Class 20: The first stars

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Outline

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- Microphysics of primordial gas
  - The role of H_2
  - Evolutionary phases of cooling
- The IMF of the first stars
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- The transition to modern star formation
  - Ionisation evolution
  - Metal buildup and metal line cooling
  - Dust buildup and dust cooling

Background

History and nomenclature

- In 1940s, Walter Baade noticed that stars could be divided into:
  - Yellowish, predominantly in bulge and globular clusters — population II
  - Bluish, found mainly in the disc — population I
- We now know that the colour difference corresponds to age and metallicity: pop II stars are old, metal-poor, while pop I stars are young, metal-rich
- In 1970s, zero metallicity stars were hypothesised to exist based on theory of Big Bang nucleosynthesis, which predicts Big Bang made almost no metals: called population III
- Note: this is yet another example of astronomy having a scale that runs backwards: pop III formed before pop II formed before pop I!

Observations of metal-poor stars

Results and constraints

- No population III stars have ever been observed — suggests that most of them must have been $\gtrsim 0.8\ M_\odot$, so they have not survived to present day
- Most metal poor stars that have been observed (population II):
  - SM0313 (Keller+ 2014 — discovered at ANU!): $[Fe/H] < -7$, $[C/H] = -2.6$
  - Caffau's star (Caffau+ 2011): $[Fe/H] = -6.2$, $[C/H] = -4.3$
- General pattern: almost no Fe, low C, but C $\gg$ Fe — called carbon enhanced metal poor (CEMP) stars
- Question: how do metal-free stars form, and how do we transition from those to very metal-poor (CEMP-like) stars?

Cosmological context I

Halo properties

- Gravity amplifies small inhomogeneities in early universe, causing baryons and dark matter to collect in collapsed halos — small at first, growing in time
- Halos decouple from expansion of the universe and collapse once their density is ≈ 200 mean density; mass-radius relation after collapse is

$$R_{\rm vir} \approx 290\ {\rm pc} \left(\frac{M_h}{10^6\ M_\odot}\right)^{1/3} \left(\frac{1+z}{10}\right)^{-1}$$

- Baryons that fall into halo shock and convert their gravitational energy to thermal energy; resulting temperature is

$$T_{\rm vir} = \frac{G M_h m_{\rm H}}{2 R_{\rm vir} k_B} \approx 900\ {\rm K} \left(\frac{M_h}{10^6\ M_\odot}\right)^{2/3} \left(\frac{1+z}{10}\right)$$

Cosmological context II

Where the first stars form

- For reasons that will become clear when we discuss thermodynamics, first stars only form in halos where virial temperature is $\gtrsim$ 1000 K
- The first halos to meet this condition generally have mass $\sim 10^6\ M_\odot$, and appear at redshift $z \sim 30$
- These halos are common enough, and spread their metals far enough, that the epoch of first star formation is mostly over by $z \sim 10$ — by this point all halos have been metal-enriched
- Thus the context for first star formation is halos at $z \sim 10$-30, mass $\sim 10^6\ M_\odot$

Thermodynamics of primordial gas

What makes first stars different

- The Big Bang created only H and He (plus tiny amounts of D and Li),
- In present-day ISM at temperatures $\lesssim$ 1000 K, heavy elements dominate cooling — either via metals in the gas phase or in the form of dust
- Lowest-lying electronic excited state of H is at $> 10^5$ K, similar for He, so ~1000 K atomic gas does not cool
- If there were no cooling at all, gas would remain hot and hydrostatic, and there would be no star formation
- Star formation happens in these halos because there *is* a cooling channel available: H_2, lowest-lying energy state 511 K above ground

