A dark brown, textured book cover with white text. The text is centered and reads: "Feedback effects at high redshift", "Benedetta Ciardi", and "MPA". The book is shown from a slightly elevated perspective, showing the top and front cover.

Feedback effects  
at high redshift

Benedetta Ciardi

MPA

## Introduction

Once upon a time,  
the first  
sources were  
formed.

Their mass  
deposition,  
energy injection,  
emitted  
radiation has  
deeply affected  
the subsequent  
galaxy/star  
formation process  
and the



Mechanical feedback

Chemical feedback

Radiative feedback

See Ciardi & Ferrara 2005  
& 2008 update on astro-ph

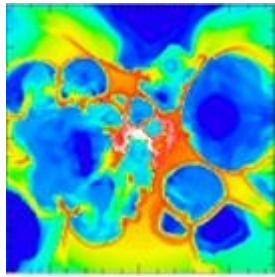
An open notebook with a dark cover and a light-colored tassel hanging from the bottom center. The left page contains text, while the right page is blank. The text is in a simple, black, sans-serif font.

## Chapter 1

### Mechanical feedback

Mechanical energy injection  
from winds and/or SN

# Mechanical feedback



Mori, Ferrara & Madau 2002

Ferrara 1998

Mac Low & Ferrara 1999

Nishi & Susa 1999

Tomoto, Shigeyama & Yoshii 1999

Ciardi et al. 2000

Scannapieco, Ferrara & Broadhurst 2000

Mori, Ferrara & Madau 2002

Bromm, Yoshida & Hernquist 2003

Wheeler, Bromm & Hernquist 2003

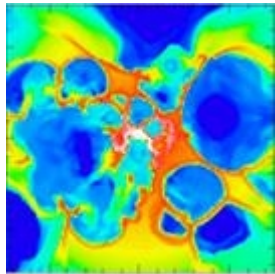
Wada & Venkatesan 2003

Ferrara, Ferrara & Schneider 2003

Kitayama & Yoshida 2005

Scannapieco, Ferrara & Scannapieco 2005

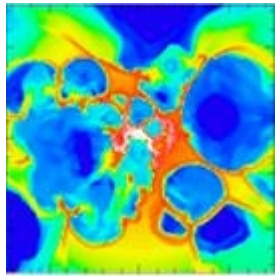
Greif et al 2007



Mechanical feedback: depletion of gas re

SN explosions can expel gas out of the host halo and  
reduce the reservoir for subsequent star formation

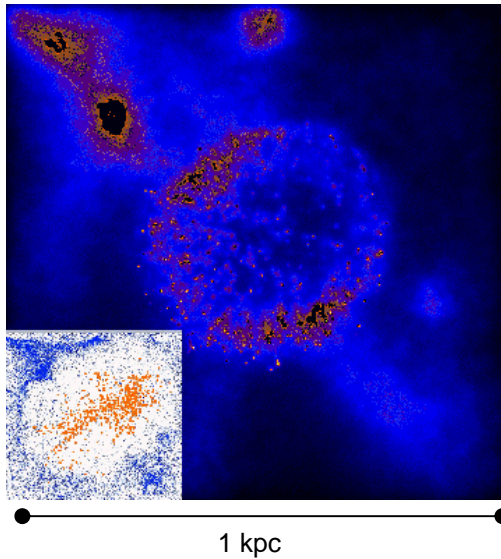
# Mechanical feedback: depletion of gas re



Mori, Ferrara & Madau 2002

## Cosmological simulation + zoom<sup>6</sup> on SN explosion

Gas distribution 10<sup>6</sup> yr after explosion with 10<sup>53</sup> ergs



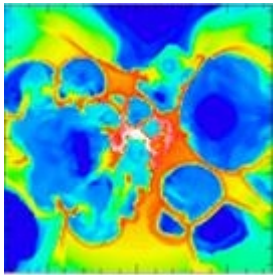
Bromm, Yoshida & Hernquist 2003

$$E_{\text{SN}} = 10^{51} \text{ erg} (M_* = 150 M_{\text{sun}}) \Rightarrow \text{intact}$$

$$E_{\text{SN}} = 10^{52} \text{ erg} (M_* = 200 M_{\text{sun}}) \Rightarrow \text{disruption}$$

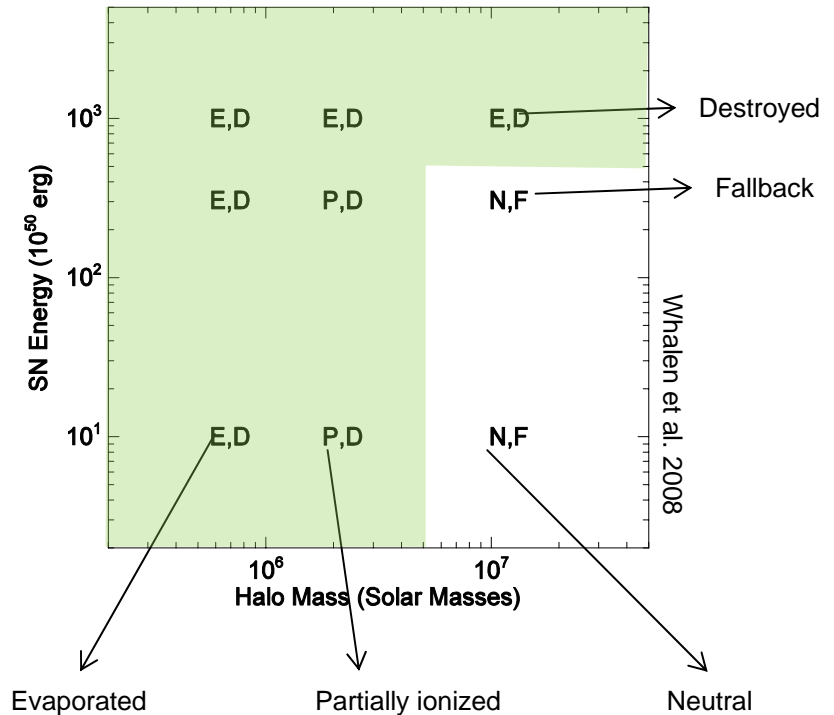
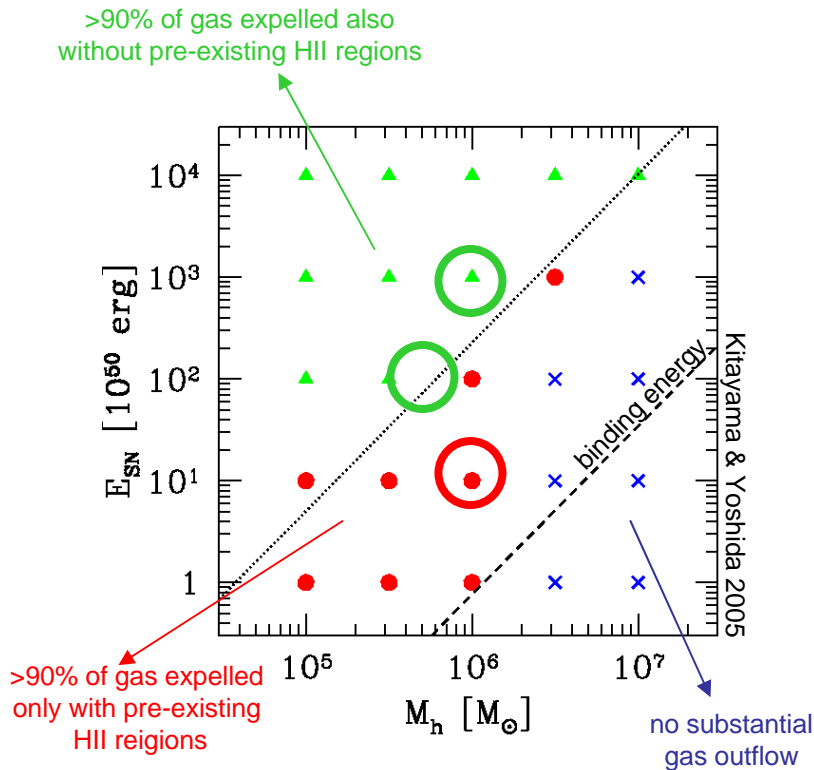
Greif et al 2007

$$E_{\text{SN}} = 10^{53} \text{ erg} (M_* = 250 M_{\text{sun}}) \Rightarrow \text{disruption}$$



