Stable Burning on Accreting White Dwarfs

(Shen & Bildsten '07, *accepted for publication in ApJ*)

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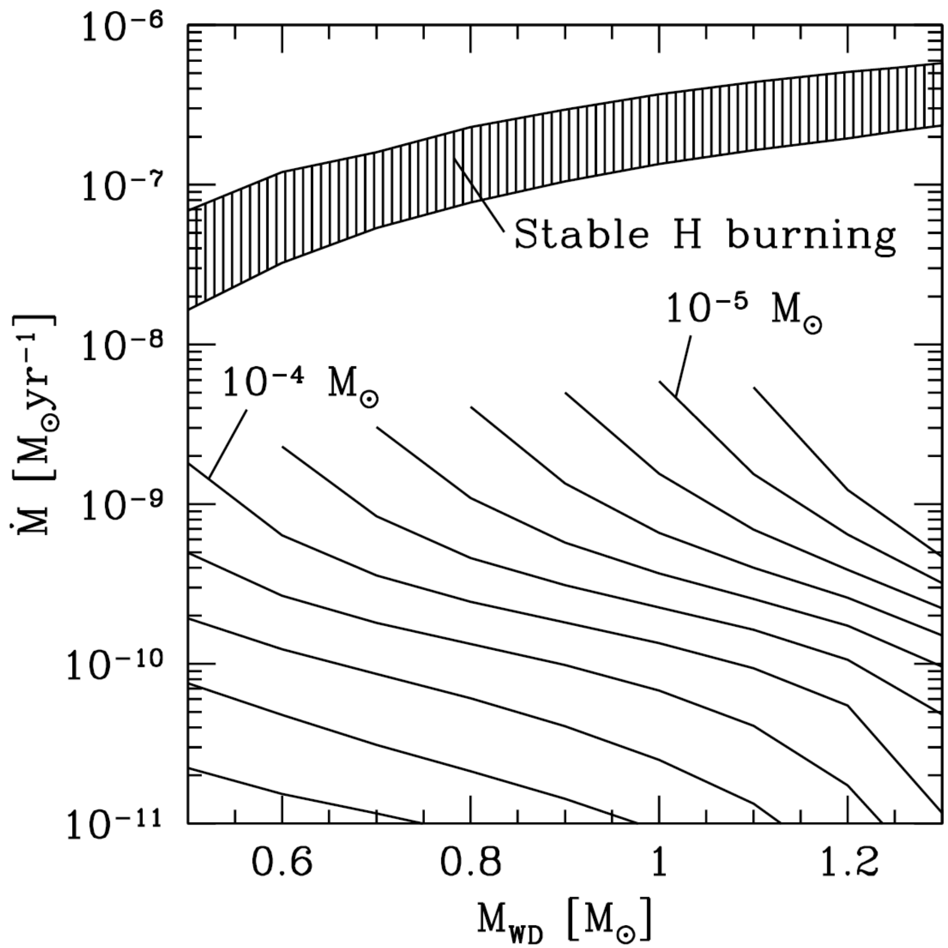
Motivation



(Nomoto et al. ‘06; Townsley & Bildsten ‘05)

- There have already been previous studies of accreting WD stability (Fujimoto ‘82; Paczynski ‘83; Nomoto et al. ‘06)
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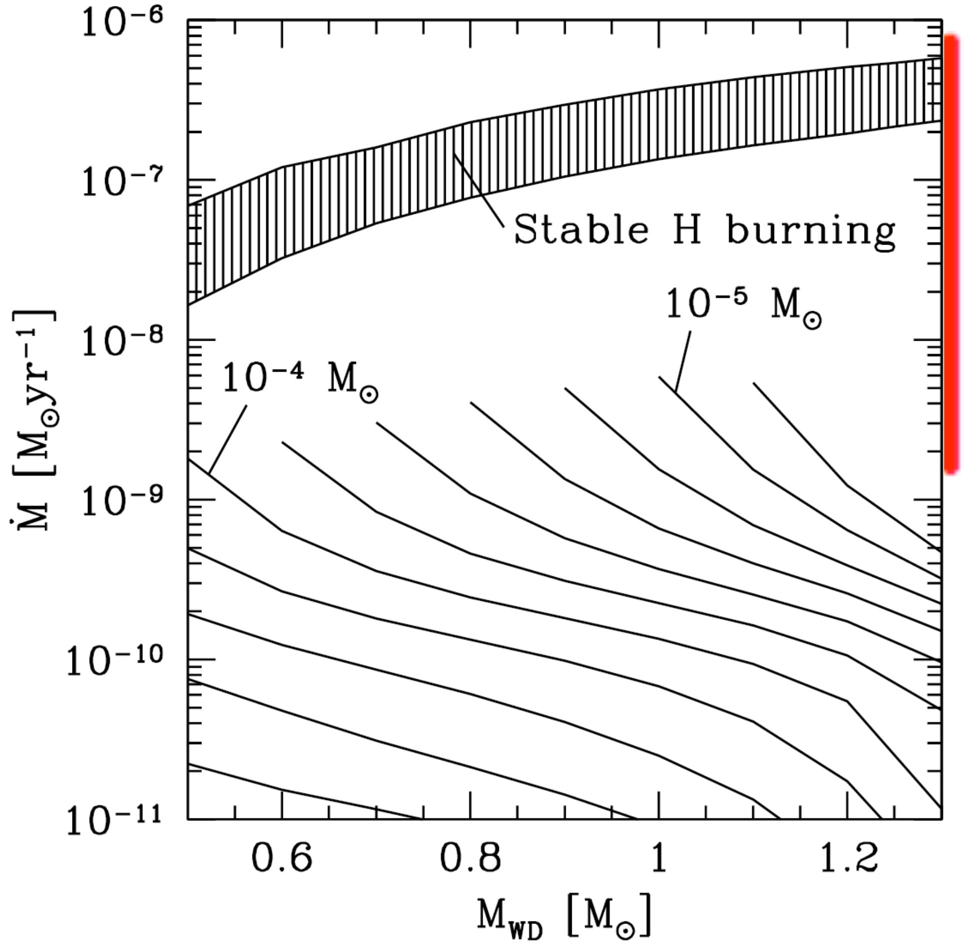

