Lecture1

Physics of Primordial Star Formation

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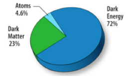
ADVANCED SUMMER SCHOOL 2019 “First Light”

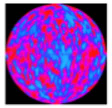
WE HAVE LEARNED

From Lecture 1 of Professor Barkana

1. The standard cosmological model



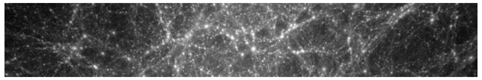
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\rho - \frac{c^2 K}{a^2} + \frac{c^2\Lambda}{3}$$



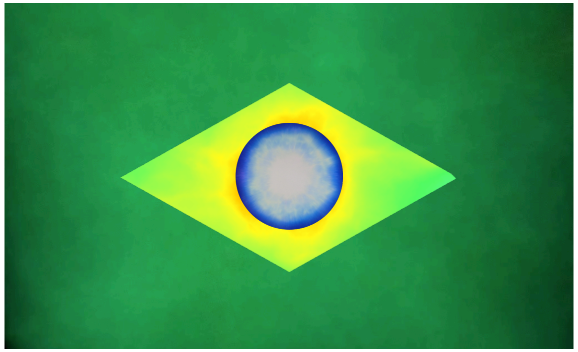
2. Growth of density fluctuations

$$\sigma^2(M) = \frac{1}{2\pi^2}\int P(k)W^2(kR)k^2\,\mathrm{d}k$$

3. Assembly of dark matter halos



Where did the first star form ?

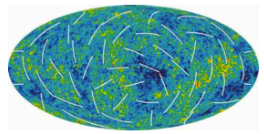


Yes, here in Brazil!

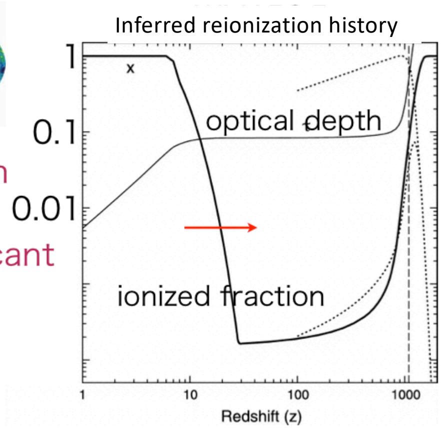
In the beginning,
there was a sea of light elements
and dark matter
....and some ripples left over
from the Big Bang.

Contents

Cosmic Reionization



CMB polarization measurement suggests significant star-formation at z ~ 10



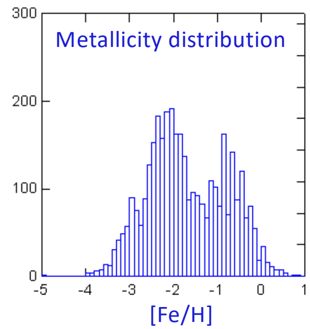
Oldest Stars in Our Backyard

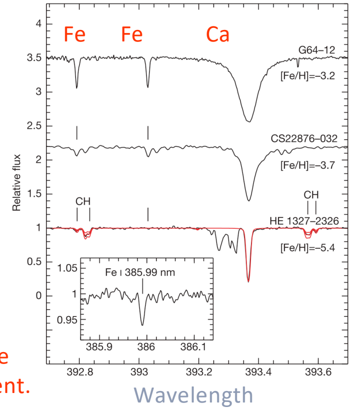
Low-mass ($<1M_{sun}$), extremely iron-poor star.
Metallicity below 4.5 x 10^{-5} *that of the sun.*

Caffau et al. 2012, Nature

A Second-Generation Star ?

Some stars contain almost no iron!!

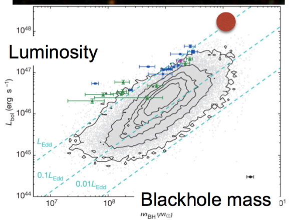




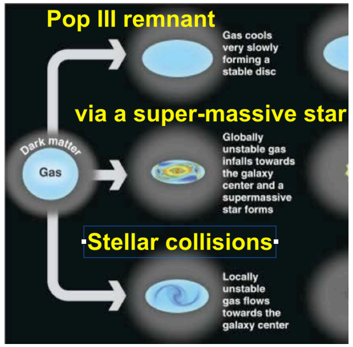
In the Milky Way halo, there are Stars with very low metal content.

MONSTROUS BLACKHOLE AT EOR

Wu et al. 2015
Banados et al. 2017
$>10^9$ solarmasses



Seed BH formation mechanism ?
Growth ?
Observational signature ?



FASCINATION WITH CURRENT ASTRONOMY & COSMOLOGY

- Peculiar, small and old stars in our Milky Way.
- Existence of monstrous blackholes at the most distant place.
- Small polarization signatures in the cosmic microwave background radiation.

These are seemingly different, and unrelated issues. But they are actually connected to each other within the big picture or the whole story of our universe.