# Mechanical feedback: depletion of gas re

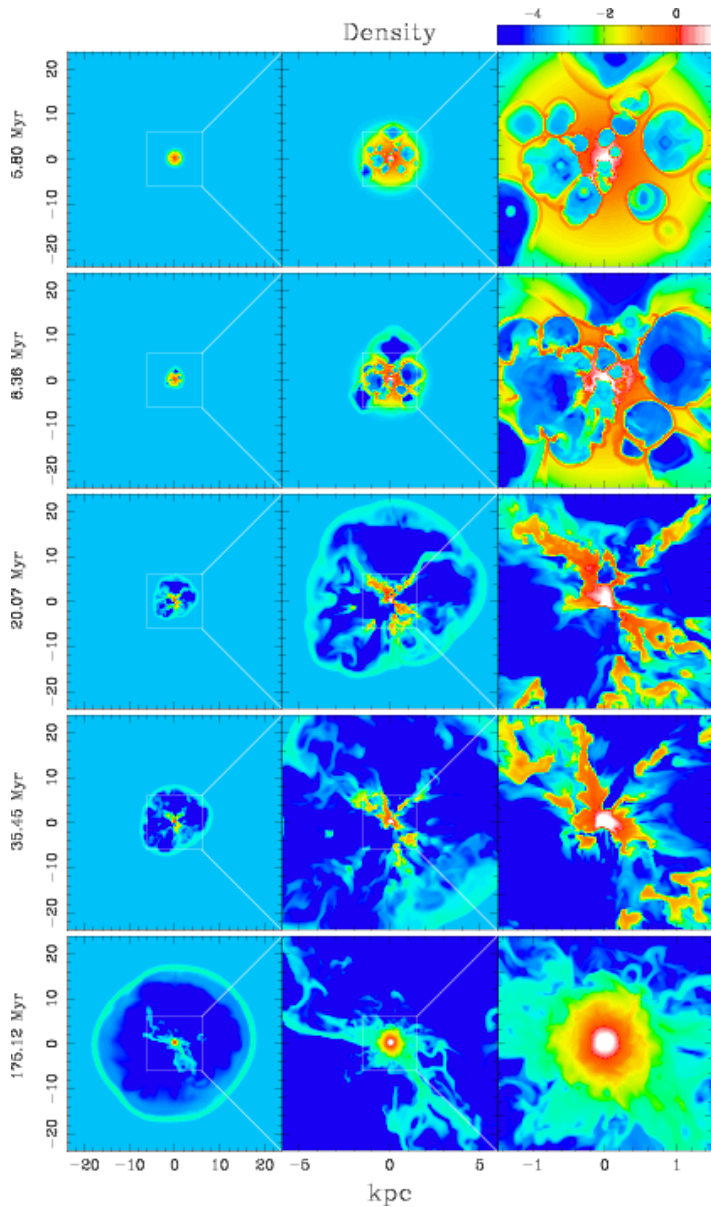
## Parametric study of SN explosions



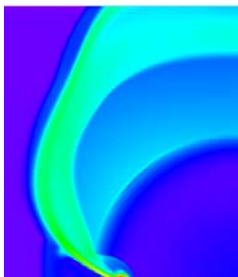
Mechanical feedback: depletion of gas re

AMR simulation of multiple SN $\beta$  explosions in M

# Mechanical feedback: depletion of gas re

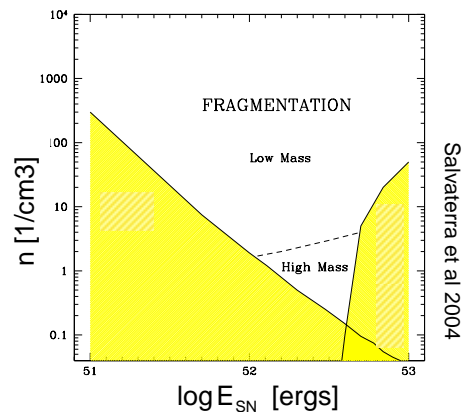


Off-center SN explosions of  
propagating shocks that pr  
second SF episode in the



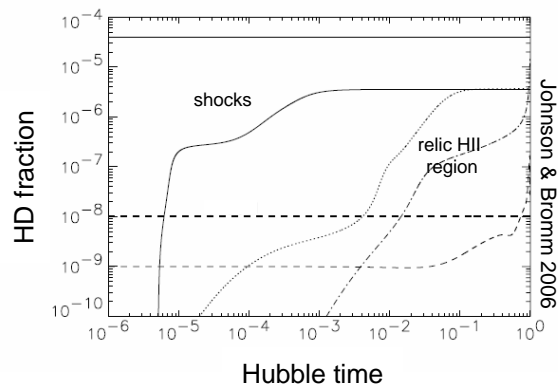
# Mechanical feedback: SF induced by shocks

The gas swept by shocks is compressed and can induce a positive feedback on star formation



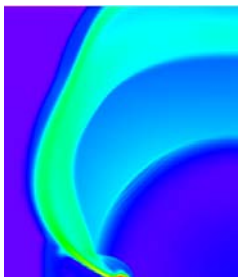
- The dense shell can fragment and

Mackey, Bromm & Hernquist 2003; Salvaterra, Ferrara & Schneider 2004



- HD formation is promoted and

Vasiliev & Shchekinov 2005; Johnson & Bromm 2006; Greif et al 2007



# Mechanical feedback: SF induced by shocks

The gas swept by shocks is compressed and can induce a positive feedback on star formation

2<sup>nd</sup> generation stars are smaller than 1<sup>st</sup> generation stars  
low metallicity, low mass stars

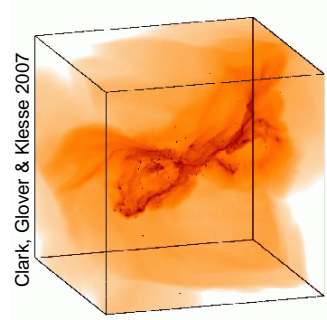
Would 3D studies find the same results?

An open notebook with a dark cover and a light-colored page. The left page contains text, while the right page is blank. The notebook is positioned centrally against a white background.

## Chapter 2

### Chemical feedback

Critical metallicity of the gas that induces a transition from massive to more standard star formation



