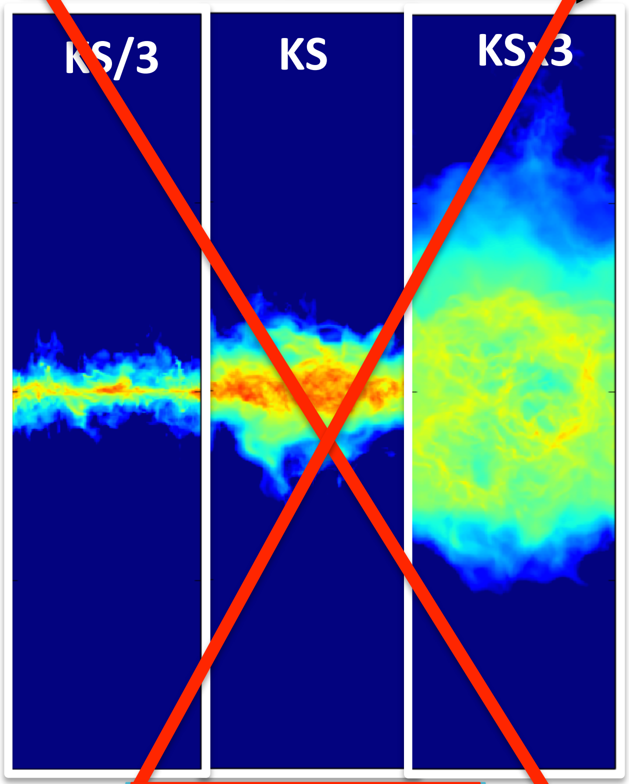
Walch et al. (2015) and Girichidis et al. (2016):

Investigate the impact of Supernova placement with respect to the dense, cold gas.

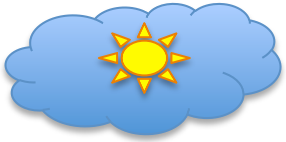


Location of Supernovae and Supernova rate changes the structure of the ISM

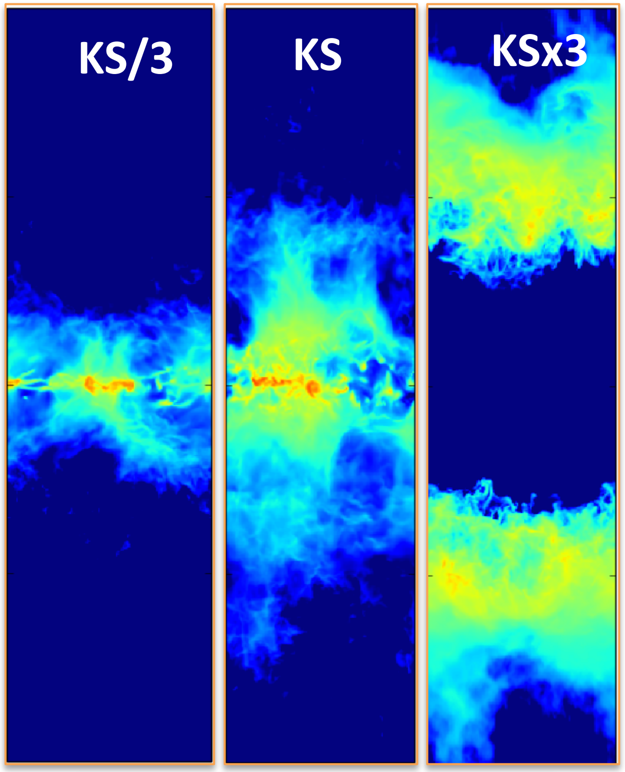
increasing Supernova rate



PEAK DRIVING
gives wrong
ISM properties

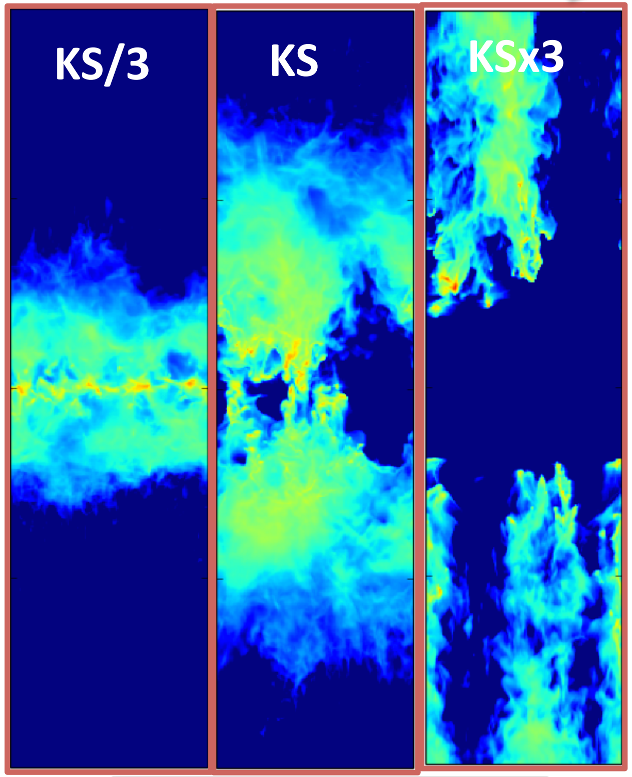


increasing Supernova rate

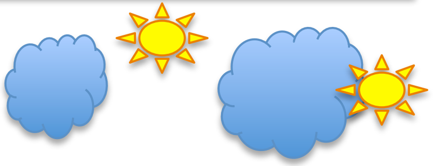


MIXED DRIVING
50% Supernovae
in MCs/ 50% random

increasing Supernova rate



RANDOM DRIVING
Supernovae
placed randomly

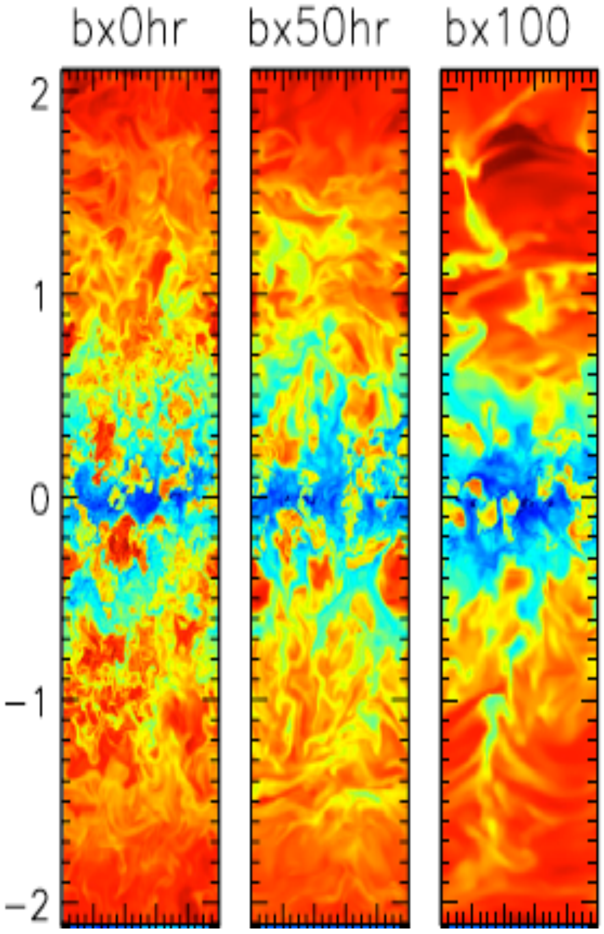


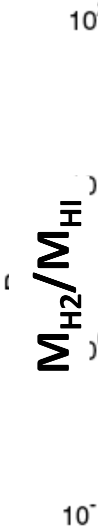
Walch et al. (2015)

Previous work: stratified disks

- **Avillez & Breitschwerdt (2005): SN driven ISM, hot gas VFF depends on SN rate**
- **Joung & MacLow (2006); Hill et al. (2012): Supernovae drive turbulence and determine the vertical stratification of the disk;**
- **Koyama & Ostriker (2009), Shetty & Ostriker (2011): Include shear: Shear seems to be important for high Σ environments: limits the size of cold clouds; Kim & Ostriker (2013): self-regulated star formation, confirming model of Ostriker & McKee (2011);**
- **Gent et al. (2013): Find a velocity correlation scale of ~100 pc from SN energy input (similar to Avillez & Breitschwerdt) -> SN explosions in low density gas;**
- **Creasey et al. (2013): Mass loading in winds; Mass loading decreases with increasing surface density.**

Hill et al. (2012)





Self-regulated star formation on large scales?

Theory

Ostriker 2010

Simulations

SN feedback:

Tasker +2009

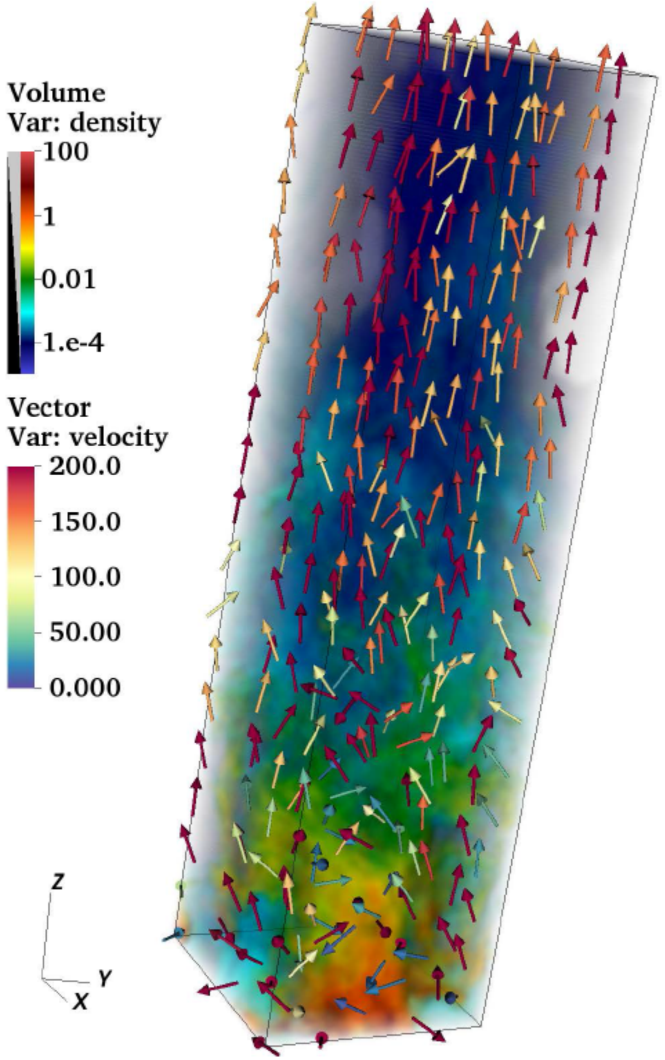
Hennebelle & Iffrig (2014)

Photo-electric heating + SNe:

Kim & Ostriker (many papers; most recent TIGRESS 2018)

Winds, radiation, SNe:

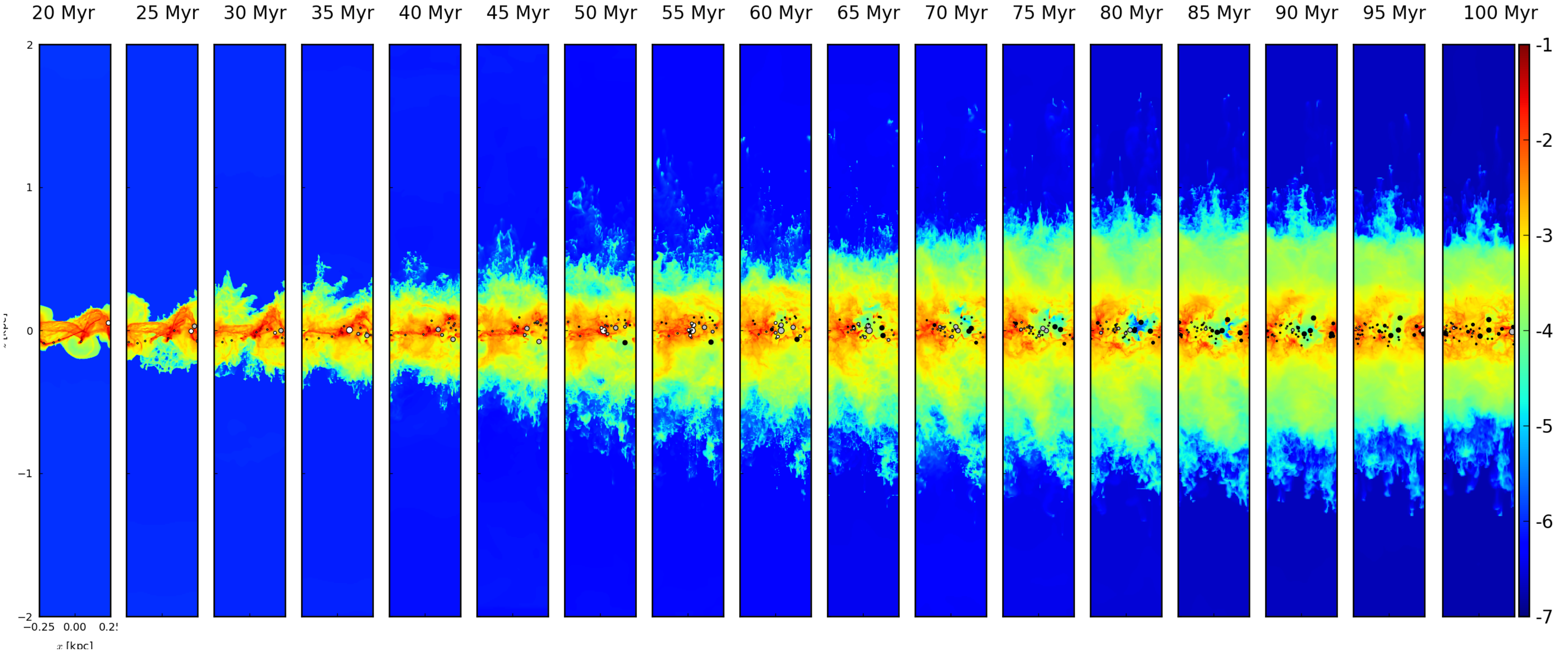
SILCC: Peters +2017, Gatto +2017



Kim & Ostriker, 2018

SILCC simulations: new algorithms

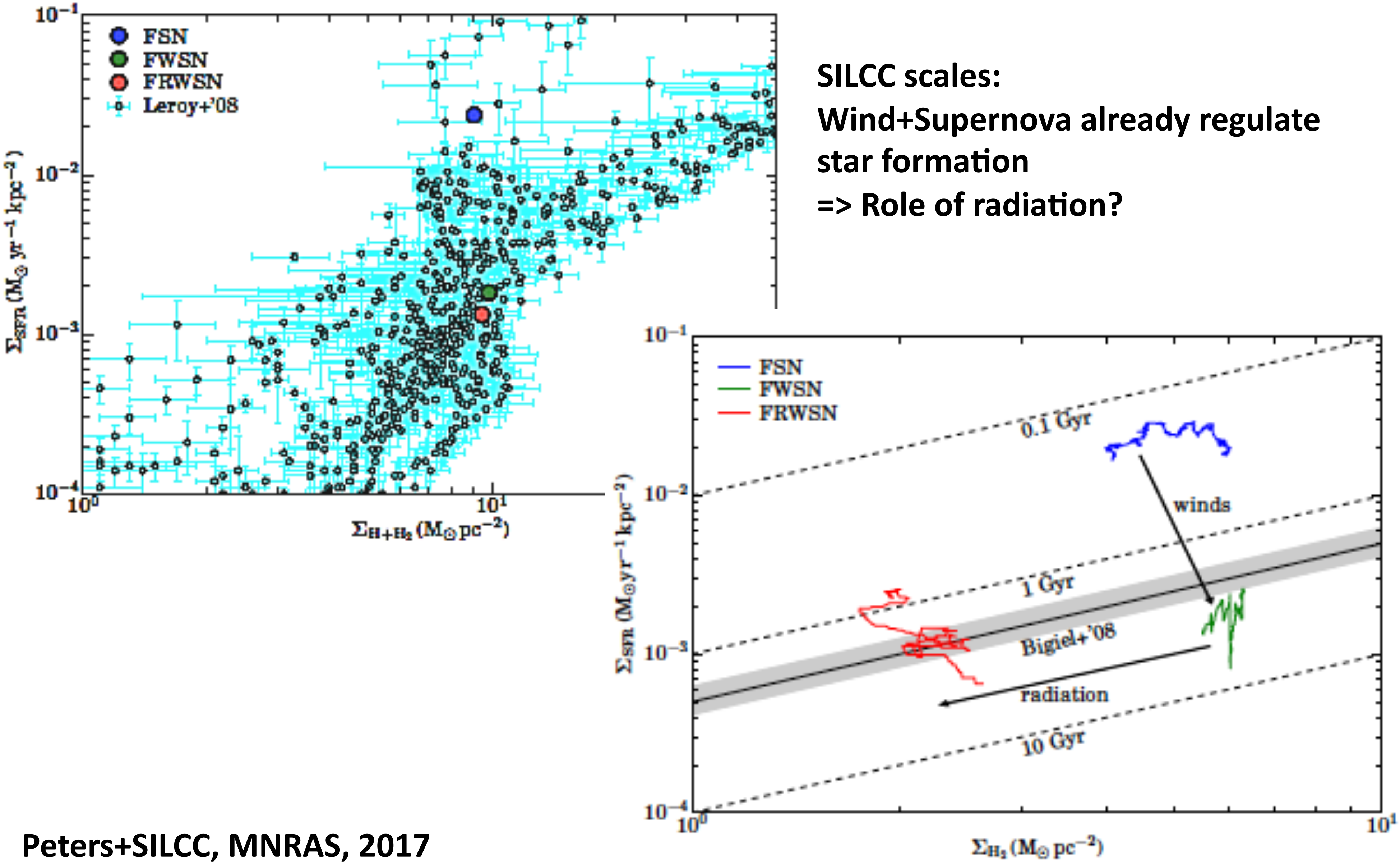
Time evolution of a simulation with ionizing radiation, wind, and Supernova feedback with TreeRay and new Hermite integration scheme for sink particles



Self-regulation of star formation (see also Kim & Ostriker, e.g. 2018 TIGRESS)

Dinnbier et al., in prep.

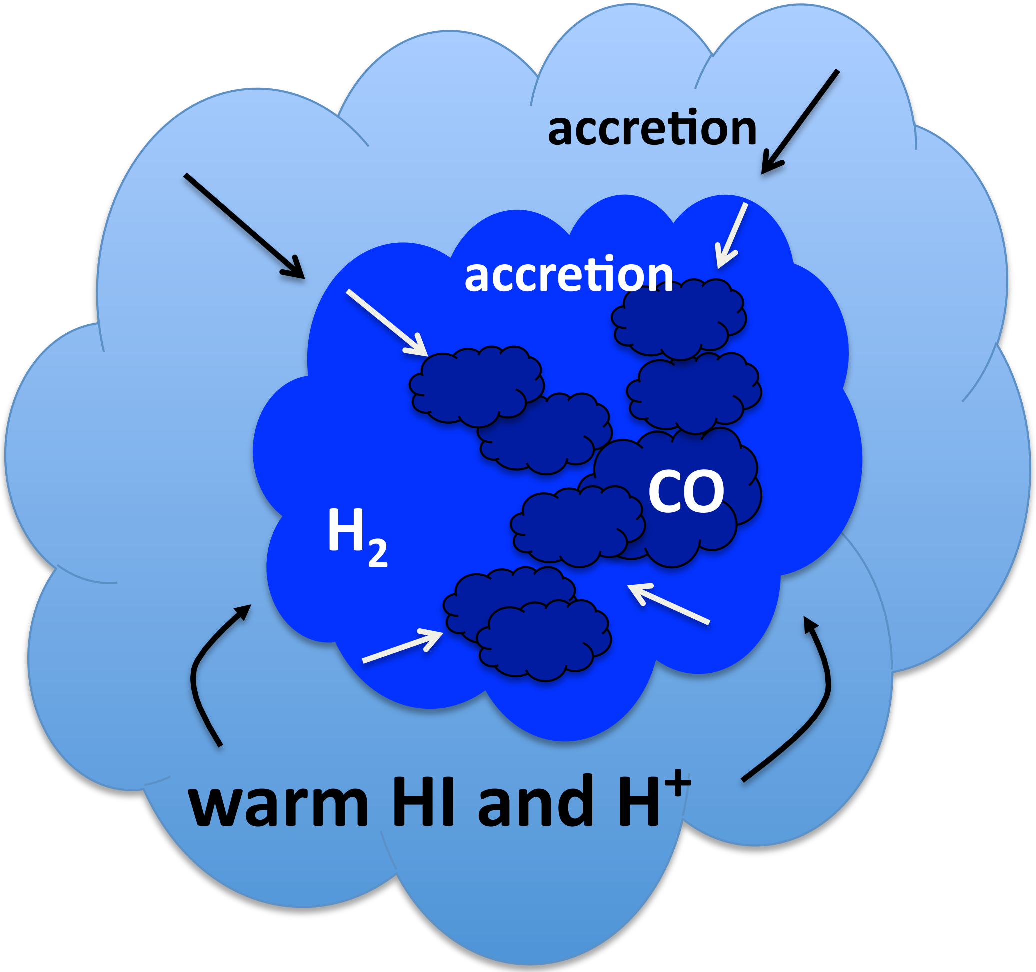
SFR vs. gas surface density

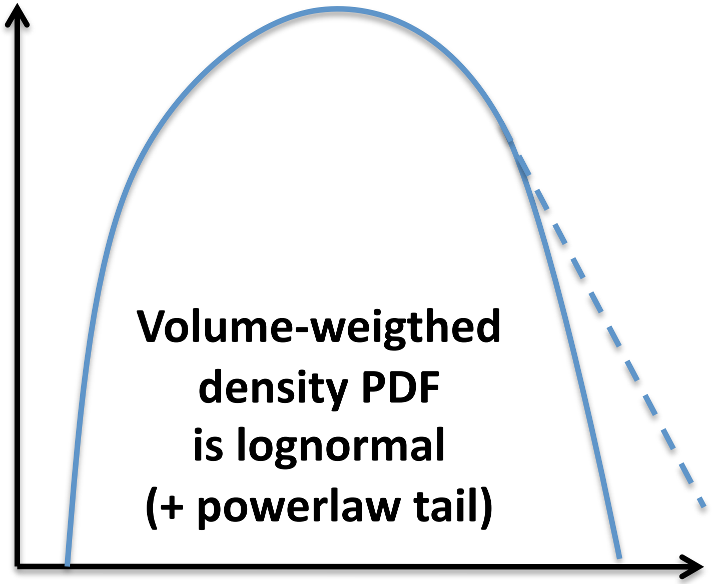


SILCC scales:
Wind+Supernova already regulate star formation
=> Role of radiation?

Peters+SILCC, MNRAS, 2017

The role of stellar feedback in molecular cloud formation and evolution?





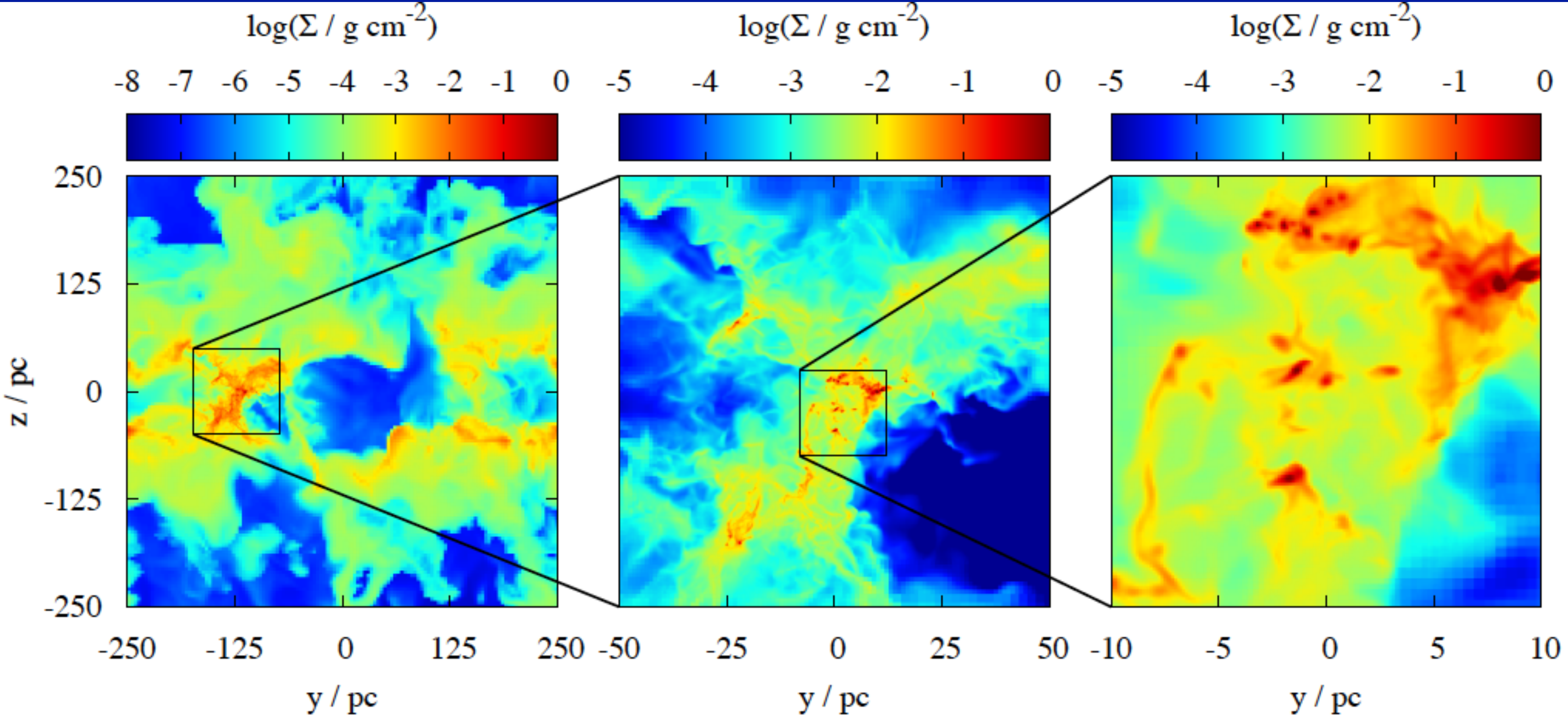
=> Large volume fraction filled with low density gas! Can be attacked by wind/ radiation

Stellar wind feedback can stop accretion!

