The First Stars

Yu-Chun Liu

28.06.2007

The First Stars

The age of the universe: 13.7 billion years

- The First Generation (1.5 million years~1 billion years after the big bang) → Population III
- The Second Generation → Population II
- The Third Generation → Population I

The First Stars

Short Overview:

A. Properties:

1. Metal-free gas at the end of cosmic dark ages
2. Very massive (>100$M_\odot$) $\longleftrightarrow$ Stars nowadays~1 $M_\odot$

B. Problems:

1. Lack of direct observational data

The First Stars

Contents

1. **The Characteristic** – *The Difference between the First Stars and the Stars Nowadays*
2. **The Parent Clouds** – *The Properties of the Primitive Clouds*
3. **The Birth** – *The Formation of the First Stars*
4. **The Growth** – *The Accretion Process*
5. **The Death** – *The First Supernova Explosions*
6. **The Observational Techniques**

The Characteristic

The Difference between the First Stars and the Stars Nowadays

The Characteristics

The Difference between the First Stars and the Stars Nowadays

Why should we compare the first stars with the stars nowadays?

∵Lack of observational information

∴1.Base the model of the stars nowadays.

2.Verify initial conditions

→ Models for the first stars

The Characteristics

The Difference between the First Stars and the Stars Nowadays

1. The Molecular Clouds:

Population I - Cold, dense, and highly molecular gas

(a) supported against gravity by turbulent velocity fields

(b) pervaded on large scales by magnetic fields

Population III - homogenous molecular gas

(a) with the absence of dynamically significant magnetic fields

The Characteristics

The Difference between the First Stars and the Stars Nowadays

2. The Influences

Population I –

are influenced by the previous episodes of star formation

Population III –

do not have any influence by the previous star formation

(∵Population III stars are the first generation of stars)

The Characteristics

The Difference between the First Stars and the Stars Nowadays

3. The Metallicity

Population I – metal-rich

Population III – metal-poor

!! "Metal": (╳)The chemical aspect

(○)Elements heavier than H & He

The Characteristics

The Difference between the First Stars and the Stars Nowadays

Why are the Population III stars "metal-free"?

∵ After the big bang, after the temperature cooled down → hydrogen were first formed

∴ The first stars are formed by cooling and collapsing of the hydrogen and helium

The Characteristics

The Difference between the First Stars and the Stars Nowadays

After the stars are formed, they would start:

→ nucleosynthesis

→ create heavier elements (mostly C & O, but even up to iron in the Periodic table)

→ died in supernova explosion *(details would be discussed later)*

The heavy elements would be *(details would be discussed later)*

→ dispersed through the universe

→ be the sources for the next generation of stars

→ → The younger generation a star is, the more metal abundance it would contain

The Characteristics

The Difference between the First Stars and the Stars Nowadays

Critical metallicity Z_{crit}:

The Transition between Population III and Population II formation modes. (Z: the mass fraction contributed by all heavy elements)

$$Z_{crit} \sim 10^{-6} - 10^{-3}\ Z_{\odot}$$

$Z_{\odot}$: the implicit assumption of solar relative abundances of metals

The Characteristics

The Difference between the First Stars and the Stars Nowadays

Separate critical abundance:

$$\mathbf{[A/H]=log_{10}(N_A/N_H)-log_{10}(N_A-N_H)_{\odot}}$$

for ionized carbon and neutral atomic oxygen:

$[C/H]_{crit}$~-3.5±0.1

$[O/H]_{crit}$~-3.05±0.2

The Parent Clouds

The Properties of the Primitive Clouds

The Parent Clouds

The Properties of the Primitive Clouds

The Primitive clouds are lack of heavy elements.

What would happen is:

∵ Heavy elements are efficient radiators:

Release thermal radiation→ suppress the temperature of clouds to very low level

∴ Lack of heavy elements

→Lack of efficient coolant

→The cloud temperature must be higher

The Parent Clouds

The Properties of the Primitive Clouds

The only coolant that a primitive star has is H_2.

