# Angular Momentum Transport in SN Ia Progenitors

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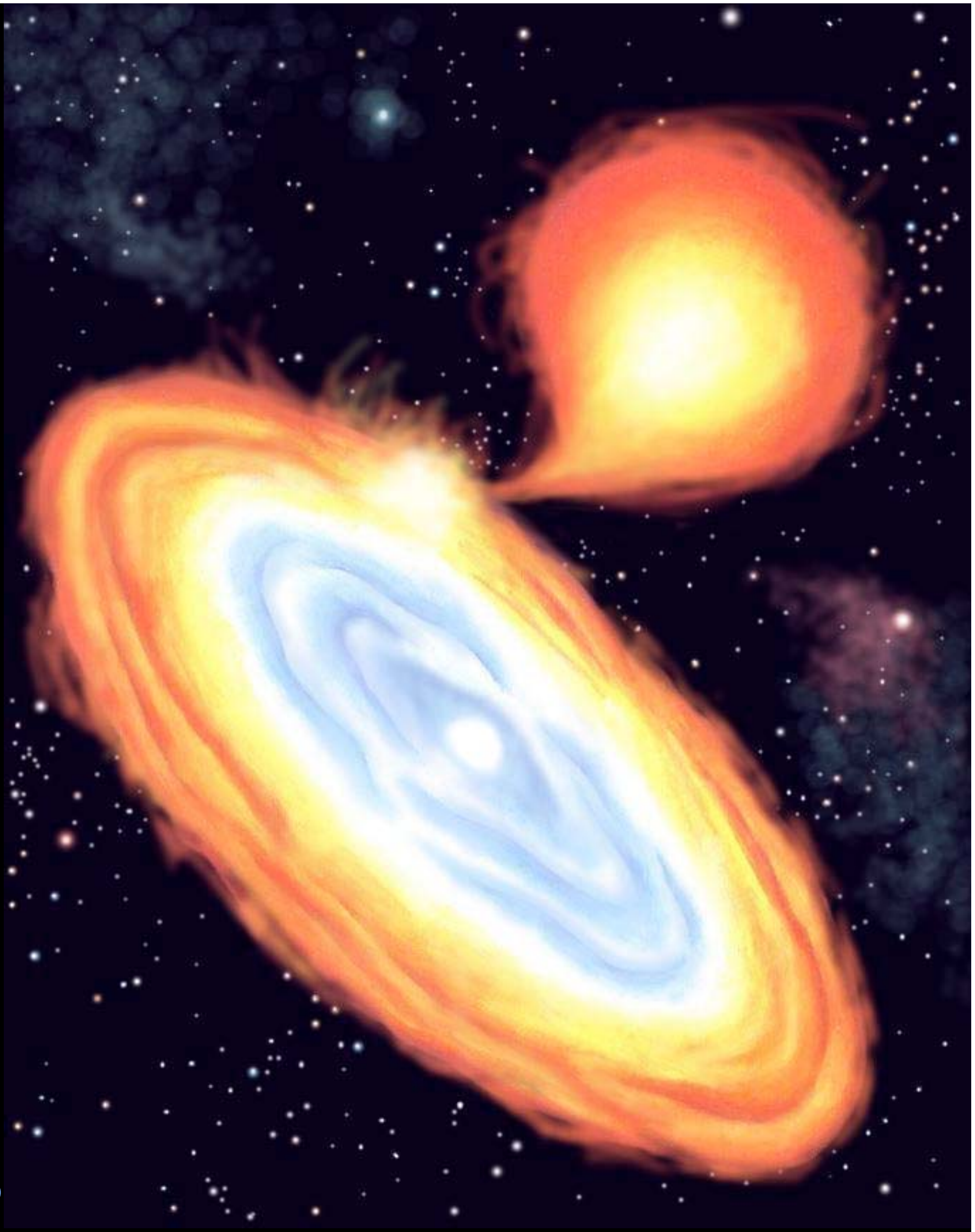


A. P. & Bildsten 2004a, ApJ 610 977

A. P. & Bildsten 2004b, ApJL 616 155

A. P. 2007 (in preparation)

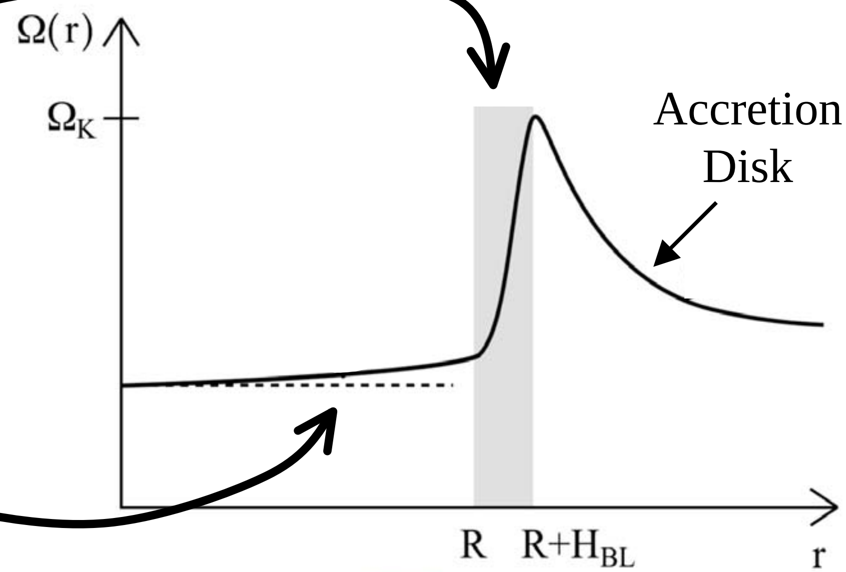
# Talk Outline

**Question:** What is the angular momentum profile of an accreting WD during the various stages before the SNe Ia deflagration begins?

## Accretion Phase

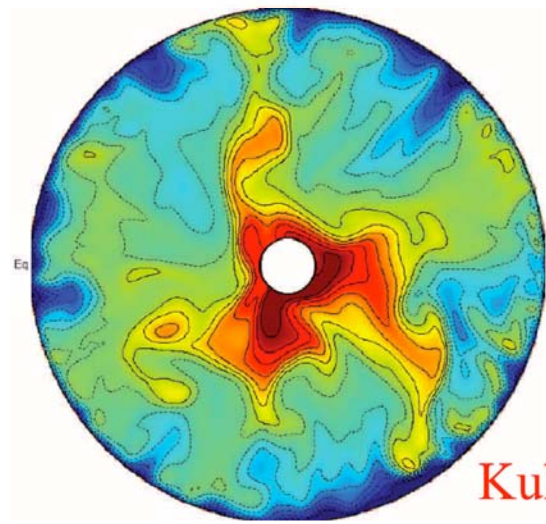
- Spreading layer (boundary layer) calculations

- Internal shear of accreting WDs




## Simmering Phase

- Redistribution of angular momentum by convection



Kuhlen et al. ‘06

## Summary & Discussion

# The Boundary Layer "Story"

Many WDs undergo dramatic (semi-periodic) accretion events called **dwarf novae**. These last ~2-20 days with quiescent intervals of ~10 days to tens of years.

Optically thin BL during quiescence ($\dot{M} \sim 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}$)

- Seen in X-rays at a temperature similar to the virial temperature

$$T = \frac{m_p}{k_\mathrm{B}} \frac{GM}{R} \approx 10^8\ \mathrm{K}$$

Optically thick BL during outburst ($\dot{M} \sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$)

- Very bright in outburst

$$\frac{1}{2} \dot{M} R^2 \Omega^2 = \frac{GM\dot{M}}{2R} \approx 10^{34}\ \mathrm{ergs\ s^{-1}}$$

- Seen in the soft X-rays and EUV

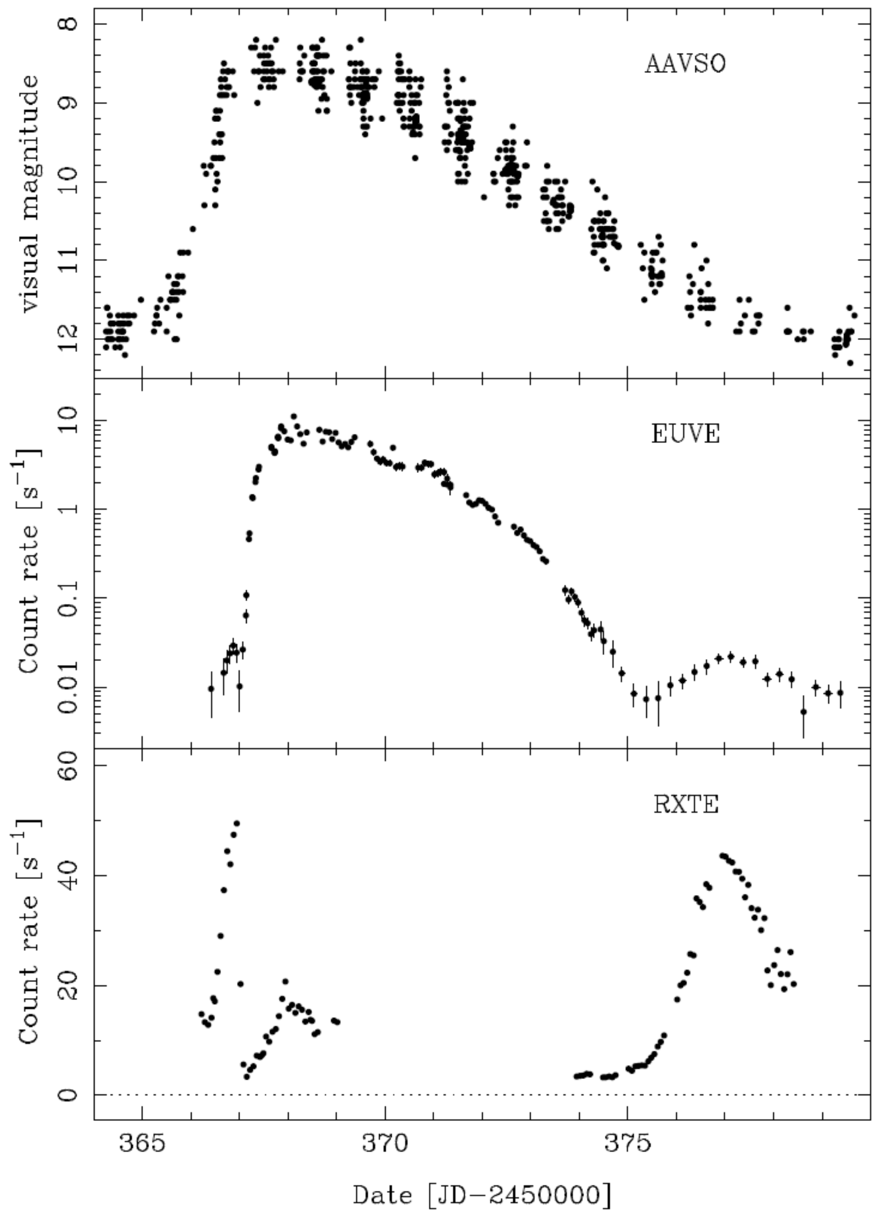
$$4\pi R H \sigma_\mathrm{SB} T_\mathrm{eff}^4 = \frac{GM\dot{M}}{2R} \qquad T_\mathrm{eff} \approx 10^5\ \mathrm{K}\ \dot{M}_8^{1/4}$$

$$\dot{M}_8 \equiv \dot{M} / 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$$

# Observations of BLs in DNe

SS Cyg; Wheatley, Mauche, & Mattei, 2003

By observing and comparing a range of photon energies we can learn a lot about the BL.



