# Massive Star Outbursts and Their Optical Transients

**Nathan Smith**
*UC Berkeley*

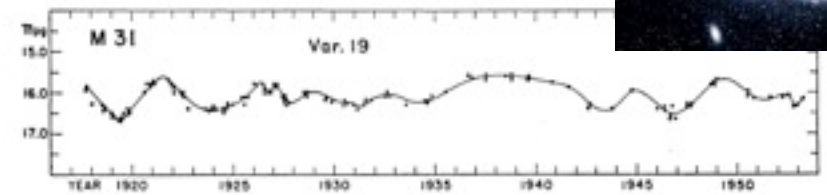



FIG. 5.—The light-curve for variable 19 in M31 from 1917 to 1953. The apparent photographic ma nude is plotted as ordinate.

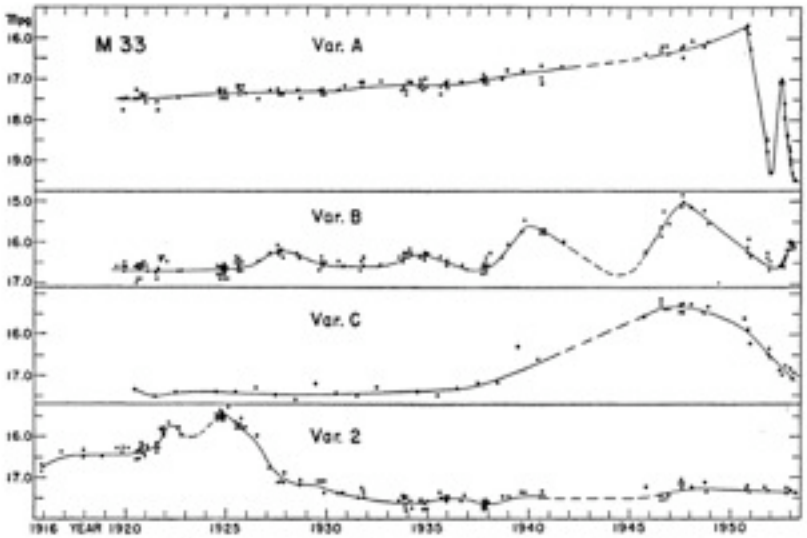



FIG. 6.—Photographic light-curves for the four variables in M33

Hubble & Sandage 1953 (M31 & M33)

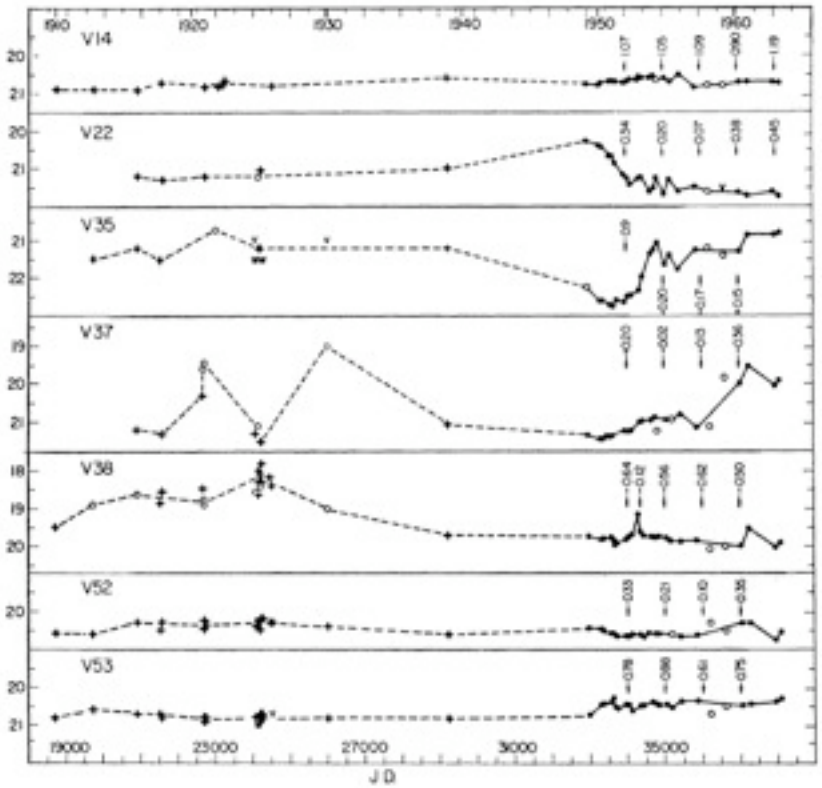



FIG. 10.—Light-curves in *B* for 7 of the 8 bright blue irregular variables listed in Table 6 from 1910 to 1963. The magnitudes are from Table A3 of the Appendix.

Tammann & Sandage 1968 (NGC 2403)

# Luminous Blue Variables (LBVs)

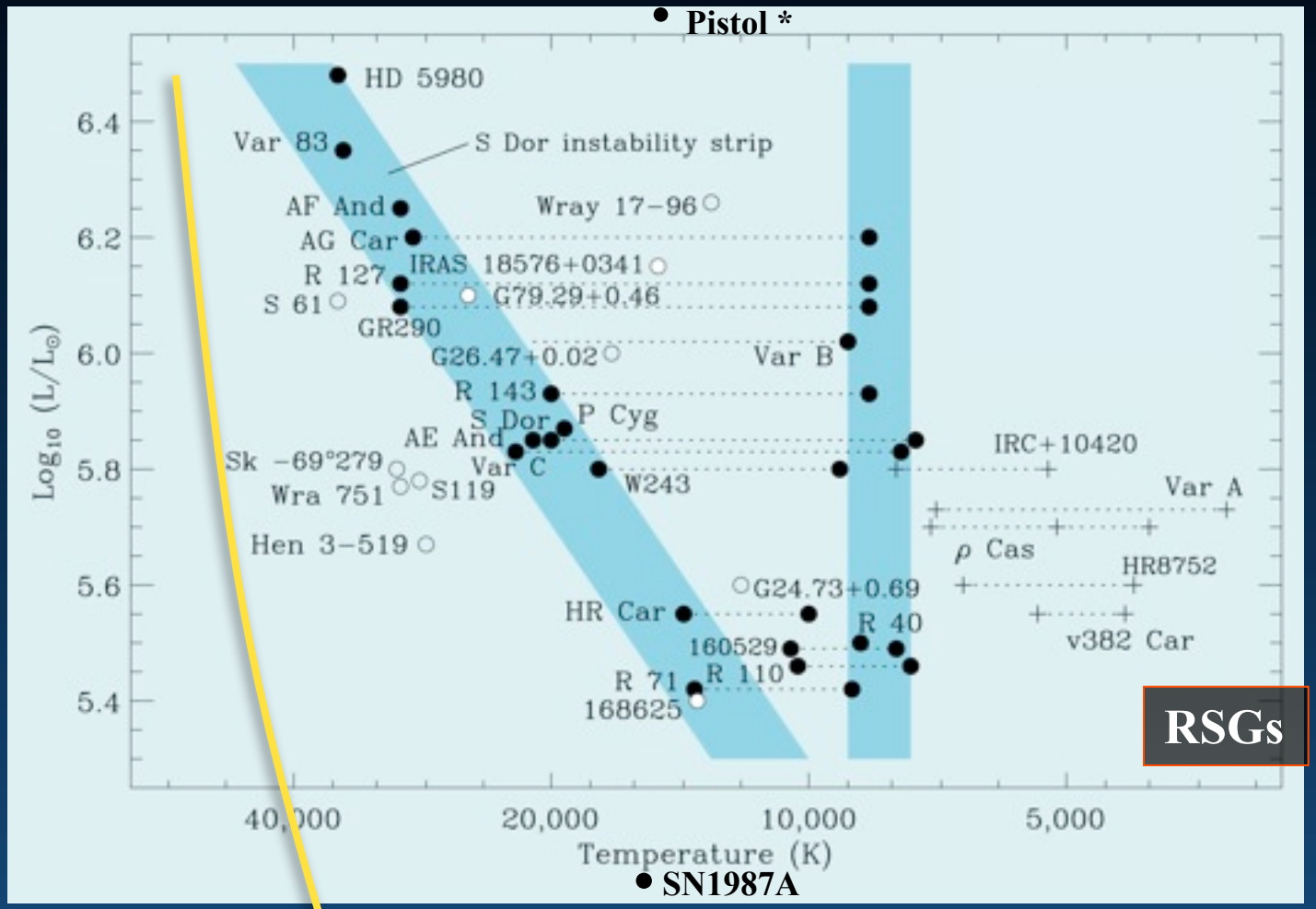
or Hubble-Sandage variables, BBIVs, S Dor variables, α Cyg variables, P Cyg stars…
(H&S 1953)

$$\Gamma = \frac{L_*}{L_{Edd}} \sim \frac{L_*}{M_*}$$

• Eta Car

• Pistol *

Γ=0.9




• SN1987A

Γ=0.6

MS

Smith, Vink, & de Koter (2004)

also: Humphreys & Davidson '79; Garmany, Conti, & Massey '87

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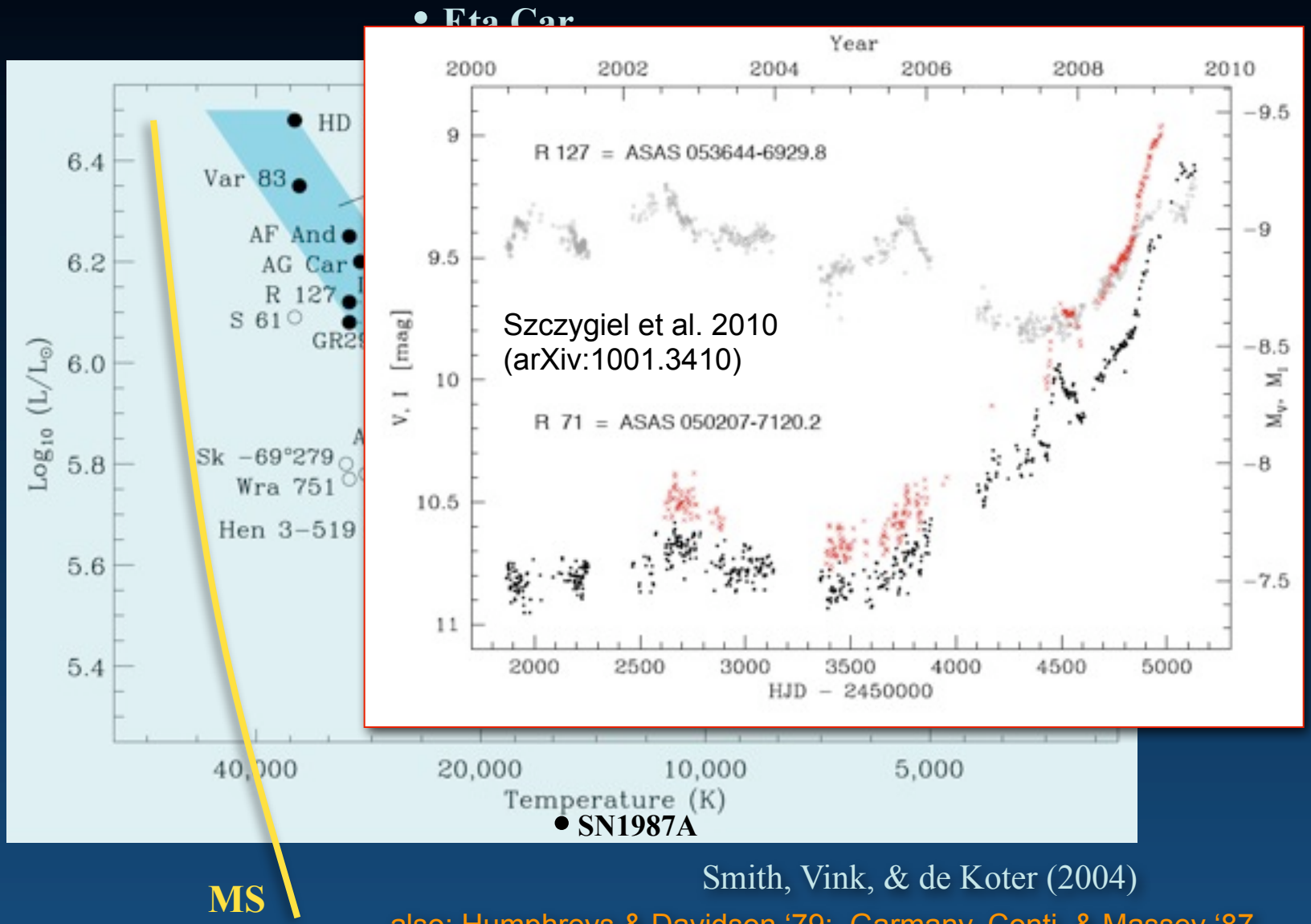


Szczygiel et al. 2010
(arXiv:1001.3410)

Smith, Vink, & de Koter (2004)

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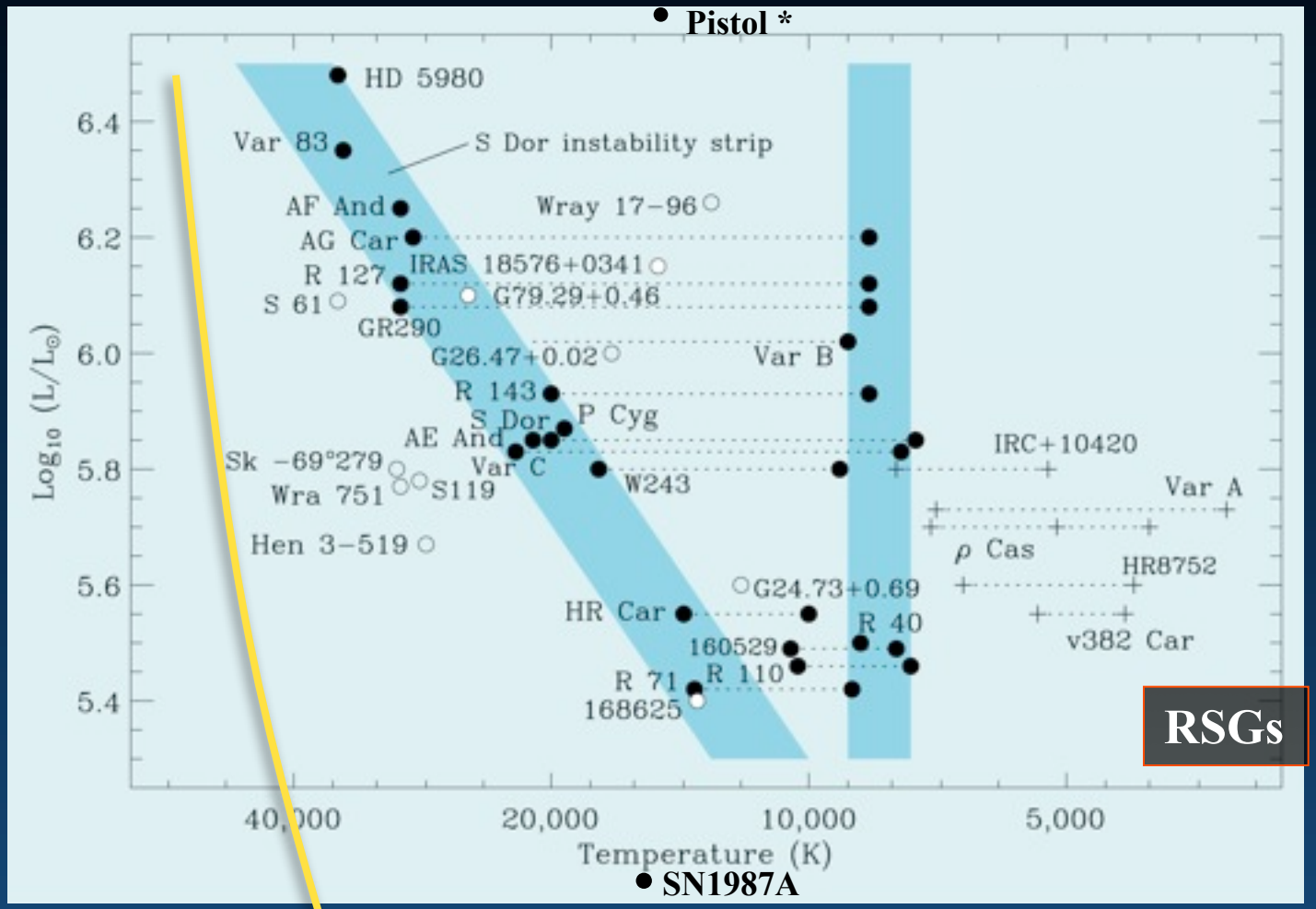