Forming H_2 in primordial gas

A hard problem

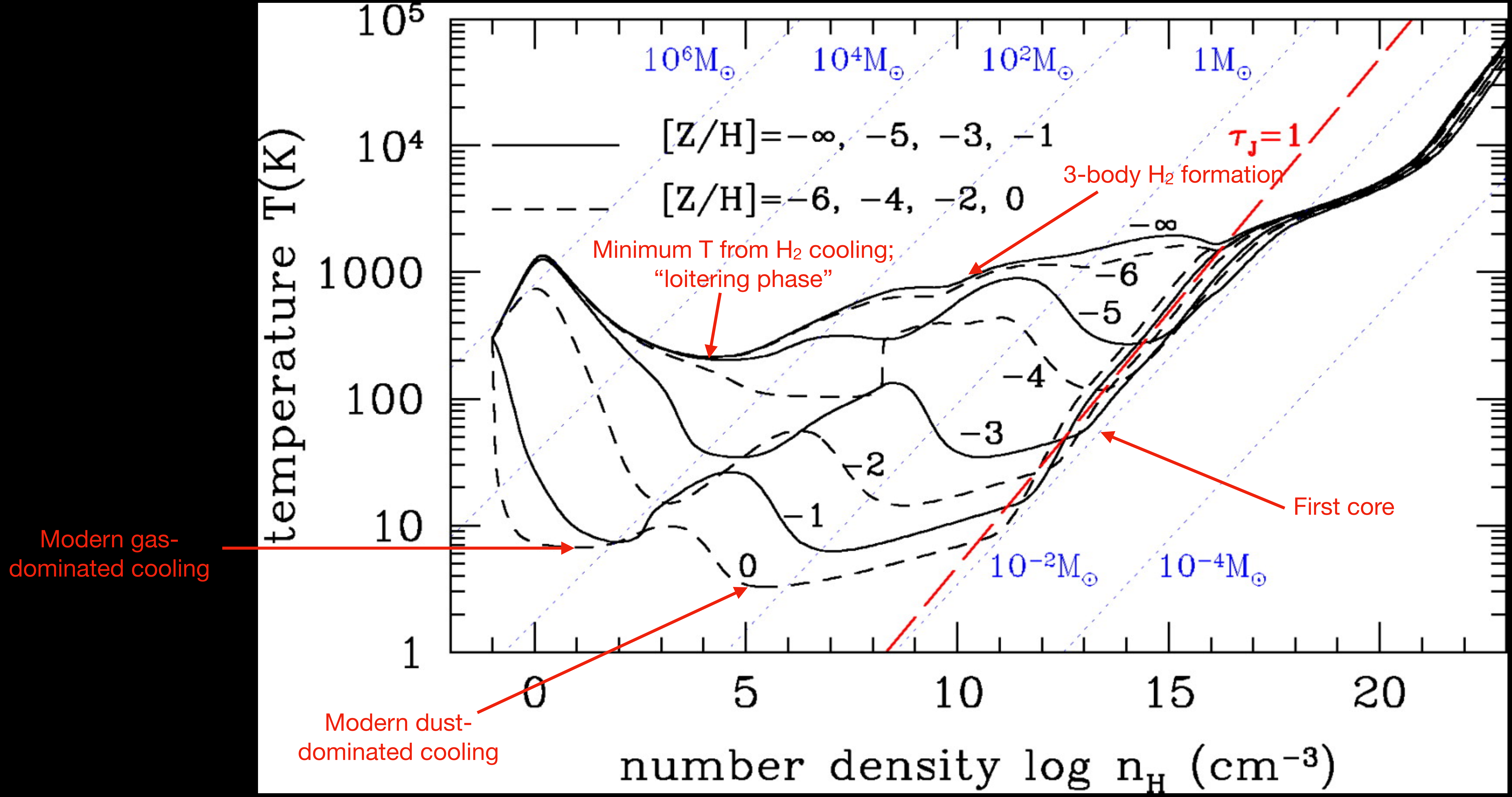
- H_2 formation via H + H → H_2 is nearly impossible, as discussed
- In present-day ISM, solution is formation on grain surface; primordial gas contains no dust grains, or any solids all
- Instead, a different catalyst dominates: free electrons left over from when the Universe recombined at $z = 1100$
- Reaction process is $$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + h\nu$$ $$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e^-$$
- First step is exothermic (binding energy 0.77 eV), rate $\approx 10^{-16}$ - 10^{-15} cm^3 s^{-1} — not huge, but not tiny; second step is much faster

