Low metallicity ISM
Goettingen
8 Oct 2012

Star Formation in Low-Metallicity Gas: thermal and chemical processes

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Outline

- Processes in zero-metallicity gas

  coolants: H_2, HD, H

  First Star Formation (${H_2}$ mode)

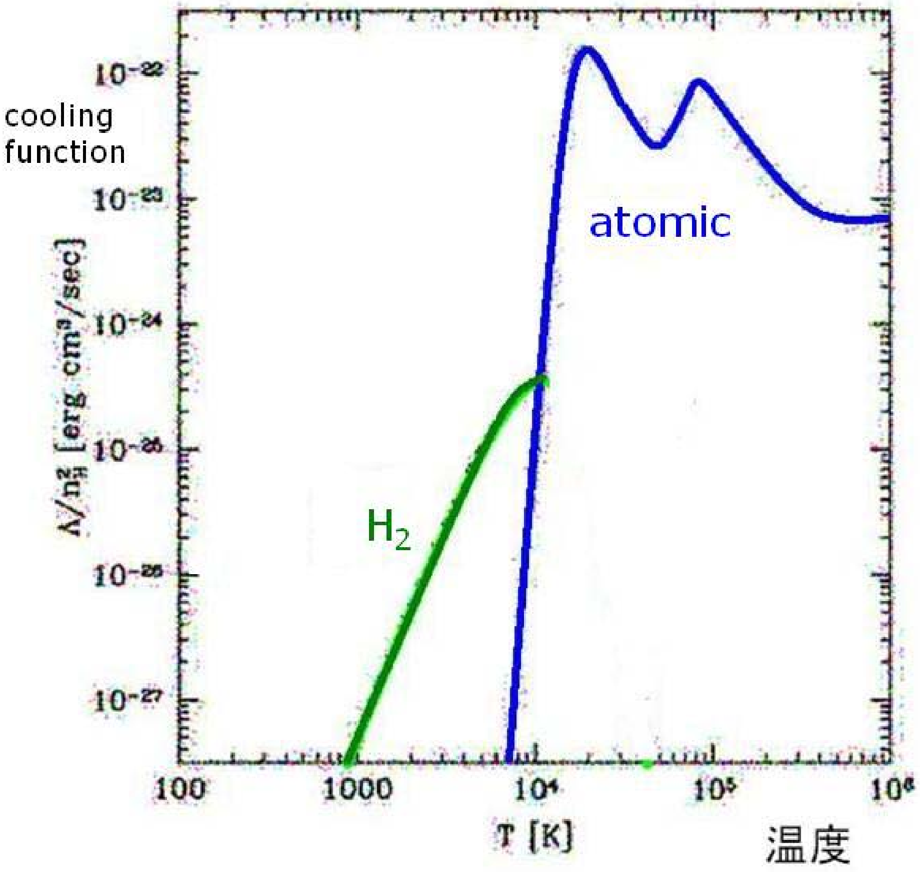
  Pop III.2 Star Formation (HD mode)

  UV effect: Supermassive Star Formation (atomic mode)
- Processes in low-metallicity gas

  coolants: H_2, HD,CI, CII, OI, CO, H_2O, OH, grain

  Low-mass Pop II Star Formation

Radiative cooling in primordial gas



Atomic cooling (H Ly a transition) efficient only T>8000K

H_2 rovibrational cooling is important in lower temperature

To make cold gas, H2 is needed.

Barkana & Loeb 2001

H_2 formation in a primordial gas

direct radiative association is prohibited

$$H + H \not\rightarrow H_2 + \gamma$$

In present-day ISM, H_2 formation is catalyzed by dust

H^- channel : e catalyzed (Peebles & Dicke 1968; Hirasawa+1969)

$H + e \rightarrow H^- + \gamma$
$H^- + H \rightarrow H_2 + e$

dominant channel in low density ($<10^8 cm^{-3}$)

H_2^+ channel : H^+ catalyzed (Saslaw & Zipoy 1967)

$H + H^+ \rightarrow H_2^+ + \gamma$
$H_2^+ + H \rightarrow H_2 + H^+$

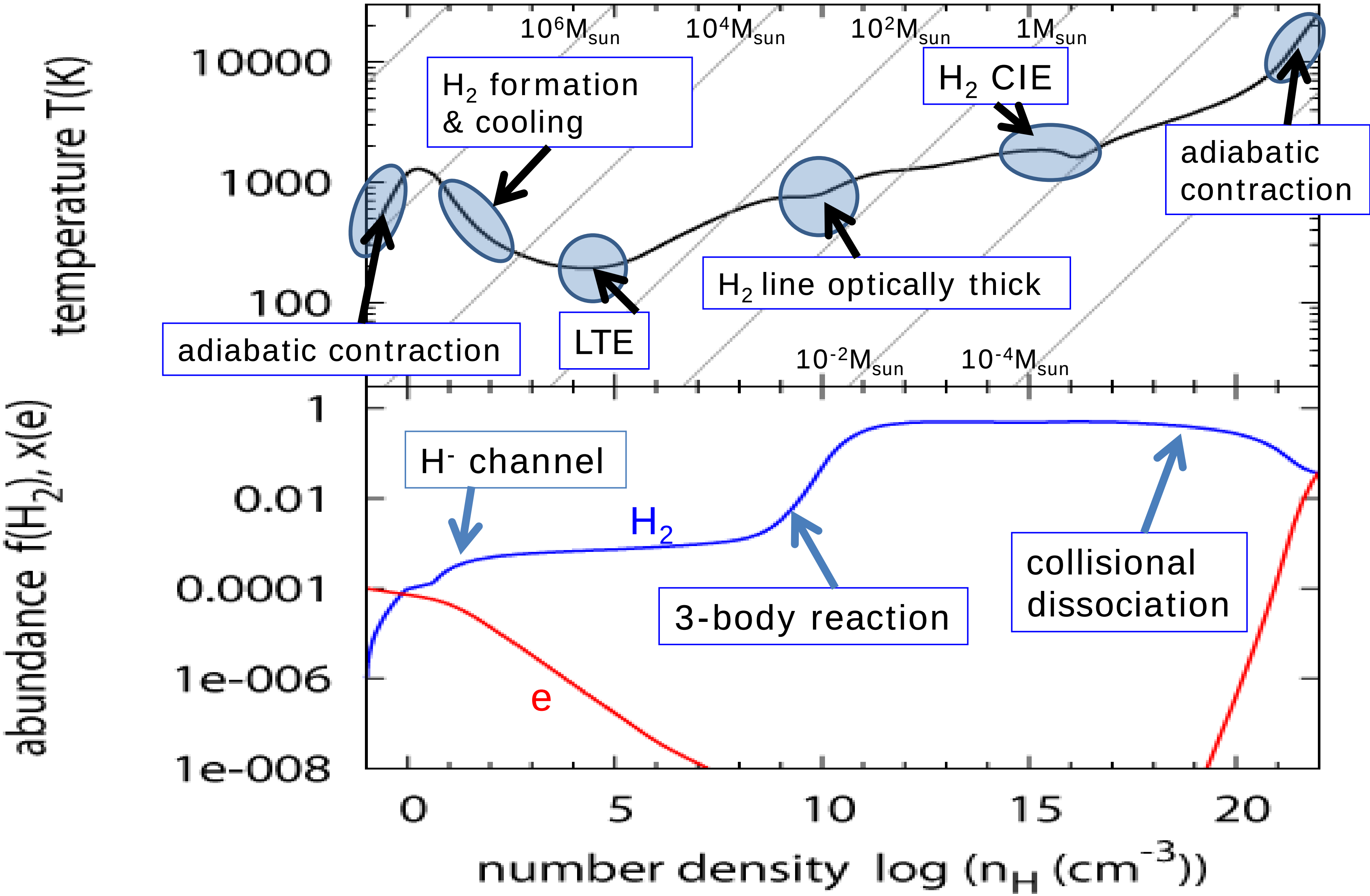
Usually only <~10% of H^- channel
dominant in very high z (>100)

three body process (Palla+ 1983)

$3H \rightarrow H_2 + H$ / $2H + H_2 \rightarrow H_2 + H_2$

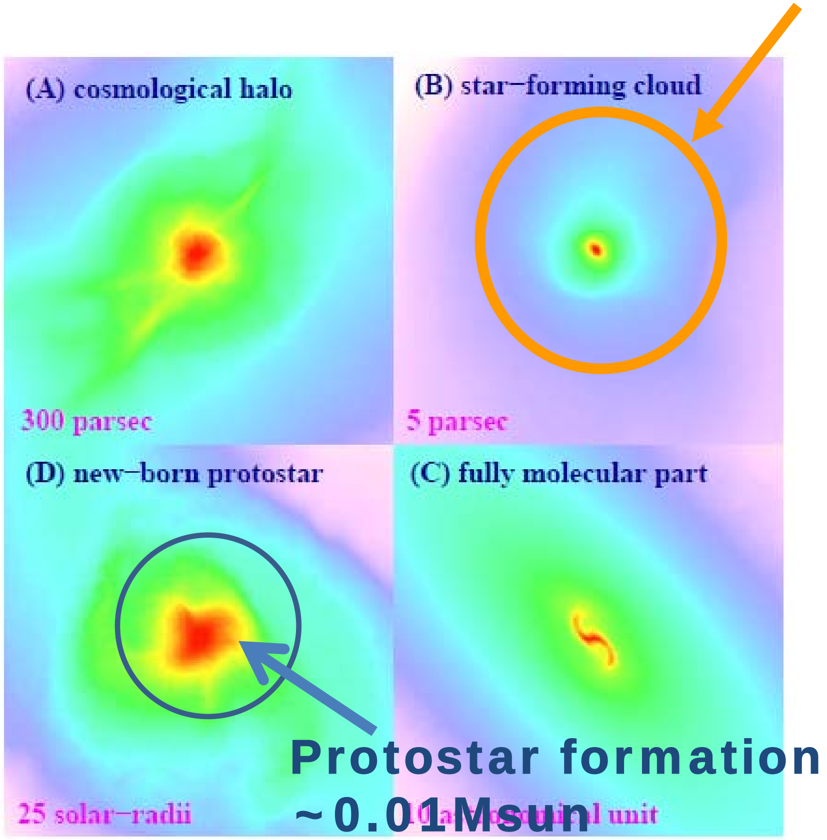
dominant in high density $>10^8 cm^{-3}$
convert all H in to H_2 at $\sim 10^{11} cm^{-3}$

