Understanding the Diversity of Type Ia Supernova Explosions

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- most Type Ia supernovae (SNe Ia) form a one-parameter family of SNe (→ Phillips relation)
- increasing number of new SNe Ia types (super-Chandra SNe?)
- link between progenitors and explosion models still very uncertain

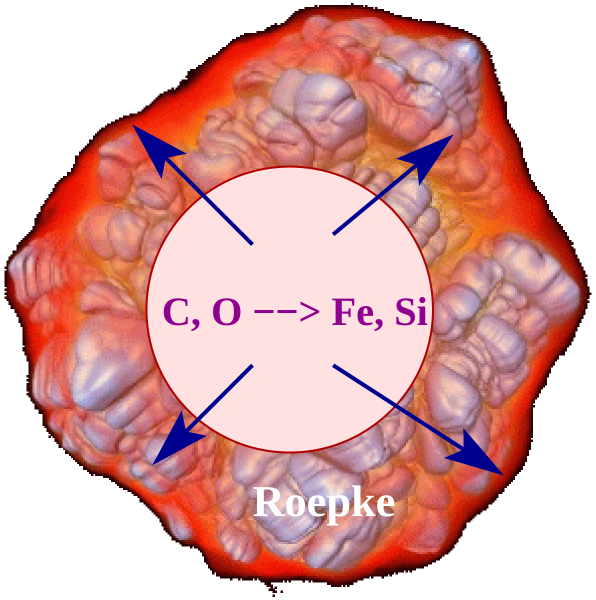
I. Type Ia Supernovae

II. The Phillips Relation and Metallicity as the Second Parameter

III. Linking Progenitor Models to Explosion Models

Thermonuclear Explosions

- occurs in accreting carbon/oxygen white dwarf when it approaches the Chandrasekhar mass
  - → carbon ignited under degenerate conditions: nuclear burning raises T, but not P
  - → thermonuclear runaway
  - → incineration and complete destruction of the star
- energy source is nuclear energy (10^{51} ergs)
- no compact remnant expected
- standardizable candle (Hubble constant, acceleration of Universe?)



but: progenitor evolution not understood

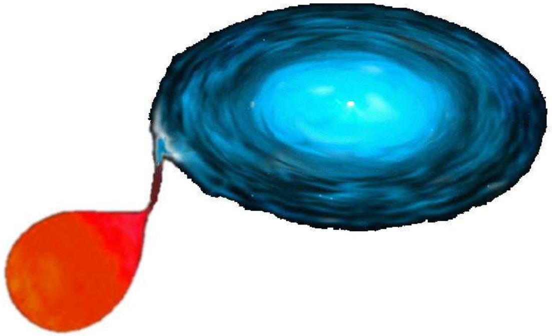
- ▷ single-degenerate channel: accretion from non-degenerate companion
- ▷ double-degenerate channel: merger of two CO white dwarfs

SN Ia Host Galaxies

- SNe Ia occur in young and old stellar populations (Branch 1994) → range of time delays between progenitor formation and supernova (typical: 1 Gyr; some, at least several Gyr; comparable integrated numbers)
- SNe Ia in old populations tend to be faint; luminous SNe Ia occur in young populations (→ age important parameter)
  - ▷ the faintest SNe Ia (SN 91bg class) avoid galaxies with star formation and spiral galaxies (age + high metallicity?)
  - ▷ the radial distribution in ellipticals follows the old star distribution (Förster & Schawinski 2008) → not expected if formed in a recent galaxy merger

→ consistent with double-degenerate model and two-population single-degenerate model (supersoft + red-giant channel)

Single-Degenerate Models



- **Chandrasekhar white dwarf accreting** from a companion star (main-sequence star, helium star, subgiant, giant)

Problem: requires fine-tuning of accretion rate

- ▷ accretion rate too low → nova explosions → inefficient accretion
- ▷ accretion rate too high → most mass is lost in a disk wind → inefficient accretion

- **Pros:**
  - ▷ potential counterparts: U Sco, RS Oph, TCrB (WDs close to Chandrasekhar mass), sufficient numbers?
- **Cons:**
  - ▷ expect observable hydrogen in nebular phase, stripped from companion star (Marietta, et al.) → not yet observed in normal SN Ia (tight limits! $0.02\,M_\odot$)
- **Recent:**
  - ▷ surviving companion in Tycho supernova remnant (Ruiz-Lapuente et al.)? Needs to be confirmed. Predicted rapid rotation is not observed (Kerzendorf et al. 2008).
  - ▷ SN 2006X (Patat et al. 2007): first discovery of circumstellar material → supports giant channel for SNe Ia

Patat et al. (2007)

