Rotation, Magnetism, and Nucleosynthesis during Smoldering Phase

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Piro & Bildsten 2008 ApJ 673 1009
Piro & Chang 2008 ApJ 678 1158
Piro 2008 ApJ 679 616
Chang & Piro 2009 (in preparation)

Outline of Talk

General summary of pre-explosive convective simmering

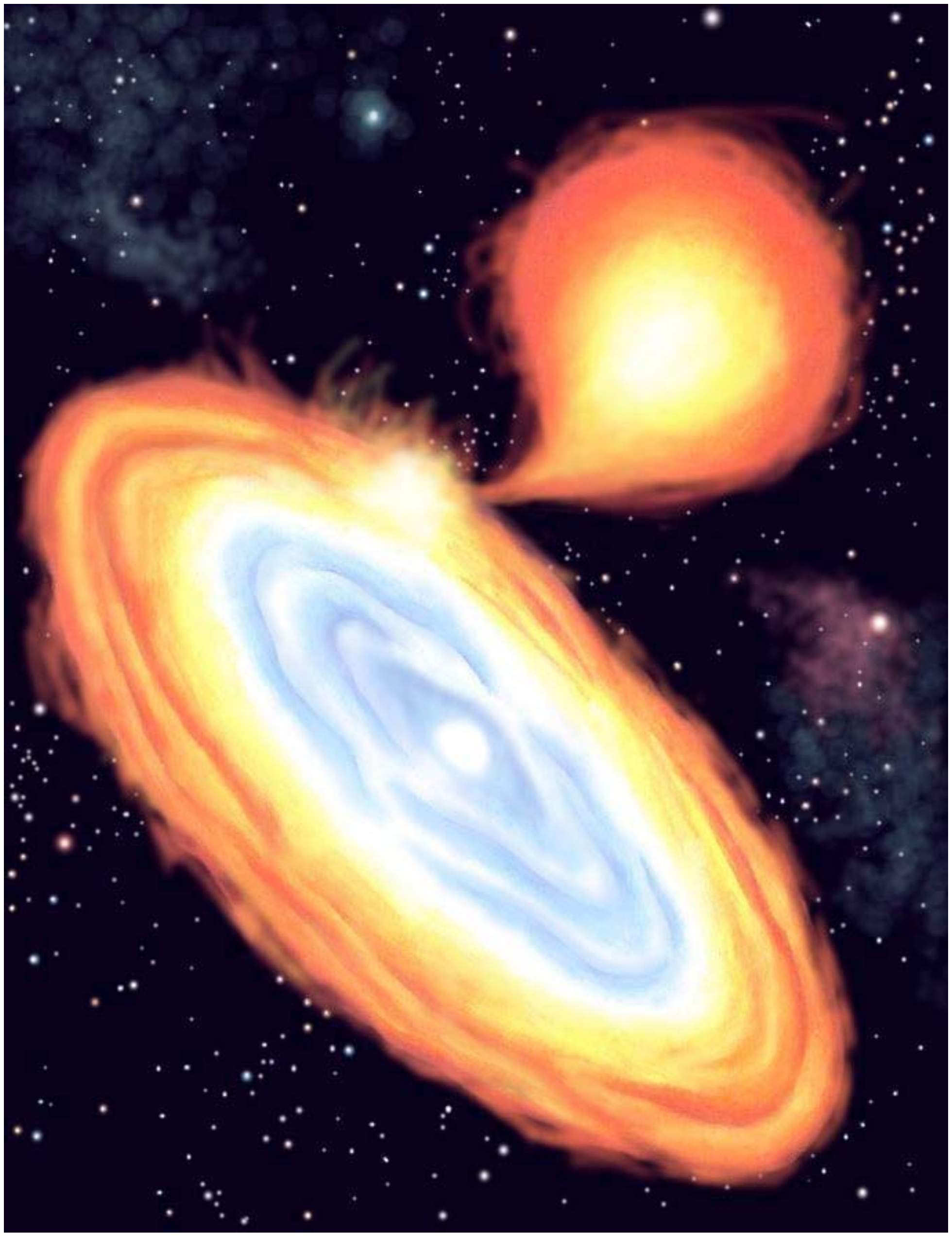
- Convective luminosity and turbulent velocities
- Size of the convective region

Impact of convective simmering

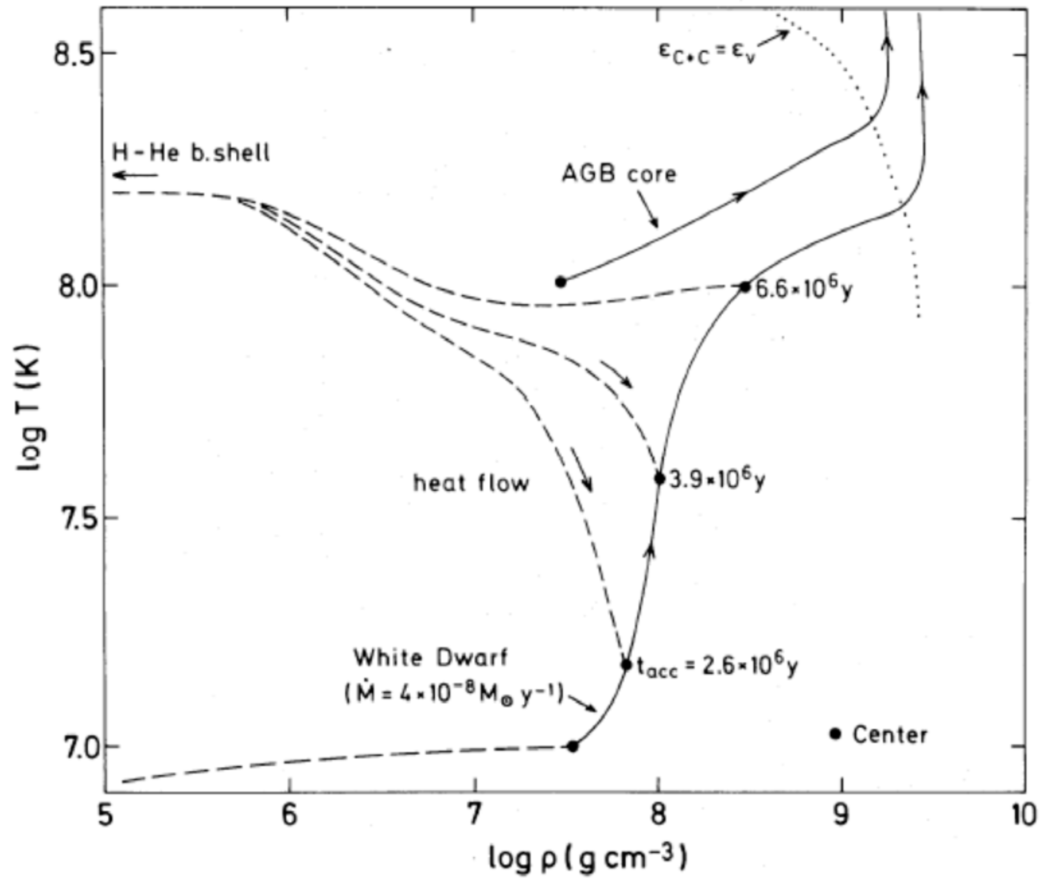
- Neutronization and production of ^{56}Ni
- Dynamo creation?

