Kavli Institute for Theoretical Physics

Galaxy-Intergalactic Medium Interactions
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The critical metallicity for cosmic star formation

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OUTLINE

- **The critical metallicity:**
  - physical concepts and current limits
- **Cosmic effects of PopIII stars:**
  - chemical feedback and star formation/reionization
  - observational constraints
- **Chemical feedback in action:**
  - lessons from distant QSOs

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)

$[O/H]_{cr} = -3.5\pm0.1$ $[C/H]_{cr} = -3.05\pm0.2$ (Bromm & Loeb 2004)

- ✓ accretion onto forming protostar: radiation force

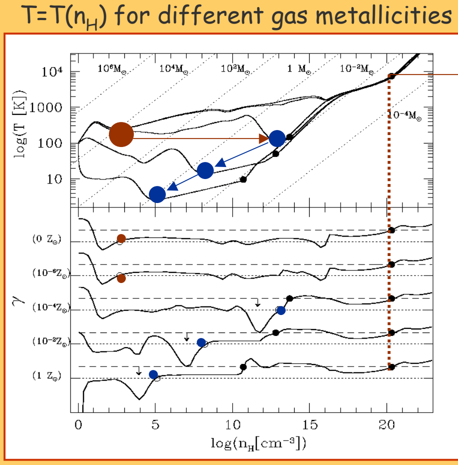
$Z_{gas}/Z_{sun} \geq 10^{-2}$ (Omukai & Palla 2003)

Stellar mass scale ←→ Fragmentation scale

←→ Thermal Jeans Mass scale

Thermal and Chemical evolution of prestellar clouds

T=T(n_H) for different gas metallicities



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

Fragmentation scale transition

10^3 M_{sun} → 0.01 M_{sun}

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

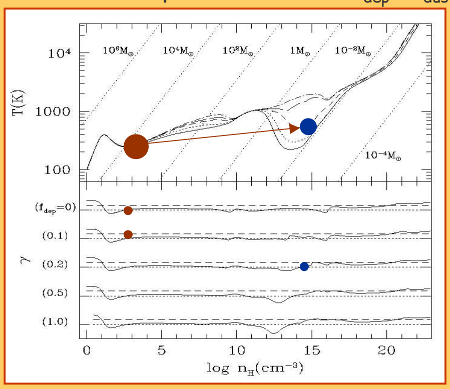
Transition induced by metals in **DUST GRAINS**

time

Schneider, Ferrara, Natarayan & Omukai (2002)

Thermal and Chemical evolution of prestellar clouds: effect of dust

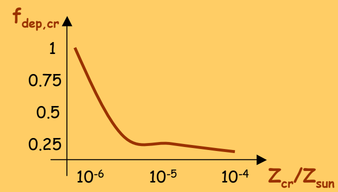
$T=T(n_H)$ for fixed $Z=10^{-5.1}\,Z_{sun}$ but different dust depletion factors: $f_{dep}=M_{dust}/M_{met}$



time

Schneider, Ferrara, Omukai & Bromm (2003)

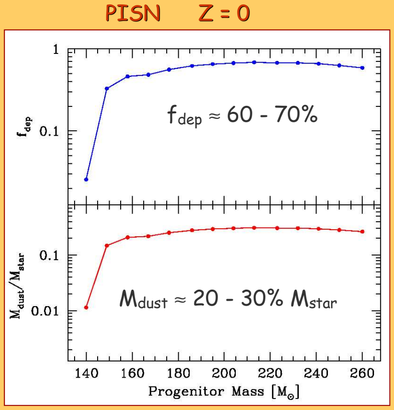
Low mass fragments can form at $Z = Z_{cr}$ if $f_{dep} > f_{dep,cr}$



DUST GRAINS activate fragmentation at the lowest Z

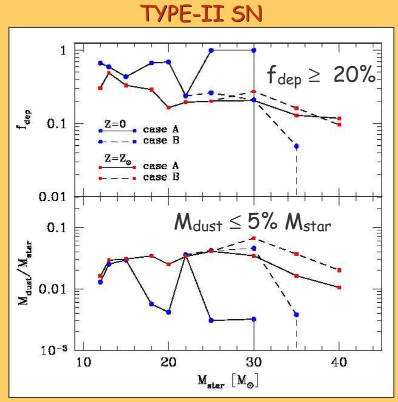
Metals and Dust from the first stellar explosions

