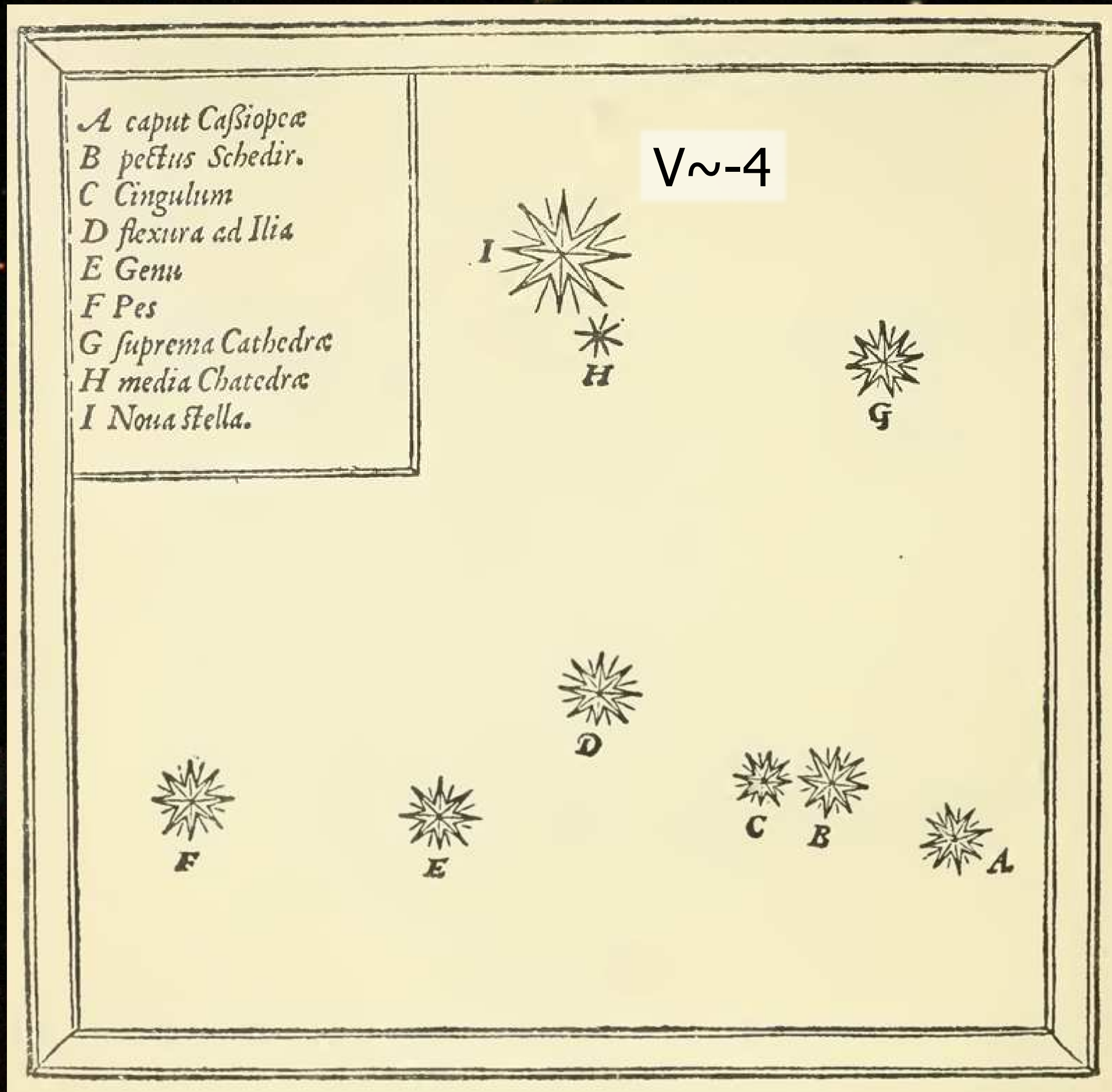
Boris Gänsicke

Type Ia supernovae and their progenitors

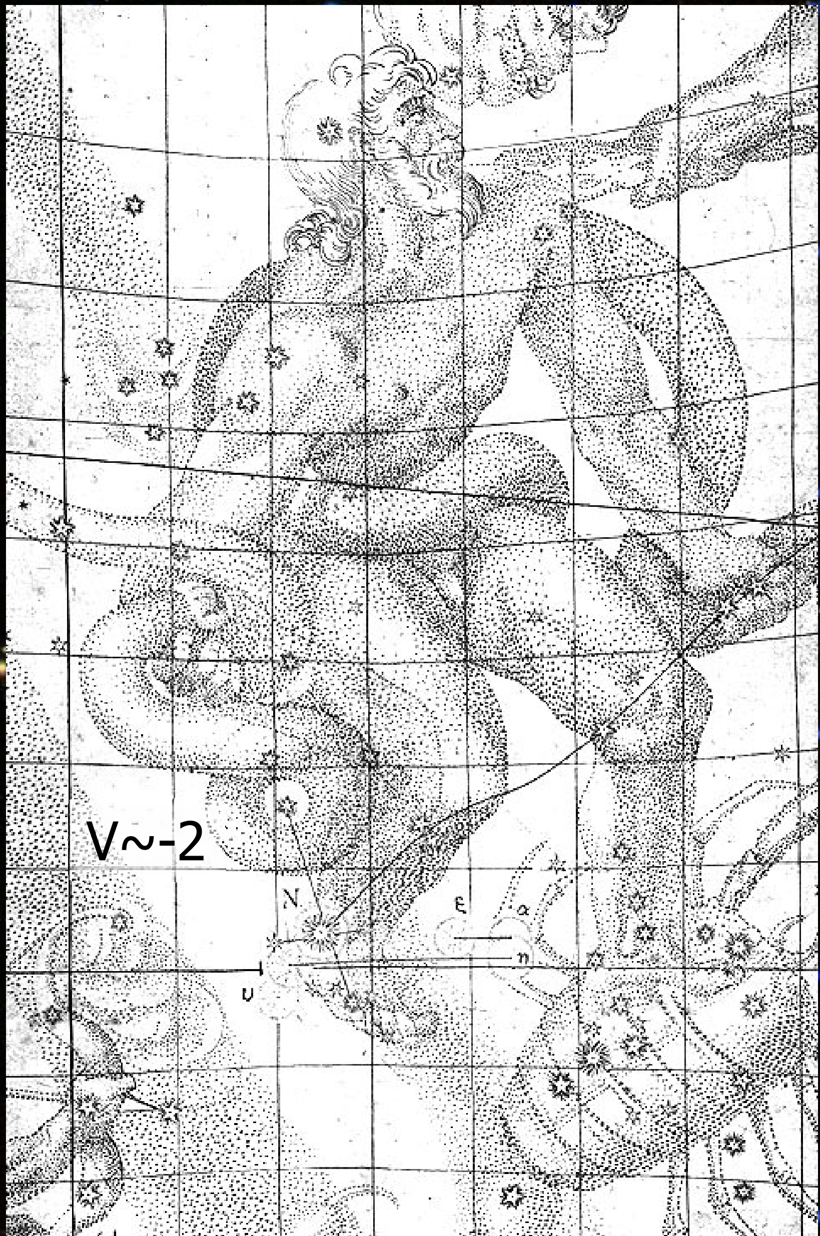
THE UNIVERSITY OF WARWICK

November 1572, in Cassiopeia: a "nova" – a new star



Tycho Brahe: *De nova et nullius aevi memoria prius visa stella* (1602)

October 9, 1604, in Ophiuchus



Johannes Kepler:
De Stella nova in pede Serpentarii (1602)

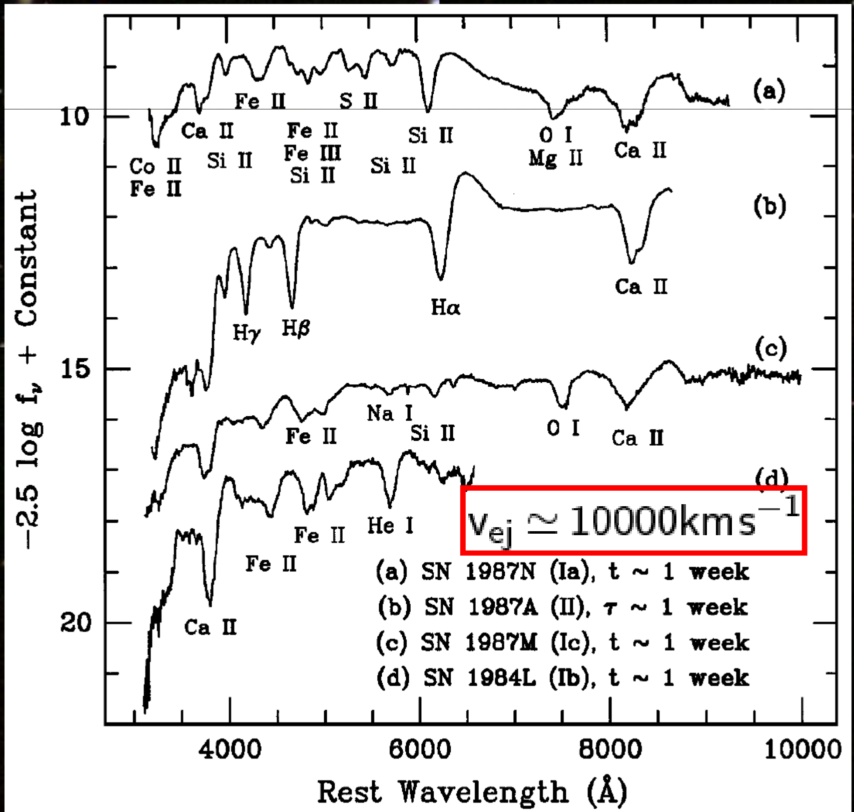
2012: > 6000 SN reported
http://www.cbat.eps.harvard.edu/lists/Supernovae.html

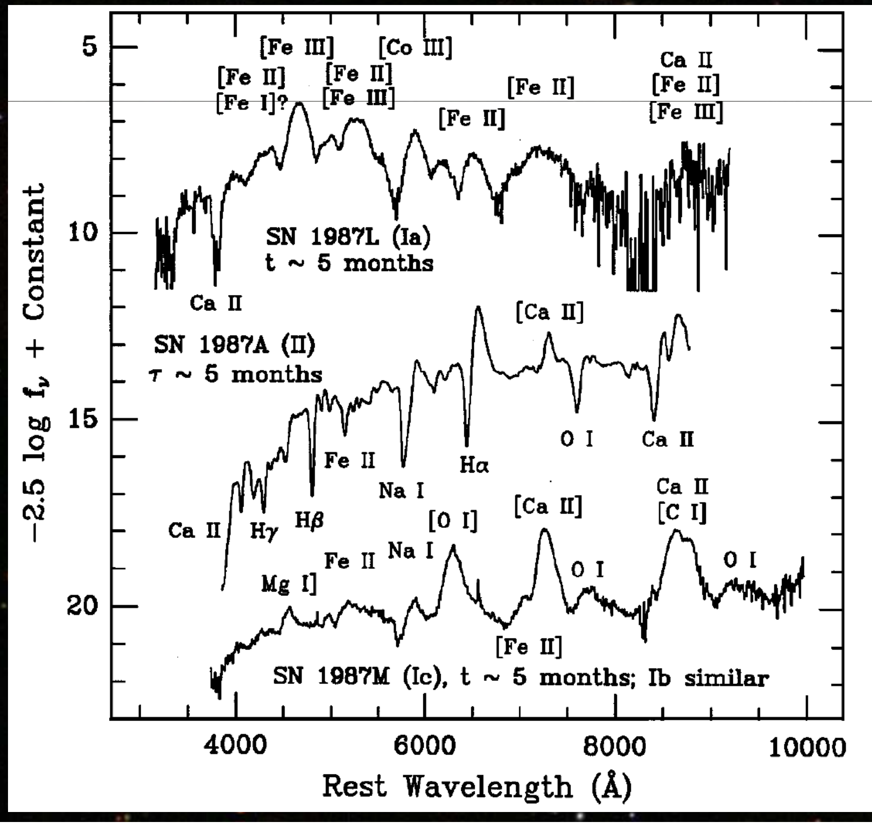
Supernovae – type Ia and all the others

- Type Ia: no hydrogen visible, strong SiII absorption lines
  [associated with old stars, well-calibrated light curve, explosion of accreting white dwarfs, no remnant]

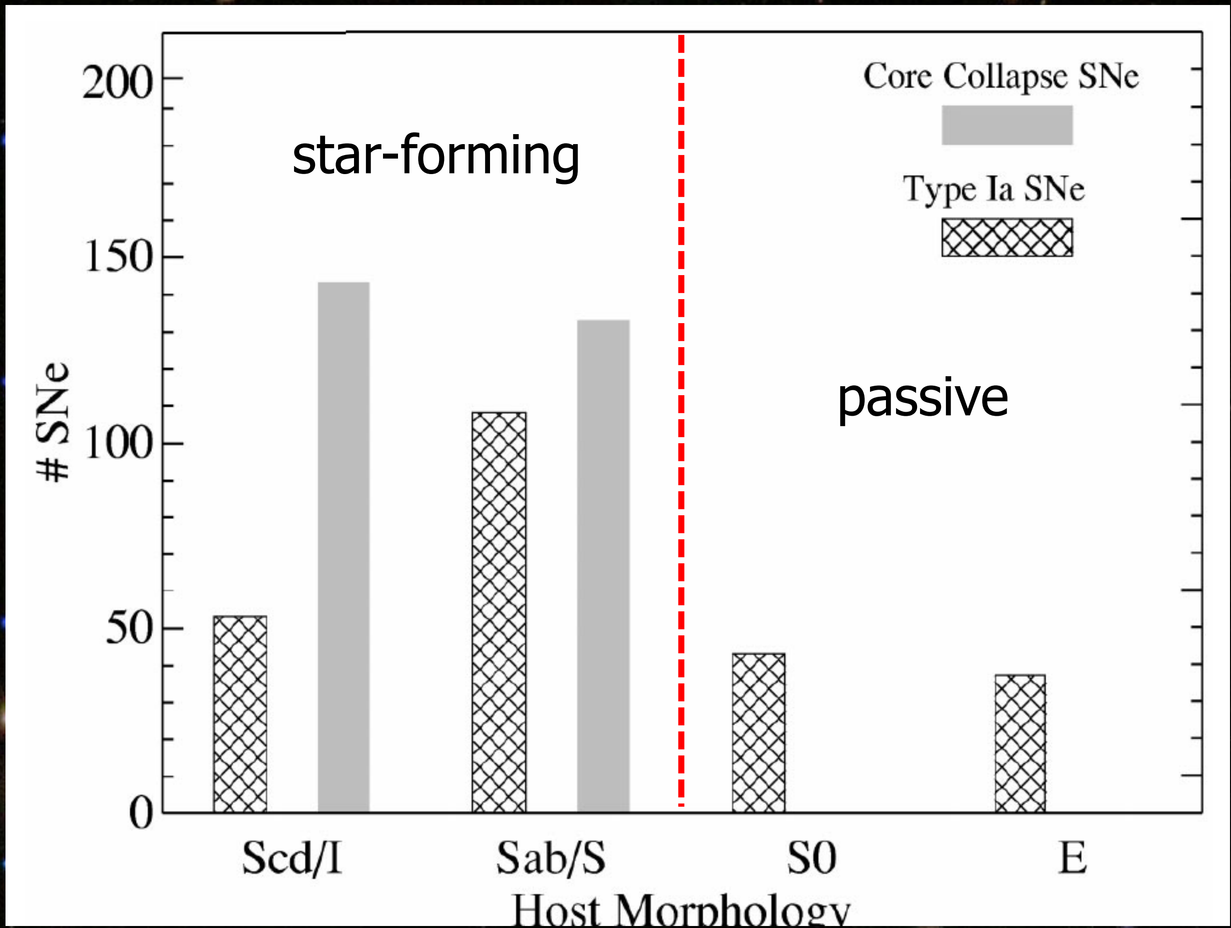
- Type Ib/c: no hydrogen visible, no SiII
- Type II: strong hydrogen lines

} [young stars, stellar collapse leave NS or BH remnant]





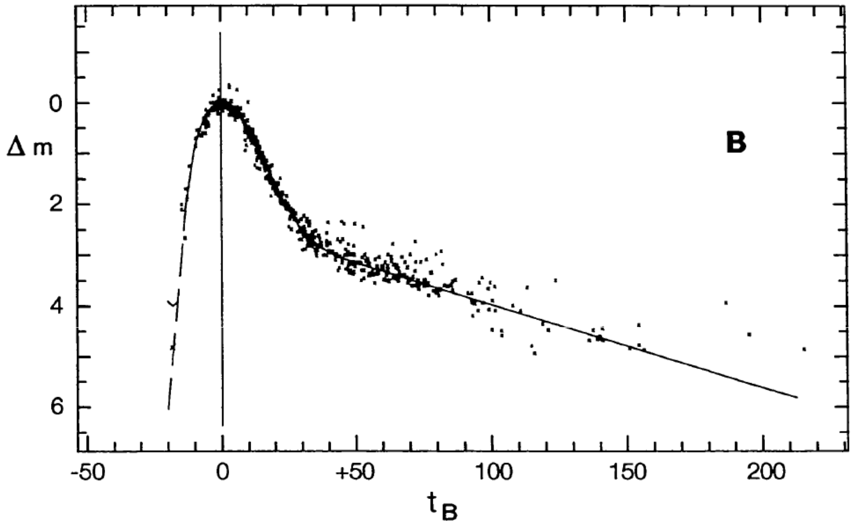
SN types as a function of host galaxy type

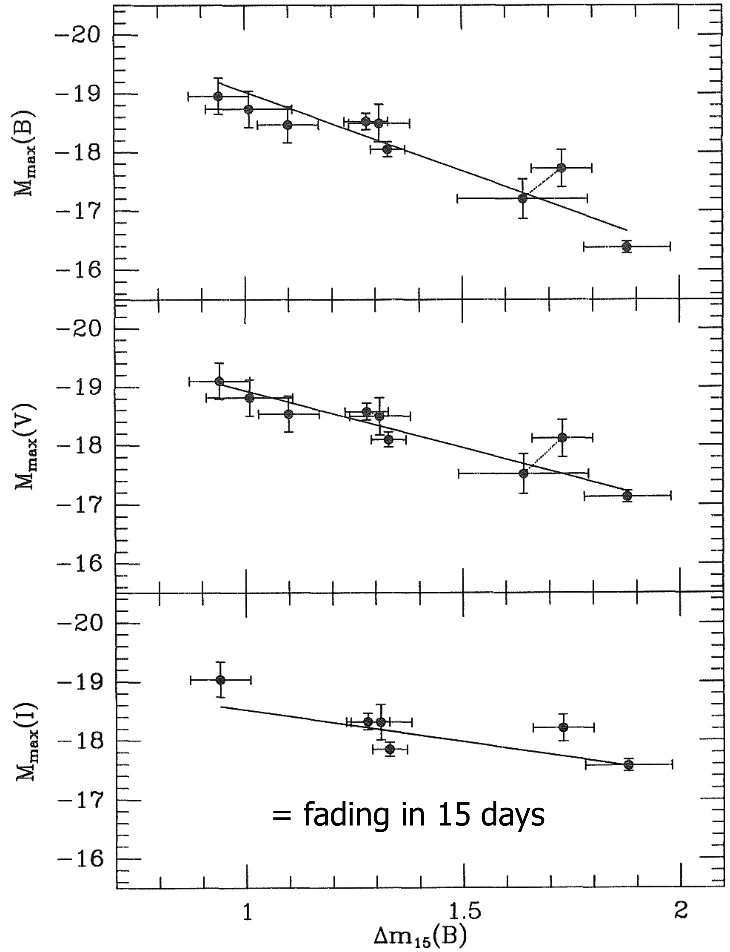


... Core-collapse SN are associated with young stellar populations (massive stars)

Supernovae as standard candles

SNIa are *standard candles* $M_V(\mathrm{SN\,Ia}) = -19.47 \pm 0.15$





"Phillips relation"

(the fastest declining light curves correspond to the intrinsically reddest events)

Cosmological distances

SNIa are *standard candles* $M_V(\mathrm{SN\,Ia}) = -19.47 \pm 0.15$

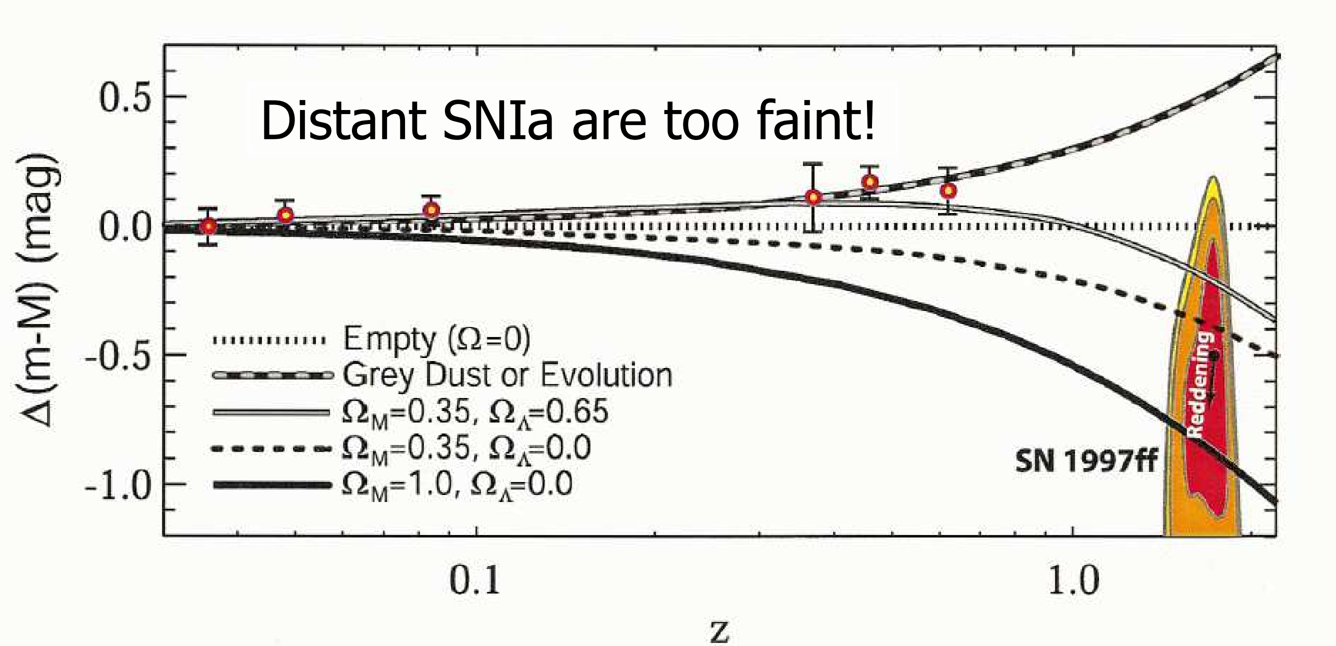
$$M - m = -5\log d[\mathrm{pc}] + 5 \longrightarrow d = 10^{(m-M+5)/5}$$