Conclusions and Discussion of Future Work

Type Ia Supernovae: The thermonuclear explosion of a C/O white dwarf



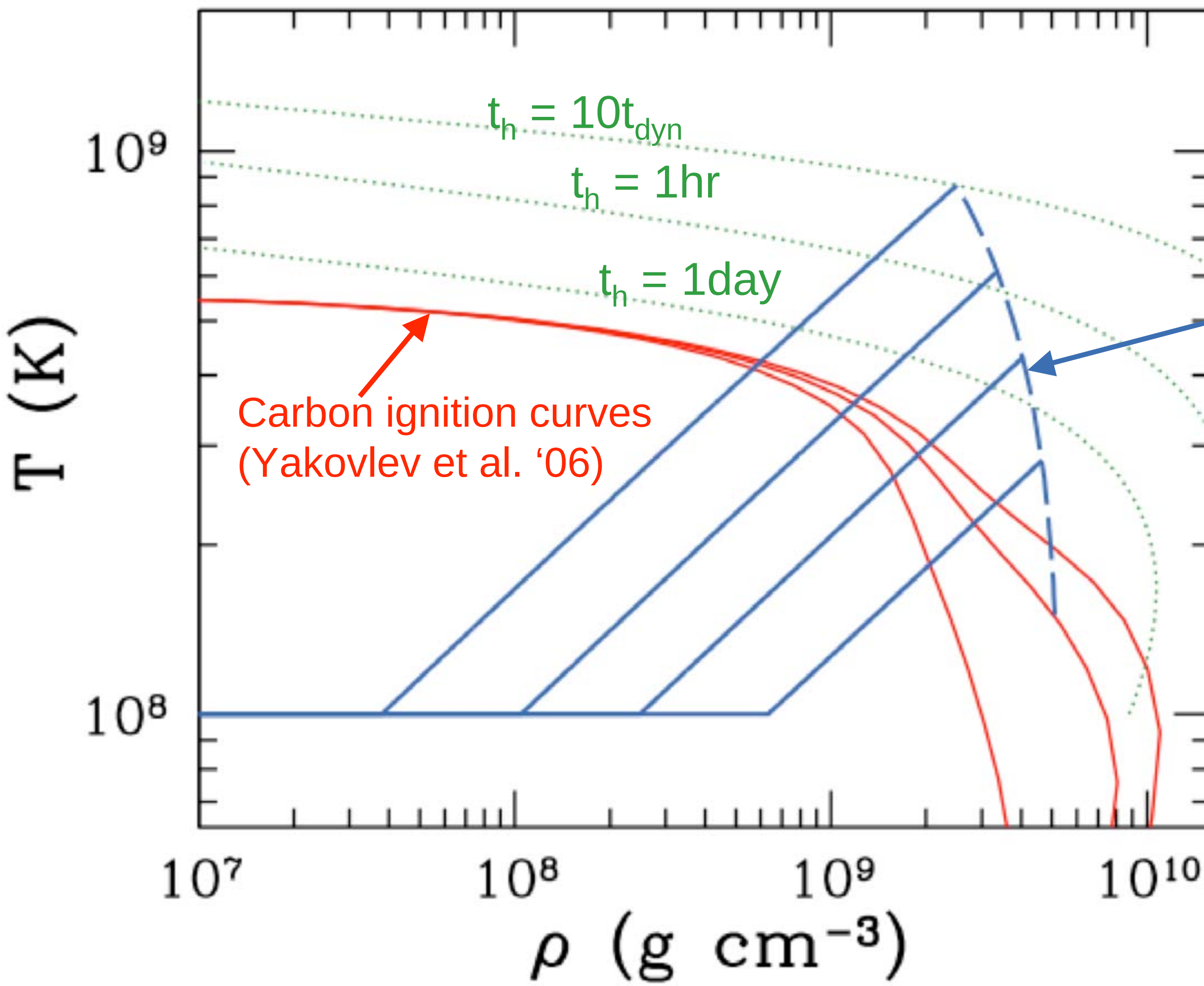
Nomoto, Thielemann, & Yokoi (1984)



Single degenerate scenario: Accretion increases central temperature and density until carbon ignites unstably $M_{\rm Ch} \sim 1.4 M_{\odot}$

When carbon first ignites, the white dwarf does NOT go KA-BOOM!

Nomoto et al. 1984; Woosley & Weaver 1986



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Previous Theoretical Studies of Simmering:

The Convective Urca Process

(Paczynski ‘72; Bruenn ‘73; Couch & Arnett ‘75; Iben ‘78, ‘82; Barkat & Wheeler ‘90; Mochkovitch ‘96; Stein et al. ‘99; Lesaffre et al. ‘05; Stein & Wheeler ‘06)

- Electron captures and beta decays occur repeatedly as nuclei are carried by convection back and forth across the electron capture threshold density (usually ^{23}Na)