# Chemical feedback

Bromm et al 2001

Schneider et al 2002

Bromm & Loeb 2003

Omukai et al 2005

Santoro & Shull 2006

Schneider et al 2006

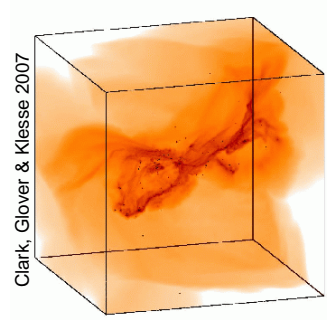
Tsuribe & Omukai 2006

Clark, Glover & Klessen 2007

Smith & Sigurdsson 2007

Santoro, Schneider & Ferrara 2007

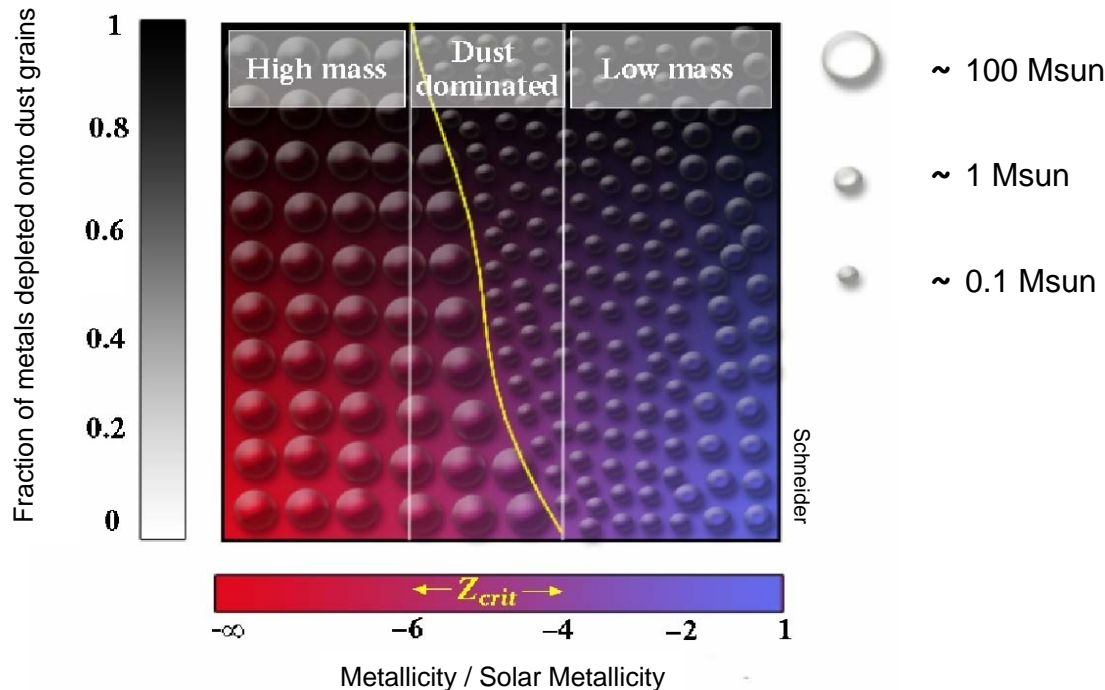
Tsuribe & Omukai 2008



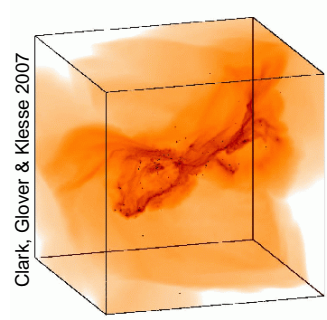
# Chemical feedback: fragmentation of gas

1D/3D simulations; cosmological IC or single cloud

Chemistry: H, He, metals,  $\text{CO}$ ,  $\text{SiII}$ ,  $\text{FeII}$  +  $\text{Ddust}$



Schneider et al 2002, 2006  
Omukai et al 2005  
Tsuribe & Omukai 2006, 2008  
Clark, Glover & Klessen 2007

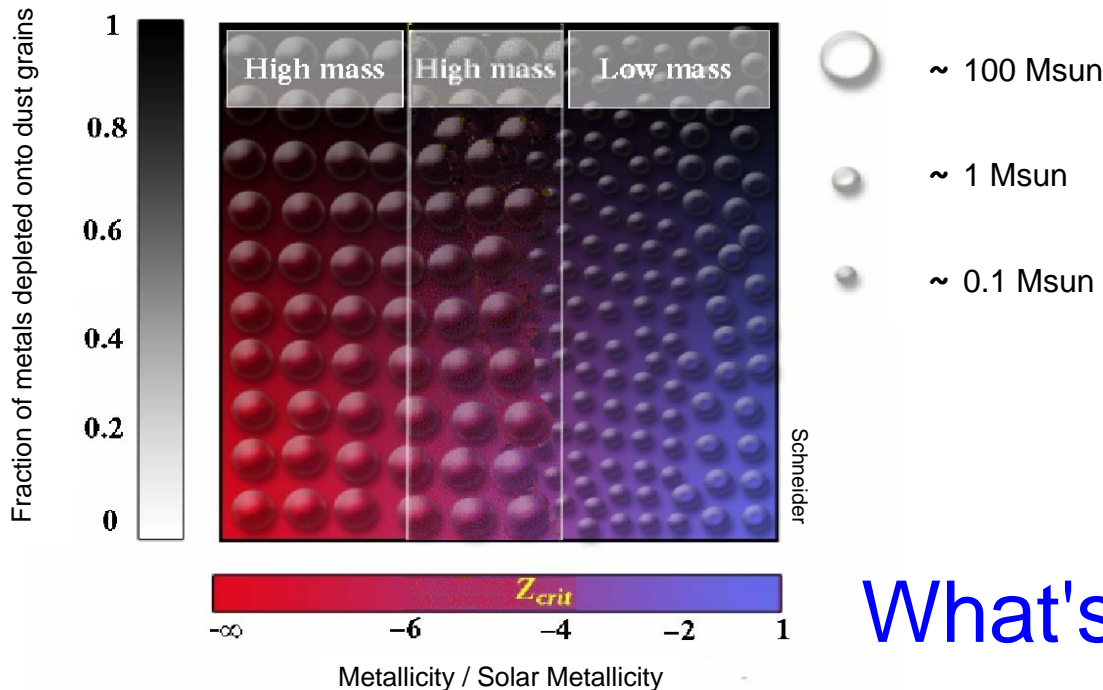


# Chemical feedback: fragmentation of gas

1D/3D simulations; cosmological IC or single cloud

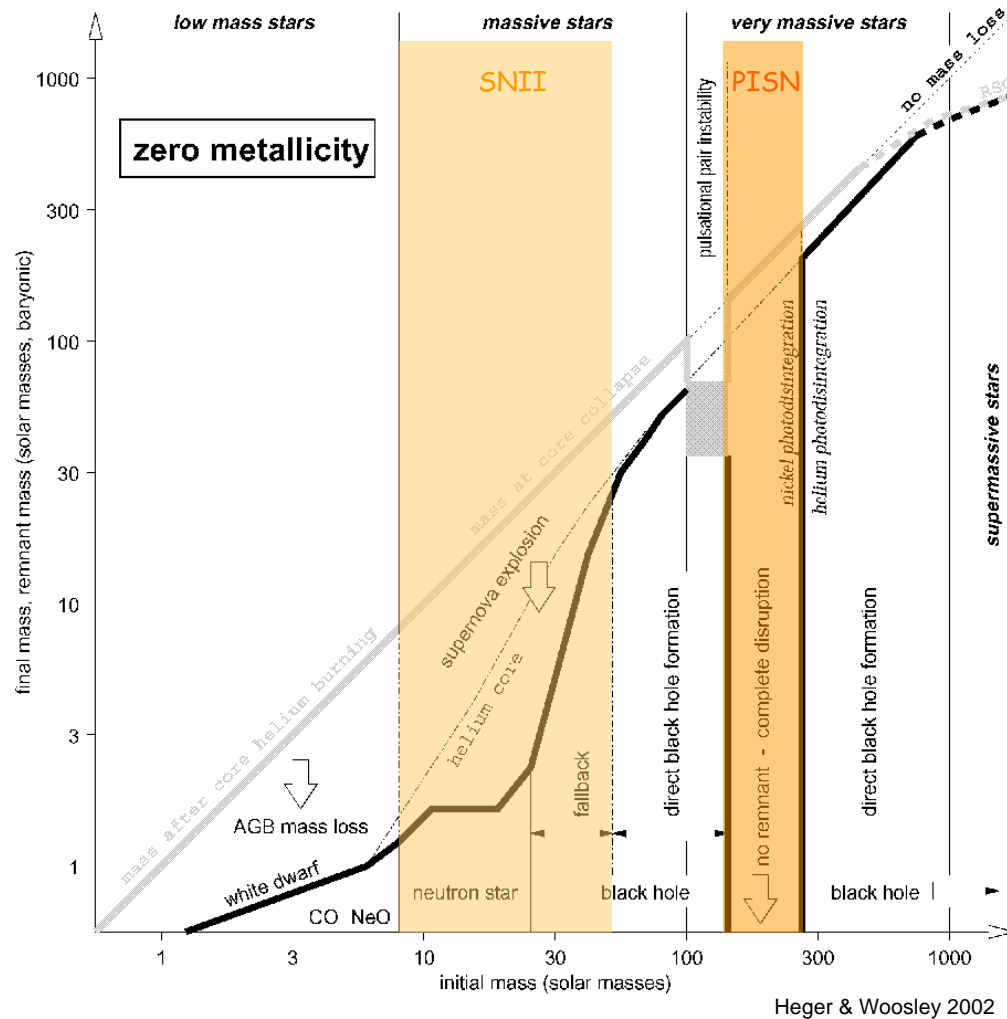
Chemistry: H, He, metals,  $\text{O}_2$ , Si, Fe,  $\text{H}_2$  +  $\text{D}_{\text{dust}}$

