Classical Novae as a Probe of Cataclysmic Variables

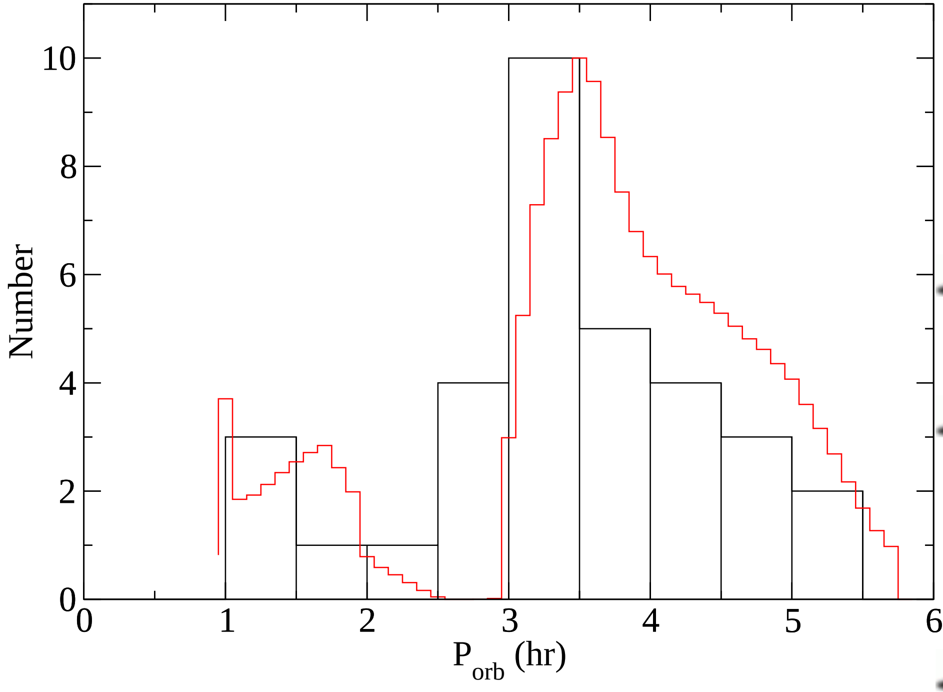
Dean Townsley

JINA, The University of Chicago

(Work performed with Lars Bildsten, U.C. Santa Barbara)

Classical Novae and the CV population

What can we learn about the CV population from the $P_{\rm orb}$ distribution of observed Classical Novae?



Data from Ritter & Kolb 2005 (RKcat7.4)

Theory from Townsley & Bildsten 2005, ApJ, in press

Reproduced using the interrupted magnetic braking for $P_{\rm orb} \rightarrow \langle \dot{M} \rangle$ and self-consistent (with respect to $T_{\rm core}$) $M_{\rm ign}$ calculations.

- Unique test of $P_{\rm orb} \rightarrow \langle \dot{M} \rangle$ predictions of binary evolution models
- We must correctly explain this distribution in order to map

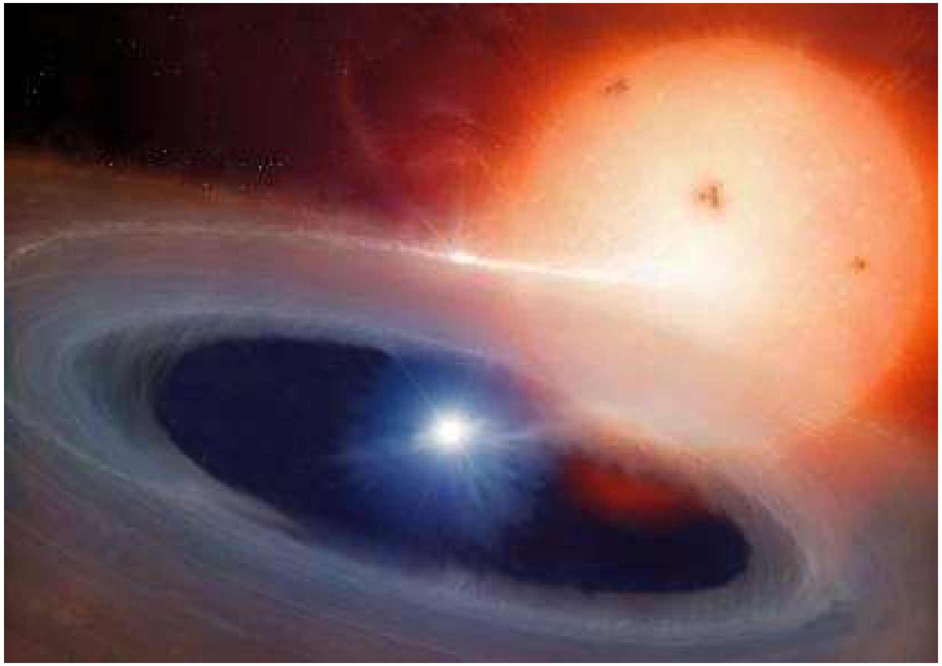
  (CN rate) $\leftrightarrow$ (total # CVs)

- Can also be used to infer CV birthrate in a given stellar population

In this talk:

- Reheating the WD core
- Equilibrium T_c and predicted $M_{\rm ign}$
- The interrupted magnetic braking scenario
- Results: what this means for CN modeling – $\langle \dot{M} \rangle$ distribution

CV WD Environment



Timescales of Classical Novae:
Outburst last < 10 years
Recurrence time 10^4 – 10^7 years

Recurrence time sensitive to $\langle \dot{M} \rangle$ due to both direct dependence and determination of $M_{\rm ign}$.

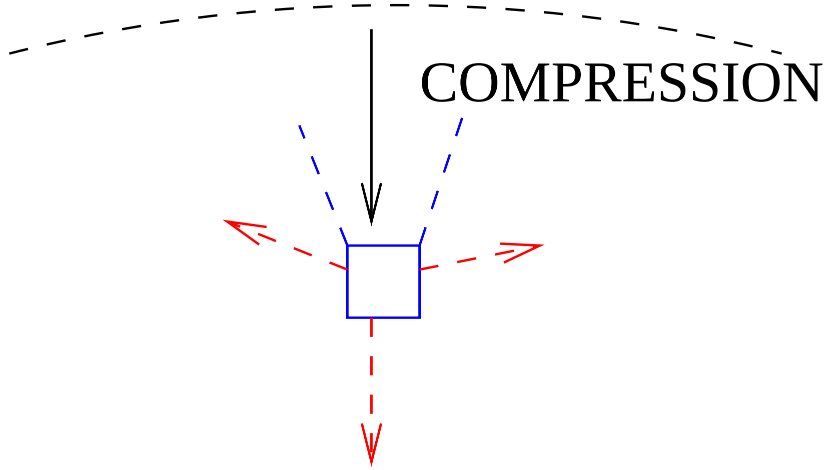
$$\tau_{\rm CN} = \frac{\langle \dot{M} \rangle}{M_{\rm ign}}$$

Using $\langle \dot{M} \rangle$ – The time averaged accretion rate – we calculated

$$M, \langle \dot{M} \rangle \quad \rightarrow \quad T_{\rm eff}, T_{\rm core}, M_{\rm ign}$$

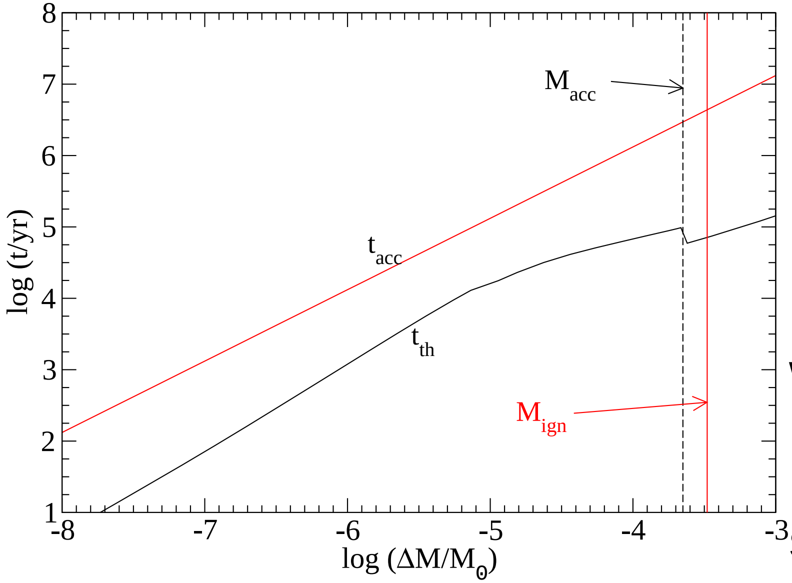
This connects the WD evolution to that of the binary.