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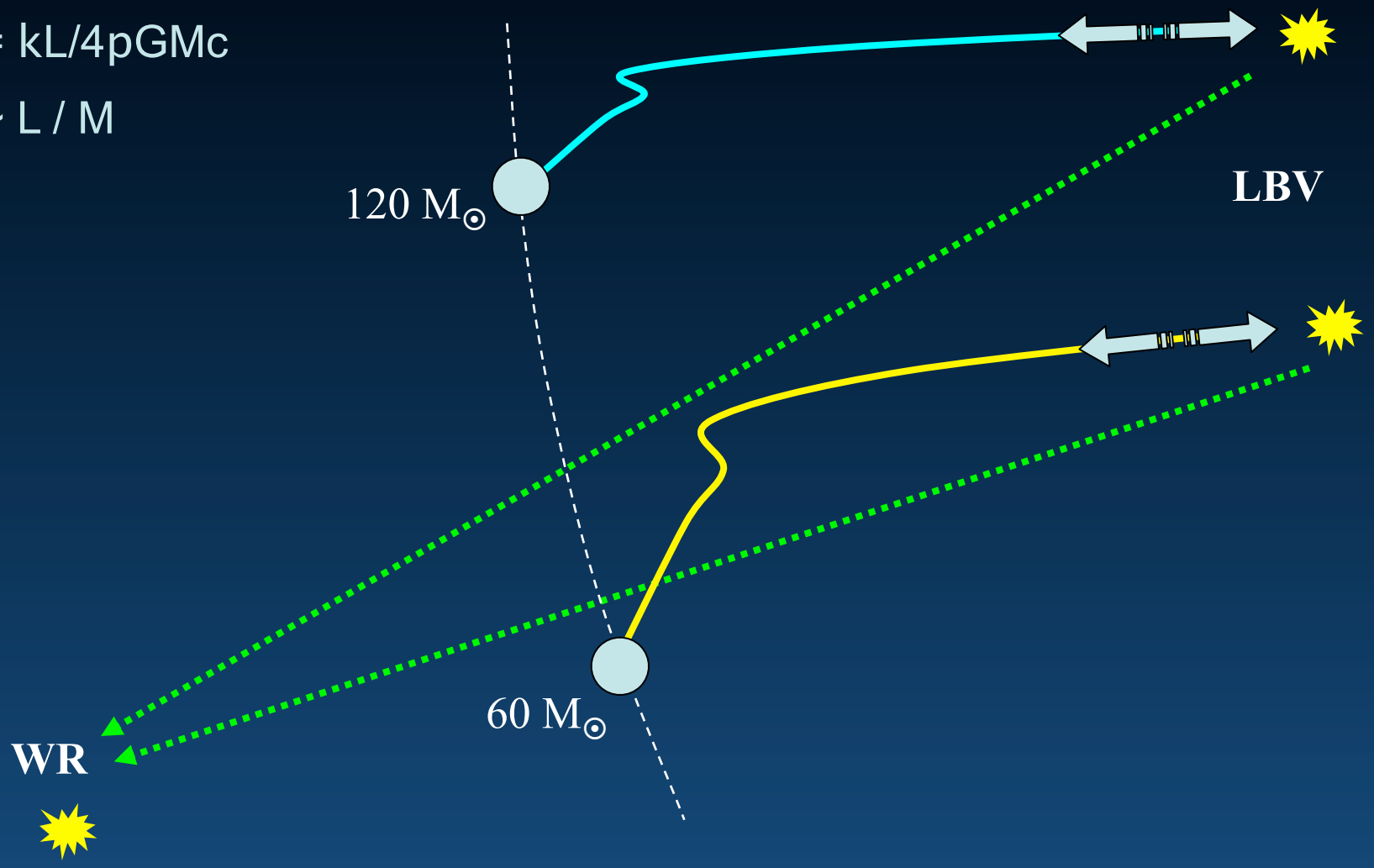
# Mass loss and stellar evolution:
## LBV winds/eruptions

G = kL/4pGMc

G ~ L / M



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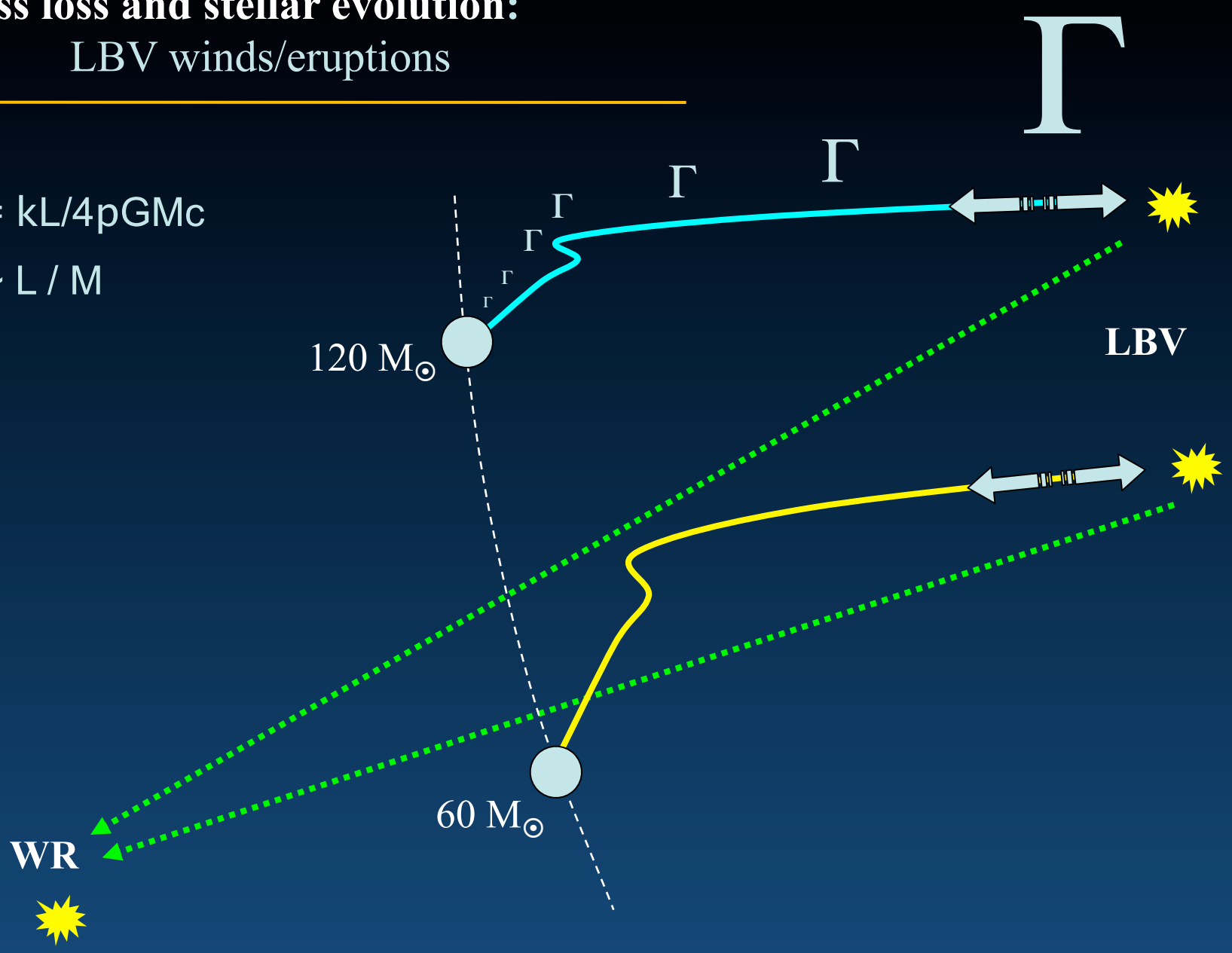

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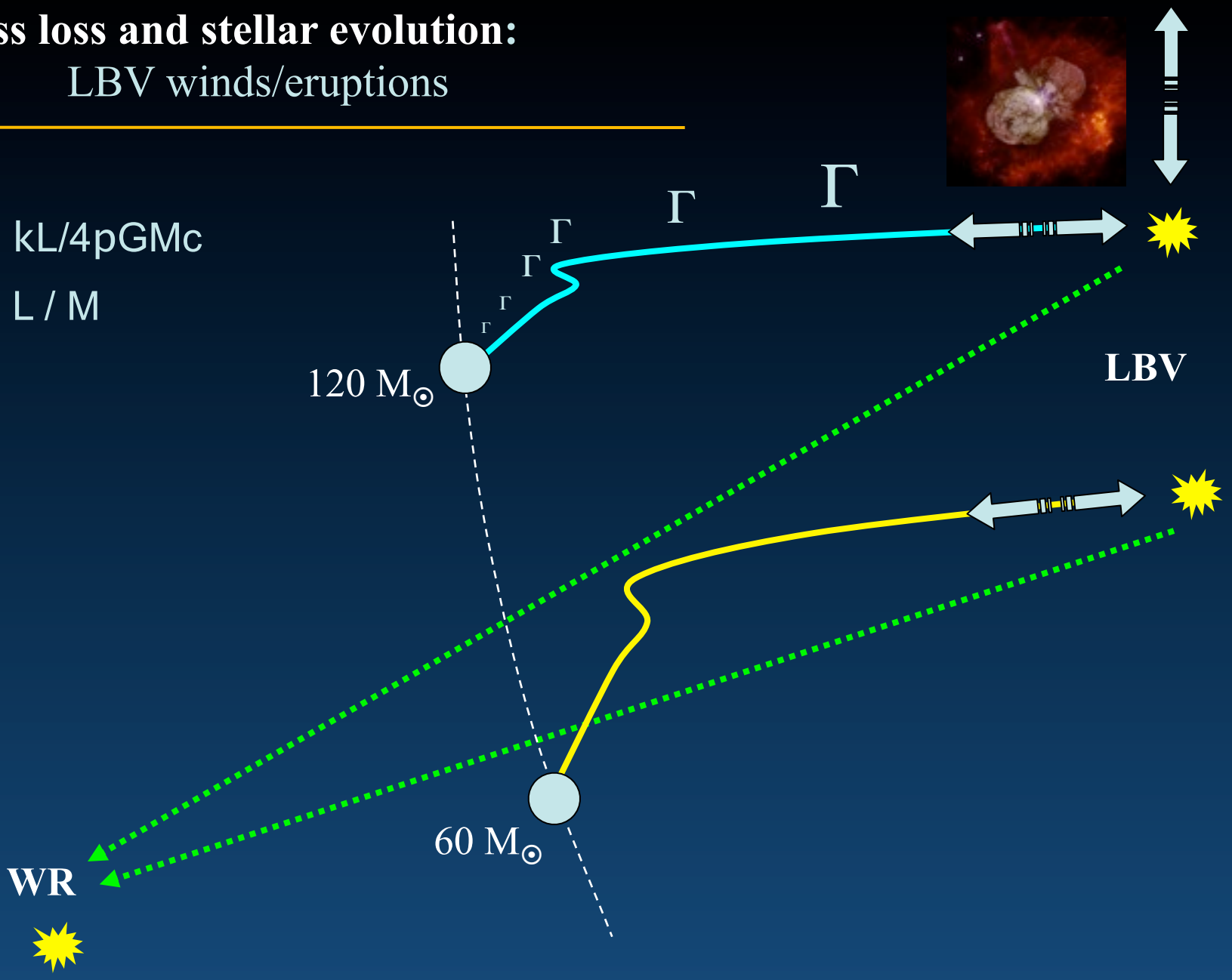


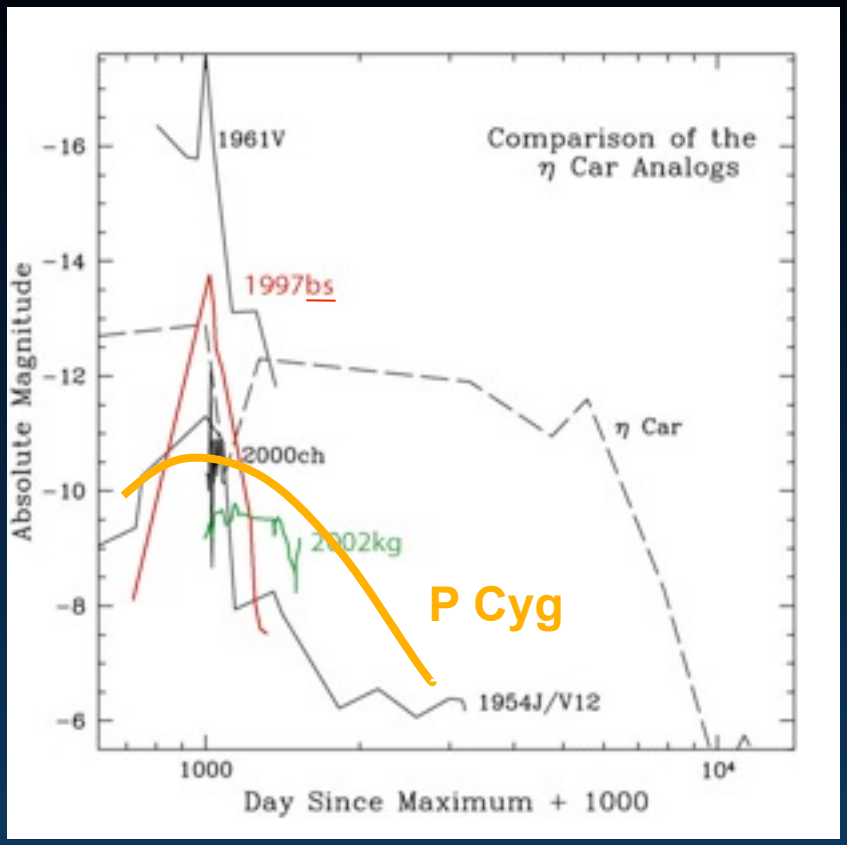
# "SUPERNOVA IMPOSTORS"