Thermal evolution of primordial gas in pre-stellar collapse



First star formation in the universe

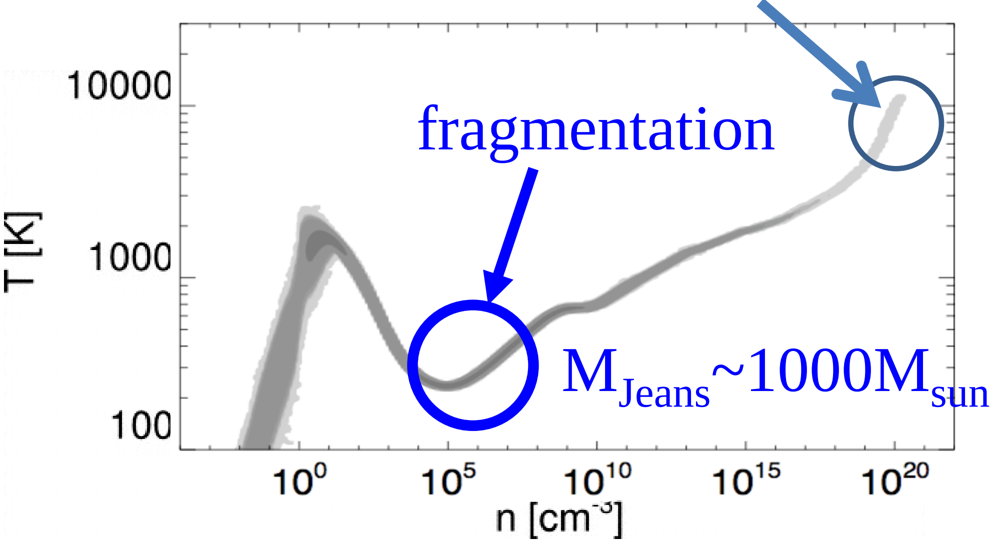
dense core (fragment) ~1000M_{sun}



Protostar formation ~0.01Msun

Yoshida, KO, Hernquist 2008

collapse stops



fragmentation

M_{Jeans}~1000M_{sun}

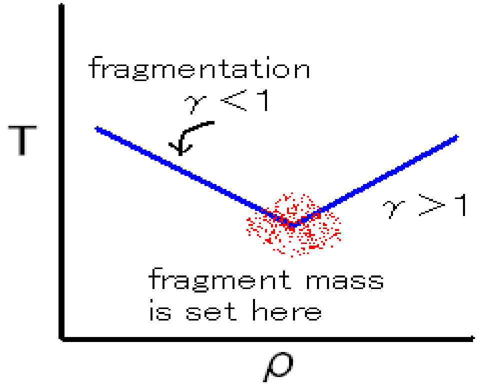
- M_{frag} ~ M_{Jeans}@T minimum (Bromm et al. 1999)

- $M_{protostar}$ ~ M_{Jeans} @EOS becomes adiabatic (KO & Nishi 1998)

Fragmentation and thermal evolution

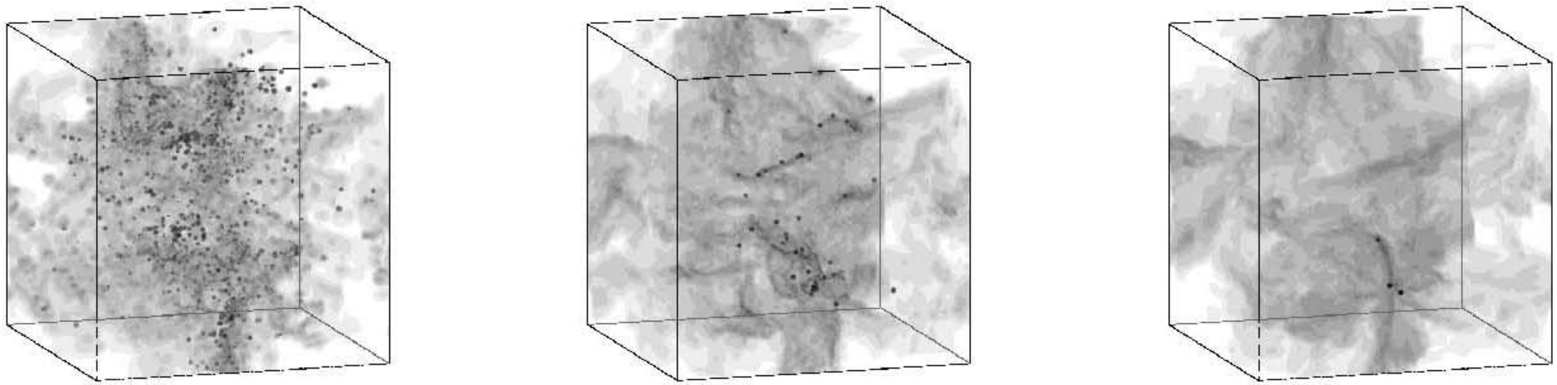
Effective ratio of specific heat

$$\gamma := \mathrm{dlog}\ p/\mathrm{dlog}\ \rho$$



- $\gamma<1$ vigorous fragmentation, $\gamma>1$ fragmentation suppressed
- The Jeans mass at γ~1 (T minimum) gives the fragmentation scale.

$M_{frag}=M_{Jeans}$@Tminimum



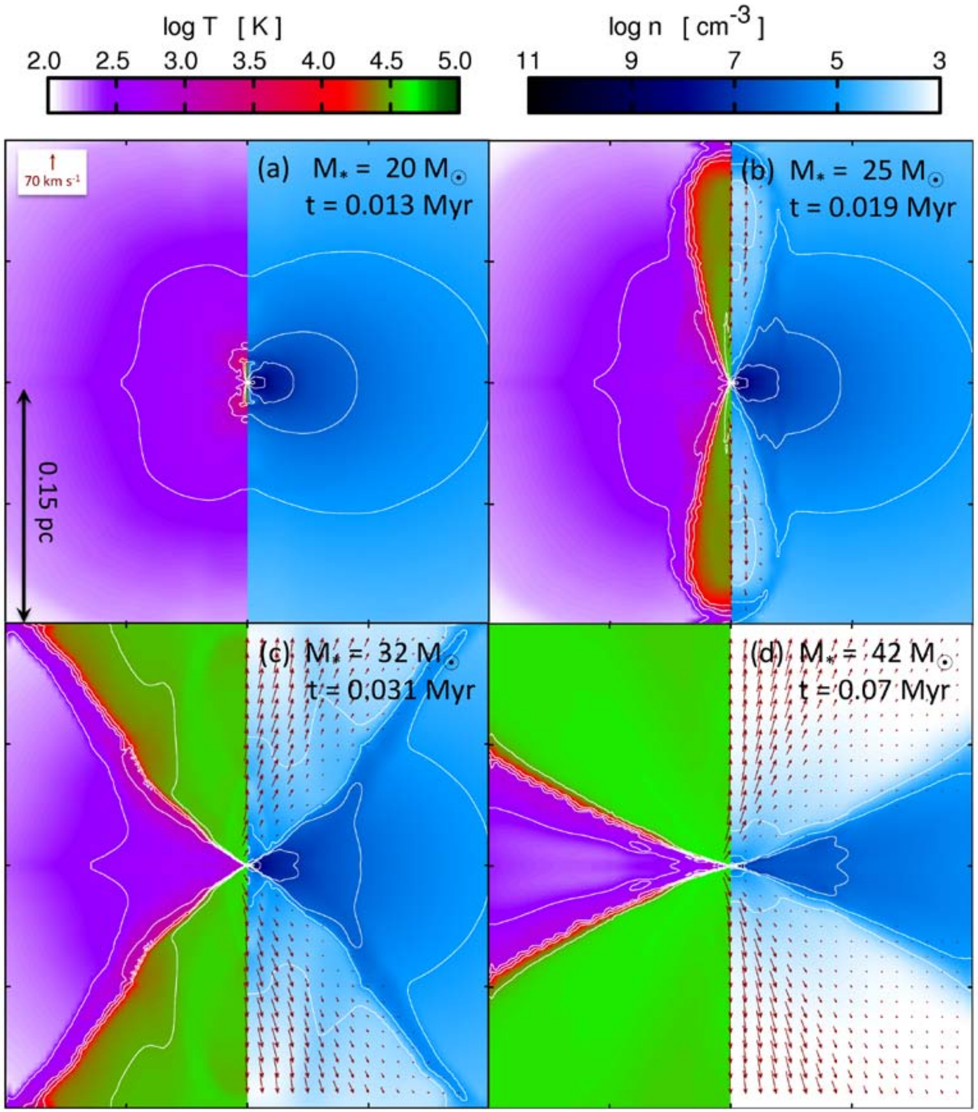
$\gamma=0.2$

$\gamma=1$ (isothermal)

$\gamma=1.3$

Li et al. 2003

Accretion evolution of first protostar



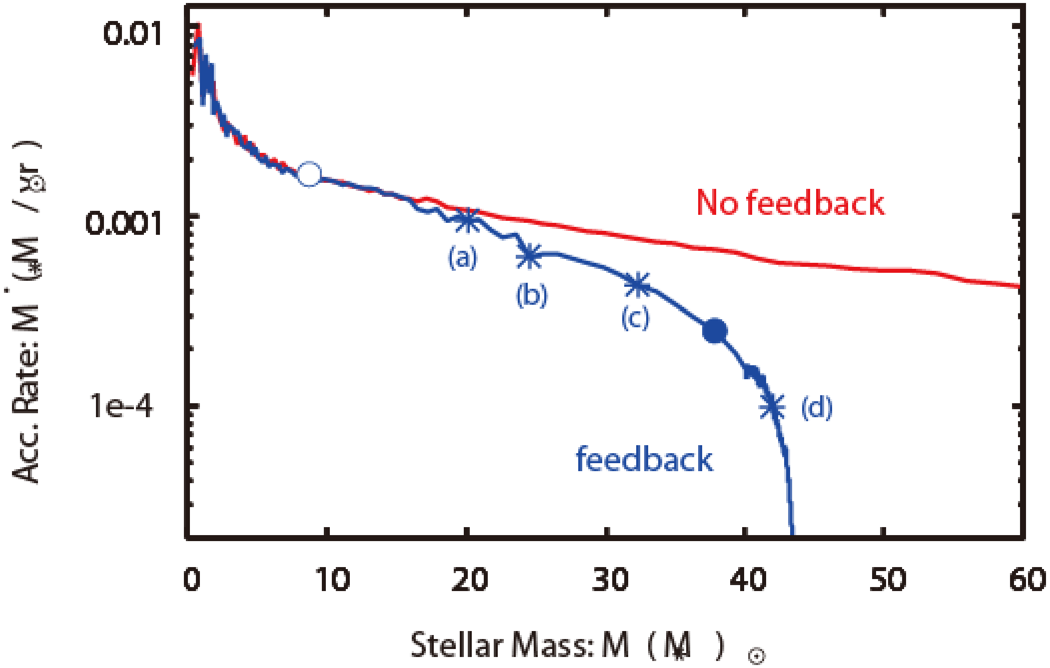
Hosokawa, KO, Yoshida, Yorke 2011

2D Radiation Hydro
+ protostellar evolution

- HII region
  - expands rapidly in the polar directions
  - becomes wider and expels the gas (except in the shadow of the disk)

- Disk photo-evaporation
  gas escapes in the polar directions with velocity of a few x 10 km/s

Accretion rate



- ➢ accretion rate is drastically reduced by protostellar UV feedback.
- ➢ the accretion terminates at 43 $M_\odot$

Massive (but not very massive) star forms
 - ends its life as the core-collapse SN,
instead of PISN

HD and LiH:

Possible coolants in lower temperature ?

