The Effect of Photoevaporation on the First Stars

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Francesco's Legacy: Star Formation in Space and Time

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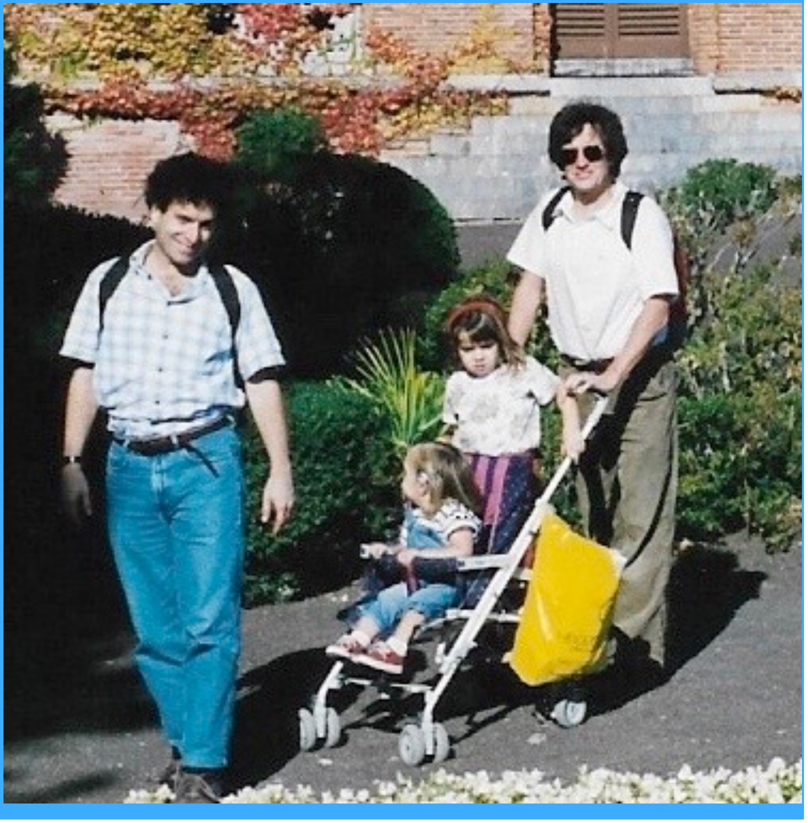
Thanks to K. Tanaka, K. Omukai, T. Hosokawa, H. Yorke, J. Tan, and F. Palla for patiently answering my questions!

Francesco



Introduction: Formation of First Stars
z~20

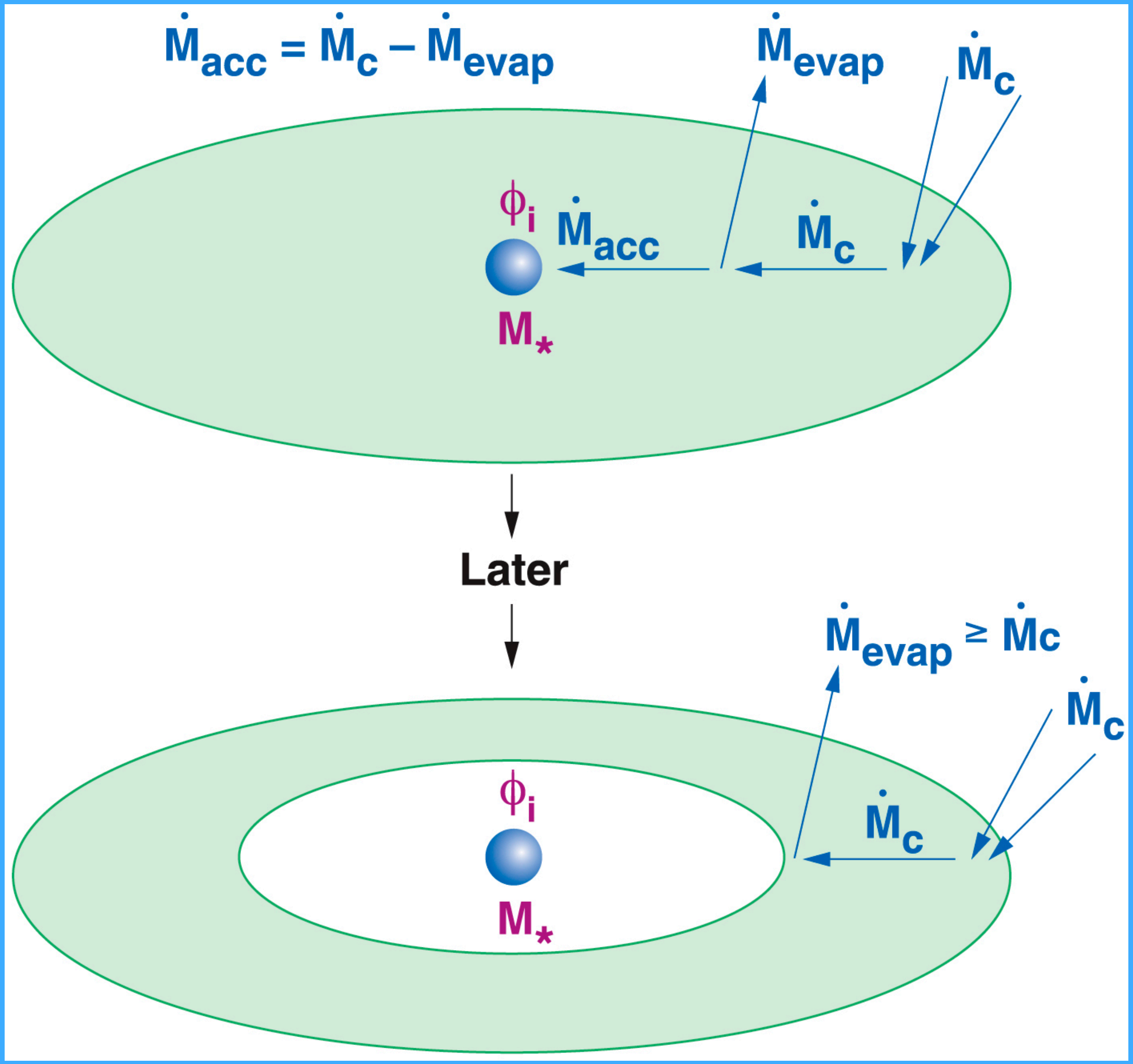
$M_{tot} \approx 10^6\, M_\odot$ but $M_{gas} \approx 10^5\, M_\odot$