Gravitational Energy Release



(very) leaky entropy advection

$$t_{\rm th} \equiv \frac{c_P T}{\left(\frac{4acT^4}{3\kappa y^2}\right)} \quad < \quad t_{\rm acc} \equiv \frac{\Delta M}{\langle \dot{M} \rangle}$$



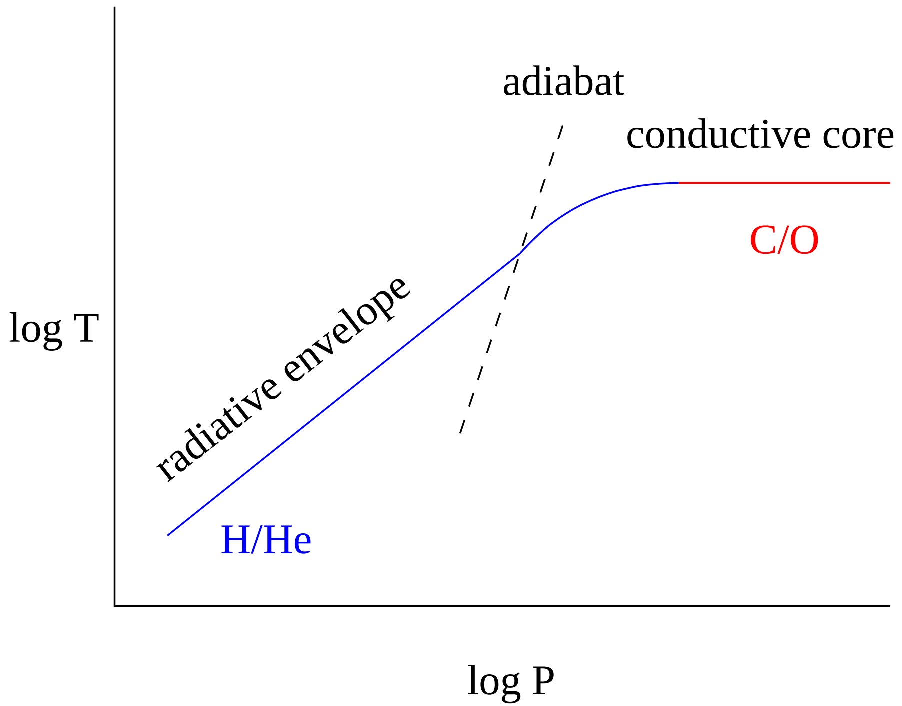
$\langle \dot{M} \rangle = 7 \times 10^{-11} M_\odot$ yr^{-1},
$T_c = T_{c,\rm eq} = 6 \times 10^6$ K

where $y = \Delta M / 4\pi R^2$ is the column depth.

Heat liberated by compression is transferred out to surface and in to core

often called “compressional heating”

Quasi-static Model



0 static

Heat equation near surface:

$$T\frac{Ds}{Dt} = T\frac{\partial s}{\partial t} + T v_r \frac{\partial s}{\partial r} = -\frac{dL}{dM_r} + \epsilon_N$$

where $v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho$. Solve with and structure equations

$$L = -4\pi r^2 \frac{ac}{3\kappa\rho}\frac{d(T^4)}{dr}, \qquad \frac{dP}{dr} = -\rho g$$

For each $\langle \dot{M} \rangle$ and $M_{\rm acc}$ this gives a map $L_{\rm surf} \to T_{\rm core}, L_{\rm core}$ or $T_c \to L_{\rm surf}, L_{\rm core}$.

Envelope Dominates

$$\frac{\langle \dot{M} \rangle}{4\pi r^2 \rho} T \frac{\partial s}{\partial r} = \frac{dL}{dM_r} + \epsilon_N$$

Without ϵ_N, $dr = g\rho dP$

$$L = -\langle \dot{M} \rangle \int_0^P T \frac{\partial s}{\partial P} dP$$

Simple integration to $M_{\rm acc} \sim 10^{-3} M_\odot$

$$L_{\rm H/He} \approx 2.5 \frac{kT_c}{\mu m_p} \langle \dot{M} \rangle \qquad L_{\rm C/O} \approx 16 \frac{kT_c}{\mu_i m_p} \langle \dot{M} \rangle$$

$\mu =$ mean molecular weight

with $\mu \simeq 0.6$ and $\mu_i \simeq 14$

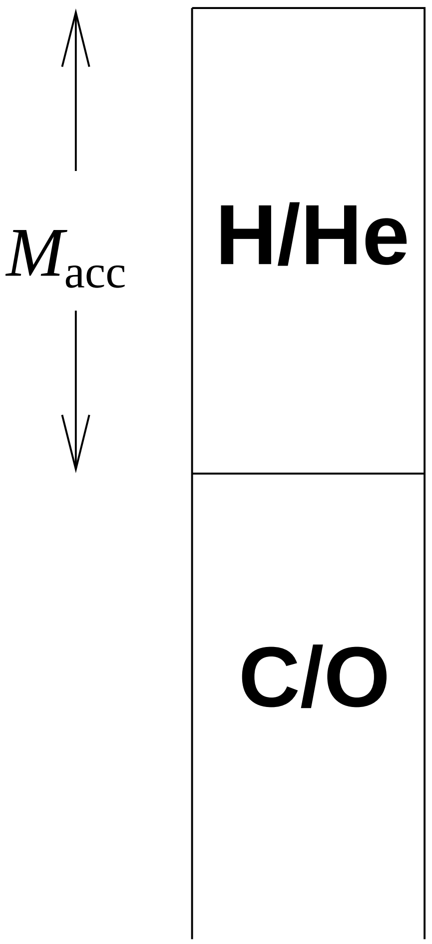
$$\frac{L_{\rm H/He}}{L_{\rm C/O}} \simeq 4$$

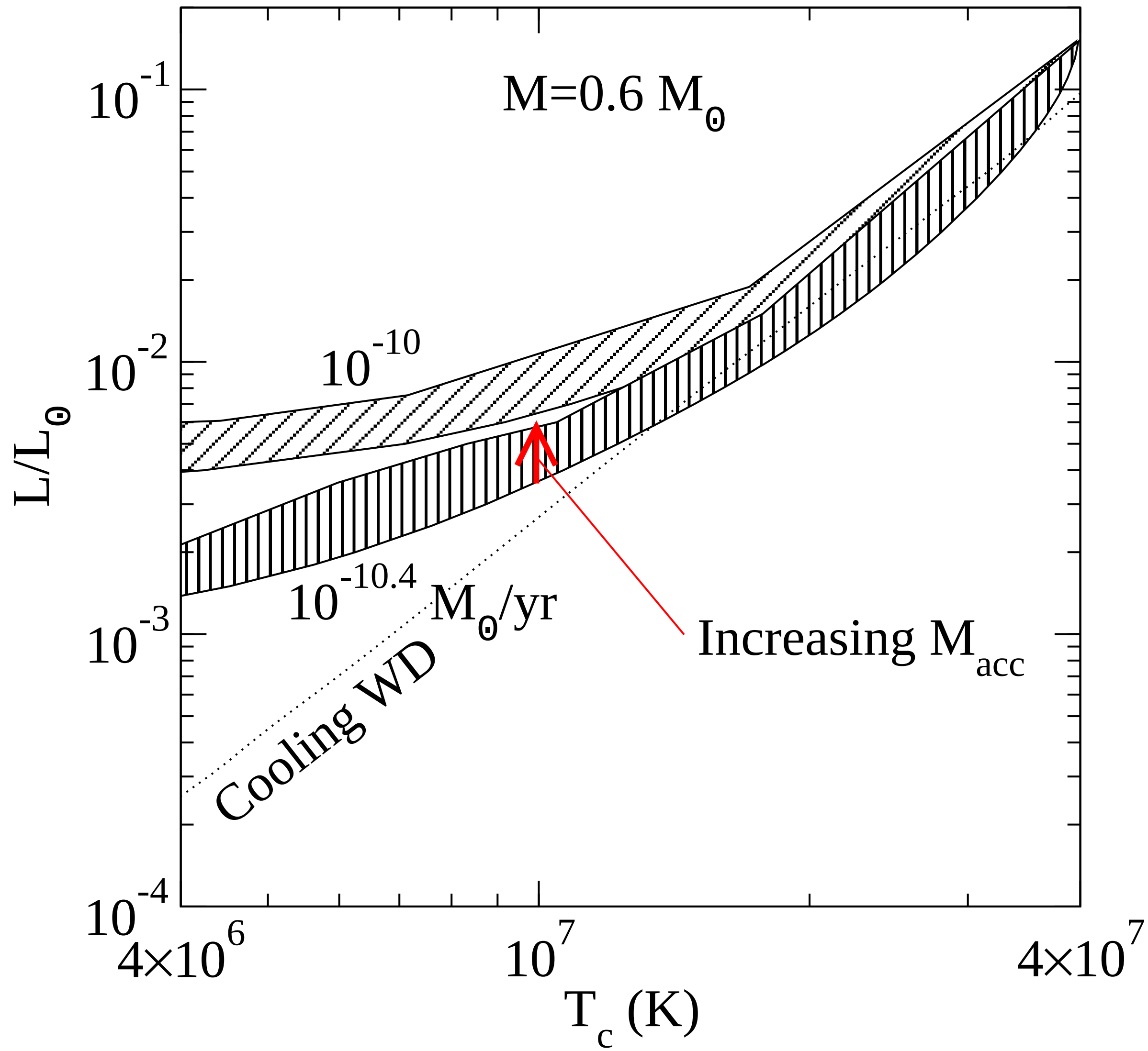
Note

$$\frac{kT}{\mu m_p} \langle \dot{M} \rangle \approx gh \langle \dot{M} \rangle$$

