宇宙の第一世代天体とWMAPのthree year result

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I. WMAP observation
II. Numerical Simulations on Pop III Stars
III. Observational Constraints for Pop III IMF
IV. Problems on Pop III IMF

Time

天体の起源

物質の起源

Redshift

10^{-44}s

10^{30}

量子ゆらぎ

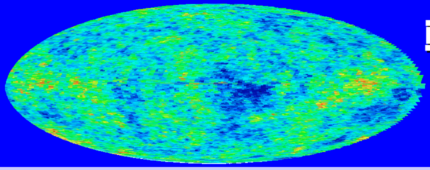
↓

古典ゆらぎ

真空エネルギー（輻射）
インフレーション

↓

ダークマター粒子生成
QCD相転移
軽元素合成(n,p,D,He,Li, Be)



CMBゆらぎ

中性水素

0.4Myr

10^3

宇宙暗黒時代

第一世代天体
（Stars, BHs）

→

超新星爆発
SN II
Hypernova

→

重元素
C,N,O,Mg, …Fe
Co,Ni,Cu,Zn,…Eu

1Gyr

宇宙再電離

10

銀河
(bulge-,disk-,halo-stars)
AGN

SN II
Hypernova
SN Ia

ダスト

Polymer

惑星系，大規模構造

有機物

13.7Gyr
(Present)

1

WMAP 1st Year

Cosmological Parameters (CDM Universe)

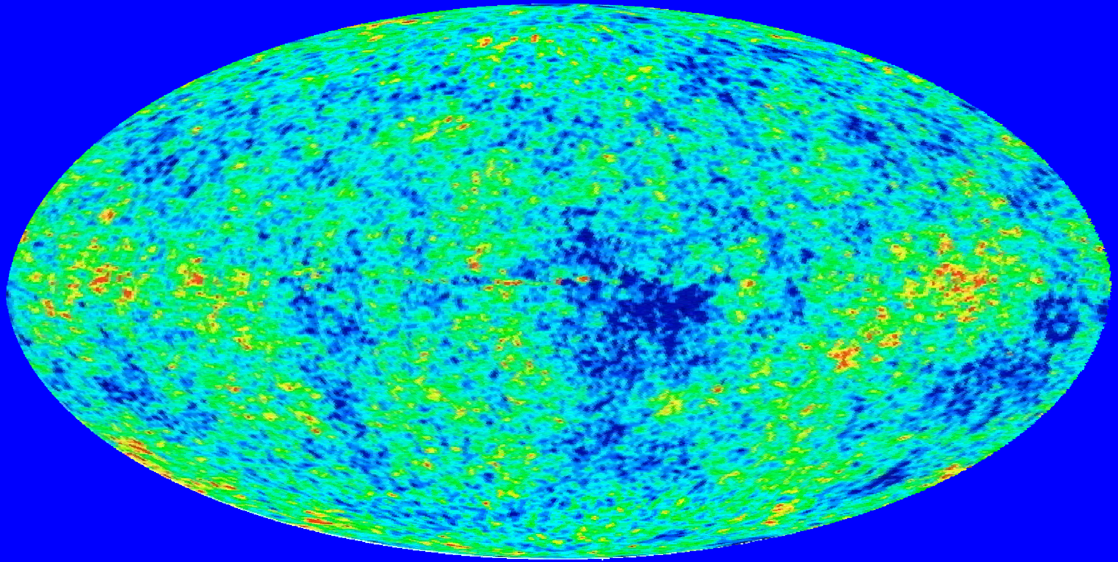
$\Omega_{tot} = 1.02$

$\Omega_{\Lambda 0} = 0.73$

$\Omega_{\mathrm{CDM}} h_0^2 = 0.135$

$\Omega_b h_0^2 = 0.0224$

$h_0 = 0.71$

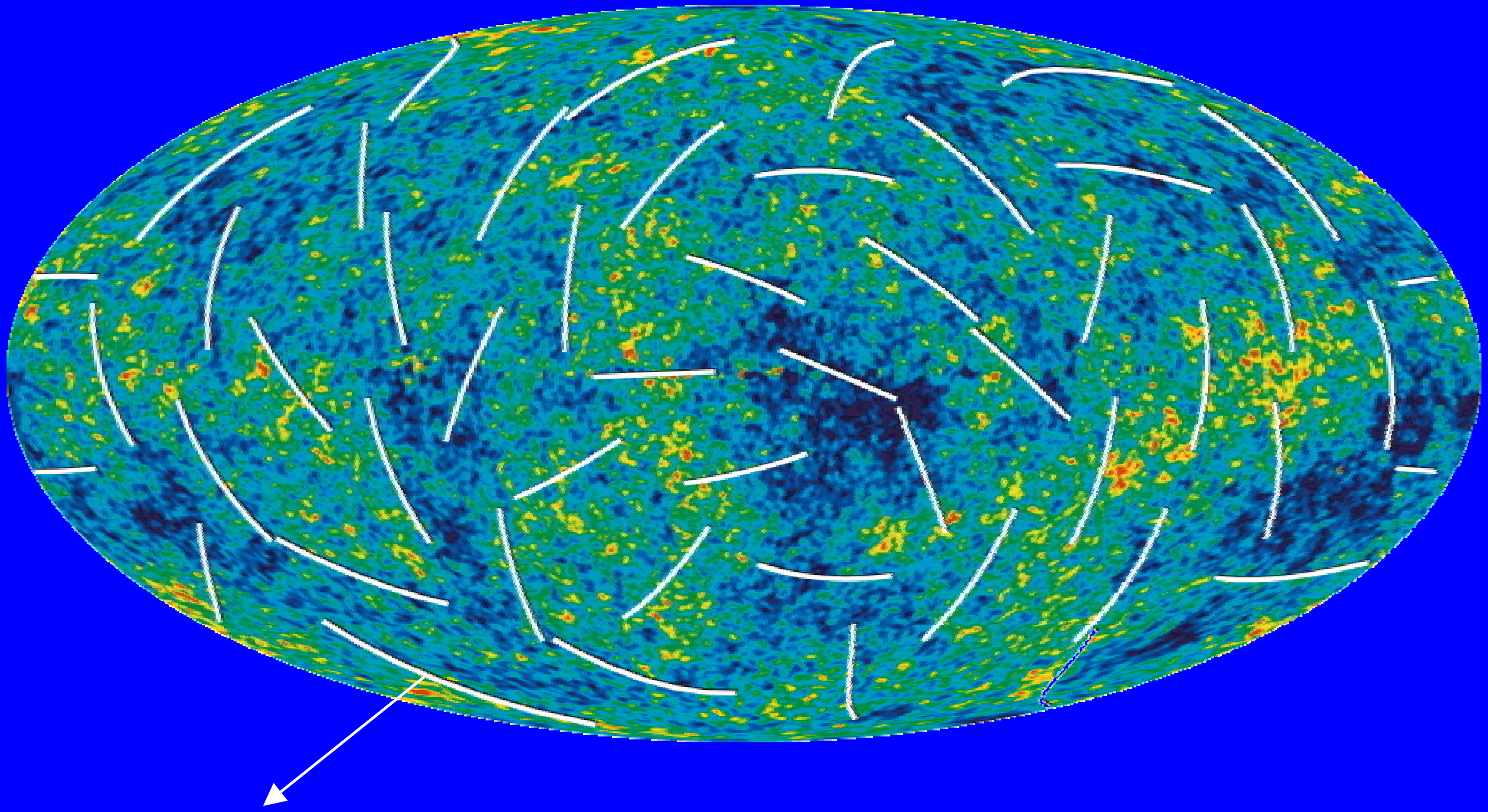


Fluctuation Spectrum (CDM)

$\sigma_8 = 0.84$

$n = 0.93$ (Harrison-Zeldovich)

WMAP Tree Year Results
&
宇宙再電離

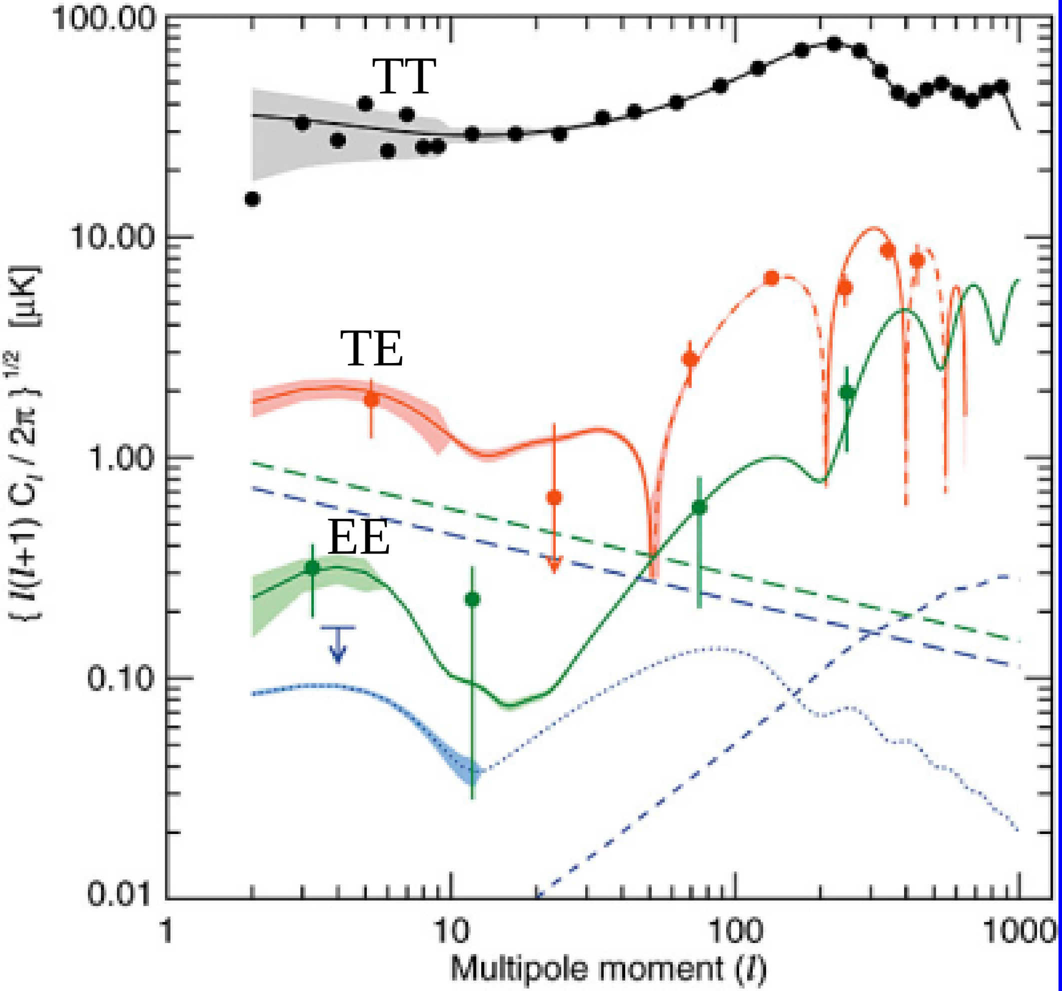


polarization pattern

$$\tau_e = 0.09 \pm 0.03$$

↓

$$\boxed{z_{\text{reion}} = 8.6 - 13.6}$$



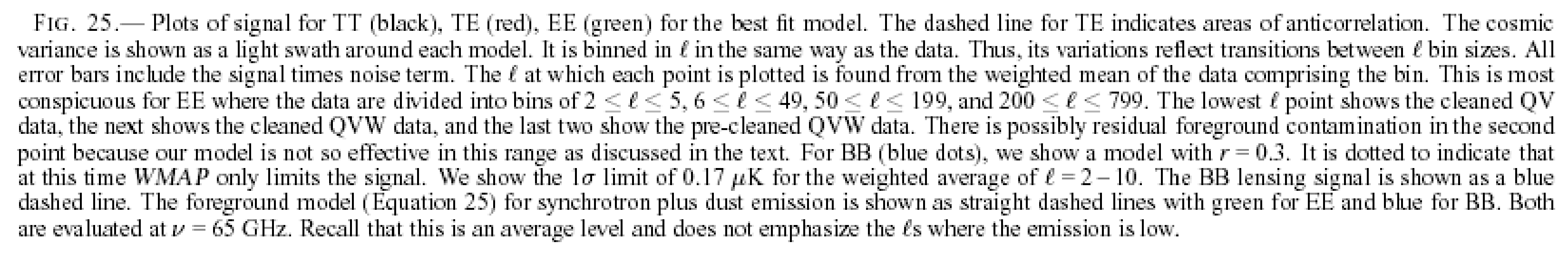
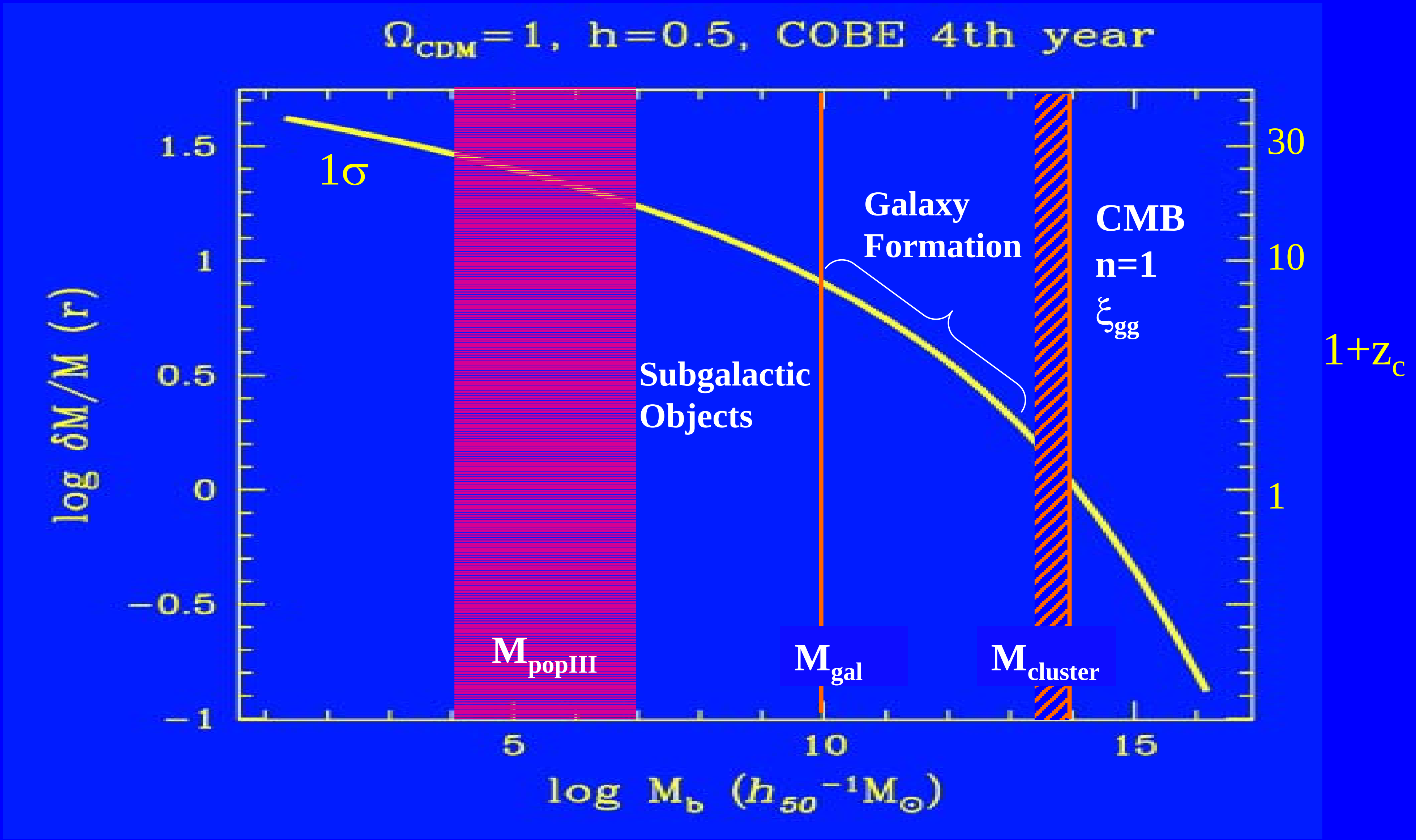


