The Progenitors of Type Ia Supernovae

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+ PTF Team

- Type Ia supernovae (SNe Ia) have been used as standardizable cosmological distance candles

→ first evidence for an accelerating Universe
(Nobel Prize 2011)

but: large diversity of SN Ia types (super-Chandra SNe?)

- link between progenitors and explosion models still very uncertain

I. Supernova Types and Cosmology

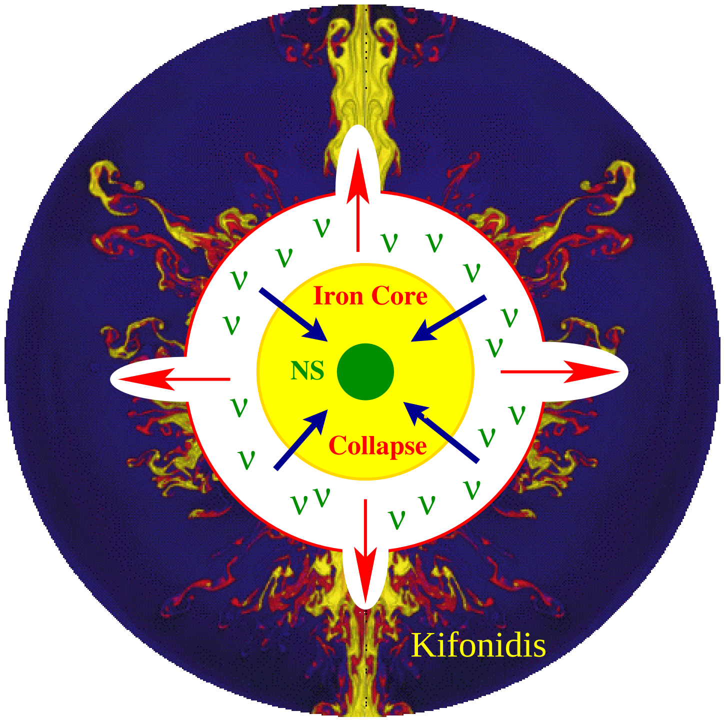
II. Constraining Supernova Progenitors

III. Recent Developments: PTF 11kly, PTF 11kx

EXPLOSION MECHANISMS

- two main, completely different mechanisms

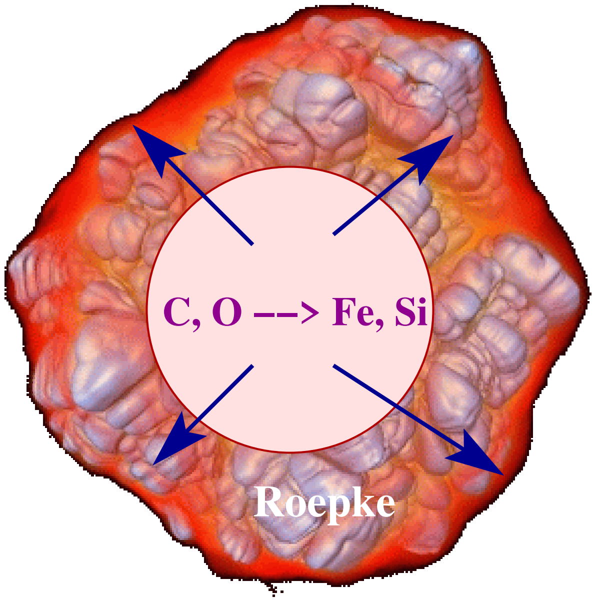
Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{53}$ ergs)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of the neutrino energy deposited ($\sim 1\,\%$, 10^{51} ergs) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

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

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Supernova Classification

SUPERNOVA CLASSIFICATION

observational:

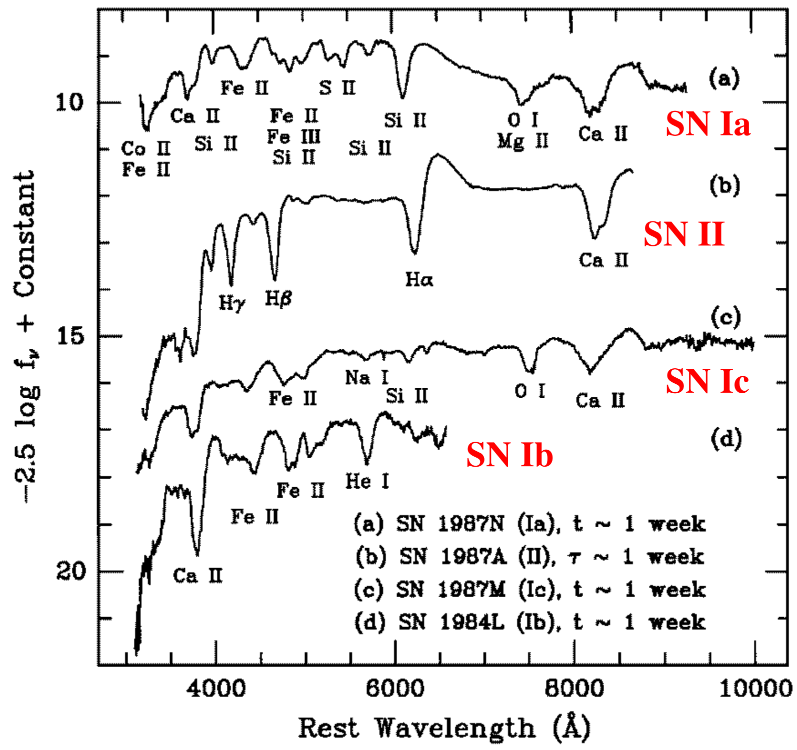
- **Type I: no hydrogen** lines in spectrum
- **Type II: hydrogen** lines in spectrum

theoretical:

- **thermonuclear explosion** of degenerate core
- **core collapse** → neutron star/black hole

relation no longer 1 to 1 → confusion

- **Type Ia (Si lines):** thermonuclear explosion of white dwarf
- **Type Ib/Ic (no Si; He or no He):** core collapse of He star
- **Type II-P:** "classical" core collapse of a massive star with hydrogen envelope
- **Type II-L:** supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)



complications:

- special supernovae like **SN 1987A**
- **Type IIb:** supernovae that change type, **SN 1993J** (Type II → Type Ib)
- some supernova "types" (e.g., IIn) occur for both explosion types ("phenomenon", not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

http://www-supernova.lbl.gov/

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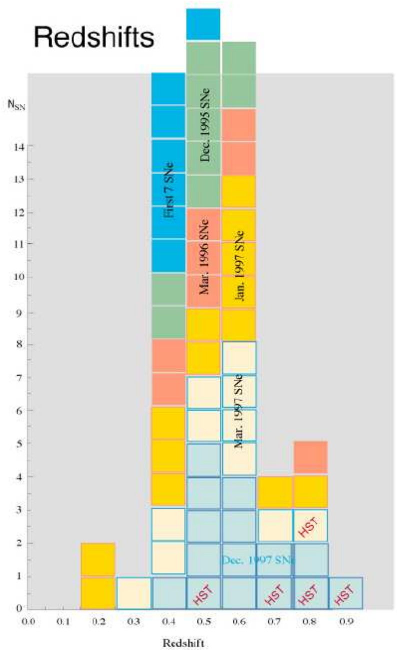
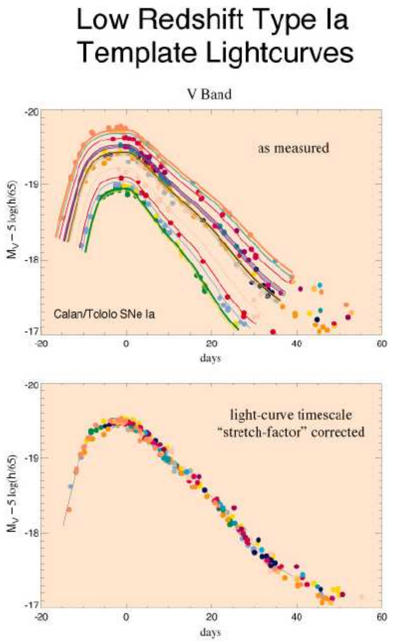


We have discovered well over 50 high redshift Type Ia supernovae so far. Of these, approximately 50 have been followed with spectroscopy and photometry over two months of the light curve. The redshifts shown in this histogram are color coded to show the increasing depth of the search with each new "batch" of supernova discoveries. The most recent supernovae, discovered the last week of 1997, are now being followed over their lightcurves with ground-based and (for those labeled "HST") with the Hubble Space Telescope.



Type Ia supernovae observed "nearby" show a relationship between their peak absolute luminosity and the timescale of their light curve: the brighter supernovae are slower and the fainter supernovae are faster (see Phillips, Ap.J.Lett., 1993 and Riess, Press, & Kirshner, Ap.J.Lett., 1995). We have found that a simple linear relation between the absolute magnitude and a "stretch factor" multiplying the lightcurve timescale fits the data quite well until over 45 restframe days past peak. The lower plot shows the "nearby" supernovae from the upper plot, after fitting and removing the stretch factor, and "correcting" peak magnitude with this simple calibration relation.

TYPE IA SUPERNOVAE

- Type Ia supernovae have been used as standard distance candles to measure the curvature of the Universe → accelerating Universe?
- Type Ia supernovae are no good standard candles! (peak luminosities vary by a factor up to 10)
- but they may be standardizable candles, i.e. there appears to be a unique relation between peak luminosity and the width of the lightcurve which can be used to derive good distances
- significant recent progress on understanding the explosion physics and the relation between lightcurve shape and peak luminosity

caveat: the progenitors of Type Ia supernovae are not known

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 ($t_{1/2} = 6.1\,\mathrm{d}$)

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

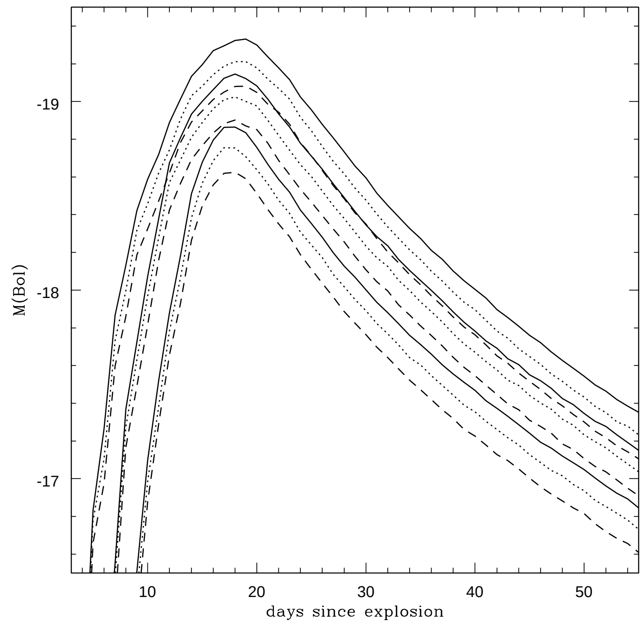
- the lightcurve width is determined by the diffusion time
  - ▷ depends on the opacity, in particular the total number of iron-group elements (i.e. ^{56}Ni, ^{58}Ni, ^{54}Fe)
  - $\rightarrow$ $t_{\mathrm{width}} \propto M_{\mathrm{iron-group}}$
  - ▷ ^{54}Fe, ^{58}Ni are non-radioactive $\rightarrow$ contribute to opacity but not supernova luminosity

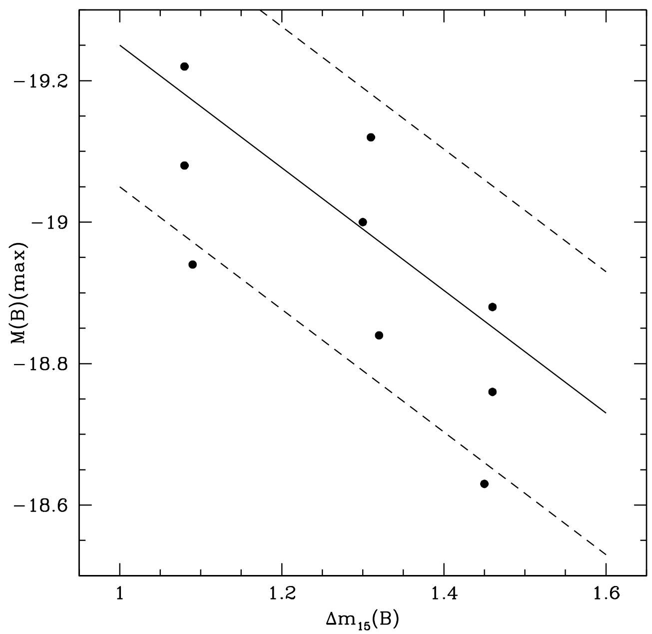
$\rightarrow$ necessary second parameter

- 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)



