Astronomy 353

(Spring 2007)

ASTROPHYSICS: From Black Holes to the First Stars

(Lecture 21: Introduction to the First Stars)

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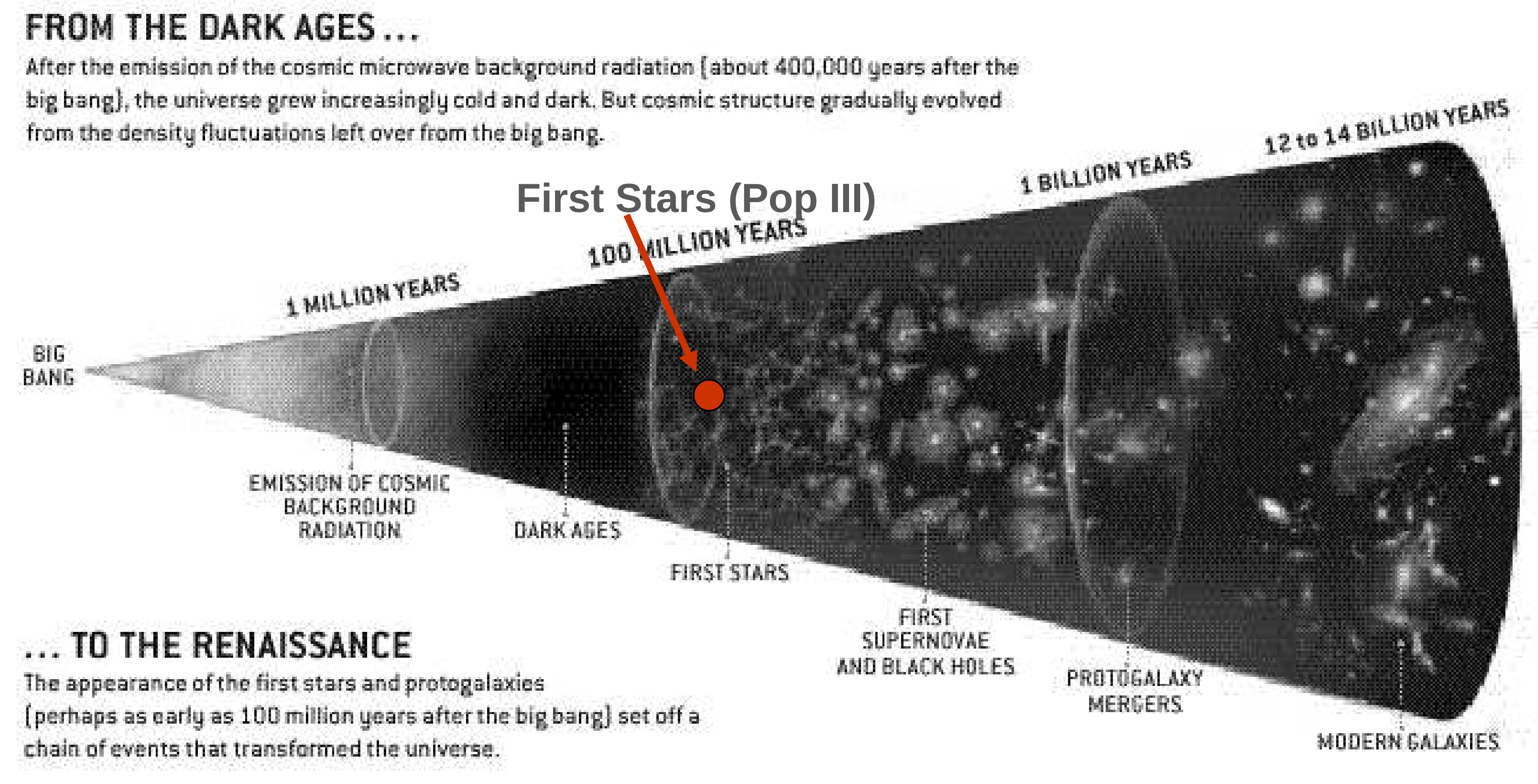
The University of Texas at Austin

From the Dark Ages to the Cosmic Renaissance



FROM THE DARK AGES ...

After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

... TO THE RENAISSANCE

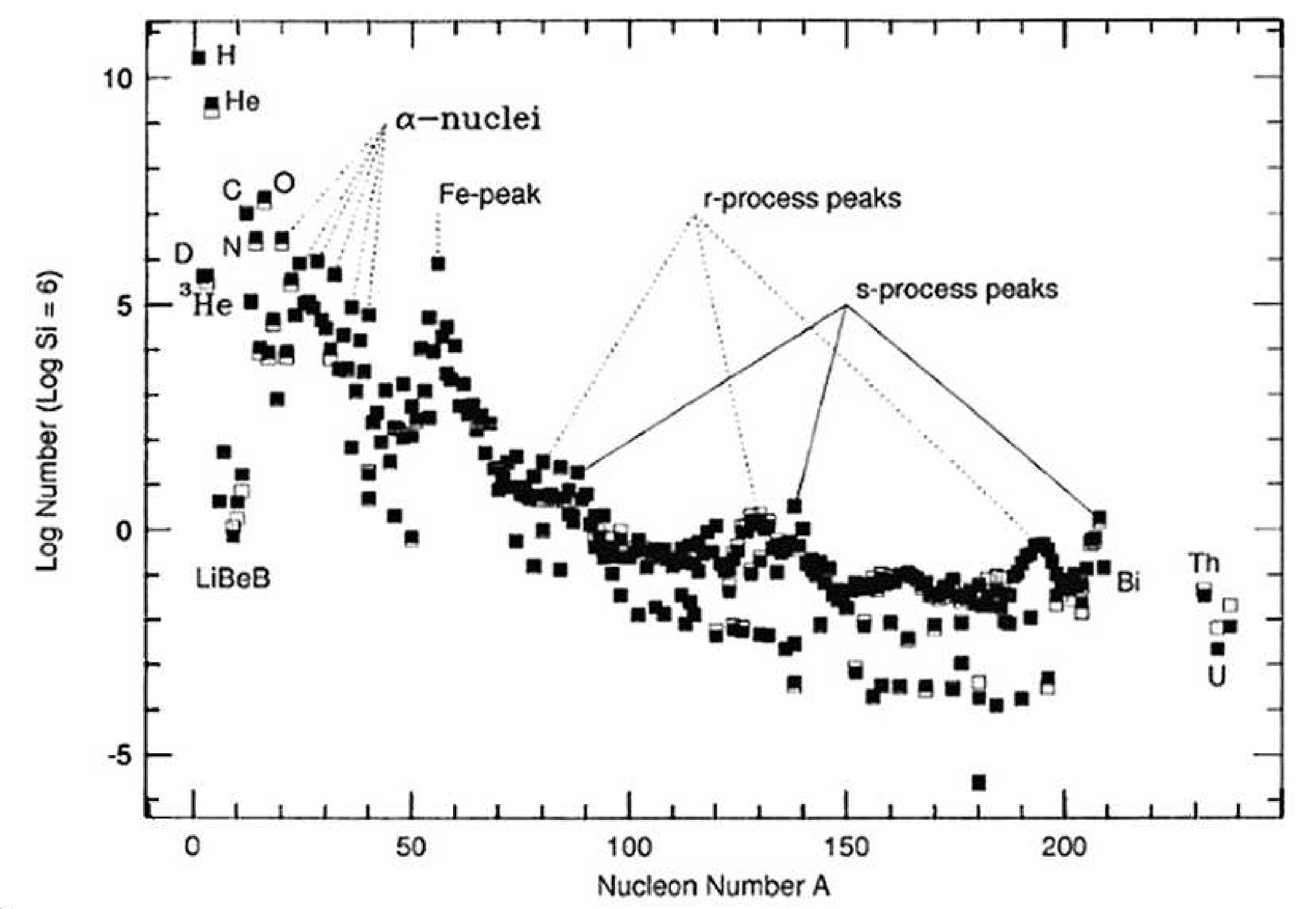
The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

(Larson & Bromm, Scientific American, Dec. 2001)

- First Stars ⟶ Transition from Simplicity to Complexity

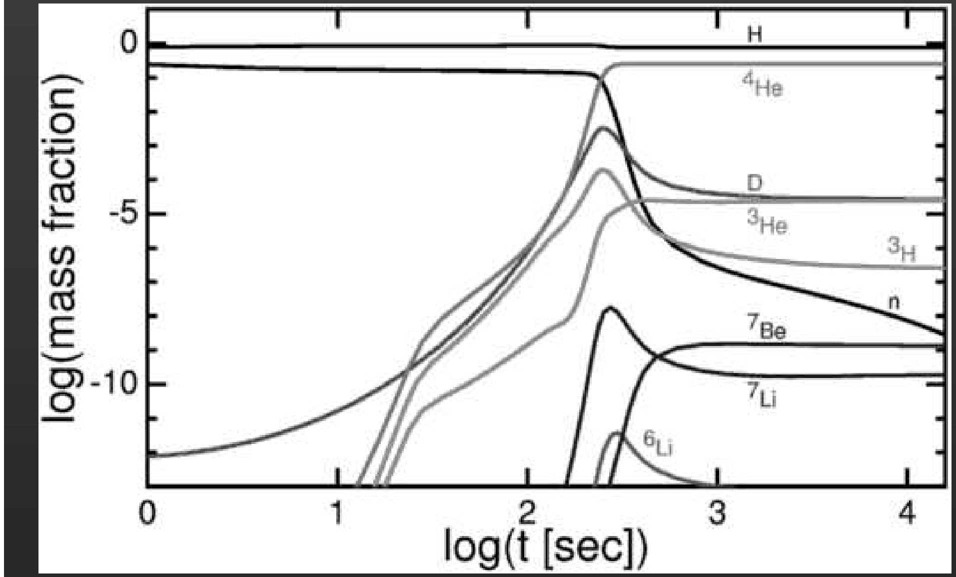
Initial Simplicity: Chemical Elements

Chemical Abundances (in Solar System)



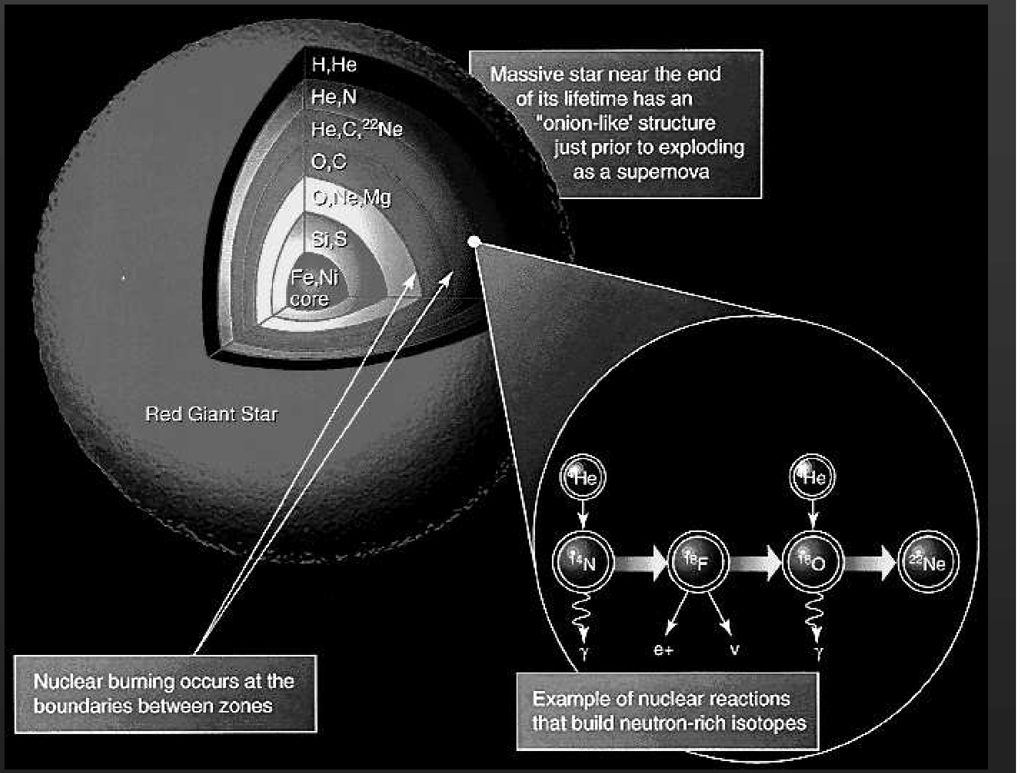
Synthesis of Chemical Elements

Big Bang:



à H, He (D, Li, Be)

Massive Stars:



Massive star near the end of its lifetime has an "onion-like" structure just prior to exploding as a supernova

Nuclear burning occurs at the boundaries between zones

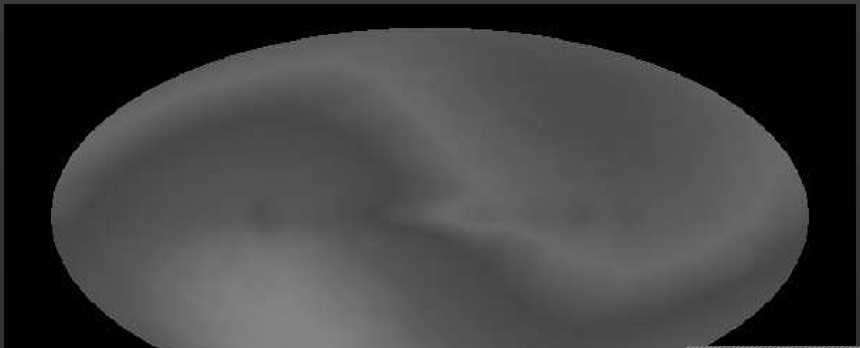
Example of nuclear reactions that build neutron-rich isotopes

à C, N, O, …, U

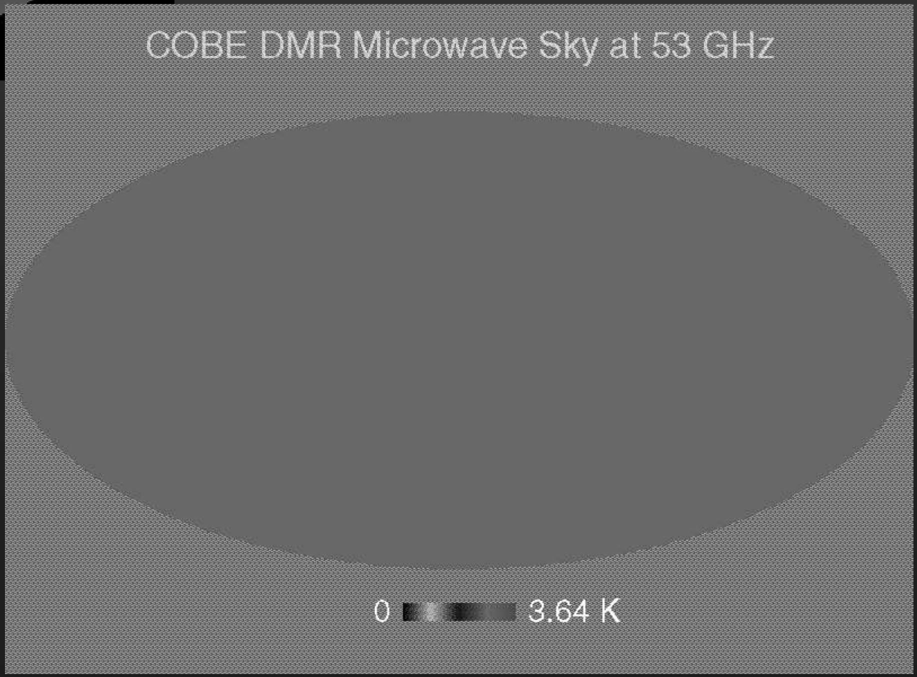
- Before First Stars: primordial gas was pure H/He!