FIG. 25.— Plots of signal for TT (black), TE (red), EE (green) for the best fit model. The dashed line for TE indicates areas of anticorrelation. The cosmic variance is shown as a light swath around each model. It is binned in ℓ in the same way as the data. Thus, its variations reflect transitions between ℓ bin sizes. All error bars include the signal times noise term. The ℓ at which each point is plotted is found from the weighted mean of the data comprising the bin. This is most conspicuous for EE where the data are divided into bins of $2 \le \ell \le 5$, $6 \le \ell \le 49$, $50 \le \ell \le 199$, and $200 \le \ell \le 799$. The lowest ℓ point shows the cleaned QV data, the next shows the cleaned QVW data, and the last two show the pre-cleaned QVW data. There is possibly residual foreground contamination in the second point because our model is not so effective in this range as discussed in the text. For BB (blue dots), we show a model with $r = 0.3$. It is dotted to indicate that at this time *WMAP* only limits the signal. We show the 1σ limit of 0.17 μK for the weighted average of $\ell = 2 - 10$. The BB lensing signal is shown as a blue dashed line. The foreground model (Equation 25) for synchrotron plus dust emission is shown as straight dashed lines with green for EE and blue for BB. Both are evaluated at $\nu = 65$ GHz. Recall that this is an average level and does not emphasize the ℓs where the emission is low.

CDM Density Fluctuations



初期ゆらぎの重力収縮

ジーンズ条件（重力エネルギー＞熱エネルギー）

$$M > M_J = \left(\frac{kT}{G}\right)^{3/2} m_p^{-2} n^{-1/2}$$

(k：ボルツマン定数，m_p：陽子質量，T：温度，n：数密度)

密度上昇 ← 冷却過程で支配される

- **現在の銀河**
  重元素冷却, ダスト冷却

- **第一世代天体**
  星が生まれていない ⇒ 重元素がない
  重元素以外の冷却 ⇒ 水素分子

水素分子形成

電気双極子モーメント=0 ⇒ $H+H \rightarrow H_2+\gamma$ 禁止

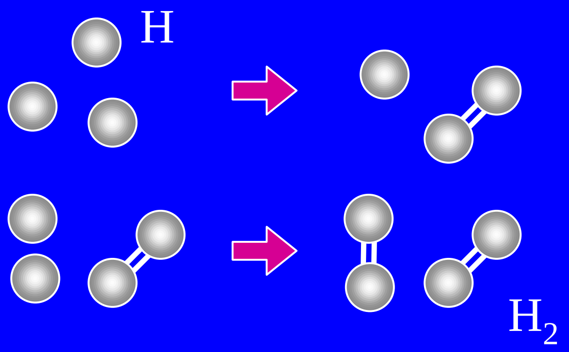
$n \gtrsim 10^8\,\mathrm{cm}^{-3}$

(高密度)

3体反応

$$3H \rightarrow H_2 + H$$

$$2H + H_2 \rightarrow 2H_2$$



$n \lesssim 10^8\,\mathrm{cm}^{-3}$

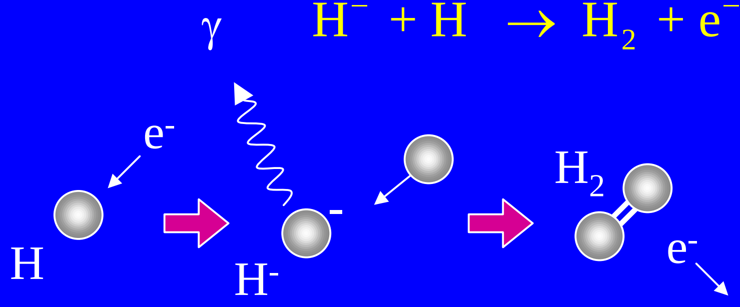
(低密度)

e.g. **宇宙晴れ上がり時** $n \approx 10^2\,\mathrm{cm}^{-3}$

電子反応 ($z \lesssim 100$)

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

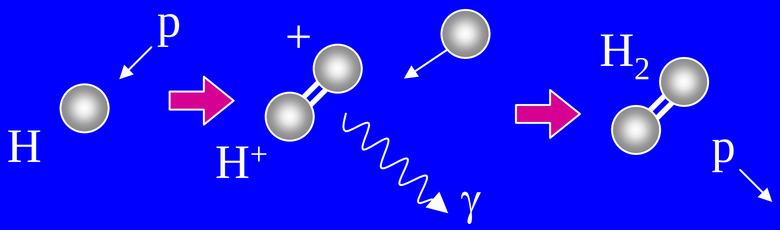
$$H^- + H \rightarrow H_2 + e^-$$



陽子反応 ($z \gtrsim 100$)

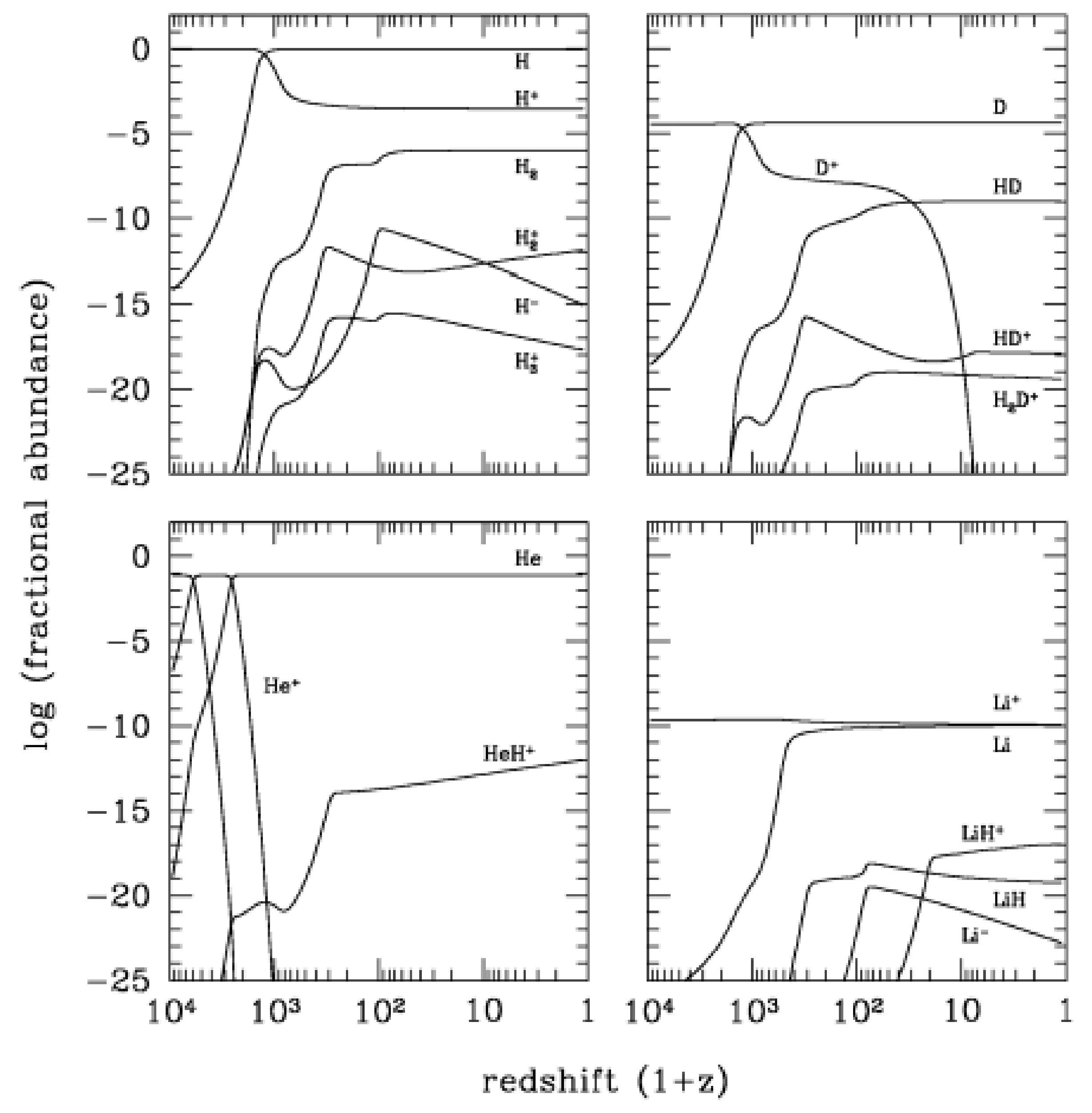
$$p + H \rightarrow H_2^+ + \gamma$$

$$H_2^+ + H \rightarrow H_2 + p$$



Galli & Palla 1998, A&A, 335, 403

残存電離による水素分子形成



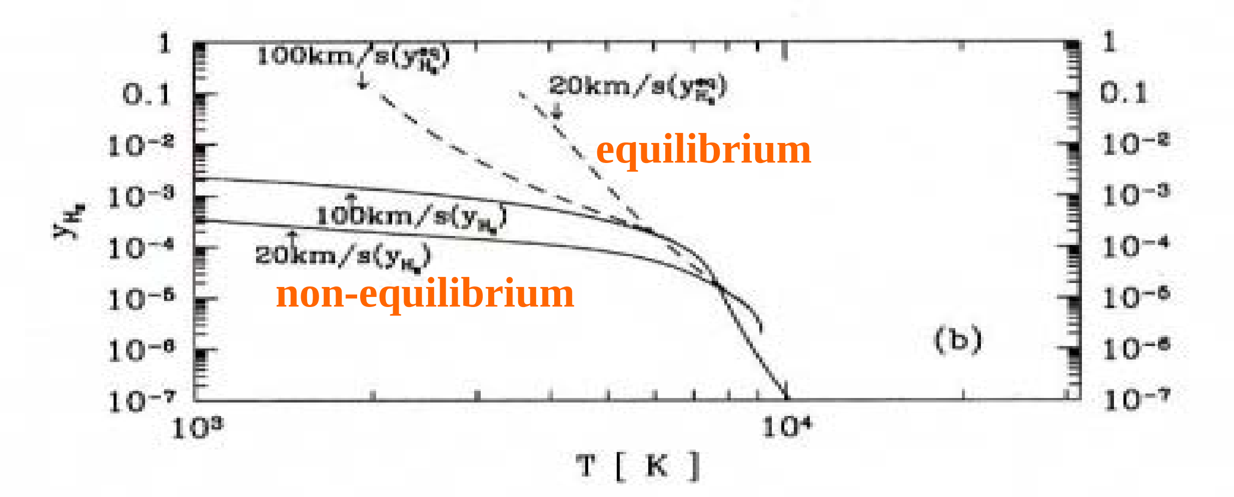
Formation of Pop III Stars

Reaction 1: $e^- + H \rightarrow H^- + h\nu \Rightarrow H^- + H \rightarrow H_2 + e^-$ ($z \lesssim 100$)

Reaction 2: $p + H \rightarrow H_2^+ + h\nu \Rightarrow H_2^+ + H \rightarrow H_2 + p$ ($z \gtrsim 100$)

Matsuda, Sato, & Takeda (1969, Prog. Theor. Phys., 42, 219)