$M_{core} \approx M_J \approx 1000\, M_\odot$, $n \approx 10^4\, cm^{-3}$, $r \approx 1$ pc, $T \approx 300$ K

$$\dot{M}_{acc} \simeq \frac{M_J}{t_{ff}} \simeq \frac{c_s^3}{G} \simeq 2 \times 10^{-3} \left(\frac{T}{10^3\, K}\right)^{3/2} M_\odot/yr$$

$M_*\,(max) \simeq \dot{M}_{acc}\, t_{ms} \sim 1000\, M_\odot$

Introduction: Feedback by EUV Disk Photoevaporation



Introduction: Outline of Talk

I. Introduction

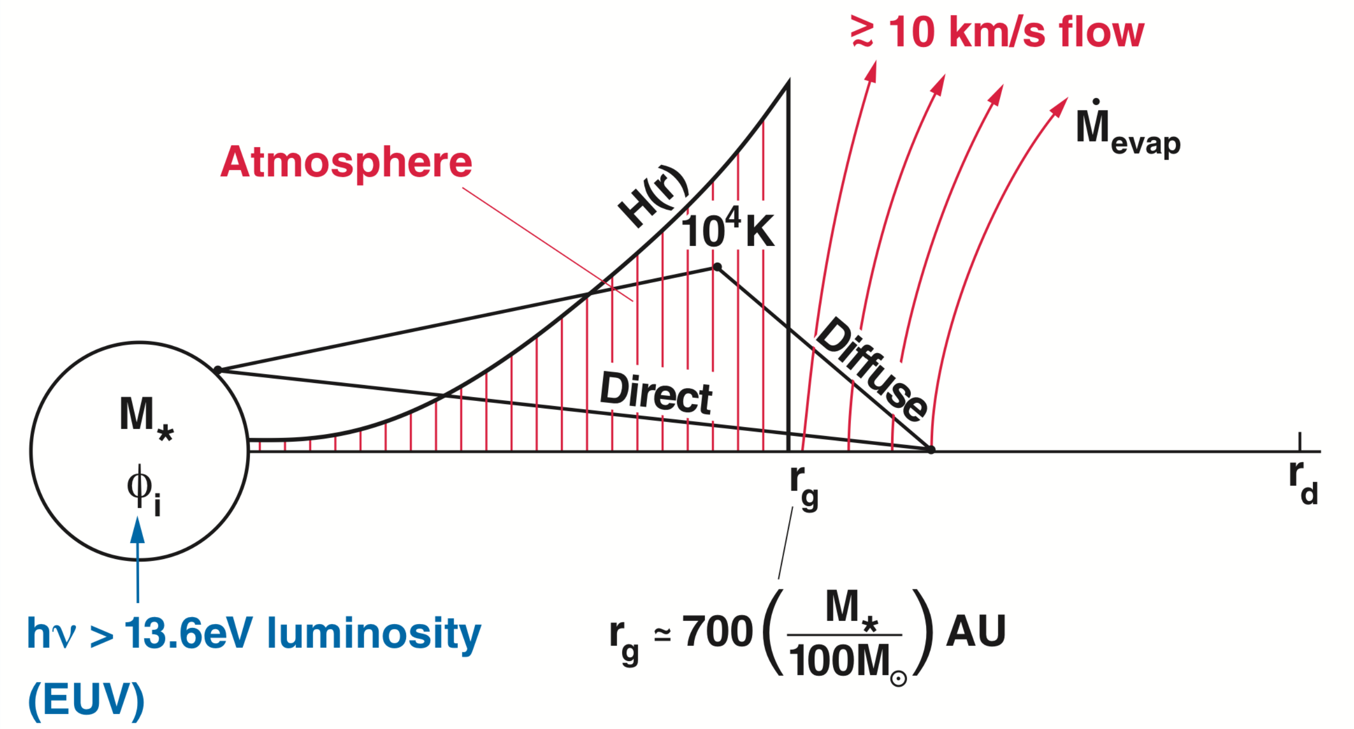
II. Initial Upper Limits on Mass of First Stars (~2005-2008)
- Unpublished work of Francesco and myself
- Comparison with McKee and Tan (2008)

III. Revision of Upper Limits on Mass of First Stars
- In part, revised (higher) photoevaporation rates from disks
- Hosokawa et al (2011)
- Tanaka et al (2013)

IV. Discussion of New Photoevaporation Rates

V. Conclusion

II. Initial Upper Limits to the Mass of First Stars



$$\dot{M}_{evap} \simeq 5.4 \times 10^{-5} \left(\frac{\phi_i}{10^{49}s^{-1}}\right)^{1/2} \left(\frac{M_*}{100M_\odot}\right)^{1/2} M_\odot\, yr^{-1}$$

