The dynamics of ionization and dissociation fronts in extremely dense primordial gas

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What determines the maximum mass of Population III stars?

- Gas exhaustion
  - Pop. III stars form in gas-rich haloes, accretion rates are high, so final masses can be large
- Fragmentation-induced starvation
  - Only effective if fragmentation efficient AND if fragments don’t merge
- Stellar feedback

Stellar feedback

- Winds
    - Lack of metal lines implies that winds are likely to be very weak (although see poster by H. Susa)
- Radiation
    - **Ionization**
    - **Photodissociation**
    - Radiation pressure

Ionization and photodissociation

- Massive stars emit high flux of EUV photons, which ionize H, He, and H_2, and Lyman-Werner (LW) photons, which dissociate H_2
- Which process dominates?
  - Stacy et al (2016): "Photodissociation"
  - Hosokawa et al (2016): "Ionization"
- Modelling these processes in 3D is extremely challenging.
- Useful to consider simpler models to illuminate basic physics

- Consider behaviour of ionizing and dissociating photons in very dense primordial gas

- “Very dense” here means $n > 10^9$ cm^{-3}: three-body H_2 formation efficient, gas is initially fully molecular

- Mean free path of EUV photons short: well-defined ionization and dissociation fronts (I and D fronts)

- How do these fronts propagate?

Early evolution

- If recombinations unimportant, I-front radius obeys:

$$\frac{\mathrm{d}R_{\mathrm{I}}}{\mathrm{d}t} = \frac{\dot{\mathrm{N}}_{\mathrm{ion}}}{4\pi R_{\mathrm{I}}^{2}\, n_{\mathrm{H}}(R_{\mathrm{I}})}$$

- If three-body H_2 formation unimportant in PDR*, then D-front radius obeys a similar equation:

$$\frac{\mathrm{d}R_{\mathrm{D}}}{\mathrm{d}t} = \frac{\dot{\mathrm{N}}_{\mathrm{LW}}\mathrm{f}_{\mathrm{dis}}}{4\pi R_{\mathrm{D}}^{2}\, n_{\mathrm{H}_2}(R_{\mathrm{D}})}$$

*It is, but explaining why will take too long

- f_{dis} is the fraction of LW photon absorptions that result in dissociation; typically ~ 15%

- For Z=0 massive stars:

$$f_{\rm dis}\dot{\rm N}_{\rm LW} \simeq 0.2\,\dot{\rm N}_{\rm ion}$$

- D-front <u>slower</u> than I-front

- Consequence: D and I fronts move together (cf. Bertoldi & Draine 1996)