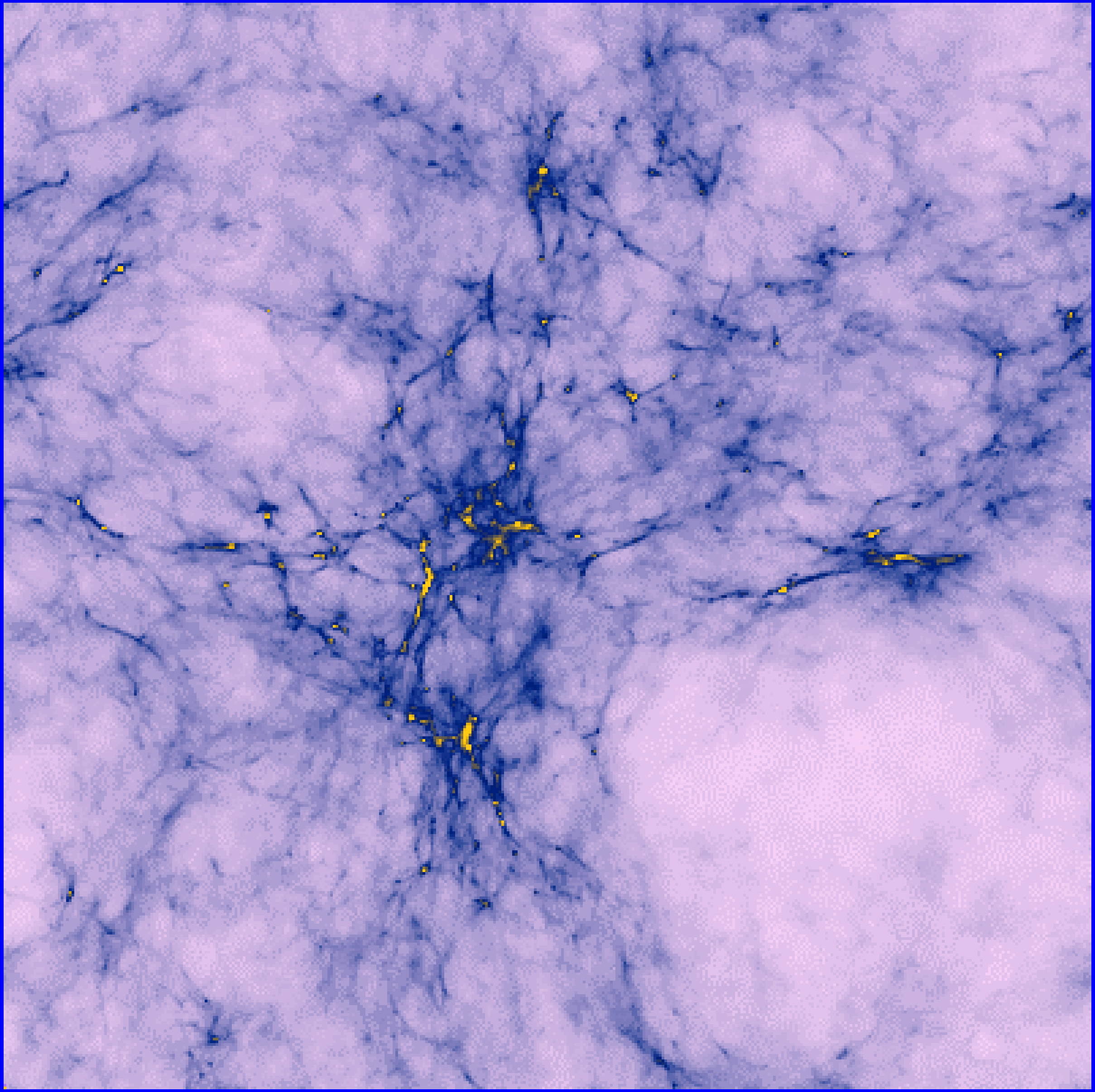
Non-equilibrium processes



Susa et al.
(1998, PTP, 100, 63)

IGM (residual ion. $\chi_e \approx 10^{-5}$): $\chi_{H2} \approx 10^{-5}$
No shock ion. ($T_s < 10^4$K): $\chi_{H2} \approx 10^{-4} - 10^{-3}$
Shock ion. ($T_s > 10^4$K): $\chi_{H2} \approx 10^{-3} - 10^{-2}$

First Object Mass



Yoshida et al.
(2003, ApJ, 592, 645)

60million particles

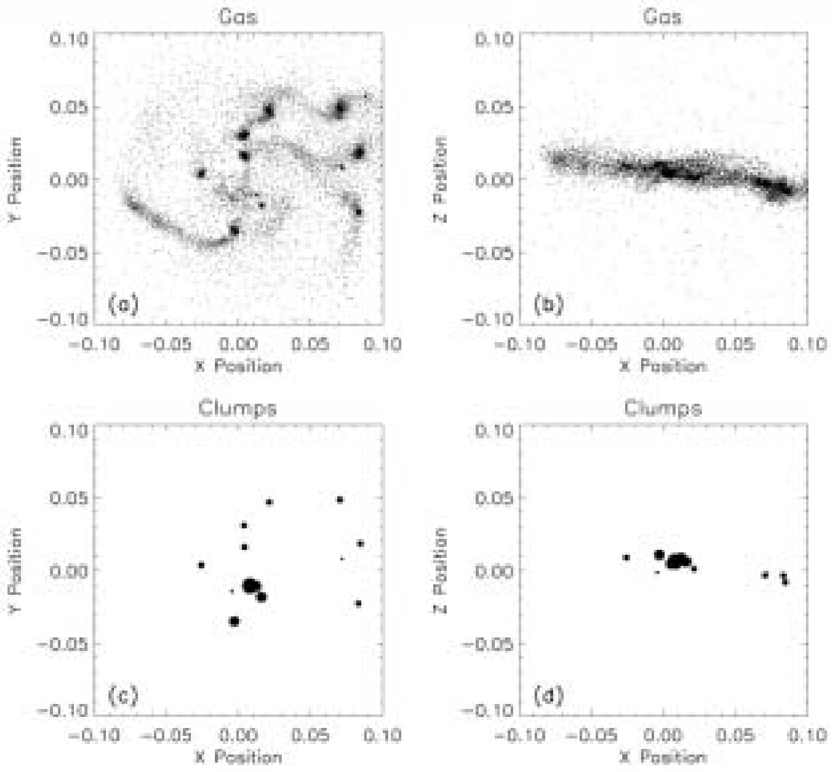
$100M_{\odot}$ per gas particle

$$M_{\mathrm{halo}} \approx 10^6 M_{\odot}$$

3D SPH Simulation in CDM Cosmology

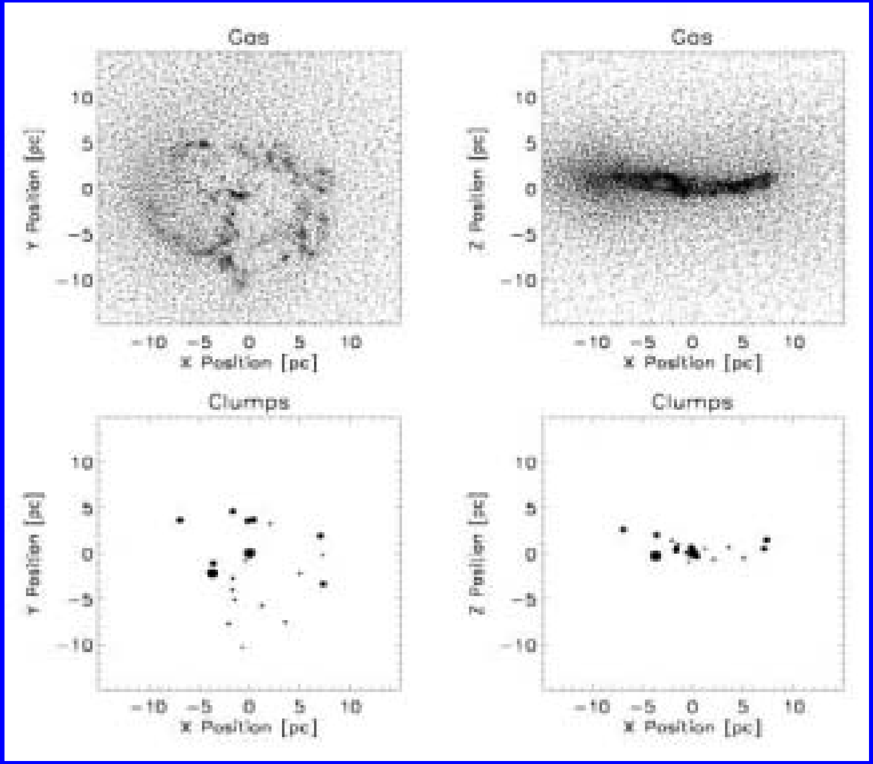
Bromm, Coppi & Larson 1999

The fragment mass is of order $\approx 10^3 M_\odot$, so that $M \gtrsim 100 M_\odot$ stars are likely to form.



Bromm, Ferrara, Coppi & Larson 2001

The fragmentation of the $Z \approx 10^{-3} Z_\odot$ gas leads to relatively numerous low-mass clumps.

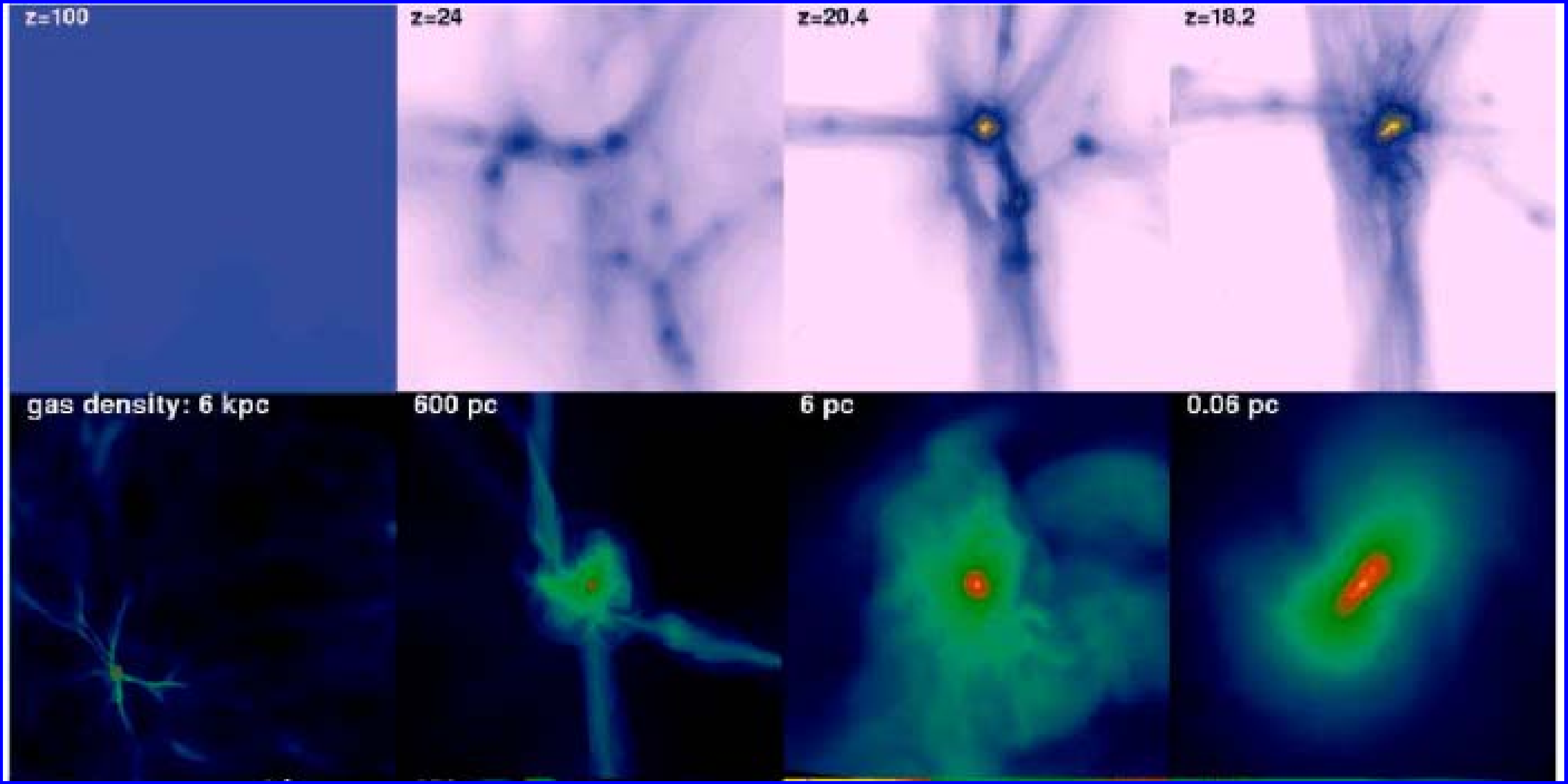


3D AMR Simulations in CDM Cosmology

T. Abel, G. L. Bryan, & M. L. Norman

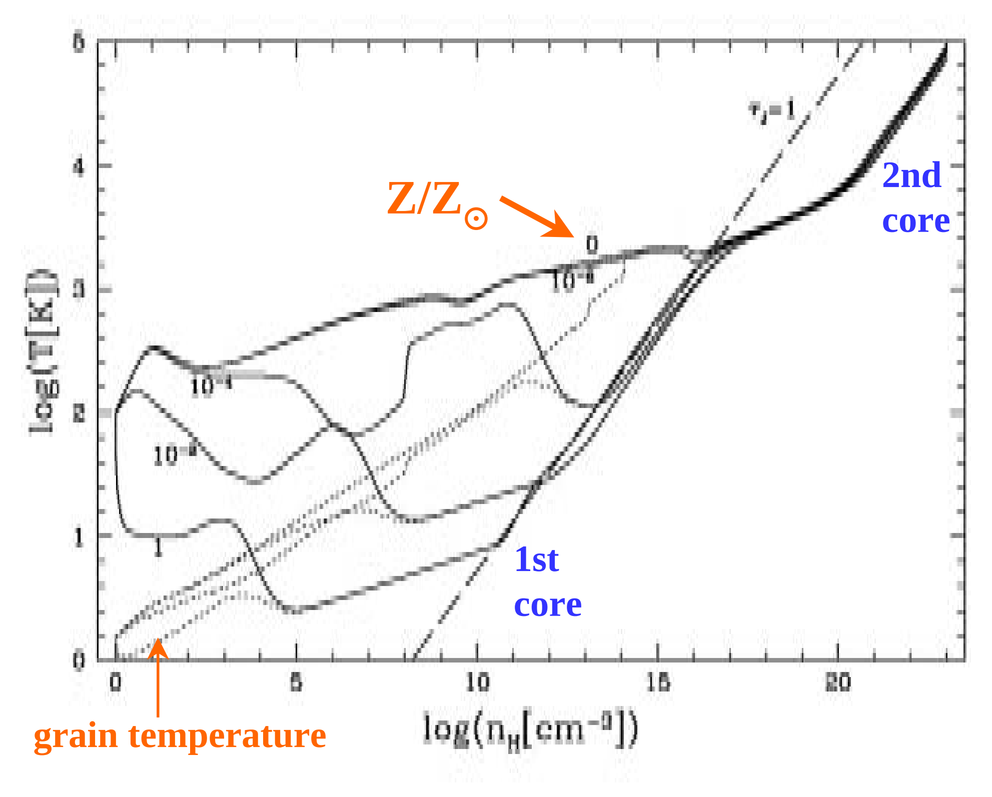
(2002, Science, 295, 5552, 93-98; astro-ph/0112088)

Runaway core collapse contraction ⇒ disk formation ⇒ no indication for further fragmentation ⇒ $\approx 100 M_\odot$ first stars