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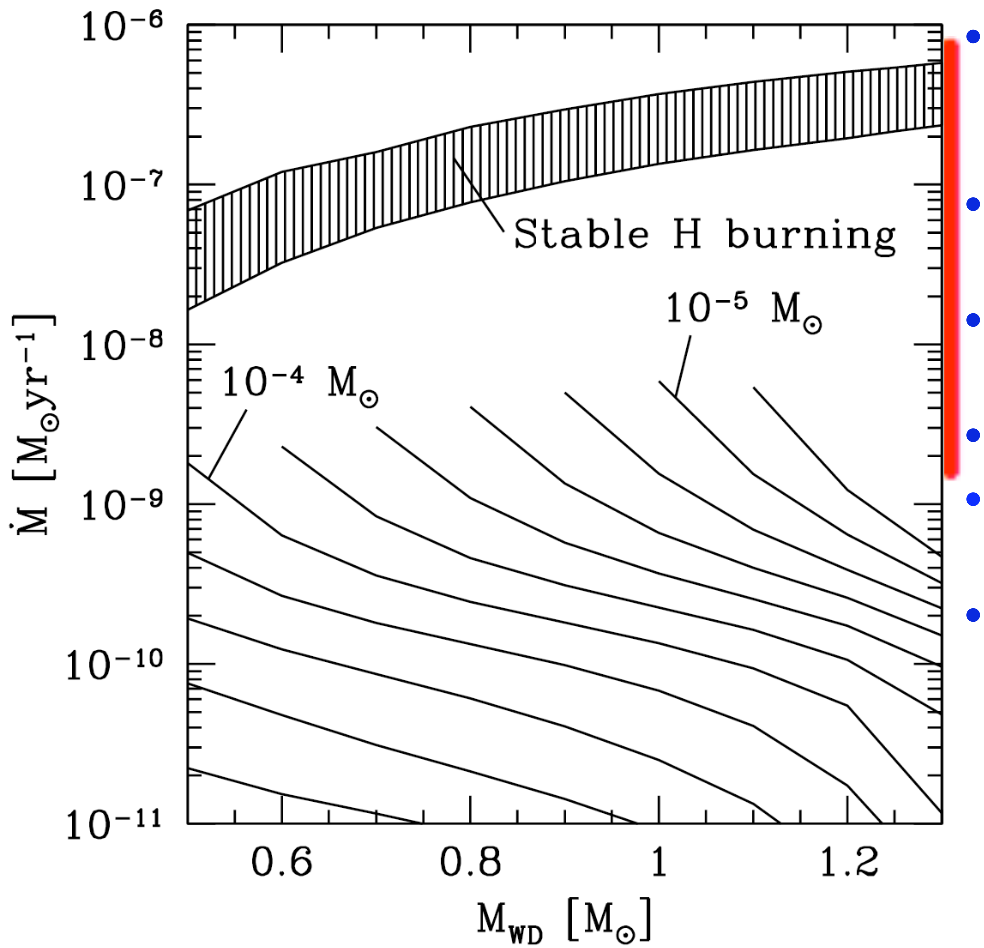

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- Hot WD? Full nuclear network?
- Supersoft X-ray sources (van den Heuvel et al. '92)
- Type Ia supernovae:
  - Likely progenitor system is white dwarf (WD) accreting from companion star until it reaches 1.4 $M_\odot$
  - Need to burn accreted material stably; otherwise material may be ejected due to thermonuclear runaway in the envelope (classical novae)
- Shell burning (H, He, etc.) occurs in post-main sequence stars

Generic stability analysis

- Assume steady-state (matter accreted and burned at the same rate)
- Solve for steady-state conditions given parameters:

$$X, Z, M, \dot{M}, L_{\rm b}$$

- Perturb entropy equation:

$$\begin{aligned} T\frac{ds}{dt} &= c_P\left(\frac{dT}{dt} - \nabla_{\rm ad}\frac{T}{P}\frac{dP}{dt}\right) \\ &= \epsilon - \frac{\partial L}{\partial M} \end{aligned}$$

- Stable if perturbation decays with time

Steady-state solutions

- In steady-state, time-derivatives are zero ($dT/dt = dP/dt = 0$), and burning equals cooling with burning determined by the accretion rate:

$$\epsilon = \frac{L - L_{\mathrm{b}}}{4\pi R^2}\frac{g}{P} \qquad L - L_{\mathrm{b}} = \dot{M} X E$$

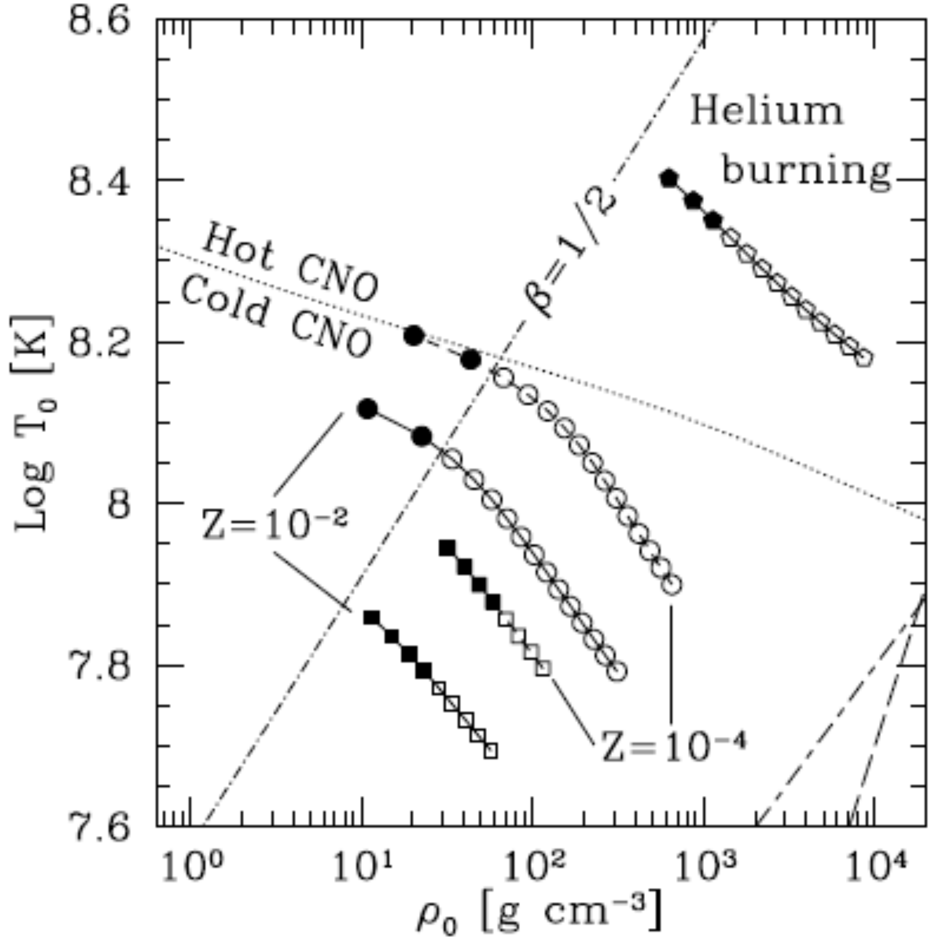
- X is the hydrogen mass fraction; E is the energy per mass from H → He
- With a form for the energy generation rate, luminosity (rad. diff.), equation of state (non-degenerate, include radiation pressure), and opacity (Thomson), we can solve for the steady-state burning conditions
- Heat transport by radiative diffusion:

$$L = \frac{4\pi G M c}{\kappa_{\mathrm{T}}}\frac{aT^4}{3P} \qquad 1 - \beta = \frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} + \frac{L_{\mathrm{b}}}{L_{\mathrm{Edd}}}$$

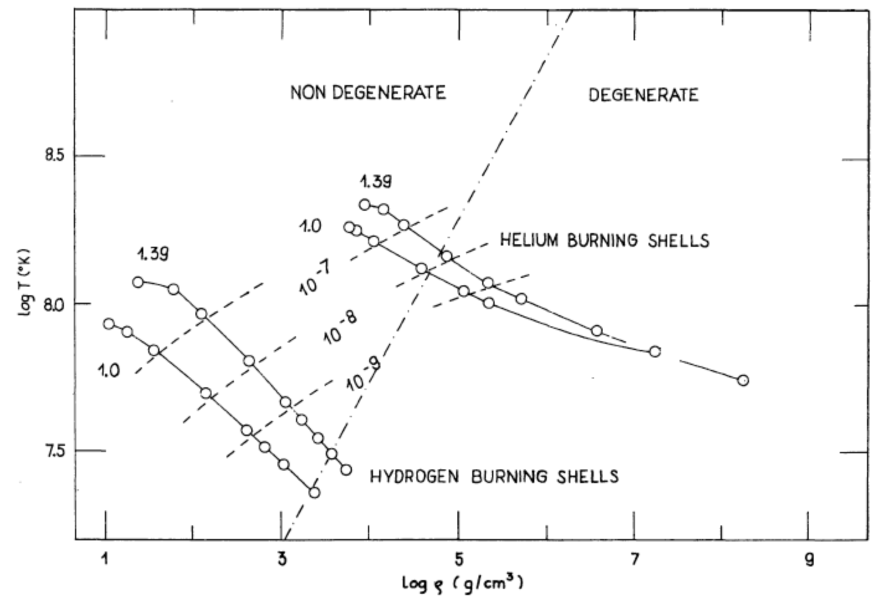
- Ratio of gas pressure to total pressure is $\beta = P_{\mathrm{gas}} / P$. Increase importance of radiation pressure by increasing accretion rate and core luminosity: Eddington standard model.

Steady-state solutions (cold CNO)

$^{12}C(p,\gamma)^{13}N(\beta^+,\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(\beta^+,\nu)^{15}N(p,\alpha)$



- Squares: 0.5 $M_\odot$; circles: 1.35 $M_\odot$
- Solutions are non-degenerate and Thomson opacity, so assumptions are self-consistent
- Cold CNO very T-sensitive ($\propto T^{10}$), so not much range in T
- Massive (ultra)-low metallicity WDs bump up into hot CNO limit; motivates later work



(Sienkiewicz '75)

