Reionizing the Universe
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The Extiction of the First Massive Stars

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Outline

- Critical Metallicity   physical concepts and current limits
- Role of the first Dust   synthetized in SN explosions
- Lessons from high-z QSOs & EMP halo stars

Critical Metallicity

Metallicity affects stellar mass-scale in two ways:

- prestellar gas thermal evolution: fragmentation scale

$10^{-4} \leq Z_{cr}/Z_{sun} \leq 10^{-3}$ (Bromm et al 2001, 2003)

$10^{-6} \leq Z_{cr}/Z_{sun} \leq 10^{-4}$ (Schneider et al 2002, 2003)

$[O/H]_{cr} = -3.5 \pm 0.1$ $[C/H]_{cr} = -3.05 \pm 0.2$ (Bromm & Loeb 2004)

- accretion onto forming protostar: radiation force

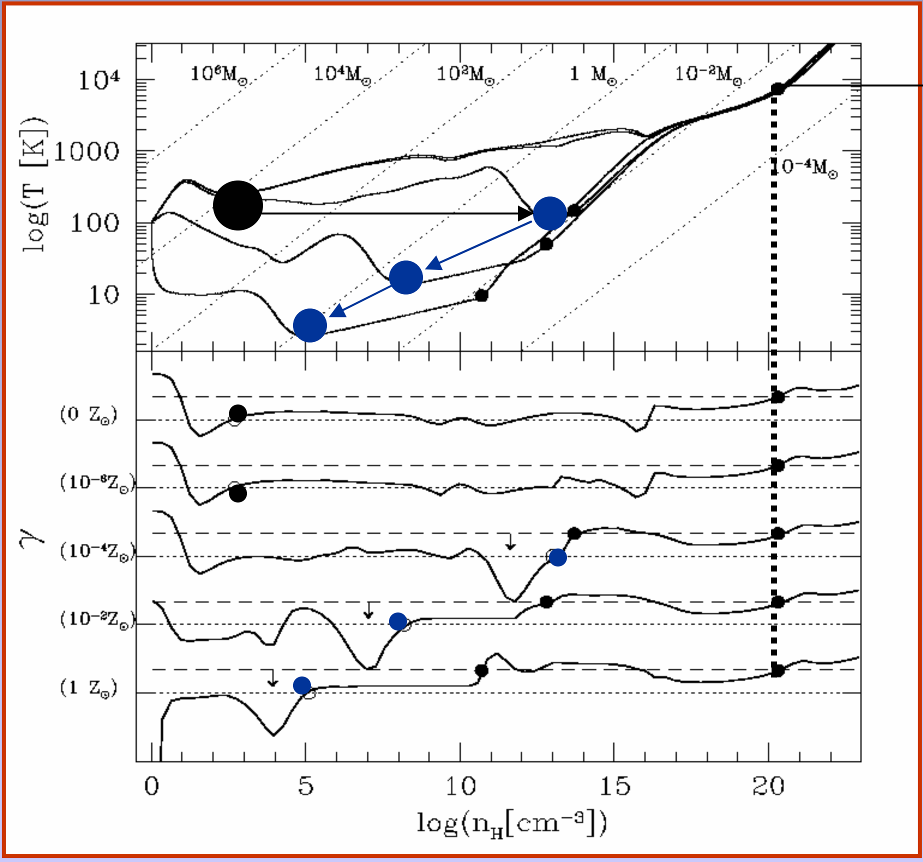
$Z_{gas}/Z_{sun} \geq 10^{-2}$ (Omukai & Palla 2003)

Stellar mass scale ←→ Fragmentation scale

←→ Thermal Jeans Mass scale

Evolution of prestellar clouds

T=T(n_H) for different gas metallicities



stellar core 10^{-3} M_{sun}

time

Fragmentation scale transition

10^3 M_{sun} → 0.01 M_{sun}

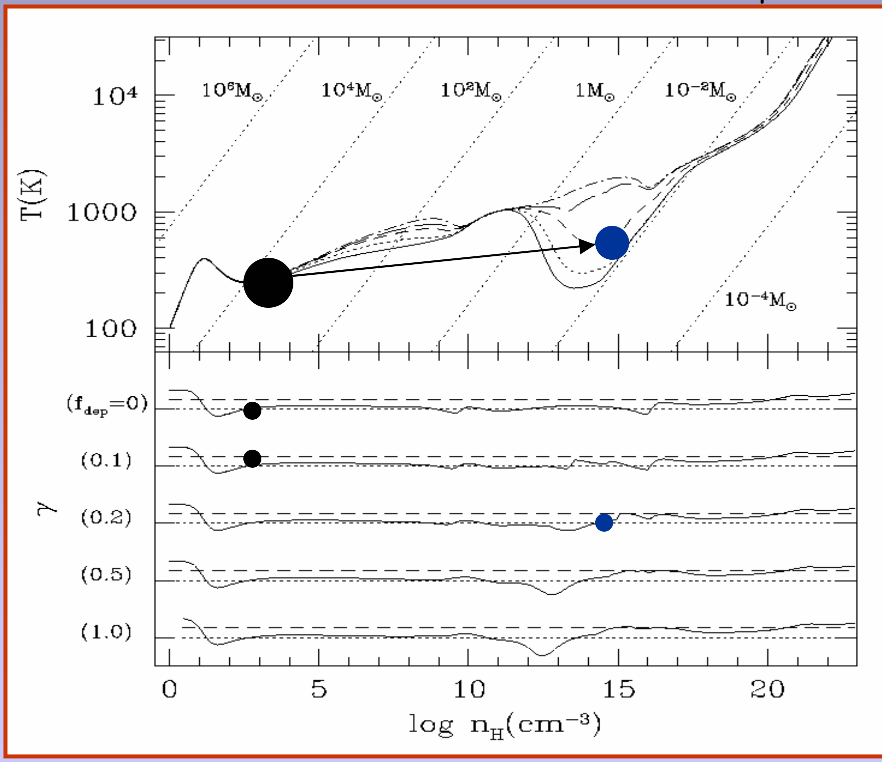
10^{-6} Z_{sun} < Z_{cr} < 10^{-4} Z_{sun}