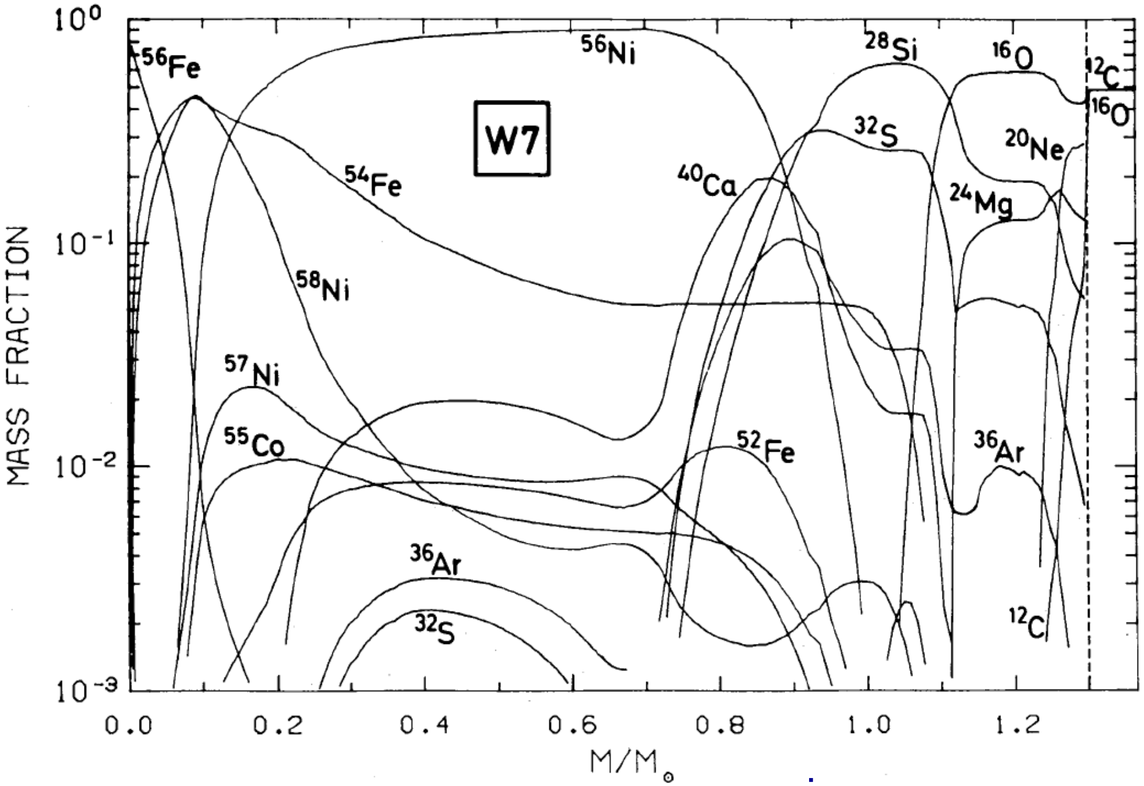


Thermonuclear Explosions

(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)

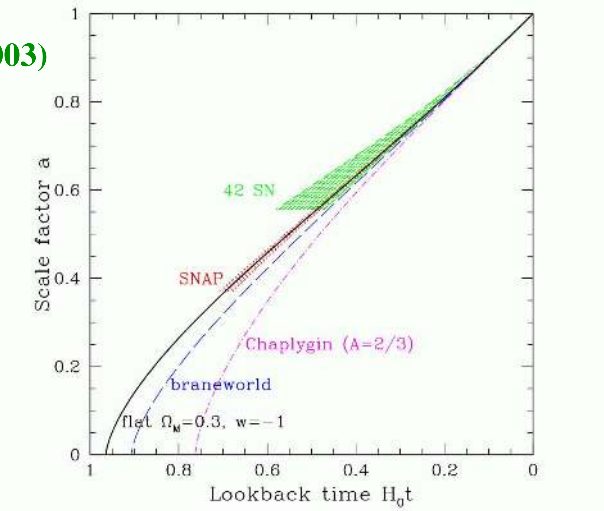
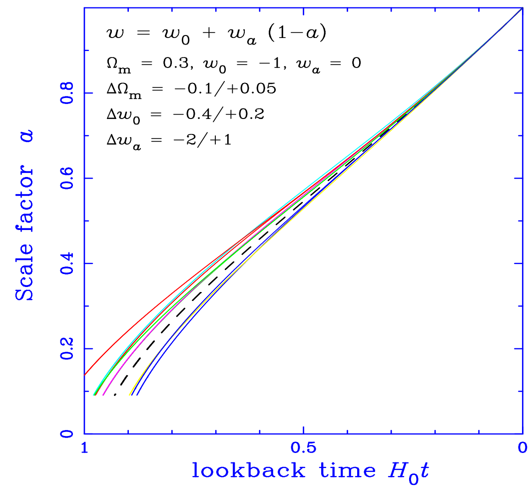


FIG. 1: Mapping the expansion history through the supernova magnitude-redshift relation can distinguish the dark energy explanation for the accelerating universe from alternate theories of gravitation, high energy physics, or higher dimensions. All three models take an $\Omega_M = 0.3$, flat universe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

The effect of metallicity evolution



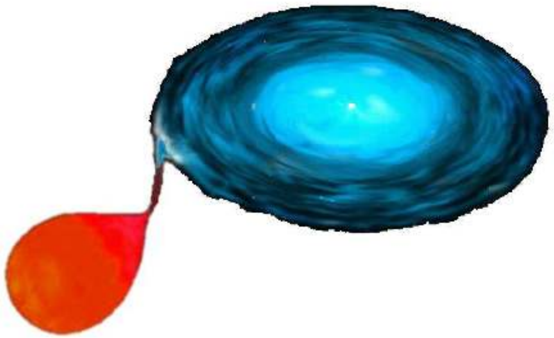
(based on PMLWF 2006)

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! $0.02\,M_{\odot}$) (Leonard 2007)
- Recent:
  - ▷ surviving companion in Tycho supernova remnant (Ruiz-Lapuente et al.)? Needs to be confirmed. Predicted rapid rotation is not observed (Kerzendorf et al. 2009).
  - ▷ SN 2006X (Patat et al. 2007): first discovery of circumstellar material → supports giant channel for SNe Ia

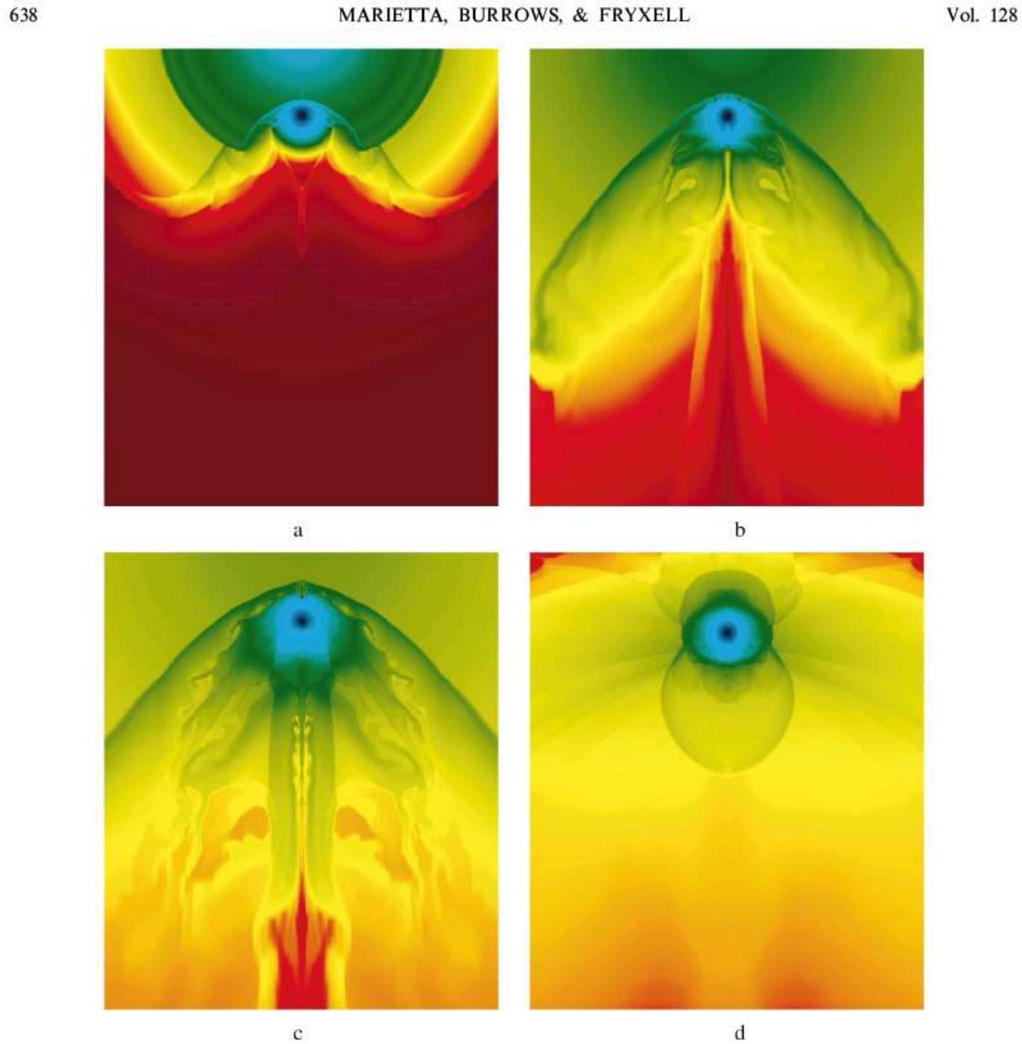
Direct Detection of Hydrogen in the post-supernova spectrum

- Marietta et al. (2000): predict substantial stripping of hydrogen from the companion; MS/SG companion: $\sim 0.15\,M_\odot$ → easily detectable in nebular phase
- problem: in some systems, very tight limits: $\lesssim 0.01\,M_\odot$ (Leonard 2007) → big problem for the SD model?

but: less stripping in more realistic companion models? Pakmor/Röpke: $0.01 - 0.02\,M_\odot$

- possible time delay between mass-transfer phase and explosion (di Stefano 2011, Justham 2011)

Note: Hydrogen has been observed in large abundance in some notional SNe Ia (e.g. SN 2002ic, PTF2010x) → symbiotic link?



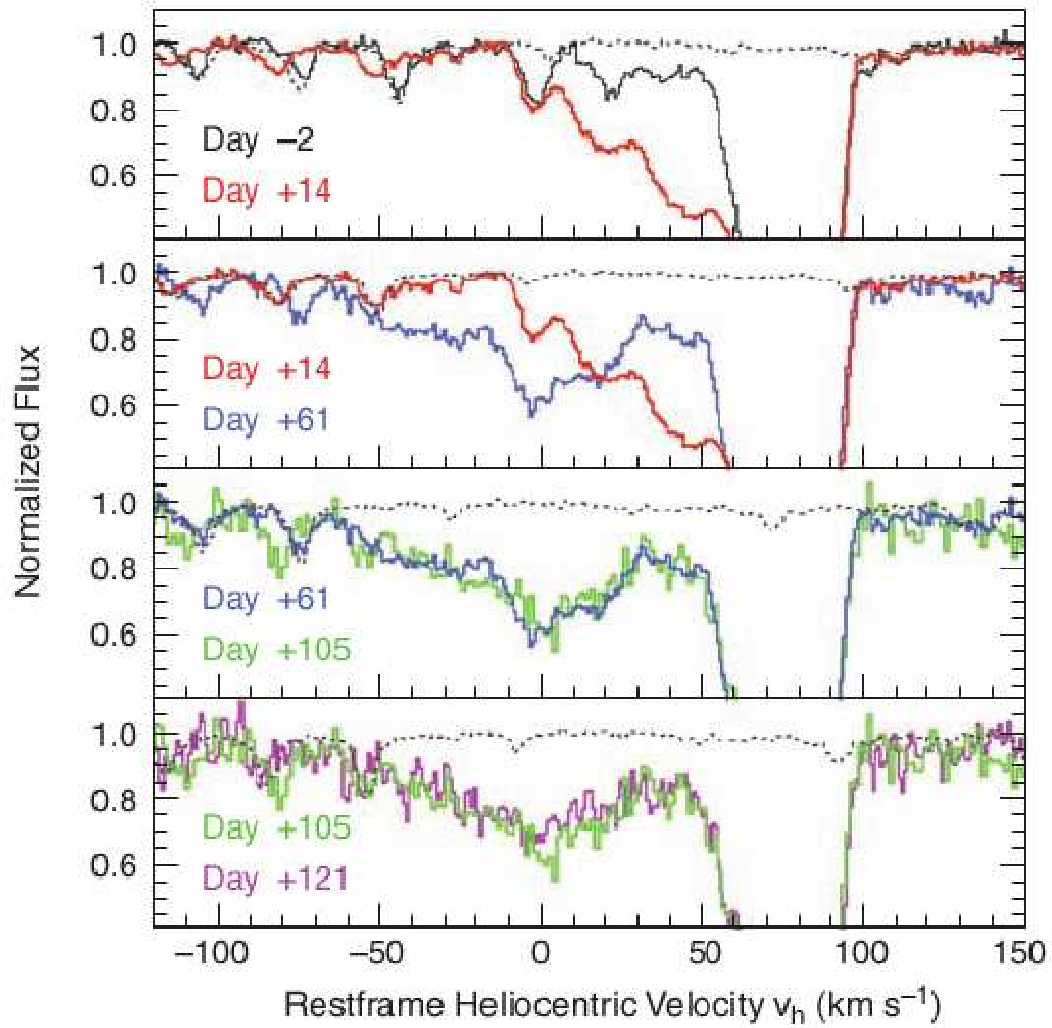
Marietta et al. (2000)

Detection of Circumstellar Wind Material

Patat et al. (2007)

- CSM material detected in SN 2006X and other since (e.g. Simon, Blondin, Sternberg)
- time-varying Na lines, flash-ionized and recombining
- distance to SN: $< 10^{16}$ cm
- consistent with variable red-giant wind (seen along orbital plane?)
- similar variability seen in about $10 - 20\,\%$ of SNe Ia
- and in RS Oph after last outburst! (Patat et al. 2011)

Patat et al. (2007)



A surviving companion in the Tycho supernova remnant?

