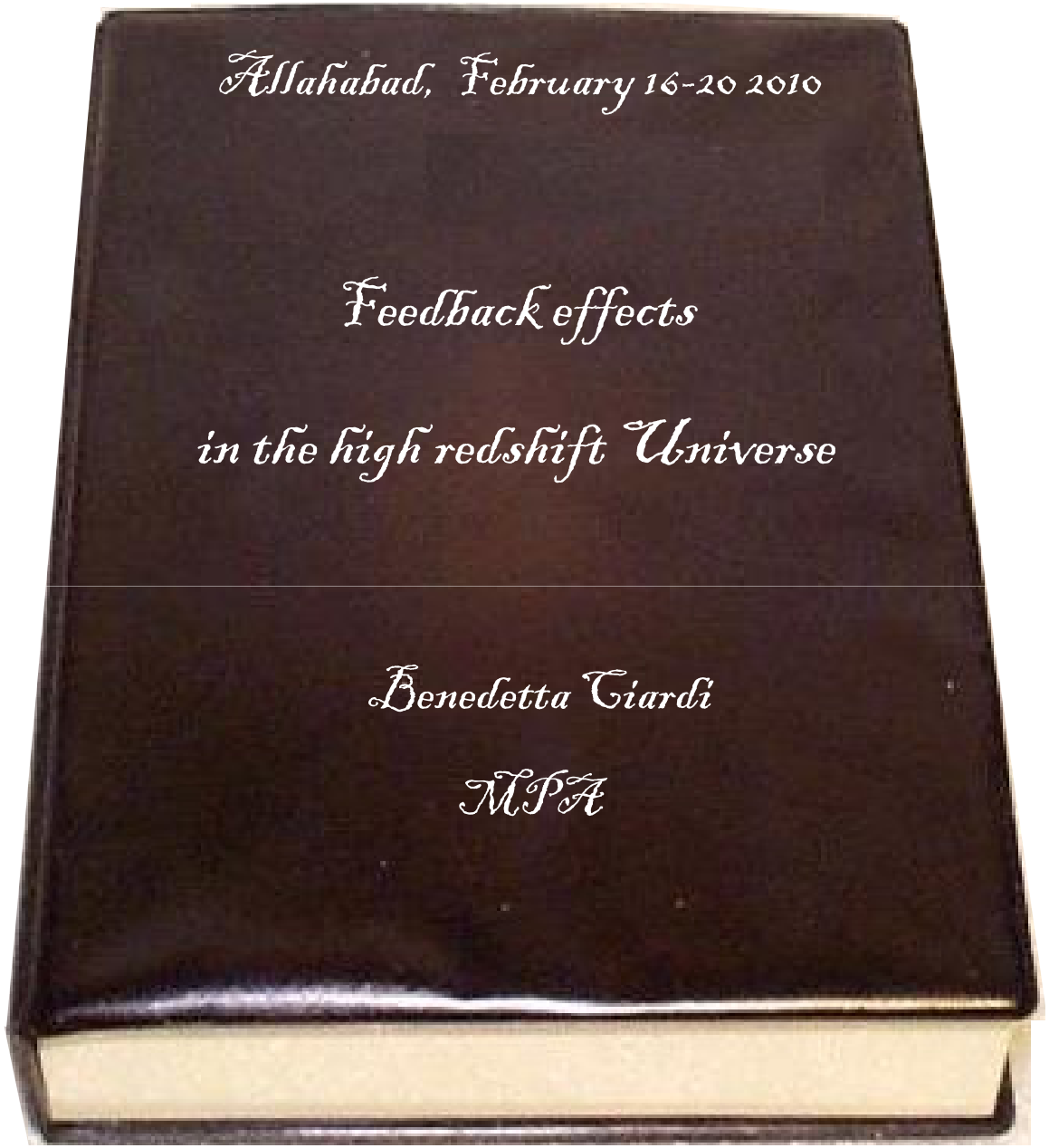
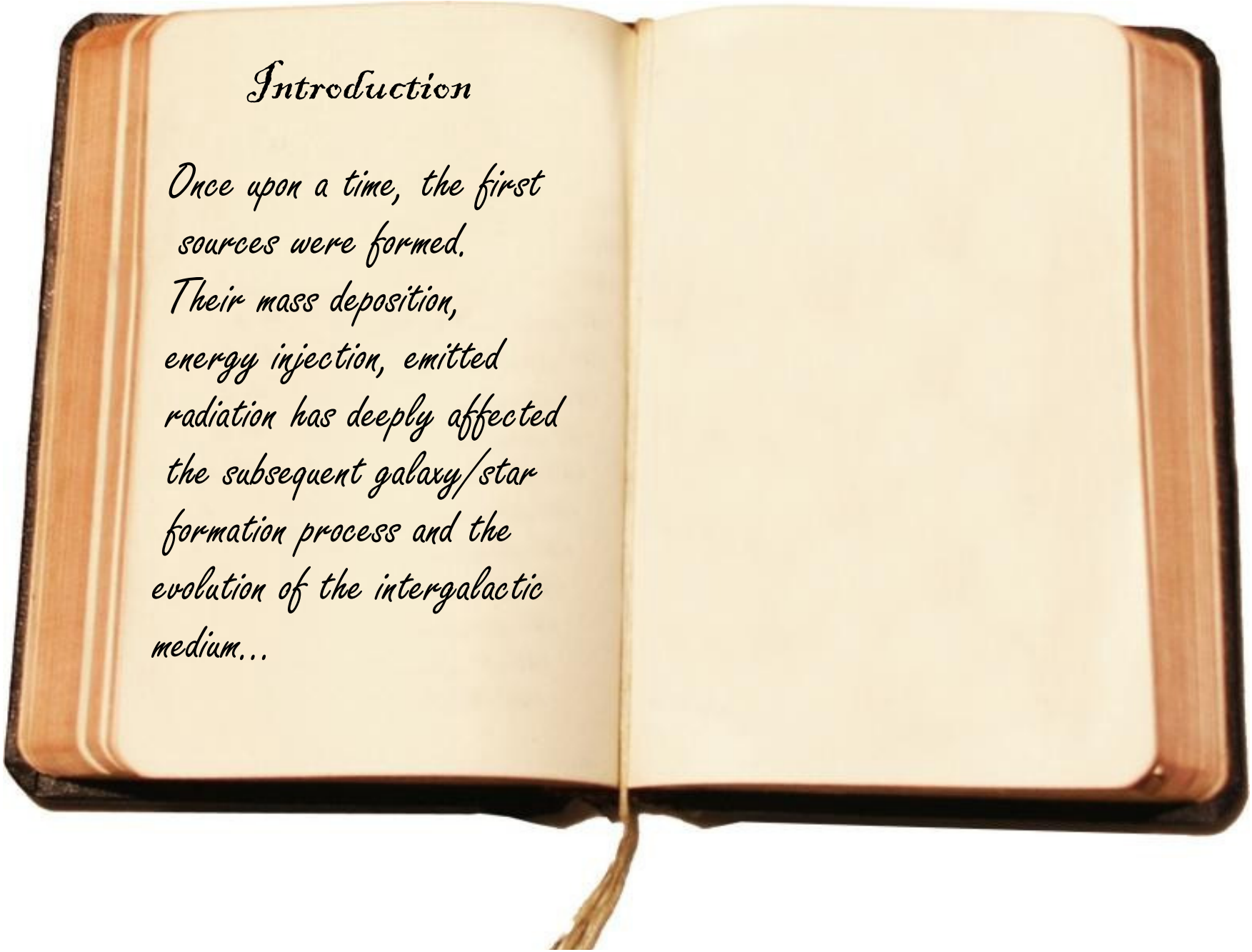
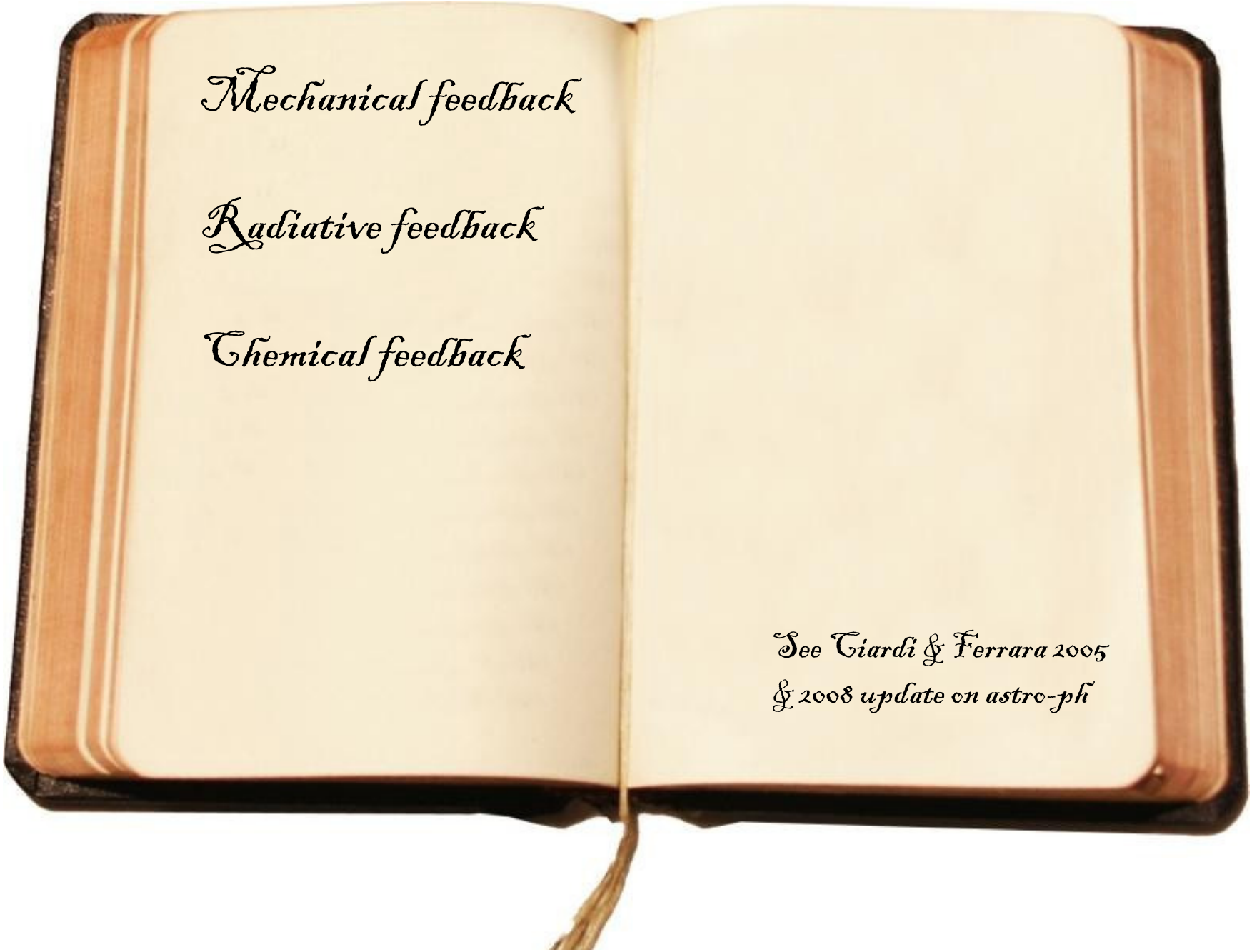
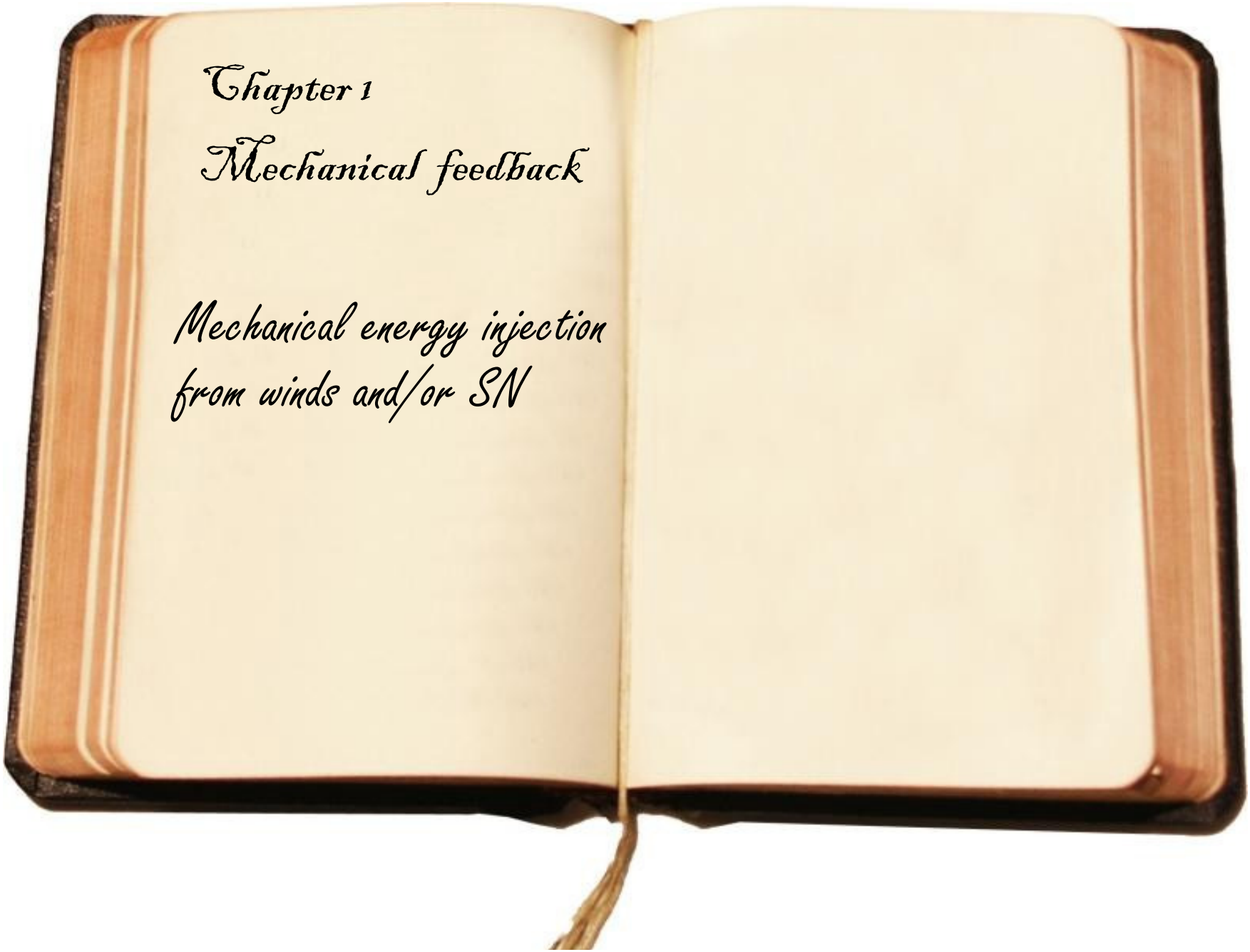
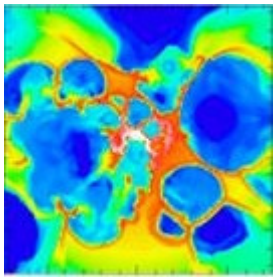

