SUPERNOVA REMNANTS
AN ODYSSEY IN SPACE AFTER STELLAR DEATH
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15 years of SN 1996al & CSM around masssive stars

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The spectacular evolution of Supernova 1996al over 15 yr: a low-energy explosion of a stripped massive star in a highly structured environment

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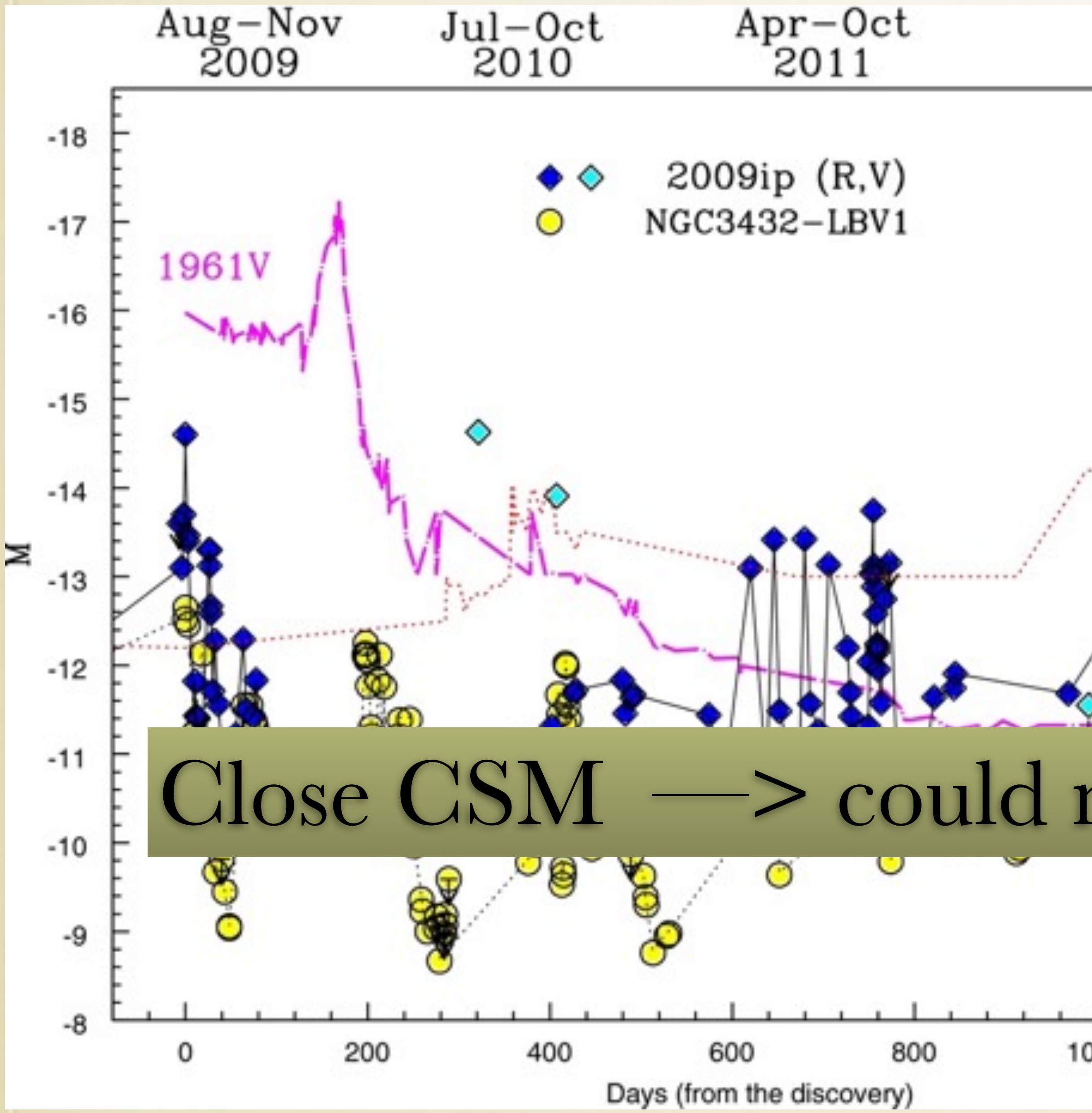
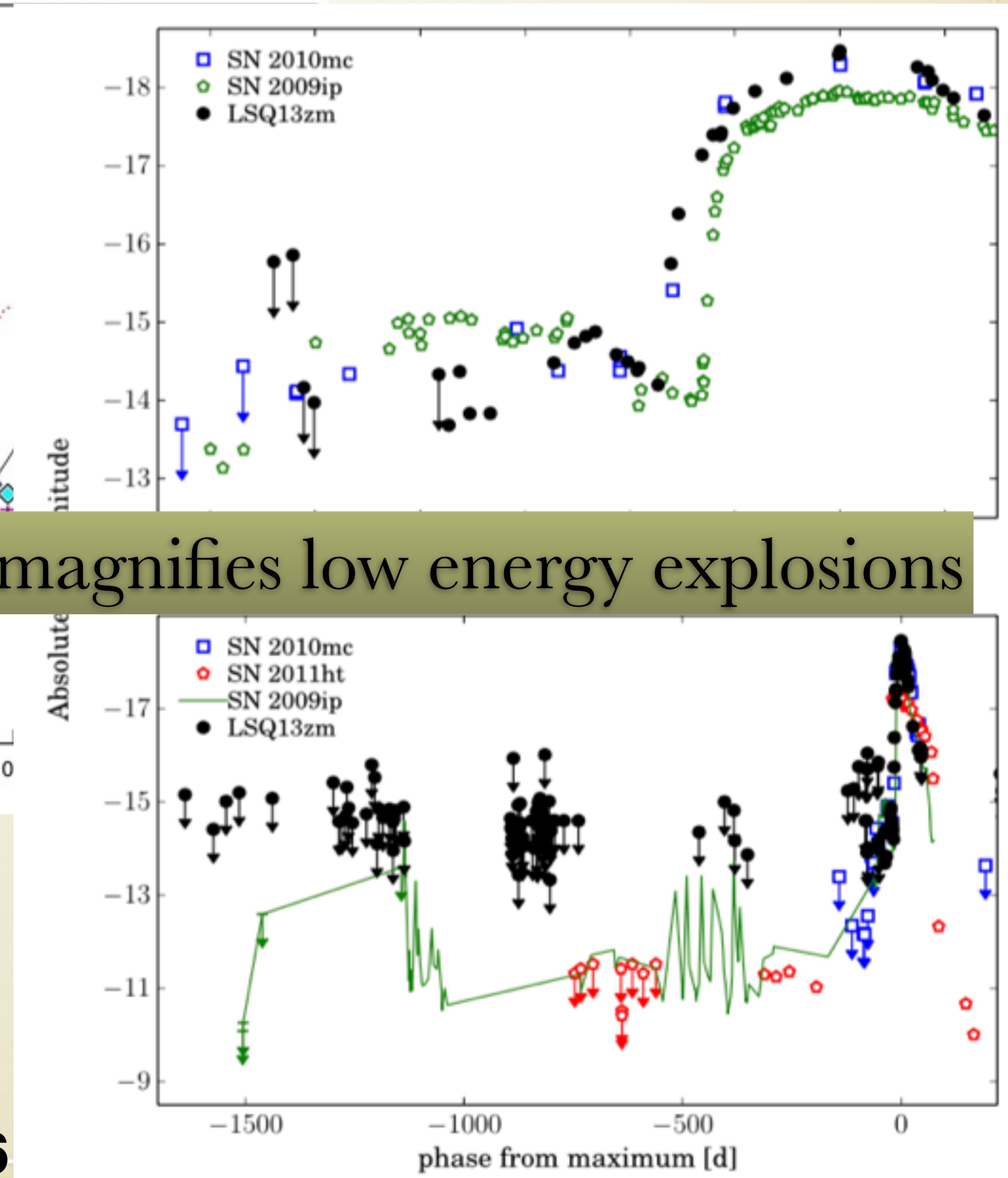
Introduction: Massive stars may show pre-explosion activity & weak explosions