Initial Simplicity: The Primordial Fireball

Cosmic Microwave Background (CMB):
à Temperature map

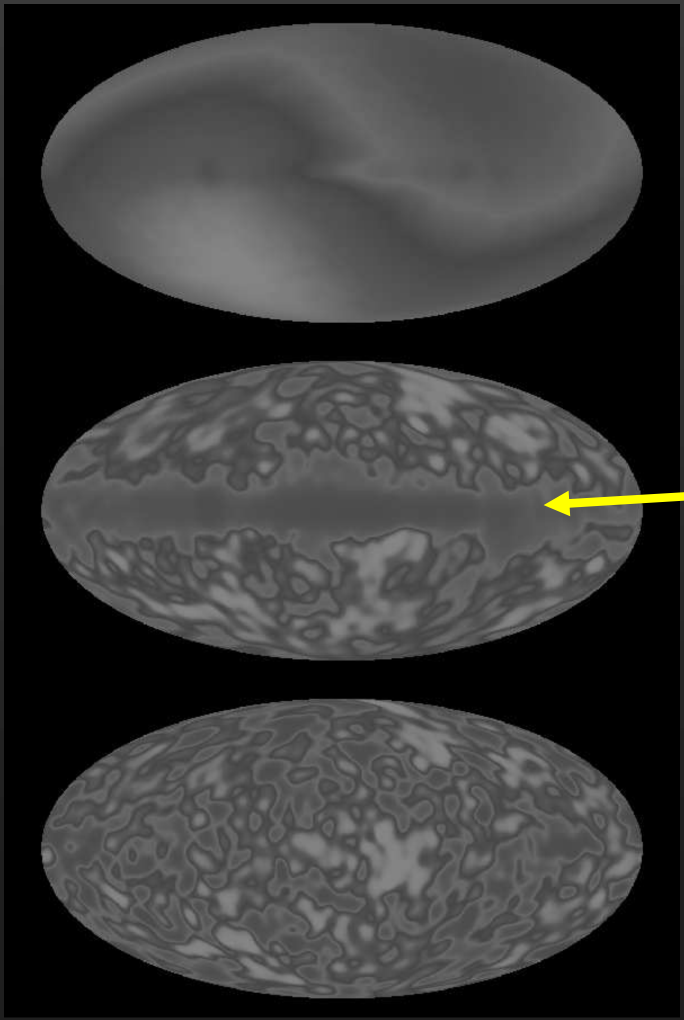


Remove “dipole”
(due to Solar System’s
Motion w.r.t. CMB): à



Initial Simplicity: Tiny Irregularities

Cosmic Microwave Background (CMB):
à Temperature map



~10^{-3}

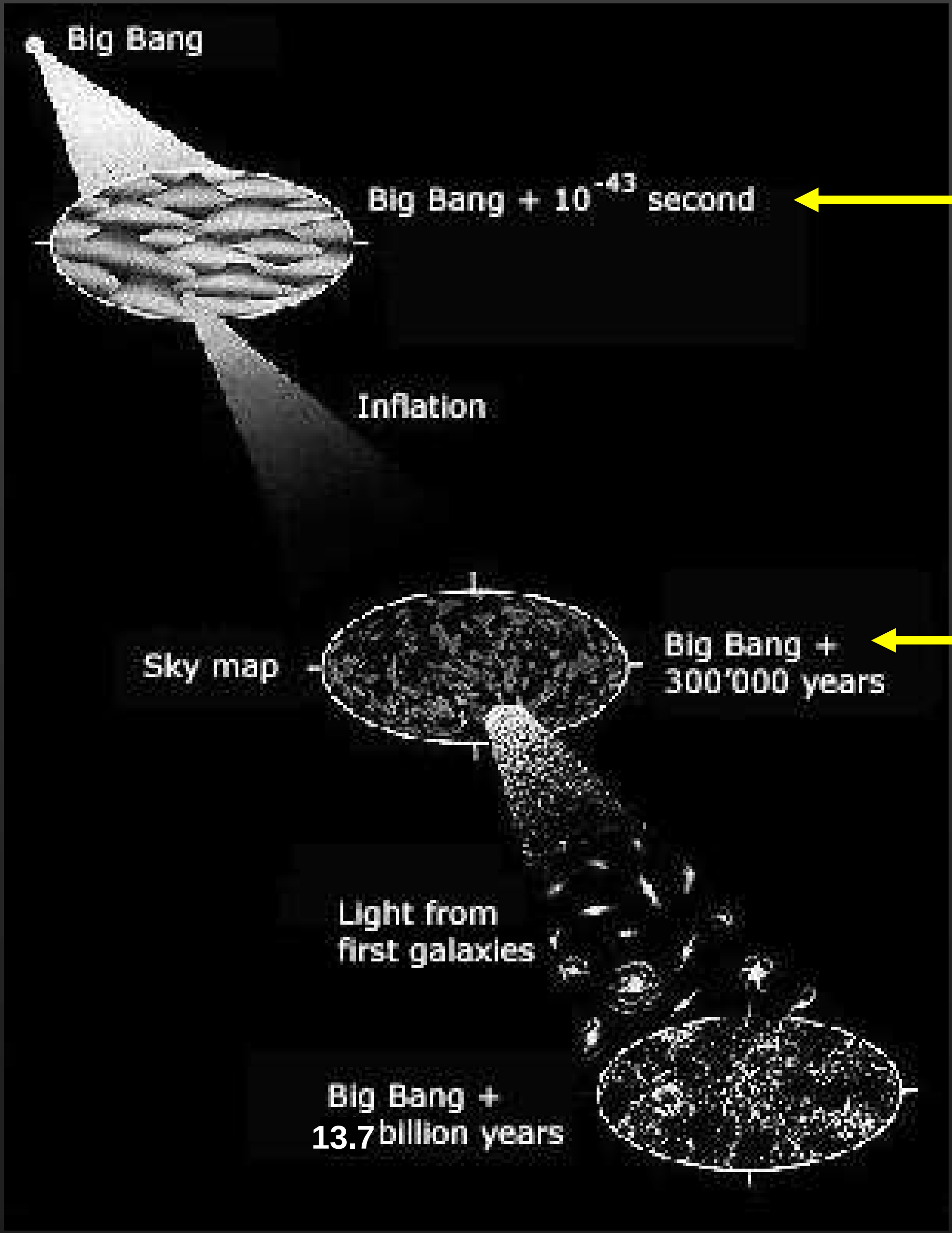
~10^{-5}

Disk of Milky Way

~10^{-5}

Seeds for galaxy formation

Initial Fluctuations: Quantum noise + Inflation



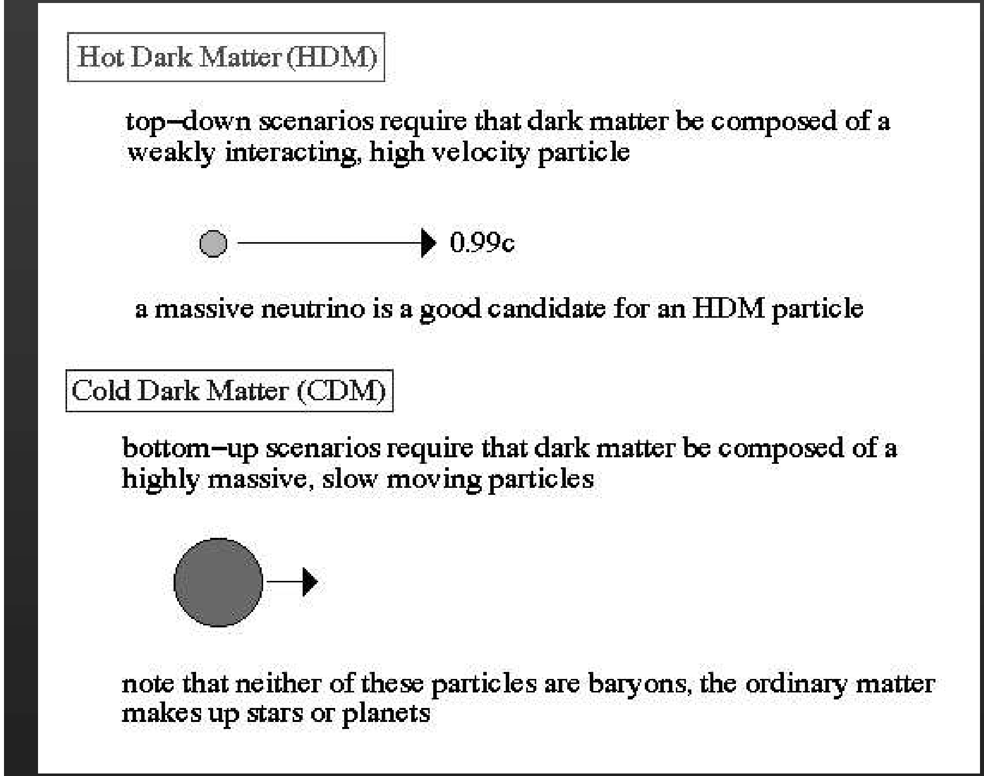
(Quantum gravity???)

“Planck time”

Photons of CMB emitted

Dark Matter Models

Two basic models:



Hot Dark Matter (HDM)

top–down scenarios require that dark matter be composed of a weakly interacting, high velocity particle

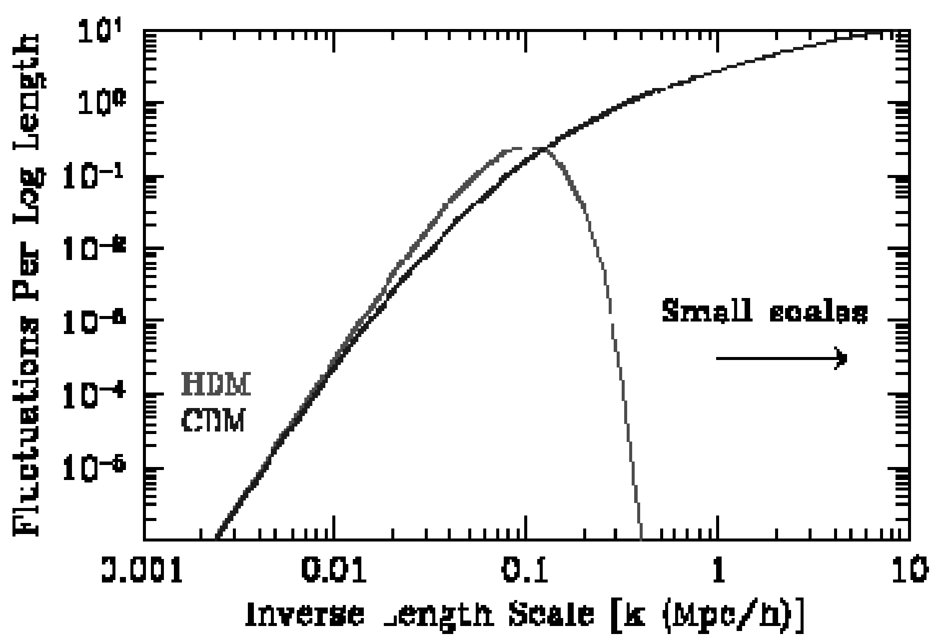
a massive neutrino is a good candidate for an HDM particle

Cold Dark Matter (CDM)

bottom–up scenarios require that dark matter be composed of a highly massive, slow moving particles

note that neither of these particles are baryons, the ordinary matter makes up stars or planets

Fluctuation Spectrum:



The Neutrino Universe

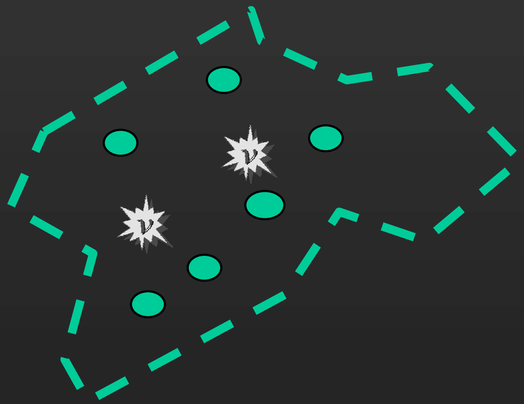
- Q: How much mass is needed to confine (coral in) neutrinos?
- Early on (first 10,000 years), neutrinos move (almost) with speed of light (thus: `Hot Dark Matter')

✸ neutrino

● Normal particles

Small mass

à Small structures are `erased' by neutrino free-streaming!



