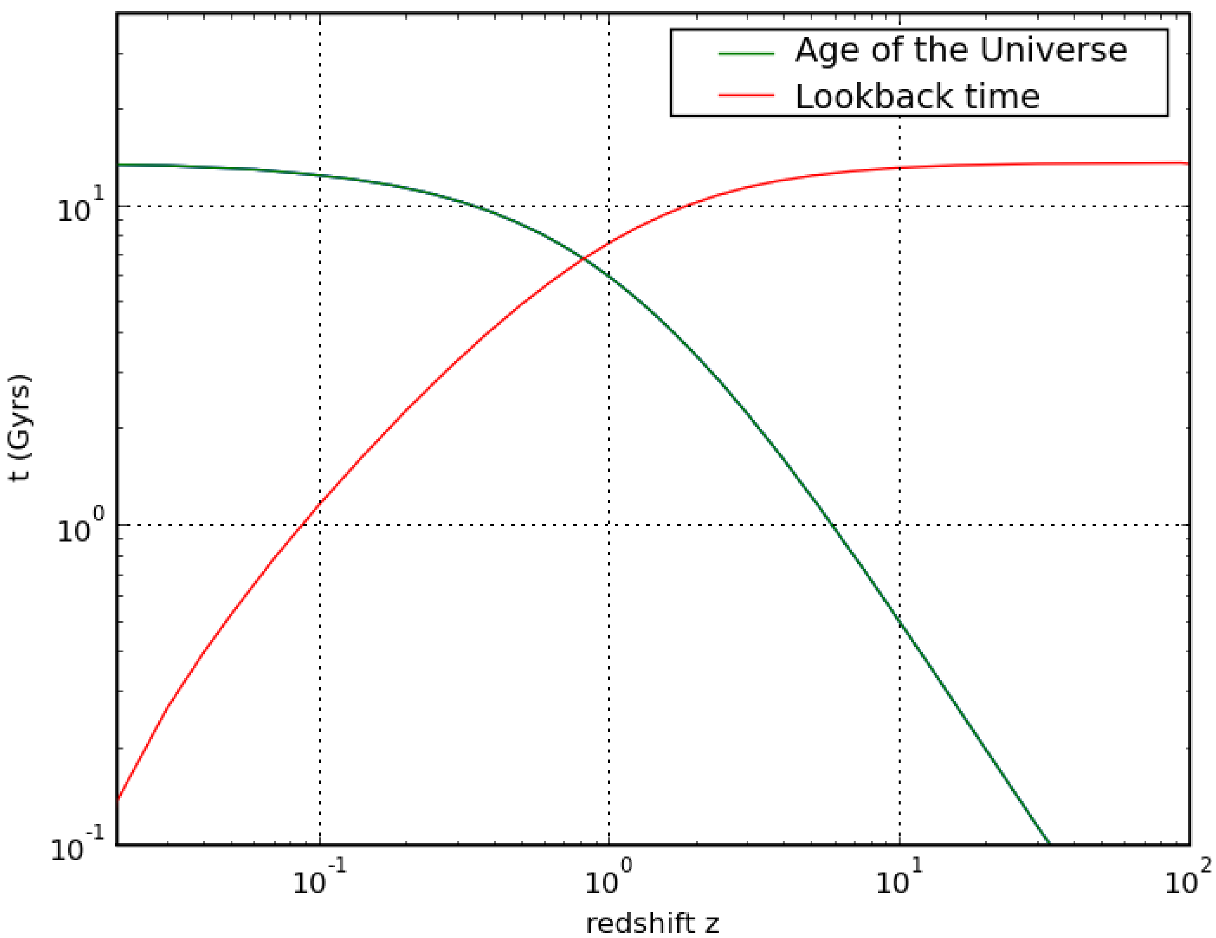
Star formation

Star Formation in the Early Universe:
Population III stars

Redshift, Age of the Universe and Lookback time



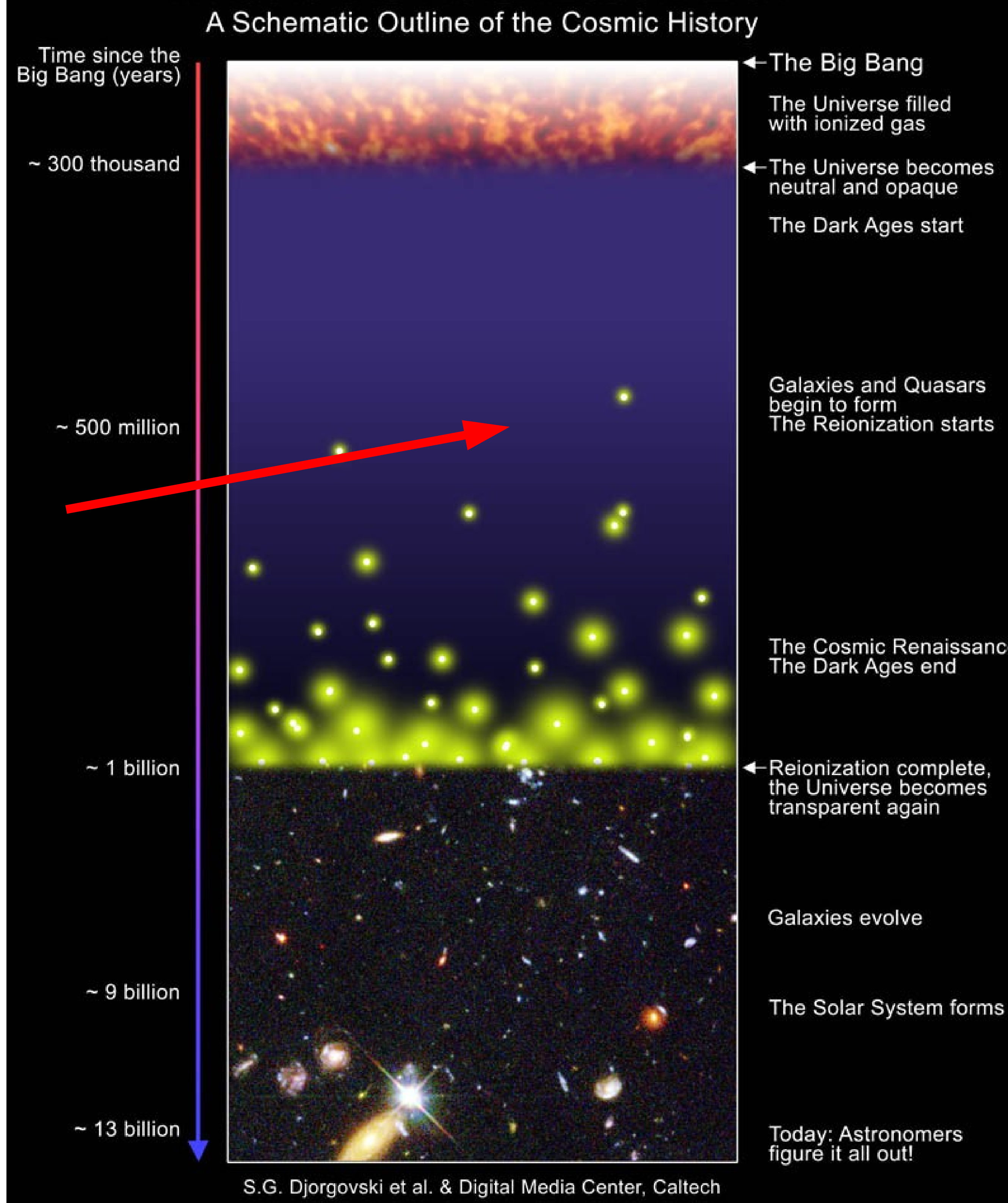
The ΛCDM Model (WMAP)

- Flat Universe
- H_0 = 73(km/s)/Mpc
- Age: 13.7 Ga
- $\Omega_\Lambda = 0.73, \Omega_m = 0.27,$ $\Omega_b = 0.044$

Dark ages

First stars here!