⇒limit the growth of individual molecular clouds

⇒regulate the global star formation efficiency

SILCC-ZOOM:
Galactic zoom-in calculations:



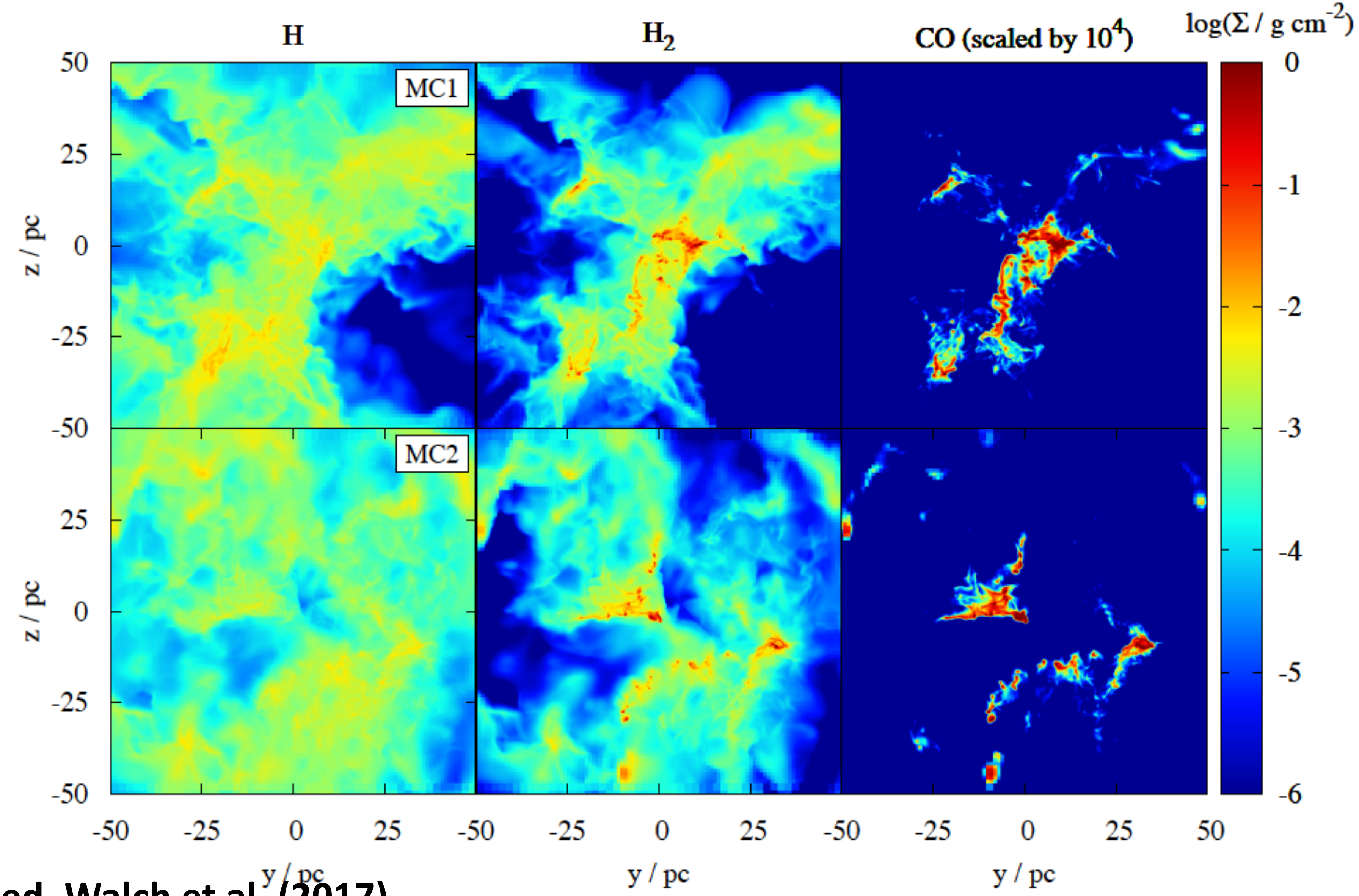
⇒pick a cloud from SILCC

⇒resolve down to 0.1 pc but
keep the galactic environment

Seifried, Walch et al. (2017)

Other recent zoom-ins:
Kuffmeier +2017 (STARPLAN)
Hennebelle (2018)

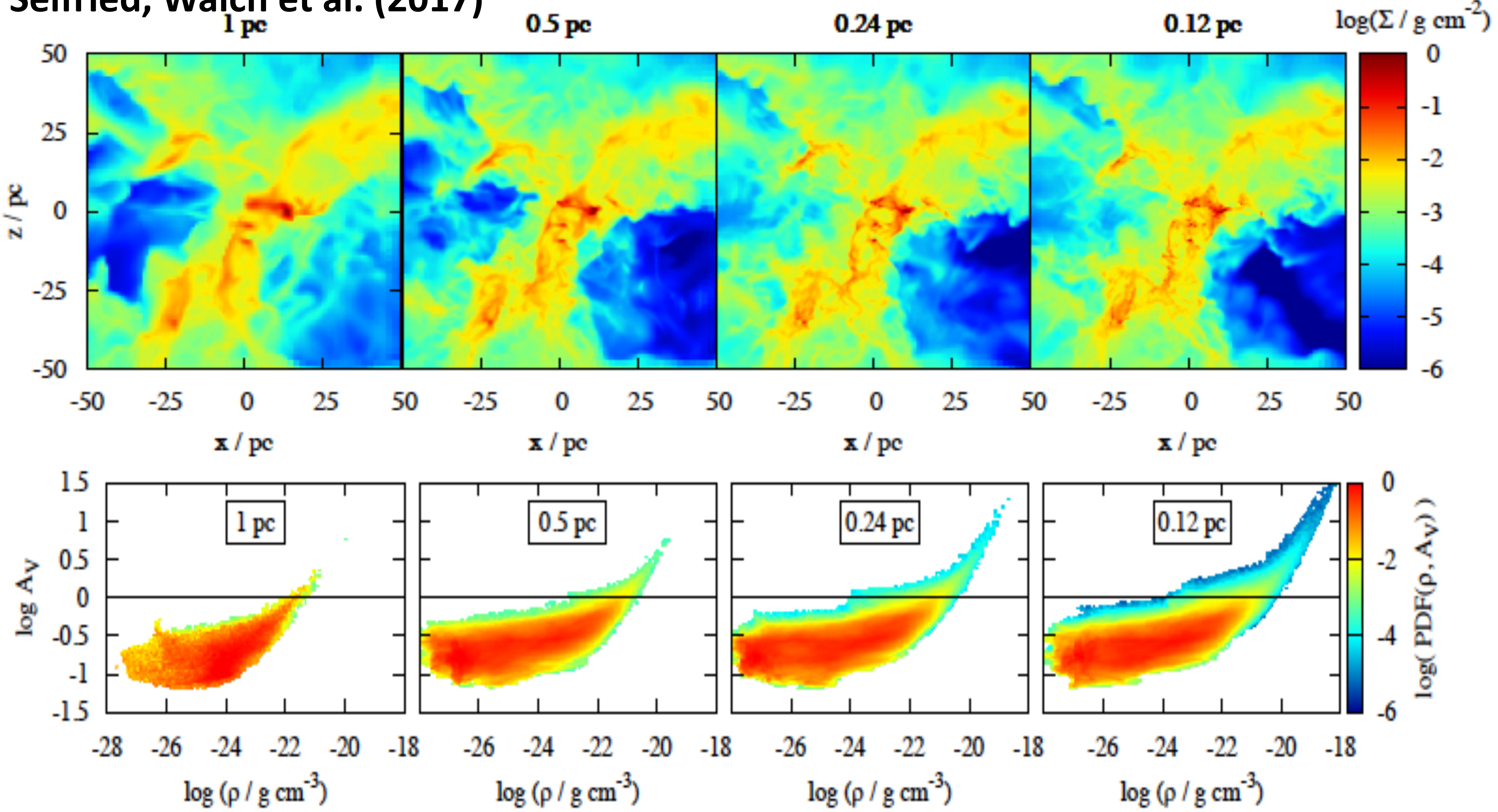
Zoom-in calculations for 2 clouds: Column density in HI, H_2, and CO



Seifried, Walch et al. (2017)

Molecular cloud 1 at different maximum resolution (t=5 Myr)

Seifried, Walch et al. (2017)

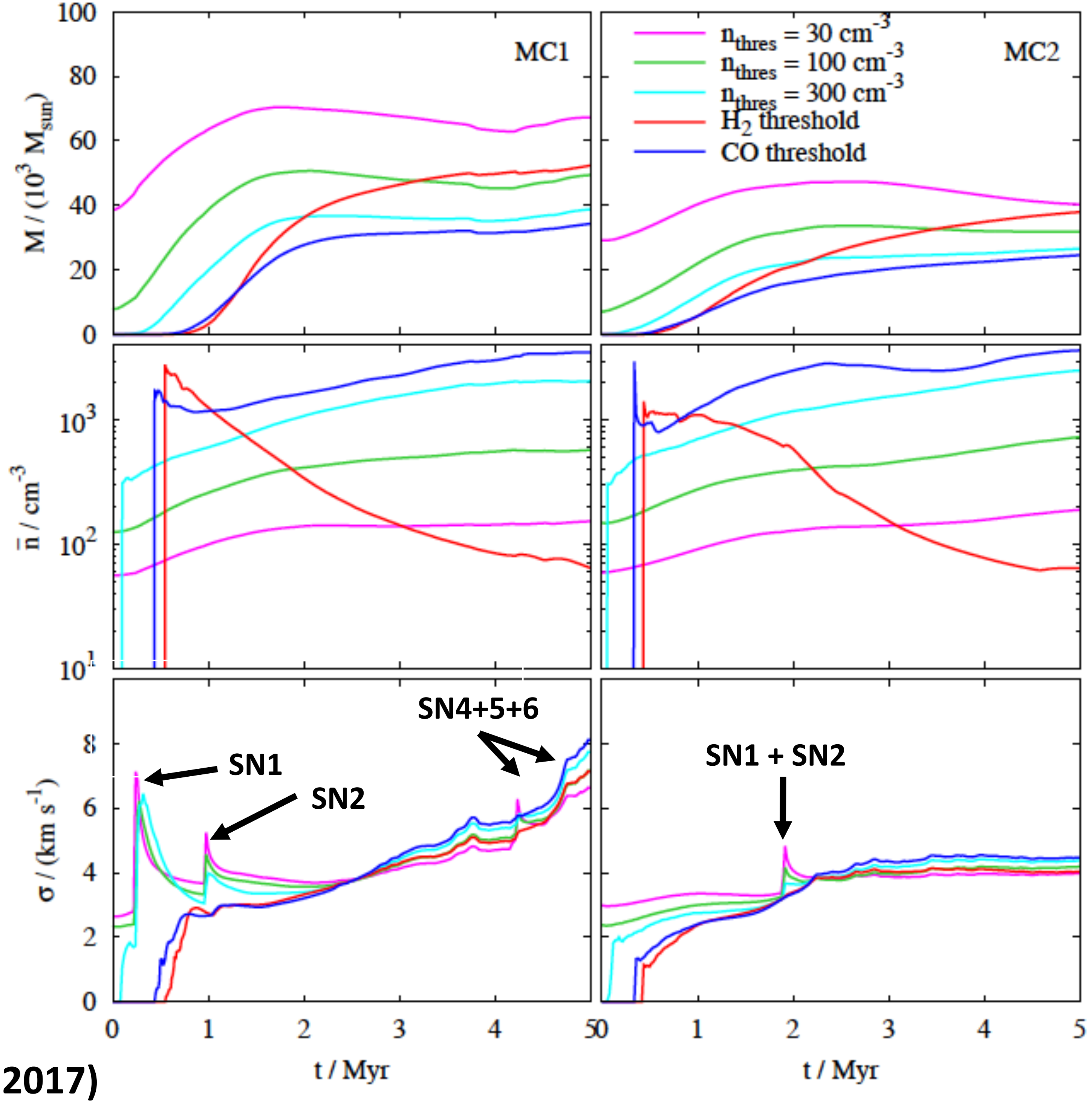


To resolve CO formation one needs to go down to 0.1 pc or smaller

Different time evolution in H_2! Higher mass growth rates in H_2!

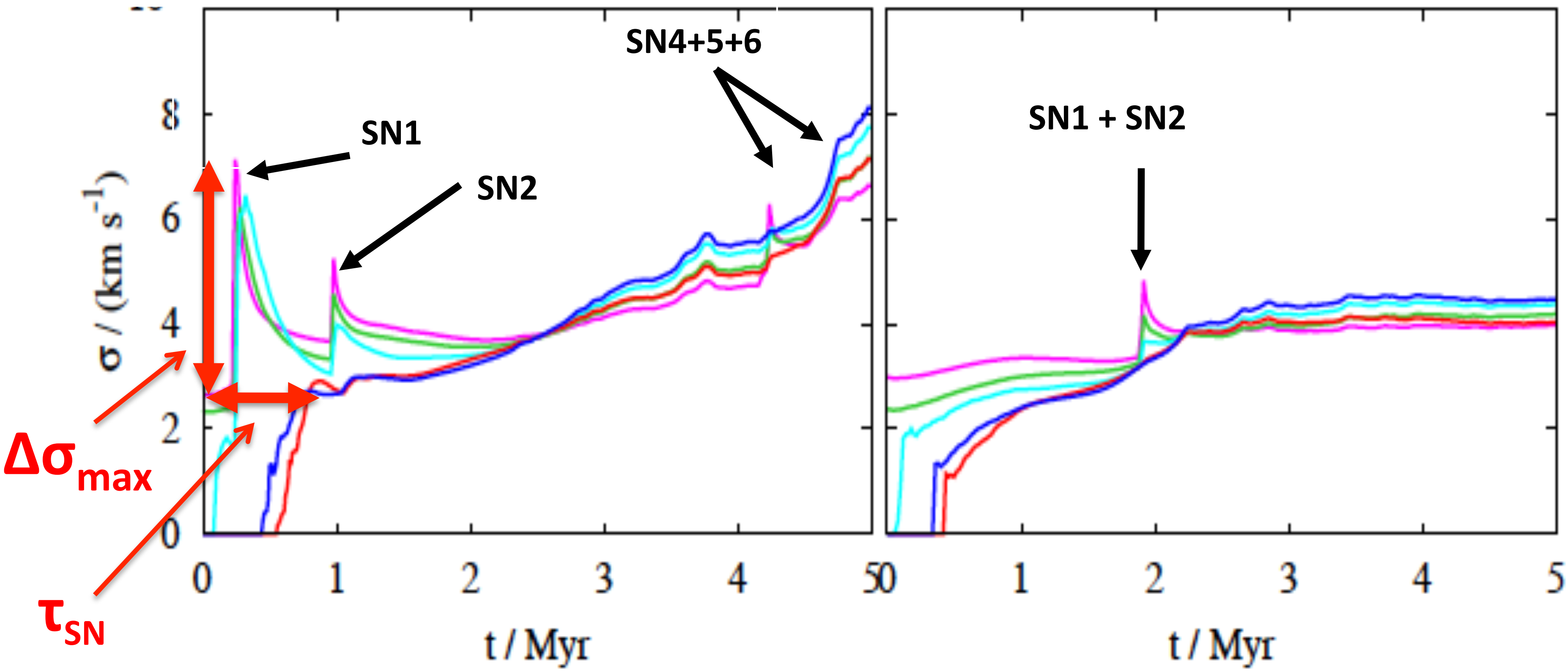
Mean density decreases for H_2 as more H_2 becomes present in lower density gas

Note that ordering of lines is reversed after 2.5 Myr => more dispersion in denser gas



Seifried, Walch et al. (2017)

Origin of turbulent velocities in molecular clouds?