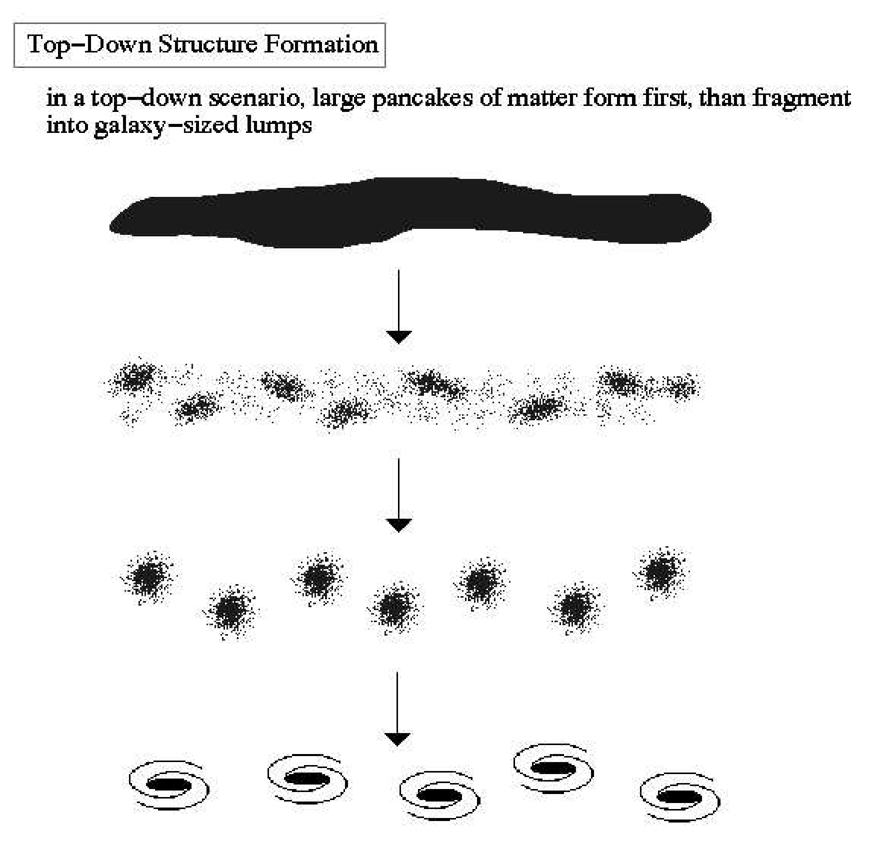
Large mass

~ 10^{15} solar masses

à mass of a cluster of galaxies (e.g., Coma)

Dark Matter Models

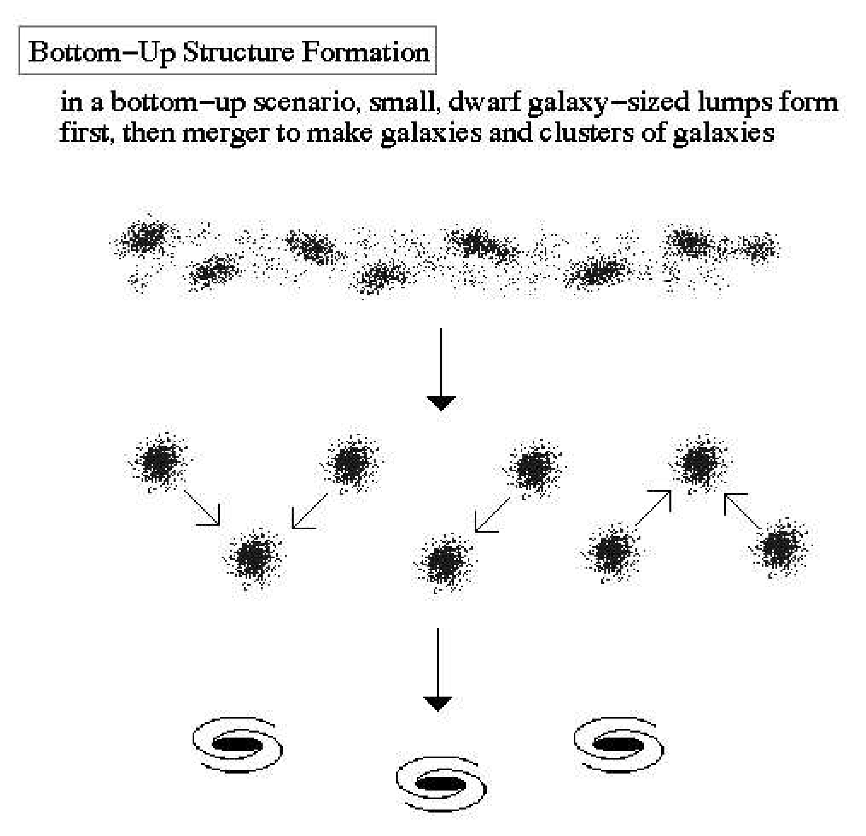
Hot Dark Matter:



Top–Down Structure Formation

in a top–down scenario, large pancakes of matter form first, than fragment into galaxy–sized lumps

Cold Dark Matter:

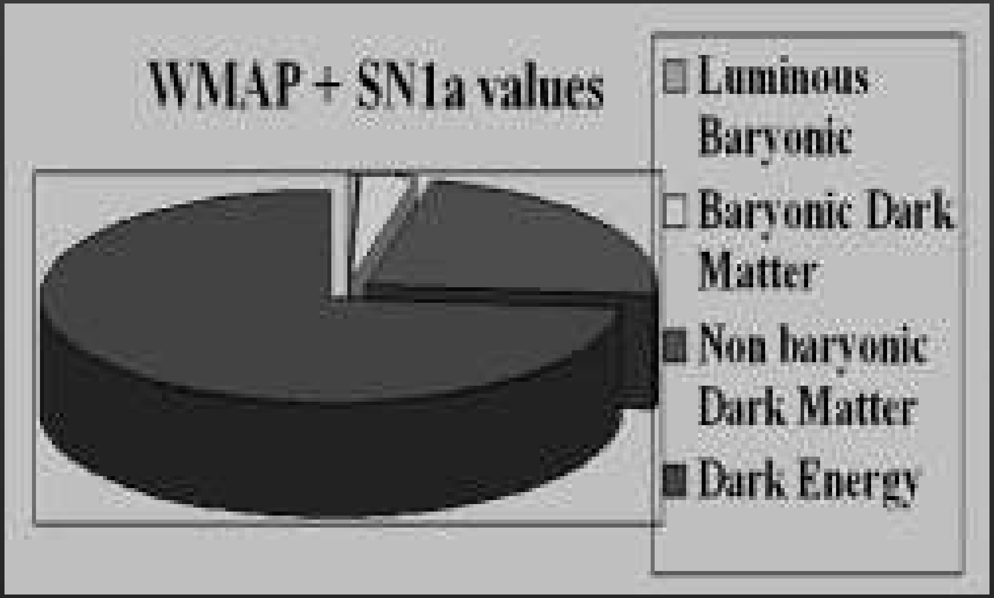


Bottom–Up Structure Formation

in a bottom–up scenario, small, dwarf galaxy–sized lumps form first, then merger to make galaxies and clusters of galaxies

à now known to be correct!

The Cold Dark Matter Model:



Hierarchical Merger Tree:

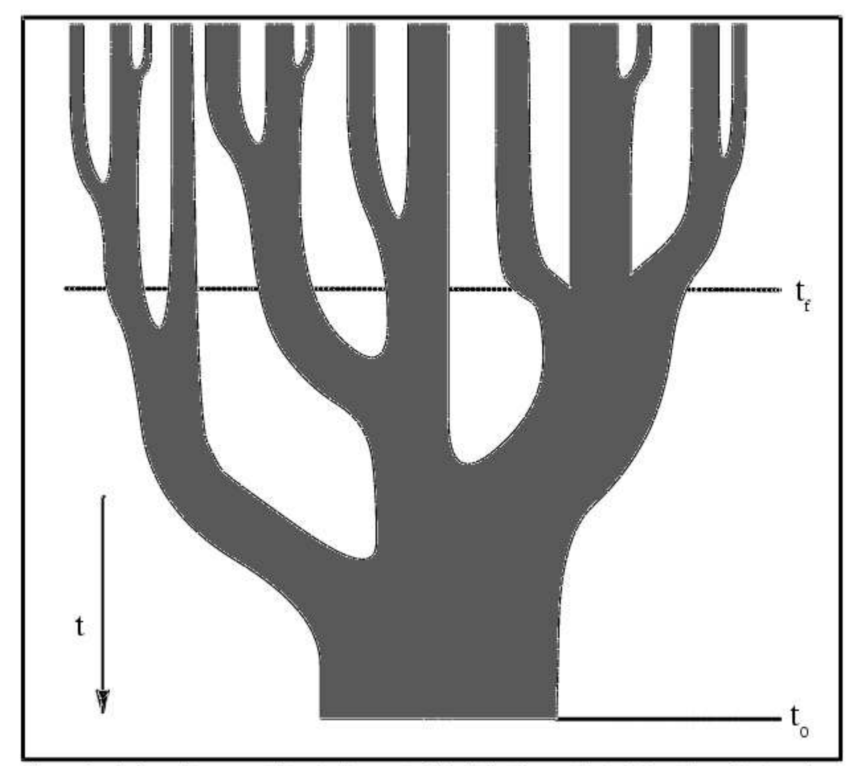
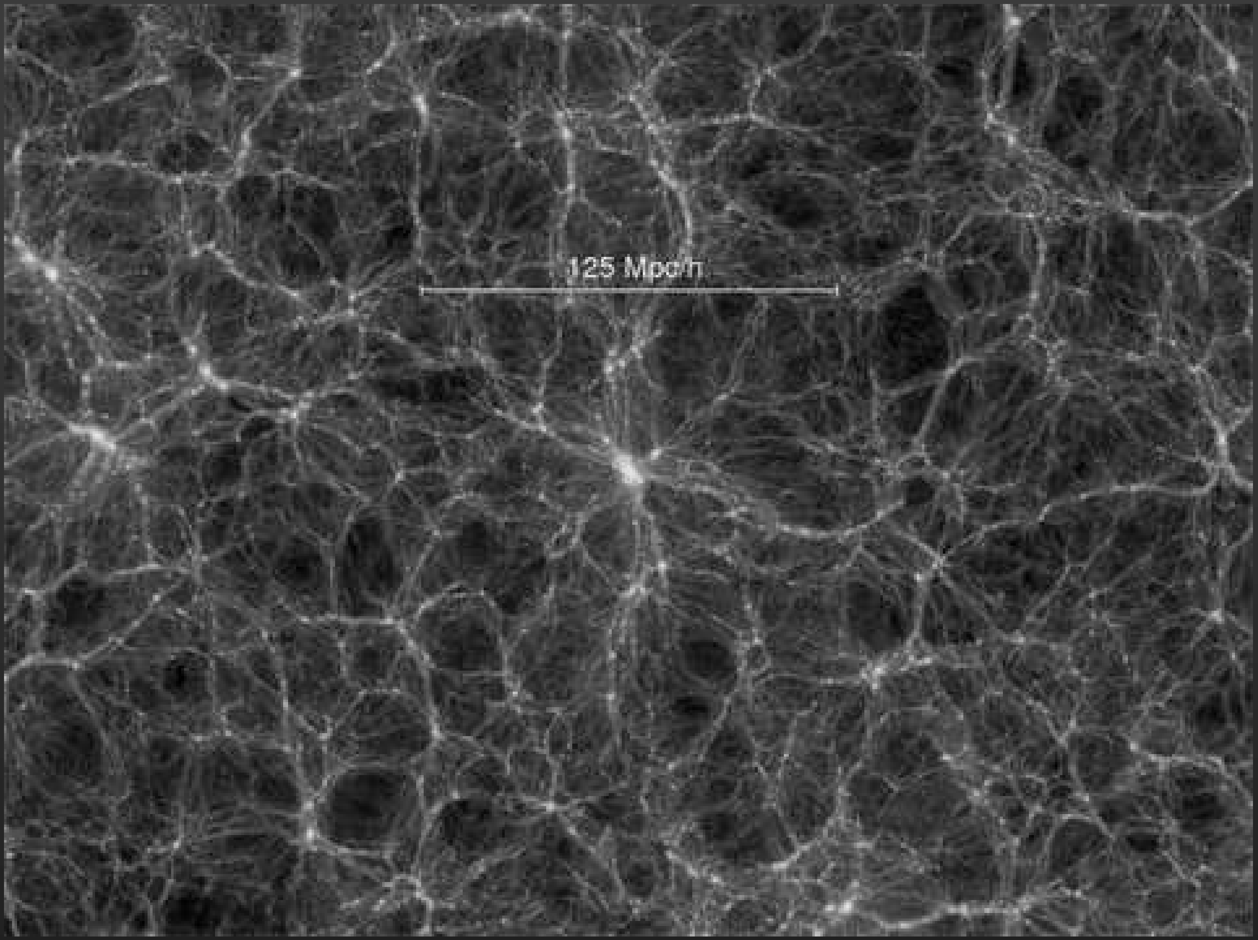


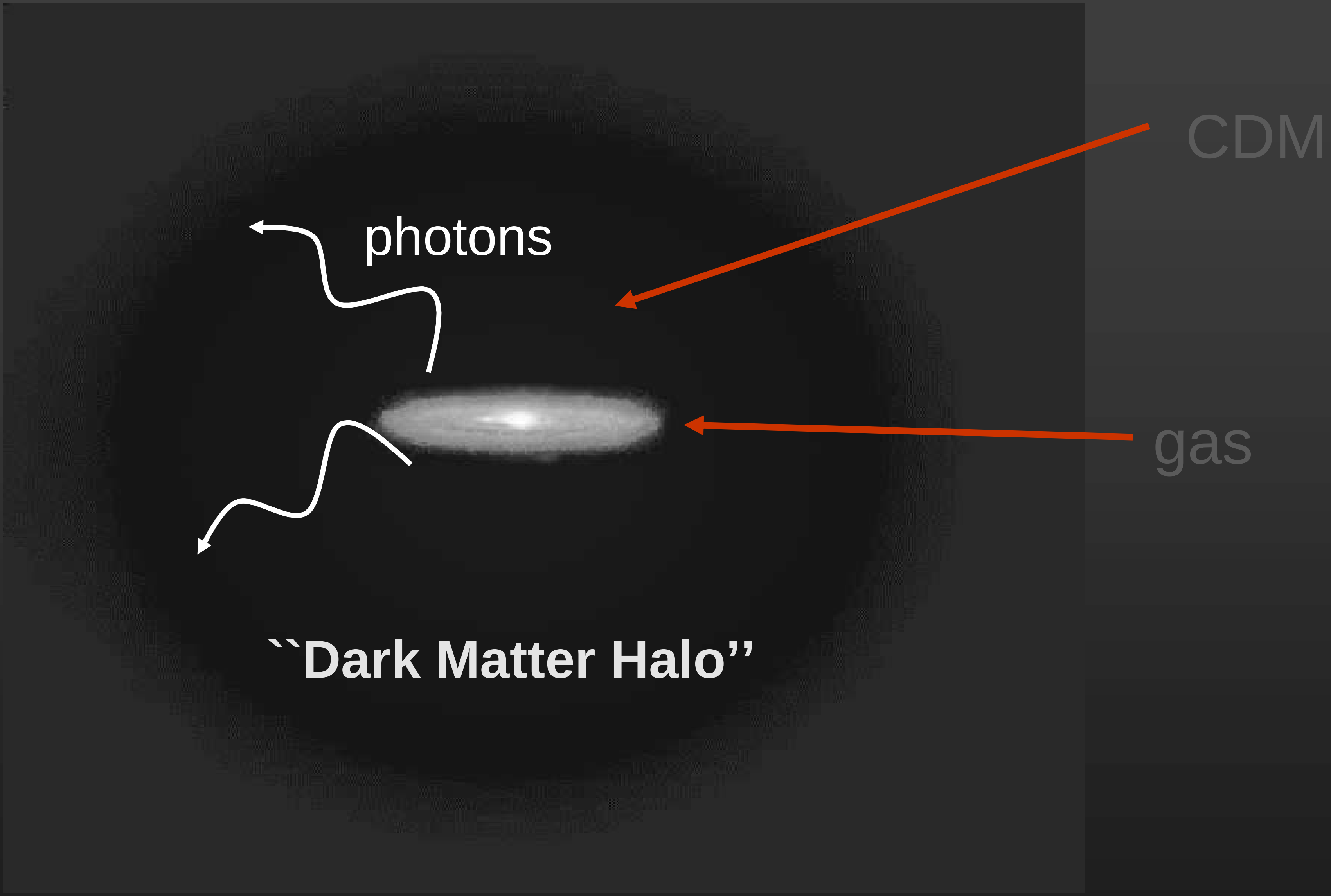
Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Cold Dark Matter Model: The Cosmic Web



- Big Q: What happens to cosmic gas?