Epoch of re-ionization: benchmark for cosmic structure formation

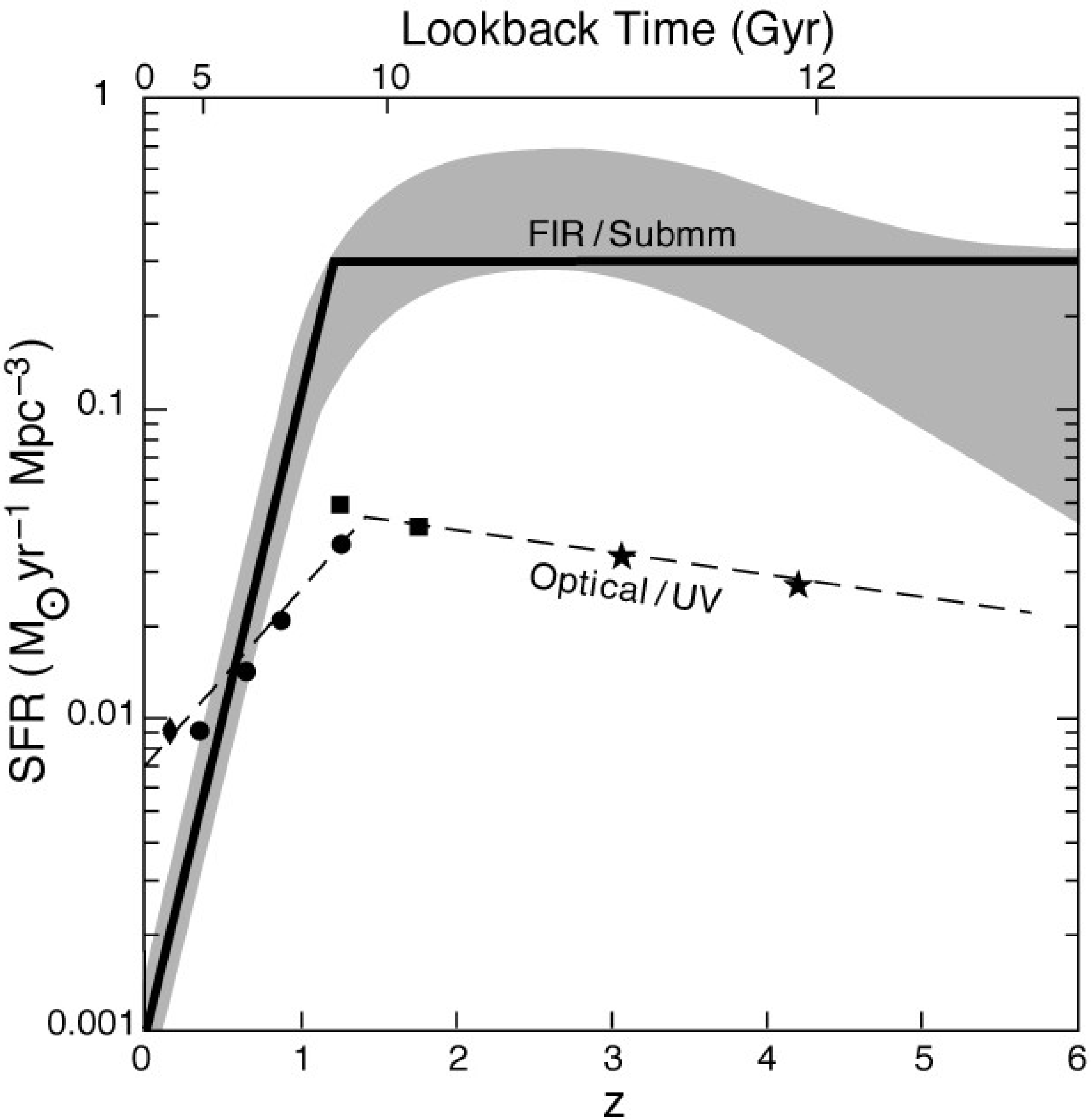


The global star formation history

Star Formation Rate versus redshift z:

•The SFR was much higher at z ≥ 2.