$$\phi_i = 7.9 \times 10^{49} \left(\frac{M_*}{100M_\odot}\right)^{1.5} s^{-1}$$

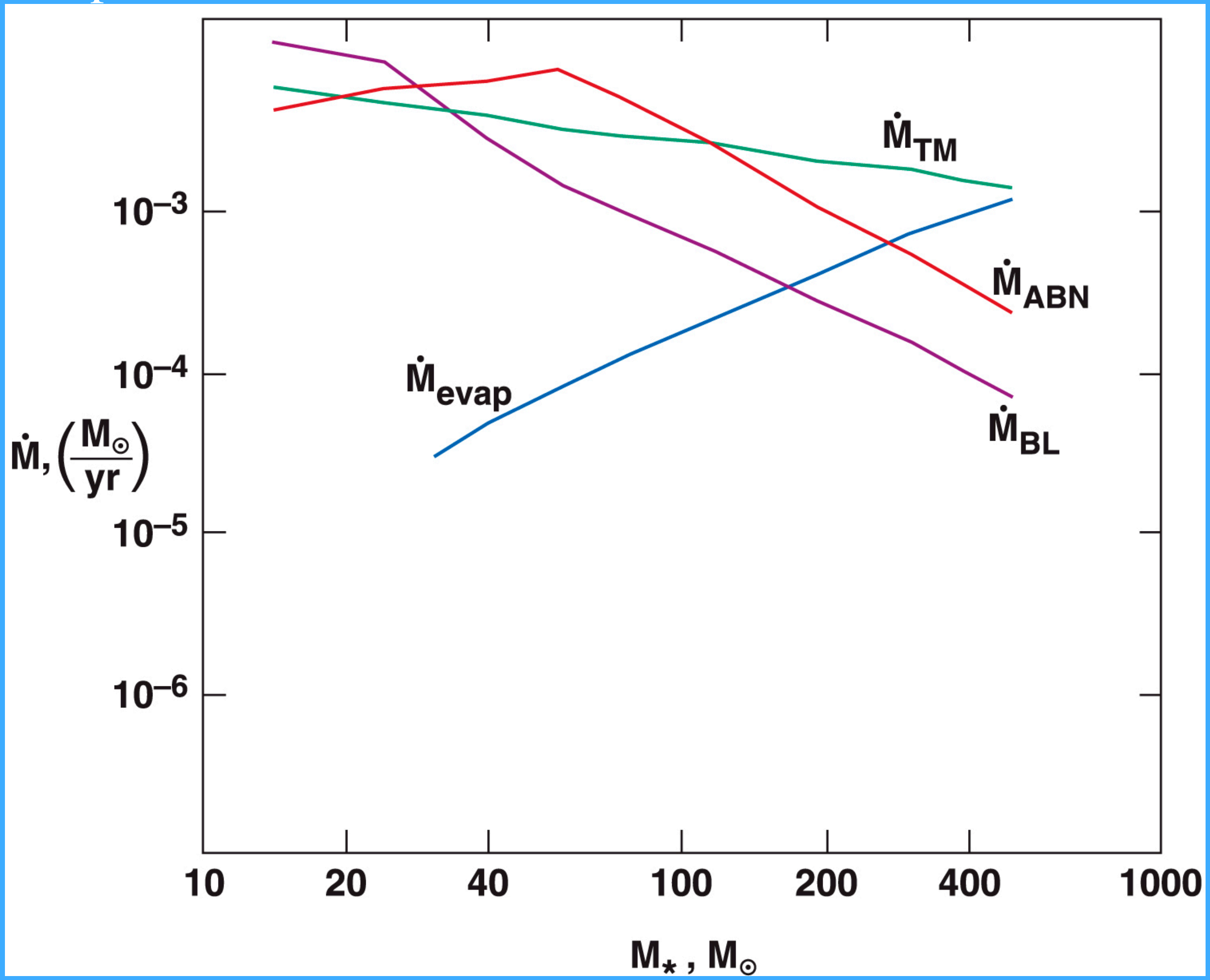
$$\dot{M}_{evap} \simeq 1.6 \times 10^{-4} \left(\frac{M_*}{100M_\odot}\right)^{1.25} M_\odot\, yr^{-1}$$

n(base) proportional to $r^{-3/2}$ for $r<r_g$

Hollenbach et al(1994) (H94)

II. Initial Upper Limits to Mass of First Stars

Unpublished work of F. Palla and D. Hollenbach ~ 2007



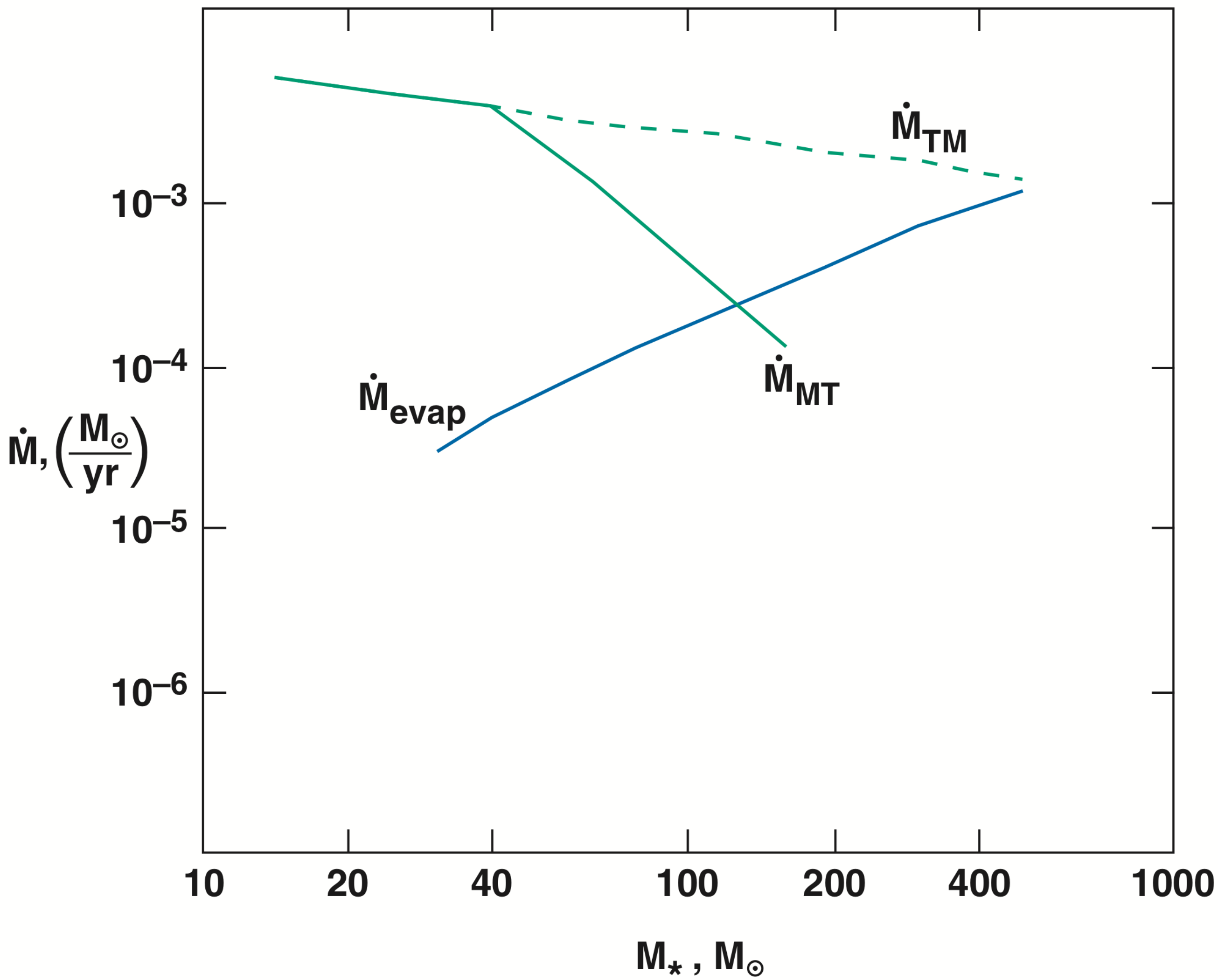
TM = Tan and McKee (2004) ~ 500 $M_\odot$