Cosmological distances

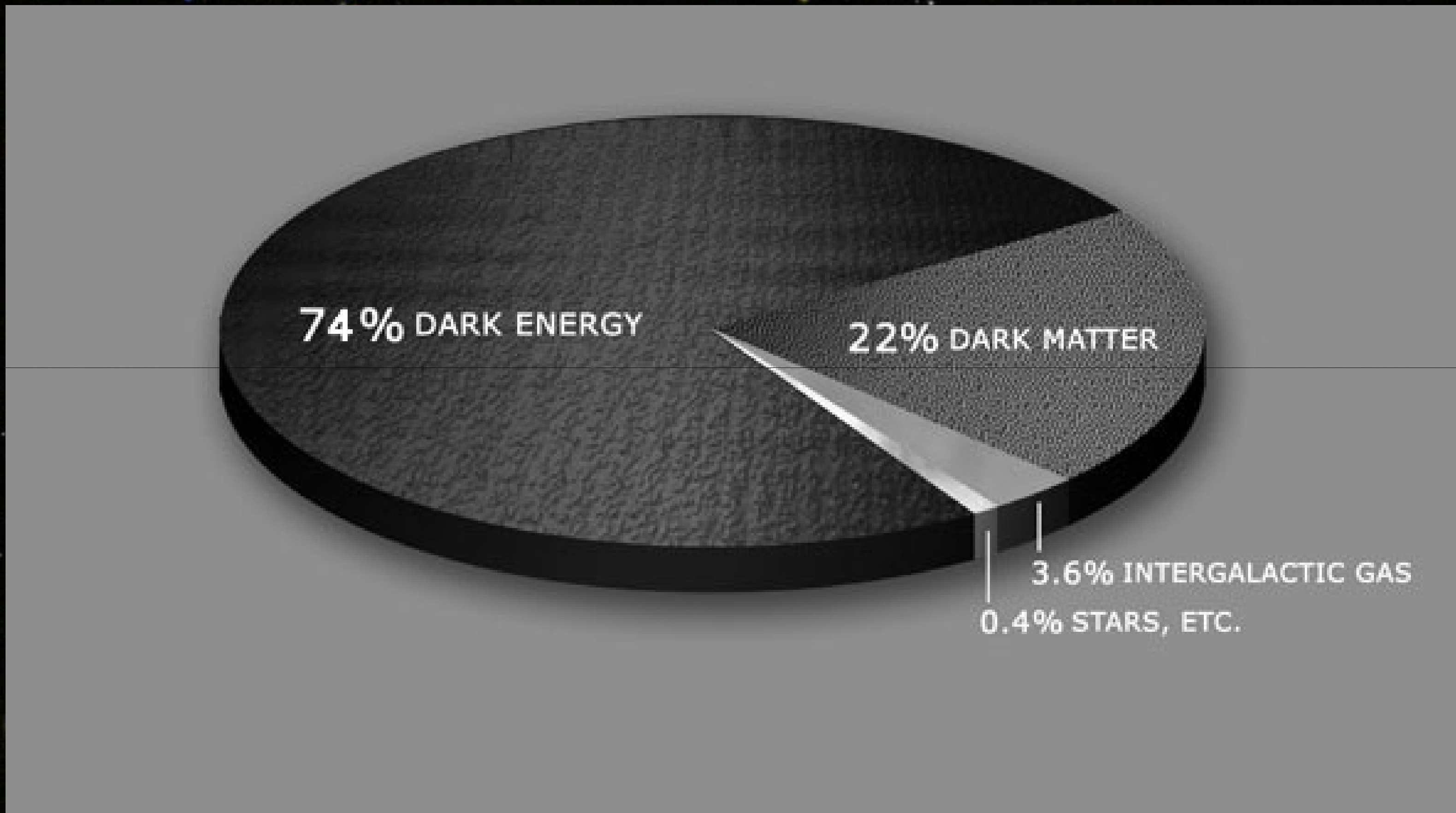
SNIa are *standard candles* $M_V(\mathrm{SN\,Ia}) = -19.47 \pm 0.15$

... probing the structure of the entire Universe!

$$D_L = cH_0^{-1}(1+z)|\Omega_k|^{-1/2}\,\mathrm{sinn}\left\{|\Omega_k|^{1/2} \times \int_0^z dz[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\right\}$$