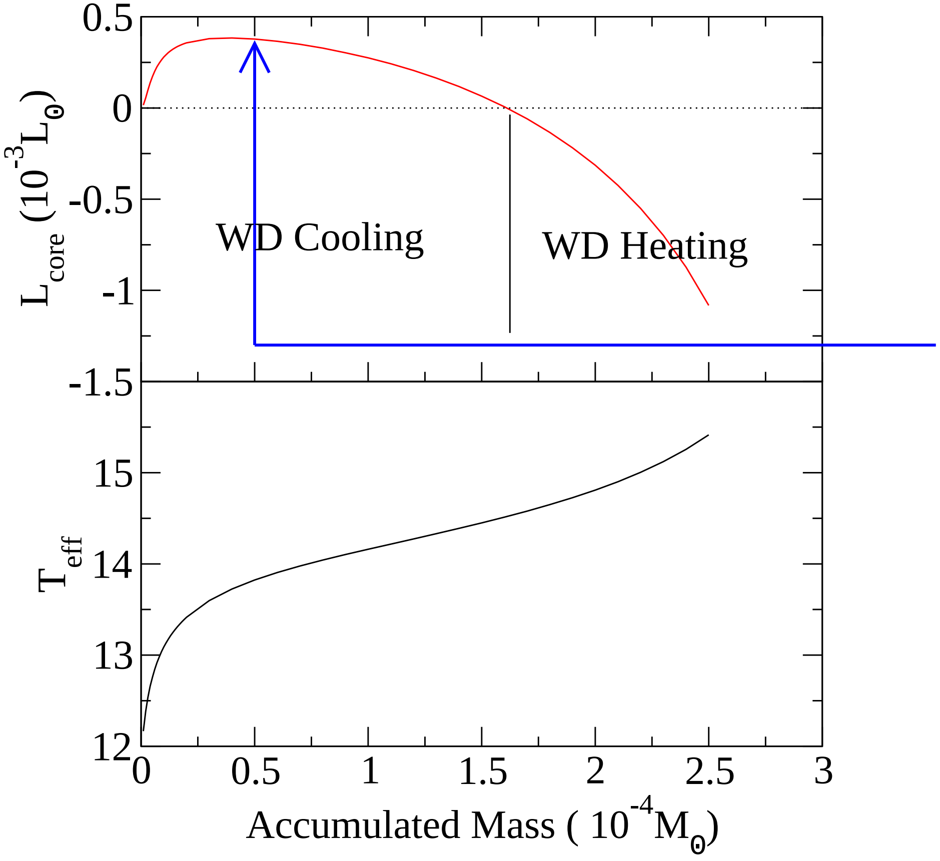
where $h = P/\rho g$ is the pressure scale height.