- trace amount by BBN

  $D/H \sim 10^{-4}$, $Li/H \sim 10^{-9}$

- lower excitation energy

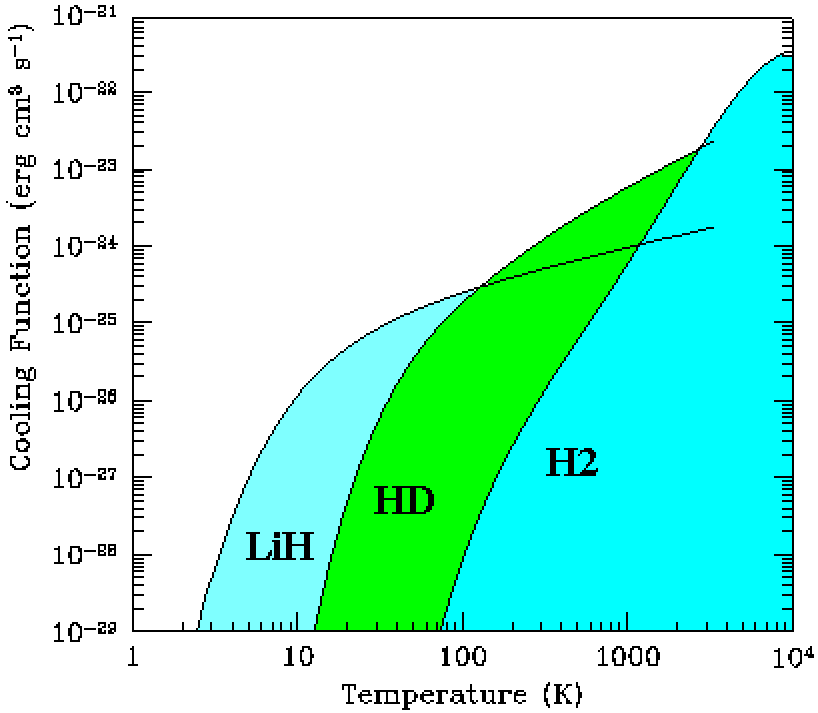
  HD J=1-0 $\Delta E/k_B = 125K$

  LiH J=1-0 41K

  than H_2 J=2-0 512K

- If most of D / Li are converted to HD / LiH, they can be important coolants in low-temperature primordial gas.

Galli & Palla 1998



Cooling function per molecule of H_2, HD, LiH in the low density limit ($n(H) \lesssim 10^2$ cm^{-3}).

HD formation

in primordial star-forming clouds

formation reaction

$D^+ + H_2 \longrightarrow HD + H^+ + Q(488K)$: exothermic

this and inverse reactions are approximately in equilibrium:

$n(HD)/n(H_2) = 2 \exp(488K/T) \times [D]/[H]$

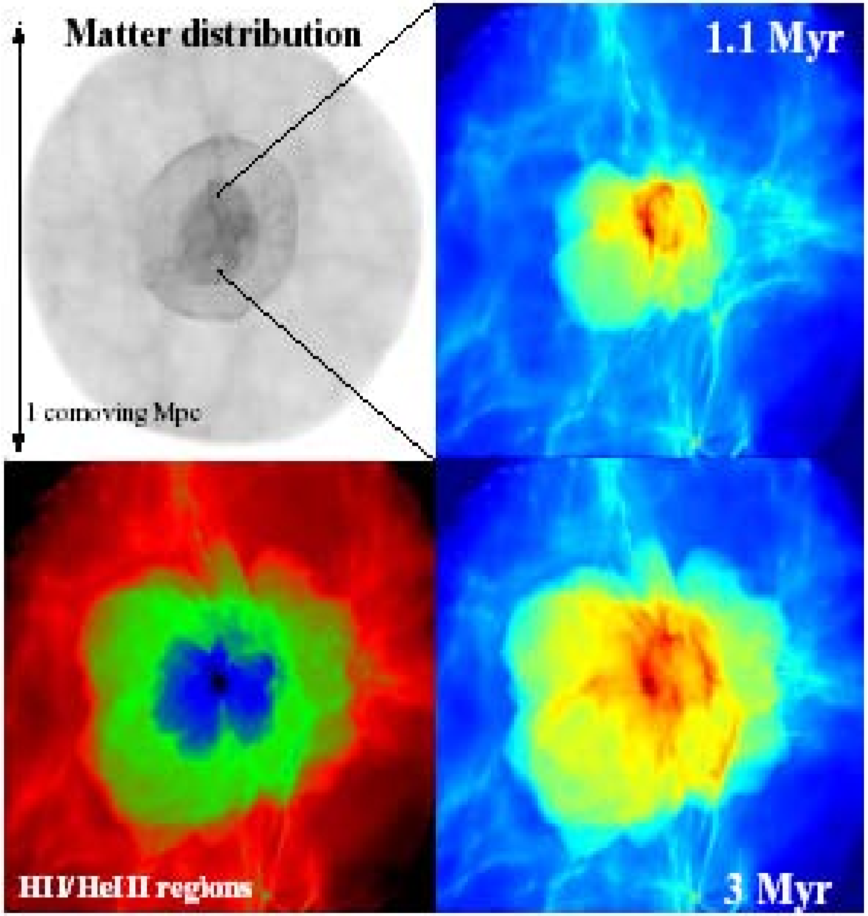
large HD fractionation in low temperature ($T<150K$) environment

→ efficient HD cooling

How such low temperature can be attained before HD cooling?

Primordial SF form pre-ionized gas

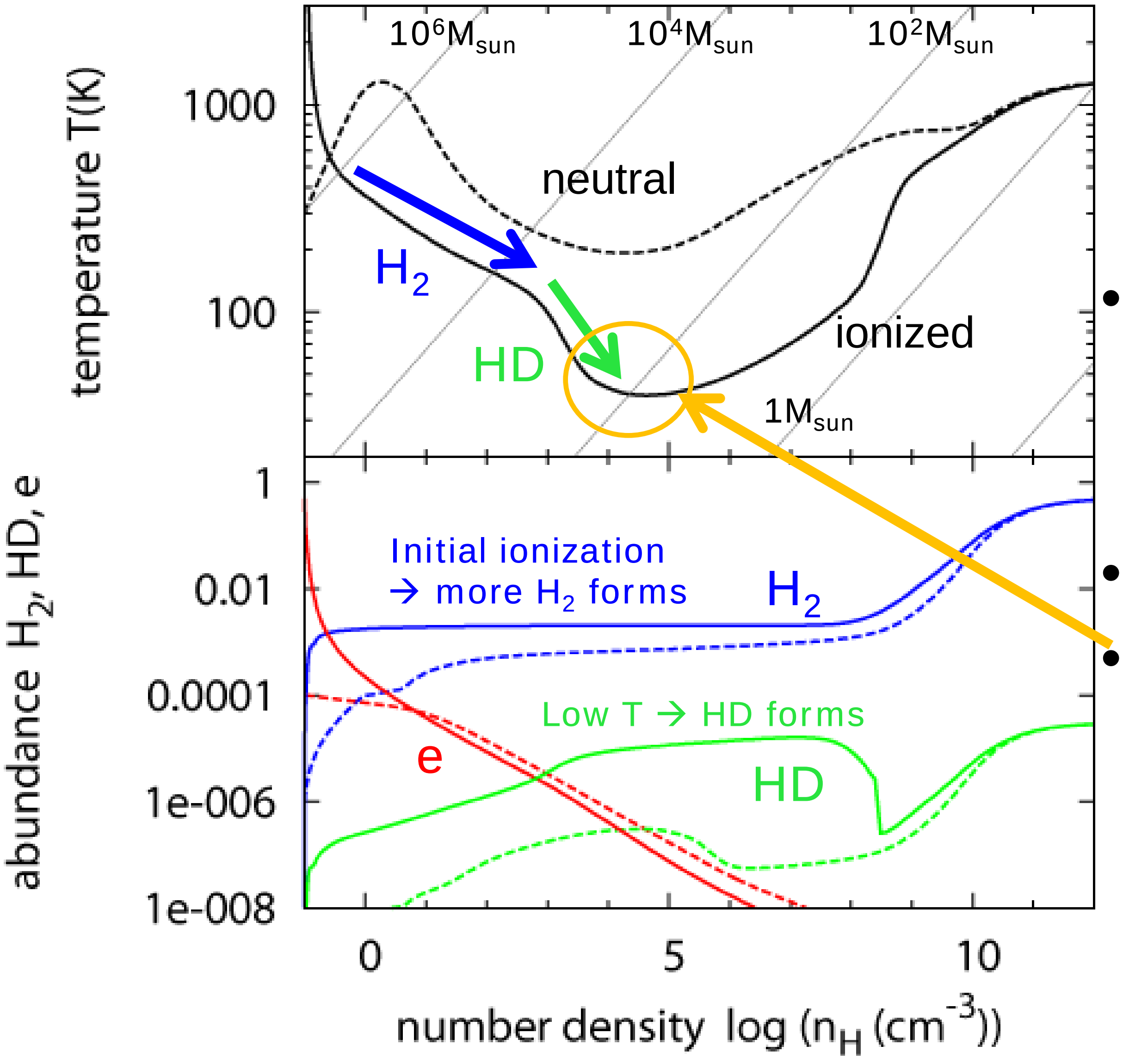
Relic HII Region



Yoshida, Oh, Kitayama, & Hernquist (2007)

- First Star creates an HII region.
- After the death of the first star, recombination proceeds in the relic HII region
- Another episode of star formation commences (**Pop III.2 stars**)

Pop III.2 (HD-mode): Star formation from pre-ionized gas



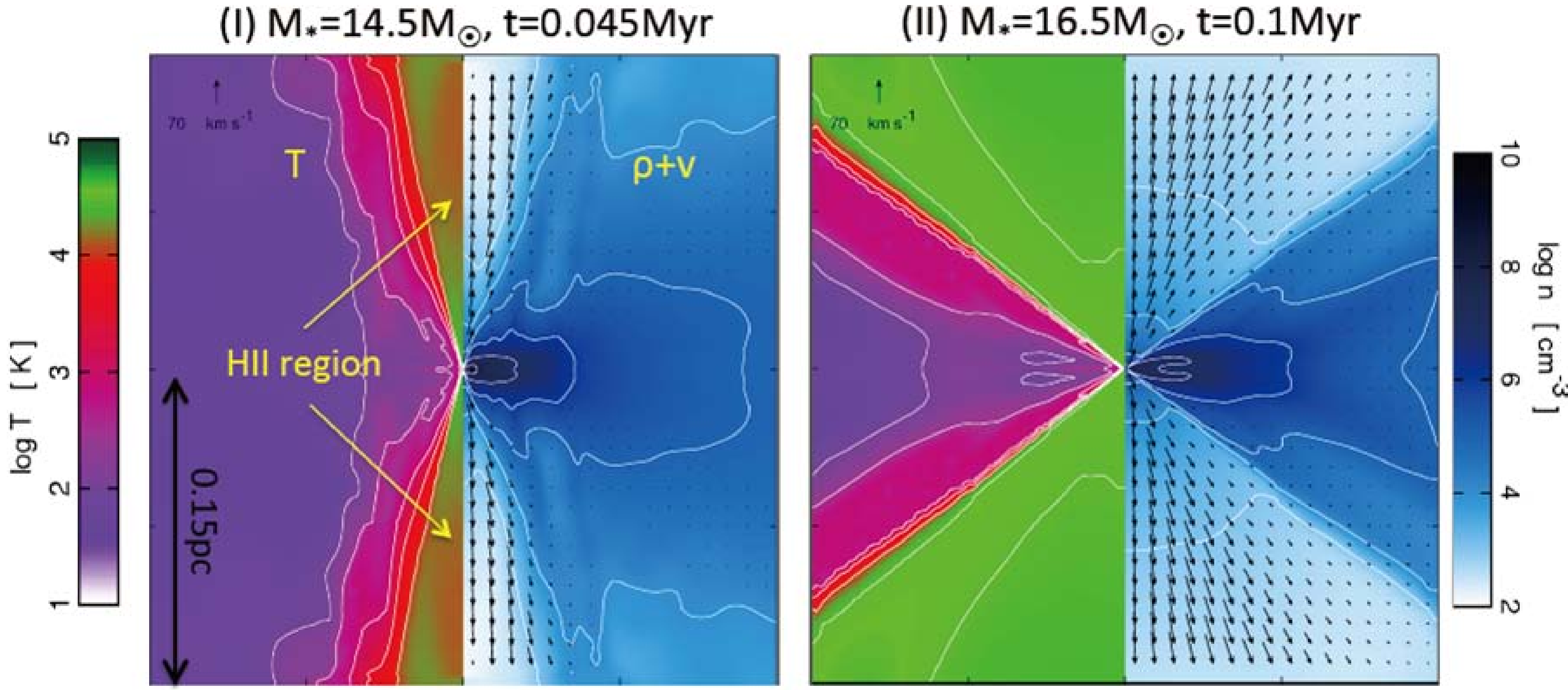
Uehara & Inutsuka 2002
Nagakura & KO 2005
Johnson & Bromm 2006
Yoshida, KO, Hernquist 2007
McGreer & Bryan 2008