•The early universe SF was deeper embedded
- Larger amount of interstellar gas?



Galaxy Formation

First structures: Dark Matter Halos

- First gravitationally bound objects of the Universe
- First ones with $M \sim 10^4 M_\odot$ form at z=20-30 (age: 200-300 Ma) out of primordial density fluctuations
- Formation of proto-galaxies (baryonic matter) in Dark Matter Halos not straightforward
  - Thermal pressure forces resist collapse (unlike for dark matter)
  - Need to lower pressure by *cooling* the gas
    - But HI cooling very inefficient

Galaxy Formation

Simulation of the density evolution of a cube with 500Mpc/h_0 size

h_0 – Hubble constant in units of 100(km/s)/Mpc

10^{10} particles starting from z=127

1. step: formation of large-scale structure in the dark matter distribution

2. step: Structure formation in the gaseous component of the universe. Formed stellar material is shown in yellow.

Millenium simulation: Springel et al. (MPA)

Stellar content of our Galaxy: Populations and Metallicity

- Population I
  - Young stars with high metallicity (Z = 1)
  - Constrained to Galactic plane
- Population II
  - Older stars with lower metallicity (Z=0.01-0.1)
  - Spherically distributed in halo, bulge and globular clusters
- Population III
  - First Generation stars with Z=0

Why are the first stars special?

- Gas is metal free ($Z = 10^{-11} – 10^{-12}$) from Big Bang nucleo-synthesis
  - Compare lowest metallicity pop II stars: $Z = 10^{-4} – 10^{-3}$
- During collapse of pre-stellar cores, the gas needs to be cooled to low temperatures
  - Molecules and dust are needed for efficient cooling
  - Simplest molecule: H_2
    - Cools down to few 100 K
    - In present Universe formed on dust surfaces
  - Heavier molecules/dust
    - Cool down to 10 K

Star formation needs heavy elements

Heavy elements are formed in stars

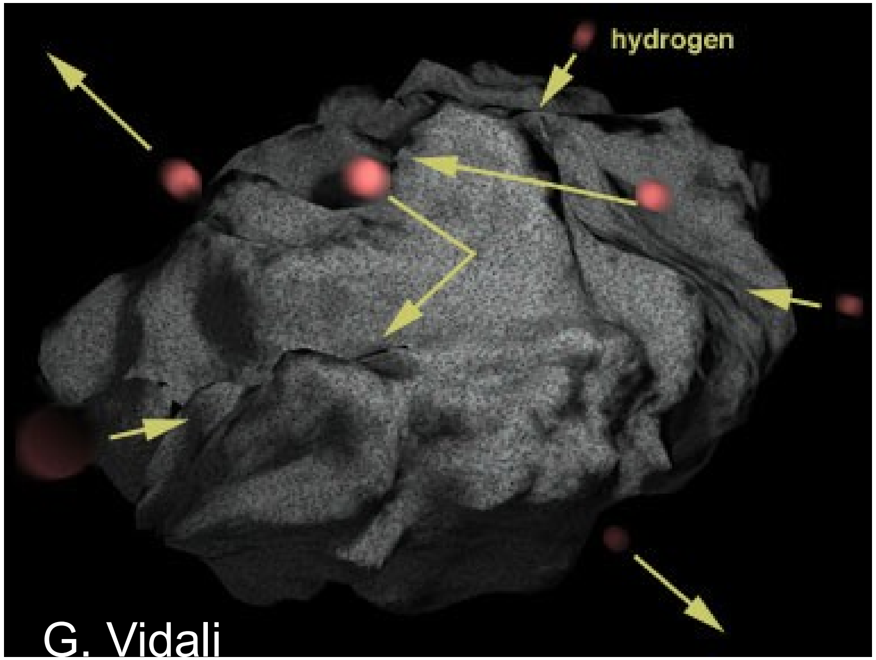
Cooling

- Removing thermal energy by
  - Transferring it to the internal energy of a particle (e.g. electronic excitation of atom, by collision)
  - Removing it from the gas in form of a photon emitted in a radiative transition
- Cooling capability depends on internal structure of cooling agent
  - Cooling by atoms works for $T > 10{,}000$ K (electronic transition)
  - Cooling by molecules works down to lower temperatures (vibrational/rotational energy levels)