The “composition” of the Universe



Nobel Prize 2011

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

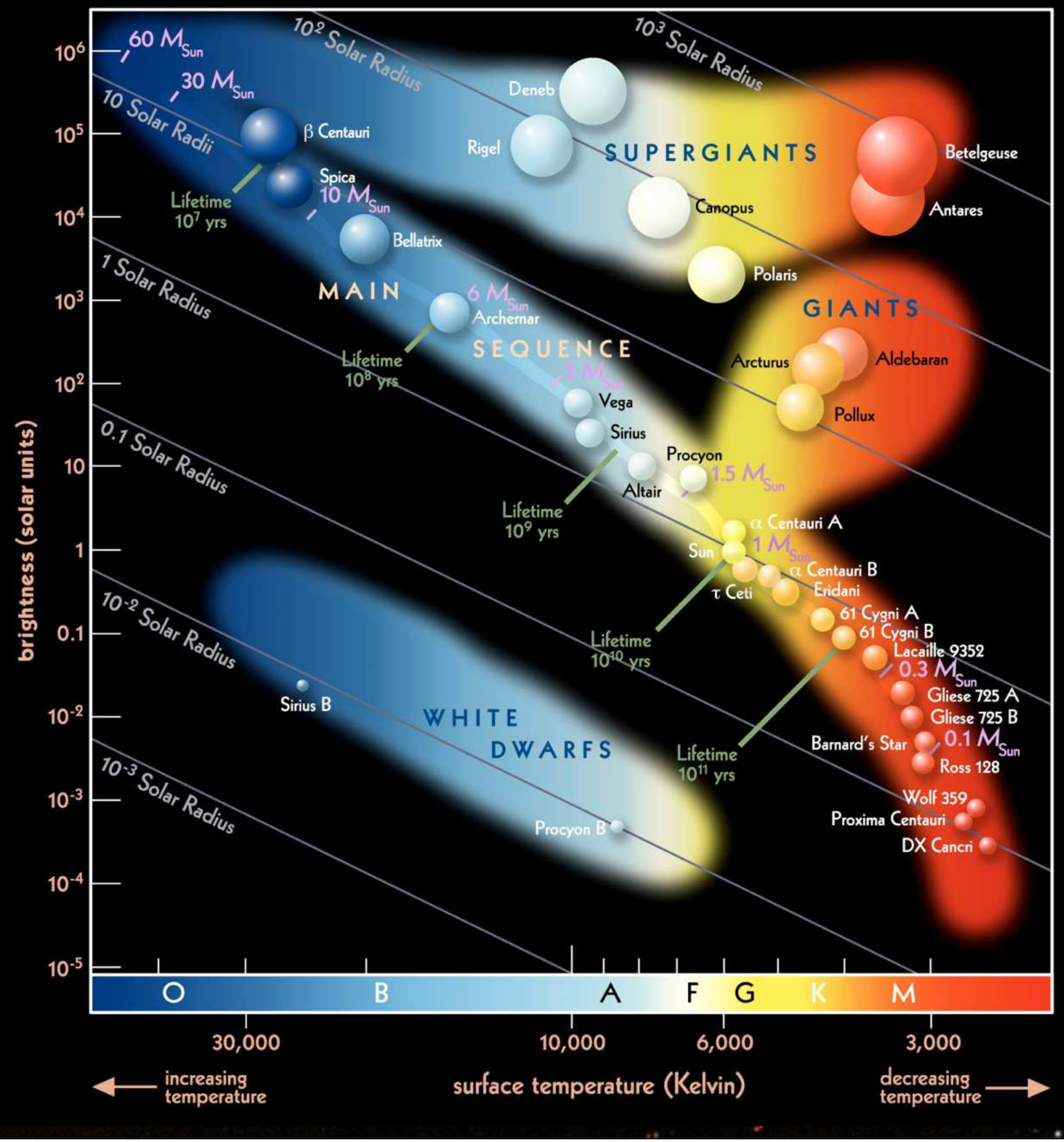
Brian P. Schmidt

Photo: Homewood Photography

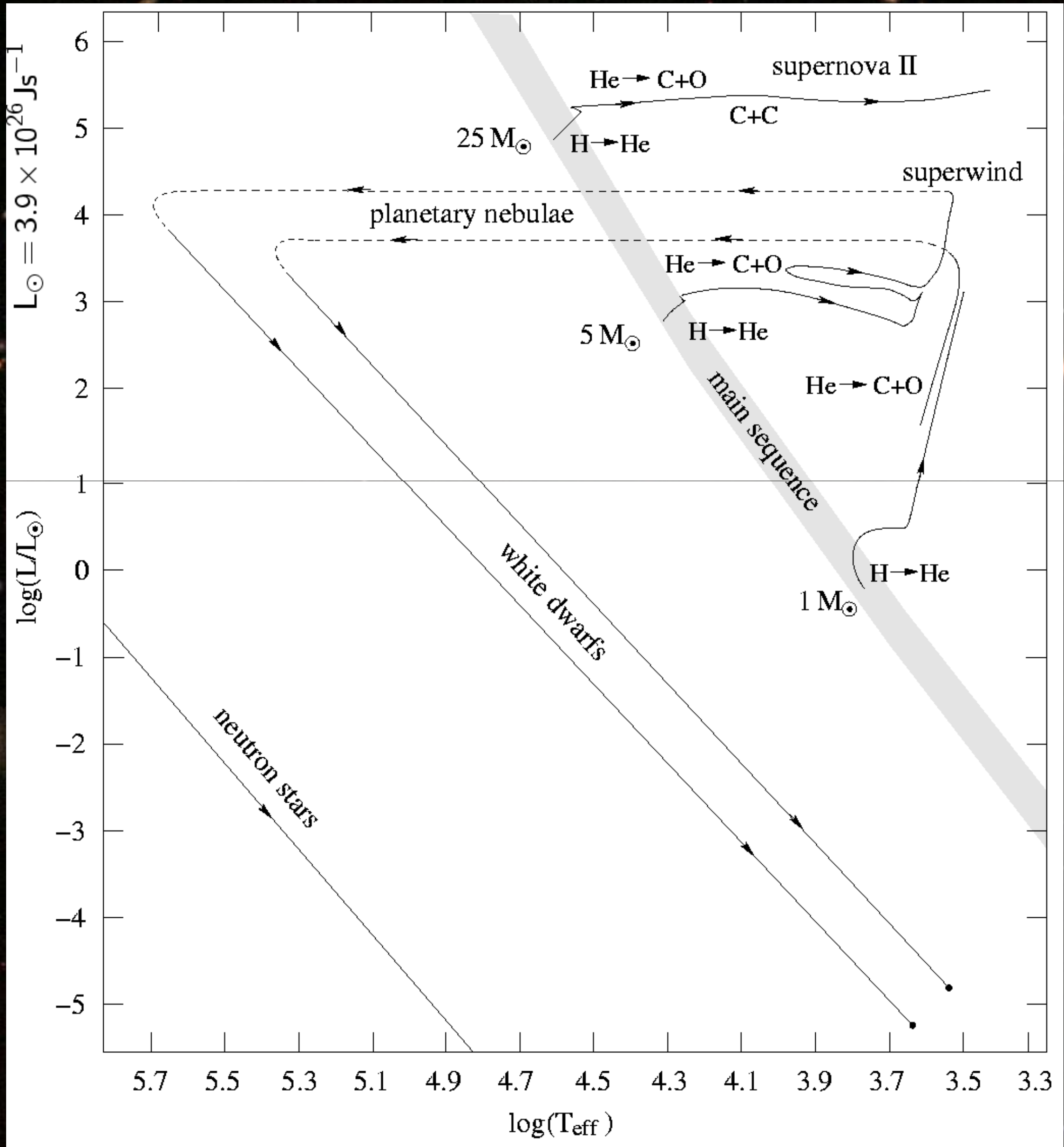
Adam G. Riess

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

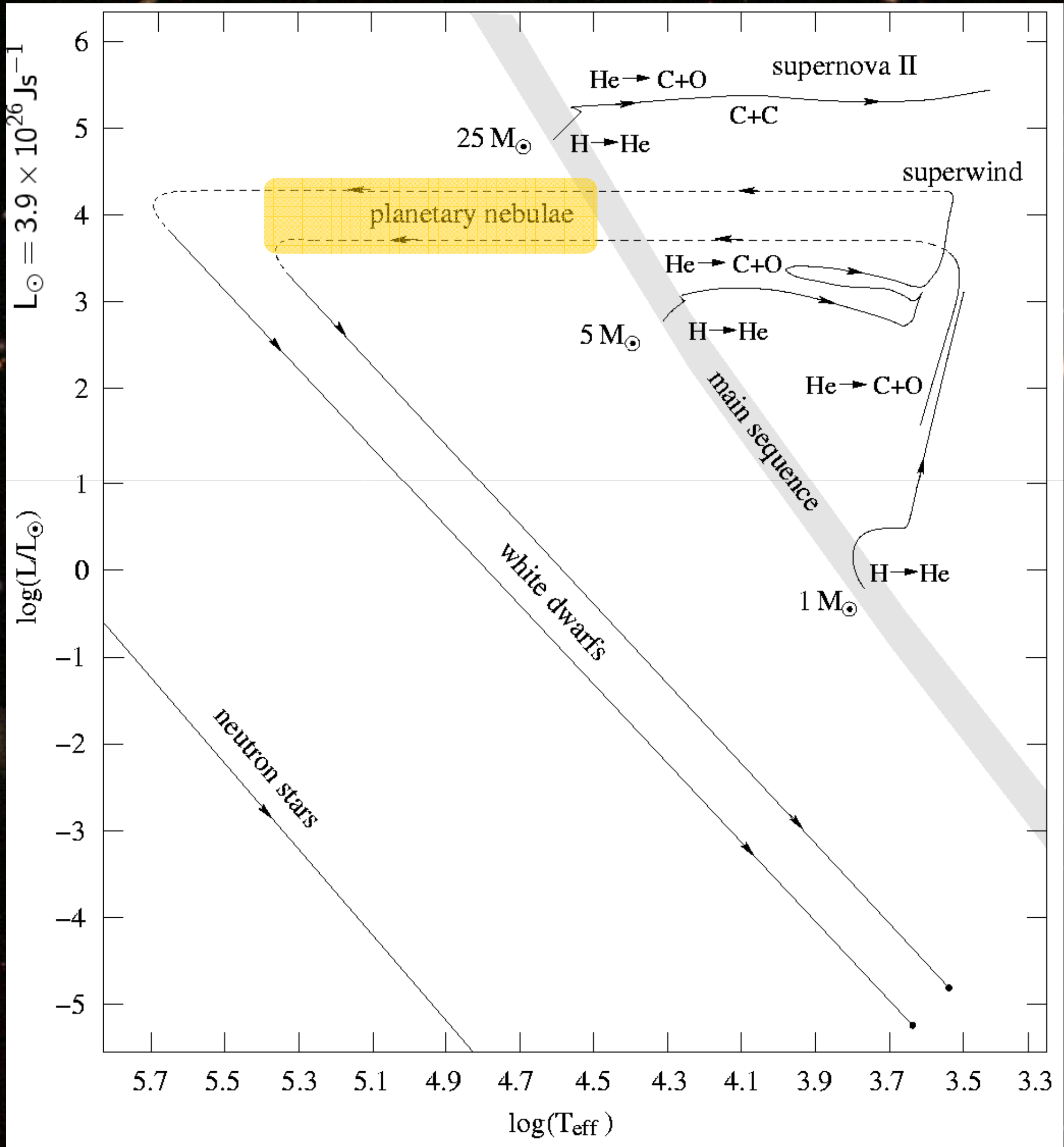
The Hertzsprung-Russell diagram



Evolution beyond the main sequence

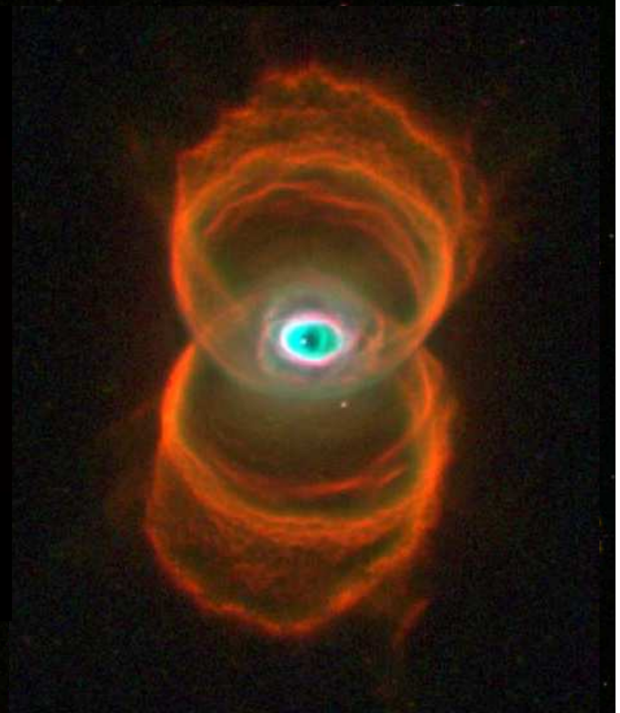


The Hertzsprung-Russell diagram

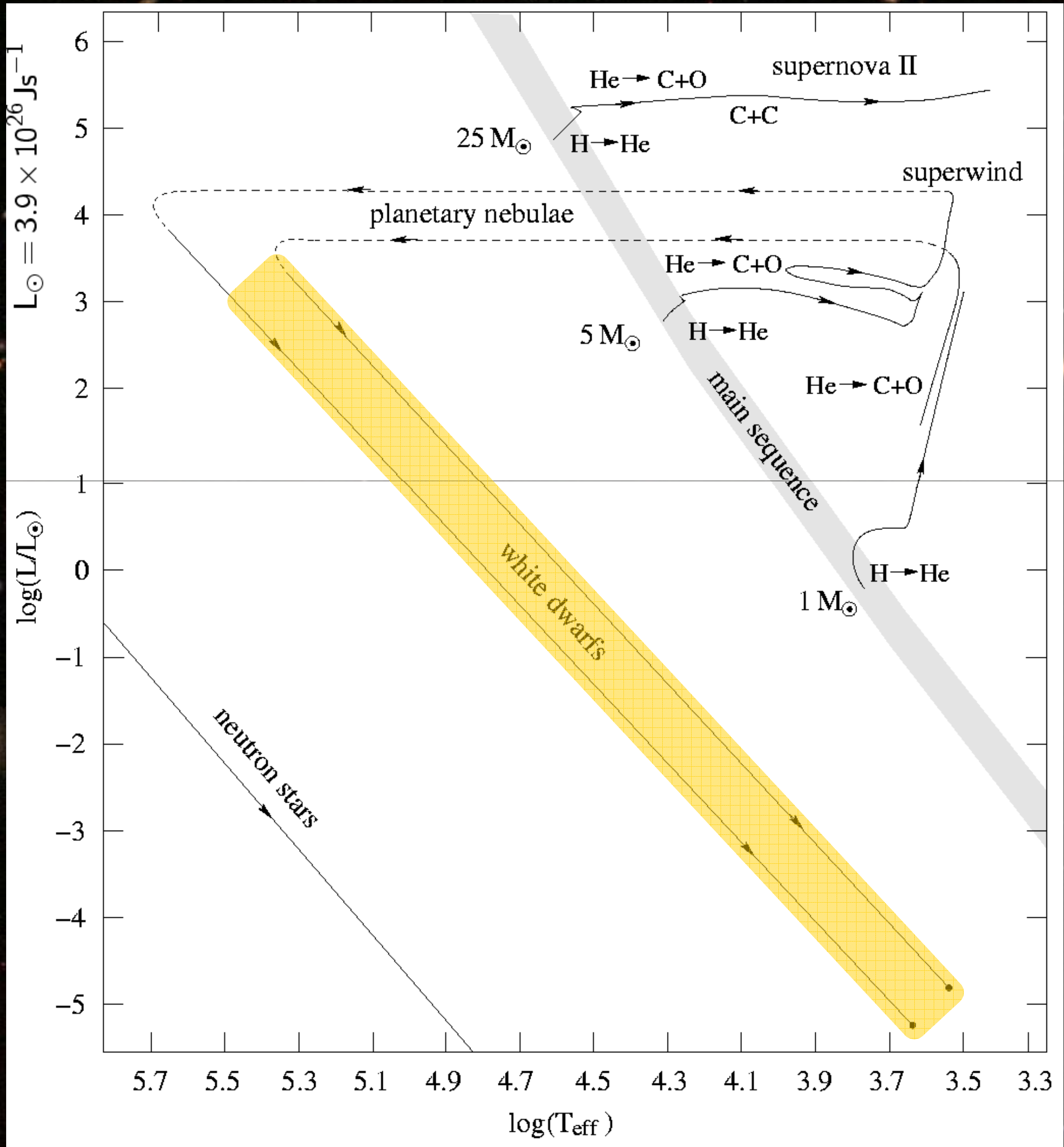


Planetary nebulae

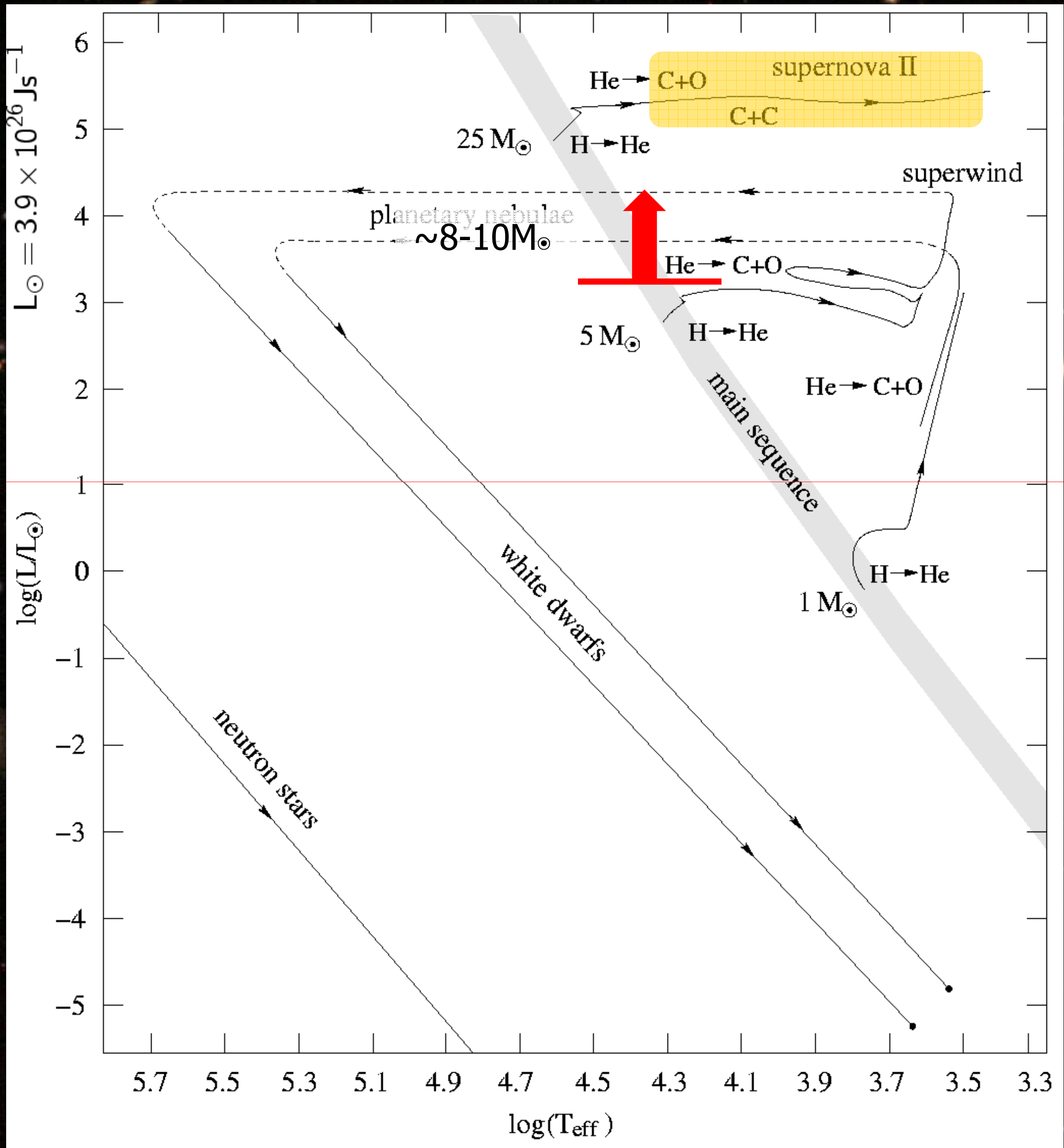





The Hertzsprung-Russell diagram



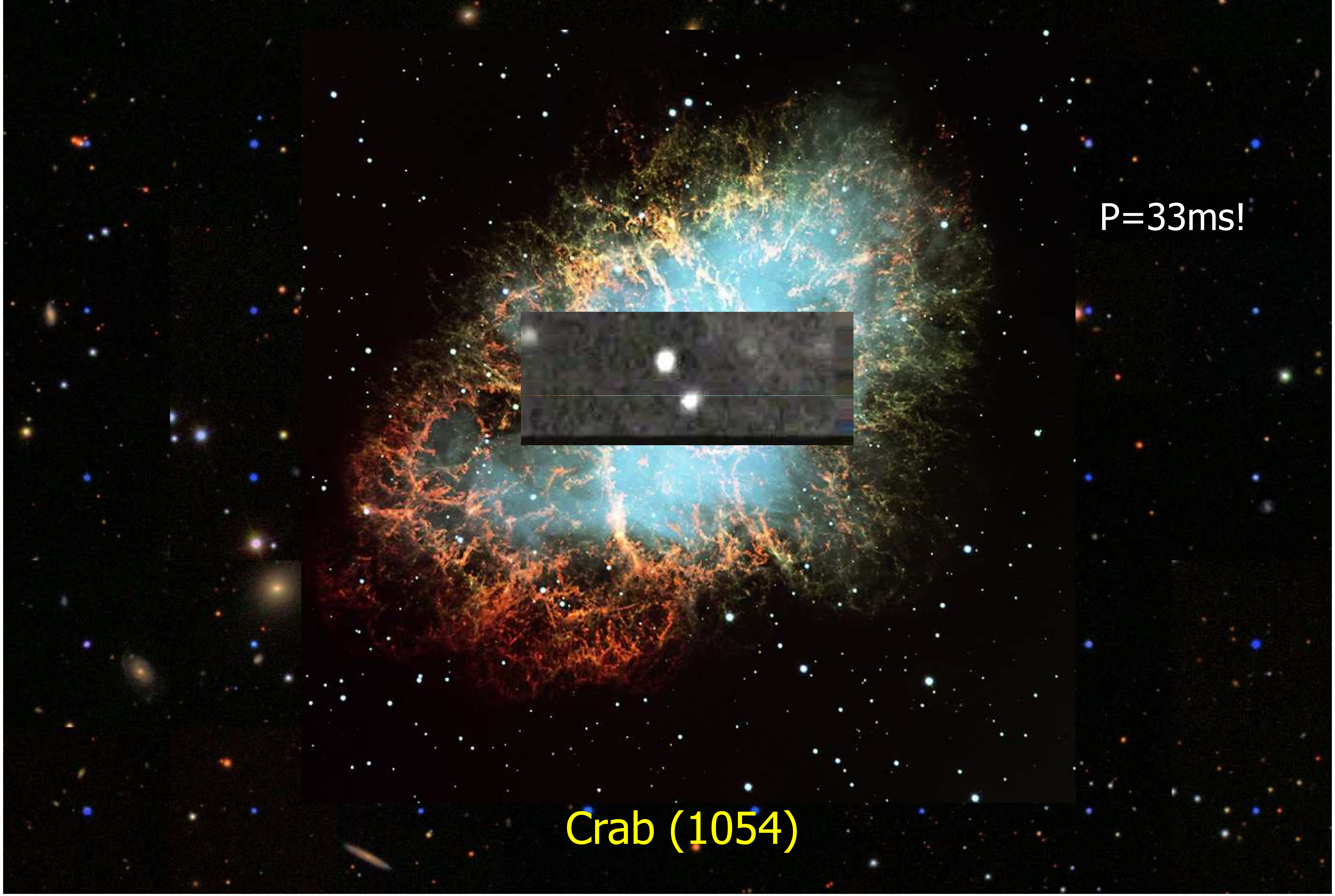
The Hertzsprung-Russell diagram



Supernova remnants

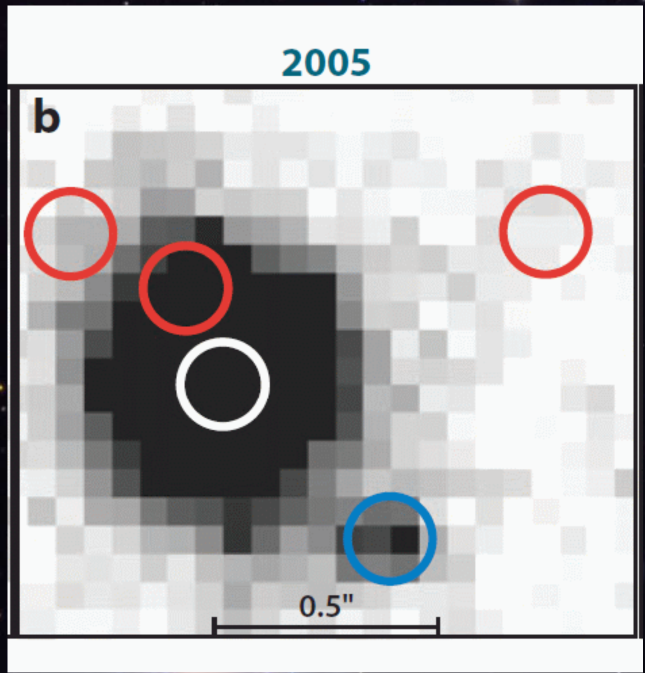
Crab (1054)

The Crab Pulsar



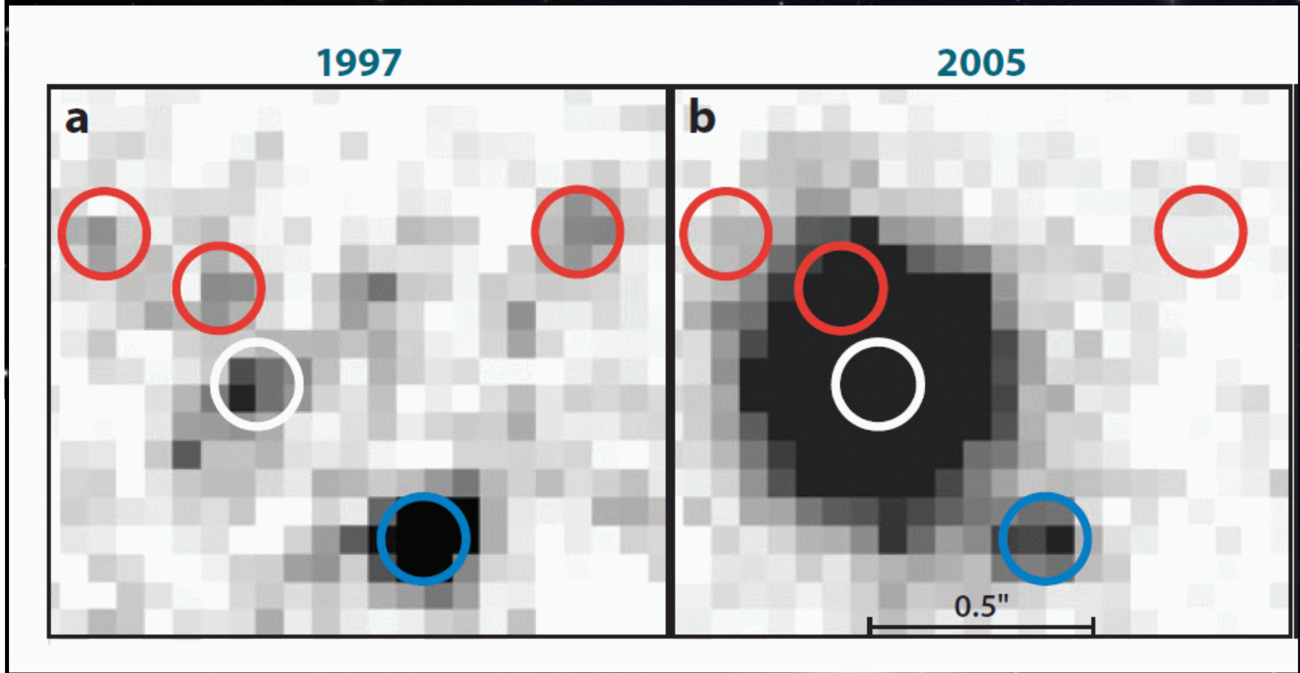
SN 2005gl in NGC 266: Now you see it – now don’t

SN 2005gl in NGC 266: Now you see it – now don’t



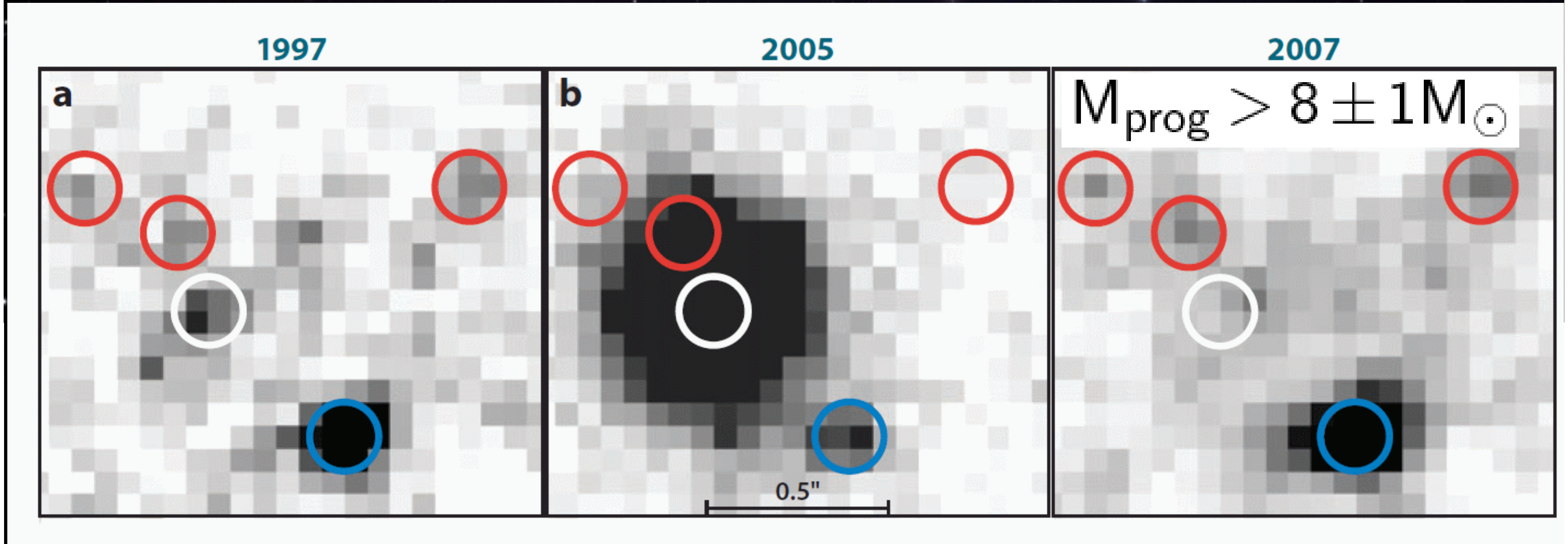
Gal-Yam & Leonard (2009, Nature 458, 865)

SN 2005gl in NGC 266: Now you see it – now don't



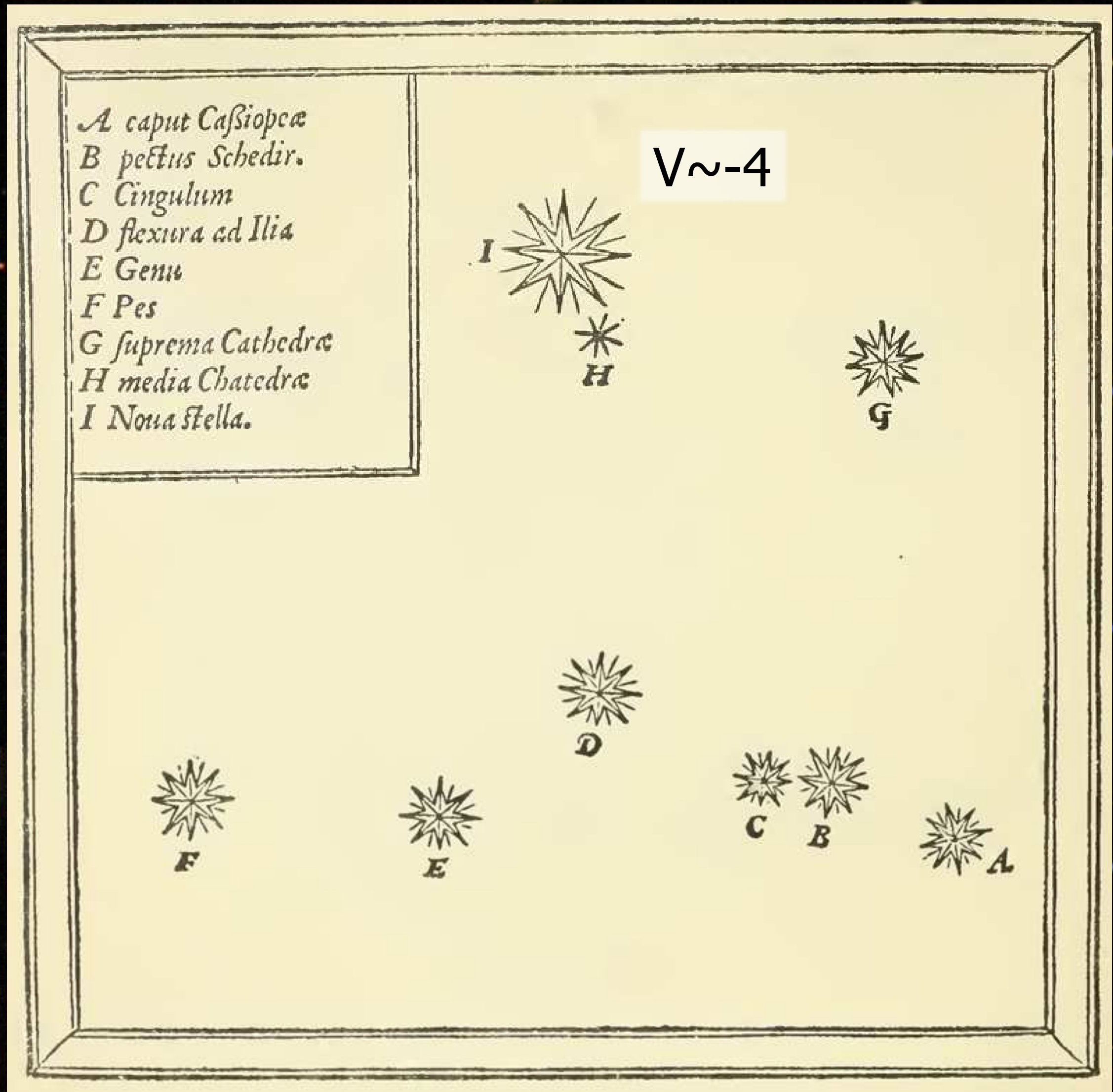
Gal-Yam & Leonard (2009, Nature 458, 865)

SN 2005gl in NGC 266: Now you see it – now don't



Gal-Yam & Leonard (2009, Nature 458, 865)

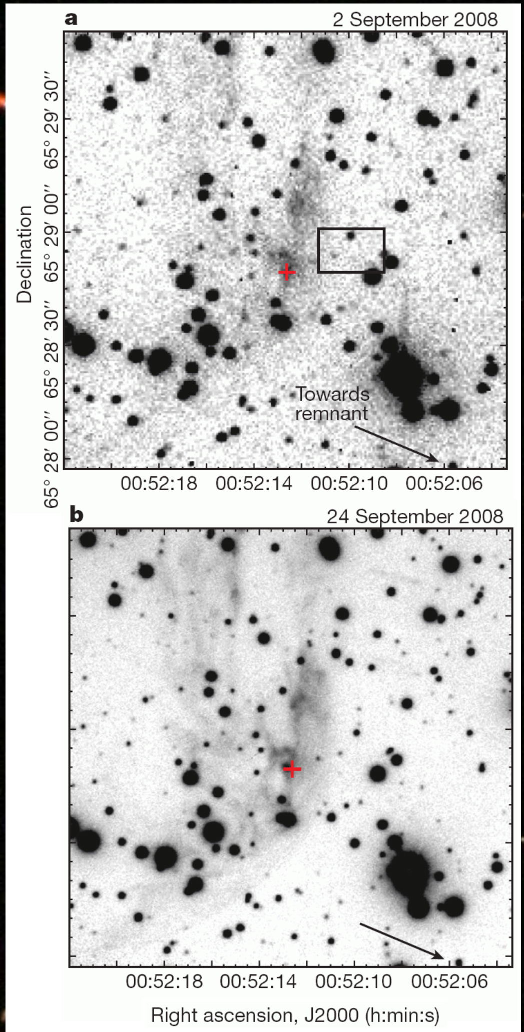
November 1572, in Cassiopeia: a "nova" – a new star