Later evolution

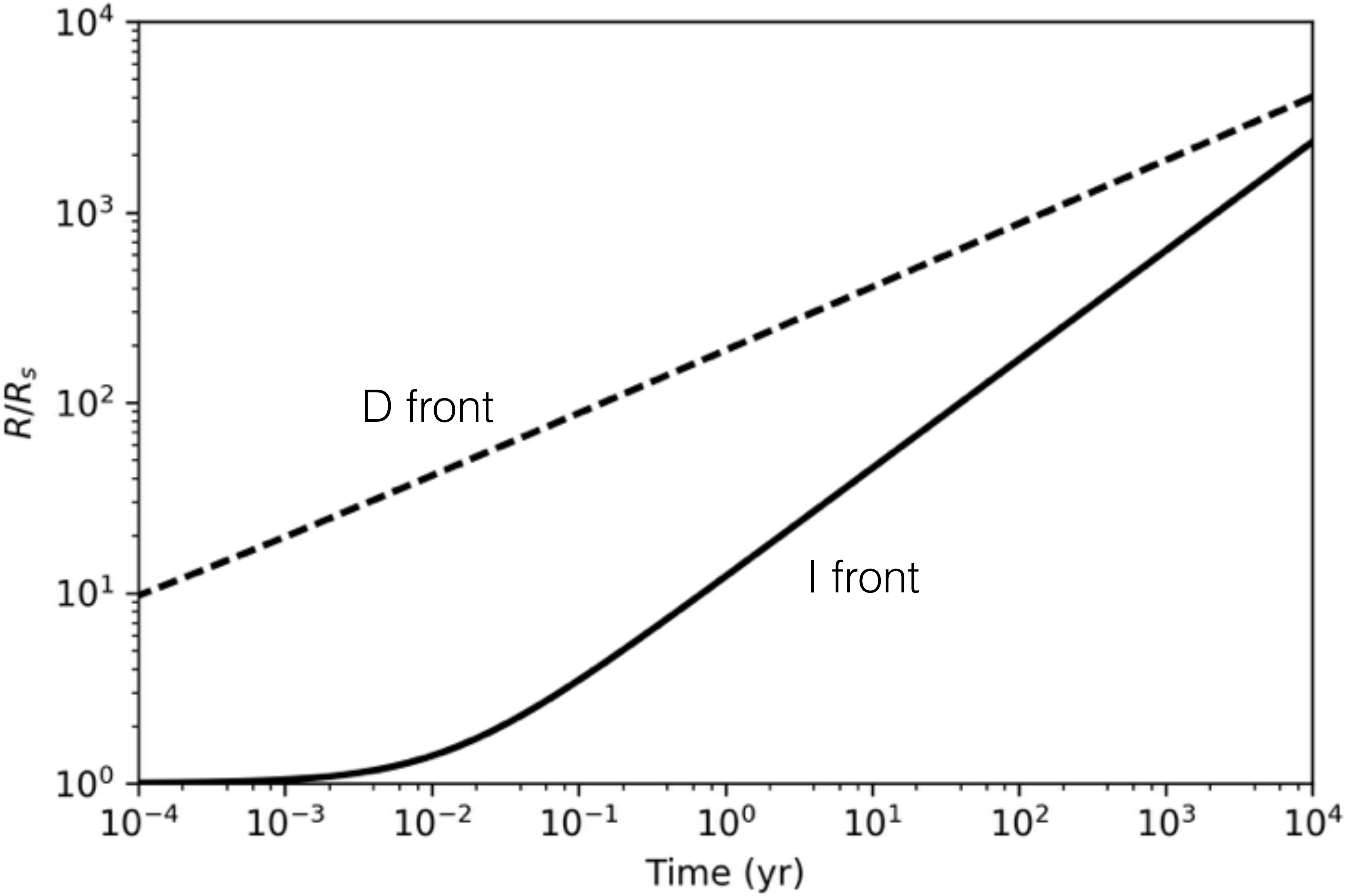
- Behaviour of I-front depends on density distribution near source
- If density gradient sufficiently steep, I-front remains R-type, D-front never separates
- If velocity of R-type front less than infall velocity, front can be trapped near star while remaining R-type (Omukai & Inutsuka 2002)
- If density gradient shallow (or density constant), I-front rapidly reaches Stromgren radius and stalls; subsequently expands as D-type front

- How does D-front evolve once I-front stalls?
- If LW photons only absorbed by H_2, then D-front velocity still obeys:

$$\frac{\mathrm{d}R_{\mathrm{D}}}{\mathrm{d}t} = \frac{\dot{\mathrm{N}}_{\mathrm{LW}}\mathrm{f}_{\mathrm{dis}}}{4\pi R_{\mathrm{D}}^{2}\, n_{\mathrm{H}_2}(R_{\mathrm{D}})}$$

- D-front rapidly separates from I-front

50 solar mass star, n = 10^{13} cm^{-3}



- This analysis ignores an important effect!