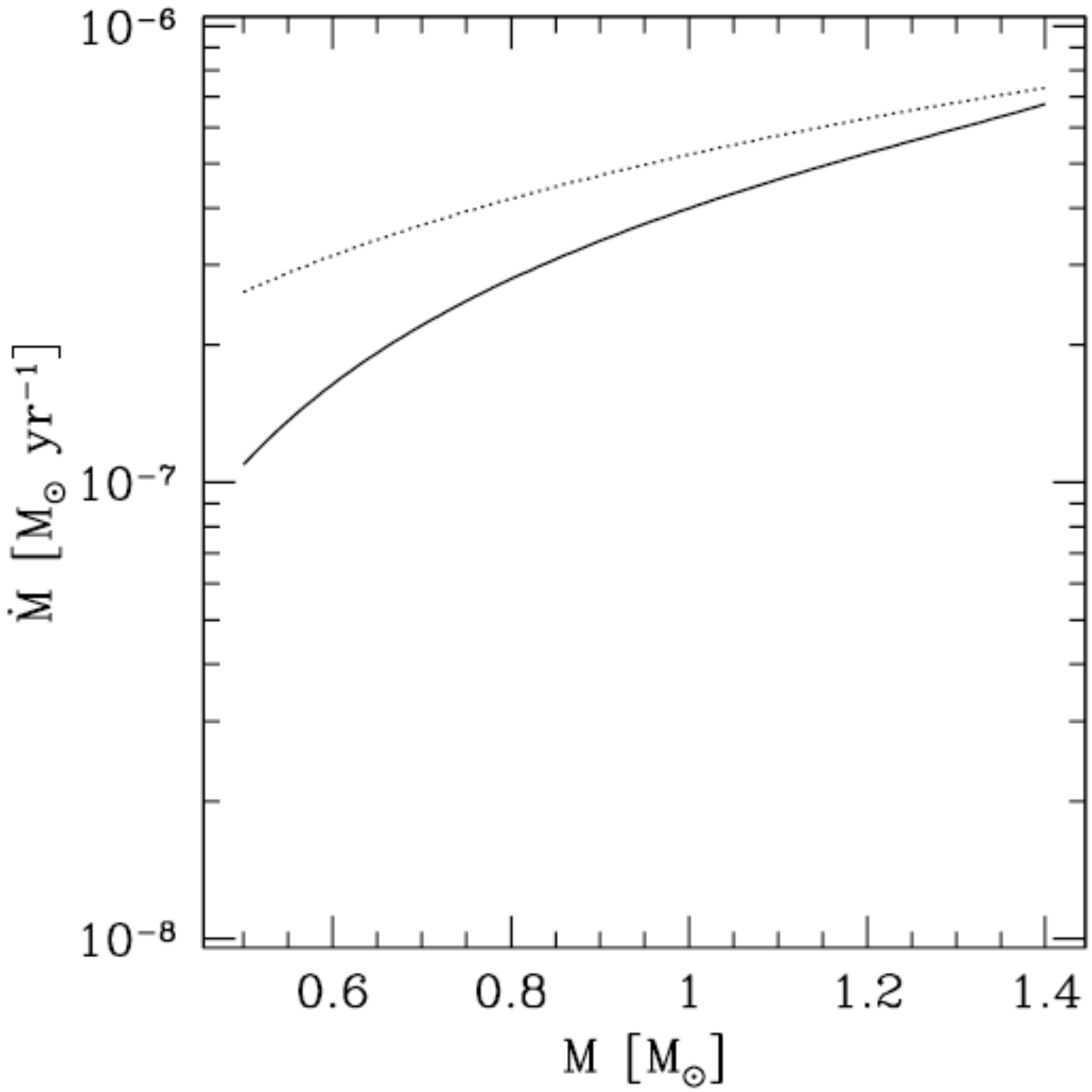
Relating $\delta\rho$ and δP to δT

- To calculate perturbation timescale, need to relate density and pressure perturbations to change in temperature
- Could do homologous expansion (e.g., Yoon et al. '04), but instead we integrate hydrostatic equilibrium (HSE) to obtain $M_{\rm env}$ and keep it fixed during perturbation
- Solving HSE yields upper bound on scale height:

$$4h < R_{\rm base} \qquad h = \frac{P}{\rho g} = \frac{k_{\rm B}T}{\beta \mu m_{\rm p} g}$$

- In other words, β can't go to zero; there is a sub-Eddington upper limit to the accretion rate, above which no steady-state HSE solutions exist. Essentially the standard RG L-$M_{\rm core}$ relationship (Paczynski '70), modulo additional He-burning.

HSE constraint



- Dotted line: nuclear Eddington limit
- Solid line: HSE constraint

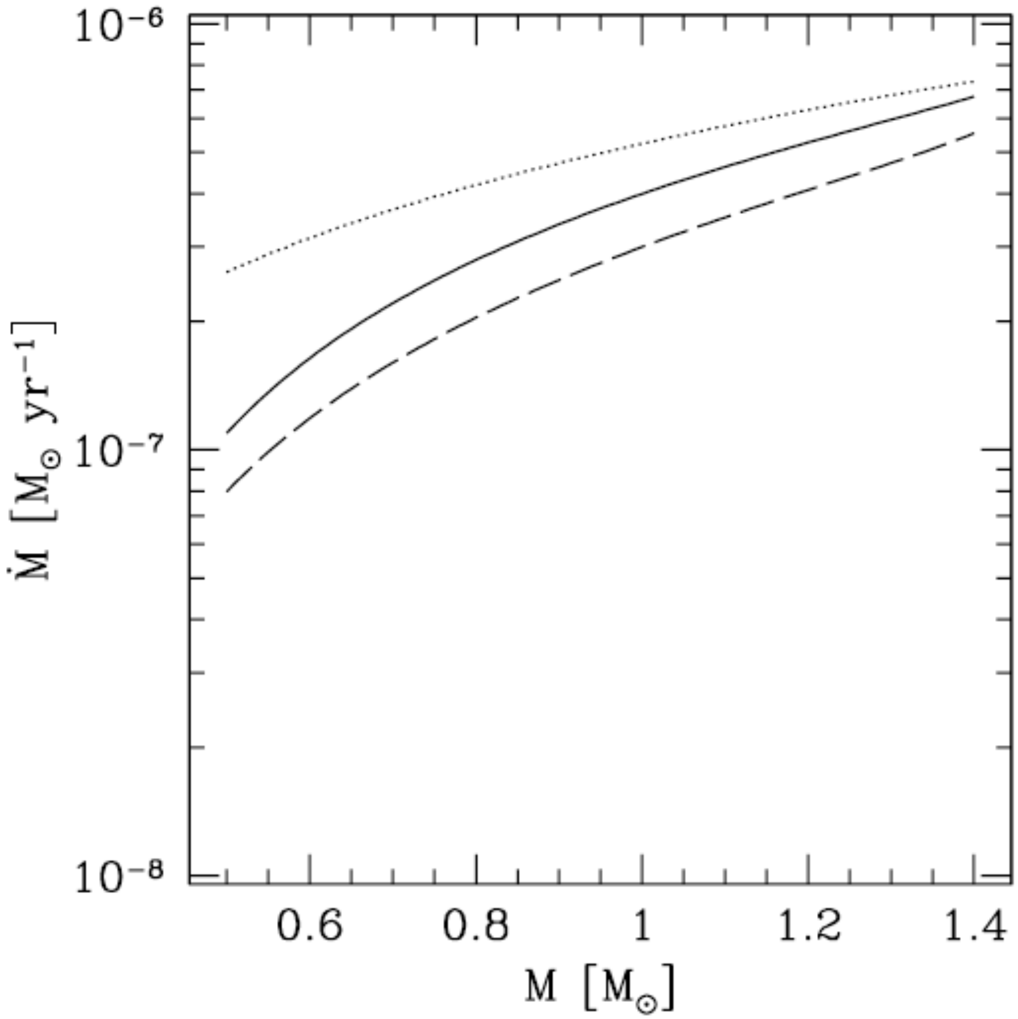
2 channels for stability: Thick shell case (higher Mdot)

- Negative gravothermal specific heat, c_*:

$$
\begin{aligned}
T\delta s &= \delta u - \frac{P}{\rho}\delta \ln \rho \\
&= c_* \delta T
\end{aligned}
$$

- Injection of heat causes an even larger amount of expansion work to be done, so internal energy and T drop
- This is what stars as a whole do; they contract, radiate energy away, and T increases: $c_* < 0$ so they're stable (the ultimate thick shell!)
- Independent of burning/cooling mechanism (aside from setting steady-state solution)

2 channels for stability: Thick shell case (higher Mdot)



- Dotted: nuclear Eddington limit
- Upper solid line: HSE constraint
- Long-dashed line: c_* switches signs