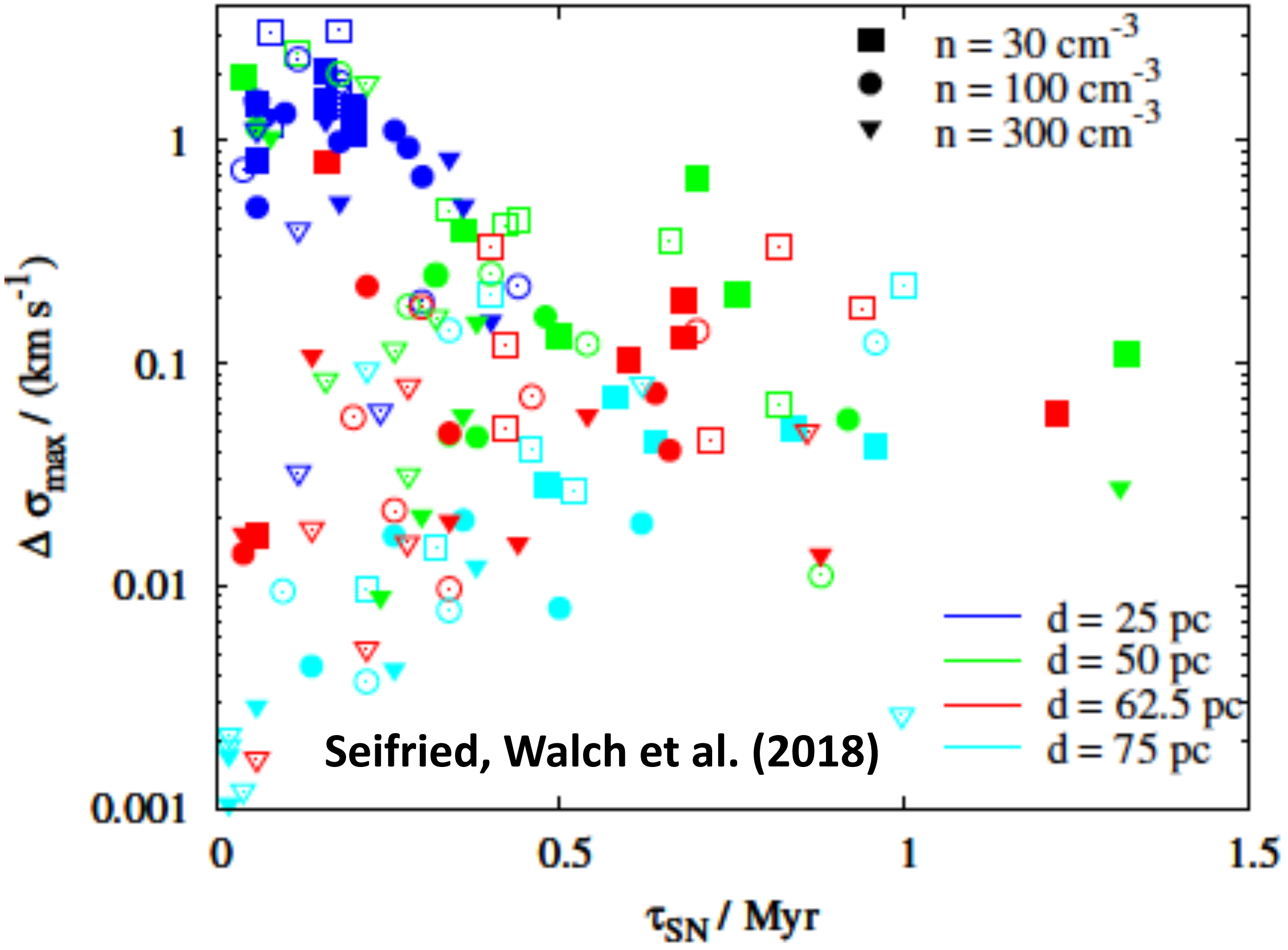


Initially, clouds inherit turbulent velocities from the parental gas

Note that ordering of lines is reversed after 2.5 Myr
⇒more dispersion in denser gas
⇒self-gravity starts to dominate the dynamics

Seifried, Walch et al. (2017)

Dispersion vs. decay time for Supernovae at different distance



Seifried, Walch et al. (2018)

Maintaining a high level of turbulence in the dense regions of the cloud by driving it from the outside does not work!

(1st) turbulence is inherited (accretion-driven, Goldbaum+2011**)**

(2nd) gravity takes over

(see also Ibanez-Mejia +2017; or Ballesteror-Paredes + 2011)

(3rd) Later on feedback-driven?

(3) Feedback: Limiting the star formation efficiency of molecular clouds

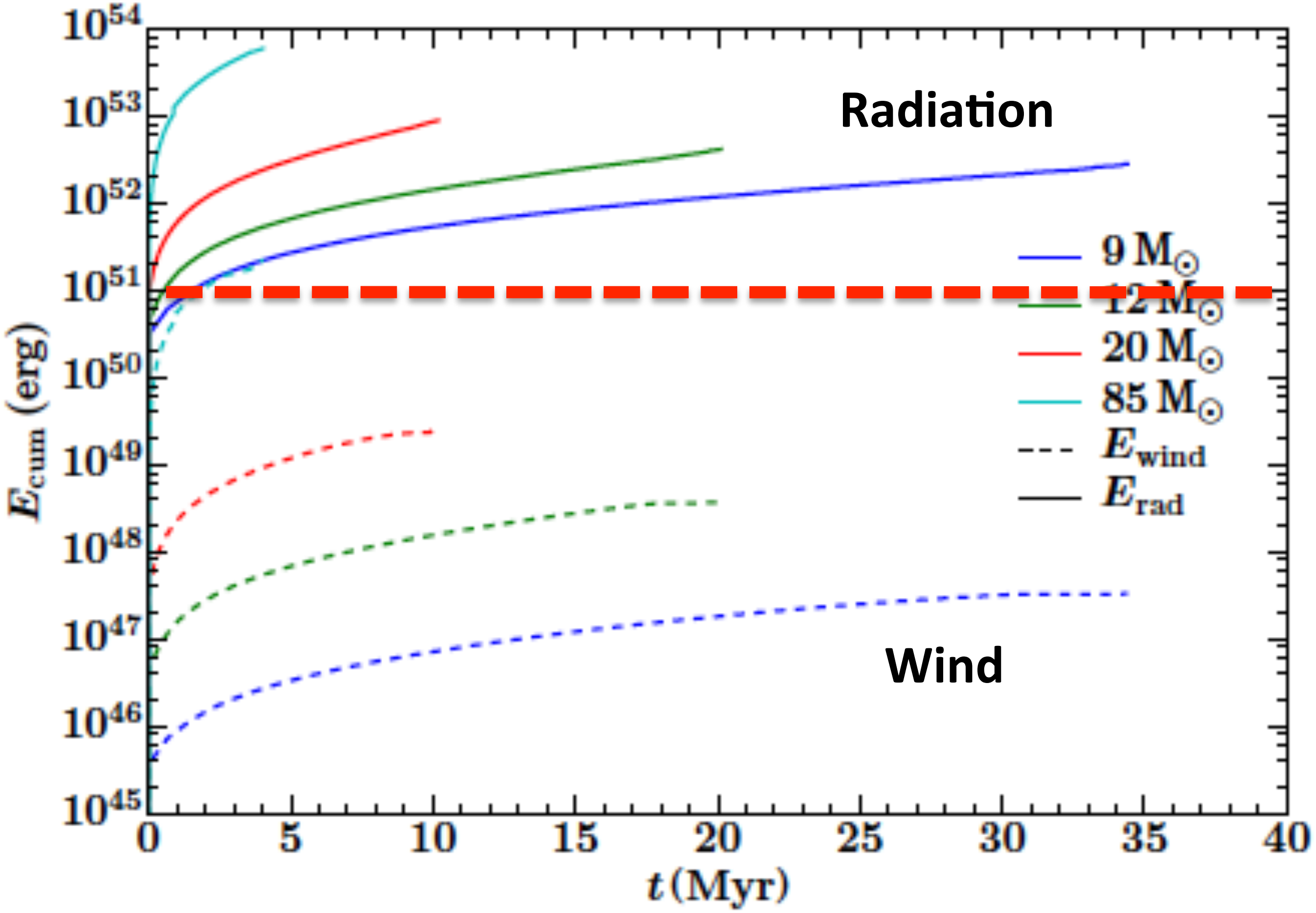
If star formation is self-regulated on large scales, is it also self-regulated on small scales (within molecular clouds)?

Most of the mass is in dense (molecular) gas; Most of the mass sits in the large GMCs (slope of GMC mass spectrum >-2).

Need to be able to self-regulate on GMC scales, (unless we are in a starburst, there self-regulation is temporarily not possible)

Problem:
Simulations show that only low-mass clouds can be dispersed!
Hmm…

Energy input:
Stellar winds, ionizing radiation and Supernovae:
How is this energy coupled to the ISM?



Supernova
1 event at
end of stellar
lifetime

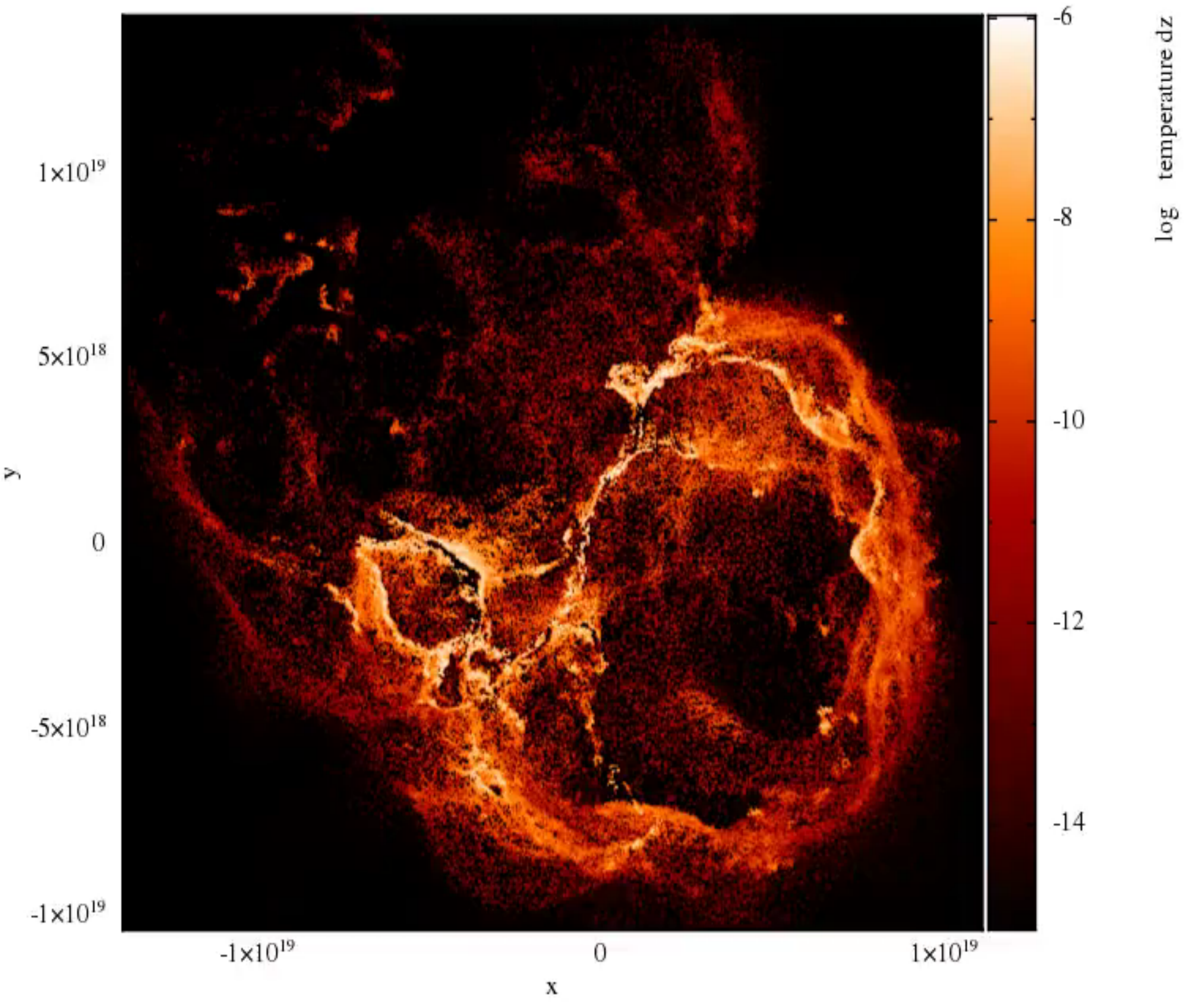
Stellar feedback
Massive stars: sources of heat and momentum

Massive stars (> 8 $M_\odot$) are rare!
~ 1 massive star per 100 $M_\odot$ of gas that forms stars

Massive stars are special!
•They have short lifetimes (few Myr)
•They die as a Supernova Type II
(Blast wave, $E_{SN}= 10^{51}$ erg)

During their life they emit:

• Ionising radiation (UV):
➢ionises and
➢heats up the environment
=> disperses the surrounding gas
• Fast stellar winds:
➢v_{wind}~few 1000 km/s,
➢dM/dt~10^{-6} $M_\odot$/yr
=> Additional momentum input



Walch et al., 2012; Walch et al., 2013;
Animation: Credit to Thomas Bisbas (UC Florida)

Wind + Supernovae

Rey-Raposo +2016
Extract clouds from galactic simulations
Dobbs & Pringle, 2013; Dobbs (2015)
and re-simulate them with star formation
+winds and/or SN feedback

=> Star formation rate is not strongly affected.

Include chemical network for H_2 and CO formation (Pettitt +2014) but simplified approximation for shielding

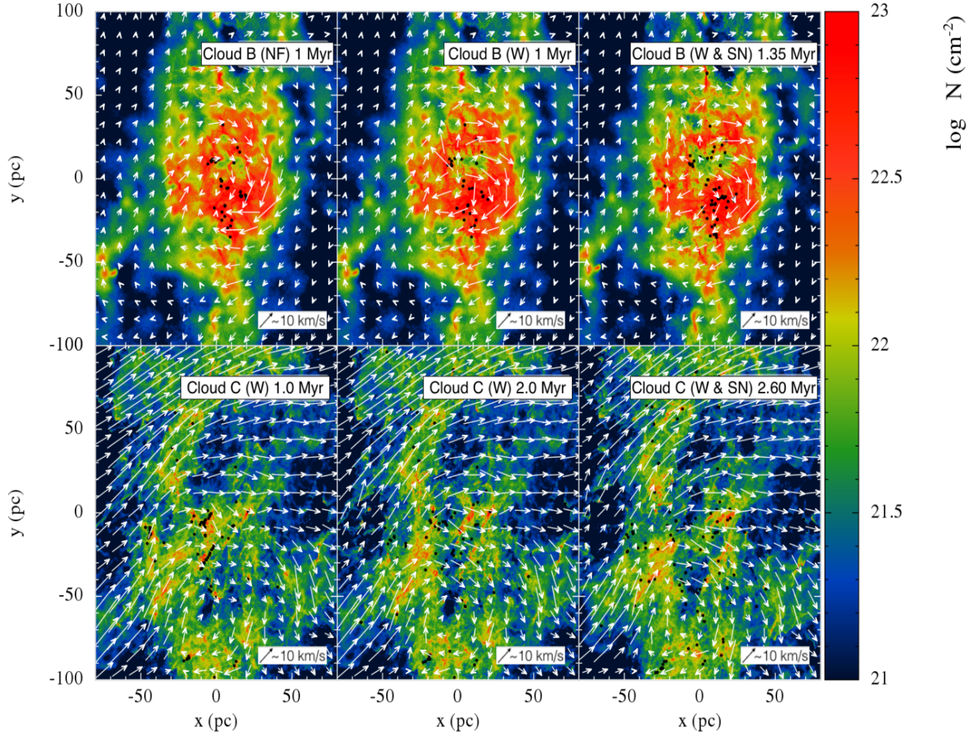
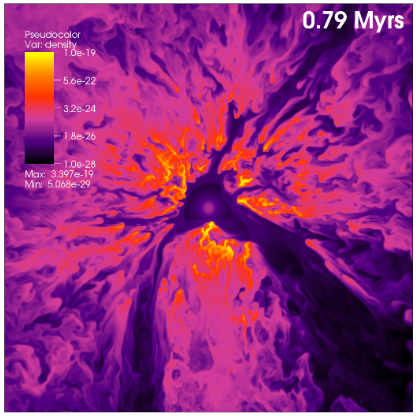


Figure 3. Column density maps of the two clouds with velocity fields for the non feedback case (left panels), winds (central panels) and winds and SNe (right panels).