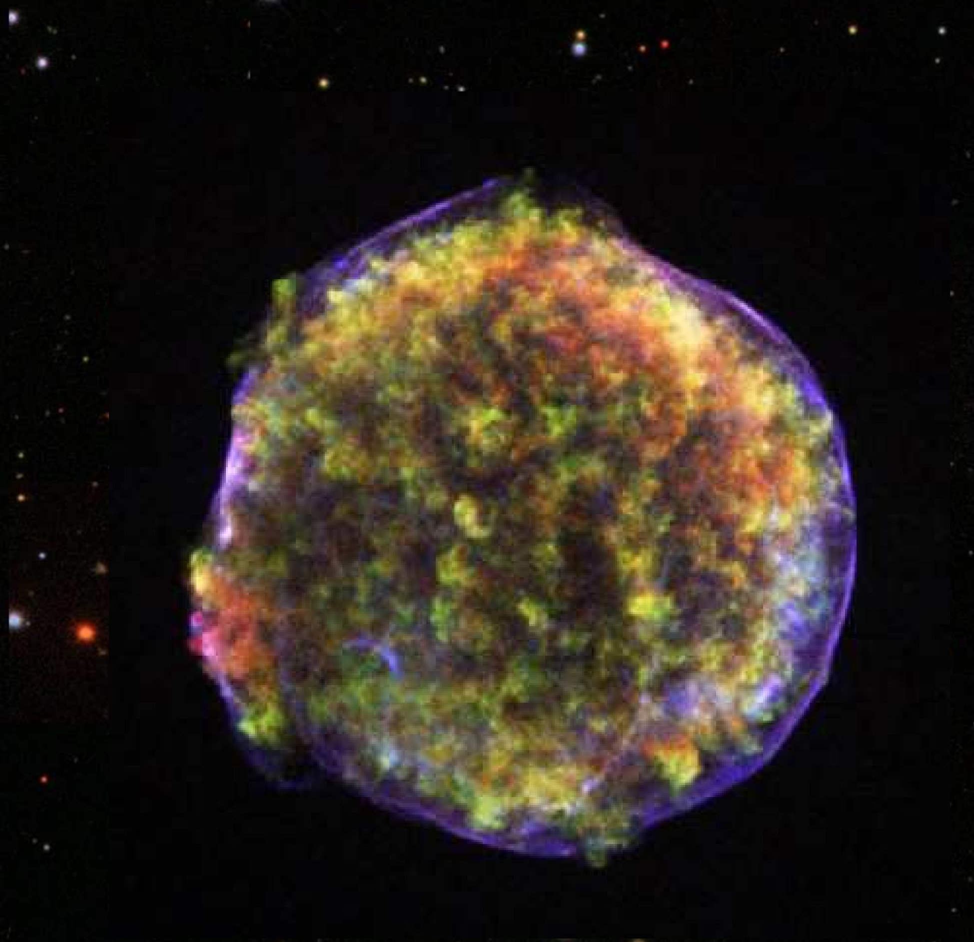


Tycho Brahe: *De nova et nullius aevi memoria prius visa stella* (1602)

SN1572, seen in 2011 with WISE

Tycho Brahe's 1572 SN: a ghost in the shell



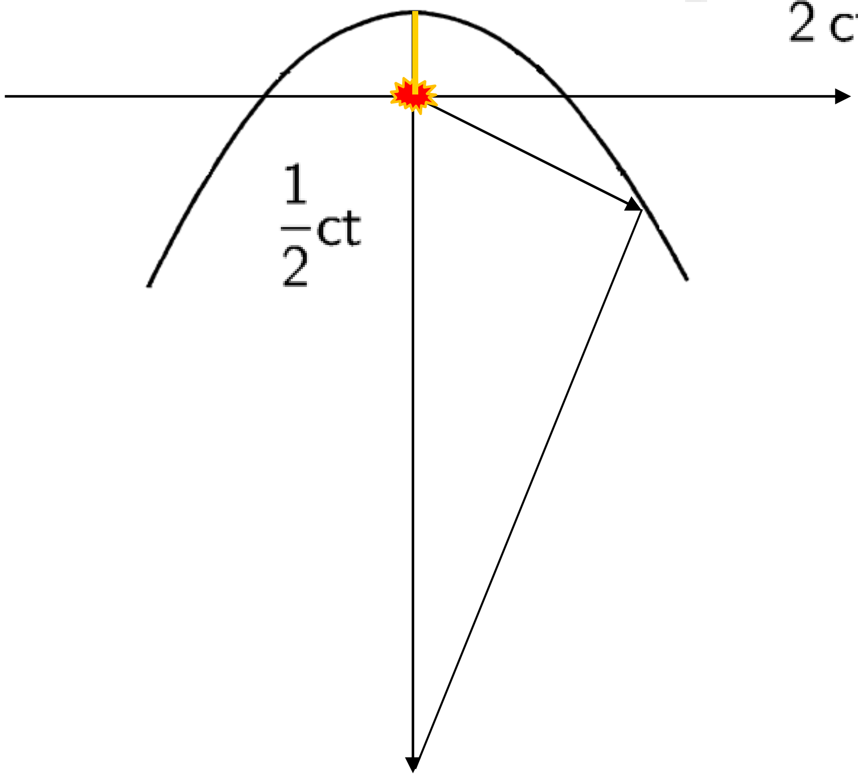


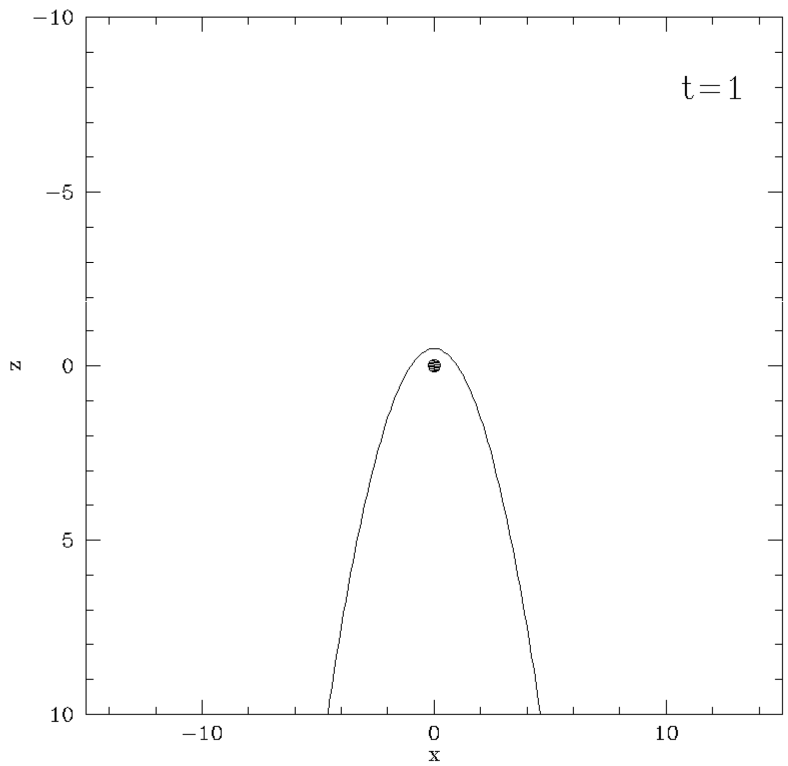
1.4±0.2″ in 22 days

Krause et al. (2008, Nature 456, 617)

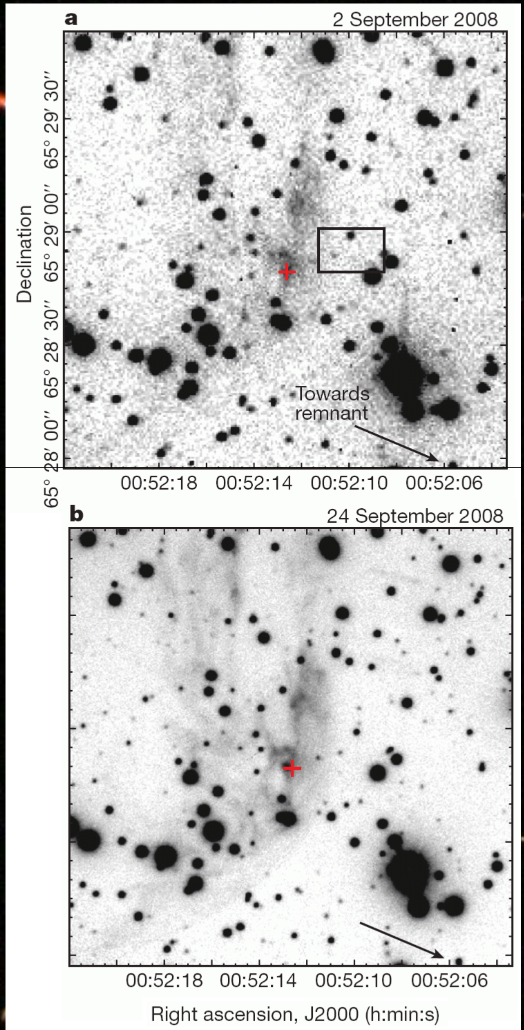
Light echos

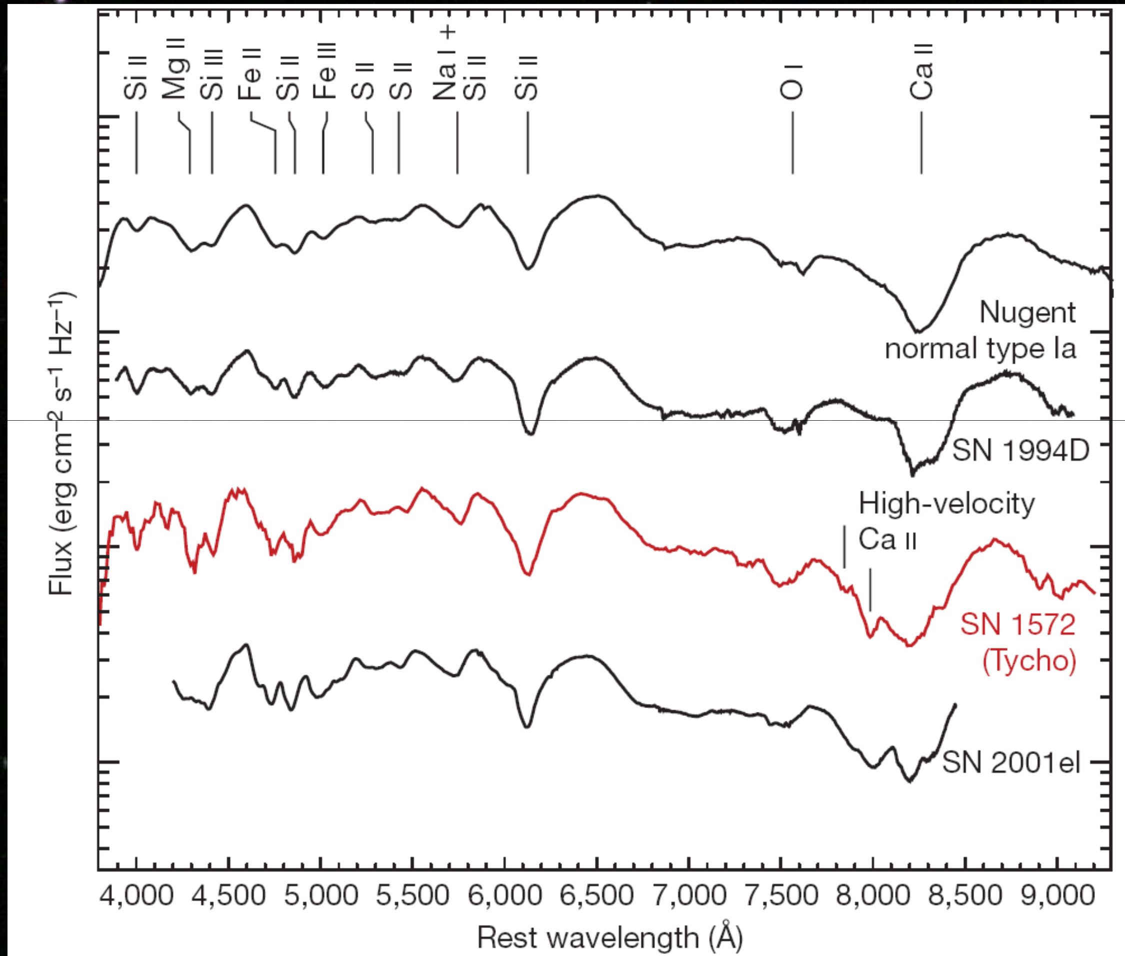
$$z = \frac{1}{2}\frac{x^2}{ct} - \frac{ct}{2}$$





Tycho Brahe's 1572 SN: a (type Ia) ghost in the shell





1.4±0.2″ in 22 days

The equation of state: degeneracy

In normal stars: $P_g = NkT$ (ideal gas)

$P_g = P_i + P_e = (N_i + N_e)kT$ i=ions, e=electrons

Heisenberg uncertainty principle: $\Delta x \Delta p_x \geq h$

$\Delta V \Delta p \geq h^3$

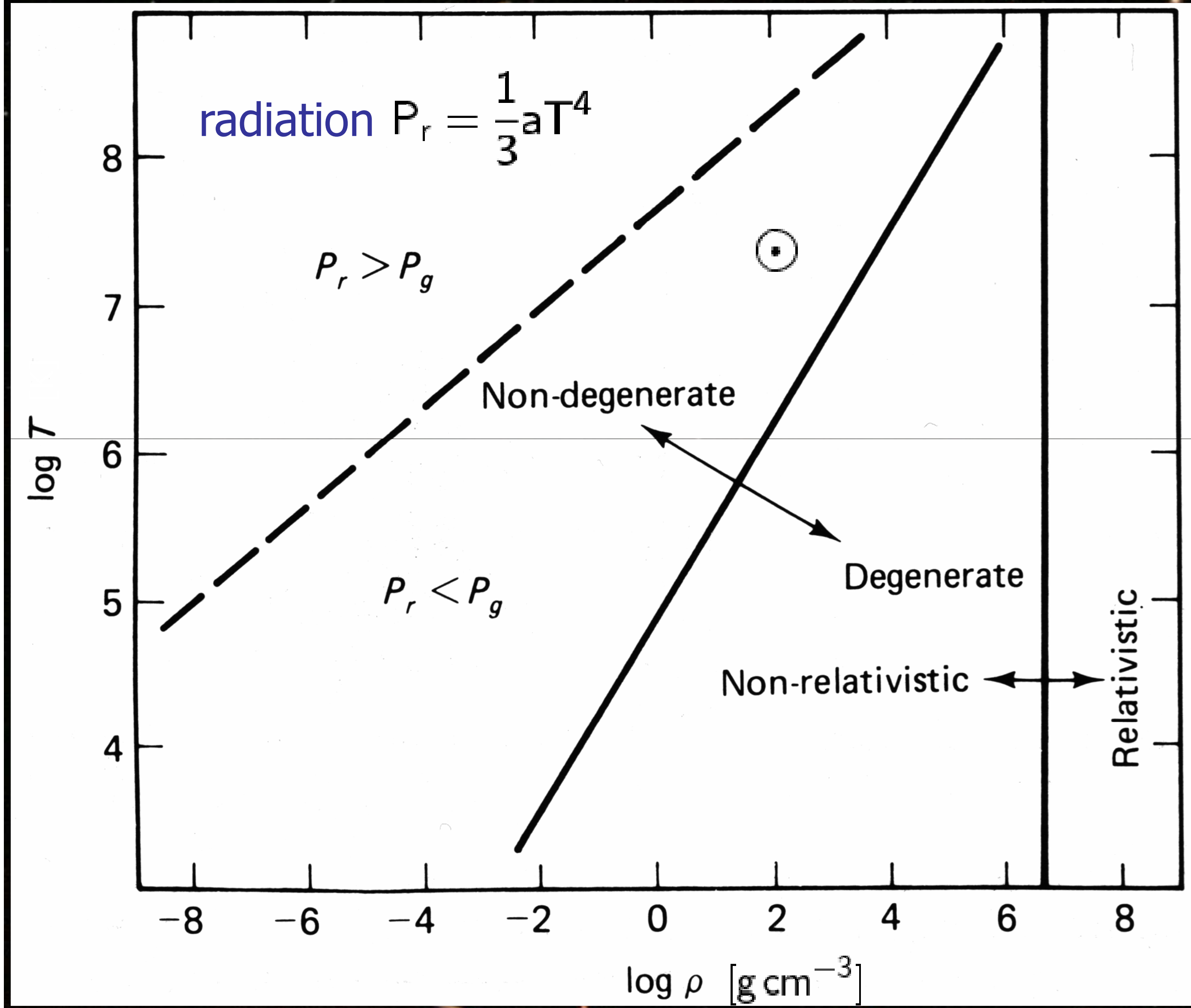
$\Delta V \propto \rho^{-1}$

Classical physics: $E_k = \frac{1}{2}mv^2 = \frac{p^2}{2m}$ $E_{th} = \frac{3}{2}kT$

Fermi Energy: $E_F = \frac{p_F^2}{2m_e}$ degeneracy: $E_F > E_{th}$

$P_{e,deg} = K_1 \left(\frac{\rho}{\mu_e}\right)^{5/3}$ P independent of the temperature! $P_{e,deg} \gg P_i$

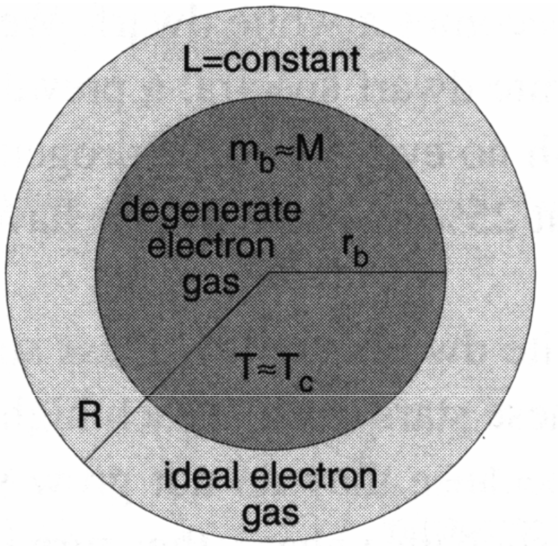
Equation of state



degenerate objects:

- white dwarfs
- neutron stars
- brown dwarfs
- Jupiter

White dwarfs: electron-degenerate stars



He, CO, or ONe core

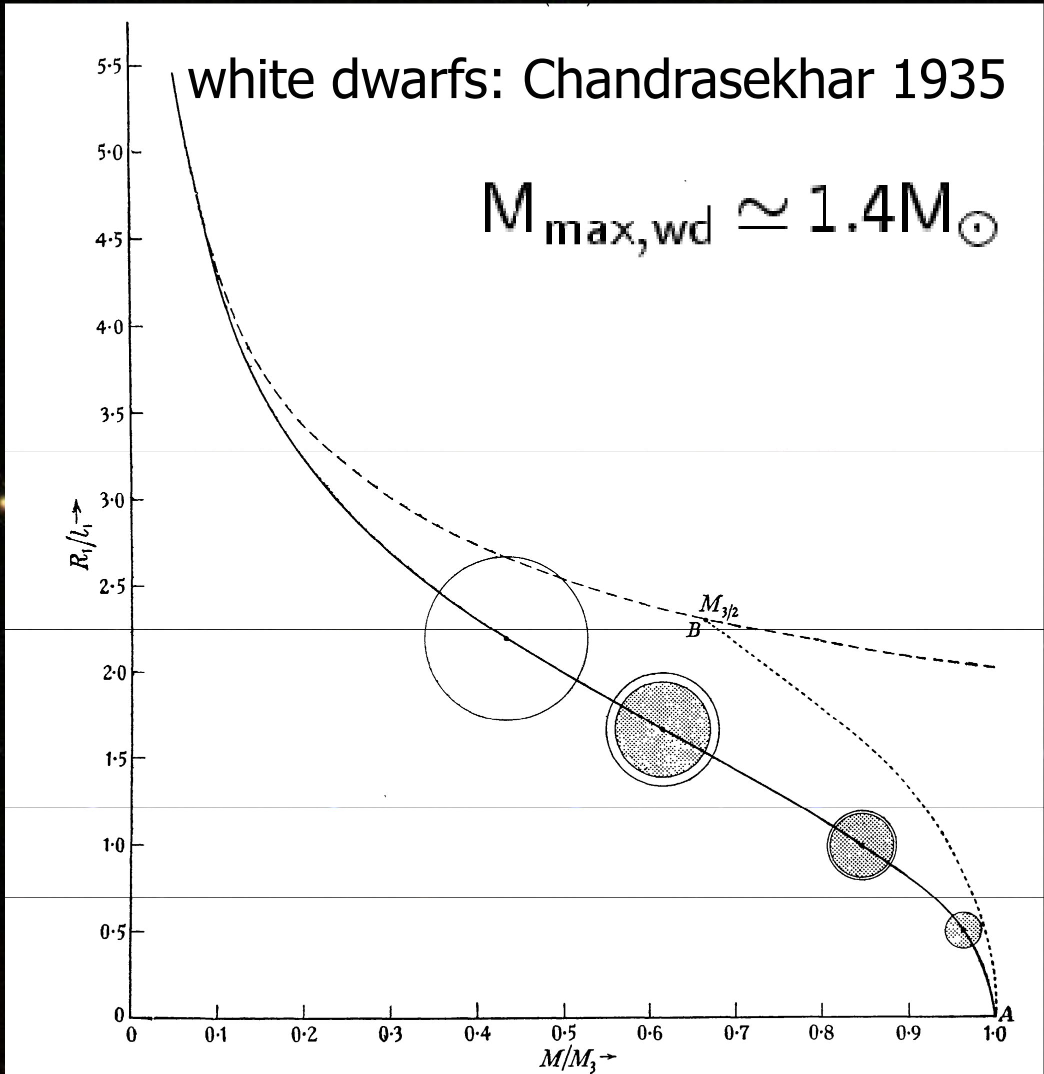
no nuclear energy production

$M \approx 0.6 M_\odot, \quad R \approx 8000\,\mathrm{km} \approx R_{\mathrm{Earth}}$

Solving the stellar structure equations: $R \propto M^{-1/3}$
i.e. the radius shrinks with increasing mass!!