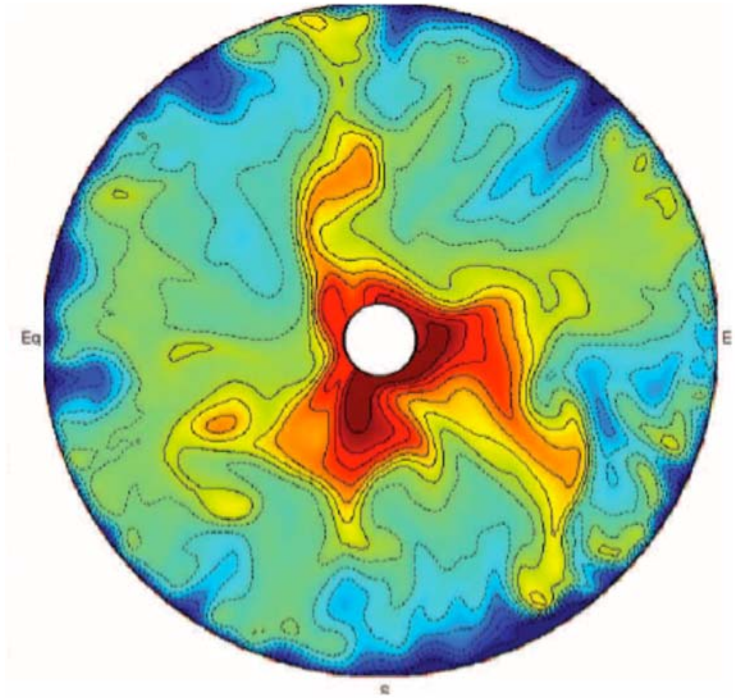
- Convective Urca does not cause global cooling, but it affects convective motions and slows heating (Lesaffre et al. ‘05).

- Only important until $T_c \approx 5 \times 10^8$ K (~10^5 s before burning wave begins)

Previous Theoretical Studies of Simmering:

Multi-point Ignition

(Woosley et al. ‘04; Wuncsh & Woosley ‘04; Kuhlen et al. ‘06; Almgren & Zingale)

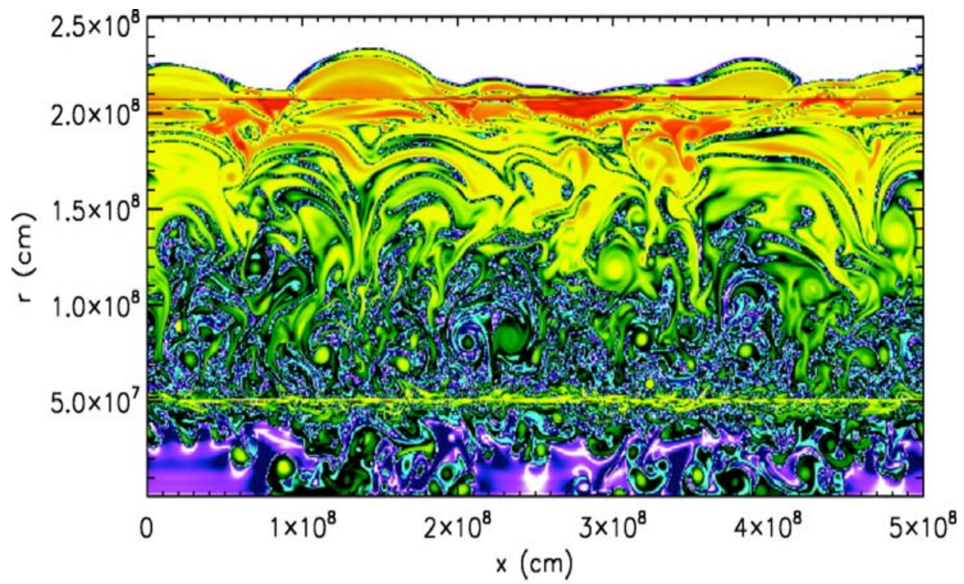


• Ignition at multiple points off-center around ~100-150 km.

• Rotation may be important for eliminating any strong dipolar component (Kuhlen, Woosley, & Glatzmaier ‘06)

• Initial flame geometry has proven to have a LARGE EFFECT on explosion strength (Niemeyer et al. ‘96; Livne et al. ‘05; Röpke et al. 2006).

• More points => more robust burning, but hard to resolve the correct number of ignition points in 3D (Röpke et al.)



Almgren, Bell, Nonaka, & Zingale 2008

Calculating the Convective Zone

Properties of the convection:

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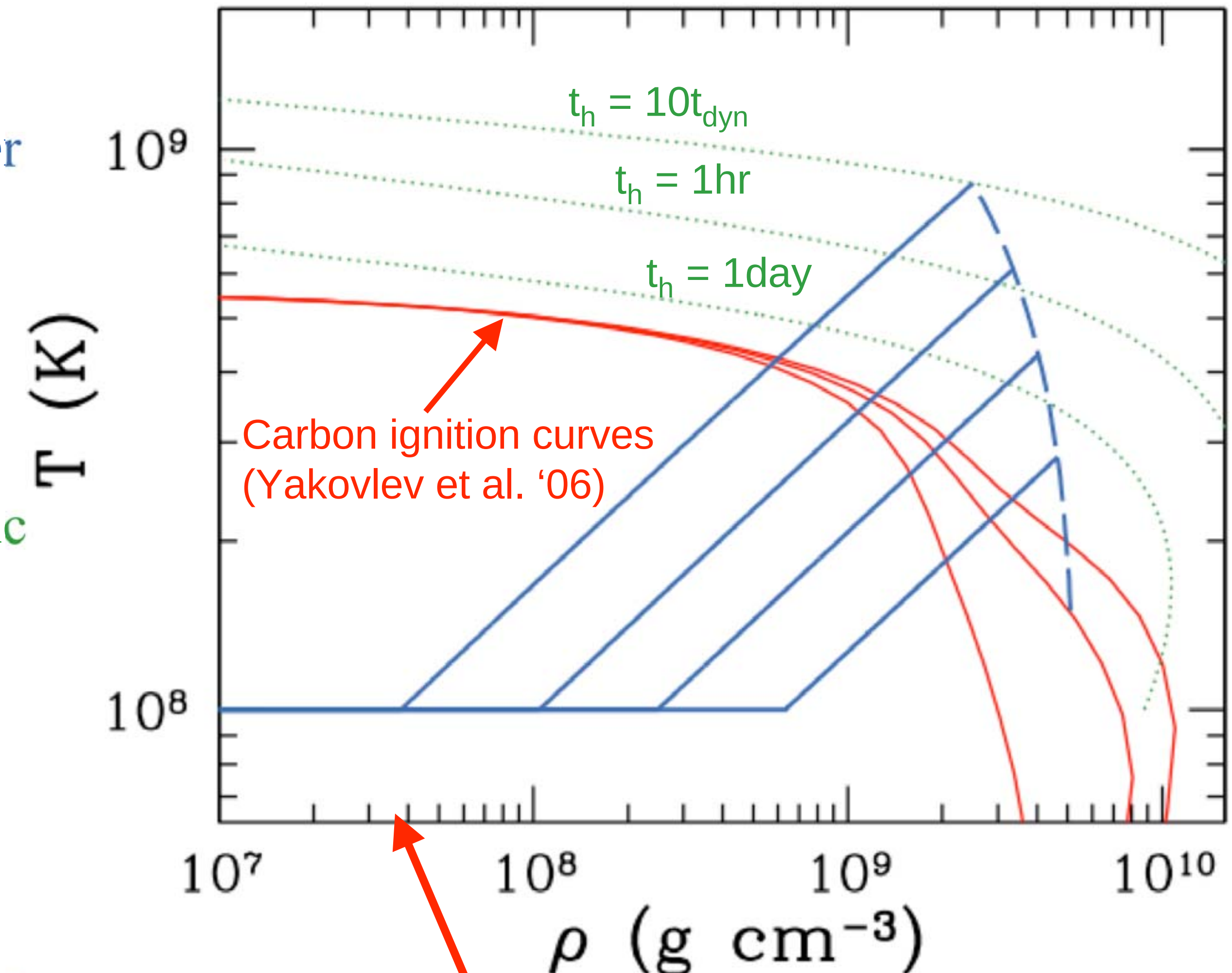
- Sub-sonic (Ma<<1)
- Heating timescale much shorter than conductive timescale