Barriers to forming H_2

Why this is slow

- Abundance of free electrons is tiny; depends on redshift, but is always $< 10^{-6}$
- At $z \gtrsim 100$, H_2 formation suppressed by photodetachment
  - H^- can be broken up by any photon with energy > 0.77 eV
  - If this happens, H^- is not able to catalyse formation of H_2
  - Present day CMB temperature = 0.23 meV, scales as $(1 + z)$, so at $z = 100$ CMB temperature = 0.023 eV
  - This is close enough to 0.77 eV that photons on the exponential tail of the Planck distribution disrupt most H^- faster than it forms H_2, suppressing H_2
- Even where it can form, H_2 abundance is never big — maximum $\sim 10^{-3}$ until density $> 10^8$ cm^{-3}

Thermodynamics of H_2-dominated cooling



Omukai+ 2005

Phases of H_2-dominated cooling

Step by step, part I

- At low density, H_2 forms at abundance up to ~10^{-3}, cools gas to ~200 K
- Can't go much lower than that because lowest level is 500 K off ground
- Critical density of H_2 $J = 2$ is $\approx 10^4$ cm^{-3}, so cooling rate per particle saturates above this density
- Result: gas gets stuck for a while near 10^4 cm^{-3}, 200 K — vaguely similar to first core phase; "loitering phase"
- Density gradually rises past loitering phase, until next change at $\approx 10^8$ cm^{-3}

Phases of H_2-dominated cooling

Step by step, part II

- At ≈ 10^8 cm^{-3}, 3-body reactions possible: $\mathrm{H} + \mathrm{H} + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$
- In this case 3rd H atom acts as catalyst to remove excess energy
- This effect quickly drives H_2 fraction to near unity
- Heating - cooling competition: every H_2 that forms heats the gas by 4.5 eV, but also adds an extra coolant atom; which effect wins depends on geometry, other complex factors, but probably no big temperature drop
- At ≈ 10^{12} cm^{-3}, gas becomes optically thick, first core forms — very similar to present-day star formation, but at higher density due to higher starting temp