- Ionized environments
  e.g., relic HII region,
  SN blast wave,
  structure formation shock
- HD formation and cooling
- An order of magnitude smaller dense core mass scale (~several 10M_{sun})

Accretion evolution in Pop III.2 case (HD mode)

Hosokawa, Yoshida, KO, Yorke 2012

- Cosmological initial setting (data from Yoshida+ 07)

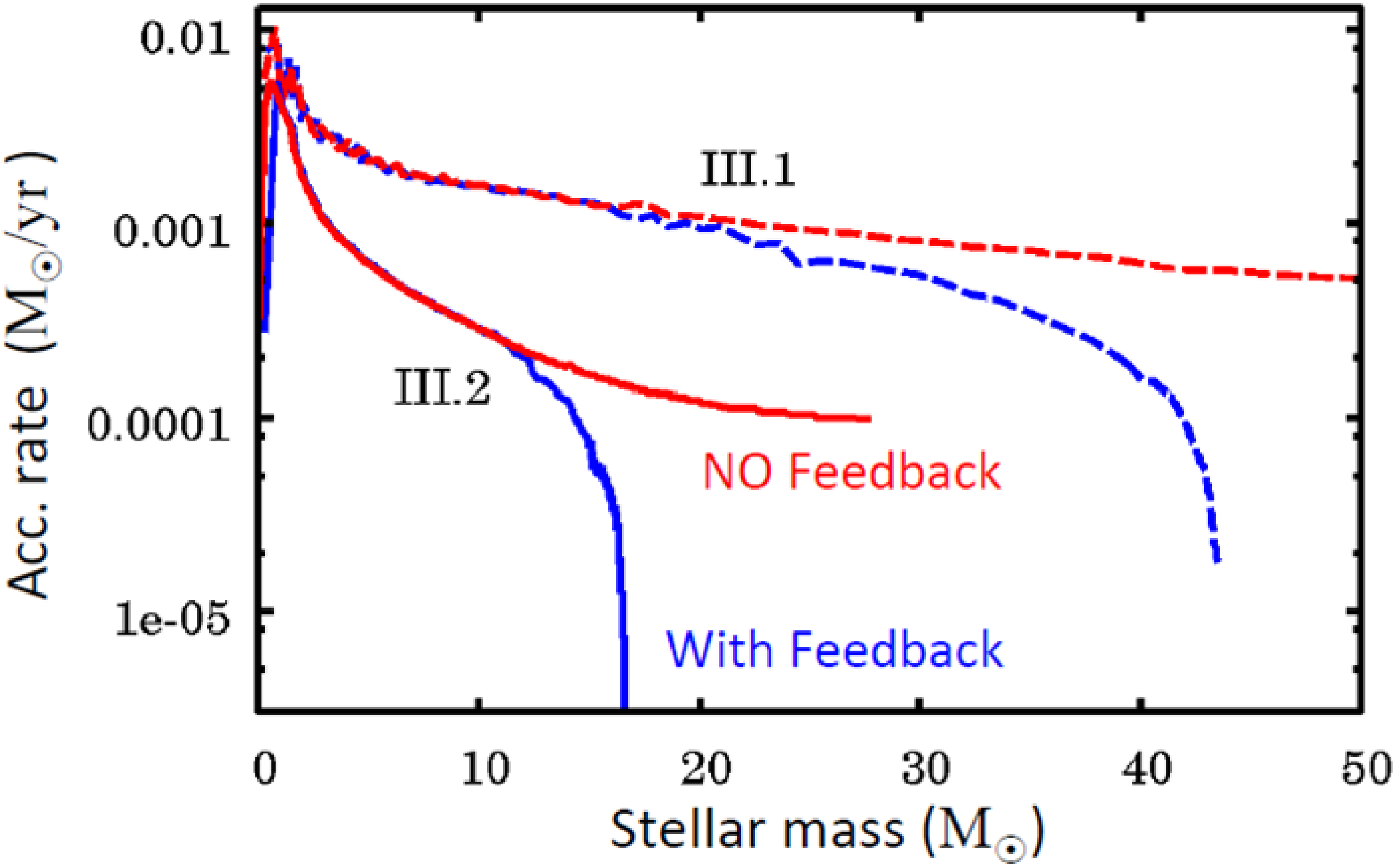


(I) $M_*=14.5M_\odot$, t=0.045Myr

(II) $M_*=16.5M_\odot$, t=0.1Myr

- HII region forms at the lower stellar mass compared to Pop III.1 case
- Evolution timescale is similar to that in Pop III.1 case (∼0.1Myr)

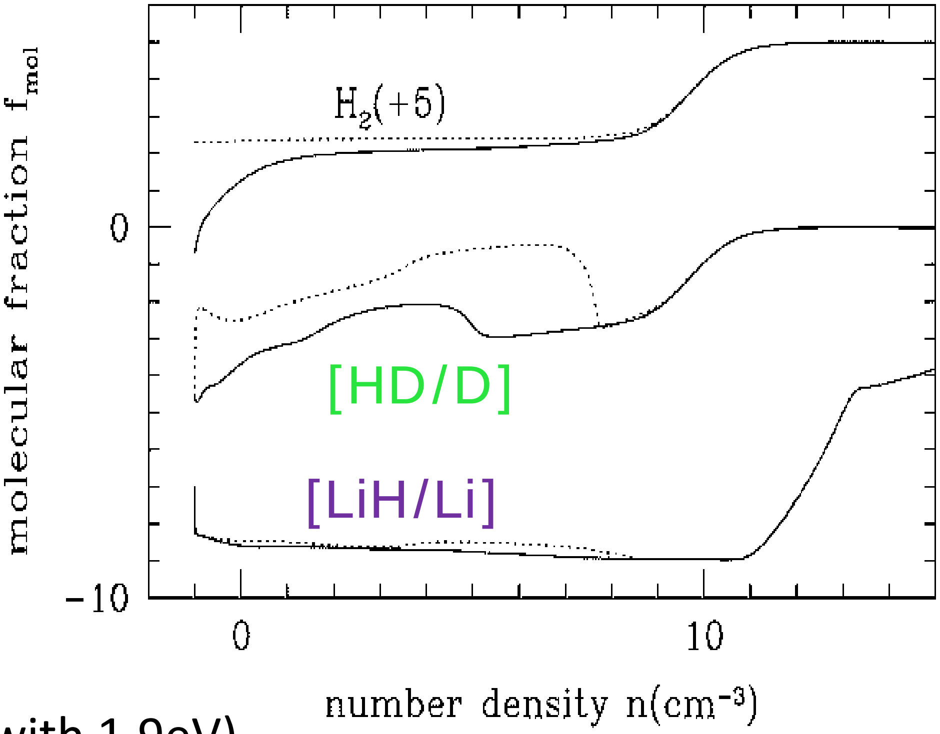
Final mass of Pop III.2 Stars



- ➢ Pop III.2: accretion rates are lower than Pop III.1 (←lower T)
- ➢ 17 $M_\odot$ star forms about 0.1Myr after the protostar's birth
- ➢ PopIII.2: less massive than PopIII.1, but only by a factor of **a few**

LiH : not important

Mizusawa, KO, Nishi 2005



LiH chemistry

(Stancil, Lepp, Dalgarno 1996; Bougleux and Galli 1997)

✓ formation

$Li + H \rightarrow LiH + \gamma$

(low density; < 10^{11}cm^{-3})

$Li + H + H_2 \rightarrow LiH + H_2$

(high denisity; > 10^{11}cm^{-3})

✓ dissociation

$LiH + H \rightarrow Li + H_2$ (exothermic with 1.9eV)

efficiently destroys most of LiH available

➔ LiH never be an important coolant because only very little Li is in the form of LiH (LiH/Li~10^{-4} ; n>10^{13}cm^{-3})

Photodissociation effects on HD formation

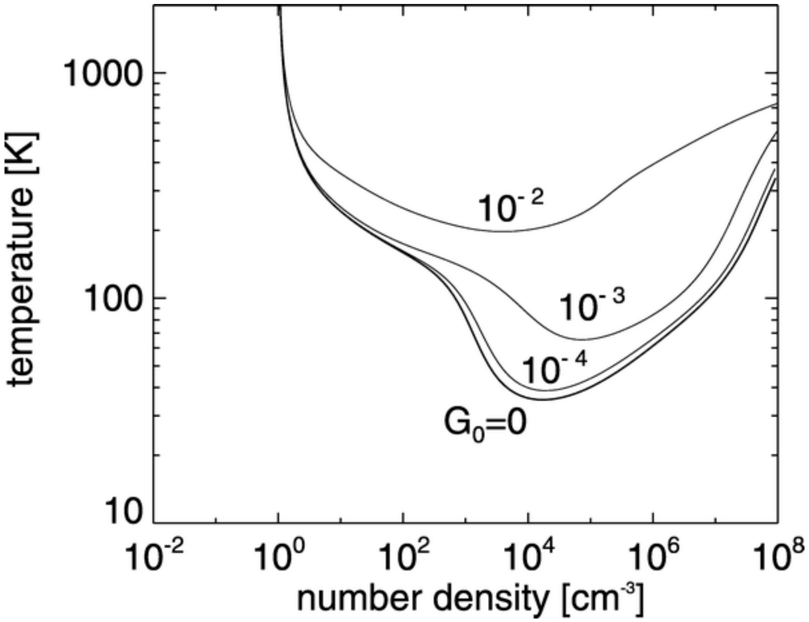
Yoshida, KO & Hernquist (2007);
Wolcott-Green & Haiman (2011)

G_0: strength of FUV
~1 in our Galactic disk
$J_{21}=30G_0$

- Vulnerable to small FUV
- $G_0>\sim10^{-2}$
  no HD cooling
- This is due to H_2 photodissociation
  (Not due to direct HD photodissociation)