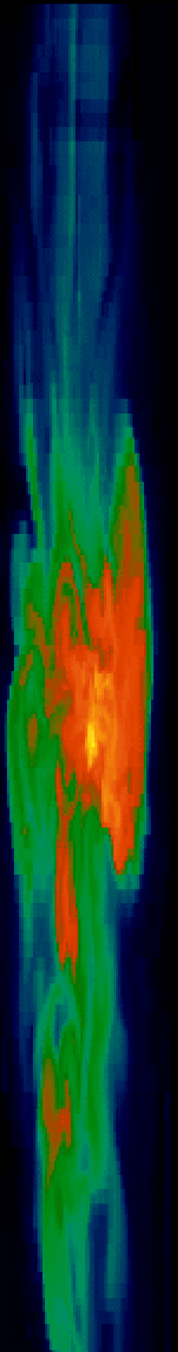
Protostellar Collapse

Omukai & Nishi 1998, ApJ, 508, 141; Omukai 2000, ApJ, 534, 809



Conversion of Kelvin-Helmholtz Contraction

Pop III	**Pop I**
$M_{\mathrm{core}} \approx 10^{-3}\, M_\odot$	$10^{-3}\, M_\odot$
$M_{\mathrm{frag}} \approx 10^{3}\, M_\odot$	$>0.1\, M_\odot$
$\dot{M} \approx 10^{-3}\, M_\odot/\mathrm{yr}$	$10^{-5}\, M_\odot/\mathrm{yr}$

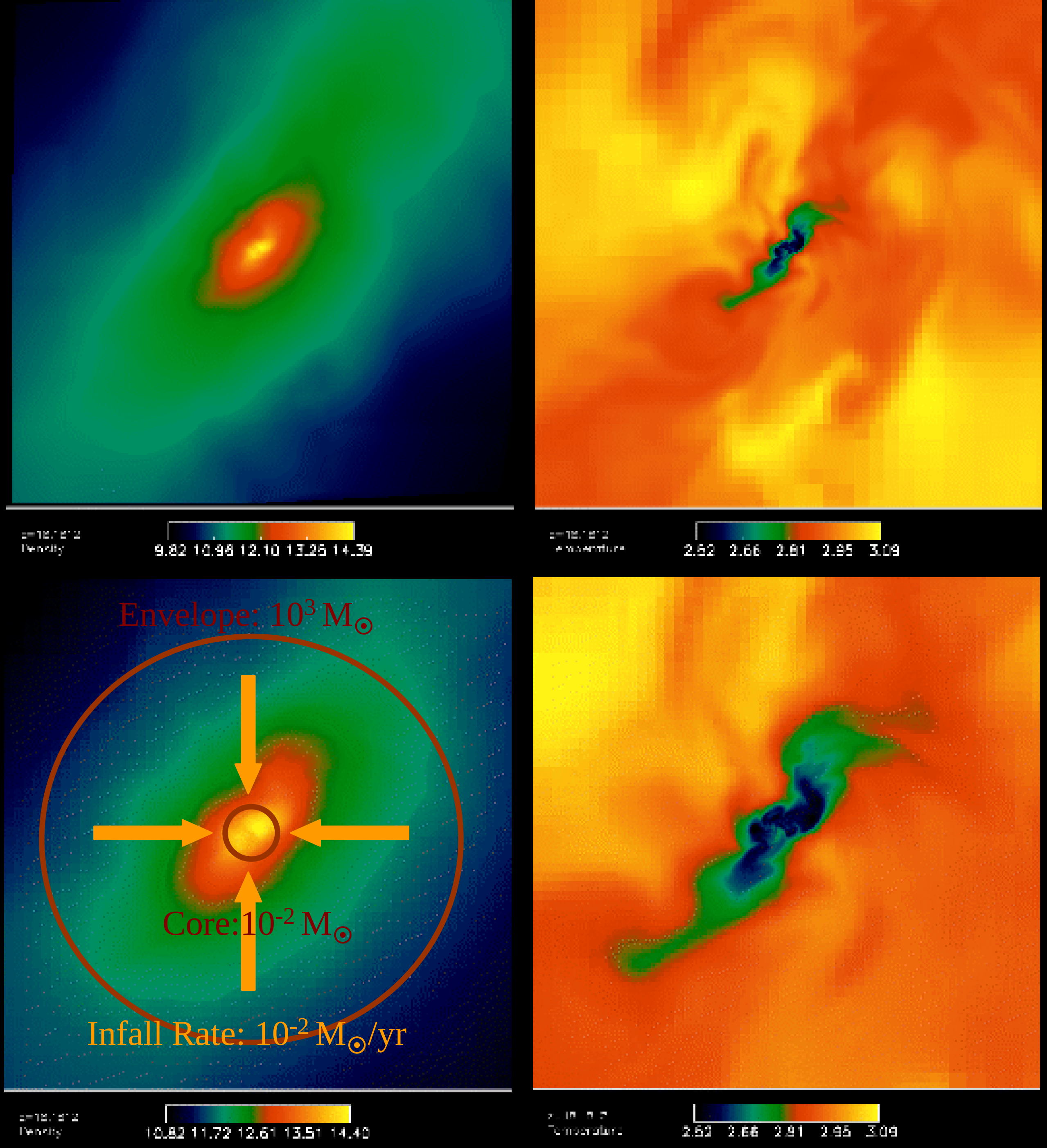


Tom Abel
Harvard Smithsonian CfA

1400 AU:

forming
protostar

550 AU:



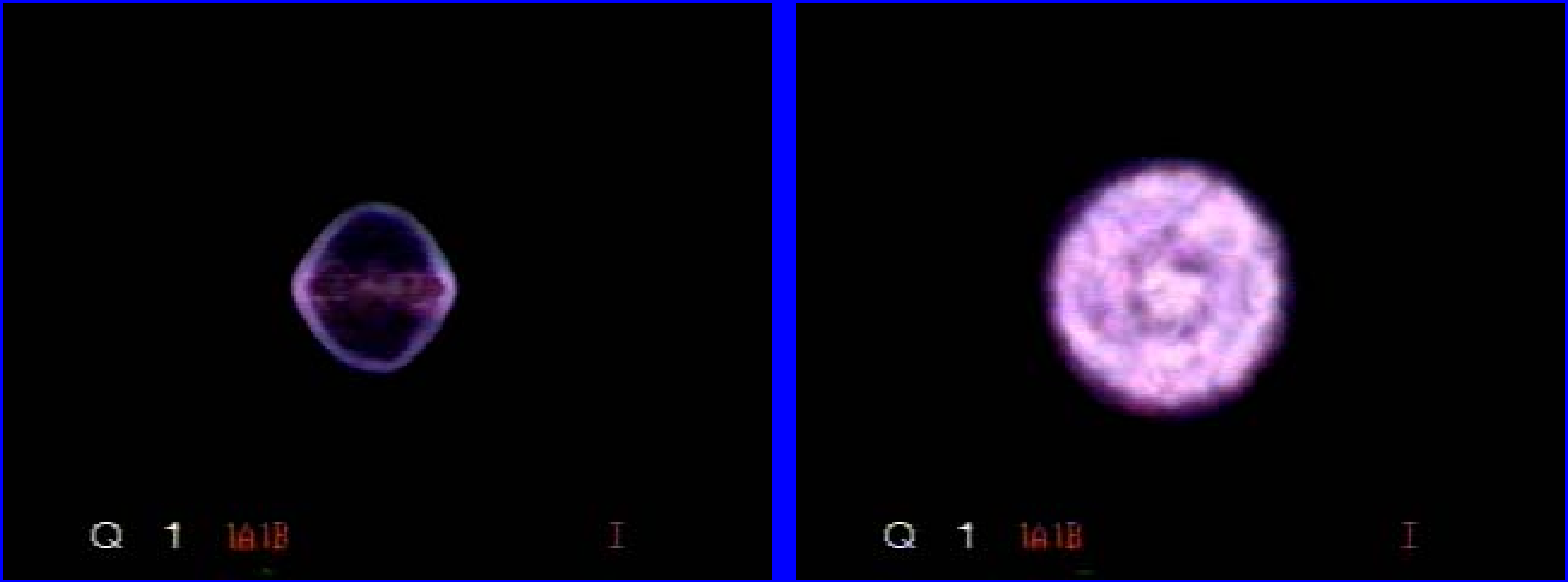
Envelope: 10^3 $M_\odot$

Core: 10^{-2} $M_\odot$

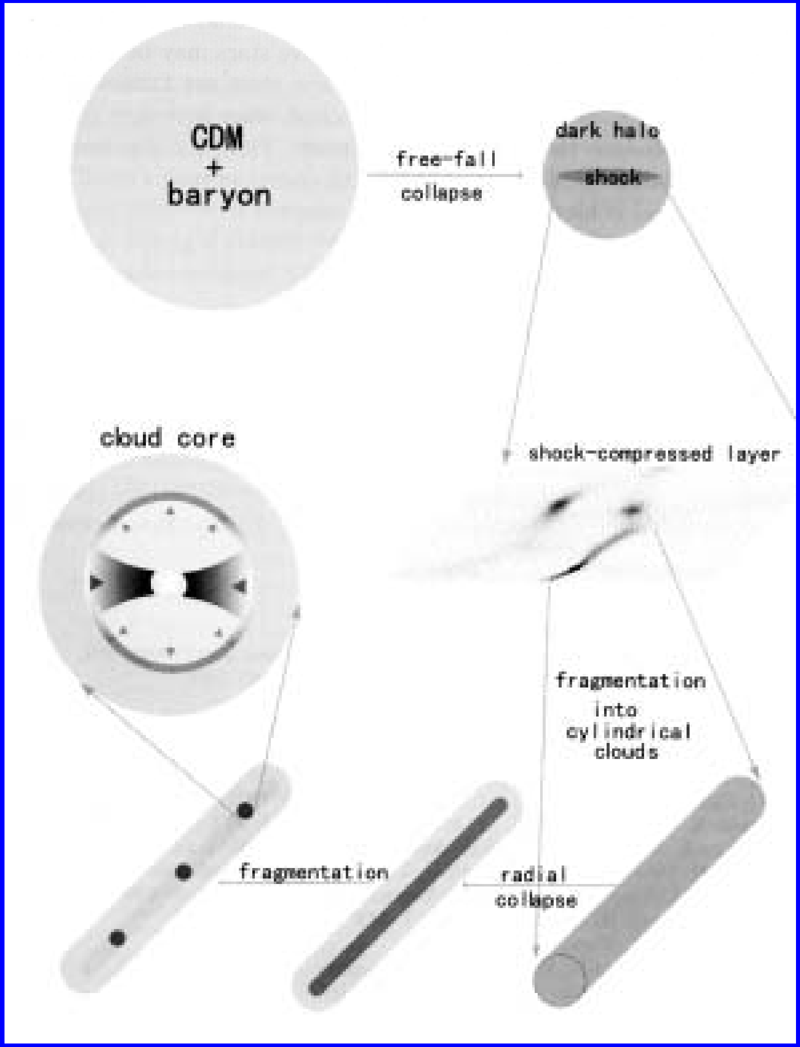
Infall Rate: 10^{-2} $M_\odot$/yr

Nonlinear Growth of Density Fluctuation

Umemura 1993



Fragmentation and Pop III Stars



Nishi et al. (1998, PTP, 100, 881)

Spherical collapse

$$m_{\min} \lesssim 0.1 M_\odot$$

Carlberg (1981, MNRAS, 197, 1021)
Palla et al. (1983, ApJ, 271, 632)

Cylindrical collapse

Analytical estimate

Uehara et al. (1996, ApJ, 473, L95)
Rees (1976, MNRAS, 176, 483)

$$m_{frag,\ \min} = \alpha_c^{-1/2} \mu^{9/4} (m_{pl}^{3} / m_p^{2})$$

$$\approx 0.5 M_\odot$$ **Chandrasekhar mass**

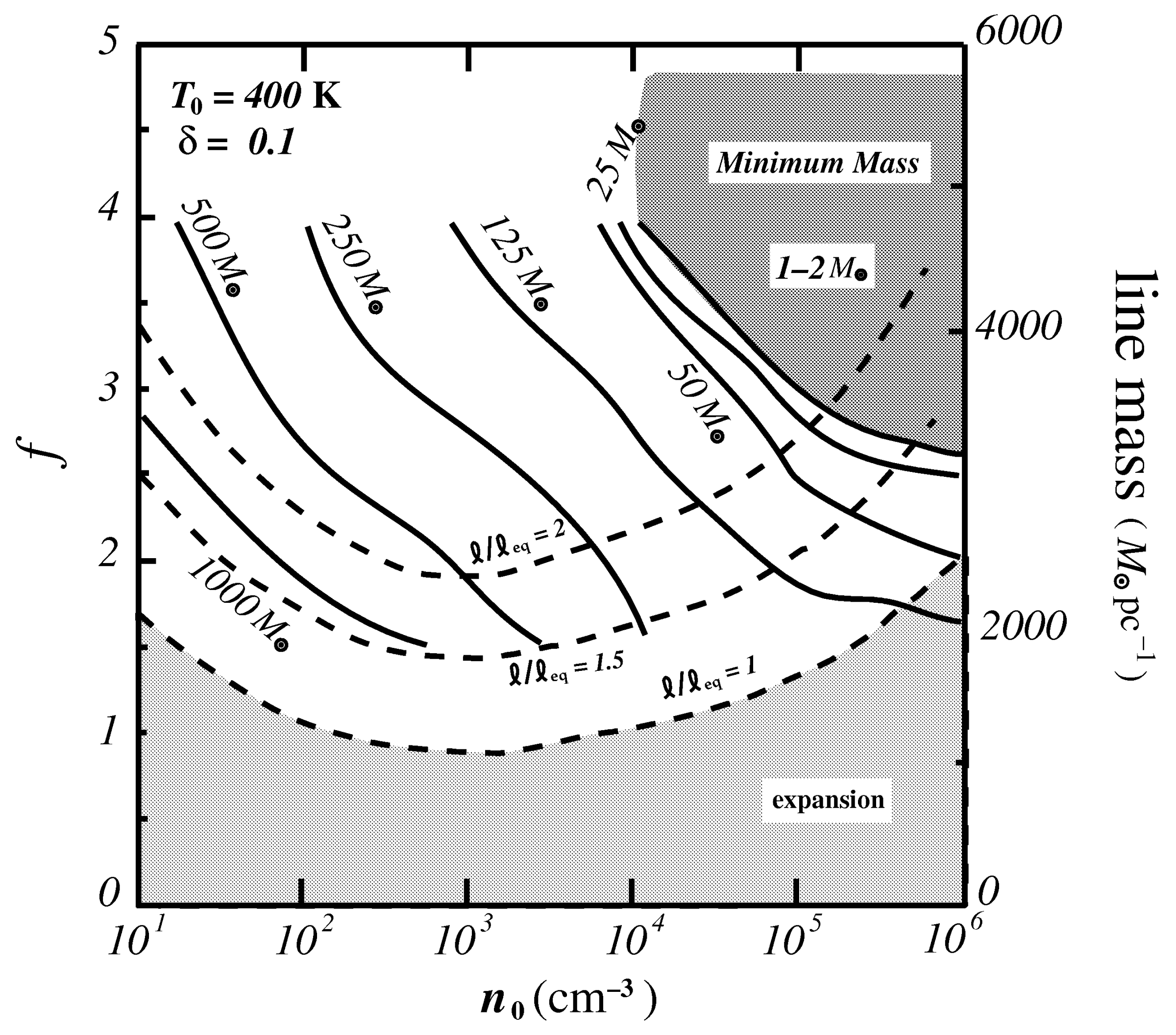
1D Simulation

Nakamura & Umemura (1999, ApJ, 515, 239)

$$m_{frag} \approx 3 M_\odot - 16 M_\odot$$

Nakamura & Umemura 2001, ApJ, 548, 19

$$f = \left(\frac{\text{gravitational force}}{\text{pressure force}} \right)_{\text{initial}}$$



$$m_{frag} \approx 2M_\odot - 10^3 M_\odot \text{ (bimordal)}$$

Initial high density leads to low fragment mass.