THE FIRST STARS

The first stars emit the "first light",

and produce the first heavy elements.

They set the scene for the subsequent

formation of galaxies, metal-poor stars,

and massive blackholes.

Primordial Star Formation

STAR FORMATION IN THE EARLY UNIVERSE

Cosmological recombination at t = 380 Kyrs

↓

Non-linear formation of dark matter clumps

↓

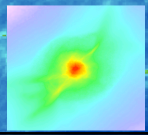
Virialization, chemical reactions take place and hydrogen molecules are formed.

↓

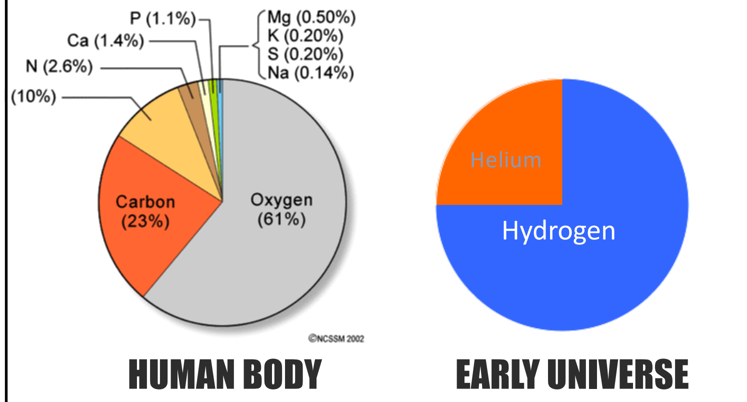
Gas condensation at the center of DM clumps

↓

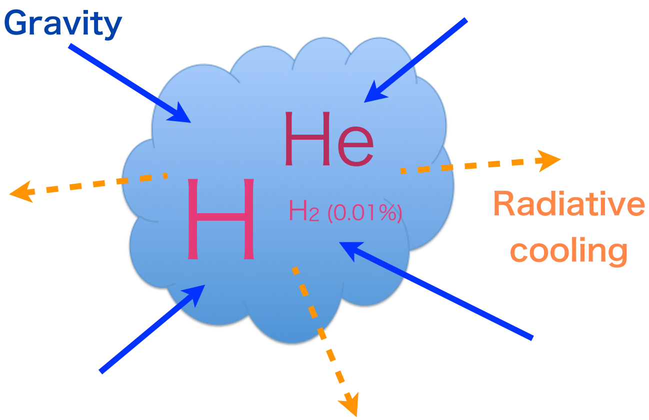
Runaway collapse when a cloud gets large enough = star-formation.



ELEMENTS NOW AND THEN



PRIMORDIAL GAS CLOUD



PRIMORDIAL GAS CHEMISTRY

e, H, H^+, H^-, H_2, H_2^+, He, He^+, He^{++}
D, D^+, D^-, HD, HD^+

Composition: 76% H, 24% He、0.001% D、little Li

- Collisional ionization, recombination
- Formation of molecules (H_2, HD, H_3^+, H_2^+, HD^+, HeH)
- Photoionization, photo-dissociation
- Radiative cooling
  collisional excitation, collisional ionization, recombination, Bremsstrahlung, compton cooling, CMB heating

About > 50 reactions, depending on the details.

CHEMICAL REACTIONS

$H + e \rightarrow H^+ + 2e$	$k_1 = \exp[-32.71396786 + 13.536556(\ln T_e) - 5.7$
	$+ 0.0348255977(\ln T_e)^5 - 0.00263197617(\ln$
$H^+ + e \rightarrow H + h\nu$	$k_2 = \exp[-28.6130338 - 0.72411256 \ln T_e - 0.02$
	$+ 4.98910892 \times 10^{-6}(\ln T_e)^6 + 5.75561414 \times$
$He + e \rightarrow He^+ + 2e$	$k_3 = \exp[-44.09864886 + 23.91596563 \ln T_e - 10$
	$+ 0.0679539123(\ln T_e)^5 - 0.00500905610(\ln$
$He^+ + e \rightarrow He + h\nu$	$k_{4r} = 3.925 \times 10^{-13} T_e^{-0.6353}$, $k_{4d} = 1.544 \times 10^{-9} T_e^{-1}$
$He^+ + e \rightarrow He^{++} + 2e$	$k_5 = \exp[-68.71040990 + 43.93347633 \ln T_e - 18$
	$+ 0.08113042(\ln T_e)^5 - 0.00532402063(\ln T_e$
$He^{++} + e \rightarrow He^+ + h\nu$	$k_6 = 2 \times k_2(T_e/4)$
$H + e \rightarrow H^- + h\nu$	$k_7 = 1.4 \times 10^{-18} T^{0.928} \exp(-T/16200)$
$H^- + H \rightarrow H_2 + e$	$k_8 = 4.0 \times 10^{-9} T^{-0.17}$
$H + H^+ \rightarrow H_2^+ + h\nu$	$k_9 = \mathrm{dex}[-19.38 - 1.523 \log T + 1.118(\log T)^2 -$
$H_2^+ + H \rightarrow H_2^* + H^+$	$k_{10} = 6.0 \times 10^{-10}$

This is just a partial list.