Allahabad, February 16-20 2010
Feedback effects
in the high redshift Universe
Benedetta Ciardi
MPA


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 evolution of the intergalactic medium...


Mechanical feedback
Radiative feedback
Chemical feedback
See Ciardi & Ferrara 2005
& 2008 update on astro-ph


Chapter 1
Mechanical feedback
Mechanical energy injection
from winds and/or SN



Mori, Ferrara & Madau 2002

Mechanical feedback

Ferrara 1998

Mac Low & Ferrara 1999

Nishi & Susa 1999

Tsujimoto, Shigeyama & Yoshii 1999

Ciardi et al. 2000

Scannapieco, Ferrara & Broadhurst 2000

Mori, Ferrara & Madau 2002

Bromm, Yoshida & Hernquist 2003

Machey, Bromm & Hernquist 2003

Wada & Venkatesan 2003

Salvaterra, Ferrara & Schneider 2003

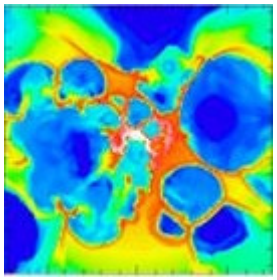
Kitayama & Yoshida 2005

Sigward, Ferrara & Scannapieco 2005

Greif et al 2007

Pawlik & Schaye 2009

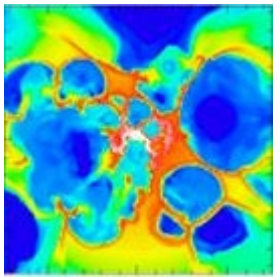
Wang et al 2009



Mori, Ferrara & Madau 2002

Mechanical feedback: depletion of gas reservoir

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

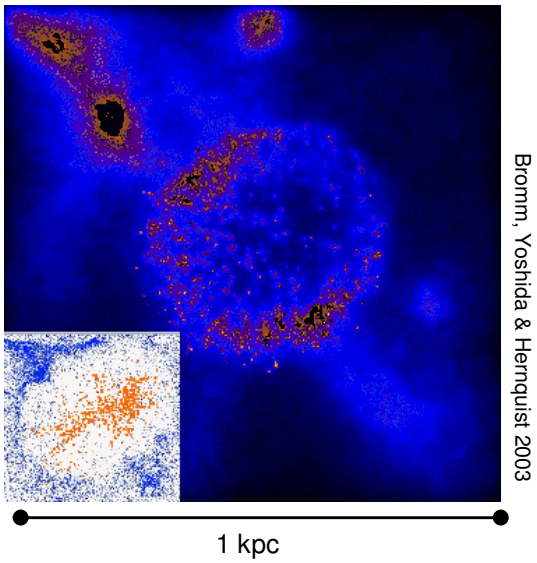


Mori, Ferrara & Madau 2002

Mechanical feedback: depletion of gas reservoir

Cosmological simulation + zoom on SN explosion in a 10^6 Msun halo at z=20

Gas distribution 10^6 yr after explosion with 10^{53} ergs



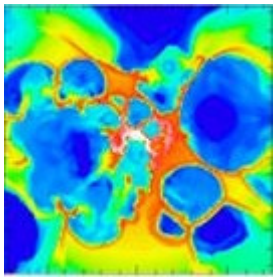
Bromm, Yoshida & Hernquist 2003

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

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

Greif et al 2007

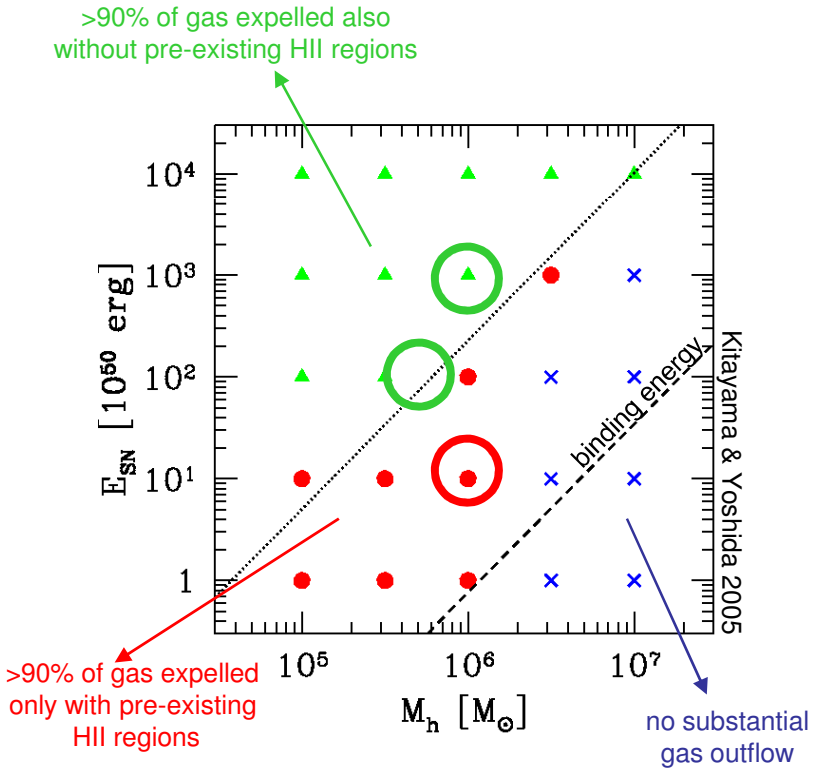
$$E_{SN} = 10^{53}\ \text{ergs}\ (M_* = 250 M_{sun}) \Rightarrow \text{disruption}$$