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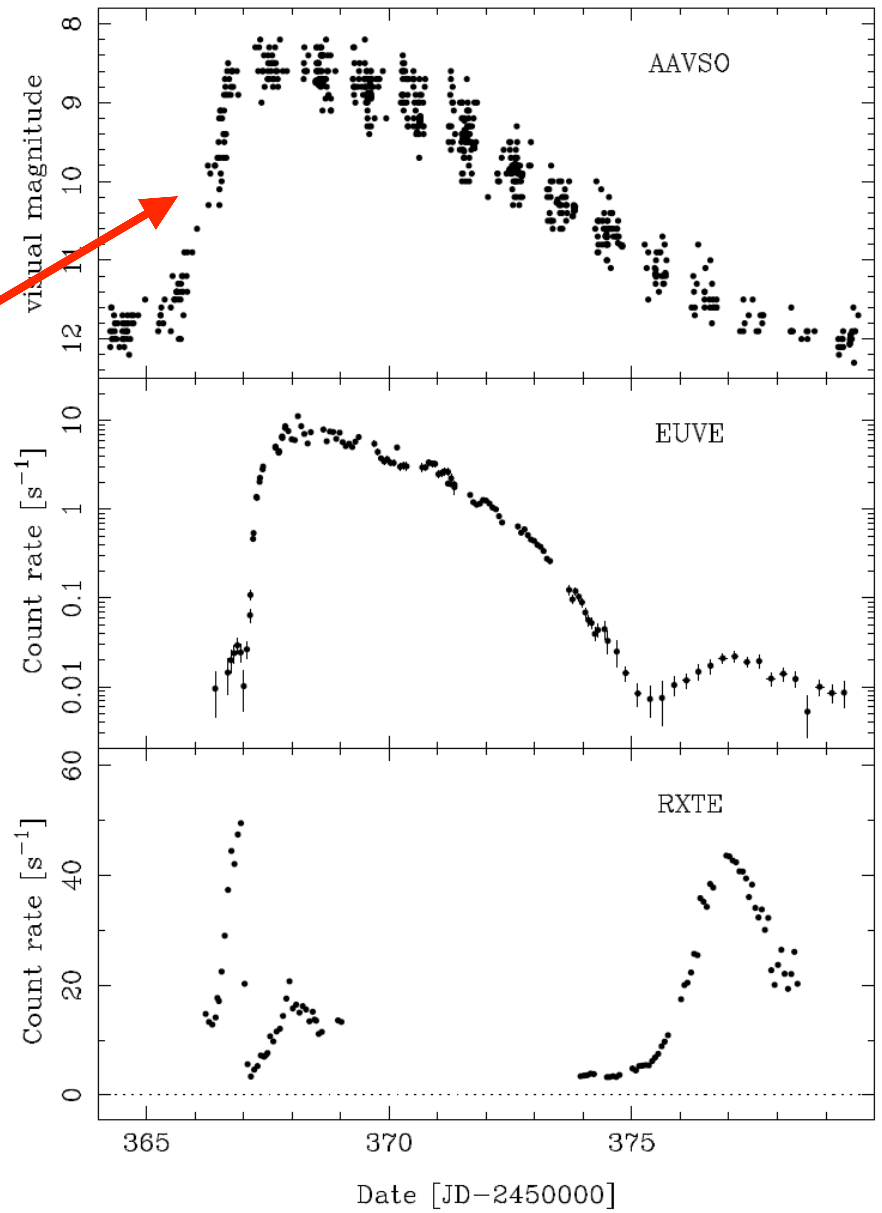

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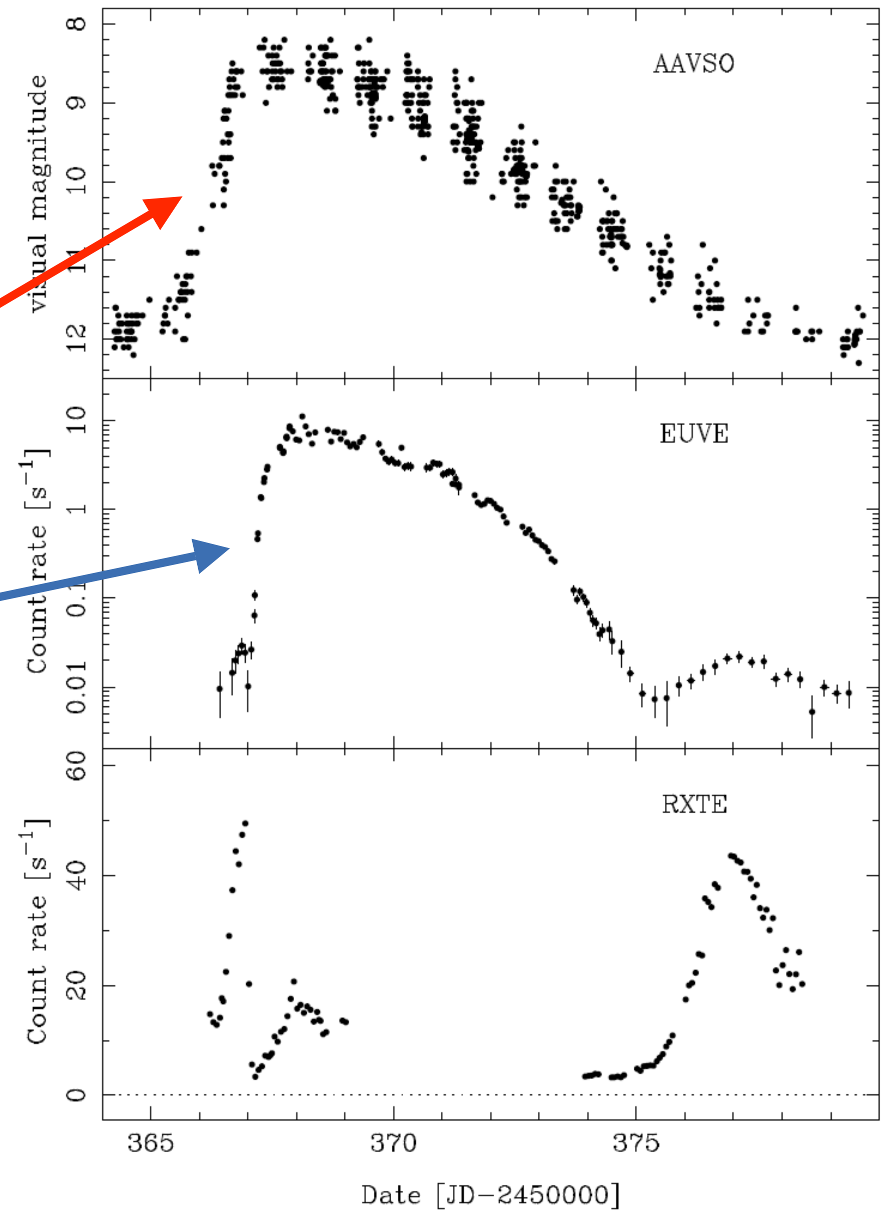

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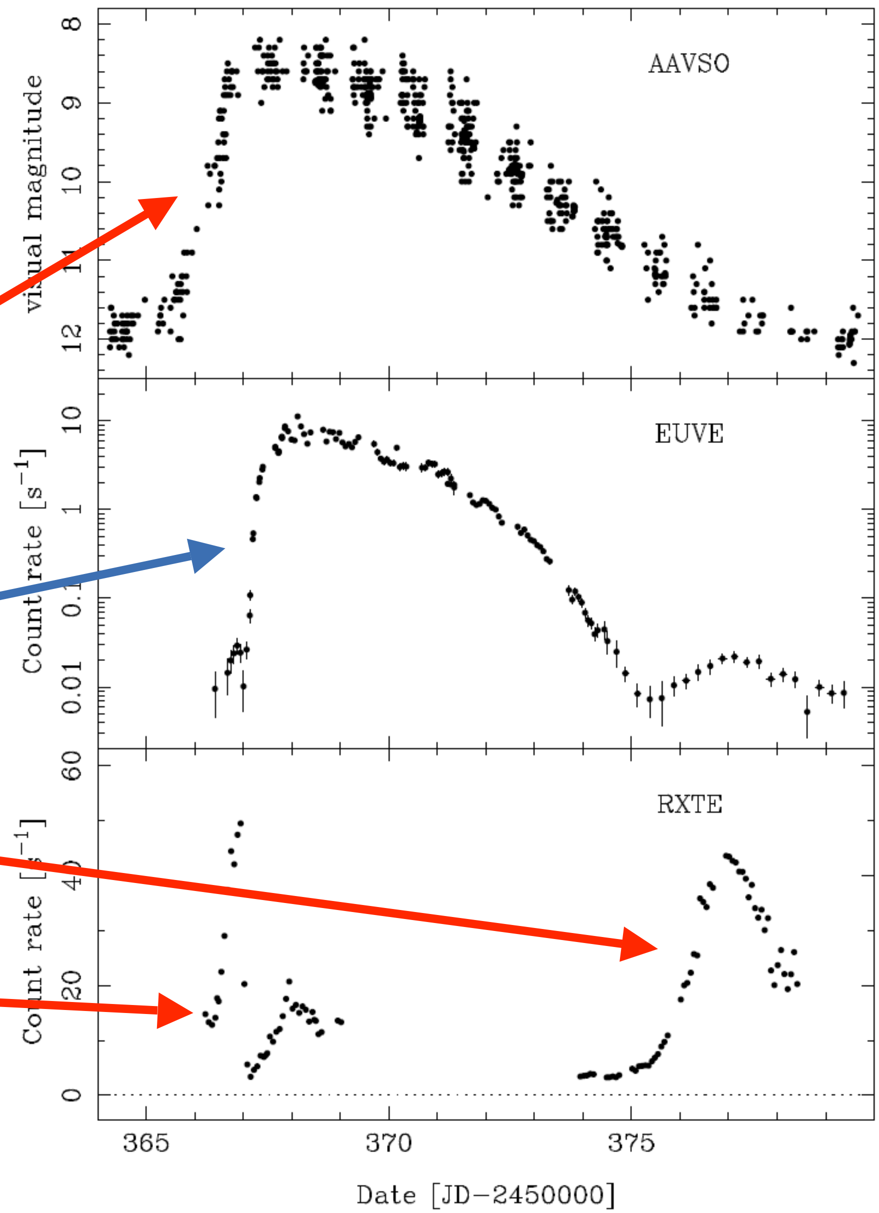
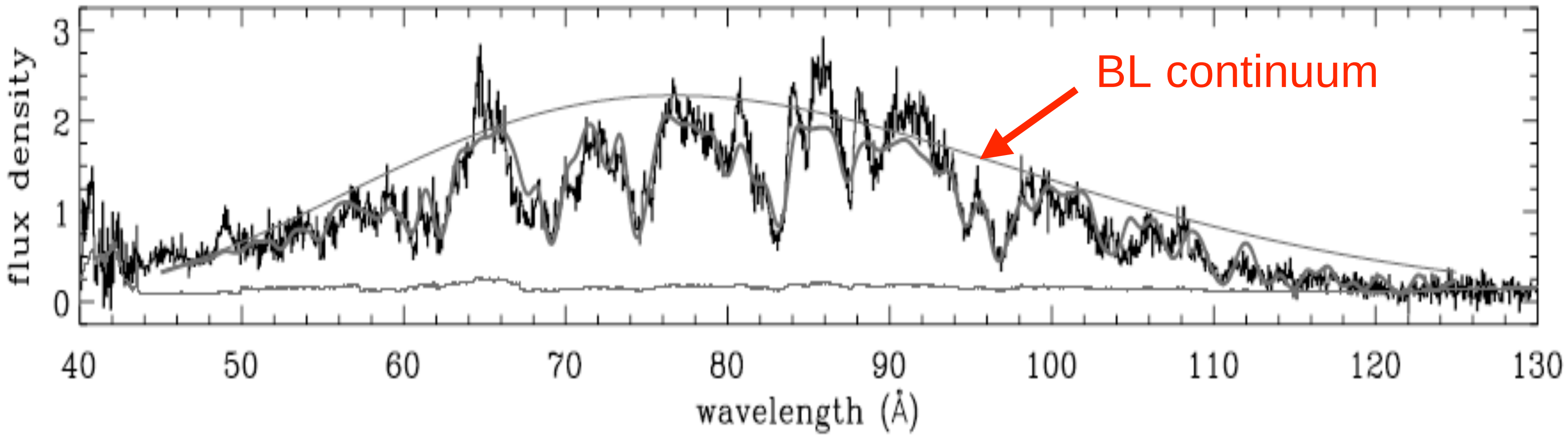
The X-rays (2.3-15.2 keV) are brightest before and after the EUV, indicating an optically thin boundary layer.