Transition induced by metals in DUST GRAINS

Schneider, Ferrara, Natarayan & Omukai (2002)

Effect of Dust

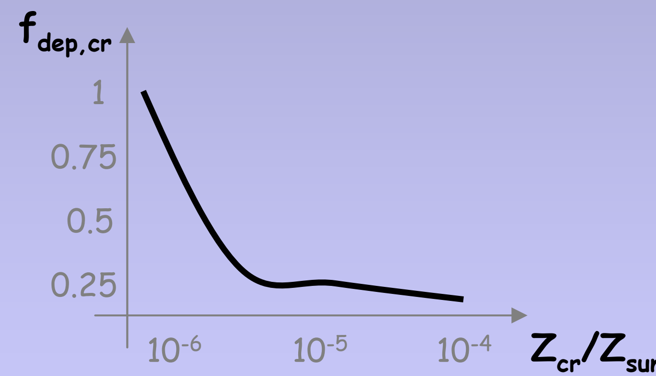
$T=T(n_H)$ for fixed $Z=10^{-5.1}\,Z_{sun}$ but different dust depletion factors: $f_{dep}=M_{dust}/M_{met}$



time

Schneider, Ferrara, Omukai & Bromm (2003)

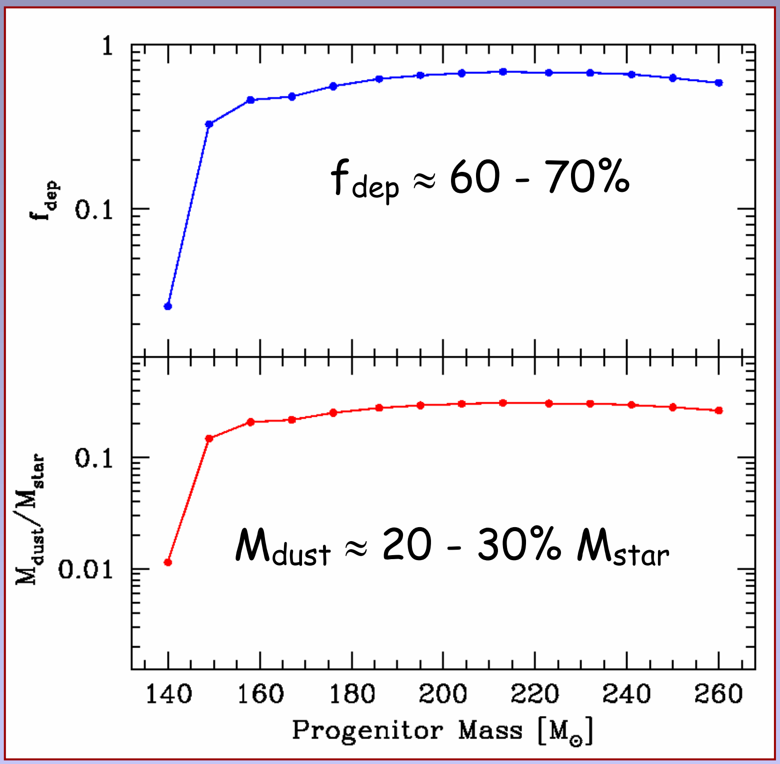
Low mass fragments can form at $Z = Z_{cr}$ if $f_{dep} > f_{dep,cr}$



DUST GRAINS activate fragmentation at the lowest Z

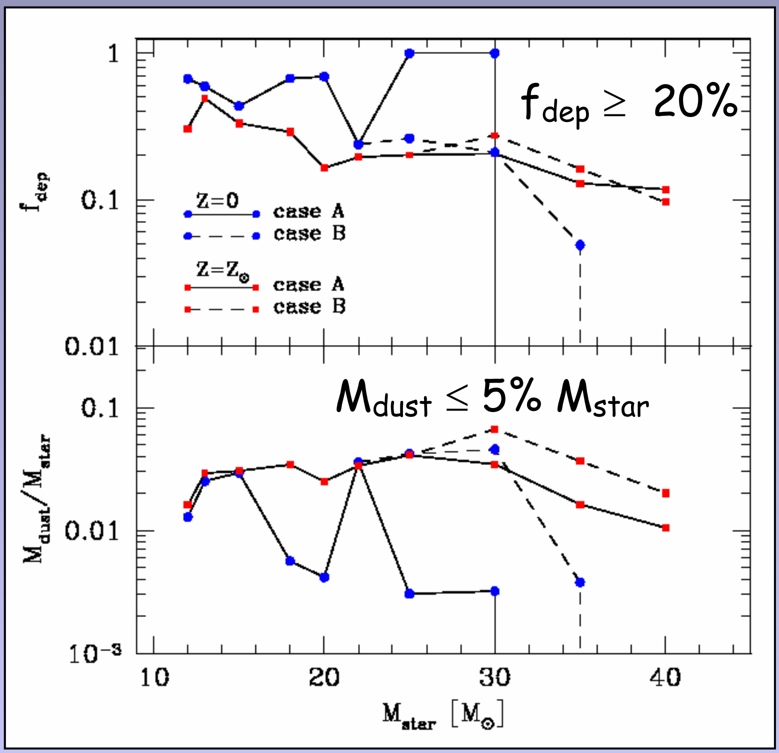
Metals and Dust from the first SN

PISN Z = 0



Schneider, Ferrara & Salvaterra (2004)