Stars are formed…

in cold, dense, molecular gas clouds.

Gravity alone does not make it. Gravitational collapse compresses and heats the gas.

We need a mechanism to cool a gas cloud.

Radiative cooling removes the excess energy (i.e., lowers the gas pressure) and makes it possible for the gas to cool and condense.

Radiative cooling operates *only* if there are coolants.

How did all this happen in the early universe ?

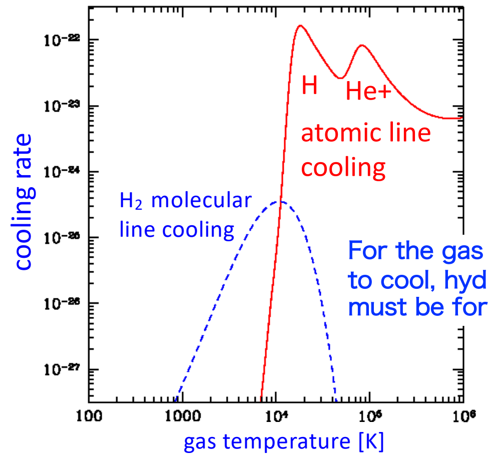
In the present-day universe…

Interstellar gas can cool by, e.g.,

- Metallic ions such as Fe, Si, O
- Molecules such as CO, OH
- Dust thermal emission

None of these coolants existed in the early universe.

RADIATIVE COOLING



For the gas in a minihalo to cool, hydrogen molecules must be formed in some way.

H_2 Formation : Gas phase reactions

Photo-attachment

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$$

H_2 formation

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$$

* There is another possible path via H_2^+ formation, which is effective only at z > 100 when the background radiation temperature is high.
(See Galli & Palla 2013, Annual Reviews)

H_2 Formation : Present-day

Formation on dust grains

H + H on dust → H_2 + dust

This reaction is much faster than the gas-phase reaction.
In the present-day inter-stellar medium, almost all the hydrogen atoms are converted to molecules at relatively low densities.
But this does not happen in the early universe.

H_2 Formation : Gas phase reactions

Photo-attachment

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$$

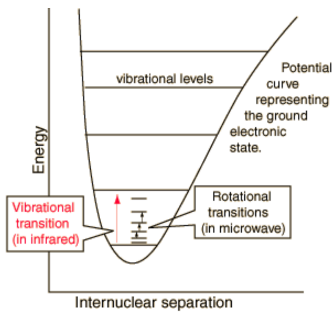
H_2 formation

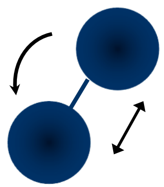
$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$$

Slow reactions, using residual electrons as catalyst.
Effective at T > 1000 K (M > 10^5 M_{sun})
Molecular fraction reaches ~ 0.001

H_2 molecular line cooling

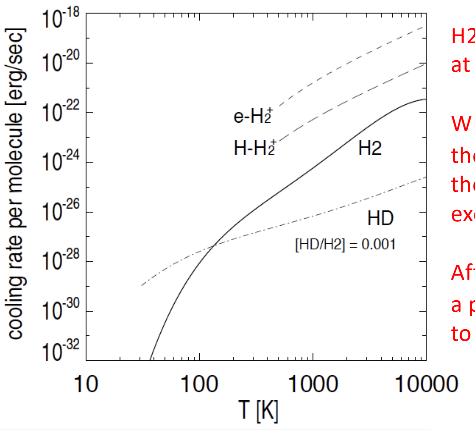
H_2 is a homo-nuclear molecule; no dipole transition
→ Only quadro-pole transition (ΔJ = 2)





The most important transition at low densities is
(J=2, v=0) to (J=0, v=0)

H2 cooling rate



H2 molecules are mostly at the ground level (J=0).

When an H atom hits, the H_2 molecule, the molecule got excited to J=2.

After a while, it emits a photon spontaneously, to be back to the J=0.

H_2 cooling: A brief History

Late 60's) Pregalactic clouds, molecular hydrogen

Matsuda-Sato-Takeda, Yoneyama, Saslaw & Zipoy

Peebles & Dicke (globular cluster)

Early 80's) Primordial star formation, fragmentation

Palla-Stahler-Salpeter, Yoshii, Silk, Couchman & Rees (CDM)

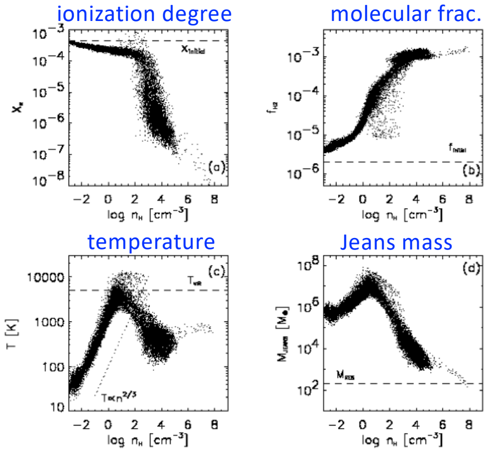
2000's) Cosmological simulations, pre-collapse