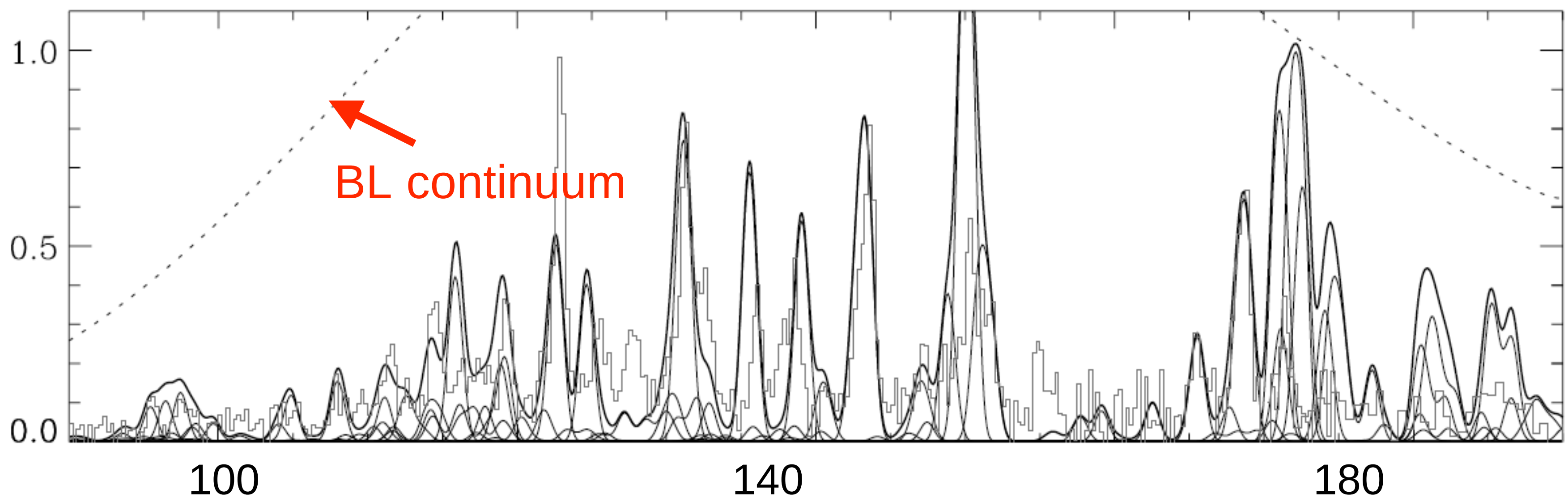


# Progress in Modeling EUV as a BL

SS Cyg; Mauche '04



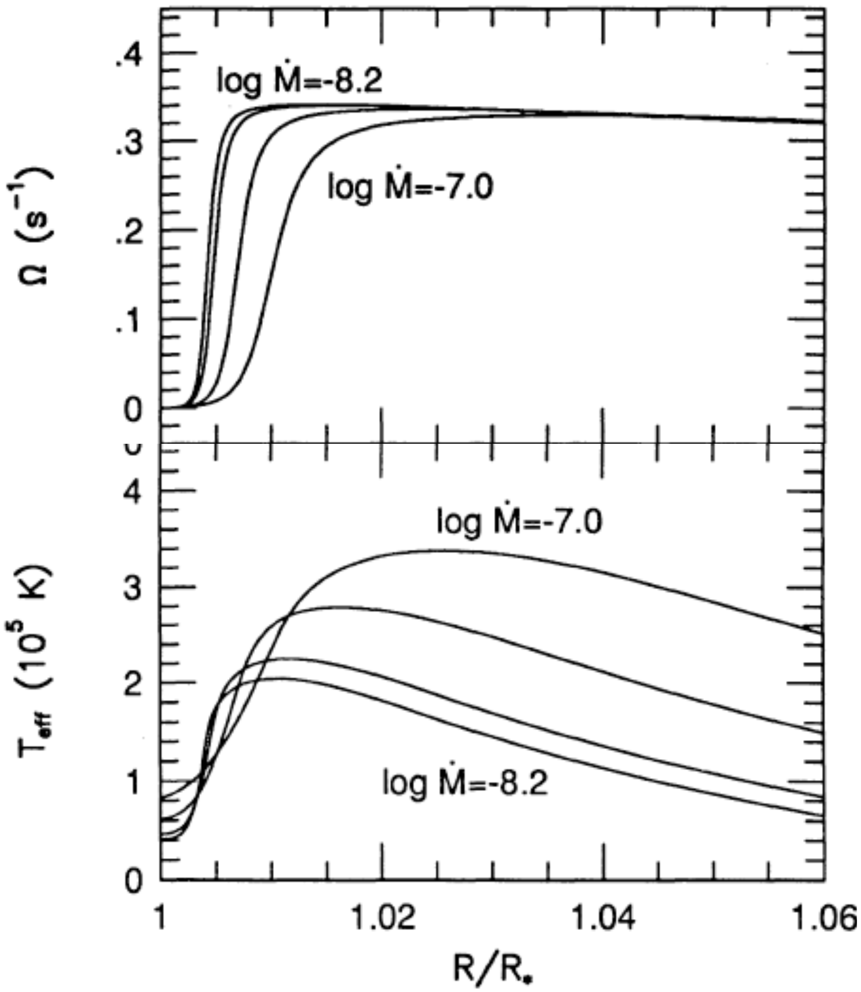

OY Car; Mauche & Raymond '00



# Previous Theoretical Work

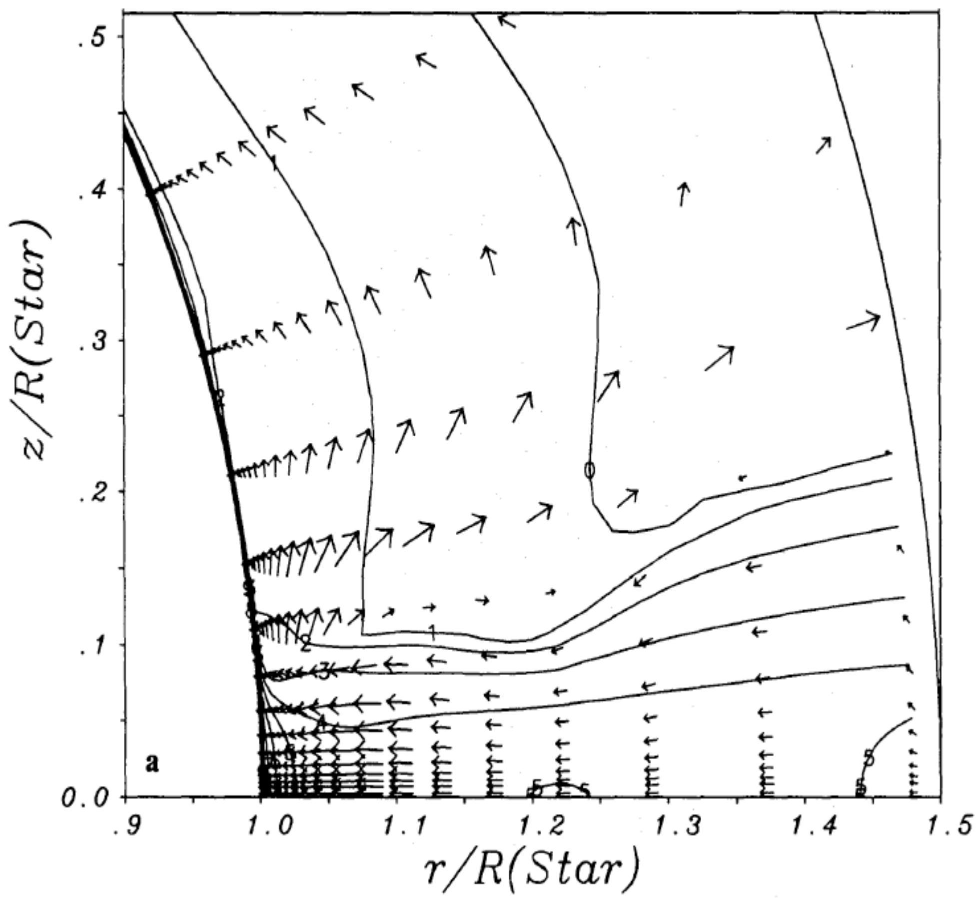
1. Assume a vertical scale height and solve for radial direction

