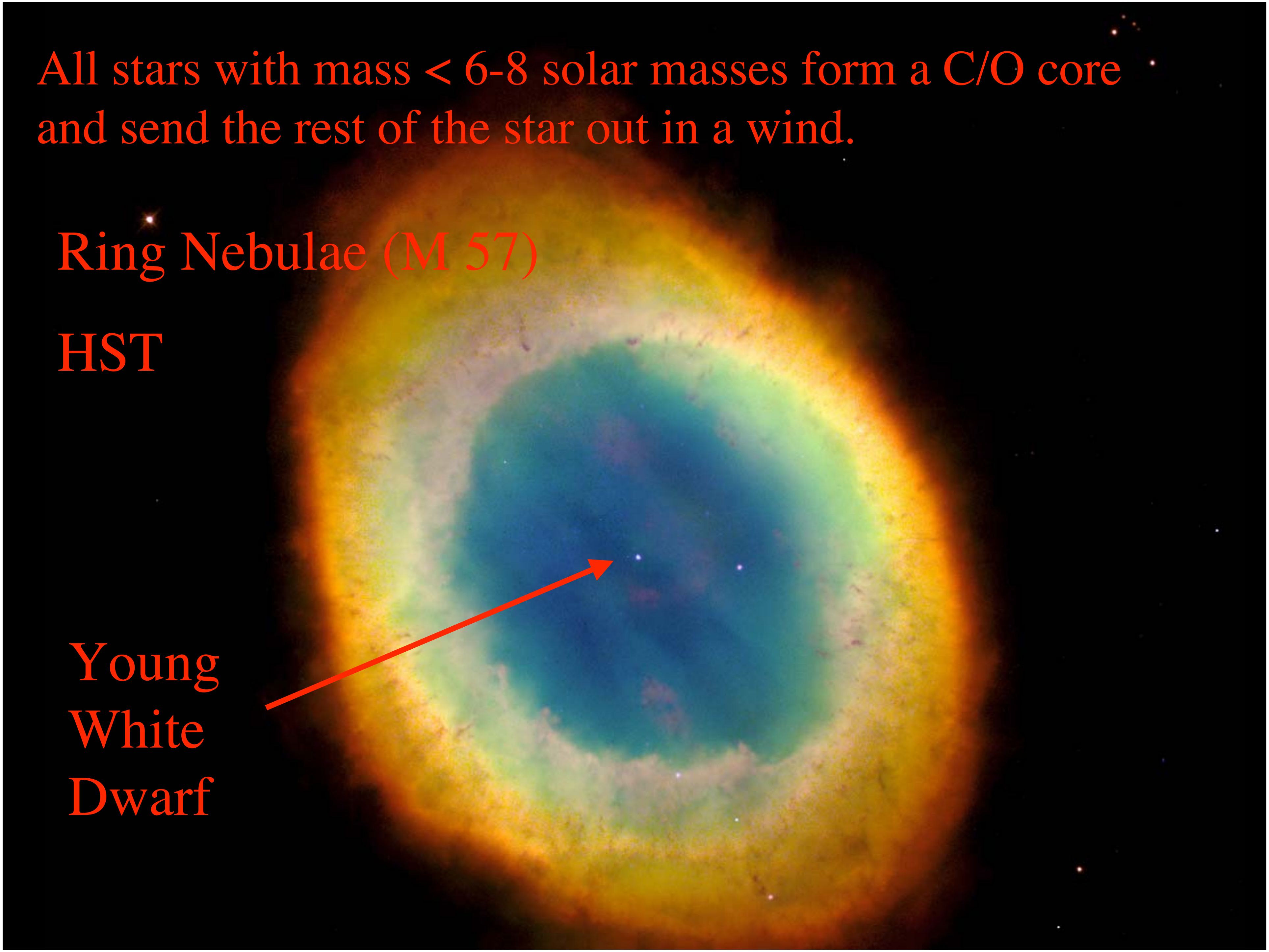
Extragalactic Transients: From Novae to Supernovae

Lars Bildsten, KITP

October 2, 2007

Extragalactic Transients: Why Now???

1. We still have much to learn about the endpoints of stellar evolution
2. New Surveys are coming online that are likely to reveal many new phenomena.
3. There are enough ‘unusual’ events already to imagine that this will be an exciting time…
4. What we know about white dwarfs certainly hints that the outcomes are not all ‘textbook’



All stars with mass < 6-8 solar masses form a C/O core and send the rest of the star out in a wind.

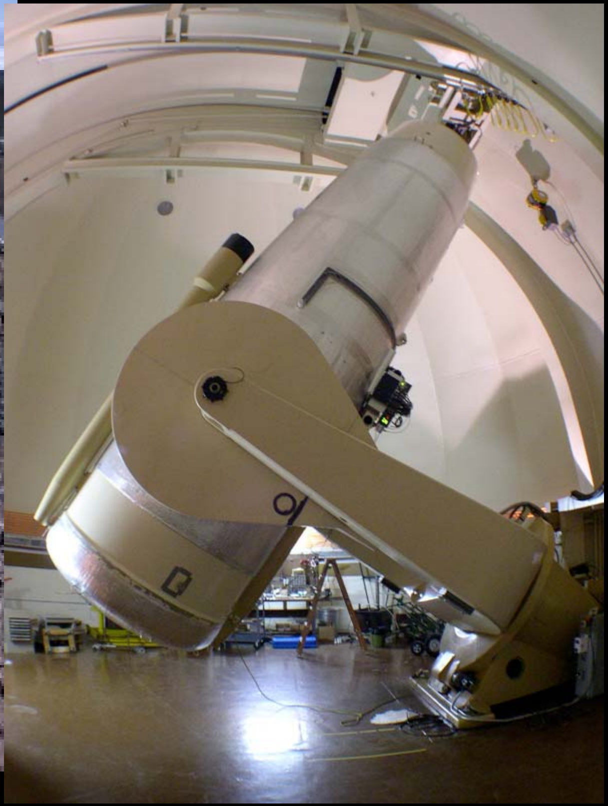
Ring Nebulae (M 57)

HST

Young White Dwarf

New Surveys. . . Data is (and will be) flooding in

Pan-Starrs1
(2008)



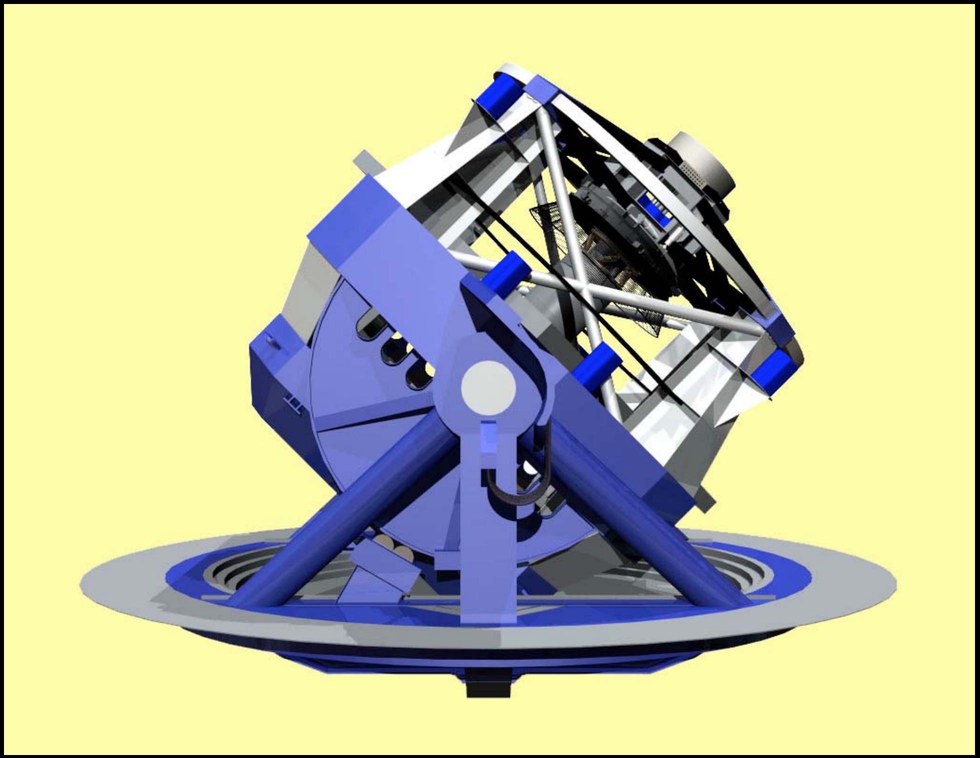
Palomar
Transient
Factory
(2008)

ROTSE (now)

Sloan Digital Sky
Survey (now)

LSST (2014)

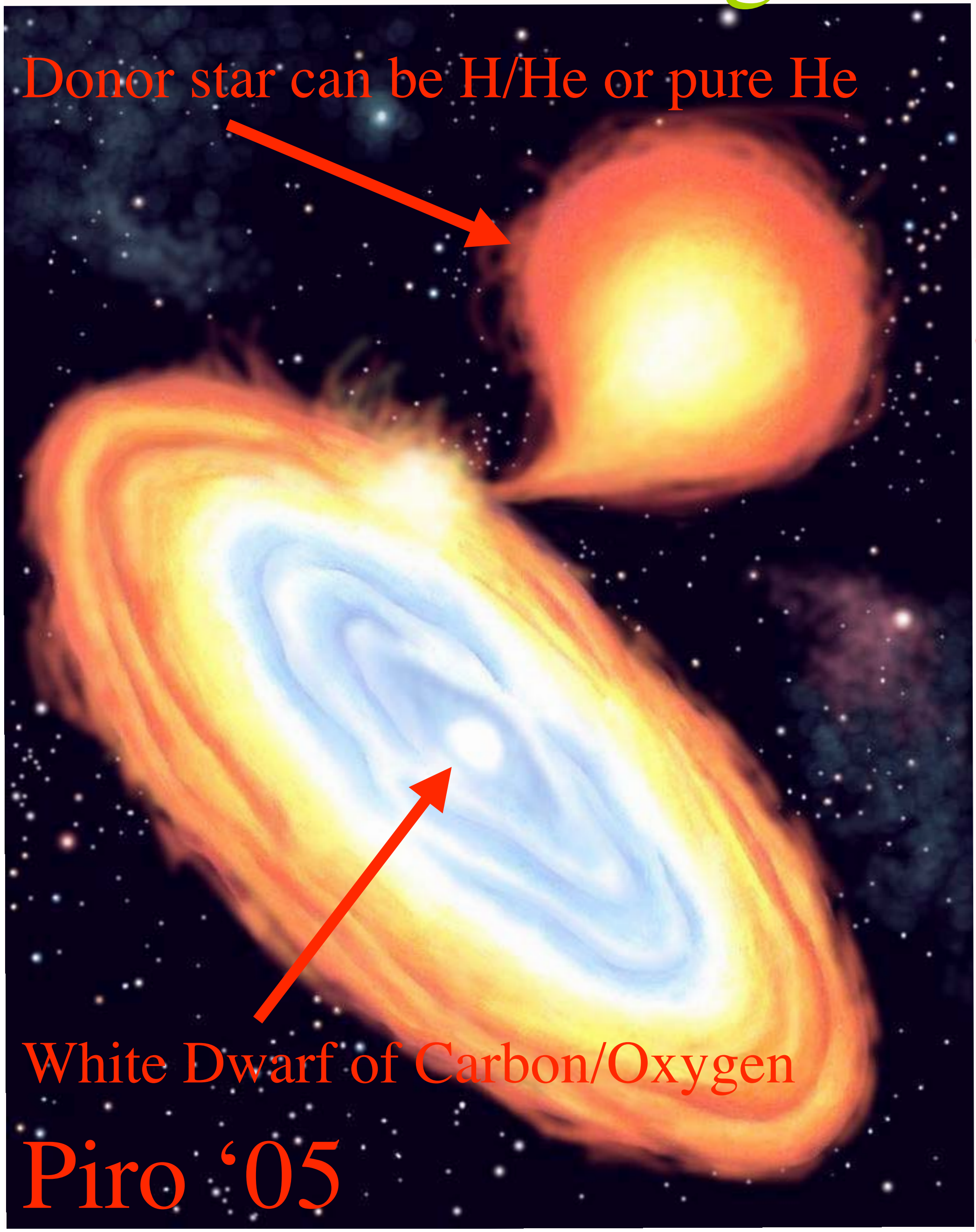
Large Synoptic Survey Telescope (LSST) is an 8.4-meter, 10 square-degree-field telescope that will image down to V of 24 across the entire sky every night. Site will be Cerra Pachon, Chile.



Stellar Termini and Transients

- Open questions remain about stellar death, but usually it is sudden
- Supernovae are ‘obvious’ only because they are bright (M_V=-18), odd SN now appearing!
- Novae can be seen in nearby galaxies and evolve on month timescales (M_V=-8), connections to Ia?
- WD-WD mergers are expected and maybe some of their long-lived aftermaths are known (R CrB stars?)
- Main Sequence mergers, binaries . . . .
- A few unusual transients seen in nearby galaxies…
- White dwarf mass and surface compositions imply mergers and H depleting events make >10% of WDs!
- Some stars ‘eaten’ by SMBH…

Accreting White Dwarfs



Donor star can be H/He or pure He

White Dwarf of Carbon/Oxygen

Piro ‘05

0.1-1% of white dwarfs are in binaries where accretion occurs, releasing gravitational energy

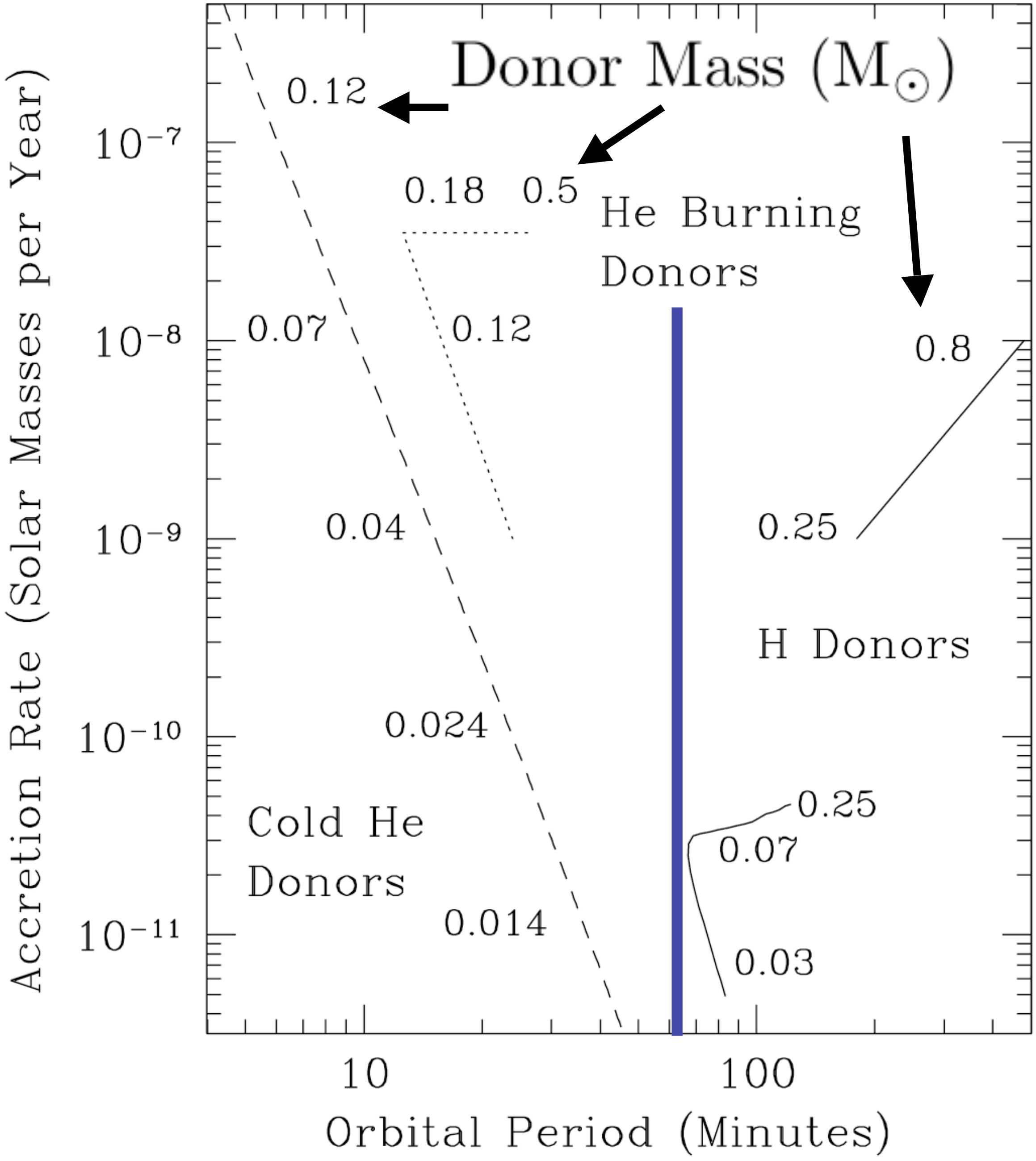
$$\frac{GM}{R} \approx 100 - 300 \ \frac{\text{keV}}{\text{nucleon}}$$

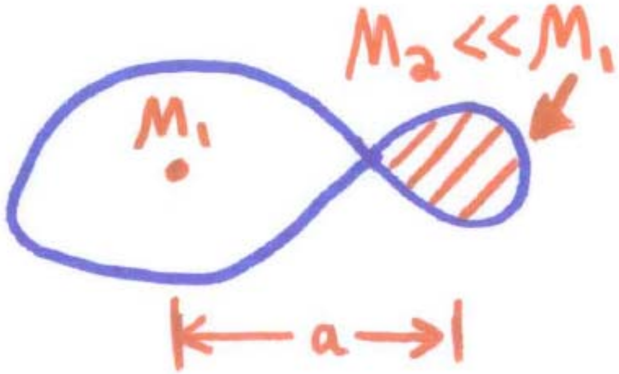
Whereas the nuclear fusion of H=>He or He=>C releases

$$1 - 5 \frac{\text{MeV}}{\text{nucleon}}$$

This contrast is further enhanced when the white dwarf stores fuel for > 1000 years and burns it rapidly, making these binaries detectable in distant galaxies during thermonuclear events.