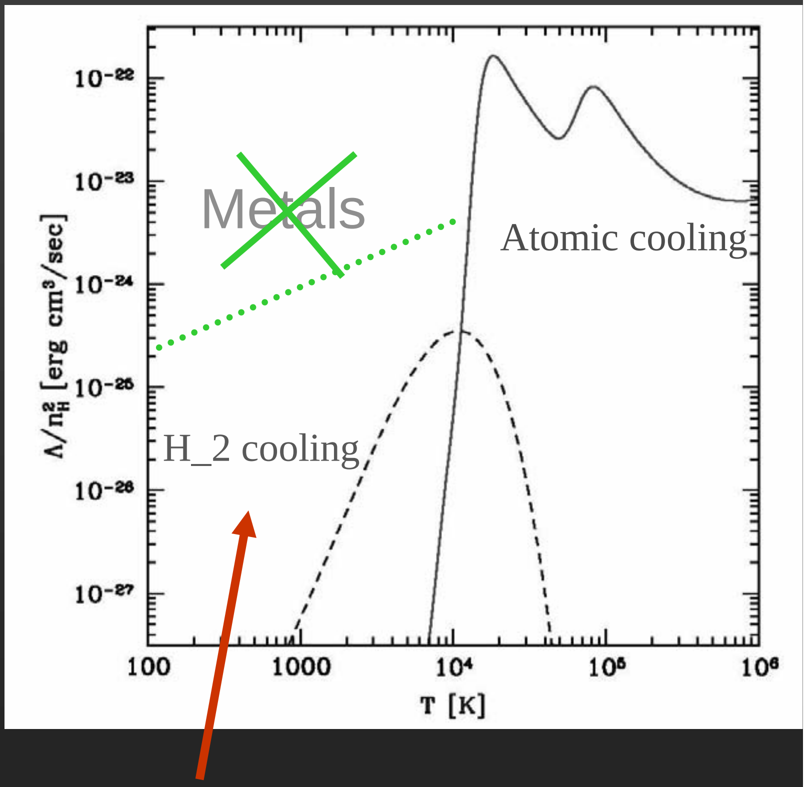
Cosmic gas (baryons): Dissipative Collapse



- Dissipation = energy loss by emitting radiation

Cooling of Primordial Gas

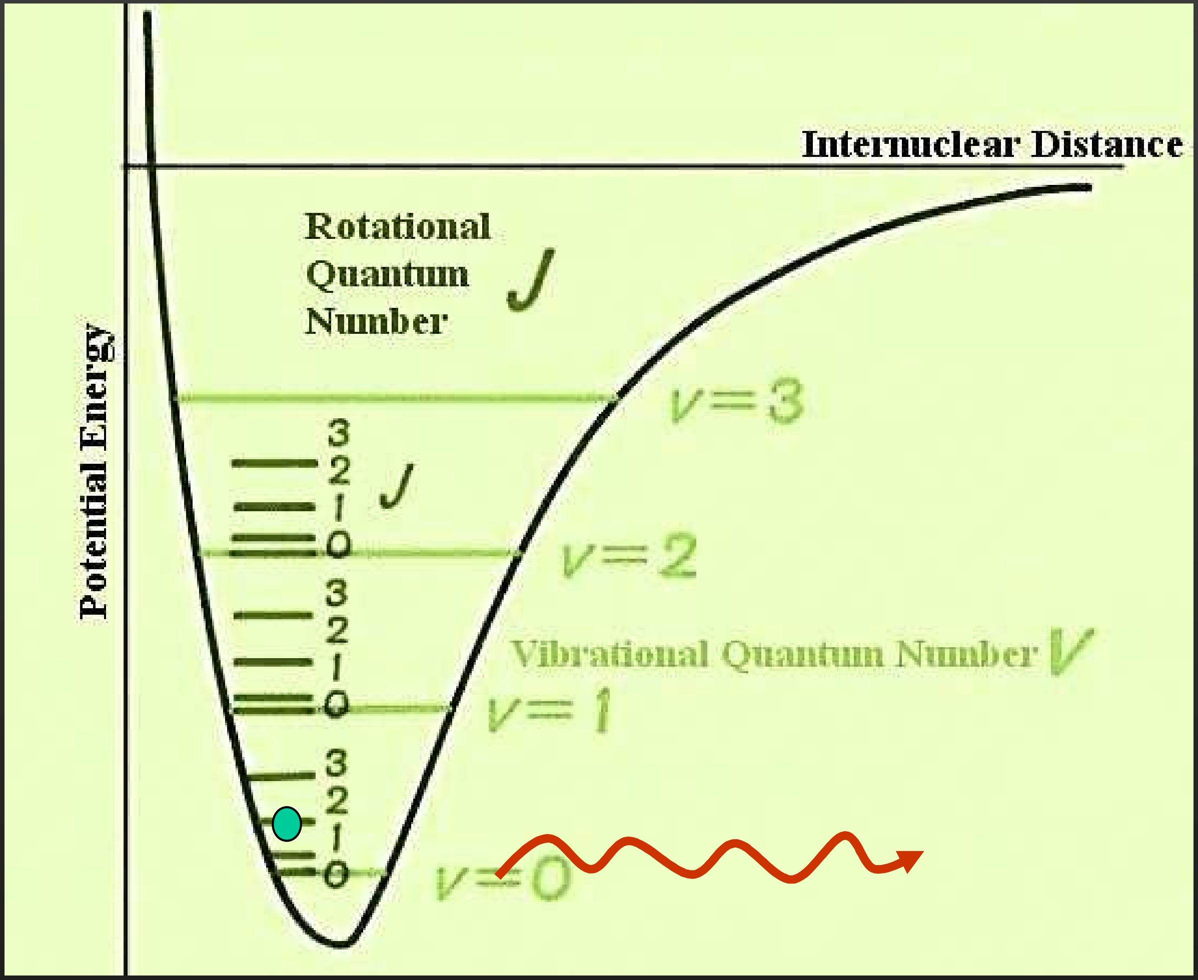
- Simplified physics
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM
    → Well-posed problem
- <u>Problem:</u>
  How to cool primordial gas?
  - No metals → different cooling
  - Below 10^4 K, main coolant is H_2



T_{vir} for Pop III

- H_2 chemistry
  - Cooling sensitive to H_2 abundance
  - H_2 formed in non-equilibrium
    → Have to solve coupled set of rate equations

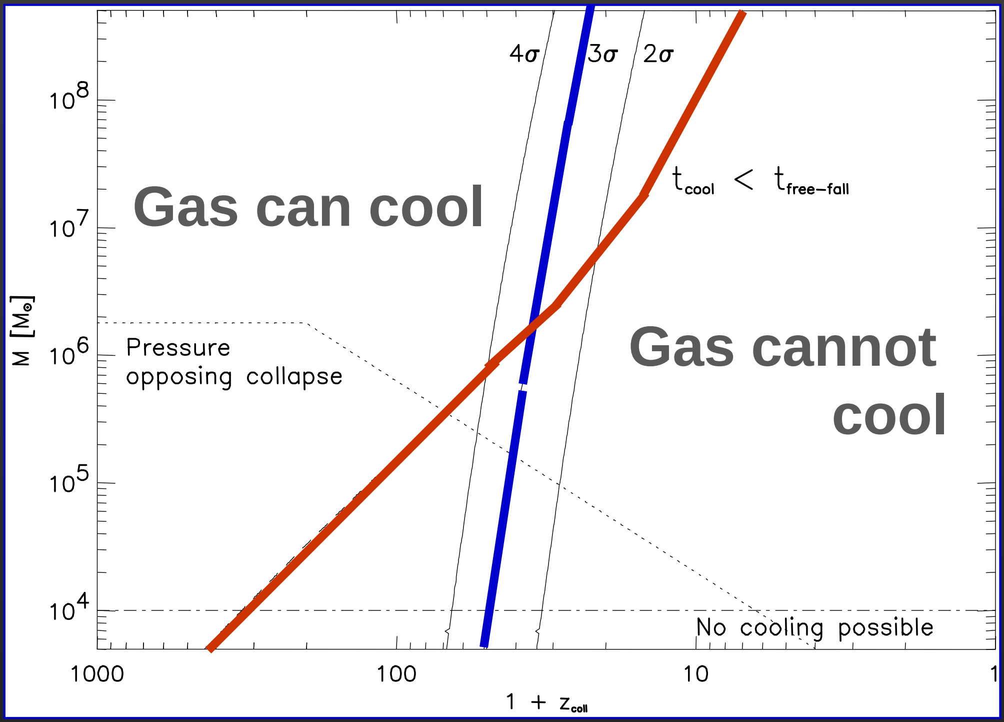
Cooling via Molecular Hydrogen (H_2)



Q: Where do First Stars Form?
A: In ``minihalos''!

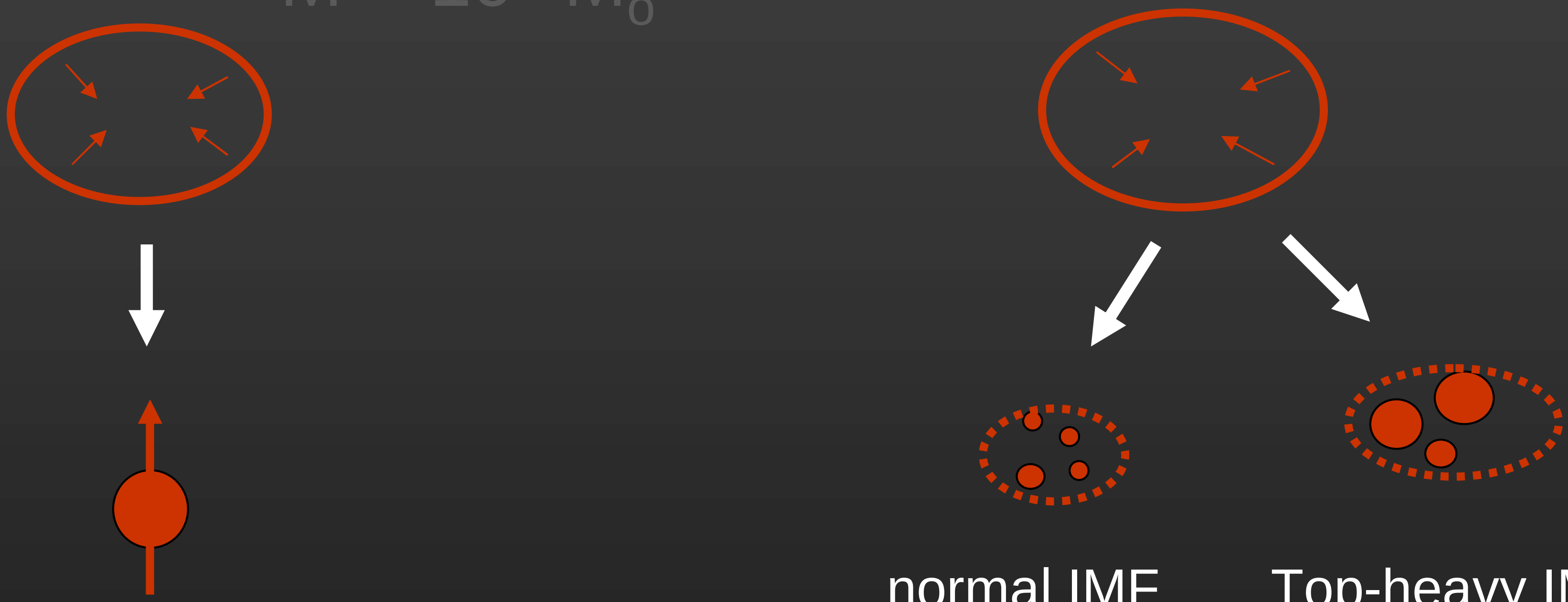
- Gravitational Evolution of DM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{cool} < t_{ff}$ (Rees-Ostriker)

Mass vs. redshift



- Collapse of First Luminous Objects expected:
  - at: z_{coll} = 20 – 30
  - with total mass: $M \sim 10^6 M_o$

What happens inside primordial minihalos?