ABN = Abel, Bryan and Norman (2002) ~ 270 $M_\odot$

BL = Bromm and Loeb (2004) ~ 160 $M_\odot$

II. Initial Upper Limits to Mass of First Stars

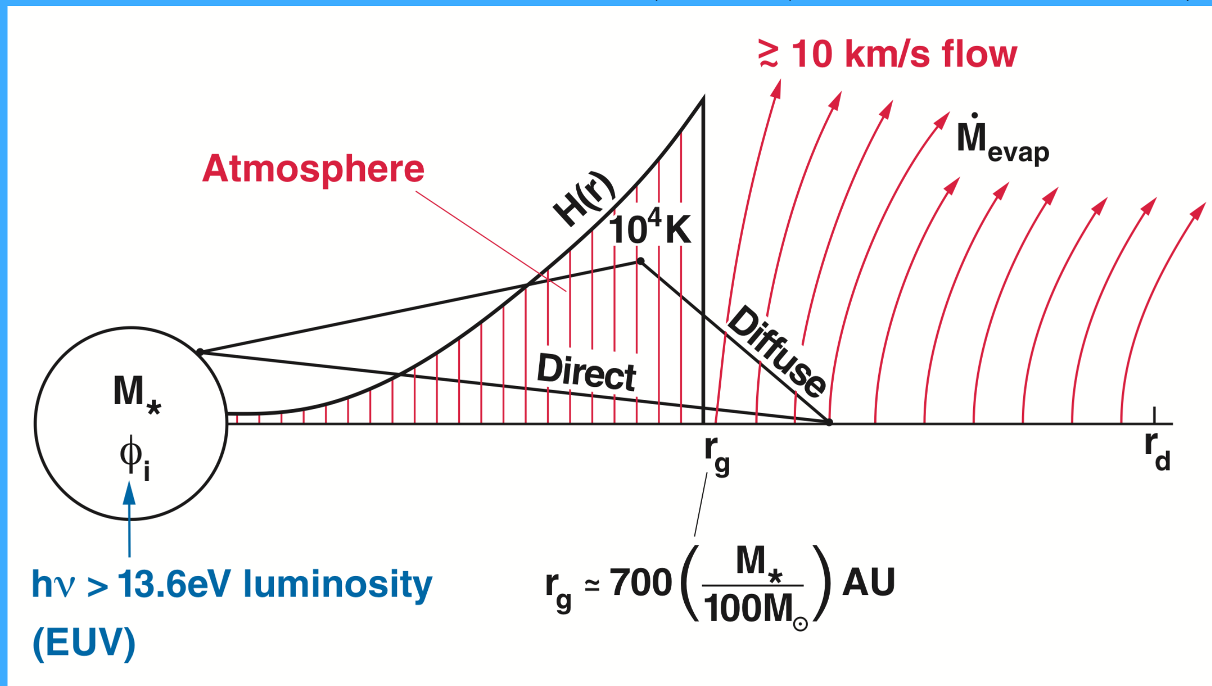
McKee and Tan (2008) Feedback limits Accretion Rate



M_* (max) ~ 140 $M_\odot$

III. Revision of Upper Limits to the Mass of First Stars

Hosokawa et al (2011), Tanaka et al (2013)



$$\dot{M}_{evap} = 1.4 \times 10^{-4} \left(\frac{\phi_i}{10^{49} s^{-1}}\right)^{1/2} \left(\frac{r_d}{10^{17} cm}\right)^{1/2} M_\odot\, yr^{-1}$$