- binary companion should survive supernova explosion
- detect runaway velocity star

Ruiz-Lapuente et al. (2004): candidate Tycho G?

letters to nature

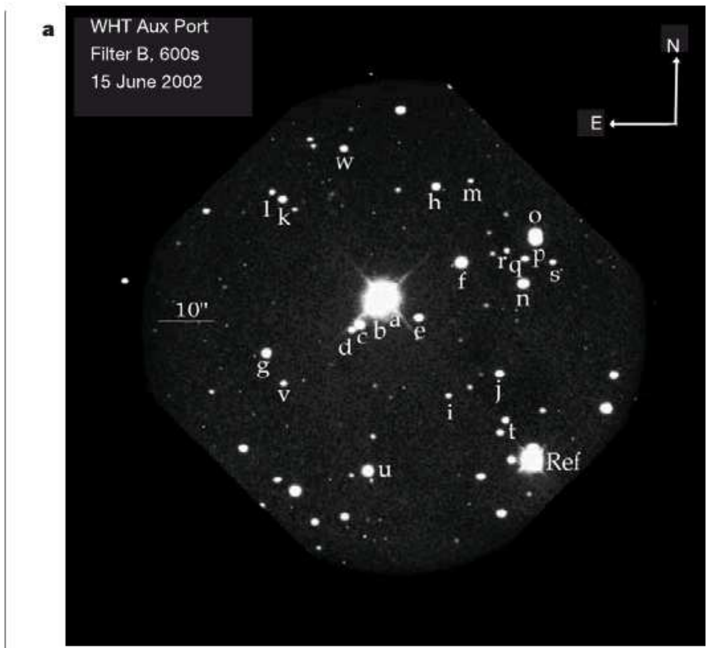
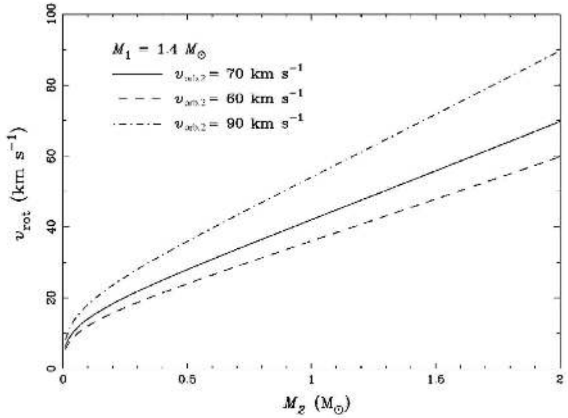


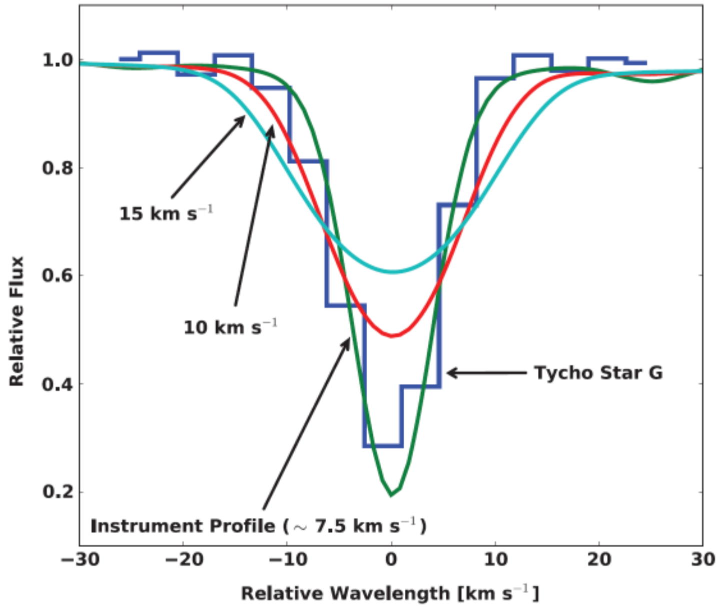
Figure 2 The SN 1572 field and radial velocity of the stars. **a**, Image from the Auxiliary

Kerzendorf et al. (2009)

- companion should have been tidally locked and rapidly rotating



- rapid rotation is not observed
- presently no good candidates left (perhaps one)



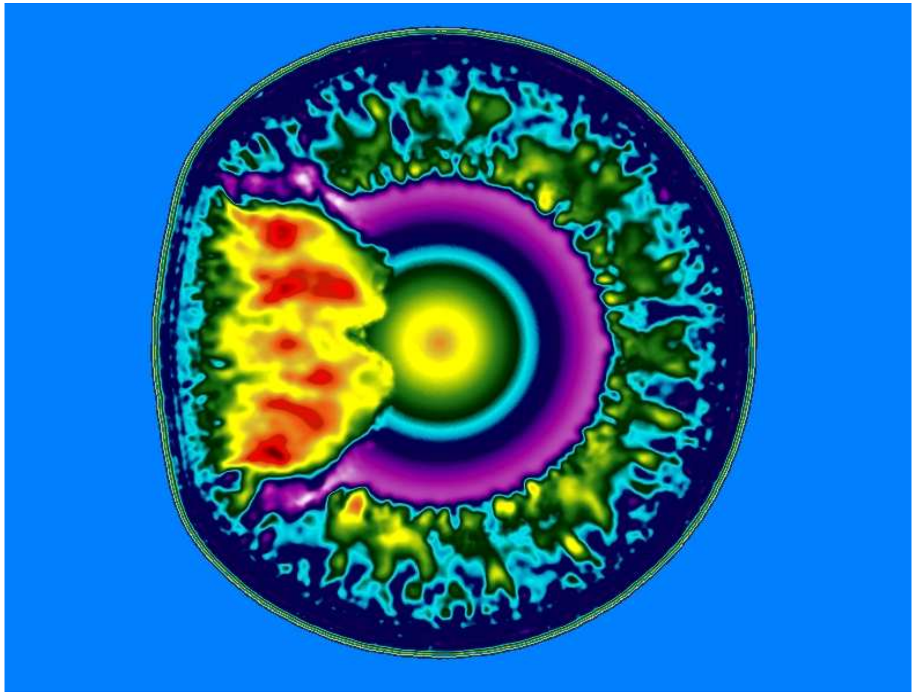
Companion Imprint on SN Ia Remannts

(Booth, Podsiadlowski 2012)

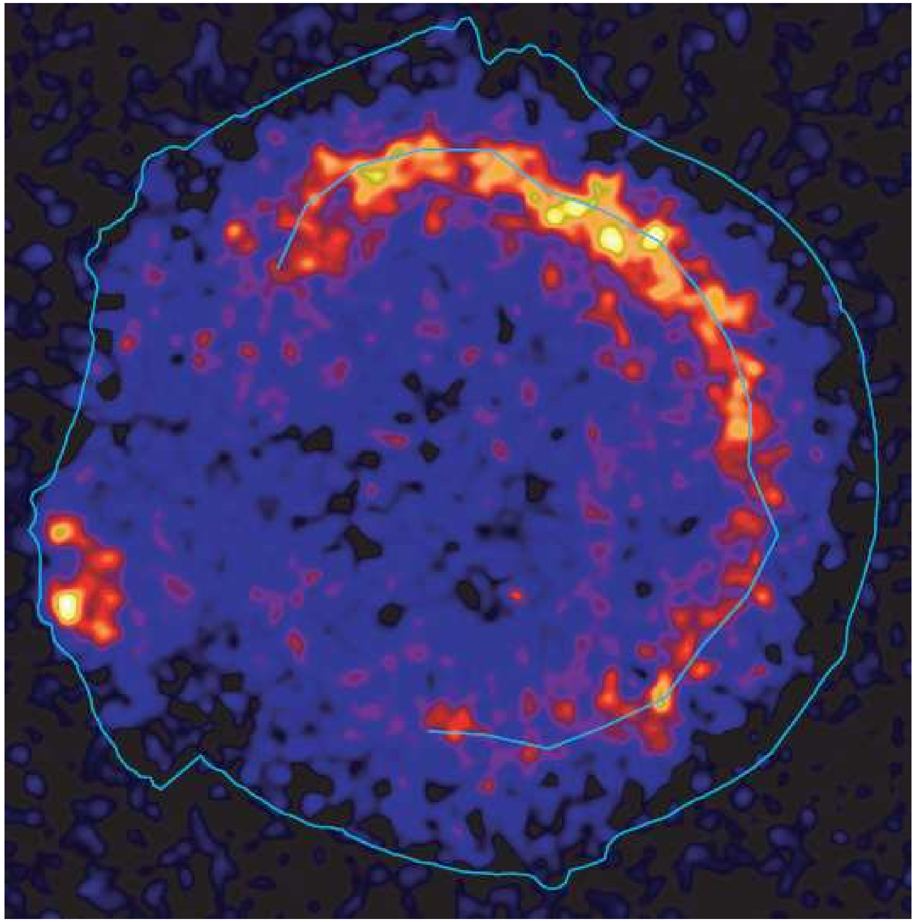
- the interaction of a the supernova ejecta with the companion produces a hole in the ejecta

→ clear imprint on supernova remnant

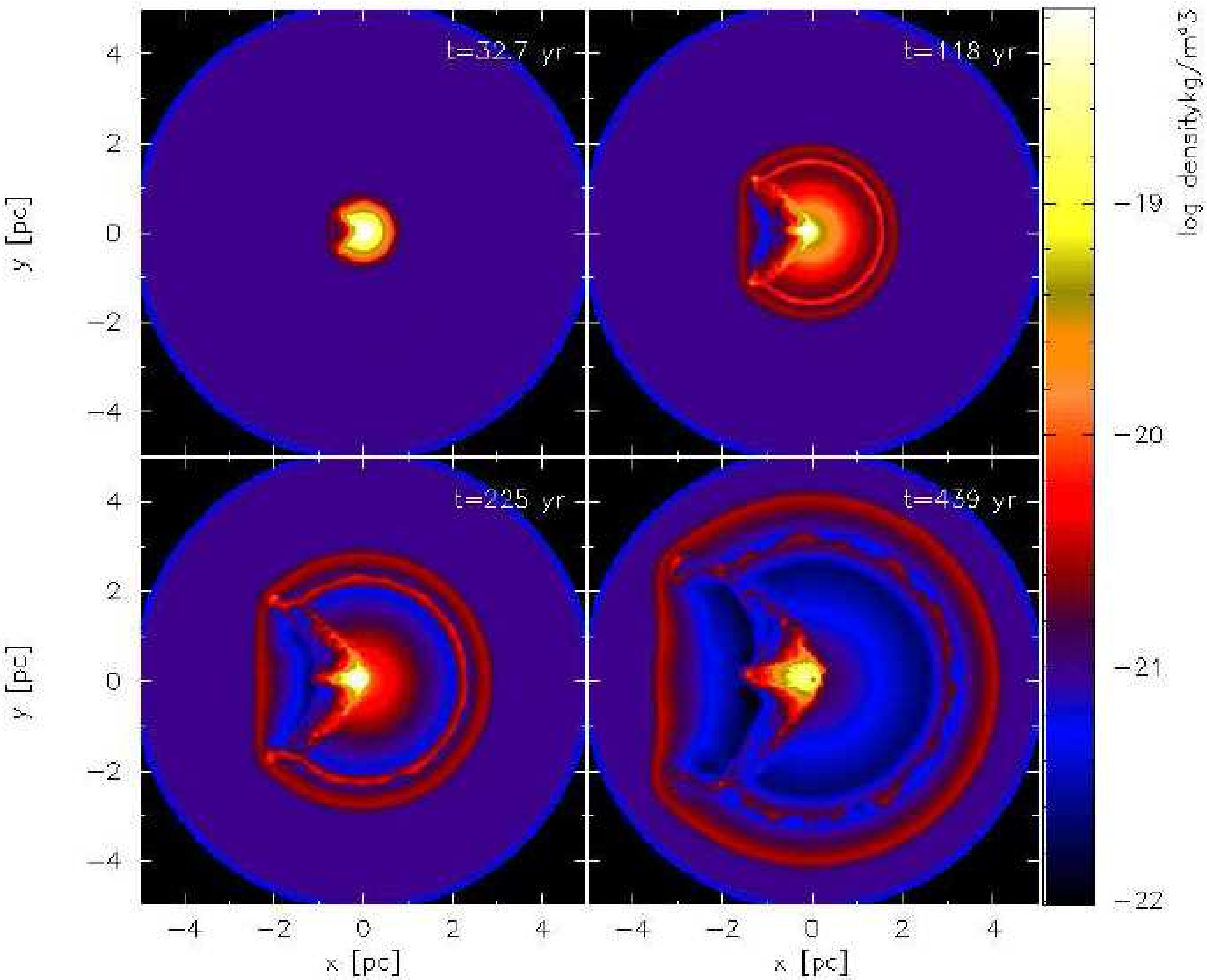
- appears not to be observed in Tycho



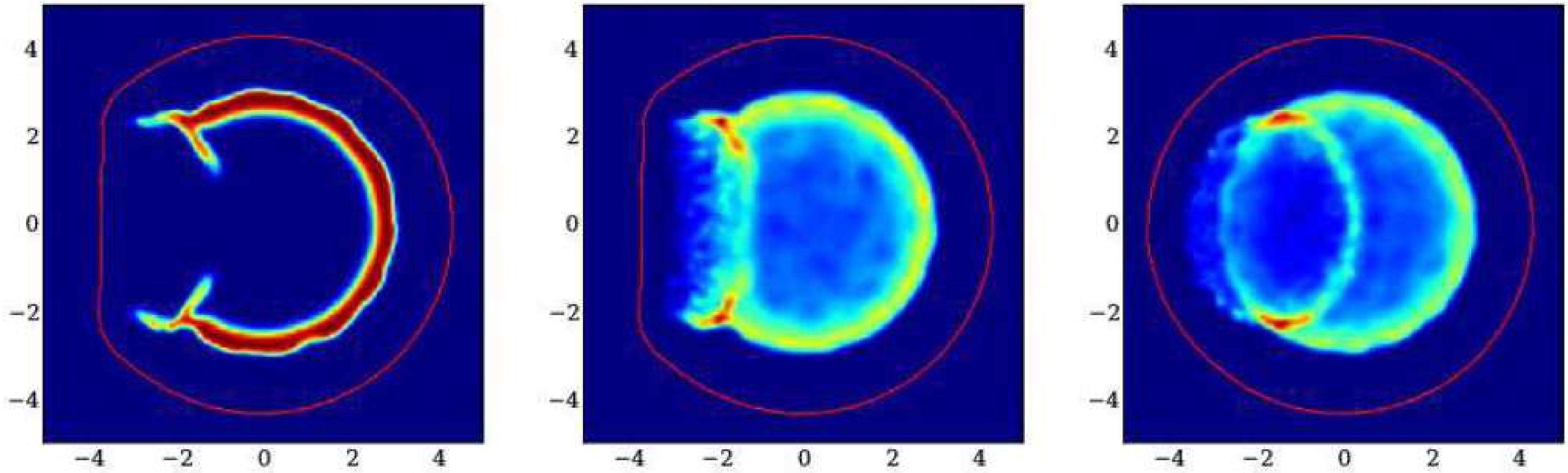
Velocity Structure Booth (2011)