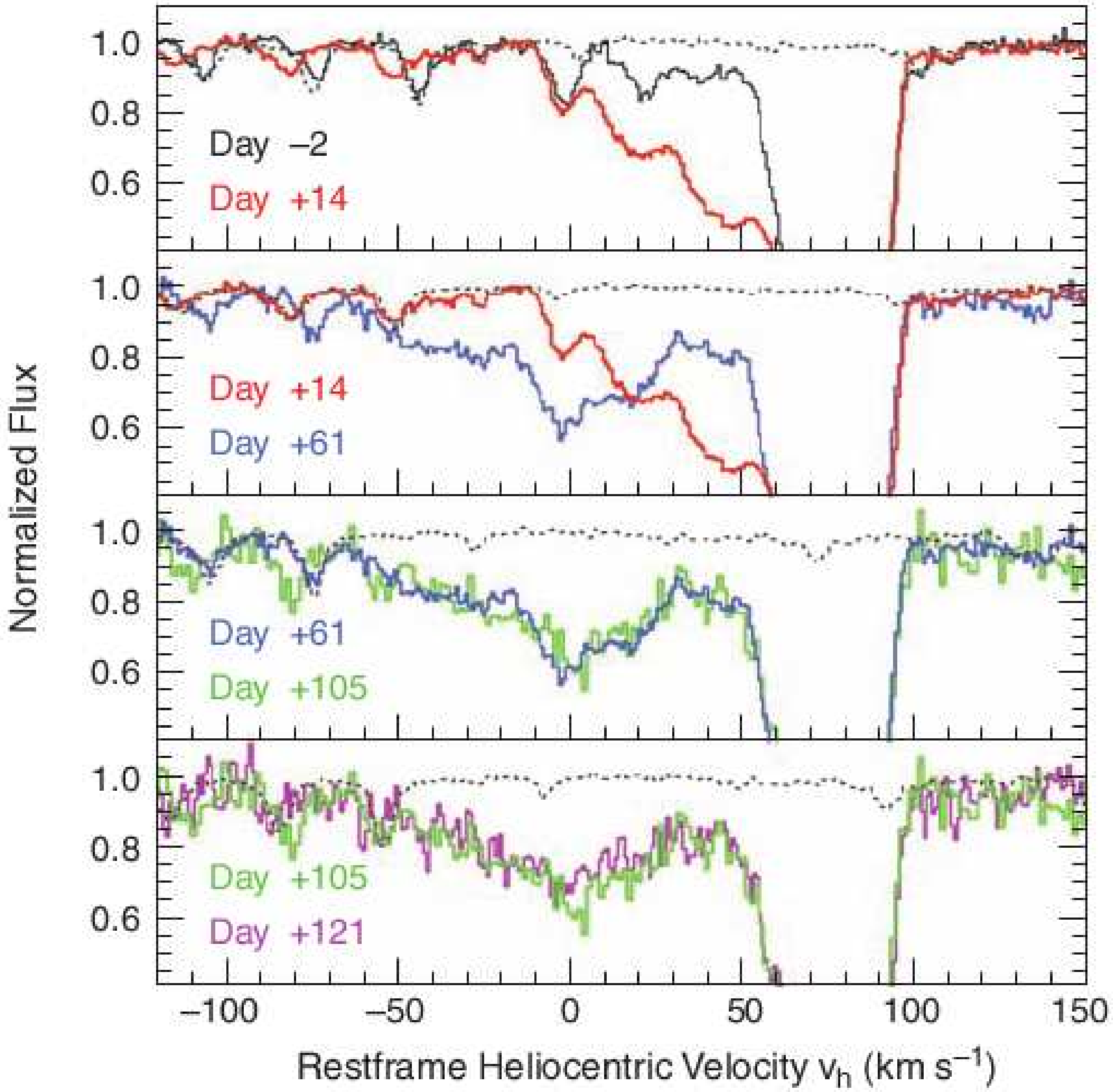


Fig. 1. Time evolution of the Na D_2 component region as a function of elapsed time since *B*-band maximum light. We corrected the heliocentric velocities to the rest-frame using the host galaxy recession velocity. All spectra have been normalized to their continuum. In each panel, the dotted curve traces the atmospheric absorption spectrum.

Double Degenerate Merger

- merging of two CO white dwarfs with a total mass > Chandrasekhar mass
- Problem:
  - ▷ this more likely leads to the conversion of the CO WD into an ONeMg WD and e-capture core collapse → formation of neutron star
- Pros:
  - ▷ merger rate is probably o.k. (few 10^{-3} yr; SPY)
- Recent:
  - ▷ Yoon, PhP, Rosswog (2007): post-merger evolution depends on neutrino cooling → conversion into ONeMg WD may sometimes be avoided → thermonuclear explosion may be possible
- multiple channels?

→ super-Chandrasekhar channel? (Howell et al. 2007)

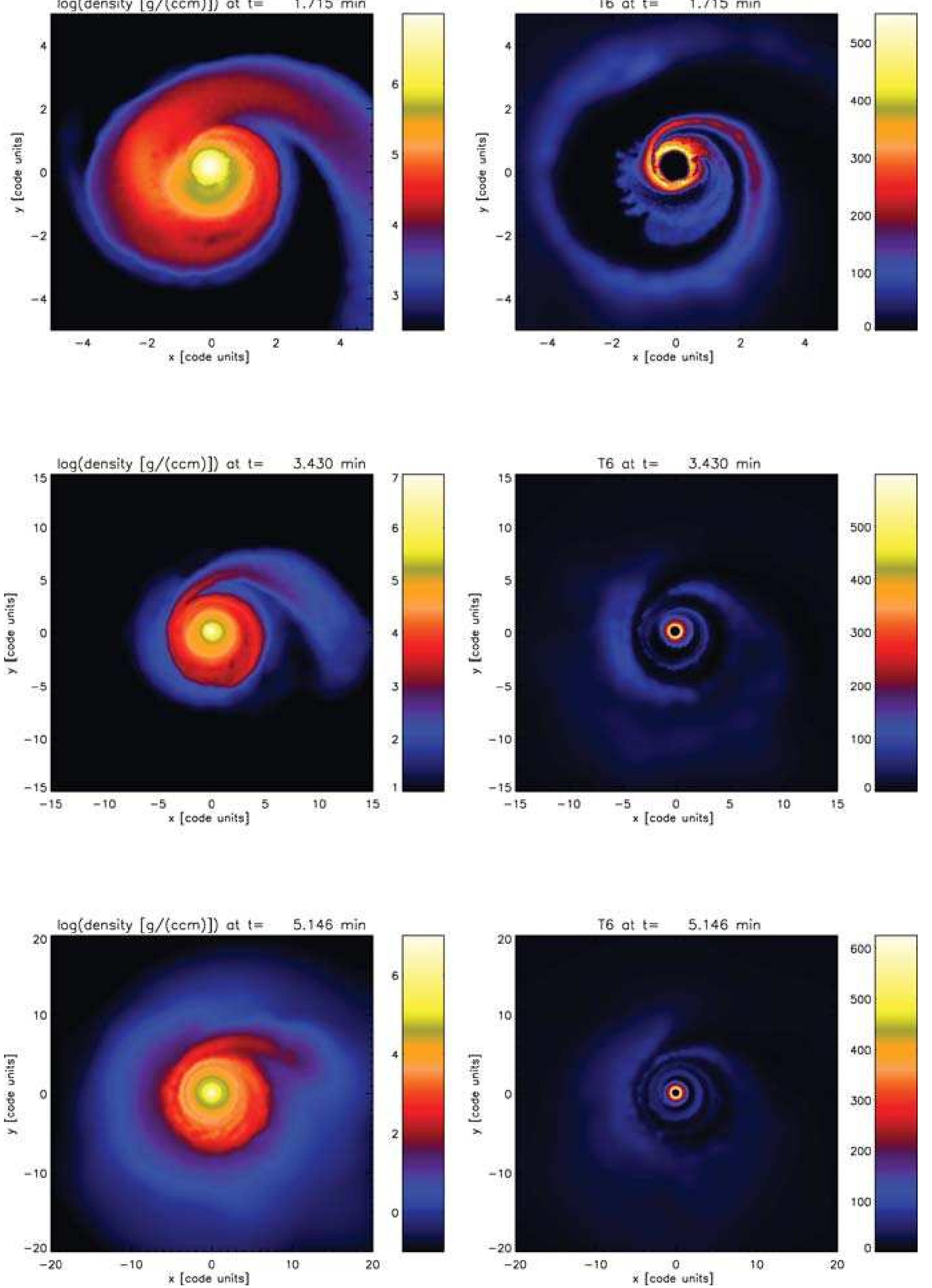


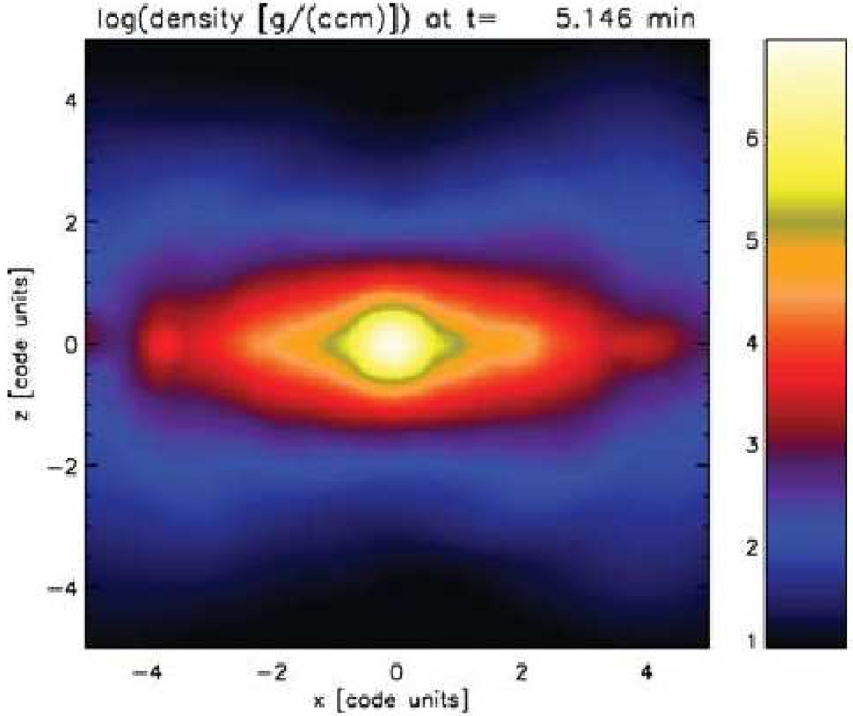
Figure 3. Dynamical evolution of the coalescence of a $0.6\,\mathrm{M}_{\odot} + 0.9\,\mathrm{M}_{\odot}$ CO white dwarf binary. Continued from Fig. 2.