TYPE-II SN

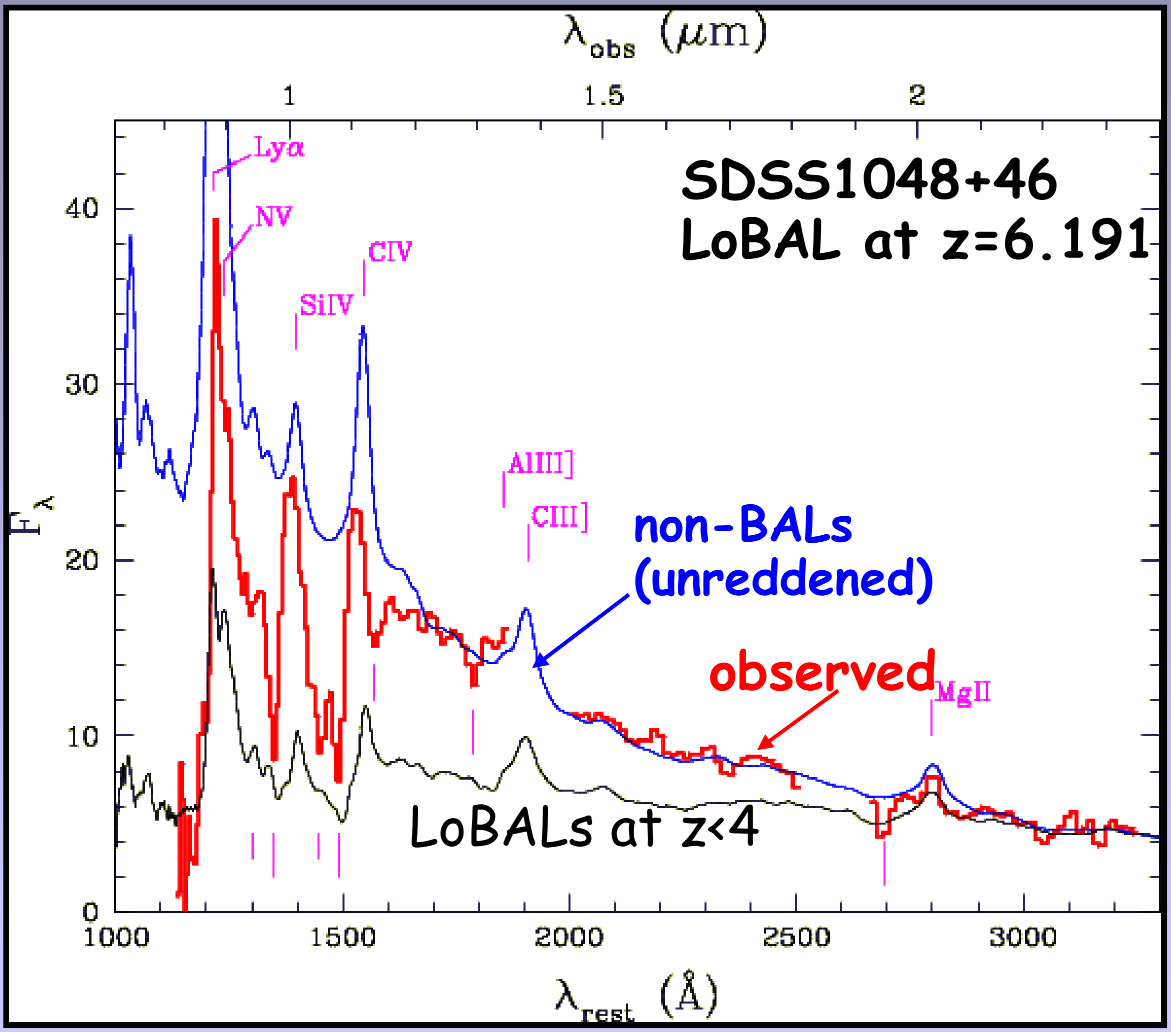


Todini & Ferrara (2001)

SN explosions pollute the surrounding gas with metals AND dust

Kozasa & Hasegawa 1987; Todini & Ferrara 2001;
Nozawa et al 2003; Schneider, Ferrara & Salvaterra 2004

The Origin of Dust



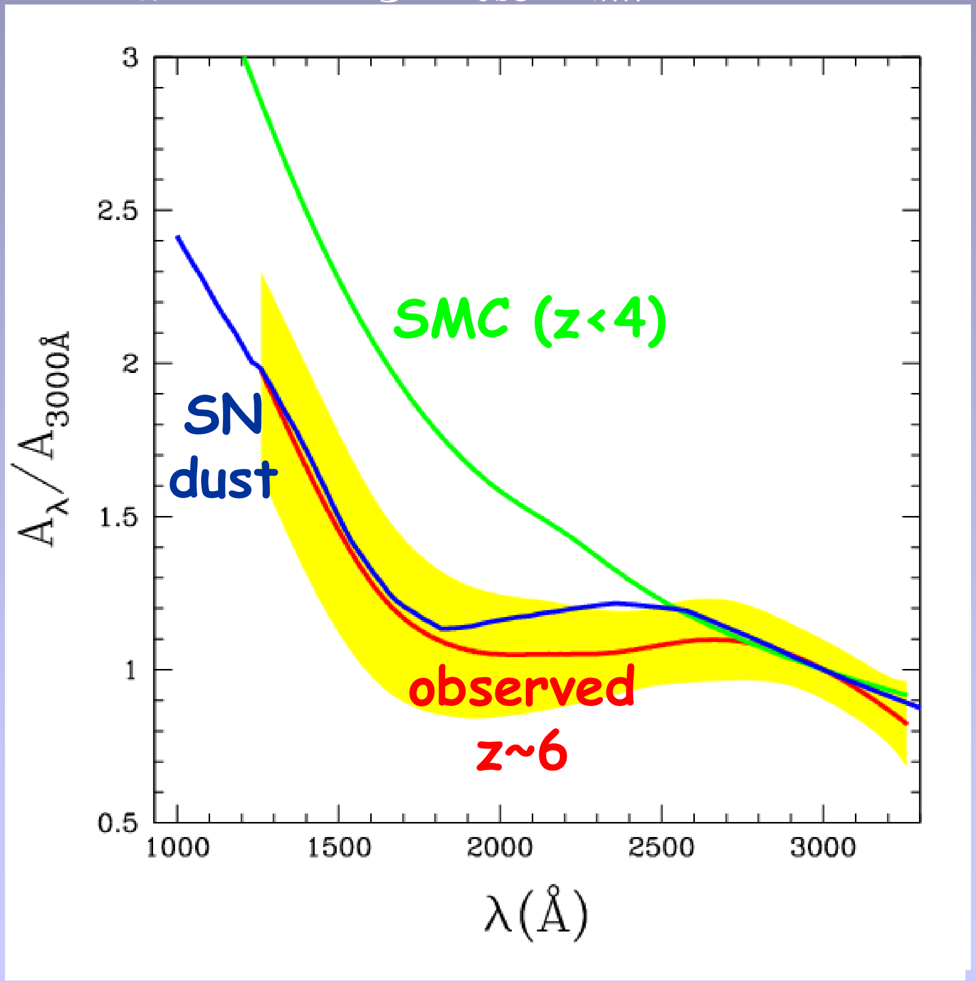
Maiolino, Schneider, Oliva, Bianchi, Ferrara, Mannucci et al 2004, Nature, 431, 533