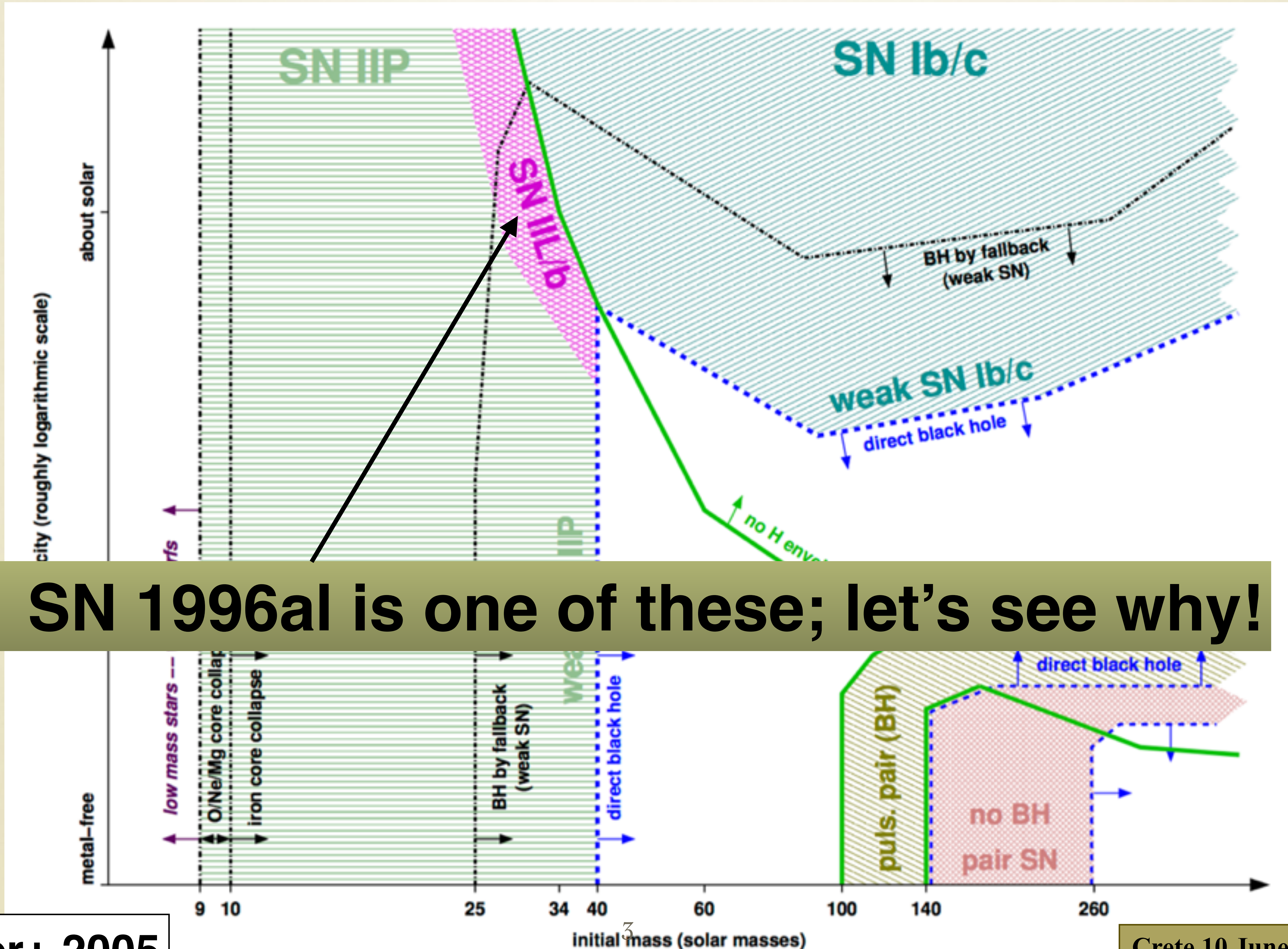
SN 2009ip - Pastorello+ 2013

Close CSM —> could magnifies low energy explosions



LSQ13zm - Tartaglia+ 2016

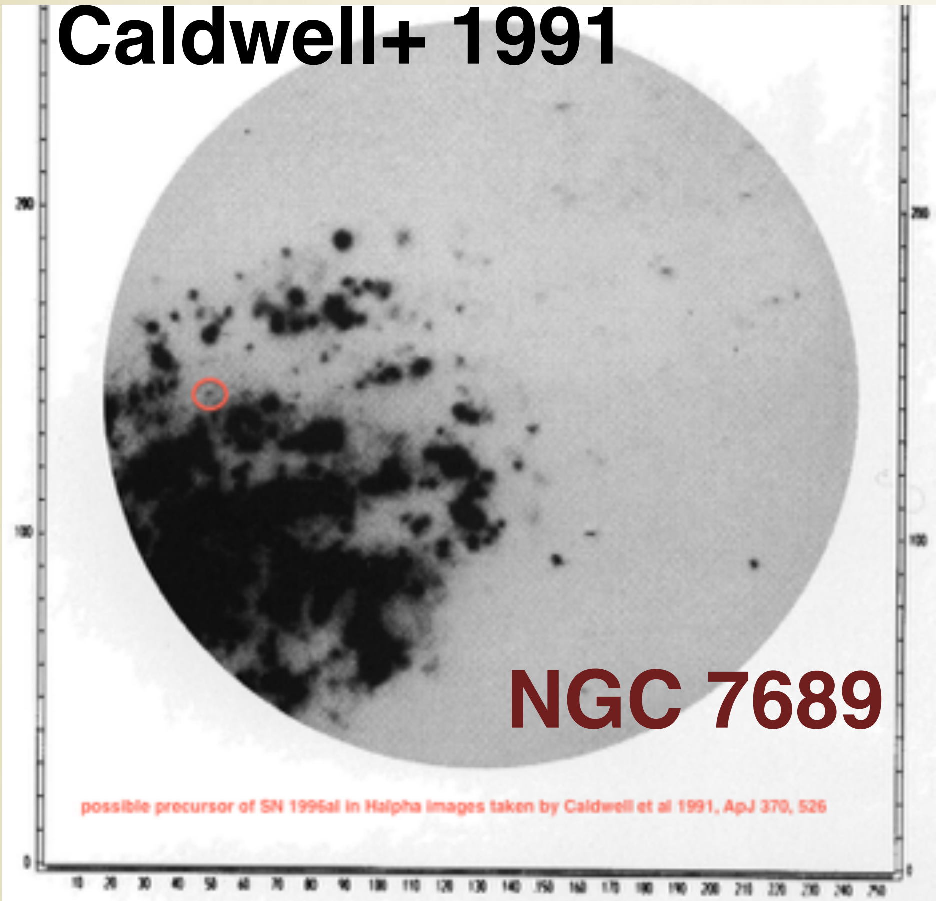
Why massive stars should end-up with dim explosions?



SN 1996al is one of these; let's see why!

Heger+ 2005

SN 1996al progenitor star has been recovered!



$L_{H\alpha}$(precursor)~37.28 dex

↓

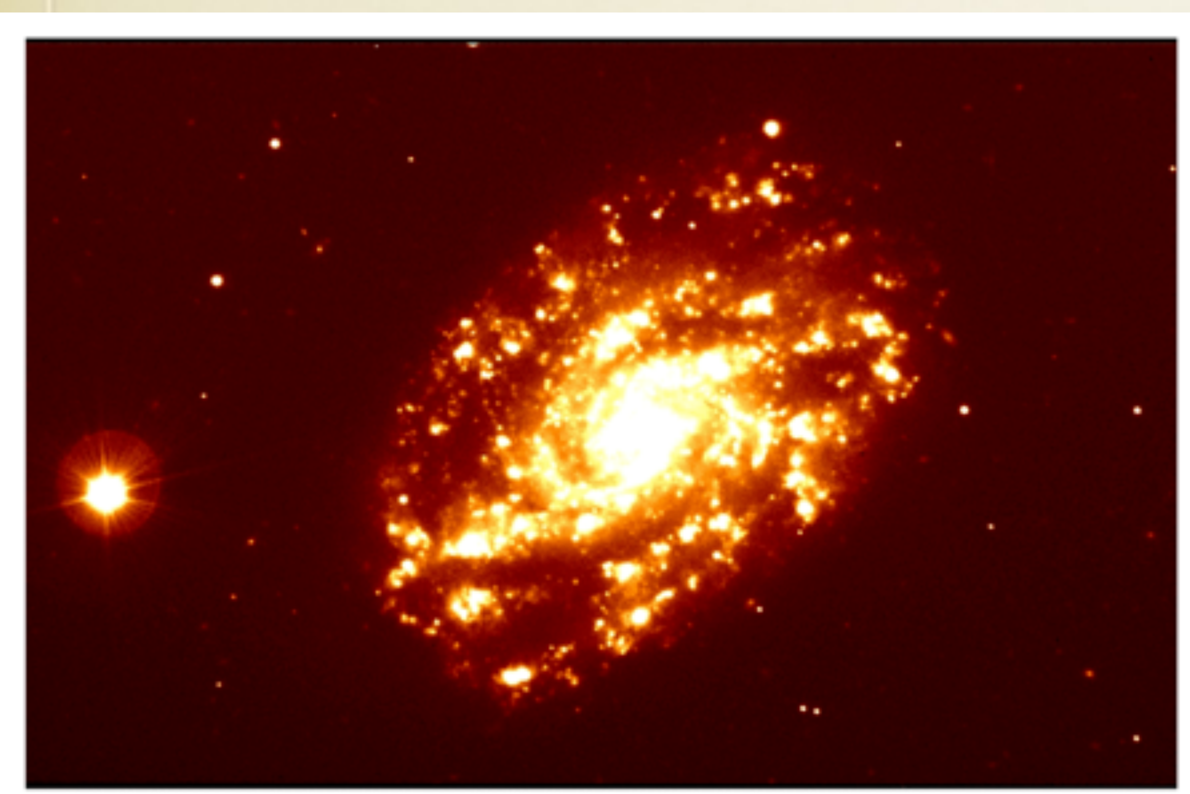
rate ionizing radiation ~10^{49} photons s^{-1}