$M \sim 10^6\ M_o$

normal IMF

Top-heavy IMF

Massive Black Hole

Stars (single or multiple)

- **Most important question: How massive were the first stars?**

Simulating the Formation of the First Stars:

- use state-of-the-art supercomputers
- multi-processor (parallel)

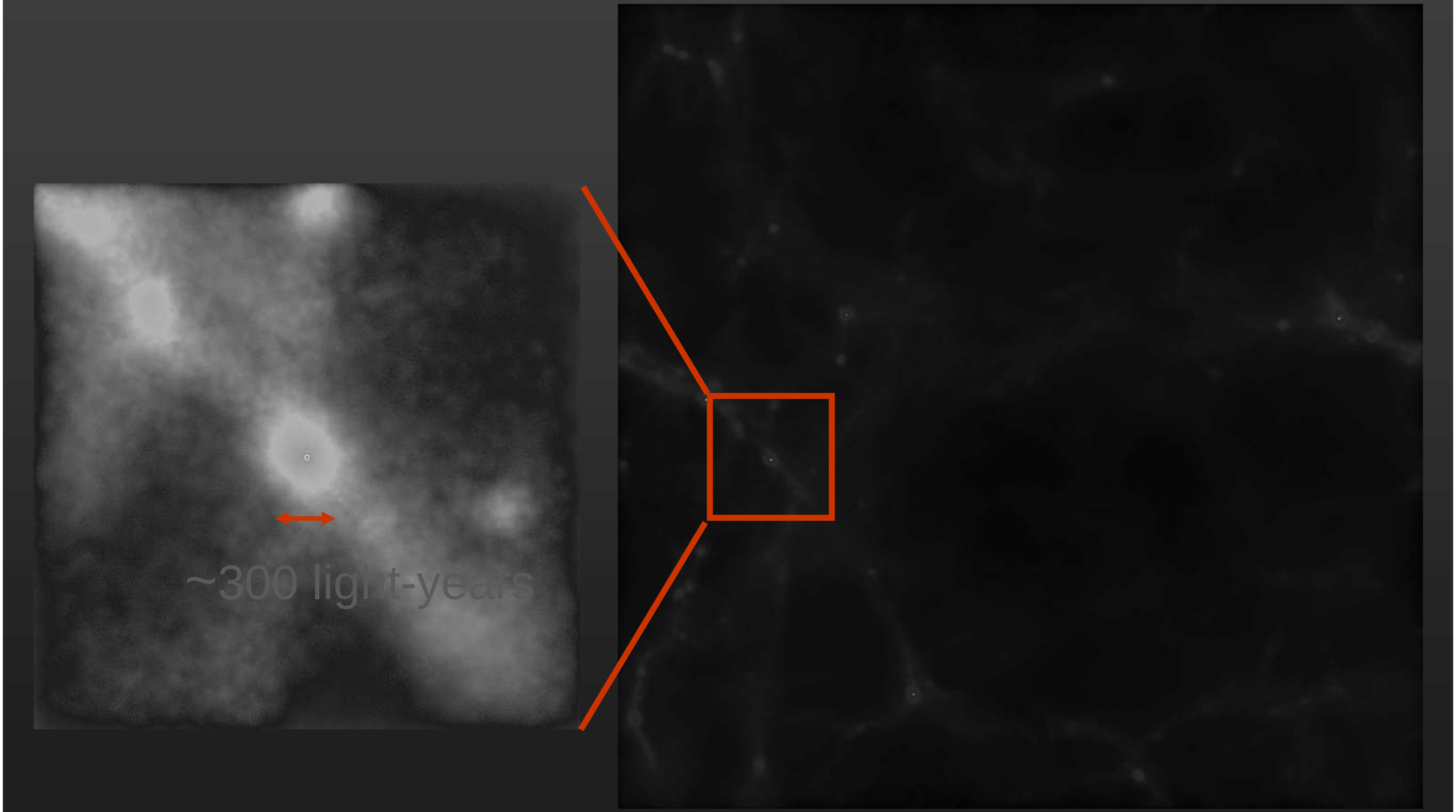
"Beowulf" machines

- "Lonestar" at Texas Advanced Computing Center

- UT Austin,
  J.J. Pickle Research Campus

The Universe at the End of the Dark Ages

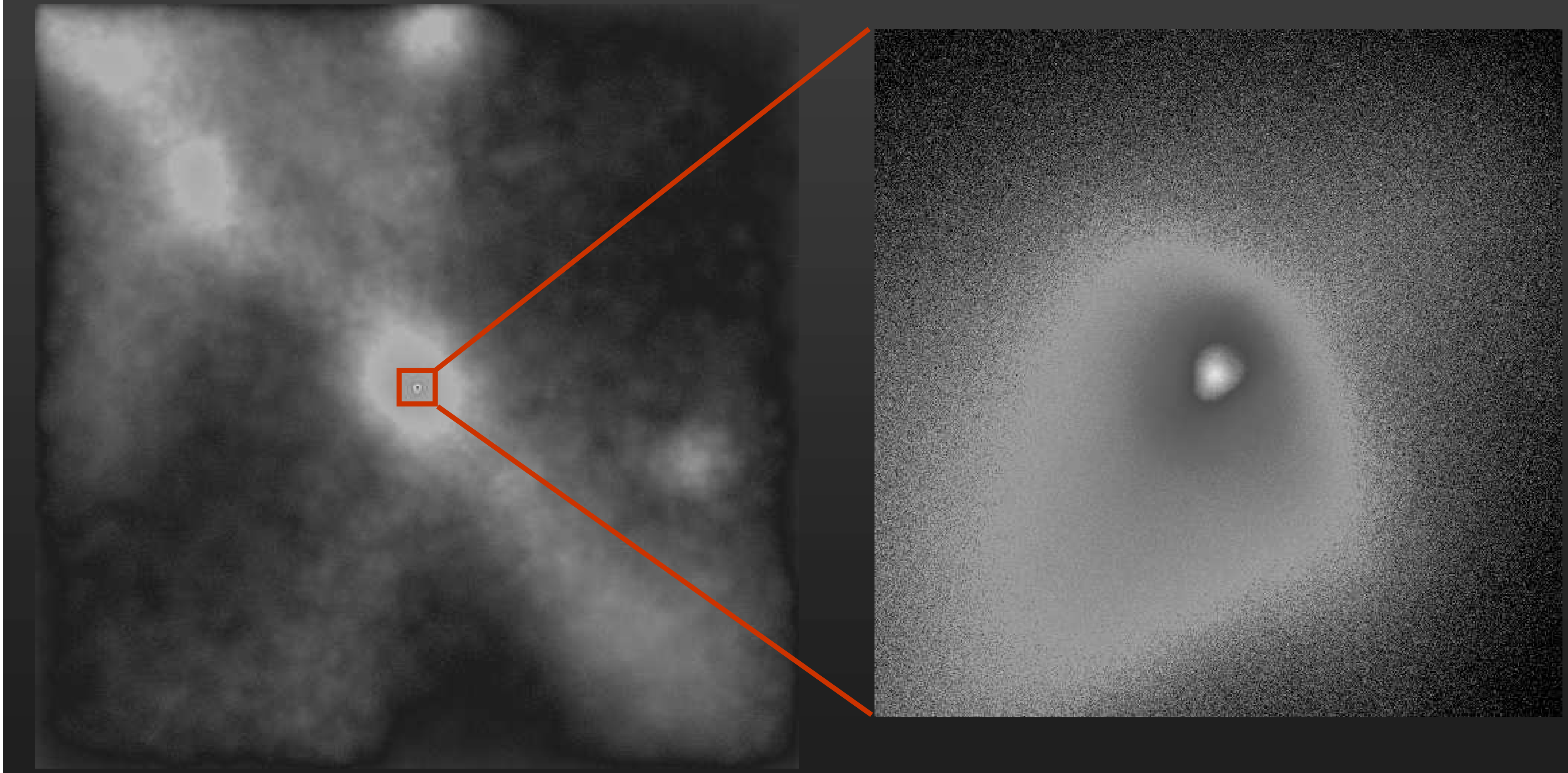
200 million years after Big Bang



~ 20,000 light-years

Formation of the First Star: Zooming-in

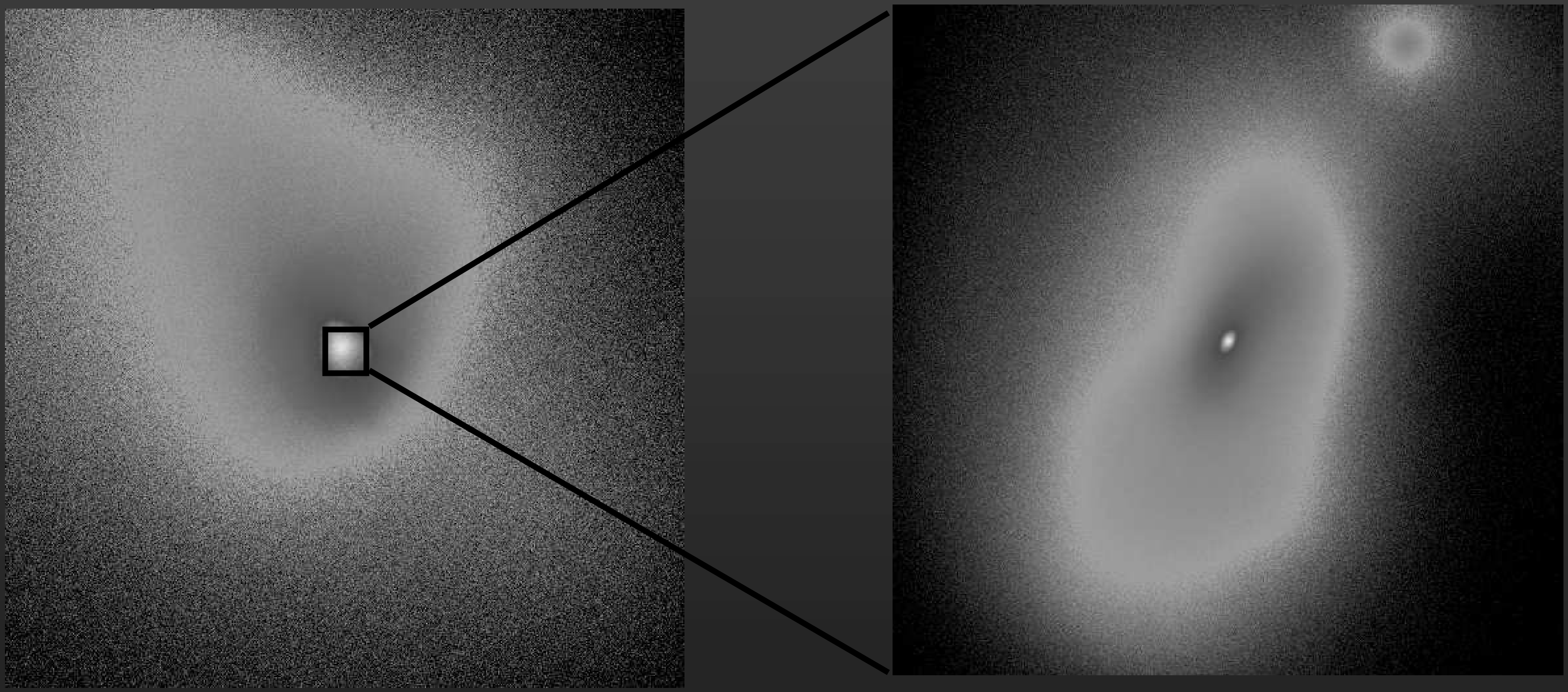
(Bromm, Coppi, & Larson 1999, 2002; Bromm & Loeb 2004)



Zooming in Further

Bromm & Loeb 2004, New Astronomy, 9, 353

- Computer simulation with very high resolution



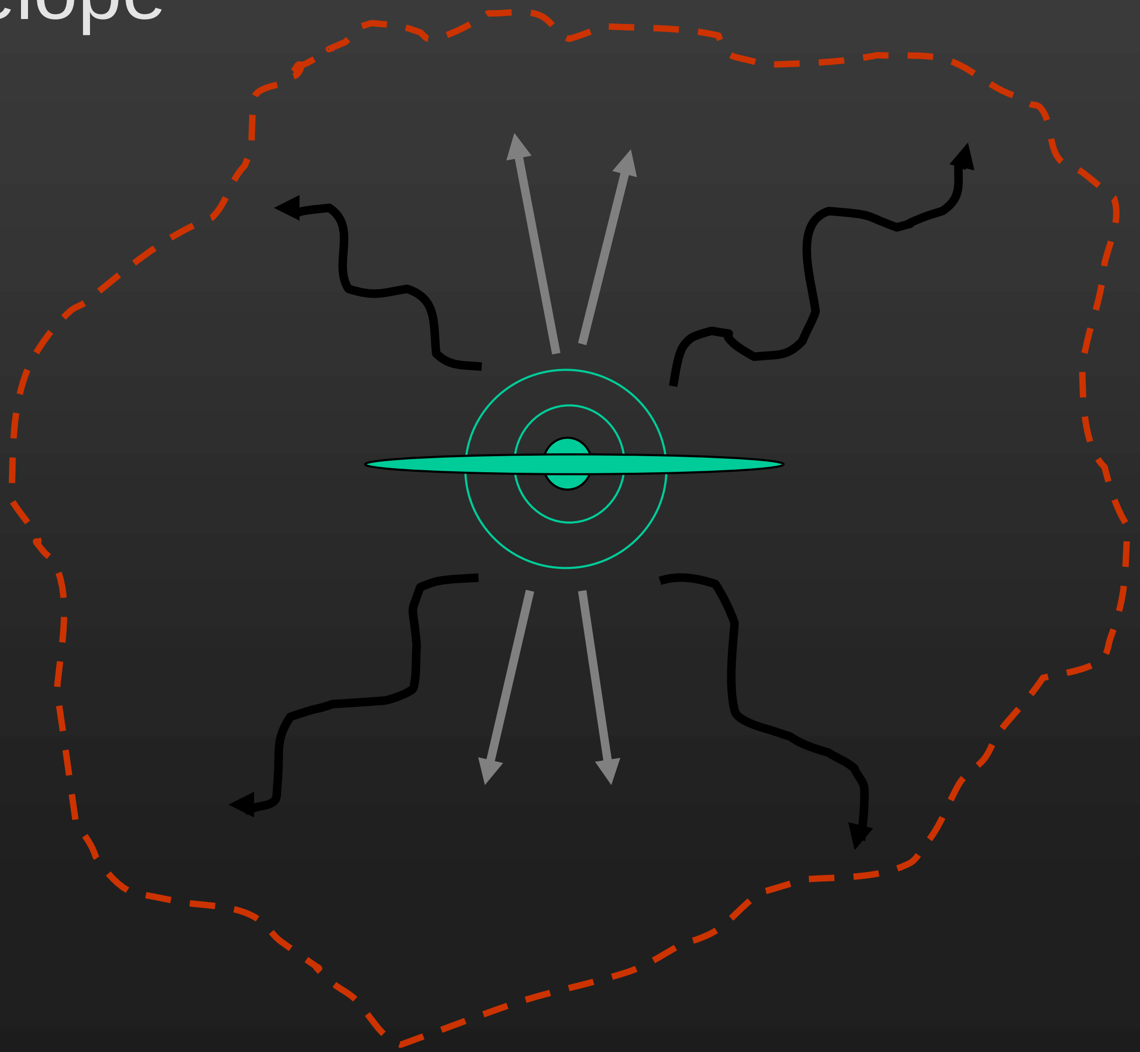
75 Light-years **1 Light-years**

- Result: The First Stars were very massive!