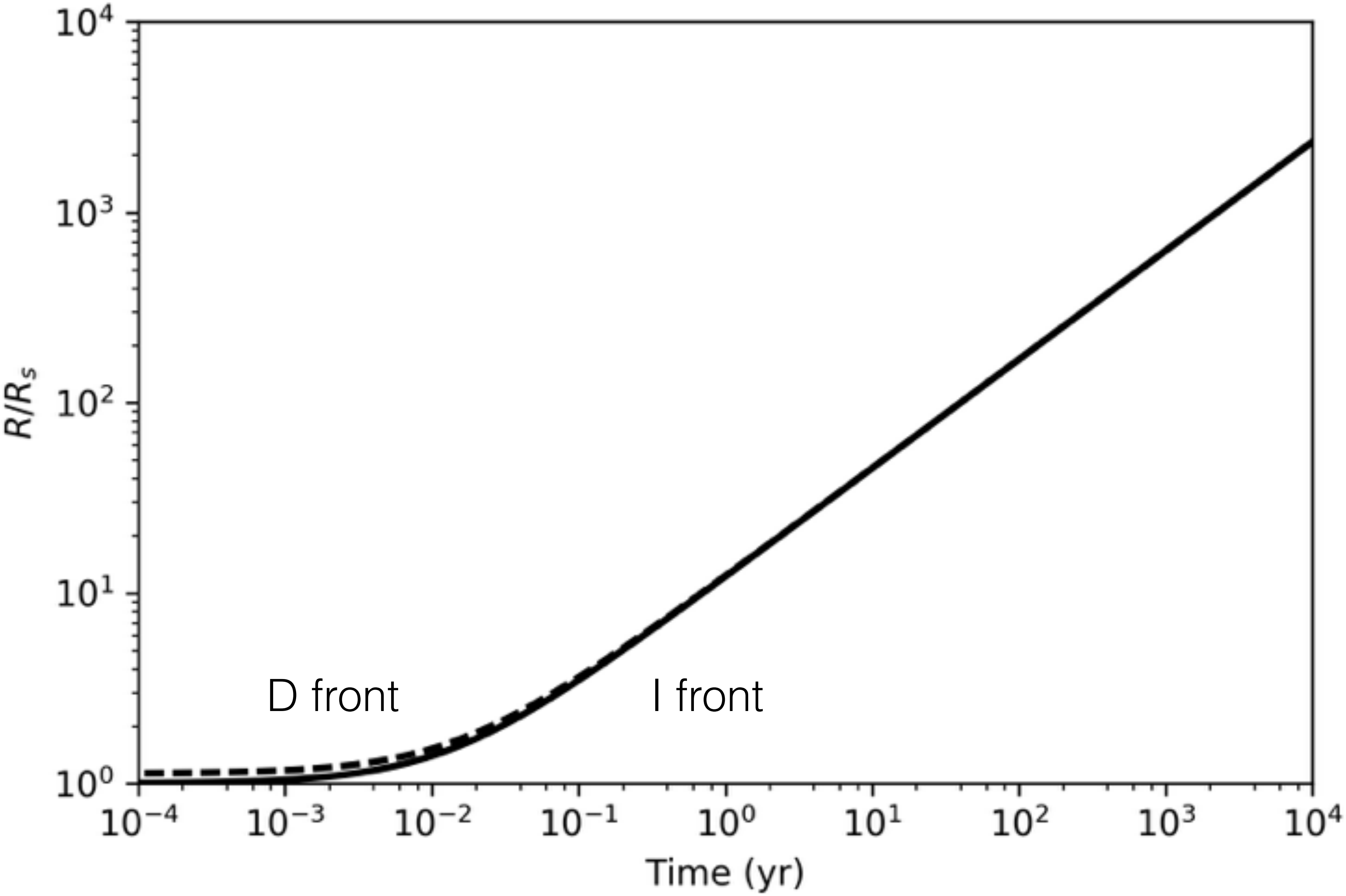
- LW photons can be absorbed by atomic hydrogen Lyman series lines (Lyman-β and above)