Post-Merger Evolution

- immediate post-merger object: low-entropy massive core surrounded by high-entropy envelope and accretion disk
- evolution is controlled by thermal evolution of the envelope → determines core-accretion rate
- despite high accretion rate, carbon ignition is avoided because of neutrino losses
- can lead to thermonuclear explosion iff
  - carbon ignition is avoided during merging process
  - and disk accretion rate after 10^5 yr is less than $10^{-5}\,M_\odot/\mathrm{yr}$

Note: explosion occurs $\sim 10^5$ yr after the merger

Yoon et al. 2007



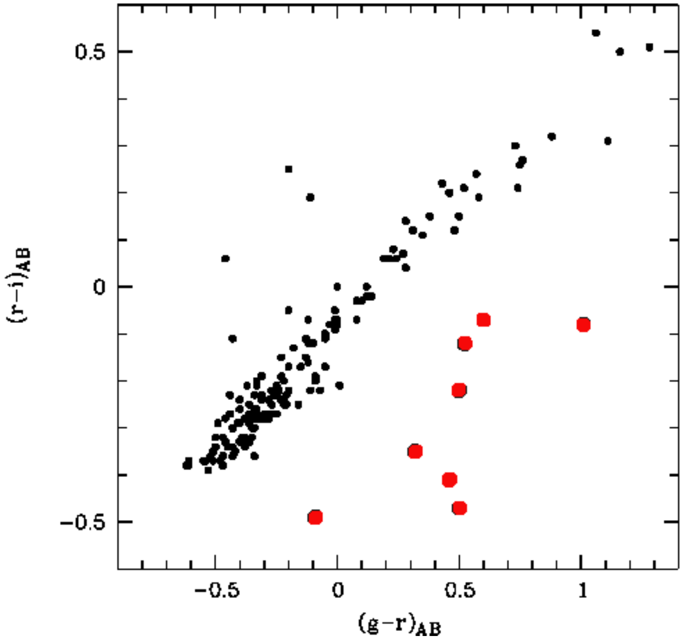
The Origin of Ultra-Cool Helium White Dwarfs

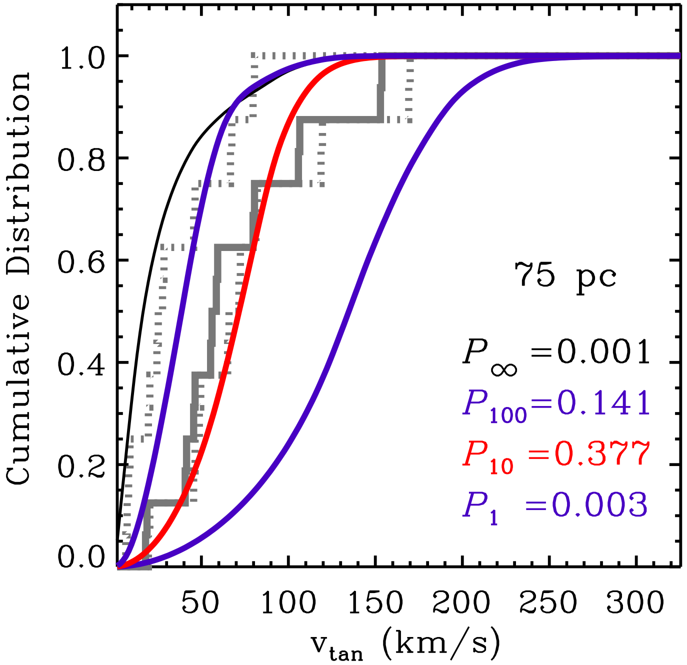
(Justham et al. 2008)

- ultra-cool white dwarfs ($T_{\rm eff} < 4000\,{\rm K}$)

→ implies very low-mass white dwarfs (cooling timescale! $\lesssim 0.3\,{\rm M}_\odot$)

- can only be formed in binaries
- some may have pulsar companions, most appear to be single (ultra-cool doubles?)
- **most likely origin:** surviving companion after a SN Ia
- **kinematics:** pre-SN period $10 - 100\,{\rm d}$ (short end of red-giant island?)





Symbiotic Binaries as SN Ia Progenitors
(Hachisu, Kato, Nomoto)

Nomoto, Umeda, Hachisu, Kato, Kobayashi, Tsujimoto: *SN Ia* 7

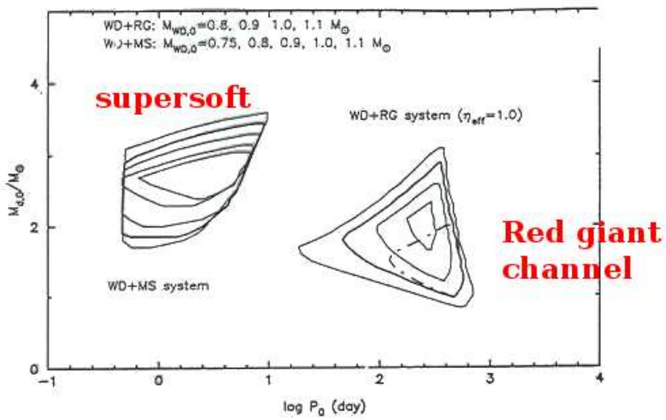


FIGURE 4. The region to produce SNe Ia in the log $P_0 - M_{d,0}$ plane for five initial white dwarf masses of $0.75M_\odot$, $0.8M_\odot$, $0.9M_\odot$, $1.0M_\odot$ (heavy solid line), and $1.1M_\odot$. The region of $M_{WD,0} = 0.7M_\odot$ almost vanishes for both the WD+MS and WD+RG systems, and the region of $M_{WD,0} = 0.75M_\odot$ vanishes for the WD+RG system. Here, we assume the stripping efficiency of $\eta_{eff} = 1$. For comparison, we show only the region of $M_{WD,0} = 1.0M_\odot$ for a much lower efficiency of $\eta_{eff} = 0.3$ by a dash-dotted line.