(100 times the solar mass)

The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope

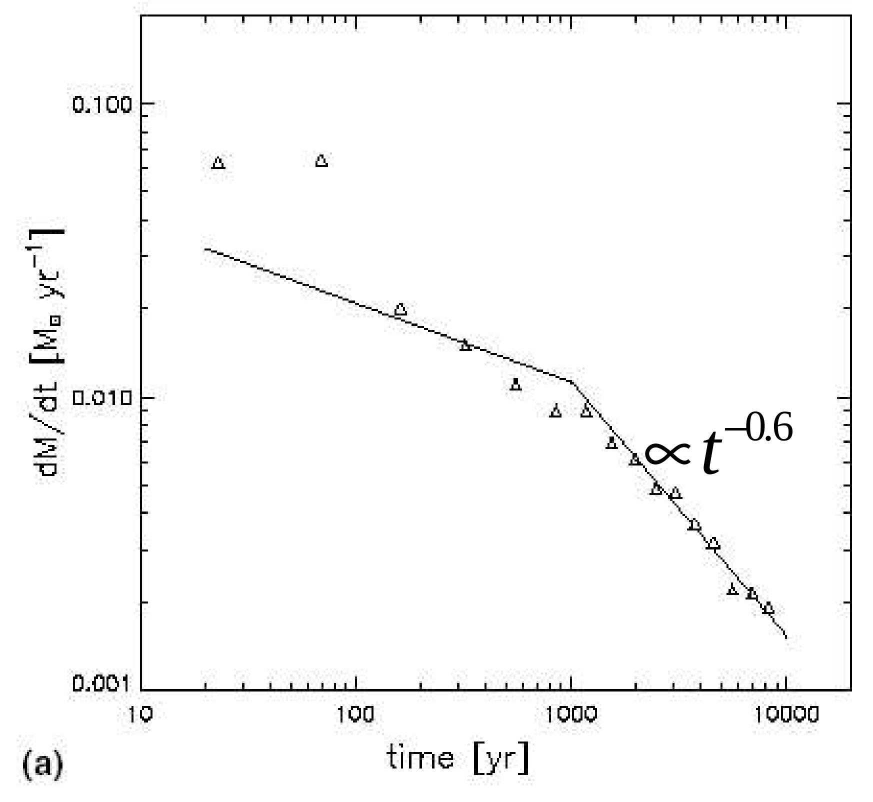


Clump:

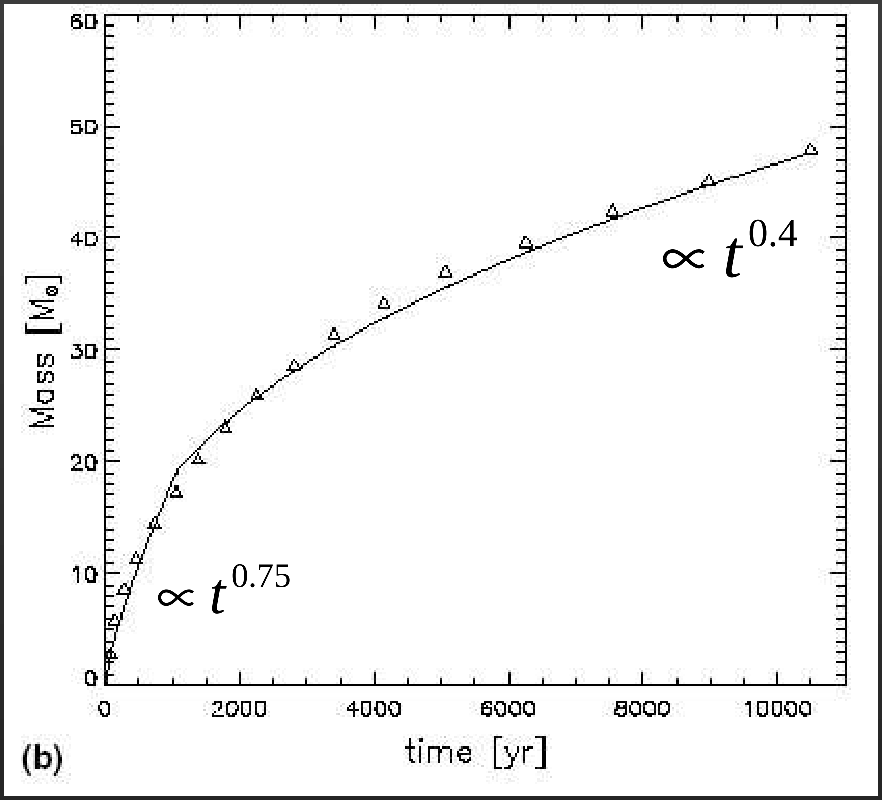
$M \sim M_J$

Accretion onto a Primordial Protostar

dM/dt vs. time

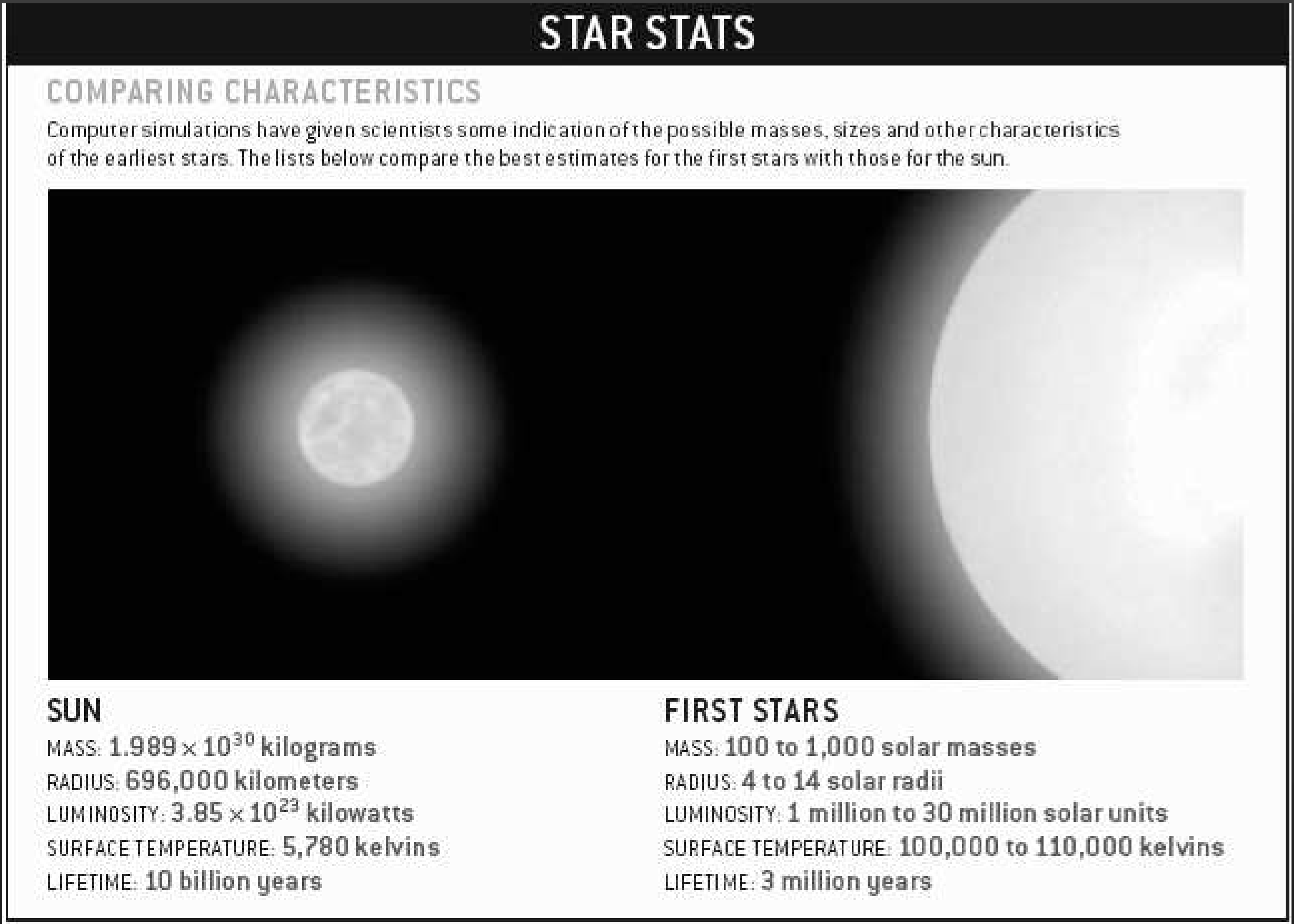


M vs. time



Upper limit: $M_* \ (t = 3 \times 10^6 \text{ yr}) \approx 500 M_\odot$

First Stars were Massive



STAR STATS

COMPARING CHARACTERISTICS

Computer simulations have given scientists some indication of the possible masses, sizes and other characteristics of the earliest stars. The lists below compare the best estimates for the first stars with those for the sun.

SUN

MASS: **1.989×10^{30} kilograms**
RADIUS: **696,000 kilometers**
LUMINOSITY: **3.85×10^{23} kilowatts**
SURFACE TEMPERATURE: **5,780 kelvins**
LIFETIME: **10 billion years**

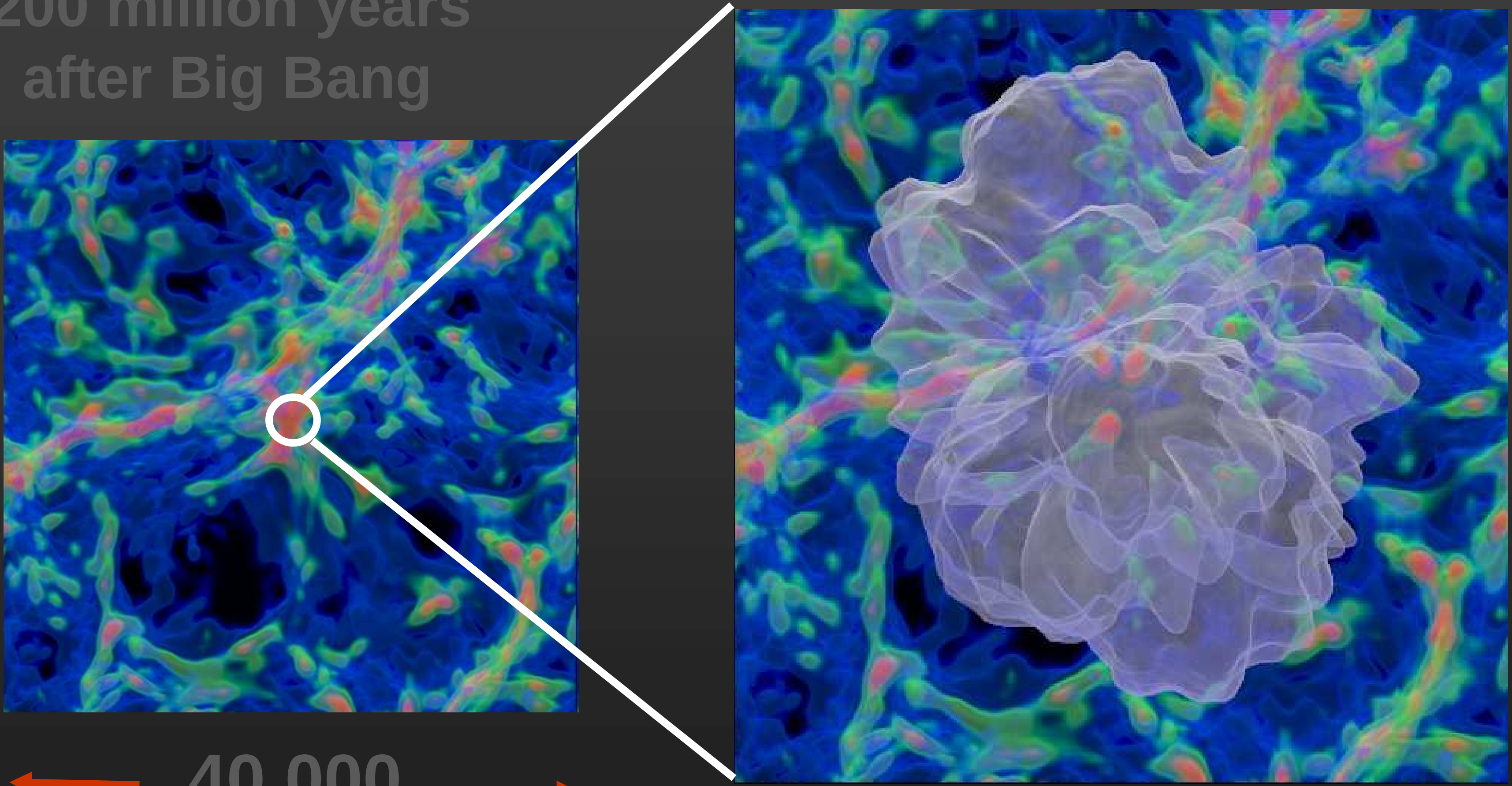
FIRST STARS

MASS: **100 to 1,000 solar masses**
RADIUS: **4 to 14 solar radii**
LUMINOSITY: **1 million to 30 million solar units**
SURFACE TEMPERATURE: **100,000 to 110,000 kelvins**
LIFETIME: **3 million years**

First Stars: High-energy Radiation

(Alvarez, Bromm, & Shapiro, *Astrophysical Journal* 2006)