Earlier work: Rogers & Pittard (2013), wind + SN with grid code
Dispersal of the clouds after a few Myr;
Similar applies for more massive clouds, just takes a bit longer



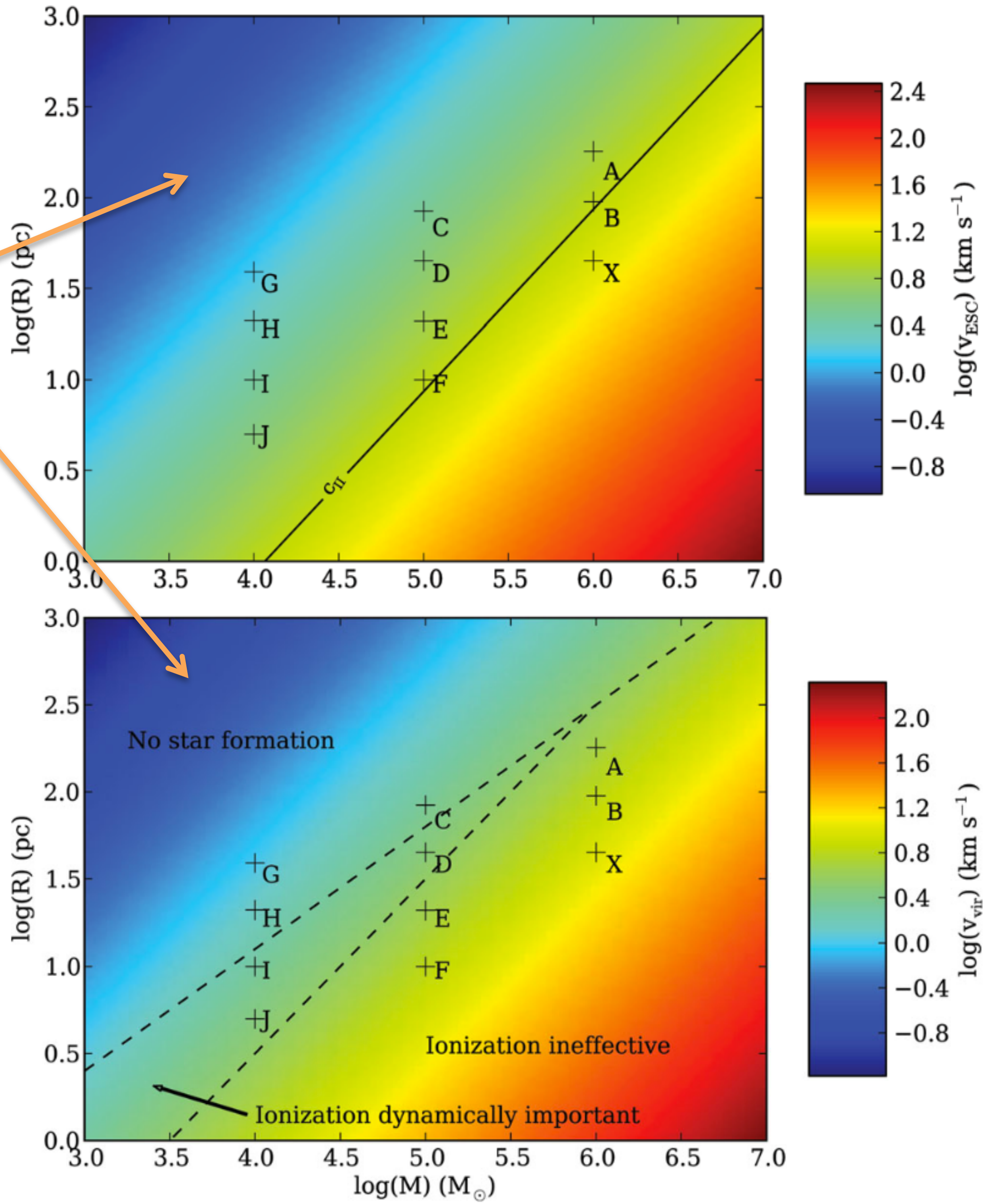
Radiative feedback

Dispersal of MCs by ionizing radiation
Walch +2012

Dale, Ercolano, Bonnell (2012)
Low-mass clouds are affected by ionizing radiation, while high-mass clouds aren't
Escape velocity is suggested to be responsible.

Dale 2017:
10^4 $M_\odot$ clouds with different virial state: does not matter much for SF
~30%-50% reduction in SFR

But also many others!
Arthur et al. 2012, Gritschneder et al. 2011, Bisbas et al. 2009, 2011



Radiative feedback

Howard, Pudritz, Harris (2017)
lowers efficiency by maximum a factor ~2 (20%-50%)
with respect to run without radiative feedback

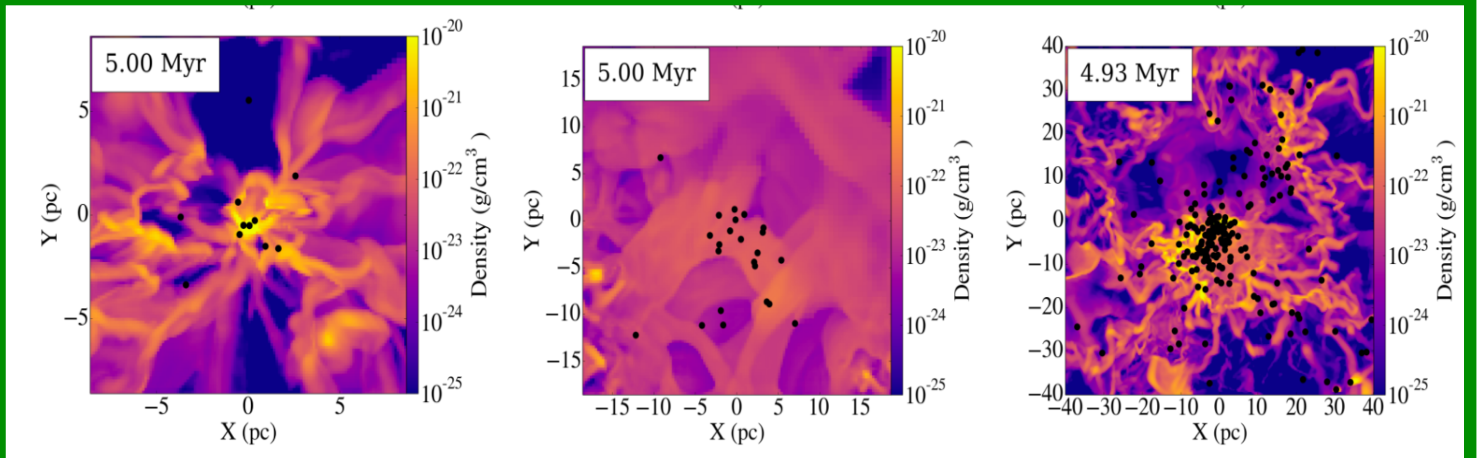
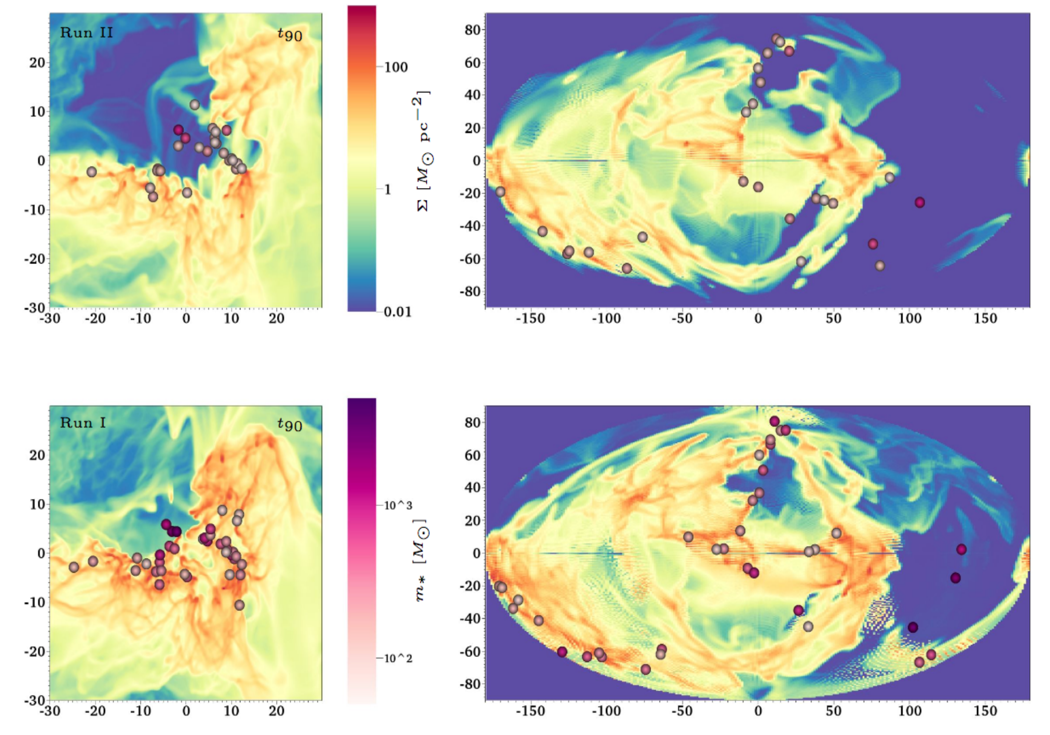


Figure 1. Density slices through the center of the simulation volume for the 10^4 (left), 10^5 (center), and 10^6 (right) $M_\odot$ GMCs. Time,

Also in Raskutti, Ostriker, Skinner (2017)
large scale filaments develop and ~50% of the radiation escapes
⇒dispersal efficiency and escape fraction go hand in hand
⇒this means that the cloud substructure really matters

⇒these simulations use an isothermal EOS for the non-ionized gas
⇒Too cold! Too filamentary! Too much radiation escapes! Too inefficient coupling!



Wind + Radiative feedback

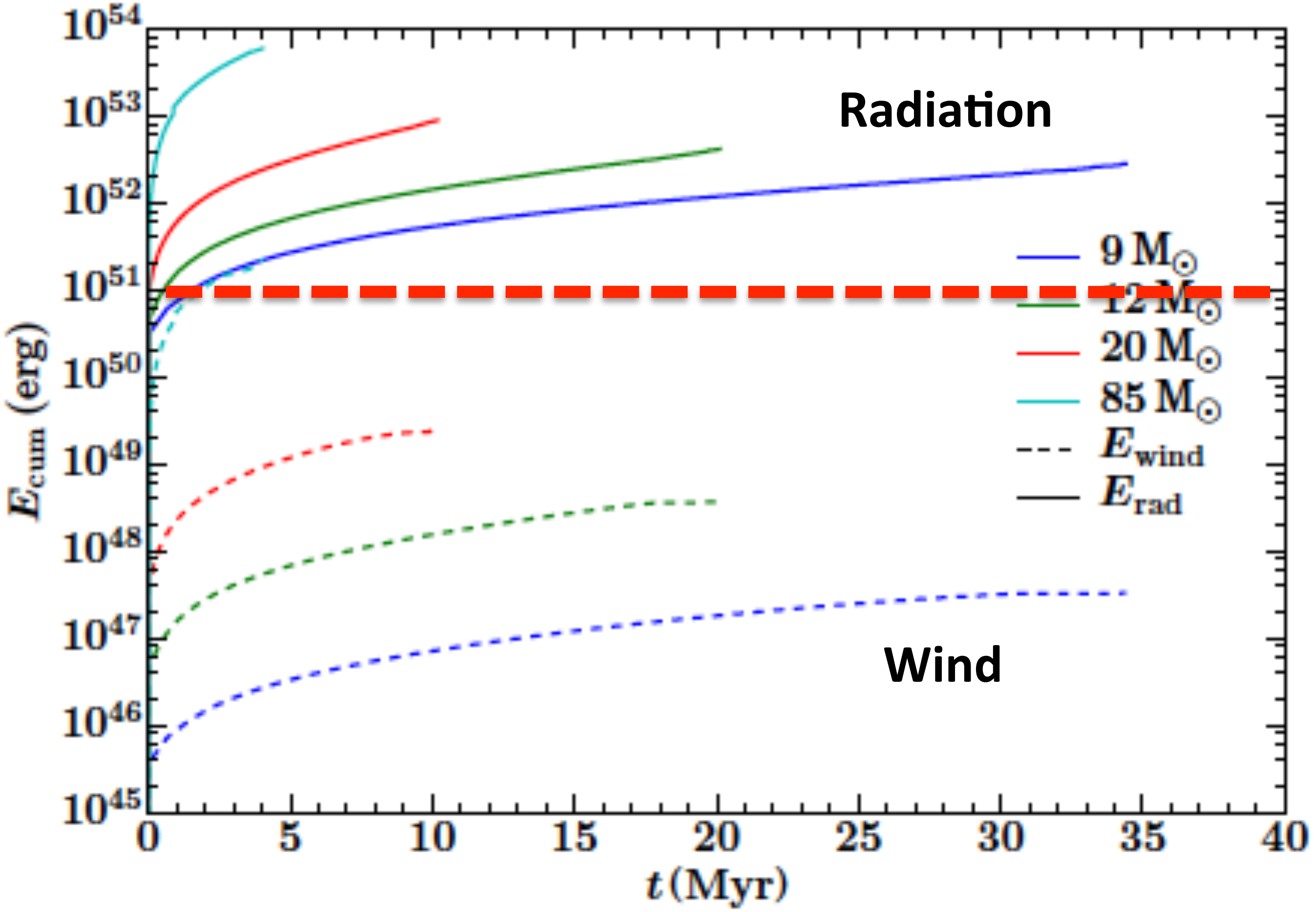
Early results:
Wind + radiation:
Dale+2014, Ngoumou+2015
⇒Wind has very little effect (if any)

Needs more investigation first (with other codes):
In uniform ambient media

e.g. Geen et al., (2015),
Haid et al. (2018, submitted)

but also Agertz et al. (2013) for larger-scale models

Energy input:
Stellar winds, ionizing radiation and Supernovae:
How is this energy coupled to the ISM?