Problem: how to get molecules

- H_2 formation on dust
  - Dust acts as a catalyst
- Heavy elements needed for formation of CO, H_2O etc.

But: in early universe
no heavy elements, no dust



- Alternative: gas-phase reactions:

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

Problem: how to get molecules

- Alternative: gas-phase reactions:

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

and (less important)

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

at very high densities ($> 10^8\,\mathrm{cm}^{-3}$)

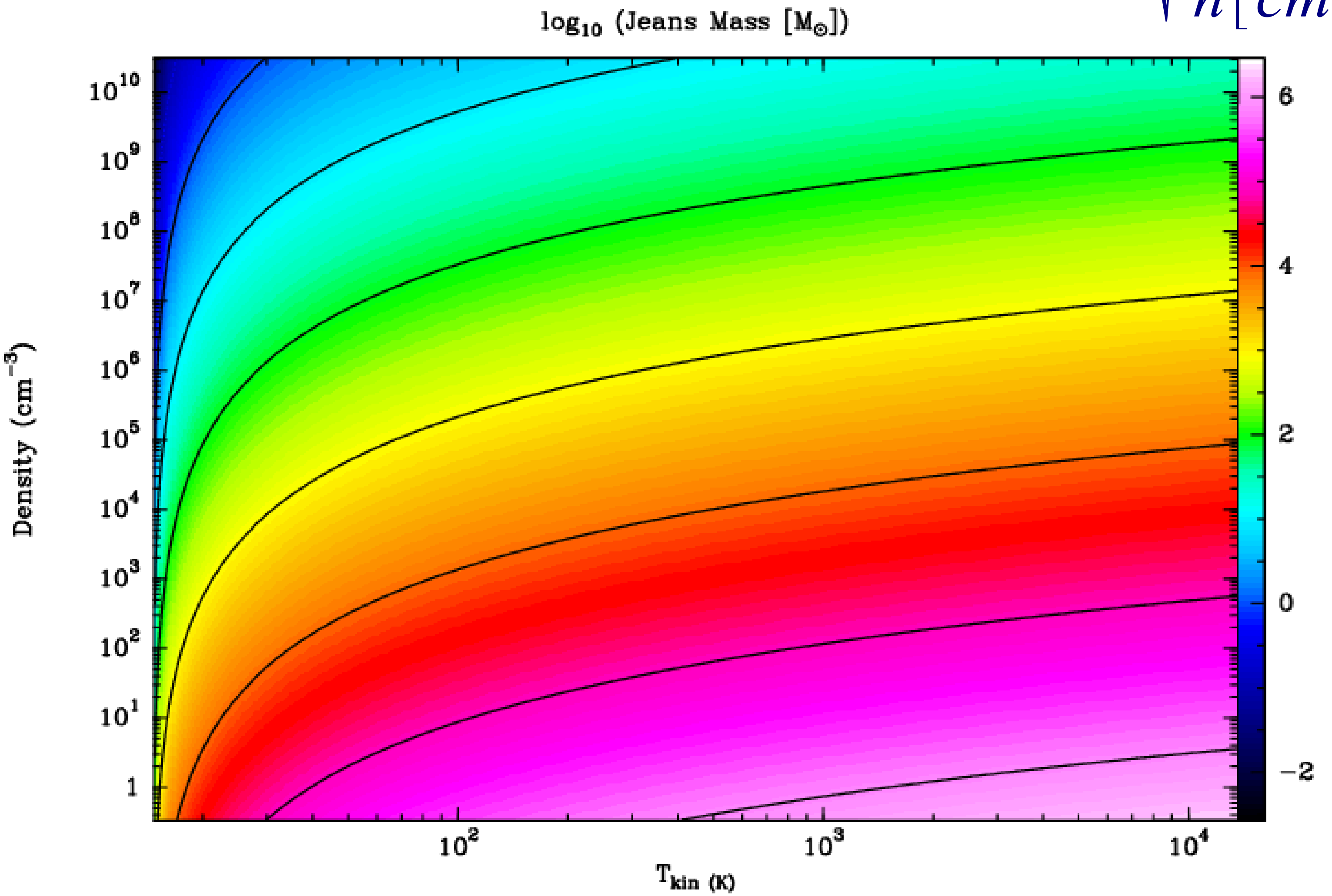
$$H + H + H \rightarrow H_2 + H$$
$$H + H + H_2 \rightarrow H_2 + H_2$$