200 million years
after Big Bang

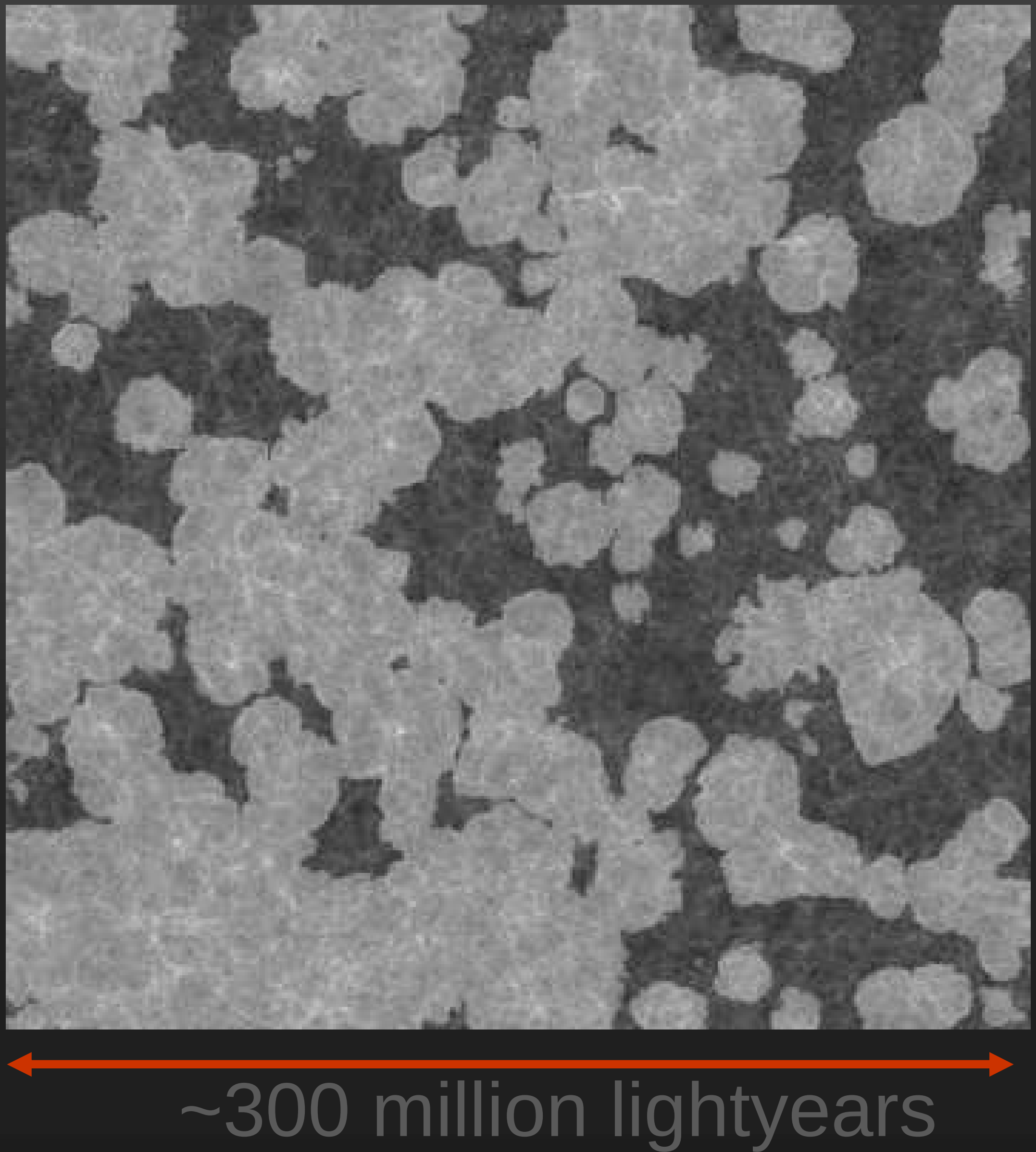


40,000
Light-years

à A bubble of ionized gas!

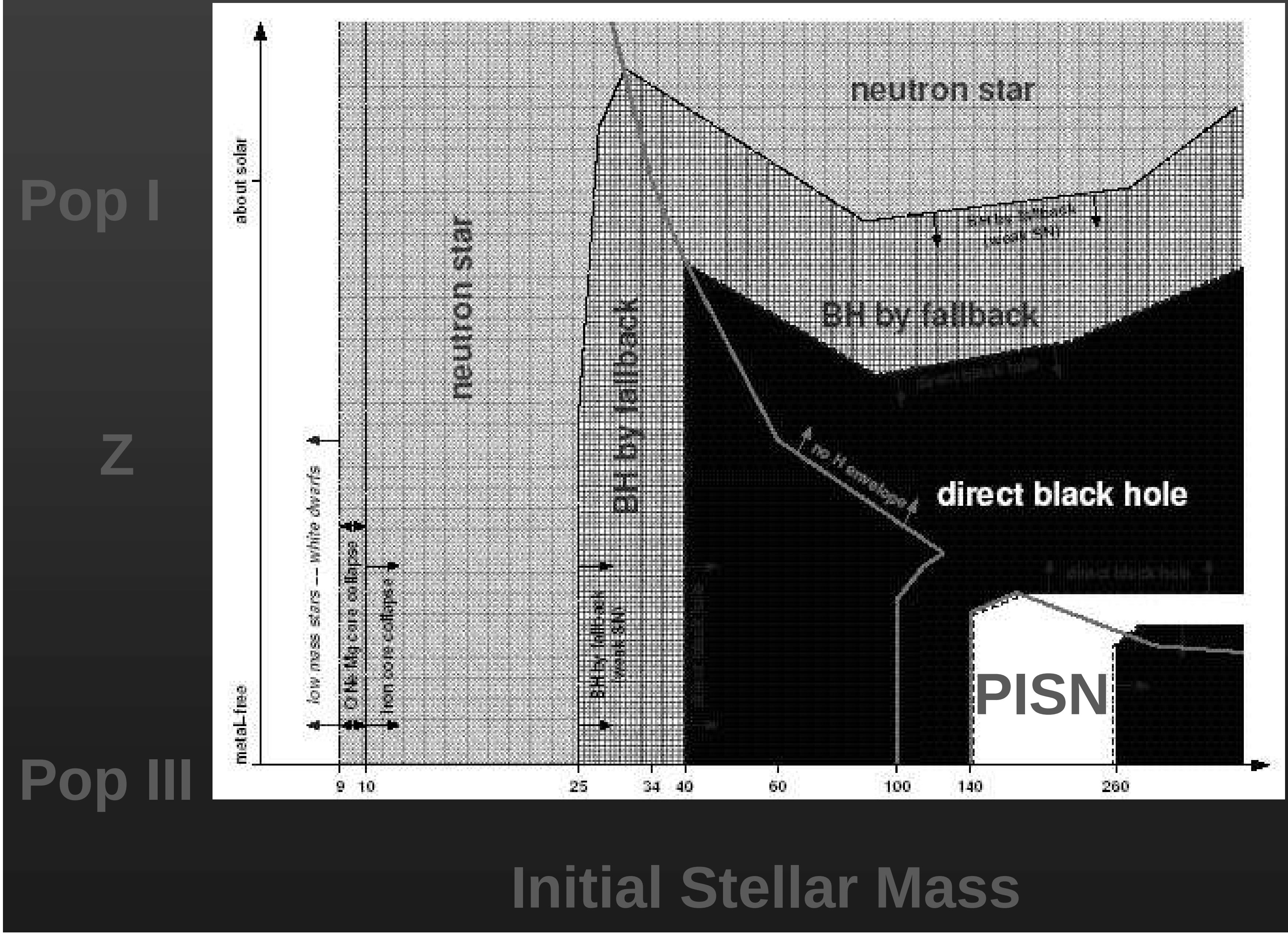
Reionizing the Universe

(Iliev et al. 2006)



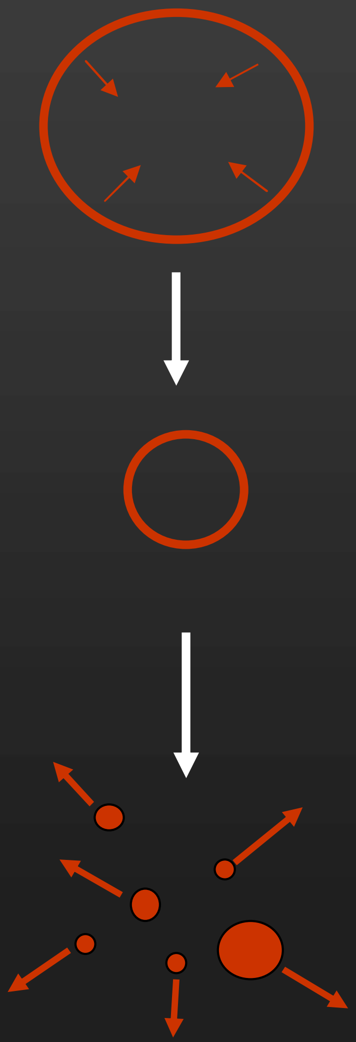
The Death of the First Stars:

(Heger et al. 2003)



Physics of Pair-instability Supernovae

M ~ 140 - 260 M_o



-$T>10^9$K

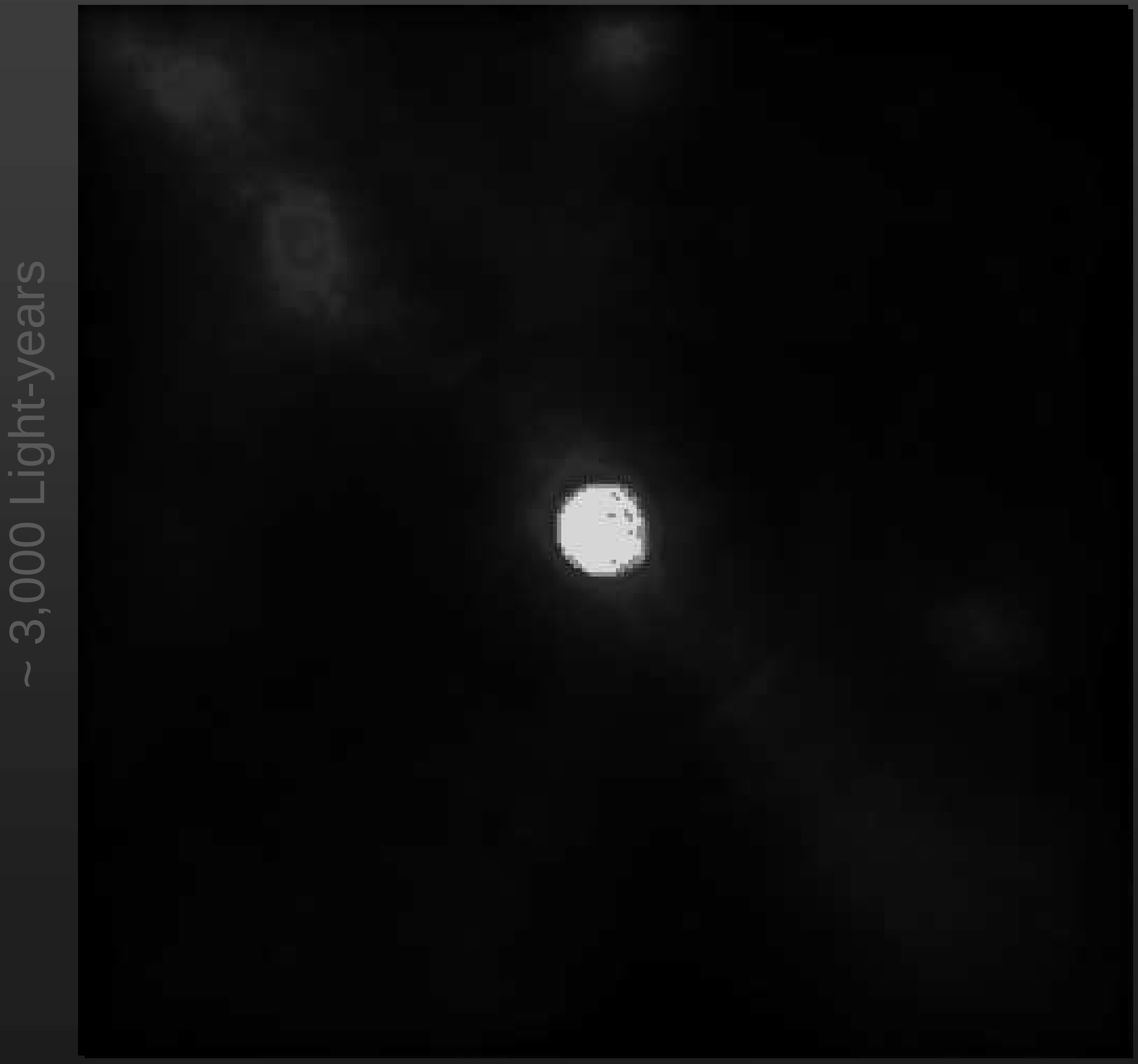
- ph+ph → e^- e^+
- grav. runaway collapse

- large jump in core T
- explosive nuclear burning
- implosion → explosion

- no compact remnant
- all heavy elements dispersed
- distinct nucleosynthetic pattern

First Stars: Supernova-Explosion

(Bromm, Yoshida, & Hernquist, *Astrophysical Journal* 2003)

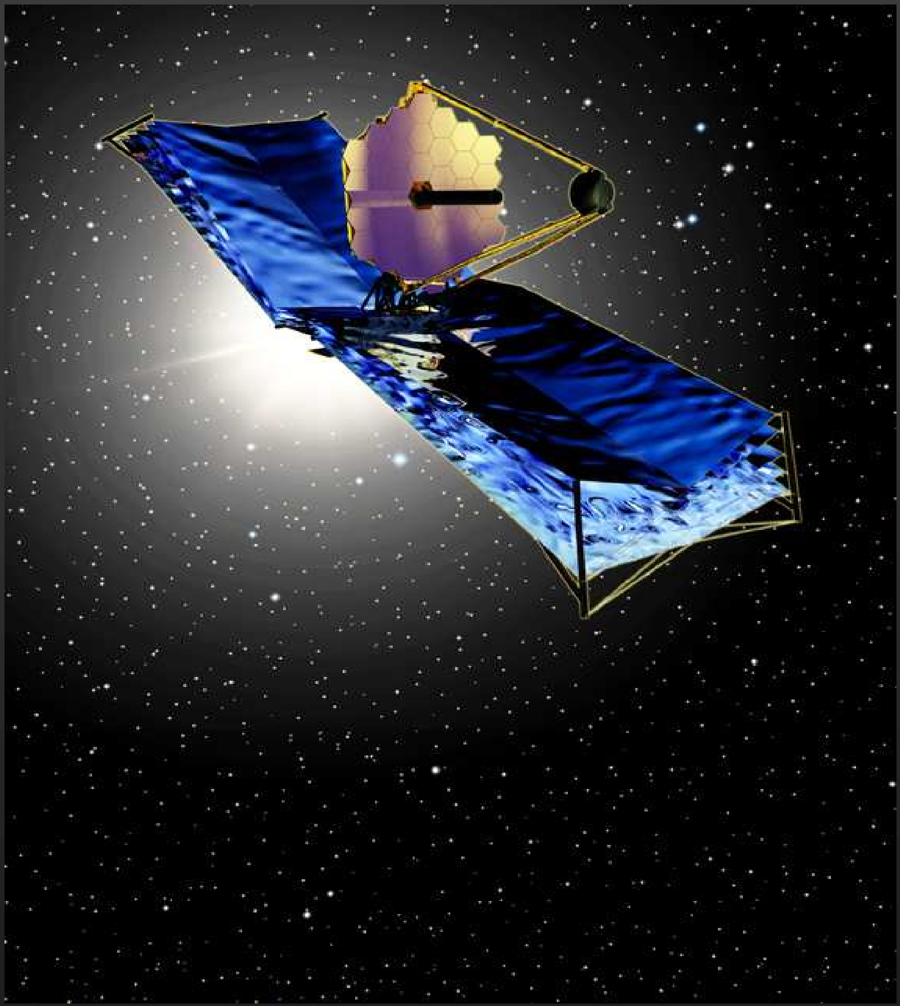


- 100 times the explosion energy of normal supernova!