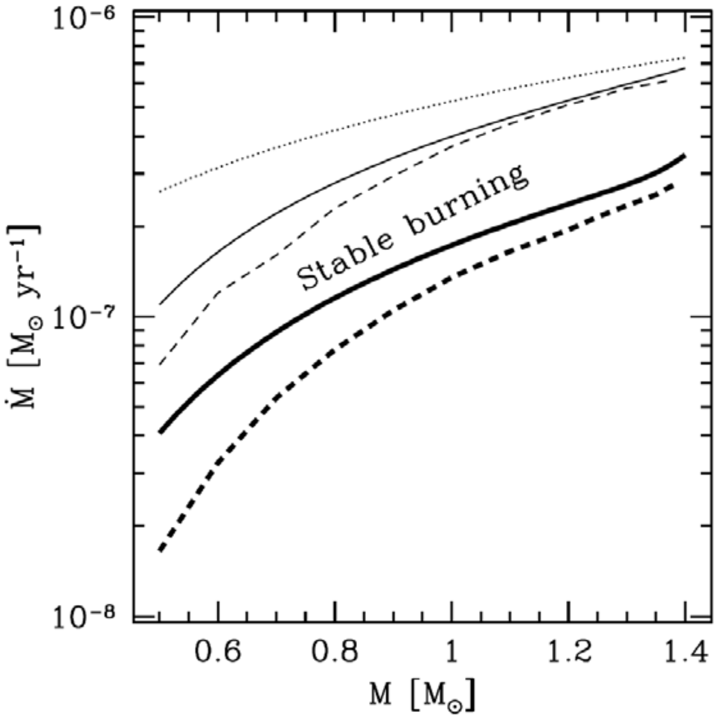
2 channels for stability: Thin shell case (lower Mdot)

- Competition between heating and cooling
- To zeroth order, stable if T-dependence of heating is lower than 4 ($L \propto T^4$)
- Also need to put in the effect of ρ and P perturbations, which help to stabilize, especially if radiation pressure is high:

$$P = \frac{\rho k_{\rm B} T}{\mu m_p} + \frac{1}{3} a T^4$$

  - Consider density change at constant pressure. If radiation pressure dominated, small increase in T yields large decrease in ρ; quenches burning even in extremely thin shell limit
  - Inclusion of drop in P makes this even more dramatic

Thermally stable Mdot's (cold CNO)

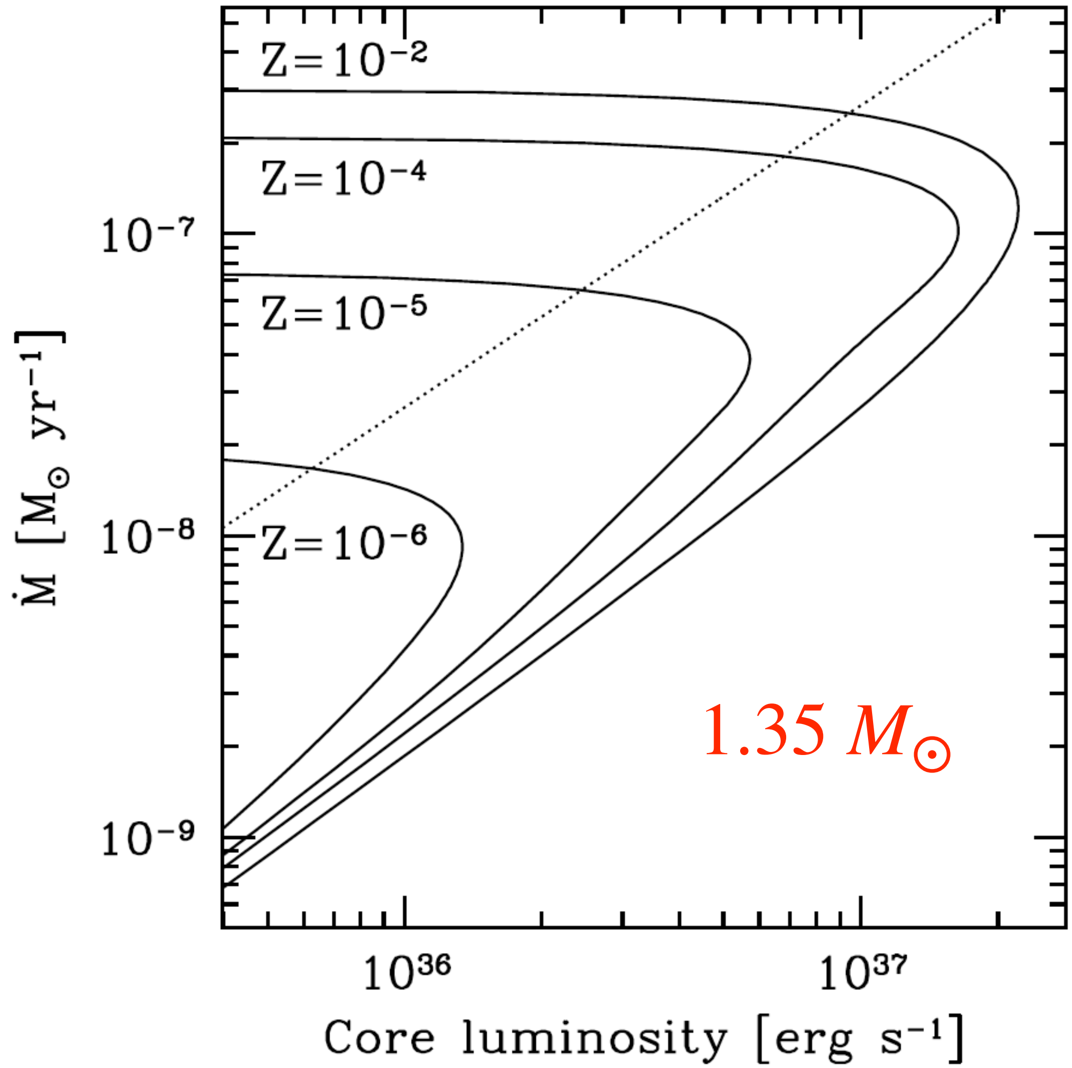


- Dotted: nuclear Eddington limit
- Upper solid line: HSE constraint
- Bottom solid line: thin shell stability
- Dashed lines: numerical work (Nomoto et al. 2006)
- Factor of 3 between min and max Mdot's
- Why a factor of 3? Can calculate ratio of max and min Mdot's, assuming burning α T^{10} and T constant over accretion range (remember steady-state plot?), to get:

$$\frac{\dot{M}_{\rm max}}{\dot{M}_{\rm min}} = 2.9\left[1 + O\left(\beta_{\rm min} - \frac{3}{4}\right)\right]$$