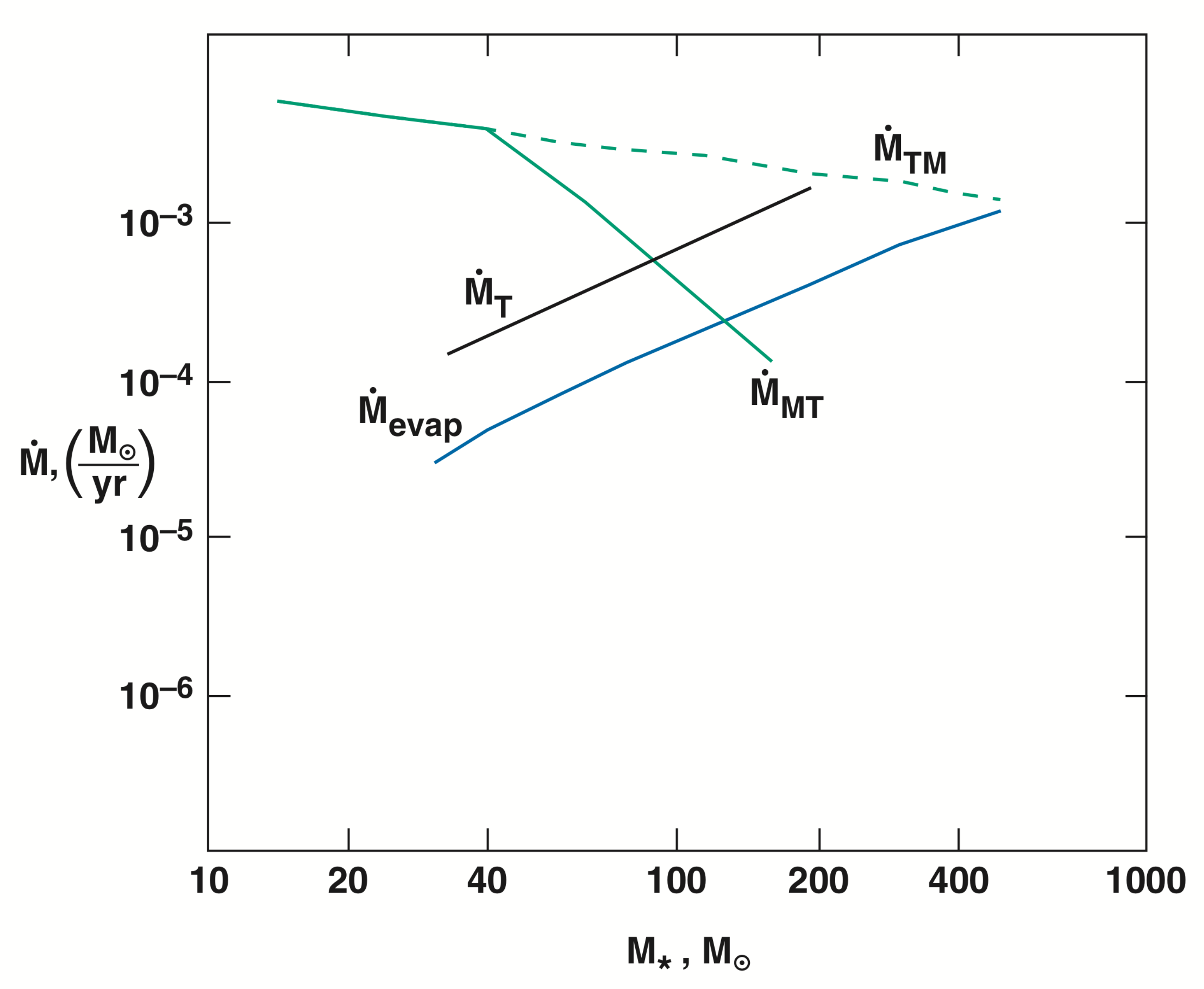
$$\phi_i = 7.9 \times 10^{49} \left(\frac{M_*}{100 M_\odot}\right)^{1.5} s^{-1}$$

$$\dot{M}_{evap} = 3.9 \times 10^{-4} \left(\frac{M_*}{100 M_\odot}\right)^{0.75} \left(\frac{r_d}{10^{17} cm}\right)^{1/2} M_\odot\, yr^{-1}$$

n(base) proportional to $r^{-3/2}$ for $r < r_d$ --ALL THE WAY!

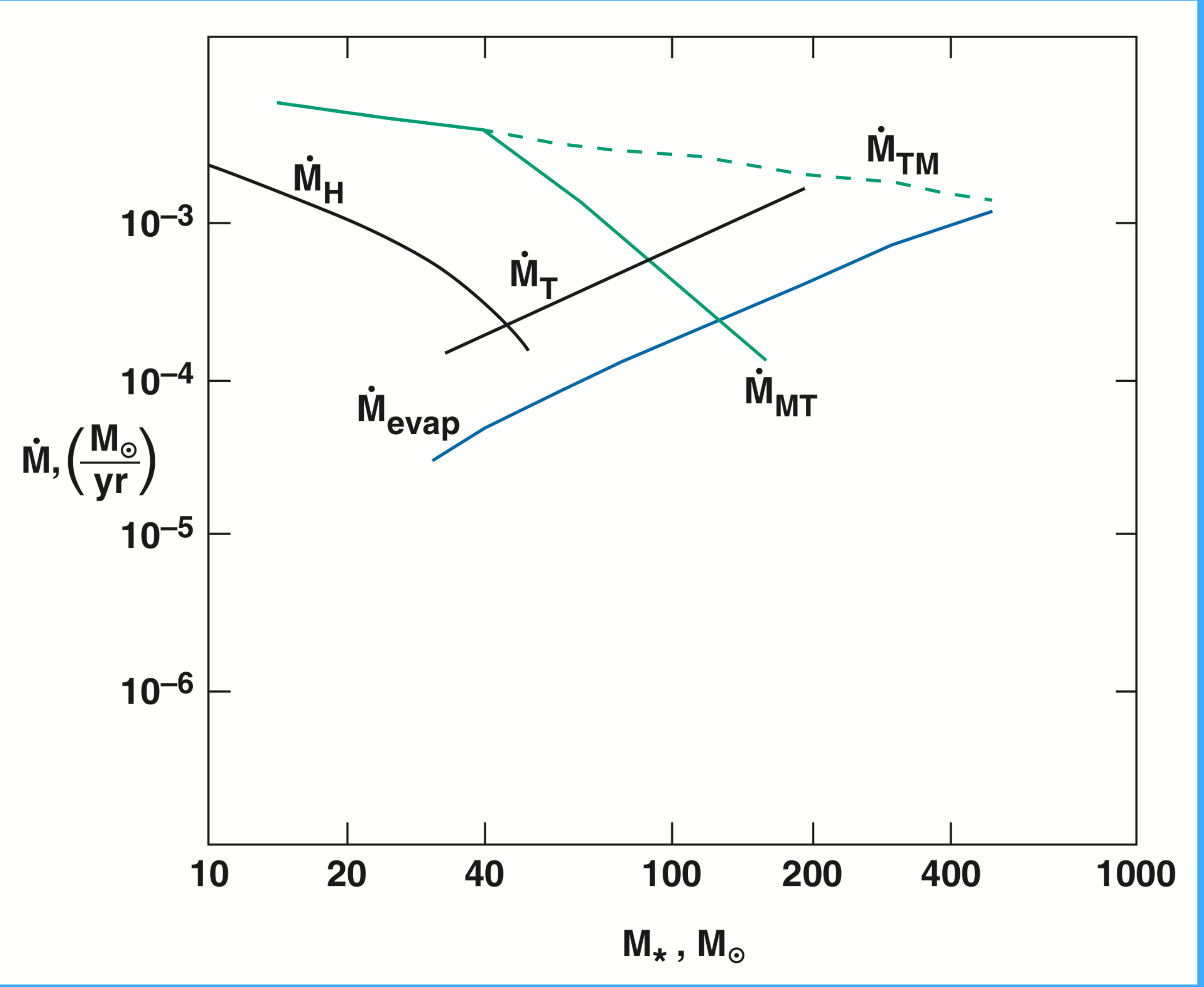
Tanaka et al (2013)