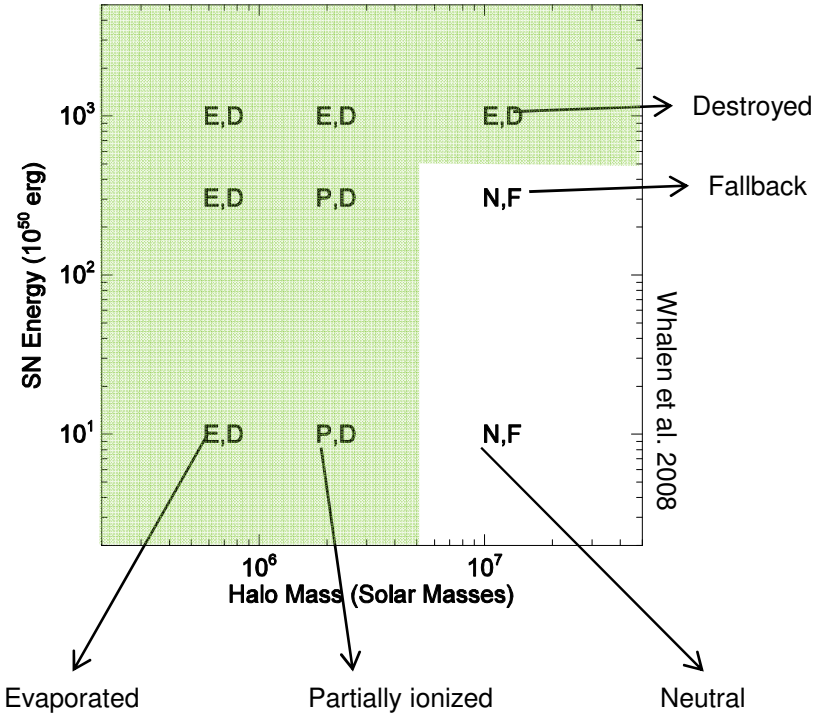


Mori, Ferrara & Madau 2002

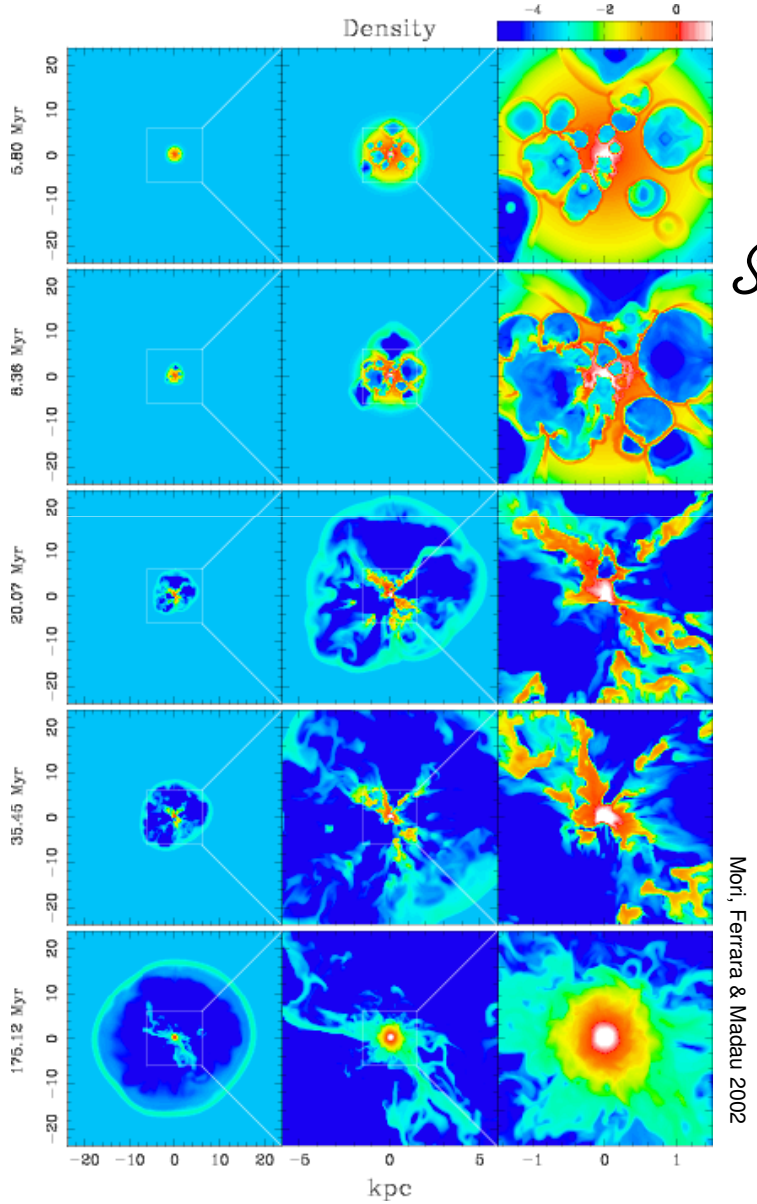
Mechanical feedback: depletion of gas reservoir

Parametric study of SN explosions





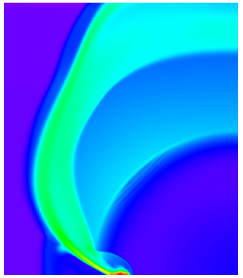
Mechanical feedback: depletion of gas reservoir



Mori, Ferrara & Madau 2002

SN explosions in M=10^8 Msun halo at z=9

Off-center SN explosions drive inward propagating shocks that promote a second SF episode in the center



MacLow & Ferrara 1998

Mechanical feedback: SF induced by shocks

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

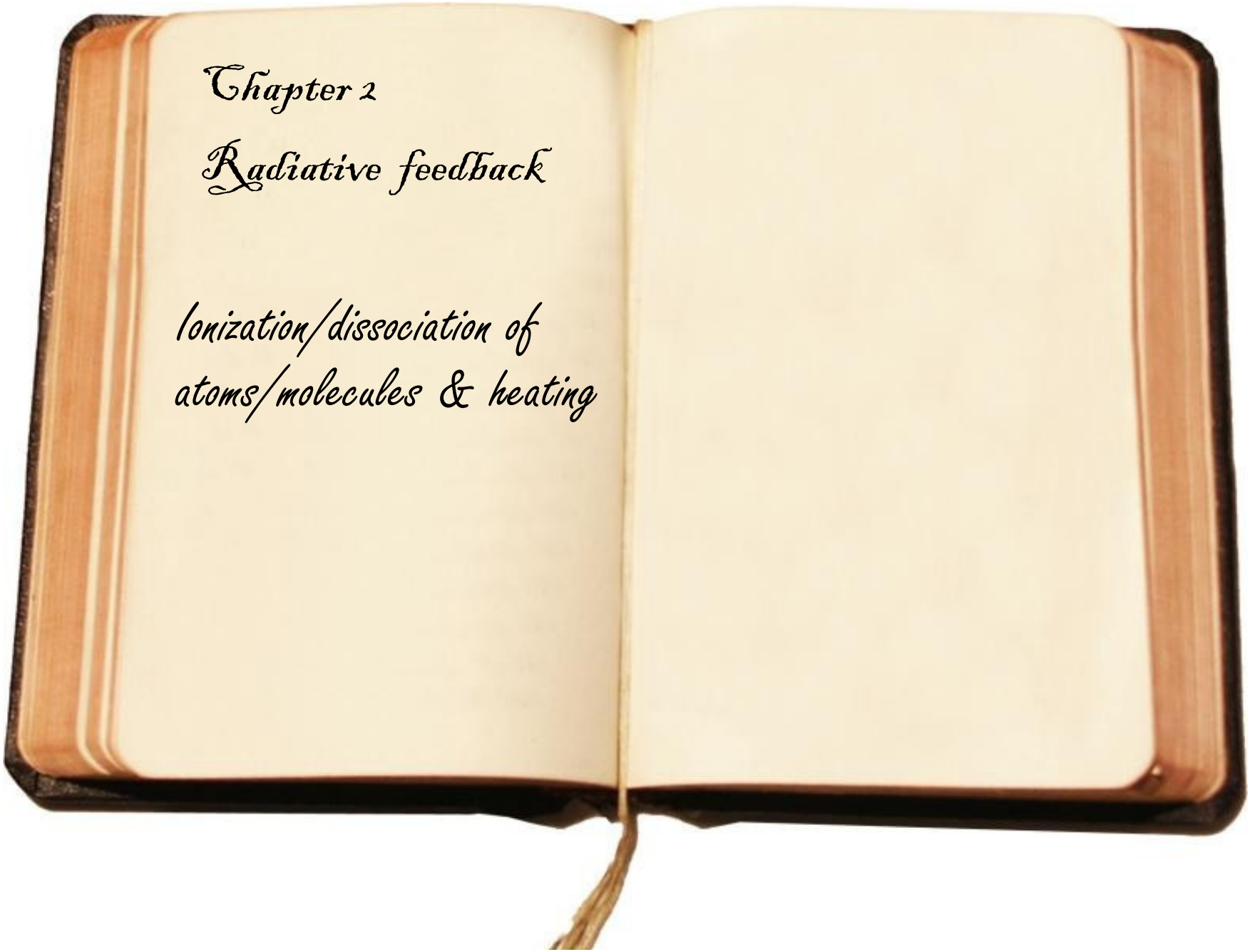
- The dense shell can fragment and form stars

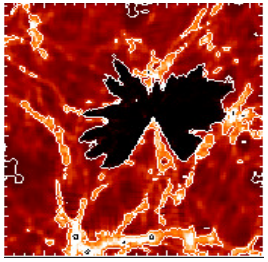
Mackey, Bromm & Hernquist 2003; Salvaterra, Ferrara & Schneider 2004

- HD formation is promoted and favour fragmentation

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

2^{nd} generation stars are smaller than 1^{st} generation $\Longrightarrow$
low - metallicity, low - mass stars


Chapter 2
Radiative feedback
Ionization/dissociation of
atoms/molecules & heating