For T<1000K, cooling is due to:

1. Collisional excitation
2. Subsequent radiative decay of rotational transition of H_2.

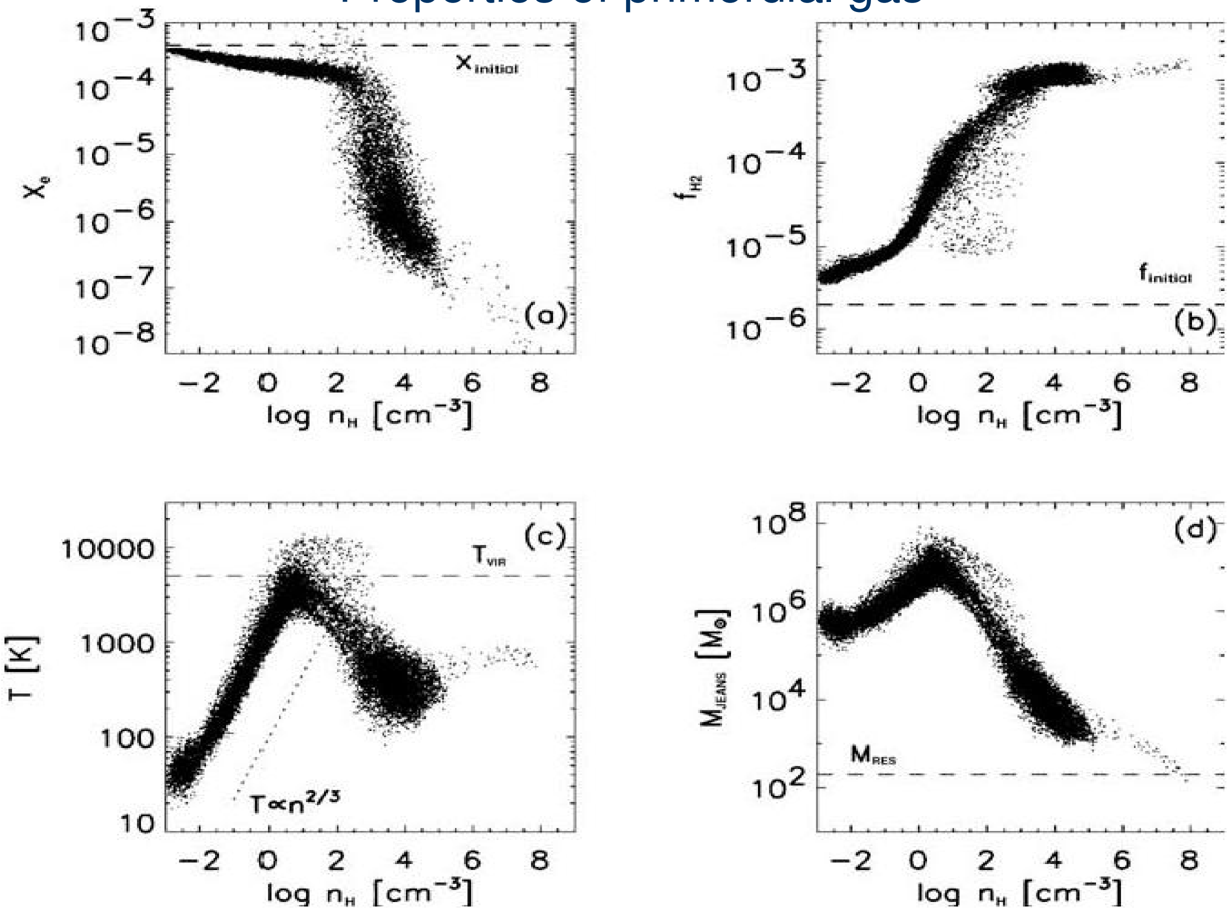
Until T~100K:

Cooling process can no more procced.

The Parent Clouds

The Properties of the Primitive Clouds

Properties of primordial gas



Source: Bromm et al, 2002.

The Birth

The Formation of the First Stars

The Birth

The Formation of the First Stars

How heavy is the initial mass of hydrostatic core of the primitive star?