Omukai-Nishi, Bromm+, Abel+, Yoshida+, Greif

2010's) Protostellar evolution, final masses

Hosokawa, Stacy+, Hirano, …

Primordial gas cloud



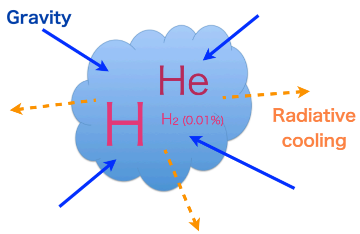
Bromm, Coppi, Larson (2002)

Physical properties of H_2 molecules determine the thermal evolution.

ΔE (J=2 - 0) ~ 512 K sets the minimum temperature.

Non-LTE cooling to LTE cooling "loitering".

The Jeans mass



A sufficiently massive cloud, its self-gravity wins against the gas pressure, triggering gravitational collapse.

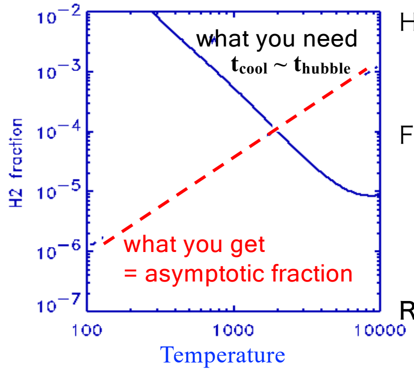
The critical mass is called the Jeans mass, which is given by

$$M_J \simeq 500 M_\odot \left(\frac{T}{200K}\right)^{3/2} \left(\frac{n}{10^4 \mathrm{cm}^{-3}}\right)^{-1/2}$$

Formation of hydrogen molecules

What you get must be more than what you need

Tegmark et al. (1997)



Hydrogen recombination

Left-over electroms

H, H-

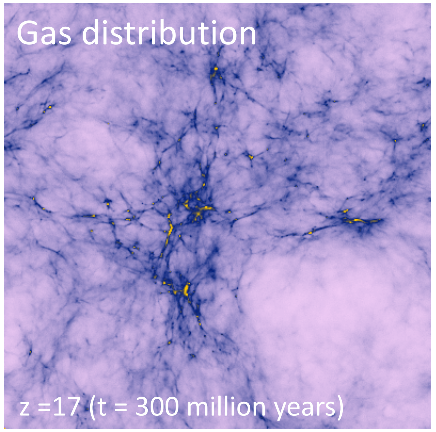
Formation of H_2

Electron depletion

H^+, e-

Radiative cooling

Cosmological First Objects



Yoshida et al. (2003) ApJ

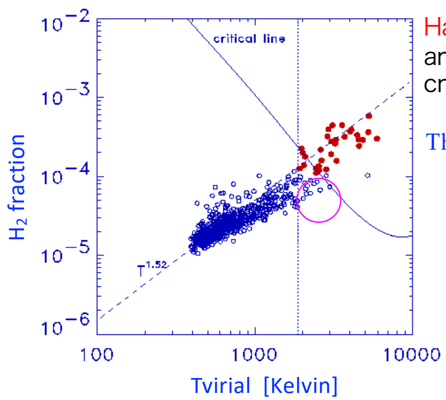
Web-like structure in the early universe.

Halo mass $\sim$ 1,000,000 M_{sun}

Gas clouds are $\sim$ 1000 M_{sun}

Strongly clustered

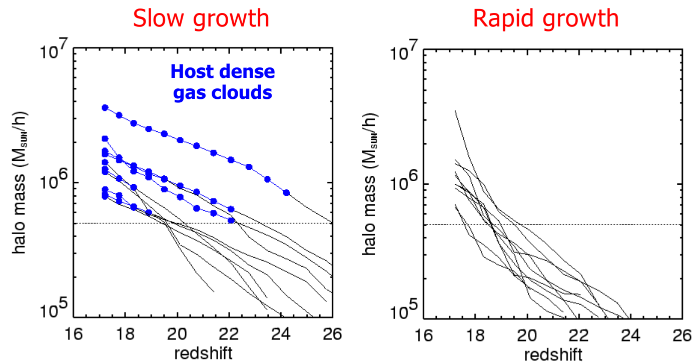
Result from a 3D cosmo. simulation



Halos that host gas clouds are populated above the critical line, as predicted.