III. Revision of Upper Limits to Mass of First Stars
Tanaka higher rate



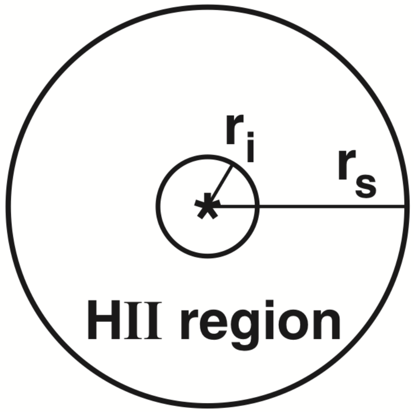
new M_* (max) ~ 90 $M_\odot$

III. Revision of Upper Limits to Mass of First Stars
Hosokawa et al, higher evap rate, less accretion



new M_* (max) ~ 43 $M_\odot$

IV. Discussion of New, Higher Photoevaporation Rates



$$\phi_i = \int_{r_i}^{r_s} \alpha_B \, n_e^2 \, 4\pi r^2 dr$$

if $\quad n_e = n_o \left(\frac{\phi_i}{10^{49} s^{-1}}\right)^{1/2} \left(\frac{r}{10^{15} cm}\right)^{-3/2}$

$$r_s = r_i \exp\left(\frac{10^4}{4\pi \, \alpha_B \, n_o^2}\right) \quad \text{(in cgs)}$$

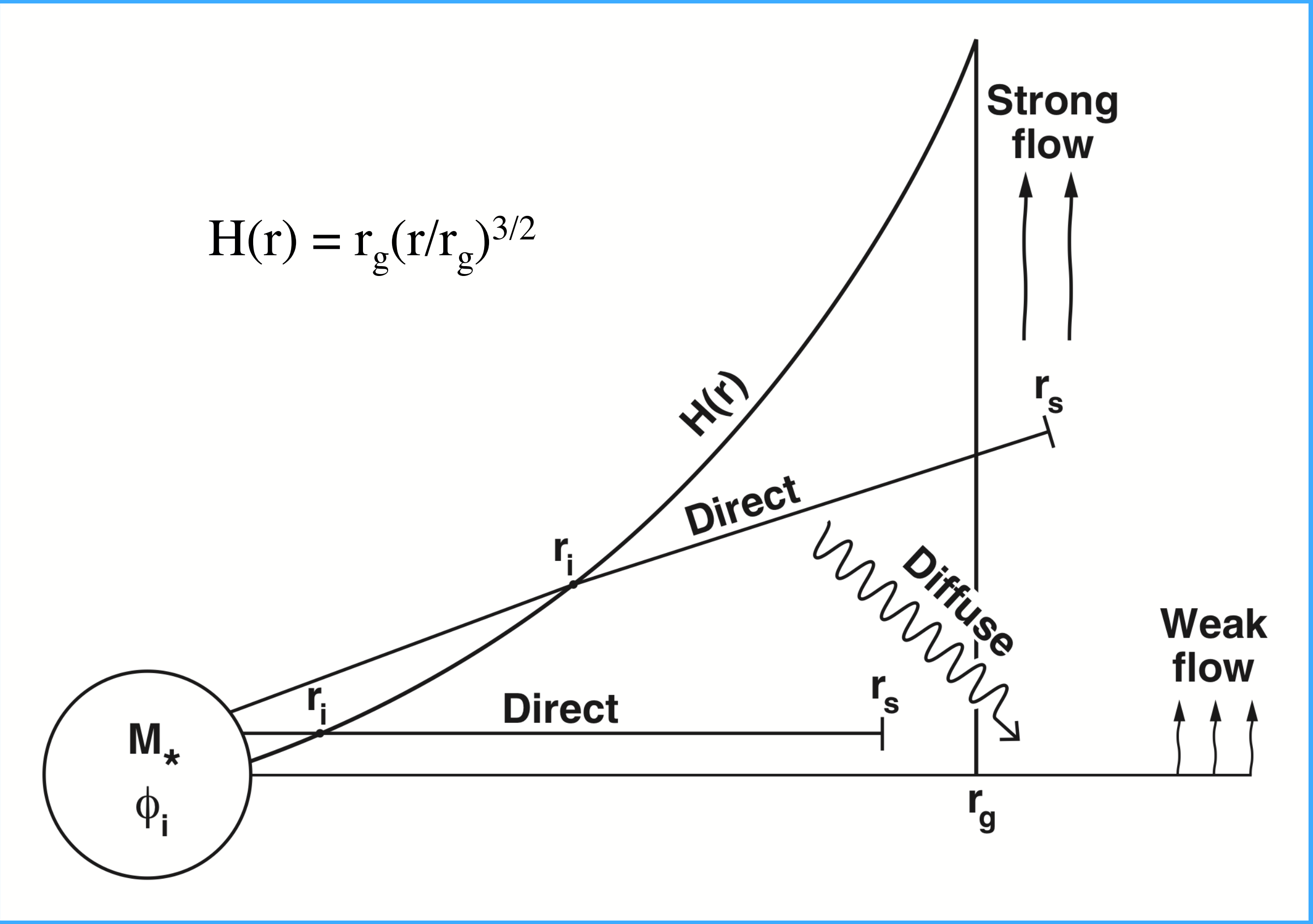
n_o(Tanaka) = 0.9 n_o(H94); exp(6.0) vs exp(4.7) !