→ SDSS1048+46 is redder than non-BAL template

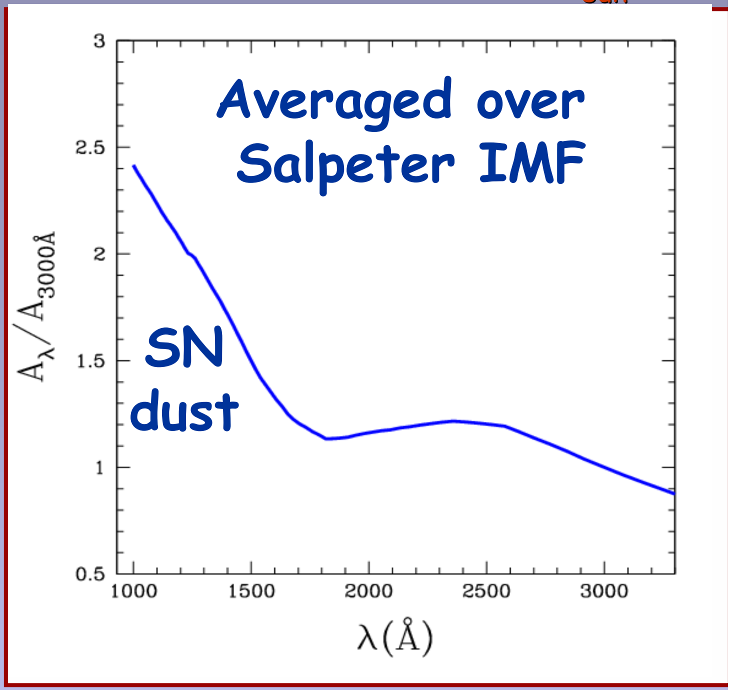
→ SDSS1048+46 is bluer than any z<4 LoBAL

Dust Extinction Curve

$A_\lambda = -2.5 \log (F_{obs}/F_{intr})$



TYPE-II SN $Z=10^{-4}\,Z_{sun}$

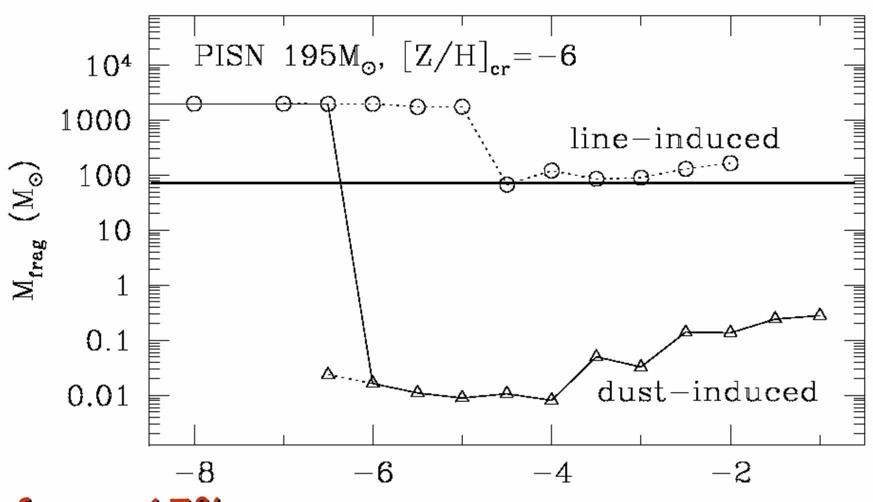


First direct evidence that dust at z>6 has been produced by SNe

Maiolino, Schneider, Oliva, Bianchi, Ferrara, Mannucci et al 2004, Nature, 431, 533