Ciardi et al 2001

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

Mesinger, Bryan & Haiman 2006

Ahn & Shapiro 2007

Ciardi & Salvaterra 2007

Johnson, Greif & Bromm 2008

McGreer & Bryan 2008

Mesinger & Dijkstra 2008

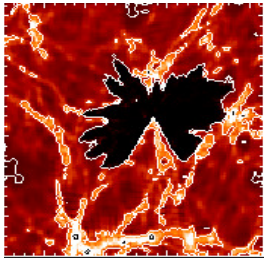
Whalen et al. 2008

Hasegawa, Umemura & Susa 2009

Mesinger, Bryan & Haiman 2009

Pawlik & Schaye 2009

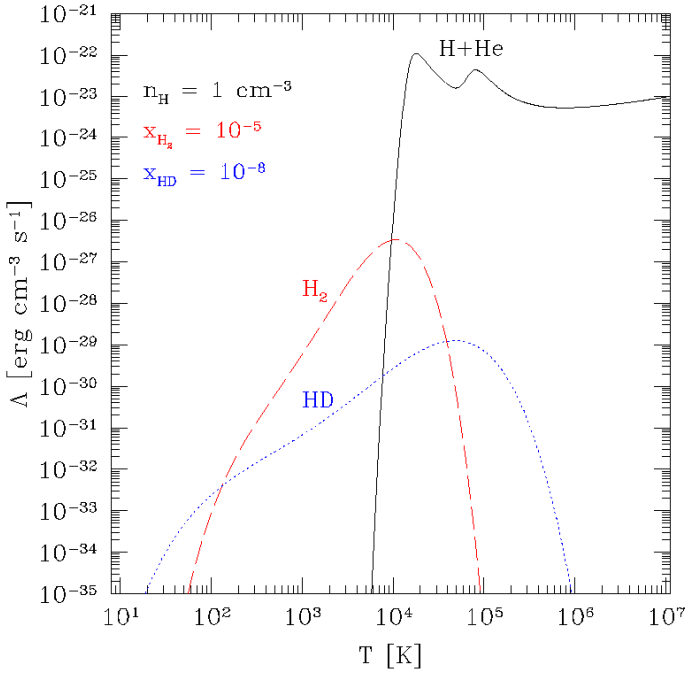
Wang et al 2009



Ciardi et al 2001

Radiative feedback: ionization/dissociation of H/H2

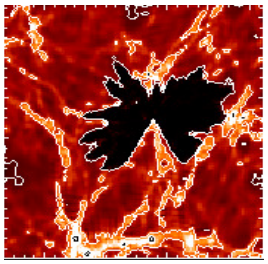
The minimum mass of objects in the absence of feedback is $M_{min} \approx 10^5 M_{sun}$



Maio et al. 2008

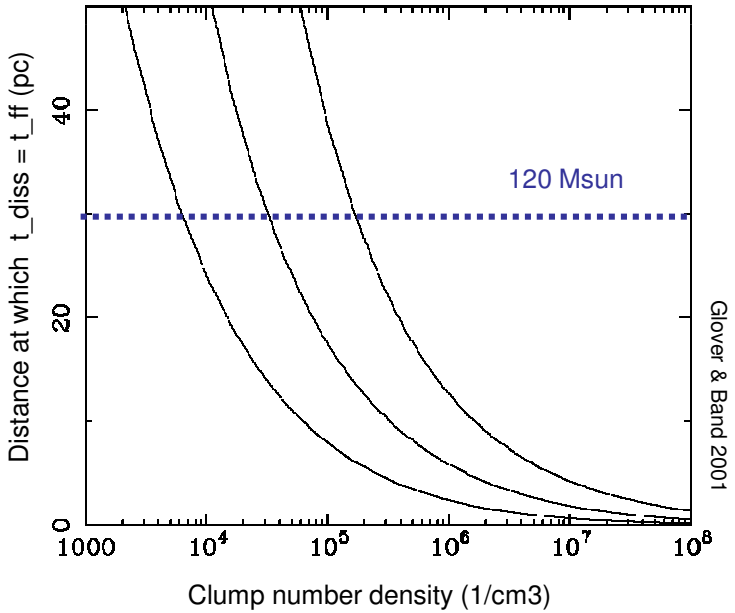
- T>10000K halo formation relies on H cooling
- T<10000K halo formation relies on H2 cooling
- H2 easily dissociated by Lyman-Werner photons:

$$H_2 + \gamma_{(11.2-13.6)eV} \rightarrow H + H$$


Ciardi et al 2001

Radiative feedback: ionization/dissociation of H/H2

Once the first generation of stars has formed in an object, it can affect the subsequent SF process by dissociating H2 in star forming clouds.



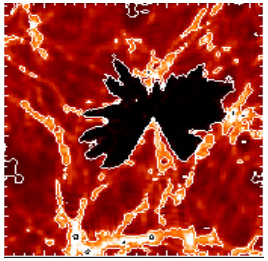
- 1 massive star produces enough radiation to dissociate the entire host halo

  Omukai & Nishi 1999; Nishi & Tashiro 2000

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

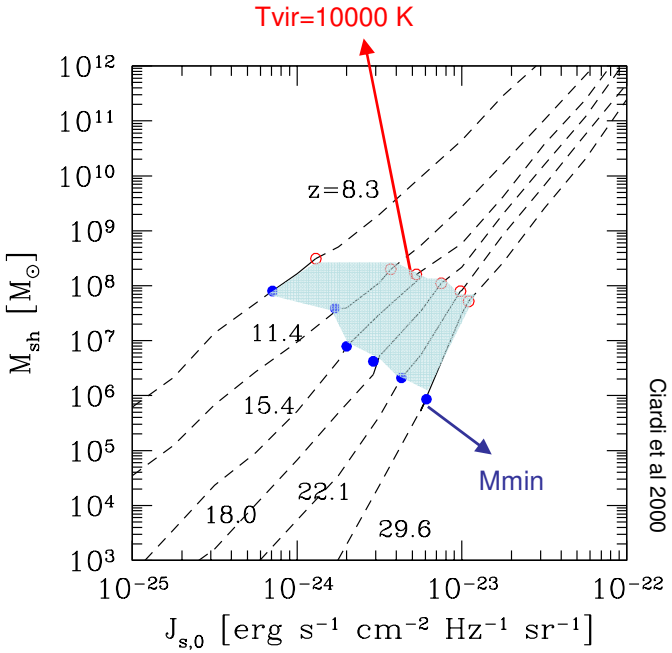
  Glover & Band 2001; Susa & Umemura 2006; Hasegawa, Umemura & Susa 2009

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

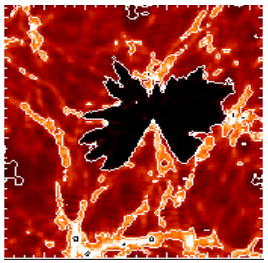


Radiative feedback: ionization/dissociation of H/H_2

Ability of a halo to self-shield against an external UV/SUV radiation



- Range affected by feedback is the shaded



Ciardi et al 2001

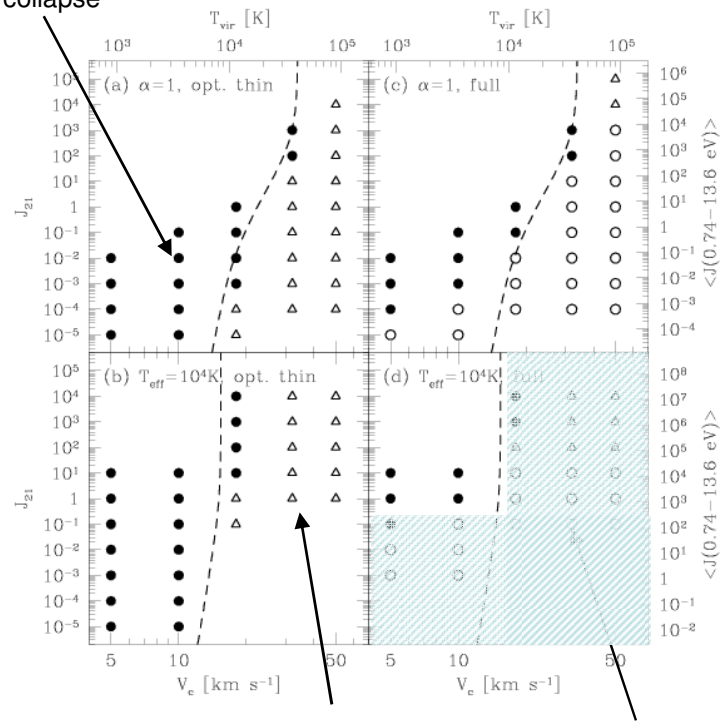
Radiative feedback: ionization/dissociation of H/H_2

1D and 3D simulations of collapse of single halo in presence of radiation

Susa, Kitayama, Umemura et al

z ~ 10

no collapse

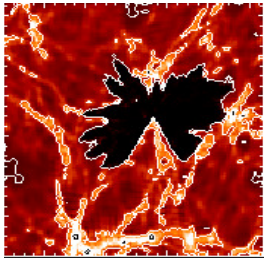


Kitayama et al. 2001

collapse

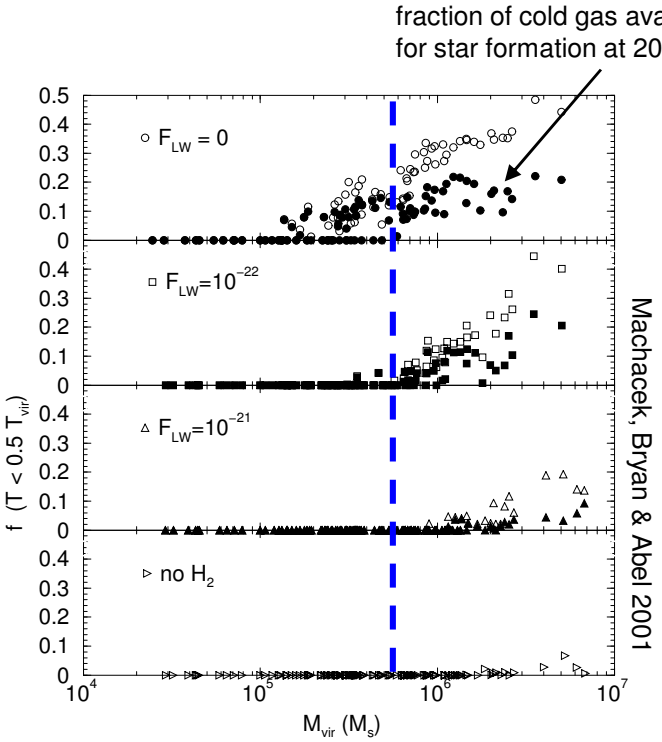
collapse & cooling

- If $J < 10^{-22}$ halos with $M > 10^6 M_{sun}$ form
- If $M > 10^8 M_{sun}$ objects collapse and cool
- Otherwise the fate depends on J, M, spectrum