↓

star with bol lum log $L/L_\odot$ >~5.4 & R ~ $10R_\odot$

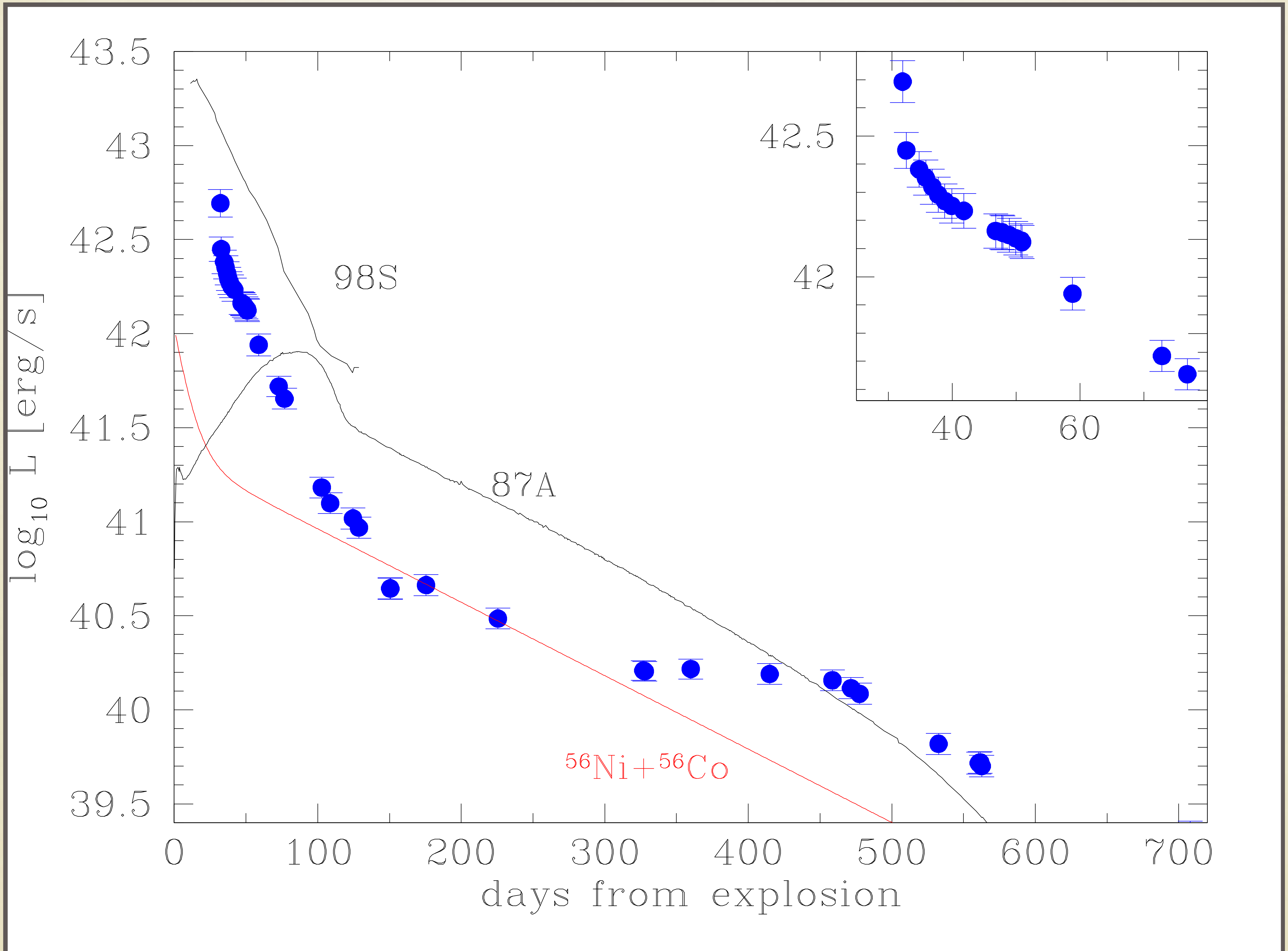
↓ (atmosphere models)

M_{ZAMS} ~ 25 $M_\odot$ -> lost most of external H mantle

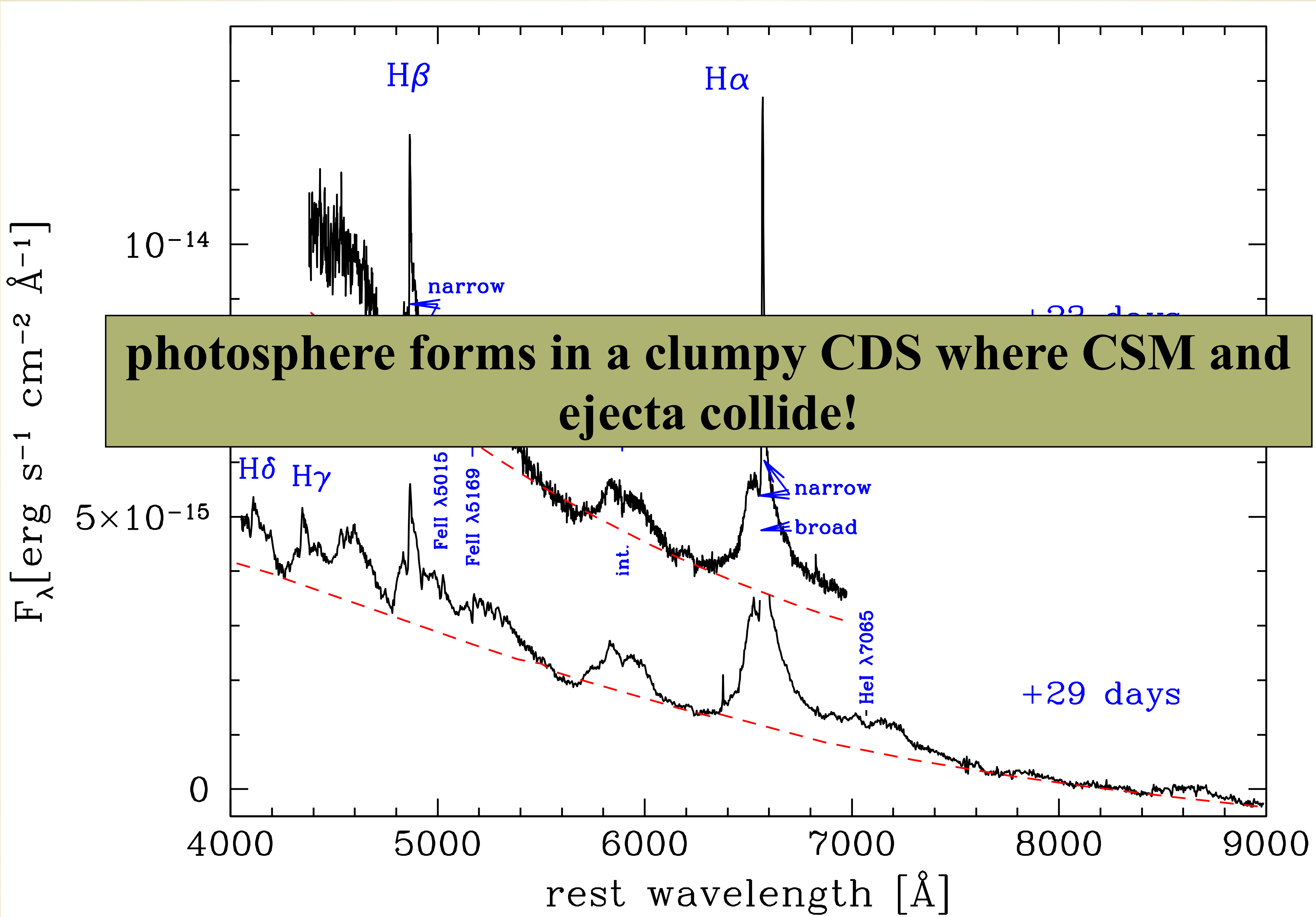


SN 1996al: a linear supernova

(L=L$_{UBVRIJ}$)