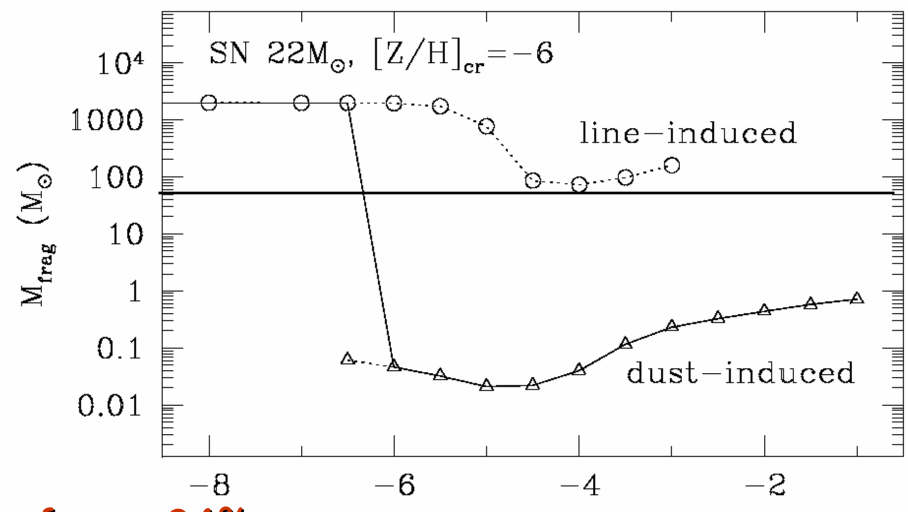
Second generation stars

PISN Z = 0 195 Msun



f_{dep} = 65%

SN II Z = 0 22 Msun



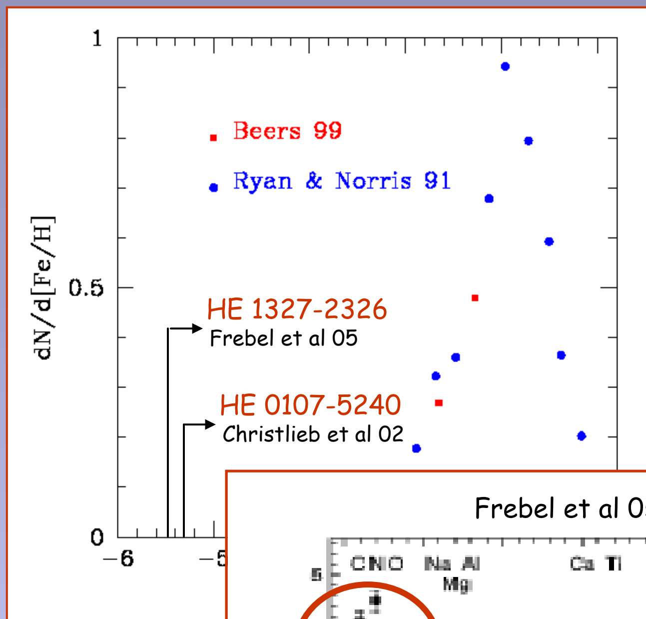
f_{dep} = 24%

Schneider, Omukai, Inoue & Ferrara, in prep

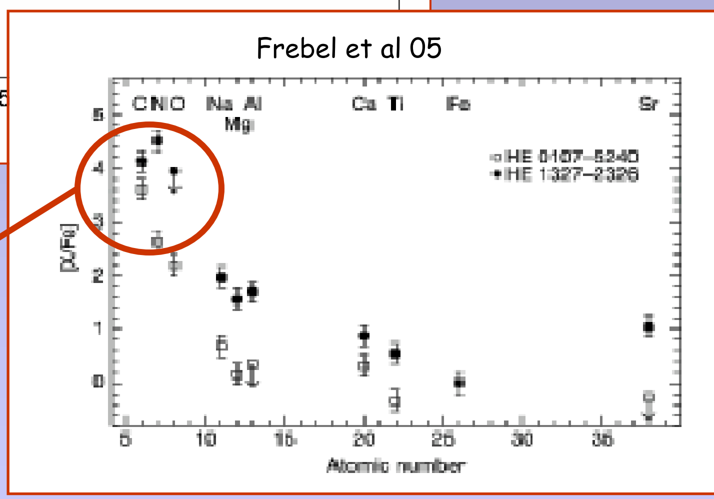
Line-induced fragmentation scale > 70 M_{sun}

Dust-induced fragmentation 0.01 M_{sun} - 0.3 M_{sun}

Stellar Archeology



- MDF dominated by [Fe/H] > -4
- 2 stars with [Fe/H]=-5.3 and -5.4
- No star with -5 < [Fe/H] < -4



Extreme C and N overabundances

? Faint TypeII SN (Umeda & Nomoto 03)

? Accretion onto low-mass PopIII
(Shigeyama et al 03; Yoshii 1981)

? Mass transfer from an AGB star
(Christlieb et al 02; Suda et al 04)

Iron - poor does not imply metal - poor Z > Zcr

Stellar Archeology

Constraining high-z star formation through the oldest living fossils

Extremely metal poor stars in the Galaxy halo and/or in dwarfs - DART

Ryan & Norris 91; Beers 99; Christlieb et al 2002 — Tolstoy et al 03-05

- The Galaxy MDF is consistent with Zcr
  Schneider et al 2002

[Fe/H]=-5.3 HE 0107-5240
Christlieb et al 02

[Fe/H]=-5.4 HE 1327-2326
Frebel et al 05

- What is the statistical occurrence of fossils with imprints from the first supernovae?

→ **Self-regulation of early star formation**

Salvadori, Schneider & Ferrara in prep

Lessons from Metal Poor Halo stars

… to be learned

- The observed MDF is consistent with Zcr
- Why is there a gap –5 < [Fe/H] < -4 ?
- What is the statistical occurrence of fossils with imprints from the first supernovae?