The initial mass of the first stars

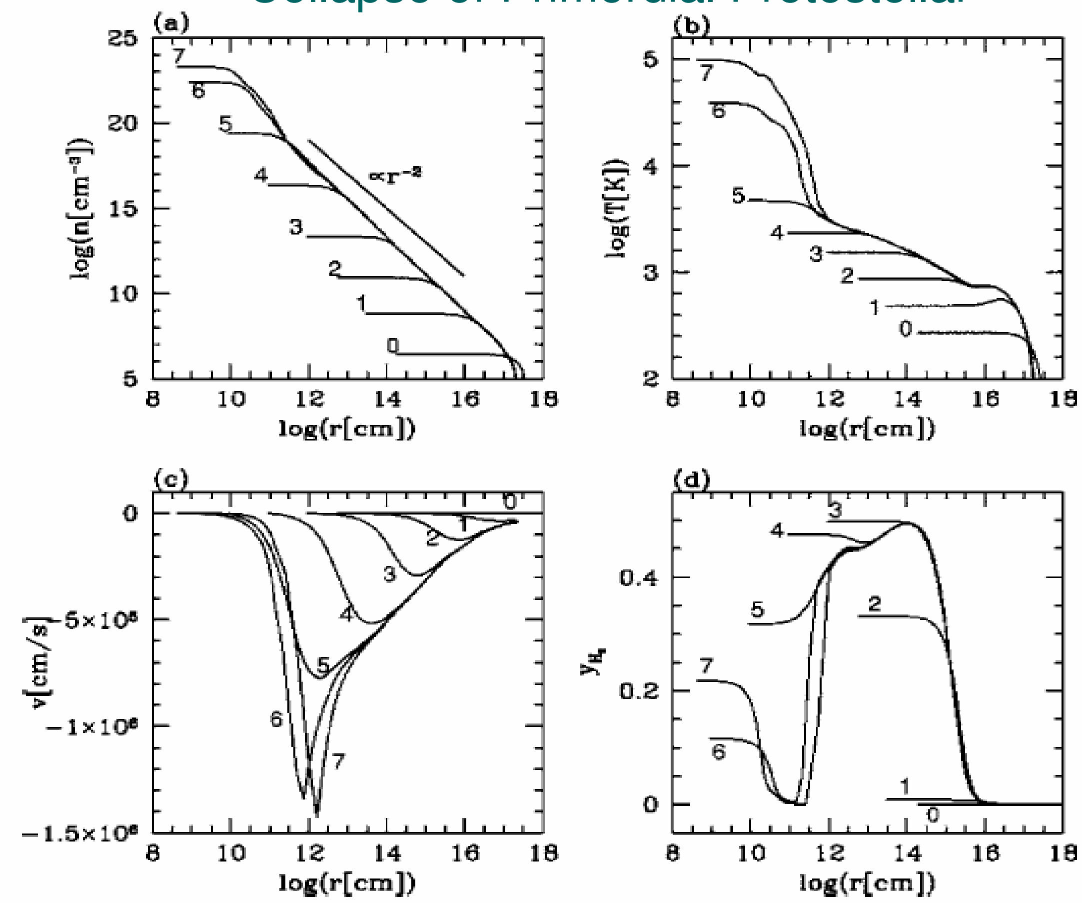
~ The initial mass of the stars nowadays

$\rightarrow M_i \sim 5*10^{-3} M_{\odot}$

The Birth

The Formation of the First Stars

Collapse of Primordial Protostellar



Source: Omukai & Nishi 1998.

The Birth

The Formation of the First Stars

(With the similar mass at the initial state, the two groups of stars end up with different masses.)

The stellar mass of the first stars ~ 100 $M_{\odot}$

The stellar mass of the stars nowadays ~ 1 $M_{\odot}$

→ ***How did the primitive stars end up so massive?***

The Growth

The Accretion Process

The Growth

The Accretion Process

The Accretion Rate: $\dot{M}_{acc} \approx \frac{c_s^3}{G} \propto T^{3/2}$

Compare the Ts of both Groups:

Pop I: T~10K

Pop III: T~200-300K

$\rightarrow \quad \frac{\dot{M}_{PopIII}}{\dot{M}_{PopI}} \sim 10^2$

The Growth

The Accretion Process

By computational analysis, there excites a critical accretion rate:

Critical Accretion Rate ~ $4*10^{-3}M_{\odot}$/yr

When the accretion rate exceed the critical accretion rate, the Protostar would:

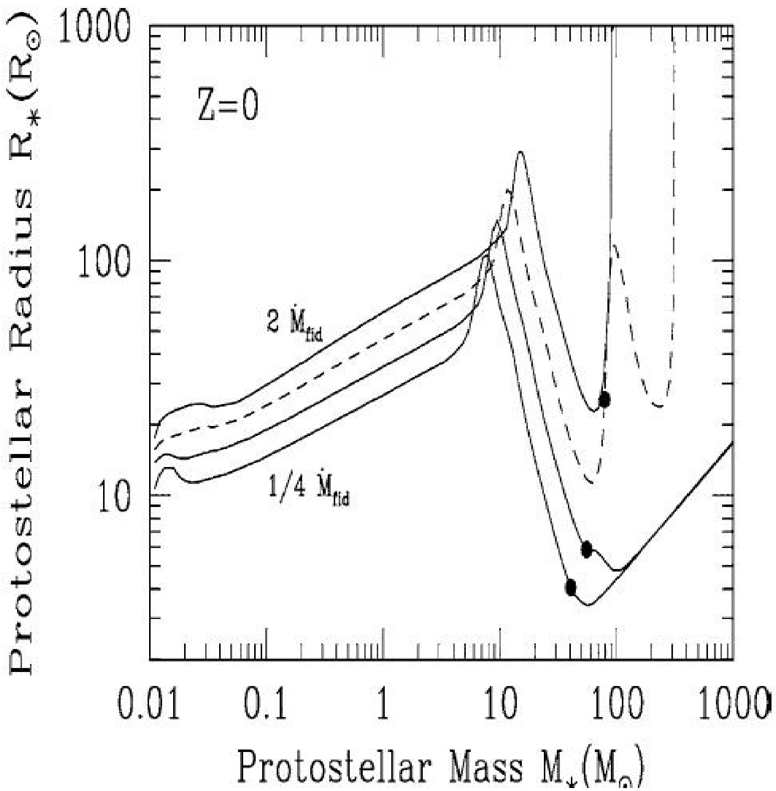
1. Stop collapsing
2. Start swelling

Source: Oukai & Palla 2003.

The Growth

The Accretion Process

Evolution of Accreting Metal-Free Protostar



Source: Omukai & Palla 2003.

The Death

The First Supernova Explosions

The Death

The First Supernova Explosions

How would the first stars die?

- $M_* < 140 M_\odot$

→ Collapse as a normal supernova

- $140 M_\odot < M_* < 260 M_\odot$:

Pair-Instability Supernova (PISN) Explosions

→Dispersing the heavy elements into the intergalatic medium

→*Contributes the heavy elements*

, $M_* > 260\ M_\odot$:

Black Holes

→The Heavy Elements would be lock up in the black holes

→*No contributions for the metallicity of the further generations*

The Death

The First Supernova Explosions

What is a Pair-Instability Supernova (PISN)?

Pair production: Production of free electrons and positrons in the collision between atomic nuclei and energetic gamma rays.

$\rightarrow$ reduce pressure of the core of a supermassive star (pressure drops)

$\rightarrow$ occurs partial collapse

$\rightarrow$ complete burning in a rapid thermonuclear explosion

$\rightarrow$ leaving no black hole remnant behind

The Death

The First Supernova Explosions

The Explosion Process:

Under what condition?

The only condition that the first supernova explosion may occurred:

The numerical simulation done by Bromm et al.(2003)

Initial Minihalo:

$M \sim 10^5 M_{\odot} - 10^6 M_{\odot}$

$z > 20$

The Death

The First Supernova Explosions

Assume that there is one single Population III star in the centre of the minihalo with mass large enough to explode as a PISN.

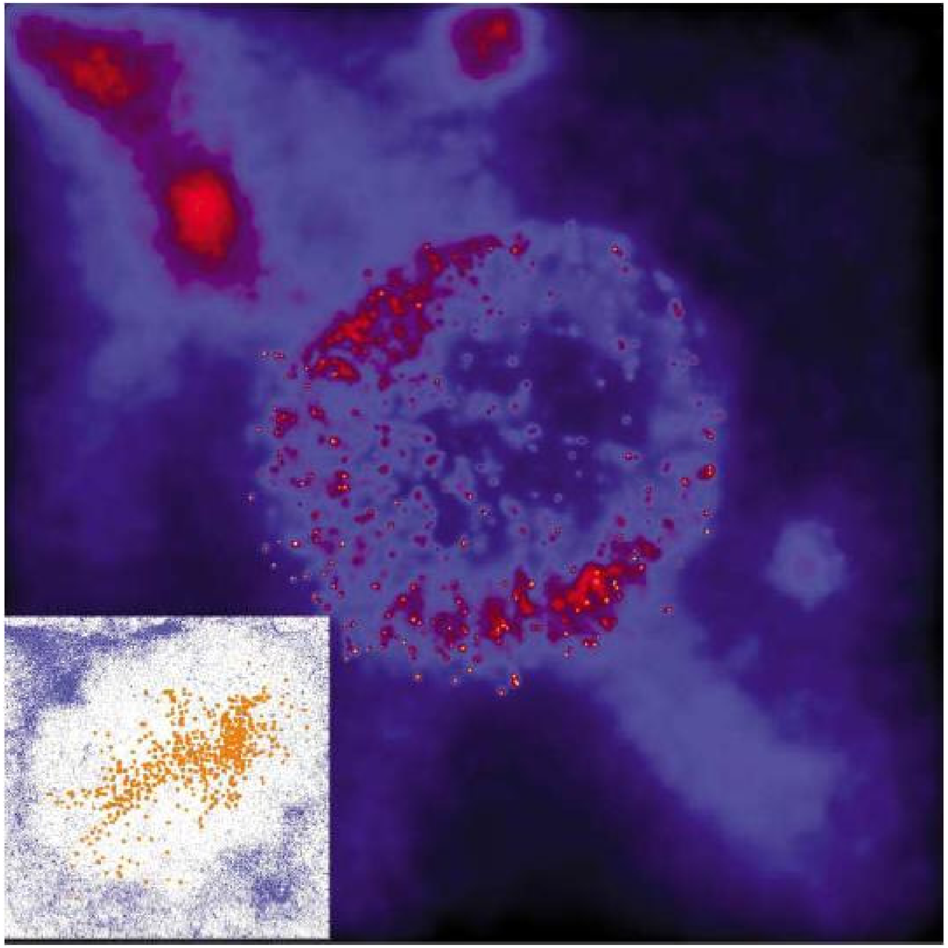
i. → **The blast wave starts evolving** into a roughly uniform medium at radii smaller than the core