Bromm et al 2001  
 Bromm & Loeb 2003  
 Santoro & Shull 2006  
 Smith & Sigurdsson 2007

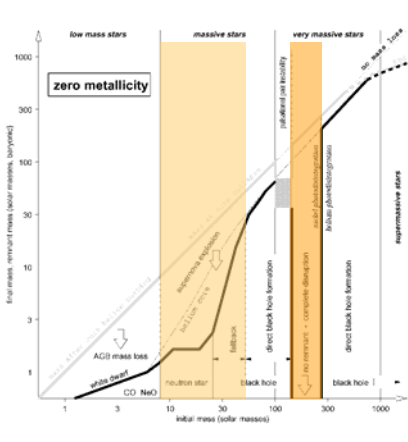


What's the role of

# Chemical feedback: missing ingredients



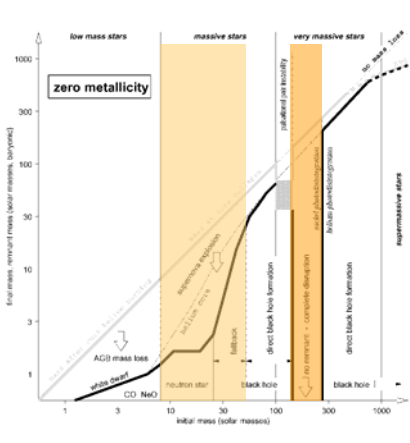
# Chemical feedback: missing ingredients



IMF of the first stars → abundance of

# Chemical feedback: missing ingredients

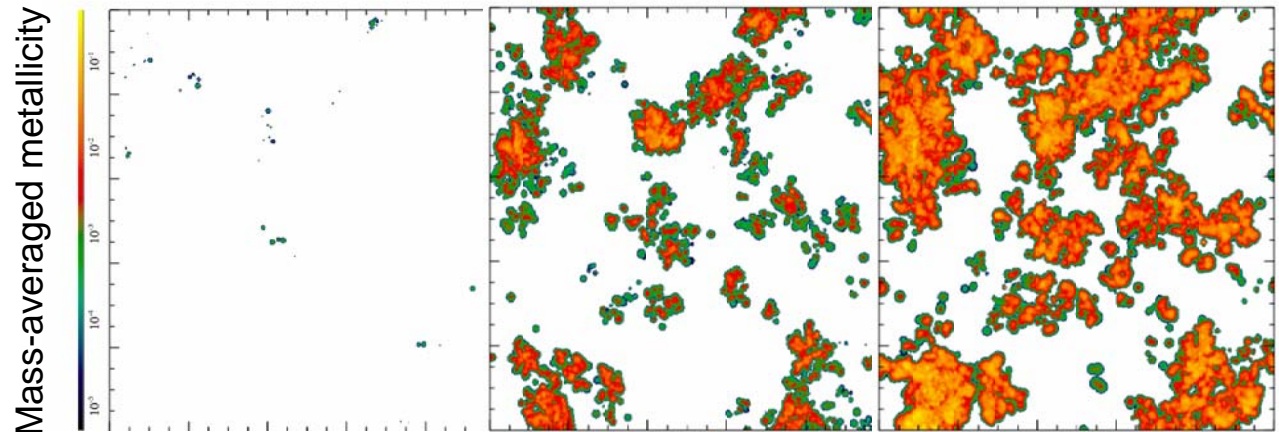
IMF of the first stars  $\rightarrow$  abundance of



$z=10$

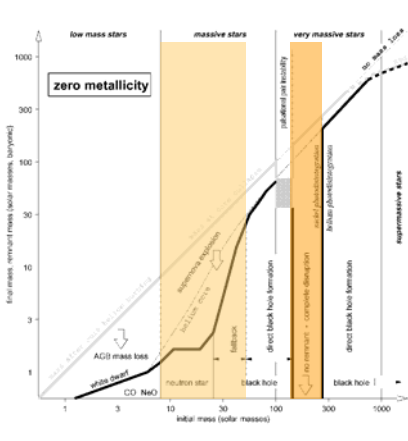
$z=5$

$z=3$

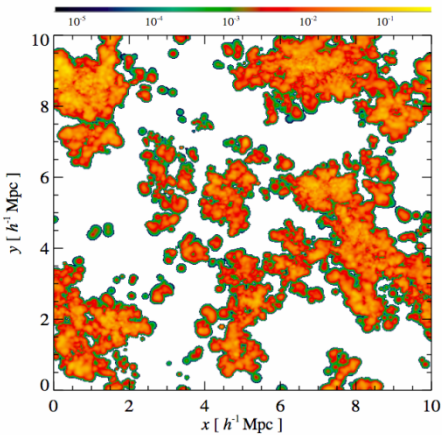


Tornatore, Schneider & Ferrara 2007

# Chemical feedback: missing ingredients



IMF of the first stars  $\rightarrow$  abundance of



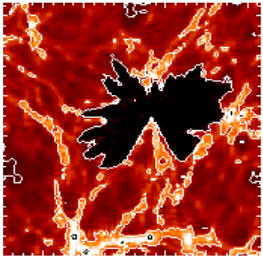
efficiency of metal enrichment  $\rightarrow$  loca

An open notebook with a dark cover and a light-colored tassel at the bottom center. The left page contains text, while the right page is blank. The text is in a simple, black, sans-serif font.