HE 0107-5240

Christlieb et al 2002, Nature, 419, 904

$M = 0.8 M_\odot$

[Fe/H] ≈ -5.3

[C/H] ≈ -1.3

[N/H] ≈ -3

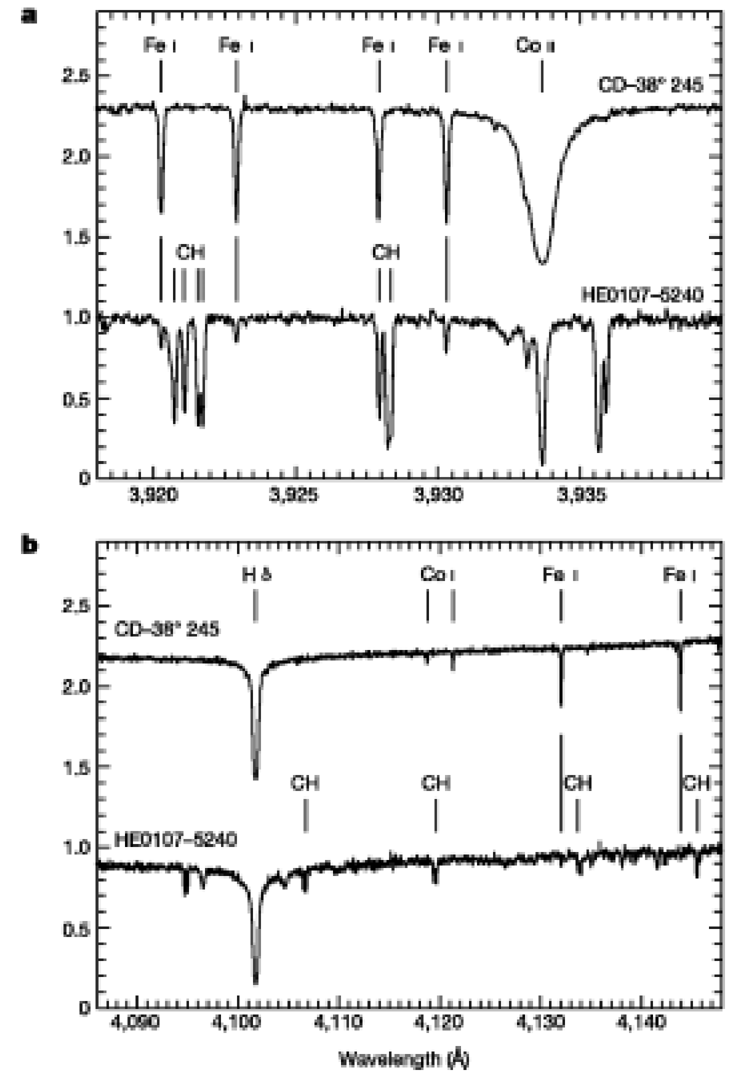
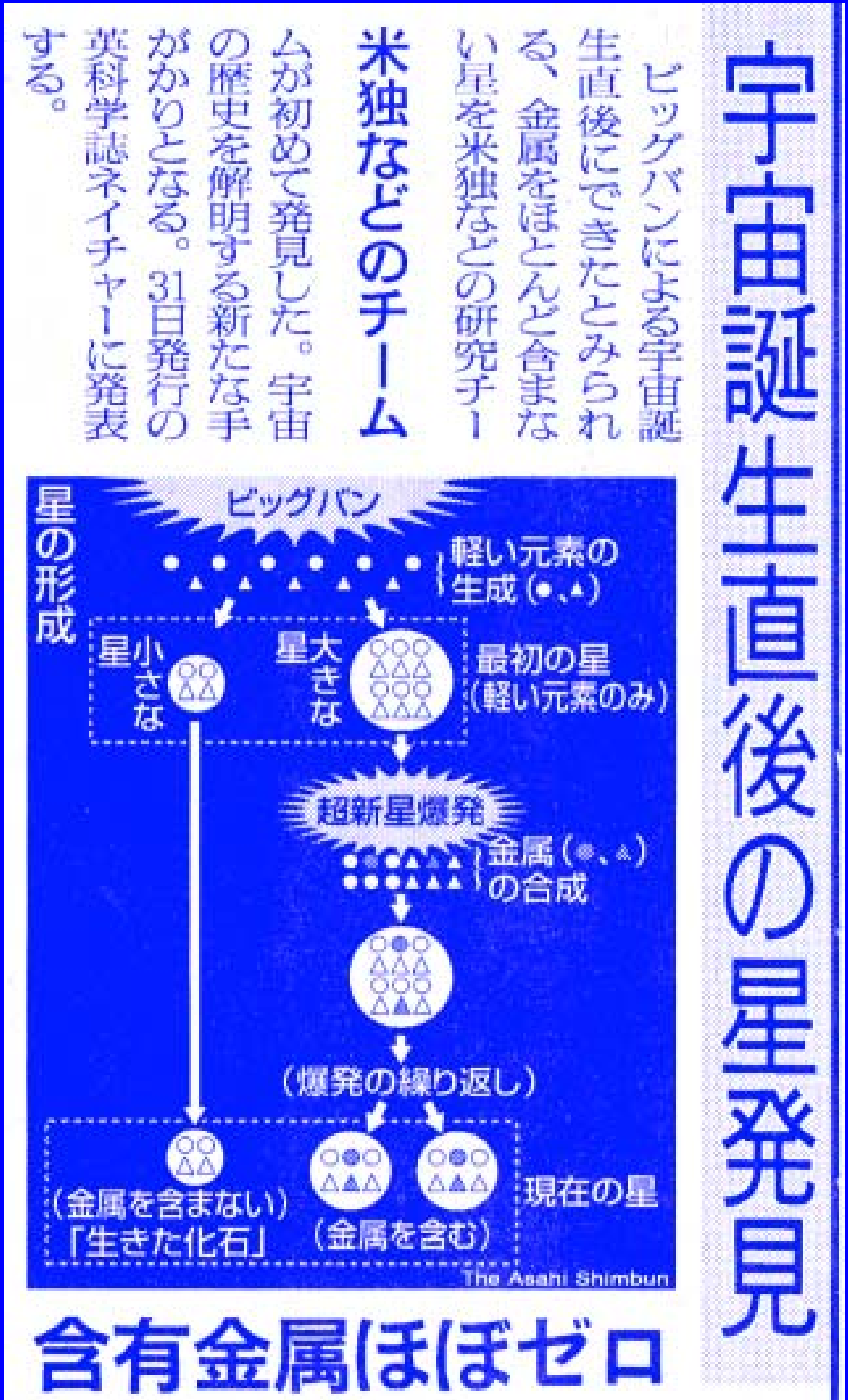


Figure 1 A portion of the spectrum of HE0107−5240, shown compared to the spectrum of CD−38° 245, the previously most iron-poor giant star known. Both spectra were obtained with VLT-UT2, and the Ultraviolet-Visual Echelle Spectrograph (UVES). We note the strong molecular CH and C_2 lines and extremely weak lines of Fe I in the spectrum of HE0107−5240. The spectra used in our analysis have a resolution of $R = \lambda/\Delta\lambda = 40,000$, and a signal-to-noise ratio (S/N) of more than 100 per pixel at $\lambda > 400.0$ nm. The covered wavelength ranges are 329.0–452.0 nm, 478.0–576.0 nm, and 583.0–681.0 nm.

2002年10月31日
朝日新聞朝刊



宇宙誕生直後の星発見

含有金属ほぼゼロ

米独などのチーム

ビッグバンによる宇宙誕生直後にできたとみられる、金属をほとんど含まない星を米独などの研究チームが初めて発見した。宇宙の歴史を解明する新たな手がかりとなる。31日発行の英科学誌ネイチャーに発表する。

HE1327–2326

Frebel et al. 2005, Nature, 434, 871

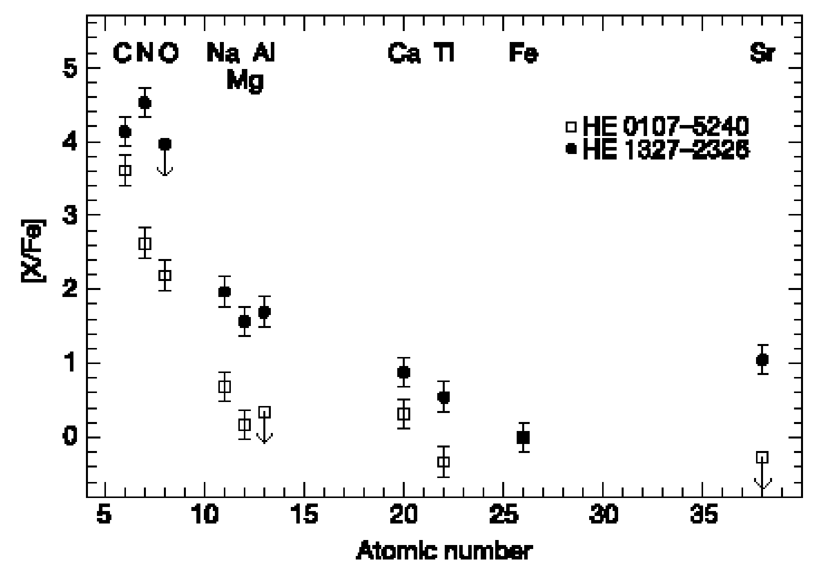
$M=0.7M_\odot$

$[Fe/H] \approx 10^{-5.4}$

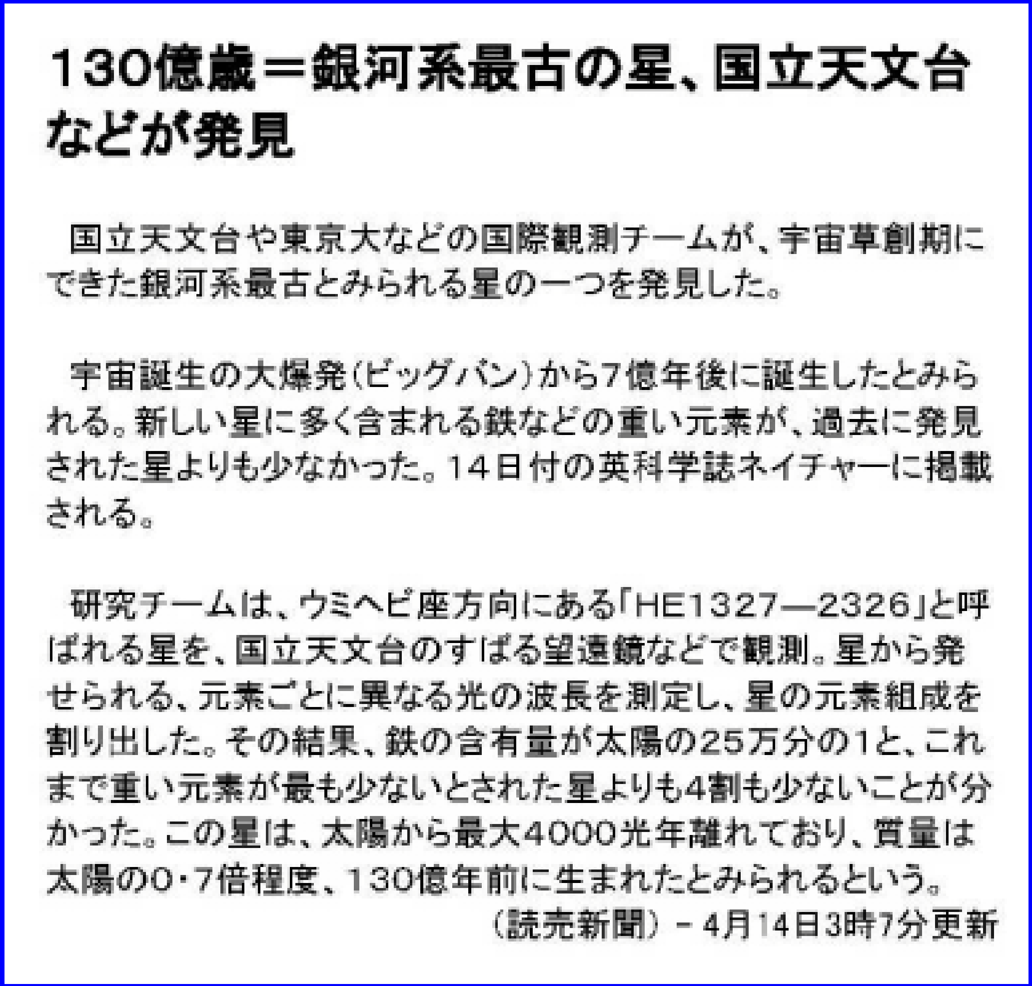
$[C/H] \approx 10^{-1.3}$

$[N/H] \approx 10^{-0.9}$

$[Sr/H] \approx 10^{-0.9}$



読売新聞
H17.4.14 朝刊



130億歳＝銀河系最古の星、国立天文台などが発見

国立天文台や東京大などの国際観測チームが、宇宙草創期にできた銀河系最古とみられる星の一つを発見した。

宇宙誕生の大爆発（ビッグバン）から7億年後に誕生したとみられる。新しい星に多く含まれる鉄などの重い元素が、過去に発見された星よりも少なかった。14日付の英科学誌ネイチャーに掲載される。

研究チームは、ウミヘビ座方向にある「HE1327—2326」と呼ばれる星を、国立天文台のすばる望遠鏡などで観測。星から発せられる、元素ごとに異なる光の波長を測定し、星の元素組成を割り出した。その結果、鉄の含有量が太陽の25万分の1と、これまで重い元素が最も少ないとされた星よりも4割も少ないことが分かった。この星は、太陽から最大4000光年離れており、質量は太陽の0・7倍程度、130億年前に生まれたとみられるという。

（読売新聞） - 4月14日3時7分更新

HE 0107-5240, HE1327–2326の可能性

① 重元素なしの第一世代星だが，第一世代天で同時に生まれた
大質量星が爆発した際に重元素が付着した。

② 第一世代ではなく，ある程度重元素汚染されたガスから生まれた
第二世代の星である。

Umeda & Nomoto 2003, Nature, 422, 871
Abundance pattern
20-130$M_\odot$ SN

Schneider et al. 2003, Nature, 422, 869
Dust formation ⇒ Low-mass star formation

EFFECTS OF HD MOLECULES

UV ionization **(e.g. Corbelli et al. 1998; Susa & Umemura 2000)**
Shock ionization **(e.g. Shapiro & Kang 1987; Ferrara 1998)**

↓

High H_2 abundance $x_{\mathrm{H}_2} \gtrsim 10^{-3}$

↓

HD Molecule Formation

$D^{+} + H_2 \rightarrow H^{+} + HD$ **Low density**

$D + H_2 \rightarrow H + HD$ **High density**

HD Cooling

- HD is less abundant than H_2 (D=4×10^{-5} by BBNS)

- HD has a finite dipole moment !!