There are unexpected halos…

Halo formation and dynamical heating



Halo formation and dynamical heating

A primordial gas can be heated adiabatically, chemically, and also *dynamically*.
The increase of the halo mass is also accompanied by Effective heating given by

$$\Gamma_{\rm dyn} = \alpha M_{\rm halo}^{-1/3} \frac{k_{\rm B}}{\gamma - 1} \frac{dM_{\rm halo}}{dt}$$

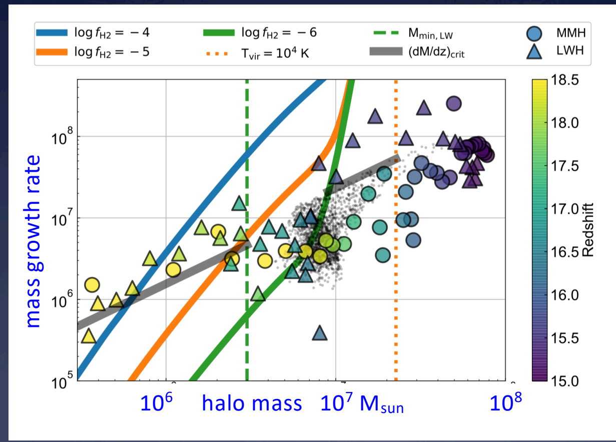
Recall Lecture 1 of Professor Barkana

$$T_{\rm vir} = \frac{\mu m_p V_c^2}{2k_{\rm B}} = 1.03 \times 10^4 \left(\frac{\Omega_m h^2}{0.141}\right)^{1/3} \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^8\ M_\odot}\right)^{2/3} \left(\frac{\Delta_c}{18\pi^2}\right)^{1/3} \left(\frac{1+z}{10}\right) \mathrm{K}$$

Heating-cooling balance can be established if

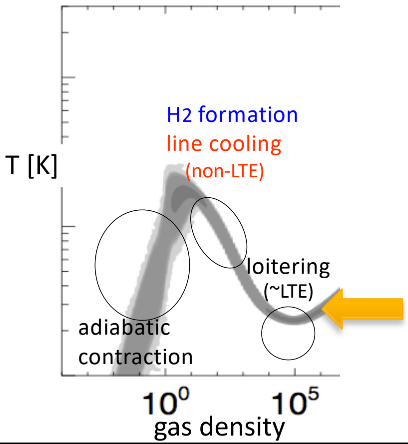
$$\left(\frac{dM_{\rm halo}}{dt}\right)_{\rm crit} = \frac{2\alpha}{3} \frac{\gamma - 1}{k_{\rm B}} M_{\rm halo}^{-1/3} n\Lambda(T_{\rm halo})$$

In the context of blackhole formation



Wise et al. 2019, Nature

THERMAL EVOLUTION OF A PRIMORDIAL GAS

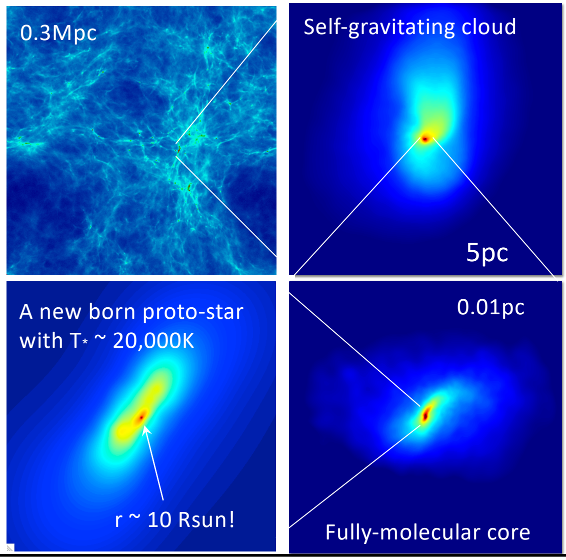


Cooling rate from NLTE (~ density^2) to LTE (~ density)

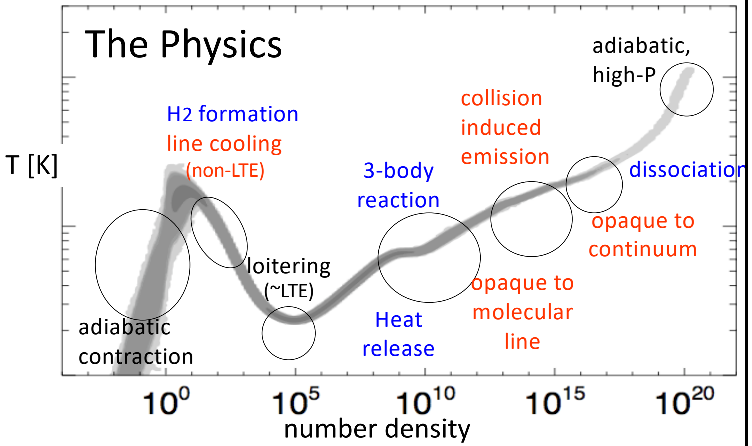
Jeans mass ∼ $T^{1.5}/n^{0.5}$
∼ 500 Msun

Run-away collapse beyond this phase

From a cloud to a protostar



THERMAL EVOLUTION OF A PRE-STELLAR GAS



On a First-Principle Basis

- Physical and chemical processes are just so complicated. Can be even boring. Although I explain many of them in my lectures, you may forget them quickly ;-)
- Details aren't important, but, it is of critical importance to know that one can make an *ab initio* approach, with all the relevant physics followed on a first-principle basis. This is a take-home message today.