Accreting White Dwarfs





To fill the tidal radius:

$$R_2 = 0.46a(M_2/M_1)^{1/3}$$

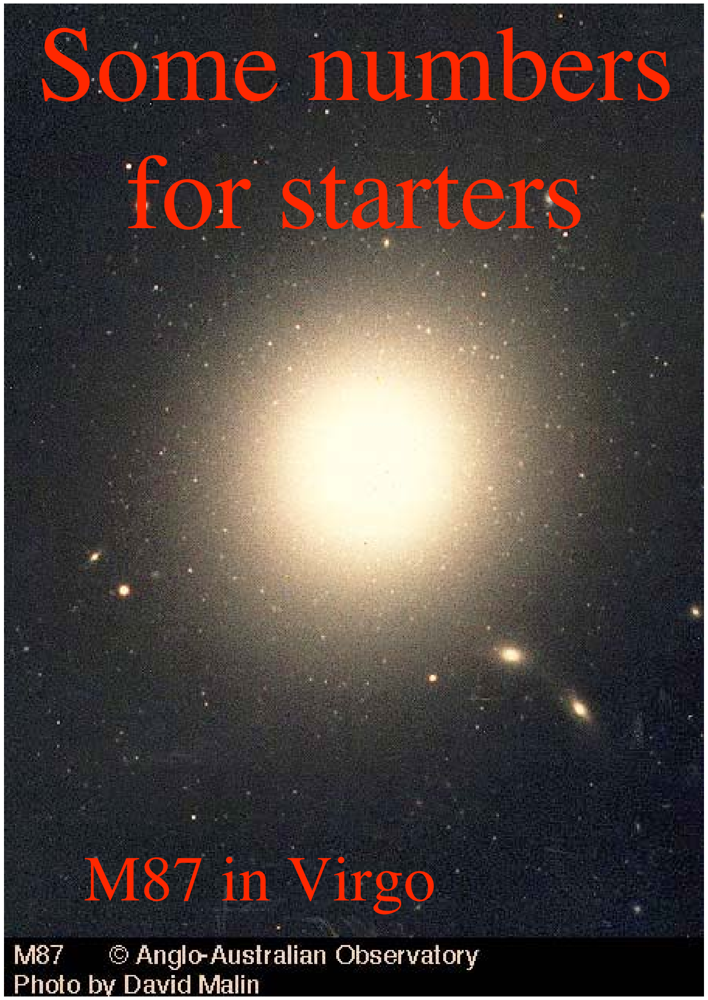
Giving the relation:

$$P_{\rm orb} = 64 \text{ m} \left(\frac{100 \text{ gr cm}^{-3}}{\rho}\right)^{1/2}$$

$$\rho = \text{Donor Density}$$

The mass transfer rate is set by angular momentum losses, typically from gravitational wave emission.

Some numbers for starters



M87 © Anglo-Australian Observatory
Photo by David Malin

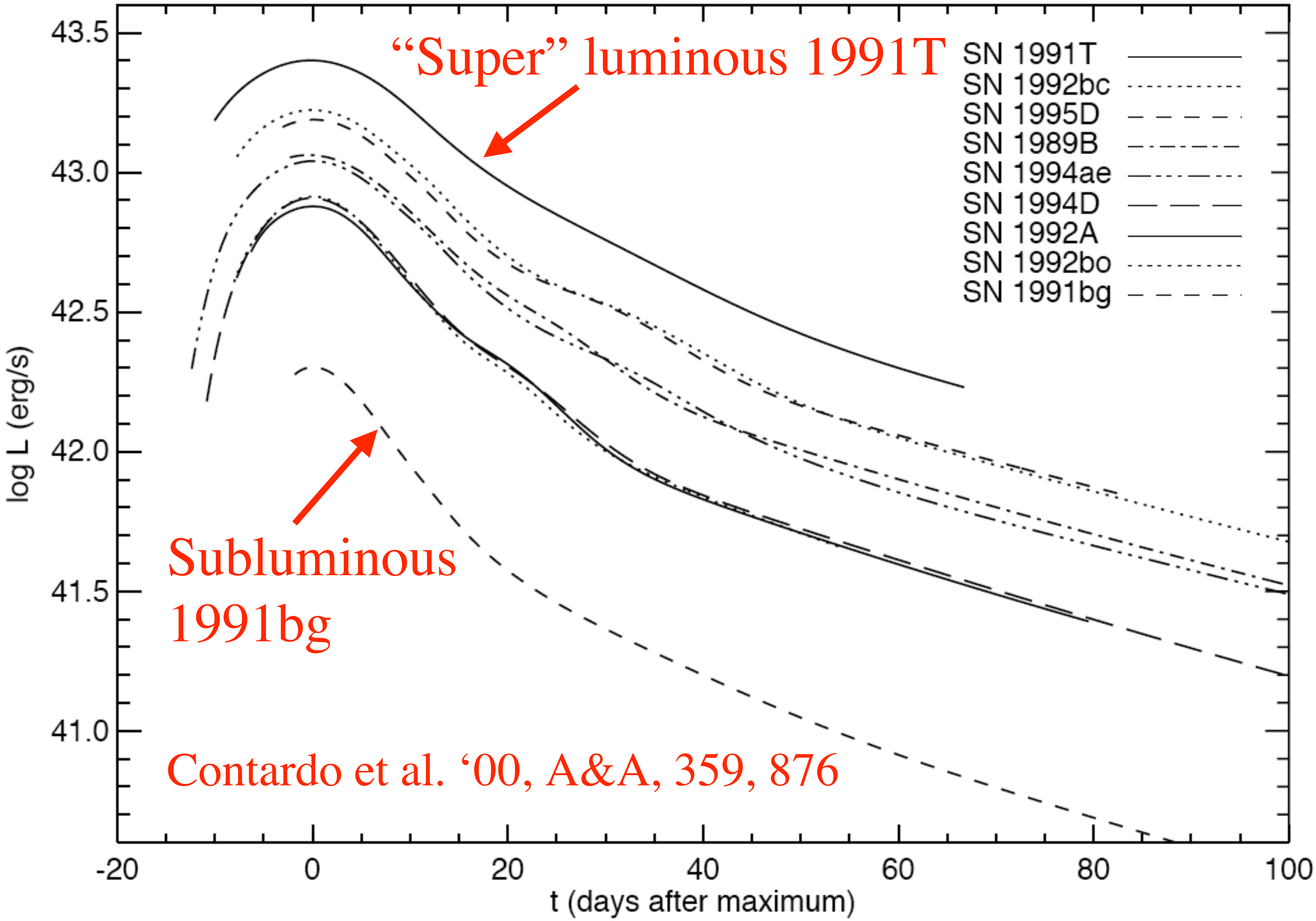
In 10^11 solar masses of old stars (e.g. E/S0 galaxy), two WDs are made per year. The observed rates for thermonuclear events are:

- 20 Classical Novae (Hydrogen fuel, triggered by accretion) per year
- One Type Ia Supernovae every 250 years, or one in 500 WDs explode!

Predicted ‘event’ rates are:

- WD-WD mergers (He or C/O accretion) every 100-500 years
- CV birthrate (H accretion) from observed Classical Novae rate is one every 200-500 years (Townsley and LB 2005)
- AMCVn birthrate (He accretion) is 1 in 5000 years (Roelofs et al. ‘07)

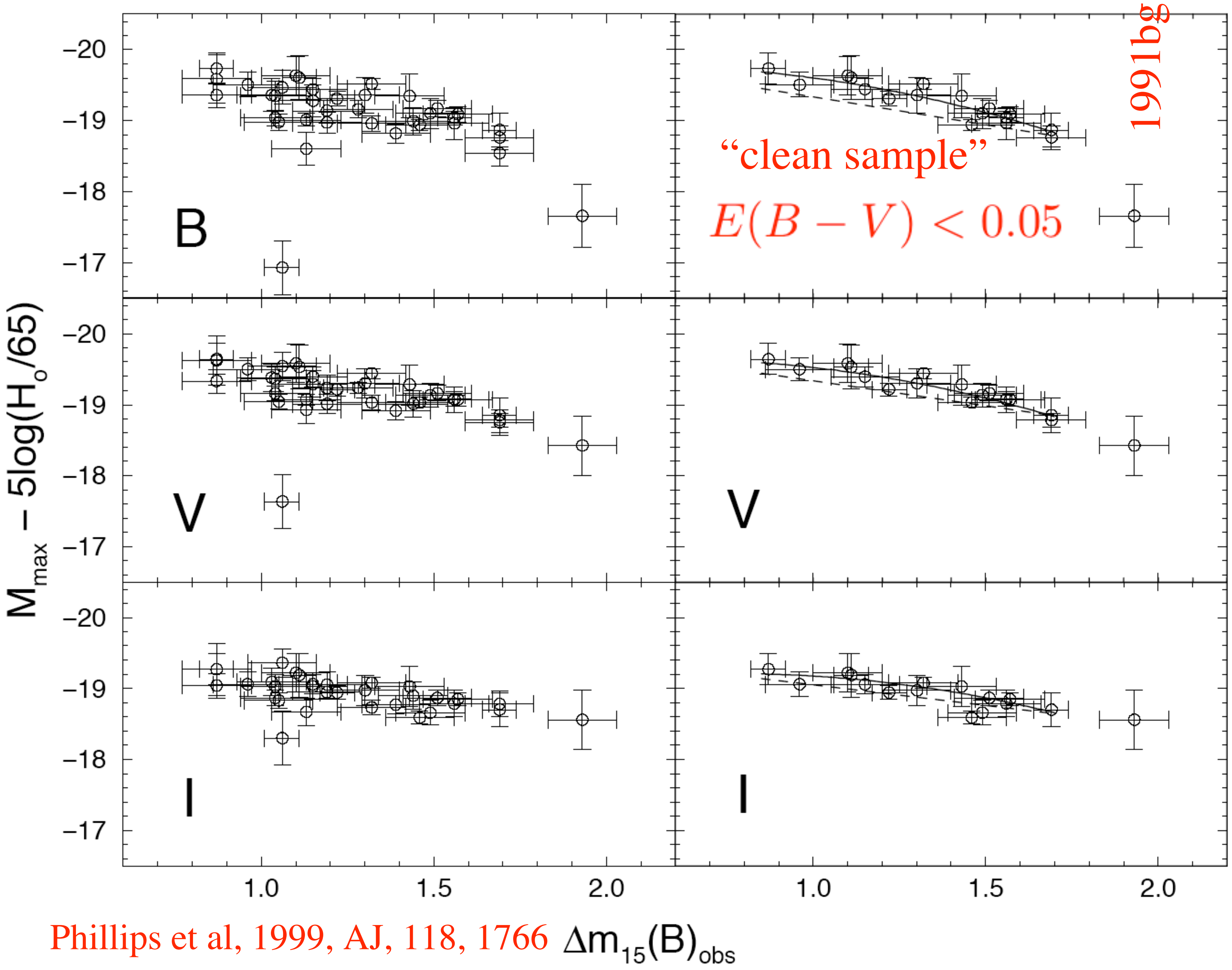
G. Contardo et al.: Epochs of maximum light and bolometric light curves



“Super” luminous 1991T

Subluminous 1991bg

Contardo et al. ‘00, A&A, 359, 876



“clean sample”

$E(B-V) < 0.05$

1991bg

Phillips et al, 1999, AJ, 118, 1766

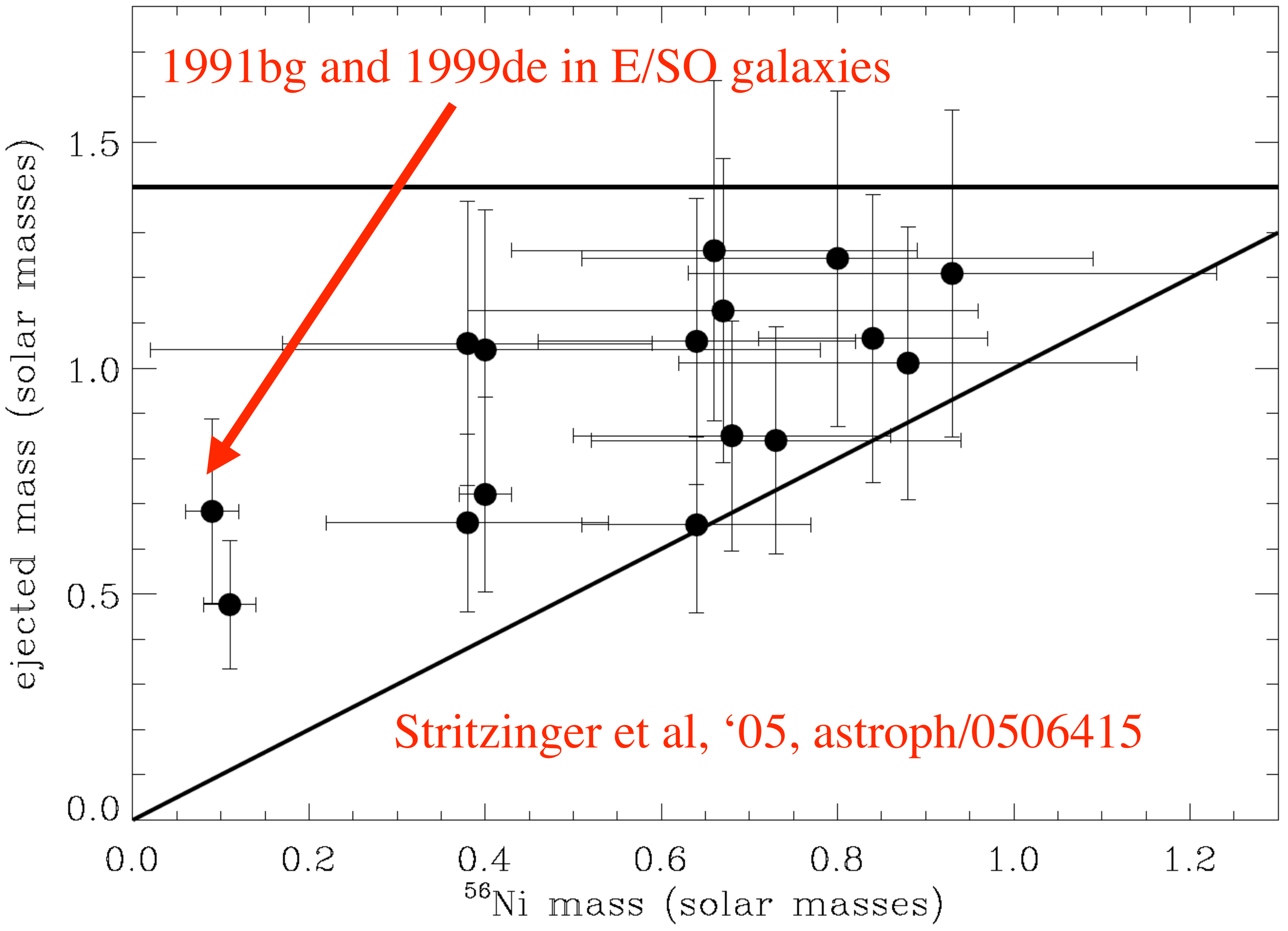
Thermonuclear Supernova Lightcurves

- Type Ia result from burning a solar mass of C/O to ~0.6 solar masses of 56Ni (rest burned to Si, Ca, Fe) and ejected at v=10,000 km/sec.
- This matter would cool by adiabatic expansion, but instead is internally heated by the radioactive decay chain 56Ni=>56Co=>56Fe
- Arnett (1982) (also see Pinto & Eastman 2000) showed that the peak in the lightcurve occurs when the radiation diffusion time through the ejected envelope equals the time since explosion, giving