  $A_{10} \sim 5.12 \times 10^{-8}$, $\Delta E_{10} \sim 128$ K

  c.f. H_2: $A_{20} \sim 2.94 \times 10^{-11}$, $\Delta E_{20} \sim 512$ K

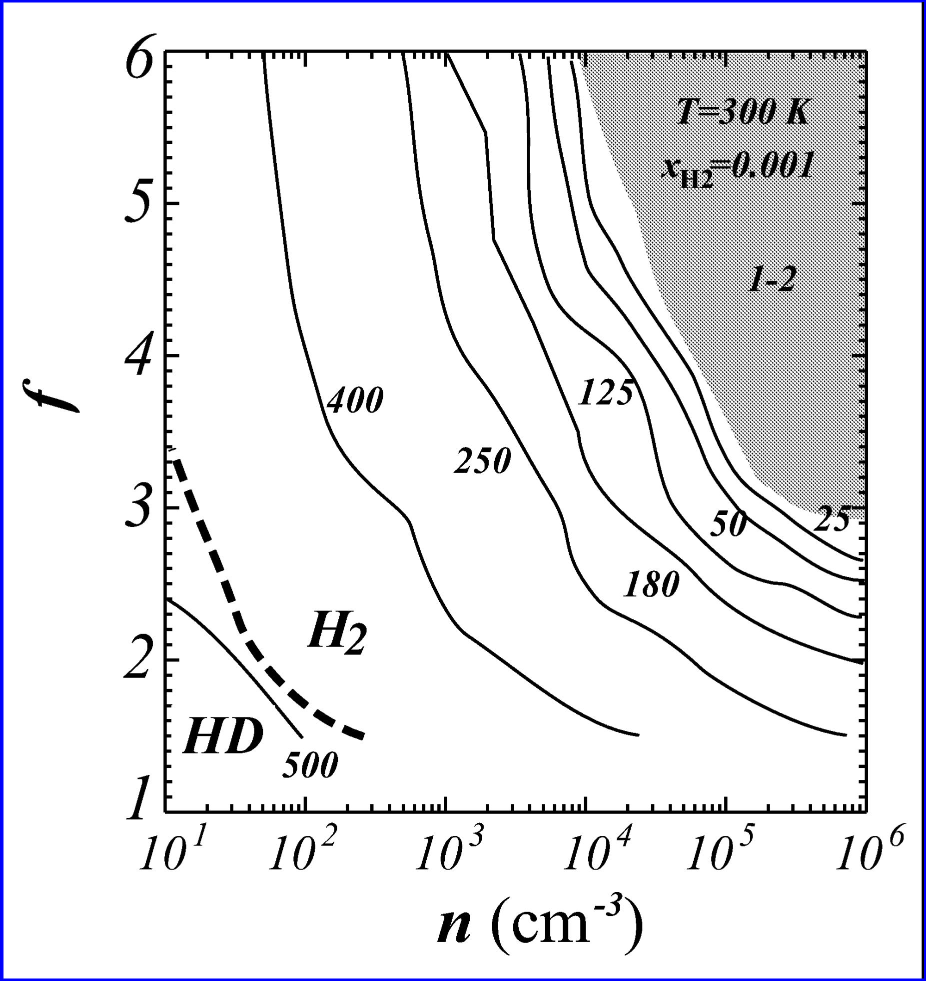
  cooling rate: $L = n\, A\, \Delta E$

- HD cooling is dominant at T<100~200 K

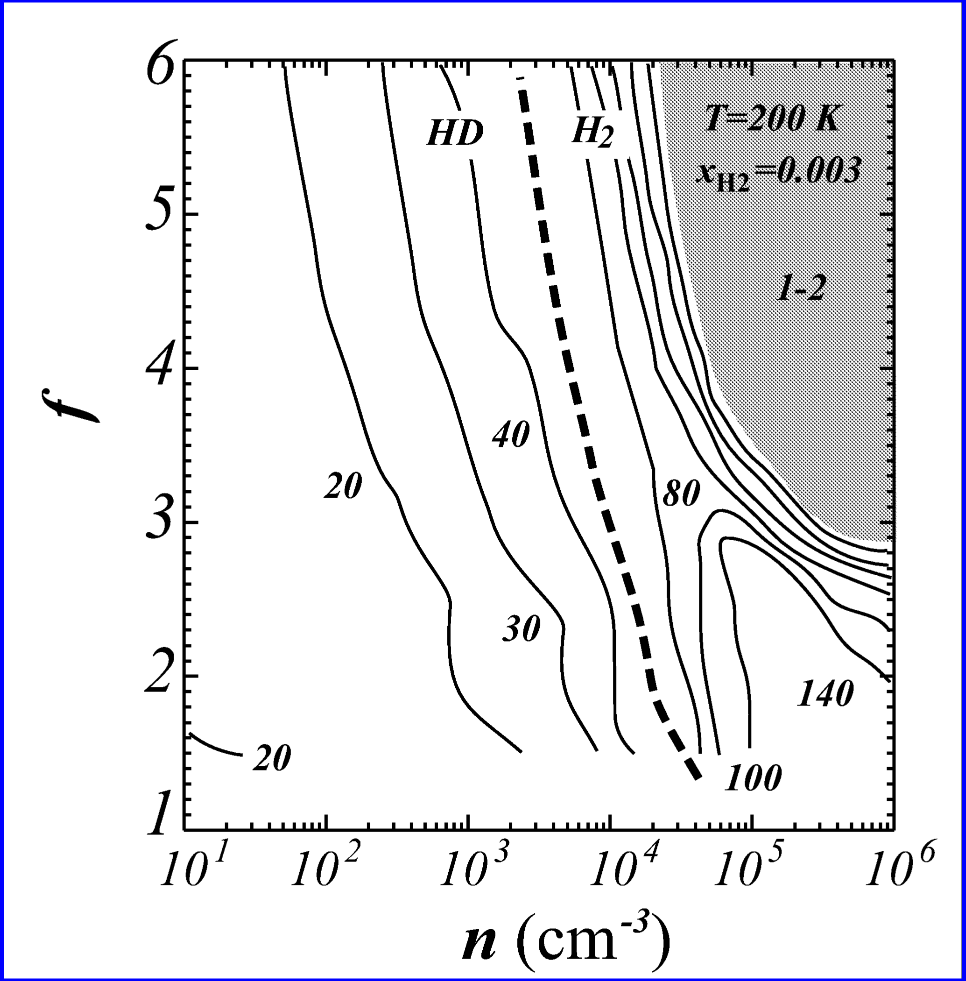
HD冷却による初代星形成

Nakamura & Umemura 2002, ApJ, 569, 549

$T_i = 300\mathrm{K},\ x_{\mathrm{H_2},i} = 1\times10^{-3}$



$T_i = 200\mathrm{K},\ x_{\mathrm{H_2},i} = 3\times10^{-3}$



Pop III星の質量

１．宇宙で最初に誕生した星は，主に100～1000$M_\odot$
　　の大質量星

２．高電離ガスからの星形成の場合，HD分子が効いて
　　主に数10$M_\odot$星形成となる可能性あり

３．高密度領域では～1$M_\odot$の星が生まれる可能性あり

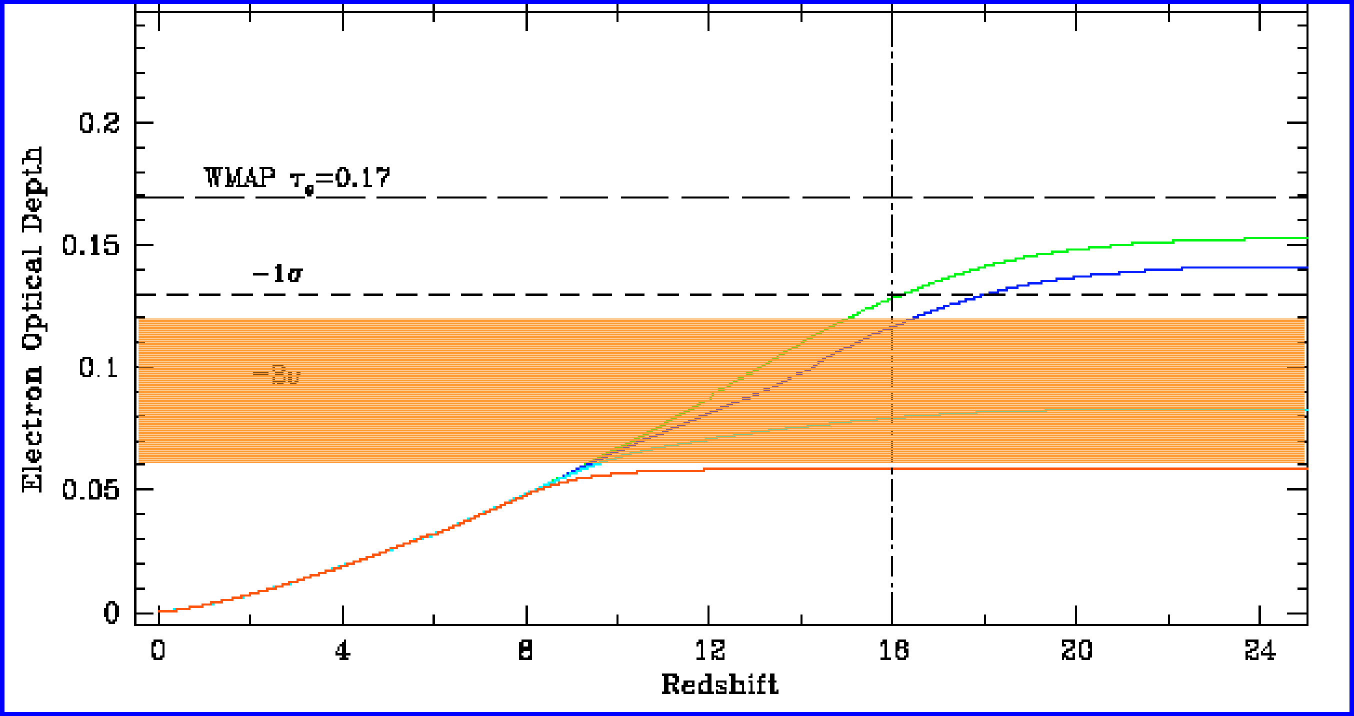
Pop III 星による宇宙再電離

Cen 2003; Ciardi, Ferrara & White 2003; Somerville & Livio 2003; Fukugita & Kawasaki 2003; Wyithe & Loeb 2003; Sokasian et al. 2004; Ricotti & Ostriker 2004

1 halo ($10^6 M_\odot$)に 1 Pop III star を仮定

$\tau_e < 0.15$

cf **WMAP 1st year** $\tau_e = 0.17 \pm 0.04$ **WMAP Three year** $\tau_e = 0.09 \pm 0.03$



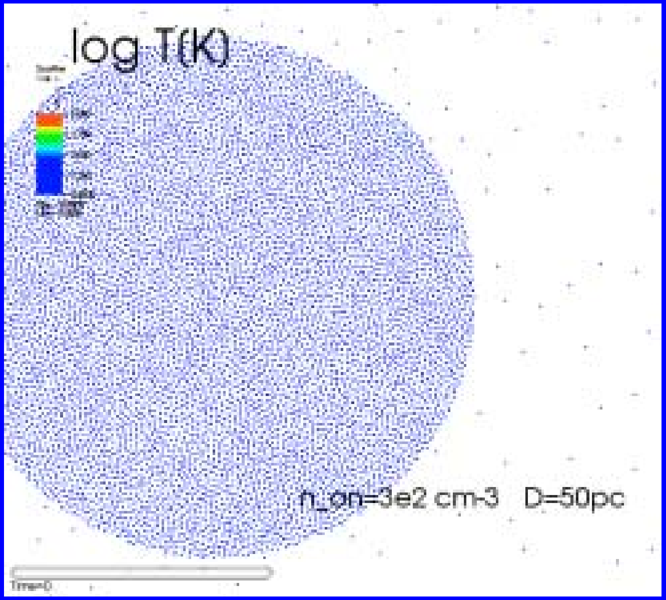
Sokasian et al. 2004, MNRAS, 350, 47

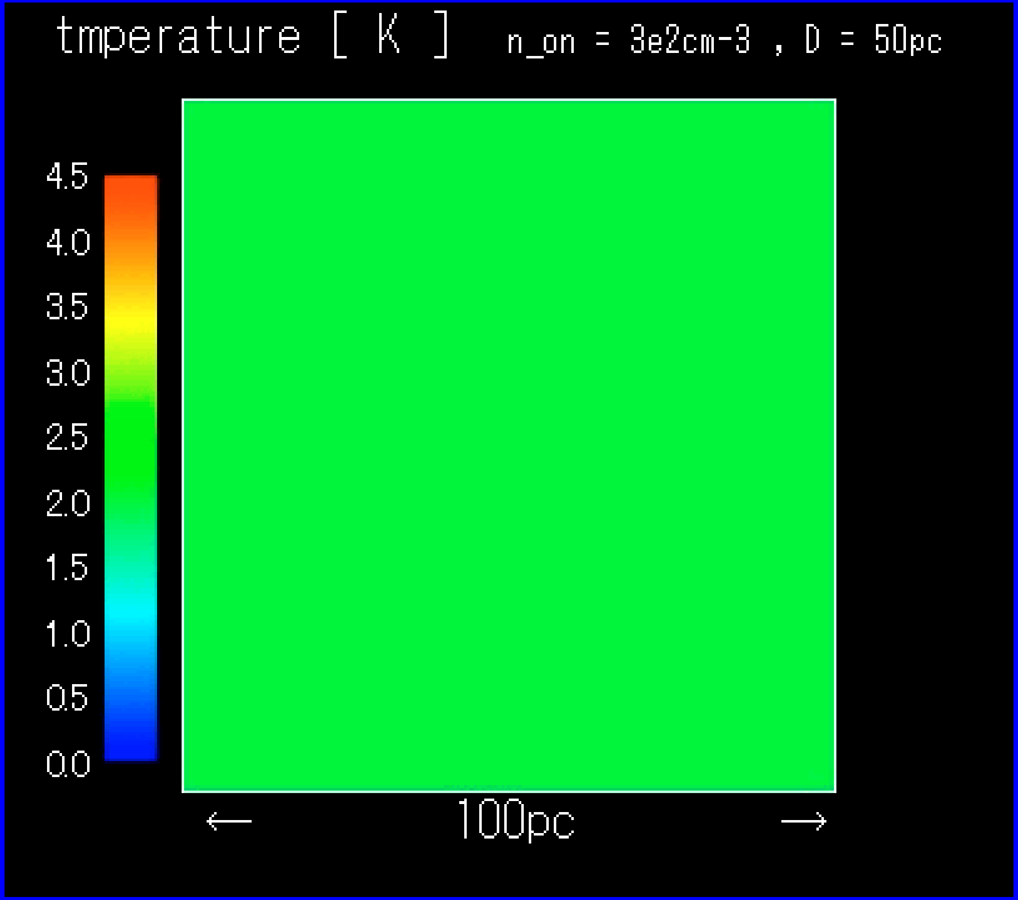
第一世代星形成の輻射流体シミュレーション

Susa & Umemura 2006, ApJ, 645, L93

以前の研究： 最初の星の周りで次の星形成が阻害
今回の研究： 最初の星の周りでも星形成が可能となる

(ダークマター52万体，バリオン52万体)