- Requires ionization
  – residual from epoch of (re)combination
    - Vanishes quickly for very dense gas
    - Finite window of opportunity for H_2 formation
- Role of HD in cooling unclear
    - HD has electric dipole moment
    - Low abundance (10^{-5} relative to H_2)

Consequence: Jeans mass

Critical mass for collapse:

$$M_J \approx 3 \sqrt{\frac{T^3[K^3]}{n[cm^{-3}]}} [M_\odot]$$



→ large cloud masses required + population III stars very massive

How massive were the first stars?

- Fragmentation
  - Jeans mass gets lower for higher density
  - Fragments can form
  - Question: where does it stop?
    - No ambipolar diffusion limit for first stars
- Jeans criterion necessary, but not sufficient for fragmentation:
  - Clouds *can* fragment if their mass exceeds the Jeans mass, but *don't have to*
- New Simulations show that final fragments have a few 100 $M_\odot$

Models of First Star Formation

- Formation should be easy to calculate
  - No heavy elements
  - No magnetic field
  - No disturbances (spiral arm waves, outflows, supernova explosions)
  - Just H atoms and gravity
- Still a lot of physics involved (heating, cooling, rotation, turbulence)
  - Very few observational constraints
  - Difficult to decide what is important and what is not
  - Numerical resolution problems
    - Process spans more than 7orders of magnitude in space and 20 in density