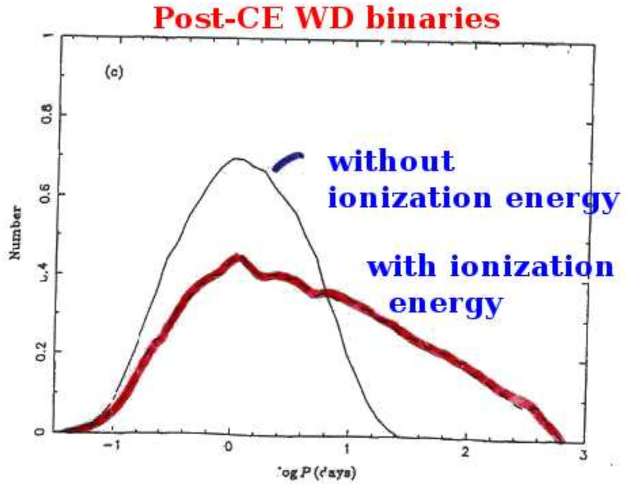


Figure 4 – continued

Han et al. (1995)

- two islands in $P_{orb} - M_2$ diagram where WDs can grow in mass
- red-giant channel: $P_{orb} \sim 100\,d$, M_2 as low as $1\,M_\odot$
- may explain SNe Ia with long time delays

Problem: binary population synthesis simulations do not produce many systems in the red-giant island ($10^{-5}\,yr^{-1}$ for optimistic assumptions (Han))

- ▷ stable RLOF → wide systems with $P_{orb} \gtrsim 10^3\,d$
- ▷ CE evolution → close systems with $P_{orb} \lesssim 10^2\,d$

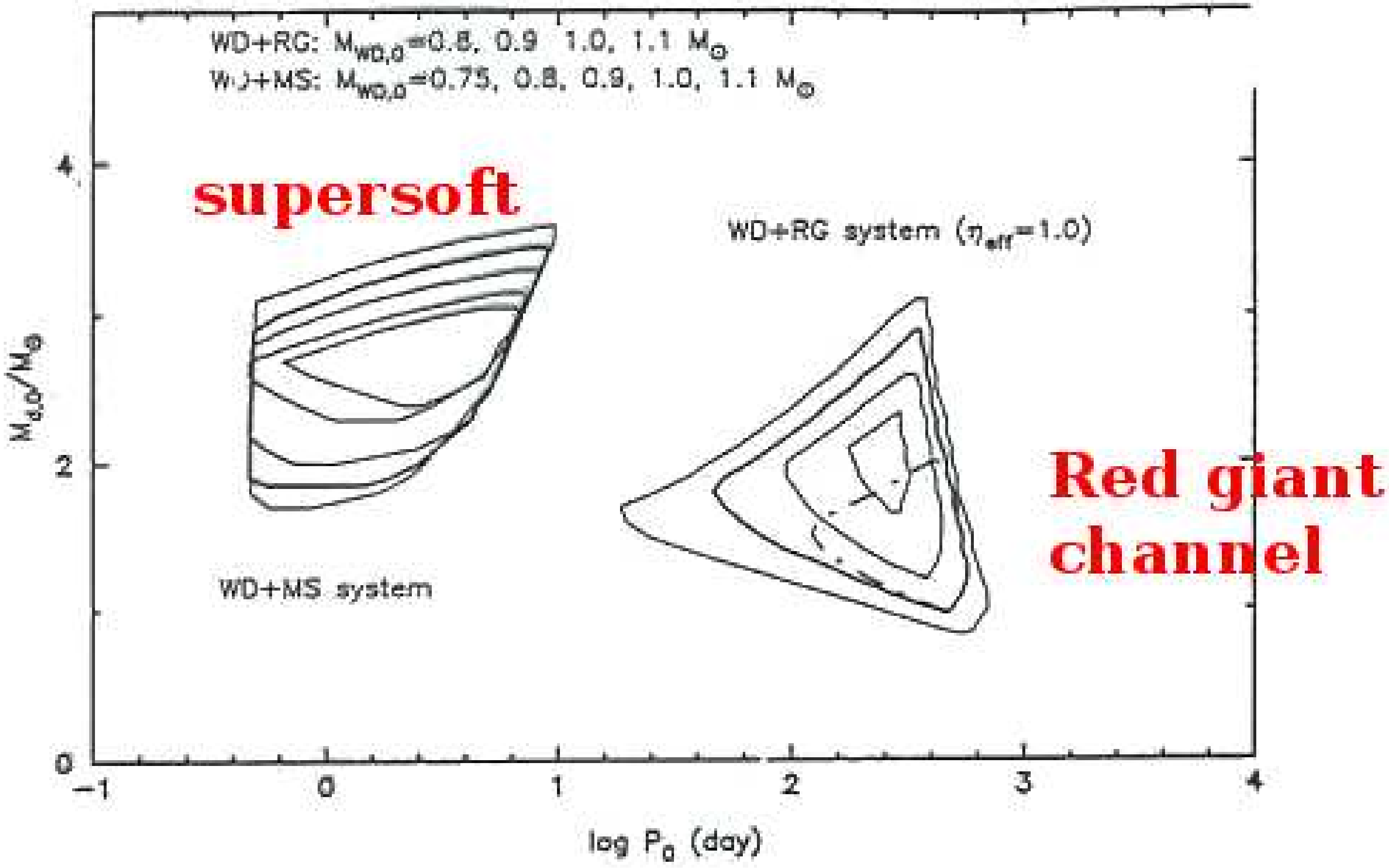
→ gap in period distribution for systems with $P_{orb} \sim 200 - 1000\,d$ (e.g. Han, Frankowski)

→ importance of RS Oph

→ suggests problem with binary evolution model

Hachisu, Kato, Nomoto

Nomoto, Umeda, Hachisu, Kato, Kobayashi, Tsujimoto: *SN Ia* 7



Quasi-dynamical mass transfer?

- **need a different mode of mass transfer (Webbink, Podsiadlowski)**
- **very non-conservative mass transfer but without significant spiral-in**
- **also needed to explain the properties of double degenerate binaries (Nelemans), υ Sgr, etc.**
- **transient CE phase or circumbinary disk (Frankowski)?**

Metallicity as a second parameter of SN Ia lightcurves (Timmes et al. 2003)

- the lightcurve is powered by the radioactive decay of ^{56}Ni to ^{56}Co ($t_{1/2} = 6.1\,\mathrm{d}$)

→ $L_{\mathrm{peak}} \propto M_{56\mathrm{Ni}}$

- the lightcurve width is determined by the diffusion time
  - ▷ depends on the opacity, in particular the total number of iron-group elements (i.e. ^{56}Ni, ^{58}Ni, ^{54}Fe)

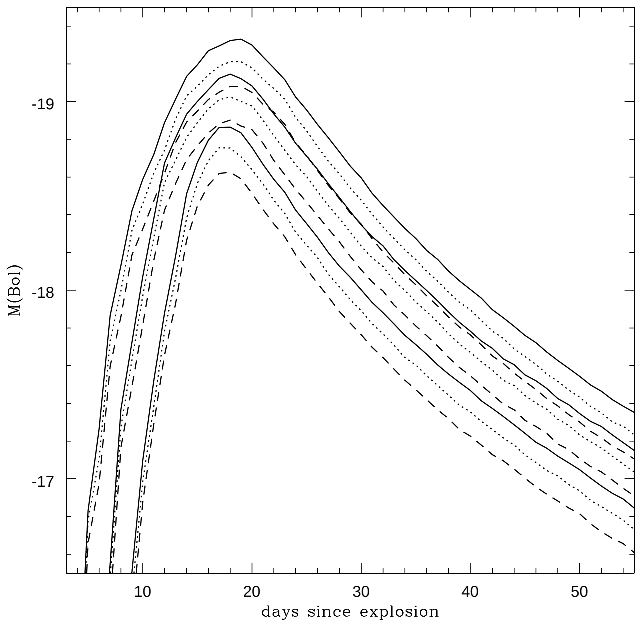
  → $t_{\mathrm{width}} \propto M_{\mathrm{iron-group}}$
  - ▷ ^{54}Fe, ^{58}Ni are non-radioactive → contribute to opacity but not supernova luminosity