Tycho in Iron-K Line (Warren et al. 2005)

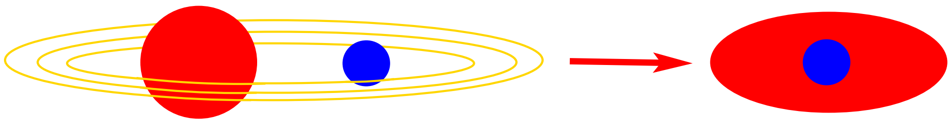


Companion Interaction Booth (2011)



Iron Lines **Booth (2011)**

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)

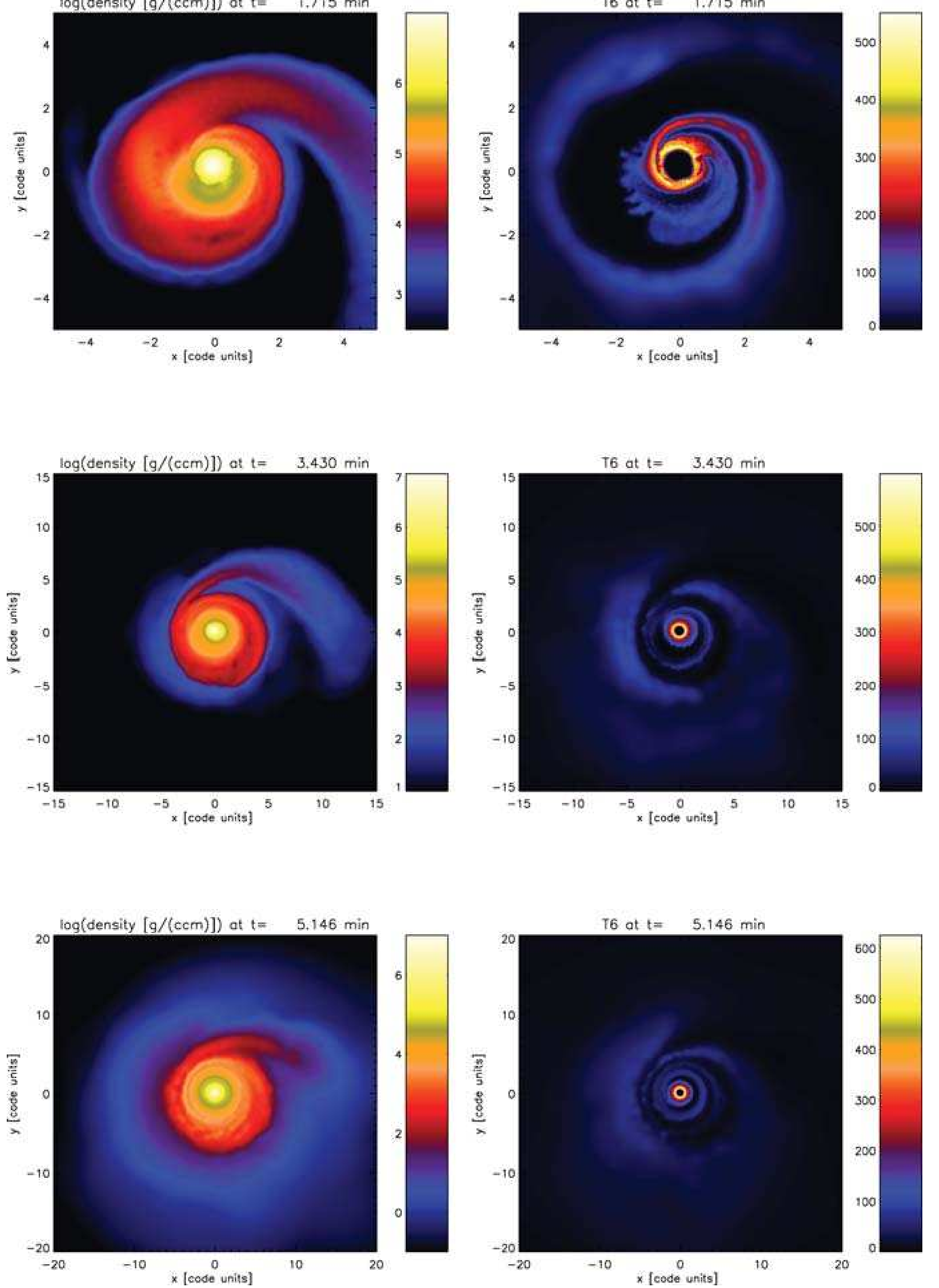


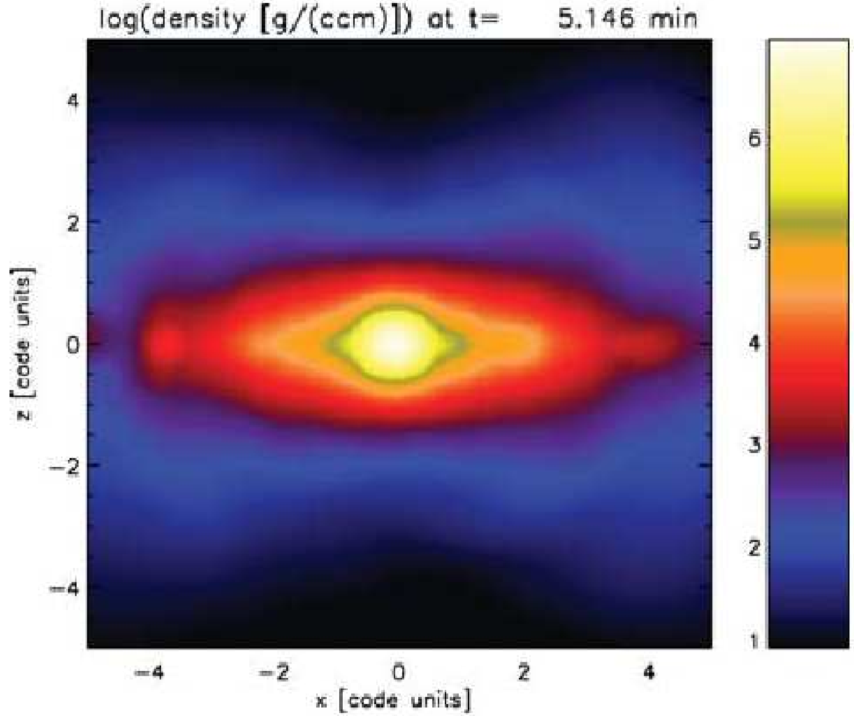
Figure 3. Dynamical evolution of the coalescence of a $0.6\,M_{\odot} + 0.9\,M_{\odot}$ CO white dwarf binary. Continued from Fig. 2.

Post-Merger Evolution

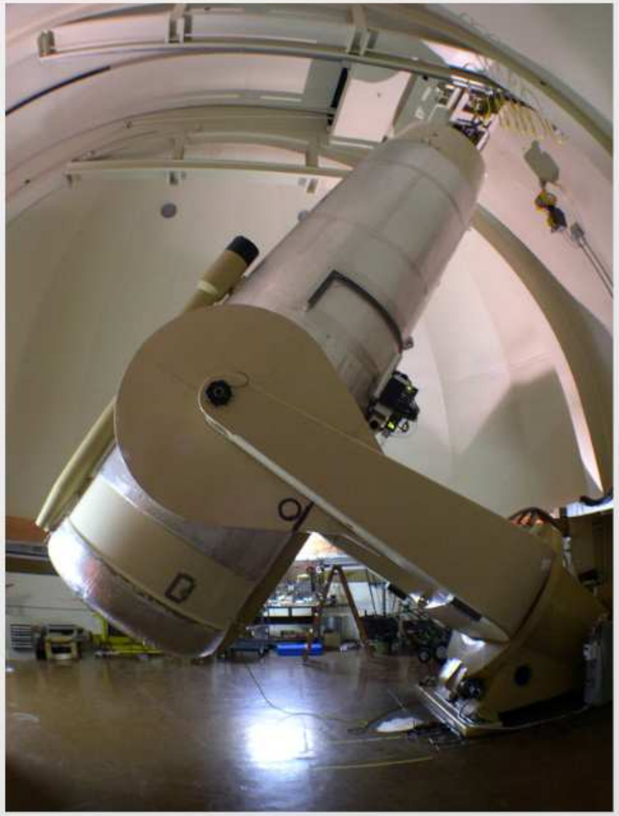
- immediate post-merger object: low-entropy massive core surrounded by high-entropy envelope and accretion disk
- evolution is controlled by thermal evolution of the envelope $\rightarrow$ determines core-accretion rate
- despite high accretion rate, carbon ignition is avoided because of neutrino losses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

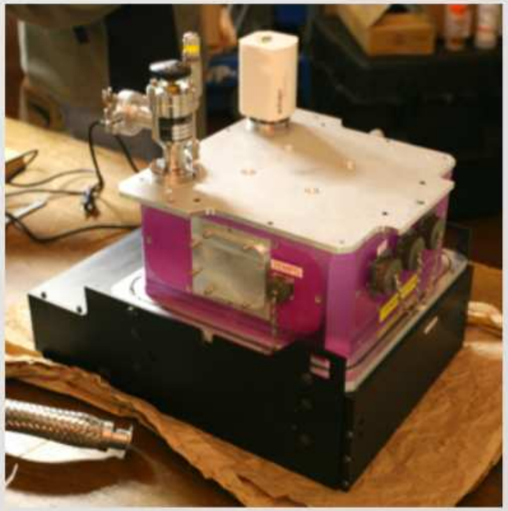
Note: explosion occurs $\sim 10^5$ yr after the merger

Yoon et al. 2007



Palomar Transient Factory (PTF)





Wide-angle, variable cadence sky survey
Looking for supernovae, novae, CVs

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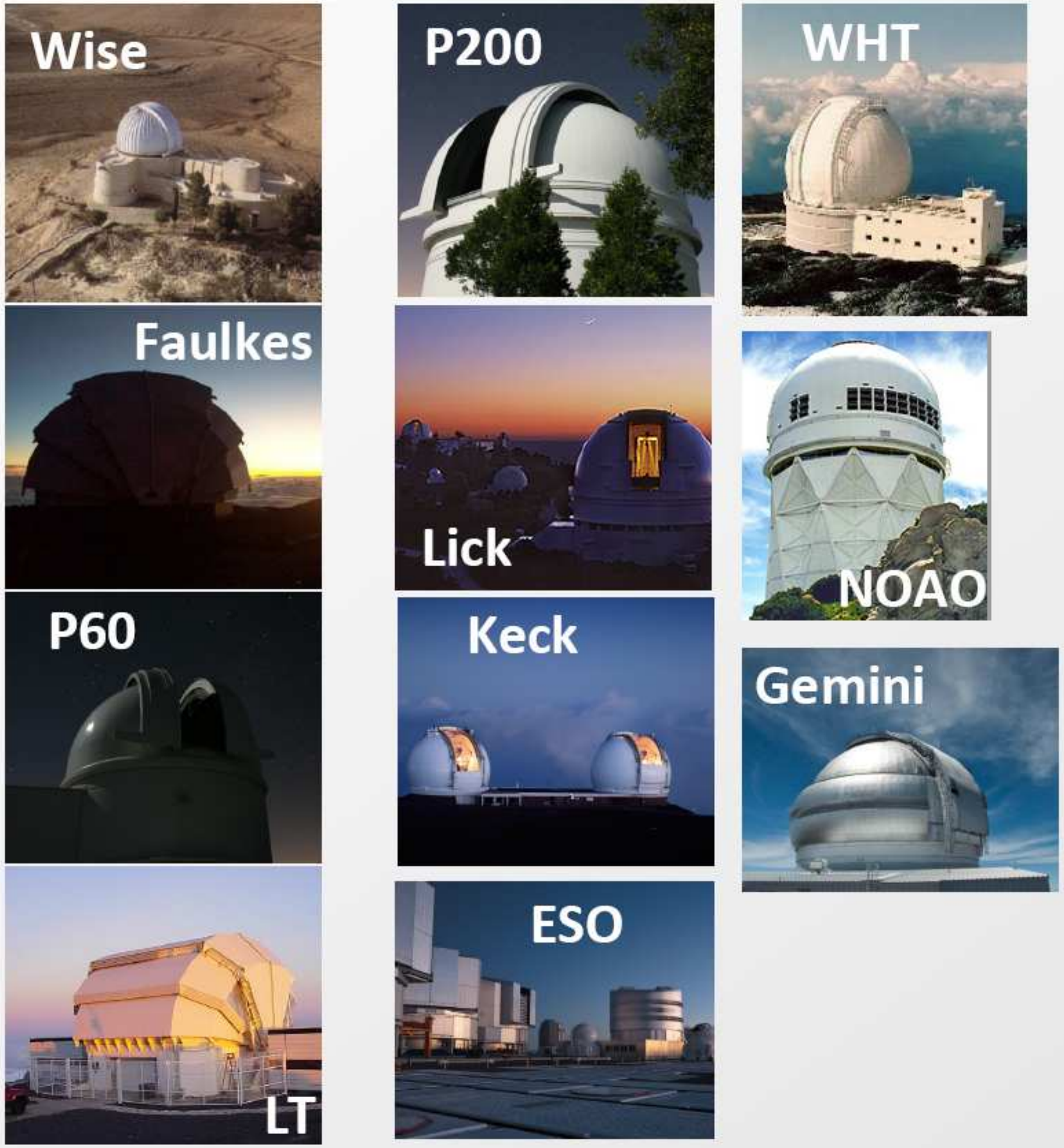
PTF Follow-up is global

Photometry

Spectroscopy



Follow-up is global

Large international programme on many facilities, including WHT, LT, Gemini

4m-class telescopes are the work-horse spectroscopic facilities: identification and follow-up