(Van Dyk et al. 2000)

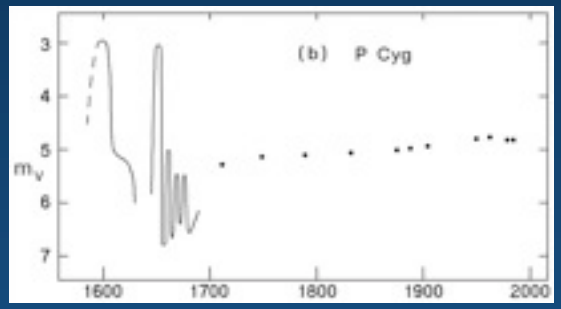
- Historical Type V supernovae:
  - Eta Carinae / P Cygni
  - SN1954j in NGC2403
  - SN1961v in NCG1058
  - V1 in NGC2363

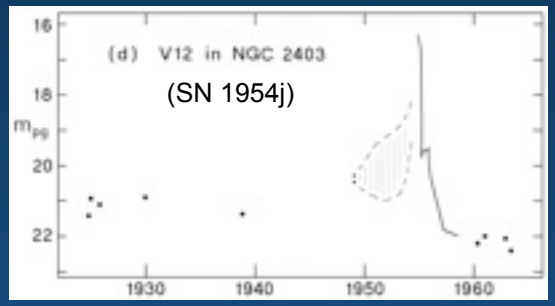
- Recent faint IIn SNe in SN searches:

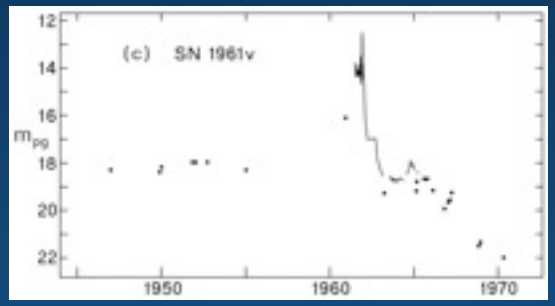
| | | | | |
|---|---|---|---|---|
| SN1997bs | NGC3627 | IIn | LOSS | (Van Dyk et al. 2002) |
| SN1999bw | NGC3198 | IIn | LOSS | |
| SN2000ch | NGC3432 | IIn | LOSS | (Wagner et al. 2004) |
| SN2001ac | NGC3504 | IIn? | LOSS | |
| SN2002bu | NGC4242 | Iin | Puckett,Gauthier | |
| SN2002kg | NGC2403 | IIn | LOSS | (Maund et al. 2006; Van Dyk et al.) |
| SN2003gm | NGC5334 | LBV | LOSS | (Maund et al. 2006) |
| 2004-OT | UGC4904 | ? | Itagaki | (Pastorello et al. 2007) |
| 2005-OT | NGC4656 | LBV | Rich | |
| SN2006bv | UGC7848 | IIn | Sehgal, Gagliano, Puckett | |
| SN2006fp | UGC12182 | IIn? | Puckett, Gagliano | |
| SN2007sv | UGC5979 | LBV | Duszanowicz | |
| SN2008S | NGC6946 | IIn | Arbour | (Smith et al. 2009) |
| 2008-OT | NGC300 | IIn | Monard | (Bond et al.; Berger et al.) |
| SN2009ip | NGC7259 | LBV | Maza, Pignata et al. (Smith et al. 2010) | |
| 2009-OT | UGC2773 | LBV | Boles | (Smith et al. 2010) |




(Humphreys, Davidson, & Smith 1999)



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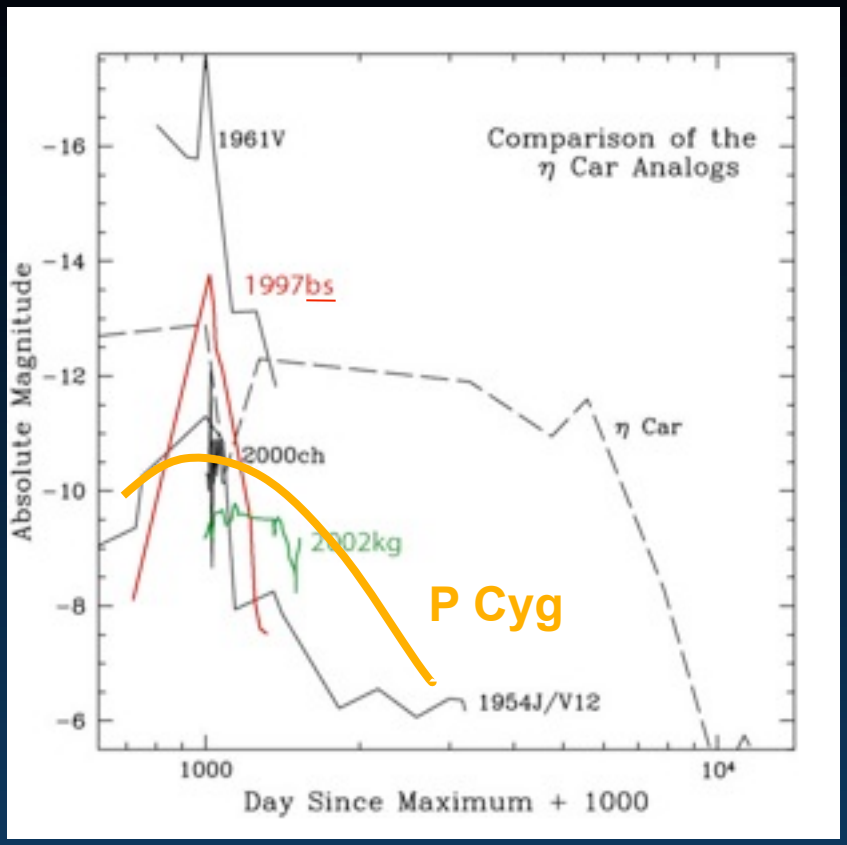


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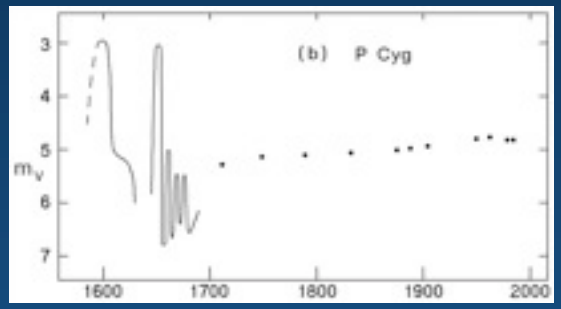


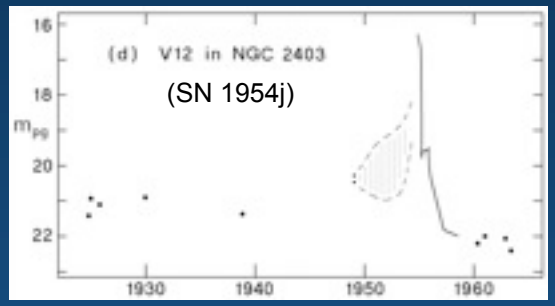


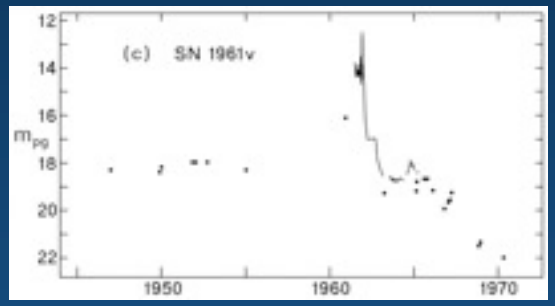

## "SUPERN

- Historical Ty
  - Eta Carinae
  - SN1954j in
  - SN1961v ir
  - V1 in NGC2
- Recent faint

| | |
|---|---|
| SN1997bs | NGC |
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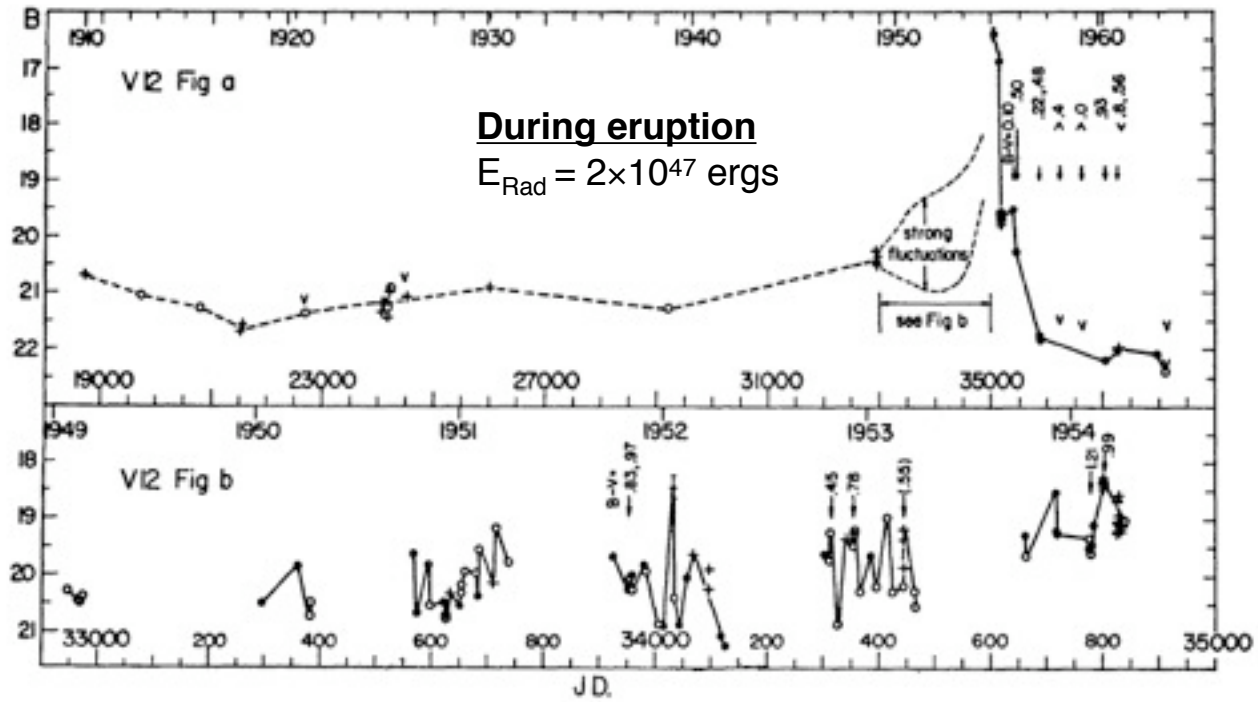
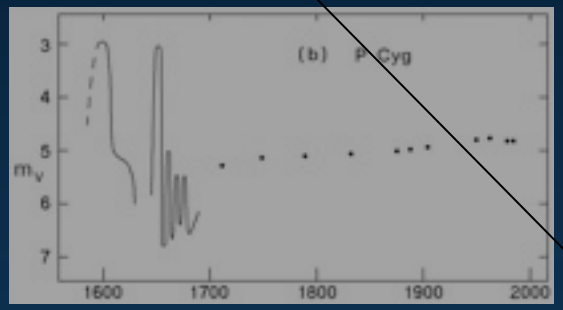
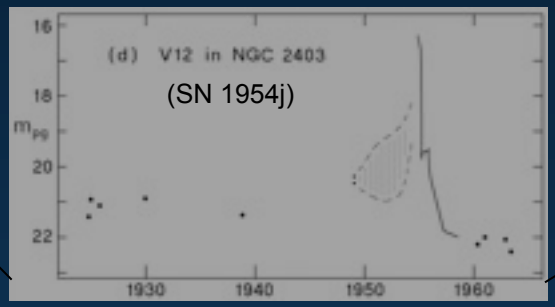


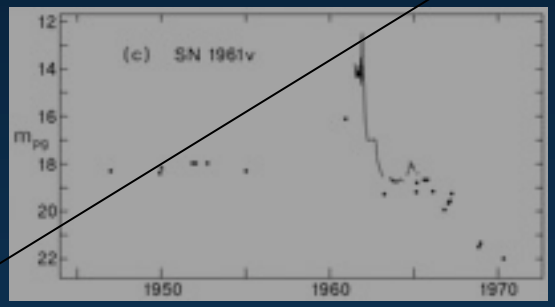

FIG. 11.—Light-curve in *B* for the bright blue irregular variable V12. The upper panel illustrates the variation from 1910 to 1963. The lower panel shows the variations from 1949 to 1954 on an expanded time scale.

Tammann & Sandage (1968)

(Humphreys, Davidson, & Smith 1999)

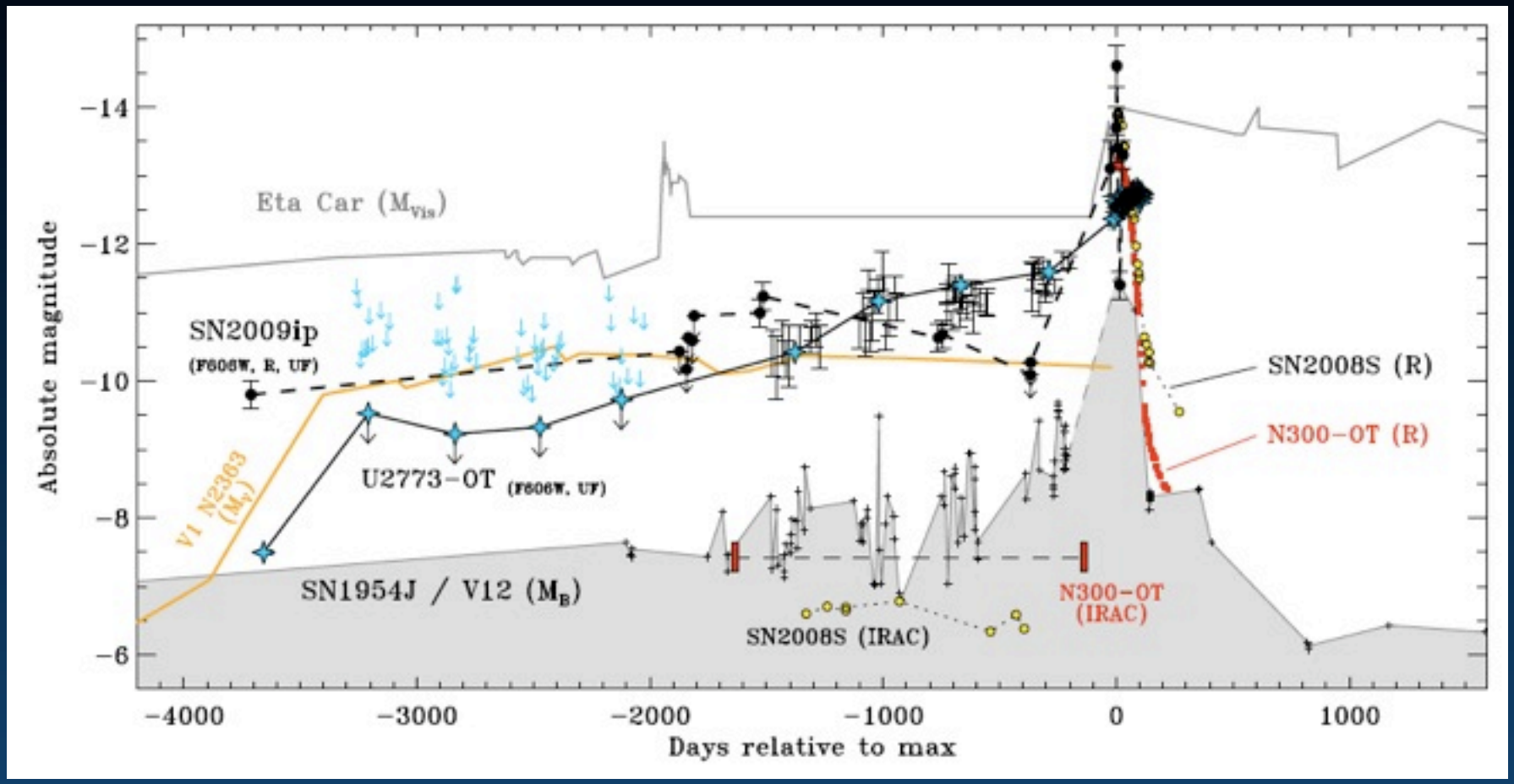


# SN 2009ip and optical transient in UGC 2773: pre-eruption variability

Smith et al. (2010, AJ, 139, 1451)