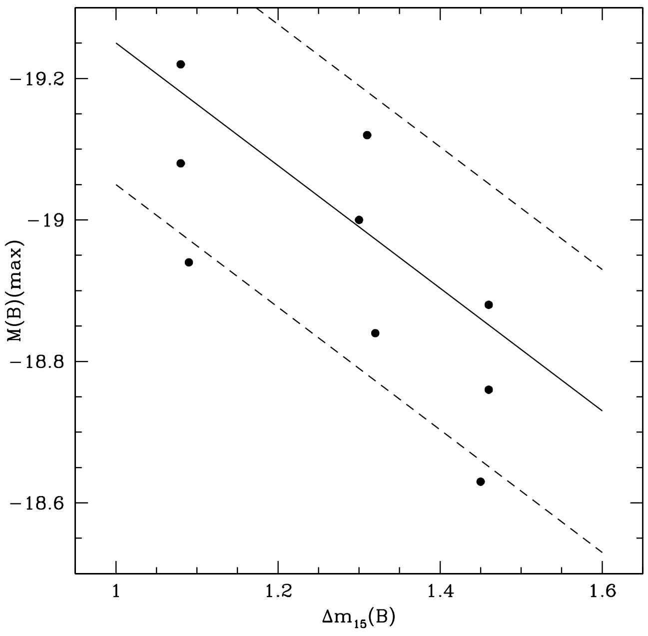
→ necessary second parameter

- the relative amount of non-radioactive and radioactive Ni depends on neutron excess and hence on the initial metallicity (Timmes et al. 2003)
- variation of 1/3 to 3 $Z_\odot$ gives variation of 0.2 mag

The Second SN Ia Parameter: (^{54}Fe + ^{58}Ni)/ ^{56}Ni

(Mazzali and Podsiadlowski 2006)





Thermonuclear Explosions

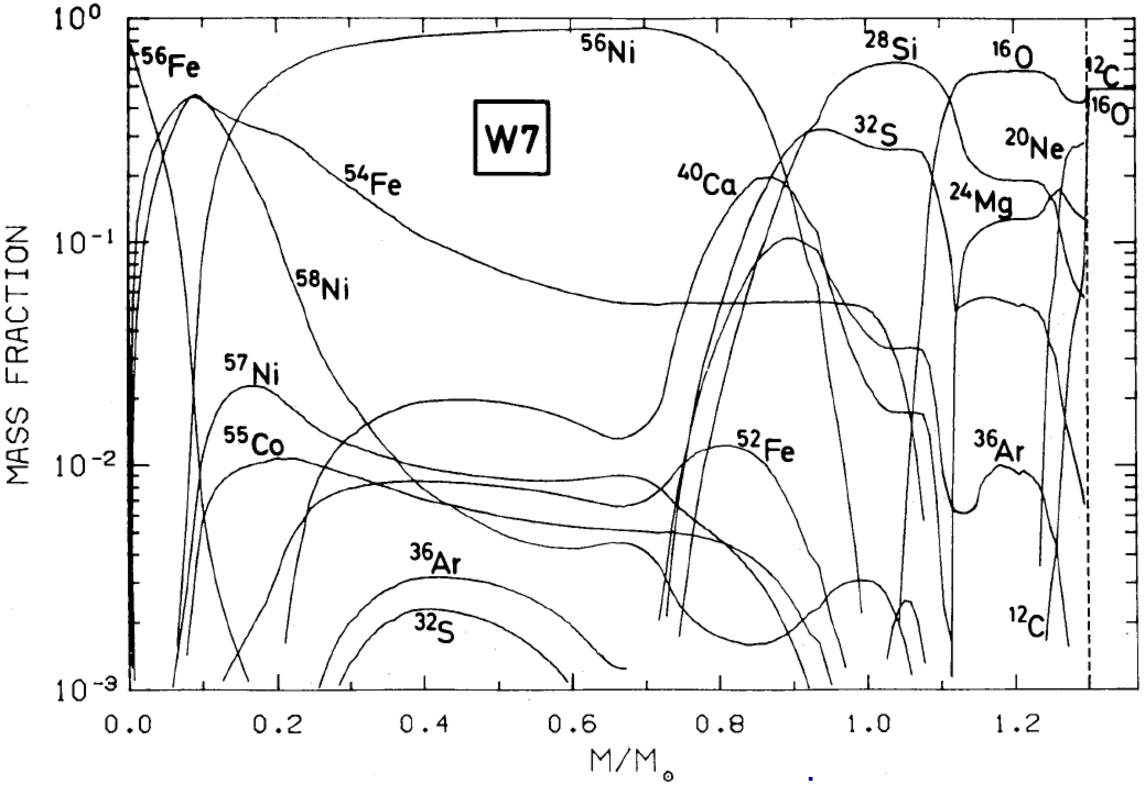
(W7; Nomoto 1984)

Burning Layer (= kinetic energy)

NSE (= opacity)

IME

unburned?



stable

radioactive
(= light)

C+O (deflagration)
O (detonation)

Podsiadlowski, Mazzali, Lesaffre, Wolf, Förster (2006)

- metallicity *must* be a second parameter that at some level needs to be taken into account
- cosmic metallicity evolution can mimic accelerating Universe

but: metallicity evolution effects on their own *appear* not large enough to explain the supernova observations without dark energy (also independent evidence from WMAP, galaxy clustering)

- it will be difficult to measure the equation of state of dark energy with SNe Ia alone without correcting for metallicity effects

Measuring the Equation of State

Linder (2003)

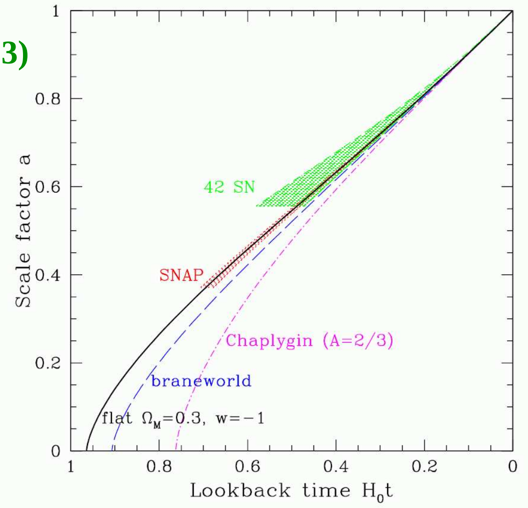
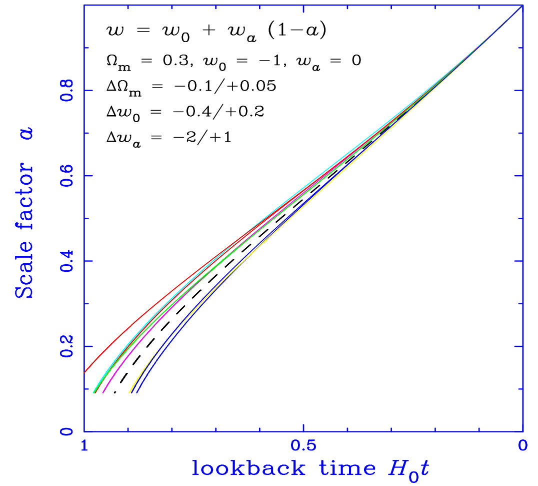


FIG. 1: Mapping the expansion history through the supernova magnitude-redshift relation can distinguish the dark energy explanation for the accelerating universe from alternate theories of gravitation, high energy physics, or higher dimensions. All three models take an $\Omega_M = 0.3$, flat universe but differ on the form of the Friedmann expansion equation.