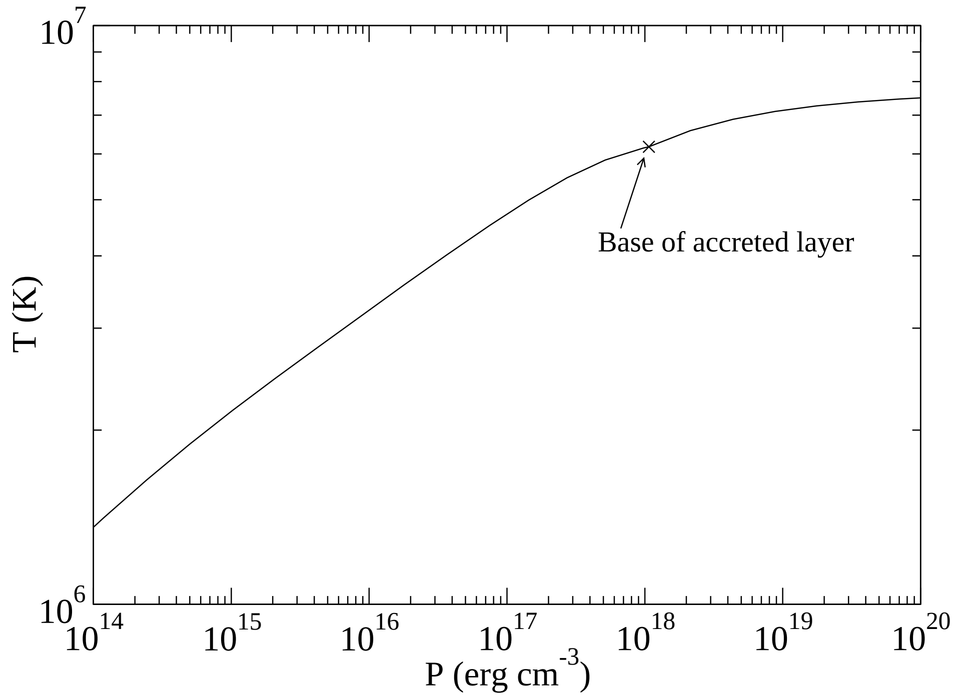
L dependence on T_c





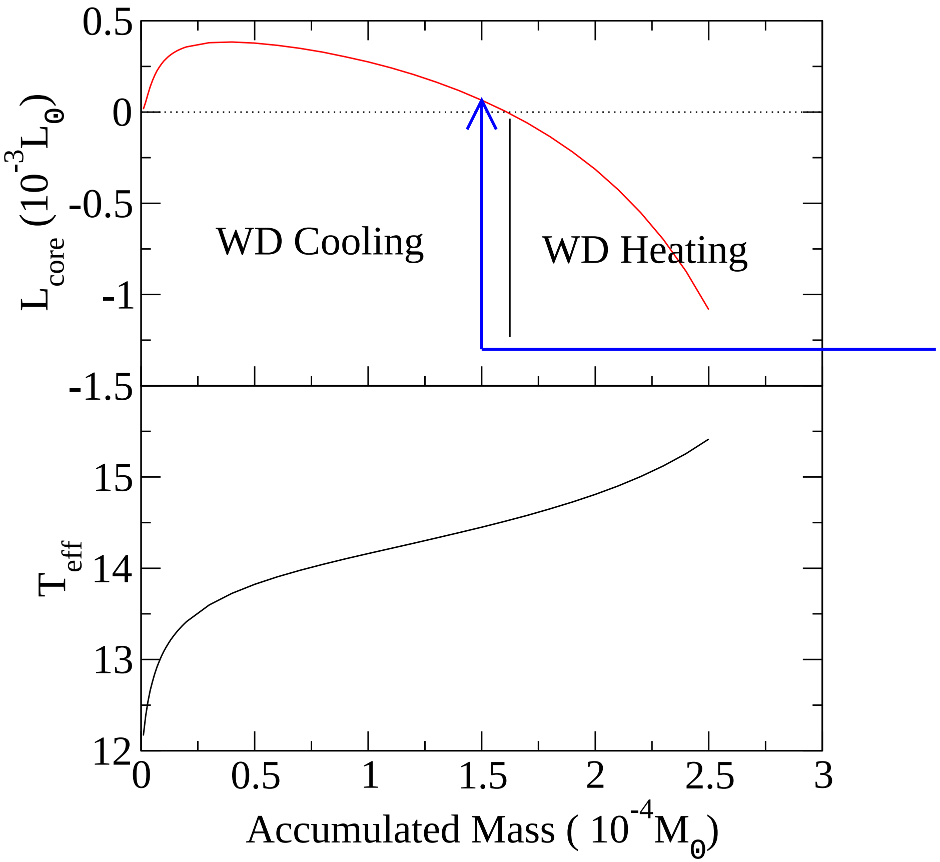
Cooling-Heating Cycle

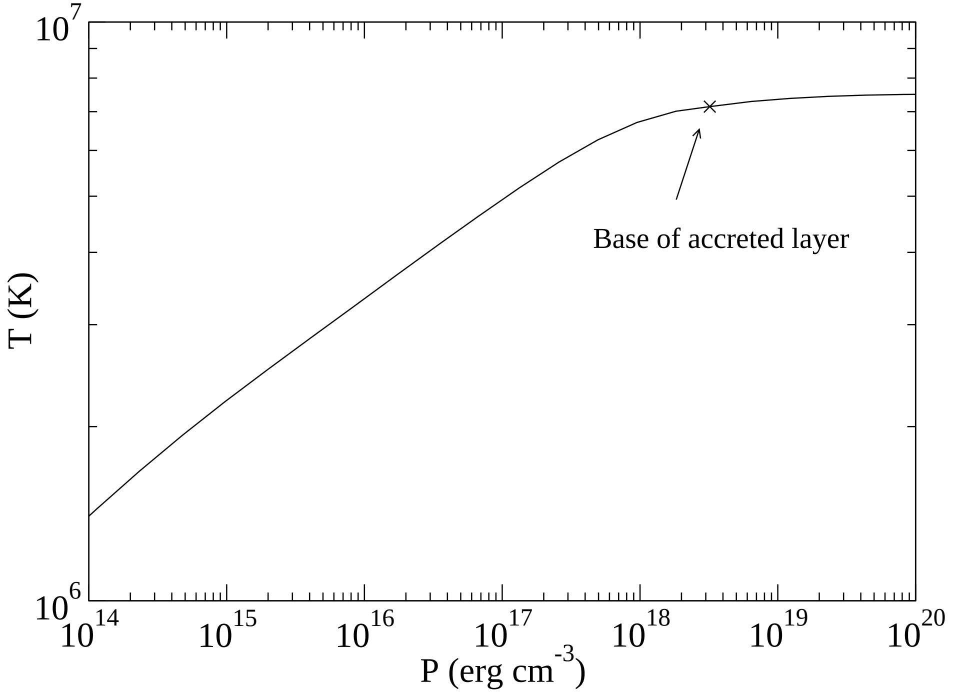




- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

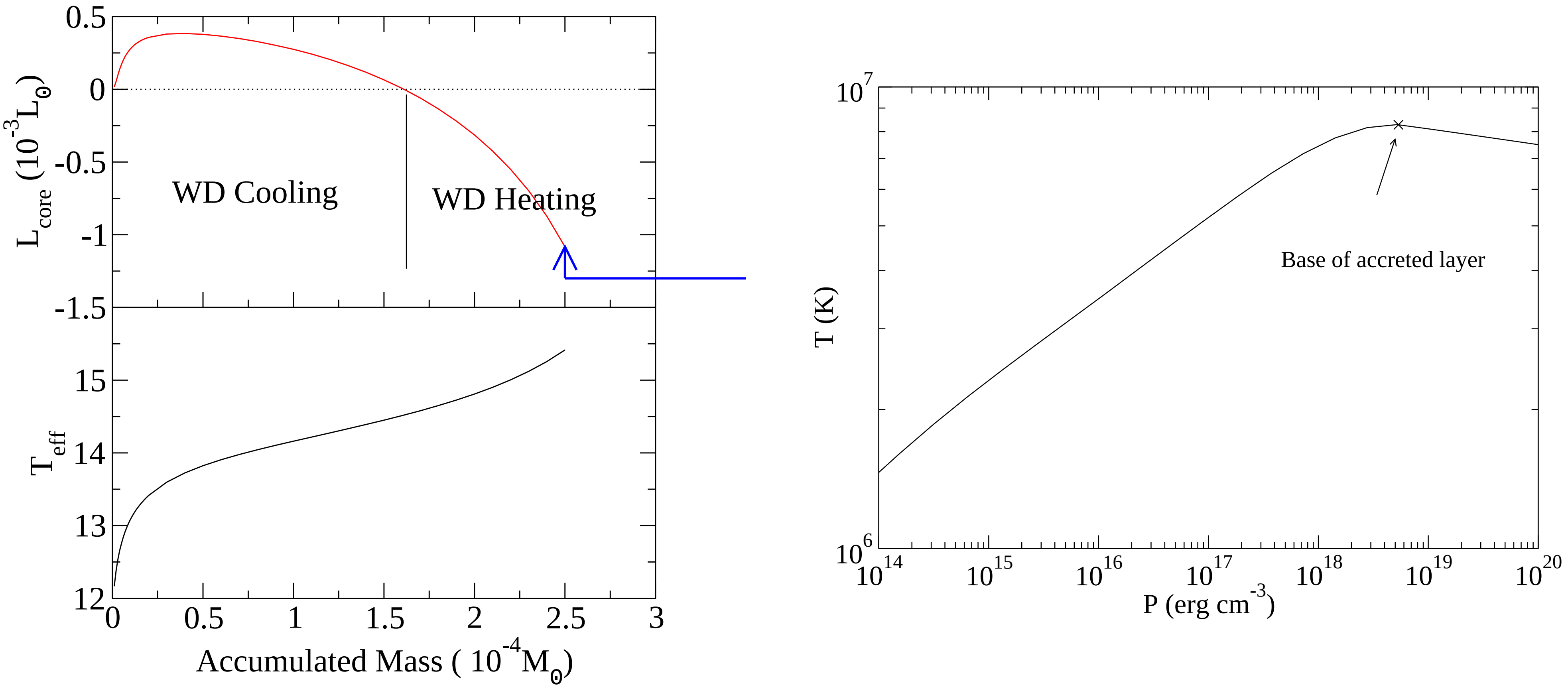
Cooling-Heating Cycle





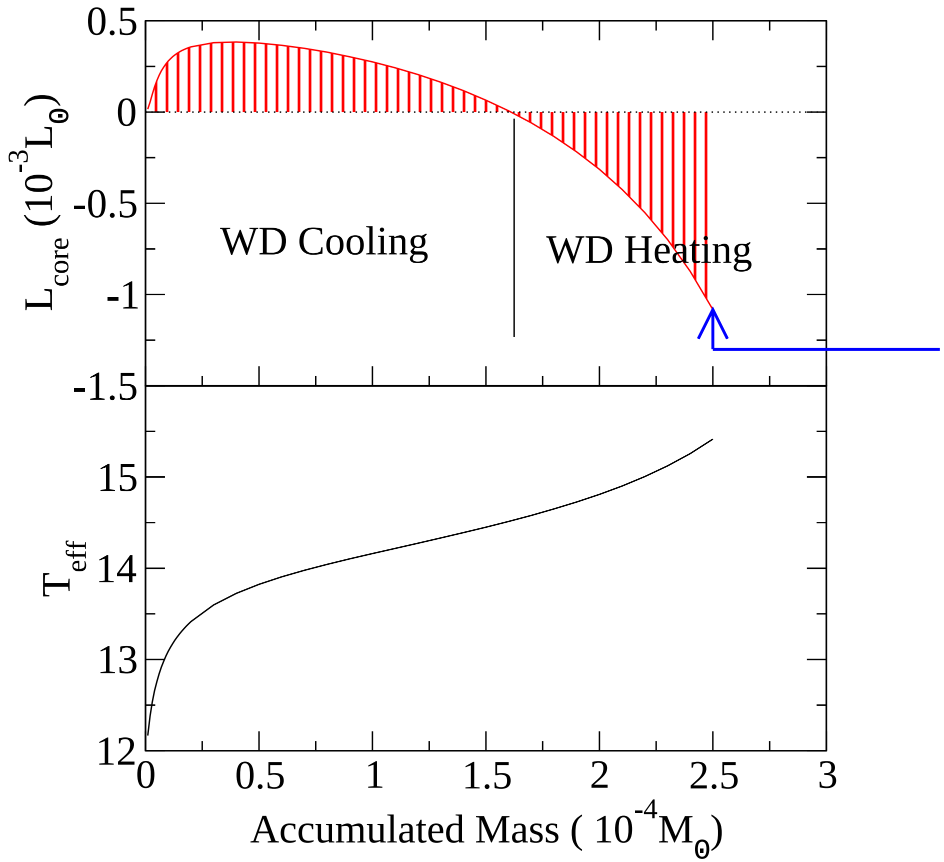
- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

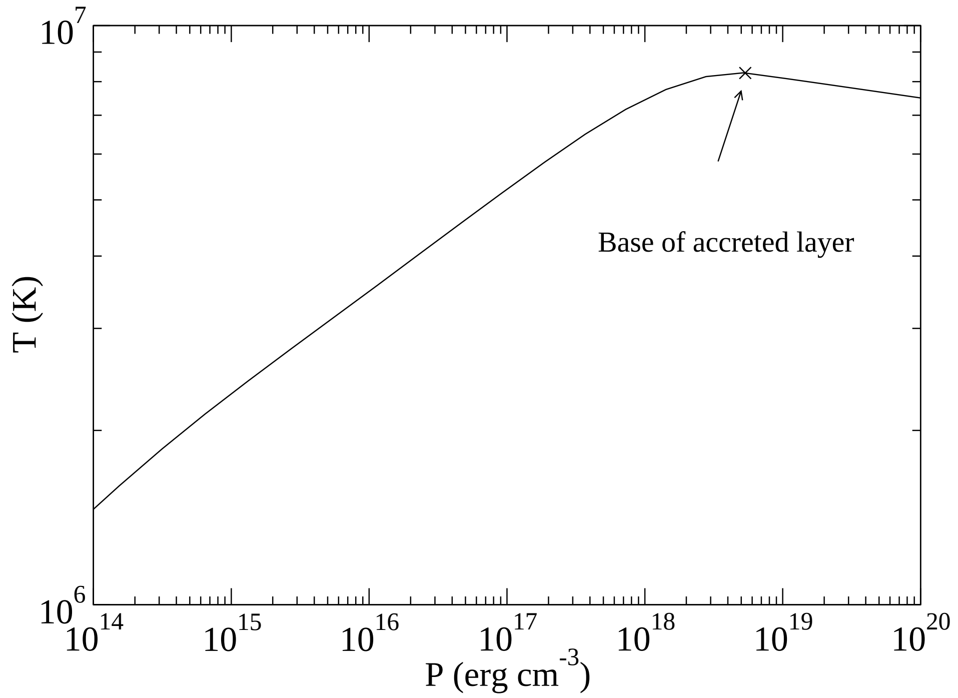
Cooling-Heating Cycle



- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

Cooling-Heating Cycle





- Core will be Reheated until equilibrium is reached.
  Core thermal time $\sim 10^8$ yr

$$\langle L_{\rm core} \rangle = \frac{1}{t_{\rm CN}} \int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