r_s = 400 r_i > 800 AU Tanaka et al with r_i > 2 AU

> 4000 AU Hosokawa et al, r_i > 10 AU

r_s = 110 r_i = 44 AU H94 with r_i = 0.4 AU

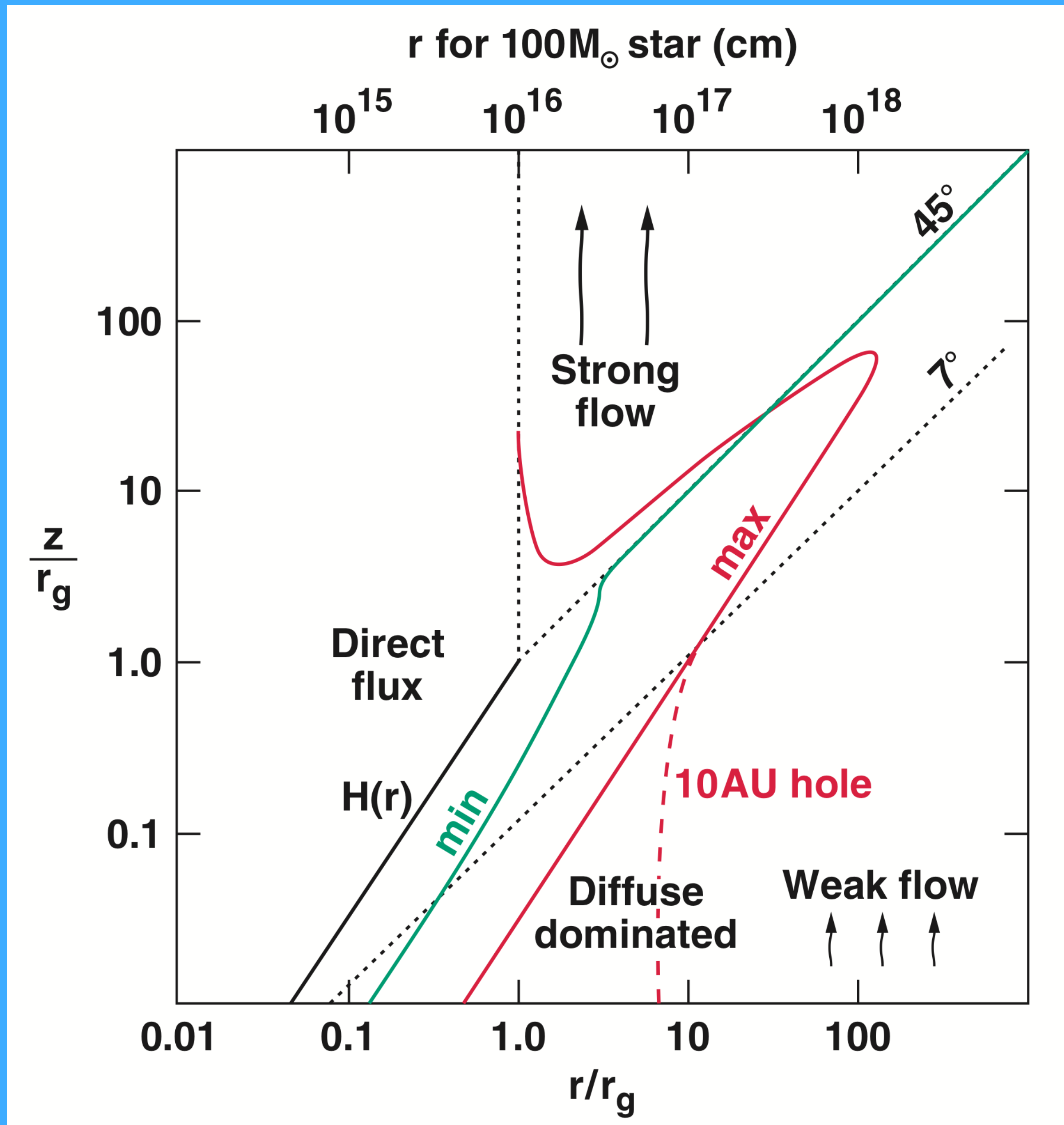
IV. Discussion of New, Higher Photoevaporation Rates