PISN Z = 0



Schneider, Ferrara & Salvaterra (2004)

TYPE-II SN



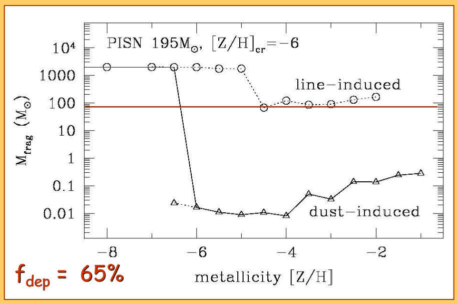
Todini & Ferrara (2001)

SN explosions pollute the surrounding gas with metals AND dust

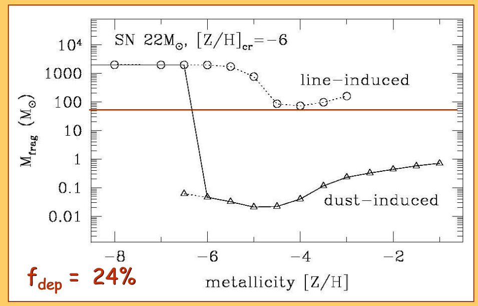
Kozasa & Hasegawa 1987; Todini & Ferrara 2001; Nozawa et al 2003; Schneider, Ferrara & Salvaterra 2004

Self consistent model for second generation stars

PISN Z = 0 195 Msun



SN II Z = 0 22 Msun



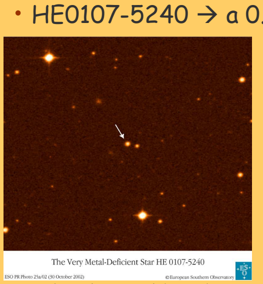
Schneider, Omukai, Inoue & Ferrara, in prep

Line-induced fragmentation scale > 70 M_{sun}

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

Stellar Archeology: the oldest stars present in the Galaxy halo

- No Z = 0 has been found → the first stars are very massive
- Most of the stars have [Fe/H] > - 4.5 → critical metallicity
- HE0107-5240 → a 0.8 M_{sun} star with [Fe/H] = -5.3



Christlieb et al (2002)

i. Mg, Ca, Ti, Fe, Ni → second generation star

ii. [C/Fe] = 4.0 [N/Fe] = 2.3

Pre-formation scenario
Umeda & Nomoto (2003)

$Z_{cloud} \approx 10^{-2} Z_{sun}$

Post-formation scenario
Christlieb et al (2002);Schneider et al (2003)

$Z_{cloud} \approx 10^{-5.5} - 10^{-5.1} Z_{sun}$

$Z_{cloud} \geq Z_{cr}$

Cosmic effects of PopIII stars

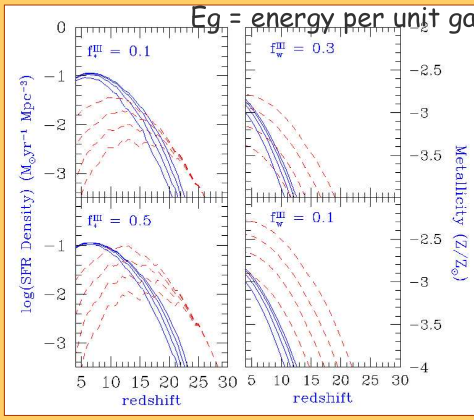
Cosmic relevance of PopIII stars depends on metal enrichment

chemical feedback

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

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

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



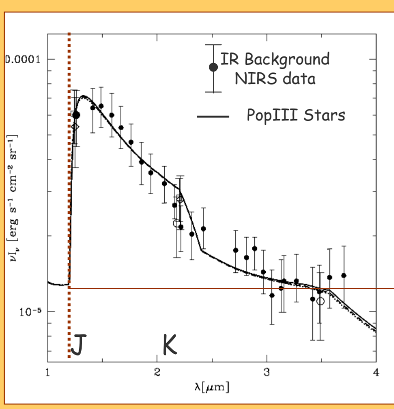
Scannapieco, Schneider & Ferrara 2003

smooth IMF transition independent of <Z>

Constraining the transition with observations: NIRB

PopIII stars can explain the Near IR Background residual and fluctuations

Santos et al 2003; Salvaterra & Ferrara 2003; Magliocchetti et al 2003; Cooray et al 2004; Kashlinsky et al 2004)