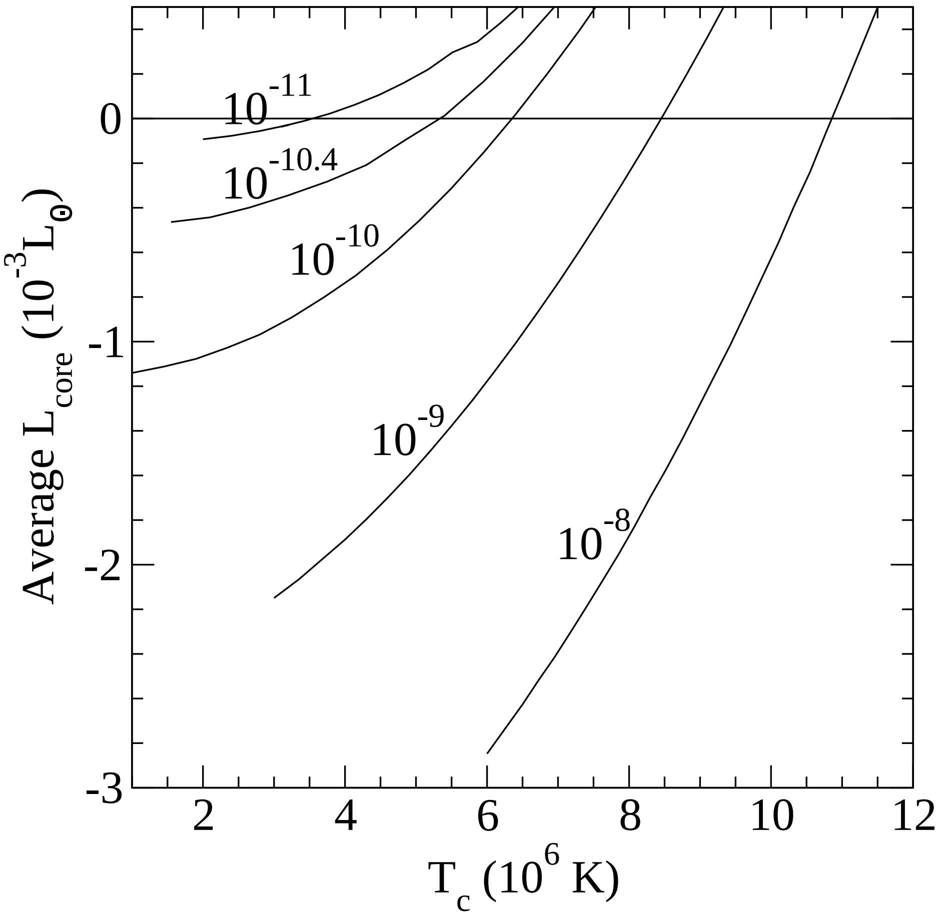
$\langle L_{\rm core} \rangle$ and the Equilibrium T_c

$$\langle L_{\rm core} \rangle = \frac{1}{t_{\rm CN}} \int_0^{t_{\rm CN}} L_{\rm core}\, dt$$

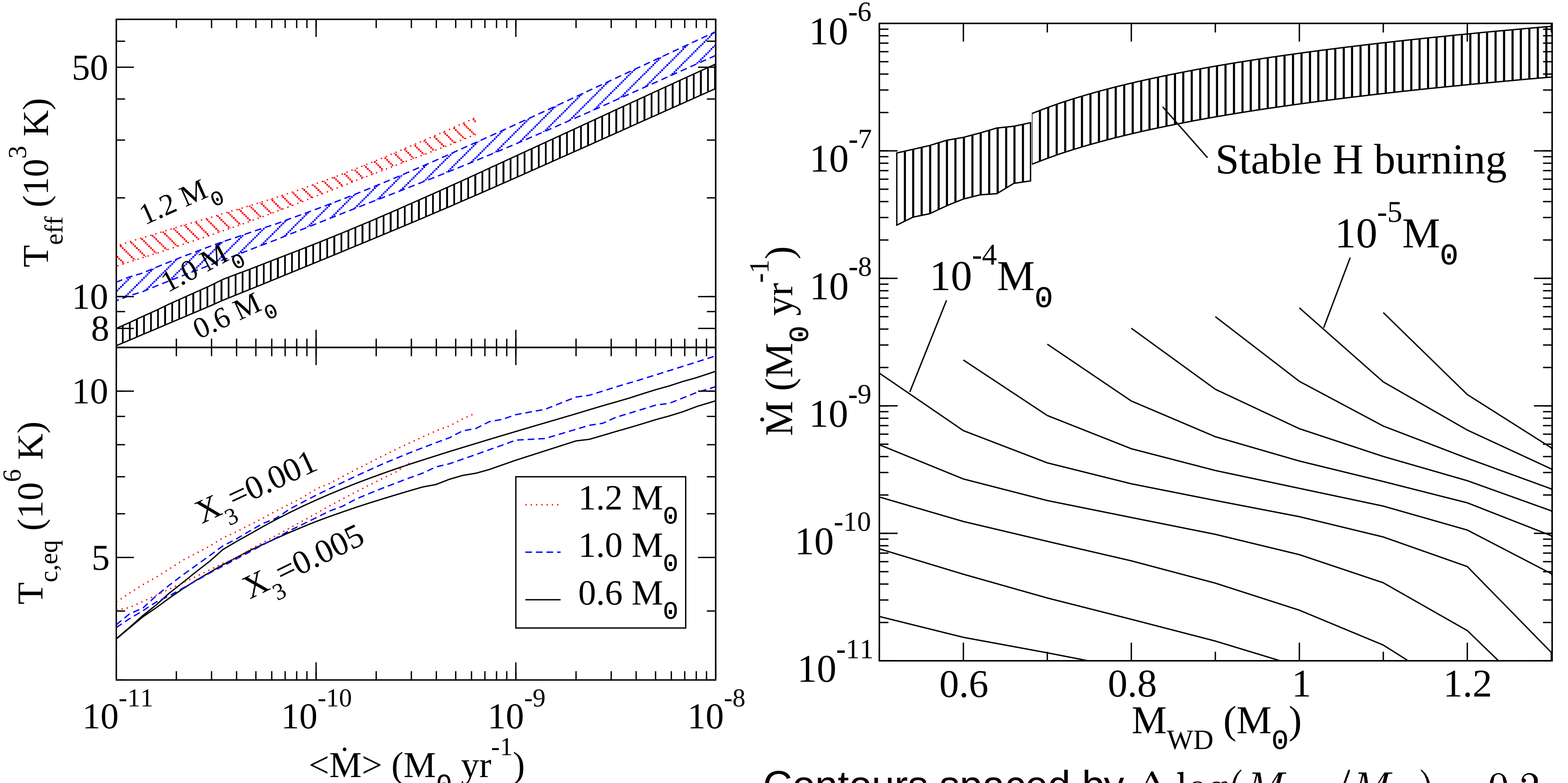
When $M_{\rm ej} = M_{\rm ign}$, $\langle L_{\rm core} \rangle = 0$ defines an

Equilibrium T_c

which is set by M and $\langle \dot{M} \rangle$



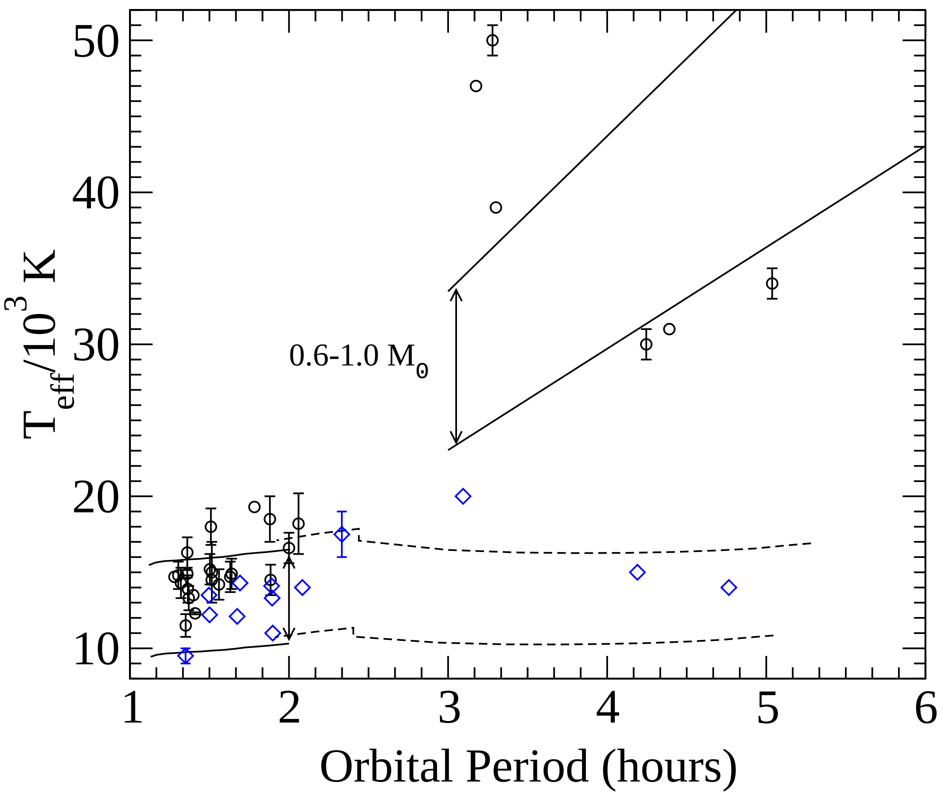
Equilibrium $T_c \rightarrow M_{\rm ign}, T_{\rm eff}$