⟶ it exists a maximum mass, $M_{\mathrm{Chandrasekhar}} \approx 1.4 M_\odot$

The Chandrasekhar mass limit



more massive stars are smaller!

1983: Nobel prize in Physics

...for his theoretical studies of the physical processes of importance to the structure and evolution of the stars

If a white dwarf grows in mass, and exceeds the Chandrasekhar limit, it will ignite CO burning, and explode in a type Ia supernova

SNIa: the last seconds of an accreting white dwarf

$R \propto M^{-1/3}$ Radius shrinks as mass increases

$P_{e,deg} = K_1 \left(\frac{\rho}{\mu_e}\right)^{5/3}$ P independent of the temperature! $P_{e,deg} \gg P_i$

- approaching the Chandrasehkar limit, WD rapidly shrinks
- ion gas (C/O) is not degenerate, hence heats up (P=NkT)
- C/O burning starts in the core, producing heavier elements up to the iron group
- nuclear flame propagates outwards:
  subsonic (deflagration) or supersonic (detonation)? Not well known
- no remnant is left behind
- a large mass of ^{56}Ni is produced during explosion powers the luminosity of the SNIa via radioactive decay

Thermonuclear fall-out of a SNIa

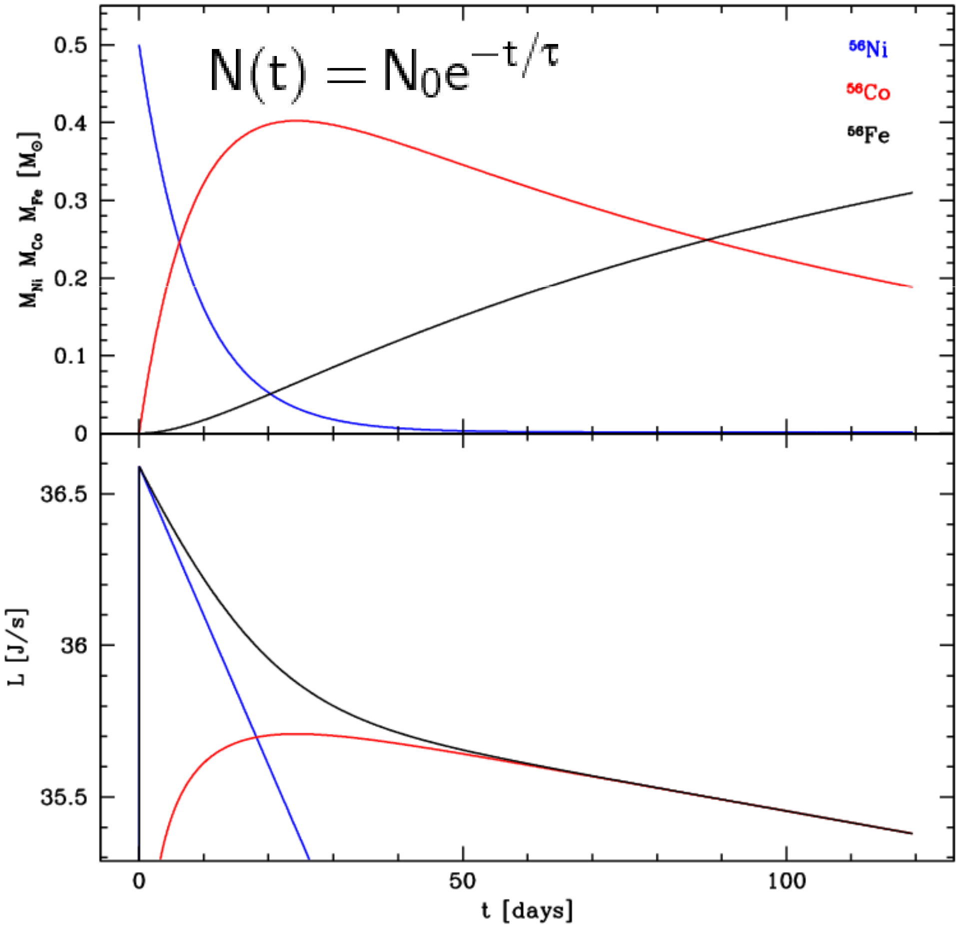
$$^{56}_{28}\mathrm{Ni} \longrightarrow ^{56}_{27}\mathrm{Co} + e^+ + \nu_e$$

$\tau(^{56}_{28}\mathrm{Ni}) = 8.8\mathrm{d}$

$$^{56}_{27}\mathrm{Co} \longrightarrow ^{56}_{26}\mathrm{Fe} + e^+ + \nu_e$$

$\tau(^{56}_{27}\mathrm{Co}) = 111.4\mathrm{d}$

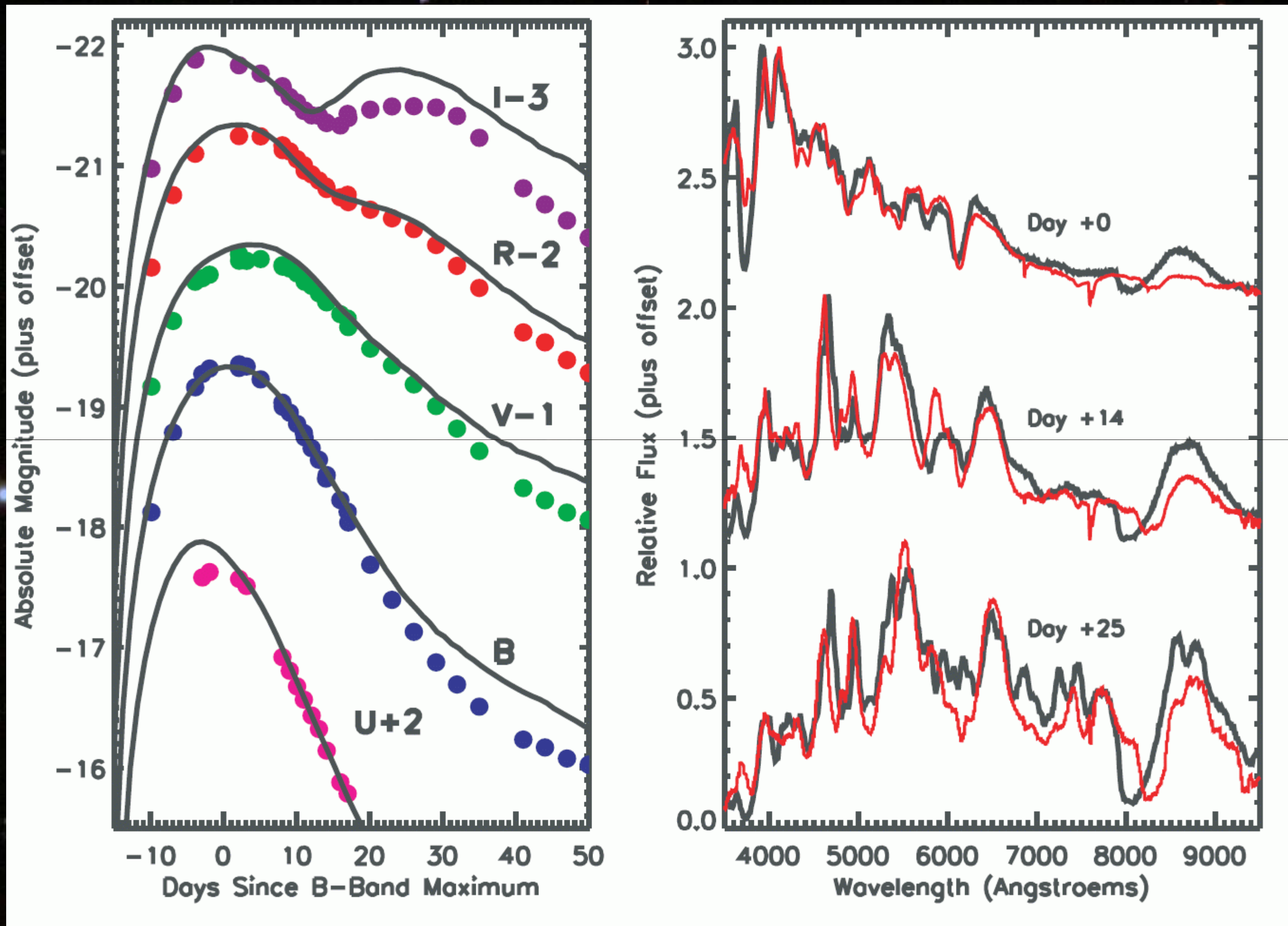
$m(^{56}_{28}\mathrm{Ni}) = 9.236394 \times 10^{-26}\,\mathrm{kg}$
$m(^{56}_{27}\mathrm{Co}) = 9.236013 \times 10^{-26}\,\mathrm{kg}$
$m(^{56}_{26}\mathrm{Fe}) = 9.235200 \times 10^{-26}\,\mathrm{kg}$

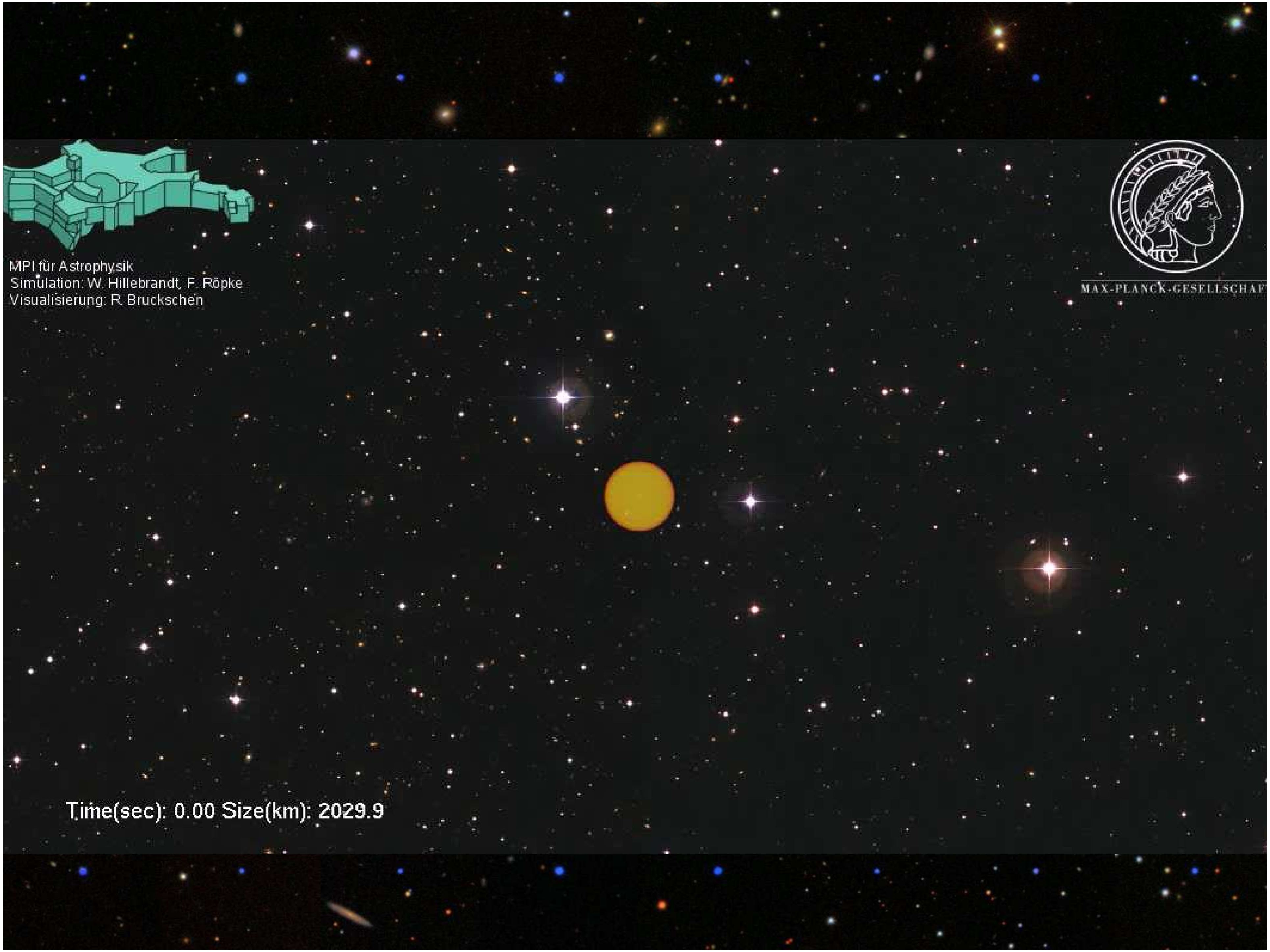


$$\Delta E(\mathrm{Ni} \rightarrow \mathrm{Co}) = \Delta m c^2$$

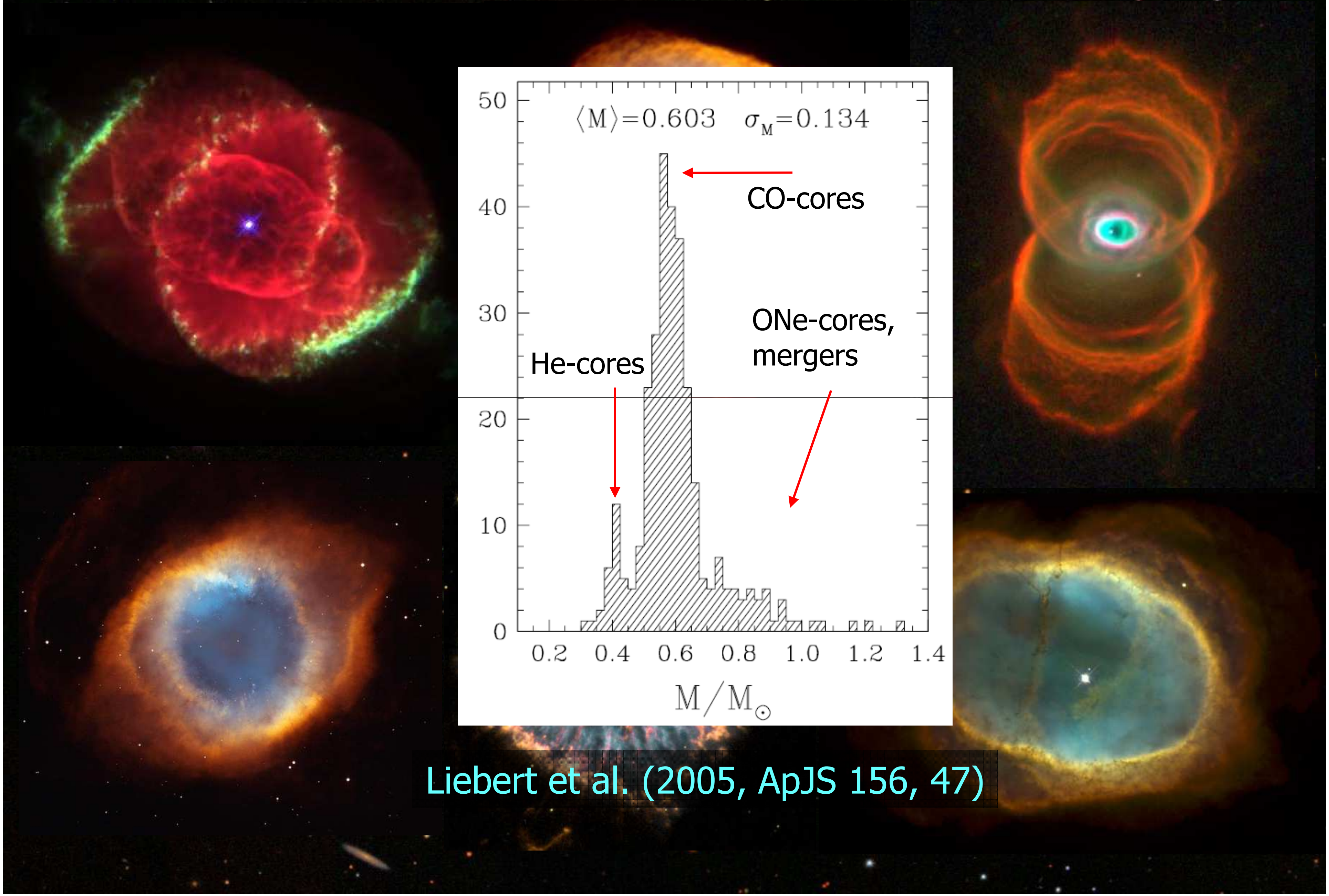
$$= [m(^{56}_{27}\mathrm{Co}) - m(^{56}_{28}\mathrm{Ni}) - m_e]c^2$$

SNIa observations & models



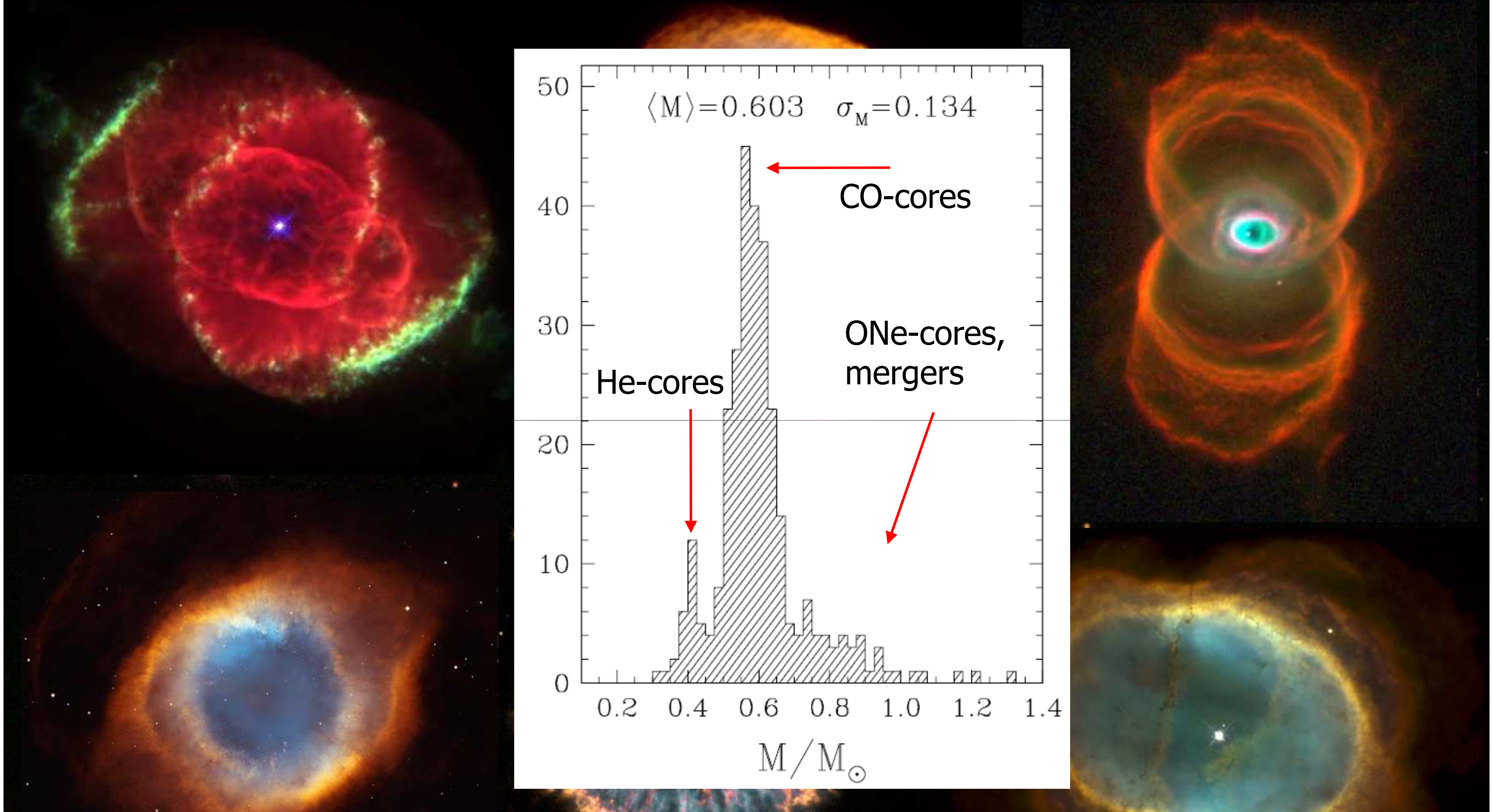

MPI für Astrophysik
Simulation: W. Hillebrandt, F. Röpke
Visualisierung: R. Bruckschen
MAX-PLANCK-GESELLSCHAFT
Time(sec): 0.00 Size(km): 2029.9