Numerical Simulation

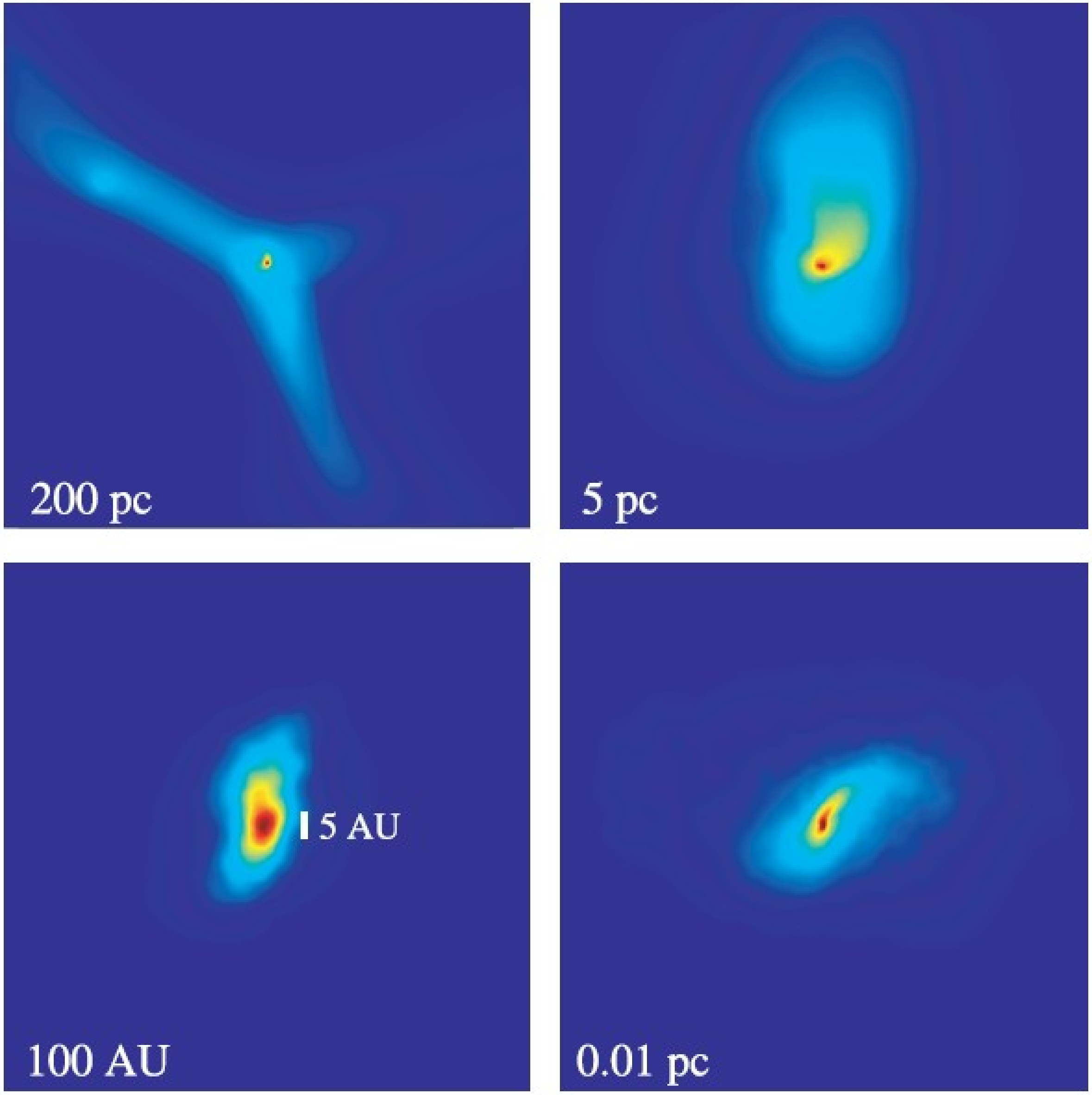


FIG. 5.—Projected density distribution for our cosmological simulations at a redshift $z \approx 19$. The physical side length is indicated in each panel.

Formation of primordial protostar at z=19:

top left:
central pc contains 300 $M_\odot$
gravitationally unstable
gas cooling by H_2

bottom left
(scale of solar system):
central patch contains a 0.01 $M_\odot$, dense ($3\ 10^{15}$ cm^{-3})
seed core that grows into a 100 $M_\odot$ star by accretion