Robotic 1–2m-class telescopes: light curves

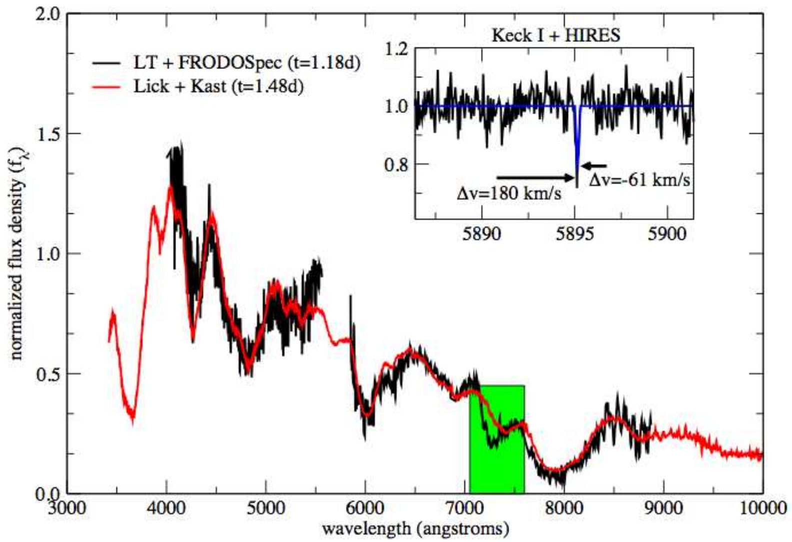
One transient every 20 minutes

PTF 11kly/SN2011fe

- brightest SN Ia (from the UK) for $> 50\,\mathrm{yr}$ (peak: 10th mag)
- occurred in M101 (pinwheel galaxy)
- spectrum: evidence for unburnt carbon and oxygen
- early light curve: compact star ($<$ a few $0.1\,R_\odot$)

$\rightarrow$ exploding CO white dwarf

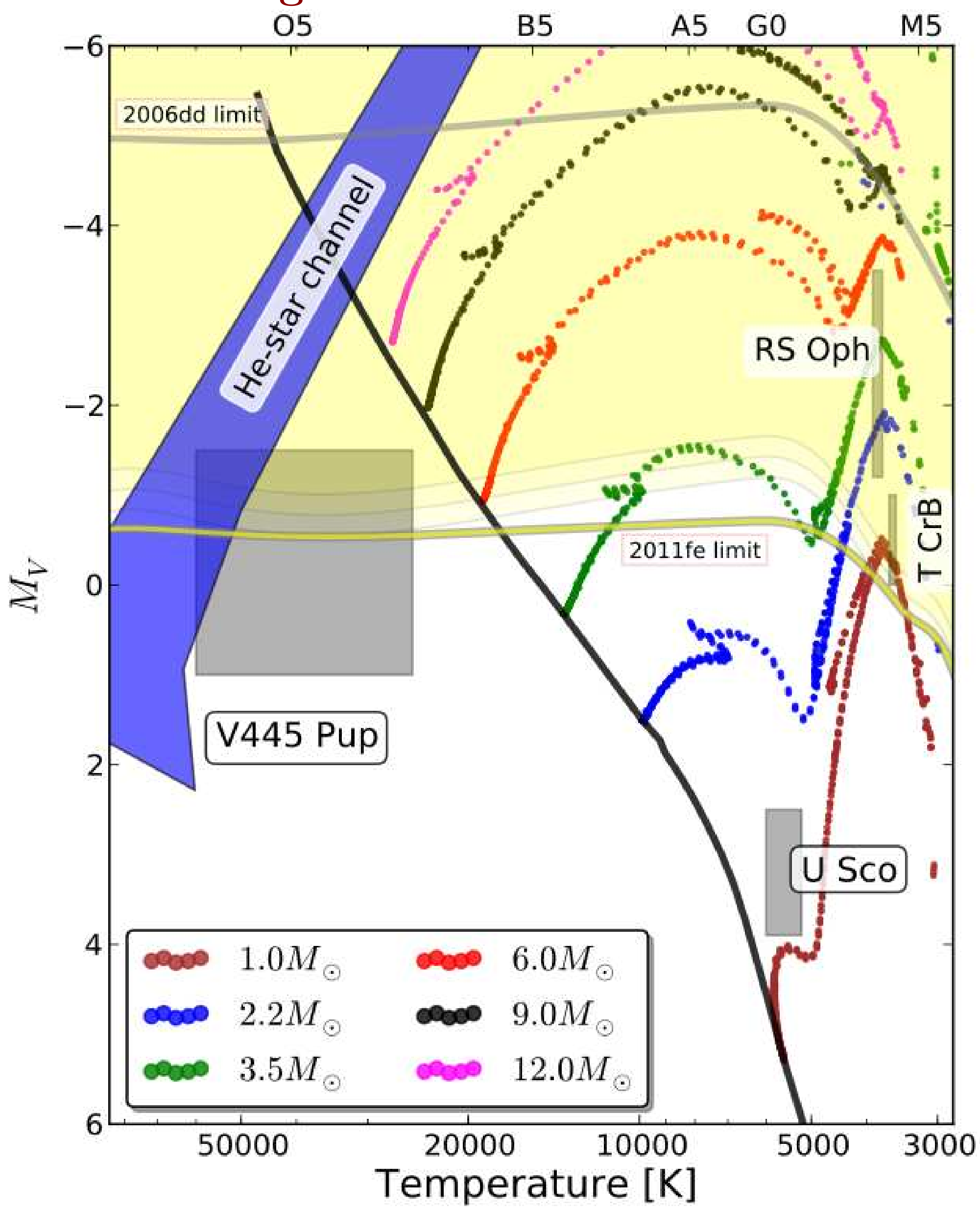
Nugent et al. 2011



Li et al. (2011)

- no progenitor detected in HST pre-explosion images
- 10 – 100 times better progenitor constraints than in the past

HR diagram



- rules out **luminous red giant** donor
- favours DD or supersoft channel

CSM around SN 2006X
Patat et al. (2007)

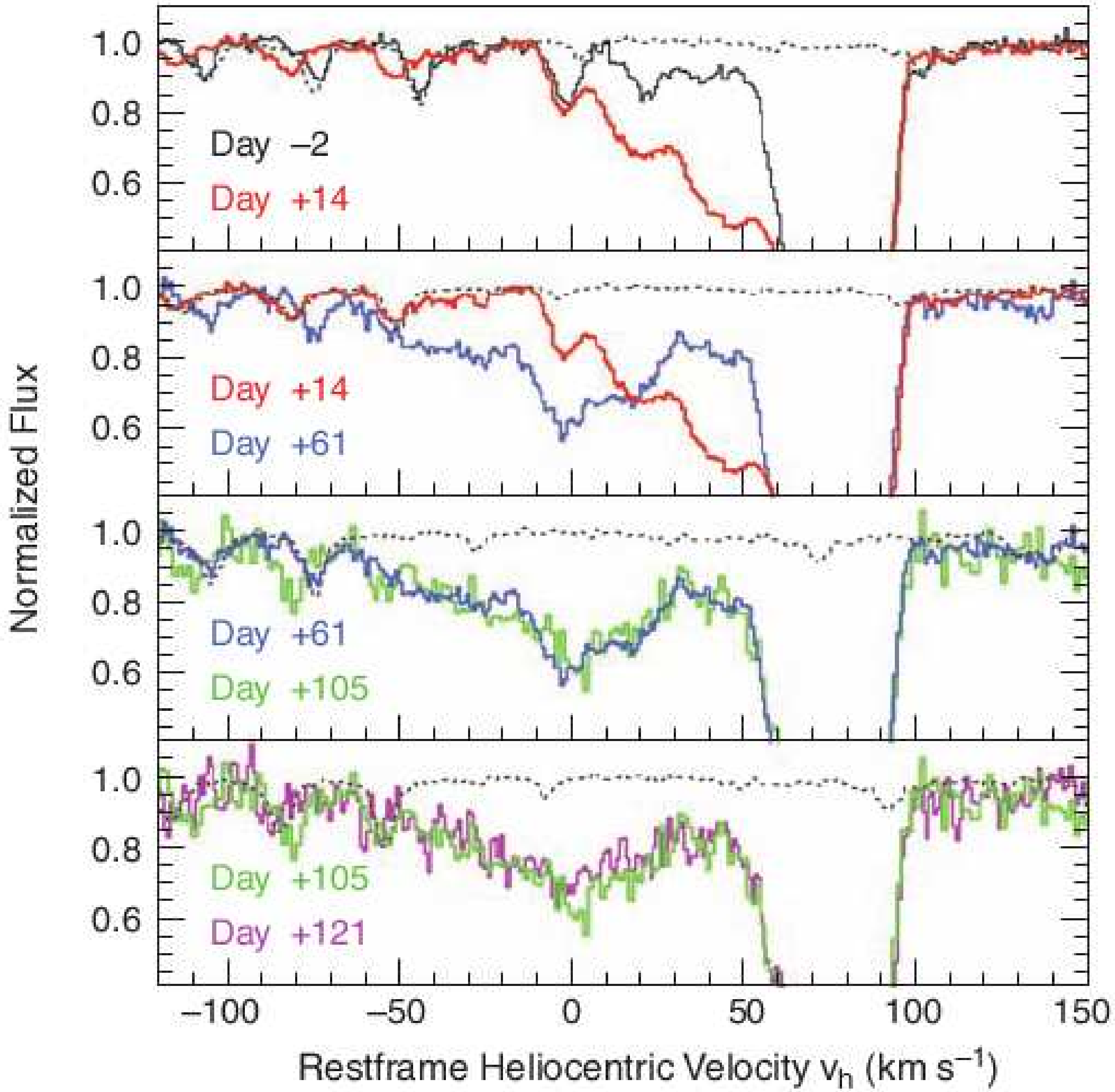
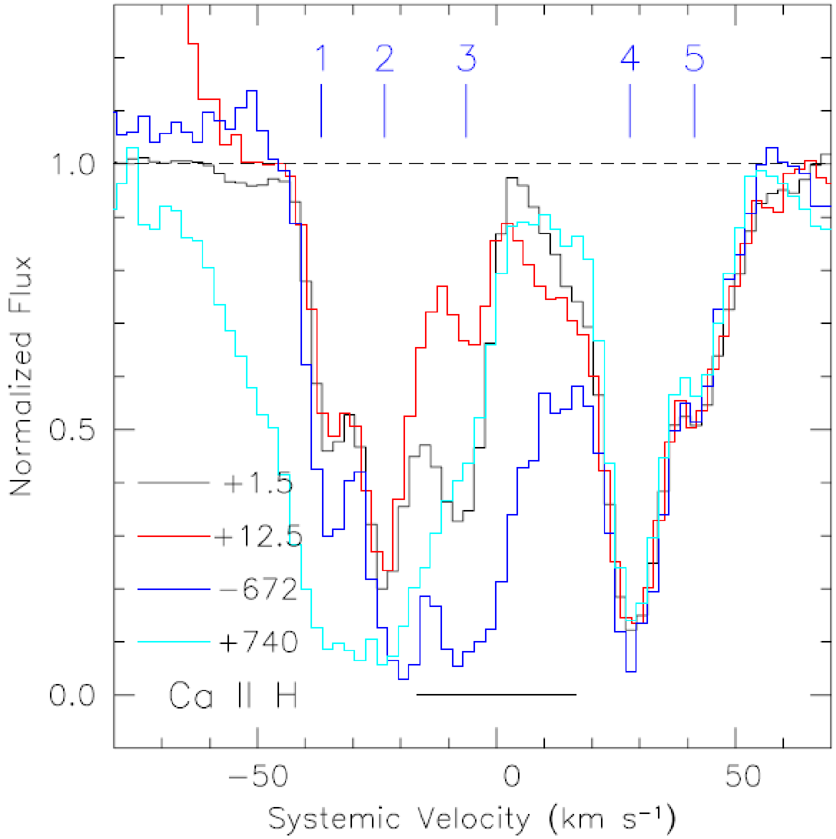
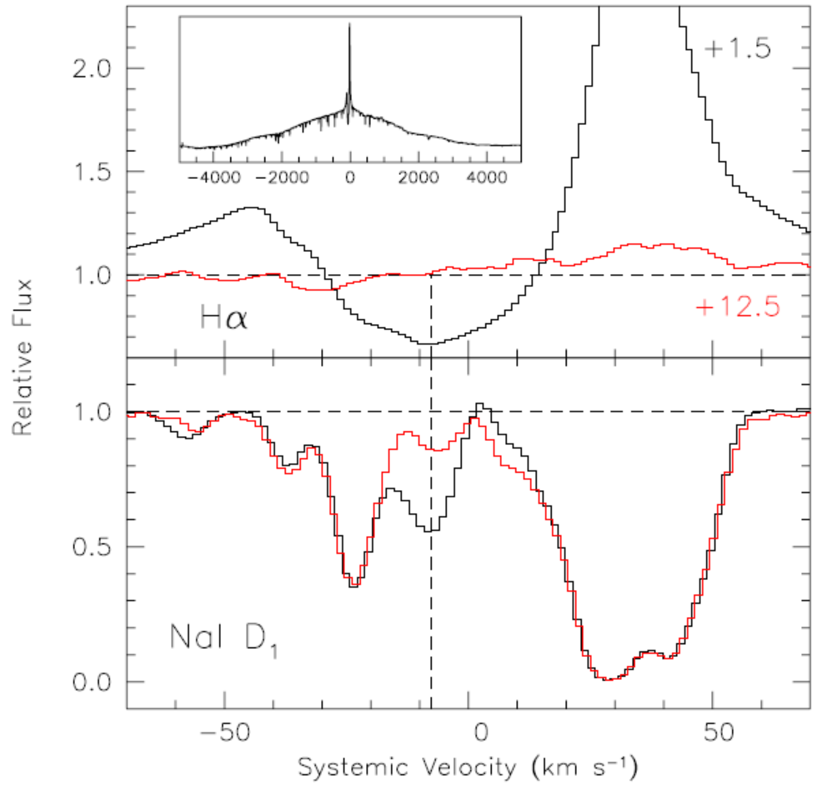