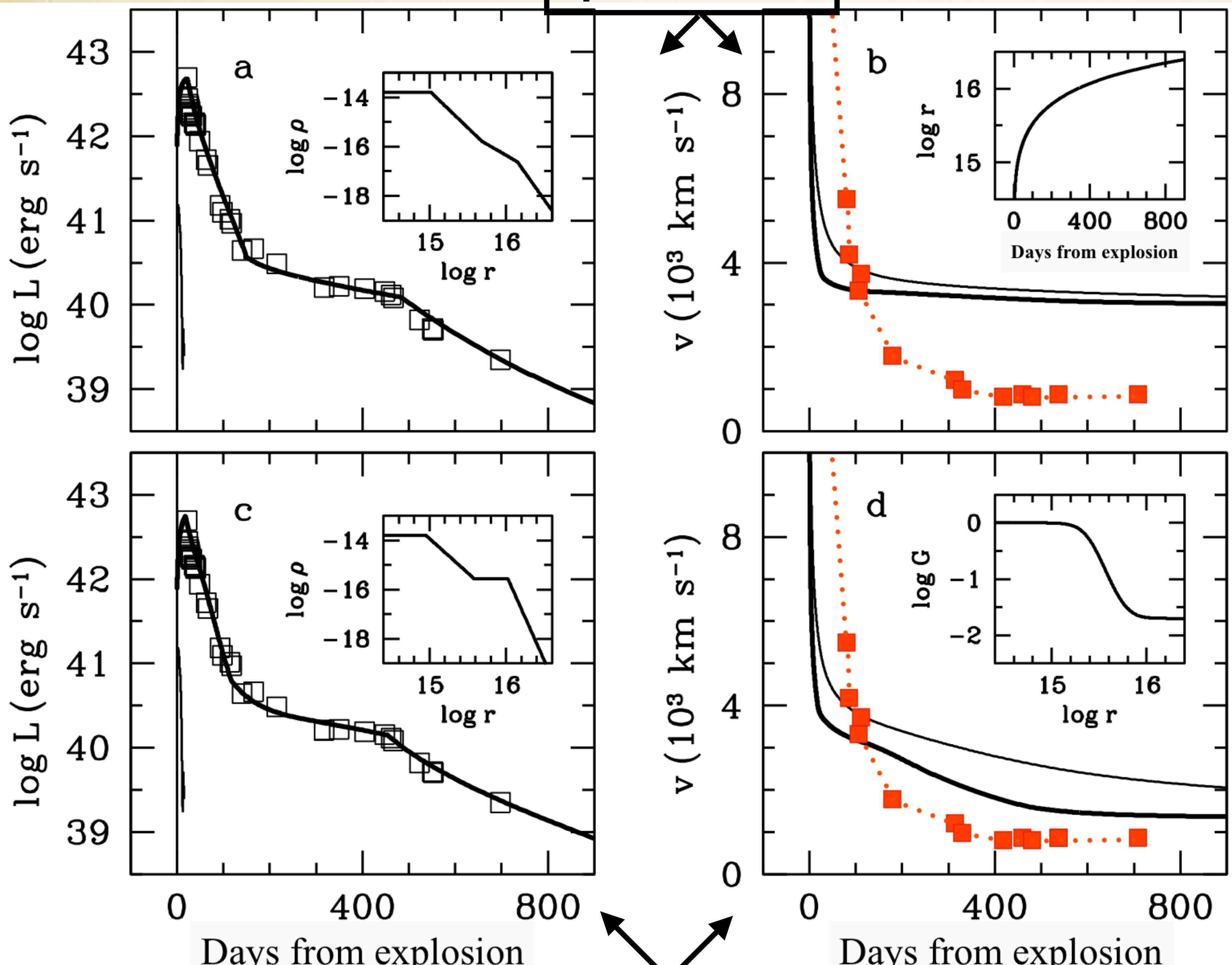
No broad P-Cygni absorptions!



photosphere forms in a clumpy CDS where CSM and ejecta collide!

Light curve modelled with a weak explosion + interaction

spherical CS



Input:
($M_{ZAMS} \sim 25\,M_\odot$; $R=10R_\odot$)
$M_{He\text{-}core} \sim 8.3M_\odot$; $M_{env} \sim 0.3M_\odot$)

Output: (VU radiation hydrodynamic c.)
$M_{ej}=1.15M_\odot$ (0.15H+1He)
$E_K=1.6\times10^{50}$erg

interacts with

$M_{CSM}=0.13M_\odot$ ($r<3\times10^{16}$cm)