Salvaterra & Ferrara 2002

•PopIII stars were massive $M \geq 100\ M_{sun}$

•PopIII stars give negligible contributions to cosmic sfr below $z_{end} = 9$

drop-out in the J-band counts

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

STRONG CONSTRAINT ON PopIII→PopII TRANSITION

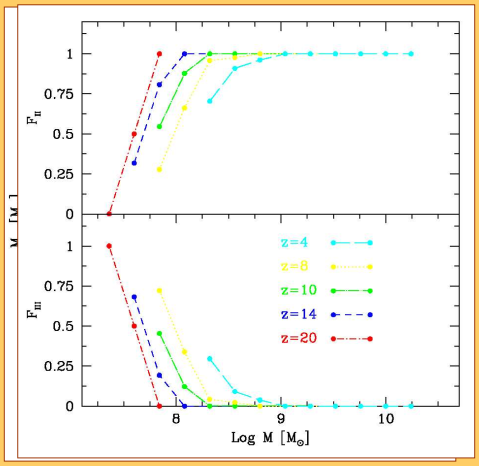
$z_{end} = 9$

Cosmic IMF transition at z = 9: why?

Chemical feedback and the hierarchy of mergers of DM halos

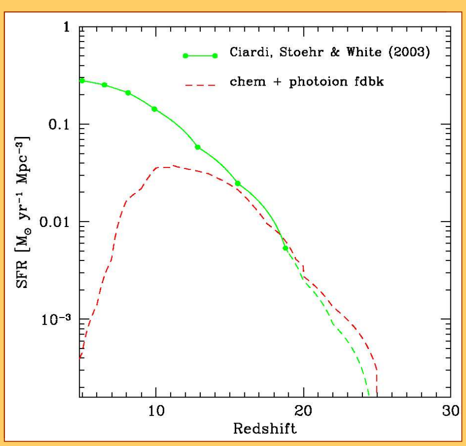
PINOCCHIO (Monaco et al 2002; Taffoni et al 2002)

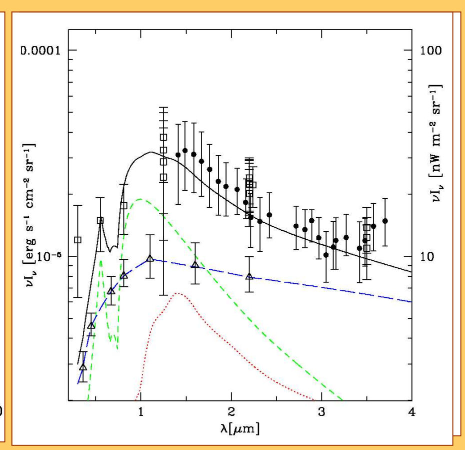
Fraction of halos hosting PopII or PopIII stars



Schneider, Salvaterra, Ferrara & Ciardi, in prep

- F_{II} grows with M and time
- PopIII stars form in < 10^9 M_{sun}
- F_{III} non negligible at z < 9





Hierarchy of mergers and chemical fdbk: transition is too smooth

NIRB excess can be explained → overproduce optical background

Photoionization fdbk due to reionization at redshift 9:
suppression of gas fraction (Gnedin 2000)

good agreement with NIRB and optical background

Lesson from NIRB data:

❖PopII and PopIII stars are coeval and give comparable contributions to the cosmic sfr at z > 15

❖The contribution of PopIII stars to the cosmic sfr drops at z < 9 because of the joint effects of:
- chemical feedback
- photoionization feedback due to reionization

❖ Reionization redshifts in the range 8 ≤ zrei ≤ 10 are still within the errorbars → $f_{esc,III} \leq 5\%$

❖ WMAP data can be reproduced → $\tau \approx 0.14 - 0.15$

❖ Non-monotonic (double reionization) history is difficult to achieve → marginal decrease in the x_i at 6 < z < 9 if $f_{esc,II} \leq 3\%$ and $C = 10$