$$t_{\rm cond} \sim 10^6 \text{ yrs}$$

Plan of attack:

- Calculate a series of hydrostatic models with different core T's.
- The convective zone is nearly an adiabat, while the outer conductive zone is nearly isothermal.
- The thermal profile is specified for any central core temperature WITHOUT having to explicitly solve the time dependent evolution.



Similar to the transition density for a DDT

Convective Luminosities & Velocities

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- In "typical" convection, the convective luminosity balances the nuclear energy generation:

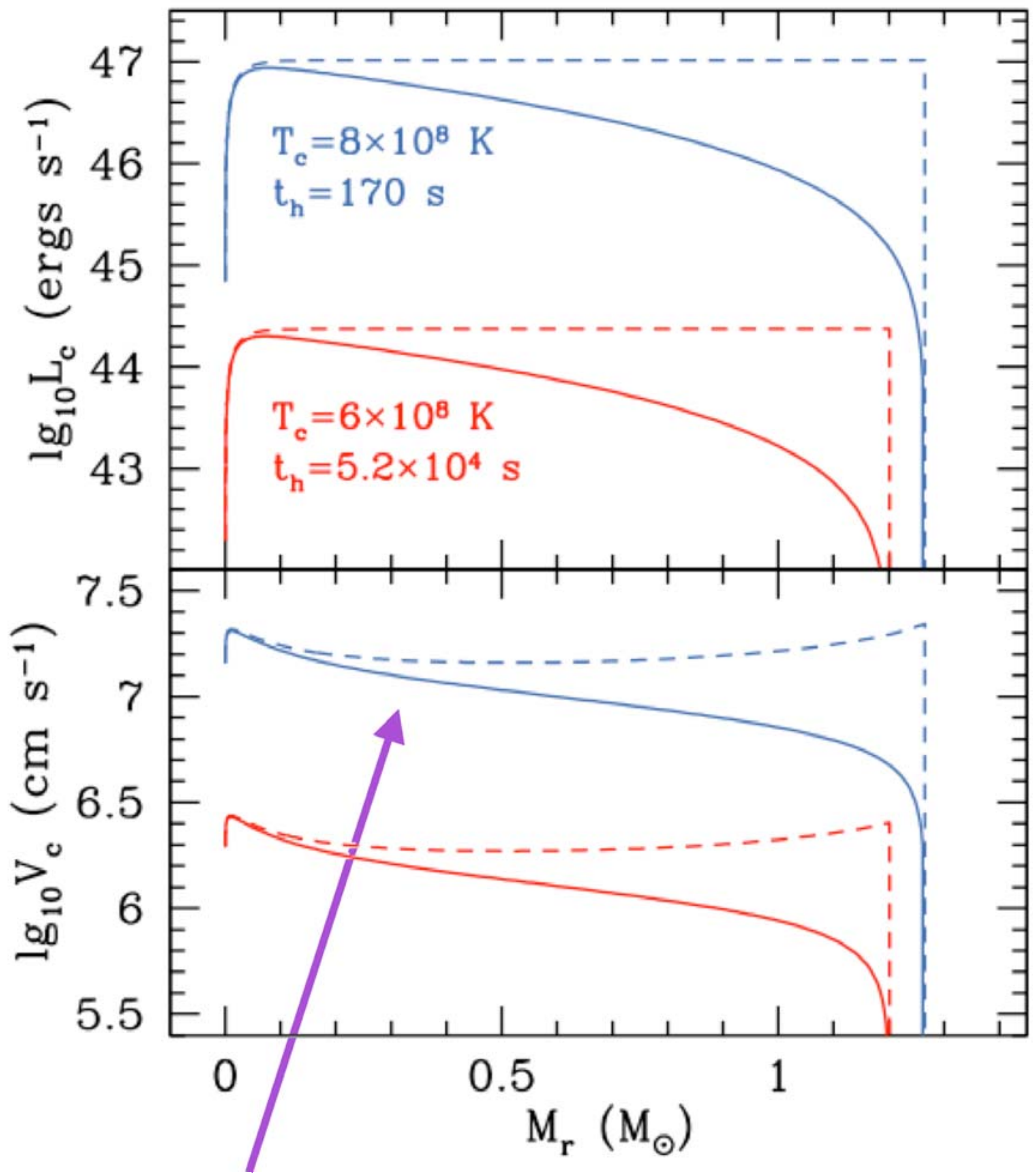
$$L_c(M_r) = L_{nuc}(M_r) = \int_0^{M_r} \epsilon dM_r$$

- For SNe Ia case, energy must go into heating the core, decreasing the convective luminosity:

$$L_c(M_r) = L_{\rm nuc}(M_r) \times \left[1 - \frac{E_{\rm th}(M_r)}{E_{\rm th}(M_c)}\frac{L_{\rm nuc}(M_c)}{L_{\rm nuc}(M_r)}\right]$$