$$\tau_m = \left(\frac{\kappa M_e}{7cv}\right)^{1/2} \approx 20 \text{ days}$$

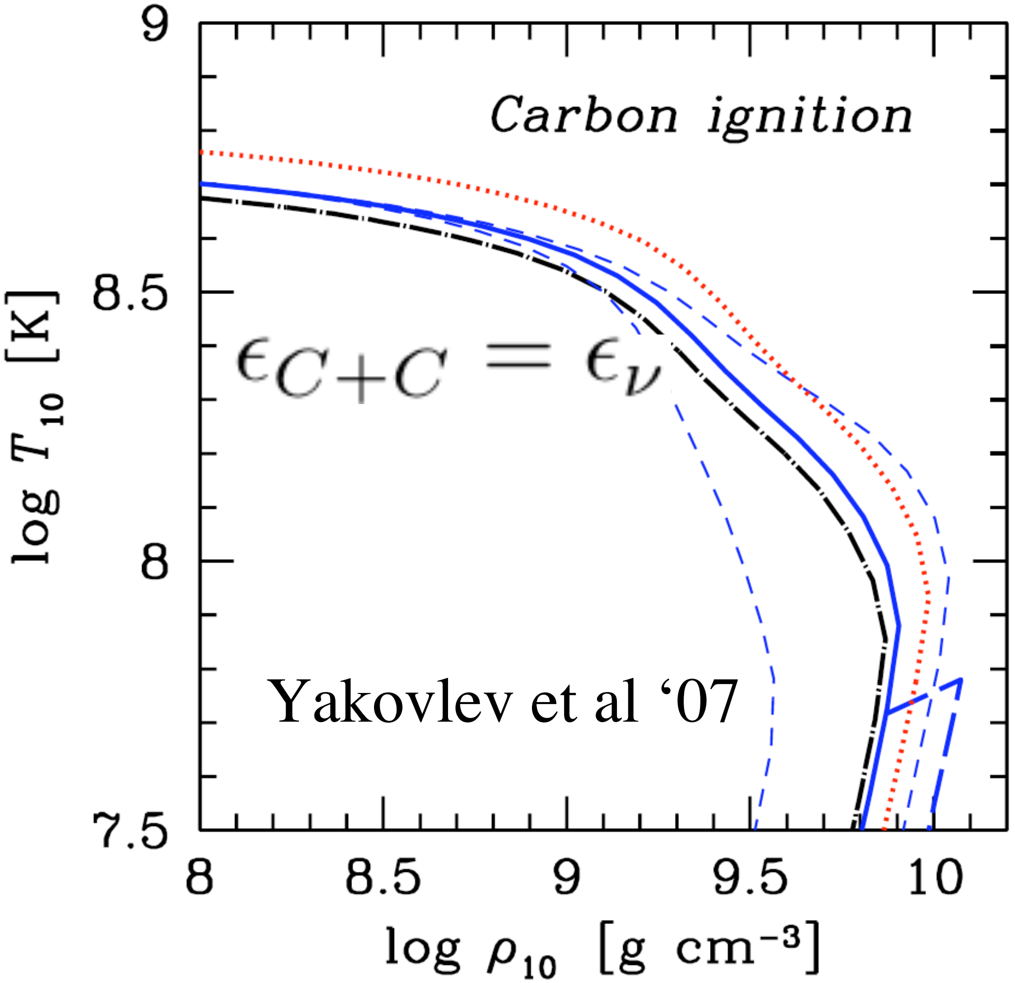
- The luminosity at peak is set by the radioactive decay heating rate ==> can measure the 56Ni mass, yielding 0.1-1.0 solar masses

Light Curve Fitting to Measure Ejected and 56Ni Masses



Carbon Ignition

If cold (T<3e8 or so), then ignition is from high densities..which only occur for massive white dwarfs, requiring accretion of mass!



$$C_P \frac{dT}{dt} = \epsilon_{C+C} - \epsilon_\nu$$

$$\rho_c = 3\times 10^8 \mathrm{g\ cm^{-3}} \rightarrow M = 1.25 M_\odot$$

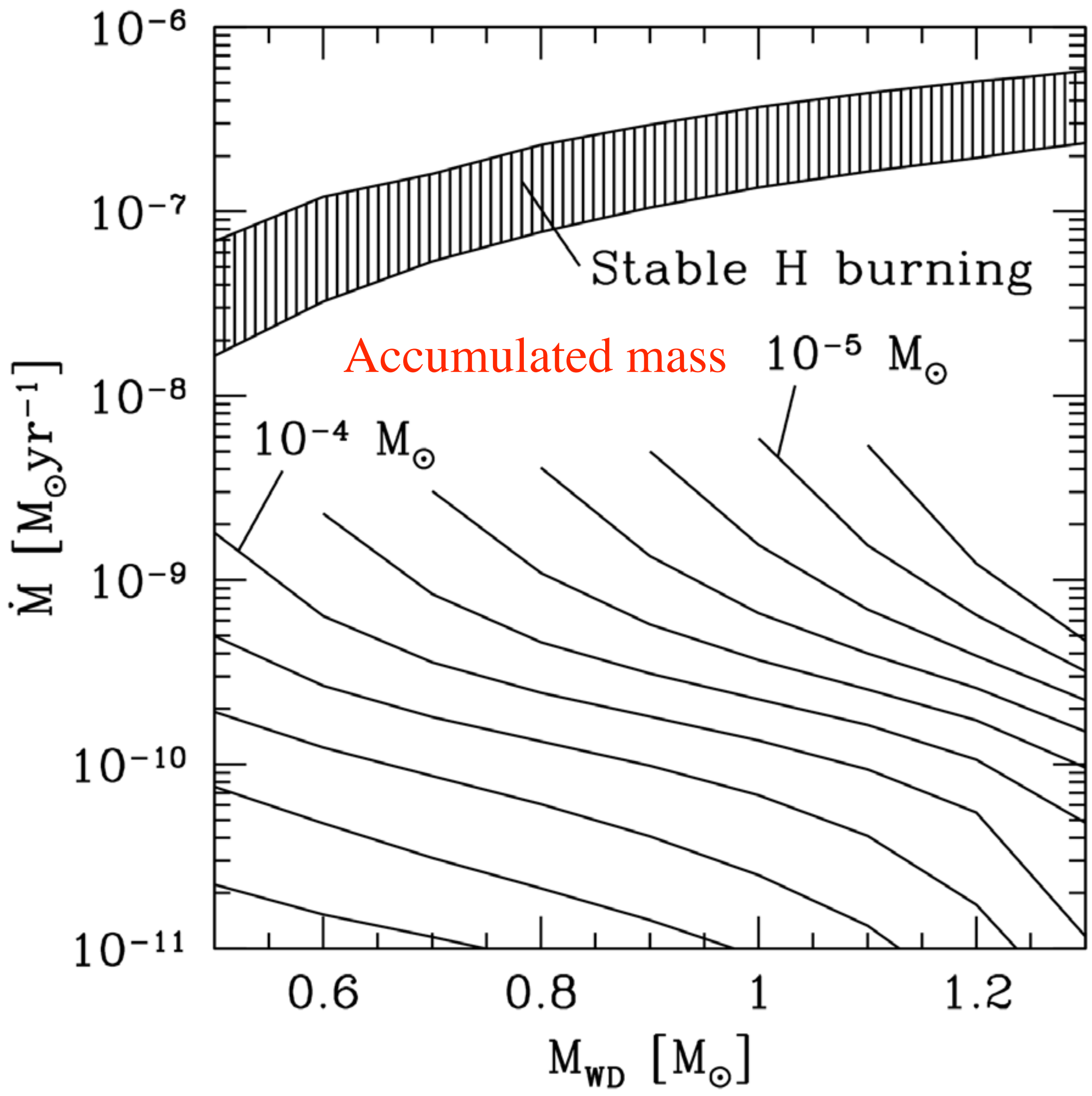
$$\rho_c = 10^9 \mathrm{g\ cm^{-3}} \rightarrow M = 1.33 M_\odot$$

$$\rho_c = 2\times 10^9 \mathrm{g\ cm^{-3}} \rightarrow M = 1.36 M_\odot$$

$$\rho_c = 3\times 10^9 \mathrm{g\ cm^{-3}} \rightarrow M = 1.37 M_\odot$$

Hydrogen Burning is Usually Unstable

Townsley & Bildsten 2005



Supersoft Sources: Burn H Stably (van den Heuvel et al 1992), or weakly unstable. Accretion phase ~100 Myrs

Cataclysmic Variables: unstable burning leads to Classical Novae. Whether the mass stays or goes is uncertain, but WDs are not massive enough!

Heat Transport in the White Dwarf Core

Townsley & LB 2004

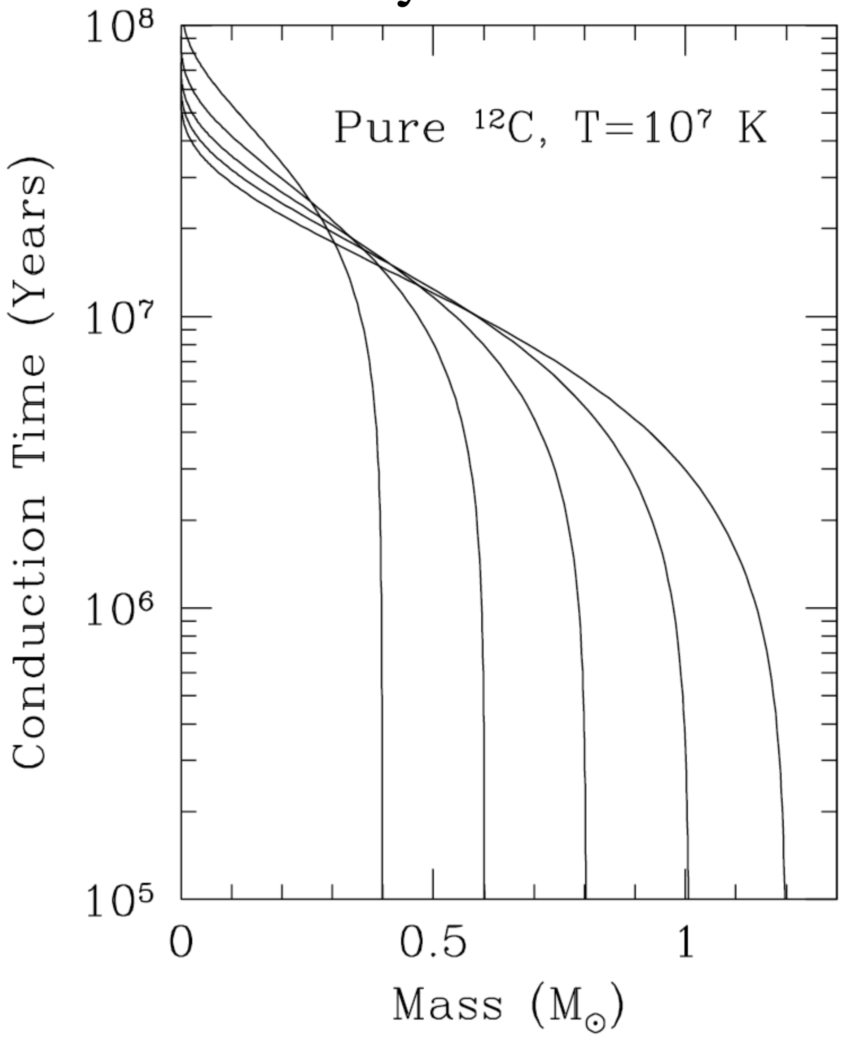


FIG. 11.—Thermal conduction time ($t_{\rm cond}$ in eq. [A2]) from the exterior of a pure carbon WD to an interior mass point. The curves are for isothermal WDs ($T = 10^7$ K) with masses $M = 0.4$, 0.6, 0.8, 1.0, and 1.2 $M_\odot$.

There are no heat sources deep in the white dwarf prior to the explosion, so to increase the core temperature for C ignition, must either:

- Compress the matter adiabatically

- Allow heat to flow in from a hotter surface set by the temperature from H or He Burning:

$$\tau_{\rm th} \approx \frac{C_P R^2}{K}$$

where K is the conductivity and

Carbon Ignition

The competition for the central fluid element is thus between density compression at the rate set by accretion of matter (on average)

(Hernanz et al. 1988; Nomoto 1982)

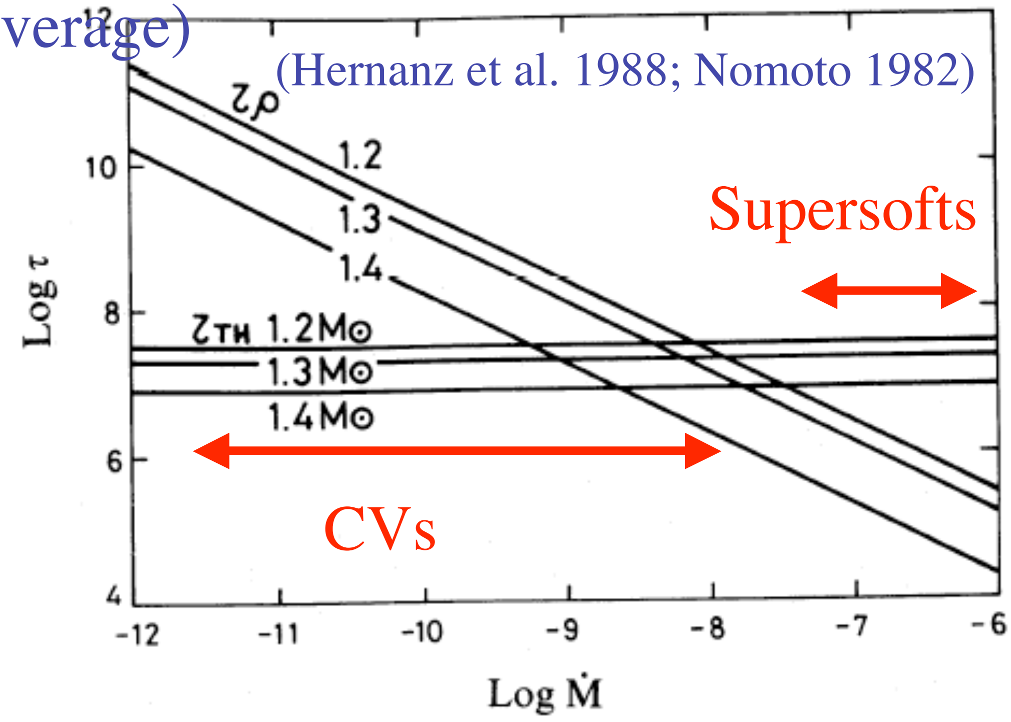


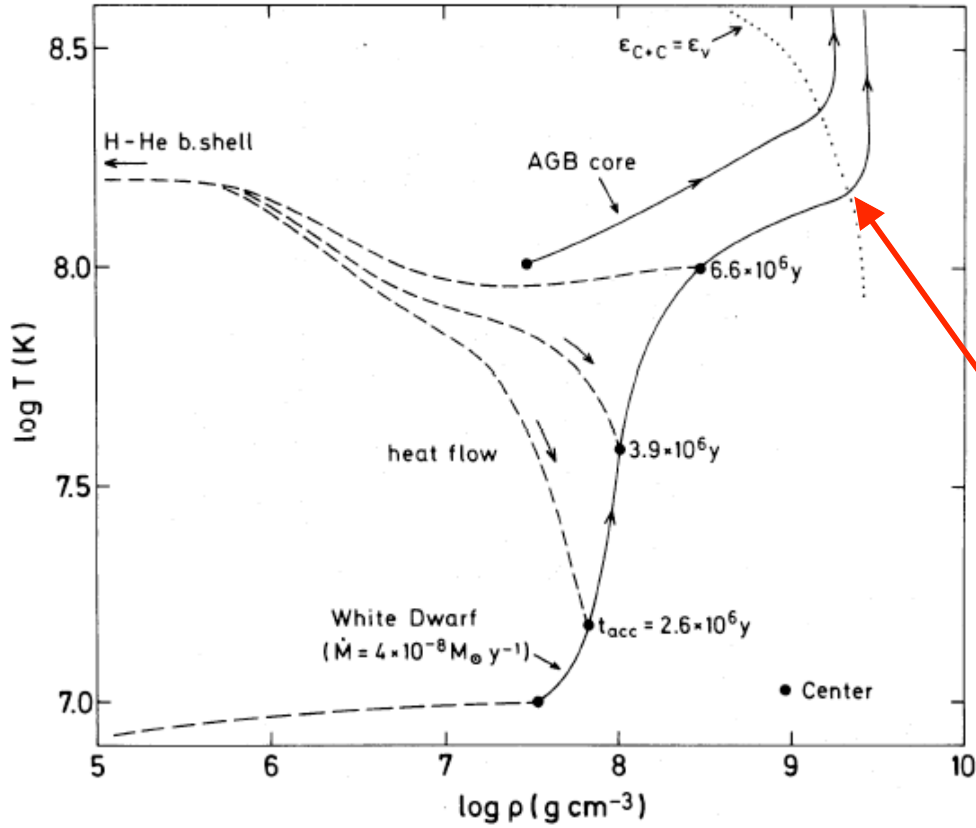
FIG. 1.—Time scale (in yr) for propagation of a thermal wave by conduction, τ_{TH}, and for central density increase (close to Chandrasekhar's limit), τ_ρ, as functions of accretion rate (in $M_\odot$ yr^{-1}) and initial mass.

$$\tau_\rho = F\frac{M}{\dot{M}}$$

(where F<<1 as the WD approaches the Chandrasekhar limit) and the thermal time. This rather clearly defines a characteristic accretion rate of 1e-7 M_sun/year, above which the star is adiabatically compressed.