The effect of metallicity evolution



(based on PMLWF 2006)

What controls the diversity of SNe Ia?

dominant post-SN parameter: M_{Ni56} → ignition density (pre-SN) → initial WD mass, age (progenitor)

other factors:

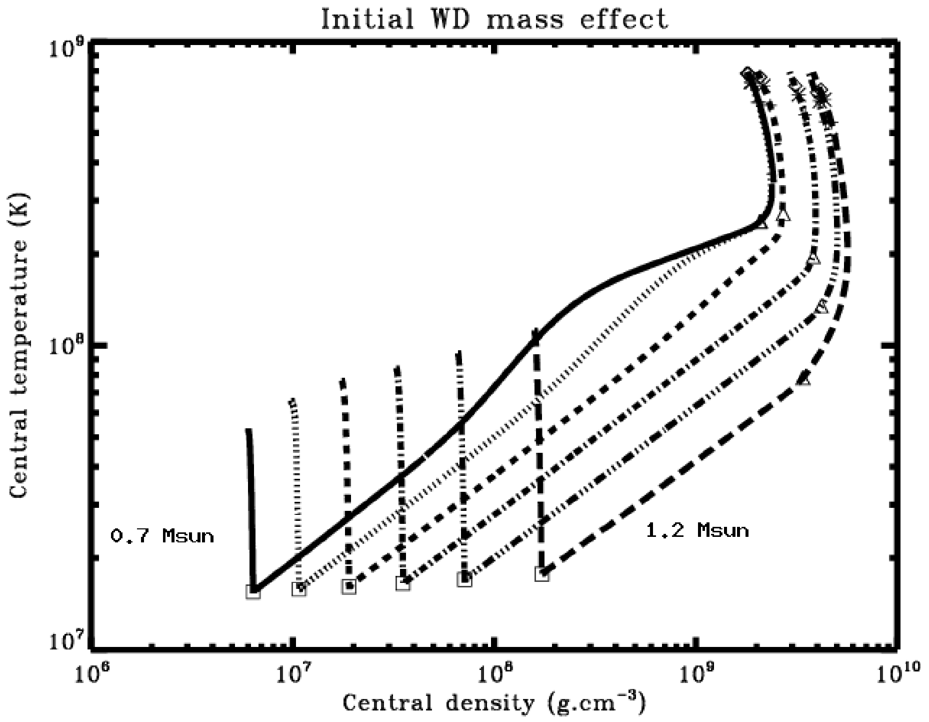
- ▷ **metallicity → neutron excess, initial C/O ratio, accretion efficiency**
- ▷ **the role of rotation? (Yoon & Langer 2005: super-Chandra WDs)**
- ▷ **the progenitor channel (supersoft, red-giant, double degenerate)**

- **complex problem to link progenitor evolution/properties to explosion properties**

The ignition conditions in the supersoft channel (Lesaffre et al. 2006)

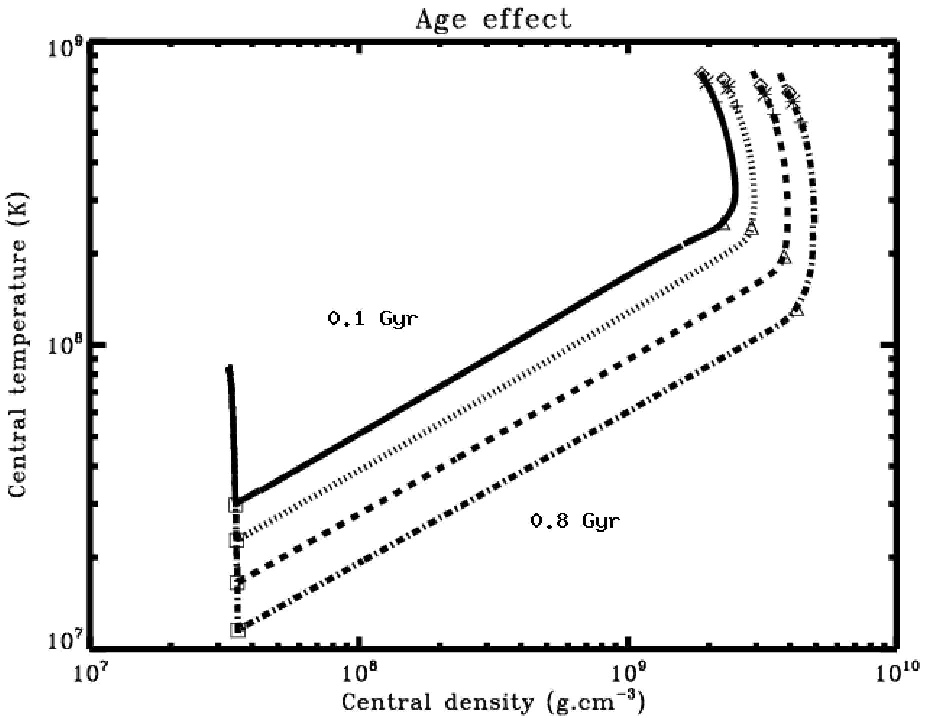
- **evolve WD till thermonuclear runaway**
- **take binary evolution models from Han & Ph.P. (2004) (based on Hachisu et al. model for WD accretion)**