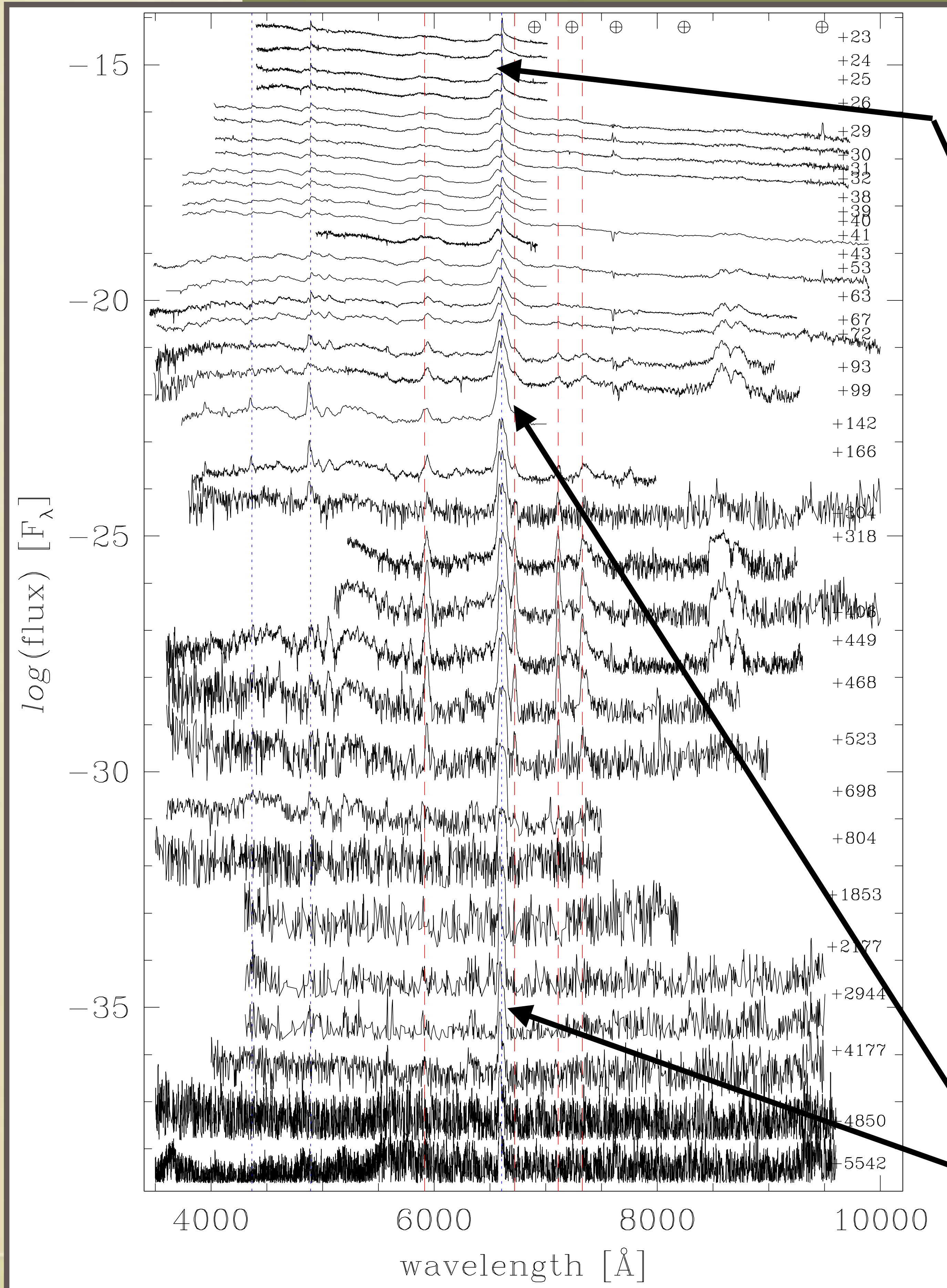
thickness eq. disk~23°

layers below He fell back >
collapsing core —> 7-8 $M_\odot$

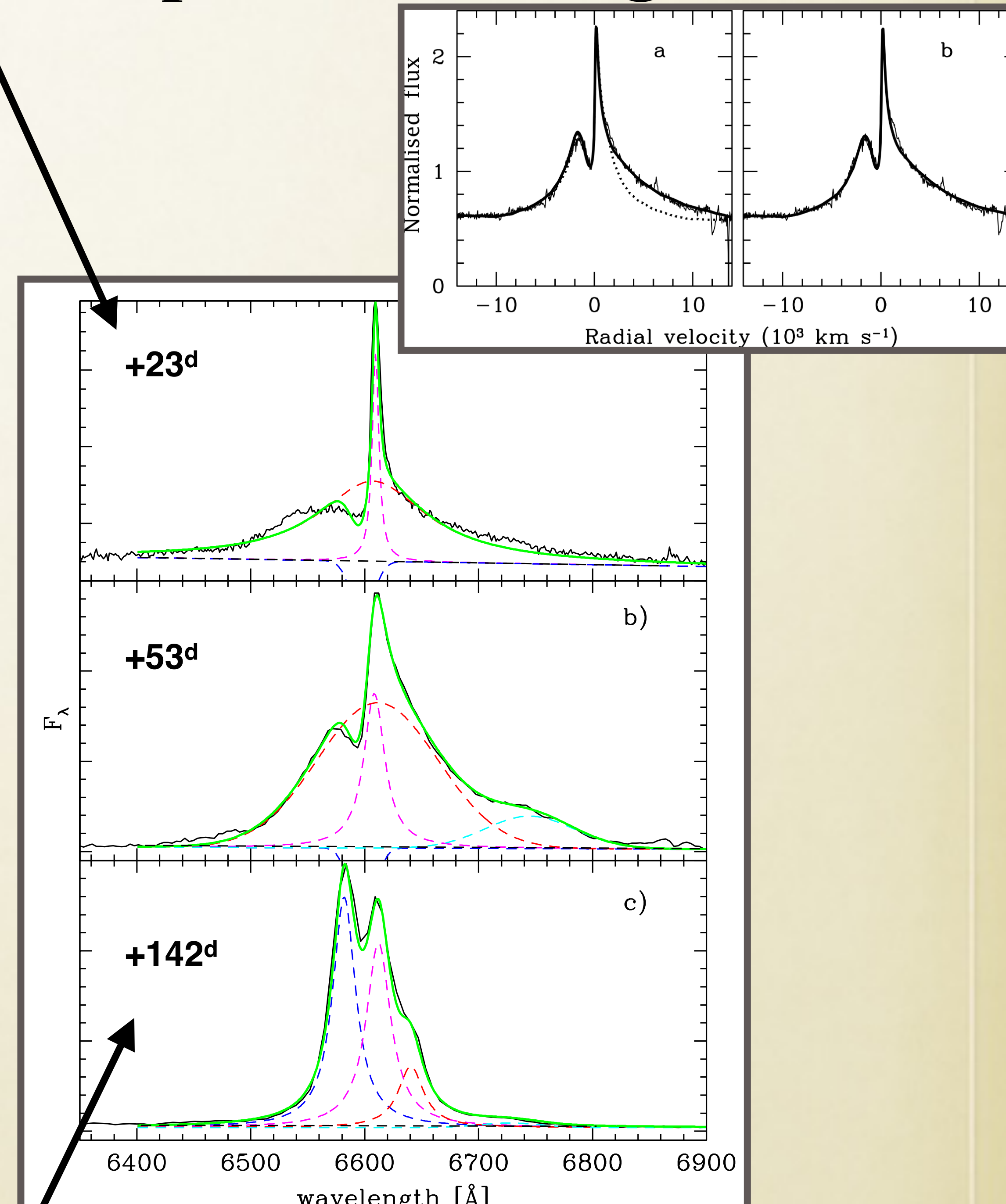
Black Hole!

anisotropic: equatorial disk-like + clumpy, more symmetric CS

Spectroscopic evolution over 15 years!