Fig. 1. Time evolution of the Na D_2 component region as a function of elapsed time since *B*-band maximum light. We corrected the heliocentric velocities to the rest-frame using the host galaxy recession velocity. All spectra have been normalized to their continuum. In each panel, the dotted curve traces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

CSM around the Recurrent Nova System RS Oph

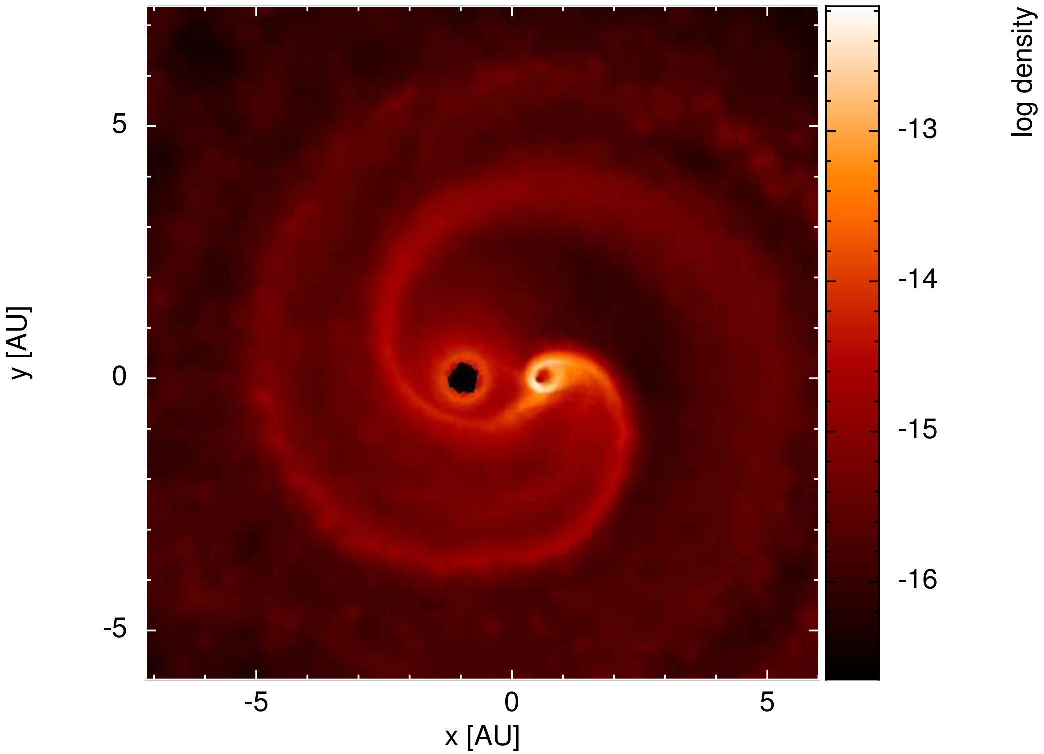
Patat et al. (2011)

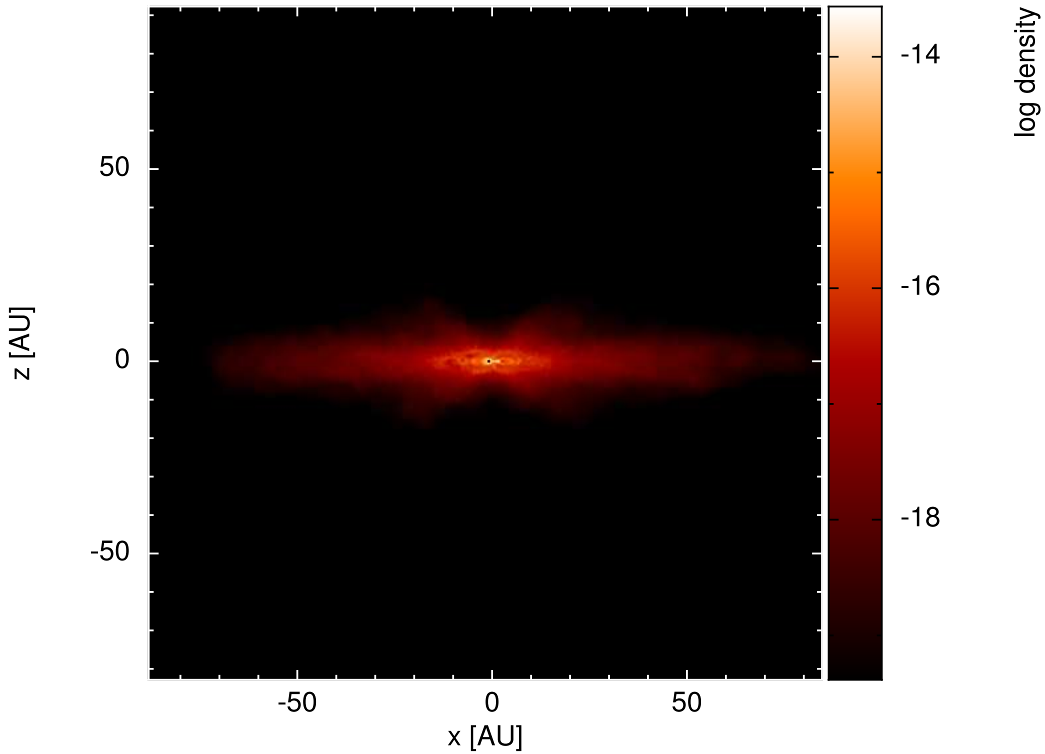




Binary Mass Loss Simulations

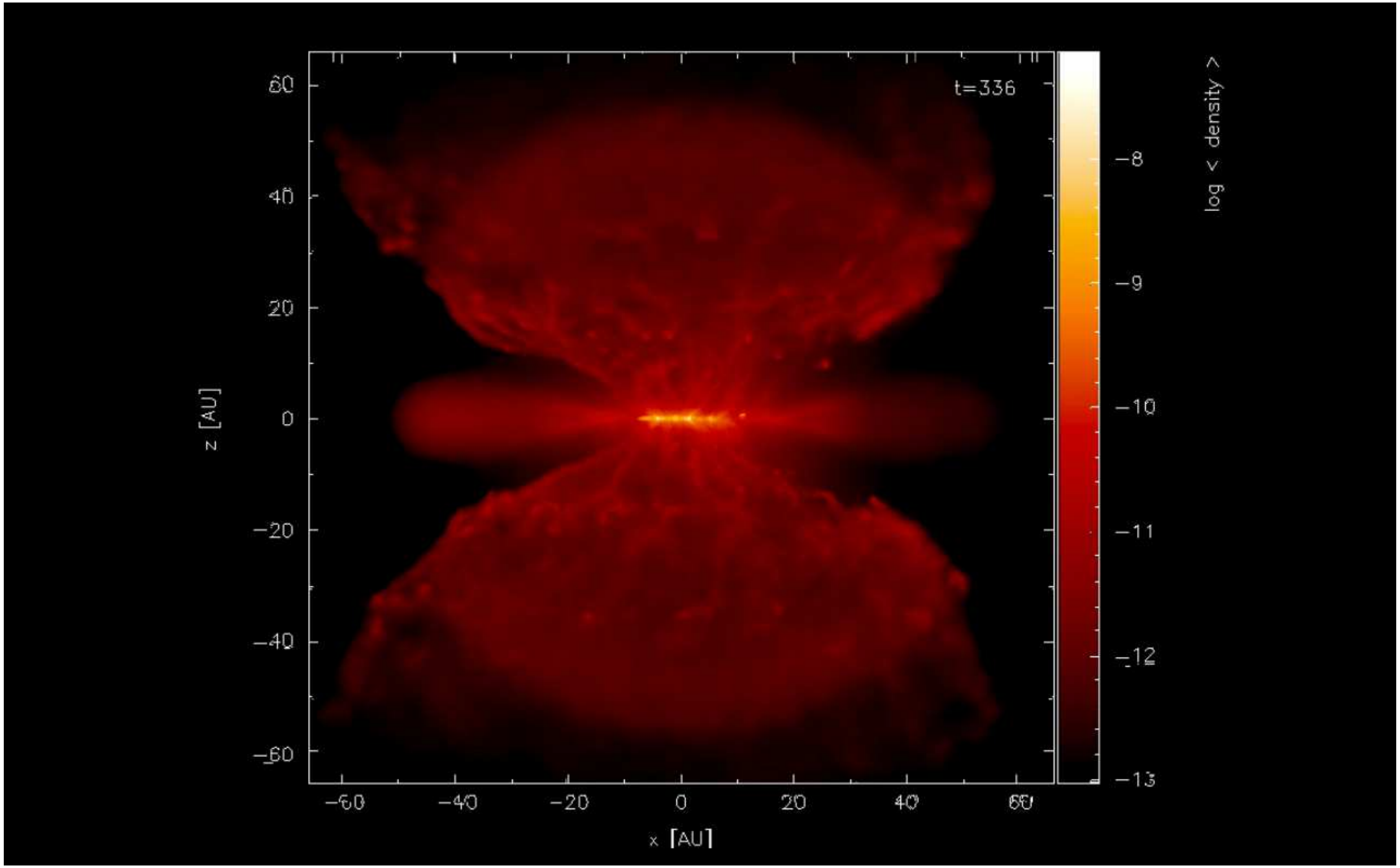
Mohamed, Booth & Podsiadlowski (2012)





Nova RS Oph 2006

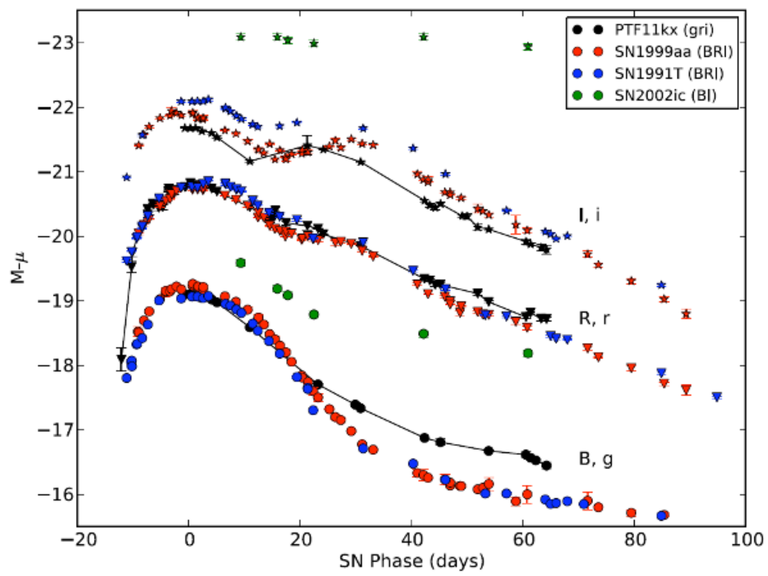
Mohamed, Booth & Podsiadlowski (2012)