Popham & Narayan ‘95



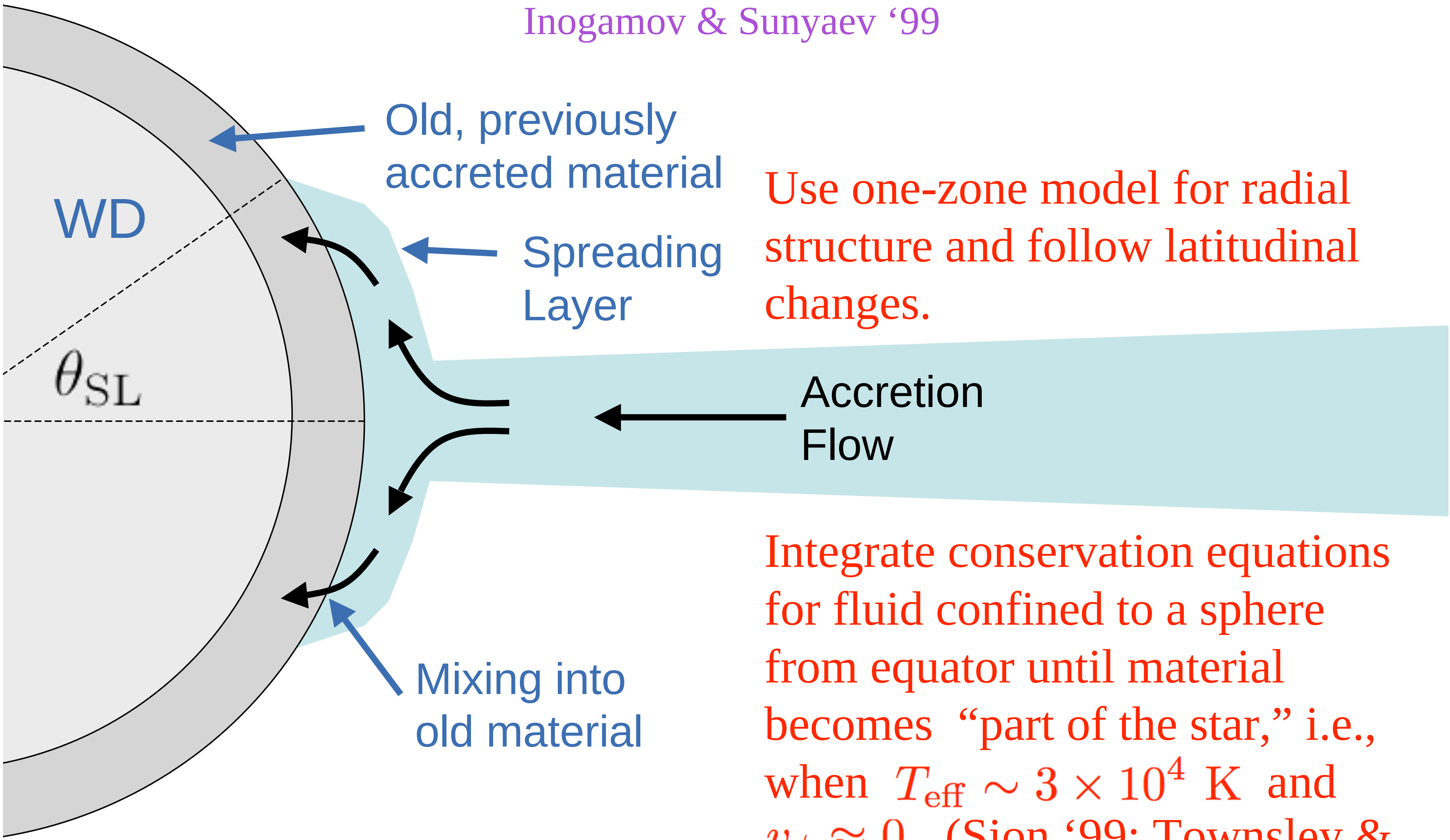

2. Solve for the 2-D structure using simulations

Kley ‘89



# The "Spreading Layer" Approach

Inogamov & Sunyaev '99



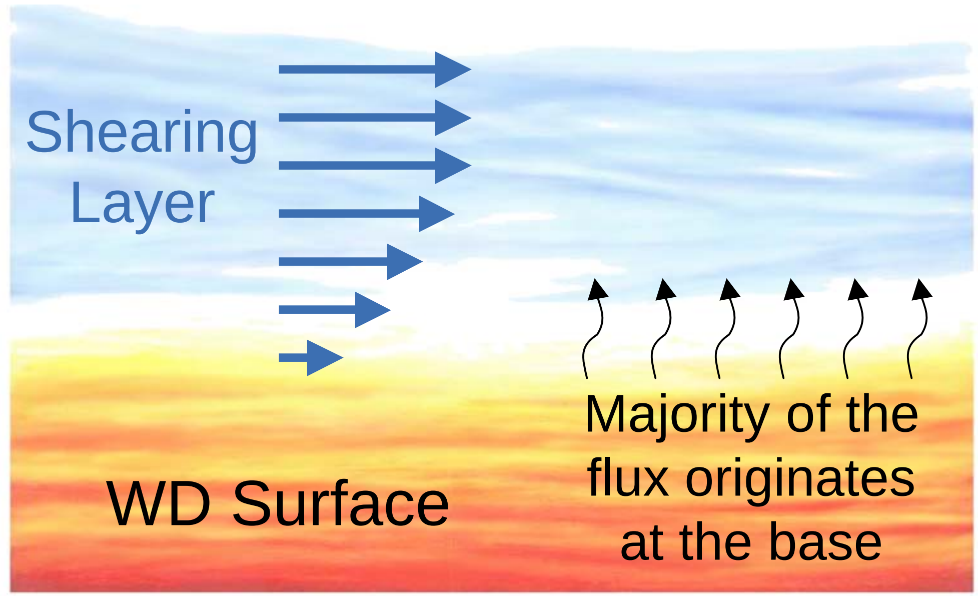

Use one-zone model for radial structure and follow latitudinal changes.

Integrate conservation equations for fluid confined to a sphere from equator until material becomes "part of the star," i.e., when $T_{\rm eff} \sim 3 \times 10^4$ K and $v_\phi \approx 0$ (Sion '99; Townsley & Bildsten '03)

# Radial Structure & Analytic Estimates

- To get a logarithmic shear profile as expected for a turbulent boundary layer (i.e., a Prandtl-Karman profile) requires a viscosity

$$\nu = \alpha H v_\phi$$




- The viscous (or spreading) time scale is therefore

$$t_{\rm SL} \sim H^2/\nu$$
$$= H/\alpha v_\phi \sim 1 \text{ min}$$

- During this time, material travels a latitudinal distance

$$R\theta_{\rm SL} \sim t_{\rm SL} v_\theta$$

$$\theta_{\rm SL} \sim \frac{H}{R} \frac{v_\theta}{\alpha v_\phi} \sim 0.01 - 0.1$$

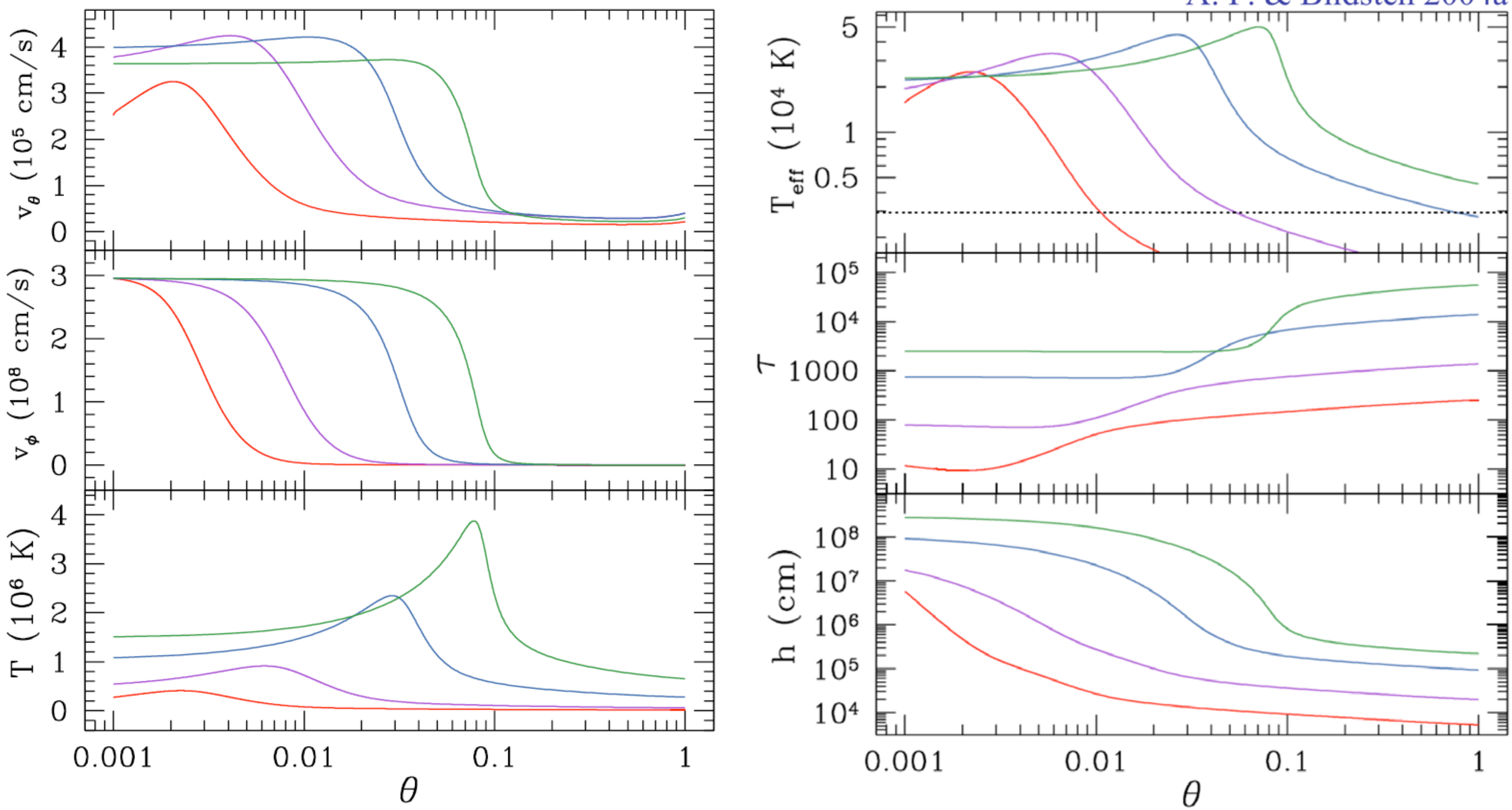
# Numerical SL Calculations

$M = 0.6 M_\odot \quad R = 9 \times 10^8 \text{ cm} \quad \alpha = 10^{-3}$

$2 \times 10^{-9}\ M_\odot\ \text{yr}^{-1} \quad 2 \times 10^{-8}\ M_\odot\ \text{yr}^{-1}$

$2 \times 10^{-7}\ M_\odot\ \text{yr}^{-1} \quad 5 \times 10^{-7}\ M_\odot\ \text{yr}^{-1}$

A. P. & Bildsten 2004a



# Comparisons to DNe Observations

• Because the spreading size increases with accretion rate, we expect a **shallower** scaling between $T_{\rm eff} - \dot{M}$ than if the size of boundary layer was fixed.

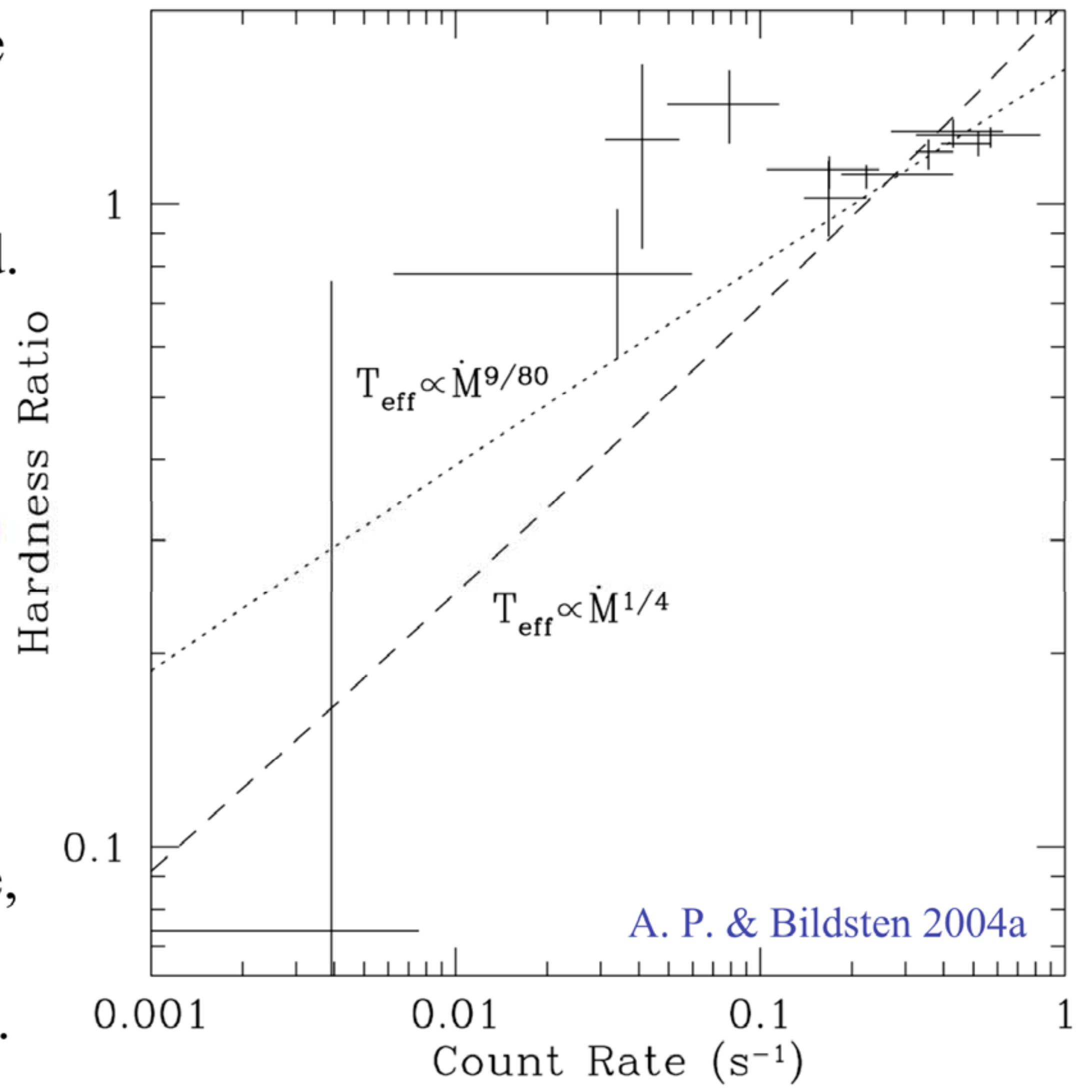
• Analytic estimates give

$$T_{\rm eff} = 2\times10^5\ {\rm K}\ \alpha_3^{1/8} \times M_1^{13/32} R_9^{-23/32} \dot{M}^{9/80}$$

$$T_{\rm eff} \propto \dot{M}^{9/80}$$

• If the SL acts like a waveguide, it may also be a source for DNOs (A. P. & Bildsten 2004b).