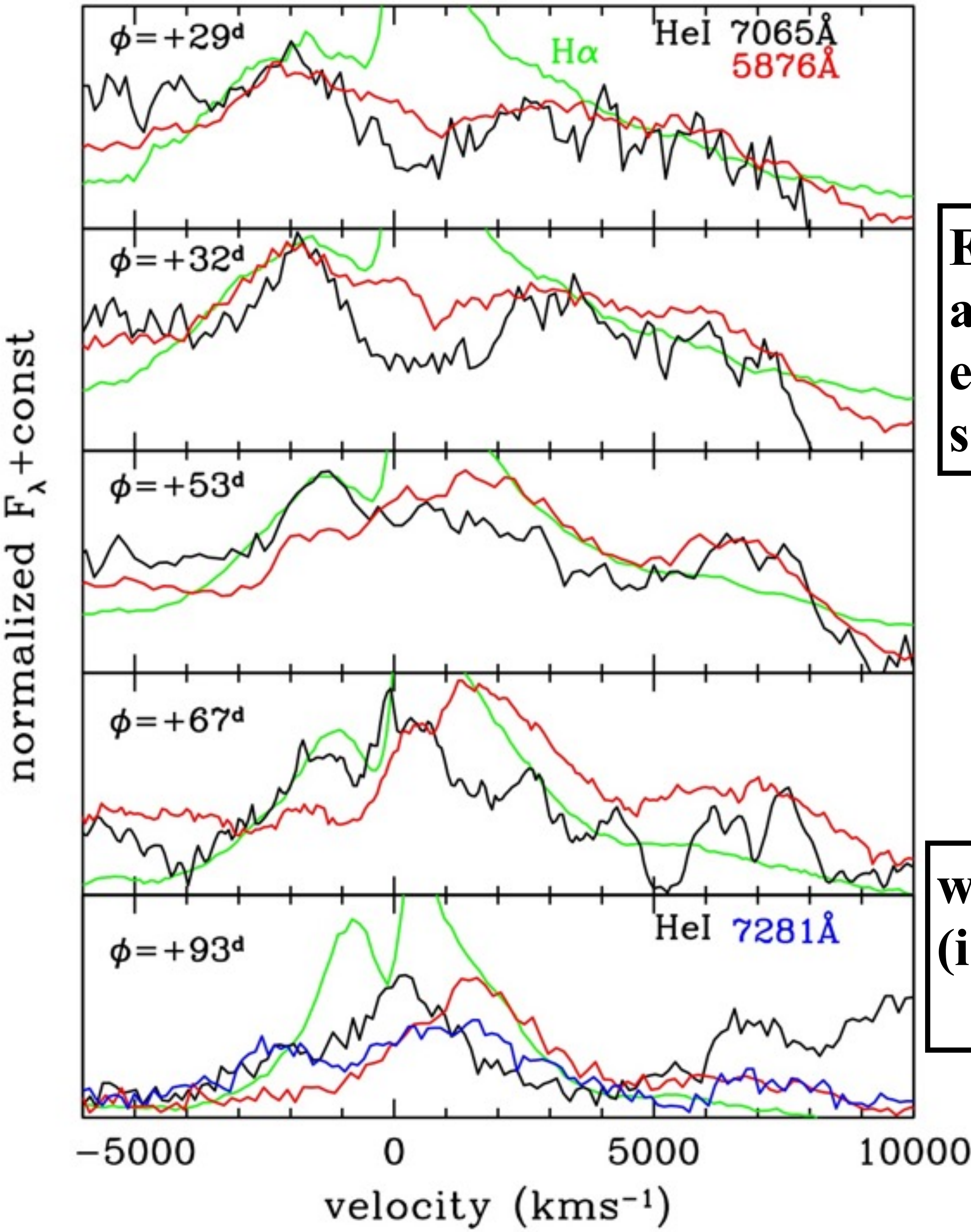


early on H_α profile more symmetric and with some Thompson scattering



H_α profile > 100d supports disk-like CS

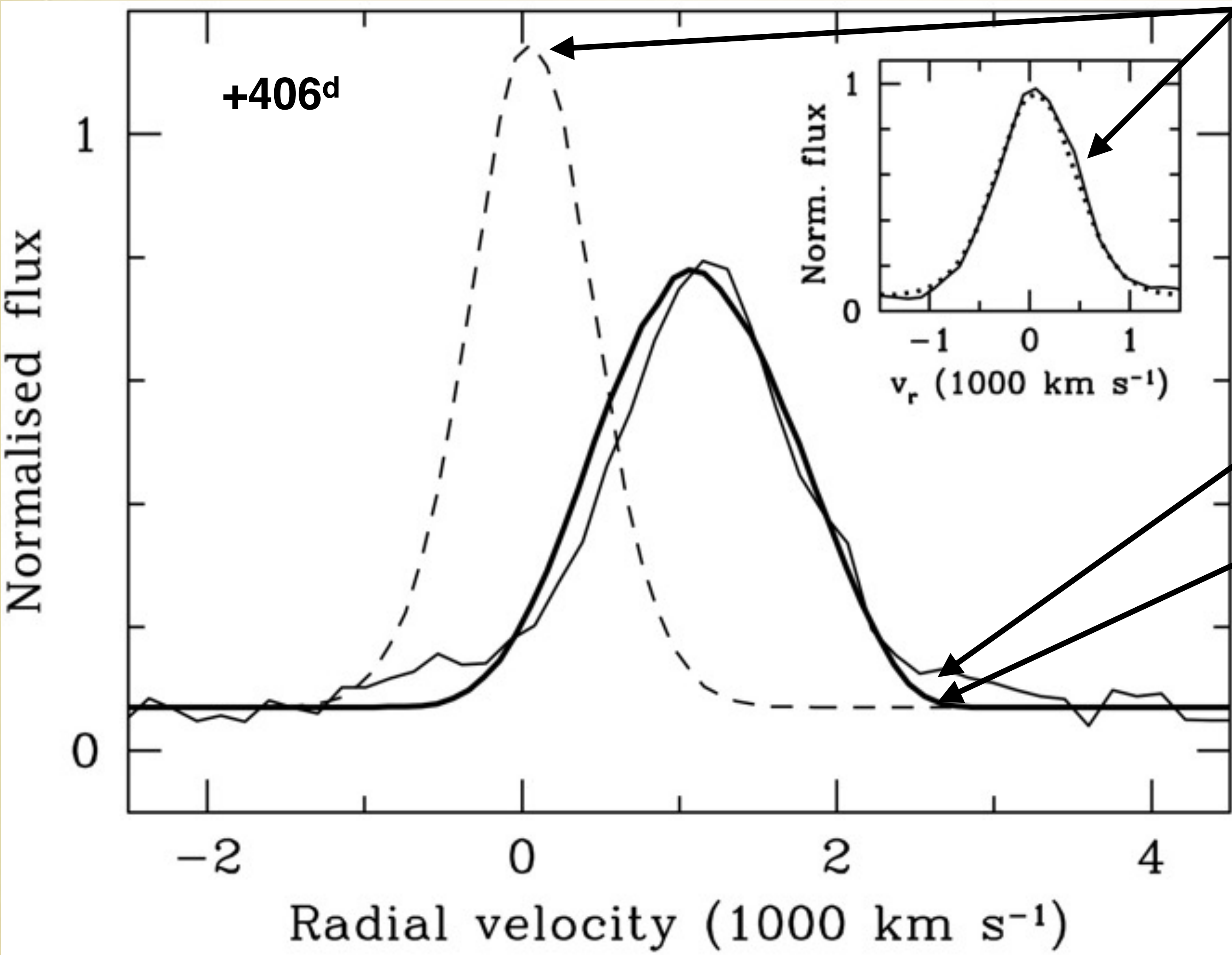
HeI line profiles



Early on HeI already shows some asymmetry! which suggests that emitting surface has an oblate shape

with time the degree of asymmetry (in He lines) tends to decrease and
HeI 5876Å -> NaID

HeI 5876Å photons coming from deep inside -> NaID



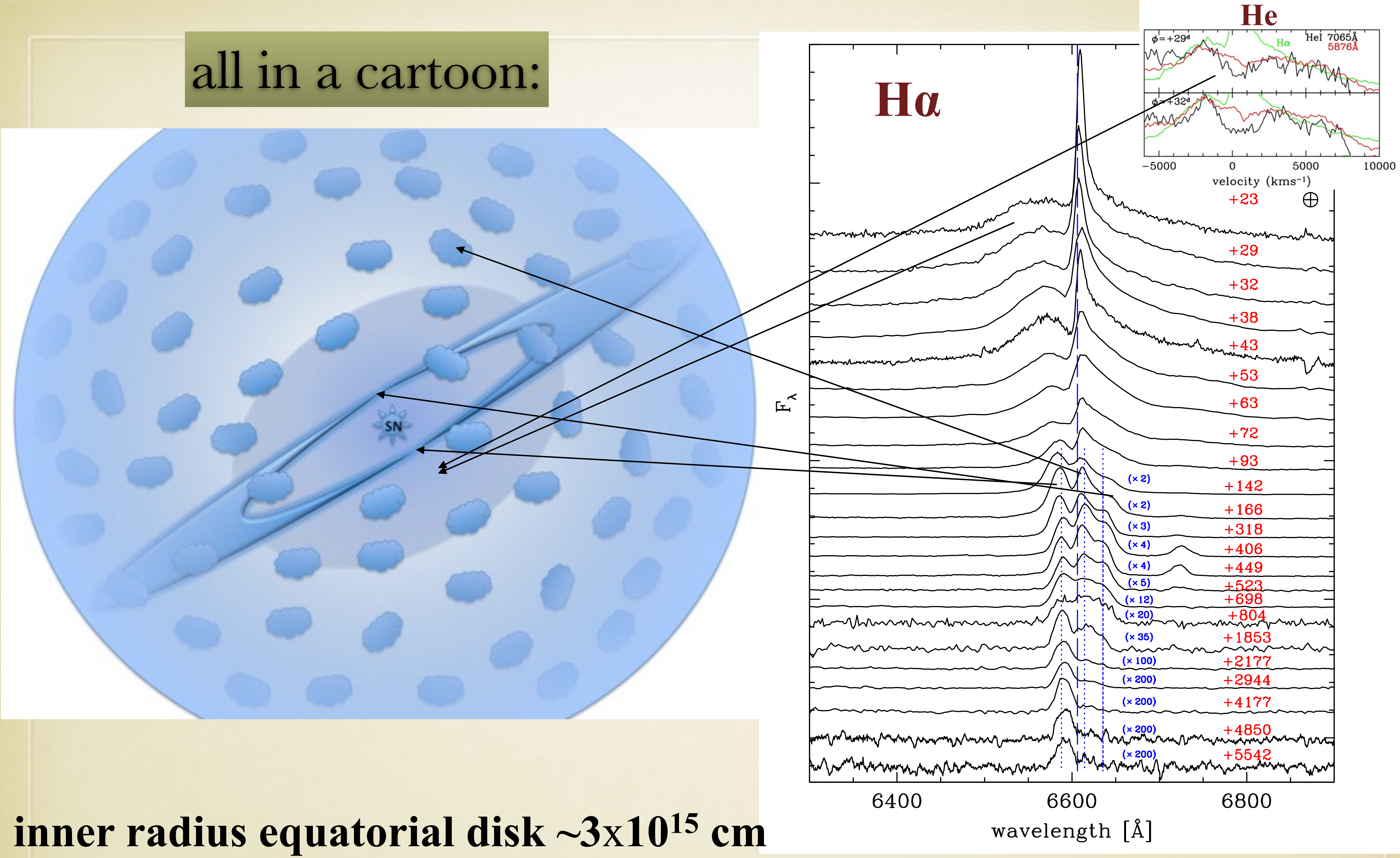
modeled HeI 5876Å from 7065Å

NaID observed line

modeled NaID as result of the scattering of HeI 5876Å photons in a freely expanding spherical ejecta

This tells that HeI 5876Å photons are emitted symmetrically deep inside the ejecta —> explosion is symmetric!!!

all in a cartoon:



inner radius equatorial disk ~3x10^{15} cm

external limit >5x10^{17}cm (0.15pc; Hα visible for 15 years)

(M_{CSM}>0.13$M_\odot$)

(thickness eq. disk~23^o)

Equatorial disks are indeed seen around massive stars!

Gvaramadze+ 2015

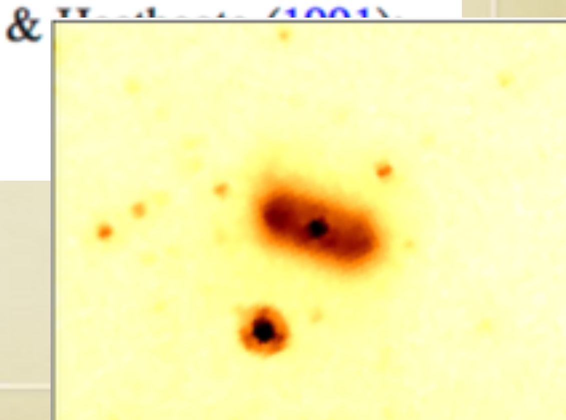
MN18 and its bipolar nebula

Table 7. Blue supergiants and cLBVs with hourglass-like circumstellar nebulae.