Single Degenerate Ignition Story

No. 2, 1984 CARBON DEFLAGRATION SUPERNOVAE 647



Runaway ignition

FIG. 2*a*

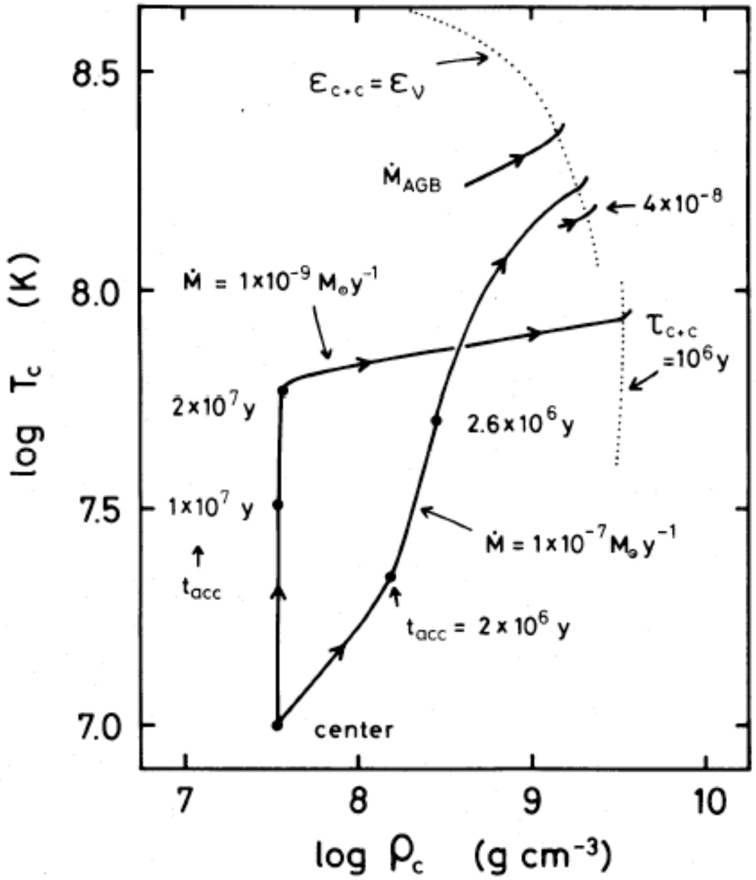


FIG. 2*b*

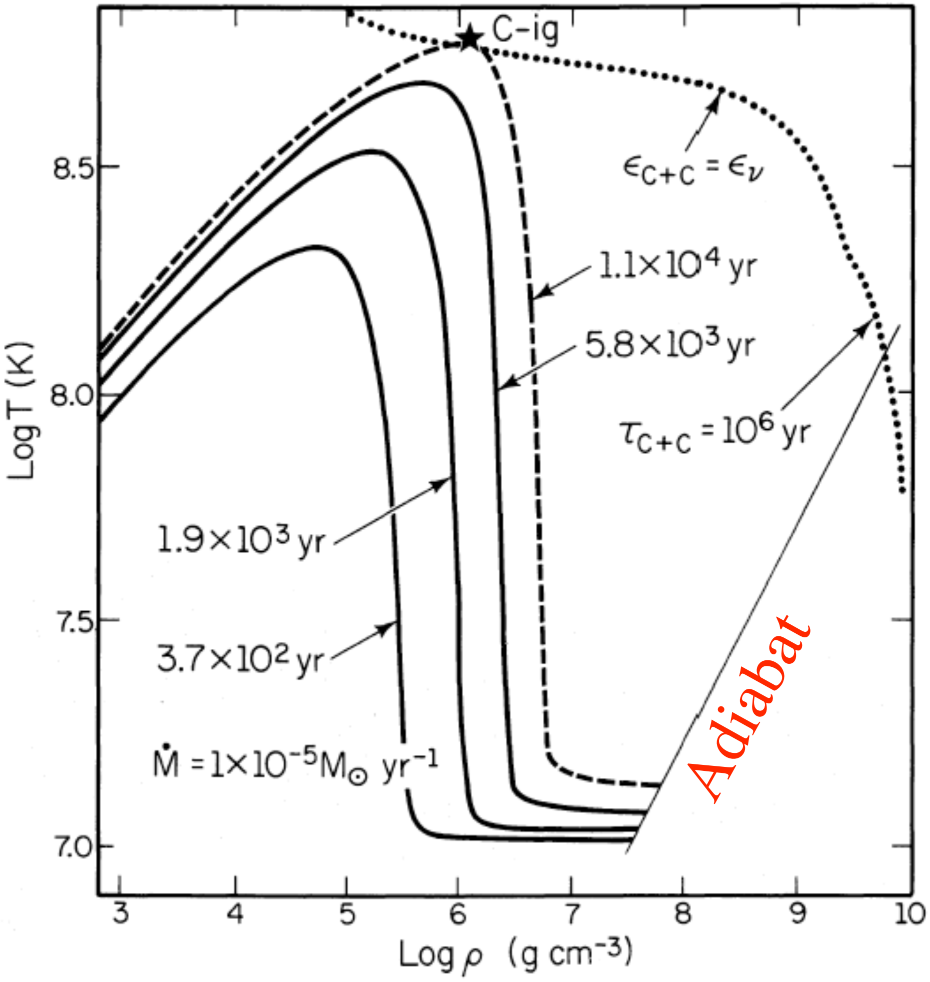
FIG. 2—(*a*) Accretion onto the white dwarf ($\dot{M} = 4 \times 10^{-8} M_\odot$ yr^{-1}) and growth of the core in the AGB star. The evolution of (ρ_c, T_c) is shown by the solid lines. Time, t_{acc}, is measured from the onset of accretion. Dashed lines are the structure lines of the white dwarf where heat flows from the surface into the interior. The dotted line is the ignition line of carbon burning defined by $\epsilon_{C+C} = \epsilon_\nu$. (*b*) Same as Fig. 2*a* but for the accretion onto the white dwarf with $\dot{M} = 1 \times 10^{-7}$ and $1 \times 10^{-9} M_\odot$ yr^{-1}. For low temperature, the carbon ignition occurs approximately at $\tau_{C+O} \equiv c_p T / \epsilon_{C+C} = 10^6$yr as indicated by the dotted line.

Nomoto, Thielemann and Yokoi 1984

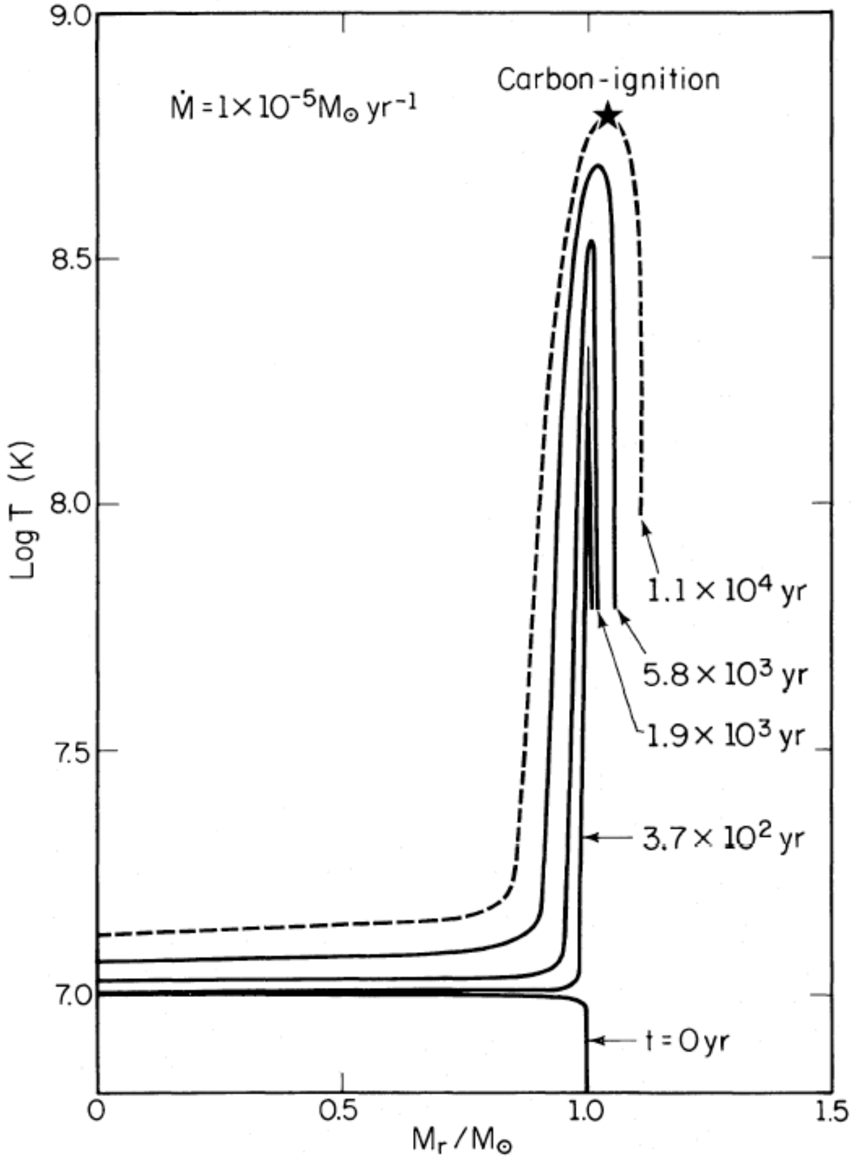
Rapid C/O Accretion from Mergers

Accretion of C/O at a high rate leads to:

1. Adiabatic compression of the core
2. Ignition at the outer edge, where there is a larger density change from accretion