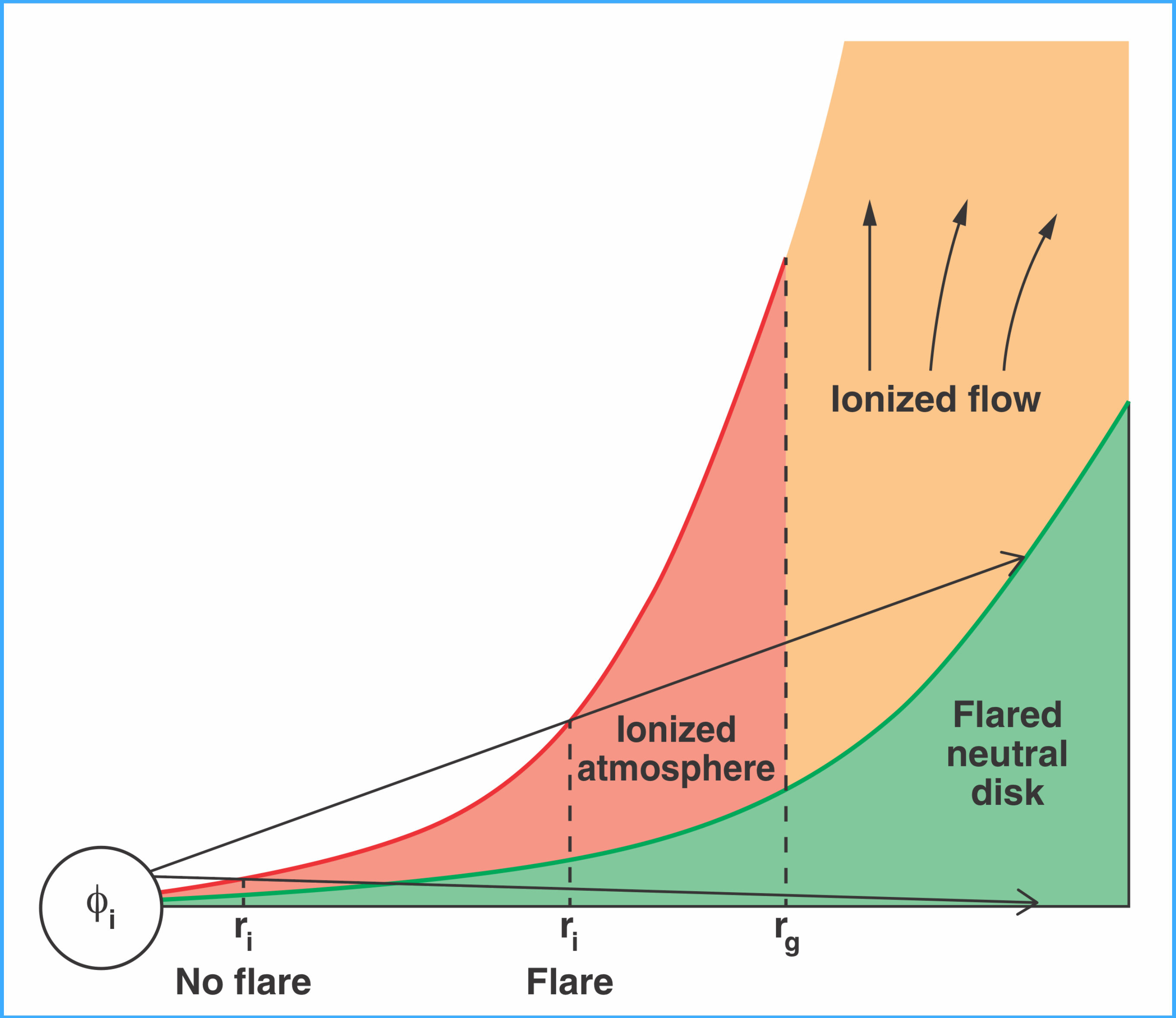
$n(r)\ \alpha\ r^{-3/2}$, and $n(z)$ constant to $z = H(r)$ for $r<r_g$

$n(z)$ constant to $z = r$ or r_d for $r>r_g$

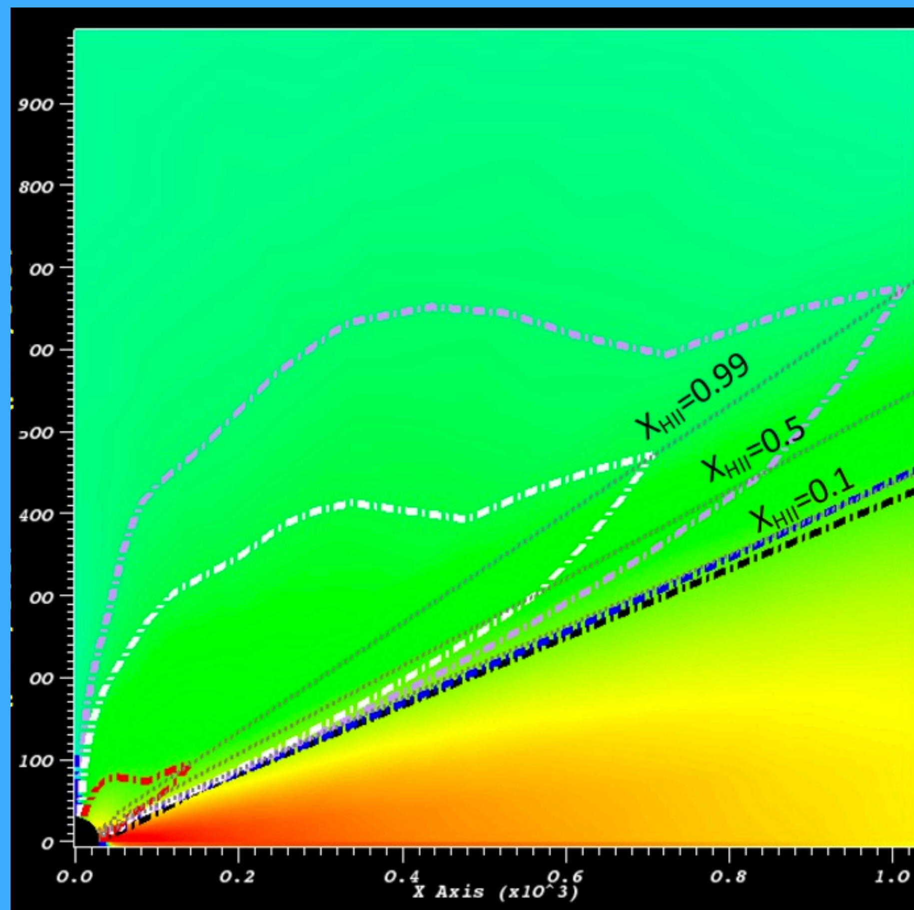
IV. Discussion of New, Higher Photoevaporation Rates



IV. Discussion of New, Higher Photoevaporation Rates



Hosokawa 2017, private communication



1000 AU

500 AU z

0 500 AU 1000 AU

r

V. Conclusions

1. Current models are likely overestimating the photoevaporative mass loss rates from disks around massive first stars, and underestimating the attenuation of EUV photons caused by the ionized atmosphere at $r < 2$-10 AU.

2. As a result, they may be underestimating the final mass of the first stars.

3. Further work needed with 2D radiation/hydro numerical models

   a. Better spatial resolution, especially at $r < 2$-10 AU and for regions just above the neutral disk surface.

   b. Explore the effects of the flaring of the neutral disk surface given the shadowing by the ionized atmosphere.

   c. Check whether the reversal of infall is the dominant process limiting stellar mass, and not photoevaporation from disk surface. Does shadowing protect the infall onto the disk?

December 2013