The IMF of the first stars

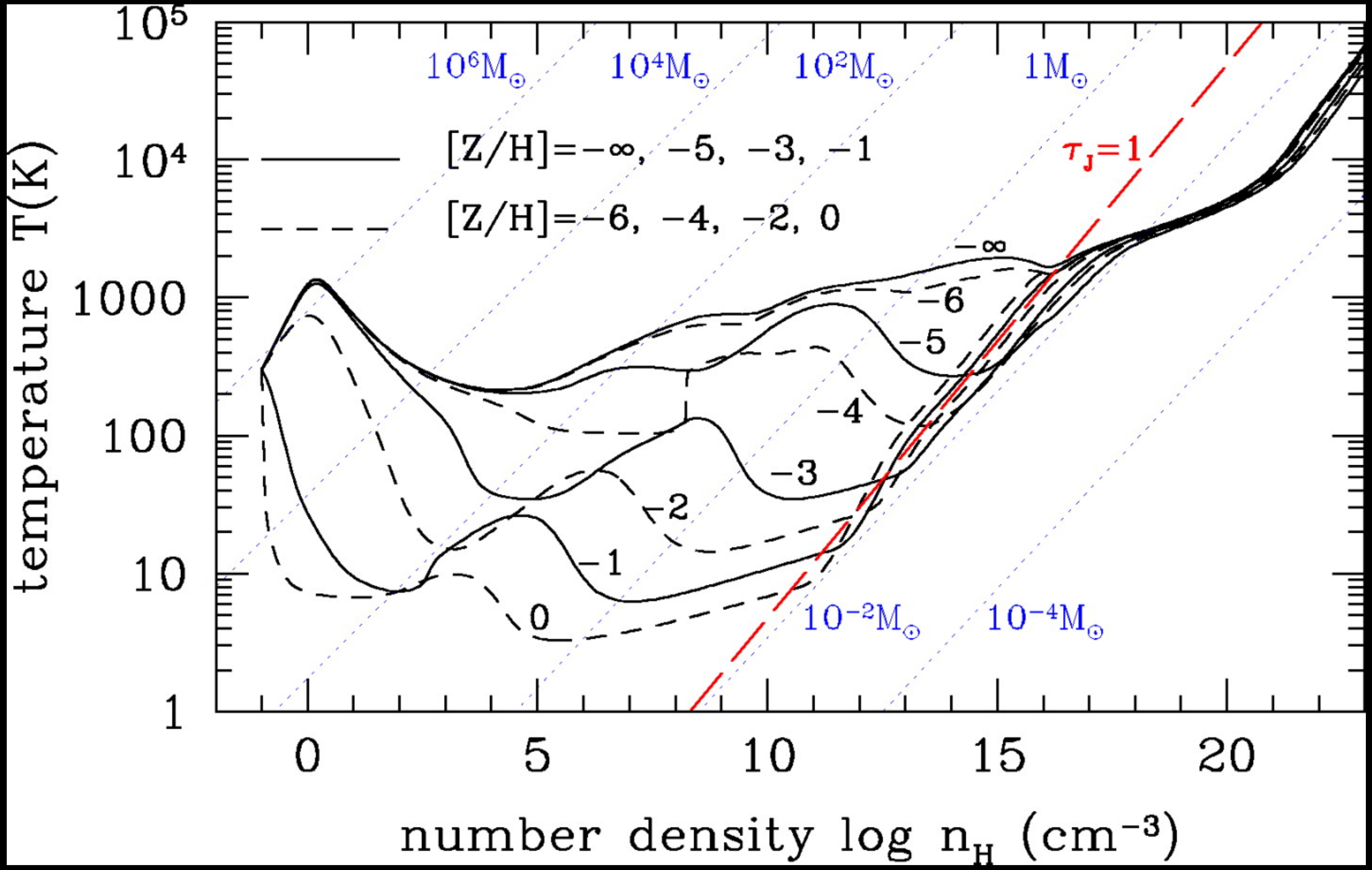
Prompt fragmentation

- Minimum Jeans mass along cooling curve for first stars is » for present-day stars

- Estimate during loitering phase:

$$M_J \approx \frac{c_s^3}{\sqrt{G^3 \rho}} \sim 300\ M_\odot \left(\frac{T}{200\ \mathrm{K}}\right)^{3/2} \left(\frac{n}{10^4\ \mathrm{cm}^{-3}}\right)^{-1/2}$$

- Suggests little fragmentation as cores collapse, massive stars



The IMF of the first stars

Disc fragmentation

- First star discs are warmer than modern discs, but also more massive and rapidly-accreting due to lack of earlier fragmentation; not dissimilar from discs around modern-day massive stars
- This suggests that disc fragmentation is possible for first stars
- Simulations confirm that this is the case: first star discs do fragment
- This is a developing area with major unsolved problems: not clear how much fragmentation there is, or what the final masses of the fragments is