SS Cyg; Wheatley, Mauche, & Mattei, 2003




A. P. & Bildsten 2004a

# Super-Solar Metallicities in Classical Novae

- Observational data indicate ejected material in CNe can be enriched in C, N, O, and Ne by >30% by mass (Livio & Truran '94; Gehrz et al. '98)

- Enrichment also needed to match fastest CNe (Truran '82)

How does this occur?

- **Diffusion** of H into underlying C/O causes burning to trigger in a diffusive tail? (Prialnik & Kovetz '84; Kovetz & Prialnik '85)

- **Convective overshooting?** (Woosley '86). Both 2-D (Glasner et al. '97; Kercek et al. 98) and 3-D (Kercek et al. '99) simulations

- **Fluid instabilities** leading to shear mixing? (Kippenhahn & Thomas '78; Fujimoto '88)

- **Wave breaking** between a quickly spinning H/He envelope shearing against the C/O core? (Alexakis et al. '04)

# How far can a turbulent BL penetrate?

The SL is *much* shallower than the CN ignition depth

$$10^3\ \mathrm{g\ cm^{-2}} << 10^{10}\ \mathrm{g\ cm^{-2}}$$

So A. M. is deposited at surface. Transferring A. M. in steady-state…

$$\alpha\rho v^2 4\pi R^2 R = \dot{M}\sqrt{GMR}$$

viscous stress — area — lever arm — angular momentum per unit time

The velocity at the depth of the C/O core (CN ignition depth) is

$$\frac{v}{c_s} \approx 3\times 10^{-6}\alpha^{-1/2}\dot{M}_8^{1/2}\left(\frac{y}{10^{10}\ \mathrm{g\ cm^{-2}}}\right)^{-1/2}$$

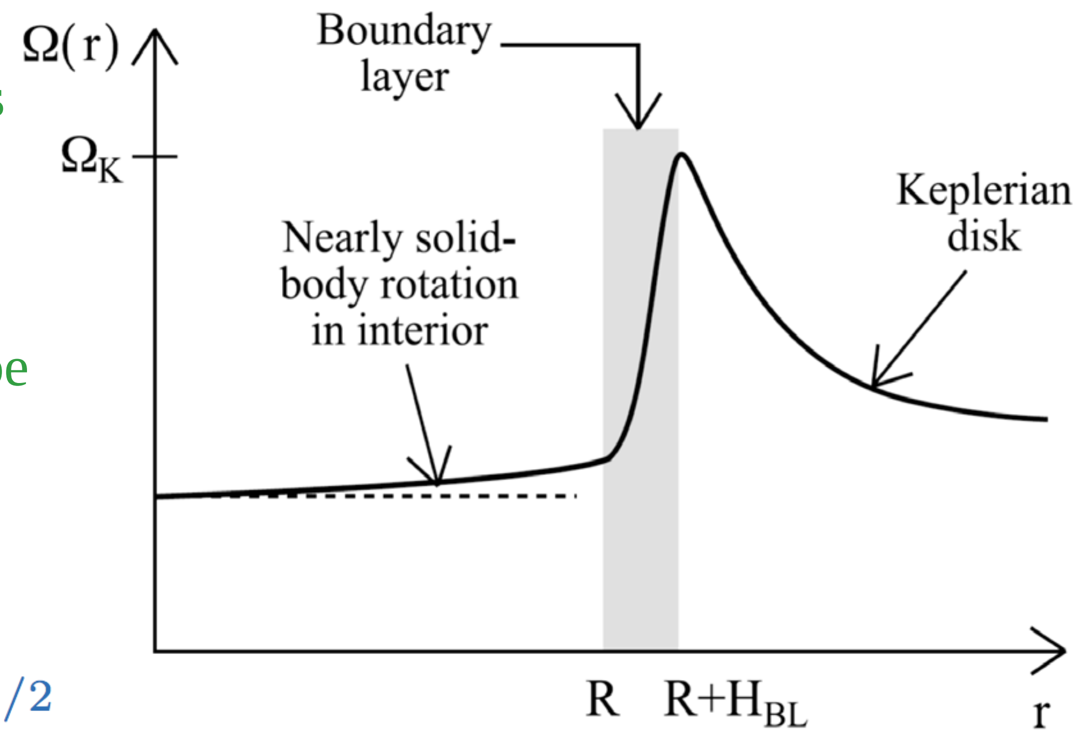
$$M = 0.6\ M_\odot \qquad R = 9\times 10^8\ \mathrm{cm}$$

This implies $\alpha < 10^{-11}$ for a Mach number close to unity!

This is similar to an ion viscosity (Spitzer ‘65), but even a radiative or magnetic viscosity (Spruit ‘02) would rule this out. Perhaps our assumption of steady-state is incorrect (?)

# Internal Shear of Accreting WDs

Figure from A. P. & Bildsten 2007




• Even though the majority of the azimuthal velocity is dissipated in the boundary layer, accretion adds angular momentum at a rate

$$\dot{M}(GMR)^{1/2}$$

A torque of this magnitude must be communicated through the WD.

• Steady-state angular momentum conservation gives (Fujimoto '93)

$$4\pi r^2 \rho \nu r \frac{d\Omega}{dr} = \dot{M}(GMR)^{1/2}$$

• By assuming steady-state we bypass the issue of supercritical rotation (Livio & Pringle '98; Langer et al. '00, references therein), which occurs in time dependent calculations.

• Since we are assuming the maximum torque allowed, the shear rates we derive should be viewed as upper limits.

# A. M. Transport Mechanisms

## Kelvin-Helmholtz instability

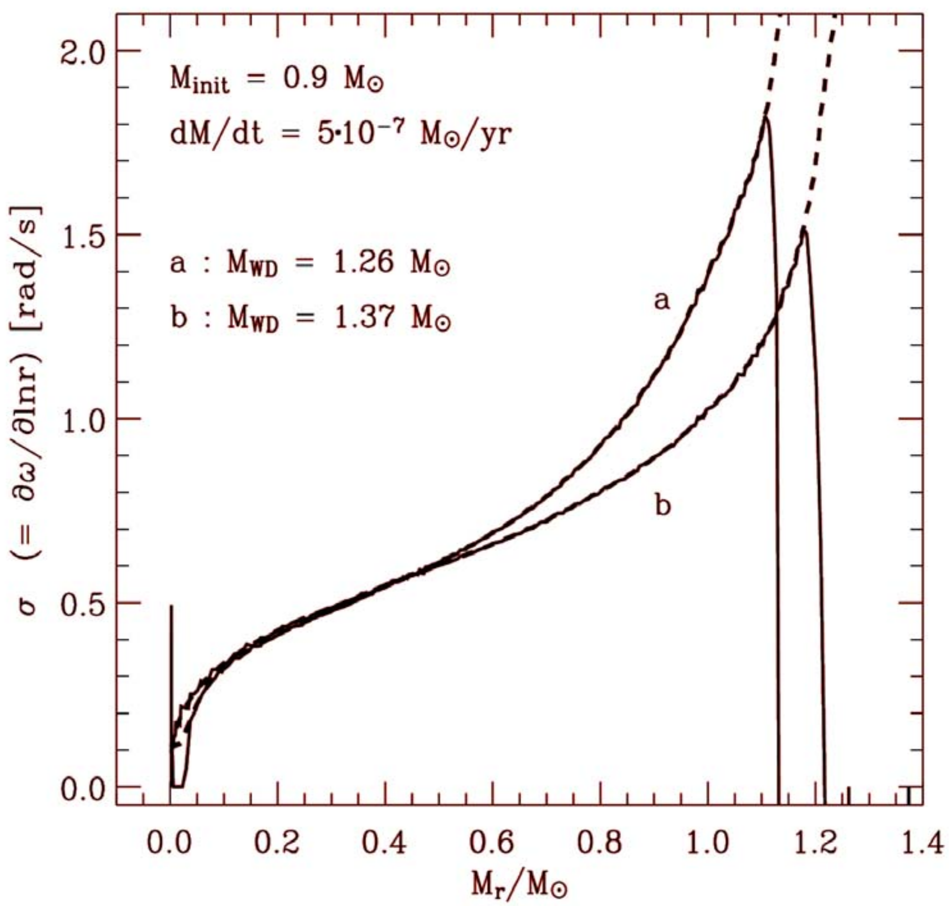
• KH instability occurs when the free energy in the shear is greater than the work required to overcome gravity

• KH instability is governed by the Richardson number and occurs when (Chandrasekhar 1968)

$$Ri \equiv \frac{N^2}{(d\Omega/\ln r)^2} < \frac{1}{4}$$

• Since this instability only occurs when Ri<1/4, the WD shear evolves until this condition is marginally satisfied (when this is the dominant viscosity mechanism).

• Large shear allows very massive WDs $> 1.7\ M_\odot$ (Muller & Eriguchi '85; Yoon & Langer '04)




Yoon & Langer 2004

# A. M. Transport Mechanisms

## Baroclinic instability

• Surfaces of constant pressure and density no longer coincide if hydrostatic balance is to be maintained when differential rotation is present.

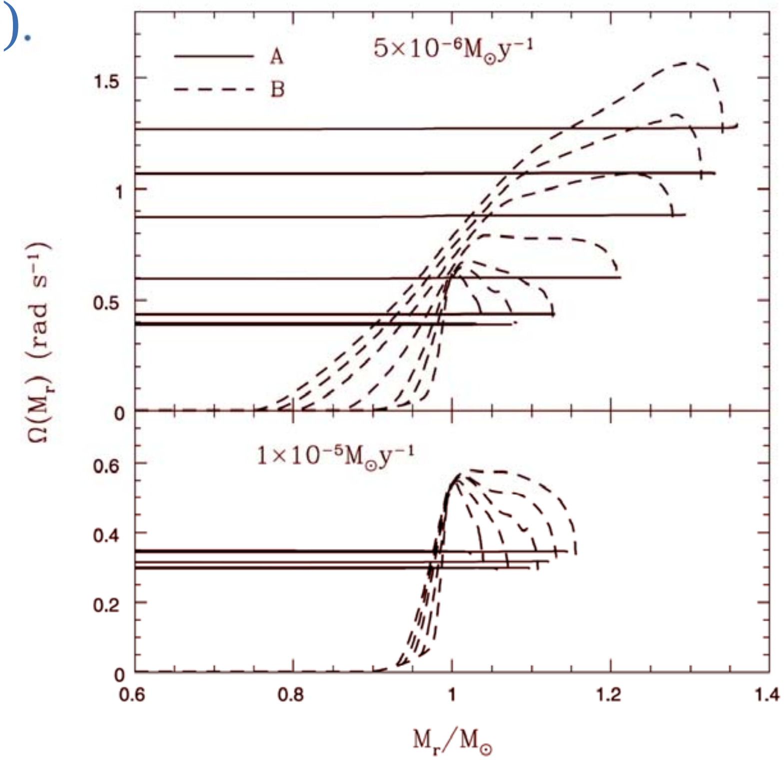
• Fluid perturbations along nearly horizontal directions are unstable, though with a sufficient radial component to allow mixing of A. M. and material (Fujimoto '87, '88; Cumming & Bildsten '00).