Mass loss: ~0.8-8MO stars become ~0.6-1.4MO WDs



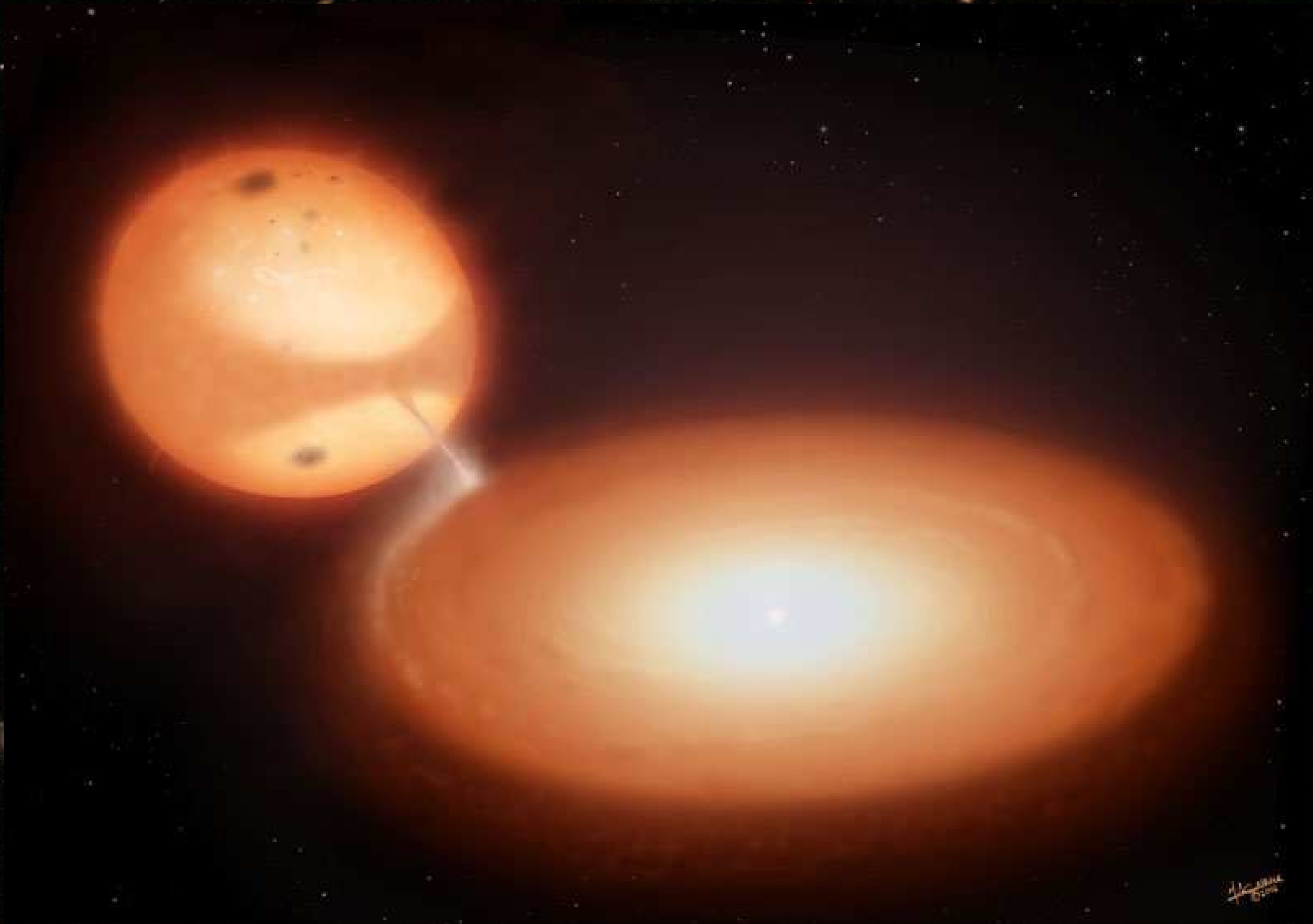
Liebert et al. (2005, ApJS 156, 47)

So … How do we reach 1.4M⊙ !?!?!

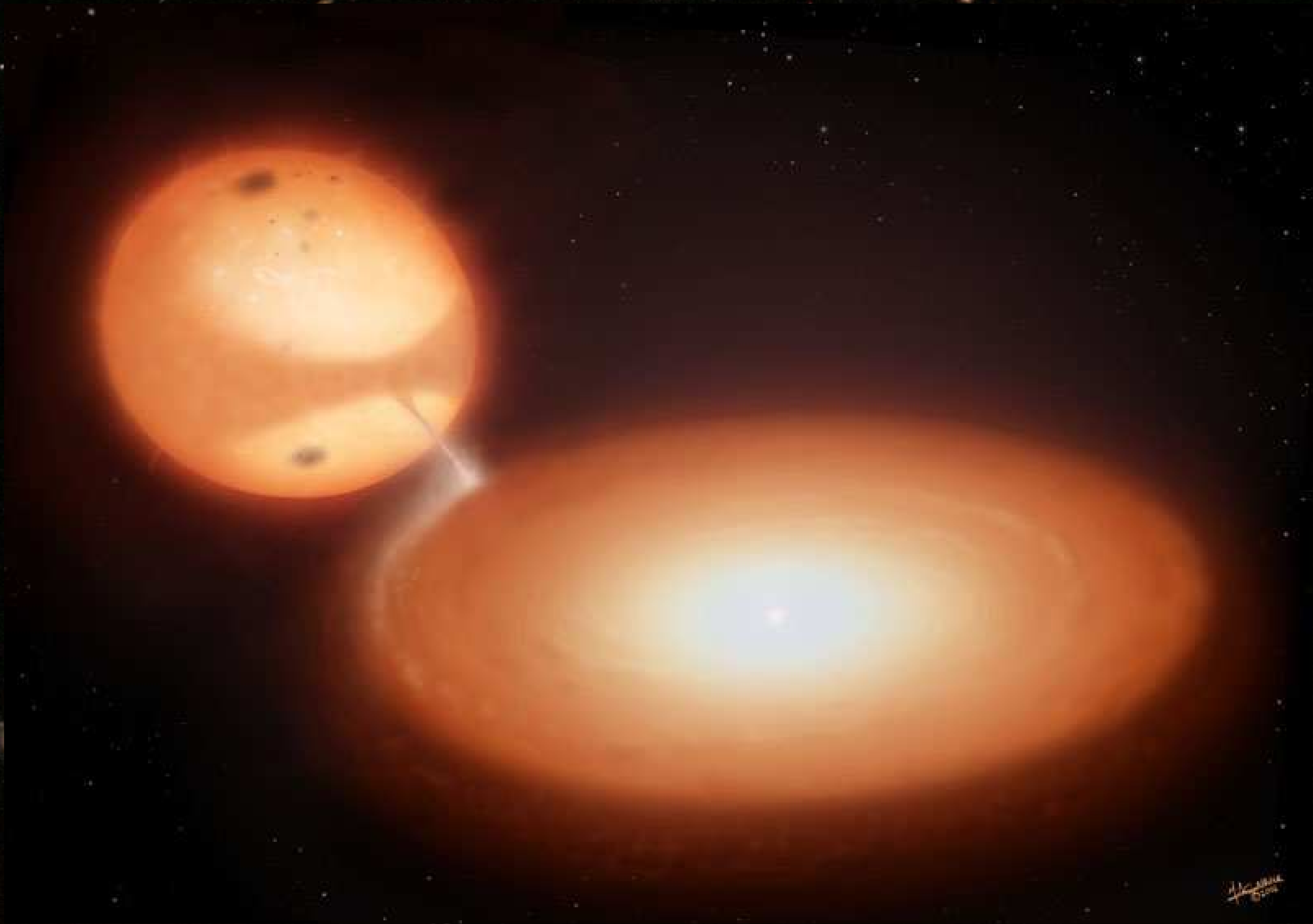


Liebert et al. (2005, ApJS 156, 47)

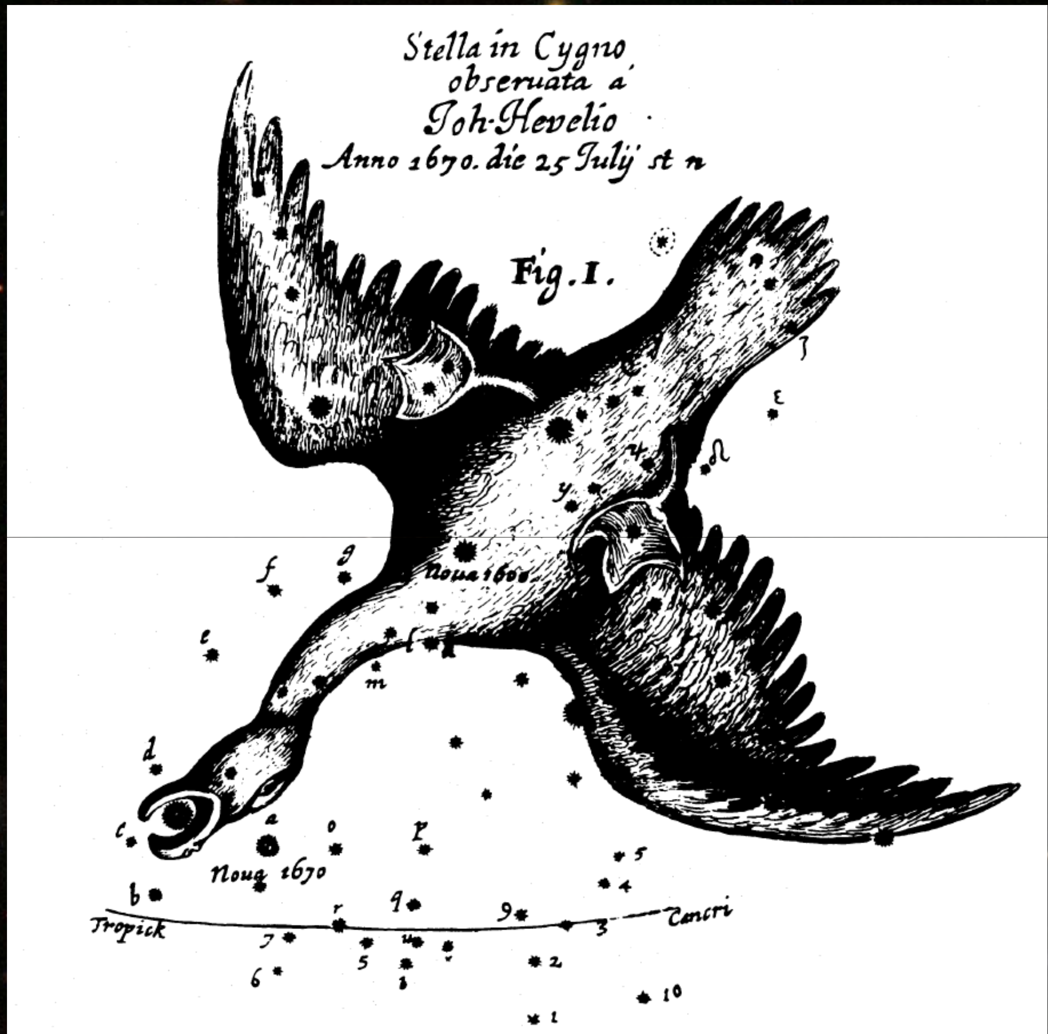
... easy, we know 100s of cataclysmic variables ...



... but ... CVs undergo classical nova eruptions ...

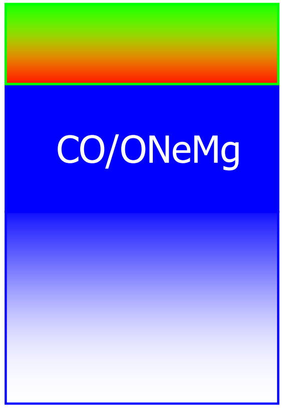


CK Vul = Nova Vulpeculae 1670



Hevelius, *Philosophical Transactions*, Vol. 5, (1670), pp. 2087-2091

Classical novae: explosive hydrogen shell burning

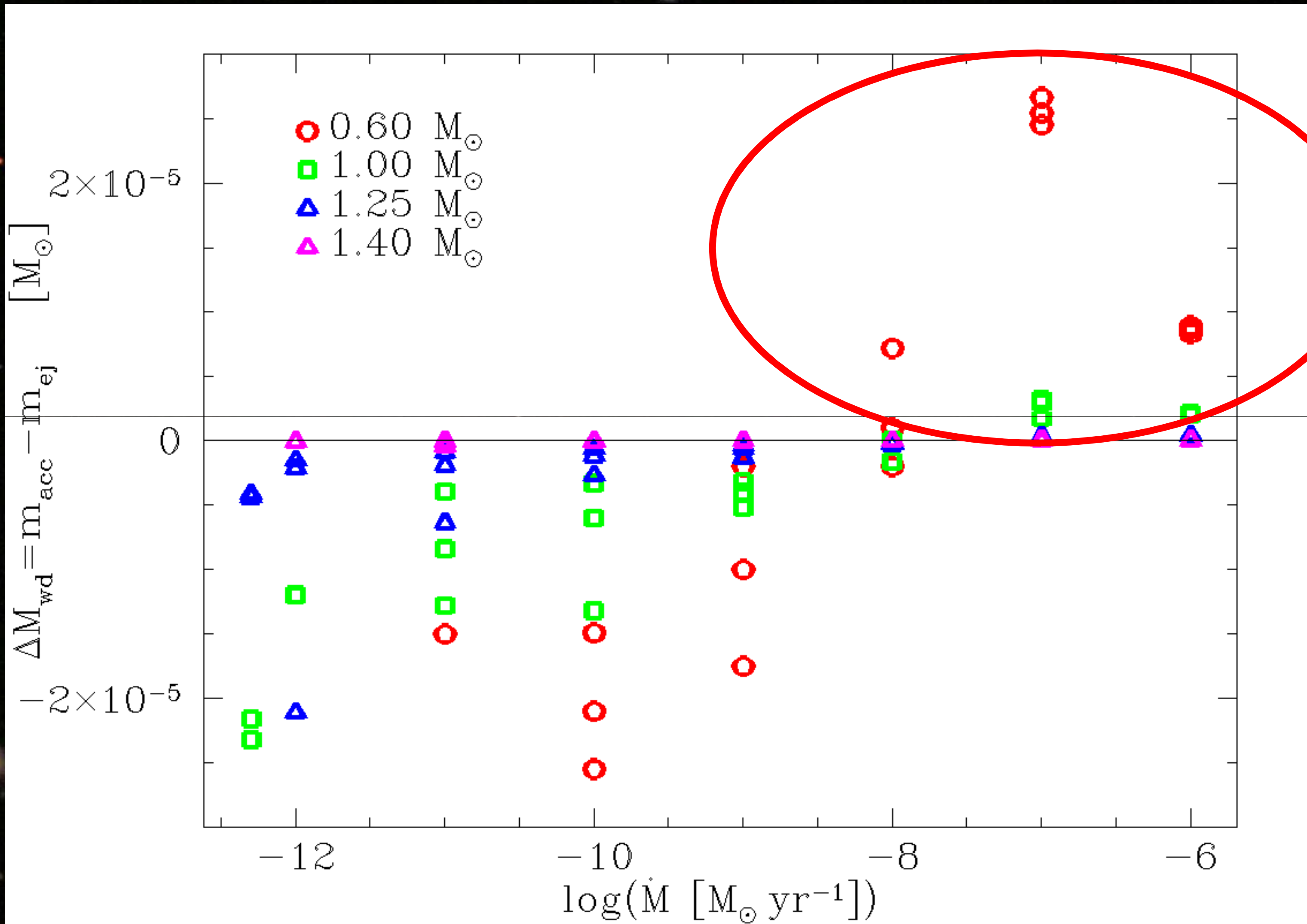


- accretion builds up an envelope of hydrogen
- T & P at the base of the envelope increase
- Eventually, conditions for hydrogen fusion are met
- If the base of the envelope is degenerate,

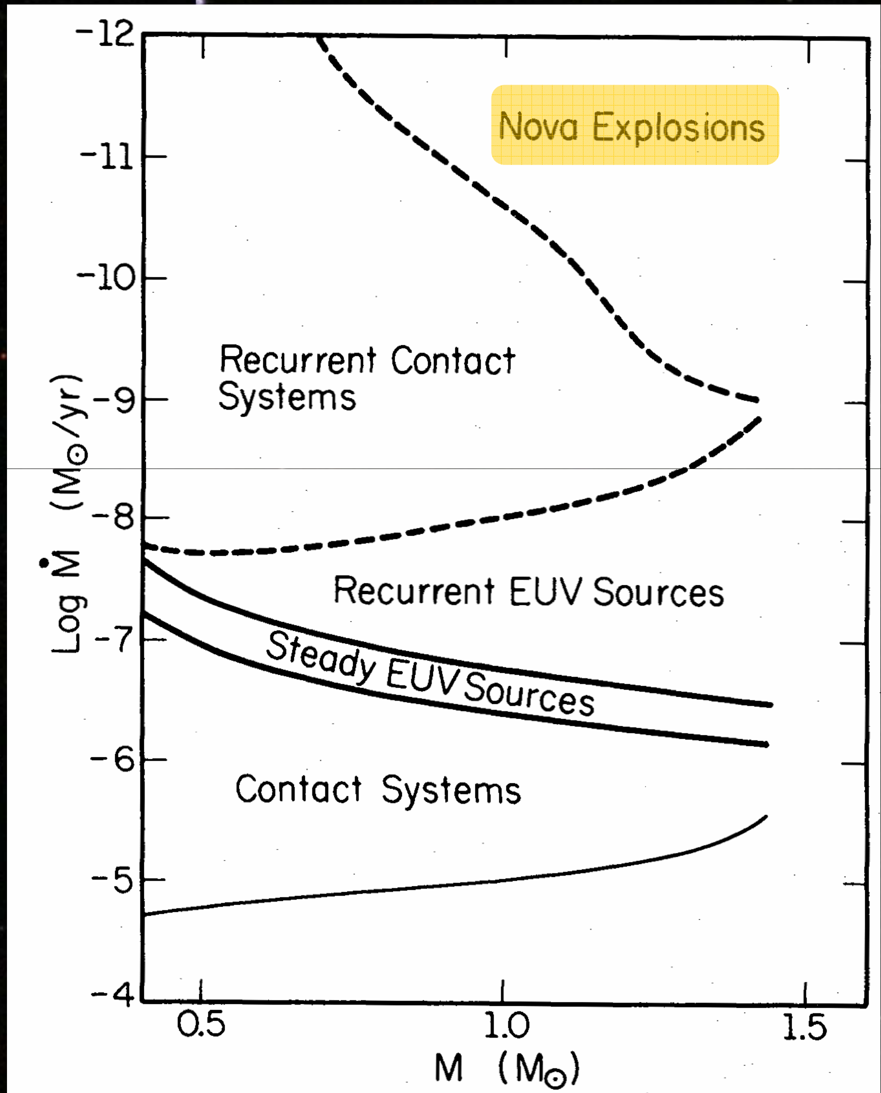
$$\rho \neq f(T) \Longrightarrow T\uparrow$$

- Eventually, $E_{th} > E_F$ degeneracy is lifted, and the nova shell expands
- Enrichment in Ne is observed in some nova, suggests dredge-up from the white dwarf core ... **Eroding the white dwarf mass!!**

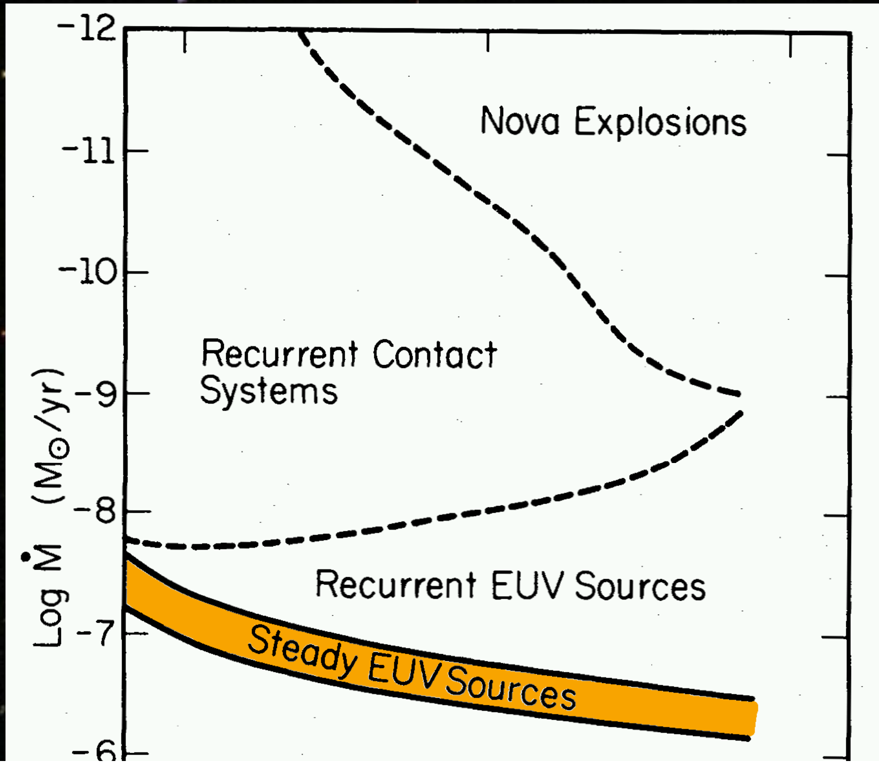
So when does the white dwarf grow in mass ...?