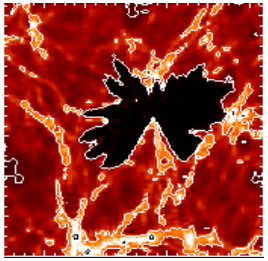


Radiative feedback: ionization/dissociation of H/H_2

Cosmological simulations + SUVB to study the fate of collapsing halos



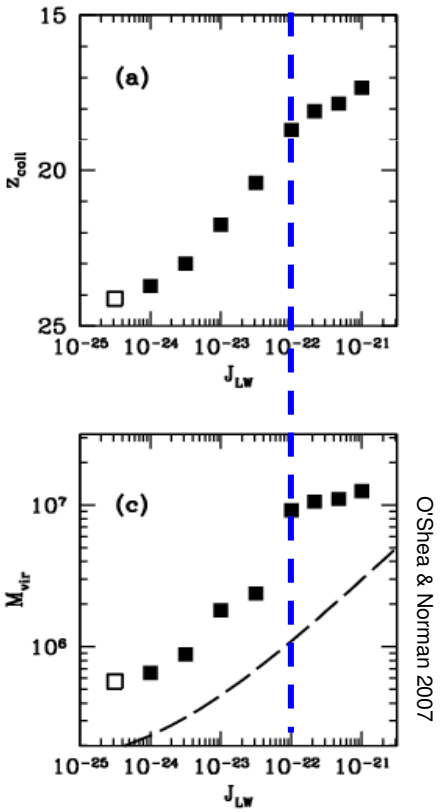
- Collapse and cooling delayed by radiation
- The amount of cold gas depends on J and M
- Objects with $M \approx \text{few} \cdot 10^5\ M_{sun}$ can form if $J < 10^{-22}$



Ciardi et al 2001

Radiative feedback: ionization/dissociation of H/H_2

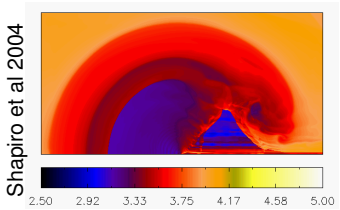
Cosmological simulations + SUVB to study the fate of collapsing halos



O'Shea & Norman 2007

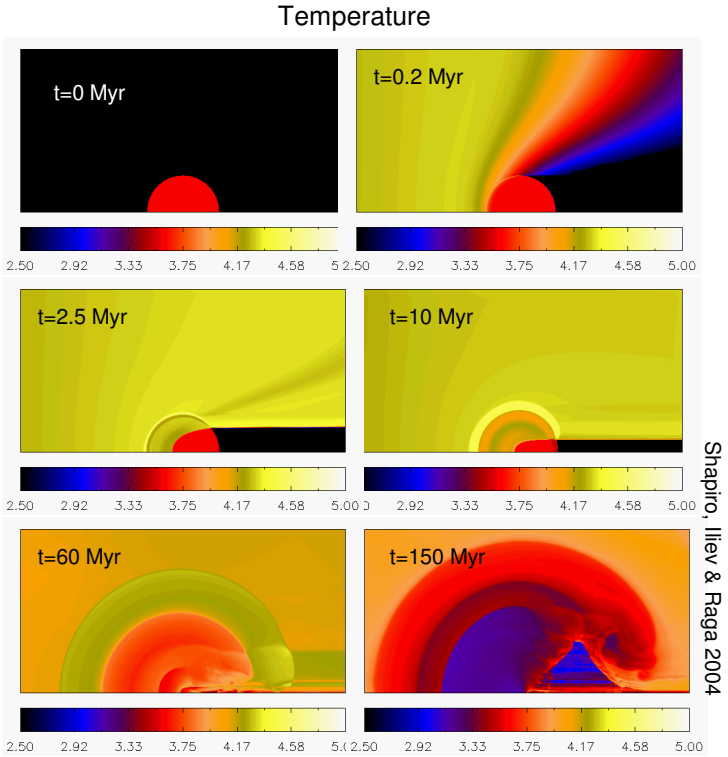
- Collapse and cooling delayed by radiation
- The amount of cold gas depends on J and M
- Objects with $M \approx \text{few} \cdot 10^5 M_{sun}$ can form if $J < 10^{-22}$
- Objects with $M \approx \text{few} \cdot 10^5 M_{sun}$ can form also if $J > 10^{-22}$
- Final fate depends on evolutionary state

Ahn & Shapiro 2007; Whalen et al. 2008



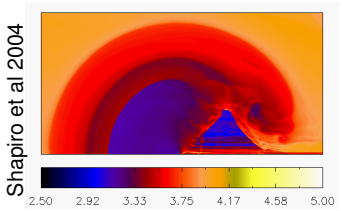
Radiative feedback: photoevaporation

Small mass halos can be photoevaporated by radiation from nearby obejcts



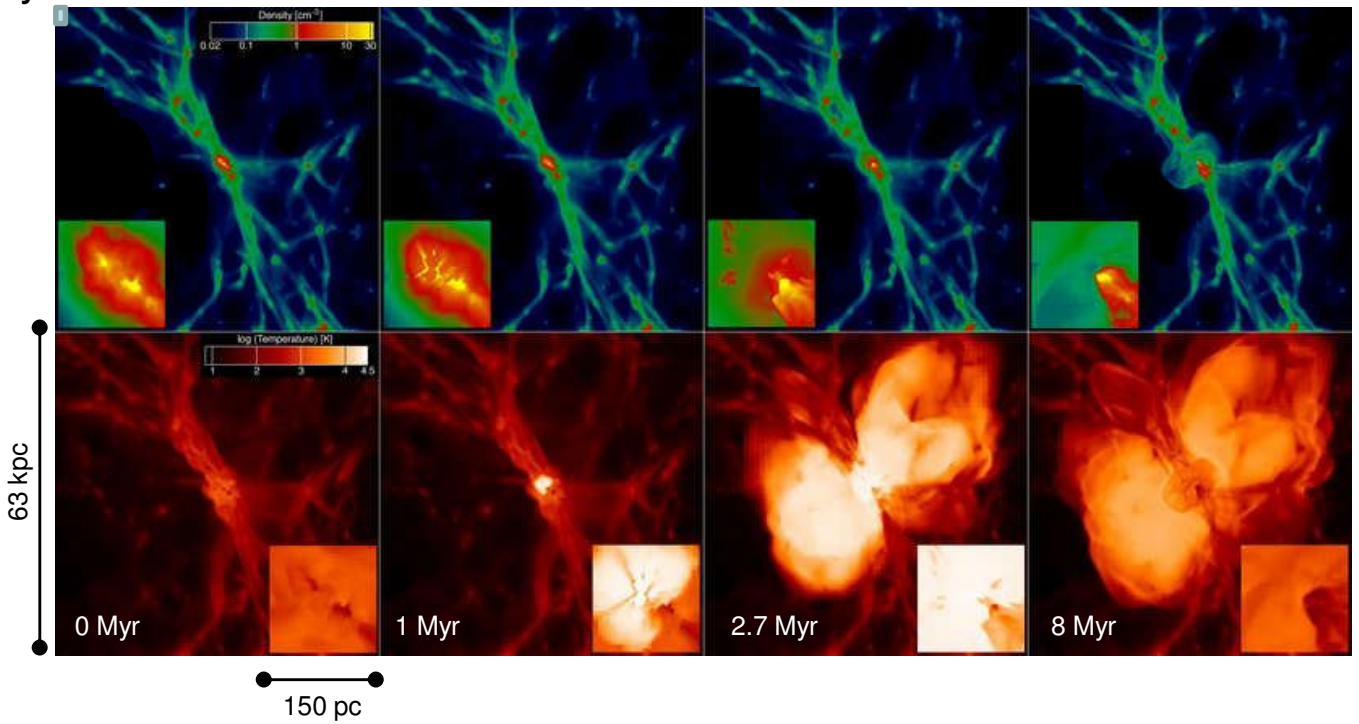
- The degree of photoevaporation depends on the evolutionary stage of halos
- The time scale for complete photoevaporation is generally larger than a massive star
- Minihalos can survive photoevaporation

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

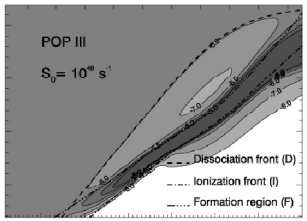


Radiative feedback: photo-ion./-diss./-evap.