First star disc fragmentation

Sharda+ 2020

First star disc fragmentation

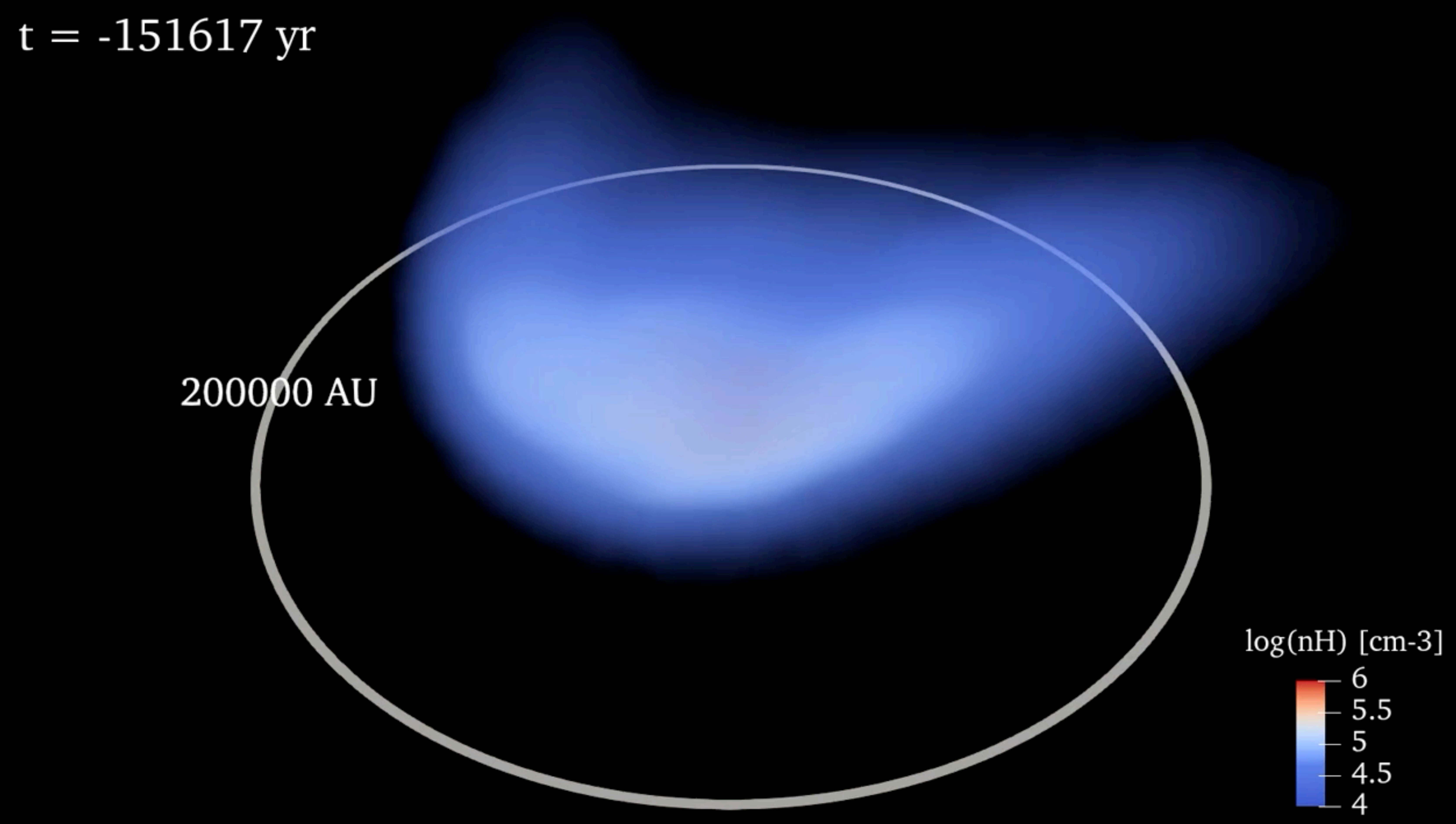
Sharda+ 2020

The IMF of the first stars

Feedback effects

- First stars might have jets, but highly uncertain — depends on magnetic field strength and geometry, not well understood
- Radiative feedback at energy $<$ 11.2 eV has little effect, because there is no dust to absorb it — it just escape freely
- Photons at $>$ 11.2 eV can be absorbed by H_2, those at $>$13.6 can ionise H
- Possible effects: photo evaporating discs, cutting of fuel supply onto disc by creating expanding HII region
- Since 10^4 K $>$ virial temperature, ionisation can even drive gas out of halo

First star feedback simulation



Sugimura+ 2020

The end of the first star epoch

How first stars give rise to later types of stars

- First feedback effect of pop III stars, before they explode as SNe (or collapse to BH), is radiation capable of dissociating H_2 and ionising H
- This is weak at intergalactic distances, but since there are no other source of high-energy radiation, effects can be significant
- Most important one turns out to be ionisation: gas affect by radiation from a pop III star will have a much higher free electron density than primordial gas
- Extra free electrons speed up H_2 formation, allow more efficient cooling, probably lower mass
- Stars that form via this route called population III.2; truly primordial is III.1

Metal line cooling

Transition from pop III to II via line cooling

- First stars end as type II SNe, which produce little Fe, lots of α elements (C, O)
- Since halos where first stars form have escape speeds $\ll$ SN blast wave speeds, these escape the halo, mix with IGM, accrete onto other halos
- First assume that the elements are purely in the gas phase, i.e., no solid grains, so we only need to worry about cooling via lines of O and C^+
- Dominant low-T cooling lines: 158 μm (C^+), 63 and 145 μm (O)
- Basic question: how much C and O do we have to add to primordial gas before cooling via these lines becomes significant?