Supernova
1 event at
end of stellar
lifetime

How is this energy coupled to the ISM?
Stellar winds vs. ionizing radiation on smaller scales:

Simulations with FLASH 4.3

Stellar winds:

- ➢ **Implementation following Gatto et al. (2017)**
- ➢ **Wind momentum input**

Ionizing radiation:

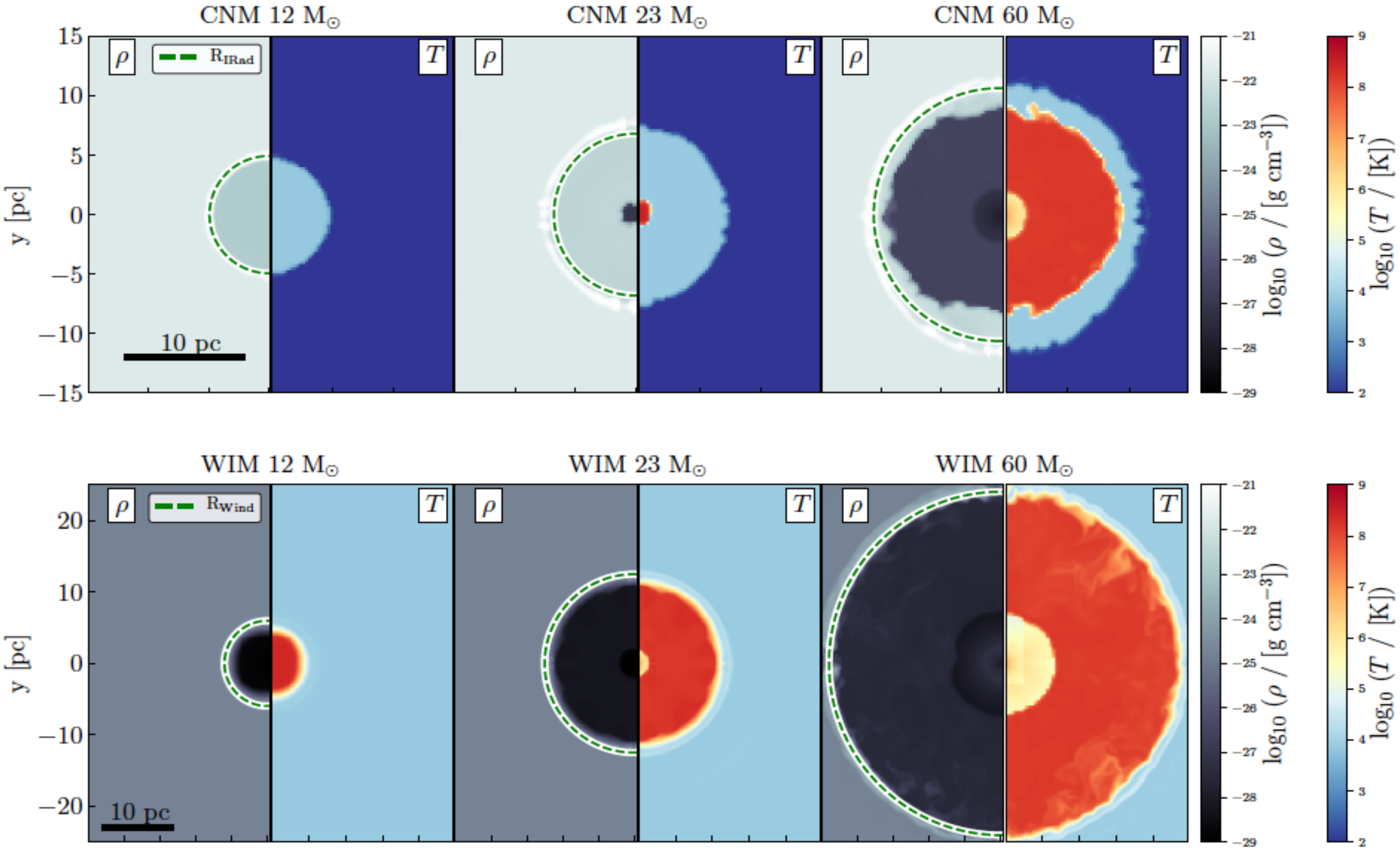
- ➢ **New implementation of a backward radiative transfer scheme, which utilizes the Barnes-Hut tree: TreeRay (Wünsch et al., 2018; and Wünsch et al., in prep.)**
- ➢ **Ionizing radiation (On-The-Spot approximation; ionization – recombination equilibrium with temperature-dependent case-B recombination coefficient)**
- ➢ **UV heating and UV field provided to the chemical network**

⇒self-consistent abundances of chemical species and HII region temperatures (depending on spectrum = mass of ionizing star)

⇒Code has been benchmarked against MOCASSIN Code (Ercolano et al., 2003)

Haid et al., 2018, submitted to MNRAS

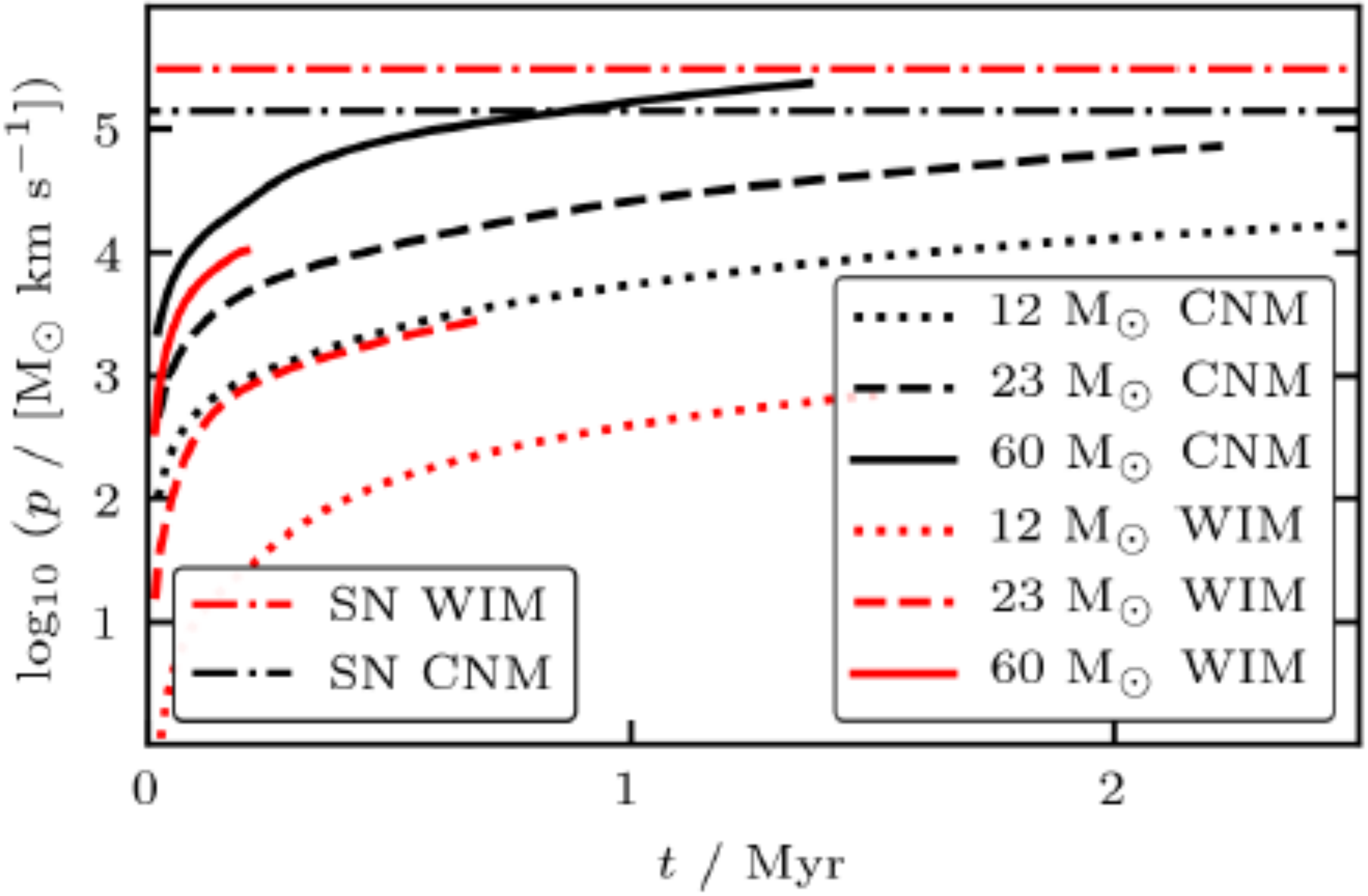
How is this energy coupled to the ISM?
Stellar winds vs. ionizing radiation:



CNM: T=20 K, n=100 cm^{-3}; WIM: T=10^{4} K, n=0.1 cm^{-3}

Haid et al., 2018, submitted to MNRAS

Momentum input:
Stellar winds, ionizing radiation and Supernovae:
Coupling of radiation is inefficient…



Supernova
1 event at
end of stellar
lifetime

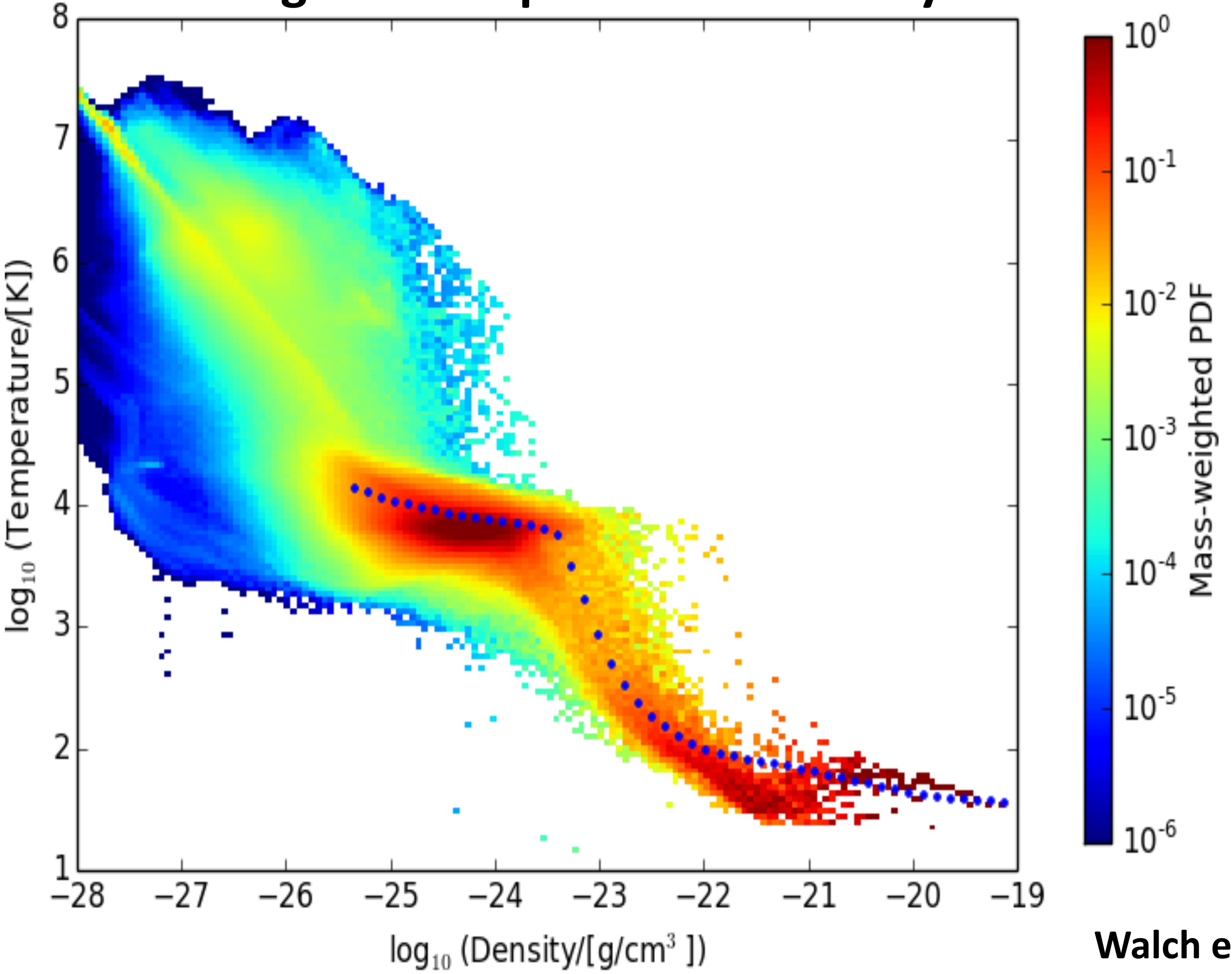
CNM: T=20 K, n=100 cm^{-3}; WIM: T=10^4 K, n=0.1 cm^{-3}

Haid et al., 2018, submitted to MNRAS

The SILCC project (www.astro.uni-koeln.de/silcc):