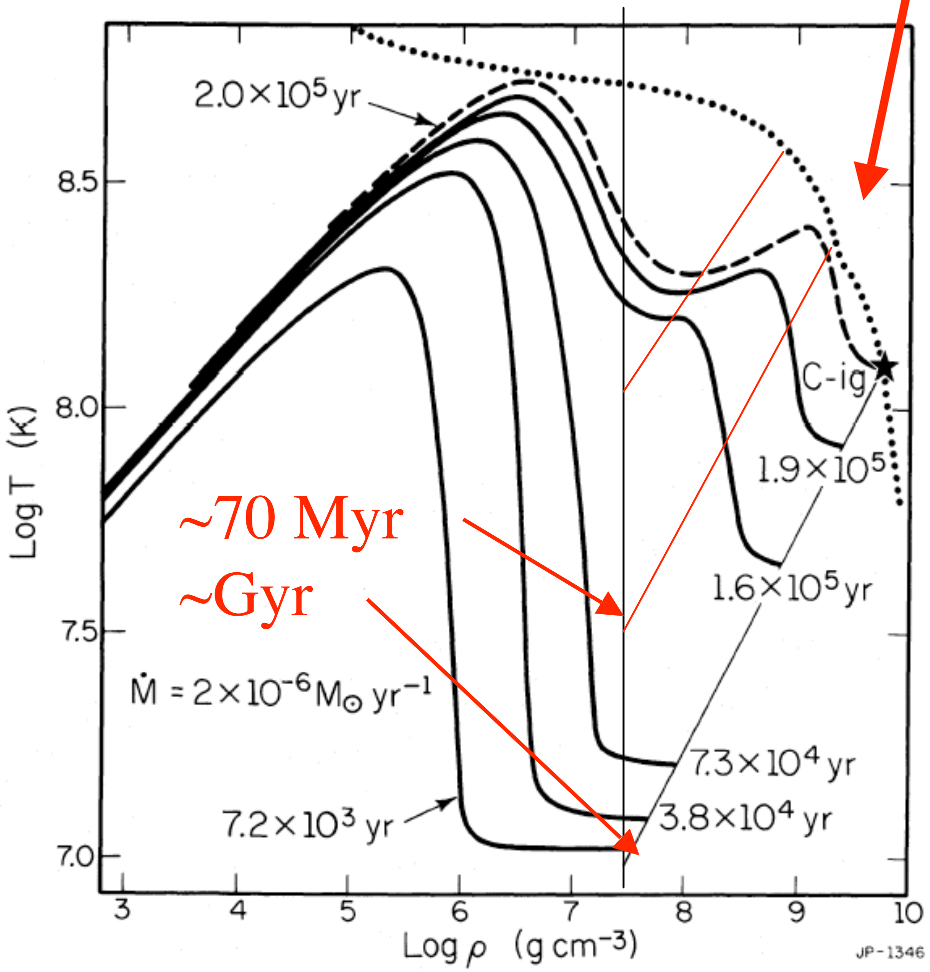


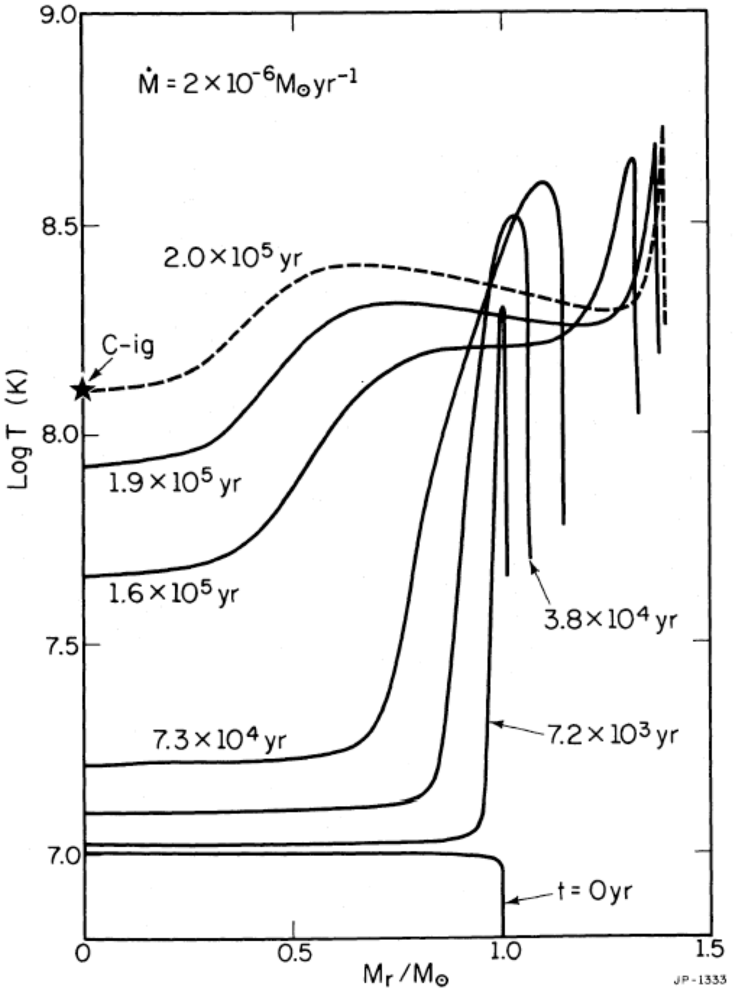
Nomoto and Iben 1985



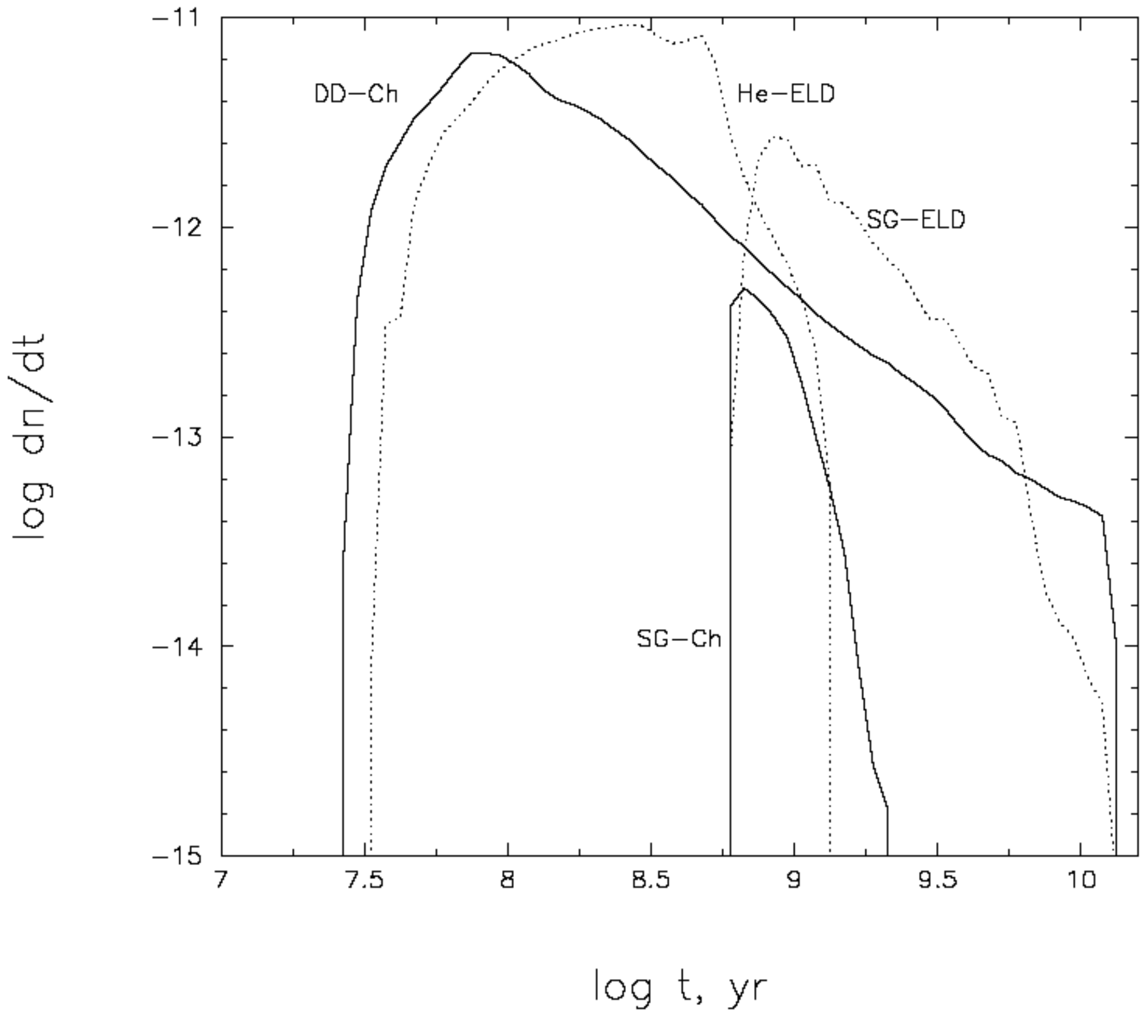
Rapid C/O Accretion (Cont.)

Rapid accretion results in an off-center ignition that likely leads to burning C/O to O/Ne and maybe NS formation, but remains actively debated. However, critical M_dot and M_tot depends on initial core temperature (i.e. age of the WD)!! (see Lesaffre et al. '06)





Rough Situation



Yungelson and Livio 2000

DD-Ch: Merged WDs

He-ELD: Helium edge lit detonations

SG-ELD: Thick Helium shell built by H burning

SG-Ch: Stable H burning, central core ignition

Type Ia Supernovae Dependence on Galaxy Type and Cosmic Rates

There are observed trends in Ia properties with galaxy type (no evidence yet for metallicity effects):

1. Brightest (e.g. 1991T) events occur preferentially in young stellar environments (hence mostly spiral and irregular galaxies)
2. Sub-luminous (and peculiar, eg. 1991bg) Ia's dramatically prefer old stellar populations . . (Elliptical and S0 Galaxies)
3. Rates track BOTH the stellar mass and the star formation rate

These are likely the result of old and young stellar populations and motivated (Scannapieco & LB, 2005, ApJ, 629, L85) simple explanation for the observed cosmic Ia rate.

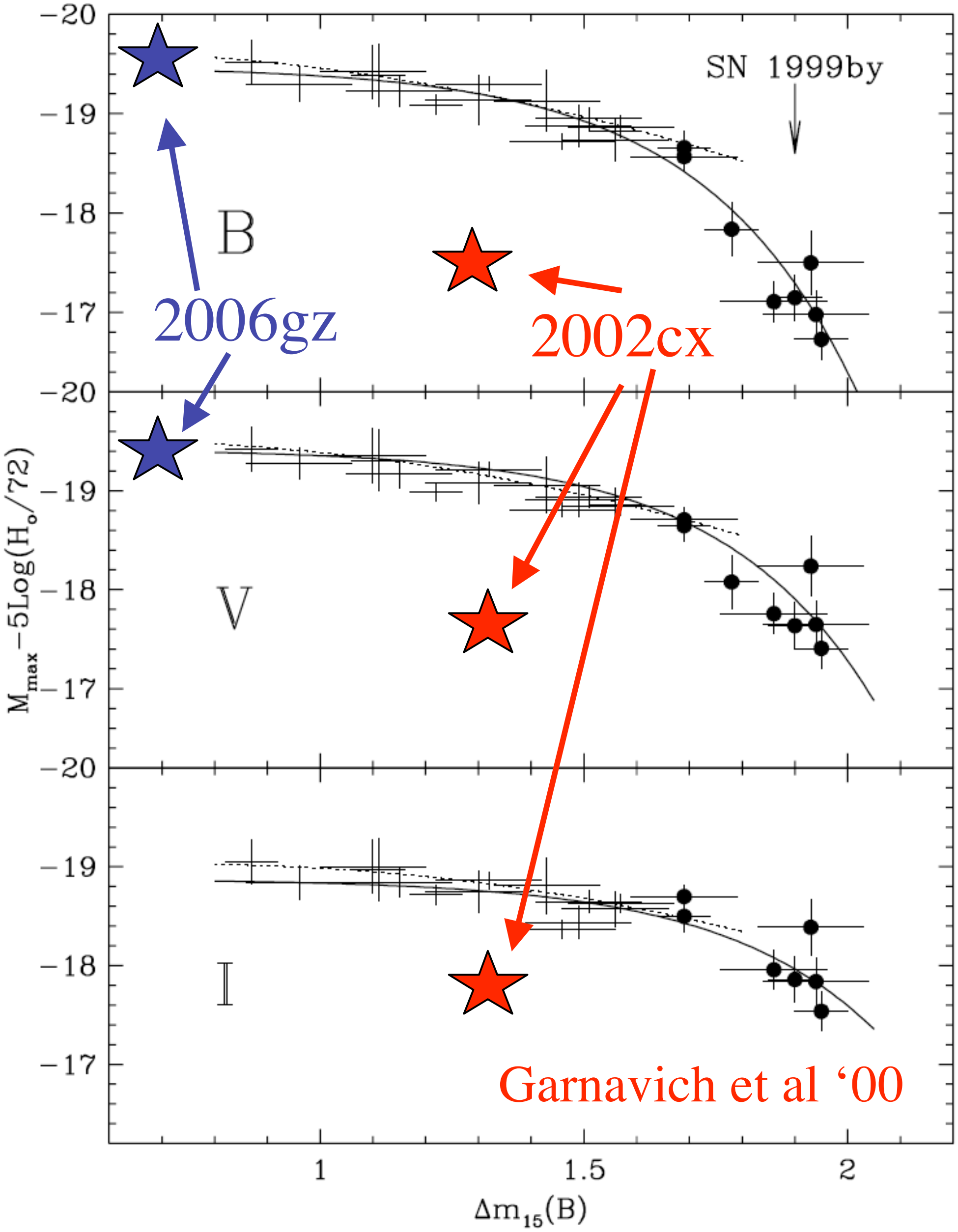


FIG. 17.—Absolute magnitudes of SNe Ia vs. $\Delta m_{15}(B)$ from Phillips et al. (1999), with so-called peculiar SNe added (*filled points*). The dotted line is the quadratic fit derived by Phillips et al. for $\Delta m_{15}(B) < 1.7$. The solid line is an exponential fit that attempts to fit all the objects represented.

- The sub-luminous Ia’s fit within the continuum of the Phillip’s relation, extending down by nearly 2.5 mags, all share the Ti II excesses
- Most prevalent in E/S0 galaxies (Howell ‘01, van den Bergh et al ‘03)
- Still other odd ones (2002cx)!

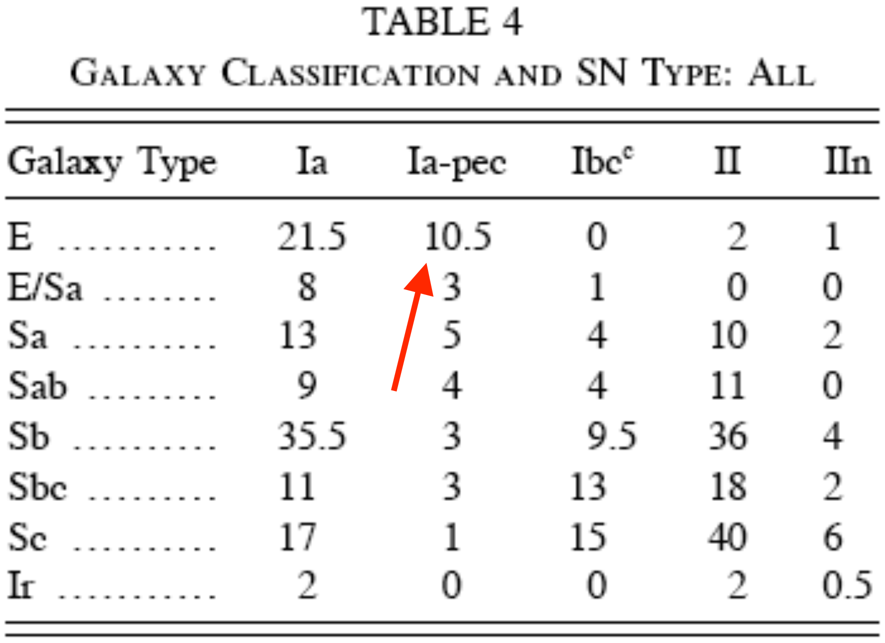


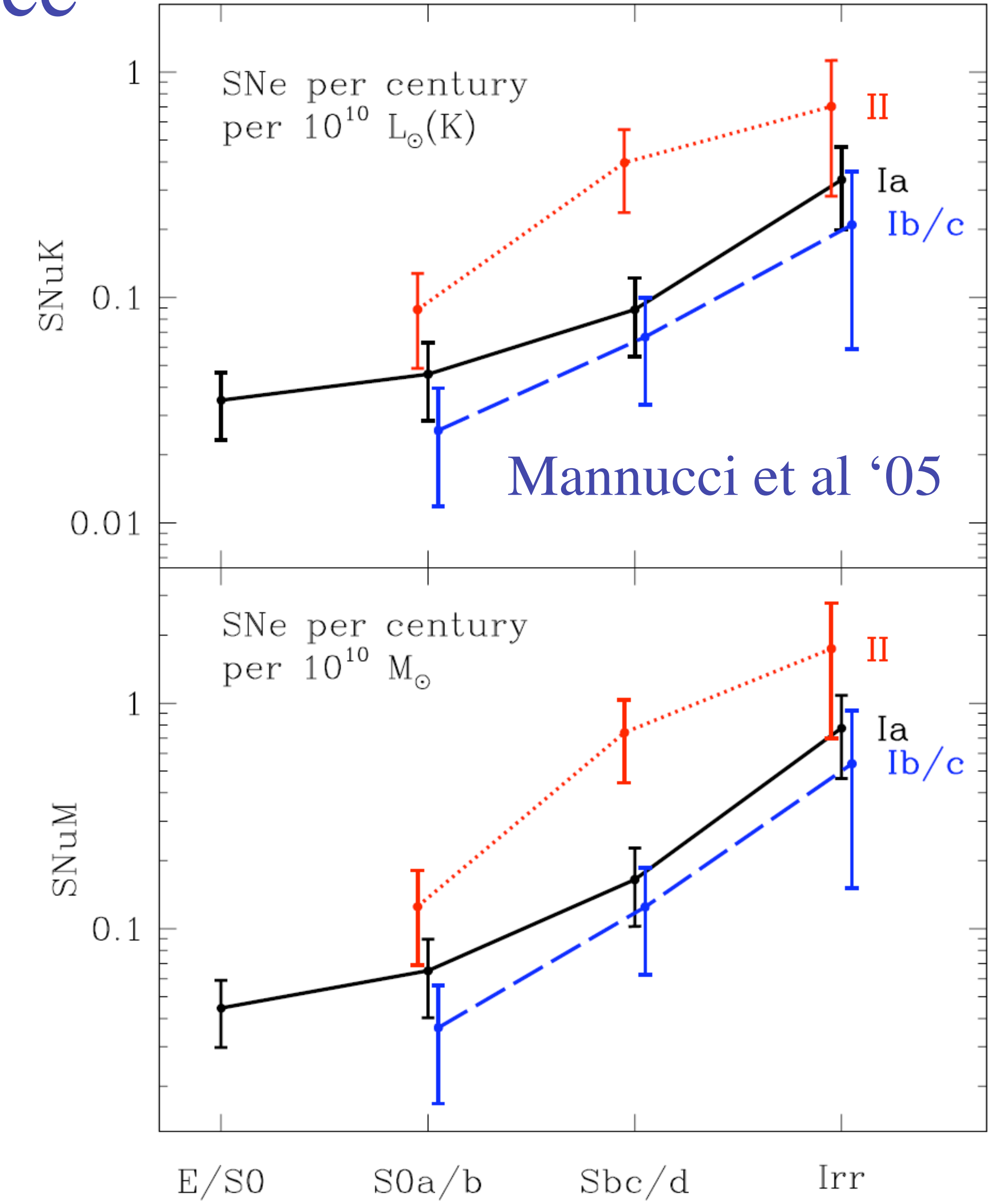
TABLE 4

GALAXY CLASSIFICATION AND SN TYPE: ALL

Galaxy Type	Ia	Ia-pec	Ibc^c	II	IIn
E	21.5	10.5	0	2	1
E/Sa	8	3	1	0	0
Sa	13	5	4	10	2
Sab	9	4	4	11	0
Sb	35.5	3	9.5	36	4
Sbc	11	3	13	18	2
Sc	17	1	15	40	6
Ir	2	0	0	2	0.5

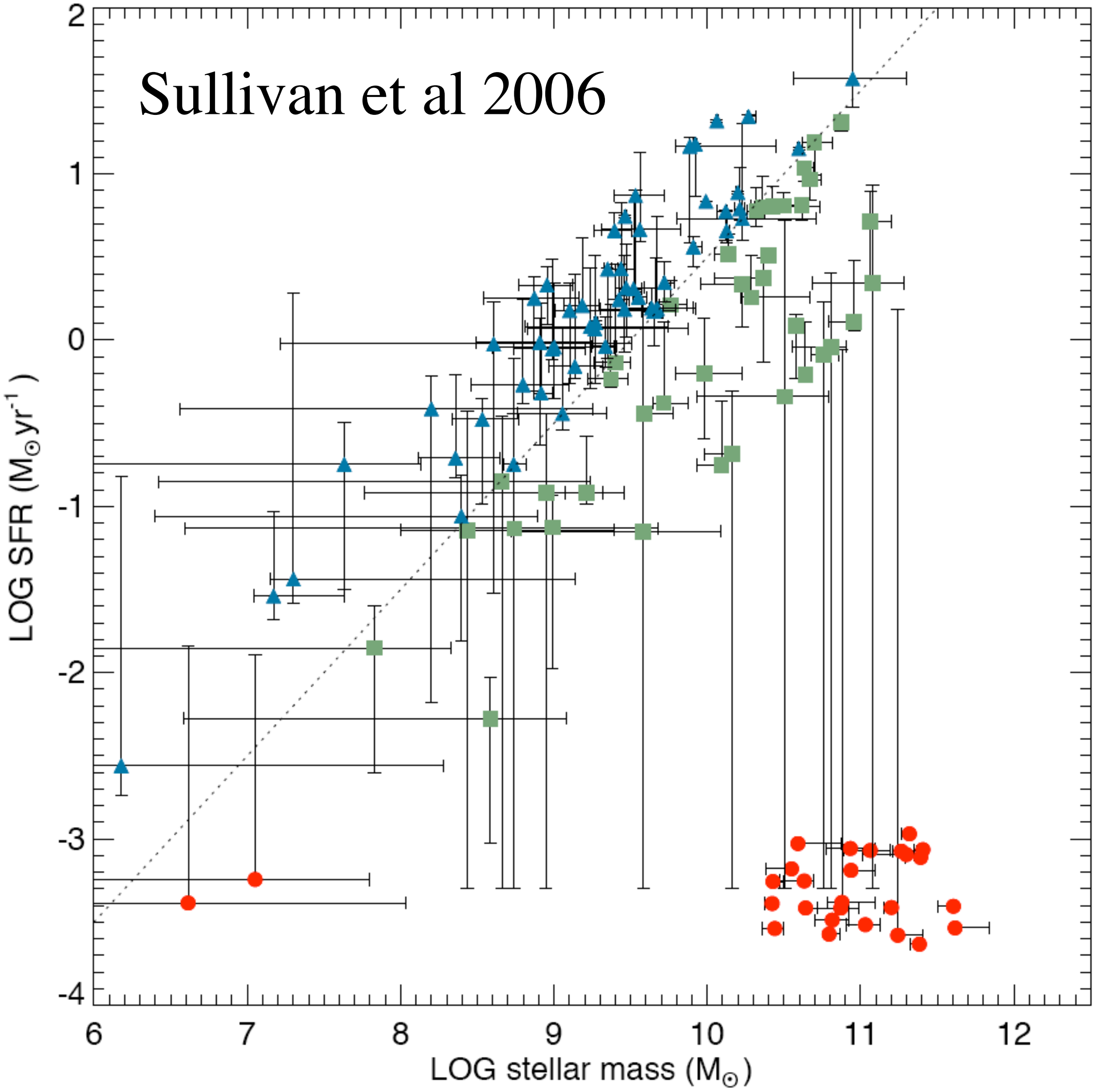
SN Rate Dependence on Galaxy Type

- Infrared luminosity used to determine the stellar mass
- Part of the Ia rate tracks the Star formation and is 1/3 the Core Collapse rate
- Ia Data can be “fit” with one term that depends on mass (confirmed in clusters: Sharon et al ‘06) and another that is 40% of the core collapse rate
- Roughly one Ia every 400 years for 1 solar mass per year of star formation.