Density



Temperature

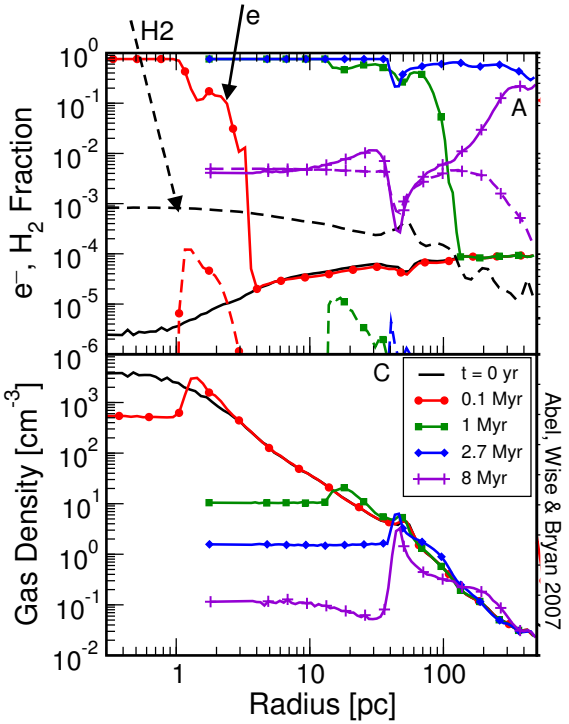


Ricotti et al 2001

Radiative feedback: positive feedback

Molecules can re-form e.g. inside relic HII regions and induce a new burst of SF

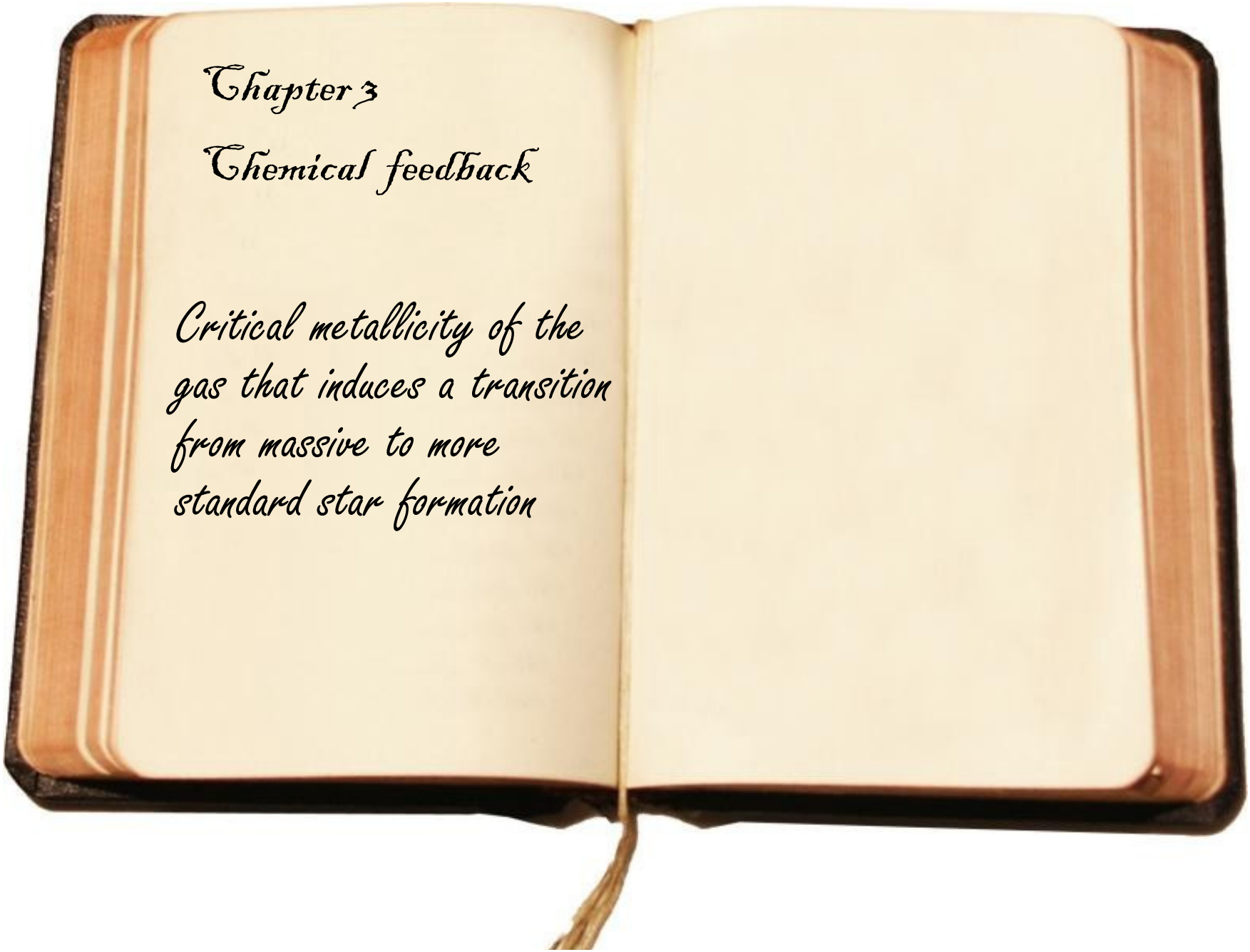
Ricotti, Gnedin & Shull 2001; Nagakura & Omukai 2005; O'Shea et al 2005;
Abel, Wise & Bryan 2007; Mashchenko, Couchman & Sills 2006; Yoshida et al 2007;
Johnson, Greif & Bromm 2008; McGreer & bryan 2008; Mesinger, Bryan & Haiman 2009

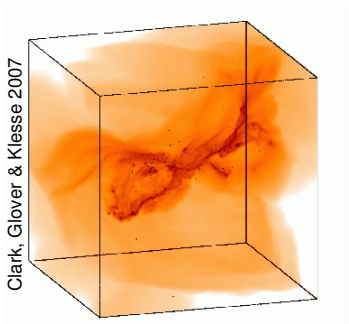


- H2 is efficiently re-formed in relic HII regions
- HD is formed and lowers T even more

  Nagakura & Omukai 2005; Johnson & Bromm 2006; Yoshida et al 2007; McGrer & Brian 2008
- Typically the mass of these second generation stars is smaller see also Yoshida, Omukai & Hernquist 2007
- Molecules formation promoted by presence of x-rays or cosmic rays

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


Chapter 3
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

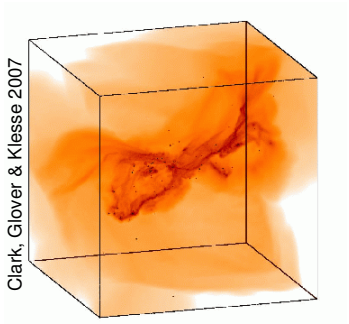
Clark, Glover & Klessen 2007

Smith & Sigurdsson 2007

Tornatore, Schneider & Ferrara 2007

Tsuribe & Omukai 2008

Maio et al 2010

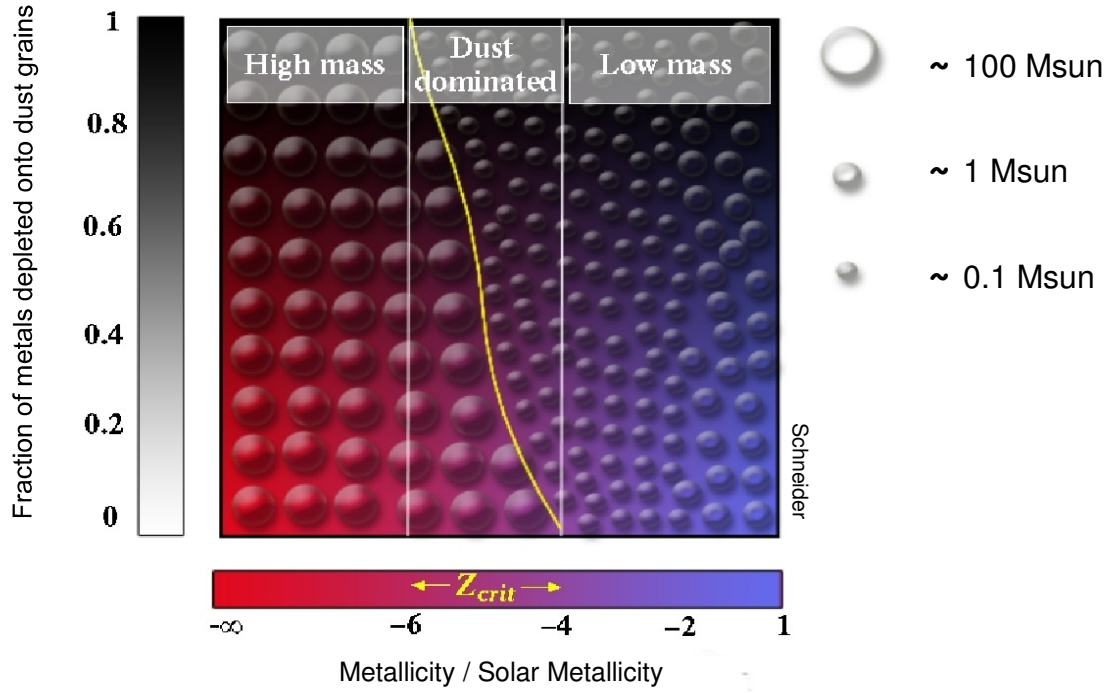


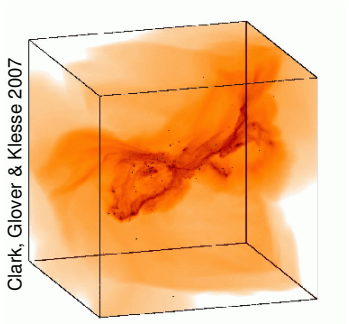
Chemical feedback: fragmentation of gas clouds

1D/3D simulations; cosmological IC or single clouds; rotating/non-rotating clouds

Chemistry: H, He, metals (Z + CII, OI, SiII, FeII) + H2 + D + dust

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





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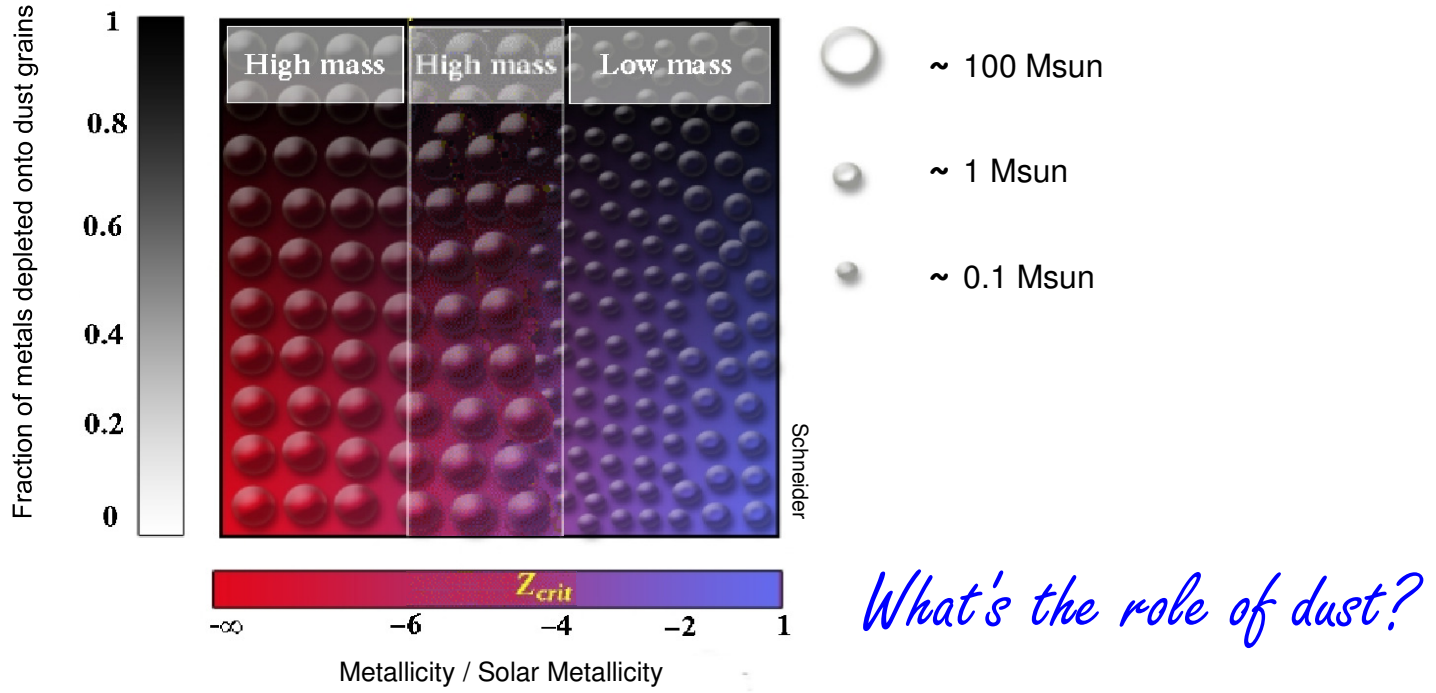
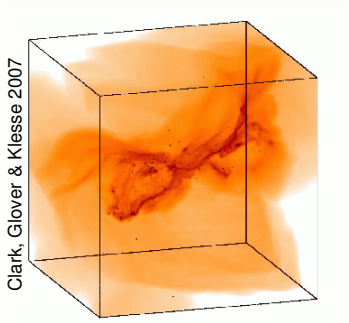
Bromm et al 2001
Bromm & Loeb 2003
Santoro & Shull 2006
Smith & Sigurdsson 2007



What's the role of dust?