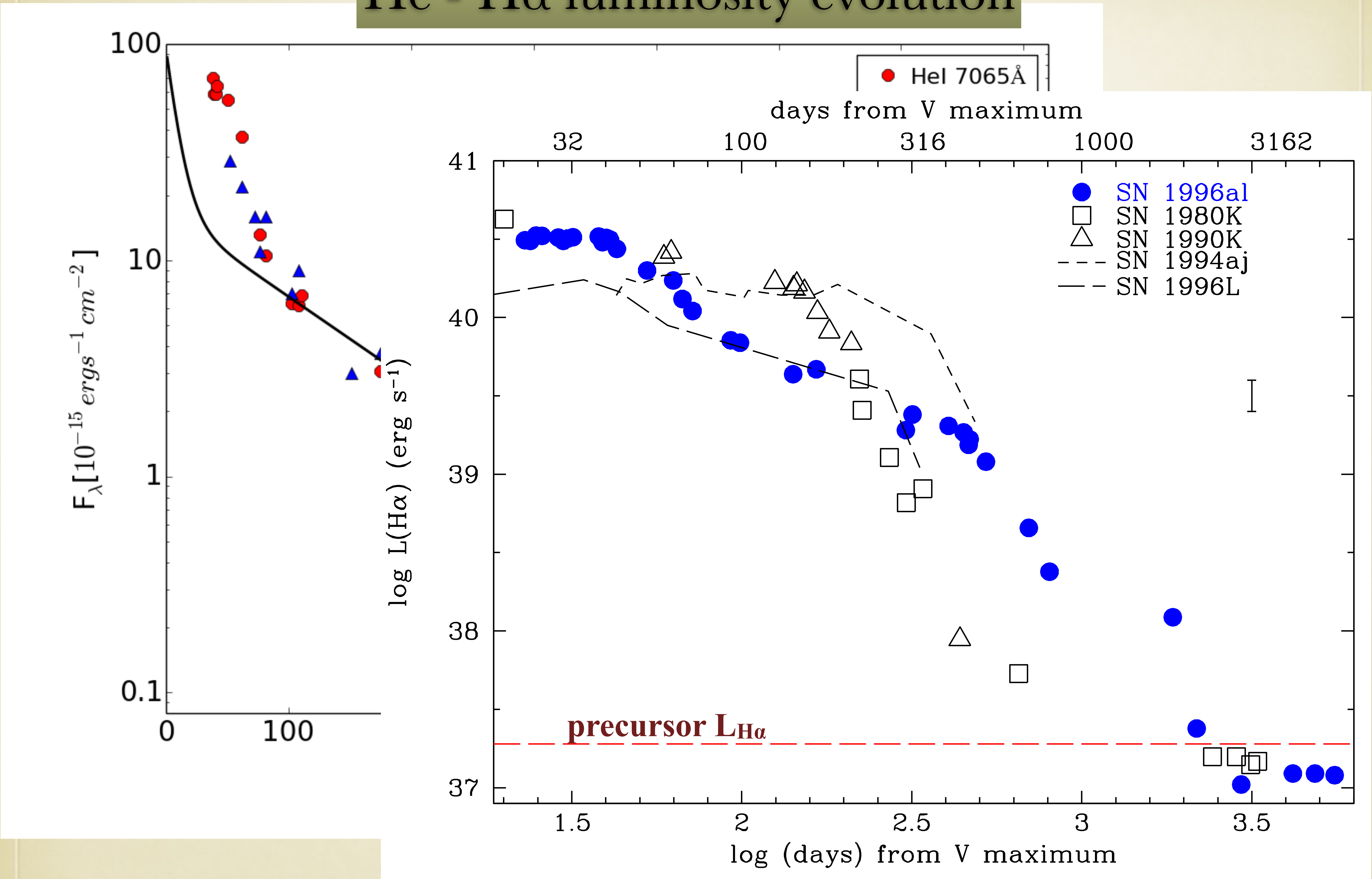
	Sk−69°202	Sher 25	HD 168625	[SBW2007] 1	MN18
Spectral type	B3 I[1]	B1.5 Iab[2]	B6 Iap[3]	B1 Iab[4]	B1 Ia
$\log(L/L_\odot)$	≈5[5]	5.8[6]	5.0–5.4[7]	4.7[8]	5.4
$T_{\rm eff}$ (kK)	16[5]	22[6]	12–15[7]	21[8]	21
$\dot{M}(10^{-7}\ M_\odot\ {\rm yr}^{-1})$	1.5–3[9, 10]	20[6]	11[7]	2–4[8]	4.2–6.8
r (pc)	0.2[11]	0.2[12]	0.2[7]	0.2[13]	0.3
$n_{\rm e}$([S II]) (cm^{-3})	∼10 000[14, a]	500–1800[15]	≈1000[7]	≈500[13]	≈600
$M_{\rm ring}$	0.06[16]	0.1[15]	0.5[7]	0.5–1.0[8]	1
$v \sin i$ (km s^{-1})	–	53	44	34	90
i (°)	43[17]	65[12]	60[18]	50[13]	60
$v_{\rm exp}$ (km s^{-1})	10[19]	30[15]	20[20]	19[13]	8
$t_{\rm kin}$ (10^4 yr)	2	0.7	1	1	3.7
$\dot{M}_{\rm kin}/\dot{M}$	10–20	7	45	250	40–60
log (N/H)+12	8.44[16]	8.91[6]	8.42[7]	7.51[13]	8.21

References: (1) Walborn et al. (1989); (2) Moffat (1983); (3) Walborn & Fitzpatrick (2000); (4) Taylor et al. (2014); (5) Arnett et al. (1989); (6) Hendry et al. (2008); (7) Nota et al. (1996); (8) Smith et al. (2013); (9) Blondin & Lundqvist (1993); (10) Martin & Arnett (1995); (11) Panagia et al. (1991); (12) Brandner et al. (1997a); (13) Smith et al. (2007); (14) Plait et al. (1995); (15) Brandner et al. (1997b); (16) Matti… (17) Jakobsen et al. (1991); (18) O'Hara et al. (2003); (19) Crotts & … (20) Hutsemekers et al. (1…

[a]Based on the fading of th… on line.