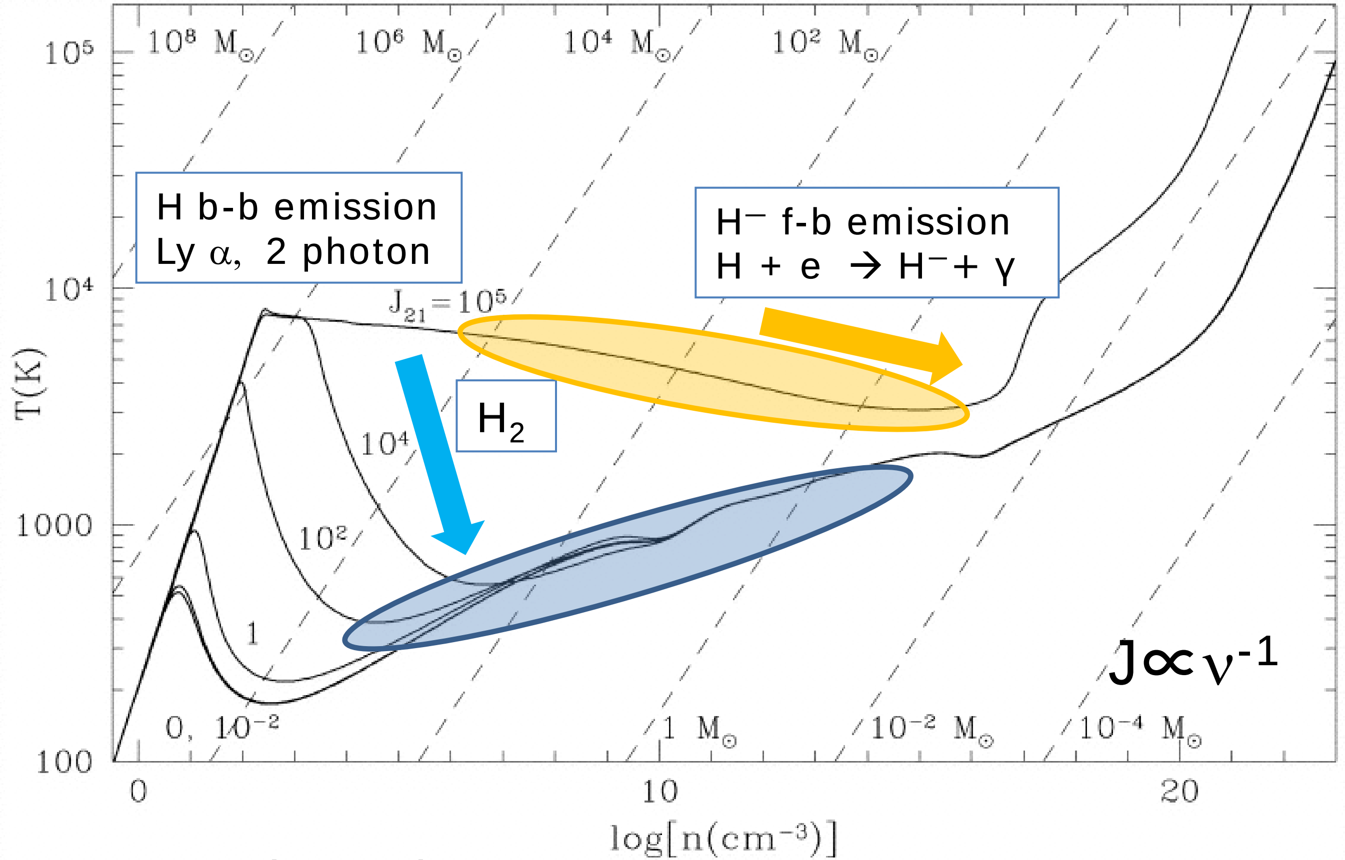
Few Pop III.2 in Relic HII regions?

Still formed in shocked region?



primordial gas in strong FUV field: atomic cooling mode

KO 2001
KO & Yoshii 2003
Shang+ 2010
Schleicher+ 2011
Inayoshi & KO 2011



FUV intensity

✓ $J<J_{crit}$

→ at some density, H_2 cooling and fragmentation

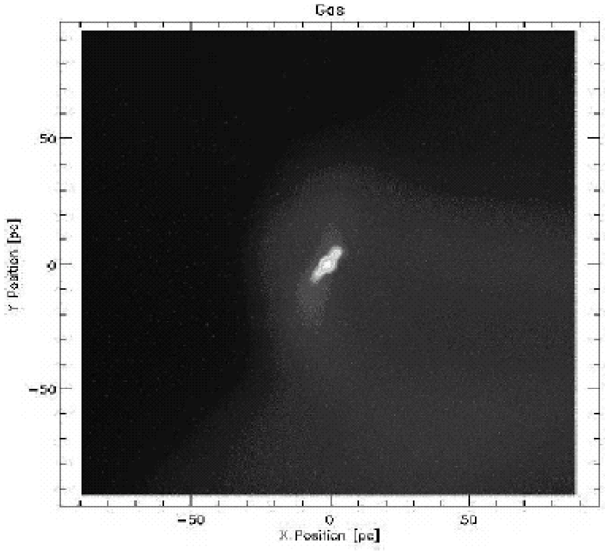
✓ $J>J_{crit}$

→ **isothermal collapse** continues

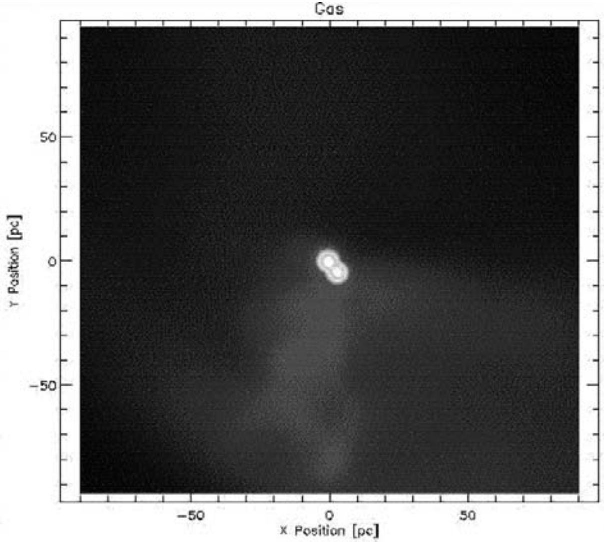
SMS formation by the isothermal collapse

Bromm & Loeb 2003

non-rotating



rotating

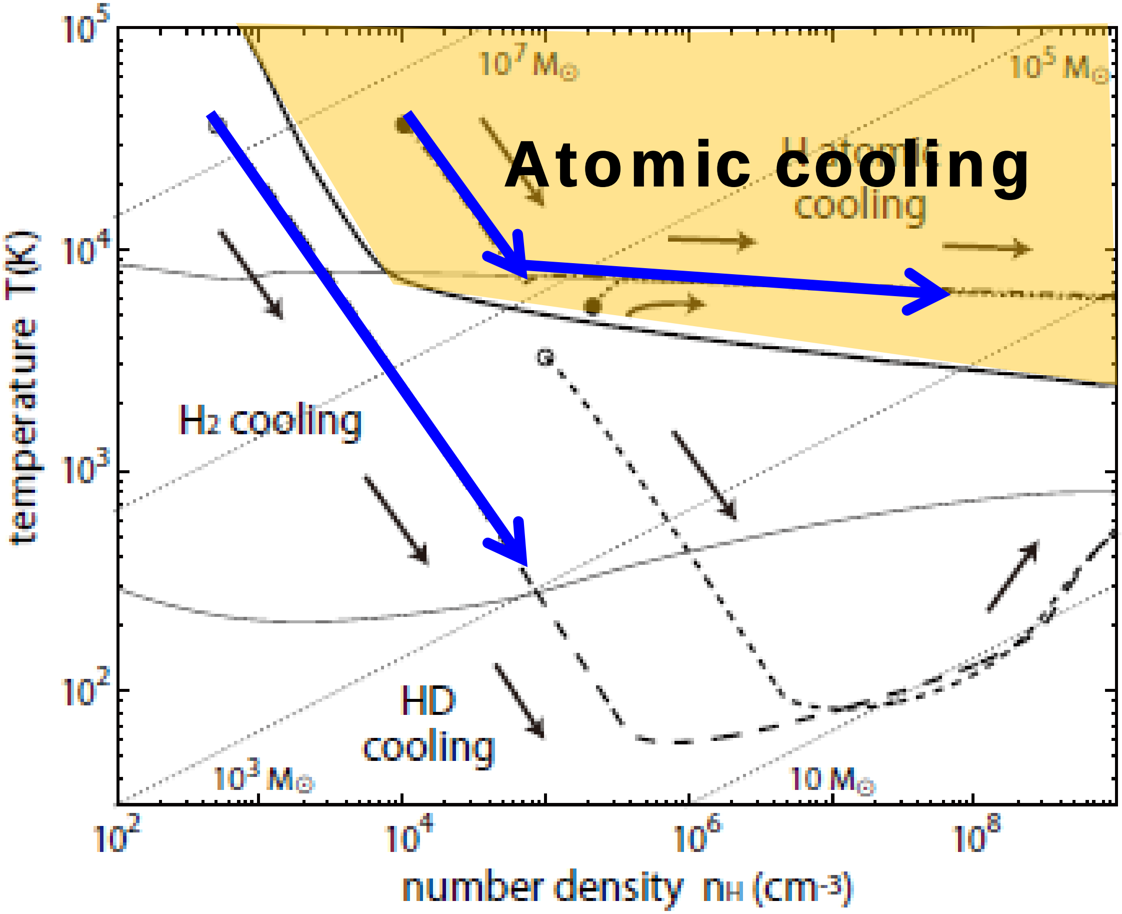


✓$M \sim 10^8 M_{sun}$ halo virializing at $z \sim 10$ (2σ over-density) with strong FUV $J_{21} \sim 4000$

✓Fragmentation is inefficient

→direct collapse to $10^6 M_{sun}$ supermassive star

Alternative mechanism for isothermal collapse: high-density shock in primordial gas

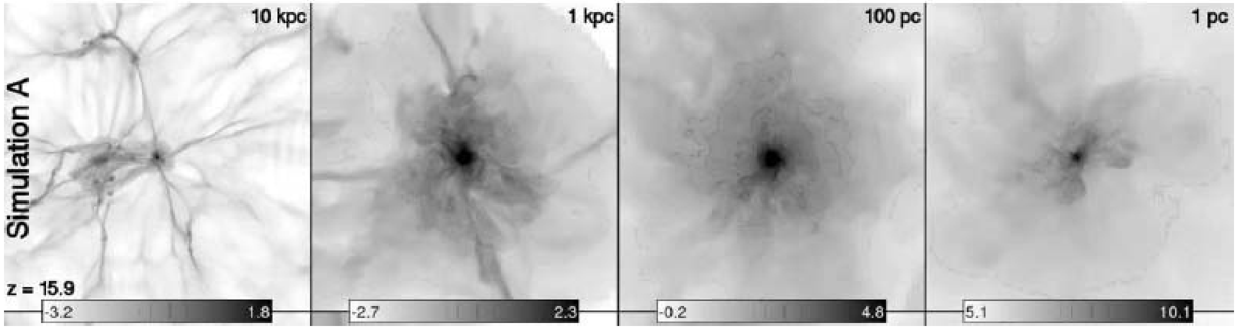


- shocks at $>10^{3\text{-}4}$/cc, with> several 10^3K
  - H_2 collisionally dissociated
  - Fragments at 8000K with $>\sim 10^5 M_{sun}$
  - Isothermal collapse by atomic cooling thereafter