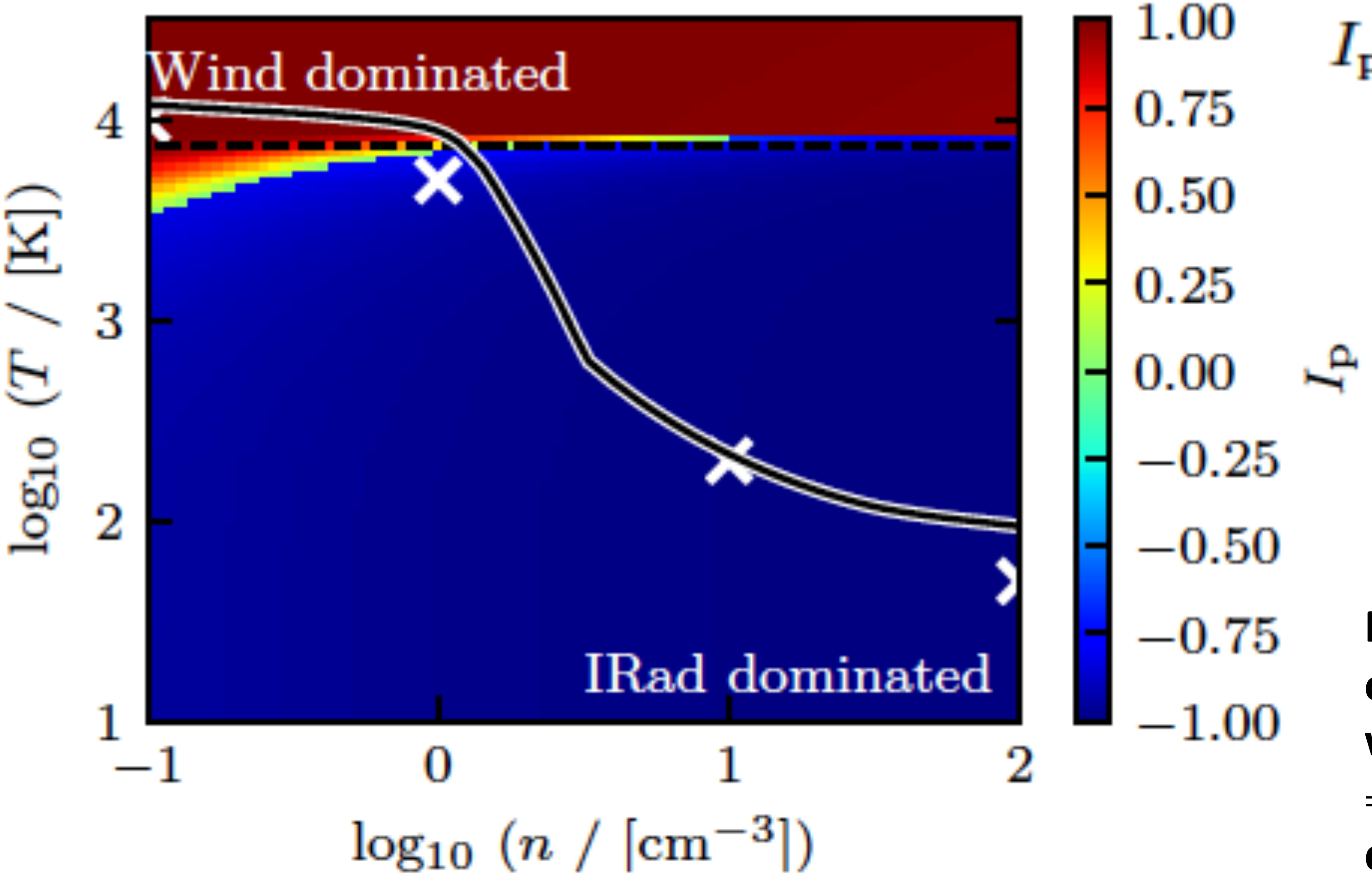
Typical mass distribution in the multi-phase ISM in a star forming galactic disk

Mass-weighted temperature – density PDF



Walch et al. (2015)

Momentum input:
Stellar winds vs. ionizing radiation:



$$I_\mathrm{p} \equiv \frac{p_\mathrm{Wind} - p_\mathrm{IRad}}{p_\mathrm{Wind} + p_\mathrm{IRad}}$$

Relative impact of wind and radiation

Here: for 23 $M_\odot$ star

Radiation does not couple in low density/ warm ambient medium
⇒stellar winds become dominant there!

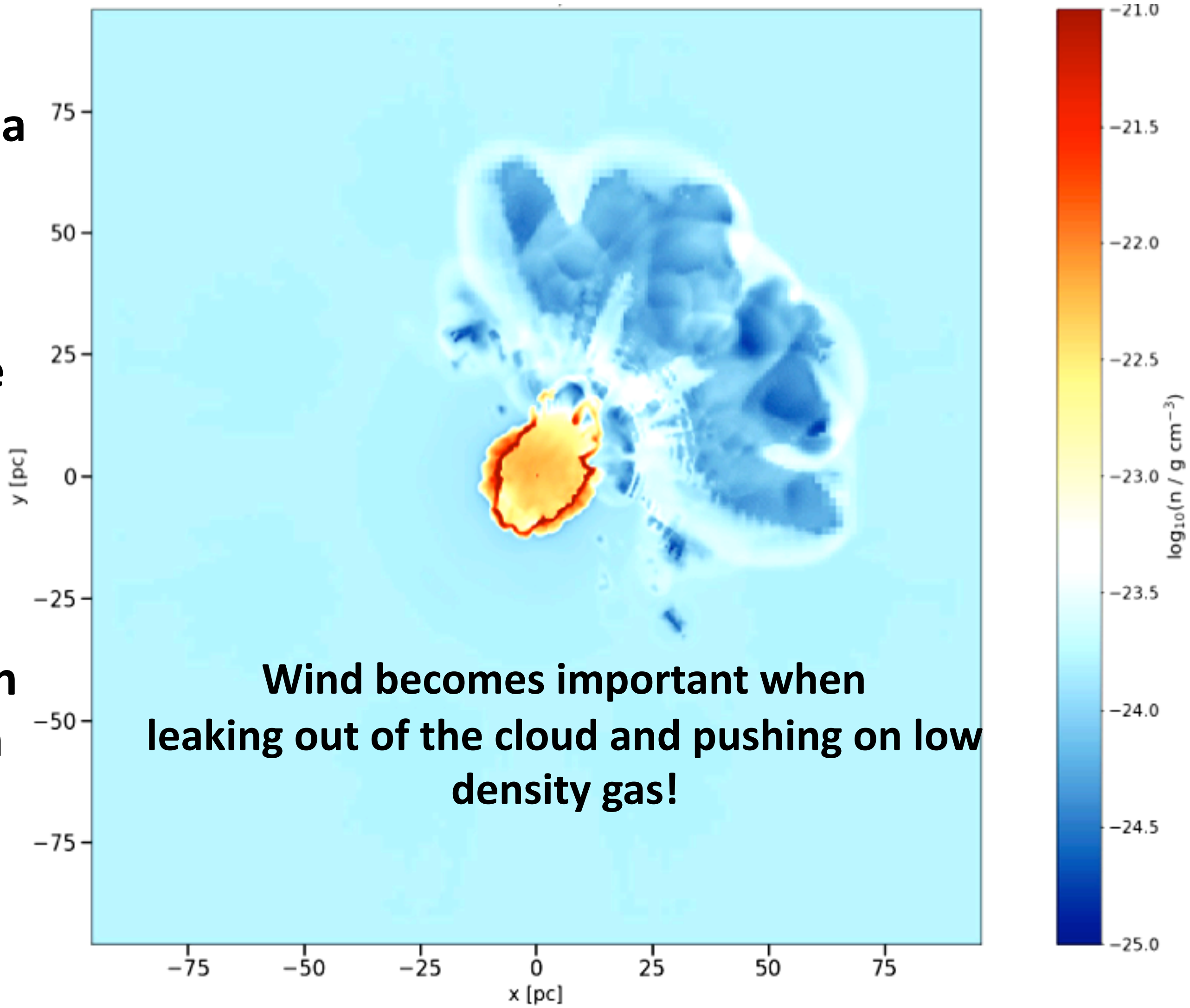
CNM: T=20 K, n=100 cm^{-3}; WIM: T=10^4 K, n=0.1 cm^{-3}

Haid et al., 2018, submitted to MNRAS

Wind needs to leak out of dense parent cloud

Typical situation:

- **Massive star is born inside a cloud and disperses it by ionizing radiation**
- **Feedback breaks out of the cloud and interacts with warm ISM**
- **Wind energy leaks out of the cloud and interacts with surrounding warm medium**



Wind becomes important when leaking out of the cloud and pushing on low density gas!

Haid et al., 2018, submitted to MNRAS

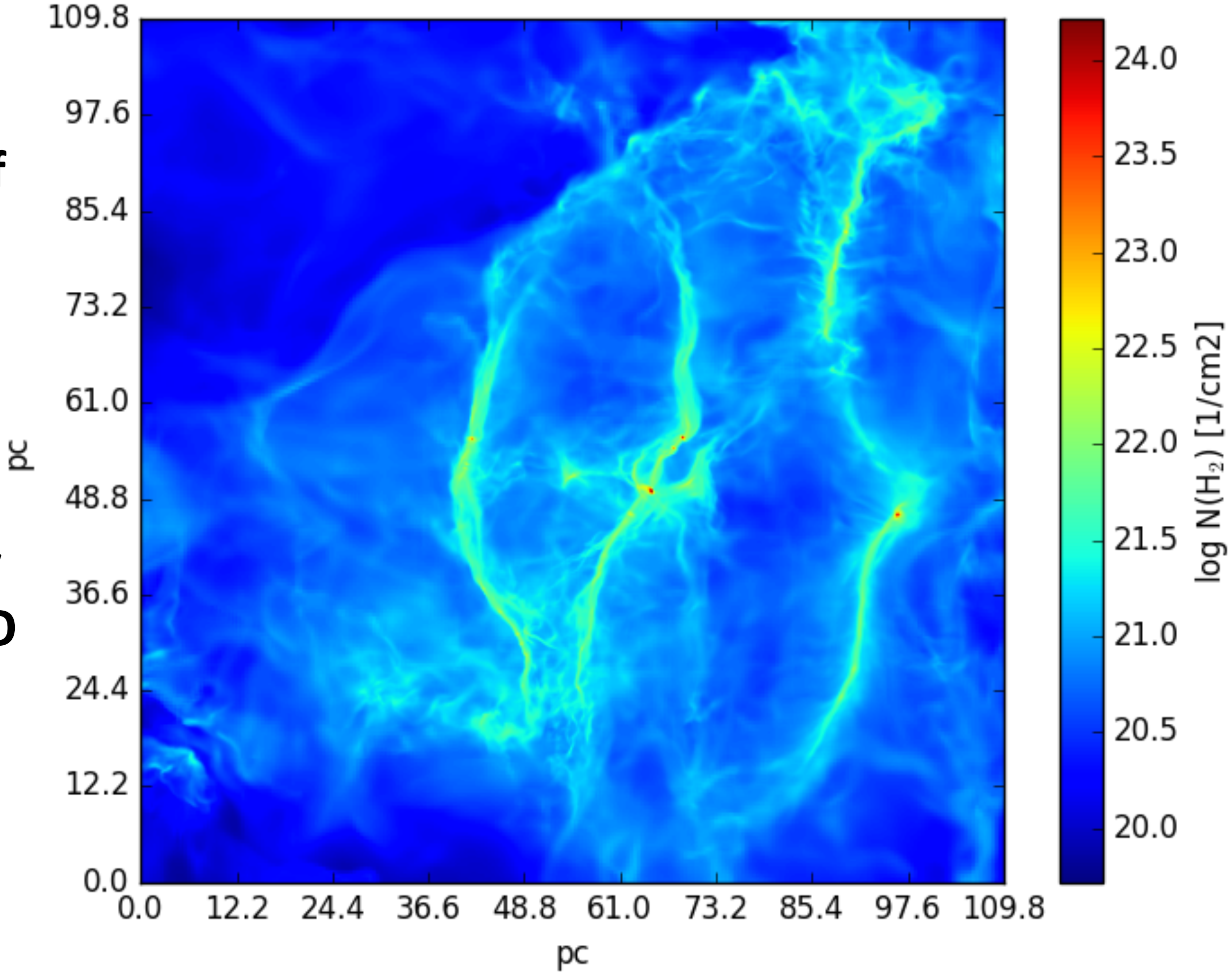
Feedback in action:
SILCC-Zoom:
Galactic zoom-in simulations of molecular cloud formation

Galactic zoom-in simulation:

Resolve individual molecular clouds which condense out of the supernova-driven, multi-phase ISM
(from SILCC simulations)

Resolve ~0.1 pc
⇒this resolution is necessary to obtain converged H_2 and CO mass fractions!!
(also Joshi et al., in prep.)