Heger & Woosley

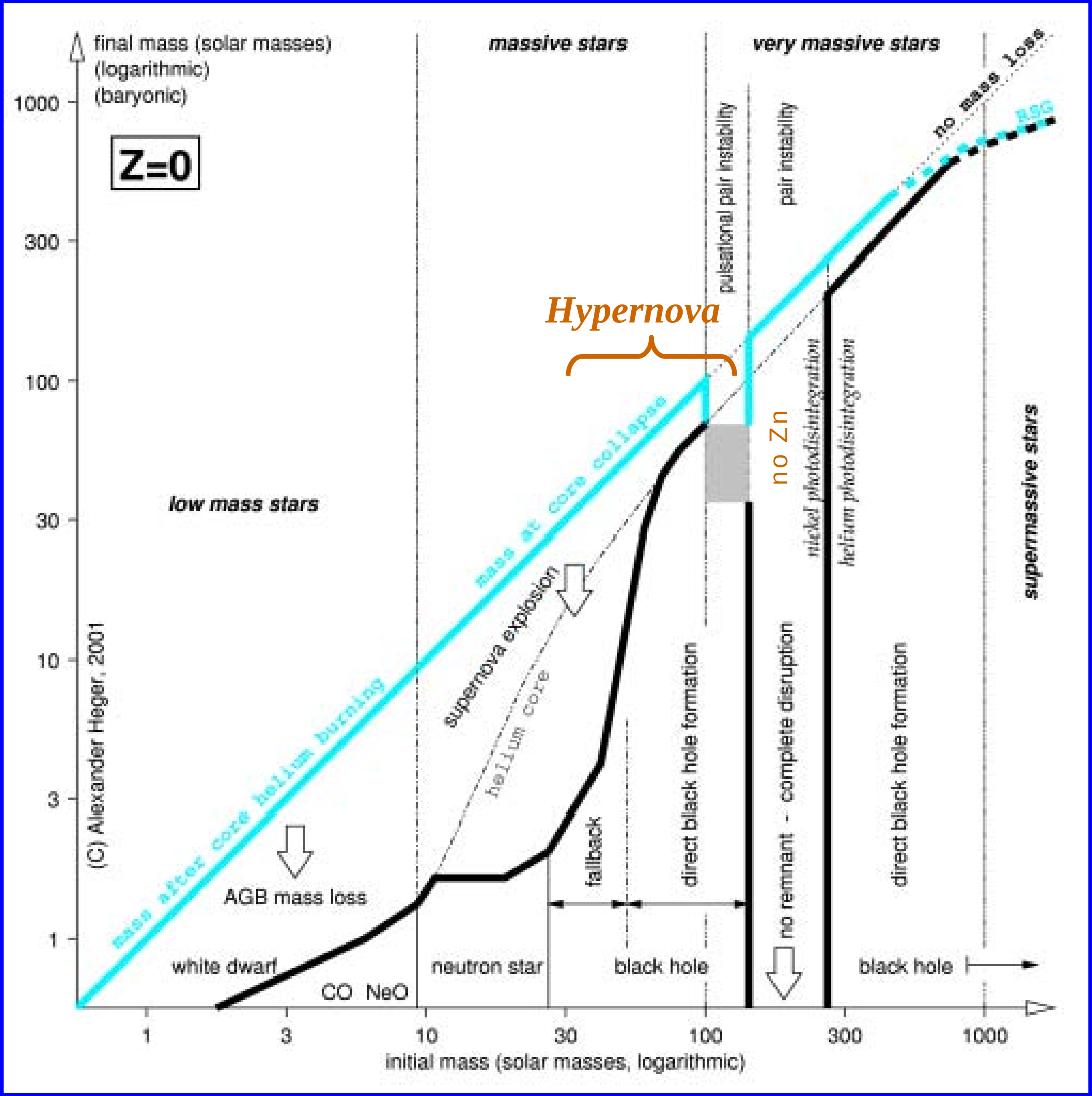
2002, ApJ, 567, 532

$8M_\odot < m \lesssim 25M_\odot$:
type II supernova

$25M_\odot \lesssim m \lesssim 140M_\odot$:
supernova (hypernova)
→ black hole (core collapse)

$140M_\odot \lesssim m \lesssim 260M_\odot$:
pair instability supernova
no *r*-, *s*- processes
α-rich freezeout

$m \gtrsim 260M_\odot$:
black hole (implosion)



大質量Pop III星の問題点

Zn Problem (abundance ratio)

Pop II stars	[Zn/Fe] ≈0.5	for $Z \approx 10^{-3.3} Z_\odot$
DLA	[Zn/Fe] ≈0.6	for $Z \approx 10^{-2} Z_\odot$

Evolution & Explosion of *zero metal* stars

(Umeda & Nomoto 2002)

$8M_\odot < m \lesssim 25M_\odot$: type II supernova ⇒ Zn production

$25M_\odot \lesssim m \lesssim 140M_\odot$: black hole (implosion)

$140M_\odot \lesssim m \lesssim 260M_\odot$: pair instability supernova (no Zn production)

$m \gtrsim 260M_\odot$: black hole (GR instability)

Fe abundance

pair instability supernova

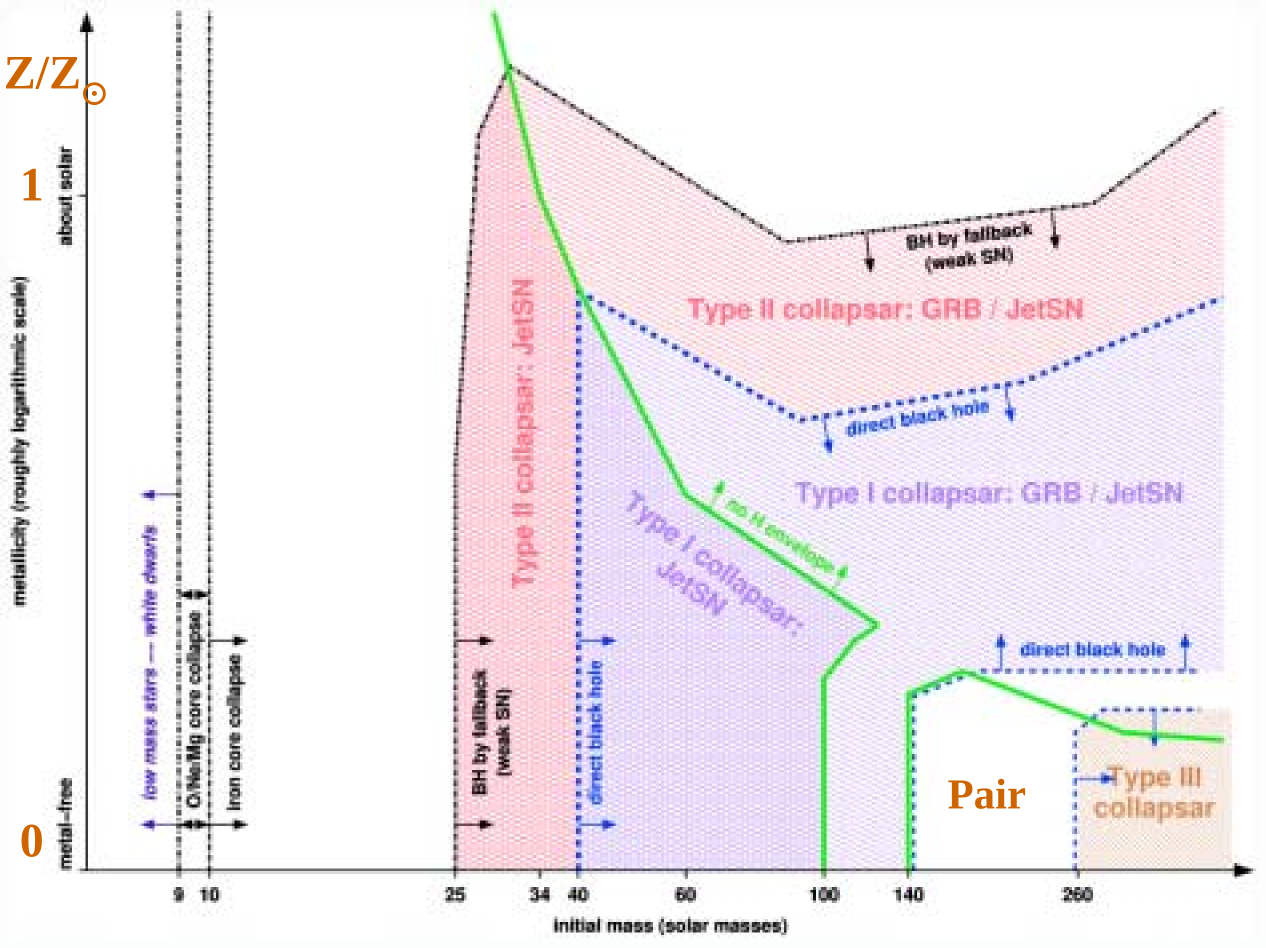
[Zn/Fe]< -0.8, [C/Fe]<0 **鉄が作られすぎる**

(Umeda & Nomoto 2002; Ohkubo et al. 2006)

Pop III BH形成に対する制限

Heger et al. 2003, ApJ, 591, 288

Type I Collapsar: BH formation by core collapse
Type II Collapsar: BH formation by fallback caused by SN shock
Type III Collapsar: BH formation without proto-neutron star formation
JetSN: Hypernova
GRB: long GR burst（a portion of Jet SNs）



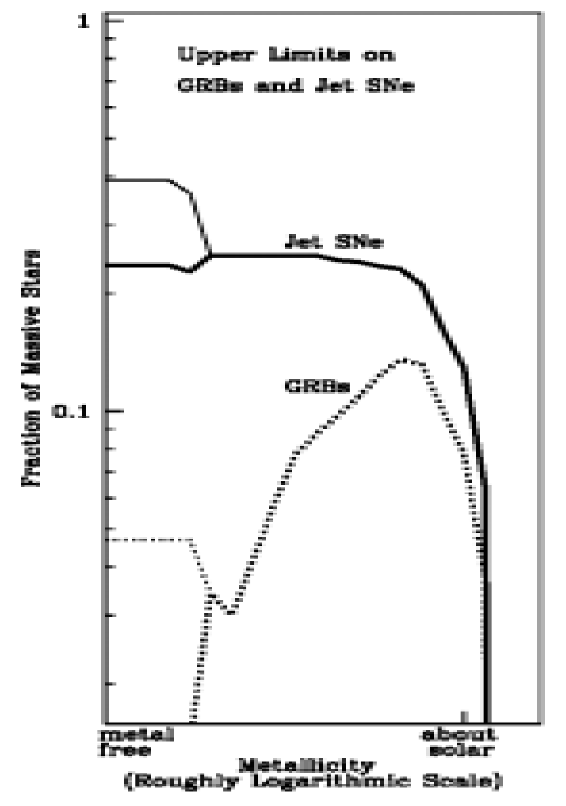


FIG. 7.—Upper limits on the fraction of massive single stars that form jet-driven supernovae and gamma-ray bursts for a Salpeter initial mass function (thick lines; Salpeter 1955). At low redshifts we use an alternate initial mass function (thin lines) from Nakamura & Umemura (2001). These upper limits are determined assuming that all massive stars have the necessary rotation rates to produce collapsars. Single stars produce GRBs mostly in a narrow range of metallicities but can produce Jet SNe at all metallicities until the metallicity is so high that mass loss prohibits the formation of black holes.