## Chapter 3

### Radiative feedback

Ionization/dissociation of  
atoms/molecules & heating



# Radiative feedback

Haiman, Rees & Loeb 1997

Ciardi, Ferrara & Abel 2000

Ciardi et al 2000

Haiman, Abel & Rees 2000

Susa & Kitayama 2000

Haiman, Abel & Madau 2001

Kitayama et al 2000, 2001

Machacek, Bryan & Abel 2001

Ricotti, Gnedin & Shull 2002

Yoshida et al 2003

Dijkstra et al 2004

Shapiro, Iliev & Raga 2004

Susa & Umemura 2004

Alvarez, Bromm & Shapiro 2006

Ahn & Shapiro 2007

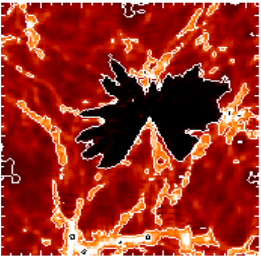
Ciardi & Salvaterra 2007

Johnson, Greif & Bromm 2008

McGreer & Bryan 2008

Mesinger & Dijkstra 2008

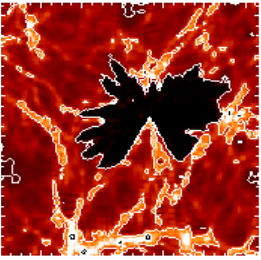
Whalen et al. 2008



## Radiative feedback: ionization/dissociation

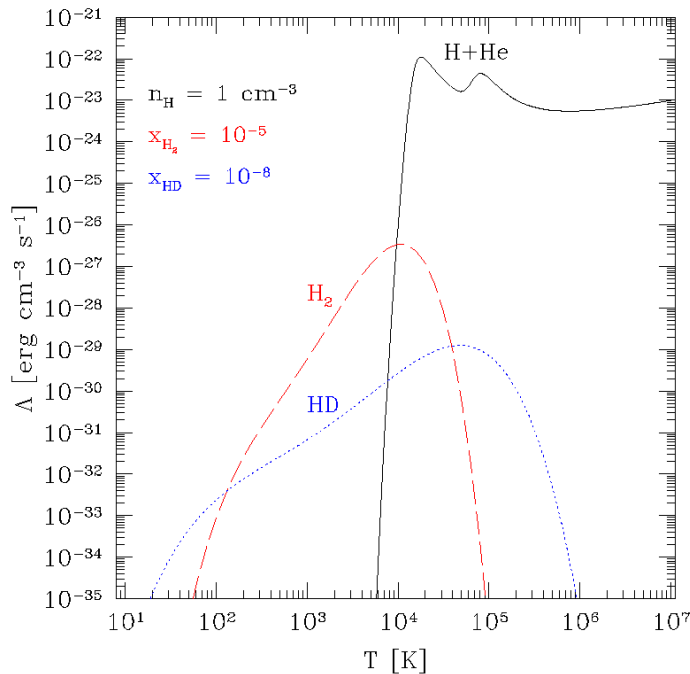
The minimum mass of objects in the  $M_{\text{min}} \approx 10^{-5} M_{\odot}$  in the absence of

In the presence of UV/SUV radiation,  $M_{\text{min}}$  increases, objects do not  
 and collapse, but the star formation can be delayed.  
 radiation intensity, mass and evolutionary stage

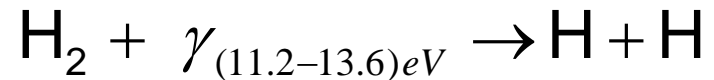


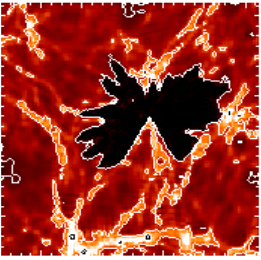
# Radiative feedback: ionization/dissociation

The minimum mass of objects in the halo  $M_{\text{min}} \approx 10^5 M_{\odot}$  in the absence of



- $T > 10000 \text{ K}$  halo formation relies on Ly $\alpha$  feedback
- $T < 10000 \text{ K}$  halo formation relies on Ly $\alpha$  feedback
- $\text{H}_2$  easily dissociated by Ly $\alpha$  feedback





# Radiative feedback: ionization/dissociation

Once the first generation of stars has formed in an object, it can affect the subsequent SF process by

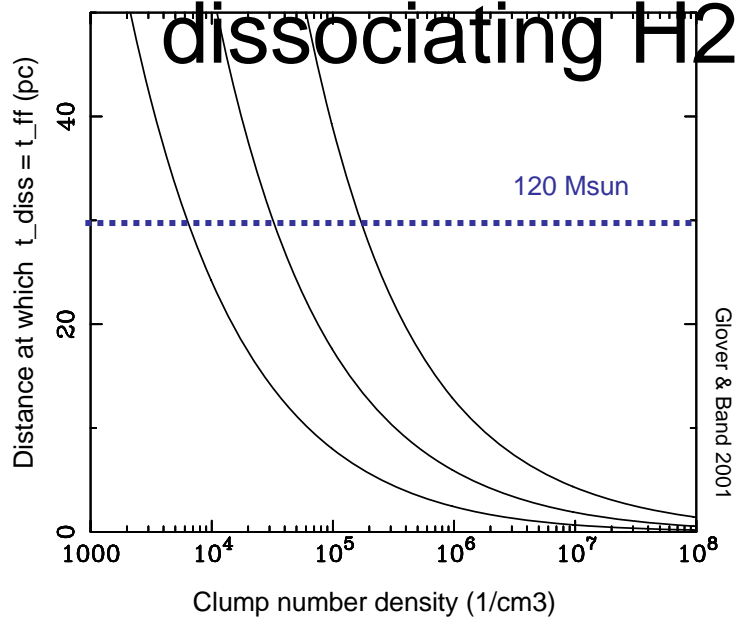
dissociating H<sub>2</sub> in star forming clouds.

- If massive star produces enough photons to dissociate the entire host halo

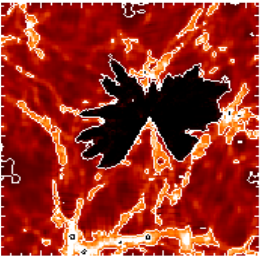
Omukai & Nishi 1999; Nishi & Tashiro 2000

- If star forming clumps are dense enough from the star, SF proceeds

Glover & Band 2001; Susa & Umemura 2006

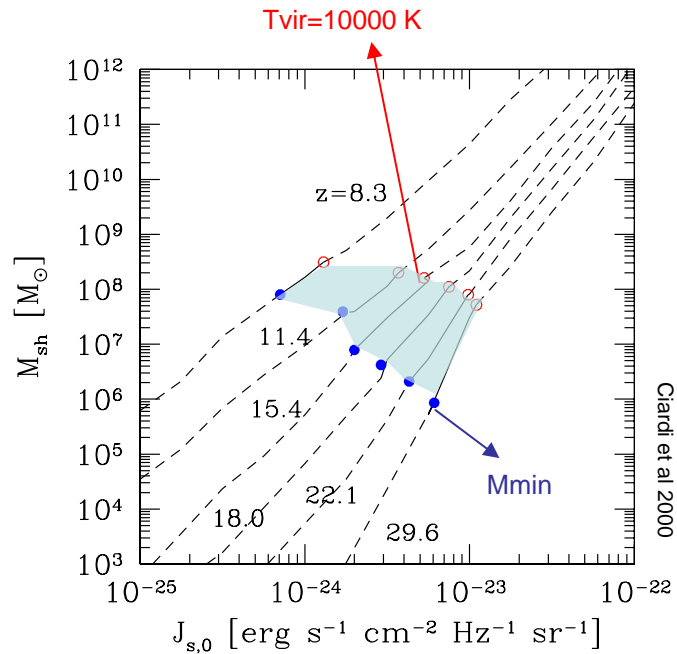


$$r_{\text{vir}} (M = 10^6 M_{\text{sun}}; z = 30) \sim 100 \text{pc}$$

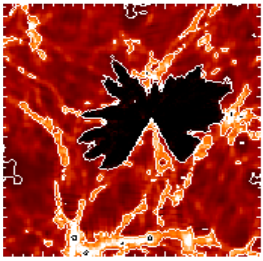


# Radiative feedback: ionization/dissociation

Ability of a halo to self-shield against an external



- Range affected by feedback

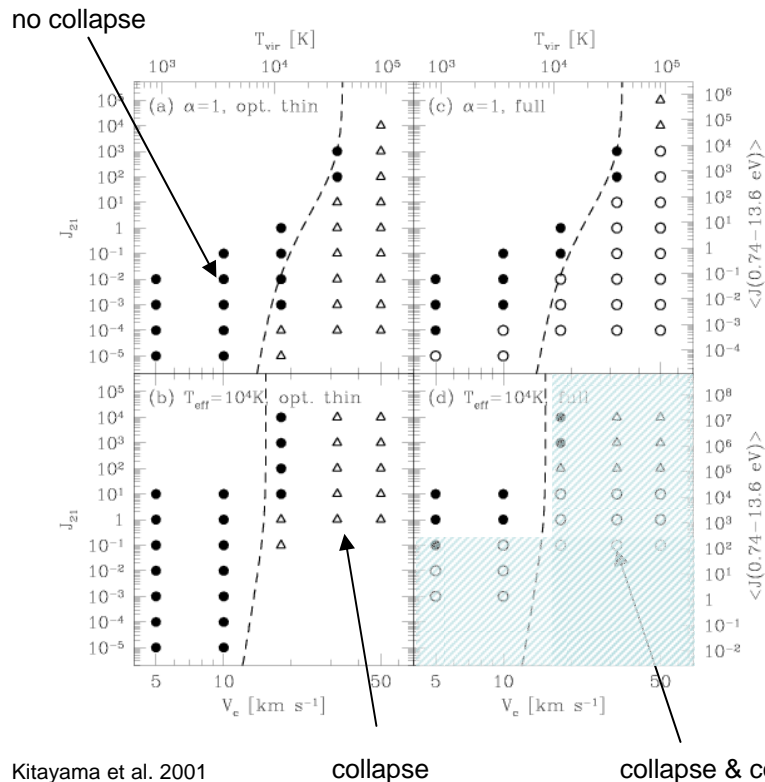


# Radiative feedback: ionization/dissociation

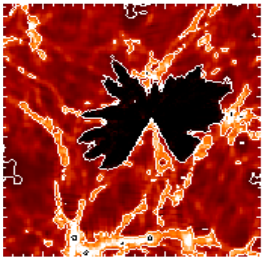
## 1D and 3D simulations of collapse of single halo