Inayoshi & KO 2012

Possible sites of high-density shocks

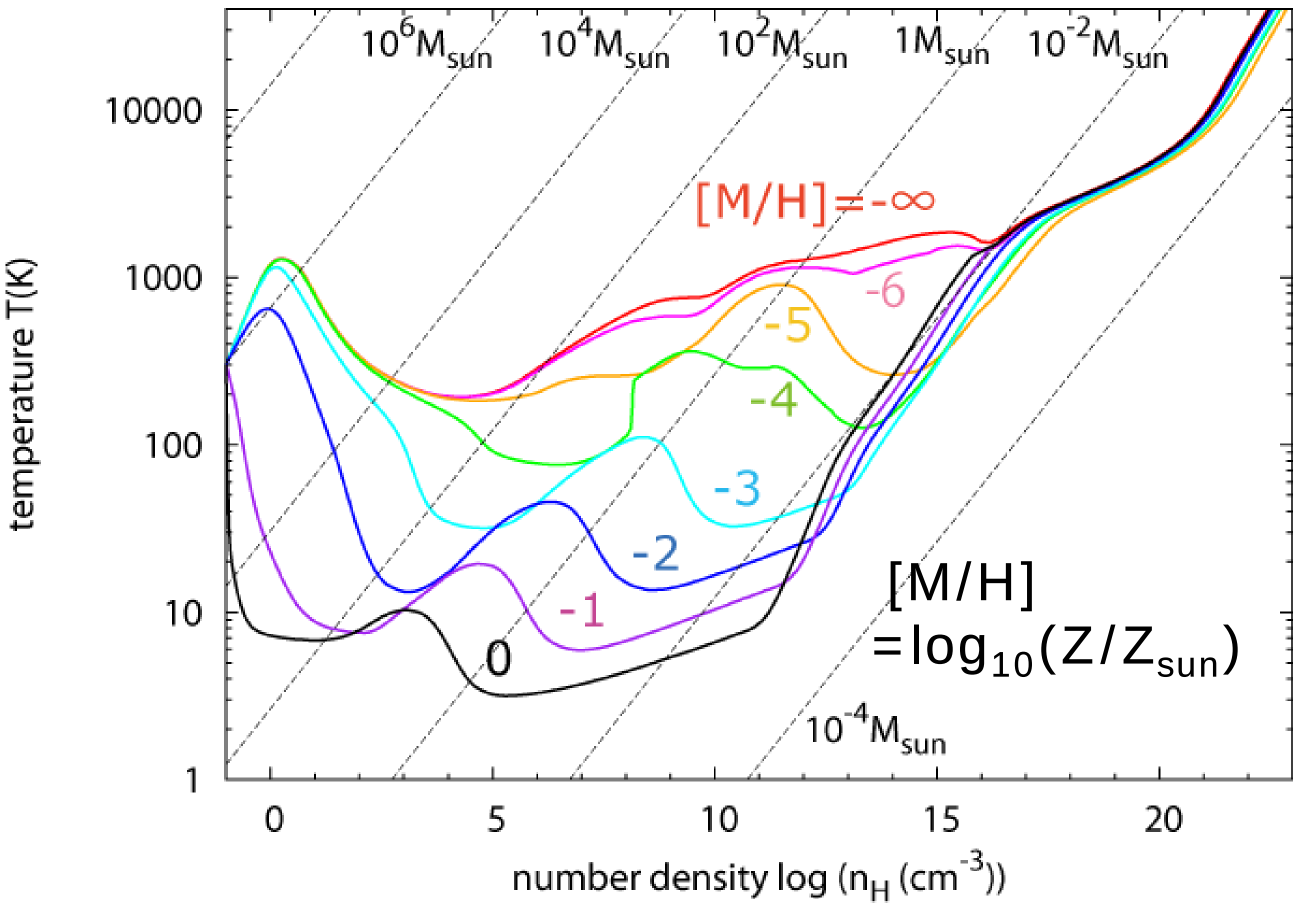
- Cold-accretion-flow shock in the central ~10pc region of the first galaxy
  (Wise, Turk & Abel 2008)



- Galaxy merger driven inflow
  (Mayer et al. 2010)
  ← probably metal-rich

Metallicity Effects

Thermal Evolution of clouds with different Z



one-zone model

- collapses in the free-fall timescale

$t_{dyn}=d\rho/(d\rho/dt) = t_{ff}$

- core size ~ the Jeans length
- dust/metal ratio same as local ISM

K.O., Tsuribe, Schneider & Ferrara (2005)

Important processes in low-Z gas

Primordial-gas process

- H&D chemistry
- H_2 (line, collision-induced emission) & HD line cooling

+

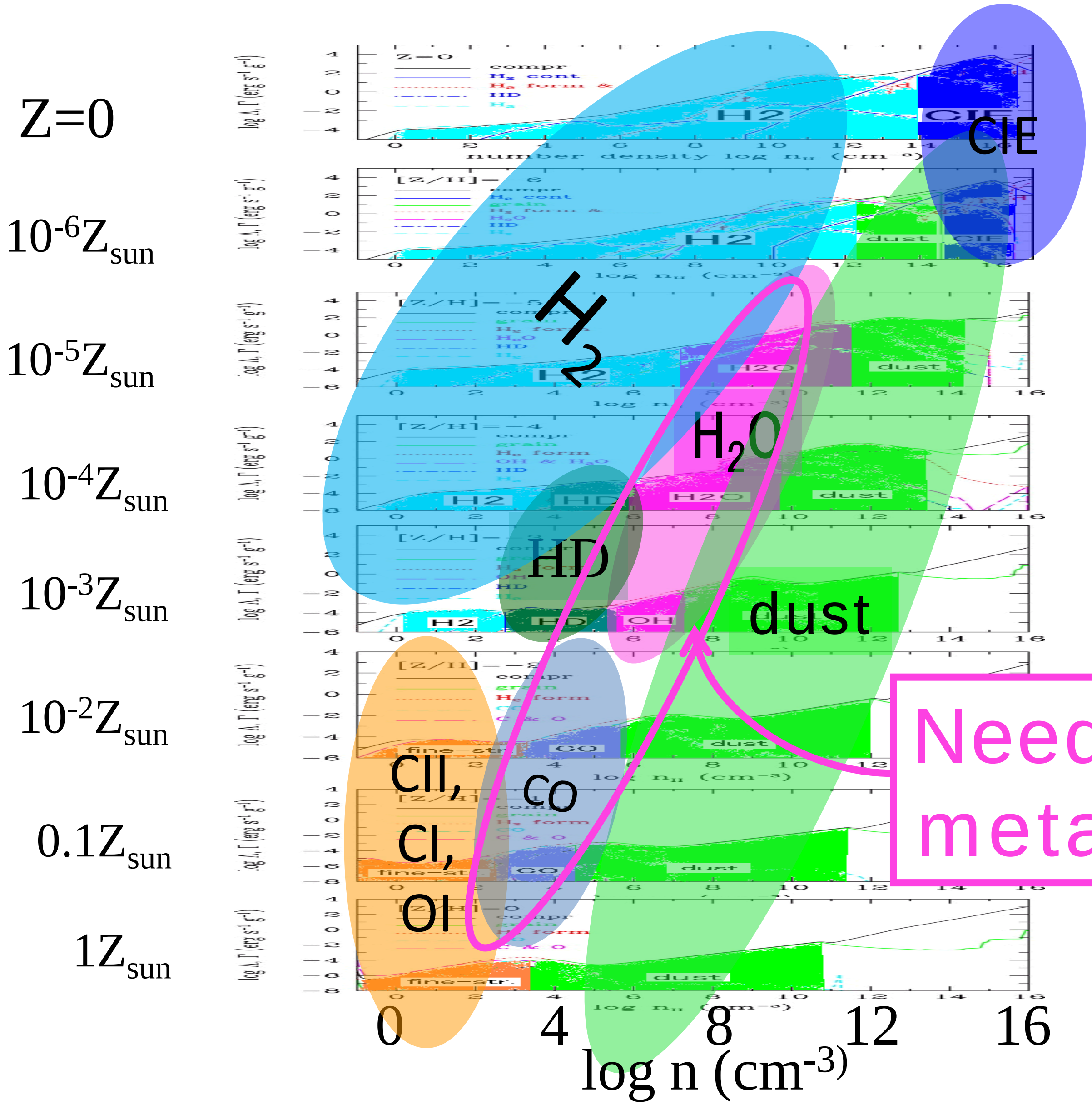
Metal-line cooling

- fine-structure lines ([CII], [CI], [OI])
- molecular lines (H_2O, OH, CO)
  ← metal chemistry

Dust processes

- H_2 formation on dust
- cooling by dust thermal emission
  ← dust temperature

Dominant coolants in low-metallicity gas



Z=0

- H_2 lines ($<10^{13}cm^{-3}$)
- H_2 CIE (10^{13}-$10^{16}cm^{-3}$)

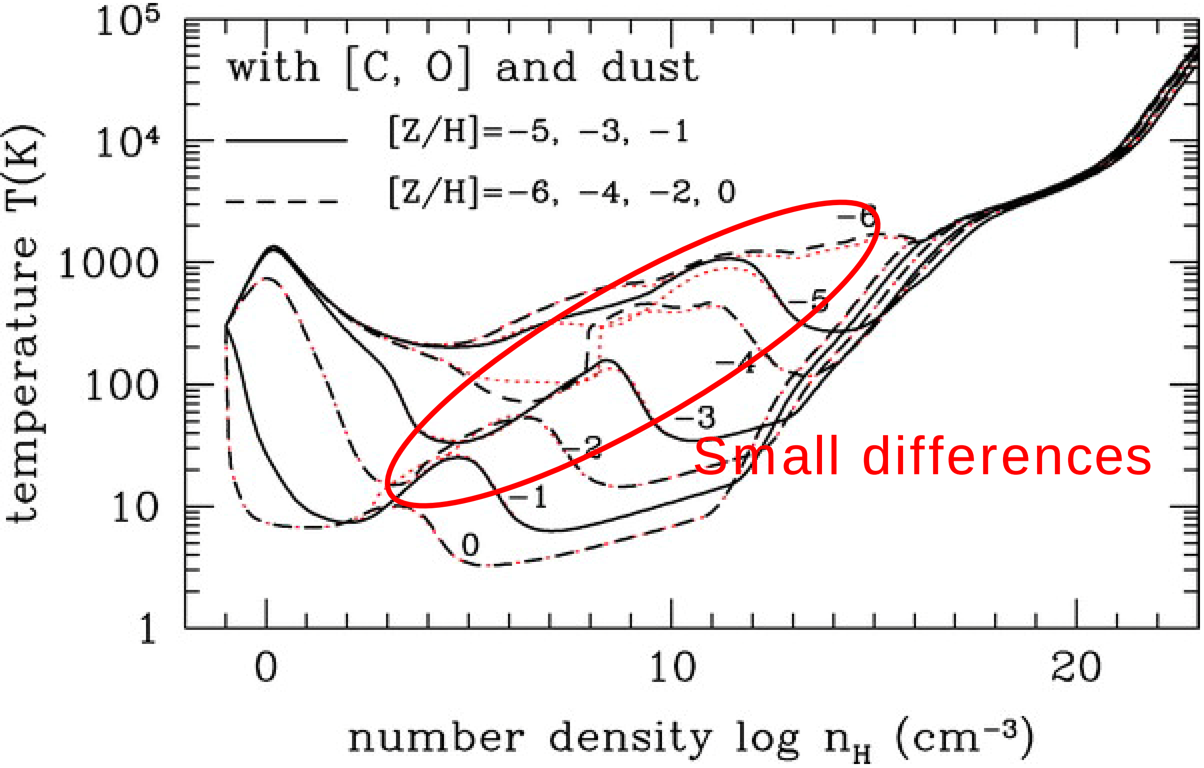
$Z=10^{-4}Z_{sun}$

- H_2 lines ($<10^{4}cm^{-3}$)
- HD (10^{4}-$10^{6}cm^{-3}$)
- H_2O (10^{6}-$10^{10}cm^{-3}$)
- dust (10^{10}-$10^{13}cm^{-3}$)

Need to solve metal chemistry

- dust (10^{6}-$10^{12}cm^{-3}$)