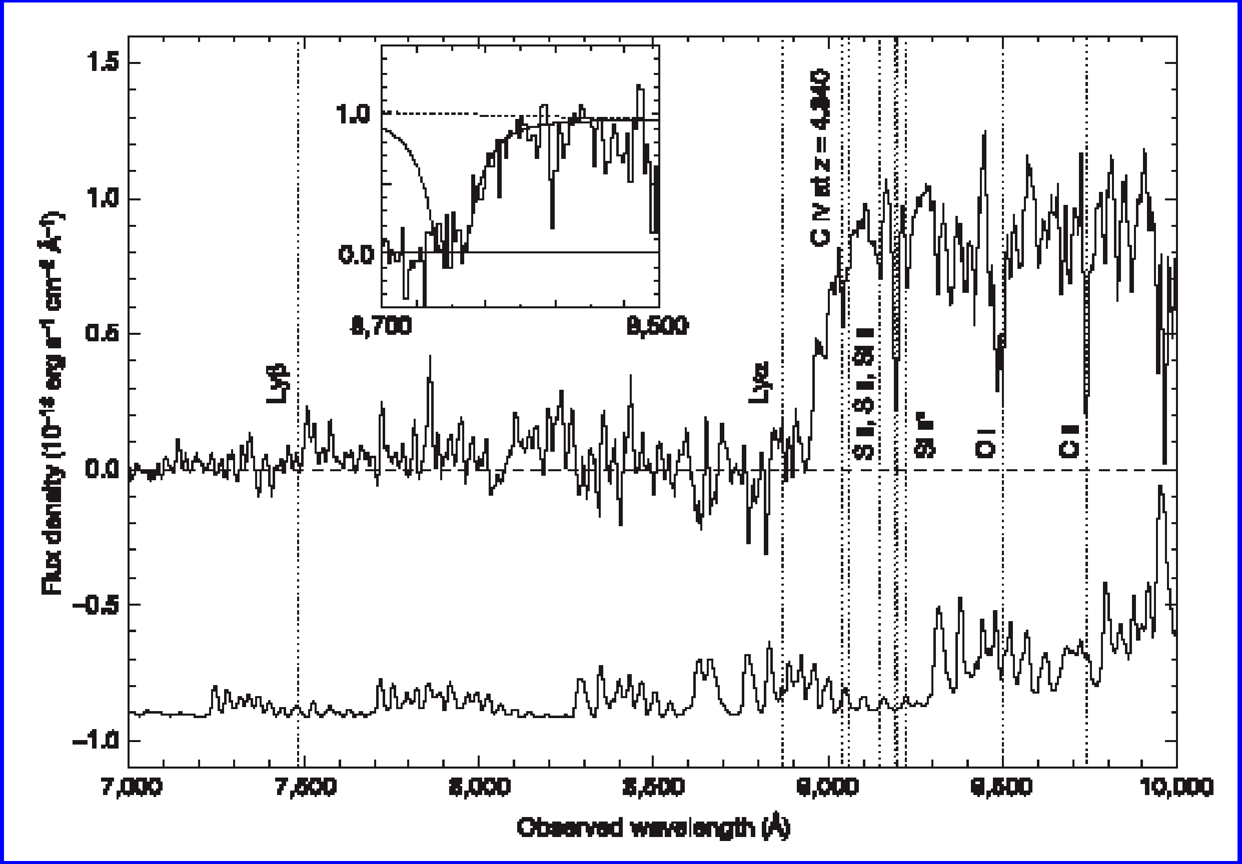
GRB 050904 (z=6.295)

Kawai et al. 2006, Nature, 440, 184

z=6.295, Z=0.05$Z_{\odot}$

Totani, et al. 2006, PASJ, 58, 485-498

$$X_{\mathrm{HI}} = 0.00 \pm 0.17 \text{ (<0.6 at 95\%CL)}$$



Observational Constraints for Pop III BHs

Integration of QSO LF

$\Omega_{\rm BH}({\rm QSO}) \approx 1.8 \times 10^{-6}$ (Yu & Tremaine 2002, MNRAS, 335, 965)

$\Omega_{\rm BH}({\rm QSO}) \approx (2.4 - 4.8) \times 10^{-6}$ (Marconi et al. 2004, MNRAS, 351, 169)

SMBH-bulge mass relation at z=0

$$\Omega_{\rm BH}({\rm bulge}) \approx 2.1 \times 10^{-6}$$

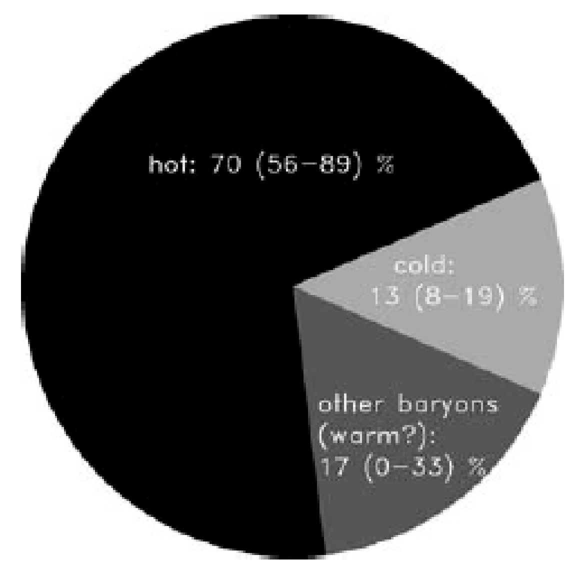
$$\Rightarrow \Omega_{\rm BH}({\rm Pop\ III}) \approx \Omega_{\rm BH}({\rm bulge}) - \Omega_{\rm BH}({\rm QSO}) < 3 \times 10^{-7}$$

BHs in halos

$$\Omega_{\rm BH}({\rm Pop\ III}) < \Omega_{\rm MACHO} \approx 0.001$$

Missing baryons

$$\Omega_{\rm BH}({\rm Pop\ III}) \lesssim 0.01$$

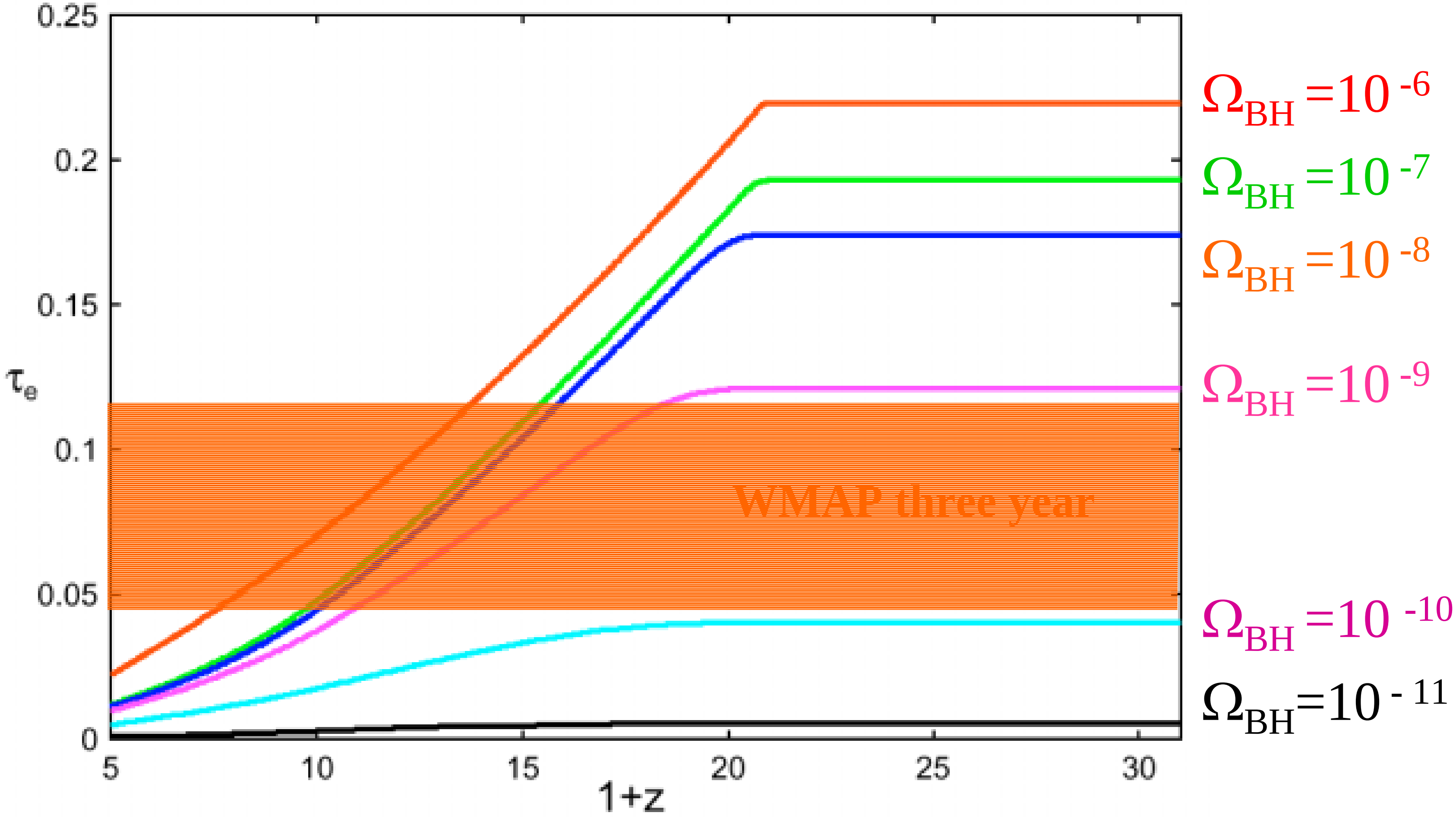


Cluster baryonic pie
Ettori 2003

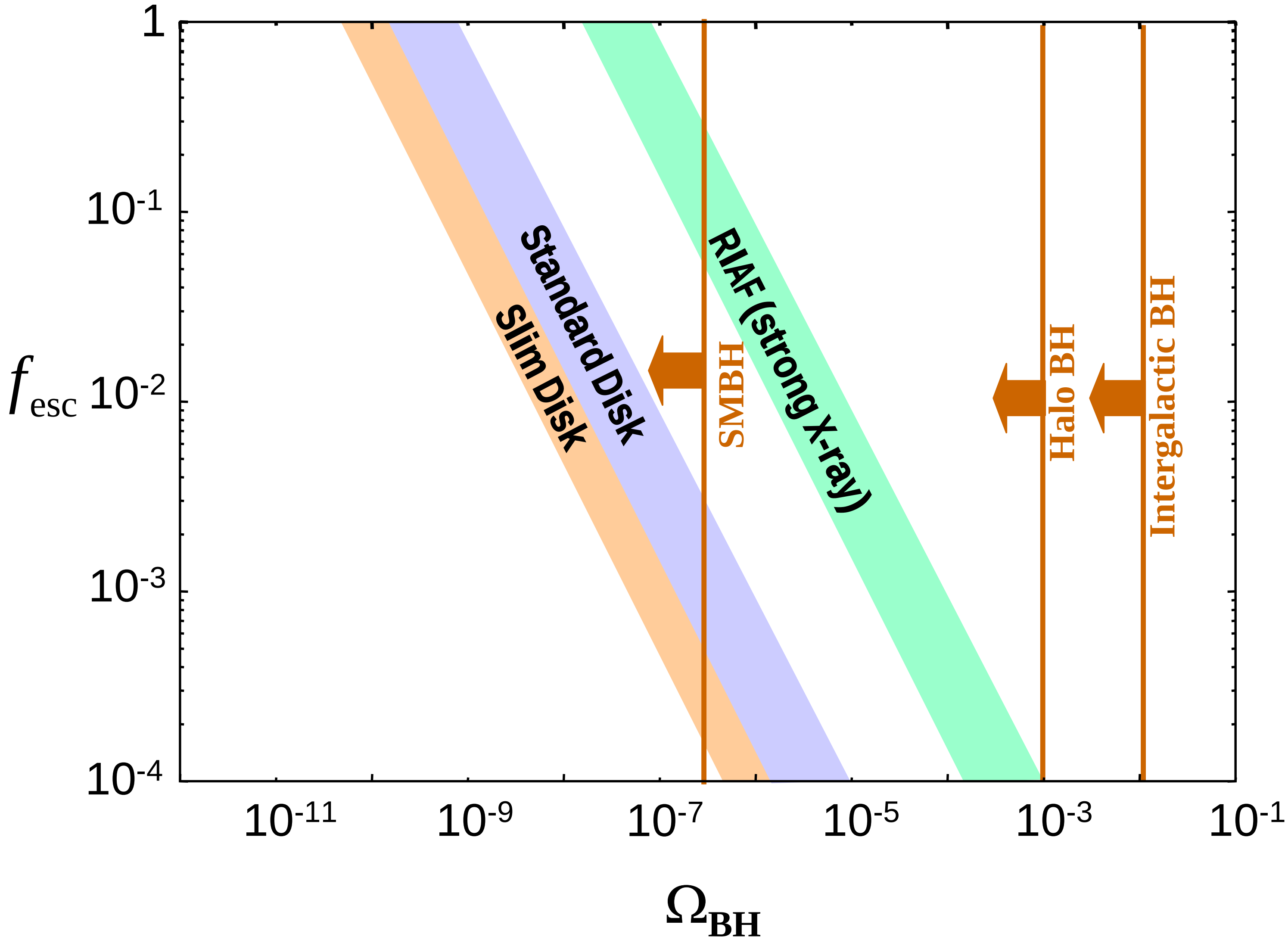
Thomson optical depth

$$\tau_e = \int (1-\chi_{HI}) n(z) \sigma_T \frac{dl}{dz} dz$$

$\eta = 0.1$, $\dot{m} = 1$, $f_{\mathrm{esc}} = 1$, $z_{\max} = 20$, $z_{\min} = 10$



Ω_{BH} (Pop III)に対する制限



WMAP Three year による Ω_{BH} (Pop III)への制限

- Standard Accretion Disk & Slim Disk

$$\boxed{3\times10^{-11} < \Omega_{\rm BH} f_{\rm esc} < 8.6\times10^{-10}} \quad (10< z < 20)$$

$f_{\rm BH}({\rm PopIII}) = \Omega_{\rm BH}({\rm PopIII}) / \Omega_b$ として

$$10^{-9} f_{\rm esc}^{-1} \lesssim f_{\rm BH}({\rm PopIII}) \lesssim 10^{-8} f_{\rm esc}^{-1}$$

- RIAF

$$1.6\times10^{-8} < \Omega_{\rm BH} f_{\rm esc} < 8.6\times10^{-8}$$

(too strong X-ray background ?)

f_{BH} (Pop III)について

assump 1: mass fraction of Pop III halos $f\,(\text{halo}) \approx 10^{-1}\text{-}10^{-2}$

assump 2: 1 Pop III star/halo $f\,(\text{Pop III}) \approx 10^{3}M_{\odot}/10^{5}M_{\odot} = 10^{-2}$

assump 3: BH fraction in Pop III stars $f\,(\text{BH}) \approx 10^{-1}$

⬇

$$f_{BH}\,(\text{Pop III}) \approx 10^{-4}\text{-}10^{-5}$$

$$\therefore\ f_{esc} \lesssim 10^{-4}$$

まとめ

1．宇宙で最初に誕生した星は, 主に100～1000$M_{\odot}$の
大質量星

2．電離ガス：　1～数10$M_{\odot}$
高密度領域：～1$M_{\odot}$

3．Zn生成のためには数10$M_{\odot}$の星が必要
130-300$M_{\odot}$ (PISNe) は鉄を作りすぎる

4．PopIII星を作りすぎるとWMAP 3year と矛盾する

5．WMAP 3year からPopIII BH量は強く制限される