Susa, Kitayama, Umemura et al

$z \sim 10$

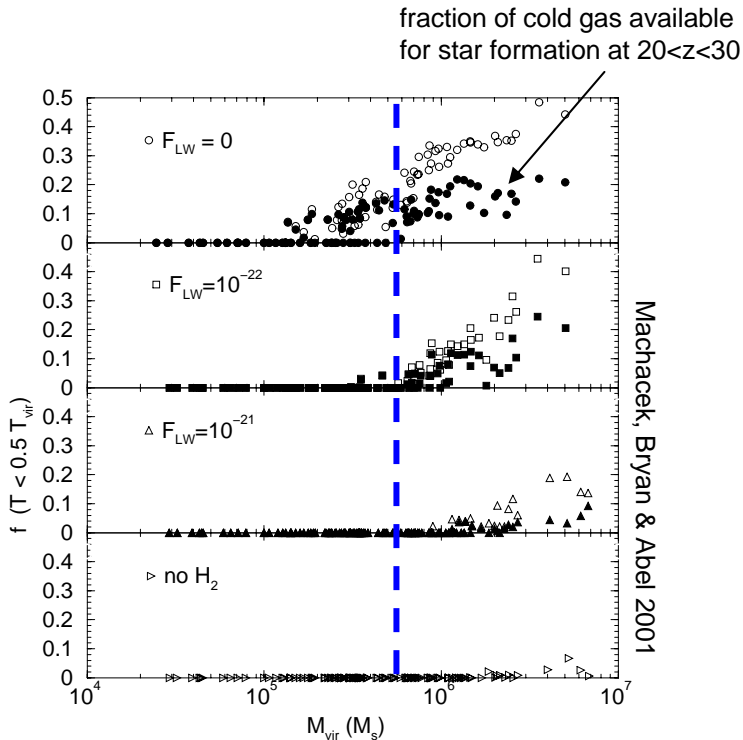


- If  $J < 10^{22}$  halos with  $10^6 M_{\text{SU}}$
- If  $M > 10^8 M_{\text{SU}}$  objects collapse
- Otherwise the fate depends on

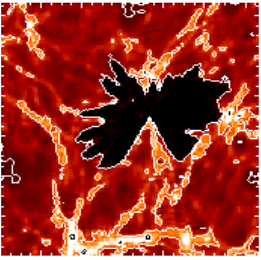


# Radiative feedback: ionization/dissociation

## Cosmological simulations + SUVB to study the feedback

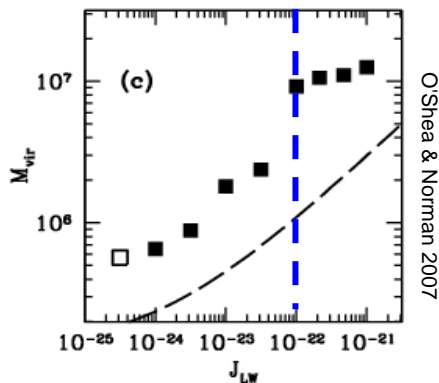
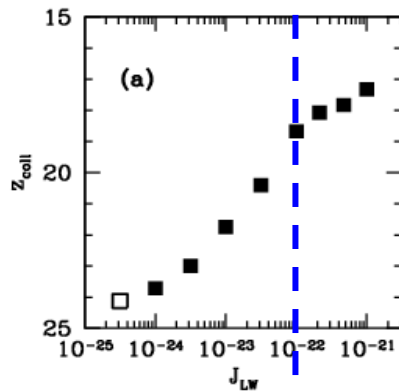


- Collapse and cooling delays
- The amount of cold gas depends on the Lyman-Werner flux
- Objects with few  $10^5 M_{\text{su}}$  can form stars if  $J < 10^{22}$

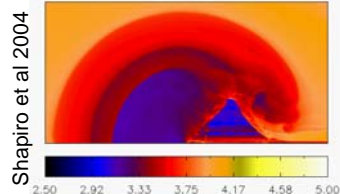


# Radiative feedback: ionization/dissociation

Cosmological simulations + SUVB to study the feedback

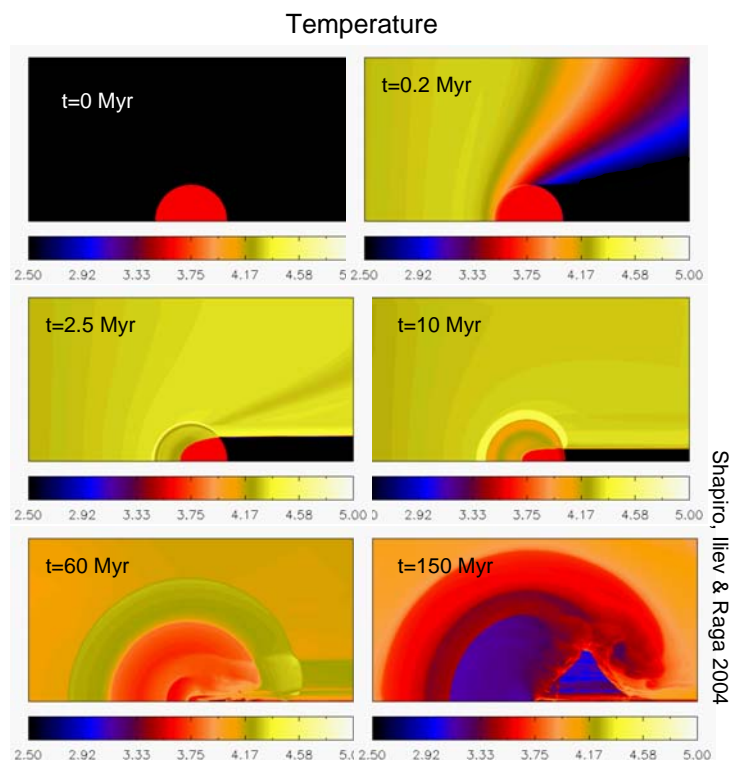


- Collapse and cooling delayed
- The amount of cold gas depends on  $J$
- Objects with few  $10^5 M_{\text{su}}$  can collapse if  $J < 10^{-22}$
- Objects with few  $10^5 M_{\text{su}}$  cannot collapse if  $J > 10^{-22}$