Canada-France-Hawaii Telescope SuperNova Legacy Survey (SNLS)

125 Ia Sne, $0.2<z<0.75$



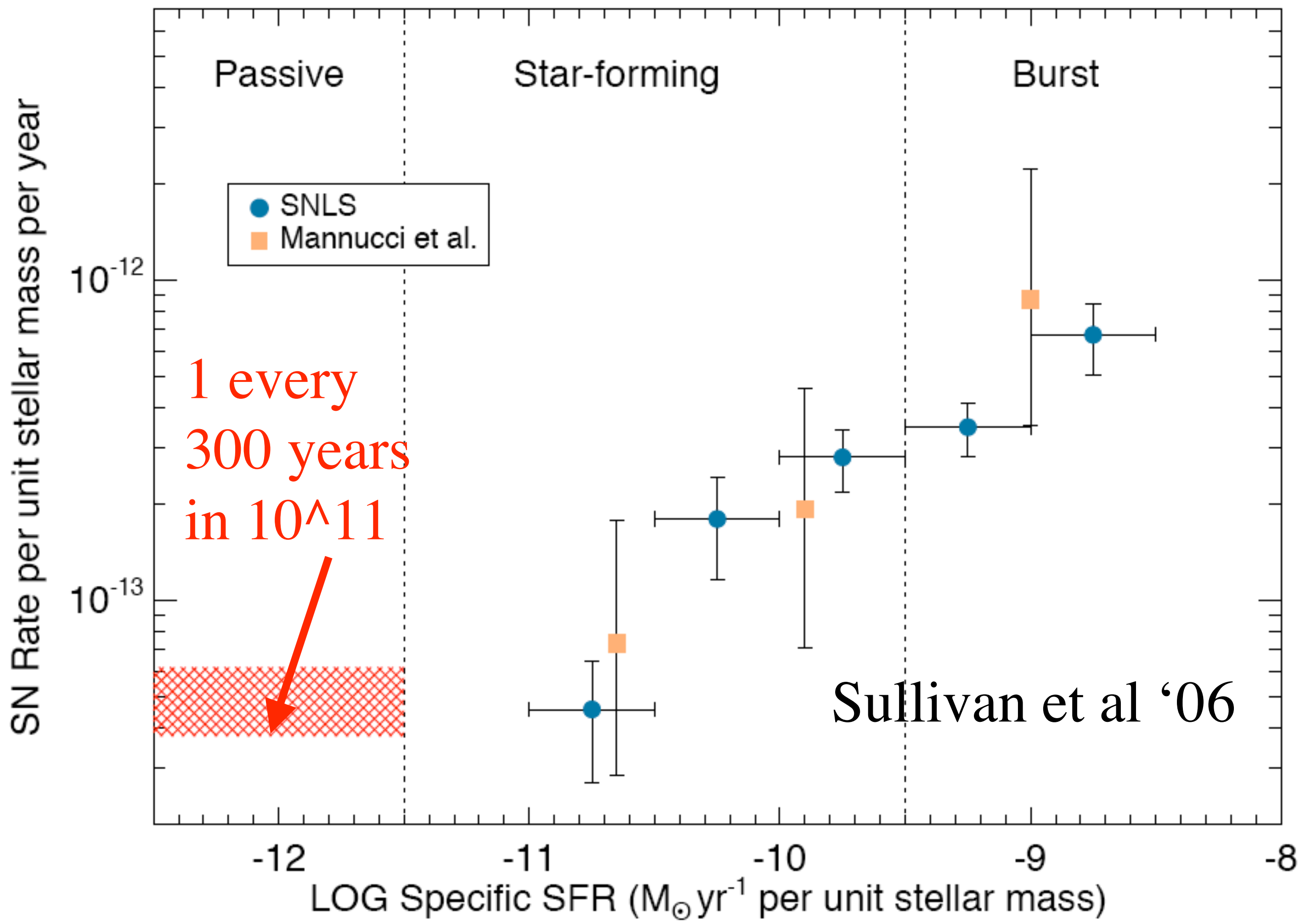
Sullivan et al 2006

- Galaxies identified from the CFHT survey. All Ia's are spectroscopically confirmed

- For the clear counterparts (some are ambiguous), the galaxies were classified via colors as vigorous star formers, star-forming, and passive.

- When SNLS is done, this list should be ~500

Scalings with Star Formation Rate

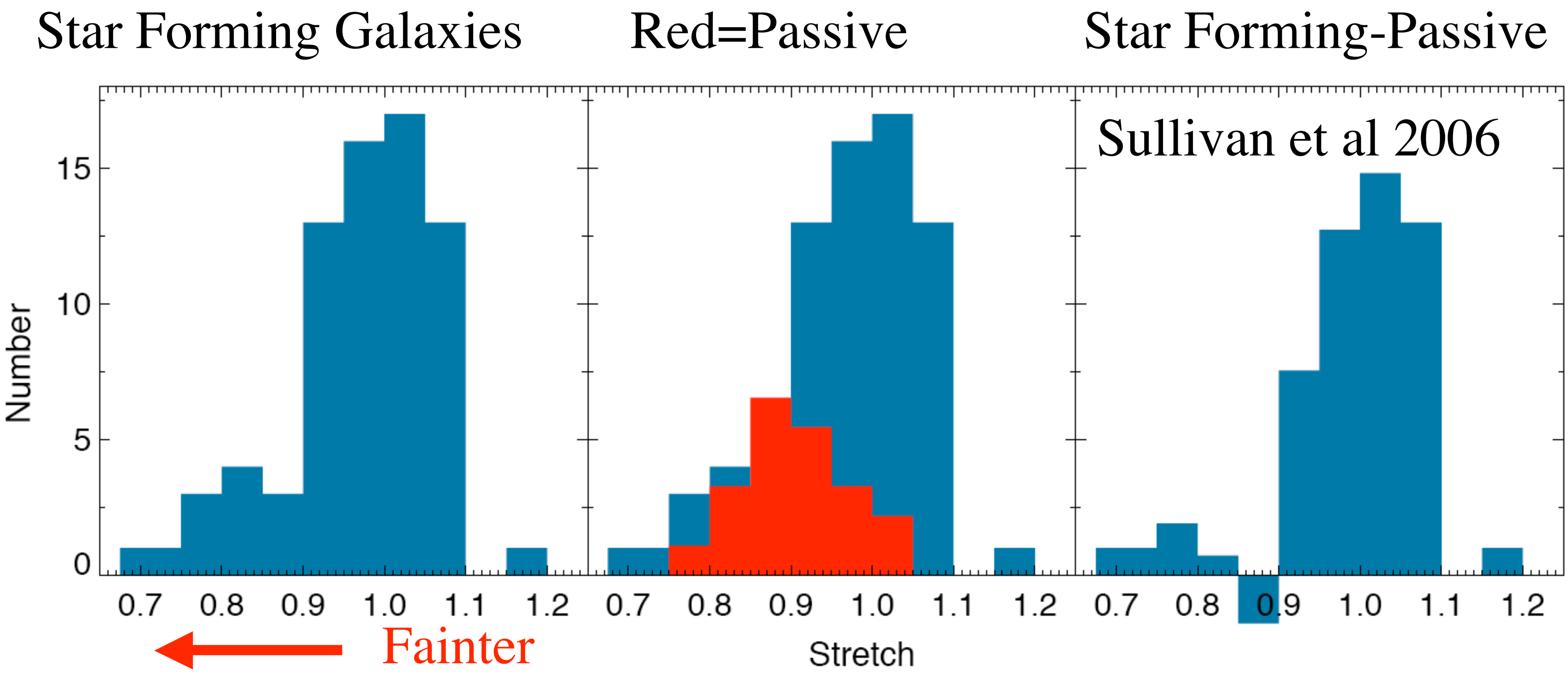


1 every
300 years
in 10^11

Sullivan et al '06

Confirmation of the mass specific rate of Mannucci et al for passive galaxies, and confirmation of the Ia rate dependence on star formation rate.

CFHT Supernovae Legacy Survey (SNLS)

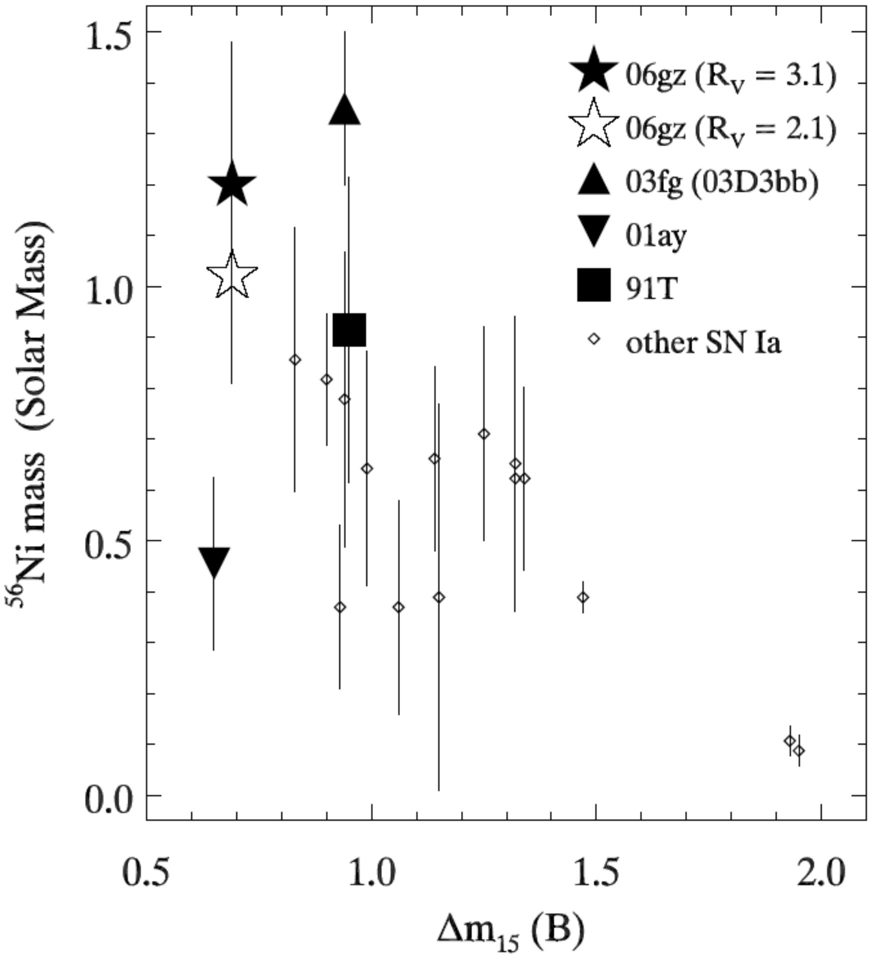


Sullivan et al 2006

The number of faint (small stretch) Ia’s in spirals is consistent with the old stellar population in the spiral galaxy.

The two populations are distinct, but overlapping in their 56Ni production levels.

Mergers of WD's?



Hicken et al '07

- Howell et al (2006) suggested that 2003fg was 'super'chandra based on:
  - Presence of carbon at early times
  - Low velocities of Si at early times
  - Luminous and broad light curve with high 56Ni
- Recent discovery of similar behavior in 2006gz (Hicken et al. '07) in a spiral and ROTSE3J011051+15..(Yuan et al; Atel 1212)

2002cx “likes”

- Only seen in active star forming galaxies
- Do NOT follow the Phillips relation
- Have very LOW velocities early and late times and very low velocities
- 6 known systems at this time.. likely to grow.
- See work by Jha, Li et al, Chornock
- Best summary is Jha’s talk at KITP online
- http://online.itp.ucsb.edu/online/snovae07/jha/

Ia Preliminary Conclusions

- There are two distinct populations of Ia that track stellar mass and star formation rate and have, on average, different (but overlapping) 56Ni masses
- New and unusual systems like 2002cx as well as ‘super-chandra’ will hopefully help unravel the physics
- Though we have not identified progenitors with specific classes of Ia’s, evidence is mounting that:
  - Ia’s at 10 Gyrs requires either a new single degenerate channel or a WD-WD merger
  - Ia’s occur within 0.5-1 Gyr of star formation.

Three Events

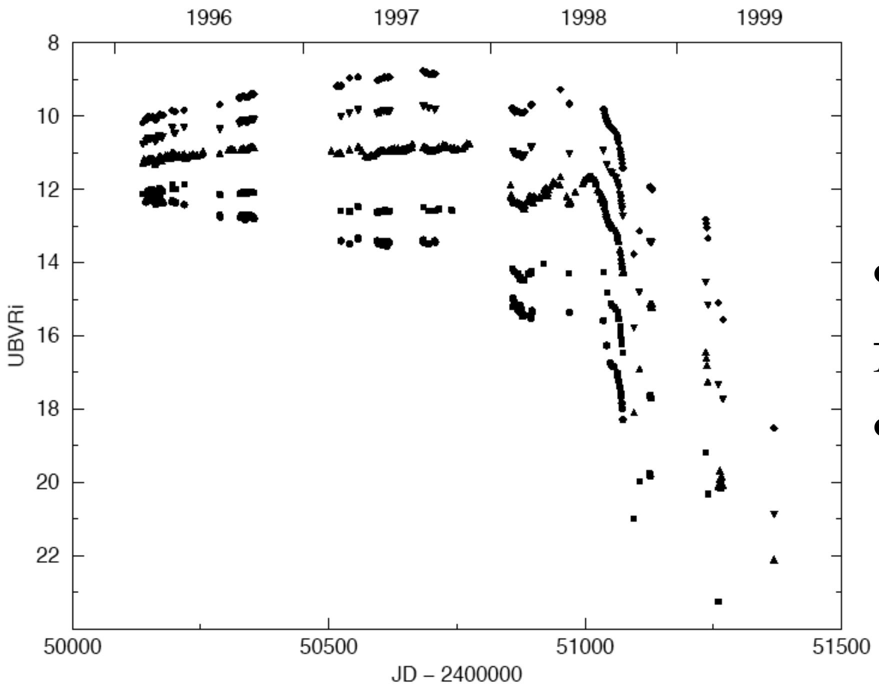


FIG. 3.—*UBVRi* light curve of V4334 Sgr. This curve includes only the observations made at the Dutch 0.91 m telescope and the Reñaca 0.2 m telescope, plus some observations at late stages made by Jacoby, Jacoby & De Marco and Benetti. *Bottom to top*: *U*, *B*, *V*, *R*, *i* light curves.

- Typically up to -5 to -8, lasts for many years, evolves to red..
- Dust is formed..