- Temperature increases on a timescale that depends on the size of convective zone:

$$t_h = E_{\rm th}(M_c)/L_{\rm nuc}(M_c)$$



Velocities similar to burning wave speeds later

Size of the Convective Zone

Since the EOS is dominated by relativistic, degenerate electrons and the profile is an adiabat, the mass of the convective zone merely depends on two parameters:

- The mean molecular weight

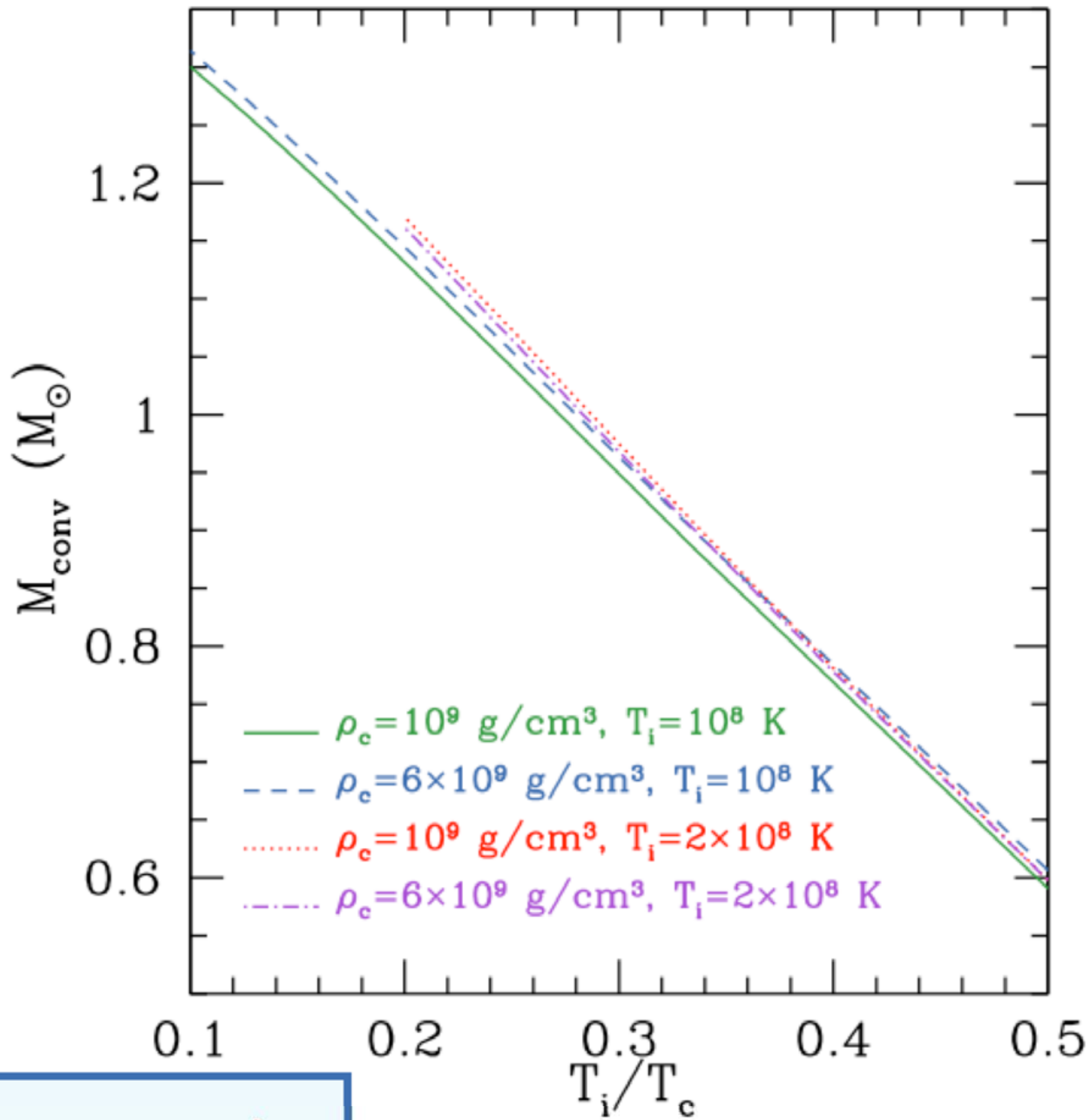
$$\mu_e$$

- The temperature ratio

$$T_i/T_c$$

A fit to the numerical integrations gives the simple relation:

$$M_{\rm conv} = 1.48\ M_\odot \left(\frac{2}{\mu_e}\right)^2 \left(1 - 1.20\frac{T_i}{T_c}\right)$$



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Radioactive Powering of the Lightcurve

• Lightcurve powered by radioactive decay ^{56}Ni => ^{56}Co => ^{56}Fe (Truran '67; Colgate & McKee '69)

• Arnett (1982) (also see Pinto & Eastman '00) showed that the peak luminosity occurs when the radiative diffusion time through the ejected envelope equals the time since explosion

• The peak luminosity measures a ^{56}Ni mass of $\sim (0.1 - 1.0) M_\odot$ (consistent with Zorro-diagram from Mazzali et al. '07)

• Outside $\sim 0.2 M_\odot$ few weak reactions occur, so the fractions of ^{56}Ni, ^{58}Ni, and ^{54}Fe can be estimated from NSE (Timmes, Brown & Truran '03)

$$X(^{56}\mathrm{Ni}) = 58 Y_e - 28$$

$$Y_e = \frac{1}{2} - \frac{2X(^{56}\mathrm{Fe})}{56} - \frac{X(^{22}\mathrm{Ne})}{22}$$

Most important piece

^{22}Ne?!?!

Where does ^{22}Ne come from?

- The slowest step during CNO-burning is proton captures on ^{14}N. All CNO catalysts pile up into ^{14}N when CNO burning is completed.

- During helium-burning the reactions

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+},\nu_e)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$$

converts all ^{14}N into ^{22}Ne. Thus ^{22}Ne tracks the metallicity

$$X(^{22}\mathrm{Ne}) = 22\left[\frac{X(^{12}\mathrm{C})}{12} + \frac{X(^{14}\mathrm{N})}{14} + \frac{X(^{16}\mathrm{O})}{16}\right]$$

But can ^{12}C simmering add neutrons?