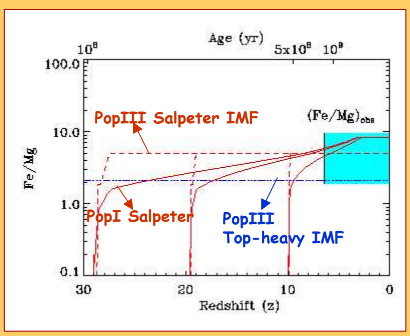
❖ Extended (monotonic) reionization is more plausible

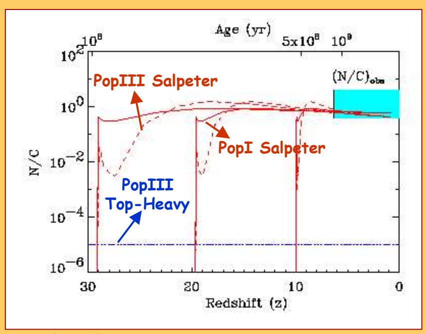
Furlanetto & Loeb 2004

QSOs provide a probe of IGM composition at the highest redshifts

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

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

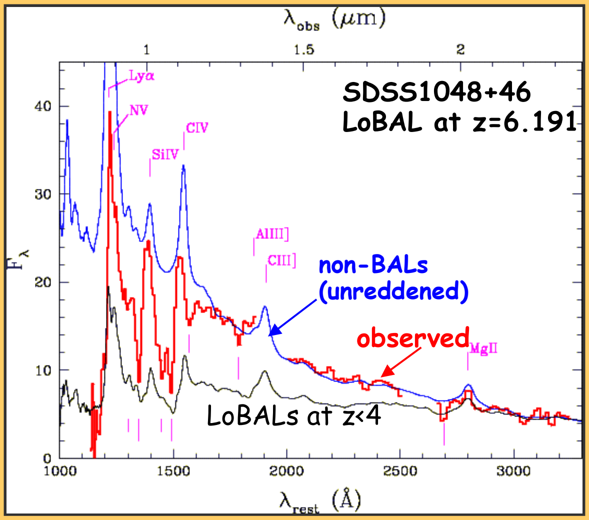




Venkatesan, Schneider & Ferrara (2004)

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

The nature of dust in a high-redshift QSO



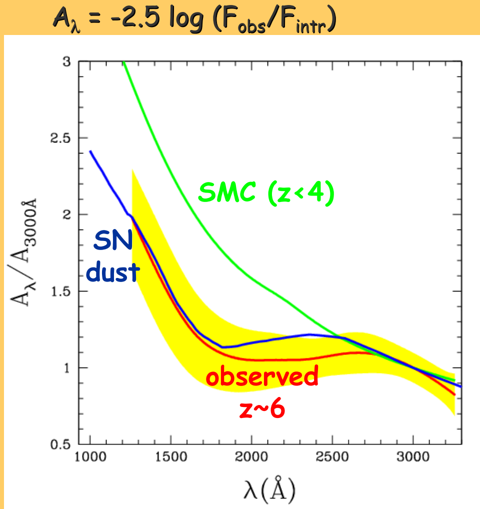
Maiolino, Schneider, Oliva, Bianchi, Ferrara,
Mannucci et al 2004, Nature, 431, 533

SDSS1048+46 is redder than non-BAL template

SDSS1048+46 is bluer than any z<4 LoBAL

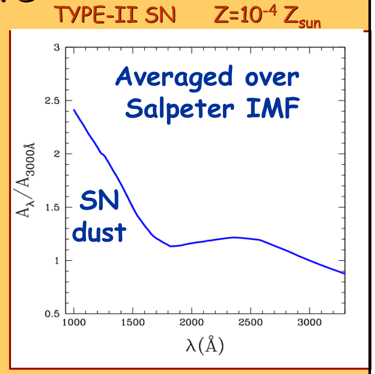
Deriving dust extinction curve

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



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

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



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

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
  - chemical feedback predicts a smooth PopIII→PopII transition
  - NIRB + optical backgrounds provides strong constraints $z_{end} > 9$
  - close connection with constraints in reionization histories

- **Chemical feedback in action:**

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