FG Sge (1894)
V605 Aql (1917) (-5)
V4334 Sgr (1992, Sakurai)

Duerbeck et al. AJ, 119, 2360 (2000)

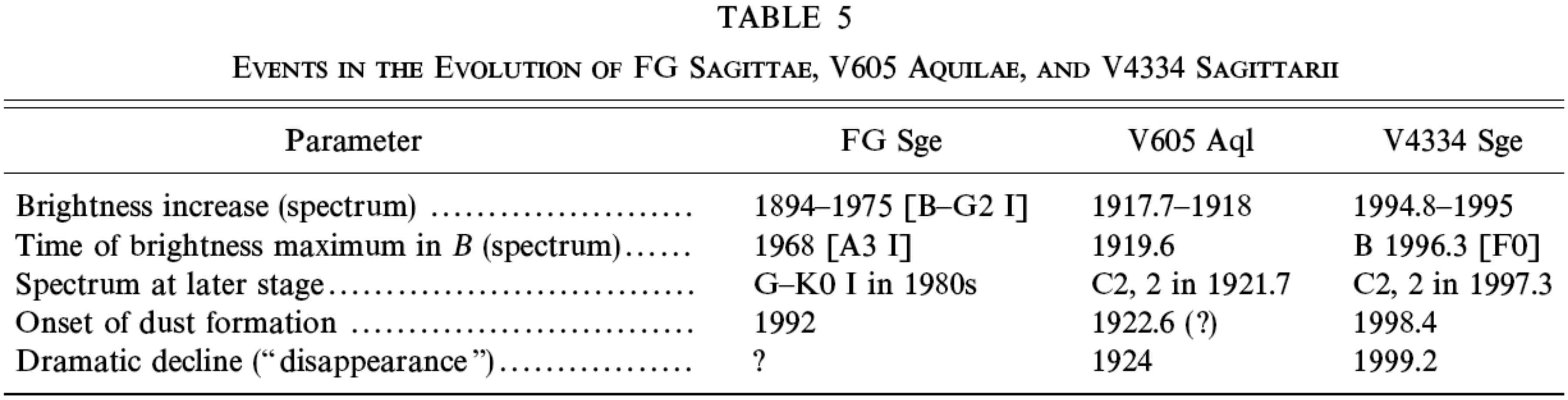
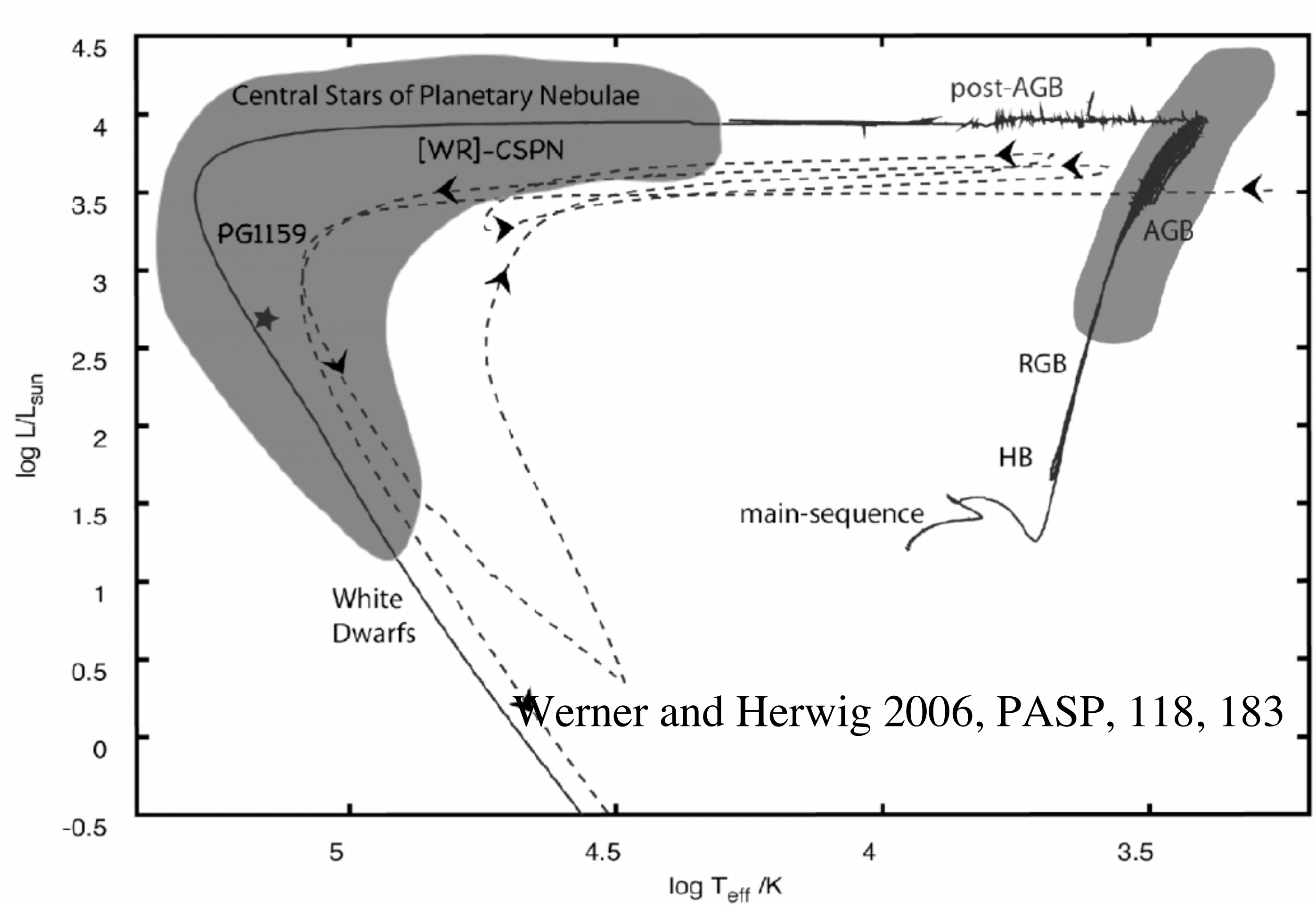


TABLE 5

EVENTS IN THE EVOLUTION OF FG SAGITTAE, V605 AQUILAE, AND V4334 SAGITTARII

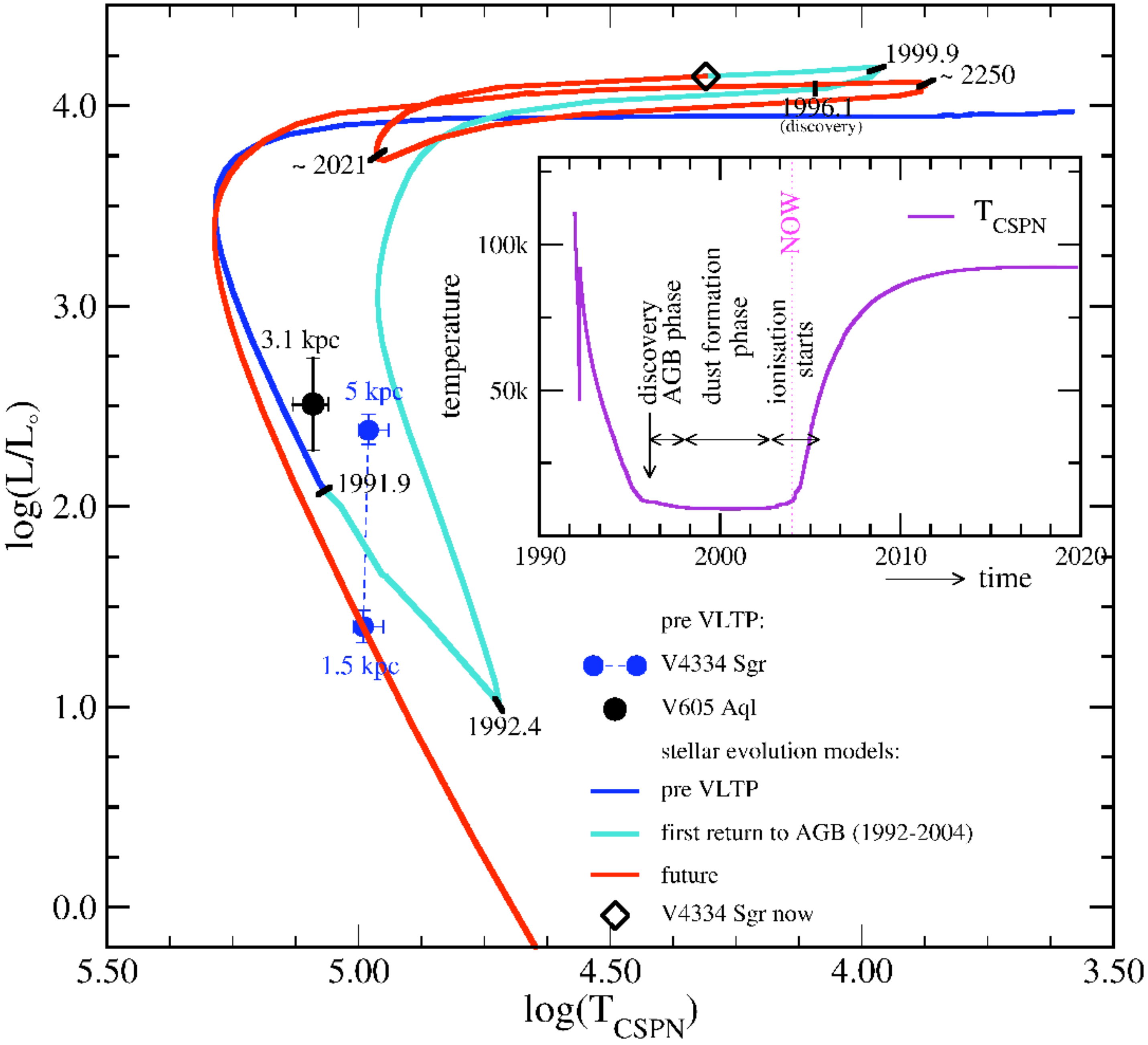
Parameter	FG Sge	V605 Aql	V4334 Sge
Brightness increase (spectrum)	1894–1975 [B–G2 I]	1917.7–1918	1994.8–1995
Time of brightness maximum in *B* (spectrum)......	1968 [A3 I]	1919.6	B 1996.3 [F0]
Spectrum at later stage..............................	G–K0 I in 1980s	C2, 2 in 1921.7	C2, 2 in 1997.3
Onset of dust formation	1992	1922.6 (?)	1998.4
Dramatic decline (“disappearance”).................	?	1924	1999.2

Late Thermal Pulses (10-20% of all WDs!)

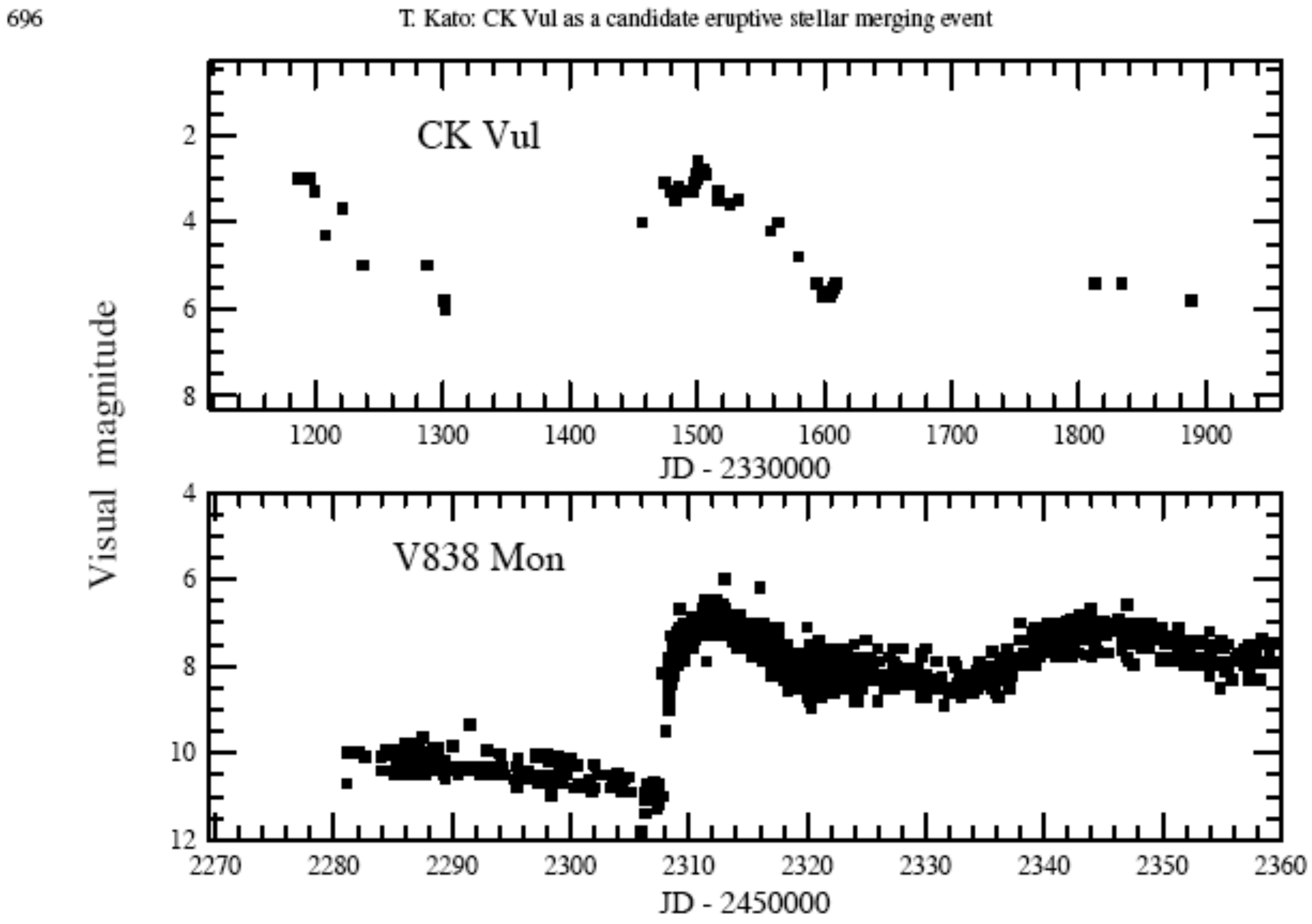


Werner and Herwig 2006, PASP, 118, 183

The depletion of H is likely why the rise is rapid and it explains the 10-20% prevalence of DB WDs…


1999.9
~ 2250
1996.1
(discovery)
~ 2021
3.1 kpc
5 kpc
1991.9
1.5 kpc
1992.4
temperature
100k
50k
T_{CSPN}
NOW
discovery
AGB phase
dust formation
phase
ionisation
starts
1990
2000
2010
2020
time
pre VLTP:
V4334 Sgr
V605 Aql
stellar evolution models:
pre VLTP
first return to AGB (1992-2004)
future
V4334 Sgr now
4.0
3.0
2.0
1.0
0.0
5.50
5.00
4.50
4.00
3.50
$\log(L/L_{\odot})$
$\log(T_{CSPN})$

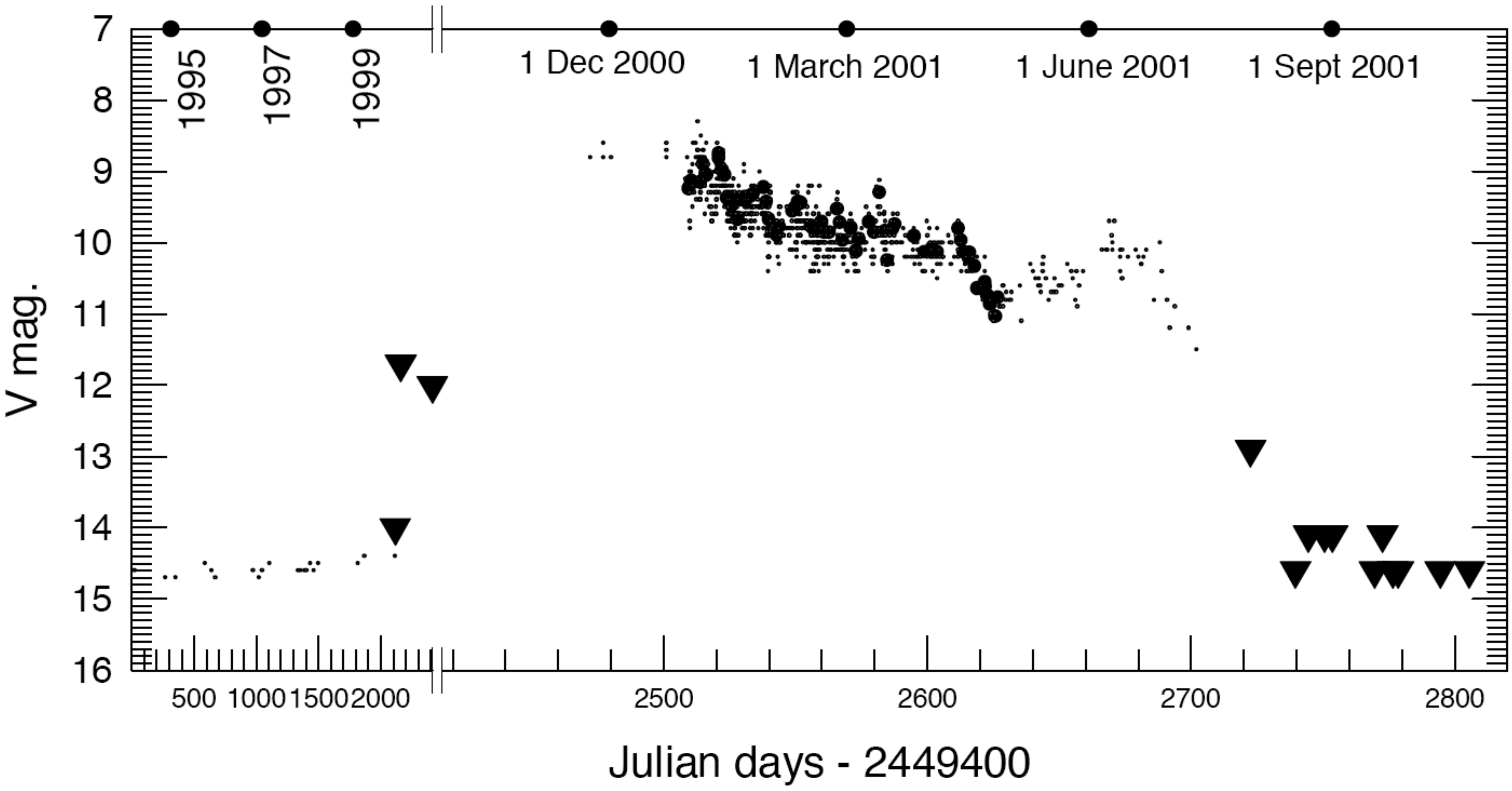
CK Vul (M_v=-7 to -8)