ii. → **The blast wave reaches beyond the core** and encounter the remainder of the halo to the scaling

iii. → **Radiative loss causes cooling** and the supernova remnant then enter its final phase

The Death

The First Supernova Explosions



Source: Bromm et al. 2003

The Death

The First Supernova Explosions

How did the heavy elements wide spread into the intergalactic medium?

1.The Mass of the minihalos are small

→Shallow potential well of the minihalos

→The metals escape more easily

2.The universe is not yet widely expanded

→The distance between the halos are shorter

→the enriched gas travel much shorter distance

→easier to establish a uniform metal distribution in the intergalatic medium

The Observational Techniques

The Observational Techniques

Based on: **Observing ionization**

Why?

- After the big bang, hydrogen and a few light elements formed.

→ the elements formed into gas clouds because of the gravity.

→ the gas cloud formed into stars and began to light (radiate).

→ the radiation turned the surrounding atoms into ions

- After the supernova explosion,

→ the ionization would in the end pervade all space

→ even now, there remain a few hydrogen between the galaxies

The Observational Techniques

Observing ionization

→The Lymann-Alpha Resonance

→21-cm Cosmology

The Observational Techniques

The Lymann-Alpha Resonance

The Lyman- α resonance of hydrogen with wavelength 1216 $\mathring{A}$: trace hydrogen gas through its absorption from quasar light.

∵The universe expanses

∴. the rest-frame absorption of the gas element

(i) at wavelength 1216 $\mathring{A}$

(ii) at redshift z

→observed today at wavelength 1216(1+z) $\mathring{A}$

The Observational Techniques

The Lymann-Alpha Resonance

The absorption of different elements:

$\rightarrow$ Distributed over the broad range of wavelength along the line of sight

$\rightarrow$ Distribution of the interglactic hydrogen is possible to be measured.

The Observational Techniques
21-cm Cosmology

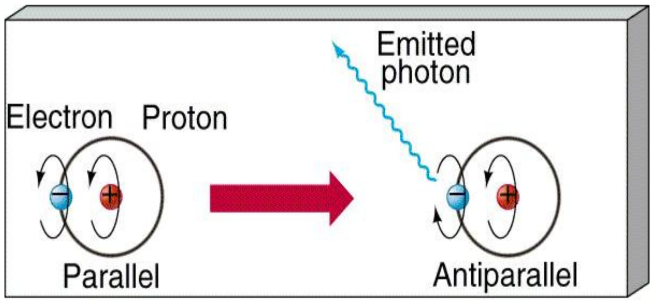
The spins of electrons or protons of H in the ground state could be either parallel or opposite.