• When spin is important (as it is for WDs) the baroclinic viscosity is (Fujimoto 1993)

$$\nu = \frac{1}{3} \frac{Ri_{\rm BC}}{Ri^{3/2}} H^2 \Omega$$

where

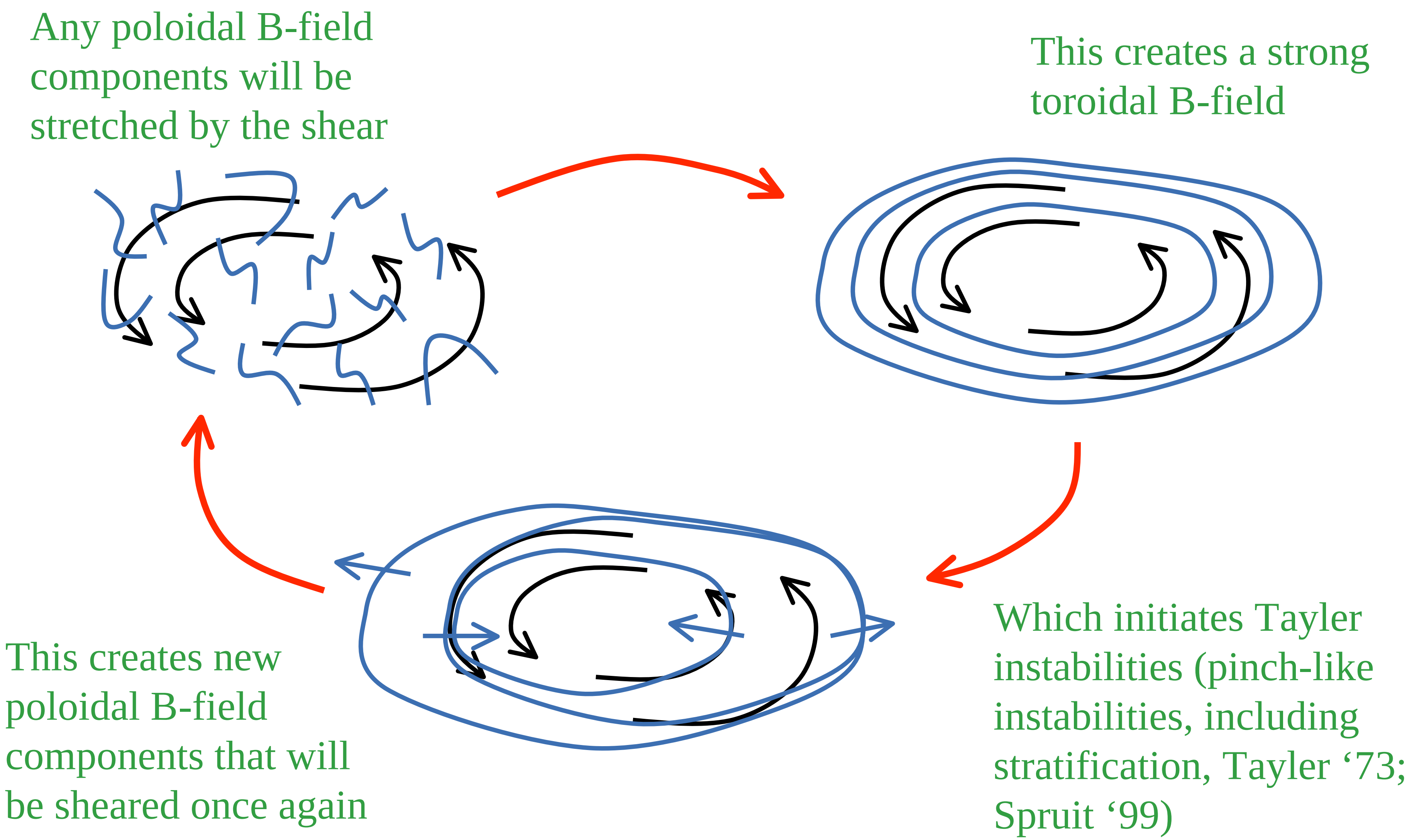
$$Ri_{\rm BC} \equiv 4 \left(\frac{r}{H}\right)^2 \left(\frac{\Omega}{N}\right)^2$$




Saio & Nomoto 2004

# A. M. Transport Mechanisms

## Tayler-Spruit Dynamo
## (Spruit 2002)



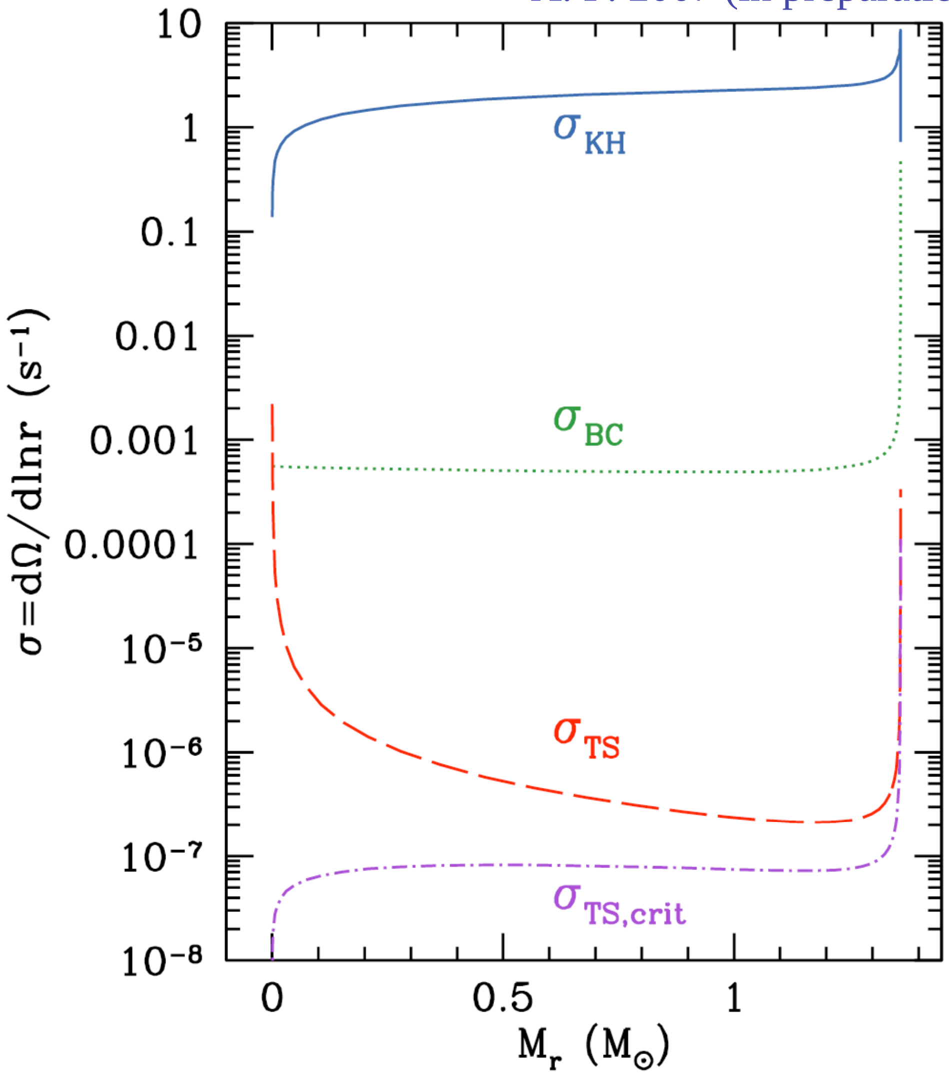
# Steady-state shearing profiles

- We use isothermal WD models to estimate the shear.
- In each case we focus on a single viscosity mechanism to isolate its effects.
- The Tayler-Spruit dynamo gives by far the smallest shear.
- Even if baroclinic instability is correct (and not Tayler-Spruit), it will limit shear well below what is needed for Kelvin-Helmholtz instability.

It appears safe to conclude that the accreting WD will be spinning with nearly uniform rotation.

- Difficult to create super-$M_{ch}$ WDs! (SN2003fg, Howell et al. '06; Steinmetz et al. '92; Pfannes '06)

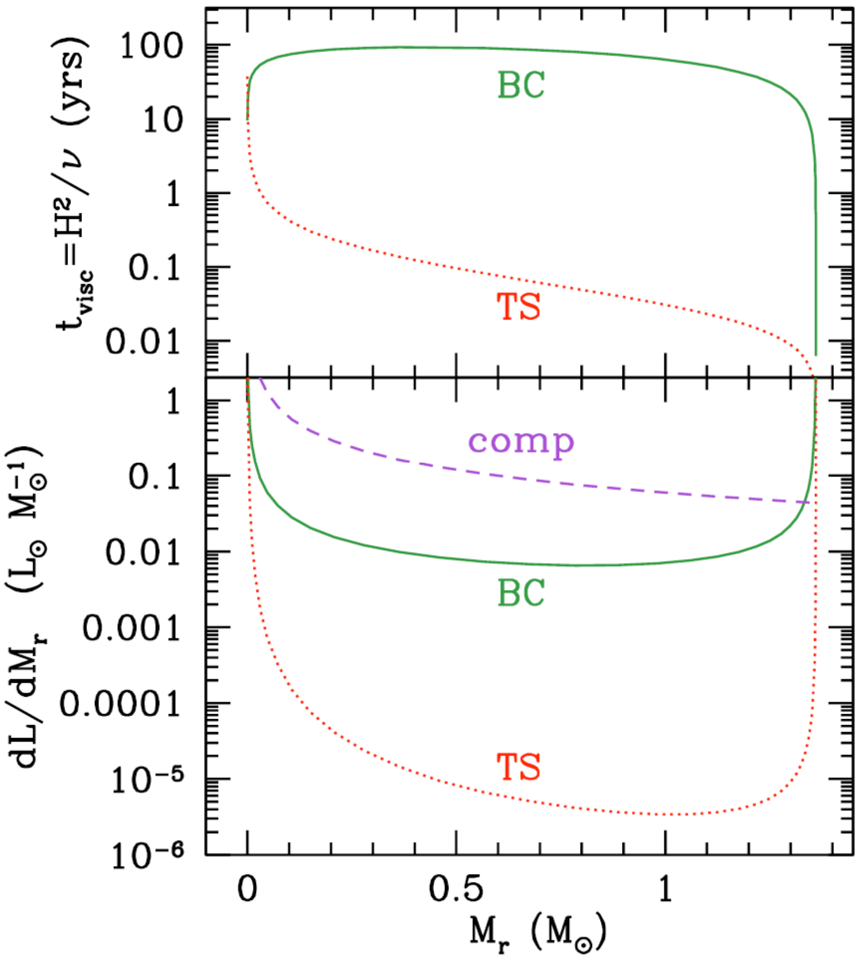
A. P. 2007 (in preparation)