696 T. Kato: CK Vul as a candidate eruptive stellar merging event

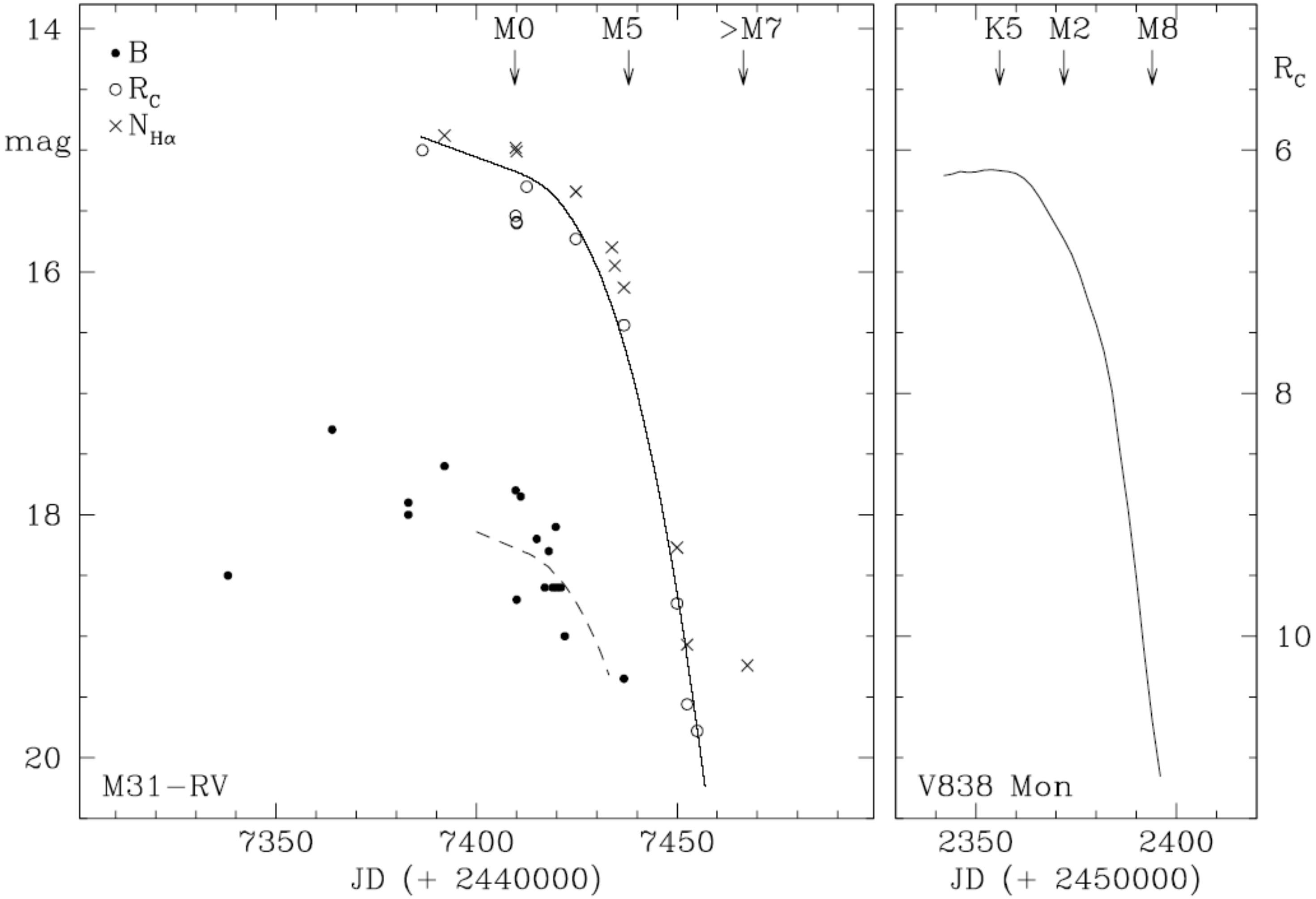
V445 Puppis= Helium Novae?

1008 N. M. Ashok and D. P. K. Banerjee: IR spectroscopy of V445 Puppis

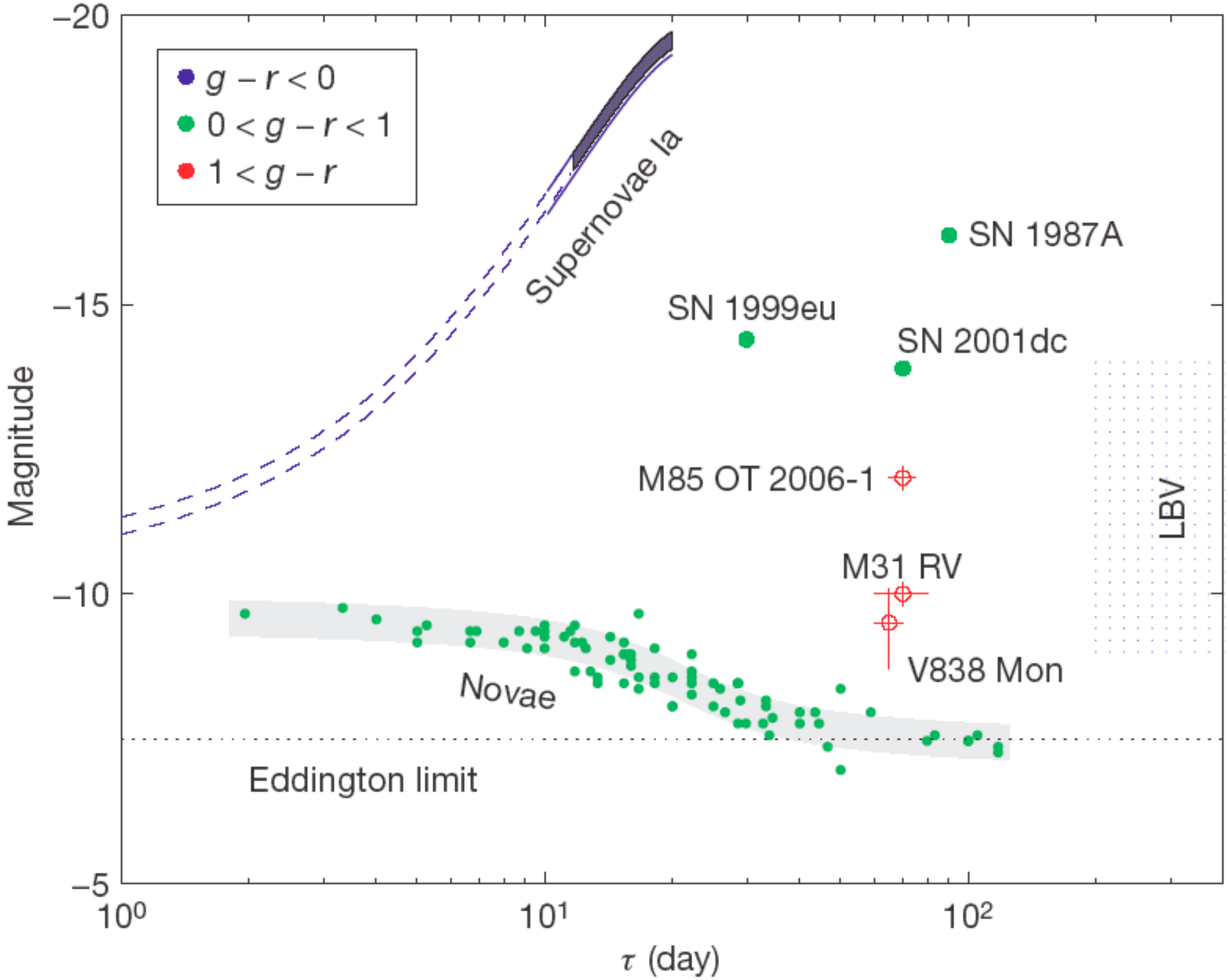


M31-RV and V838 Mon

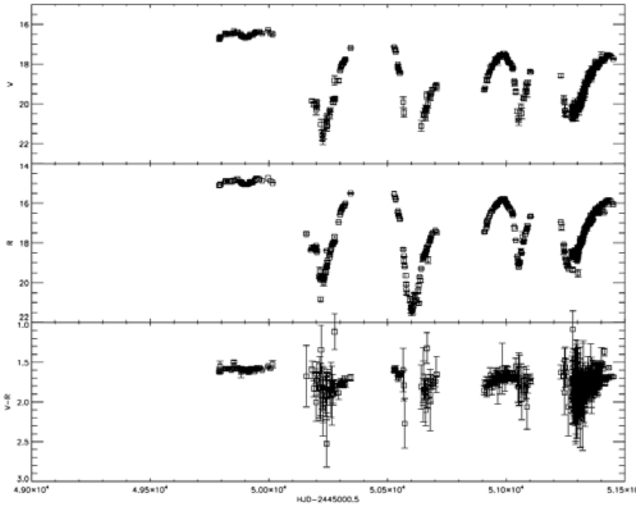
F. Boschi and U. Munari: M 31-RV evolution and its alleged multi-outburst pattern

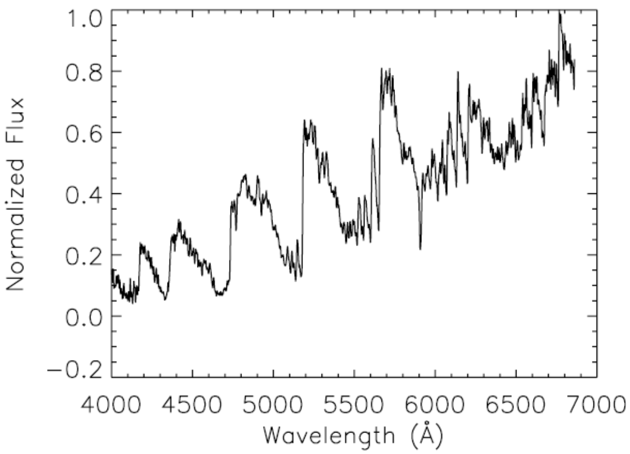


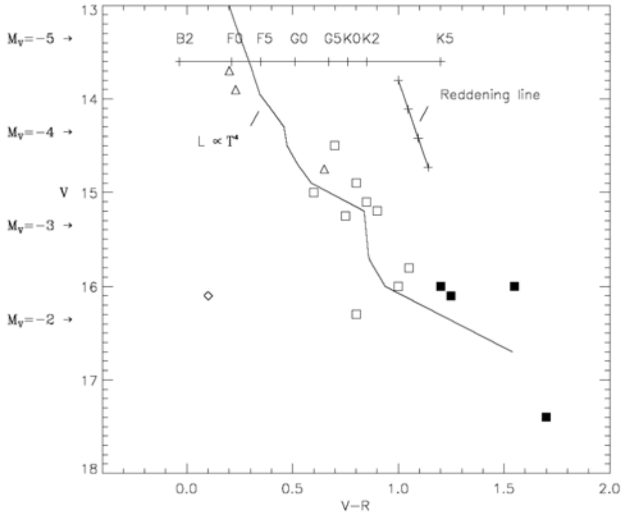
M85 OT (Kulkarni et al. 2007)



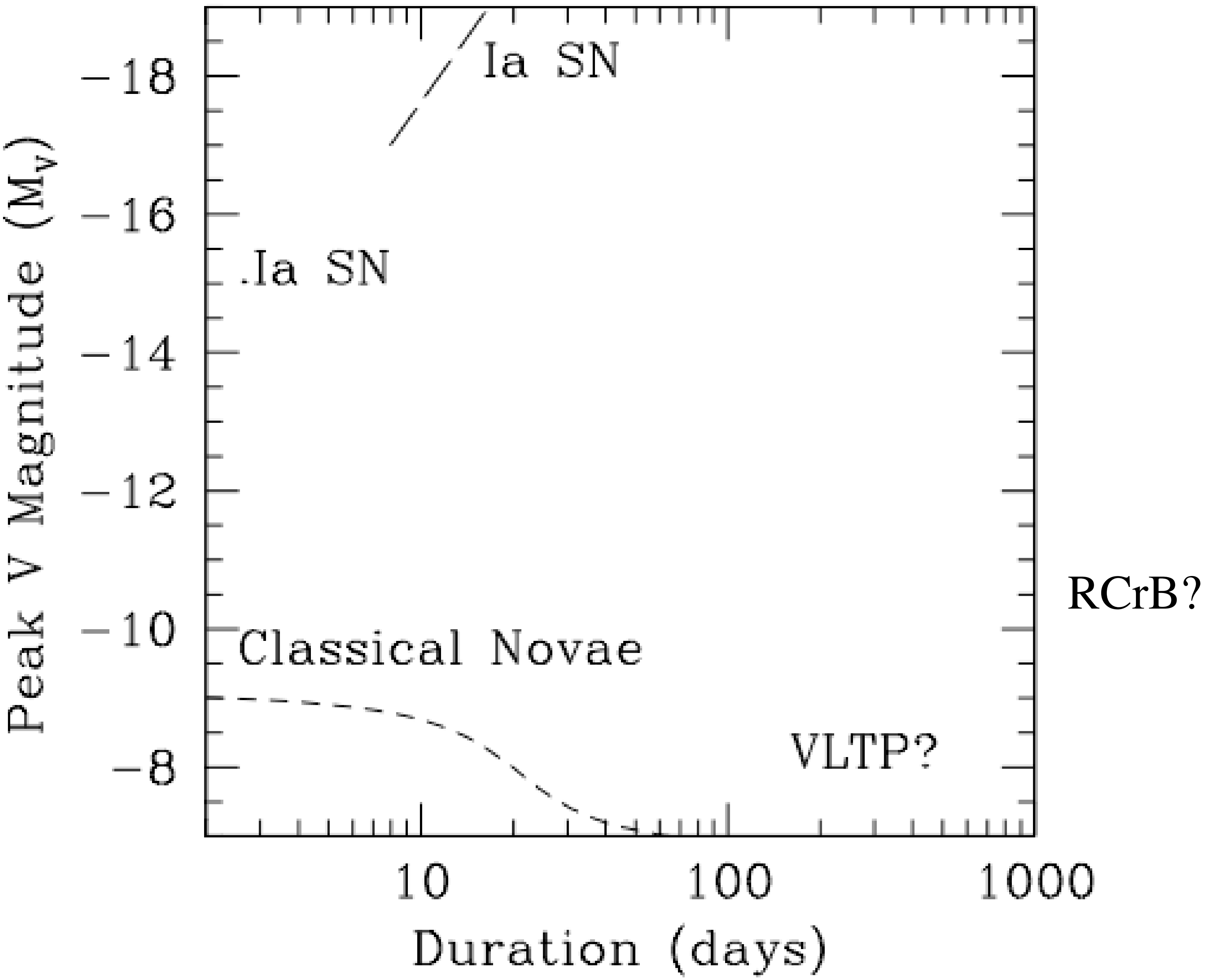
WD-WD Mergers: R Cr B stars?







- Variable stars at M_v=-4 to -5. No hydrogen present, pure He+ carbon. Variability due to dust formation episodes.
- MACHO found many, rough numbers for our galaxy are 3000 (Alcock et al. 2001)
- Current hypothesis is He+C/O mergers, followed by burning for 100,000 years=> birthrate is 3 in 100 years..


Ia SN
.Ia SN
Classical Novae
VLTP?
RCrB?
Peak V Magnitude (M_V)
−18
−16
−14
−12
−10
−8
10
100
1000
Duration (days)