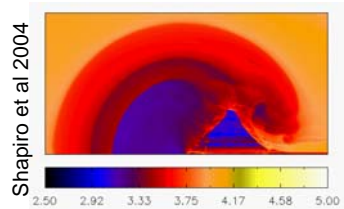
# Radiative feedback: photoevaporation

Small mass halos can be photoevaporated by radiation



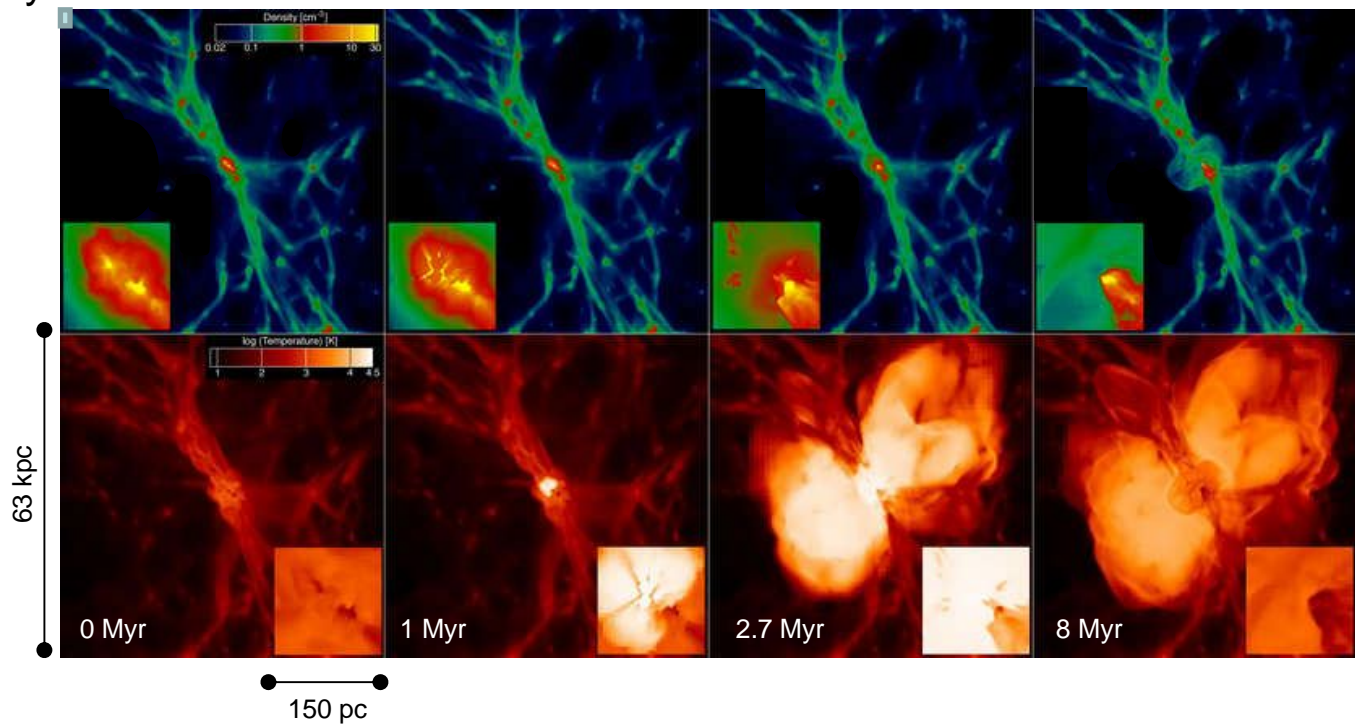
- The degree of photoevaporation depends on the evolutionary stage of the protostar
- The time scale for complete photoevaporation is generally larger than a million years
- Minihalos can survive photoevaporation

Alvarez, Bromm & Shapiro 2006; Abel, Wise & Bryan 2007; Ahn & Shapiro 2007; Yoshida et al. 2007; Whalen et al. 2008

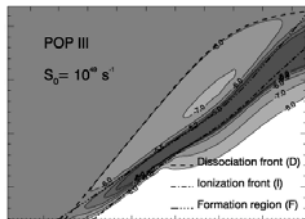


# Radiative feedback: photo-ion./-diss./-eva

Density



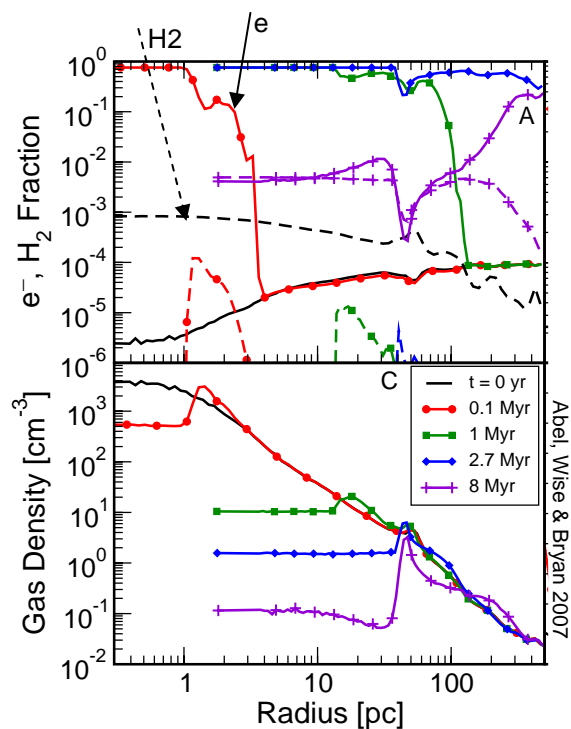
Temperature



# Radiative feedback: positive feedback

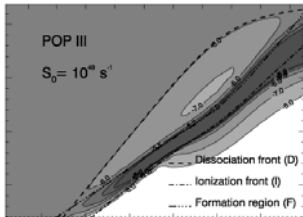
Molecules can re-form e.g. inside relic HII regions

Ricotti, Gnedin & Shull 2001; Nagakura & Omukai 2005; O'Shea et al 2005;  
 Abel, Wise & Bryan 2007; Mashchenko, Couchman & Sills 2006; Yoshida et al 2007;  
 Johnson, Greif & Bromm 2008; McGreer & bryan 2008