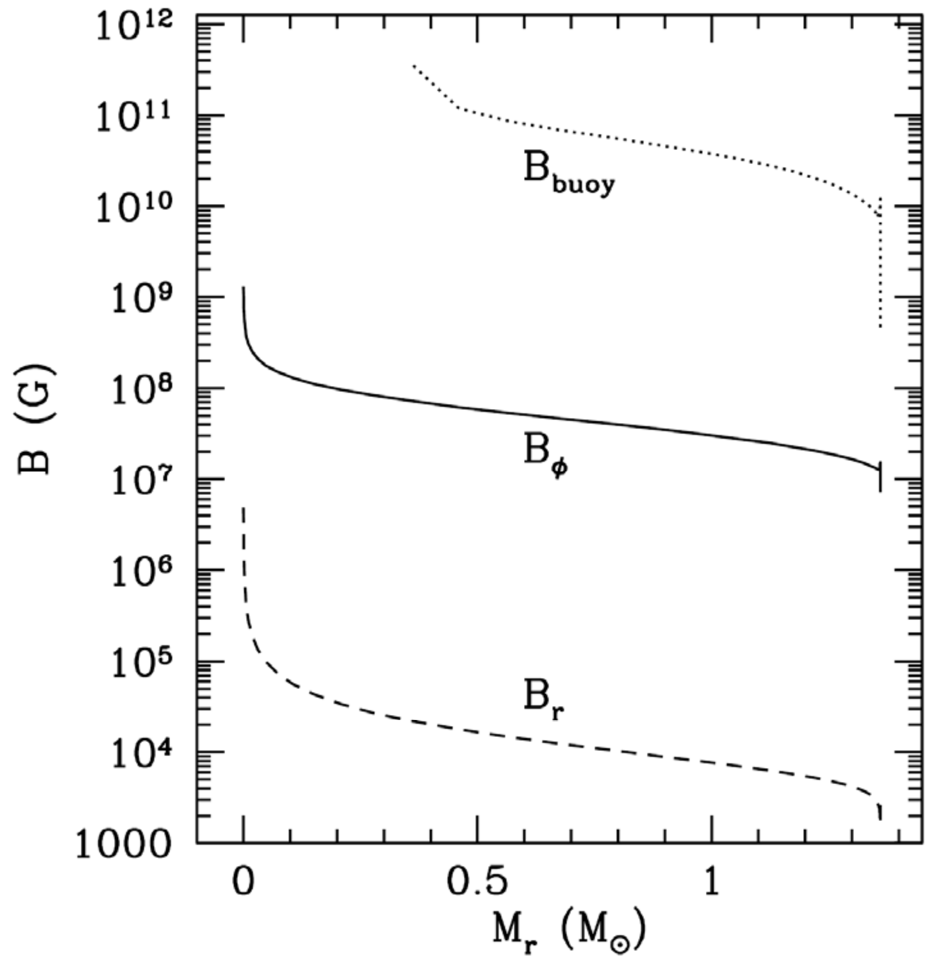



$$\dot{M} = 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$$

$$T = 10^8\ \mathrm{K}$$

# Other properties of the shearing




- Steady-state is a good approximation

- Heating from compression beats viscous heating for $\dot{M} > 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ (also see Saio & Nomoto 2004)

$$B_\phi, B_r \propto \dot{M}^{1/2}$$

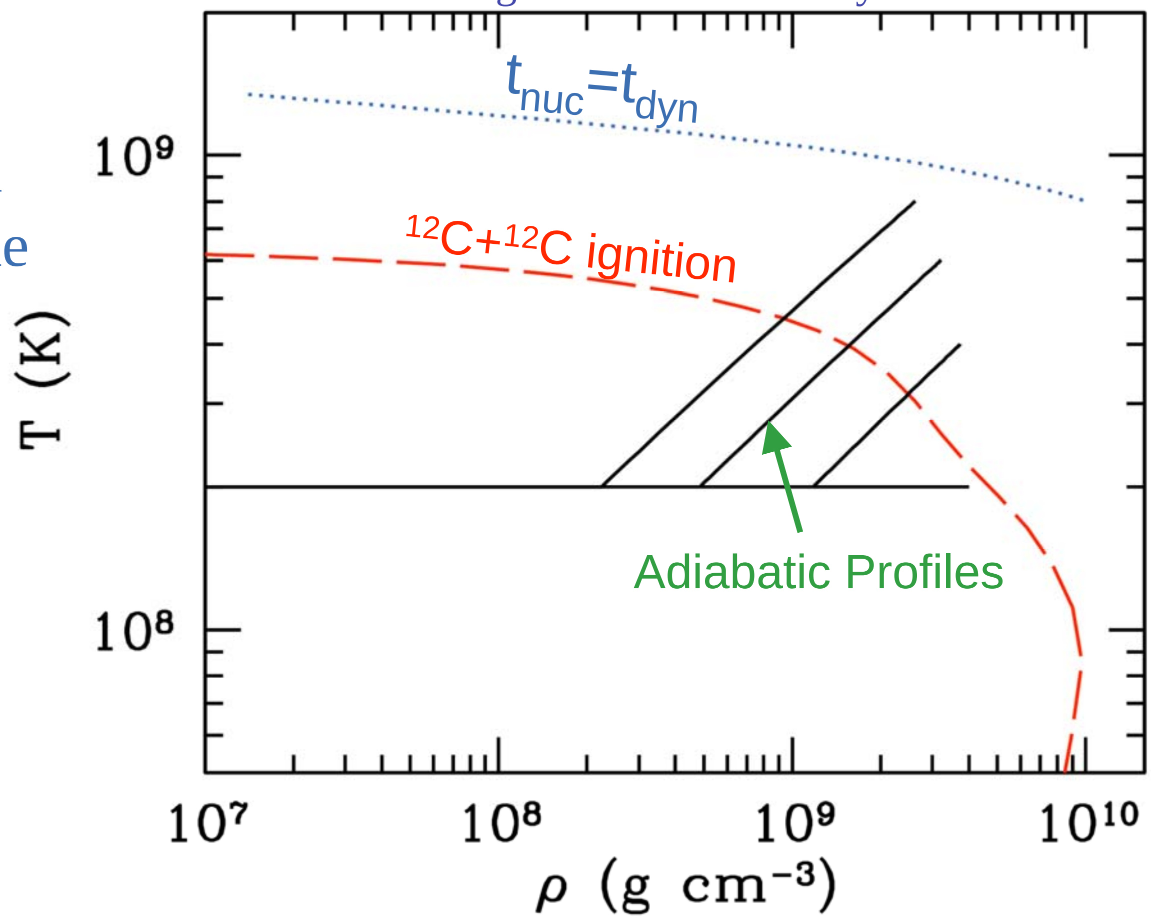
- If there is an observable that depends on this B-field strength it would be an important discriminate between progenitor models

# Simmering and Convection

- When carbon ignites, a convective region grows at the WD center. Convection envelopes $\sim 1\ M_{\odot}$ of the WD over ~1000 yrs, until the deflagration finally initiates.

- This phase has received attention in recent years because it sets the distribution of ignition points, which is important for the flame (Woosley et al. '04; Wunsch & Woosley '04; Kuhlen et al. '06)

Ignition curve courtesy D. M. Yakovlev



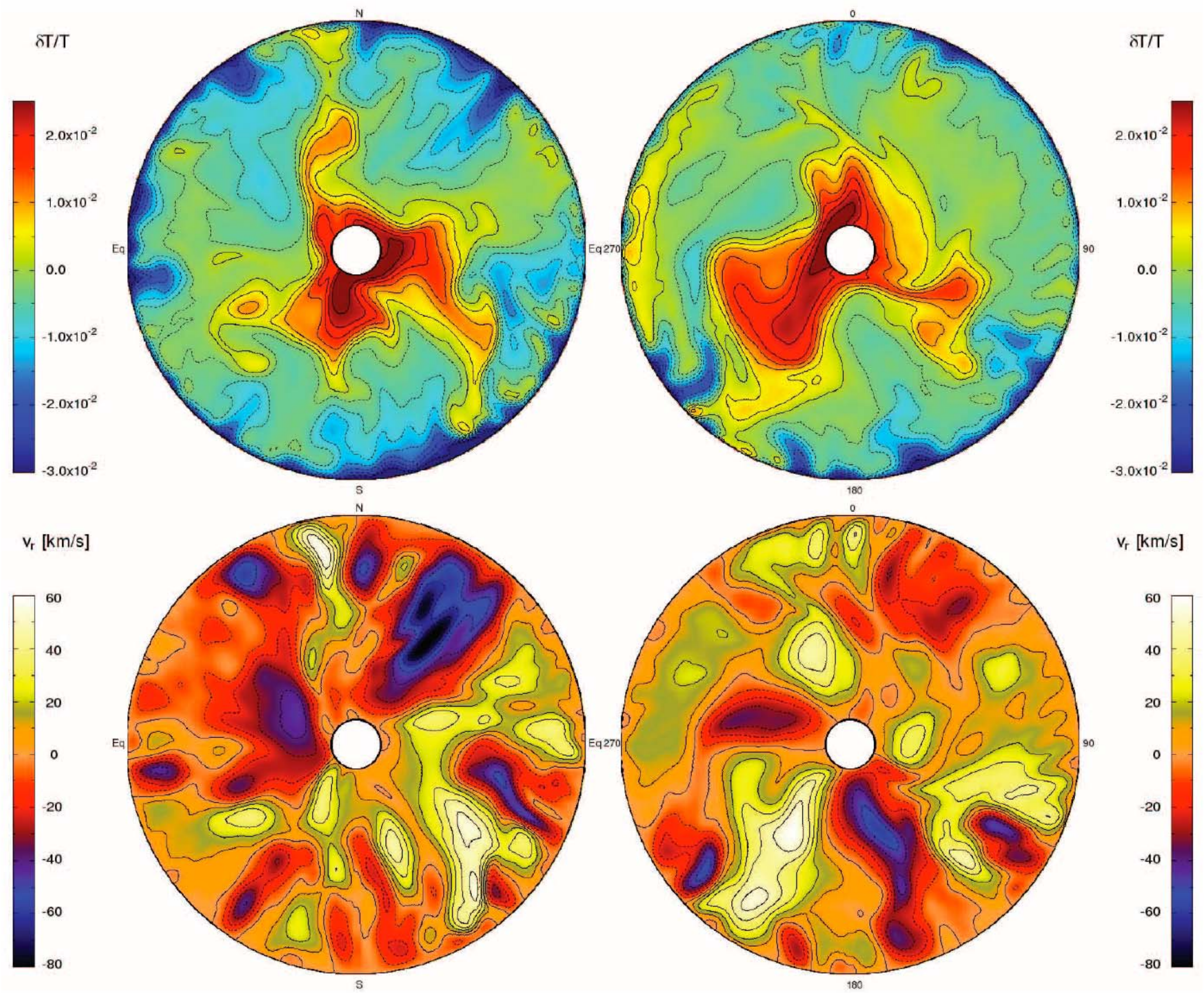

Characteristic Parameters of Convection

| | | |
|---|---|---|
| Ra ~ $10^{25}$ | Pr ~ $10^{-3}$ | Re ~ $10^{14}$ |
| Ro ~ $10^{-1}$ | Ma ~ $10^{-3}$ | Ek ~ $10^{-14}$ |