- Ratio not very dependent on T exponent: pre-factor ~3 for $T^{9\text{-}12}$

Flux stabilization

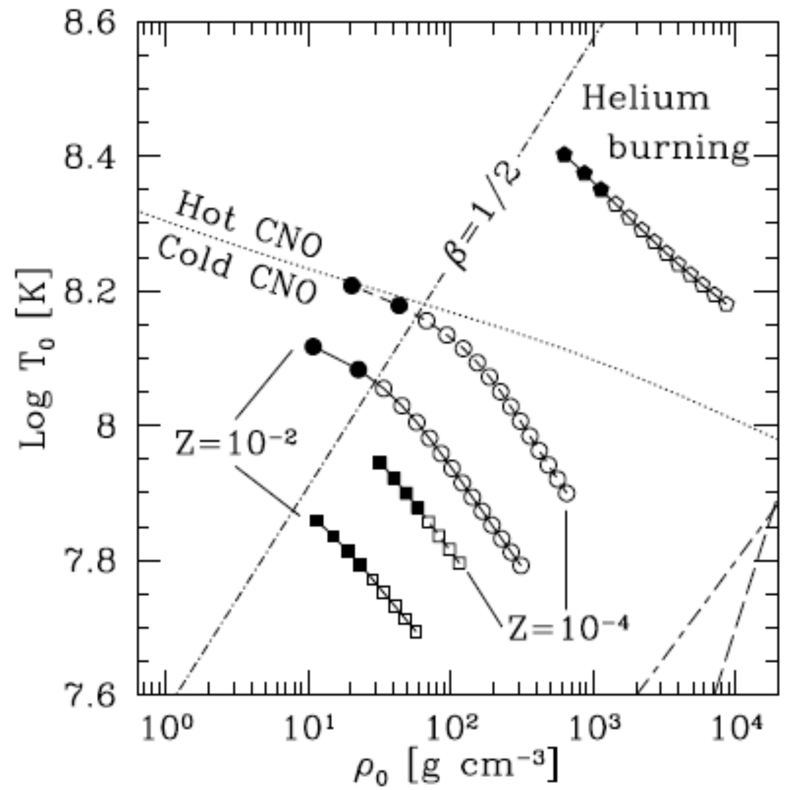


- So far, I've assumed negligible core luminosity
- Take limiting case of ultra-high L_{core}; then conditions in envelope are set purely by this, so it's always stable
- But can't have arbitrarily high L_{core} for duration of accretion; max possible is from steady burning of He layer below (*dotted line*), which doesn't open up much parameter space

Hot CNO stabilization

$$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\mathrm{p},\gamma)^{14}\mathrm{O}(\beta^+,\nu)^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}(\beta^+,\nu)^{15}\mathrm{N}(\mathrm{p},\alpha)$$

- If the layer is really hot/dense, proton captures occur faster than the T-independent β-decays. Rate-limiting steps are the two β-decays, and H-burning is stable (like on NSs).
- So what do we have to do to get the β-decays to matter? Increase g and decrease Z_{CNO} (which result in hotter/denser conditions).
- To test stability, same procedure as before: solve for steady-state solutions; calculate T- and ρ-dependences of burning in equil. (fun exercise in algebra and pre-calc!); see if perturbation decays or grows.