- This would add an additional term to determining Y_e

$$Y_e = \frac{1}{2} - \frac{2X(^{56}\mathrm{Fe})}{56} - \frac{X(^{22}\mathrm{Ne})}{22} - fX(^{12}\mathrm{C})$$

Fudge factor depending on amount of ^{12}C burned and neutrons per reaction

Neutronization During Simmering

Piro & Bildsten 2008 (also see Chamulak et al. '08)

Reactions during simmering add to the neutronization

$^{12}C(^{12}C, p)^{23}Na$

$^{12}C(^{12}C, \alpha)^{20}Ne$

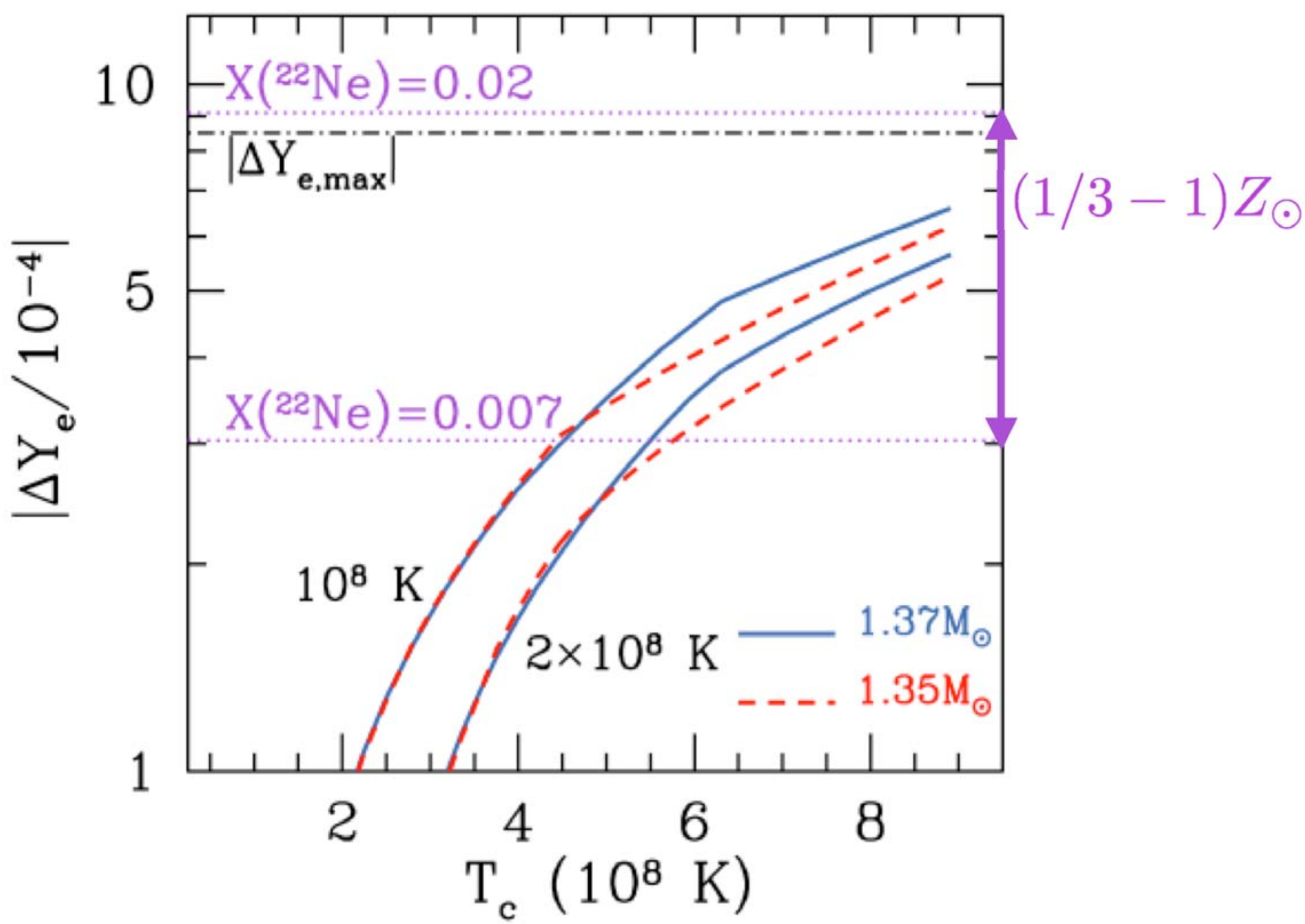
$^{12}C(p, \gamma)^{13}N$

$^{13}N(e^-, \nu_e)^{13}C$

$^{13}C(\alpha, n)^{16}O$

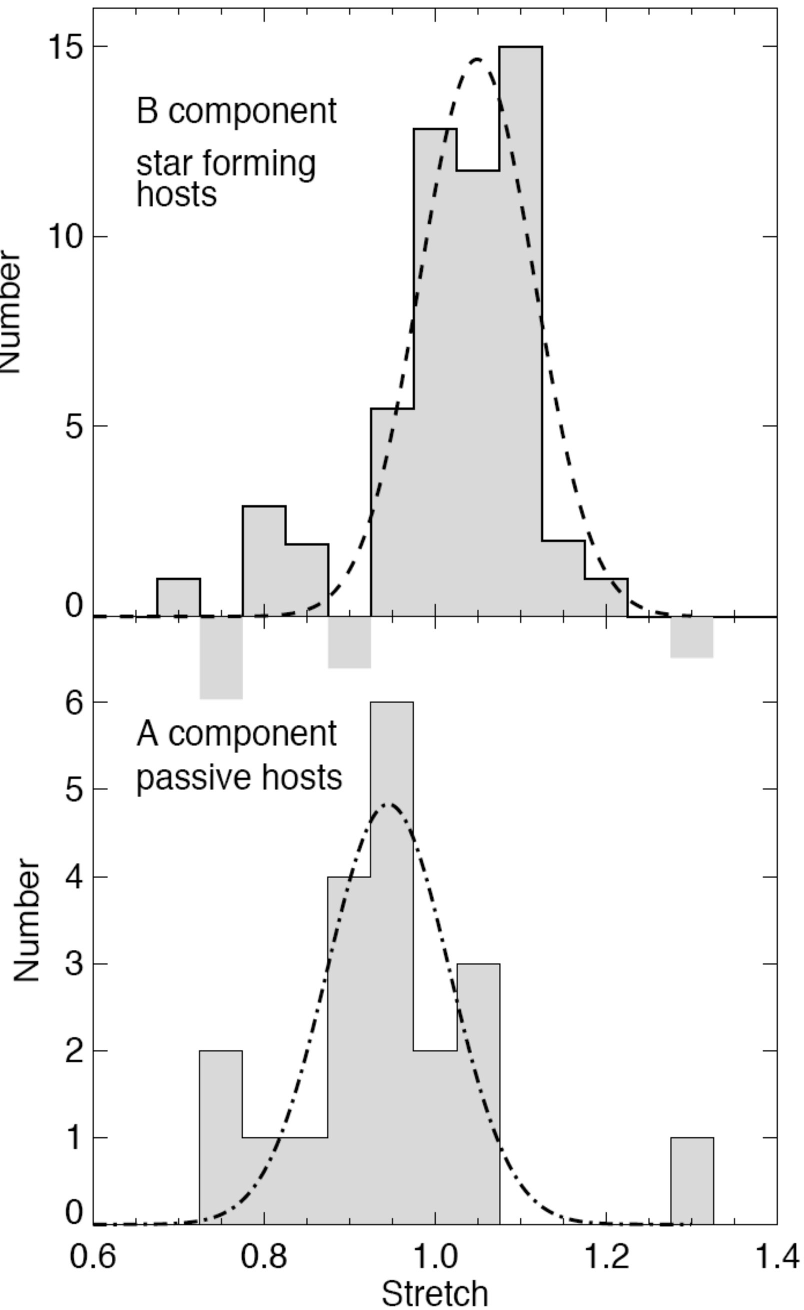
$^{12}C(n, \gamma)^{13}C$

$^{23}Na(e^-, \nu_e)^{23}Ne$



For every 6 ^{12}C burned either 1 or 2 additional neutrons are made (depending on density).

Can Neutronization Explain Diversity?



Howell et al. ‘07, ApJL, 667, L37

• Using the average luminosity in each population with Mazzali et al.’s (‘07) relation $\approx 0.13 M_\odot$ more ^{56}Ni is made in SNe Ia in star forming galaxies

• Using the mass-metallicity relation of Tremonti et al. ‘04, SNe in ellipticals have twice as much ^{22}Ne as those in spirals

• In contrast, explaining the 56Ni range requires a contrast $\Delta X(^{22}\mathrm{Ne}) \approx 0.06$ (nearly 3 times solar)

Even including simmering neutronization can’t bridge this discrepancy!