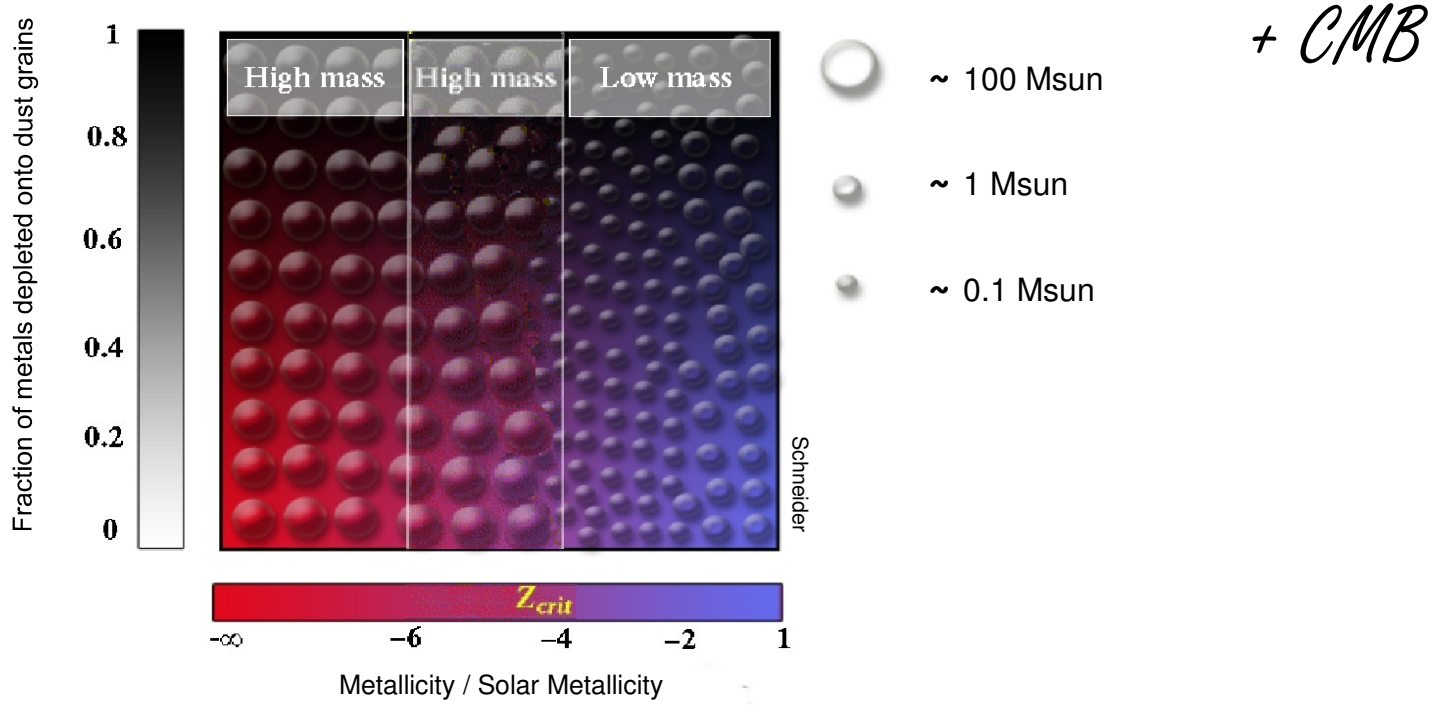


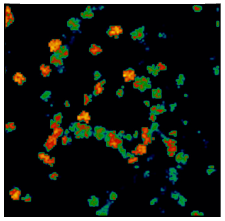
Chemical feedback: fragmentation of gas clouds

1D/3D simulations; cosmological IC or single clouds; rotating/non-rotating clouds

Chemistry: H, He, metals (Z + CII, OI, SiII, FeII) + H2 + D + dust + CMB

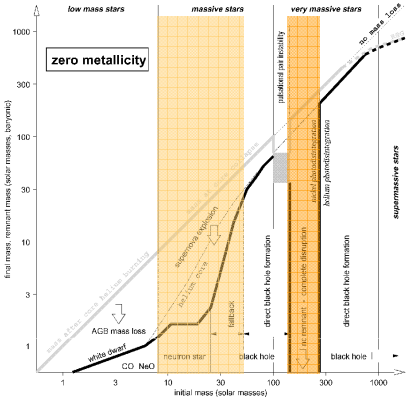
Smith et al 2009
Schneider & Omukai 2010

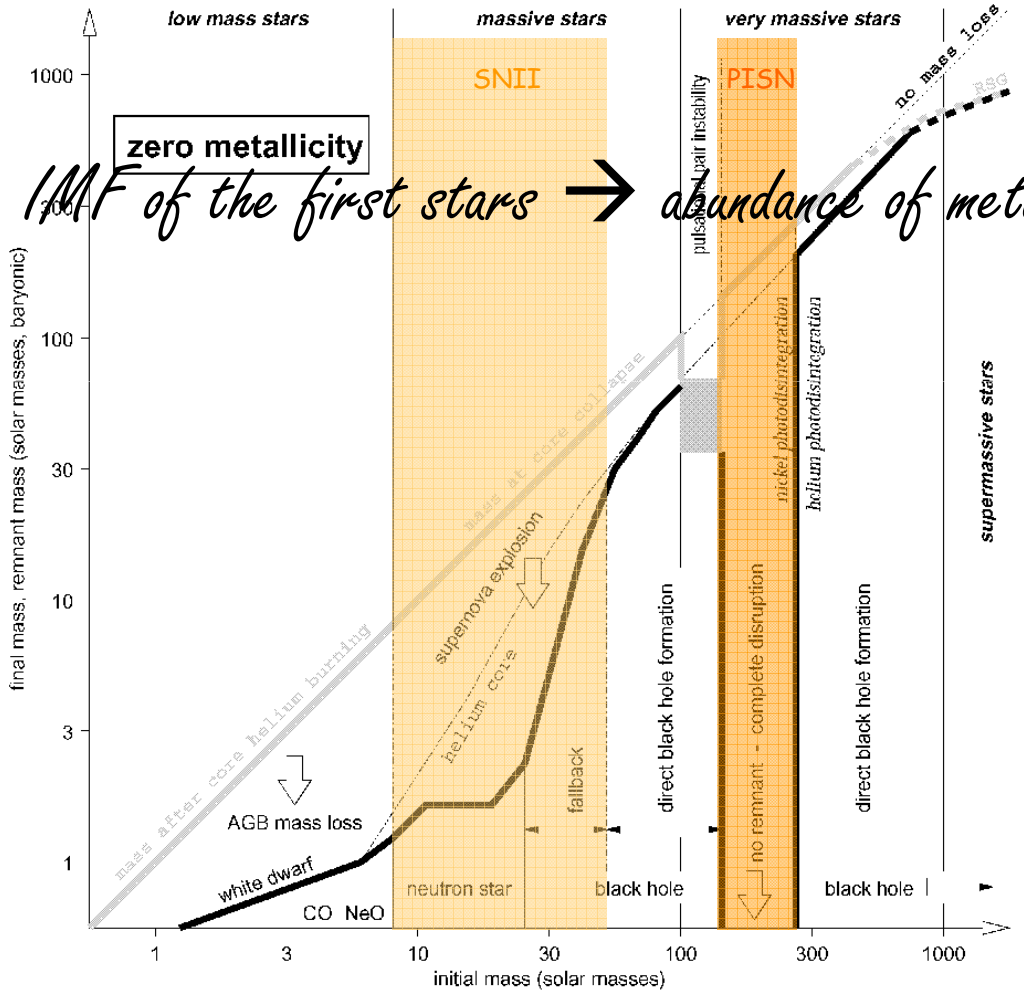




Maio et al. 2010

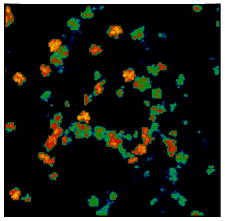
Chemical feedback: missing ingredients





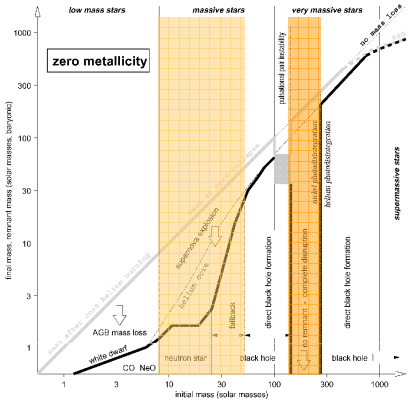
IMF of the first stars → abundance of metals/dust produced