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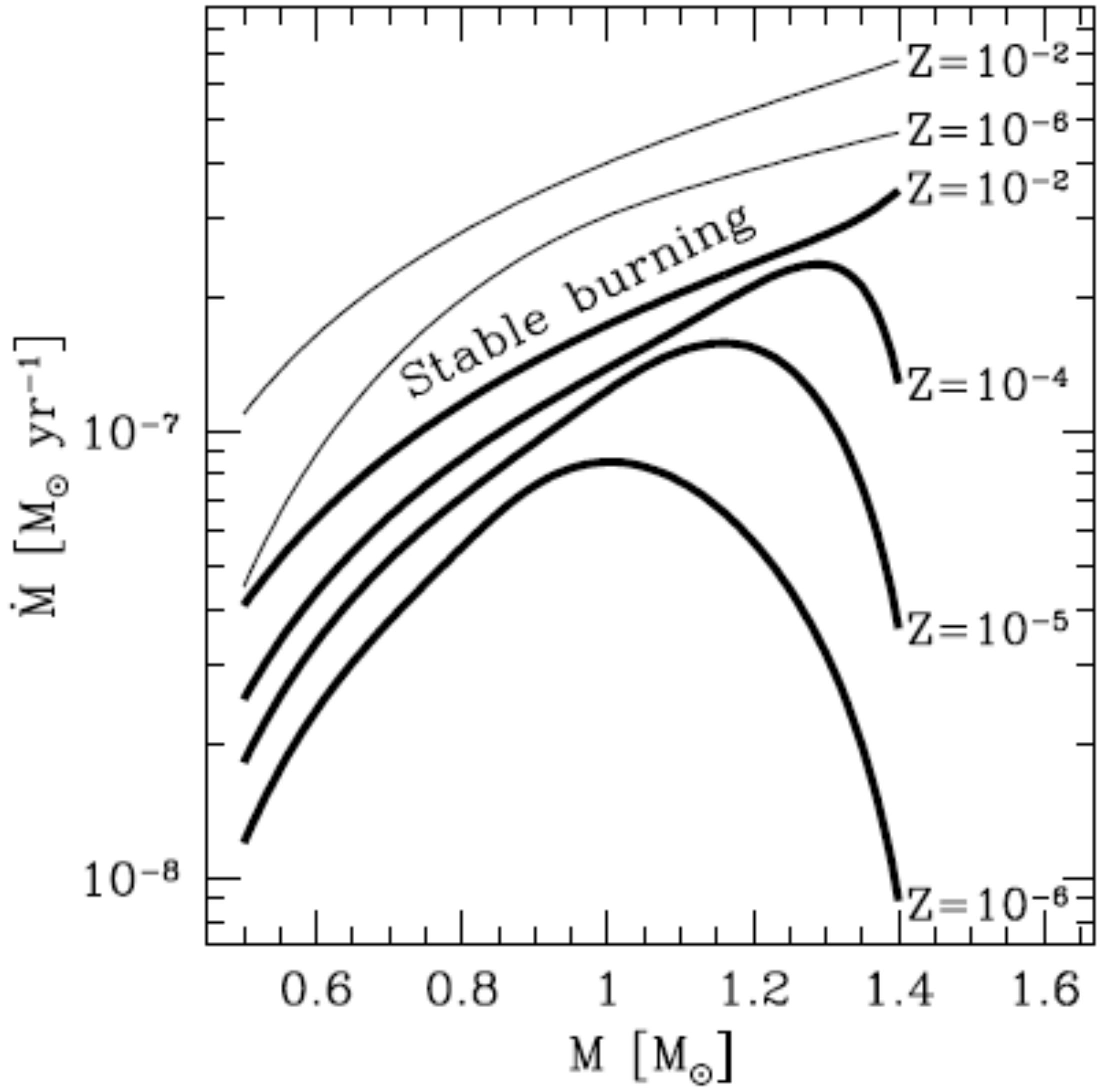
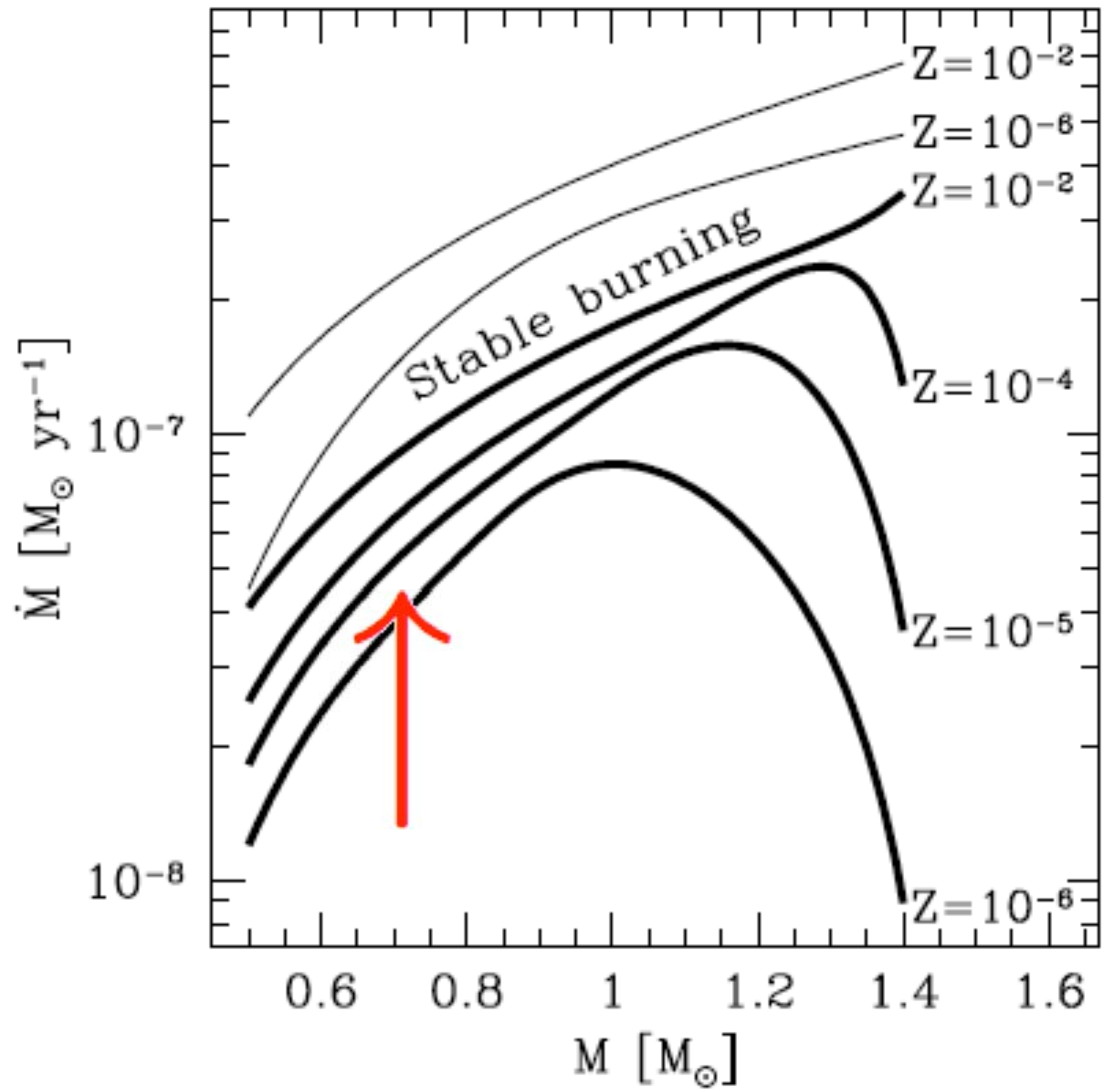


Thermally stable Mdot's (full CNO)

- Low masses, still burning via cold CNO. Lower stable Mdot's because lower Z_{CNO} means higher T and weaker T-dependence of cold CNO burning. Ratio of min and max Mdot's still ~3.



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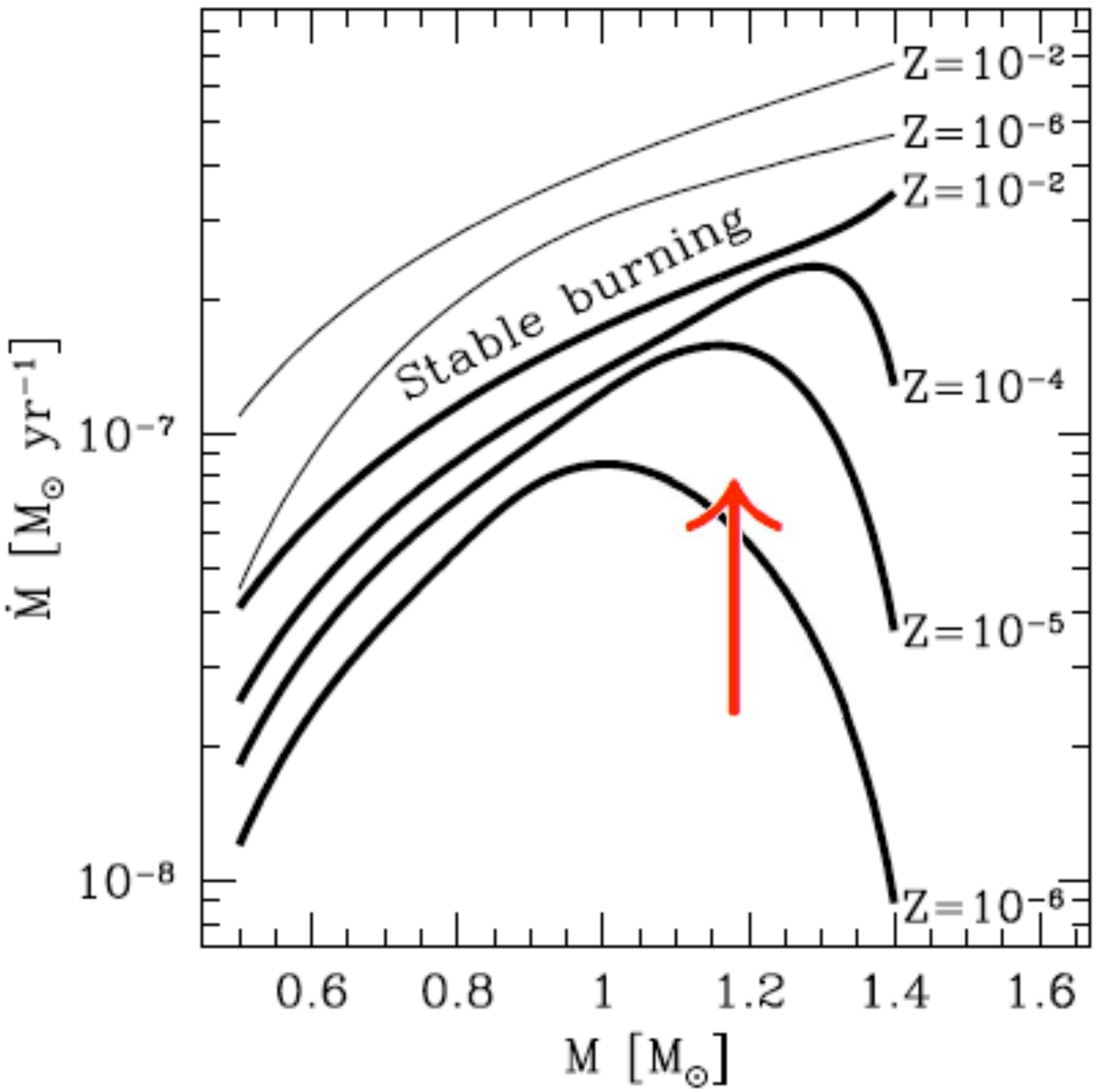