Contours spaced by $\Delta \log(M_{\rm ign}/M_\odot) = 0.2$

X_3 = mass fraction of ^{3}He in accreted material

T_{eff} vs. P_{orb}



○ Low disk state systems (DN, SW Sex)

◇ Magnetics

Townsley & Gänsicke, in preparation

Theory range shown: 0.6-1.0$M_\odot$

Factor of $\sim 10 \; \langle \dot{M} \rangle$ contrast across period gap confirmed

Current Mag. Braking prescription matches well with DN at 4-5 hours

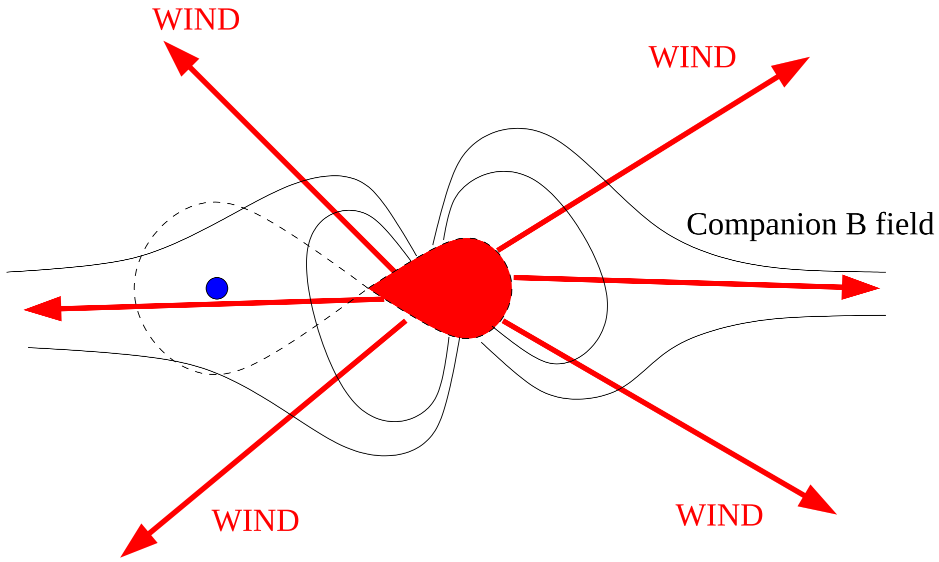
Separate population of high $\langle \dot{M} \rangle$ at 3 hours?

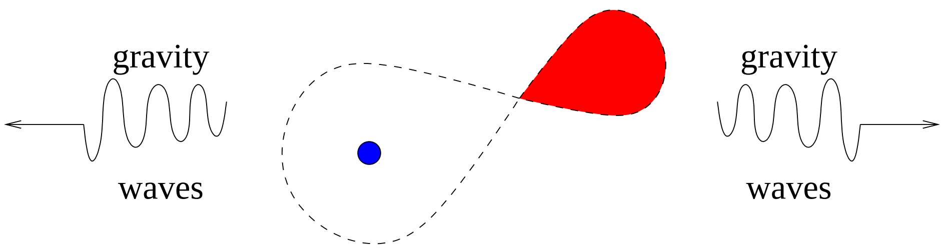
Magnetic CVs above gap near Grav. Radiation prediction – WD magnetic field preventing magnetic braking?!

(Li, Wu, & Wickramasinghe 1994, MNRAS, 268, 61)

Angular Momentum Loss

$\dot{J}$ determines evolution of compact binary





Magnetic Braking

high $\dot{J}$, $P_{\rm orb} \gtrsim 3$ hours

Magnetically attached wind from companion star

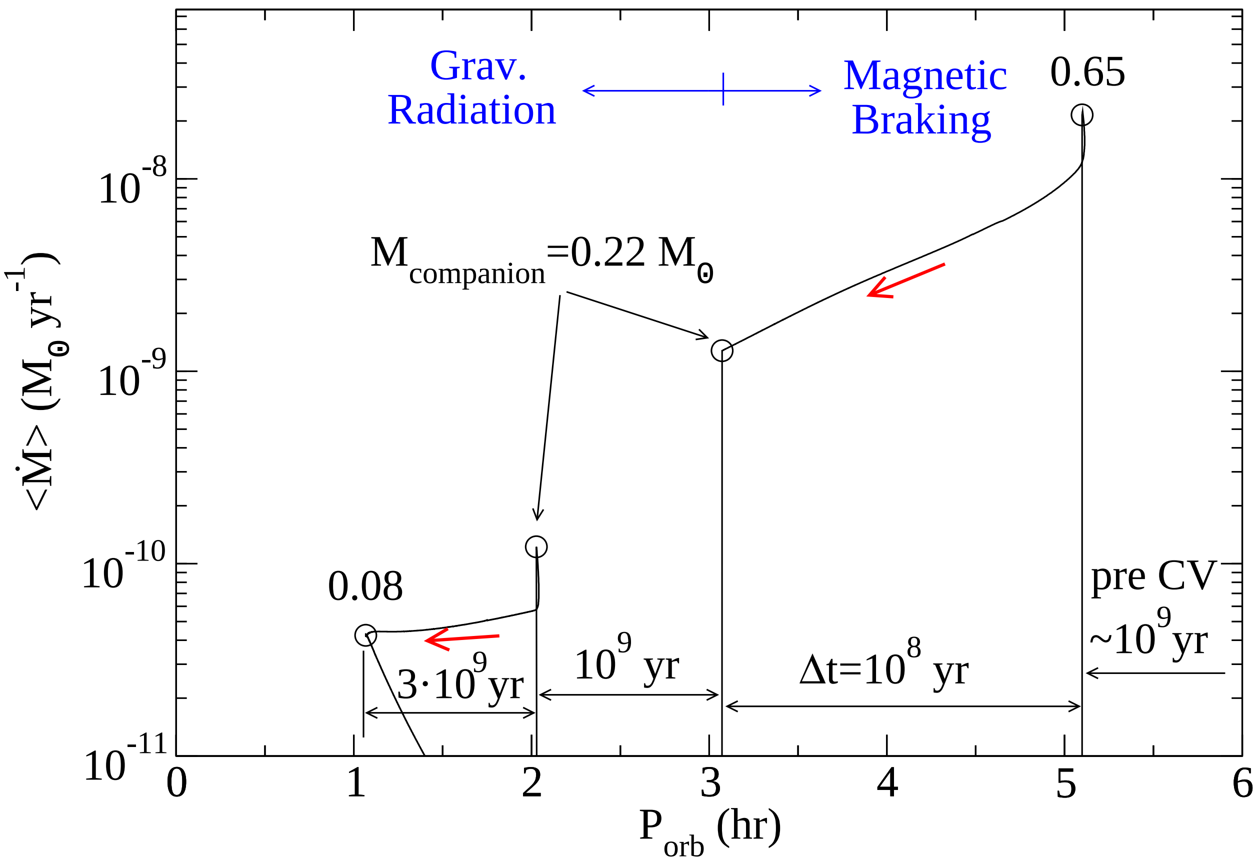
$$\dot{J}_{\rm mb} = -9.4 \times 10^{38} \text{ erg} \left(\frac{M_2}{M_\odot}\right) \left(\frac{R_2}{R_\odot}\right)^3 \left(\frac{P_{\rm orb}}{\rm hr}\right)^{-3}$$

Gravitational Radiation

low $\dot{J}$

$$\dot{J}_{\rm gr} = -\frac{32 G Q^2 \omega^5}{5 c^5}$$
$$= -2.7 \times 10^{37} \text{ erg} \left(\frac{a}{R_\odot}\right)^4 \left(\frac{M_{\rm WD} M_2}{M_t M_\odot}\right)^2 \left(\frac{P_{\rm orb}}{\rm hr}\right)^{-5}$$

Interrupted Magnetic (Wind) Braking?