[Fe/H]=-5.3 HE 0107-5240
Christlieb et al 02

[Fe/H]=-5.4 HE 1327-2326
Frebel et al 05

↕

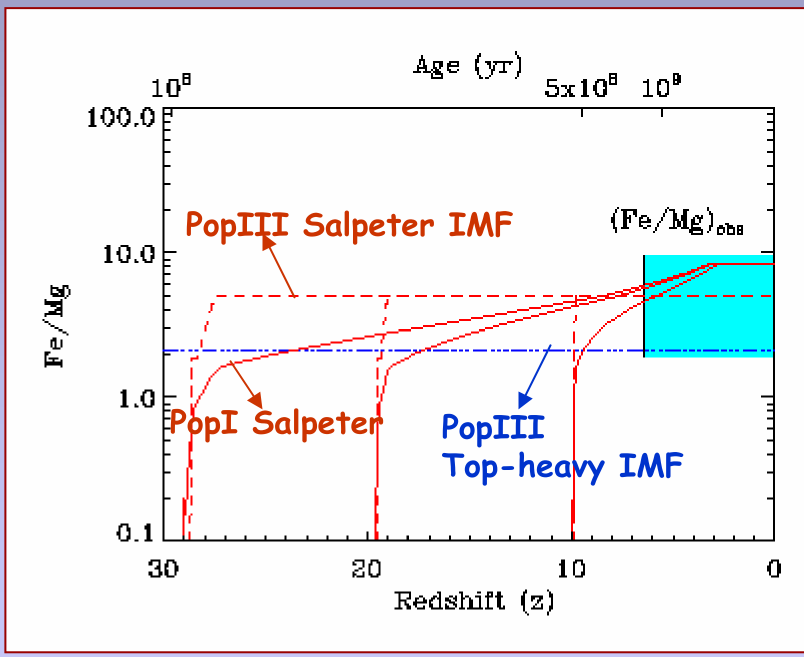
Self-regulation of the first star formation epoch

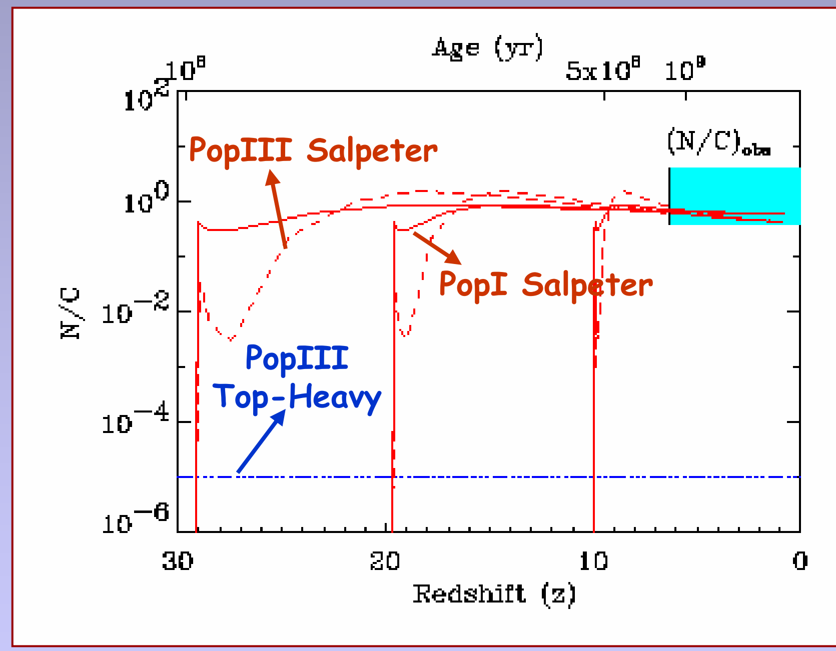
Salvadori, Schneider & Ferrara in prep

Lessons from high-z QSOs

Observations of Broad Emission Line Region: NV/CIV and FeII/MgII

solar or supersolar metallicities up to z=6.4 (Freudling et al. 03)





Venkatesan, Schneider & Ferrara (2004)

→ In the over-dense regions probed by QSOs
the IMF "transition" has occurred early-on