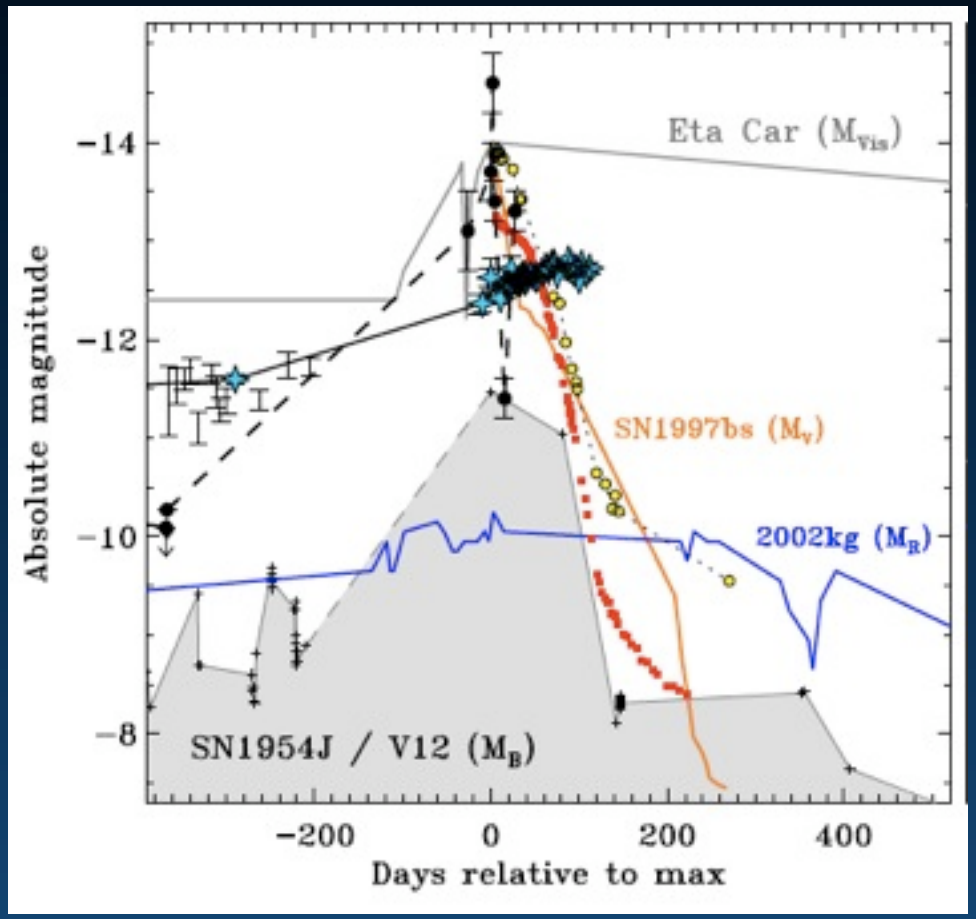



**Precursor outburst suggests 5-10 yrs for buildup of instability preceding main eruption.**

LBVs span a range of progenitor luminosity/mass

# SN 2009ip and optical transient in UGC 2773: peak and decay

Smith et al. (2010, AJ, 139, 1451)



# SN 2009ip and optical transient in UGC 2773: spectral diversity

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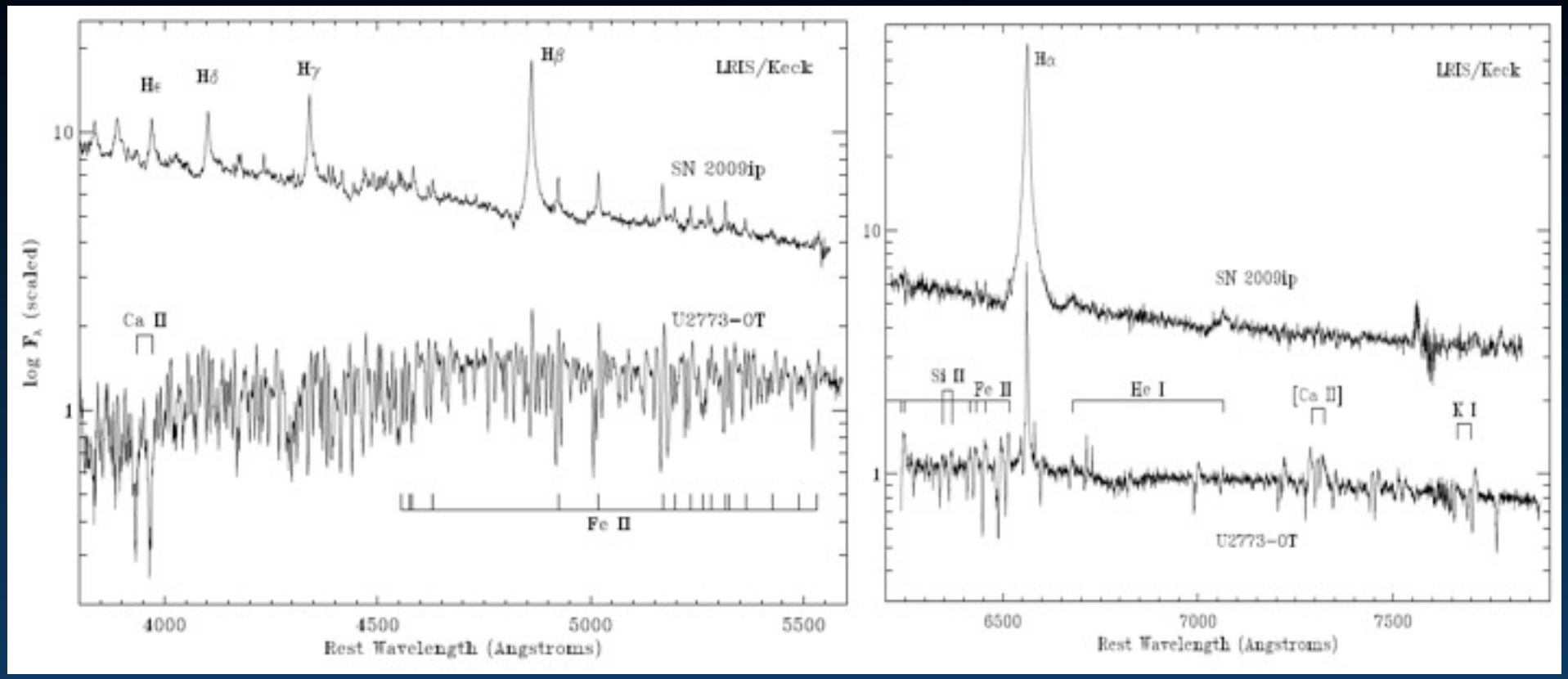


Dichotomy: Some are hot/some are cool

SN2009ip: looks like "Hot" LBV, Lorentzian profiles, weak P Cyg abs., weak He I lines

UGC 2773-OT: looks like "Cool" LBV, F-type supergiant, narrow absorption

Both are typical for spectra of LBVs in hot/cool states.

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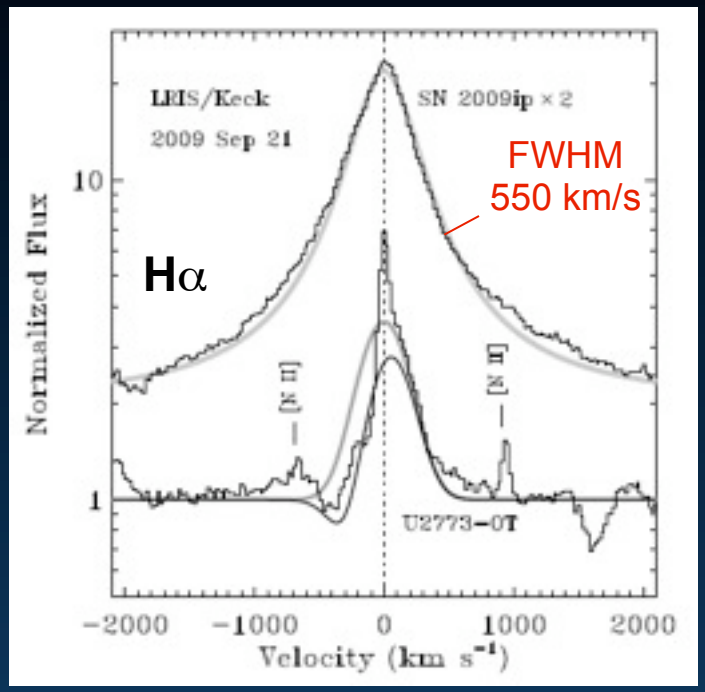
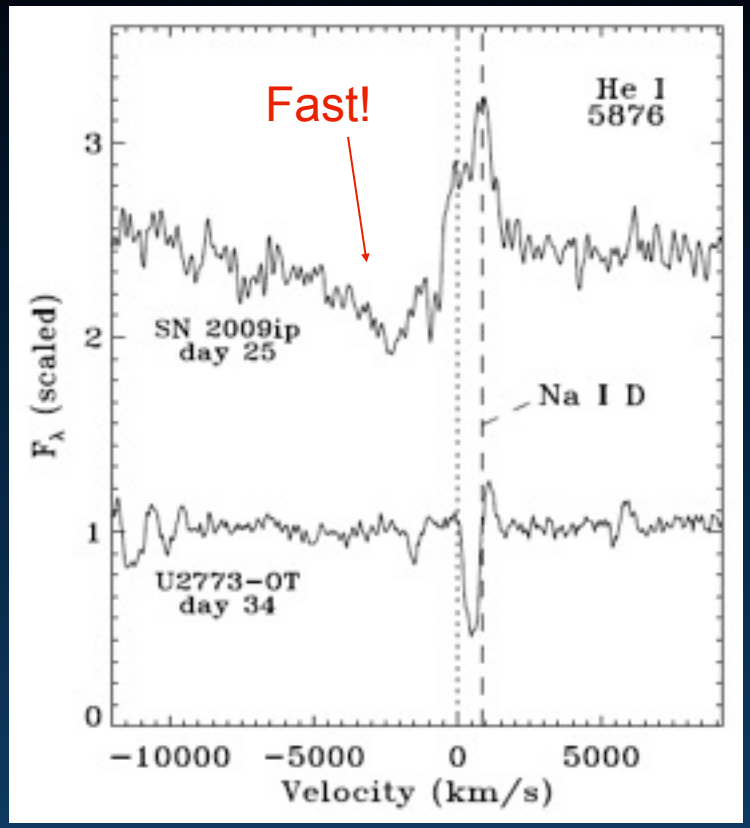


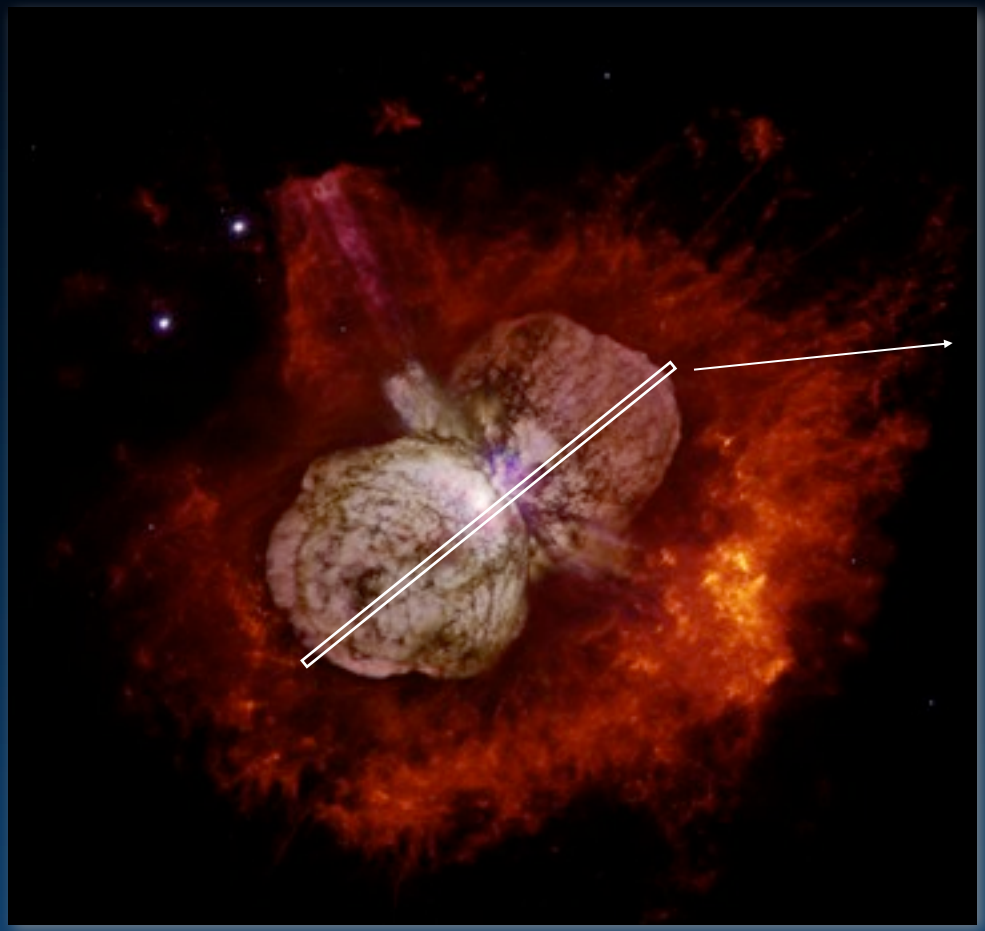

Hα and most em. lines indicate modest outflow speeds for most of the mass:

SN2009ip: 550 km/s
UGC 2773-OT: 350 km/s

Typical for LBV winds/ejecta

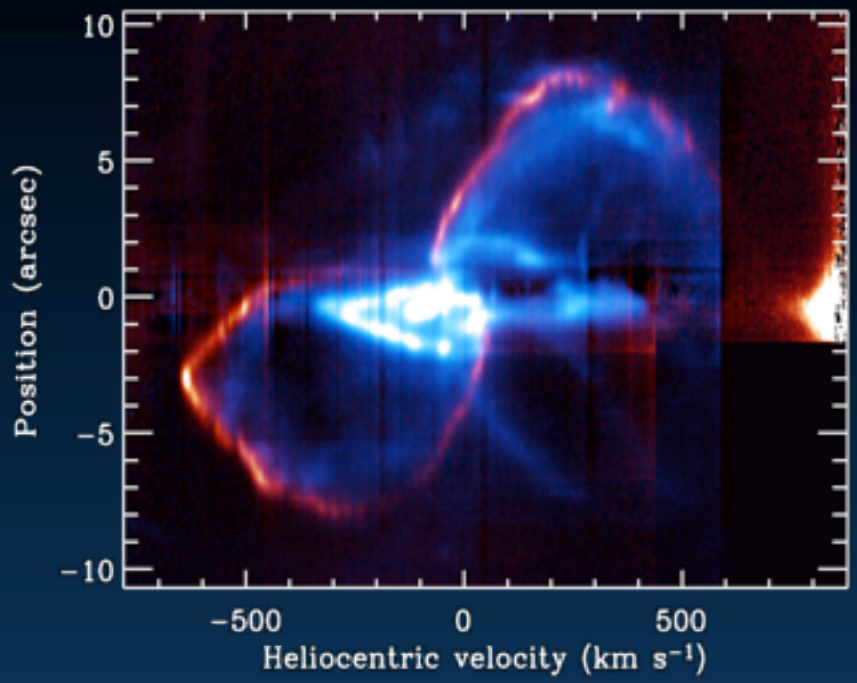
SN2009ip also shows evidence for fast outflow speeds of 3,000-5,000 km/s

Very fast ejecta/shock wave…
Does CSM interaction make it hot?