The Initial WD Mass



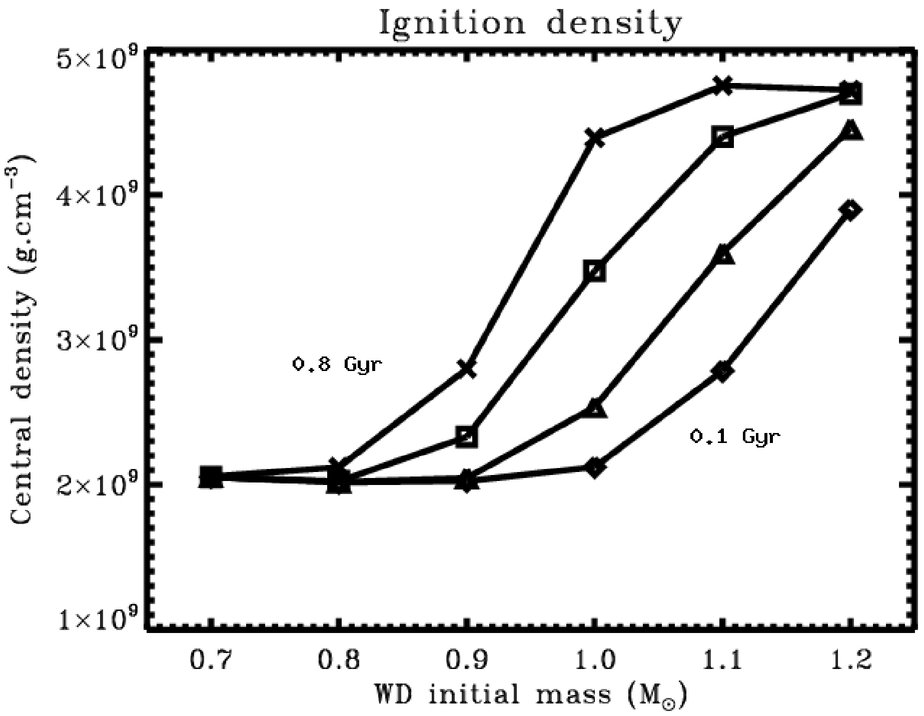
- **Higher M_{WD}:** start with higher density and lead to higher ignition density
- **Small M_{WD}:** thermal diffusion is faster than accretion, all have the same evolution (Branch normal SNe Ia?)
- **High density:** electron screening effects in the burning rate fix ignition density

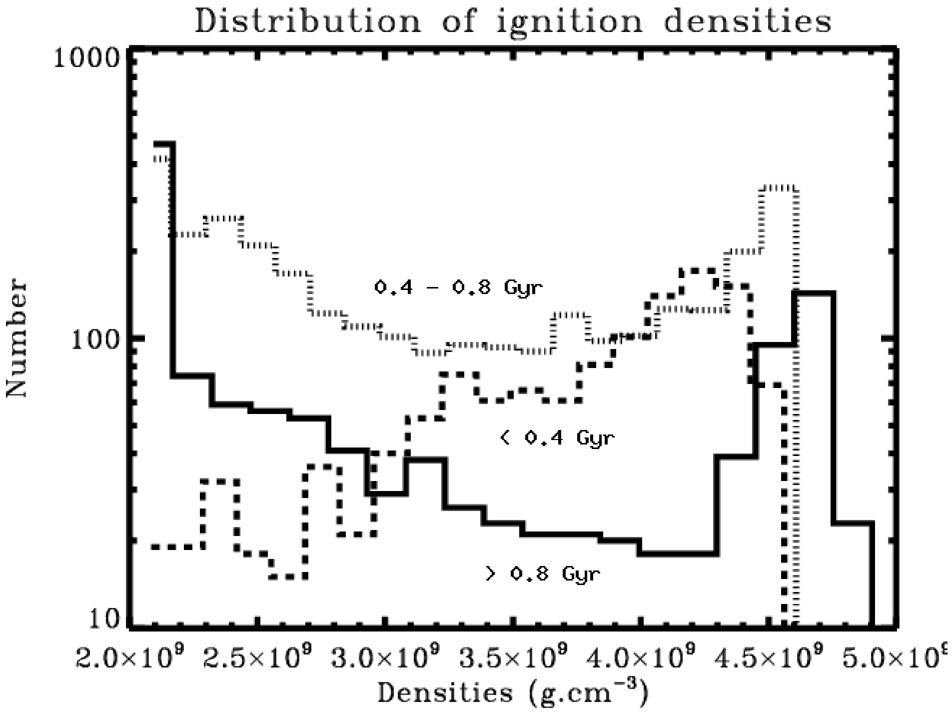
Age Effect



- **Younger systems** start at higher temperature and ignite at smaller density
- for **old age** and high initial mass, Coulomb screening effects yield **same ignition density**

Ignition Conditions: the Central Density





- a range of ignition density
- the minimum density corresponds to the global thermal equilibrium
- the maximum density corresponds to screening effects on the ignition curve

- bimodal distribution
- young systems ignite at higher density (density → luminosity?)
- quantitatively incorrect! → work in progress

The Final Simmering Phase

- before the final thermonuclear runaway, there is a long phase ('simmering' phase) of low-level carbon burning, lasting up to $\sim 1000\,\mathrm{yr}$
- this can significantly alter the WD structure
  - ▷ significant neutronization (up to $\Delta X_C \sim 0.1$ may be burned)
  - ▷ density profile
  - ▷ convective velocity profile

Neutrino cooling time: t_ν
Convective turnover time: t_c
Carbon fusion time: t_f

- $t_c < t_\nu < t_f$: mild C burning: neutrino cooling gets rids of the energy generated
- $t_c < t_f < t_\nu$: C flash: convection sets in, convective core grows rapidly
- $t_f < t_c < t_\nu$: C ignition: thermonuclear runaway

The Convective Urca Process

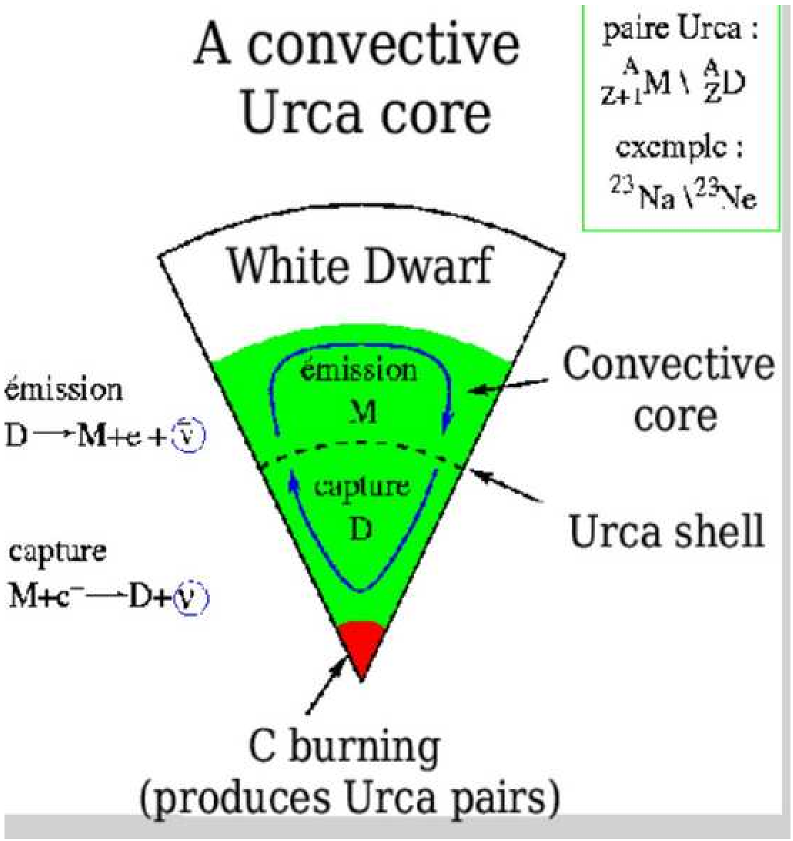
- at high densities, electron captures enter into play
- neutrino losses due the Urca process