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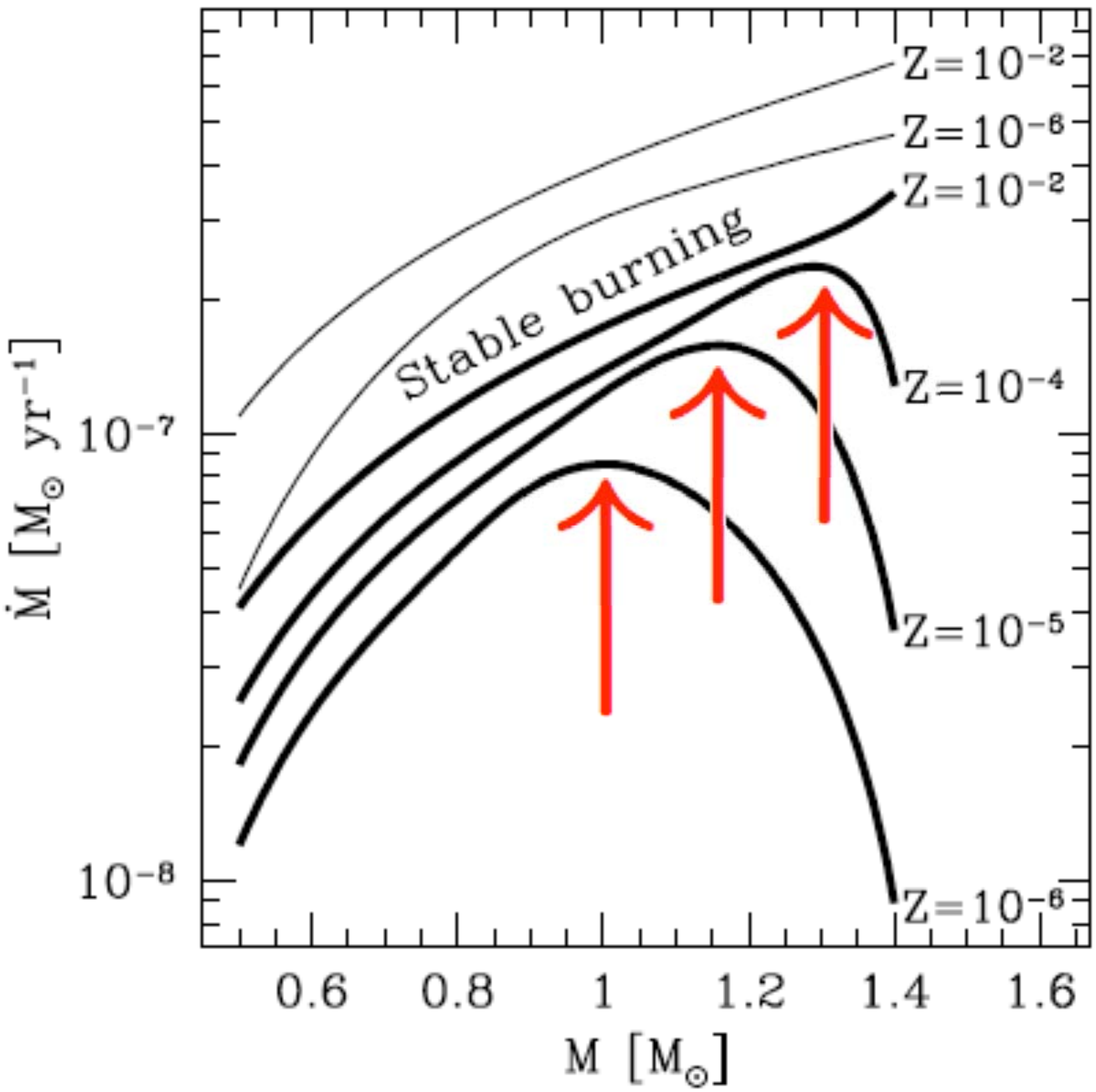
- The lower Z is, the lower the mass that hot CNO starts to matter



Conclusions

- Thermally stable accretion rate range on WDs is narrow:
  - Upper bound from HSE constraint
  - Thick shell stability for higher Mdot's is due to negative gravothermal specific heat
  - Thin shell stability for lower Mdot's is due to competition between heating and cooling (radiation pressure is important!)
  - Yields factor of ~3 in accretion rate range
- Core luminosity can stabilize, but need a LOT of it
- Hot CNO can stabilize, but need VERY low metallicity (or high gravity)

- Will post on astro-ph this afternoon
- Many thanks to Lars Bildsten and Tony Piro