See the recent study by Howell et al. ‘09, which confirms these results and argues that age may be a stronger factor.

May the effect of neutronization be larger?

Counting argument from neutronization does not simply explain the observed diversity, but there are many interesting complications:

• The flame speed can change by as much as 30% for different ^{22}Ne abundances (Chamulak, Brown, & Timmes 2007). Although Townsley et al. 2009 find there may be little noticeable effect.

• ^{22}Ne sedimentation (Bildsten & Hall '01; Deloye & Bildsten '02) may enhance central concentration and decrease convective zone size

• Size of the convection zone may change (see next slide!)

Neutronization (metallicity+simmering) may be a secondary parameter for the width-luminosity relation with something else (DDT transition density? Age?) as the primary parameter.

Compositional Effects

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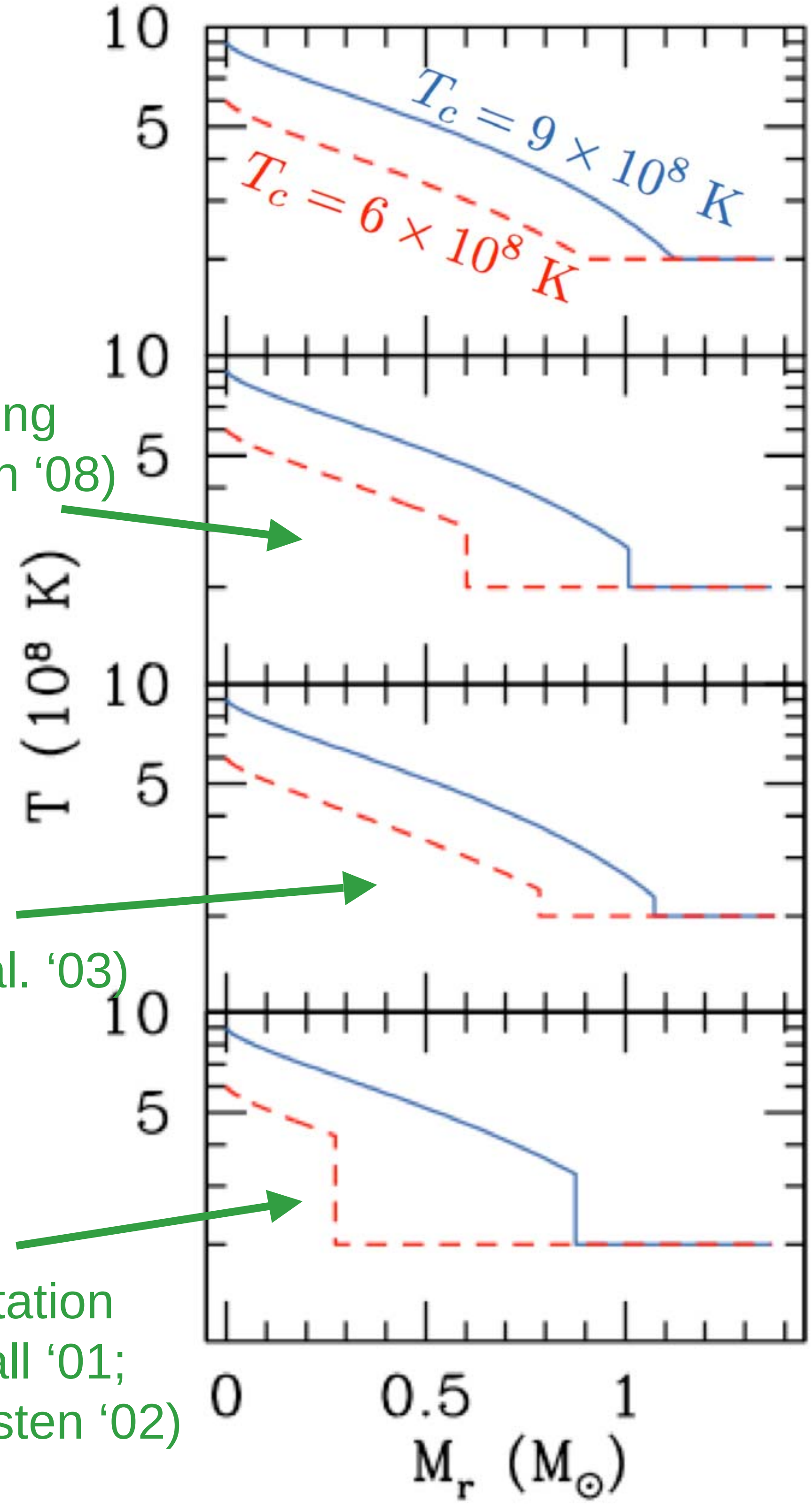
- Buoyantly rising eddies ascend until their density matches their surroundings.
- **Compositional gradients** result in **temperature discontinuities** at the top of the convective zone.
- Such effects are important if the DDT is affected by the extent of convection.
- The metallicity of the progenitor can be estimated from SN Ia remnants, which will be affected by extent of convection (Badenes et al. '08 infer super-solar metallicity)