Gemini South/Phoenix R=60,000

1.644 μm [Fe II] 2.122 μm $H_2$ 1-0 S(1)




Smith (2006) ApJ, 644, 1151

Range of Ejecta
Speed = 40 - 650 km/s

Follows a Hubble law

Eta Carinae's
1843 eruption:

Ejected mass = 10-15 $M_\odot$

KE = $10^{49.6}$ - $10^{50}$ erg

$E_{rad}$ = $10^{49.7}$ erg"

← $KE/E_{rad} \approx 1$

***Wind or Explosion?***

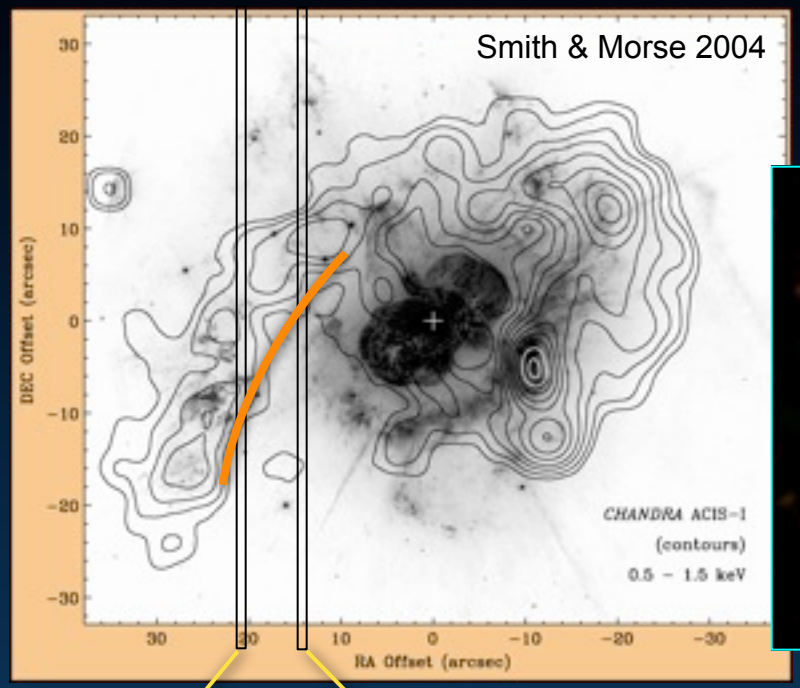
# A BLAST WAVE FROM THE 1843 ERUPTION OF ETA CARINAE?

Spectra of [N II] reveal ***fast*** material with Doppler shifts up to ~3000 km/s.

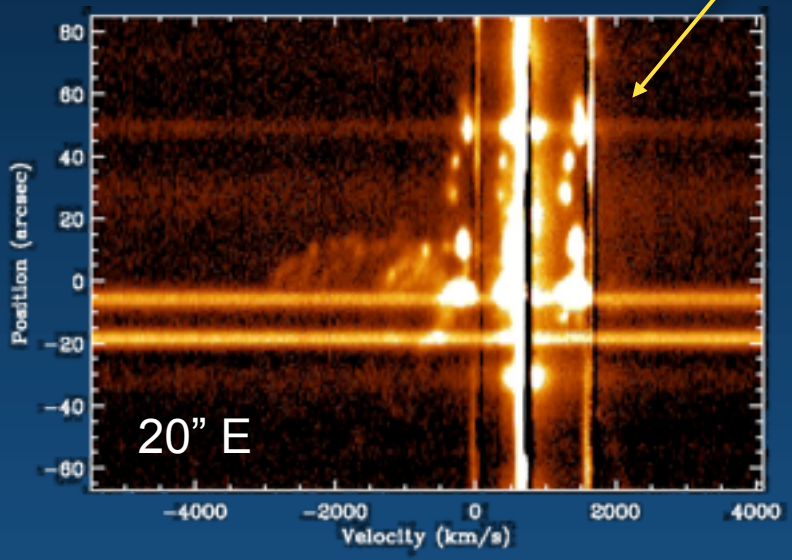
**True velocities of 5000 to 6000 km/s.**

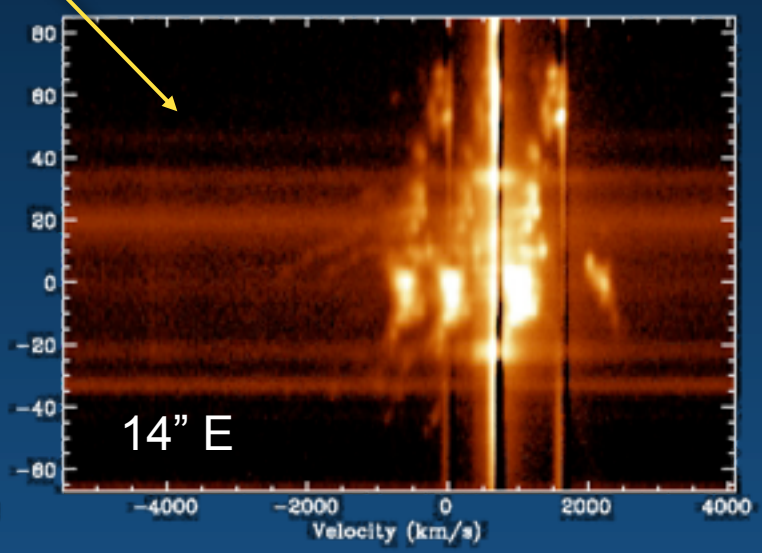
Is this a blast wave from the 1840's event?

again: ***explosion***








Smith (2008)
Nature, 455, 201

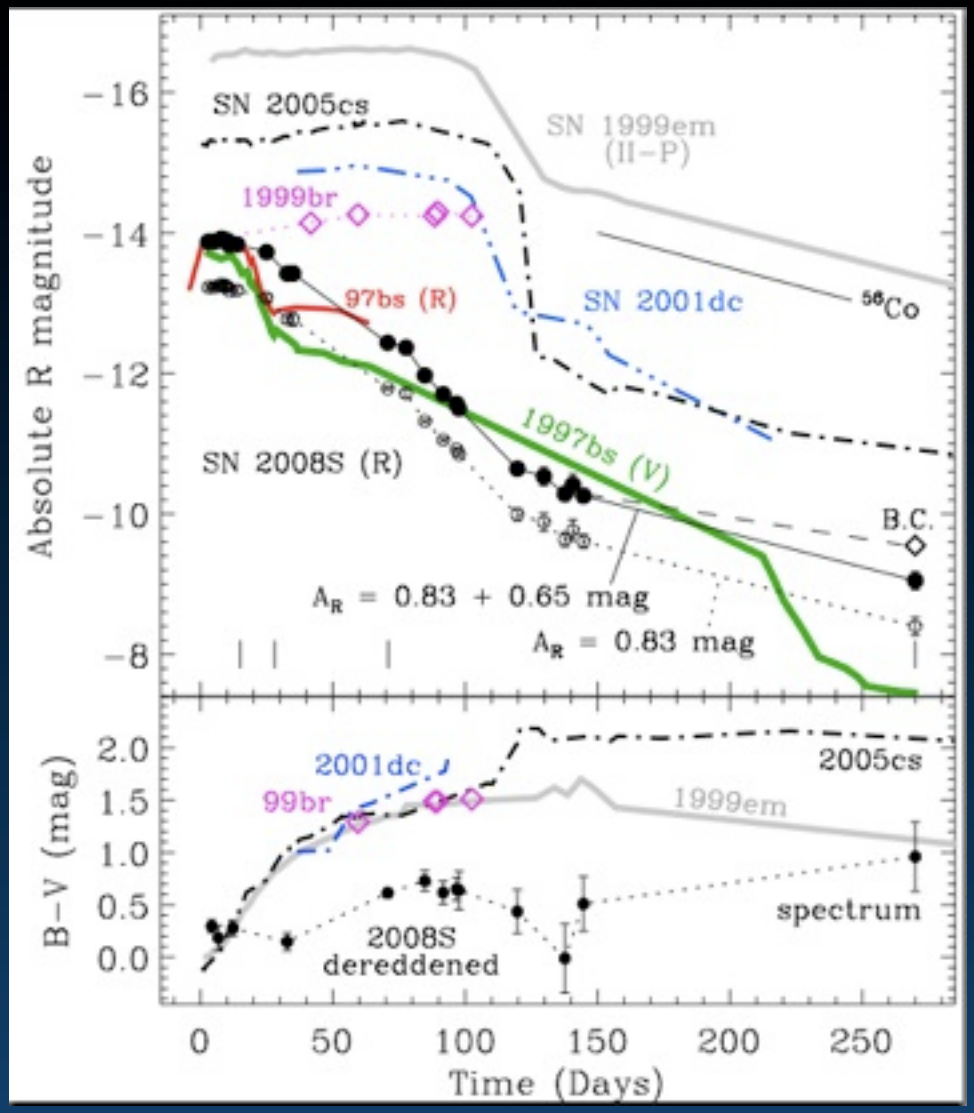
# SN 2008S:

A relatively low-mass (10-20 $M_\odot$), dusty progenitor detected by *Spitzer* (Prieto et al. 2008).

~$10^{48}$ erg eruption with a light curve like other SN impostors (Smith et al. 2009).

Spectrum of outburst resembled IRC+10420 (Smith et al. 2009) but was different from weak SNe II-P.

- LBV-like, stagnated super-Eddington wind in a 10-20 $M_\odot$ star? (Smith et al. 2009)
- A new class of transients from RSGs/AGBs? (Thompson et al. 08)
- electron-capture SN? (Thompson+08; Botticella+09)

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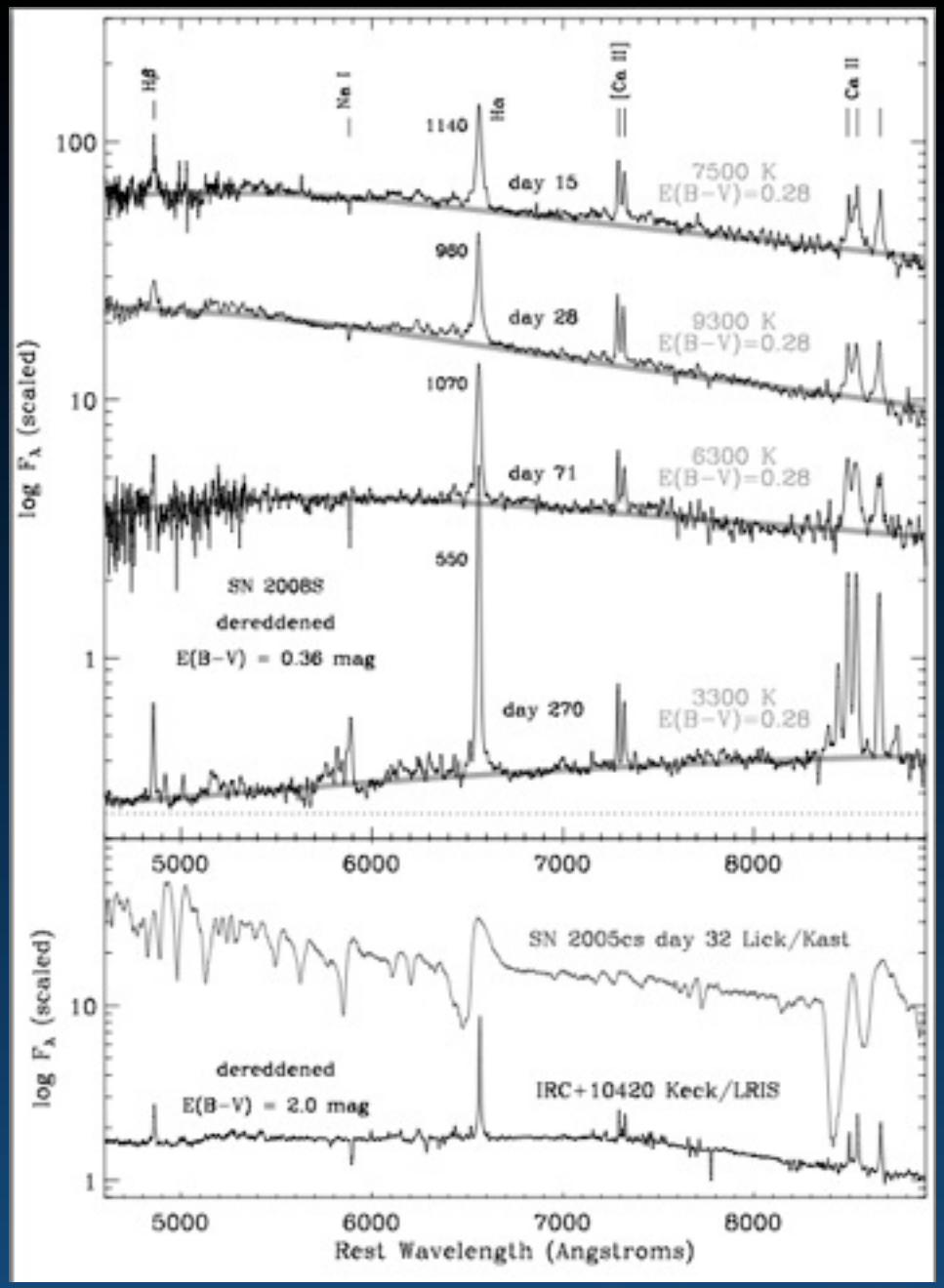
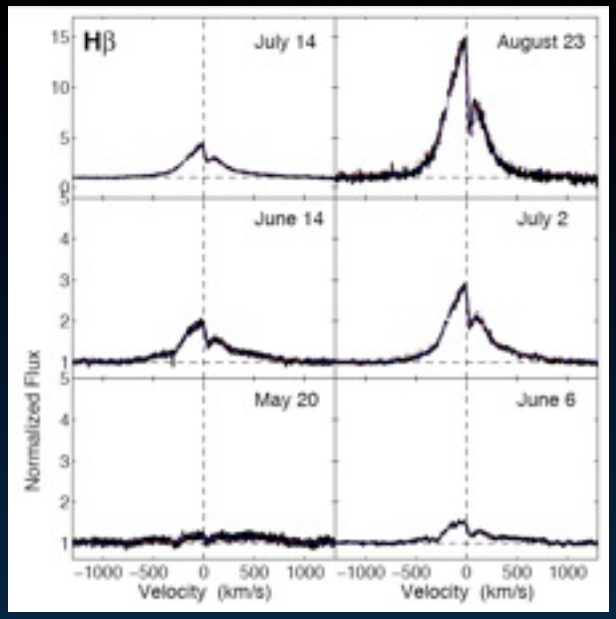