Heger & Woosley 2002

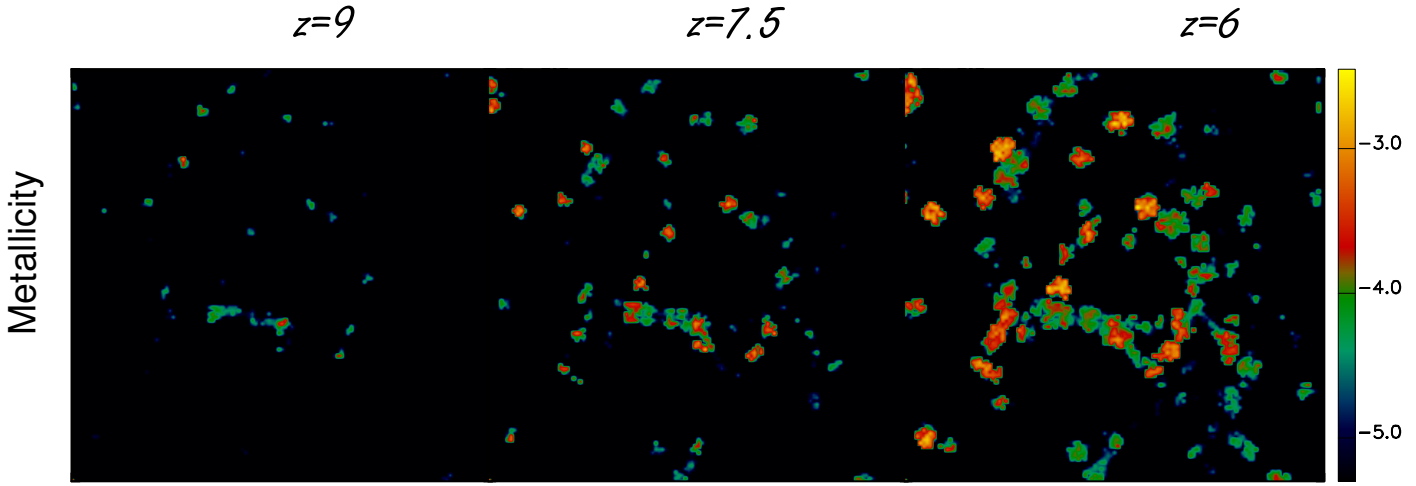


Maio et al. 2010

Chemical feedback: missing ingredients

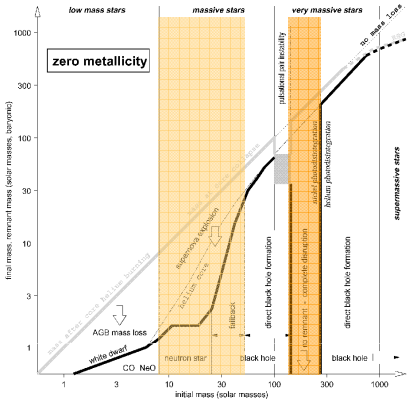


IMF of the first stars → abundance of metals/dust produced

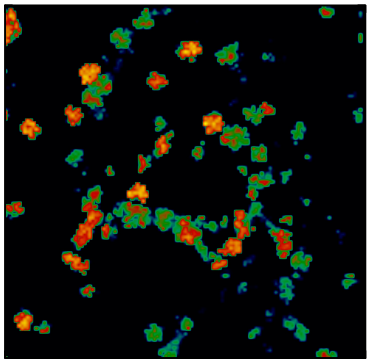


Maio et al 2010

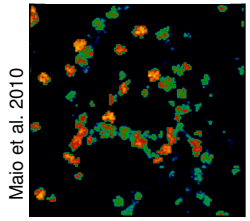
Chemical feedback: missing ingredients



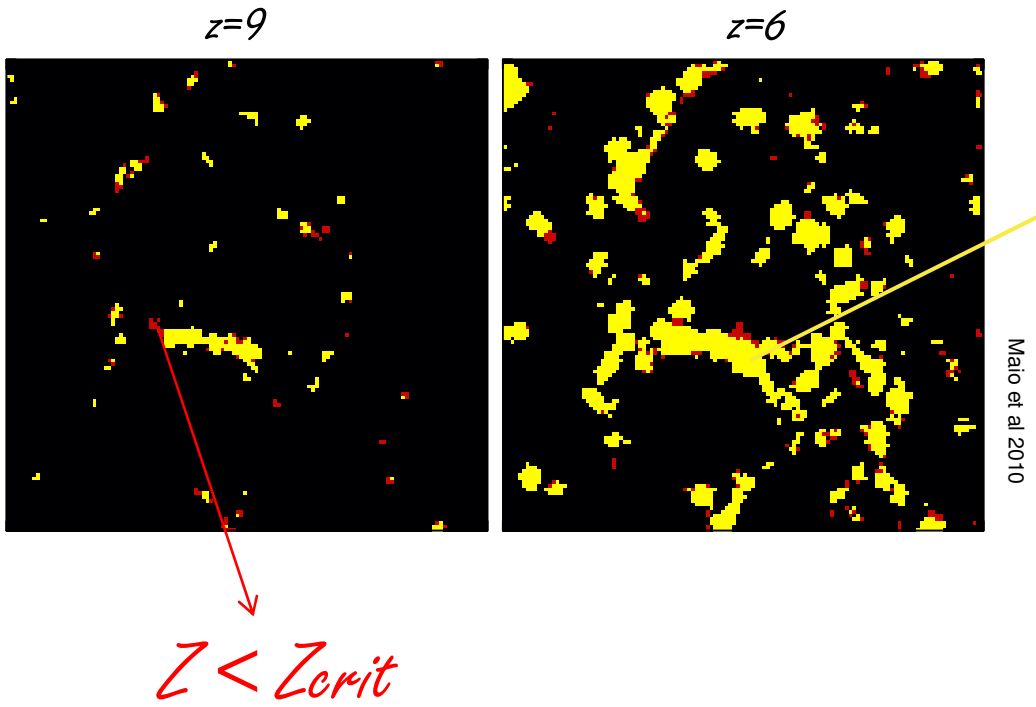
IMF of the first stars → abundance of metals/dust produced

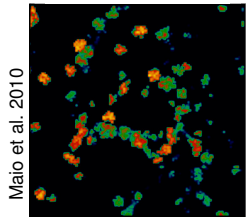


efficiency of metal enrichment → location of transition



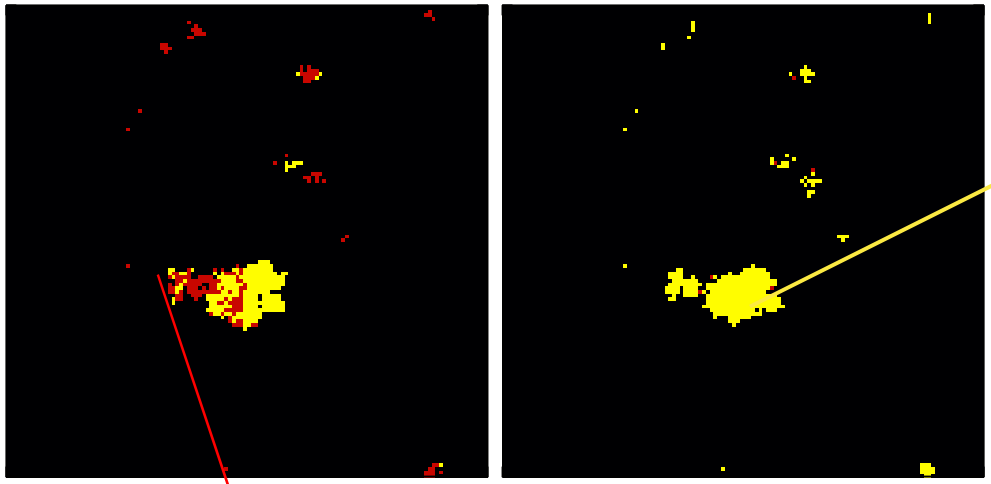
Chemical feedback: a local process





Chemical feedback: a local process

$Z_{crit} = 10^{-3} Z_{sun}$ $Z_{crit} = 10^{-6} Z_{sun}$



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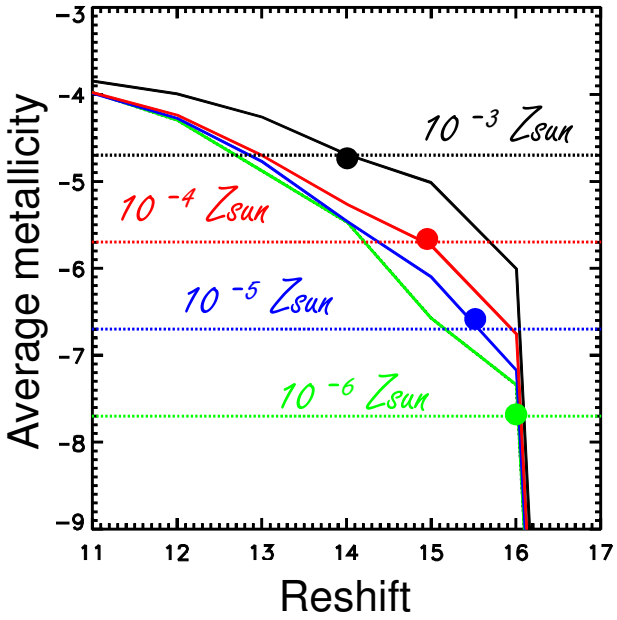
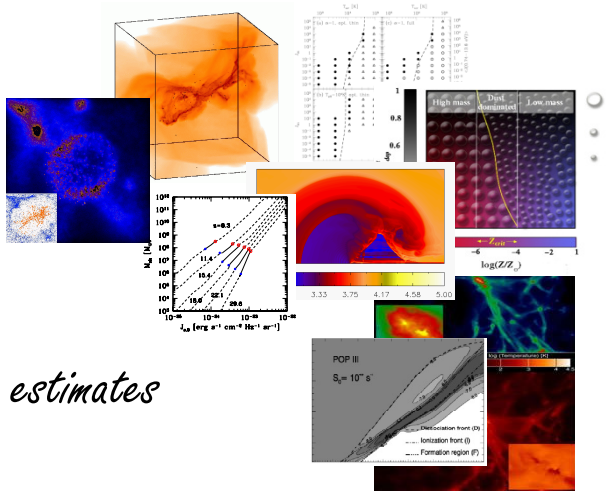
$Z > Zcrit$

$Z < Zcrit$

$z=11$



Conclusions



1. Typically feedback is not as efficient as expected from purely energetic estimates
2. Both its intensity and its sign depends on J, M, environment....
3. The range of masses affected by feedback is few $\cdot 10^5 M_{sun} < M < 10^8 M_{sun}$
4. Negative feedback can act inside the same object (by dissociating star forming clumps) and on the surrounding IGM/nearby objects (by delaying their formation, reducing their reservoir of gas for SF and photoevaporating them)
5. Positive feedback is possible in case of multiple SN explosions, in the dense shell swept by the shocks, inside relic HII regions
6. The metals produced by the first stars are responsible for chemical feedback


The
End