Neutronization during simmering (Piro & Bildsten '08)

$^{12}C/^{16}O$ comp. gradients (Straniero et al. '03)

^{22}Ne sedimentation (Bildsten & Hall '01; Deloye & Bildsten '02)



Spin + Convection = Dynamo?

• Simulations of core convection in A-stars (Brun et al. 2005) find interaction of spin and convection leads to a dynamo in equipartition with convective velocities.

• Core convection in WDs is similar in many ways, including a similar convective Rossby number

• For an initial guess, let's see what equipartition gives for the magnetic field strength:

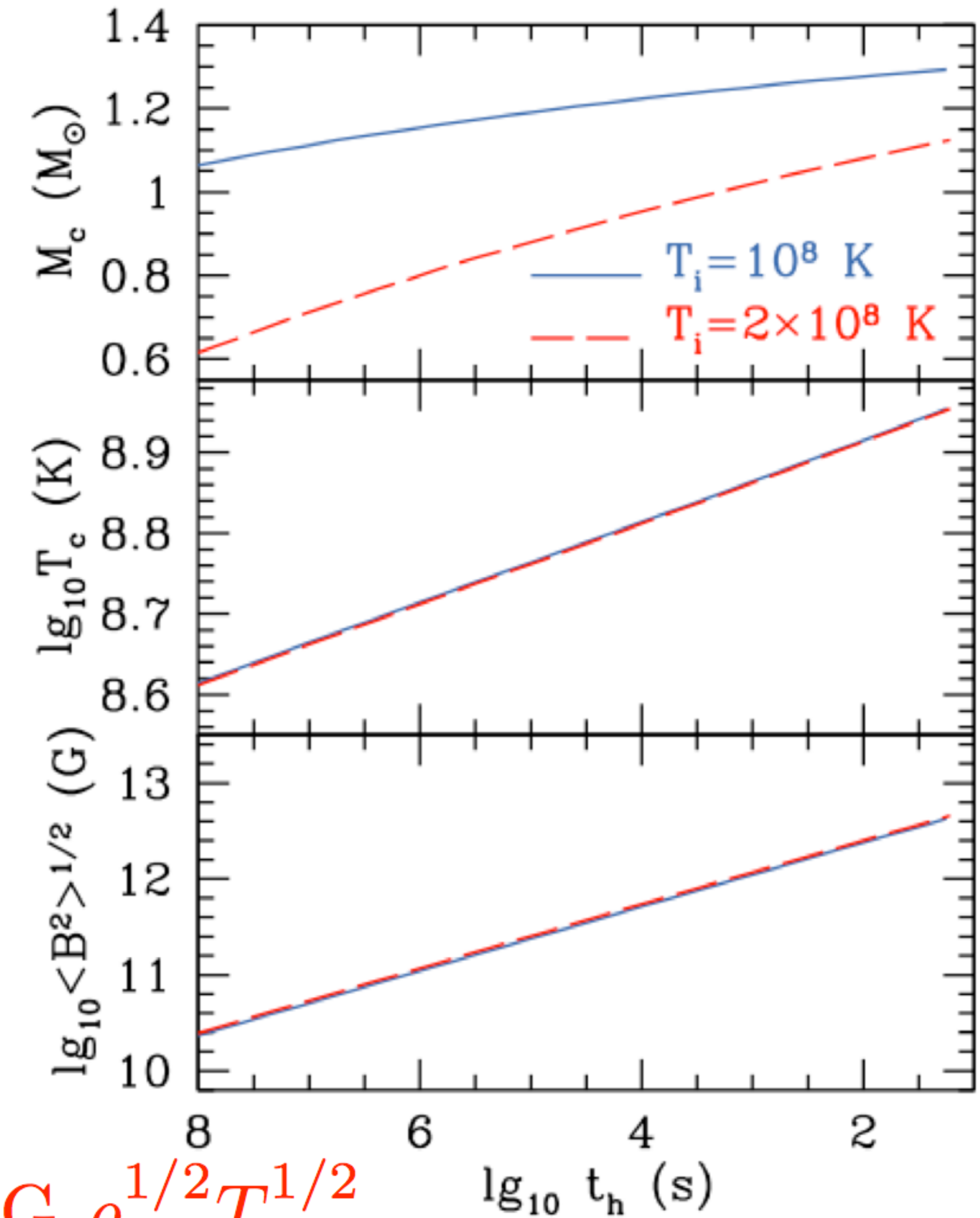
$$B^2/(8\pi) \sim \rho V_c^2$$

• At late stages, convective energy density is nearly equal to the thermal energy

$$\rho V_c^2 \sim \rho \frac{k_B T_c}{A m_p}$$

$$B \sim 10^{12}\ \mathrm{G}\ \rho_9^{1/2} T_9^{1/2}$$

Chang & Piro 2009 (in prep.)



Conclusions

- The WD undergoes ~1000 yrs of convection prior to explosion. Characteristic velocities are ~200 km/s at late stages.

- The size of the convective region is sensitive to compositional gradients. Most important may be ^{22}Ne sedimentation.

- Neutronization during simmering is competitive with metallicity effects at $Z < (2/3)Z_{\odot}$, but the observed range of ^{56}Ni production is not simply explained.

- Equipartition of convective velocities with magnetic fields argues for a strong internal magnetic field (~10^{12} G) that may have interesting consequences.

Future Work

- Convection produces g-modes that transmit energy to the conductive regions and may have an affect on the non-convective surface region

- These simple models should be tested with convective simulations.