# Simulations of Convection for WDs

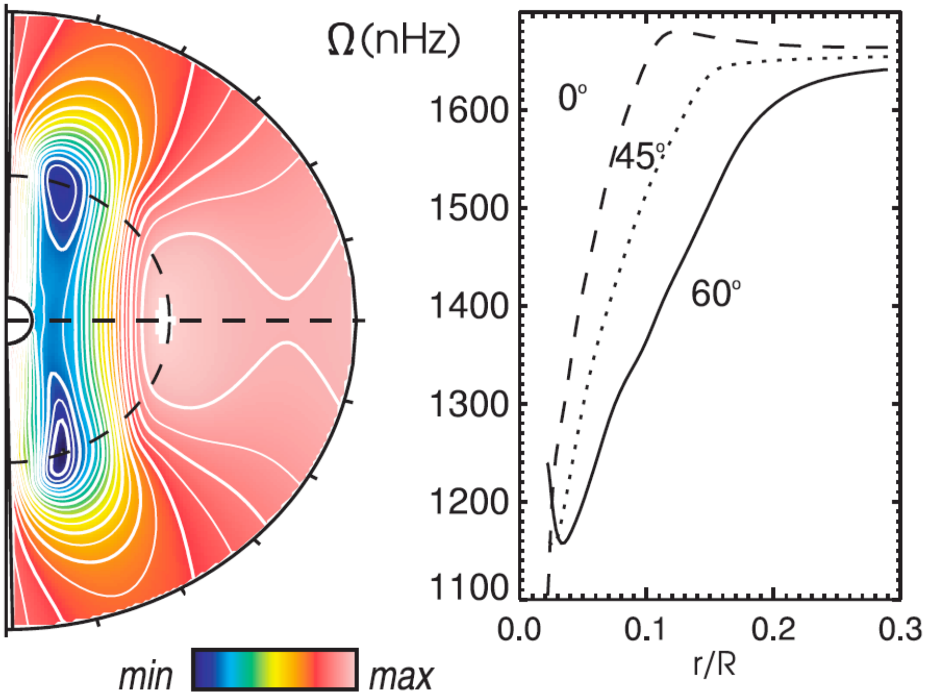
Kuhlen et al. 2006

- Simulations of SN Ia convection focus on ignition points for subsequent burning.
- Uniform rotation is set as a fixed background state.
- Is it possible for convection to redistribute angular momentum during the simmering phase?

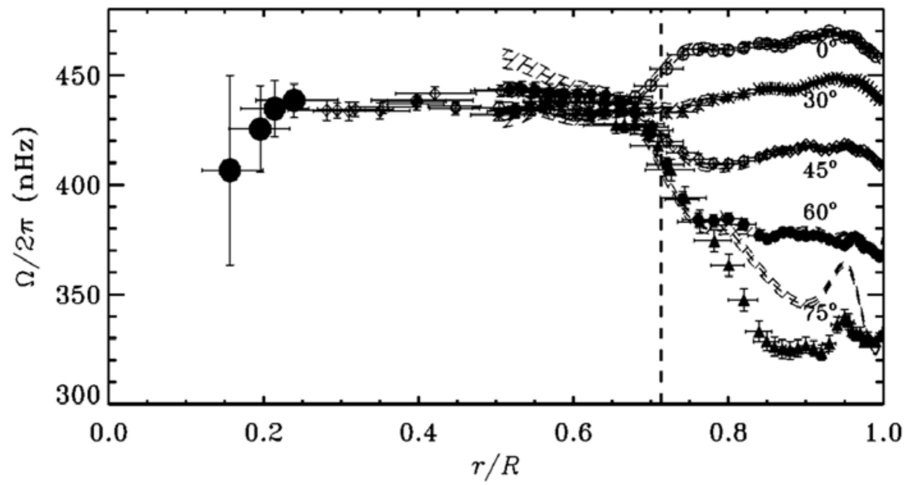


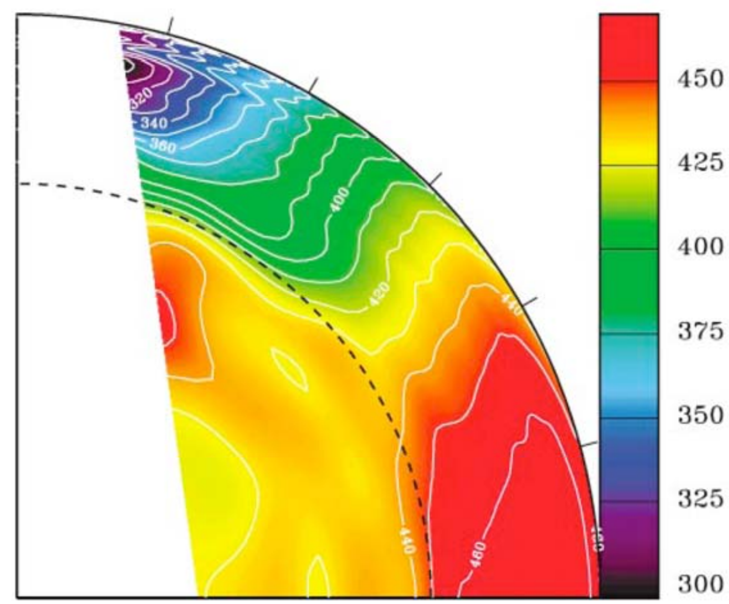
# Convection and Rotation Together

Simulations of Rotating A-Stars; Browning et al. 2004




Helioseismic measurements; Thompson et al. 2003



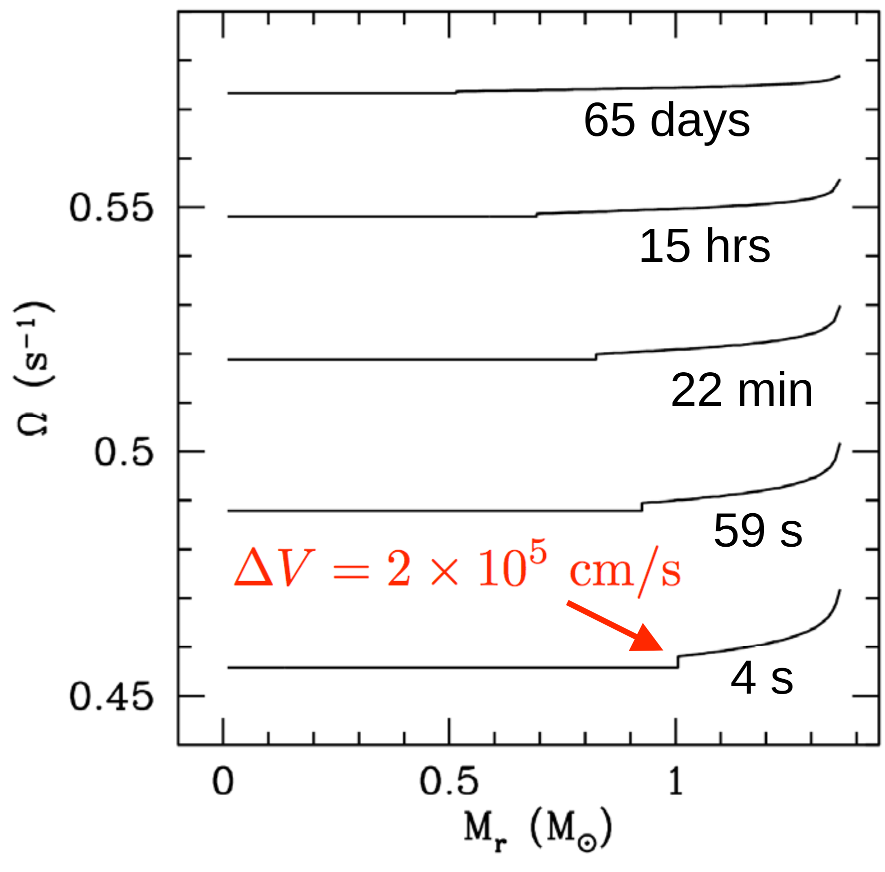




A generic feature of low Rossby number convection is angular momentum transport toward the equatorial region (Gilman '79; Miesch et al. '00; Brun & Toomre '02).

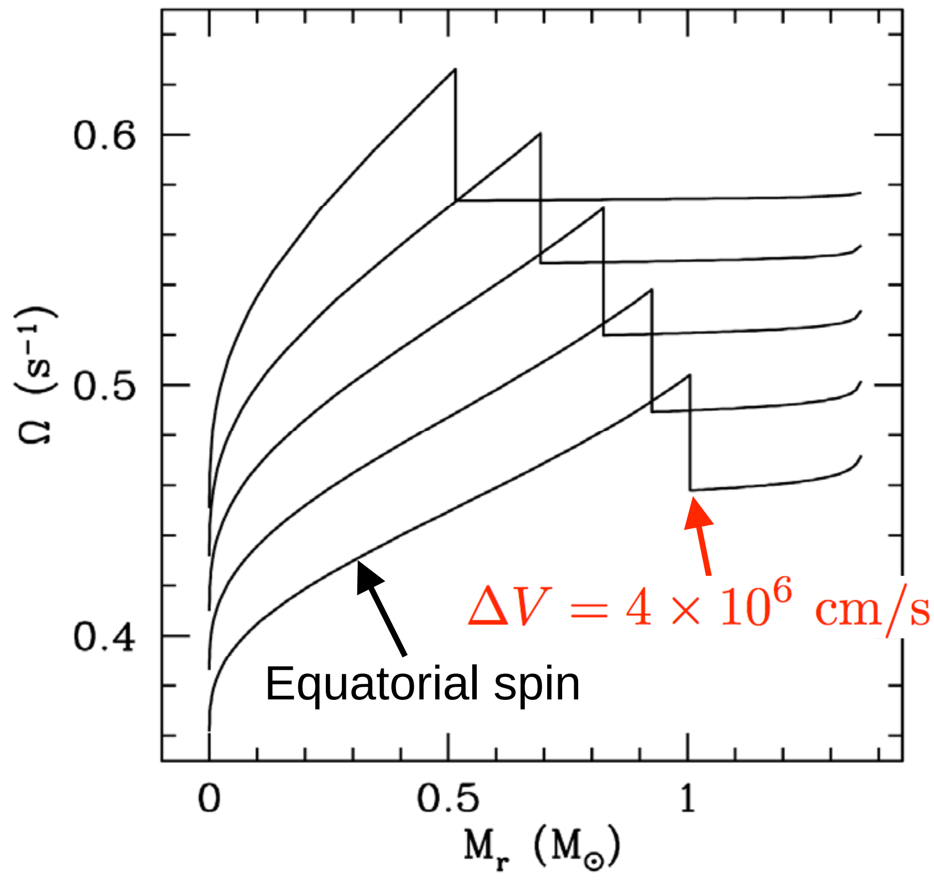
This leads to Taylor-Proudman-like features in simulations.

# Redistribution of A. M. By Simmering

- Convection assumed to enforce solid body rotation.
- Convectively stable region obeys local angular momentum conservation
- Shearing between regions is modest.




- Convection assumed to have cylindrical rotation law with 40% increase (like other low Rossby number examples)
- Much greater shearing is found



# Summary and Conclusions

## Spreading layer

• Boundary layer calculations show that azimuthal velocity becomes very sub-Keplerian within a short amount of time.

• Spreading implies shallower effective temperature dependence on accretion rate than if angle was fixed, which may be revealed in dwarf novae.

## Shearing in core

• The WD core must have a shearing profile to transmit the torque from accretion. This shearing is so small that uniform rotation is probably a good approximation.

• The lack of much shear makes it difficult to create super-$M_{Ch}$ mass WDs.

• The TS-dynamo creates an azimuthal B-field with a strength of $10^7$-$10^9$ G.

## Simmering phase

• Redistribution of angular momentum by convection may introduce shearing between the convective.

• If this shearing is able to persist it may have interesting interactions with flame