Full chemistry vs no metal chemistry



Red dotted
full chemistry

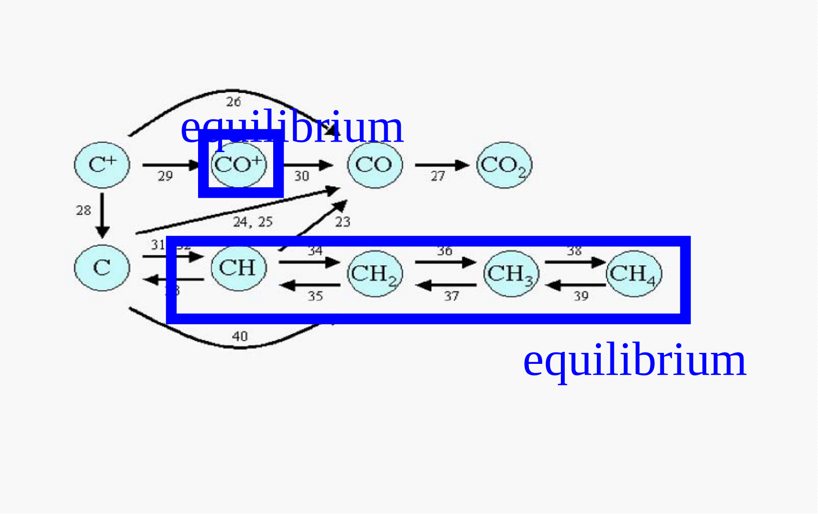
Black (solid & dashed)
with only [C,O] and dust
(no C, O chemistry)

For those care about metal chemistry

Reduced chemical model (KO, Hosokawa, Yoshida 2010)

C chemistry:

$C^+ \rightarrow C^0 \rightarrow CO \rightarrow CO_2$

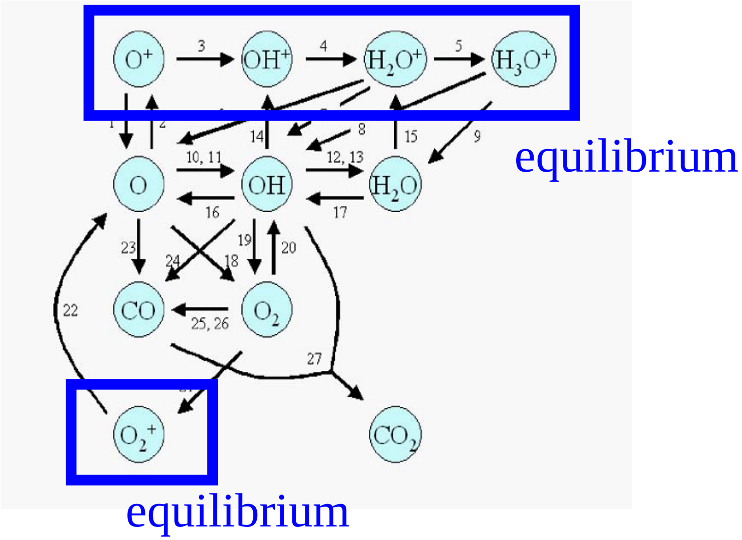


O chemistry:

$O \rightarrow OH \rightarrow H_2O$

$\rightarrow O_2$

$\rightarrow CO \rightarrow CO_2$



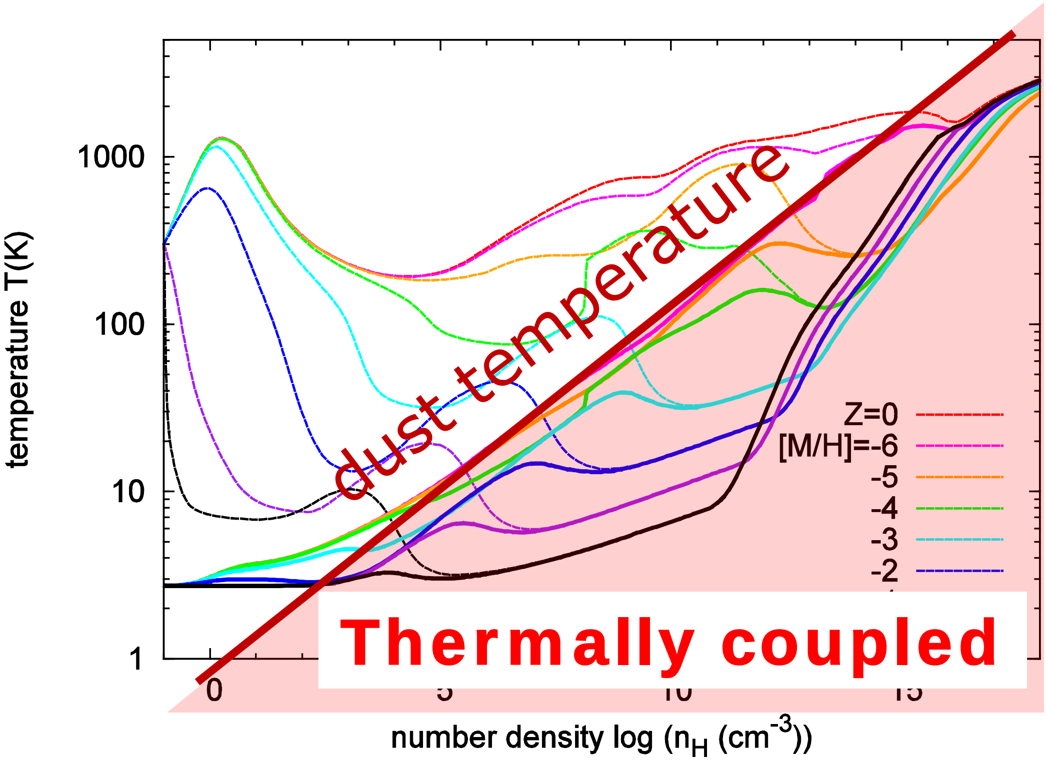
Non-equilbrium chemistry among 15 species (H, H_2, H^+, e, D, HD, D^+, C, CO, CO_2, C^+, O, OH, H_2O, O_2) reproduces well result of the full chemistry with 50 species

Dust temperature ≠ gas temperature

radiative cooling collisional heating

$$4\kappa_P \rho_{gr} \sigma T_{gr}^4 = n_{gr} \sigma_{gr} \overline{nv} \left(2kT - 2kT_{gr}\right)$$

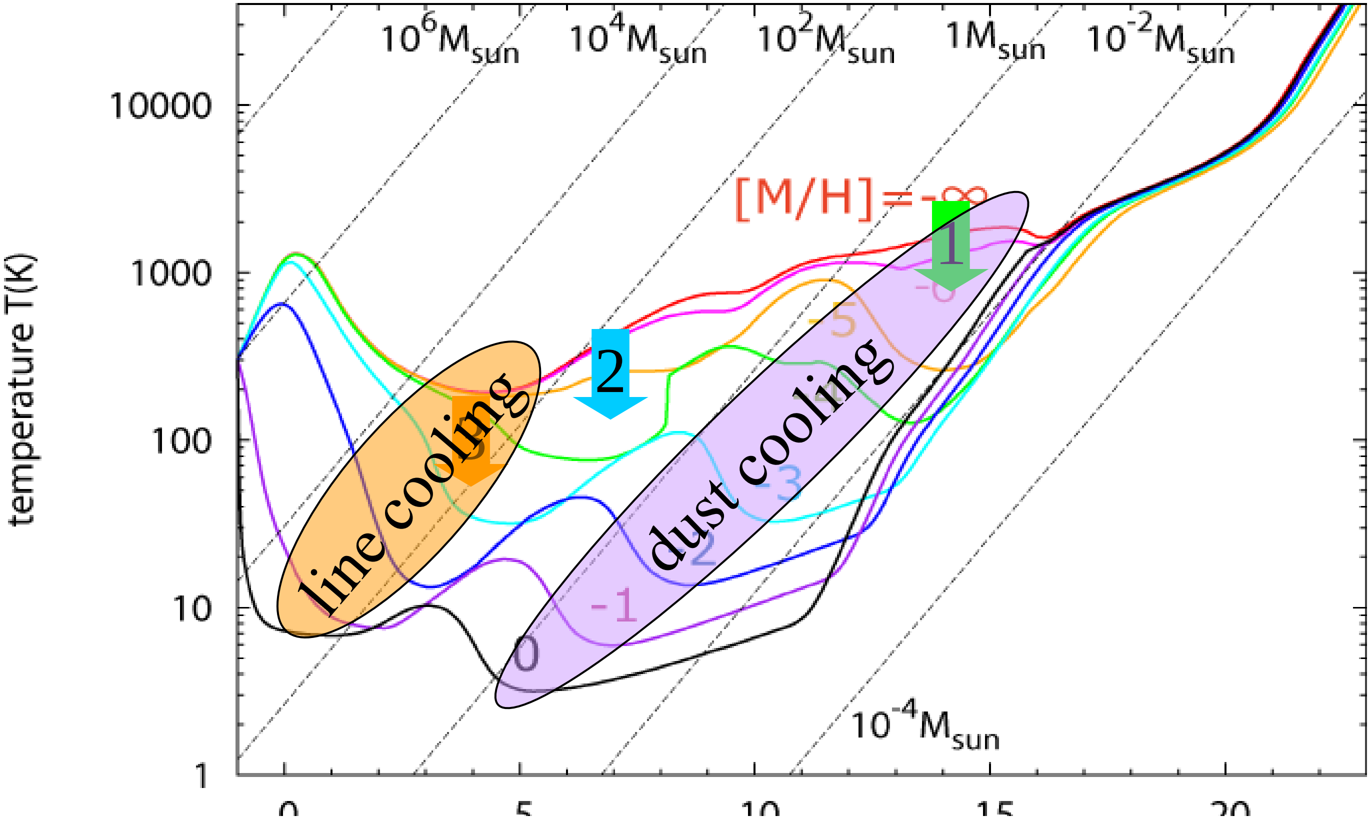
$$\Rightarrow T_{gr} \simeq 120\,K \left(\frac{T}{100K}\right)^{0.3} \left(\frac{n}{10^{10}cm^{-3}}\right)^{0.2}$$



- In lower Z gas, dust and gas temperatures don't couple until higher density.
- Need to solve dust temperature separately.

Thermal evolution of clouds with different Z

1) Cooling by dust thermal emission: [M/H] > -5
2) H_2 formation on dust : [M/H] > -4
3) Cooling by fine-str. lines (C and O): [M/H] > -3



KO+2005
input physics
updated

Low-mass fragments are formed only in the dust-induced mode.

How much dust is needed?

✓***Primordial stars*** (Pop III.1,2 stars)

theoretically predicted to be massive(～ several 10M_{sun})

✓***Stars in the solar neighborhood*** (Pop I)

typically low-mass(0.1-1M_{sun})

Low-mass Pop II stars exist in the halo.