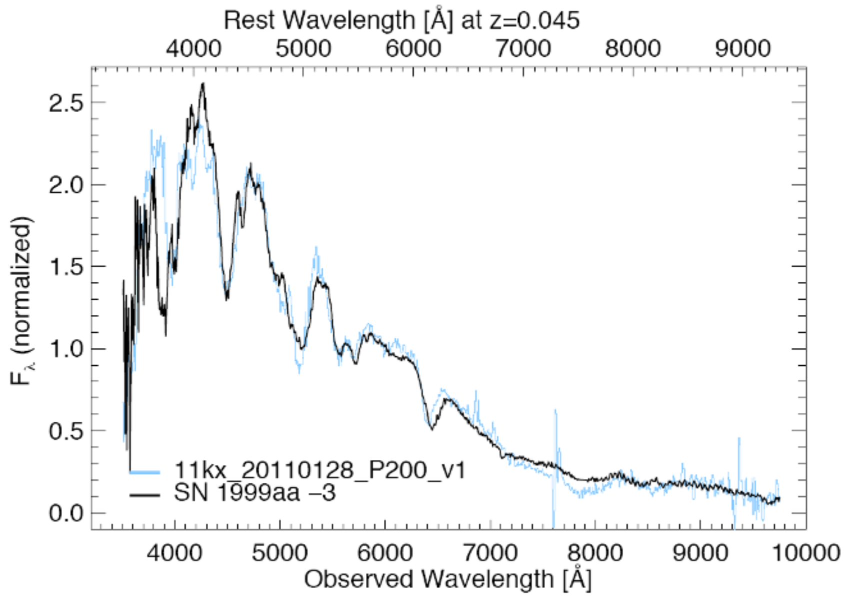


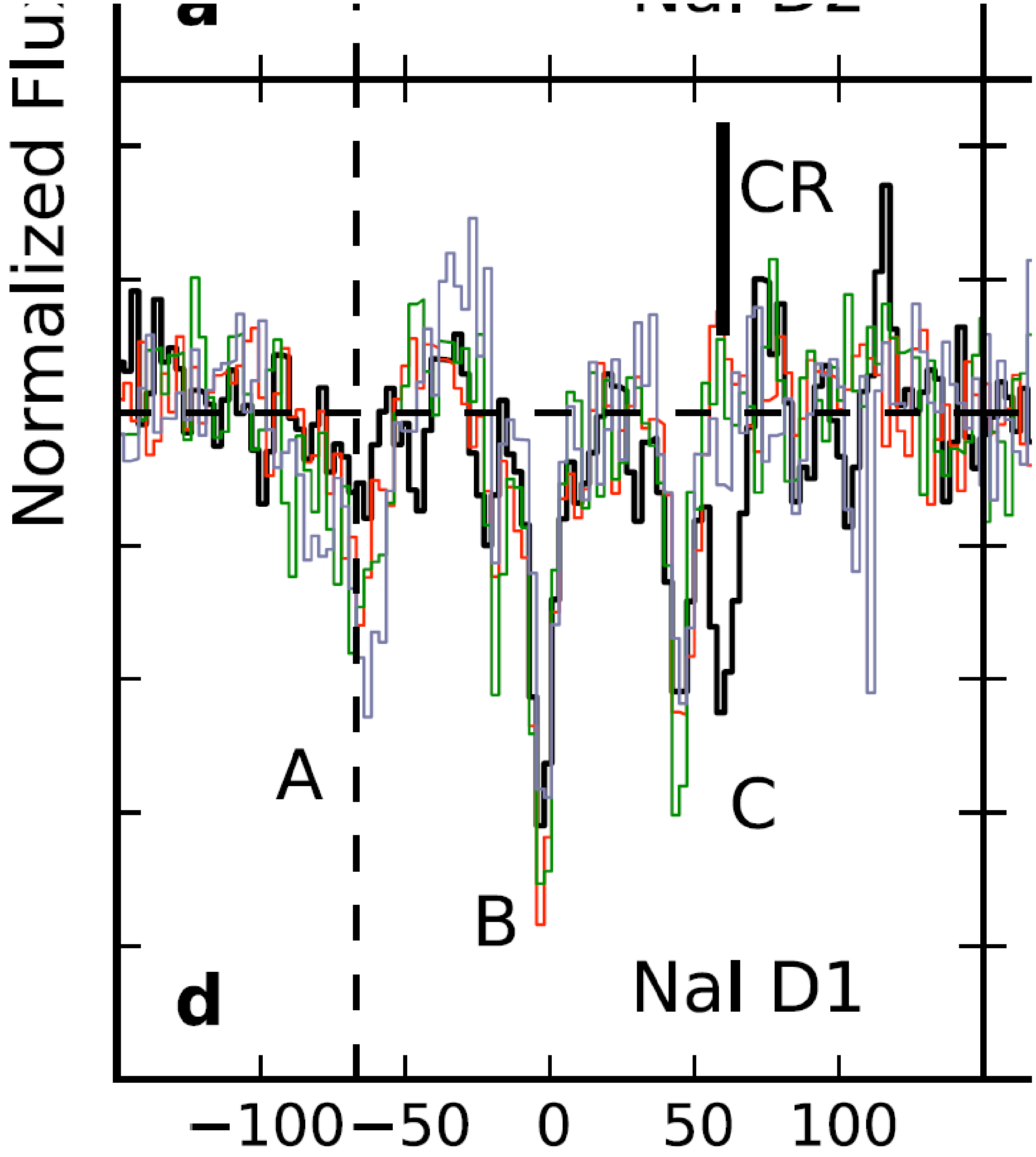
PTF 11kx

- discovery date: January 16, 2011
- z = 0.0466 (SDSS)
- slightly luminous: ($M_V \approx -19.3$; similar to SN 1999aa)
- high-resolution spectra (R = 48000) with Keck

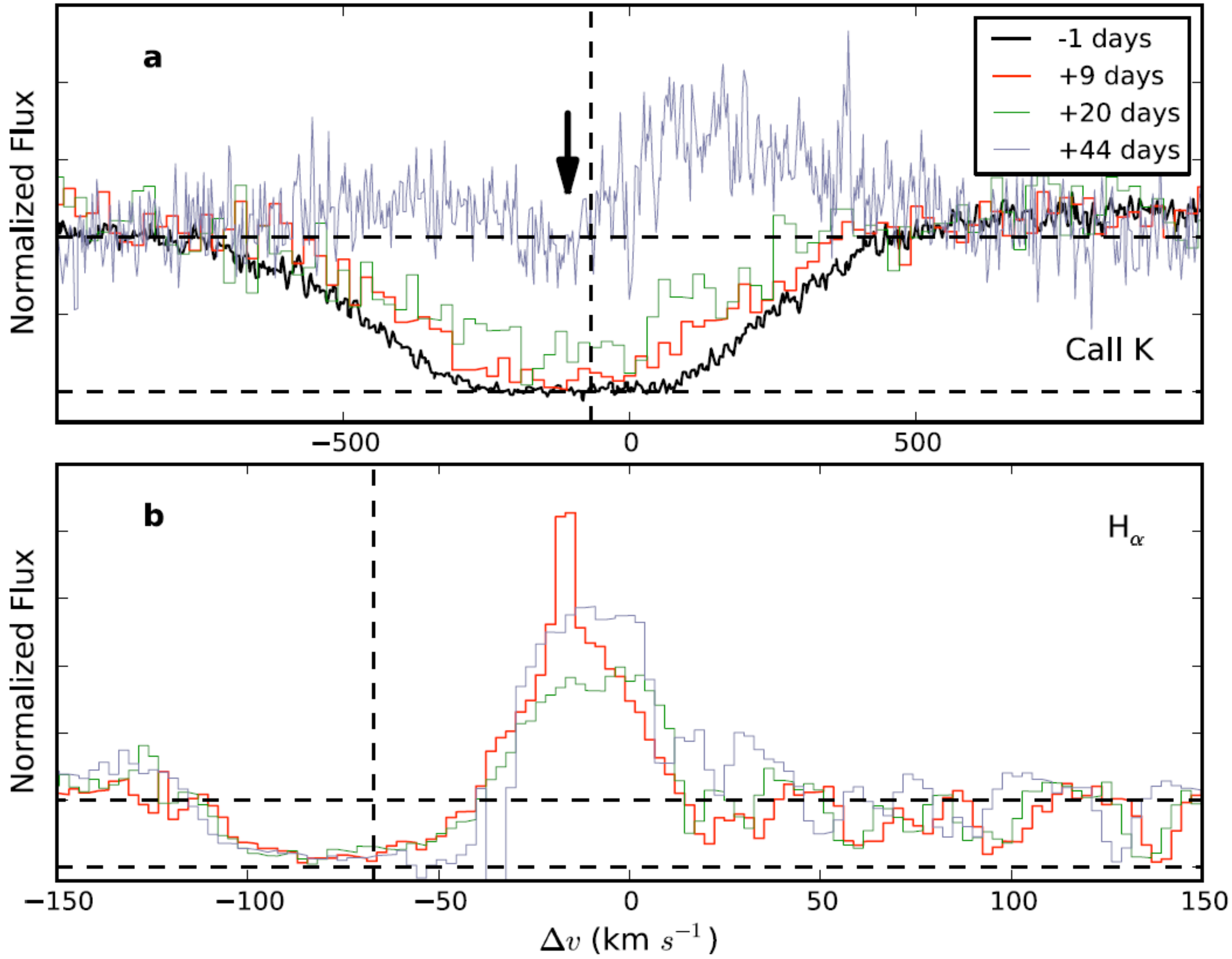
  → narrow absorption lines similar to RS Oph, including hydrogen
- strong interaction with the CSM
  - ▷ late lightcurve 3 mag brighter than expected
- late spectrum similar to SN 2002ic (very H-rich SN Ia?)
- evidence for disk structure?







Dilday et al. (2012)



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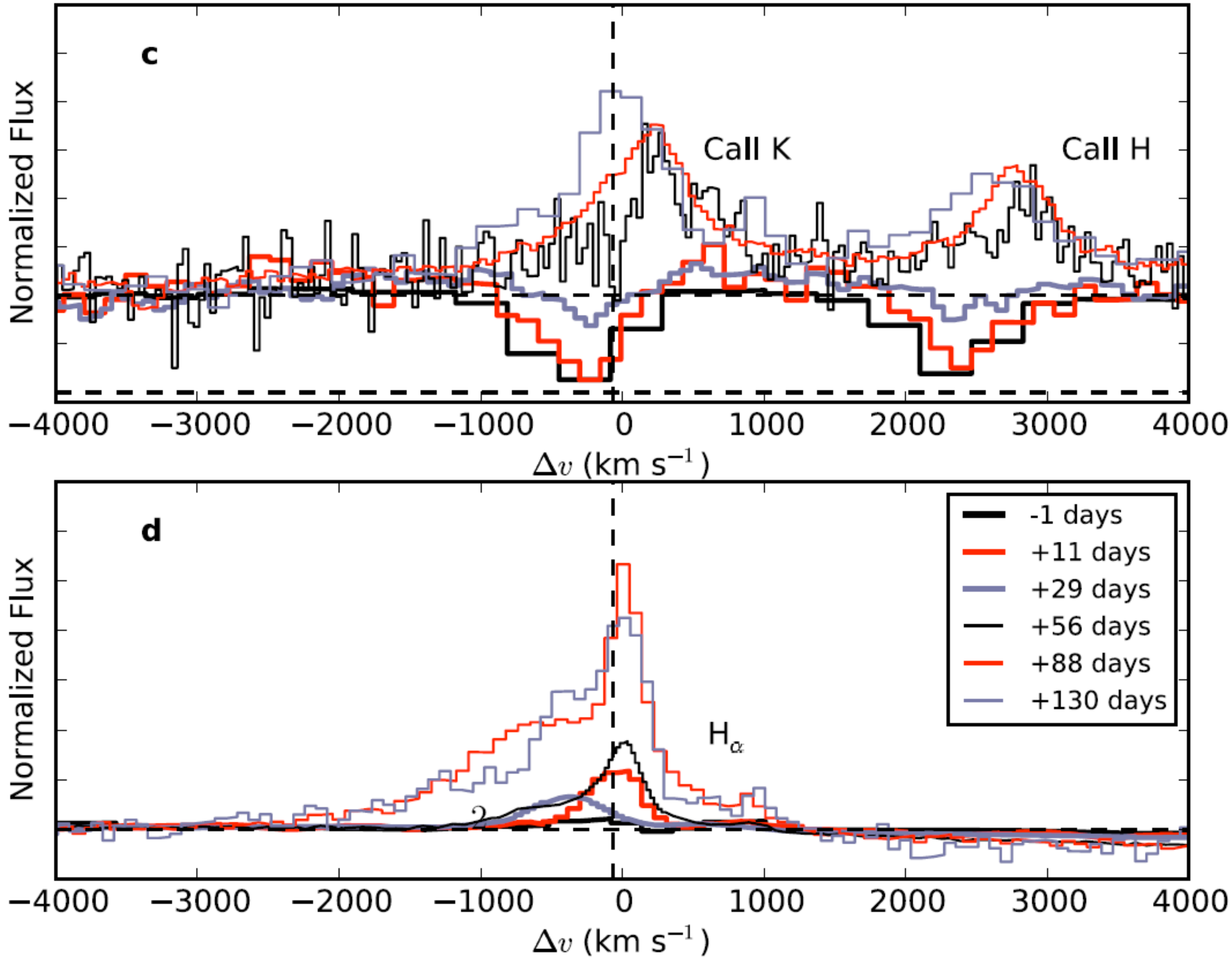

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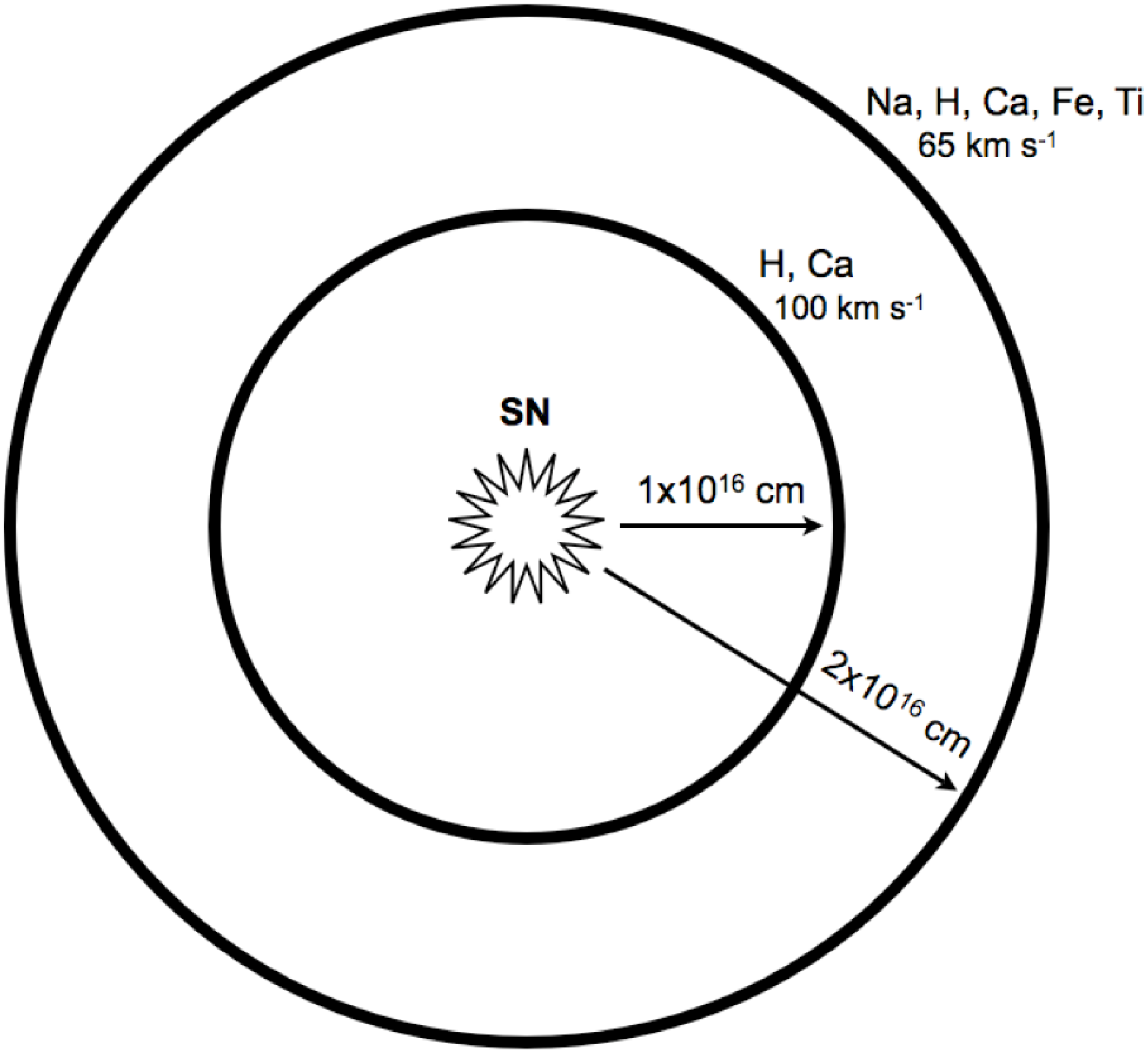
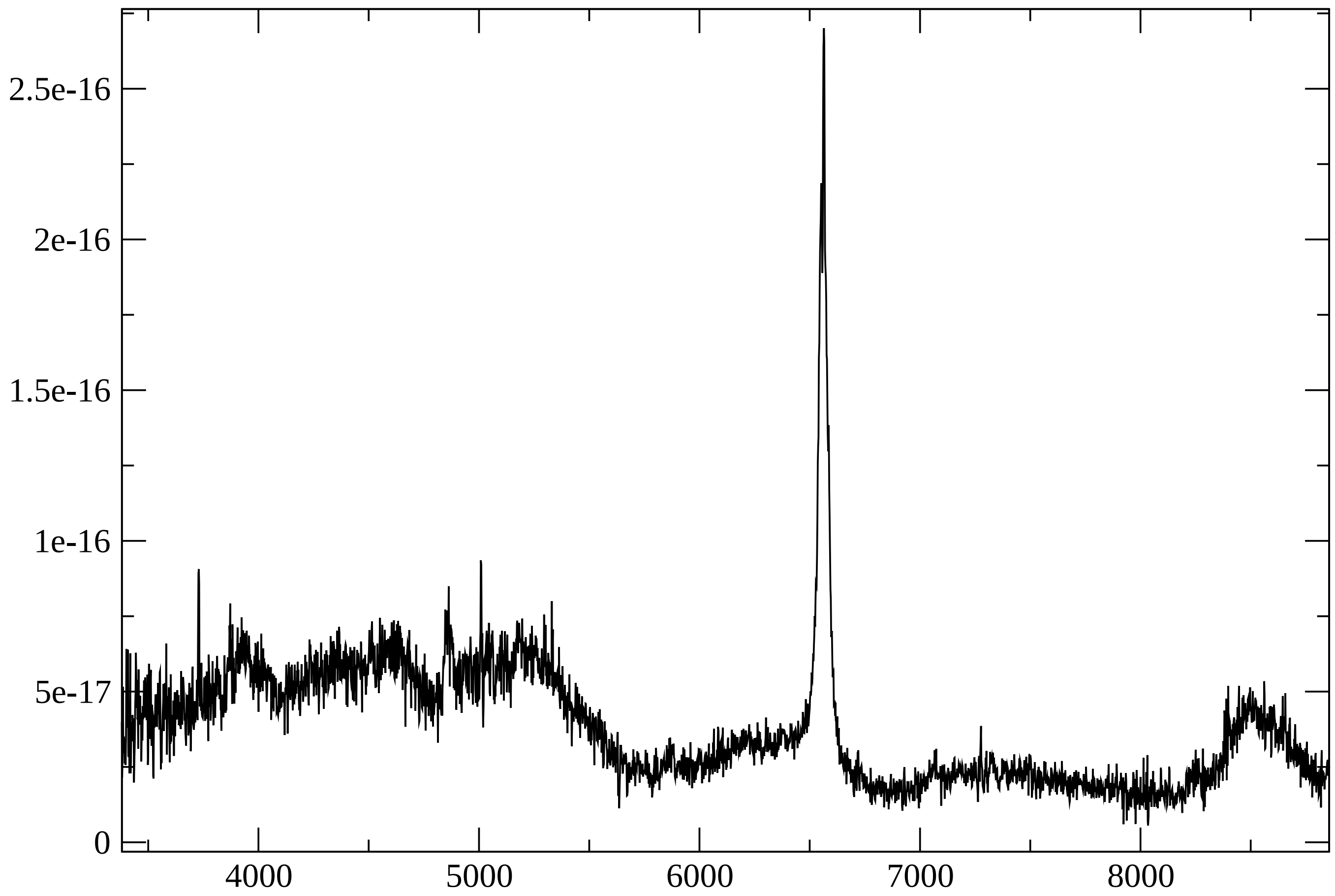