- Complete disruption (no remnant left behind)!

The James Webb Space Telescope:

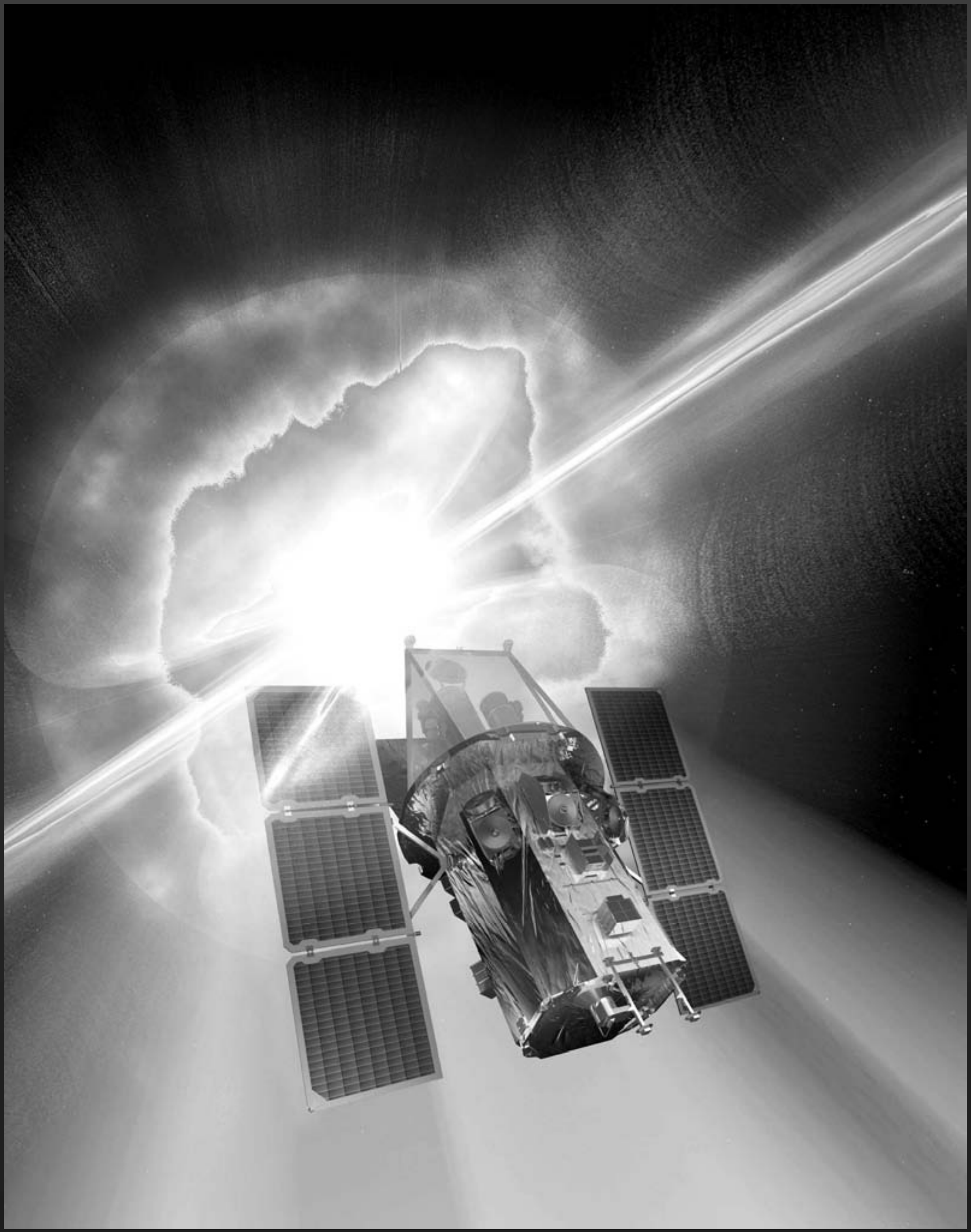
(NASA's successor to the *Hubble*)



- Launch in ~2013
- Near IR sensitivity of ~ 1 nJy
- ~ 4' x 4' FOV

→ **Direct Imaging of the First Stars**

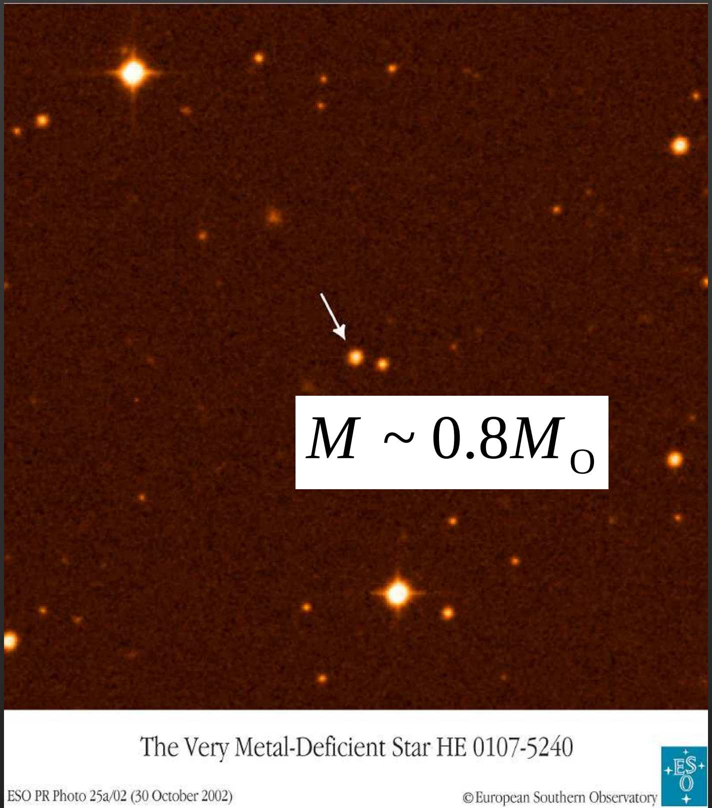
Gamma-Ray Bursts as Probes of the First Stars:



- GRB progenitors → massive stars
- GRBs expected to trace star formation
- *Swift* mission:
  - Launched in 2004
  - Sensitivity → GRBs from z > 15

Relic from the Dawn of Time:

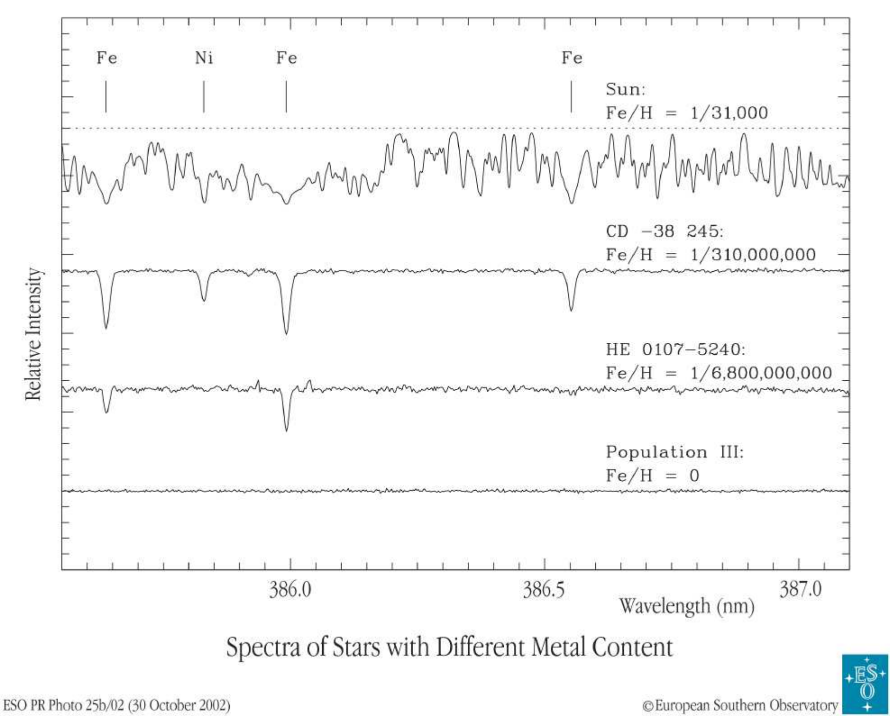
- **HE0107-5240**: [Fe/H] = - 5.3 (Christlieb et al. 2002)


$M \sim 0.8 M_{\odot}$

The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)

©European Southern Observatory



Spectra of Stars with Different Metal Content

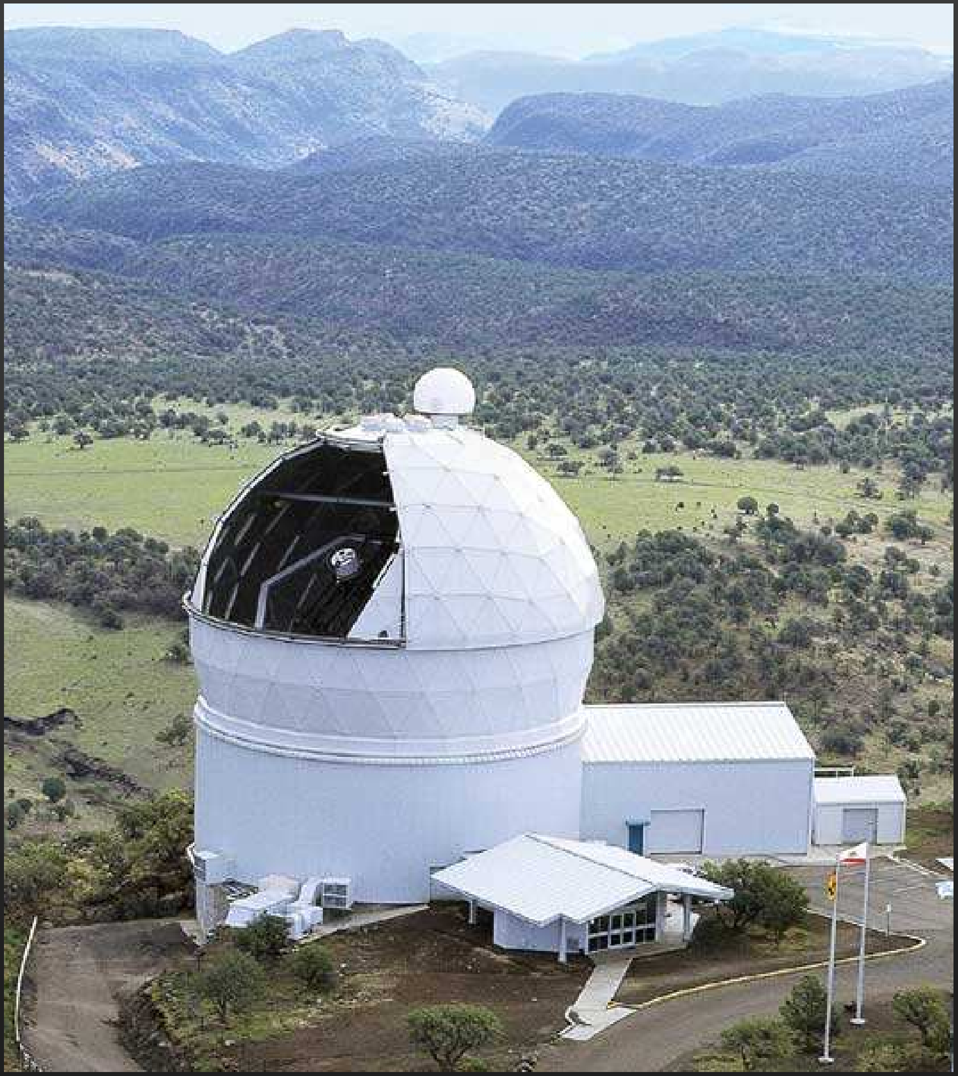
ESO PR Photo 25b/02 (30 October 2002)

©European Southern Observatory

- How could such a low-mass star have formed ?

Probing the First Stars: Hobby-Eberly Telescope

à Extending famous Sloan Sky Survey!

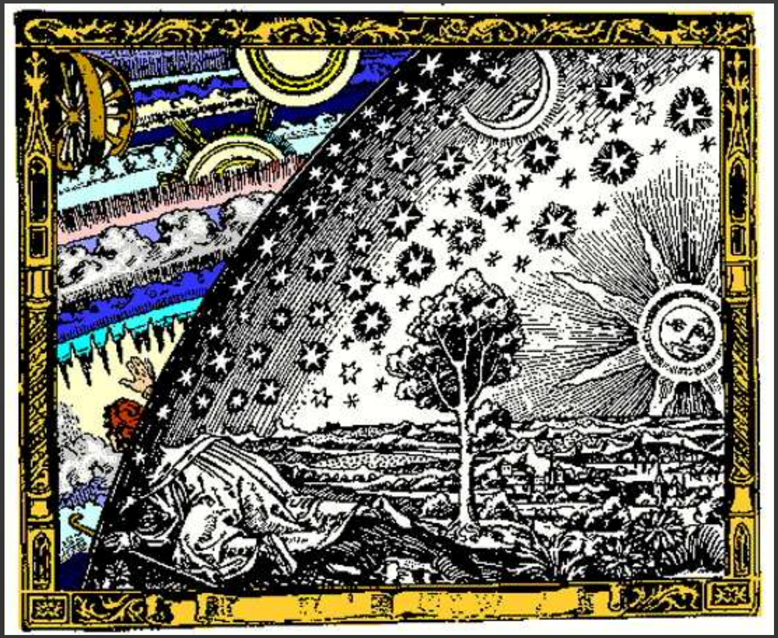


- High-resolution →

Spectra of oldest stars in our Milky Way

- pattern of chemical elements tells us about first stars and supernovae

Perspectives:



- Very dynamic, rapidly developing field
- Closing the final gap in our worldview
- driven by supercomputers and our best telescopes
- Texas will play an important role (HET, theory,…)