From the suggest reading:

In this article, we review recent progress in the theory of structure formation in the early universe. We focus on physical processes relevant to the formation of the first stars. We also introduce the results from state-of-the-art computer simulations. There are two major reasons that we expect super-computer simulations play an important role in the study on early cosmic structure formation: (1) the initial conditions, as determined through a broad range of astronomical observations, are well-established, so that an accurate representation of the early Universe can be generated as a complete computer model, and (2) the important basic physics such as gravitation, hydrodynamics, and chemical reactions in a cosmic primordial gas are identified and understood. In principle, it is possible to understand purely theoretically the formation of early structure and of the first stars in an expanding universe. We describe the basic elements in such super-computer simulations. The implications of the obtained results are discussed.

Hydrogen molecules can

Rotate, and vibrate

Quantum energy levels

Emit and absorb photons

Radiative cooling (gas temperature↓)

Be formed, and destroyed

Chemical cooling and heating (T ↓↑)

Collide with other atoms

Interact with photons, cooling and heating

H_2 formation by 3-body reactions

At high densities, H_2 molecules are formed by

$$\mathrm{H} + \mathrm{H} + \mathrm{H} \rightarrow \mathrm{H_2} + \mathrm{H}$$

$$\mathrm{H} + \mathrm{H} + \mathrm{H_2} \rightarrow 2\mathrm{H_2}$$

- The reaction rate scales as density^3.
- The core becomes almost fully molecular
- Significant heat release (4.48eV per molecule)

$10^{10\text{-}14}$

Radiative Transfer 1: molecular lines

Example) H2 J=6 → 4 transition at T = 1000 K

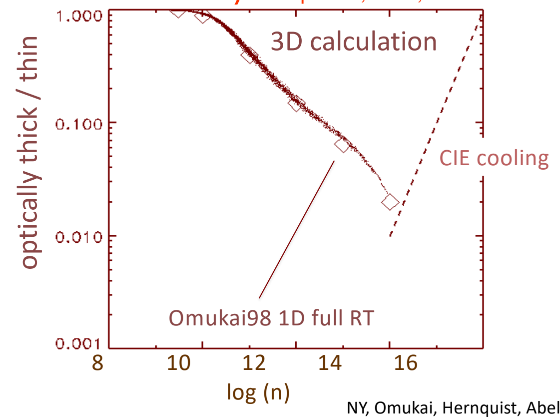
$$\alpha_{4,6} = \frac{\Delta E_{6,4}}{4\pi}\, n_4\, B_{4,6} \left(1 - e^{-\Delta E_{6,4}/kT}\right) \phi(\nu)$$

$$\tau_{4,6} = \alpha_{4,6}\, L_{\mathrm{H_2 core}}$$

For τ>0.1, the cloud core becomes optically thick to H2 lines、and then line cooling is inefficient （$\tau_{4,6}$~1 for L_{core}~0.0001pc）

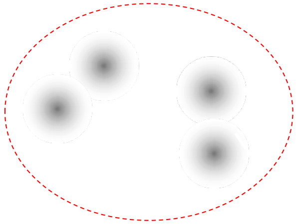
Net molecular cooling rate

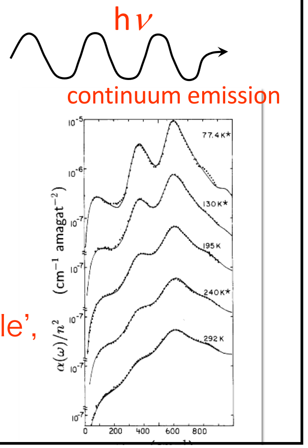
Λthick = $\sum \beta_{escape}\, n_{k,l}\, A_{k,l}\, h\nu$



NY, Omukai, Hernquist, Abel (2006)

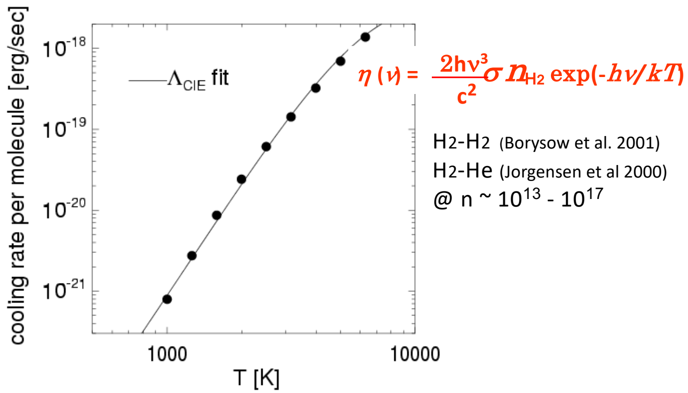
10^{14-17} Cooling by continuum:
Collision Induced Emission





During collisions, a collision pair acts as a 'super-molecule', generating an induced electric dipole.