Dilday et al. (2012)



Dilday et al. (2012)

Conclusions

- significant progress on understanding the progenitors
- at least some SNe Ia come from the single degenerate channel
  - ▷ PTF 11kx: red-giant donor like RS Oph
  - ▷ PTF 11kly: no red-giant donor
- need for multiple channels?
- still need to understand short and long time delays
- most SNe Ia are similar but a significant subset shows large diversity
- metallicity should be a second parameter for SN lightcurves

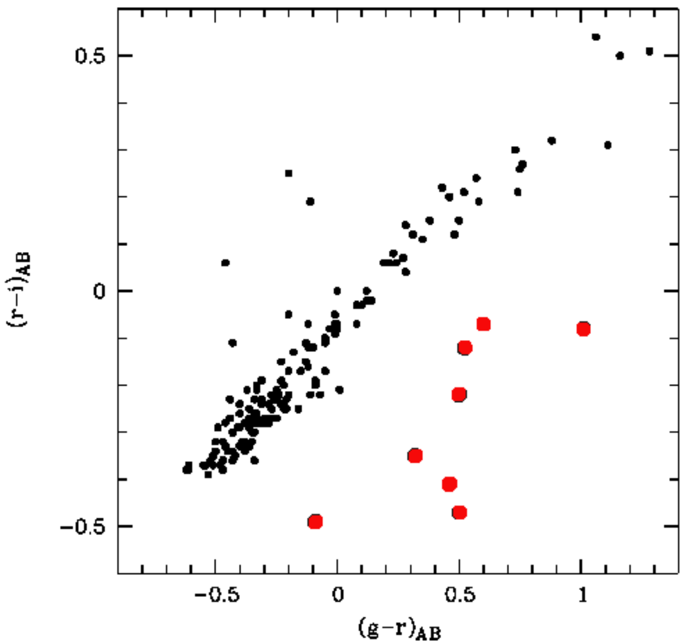
The Origin of Ultra-Cool Helium White Dwarfs

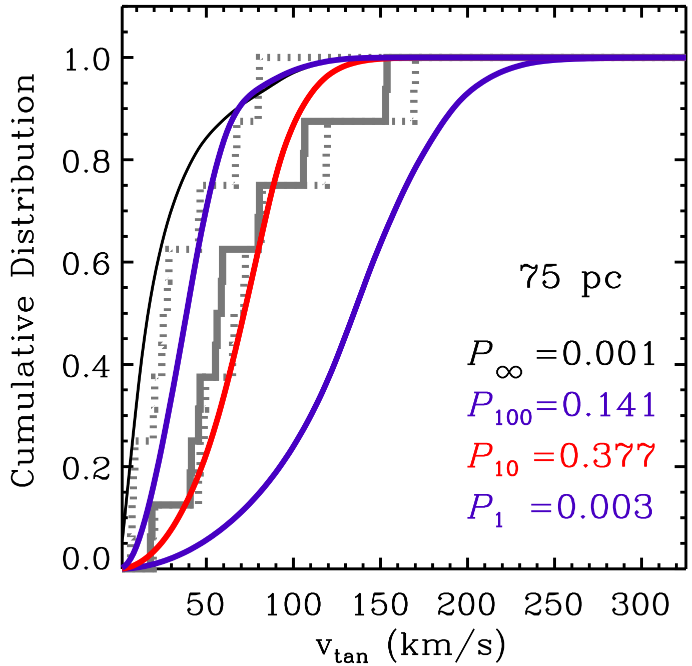
(Justham et al. 2008)

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

→ implies very low-mass white dwarfs (cooling timescale! $\lesssim 0.3\,M_\odot$)

- 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 $10 - 100\,d$ (short end of red-giant island?)





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

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

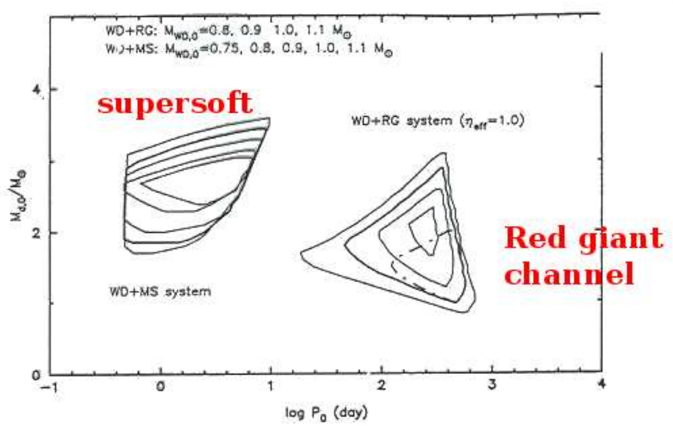


FIGURE 4. The region to produce SNe Ia in the $\log P_0 - M_{d,0}$ plane for five initial white dwarf masses of $0.75 M_\odot$, $0.8 M_\odot$, $0.9 M_\odot$, $1.0 M_\odot$ (heavy solid line), and $1.1 M_\odot$. The region of $M_{WD,0} = 0.7 M_\odot$ almost vanishes for both the WD+MS and WD+RG systems,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

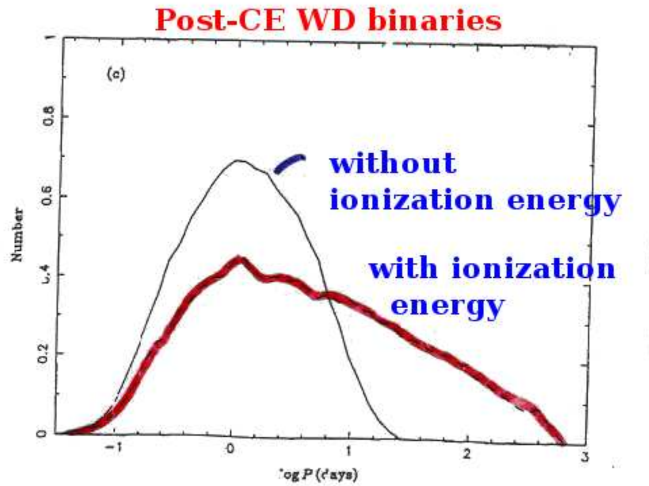


Figure 4 – continued

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))

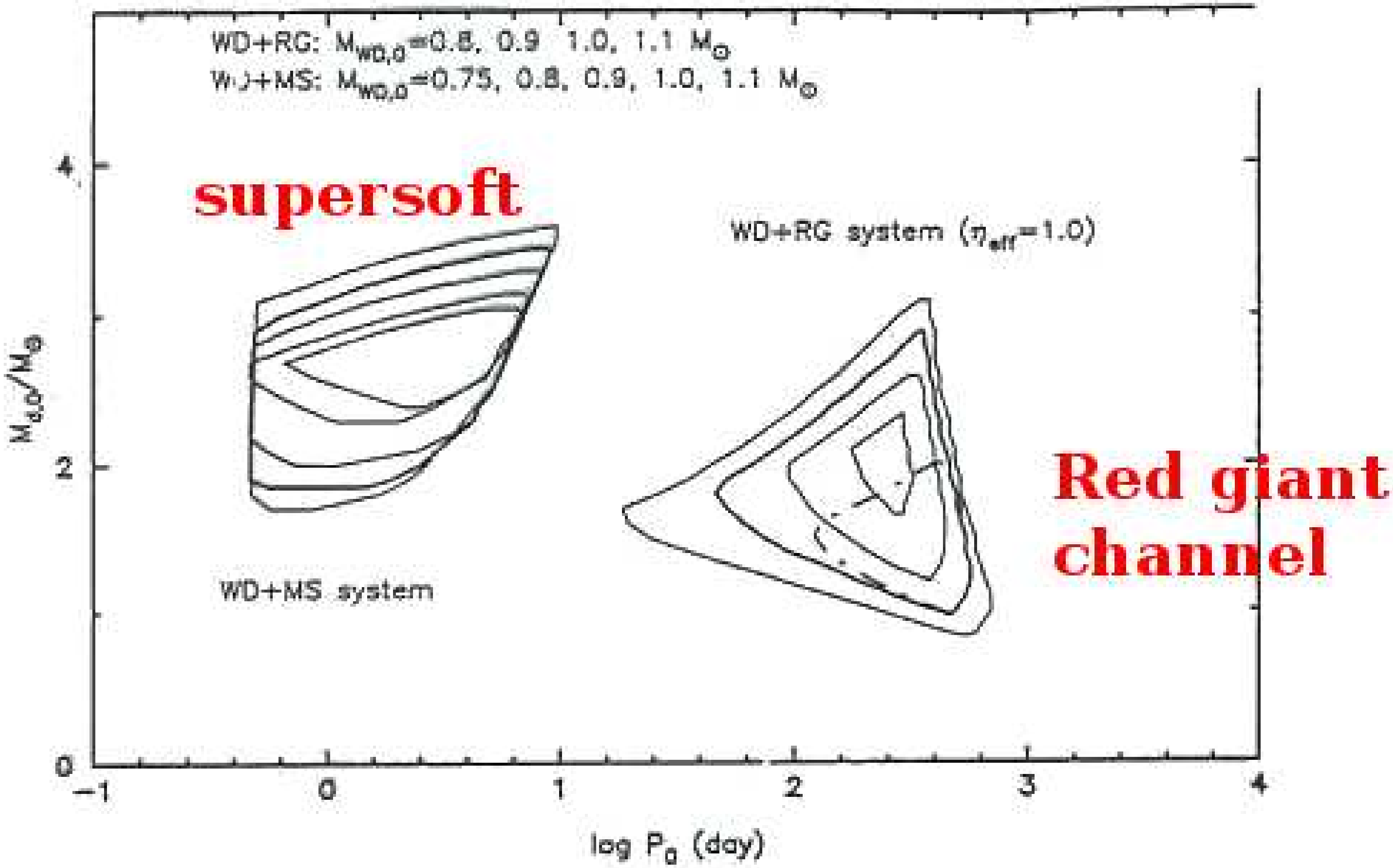
- ▷ stable RLOF → wide systems with $P_{orb} \gtrsim 10^3\,d$
- ▷ CE evolution → close systems with $P_{orb} \lesssim 10^2\,d$

→ 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



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 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: $\mathrm{M} + \mathrm{e}^- \to \mathrm{D} + \nu$

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

  (M: mother; D: daughter)
- most important pair: ^{23}Na/^{23}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