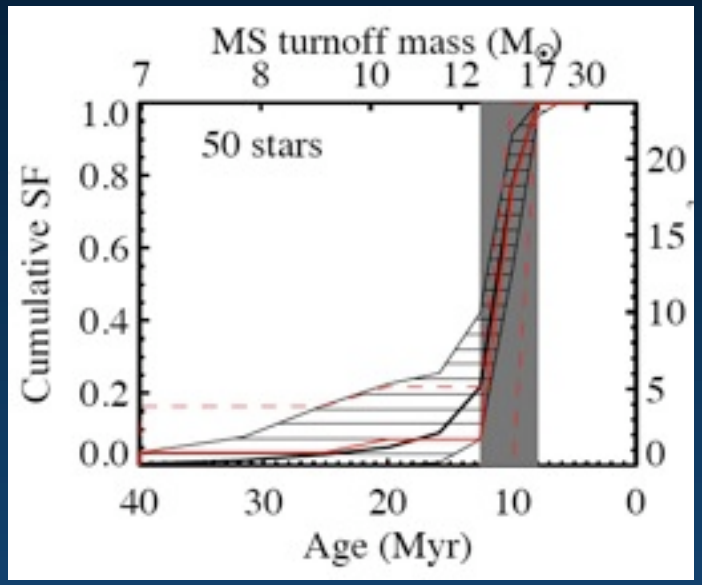

Smith et al. 2009

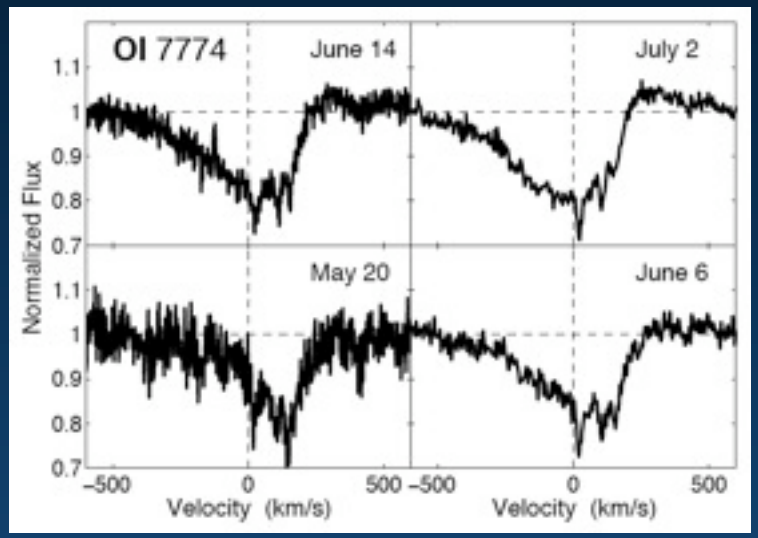
# NGC 300 variable (2008):

Basically same thing…but closer.
(Prieto+08; Bond+09; Berger+09).

Spectrum of outburst also resembled IRC+10420 (Bond+09; Berger+09).



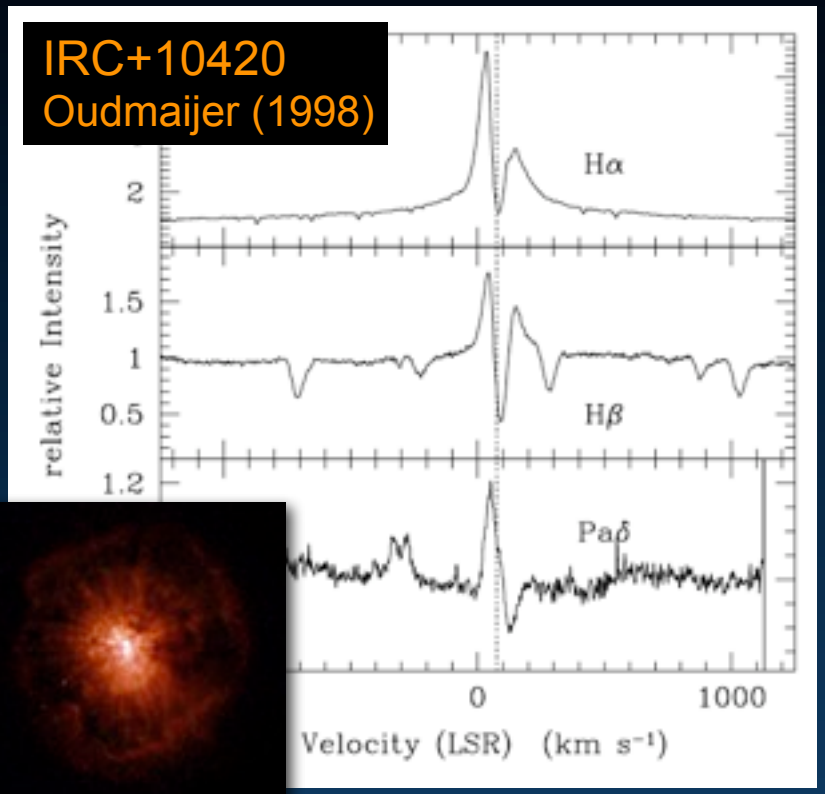




Berger et al. (2009)

Gogarten et al. (2009) find likely ZAMS mass of 12-25 $M_\odot$ from S.F. history of surrounding stars

# Redshifted absorption:
# Simultaneous outflowing wind and infalling material




IRC+10420: a partly stalled wind
(Humphreys, Davidson, & Smith 2002)

super-Eddington wind in SN 2008S
(Smith et al. 2009)

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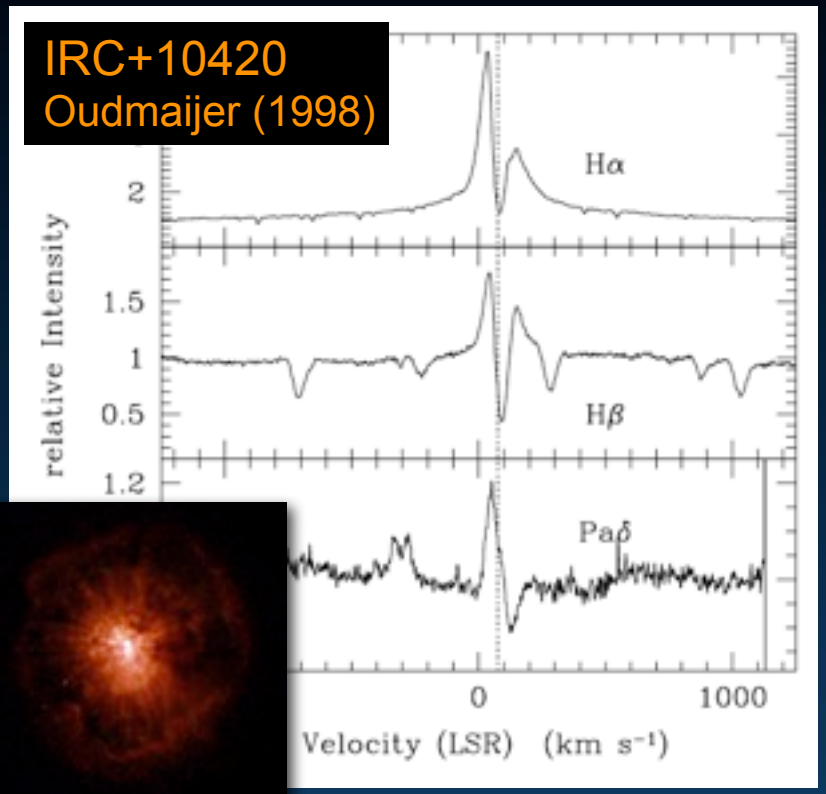
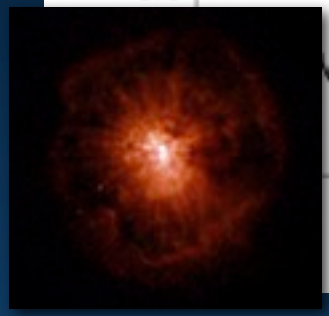
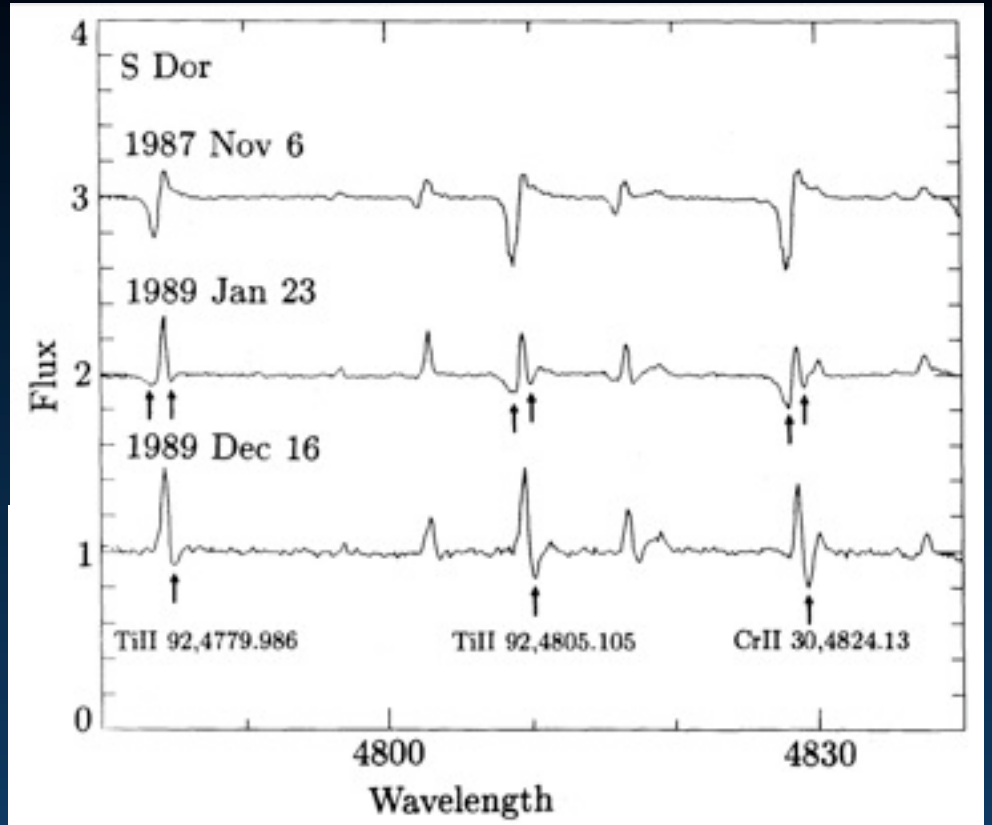


IRC+10420: a partly stalled wind
(Humphreys, Davidson, & Smith 2002)

super-Eddington wind in SN 2008S
(Smith et al. 2009)




**Inverse P Cygni-type profiles in the spectrum of the Luminous Blue Variable S Doradus***

B. Wolf and O. Stahl
Landessternwarte Königstuhl, D-6900 Heidelberg 1, Federal Republic of Germany

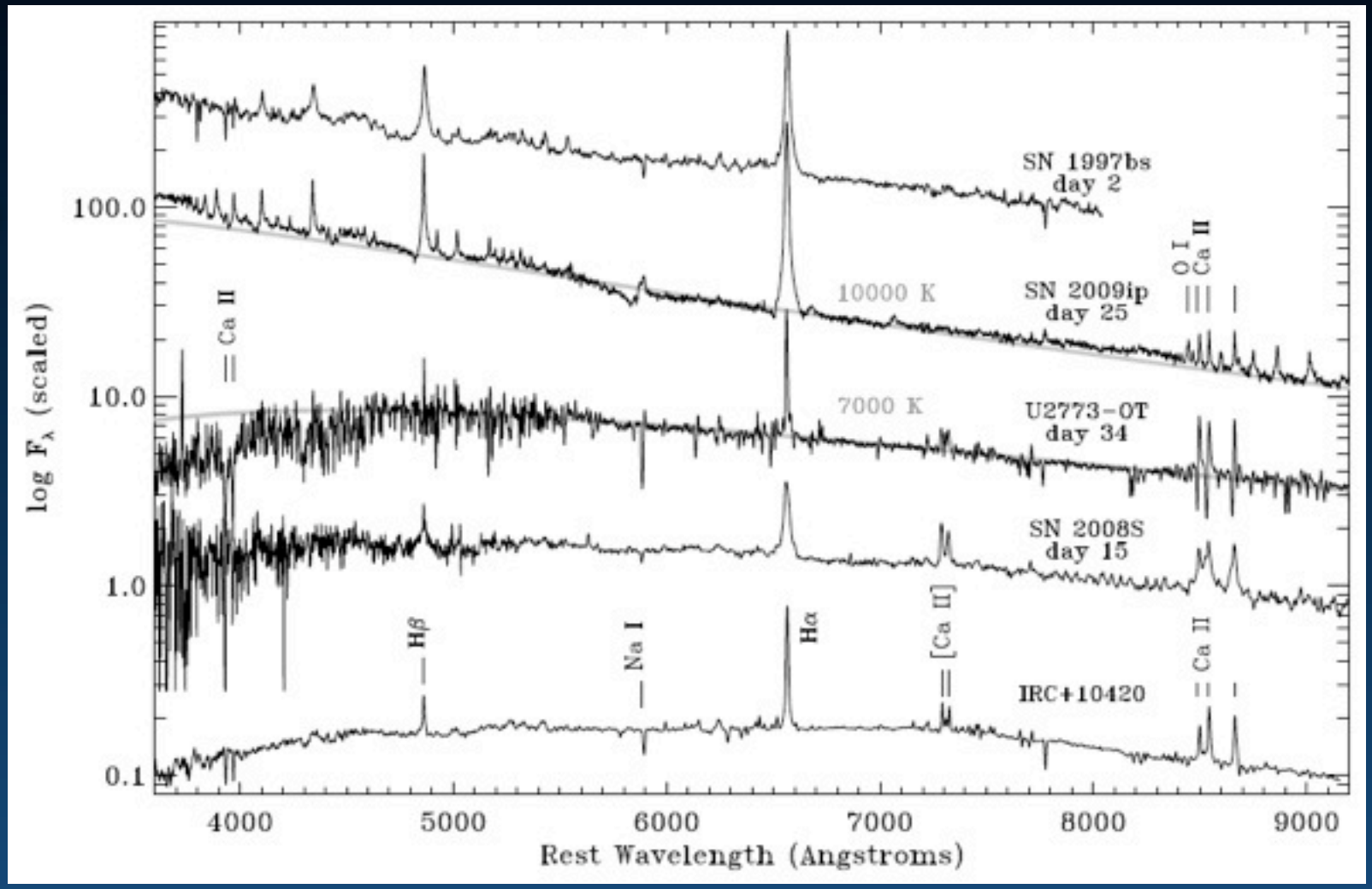
Received February 22; accepted March 24, 1990