  electron capture: $\mathrm{M} + \mathrm{e}^- \rightarrow \mathrm{D} + \nu$

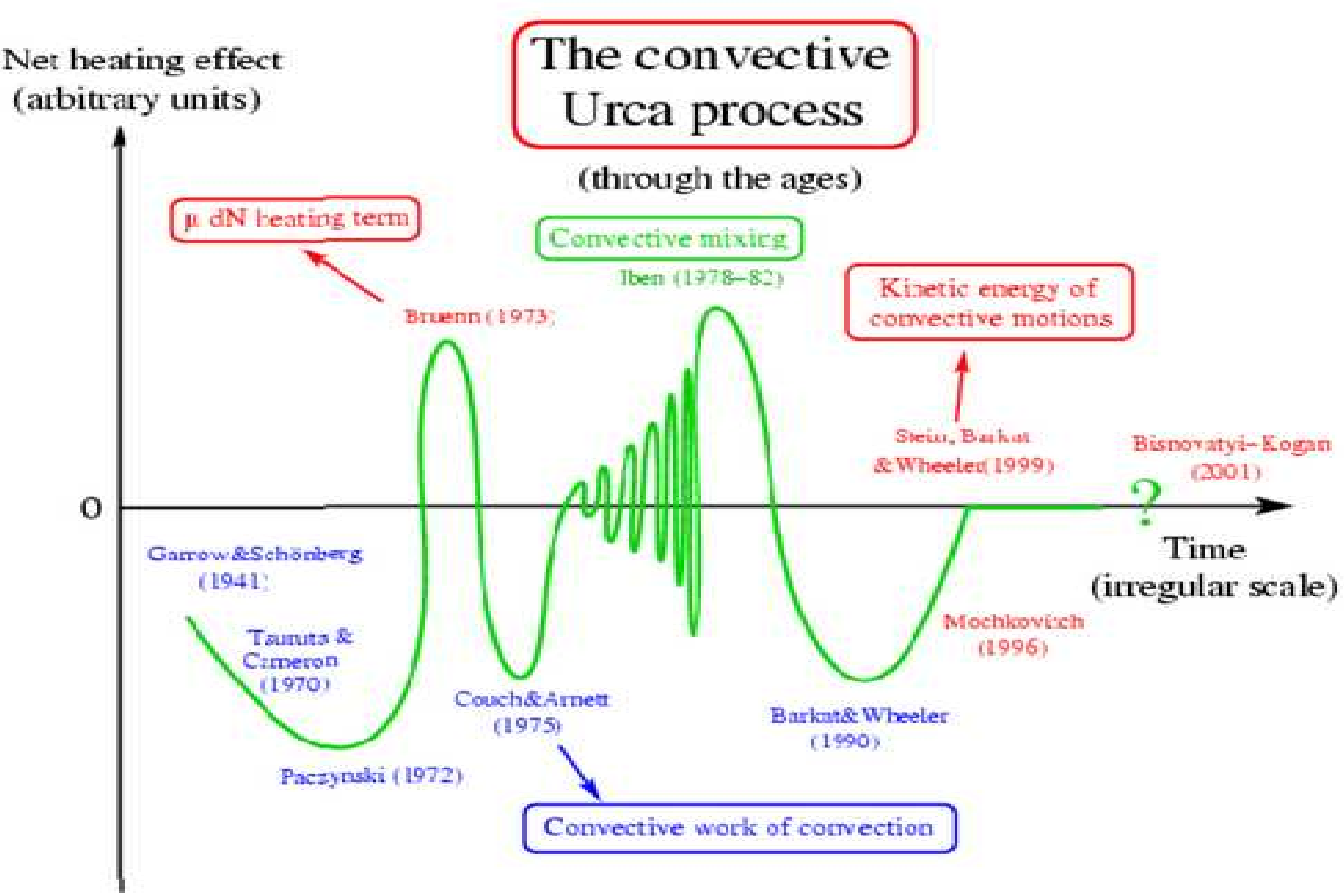
  beta decay: $\mathrm{D} \rightarrow \mathrm{M} + \mathrm{e}^- + \bar{\nu}$

  (M: mother; D: daughter)

- most important pair: ${}^{23}\mathrm{Na}/{}^{23}\mathrm{Ne}$ with threshold density $\rho_{\mathrm{th}} = 1.7 \times 10^9\,\mathrm{g\,cm^{-3}}$
- most efficient cooling near Urca shell ($\rho \simeq \rho_{\mathrm{th}}$)
- net heating outside Urca shell
- long history of yet inconclusive investigations



The Convective Urca Process through the Literature (Lesaffre)

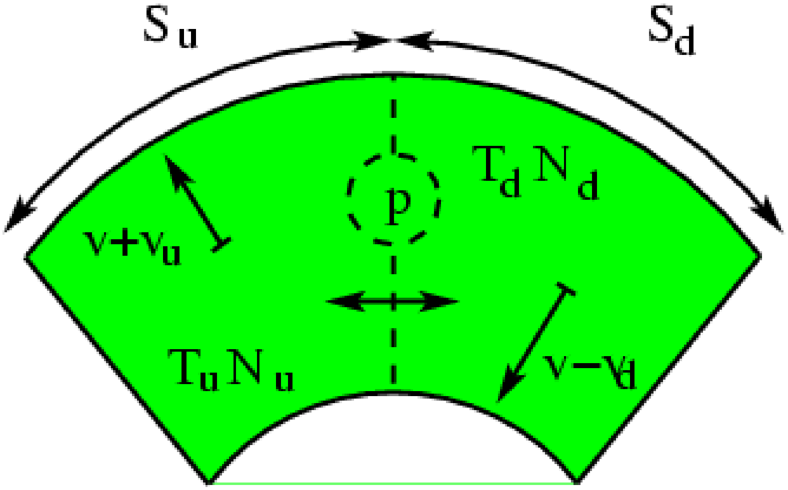


A Two-Stream Formalism for the Convective Urca Process

(Lesaffre, PhP, Tout 2005)

Input:

- spherical symmetry
- no viscosity
- mixing-length theory for horizontal exchanges



Output:

- correct energy and chemical budget
- differential reactivity
- Ledoux criterion and convective velocities depend on chemistry
- time-dependent model
- handles convective velocity asymmetries (overshooting)
- handles interactions with the mean flow

Preliminary Results

- the final pre-SN WD structure is drastically altered
- inclusion of convective work:
  - ▷ chemical dependence of the convective luminosity
  - ▷ chemical dependence of the convective velocity
- Urca reactions slow down convective motions

→ smaller convective cores at the time of the explosion?

- significant addition neutronization? (cf. Stein & Wheeler 2006 [2D]; Piro & Bildsten 2007; Chamulak et al. 2007)

Note: extreme numerical problems when the convective core approaches the Urca shell

Future Work (in progress)

- modelling the convective Urca process is essential for modelling the final pre-SN WD structure
- will allow to link the properties of the progenitor to the actual explosion → close the loop
- will allow detailed investigation of the diversity of SNe Ia
  - ▷ metallicity dependence
  - ▷ initial C/O ratio
  - ▷ WD accretion rate
  - ▷ initial WD mass
- provide physical foundation for using SNe Ia as cosmological distance candles

Conclusions

- significant progress on understanding the progenitors, but still no firm conclusions
- need short and long time delays
- most SNe Ia are similar but a significant subset shows large diversity
- need for multiple channels?
- metallicity should be a second parameter for SN lightcurves