It all depends on the WD mass and accretion rate



Steady nuclear shell burning



(supersoft X-ray sources)

Astron. Astrophys. 61, 363—367 (1978)

ASTRONOMY AND ASTROPHYSICS

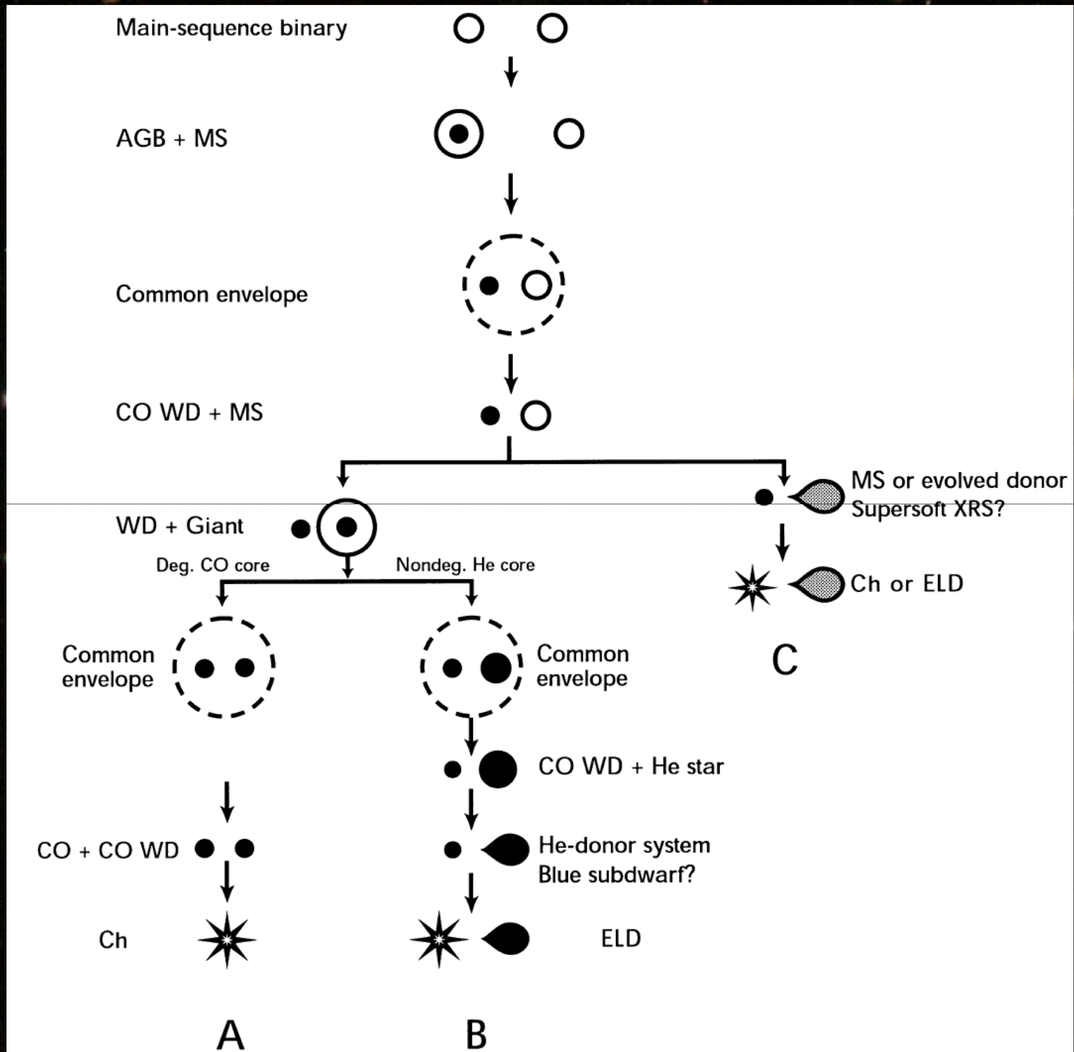
Non-ejecting Novae as EUV Sources

M. M. Shara*, D. Prialnik and G. Shaviv

Department of Physics and Astronomy, Tel Aviv University, Ramat Aviv, Tel Aviv, Israel

Received February 21, 1977

SN Ia progenitors



Iben & Tutukov

SN Ia progenitors

- **Single-degenerate (SD) models:**

A white dwarf accretes from a non-degenerate companion, this could be a main-sequence star (supersoft X-ray sources and recurrent novae), or a red (sub)giant (symbiotic binaries).

Main problem: SNIa are *by definition* hydrogen-free, but the explosion of the white dwarf should strip off visibile anounts of hydrogen from the companion.

- **Double-degenerate (DD) models:**

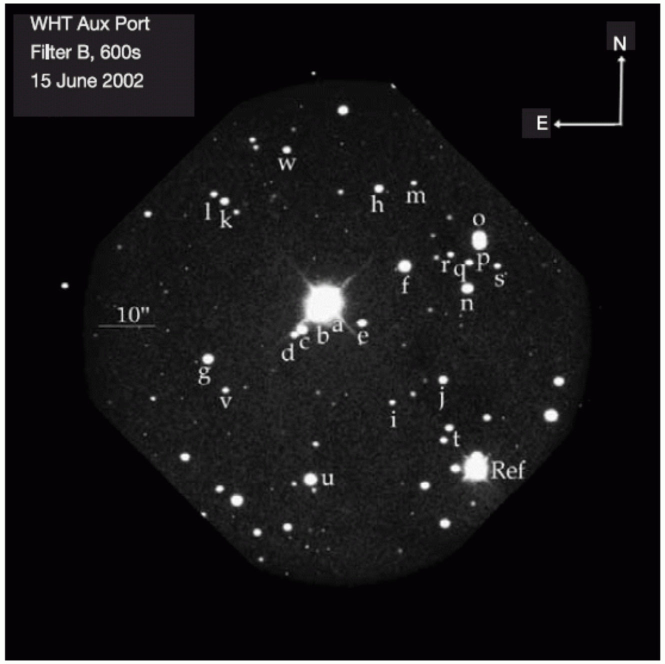
Two white dwarfs in a close binary eventually merge.

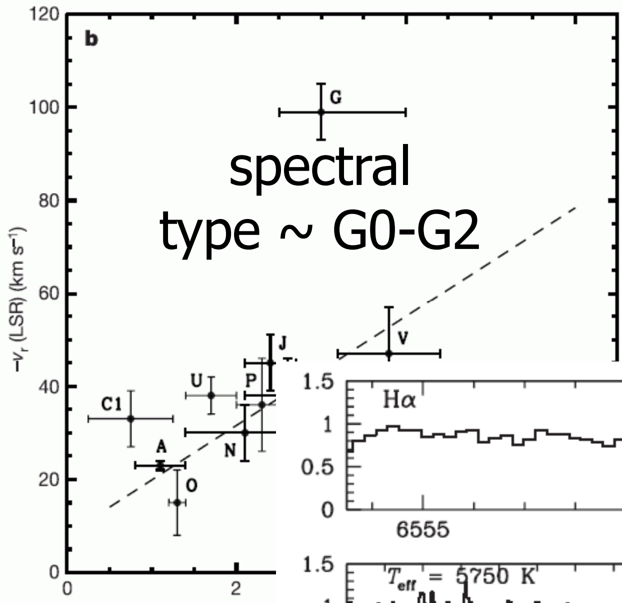
Main problem: theoretical models of the merger suggest that the two white dwarfs are more likely to collapse into a neutron star, than to explode.

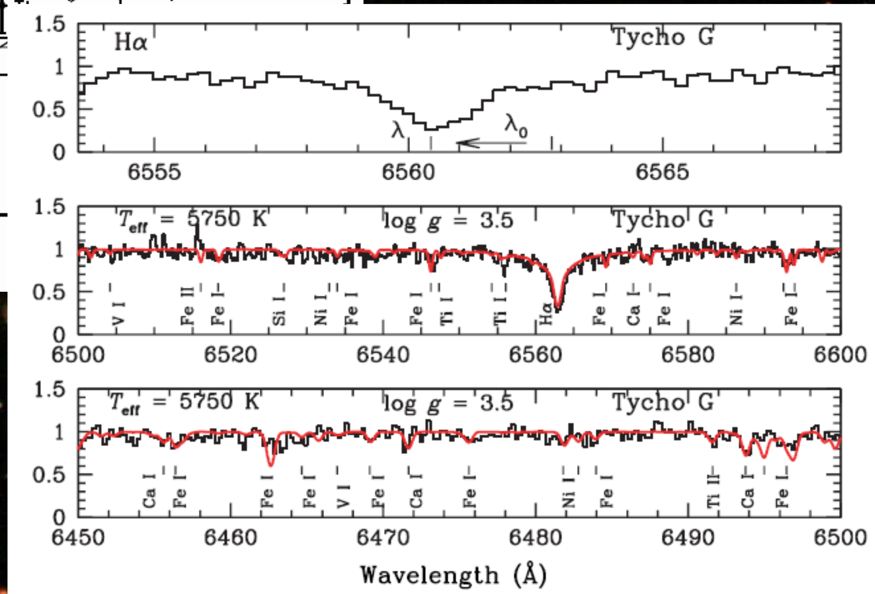
The binary progenitor of Tycho Brahe's 1572 supernova

Pilar Ruiz-Lapuente[1,2], Fernando Comeron[3], Javier Méndez[1,4], Ramon Canal[1], Stephen J. Smartt[5], Alexei V. Filippenko[6], Robert L. Kurucz[7], Ryan Chornock[6], Ryan J. Foley[6], Vallery Stanishev[8] & Rodrigo Ibata[9]

(2004, Nature 431, 1069)







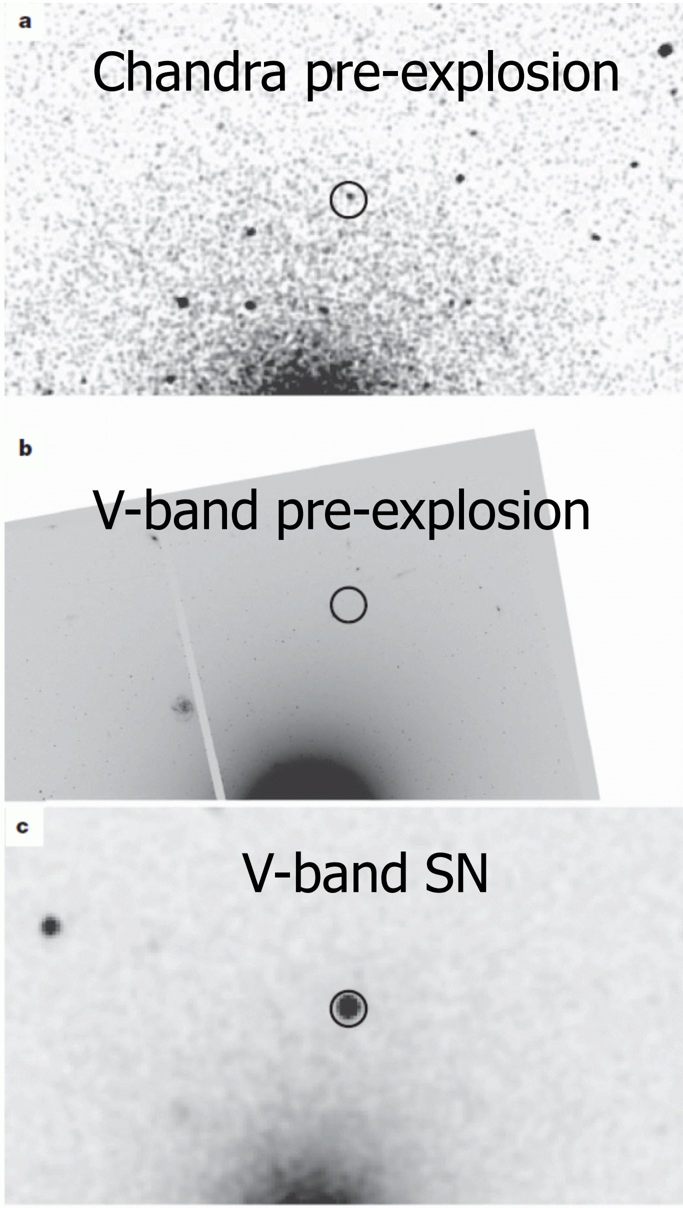
SD:1 DD:0

nature Vol 451|14 February 2008|do

LETTERS

Discovery of the progenitor of the type Ia supernova 2007on

Rasmus Voss[1,2] & Gijs Nelemans[3]



SD:2 DD:0

(2008 Nature 451, 802)

nature Vol 463|18 February 2010|doi:10.1038/nature08685

LETTERS

An upper limit on the contribution of accreting white dwarfs to the type Ia supernova rate

Marat Gilfanov[1,2] & Ákos Bogdán[1]

supernova rate from their K-band luminosities. We conclude that no more than about five per cent of type Ia supernovae in early-type galaxies can be produced by white dwarfs in accreting binary systems, unless their progenitors are much younger than the bulk of the stellar population in these galaxies, or explosions of sub-Chandrasekhar white dwarfs make a significant contribution to the supernova rate.

(2010, Nature 463, 924)

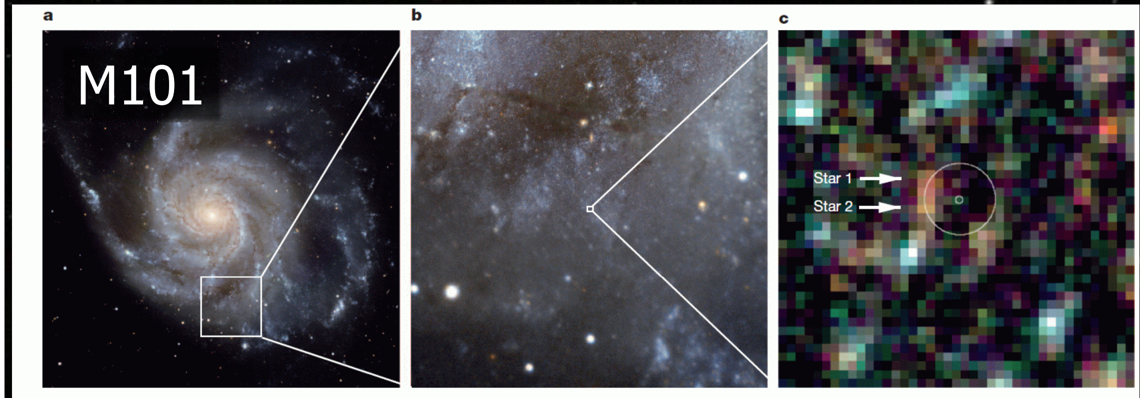
SD:2 DD:1

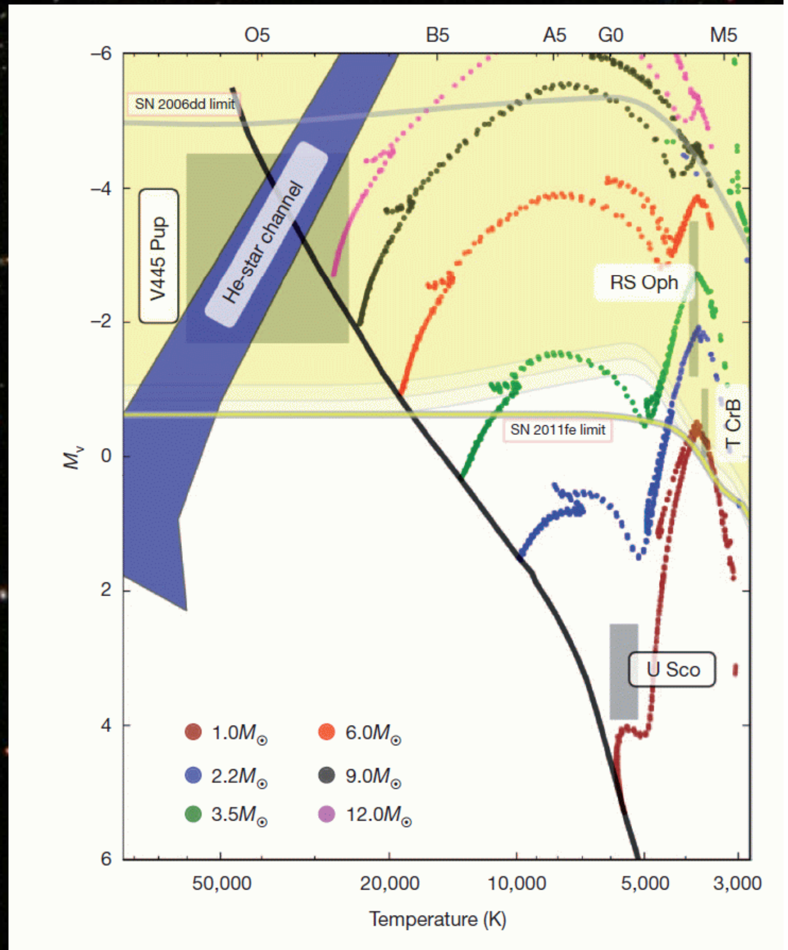
LETTER
doi:10.1038/nature10646

(2011, Nature 480, 348)

Exclusion of a luminous red giant as a companion star to the progenitor of supernova SN 2011fe

Weidong Li[1], Joshua S. Bloom[1], Philipp Podsiadlowski[2], Adam A. Miller[1], S. Bradley Cenko[1], Saurabh W. Jha[3], Mark Sullivan[2], D. Andrew Howell[4,5], Peter E. Nugent[1,6], Nathaniel R. Butler[7], Eran O. Ofek[8,9], Mansi M. Kasliwal[10], Joseph W. Richards[1,11], Alan Stockton[12], Hsin-Yi Shih[12], Lars Bildsten[5,13], Michael M. Shara[14], Joanne Bibby[14], Alexei V. Filippenko[1], Mohan Ganeshalingam[1], Jeffrey M. Silverman[1], S. R. Kulkarni[8], Nicholas M. Law[15], Dovi Poznanski[16], Robert M. Quimby[17], Curtis McCully[3], Brandon Patel[3], Kate Maguire[2] & Ken J. Shen[1]





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THE MERGER RATE OF BINARY WHITE DWARFS IN THE GALACTIC DISK

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ABSTRACT

We use multi-epoch spectroscopy of ∼4000 white dwarfs in the Sloan Digital Sky Survey to constrain the properties of the Galactic population of binary white dwarf systems and calculate their merger rate. With a Monte Carlo code, we model the distribution of ΔRV_{max}, the maximum radial velocity shift between exposures of the same star, as a function of the binary fraction within 0.05 AU, f_{bin}, and the power-law index in the separation distribution at the end of the common-envelope phase, α. Although there is some degeneracy between f_{bin} and α, the 15 high-ΔRV_{max} systems that we find constrain the combination of these parameters, which determines a white dwarf merger rate per unit stellar mass of $1.4^{+3.4}_{-1.0} \times 10^{-13}$ yr^{-1} $M_\odot^{-1}$ (1σ limits). This is remarkably similar to the measured rate of Type Ia supernovae (SNe Ia) per unit stellar mass in Milky-Way-like Sbc galaxies. The rate of super-Chandrasekhar mergers is only $1.0^{+1.6}_{-0.6} \times 10^{-14}$ yr^{-1} $M_\odot^{-1}$. We conclude that there are not enough close binary white dwarf systems to reproduce the observed SN Ia rate in the "classic" double degenerate super-Chandrasekhar scenario. On the other hand, if sub-Chandrasekhar mergers can lead to SNe Ia, as has been recently suggested by some studies, they could make a major contribution to the overall SN Ia rate. Although unlikely, we cannot rule out contamination of our sample by M-dwarf binaries or non-Gaussian errors. These issues will be clarified in the near future by completing the follow-up of all 15 high-ΔRV_{max} systems.