**Main Lesson:** LBVs and related phenomena are more diverse than we thought

Broad spectrum of energy, luminosity, duration, spectral properties…

HOT
(explosive)

COOL
(wind)



**Main Lesson:** LBVs and related phenomena are more diverse than we thought

Broad spectrum of energy, luminosity, duration, spectral properties…

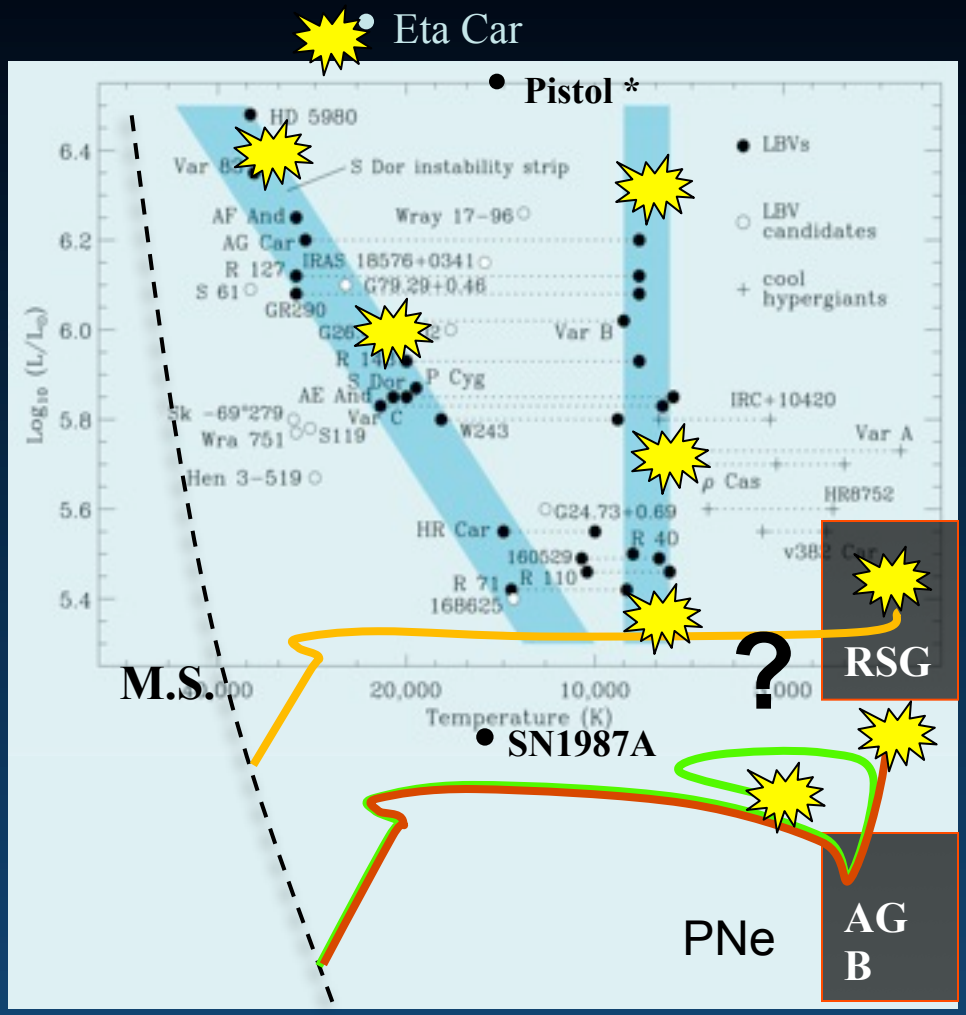
- Explosions / eruptions / winds

  Surface instability? …or deep energy deposition?

- Covering a wider range of initial Mass?

*THIS IS A PARADIGM SHIFT!*
Don't have good observational constraints on brief and relatively faint eruptive events.

(so far, just tip of the iceberg…)
…PTF, Pan-STARRS, LSST




also: binary mergers, electron capture SNe, etc.

## Models for the Physical Mechanism of LBV eruptions:

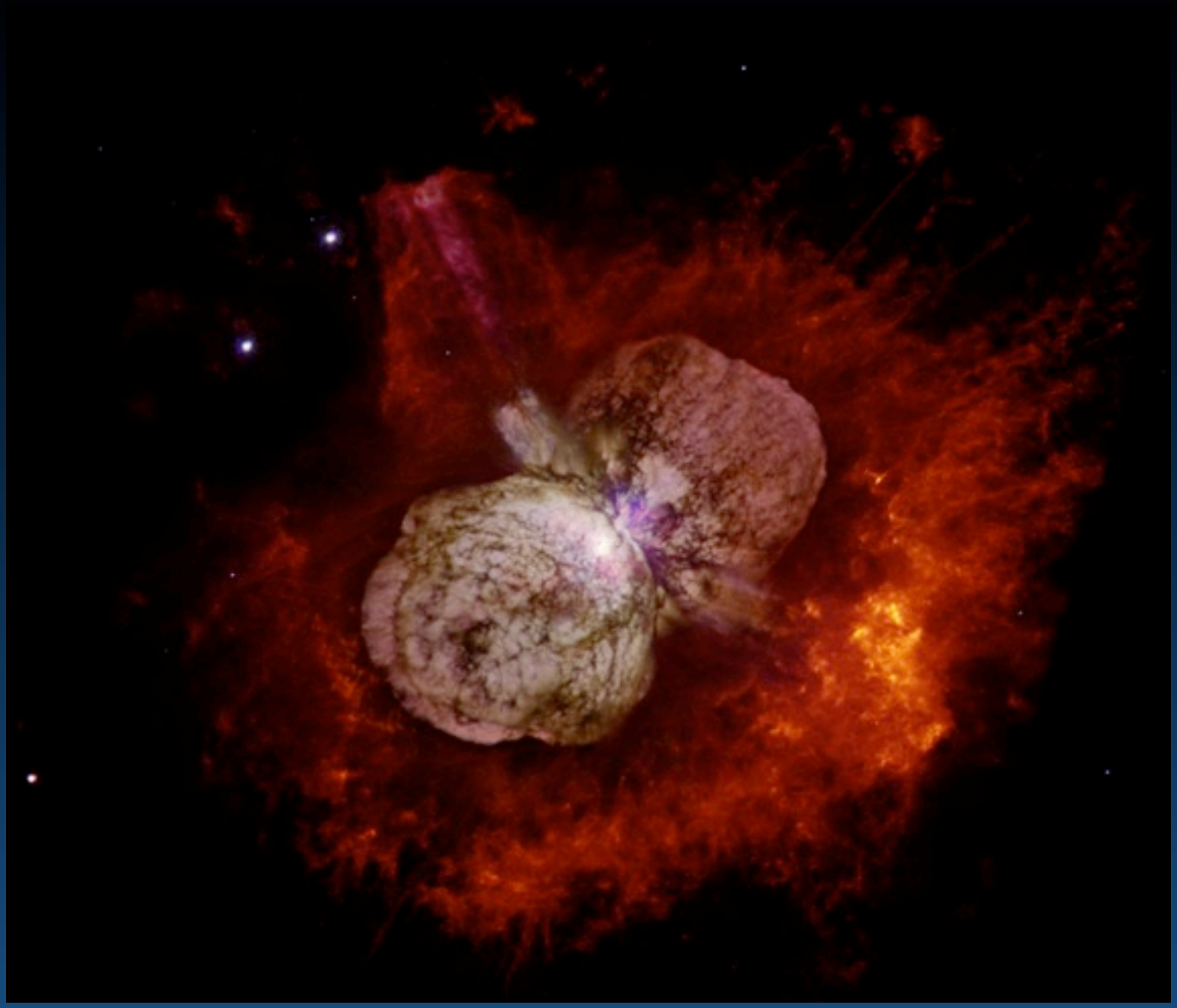
## ~~Models~~ for the Physical Mechanism of LBV eruptions:

Vague ideas

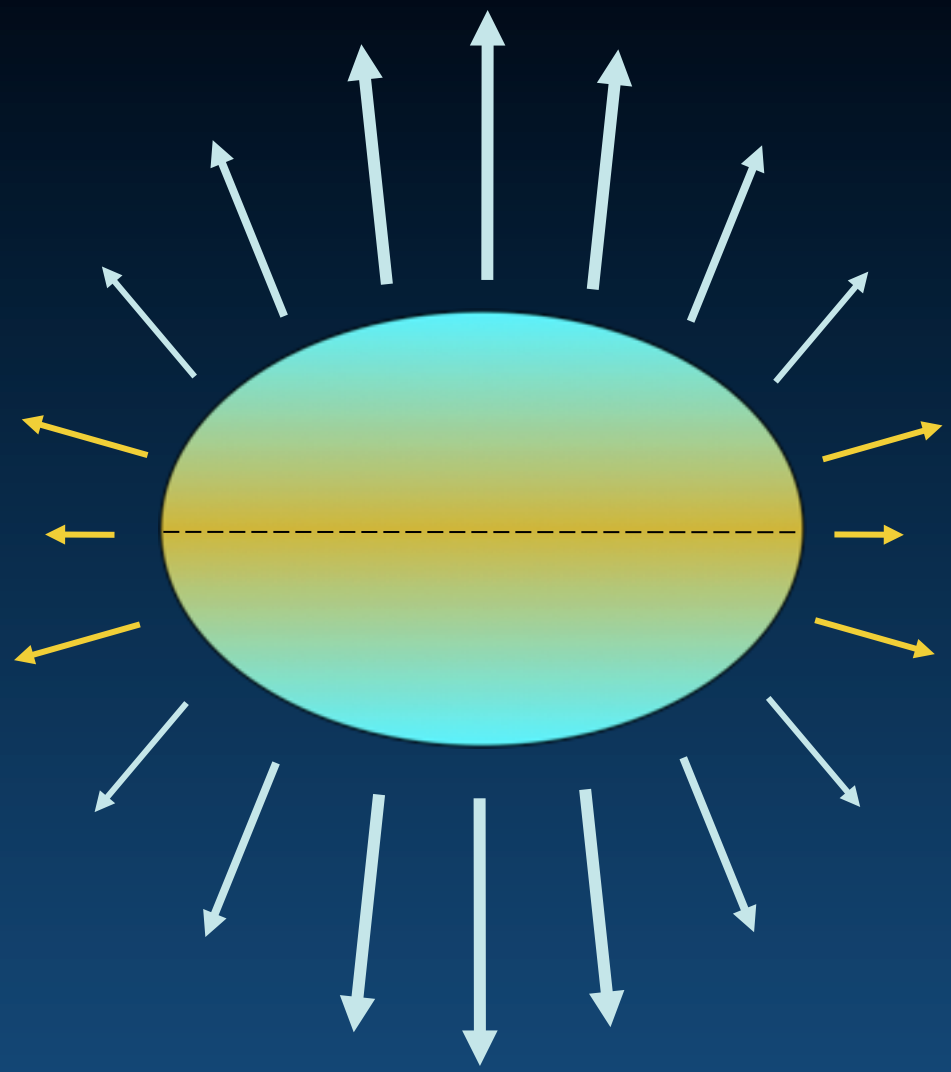
- Continuum-driven super-Eddington winds: Owocki et al. 2004; Shaviv 2001
  - Can drive strong wind, but doesn't explain increased L.
- Astrophysical "Geyser": Davidson et al. 1987
  - Mass ejection leads to runaway mass loss.
- Pulsational pair-instability events: Heger & Woosley 2002
  - Matches most extreme bursts w/ 10 $M_\odot$, $10^{50}$ ergs:
    - Doesn't explain lower M, lower KE events,
    - Limited to most massive stars M > 95 $M_\odot$,
    - Limited to immediate pre-SN stages.
- Explosive core/shell burning events (hypothetical): see Dessart et al. 2009; arXiv:0910.3655
  - Biggest energy dep: Unbind outer envelope.
  - Smaller energy dep: Puff up envelope, increase L, drive wind.
  - Smallest energy dep: Undetectable? Normal LBV variability?
- Others? Binary mergers/accretion events, magnetic bombs : eh...

## Obvious things we want:

- A brave theorist or two:
  - Models for the mechanism?
  - Radiative transfer models: deriving $M_{ej}$, abundances
- Pre-Outburst information on progenitor or environment:
  - HST/Spitzer archive: progenitor L, $T_{eff}$, M.
- Multi-band photometry:
  - Timescales of weeks to decades (or even centuries):
  - current surveys/LSST + archival data
  - IR data -- dust? Late-time data.
- Spectra:
  - Outflow speeds, excitation, shocks vs. winds, kinetic energy.
  - Spectropolarimetry: asymmetry?
- Evidence for explosions/shocks:
  - Shock breakout/CSM interaction: rapid follow-up, faint X-rays?

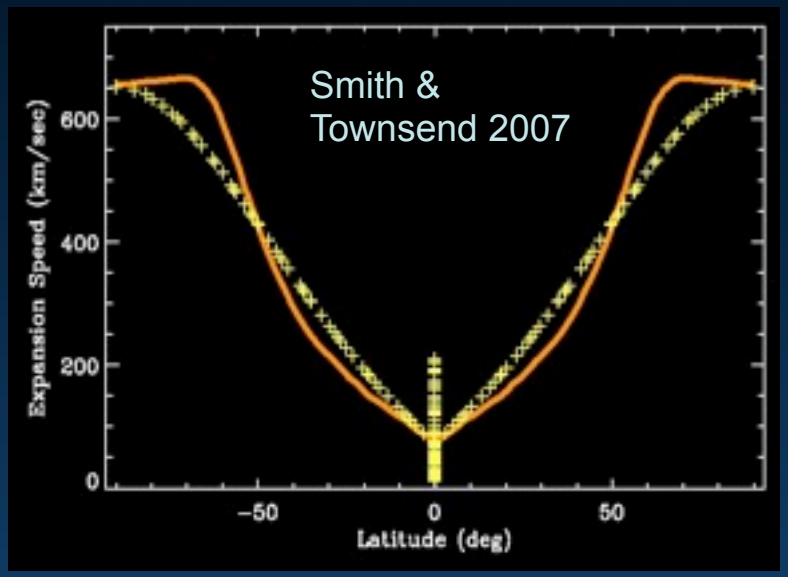


# *Bipolar Geometry ...a rotating single star?*



Latitude-dependent escape speed on a rotating star:

$$v_\infty = v_{pole}(1-\Omega^2\cos^2\theta)^{1/2}$$




Also: Higher mass flux toward poles in a radiation-driven wind (many papers by Owocki et al.)