Optically thin CIE cooling rate



$>10^{16}$ Equilibrium chemistry: the Saha equations

A set of coupled equations including the energy equation are solved self-consistently:

H-H+

$$\frac{n_{H+}^2}{n_H} = \frac{2}{z_H}\left(\frac{2\pi k m_e T}{h^2}\right)^{3/2} \exp\left(-\frac{\chi_H}{kT}\right)$$

$\chi_H = 13.598$ eV

H-H2

$$\frac{n_{H_2}}{n_H^2} = \frac{z_{H_2}}{z_H^2}\left(\frac{h^2}{\pi k m_H T}\right)^{3/2} \exp\left(\frac{\chi_{H_2}}{kT}\right)$$

$\chi_{H_2} = 4.48$ eV

Non-ideal gas effects

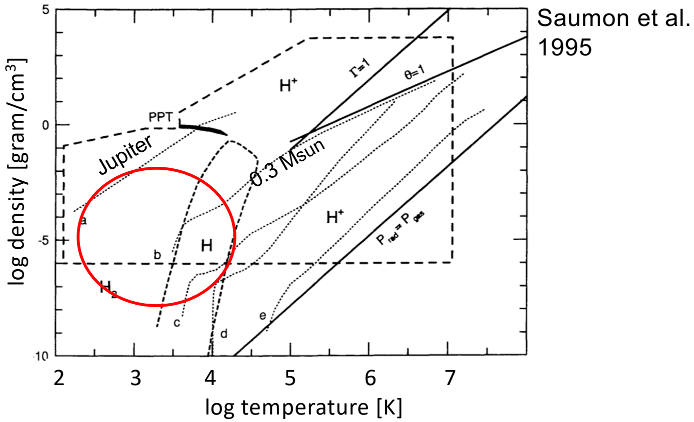
At $\rho \sim 0.01$ gram/cc ($n \sim 10^{21}$ /cc), atoms and molecules interact strongly and forms a non-ideal fluid.

At $\rho \sim 0.1$ gram/cc, the Saha equations for ionization and dissociation becomes inaccurate.

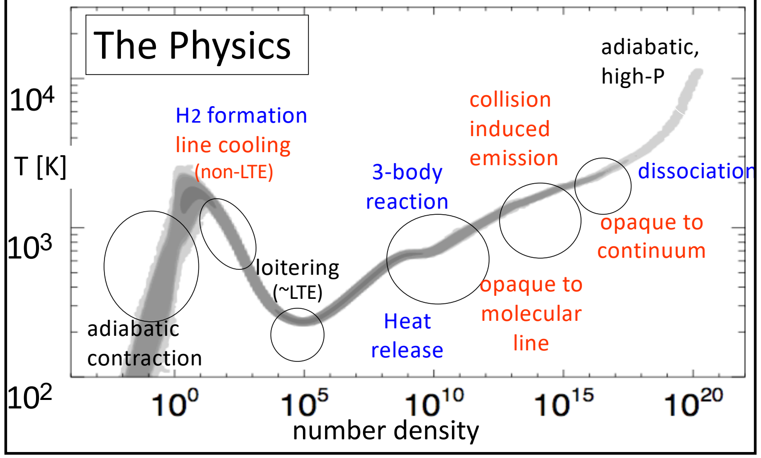
"An equation's got to know its limitations."

At $\rho \sim 1$ gram/cc, the mean distance between H atoms becomes comparable to the classical Bohr radius.
Then the electric wavefunctions of nearby atoms overlap.
The so-called *pressure ionization.*

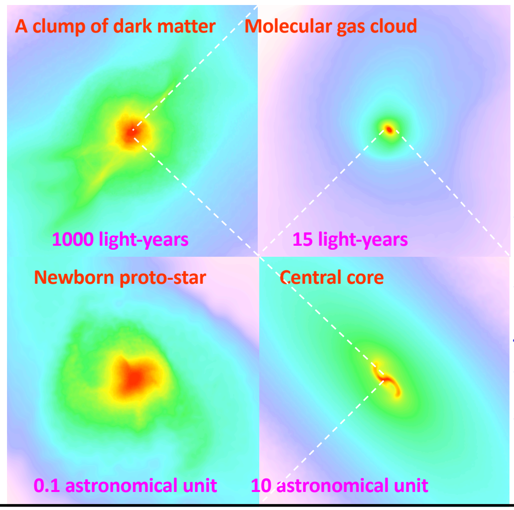
Hydrogen Phase Diagram



Thermal Evolution of a Pre-Stellar Gas



Primordial Protostar

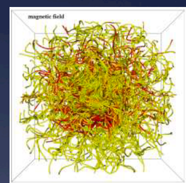


Yoshida, Omukai, Hernquist, 2008, Science

Where are these elements ?