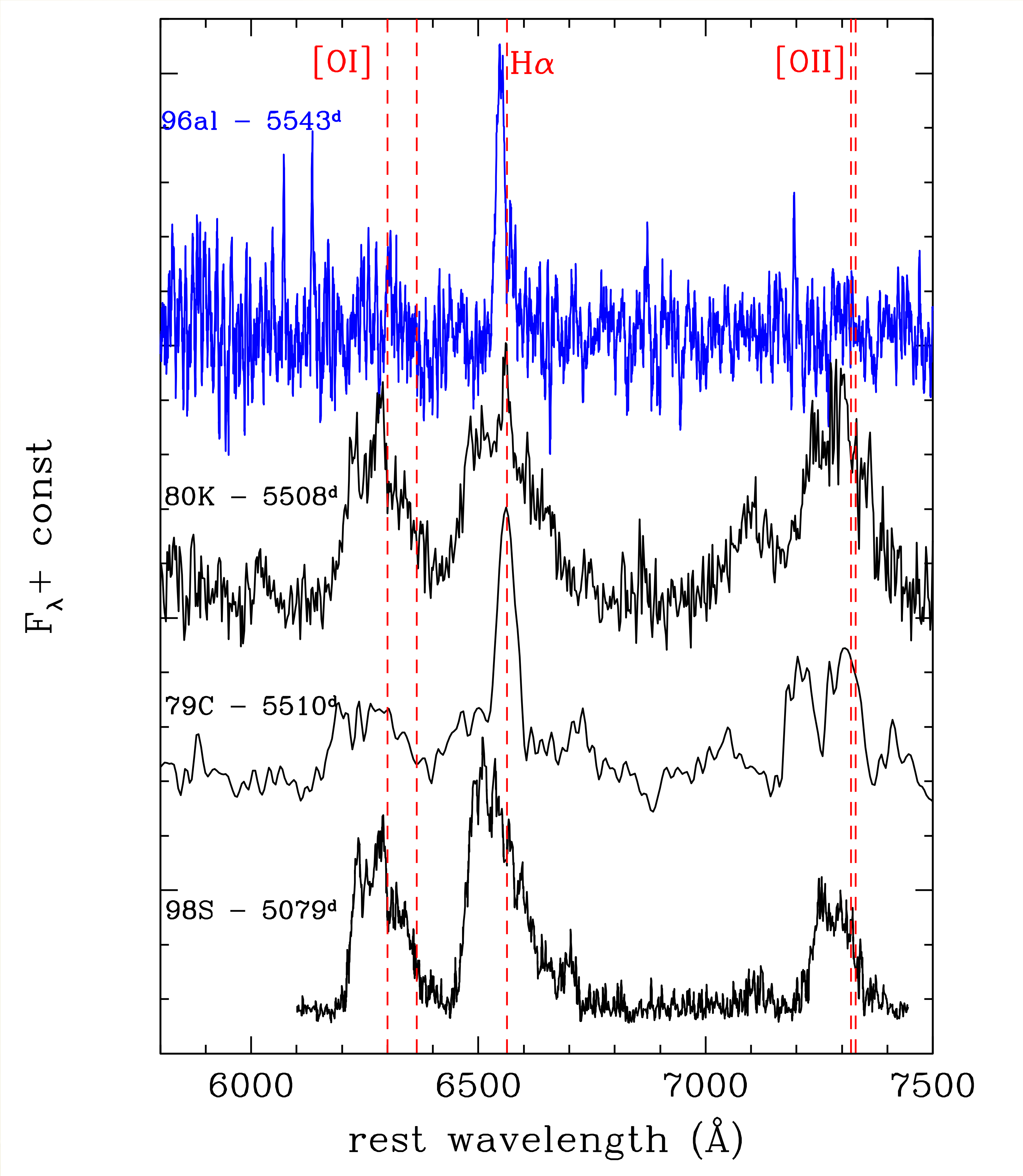


He - Hα luminosity evolution

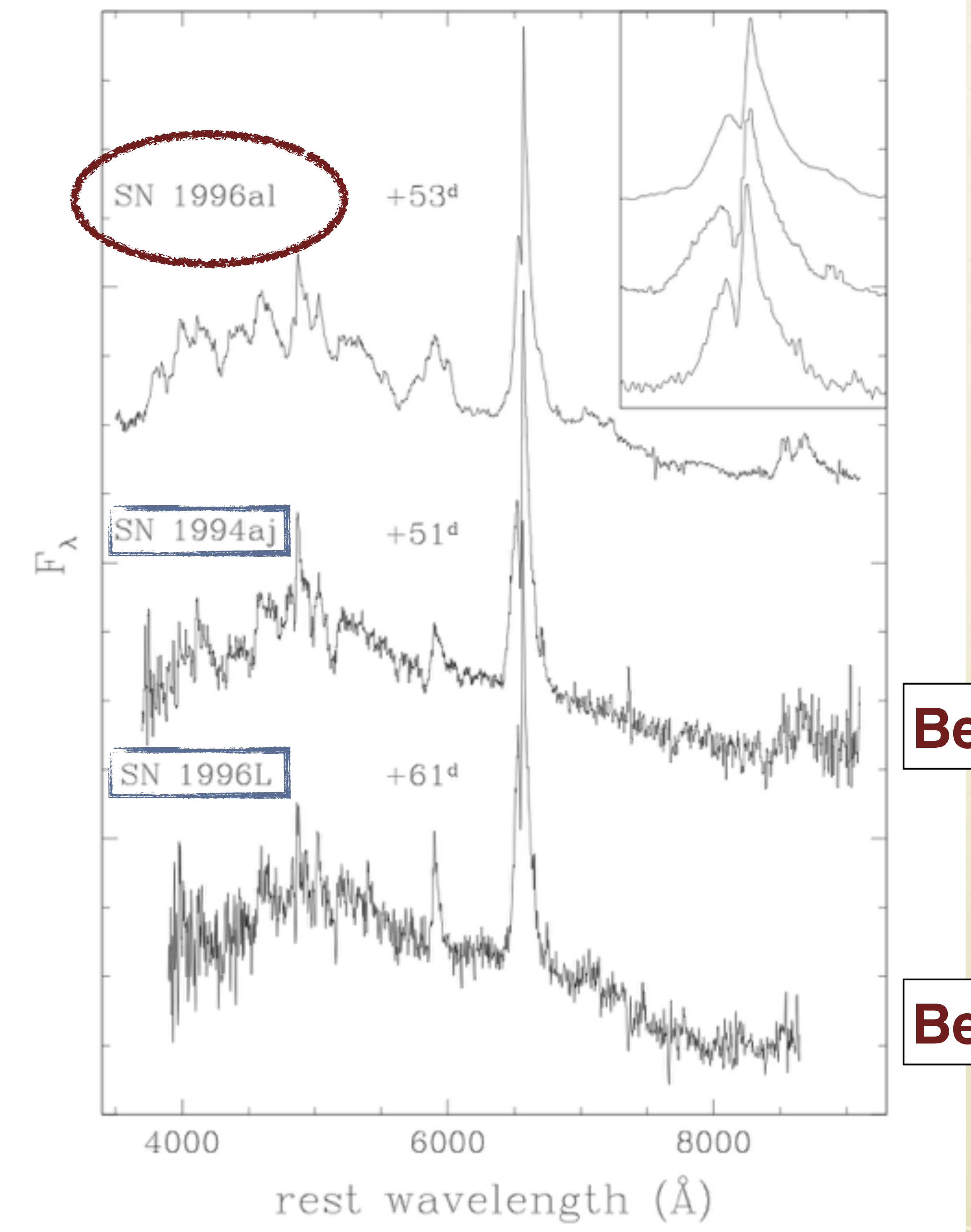


re-brighting due to late fall-back, interaction?

No Oxygen in late time spectra: fall back confirmed!



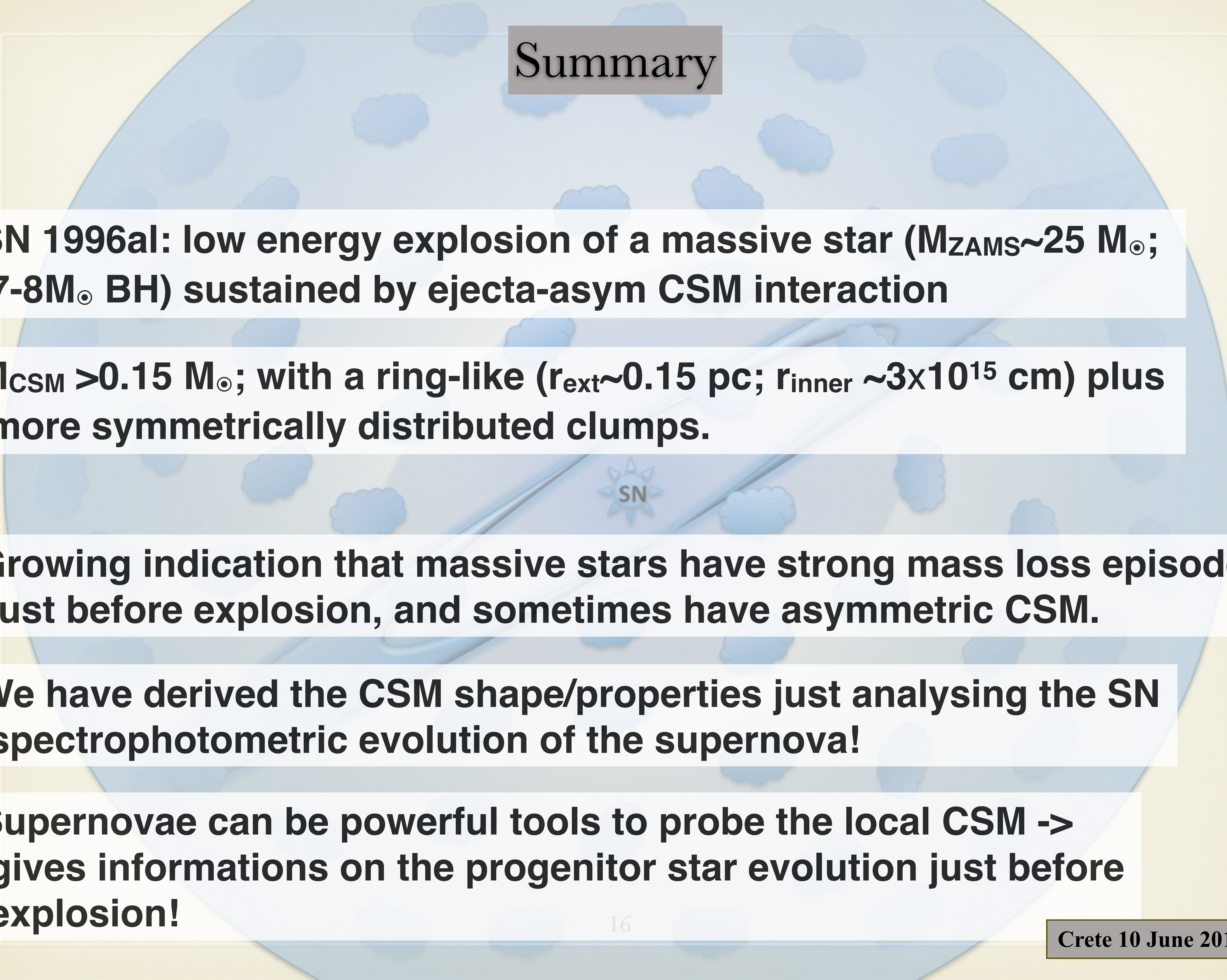
Not the only one!



Benetti+ 1998

Benetti+ 1999

Summary



SN 1996al: low energy explosion of a massive star (M_{ZAMS}~25 $M_\odot$; 7-8$M_\odot$ BH) sustained by ejecta-asym CSM interaction

M_{CSM} >0.15 $M_\odot$; with a ring-like (r_{ext}~0.15 pc; r_{inner} ~3x10^{15} cm) plus more symmetrically distributed clumps.

Growing indication that massive stars have strong mass loss episodes just before explosion, and sometimes have asymmetric CSM.

We have derived the CSM shape/properties just analysing the SN spectrophotometric evolution of the supernova!

Supernovae can be powerful tools to probe the local CSM -> gives informations on the progenitor star evolution just before explosion!

Thanks!