SD:3 DD:2

PTF 11kx: A Type Ia Supernova with a Symbiotic Nova Progenitor

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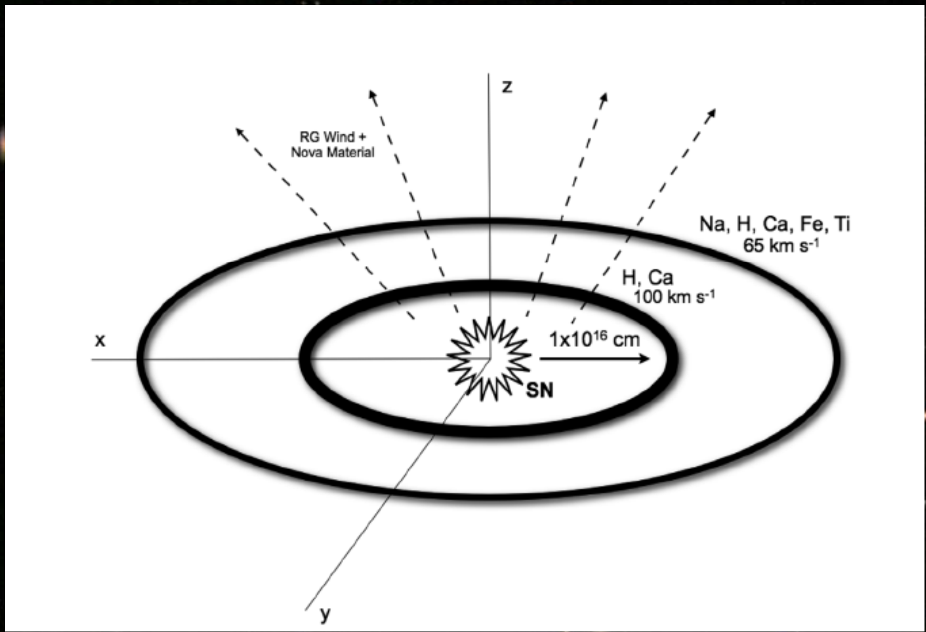
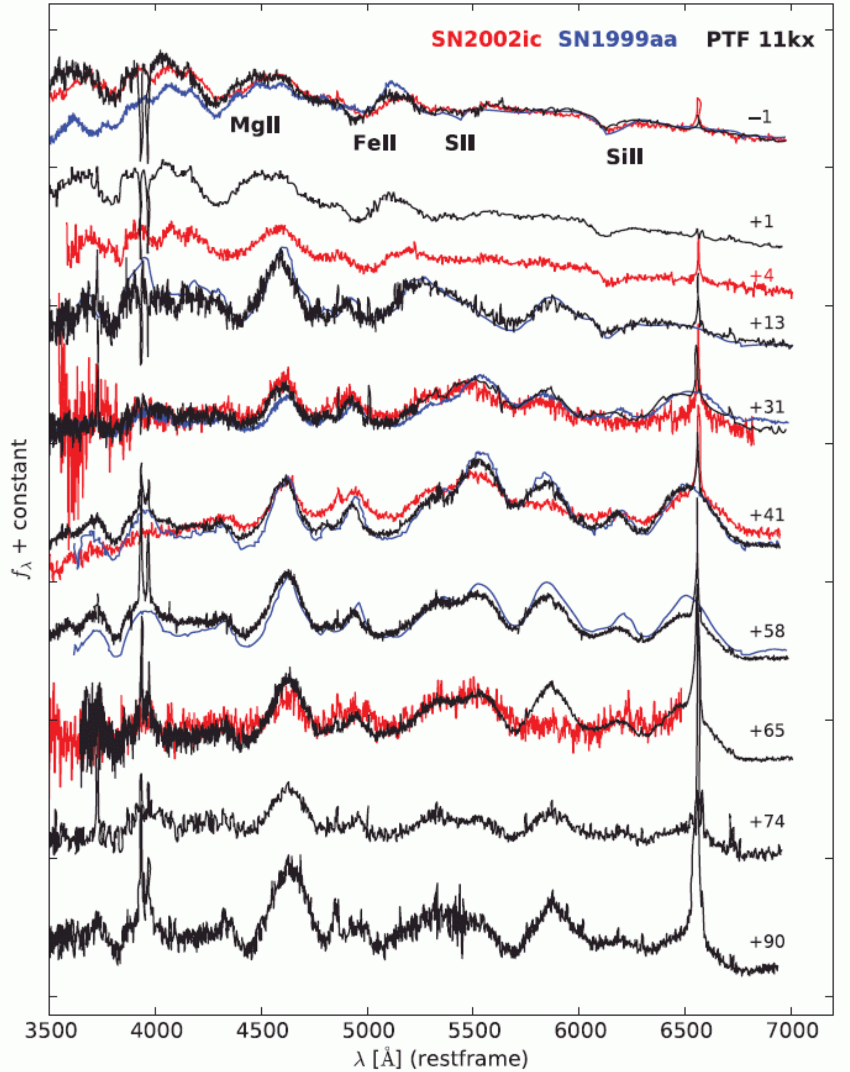
(2012, Science 337, 942)





SD:4 DD:2

LETTER

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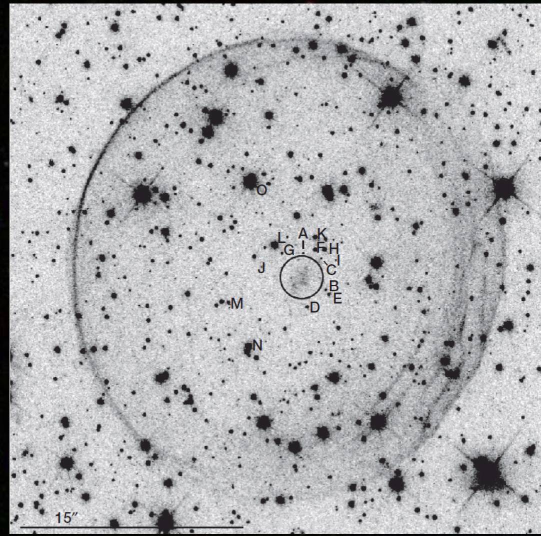
An absence of ex-companion stars in the type Ia supernova remnant SNR 0509−67.5

Bradley E. Schaefer[1] & Ashley Pagnotta[1]



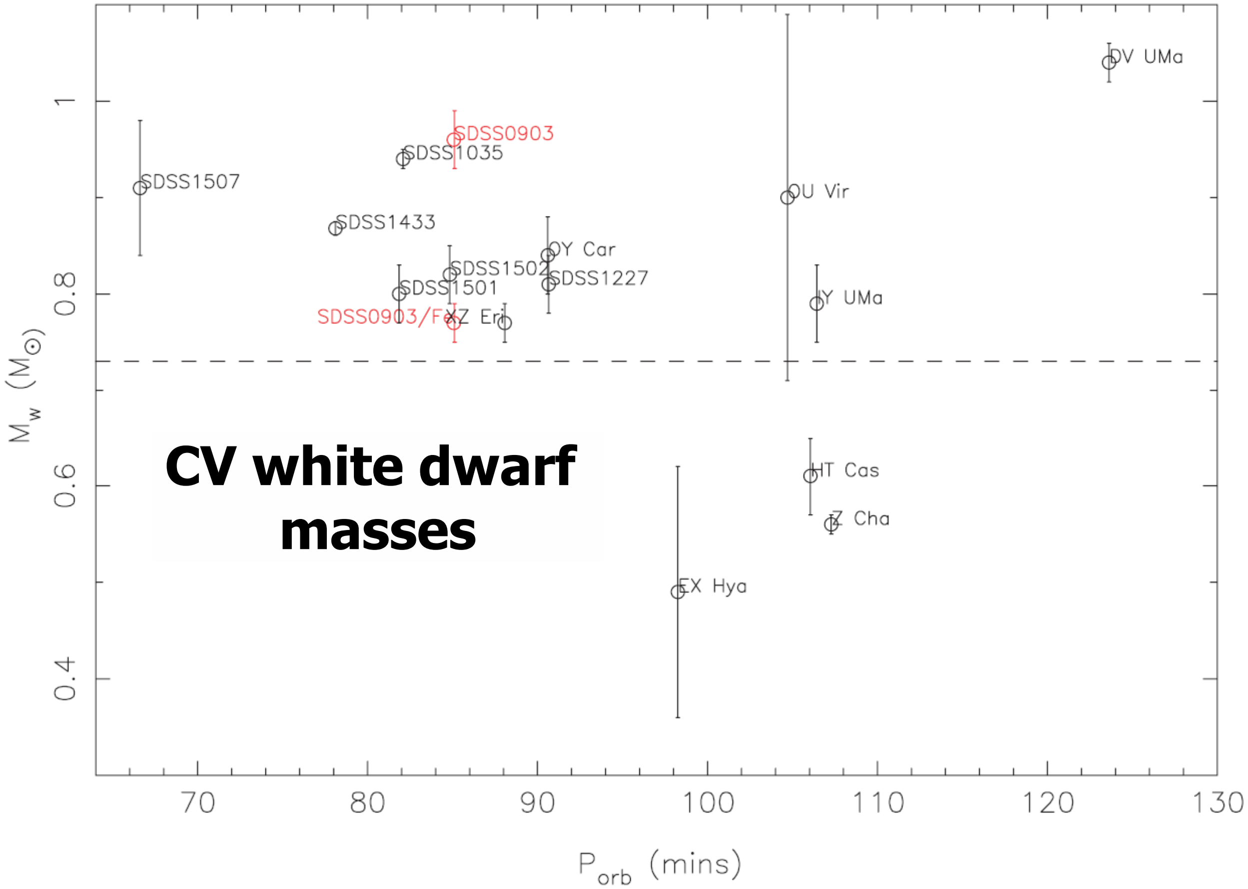
a companion could have been 'kicked' by the explosion.) This lack of any ex-companion star to deep limits rules out all published single-degenerate models for this supernova. The only remaining possibility is that the progenitor of this particular type Ia supernova was a double-degenerate system.

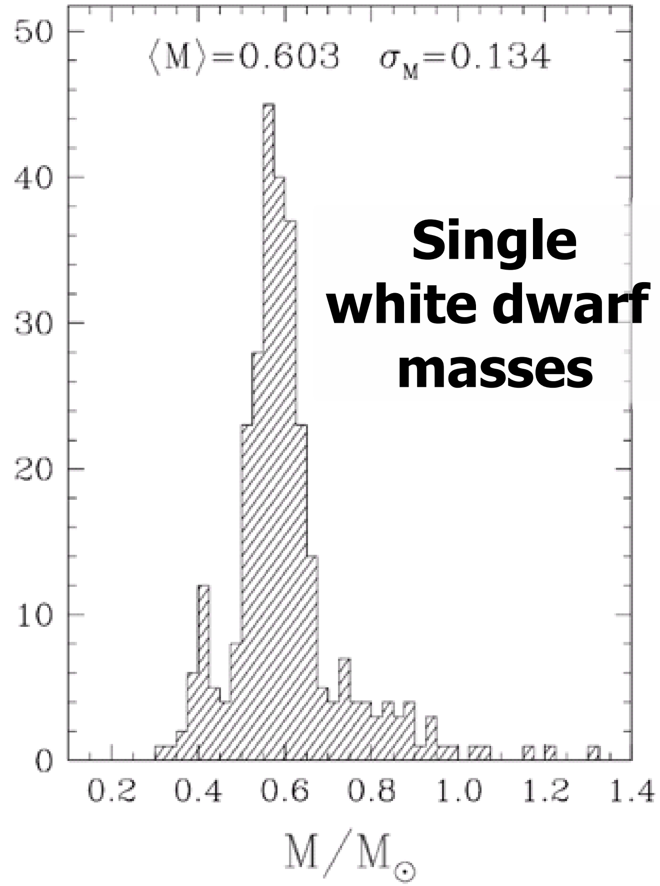
Table 1 | Candidate progenitor classes

Candidate class	P_{orb} (d)	$v_{ex\text{-}comp}$ (km s^{-1})	Surviving companion	M_V (mag)	V range in LMC (mag)
Double-degenerate	NA	NA	None	NA	NA
Recurrent nova	0.6–520	50–350	Red giant or subgiant	−2.5 to +3.5	16–22
Symbiotic star	245–5,700	50–250	Red giant	−2.5 to +0.5	16–19
Supersoft source	0.14–4.0	170–390	Subgiant or $>1.16\ M_{\odot}$ MS	+0.5 to +4.2	19–22.7
Helium star donor	0.04–160	50–350	Red giant or subgiant core	−0.5 to +2.0	18–20.5
Spin-up/spin-down	245–5,700	50–250	Red giant or subgiant core	−0.5 to +2.0	18–20.5

SD:4 DD:3

... now towards heresy ...

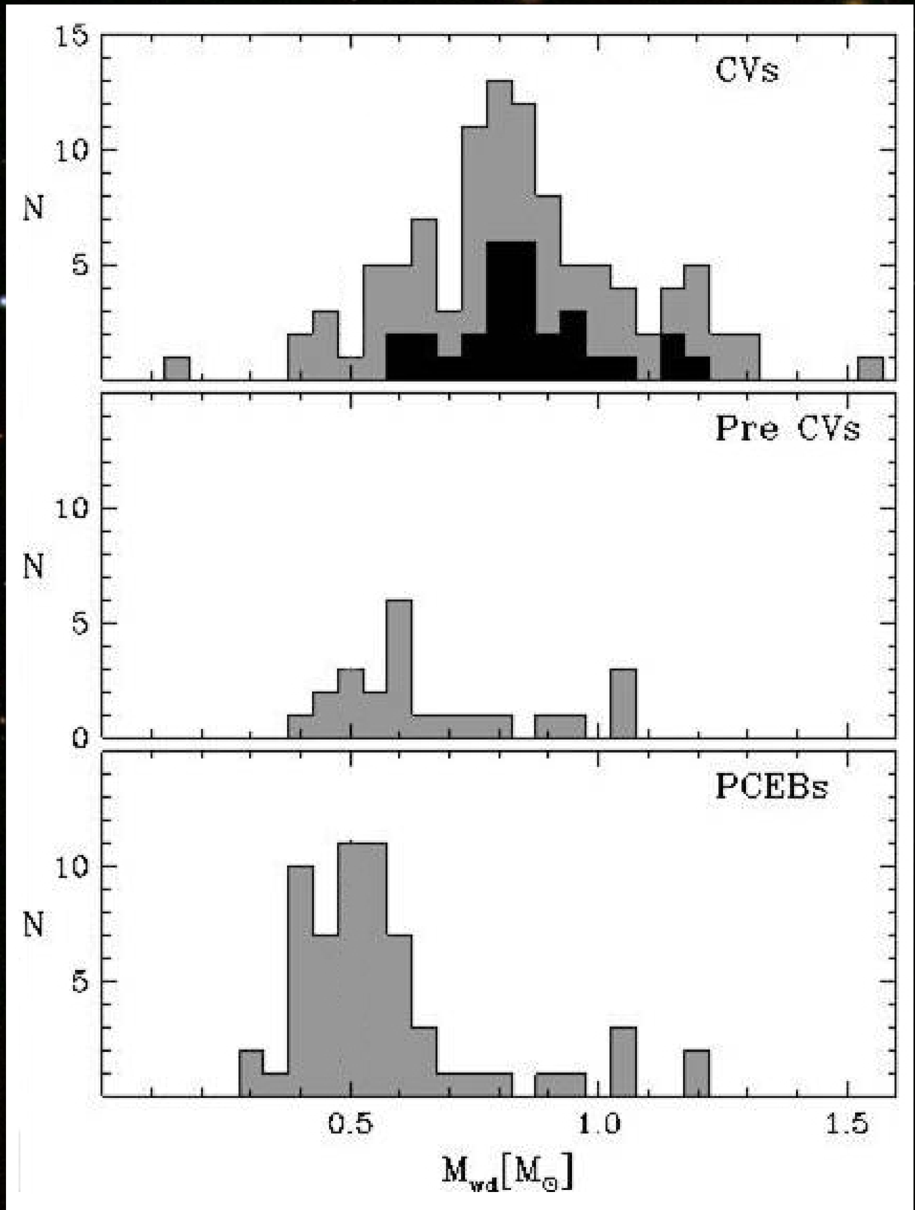




Feline et al. (2004),
Littlefair et al. (2006, 2007, 2008)
Savoury et al. (2011)

Liebert et al. (2005)

CVs versus pre-CVs and PCEBs



$\langle M_{wd} \rangle = 0.83 \pm 0.23\ M_\odot$

$\langle M_{wd} \rangle = 0.67 \pm 0.21\ M_\odot$

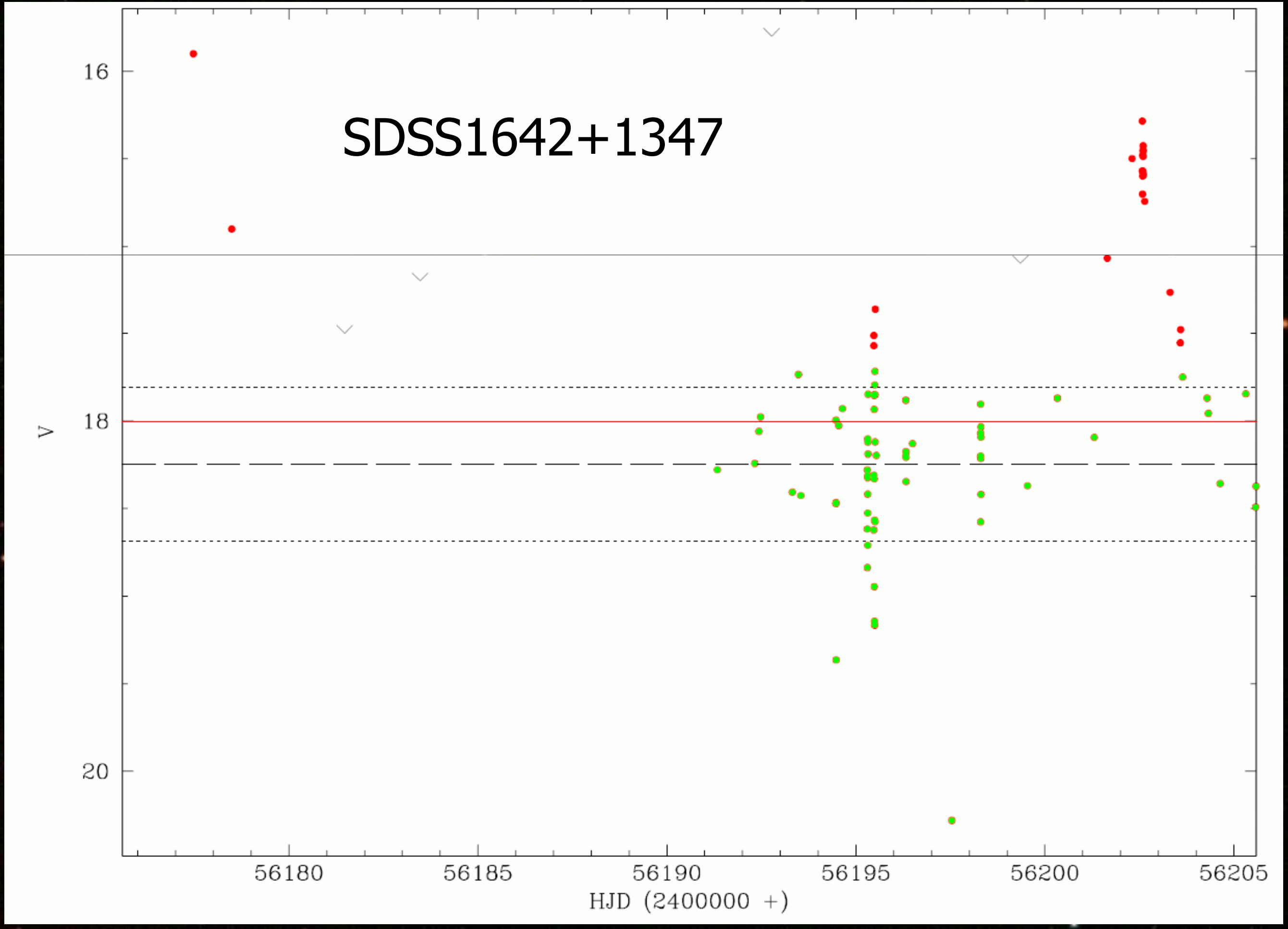
$\langle M_{wd} \rangle = 0.58 \pm 0.20\ M_\odot$

$\Rightarrow$ the white dwarfs in CVs can grow in mass !?

We need more data: a large, 122-orbit HST program!

... One tiny problem: CVs can brighten by ~4-8 magnitudes, and destroy the detectors of the COS spectrograph ...

... Hence intense monitoring of the HST targets required!!



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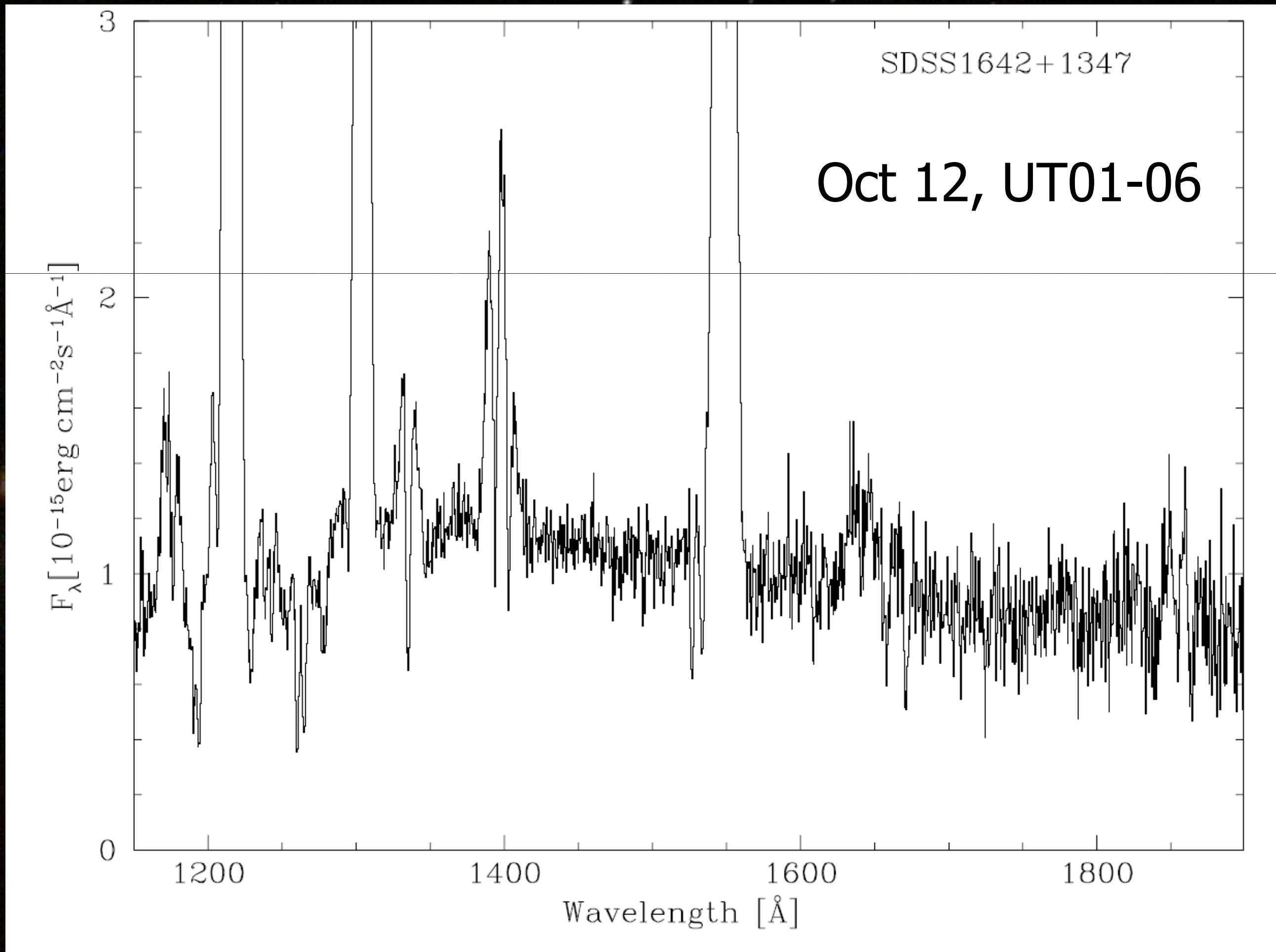


The end