$\longrightarrow$ the energy difference corresponds to the frequency

$$\Delta f = 1420.4 MHz$$

$\longrightarrow$ the transition between the two hyperfine structure of the energy correspond to the wavelength

$$\lambda = {}^{c}\!/_{f} = 21.049 cm$$



Source: http://physics.uoregon.edu/~courses/BrauImages/Chap18/FG18_016.jpg

The Observational Techniques

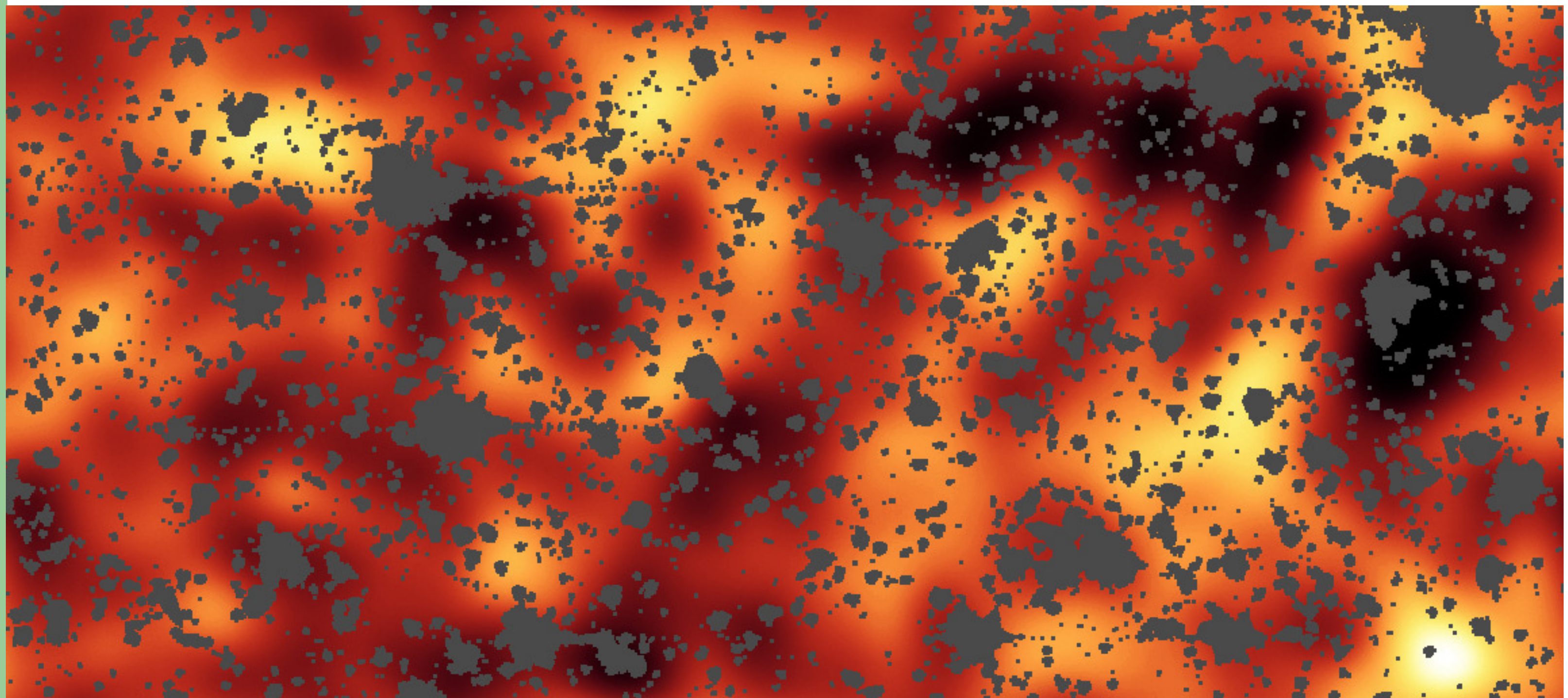
21-cm Cosmology

For such wavelength, much longer then optical photons, it won't be easily absorbed by the intergalactic medium.

$\rightarrow$ detect the signals

$\rightarrow$ map the density or temperature of the clouds

The First Stars



(Source: NASA/JPL-Caltech/A. Kashlinsky (GSFC) et al. NASA's Spitzer telescope.)

References

- The First Stars – V. Bromm, R.B. Larson – Annu. Rev. Astron. Astrophys. 2004. 42:79-118
- The First Stars in the Universe and Cosmic Reionization – R. Barkana – arXiv:astro-ph/0608450v1 21 Aug 2006
- The First Supernova Explosions in the Universe – V. Bromm, N. Yoshida, L. Hernquist - arXiv:astro-ph/0305333v3 17 Oct 2003
- The Formation of Primordial Stars – S. W. Stahler – Publication of the Astronomical Society of the Pacific 98:1081-1087, 1986

- Fundamental Astronomy – 3rd. Ed. – Karttunen