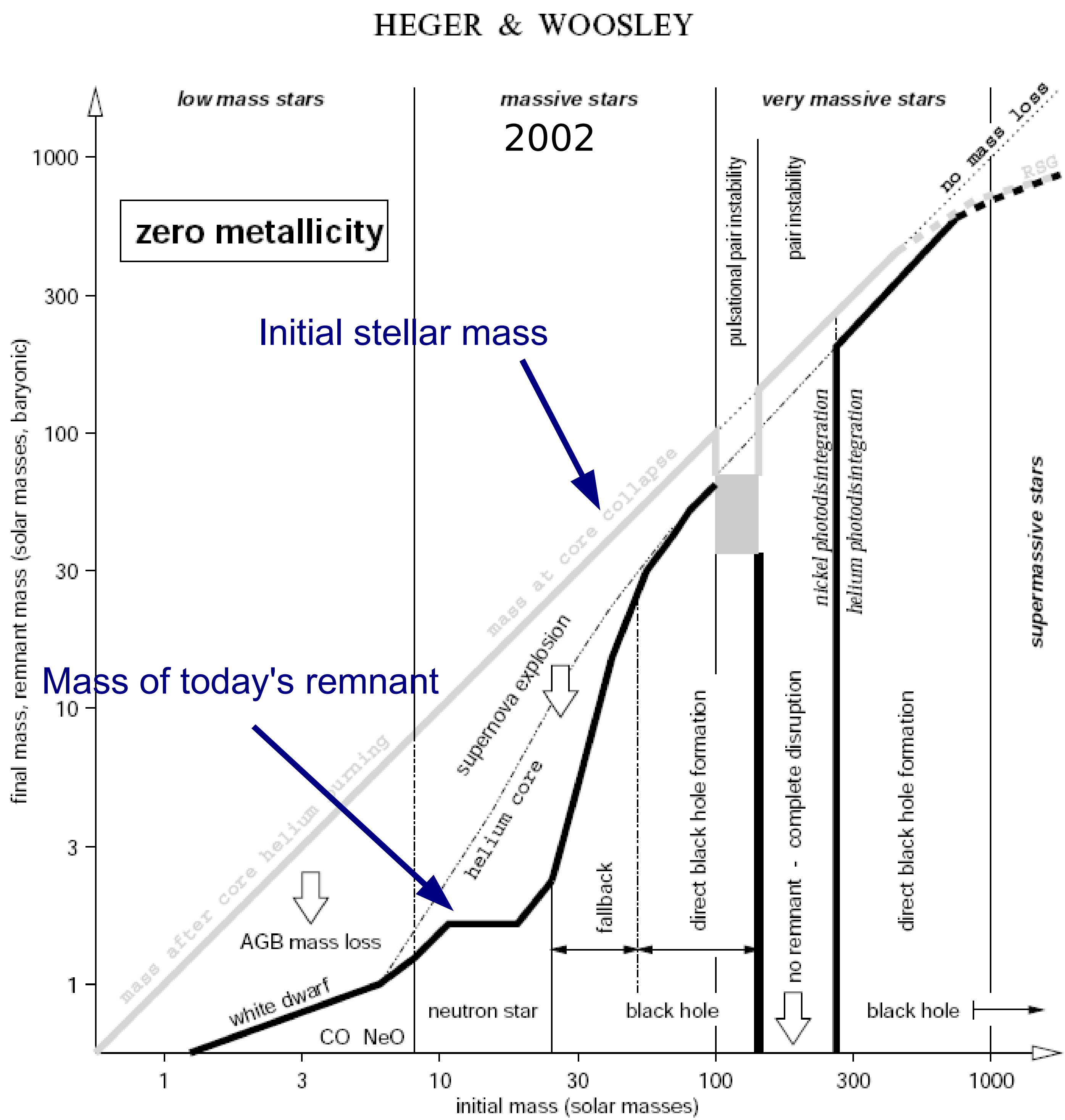
Yoshida et al. (2006)

Observational constraints

- Observations favor high masses for first stars too
  - Reionization requires massive stars with many UV photons
  - Even highly redshifted galaxies already have a lot of dust
    - Heavy element production must have been fast
  - No low-mass metal-free stars known today

Fate of First Stars

Special evolutionary tracks for zero-metallicity stars



Direct observations

- Low-mass Pop III stars, if they exist
  - Low Mass Stars with very low iron
  - Single Pop III star too faint to observe
    - Pop III in highly redshifted galaxies, in Lyα, He, cooling gas in H_2 and HD possible
- Pop III SN
  - γ ray bursts by the SWIFT satellite – rare
  - Neutrinos from Pop III SN - questionable
  - Direct observations by JWST – only upper energy range, rare
  - Gravitational waves by collapse
- Black Hole leftovers – hard to detect, may have merged into supermassive black holes in galactic nuclei

Summary/Outlook

- Can we model the formation of first stars at the right time?

Yes, we can!

  - Formation around $z=20\text{-}30$
  - $M > 100\ M_\odot$
- Open questions remain
  - How many stars per core?
  - Feedback?
- Observationally still elusive