Cosmic Relevance of PopIII stars

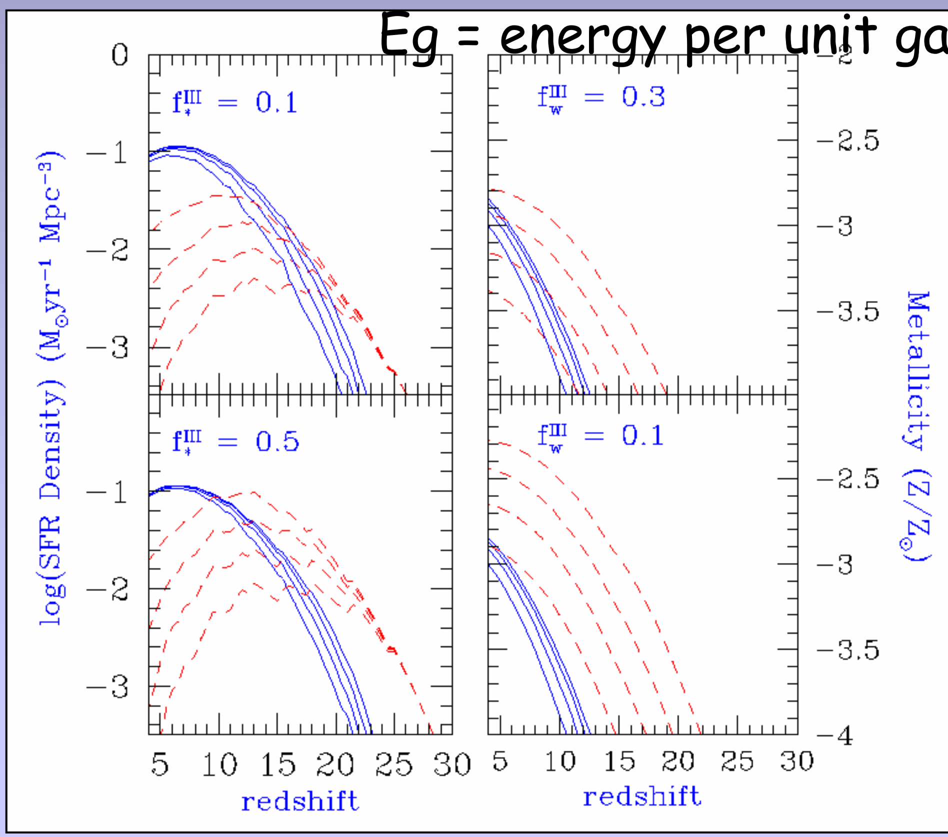
depends on metal enrichment

chemical feedback

i. Metal yields and energetics of individual starbursts → f_* N_{pisn} ε_{pisn}

ii. Properties of SN-driven outflows → f_w f_{met}

Eg = energy per unit gas mass = $f_* f_w N_{pisn} \varepsilon_{pisn}$



Scannapieco, Schneider & Ferrara 2003

PopIII

PopII

- Smooth IMF transition
- Independent of <Z>igm

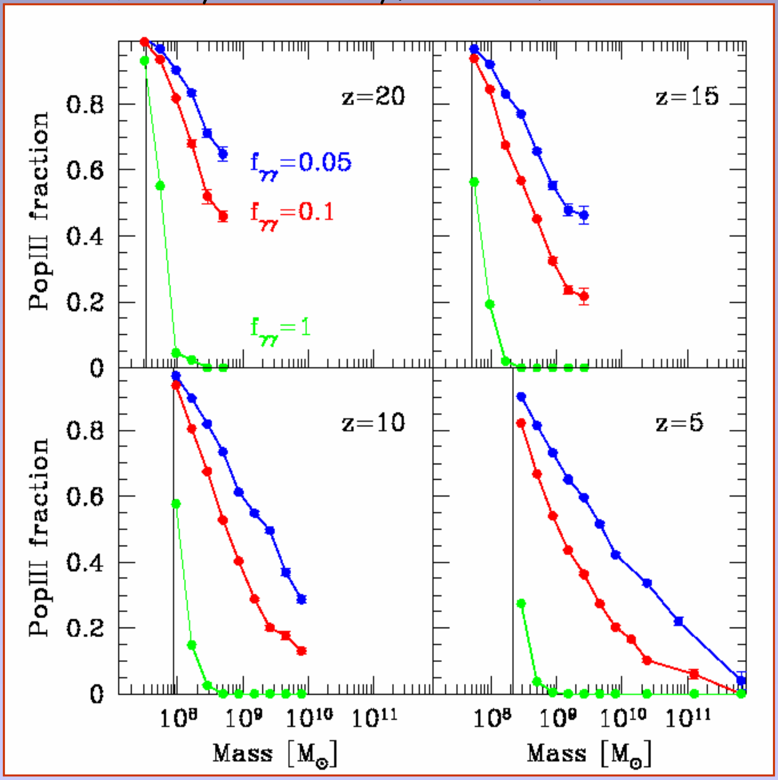
Implications

- Metal-free SF is not confined to very high z
- Late metal-free SF occurs in the smallest galaxies with $T_{vir}>10^4$K

Chemical feedback

$f_{\gamma\gamma}=N_{pisn}/N_{popIII}$

Schneider, Salvaterra, Ferrara & Ciardi 2005



PINOCCHIO

Monaco, Theuns, Taffoni 2002
Taffoni, Monaco & Theuns 2002

L_{box}=7.7 h^{-1} Mpc
N=256^3

- H2 formation largely unaffected by external UV fields
  ≠ from early minihalos (Yoshida et al. 03)

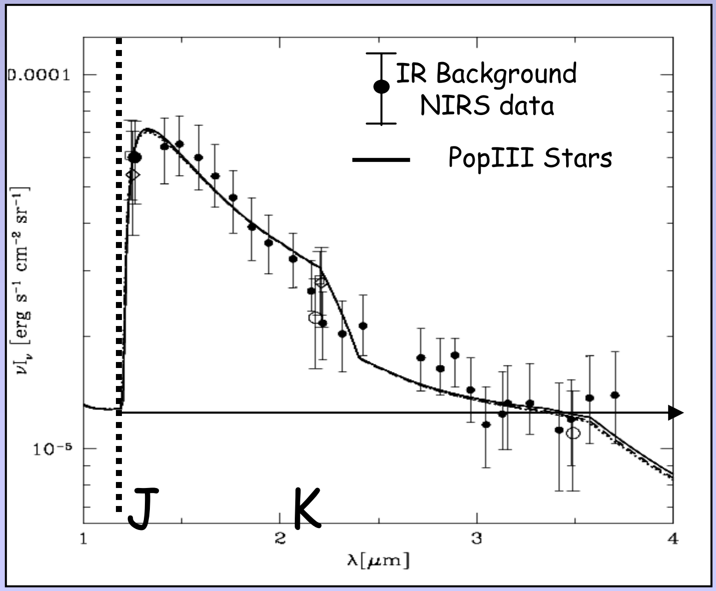
NIRBackground

- excess isotropic emission at [1.2 – 4] μm in COBE/DIRBE and IRTS/NIRS data
  Wright 2001 Cambresy et al 2001 Matsumoto et al 2004
- NIRB fluctuations at 1"-30" (2MASS) and >0.5° (DIRBE) Kashlinsky & Odenwald 2000, Kashlinsky et al 2002

Can not be accounted by normal galaxies

- Redshifted UV light from PopIII stars at z ~ 10

Santos et al 2002
Magliocchetti et al 2003
Cooray et al 2004
Salvaterra & Ferrara 2003
Kashlinsky et al 2004
Madau & Silk 2005



Salvaterra & Ferrara 2003

- M>100 Msun
- fstar ≈ 40%
- for z < 9 fstar <<1

? Chemical Feedback

? Photoionization

$\lambda_{obs} = \lambda_{Ly\alpha}\,(1+z_{end})$

Summary

- ## The critical metallicity:

  - metals in solid dust grains play a major role at $Z_{cr} = 10^{-5\pm1} Z_{sun}$
  - (metal) line cooling never leads to small (< 1 M_{sun})

- ## Cosmic effects of PopIII stars:

  - strongly related to chemical feedback → metal enrichment
  - the transition depends on the environment

- ## Chemical feedback in action:

  - most distant QSOs show enrichment histories (metals and dust) which require Pop II stars at z >> 6
  - early PopIII→PopII transition in QSOs environments