- Turbulence, magnetic field, and dust

Seed magnetic field is very weak
B $\sim 10^{-9}$ gauss in mini-halos (Xu+ 2008)

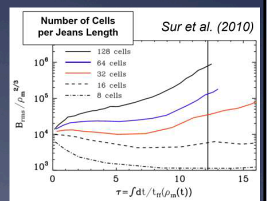


Amplification during the collapse:

- Flux freezing not strong (neutral gas)
- Small-scale dynamo
  ← convergence problem,
  but *at most half* the kinetic energy

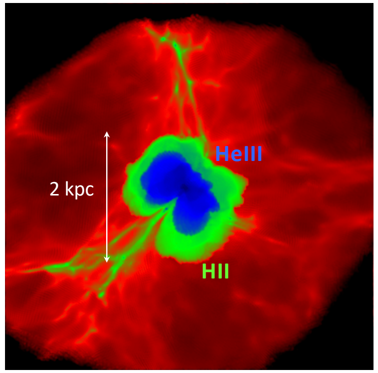
If strong enough B-field exists:

- Magnetic breaking surppress disk formation and fragmentation
- Enhances mass accretion (Pandey+ 19)



PopIII.2 Stars: Primordial Star Formation in a Reionized Gas

Early HII/HeIII region



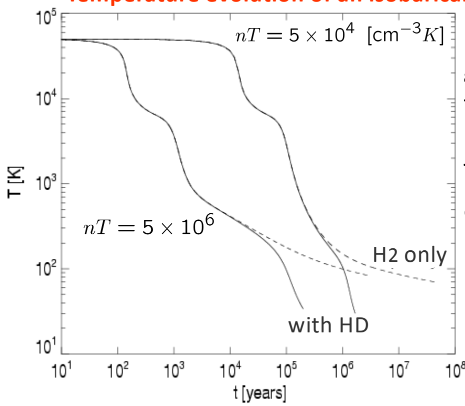
Almost fully ionized within the HeIII region.

H in HeIII region kept ionized by recombination (HeII Ly-a, HeII-Balmer, HeII two-photon) photons (Osterbrook 1989)

HII/HeII regions have (almost) the same extent.

Cooling and chemical fractionation

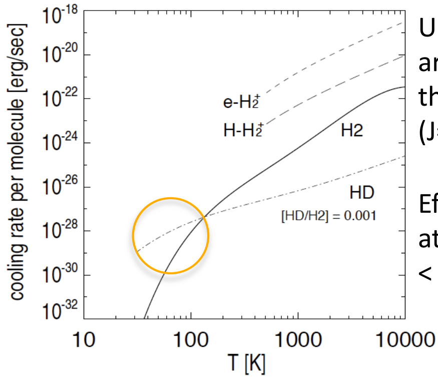
Temperature evolution of an isobarically cooling gas



In an initially ionized gas, there are plenty of free electrons, to be used for H2 formation. The gas temperature can reach as low as 100K.

Evolution of a cooling gas and the role of HD molecules

Molecular cooling rate



Unlike H2, HD molecules are hetero-nuclear, and thus dipole transitions (J=1 to 0) are allowed.

Effective cooling process at low temperatures < 100K.

Chemical fractionation

D ionization

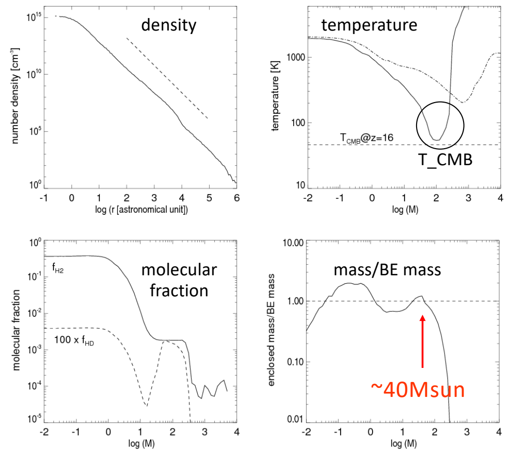
$$D1, D2 : \mathrm{D} + \mathrm{H}^+ \leftrightarrow \mathrm{D}^+ + \mathrm{H}$$

HD production

$$D3, D4 : \mathrm{D}^+ + \mathrm{H}_2 \leftrightarrow \mathrm{H}^+ + \mathrm{HD}$$

$$\frac{n(\mathrm{HD})}{n(\mathrm{H}_2)} = \frac{k_{D3}k_{D1}n(\mathrm{D})}{k_{D4}k_{D2}n(\mathrm{H})} = 2\ \exp(\frac{421\mathrm{K}}{T})\frac{n(\mathrm{D})}{n(\mathrm{H})}$$

PopIII.2 star



HD cooling.

Summary of Lecture 1

1. Physics of a primordial gas. Many processes, but not infinite number.
2. Role of hydrogen molecules.
3. Hierarchical structure formation.
4. On Wednesday, we'll learn proto-stellar evolution.