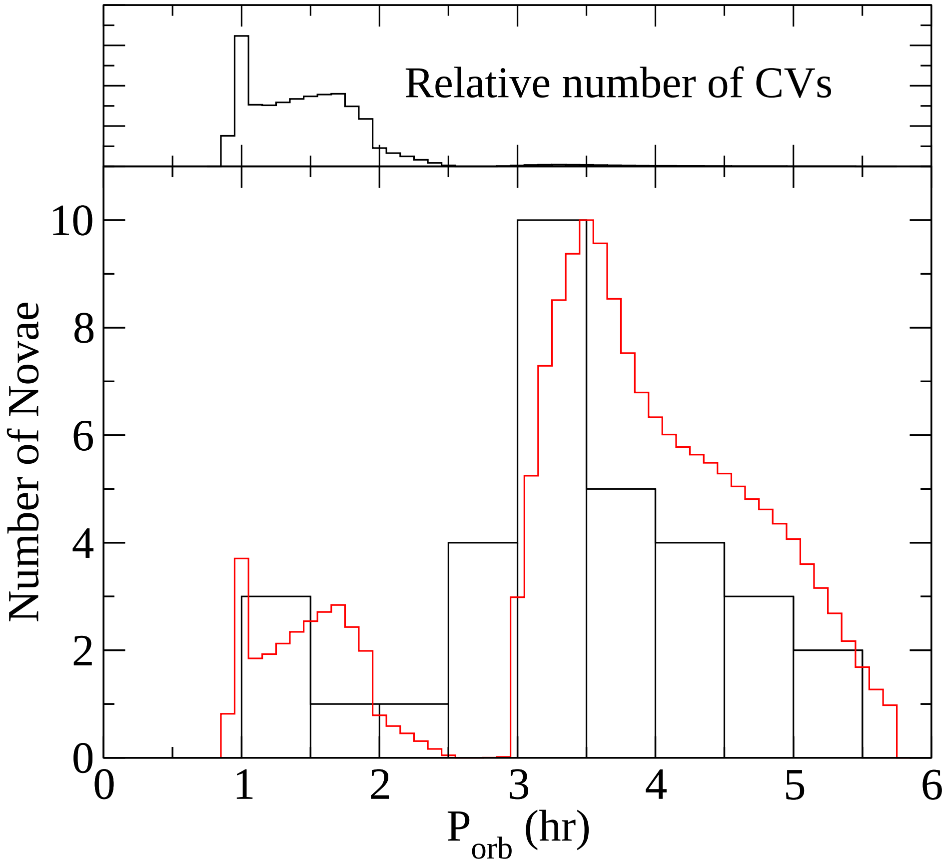
$M_{\rm WD} = 0.7 M_{\odot}$, Howell, Nelson, & Rappaport 2001, ApJ 550, 897

Open Questions:

- Is Mag. Braking prescription right?
- Does this fit observed population?

We can test this!

Classical Nova $P_{\rm orb}$ Distribution



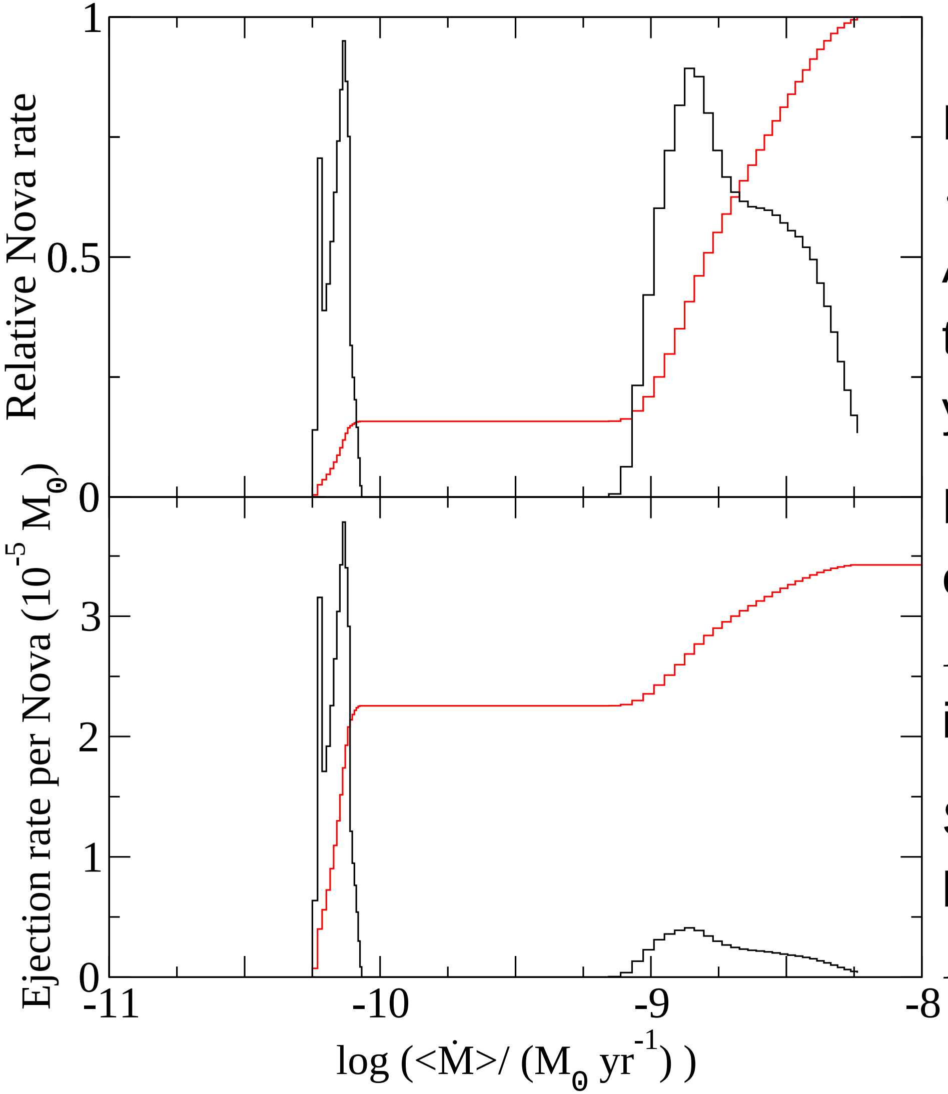
Theory curve uses Interrupted Magnetic Braking for $P_{\rm orb}(\langle\dot{M}\rangle)$ and population n_P

(Howell, Nelson, Rappaport 2001, ApJ 550, 897)

$$\nu_{CNP} = n_P \frac{\langle\dot{M}\rangle}{M_{\rm ign}}$$

- Supports a factor of >10 drop in $\langle\dot{M}\rangle$ across gap
- Consistent with idea that CVs evolve across the gap
- Possible population of magnetic systems filling in gap
- Ignores selection effects – hard to quantify

Classical Nova $\langle \dot{M} \rangle$ Distribution



Most observed Novae have high $\langle \dot{M} \rangle \sim 10^{-9} M_\odot$ yr^{-1}
A similar amount of matter is ejected from these and from Novae with $\langle \dot{M} \rangle \sim 10^{-10} M_\odot$ yr^{-1}.

Features of Novae which depend on $\langle \dot{M} \rangle$ are expected to have a bimodal character. The $P_{\rm orb}$ distribution below 6 hours shows initial indications of this.

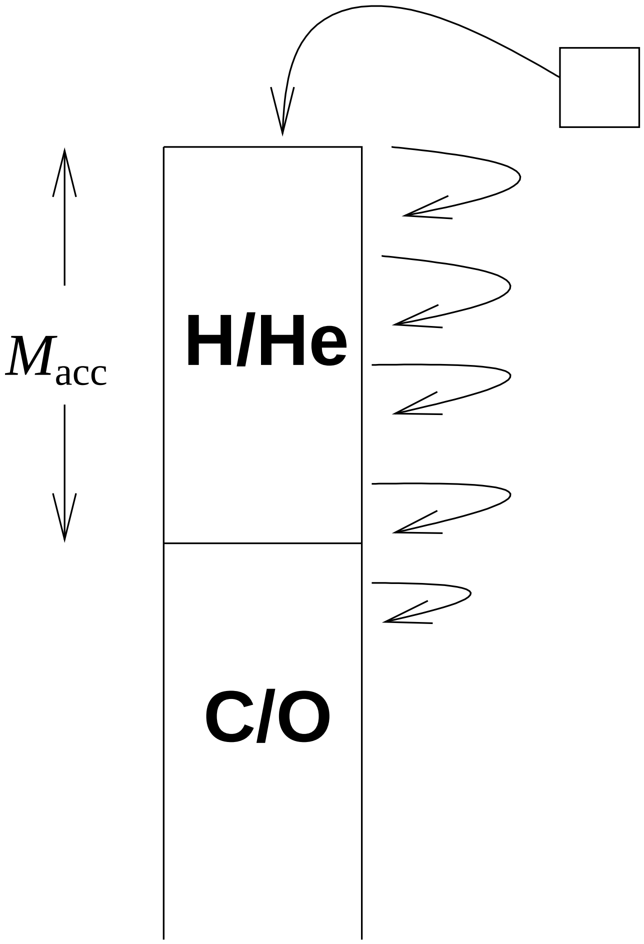
So far there are only 5 Novae with $P_{\rm orb} < 2$ hours 7 observed Novae (About 15%) have $P_{\rm orb} > 10$ hours (not CV-like)

Inferences for the CV Population

With nominally verified theoretical predictions for $\langle \dot{M} \rangle$ and $M_{\rm ign}$, we can convert Nova rate to number of CVs. (We will only count pre-period minimum CVs.)