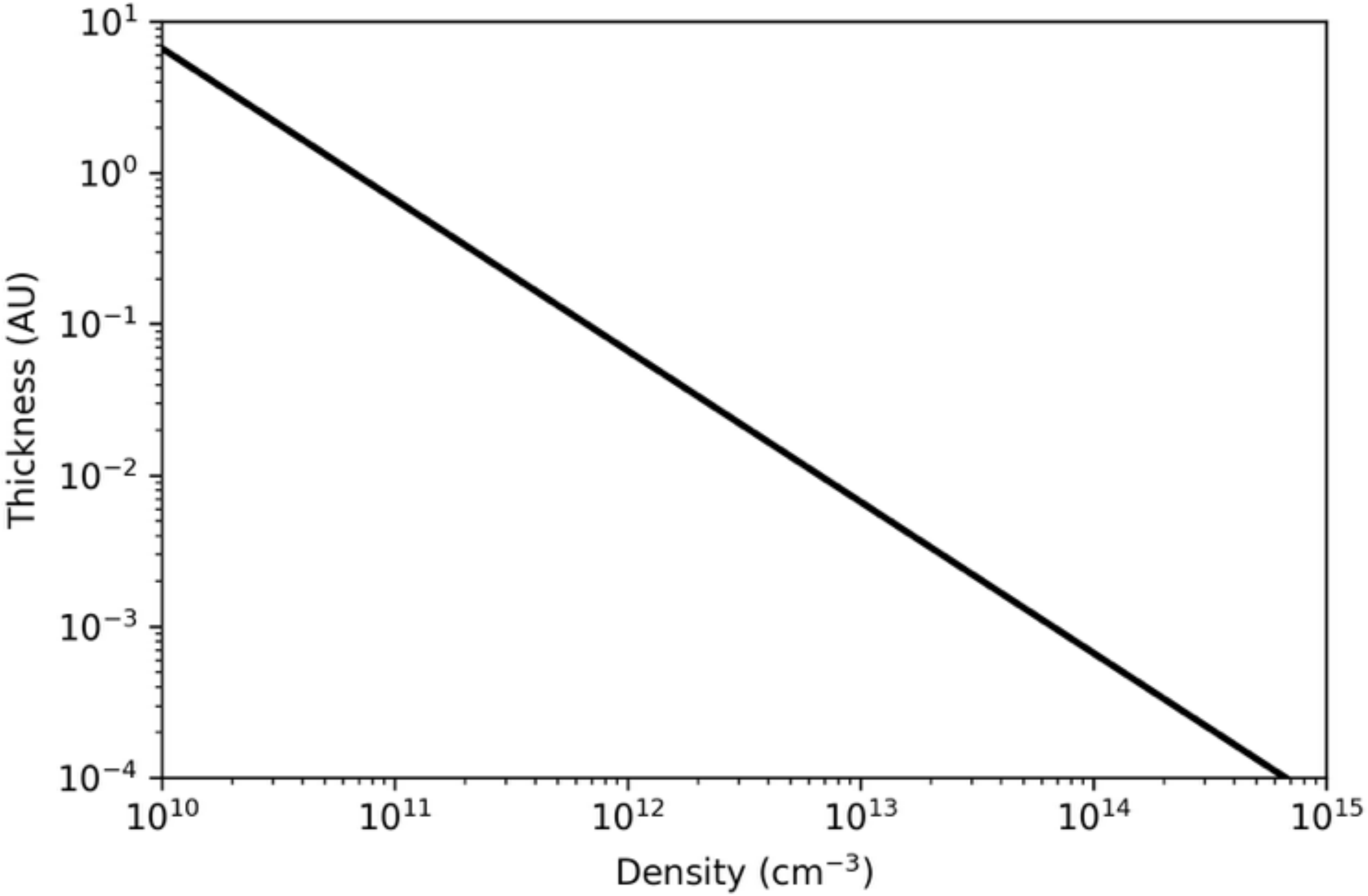
- Photons scatter in these lines and are eventually down-converted to Lyman-α

- Once $N_H > 10^{24}$ cm^{-2}, almost all LW photons absorbed by H, not H_2 (Wolcott-Green & Haiman 2011)

- D-front stalls once column density of H between D-front and I-front exceeds a few times 10^{24} cm^{-2}

50 solar mass star, n = 10^{13} cm^{-3}




Thickness (AU)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Density (cm^{-3})

- In very dense gas, D-front remains close to I-front even in D-type regime
- Separation of > 1 AU only once $n_H < 10^{11}$ cm^{-3}
- PDR can expand to large volumes only once column density of H surrounding HII region becomes small enough
- At early times, modelling this requires sub-AU resolution

Open questions

- What is the dynamical impact of the LW radiation?
  - Each photon deposits a few E/c of momentum; is this ever significant?
- Is LW feedback important for regulating accretion onto massive Pop. III stars?
  - Seems unlikely to play a role close to the star. Important on larger scales?

Summary

- R-type I-front: no separation between I, D fronts
- D-type I-front: separation small if column density of H in PDR layer exceeds 10^{24} cm^{-2}
- Accurate modelling of D-front expansion requires accurate modelling of H column density in PDR
  - At early times, this implies sub-AU resolution
- Small separation between I, D fronts suggests that LW feedback is probably not dynamically important