Critical metallicity

For cooling by C and O

- Consider conditions in primordial halo, $n \sim 100\ \mathrm{cm}^{-3}$, $T \sim 1000$ K
- This is ≪ critical density for lines, ≫ temp required to excite lines → limit where emission rate = collisional excitation rate, and $e^{-E/kT} \approx 1$
- Assume same C/O ratio as Sun, so C/H = Z' (C/H)$_\odot$ and same for O
- Compare adiabatic heating rate to metal line cooling rate:

$$\Gamma = -p\frac{d}{dt}\left(\frac{1}{\rho}\right) \approx k_B T\sqrt{\frac{32Gn}{3\pi\mu m_{\mathrm{H}}}} \qquad \Lambda = \frac{1}{n\mu m_{\mathrm{H}}}\sum_{\mathrm{C,O}}\frac{hc}{\lambda}n n_{\mathrm{C,O}} k_{\mathrm{coll.exc.}} \approx 0.01 n Z'\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

- Rates balance at $Z' \approx 4.5\times 10^{-4}\left(\frac{T}{1000\ \mathrm{K}}\right)\left(\frac{n}{100\ \mathrm{cm}^{-3}}\right)^{-1/2}$: critical metallicity

Dust cooling

Background and basic considerations

- Calculation suggest metal-line cooling should induce a transition to pop II and something like a “normal” IMF when Z’ $\gtrsim 10^{-3.5}$
- Problem: Caffau’s star has [C/H] = –4.3, an order of magnitude smaller
- So how did something low mass like the form?
- Possible answer: dust is a much more efficient radiator than gas-phase metals, so maybe there was dust and that provided cooling
- Repeat calculation we just carried out: how much dust do we need for it to be a significant coolant?

Dust cooling

Critical dust mass

- Rate-limiting step is thermal exchange between dust and gas via collisions
- Let D = dust to gas mass ratio, S = dust cross sectional area per unit mass — 10^5 cm^2 g^{-1} for MW dust sizes, completely unknown for early universe
- Collision rate / unit gas mass = $nDS\sqrt{\frac{8k_BT}{\pi\mu m_\mathrm{H}}}$ ← Dependence on T, μ from variation of mean particle velocity
- Mean energy transfer / collision = $2\alpha k_BT$ ← Collision-weighted mean particle energy = 2kT, fraction $\alpha \approx 0.5$ transferred to grain
- Product gives cooling rate; setting equal to adiabatic heating rate gives

$$D = \frac{1}{\alpha S}\sqrt{\frac{G}{3nk_BT}} \approx 8\times 10^{-9}\left(\frac{\alpha}{0.5}\right)^{-1}\left(\frac{S}{10^5\ \mathrm{cm}^2\ \mathrm{g}^{-1}}\right)^{-1}\left(\frac{n}{10^{12}\ \mathrm{cm}^{-3}}\right)^{-1/2}\left(\frac{T}{1000\ \mathrm{K}}\right)^{-1/2}$$

Density when gas becomes optically thick, cooling shuts off

Implications of dust critical mass

- D for Solar neighbourhood ≈ 0.01, so this is 6 orders of magnitude smaller
- Suggest dust enables fragmentation at very low metallicity, if S is similar to value in MW
- Big uncertainty: what is the mapping between dust and metallicity?
- Probably *not* a good assumption that dust / metals ratio is same as in MW — observed dust / metals ratio decreases at metallicities < 10% Solar
- Possible dust produce directly in first star SNe: we know dust is produced early in SN evolution from observing 1987A, but unclear how much survives passage of reverse shock when SN ejecta decelerate