Eddington-limited emission from accreting miniquasars

Cooray & Yoshida 2004
Madau & Silk 2005
Salvaterra, Haardt & Ferrara 2005

- IMBHs from PopIII stars
- $\Omega_{IMBH}(z = 9) \approx 50\ \Omega_{SMBH}(0)$
- saturate the unresolved SXB unless X-ray quite

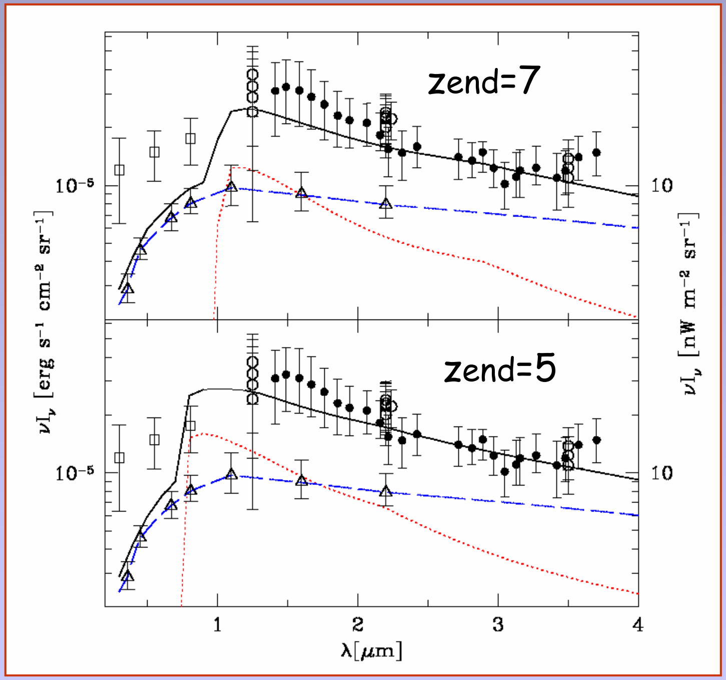
Pop III interpretation vs Chemical Feedback

- <5% of PopIII stars explode as PISN
- IMBHs wandering in galaxy halos
- fstar > 0.4 -0.7 for 5 < zend < 7
- $\Omega_{IMBH}(zend) \approx 3.8 - 4.6\ 10^{-2}\ \Omega_B$

Madau & Rees 2001
Volonteri et al 2003
Islam et al 2003

➡ transition too smooth z < zend

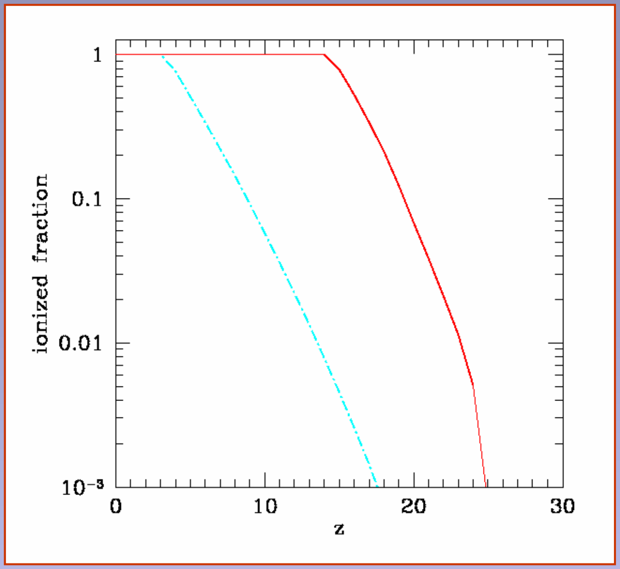
fesc ~ 1%   zrei ~ 14.5 τ ~ 0.2



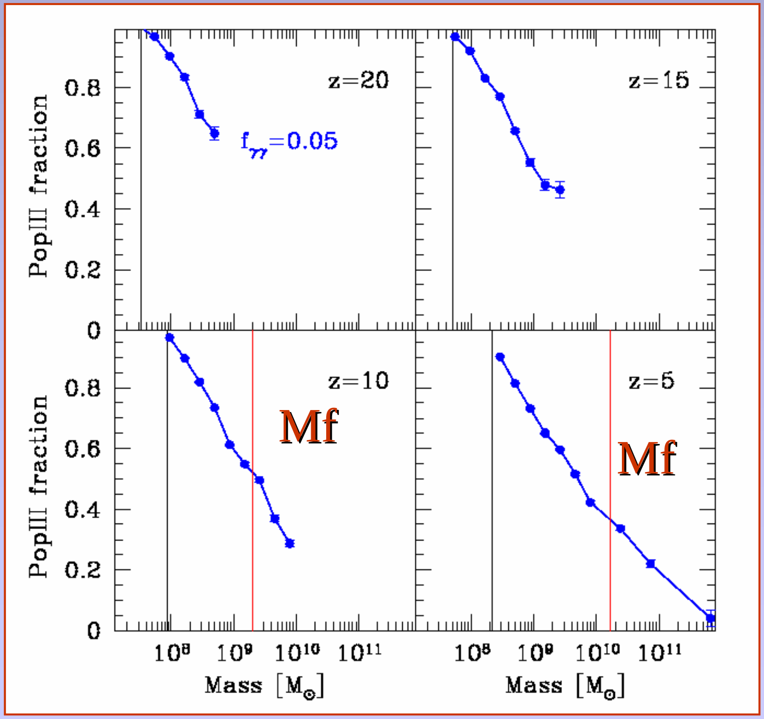
Schneider, Salvaterra, Ferrara & Ciardi 2005

Photoionization feedback

fesc ~ 1%
zrei ~ 14.5
τ ~ 0.2



- photoionization feedback z < zrei



- 50% of PopIII halos are affected at z=10
- 30% of PopIII halos are left z < 5