●transition of characteristic stellar mass in the early universe from massive to low-mass

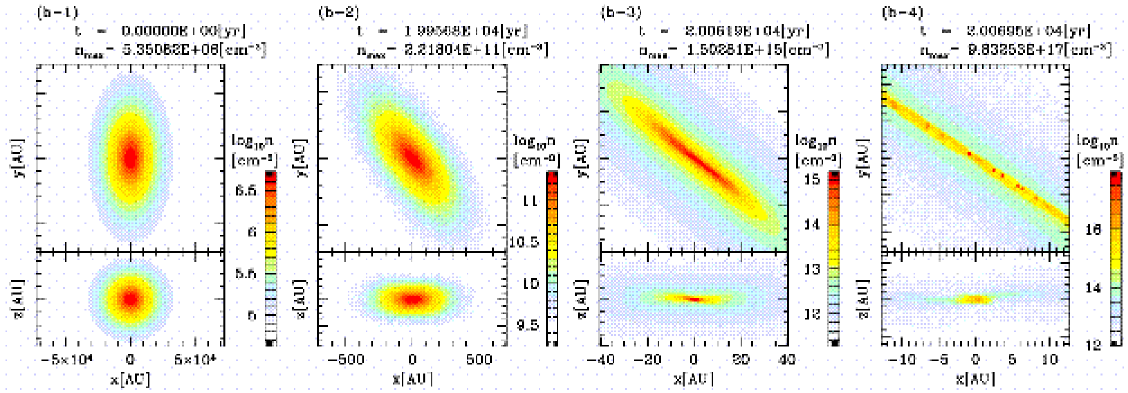
Pop III-II transition

●This transition is probably caused by accumulation of a certain amount of metals and dusts in ISM ***critical metallicity***

Dust-induced fragmentation

Tsuribe & KO (2006; 2008)

[M/H]=-5.5 ($Z=3\times10^{-6}Z_{sun}$)



$Z>\sim10^{-6}Z_{sun}$

→ long filament forms during dust-cooling phase

→ fragmentation into low-mass (0.1-1M_{sun}) objects

Using barotropic temperature relation from one-zone model

Standard dust

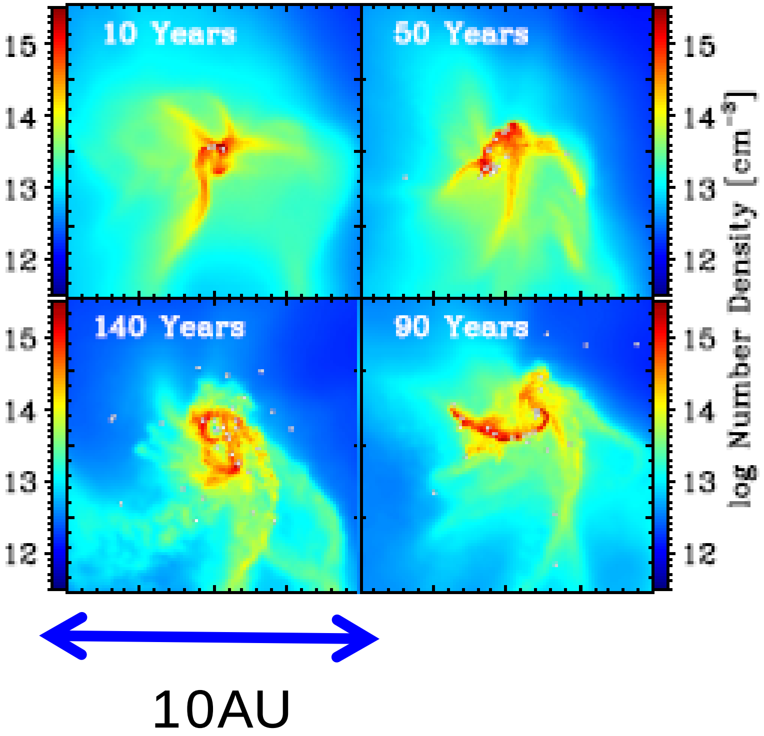
$$\boxed{Z_{cr}\sim10^{-6}\text{-}10^{-5}\ Z_{sun}}$$

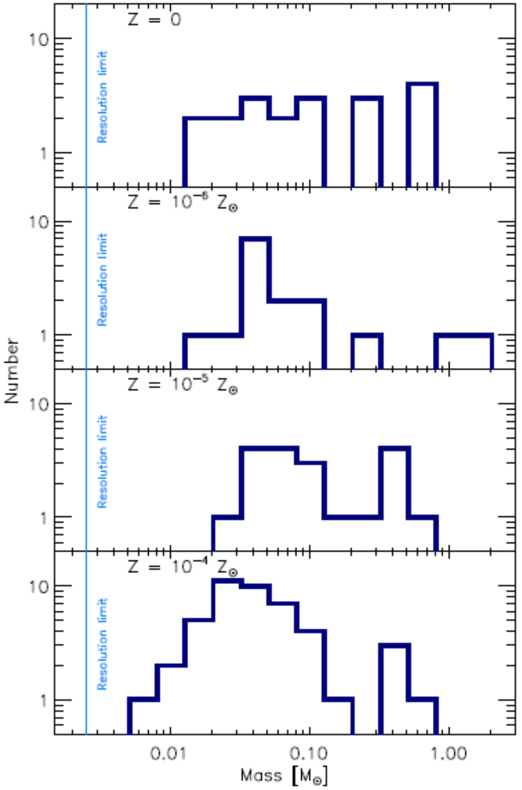
First dust

Dust-induced fragmentation

Clarke +(2008), Dopcke + (2011, 12)

$[M/H]_{dust} = -4$





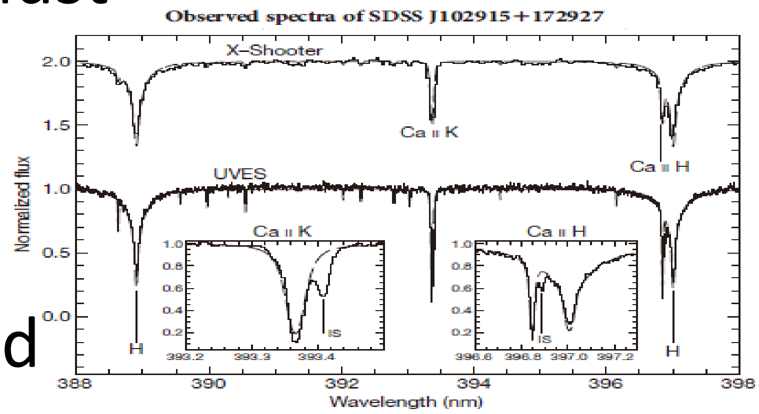
- Rapid cooling by dust at high density ($n \sim 10^{14}$cm^{-3}) leads to core fragmentation. $M_{frag} \sim 0.1\ M_{sun}$
- With slight dust enrichment, characteristic stellar mass shifts to low-mass
- Pop II transition proceeds as a change in the shape of IMF, rather than abrupt shift in the mass scale.

Recent discovery in support of the dust fragmentation theory

An extremely primitive star in the Galactic halo

Elisabetta Caffau[1,2], Piercarlo Bonifacio[2], Patrick François[2,3], Luca Sbordone[1,2,4], Lorenzo Monaco[5], Monique Spite[2], François Spite[2], Hans-G. Ludwig[1,2], Roger Cayrel[2], Simone Zaggia[6], François Hammer[2], Sofia Randich[7], Paolo Molaro[8] & Vanessa Hill[9]

- Lowest metallicity (including C and O) star ever found $4.5 \times 10^{-5} Z_{sun}$
- Dust-induced fragmentation is able to explain its formation.



Caffau + 2011

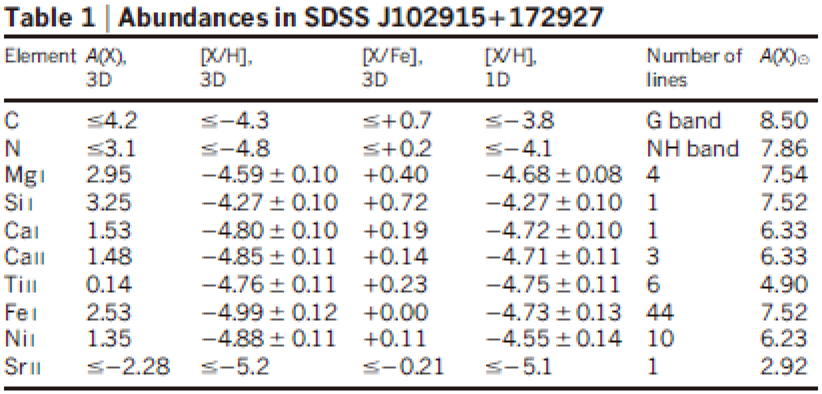
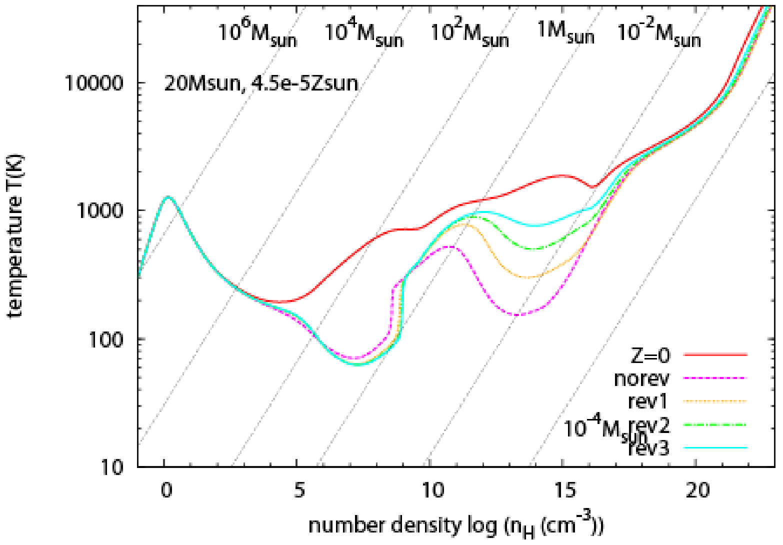


Table 1 | Abundances in SDSS J102915+172927

Element	A(X), 3D	[X/H], 3D	[X/Fe], 3D	[X/H], 1D	Number of lines	$A(X)_\odot$
C	≲4.2	≲−4.3	≲+0.7	≲−3.8	G band	8.50
N	≲3.1	≲−4.8	≲+0.2	≲−4.1	NH band	7.86
Mg I	2.95	−4.59 ± 0.10	+0.40	−4.68 ± 0.08	4	7.54
Si I	3.25	−4.27 ± 0.10	+0.72	−4.27 ± 0.10	1	7.52
Ca I	1.53	−4.80 ± 0.10	+0.19	−4.72 ± 0.10	1	6.33
Ca II	1.48	−4.85 ± 0.11	+0.14	−4.71 ± 0.11	3	6.33
Ti II	0.14	−4.76 ± 0.11	+0.23	−4.75 ± 0.11	6	4.90
Fe I	2.53	−4.99 ± 0.12	+0.00	−4.73 ± 0.13	44	7.52
Ni I	1.35	−4.88 ± 0.11	+0.11	−4.55 ± 0.14	10	6.23
Sr II	≲−2.28	≲−5.2	≲−0.21	≲−5.1	1	2.92



SUMMARY (1)

Three modes of Metal-free star formation

First stars – stars from pristine gas (Pop III.1 stars)
H_2 cooling
several $10^2 M_{sun}$ core → $40 M_{sun}$ star

Stars from pre-ionized gas (Pop III.2 stars)
H_2 and HD cooling
several $10 M_{sun}$ core → $20 M_{sun}$ star
but, HD fragile in FUV field

If H_2 is totally absent (due to photo-/ collisional dissociation)
atomic (Lyα, H^- f-b) cooling :
→ supermassive ($>\sim 10^5 M_{sun}$) star formation

SUMMARY (2)

With a small amount of metals

Metal-line cooling (at low density $<\sim 10^8$cm^{-3})
fine-structure lines ([CII], [OI]),
molecular lines (CO, H_2O, OH) :sub-dominant
affects the thermal evolution only at low densities
where the Jeans mass is still high (>10-$100M_{sun}$).

Dust cooling (at high density $>\sim 10^8$cm^{-3})
causes a sudden temperature drop at high density where
$M_{Jeans} \sim 0.1M_{sun}$, which induces low-mass fragmentation.

The critical metallicity for dust-induced fragmentation
$[Z/H]_{cr} \sim -5$
consistent with recent finding of the most primitive star
(Caffau 2011)