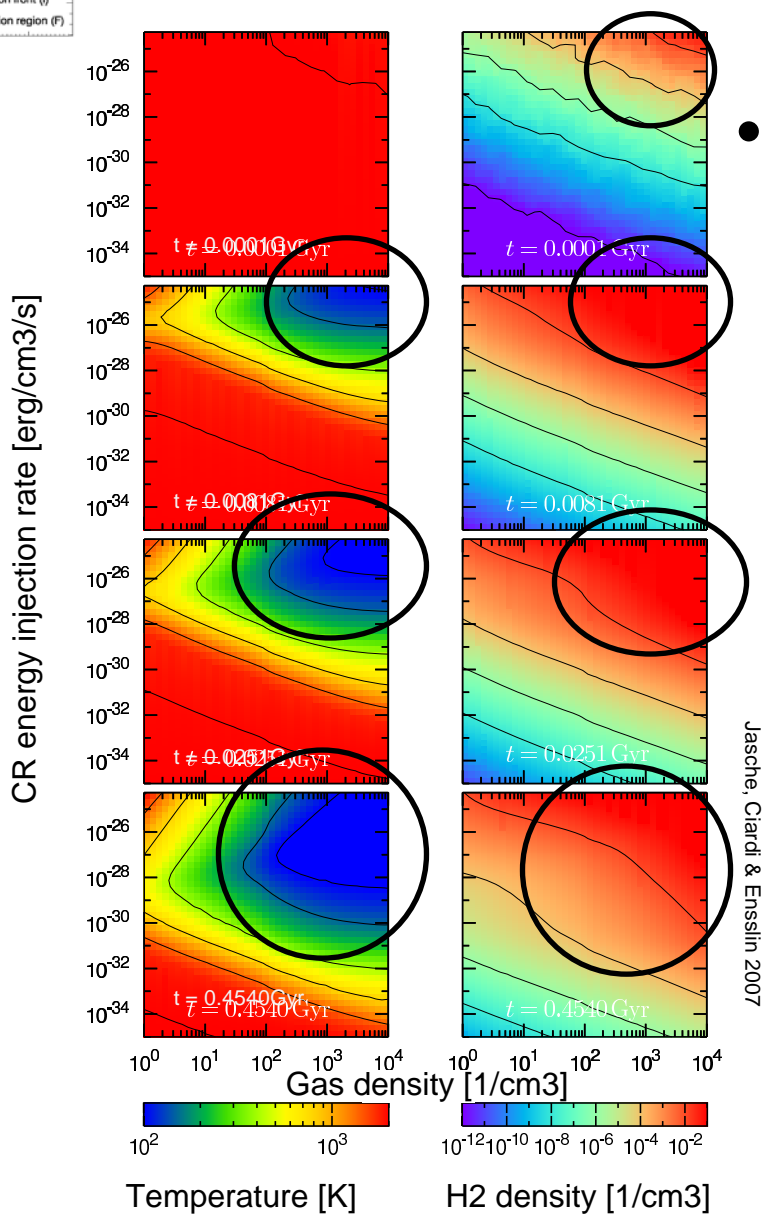


- $H_2$  is efficiently re-formed in relic HII regions
- HD is formed and lowers  $T_{\text{evap}}$  even further  
Nagakura & Omukai 2005; Johnson & Bromm 2006; Yoshida et al 2007; McGreer & Brian 2008
- Typically the mass of these second generation stars is smaller  
see also Yoshida, Omukai & Hernquist 2007
- Molecules formation promoted by x-rays or cosmic rays

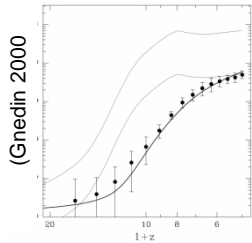
Shchekinov & Vasiliev 2004; Kuhlen & Madau 2005; Jasche, Ciardi & Ensslin 2007; Stacy & Bromm 2007;  
 Ripamonti, Mapelli & Zaroubi 2008



# Radiative feedback: positive feedback



- For given  $\dot{\epsilon}_{CR}$ ,  $n_{gas}$  and  $H_2$  is promoted and T drops



# Radiative feedback: photoheating

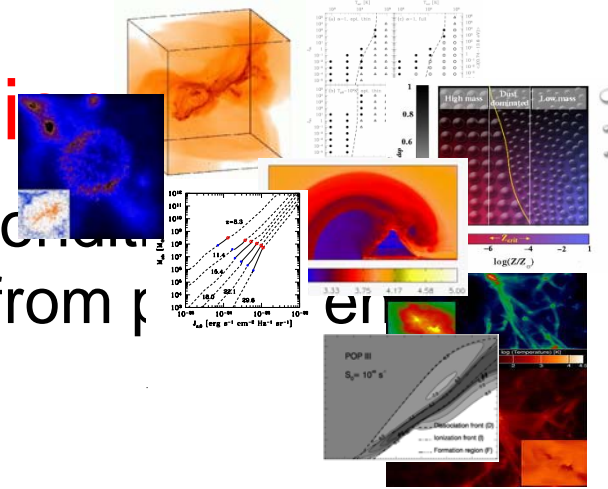
- Relic HII regions have an entropy floor that prevents cooling in subsequent generations of small halos

Oh & Haiman 2003; Kramer, Haiman & Oh 2006

- Heating associated with photoionization and Ly $\alpha$  forest transmission leads to a suppression of the fraction of gas in small masses

e.g. Gnedin 2000; Ciardi & Salvaterra 2007

# Conclusions



- 1. Feedback depends on the specific local conditions
- 2. Feedback is not as efficient as expected from previous estimates



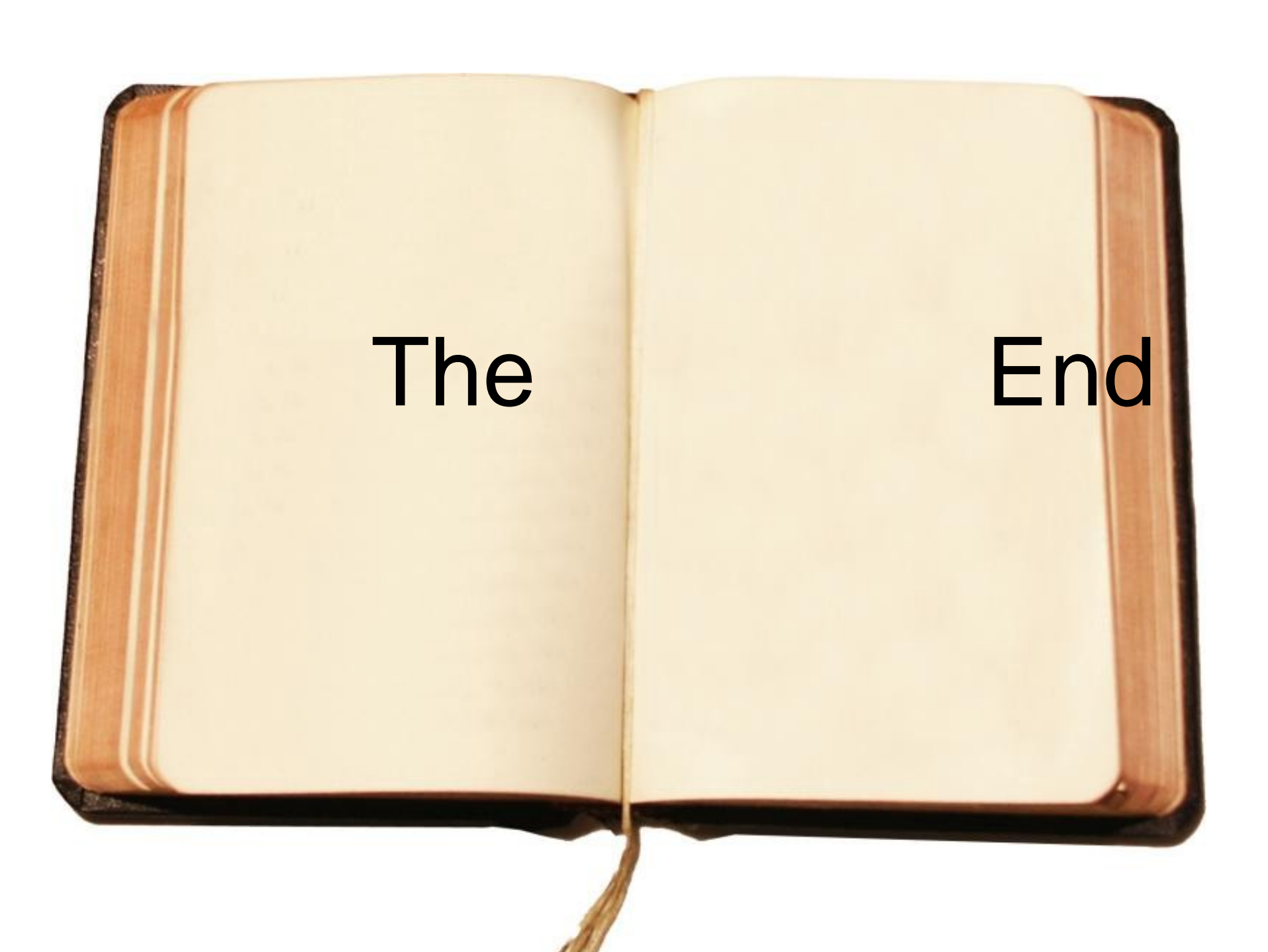
- 3. Star forming regions further than few tens of pc not affected by its radiation

- 4. Its UV radiation delays and limit the collapse of cold gas in nearby objects

- 5. Photoevaporation of nearby minihalos seems to be inefficient
- 6. Formation of H2 and HD in relic HII regions promote structure

PISNe formation

- 7. The host halo is completely disrupted if  $M_{rem} < 10^6 M_{\odot}$
- 8. After explosion gas in shells can fragment and form stars
- 9. Metals/dust are expelled and induce a transition to standard SF

An open book with two blank, cream-colored pages. The book has a dark brown cover and a tassel hanging from the bottom center. The text "The End" is overlaid on the pages in a large, black, sans-serif font.

**The**

**End**