HST/ACS (courtesy Peter Challis)

## SN1987A:

star: B3 I
home: 30 Dor

Ring Radius = **0.2 pc**

age: ~20,000 yr

Nitrogen rich? *yes*
(N/O = 1.6)

rapid rotator? *no?*

*ejected as RSG ?*
*...or as a BSG?*

## Sher 25:

star: B1.5 Ia
home: NGC3603

Ring Radius = **0.2 pc**

age: 7,000 yr

Nitrogen rich? *so/so*
(N/O = 0.36)

rapid rotator? *no*

*ejected as BSG*

HST/WFPC2 (Brandner et al. 1997)

## TWO NEW RING NEBULAE

Spitzer/IRAC (Smith 2007)

## HD168625:

star: LBV/B4-6 Ia
home: M17

Ring Radius = **0.1 pc**

age: ~5,000

Nitrogen rich? *so/so*
(N/H = 1.5-3 solar)

rapid rotator? *no*

*ejected as LBV/BSG*

## SBW 1:

star: B1.5 Iab
home: Carina (?)

Ring Radius = **0.2 pc**

age: ~10,000 yr

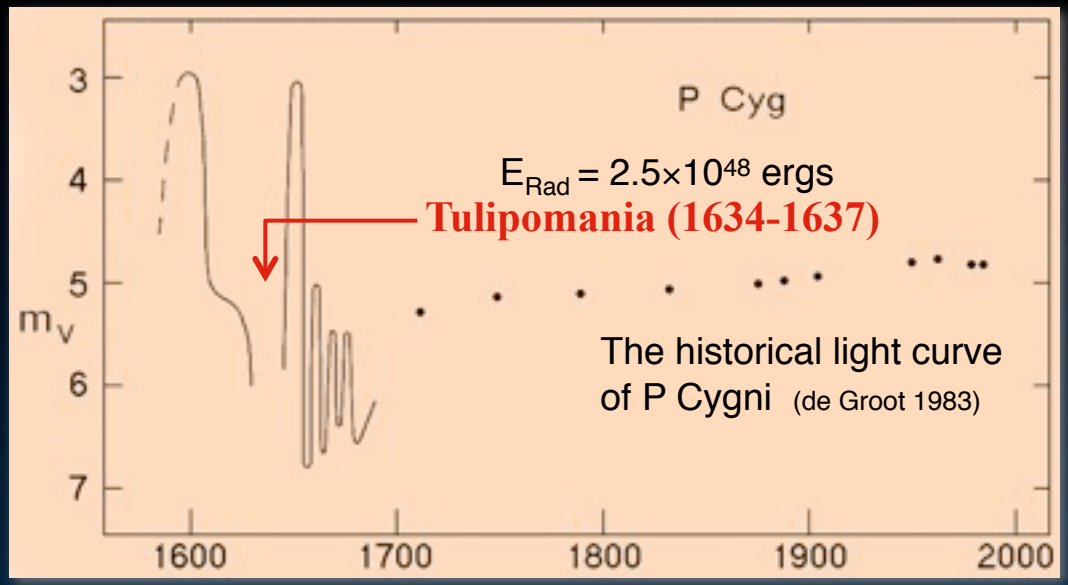
Nitrogen rich? *no*
(N/H < 1 x solar)

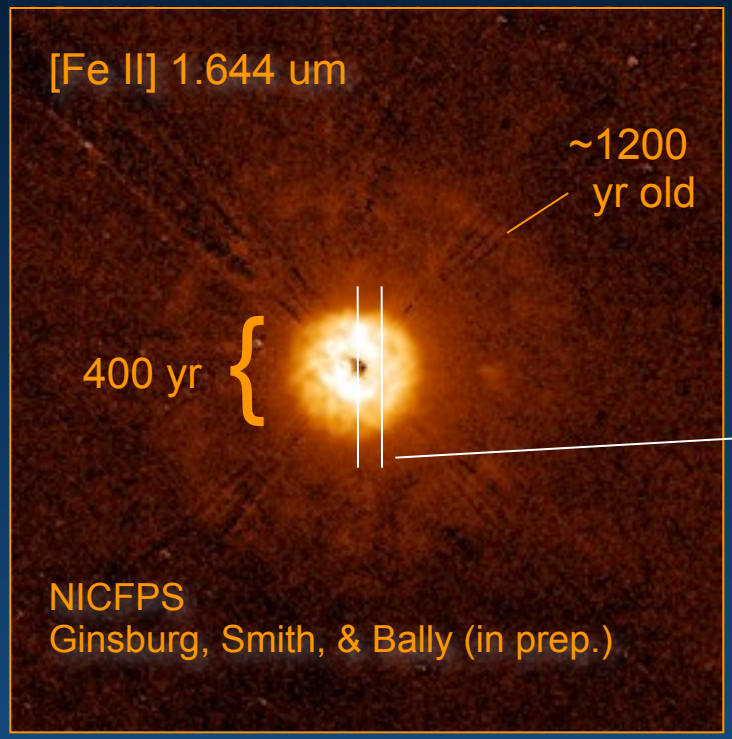
rapid rotator? *no*

*ejected as BSG*

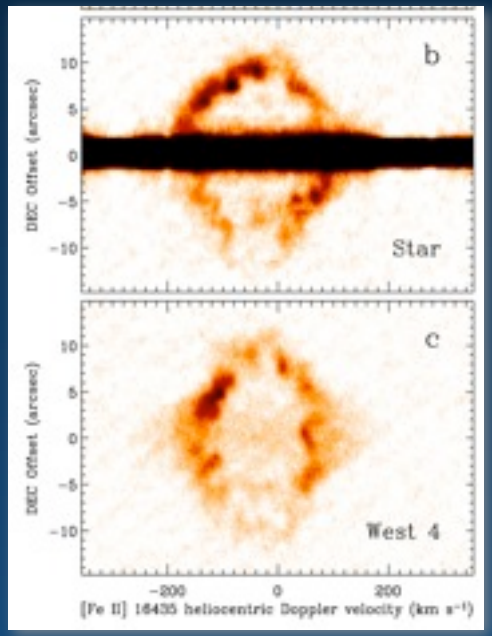
Magellan (Smith et al. 2007)

# P Cygni


Smith & Hartigan
2006, ApJ, 638, 1045




**1600 AD shell:**

From [Fe II] lines:

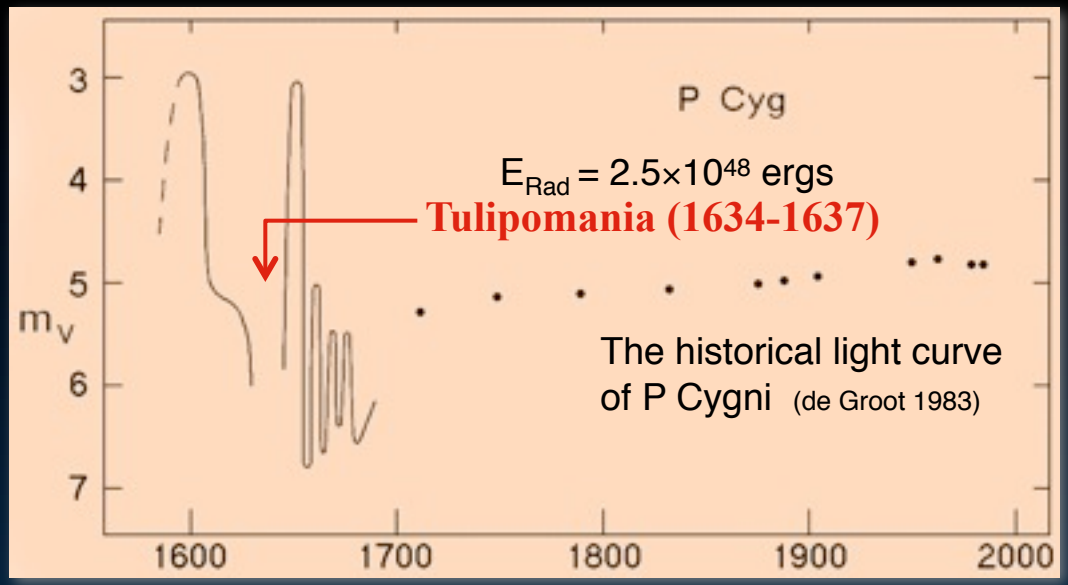
$M = 0.1\text{-}0.2\ M_\odot$

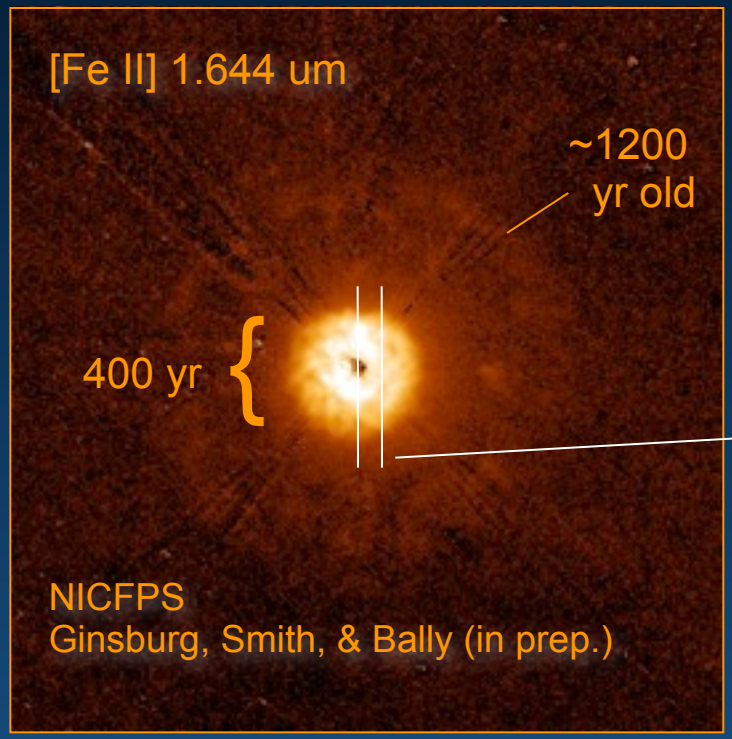
$\dot{M} = 0.01\ M_\odot/yr$

$KE = 10^{47}$ ergs

Mass and KE similar to 1890 outburst of Eta Car's Little Homunculus.

# P Cygni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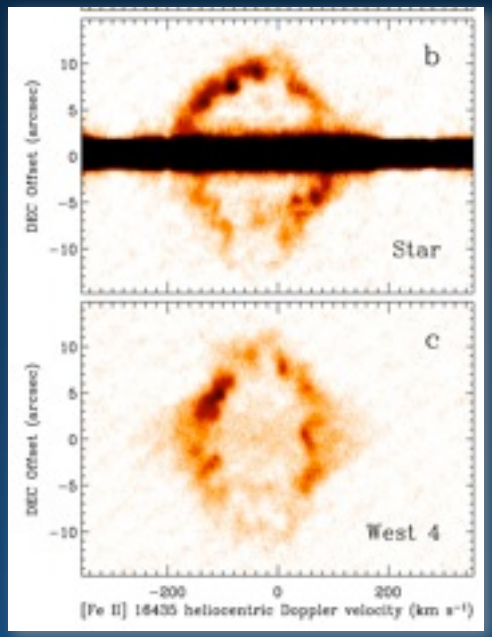


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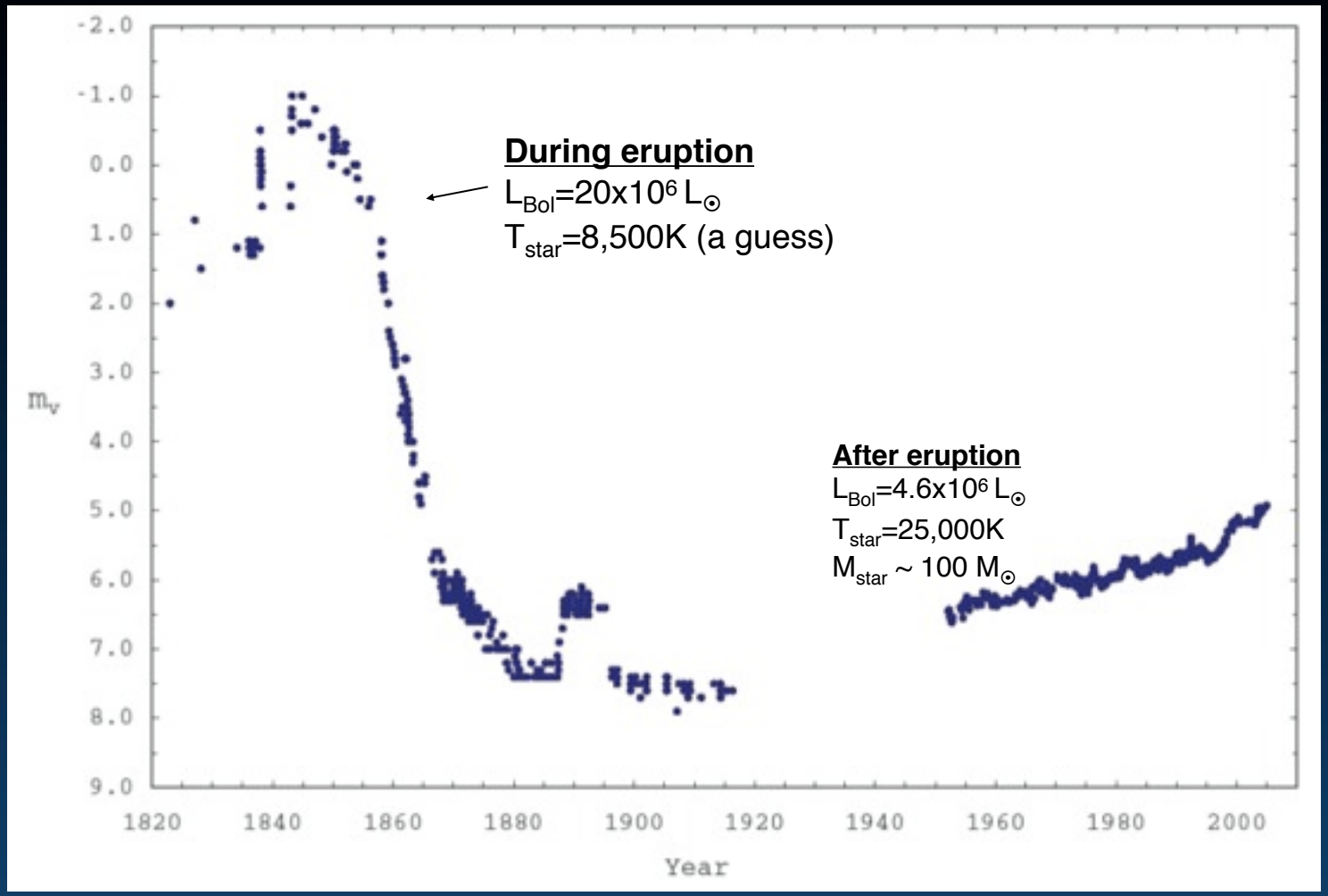


Eta Carinae (Frew 2004)