⇒ For now: typical solar neighbourhood clouds with mass few x 10^4 $M_\odot$

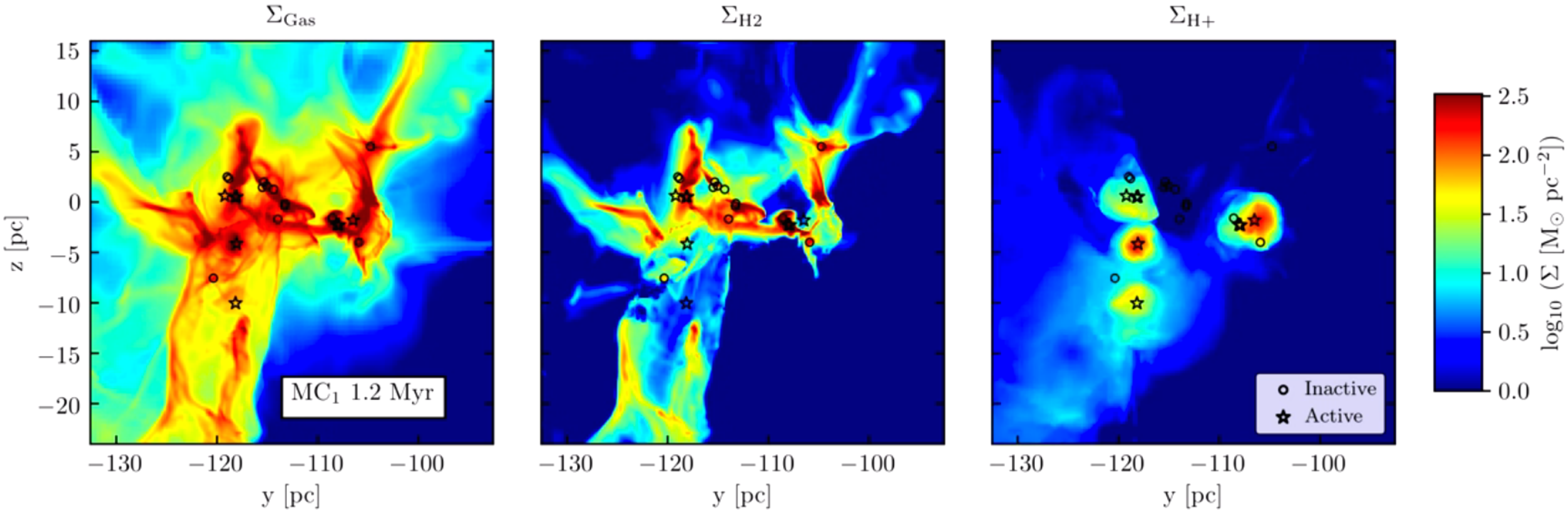


Seifried et al., 2017, Seifried et al., 2018

Feedback inside molecular clouds: ionizing radiation disperses the clouds

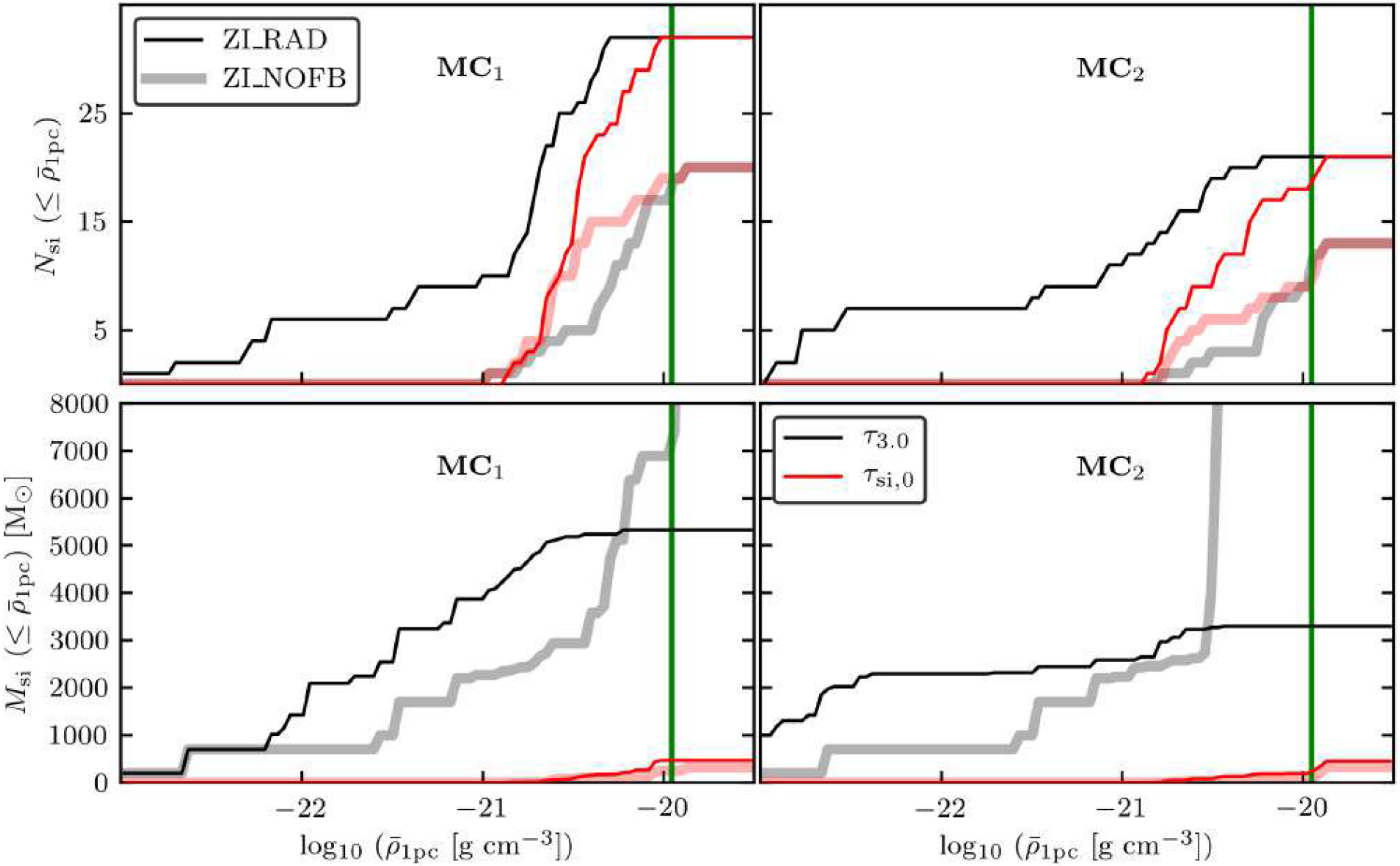
SILCC-Zoom II: Star cluster formation and feedback inside these molecular clouds:

- **Ionizing radiation disperses the parental cloud on time scales of ≥ 3Myr**
  Consistent with e.g. Walch et al.(2012)
- **Triggered star formation (higher # of sinks w.r.t. simulation without feedback)**
  BUT
- **Highly reduced star formation efficiency with feedback! ~10%**

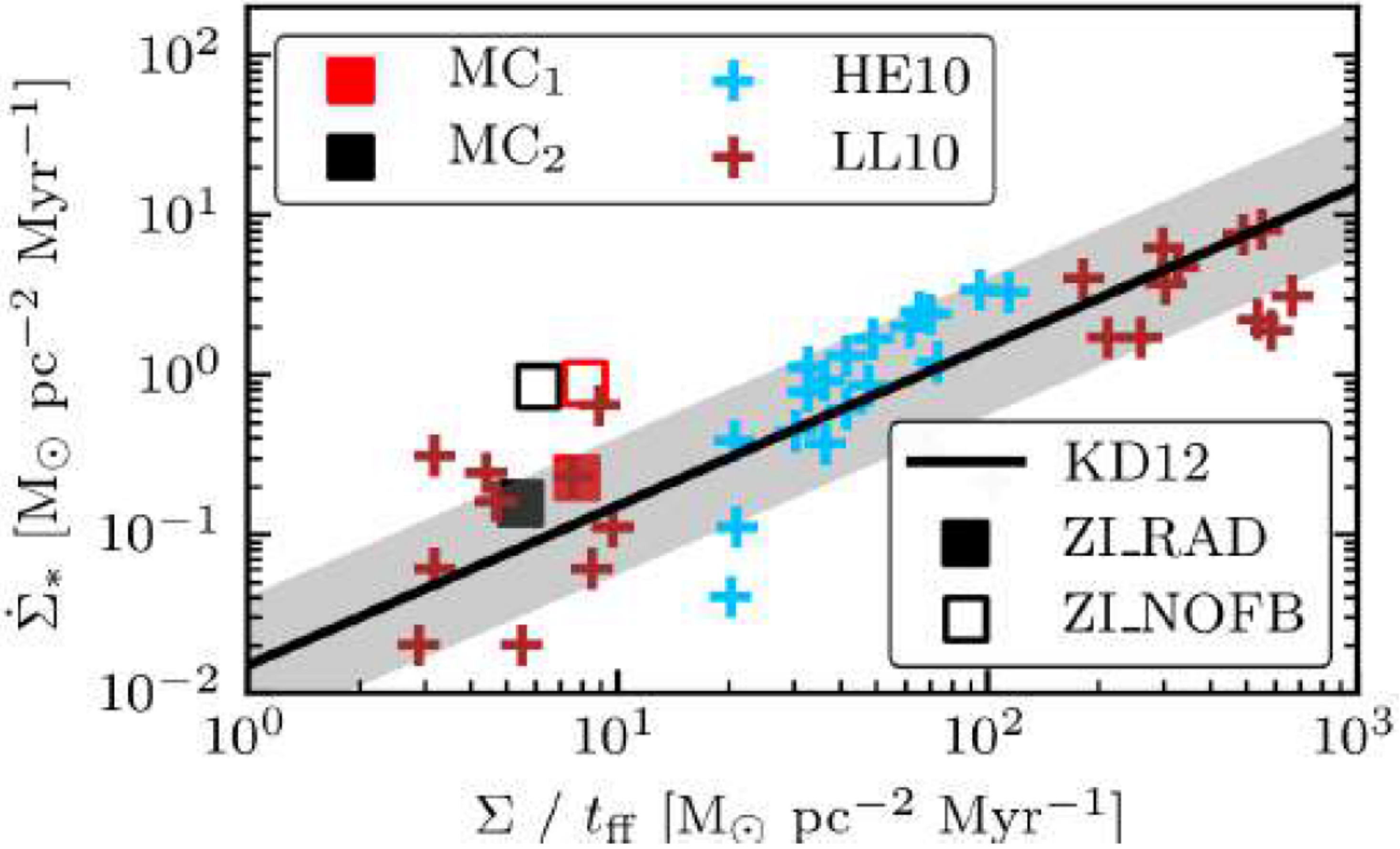


Haid et al., 2018, submitted to MNRAS

Feedback inside molecular clouds: Triggered star formation but low SFE

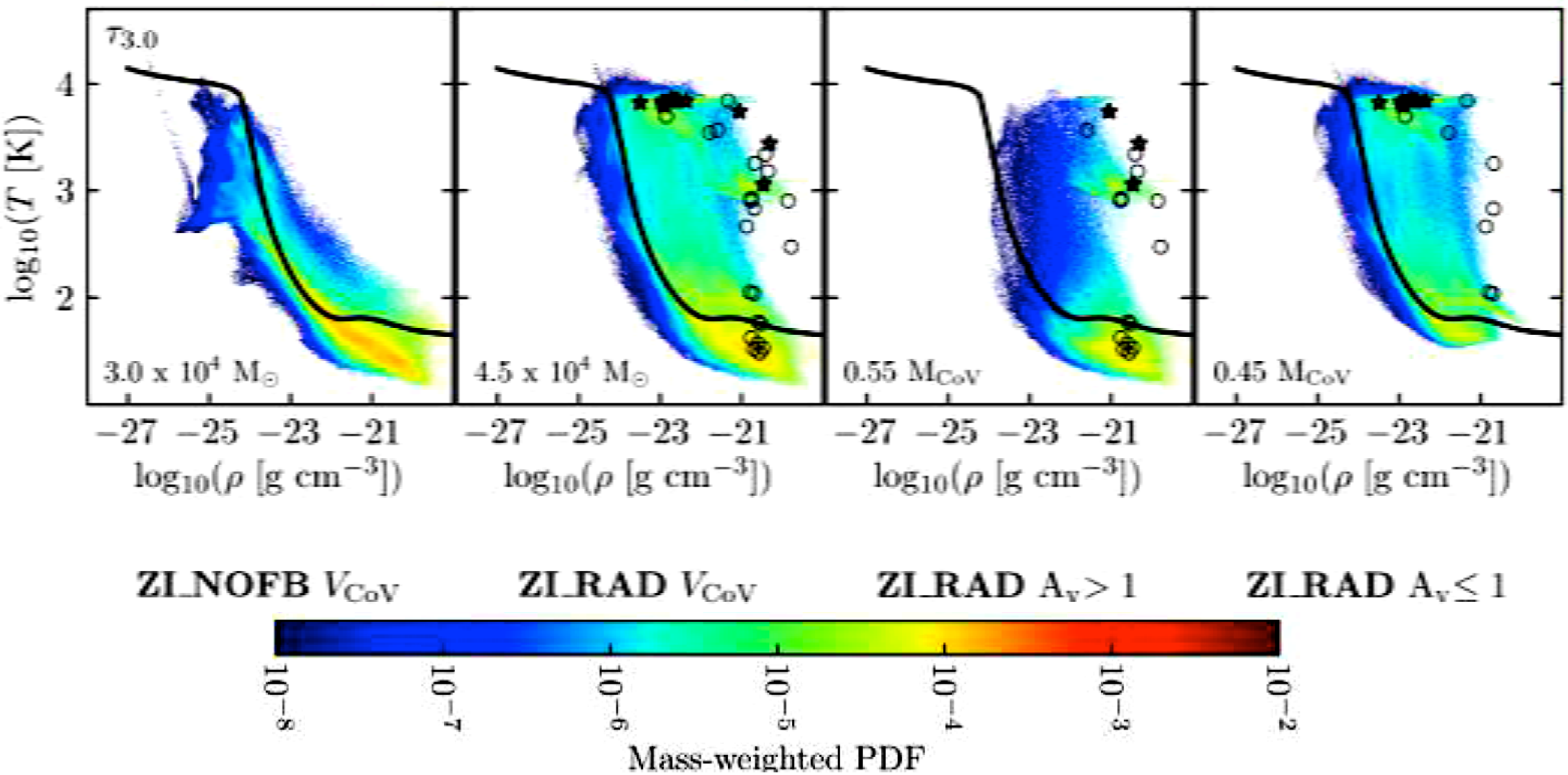


Feedback inside molecular clouds: Star formation rate surface density vs. gas surface density over free-fall time



In our models: Feedback has a large impact on SFR! Factor ~4 (rather than max. 50%)
Clouds with radiative feedback (full symbols) lie on top of comparable solar neighbourhood clouds (Taurus, Ophiuchus, Lupus 3)!
Caution: depends on def. of "molecular cloud", i.e. which mass/area is considered

Feedback inside molecular clouds: Temperature-density distribution



Phase structure of the medium below ~104 K is completely changed by radiative feedback

=> Lots of gas in "thermally unstable" regime (above equlibrium curve, black line)

Conclusions

Scale: several 100 parsec:

Stellar feedback (wind/photo-ionization) regulates

✧The star formation efficiency of individual star-forming regions by stopping **accretion** onto the star-forming molecular clouds

✧Locally, the star formation efficiency could be high, globally it is in agreement with the Kennicutt-Schmidt-Σ_{SFR} and long depletion time scale

Stellar feedback (Supernovae)

✧can drive pressure-driven galactic outflows

✧a high volume filling fraction of hot gas in the disc midplane is required to get significant mass loading

Molecular cloud scales (Zoom-ins)

RESOLUTION OF ~0.1 pc required to get converged molecular gas fraction!

✧Radiation is the dominant feedback mechanism inside molecular clouds

✧Clouds (few x 10^4 $M_\odot$) are dispersed before the first SN goes off

✧Although star formation is triggered, the star formation efficiency is ~10%

✧We find much stronger impact of feedback on SFR inside single clouds

=> probably because the gas thermodynamics is properly modeled?!

Demanding multi-physics models utilizing HPC technologies

⇒Ask me about numerics if you are interested…