- Each CN/yr implies [for average WD $M = 1.0\text{-}0.6 M_\odot$]
  - $3\text{-}9 \times 10^5$ CVs (pre-period minimum)
  - $\dot{M} = 3\text{-}9 \times 10^{-5} M_\odot \text{ yr}^{-1}$ ejected into the ISM
  - $1\text{-}2 \times 10^{-4} \text{ yr}^{-1}$ new CVs born
- External galaxies exhibit a universal Nova rate of 2 ± 1 CN/yr per $10^1 0 L_{\odot,K}$ (Williams & Shafter 2004, ApJ, 612, 867), which implies
  - A universal CV birthrate of $2\text{-}4 \times 10^{-4}$ yr^{-1} per $10^{10} L_{\odot,K}$, very similar to the luminosity specific Type Ia supernova rate in elliptical galaxies.
  - 60-180 CVs for every $10^6 L_{\odot,K}$ in an old stellar population.
    The population of X-ray identified CVs in the globular cluster 47 Tuc is similar to this number, showing no overabundance relative to the field. (Heinke et al. 2005)
  - 9-27$\times 10^{-6}$ CV pc^{-3}, from the local Galactic K-band luminosity density. Similar to a theoretical prediction of 2×10^{-5} pc^{-3} (Politano 1996, ApJ 465,338) and slightly more than the PG survey estimate of 6×10^{-6} pc^{-3} (Ringwald 1996).

Accreting WD Envelope



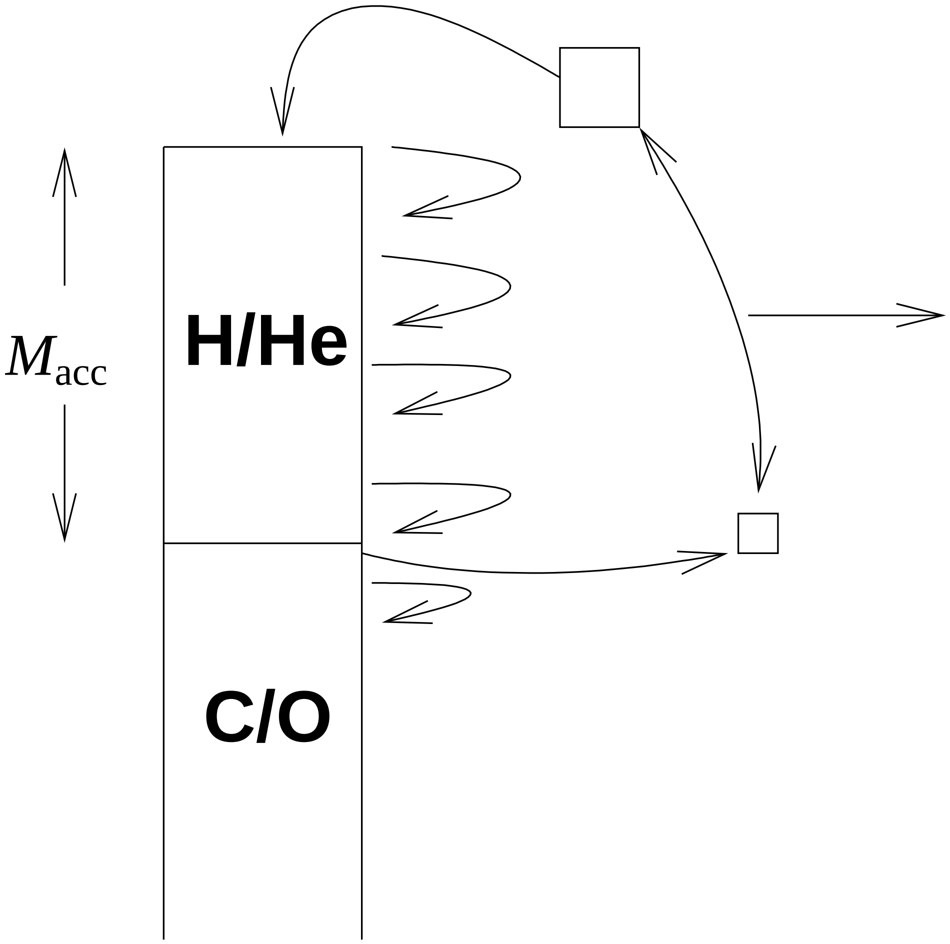
Envelope thermal time

$$\sim 10^3 \text{ yr}$$

Infall energy deposited near surface and quickly radiated away

Interested in energy deposited deep in the envelope

Accreting WD Envelope



quasi-static envelope

$$L_{\rm env} \sim gh\langle\dot{M}\rangle \sim \langle\dot{M}\rangle\frac{kT_c}{\mu m_p}$$

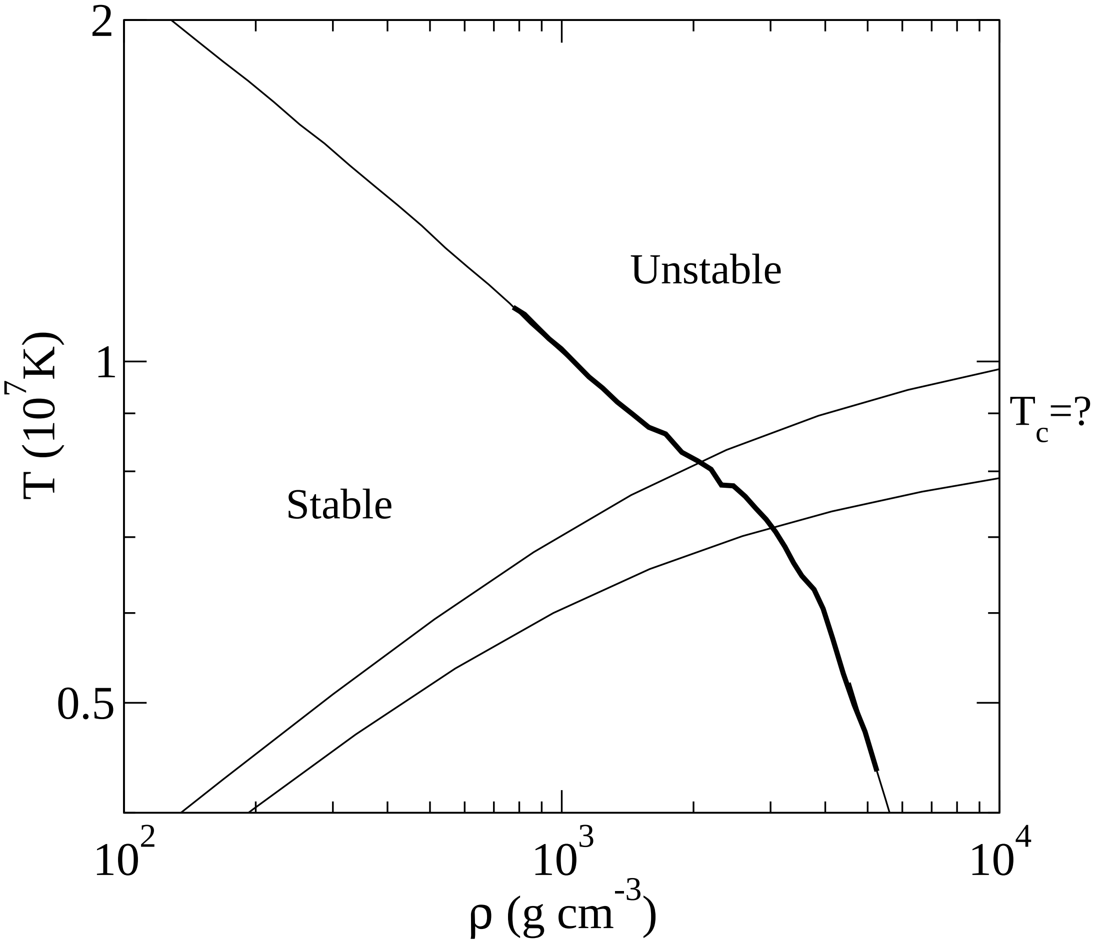
So actually:

$$T_{\rm eff}(M, \langle\dot{M}\rangle, M_{\rm acc}, T_c)$$

$$M_{\rm ign}(M, \langle\dot{M}\rangle, T_c)$$

T_c and Classical Nova Ignition

Conditions at base of H/He:



Evaluating envelope stability:

$$\frac{\partial \epsilon_N}{\partial T} = \frac{\partial \epsilon_{\rm cool}}{\partial T}$$

What thermal state (T_c) corresponds a given $\langle \dot{M} \rangle$?